Dark Matter

(and direct searches for it)

School for Astroparticle Physics 2018
Obertrubach-Bärnfels

Marc Schumann, University of Freiburg
marc.schumann@physik.uni-freiburg.de

Content

• **Dark Matter**	1	Evidence for Dark Matter	**Wed**
	2a	The Standard Halo Model	
	2b	Dark Matter Candidates	
• **Direct Detection**	3	Basics: Rates and signatures	**Thu**
	4	Backgrounds: Sources, reduction	
• **Detectors**	5	Crystals, cryogenic, directional detectors NaI, Germanium	**Fri**
	6	Cryogenic liquids Xenon and Argon	

Some Literature (incomplete!)

- Perkins: *Particle Astrophysics, Oxford University Press*
- *Bertone (ed): Particle Dark Matter, Cambride University Press*
- *Bertone, Hooper: A History of Dark Matter, arXiv:1605.04909*

- Lewin/Smith: *Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil*, *pa.brown.edu/articles/Lewin_Smith_DM_Review.pdf*
- Baudis: *Direct Dark Matter Detection*, *arXiv:1211.7222*
- Schumann: *Dark Matter 2014*, *arXiv:1501.01200*
- Marrodan/Rauch: *Direct Detection Experiments, arXiv:1509.08767*
- Heusser*: Low-radioactivity background techniques, http://fizisist.web.cern.ch/fizisist/research/Low-RadioactivityBackgroundTechniques.pdf*

1 Evidence for dark matter

- There is evidence for dark matter at all length scales
  → from the virial theorem and Galaxy clusters
  → the rotation curve of galaxies
  → precision cosmology with the CMB
- The ΛCDM Model is the „standard model of cosmology".
  → it describes the Universe with only 6 parameters
  → one of the parameters is the dark matter density

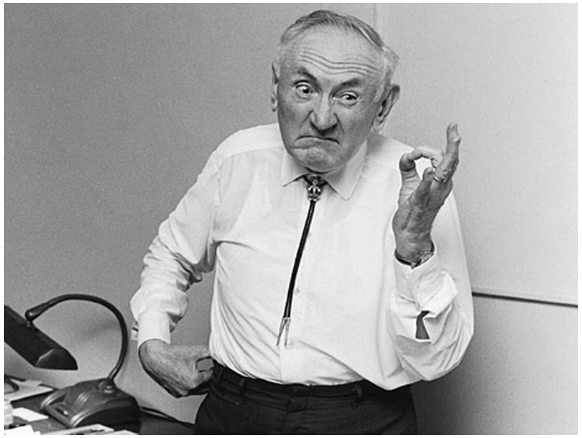
Coma Cluster

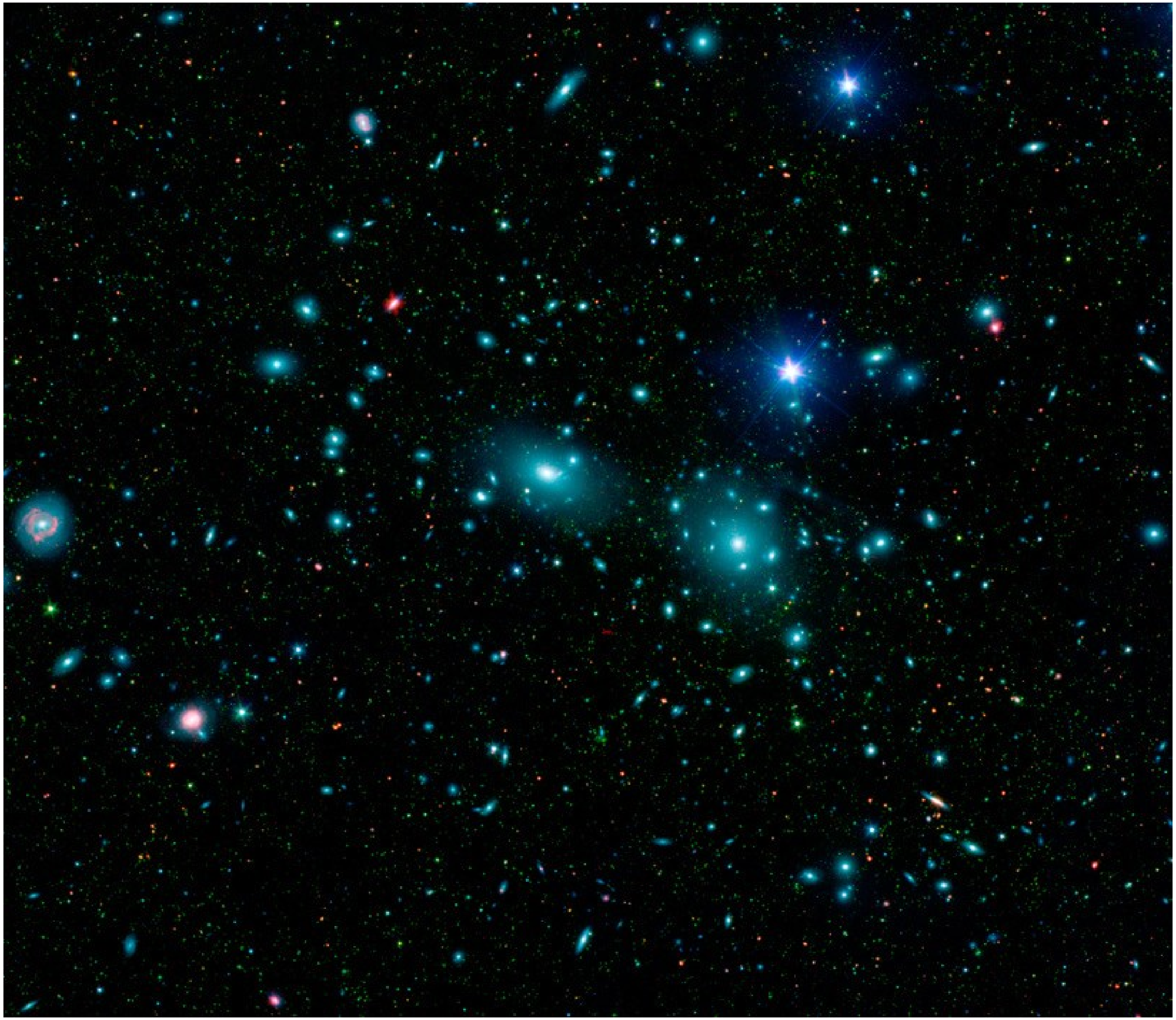
$R \sim 2 \times 10^6$ LY

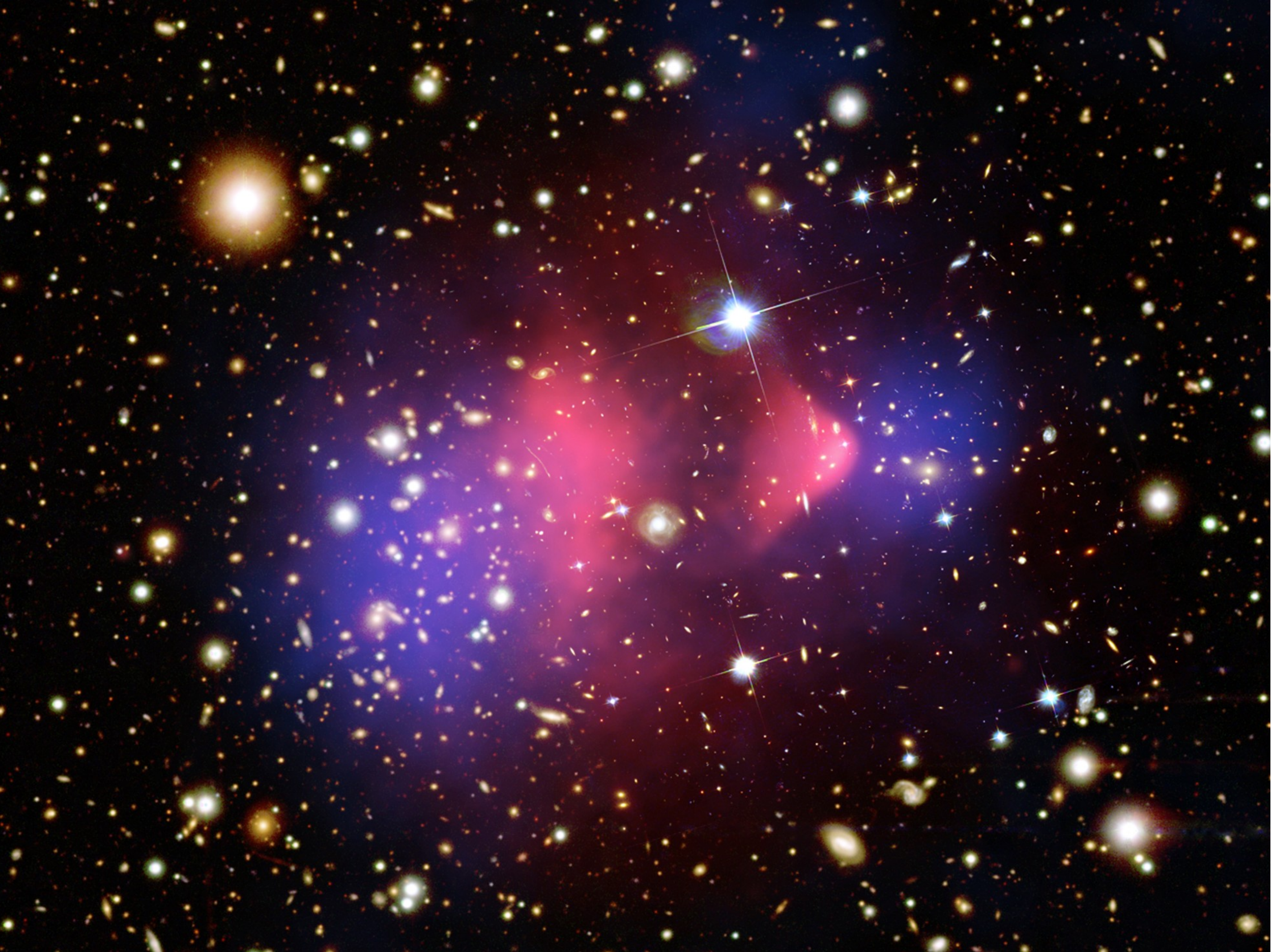
$= 1.9 \times 10^{22}$ m

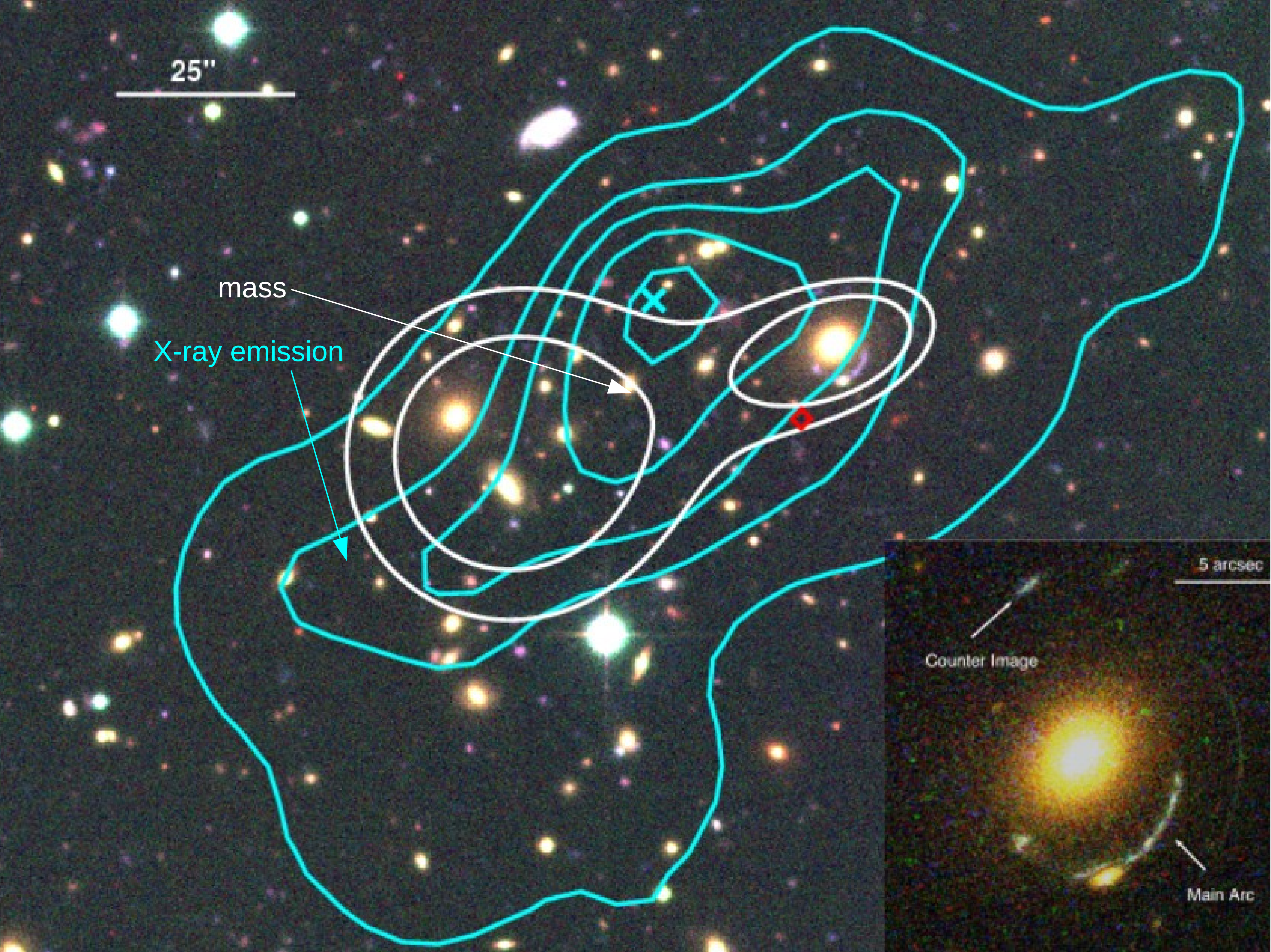
$\langle v^2 \rangle \sim 5 \times 10^{11}$ m^2/s^2

F. Zwicky



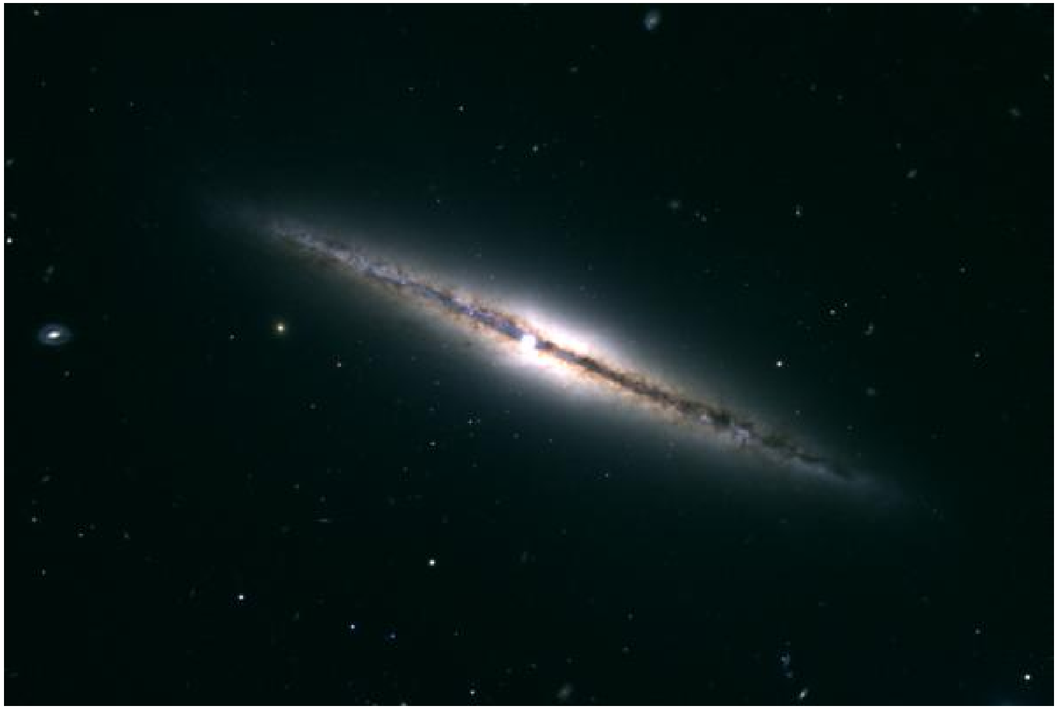




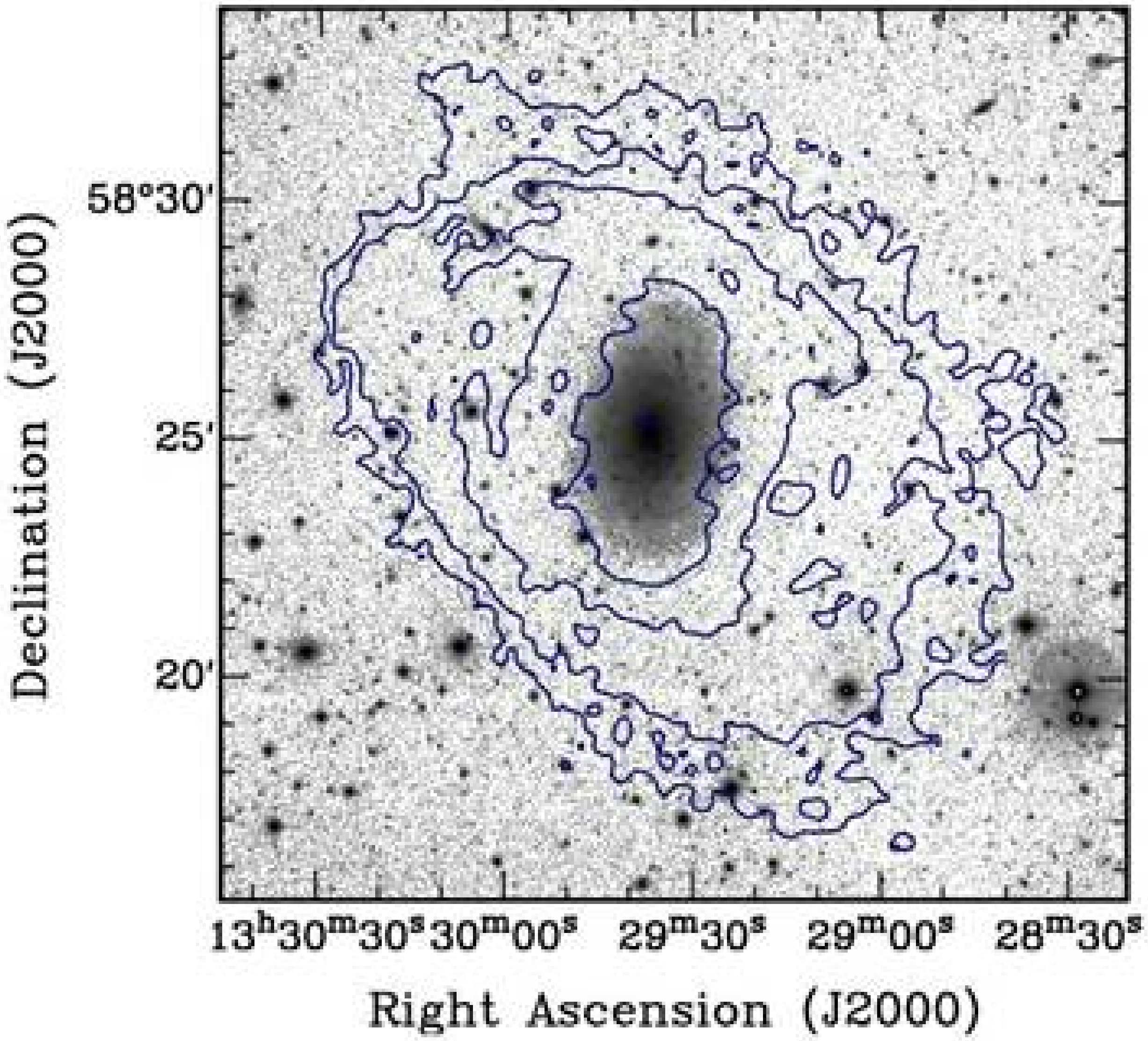


25''
mass
X-ray emission
5 arcsec
Counter Image
Main Arc

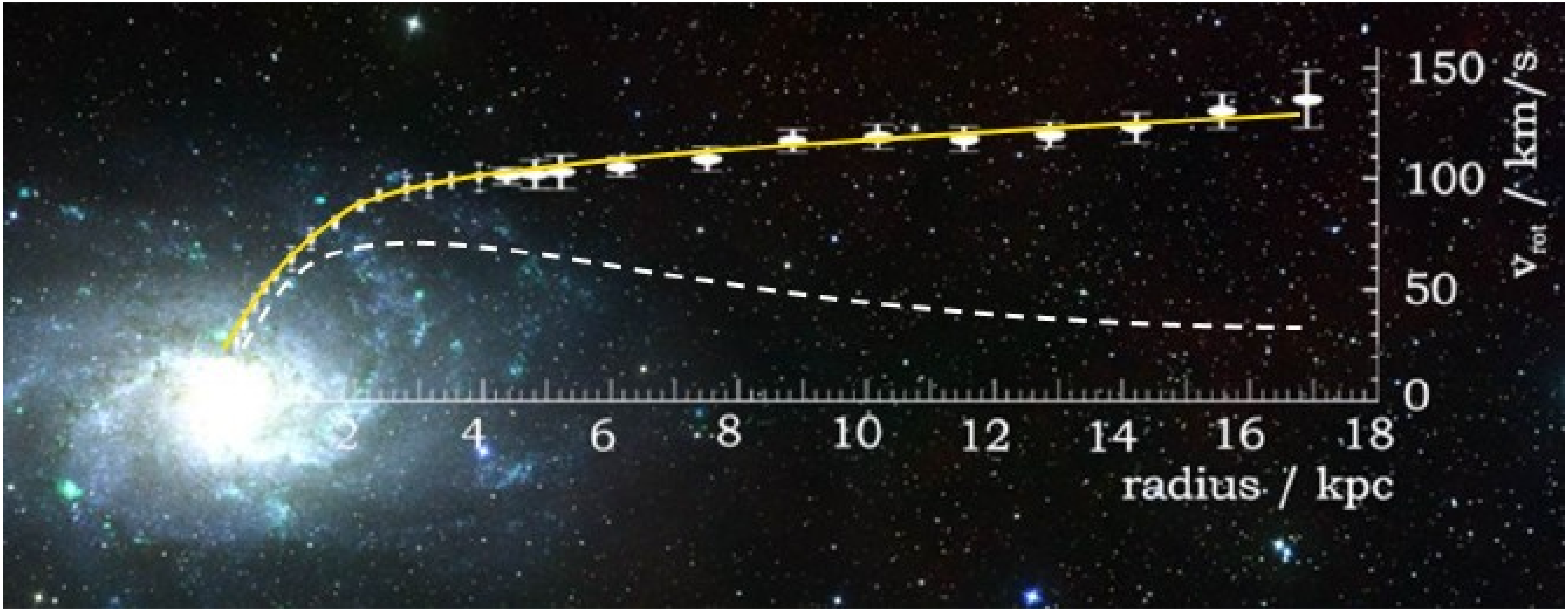
Spiral Galaxies



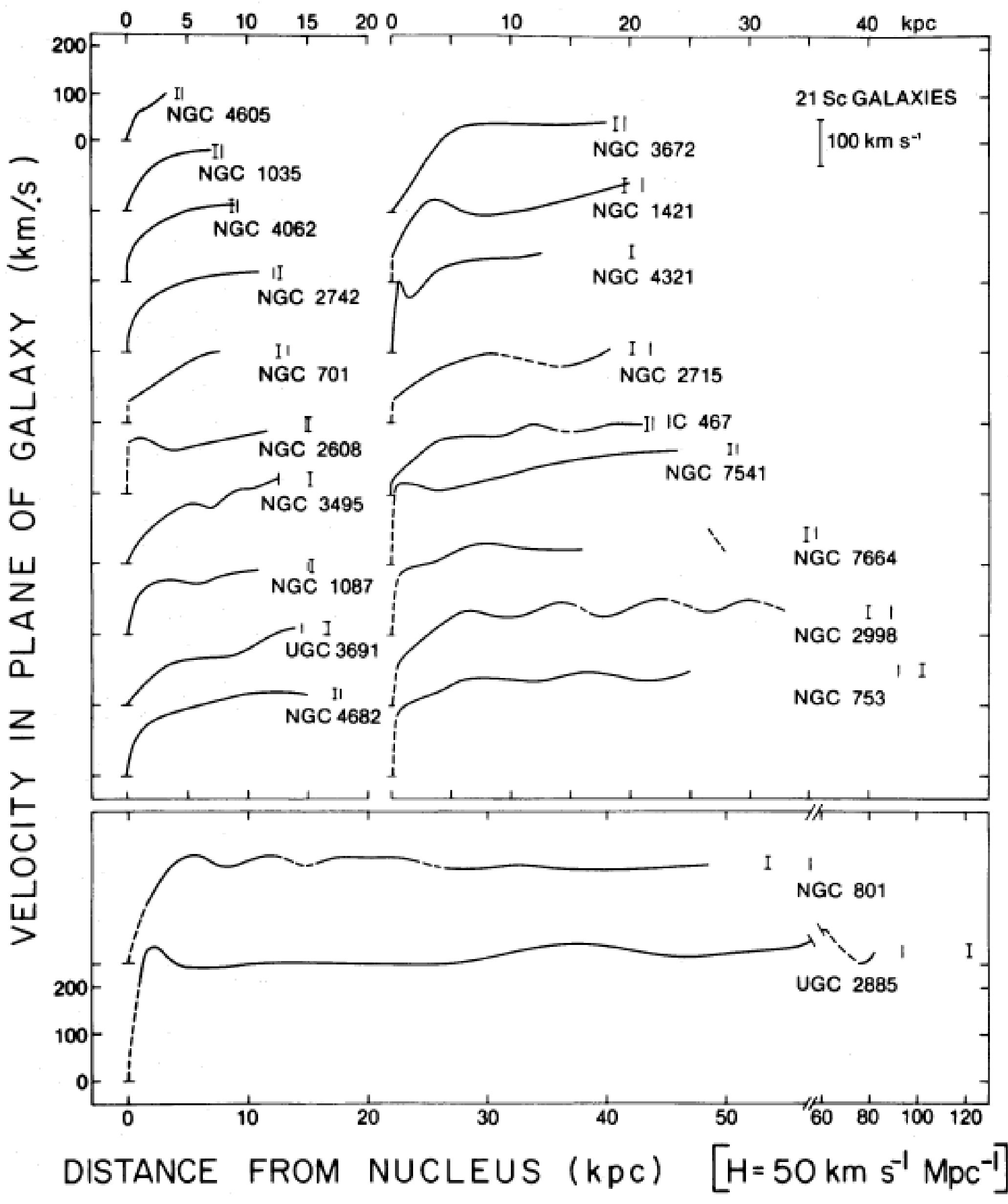
Use HI regions

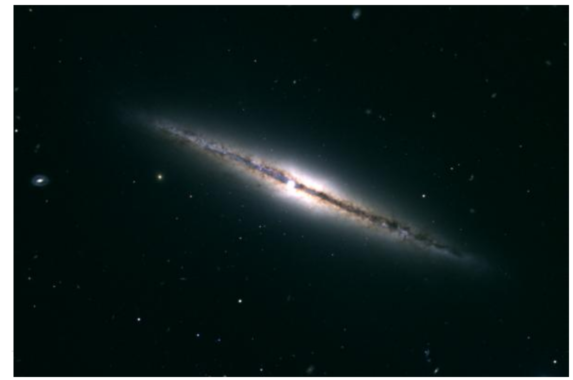


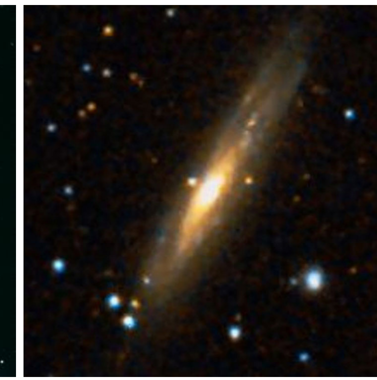
M33



Galactic Rotation Curves

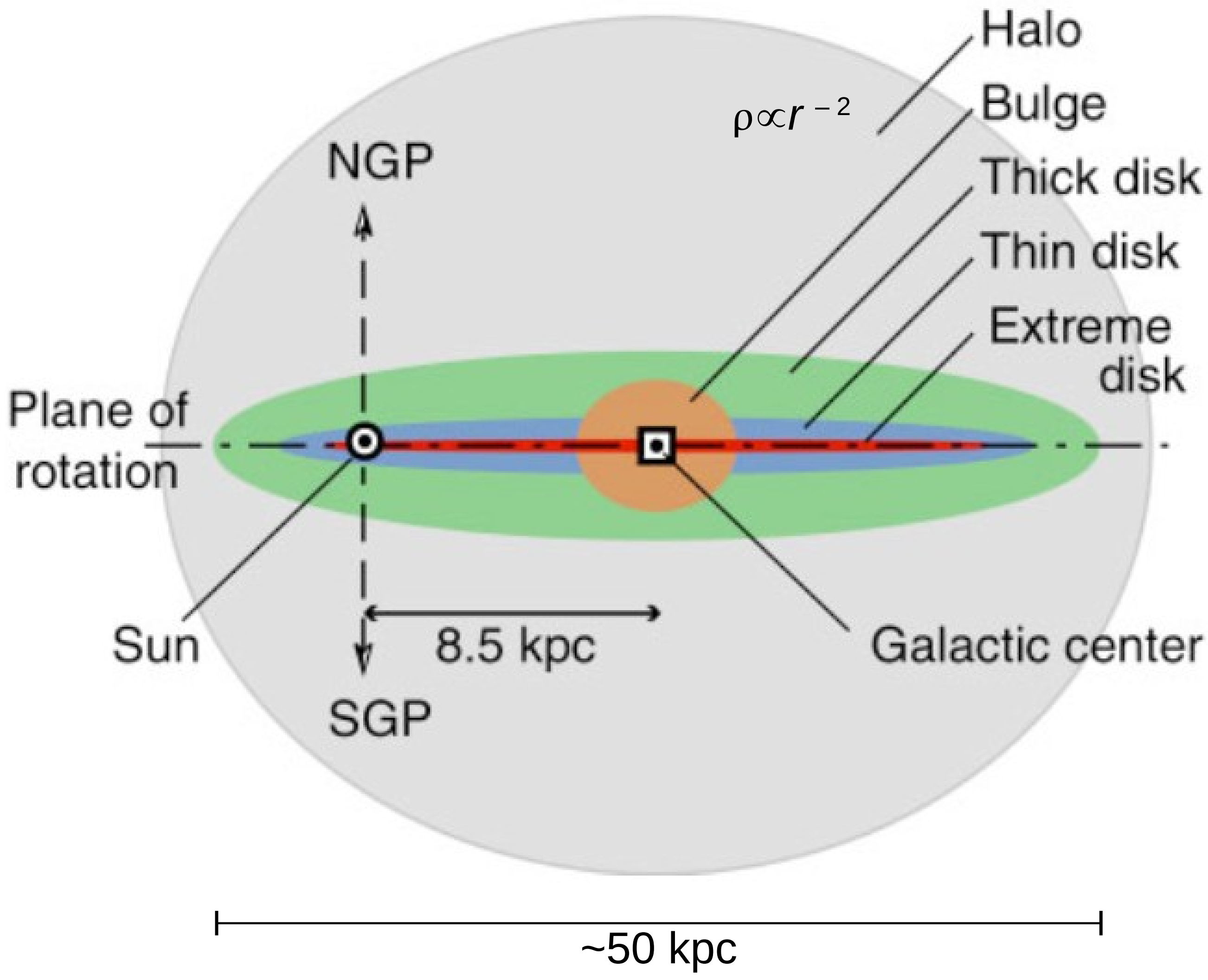




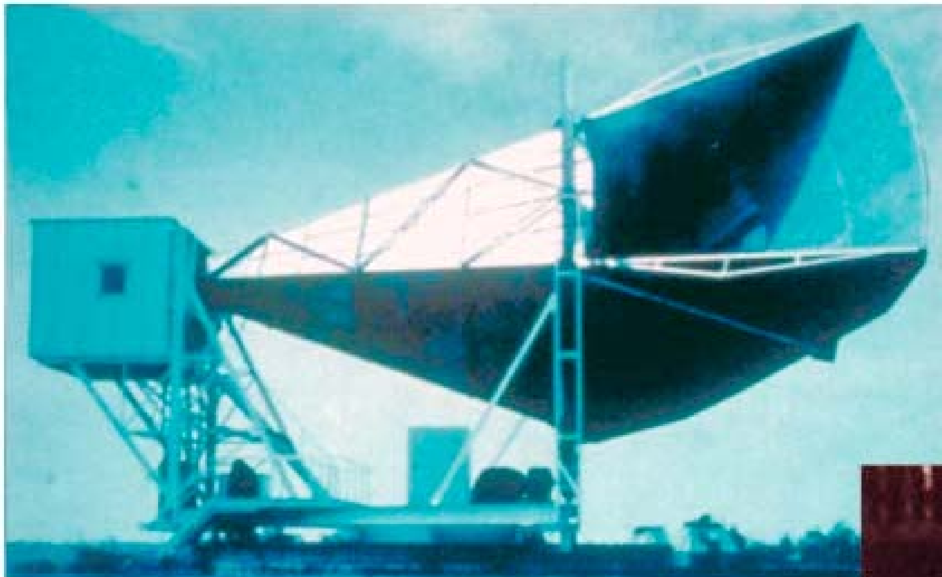


V. Rubin:

The Milky Way

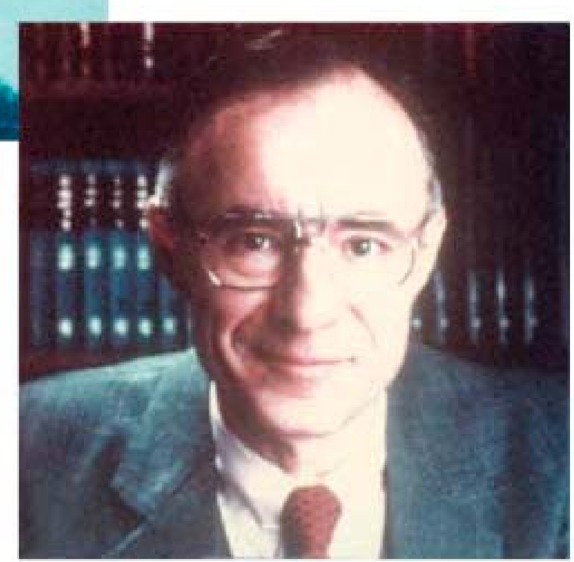


Discovery of the CMB



Microwave Receiver

Nobel prize 1978

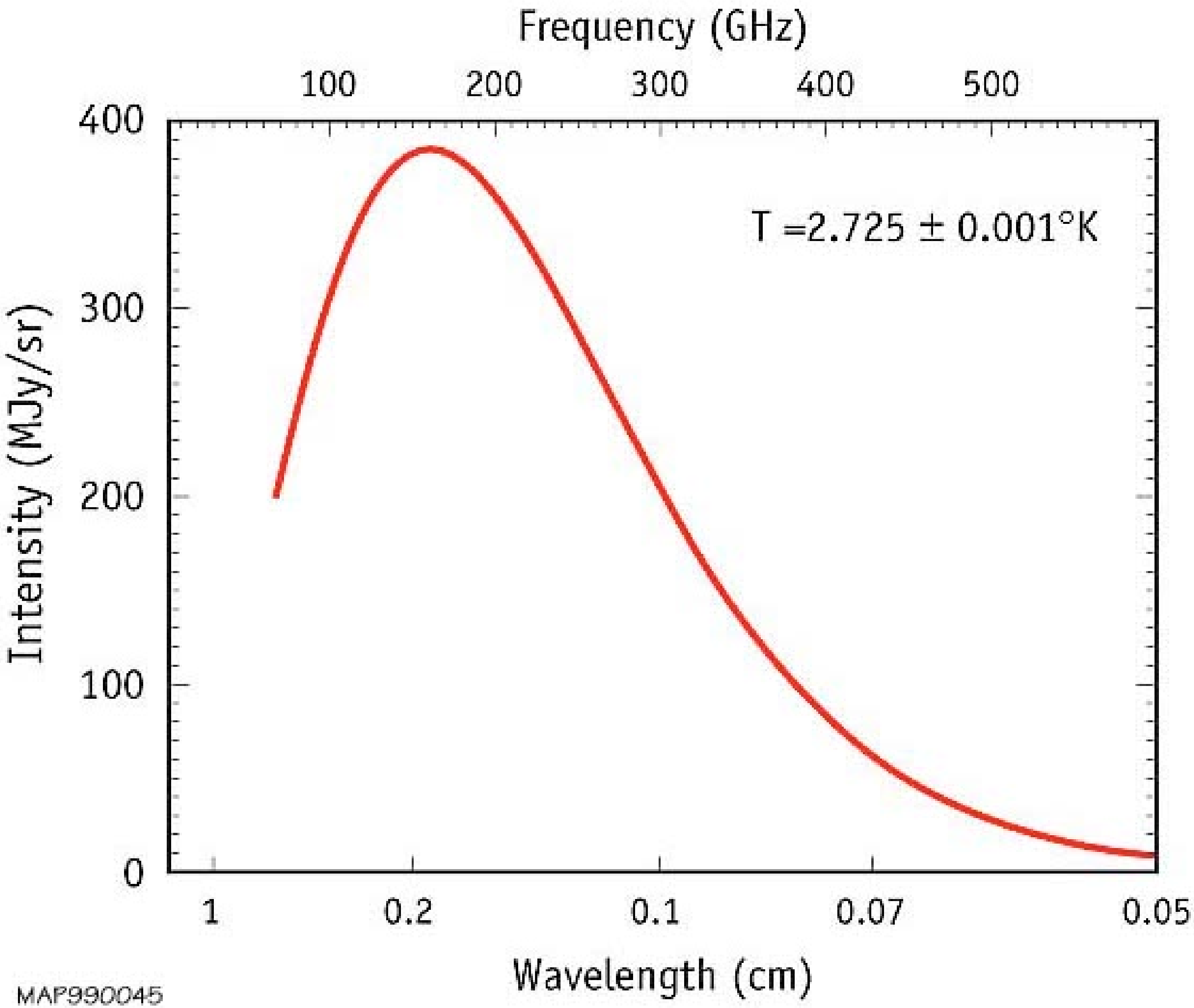


Arno Penzias

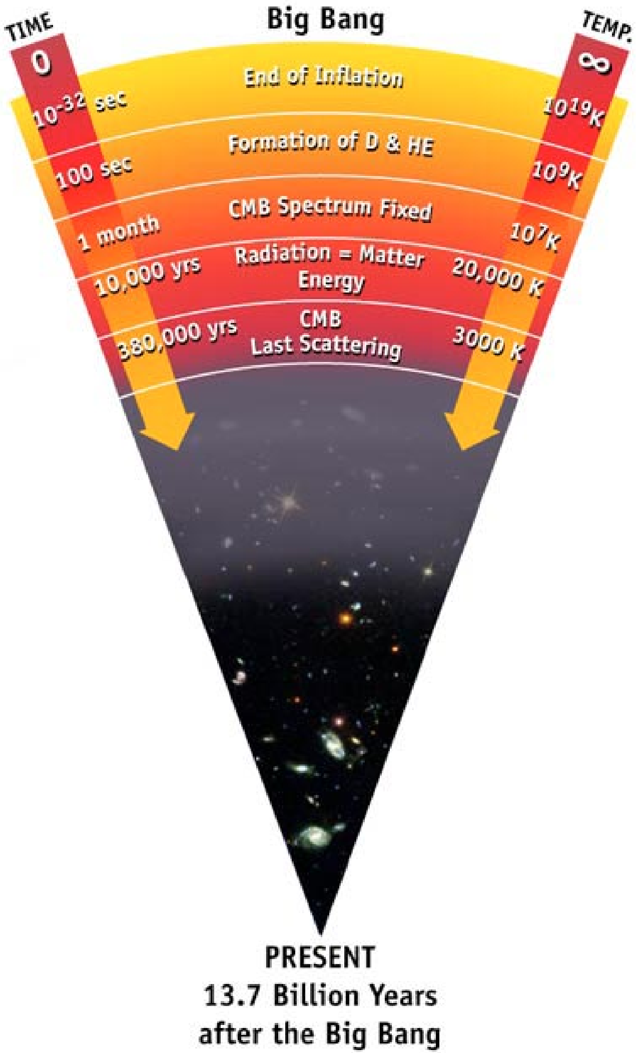
Robert Wilson

MAP990045

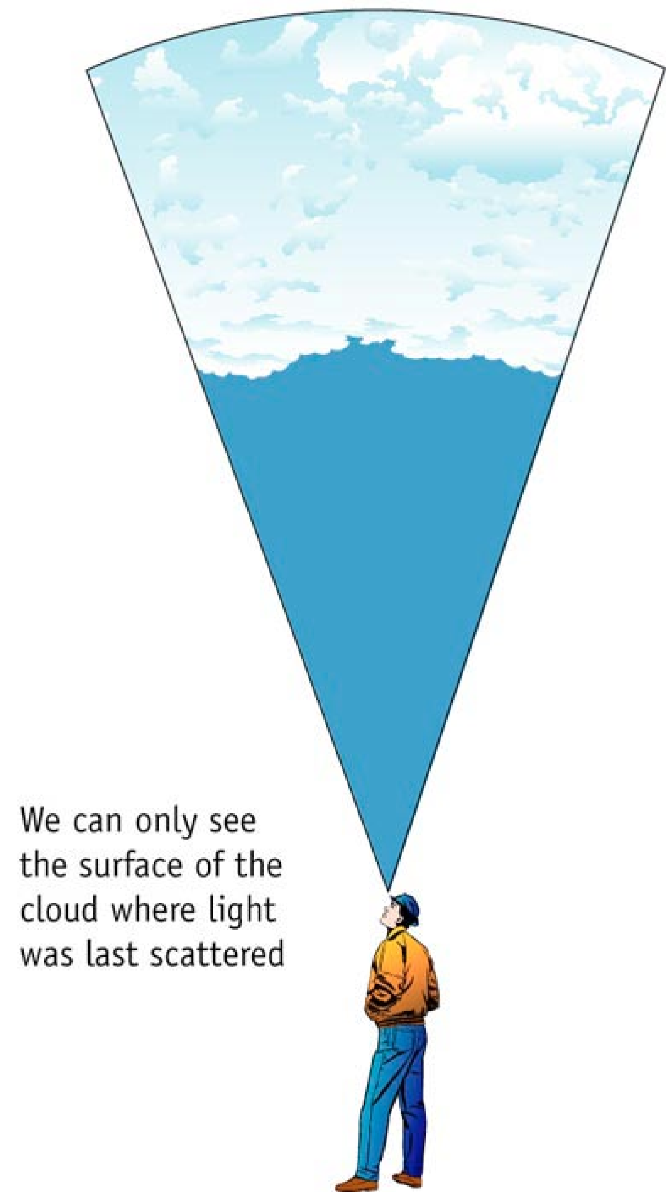
What is the CMB?

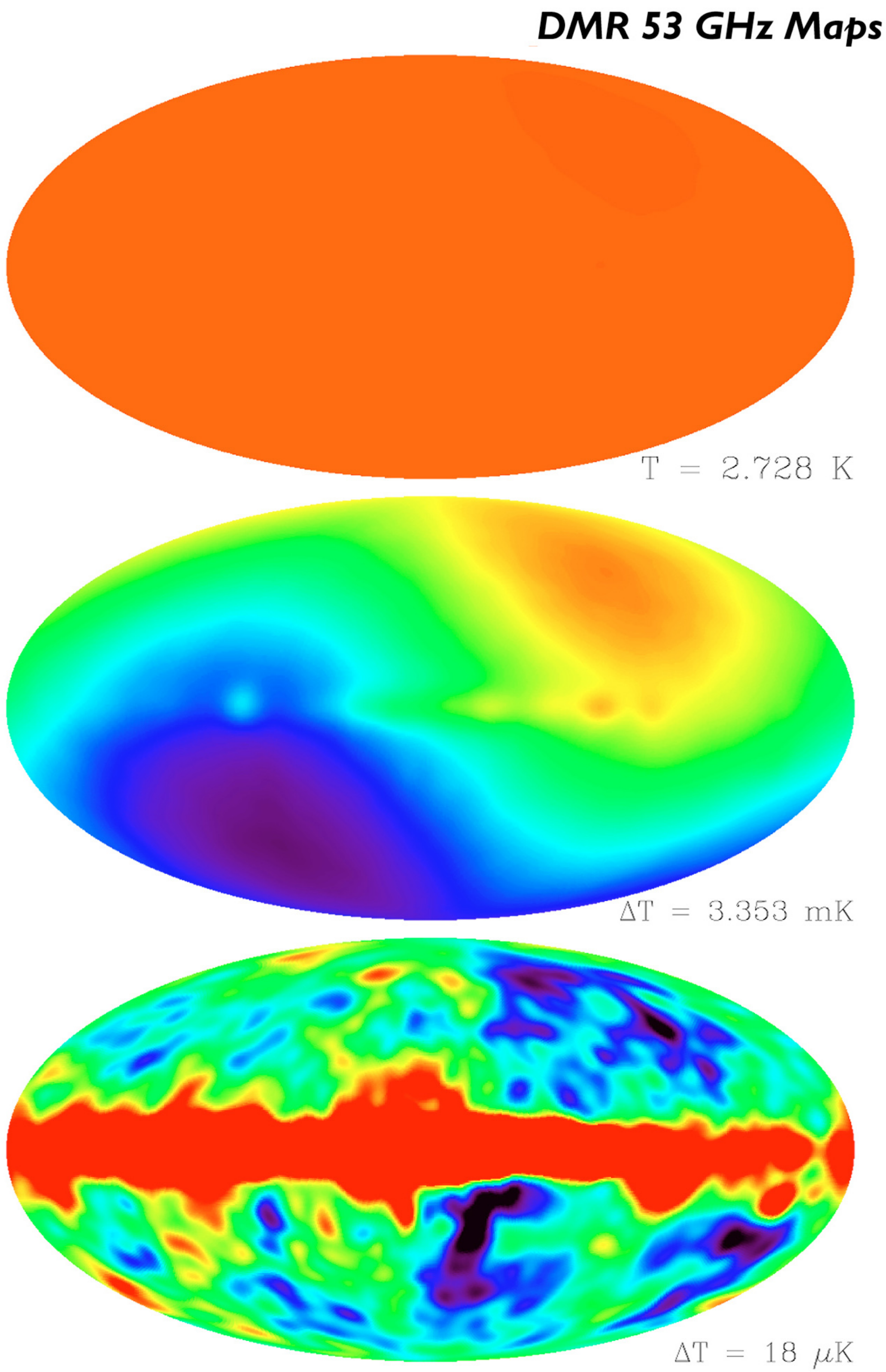


CMB: The „surface of last scatter“



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

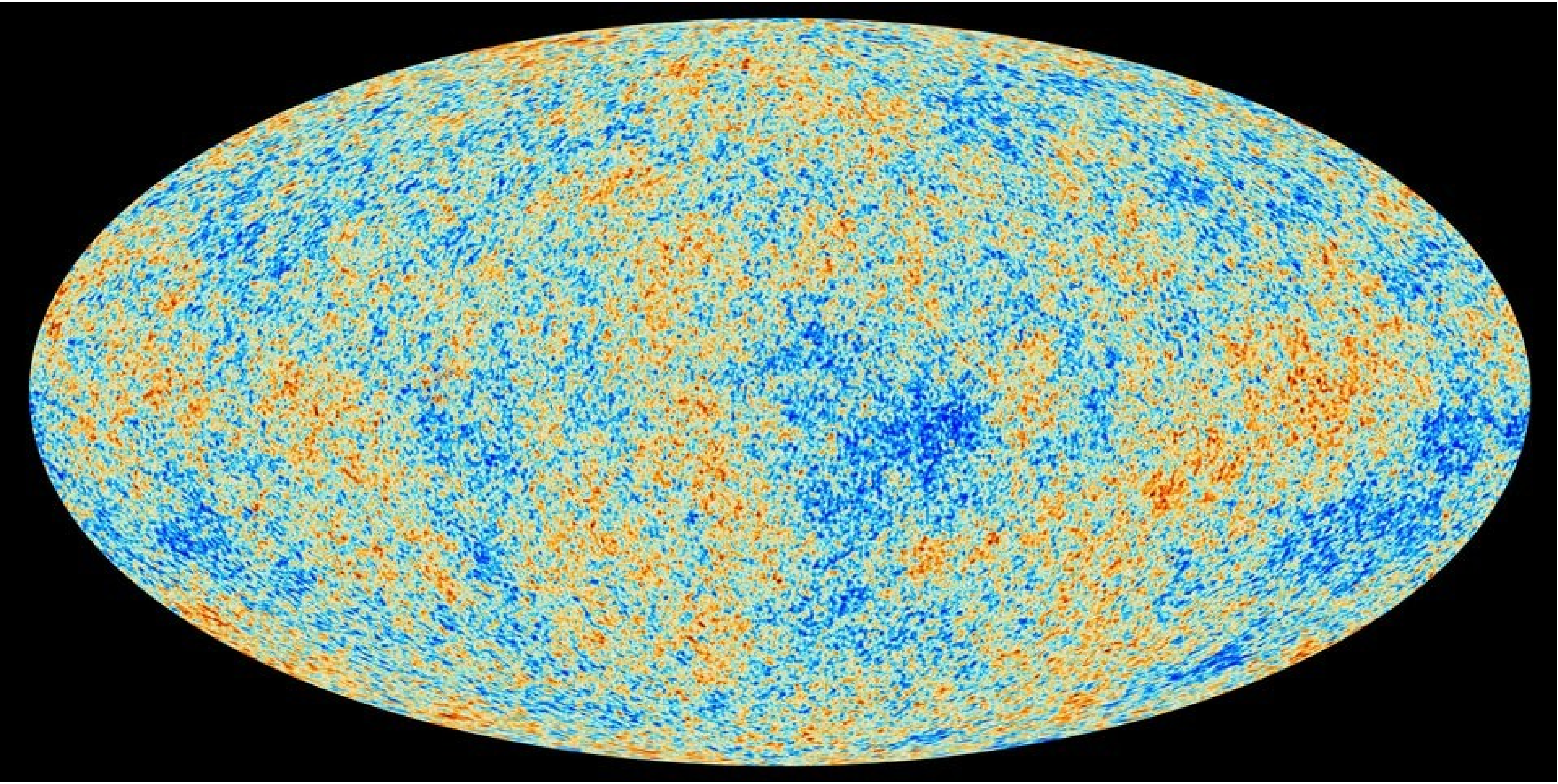




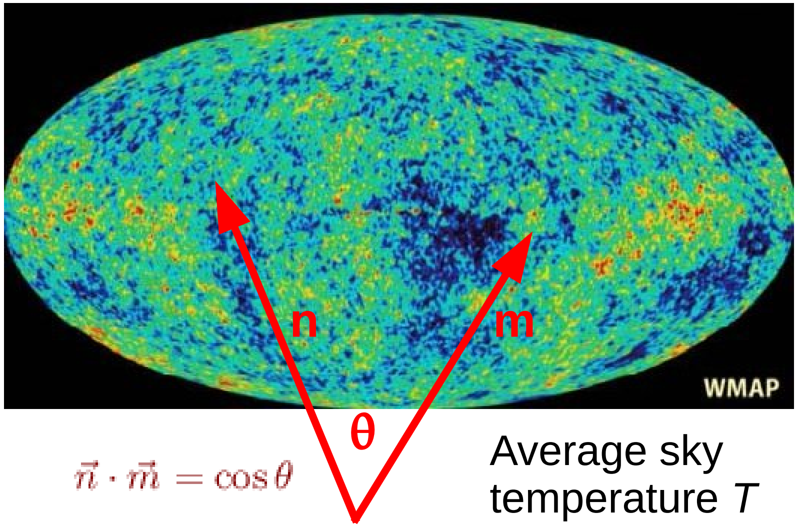
CMB is remarkably isotropic
→ perfect black body spectrum

$\Delta T/T = 10^{--3}$
→ large dipole visible from Doppler effect since Earth is moving wrt the CMB

$\Delta T/T = 10^{--5}$
→ primoridial fluctuations become visible
strong signal from Milky Way



Analyzing the CMB



$\vec{n} \cdot \vec{m} = \cos\theta$

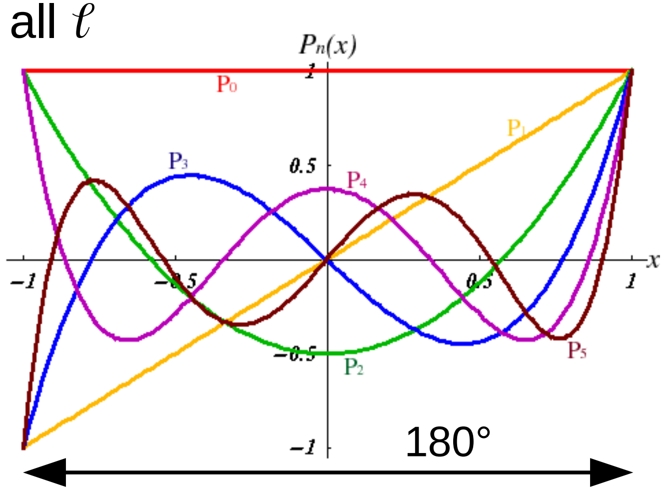
Average sky temperature *T*

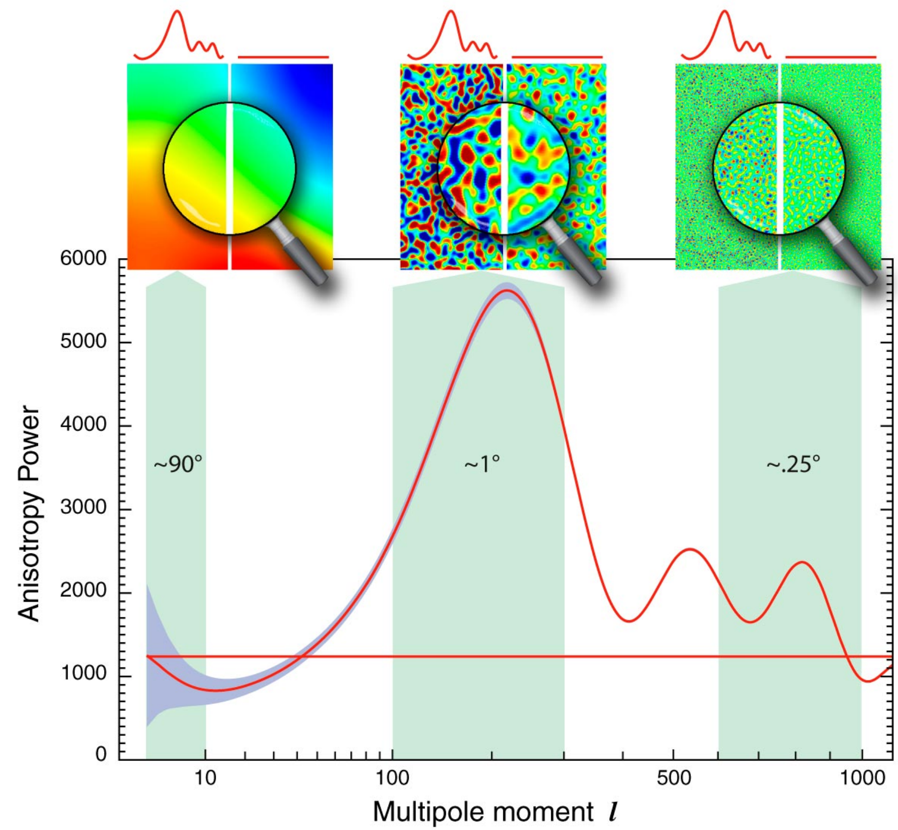
Correlation between pairs of points of the CMB:

$$C(\theta) = \left\langle \left(\frac{\Delta T(\vec{n})}{T}\right) \left(\frac{\Delta T(\vec{m})}{T}\right) \right\rangle = \frac{1}{4\pi} \sum (2\ell+1) C_\ell P_\ell(\cos\theta)$$

The $P_\ell(\cos\theta)$ are the Legendre polynomials, running over all ℓ

$$\Delta\theta \approx \frac{\pi}{\ell} = \frac{180}{\ell}$$



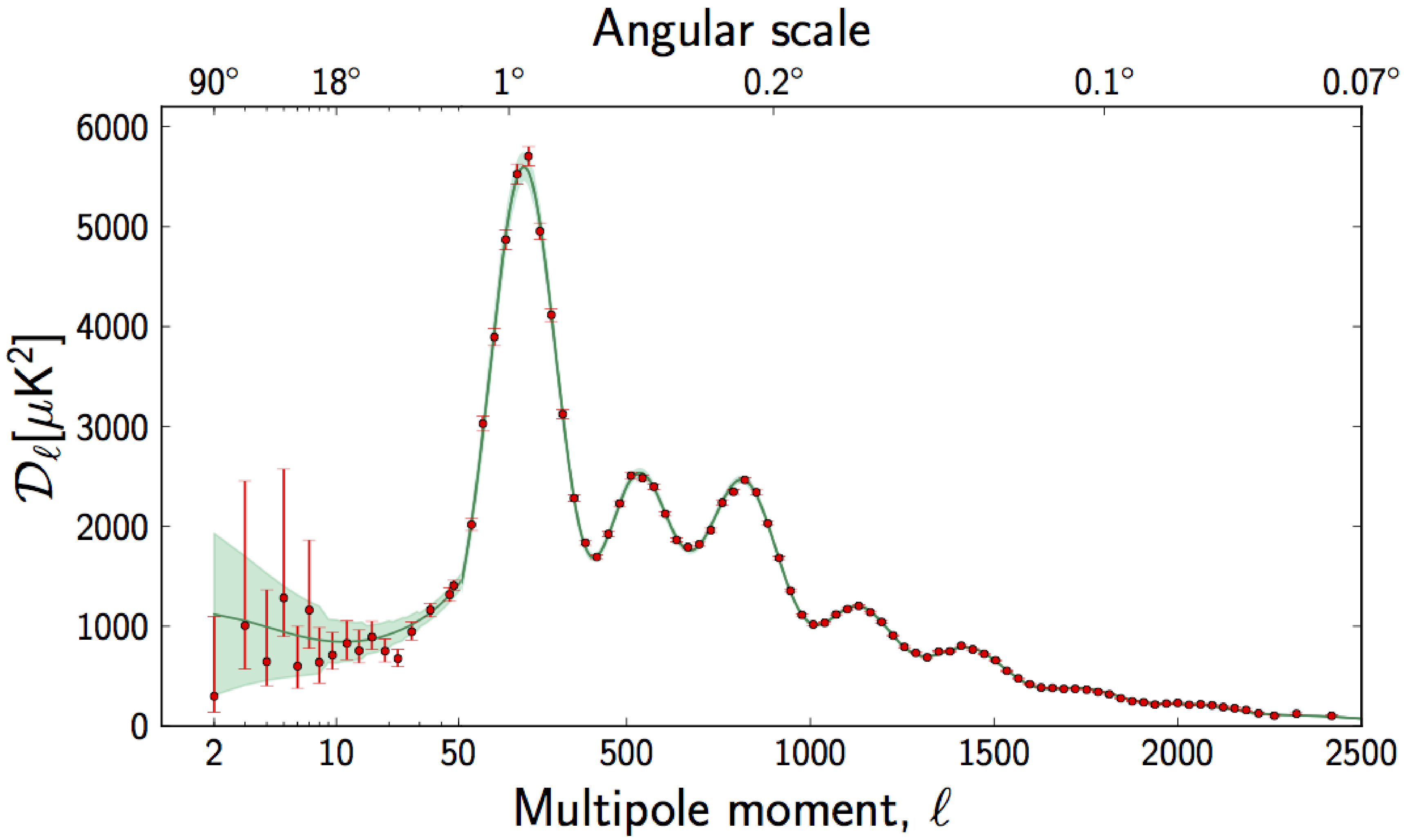


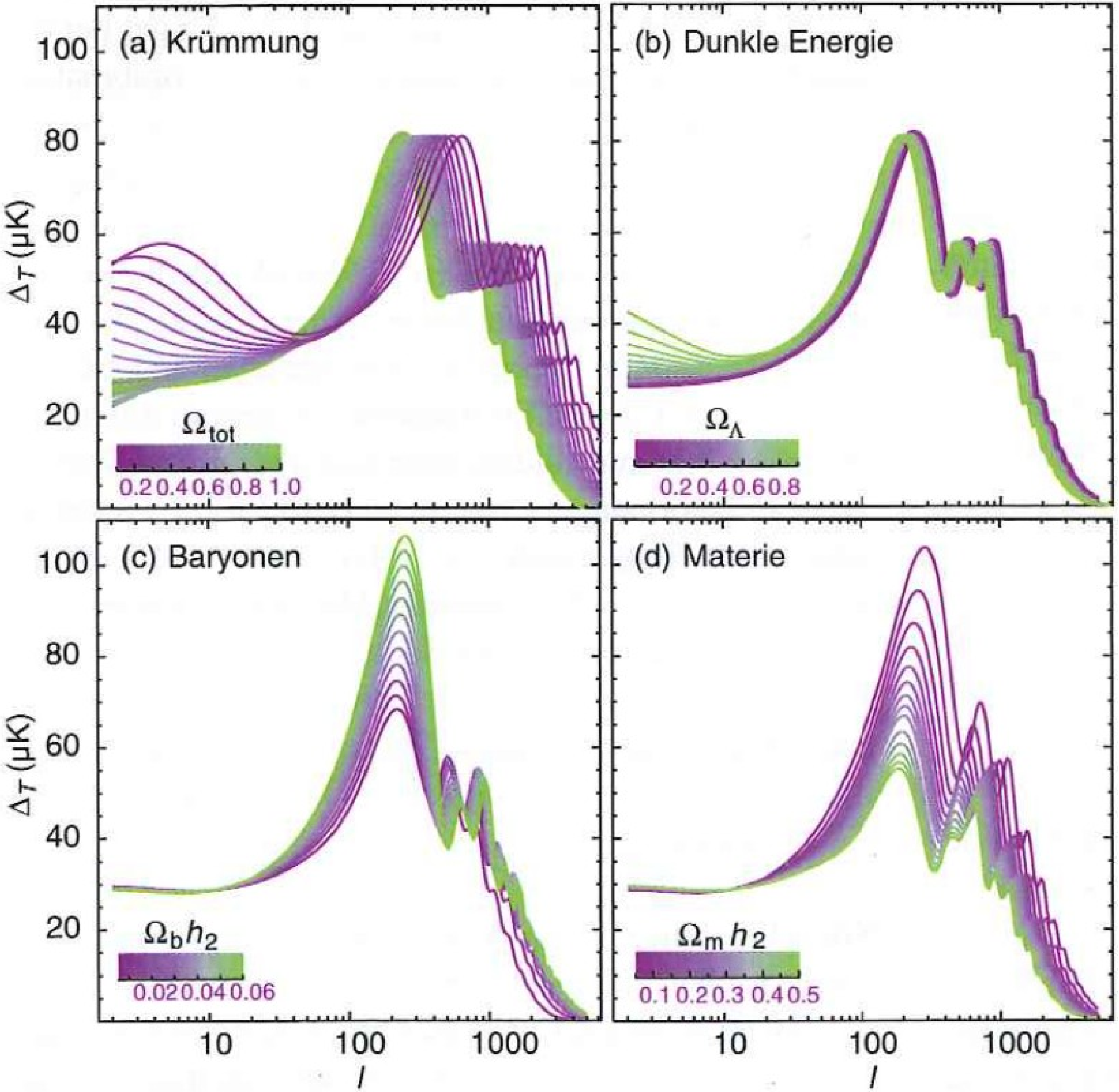
ℓ = 8.. 10 → ~90°

ℓ = 100.. 300 → ~1°

ℓ = 600..1000 → ~0.25°

The Planck spectrum



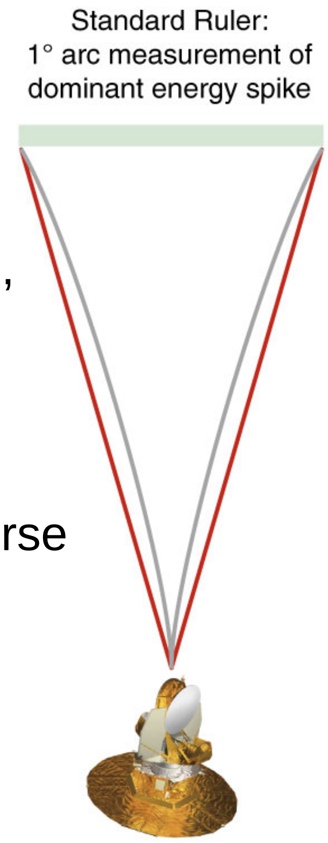


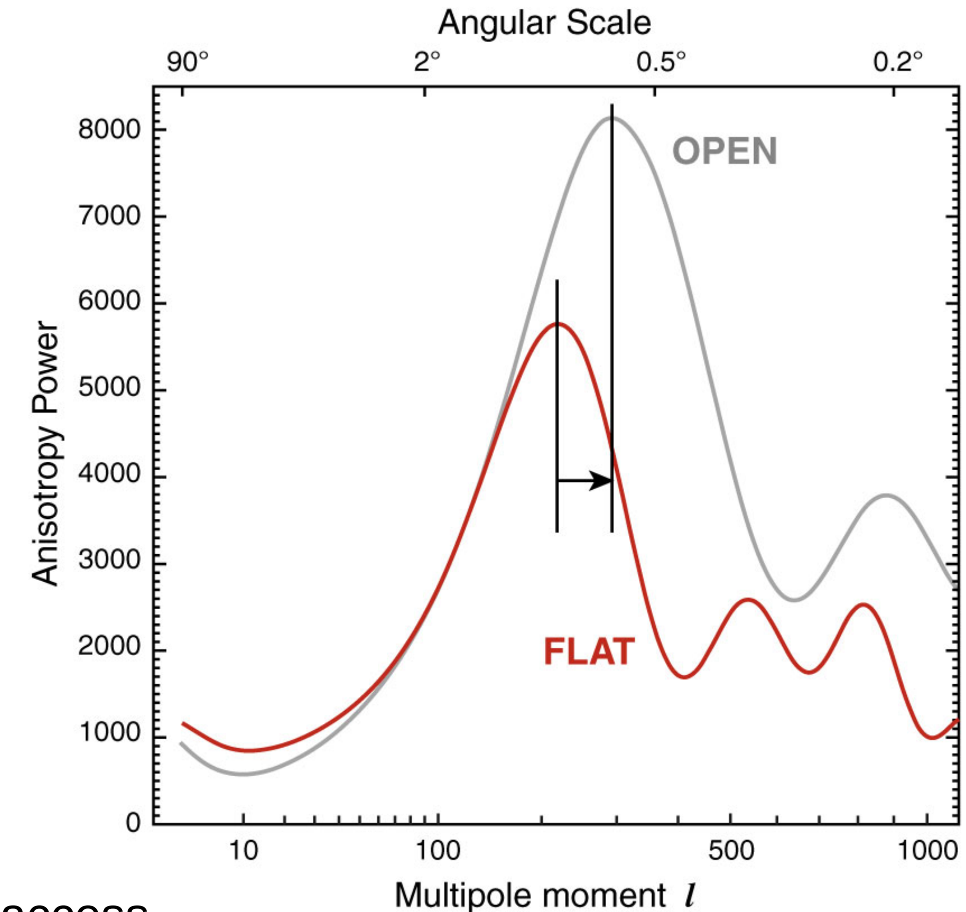
Abhängigkeit der CMB-Fluktuationen von kosmologischen Parametern. In allen Fällen ist das Referenzmodell beschrieben durch $\Omega_m + \Omega_\Lambda = 1$, $\Omega_\Lambda = 0.65$, $\Omega_b h^2 = 0.02$, $\Omega_m h^2 = 0.147$ und einer Steigung des primordialen Dichtespektrums $n = 1$, entsprechend dem Harrison–Zeldovich-Spektrum. In den vier Darstellungen wird jeweils einer dieser vier Parameter variiert, während die anderen drei festgehalten werden

CMB – 1st peak and curvature

• Red: straight light paths to us from opposite sides of a typical hot spot in the CMB, as would be the case in a "flat" universe;

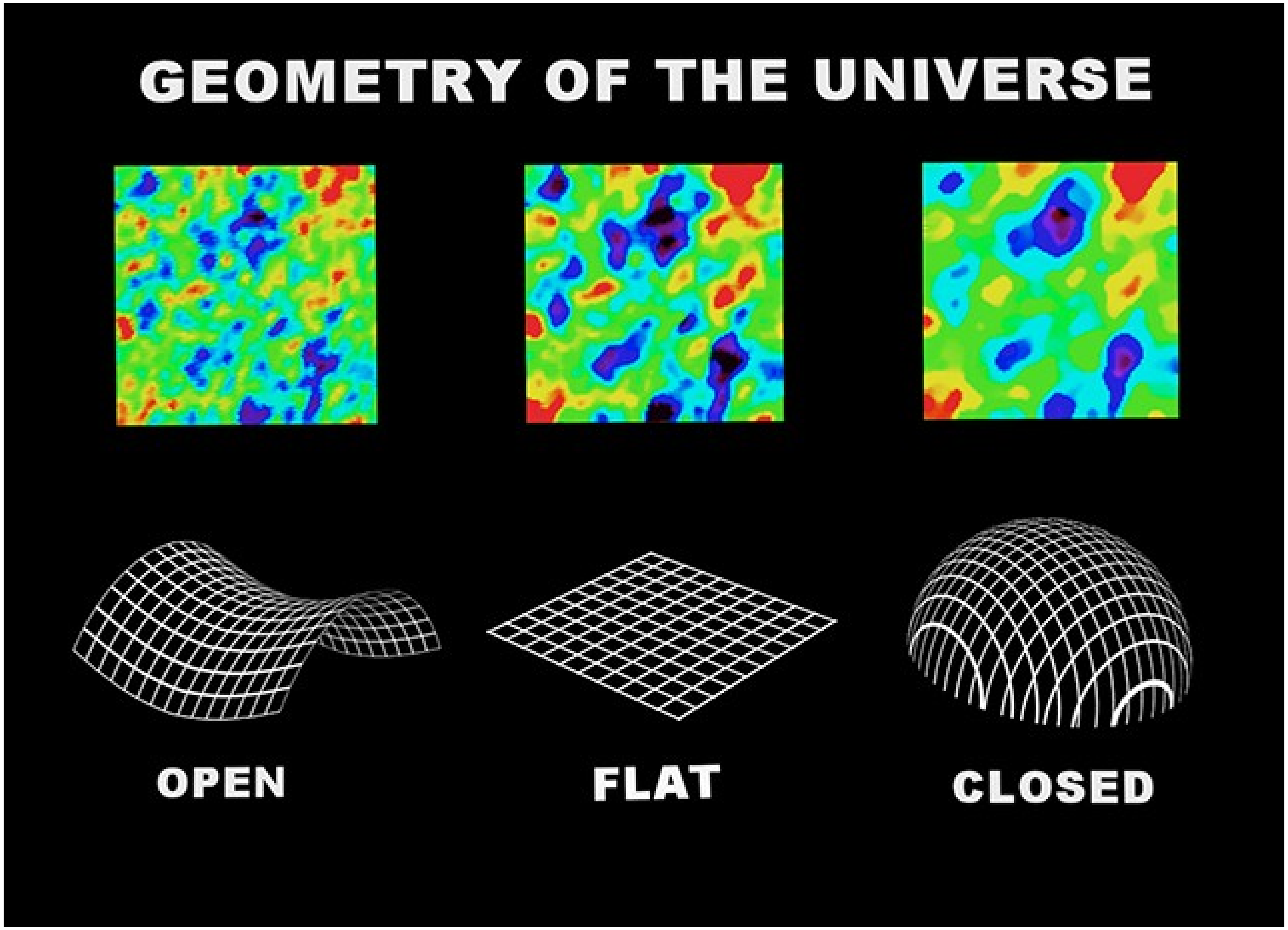
• Gray: curved light paths as they would appear in a universe with "negative curvature".



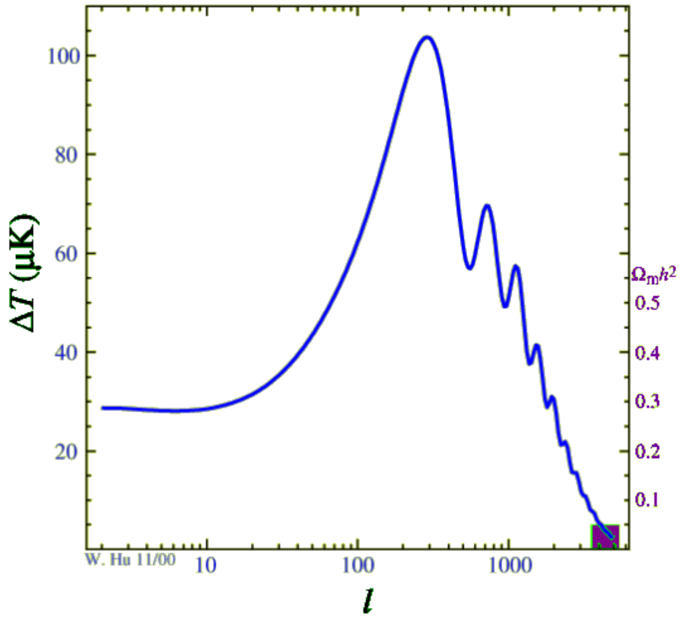


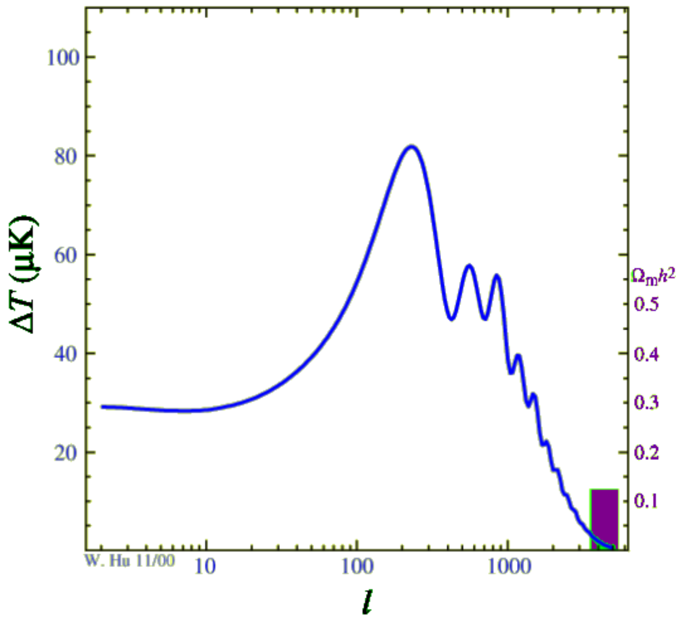
• The apparent (angular) size of the spots gives access to the information which sets of lines the light followed.

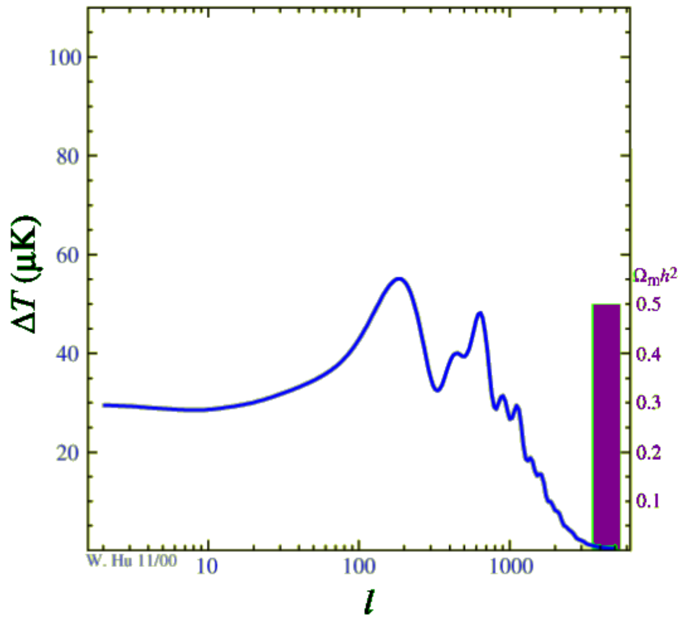
• The location of the main peak in the spectrum determines the average spot size:
flat universe – main peak at ℓ~220
negatively curved Universe („open“) → shifted to right
positively curved Universe („closed“) → shifted to left


GEOMETRY OF THE UNIVERSE
OPEN
FLAT
CLOSED

The 3rd CMB Peak – Dark Matter







less dark matter more

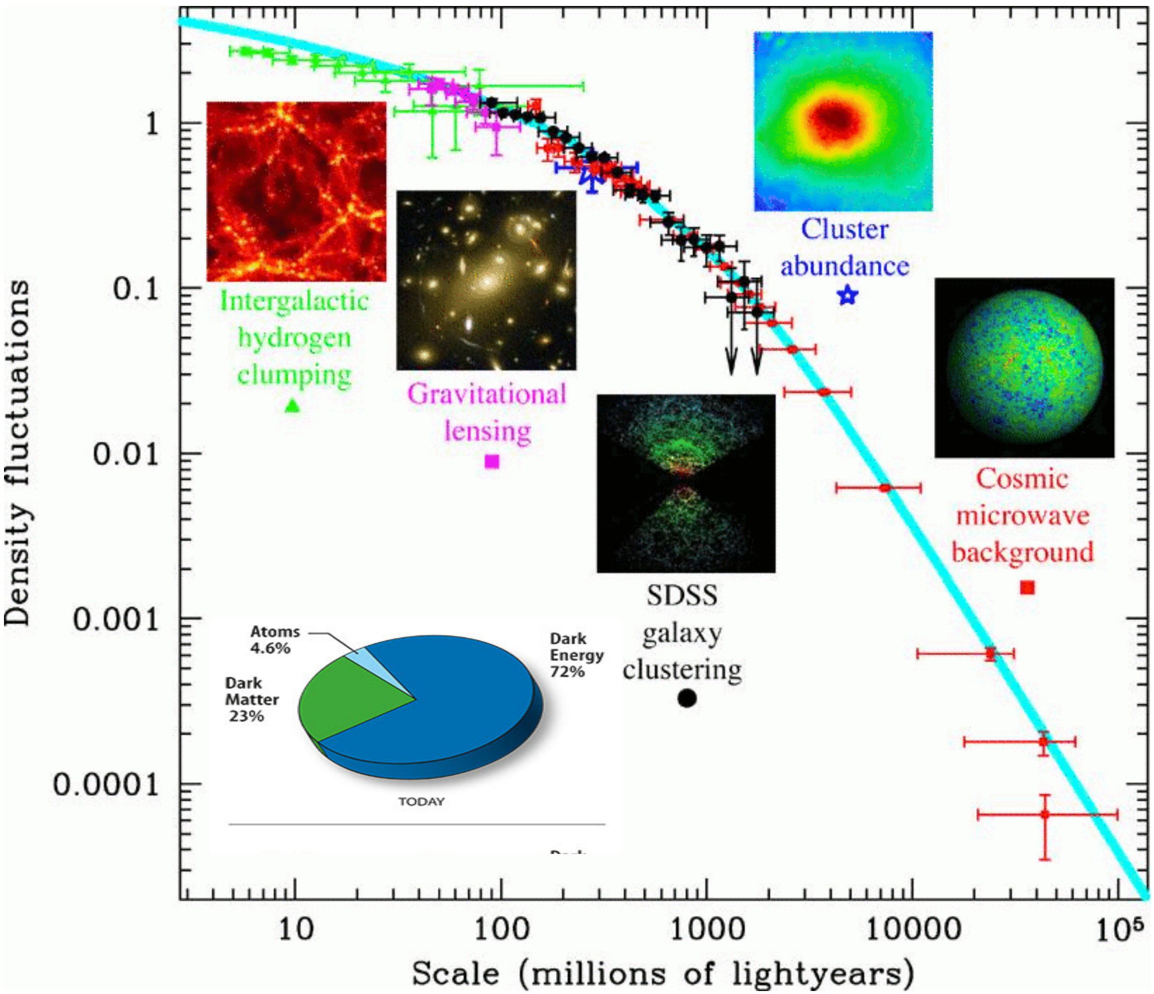
ΛCDM Model

The Standard Model
of Cosmology
(„Concordance Model")

Describes the Universe since the Big Bang with a few parameters only (6)

Uses Friedmann equation to describe evolution of Universe since Inflation

Agrees with the most important cosmological observations:
- CMB Fluctuation
- Large Scale Structures
- Accelerated Expansion (SN observations)
- Distribution of H, D, He, Li



Ingredients:
Λ Cosmological Constant
CDM Cold Dark Matter

The six parameters are (WMAP 7, Komatsu et al. 2008):

1. physical baryon density, $\Omega_b h^2 = 0.026 \pm 0.00053$,
2. physical dark matter density, $\Omega_c h^2 = 0.1123 \pm 0.0038$,
3. dark energy density, $\Omega_\Lambda = 0.728^{+0.015}_{-0.016}$,
4. scalar spectral index, $\mathrm{n}_s = 0.963 \pm 0.012$,
5. curvature fluctuation amplitude, $\Delta^2_{\mathcal{R}} = 2.441^{+0.088}_{-0.097} \times 10^{-9}$, $k_0 = 0.002 Mpc^{-1}$
6. reionization optical depth, $\tau = 0.087 \pm 0.014$

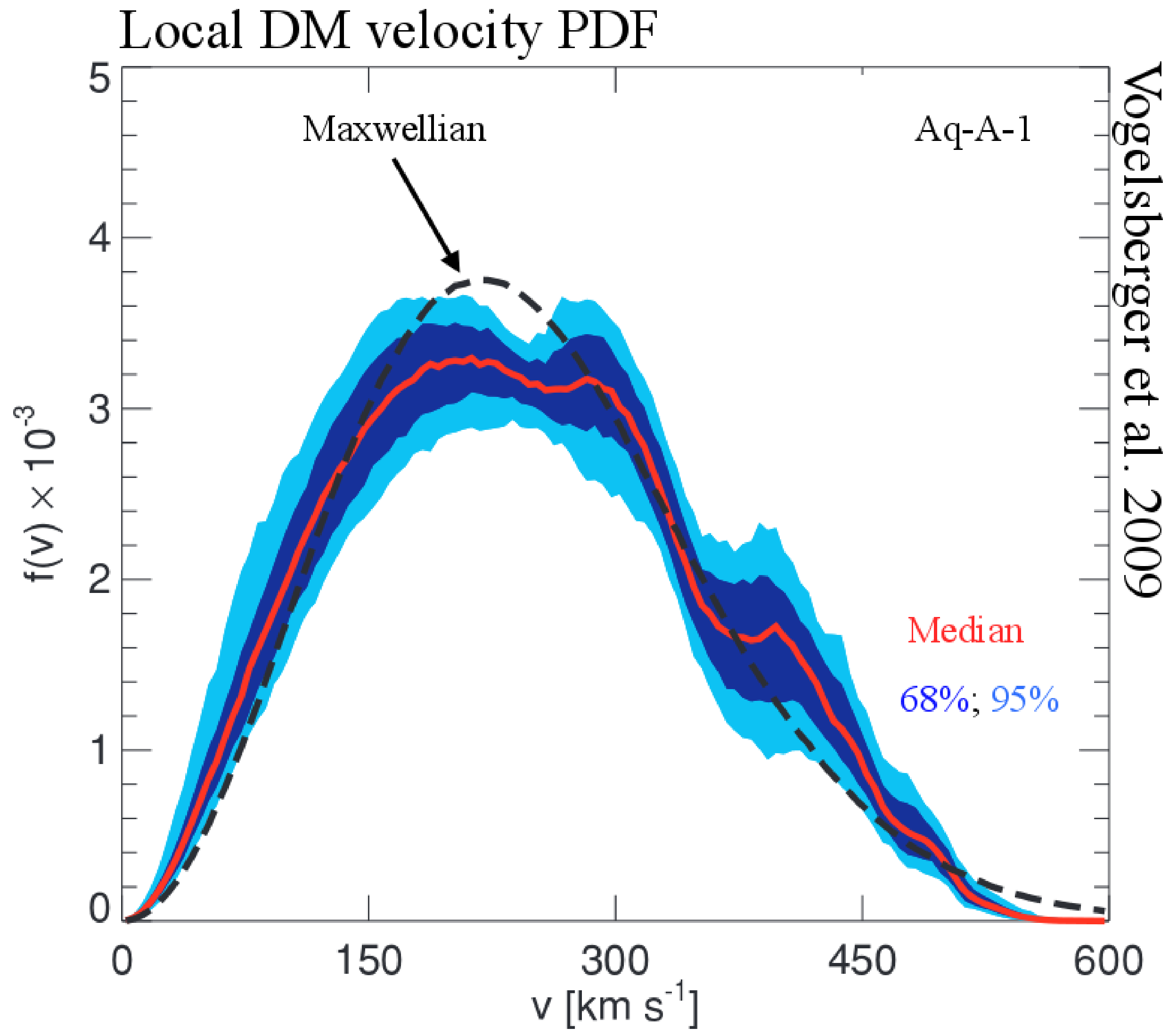
2 The standard halo model + DM Candidates

- The simplest expression for the galactic dark matter halo is the isothermal sphere
  → standard halo model = isotropic, isothermal sphere of dark matter with Maxwellian velocity distribution
- Large N-body simulations tell us about the validity and the limitation of the model
  → NFW density profile
  → core-vs-cusp in the galaxy center?
- Dark Matter Candidates
  → no known candidate
  → need new physics

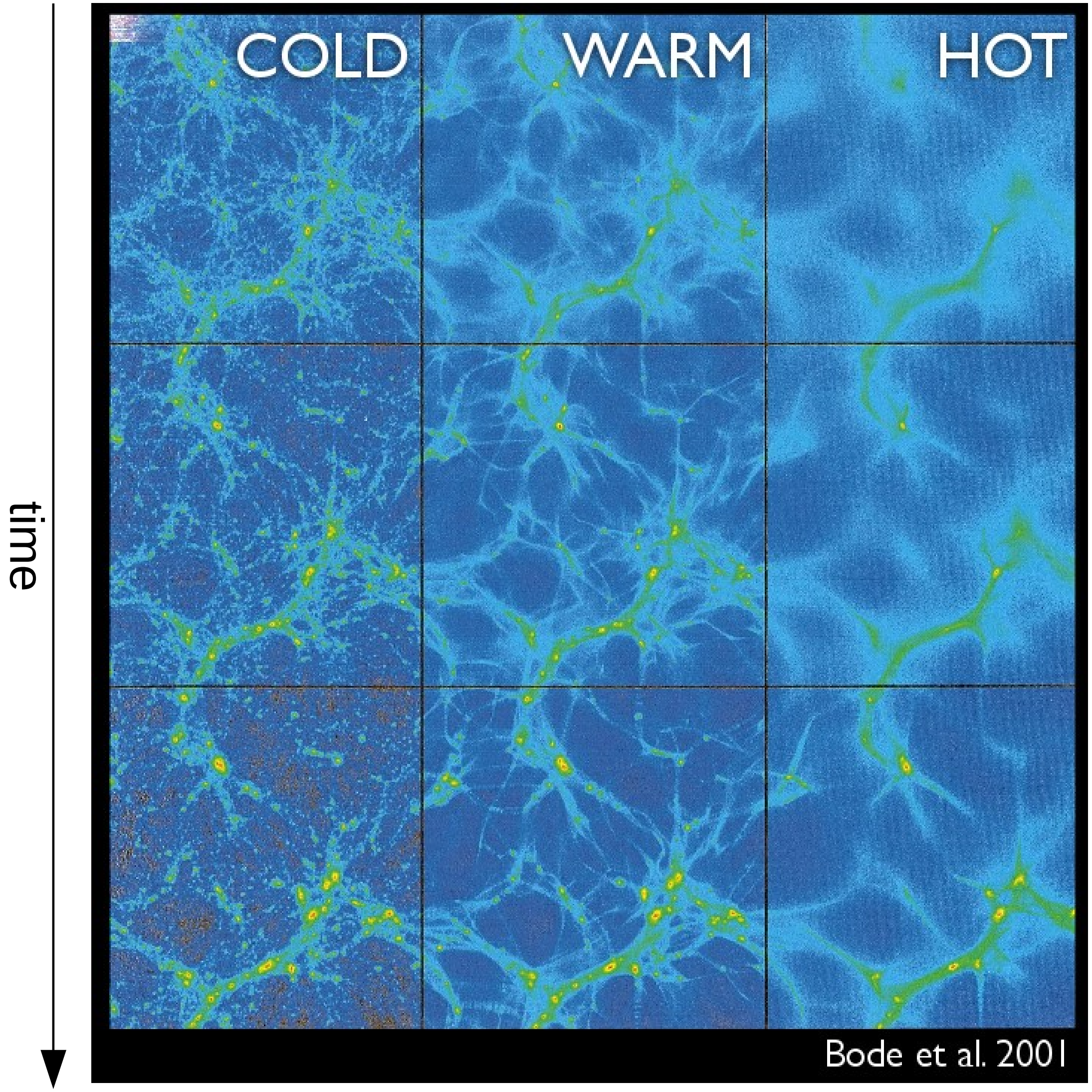
GHALO Simulation

dark matter distribution within the inner 200kpc of our Galactic halo

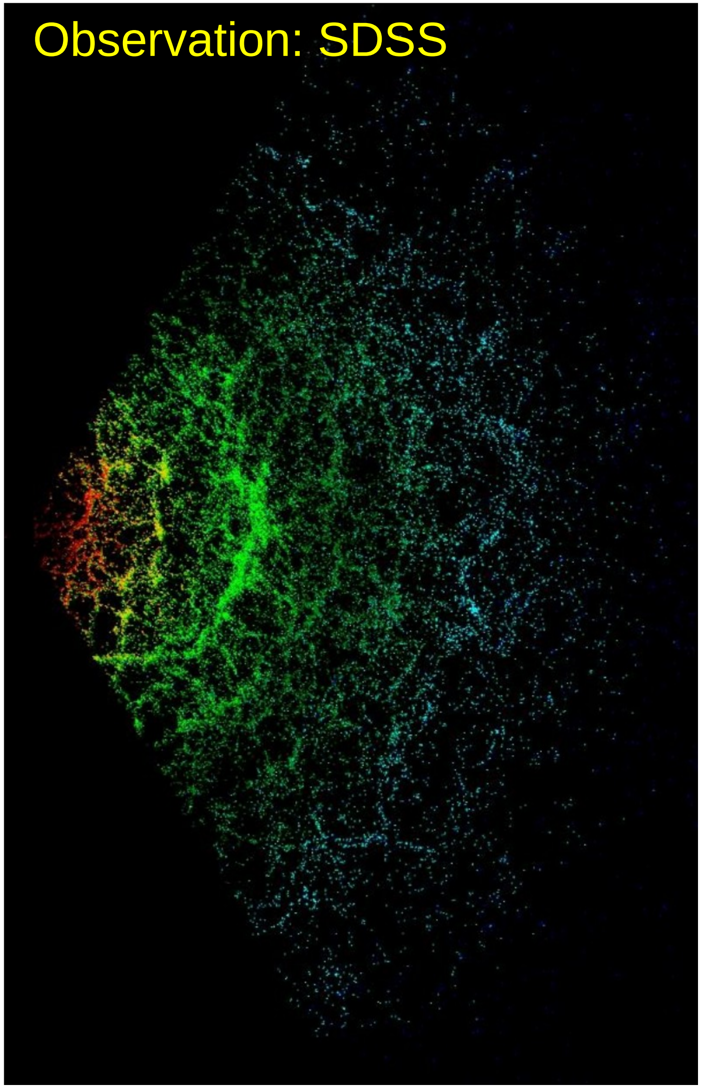
Check velocity distribution



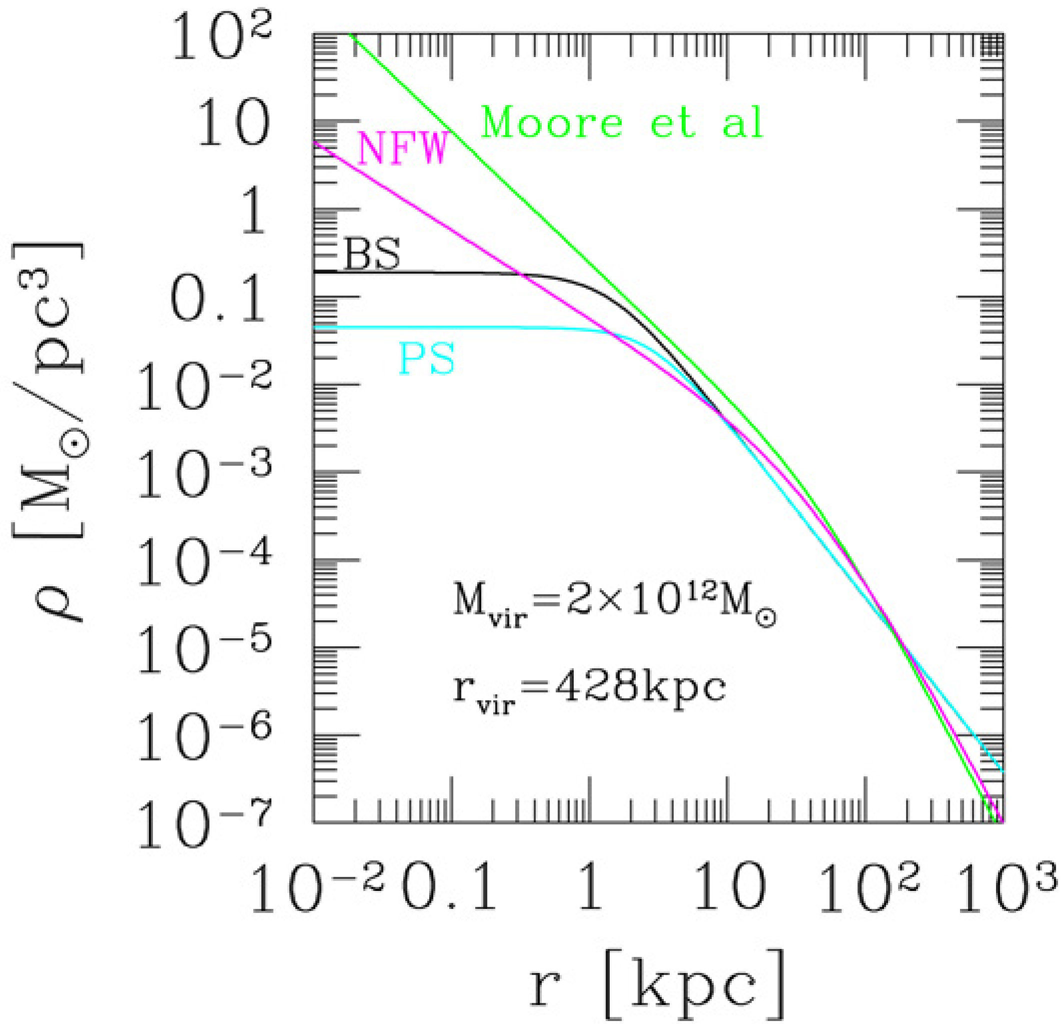
Cold vs hot dark matter



Dark Matter-only simulation



Galactic Density Profiles



avoids the divergence at r=0 and leads to a flat inner core

cored isothermal profile:

$$\rho_{\rm BS}(r) = \frac{\rho_0 a^2}{r^2 + a^2},$$

profile from fits to 100s of rot. Curves:

$$\rho_{\rm PS} = \rho_0 \frac{a^2(r^2 + 3a^2)}{3(r^2 + a^2)^2},$$

From numerical simulations...

Navarro, Frenk & White:

$$\rho_{\rm NFW}(r) = \frac{\rho_s r_s^3}{r(r + r_s)^2},$$

Moore (a bit steeper):

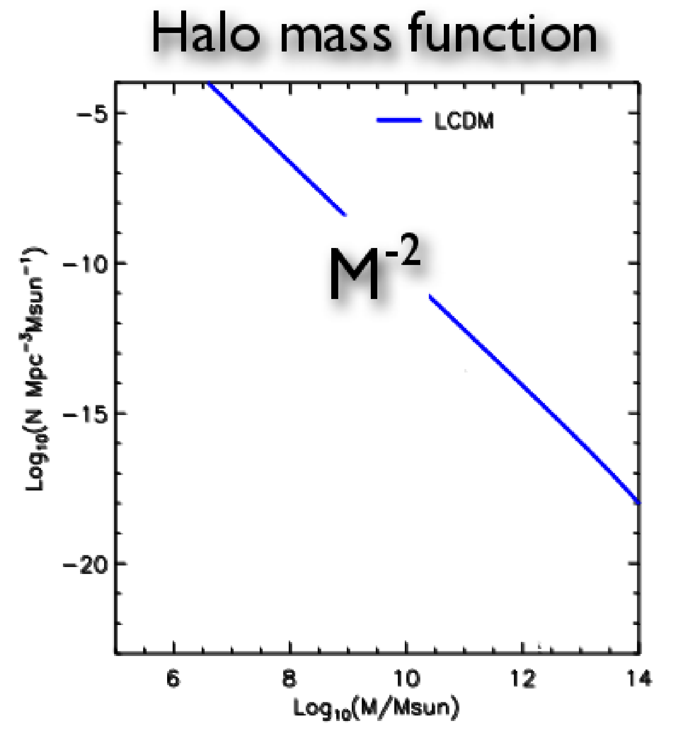
$$\rho_{\rm Moore}(r) = \frac{\rho_s r_s^3}{r^{3/2}(r + r_s)^{3/2}}.$$

→ All show the same behavior at larger radii, main difference in the center

defines where radial dependence changes from $1/r$ to $1/r^3$. The observed $1/r^2$ is seen only approximately.

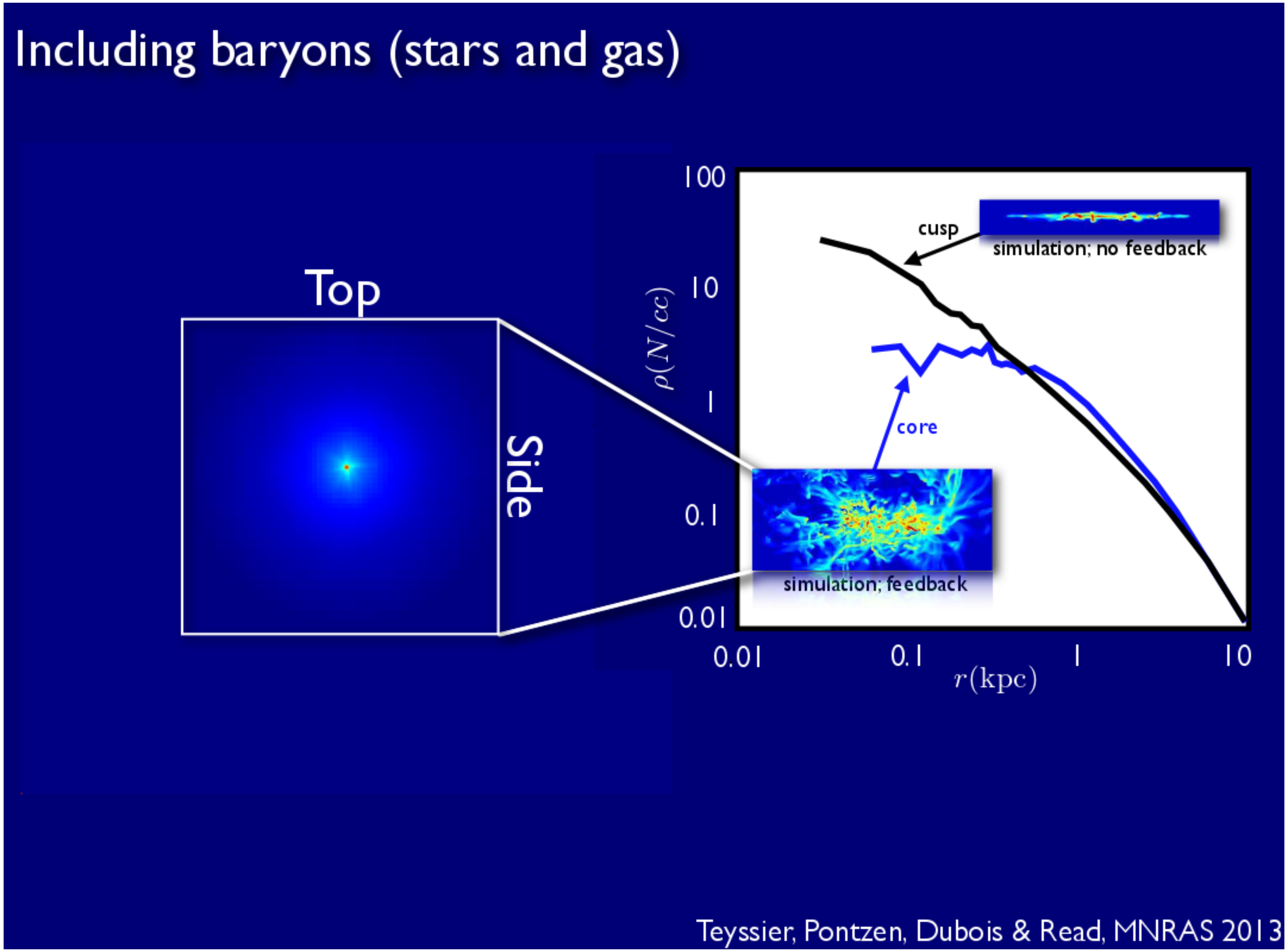
Simulations vs Observations

- **Cusp-Core Problem**
  Simulations predict a cuspy galactic center, while observations indicate large cores
- **Missing satellite problems („too big to fail problem“)**
  ΛCMD simulations predict satellite galaxies, which are not observed (Milky way: has ~50 while ~500 are expected)



Carlos Frenk: There is no problem!

Important: Baryonic Feedback



2 important observations when baryons are included:

- Galaxy center becomes less cuspy → flatter core
- cored halos are more easily tidally disrupted → expect fewer satellites

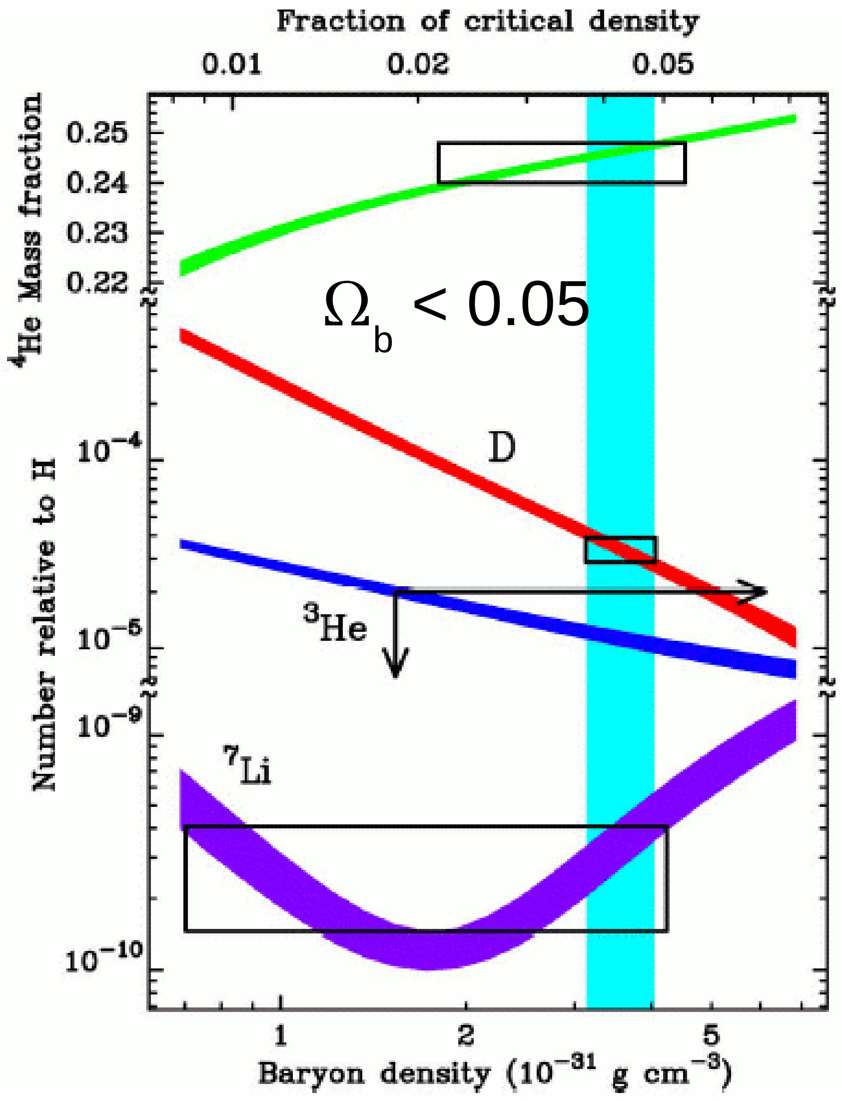
Dark Matter Candidates

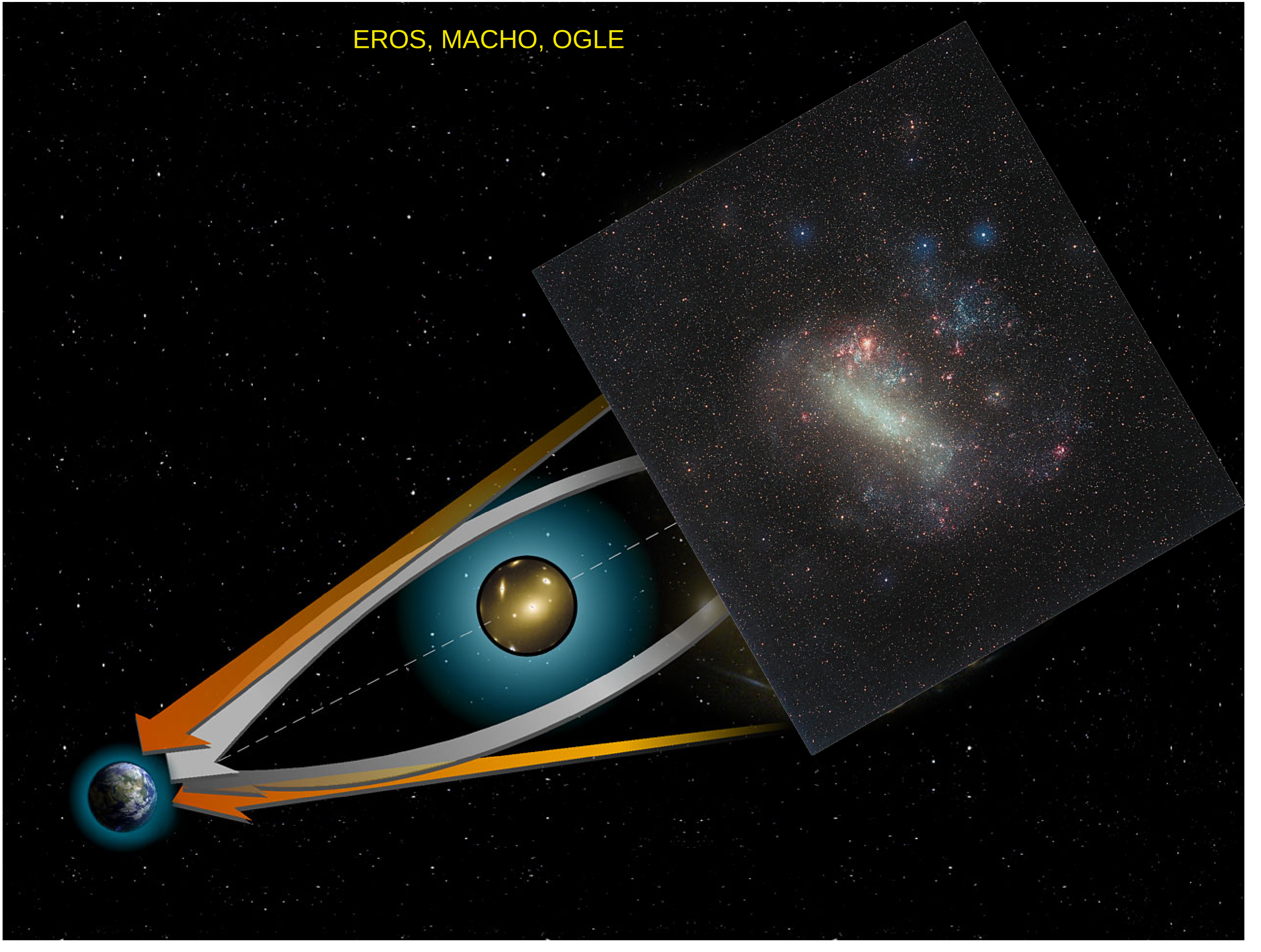
What is dark matter????

?

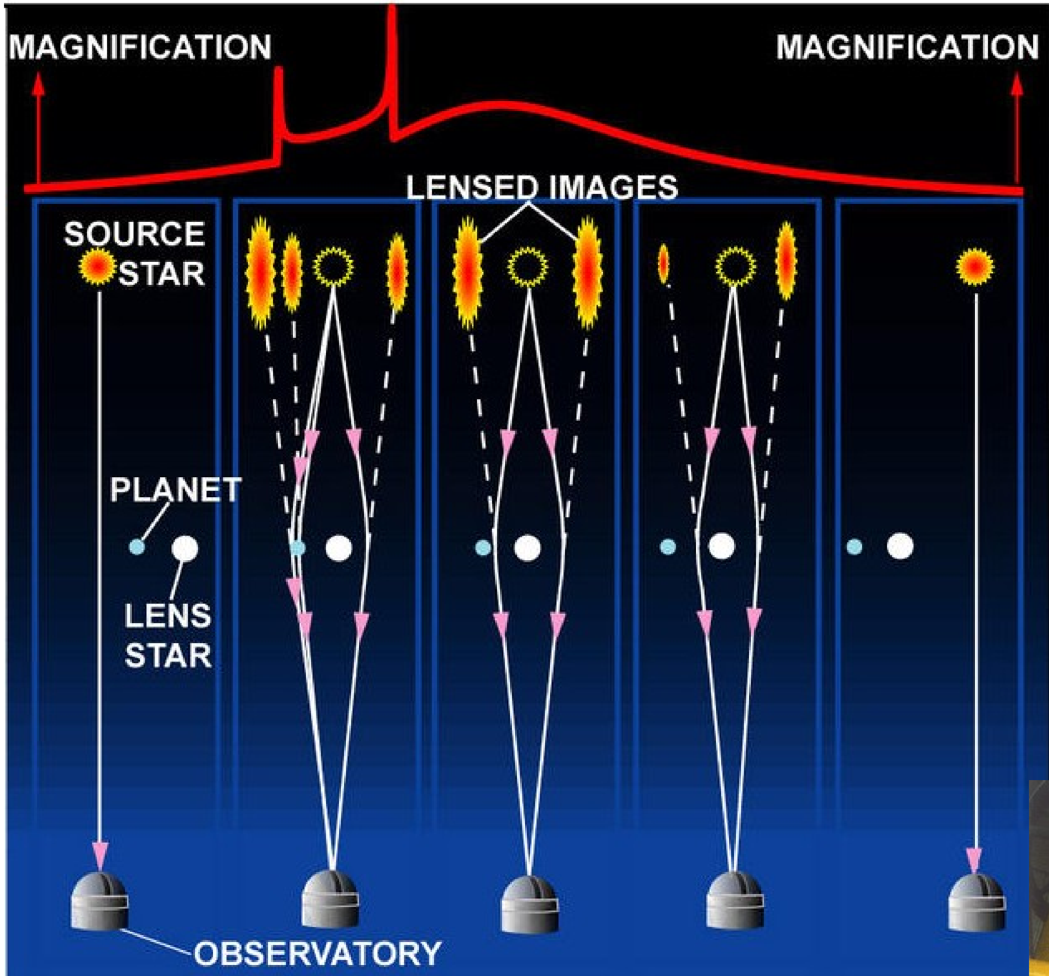
Why not Baryonic (Dark) Matter?

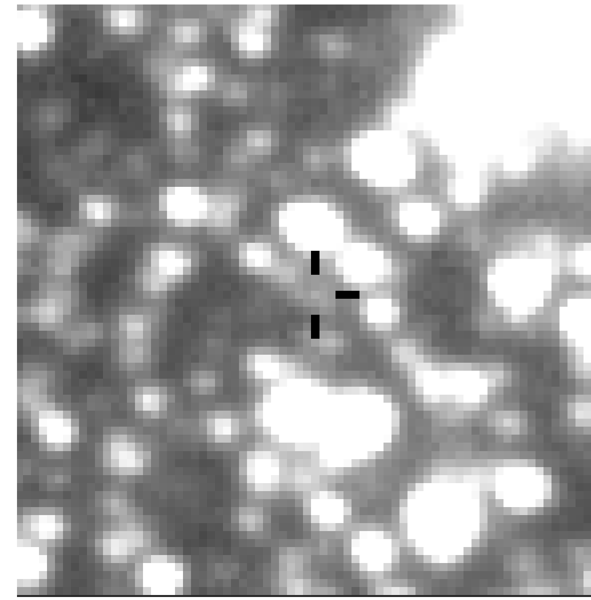
- too little: $\Omega_b < 0.05$
- **Big Bang Nucleosynthesis**
  fixes Ω_b quite precisely (+CMB)
  (1940s: Gamov, Alpher, Herman)
  - abundances of light elements depend on baryon/photon ratio
  - D production is most sensitive
- not collisionless
- not found in microlensing searches
- Black Holes? → No

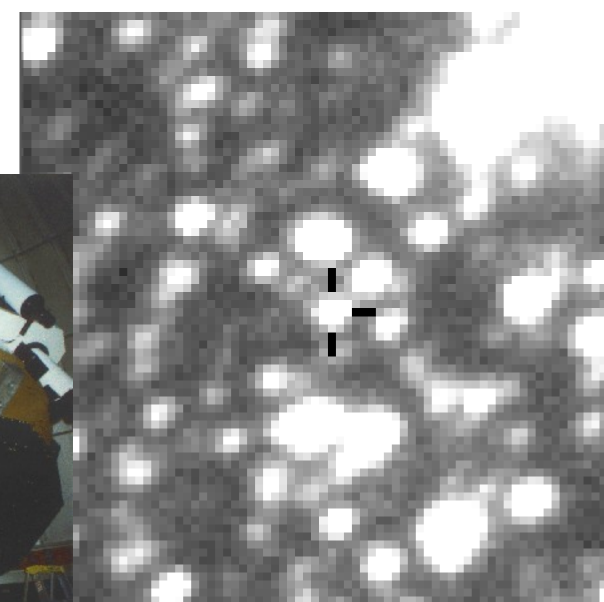


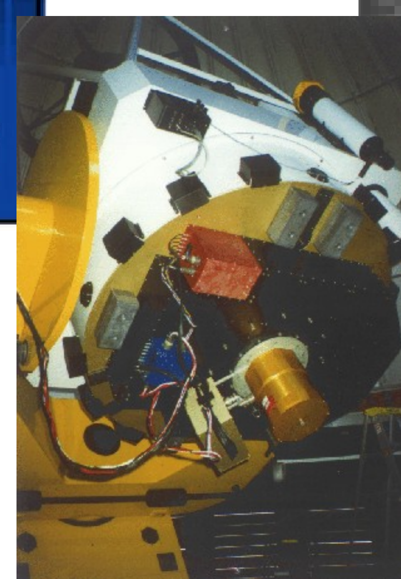

EROS, MACHO, OGLE

Microlensing with OGLE





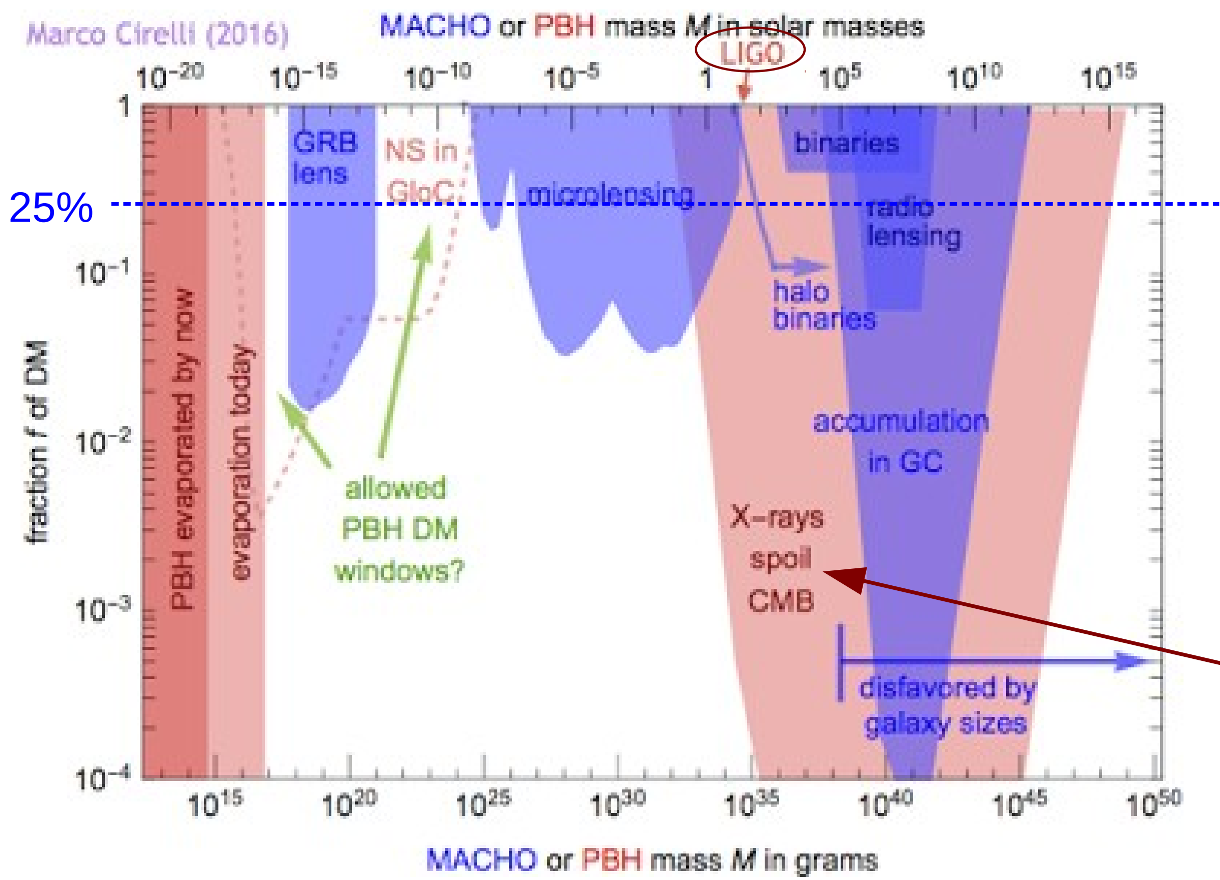


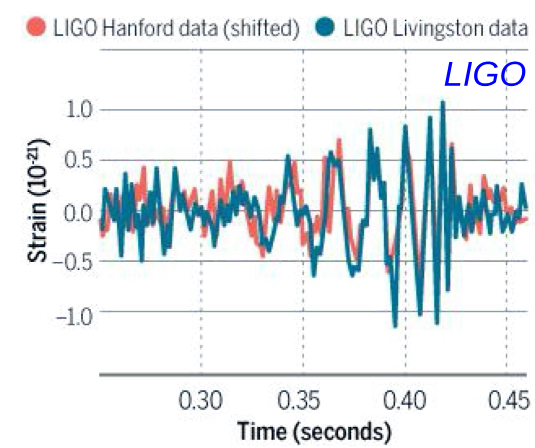


- Polish project started 1992
- telescope located in Chile
- main targets: GMC and galactic bulge
- some MACHOs and extrasolar planets found so far

Primordial Black Holes?

Can primordial black holes (PBH) formed in the big bang be the dark matter?





Black holes moving in early dense universe accrete matter and produce X-rays
→ ionize atoms
→ affect CMB

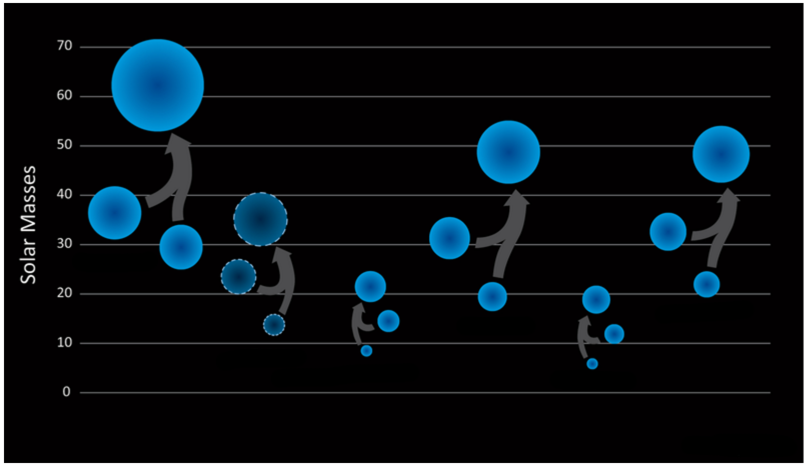
constraints in 10-100 M_{sun} range (LIGO):

– **PBHs cannot constitute >0.01% of dark matter**

– *but*: new discussion about PBH dark matter started
maybe PBH not dark matter but faster merger rate

Astrophys.J. 680, 829 (2008)
PRL 116, 201301 (2016)
PRL 117, 061101 (2016)

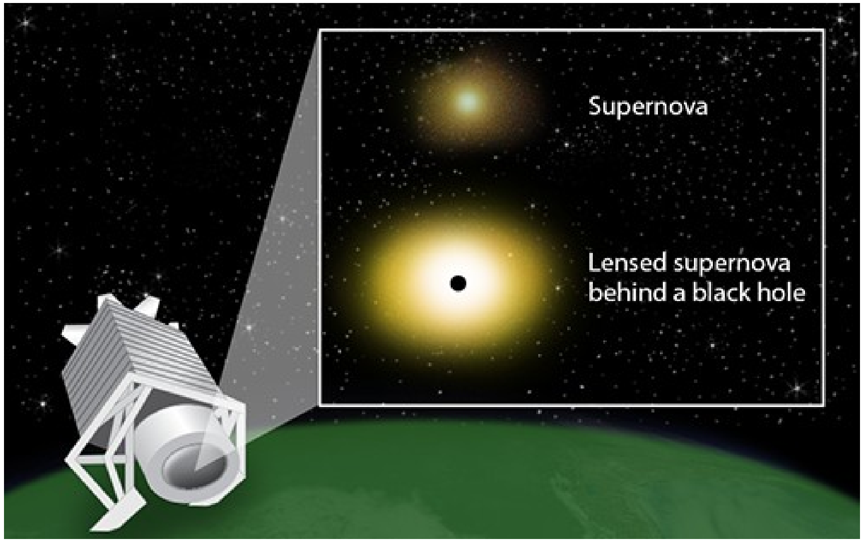
Primordial Black Holes?



- If PBH of 10-300 Msun are all DM, expect hundrets of BH mergers in first LIGO run (detected: 5)
→ **PBHs can only be 1% of DM**
PRD 96, 12 (2017)

- No microlensing of Magellanic cloud stars detected
→ **strong constraints on PBHs of 10–8-10 M_{sun} being DM**
MACHO: Astrophys. J. Lett. 550, L169 (2001)
OGLE: Mon. Not. R. Astron. Soc. 416, 2949 (2011)

- New: no microlensing of >1300 SN1a observed
→ **PBHs of >0.01 M_{sun} (up to largest masses) cannot account for >40% of the DM**
PRL 121, 141101 (2018)



Why not Neutrinos?

Neutrinos are a part of the SM

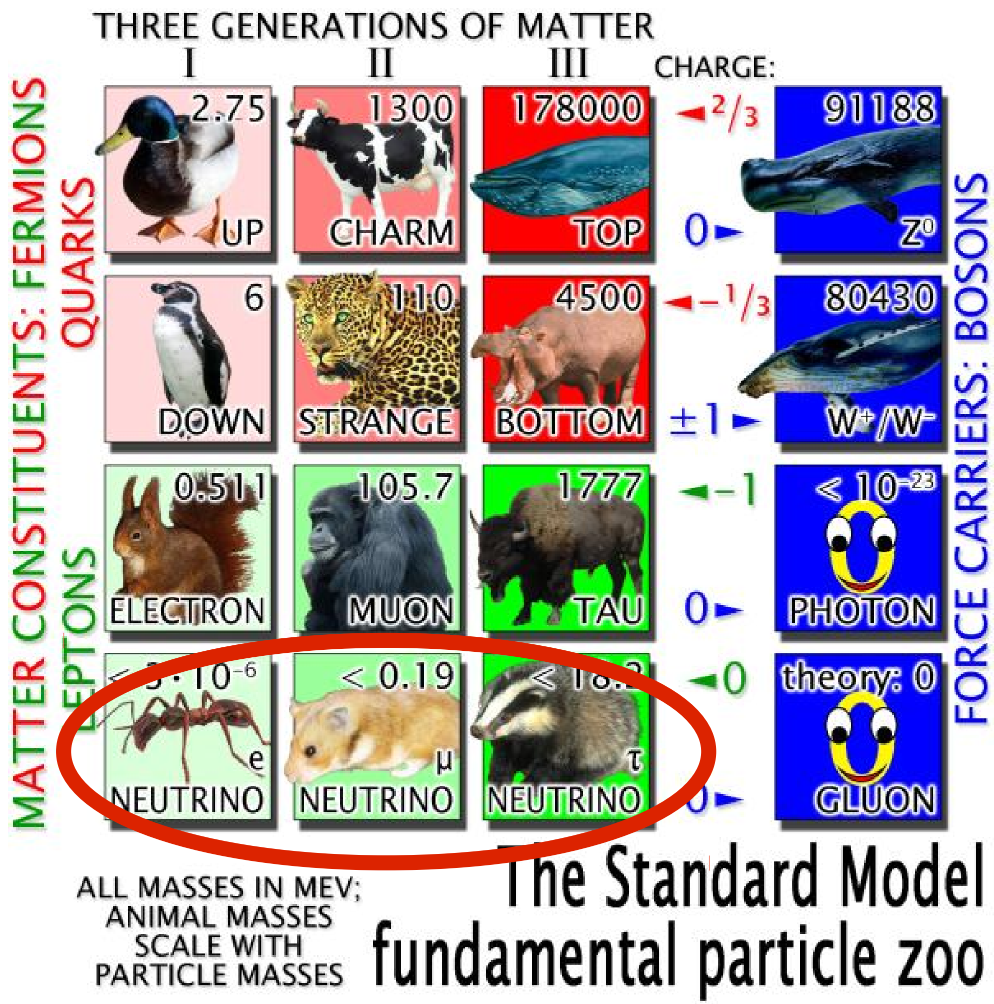
- collisionless
- massive (→ ν-oscillations)
- produced in the early Universe:
  decouple at kT ~ 3 MeV
  $n_\nu \sim 115\ \mathrm{cm}^{-3}$
- compare with critical density

  $\rho_{crit} = 5.1\ \mathrm{GeV/m^3}$
  $= 5100\ \mathrm{eV/cm^3}$

→ neutrinos can make up the entire energy content of the Universe if

$$\sum_{e,\mu,\tau} m_\nu c^2 = 44\mathrm{eV}$$

much too large!



Large Scale Structures

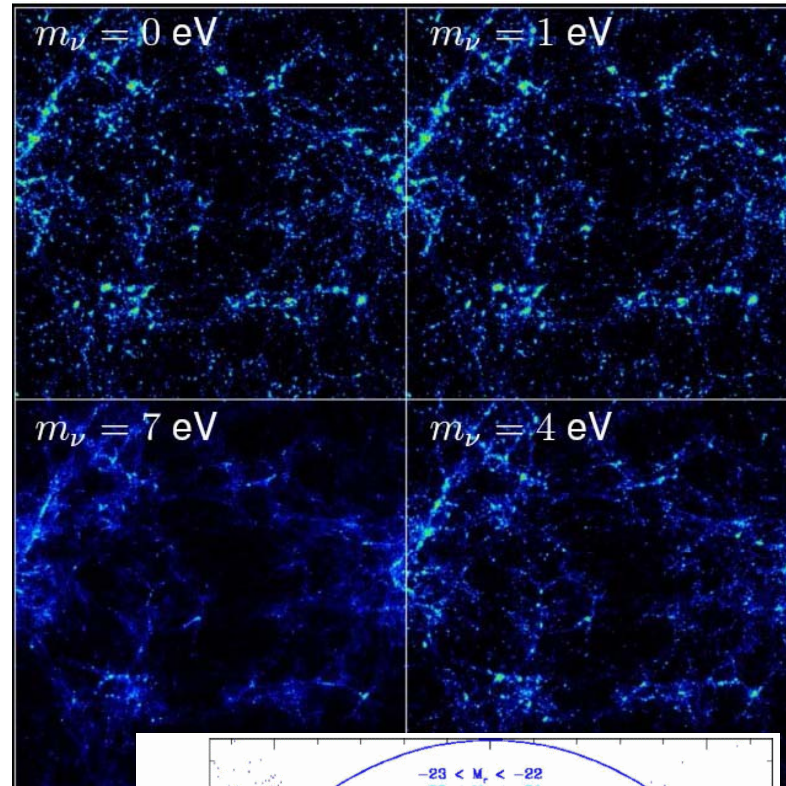
BUT: neutrinos move too far and too fast (decoupling at kT=3 MeV)

$$v_\nu = \frac{p_\nu c^2}{E_\nu} \approx \frac{10^{-4}\ \text{eV}}{m_\nu c}$$

$\sum m_\nu c^2 <$ 0.1 eV

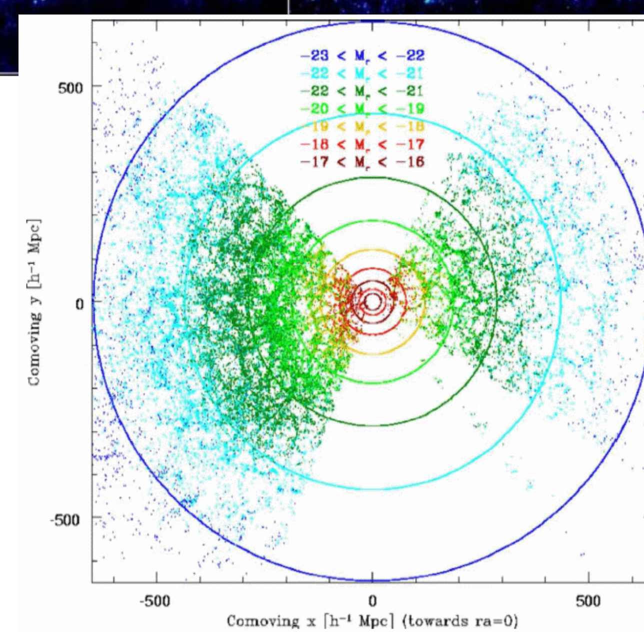
From direct νe mass limit;
ν oscillations;
Planck data

⇒ hot Dark Matter



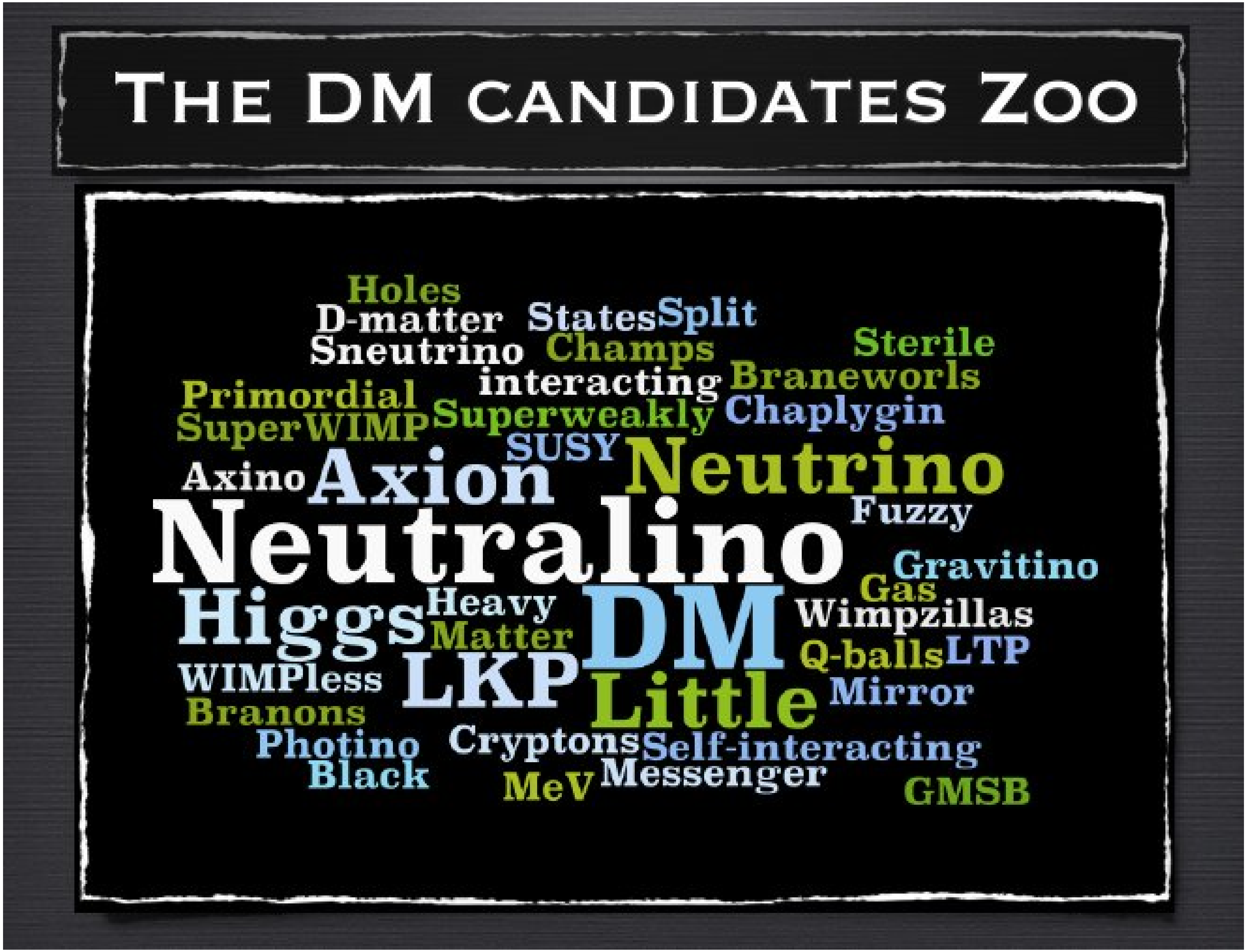
The smallest scale with „clumpy“ structure sets a lower limit on the particle mass:

low mass
→ high speed (if created thermally)
→ travels large distances
→ scale on which density perturbations are washed out



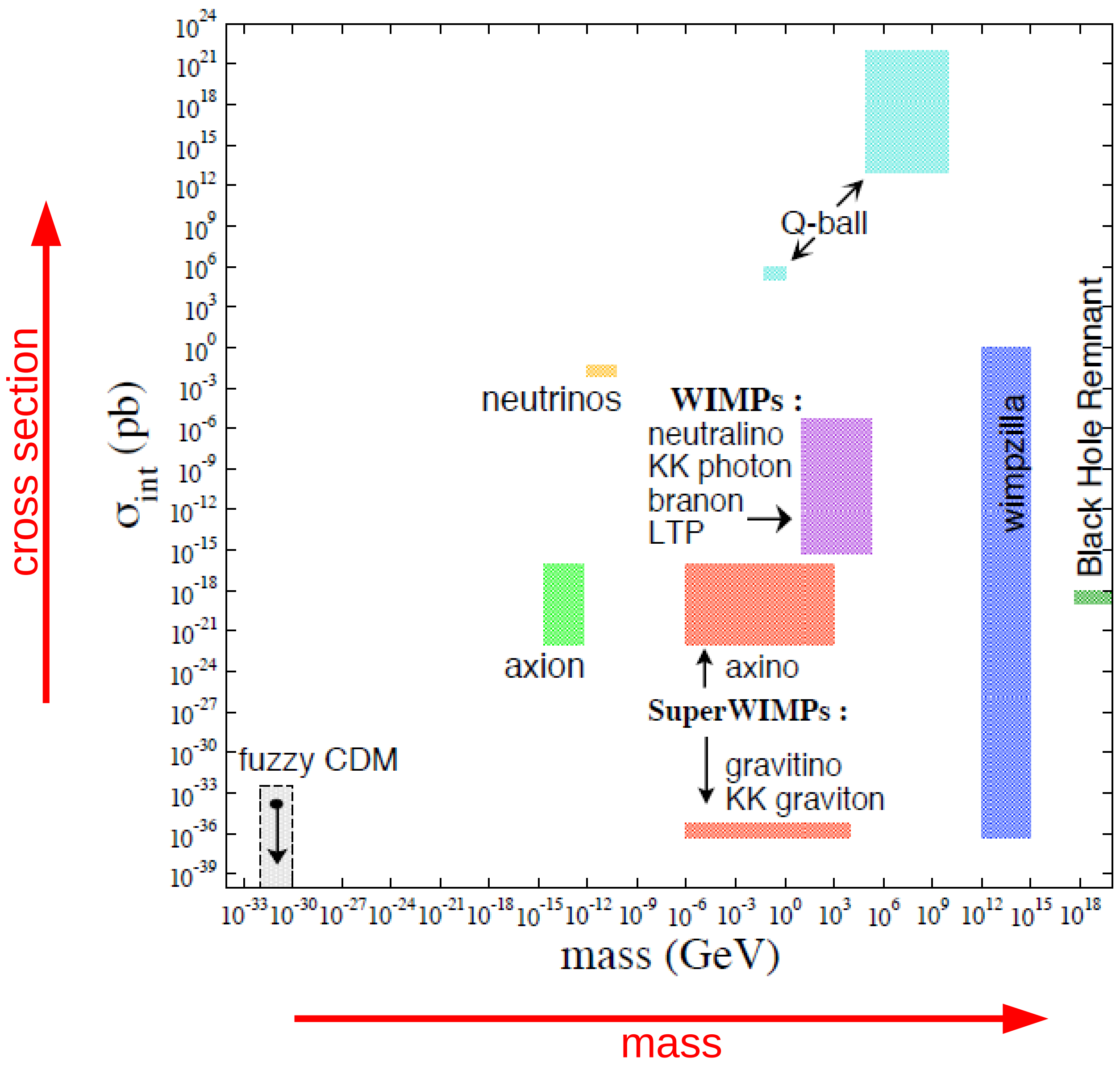
Probing small scale structures at z~3: $m_{DM} \gtrsim 2$ keV

Non baryonic DM:
new particles or „old“ particles with non-standard properties



stolen from Gianfranco Bertone

(Some) Dark Matter Candidates



- Axion
- WIMPs
  - Neutralino
  - (LKP)
- sterile neutrinos

DM Production

Two production mechanisms:

Thermal Production	Non thermal production
In thermal equilibrium with the Universe („freeze out“)	Production in a Phase Transition
→ WIMPs	→ Axions

Candidates for non-baryonic DM must be

- stable on cosmological time scales
  (otherwise they would have been decayed by now)
- must interact very weakly
  (otherwise would not be considered as Dark Matter)
- must have the right relic density (=amount of DM)

Note: There is a 3rd production mechanism at very large T, soon after or soon before inflation. These particles are usually superheavy, e.g. Wimpzillas

WIMPs

- Weakly Interacting Massive Particles
- Some of the best motivated candiates from „new“ physics
- WIMPs interact only via gravity and weak (new?) interactions
- WIMPs are somewhat similar to neutrinos, but far more massive (>GeV) and slower
- sub-GeV WIMPs could be Light Dark Matter

- Why are weak scale masses/interactions interesting??

Thermal WIMP Production

„The WIMP Miracle“

- suppose WIMP candidates χ can be created/annihilated in pairs
- assume that the χ's are in thermal eq. with all light particles
- number density n_χ follows the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle_T \left[(n_\chi)^2 - (n_\chi^{eq})^2\right]$$

dilution by Universe expansion ($3Hn_\chi$)

thermally averaged annihilation cross section ($\langle\sigma_A v\rangle_T$)

$\chi\bar{\chi} \rightarrow P\bar{P}$ ($(n_\chi)^2$)

$P\bar{P} \rightarrow \chi\bar{\chi}$ ($(n_\chi^{eq})^2$)

- when $T < m_\chi$, pair creation needs χ from tail of v-distribution
  → in equilibrium, number density falls exponentially

$$n_{eq} \propto (mT)^{3/2} \exp\left[\frac{-m_\chi c^2}{kT}\right]$$

Thermal WIMP Production II

When the annihilation rate $N\chi\langle\sigma v\rangle$ < expansion rate H, the probability for χ to find a partner for annihilation becomes small

expanding Universe: „freeze out“

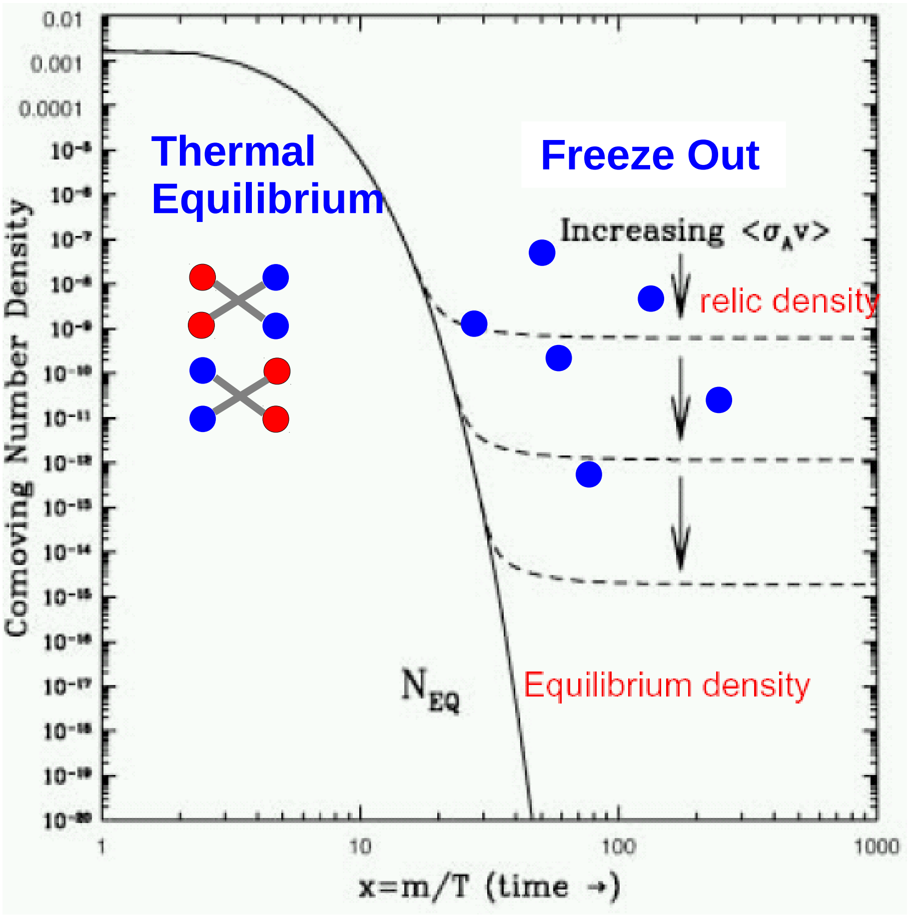
WIMPs fall out of equilibrium, cannot annihilate anymore

$$k_B T \sim \frac{m_\chi c^2}{20}$$

→ non relativistic when decoupling from thermal plasma

→ constant DM relic density

→ relic density depends on σ_A

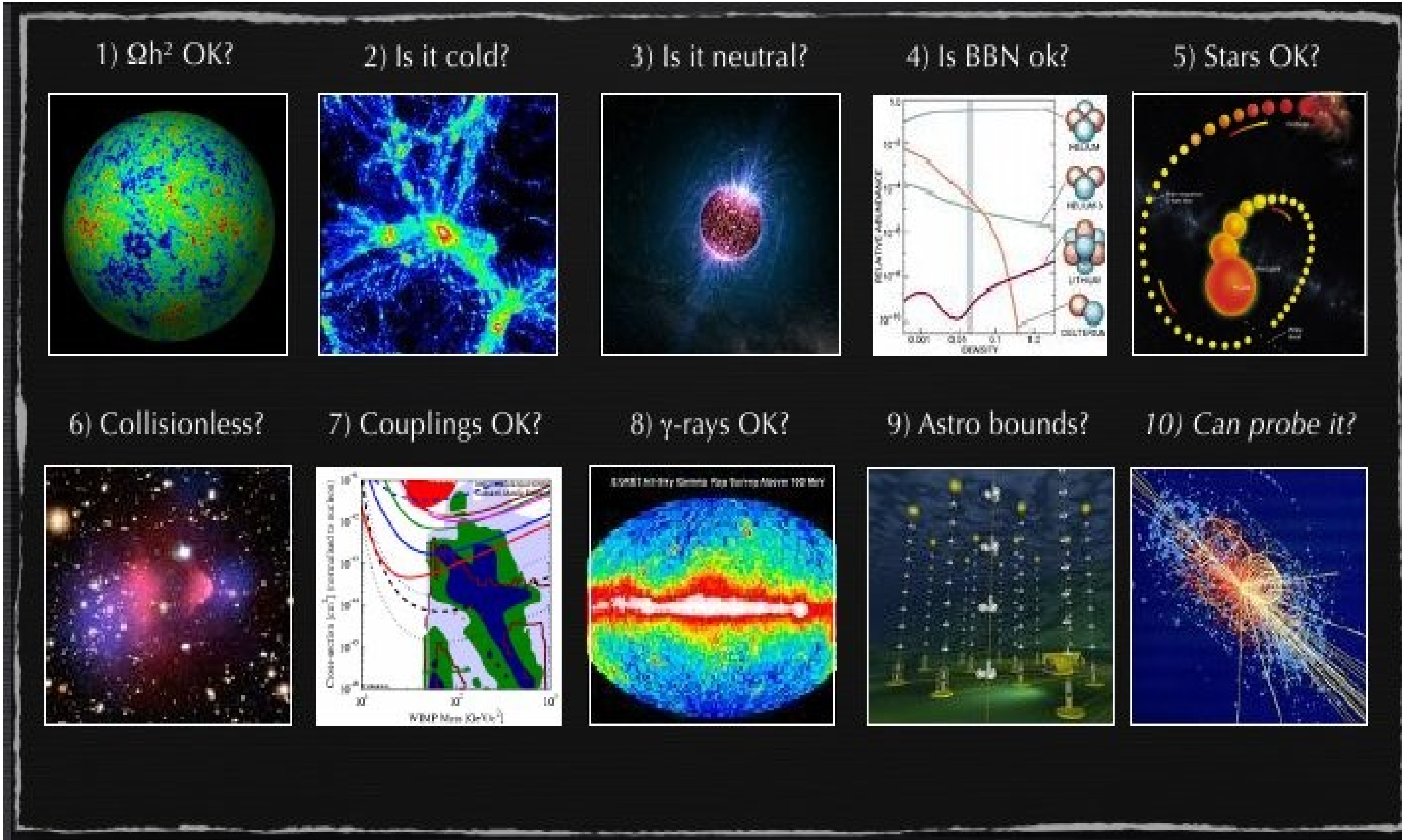


WIMP relic density:

$$\Omega_\chi h^2 \approx \text{const.} \frac{T_0^3}{M_{Pl}^3 \langle\sigma_A v\rangle} \approx \frac{0.1\text{pb}}{\langle\sigma_A \; v/c\rangle}$$

O(1) when $\sigma_A \sim 10^{-36}$ cm² → weak scale

The 10 Points Test for new Particles



stolen from Gianfranco Bertone, arXiv:0711.4996