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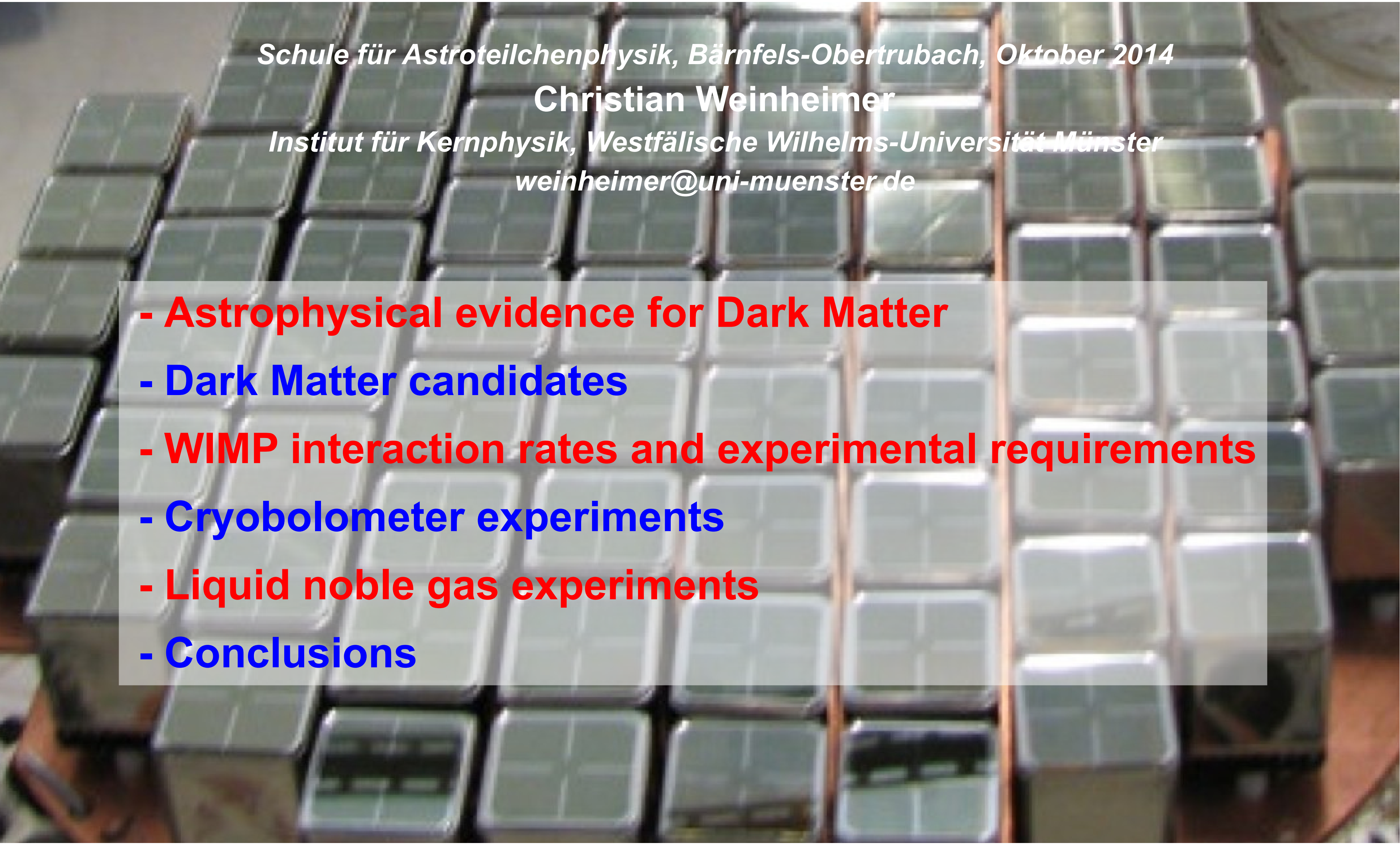
Münster



Schule für Astroteilchenphysik, Bärnfels-Obertrubach, Oktober 2014

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- **Astrophysical evidence for Dark Matter**
- **Dark Matter candidates**
- **WIMP interaction rates and experimental requirements**
- **Cryobolometer experiments**
- **Liquid noble gas experiments**
- **Conclusions**

Period of revolution of the planets in our solar system (3rd Kepler's law)

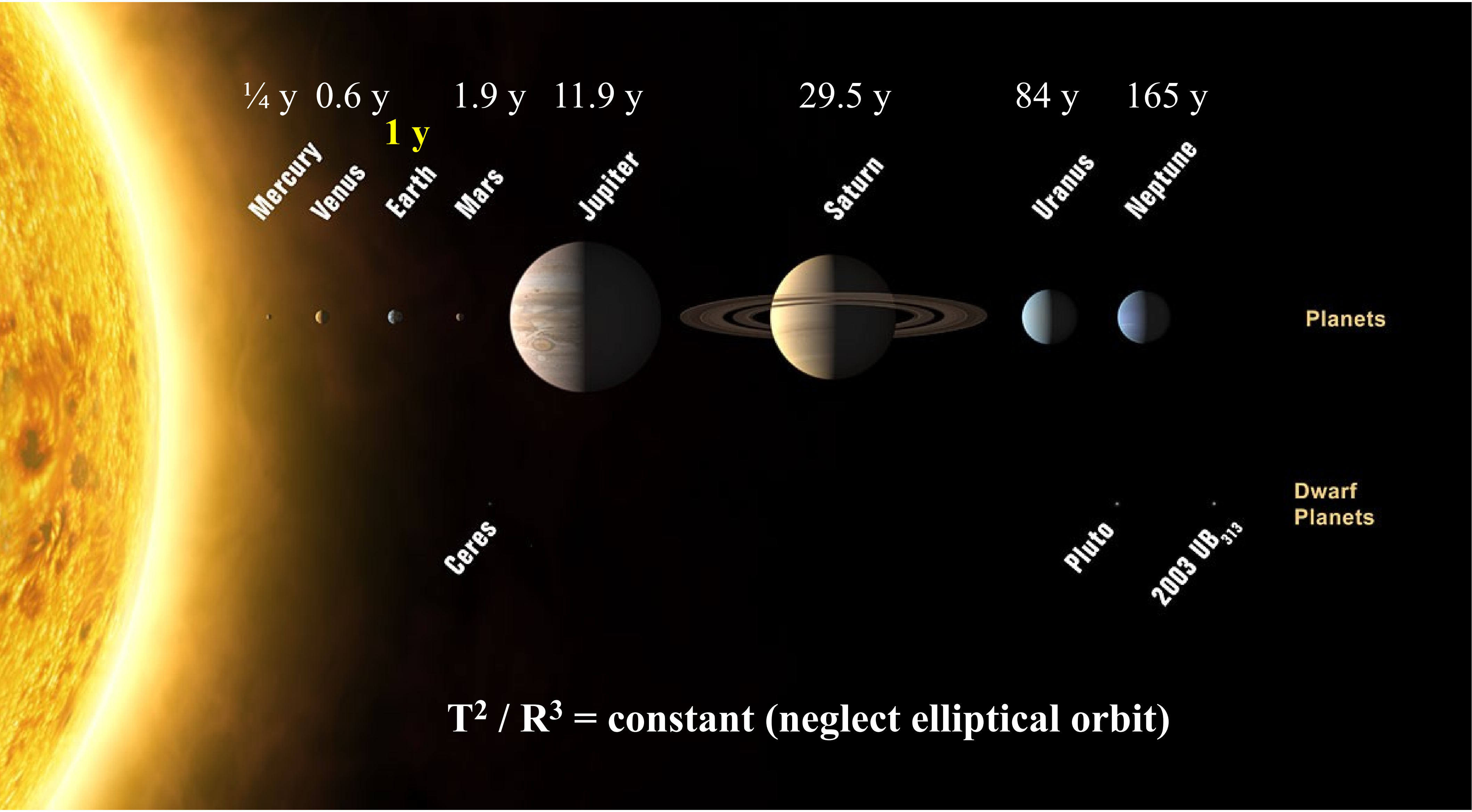
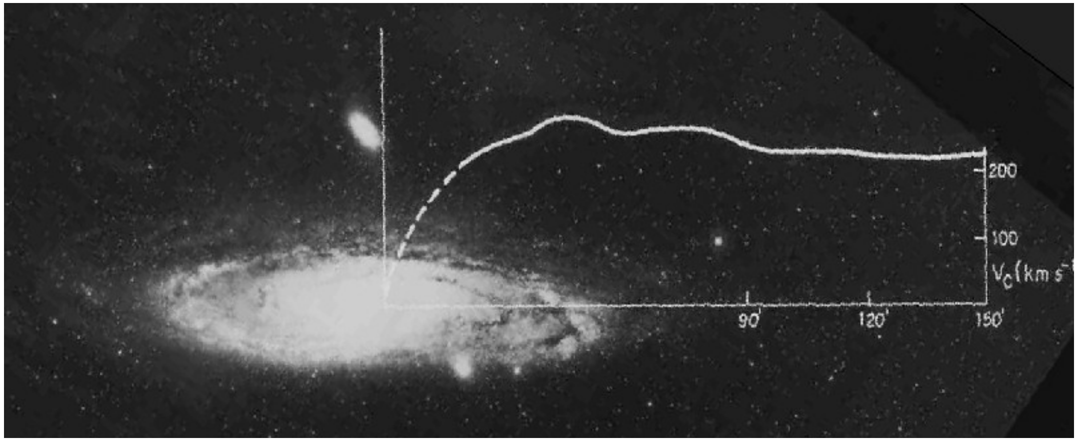


Bild: The International Astronomical Union/Martin Kornmesser

Hints towards Dark Matter: Rotational curves of galaxies



Expectation, that the mass is there,

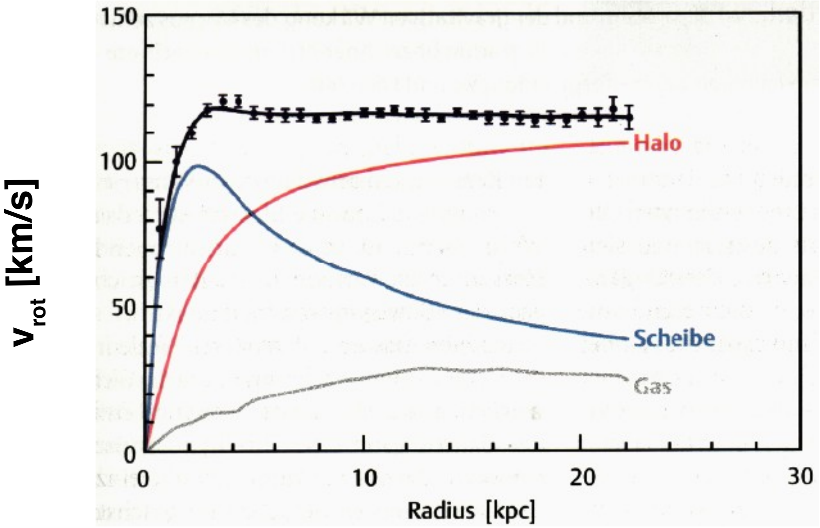
where the light comes from:

velocity of single stars versus distance to centre:

$v_{rot} \propto 1 / \sqrt{r}$ (for rotationally symmetric mass distribution)

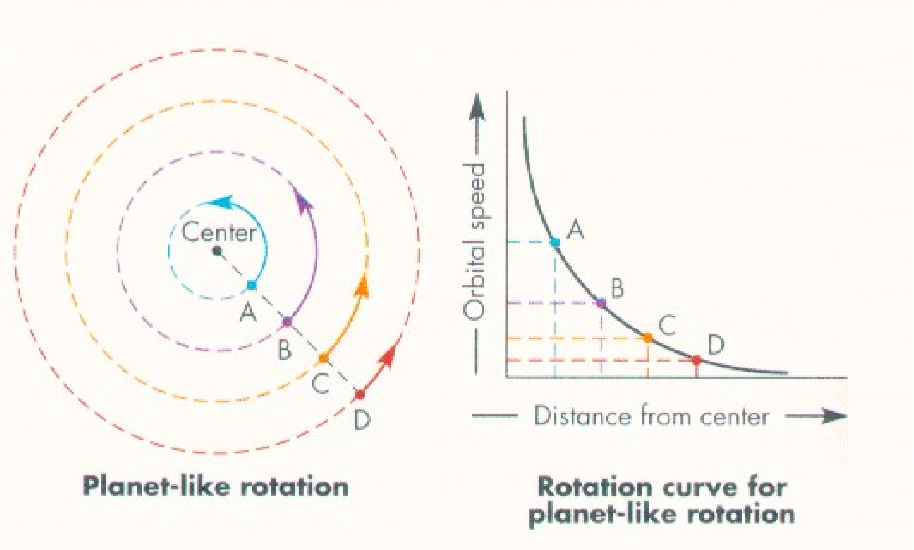
but measurements of many galaxies (incl. ours) yield:

$v_{rot}(r) \approx$ const.



In the outer part of the galaxy there is a far-ranging dark "halo" ⇒ **"Dark Matter"**

Satellite equation for sun (star) rotating around center of galaxy



Now star with mass m_0, at radius r_0, rotating around center with velocity v_0

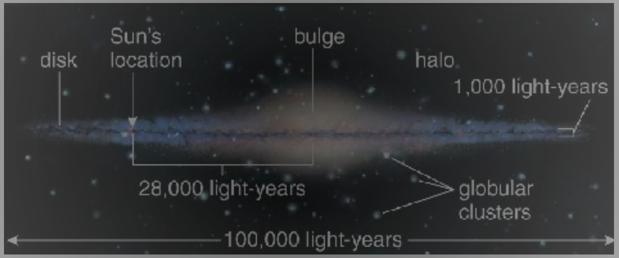
$$\frac{m_0 \cdot v_0^2}{r_0} = G \cdot \frac{m_0 \cdot M(r)}{r_0^2} \quad \text{with} \quad M(r) = \int_0^{r_0} 4\pi\rho(r) r^2 dr$$

$$\Rightarrow \quad v_0 = \sqrt{\frac{G \cdot M(r)}{r_0}}$$

$$\Rightarrow \quad v_0 \propto \sqrt{\frac{1}{r_0}} \quad \text{outside the galaxy}$$

$$v_0 = \text{const.} \quad \Rightarrow \quad \rho(r) \propto \frac{1}{r^2} \quad \text{“Halo”}$$

Halo models



Halo models

Cored spherical isothermal halo model:

$$\rho(r) = \rho_0 \cdot \frac{a^2 + r_0^2}{a^2 + r^2} \quad \text{with} \quad a \text{ being the core radius}$$

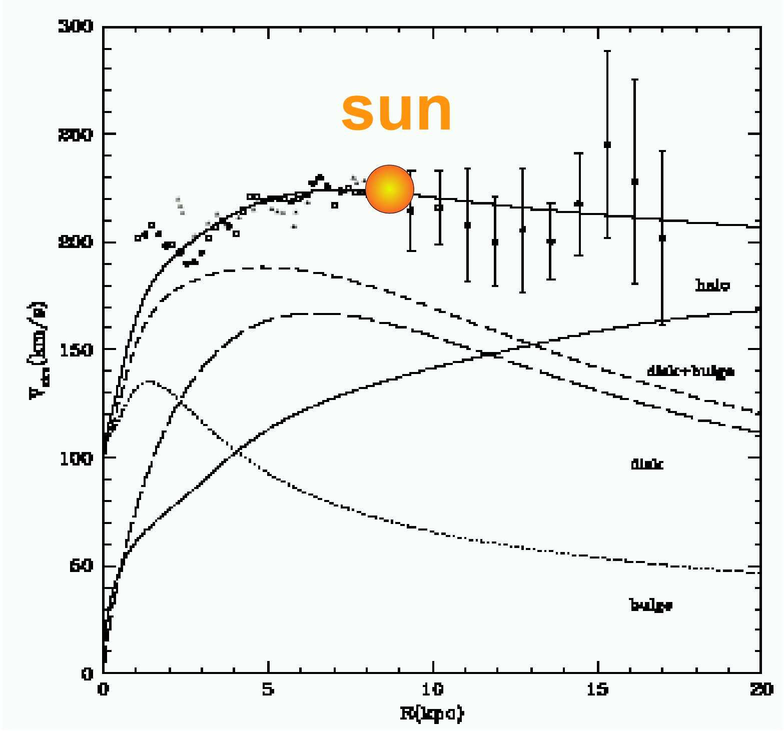
Navarro, Frenk, White (1997, "NFW") halo model from N-body simulations:

$$\rho(r) = \rho_0 \cdot \frac{1}{\frac{r}{R_s} \cdot \left(1 + \frac{r}{R_s}\right)^2} \quad \text{with} \quad R_s \text{ describing a typical length scale}$$

Halo models and halo of our Milkyway

more sophisticated: Klypin, Zhao, Somerville [astro-ph/0110390]

and there are many more ...



Local (dark) matter density at our sun

$$\rho_0 = \rho_\odot = 0.3\ \frac{\text{GeV}}{\text{cm}^3} \qquad \text{corresponds to 1 proton per 3 cm}^3$$

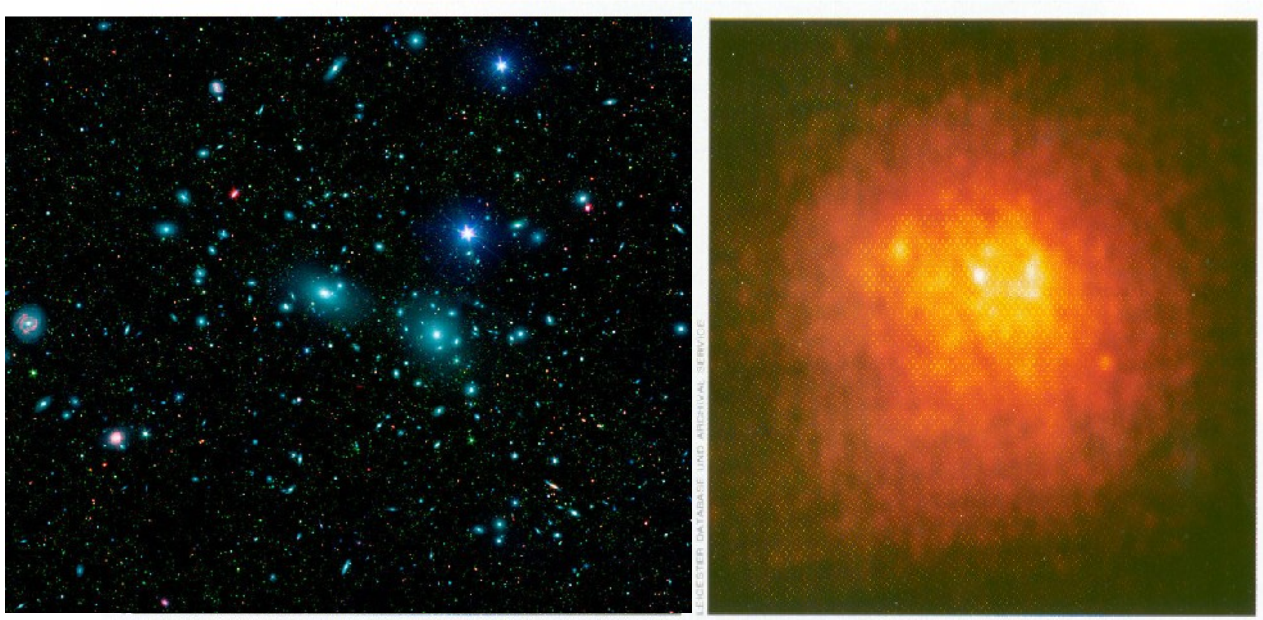
Compare to **critical density** of the universe:

$$\rho_c = \frac{3H_0^2}{8\pi G} = 5.3\ \frac{\text{keV}}{\text{cm}^3} \qquad \text{corresponds to 6 protons per m}^3$$

Further evidences for dark matter

Coma cluster

by IR & visible light / by x-rays



Virial theorem: $E_{pot} = -2\, E_{kin}$

Connection between depth of gravitational potential $E_{pot} \sim M_{tot}^2 \sim I_{light}^2$

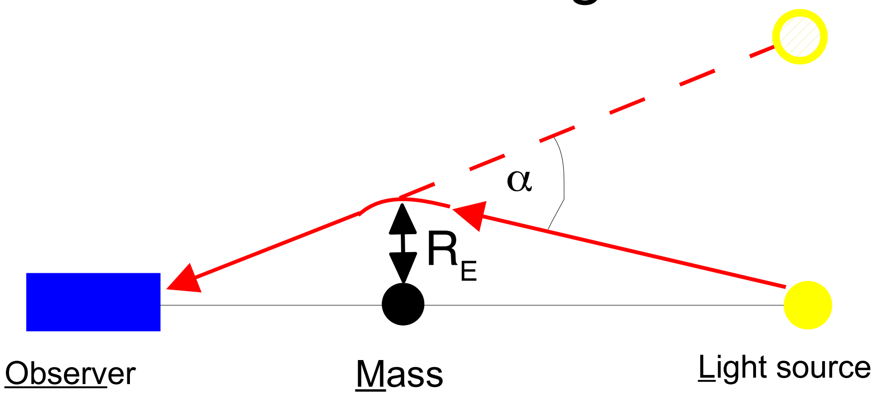
and kinetic energy from temperature (x-ray spectrum) $T \sim E_{kin}$

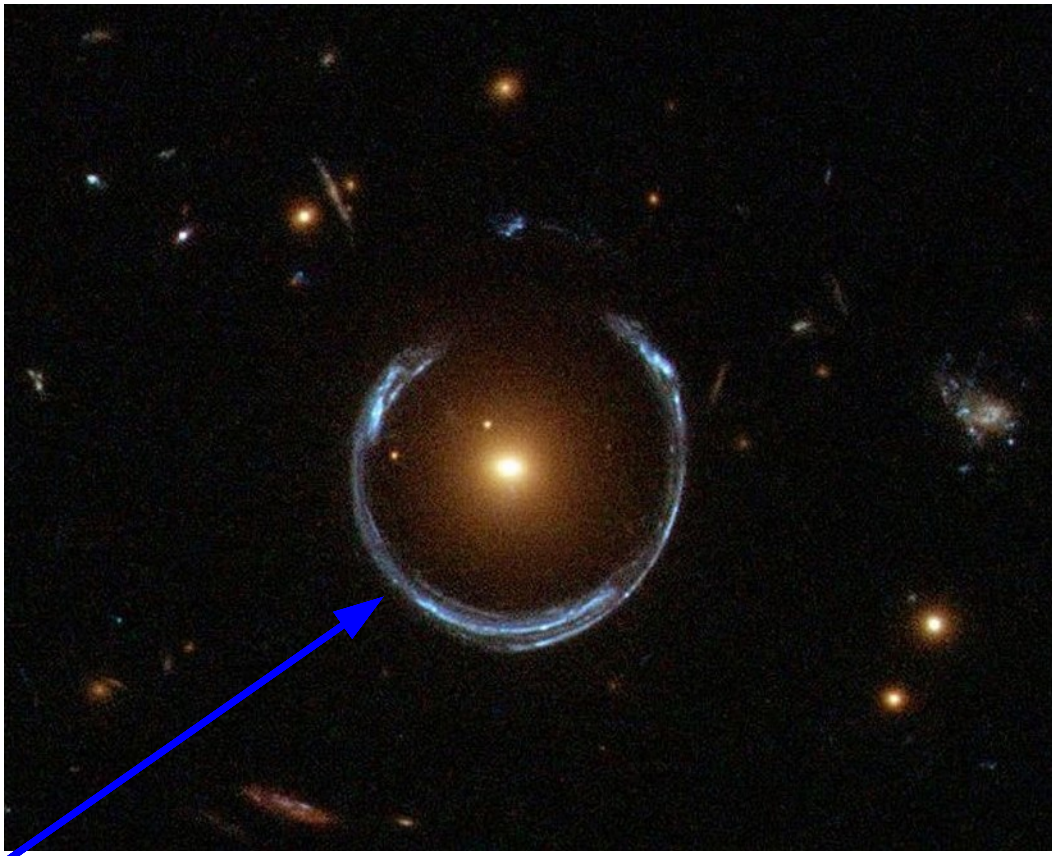
Measurement of temperature: much too hot for the amount of visible mass

⇒ Dark Matter, which only shows up by gravity

More hints for Dark Matter by graviational lensing

"Gravitational lensing"





HST, www.discovery.com

Light deflection due to mass according to Einstein´s general relativity

Can determine mass of galaxy cluster in the foreground !

If foreground mass and background galaxy are perfectly aligned: Einstein ring, otherwise segments of the Einstein ring

Gravitational lensing as consequence of Einstein's general relativity

Schwarzschild metric in distance *r* of point-like mass *M*

$$g_{\mu\nu} = \begin{pmatrix} 1-\frac{R_S}{r} & 0 & 0 & 0 \\ 0 & \frac{1}{1-\frac{R_S}{r}} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2\sin^2\theta \end{pmatrix}$$

with Schwarzschild radius R_S

$$R_S = 2G_N M \approx 2.9\ \mathrm{km}\ \frac{\mathrm{M}}{\mathrm{M}_\odot}$$

angular deflection
(first detection in 1919: light bent at the boundary of the sun during eclipse)

$$\alpha_{\mathrm{tot}} = 2\frac{R_S}{r_{\mathrm{min}}} \quad \sim\mathrm{M}$$

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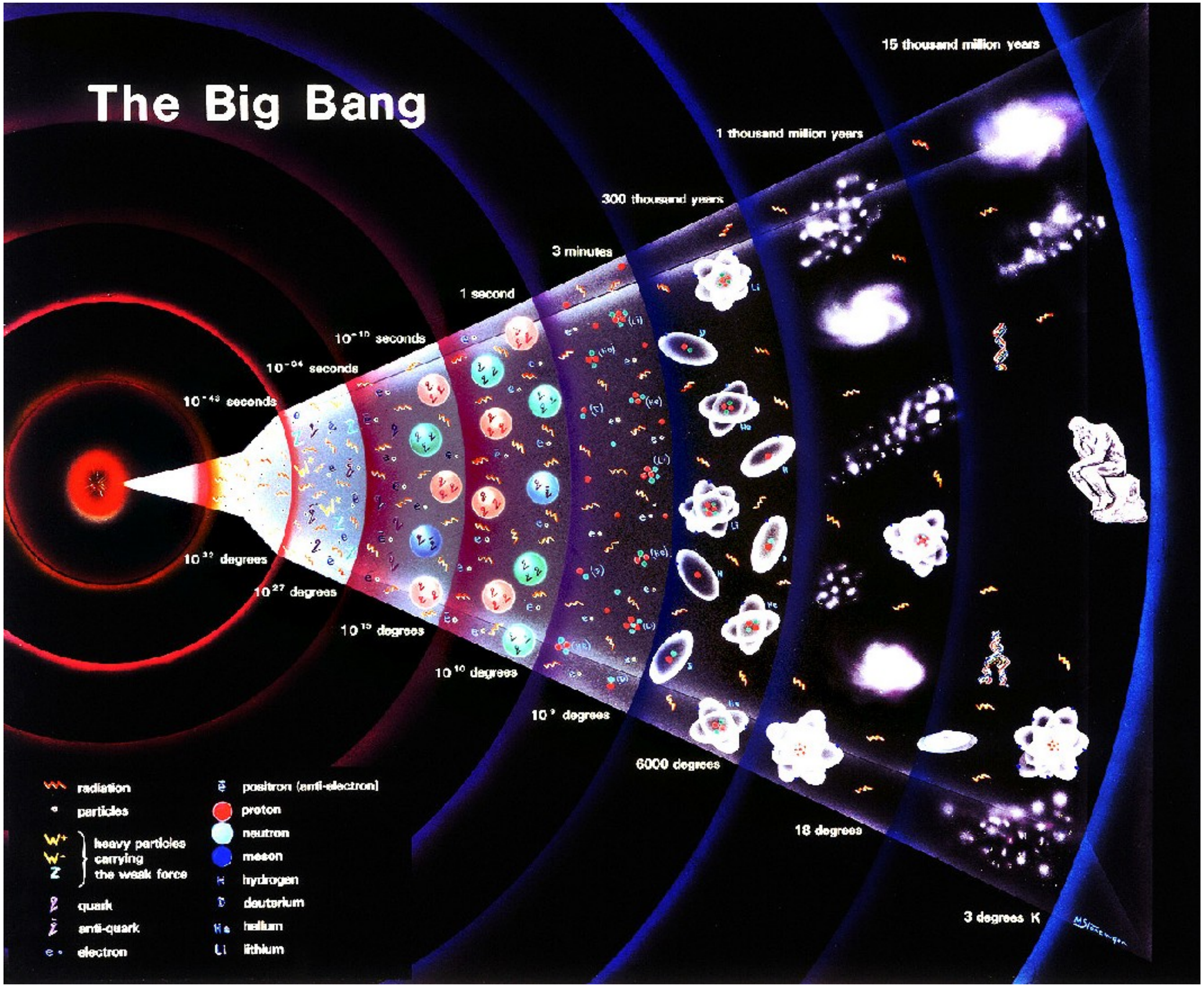
More hints for Dark Matter by graviational lensing

segments of the Einstein ring

The early universe: Big bang & structure formation



“big bang”

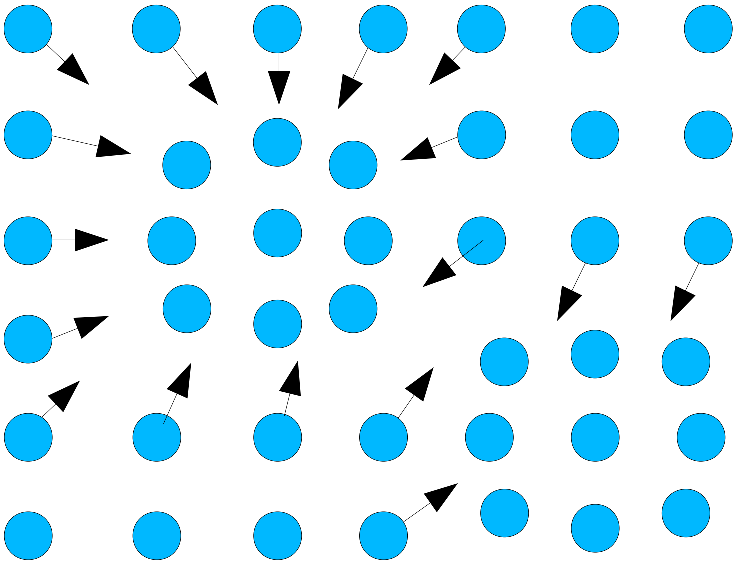
structure formation

Structure formation

Gravitation is always attractive never repelling

→ Primordial density fluctuations should enhance

→ Every stuff should clump together
if there was not the expansion of the universe



Structure formation

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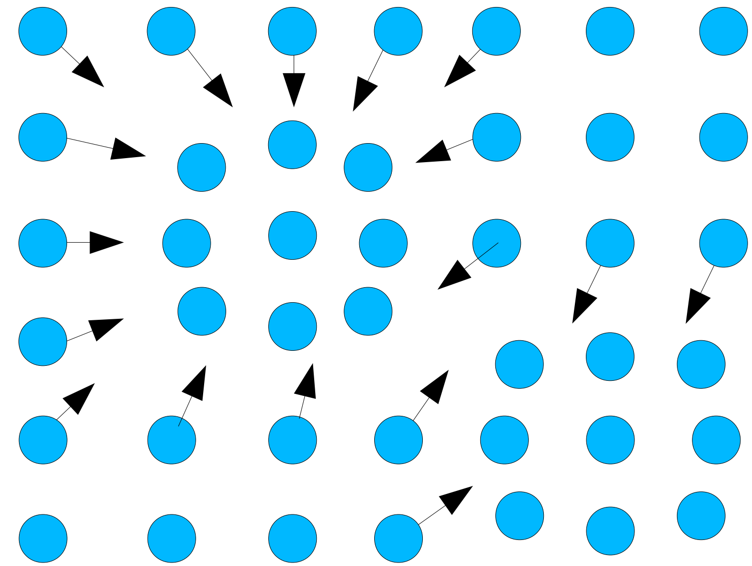
→ Primordial density fluctuations should enhance

→ Every stuff should clump together
if there was not the expansion of the universe

Calculation of the structure formation with N-Body"
simulations on big computers

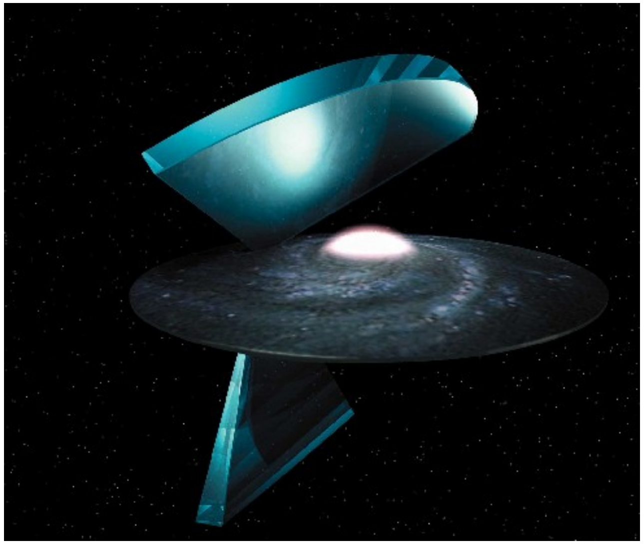
Criteria to check:

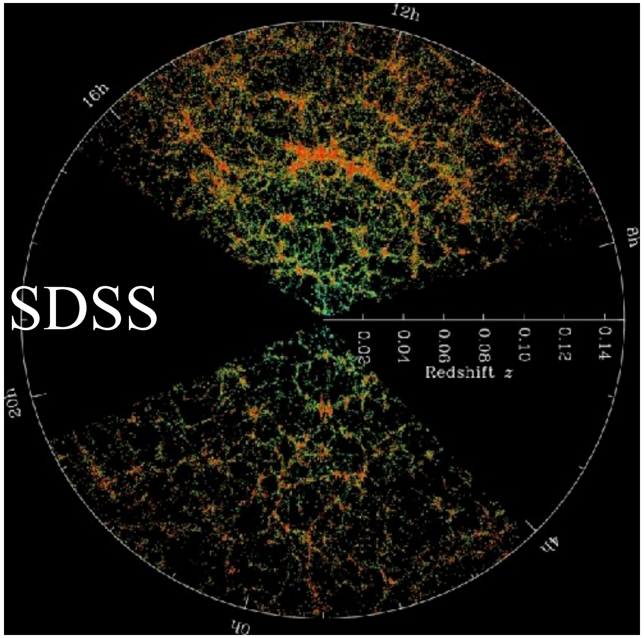
Todays structure of the universe on all scales
(stars with planets, galaxies, galaxy clusters,
larger structures, ...)



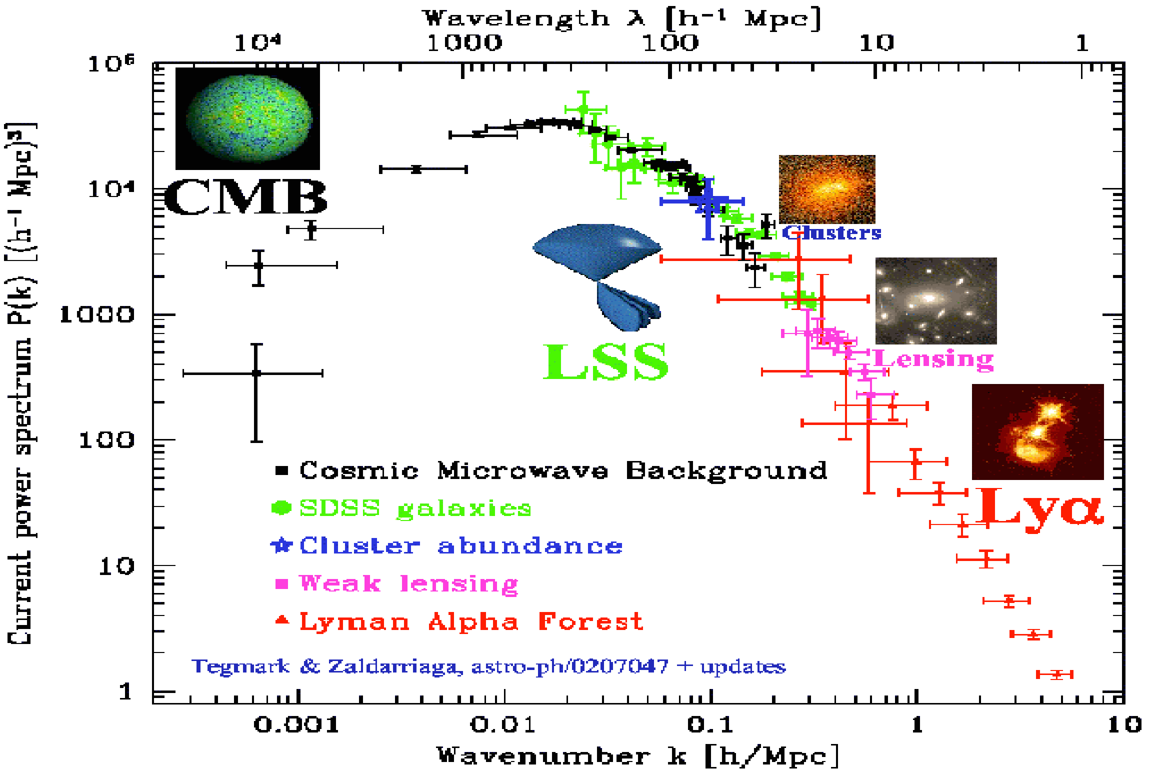
Source: National Center for SuperComputer Simulations,
http://cosmicweb.uchicago.edu/sims.html

Measurement of matter distribution with 2dF, SDSS





spectral analysis in spatial coordinates:
"power spectrum" in wave numbers



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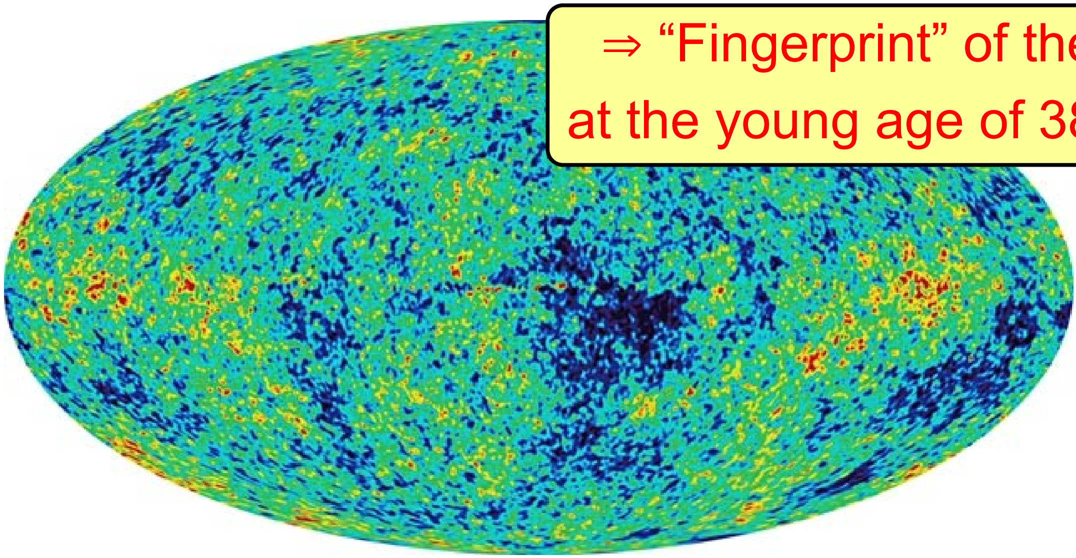
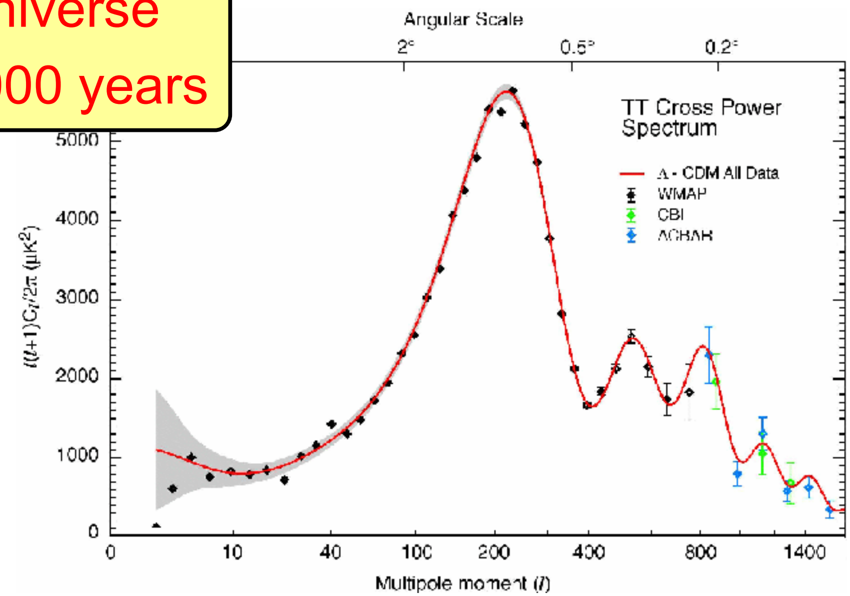
Cosmic microwave background radiation (CMB) from the WMAP mission



⇒ “Fingerprint” of the universe at the young age of 380000 years



source: D.N. Spergel et al., astro-ph/0302209

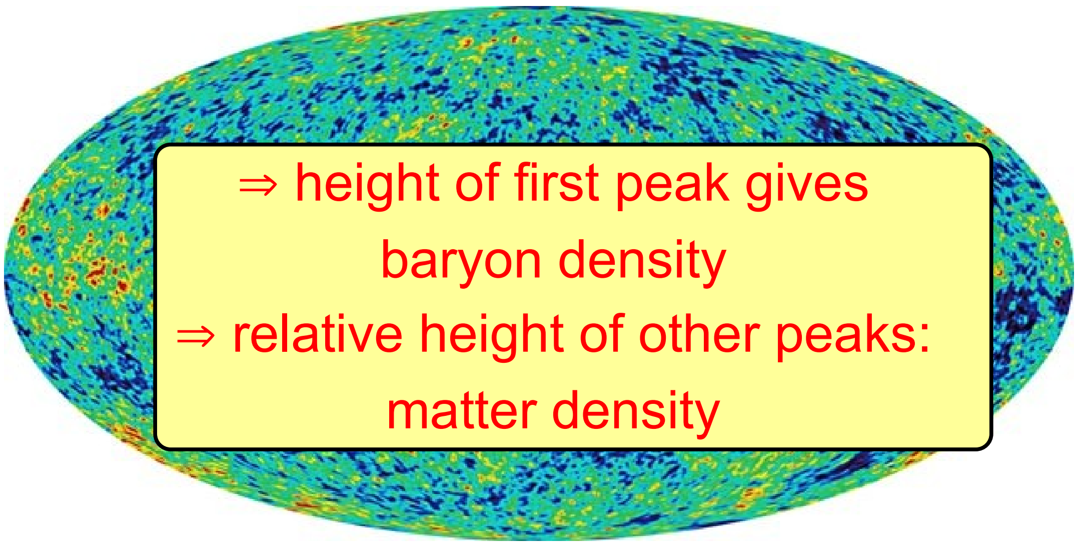
CMB-result: $\Omega_M + \Omega_\Lambda = 1$ with $\Omega_M \approx 0.3$

But the known baryonic matter density is much smaller $0.045 = \Omega_B \subseteq \Omega_M$

Relic neutrinos help, but not much:
$0.005 \leq \Omega_\nu \leq 0.05$

What are the residual 25% of matter density?
What are the 70% of the energy density?

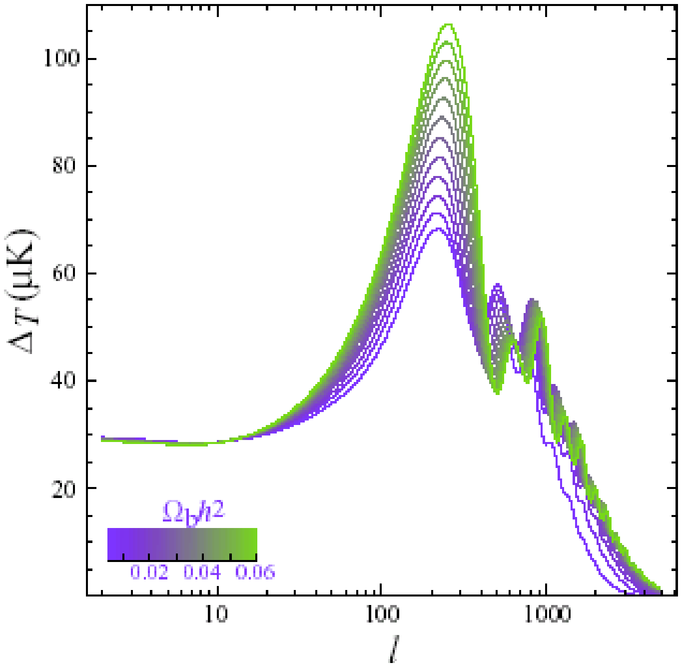
Cosmic microwave background radiation (CMB) from the WMAP mission



⇒ height of first peak gives baryon density

⇒ relative height of other peaks: matter density

source: D.N. Spergel et al., astro-ph/0302209



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What are the residual 25% of matter density?
What are the 70% of the energy density?

Different informations about matter / energy density in the universe

total matter/energy density $\Omega_{tot} = 1$

Ratio of the various maxima: WMAP (Planck 2013)

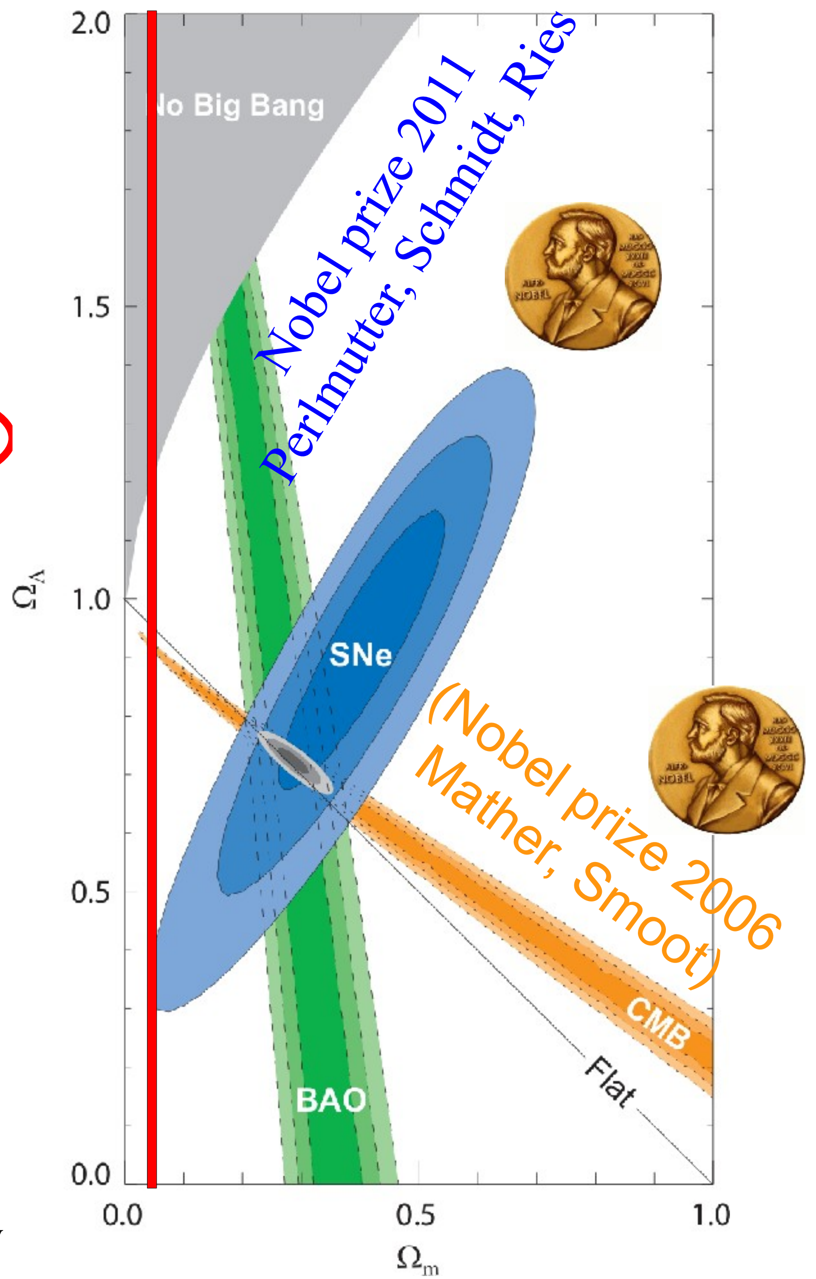
mass density $\Omega_M = 0.28\ (0.32)$

baryonic mass dens. $\Omega_M = 0.046\ (0.049)!$

Discrepancy:
⇒ evidence for exotic Dark Matter

and the remaining density ?

Dark Energy $\Omega_\Lambda = 0.72\ (0.68)$!



Quelle: Particle Data Group, pdg.lbl.gov

"Direct evidence" for exotic Dark Matter ?

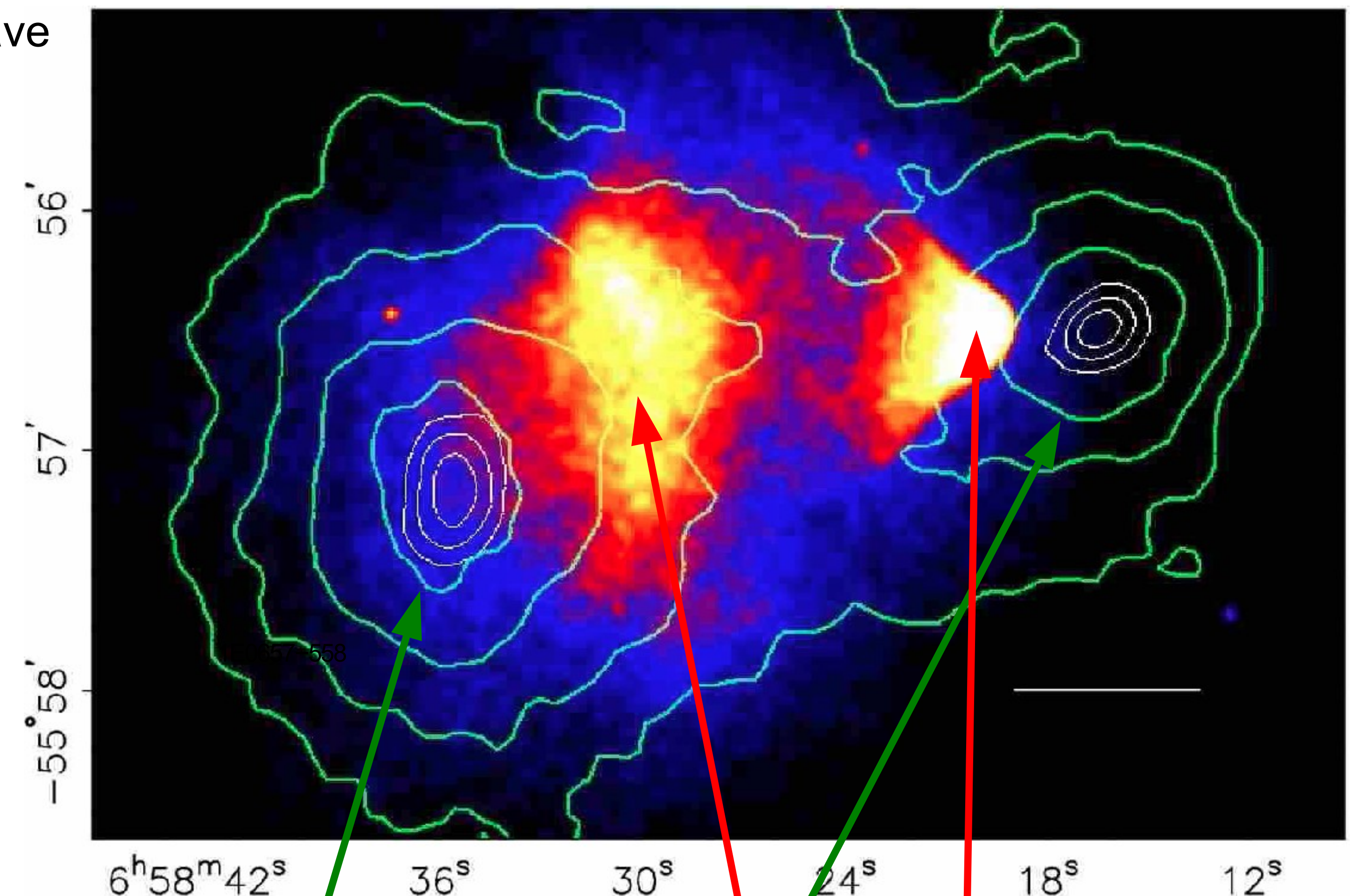
Two galaxy cluster, which have crossed:

Bullet cluster 1E0657−558

d =1Gpc, z = 0.296

Gas (Chandra x-ray telescope) stays behind the massive stars and Dark Matter due to electromagnetic interaction

→ Dark Matter interacts only gravitationally !



mass from gravitational lensings with HST

gas from Chandra x-ray telescope

D. Clowe et al., astro-ph/0608407

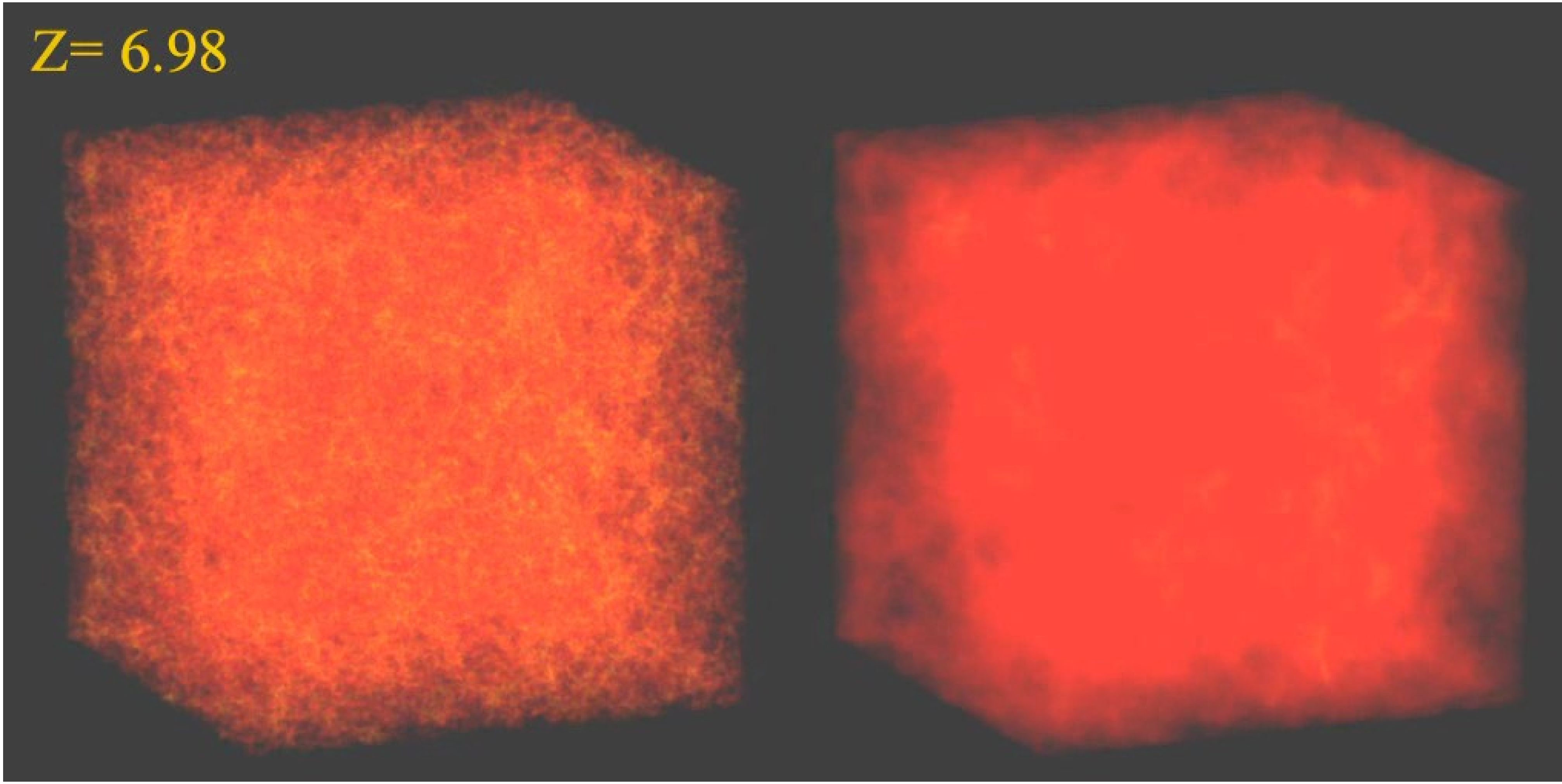
Candidates for Dark Matter: particle Dark Matter

a) Neutrinos (336 relic neutrinos per cm^3 from big bang):

only known Dark Matter so far, but small fraction → Hot Dark Matter“

„Hot“: relativistic during structure formation, smearing out small scales

Too heavy relic neutrinos do not fit: they wash out small scales

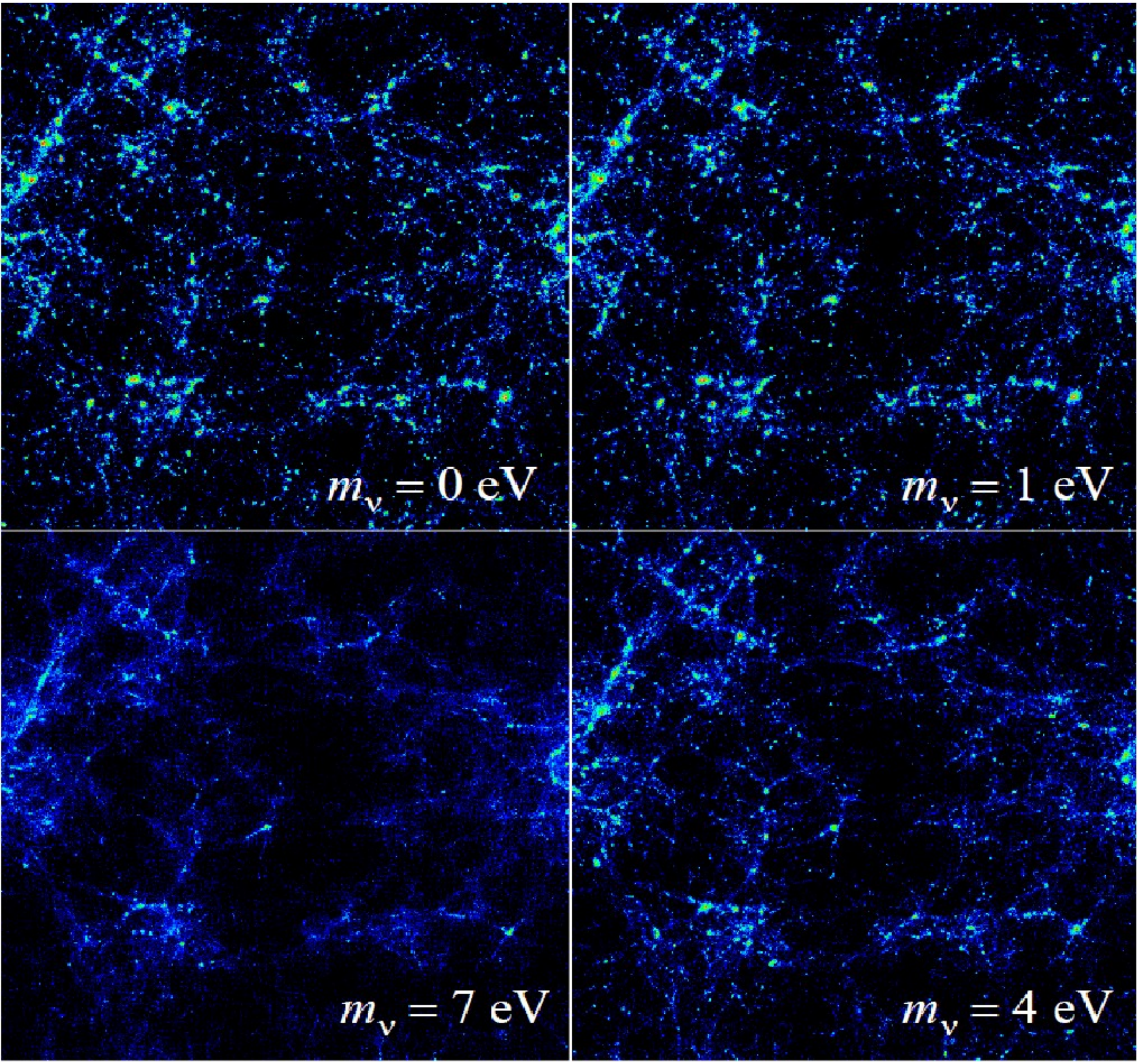


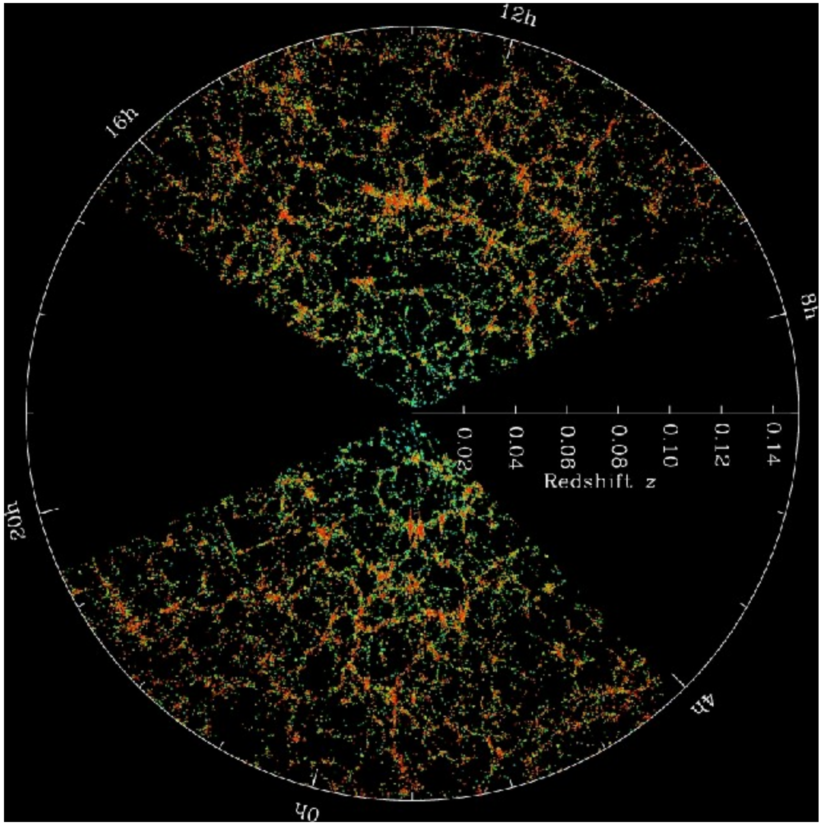
Cold dark matter

Cold dark matter with neutrinos, $\Sigma m(\nu)$ = 6.9 eV

Source: Dr. Troels Haugboelle, Kopenhagen, http://users-phys.au.dk/haugboel/projects.shtml

Hot dark matter (neutrinos) and structure formation

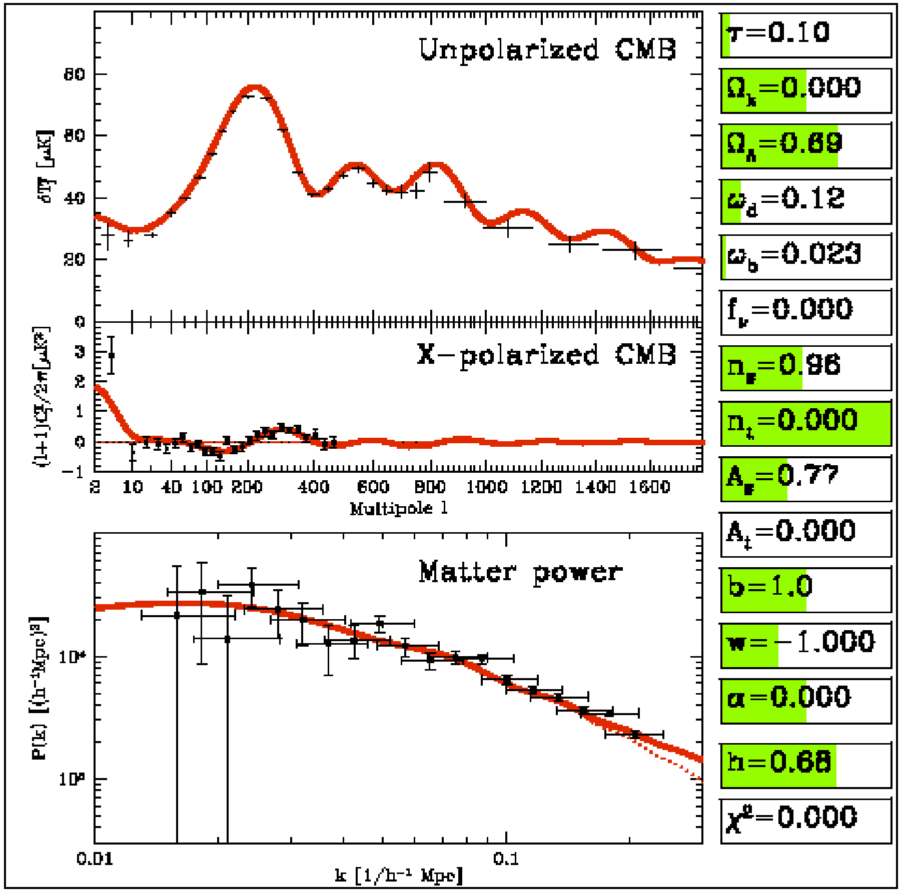




→ **Neutrinos must not be too heavy**

→ **neutrinos form only a small part of hot dark matter**

"Hot" (gravitational unbound) versus "cold" (gravitational bound) DM



source: http://space.mit.edu/home/tegmark/movies_60dpi/fn_movie.gif

Too much "Hot" Dark Matter would suppress fluctuations at small scales too much

→ need Cold Dark Matter

Candidates for Dark Matter: particle Dark Matter

a) Neutrinos: only known Dark Matter so far, but small fraction → Hot Dark Matter“

„Hot“: relativistic during structure formation, smearing out small scales

b) Axions: only small parameter range open, some search

c) Axinos: supersymmetric partner of axions

d) Gravitinos: supersymmetric partner of graviton

e) Weakly Interacting Massive Particles (WIMPs):

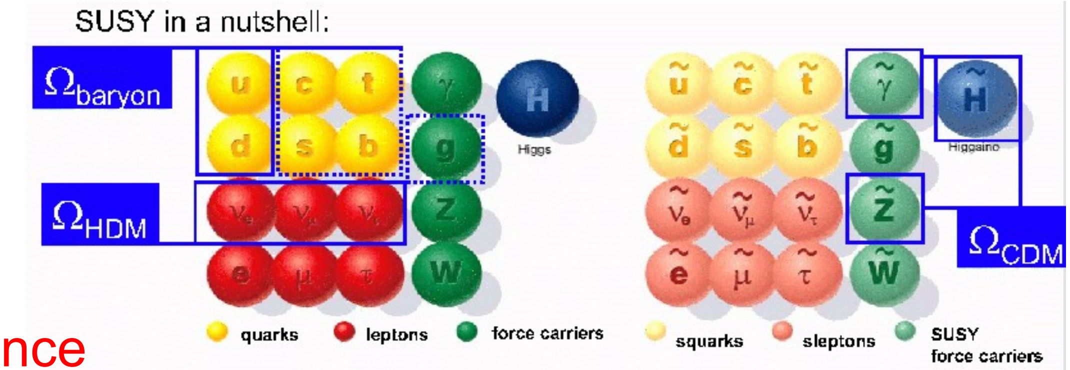
„The natural Cold Dark Matter candidate“

„Cold“: non-relativitistic during structure formation

Supersymmetry is a nice way to avoid divergences of the SM at high energies

SUSY provides a natural candiate:

LSP (lightest supersymmetric particle)



LSP has about the right relic abundance

WIMP/LSP/Neutralino: $\tilde{\chi}^0 = a_1 \tilde{\gamma} + a_2 \tilde{Z}^0 + a_3 \tilde{H}^0_1 + a_4 \tilde{H}^0_2$

WIMP Dark Matter: Relic density from the big bang

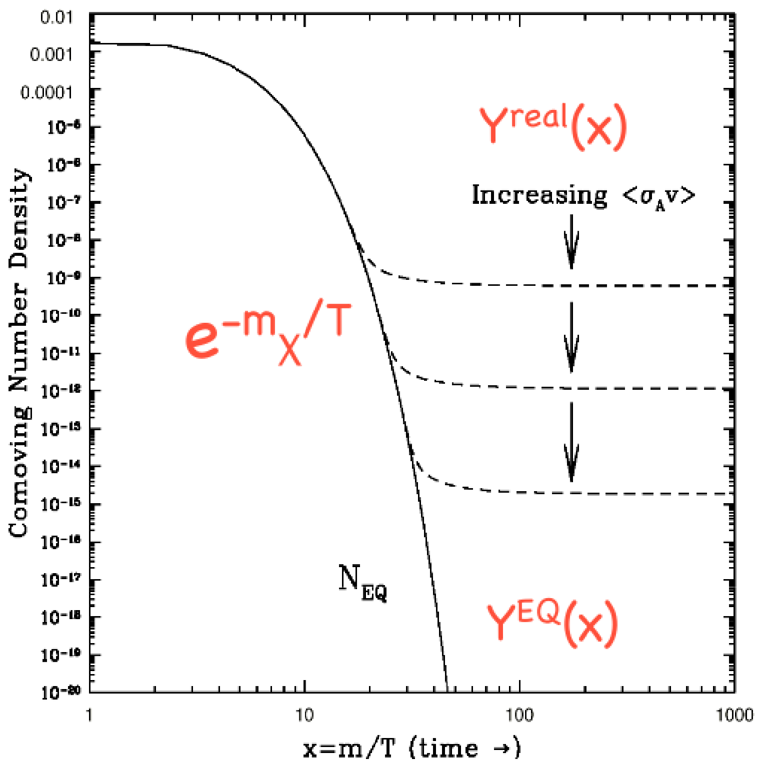
Assume existence of a neutral, massive and only weakly interacting particle (WIMP) in the early universe:

a) WIMPs are in equilibrium with the other particles by the annilation rate Γ:

$$\tilde{\chi} + \tilde{\chi} \leftrightarrow X + \bar{X}$$

b) The WIMPs decouple when $\Gamma \ll H$:

$$\Rightarrow \Omega_\chi \cdot h^2 = \frac{3 \cdot 10^{-27}\,\mathrm{cm^3 s^{-1}}}{\langle \sigma_A v \rangle}$$



Estimate of order of magnitude:

Let $\Omega_\chi \cdot h^2 = 0.1 \quad \Rightarrow \quad \langle \sigma_A v \rangle \approx 1\,\mathrm{pb} \cdot c$

(typical weak interaction)

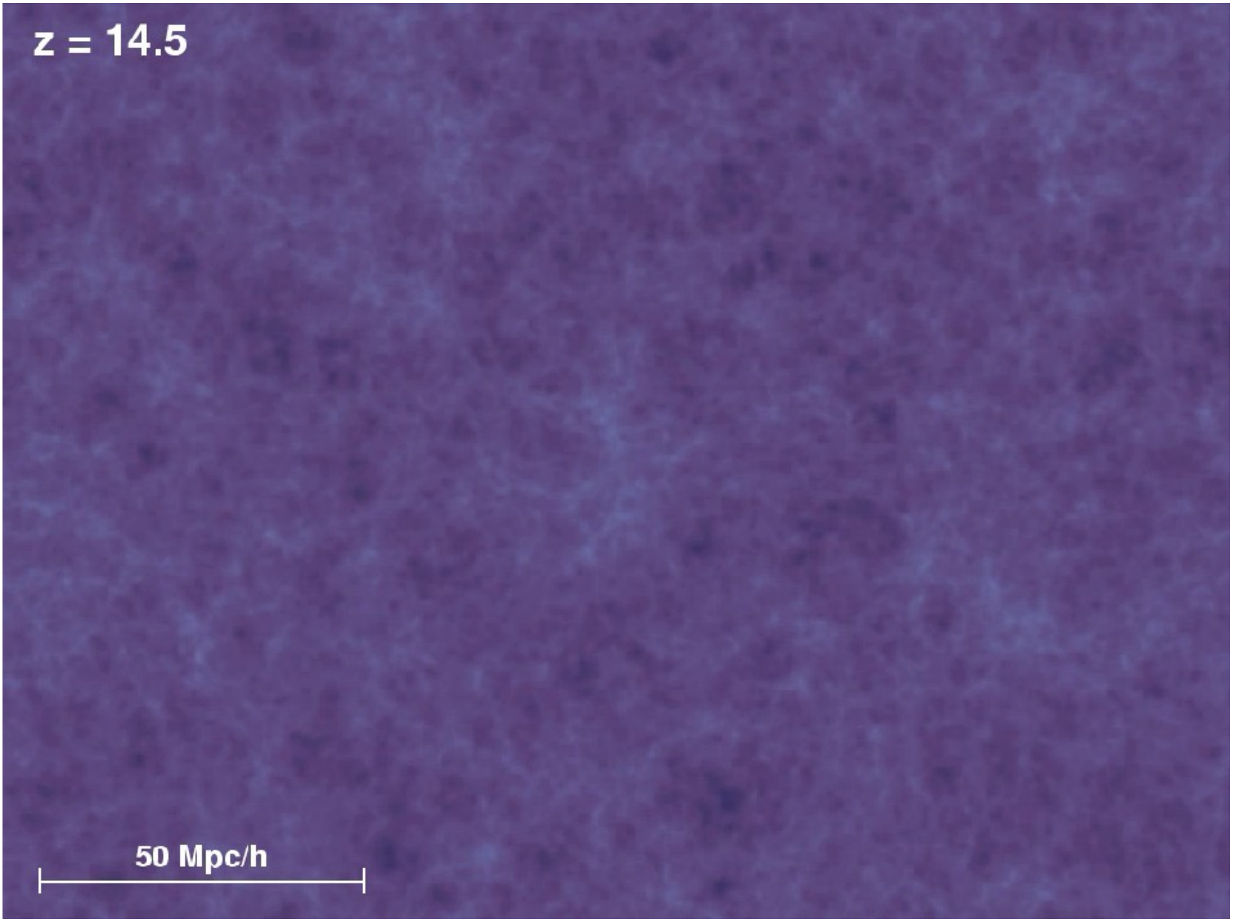
$\sigma_A \propto \alpha_W^2 / m_\chi^2 \quad \Rightarrow \quad m_\chi \approx 100\,\mathrm{GeV} – 1\,\mathrm{TeV}$

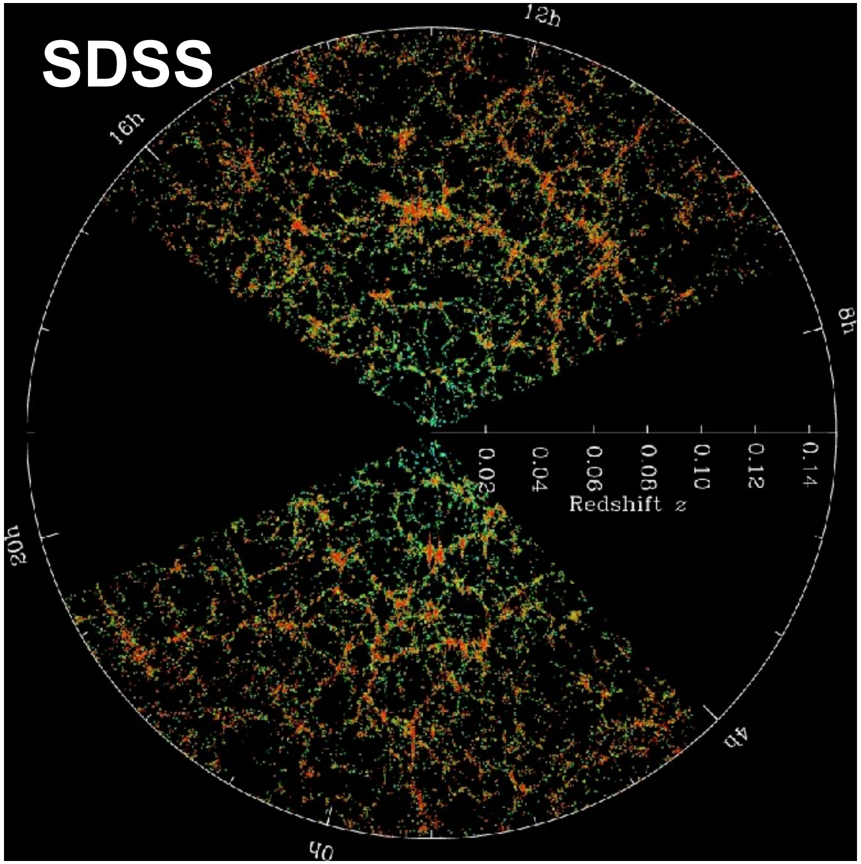
(typical SUSY scale)

thermal equilibum

freeze-out density $\propto 1 / \langle\sigma_\chi v\rangle$

Simulation with cold dark matter: Millenium Run





Source: V. Springel, Max-Planck-Institut für Astrophysik, München, www.mpa-garching.mpg.de/galform/presse/

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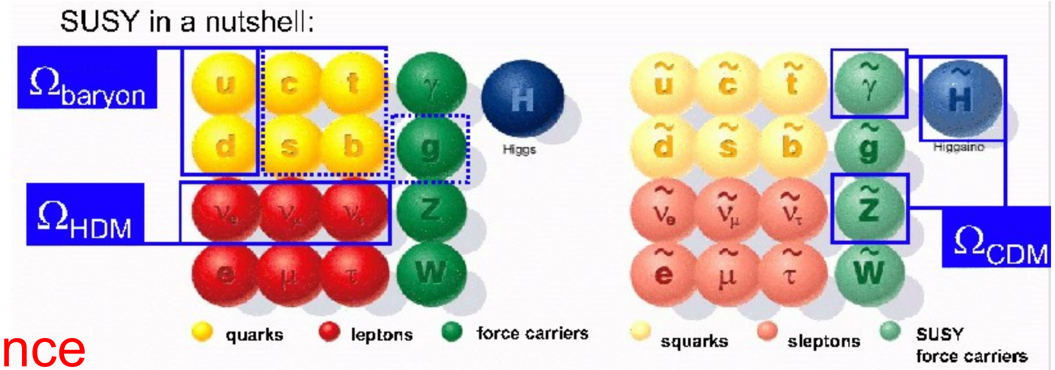


LSP has about the right relic abundance

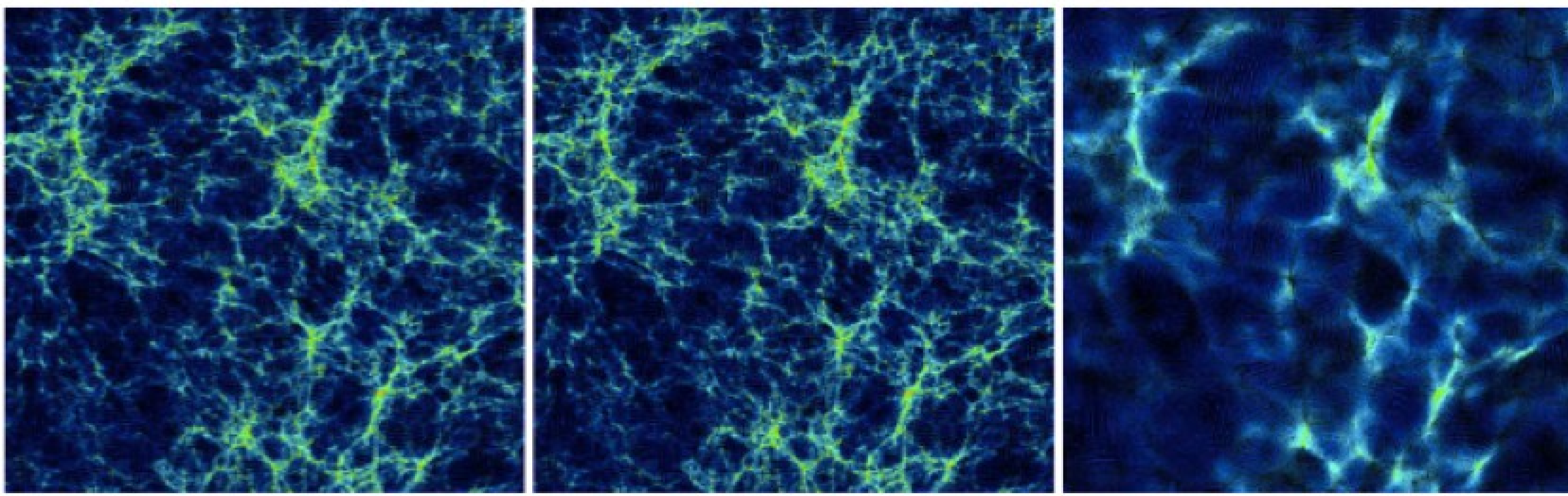
f) Warm dark matter: keV neutrinos

Warm dark matter (keV neutrinos) do not smear out small scales and are possible

ΛCDM

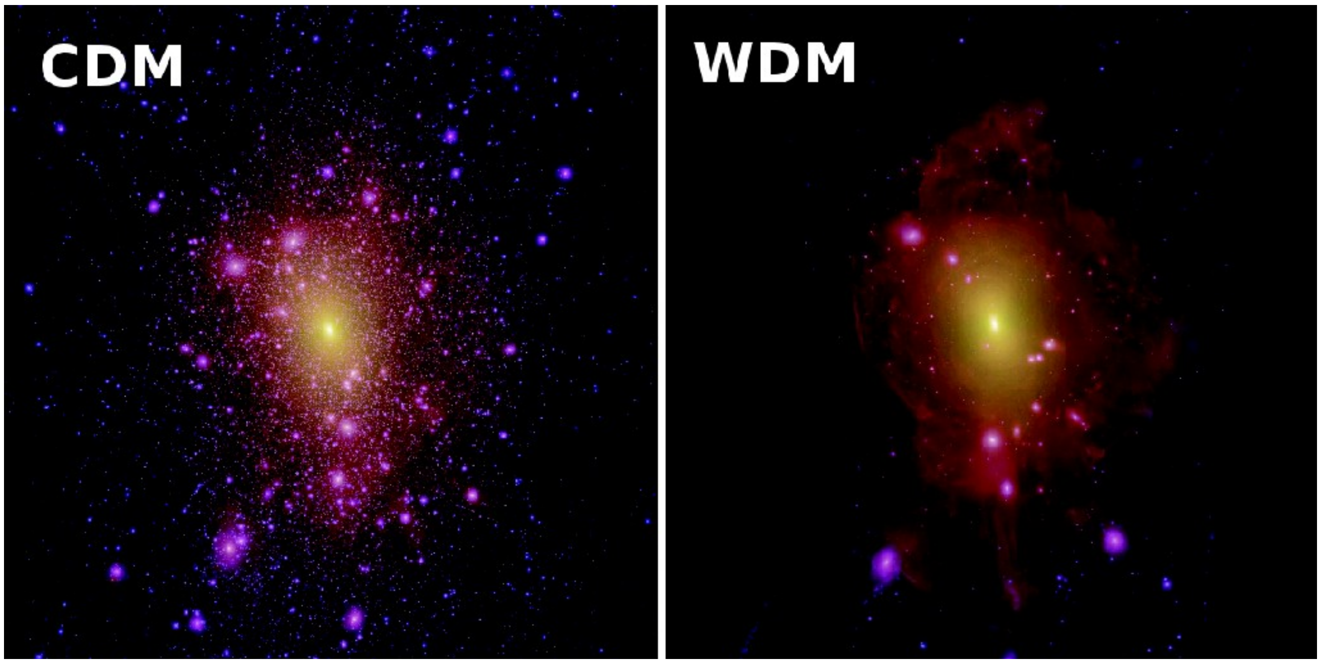
WDM
1 keV

HDM
O(eV)



Hints for a 2nd sterile neutrino: Warm Dark Matter in the universe

ΛCDM (Cold Dark Matter with cosmological constant) models (masses of about 100 GeV) predict to much structure at galactic scales (too many satellite galaxies)



(e.g. Lovell et al. at Meudon Workshop 2012)

In contrast to observations ! (here only artist view on the right)

Warm Dark Matter (masses of a few keV, e.g. sterile neutrinos) would smear out these structures

http://chandra.harvard.edu/graphics/resources/illustrations/milkyWay/milkyway_magellanic_clouds.jpg

Neutrino mixing with 3 active neutrinos: active = coupling to Z^0 and $W^{+/-}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U is unitary 3 x 3 matrix

3 active neutrinos plus a sterile neutrino

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & 0 \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & 0 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$\nu_{sterile}$ does not couple to Z^0 and $W^{+/-}$

Now we have an unitary 4 x 4 matrix, but still the 3 x 3 submatrix is unitary

$\nu_{sterile}$ and ν_4 do not play any physical role (except for gravitation)

3 active neutrinos plus a sterile neutrino with non-vanishing mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$\nu_{sterile}$ does not couple to Z^0 and $W^{+/-}$

Now we have an unitary 4 x 4 matrix, but usually $U_{s1}, U_{s2}, U_{s3}, U_{e4}, U_{\mu 4}, U_{\tau 4} << 1$

But the 3 x 3 submatrix is not unitary anymore !

$\nu_{sterile}$ and ν_4 do play a physical role by their mixing:

$$\nu_e = \sum_{i=1}^{3} U_{ei}\,\nu_i + U_{e4}\,\nu_4$$

$$m^2(\nu_e) := \sum_{i=1}^{3} |U_{ei}|^2\, m^2(\nu_i) + |U_{e4}|^2\, m^2(\nu_4)$$

$$\approx \cos^2(\theta)\, m(\nu_{1,2,3})^2 + \sin^2(\theta)\, m(\nu_4)^2$$

3 active neutrinos plus a sterile neutrino with non-vanishing mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{sterile} \end{pmatrix} = \begin{pmatrix} \boldsymbol{U_{e1}} & \boldsymbol{U_{e2}} & \boldsymbol{U_{e3}} & U_{e4} \\ \boldsymbol{U_{\mu 1}} & \boldsymbol{U_{\mu 2}} & \boldsymbol{U_{\mu 3}} & U_{\mu 4} \\ \boldsymbol{U_{\tau 1}} & \boldsymbol{U_{\tau 2}} & \boldsymbol{U_{\tau 3}} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & \boldsymbol{U_{s4}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Are sterile neutrinos a crazy idea ?
Not a all:
We expect 3 right-handed („sterile“) neutrinos from the sea-saw mechanism to create the light neutrino masses ν_1, ν_2 ν_3

The only new thing is, that one (ν_4) or two neutrinos (ν_4, ν_5) do not have masses of 10^x GeV but are very light

Summary of 1st lecture

There is **compelling evidence** on all astrophysical scales
(rotation curve of galaxies, gravitational lensing, CMB, structure formation, ..)
for non-baryonic dark matter
5 times more than baryonic matter !

Possible candidates are many:
presently top candidates:
WIMPs (weakly interaction massive particle)
twice motivitated by WIMP miracle
very light **axions**
keV neutrinos