Dark matter & Axions

Javier Redondo (Zaragoza U. & MPP Munich)

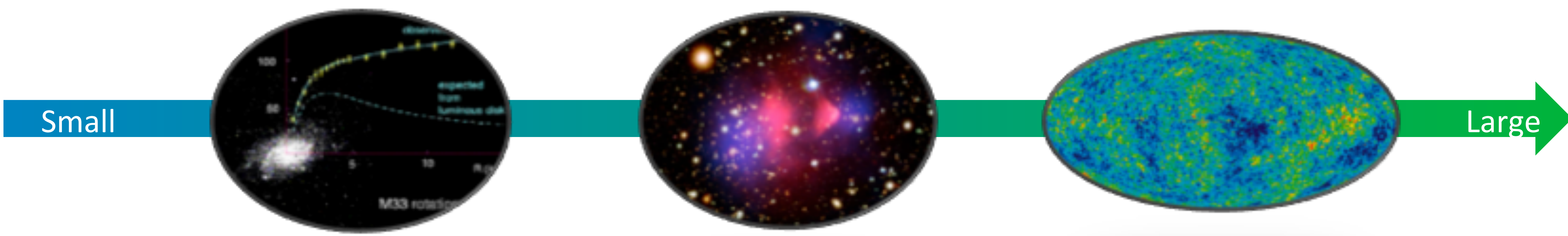
Evidence for Dark matter

Dark matter: nonluminous matter not yet directly detected by astronomers that is hypothesized to exist to account for various observed gravitational effects.

www.merriam-webster.com

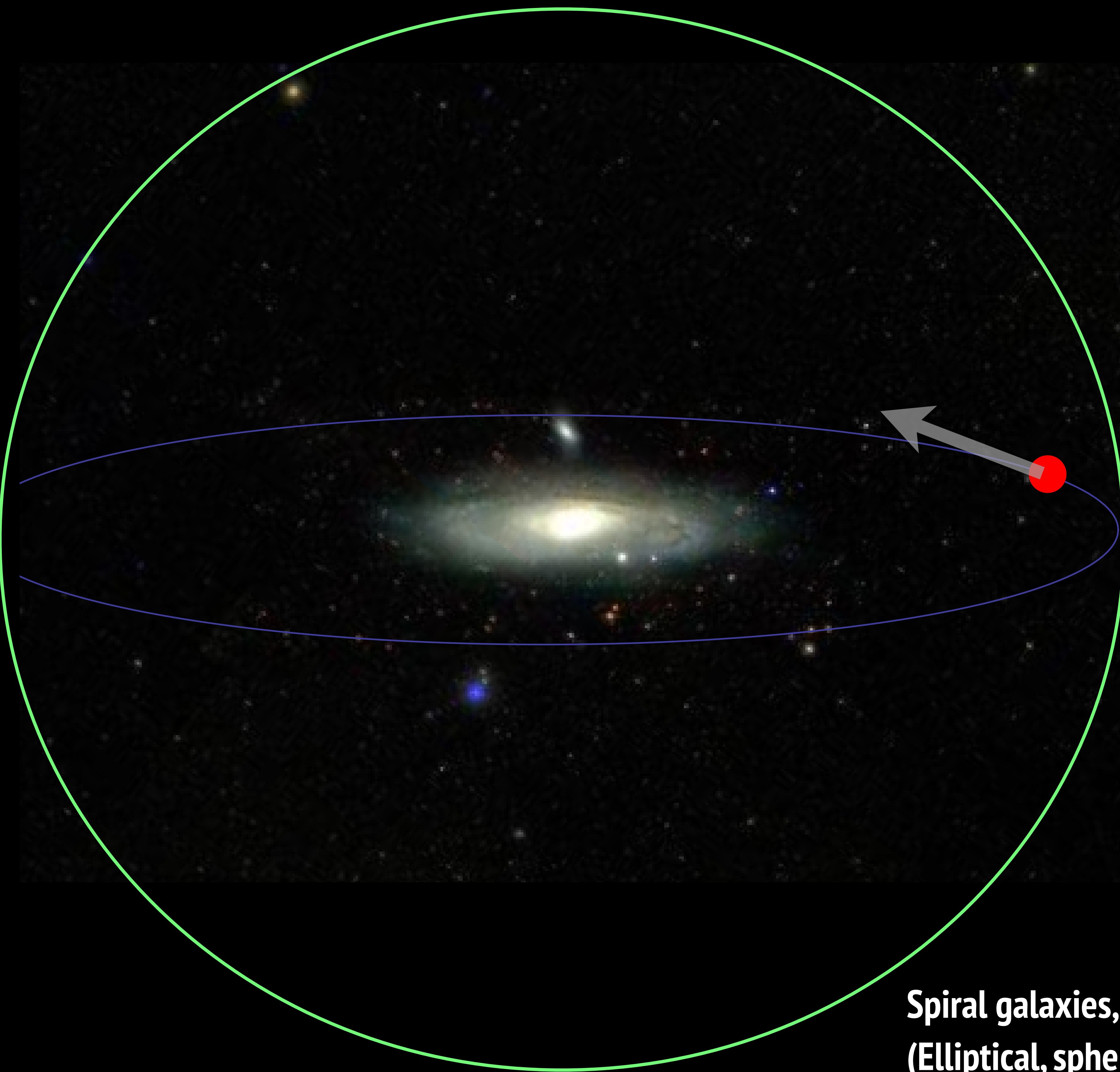
A long history (astronomers miss a lot of matter)

Evidences in a huge range of scales !



galactic   galaxy clusters   large scale structure

Galactic rotation velocity curves

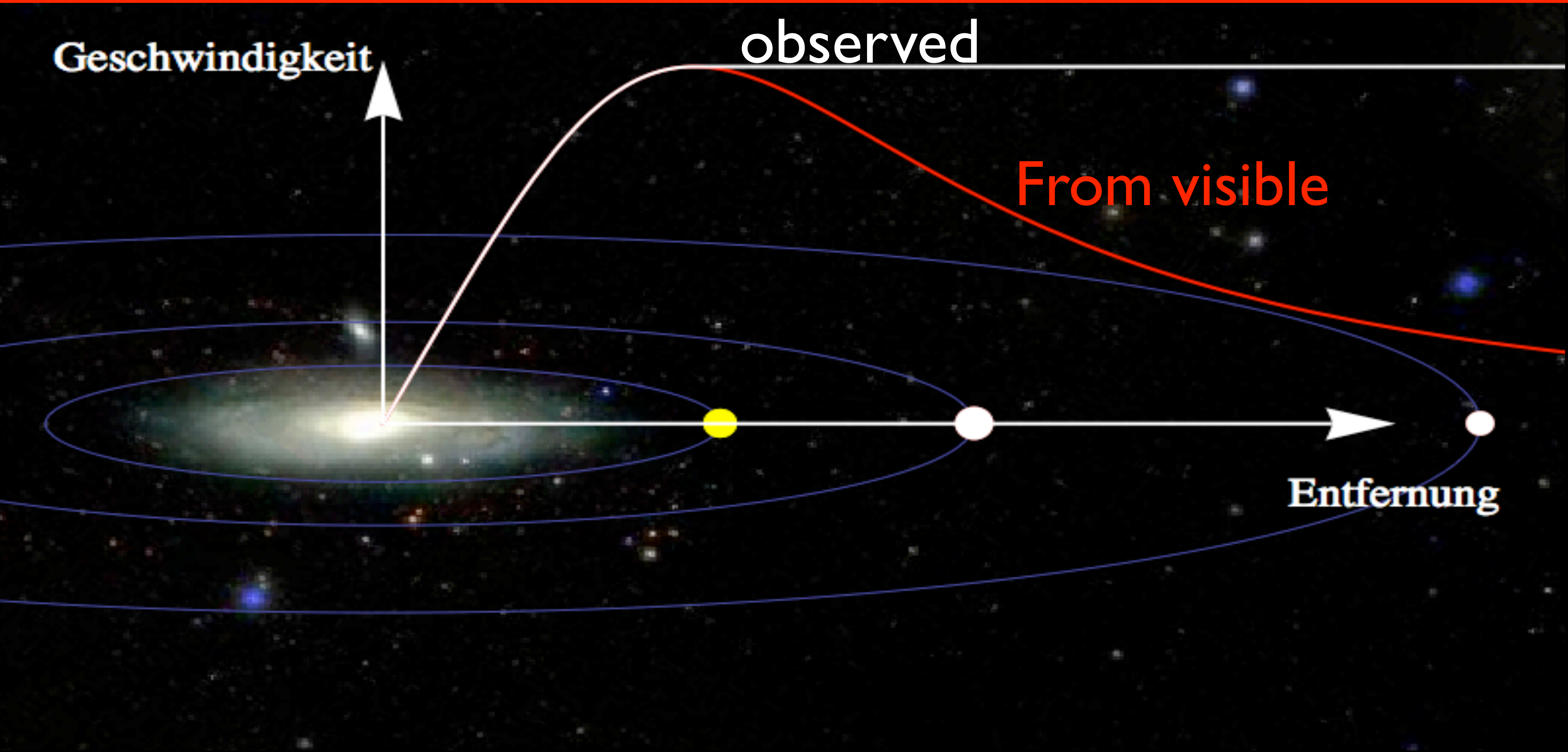


$$v^2 \sim \frac{\mathcal{M}}{r}$$

Spiral galaxies, supported by rotation $v_r \gg \delta v$

(Elliptical, spheroidal is more complicated)

Galactic rotation velocity curves



Prediction from the observed mass decays after the disk, which contains most "visible" mass (stars+gas)

$$v \to \sqrt{GM/r}$$

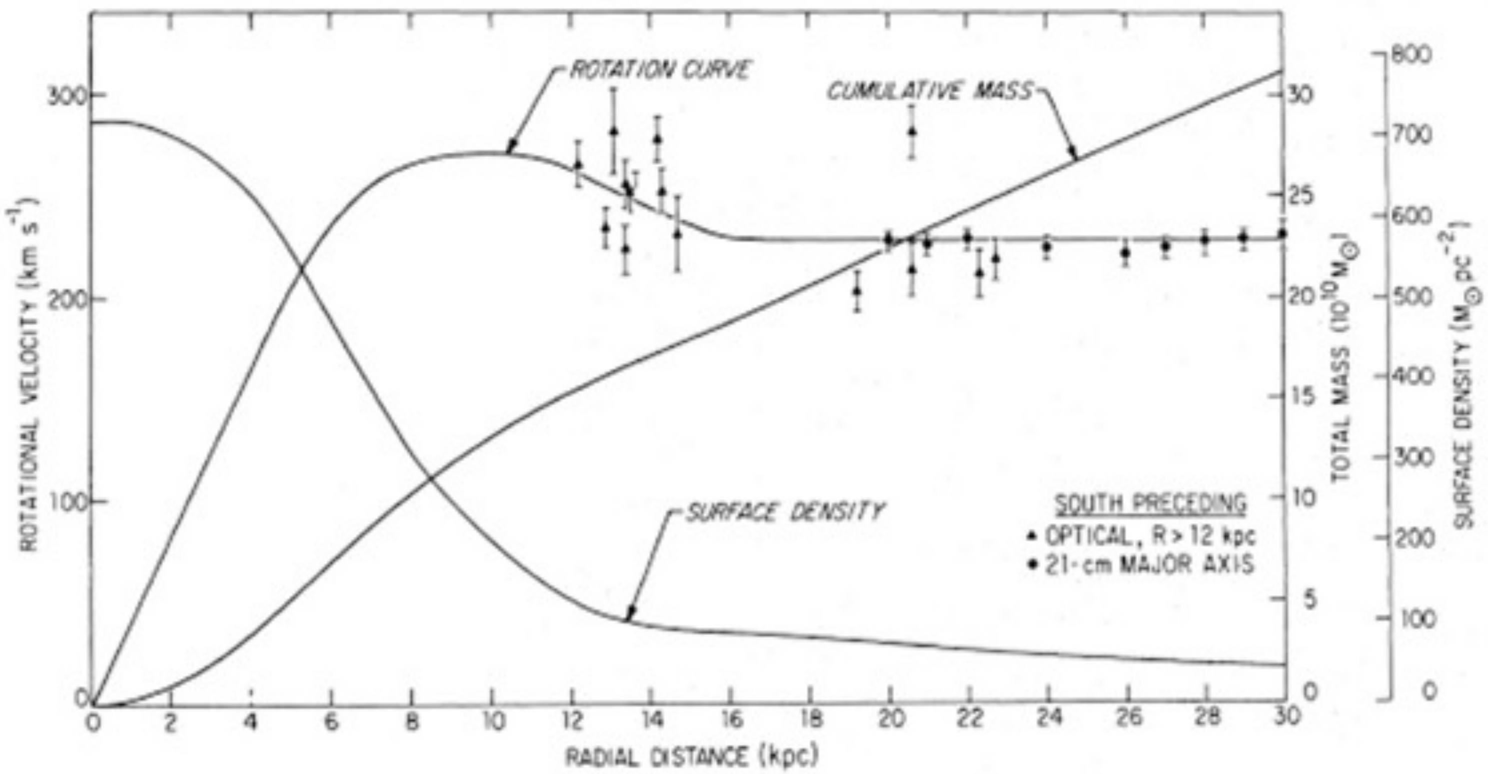
A halo of "dark matter" extending further than the disk

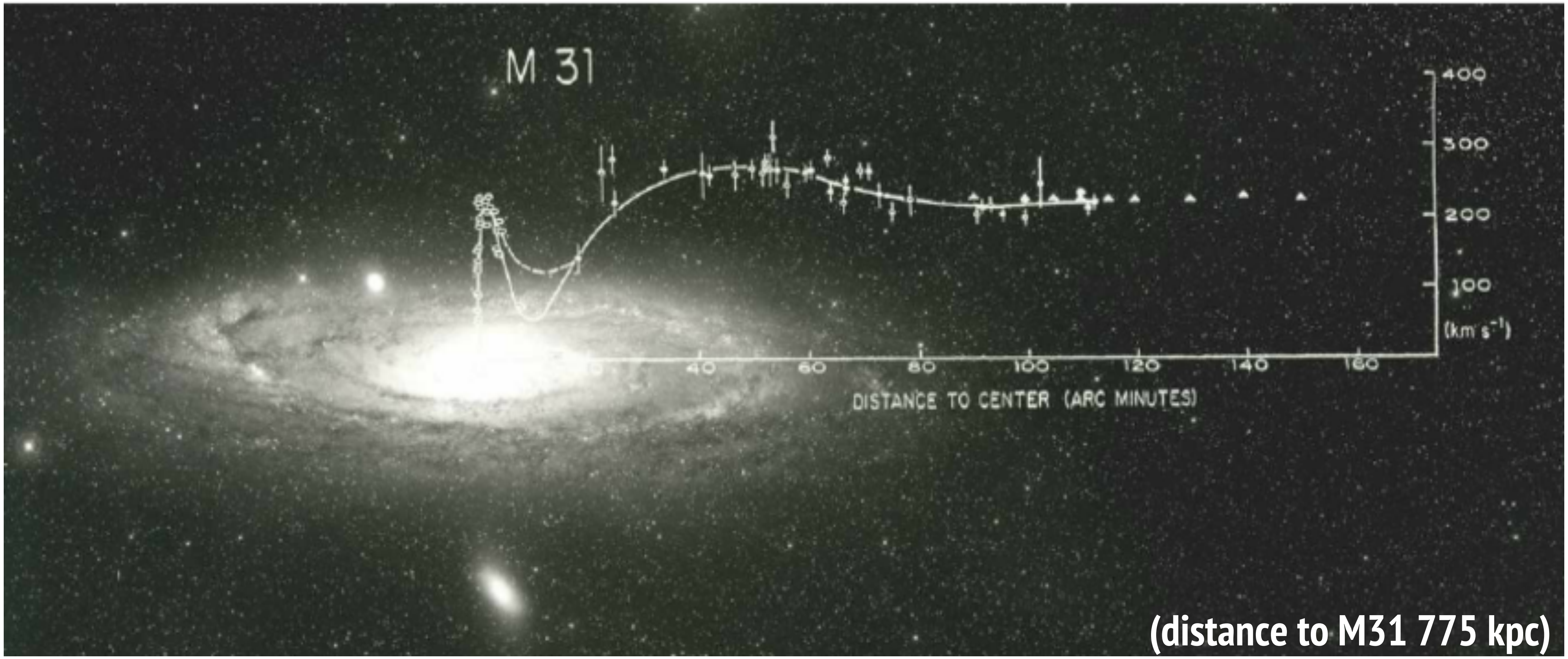
$$M = M_{\text{vis}} + M_{\text{DM}}$$

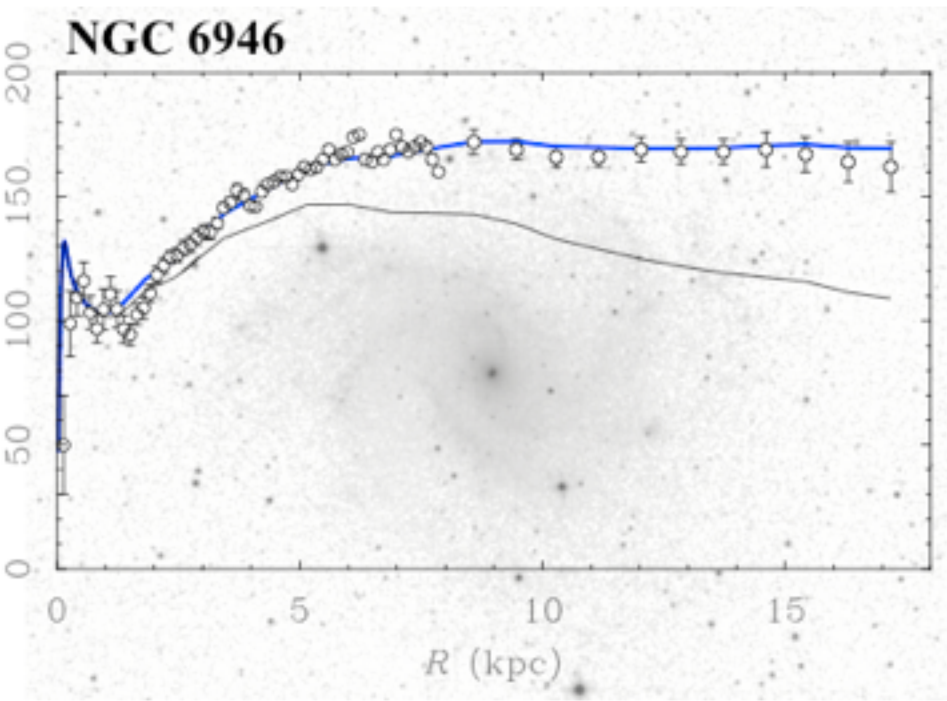
$$M_{\text{DM}} \propto r = \int^r dV \, \rho_{\text{DM}} \to \rho \propto 1/r^2$$

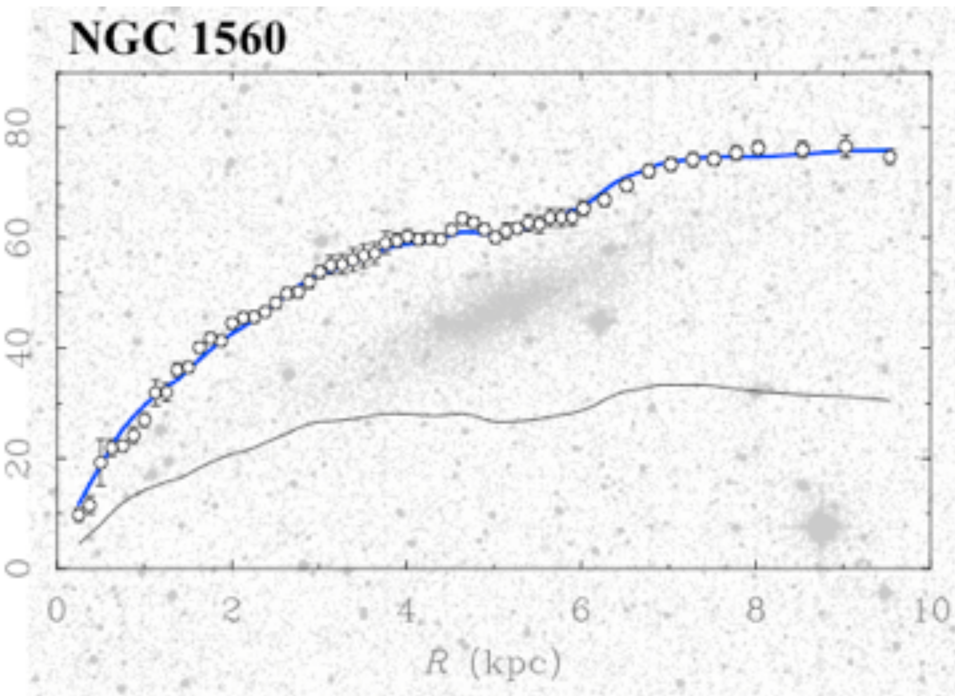
M31

Vera Rubin (1928-2016)
Astrophys Journal. 159: 379–404:
"Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions".

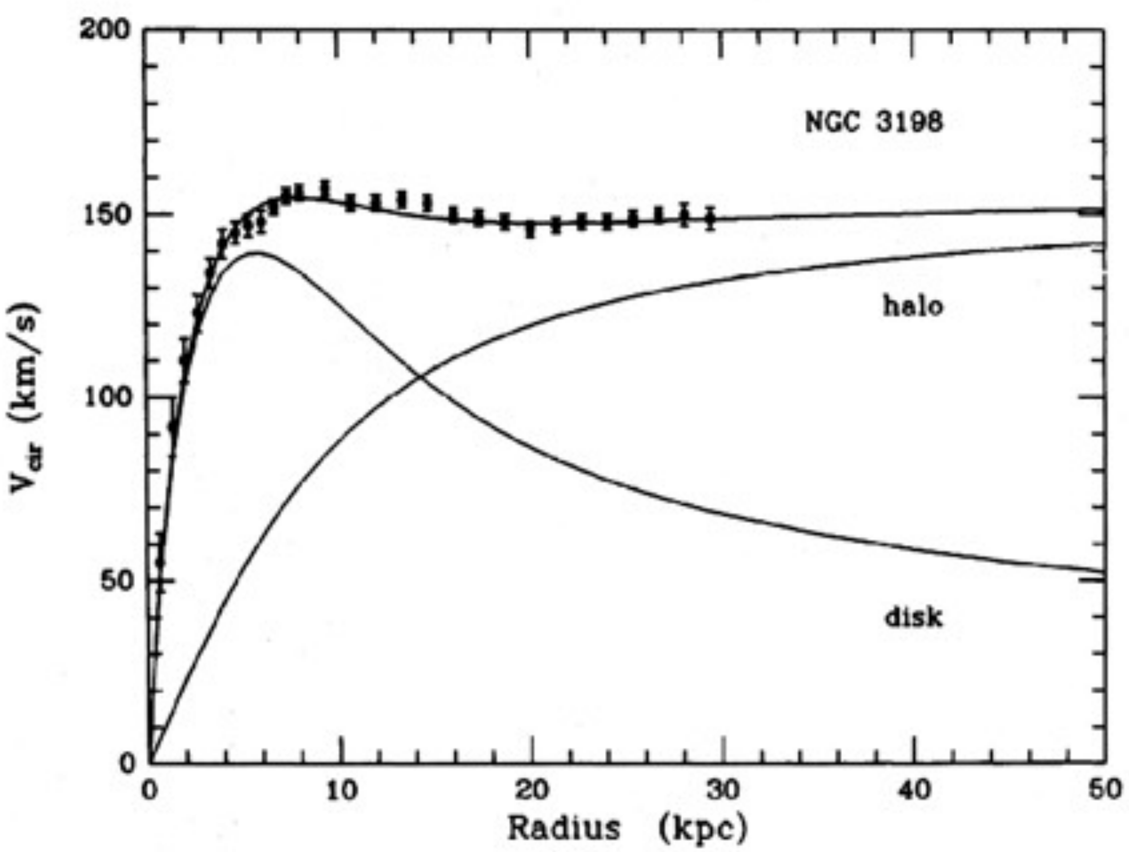


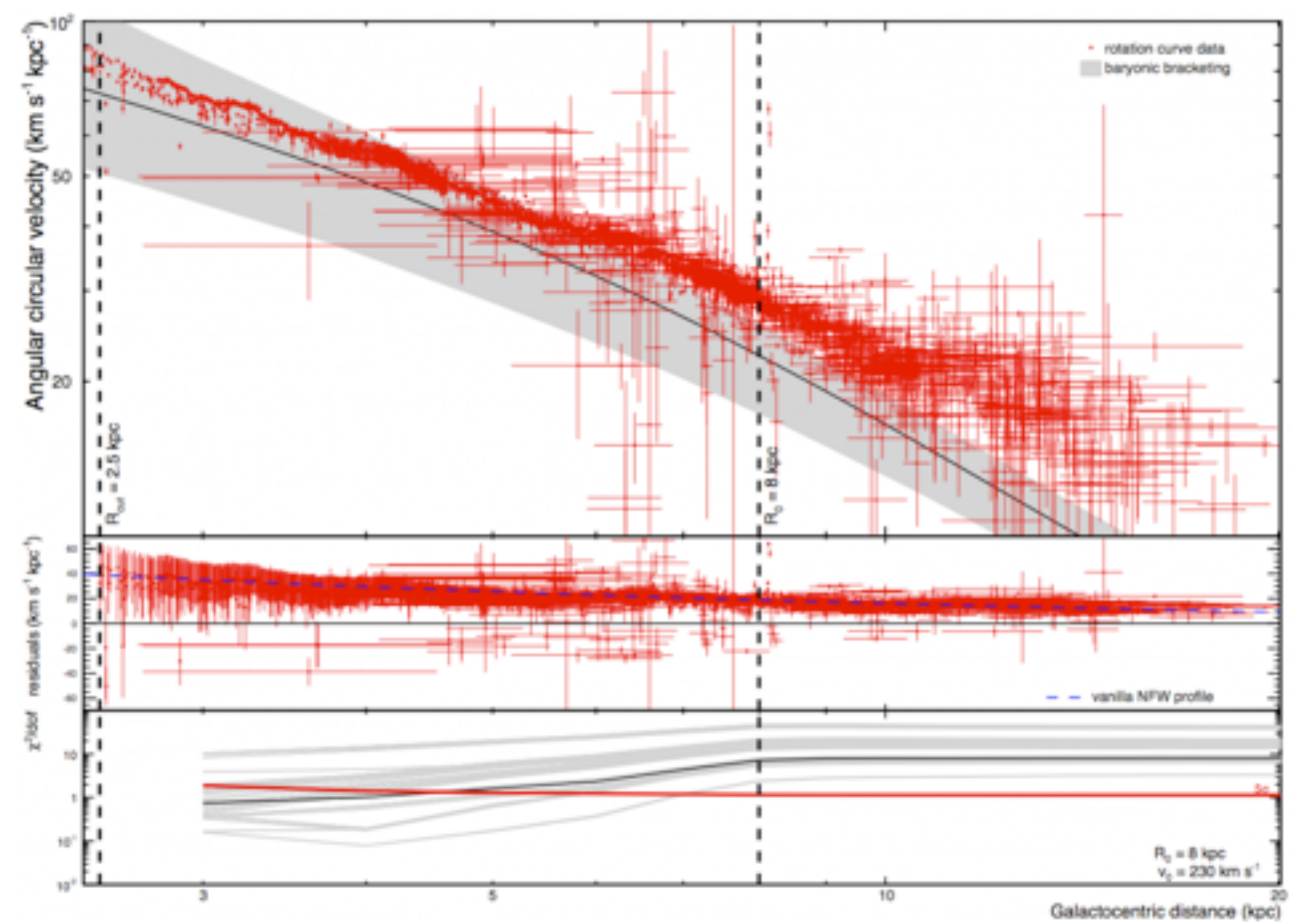




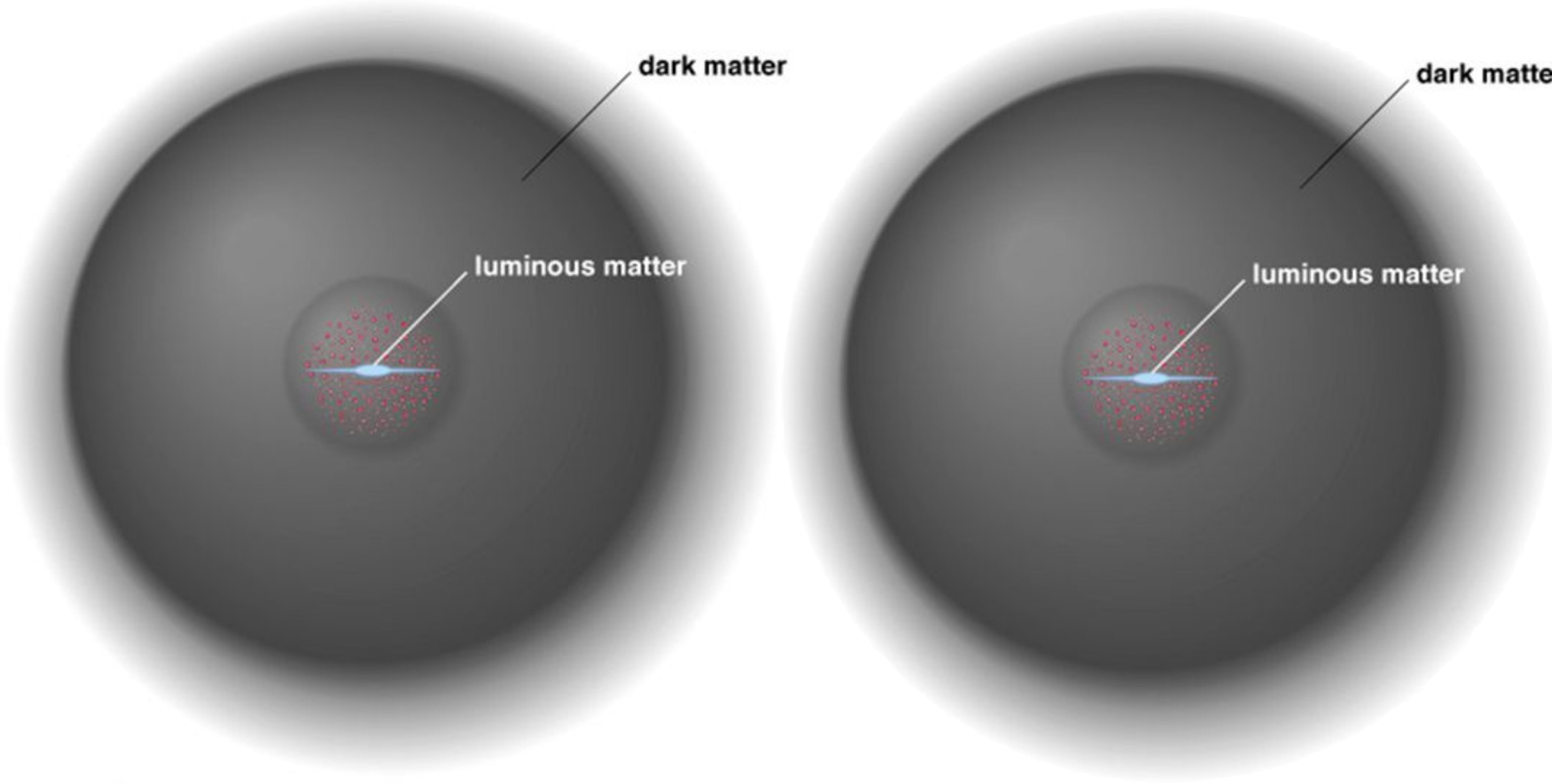


DISTRIBUTION OF DARK MATTER IN NGC 3198





Dark matter Halos



- Galaxies surrounded by halos of some "dark matter"
- Amount inside the galaxy is not much <u>but</u> dominates at large distances
- DM does not clump as ordinary matter (H gas, stars...)

An alternative: Modyfied Newtonian Dynamics (MOND)

- Gravity not probed at ultra low acceleration;
  try an empiric approach with a new parameter a0

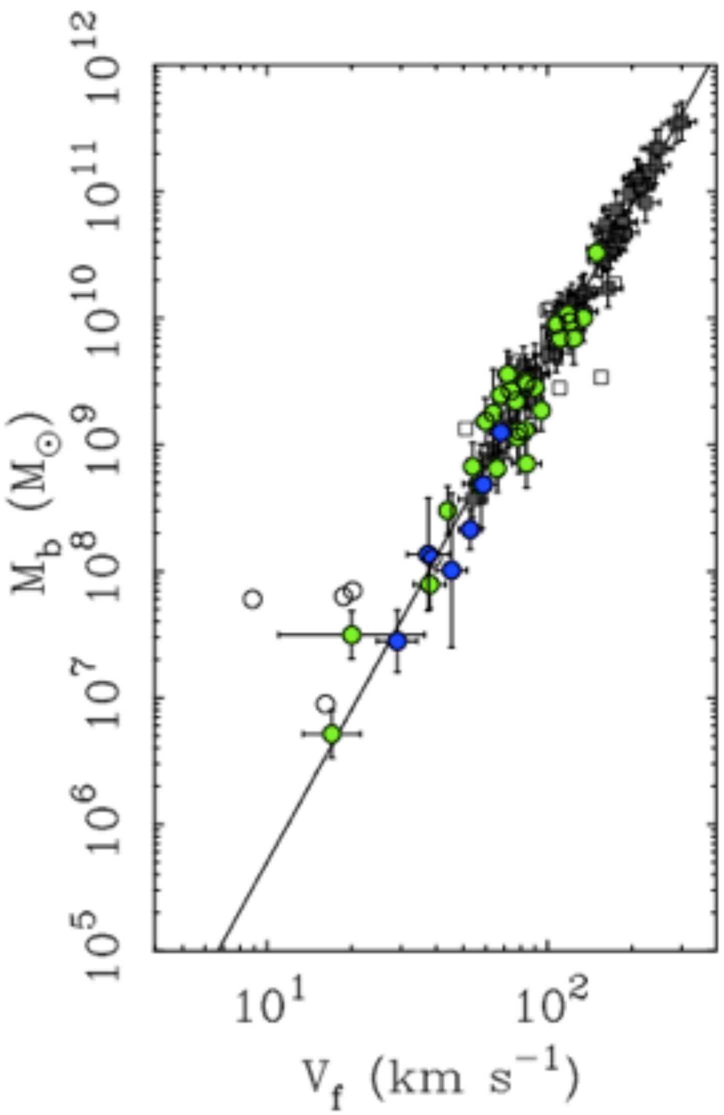
$$\vec{F}_g = m\,\vec{a} \times \sqrt{\frac{|a|^2}{|a|^2 + |a_0|^2}}$$

Mordehai Milgrom (1983)

- Gravity vs centripetal force (a<<a0) gives now flat rotation curves

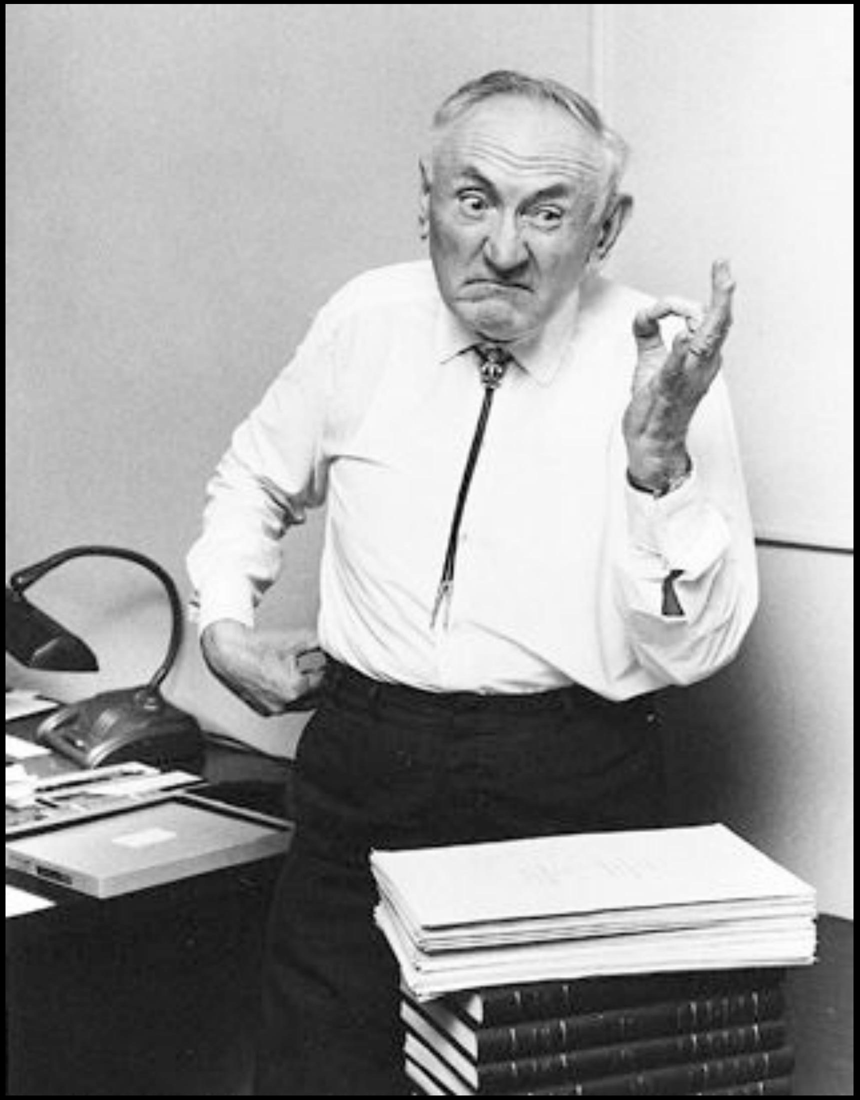
$$\frac{GMm}{r^2} = m\frac{\left(\frac{v^2}{r}\right)^2}{a_0} \rightarrow v = \sqrt[4]{GMa_0}$$

- Fits the "Baryonic Tully-Fischer relation" $M = M_b \propto v^4_{\text{plateau}}$ →

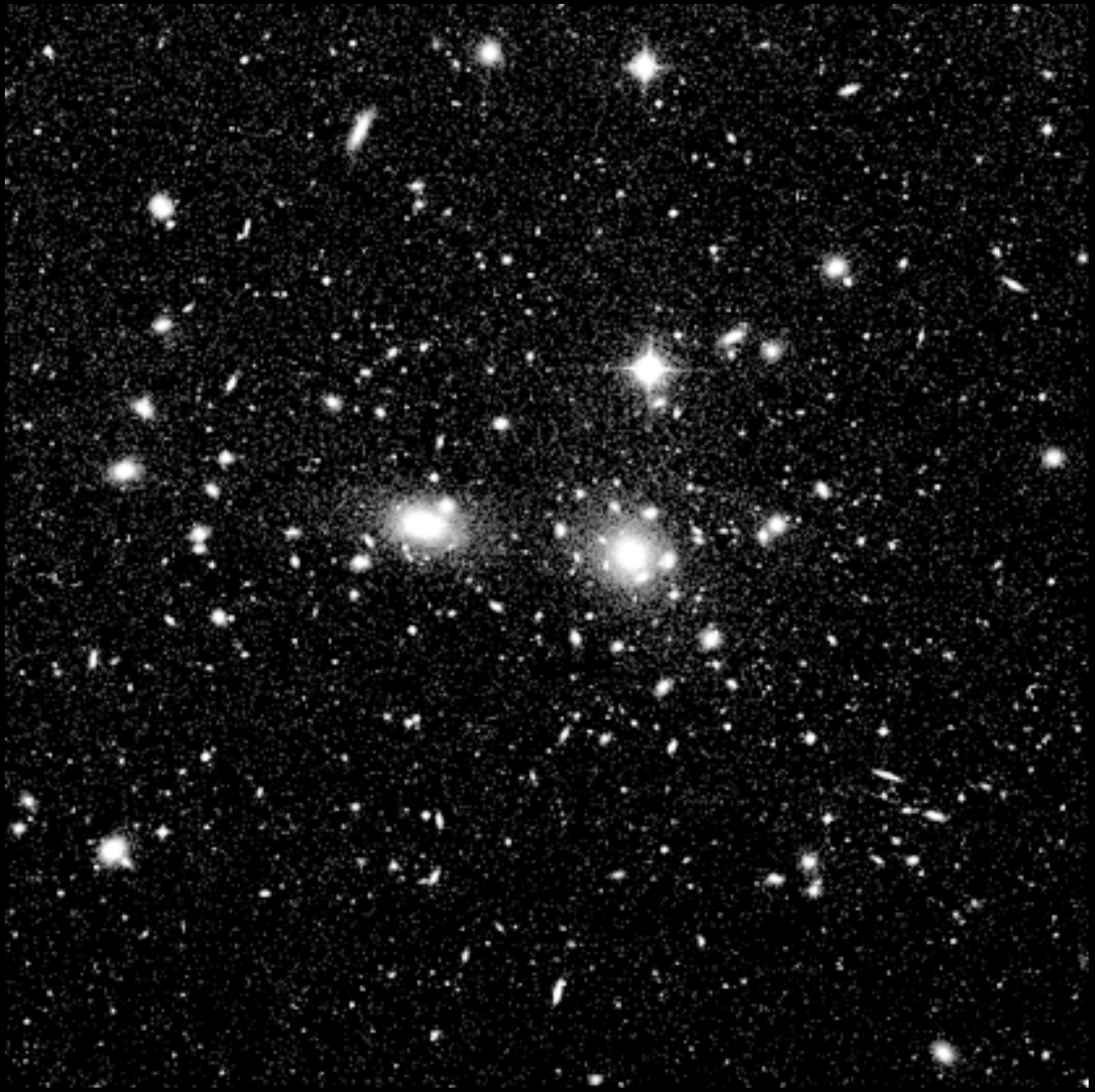


- Relativistic Generalisations: TeVes, (Bekenstein '2004) BIMOND
  tend to have problems to explain other DM hints
  (and they do not pertain a Particle-Physics School!)

Clusters of Galaxies



Fritz Zwicky
http://scienceblogs.com

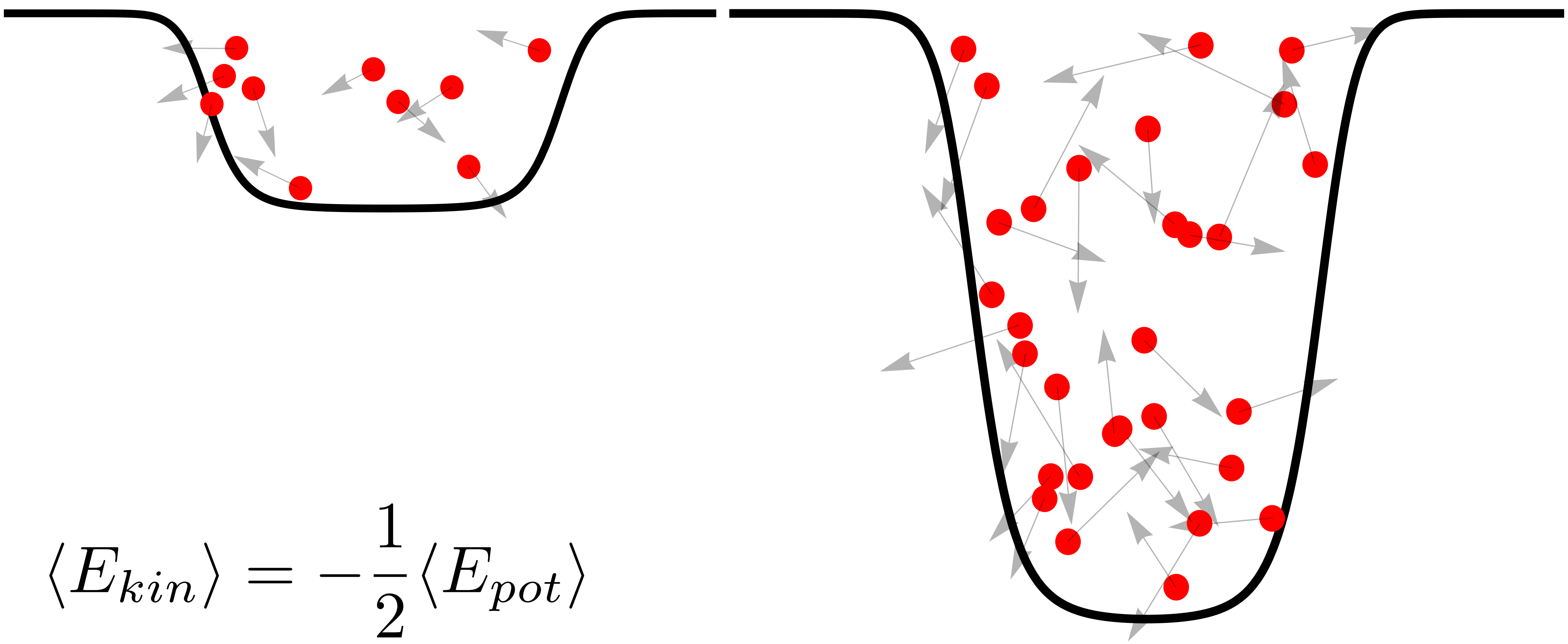


Coma Cluster
http://spiff.rit.edu/

~1000 galaxies

Virial theorem for Galaxies

velocity squared $\propto$ total cluster mass



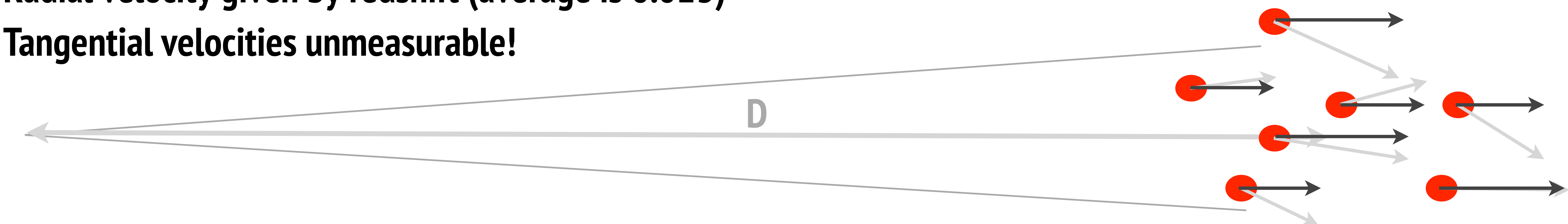
$$\langle E_{kin} \rangle = -\frac{1}{2} \langle E_{pot} \rangle$$

$$\frac{1}{2} m v^2 \sim \frac{1}{2} \frac{G_N M_{\text{tot}} m}{r}$$

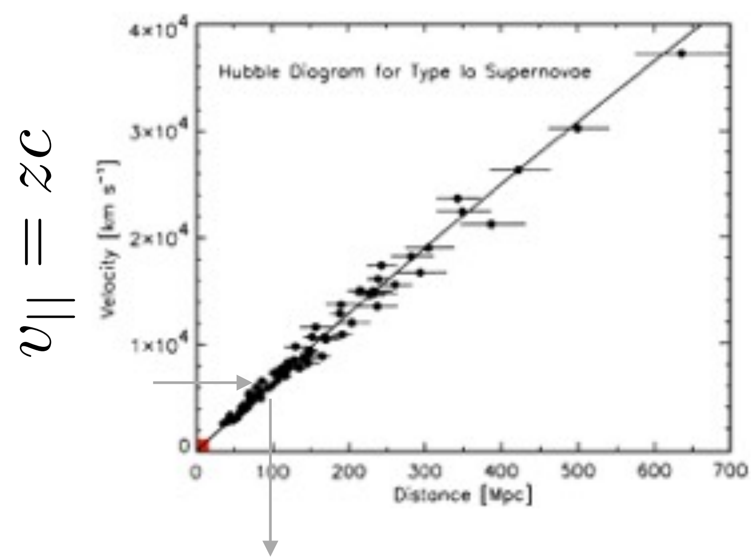
redshift, Distance, radius, velocity^2, Mass

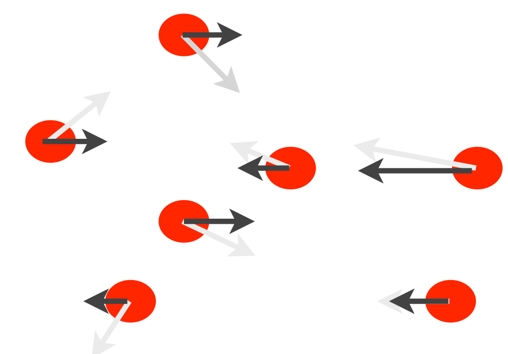
Radial velocity given by redshift (average is 0.023)

Tangential velocities unmeasurable!



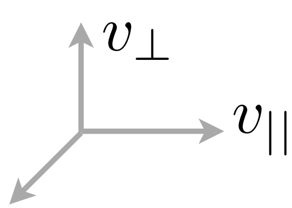
Substract average velocity (Hubble flow, expansion of the Universe)





D~100 Mpc → total Diameter ~ 10 Mpc

Assume isotropic dispersion

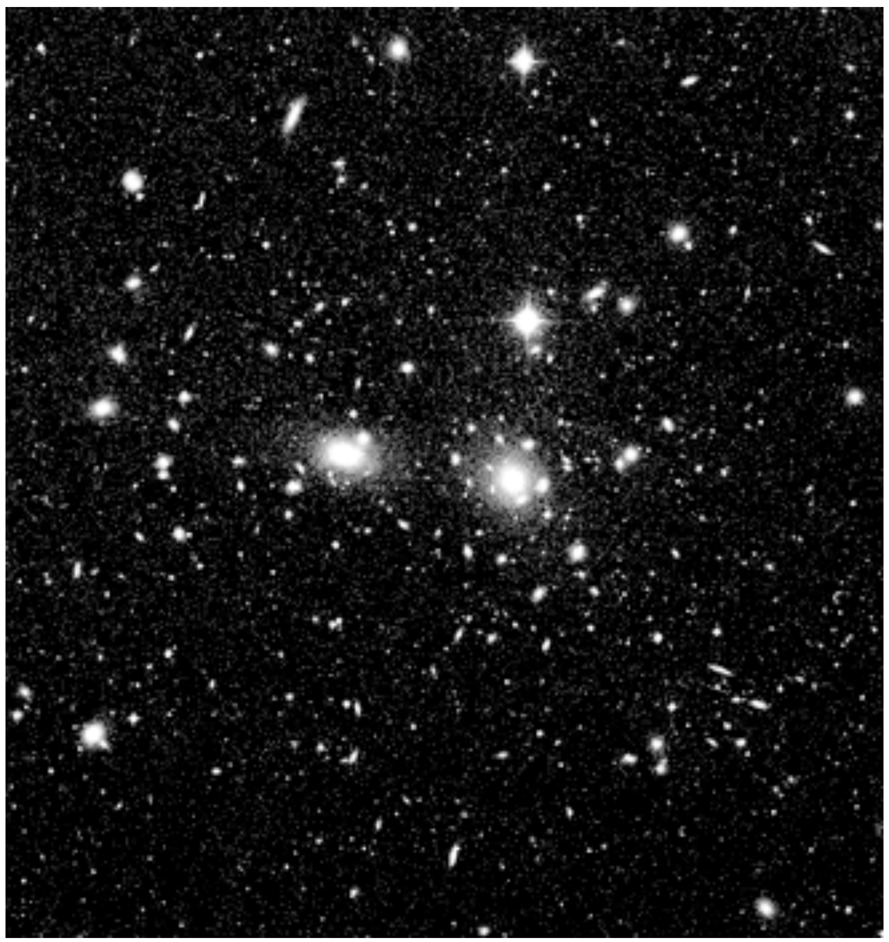


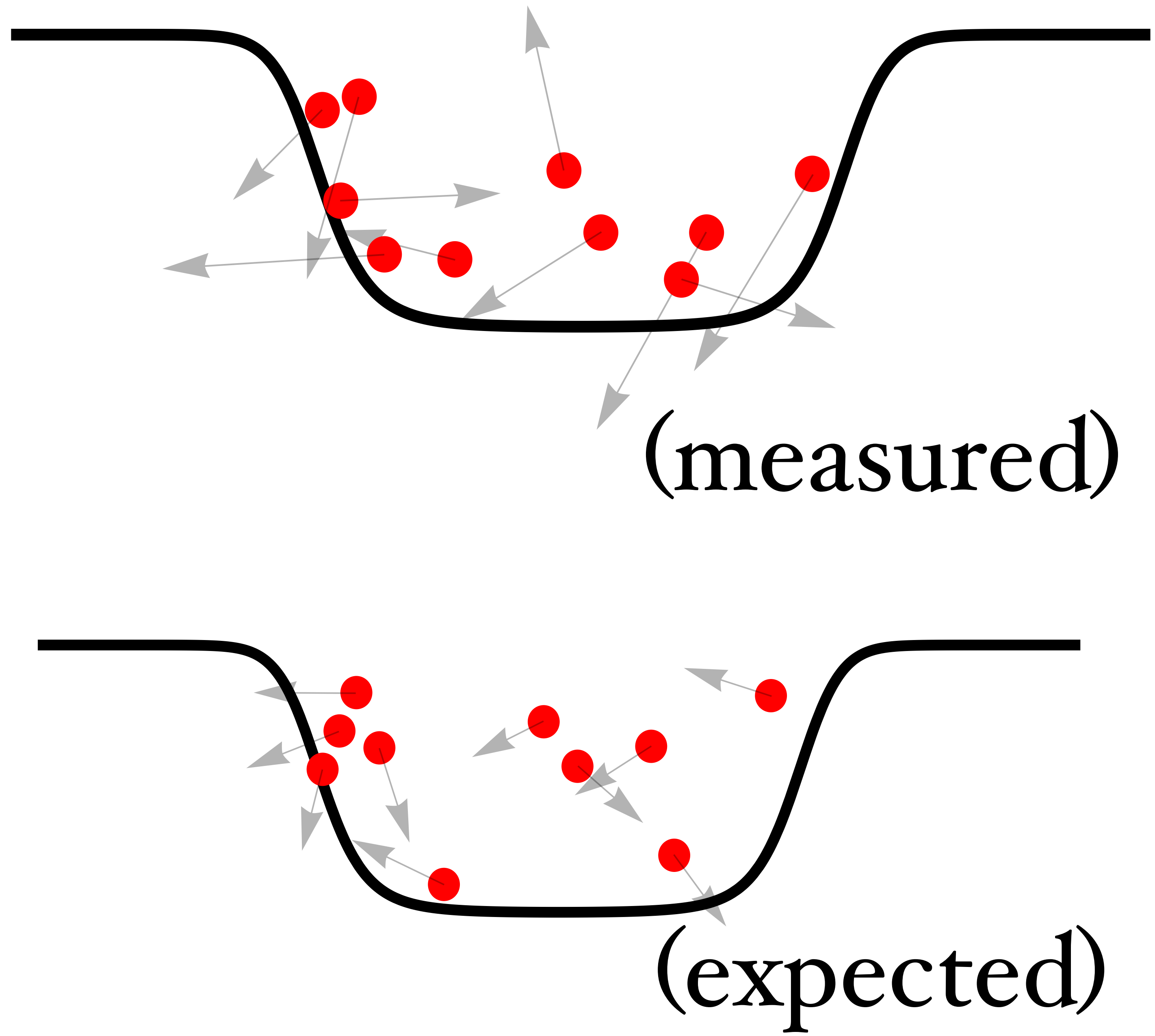
$$\delta v^2 \sim 3\delta v_{||}^2 \sim 3c(\delta z)^2$$

Estimate Mass from Average Galactic luminosity

Virial theorem for Coma

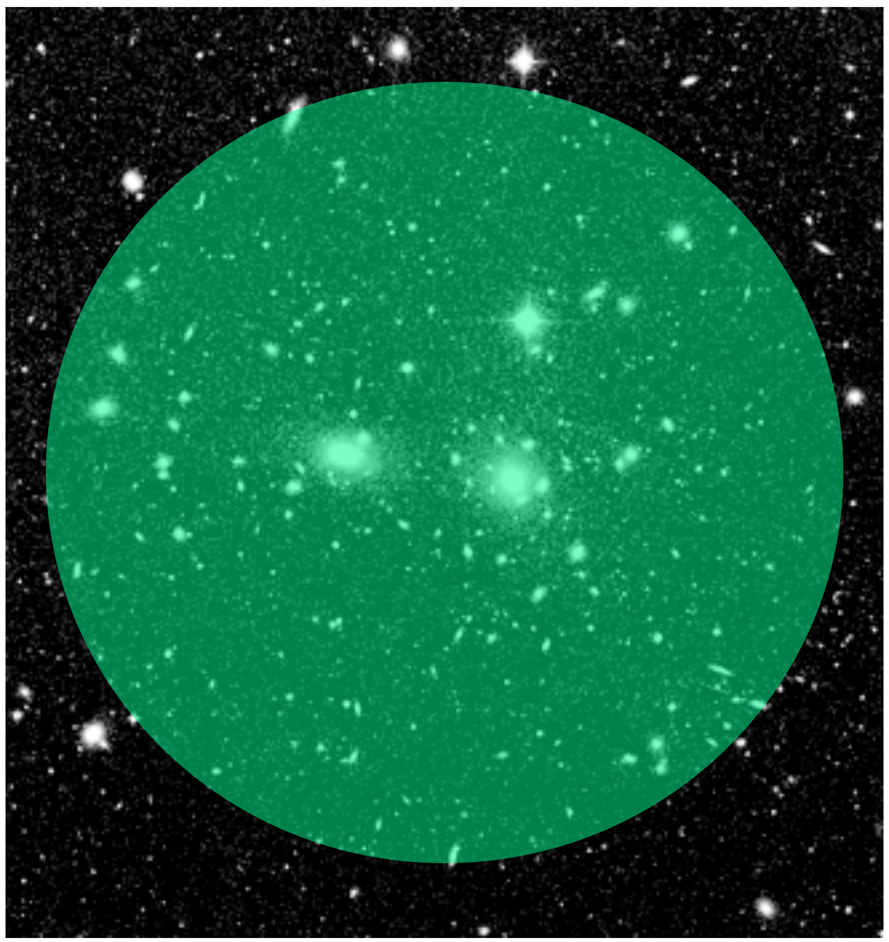
obtained velocity dispersion was too fast by ~ 10

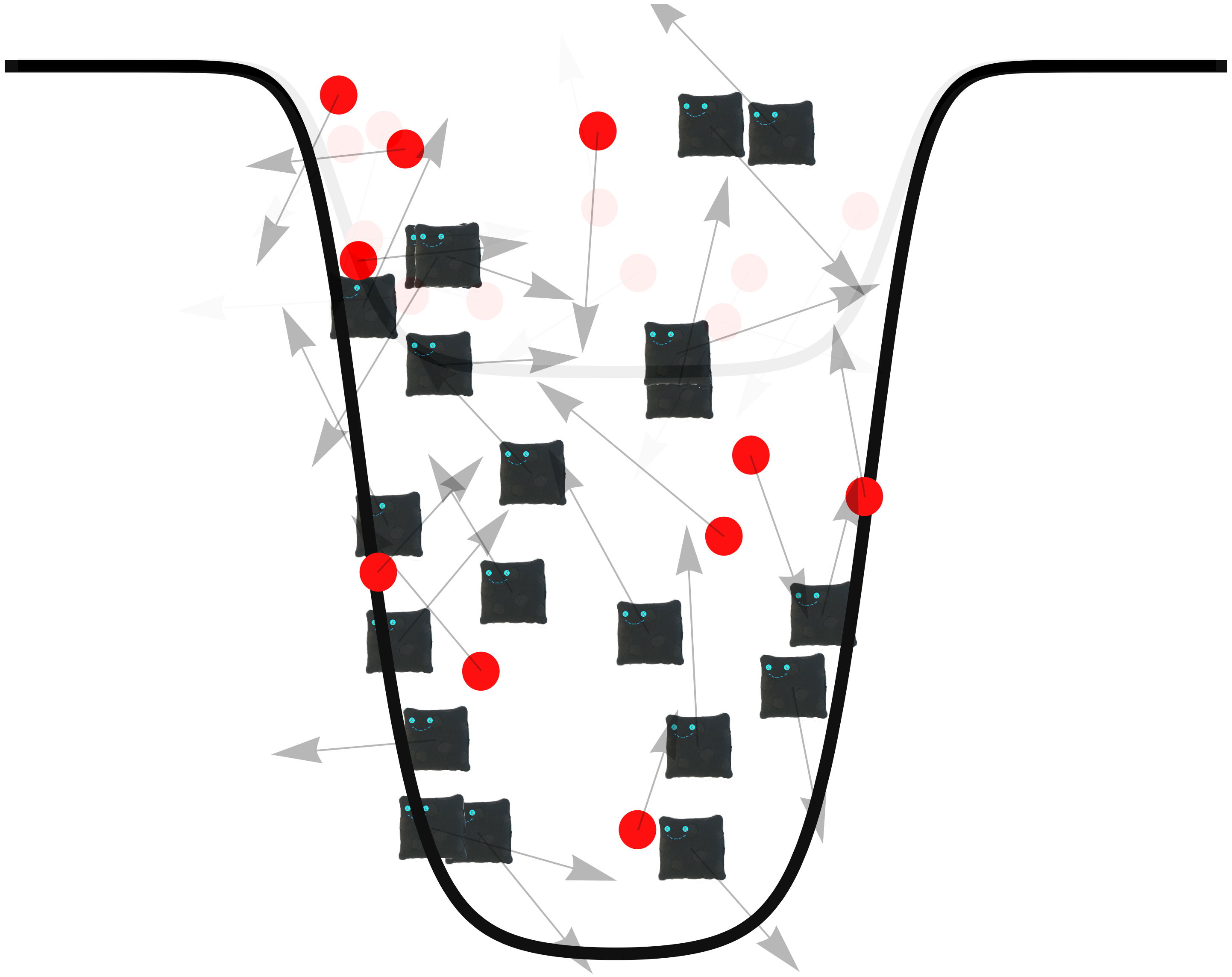




Virial theorem for Coma

obtained velocity dispersion was too fast by ~ 10

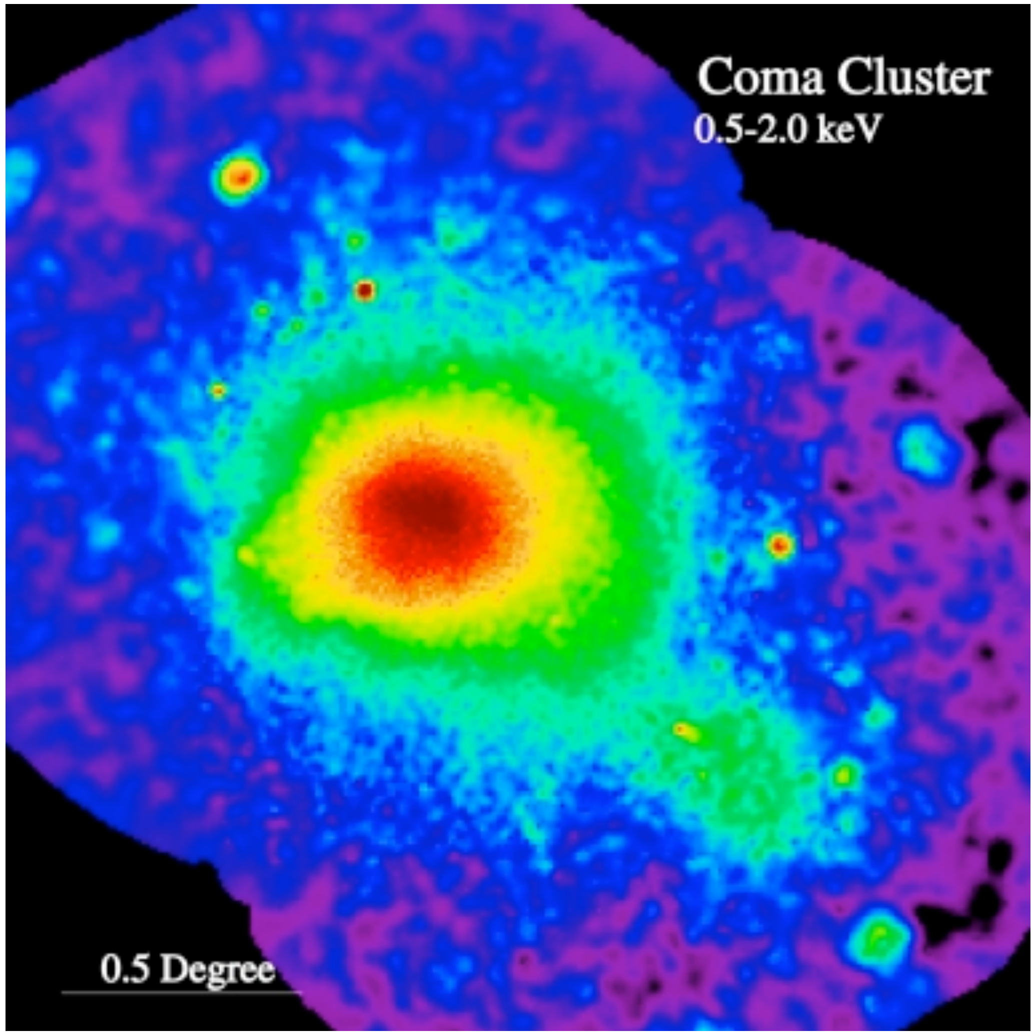




there should be some dark matter!

Estimate velocities with X-ray emission

Large fraction of baryons in GCs are hot intracluster gas (T~keV)



Model emission T = T(r)

$$v^2 \propto T$$

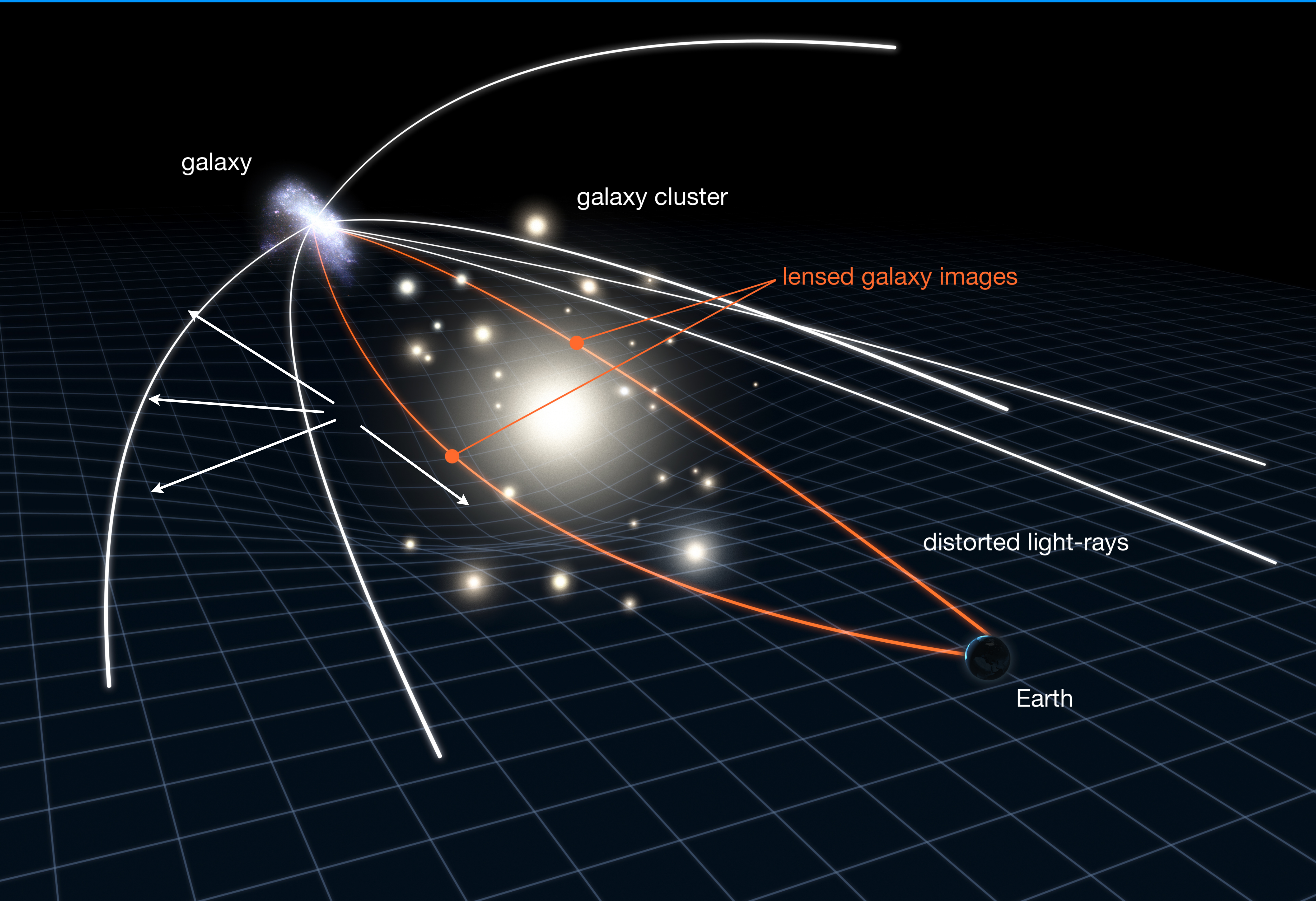
Estimate Mass with the Virial theorem

$$GM(r) \sim v^2 r \propto Tr$$

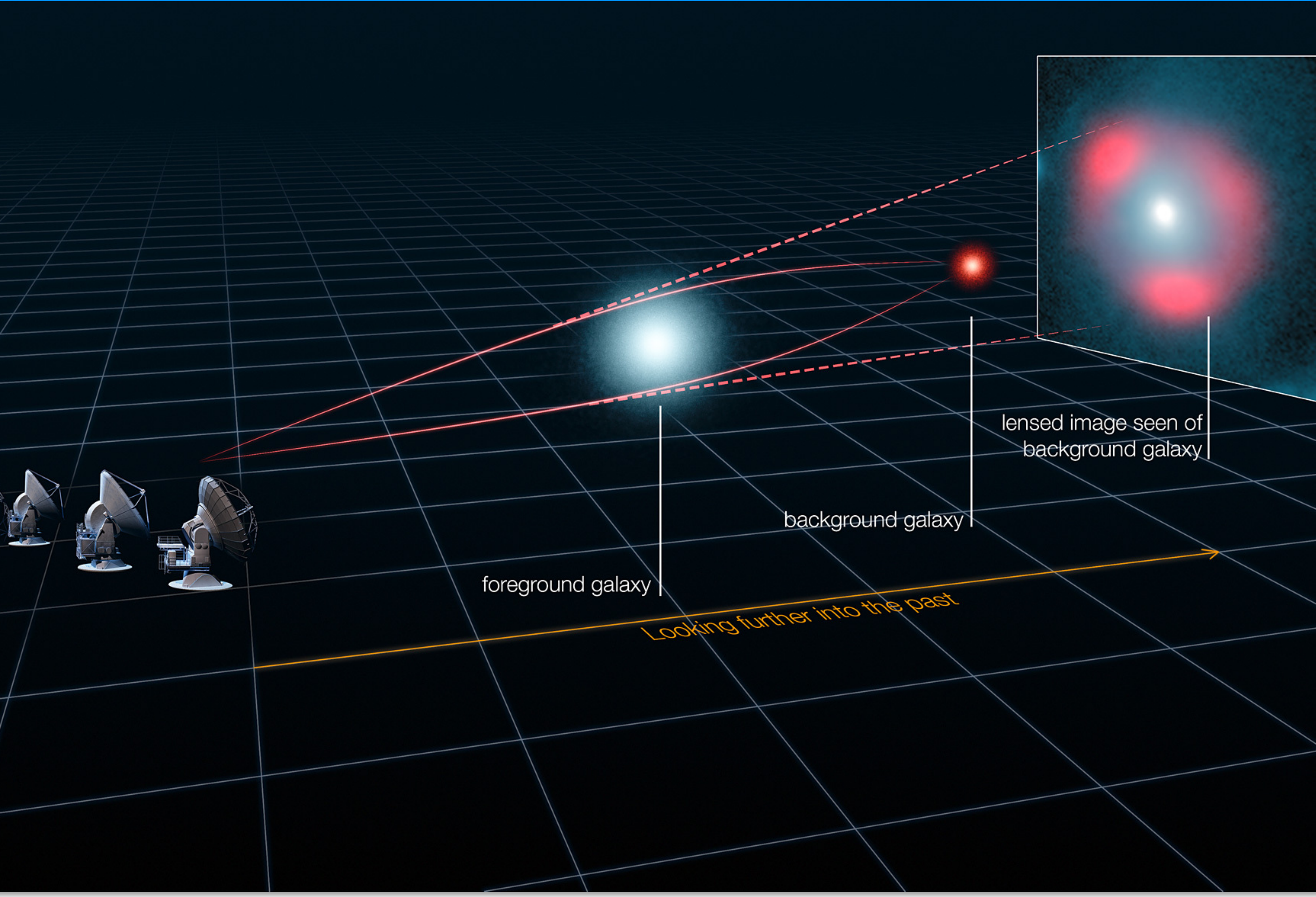
Total baryon mass/ total mass ~ 15%

Hot baryons would even scape from the cluster w/o DM

Estimate GC mass with Lensing

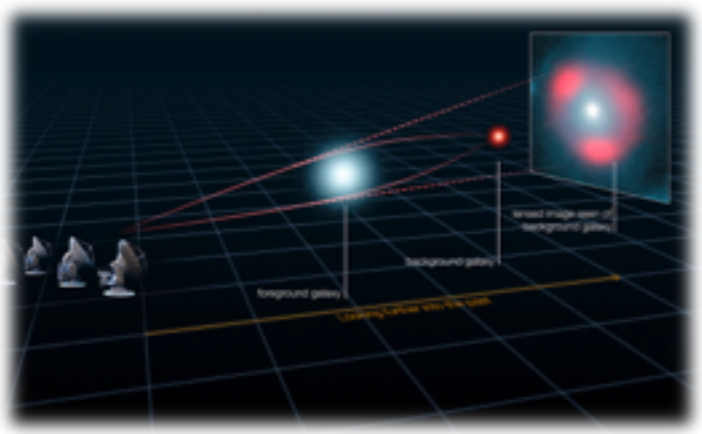


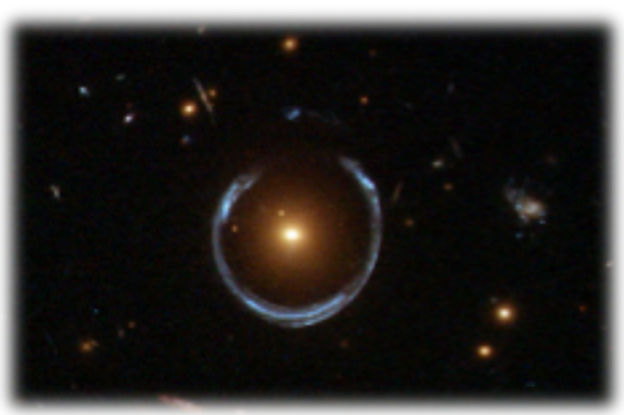
Estimate GC mass with Lensing



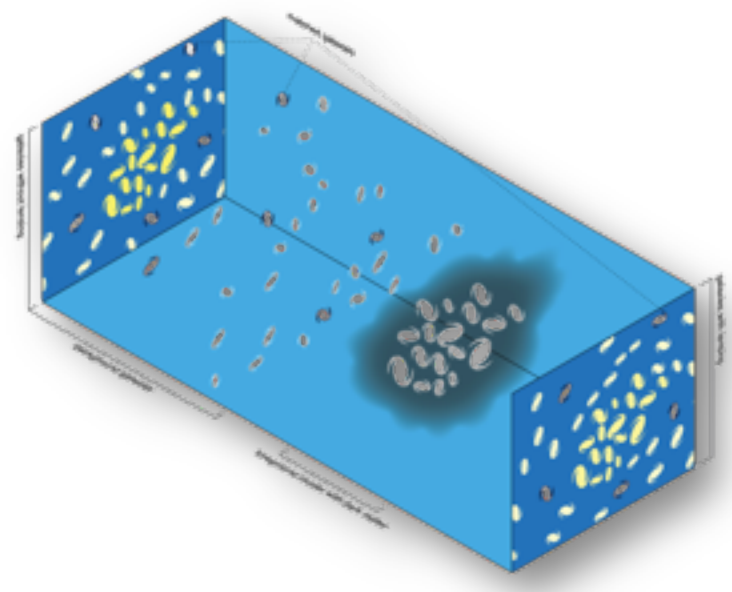
Types of gravitational lensing

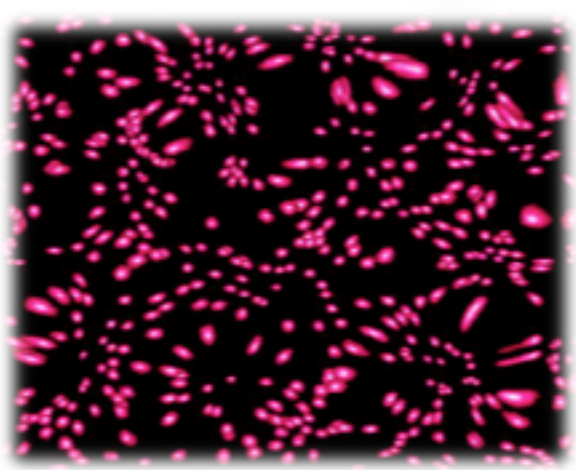
Strong lensing





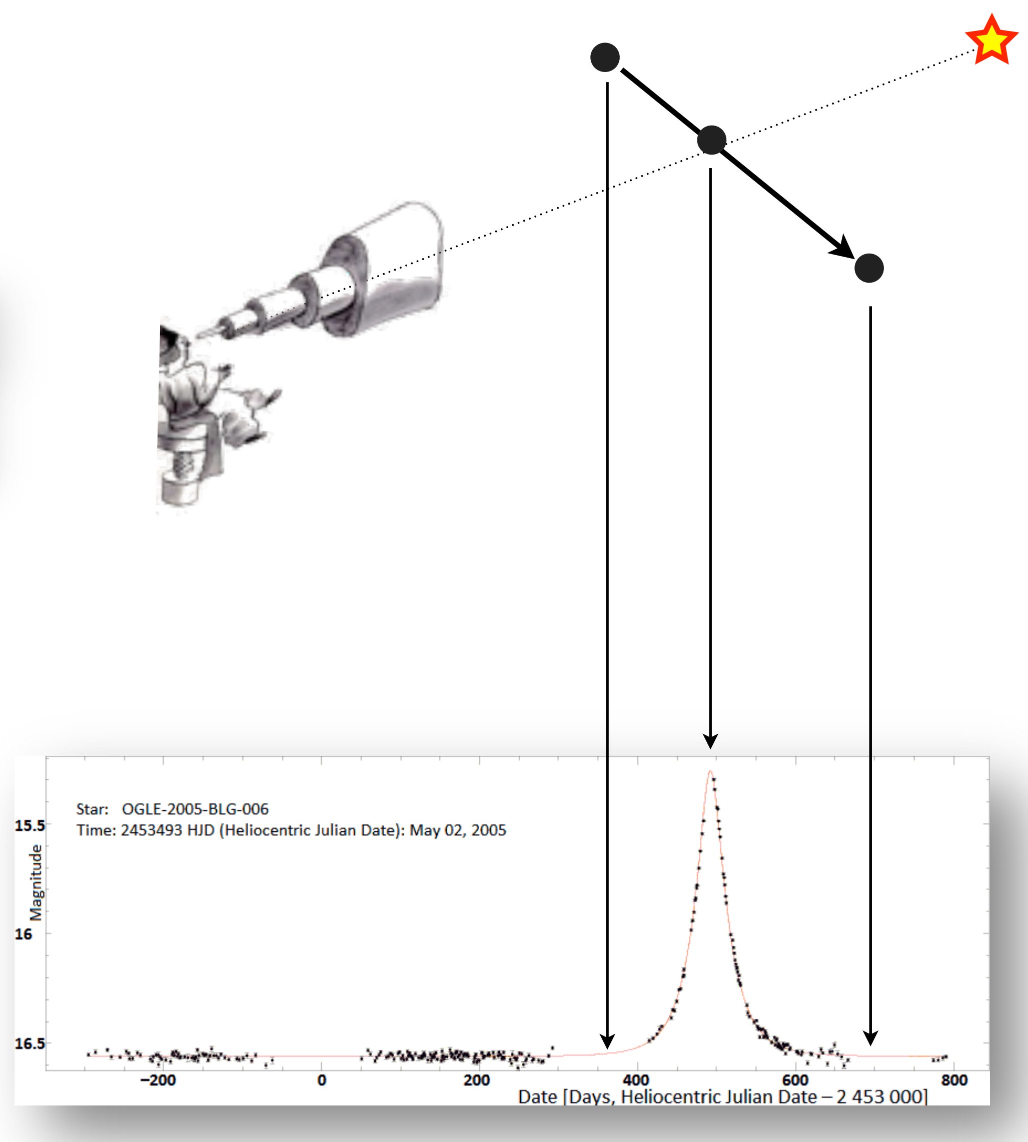
Weak lensing



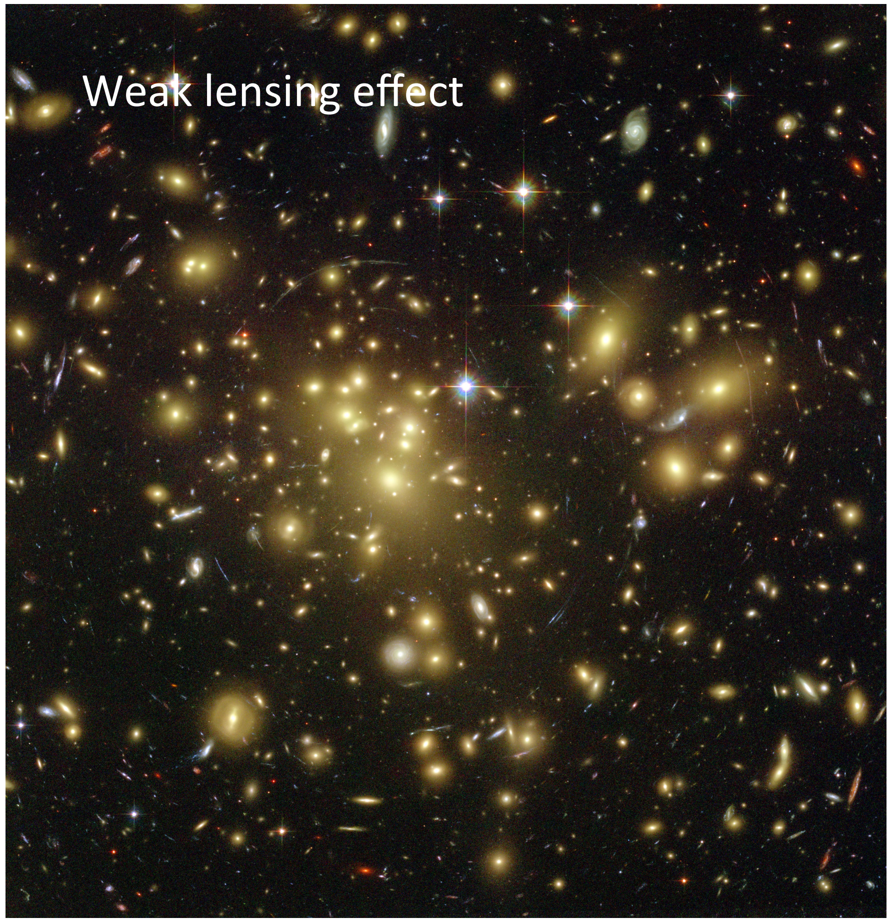


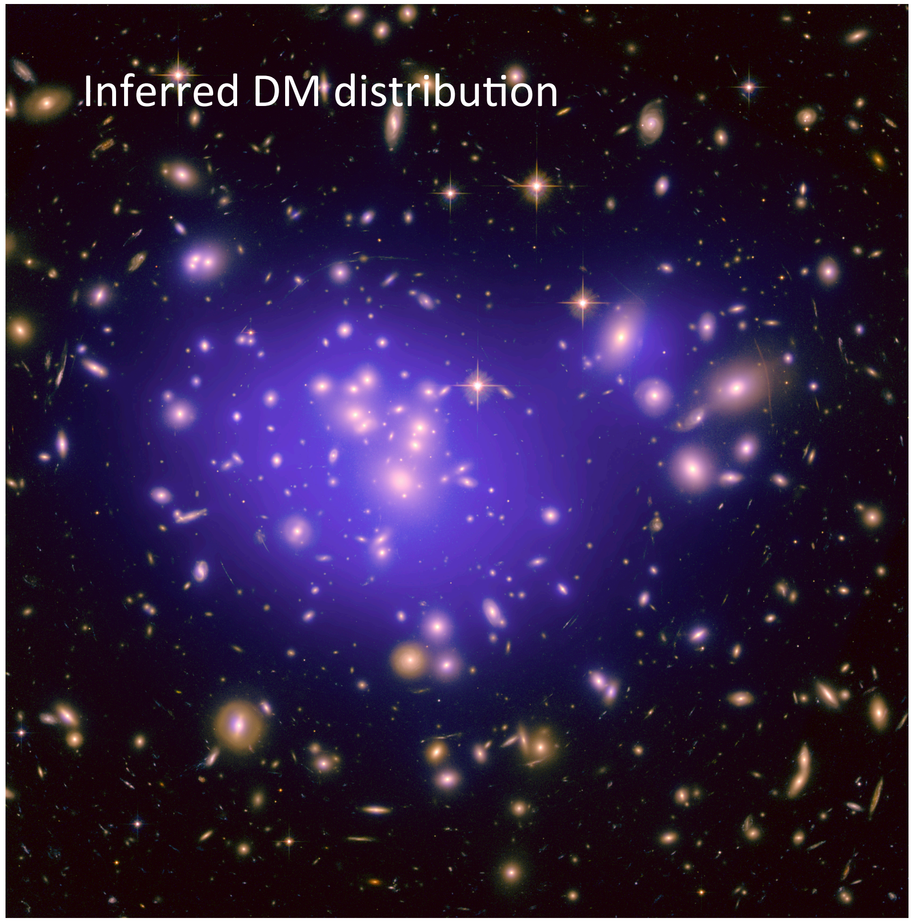
Microlensing

(no lensed image!
temporary change of
luminosity as starlight is lensed)



Weak lensing





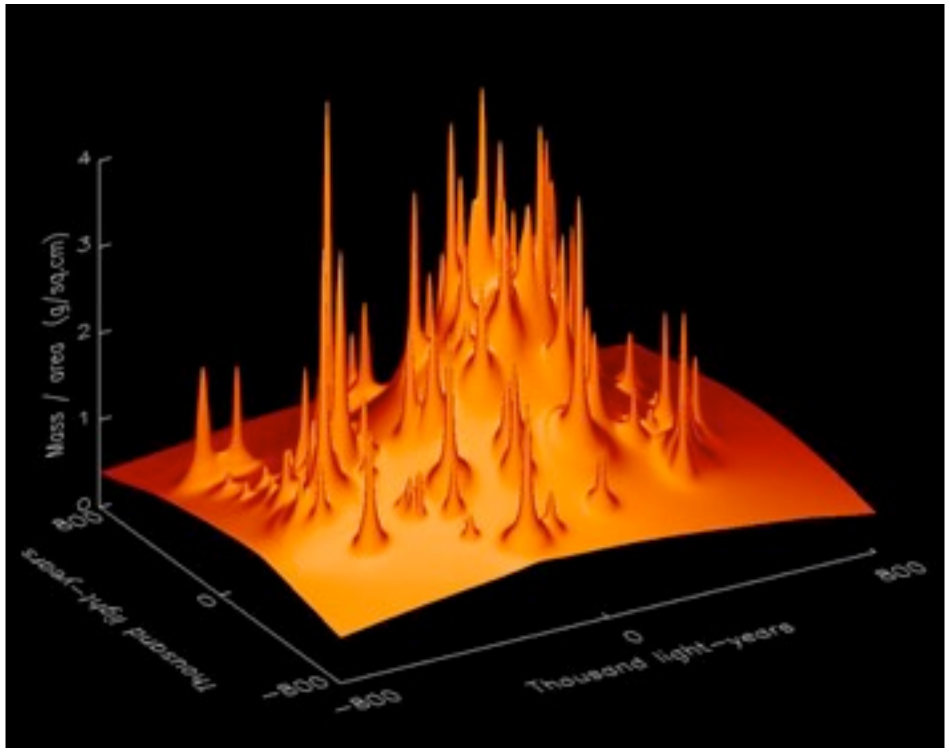
Density maps show:

- peaks (galaxies)

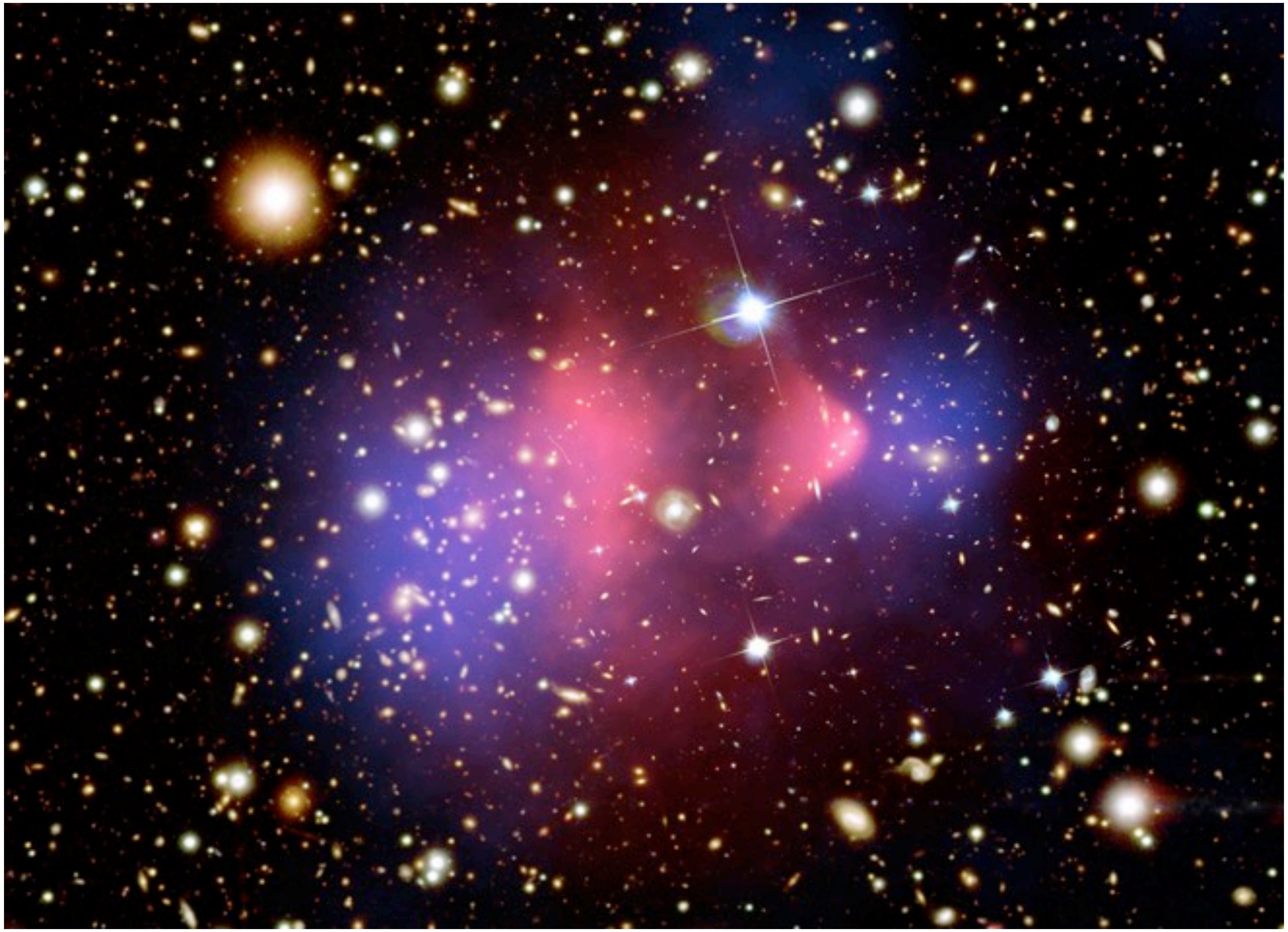
- extended mass distribution (DM+gas)

DM is distributed smoothly, unlike baryons

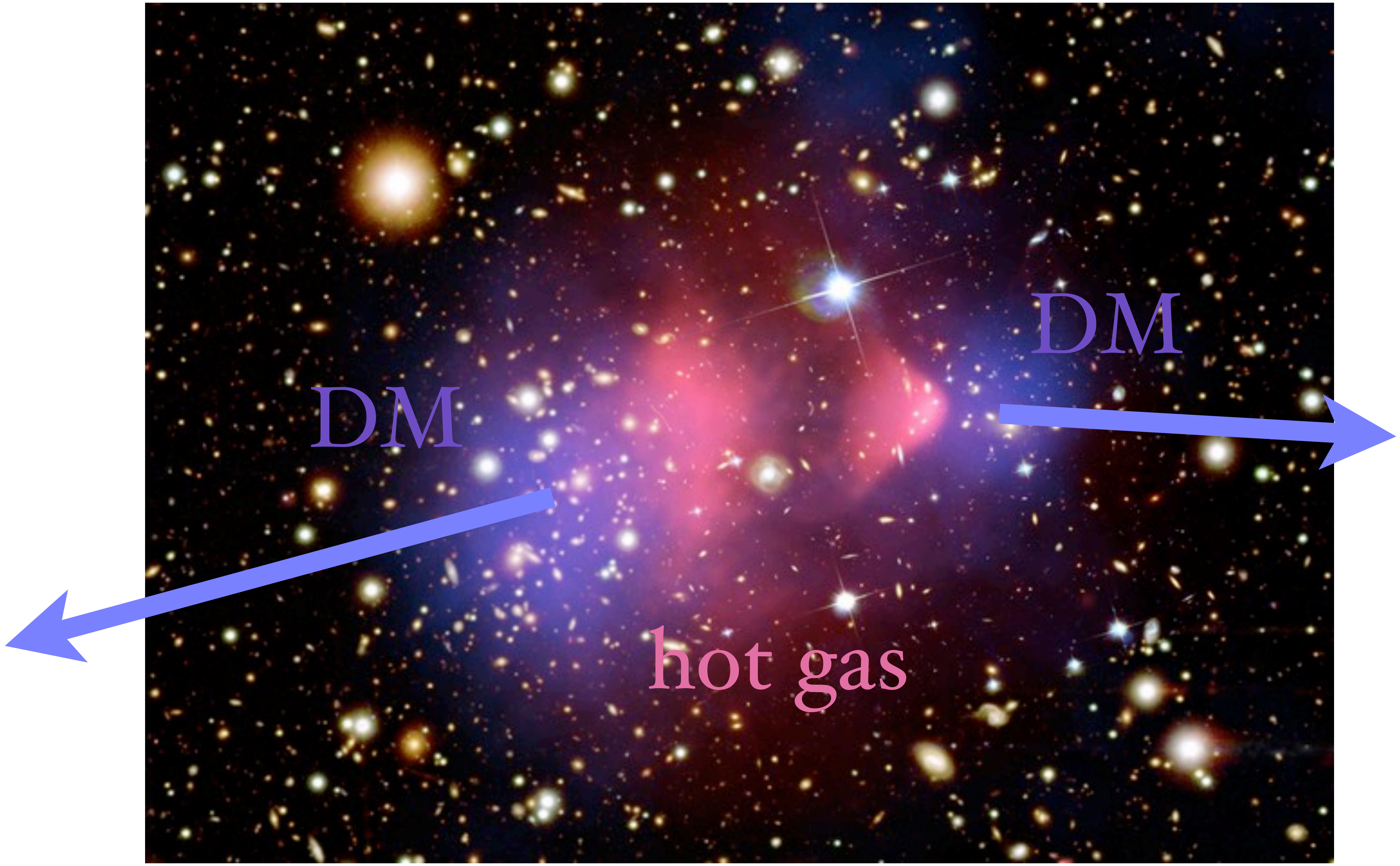
Total baryon mass/ total mass ~ 15%



Colliding clusters



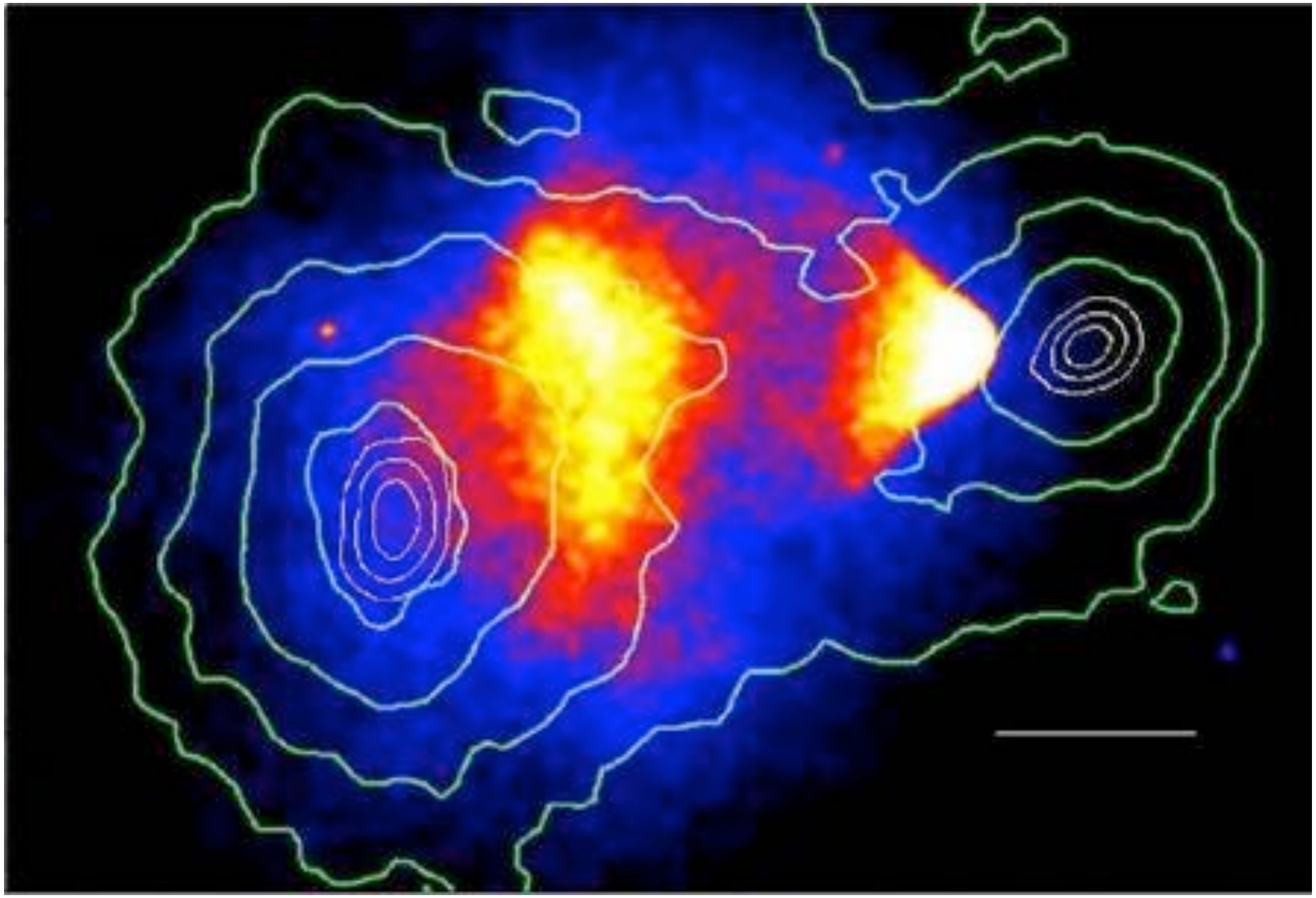
Bullet cluster



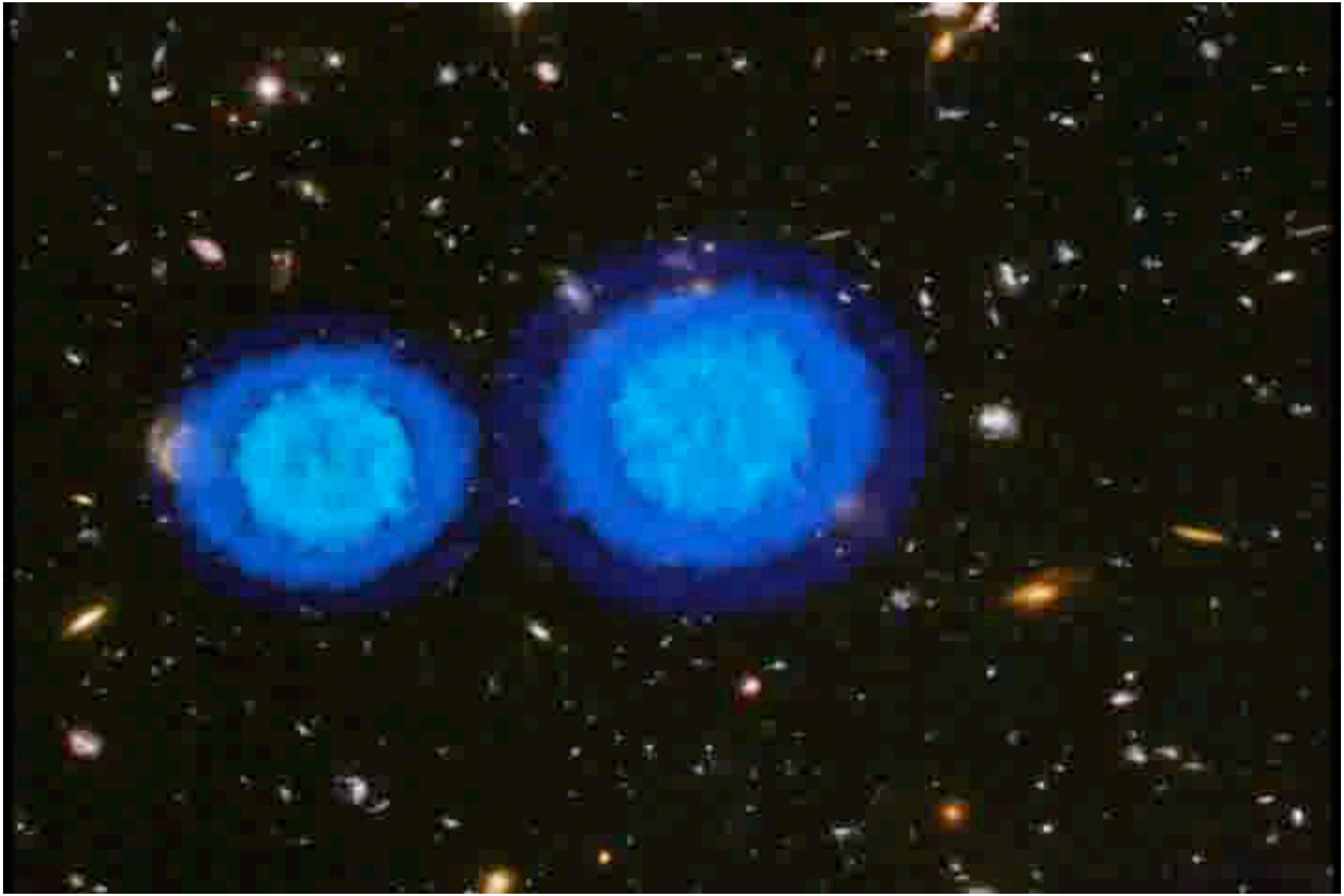
matter didn’t experience friction (collisions) -> weakly interacting

Bullet cluster

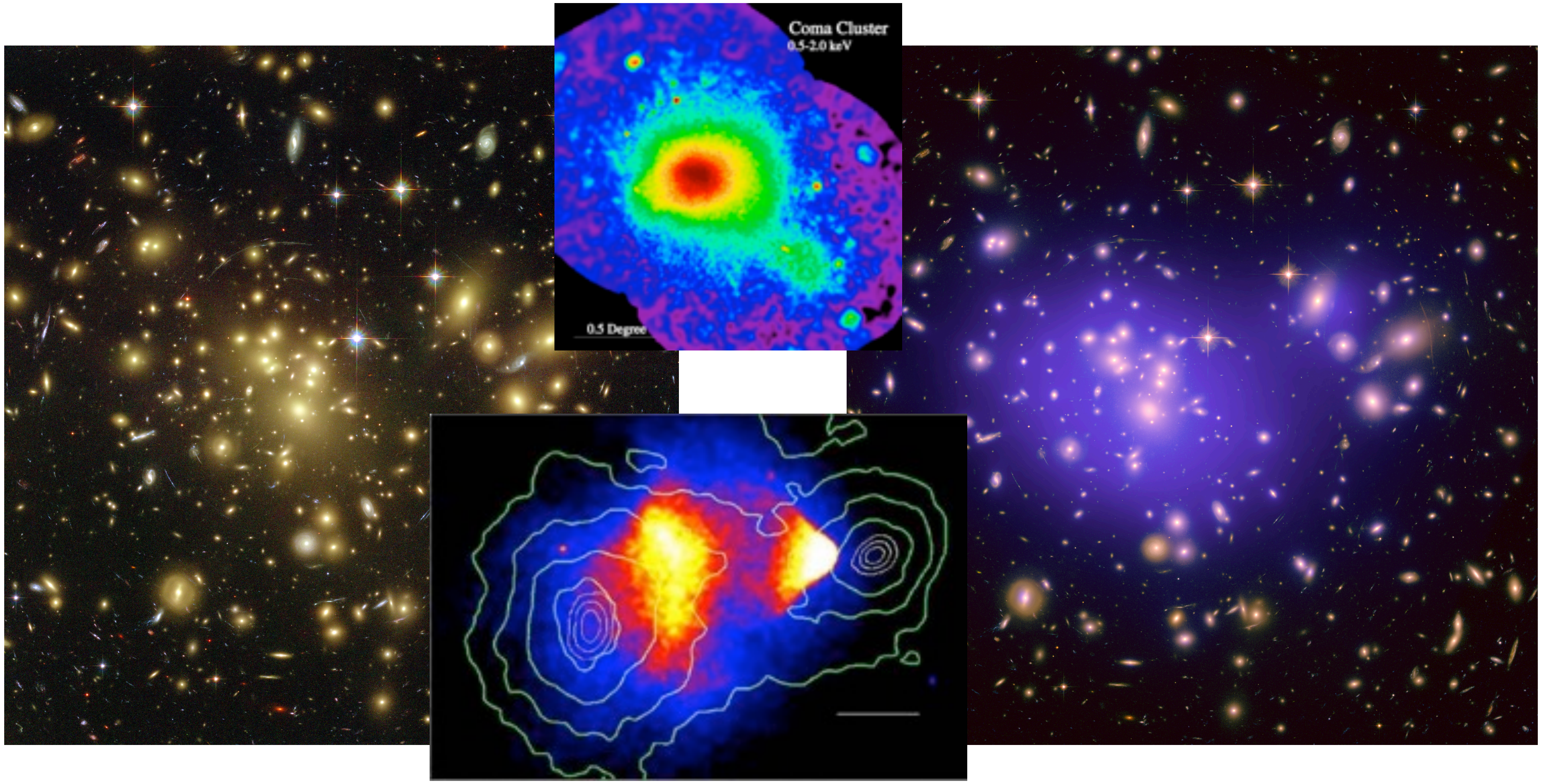
X-ray traces hot gas



weak lensing traces mass



Learned from Clusters



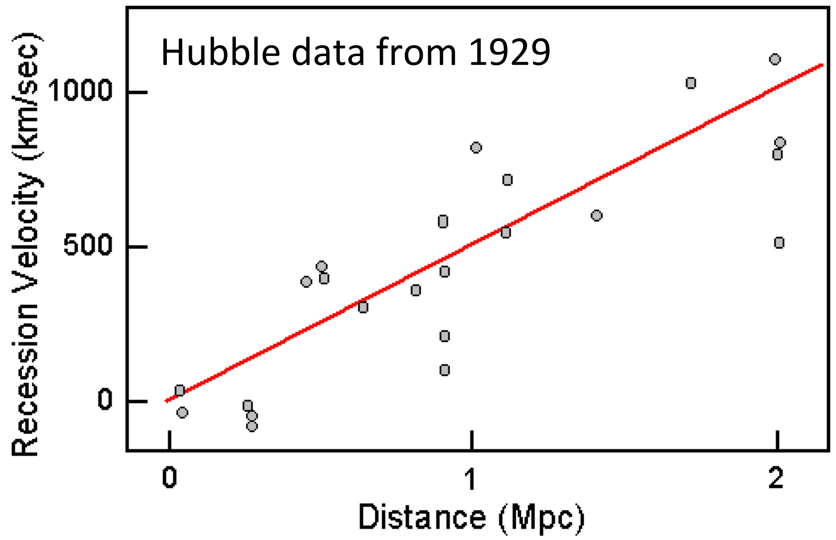
Total baryon mass/ total mass ~ 15%

- DM does not clump as tight as baryons
- DM has very low friction (weak interactions) with itself and with ordinary gas

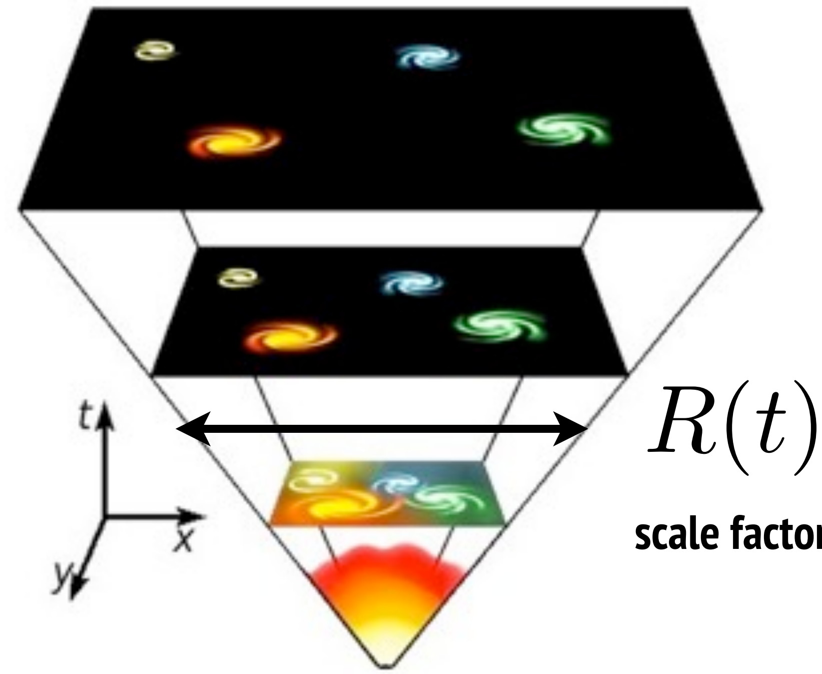
Expansion of the Universe

- **Hubble's expansion law: Galaxies recede from us**
  velocity ~ distance

Edwin Hubble
1889 - 1953



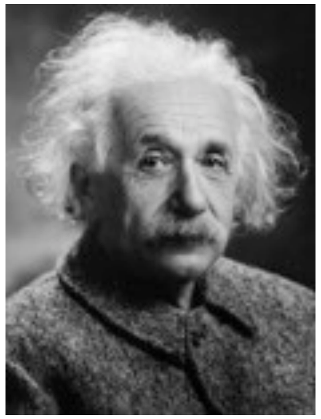
- **Cosmological principle (no place is special)**
  all receding from all -> Universe expansion



- **Friedman, Lemaitre use Einstein's General Relativity to describe an expanding Universe**

Alexander Friedman
1888 - 1925

Georges Lemaître
1894 - 1966



Albert Einstein
1879 - 1955

$$d\tau^2 = dt^2 - R^2(t)\left(dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)\right)$$

comoving coordinates

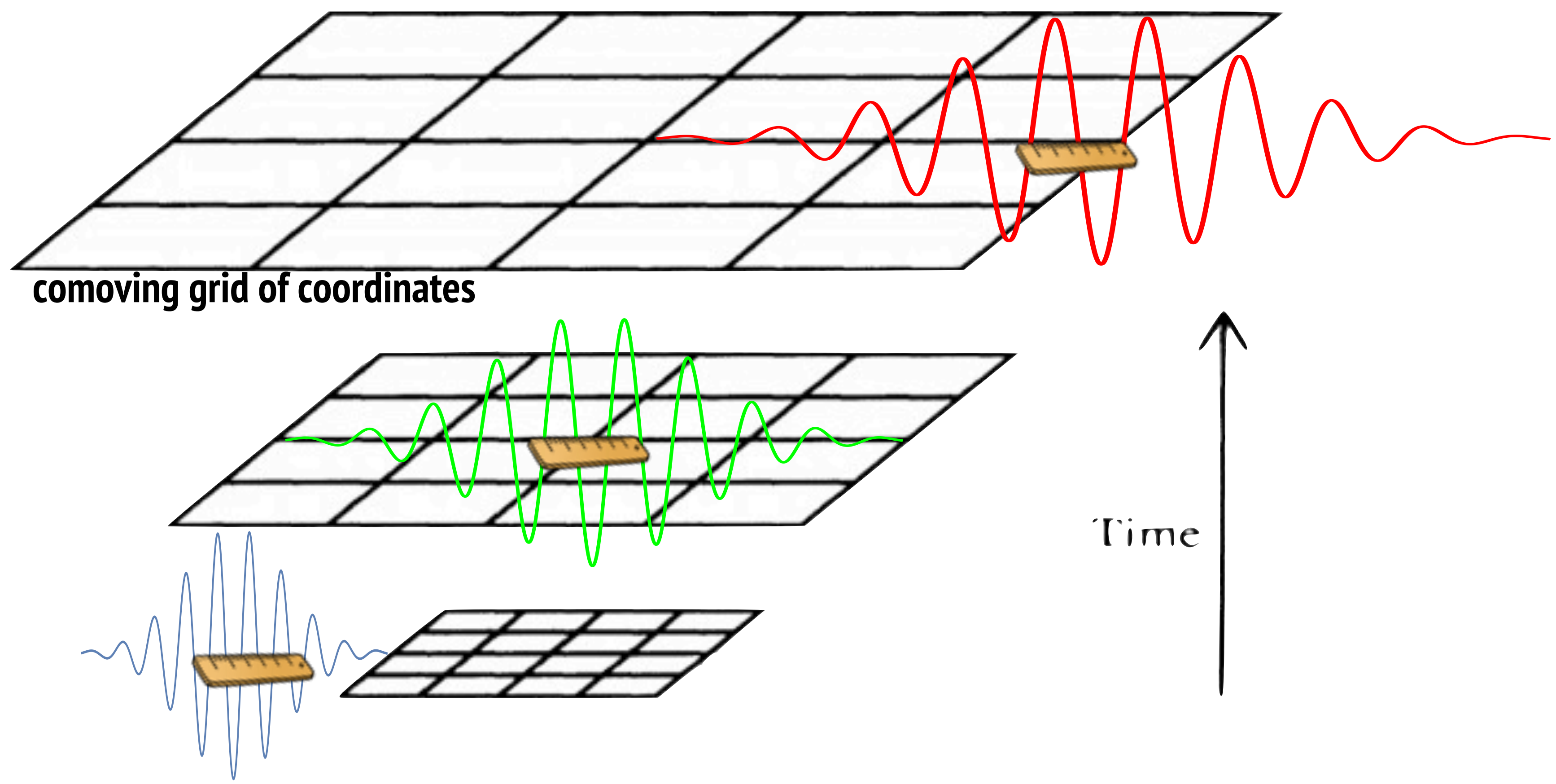
$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N}{3}\rho$$

Expansion depends on the energy density

In these lectures I assume the Universe is spatially flat (it is well checked experimentally and we have good reasons to expect so... now)

Redshift

$$\frac{\lambda_{\text{today}}}{\lambda(t_e)} = \frac{R_{\text{today}} \equiv 1}{R(t_e)}$$



- **Redshift defined as** $z \equiv \dfrac{\lambda_{\text{today}} - \lambda(t_e)}{\lambda(t_e)}$

- **Recession velocities are measured with redshift (interpreted as doppler effect)** $v_{||} = cz$

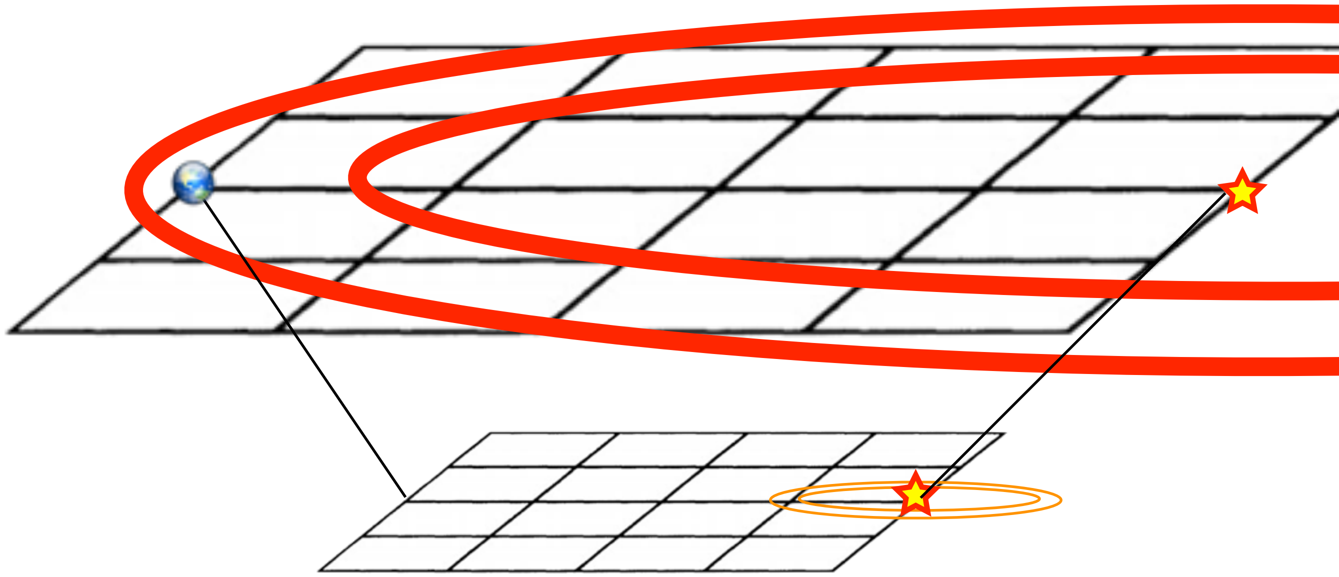
Hubble's law is $cz = H_0 d$ **and Hubble's constant** $H_0 \sim 70 \dfrac{\text{km/s}}{\text{Mpc}} \equiv h \times 100 \dfrac{\text{km/s}}{\text{Mpc}}$

- **We can parametrise time with the redshift (z that we would see from emission at time t)** $R(t_e) = \dfrac{1}{1+z}$

Hubble law

Source emits light at time te (redshift z), comoving radius re ... we receive it at t0

$$\text{Flux} = \frac{\text{Luminosity}}{4\pi\,\text{distance}^2}$$ **(Energy/dt)**



Luminosity distance

$$d_L^2 \equiv \frac{\text{Luminosity}}{4\pi\text{Flux}}$$

Luminosity ⟶ **known (assumed)**

Flux ⟶ **to be measured**

$$d_L^2 = r_e^2(1+z)^2$$ **(photons conserved, but dt increases, E decrease)**

$$d_L = r_e(1+z) \sim z/H_0$$

$$\boxed{z = H_0 d_L = (\dot{R}/R)_0 d_L}$$

- **Photons move on geodesics** $d\tau^2 = dt^2 - R^2(t)\left(dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)\right) = 0$

  $r_e \sim t_0 - t_e$ **scale factor**   **comoving coordinates**

- **Expansion of scale factor** $R(t_e) = 1 + H_0(t_e - t_0) + \ldots = \dfrac{1}{1+z} \rightarrow (t_0 - t_e) \simeq \dfrac{z}{H_0(1+z)}$

but ... the Hubble constant is not constant

Hubble's law

$$z = H_0 d_L = (\dot{R}/R)_0 d_L$$

Friedman's equation

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N}{3}\rho$$

Expansion depends on the energy density

... because the energy density changes as the Universe expands

$$\rho = \rho_\Lambda + \frac{\rho_{\mathrm{matter},0}}{R^3} + \frac{\rho_{\mathrm{radiation},0}}{R^4}$$

(this effectively defines what we understand as matter, radiation and lambda)

We normalise densities with a critical density

$$\rho_c = \frac{3H^2}{8\pi G_N} \qquad \Omega_i = \frac{\rho_i}{\rho_c}$$

Friedman's equation $1 = \sum \Omega_i$

$$H = H_0\sqrt{\Omega_\Lambda + \Omega_m^0(1+z)^3 + \Omega_r^0(1+z)^4}$$

In geneal, the redshift-distance relationship is more complicated... and depends upon $\Omega' s$

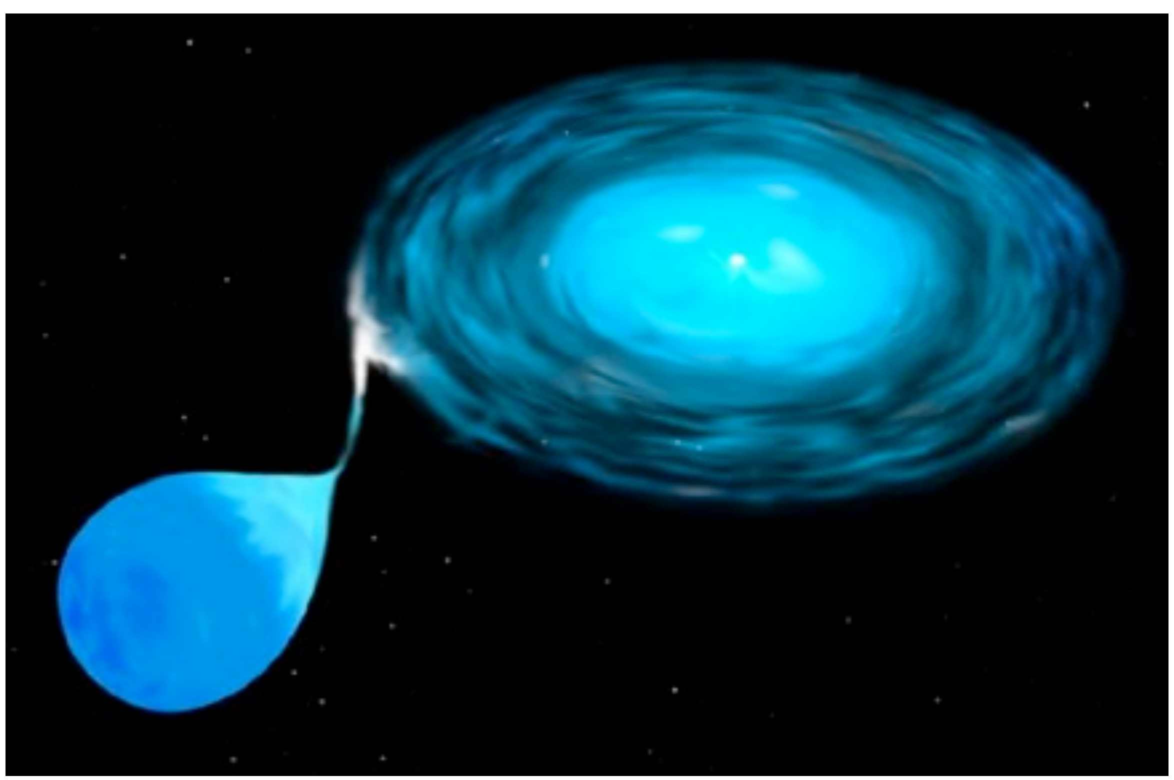
$$z = F(H, d_L)$$

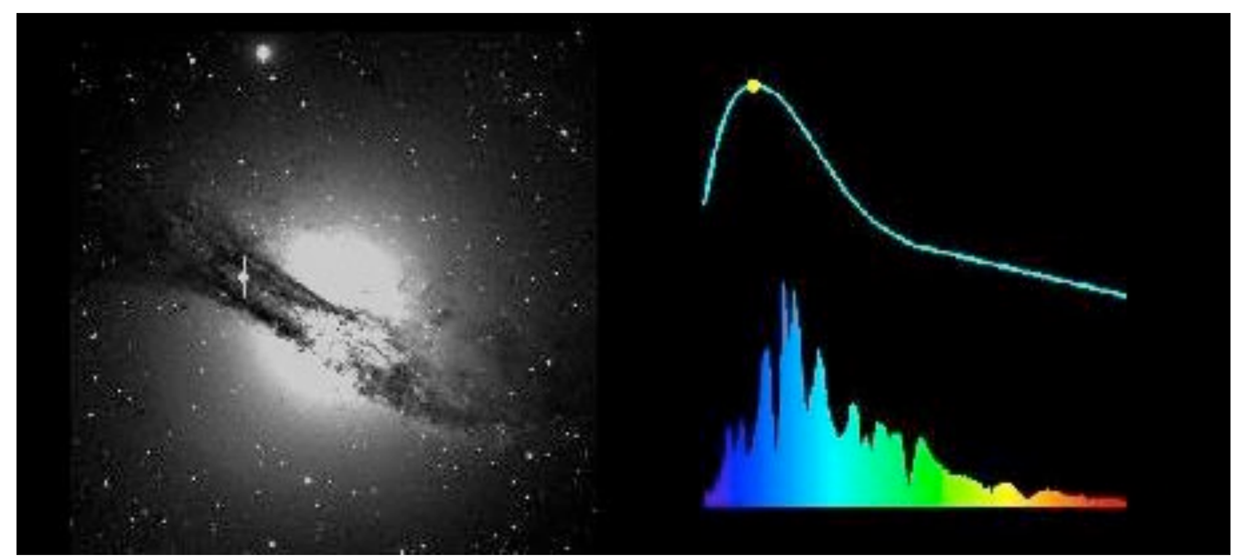
Supernovae Type I

- Low mass stars end their evolution as CO white dwarves
- WDs are dead stars, no massive enough to compress CO and produce further nuclear reactions
- They are supported by electron degeneracy pressure, fermi exclusion principle at work!
- Chandrasekhar limit $M < 1.44 M_{\odot}$

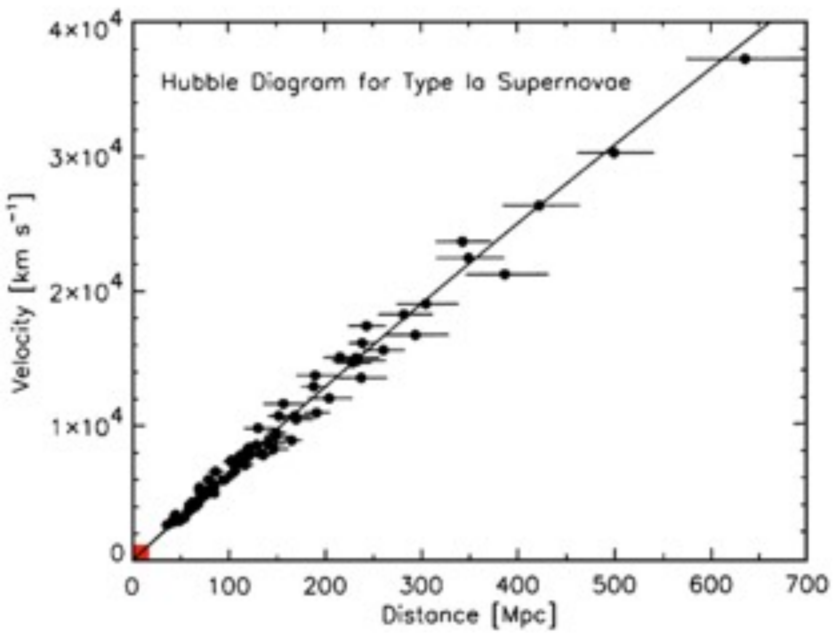
- WDs in binary systems approach the CL by accreting from the companion
- Just before reaching it (99%) they start to ignite C, O and heavier
- The energy release in few seconds is huge, $\sim 10^{44} J$, super explosion can be seen from afar

- Because the WD are all close to the CL, all explosions are very similar, similar luminosity





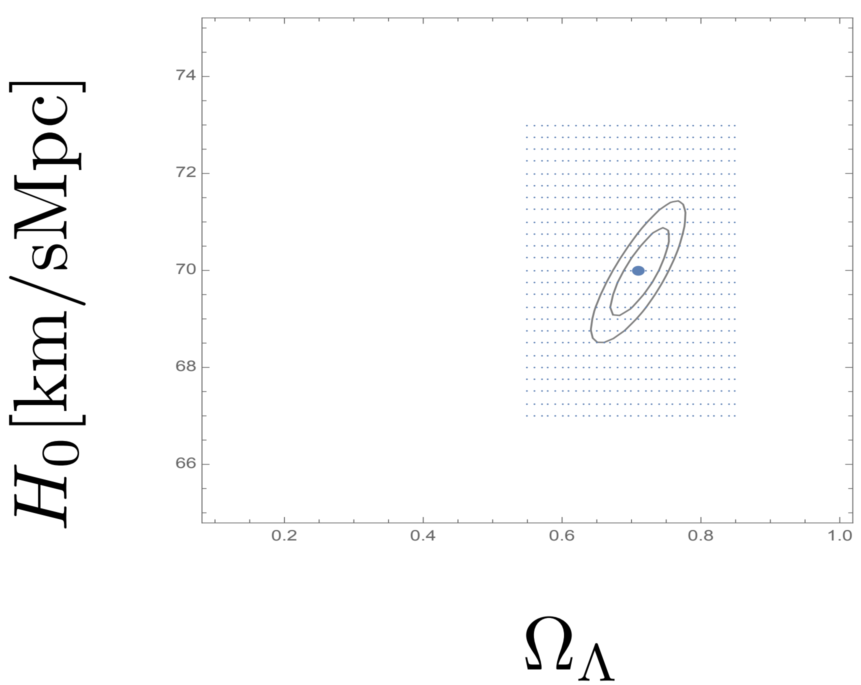
Weighting the Universe $\Omega_m \sim 0.3$



Relationship for a flat Universe (neglect radiation)

$$d_L = \frac{1+z}{H_0}\int_0^z \frac{dz}{\sqrt{\Omega_\Lambda + (1-\Omega_\Lambda)(1+z)^3}}$$

Extract $H_0, \Omega_\Lambda, \Omega_m = 1 - \Omega_\Lambda$



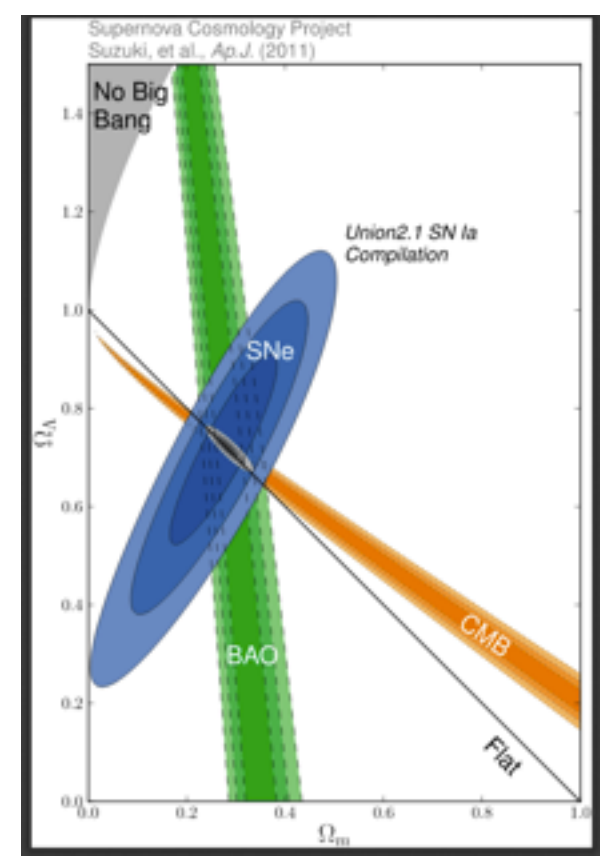
$$\Omega_\Lambda \sim 0.7$$

$$\Omega_m \sim 0.3$$

$$H_0 \sim 70\frac{\mathrm{km/s}}{\mathrm{Mpc}}$$

$$\rho_c = 10h^2\frac{\mathrm{keV}}{\mathrm{cm}^3} \sim 5\frac{\mathrm{keV}}{\mathrm{cm}^3}$$

With curvature



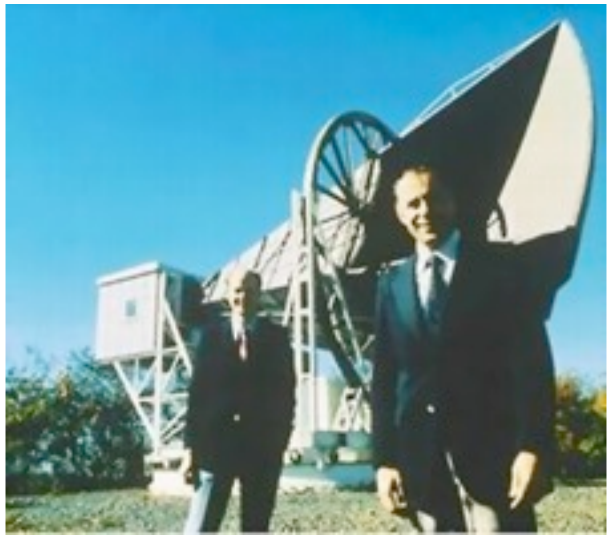
Note CMB -> flat

what about the known matter? ... Ω_b from BBN

Big Bang Nucleosynthesis: the moment when the baryons (p,n) left from early big bang combine into He, D...

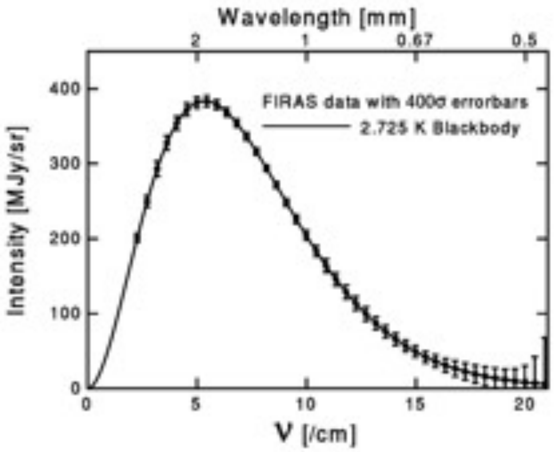
Nuclear reactions take place at very high temperatures ... T~ keV (~billion K)

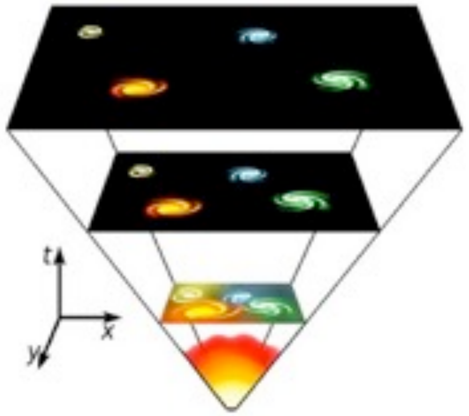
Nowadays the temperature of the Universe is 2.725 K



Penzias and Wilson discovered the Cosmic Microwave Background in '64

an (~)isotropic blackbody radiation remnant from the Big Bang





$$\rho_r^0 = \frac{\pi^2}{15} T^4 = 5 \times 10^{-5} \rho_c^0$$

... but remember wavelengths were shorter at early times $\lambda \propto \lambda_0 (1+z)$

We need to make a trip to $z \sim 10^8$ $\rho_r / \rho_m \sim z (\rho_r / \rho_m)_0 \gg 1$

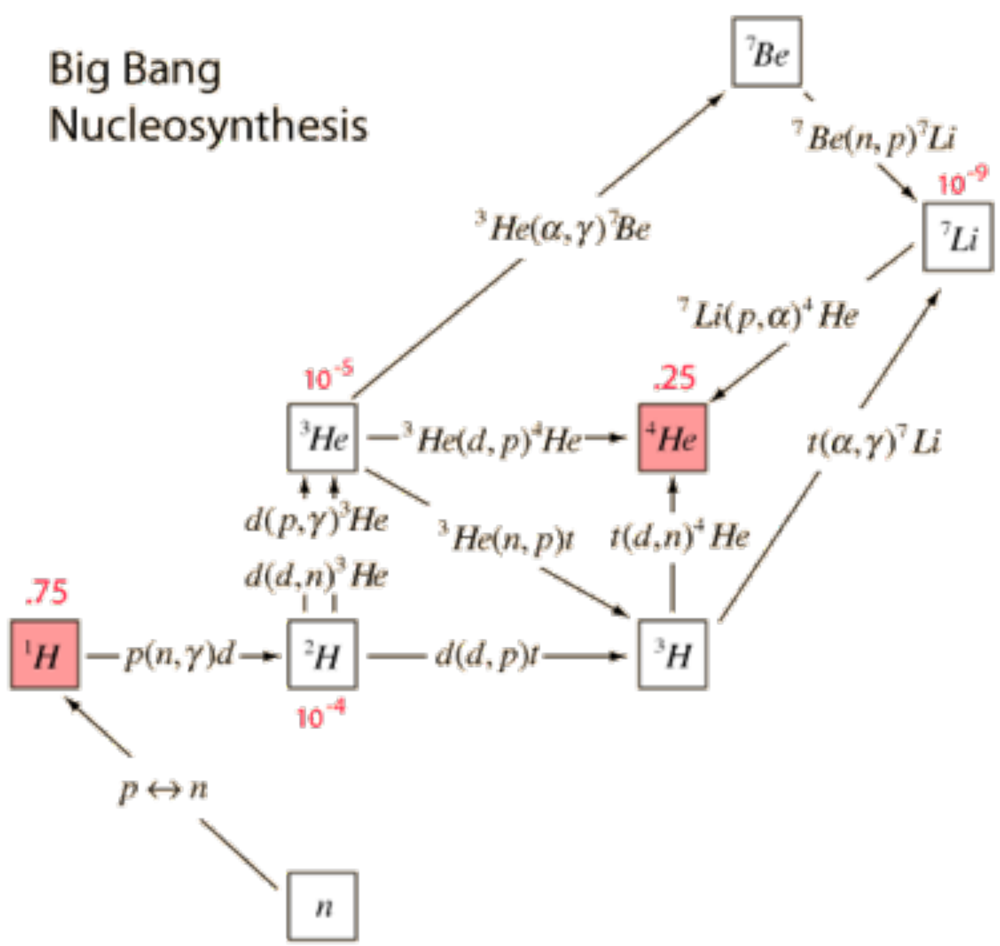
Big Bang Nucleosynthesis

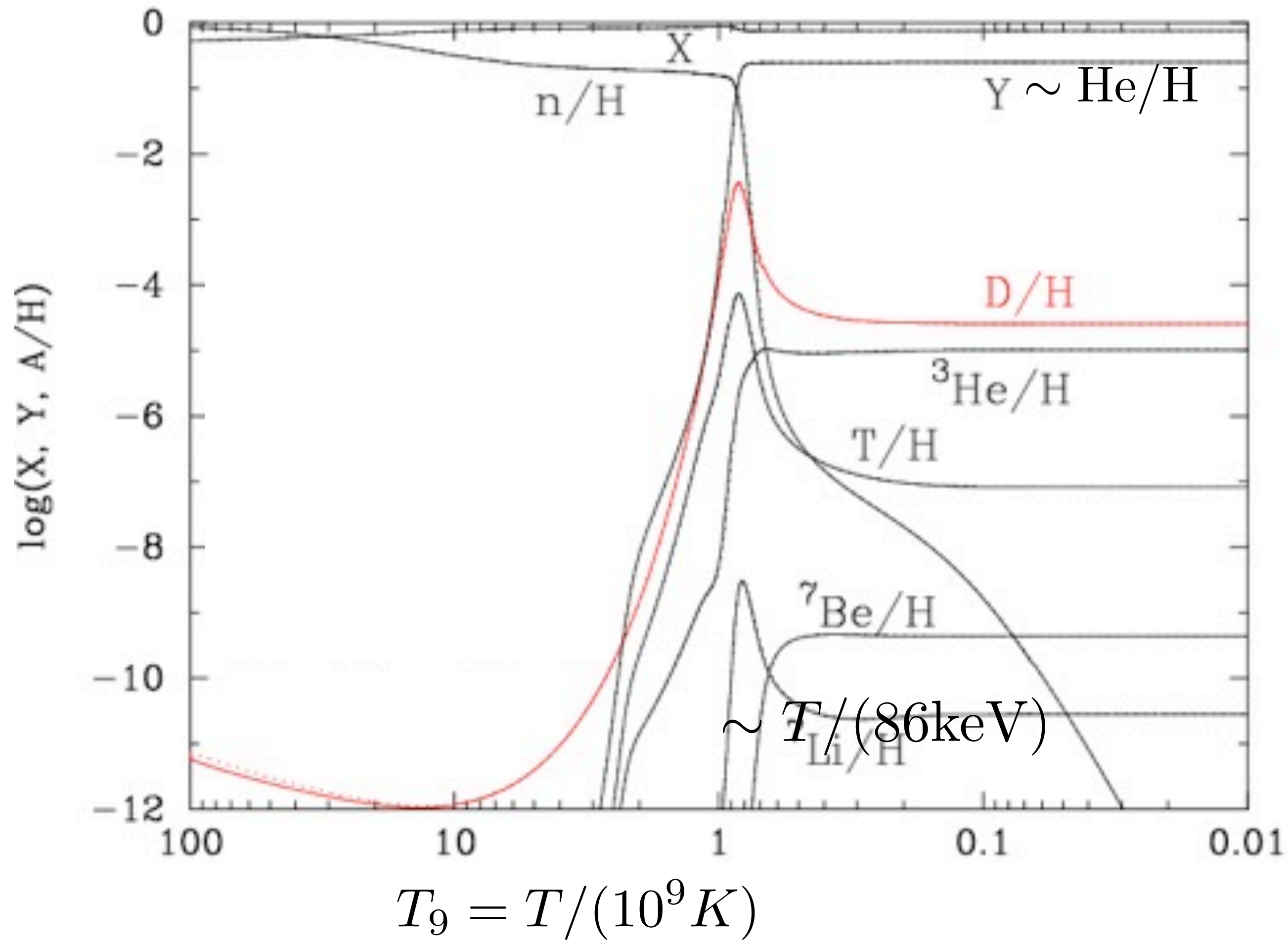
- **At high T, all the Universe ionized, p, n, electrons and a LOT of photons** $\eta_0 = \left(\frac{n_b}{n_\gamma}\right)_0 < 4 \times 10^{-9}$ **... conserved**

$$\Omega_b < 0.3$$

- **When beta reactions freeze-out,** $p^+ + e^- \leftrightarrow n + \nu_e$ **, n's can only decay**
- **Unless they combine rapidly with p's to form stable nuclei!**

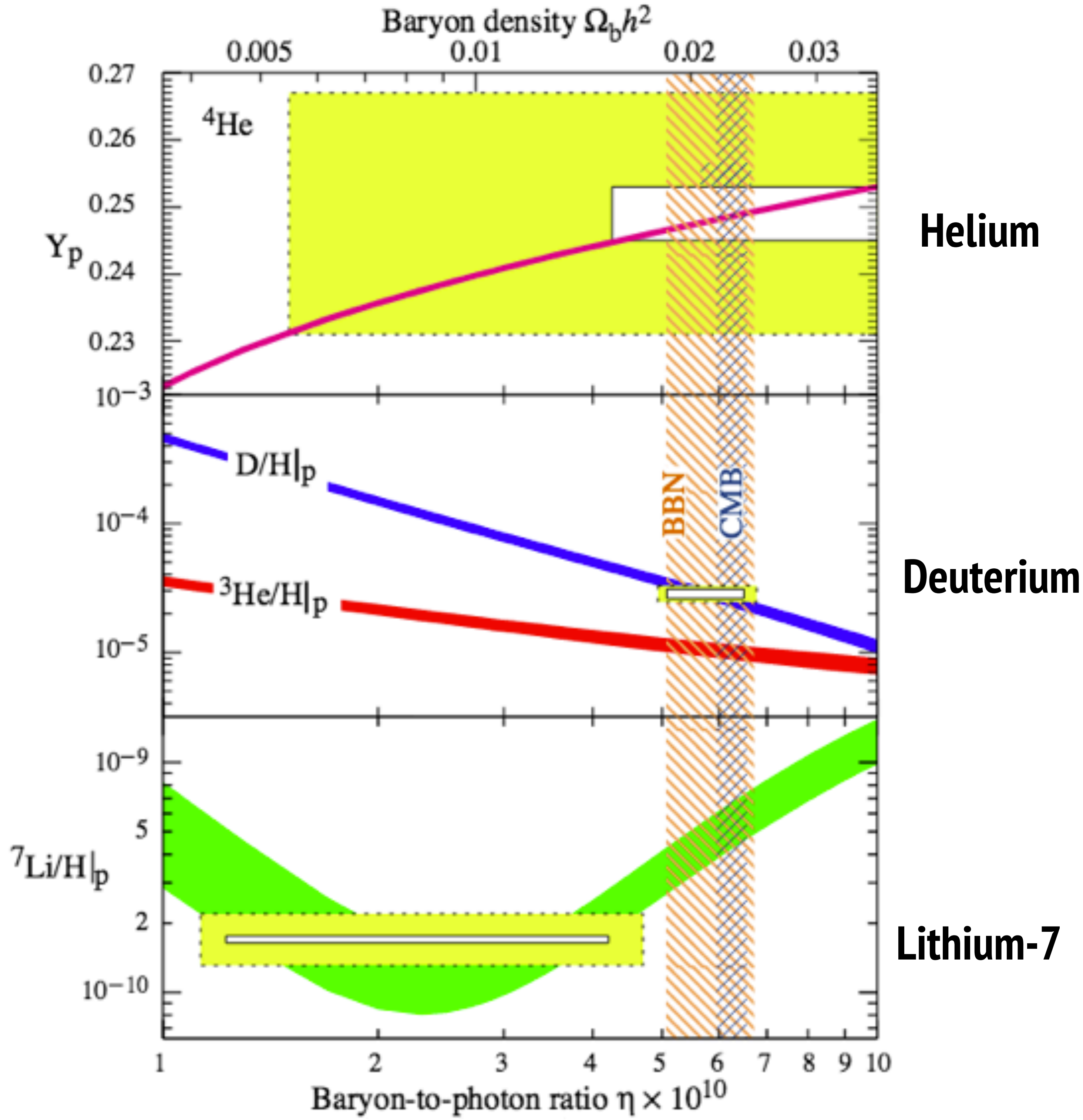
- **Deuterium photodesintegration delays BBN until relatively low T**



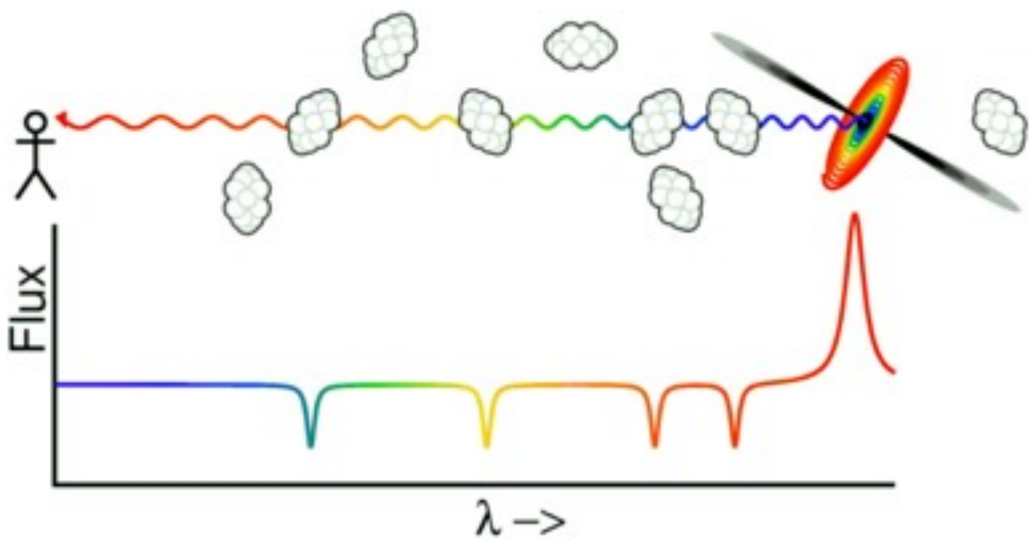


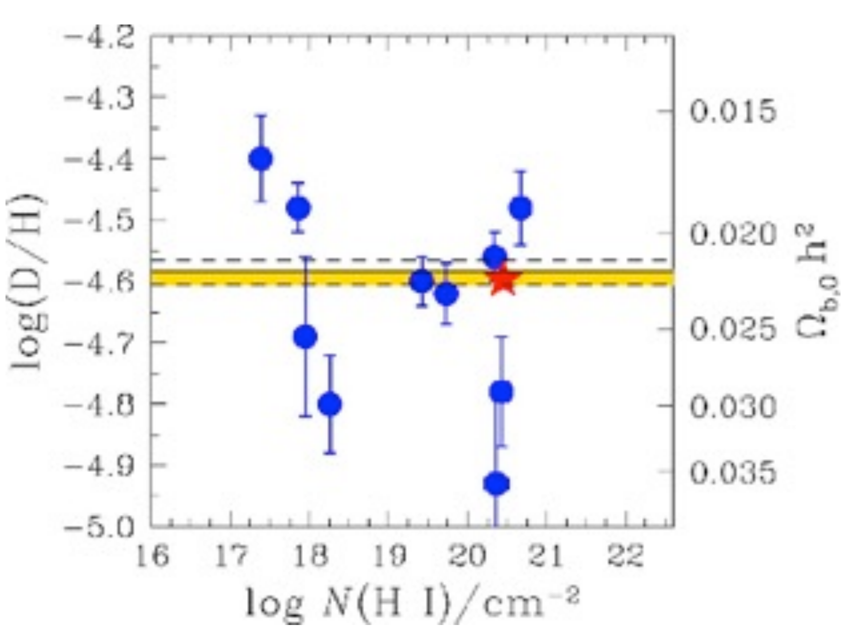
Helium and D yield depend strongly on η

- The basic rule is, the more baryons, the most efficient is to convert them to Heavy nuclei (2body reactions!)



Primordial element abundances (measured) against predictions





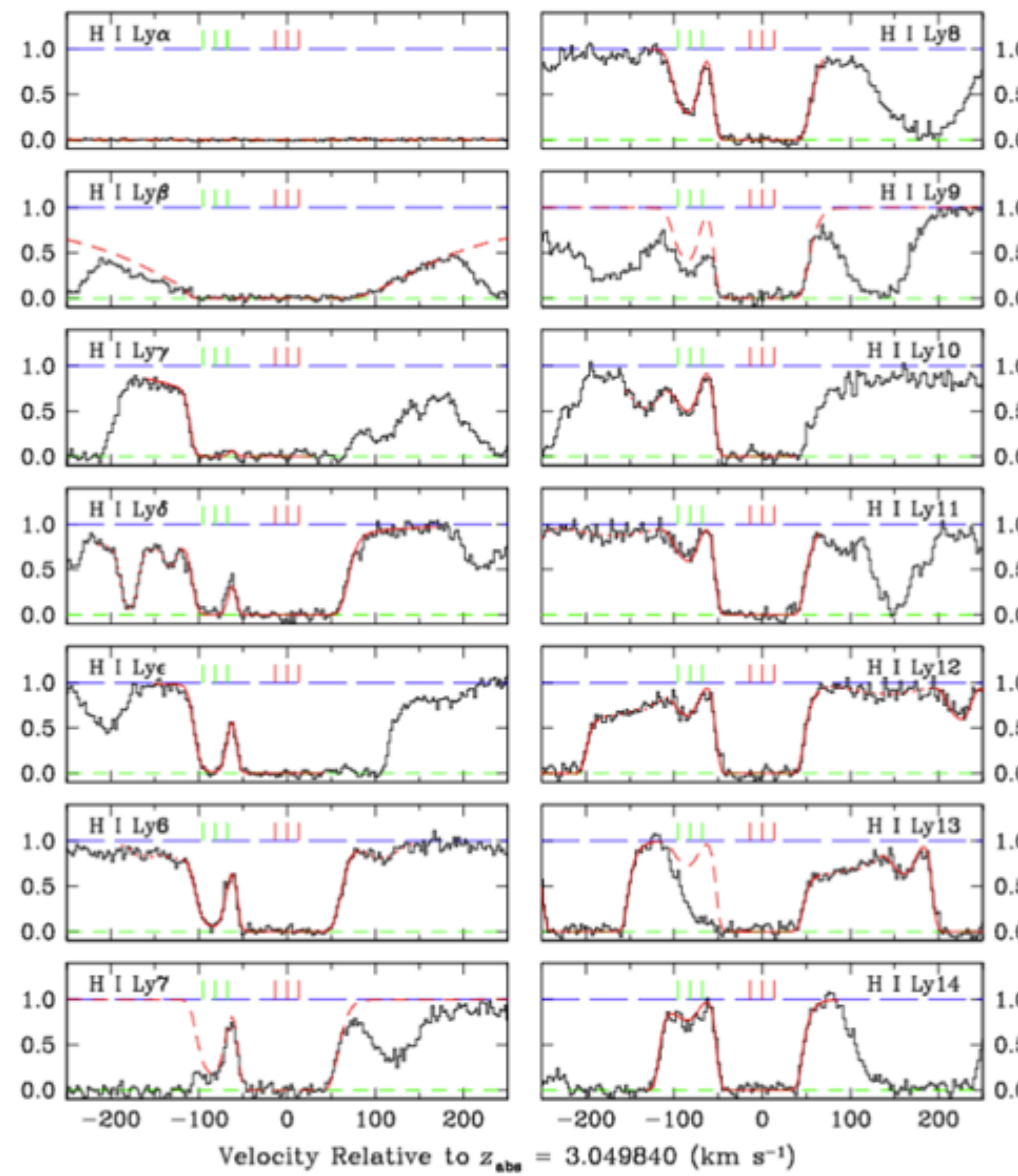
A new, precise measurement of the primordial abundance of Deuterium *

Max Pettini[1,2]† and Ryan Cooke[1,2]

[1] Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA

[2] Kavli Institute for Cosmology, Madingley Road, Cambridge, CB3 0HA

arXiv:1205.3785v2

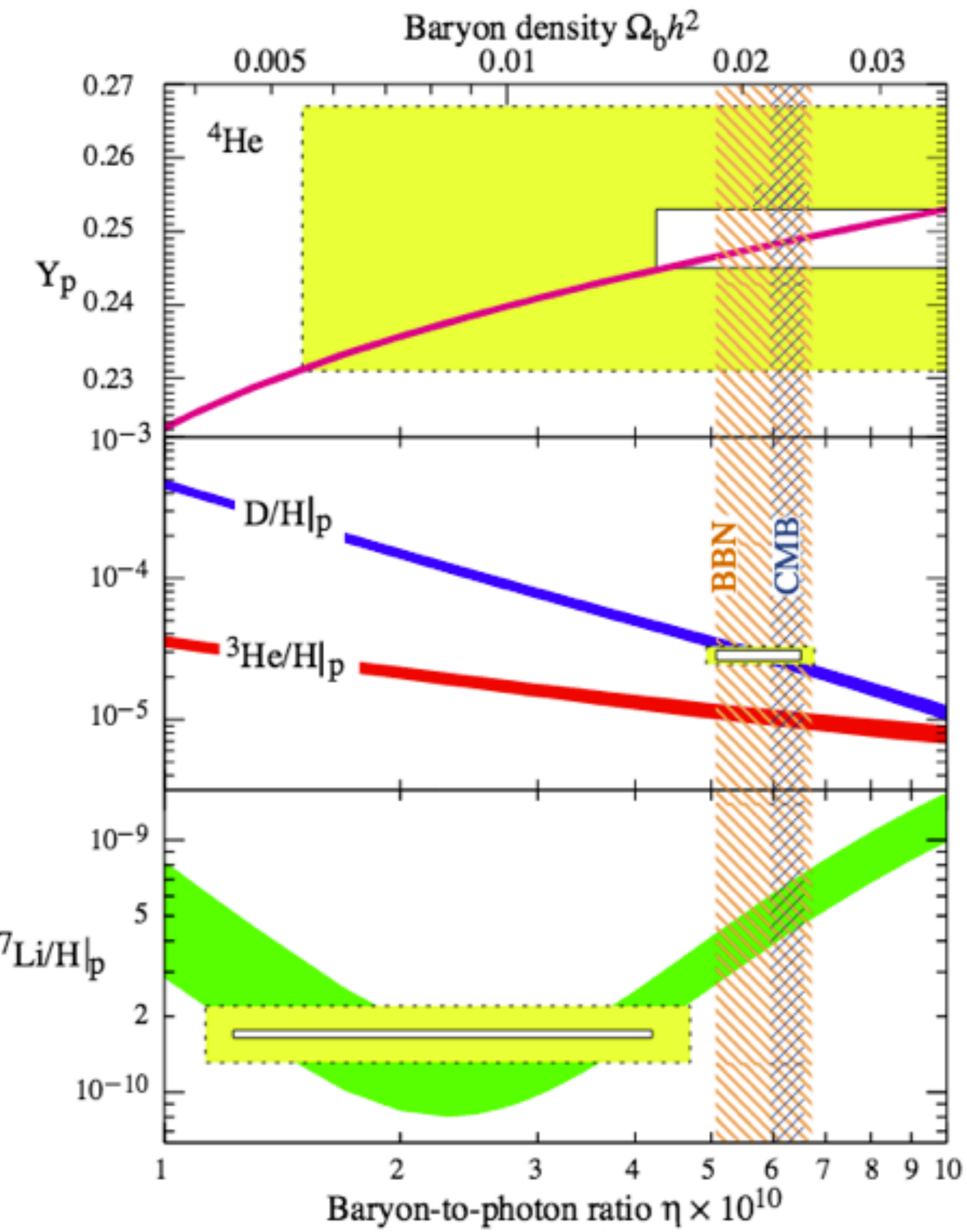


Baryon to photon ratio from BBN

Primordial element abundances (measured) against predictions

$$\Omega_b h^2 = 0.022 \pm 0.001$$

$$\Omega_{bm} \sim 0.044$$



Helium

Deuterium

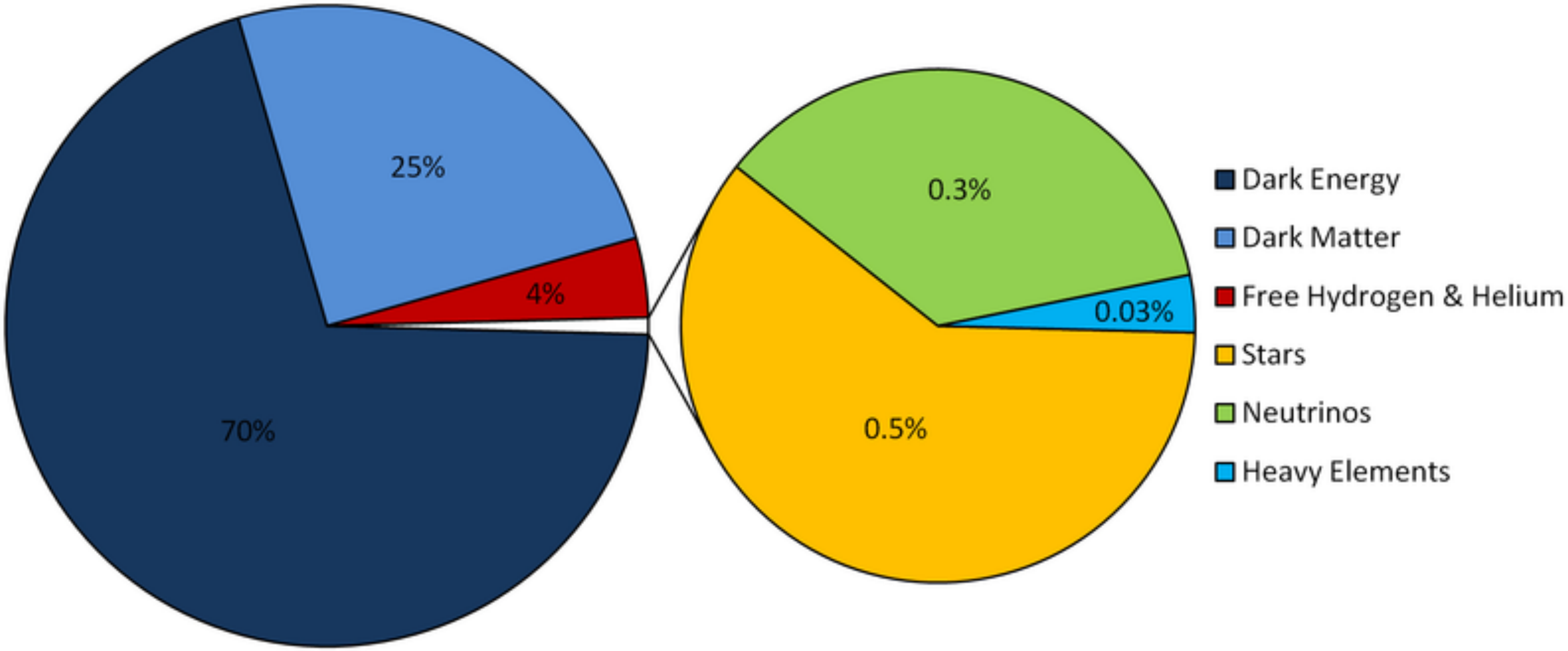
Lithium-7

Only a 5% of the total density is in baryons!
p, He, D…

Total matter density = baryons + what?

30% = 5% + 25%

The cosmic pie



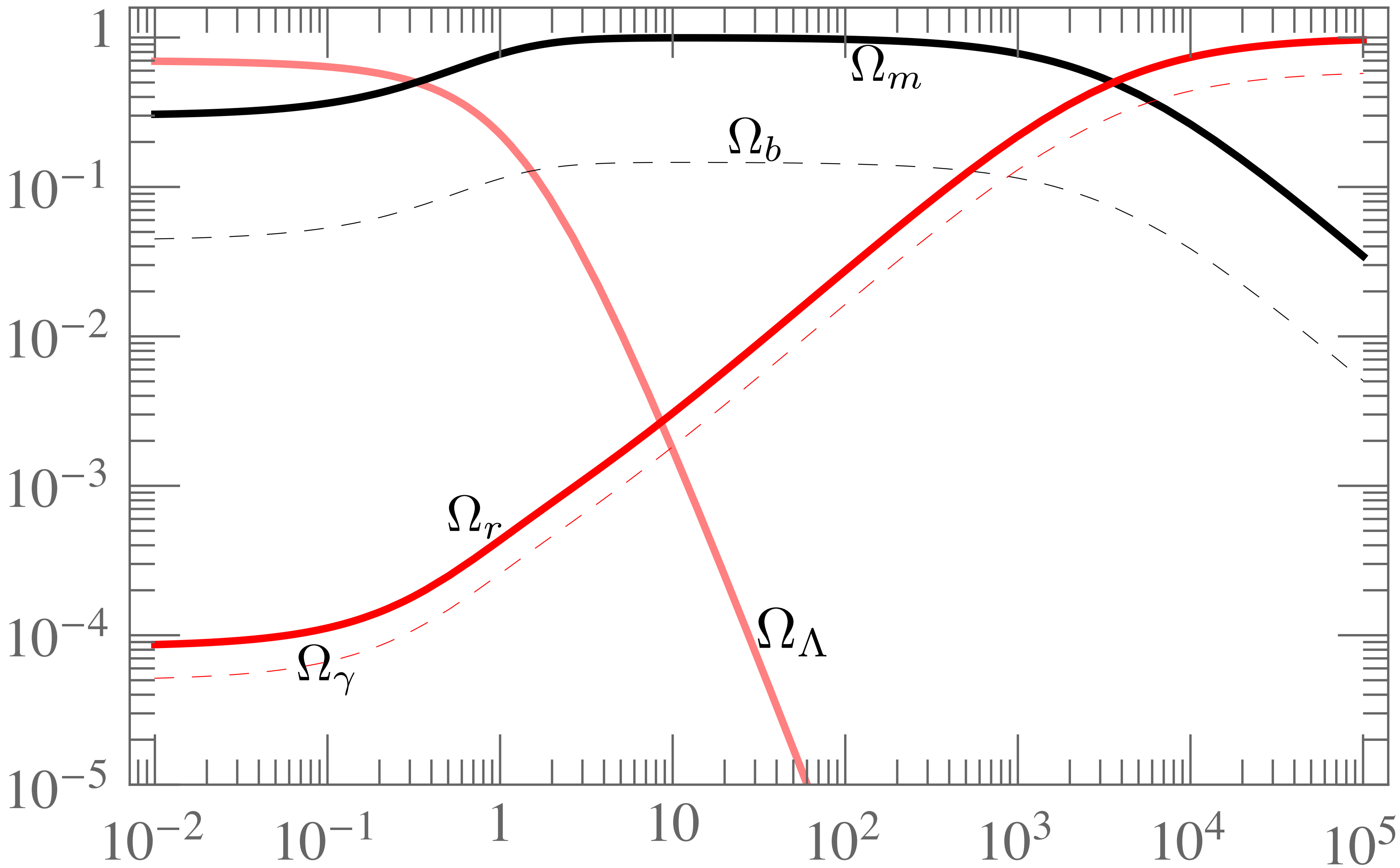
$$1 = \Omega_\Lambda + \Omega_m + \Omega_r$$

Universe Composition / Stages

Our simple Universe composition as a function of redshift

$$H = H_0 \sqrt{\Omega_\Lambda + \Omega_m^0 (1+z)^3 + \Omega_r^0 (1+z)^4}$$

$$\Omega_j = \frac{\rho_j}{\sum_i \rho_i}$$

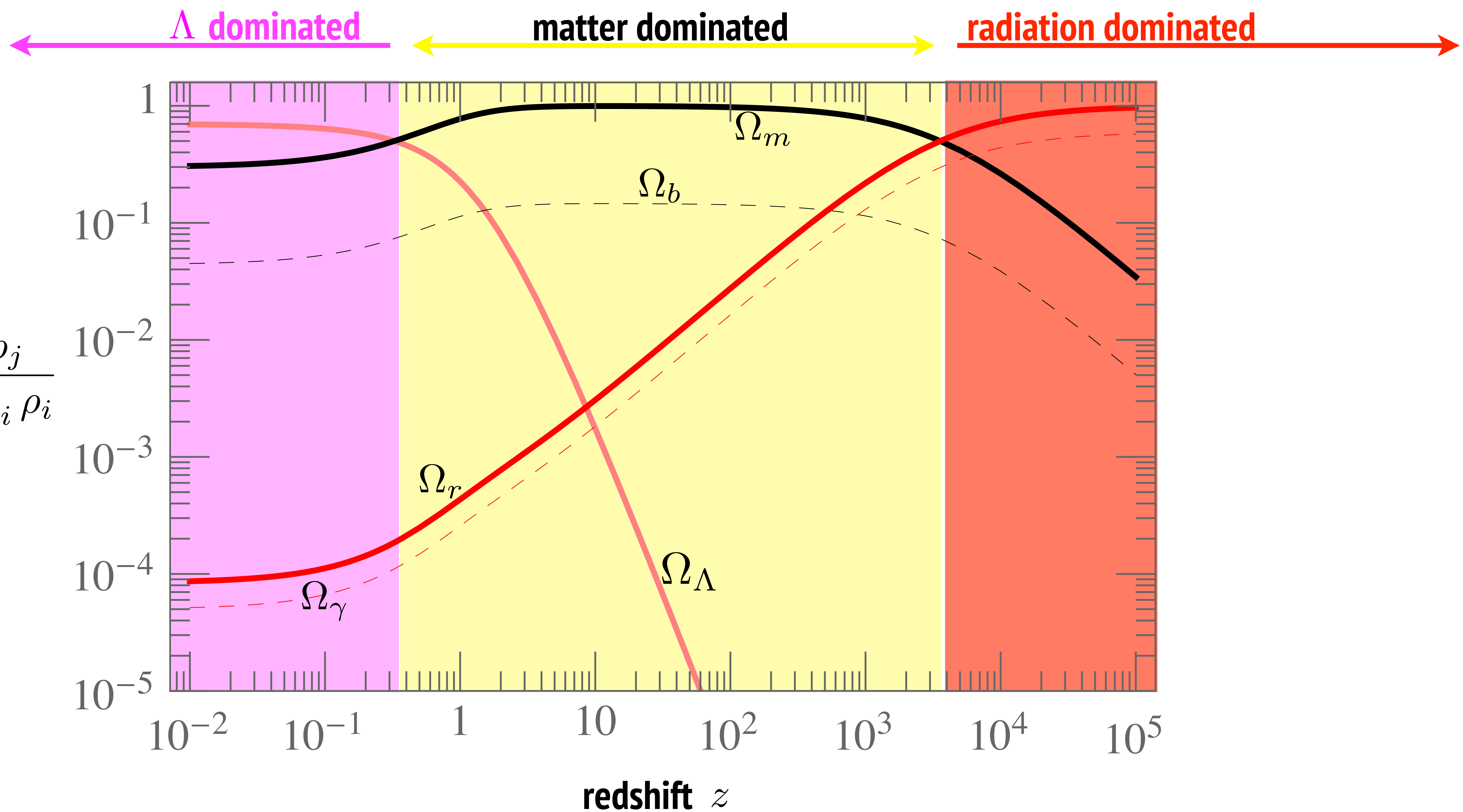


Universe Composition / Stages

Our simple Universe composition as a function of redshift

$$H = H_0\sqrt{\Omega_\Lambda + \Omega_m^0(1+z)^3 + \Omega_r^0(1+z)^4}$$

$$\Omega_j = \frac{\rho_j}{\sum_i \rho_i}$$



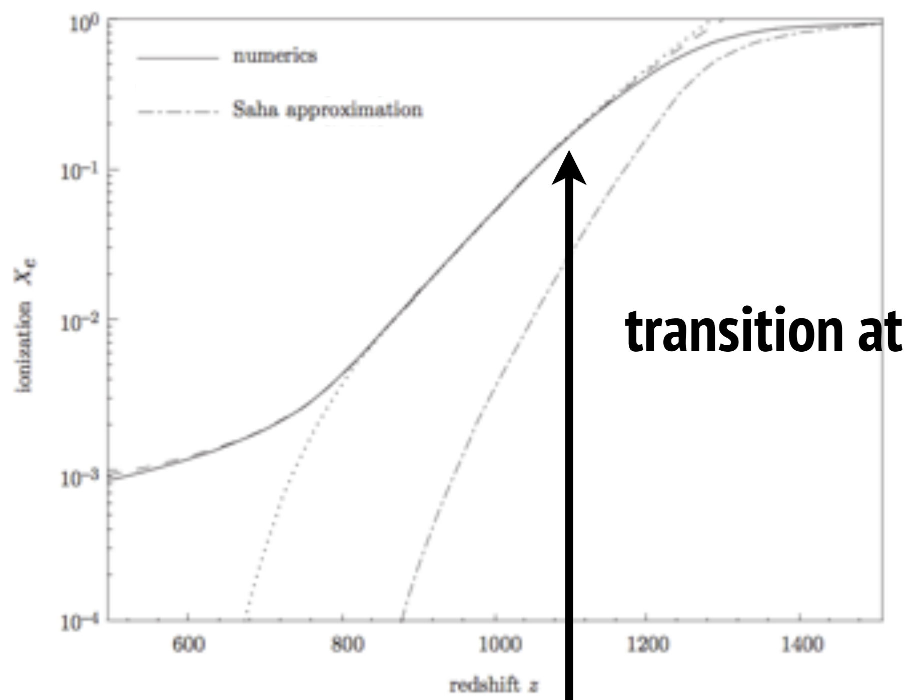
and when the CMB is born

$$n_p \sim \frac{\rho_b}{m_p} \sim n_e$$ number of protons ~ number of baryons (only few neutrons in He)

$$\frac{n_b}{n_\gamma} \sim 6 \times 10^{-10}$$ from BBN

Ionisation evolution $p^+ + e^- \leftrightarrow \mathrm{H} + \gamma$ SAHA eq. $\frac{X_e^2}{1-X_e} = \frac{1}{n_{b,0}(1+z)^3}\left(\frac{T_0(1+z)m_e}{2\pi}\right)^{3/2}\exp\left(-\frac{13.6\mathrm{eV}}{T_0(1+z)}\right)$

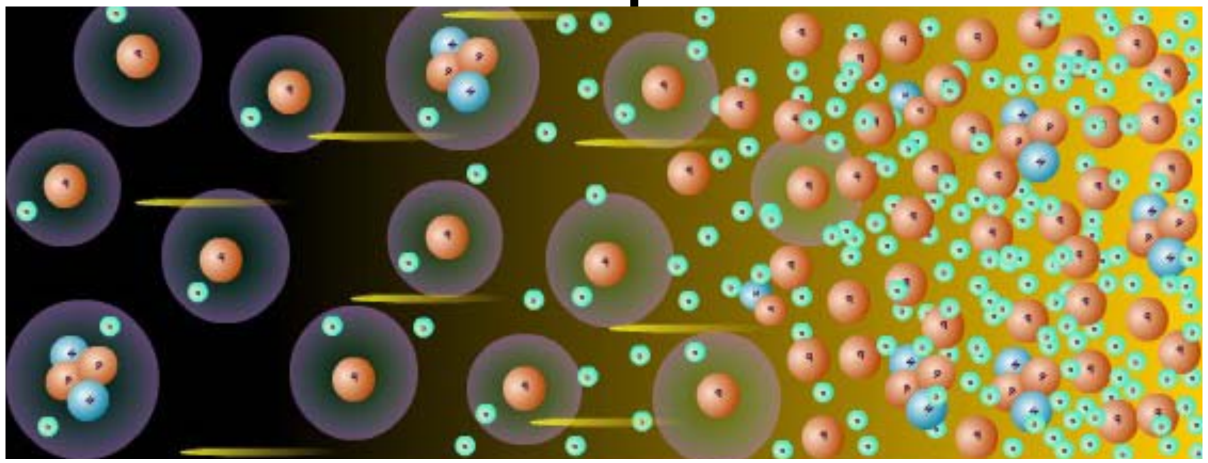
$$\frac{e^-}{e^- + H}$$



transition at z~1100

neutral Hydrogen
Universe almost transparent

CMB is released!



free-electrons
(Universe opaque)

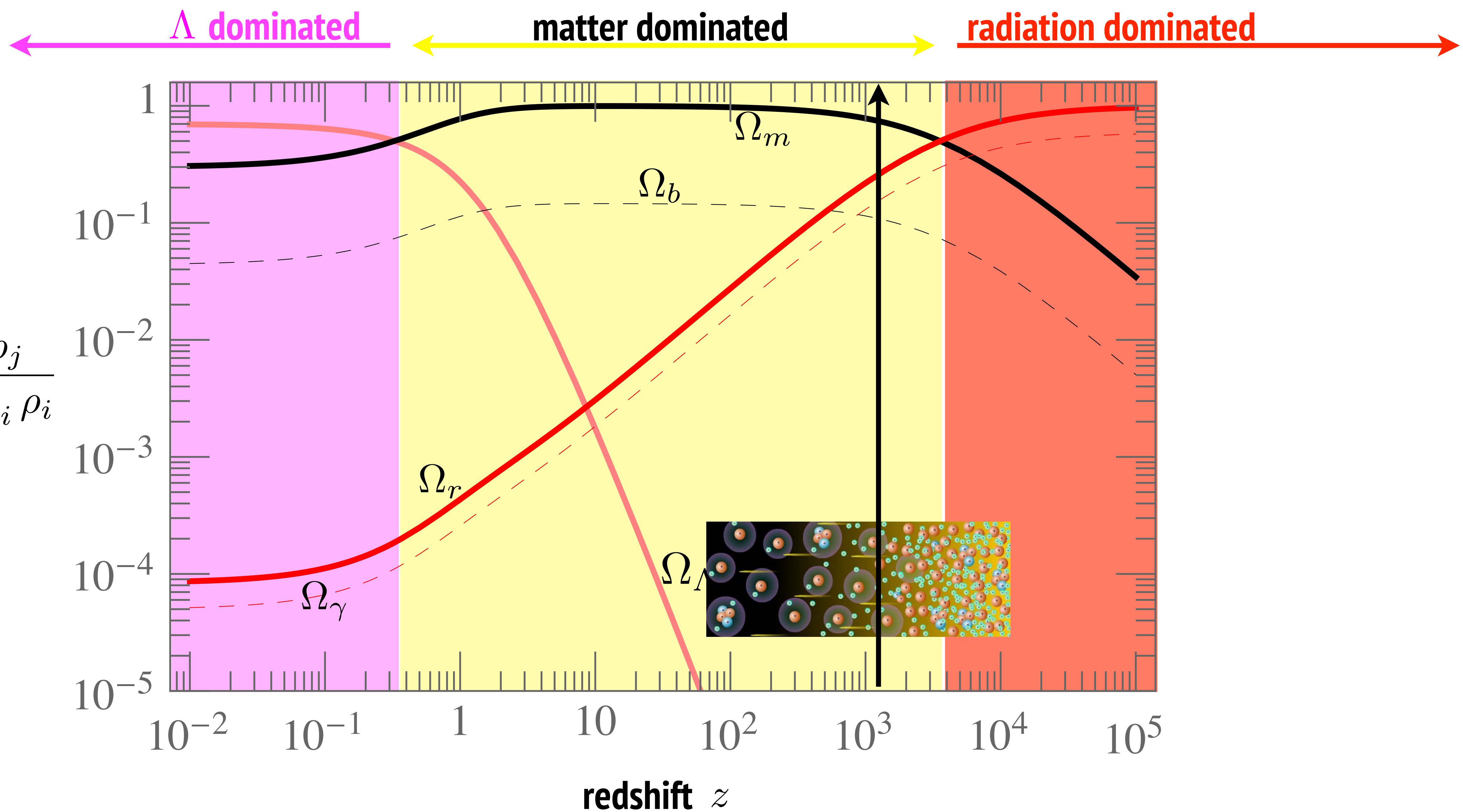
Photons in Thermal eq.

Universe Composition / Stages

Our simple Universe composition as a function of redshift

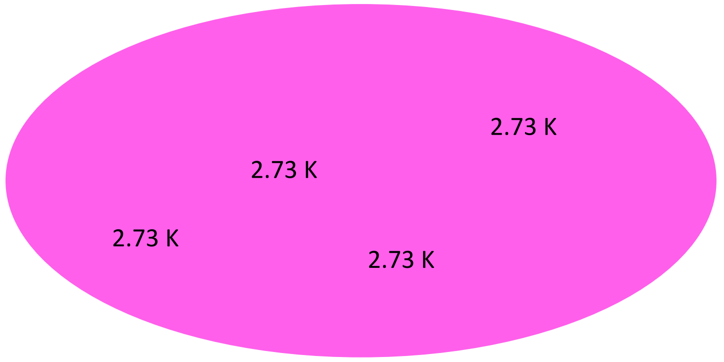
$$H = H_0\sqrt{\Omega_\Lambda + \Omega_m^0(1+z)^3 + \Omega_r^0(1+z)^4}$$

$$\Omega_j = \frac{\rho_j}{\sum_i \rho_i}$$



Structure formation

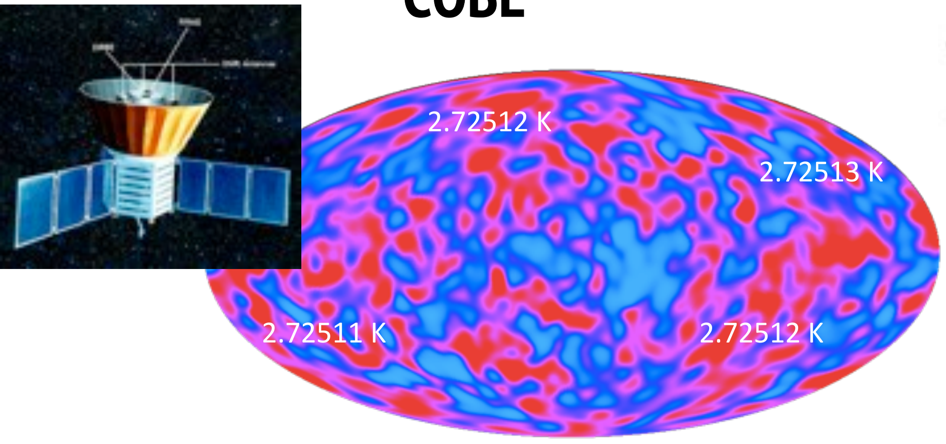
The CMB is isotropic, how did all the structure we see today formed?



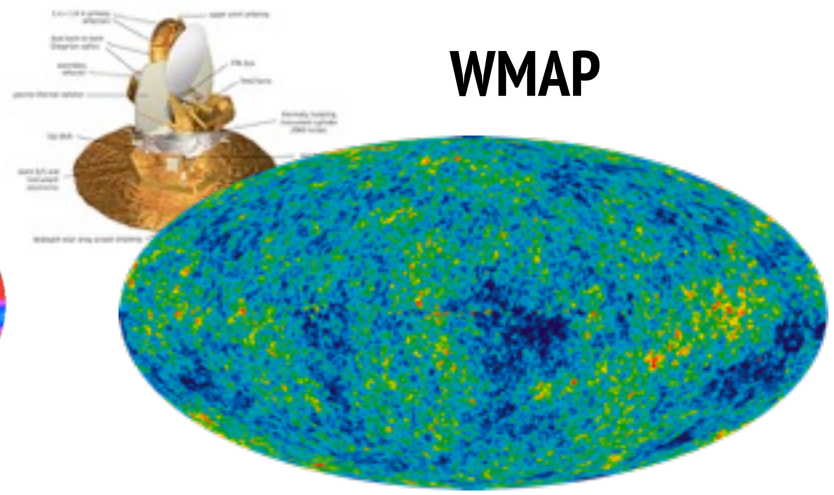
By gravitational amplification of very small density fluctuations!

$\Delta T/T \sim 10^{-5}$ **found by the COBE and studied in detail by the WMAP and Planck**

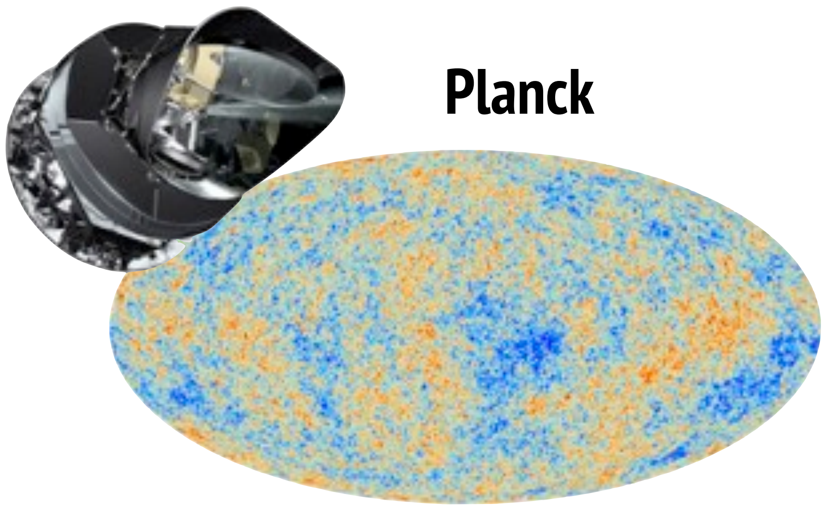
COBE



WMAP



Planck



And this doesn’t work without dark matter as well

Gravitational instability

Consider a matter (perfect) fluid of density $\rho = \rho_0(1+\delta(x))$ velocity $\vec{u}(x)$

Evolution under gravity given by

Continuity eq. (mass conservation)	$\dot{\rho} + \nabla(\rho\vec{u}) = 0$
Euler eq. (momentum conservation)	$\dot{\vec{u}} + (\vec{u}\cdot\nabla)\vec{u} + \frac{1}{\rho}\nabla P + \nabla\phi = 0$
Poisson (gravity)	$\nabla^2\phi = 4\pi G\rho$

Linearise and combine using EOS

$$c_s^2 = \frac{\partial p}{\partial \rho} \qquad \ddot{\delta} - (4\pi G\rho_0 + c_s^2\nabla^2)\delta = 0$$

Solutions are plane waves $\delta \sim A\exp(-i\vec{k}\cdot\vec{x} + i\omega t)$ $\omega = \sqrt{c_s^2k^2 - 4\pi G\rho_0}$

Short wavelength perturbations $k \gg \frac{\sqrt{4\pi G\rho_0}}{c_s} = k_J$ oscillate (pressure wins over gravity)

Long wavelength perturbations $k \ll k_J$ grow exponentially!

Jeans length $L_J \sim \sqrt{\frac{\pi c_s^2}{G\rho_0}}$

Gravitational instability in an expanding Universe

Consider a matter (perfect) fluid of density $\rho = \rho_0(1+\delta(x))$ velocity $\vec{u}(x)$

I save you the details $$\ddot{\delta}_k + 2H\dot{\delta}_k - \left(4\pi G\rho_0 - \frac{c_s^2 k^2}{R^2}\right)\delta_k = 0$$

Expansion enters as damping

k is a comoving wavenumber

Used a plane wave trial function $\delta_k \sim \delta_k(t)\exp(-i\vec{k}\cdot\vec{x}/R)$

What is the effect of the expansion? three cases

short wavelength perturbations

δ_k oscillates with a decaying amplitude

Long wavelength perturbations

(Remember ... for $k \ll k_J$ grew exponentially in static case!)

Smooth Radiation domination $\ddot{\delta}_k + \frac{1}{t}\dot{\delta}_k \simeq 0$ $\delta_k \sim \log(t)$ don't grow much ...

Matter domination $\ddot{\delta}_k + \frac{4}{3t}\dot{\delta}_k - \left(\frac{2}{3t^2}\right)\delta_k = 0$ $\delta_k \propto t^{2/3} \propto R$ grow with the scale factor

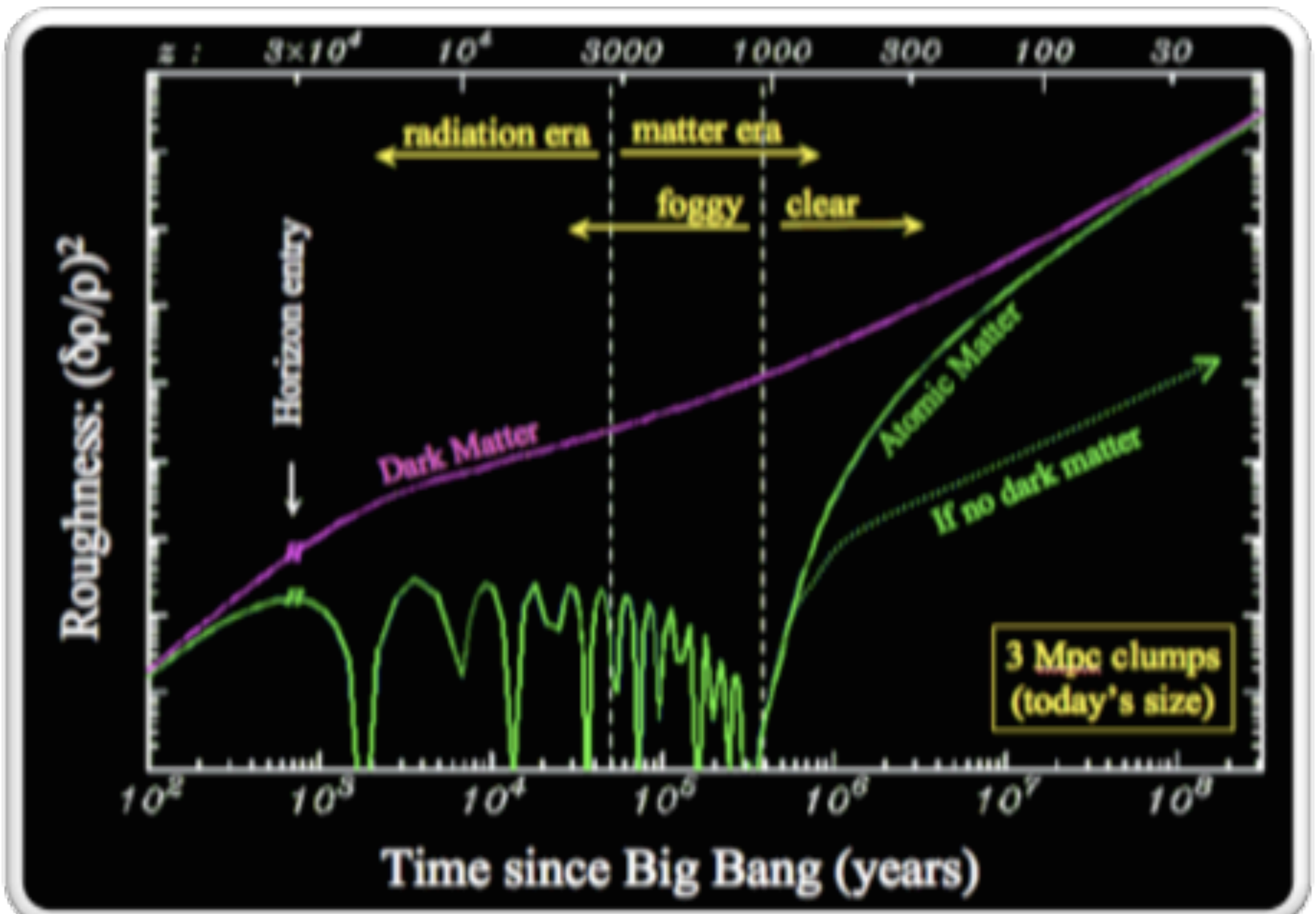
DM and fully developed structure today

DM density perturbations grows logaritmically*

Baryons are kept tight to photons (large cs) oscillate and decay

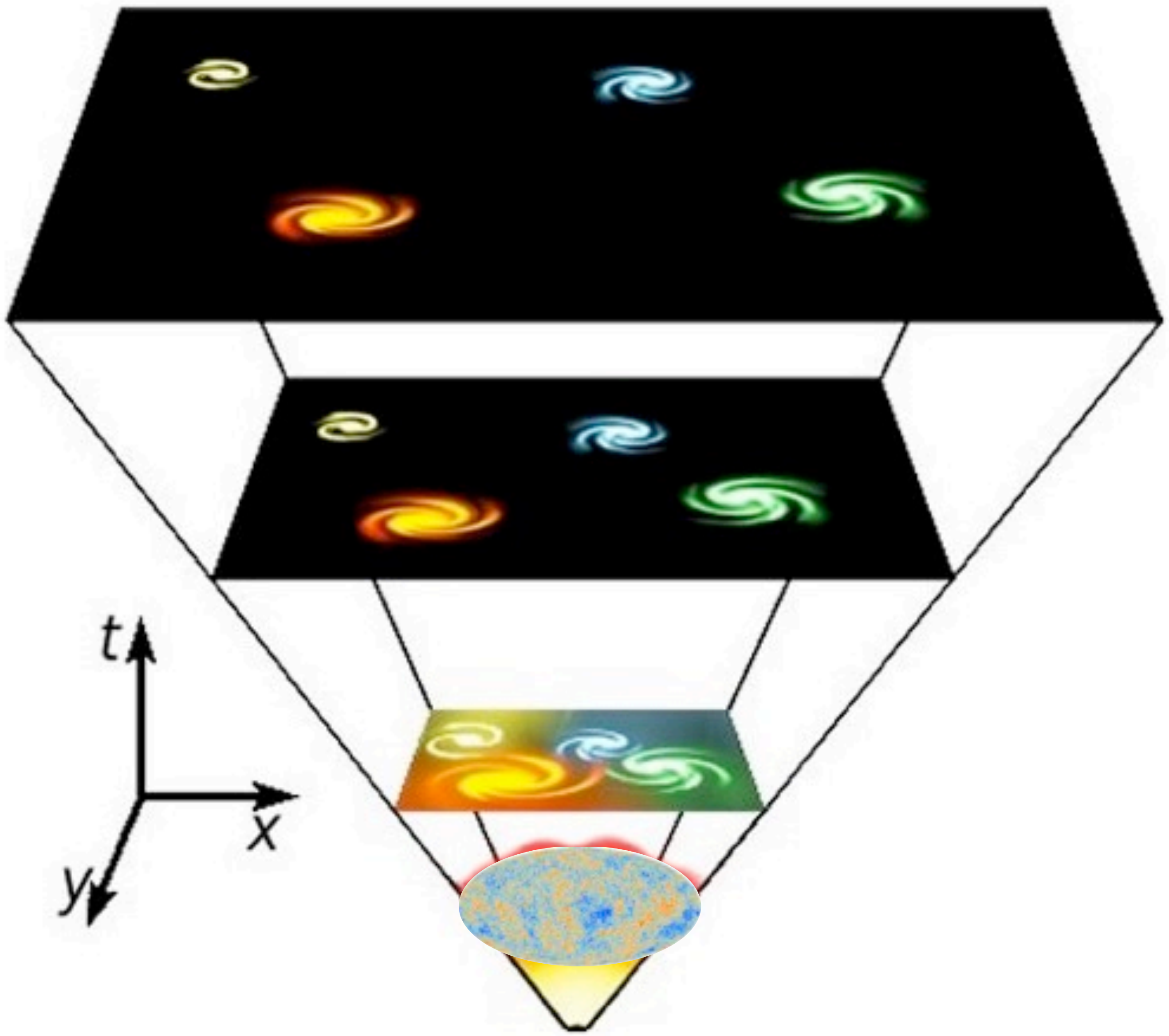
DM density perturbations grows ~ R

Baryons are free from photons, fall into DM gravitational wells!!

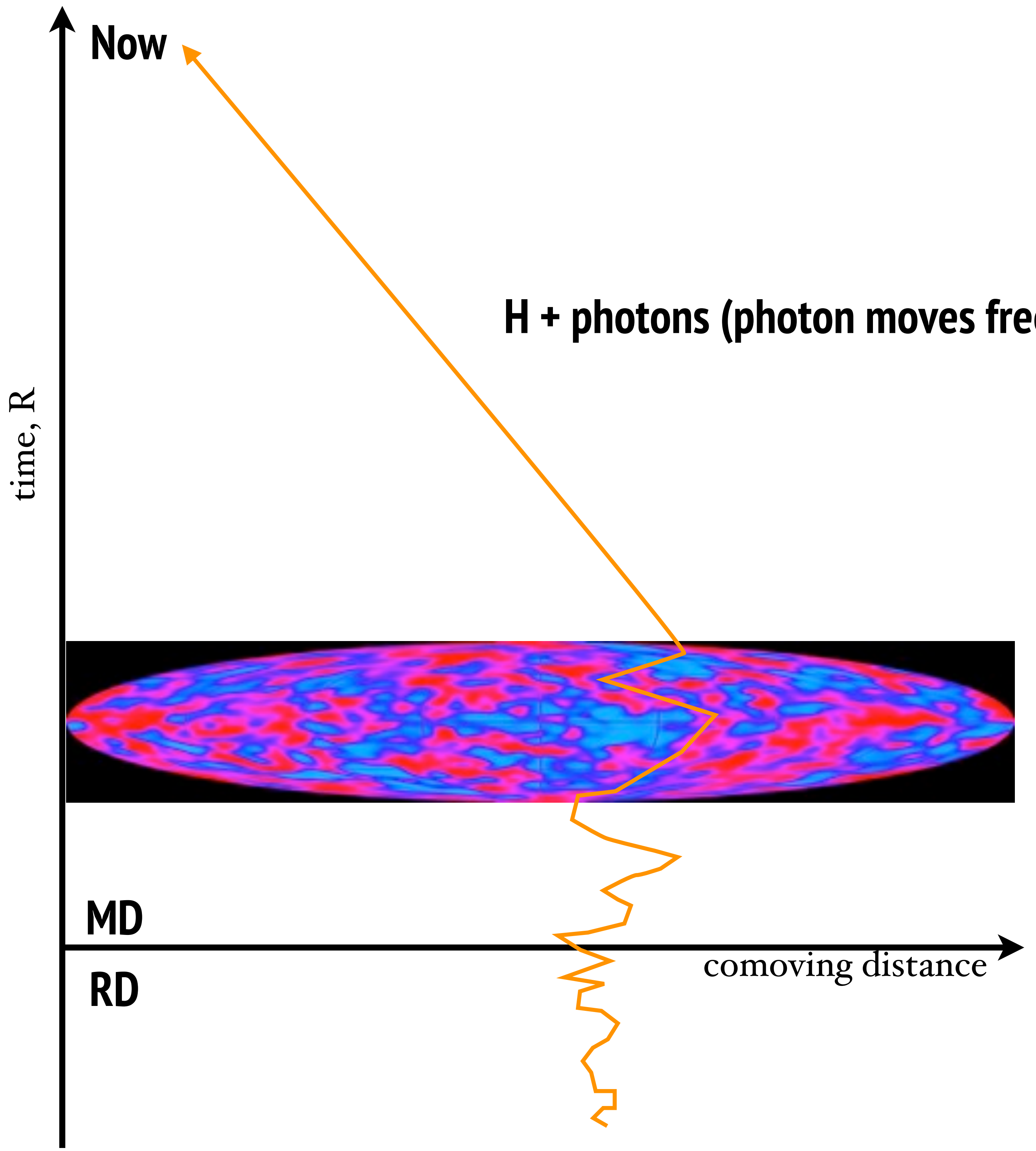


Without DM baryon overdensities cannot grow to O(1) by today!

DM and fully developed structure today



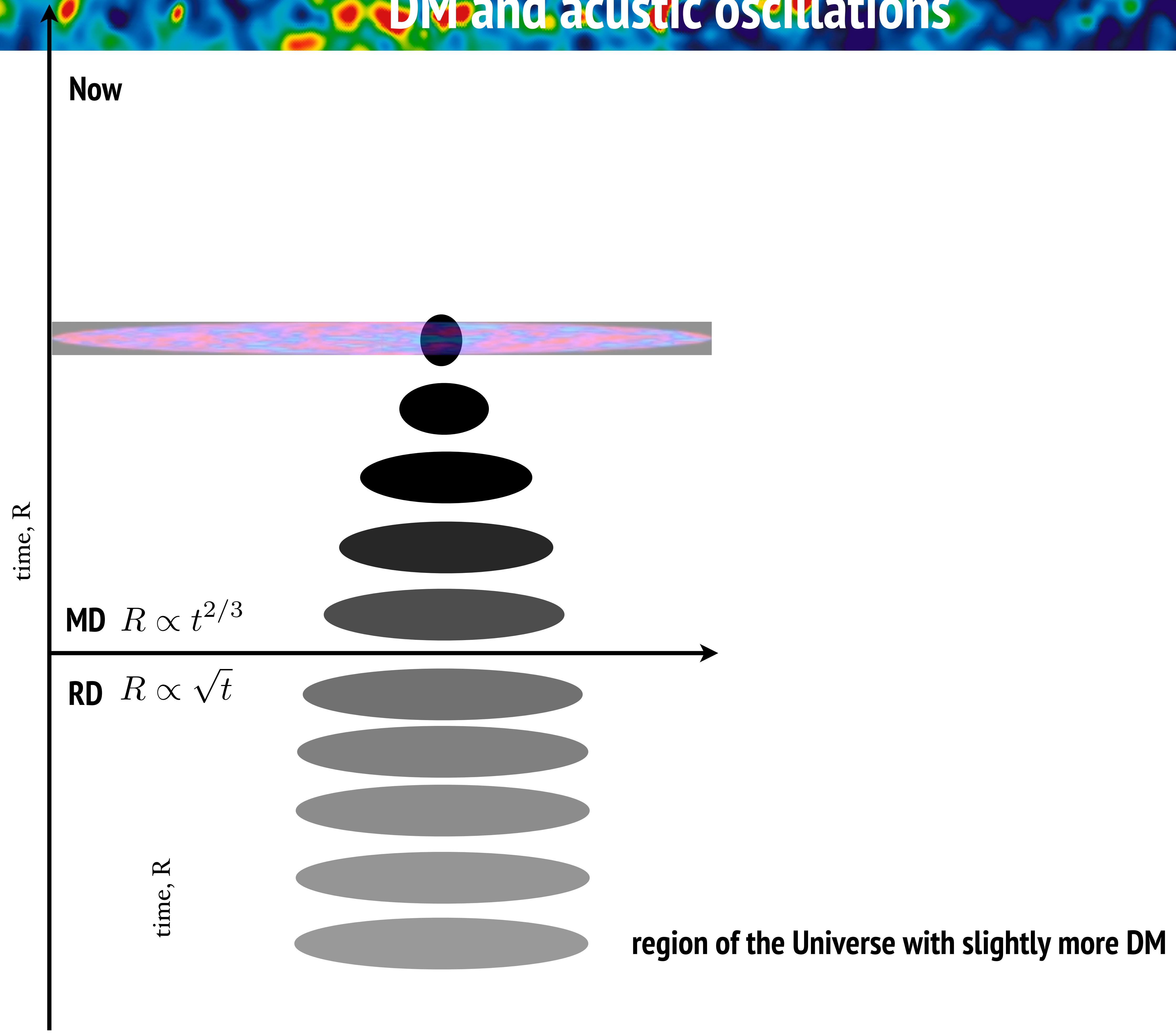
DM and acustic oscillations



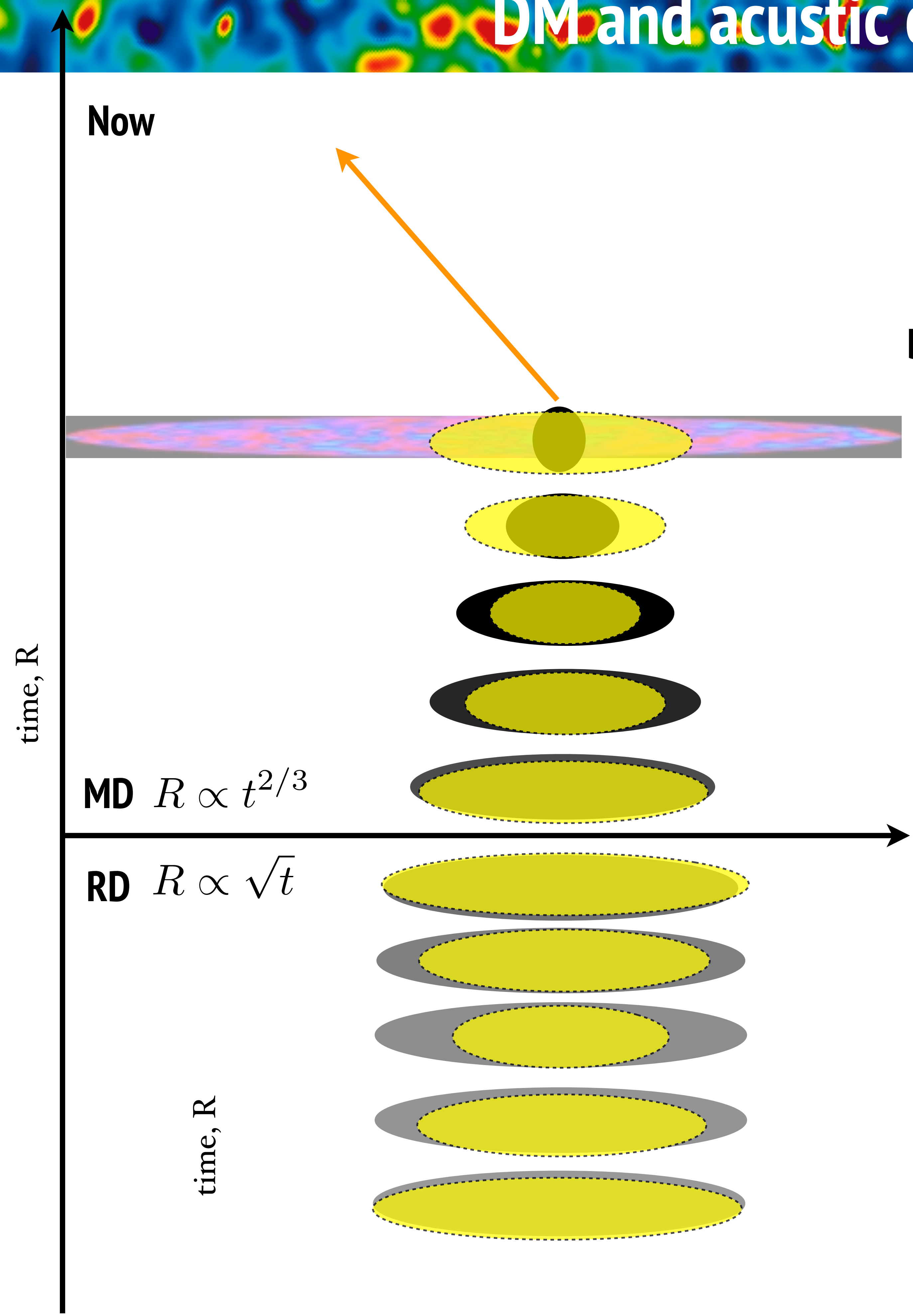
protons and electrons recombine

tight baryon-electron-photon plasma
m.f.p. photon small

DM and acustic oscillations



DM and acustic oscillations



region of the Universe with slightly more DM
with its baryon-photon plasma

baryon-photon plasma oscillates (pressure waves)

oscillations

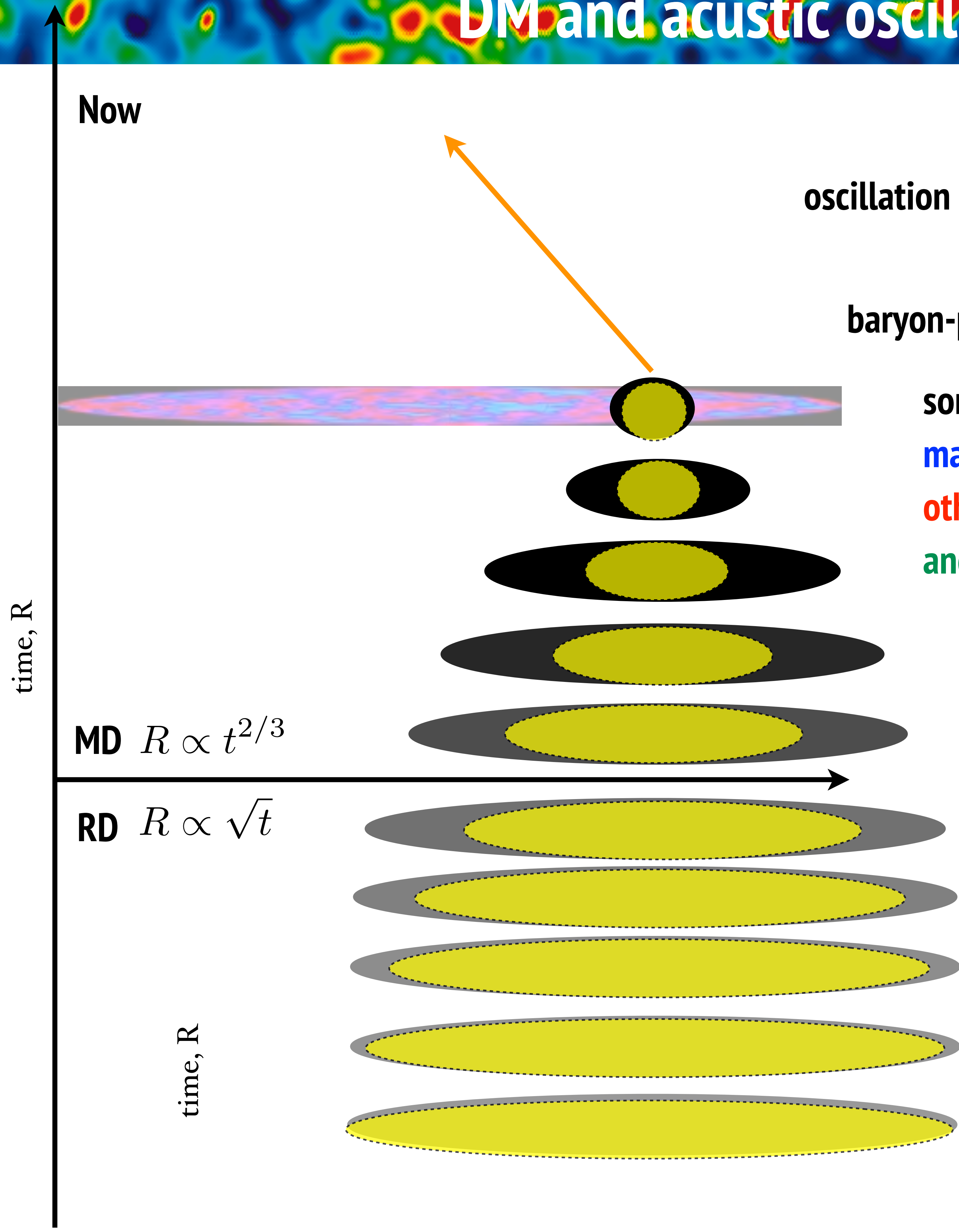
rarefaction

too much pressure

gravity ->compression

pressure waves move almost at c (photons)

DM and acustic oscillations



oscillation frequency depends with size (sound speed)

baryon-photon plasma oscillates (pressure waves)

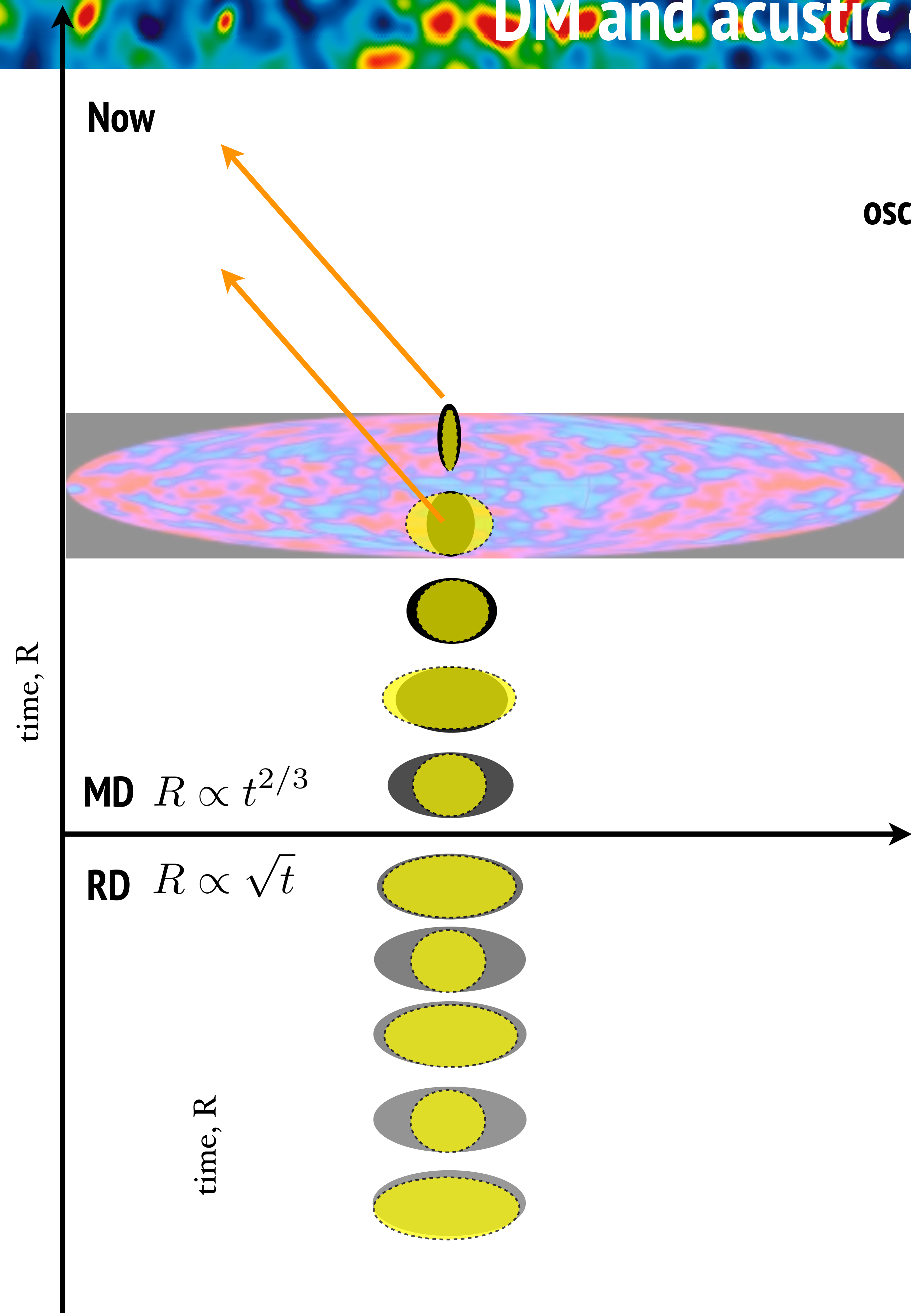
some sizes arrive at decoupling exactly at

maxima of pressure (temperature),

others at minima

and others at delta T = 0

DM and acustic oscillations

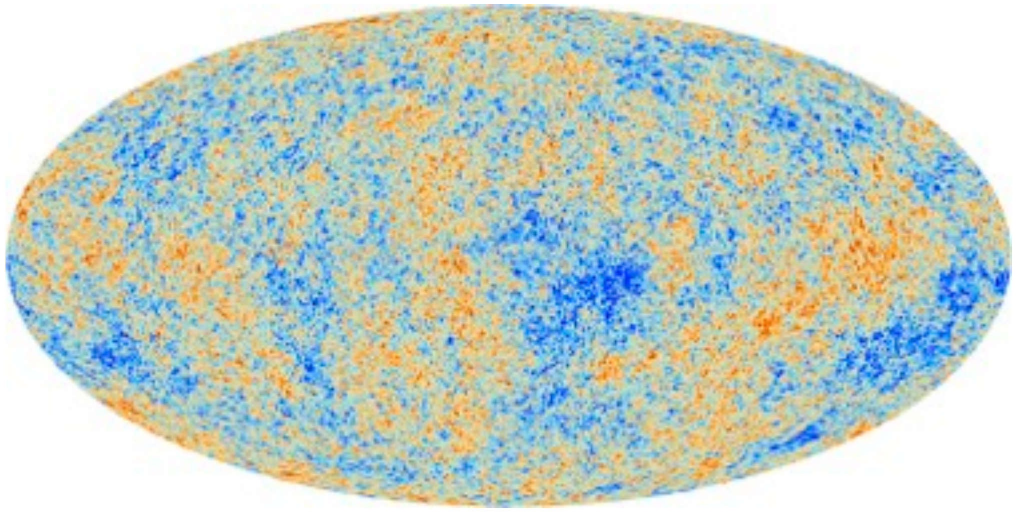


oscillation frequency depends with size (sound speed)

baryon-photon plasma oscillates (pressure waves)

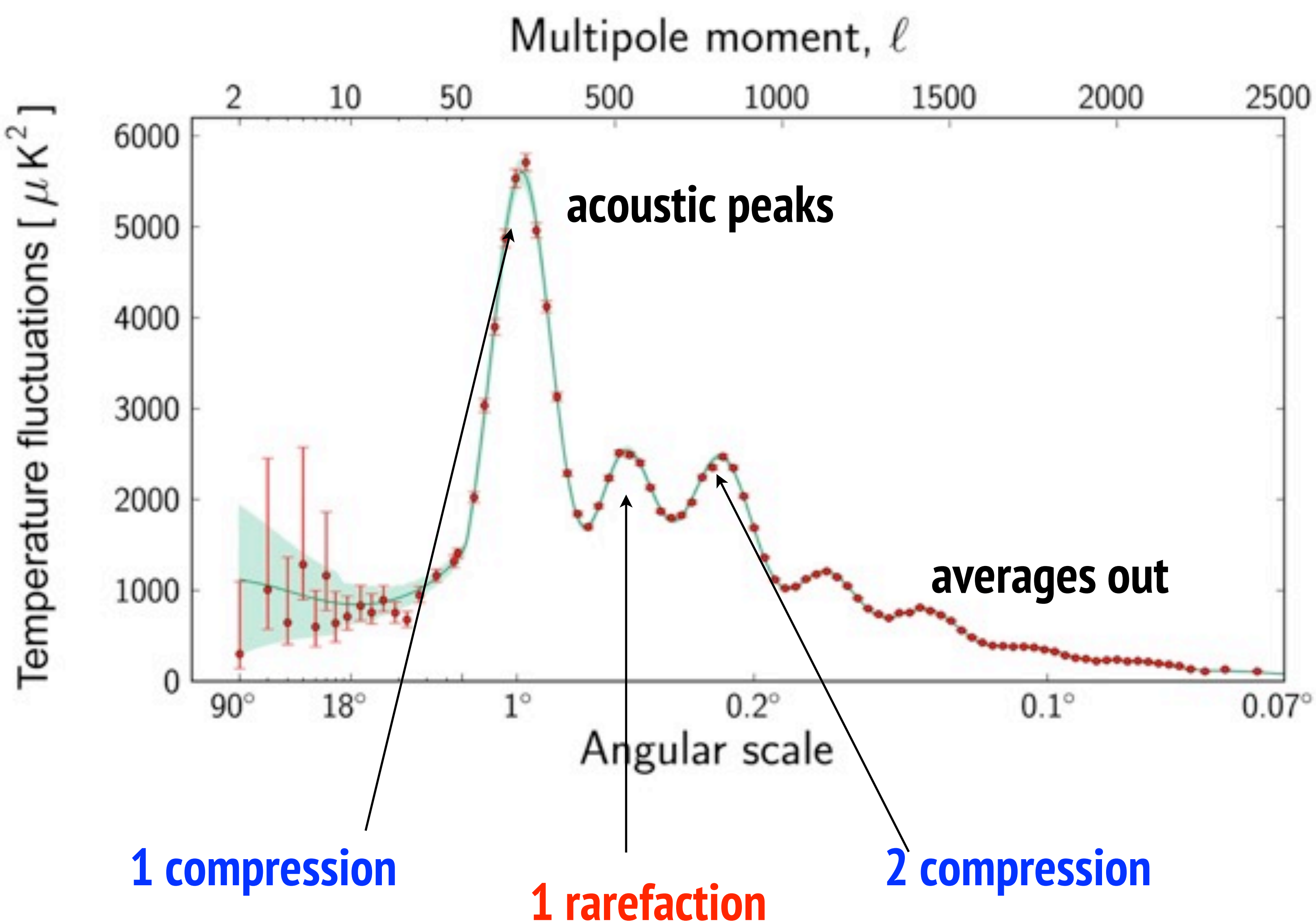
If oscillations are fast, finite size decoupling averages out

Primordial MW sky by Planck



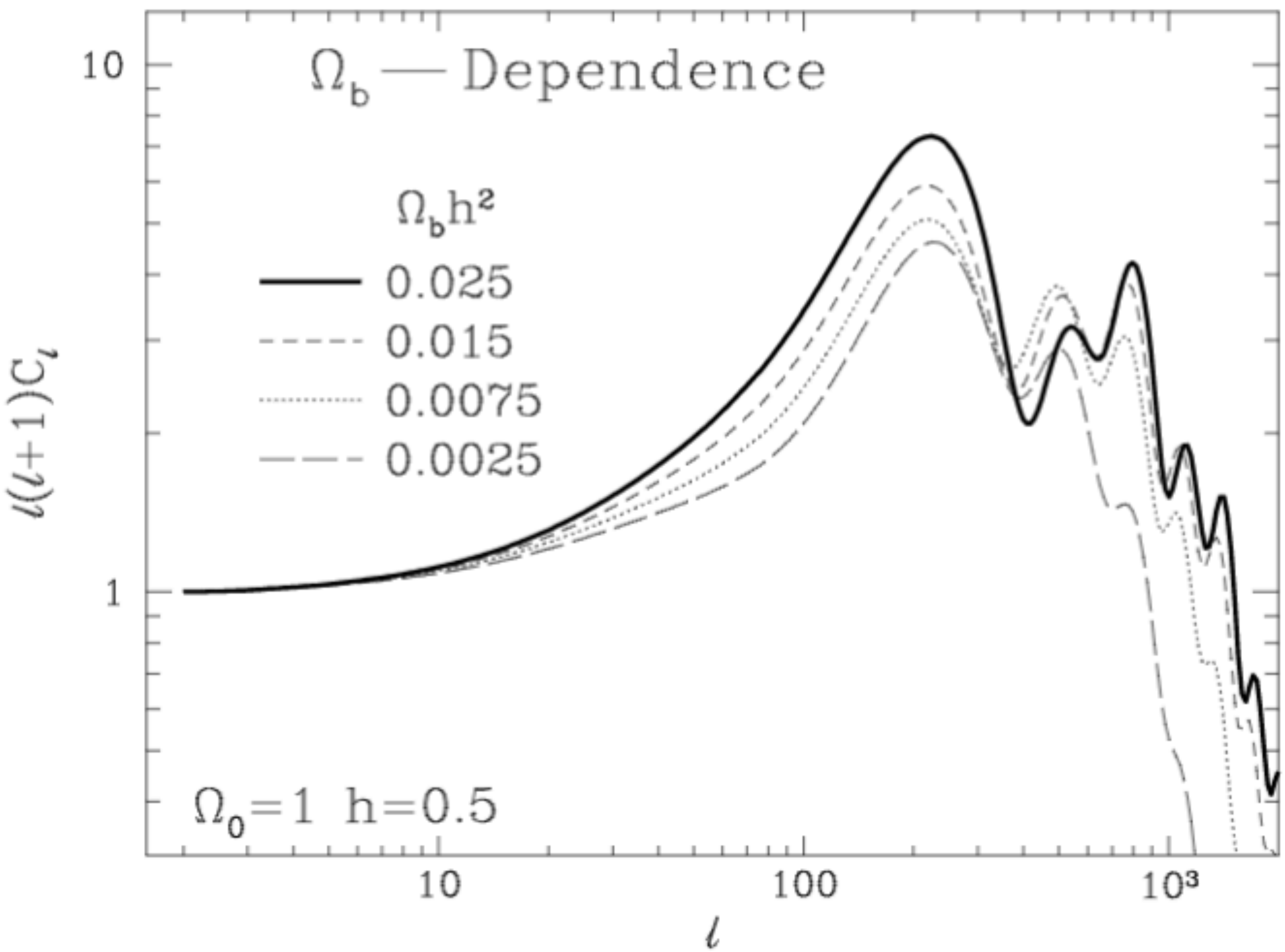
$$T_0 = 2.725\text{K}$$

$$\frac{dT}{T} \sim O(10^{-5})$$



Dependence with baryon fraction

compression peaks enhanced! (DM+baryons together)

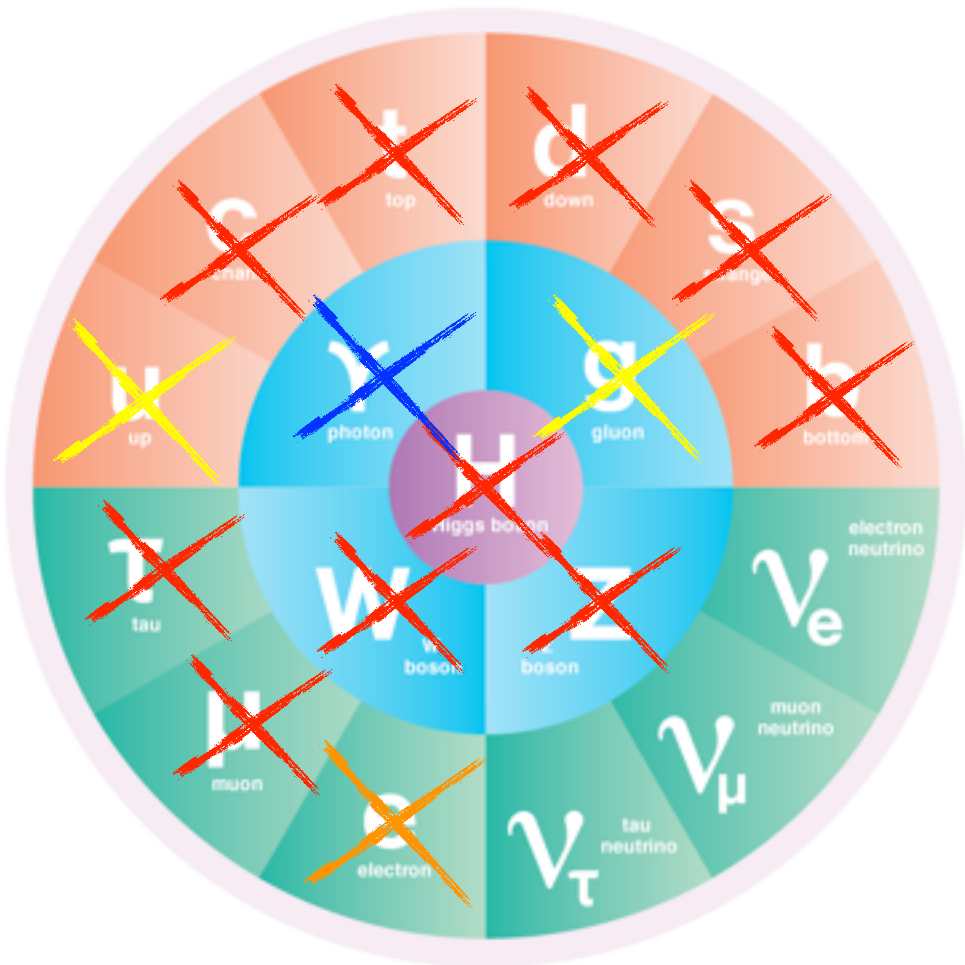


	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10}A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

Table 5. Best-fit values and 68% confidence limits for the base ΛCDM model. Beam and calibration parameters, and additional nuisance parameters for "highL" data sets are not listed for brevity but may be found in the Explanatory Supplement (Planck Collaboration ES 2013).

Finding the right DM particle

- Weakly interacting with itself (Bullet, CMB)
- Present in galaxies-clusters, dominates matter in the Universe
- Non baryonic
- what can it be?



- Unstable
- Baryonic
- Interacts quite a bit with light
- Massless

neutrinos?? are too light

Neutrino free-streaming

- Neutrinos produced thermally Early Universe, decouple at T~ MeV
- After, they freely propagate ... in all directions (not a perfect fluid!)
- what distance they travelled at CMB release? z~1100?

- comoving distance travelled

$$\lambda_{\mathrm{FS}} = \int_0^{\mathrm{CMB}} \frac{dt}{R(t)} v = \int_{z_{\mathrm{CMB}}}^{\infty} \frac{dz}{H} v$$

velocity is $v = \dfrac{p}{E} = \dfrac{p}{\sqrt{m^2+p^2}}$

momentum redshifts! $xT_0(1+z)$

neutrinos become non-relativistic $v \sim 1 \rightarrow v \sim xT_0(1+z)/m$ at $z_{nr} \sim m/xT_0$

$$\lambda_{\mathrm{FS}} \sim \frac{1}{H_0\sqrt{\Omega_\gamma^0}} \left[\int \frac{dz}{(1+z)^2} v\right] \sim \frac{1}{H_0\sqrt{\Omega_\gamma^0}} \left(\frac{1}{1+z_{nr}} + \frac{xT_0}{m} \log(z_{nr}/z_{cmb})\right) \sim \frac{1}{H_0\sqrt{\Omega_\gamma^0}} \frac{xT_0}{m}$$

$$\boxed{\lambda_{\mathrm{FS}} \sim 100\,\mathrm{Mpc} \left(\frac{1\,\mathrm{eV}}{m_\nu}\right) \times x}$$

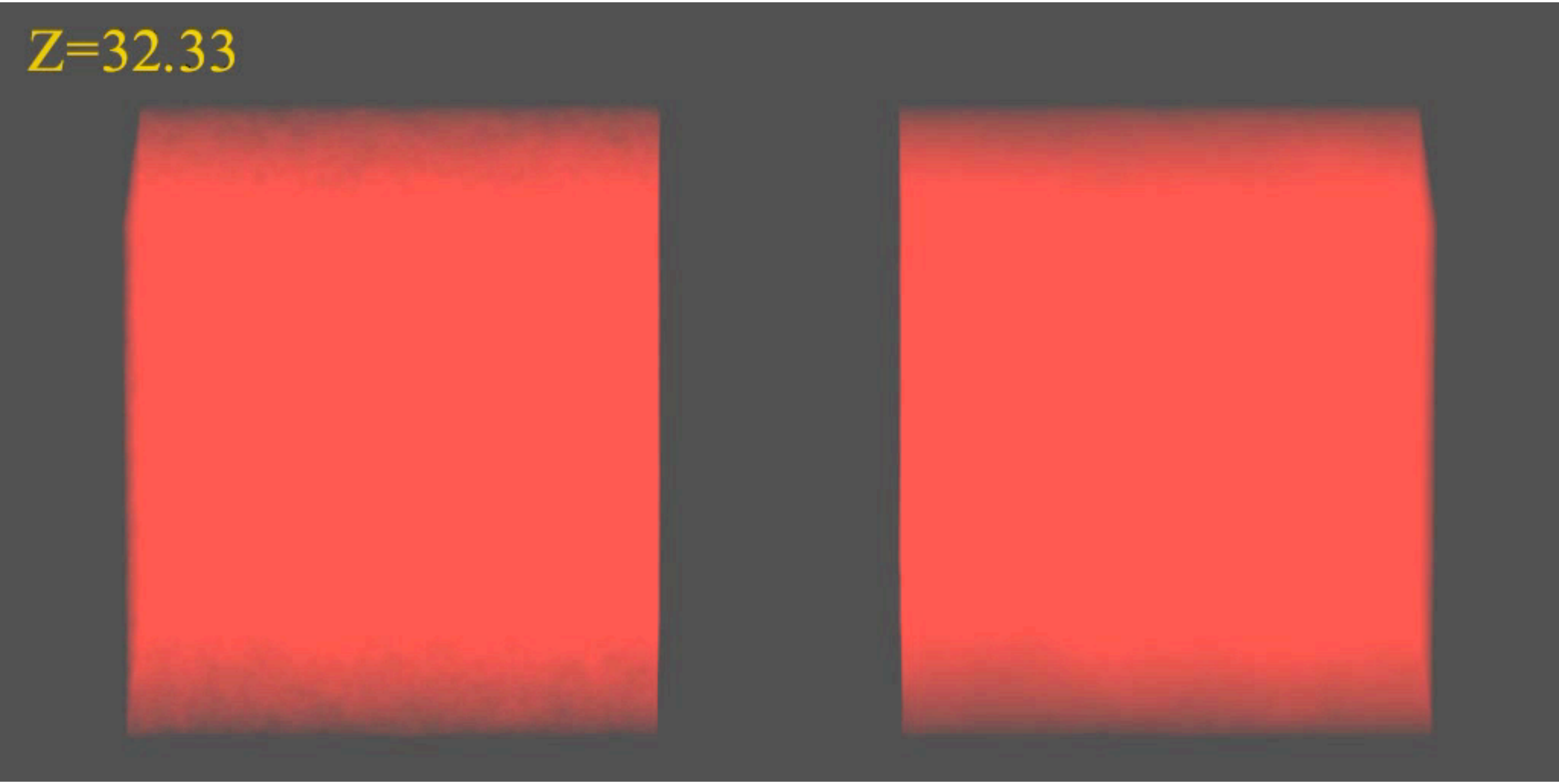
that is huge!!! Neutrinos cannot be ALL the dark matter...
<u>would free stream and erase density fluctuations</u> below ~100 Mpc/m!

- This formula is valid only down to m~0.26 eV (question ... why???)
- Luckily the neutrino <u>DM abundance is subdominant</u> in this regime $\Omega_{\nu,m} \simeq \dfrac{\sum m_\nu}{46\,\mathrm{eV}}$

(S. Pascoli lectures)

hot dark matter

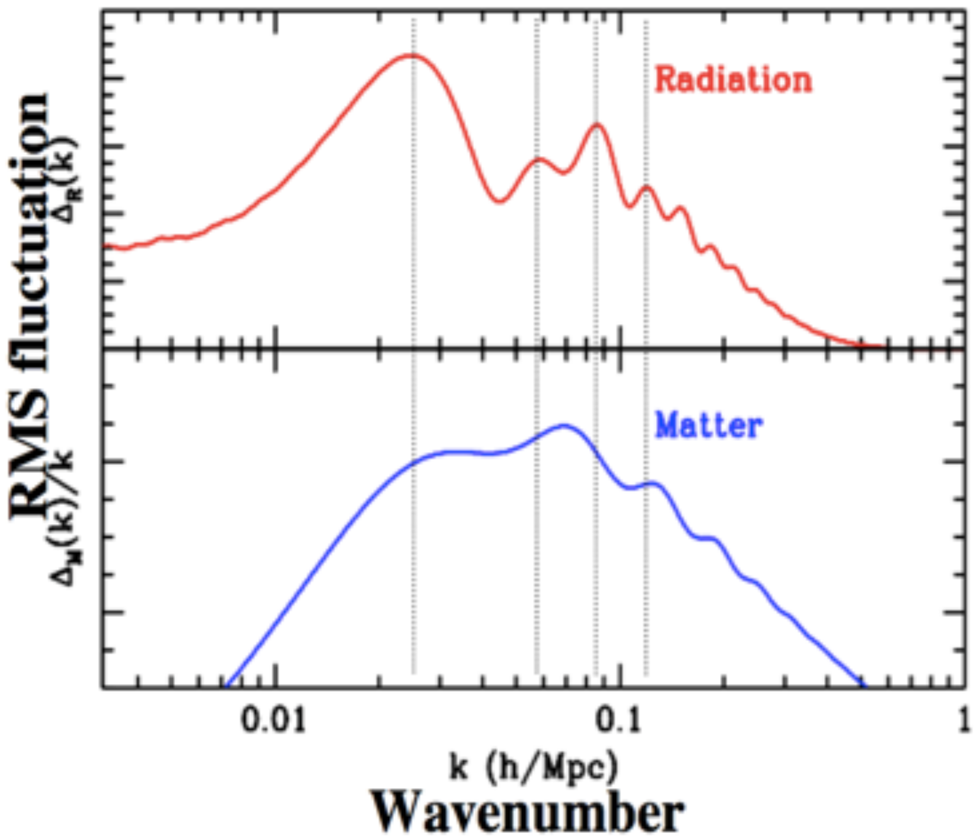
CDM nuDM $m_\nu \sim 7\text{eV}$



- nu's cannot be so abundant ... (tomorrow) but also are too fast (hot)!

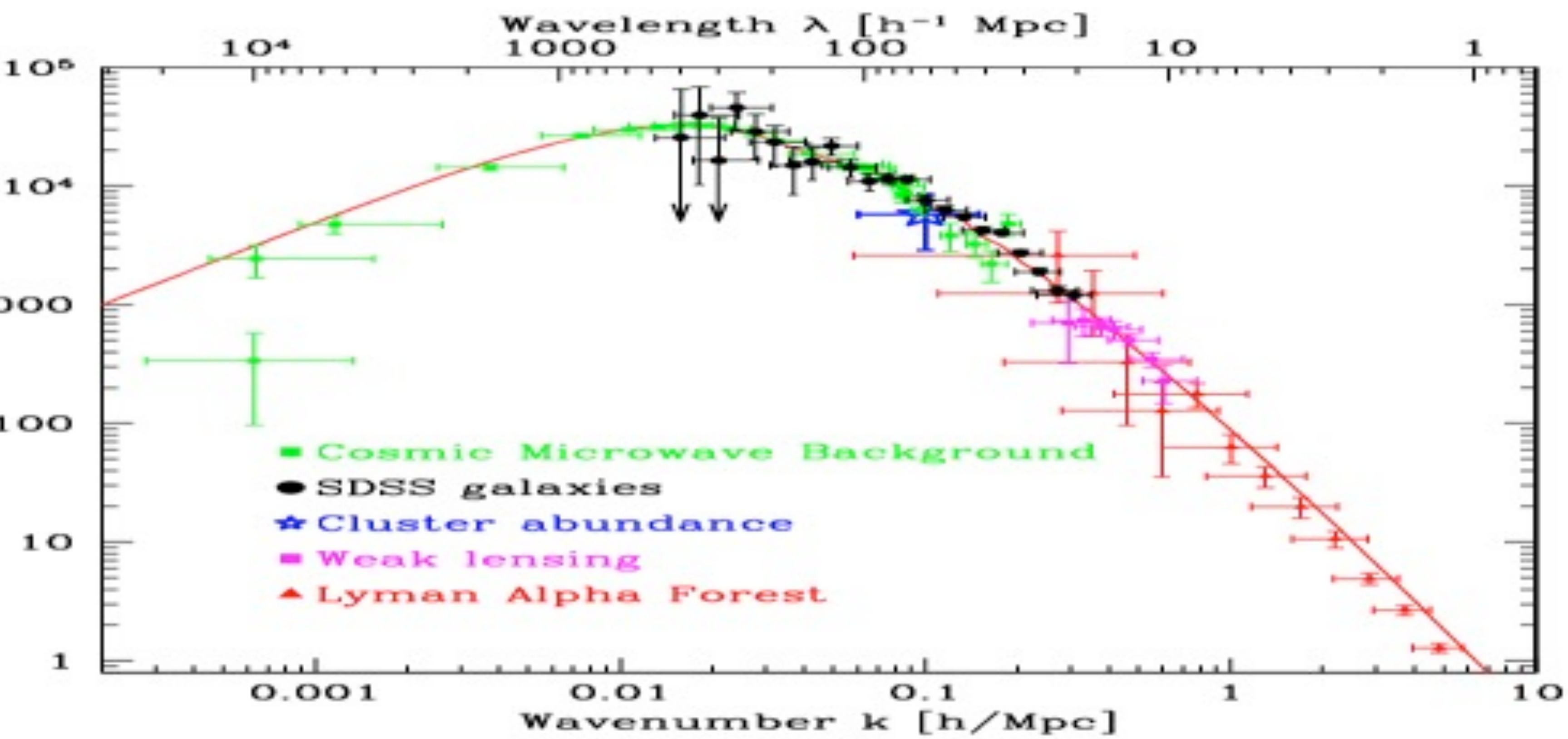
Matter power spectrum

Just as we make statistics of temperature fluctuations we can also do of density fluctuations



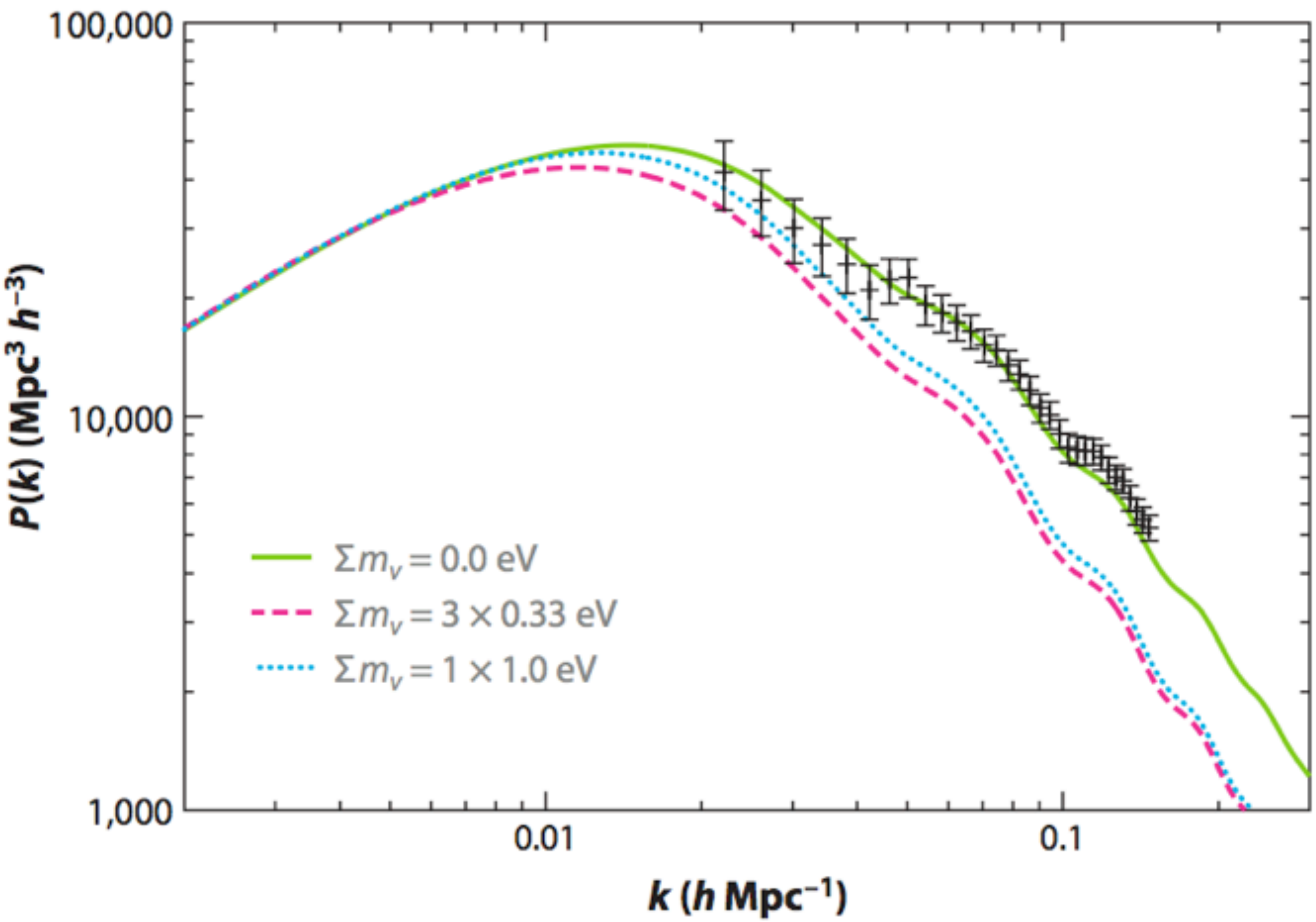
fluctuations in the CMB temperature

fluctuations in the density of galaxies



Matter Power spectrum with neutrino DM

Neutrino free streams out of small scale perturbations smoothing the fluctuations



Wong 2011

Dark matter must be COLD

- The dominant component of the Dark matter must be cold
- The free-streaming length must be kept below a fraction of a Mpc

$$\boxed{\lambda_{\rm FS} \sim 0.1\,{\rm Mpc}\left(\frac{1\,{\rm keV}}{m_{\rm CDM}}\right) \times x}$$

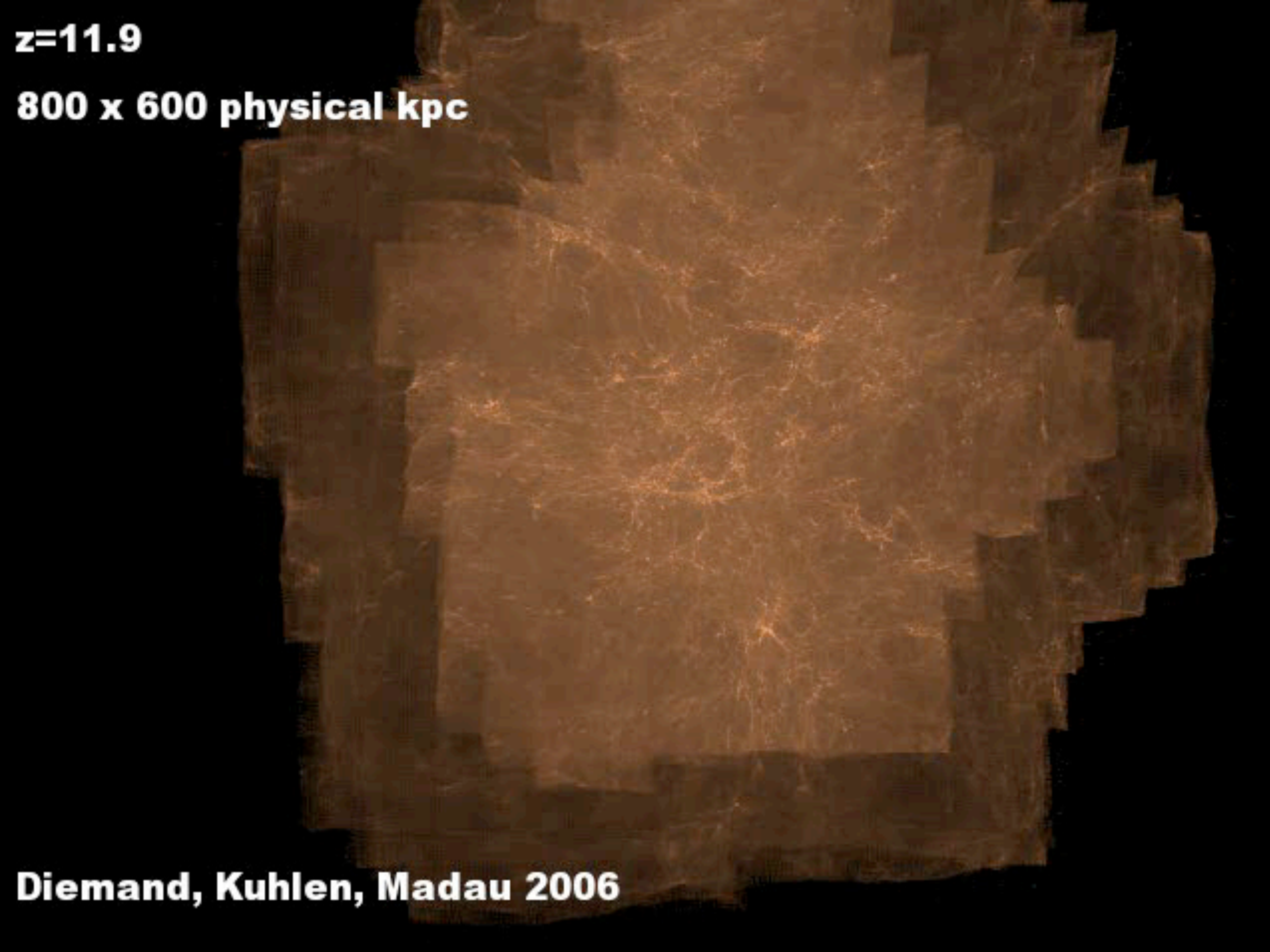
(DM particles that reached 0.1 Mpc at CMB release have a velocity $v \sim O(10^{-3})c$)

- Thermal relics (created with p~T) must have large mass

(Examples are WIMPs, ~sterile neutrinos, etc...)

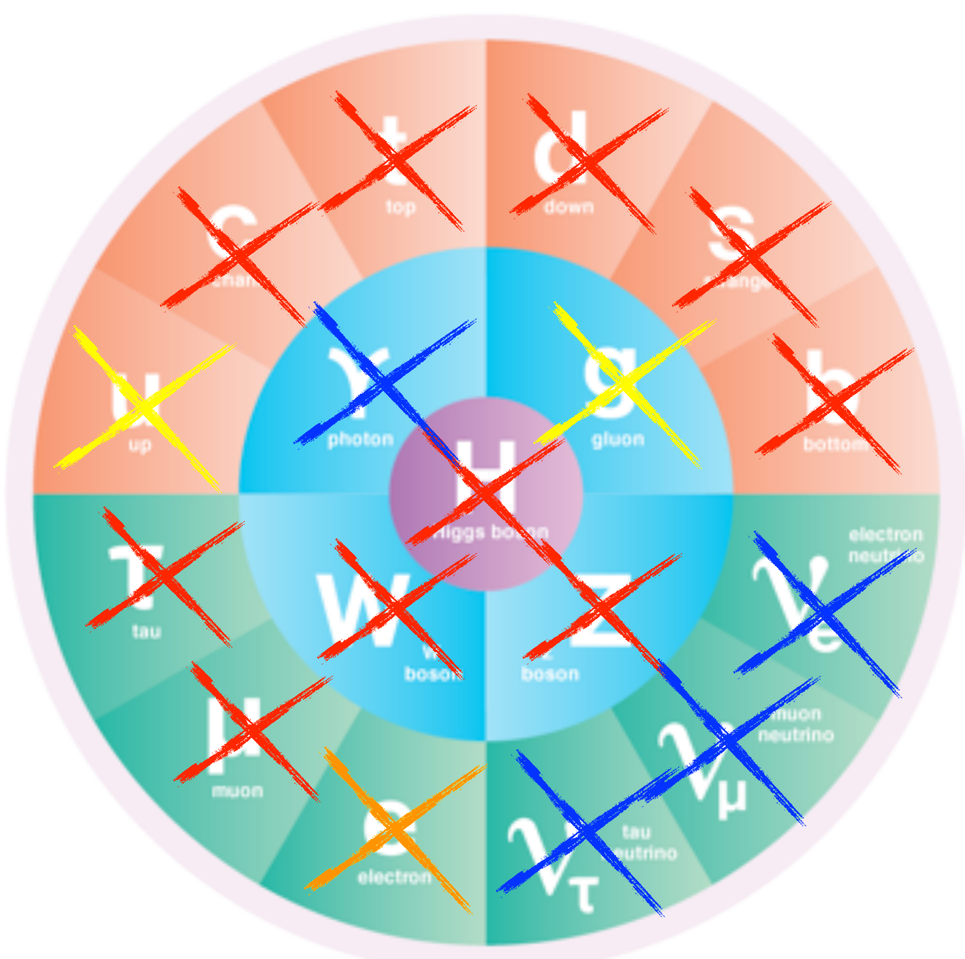
- Low mass DM candidates (m<keV) must be produced NON-THERMALLY

(Examples are axions, axion-light particles, hidden photons)


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

Finding the right DM particle ...

- Weakly interacting with itself (Bullet, CMB)
- Present galaxies-clusters-universe
- Non baryonic
- what can it be?



- Unstable
- Baryonic
- Interacts quite a bit with light
- too hot (relativistic)

need something beyond the SM