Observational motivation for Dark Matter

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מכון ויצמן למדע
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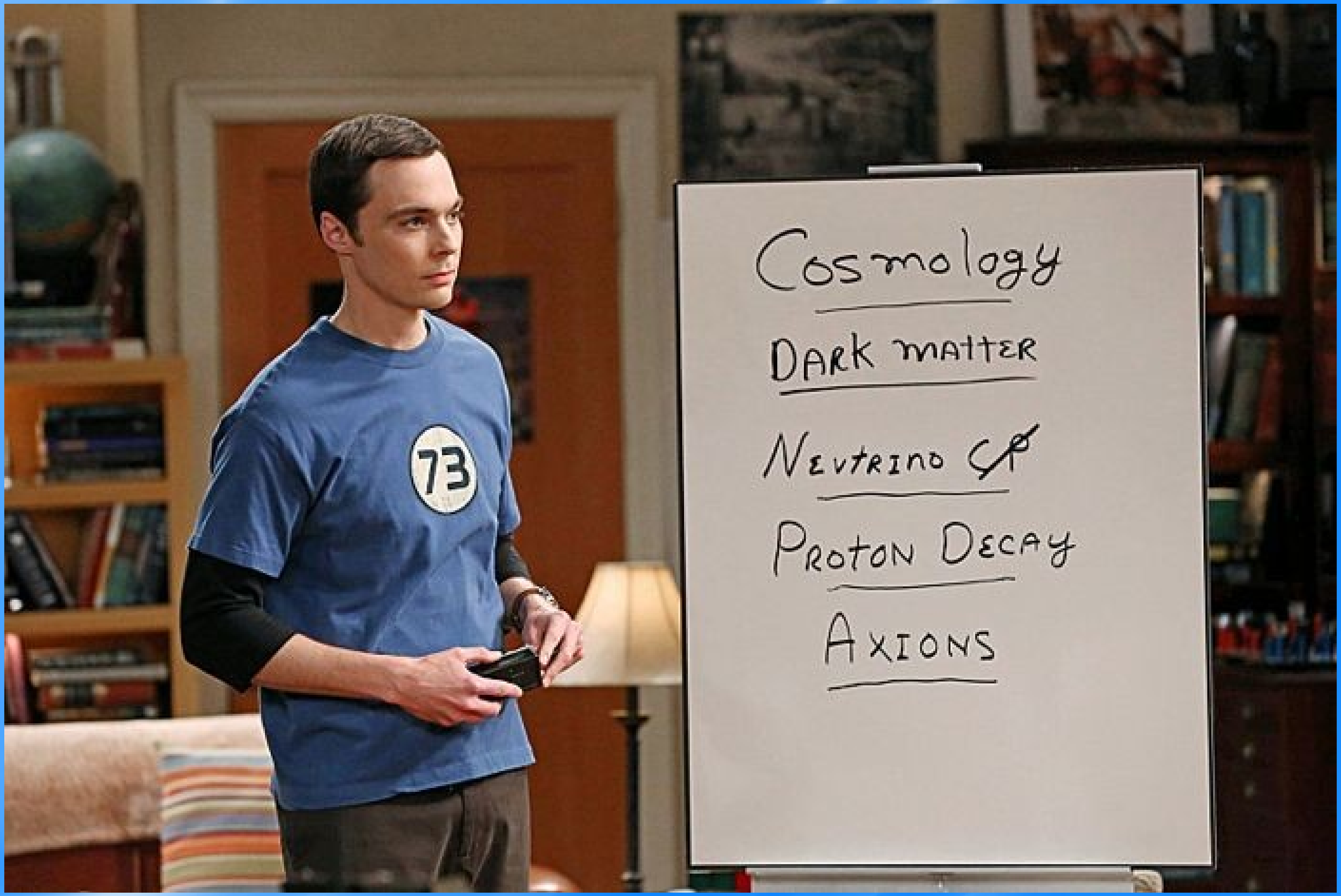
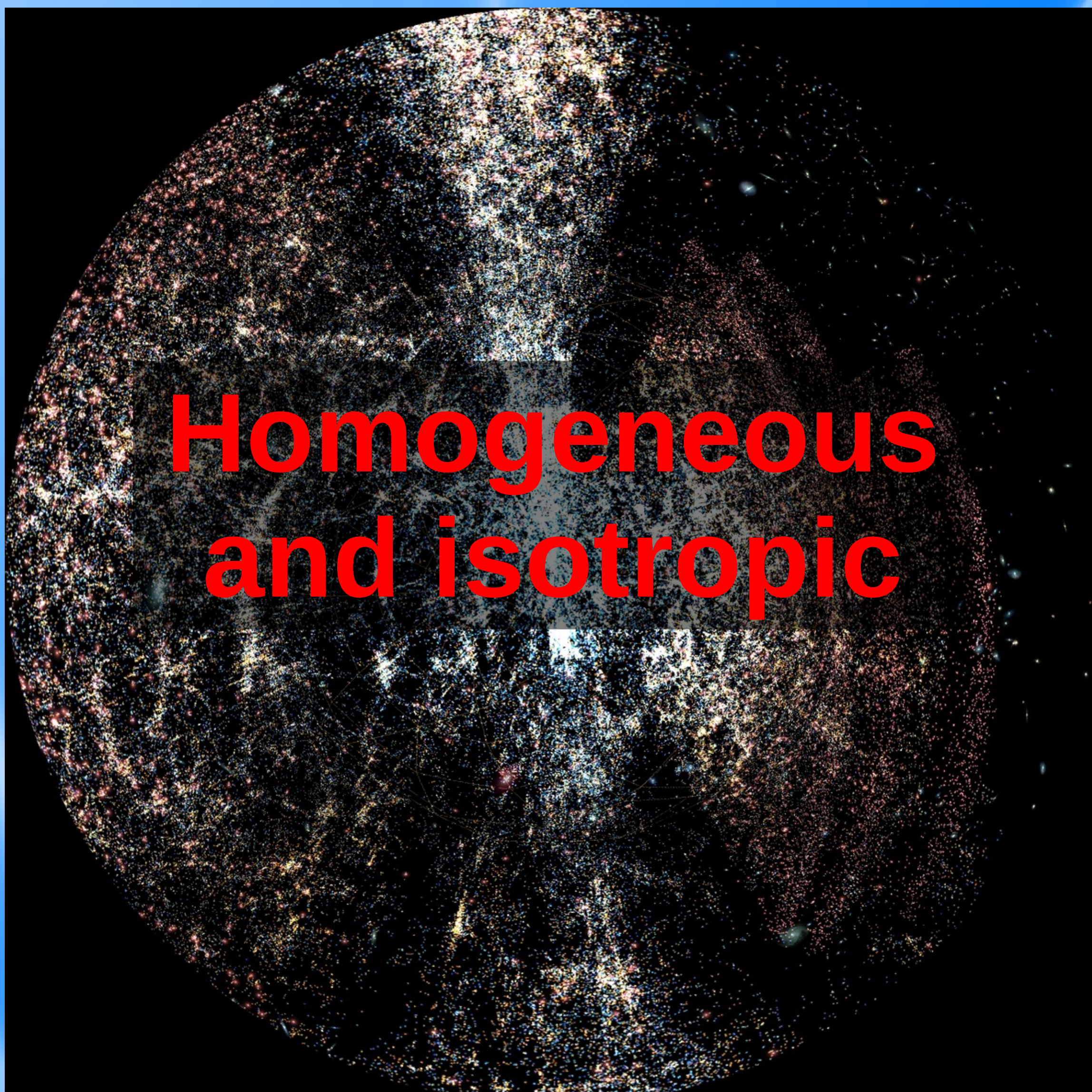
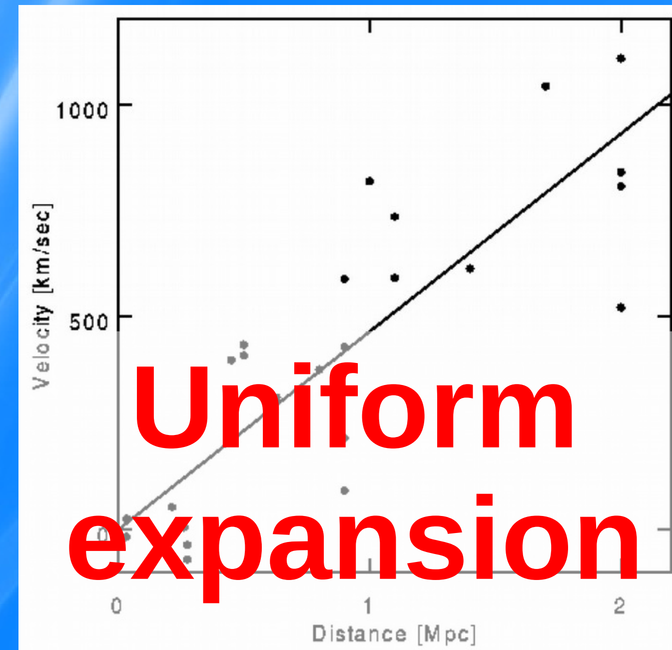
Crash course in cosmology



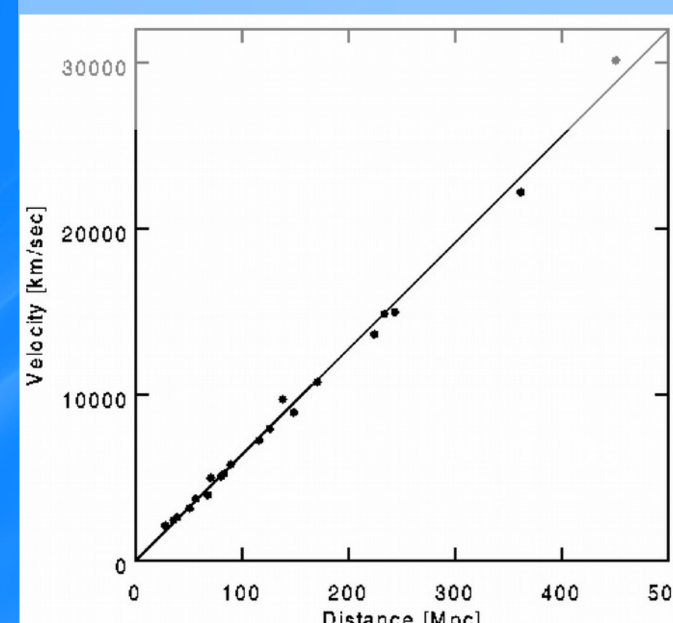
Big Bang basics



Homogeneous and isotropic



Uniform expansion



FRW metric

- Most general distance element and metric:

$$ds^2 = g_{00}dt^2 + 2g_{0i}dx^i dt - \sigma_{ij}dx^i dx^j$$

- Applying isotropy, redefining time units:

$$g_{0i} = 0 \qquad d\tau = \sqrt{g_{00}}dt \rightarrow g_{00} = 1$$

- Using again isotropy and equality of all space directions:

$$ds_3^2 = \sigma_{ij}dx^i dx^j = a^2(t)\lambda^2(r)[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)]$$

FRW – cont.

- After allowed scaling and manipulation:

$$ds^2 = dt^2 - a^2(t)[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)]$$

Scaled time

Scale factor

Global sign of curvature
Can be normalized to:
-1, 0 or 1

- Distance on a null geodesic (i.e. photon propagating):

$$D = cdt \approx a(t)dr$$

$$\dot{D} = \dot{a}dr = HD$$

$$H = \frac{\dot{a}}{a}$$

Definition of the "Hubble Constant"

FRW – cont.

- Features of FRW:

$$\frac{d\lambda}{\lambda} = \frac{v}{c} = \frac{HD}{c} = -H\,dt = -\frac{da}{a}$$

How photon wavelength changes with space and time

$$z = (\lambda_e - \lambda_0)/\lambda_0 \qquad 1 + z = a^{-1}$$

Defining "Redshift"

- Writing Einstein eq.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \kappa^2 T_{\mu\nu} \qquad \kappa^2 = 8\pi G/c^4$$

Friedman Equations

- The solution gives:

(In natural units)

$$H^2 = \frac{8\pi}{3}\rho - \frac{k}{a^2}$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}(\rho + 3p)$$

$$H = \frac{\dot{a}}{a}$$

Natural normalization

$$\rho_c = \frac{3H^2}{8\pi G}$$

$$\Omega = \frac{\rho}{\rho_c}$$

- Density-Pressure relations (EOS):

Non relativistic

$$p = 0$$

$$\dot{\rho}/\rho = -3\dot{a}/a$$

$$\rho \sim a^{-3}$$

$$a \sim t^{2/3}$$

Relativistic

$$p = \frac{1}{3}\rho$$

$$\dot{\rho} = -4H\rho$$

$$\rho_R \sim a^{-4}$$

General

$$p = w\rho$$

$$\rho \sim a^{-3(1+w)}$$

$$a \sim t^{2/3(1+w)}$$

History of the universe: Matter vs. Radiation

- Normalizing everything to values TODAY:

$$H^2 = \frac{8\pi}{3}(\rho_m a^{-3} + \rho_\gamma a^{-4} + \rho_k a^{-2}) = H_0^2(\Omega_m a^{-3} + \Omega_\gamma a^{-4} + \Omega_k a^{-2})$$

$$\begin{aligned} \rho_m &= \rho_{m,0} a^{-3} \\ \rho_\gamma &= \rho_{\gamma,0} a^{-4} \end{aligned}$$

+

$$\rho_{c,0} = \frac{3H_0^2}{8\pi G} \approx 2 \cdot 10^{-29} h^2 gcm^{-3}$$

$$\Omega_\gamma = \frac{\rho_\gamma}{\rho_{crit}} \simeq 4.3 \cdot 10^{-5} h^{-2}$$

From CMB

=

$$1 + z_e = a_e^{-1} = \left(4.3 \cdot 10^{-5}\right)^{-1} \Omega_m h^2 = 23,000 \Omega_m h^2$$

$h = 0.7$ Approximately, from Hubble expansion measurements

Thermal history: BBN

- After creating a Baryon Asymmetry (hmmm...) we get a soup of p, n, e and radiation
- Radiation drops in T, but is very dominant in number density:

$$\eta = \frac{n_B}{n_\gamma} = 2.68 \cdot 10^{-8} (\Omega_b h^2)$$

- After radiation stops producing n's, they decay and produce heavy elements at the same time

$$Y = \frac{4(n_n/2)}{n_n + n_p} \approx 0.25$$

Mass fraction of ^{4}He, with very simplifying assumption that all n go into He

- D, ^{7}Li are produced, and are sensitive to eta

Thermal history: radiation decoupling

- After transition to matter domination, T drops but Baryons and photons are still connected
- Due to abundance of photons, only when T~eV matter suddenly recombines
- Transfer from Thomson cross section to neutral Hydrogen makes the universe transparent to photons (but not to electrons!)

$$z_{dec} \approx 1100$$

Requires a full solution of the ionization and recombination, including multi-body processes, and setting it when the optical depth of a photon drops to 1 at the age of the universe

Perturbation growth

- From the time that matter dominates the universe, gravitational collapse increases density fluctuations (before that it is suppressed by radiation)
- Until decoupling, radiation also gives a pressure “kickback” that, through sound waves, bounces back collapsing structures

Perturbation growth

$$\delta = \delta\rho/\rho$$

We put perturbations on the energy momentum tensor, T:

$$\begin{aligned}\delta T^0_0 &= \delta\rho \\ \delta T^1_1 &= \delta T^2_2 = \delta T^3_3 = -c_s^2\delta\rho \\ \delta T^i_0 &= (1+w)\rho v^i\end{aligned}$$

Peculiar velocity compared to the rest frame of the universe

$$c_s^2 \equiv \frac{\delta p}{\delta\rho}$$ Speed of sound

$$p = w\rho$$ Equation of state

$$\mathcal{H} = \frac{1}{a}\frac{da}{d\tau}$$

$$k < \mathcal{H}(\tau)$$

K here is the wave number, and is corresponding to a scale larger than the horizon

For scales above the horizon, perturbations do not grow

Perturbation growth

- For scales below the horizon, sound velocity enters the equations:

$$c_s^2 = \frac{\delta p}{\delta \rho} \ll 1$$

→

$$\ddot{\delta} + \mathcal{H}\dot{\delta} + \left(k^2 c_s^2 - \frac{3}{2}\mathcal{H}^2\right)\delta = 0$$

- Perturbations do not grow if: $k^2 c_s^2 - \frac{3}{2}\mathcal{H}^2 > 0$

$$\lambda = 2\pi a/k$$

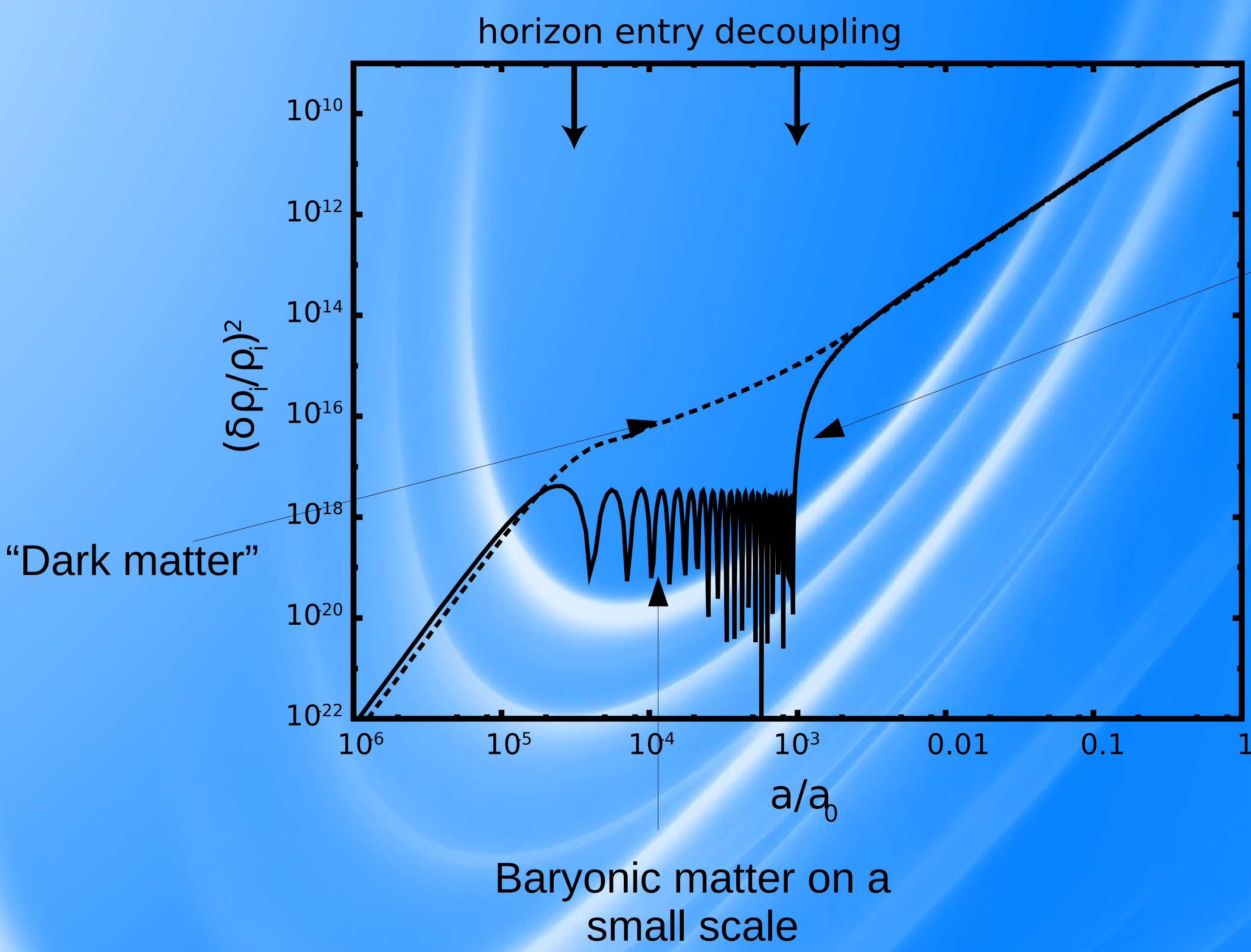
$$\lambda_J = c_s\sqrt{\frac{\pi}{\rho}}$$

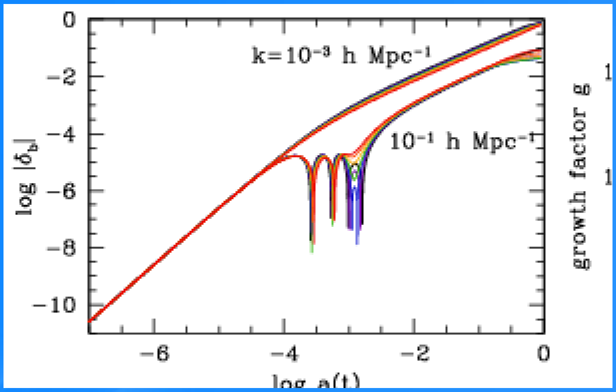
The Jeans scale sets the limit above which perturbations can grow

For photons only c_s=c/sqrt(3), and the Jeans scale is approximately the horizon → no growth

Growth before decoupling

- Before matter dominates, growth is suppressed
- Afterwards, growth depends on sound velocity and amount of non interacting matter
- On small scales, pressure will bounce back the perturbations, depending on the sound crossing time and time since passing the Jeans scale



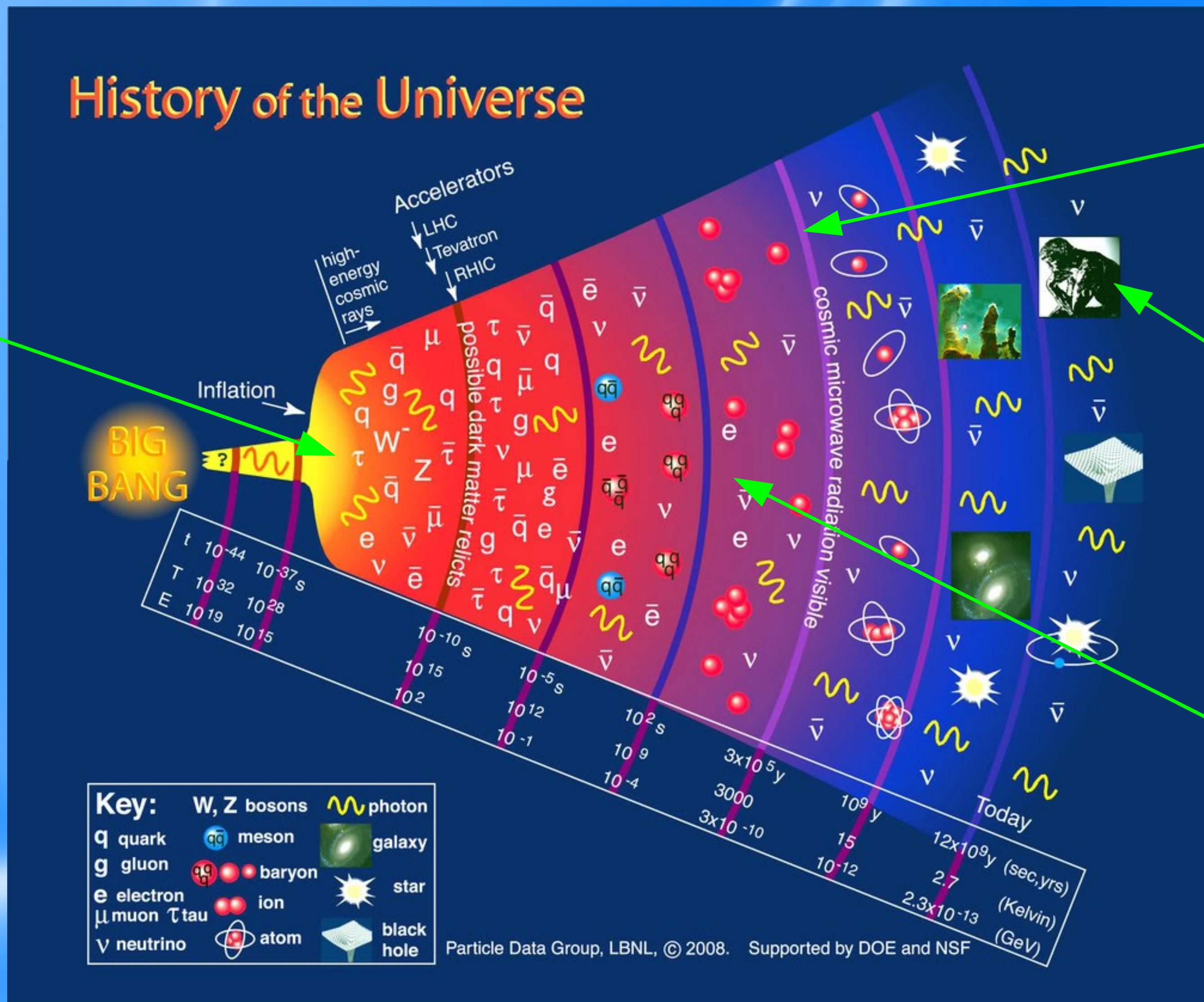


At decoupling, radiation "sampling" the inhomogeneities and velocity fields is emitted and travels with very little interaction until today

What we threw out

- Inflation (horizon problem, flatness, perturbation spectrum)
- Cosmological constant (and its smallness problem)
- Non linear structure formation (the dirty world)
- Where new physics can make changes (everywhere)
- Many details

Big bang in a nutshell



BaryoGenesis

CMB

???

BBN

Chronological overview

- **Dark Matter in clusters**
- Dark Matter in Galaxies
- Cosmological Dark Matter
- Alternatives

The Virial theorem

$$2\overline{T} = \overline{\sum_a \mathbf{r}_a \cdot \partial U / \partial \mathbf{r}_a}$$

$$2\overline{T} = -\overline{U}$$

Zwicky (1933): Coma cluster of galaxies

Virial theorem for a bound system in gravitational equilibrium: $GM/r \sim \langle v^2 \rangle$

Radius R von ca. einer Million Lichtjahren (gleich 10^{24} cm) und enthält 800 individuelle Nebel von je einer Masse entsprechend 10^9 Sonnenmassen. Die Gesamtmasse M des Systems ist deshalb

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45} \text{ gr.} \qquad (5)$$

Daraus folgt für die totale potentielle Energie Ω:

$$\Omega = -\frac{3}{5} \Gamma \frac{M^2}{R} \qquad (6)$$

Γ = Gravitationskonstante

oder

$$\bar{\varepsilon}_p = \Omega / M \sim -64 \times 10^{12} \text{ cm}^2 \text{ sek}^{-2} \qquad (7)$$

und weiter

$$\bar{\varepsilon}_k = \overline{v^2}/2 = -\bar{\varepsilon}_p/2 = 32 \times 10^{12} \text{ cm}^2 \text{ sek}^{-2}$$

$$(\overline{v^2})^{1/2} = 80 \text{ km/sek} . \qquad (8)$$

Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

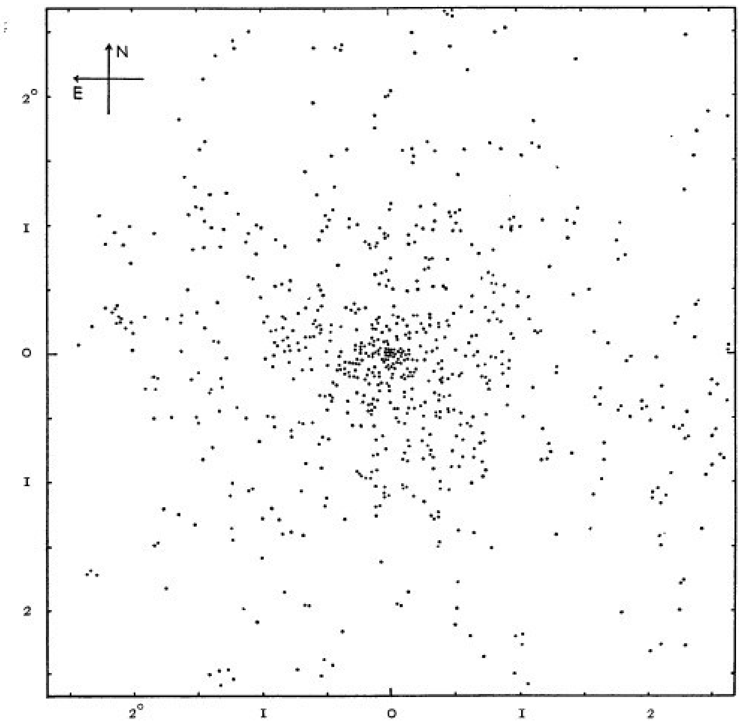


FIG. 3.—The Coma cluster of nebulae

in the Coma cluster would be of the order

$$\gamma = 500 , \qquad (37)$$

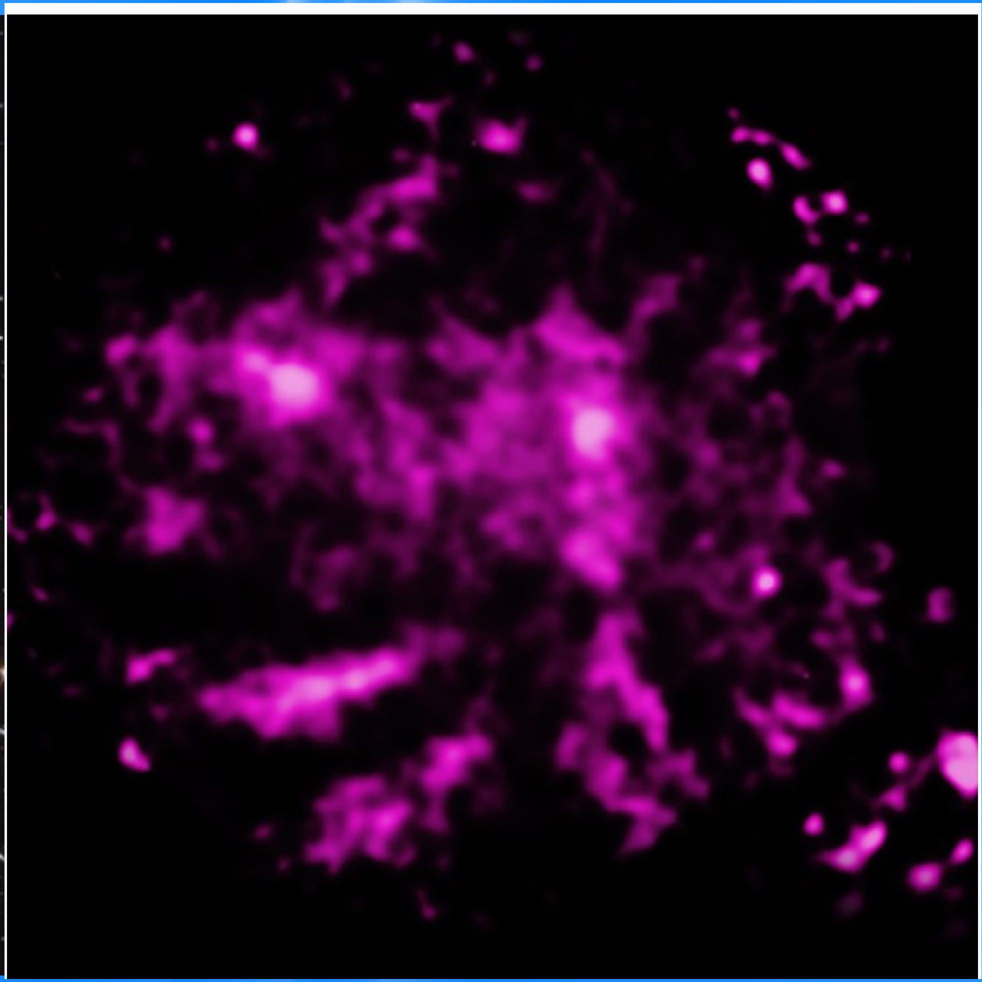
as compared with about $\gamma' = 3$ for the local Kapteyn stellar system.

Stars can only account for under 1% of the mass!

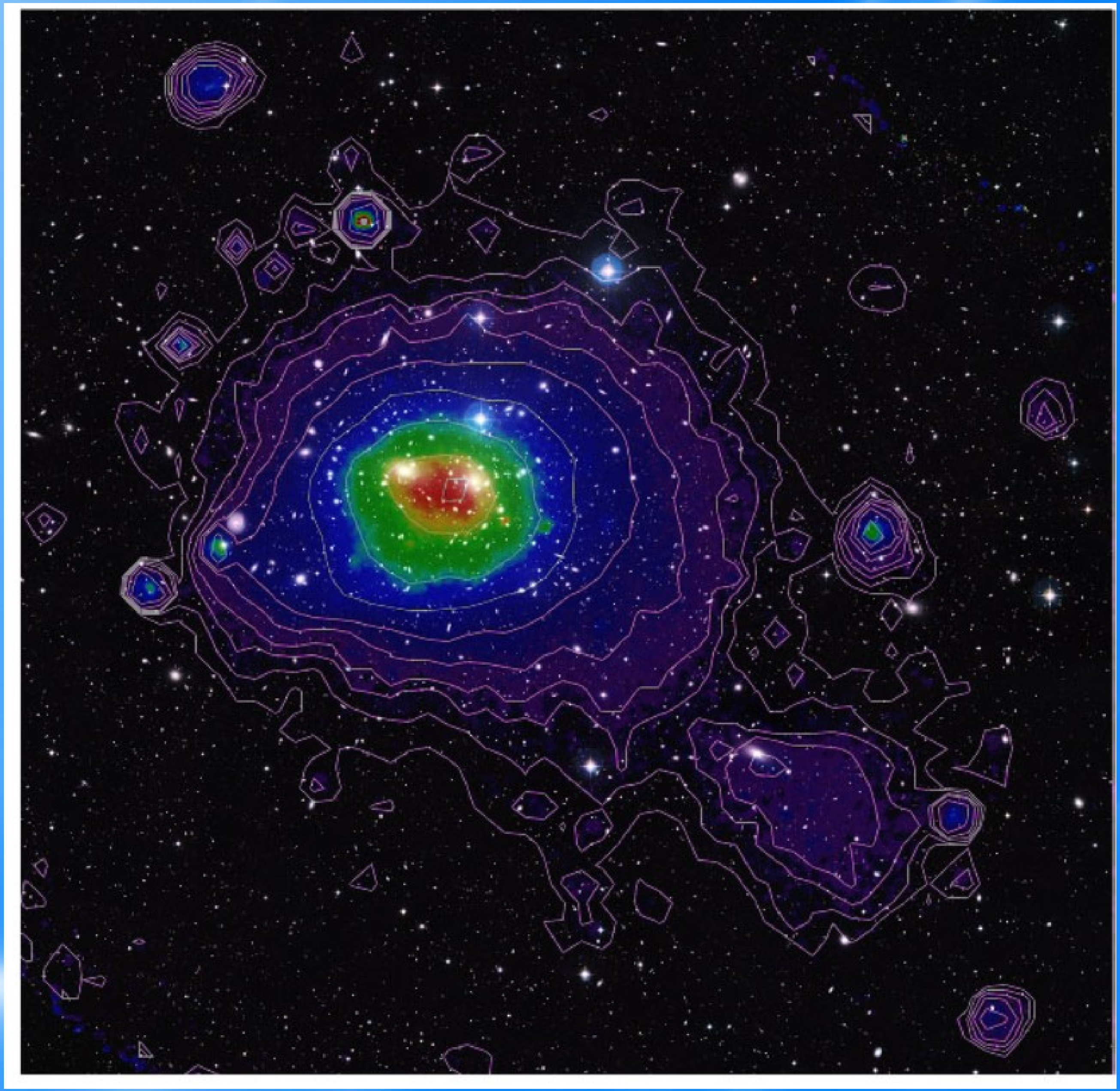
Coma cluster

optical light

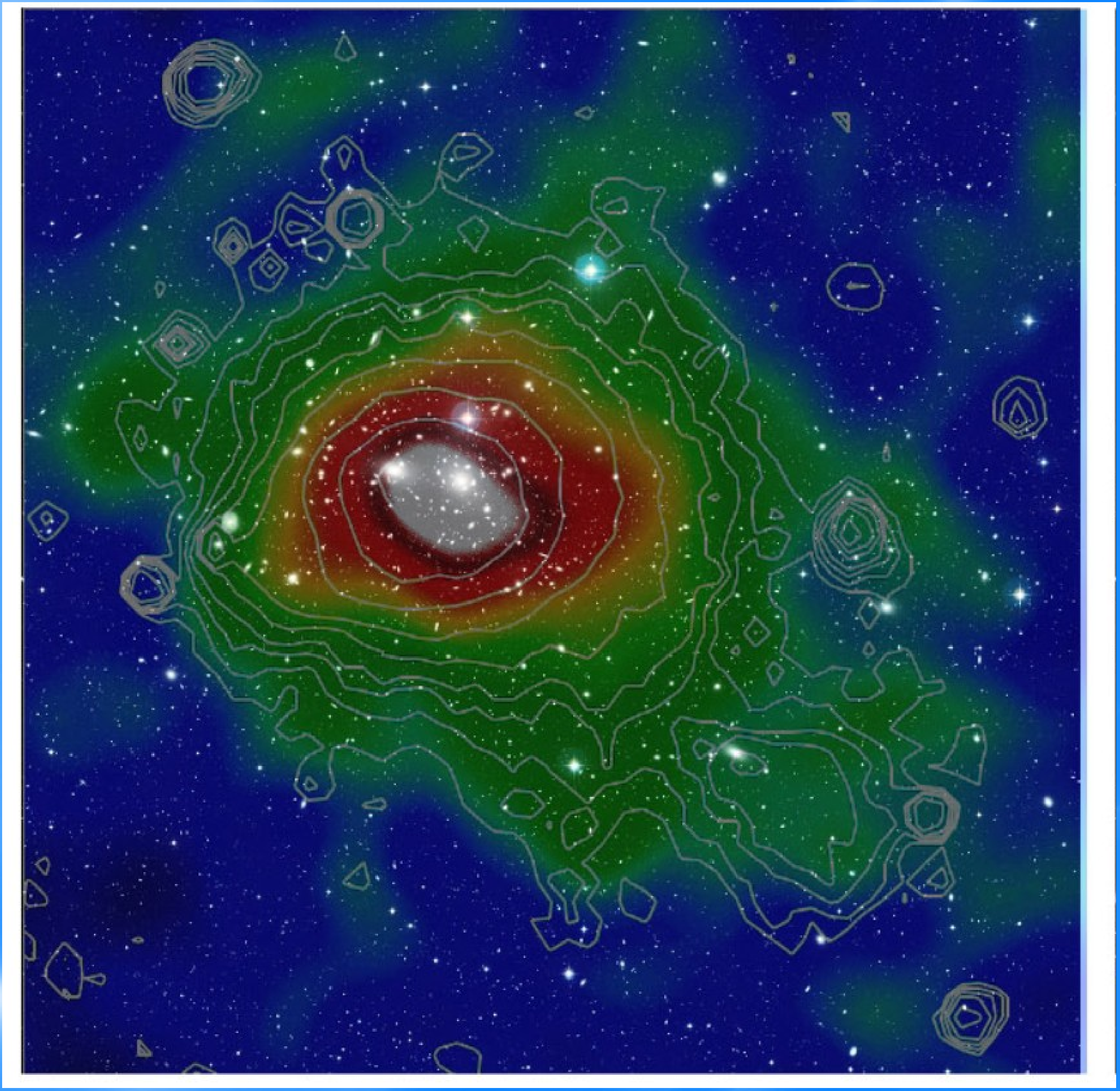
X-rays



optical (stars) + thermal X-ray (10~keV gas)



optical (stars) + thermal X-ray (10~keV gas) + radio 0.3-3 mm (SZ Compton upscattering of CMB photons by hot gas)

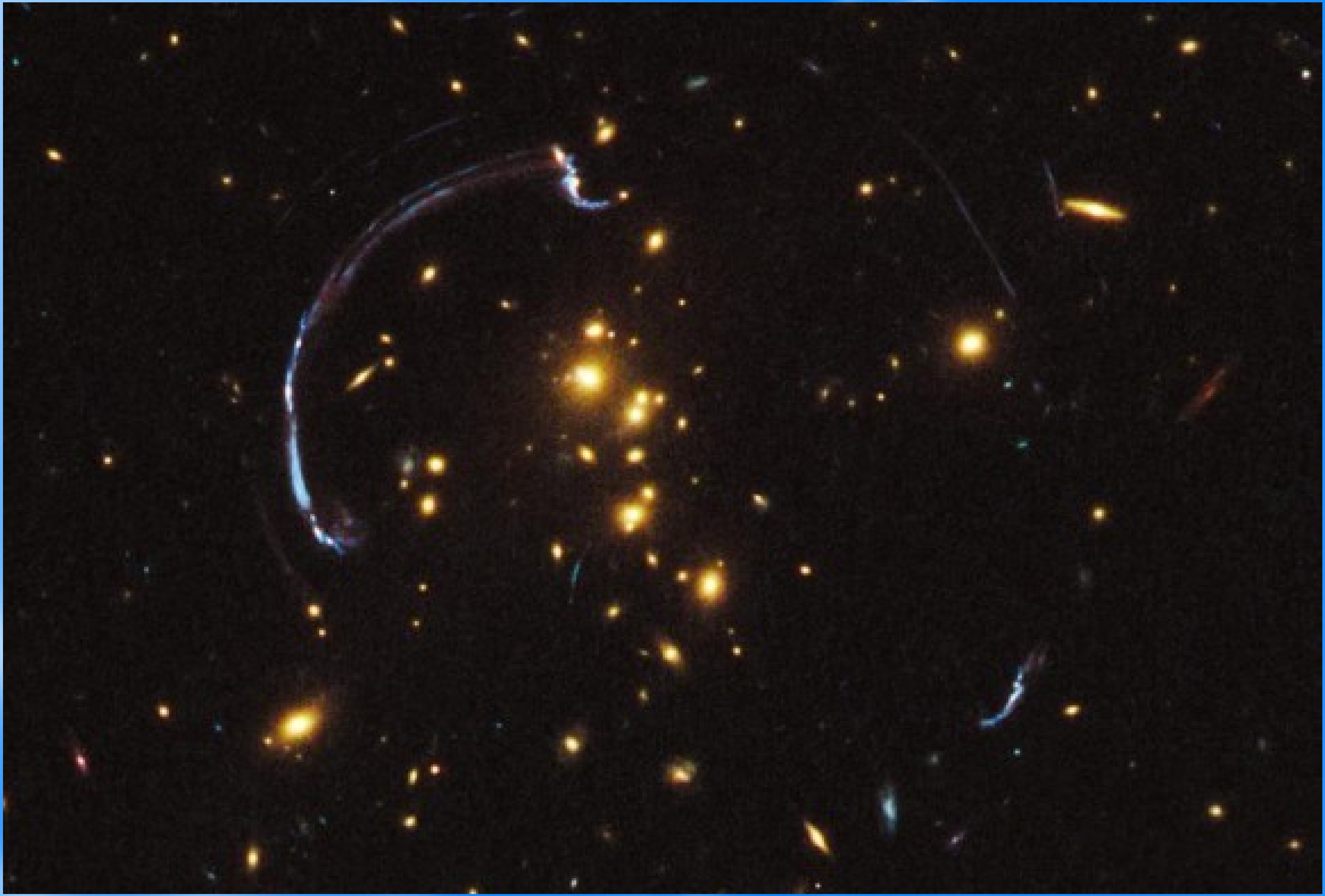


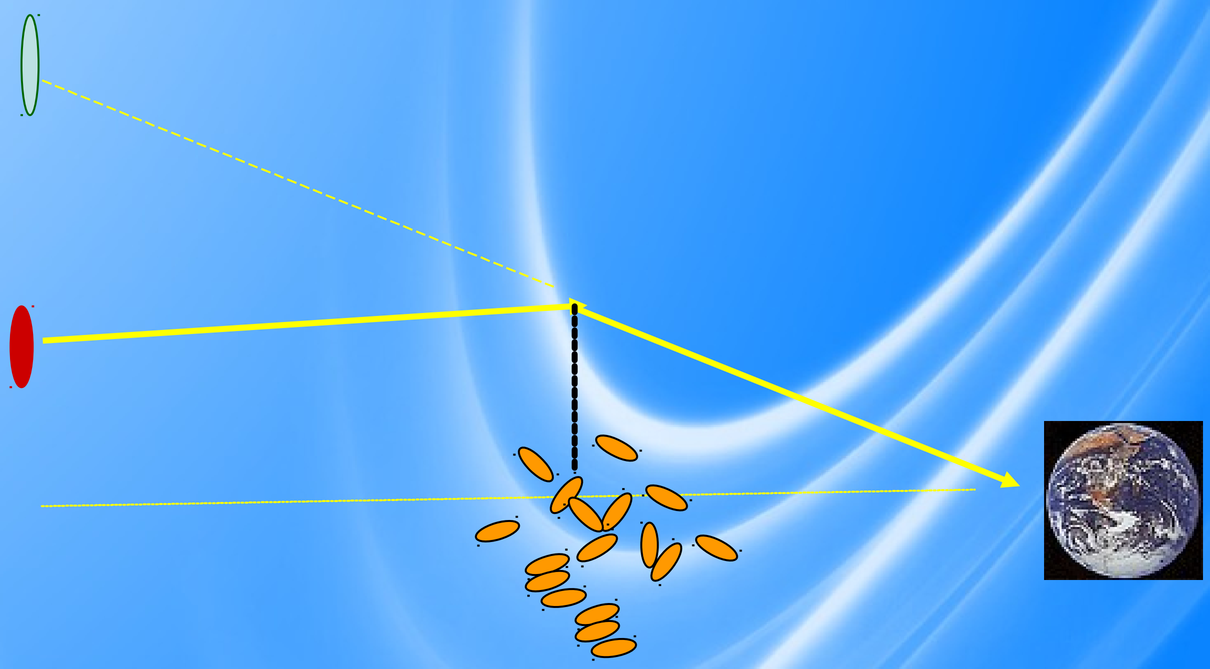
90% of baryonic mass is in hot intracluster gas -- not really "dark", just dark in optical light. However, 85% of the total cluster mass really is dark.

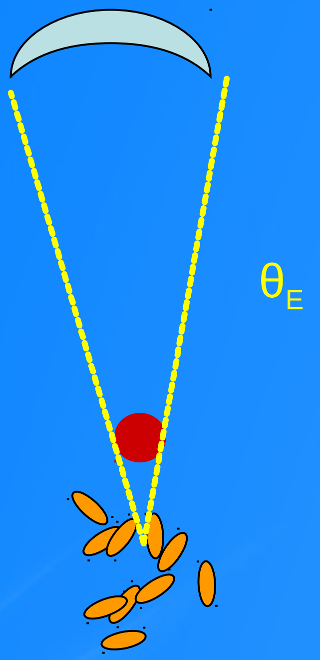
Cluster galaxy kinematics: $GM/r \sim \langle v2 \rangle$

Cluster gas temperature: $GM/r \sim kT/m_p$

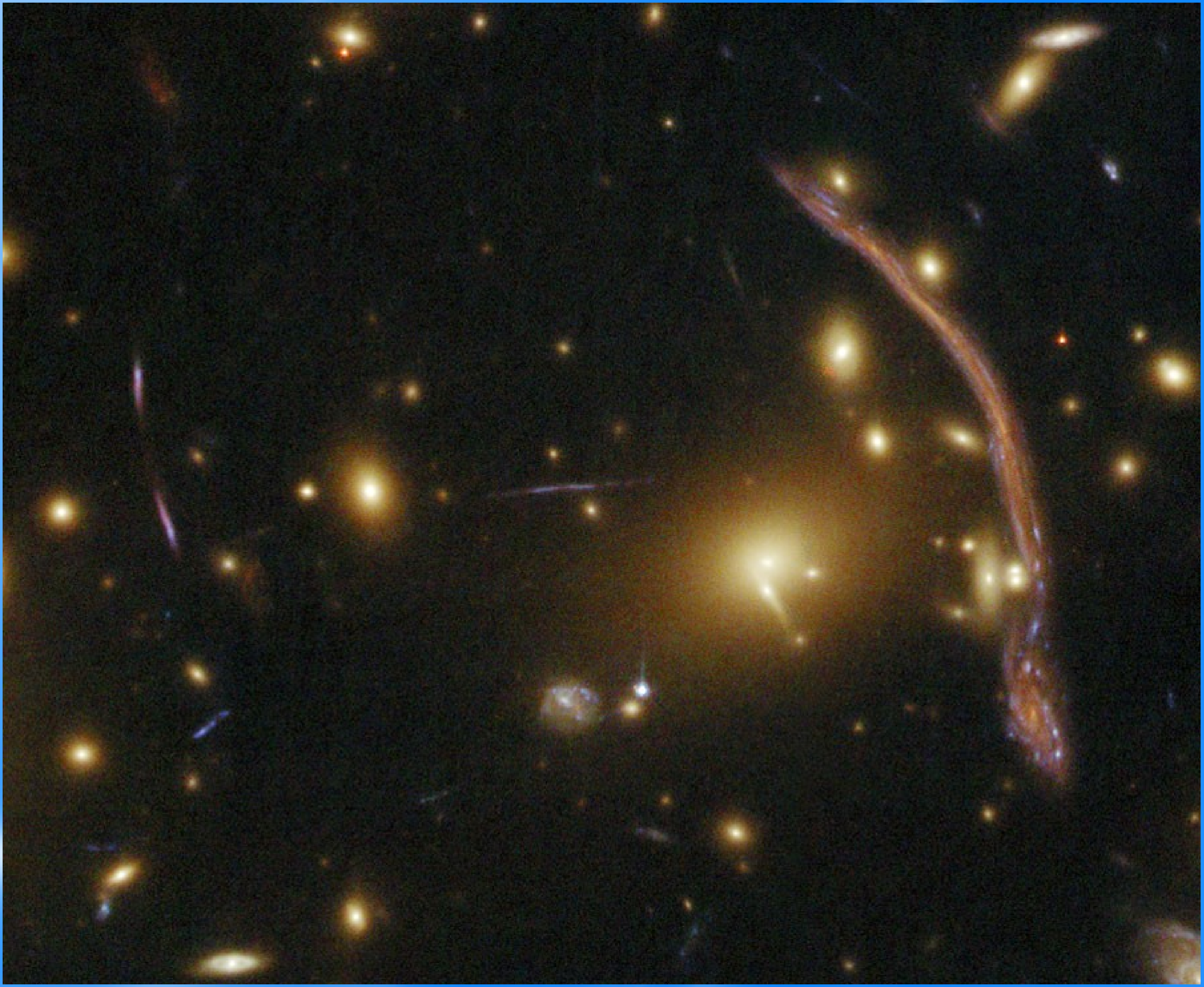
Strong lensing: $4GM/c^2 \sim 2\ \theta_E^2\ D$

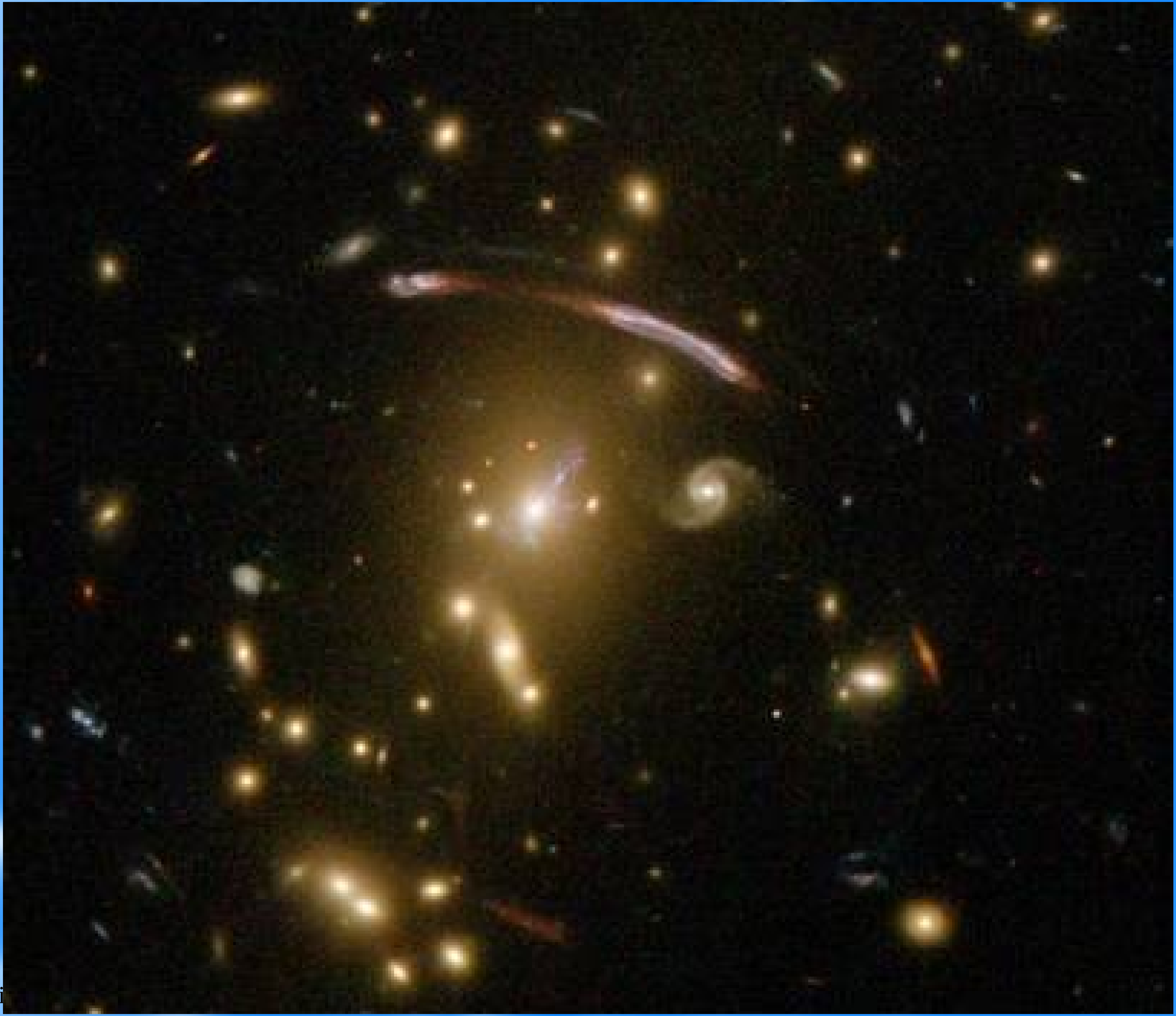






$$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{\rm ls}}{D_{\rm ol} D_{\rm os}} \right)^{1/2} .$$





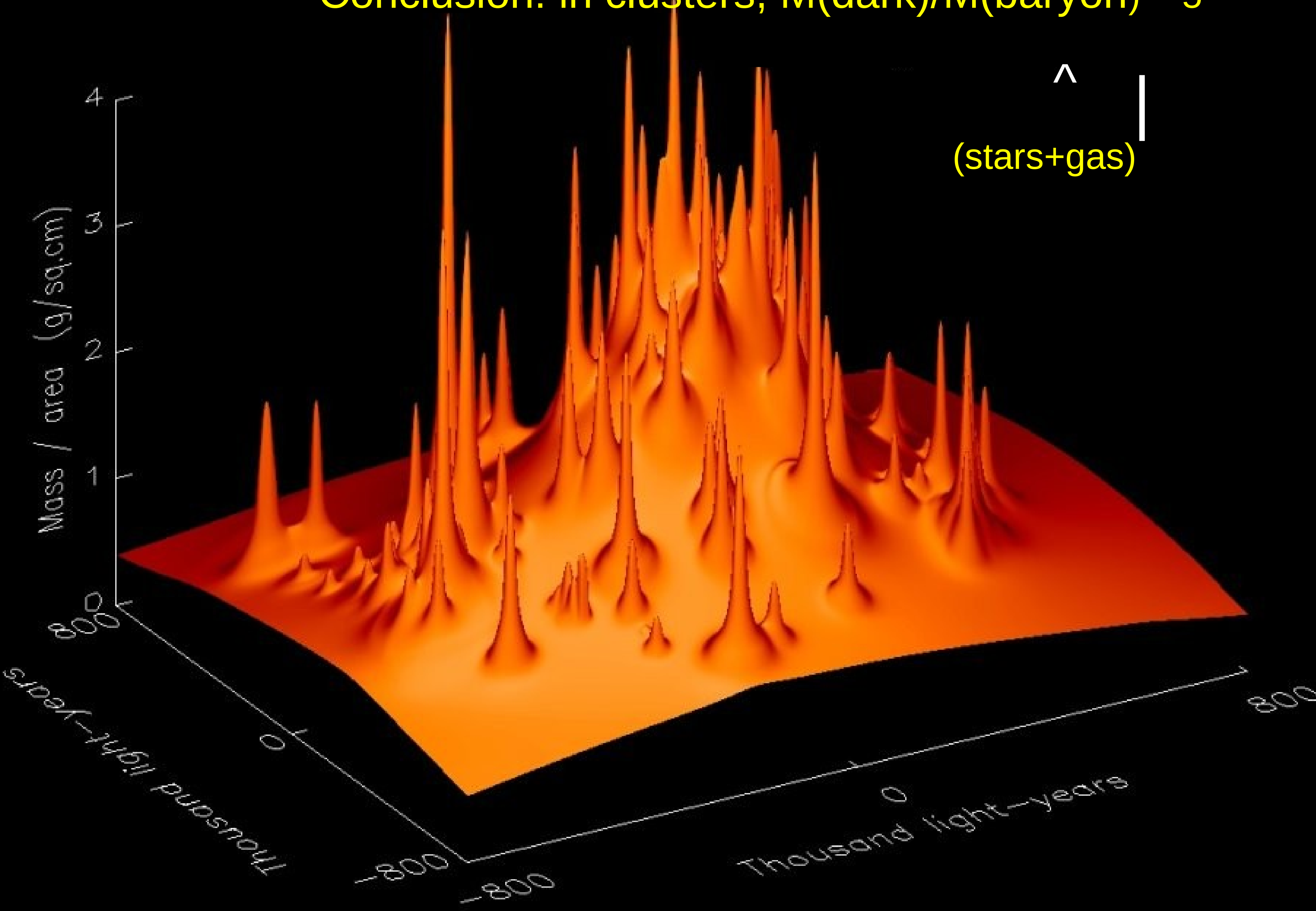
R. Budn

A. Tyson

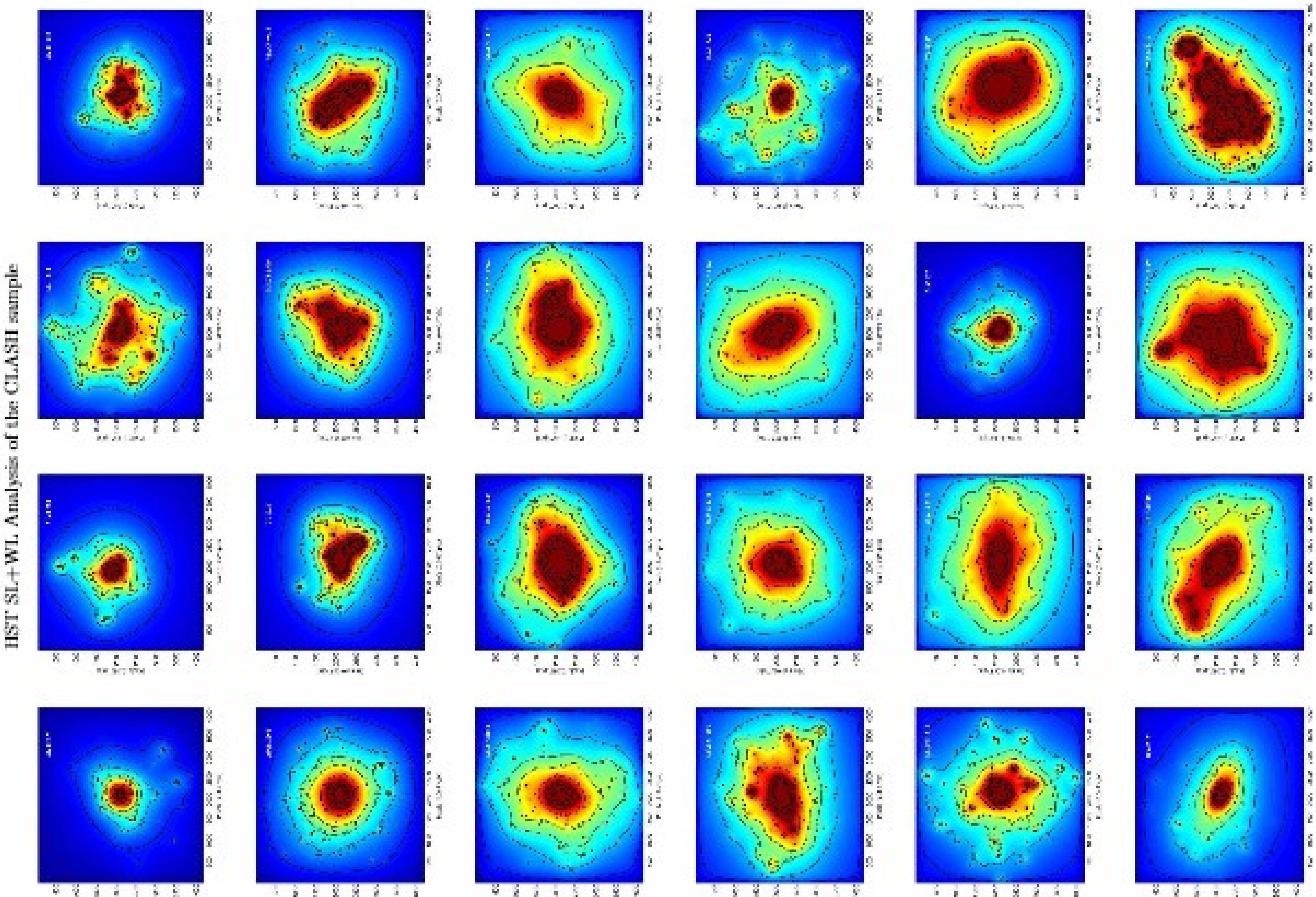
Conclusion: in clusters, M(dark)/M(baryon) ~ 5

^ |

(stars+gas)

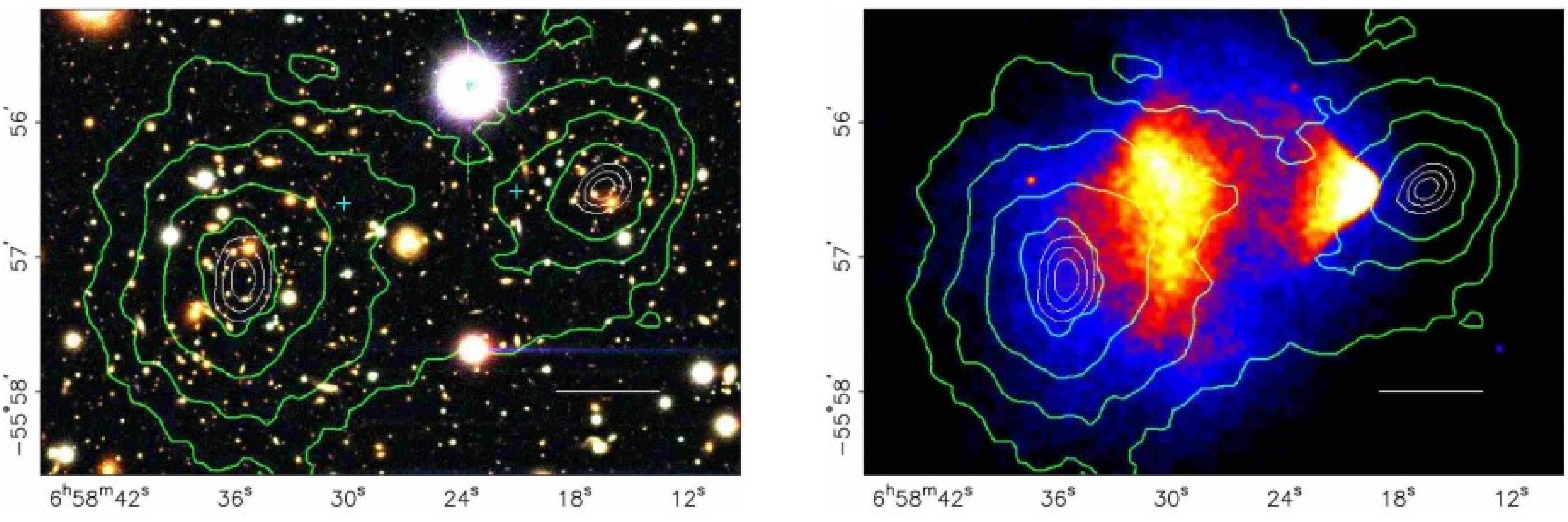


(Zitrin+14): mass distributions for 24 clusters from Hubble CLASH program



The “Bullet Cluster”: X-ray gas and dark matter are separated in collision between two clusters;

Dark matter is weakly interacting, and following the galaxies



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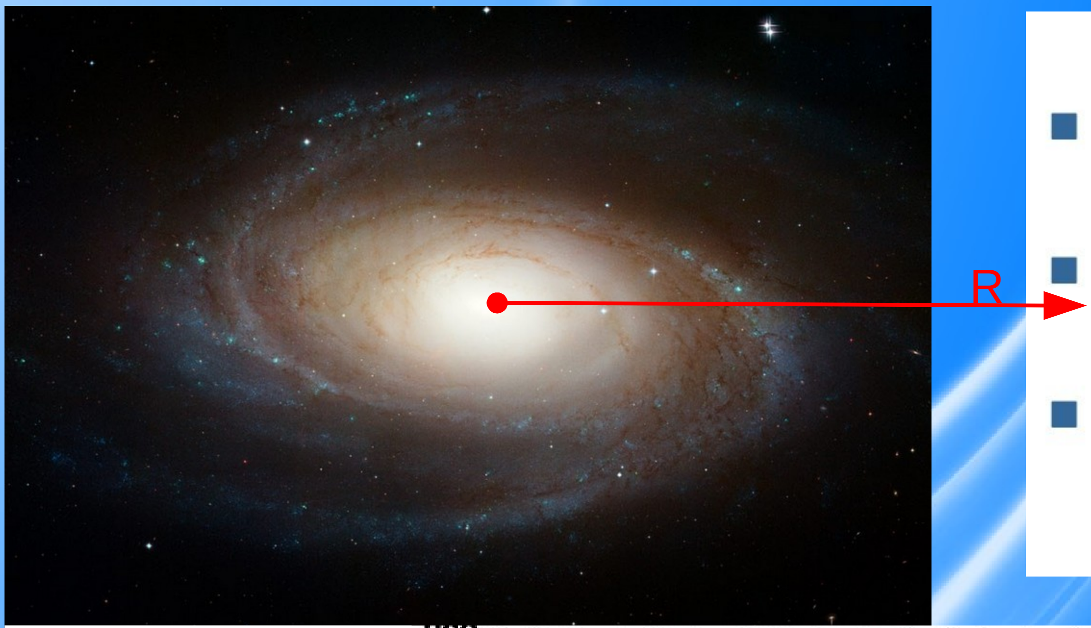
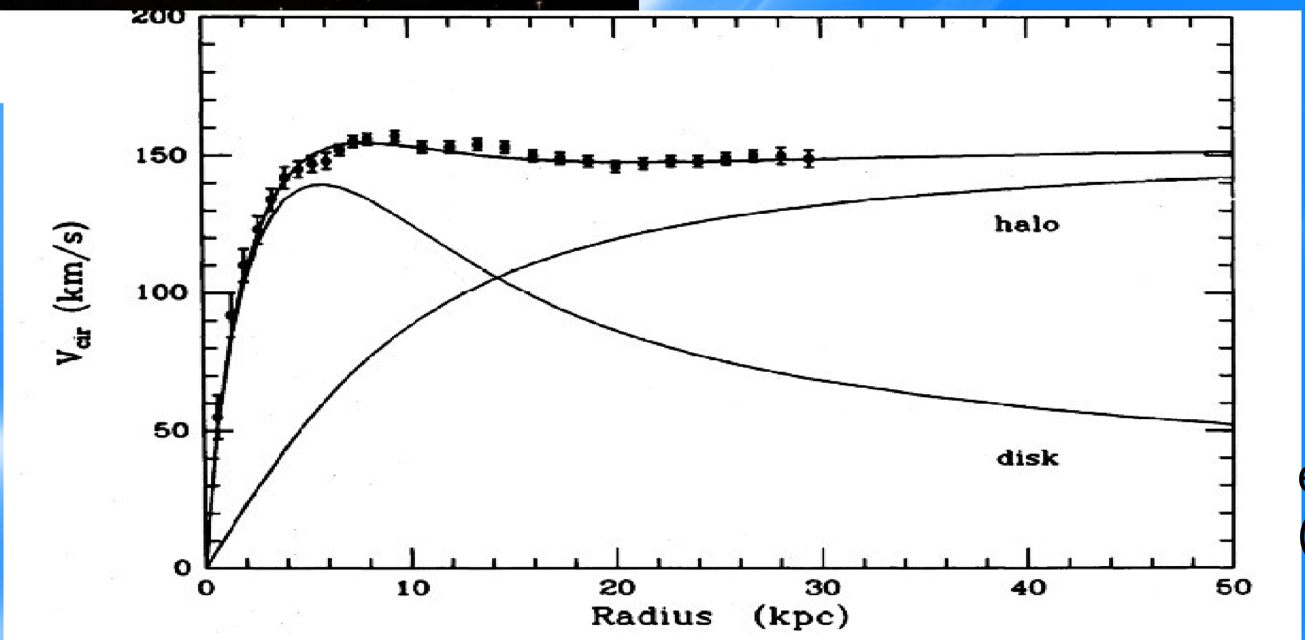
Dark Matter in Galaxies

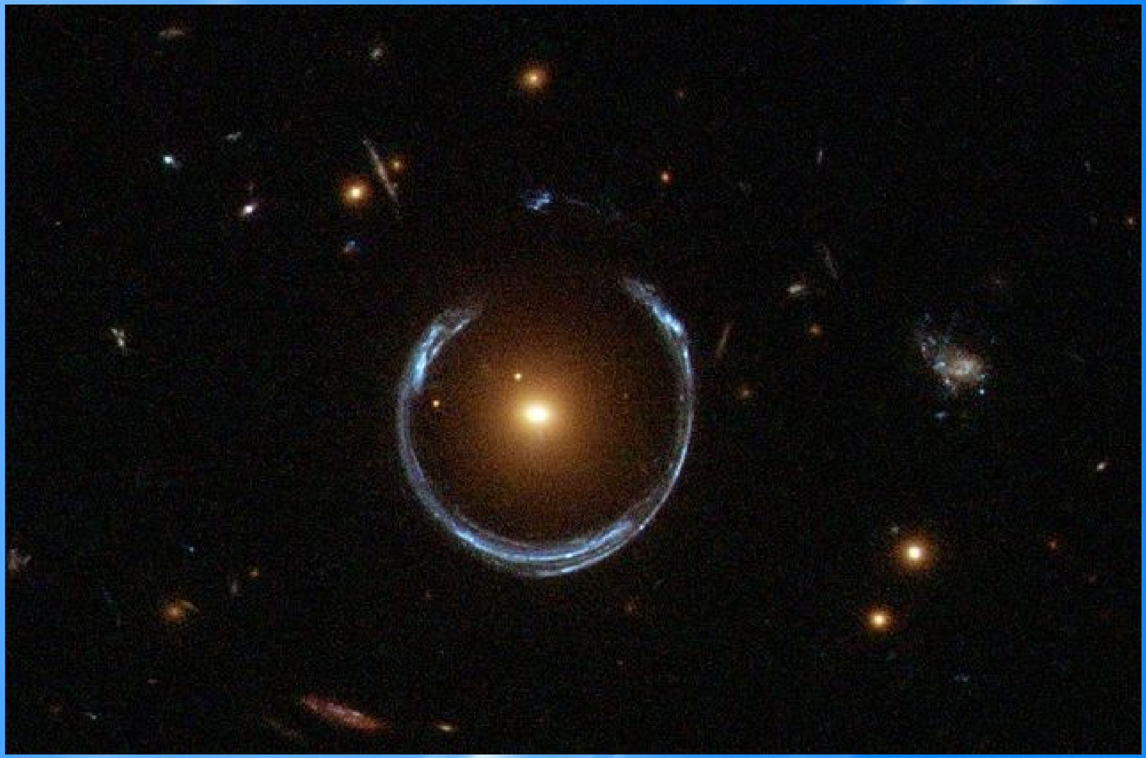


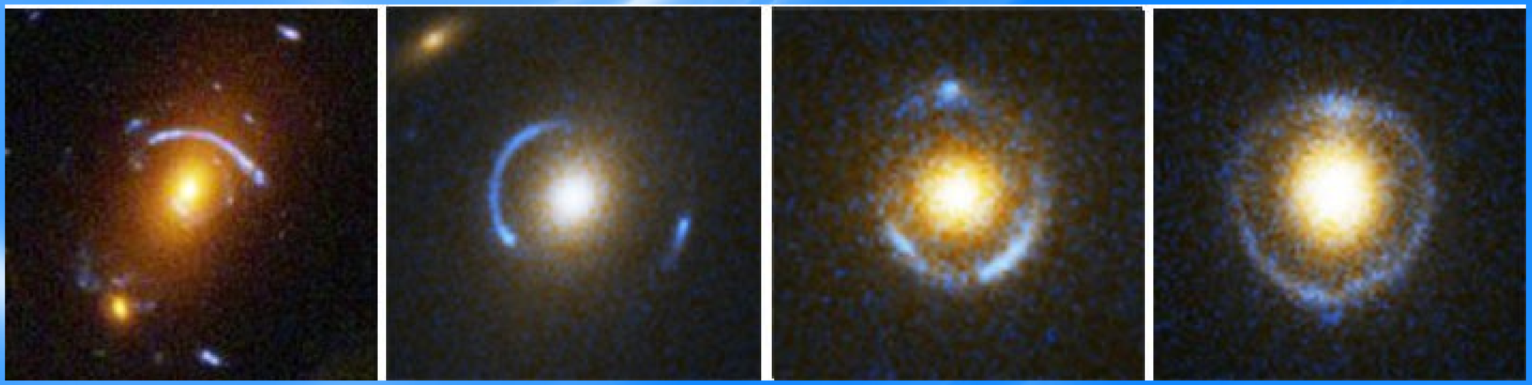
- If only visible matter is responsible for gravity, $v \propto r^{-1/2}$ beyond the visible edge
- Rotation curves tend to constancy beyond the visible edge $\rho(r) \propto r^{-2} \Rightarrow M \propto r$
- Compatible with an isothermal sphere of non relativistic matter.



e.g. Rubin and Ford (1970)

Elliptical galaxies also have dark halos proportional to their baryonic mass; would also have “flat” rotation curves





Dwarf galaxies are dark-matter dominated throughout.

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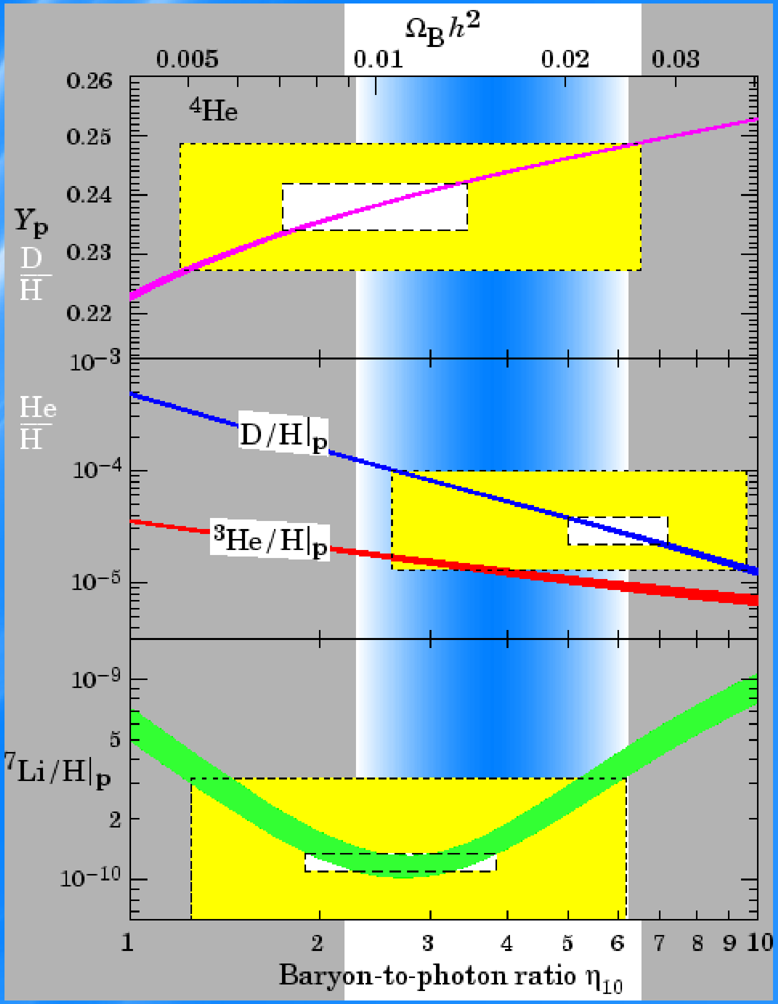
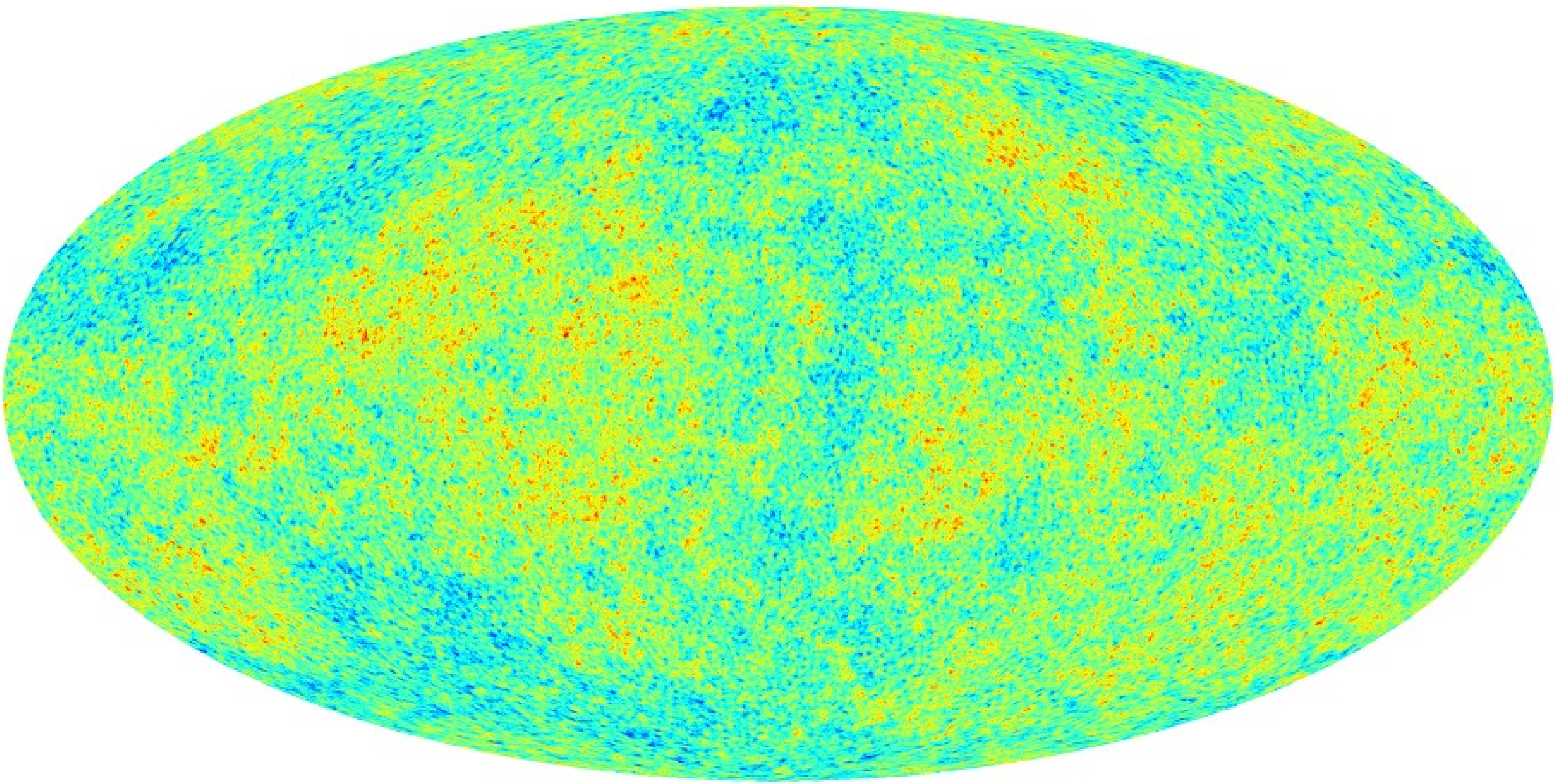
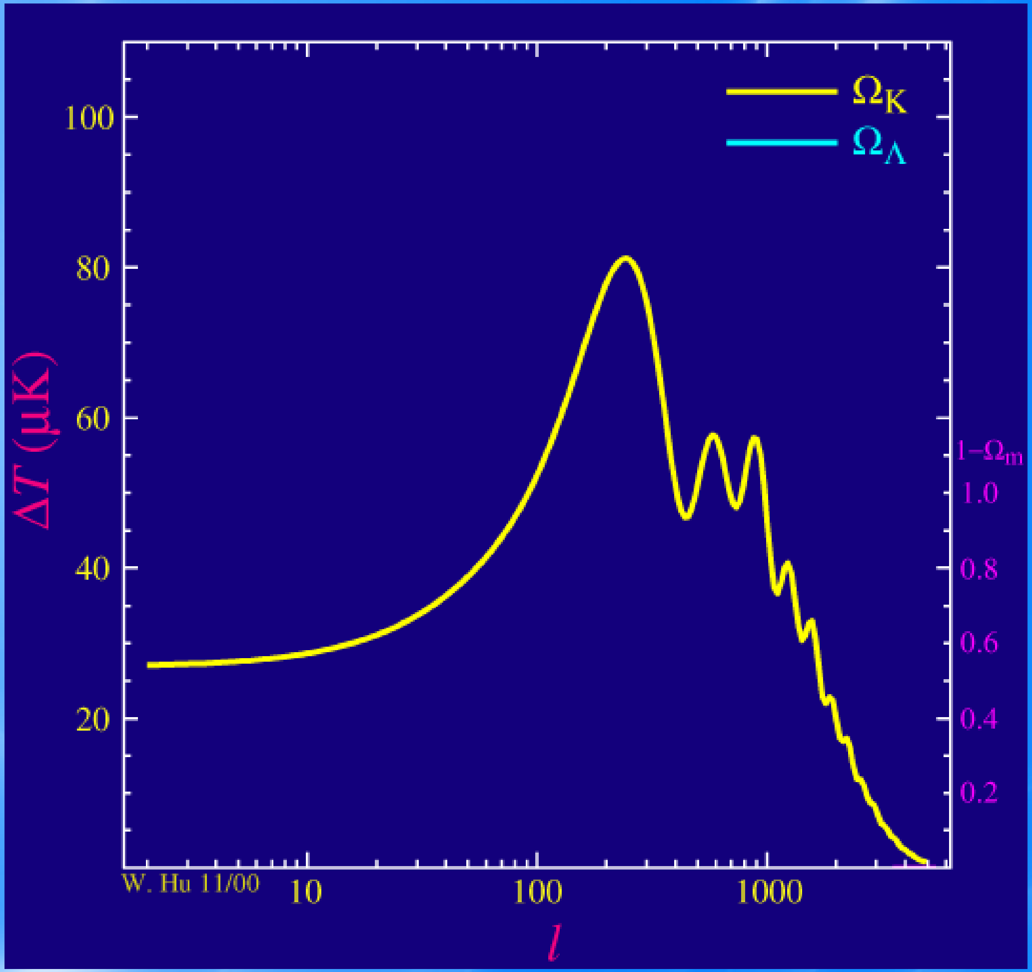
BBN results

- He, D and ^{7}Li measured with different methods
- Combined they strongly limit the number of baryons at the time of BBN (T~MeV)

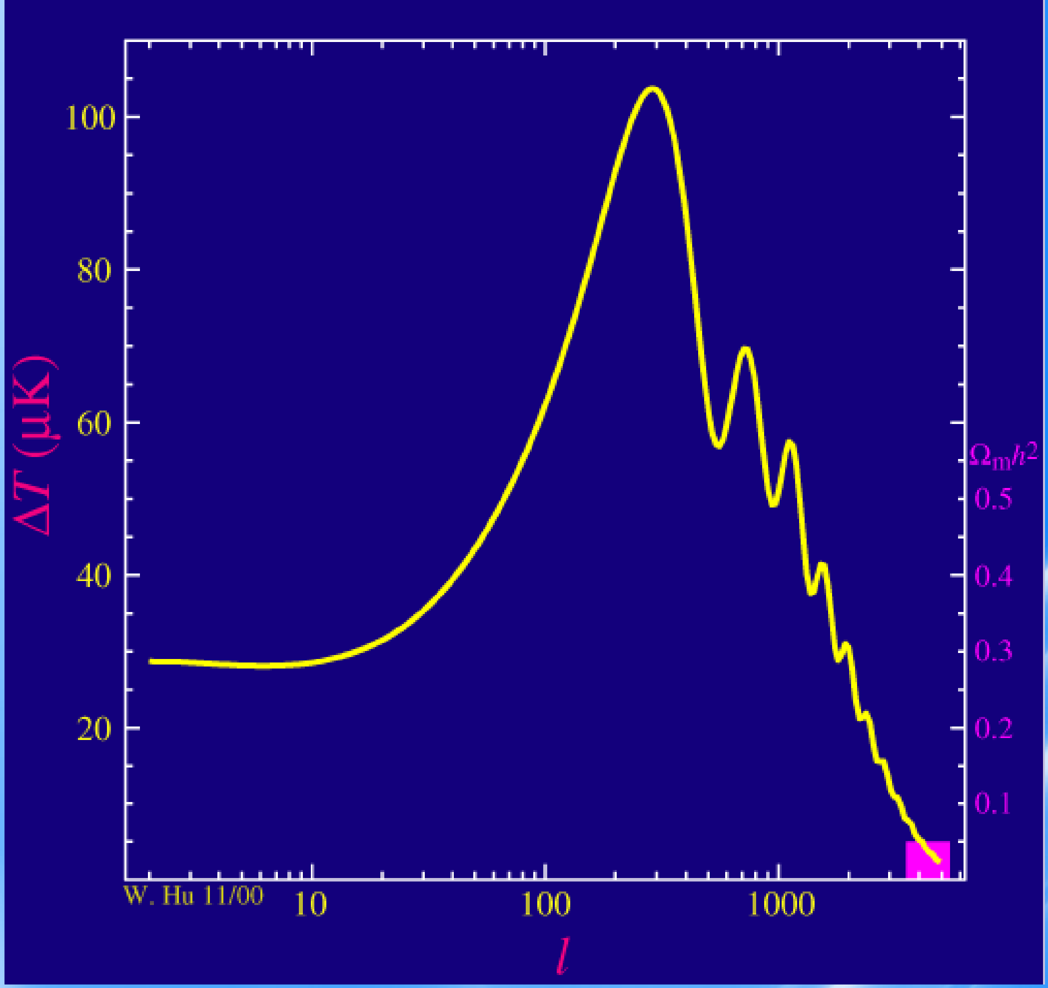


Planck Mission: cosmic microwave background – last scattering surface, 370,000 yr after Big Bang

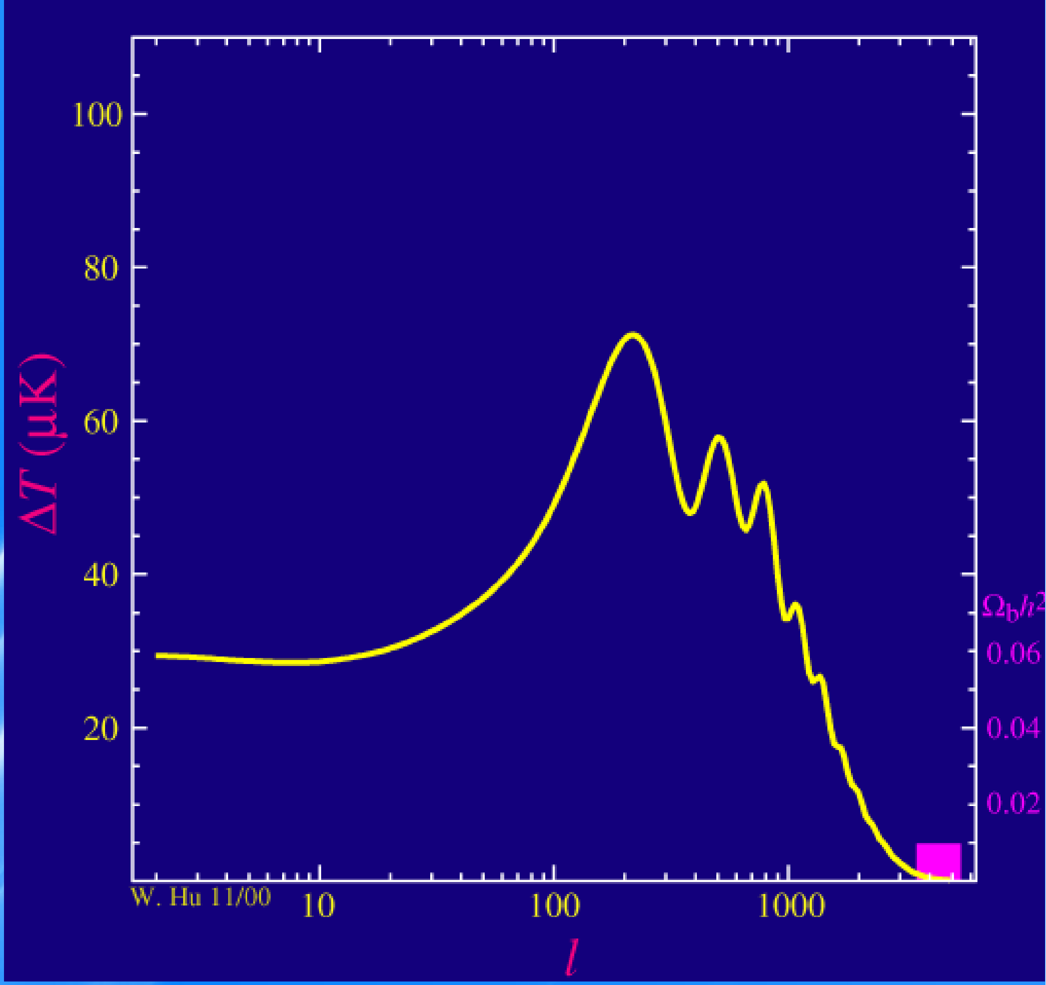




curvature and dark energy

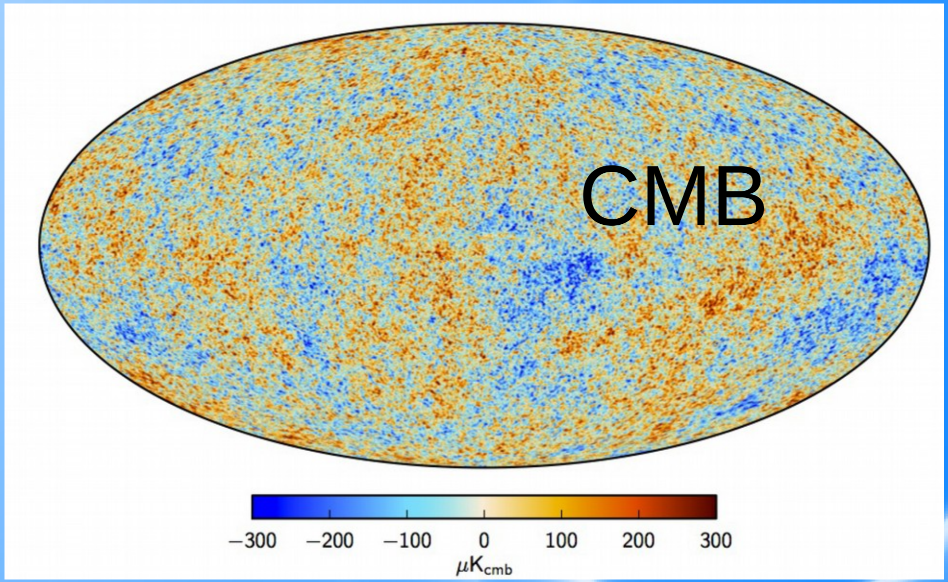


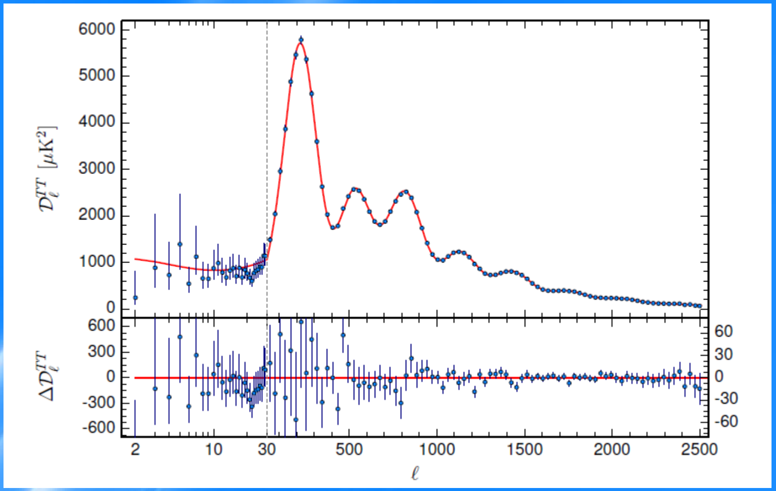
matter density

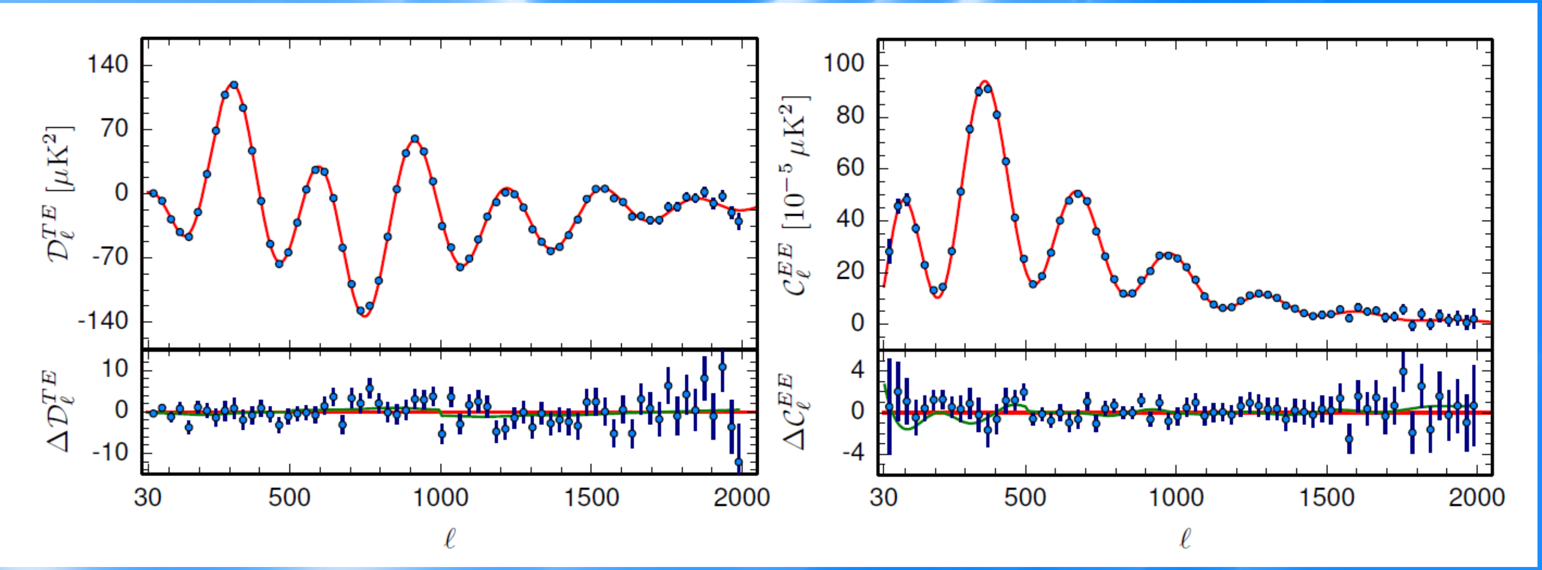


baryon density

Animations: Wayne Hu



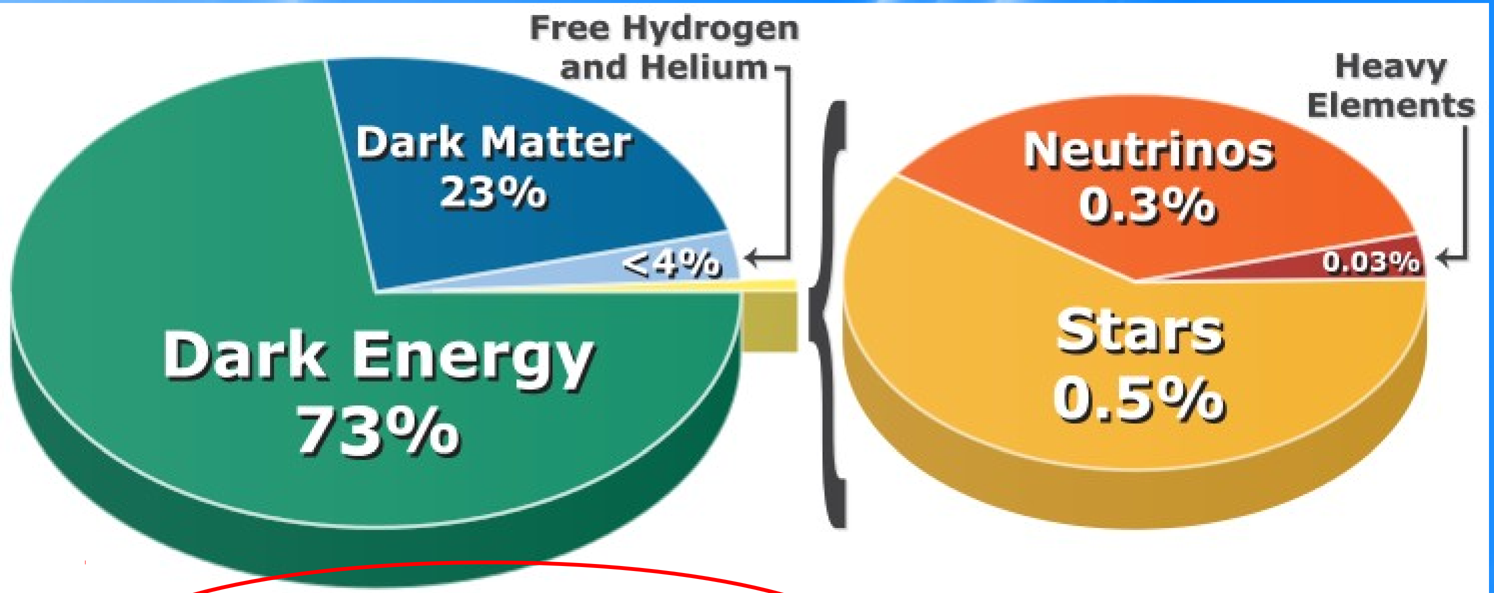




Measurements of correlations with polarization break degeneracies (e.g. recombination width, reionization) and adds information of types of perturbations

Planck 2015

Matter and Energy Content of our Universe



$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

Planck 2014

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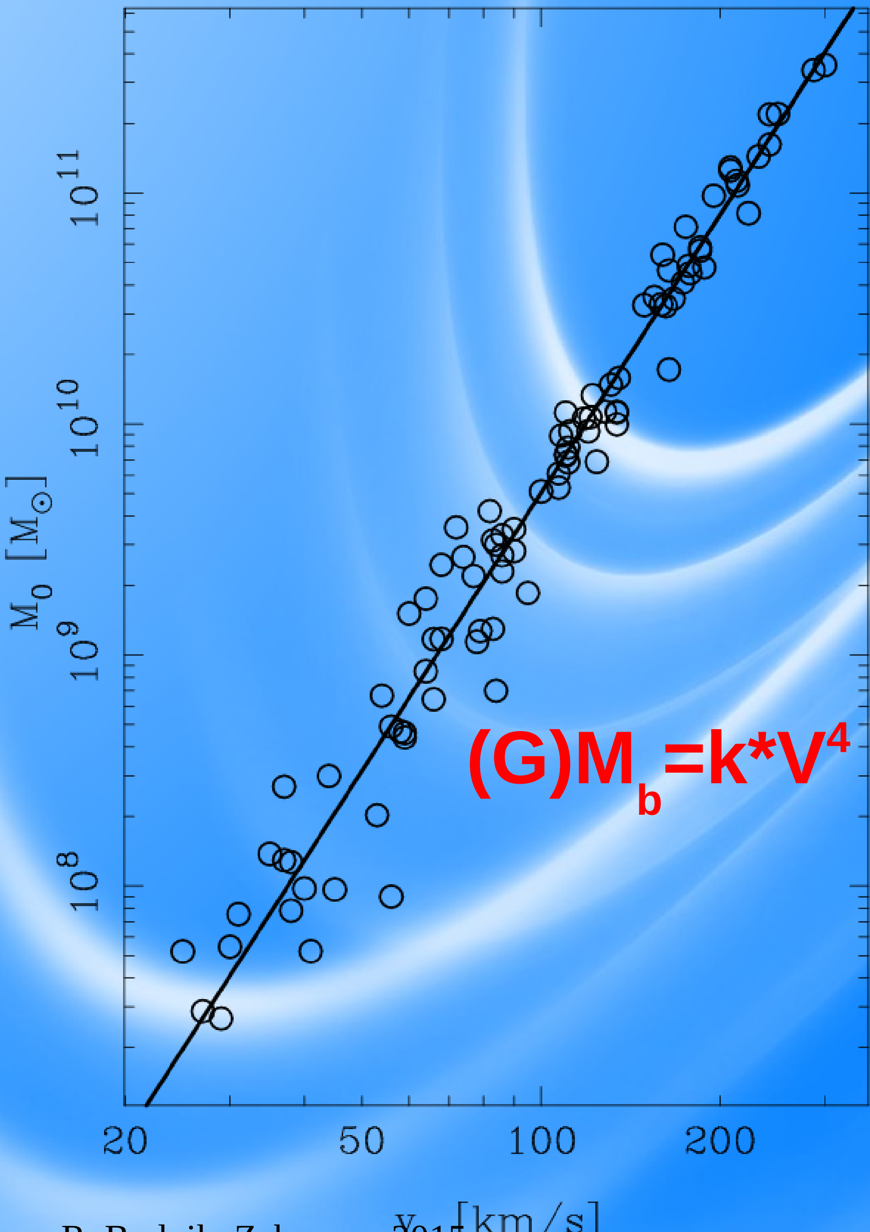
Problems with LCDM

- New physics...
- Baryonic Tully Fisher
- “Cusp vs. Core” for galaxies and clusters
- “Missing Baryons”
- “Missing Satellites”

Modifying Gravity

- All evidence for DM is eventually based on gravitational effect on other objects (except BBN)
- It is appealing to find a “correction” to Newton/GR gravity that will fix this need
- There are quite a few attempts, most suffer from all kind of problems (consistency, observations)

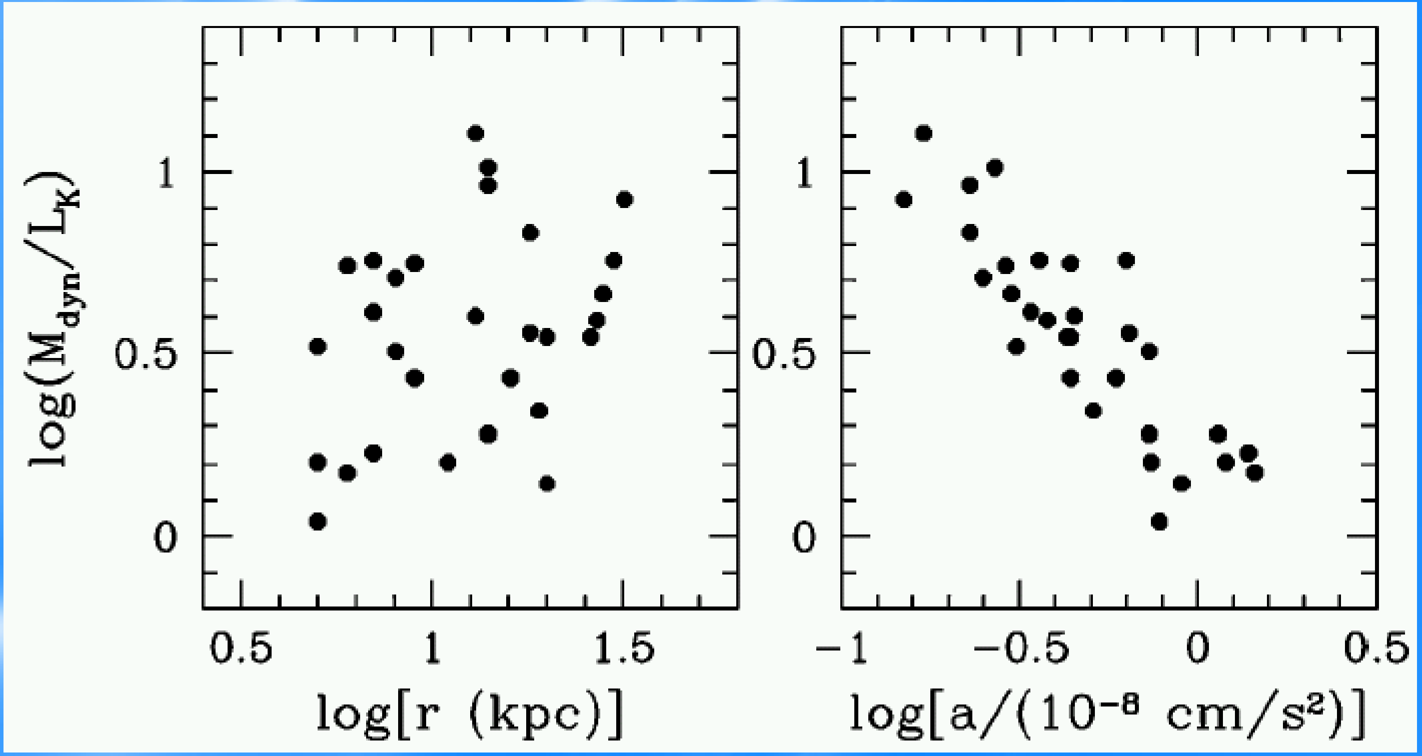
Tully Fisher



- Why would baryons "dictate" the total potential of the galaxy?
- Why the special acceleration (k has units of 1/a)?

MOND

- One can test the mass discrepancy as a function of radius, or as a function of acceleration:



MOND

- Developed by Milgrom (1982), a new idea about modifying gravity:

$$a_0 \approx 1.2 \times 10^{-8} \text{ cm s}^{-2}$$

– acceleration scale

$$a = \frac{F}{m}$$

for $a \gg a_0$

"Stronger gravity" on large scales

$$a = \sqrt{a_0 \frac{F}{m}}$$

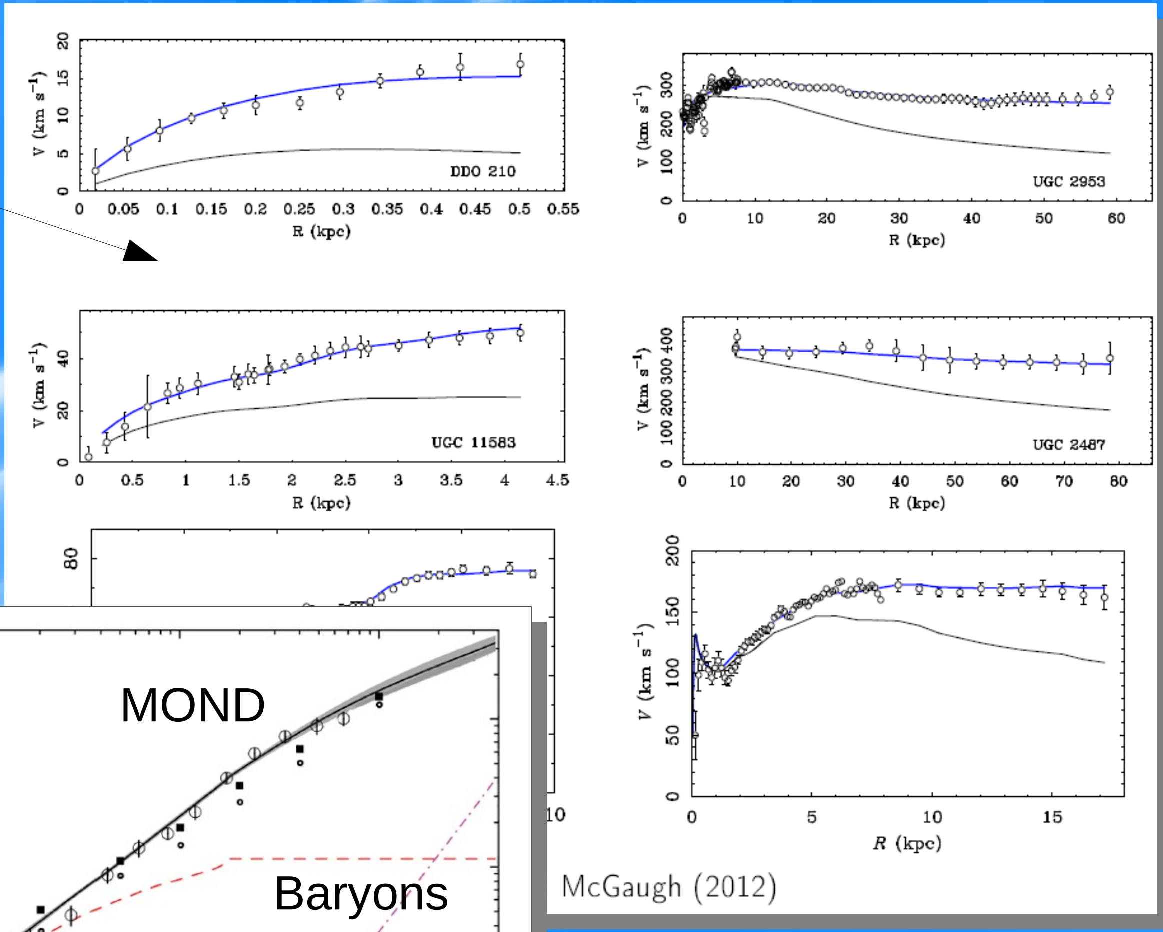
for $a \ll a_0$

Many modifications of these laws appeared later

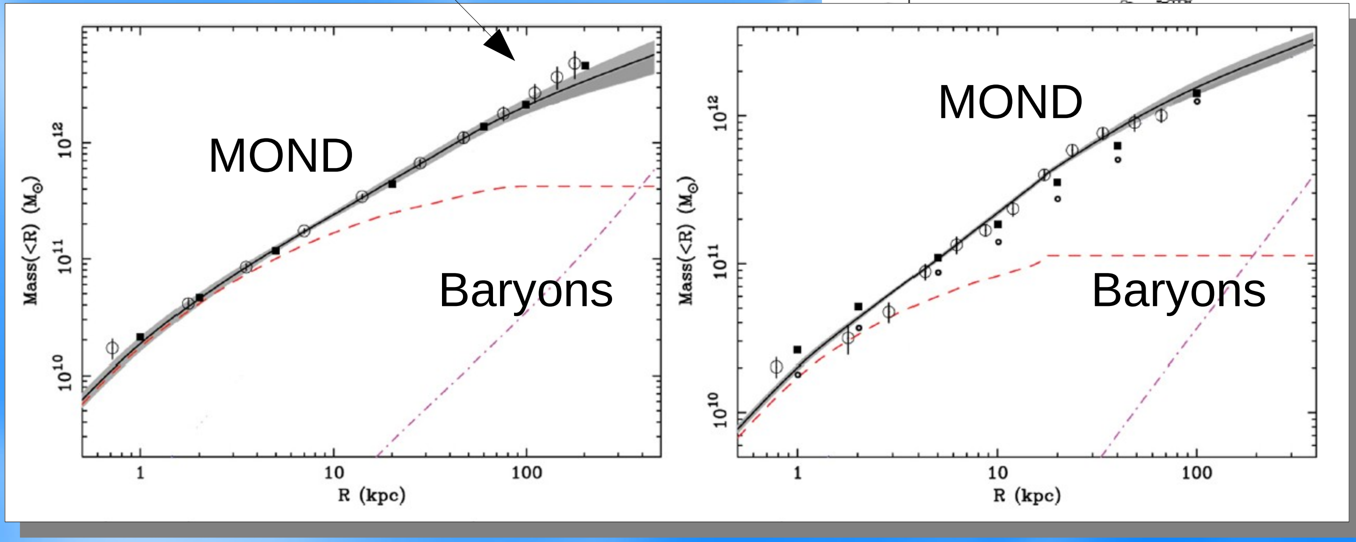
MOND - results

- Many successes on galactic scales

Disc

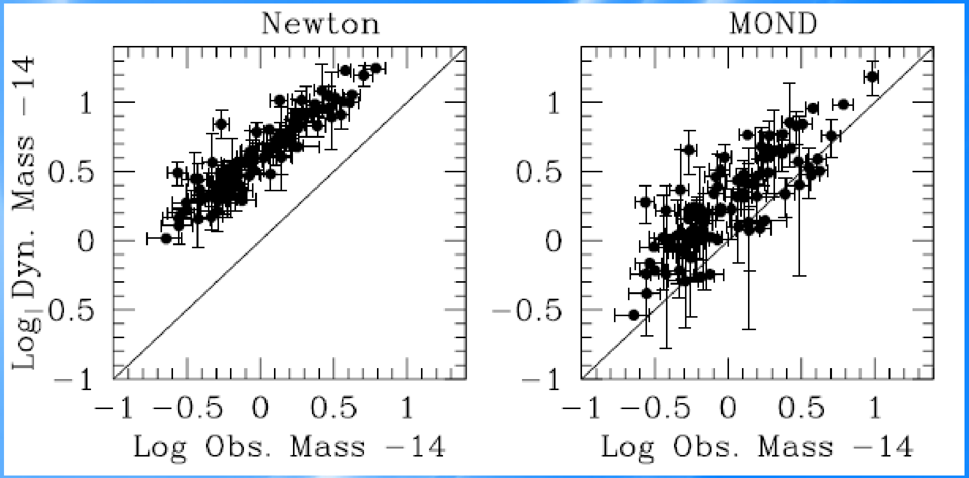


Ellipticals



MOND – the problems

- Galaxy clusters still fail



- No accepted relativistic extension, hence no possibility to predict CMB, LSS

Summary

- We saw the evidence for DM on scales from Galactic, to clusters, to the visible universe
- Manuel Drees will talk about models for particle DM
- I will talk about detecting cosmological DM: Directly and indirectly