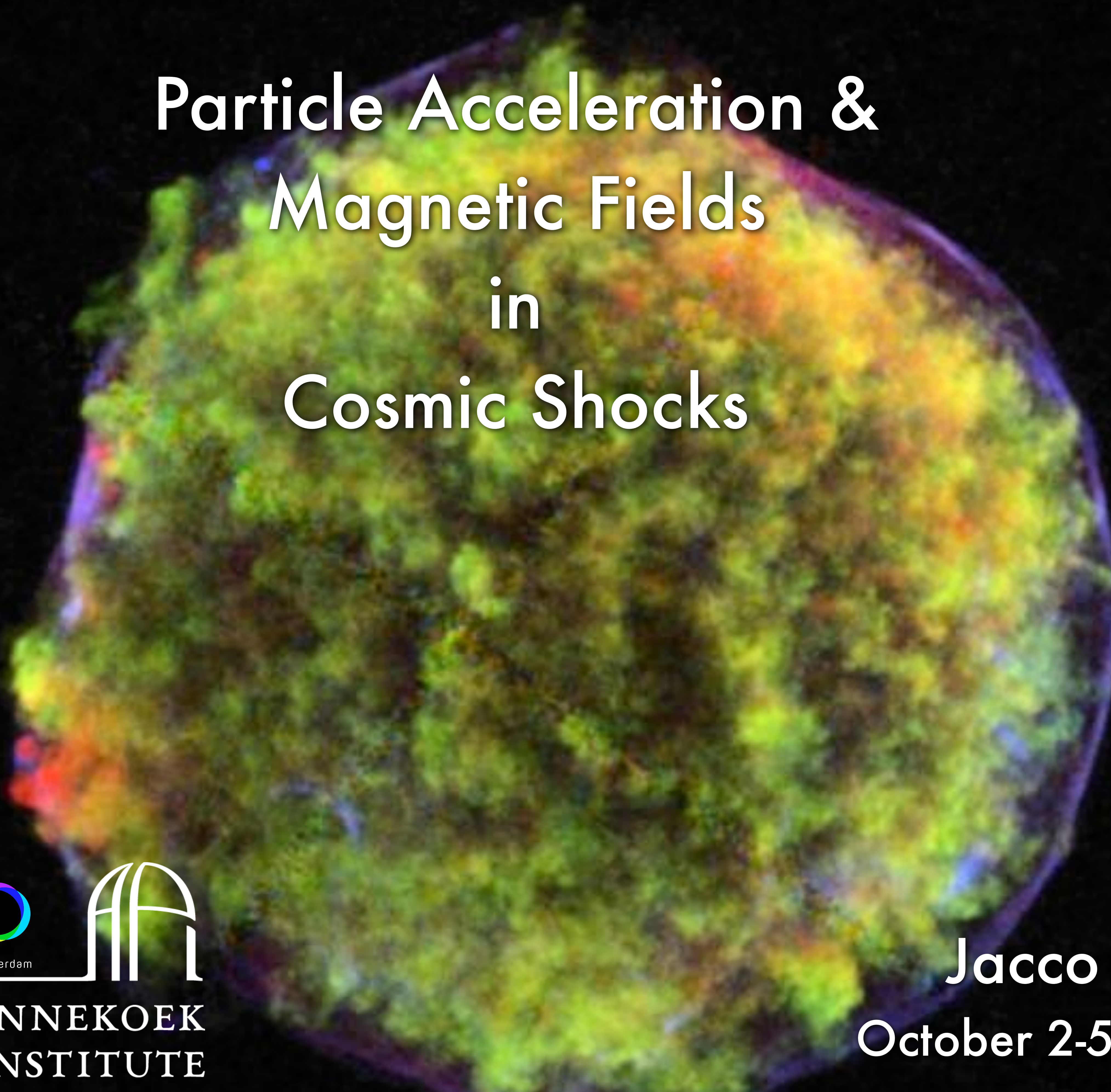

# Particle Acceleration & Magnetic Fields in Cosmic Shocks

GRAPPA
GRavitation AstroParticle Physics Amsterdam
ANTON PANNEKOEK INSTITUTE

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October 2-5 2019

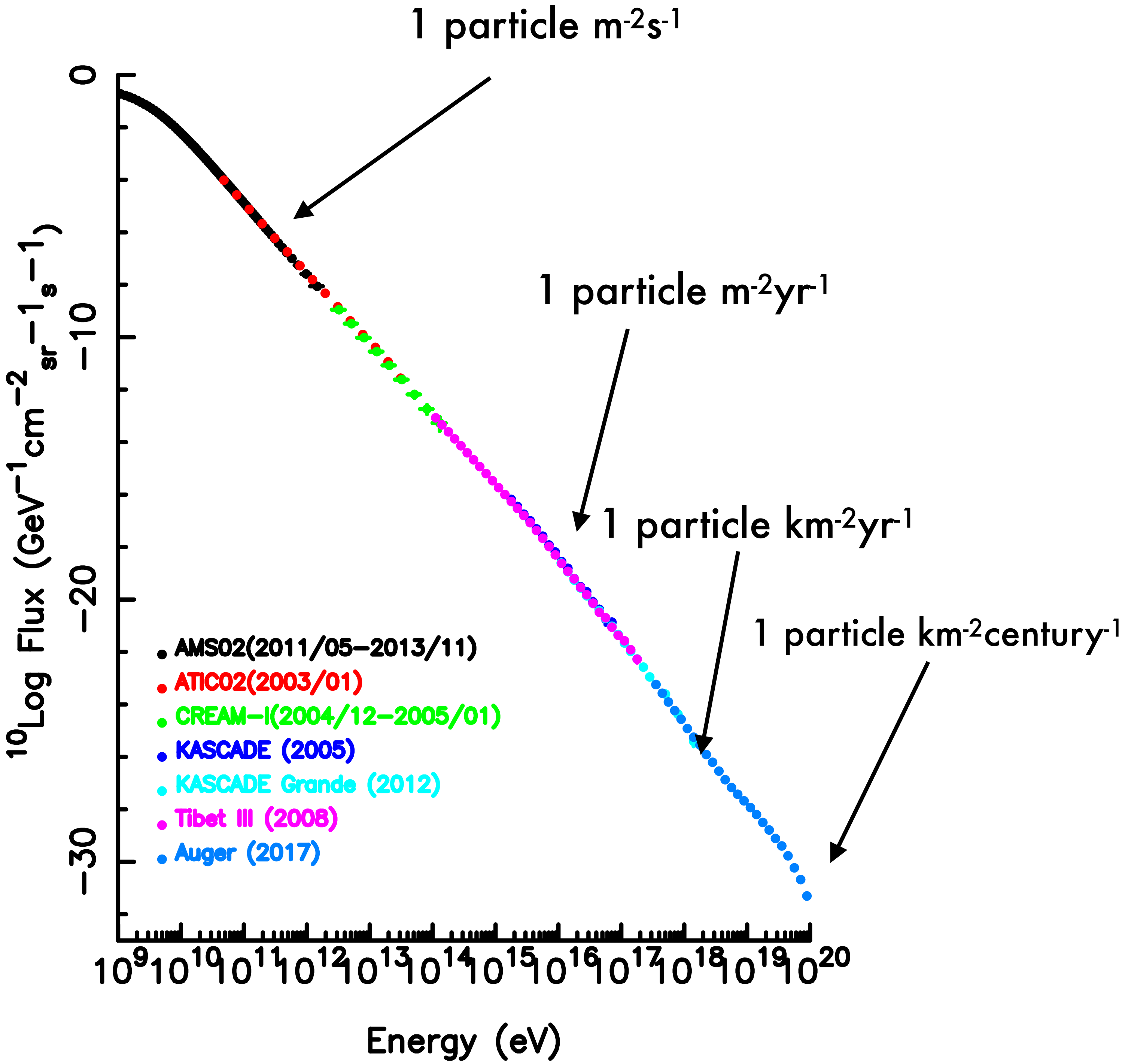
# Overiew

- Wednesday:
  - Cosmic rays, transport, potential sources
  - Shocks and diffusive shock acceleration
- Thursday:
  - X-ray synchrotron observations & evidence for magnetic-field amplification
  - Theory behind magnetic field amplification
  - Non-linear shock acceleration
- Friday:
  - Recent results from gamma-rays
  - A brief look relativistic shocks/reconnection
  - If time permits: pulsar wind nebulae

# 1 Cosmic rays: introduction & transport

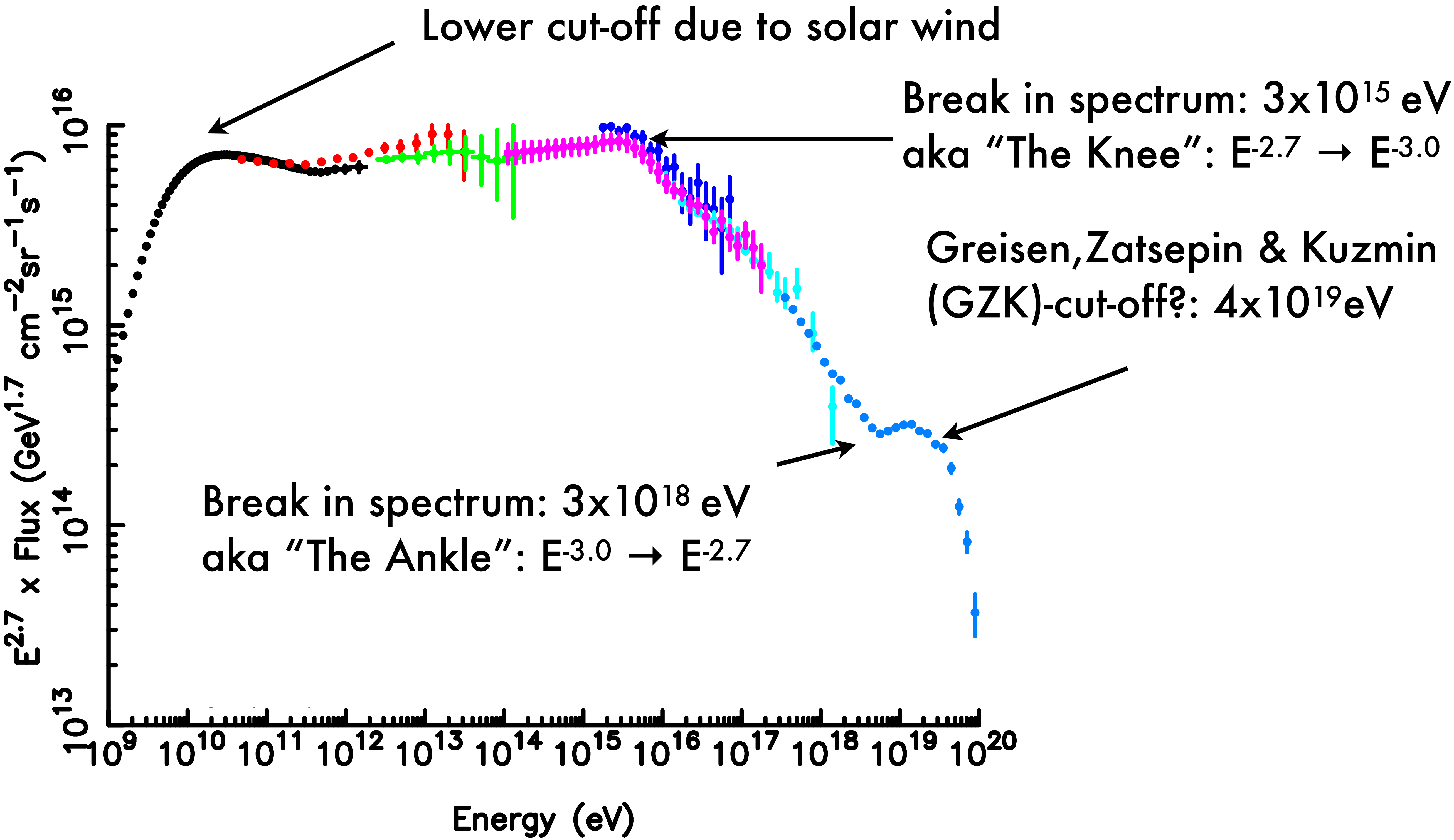
Victor Hess about to discover cosmic rays (1911)

# Cosmic-ray spectrum

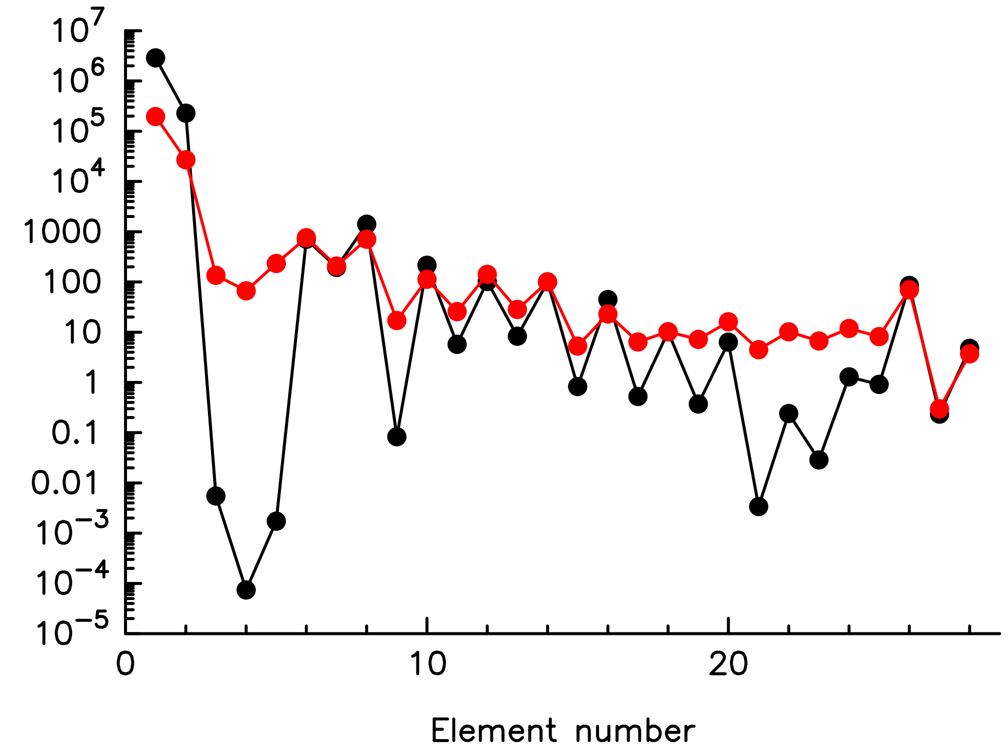



- Cosmic-ray spectrum is nearly a power law: $N(E)dE = KE^{-q}dE$
- Spectral index q≈2.7

# Cosmic-ray spectrum multiplied by $E^{2.7}$



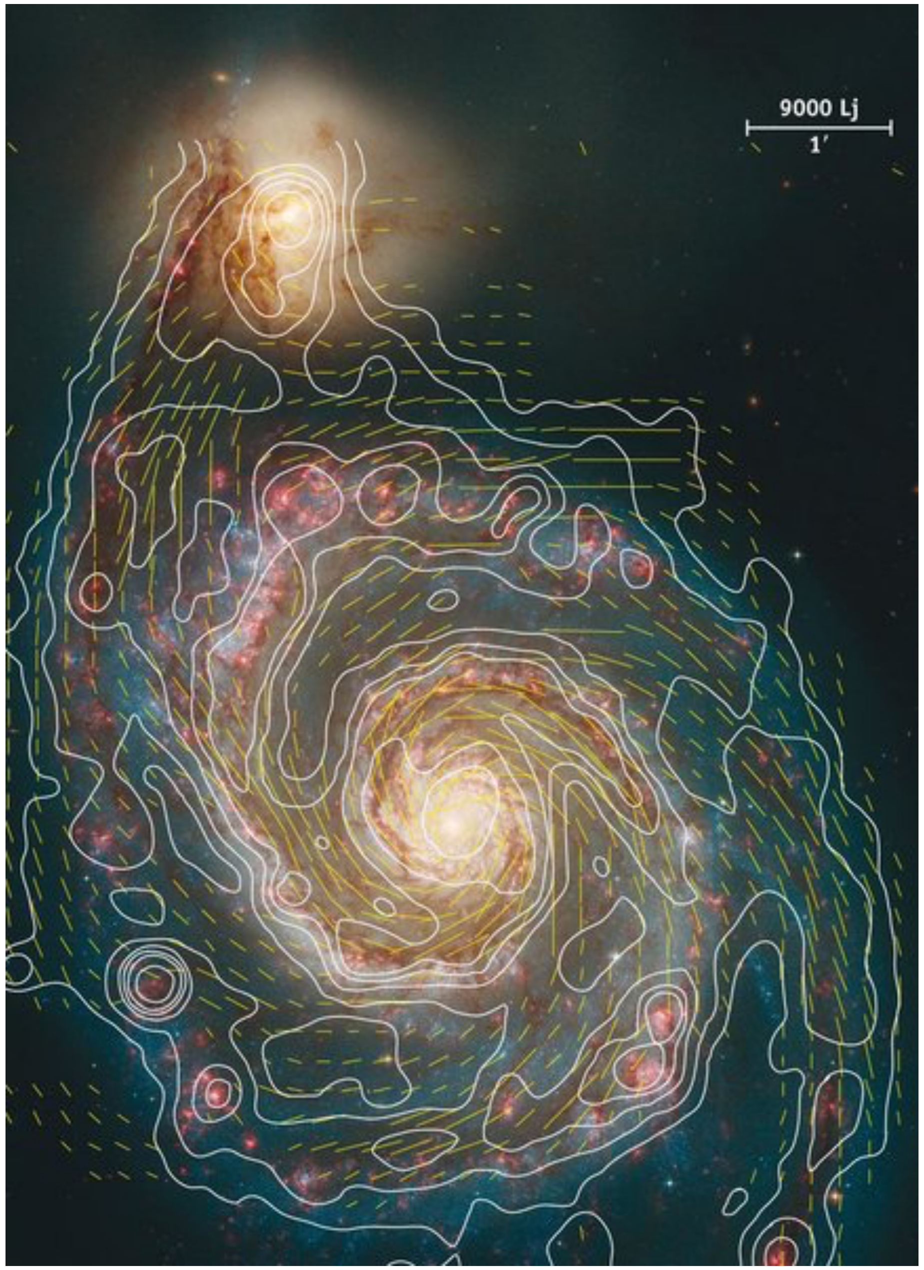
# Cosmic-ray composition




- At low energies (<10 GeV) composition can be measured
- Follow cosmic/solar abundance pattern
- But odd elements are more abundant
  - Cosmic rays collide with background atoms producing
    - -odd elements
    - -radio-active elements → can be used to measure resident times
- Cosmic rays also contain
  - *electrons*: about 1% of all cosmic rays
  - positrons: very small fraction → by-product of collisions
  - anti-protons
- Above $10^{14}$ eV: see lectures by K. H. Kampert

# Magnetic fields in the Galaxy

- Magnetic field in the Milky Way: B≈3 μG
- Magnetic field has a structured component (following spiral arms?)
- On top of that an irregular structure
  - Induced by supernova explosion, winds, gravitational contraction etc.
- Structured component: particles follow field lines
- Unstructured component: particles perform a "random walk" → diffusion
- Magnetic fields tied to gas → winds may also give rise to transport (*advection*)
- Cosmic-ray propagation models: often concentrate on diffusion




M51 magnetic field (Beck/Fletcher)

# Magnetic field turbulence and Alfvén waves

- Magnetic field turbulence induced by energy input into interstellar medium
- Disturbances can propagate: sound waves and Alfvén waves.
- Alfvén waves are magneto-hydronamic (MHD) waves
- MHD, force free (only B no E):

$$\rho \frac{\partial \mathbf{v}}{\partial t} = -\nabla P + \frac{1}{c}\mathbf{J} \times \mathbf{B} = -\nabla P + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi}$$

$$4\pi \mathbf{J} + \partial E/\partial t = c\nabla \times \mathbf{B}$$

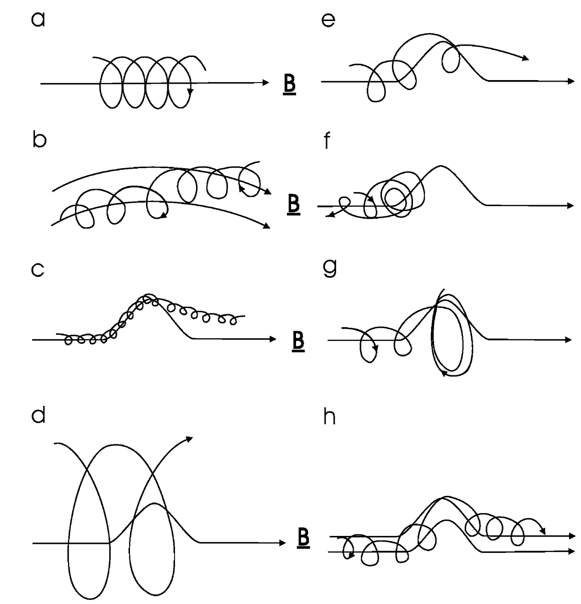
$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

- Dispersion relation (fill in v=δv exp(ikx-iωt),B=δB exp(ikx-iωt)):

$$v_{\mathrm{A}}^2 = \frac{\omega^2}{k^2} = \frac{B^2}{4\pi\rho}$$ Alfvén velocity

- Take B=5μG, $\rho=10^{-24}$ g/cm$^3$: $v_A \approx 5\times10^6$ cm/s= 50 km/s

# Particle-wave interaction




- Charge particles: spiral along B-field:

$$v_x = v\cos(\Omega t + \phi),\, v_y = v\sin(\Omega t + \phi)$$

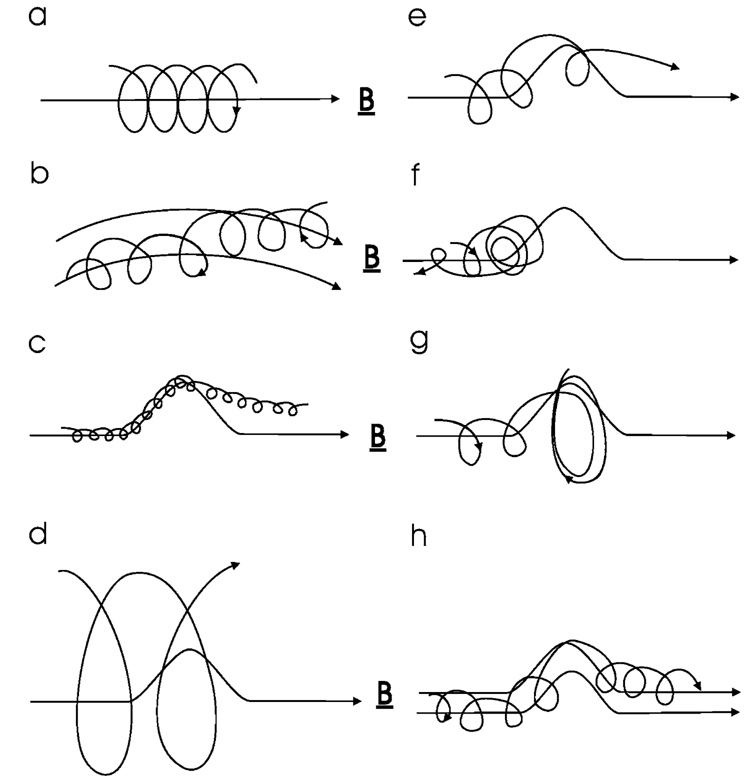
- Ω=Larmor frequency
- Alfvén wave: magnetic field changes during passage: $B_z = \delta B_z \sin(kz - \omega t)$
- Lorentz force $F_L = \frac{1}{c} Zev_y \delta B \sin(kz - \omega t)$ (ω frequency of wave)
- B-field: Lorentz force ⊥ momentum (p): change in direction, |p|

$$\Delta p_{\parallel} = \int \frac{1}{c} eZv_y \delta B \sin(kz - \omega t) dt = \frac{1}{2}\frac{1}{c} eZv_{\perp}\delta B \int \left\{ \cos\left[(kv_{\parallel} - \omega - \Omega)t + kz_0 - \phi\right] - \cos\left[(kv_{\parallel} - \omega + \Omega)t + kz_0 + \phi\right] \right\} dt\,.$$

- First term integrates out (many cosine cycles).
- Second term not, if resonance between gyroradius and Alfvén wavelength

$$\Omega + kv_{\parallel} - \omega \approx 0$$

# Particle-wave interaction




- Integrate over dt≈1/Ω

$$\Delta p_{\parallel} \approx \frac{1}{2}\frac{1}{c} eZv_{\perp}\delta B\ \cos(kz_0-\phi)\Delta t = \approx \pi \frac{eZv_{\perp}\delta B}{c\Omega}\cos(kz_0-\phi) = \pi \frac{eZv_{\perp}}{c}\frac{\delta B \Gamma mc}{eB}\cos(kz_0-\phi) = \pi p \sin\theta \frac{\delta B}{B}\cos(kz_0-\phi)\,.$$

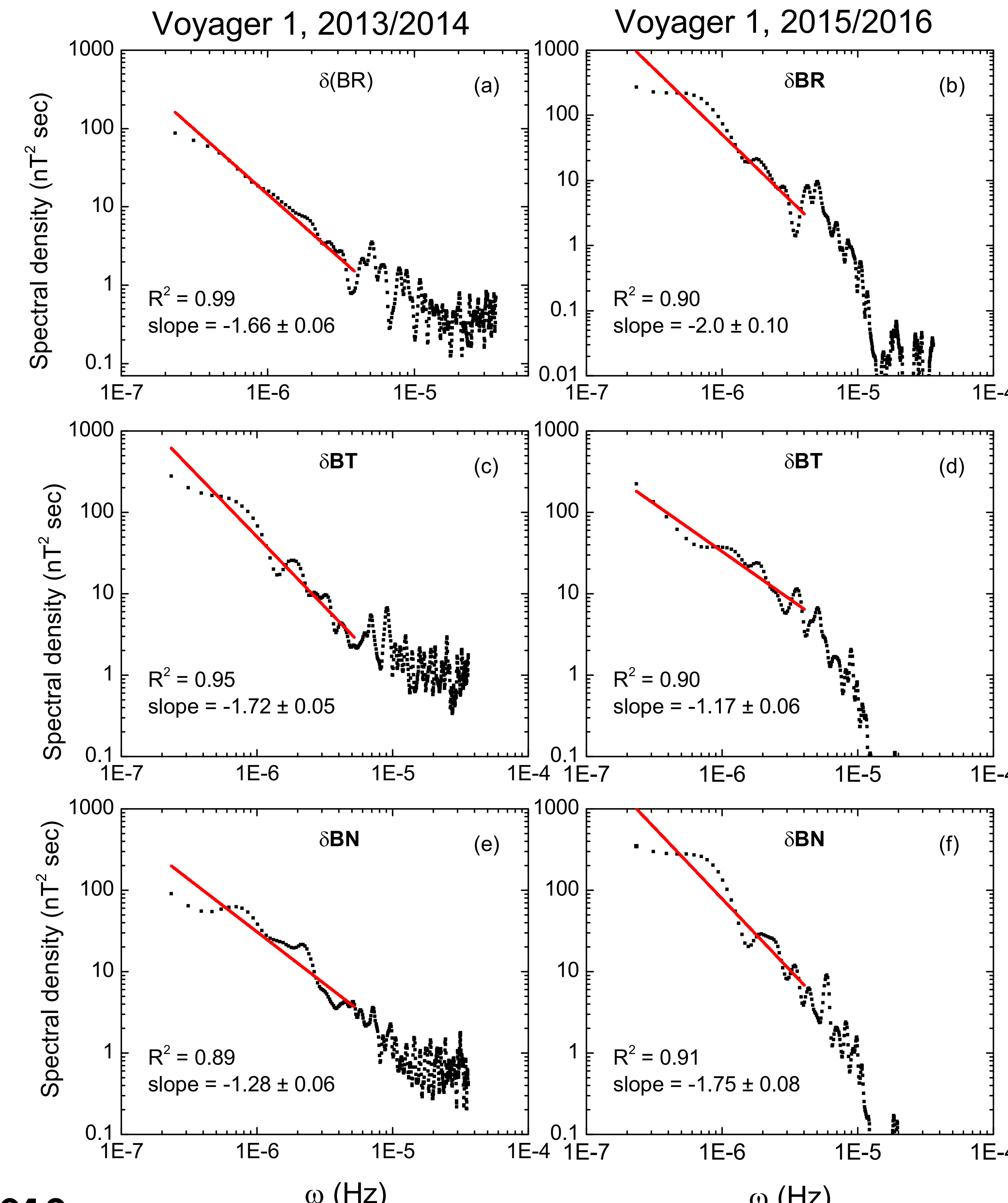
- Particles interact dominantly with waves the size of their gyroradius
- Assume random Alfvén wave packages (few wavelengths long)
- p changes substantially during one wavelength (Δp/p∼1)

- The "mean free path" i.e. the length scale motion change is

$$\lambda_{\rm mfp} \approx v\tau_{\rm iso} \approx \frac{4}{\pi} r_{\rm g} \left\langle \left(\frac{\delta B}{B}\right)^2 \right\rangle^{-1}$$

- When $\lambda_{\rm mfp} = r_{\rm g}$ we call it *Bohm diffusion*

# Magnetic field turbulence measured by Voyager 1




- V1/2 still sending data!!
- Magnetic field turbulence important for diffusion

Burlaga+, 2018

# Diffusion coefficient for cosmic rays

- Diffusion coefficient: $D = \frac{1}{3}\lambda_{\rm mfp} v$

- D is energy dependent: mean free path increases with energy
- For very tangled magnetic fields, assume mean free path ≅ gyro-radius

$$r_{\rm g} = \frac{p_\perp}{ceZB} \approx \frac{E}{eZB} \approx 0.28 Z^{-1} \left(\frac{E}{10^{15}{\rm eV}}\right) \left(\frac{B}{5\mu{\rm G}}\right)^{-1} \ {\rm pc}$$

- Expression for diffusion coefficient (cgs):

$$D = \eta \frac{1}{3} c \frac{E}{eZB} \approx 6.7 \times 10^{27} \eta Z^{-1} \left(\frac{E}{10^{15}{\rm eV}}\right) \left(\frac{B}{5\mu{\rm G}}\right)^{-1} \ {\rm cm^2 s^{-1}}$$

- **η** is parameterisation (**λ=ηr$_g$**): $\eta \approx \left\langle \left(\frac{\delta B}{B}\right)^2 \right\rangle^{-1}$

- **η**=1 : *Bohm*-diffusion (smallest diffusion coefficient possible)
- Diffusion coefficient energy dependence is function of turbulence spectrum of magnetic fields

# Cosmic-ray propagation: some words on diffusion

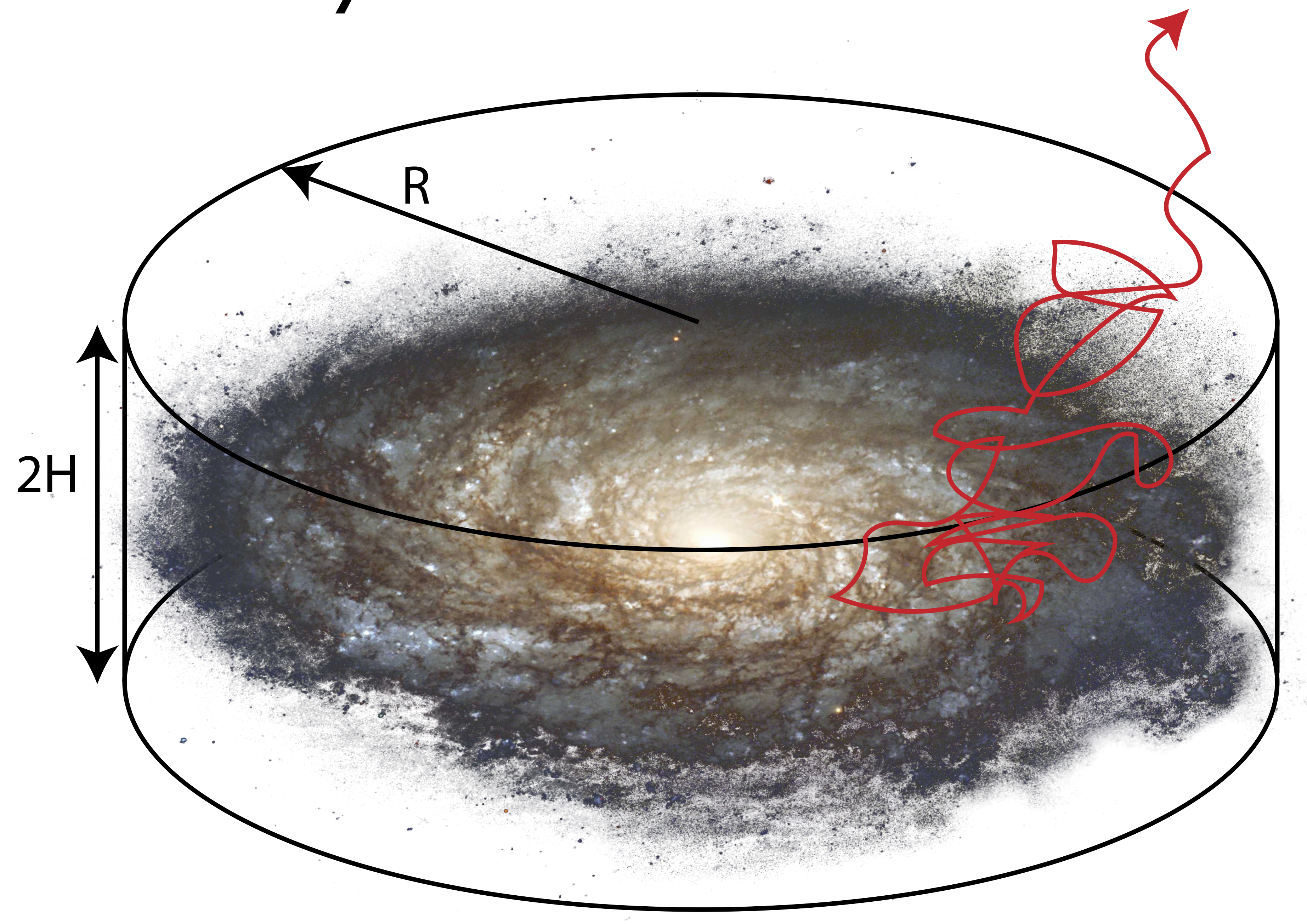
- Cosmic-ray transport equation:

$$\frac{\partial N_i(E)}{\partial t} = \nabla\left(D(E_i)\nabla N_i(E)\right) - \nabla \mathbf{v} N_i(E) - \frac{N_i(E)}{\tau_i} - \frac{\partial}{\partial E}\left[b_i(E) N_i(E)\right] + \sum_{j>i} \frac{P_{ij}}{\tau_j} N_j + Q_i(E)$$

diffusion — advection — radio-activity — gains/losses — spallation — source term

- Advection: go with the flow
- Diffusion: random walk through space
- D= diffusion coefficient [cm$^2$s]
- With only left hand-side and first term: Fick's second law for diffusion
- Diffusion also important for astrophysical particle acceleration:
  *Diffusive* Shock Acceleration (DSA)

# Cartoon of Leaky Box model




- Assume all CRs are trapped in box
- CRs are well mixed inside box
- Every now and then a CR particle is taken from the box

# Estimating diffusion coefficient

- Approximate

$$\frac{\partial N_i}{\partial t} = D\nabla^2 N_i(E) + \frac{\partial}{\partial E}\left[b(E)N_i(E)\right] + Q_i(E) - \frac{N_i}{\tau_i} + \sum_{i>i}\frac{P_{ij}}{\tau_j}N_j$$

- Assume steady state: dN/dt=0 and "Leaky Box" approximation:

$$D\nabla^2 N_i(E) \approx -\frac{N_i}{\tau_{\rm esc}}$$

- Further approximation

$$D\frac{N_i(E)}{L^2} \approx \frac{N_i(E)}{\tau_{\rm esc}(E)}$$

- Using typical escape time (1.5x10$^7$yr) and *Galactic scale height* 1500pc:

$$D \approx \frac{L^2}{\tau_{\rm esc}} \approx \frac{(1500\ {\rm pc})^2}{1.5\times 10^7{\rm yr}} \approx 4.5\times 10^{28}\ {\rm cm^2 s^{-1}}$$

- This corresponds to mfp of 1.5 pc, energies ≈1-10 GeV, and $\eta \sim 10^6$

# Source spectrum versus cosmic-ray spectrum

- Consider again $$\frac{\partial N_i(E)}{\partial t} = \nabla\left(D(E_i)\nabla N_i(E)\right) - \nabla \mathbf{v} N_i(E) - \frac{N_i(E)}{\tau_i} + \frac{\partial}{\partial E}\left[b_i(E)N_i(E)\right] + \sum_{j>i}\frac{P_{ij}}{\tau_j}N_j + Q_i(E)$$
- Assume diffusion coefficient is energy (rigidity) dependent:

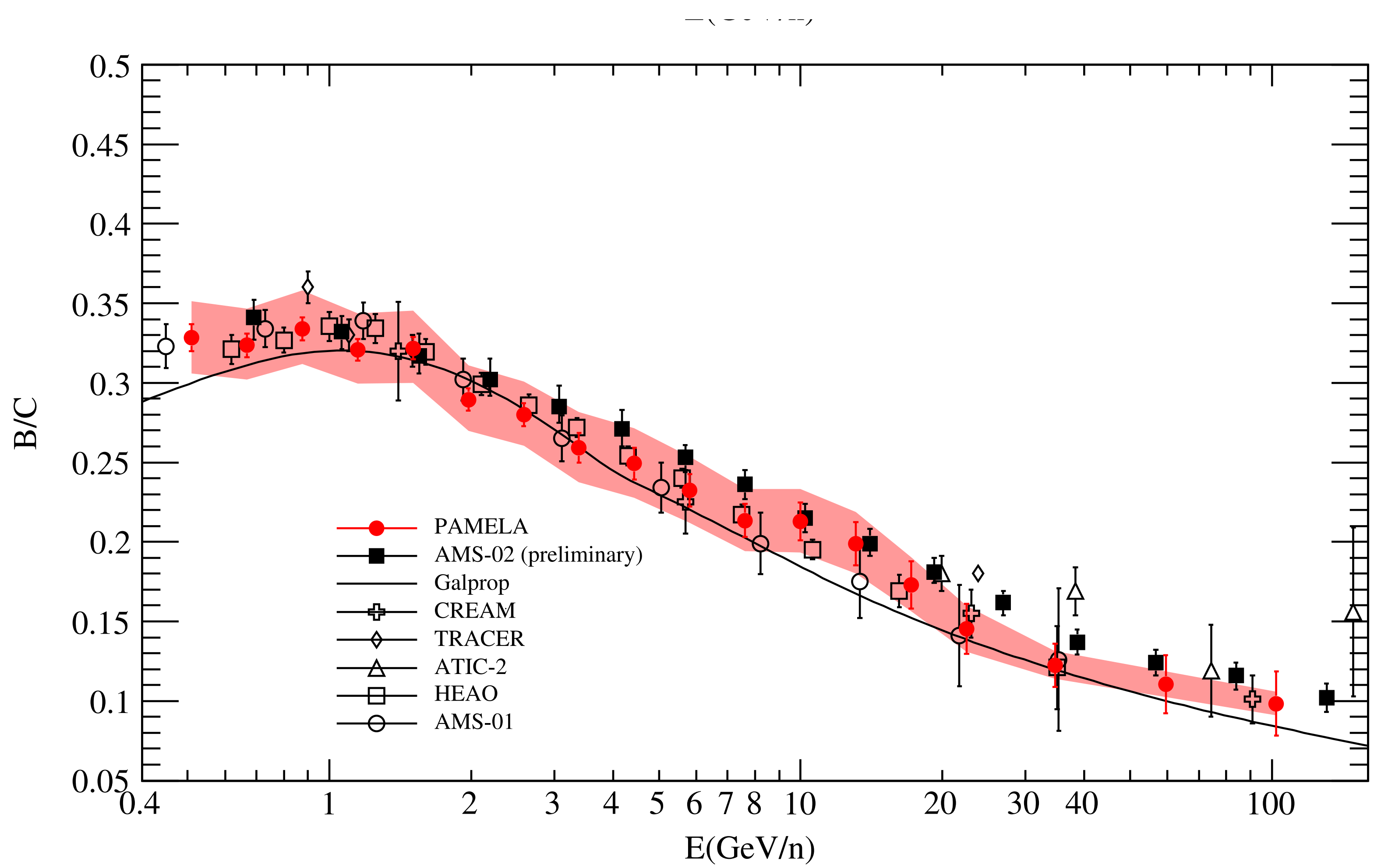
$$D(R) = D_0\left(\frac{R}{R_0}\right)^{\delta} \approx D_0\left(\frac{E}{E_0}\right)^{\delta} \qquad R \equiv pc/eZ$$

- Escape time ($r = \sqrt{2Dt}$) scales as $\tau_{\rm esc} \propto D^{-1} \propto E^{-\delta}$
- Approximate: $dN/dt = 0$, use Leaky Box, and ignore losses:

$$0 = \frac{N_i}{\tau_{\rm esc}} + Q_i(E)$$

- For input spectrum $Q_i(E) = KE^{-q}$: $N_i(E) \propto E^{-q-\delta}$
- Estimate δ=0.3-0.7, q+δ=2.7 ⇒ q≈2.0-2.4
- Often assumed δ=0.3, corresponds to Kolmogorov turbulence spectrum

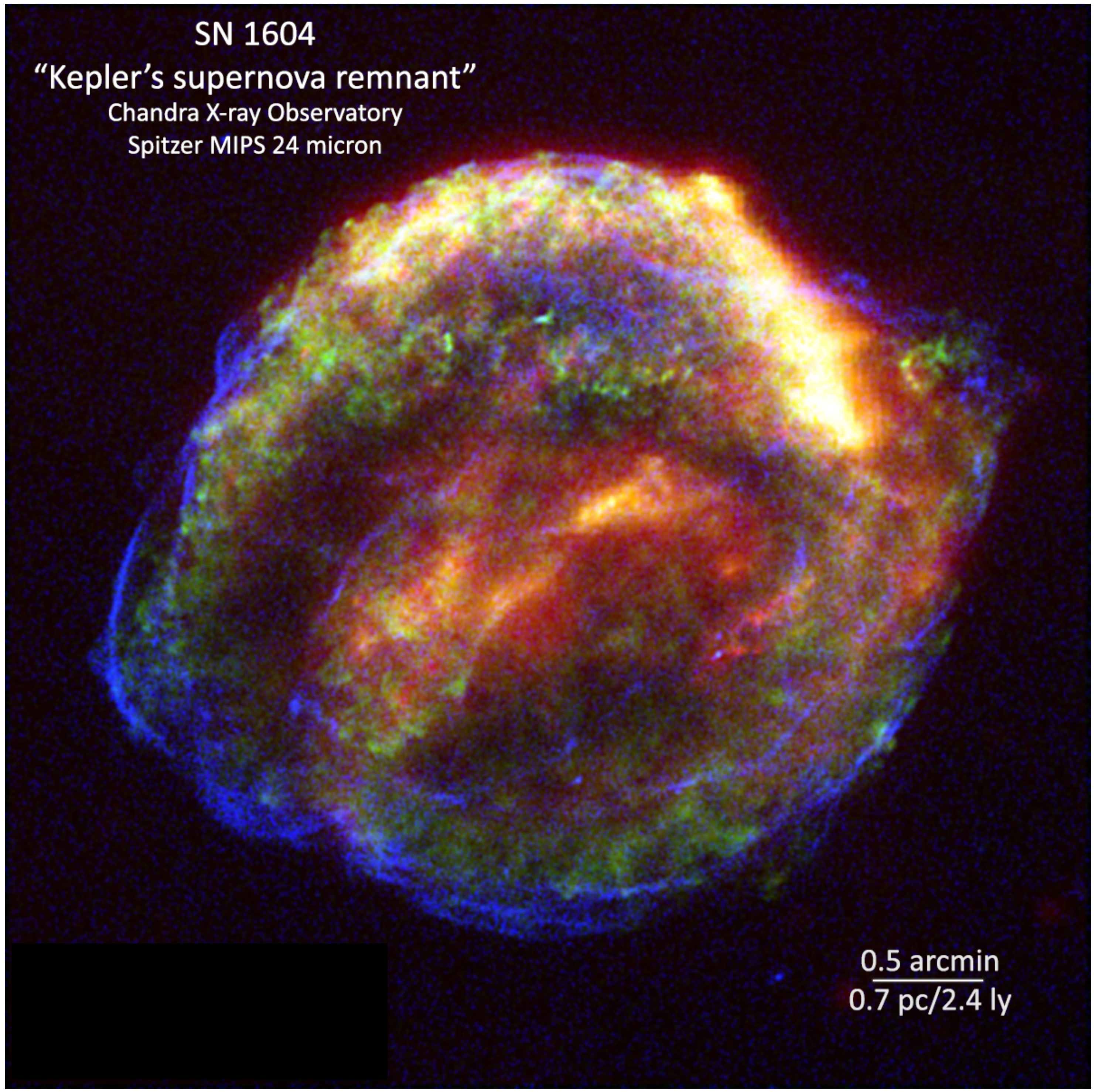
# Boron/Carbon (Pamela)



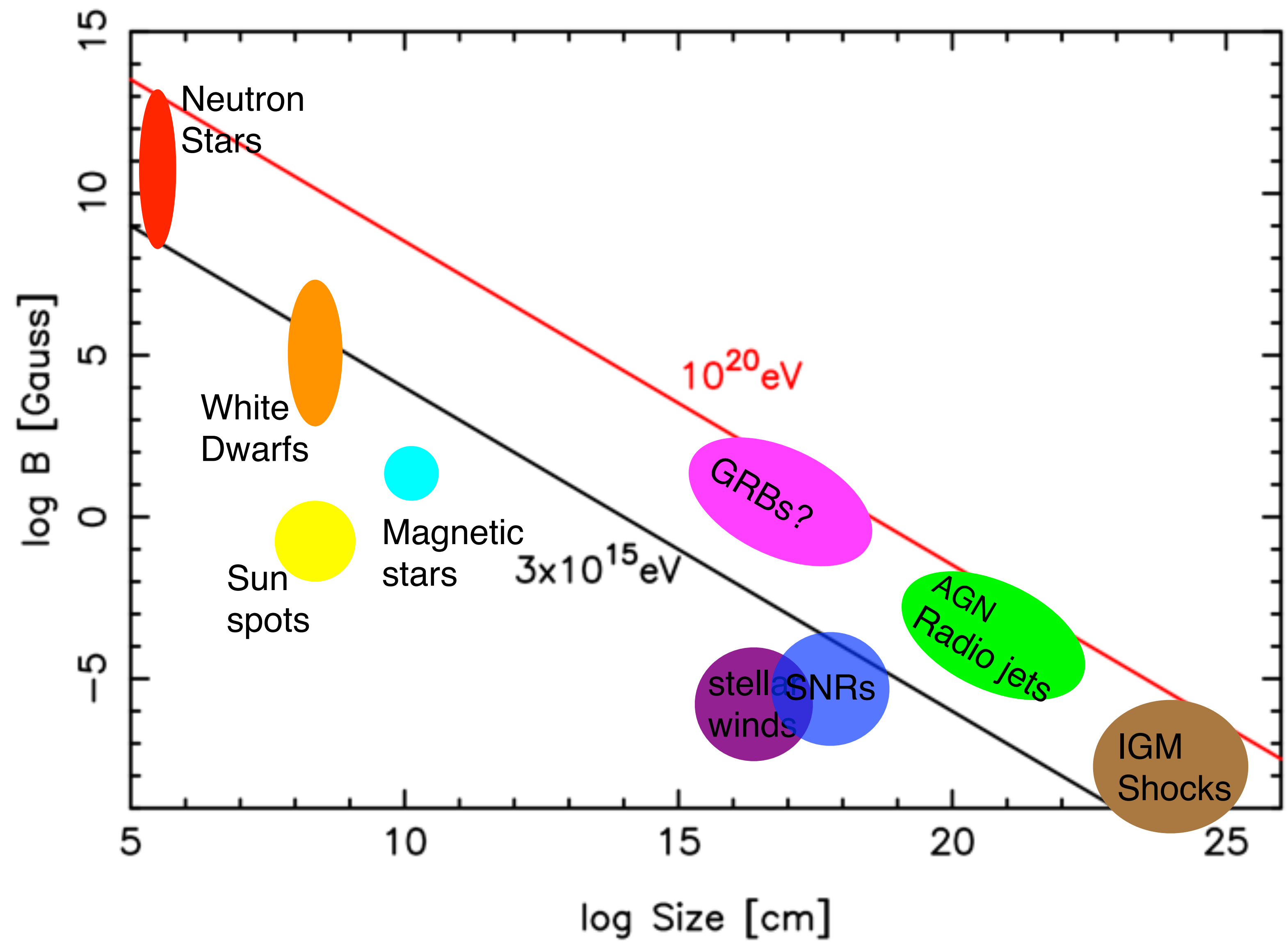

Adriani+ 2014

GALPROP runs. The values for the other parameters have been taken from (Vladimirov 2012). The diffusion coefficient is found to have a fitted slope value of $\delta = 0.397 \pm 0.007$ and a normalization factor $D_0 = (4.12 \pm 0.04) \times 10^{28}$ cm$^2$ s$^{-1}$.

# 2 Sources of (Galactic) cosmic rays



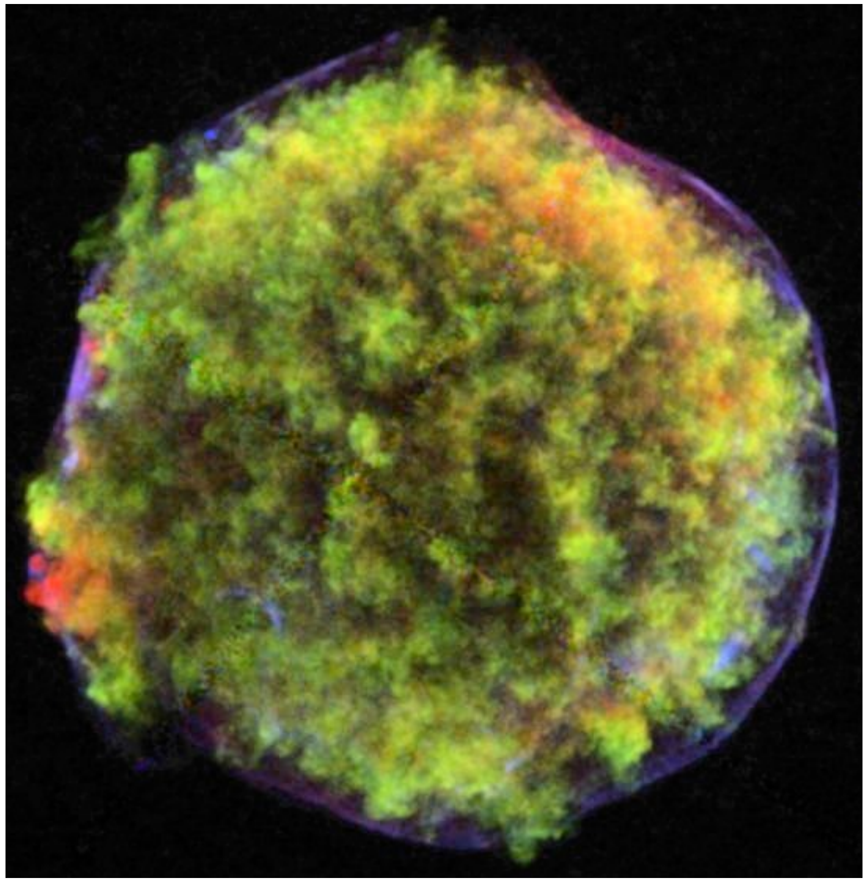
# Hillas Diagram: what are the sources of cosmic rays?



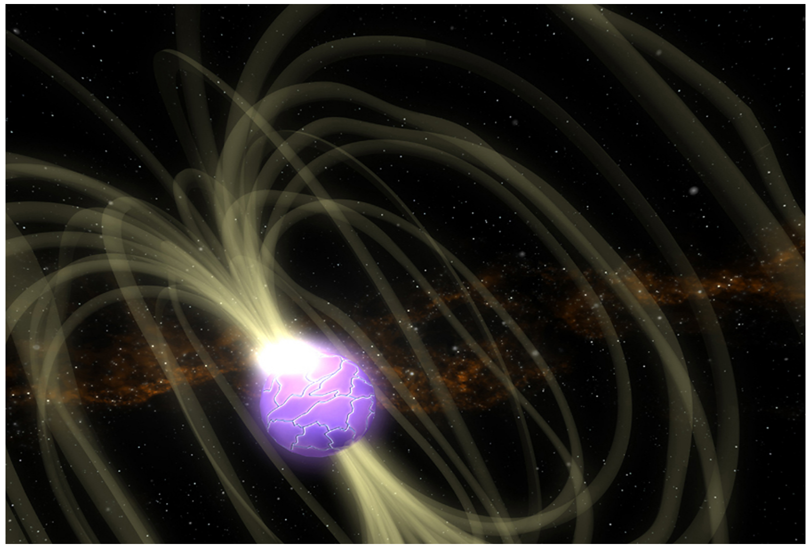

- Hillas diagram generalizes notion that in order to accelerate particles you need to confine them to source:
  - Gyroradius needs to be ≈0.1x size of object
  - Either large scale objects (IGM shocks) with low magnetic field
  - Or small objects with large fields (neutron stars)
- Hillas diagram does not tell whether acceleration occurs

# Some potential sources of cosmic rays

Galactic

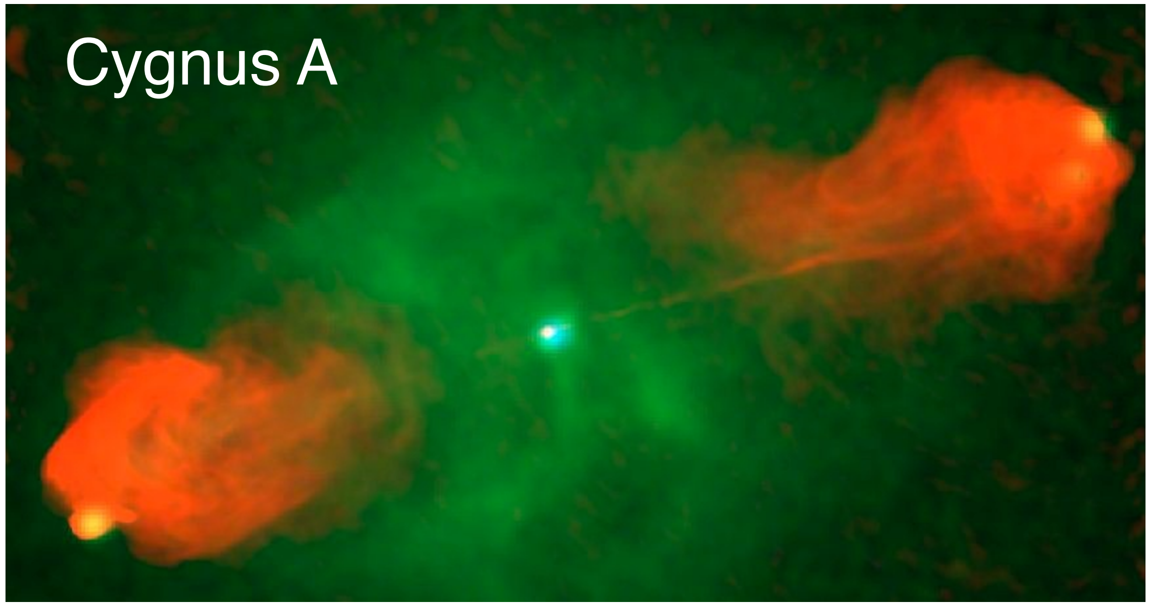


supernova remnant

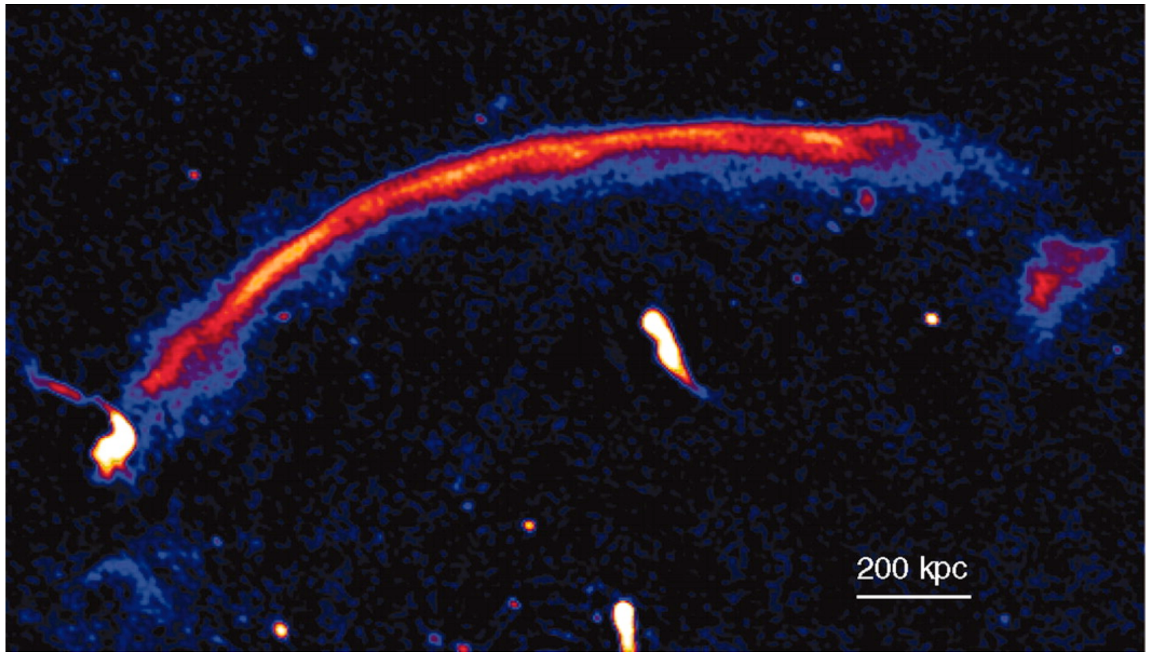


Pulsar/magnetar

extragalactic

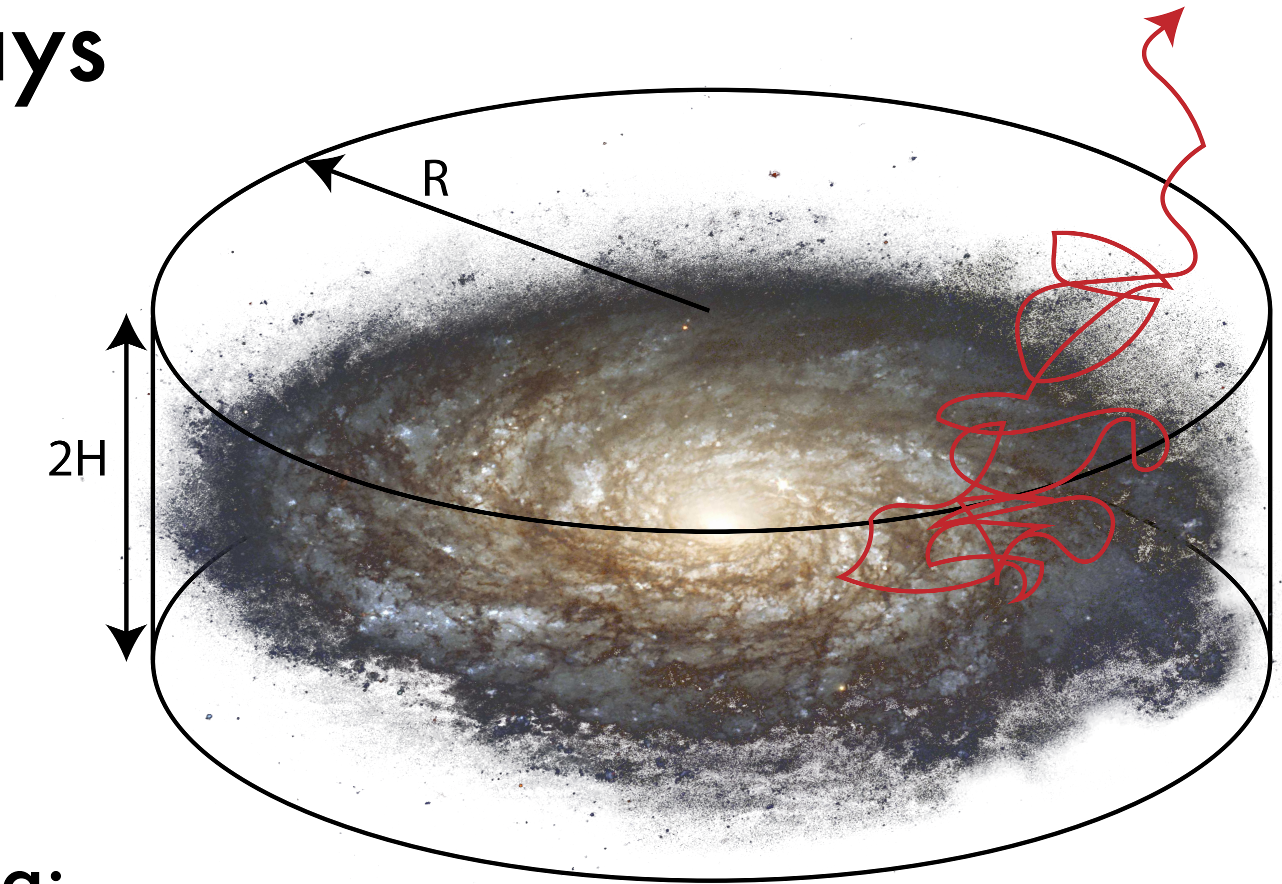



Active galaxy




Large scale shock in cluster

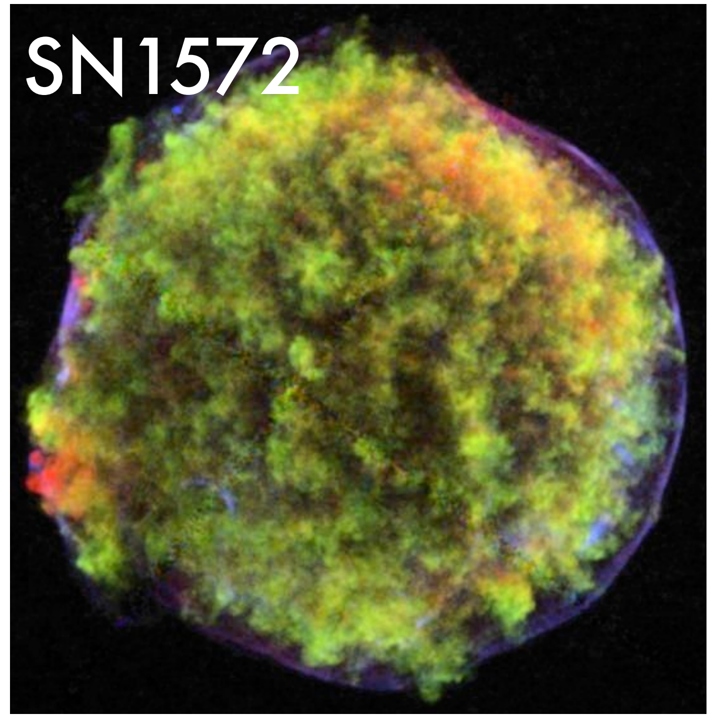
# Origin of Galactic cosmic rays

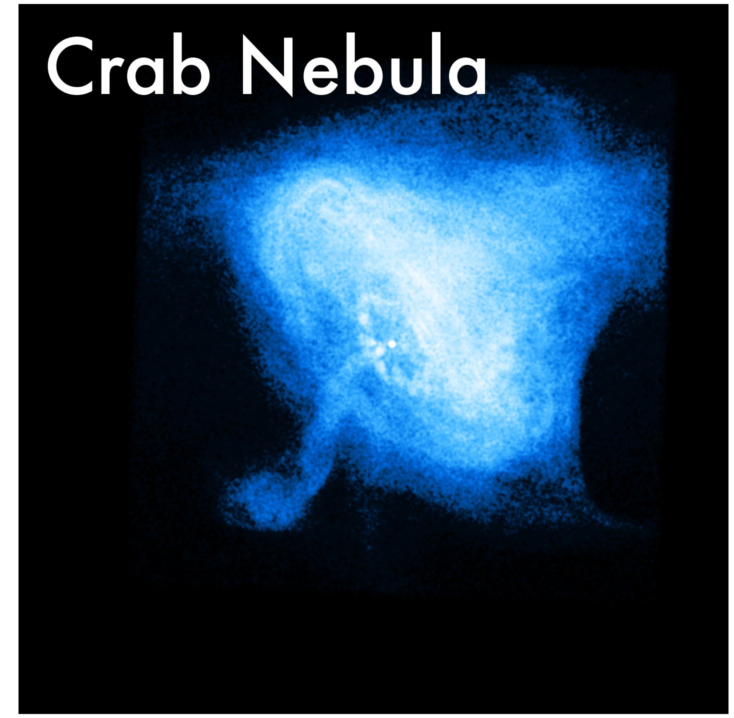



- Assume there is a dominant source
- This source needs to fullfill two criteria:
  1. Able to accelerate particles up to $3x10^{15}$eV or beyond
  2. Able provide enough energy to sustain cosmic-ray energy Galaxy

- Criterion 2:
  - assume steady state
  - energy density in cosmic rays $U_{cr} \approx 1$ eV cm$^{-3}$
  - Volume of Milky Way $V=\pi R^2(2H) \approx 6x10^{11}$pc$^3$, $R \approx 10$ kpc, $H \approx 1000$ pc
  - Energy $E \approx 3x10^{55}$ erg
  - Power needed: $P=dE/dt \approx 3x10^{55}$erg$/1.5x10^7$ yr$\approx 6x10^{40}$ erg/s

# Origin of Galactic cosmic rays



http://apod.nasa.gov/apod/ap051107.html

- Two constraints for Galactic sources:
  - Is total power provided enough?
  - Are they capable of accelerating up to $3x10^{15}$eV?

# 4 Supernovae (remnants) as sources of Galactic cosmic rays

Walther Baade

Frits Zwicky

*COSMIC RAYS FROM SUPER-NOVAE*

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

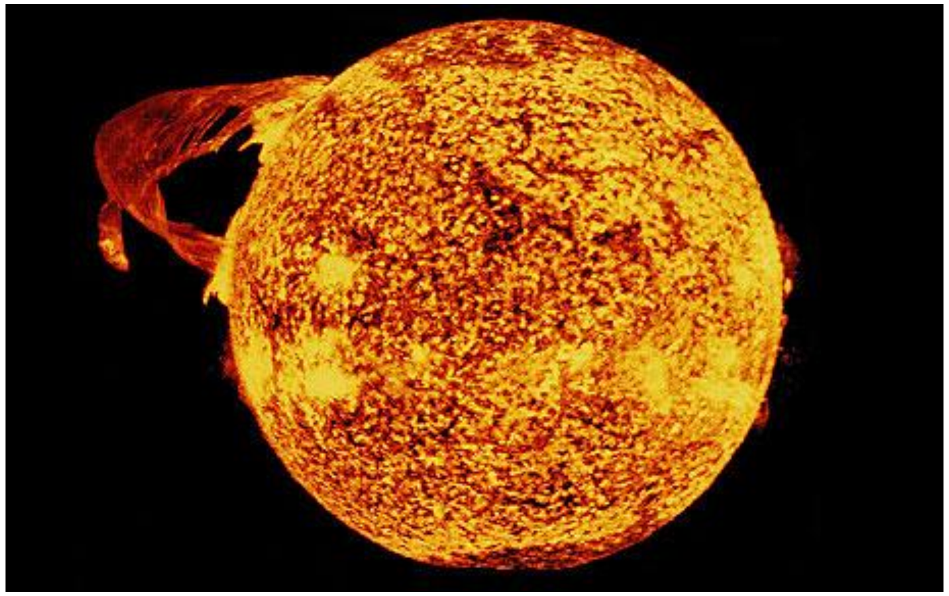
In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place, where also will be mentioned some observations that tend to support the idea of stellar bodies made up mainly of neutrons.

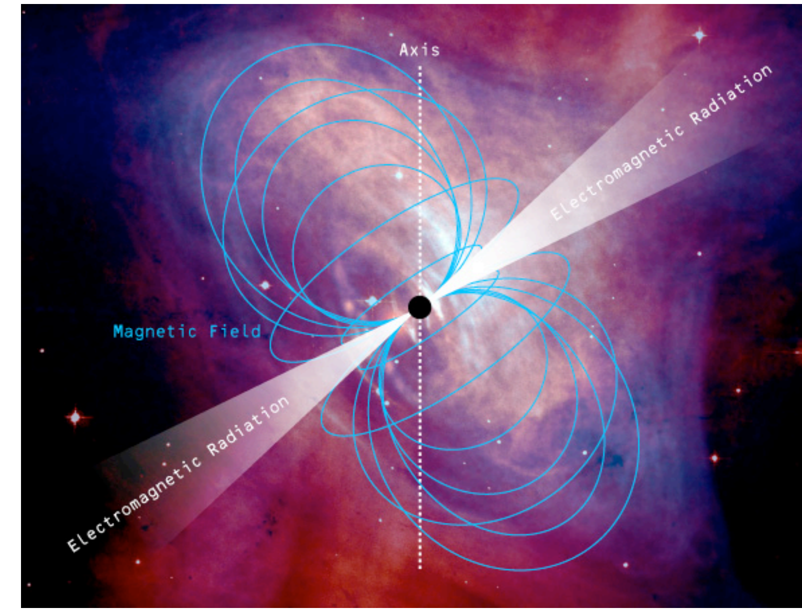
# Are Galactic cosmic rays powered by supernovae?

- Energetic requirements are good:
  - supernovae surveys: $\sim$ 2 SNe per century for Milky Way-like galaxies
  - supernova energy ≈ $10^{51}$ erg
  - total power $dE/dt=10^{51}/(50\ \mathrm{yr})\approx 6\times10^{41}$ erg = 10% $(dE/dt)_{cr}$
  - efficiency <100% but high

- When and how is this energy used?
  - Baade & Zwicky: supernova directly accelerates
  - Radio observations: synchrotron radiations from supernova remnants
    - synchtrotron → need accelerated electrons
    - perhaps cosmic ray acceleration occurs in supernova remnant stage

# Other potential sources?

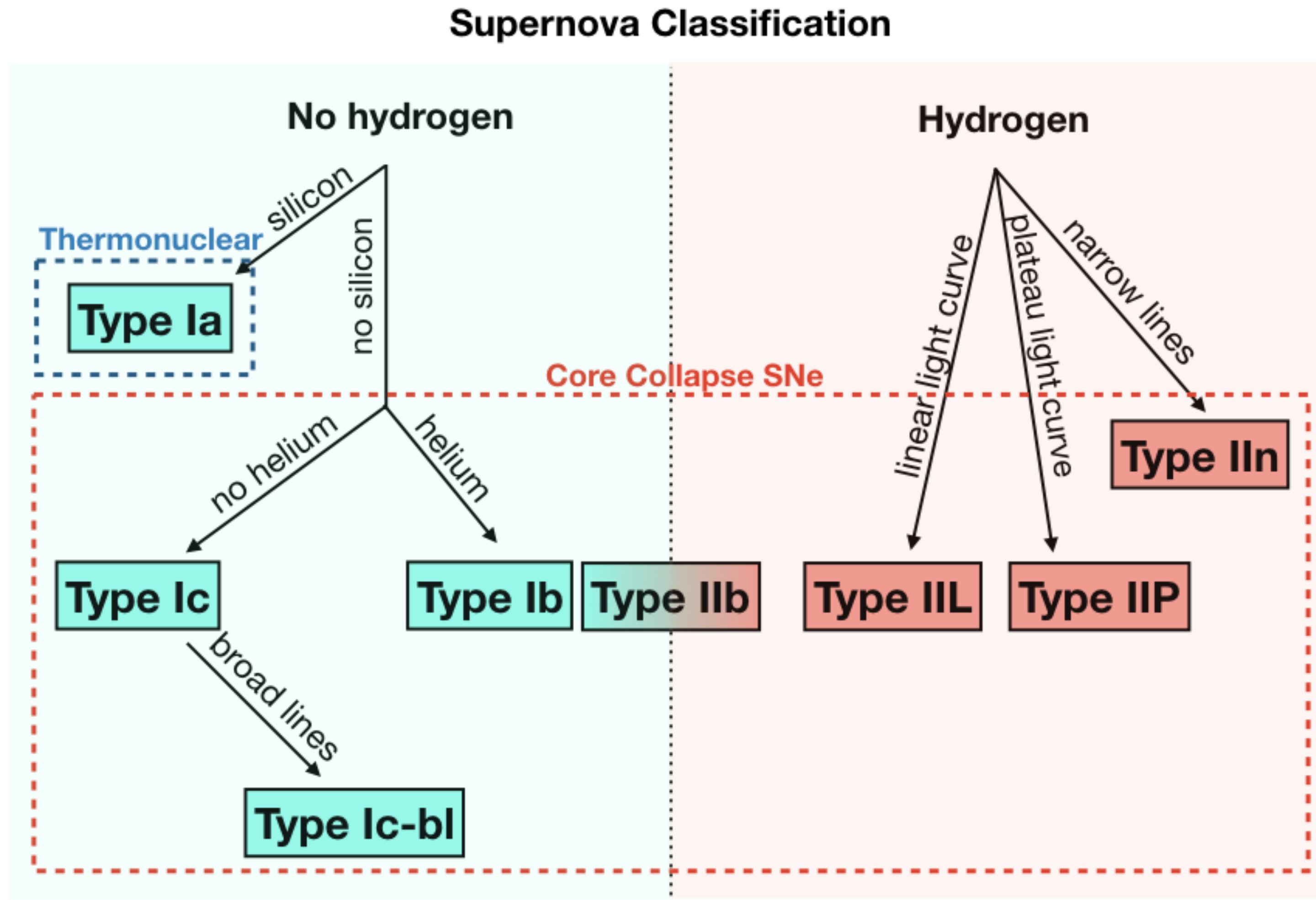





| Source type | Primary energy source (erg) | Frequency ($yr^{-1}$) | Total Galactic Power (erg $s^{-1}$) |
|---|---|---|---|
| supernova remnants | $10^{51}$ | $\approx 1/30$ | $\approx 10^{42}$ |
| pulsars | $E_{rot} = 5 \times 10^{48} (P/100 \text{ ms})^{-2}$ erg | $< 1/30$ | $\lesssim 2 \times 10^{40}$ |
| stellar winds | $\approx 2 \times 10^{49}$ | $< 1/30$ | $\lesssim 5 \times 10^{40}$ |
| superbubbles | $10^{51}$ | $< 1/30$ | $\lesssim 10^{42}$ |
| Novae | $\approx 10^{46}$ | $\approx 50$ | $\approx 2 \times 10^{40}$ |
| X-ray binaries/micro-quasars | $< 10^{49}$ | $50 - 200$ sources | $\lesssim 2 \times 10^{40}$ |
| Central Black Hole | | ? | $10^{36} - 10^{40}$? |

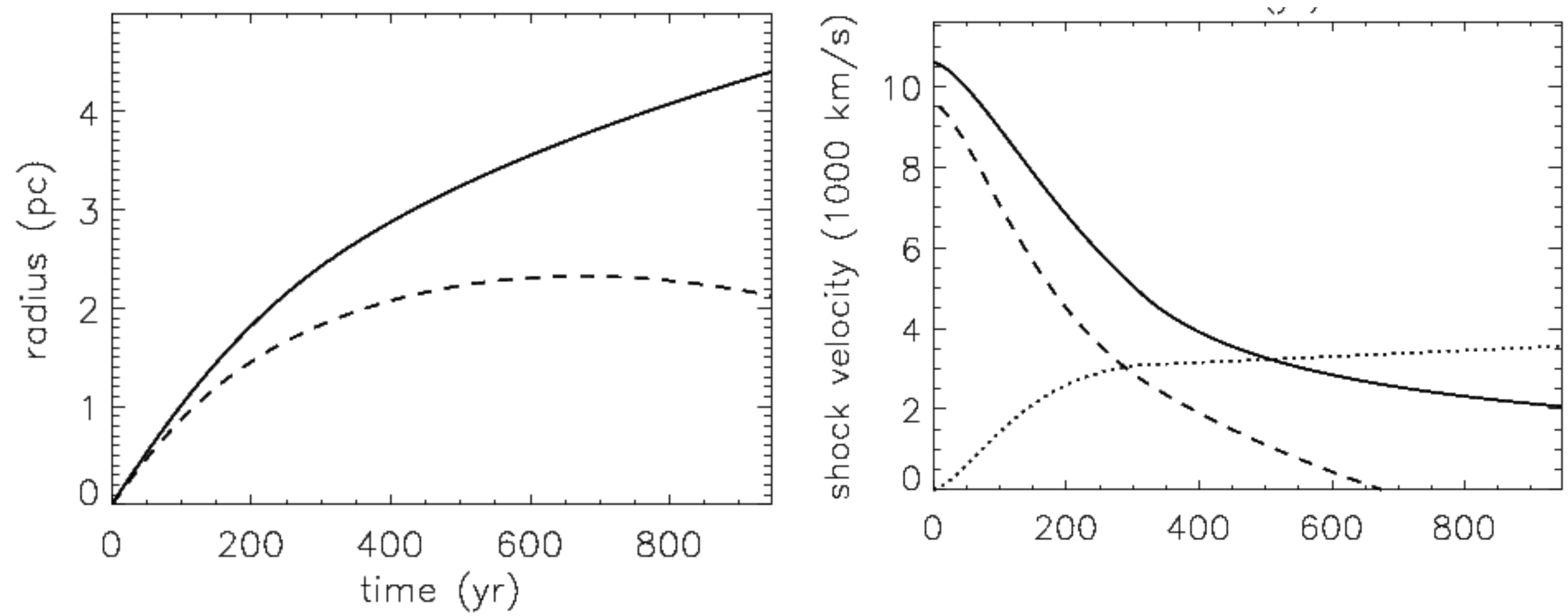
- NB: pusars are thought to accelerate electron/positrons pairs

# A brief intro on supernova remnants



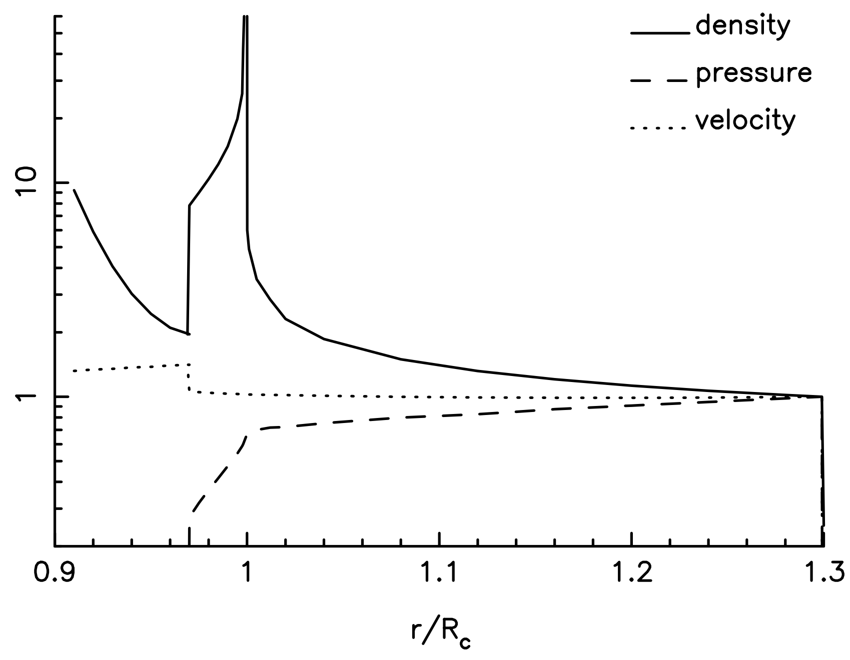

- Optical classification: based on SN spectrum and light curve
- Physical classification:
  - Massive star: Core implodes → NS forms → neutrino emission →explosion
    - Hydrogen layer → Type II (L/P) or Type IIb
    - Hydrogen layer stripped →Type Ib/c
  - White dwarf in binary: CO WD accretes → pressure in core high →C&O fuses →runaway process → thermonuclear explosion → Type Ia

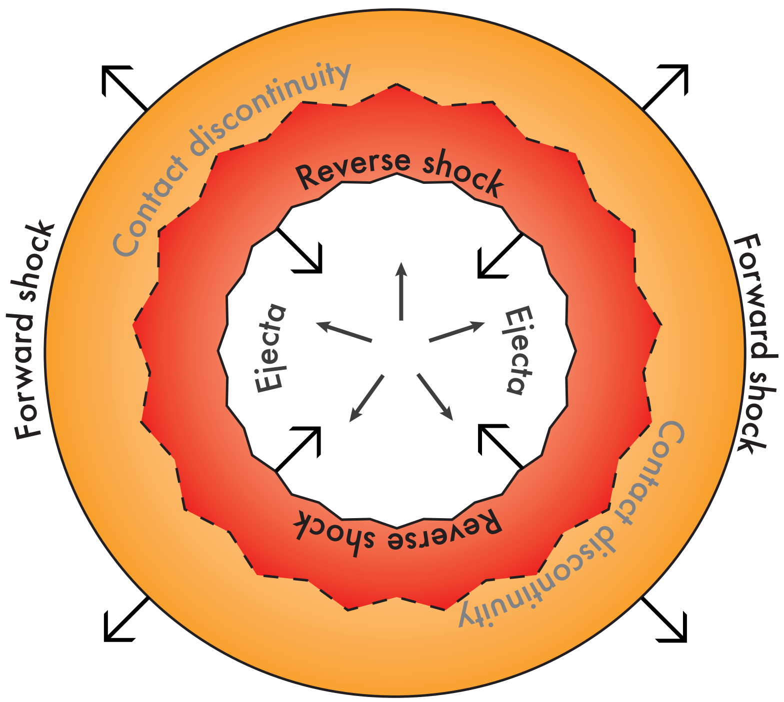
# Supernova remnants




- Supernova explosion sets off a shock wave in ambient medium
  - Can be (initially) through stellar wind of progenitor star
  - ISM: relatively low density
  - Former stellar wind: high density, but dropping as $1/r^2$
- Shock wave heats and sets in motion the ambient
  - energy of explosion spread out over more mass
  - swept up mass: $M_{\mathrm{sw}} = \int_0^{R_{\mathrm{s}}} 4\pi r^2 \rho(r) dr$
  - energy conserved so shock velocity decelerates
- Once $V_{\mathrm{s}} = \frac{dR_{\mathrm{s}}}{dt} < 200\ \mathrm{km\ s^{-1}}$: $T<10^6$ K and line cooling drains energy
  - This happens around t=10,000-20,000 yr

# The reverse shock



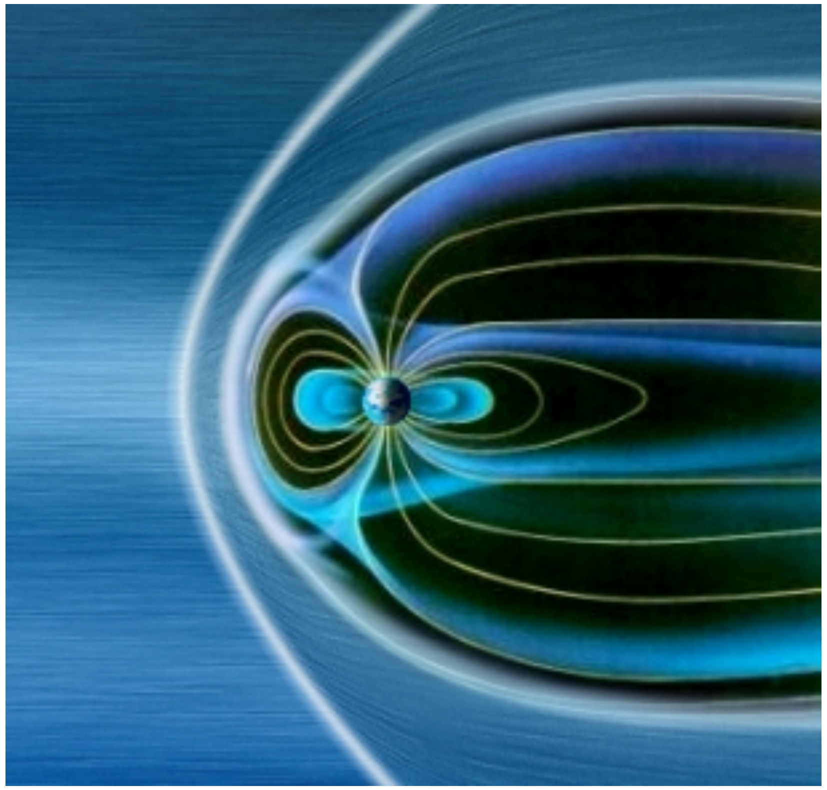

- An SNR in its early phases has two shocks:
  - Forward shock or blast wave → shocks ambient medium
  - Reverse shock:
    - supernova ejecta have cooled since explosion
    - ejecta have low pressure
    - shell heated by forward shock has high pressure
    - a shock forms heating again the supernova material
    - the shocked ejecta insert energy to the shell
- Reverse shock initially moves outward (but slower than outer unshocked ejecta)
- Later reverse shock moves backward
- Finally: reverse shock reaches center

# 5 Shock waves

- Shocks are encountered in nature whenever flows are *supersonic*
  - i.e. the flow is faster than the local sound speed
  - more general super-*magnetosonic waves*
    - takes also into account Alfven waves $v_A{}^2=2P_B/\rho=(B^2/4\pi)\rho$
- In shocks bulk motion is convert into thermal motion (pressure)
- Behind a shock the plasma is *subsonic* (in most cases)

# Astrophysical shocks

- Shocks are found in/around many high energy astrophysical sources:
  - the sun and solar system:
    - interplanetary shocks induced by coronal mass ejections
    - the Earth bow shock
    - the solar wind termination shock
  - Compact objects: accretion shocks
  - Interstellar medium
    - supernova remnants
    - nova remnants
    - stellar winds
  - Extra-galactic shocks
    - AGN (relativistic)
    - GRBs (relativistic)
    - Clusters of galaxies
- *Many of these astrophysical shocks are also sources of high energy particles!!*



# Collisionless shocks

- Atmospheric shocks: heating in shock due to particle-particle collisions
- In astrophysical plasmas: density (n) is very low
- Mean free path= $1/n\sigma$ can be very long for particles

- Estimate of cross sections, two particle $m_1$ and $m_2$, charge $Z_1$,$Z_2$
- Impact parameter = b
- Relevant b: kinetic energy=potential energy

$$\frac{1}{2}\frac{m_1 m_2}{m_1+m_2}v^2 = \frac{Z_1 Z_2 e^2}{b}$$

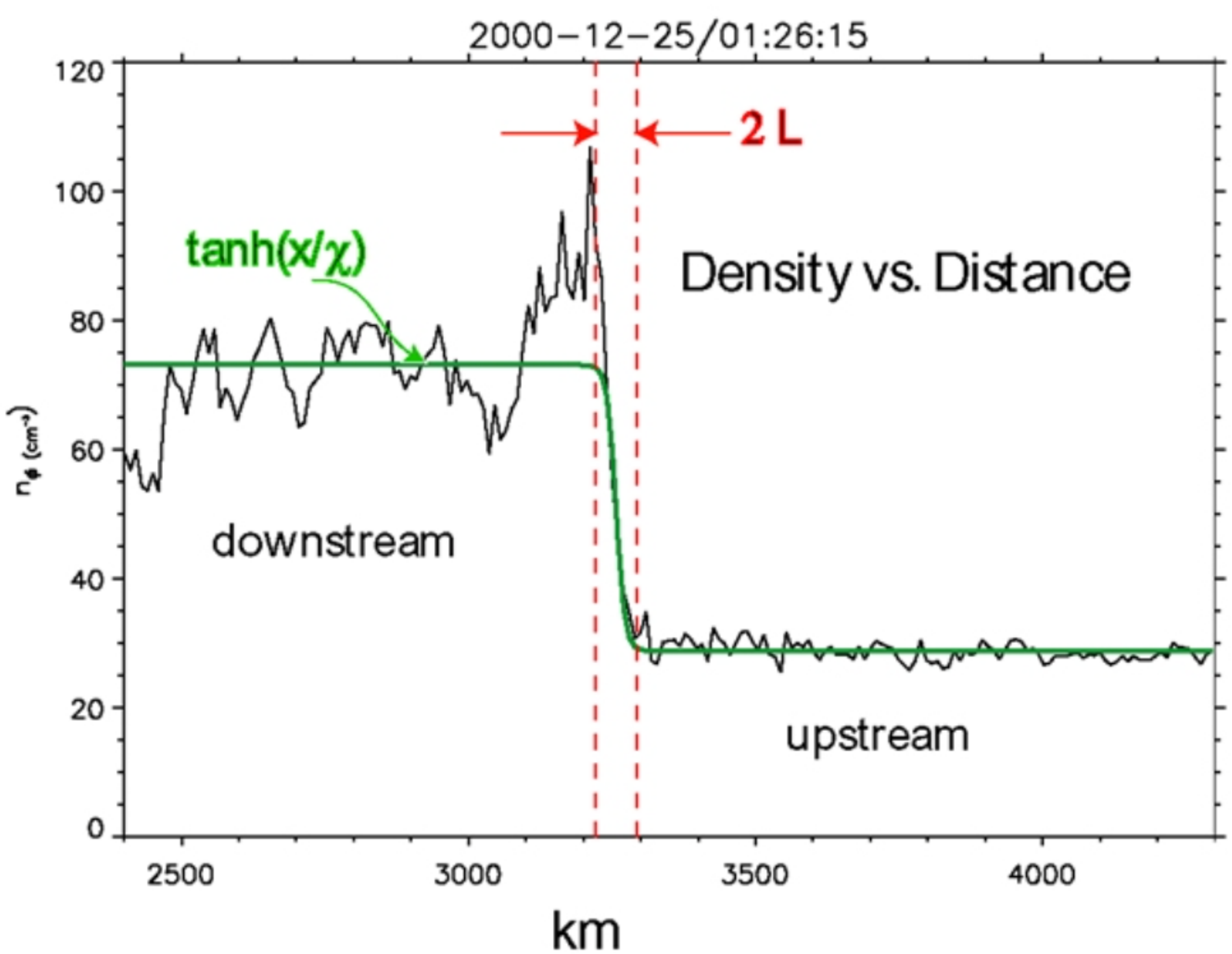
$$\sigma_{\rm Coulomb} \approx 4\pi \frac{Z_1^2 Z_2^2 e^4}{v^4}\left(\frac{m_1+m_2}{m_1 m_2}\right)^2$$

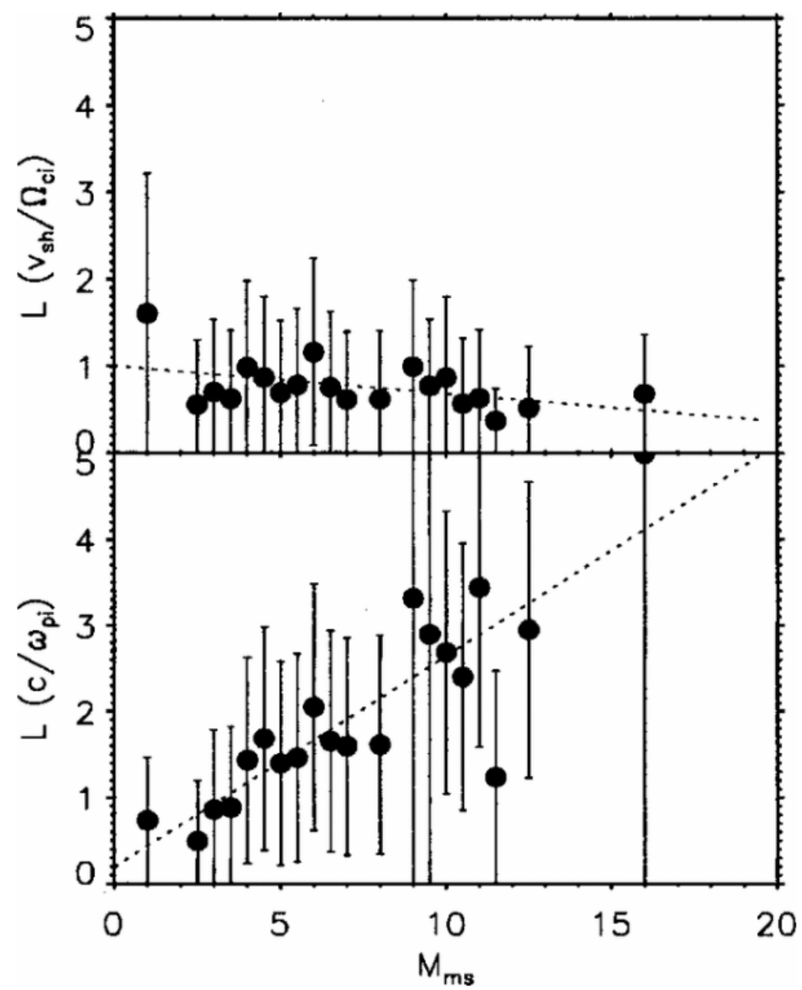
- For $v \approx 1000$ km/s, $n=1\,\mathrm{cm}^{-3}$ one finds for proton-proton

$$\lambda_{\rm p} \approx 10^{20} n_{\rm p}^{-1} \ {\rm cm}$$

- This is larger than the size of most supernova remnants!!
- Hence: shocks must be *collisionless*
- Heating due to *electric/magnetic (Alfvén) waves*!!

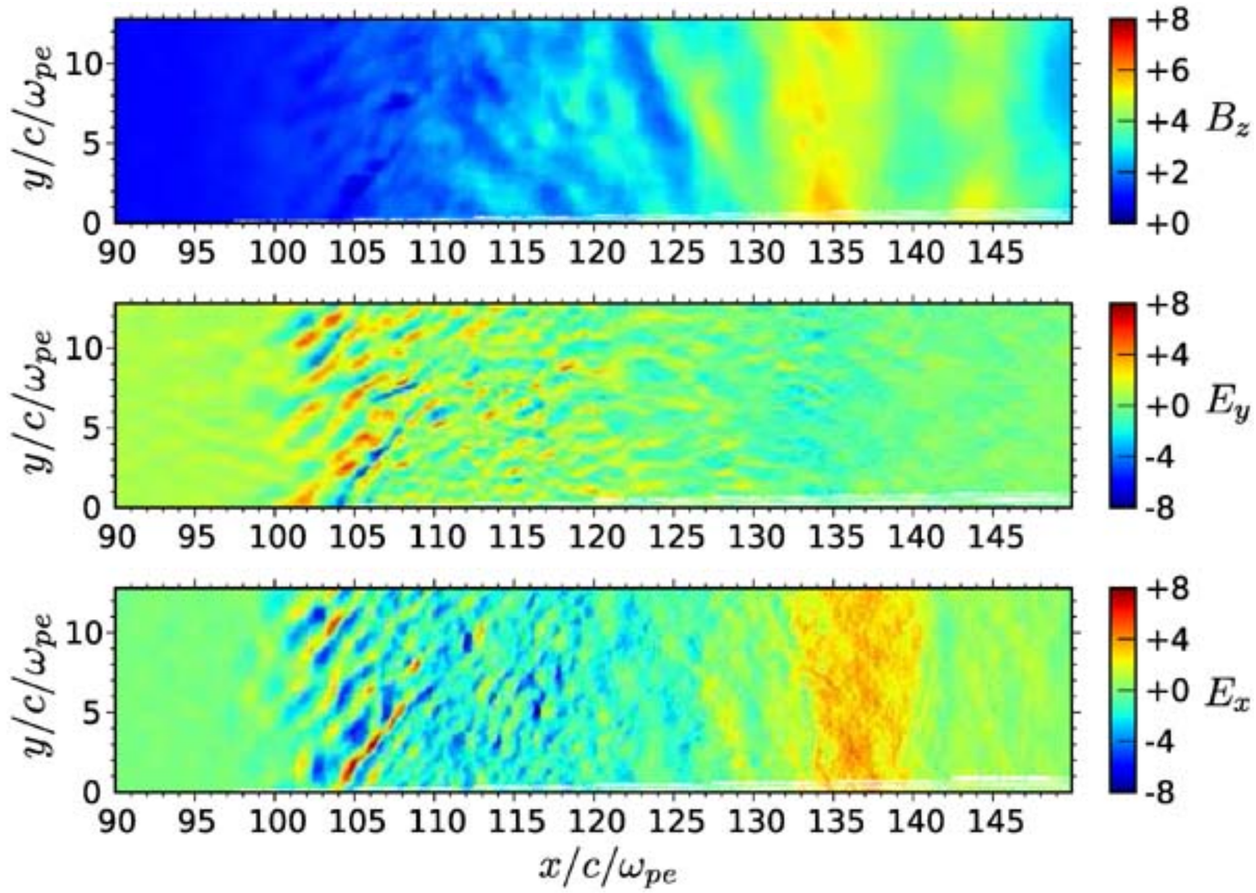
# Direct observation of collisionless shocks



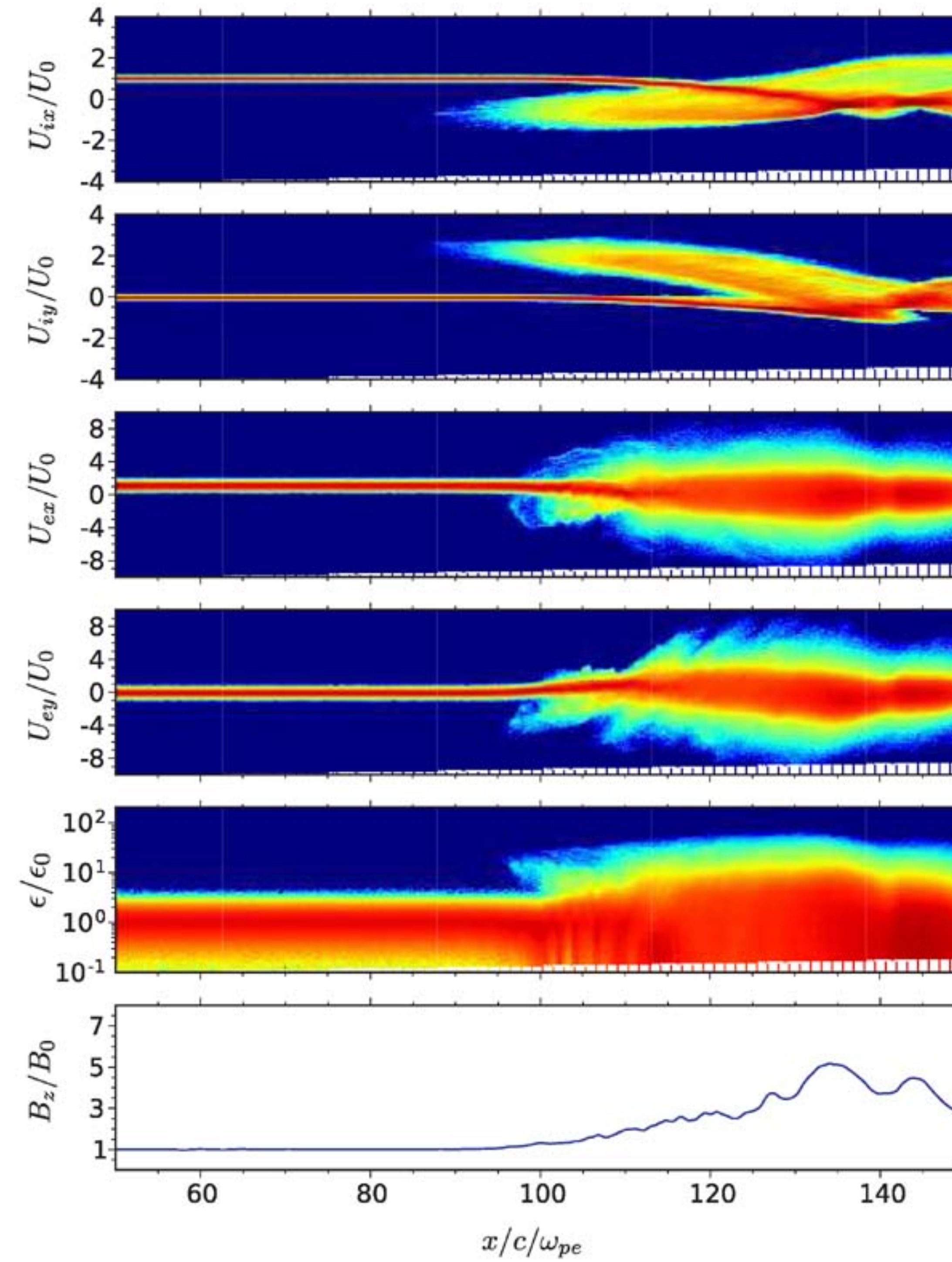




Bale et al. 2003:
Shock transition scale a few proton gyro radii

# Particle in Cell (PIC) Simulations

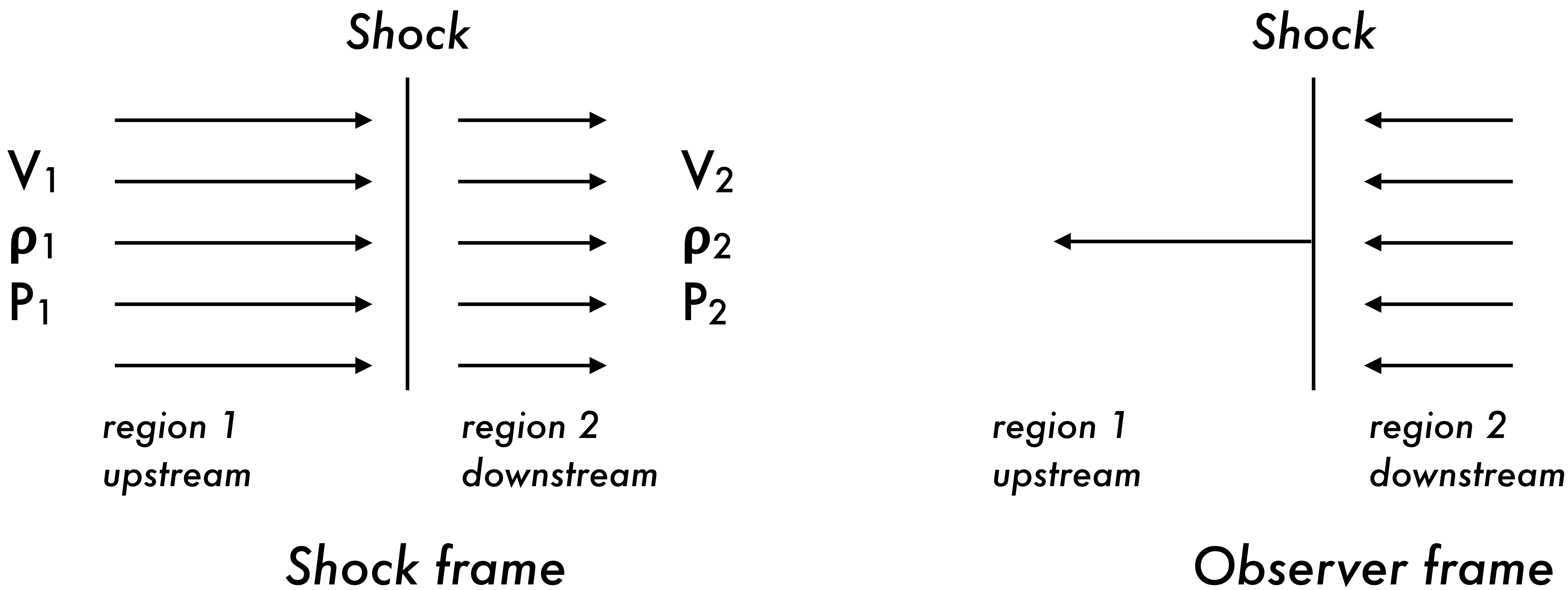



Amono&Hoshino 2008




- Theory of collisionless shocks difficult
- Insights from PIC simulations
  - two types of charged particles
  - calculate resulting E and B-field on grid
  - complicated phase space behaviour near shock

# Shock notation




- Standard shock equations take into account conservation of mass-, momentum- (pressure), and energy-flux
- *Consider in a system in which shock is at rest*
- Notation:
    - region 1=*upstream*=undisturbed flow
    - region 2=*downstream*=shocked plasma

# Shock equations (Rankine-Hugoniot relations)

- Take frame comoving with shock
- Mass-flux conservation: $\rho_1 v_1 = \rho_2 v_2$
- Momentum conservation (pressure equilibrium): $P_1 + \rho_1 v_1^2 = P_2 + \rho_2 v_2^2$
- Enthalpy/Energy-flux: $\left(U_1 + P_1 + \frac{1}{2}\rho_1 v_1^2\right) v_1 = \left(U_2 + P_2 + \frac{1}{2}\rho_2 v_2^2\right) v_2$

- Note: dQ=PdV+ dU,
- Hence both pressure and internal energy density U occur: $U = \frac{1}{\gamma - 1} P$

- Two dimensionless quantities
  - *Compression ratio:* $\chi \equiv \frac{\rho_2}{\rho_1} = \frac{v_1}{v_2}$
  - *Mach number:* $M \equiv v/c_s$

$$c_s = \sqrt{\gamma \frac{P}{\rho}}, \; \frac{P_1}{\rho_1 v_1^2} = \frac{1}{\gamma M^2}$$

# Shock solutions

- Convenient to use $$P_2 = P_1 + \rho_1 V_\mathrm{s}^2 \left[1 - \frac{1}{\chi}\right]$$

- Enthalpy-flux conservation

$$1 + 2\frac{\gamma}{\gamma-1}\frac{P_1}{\rho_1 V_\mathrm{s}^2} = 2\frac{\gamma}{\gamma-1}\frac{1}{\chi}\left[\frac{P_1}{\rho_1 V_\mathrm{s}^2} + \left(1 - \frac{1}{\chi}\right)\right] + \frac{1}{\chi^2}$$

- In dimensionless quantities:

$$\left[\left(\frac{2\gamma}{\gamma-1}\right)\frac{1}{\gamma M^2} + 1\right]\chi^2 - \left(\frac{2\gamma}{\gamma-1}\right)\left(1 + \frac{1}{\gamma M^2}\right)\chi + \left[\left(\frac{2\gamma}{\gamma-1}\right) - 1\right] = 0$$

- Quadratic equation
- One solution X=1 (trivial)
- Other (shock) solution:

$$\boxed{\chi = \frac{(\gamma+1)M^2}{(\gamma-1)M^2 + 2}.}$$

# Strong shocks

- Strong shocks (M→∞): neglect $P_1$ in pressure equilibrium

$$P_2 = \cancel{P_1} + \rho_1 V_s^2 \left[1 - \frac{1}{\chi}\right]$$

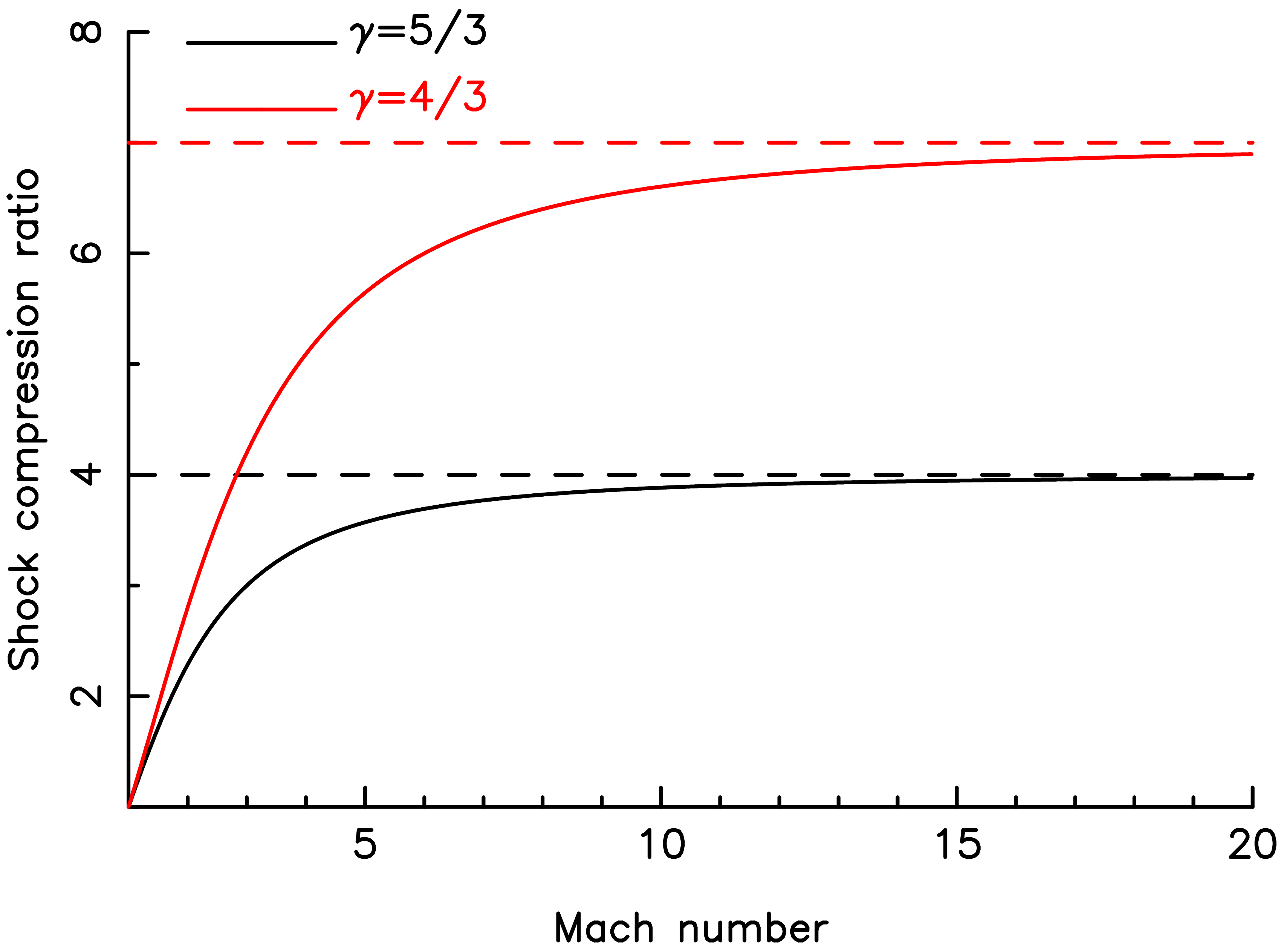
- Effect:
  - compression independent of Mach number

$$\boxed{\chi = \frac{(\gamma+1)M^2}{(\gamma-1)M^2+2}.}$$

$$\chi \longrightarrow \frac{\gamma+1}{\gamma-1}$$

- For monatomic gas γ=5/3 → X=4
- For relativistic gas γ=4/3 → X=7

# Compression factor versus Mach number



# Downstream temperatures

- Note P=nkT
- We can rewrite in

$$P_2 = P_1 + \rho_1 V_\mathrm{s}^2 \left[1 - \frac{1}{\chi}\right]$$

$$P_2 = n_2 kT_2 = \frac{\rho_2}{\mu m_\mathrm{p}} kT_2 = P_1 + \rho_1 V_\mathrm{s}^2 \left[1 - \frac{1}{\chi}\right]$$

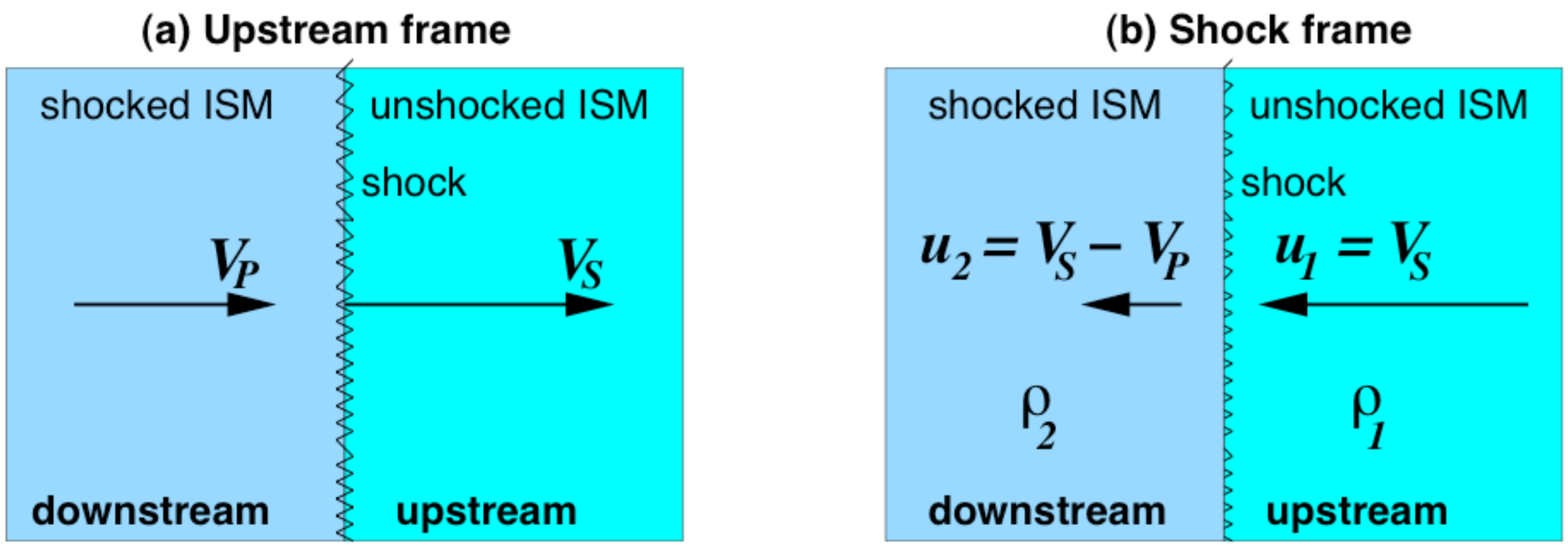
$$kT_2 = \frac{1}{\chi}\left(\frac{1}{\gamma M^2} + \left[1 - \frac{1}{\chi}\right]\right)\mu m_\mathrm{p} V_\mathrm{s}^2.$$

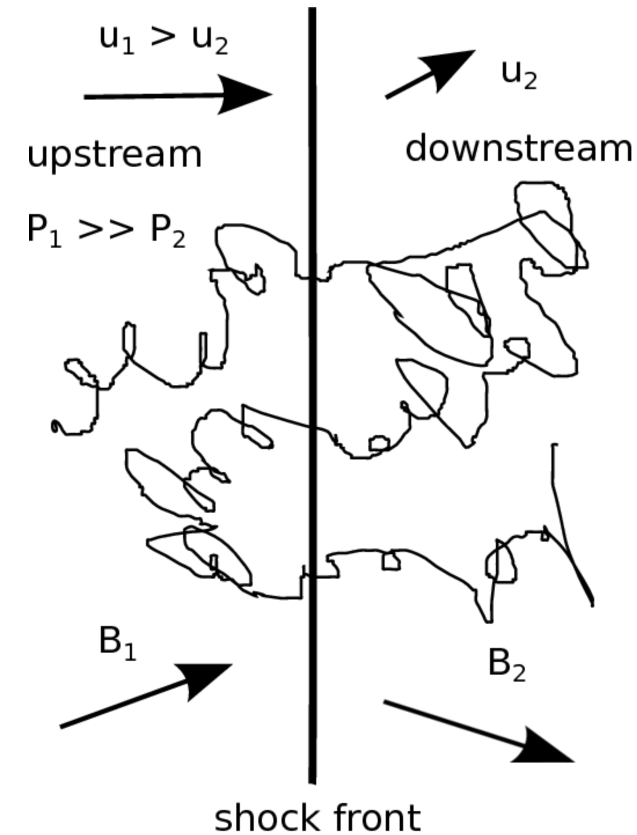
- For strong shock and γ=5/3:

$$\boxed{kT_2 \approx \frac{3}{16}\mu m_\mathrm{p} V_\mathrm{s}^2.}$$

- This is smaller than if all kinetic energy is transferred to thermal energy
  - There is still bulk flow downstream of the shock!

# First order Fermi acceleration/ Diffusive shock acceleration (DSA)




- Discovered independently by four groups (1977-78):
  - Krimsky 1977, Axford+ 1977, Blandford & Ostriker 1978, Bell 1978
- Idea:
  - In shock two plasmas continuously collide: converging flows
  - Only energy gains, no collisional losses (elastic scattering)
  - Particles isotropic momentum distribution both sides of shock
  - Gives a gain that is *linear* in $V_s/v_{part}$: *first order Fermi acceleration*
  - Other name: *diffusive shock acceleration*

# First order Fermi acceleration

- Particles *elastically scatter* on either side of the shock
  - scattering centers: turbulent magnetic fields
- Particles going from upstream to downstream appear to have some excess momentum, but also the other way around:
  $\Delta v = v_1 - v_2 = (1 - 1/\chi)v_1 = (3/4)V_\mathrm{s}$
- Lorentz transformation (with $\Delta v = (3/4)V_\mathrm{s}$): $E = \Gamma_{\Delta v}(E' + p'\Delta v \cos\theta)$

- Non-relativistic shock/rel. particle: $\Gamma \approx 1$, $p = E/c$
  (note flux scales with cos Θ)

$$\left\langle \frac{\Delta E}{E} \right\rangle \approx \frac{2\pi \int_0^{\pi/2} \left(\frac{\Delta v}{c}\cos\theta\right)\cos\theta\sin\theta d\theta}{2\pi \int_0^{\pi/2} \cos\theta\sin\theta d\theta} = \frac{2}{3}\frac{\Delta v}{c}$$

- Full cycle (back and forth):

$$\left\langle \frac{\Delta E}{E} \right\rangle_{\mathrm{fullcycle}} \approx \frac{4}{3}\frac{V_{\mathrm{sh}}}{c}\left(1 - \frac{1}{\chi}\right)$$

- After n full shock crossings (exponential growth):

$$E_N = E_0 \left[1 + \frac{4}{3}\frac{V_\mathrm{s}}{c}\left(1 - \frac{1}{\chi}\right)\right]^N$$

# Expected particle spectrum

- There are two competing processes:
  1. recrossing shock: gaining energy
  2. particles are swept downstream → taken out of acceleration process
- Number rate of particles crossing shock: $\frac{1}{4} n_{cr} c$
- Number rate of particles escaping downstream: $1/X n_{cr} V_s = 1/4 n_{cr} V_s$
  - Escape chance:

$$\mathscr{P}(\text{escape}) = \frac{n(p) v_2}{\frac{1}{4}\beta c n(p)}$$

  - Survival chance after N cycles

$$\mathscr{P}(n \geq N) = \mathscr{P}(E \geq E_N) \approx \left[1 - \frac{4V_{\text{sh}}}{c\chi}\right]^N$$

  - Obtain N from

$$E_N = E_0 \left[1 + \frac{4}{3}\frac{V_{\text{sh}}}{c}\left(1 - \frac{1}{\chi}\right)\right]^N$$

  - Chance for >N cycles (using ln(1+x)≈x)

$$\ln \mathscr{P}(E \geq E_N) = N \ln\left[1 + \frac{4V_{\text{sh}}}{c\chi}\right] = \ln\left(\frac{E_N}{E_0}\right) \frac{\ln\left[1 - \frac{4V_{\text{sh}}}{c\chi}\right]}{\ln\left[1 + \frac{4V_s}{3c}\left(1 - \frac{1}{\chi}\right)\right]}$$

$$\approx -\ln\left(\frac{E_N}{E_0}\right)\frac{3}{\chi - 1},$$

  - This gives integrated spectrum (all N larger than E)
  - Differential spectrum gives

$$q = \frac{3}{\chi - 1} + 1 = \frac{\chi + 2}{\chi - 1}.$$

  - For X=4, q=2

# The convection diffusion equation

- The behaviour of collisionless particles in phase-space (x,p) is determined by the convection-diffusion equation

$$\frac{dn}{dt} + \frac{\partial vn}{\partial x} - \frac{\partial}{\partial x}\left(D\frac{\partial n}{dx}\right) = \frac{1}{3}\left(\frac{\partial v}{\partial x}\right)p\frac{\partial n}{\partial p},$$

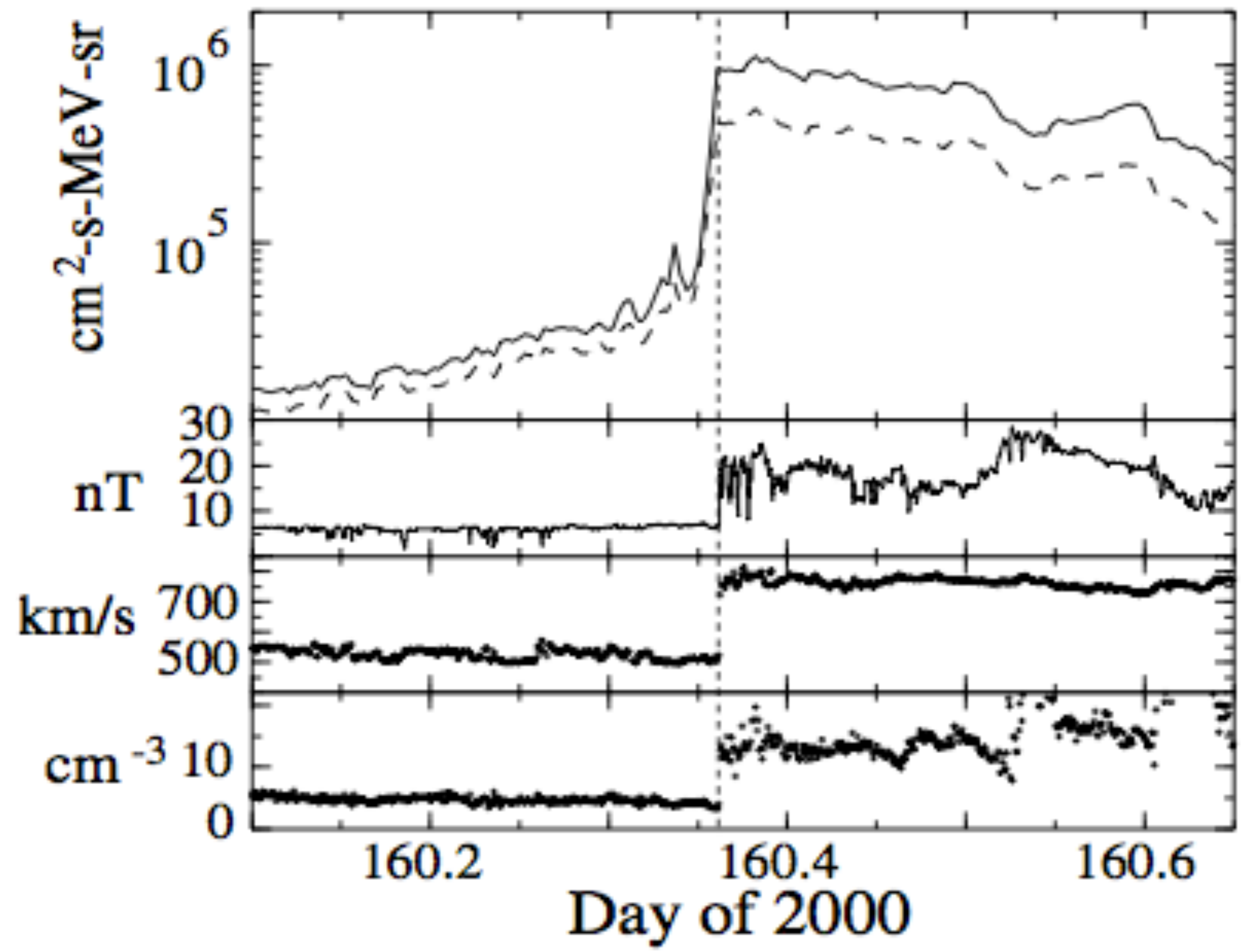
- It is similar to cosmic-ray transport equation
- Here everything is done using momentum (more correct)
- Note that p is a vector, so here one-dimensional changes are considered
- The term on the right-hand side: work done due to volume change
  - A change in v leads to increase in momentum (Liouville's theorem)
- We assume that dn/dt=0 (steady state):
  - at each moment the particle phase-space in the comoving frame looks the same

# The convection diffusion equation

$$\frac{dn}{dt} + \frac{\partial vn}{\partial x} - \frac{\partial}{\partial x}\left(D\frac{\partial n}{dx}\right) = \frac{1}{3}\left(\frac{\partial v}{\partial x}\right) p\frac{\partial n}{\partial p}$$

- Consider the distribution upstream of the shock
  - There v=$v_1$=$V_{sh}$ = constant →$\partial v/\partial x = 0$
  - Steady state in shock frame:dn/dt=0
- Solution: $$\frac{\partial vn}{\partial x} = \frac{\partial}{\partial x}\left(D\frac{\partial n}{dx}\right) \Rightarrow \frac{1}{n}\frac{\partial n}{\partial x} = \frac{v}{D} + C$$
- Hence: $n_1(p,x) = [n_1(p,0) - n_{\rm cr}(p)]\exp\left(-\frac{|x|}{l_{\rm diff}}\right) + n_{\rm cr}(p)$
- Diffusion length scale: $l_{\rm diff} = \frac{D_1}{v_1}$
  - Downstream: same applies, but either pick a constant n(p) or ~~exponentially growing~~.

# An observed accelerating shock: solar system




CME induced shock (ACE, Giaccalone '12)

- Space craft overrun by shock (time coordinate=space coordinate)
- An accelerated shock has less sudden changes
- Gas density/velocity/B-field has steep jump (lower panels)
- But: accelerated particles are found on both sides of the shock
  - In front of shock: exponential fall-off of particles

# Acceleration time scale

- The acceleration time scale (how fast is a certain energy reached)
- How many particles go from upstream to downstream (and vice versa)?
  - Particle flux: $F_{\mathrm{cross}}(p)dp = n_{\mathrm{cr}}(p)\beta c \cos\theta dp$
  - Averaging: $F_{\mathrm{cross}} = n_{\mathrm{cr}}\beta c/4$

- What is the volume from which particles are crossing?
  - Corresponds to length $$l = \int_0^\infty \exp\left(-\frac{xD}{v}\right)dx \approx \int_0^\infty \exp\left(-\frac{x}{l_{\mathrm{diff}}}\right)dx = l_{\mathrm{diff}}.$$
  - So volume is $Al_{\mathrm{diff}}$
- Average time: $\Delta t = n_{\mathrm{cr}}(p)Al_{\mathrm{diff}}/(AF_{\mathrm{cross}})$
- Hence:

$$\Delta t = \frac{4}{\beta c}(l_{\mathrm{diff},1} + l_{\mathrm{diff},2}) = \frac{4}{\beta c}\left(\frac{D_1}{v_1} + \frac{D_2}{v_2}\right)$$

$$\frac{dE}{dt} \approx \frac{\Delta E}{\Delta t} = \frac{\frac{4}{3}\frac{\Delta v}{c}E}{\frac{4}{\beta c}\left(\frac{D_1}{v_1} + \frac{D_2}{v_2}\right)} \approx \frac{(v_1 - v_2)}{3}\frac{E}{\frac{D_1}{v_1} + \frac{D_2}{v_2}}$$

- Acceleration time $$t_{\mathrm{acc}} = \frac{3}{v_1 - v_2}\int_{E_0}^{E}\left(\frac{D_1(E')}{v_1} + \frac{D_2(E')}{v_2}\right)\frac{dE'}{E'}.$$

# Dependence on shock velocity

- Describe the diffusion coefficient as $D_1 = \frac{1}{3}\eta_{\max}\left(\frac{E}{E_{\max}}\right)^{\delta-1}\frac{cE}{eZB}$
- Assume η constant upstream/downstream
- Assume a magnetic compression $1<\chi_B<4$

$$
\begin{aligned}
t_{\rm acc} &= \frac{3\chi}{V_{\rm sh}^2(\chi-1)}\left(1+\frac{\chi}{\chi_B}\right)\int_{E_0}^{E_{\max}} D_1\frac{dE}{E}\\
&= 3E_{\max}V_{\rm sh}^{-2}\left(1+\frac{\chi}{\chi_B}\right)\left(\frac{\chi}{\chi-1}\right)\frac{\eta_{\max}}{\delta}\frac{c}{eZB_1}\left[1-\left(\frac{E_0}{E_{\max}}\right)^{\delta}\right] =\\
&\approx 3\delta^{-1}\left(1+\frac{\chi}{\chi_B}\right)\left(\frac{\chi}{\chi-1}\right)\frac{D_1(E_{\max})}{V_{\rm sh}^2}\\
&\approx 1014\frac{\eta_{\max}}{\delta Z}\left(\frac{E_{\max}}{10^{14}\ {\rm eV}}\right)\left(\frac{V_{\rm sh}}{5000\,{\rm km\ s^{-1}}}\right)^{-2}\left(\frac{B_1}{10\ \mu{\rm G}}\right)^{-1}\frac{\left(1+\frac{\chi}{\chi_B}\right)\left(\frac{\chi}{\chi-1}\right)}{8/3}\ {\rm yr}
\end{aligned}
$$

- We see $E_{\max} \propto \eta^{-1} t B V_s^2$
- In order to reach “knee” we need:
  - high shock velocity (>5000 km/s)
  - long time scales (>1000 yr)
  - and/or: high magnetic field (B>10 μG)
  - turbulent magnetic field $\eta \approx 1$
- Bottom line: difficult to reach $10^{15}$eV in 1000 yr

# The problem with reaching the "knee"

## The maximum energy of cosmic rays accelerated by supernova shocks

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**Summary.** The aim of this paper is to evaluate the maximum energy $E_{max}$ that particles subjected to the process of diffusive shock acceleration can acquire during the lifetime of a supernova remnant. The rate of acceleration depends on the particle diffusion coefficient, which is determined by the level of hydromagnetic wave energy present at a scale comparable to the particle Larmor radius. We study the variations of the diffusion coefficient as a function of momentum, space, and time.

In the most optimistic case, the diffusion mean free path is everywhere comparable to the particle Larmor radius; then $E_{max} \sim 10^5$ GeV/n. Considering a more realistic behaviour of the diffusion coefficient, we obtain $E_{max} \lesssim 10^4$ GeV/n. Thus, supernova shock acceleration cannot account for the observed spectrum of galactic cosmic rays in the whole energy range $1$–$10^6$ GeV/n.

**Key words:** cosmic-ray acceleration – shock waves – hydromagnetic waves

interstellar turbulence, responsible for the scattering of cosmic rays throughout the galaxy. We find that, if only this turbulence were available, the acceleration process would be so slow that during the lifetime of a supernova remnant a particle can at most acquire a few GeV.

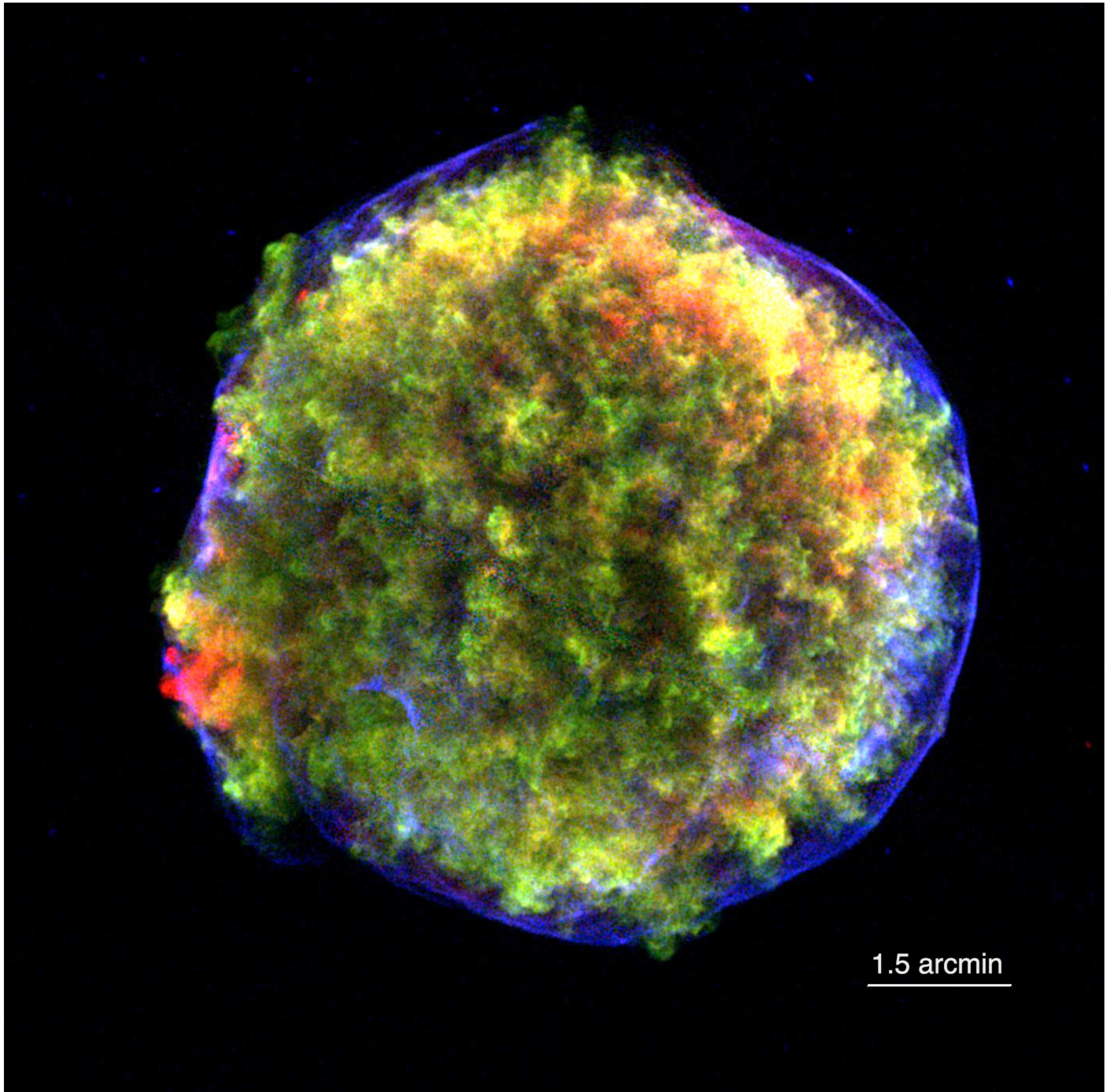
In fact, in the vicinity of the shock, the level of turbulence is expected to be much above that of an average region of the interstellar medium. Upstream of the shock, the flux of cosmic rays interacting with the shock is highly anisotropic, and thus very unstable to the generation of hydromagnetic waves. These waves are in turn amplified by the shock, so that the downstream region must also be highly turbulent. Section III is devoted to the study of this self-generated turbulence, and its effect on cosmic ray diffusion. The rate of wave generation increases with the cosmic ray flux, and thus depends on the rate of injection of particles in the acceleration mechanism. We find that when the damping of the turbulence is ignored, the steady state solutions predict a cosmic ray diffusion coefficient at the shock which is below its lowest

# Summary: shocks and diffusive shock acceleration

- Astrophysical shocks common in/around high energy sources
- Astrophysical shocks are often *collisionless*
- Shocks are governed by flux conservation laws
- Important parameter: Mach number
- For high Mach numbers: compression ratio NR shocks X=4

- Fermi shock acceleration (=DSA) occurs due to particles bouncing between two shock regions (upstream-downstream) + elastic scattering
- Each shock crossing leads to energy/momentum gain $dp/p \propto V_s/c$
- Downstream: small chance in each cycle particle will move too far from shock → loss of particles
- Upstream exponentially falling off population of particles:
  - *cosmic-ray shock precursor*
- Combination of exponential momentum gain/exponential rising likelihood of having escaped gives *power law spectrum*
- *Spectral power law slope depends on shock compression ratio*
- *X=4* → *q*=2 (close to what is needed to explain cosmic rays)
- Maximum energy scales with $\eta^{-1}$,B,t, $V_{sh}^2$

# 7 X-ray synchrotron emission and magnetic fields



# Importance of magnetic field

- The speed of acceleration depends on B and magnetic field turbulence (contained in η):

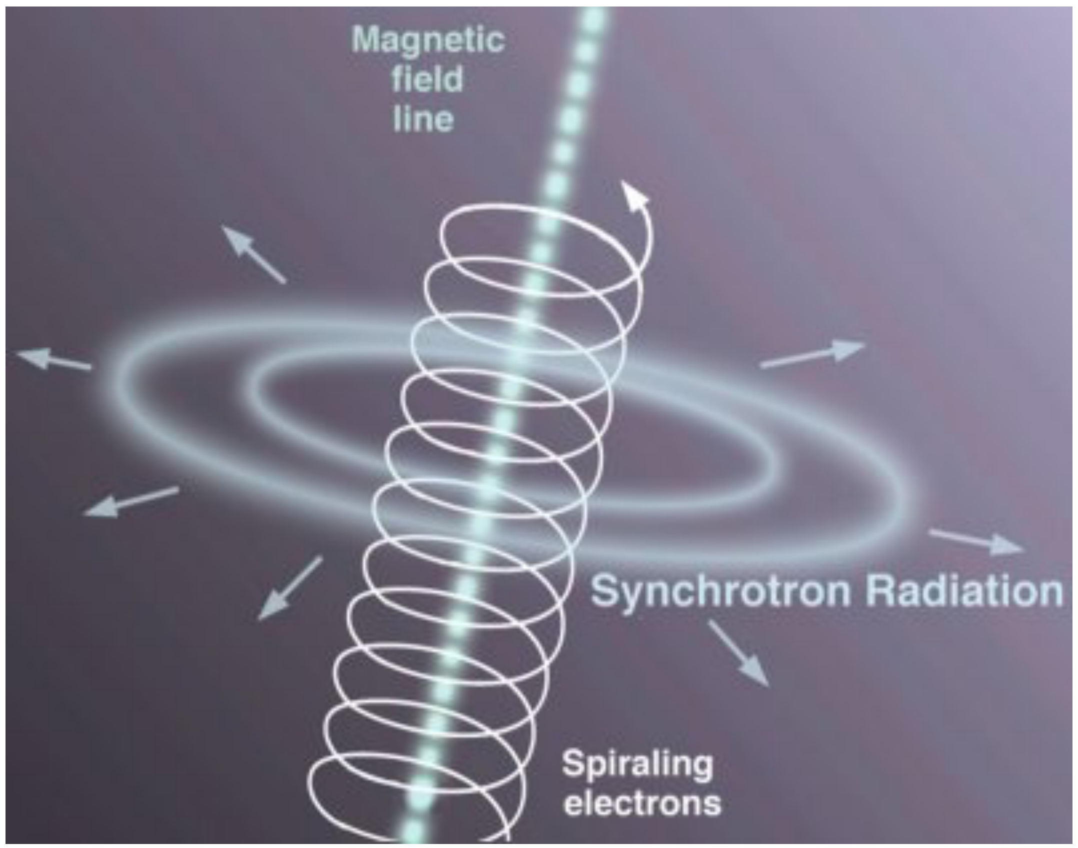
$$t_{\rm acc} = \frac{3}{v_1 - v_2}\int_{p_1}^{p_2}\left(\frac{D_1}{v_1}+\frac{D_2}{v_2}\right)\frac{dp}{p} \qquad D = \frac{1}{3}\eta\frac{cE}{eB}$$

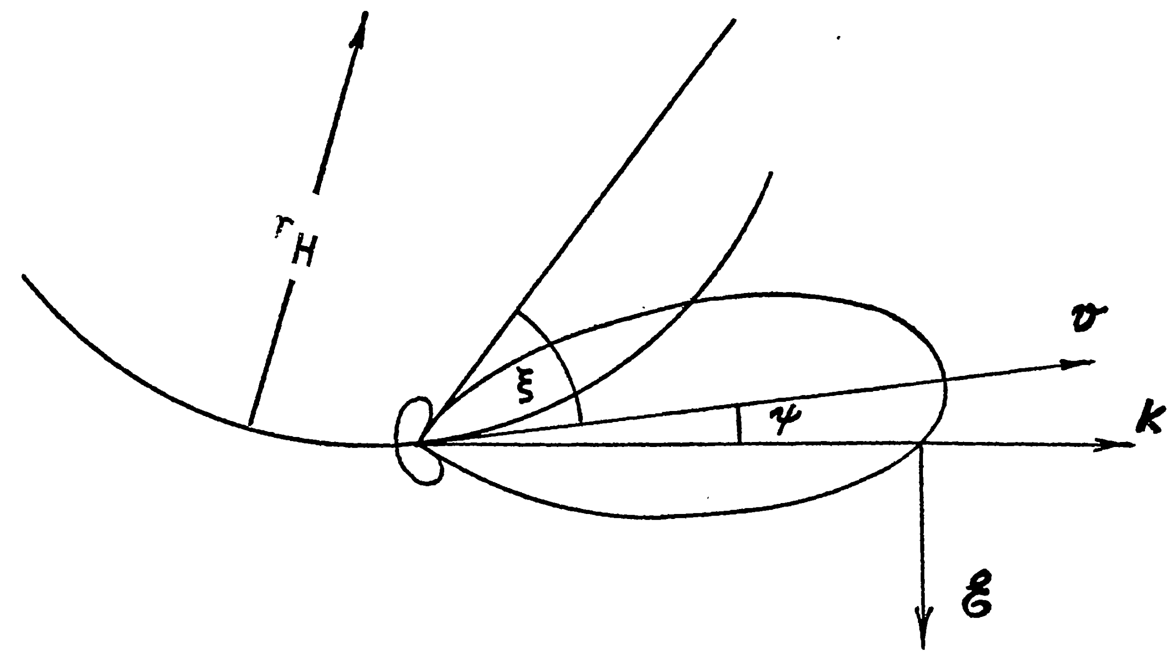
- Maximum energy of electrons/protons/particles, either:
  - escape (mean free path $\gtrsim$ 0.1 $R_s$)
  - energy losses (electrons)
  - adiabatic losses
  - time available!

- In 1980ies: assume $B=B_{ISM}\approx 5\mu G$ and $\eta>100$

  → not possible for $V\approx5000$ km/s to accelerate to $3\times10^{15}$eV

# Synchrotron radiation




Ginzburg & Syrovatskii '65

# Synchrotron emission

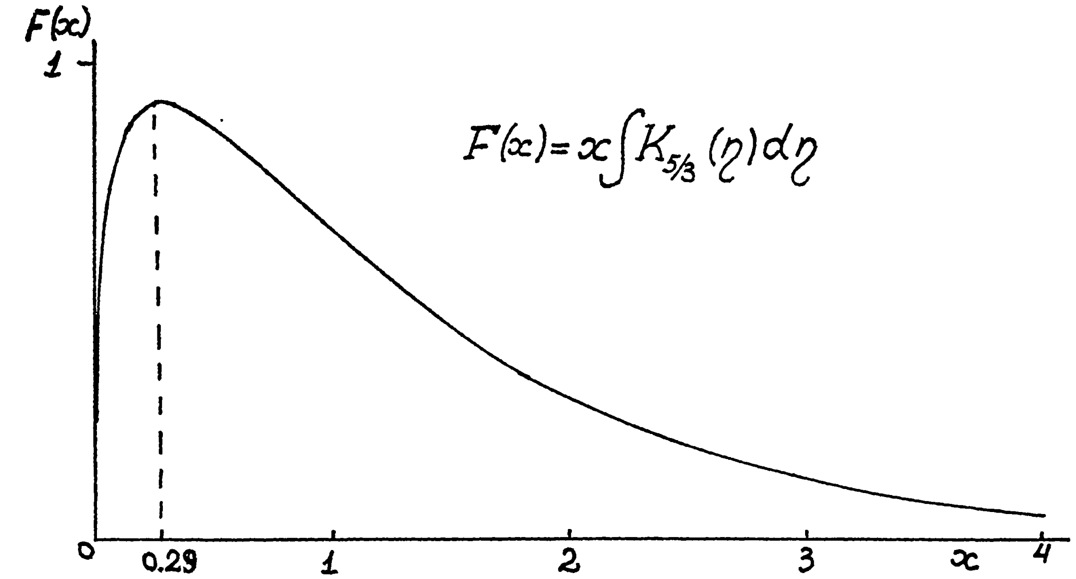



FIG. 7. The spectral distribution of the power of the total (over all directions) radiation from charged particles moving in a magnetic field.

- Expected frequency

$$\nu_{\rm max} = 0.29\nu_{\rm c} = 1.8\times10^{18} B_\perp E^2$$
$$= 0.46 \left(\frac{B_\perp}{100\mu{\rm G}}\right)\left(\frac{E}{\rm GeV}\right)^2 {\rm GHz}$$
$$E_{\rm max} = 0.19 \left(\frac{B_\perp}{100\mu{\rm G}}\right)\left(\frac{E}{10{\rm TeV}}\right)^2 {\rm keV}$$

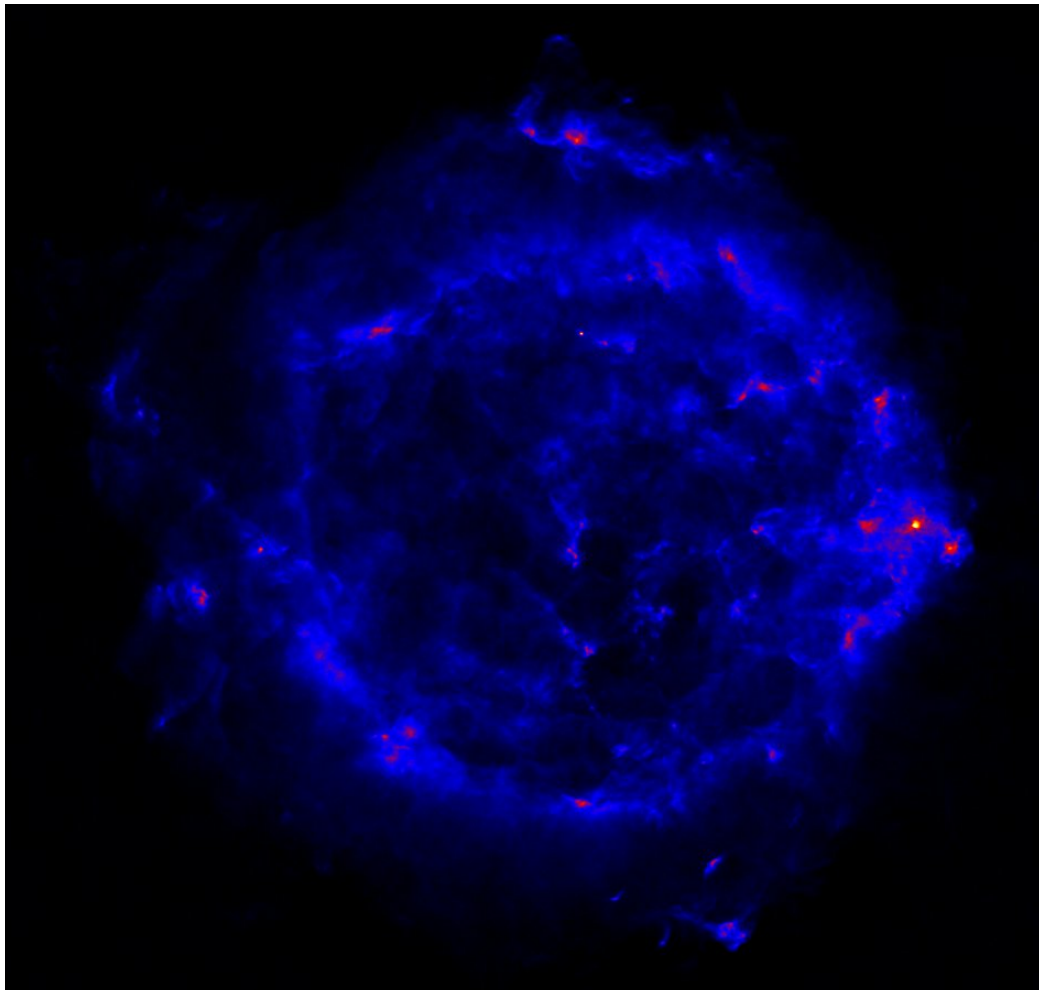
- Total synchrotron power

$$P_{\rm syn} = \frac{2}{3}\frac{e^2}{m_{\rm e}^2 c^3}\gamma^2 (e\beta B_\perp)^2 \longrightarrow P_{\rm syn} = \frac{4}{3}\sigma_{\rm T} c\beta^2\gamma^2 U_{\rm B}$$

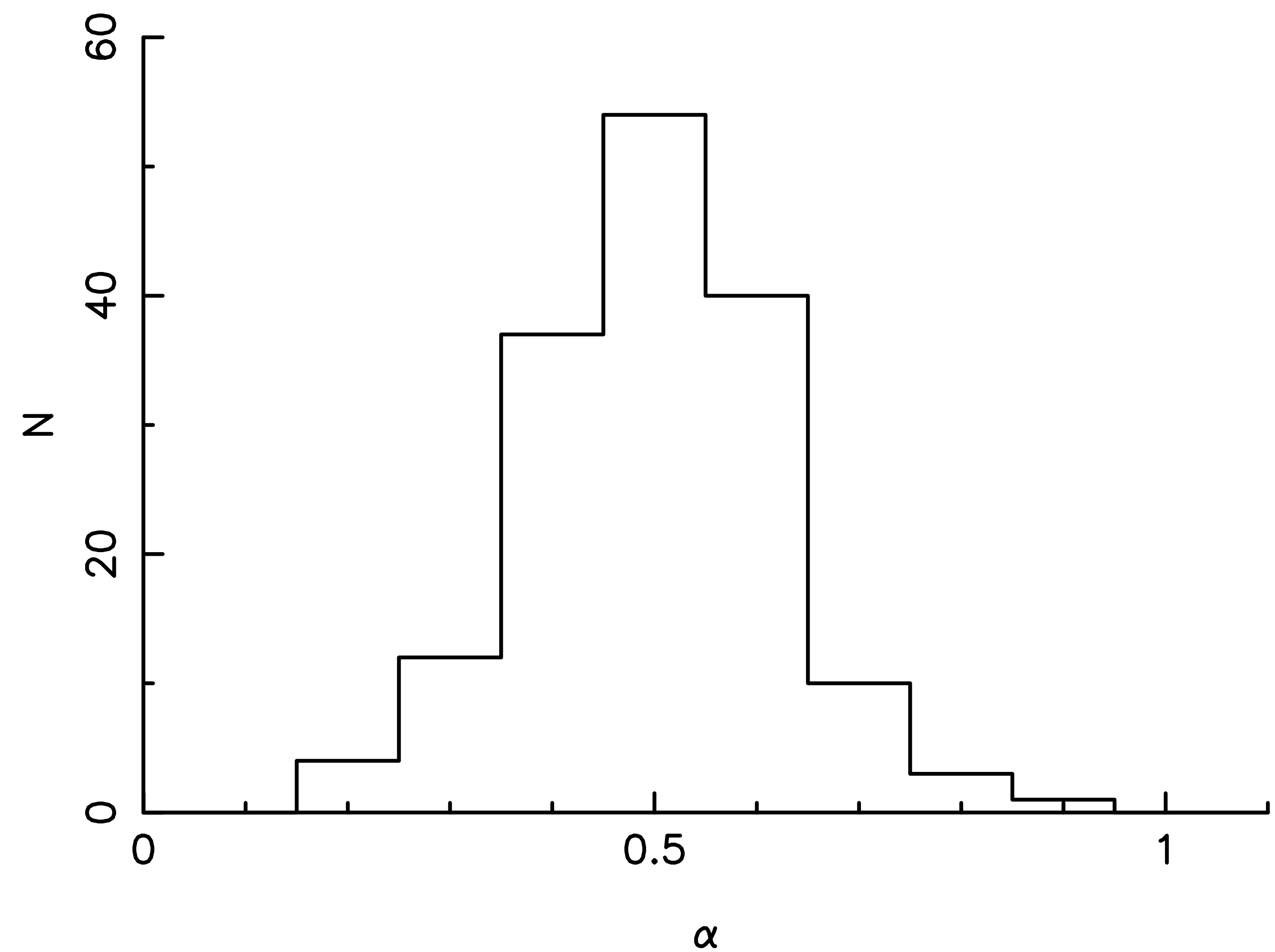
$$\sigma_{\rm T} \equiv \frac{8\pi}{3}\left(\frac{e^2}{m_{\rm e}c^2}\right)^2 = \frac{8\pi}{3} r_{\rm e}^2 = 6.6524\times10^{-25}\ {\rm cm}^2 \qquad U_{\rm B} = \frac{B^2}{8\pi}$$

- Electron pl index q, **α=(q-1)/2, Γ=α+1**
- For power-law index with exponential cut-off or broken power:
  - Peak SED where power steepens beyond: **α=1 (Γ=2)**:

# Radio spectral index

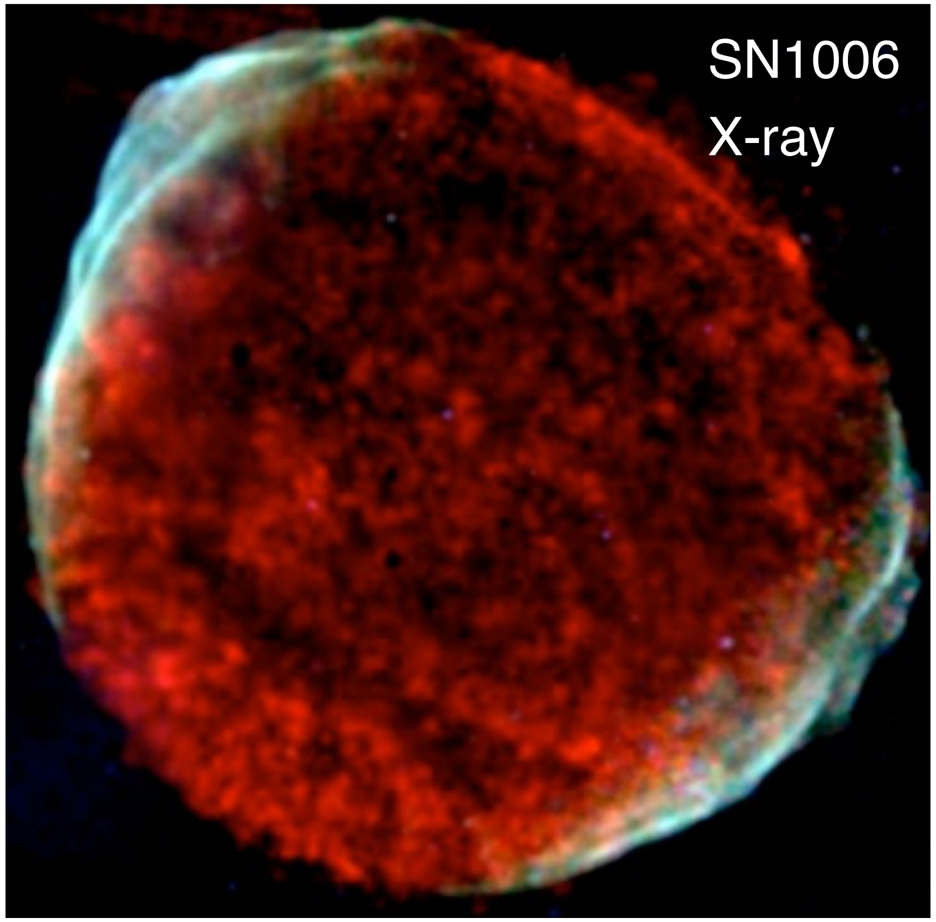


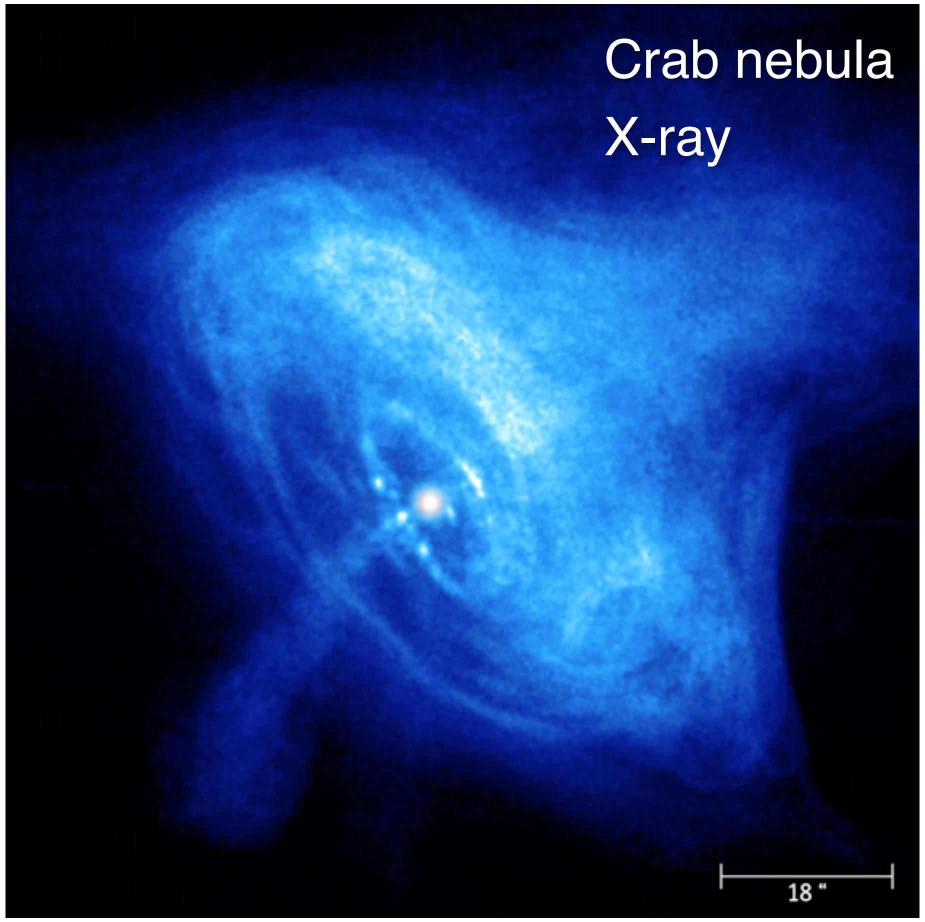
Cas A (VLA)




- 1st order fermi acceleration predicts $q \approx 2$
- Today: radio spectral index $\alpha = (q-1)/2 \approx 0.5$
- Agrees with radio observations, but large variance
- Radio observations: first evidence for accelerated particles (electrons) in SNRs

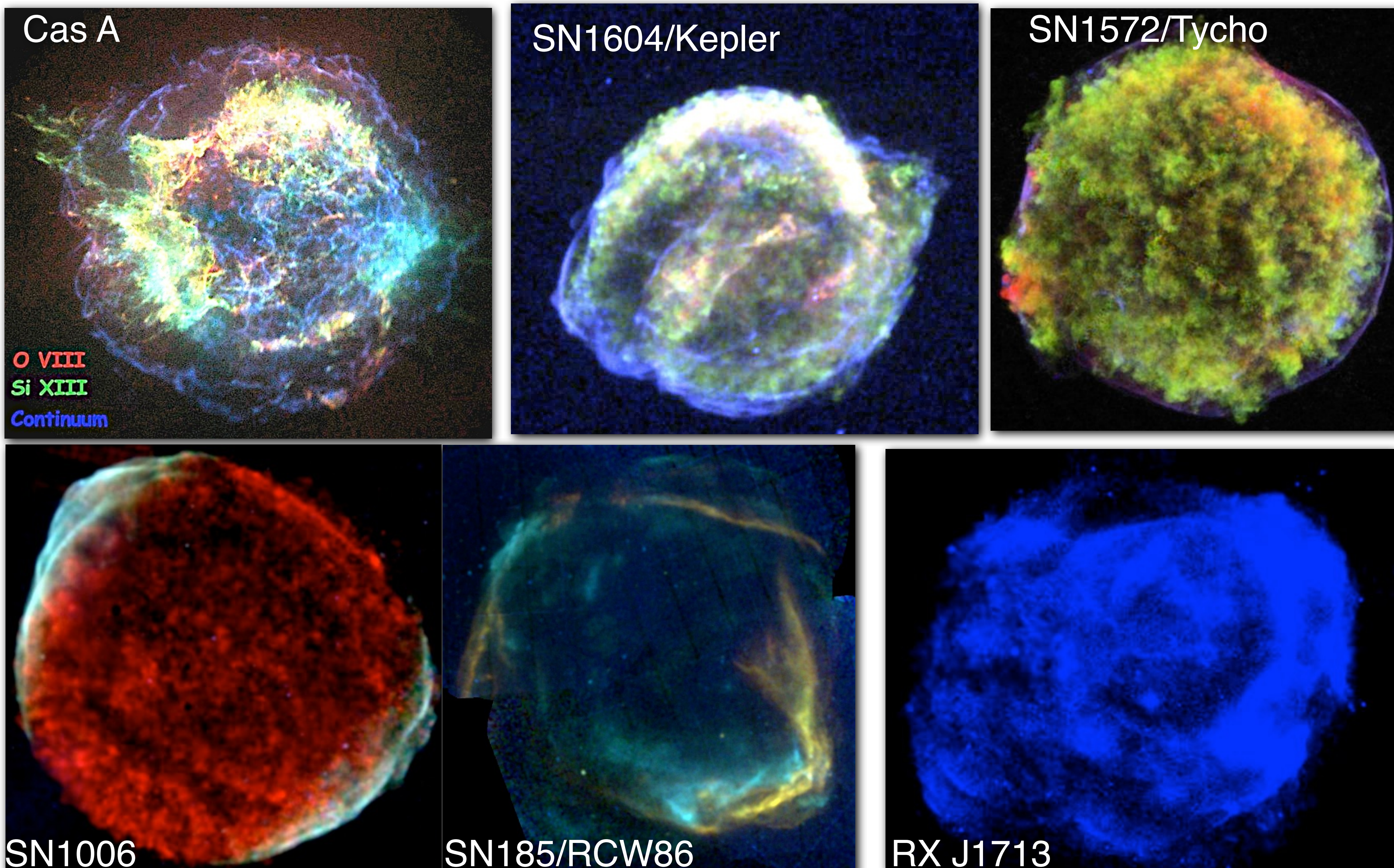
# X-ray synchrotron emission




- X-ray synchrotron emission first proven in 1995 for SN1006 by Koyama et al.
  - For SNRs. For PWNe much longer known (e.g. Crab nebula)
- X-ray synchrotron emission implies presence of 10-100 TeV electrons!!
- 10-100 TeV can cool very fast → information on where electrons are accelerated

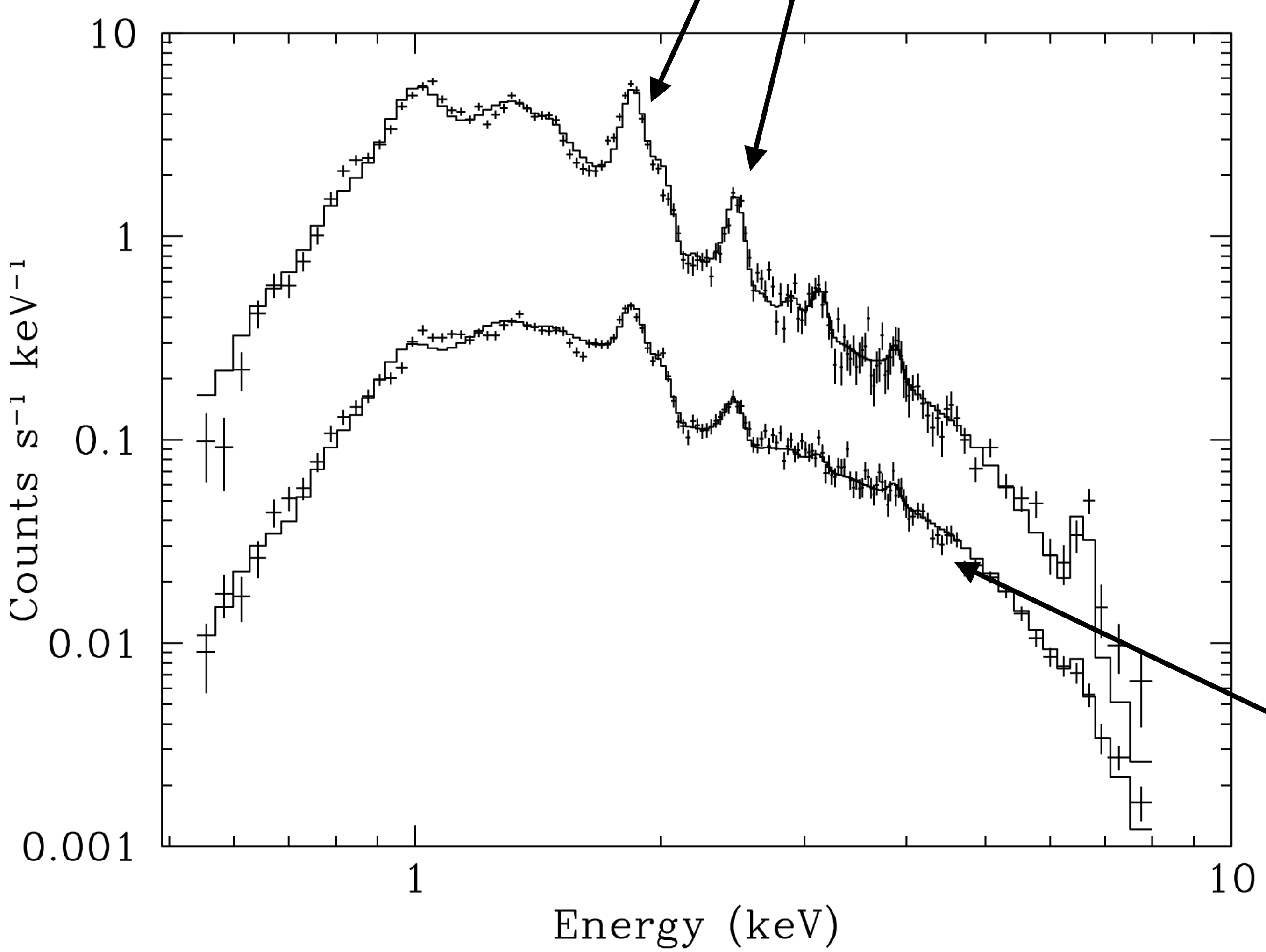
# X-ray images of young supernova remnants



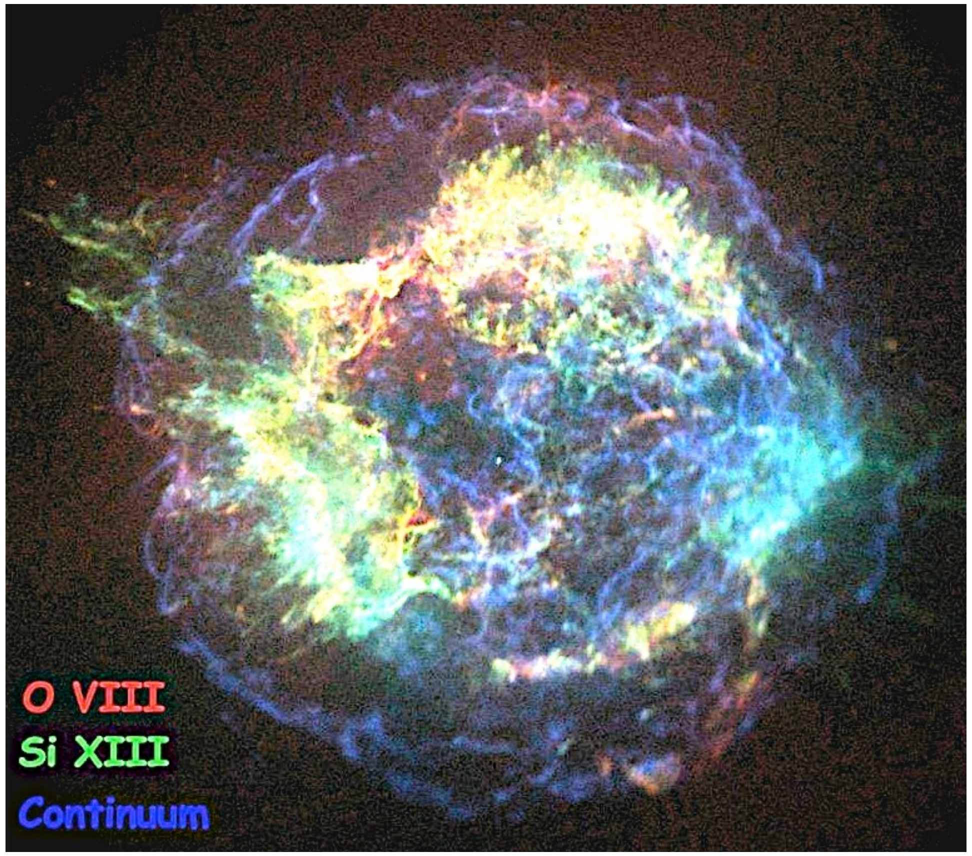

- Since 1995 many identifications of X-ray synchrotron emission from young SNRs
- Some SNRs: no X-ray line emission → X-ray synchrotron dominated (e.g RXJ1713)
  - Why do we not detect hot, line emitting plasma?

# X-ray spectrum from two regions Cas A

X-ray emission lines (thermal plasma)




X-ray continuum emission (mostly X-ray synchrotron)



# Loss limited versus age limited electron spectra

- The maximum photon energy (or exponential break) is determined either by
  1) how much time was there to accelerate electrons?: *age limited*
  2) at what energy: acceleration gains=radiation losses?: *loss limited*
- Most young SNRs seem to have loss limited spectra (but discussion ongoing)
- For loss limited case, *characteristic cut-off frequency independent of B:*
  - Comparing loss- and acceleration time scales:

$$\tau_{\rm syn} = \frac{E}{P_{\rm syn}} \approx \frac{634}{B^2E}, \qquad \tau_{\rm acc} \propto \frac{D}{V_{\rm s}^2} \propto \frac{E}{BV_{\rm s}^2}$$

  - $E_{max}$: $\tau_{\rm syn} \approx \tau_{\rm acc} \Rightarrow \frac{1}{B^2E_{\rm max}} \approx \frac{CE_{\rm max}}{BV_{\rm s}^2} \Rightarrow E_{\rm max}^2 \propto \frac{V_{\rm s}^2}{B}$
  - Dependence photon energy on E and B: $h\nu \propto E^2B \quad \rightarrow \quad h\nu_{\rm max} \propto V_{\rm s}^2$

- Taking account of all constants etc.:

$$h\nu_{\rm max} = 1.4\eta^{-1}\left(\frac{\chi_4 - \frac{1}{4}}{\chi_4^2}\right)\left(\frac{V_s}{5000\ {\rm km\,s^{-1}}}\right)^2\ {\rm keV}$$

# Implications X-ray synchrotron emission

- Synchrotron emissivity profile broad: gradual steepening beyond break
- Fact that young SNRs are synchrotron emitters: acceleration must proceed close to Bohm-diffusion limit!

$$\eta \lesssim 10$$

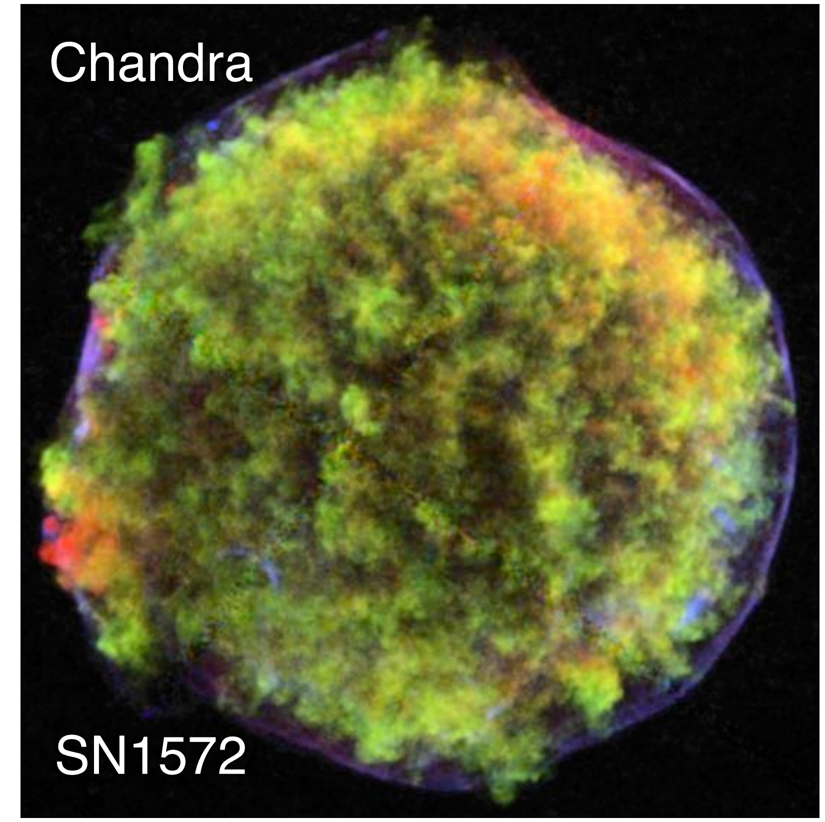
- The higher the B-field -> faster acceleration, but for electrons: $E_{max}$ lower!
- For B=10-100 μG: presence of $10^{13}$-$10^{14}$ eV electrons
- Loss times are:

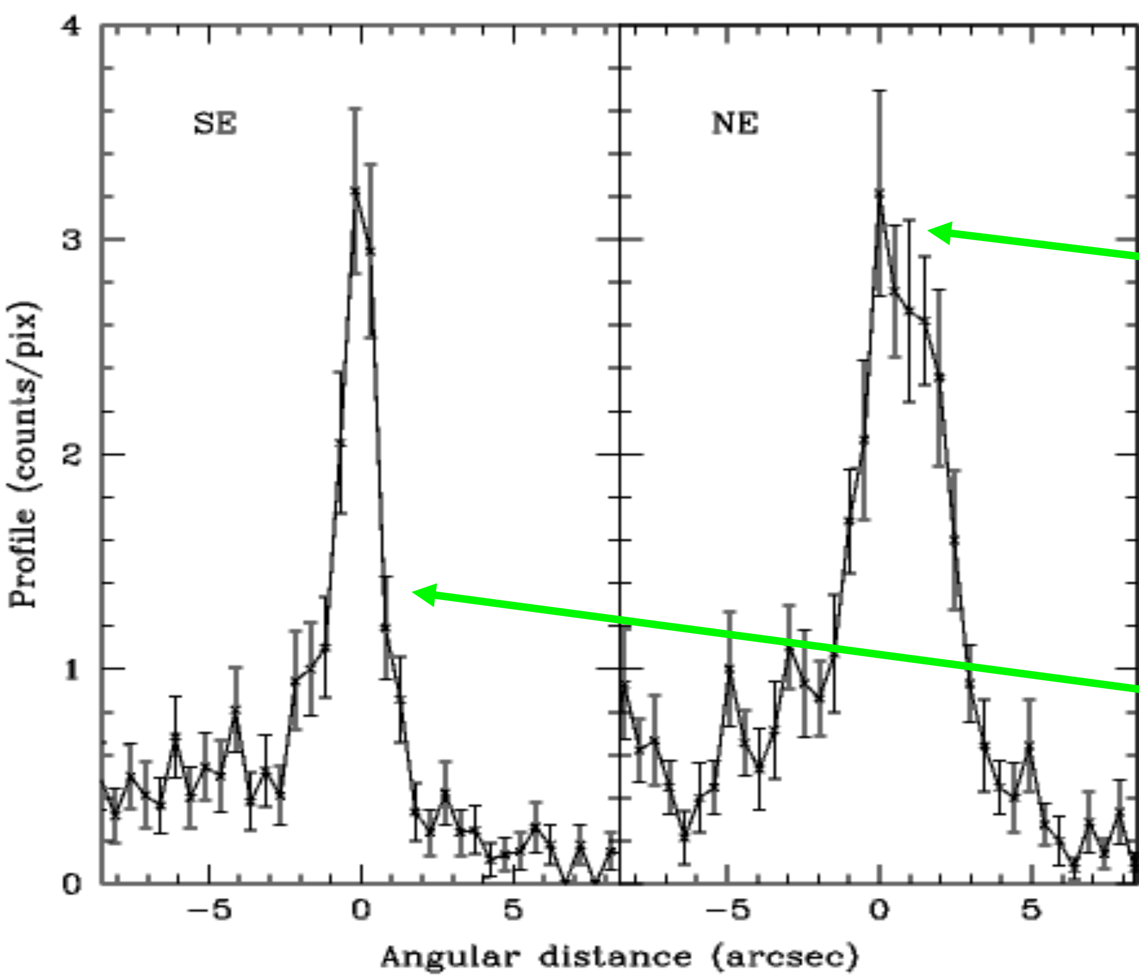
$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100\ {\rm TeV}}\right)^{-1} \left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2}\ {\rm yr}.$$

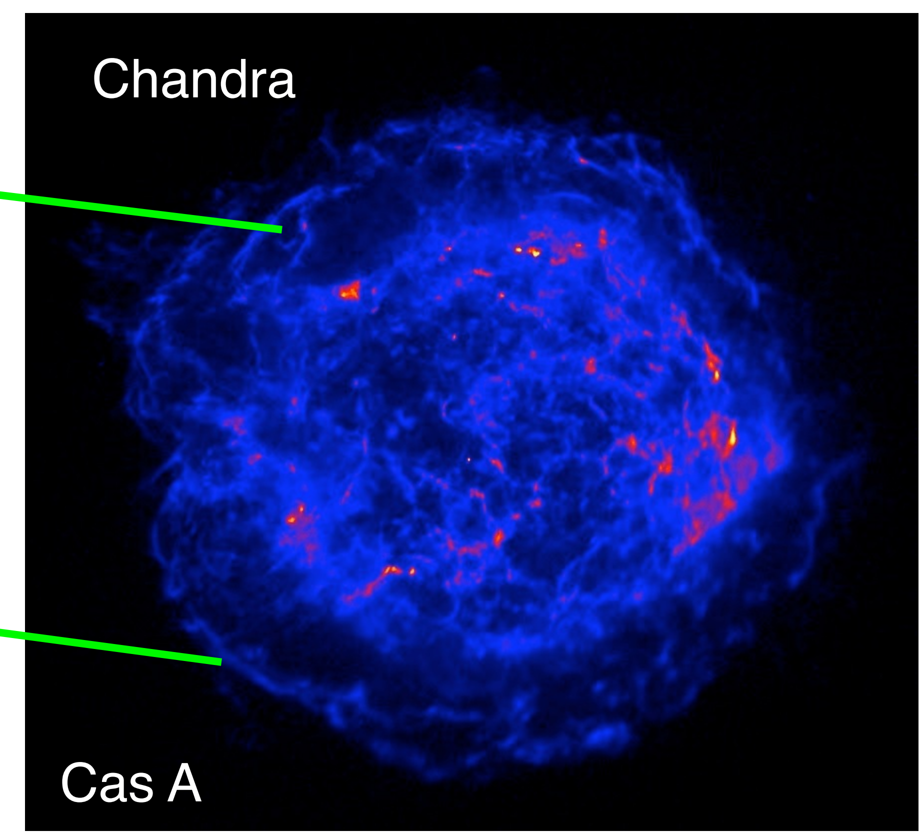
X-ray synchrotron emission tells us that
- electrons can be accelerated fast (≈10-100 yr)
- that acceleration is still ongoing (loss times ≈10-100 yr)
- that particles can be accelerated at least up to $10^{14}$ eV

# Narrow X-ray synchrotron filaments

- In some cases X-ray synchrotron filaments appear very narrow (1-4")
- Correcting projection effects: l≈$10^{17}$cm



# Why are the synchrotron filaments narrow?

•Two possible ways of reasoning:

- length scale associated with synchrotron loss time & advections:

$$l_{\rm adv} = \tau_{\rm syn}\Delta v = \tau_{\rm syn}\frac{V_s}{\chi}$$

- length scale corresponds to diffusion length scale of 10-100 TeV electrons:

$$l_{\rm diff} = \frac{D_2}{v_2} = \frac{\chi}{3}\frac{\lambda_{\rm mfp}c}{V_{\rm s}} = \frac{\chi}{3}\eta\frac{E}{eB}$$

• Turns out the two are more or less equivalent

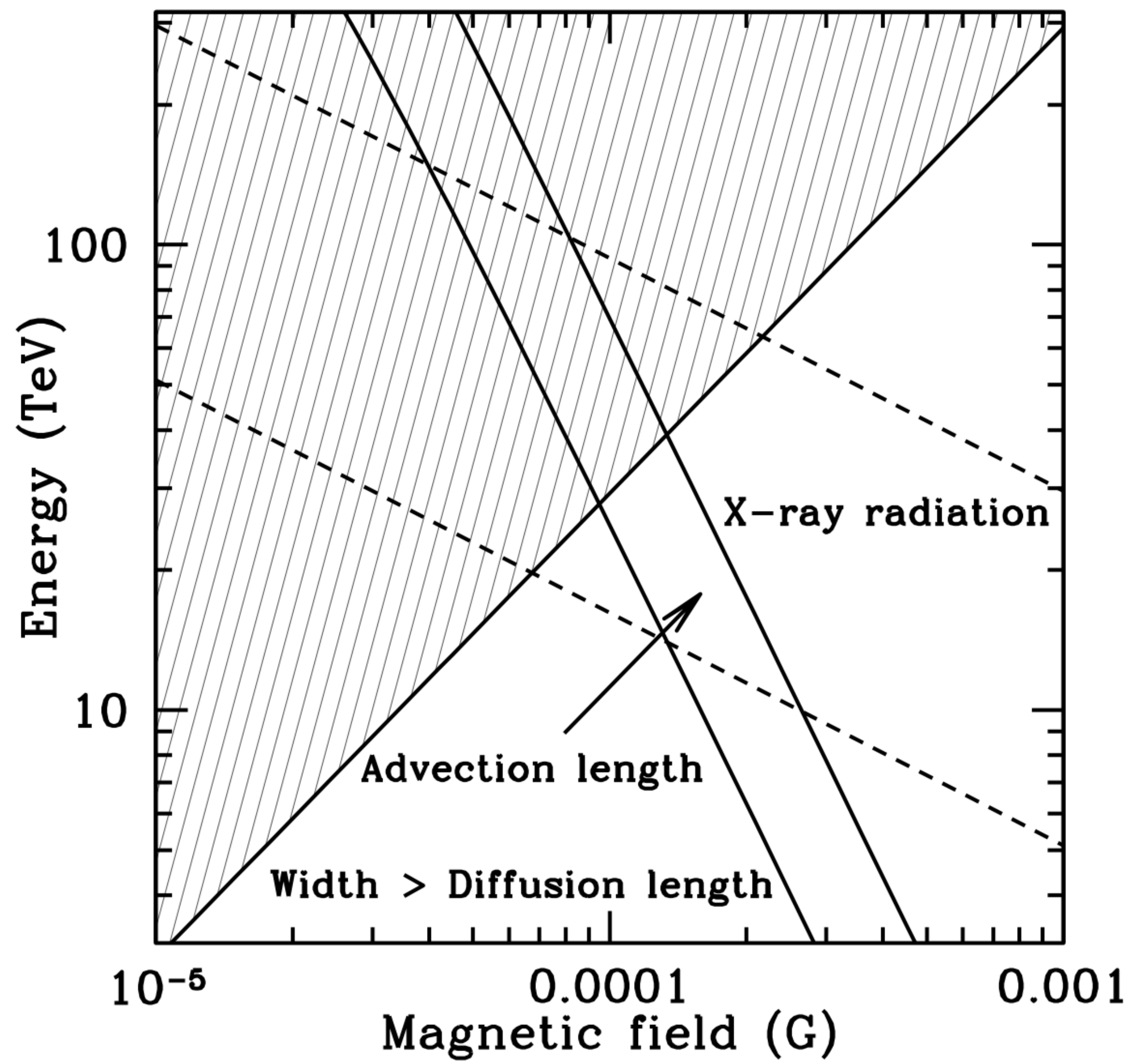
$$\tau_{\rm acc} = \frac{2D}{\Delta v^2} = \frac{l_{\rm diff}}{\Delta v}$$

$$\tau_{\rm syn} = \frac{l_{\rm adv}}{\Delta v}$$

• So near break frequency: $\tau_{\rm syn} \approx \tau_{\rm acc} \leftrightarrow l_{\rm adv} \approx l_{\rm diff}$

• Combining advection/diffsion: $B_2 \approx 26\left(\frac{l_{\rm adv}}{1.0\times10^{18}{\rm cm}}\right)^{-2/3}\eta^{1/3}\left(\chi_4 - \frac{1}{4}\right)^{-1/3}\ \mu{\rm G}$

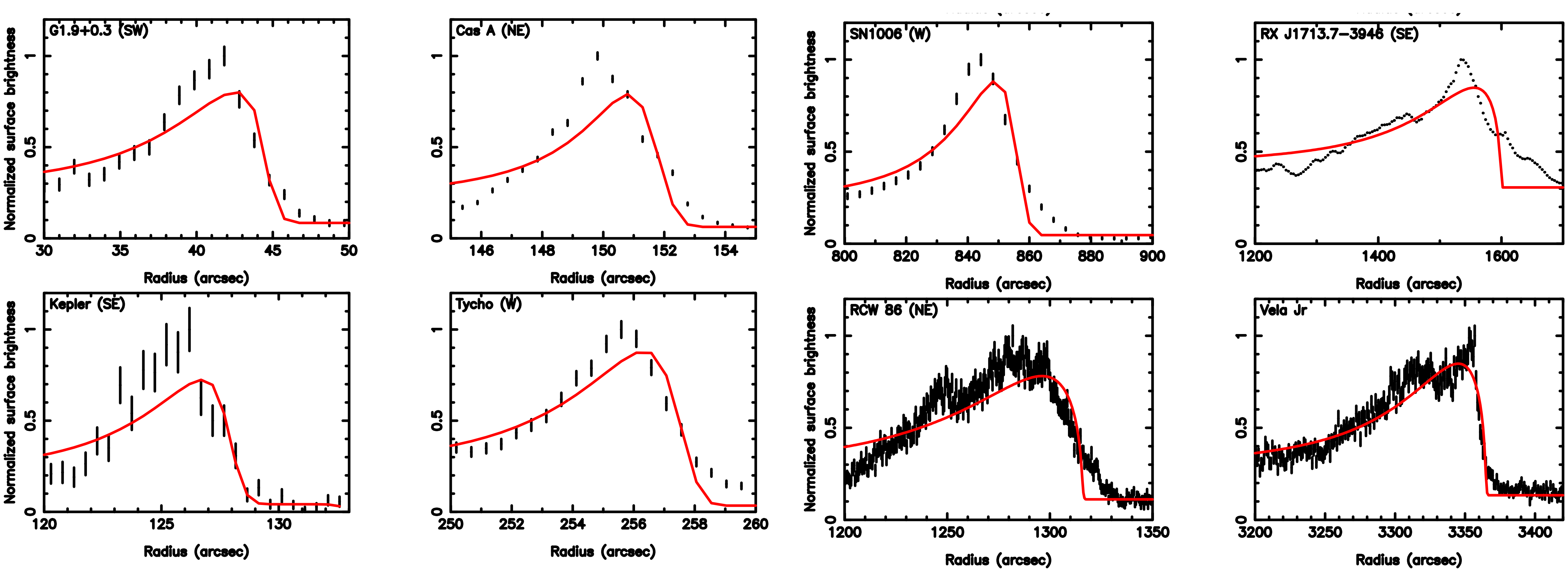
# Diagram: using width/photon energy to decouple electron energy and magnetic field




Vink&Laming 2003

- Narrowness filaments: magnetic field near shock front is rather high 100-500 μG

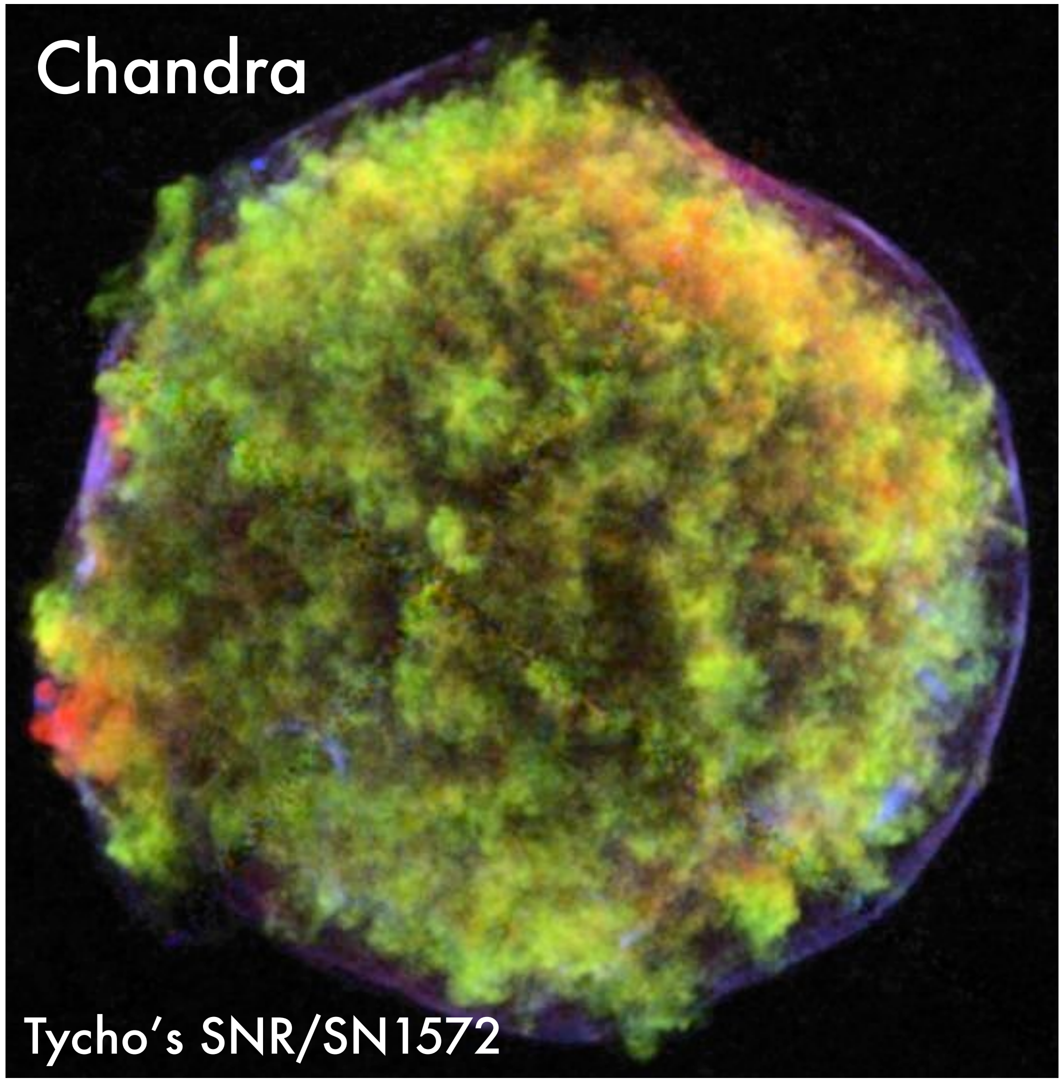
# X-ray synchrotron profiles

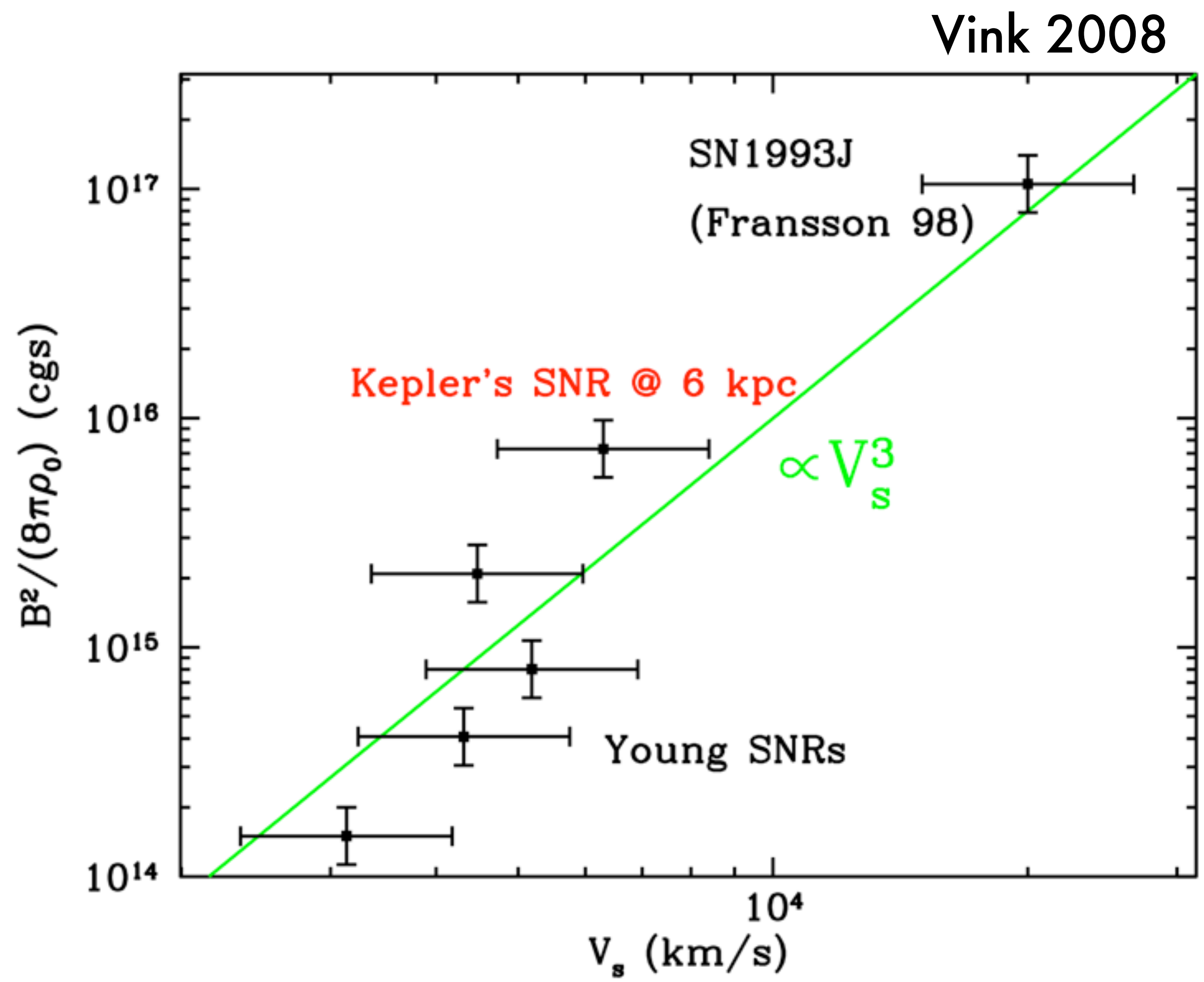



Helder, JV, et al. 2012

- Model: sudden increase at shock + exponential fall off (projected)
- Models do generally not fit very well (exception Vela jr)
- Some filaments (e.g. Cas A & SN1572) very narrow: <1″ or $10^{17}$cm

# Evidence for magnetic field amplification

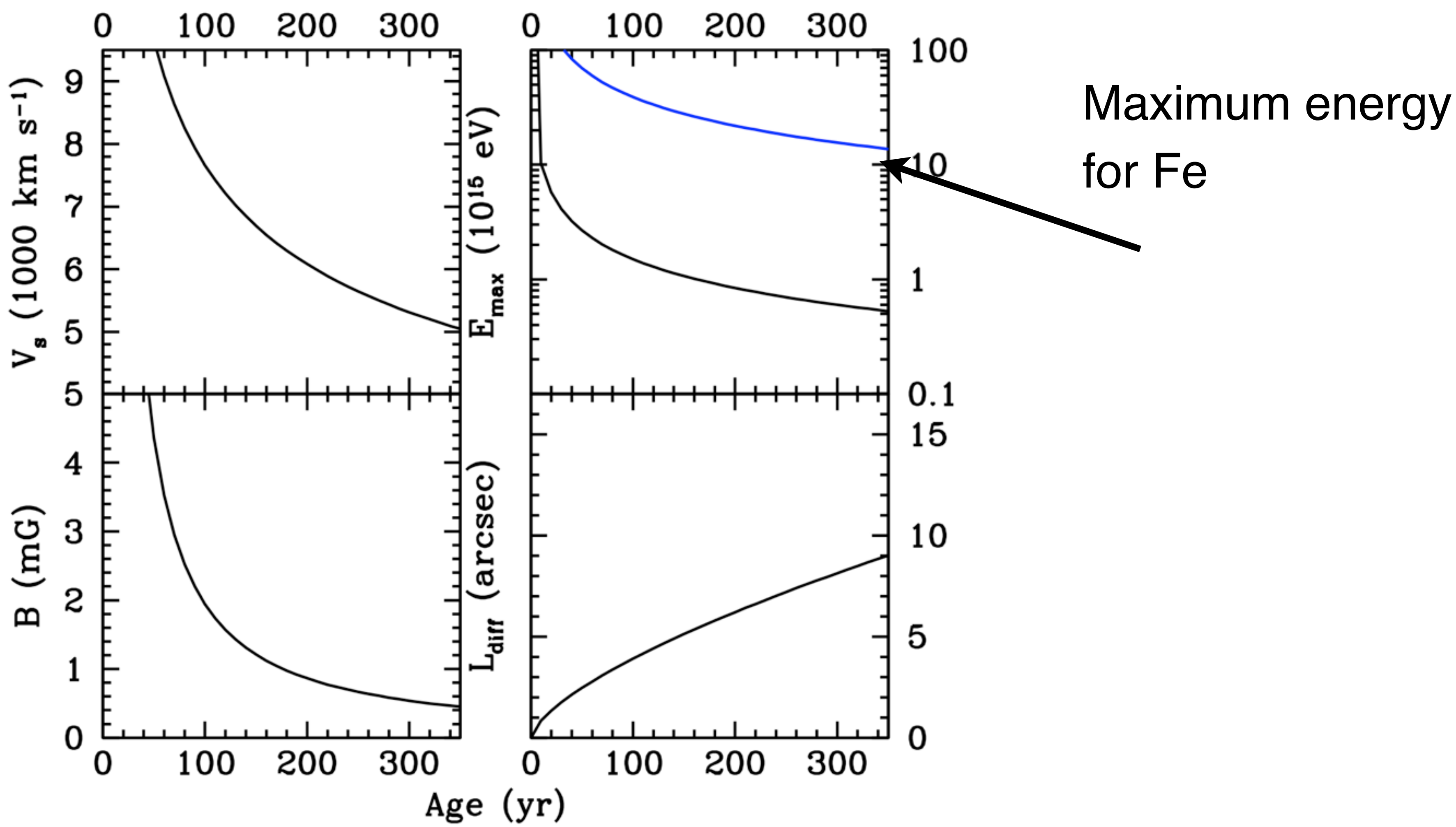



- X-ray synchrotron confined to shock region:
  synchrotron energy losses large ⇒ B-fields must be large (100-500 μG)
- X-ray synchrotron radiation only possible with fast acceleration
- *Cosmic rays likely amplify magnetic fields and make them turbulent!*
  - *Evidence that* $B^2 \propto \rho V_s^3$ *(or* $\rho V_s^2$*):*

    *at higher densities faster shocks: faster acceleration*

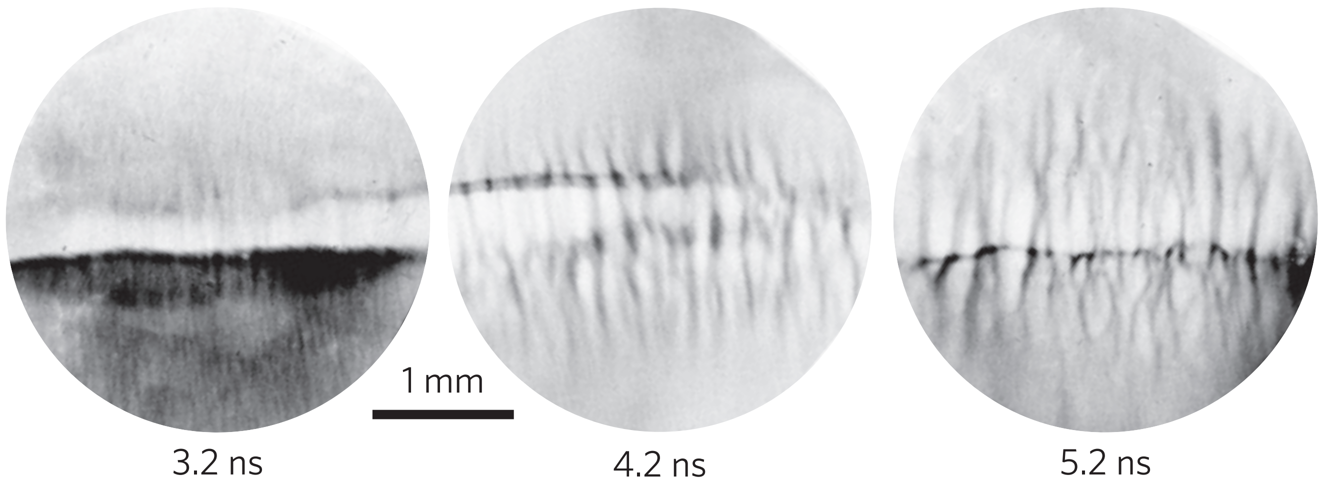
# Toy model for past acceleration Cas A




- Using relation $B^2 \propto \rho V s^3$
- Using current age, velocity for Cas A
- Suggests that maximum energy was reached in the past!!

# 8 Magnetic field amplification

Experimental proton radiographs from 14.7 MeV (D–$^3$He) protons

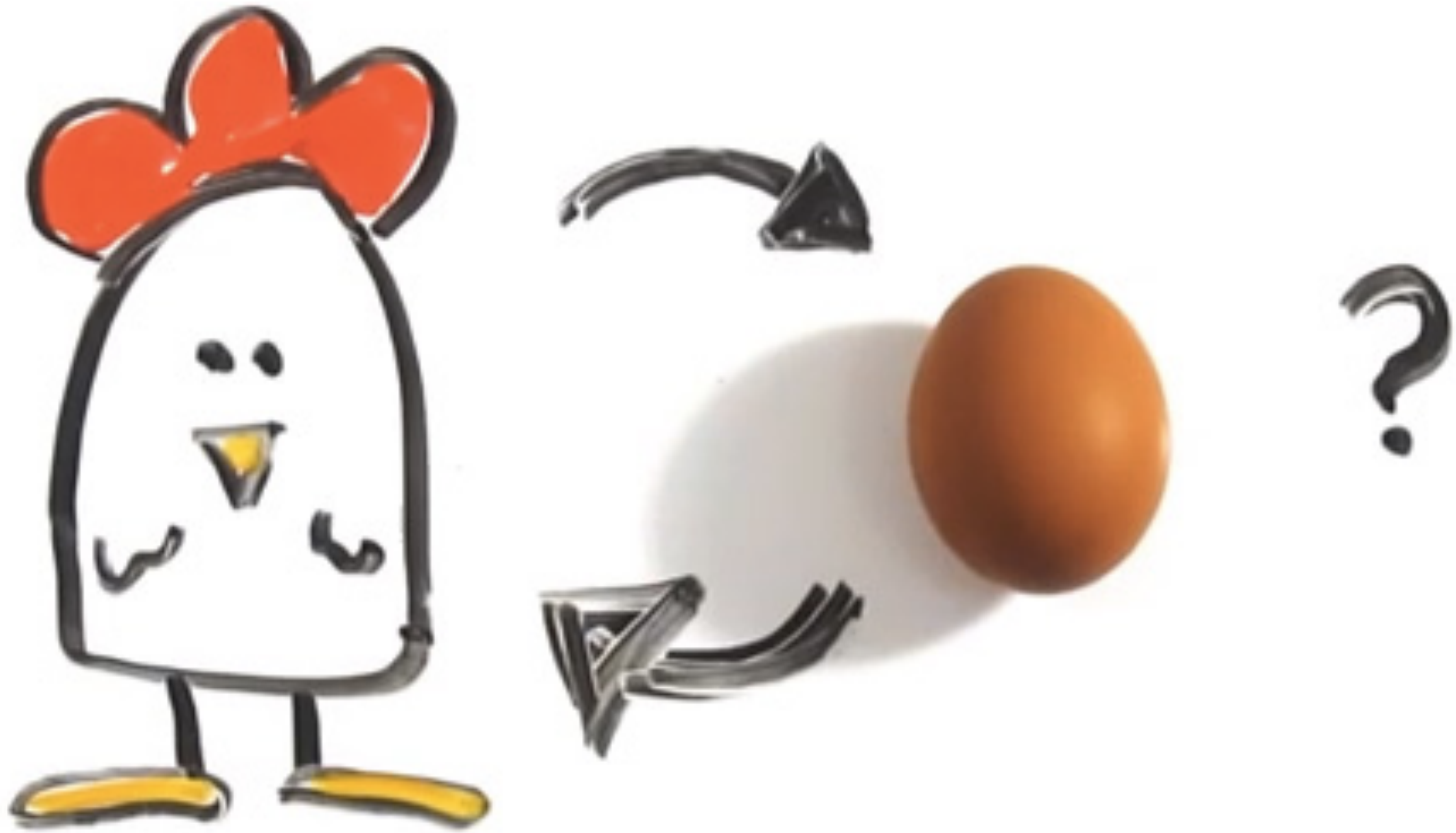



Huntington+ 2015
experimental verification Weibel instability

- X-ray synchrotron: evidence for high B-fields & turbulent B-fields
- Ingredients for acceleration: high B-field & turbulent B-fields
- How come B-fields higher than (compressed) Galactic fields?
- Several ways of enhancing/creating magnetic fields:

1. Collisionless shocks → streaming of electrons/ions → current generate fluctuating B-field → B-field bunches particles together in filaments with enhances B-field further (operates near shock)
2. Interaction B-field with single particles: Alfven wave generation with $\lambda_{\mathrm{A}} \approx r_{\mathrm{g}}$ (is called resonant Alfvén wave excitations) → important for turbelence with right wavelengths
3. Non-resonant magnetic field amplification (Bell instability)

# B-fields and cosmic rays



# Non-resonant Bell instability

- Start with MHD equation of motion, but add a large scale current:

$$\rho \frac{\partial \mathbf{v}}{\partial t} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} + \frac{\mathbf{J}_{\rm cr} \times \mathbf{B}}{c}$$

- Effect of perturbation in B and v:

$$v_{\perp} = (\delta v + i\delta v)\exp\left[i(kz - \omega t)\right], B_{\perp} = (\delta B + i\delta B)\exp\left[(kz - \omega t)\right]$$

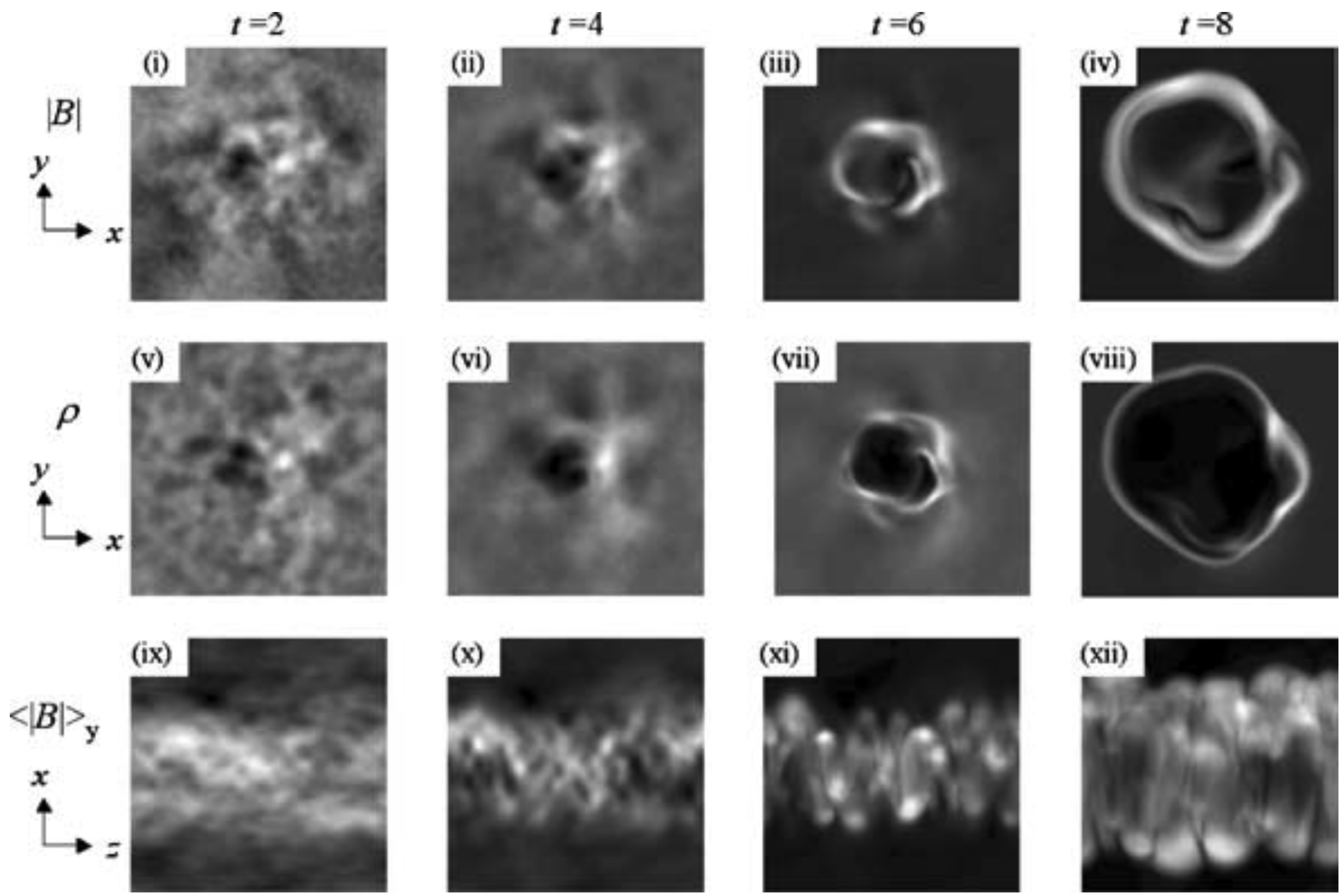
- Applying gives:

$$-i\omega\rho(1+i)\delta v = + \frac{ik\delta(1+i)\delta B B_{z,0}}{4\pi} + (1-i)\frac{1}{c}J_{\rm cr}\delta B,\ i\omega\delta B(1+i) = (1+i)\delta v ik B_{z,0}$$

- Combining: $\omega^2(1+i) = k^2 v_{\rm A}^2(1+i) + \frac{kJ_{\rm cr}}{\rho c}(1-i)$
- Without $J_{cr}$ we get Alfvén wave equation
- With $J_{cr}$: we get an imaginary(=exponentially growing) mode: Bell's instability

$$\gamma_{\rm max} = i\omega = \frac{1}{2}\left(\frac{4\pi}{\rho}\right)^{1/2}\frac{J_{\rm cr}}{c}.$$

# Non-resonant Bell instability




- Numerical simulations show B-field growth ring-like filaments
- Theoretical growth time scale:

$$\tau_{\rm Bell} \approx 12 \left(\frac{w}{0.1}\right)^{-1} \left(\frac{\ln(p_2/p_1)}{11.6}\right) \left(\frac{n_{\rm H}}{1\ {\rm cm^{-3}}}\right)^{-1/2} \left(\frac{E_{\rm max}}{10^{14}\ {\rm eV}}\right) \left(\frac{V_{\rm sh}}{5000\ {\rm km\ s^{-1}}}\right)^{-3}\ {\rm yr}\,.$$

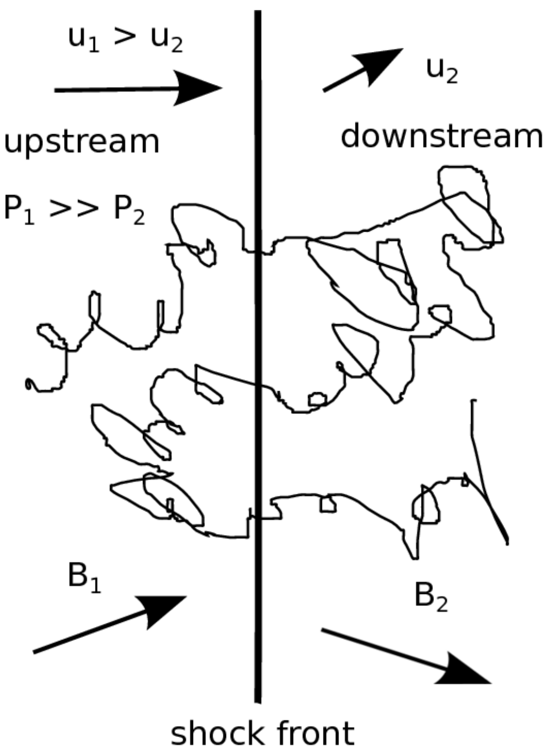
# 9 Non-linear diffusive shock acceleration

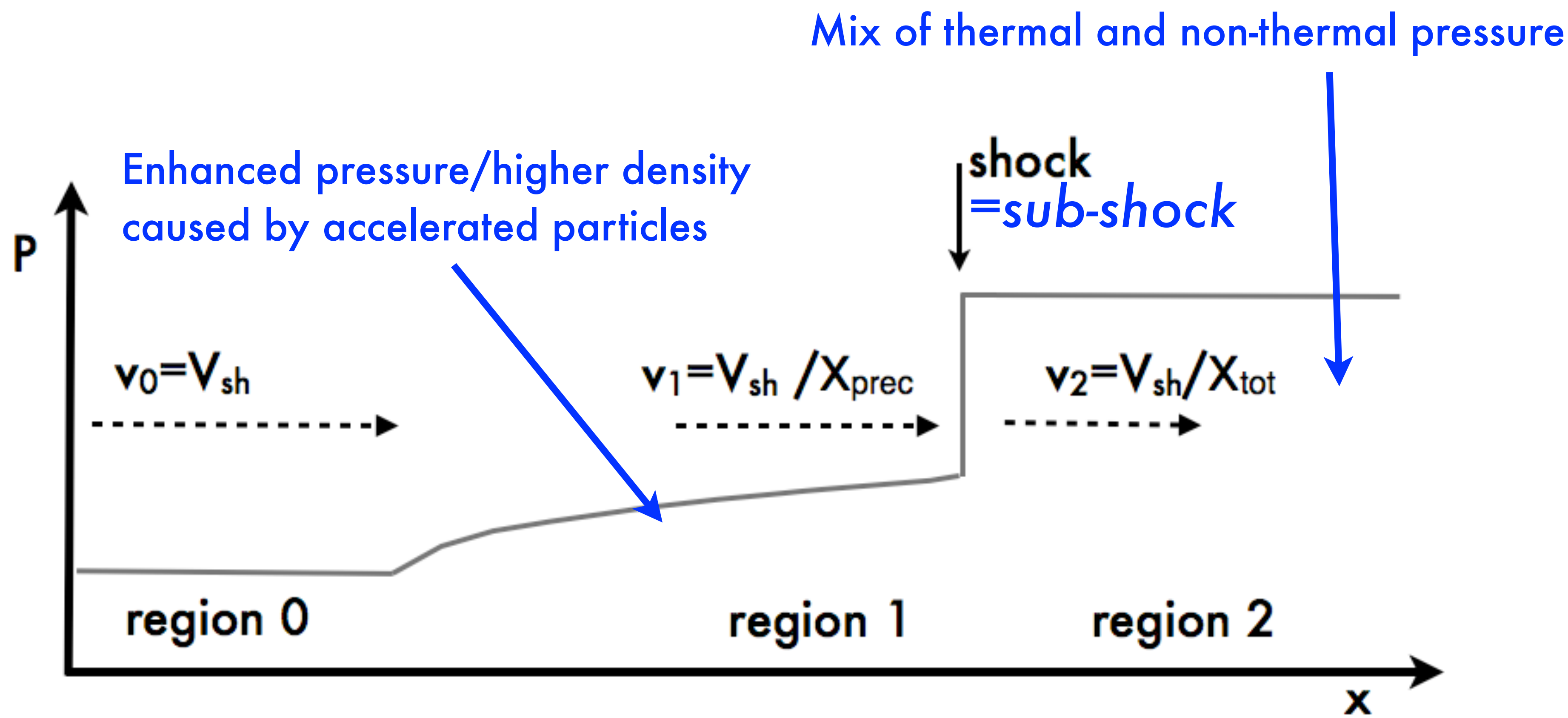
- The particles scatter off the plasma waves and gain energy from it
- This means plasma must somehow loose energy (there is a drag)
- Tueday's lecture: supernova remnants put 5-10% of energy in cosmic rays!

  ⇒ the test particle approach needs modification

- Modern theories: *non-linear* diffusive shock acceleration
- People involved (since 1980ies): D. Eichler, L. Drury, M. Malkov, D. Ellison, P. Blasi, etc
- Review: http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2001RPPh...64..429M&link_type=ABSTRACT
- Challenge: self-consistently calculate effect of accelerated particles on shock structure/plasma flow

# Non-linear diffusive shock acceleration II



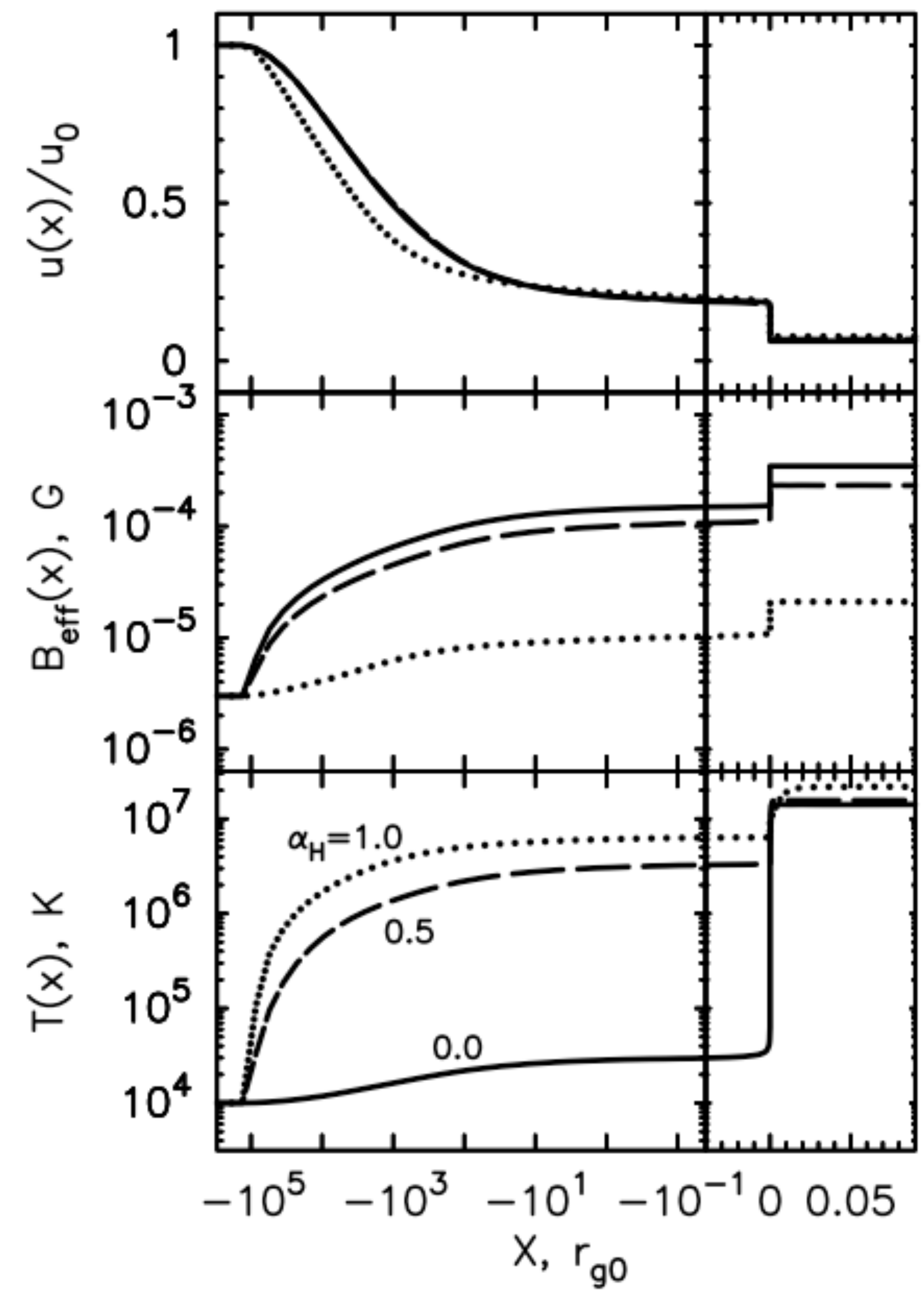

- Non-linear shock acceleration:
  - Shock-structure larger: accelerated particles upstream (=*cosmic-ray precursor*) push against plasma
  - Particles set plasma in motion, *compress* it, and *pre-heat* it
    $\Rightarrow$Mach number at shock will be lower!
  - *Equation of state* changes: mix of non-relativistic and relativistic particles
  - Escape of cosmic rays drain energy (escape upstream not downstream!!)
  - Terminology: actual shock is now called the *sub-shock*
  - Idea of shock vs sub-shock challenge idea of a shock as a sudden jump

# Non-linear diffusive shock acceleration III

- Size of shock precursor:

$$l_{\rm diff} \approx \frac{D}{V_{\rm s}} \approx \frac{\eta c E}{3eBV_{\rm s}} \approx 7\times 10^{17}\eta \left(\frac{E}{10^{15}\ {\rm eV}}\right)\left(\frac{B}{100\ {\rm muG}}\right)^{-1}\left(\frac{V_{\rm s}}{5000\ {\rm km/s}}\right)\ {\rm cm.}$$

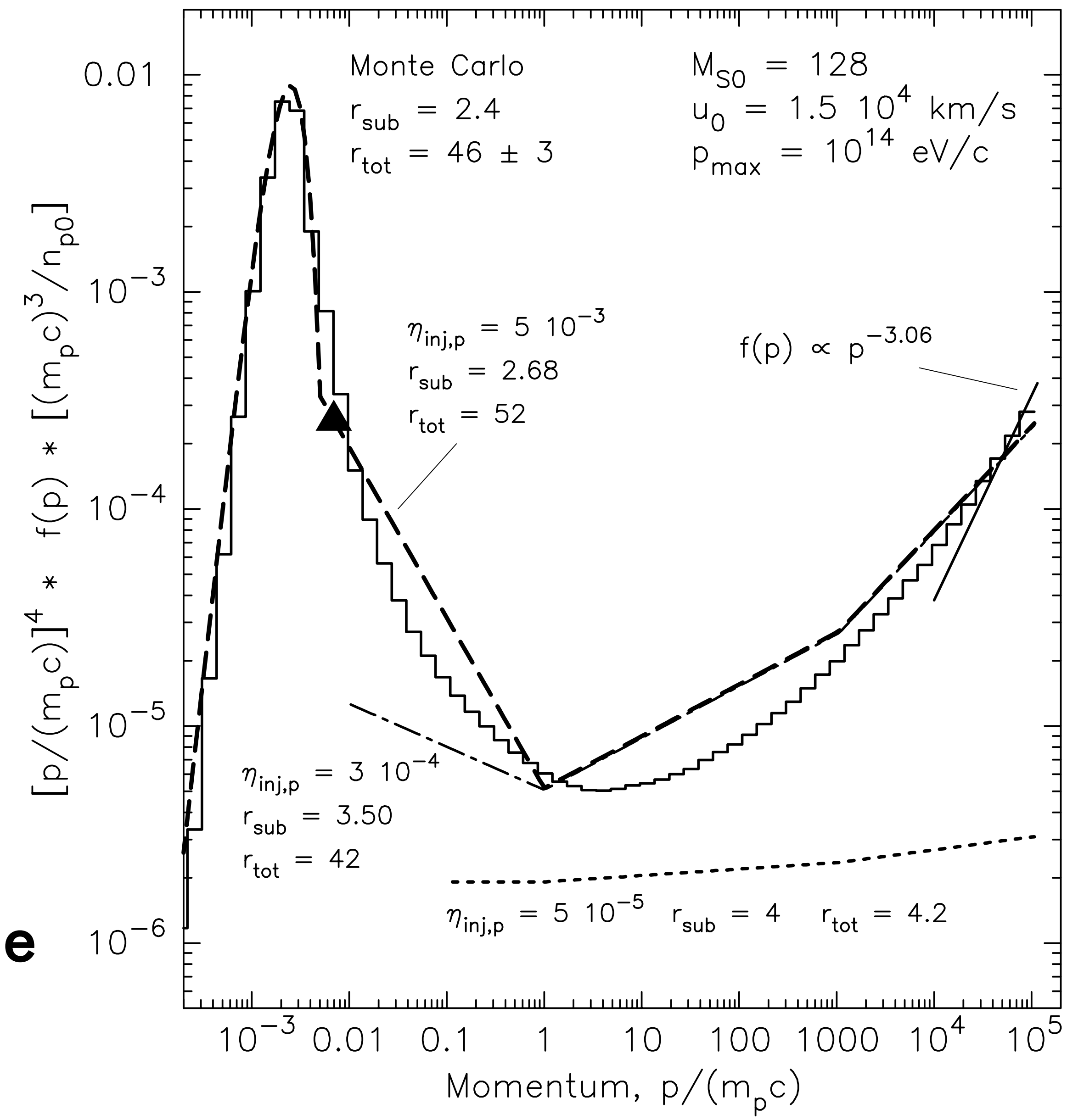
- Can be 1/3 of a parsec!!
- Depends on where most cosmic ray energy is:
  - q<2: highest energy particles (the knee?)
  - q>2: around $E = m_p c^2 \approx 1$ GeV
- According to early theories of non-linear acceleration: $q = 1.5$




Vladimirov, Bykov, & Ellison 08

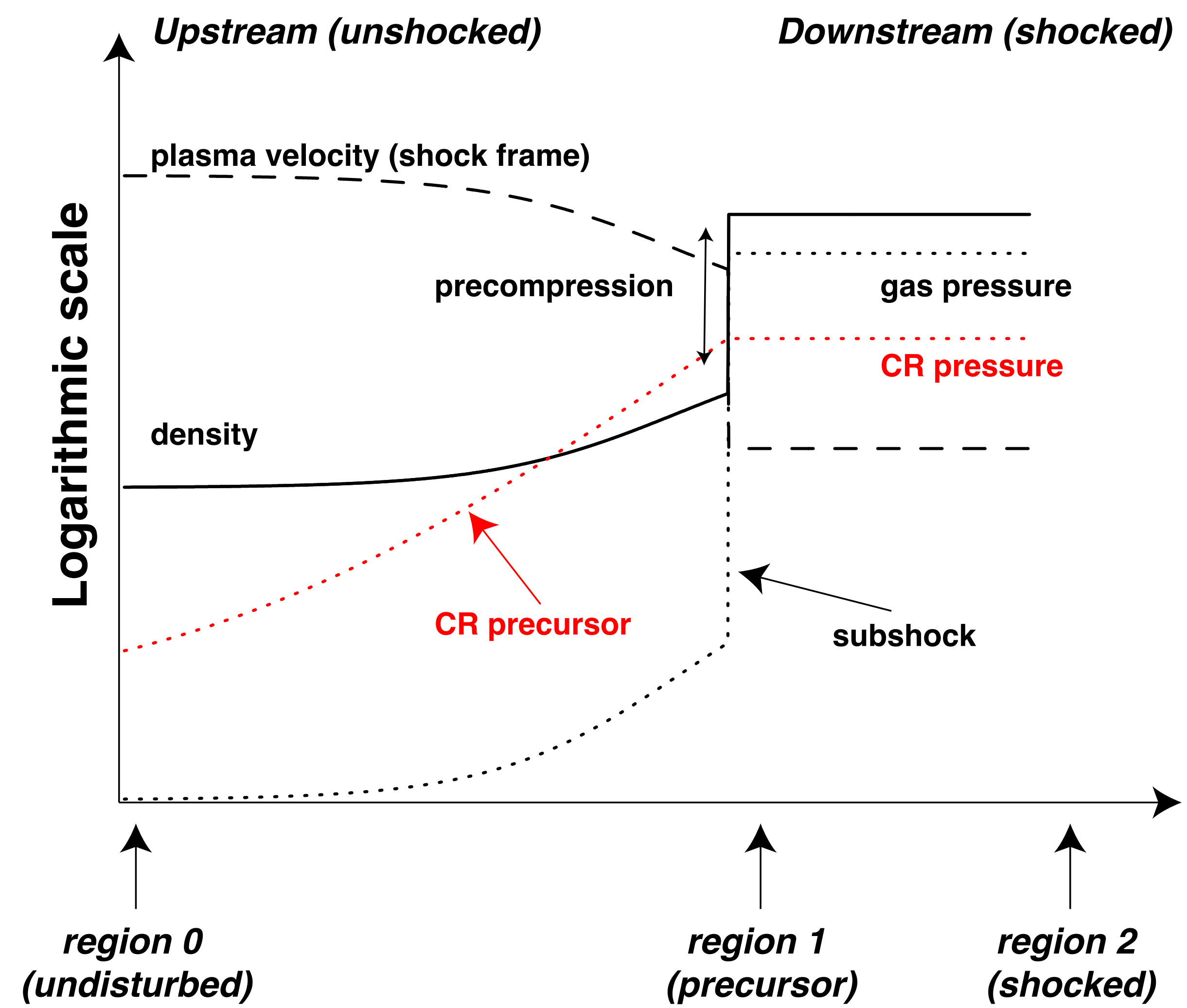
# Non-linear shock acceleration model

- Effect of non-linear acceleration:
  - low M at *sub-shock*= lower compression
  - *overall* compression (incl. precursor) can be (much) larger)
- Non-linear shock model with escape: extreme compression ratios (Figure: X=42!, $X_{sub}$=3.5)
- Curved spectrum
  - Low energy particles only scatter across sub-shock (lower velocity gradient)
  - Highest energy particles sample complete velocity field




Ellison, Berezhko, Baring, 2000

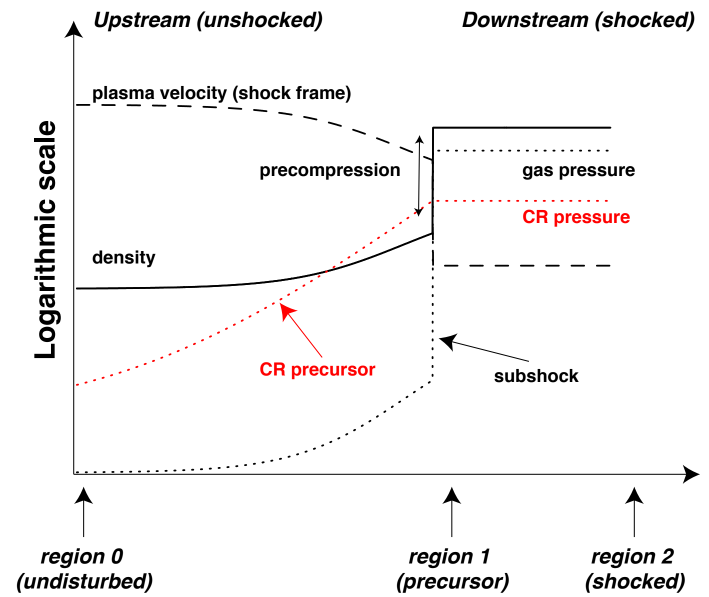
# Extending Rankine-Hugoniot relation with accelerated particles I




- Assume two "fluids":
    1. plasma with $\gamma_g$=5/3,
    2. cosmic rays with $4/3<\gamma_{cr}<5/3$
- Allow for energy to escape (cosmic rays leaving system): $\epsilon \equiv F_{cr,esc}/(\frac{1}{2}\rho_0 v_0^3)$
- Close equations by evaluating conditions in three regions:
    1. undisturbed medium
    2. in cosmic-ray precursor, just ahead of shock
    3. shocked medium
- Closing relation: *cosmic-ray pressure continuous across shock* (boundary 1 & 2)

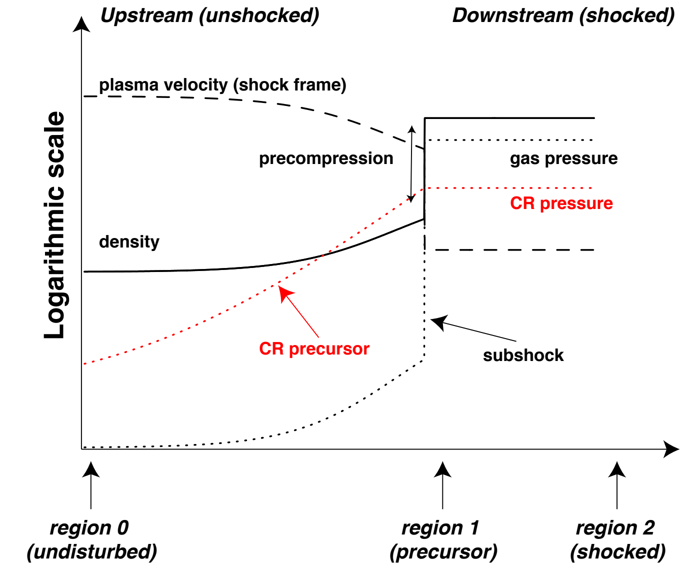
# Extending Rankine-Hugoniot relation with accelerated particles II

(Vink+ 2010, Vink & Yamazaki 14)




- One *running parameter*: precursor compression $X_{prec}$
- Assume value of $\gamma_{cr} \in [4/3 - 5/3]$
- In region adiabatic compression of gas due to cosmic rays:
  - $P_1 = P_0 \chi^\gamma$
  - $\rho_1 = \chi \rho_0$
  - Hence, the Mach number at shock changes: $M_{g,1} = M_{g,0} \chi_{prec}^{-(\gamma_g+1)/2}$
- (Sub)shock compression ratio still given by $\chi = \dfrac{(\gamma_g + 1) M_1^2}{(\gamma_g - 1) M_1^2 + 2}$
- So total compression ratio $\chi_{tot} = \chi_{prec} \chi_{sub} = \dfrac{(\gamma_g + 1) M_{g,0}^2 \chi_{prec}^{-\gamma_g}}{(\gamma_g - 1) M_{g,0}^2 \chi_{prec}^{-(\gamma_g+1)} + 2}$
- Define a measure for cosmic-ray efficiency (downstream CR pressure/total pressure) $w \equiv \dfrac{P_{cr,2}}{P_{tot,2}}$

# Extending Rankine-Hugoniot relation with accelerated particles III




- Assume momentum conservation eq. holds: $P_0+\rho_0 v_0^2= P_1+\rho_1 v_1^2= P_2+\rho_2 v_2^2$
- From region 1 to 2 (CR pressure on both sides drop out, $P_{cr,2}=P_{cr,1}$):

$$P_{\mathrm{gas},2} = P_0 \chi_{\mathrm{prec}}^{\gamma} + \left(1 - \frac{1}{\chi_{\mathrm{sub}}}\right) \rho_1 v_1^2$$

- But should equal (region 0 to 2):

$$P_{\mathrm{gas},2} = (1-w)\left[P_0 + \left(1 - \frac{1}{\chi_{\mathrm{tot}}}\right)\right] \rho_0 v_0^2$$

- Can be use to derive

$$w_2 \equiv \frac{P_{\mathrm{cr},2}}{P_{\mathrm{tot},2}} = \frac{(1-\chi_{\mathrm{prec}}^{\gamma_{\mathrm{g}}}) + \gamma_{\mathrm{g}} M_{\mathrm{g},0}^2 \left(1 - \frac{1}{\chi_{\mathrm{prec}}}\right)}{1 + \gamma_{\mathrm{g}} M_{\mathrm{g},0}^2 \left(1 - \frac{1}{\chi_{\mathrm{tot}}}\right)}$$

- Finally, look at energy equation (only compare region 0 and 2)
- Allow particles to escape upstream

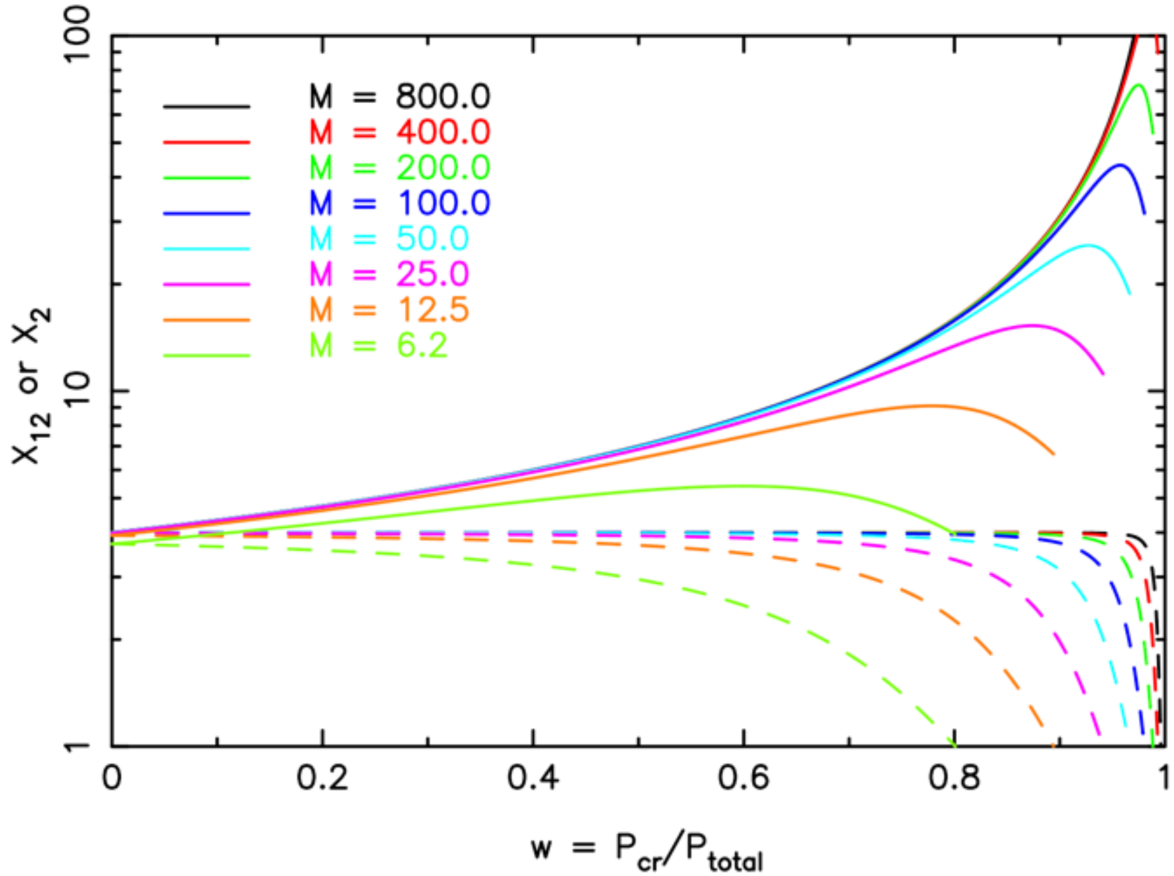
$$\left[P_0 + U_0 + (1-\varepsilon)\frac{1}{2}\rho_0 v_0^2\right] v_0 = \left[P_2 + U_2 + \frac{1}{2}\rho_2 v_2^2\right] v_2$$

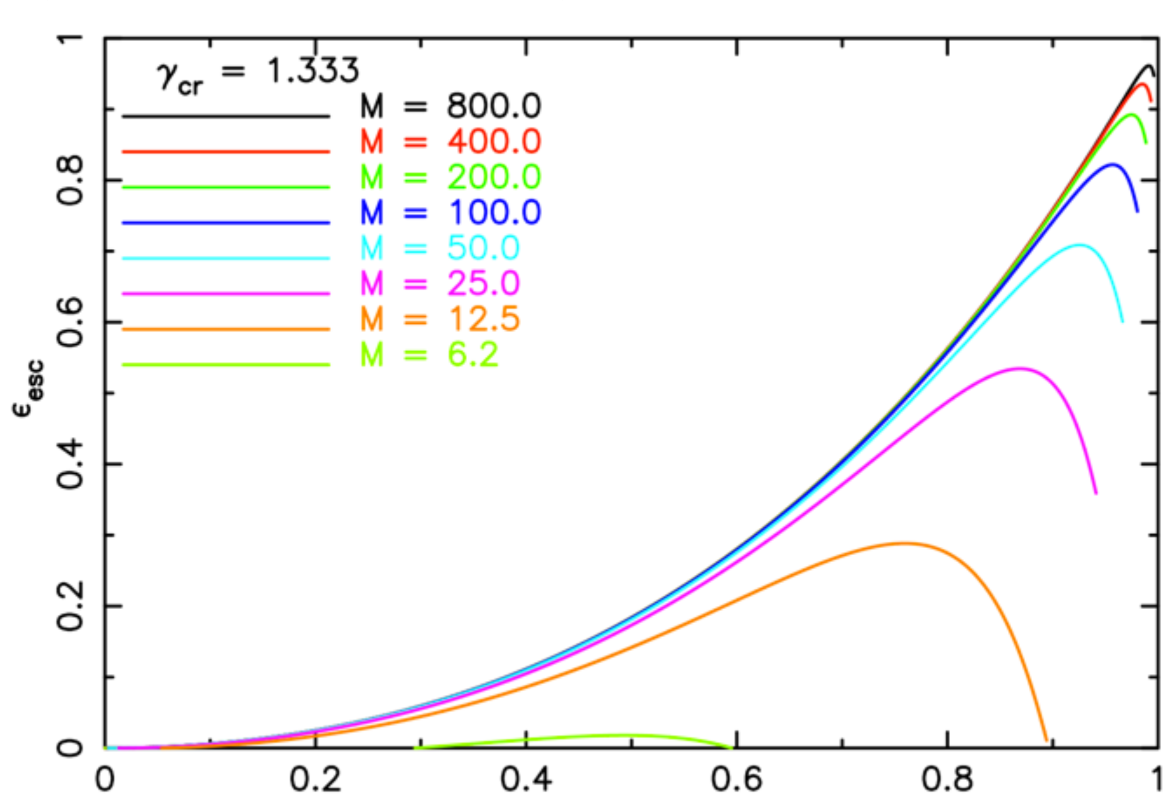
$$\epsilon = 1 + \frac{2}{\gamma_{\mathrm{g}} M_{\mathrm{g},0}^2}\left[G_0 - \frac{G_2}{\chi_{\mathrm{tot}}}\right] - \frac{2G_2}{\chi_{\mathrm{tot}}} + \frac{1}{\chi_{\mathrm{tot}}^2}(2G_2 - 1)$$

$$G_2 \equiv w_2 \frac{\gamma_{\mathrm{cr}}}{\gamma_{\mathrm{cr}} - 1} + (1 - w_2)\frac{\gamma_{\mathrm{g}}}{\gamma_{\mathrm{g}} - 1}$$

# Predicted compression ratios and escape flux as a function of cosmic-ray pressure

Vink et al. 2010, Vink &Yamazaki, 2014



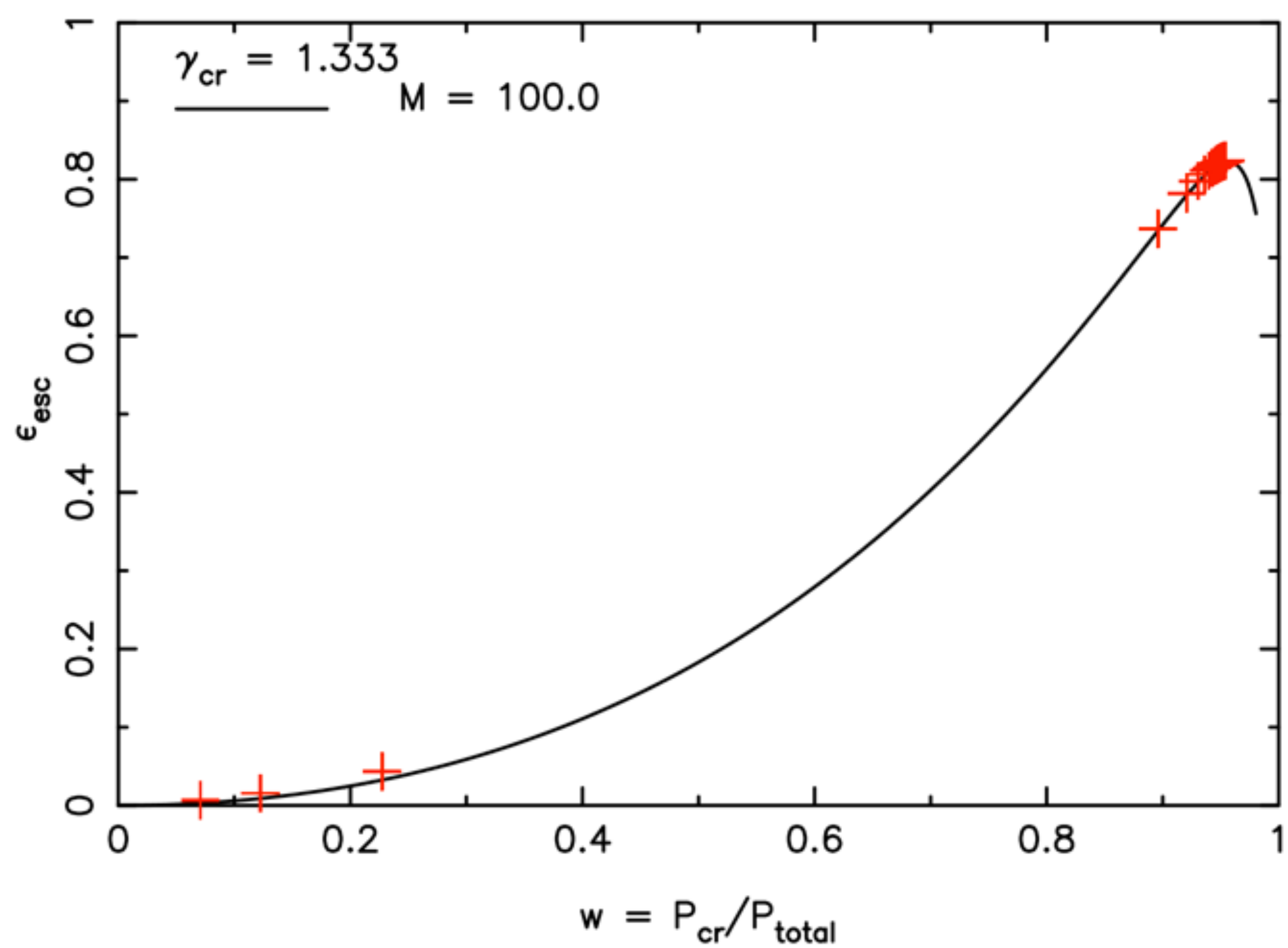




$w_2 = P_{cr}/P_{tot}$

Total and shock compression ratio

Energy flux escape

# The models agrees with the kinetic non-linear acceleration model of Blasi et al. (2005)

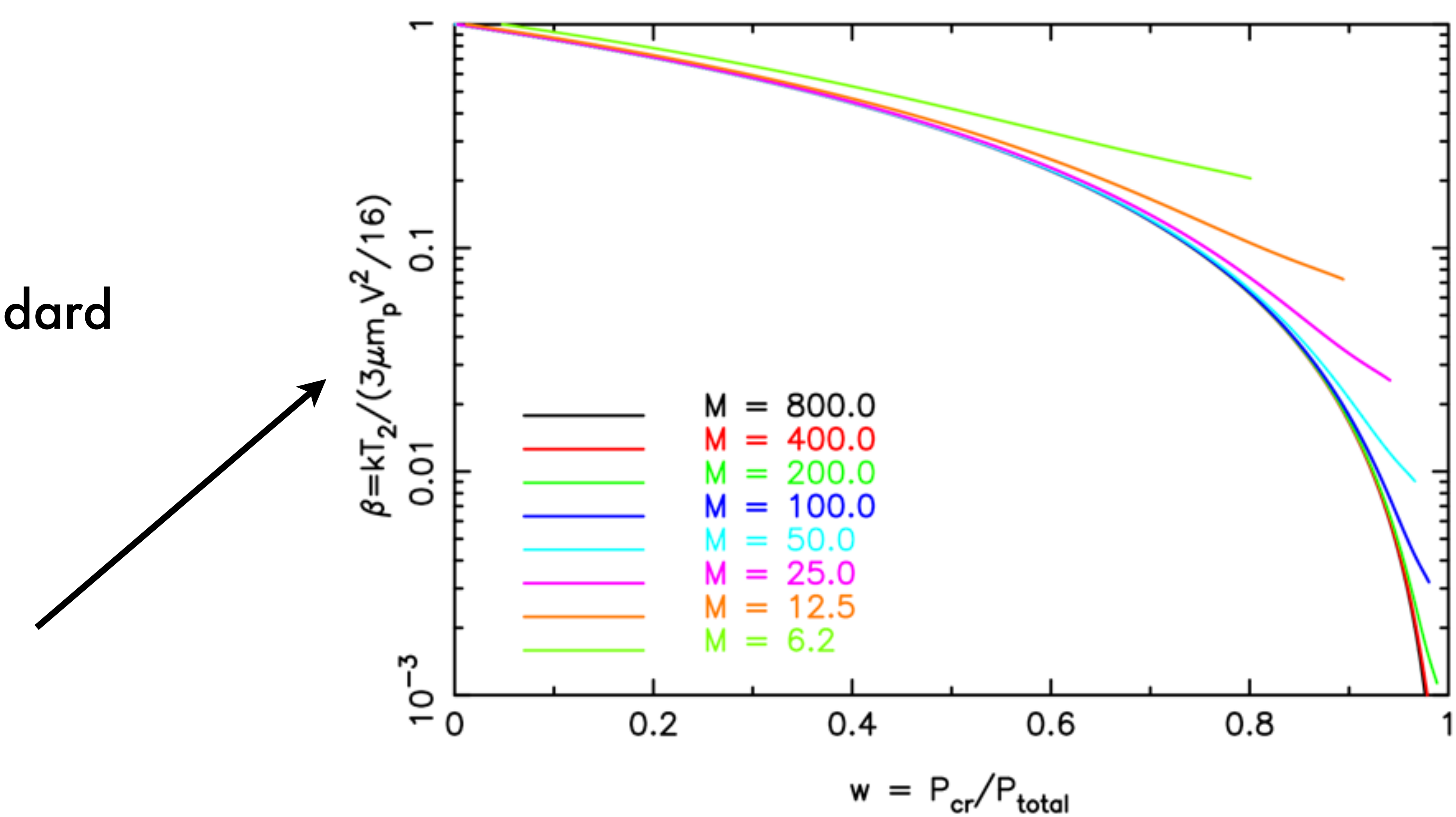



- Crosses: Blasi model for different $E_{max}$
- Blasi model: one solution (depends on acceleration details)
- Extended Rankine-Hugoniot: allowed possibilities

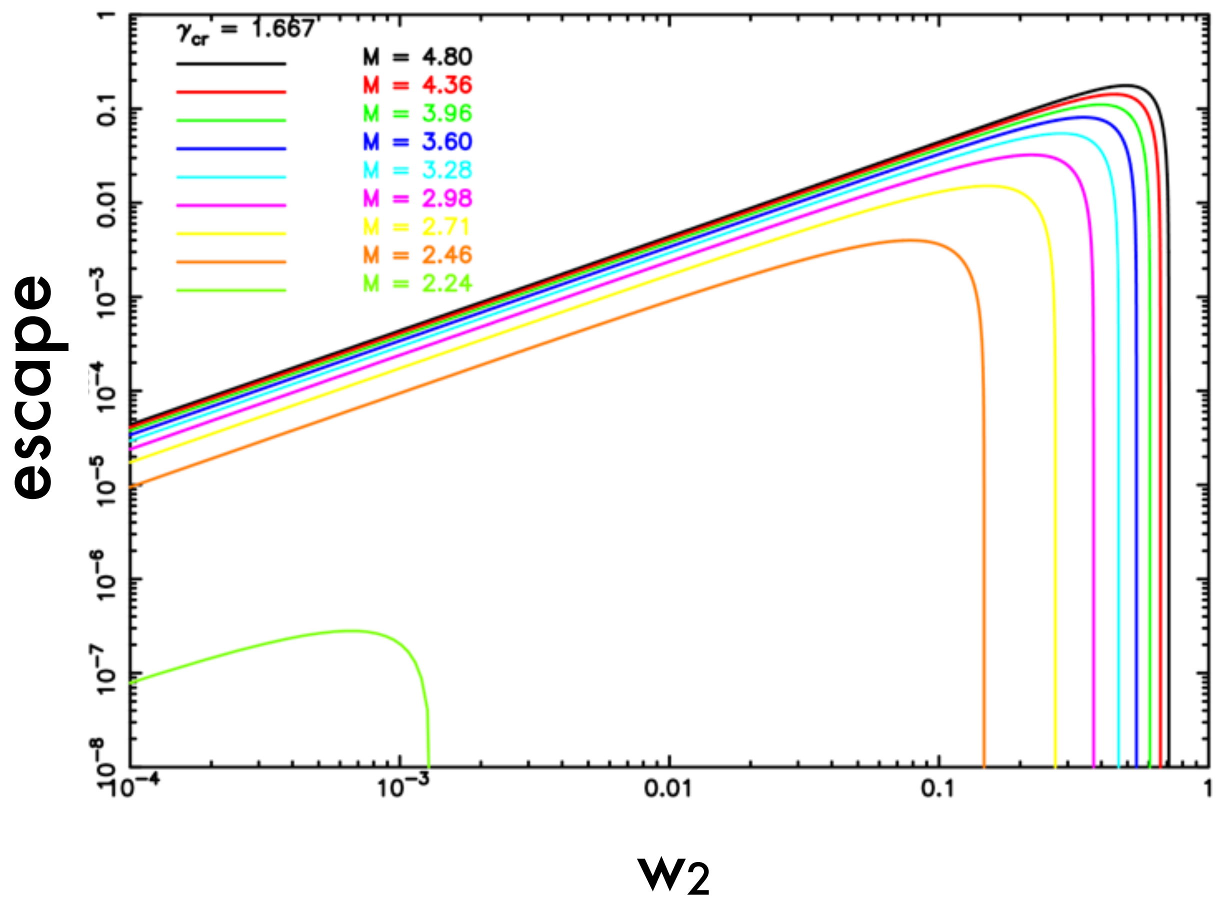
# By measuring the post-shock temperature the cosmic-ray efficiency can be measured

correction w.r.t. standard Hugoniot result

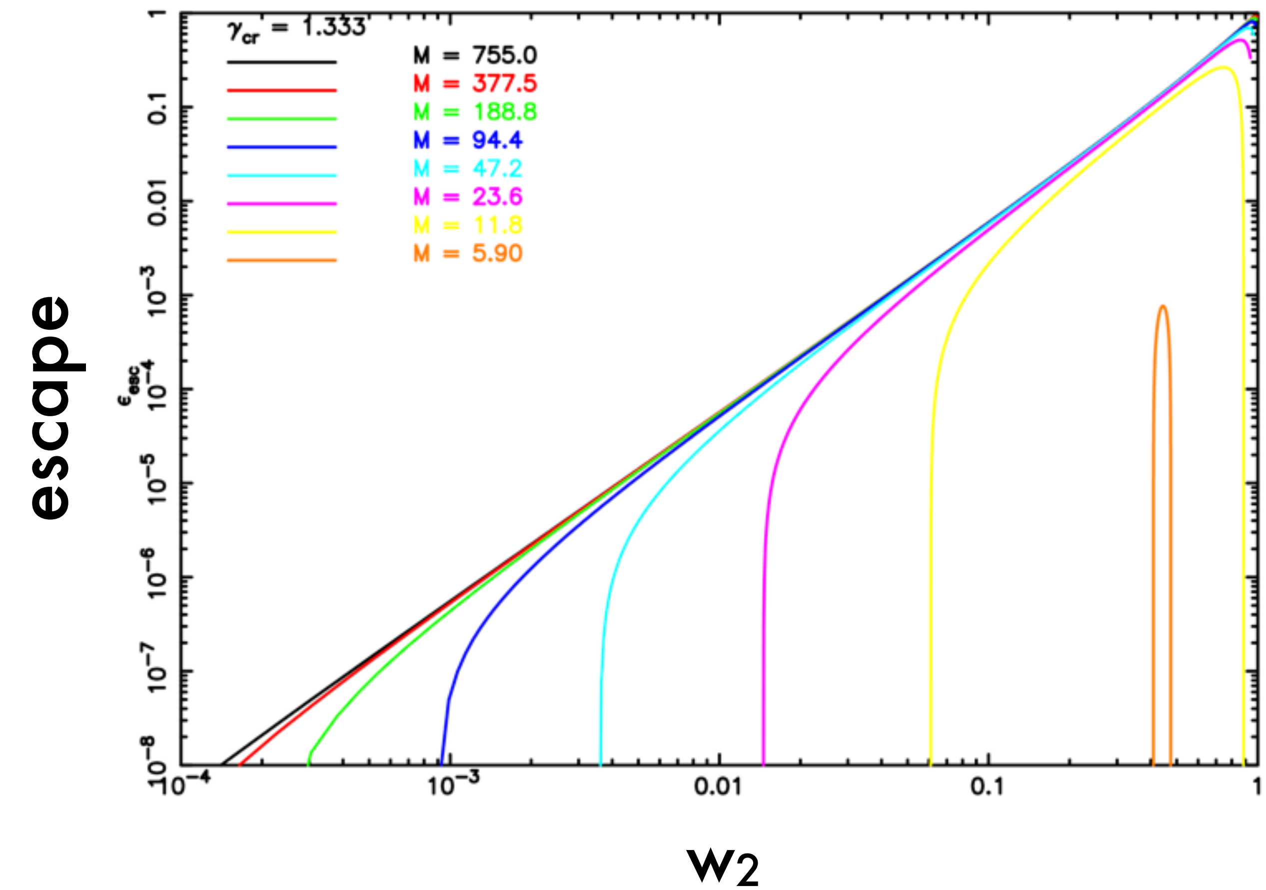
$$\overline{kT} = \frac{3}{16}\overline{m}V_s^2$$



# Dramatic decline in potential cosmic-ray pressures near critical Mach numbers



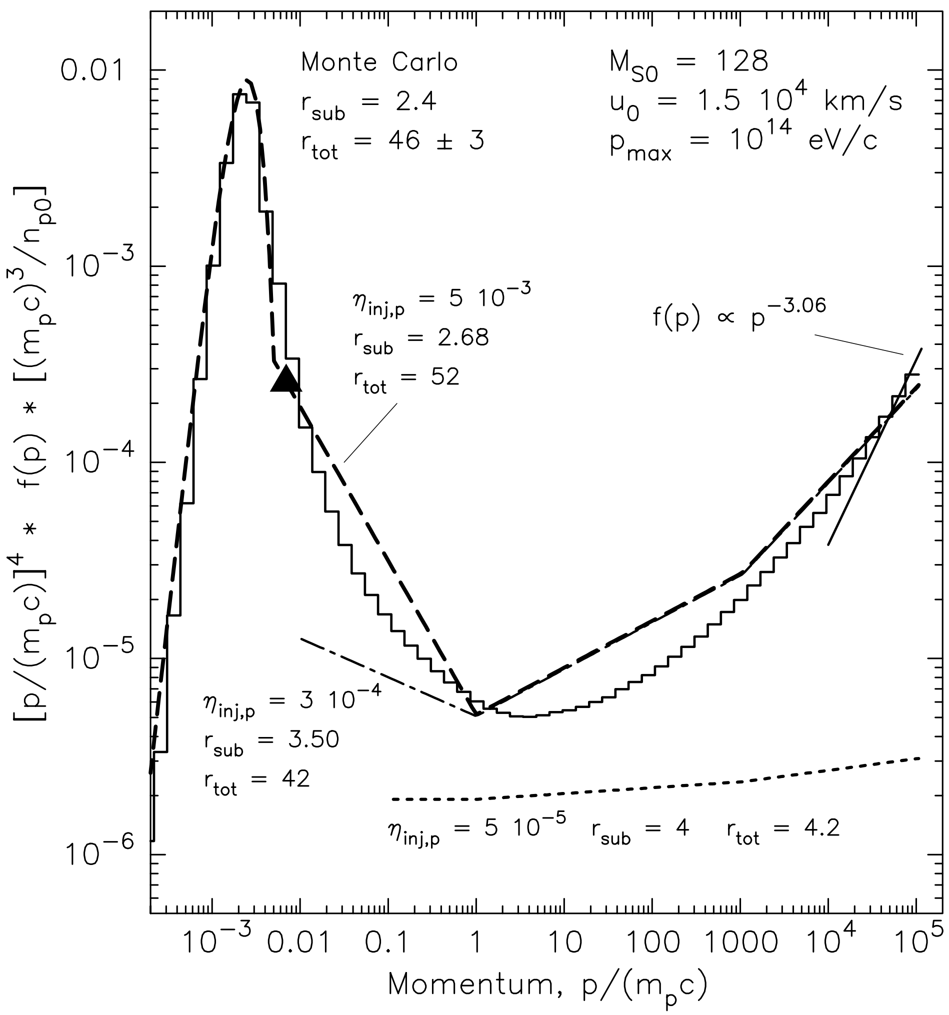
Non-relativistic particle population



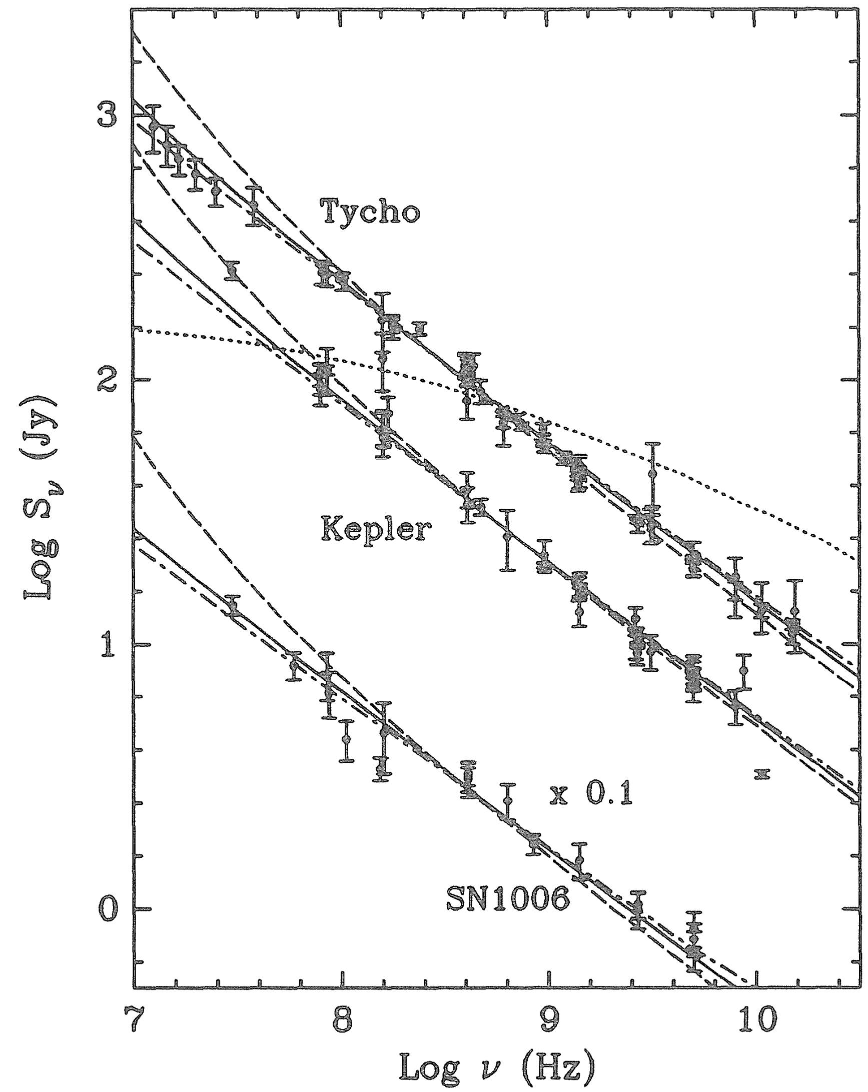
Relativistic particle population

- For non-relativistic cosmic rays: $M > \sqrt{5} \approx 2.236$
- For relativistic dominated particles ($\gamma_{cr}=4/3$): Mach nr $M > 5.88$
- Different behavior for $\gamma_{cr}=4/3$ and $\gamma_{cr}=5/3$

# Variable spectral index



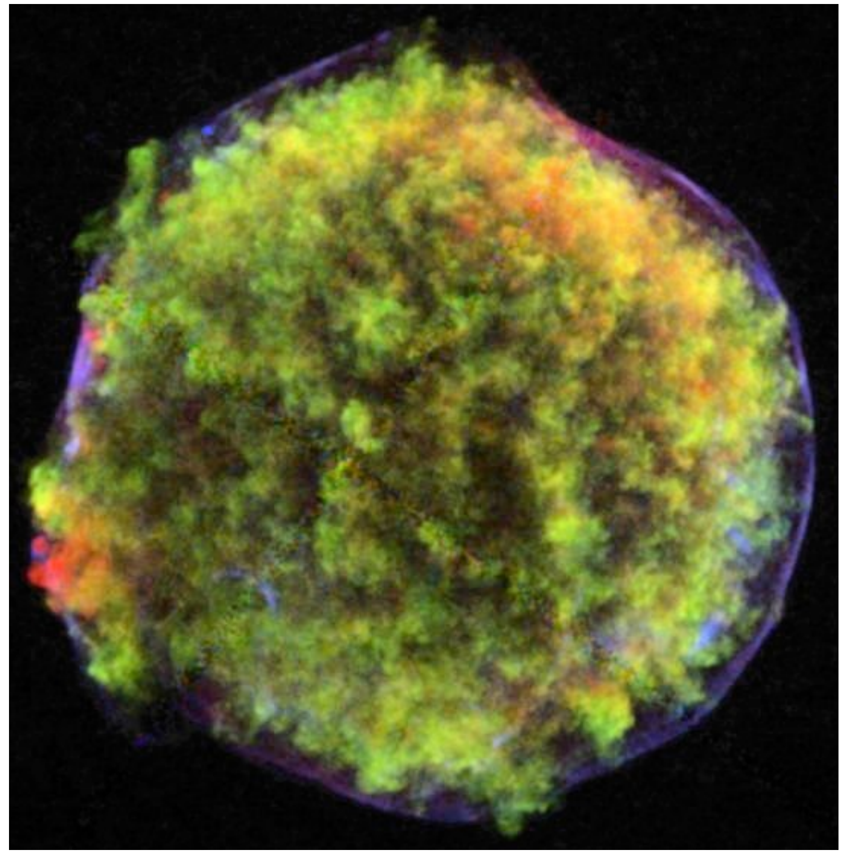

Ellison, Berezhko, Baring, 2000



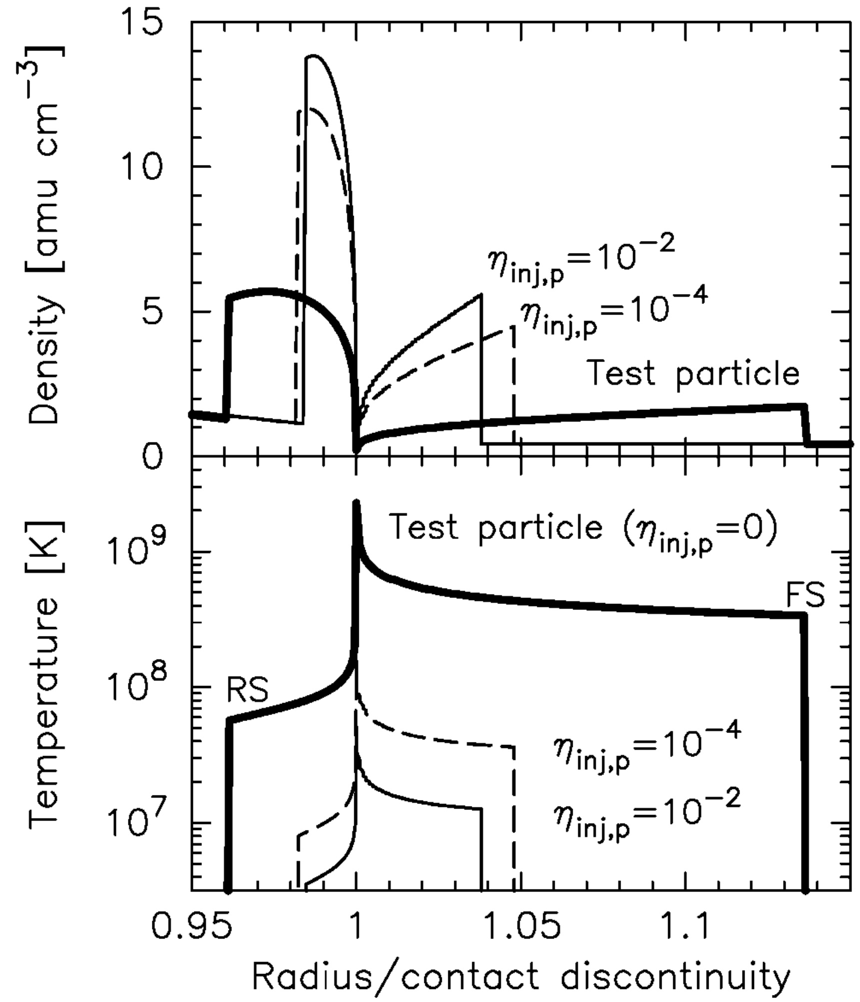

Reynolds & Ellison 1992

- Non-linear shock acceleration:
  - no longer a fixed power-law slope
  - slope is steep at low energies (smaller compression ratio)
  - slope is flat at high energies
- However: effect not seen as strongly as predicted

# Further evidence for non-linear shock acceleration?

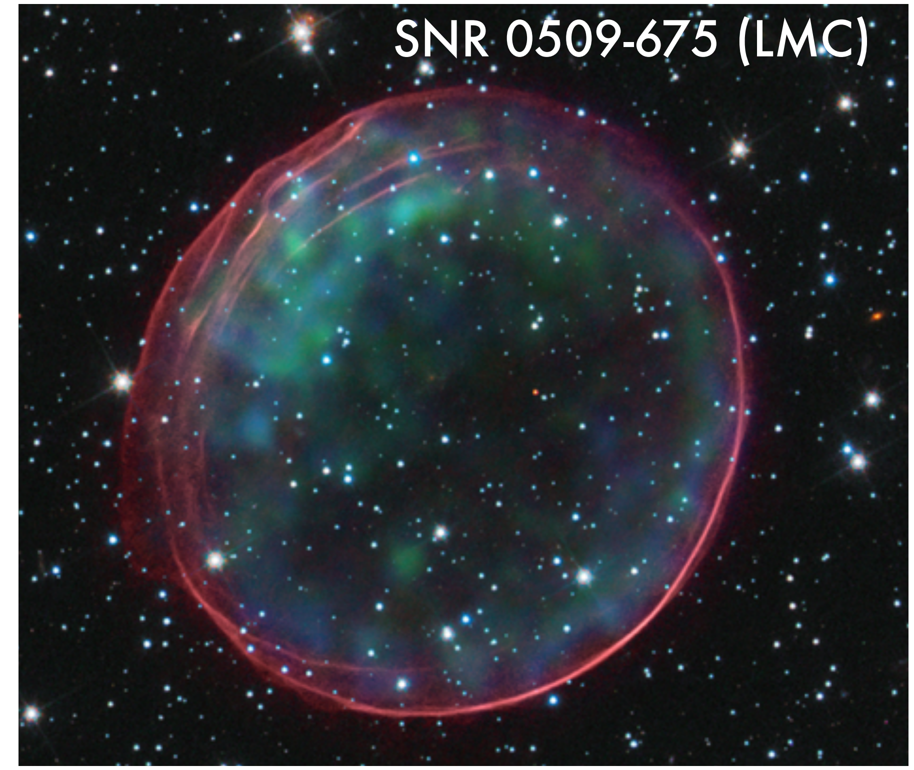


Decourchelle+ 2000
Warren+ 2005




- Recall: non-linear acceleration→ higher compressions, lower temperatures
- Ejecta from supernova in Tycho's SNR (SN1572) very close to shock front
- Evidence for high compression ratios?
- Or due to hydrodynamic instabilities (turbulence)?

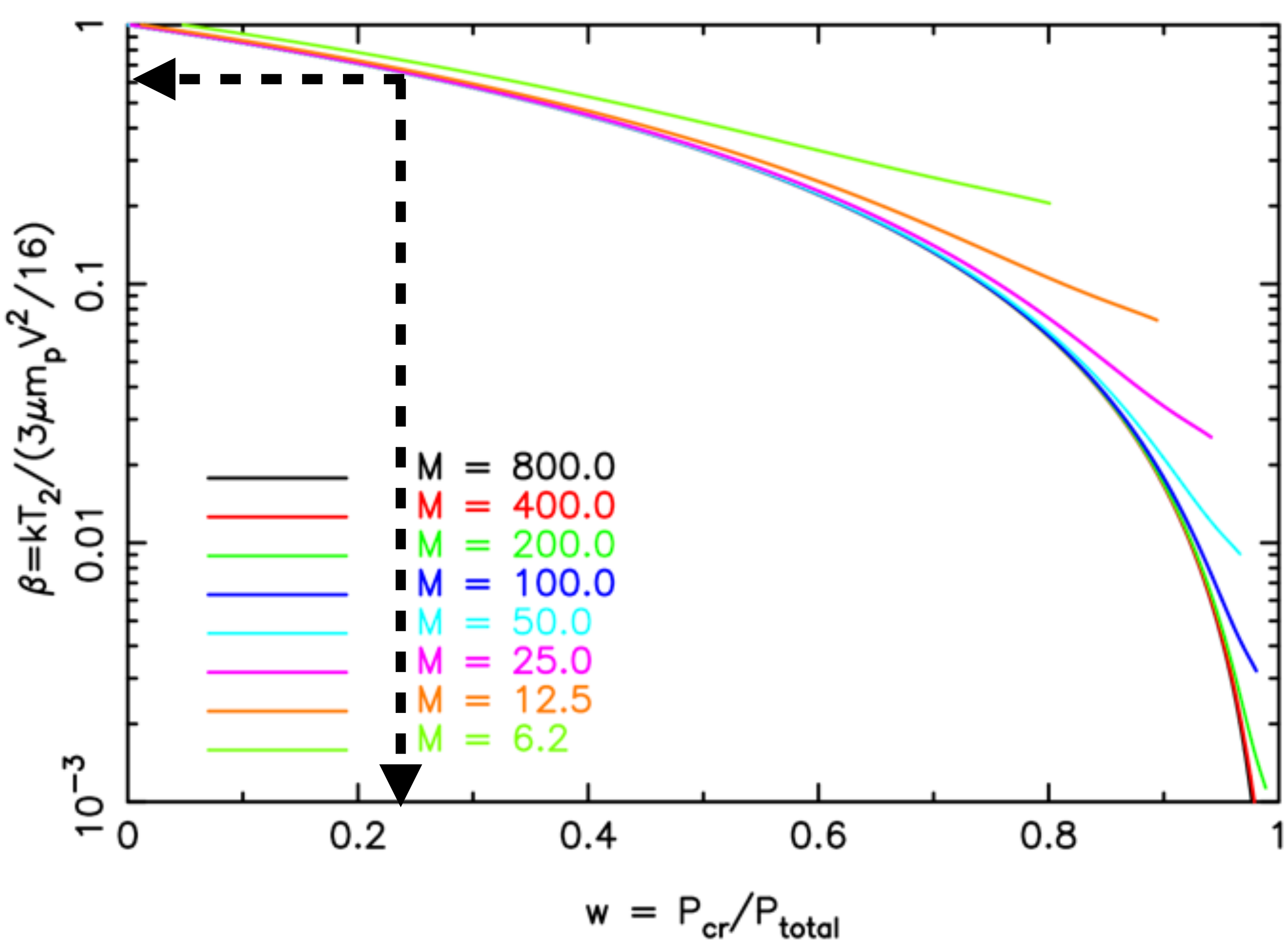
# Measuring temperatures

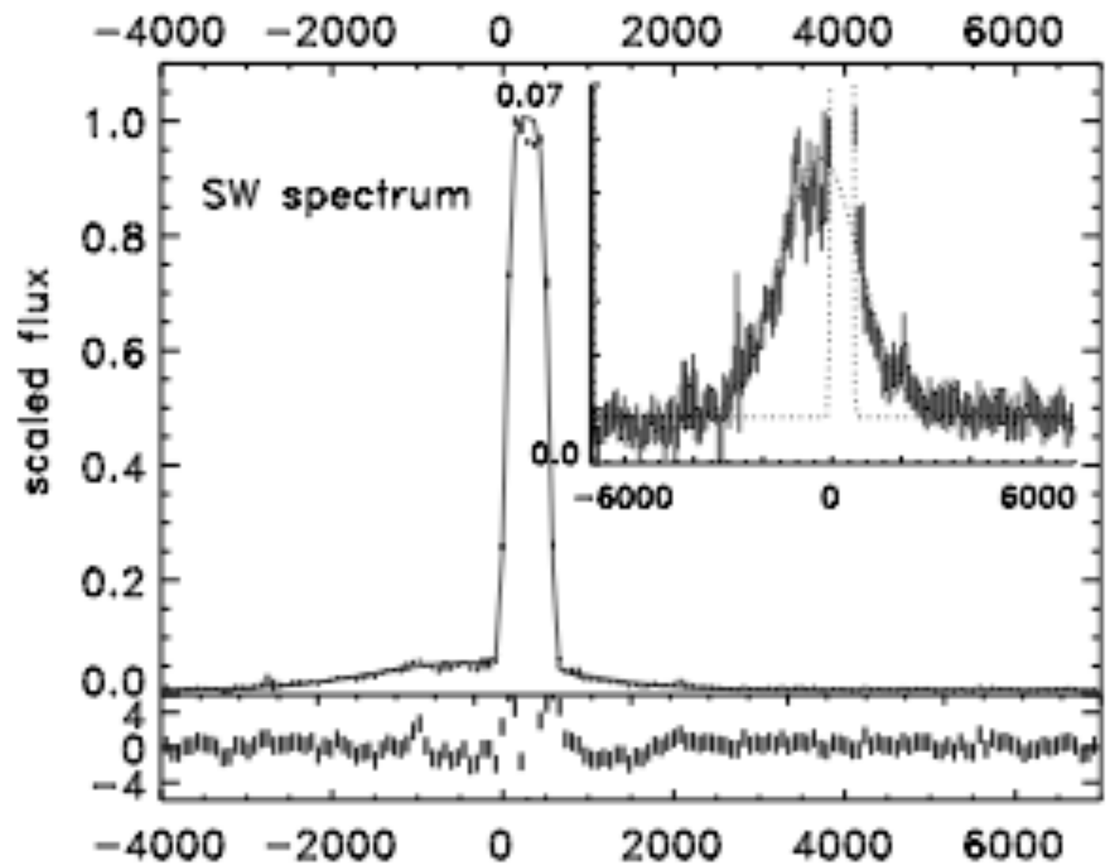



- Other effect: lower temperatures
- In X-rays: measure *electron* temperatures
  - Is it equal to the proton/plasma-temperature?
- Remedie: measure proton/ion temperatures
- Best: in optical
  - neutral atoms entering shock either
    - -excite and ionization → gives narrow emission line
    - -charge exchange with hot proton + ionisation → gives broad emission line
- Disadvantage: not all SNRs in environment with neutral hydrogen

# A measurement of the cosmic-ray efficiency in a fast supernova remnant shock 0509-675

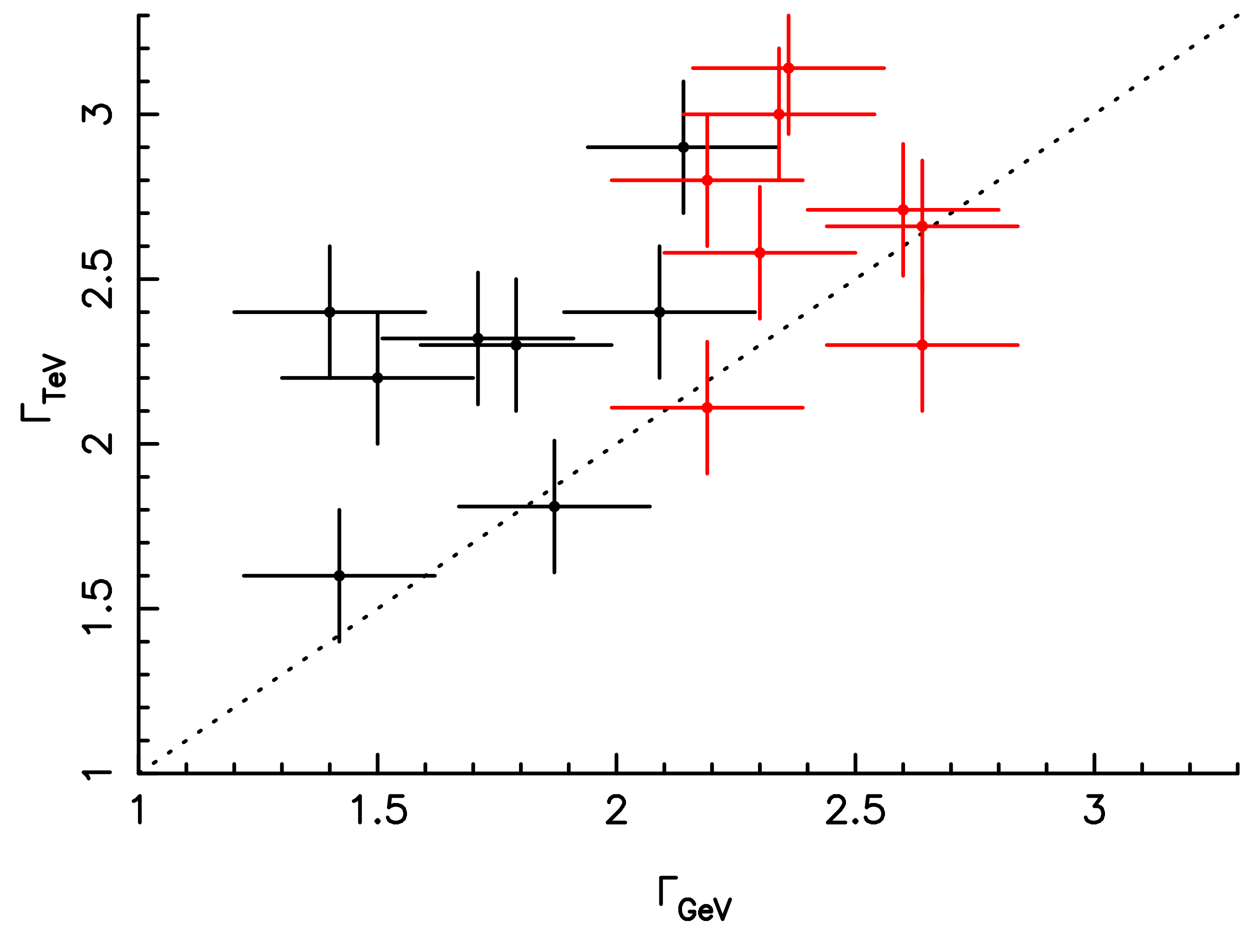
Helder, Kosenko, Vink '10



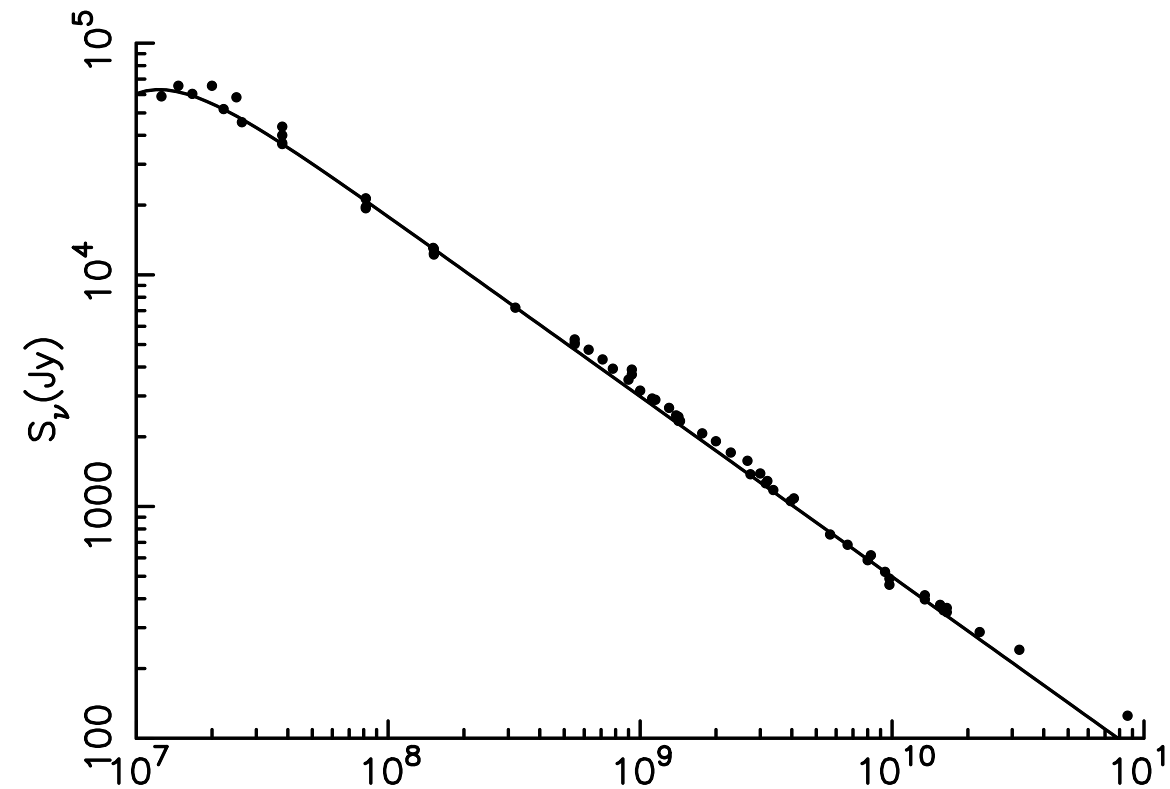

- Distance known (LMC, 50 kpc)
- Shock velocity: X-ray line broadening + Chandra expansion: Vs> 5000 km/s
  - One of the fastest shocks in a known SNR!
- Hα broad line widths: 2680 ± 70 km/s (SW), 3900 ± 800 km/s
- Discrepancy in kT: $kT_{measured}/kT_{exp} \leq 0.7$
- Hence: cosmic-ray efficiency w≥25%
- Since 2010 claim disputed (shock velocity lower than claimed?)

# Why non-linear shock theory is now less popular




- Early non-linear shock theories: spectral index 1.5
- Observed in gamma-rays: 1.4-2.8
- But: 1.5 likely due to inverse Compton scattering; recall: $\Gamma = (q+1)/2 \approx 1.5$
- For hadronic emission index seems consistent with q=2
- Furthermore: cosmic ray content ≈5% of SN energy: non-linear effects not as extrem as predicted

# Why you should still care about non-linear acceleration




- Radio spectral index of young SNR Cas A and of radio supernovae: >0.7
  - Example: Cas A has $\alpha = 0.77$ corresponds with q=2.5
  - Implies much steep index, and low Mach number shocks (prediction of non-linear acceleration)
- X-ray measured temperatures of SNRs too low:
  - Non-linear effect? Or: electron and ion temperature diffferent?
- Magnetic field amplification seems solid:
  - is also non-linear effect
  - requires substantial cosmic-ray streaming ahead of shock

# Summary

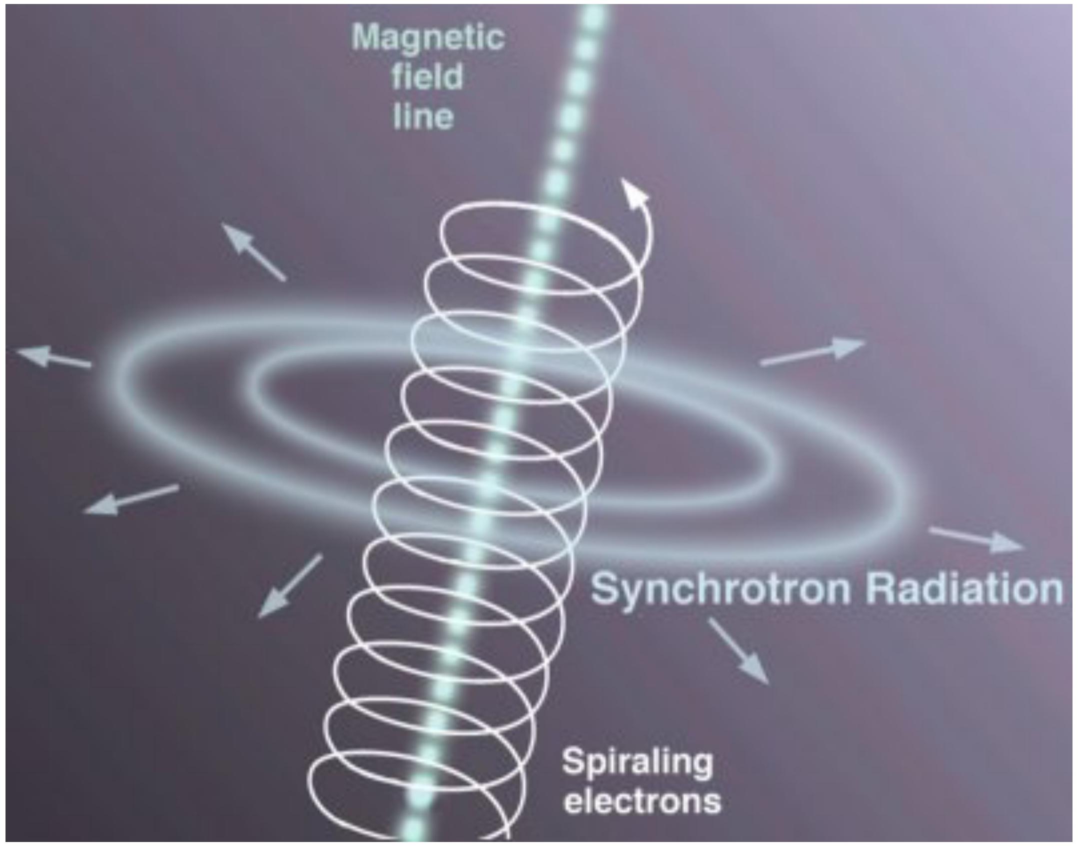
- Detection of X-ray synchrotron emission:
  - Requires fast acceleration: need high B-field turbulence $(\eta \approx 1)$
  - Narrow filaments: suggest rapid post-shock cooling → high B (~100μG)
  - B-fields amplification depends on density and shock velocity
- Magnetic field amplification
  - Immediately near shocks:Weibel instability/filamentation
  - Alfvén wave mode excitation: resonant with gyro-radius cosmic rays
  - Bell's instability: induced by large scale electric current

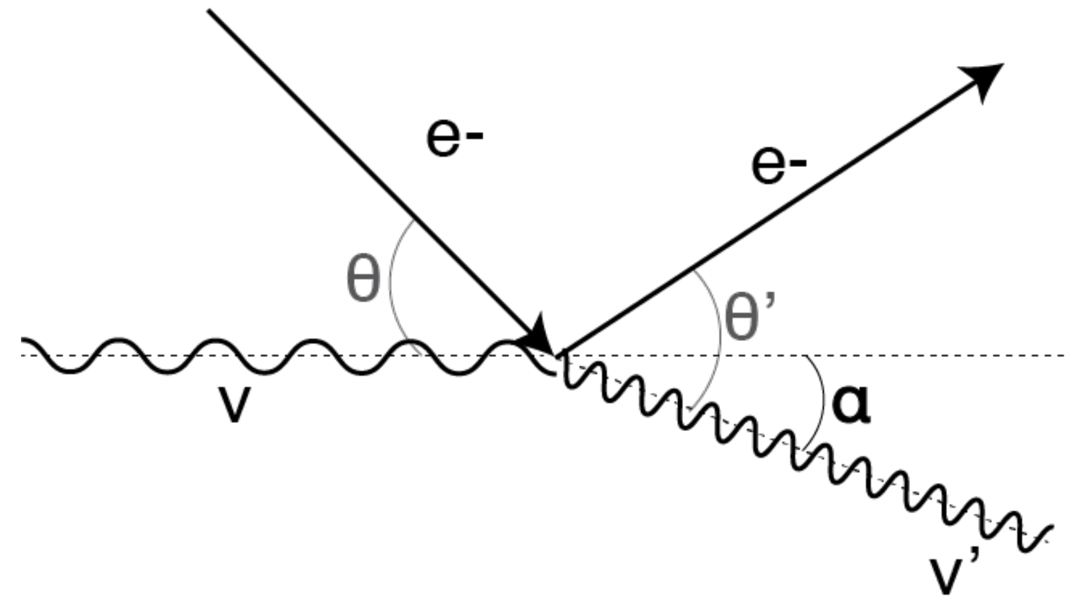
# Summary II

- Non-linear diffusive shock acceleration:
  - Accelerated particles form a shock-precursor
  - Plasma set in motion, pre-compresses, adiabatic heating
  - Shock structure changes:
    - -lower Mach number at sub-shock
    - -lower compression ratio at sub-shock
    - -overall compresion (subshock x precursor) larger
    - -requires in most cases energy losses
  - No longer pure power law spectrum: spectrum curved
  - Theory popular before 2008: lack of unambiguous evidence

# Friday

# 10 Non-thermal radiation processes




- Subdivision: leptonic versus hadronic
  - Leptonic caused by electrons and positrons (and muons)
    - -synchrotron radiation (radio to X-rays)
    - -inverse Compton scattering (X-rays to gamma-rays)
    - -non-thermal bremsstrahlung (X-rays to gamma-rays)
  - Hadronic: caused by protons/ions
    - -only pion decay (gamma-rays and neutrinos)
    - -only direct radiative signature of accelerated ion cosmic rays!!

# The spectral energy distribution (SED)

- Important concept: at what frequency is radiation maximized?
- Calculate bolometric flux (or luminosity)

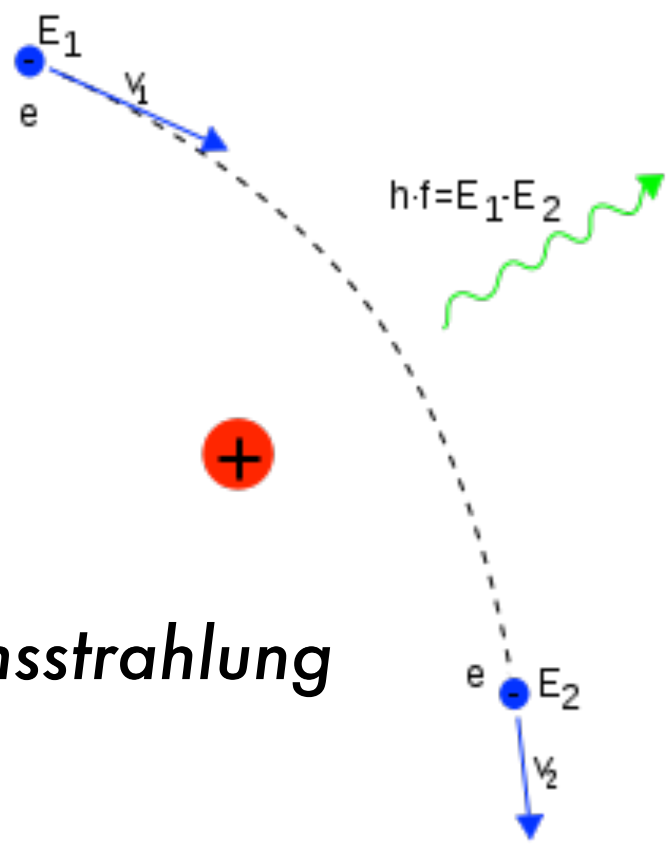
$$F_{\rm bol} = \int f_\nu(\nu) d\nu \xrightarrow[\text{power law}]{} \propto \frac{\nu^{-\alpha+1}}{-\alpha+1} \propto \nu f_\nu$$

$$F_{\rm bol} = \int E N(E) dE \xrightarrow[\text{power law}]{} \propto \frac{E^{-\Gamma+2}}{-\Gamma+2} \propto E^2 N(E)$$

- By plotting spectra as $\nu f_\nu$ or $E^2N(E)$ we see what part of the spectrum contributes most to bolometric flux/luminosity
- Such a plot is called a spectral energy distribution (SED)

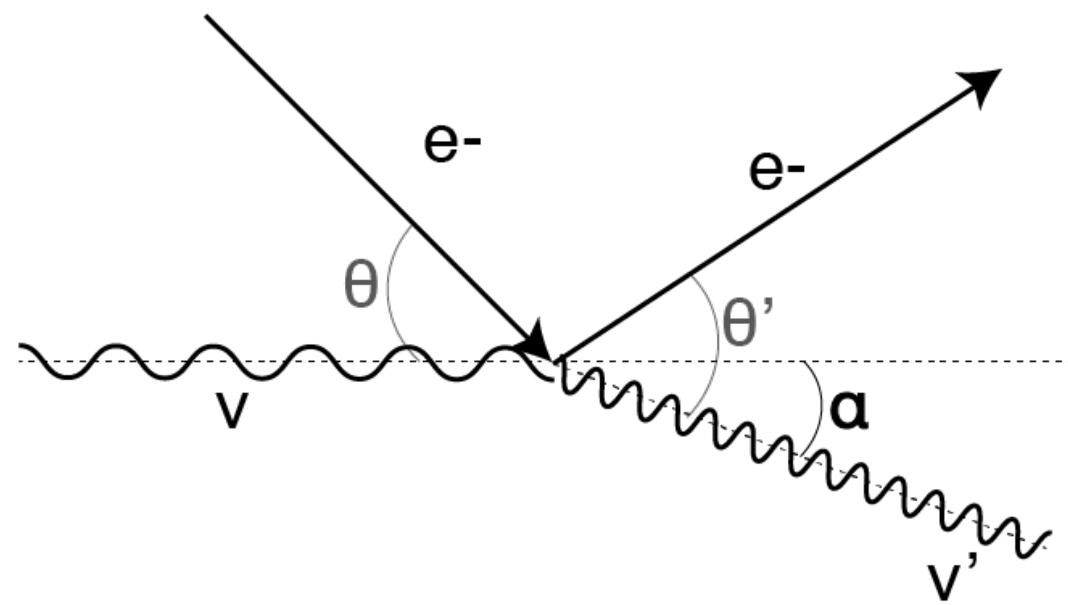
# Gamma-ray radiation processes

*Leptonic processes:*

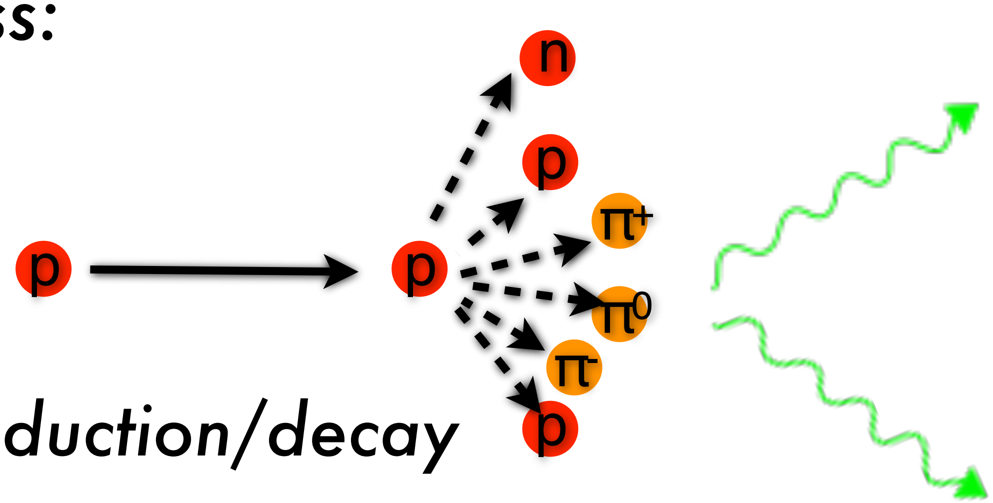



*Bremsstrahlung*

*Inverse compton scattering*



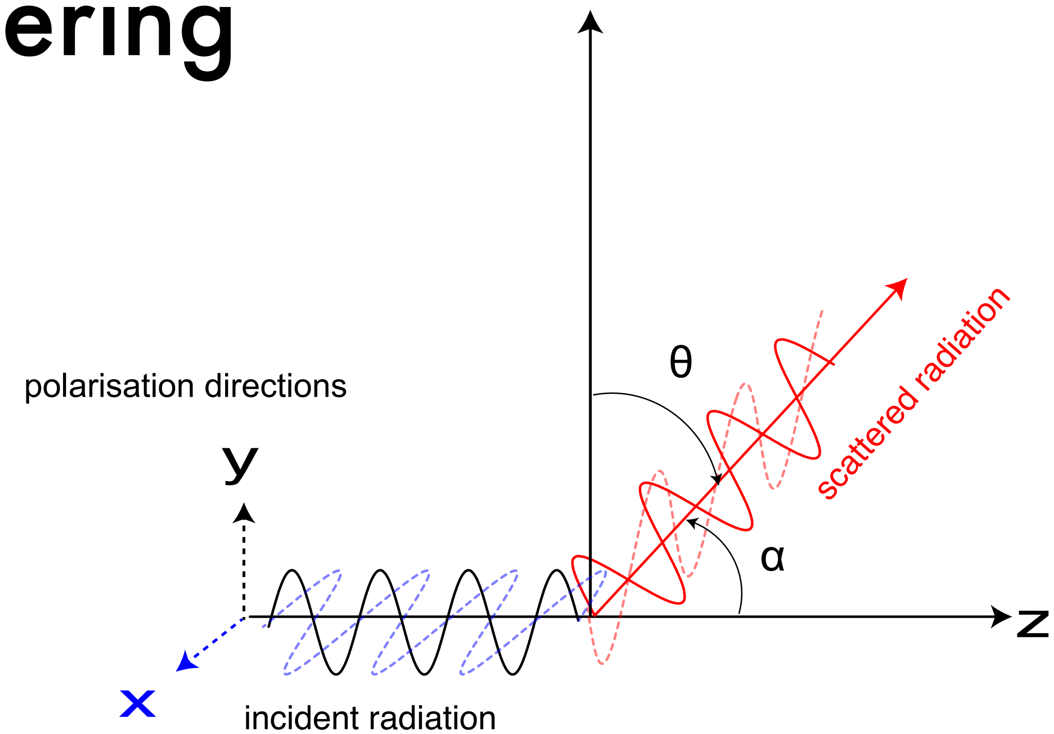

*Hadronic process:*

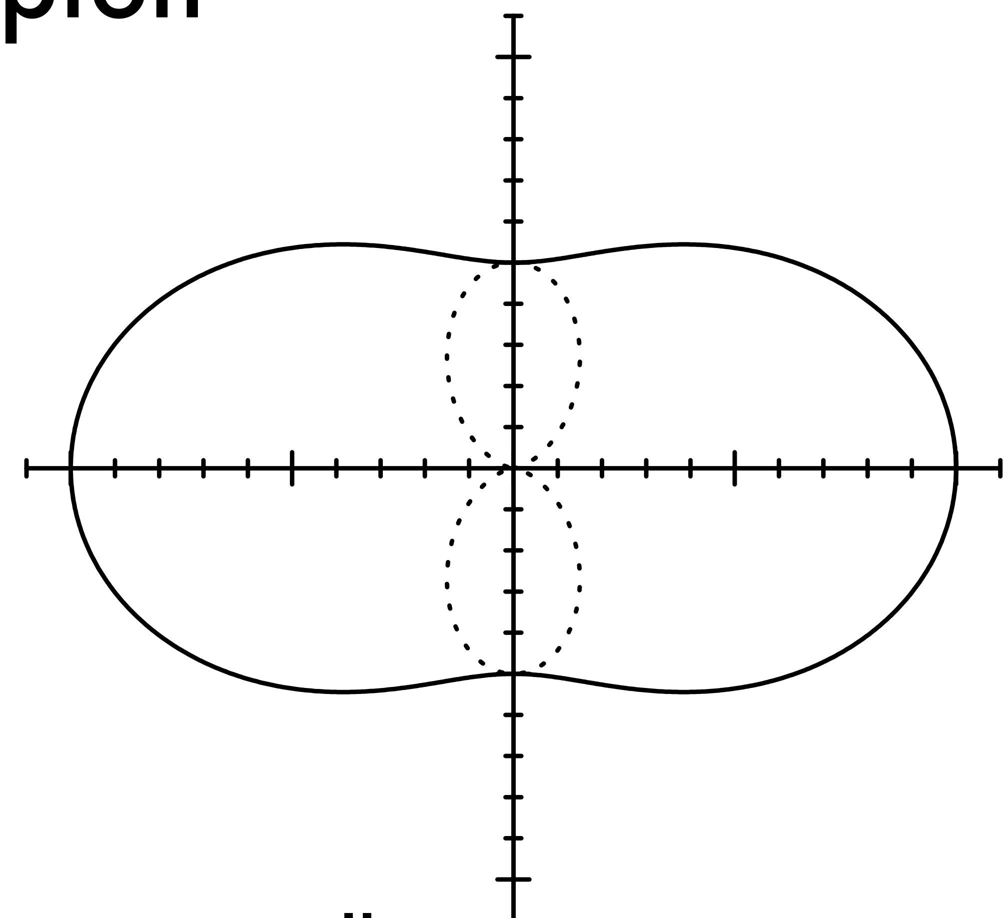



*Neutral pion production/decay*

$$\pi^0 \rightarrow \quad 2\gamma$$
$$\pi^+ \rightarrow \quad \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \quad \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

# Thomson scattering/Inverse Compton scattering



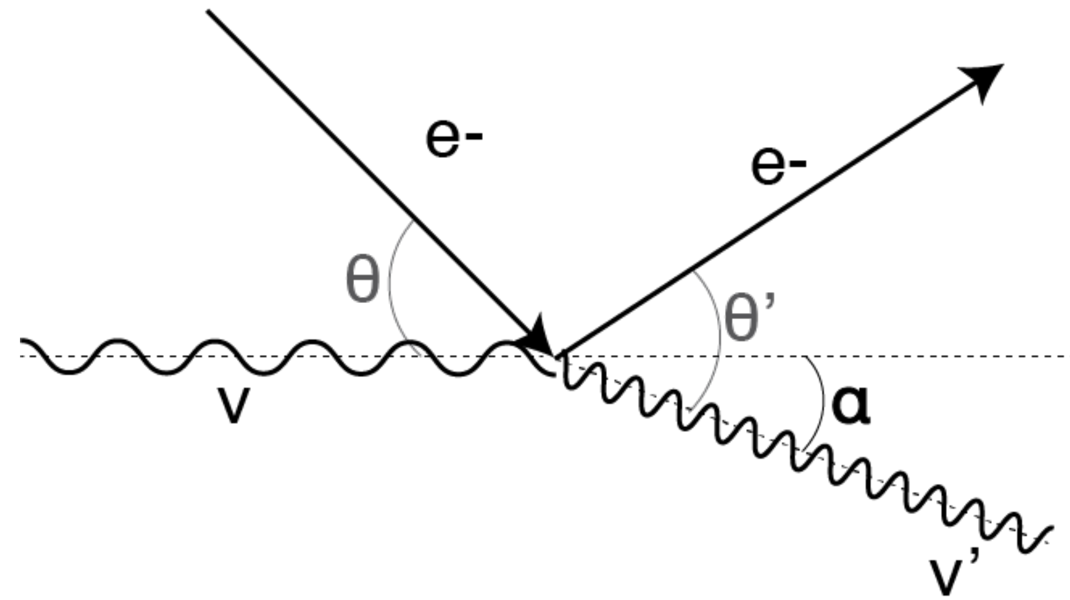



- Thomson scattering: radiation induced electron oscillation
  - Electron oscillation: radiation (hence scattering)
  - No change in frequency (photon energy)
  - Only change in direction
  - Gives strong polarisation for certain directions
  - Cross section

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z^2 e^2}{mc^2}\right)^2 \left(1 + \cos^2 \sin\right) = \left(\frac{Z^2 e^2}{mc^2}\right)^2 \left(1 + \cos^2 \alpha\right)$$

$$\sigma_{\mathrm{T}} \equiv \frac{8\pi}{3}\left(\frac{e^2}{m_{\mathrm{e}} c^2}\right)^2 = \frac{8\pi}{3} r_{\mathrm{e}}^2 = 6.6524 \times 10^{-25}\ \mathrm{cm}^2$$

# Inverse Compton scattering




- For sufficiently energetic photons: electron will pick up momentum (recoil)
- If electron is moving (β>0): photon may gain or lose energy

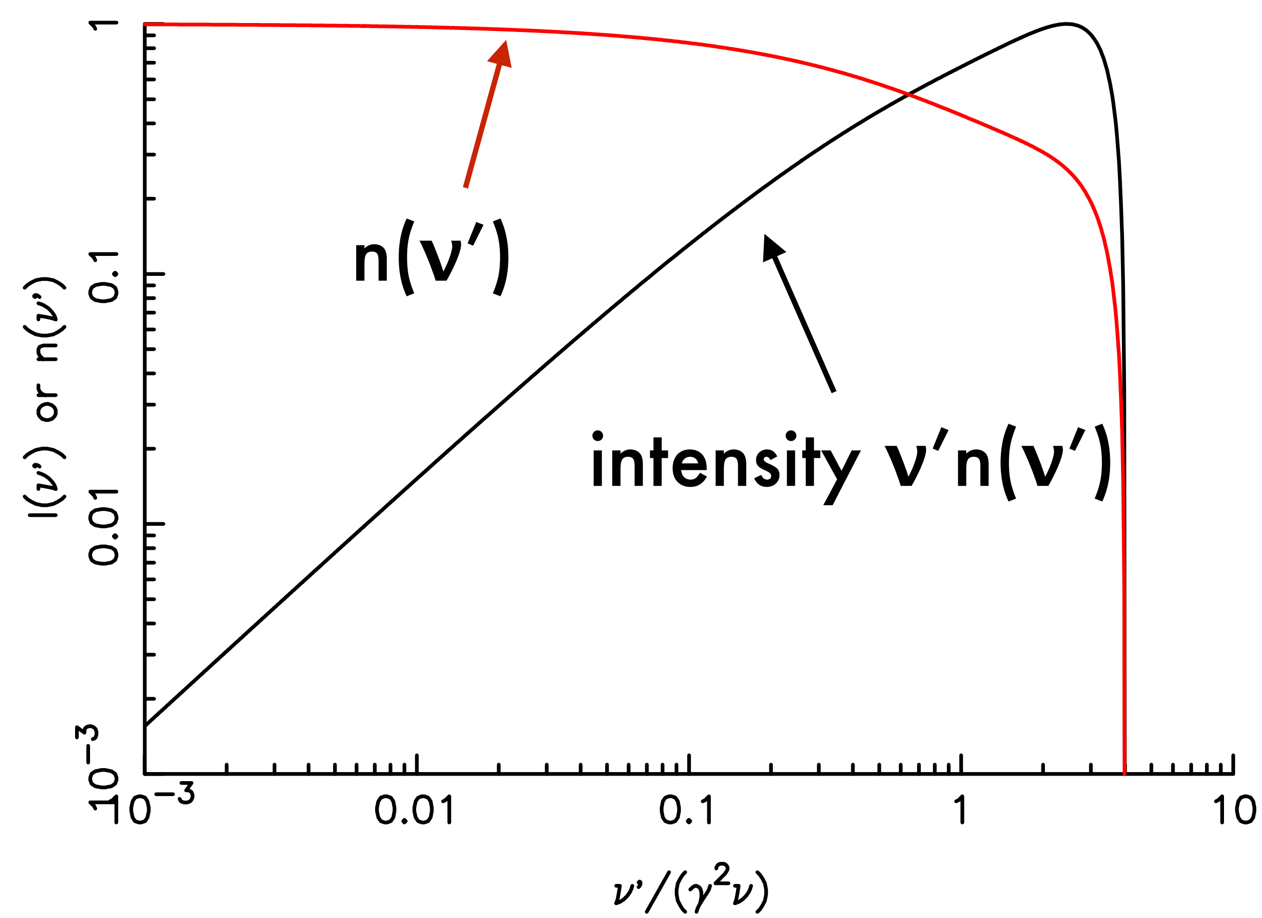
$$\frac{\nu'}{\nu} = \frac{1 - \beta\cos\theta}{1 - \beta\cos(\theta - \alpha) + \frac{h\nu}{\gamma m_e c^2}(1 - \cos\alpha)}$$

- Maximum for head on collision: $\cos\theta = -1, \cos(\alpha - \theta) = 1$

$$h\nu'_{\max} = \frac{1+\beta}{1-\beta}h\nu = \gamma^2(1+\beta)^2 h\nu \approx 4\gamma^2 h\nu$$

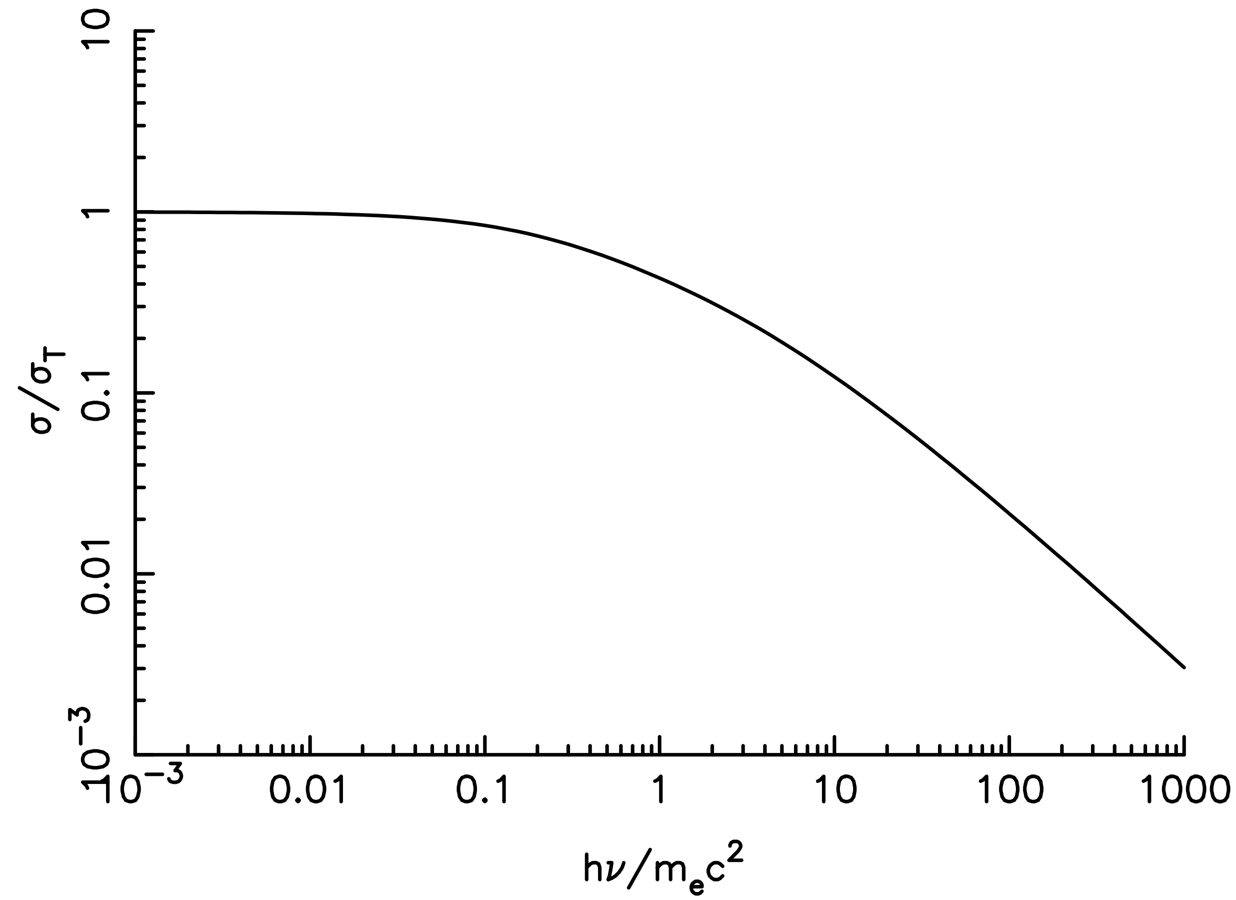
- Mean energy gain: $\overline{h\nu'} = \frac{4}{3}\gamma^2 h\nu$

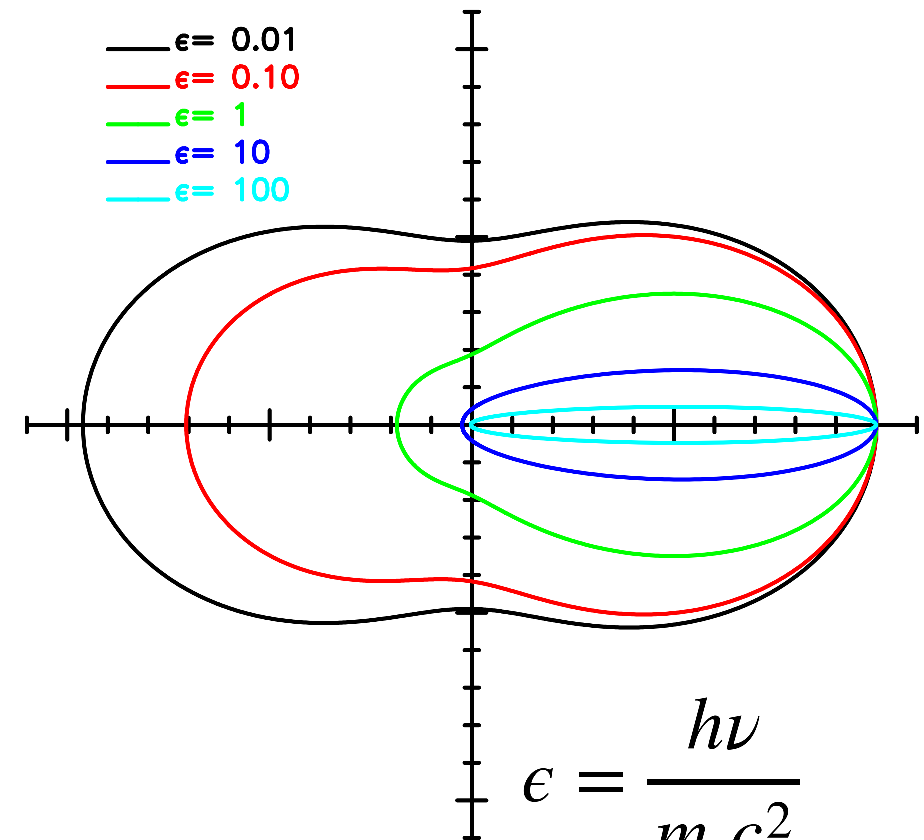
# Inverse Compton scattering




- Qualitative understanding IC
  - scattering in frame of electron: photon is mostly blue shifted
    electron scatters electron of energy $\sim\gamma h\nu_0$
  - scattered photon: back to observer frame: another Lorentz boost $\sim\gamma$
  - so photon energy in obersever fram: $\sim\gamma^2 h\nu_0$

# Inverse Compton scattering: Klein-Nishina effects



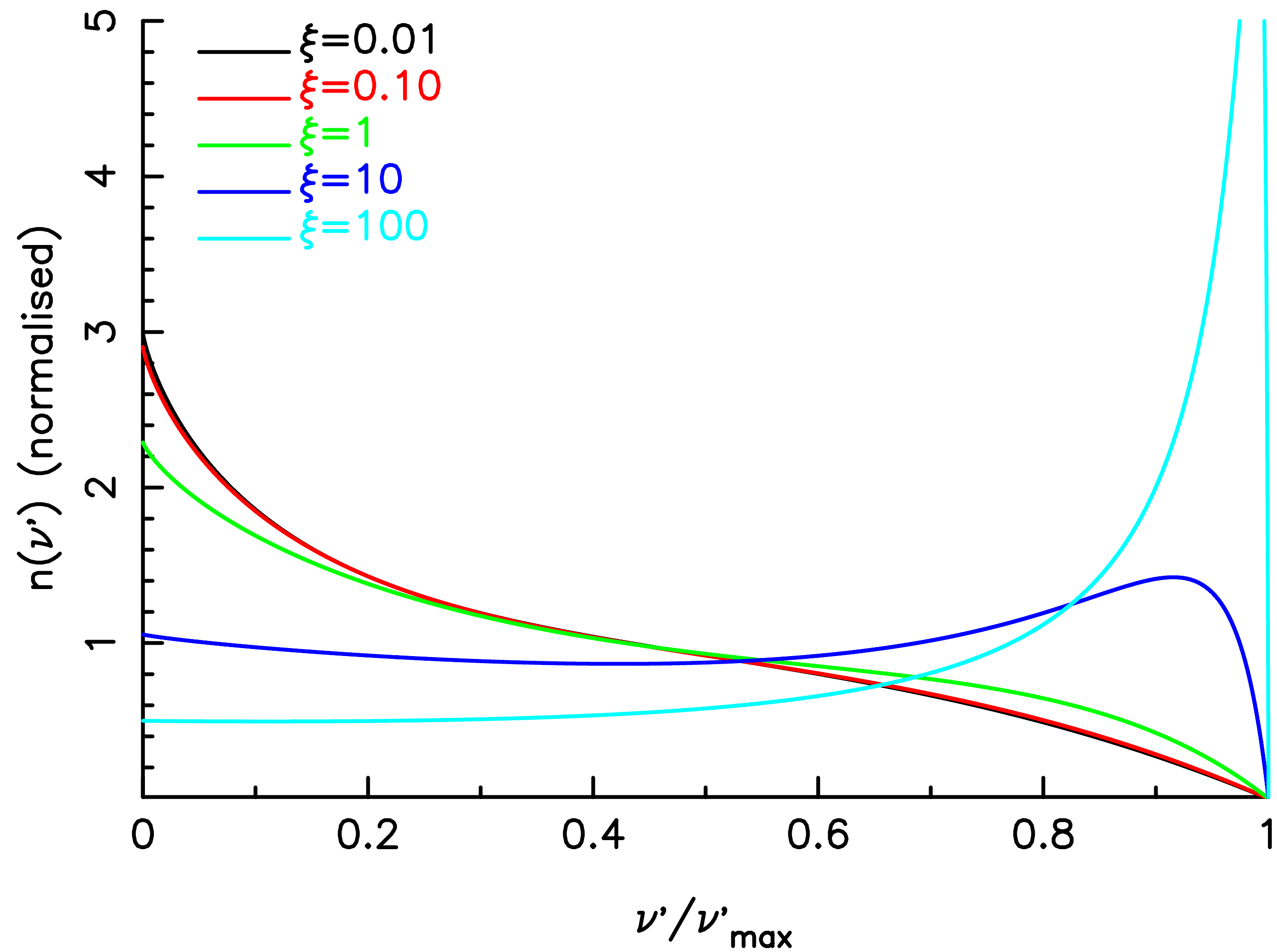

$$\epsilon = \frac{h\nu}{m_e c^2}$$

- For electrons at rest: cross section reduces for $h\nu \gtrsim m_e c^2$
  - Cross section changes from Thomson to Klein-Nishina cross section
- For inverse Compton, KN effect important if $h\nu \gtrsim m_e c^2$ in electron frame
- Hence, IC scattering strongly reduced for $\gamma h\nu \gtrsim m_e c^2$

- Scattering increasingly forward dominated
- KN cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{\nu'}{\nu}\right)^2 \left[\left(\frac{\nu'}{\nu}\right) + \left(\frac{\nu'}{\nu}\right)^{-1} - \sin^2\theta\right]$$

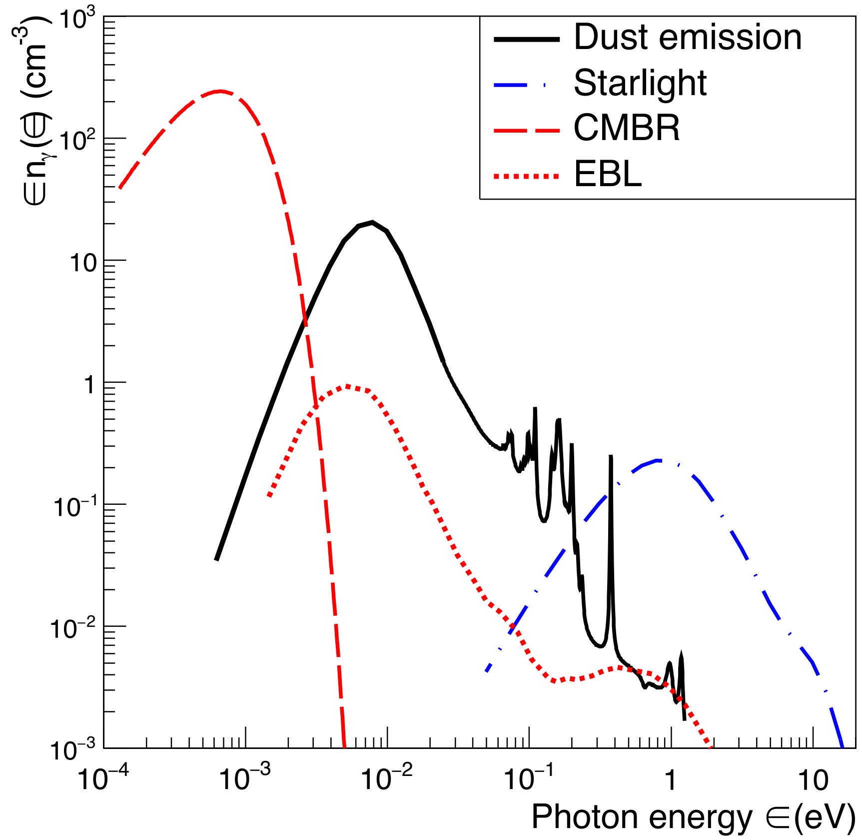
# Inverse Compton scattering: Klein-Nishinina effects




- Forward scattering in electron frame leads to peaking of n(ν′) to $\nu'_{max}$
- Maximum energy of scattered photon reduced:

$$h\nu'_{\rm max} = \frac{4\gamma^2 h\nu}{1 + 4\gamma \frac{h\nu}{m_{\rm e}c^2}} \leq \gamma m_{\rm e} c^2 \, .$$

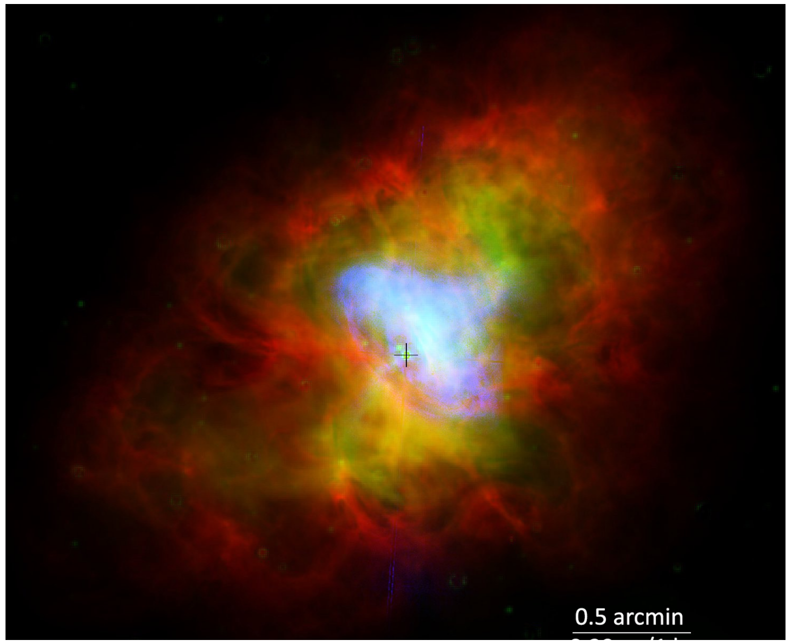
# Inverse Compton scattering: radiation fields

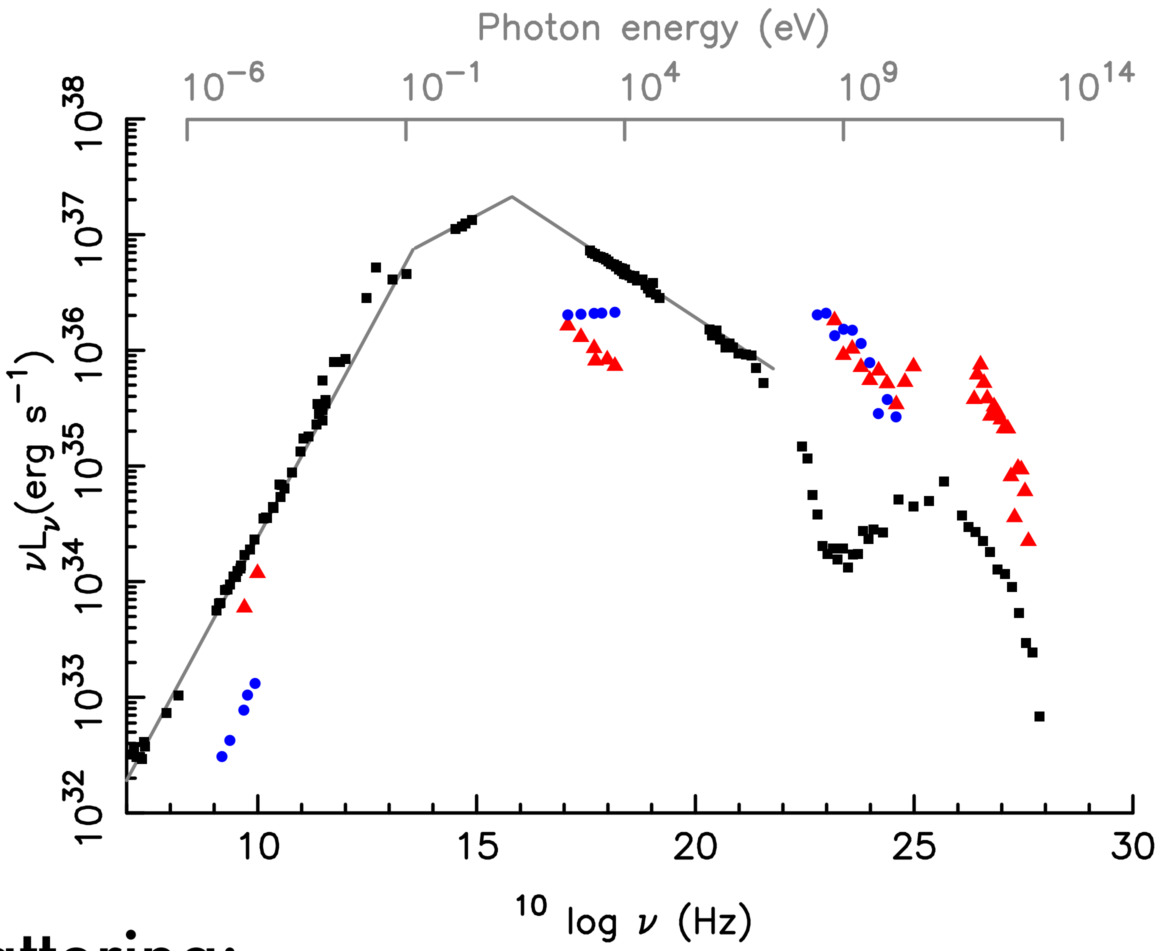



Venetto & Lipari 2016

- Photons are everywhere:
  - CMB photons: 410 cm$^{-3}$, h$\nu\approx 6.6\times10^{-3}$ eV
  - Infrared dust emission in galaxy
  - Star light
- Note:
  - for a given gamma-ray energy, lower energy electrons needed for starlight as compared to CMB
  - there are more low energy electrons than high energy electrons
  - compensates somewhat for the lower photon densities
  - Result: CMB, IR, optical/UV have nearly equal contributions
- NB: CMB redshift dependent, IR/starlight vary through galaxy

# Connection inverse Compton & synchrotron radiation



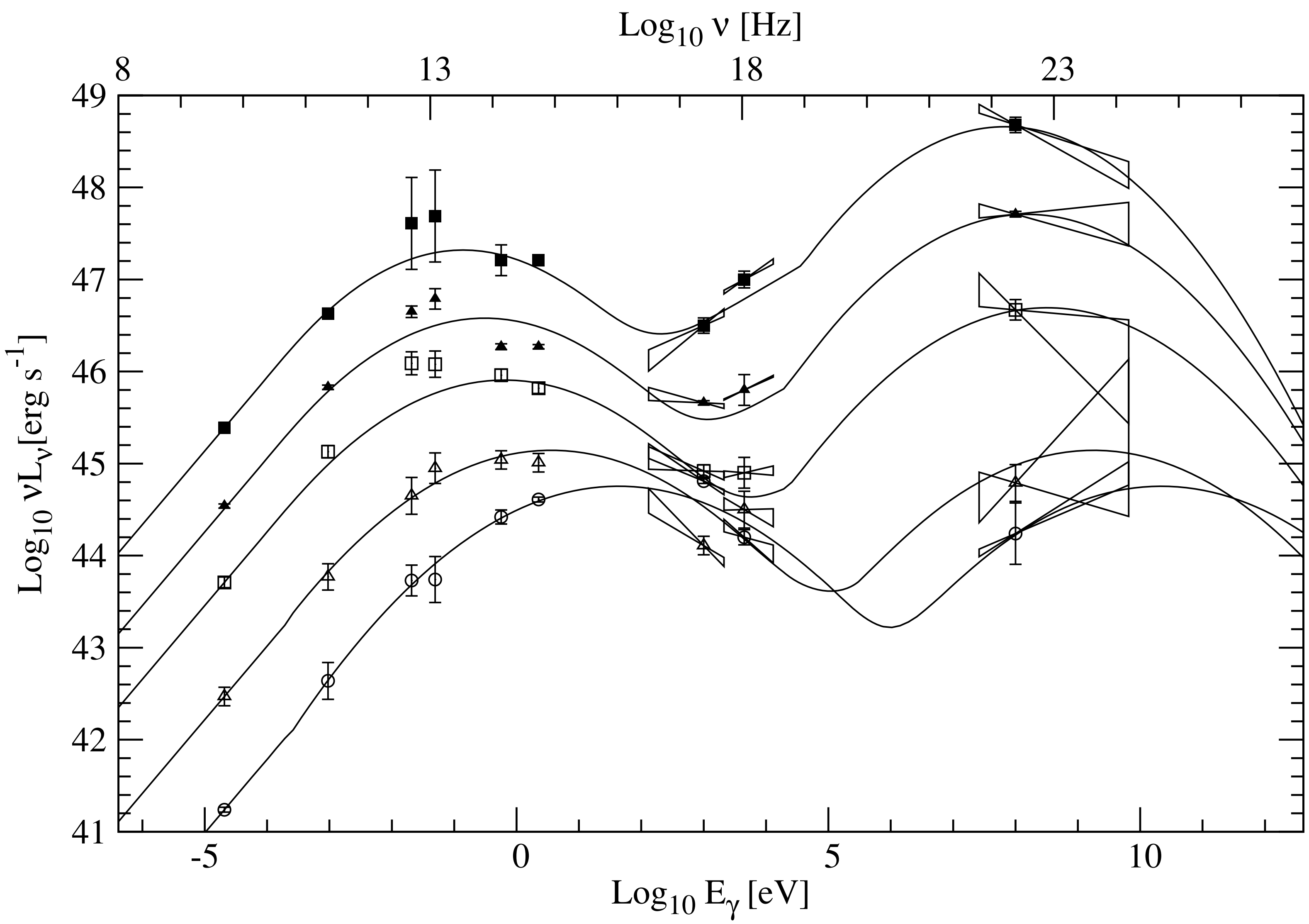

- Total power radiated in inverse Compton scattering:

emission per electron $\approx \frac{4}{3} c \sigma_T \gamma^2 h\nu n_\nu = \frac{4}{3} c \sigma_T U_{rad}$

- Compare synchrotron radiation: $P_{syn} = \frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_B$

- Power per electron similar but does depend on $U_{rad}$ or $U_B$
- Frequencies for synchrotron (radio-X-ray) and IC different (gamma-rays)
- SED: shows power → peak differences synchrotron/IC: depends on $U_{rad}/U_B$

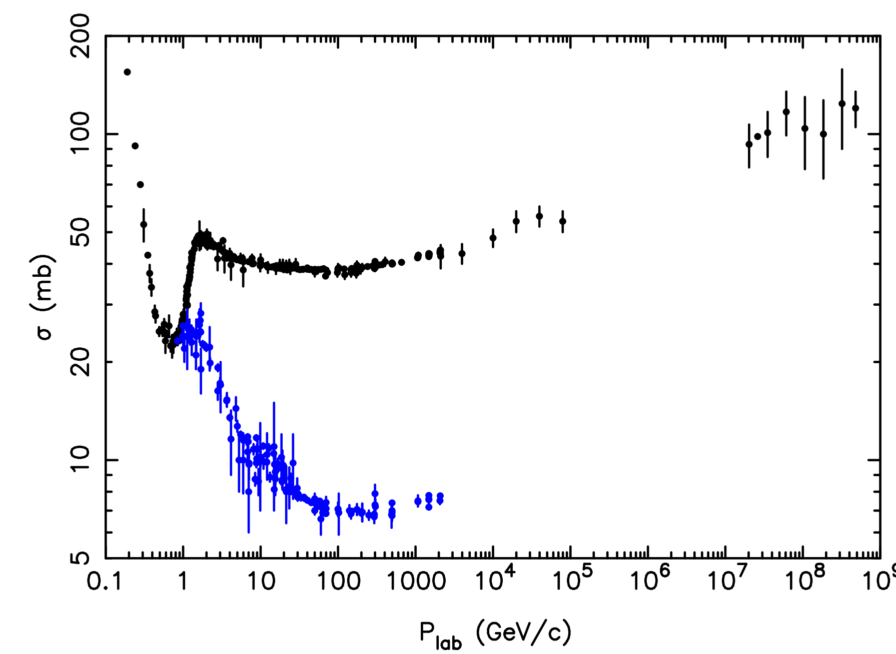
# Example 2: blazar SED's




- Blazars discussed in future lecture
- Powerful AGN jets directed toward us
- X-ray emission: sometimes synchrotron sometimes inverse Compton

# Pion decay

$$\pi^0 \rightarrow \quad 2\gamma$$
$$\pi^+ \rightarrow \quad \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \quad \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$




- Pions are particles consisting of two quarks, and come in three flavors: $\pi^0, \pi^-, \pi^+$
- Are produced in proton-proton/proton-neutron/neutron-neutron/ion-ion collisions
- Mass:
  - $m(\pi^0) = 135$ MeV/$c^2$
  - $m(\pi^{+/-}) = 139.6$ MeV/$c^2$
- When E>> $E_{thr}$ multiple pions, protons, neutrons, etc. can be made (charge conserved)
- Number of particles created: *multiplicity*
- $\pi^0$ decay immediately into two photons → gamma-ray radiation
- *NB* 1 $\pi^{+/-}$ are the source of high energy neutrinos (IceCube & KM3NeT)

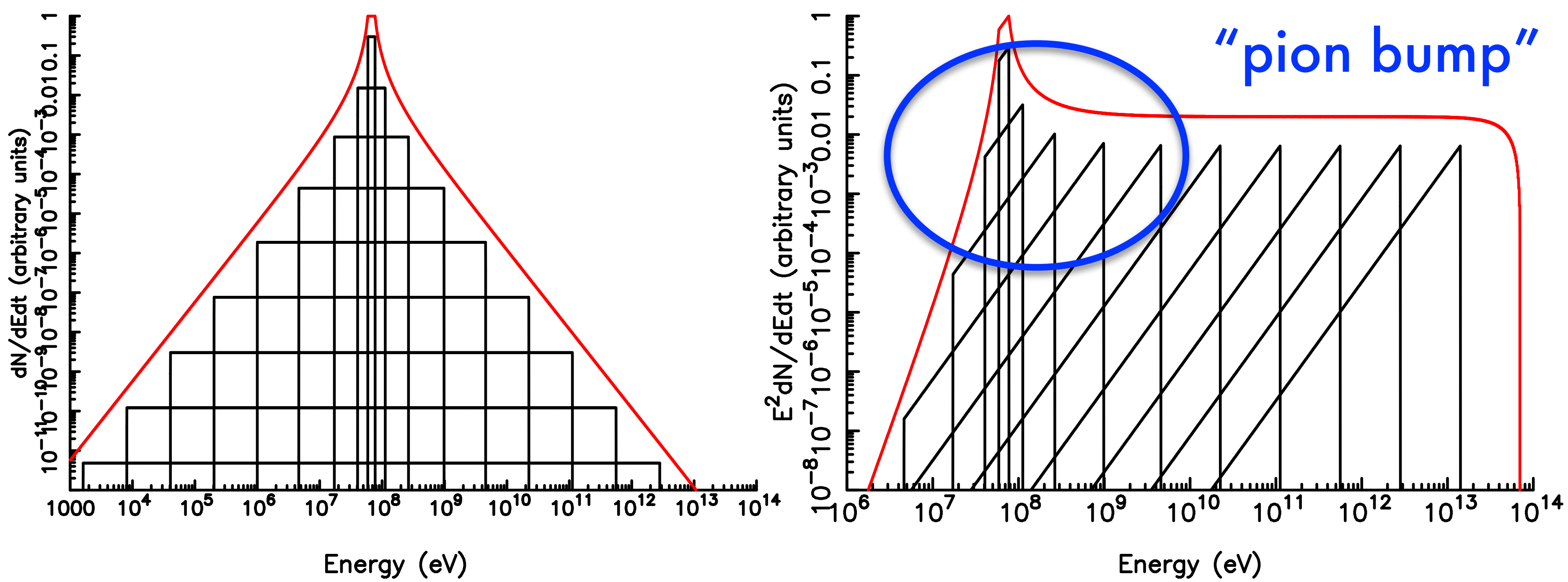
# Pion production

- In SNRs dominant production of pions: CR + background gas→ pions
- Threshold energy: 280 MeV for CR proton on proton at rest

$$
\begin{aligned}
p + p &\rightarrow p + p + \pi^0, \\
p + p &\rightarrow p + n + \pi^+, \\
p + p &\rightarrow p + p + \pi^+ + \pi^-, \\
p + p &\rightarrow \pi^0 + X,
\end{aligned}
$$

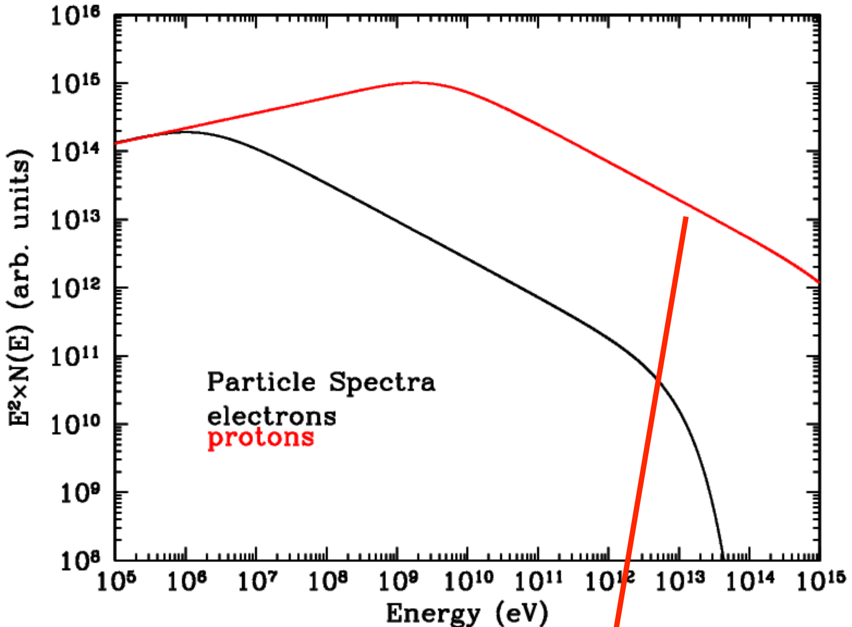
$$
\begin{aligned}
&\pi^0 \rightarrow 2\gamma, \\
&\pi^+ \rightarrow \mu^+ + \nu_\mu \\
&\qquad\quad \downarrow \\
&\qquad\quad e^+ + \nu_e + \overline{\nu}_\mu, \\
&\pi^- \rightarrow \mu^- + \overline{\nu}_\mu \\
&\qquad\quad \downarrow \\
&\qquad\quad e^- + \overline{\nu}_e + \nu_\mu.
\end{aligned}
$$

- Pion in rest frame: 2 photons each 67.5 MeV
- Doppler shifts: Lorentz boost + red and blueshift

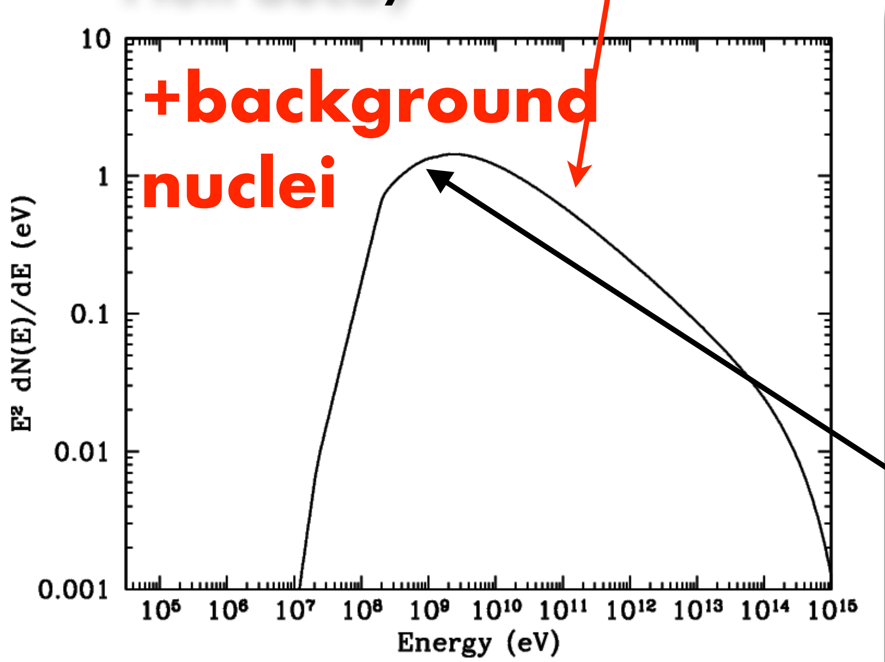


# Hadronic process: pion production + decay

Particle spectra



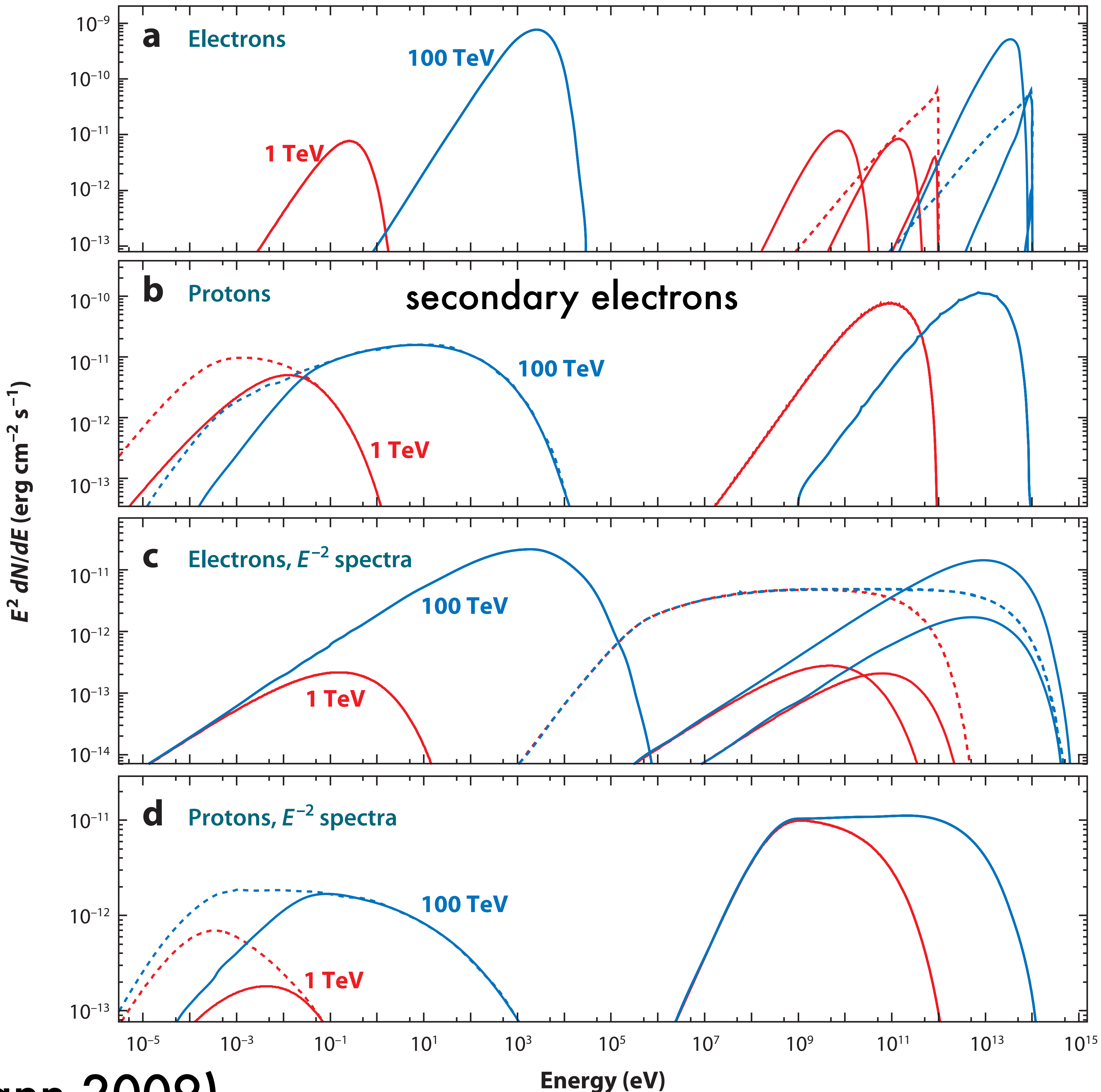

Pion decay




- Ion-ion collisions produce pions ($\pi^0,\pi^+,\pi^-$)
- Radiation: p+p → $\pi^0$ → 2γ
- Threshold energy: *279 MeV*
  (bump in GeV to TeV range)
- Detecting pion decay →
  *direct evidence for ion acceleration*
- Clearest sign for pion-decay:
  - detecting *pion-bump* around 1 GeV

pion bump

# SEDs



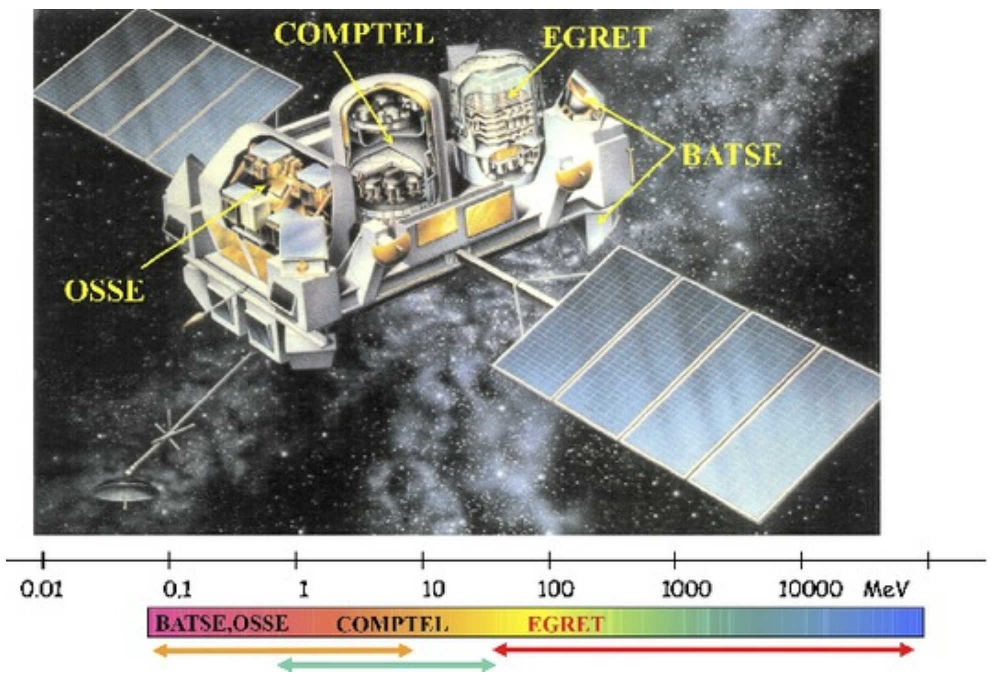

(Hinton & Hofmann 2009)

# 11 Gamma-ray observations

- Gamma-ray radiation consists of photons between 100 keV → 100 TeV
  - Lower boundary not sharp: 100 keV sometimes called hard X-rays
  - Physical definition: > 511 keV (rest mass electron/positron)
  - Upper boundary: no real boundary, but very few photons > 100 TeV

- Gamma-ray regimes
  - 0.1 -200 MeV: *MeV gamma-rays*
    -nuclear lines (up to 10 MeV): radio-activity, excitation due to cosmic rays
    - 511 keV $e^+/e^-$ annihilation lines
    -continuum processes: (synchrotron), inverse Compton scattering, positronium continuum
    -detection: balloon or satellite experiments
  - 200 MeV - 10 GeV: *high energy gamma-rays* (GeV gamma-rays)
    - continuum processes only (inverse Compton, bremsstrahlung, pion-decay)
    - detection: satellite experiments
  - 10 GeV- 100 TeV: *very high energy* (*VHE*) gamma-rays (TeV gamma-rays)
    - continuum processes only
    - detection: air Cherenkov telescopes, water Cherenkov telescopes

# High Energy Gamma-rays (GeV)

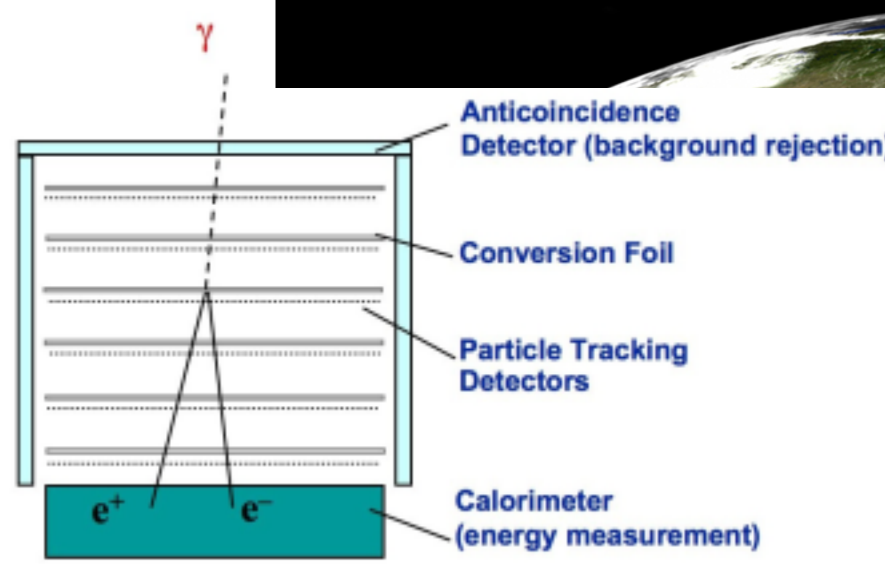



On board NASA's Compton Gamma-ray Observatory (CGRO) 1991-2000:

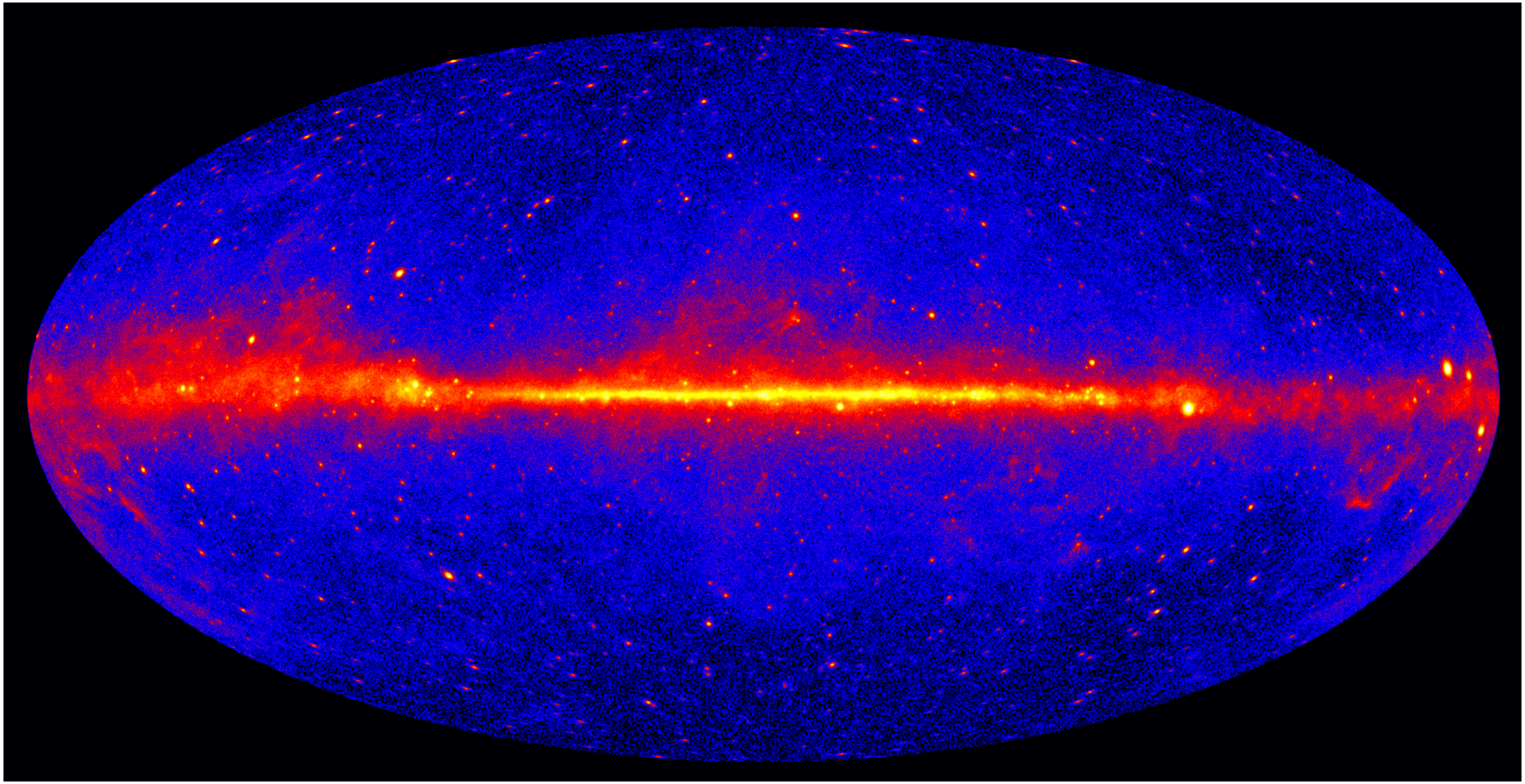
- EGRET (20 MeV-30 GeV):
  - Spark chamber:
    - -photon makes $e^+/e^-$ pair
    - -NaI scintillation detects pair

NASA's Fermi satellite (2008-)

- Large Area Telescope (LAT, 20 MeV-300 GeV):
  - Si-strip detectors
    - -photon makes $e^+/e^-$ pair
    - -Si-strip detect path
  - CsI scintillation detector: measure total energy
  - Better spatial resolution and sky coverage than EGRET:
    - -3deg @ 20 MeV, 0.04 deg @ 100 GeV
    - -FoV: 60 degrees

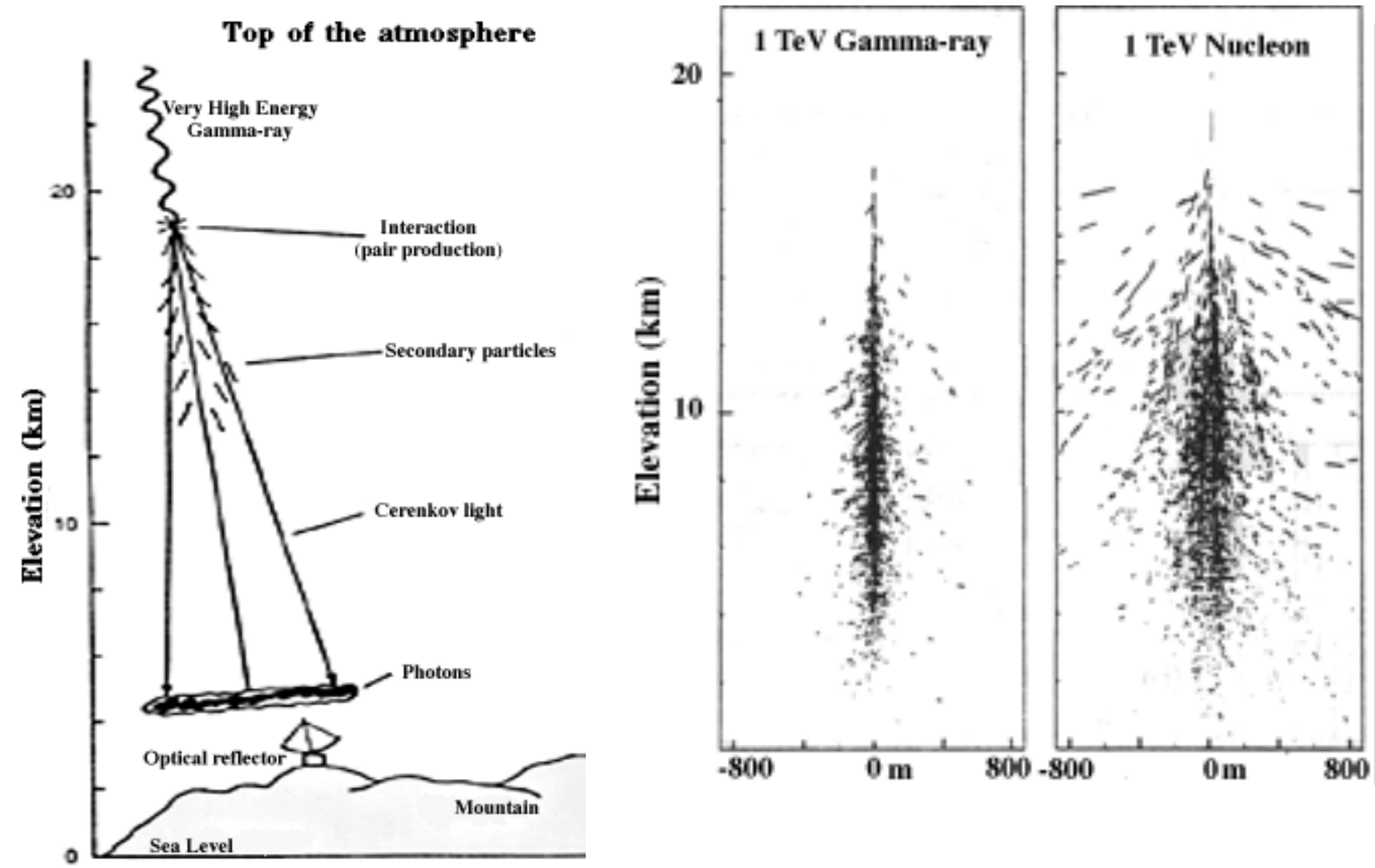


# The high-energy gamma-ray sky (>1 GeV)



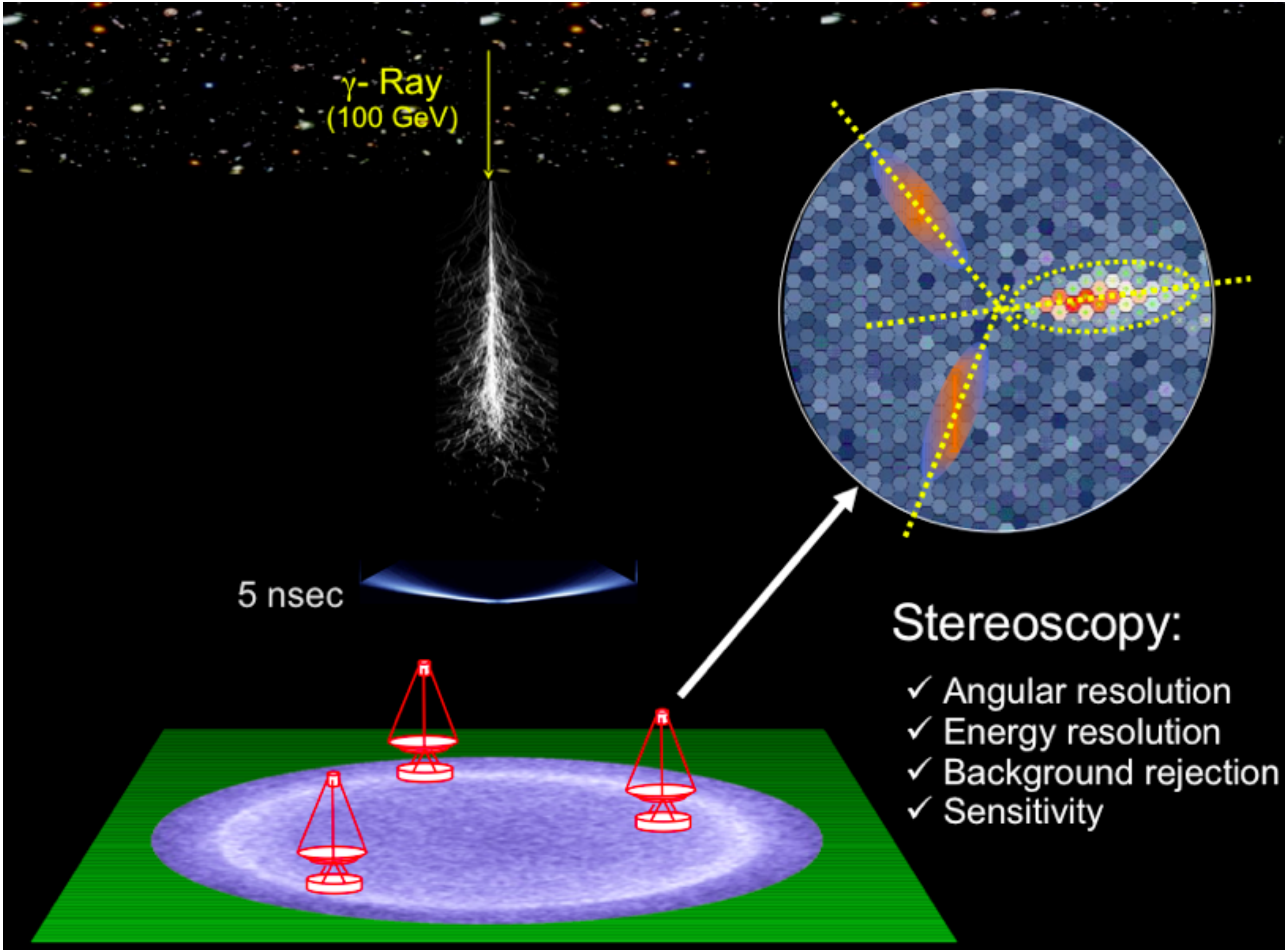
Fermi-LAT 5 yr observation

# Very High Energy Gamma-rays: *Imaging Atmospheric Cherenkov Telescopes* (IACTs)

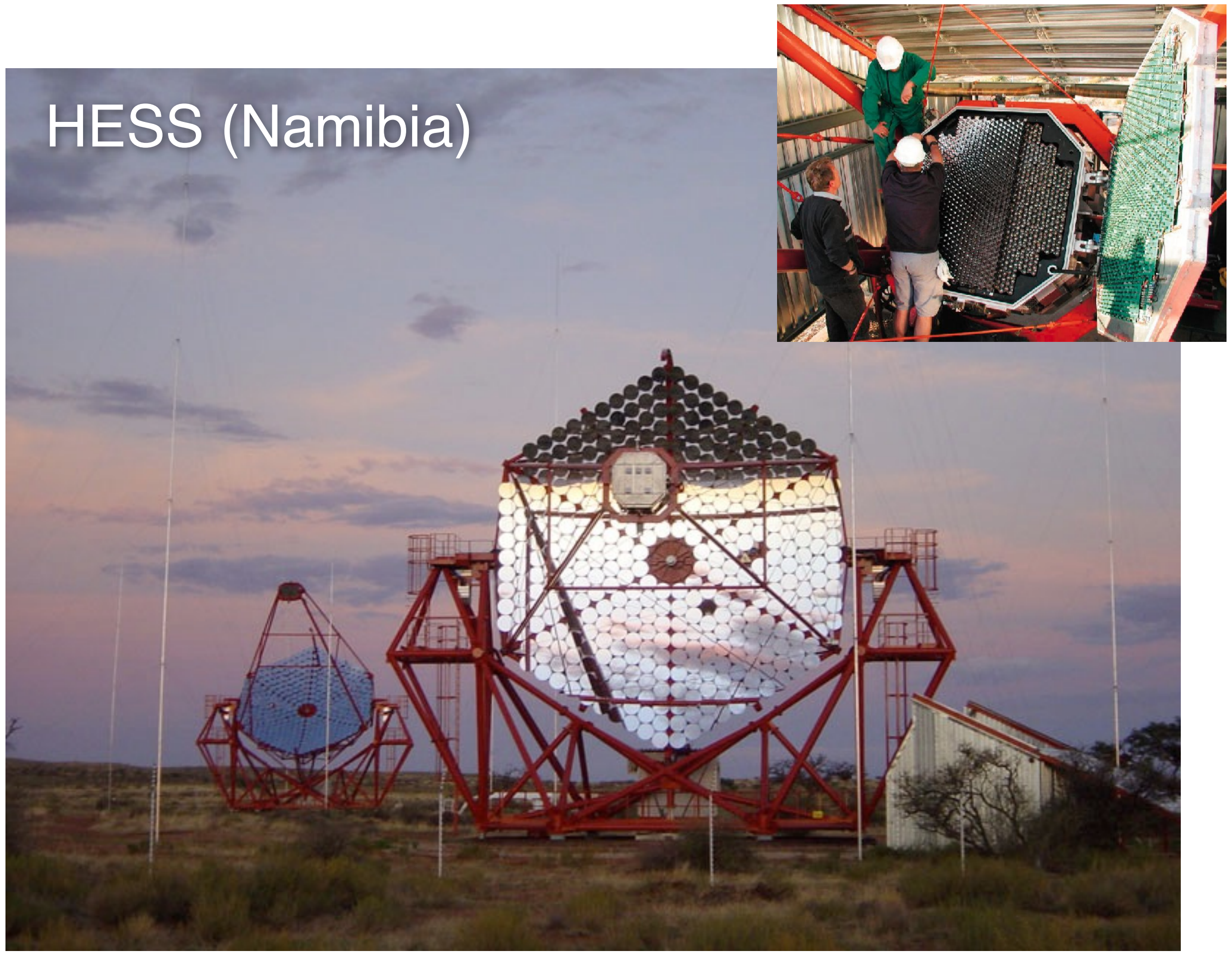


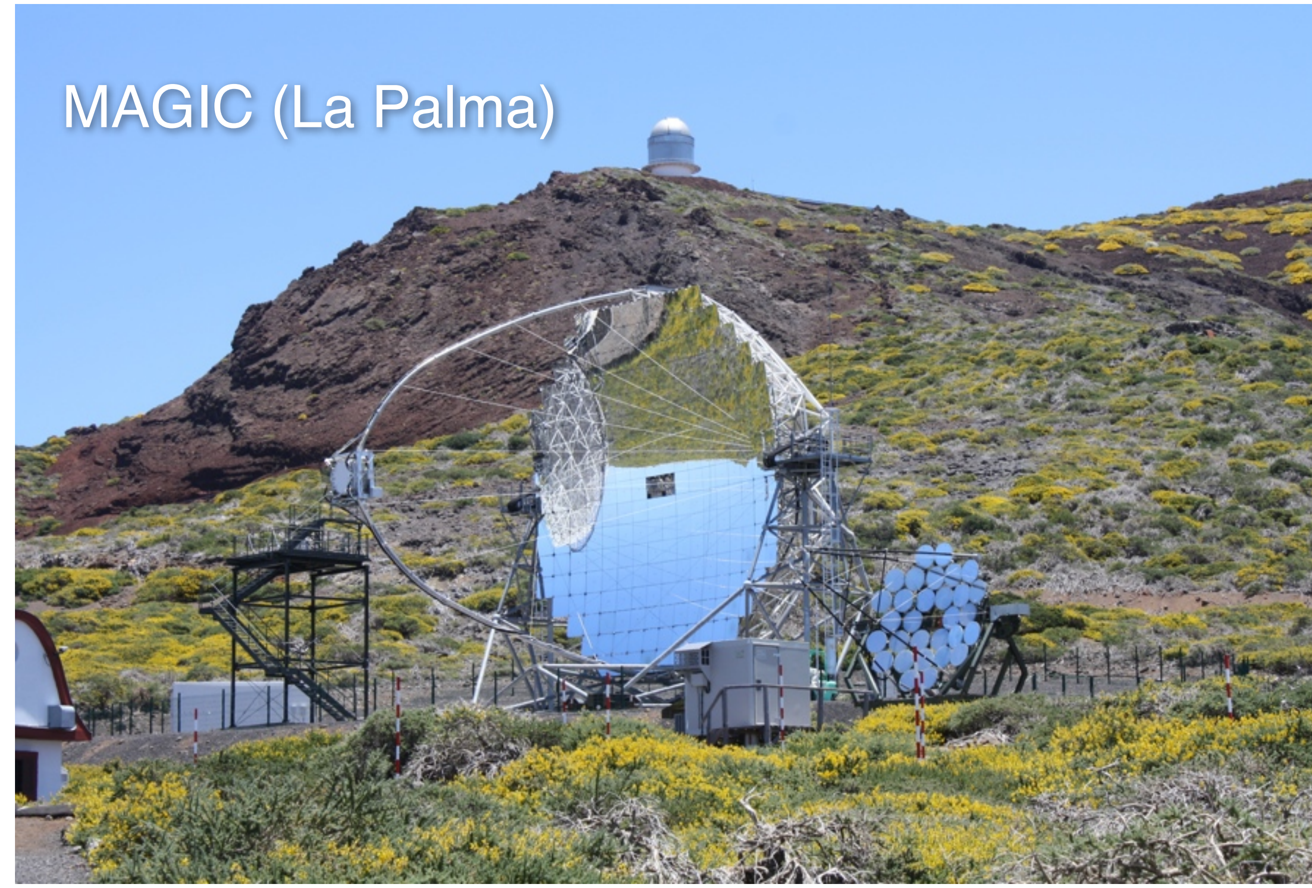

- Above 10-100 GeV: satellites too small to effectively detect photons
- Instead of heavy material as detector, use atmosphere as detector:
  - photon generates air shower in atmosphere
  - image the sky with big telescopes to see the Cherenkov light
  - record the air shower and use shape and heigh of shower to distinguish photons from cosmic rays

# Stereoscopy

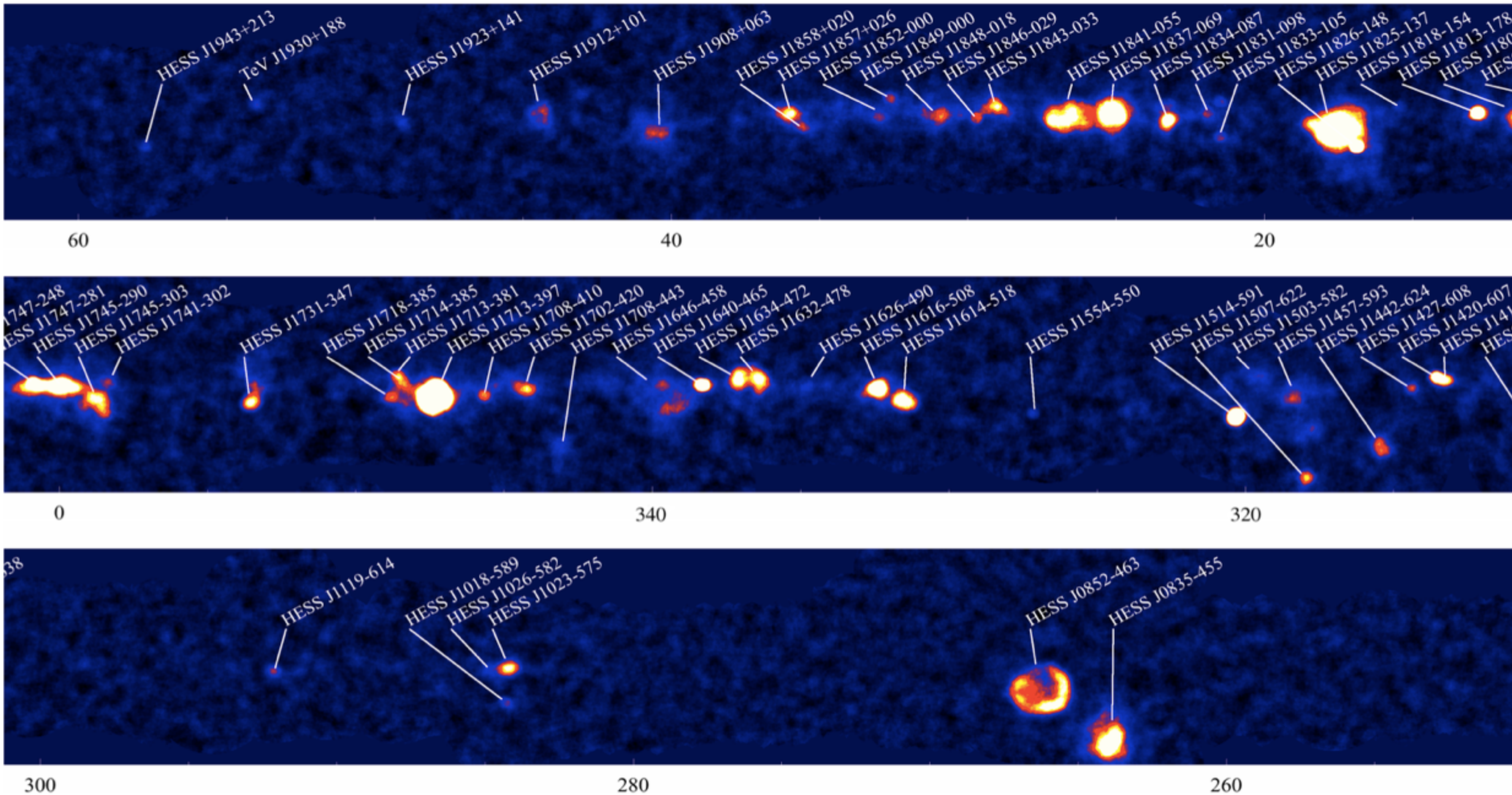


# Current Cherenkov Telescopes

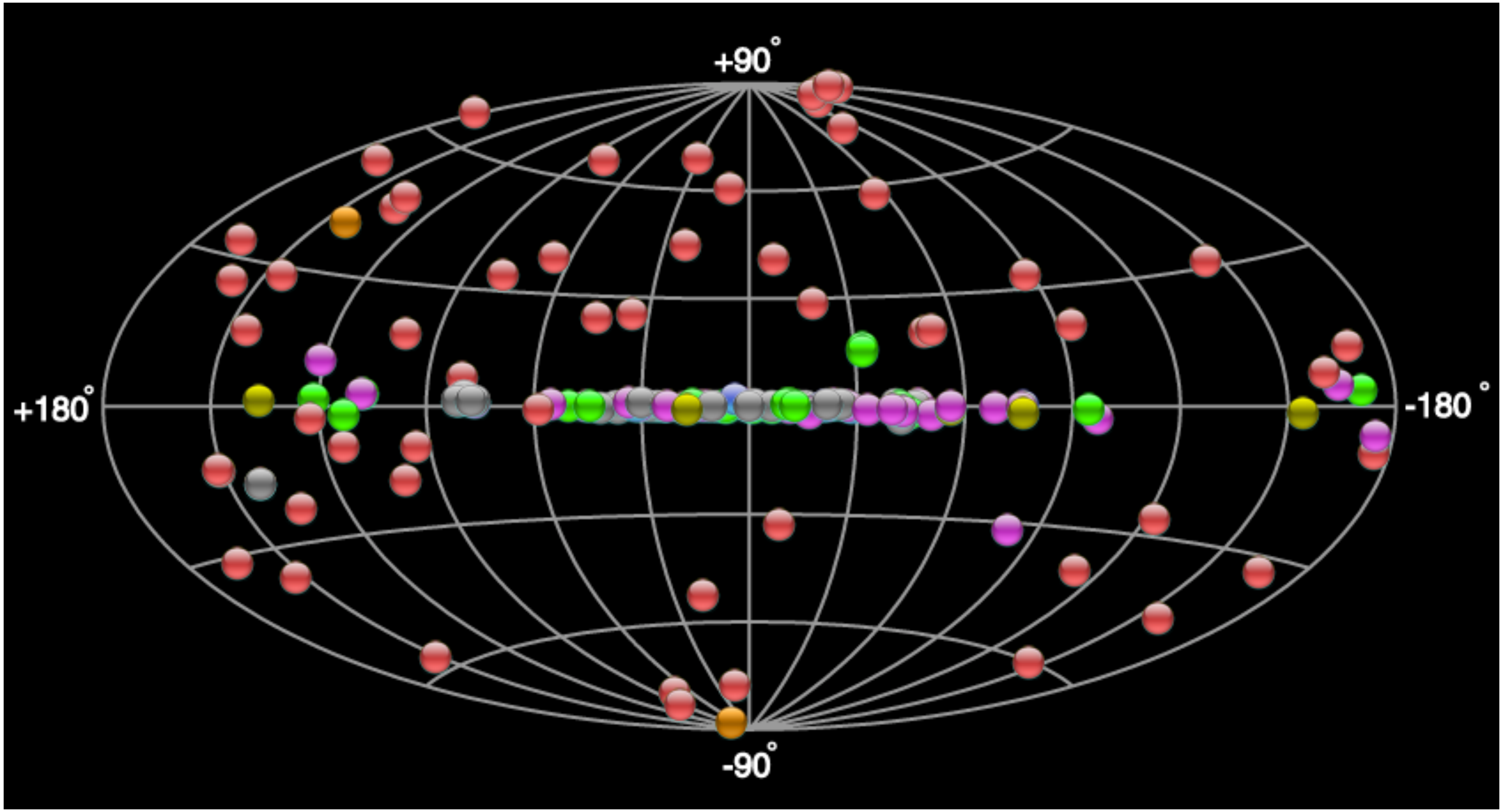



# HESS survey inner Galactic plane

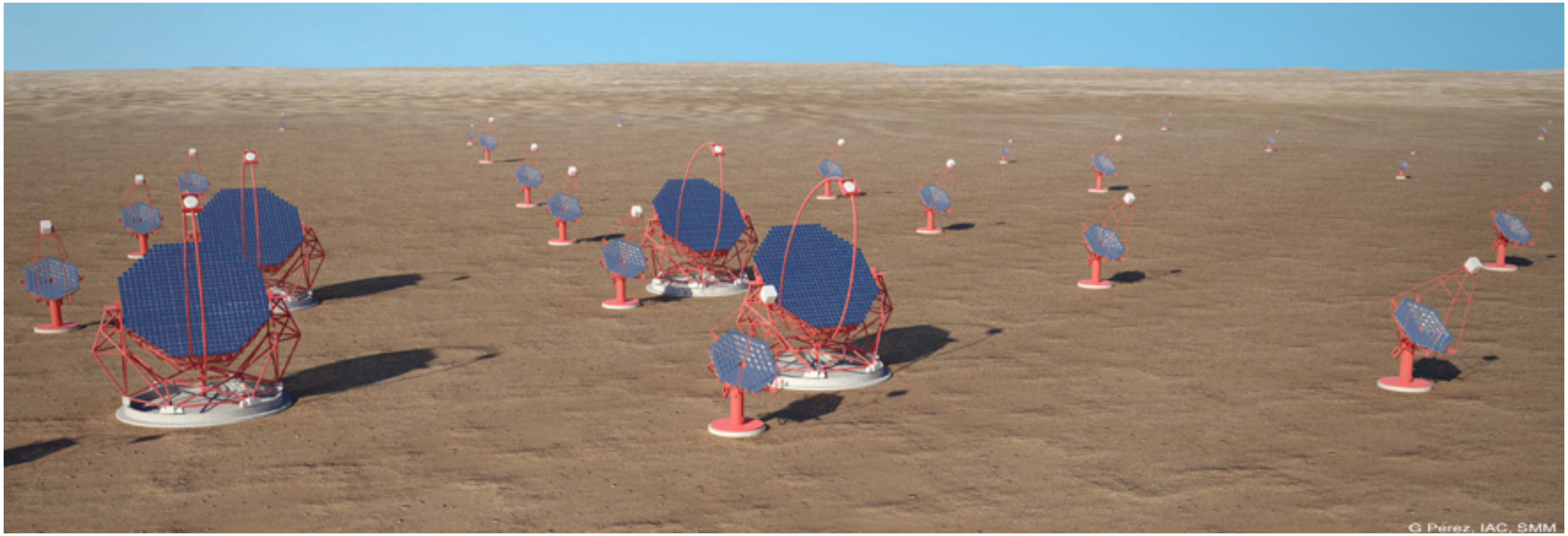


# TeV catalogue



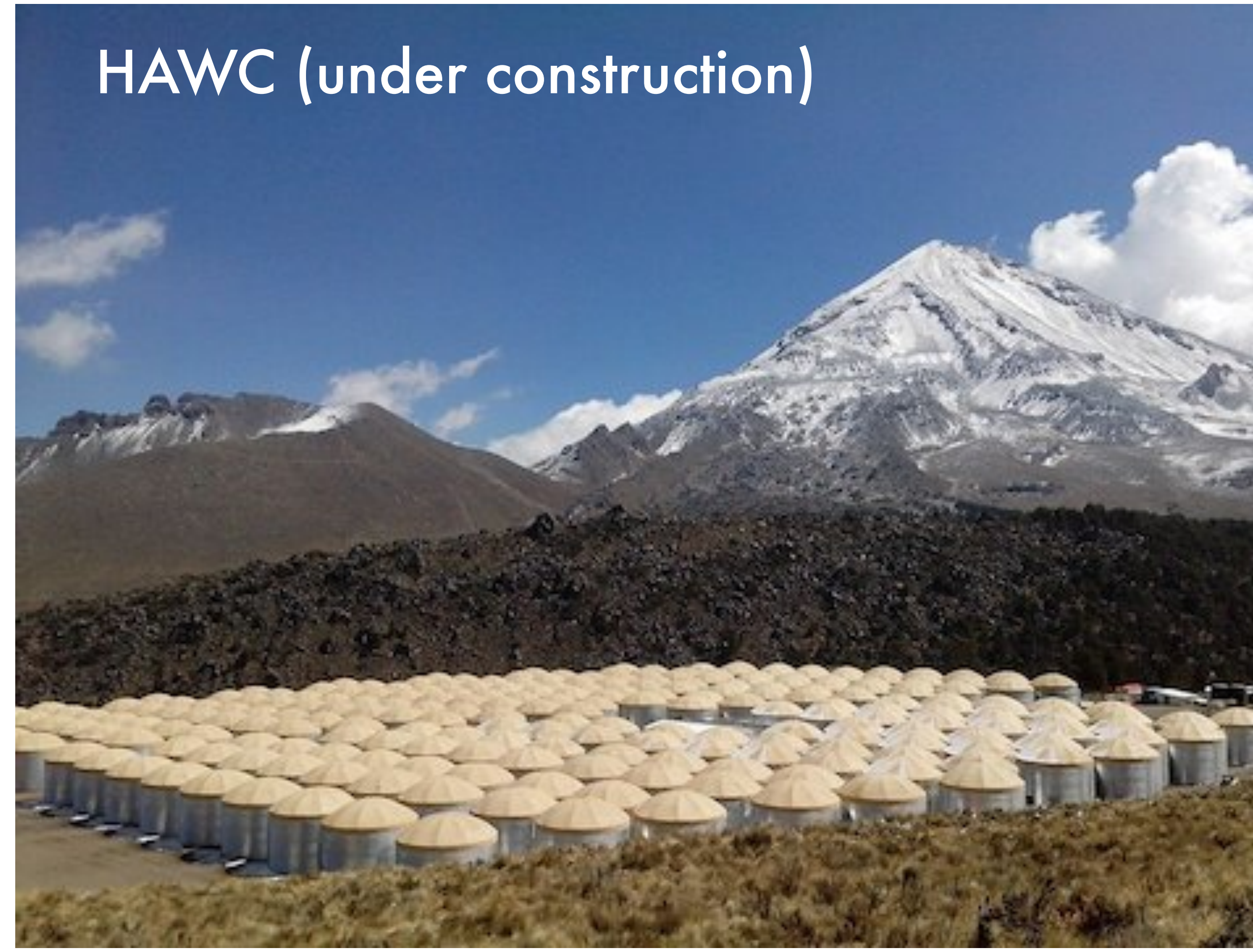

http://tevcat.uchicago.edu

# Cherenkov Telescope Array (CTA)




- To be build by 2024 (northern and southern site)
- Southern will consist of >70 telescopes (large eff. area, better angular resolution)
- Three types of telescopes
  - Small-sized telescopes (4-5m): many telescopes: detect bright, but rare photons above 5 TeV
  - Medium-sized telescopes (12m): fewer than SSTs, mid range
  - 2-4 Large Sized telescopes (24m): collect faint, but abundant low energy photons (10-20 GeV)

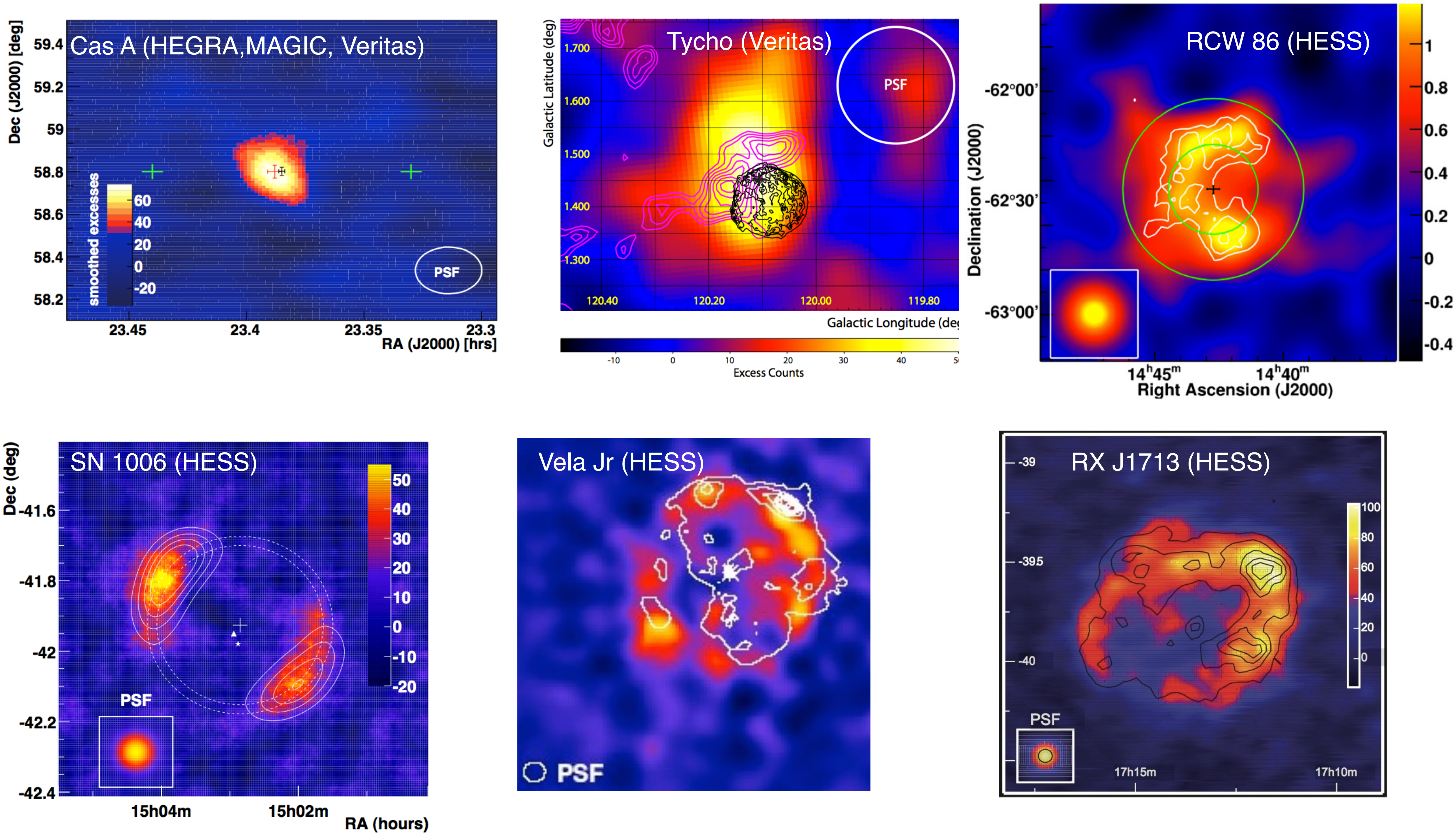
# Watertank Cherenkov Telescopes




- At high altitude one can also observe directly the particles of the air shower:
  - Cherenkov light of particles in dark water tanks
- Advantage:
  - always operational (no dark nights needed)
  - large field of view
- Two experiments:
  - Milagro (2000-2008)
  - High Altitude Water Cherenkov (HAWC) (http://www.hawc-observatory.org)

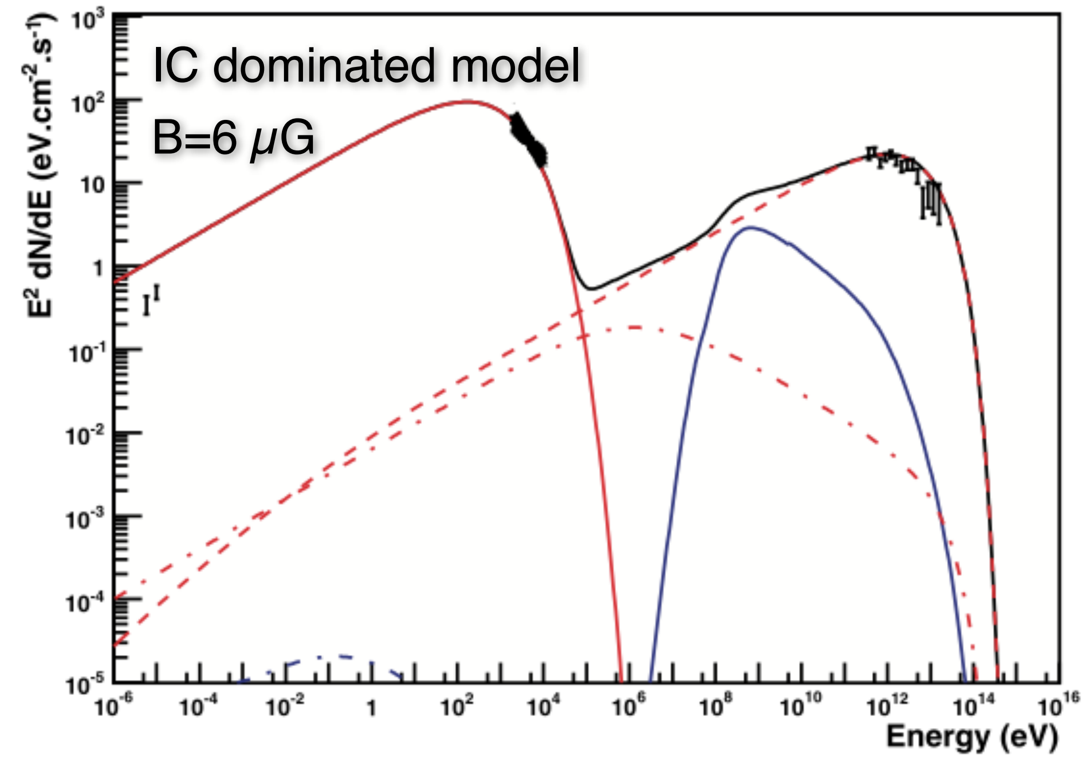
# Break

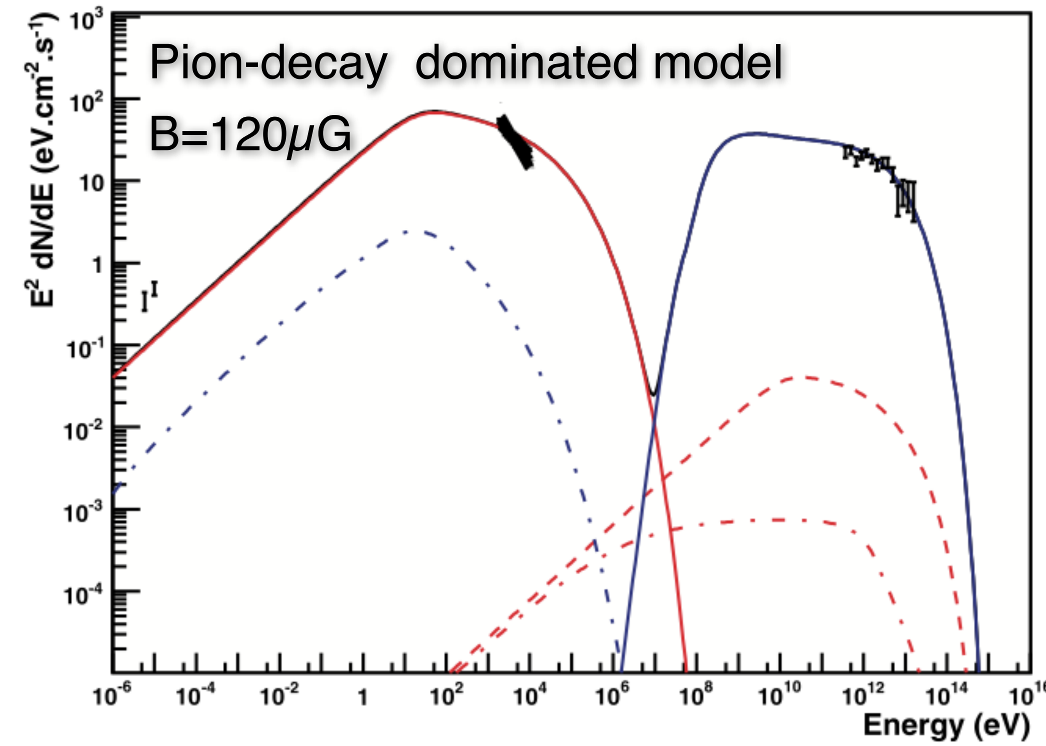
# VHE gamma-ray emission from young SNRs



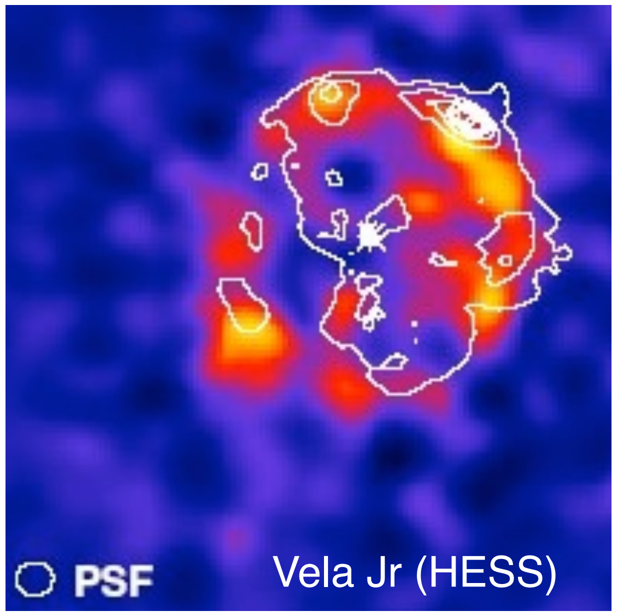

- Most of VHE gamma-ray detected SNRs: X-ray synchrotron sources

# Determining hadronic vs leptonic origin

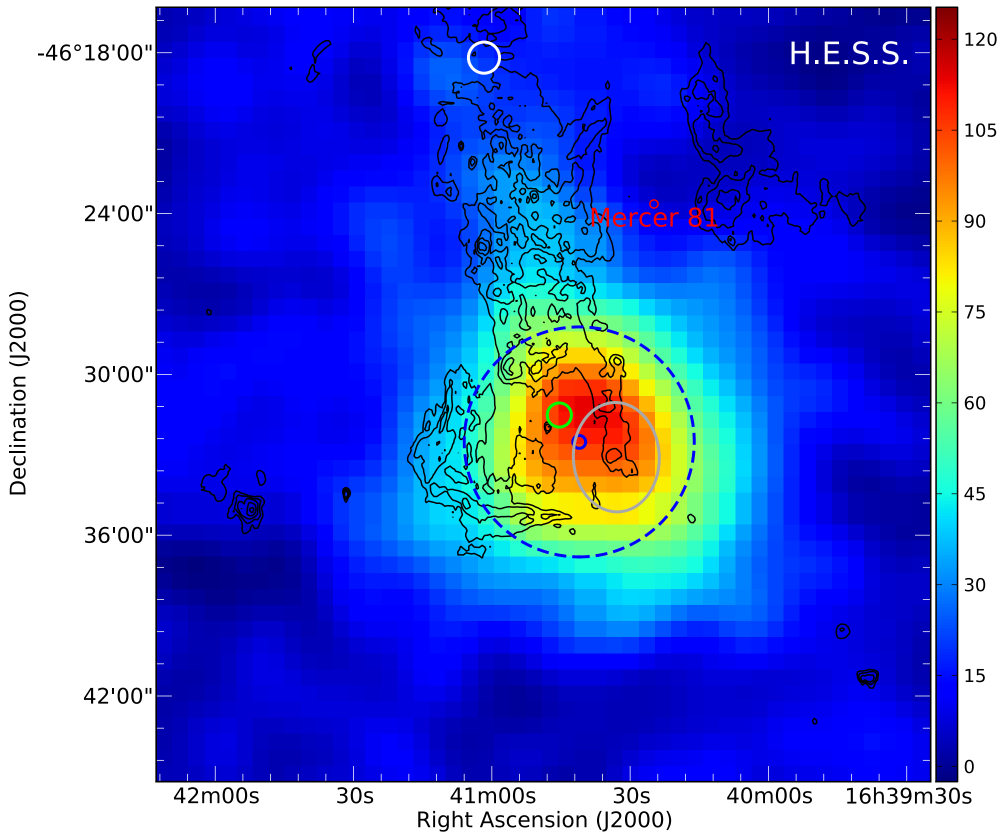


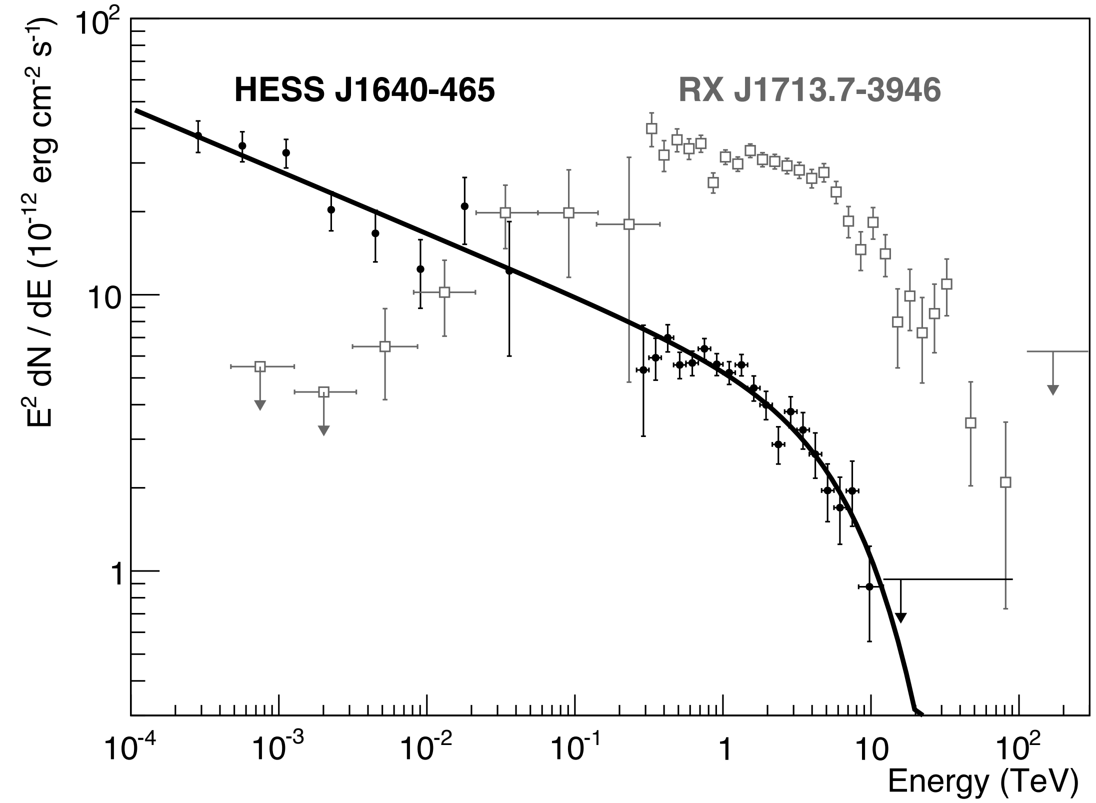




- Heated debates on gamma-ray emission:
  - pion decay:
    - proofs existence of cosmic-ray nuclei
    - requires high local background densities
  - inverse Compton:
    - from same electrons as X-ray synchrotron emission
    - what kind of photon field?
  - Solving puzzle: requires independent information on magnetic field and local plasma density



# Difficulty of assigning sources




- HESS collaboration 2014: HESS J1640−465
- Is it due to a pulsar wind nebula or a supernova remnant?
- If SNR: one of the brightest TeV SNRs?
  - Requires high densities: >150 $cm^{-3}$
- If PWN: why not seen at at other wavelengths?

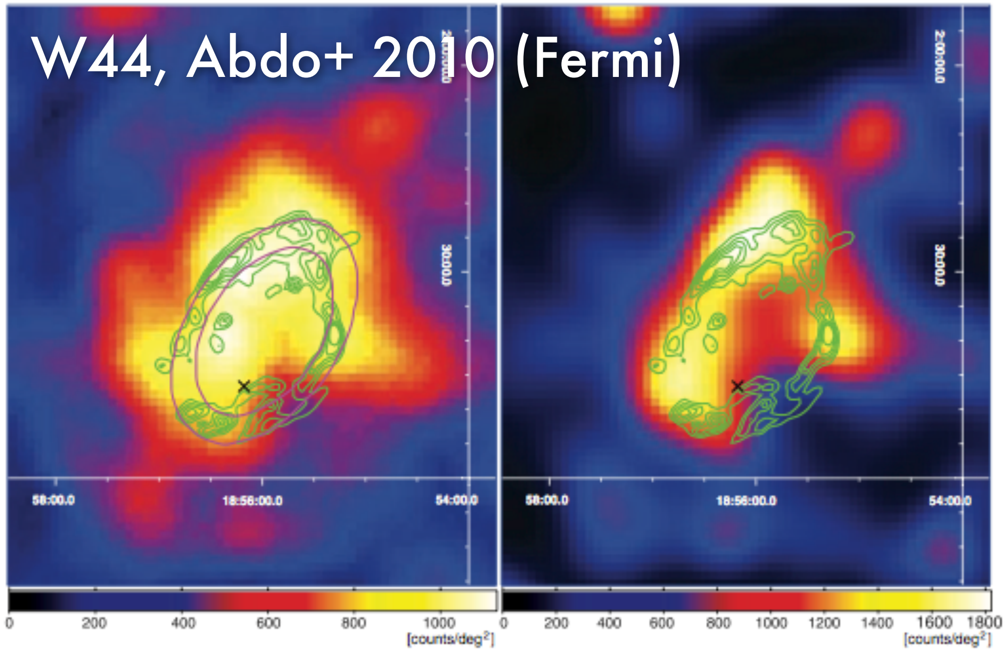
# GeV emission from mature SNRs

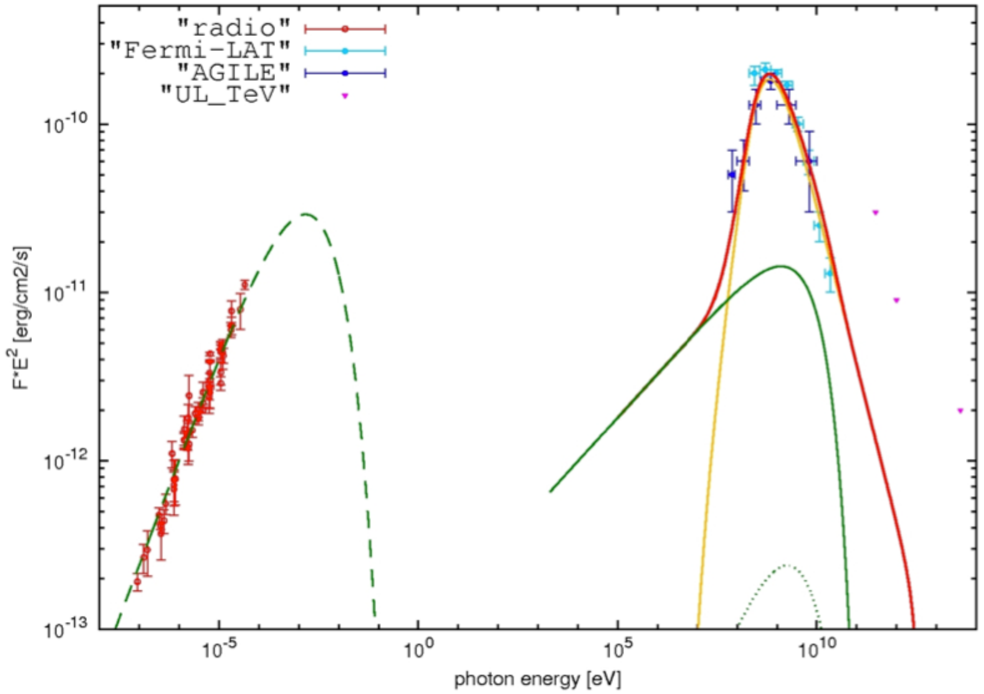
- EGRET provided only tentative evidence for SNR/ mol. cloud associations (Esposito+ '96)
- Fermi + AGILE: many GeV detections!!
- Most prominent sources: SNRs interacting with molecular clouds

  Examples: W44, W28, IC443, W51C
- These SNRs were previously classified as *mixed-morphology* (=bright central X-rays) SNRs

  →probably reason: mixed-morphology+GeV emission: *tracers of high density environments*
- Spectral shapes:
  - *pion bump*: likely pion decay origin

    (e.g. Guiliani+ 11)
  - *Cut-off energies ≈$10^{10}$-$10^{11}$ eV*
  - *Suggests highest energy CRs escaped*

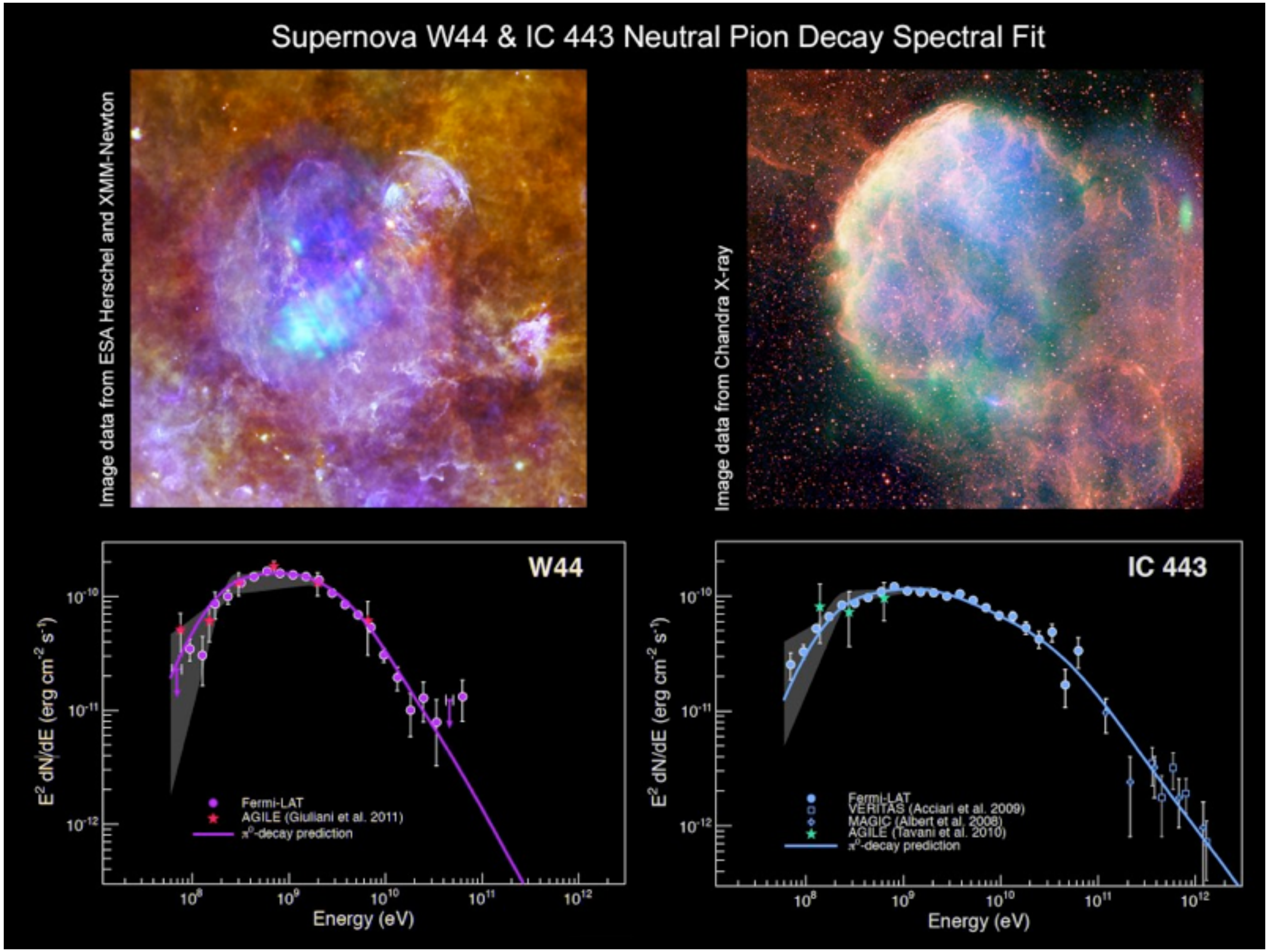



W44, Guiliani+ '11 (AGILE satellite)

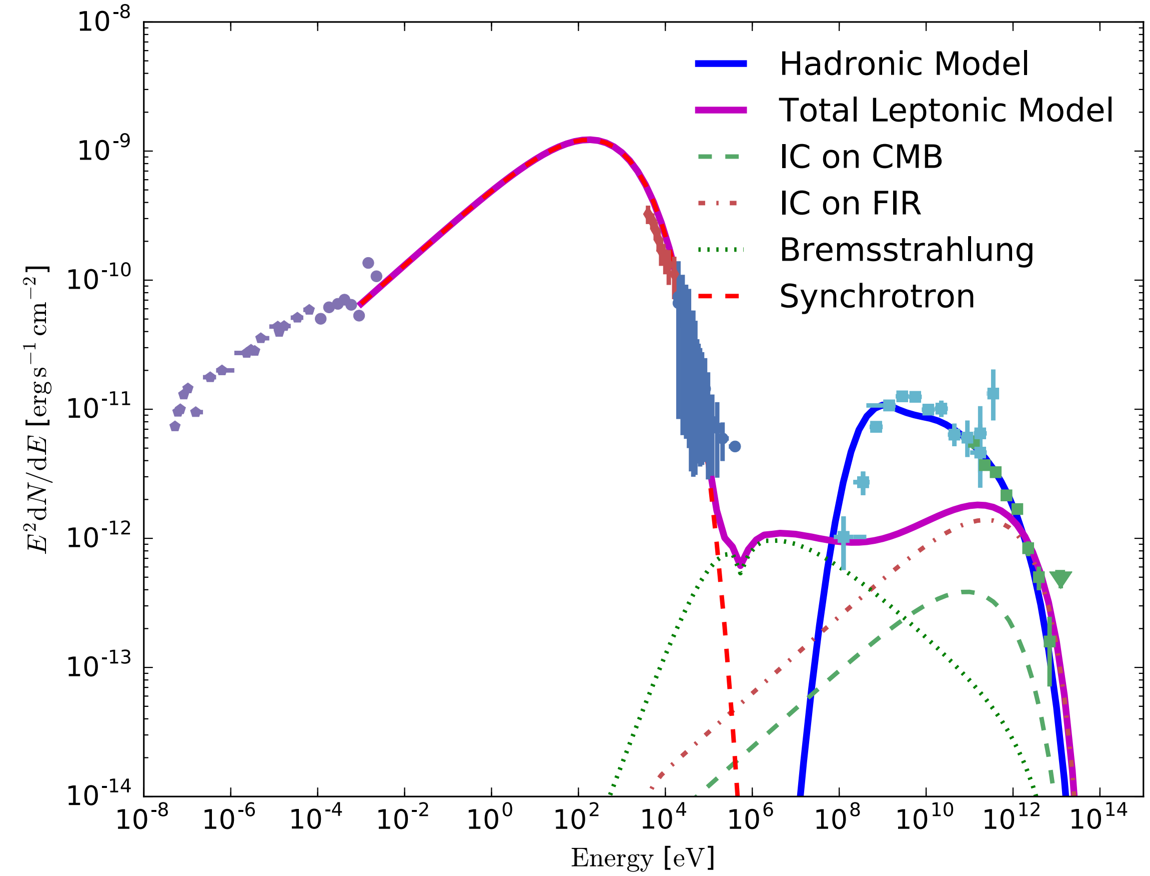
# Fermi detection of pion bumps

Ackermann+ 2013



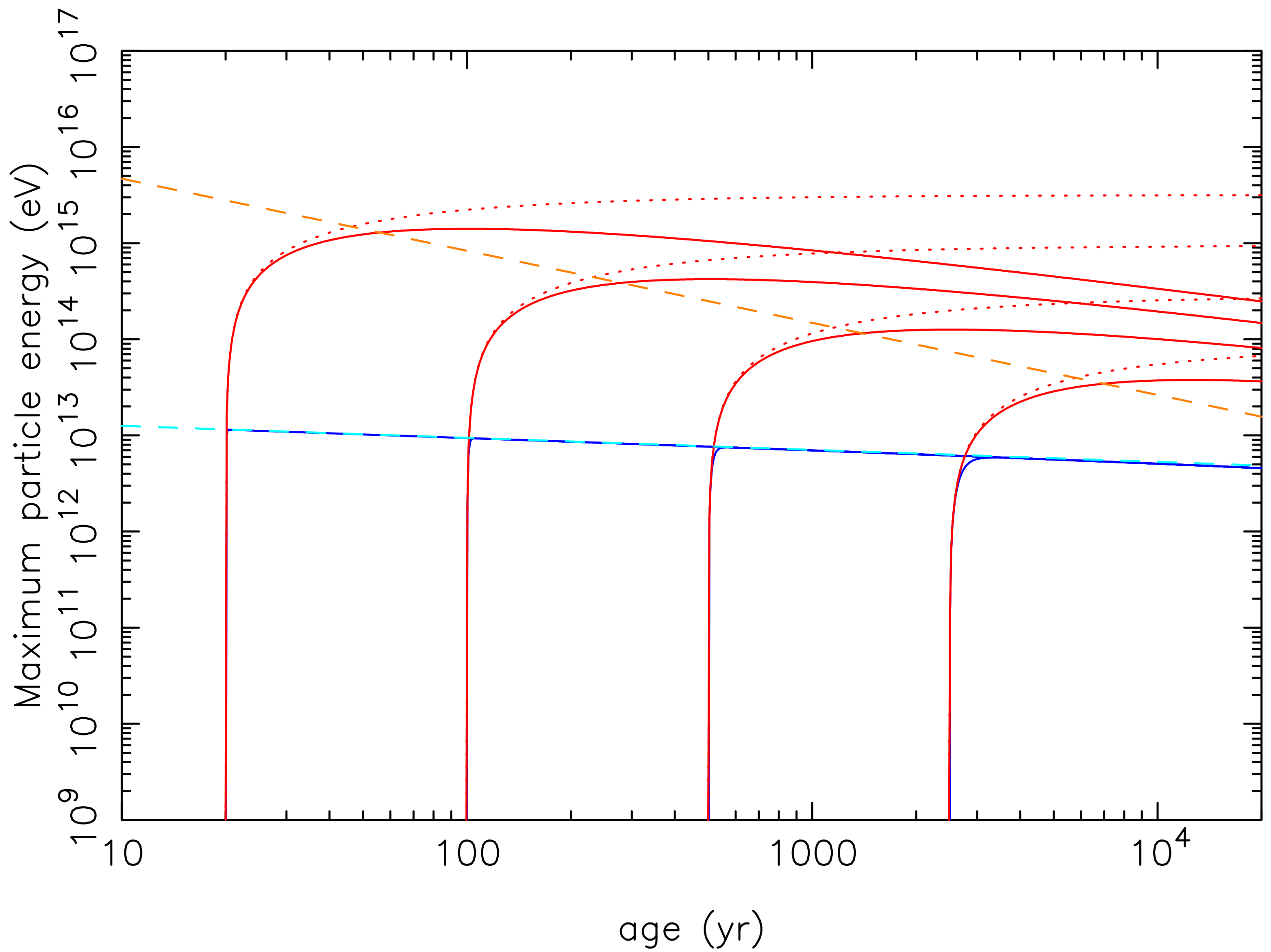

- These are older SNRs (>5000 yr)
- Break in gamma-ray spectrum around  10 GeV: higher protons escaped?

# Recent MAGIC result for Cas A



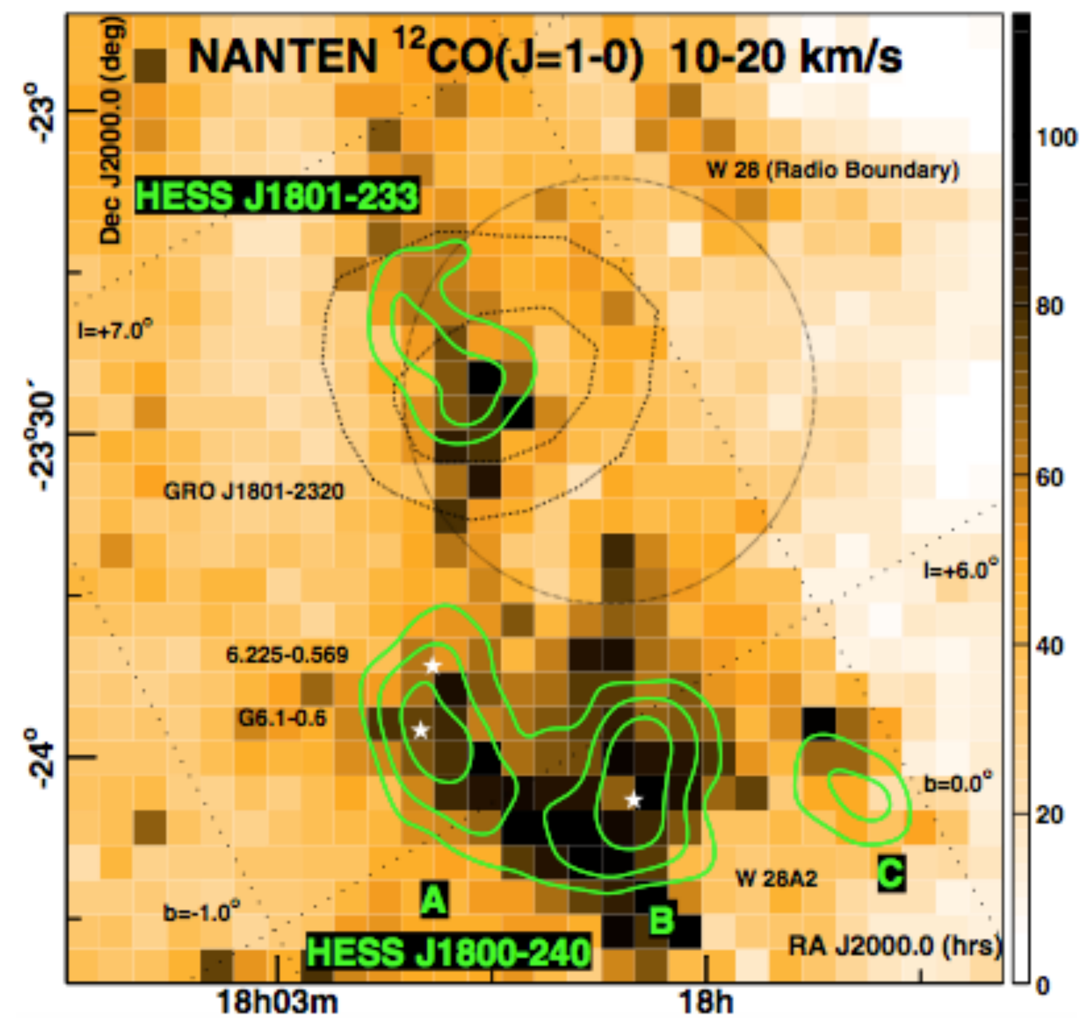

- Broad gamma-ray spectrum: emission mostly hadronic (pion bump)
- But: photon cut-off around 3.5 TeV → proton cut-off around 10 TeV
  - Problems:
    - Cas A is not a PeVatron (i.e. accelerator beyond $10^{15}$eV)
    - Cut-off similar to electron cut-off: how is this possible?
- Possible solutions:
  - Need to also revise synchroton model
  - One zone modelling to simple (at lower level harder spectrum?)
  - Composition of particles needs to be better taken into account

# Acceleration and escape




- Red: energy of protons
  - After some time they lose energy
  - But: protons probably escape when they reach maximum
- Blue: electrons (loss limited)

# VHE gamma-rays from mature SNRs



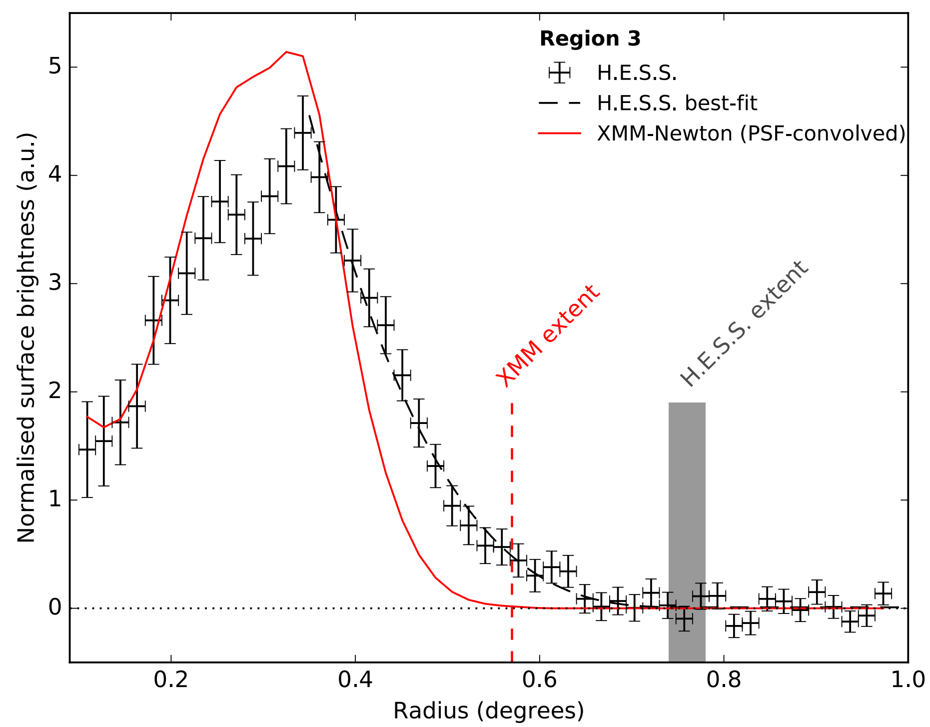

W28 region
colors: CO
contours: TeV gamma-rays

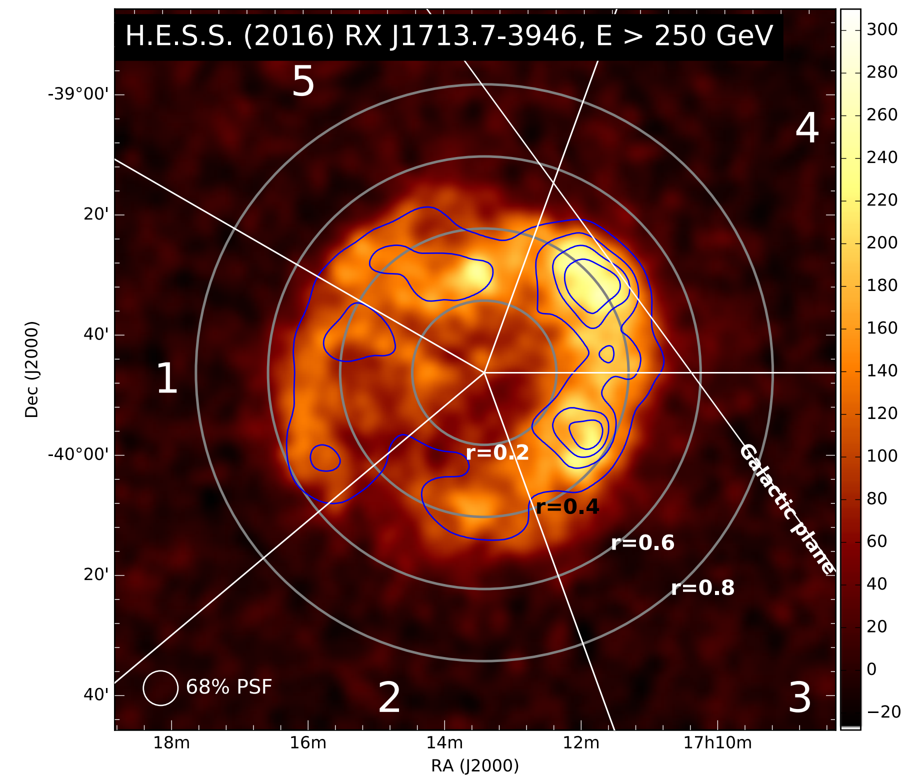
- Mature SNRs in general not TeV sources
- Suggest >TeV cosmic rays escape!

- The TeV detections of mature SNRs are SNRs/ molecular cloud associations!
- Interesting example: W28, offset between SNR and TeV source(s)

# Escape of cosmic rays?

HESS collaboration 2018

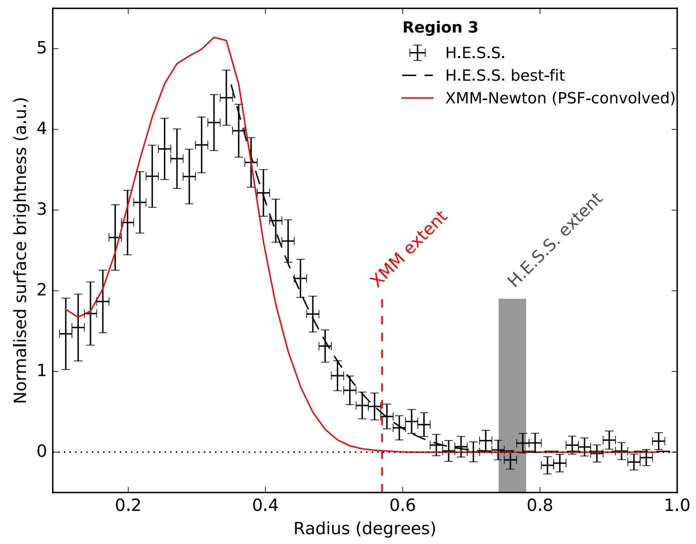



- Gamma-ray emission ahead of X-ray emission:
  - Population of particles ahead of shock
    - Escape: i.e. particles will not be over run by shock?
    - Cosmic-ray precursor? (i.e. particles still being accelerated)
- Either way: requires a low value of B/η
  - Slowing down of shock in region 3? Drop in B turbulence?

$$\frac{B}{\eta} \approx 0.36 \left(\frac{E}{10\,\mathrm{TeV}}\right)\left(\frac{u_{\mathrm{shock}}}{3000\,\mathrm{km\,s^{-1}}}\right)^{-1}\left(\frac{\Delta r}{\mathrm{pc}}\right)^{-1}\mu\mathrm{G}$$

# Maximum size of precursor

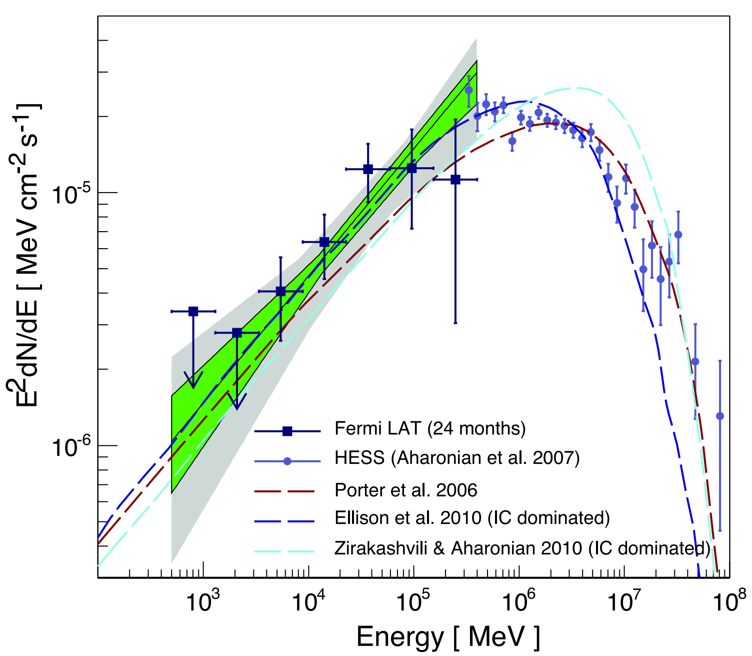


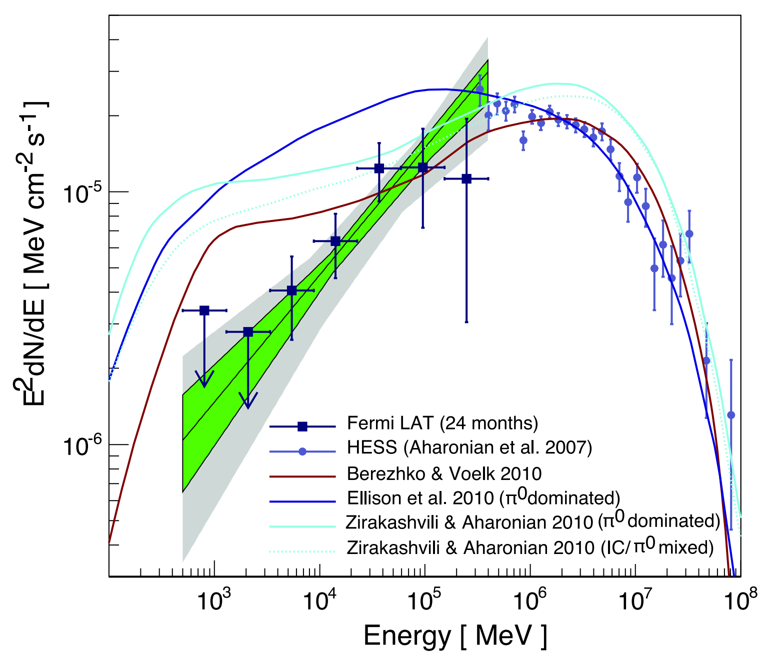

- When is the length scale upstream to large to beconsidered a precursor?
- Go back to acceleration time scale: $t_{\rm snr} > t_{\rm acc} > 8\frac{D_1}{V_{\rm sh}^2} = 8\frac{l_{\rm diff}}{V_{\rm sh}}$
- Use approximate evolution of shock radius SNR: $R \propto t^m \Rightarrow V_{\rm s} = m\frac{R}{t}$
- Young SNRs m≈0.7, old SNRs m≈0.4
- Fill in $V_{\rm s} \approx mR_{\rm s}/t_{\rm snr}$ and rework: $l_{\rm diff} < \frac{m}{8}R_{\rm sh}$ .

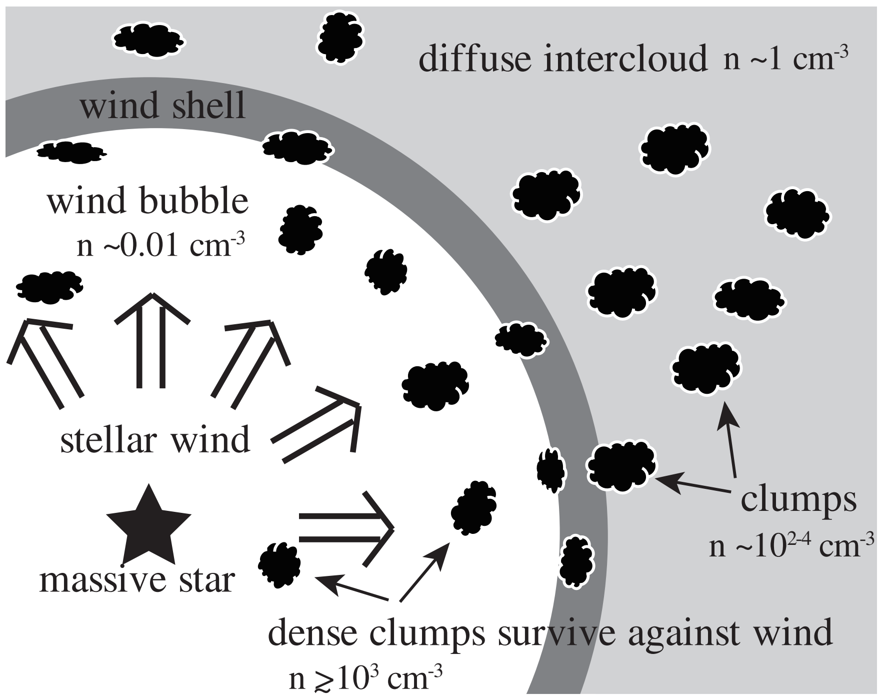
- Conclusion: the $l_{\rm diff}$ should be less than 9% of shock radius
- H.E.S.S. result: $l \approx 13\,\%\,R_{\rm s}$
- Likely we see escaping cosmic rays
- Uncertainties:
  - geometrical projection effects
  - How well constraint is shock location?

# Emission RX J1713: hadronic or leptonic?

Abdo et al 2011



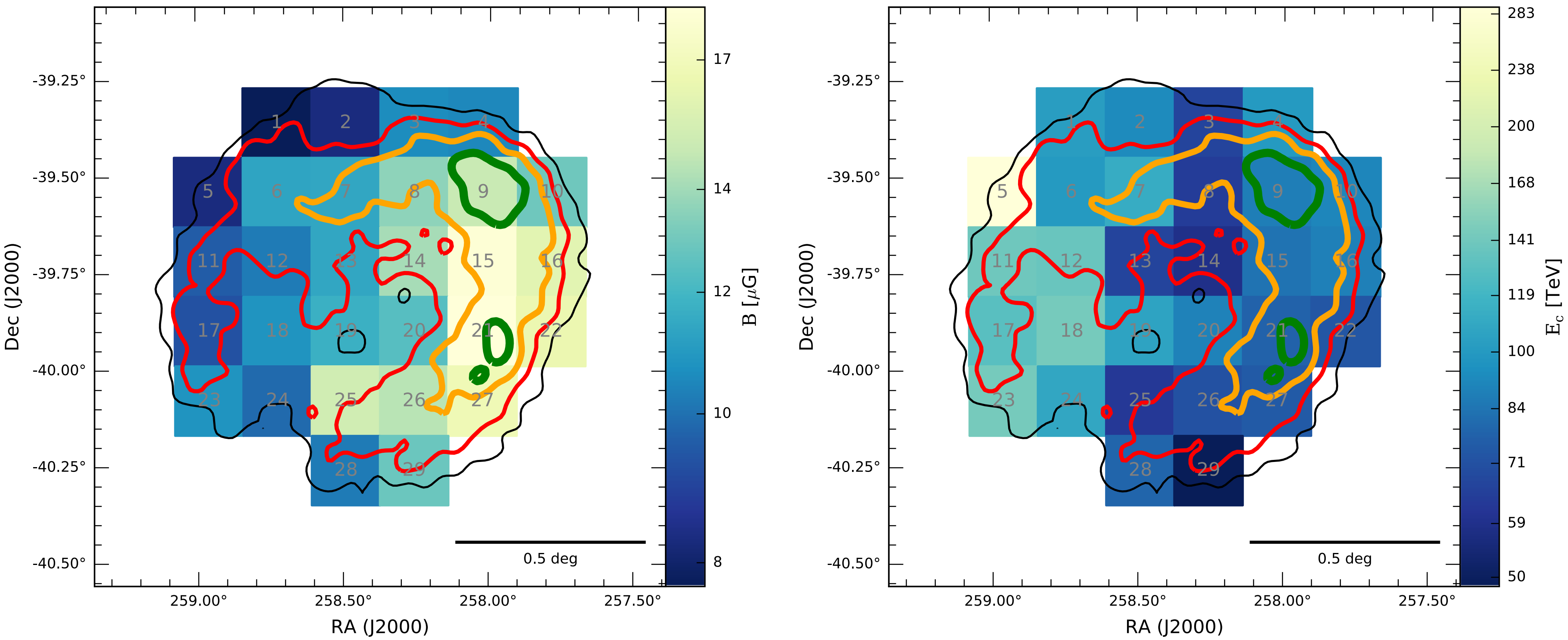



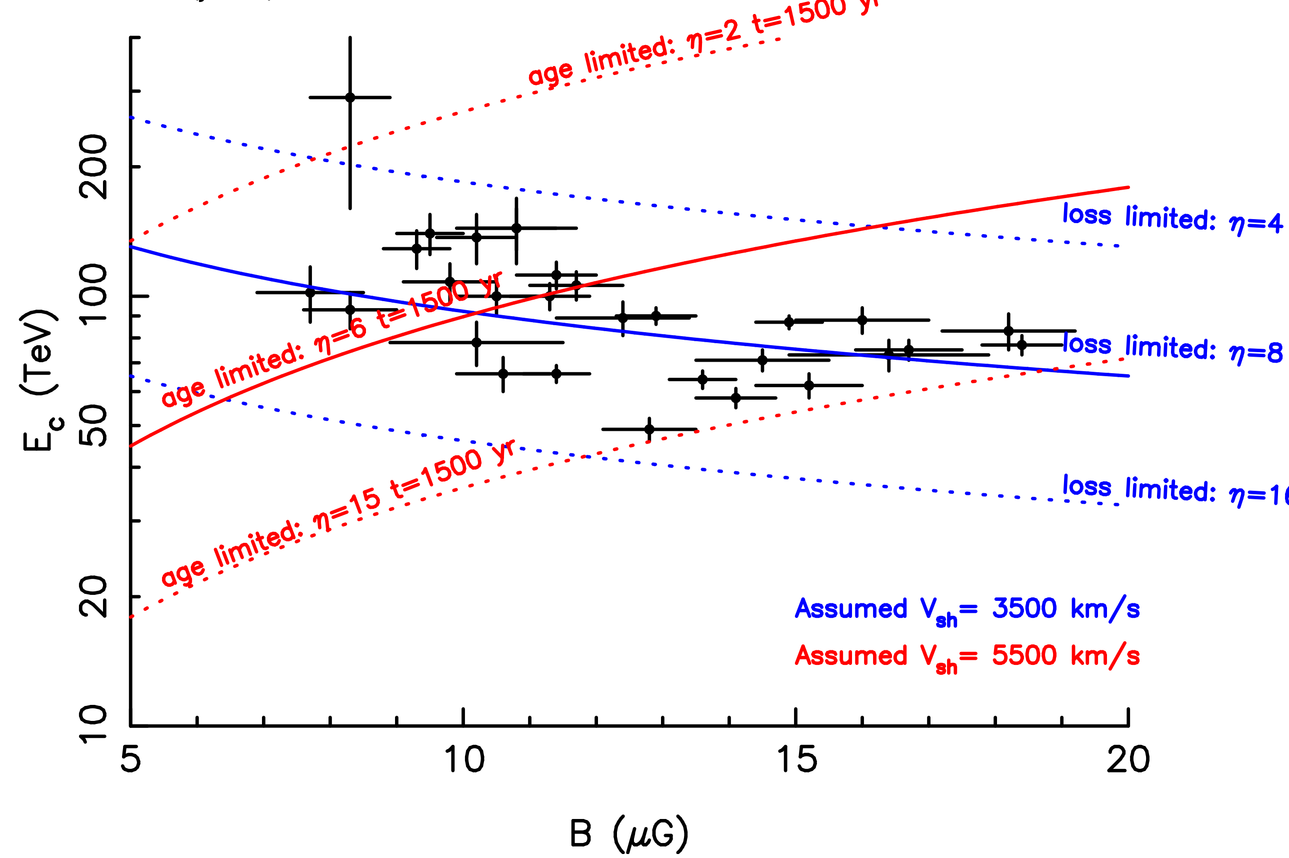

- Spectral hardness suggests inverse Compton emission
- Alternative: emission from clumps irradiated by hadronic cosmic rays (Inoue+ '13, Gabici & Aharonian '15)

# Magnetic field map RX J1713

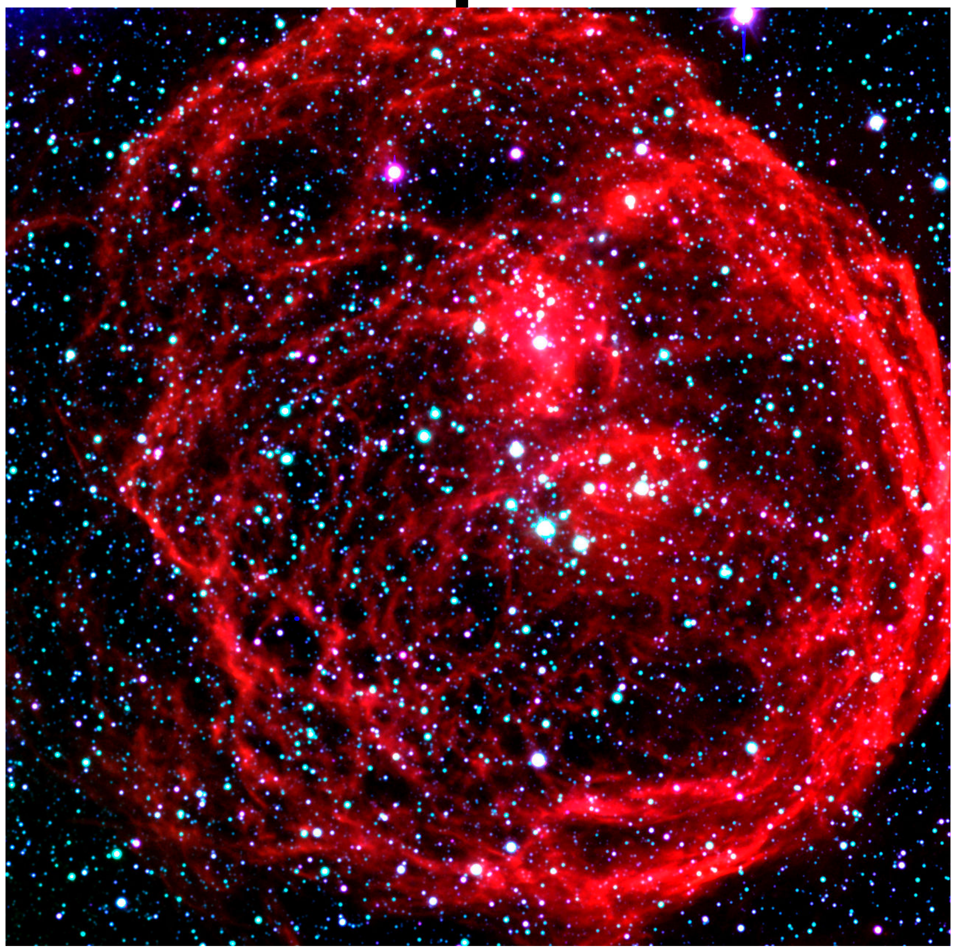
HESS collaboration 2018




- Assumes leptonic emission
- Cut-off consistent with B-field and age

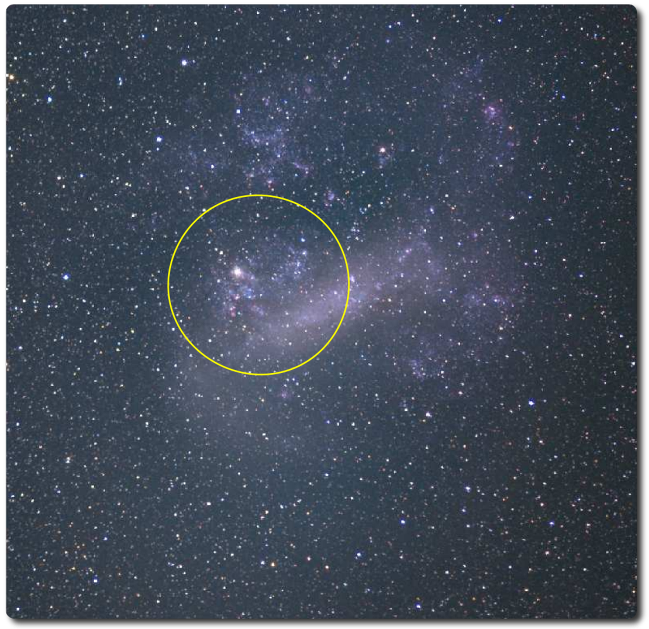


# 12 The superbubble hypothesis




- Superbubbles are created by winds/supernovae in OB associations
- Consist of hot tenuous plasma, surrounded by slow moving shell
- A. Bykov, E. Parizot (1988+): superbubbles ideal for cosmic ray acceleration
  - Combine power of multiple SNe/stellar winds
  - Turbulent interior: enhanced magnetic fields
  - Super bubbles exist few $10^6$ yr: more time for acceleration then SNR
  - Super bubbles are larger than SNRs: easier to confine CRs → *Hillas plot!*

# H.E.S.S. detection of a superbubble in LMC

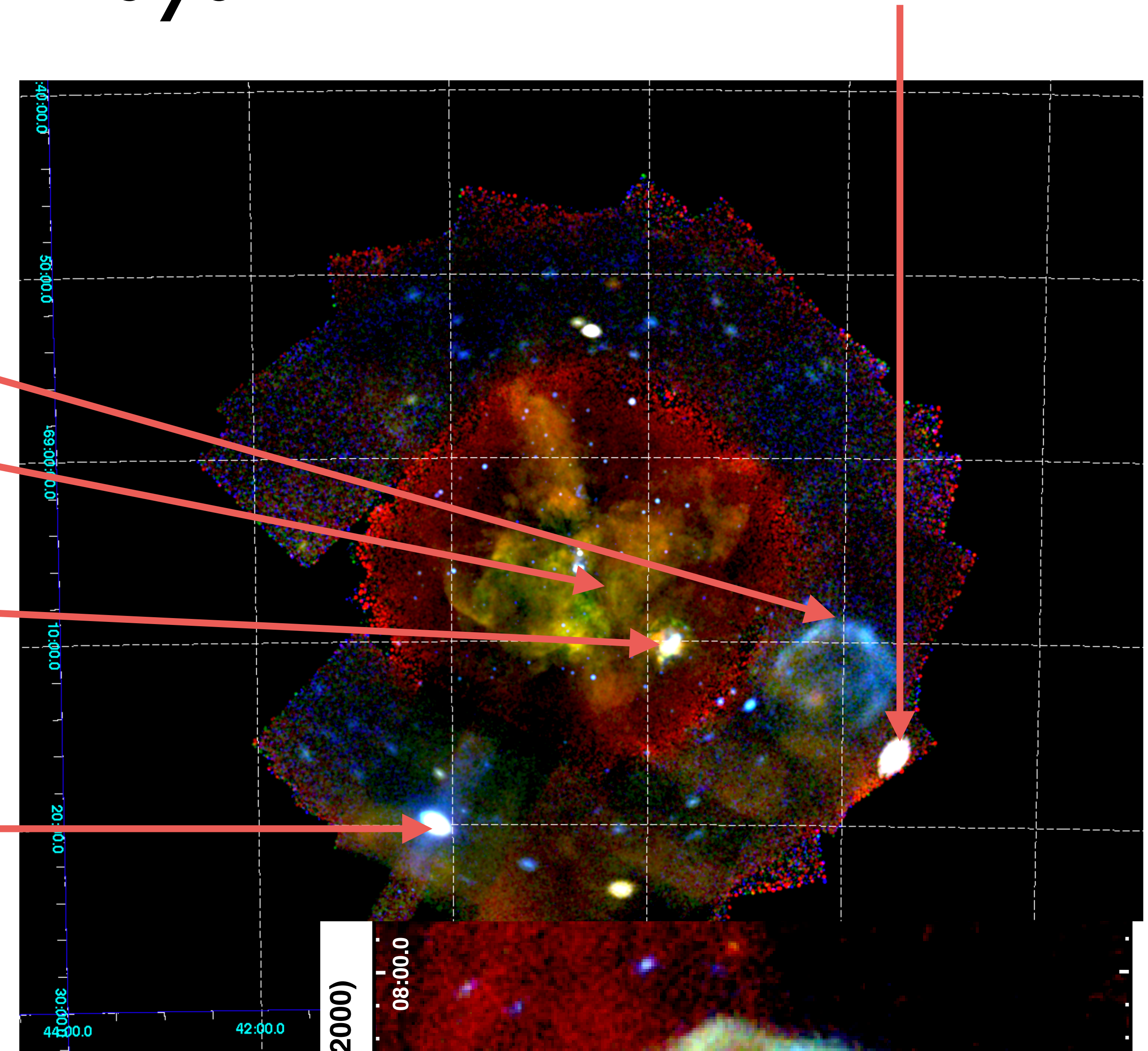


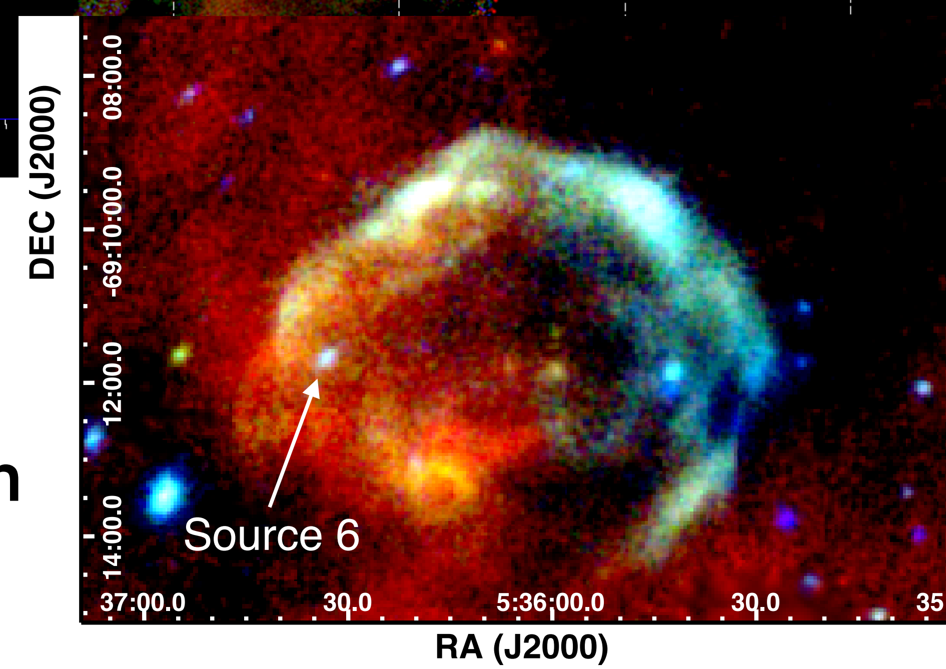
- 210 hr of H.E.S.S. observations
- spatial coverage
  - targets: N 157B (PSR J053747.39), SN 1987A, N 132D

Published:

"The exceptionally powerful TeV gamma-ray emitters in the Large Magellanic Cloud"
The H.E.S.S. Collaboration, 2015 Science 347, 406
(corr. authors: Chia-chun Lu, Nukri Komin, Michael Mayer Stefan Ohm, Jacco Vink)

# The superbubble 30 Dor C in X-rays

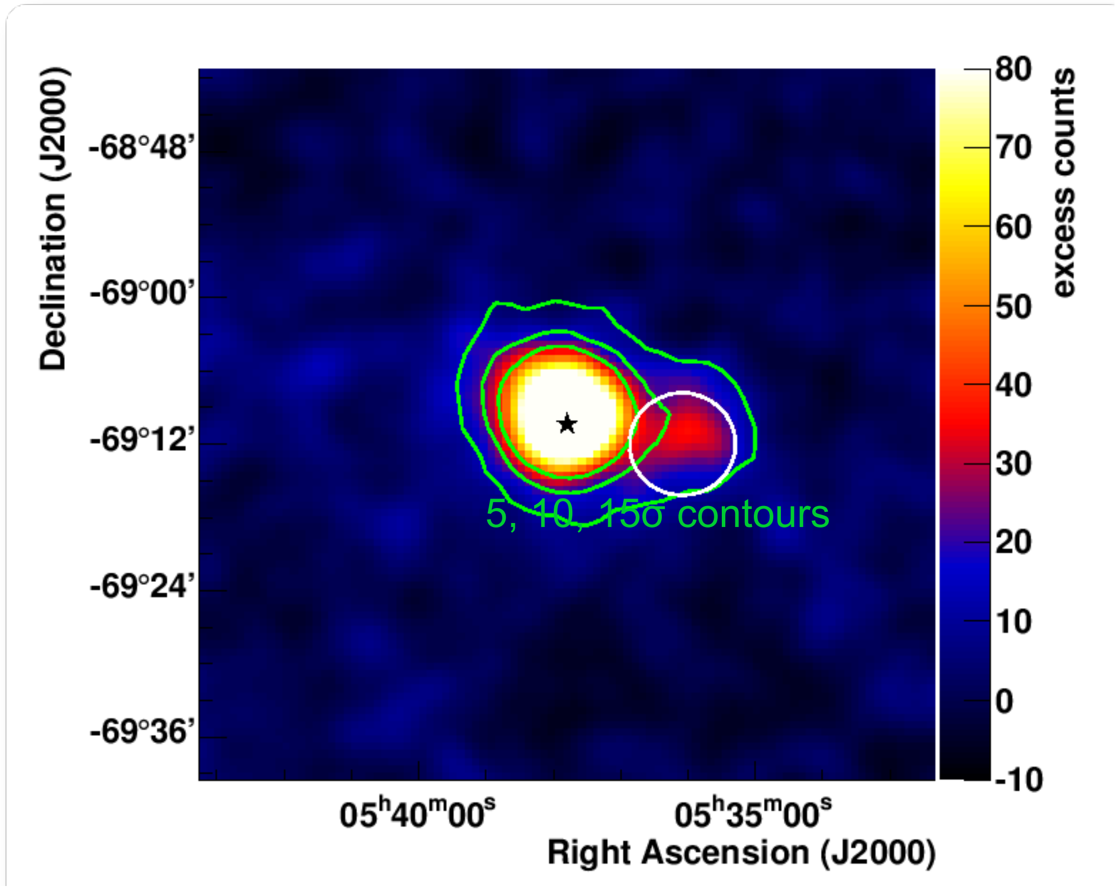


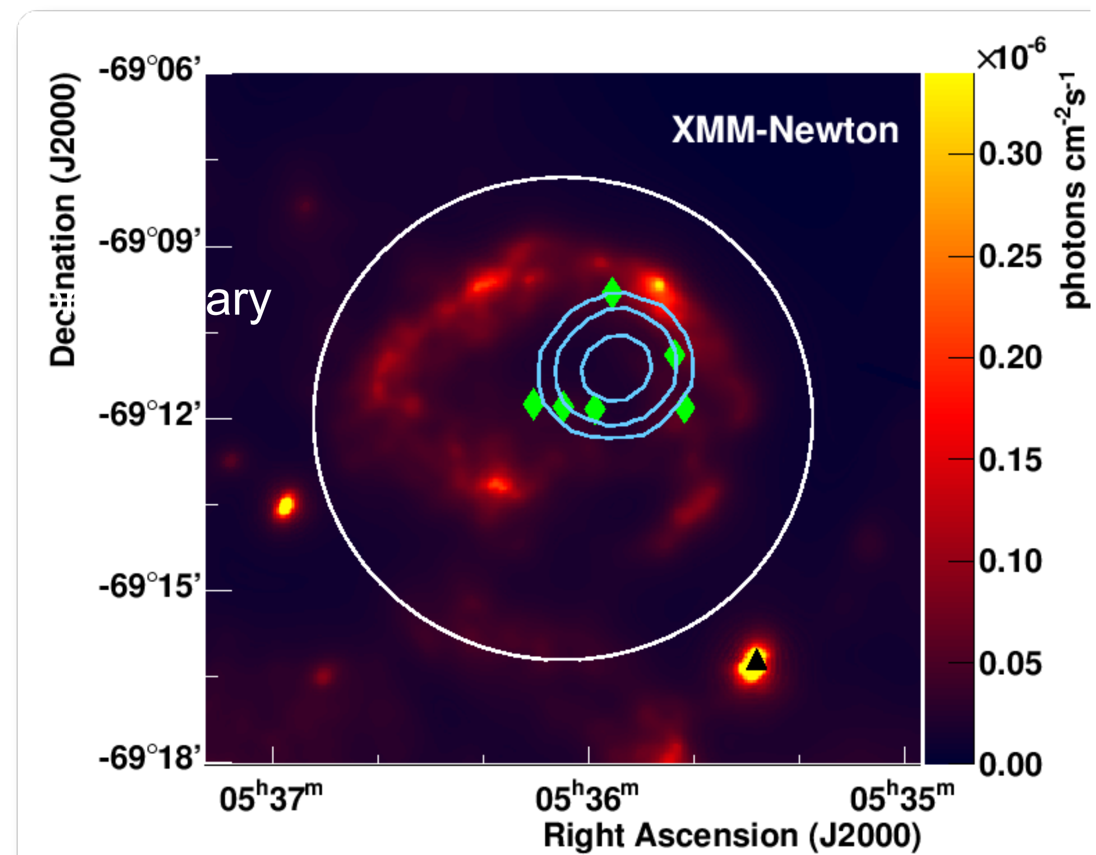

- Doradus region: starburst conditions
- 30 Dor C: partially X-ray synchrotron emission

Bamba+ '04, Kavanagh+ '15

# H.E.S.S. detection of the superbubble 30Dor C

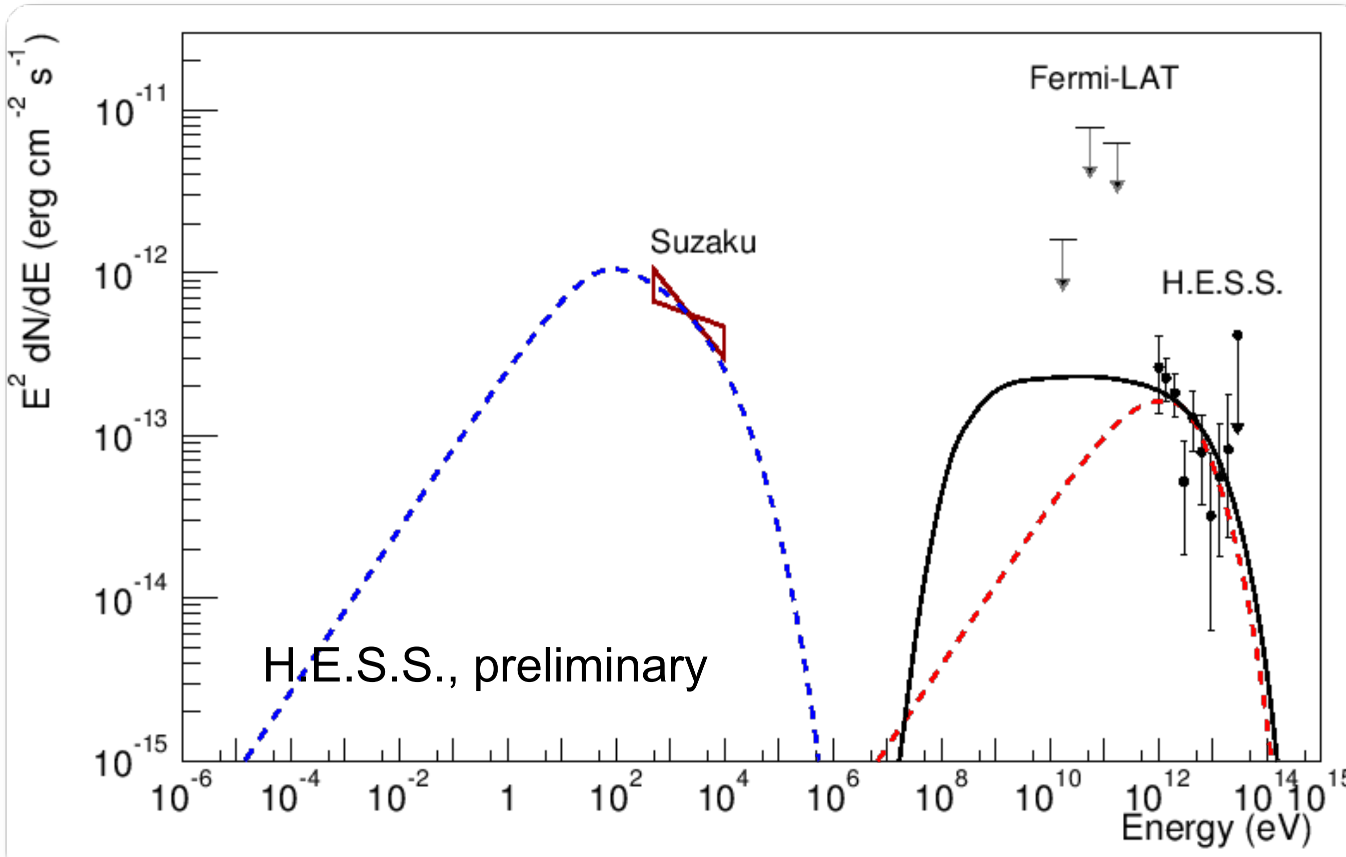



- Additional emission SW of PWN
  - 130 pc at 50 kpc
- >5 σ above spill-over
- Two-source morphology favoured at 8.8σ




- Position (contours) compatible with
  - shell of superbubble 30 Dor C
  - star clusters of LH 90
- Note: angular resolution does not allow conclusion on morphology

# Interpretation TeV ϒ-ray emission 30DorC



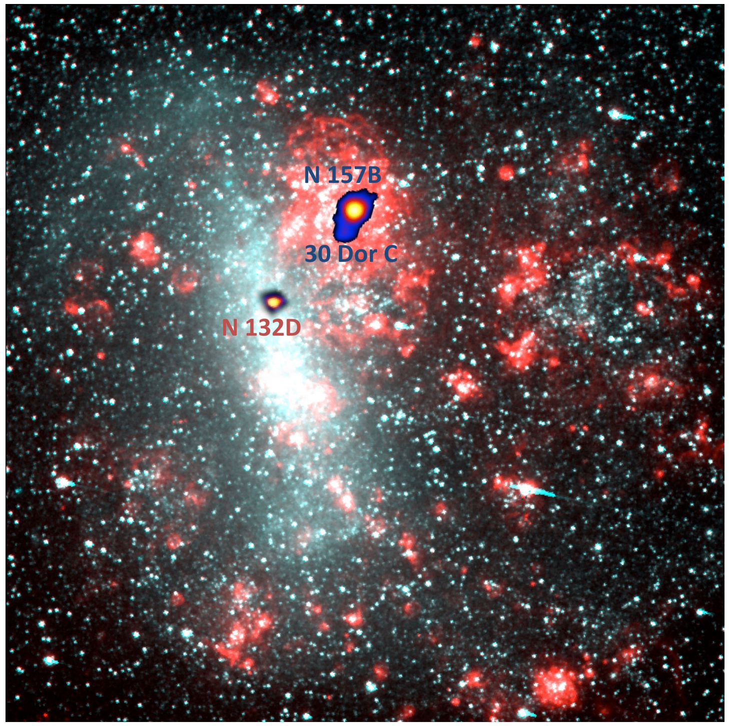

- **hadronic scenario**
  - energy in protons
  - $W_{pp}$ = (0.7 – 25) x $10^{52}$ ($n_H$ /cm$^{-3}$)$^{-1}$ erg
  - even for 5 supernova explosions high density needed: $n_H > 20$ cm$^{-3}$
  - thermal X-rays indicate low density: $n_H \sim 0.4$ cm$^{-3}$
    Bamba+ 04, Kavanagh+ '14
- **leptonic scenario**
  - magnetic field: ~15 μG
  - 4 x $10^{48}$ erg in electrons
  - + X-ray synchrotron: high shock velocity ⇒ low interior density $10^{-4}$-$10^{-3}$cm$^{-3}$

# On the leptonic scenario for ϒ-rays from 30Dor C

- The leptonic scenarios makes use of X-ray synchrotron detection: $V_s \gtrsim 3000$ km/s
- Assuming Sedov type of evolution:
  - $t=0.4\ R/V_s \approx 6000$ yr
  - Model 30Dor C: $\simeq 5$ SNe went off,
  - But in 6000 yr? → may be one or two?
  - Sedov model density estimate:
    $R = 2.8 \times 10^8 (Et^2/n_H)^{1/5}$ cm → $n_H \approx 5 \times 10^{-4} E_{51}^{1/5} \mathrm{cm}^{-3}$
  - density much lower than inferred from thermal emission SE ($0.4 \mathrm{cm}^{-3}$)

- X-ray synchrotron/leptonic scenario:
  - Need extremely low density
  - Adding more energy does not help much ($R \sim E^{1/5} t^{2/5}$)
- *Likely scenario:*
  - *Superbubble creates very low densities (multiple SNe/winds)*
  - *Last supernova remnant moves very fast through tenuous medium*
  - *X-ray synchrotron/ϒ-rays only intermittent periods of 5000-10000 yr*

# Implications 30Dor C for acceleration in super bubbles



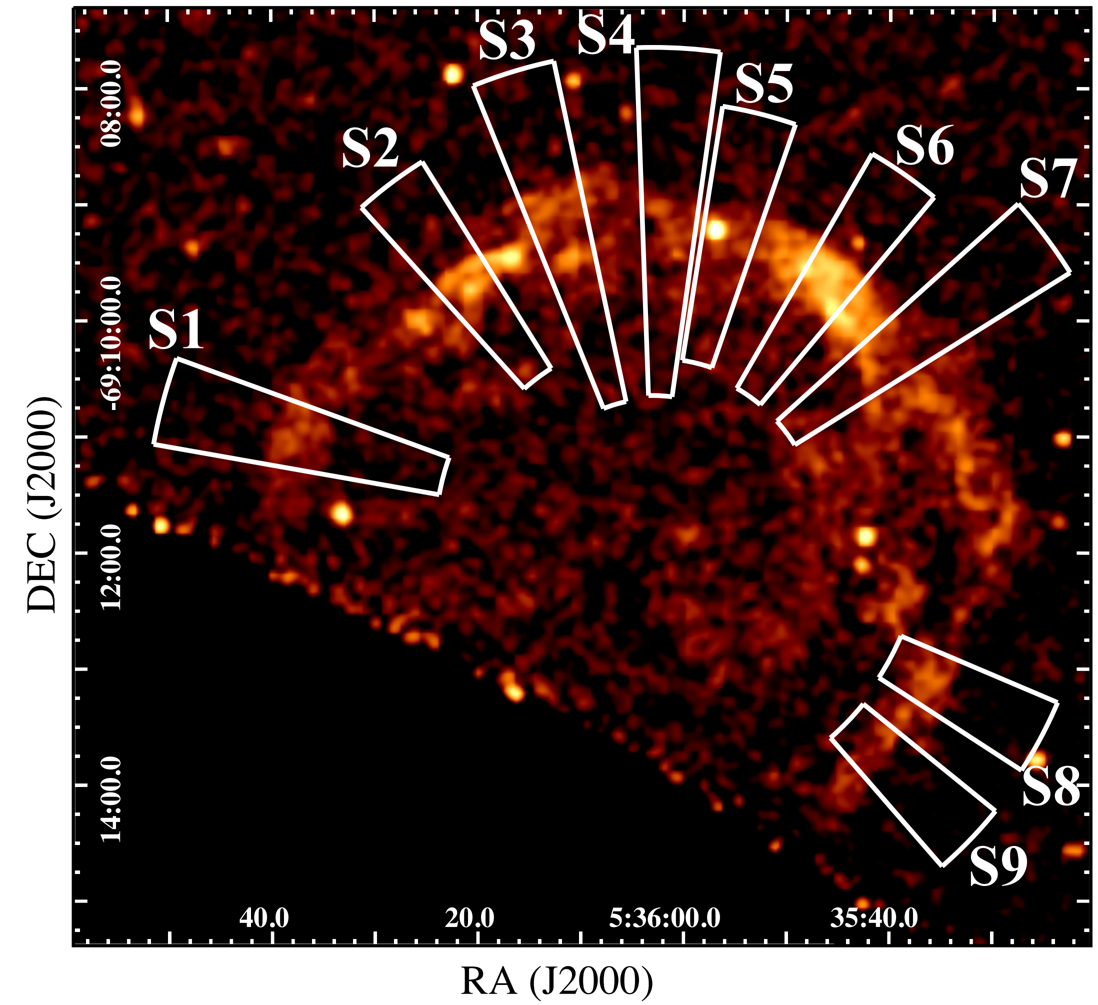

- Inside super bubbles particles accelerated > 10 TeV
- Shells with velocities > 1000 km/s probably exist
- It is not clear whether hadrons accelerated abundantly

- But Hillas argument still holds!! $B_{\mu\mathrm{G}} L_{\mathrm{pc}} > 2E_{15}/Z\beta$

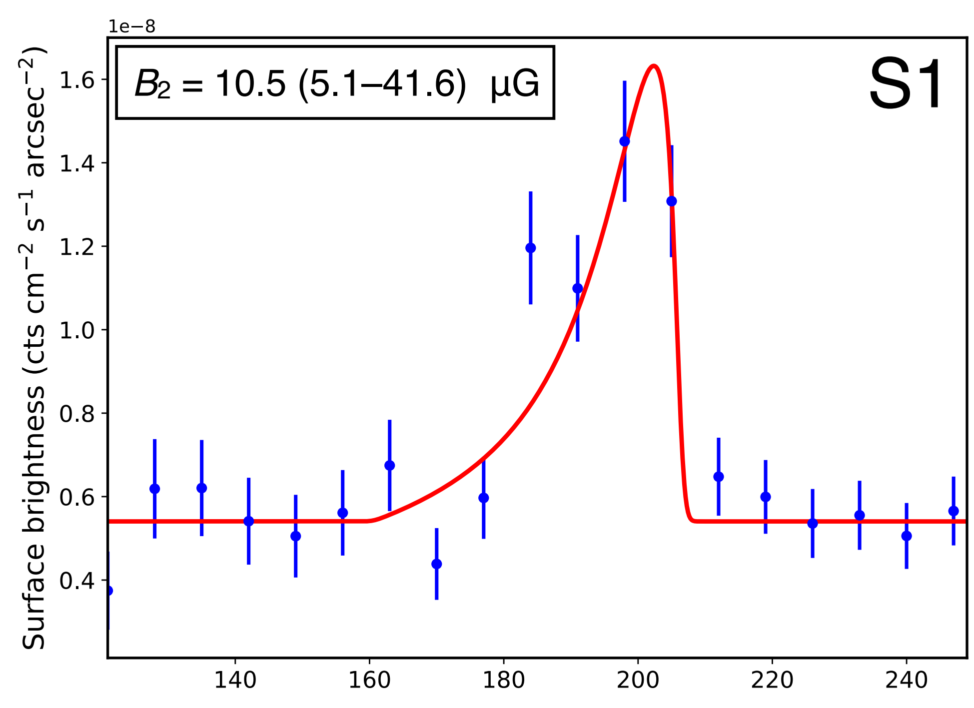
- For $\beta$=0.03, B=10 μG, L=47pc: $E_{max}=7\times10^{15}$eV!!
  - **We may detect or not detect the hadrons, but Hillas condition for accelerating hadrons to "the knee" fullfilled!**

# New: X-ray B-field determination 30 Dor C with Chandra
(Kavanagh, JV+ 2018)

| Sector | binning (arcsec) | $R$ (arcsec) | $l_{obs}$ (arcsec) | $l_{obs}/R$ (%) | $\chi^2_\nu$ | $B_2$ ($\mu G$) |
|---|---|---|---|---|---|---|
| S1 | 7 | 206.5 (204.5–212.7) | 4.7 (1.2–9.6) | 2.3 (0.6–4.7) | $1.20_{17}$ | 10.5 (5.1–41.6) |
| S2 | 9 | 172.6 (172.6–178.5) | 2.6 (1.9–7.0) | 1.5 (1.1–4.1) | $1.36_{11}$ | 19.3 (7.0–25.4) |
| S3 | 10 | 191.5 (190.6–198.0) | 6.3 (3.3–13.3) | 3.3 (1.7–7.0) | $0.59_{15}$ | 7.9 (3.7–14.7) |
| S4 | 10 | 180.8 (180.0–182.6) | 10.1 (7.9–18.5) | 5.6 (4.3–10.2) | $1.51_{15}$ | 4.9 (2.7–6.2) |
| S5 | 7 | 182.8 (175.9–183.7) | 19.3 (9.0–20.1) | 10.6 (4.9–11.4) | $0.69_{16}$ | 2.6 (2.5–5.5) |
| S6 | 5 | 195.8 | 3.8 | 1.9 | $3.81_{25}$ | 13.0 |
| S7 | 6 | 197.6 | 11.9 | 6.0 | $2.07_{25}$ | 4.1 |
| S8 | 8 | 181.2 (180.3–188.3) | 3.9 (1.7–10.9) | 2.2 (0.9–6.0) | $1.14_{9}$ | 12.7 (4.5–28.6) |
| S9 | 8 | 180.3 (172.3–181.2) | 6.1 (1.2–10.9) | 3.4 (0.7–6.3) | $1.51_{9}$ | 8.1 (4.5–41.6) |




- Using X-ray synchrotron widths:
  - B= 5 to 20 μG
- Agrees with the leptonic scenario

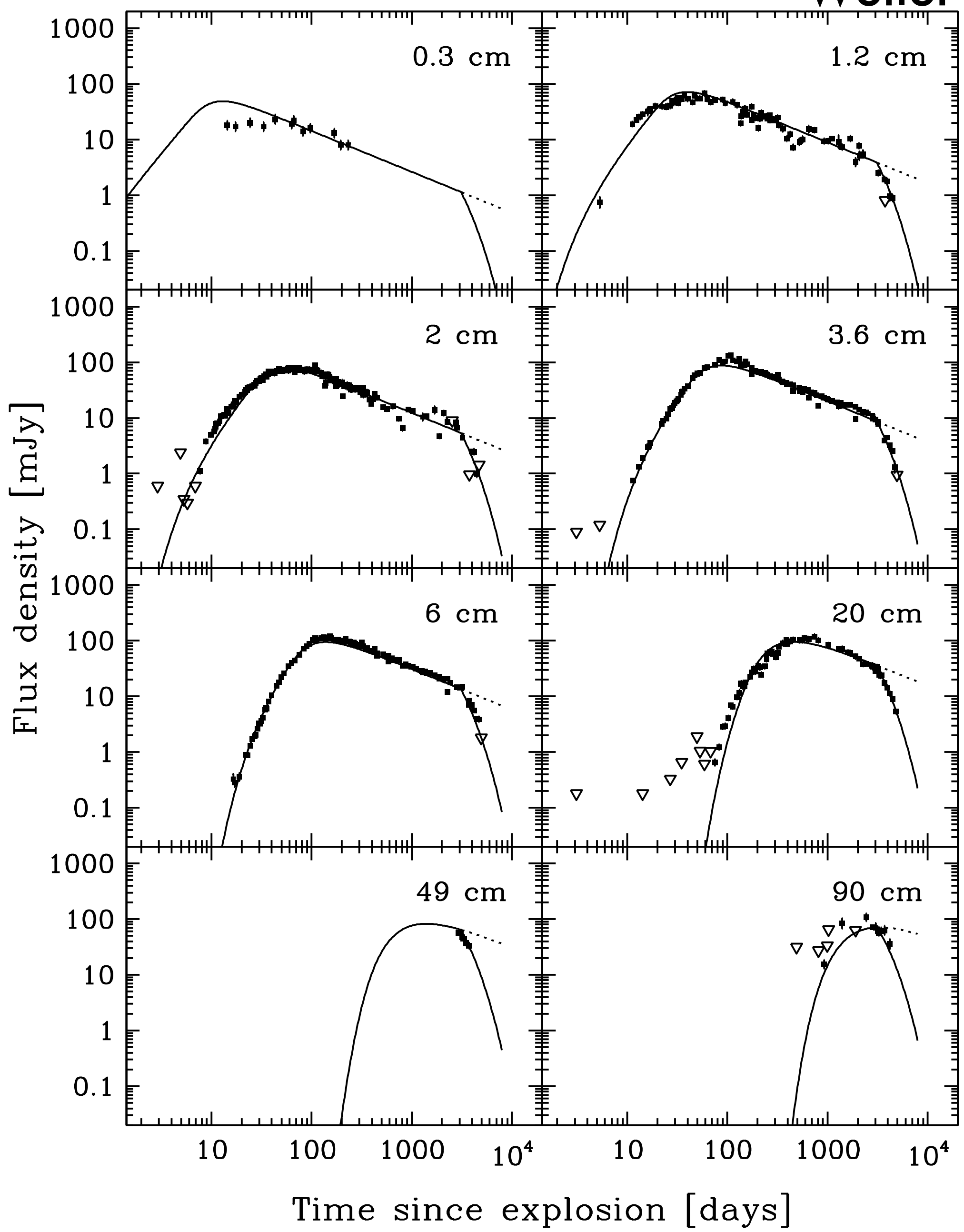


# 13 The early supernova remnant hypothesis

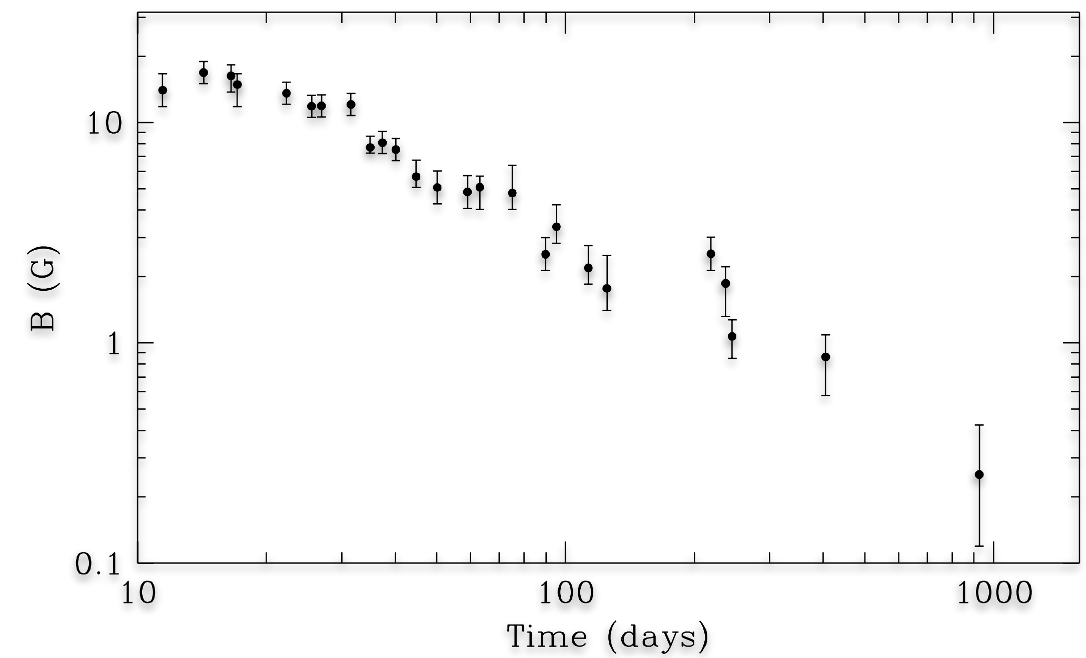
- Idea that early stages are important for cosmic rays made by several people
  (Ptuskin, Bell, Tatischeff, Marcowith,...)
- Need two conditions:
  - Dense wind: $\rho_{\mathrm{w}} = \dfrac{\dot{M}}{4\pi r^2 v}$
  - High B-field since $E_{\mathrm{max}} \propto \eta^{-1} B V_{\mathrm{s}} t$
- Note $V_s$ can be as high as 20,000 km/s
- High density and Vs lead to strong amplification: $B^2 \propto \rho V^3$
- These conditions are found in "radio supernovae"

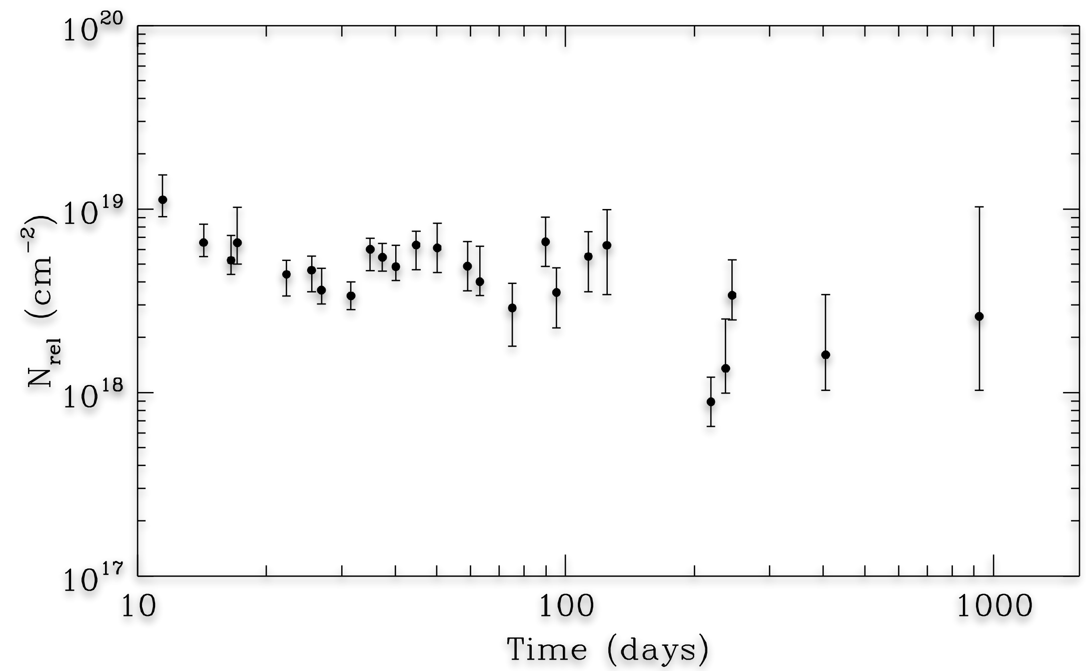
# Radio supernova SN 1993J

Weiler+ 2007



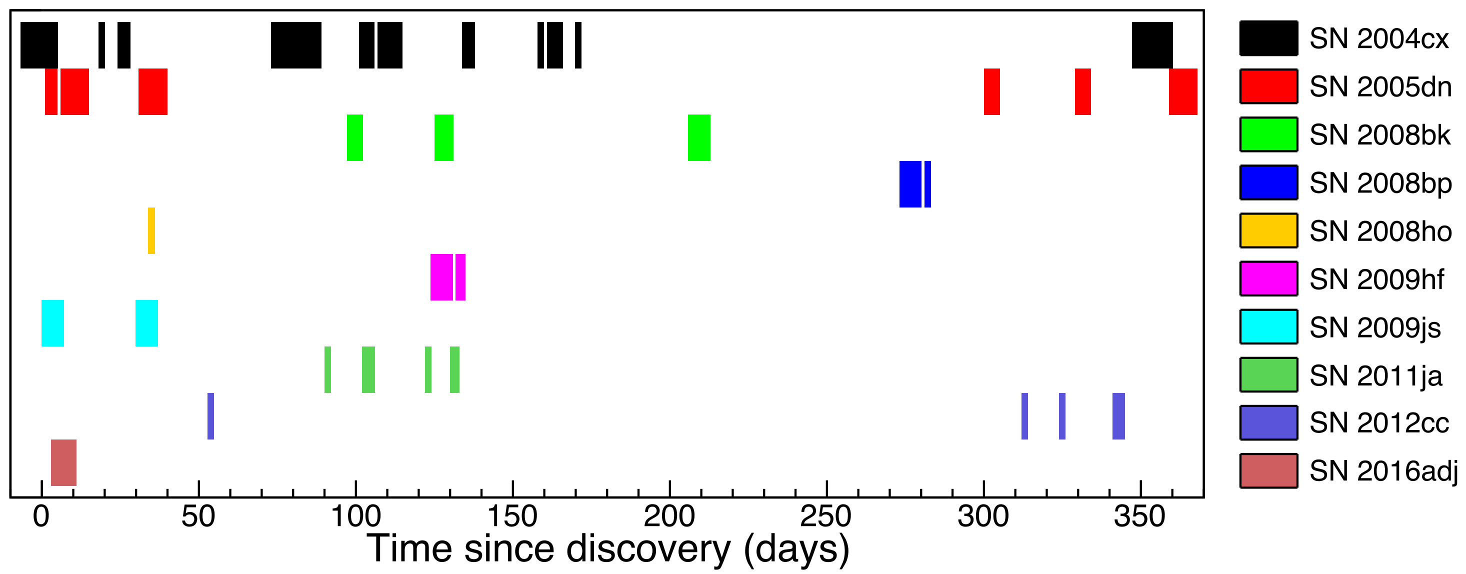

Fransson 1998
SN 1993J




- SN1993J: a Type Ib (like Cas A)
- Early radio emission bright and self-absorbed
- B-field very high 1-10 G!

# H.E.S.S. search for gamma-ray emission




- Initially based on serendipous observations: H.E.S.S. observed galaxy with young supernova (<1 yr)
- All core-collapse SNe considered (uncertain whether radio supernovae)
- Later one pointed observation SN2016adj
- Currently: nearby SNe are TOO targets

# Expected emission

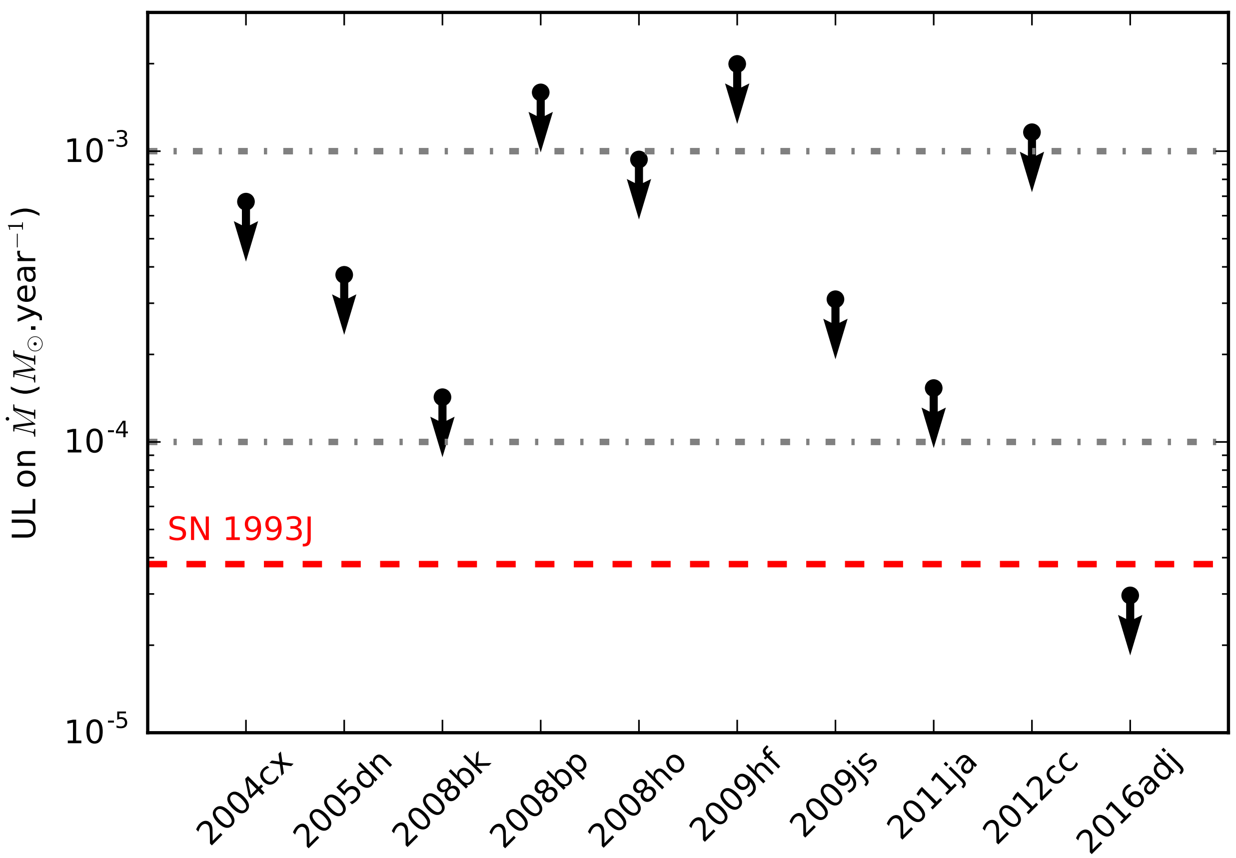
- Strong B-fields: low $E_{max}$ for electrons
- Gamma-rays expected to have hadronic origin
- Emission depends on $\propto n_{\rm cr} n_{\rm w} R^3$
- Since $R = mV_{\rm s}t$ we expect $L_\gamma \propto \left(\frac{\dot{M}}{v_{\rm w}}\right)^2 \frac{1}{t}$
- More eloborate:

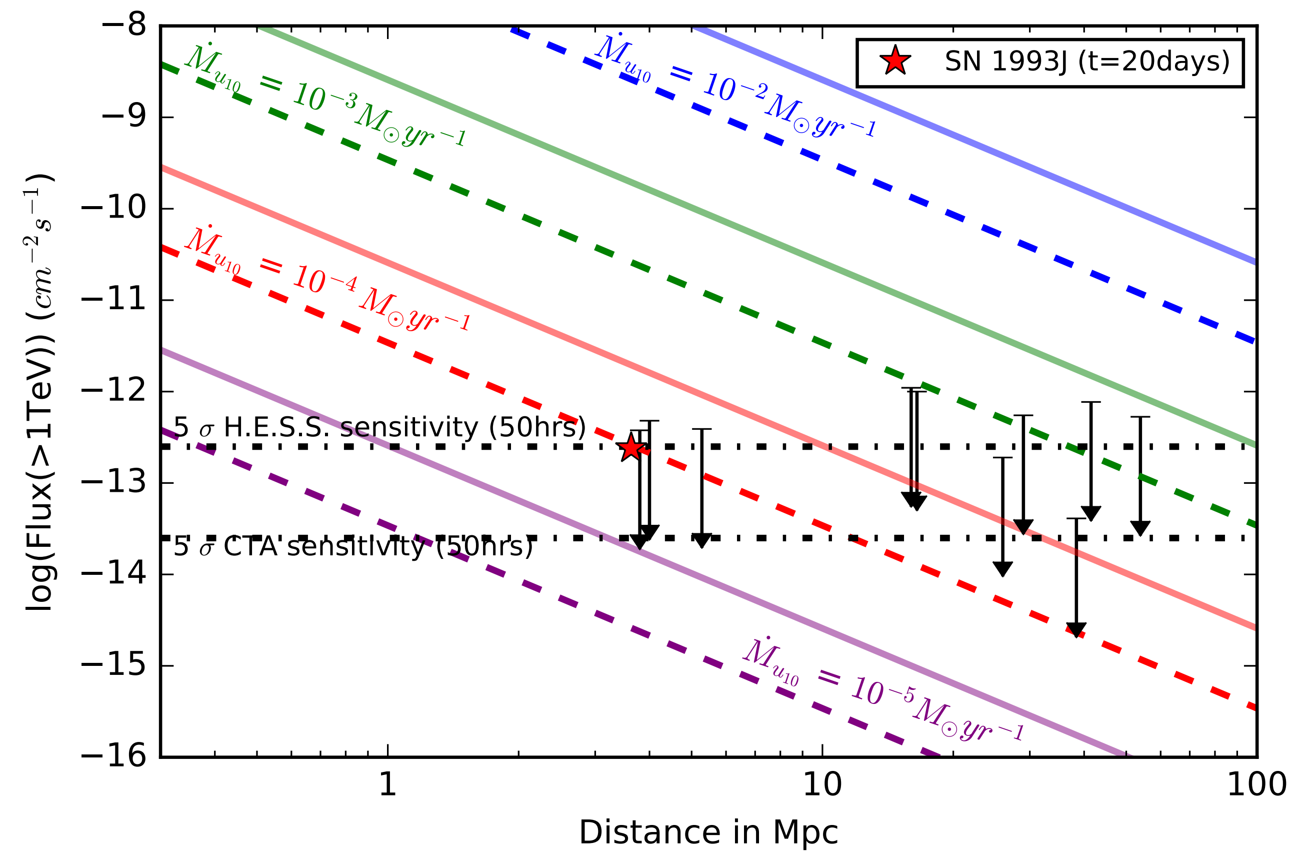
$$F_\gamma(E_0, t) = \frac{3q_\alpha \xi(V_{\rm sh}) m^2}{32\pi^2(3m-2)\beta\mu m_{\rm p}} \left[\frac{\dot{M}}{u_{\rm w}}\right]^2 \left(\frac{1}{d^2}\right)\left(\frac{1}{t}\right)$$

- No detection by H.E.S.S. yet → flux UL converted to $\dot{M}/v_{\rm w}$

# H.E.S.S. results on gamma-rays from supernovae

Plots by R. Simoni




- Upper limits $\dot{M}/v_{\rm w}$ depend on date of obs ($t_{sn}$) and distance
- RSG stars have $v_w \approx 10$km/s
- Realistic mass losses: $\dot{M} \approx 10^{-6} - 10^{-7} \mathrm{M}_\odot \mathrm{yr}^{-1}$
- For few SNe ULs are already constraining!
- Needed: patience, luck (rightnearby SN), and CTA will help!

# Grand summary

- Origin of cosmic rays still a puzzle!
- Galactic cosmic rays: supernova remnants prime suspects
- Acceleration mechanism: diffusiive shock acceleration
- To reach the "knee" needed:
  - High B (>100μG)
  - Turbulent B, i.e. $\eta \approx 1$
- X-ray synchrotron:
  - B is indeed higher than expected (>100μG)
  - B-field turbulent ($\eta \lesssim 5$)
  - Fast acceleration (10-100 yr to $10^{14}$eV)
- Magnetic field likely amplified by cosmic rays
- Gamma-rays:
  - First evidence for hadronic cosmic rays
  - No evidence for acceleration $>10^{14}$ eV
  - We see evidence for escape of cosmic rays
- Sources for CRs with $>10^{15}$eV:
  - super bubbles? (first detection!)
  - supernovae? (no detection yet)


"That's all Folks!"