Neutrino Telescopes and Multi-Messengers Approach

Elisa Resconi

Schule für Astroteilchenphysik 2009
Universität Erlangen-Nürnberg

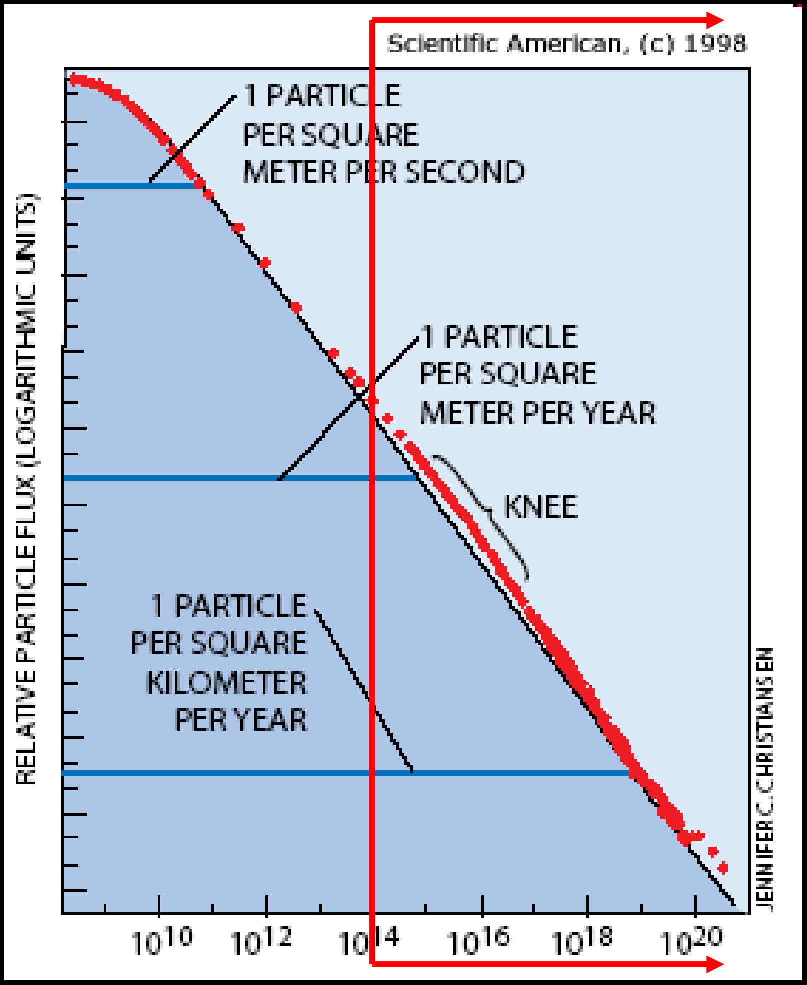
Content

1. Cosmic Particles Flow Chart

2. Neutrino Telescopes

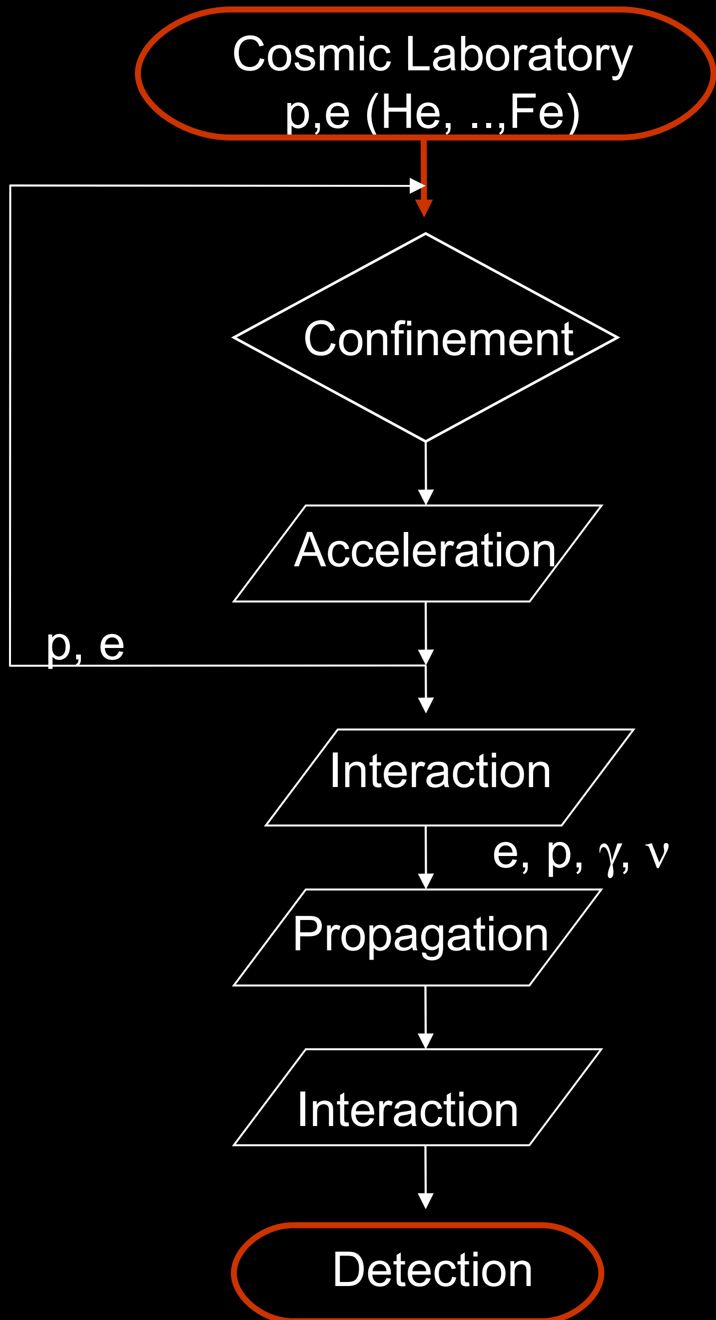
3. The Hunt for Neutrino Sources
   - multi-wavelength

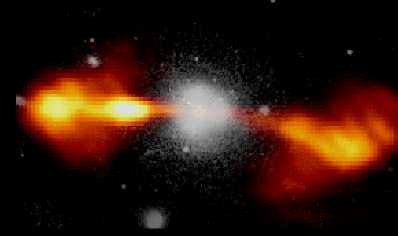
Cosmic (Rays) Particles: the crucial sense of wonder



Power law spectrum [10^9 – 10^{20} eV] $\propto E^{-2.7}$

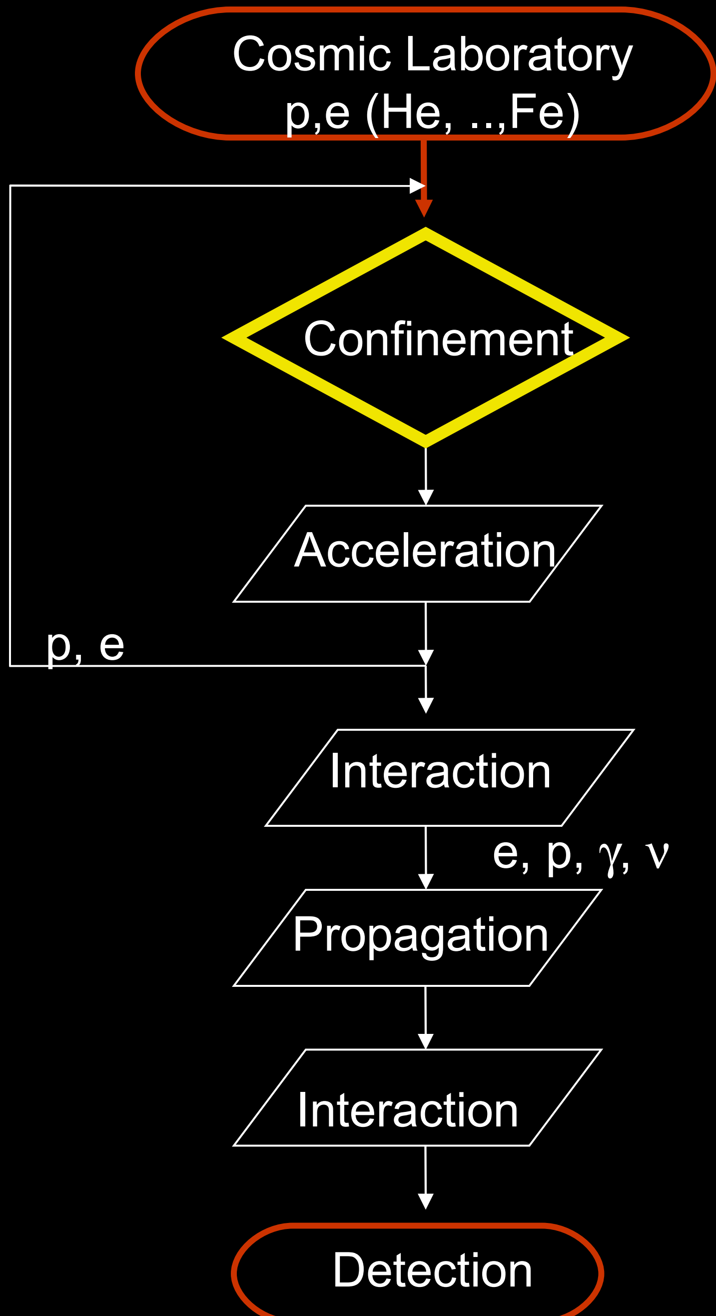
2 features: knee (~ 10^{15} eV), ankle (~ 10^{19} eV)

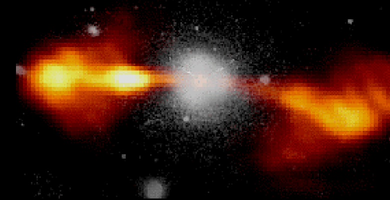




Cosmic particles flowchart

Cosmic particles flowchart

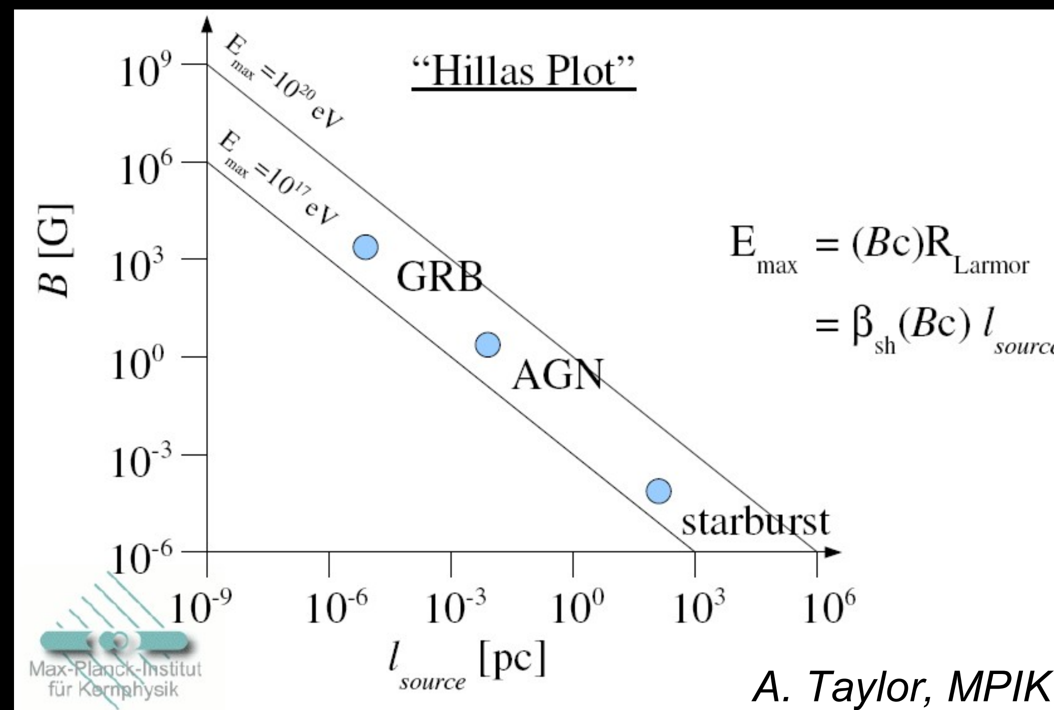


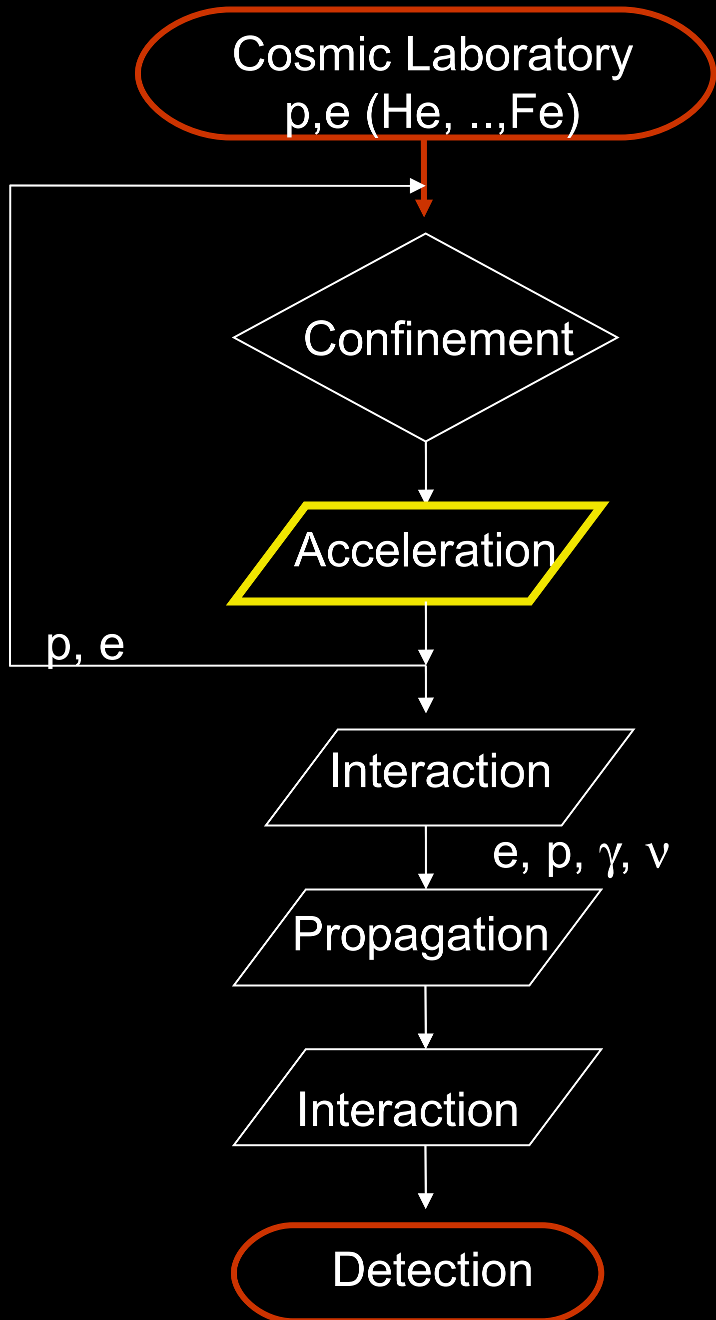


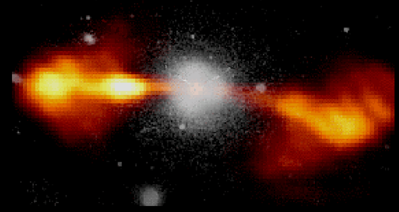
Source size, Magnetic Field

A. M. Hillas,

Ann. Rev. Astron. Astrophys. **22, 425 (1984)**

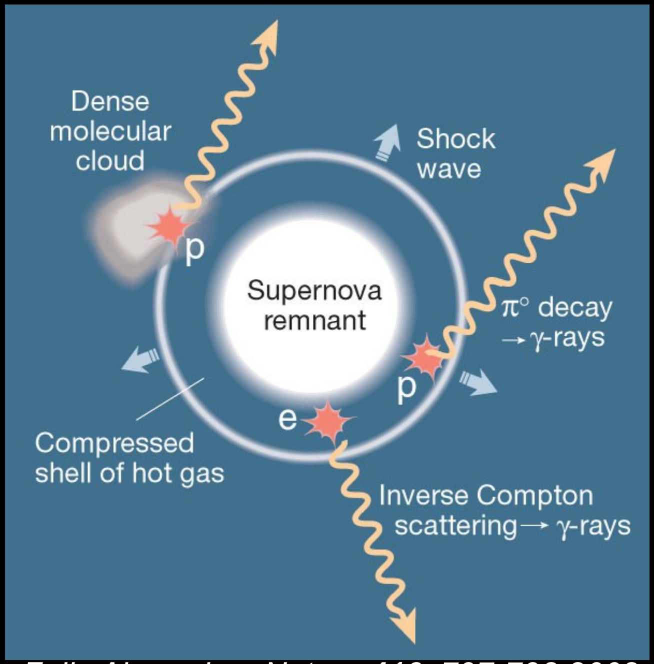




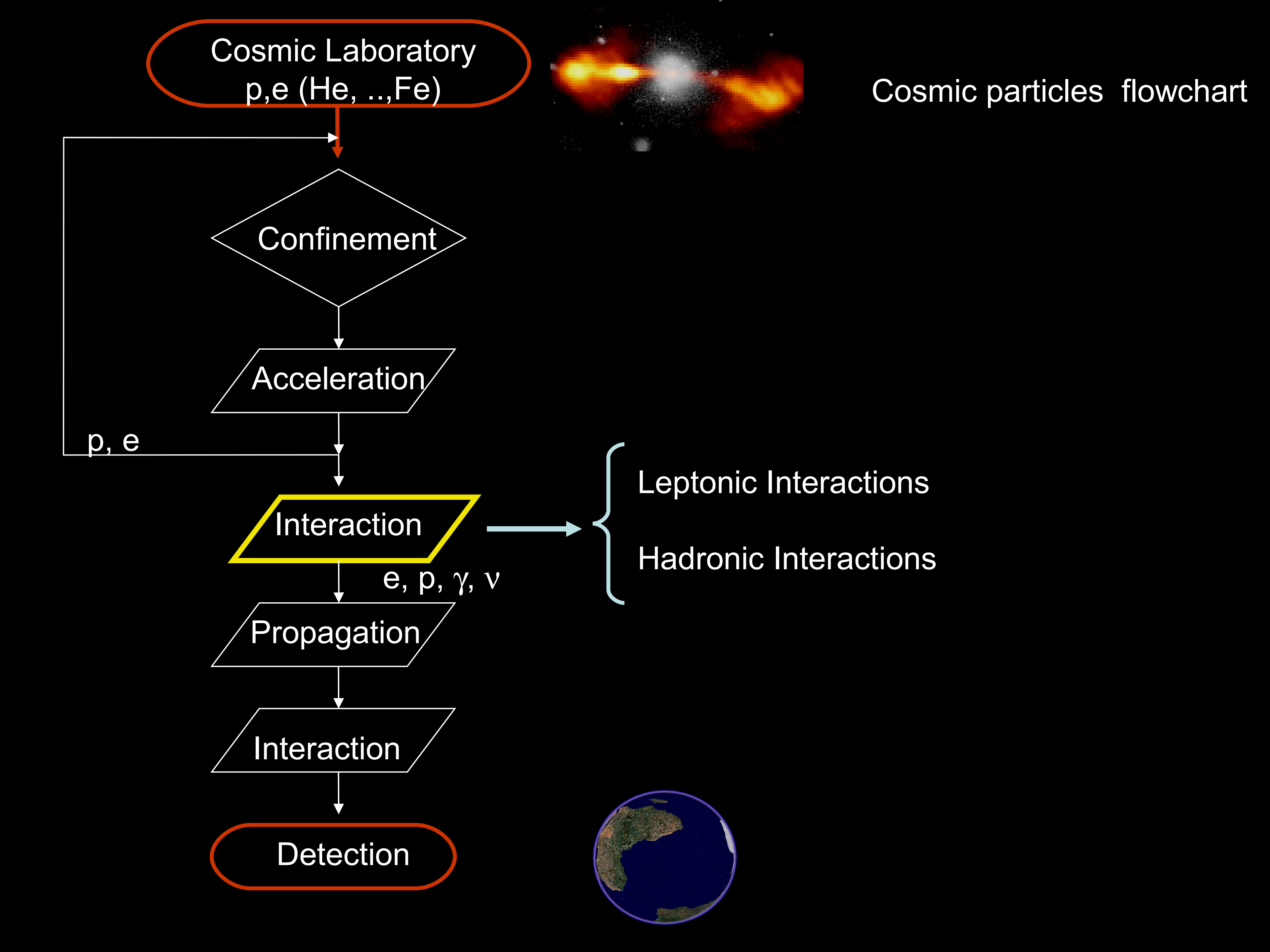


Cosmic particles flowchart

Various ideas:
Diffusive shock acceleration



Felix Aharonian, Nature ***416****, 797-798,2002*


Cosmic particles flowchart
Cosmic Laboratory
p,e (He, ..,Fe)
Confinement
Acceleration
p, e
Interaction
e, p, γ, ν
Leptonic Interactions
Hadronic Interactions
Propagation
Interaction
Detection

Interaction

Hadronic Interactions

Energy spectra of γ, electrons and neutrinos from:

- pγ interactions (analytic)

S.R. Kelner, F.A. Aharonian,
Phys.Rev.D78:034013,2008
e-Print: arXiv:0803.0688 [astro-ph]

- pp interactions (analytic)

S.R. Kelner, F. A. Aharonian,V.V. Bugayov,
Phys.Rev.D74:034018,2006, Erratum-ibid.D79:039901,2009
e-Print: astro-ph/0606058

- MonteCarlo approach:

A. Reimer et al., SOPHIA MonteCarlo, http://ebl.stanford.edu/
(Simulations Of Photo Hadronic Interactions in Astrophysics)

Interaction

Hadronic Interactions, $p\gamma$ interactions

- Inverse Compton Scattering: $p\gamma \rightarrow p\gamma'$
  Like for e^- but energy loss-rate suppressed
  Not dominant effect

- $e^+ e^-$ pair production: $p\gamma \rightarrow pe^+e^-$
  Cross-section (Bethe-Heitler) large
  Only a small fraction of the p energy into secondary electrons

ix) Photomeson production: $p\gamma \rightarrow N + k\pi$
Cross-section smaller then ii)
Higher fraction of p energy into secondary products
For hadronic interaction: dominant effect

Interaction

Hadronic Interactions, $p\gamma$ interactions, photomeson production

Assumptions:

- Low density of ambient medium $\Rightarrow$ mesons decays before energy losses
- p, γ isotropically distributed
- Energy of colliding particles sutisfies the conditions:

  E (target photon) << $m_{\pi}c^2$ & E (proton) >> $m_{p}c^2$

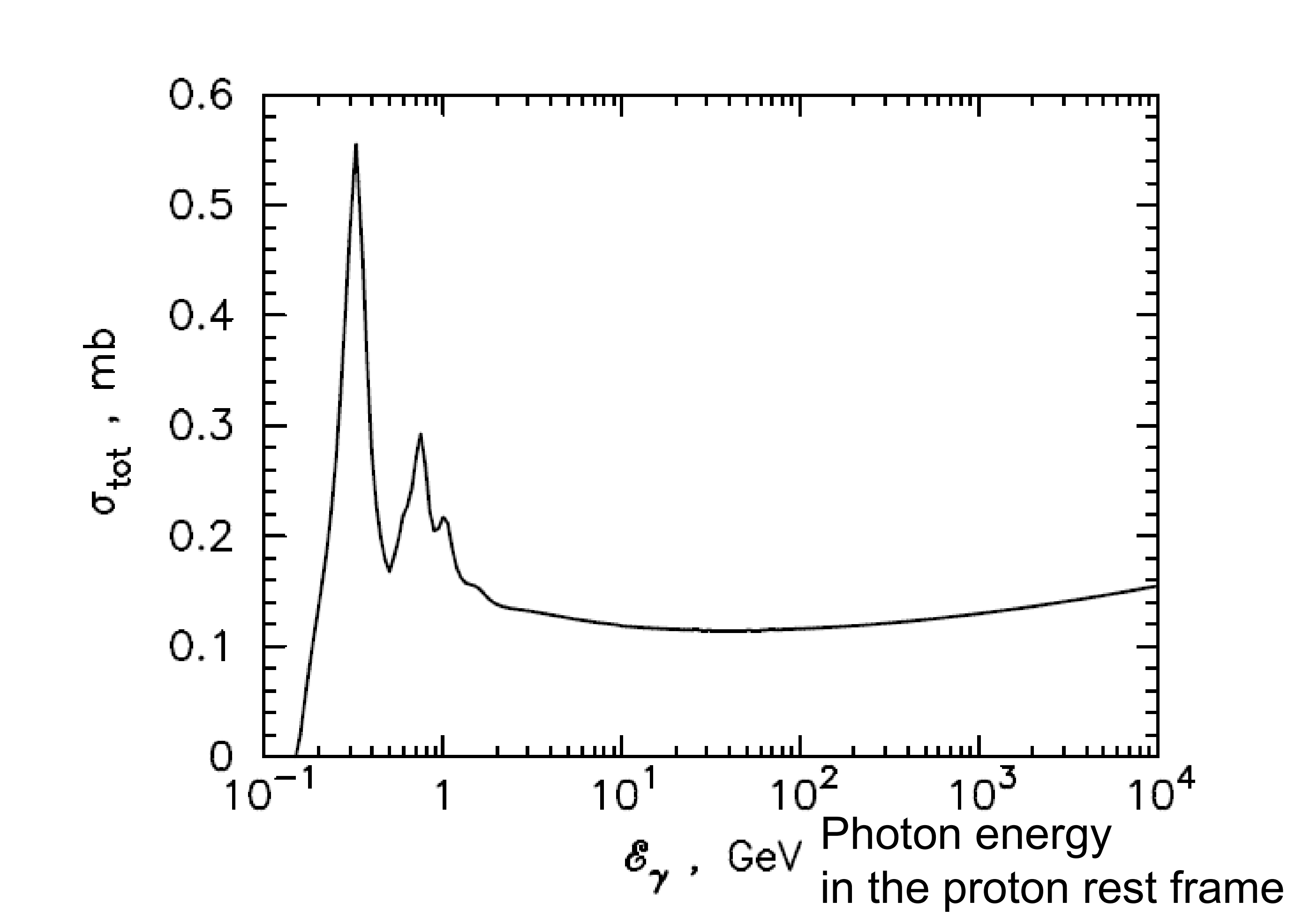
- Delta-functional approach

Cross sections determined with SOPHIA MonteCarlo

Interaction

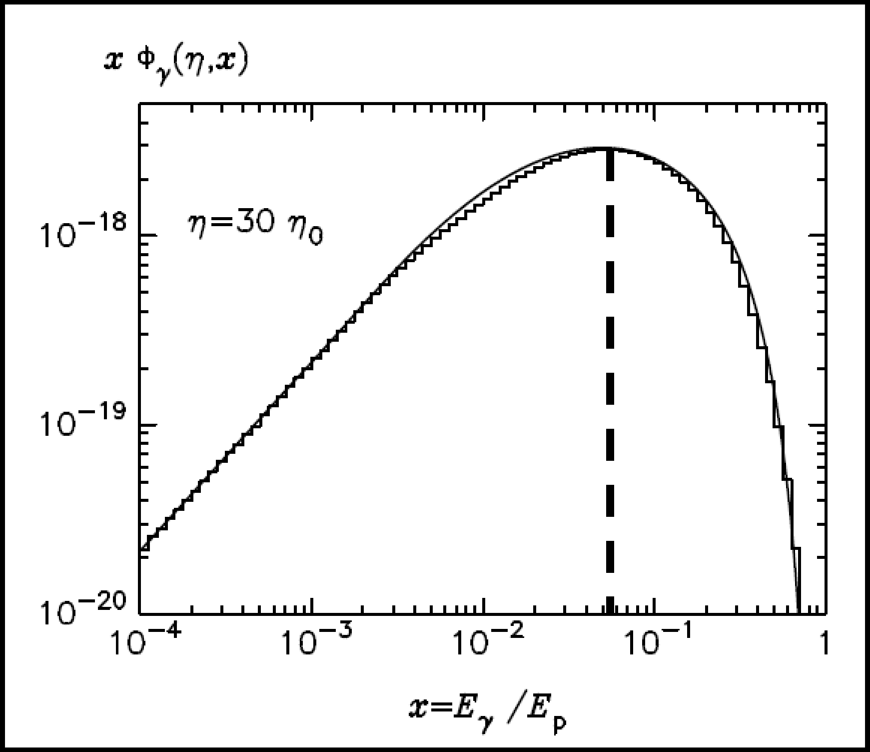
Hadronic Interactions, pγ interactions, photomeson production

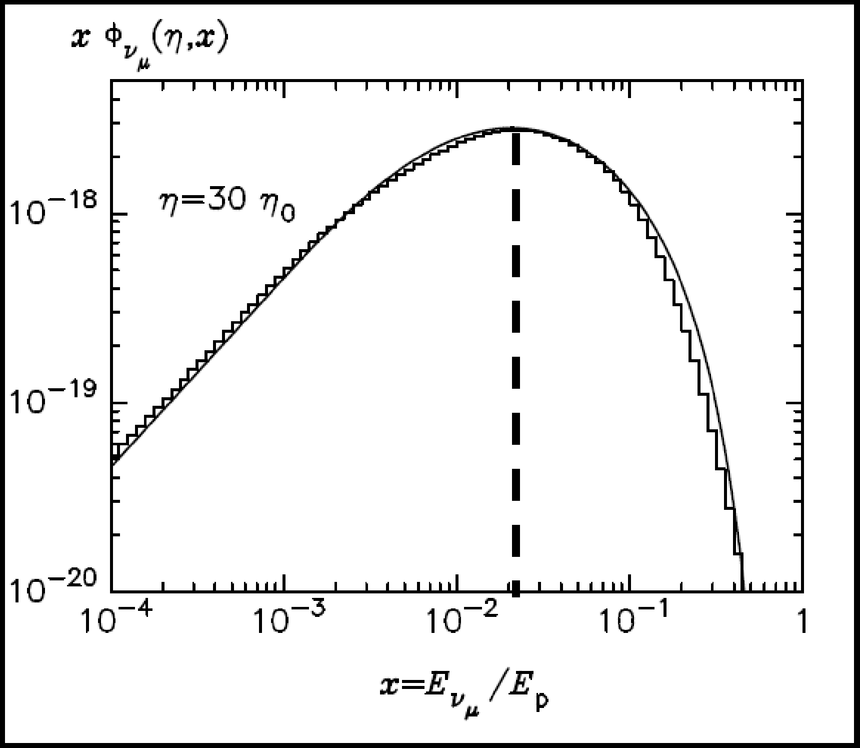
Total cross-section pγ interaction



Interaction

Hadronic Interactions, pγ interactions, photomeson production





Hadronic Interactions, pp interactions

Simulation of pp interactions
based on phenomenological models and data from accelerators

- PYTHIA, T. Sjöstrand, L. Lonnblad, S. Mrenna,
  http://home.thep.lu.se/~torbjorn/pythia8/worksheet8107.pdf

- SIBYLL, R.S. Fletcher, T.K. Gaisser, P. Lipari, T. Stanev
  Phys.Rev.D 50, 5710(1994)

- QGSJET, NN. Kalmykov, S.S Ostapchenko, A.I. Pavlov
  Nucl.Phys.B, Proc. Suppl 52, 17 (1997)

- Last two combined in: CORSIKA
  simulation of extensive air showers
  initiated by high energy cosmic ray particles
  http://www-ik.fzk.de/corsika/

Interaction

Hadronic Interactions, pp interactions

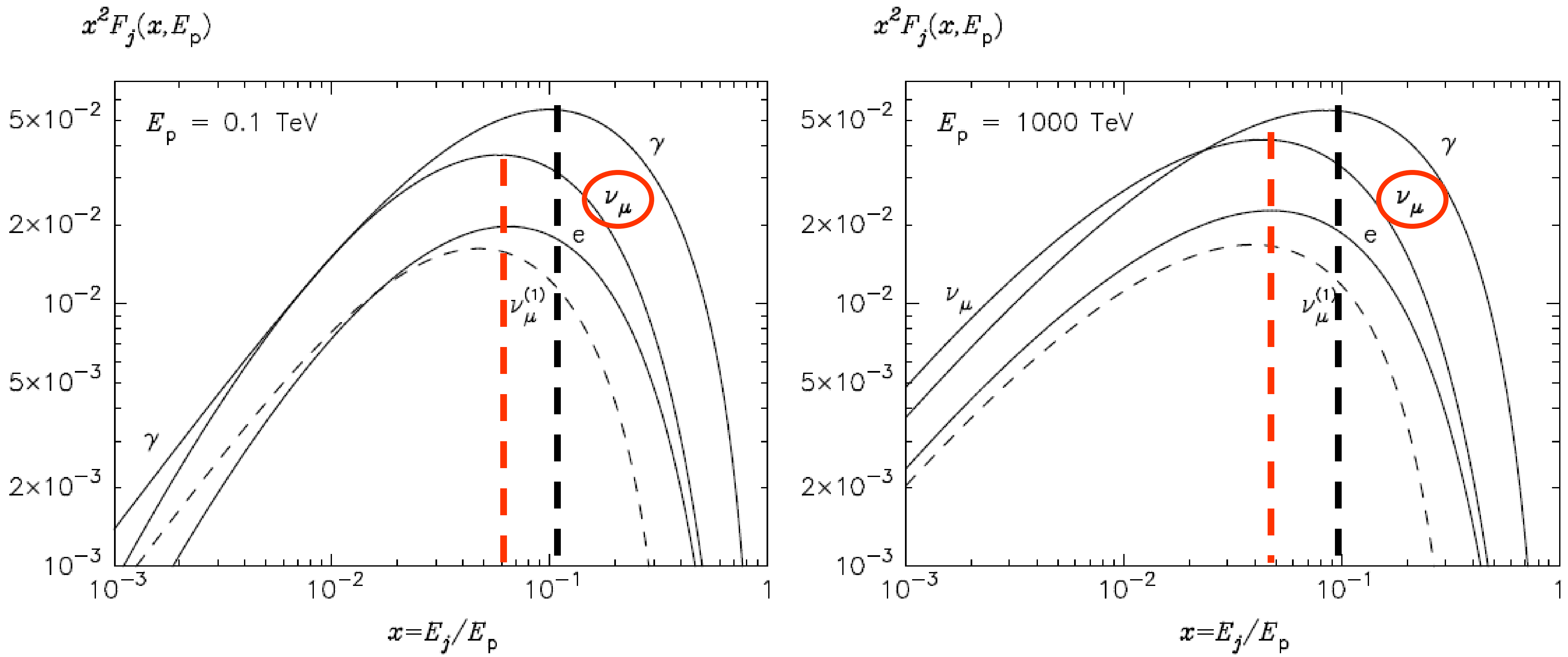
Delta-functional approach: WARNING

- Similar spectral shape for proton and γ, just shifted
- But sharp cutoff in p translates in less sharp cutoff in γ

$\Rightarrow$ Be carefull with simple approximations in cutoff regions

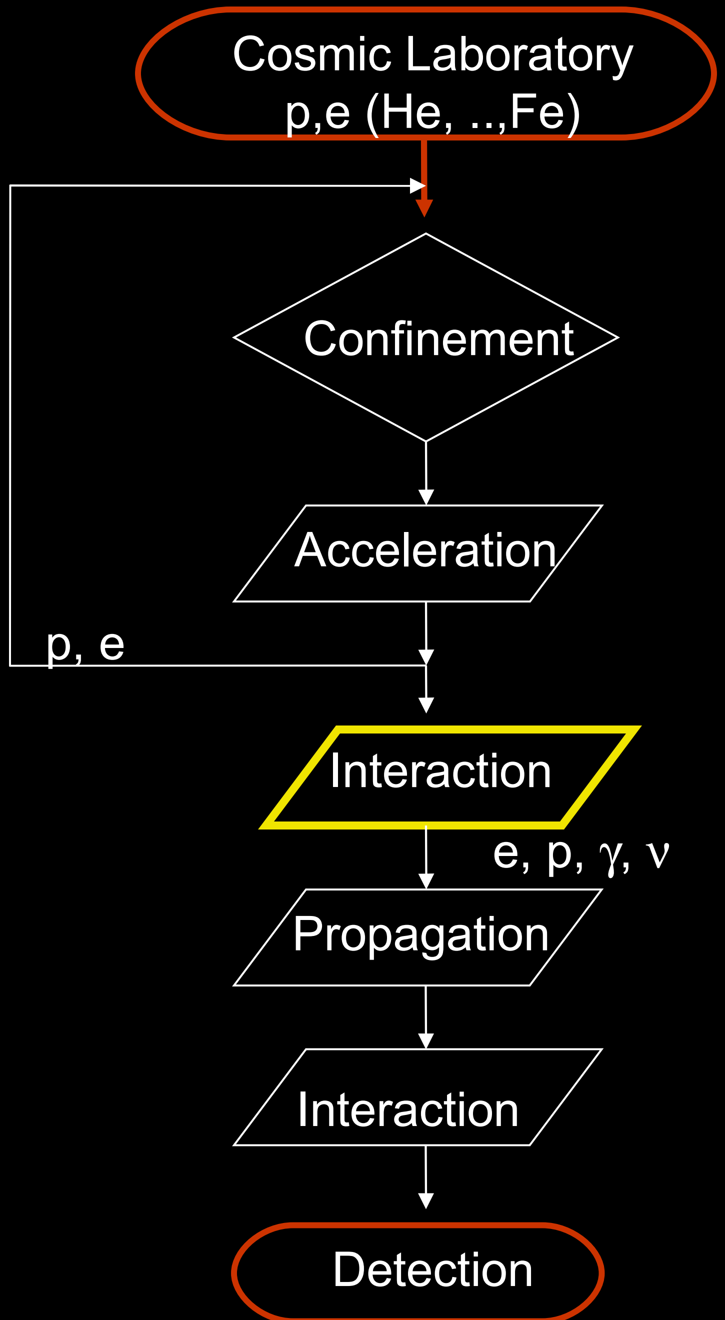
Interaction

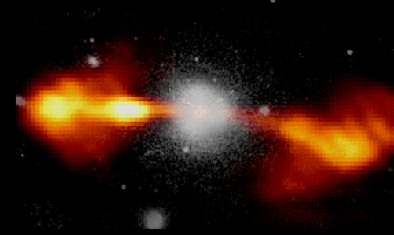
Hadronic Interactions, pp interactions

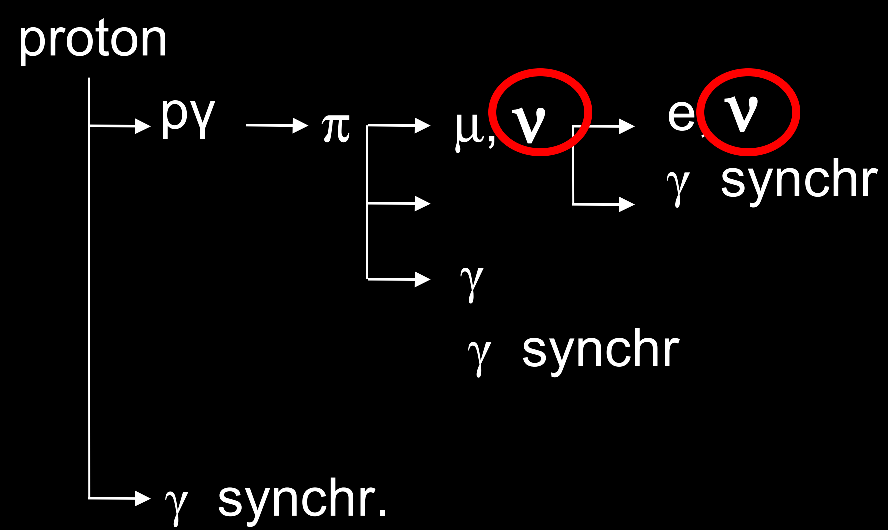


Energy spectra of all decay products produced at pp interaction for two energies of incident protons

Cosmic particles flowchart

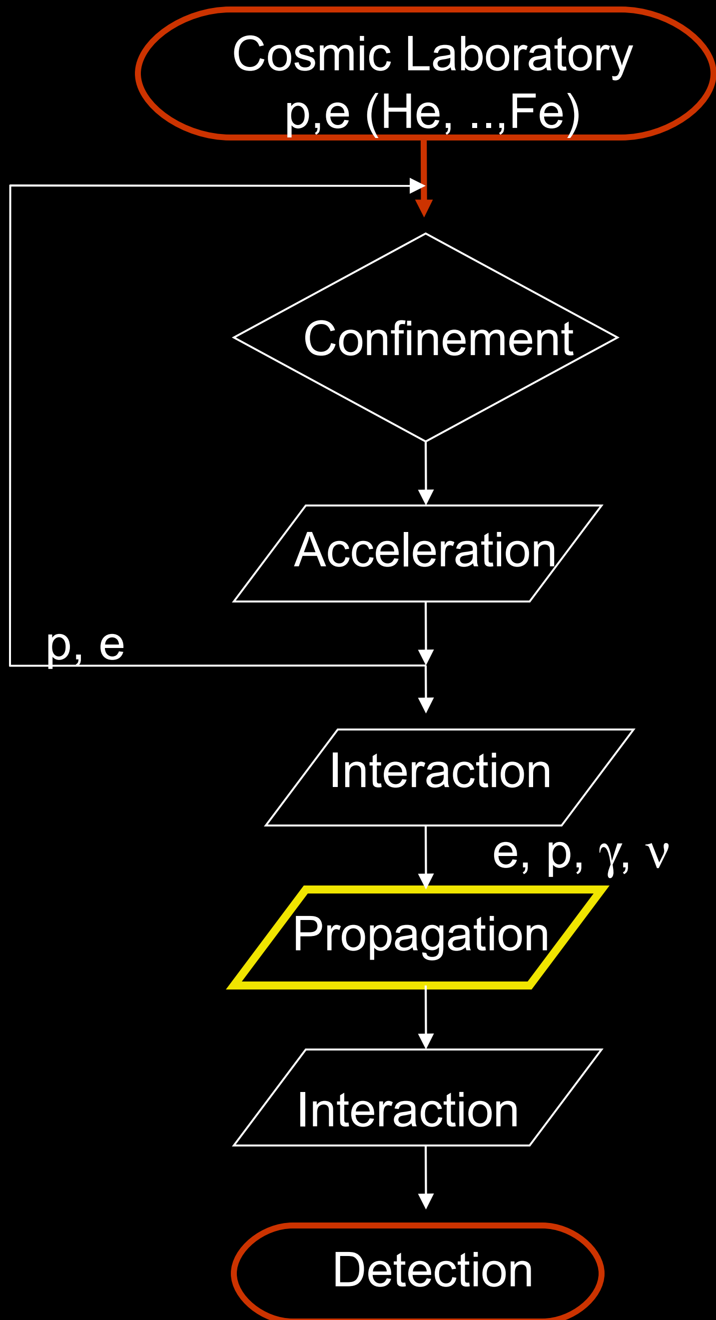


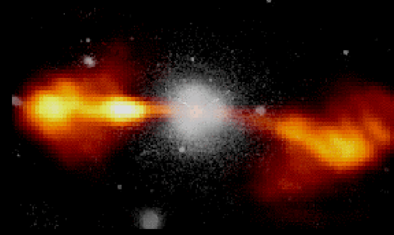




Three Messengers:

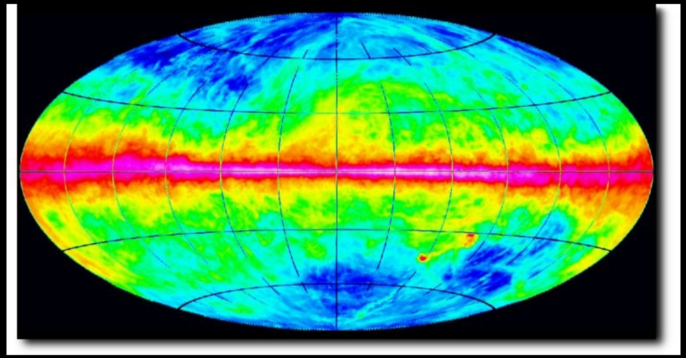
Charged Particles, Gamma-rays and Neutrinos





Cosmic particles flowchart

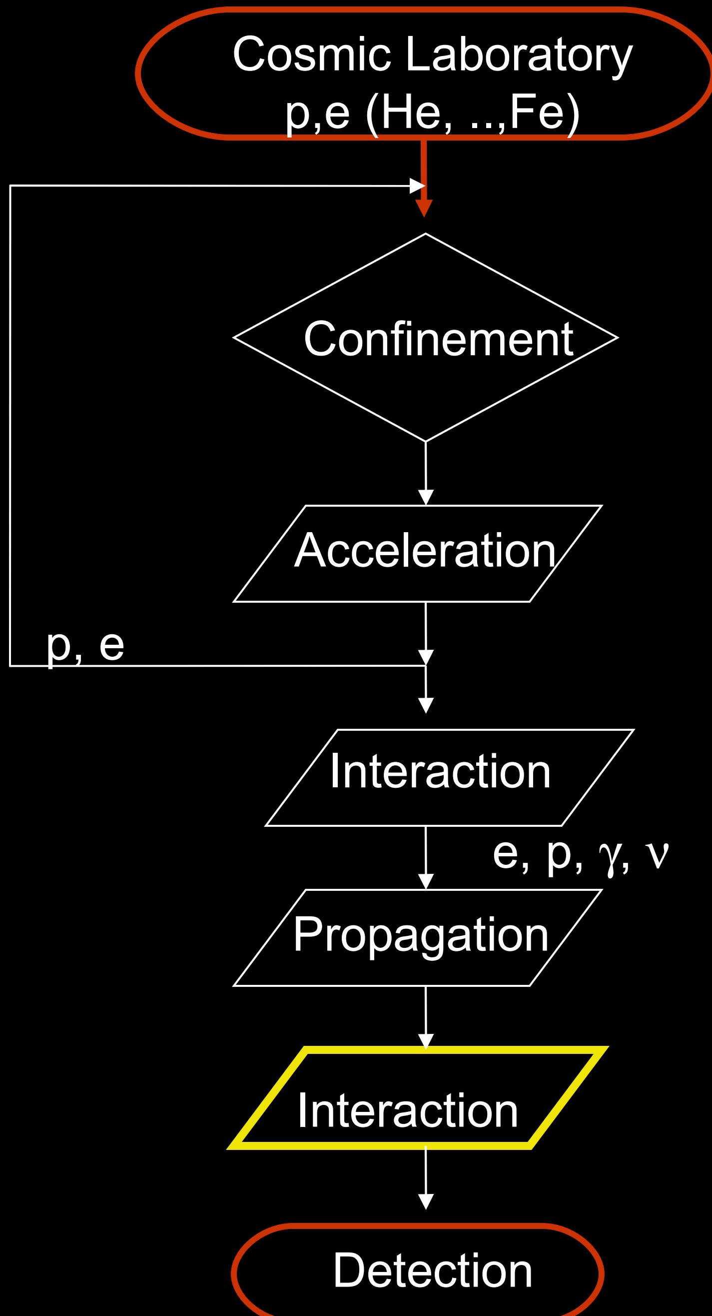
The Leiden/Argentine/Bonn (LAB) Survey of Galactic HI

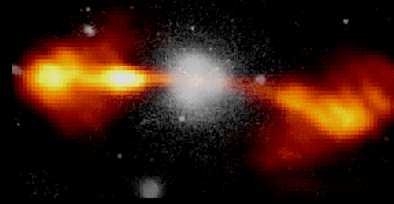


H2, NANTEN

Lorentz Invariance Violation?

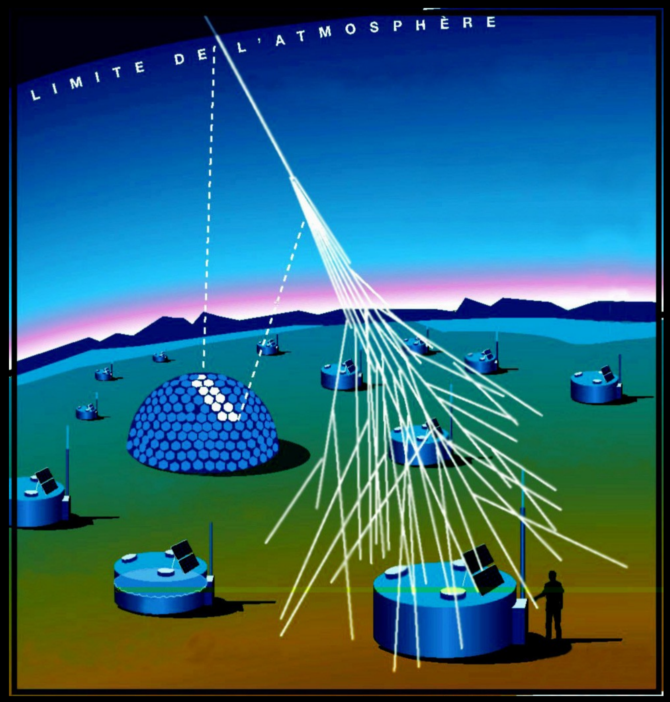
p: magnetic field deviation
γ: absorption
ν: no interaction, point back to the source

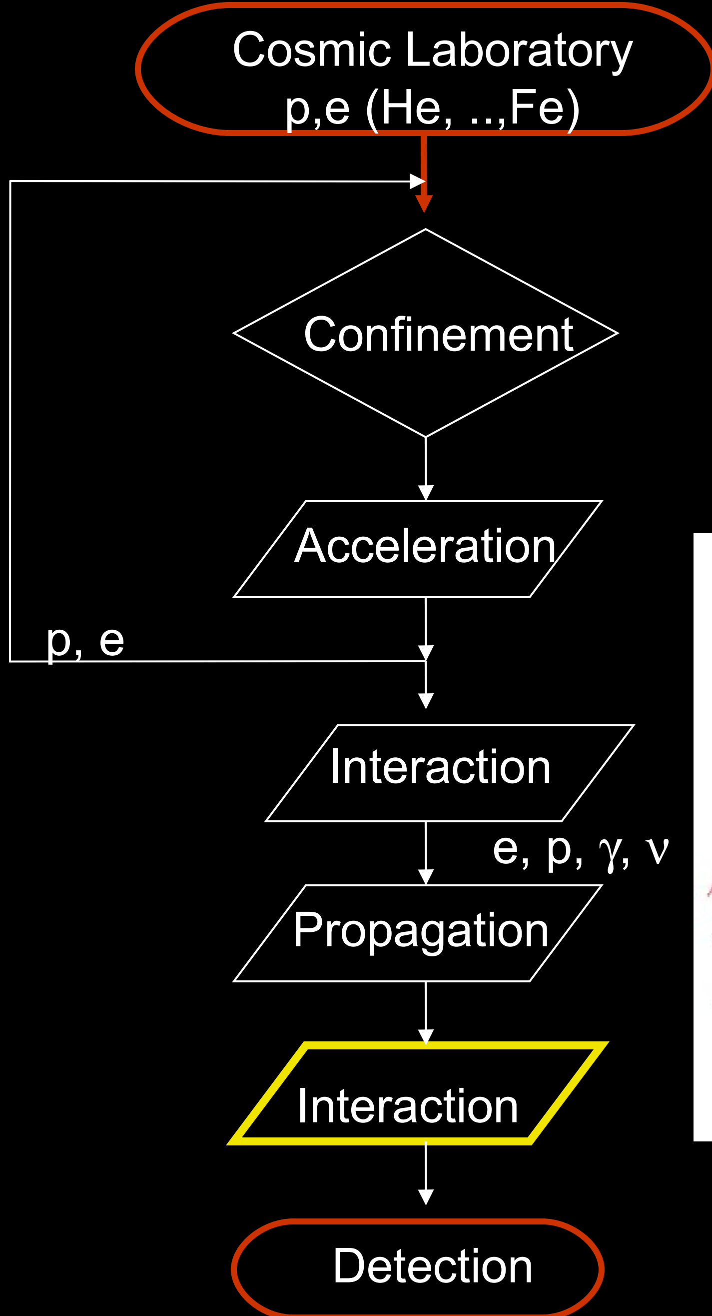


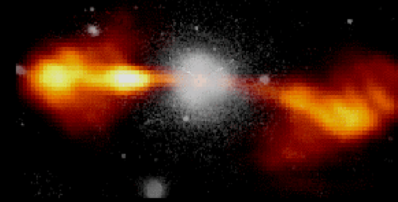


Cosmic particles flowchart

Proton interaction in Earth atmosphere
Air showers

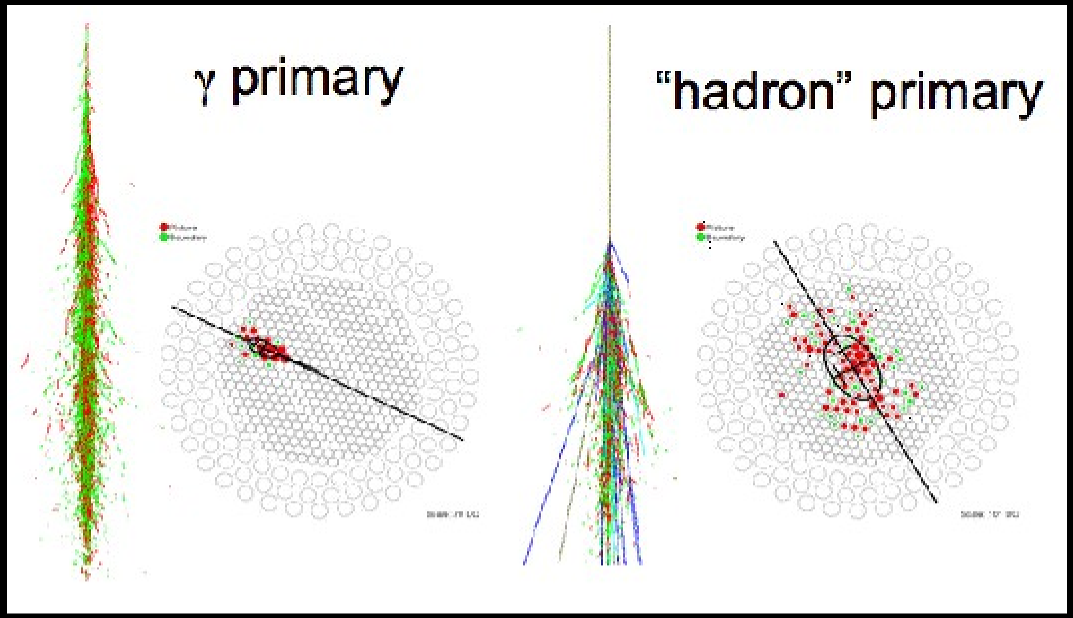




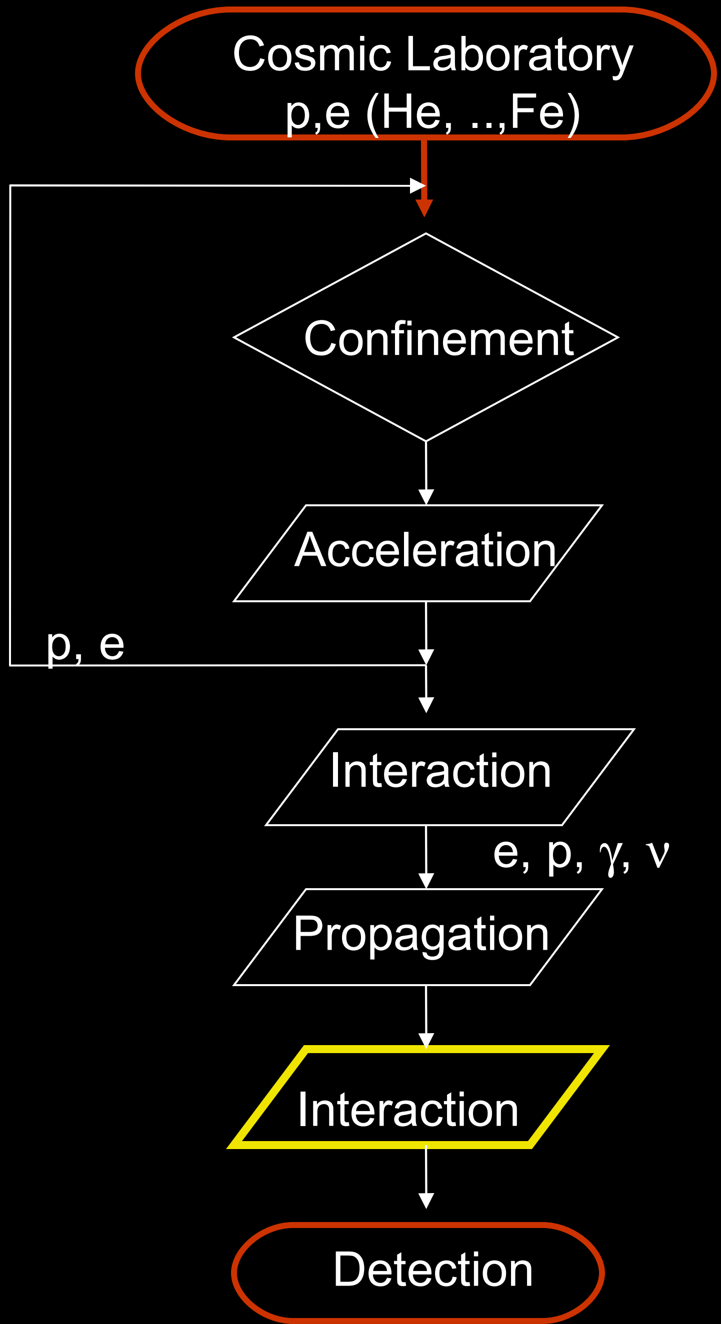


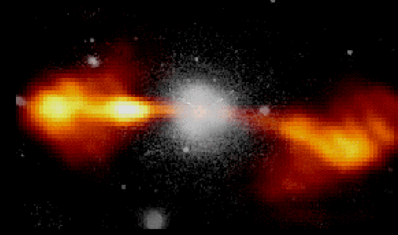
Cosmic particles flowchart

Proton and γ-rays interaction in Earth atmosphere
Air showers

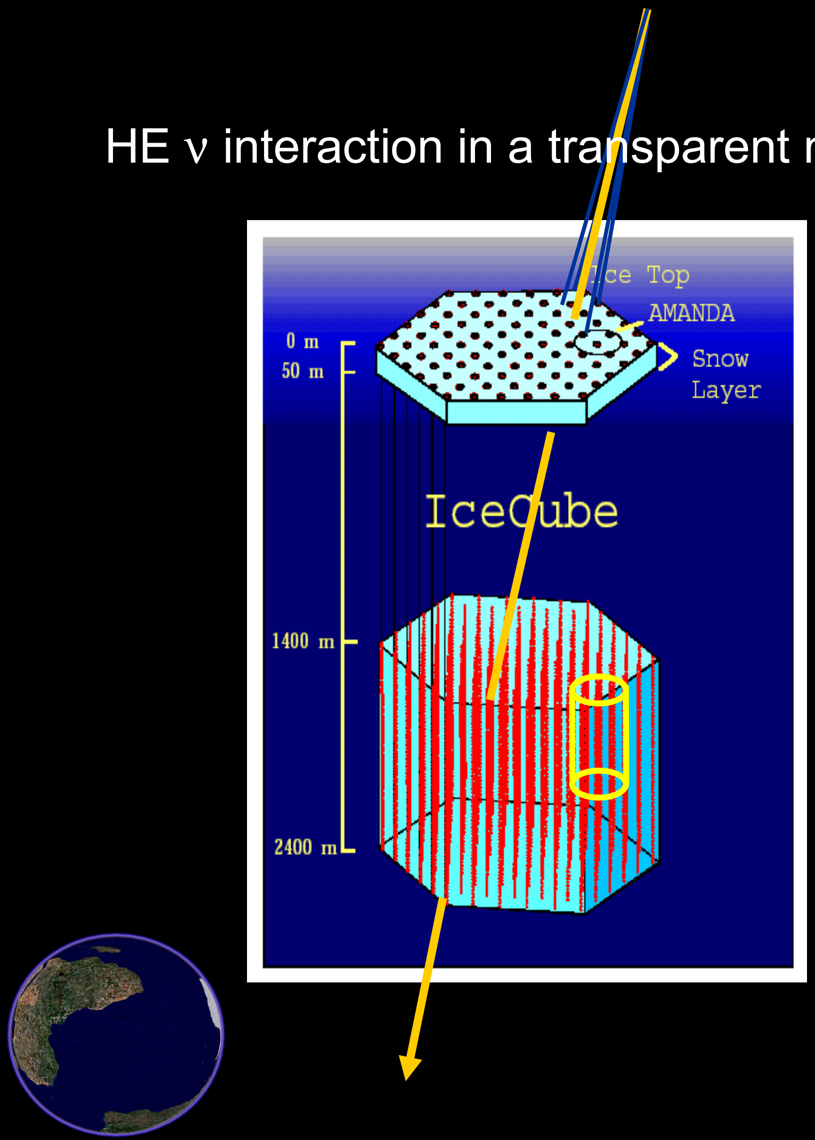


Cosmic particles flowchart





HE ν interaction in a transparent medium



Summary 1

- Cosmic Ray Energy Spectrum:
  $\Rightarrow$ a natural wonder

- Interaction of CR produce: γ-rays, neutrinos

- CR - γ - neutrinos =
  = messengers for the high energy universe

Questions ?

Content

1. Cosmic Particles Flow Chart

2. Neutrino Telescopes

3. The Hunt for Neutrino Sources
   - multi-wavelength

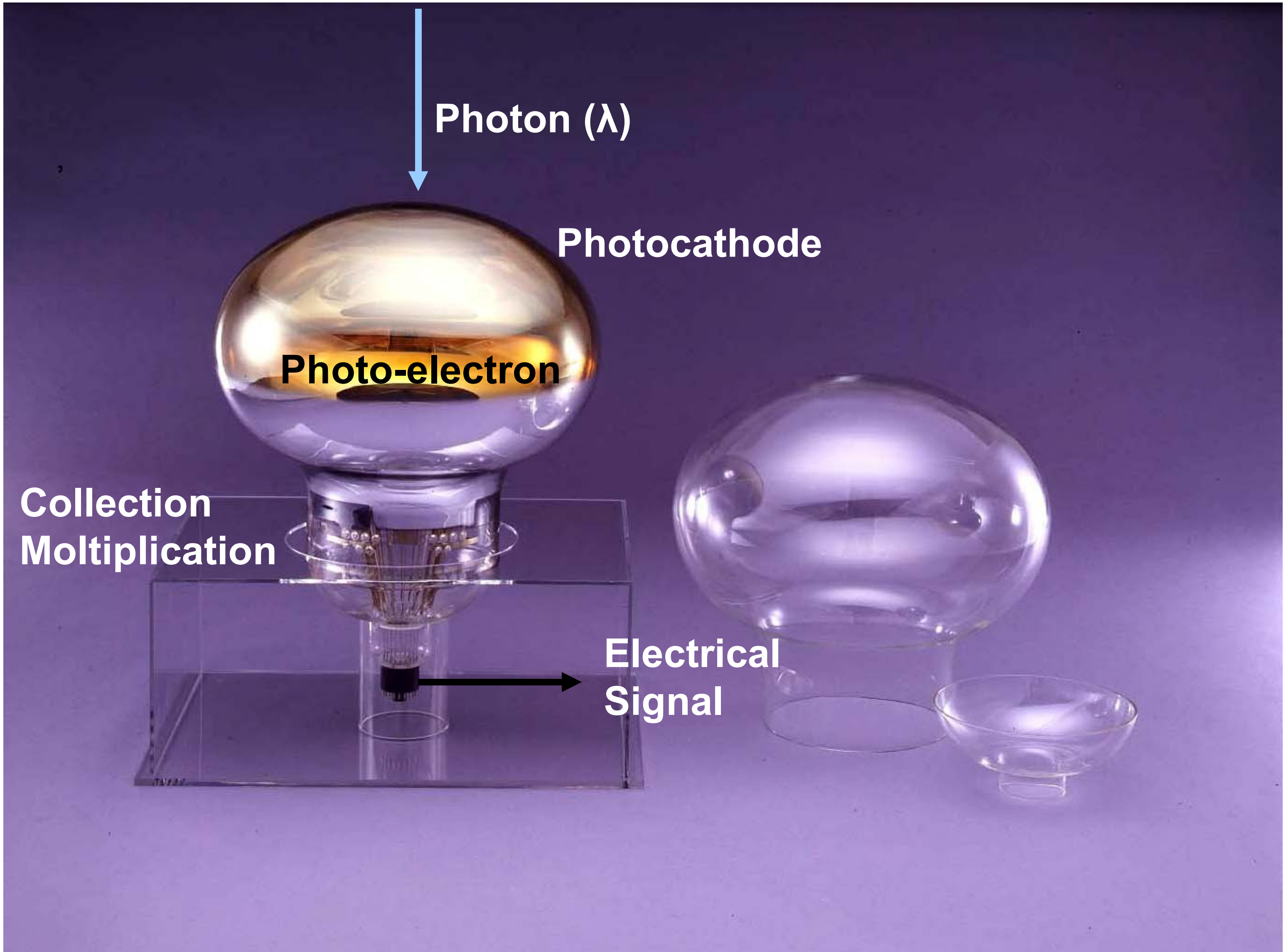
What is a Neutrino Telescope?

- Detector Component:
  - phototubes encapsulated in glass pressure sphere
  - DAQ: extract charge, arrival time

- Detector Geometry:
  - matrix of different shapes
  - Shape influence detector response
    (energy range, angular resolution etc)

- Detector Materials:
  - natural transparent material (water, ice)
  - Atmosphere; surrounding material (rock, earth..)

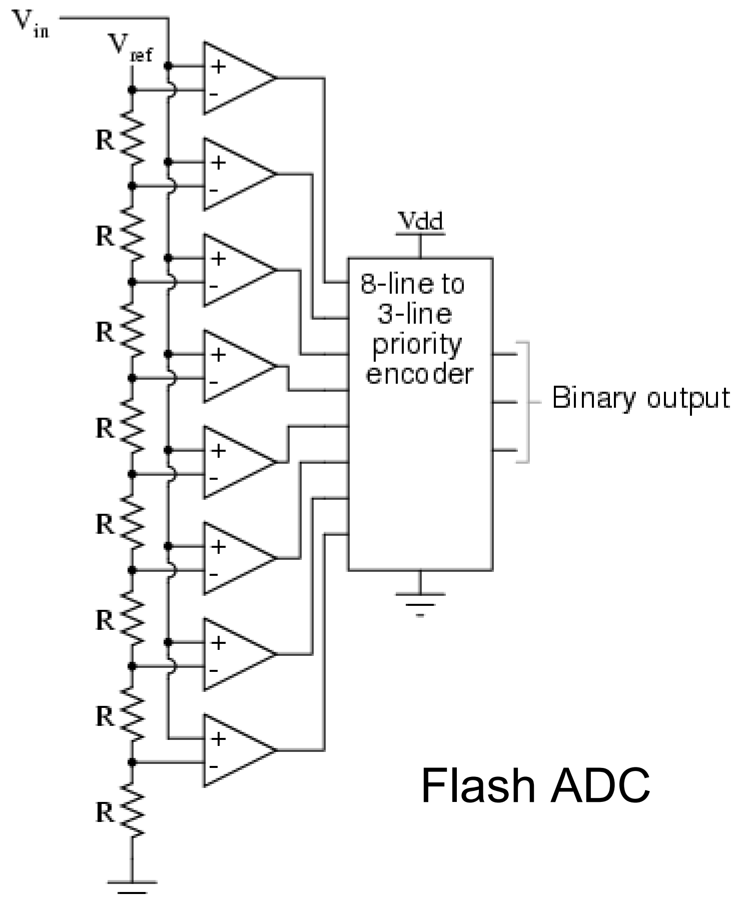
Photo-Multiplier-Tube (PMT)



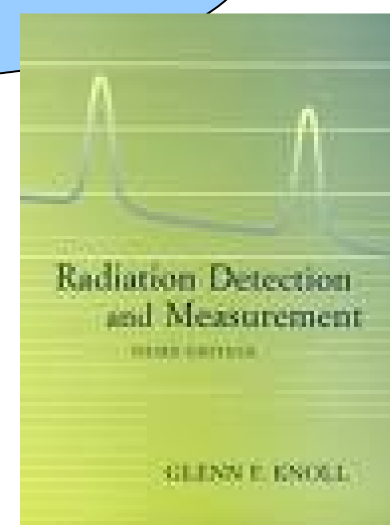
Signal and Data AcQuisition (DAQ)

Analog: Con

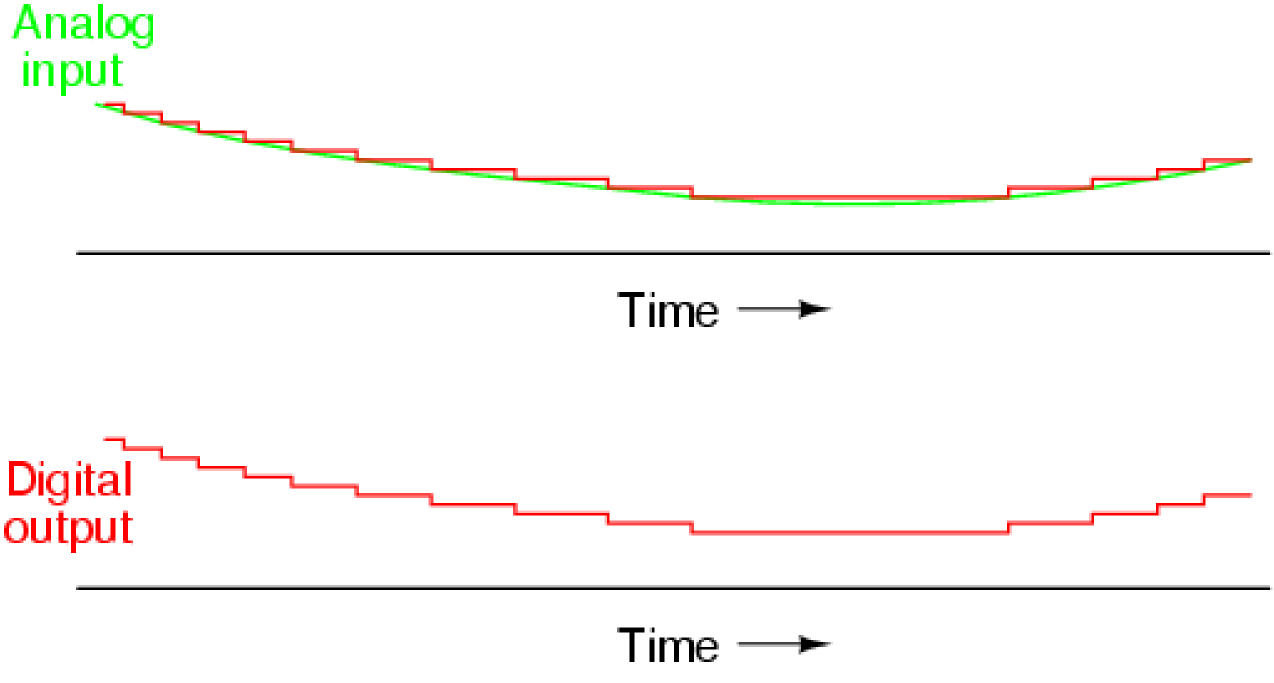
Discrete in Time



Flash ADC



Signal and Data AcQuisition (DAQ)



Signal and Data AcQuisition (DAQ)

Analog: Continue in Time

Digital: Discrete in Time

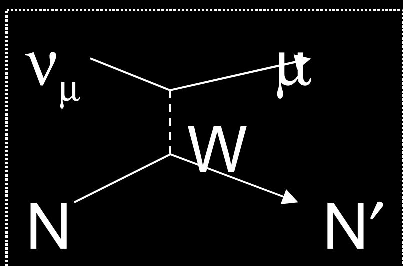
Processing:

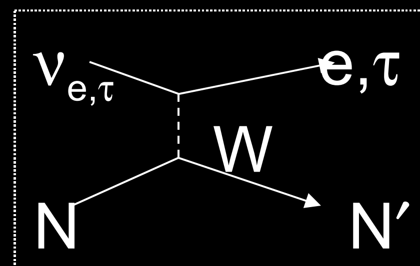
- storage
- reconstruction
- separation between signal and noise,
- feature extraction etc

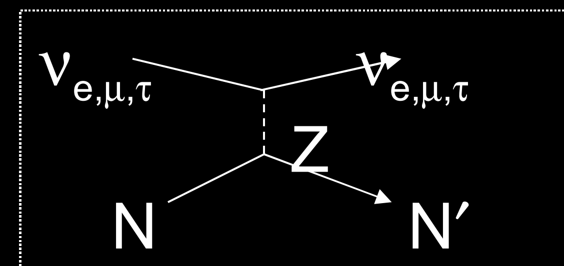
Neutrino Channels

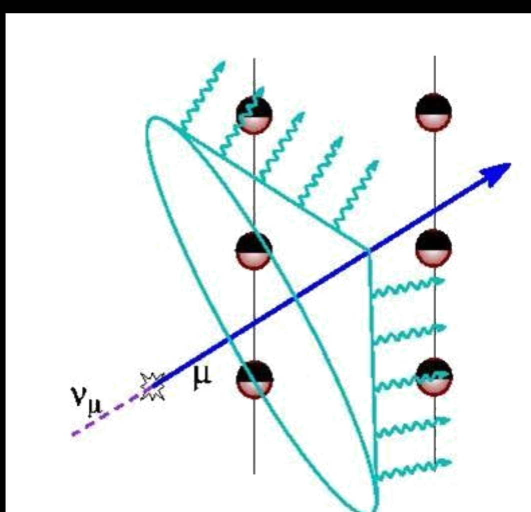
μ tracks (ν_μ)

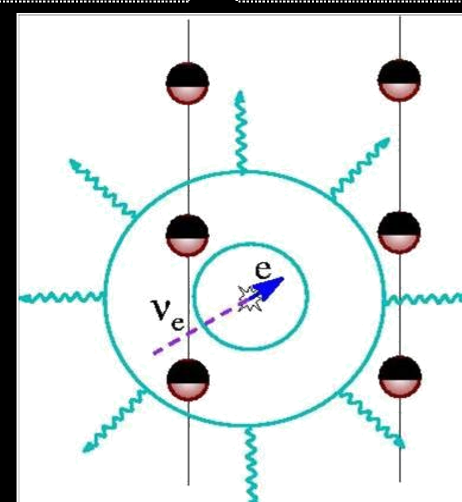
Cascades ($\nu_{e,\tau}$ CC, $\nu_{e,\mu,\tau}$ NC)











esconi

The Cherenkov effect

- A charged particle radiates if its velocity is larger than the phase velocity of light $v > c / n$

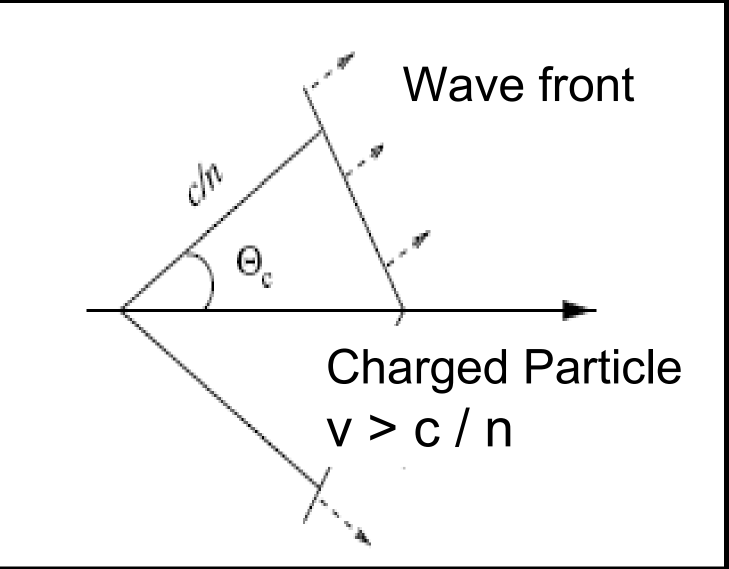
- Electrons start vibrating due to particle electro-magnetic field and some of the particle energy is converted in light

- If the media is transparent the Cherenkov light can be detected

If the particle is ultra-relativistic $\beta \sim 1$

Θ_c = const

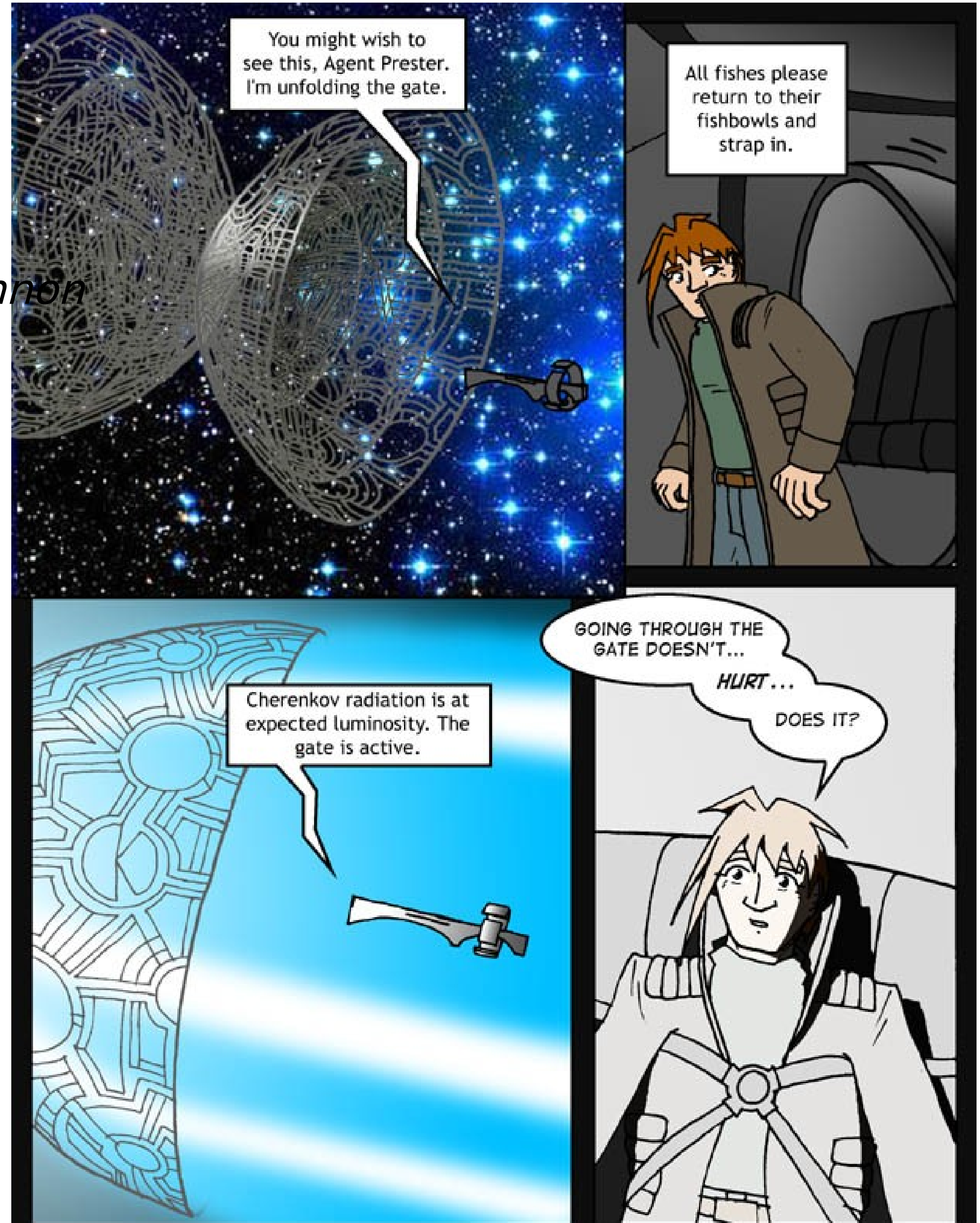
In water $\Theta_c = 43^\circ$, in ice 41°



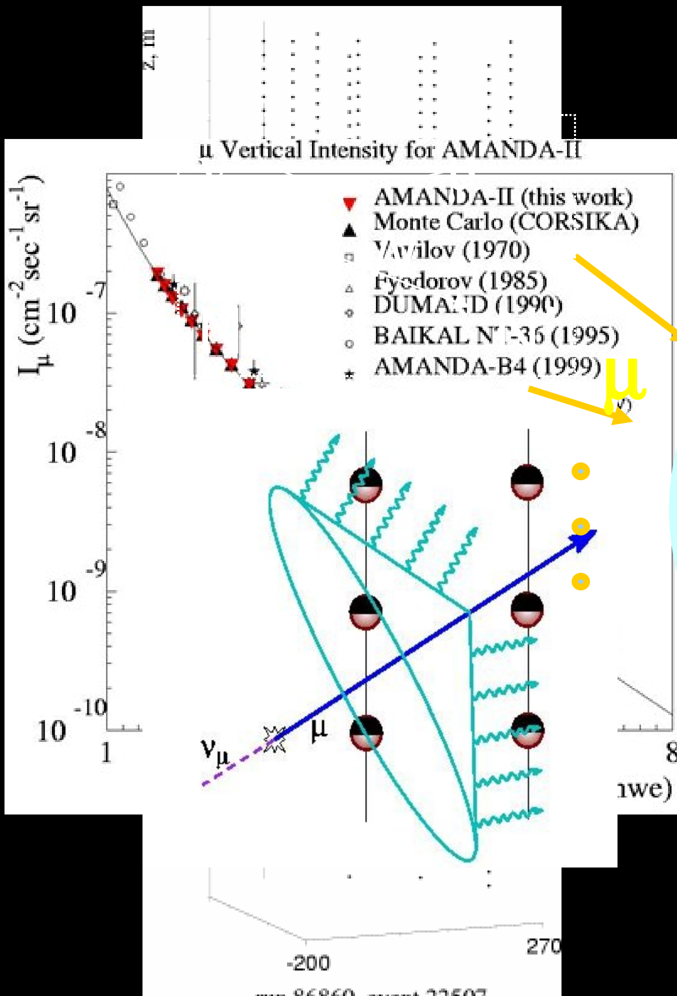
$$\frac{d^2N_\gamma}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi}{\lambda^2}\,\alpha\,\sin^2\theta_c$$

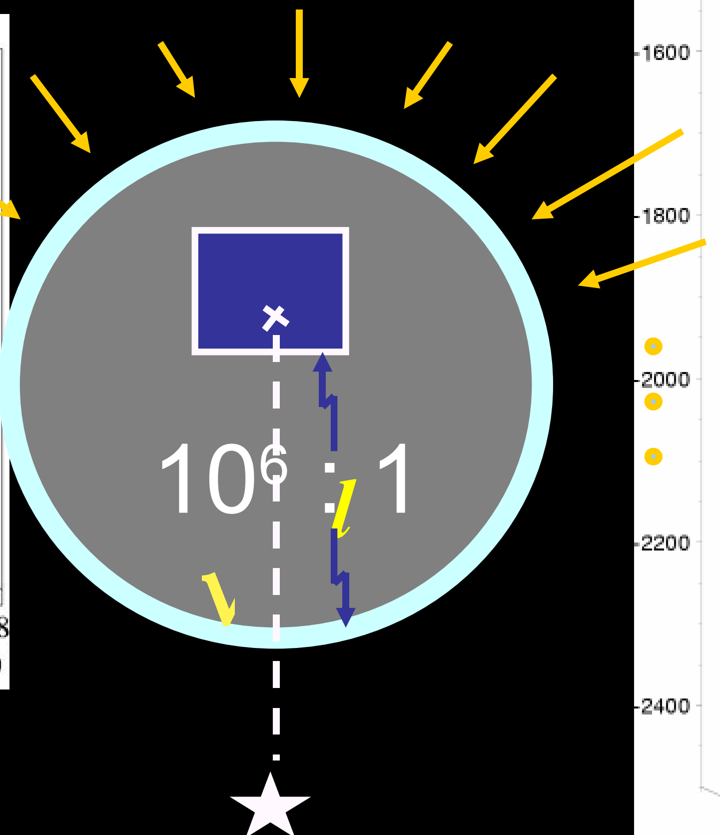
Miracle of Science, by Jon Kilgannon

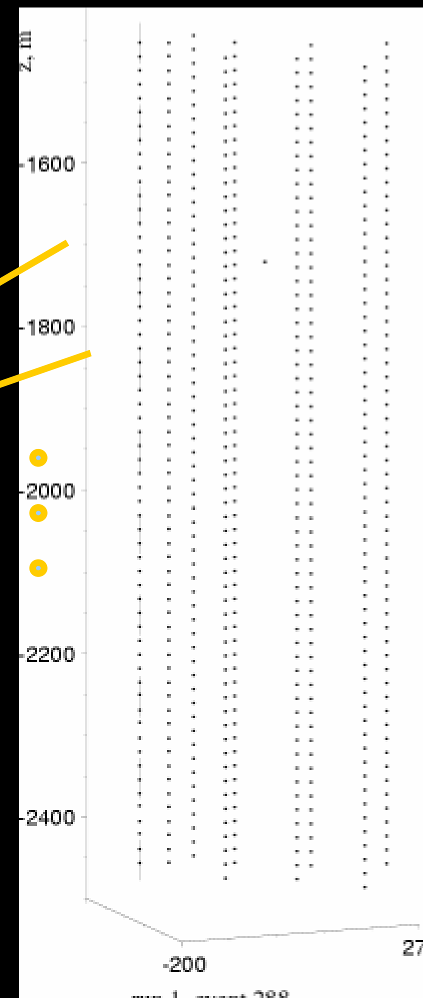
nd drawn by Mark Sachs



How do neutrino telescopes work ?
Neutrino Interaction

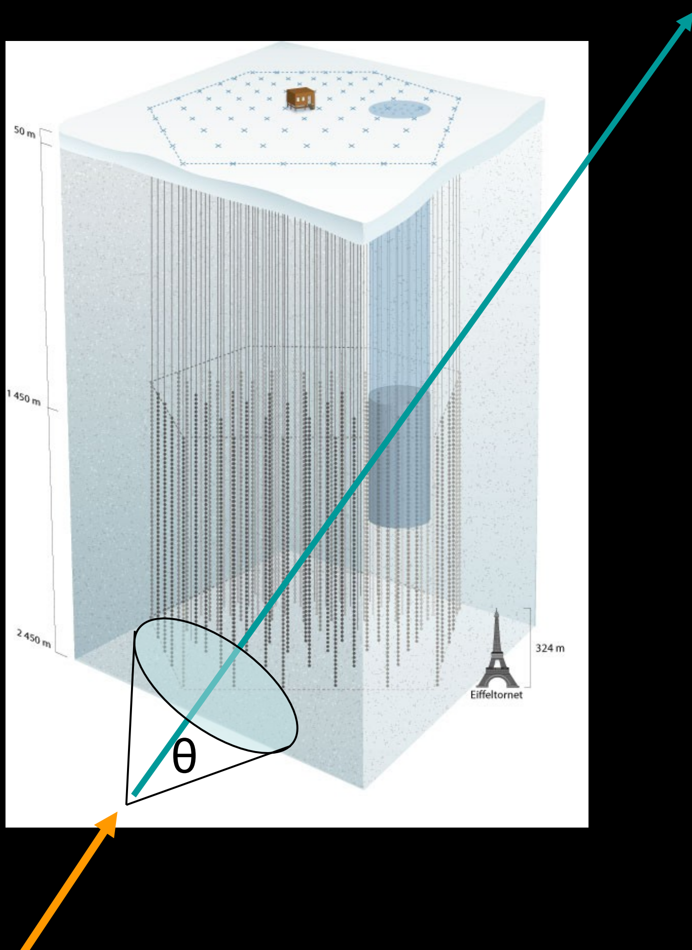


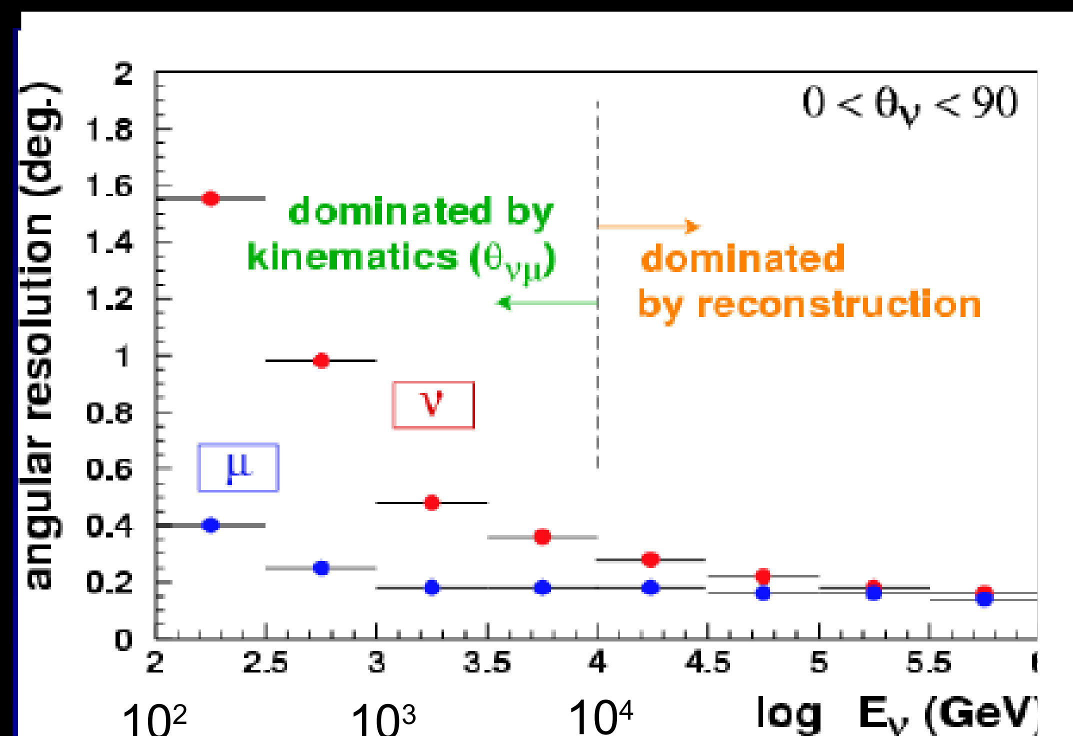




How do neutrino telescopes work?
Neutrino-Muon Angle

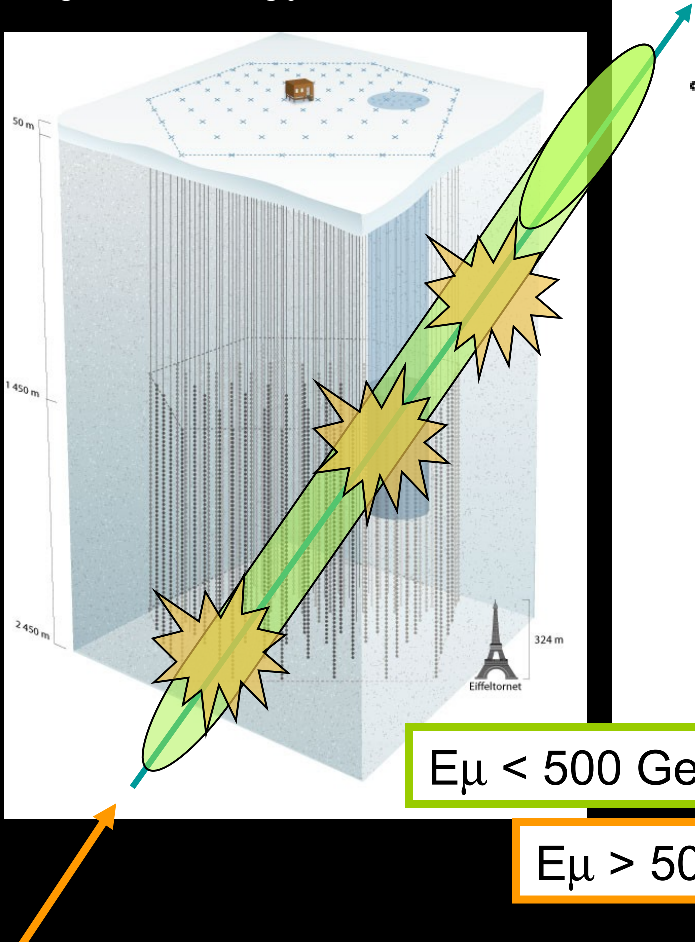
$$\langle\theta_{\nu\mu}\rangle \approx 0.7^{\circ} \cdot \left(\frac{E_\nu}{1\ \text{TeV}}\right)^{-0.7}$$



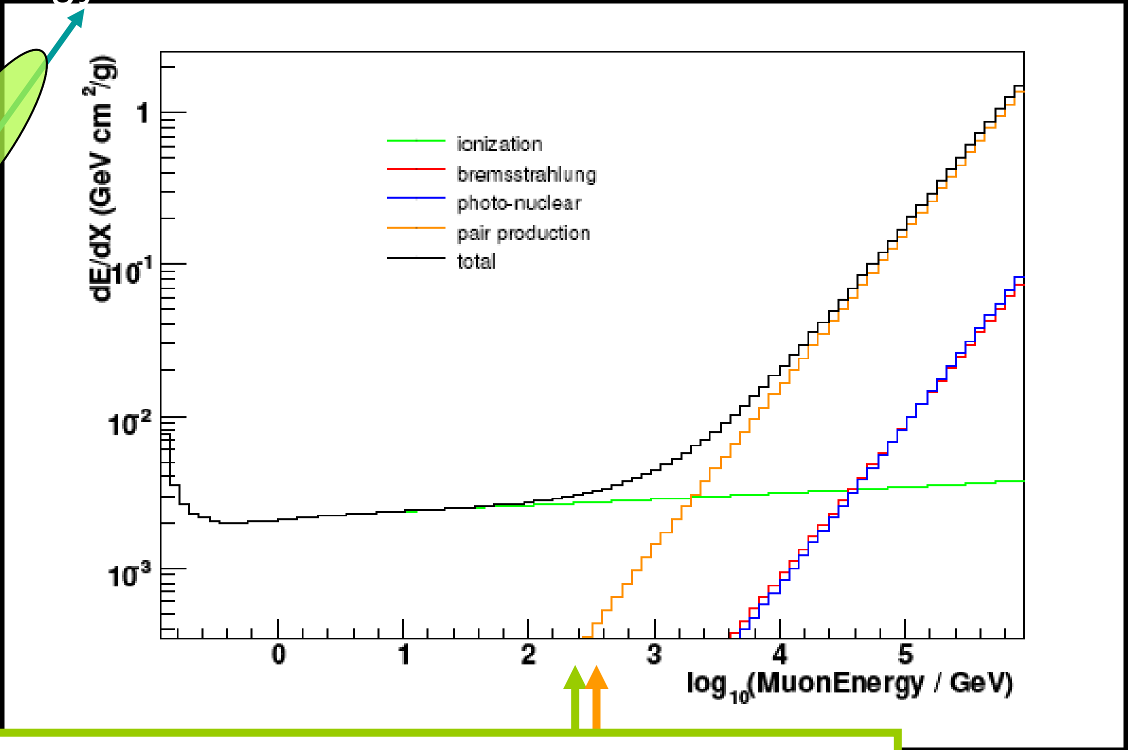


How do neutrino telescopes work?
Muon Energy Loss

Muon: 100 GeV ~ 500 m
Higher energy: stochastic energy loss



Muon Energy Loss in Ice



Eμ < 500 GeV ionization dominant (~ 2 MeV / cm)

Eμ > 500 GeV stochastic energy loss dominant

How do neutrino telescopes work?

Muon Energy Loss, What do we detect?

- from electromagnetic interaction of the bare muon:

$$\sim 3 \cdot 10^4 \text{ Cherenkov photons/ m}$$

- short cascades along the muon track

[the knock-on electrons, bremsstrahlung, electron pairs, and photonuclear]
⇒increasing the “effective length” of the muon by about 4 m· E/GeV

- approximation of the muon energy losses,

$$dE/dx = a + b \cdot E$$

Above the critical energy (1 TeV), the second term begins to dominate the energy losses

How do neutrino telescopes work?

Muon Energy Loss, What do we detect?

Some references:

* “Muon Monte Carlo: a high-precision tool for muon propagation through matter”, D. Chirkin, hep-ph/0407075.

* “Muon energy reconstruction and atmospheric neutrino spectrum unfolding with the IceCube detector”

J. Zornoza, D. Chirkin, for the IceCube Coll, ICRC07

http://indico.nucleares.unam.mx/getFile.py/access?contribId=190&sessionId=40&resId=0&materialId=paper&confId=4

If a telescope big enough then

We can look UP ….

Challenge:

Reject down-wards muons

(~ 10^6 μ : 1ν)

Strategy:

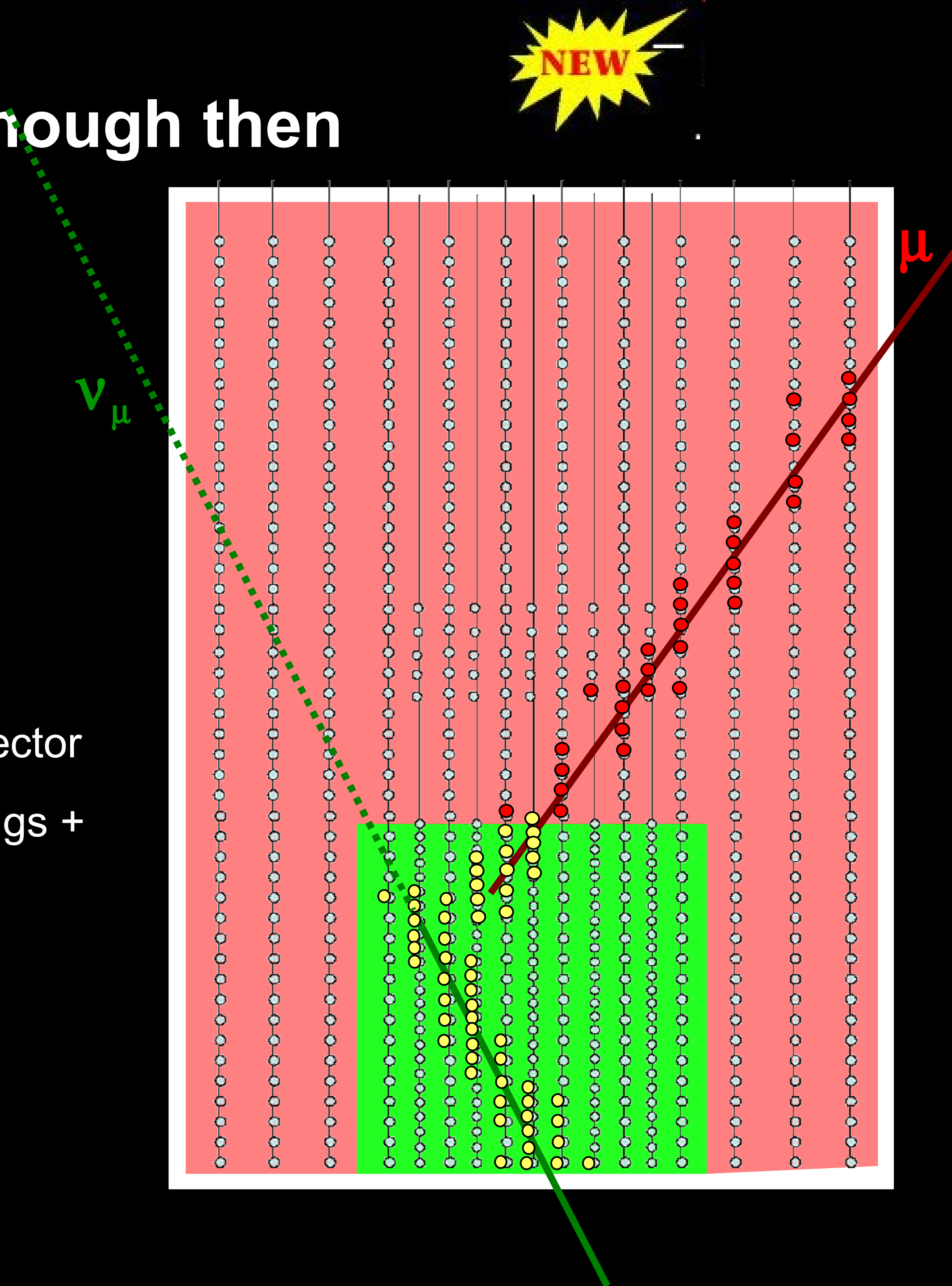
Muon Veto: outer part of the detector

Fiducial volume: Deep Core strings +

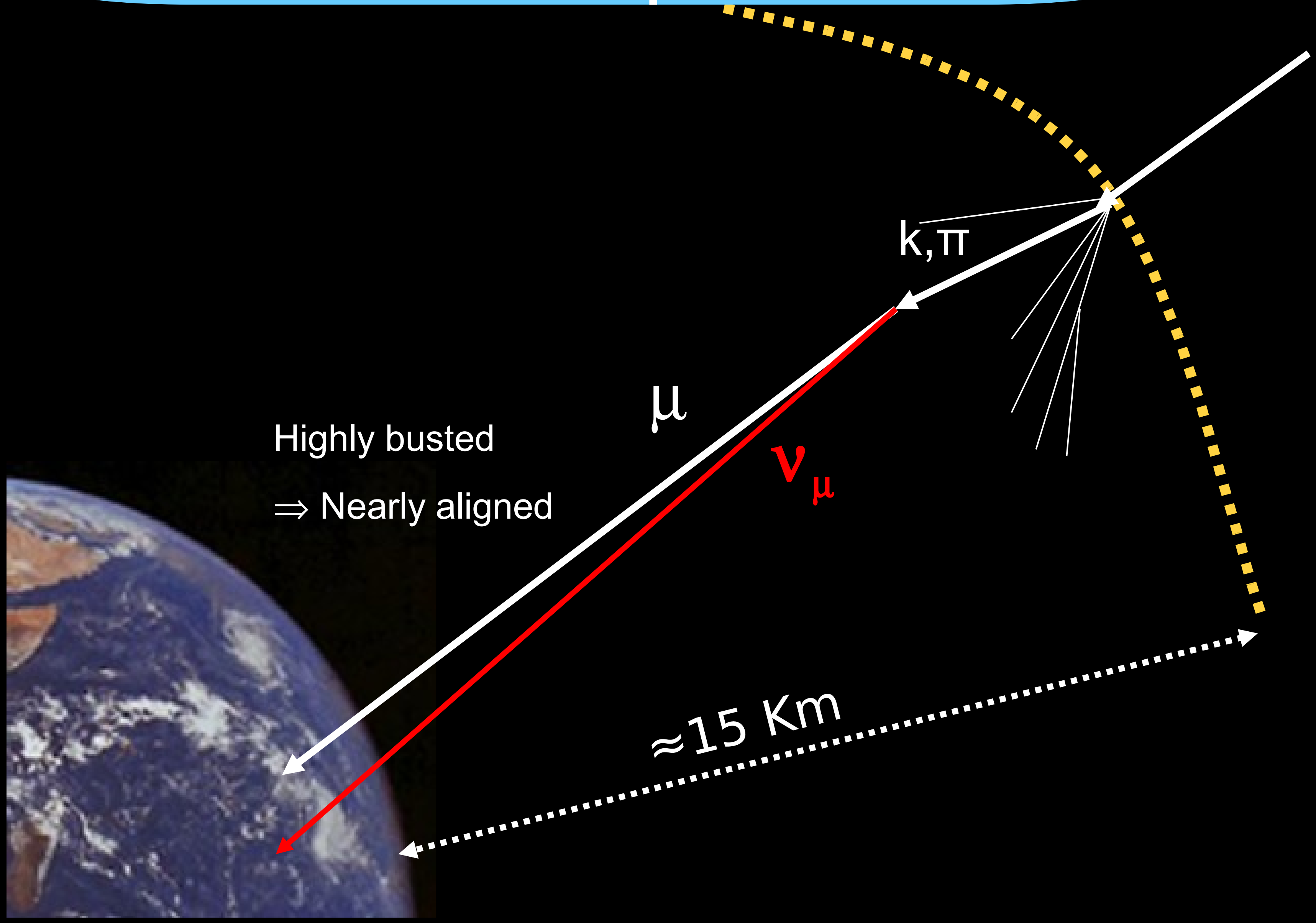
IceCube central strings

Status in IceCube, Deep Core

Muon Veto: feasible!



…. AND veto Atmospheric Neutrinos



…. AND veto Atmospheric Neutrinos

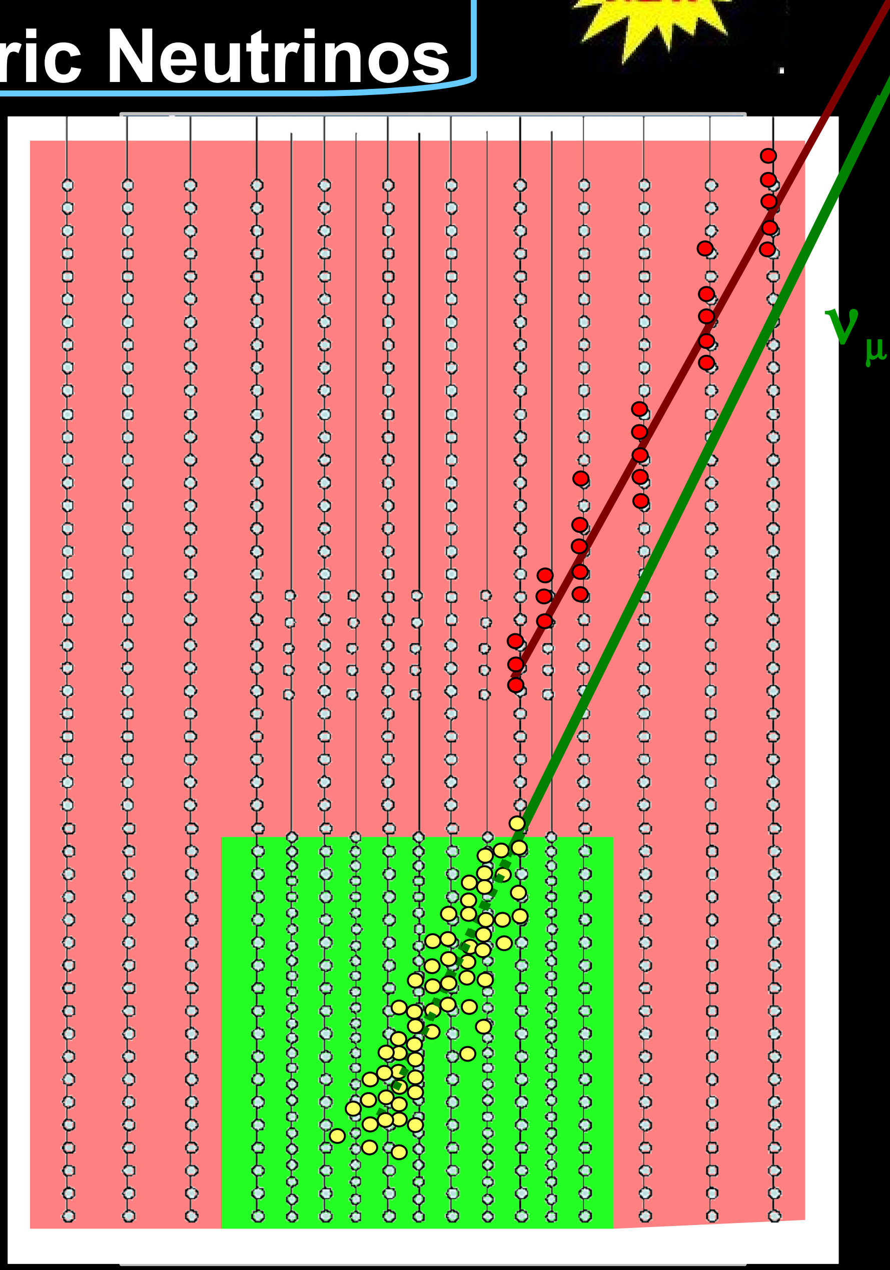
NEW

Strategy:

Muon Veto: will veto atmospheric neutrinos

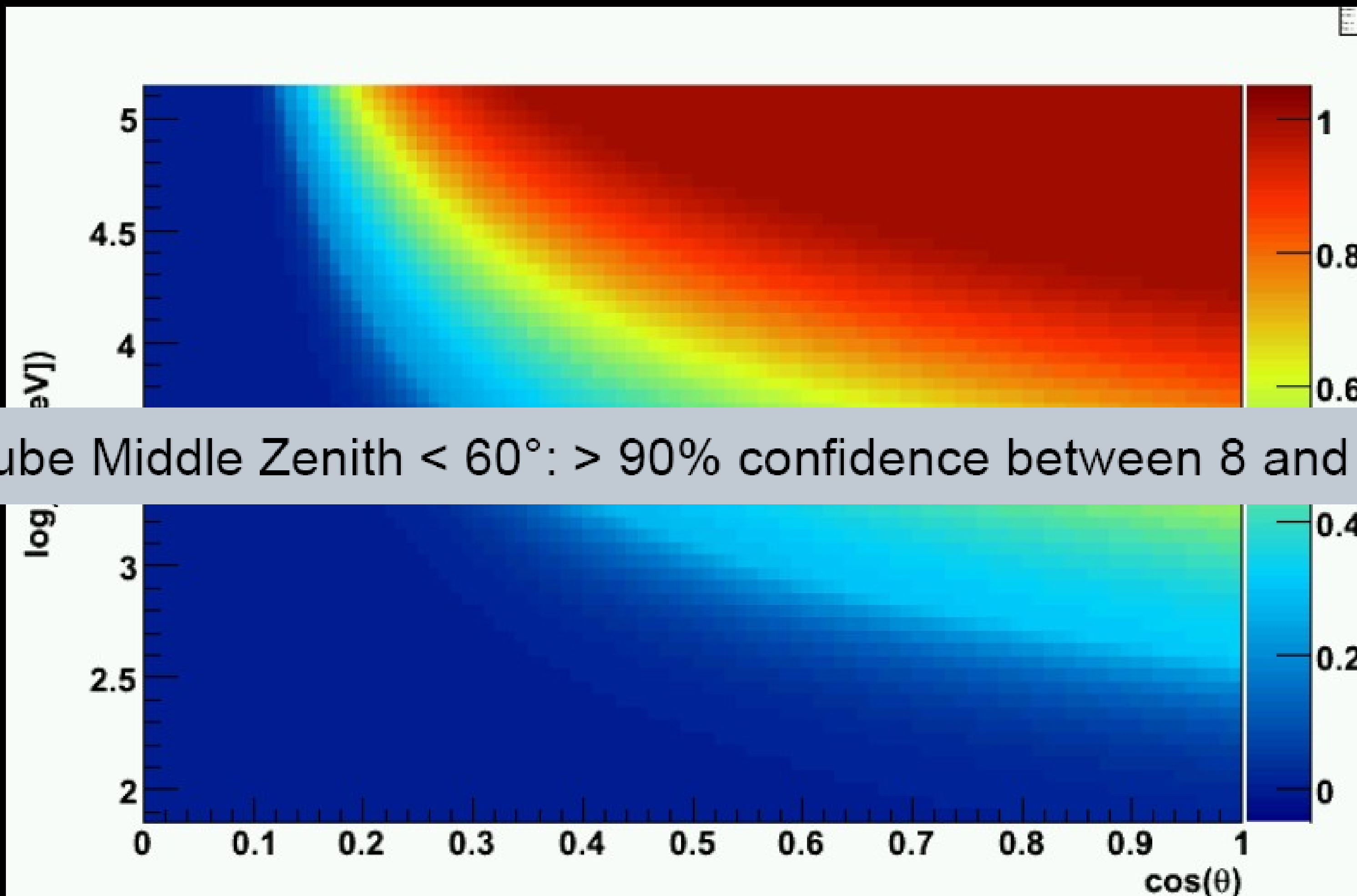
Status:

MonteCarlo study, analytical calculation



…. Atmospheric Neutrinos Veto Probability

Depth: 1800 mwe



IceCube Middle Zenith < 60°: > 90% confidence between 8 and 23 TeV

S.Schönert, T. Gaisser, E.R., O. Schulz, PRD79, 043009 (2009)

Neutrino Astronomy: history I

•First estimations of atmospheric and astrophysical HE (E ~ 1-1000 GeV) neutrino fluxes had been carried out in 1958-1960 by Markov and Greisen, Reines.

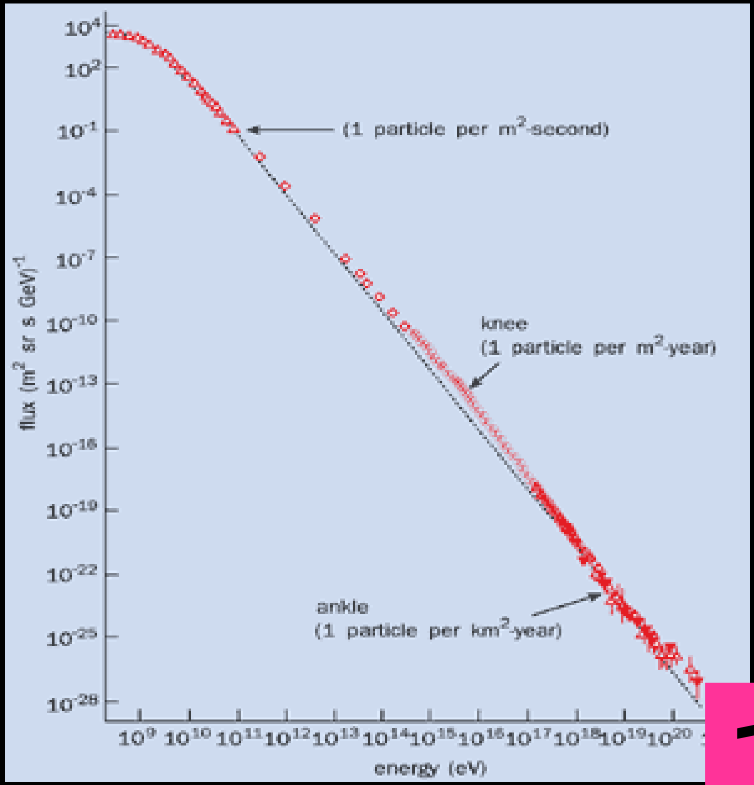
•Fluxes of HE atmospheric neutrinos are higher than astrophysical ones produced by standard Cosmic Rays.

But: productive astrophysical neutrino sources might exist !

•Markov proposed neutrino detection in open water. In 70th it was understood that kiloton HE neutrino telescopes which were under construction (Baksan et al) would not be able to register HE cosmic neutrinos.

•1975: Fred Reines, John Learned, Arthur Roberts, Vic Stenger et al – idea of Gigaton underwater HE Neutrino Telescope (DUMAND).

Neutrino Telescope: how big ?



Upper bound on HE ν:
→ 100 % protons energy in π
→ ν energy loss due to redshift
→ Redshift evolution (QSO)

⇒ Waxmann-Bahcall limit
$E\nu^2\, dN/dE\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
~ 2×10^{-8}

AMANDA-II 4yr sens. ~ 1.1×10^{-7}
1km^3 1yr sens. ~ 10^{-9}

1 km^3 detector ?

Neutrino Telescope: where ?

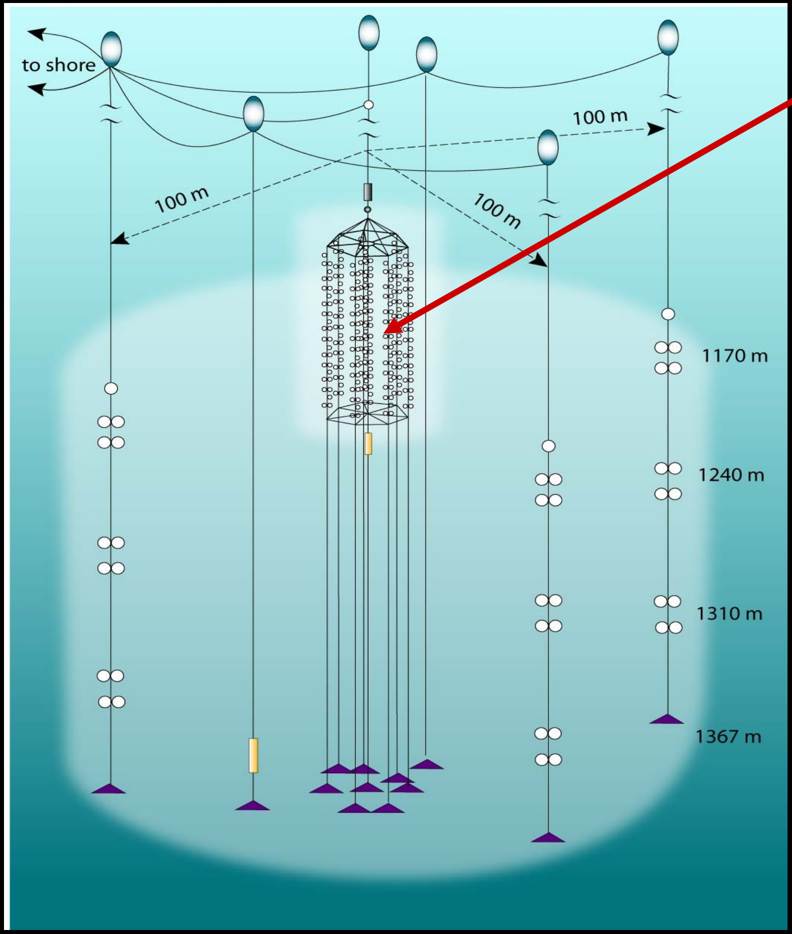
Ocean, Lakes, South Pole ice cap

Neutrino Astronomy: history II

•DUMAND project never happened

•1980 - start of the Baikal Project started
•1981/83 - start of environment investigations
•1984/90 - stationary detectors GIRLYANDA : 12..36 FEU-49B, 270 days of life time totally
•1988 - project for the second stage detector NT-200 (Neutrino Telescope with 200 PMTs) started to be envisaged
•1991 - the first species of the hybrid mushroom-shaped phototube QUASAR-370 (370 mm diameter)
•1993/97 NT-36, NT-72 and NT-96 arrays - life time 700 days
•1997 NT-144 detector with 144 optical modules on 6 strings
•1998 NT-200 (192 optical modules on 8 strings) completed.
•2005 NT-200+ (3 new strings)

Neutrino Telescopes: Baikal



NT-200

- 8 strings/192 optical modules
- 72 m height, 1070 m depth
- Effective area >2000 m² (E_{μ}>1 TeV)
- Running since 1998

NT-200+

- Commissioned April 9, 2005
- 3 new strings, 200 m height
- Optimized for 20 TeV-10 PeV cascades

The Baikal Collaboration

- **Institute for Nuclear Research, Moscow, Russia.**
- **Irkutsk State University, Irkutsk, Russia.**
- **Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia.**
- **DESY-Zeuthen, Zeuthen, Germany.**
- **Joint Institute for Nuclear Research, Dubna, Russia.**
- **Nizhny Novgorod State Technical University, Nizhny Novgorod, Russia.**
- **St.Petersburg State Marine University, St.Petersburg, Russia.**
- **Kurchatov Institute, Moscow, Russia.**


13:11:32

Neutrino Astronomy: Antares

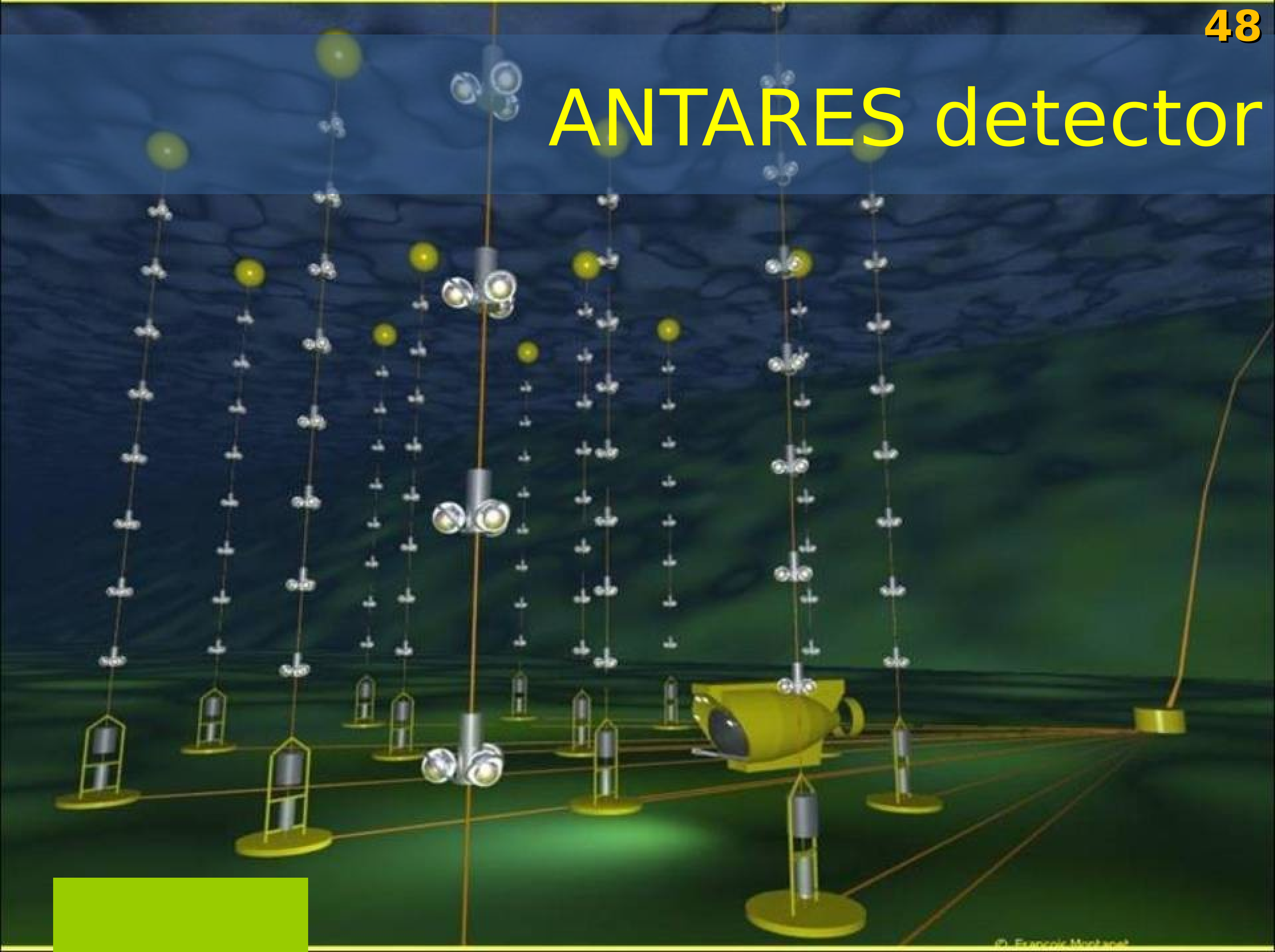
see

May 2008

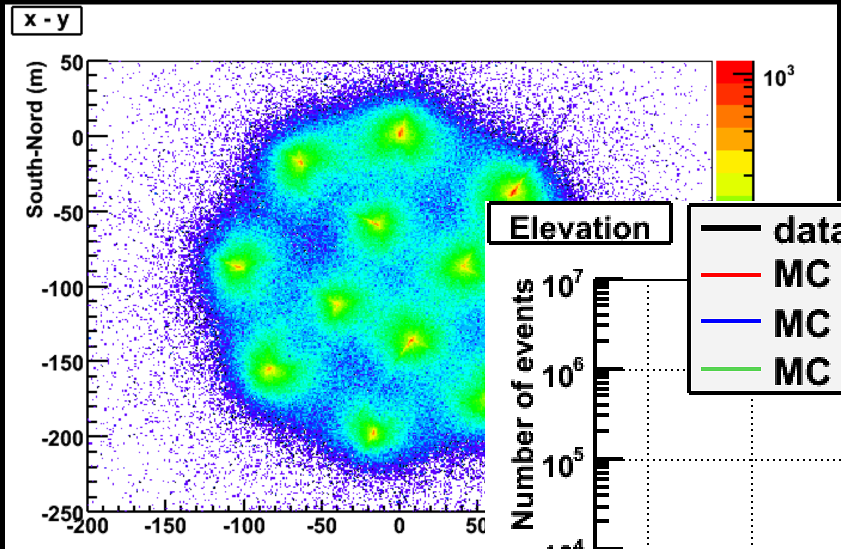
line for

rs

ANTARES detector

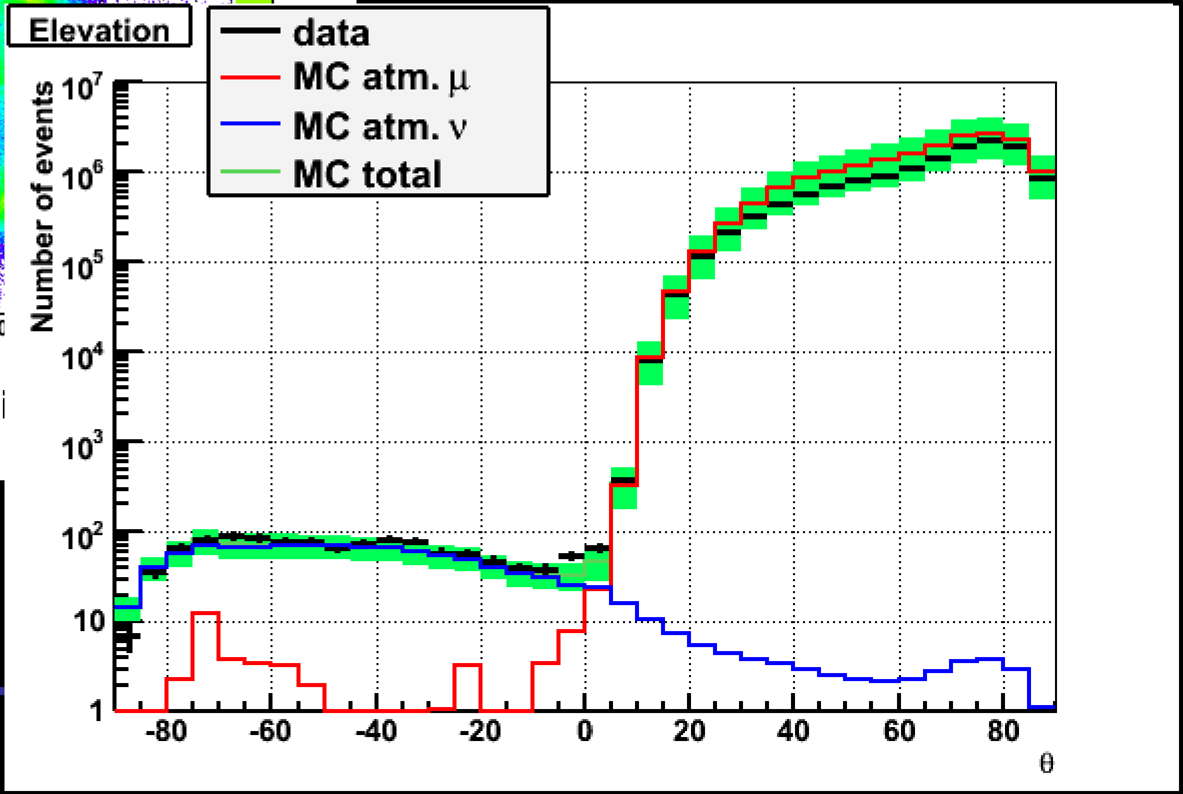


Neutrino Astronomy: Antares



Footprint of the 12-li
atmospheric

5 lines results ready soon



Neutrino Telescope @ South Pole

South Pole IceCap:

- Ice cap holds over 90% of the world's fresh water in a frozen state

- The average thickness is over 2,500 metres (2,800 m, South Pole)

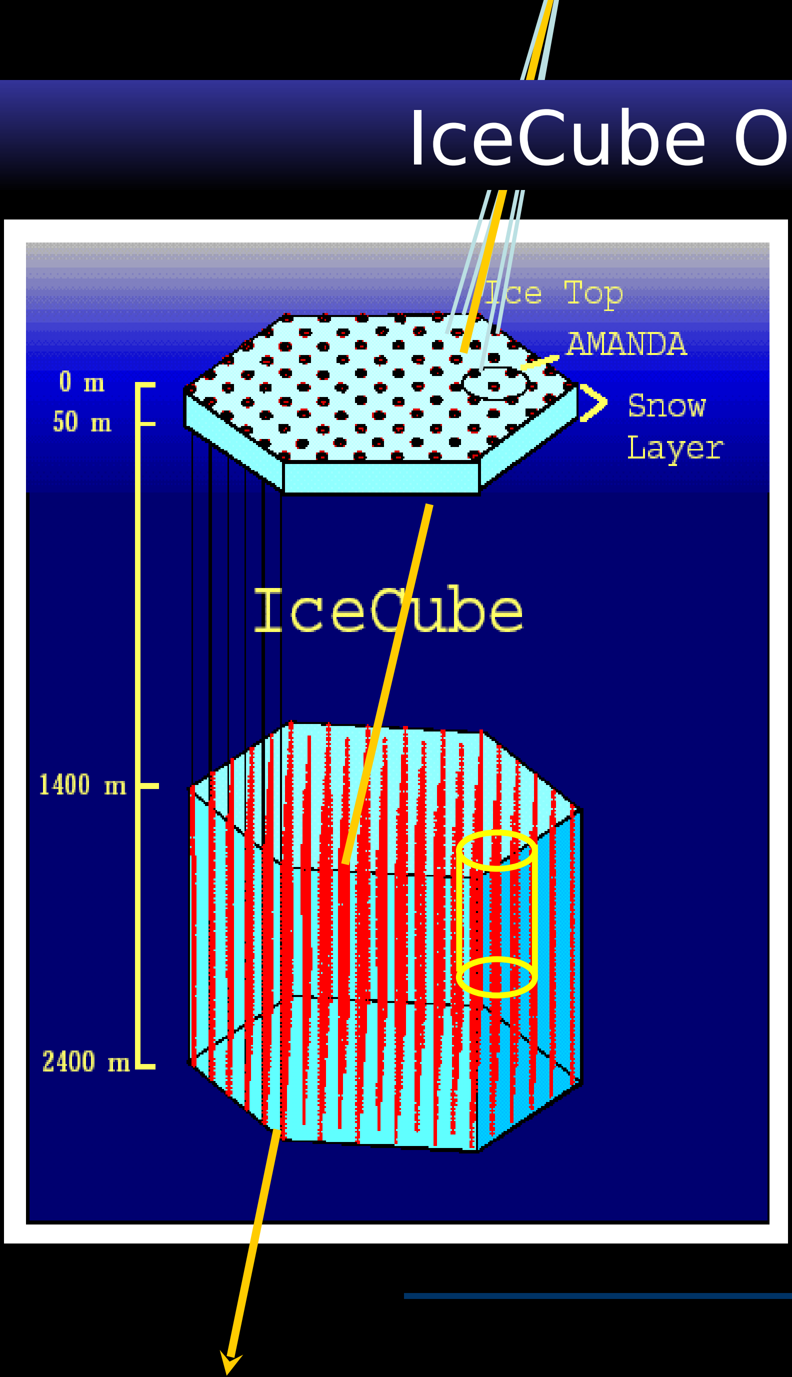
- The first South Pole base was Amundsen's tent (1912). Latest construction in 2004.

NASA. Catalog # PIA00728

Amundsen-Scott South Pole Station

American research station at Earth's South Pole

IceCube Observatory



Deep Ice Array

- A_{eff} > 1km^2 [10 TeV – PeV]
- 80-86 strings
- 59 string deployed

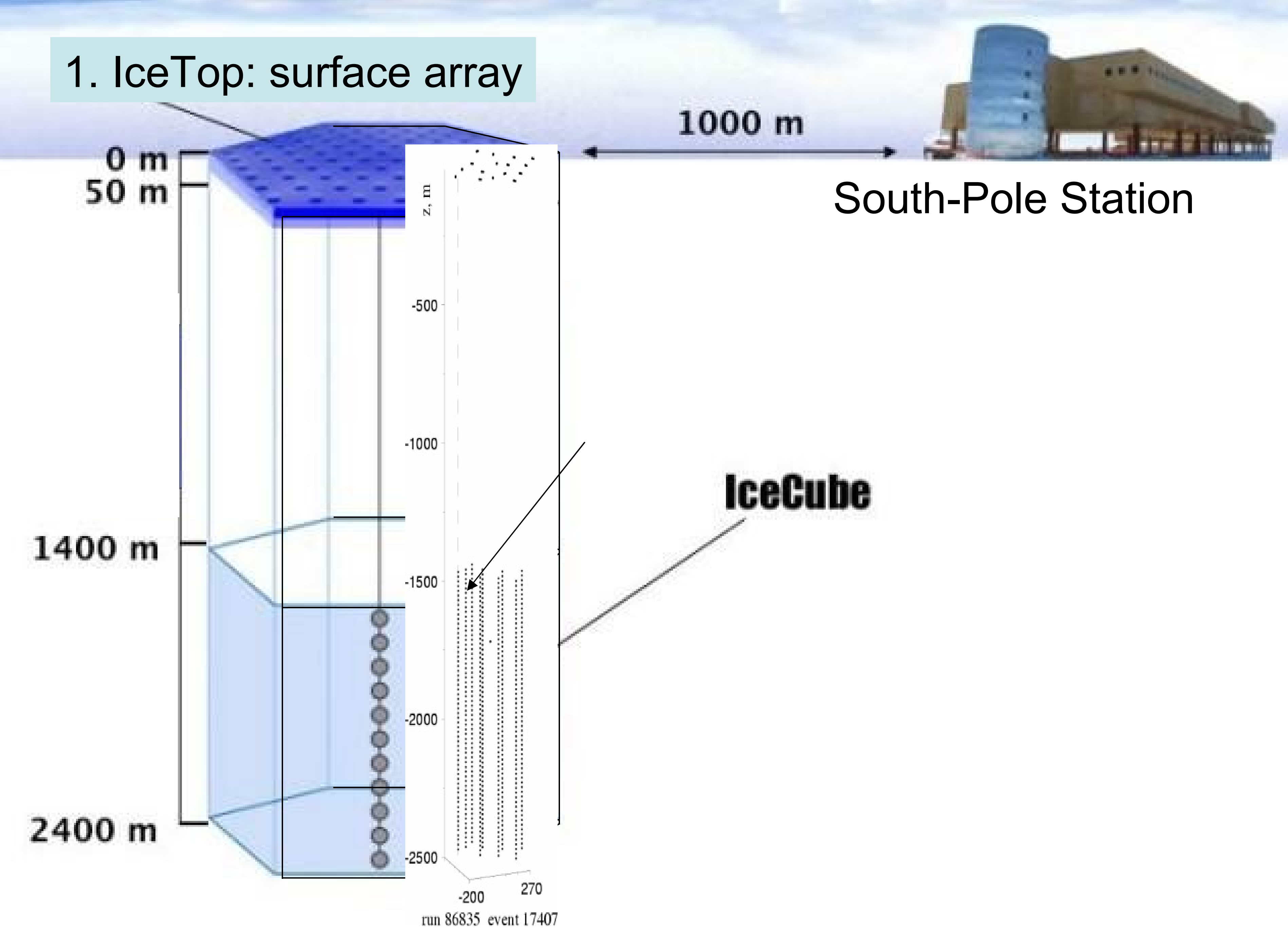
IceTop

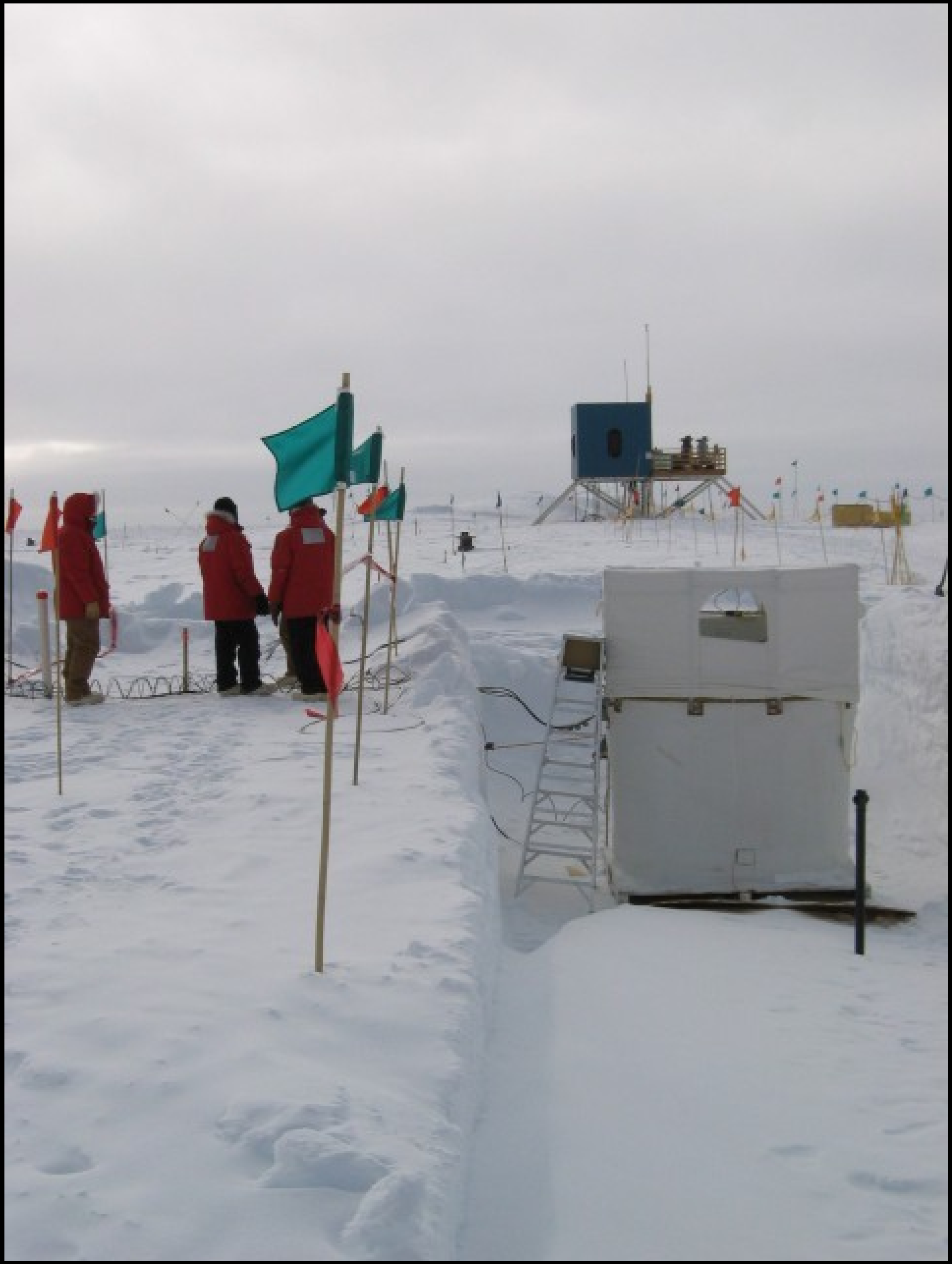
- Cosmic-ray physics from “knee” to “ankle” (20 stations)

Deep Core

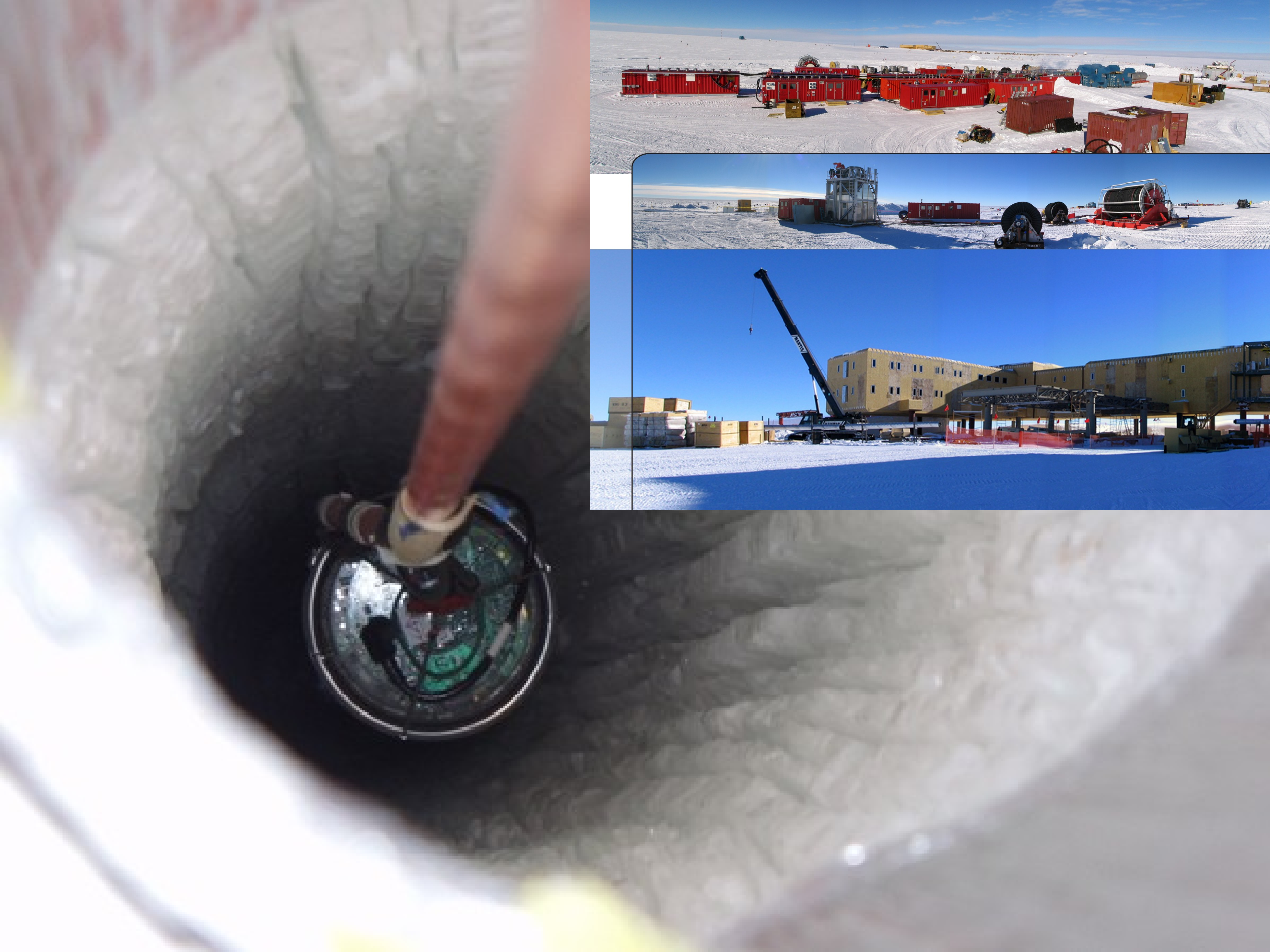
- A_{eff} > 0.01 km^2 [100 Gev – 100 TeV]
- 6-8 strings
- First string deployed 08-09
- Ready 09-10

Elisa.Resconi@mpi-hd.mpg.de


1. IceTop: surface array
1000 m
South-Pole Station
0 m
50 m
1400 m
2400 m
IceCube
z, m
-500
-1000
-1500
-2000
-2500
-200
270
run 86835 event 17407



IceTop tank under filling



Summary 2

A neutrino telescope:

- is a matrix of phototubes in a transparent material

- it has to be BIG

- detects Cherenkov light

- looks down (but we are working on that …)

- 3 Projects:
  Baikal, Antares, IceCube

- Under discussion: km3Net

Content

1. Cosmic Particles Flow Chart

2. Neutrino Telescopes

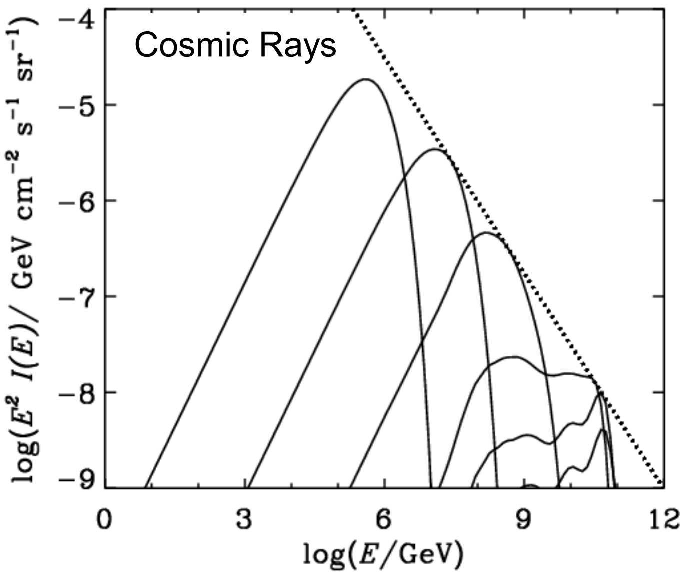
3. The Hunt for Neutrino Sources

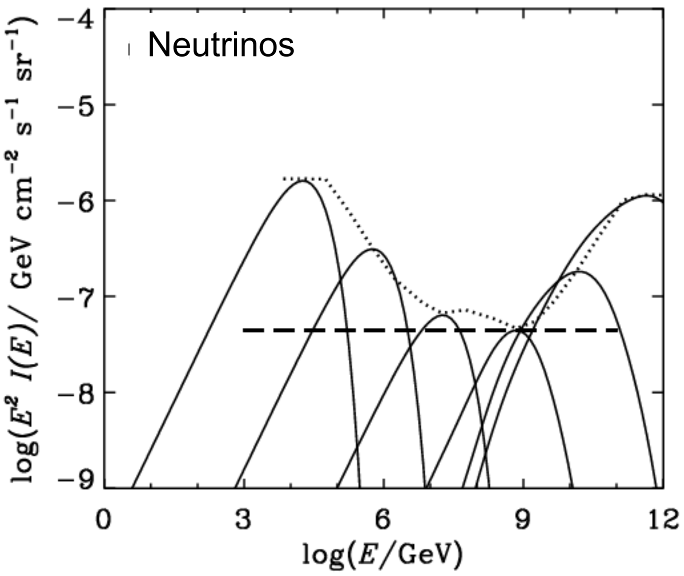
   - multi-wavelength

CR - ν Connection
Diffuse Flux

Proton luminosity ⟶ Upper bound HE ν flux

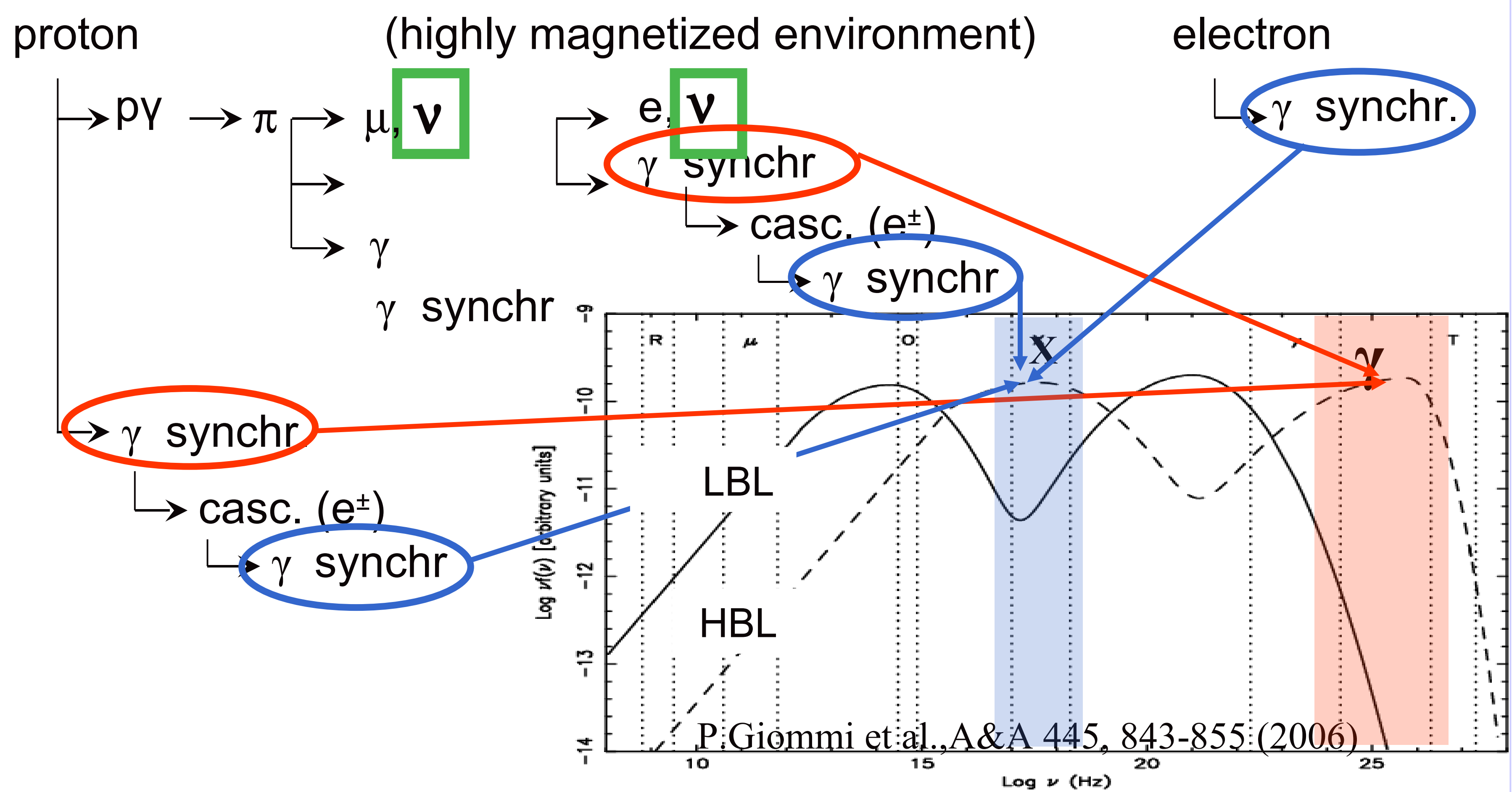
K. Mannheim, R.J. Protheroe, J. P. Rachen, Phys.Rev. D63 (2001) 023003



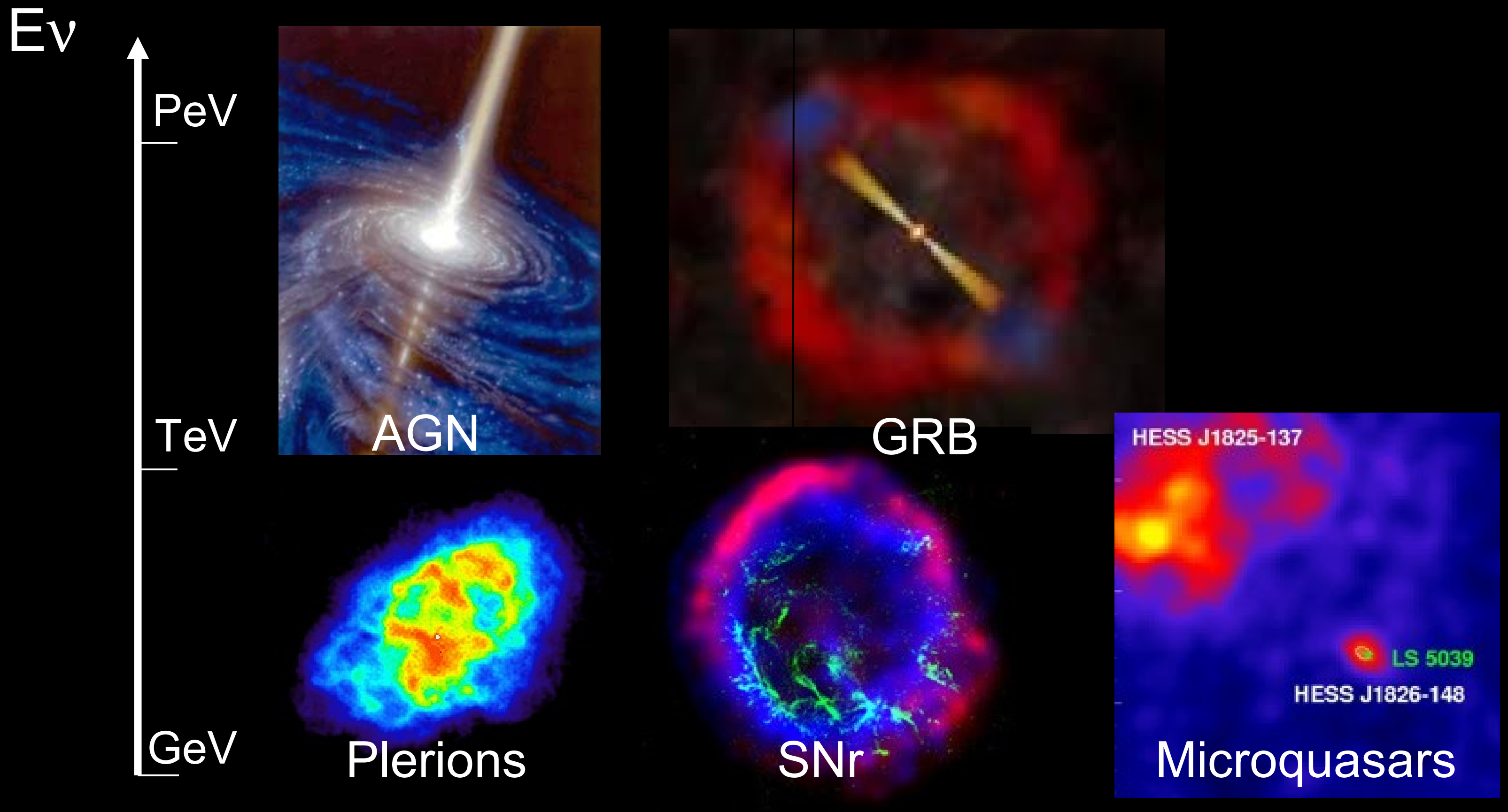


CR - γ - ν Connection
Point Sources

Synchrotron proton blazar model (ref. A. Mücke et al, Astroparticle Phy, 18 (2003) 593-613)



ν candidate sources



Neutrino Astronomy

$$\Phi_\nu (E, \Omega) = \Phi_{atm} + \Phi_{galactic} + \Phi_{extra\text{-}galactic}$$

Cosmic ray showers in
the Earth's atmosphere:
- π, K decay

$\propto E^{-3.7}$
~ 20% uncertainty

"diffuse" flux:
CR interaction with
interstellar gas

"point-like":
galactic sources

$\propto E^{-2 \pm ?}$

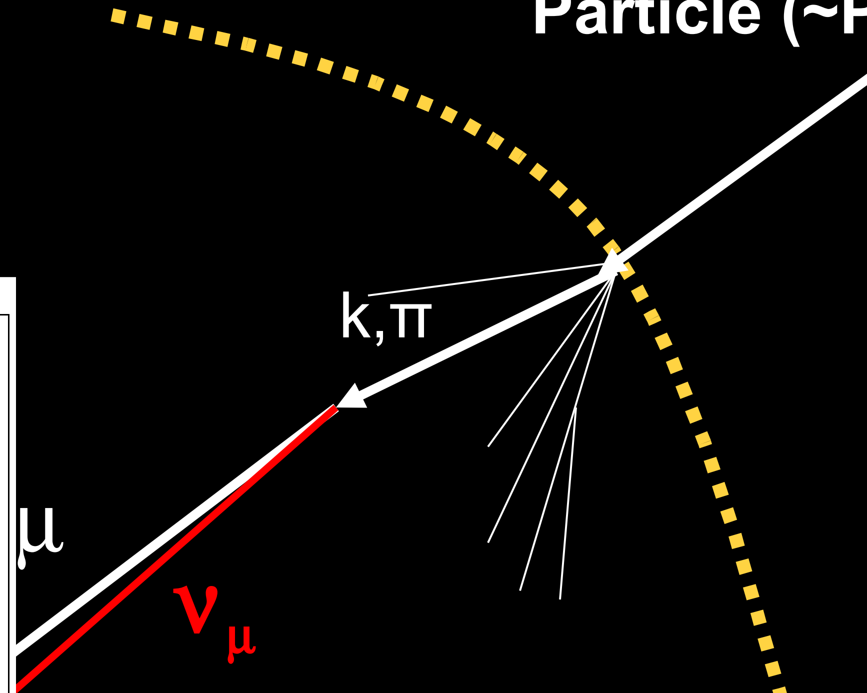
"diffuse" flux:
$p\gamma$ interaction
with 2.7°K cosmic radiation

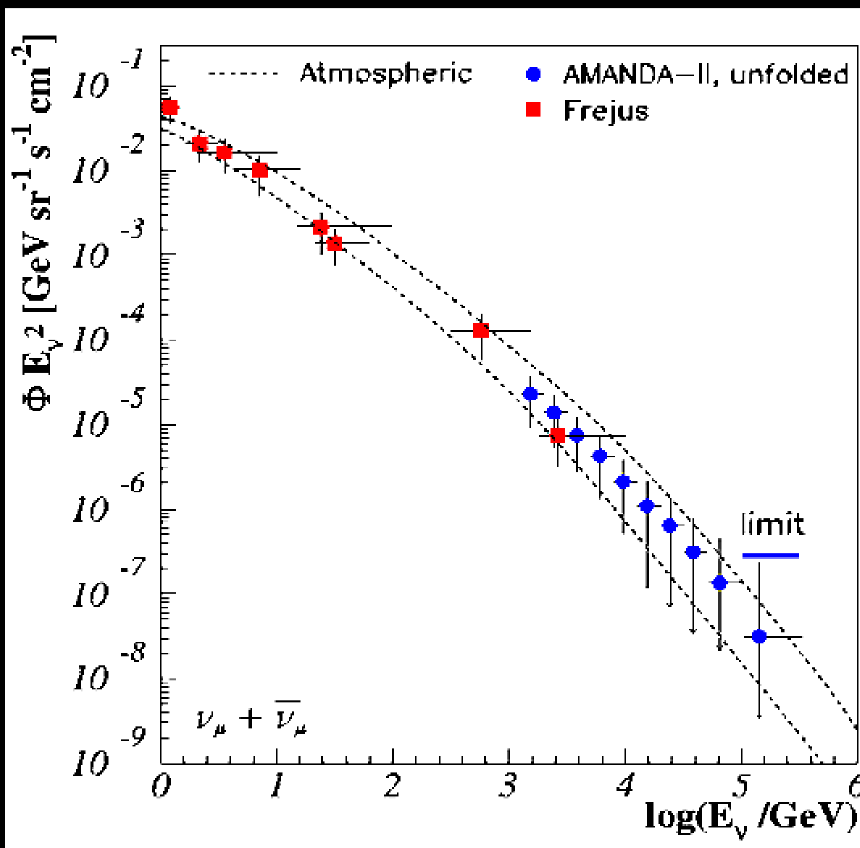
"point-like":
extra-galactic sources

$\propto E^{-2 \pm ?}$

$\Phi_{atm}(E,\Omega)$

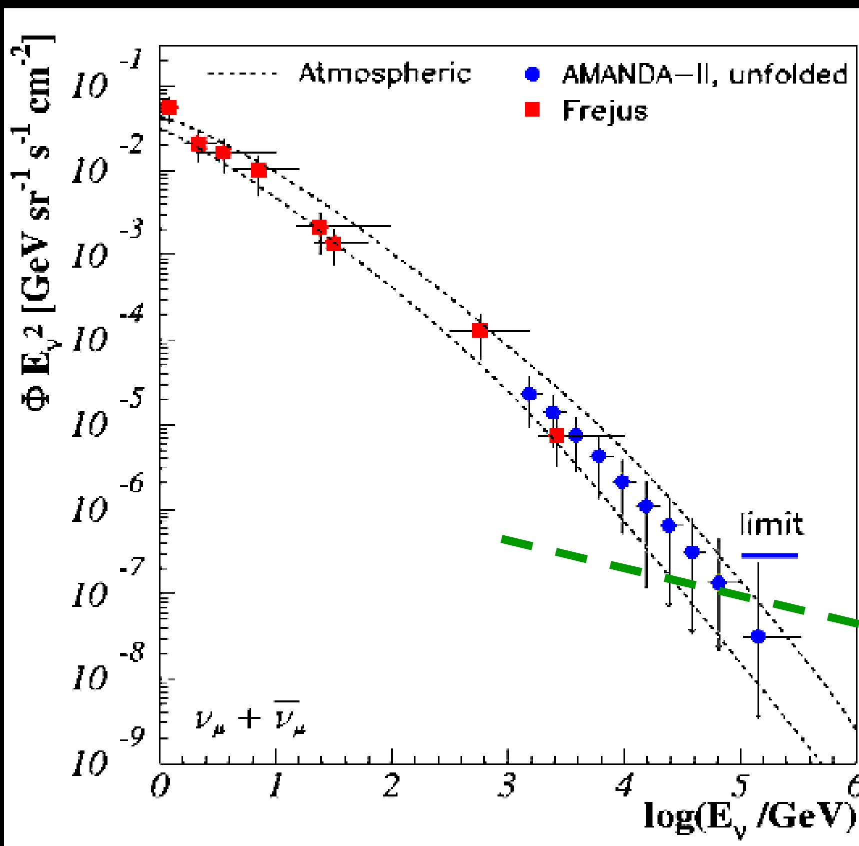
HE Cosmic Particle (~PeV)





- Declination dependence
- $E^{-3.7}$
- Uniform in time
- 20 % uncertainty on the flux prediction

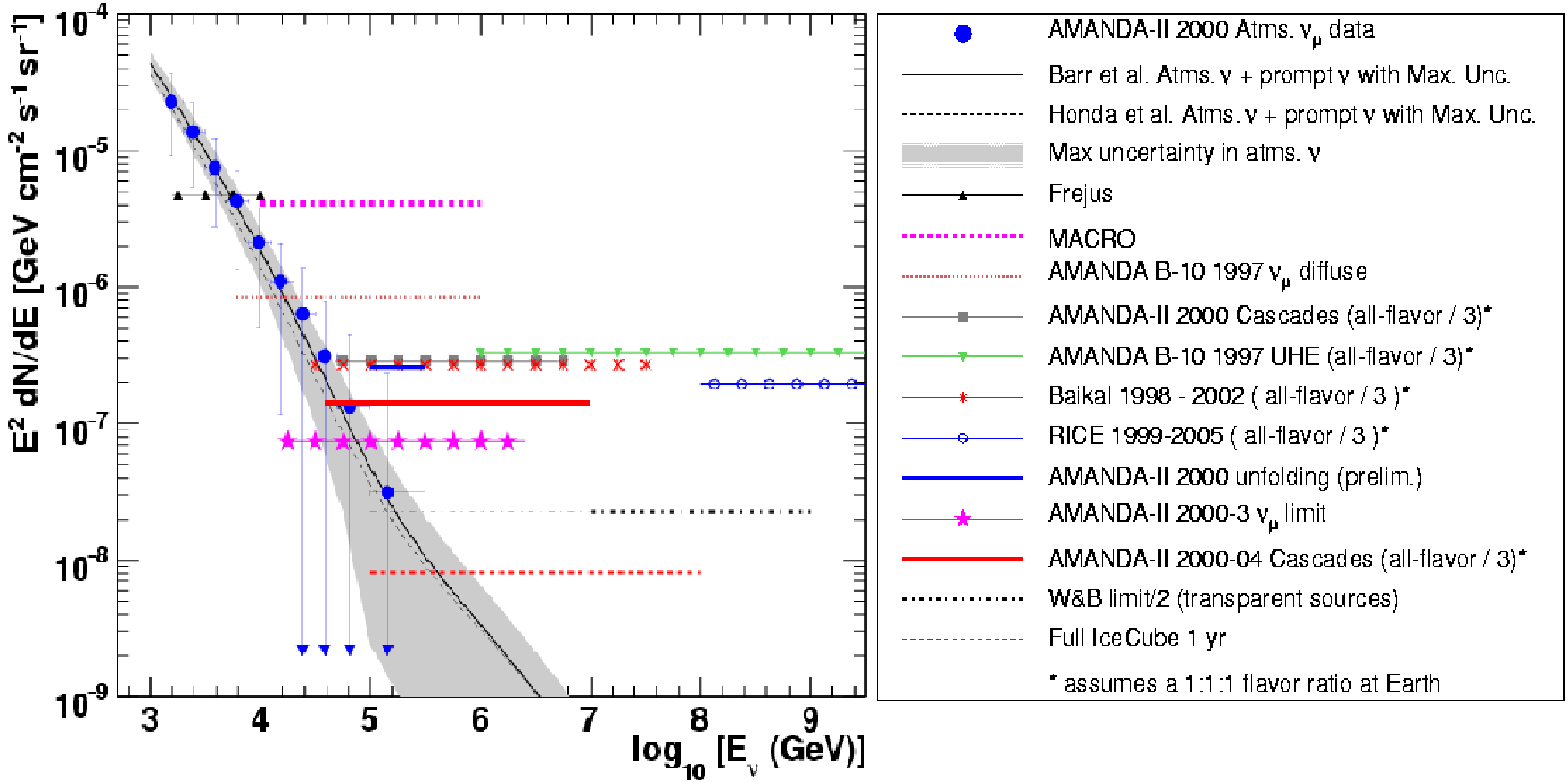
$\Phi_{atm}(E,\Omega)$ vs $\Phi_{galactic}(E,\Omega)$, $\Phi_{extra\text{-}galactic}(E,\Omega)$



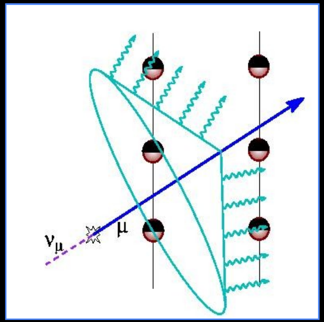
- High energy
- High statistics

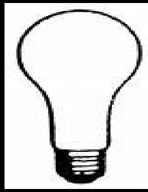
- Alternative: discriminate against atmospheric neutrino at lower energy

$\Phi_{atm}(E,\Omega)$ vs $\Phi_{galactic}(E,\Omega)$, $\Phi_{extra\text{-}galactic}(E,\Omega)$



Point Source Searches

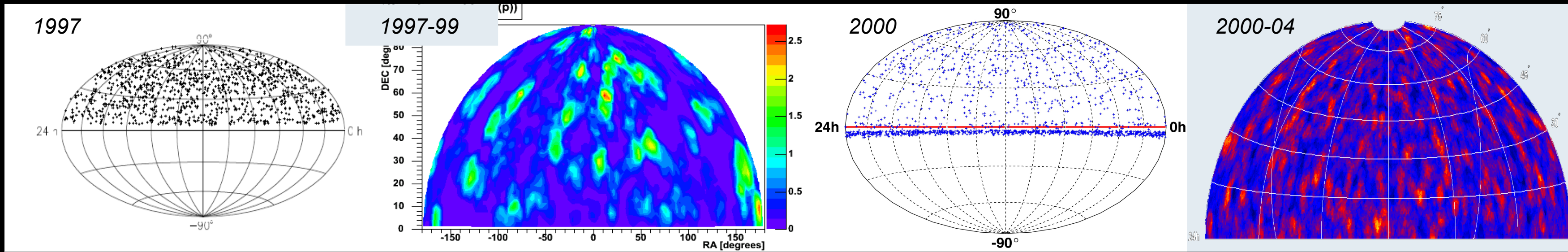




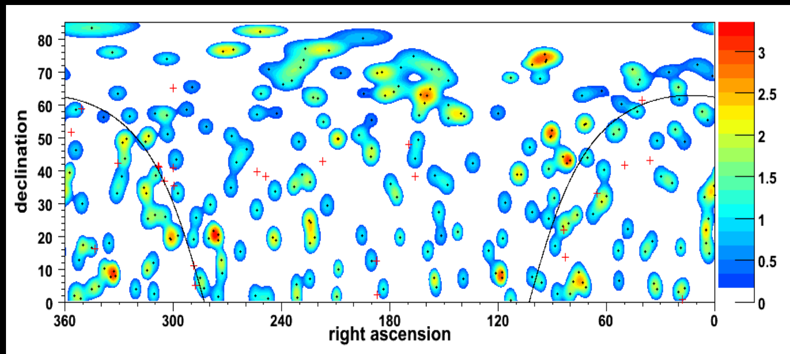
Point Source Searches

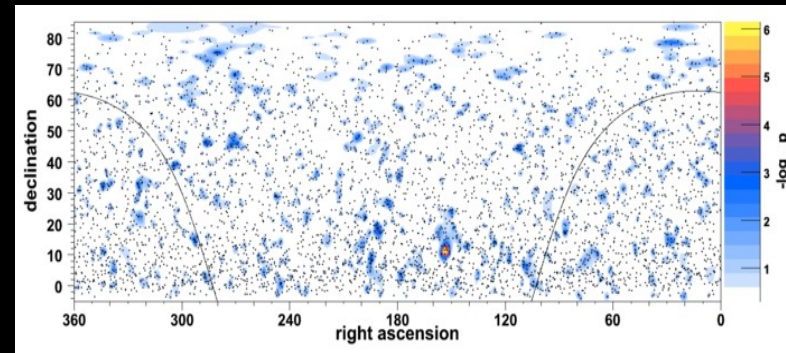
-
    - bin and
    - un-binned method
-
-

-
-



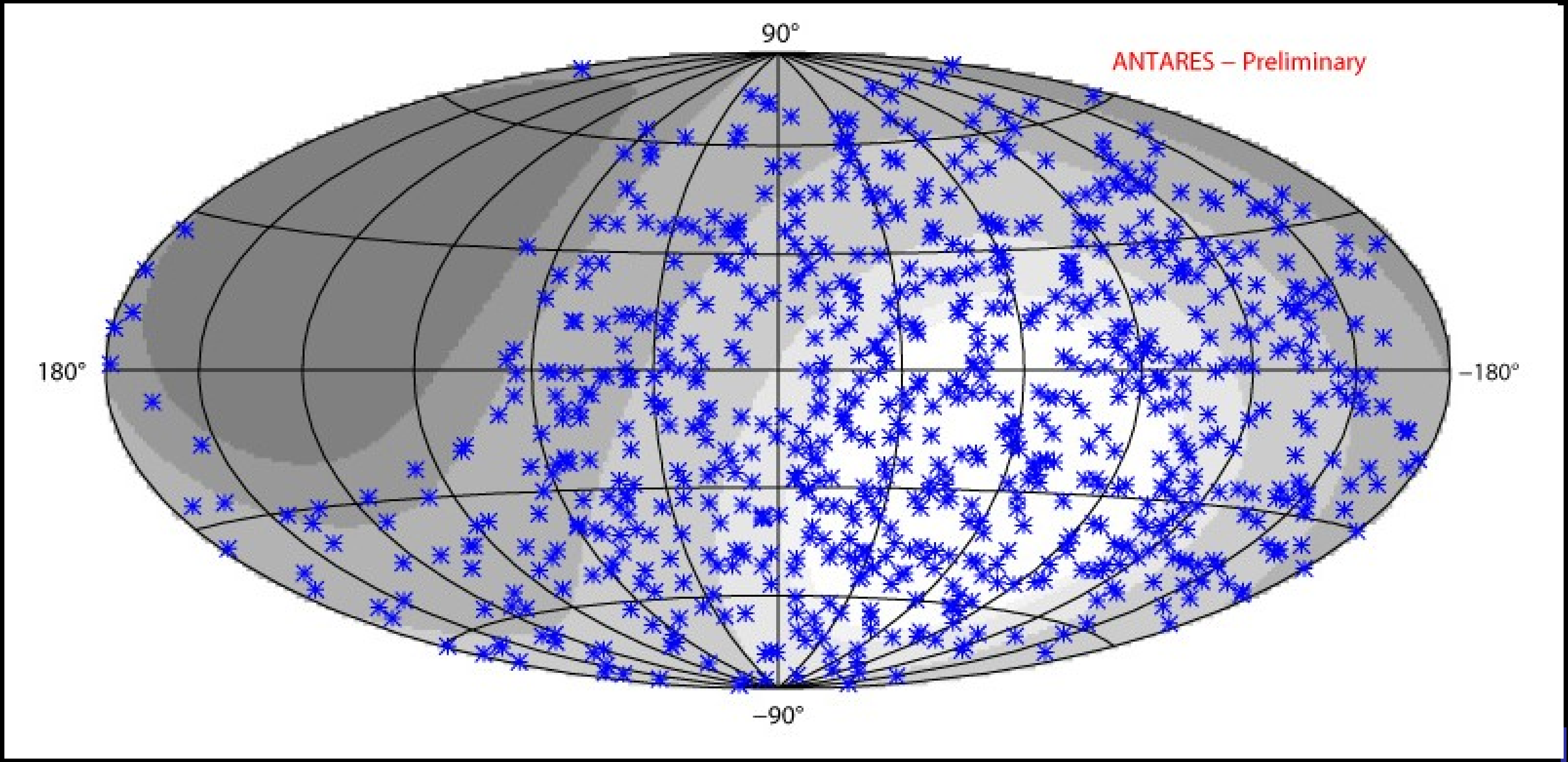
Detector	Energy Window (TeV)	Exposure Time (days)	Limit (TeV^{-1} cm^{-2} s^{-1})
AMANDA-B10 (1997-99)	~1 – 1000	623	$4.0\cdot10^{-10}$
AMANDA-II (2000-04)	1.6 - 2600 Phys.Rev.D75:102001,2007	1001	$5.5\cdot10^{-11}$
AMANDA-II (2005-06)			$7.0\cdot10^{-11}$

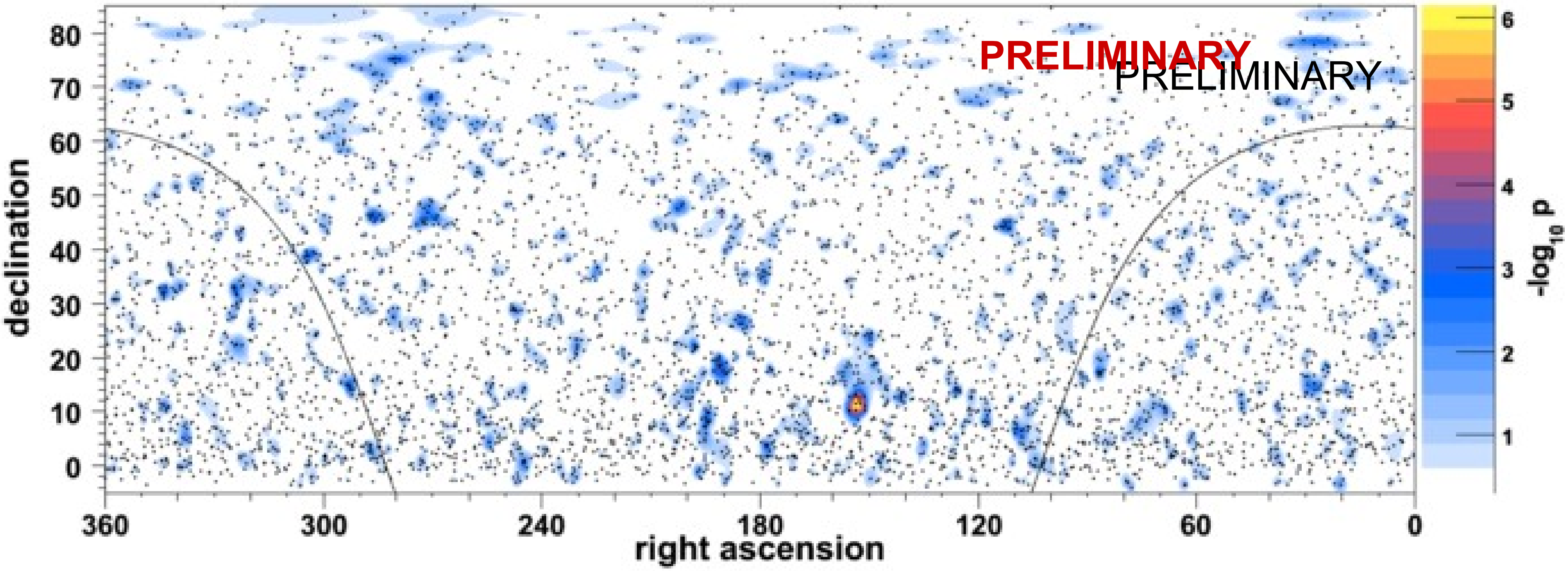


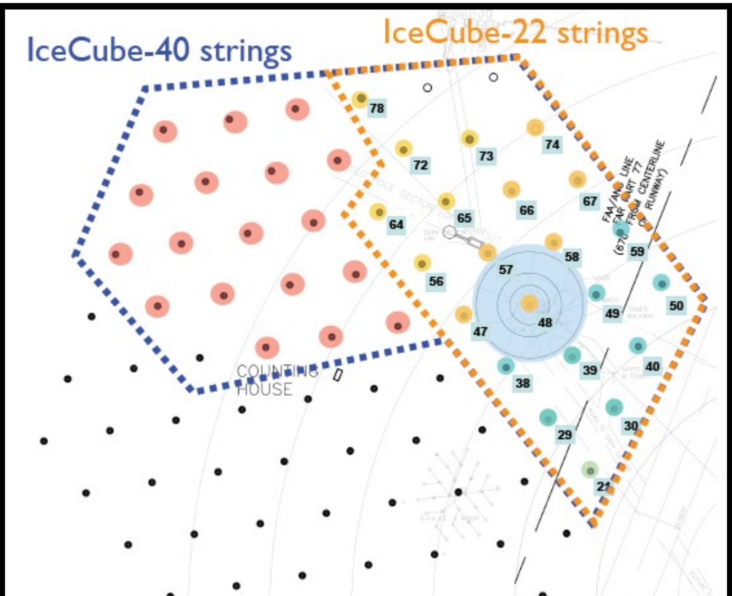


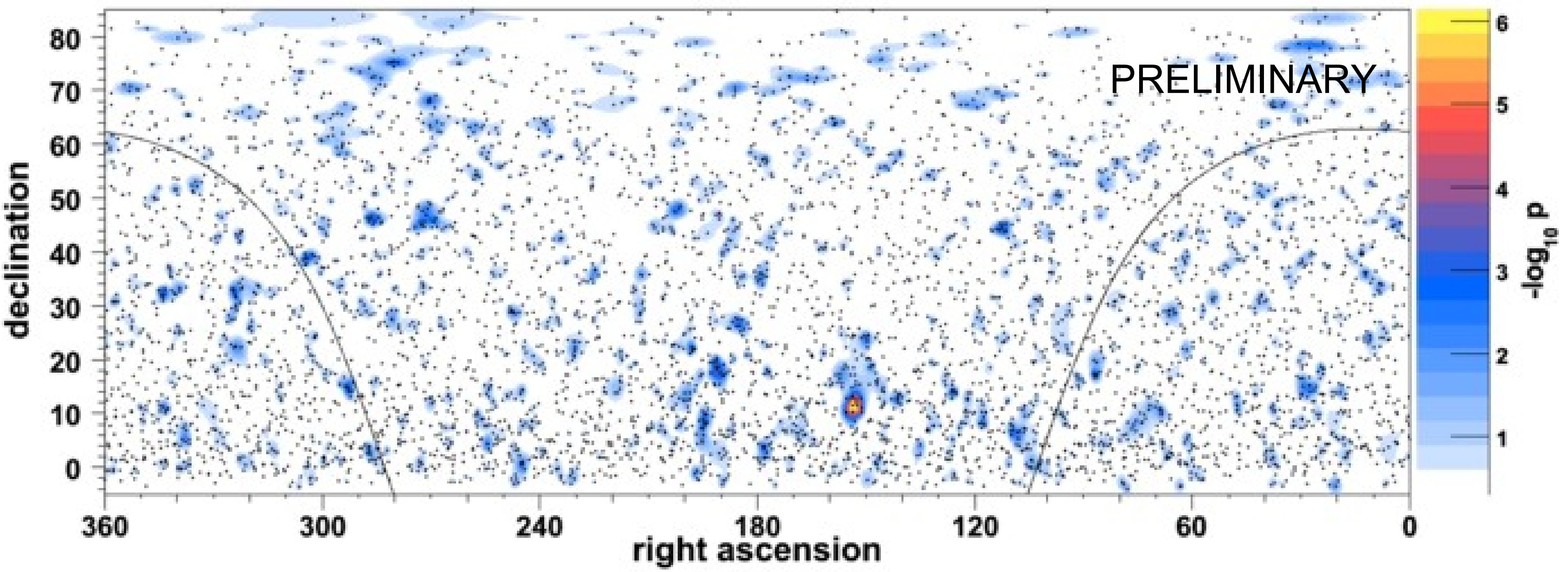
Detector	Energy Window (TeV)	Exposure Time (days)	Limit (L) Sensitivity (S) (TeV^{-1} cm^{-2} s^{-1})
IC9 (2006)	~ 5 - 1000	137	$1.2 \cdot 10^{-10}$ (L)
IC22 (2007) IC22 + AMANDA	~ 5 – 5000 ~ 0.5 - 10	240	$\sim 10^{-11}$ (S) Only for specific
IC80	~ 5 - 5000	3 years	$2 \cdot 10^{-12}$ (S)

Antares first sky-map




PRELIMINARY
PRELIMINARY
declination
right ascension
$-\log_{10} p$
80
70
60
50
40
30
20
10
0
360
300
240
180
120
60
0
1
2
3
4
5
6

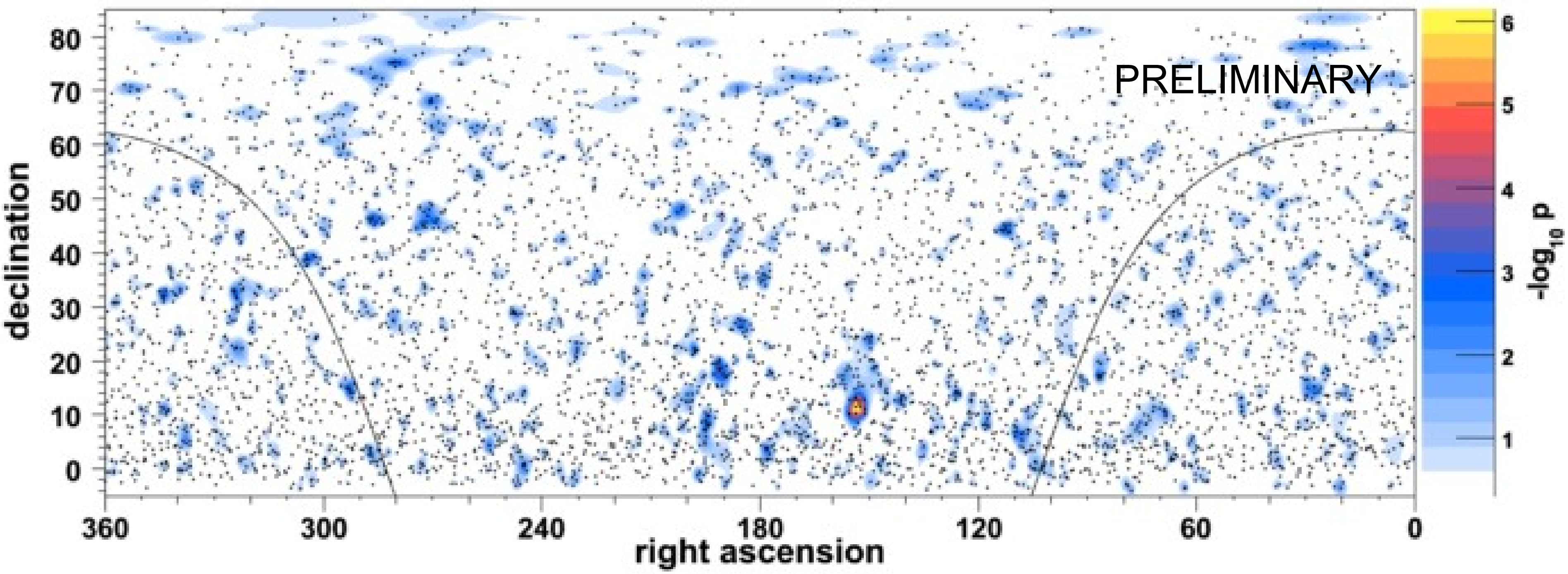

IceCube-40 strings
IceCube-22 strings
COUNTING HOUSE
78
72
73
74
64
65
66
67
56
57
58
59
47
48
49
50
38
39
40
29
30
21



$$\mathcal{S}_i = \frac{1}{2\pi{\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

individual point spread functions for each event

energy estimators (MonteCarlo)

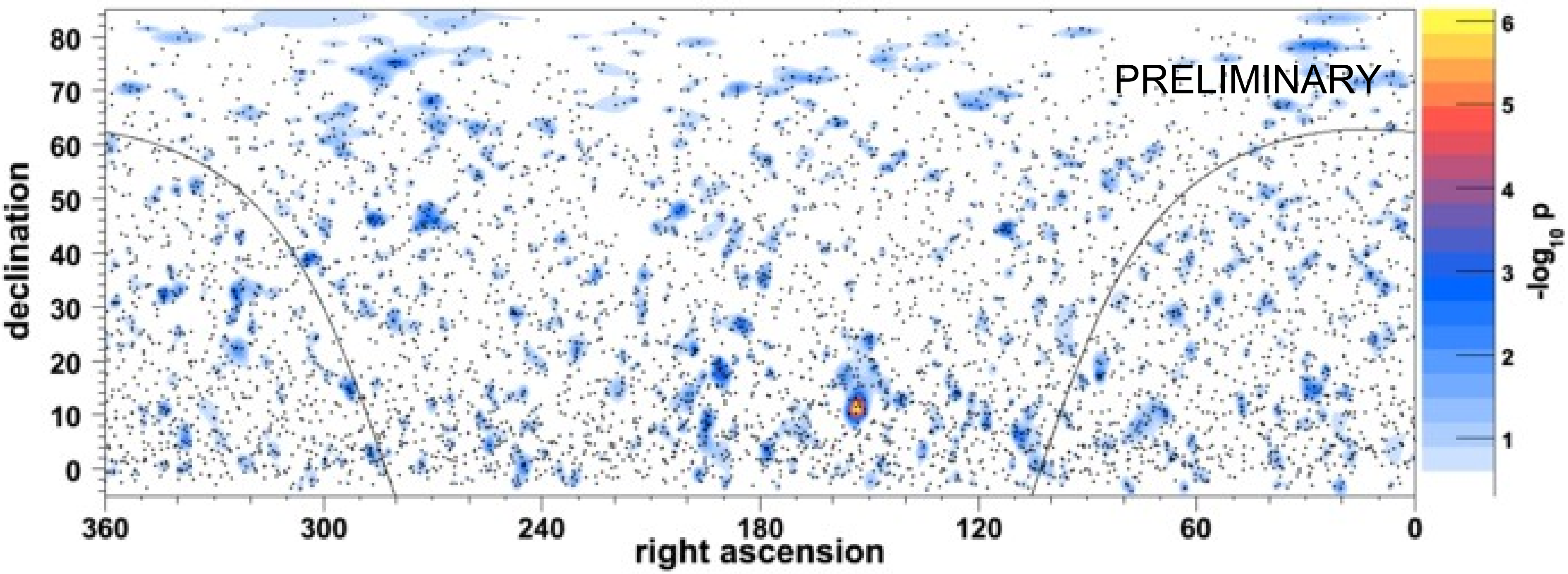


$$\mathcal{B}_i = B_{\mathrm{zen}} \cdot P_{\mathrm{atm}}(E_i)$$

data, no MonteCarlo dependences

p-values solid

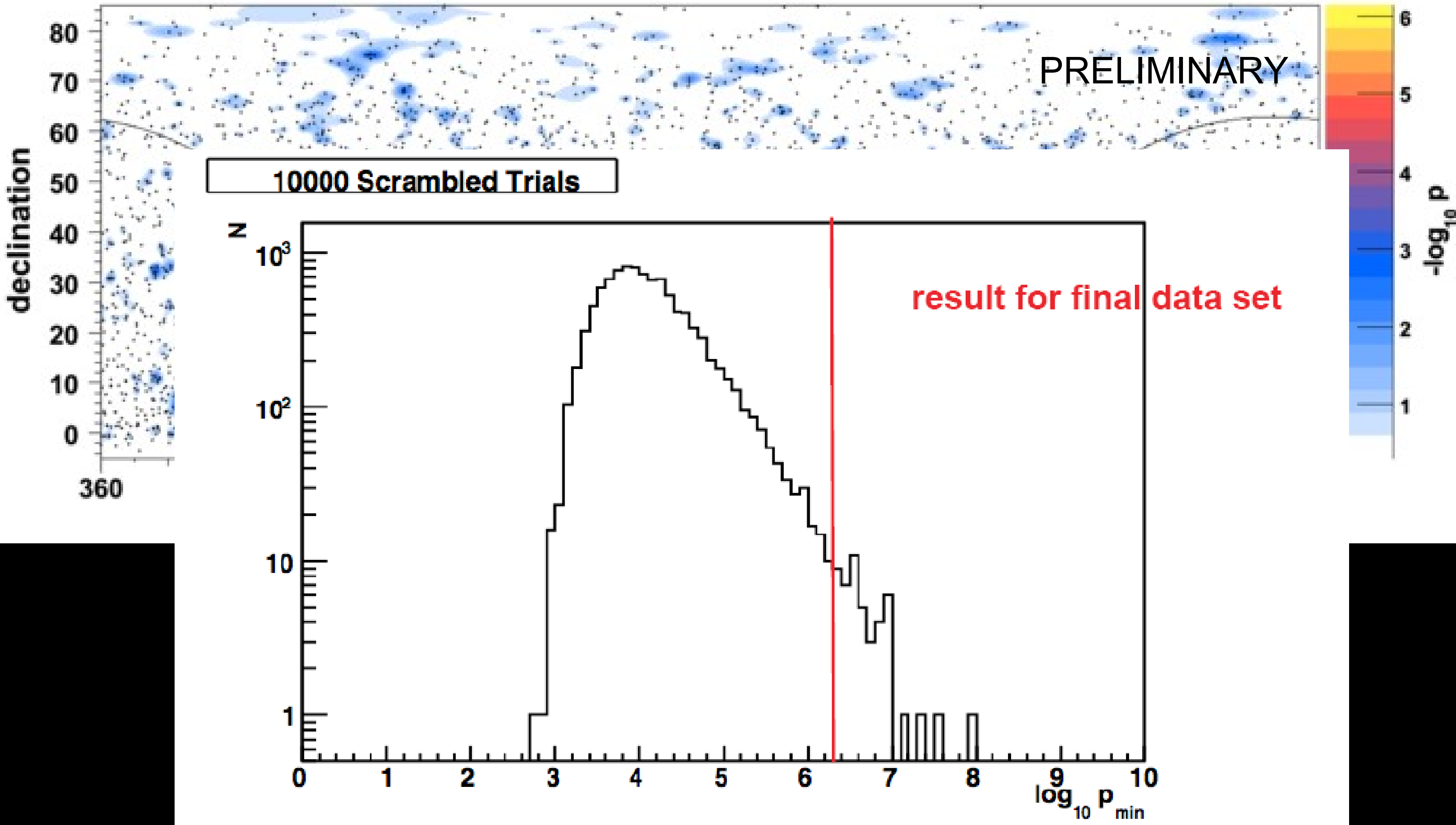
[redacted]

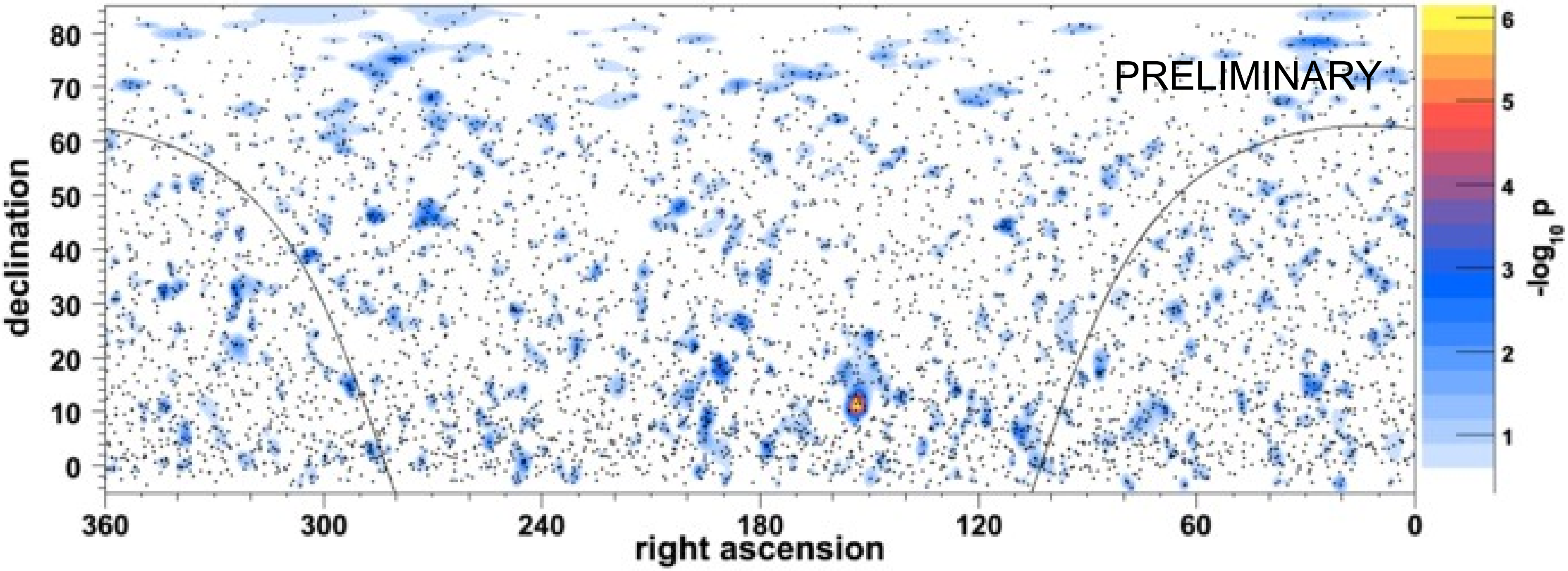


$$P_i(x, n_s) = \frac{n_s}{N} S_i(x) + \frac{N - n_s}{N} B_i(x)$$

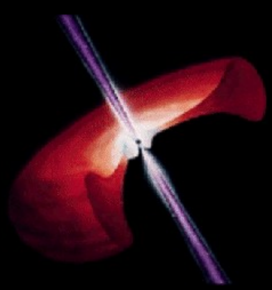
$$L(n_s) = \prod P_i(x_i, n_s)$$

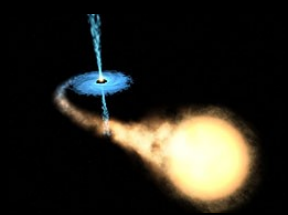
$$\log \lambda = \log \frac{L(\hat{n}_s)}{L(n_s = 0)}$$

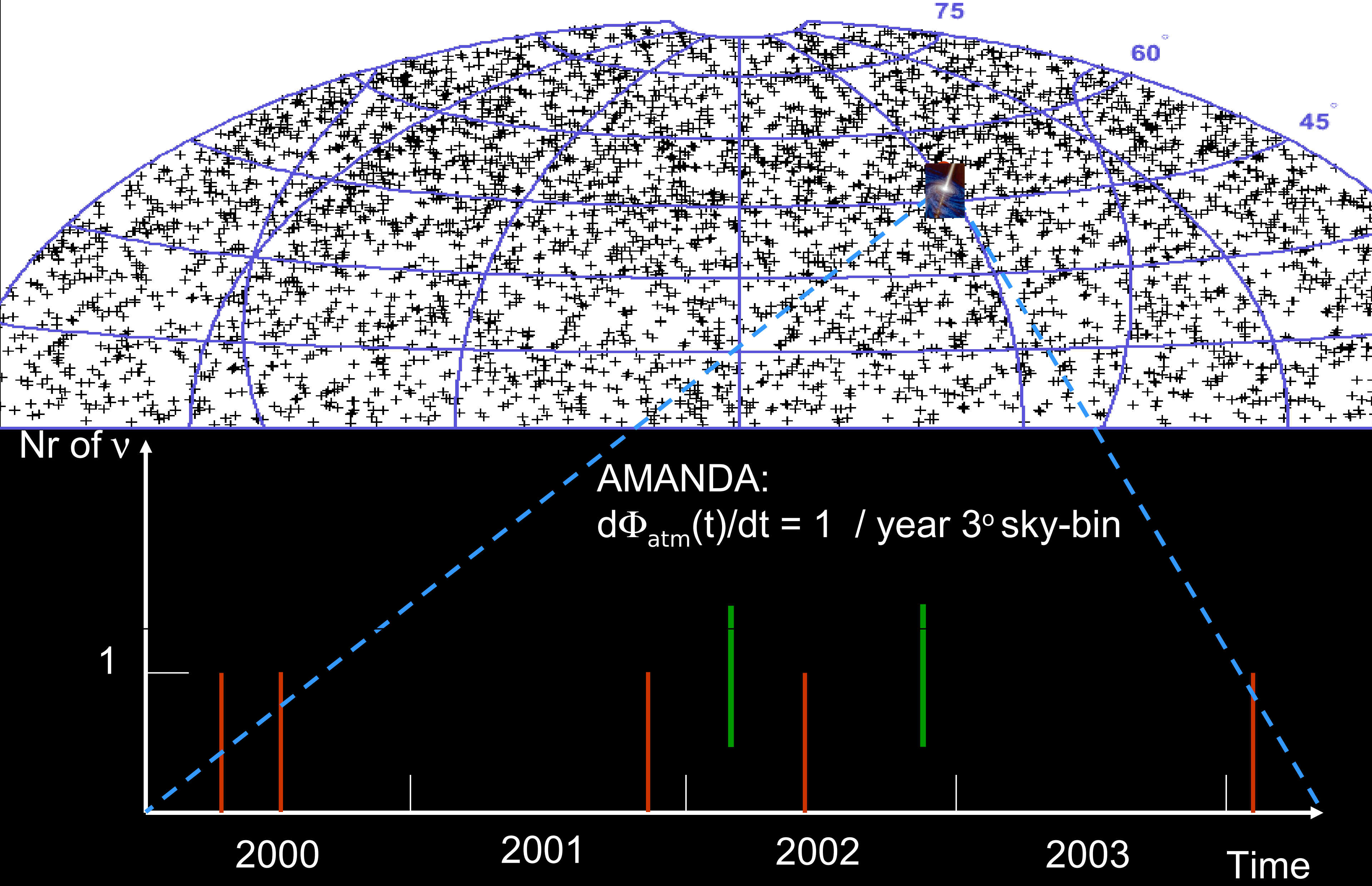

PRELIMINARY
declination
80
70
60
50
40
30
20
10
0
360
$-\log_{10} p$
10000 Scrambled Trials
N
10^3
10^2
10
1
result for final data set
0 1 2 3 4 5 6 7 8 9 10
$\log_{10} p_{min}$


PRELIMINARY
declination
right ascension
-log10 p
360
300
240
180
120
60
0
80
70
60
50
40
30
20
10
0
6
5
4
3
2
1

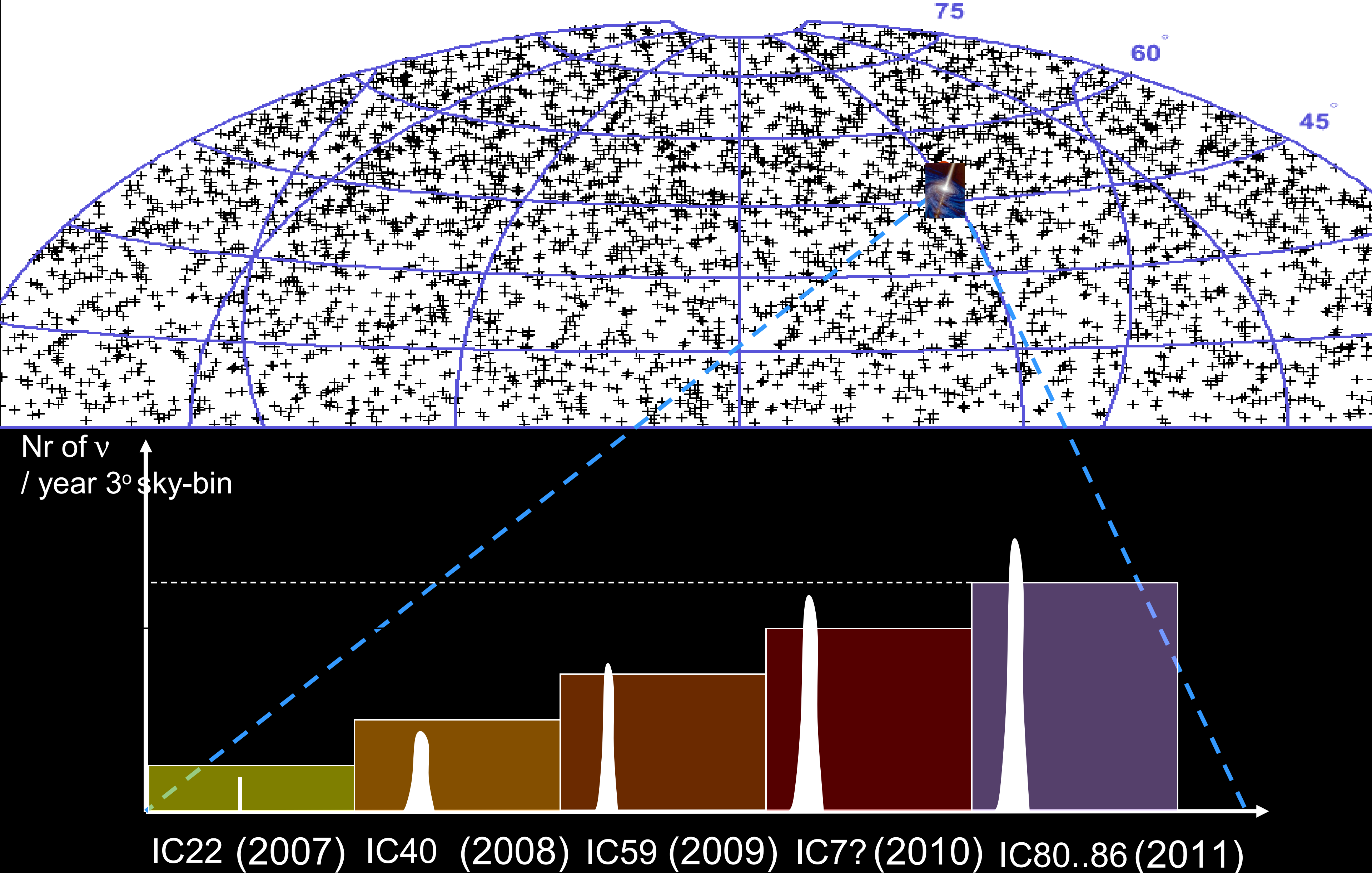
Muon Channel
Point Source

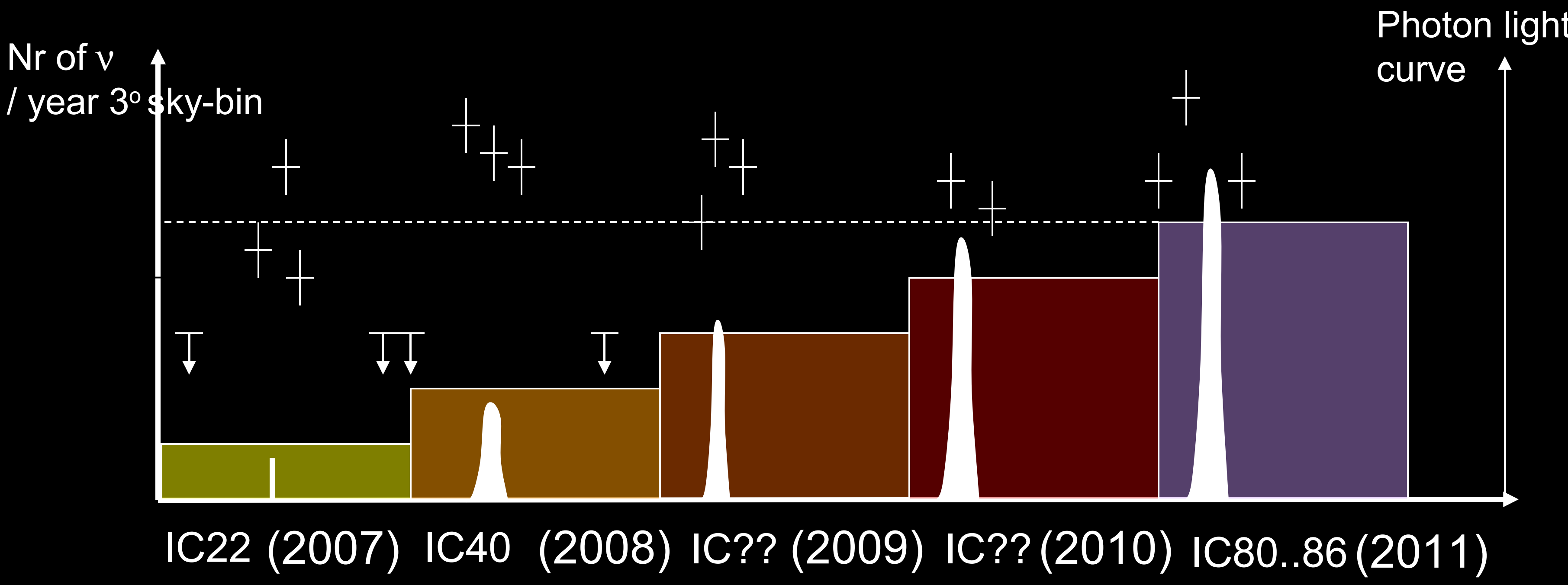






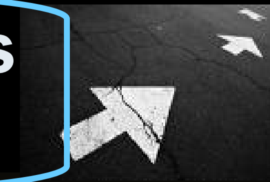
75
60
45
Nr of ν
AMANDA:
dΦatm(t)/dt = 1 / year 3° sky-bin
1
2000
2001
2002
2003
Time

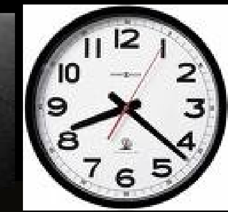

75
60
45
Nr of ν
/ year 3° sky-bin
IC22 (2007)
IC40 (2008)
IC59 (2009)
IC7? (2010)
IC80..86 (2011)



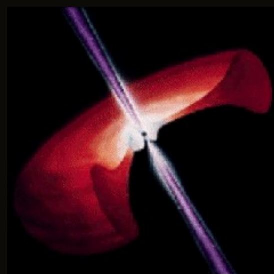
Nr of ν
/ year 3° sky-bin
Photon light
curve
IC22 (2007)
IC40 (2008)
IC?? (2009)
IC?? (2010)
IC80..86 (2011)

Multiwavelength approach: sources vs wavebands





Active Galactic Nuclei

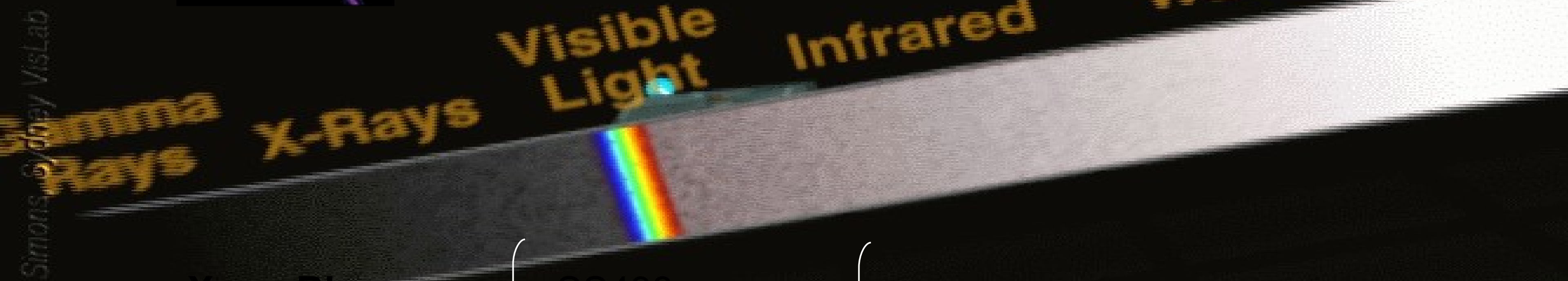


Mkn 421
Mkn 501
1ES1959+650

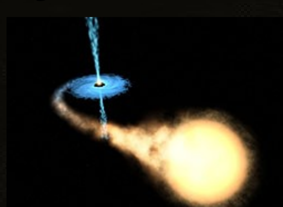
X- and γ-rays

3C273

Radio and X-rays



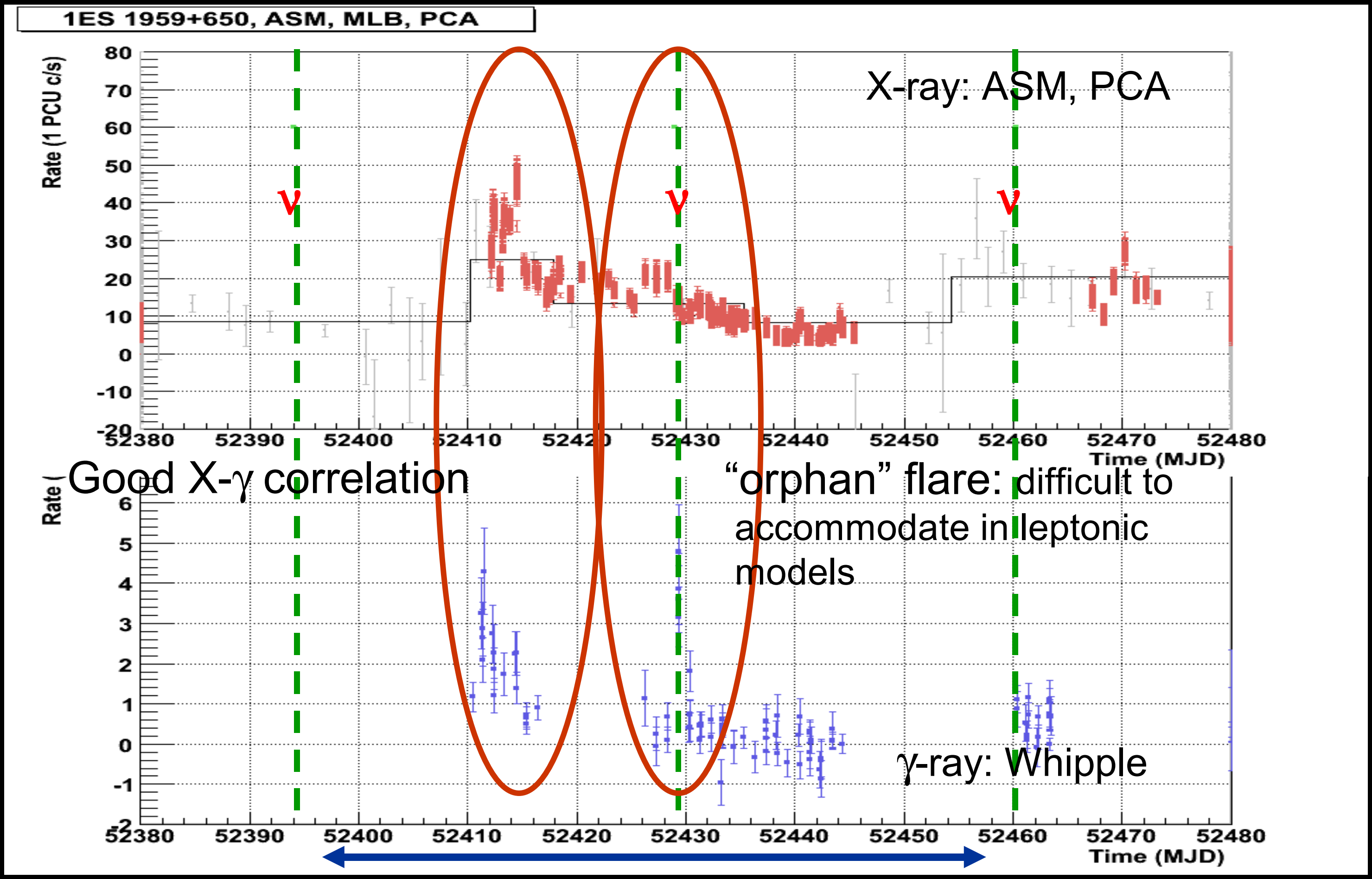
X-ray Binary Systems



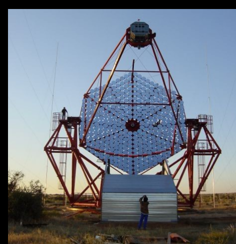
SS433
LSI +61 303
Cyg X-1
Cyg X-3
.....

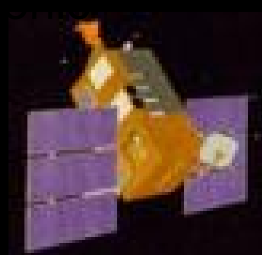
Radio
Periodicity (multiwavelength)

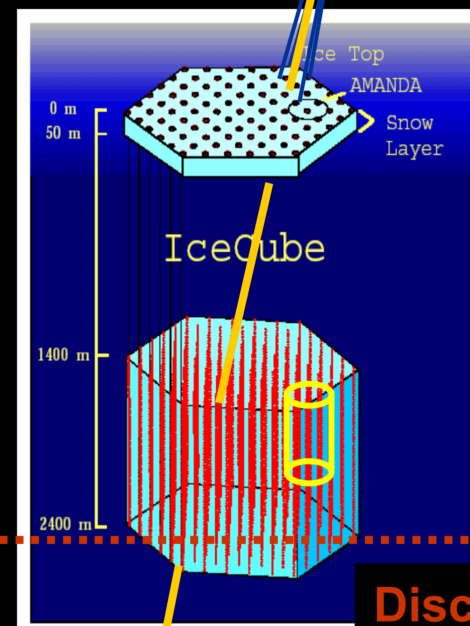
The hint: 1ES1959+650



Future: Multi-Messenger

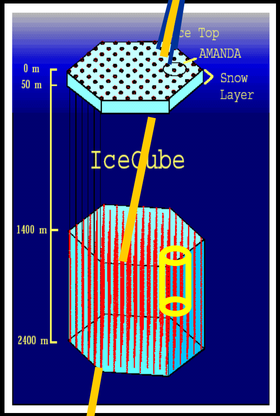




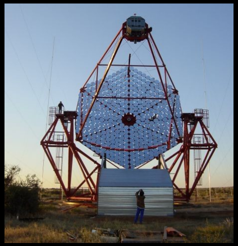


Discovery time

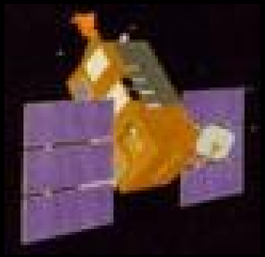
Future: we will be limited by …



- limited statistics
- too small



- Field-of-view
- Duty cycle



- detection area limited
  Detail study of temporal and spectral characteristic of highly variable sources limited

Conclusions

Cosmic Ray Energy Spectrum: the 8th Natural Wonder

For study them you need:

- Cosmic Rays observatory
- γ-rays observatory
- HE neutrino observatory

The use of their results: multi-messenger approach

The puzzle of the origin of cosmic rays not yet solved:

$\Rightarrow$ I bet on Neutrinos!