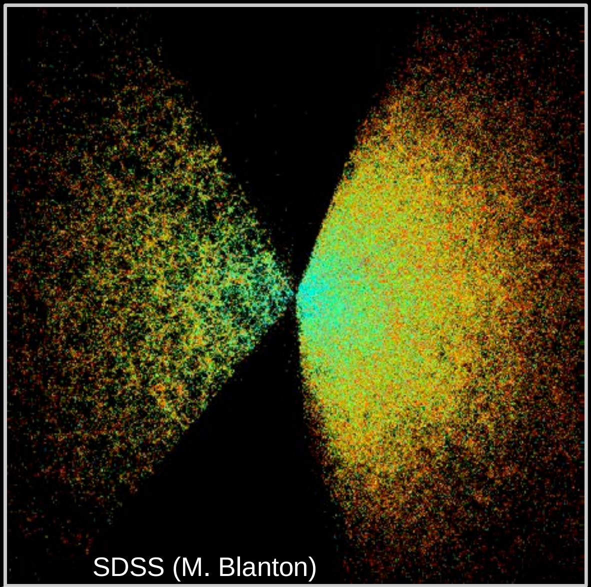
# Introduction to Dark Matter

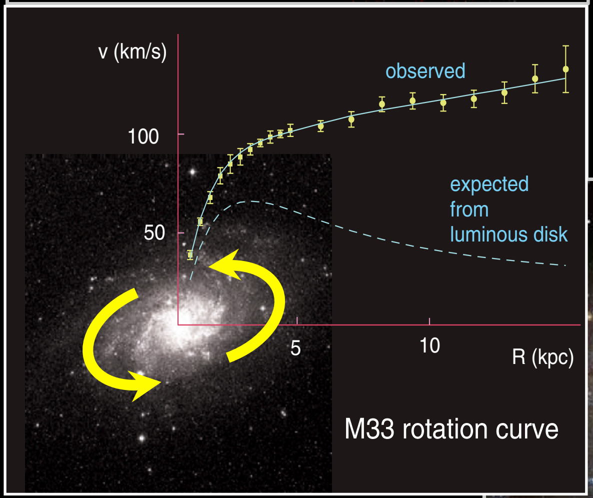
*Paolo Gondolo*

*University of Utah*

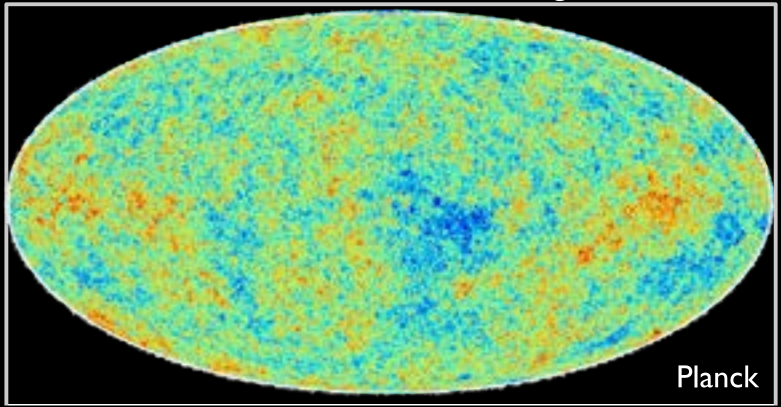
# Evidence for cold dark matter

Large Scale Structure



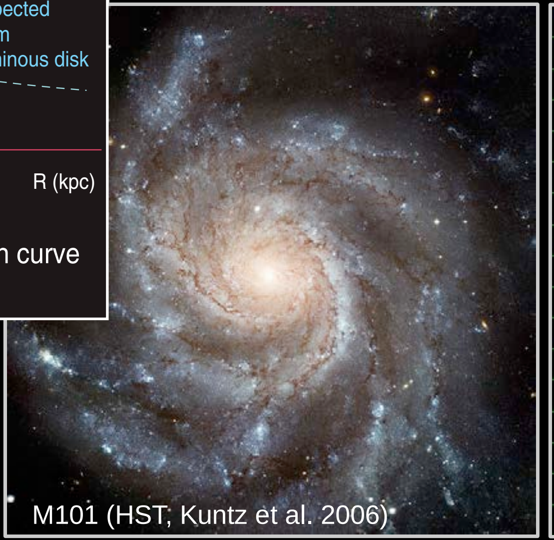




Cosmic Microwave Background

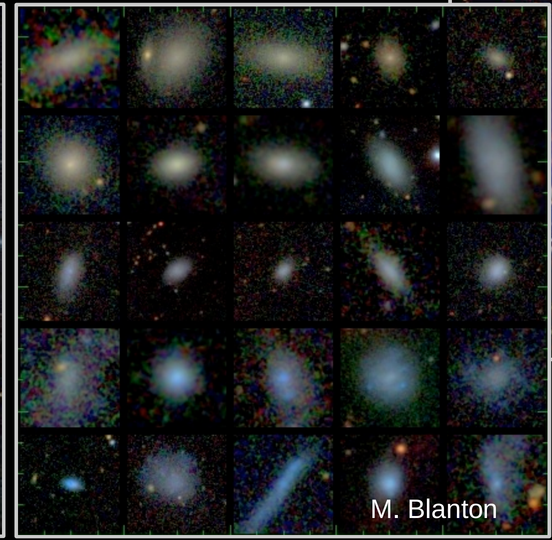



Supernovae

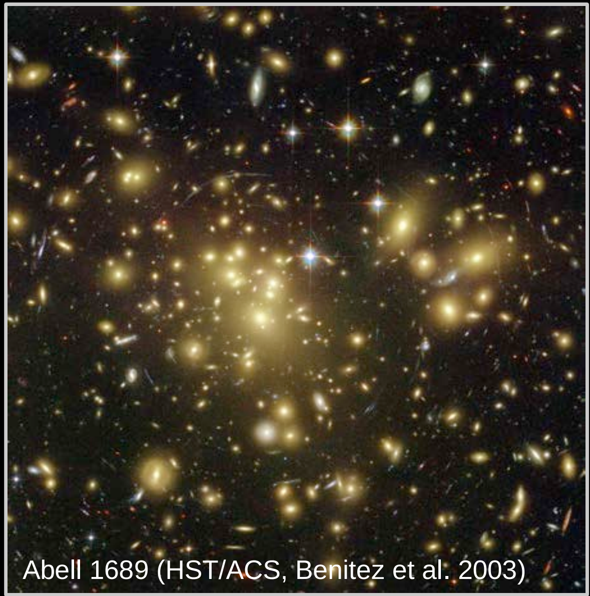

Galaxies

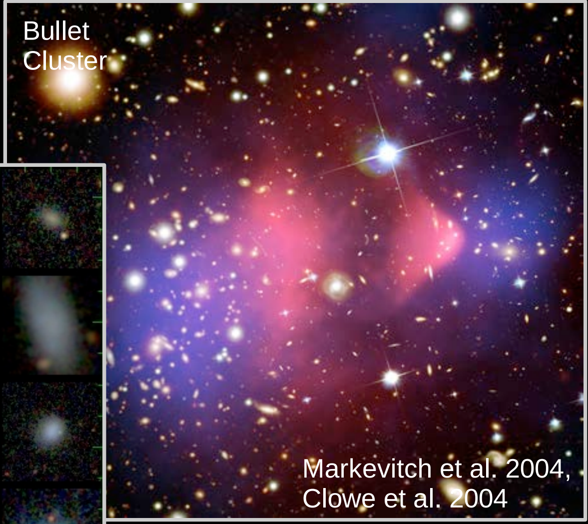



Dwarf Galaxies



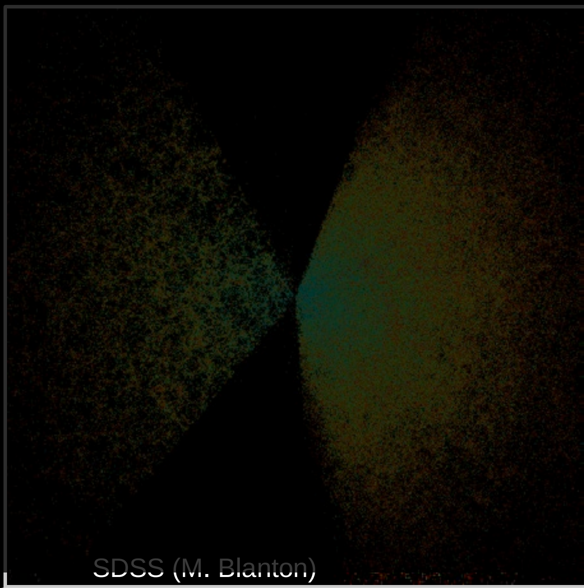

Galaxy Clusters



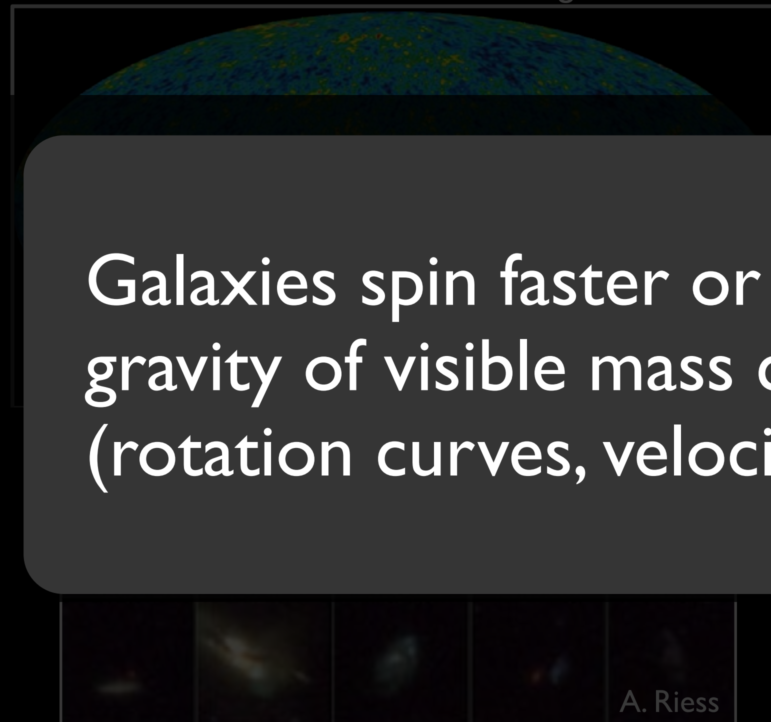



# Galaxies

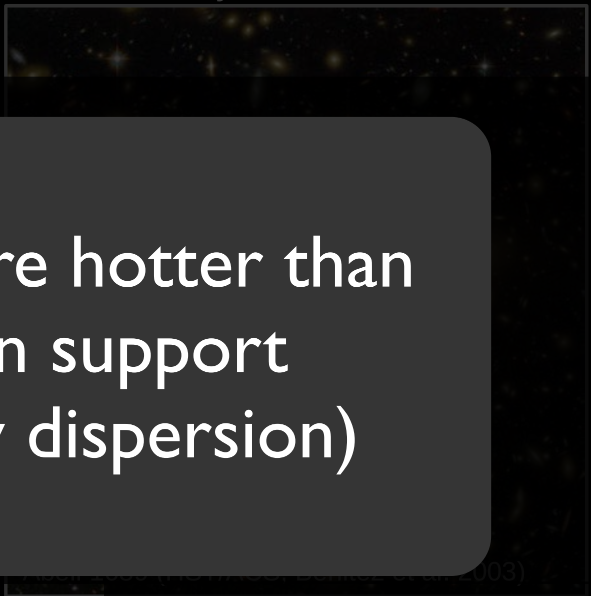
Large Scale Structure

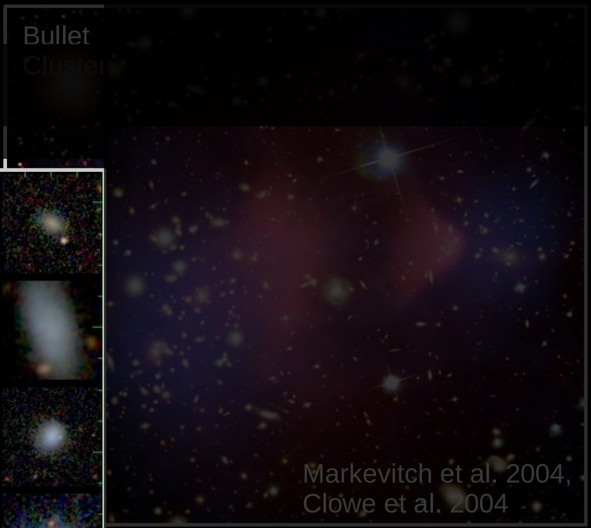



Cosmic Microwave Background

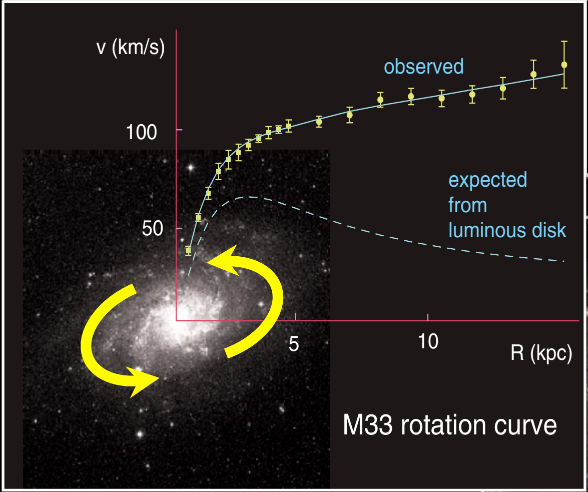



Galaxy Clusters



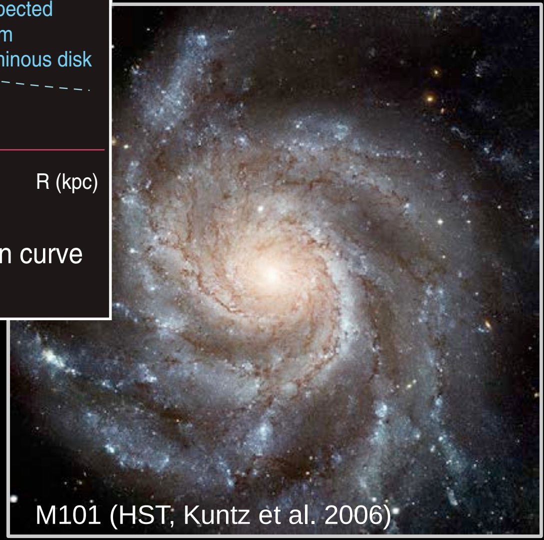



Galaxies spin faster or are hotter than gravity of visible mass can support (rotation curves, velocity dispersion)



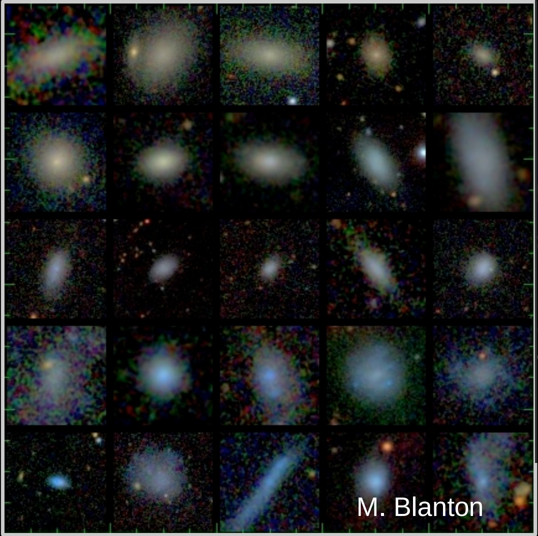

M33 rotation curve

Galaxies



M101 (HST; Kuntz et al. 2006)

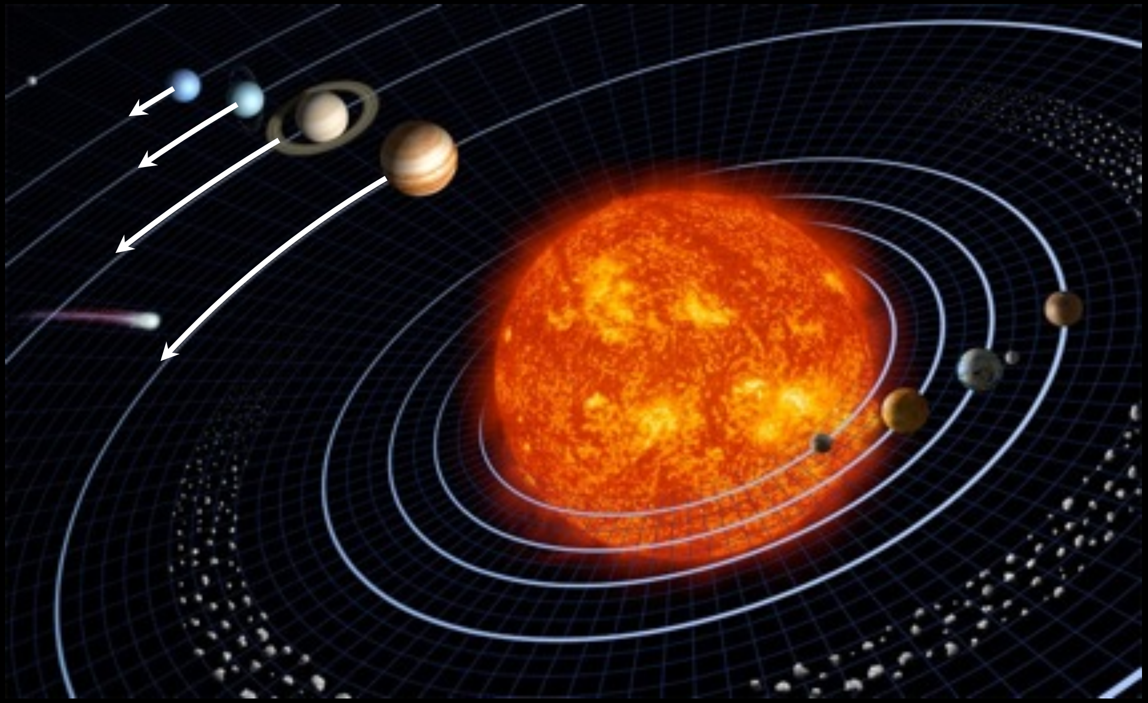
Dwarf Galaxies



M. Blanton

# Galaxies

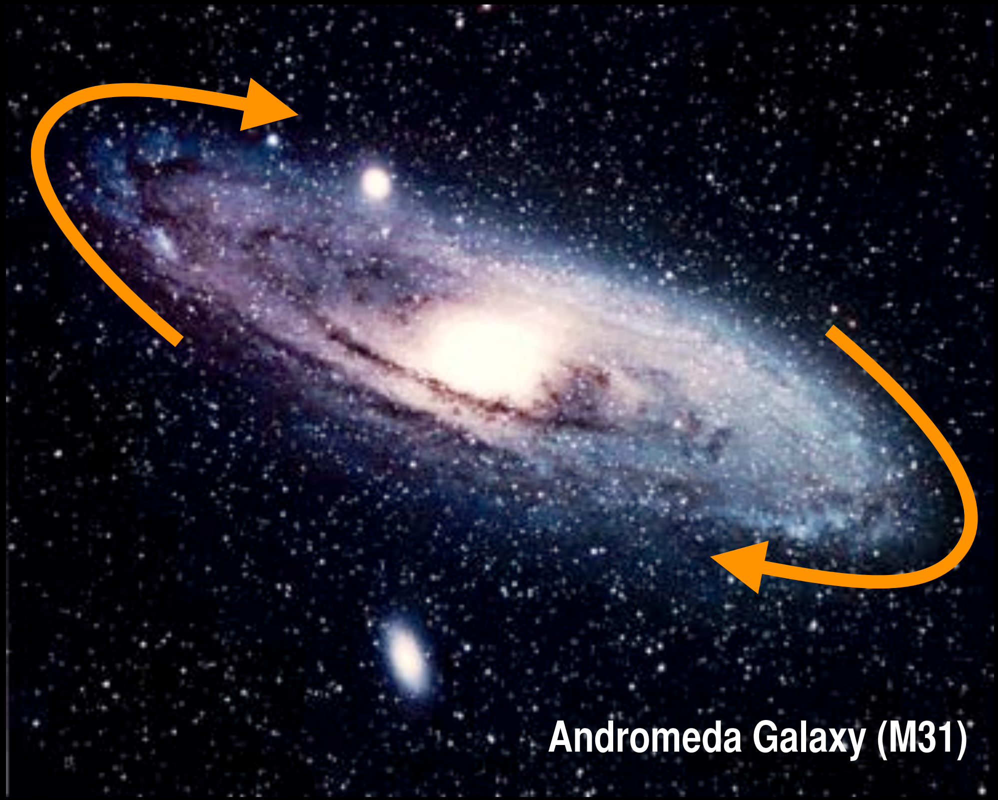
## The method: more mass, faster orbits



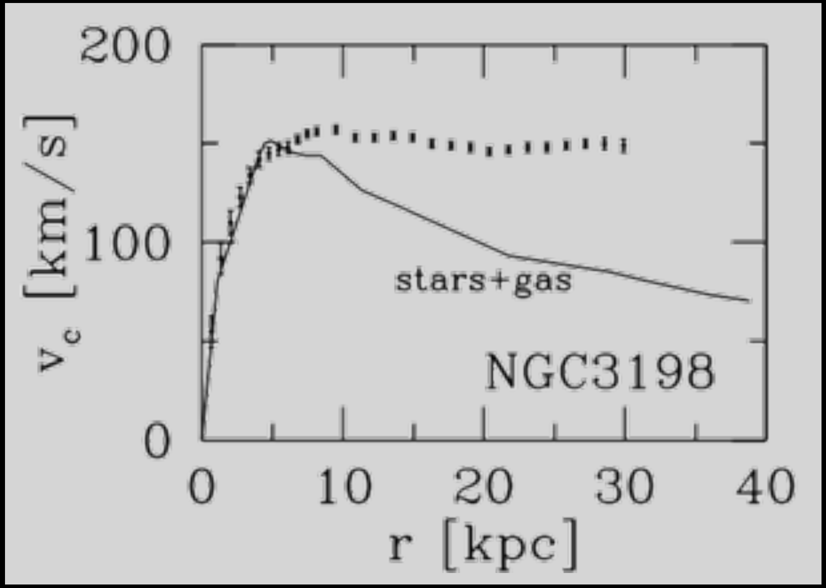
*Gravity of sun keeps planets in orbit*

$$\frac{GM}{r^2} = \frac{v^2}{r}$$

# Galaxies

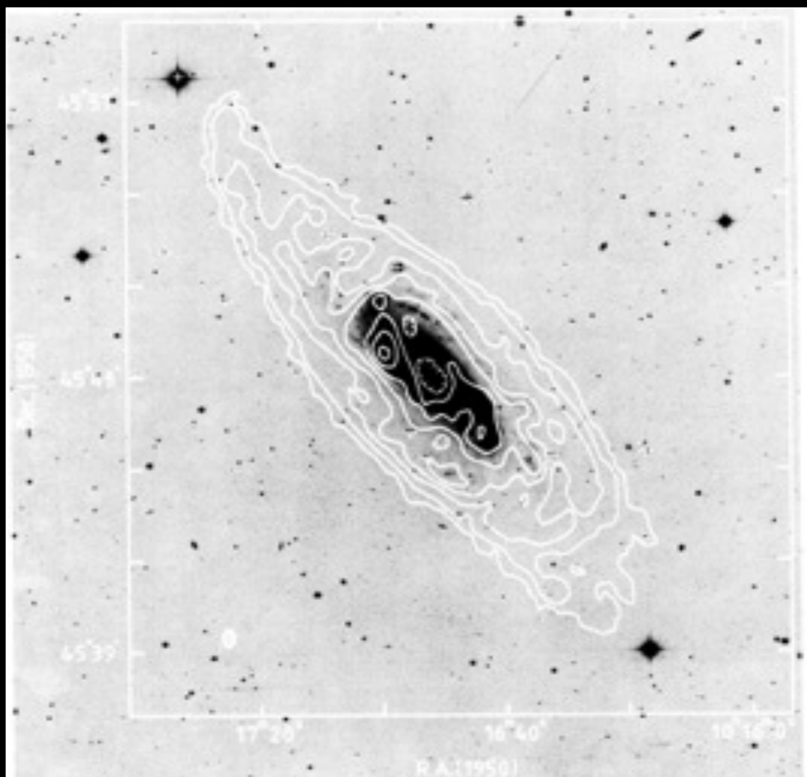

Andromeda Galaxy (M31)

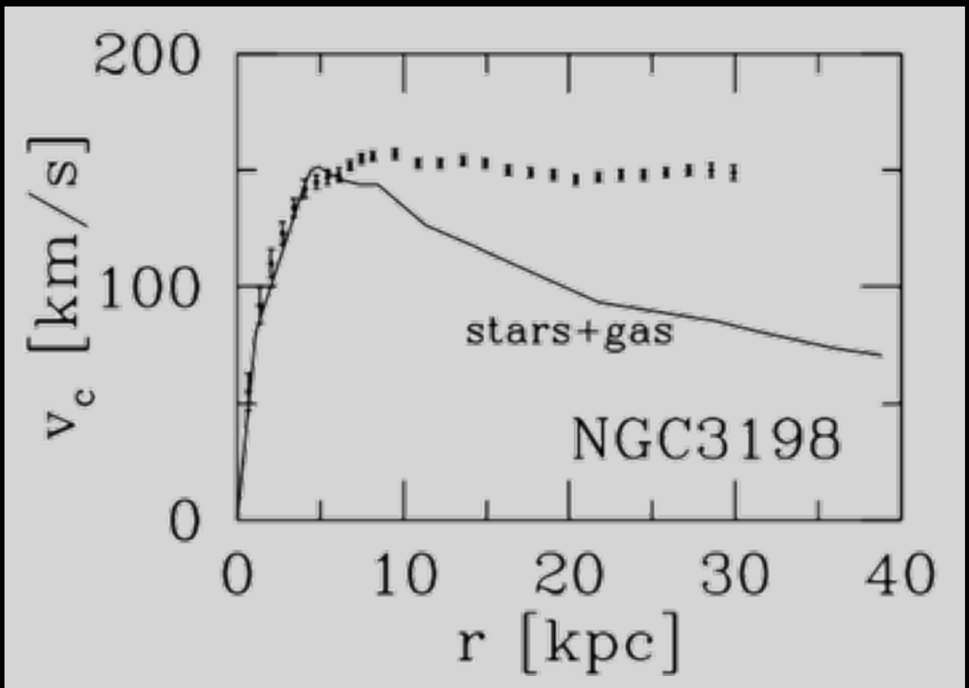

Vera Rubin


200
100
0
$v_c$ [km/s]
stars+gas
NGC3198
0
10
20
30
40
r [kpc]

# Galaxies

Galaxies spin faster than gravity of known matter can support






$$M = 1.6 \times 10^{11} M_{\odot} (r/30\,\text{kpc})$$
$$M_{\text{stars+gas}} = 0.4 \times 10^{11} M_{\odot}$$

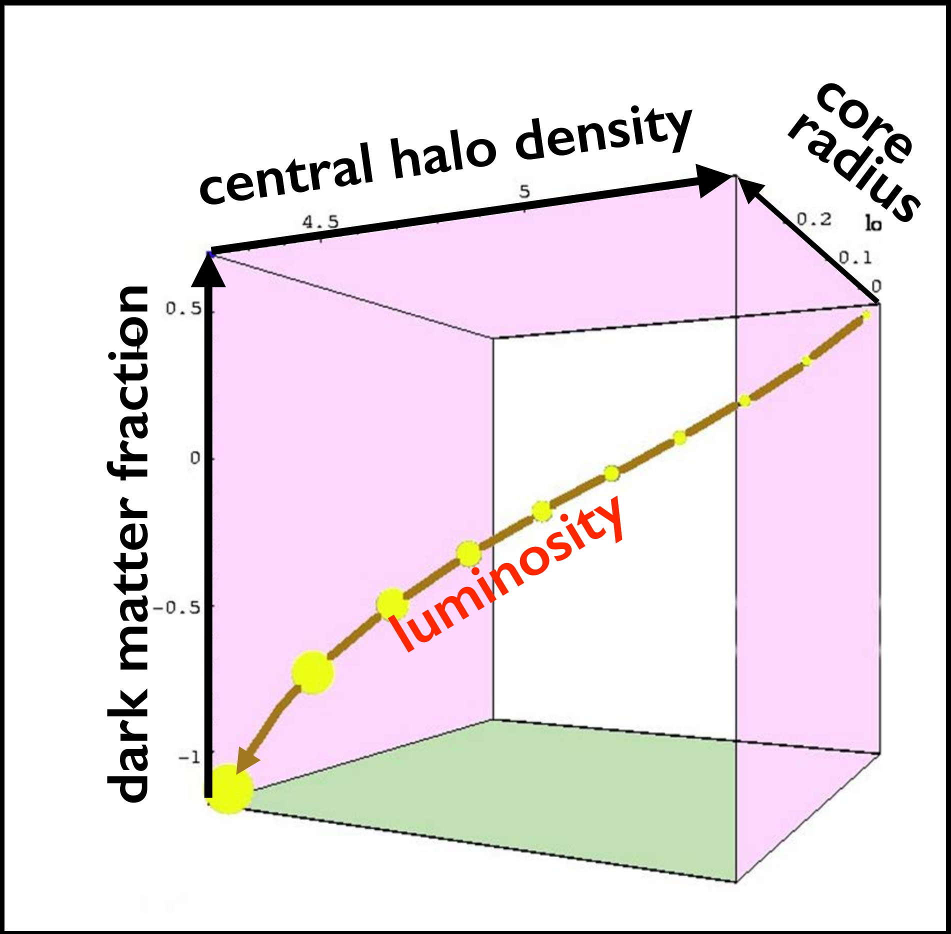
$$\frac{M_{\text{total}}}{M_{\text{visible}}} > 4$$

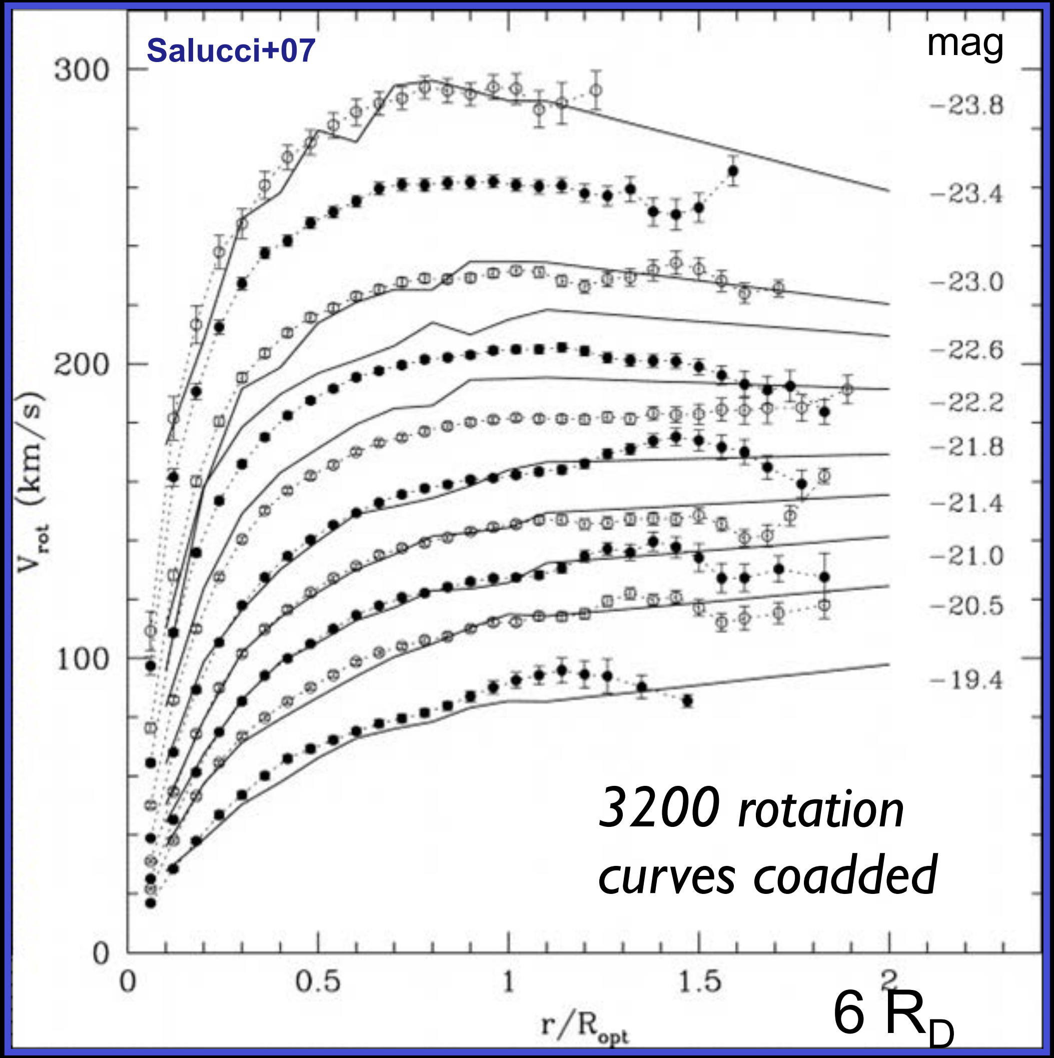
**Dark matter**

1 pc = $3.08 \times 10^{16}$ m

# Galaxies

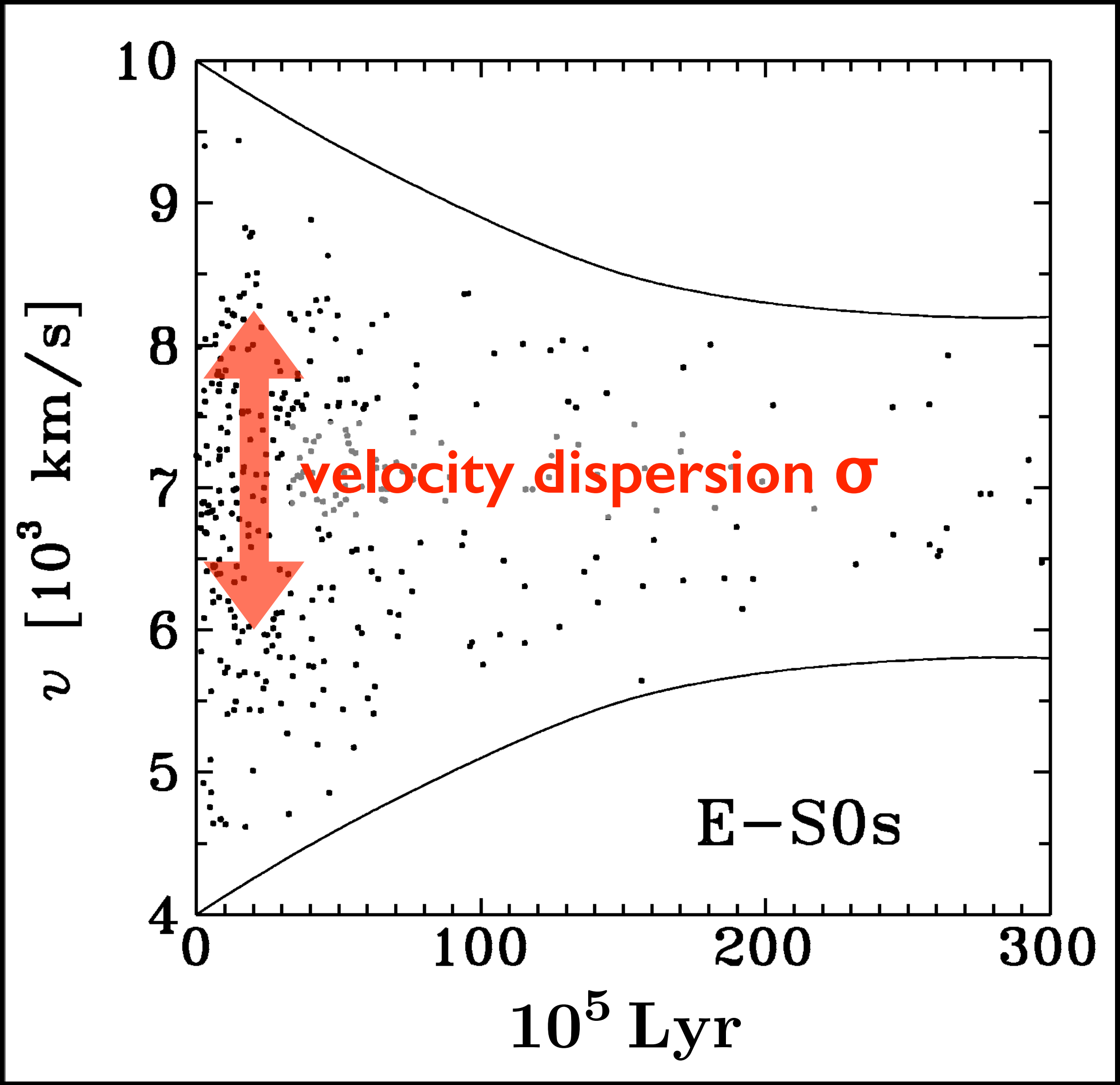
Empirical correlations found from thousands of spiral galaxy rotation curves




*Salucci et al 2007*

# Galaxies




*Lokas, Mamon 2003*

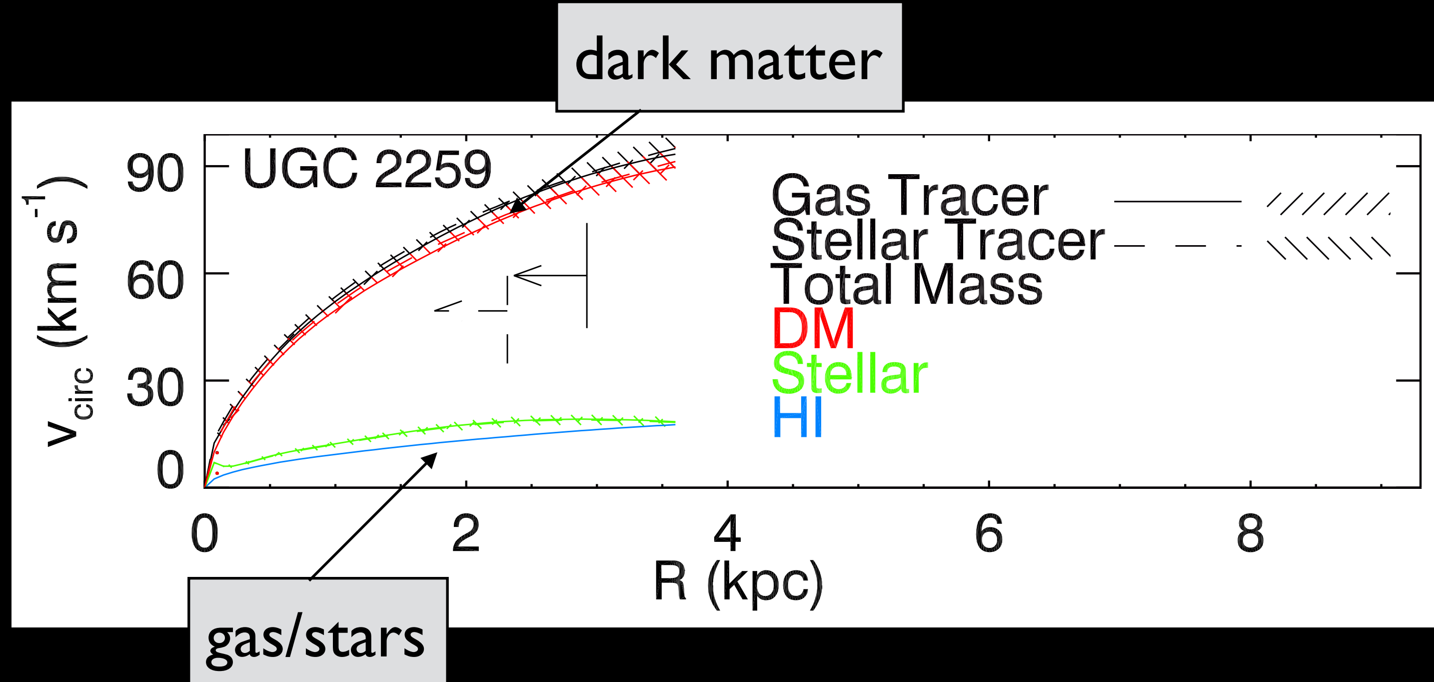
Velocity dispersion measurements reveal dark matter in elliptical galaxies

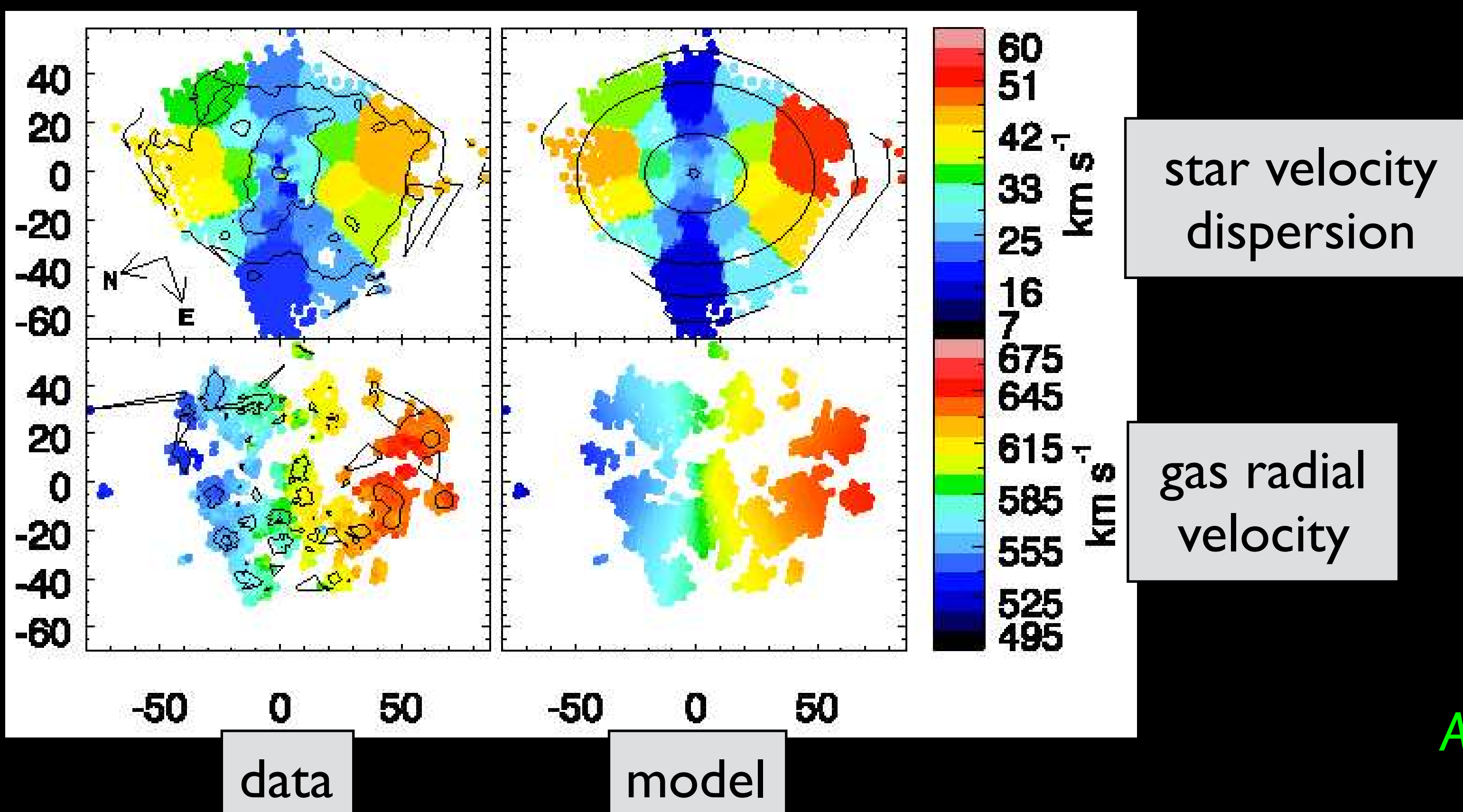
$$\sigma^2 \propto \frac{GM}{r}$$

$$M_{\rm dyn} \sim 10^{15}\, M_\odot$$

# Galaxies

Dwarf galaxies are dominated by dark matter.




*Adams et al 2014*

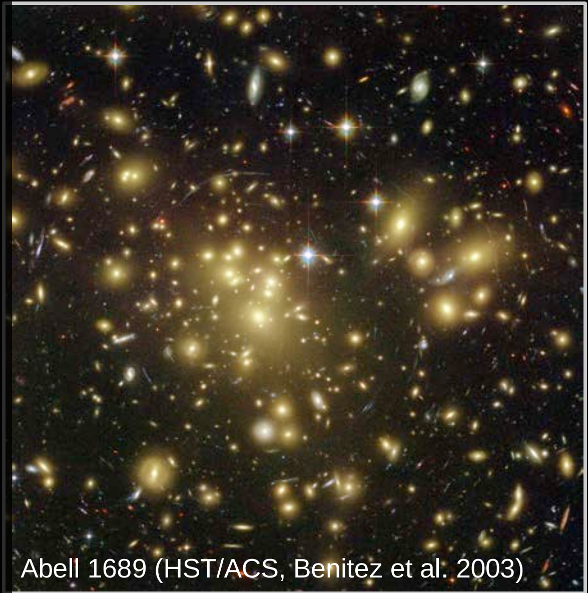
# Galaxy clusters

Large Scale Structure

Cosmic Microwave Background

Galaxy Clusters

Galaxy clusters are mostly invisible mass (motion of galaxies, gas density and temperature, gravitational lensing)

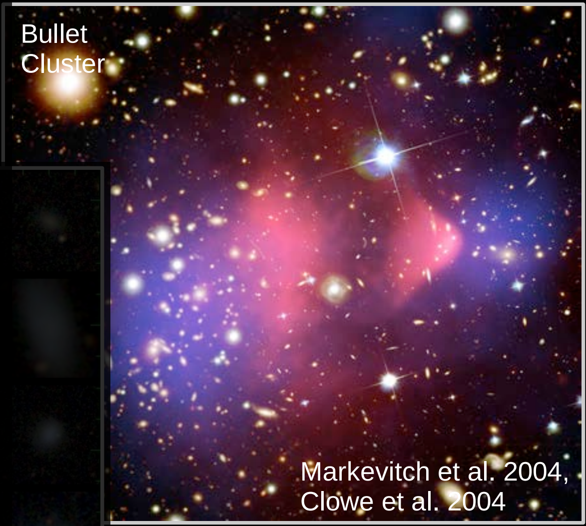


Abell 1689 (HST/ACS, Benitez et al. 2003)

SDSS (M. Blanton)

A. Riess

Dwarf Galaxies



Bullet Cluster

Markevitch et al. 2004, Clowe et al. 2004

Fritz Zwicky

M33 rotation curve

M101 (HST, Kuntz et al. 2006)

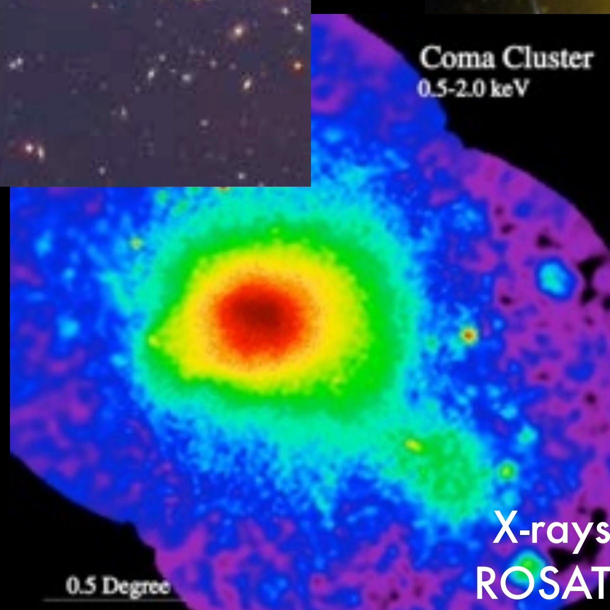
M. Blanton

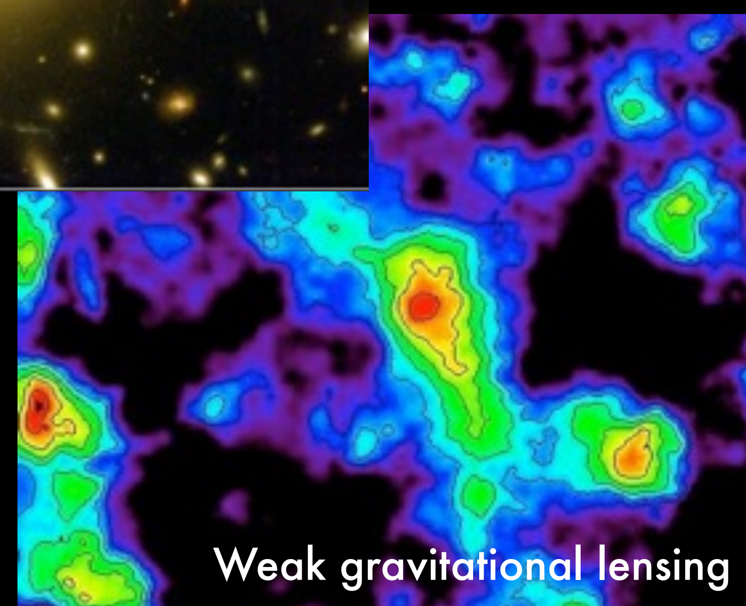
# Galaxy clusters

Different methods lead to the same conclusion: dark matter



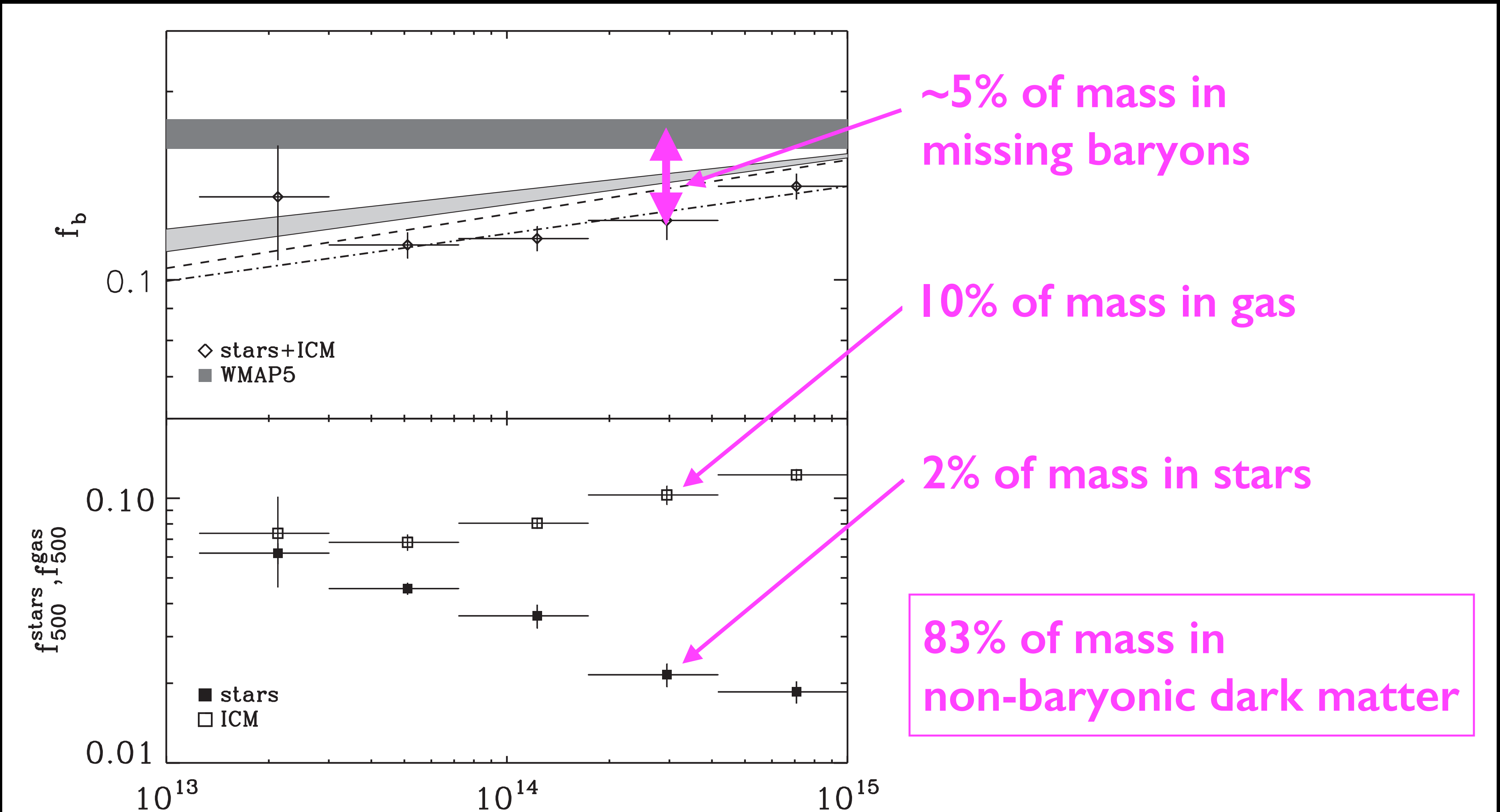
$$\frac{M_{\text{total}}}{M_{\text{visible}}} \approx 6$$



# Galaxy clusters

*Galaxy clusters are mostly dark matter with some gas and a sprinkle of galaxies*




Giodini et al 2009

# Cold dark matter, *not* modified gravity

## The Bullet Cluster

*Symmetry argument: gas is at center, but potential has two wells.*

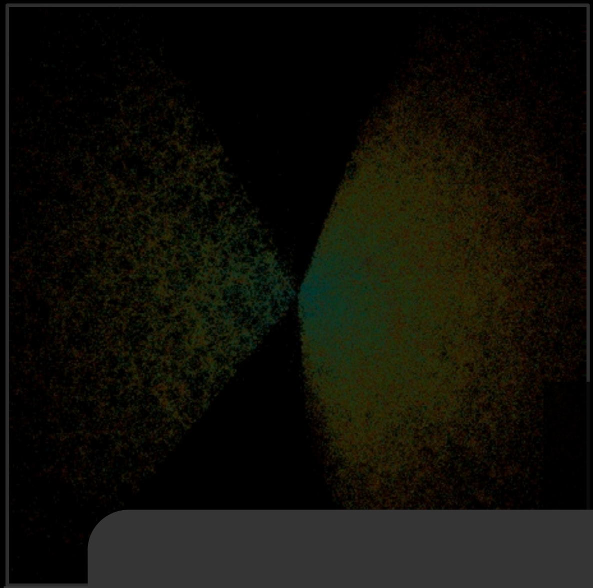
Galaxies in optical (Hubble Space Telescope)

X-ray emitting hot gas (Chandra)

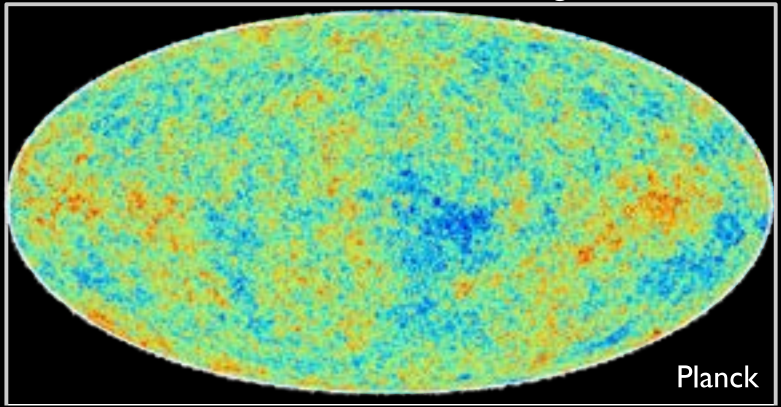
Gravitational potential from weak lensing

# Early universe

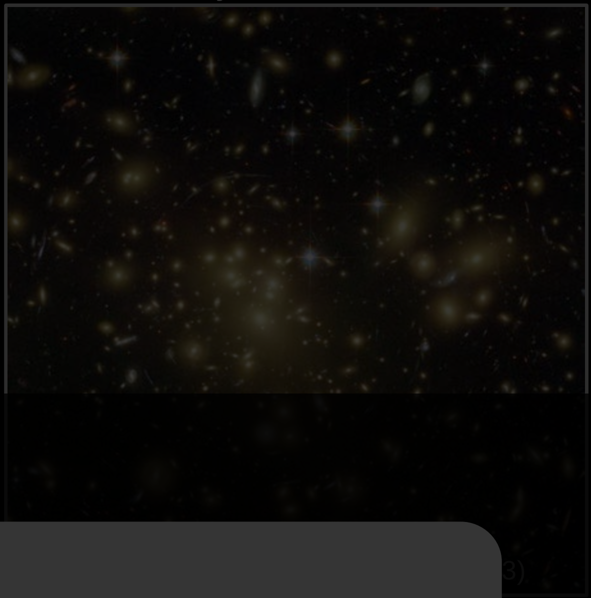
Large Scale Structure



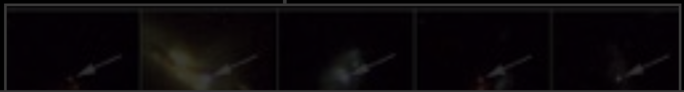
Cosmic Microwave Background



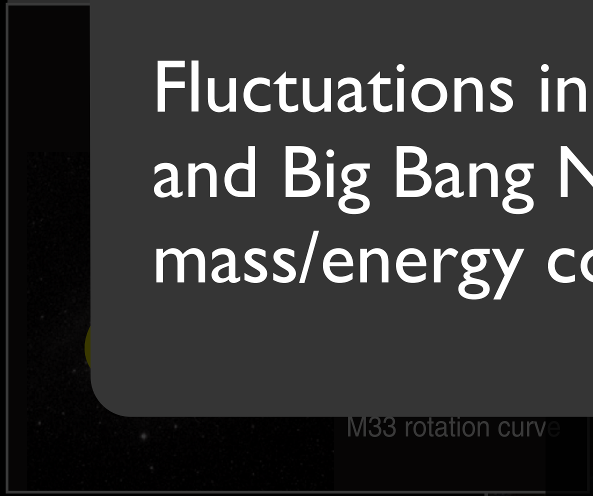

Galaxy Clusters



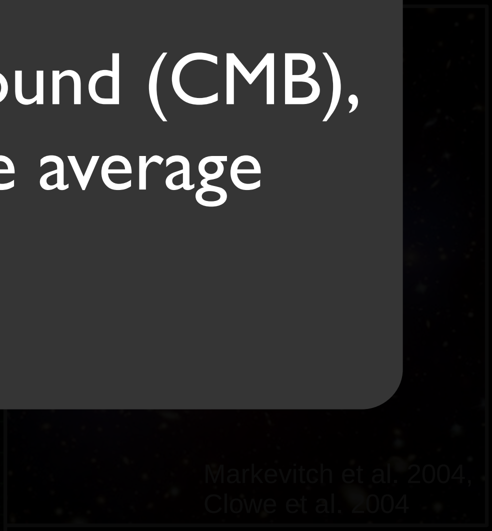
Supernovae



Fluctuations in the Cosmic Microwave Background (CMB), and Big Bang Nucleosynthesis (BBN) reveal the average mass/energy content of the universe.



M33 rotation curve



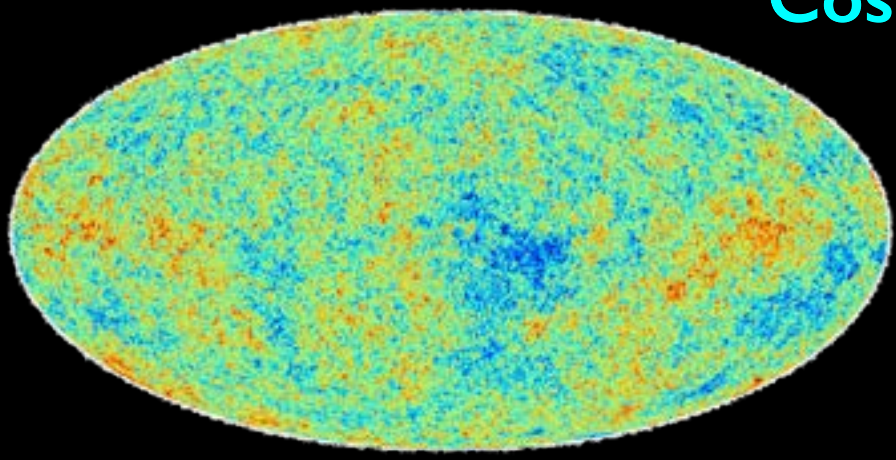
Markevitch et al. 2004,
Clowe et al. 2004

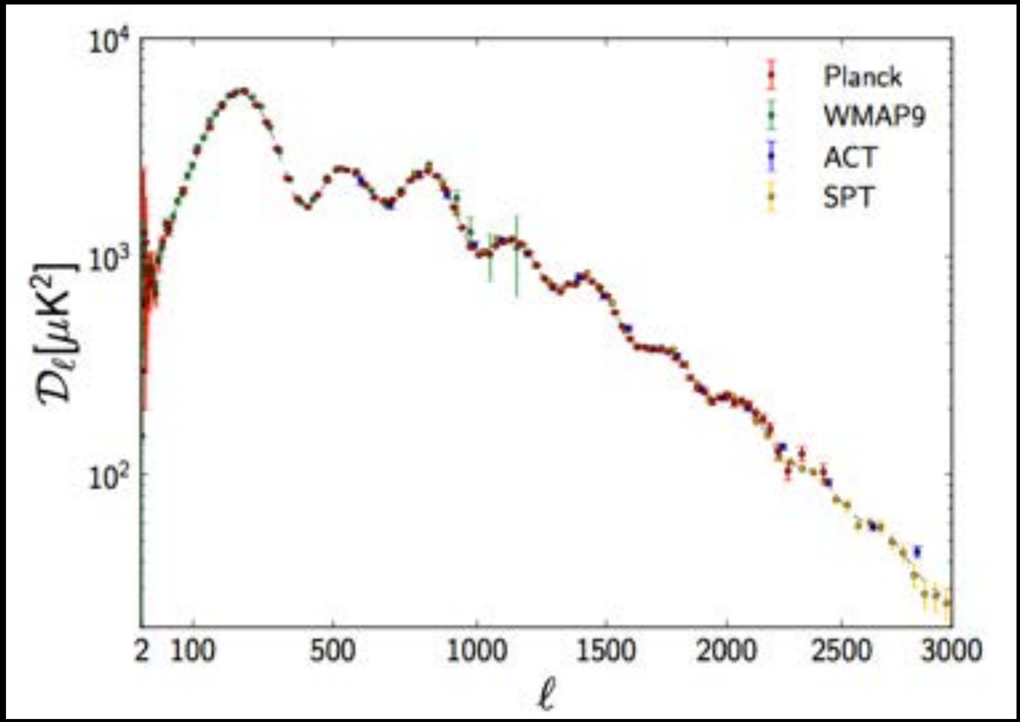
M101 (HST; Kuntz et al. 2006)

M. Blanton

# Early universe

## Cosmic Microwave Background fluctuations






| | *Planck*+WP+highL+BAO | |
|---|---|---|
| Parameter | Best fit | 68% limits |
| $\Omega_b h^2$ . . . . . . . . . . . | 0.022161 | $0.02214 \pm 0.00024$ |
| $\Omega_c h^2$ . . . . . . . . . . . | 0.11889 | $0.1187 \pm 0.0017$ |
| $100\theta_{MC}$ . . . . . . . . | 1.04148 | $1.04147 \pm 0.00056$ |
| $\tau$ . . . . . . . . . . . . | 0.0952 | $0.092 \pm 0.013$ |
| $n_s$ . . . . . . . . . . . . | 0.9611 | $0.9608 \pm 0.0054$ |
| $\ln(10^{10} A_s)$ . . . . . . . | 3.0973 | $3.091 \pm 0.025$ |
| $\Omega_\Lambda$ . . . . . . . . . . . . | 0.6914 | $0.692 \pm 0.010$ |
| $\sigma_8$ . . . . . . . . . . . . | 0.8288 | $0.826 \pm 0.012$ |
| $z_{re}$ . . . . . . . . . . . . | 11.52 | $11.3 \pm 1.1$ |
| $H_0$ . . . . . . . . . . . . | 67.77 | $67.80 \pm 0.77$ |
| Age/Gyr . . . . . . . . | 13.7965 | $13.798 \pm 0.037$ |
| $100\theta_*$ . . . . . . . . . . | 1.04163 | $1.04162 \pm 0.00056$ |
| $r_{drag}$ . . . . . . . . . . | 147.611 | $147.68 \pm 0.45$ |

*Planck* (2013)

linear perturbation theory

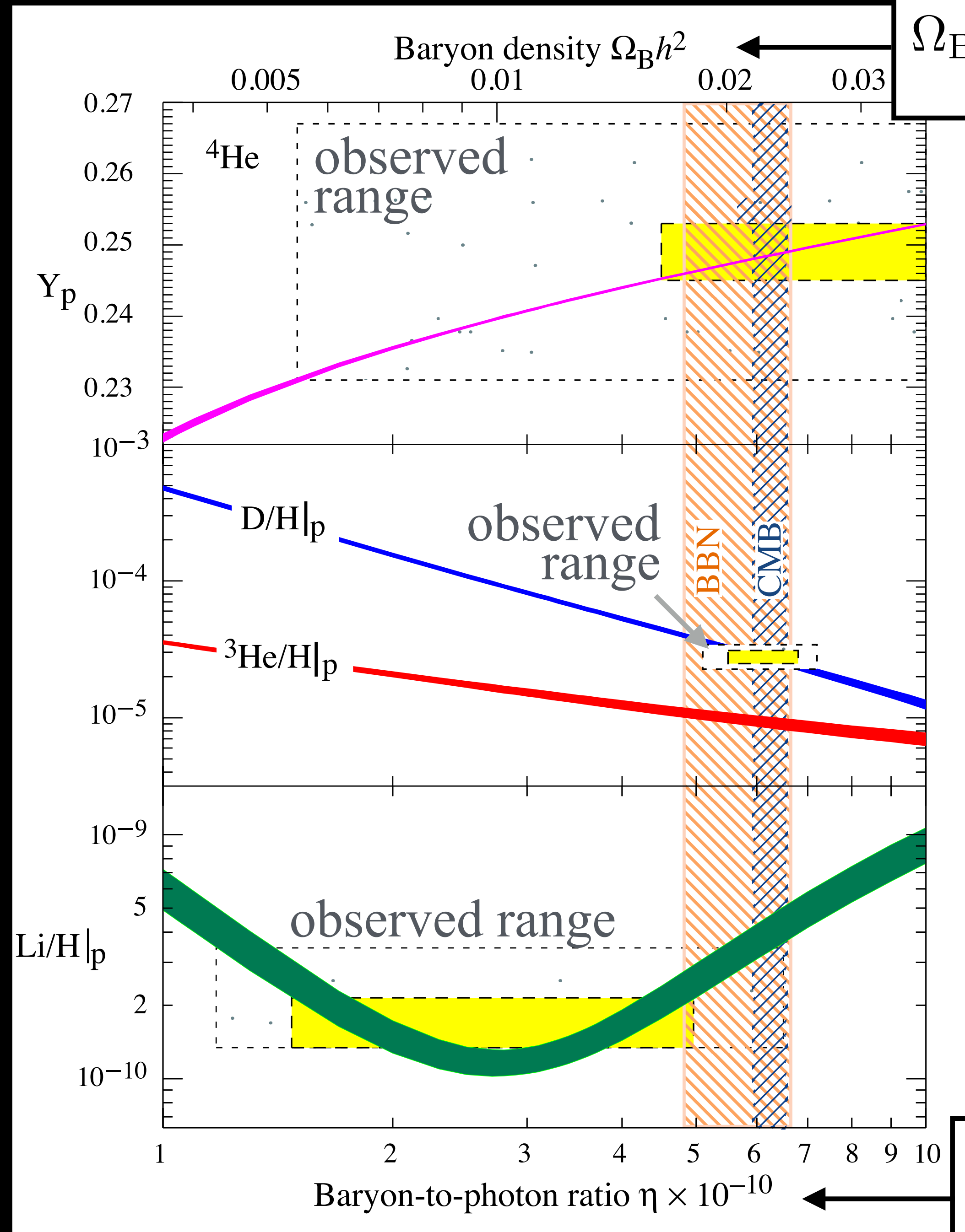
*general relativity and statistical mechanics at $10^4$ K ~ 1 eV/k*

# Early universe

## Big Bang Nucleosynthesis

*Nuclei formation rates depend on the density of baryons (strictly speaking, neutrons)*

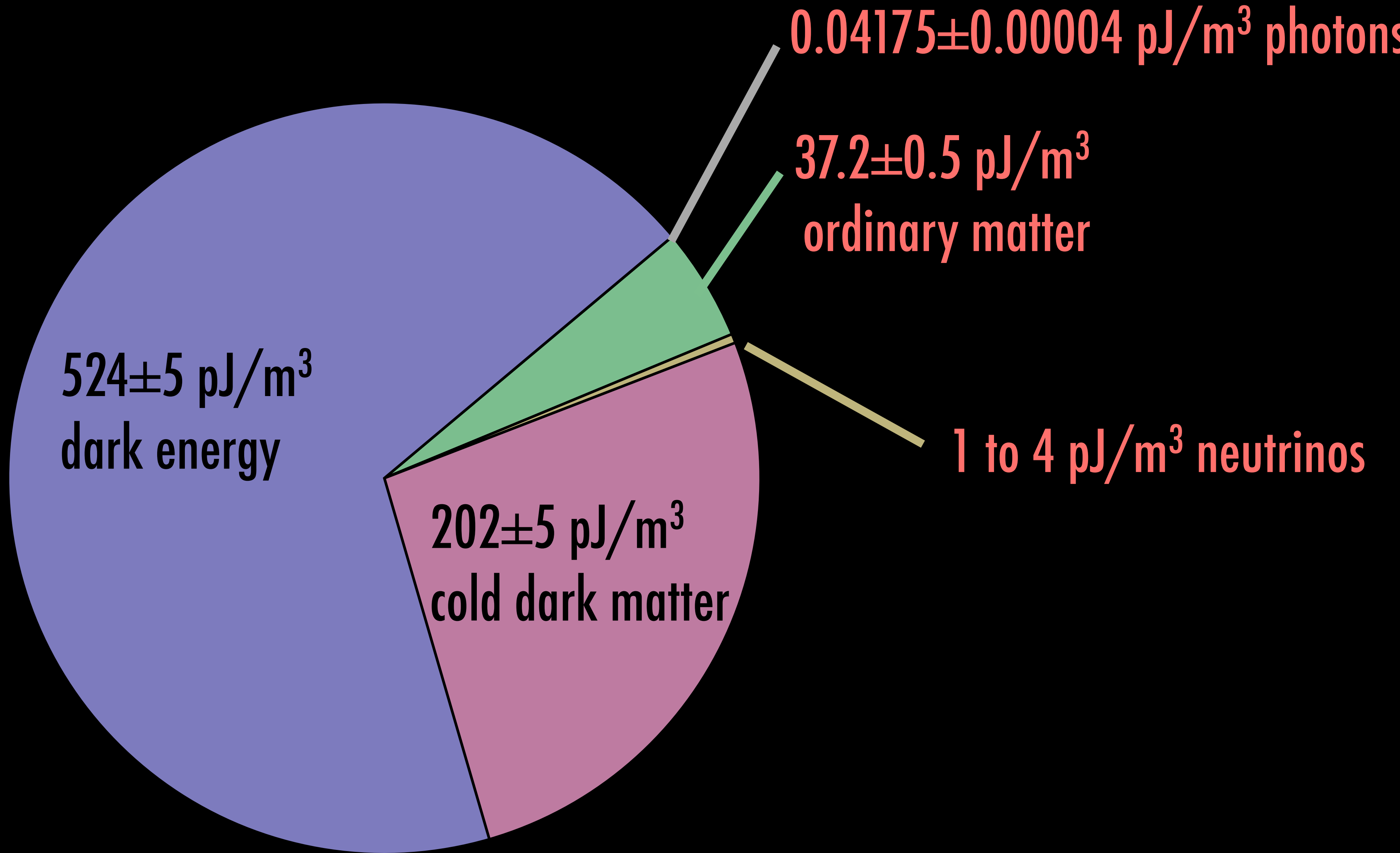
*Agreement between CMB and BBN densities*




$$\Omega_B = \frac{\rho_B}{\rho_{crit}}$$

$$\eta = \frac{n_B}{n_\gamma}$$

# The observed energy content of the Universe

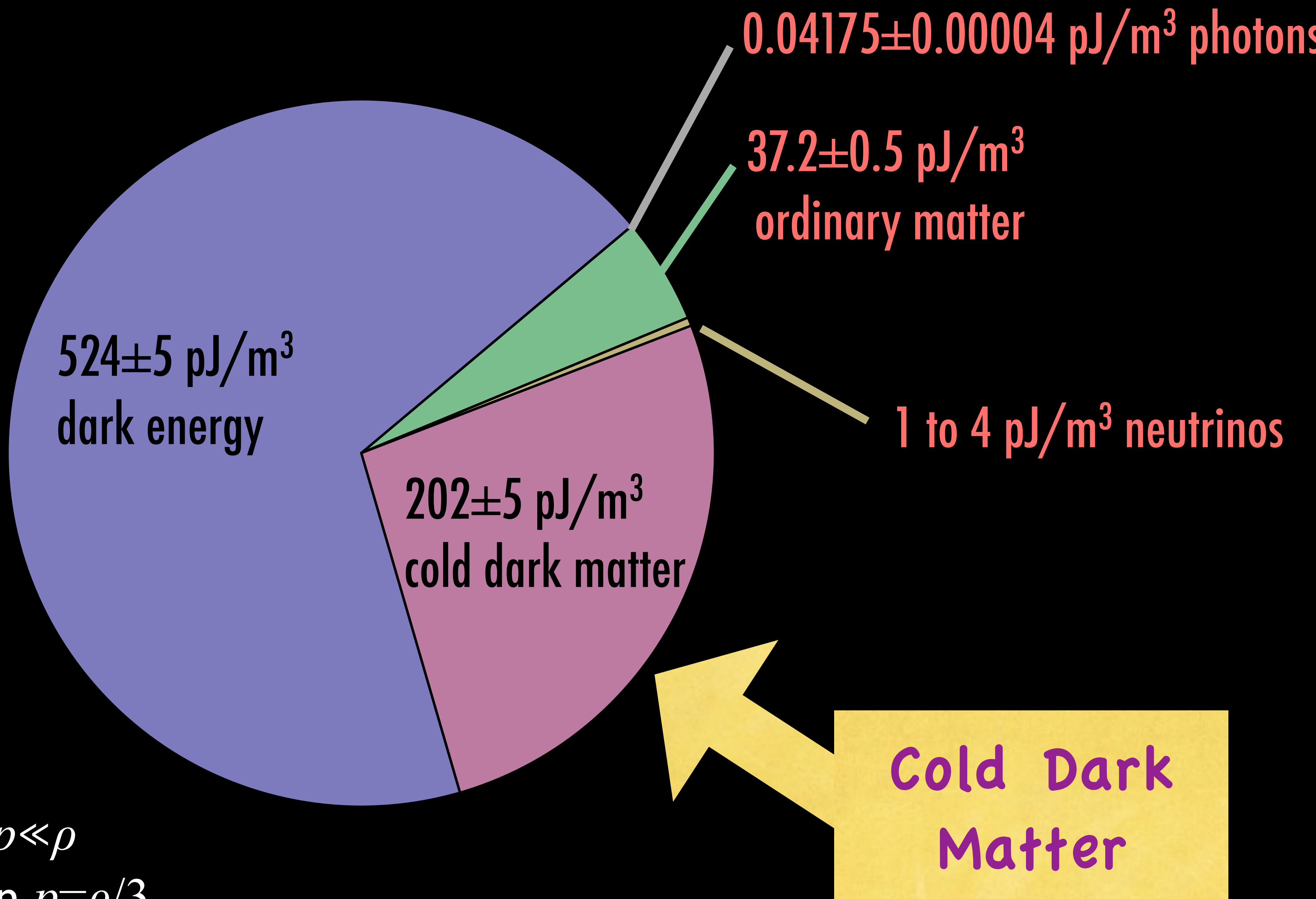



matter $p \ll \rho$
radiation $p = \rho/3$
vacuum $p = -\rho$

*Planck (2013)*

1 pJ = $10^{-12}$ J

# The observed energy content of the Universe




matter $p \ll \rho$

radiation $p = \rho/3$

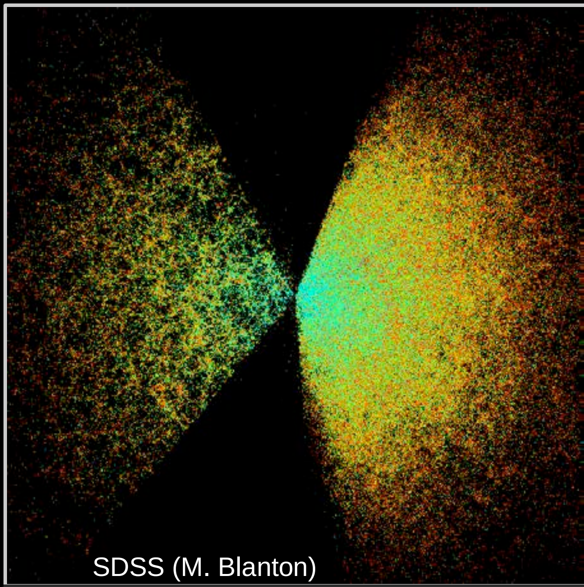
vacuum $p = -\rho$

*Planck (2013)*

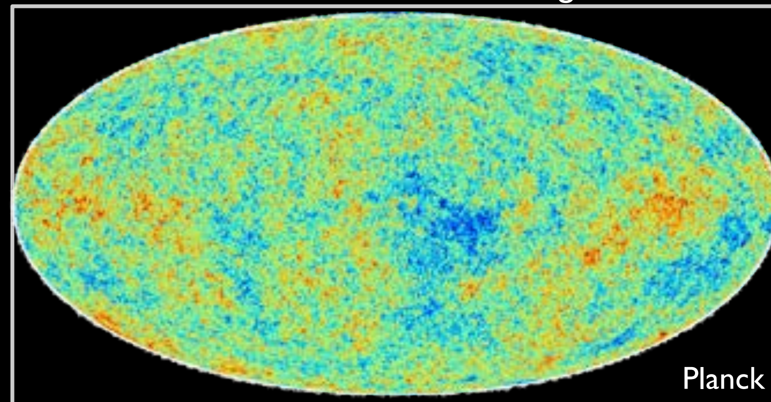
1 pJ = $10^{-12}$ J

# From CMB fluctuations to galaxies

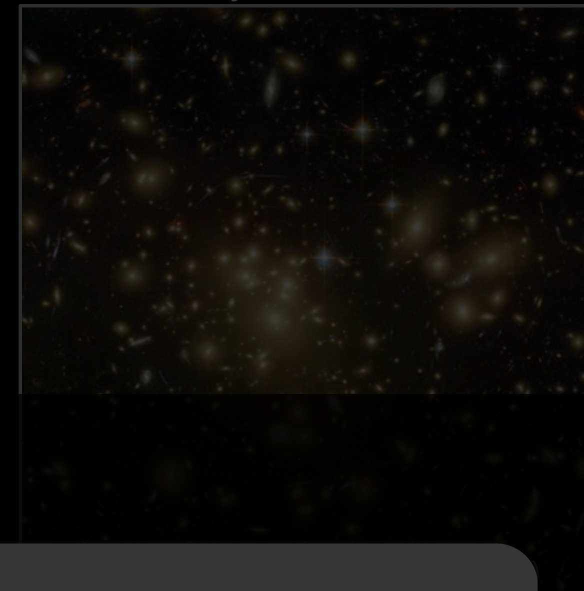
Large Scale Structure



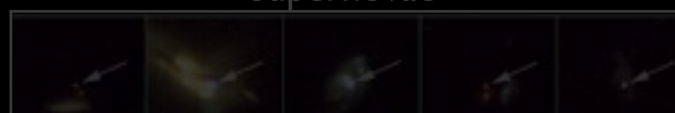

Cosmic Microwave Background

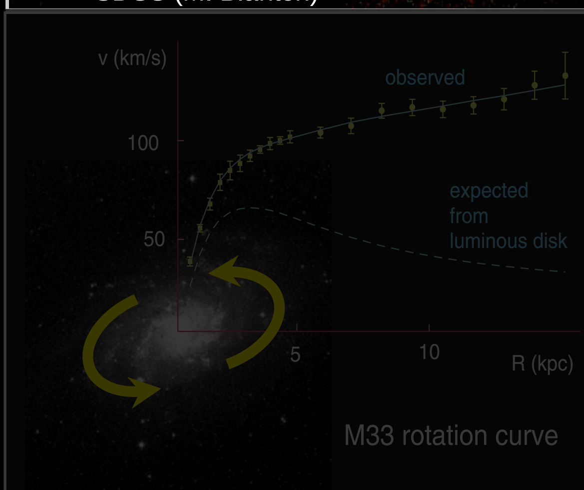


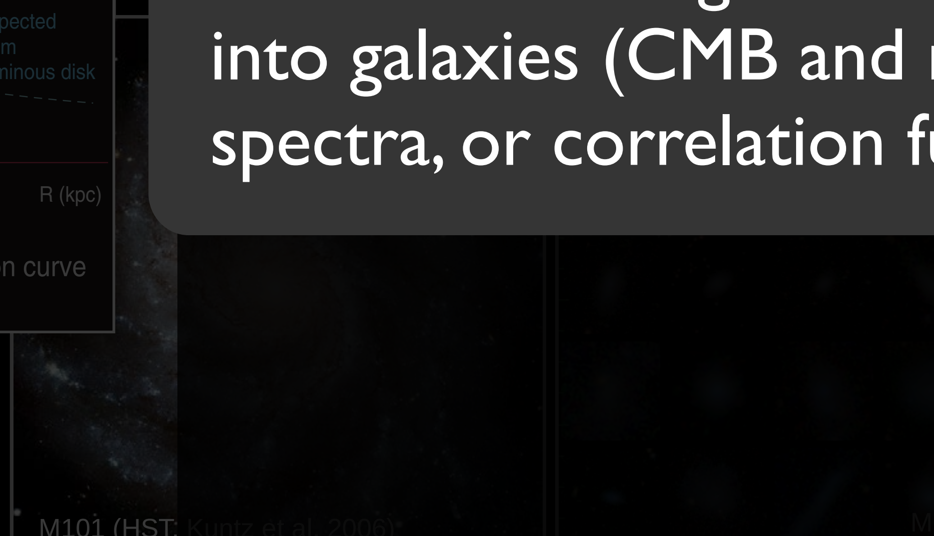

Galaxy Clusters



Supernovae

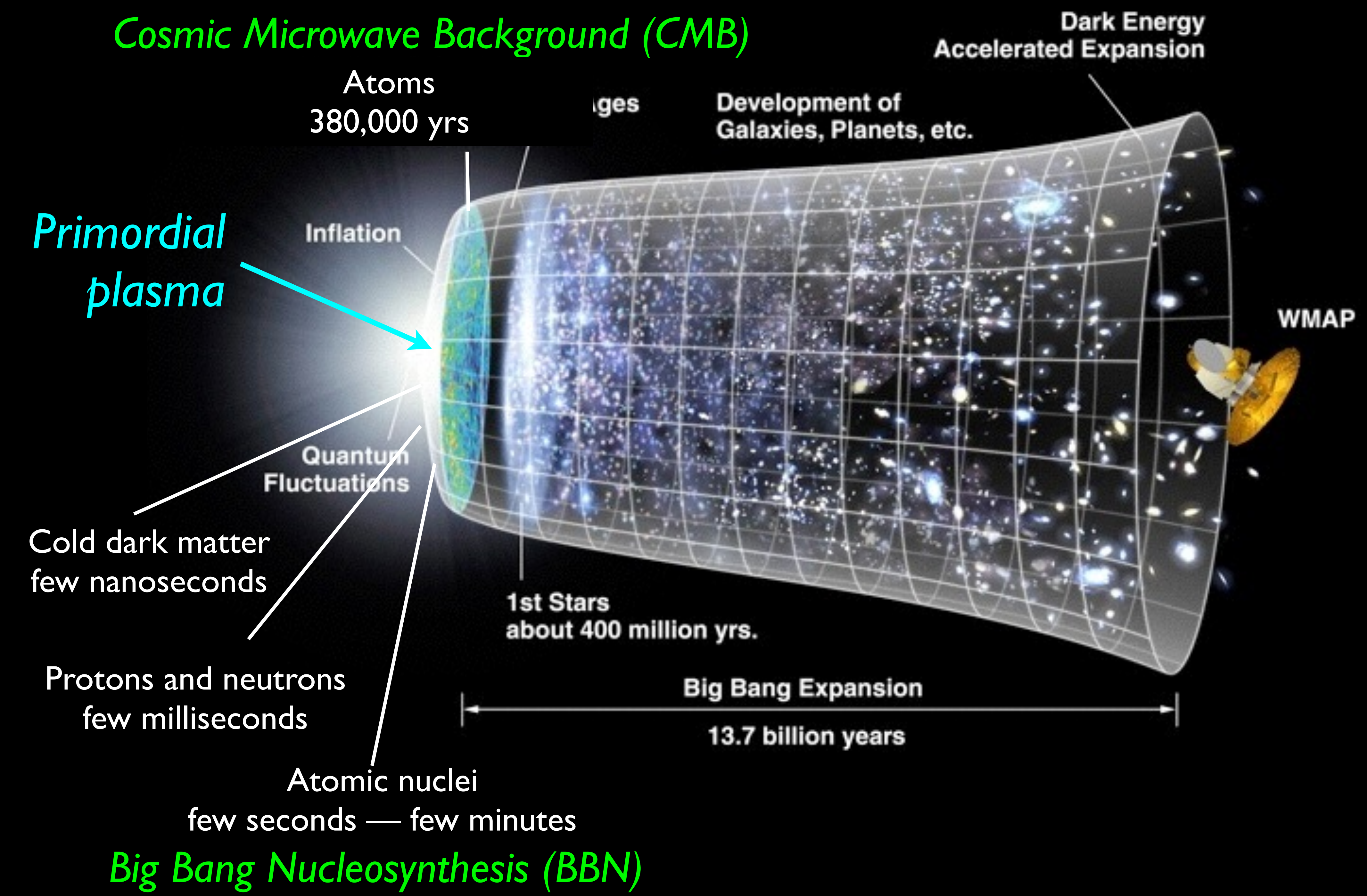




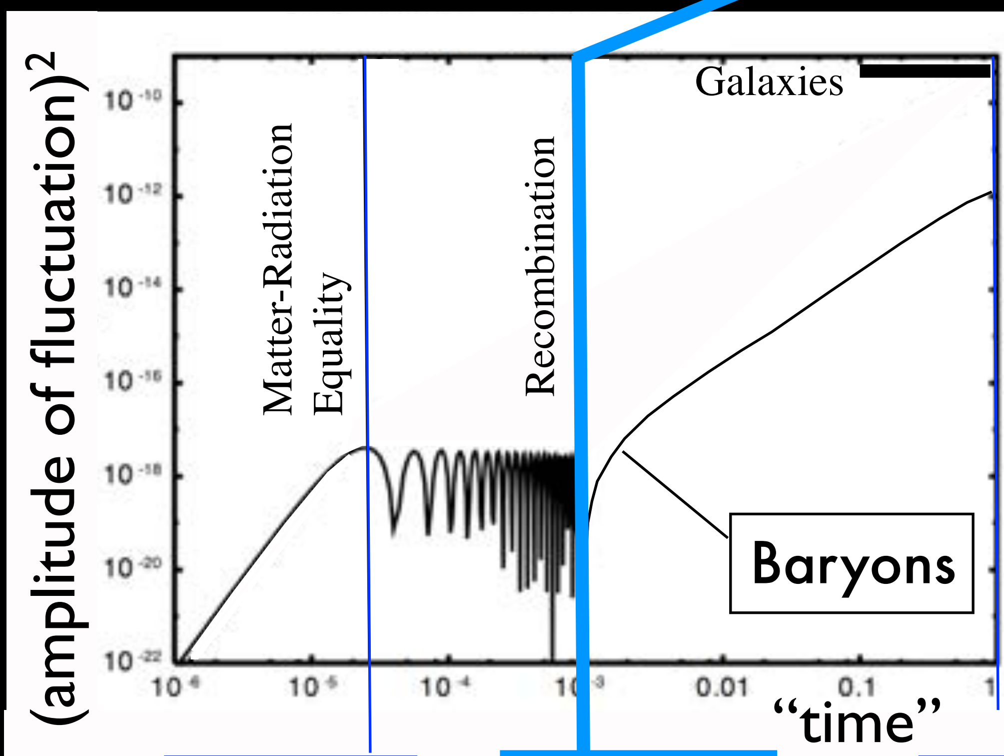




An invisible mass makes the Cosmic Microwave Background fluctuations grow into galaxies (CMB and matter power spectra, or correlation functions)

# From CMB fluctuations to galaxies



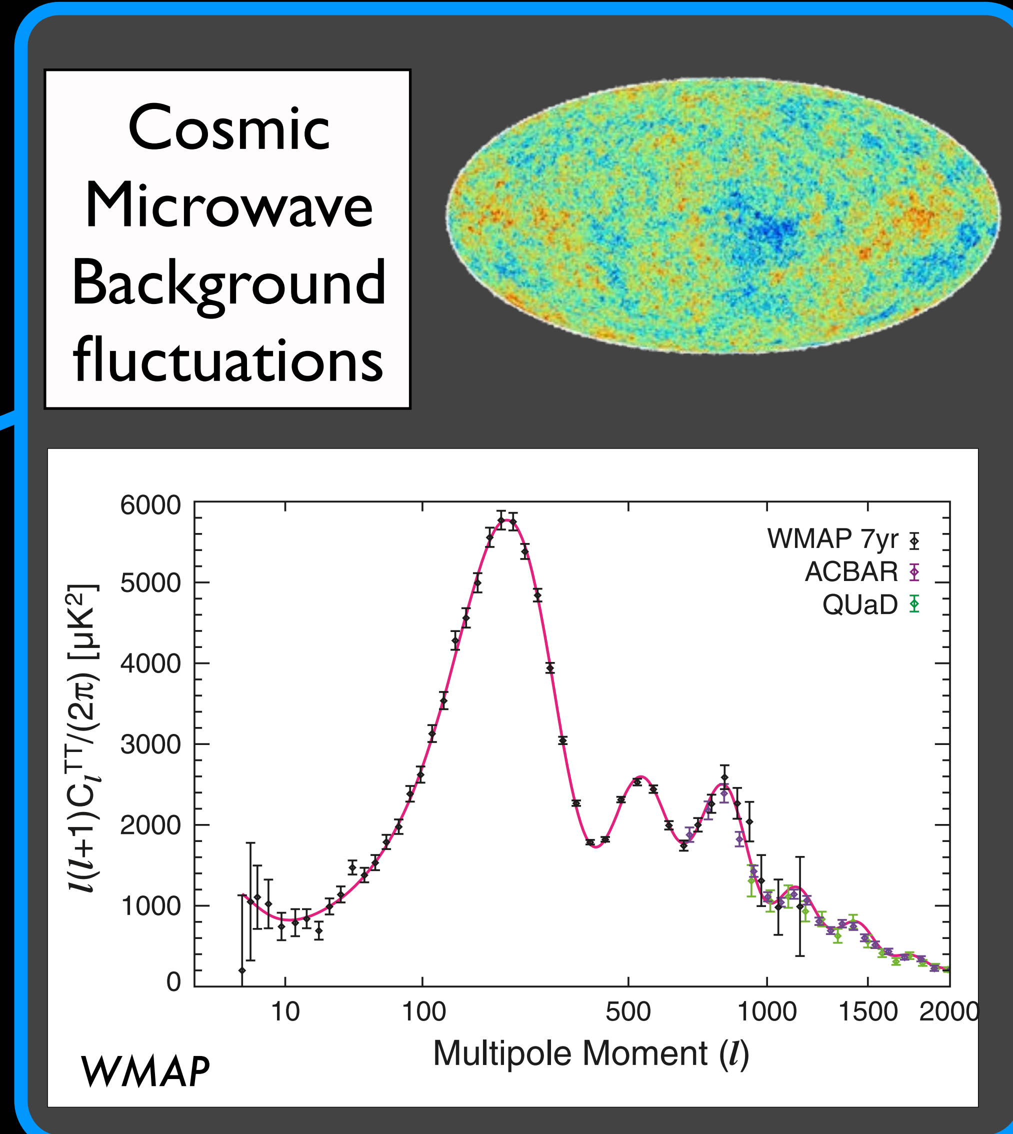
# From CMB fluctuations to galaxies




T=1.28 eV

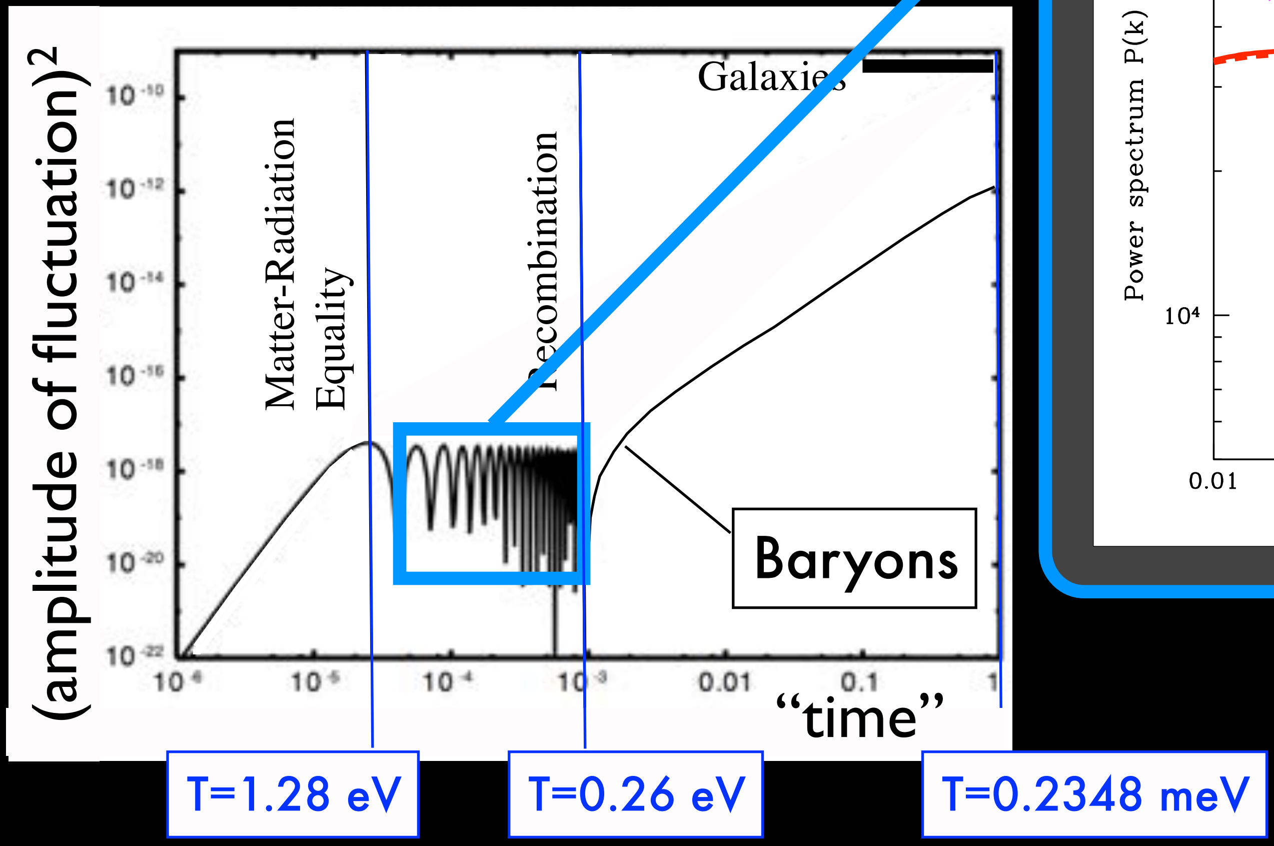
T=0.26 eV

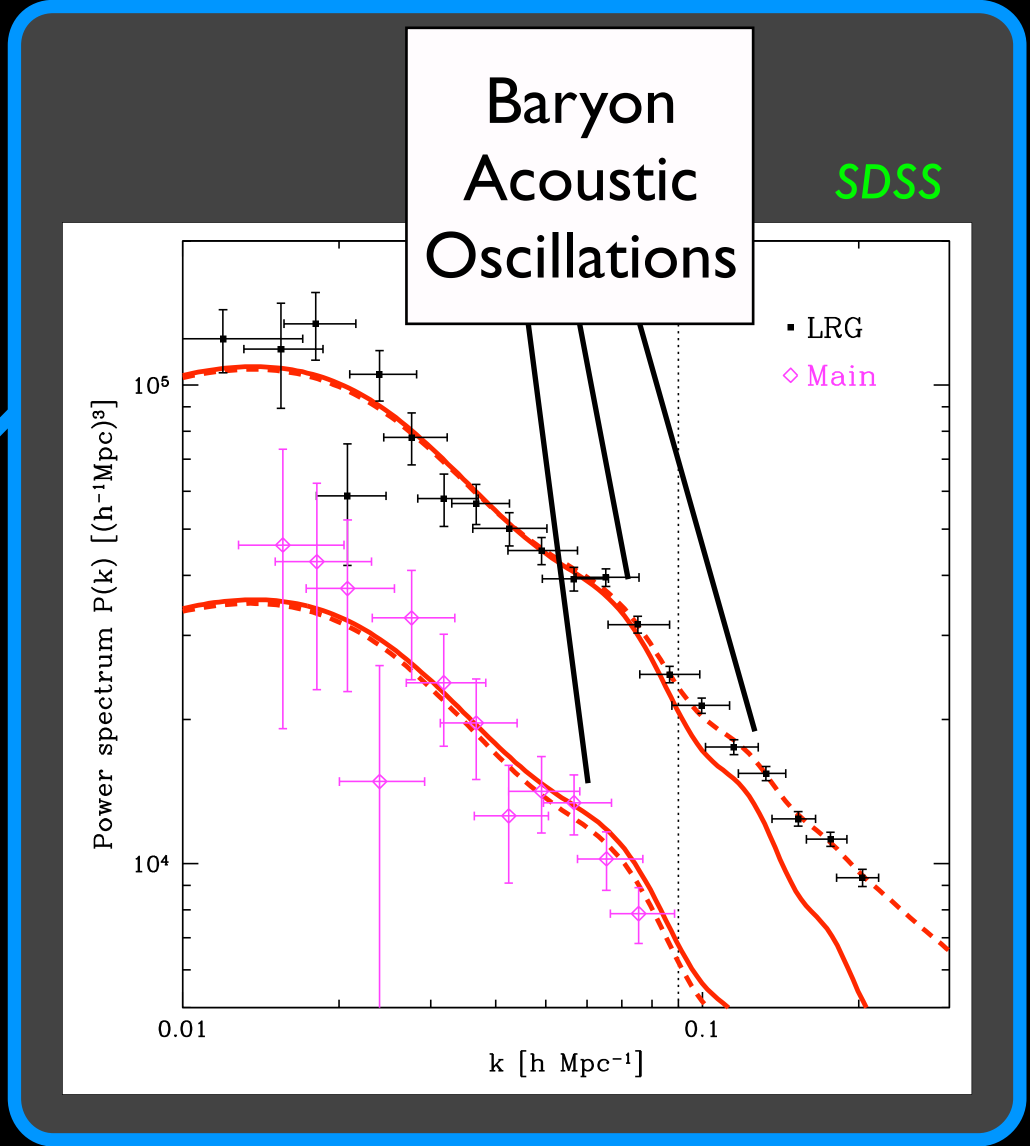
T=0.2348 meV



# From CMB fluctuations to galaxies

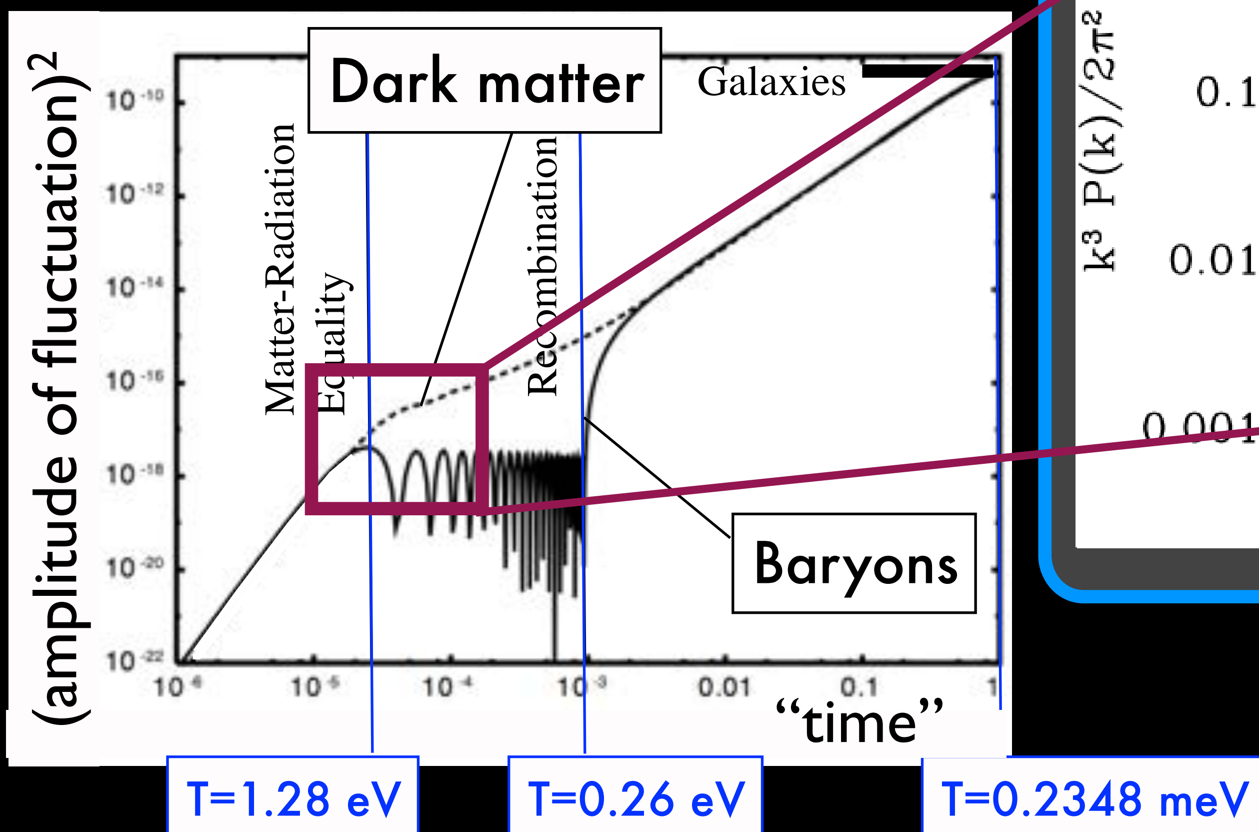
Fluctuations are too small to gravitationally grow into galaxies in the given 13 billion years.



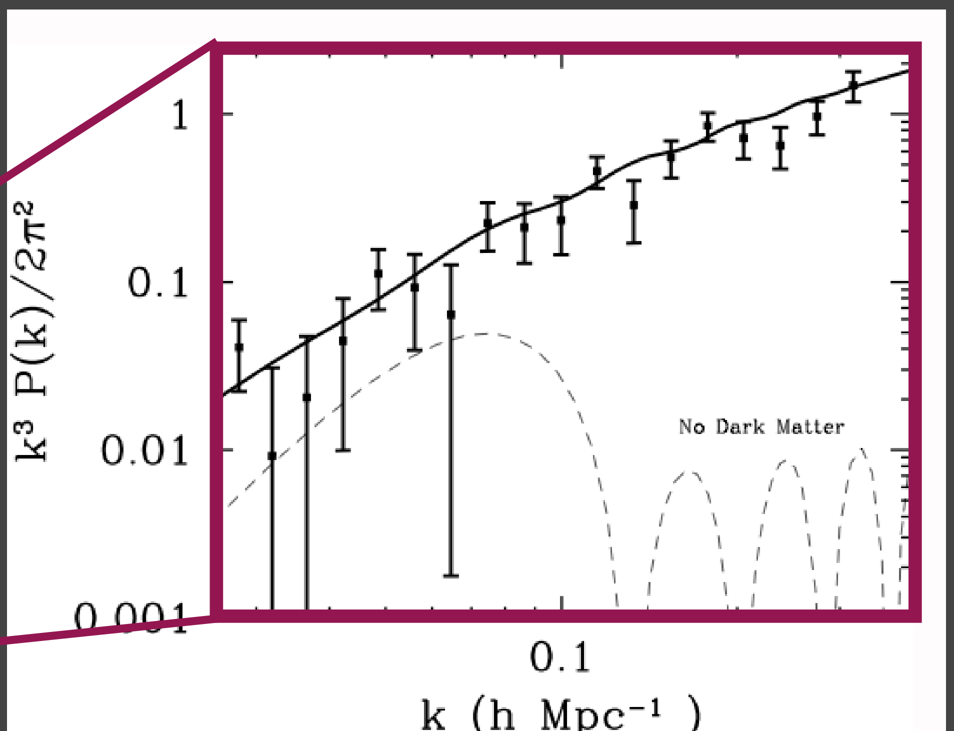
# From CMB fluctuations to galaxies

Fluctuation uncoupled to the plasma have enough time to grow

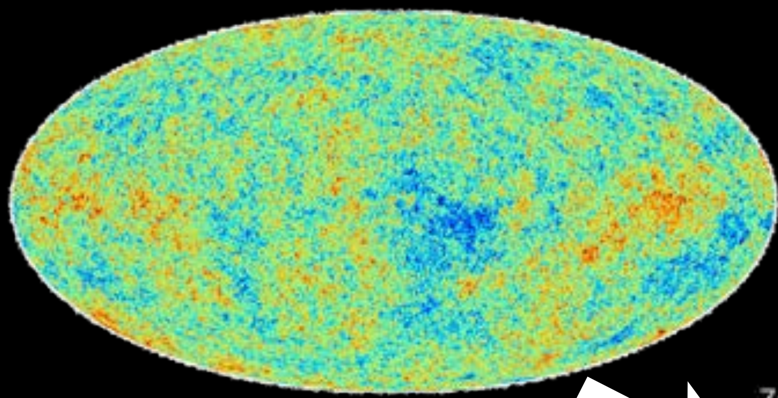


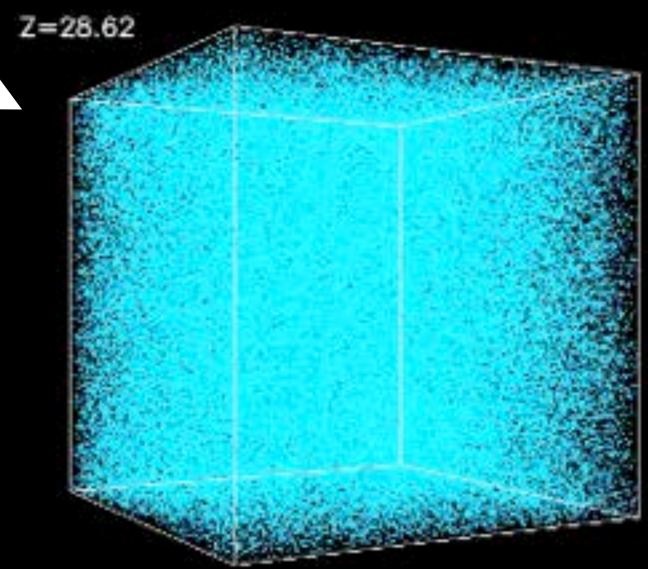

*More than 80% of all matter does not couple to the primordial plasma!*

SDSS

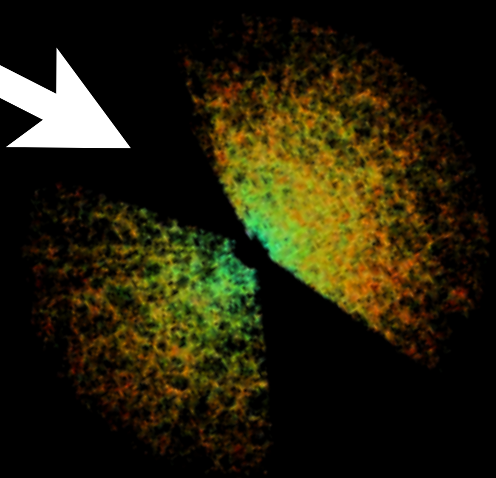


# From CMB fluctuations to galaxies



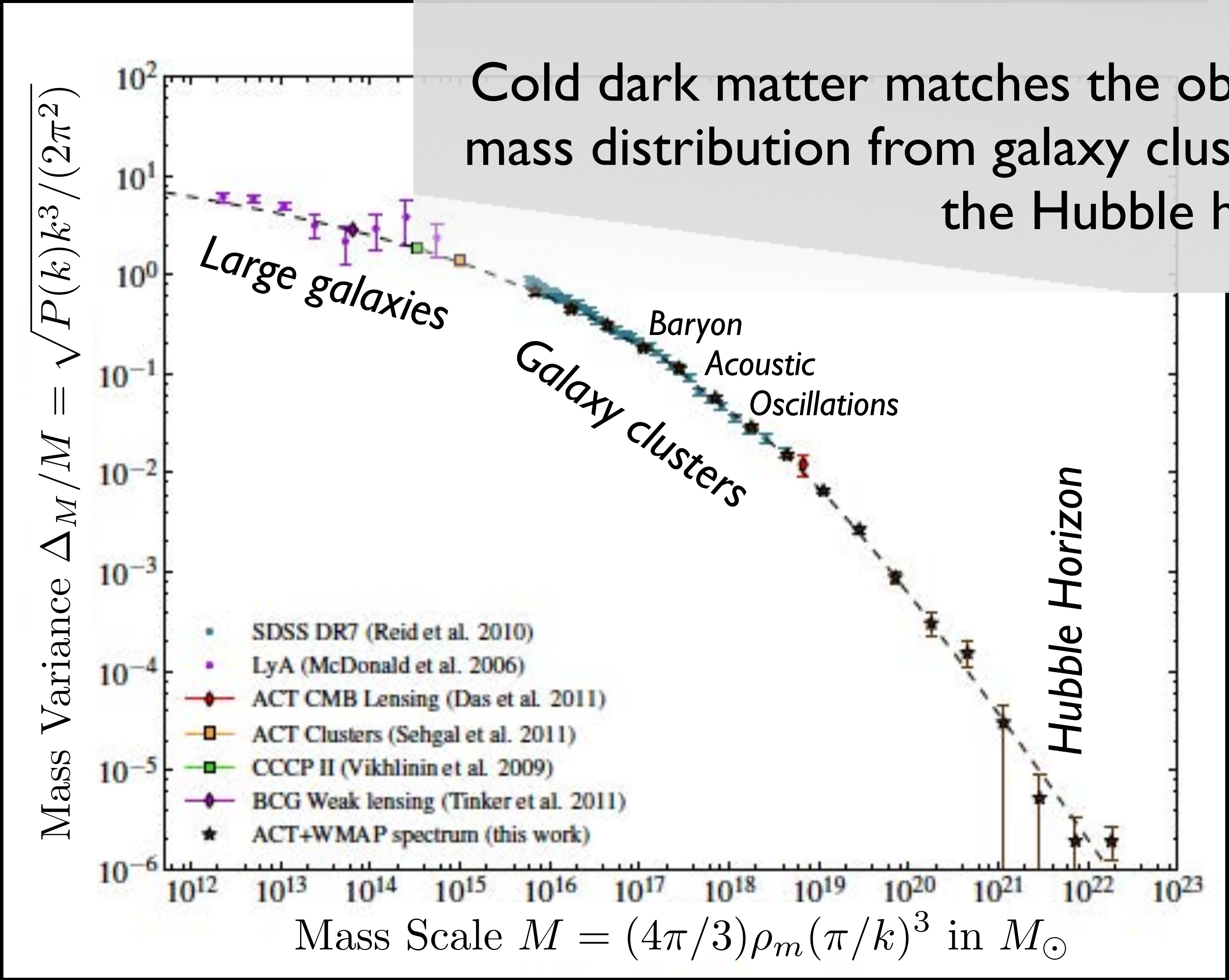



Kravtsov, Klypin



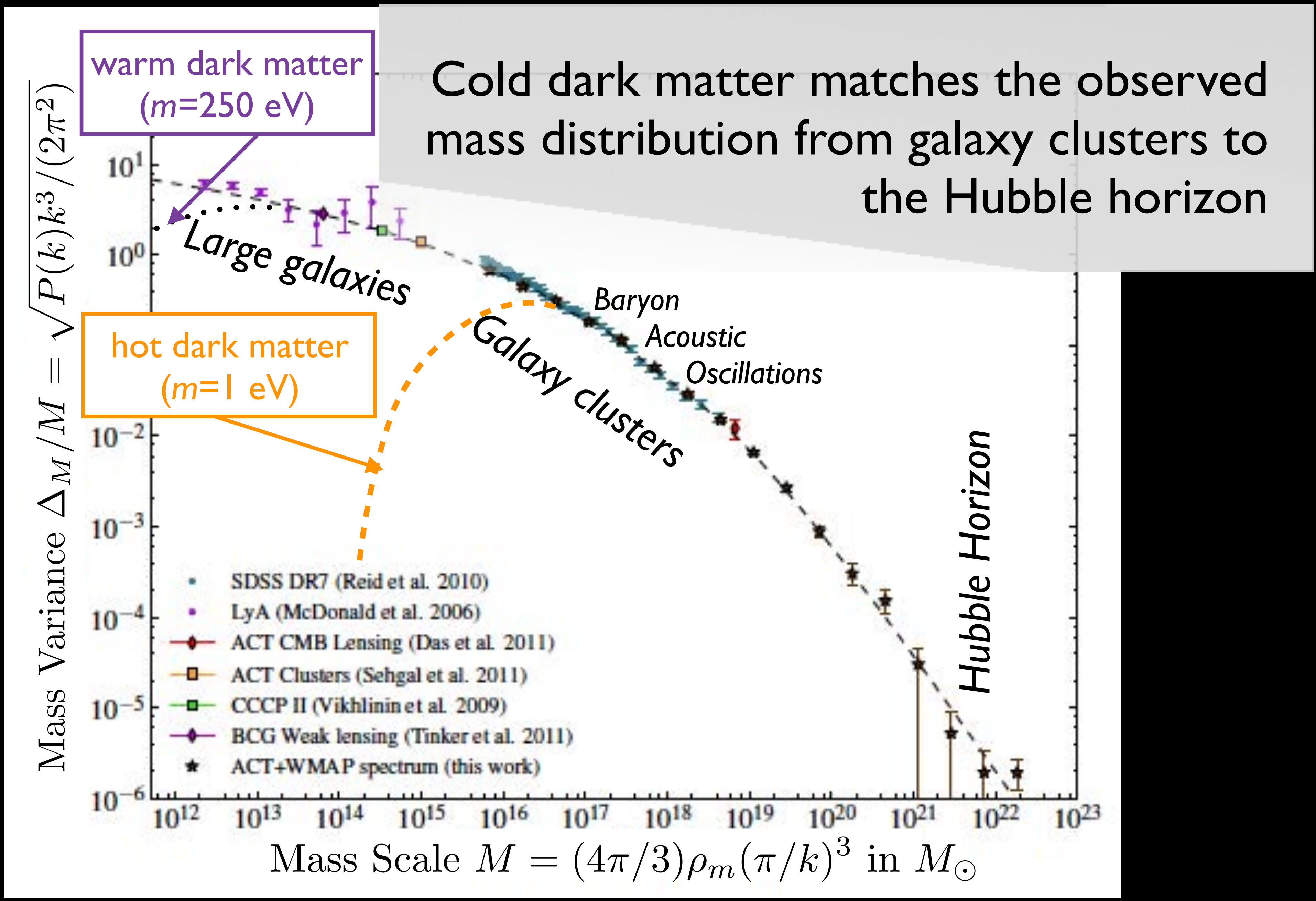
# From CMB fluctuations to galaxies

Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon



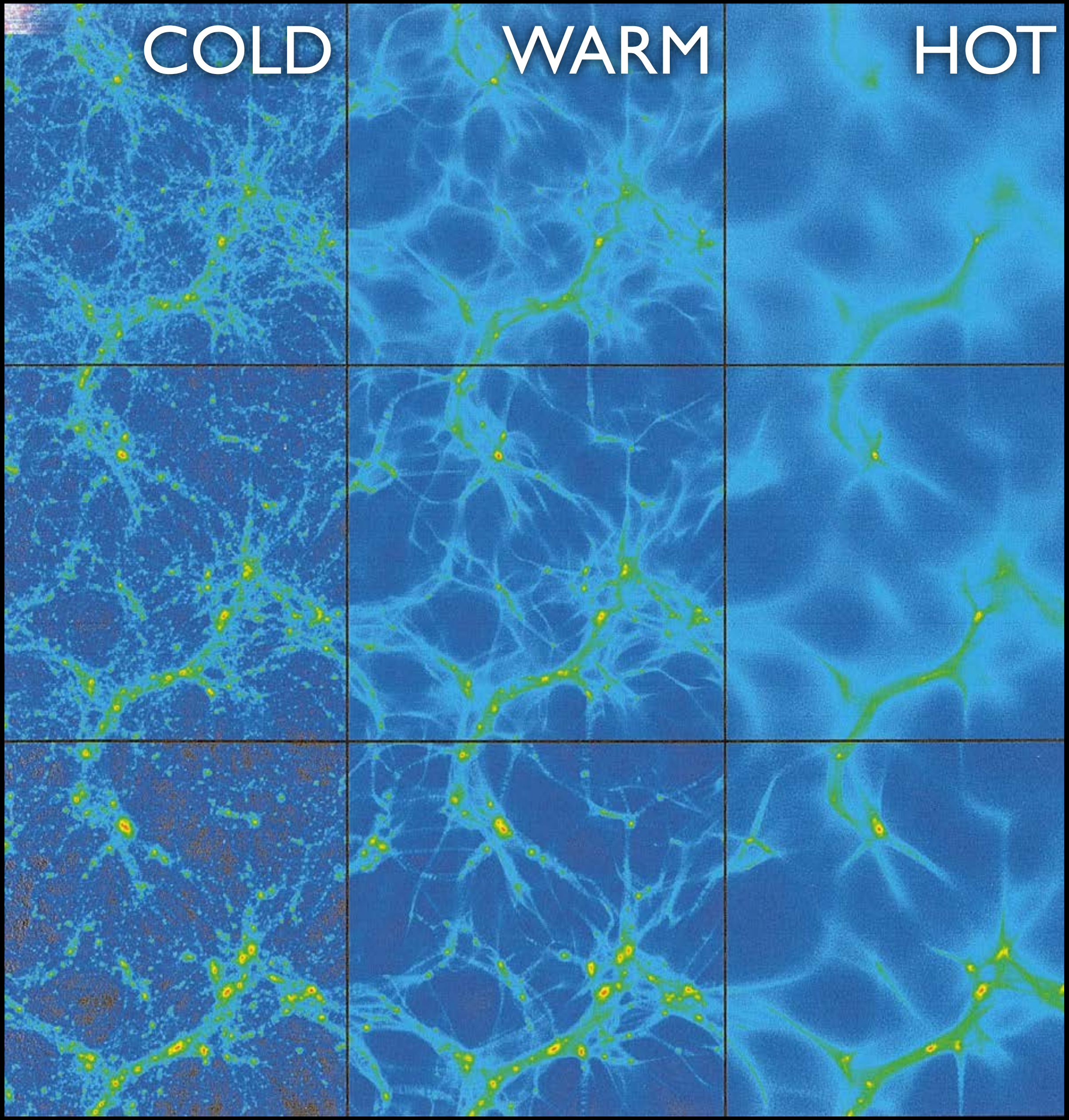

*Hlozek et al 2012*

# From CMB fluctuations to galaxies




*Hlozek et al 2012*

# From CMB fluctuations to galaxies



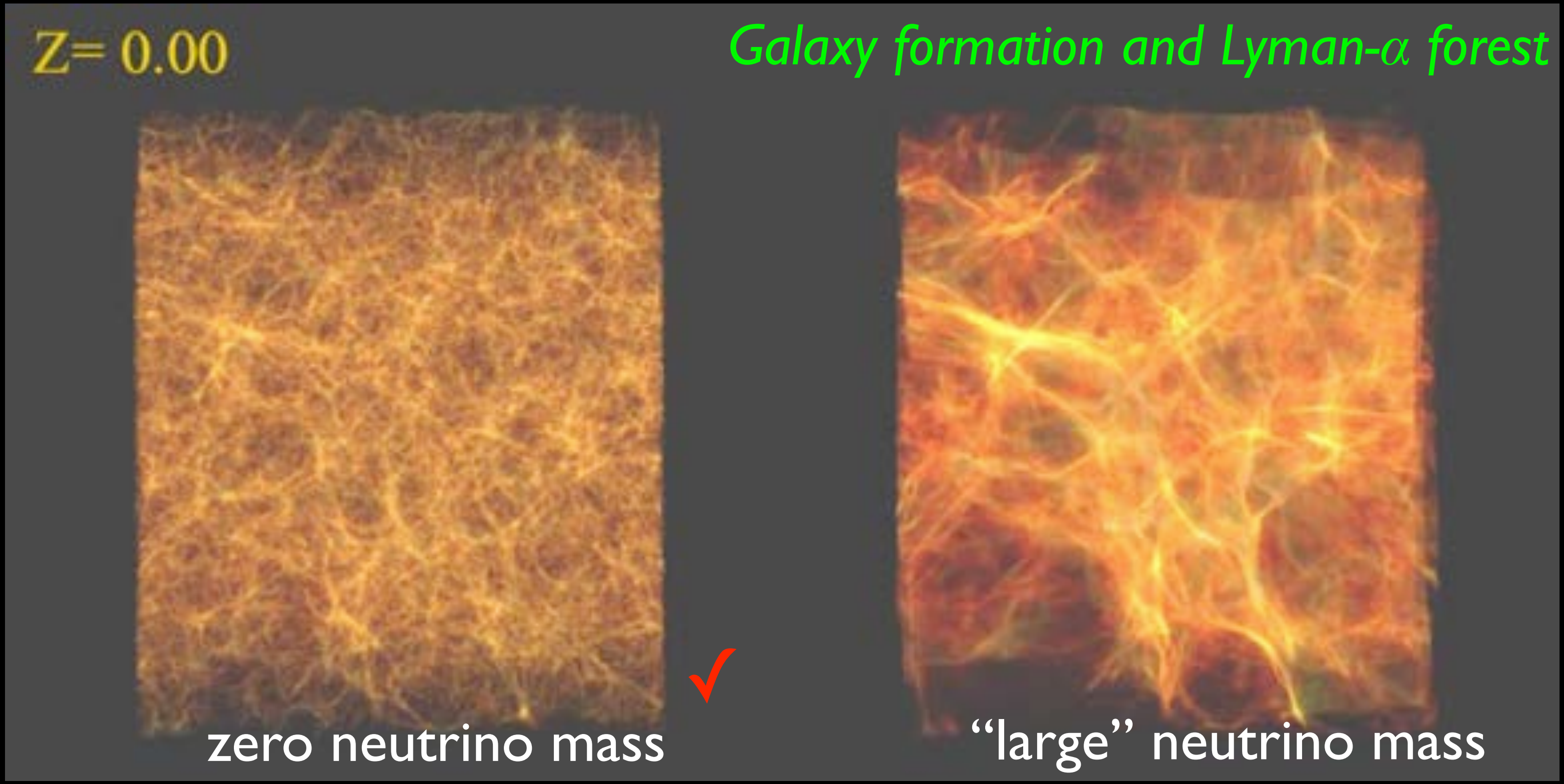

*Bode et al 2001*

# Neutrinos as dark matter

Cosmology provides upper limits on neutrino masses

$\sum m < 0.25$ eV

*Future reach*
$\sim 0.06$ eV

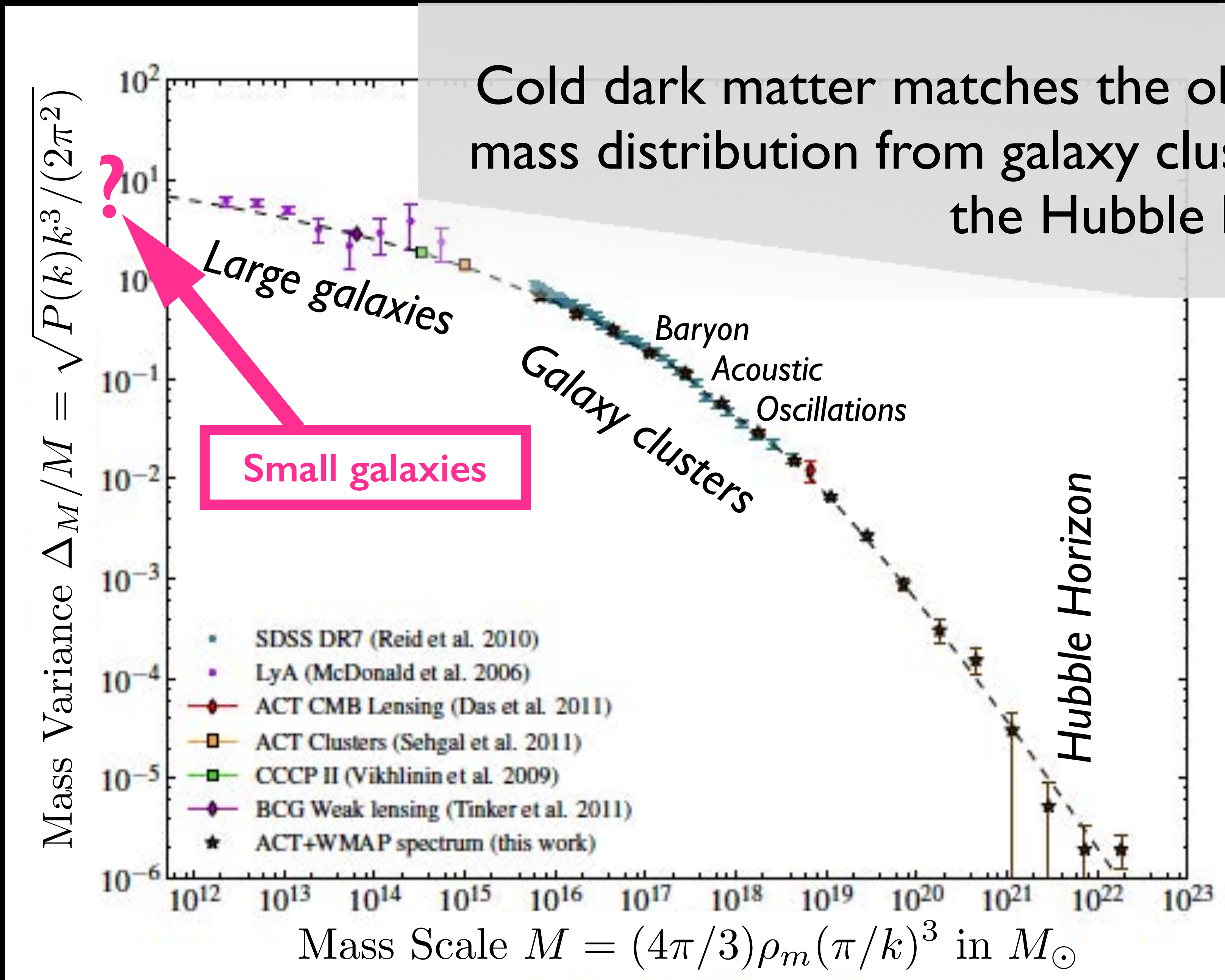


# Neutrino as dark matter

- Neutrino oscillations (largest $\Delta m^2$ from SK+K2K+MINOS) place a lower bound on one of the neutrino masses, $m_\nu > 0.086$ eV *Gonzalez-Garcia et al 2012*
- Cosmology places an upper bound on the sum of the neutrino masses, $\sum m_\nu < 0.23$ eV *Planck+WP+ACT/SPT+BAO 2013*
- Therefore neutrinos are *hot dark matter* ($m_\nu \ll T_{eq}$=1.28 eV) with density $0.0009 < \Omega_\nu h^2 < 0.0025$

*Detecting this Cosmic Neutrino Background (CNB) is a big challenge*

# Small galaxies and dark subhalos

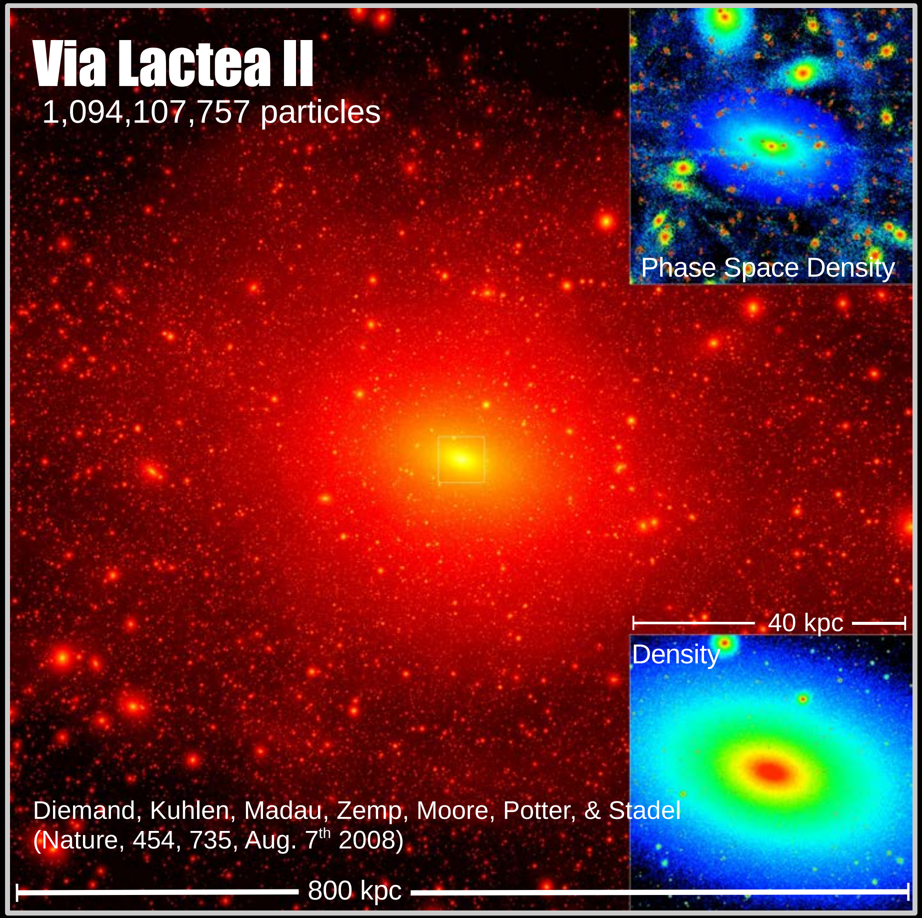



Cold dark matter matches the observed mass distribution from galaxy clusters to the Hubble horizon

*Hlozek et al 2012*

# Small galaxies and dark subhalos

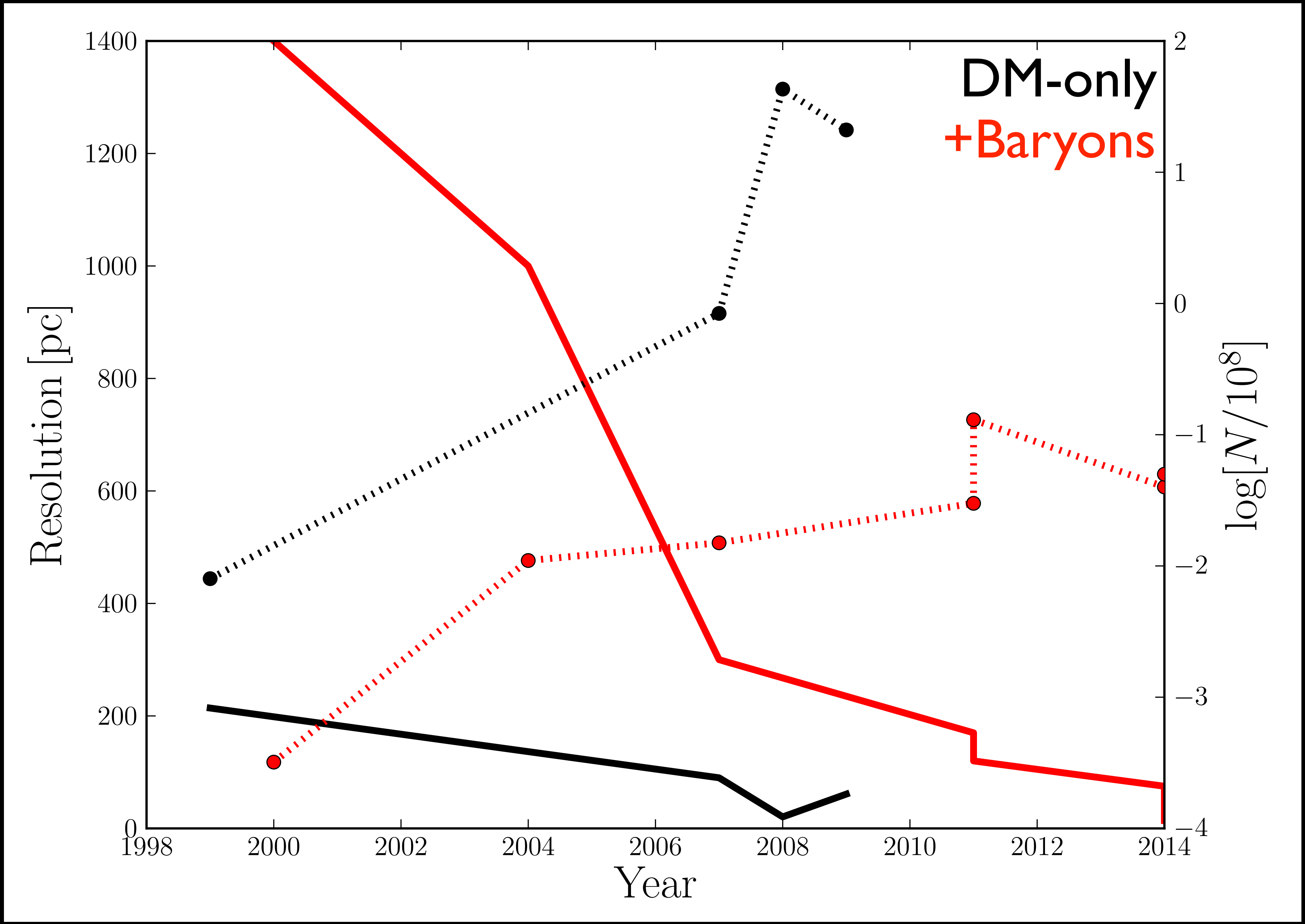
Dark-matter-only simulations do not match observations at small scales (~kpc)




They incorrectly predict:

- Too many galactic bulges (too much low angular momentum gas)
- Steep density profiles in dwarf galaxies (cusp/core problem)
- Too dense subhalos/satellites ("too big to fail" problem)
- Too many subhalos/satellites

# Small galaxies and dark subhalos



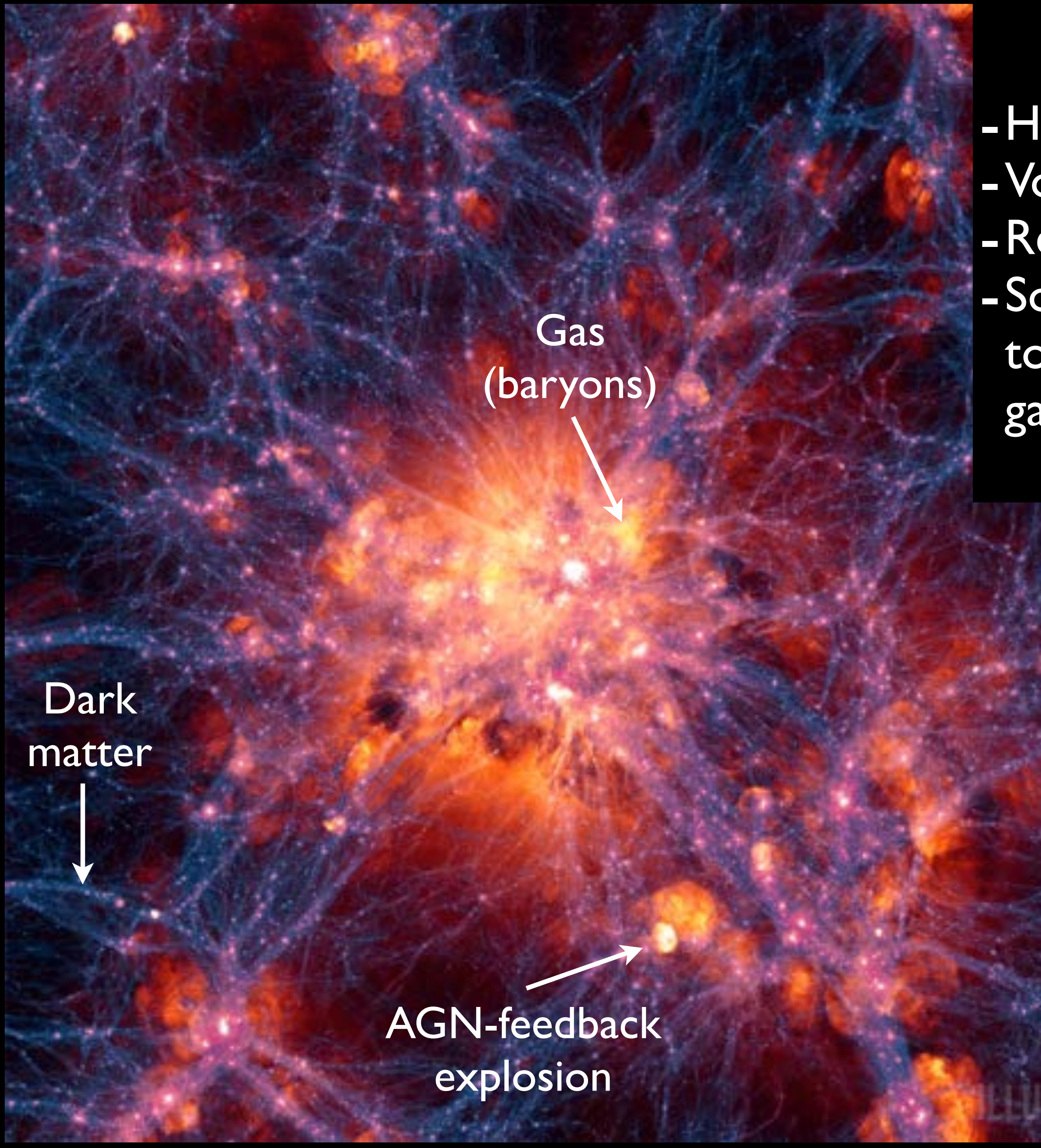

Read 2014

# Small galaxies and dark subhalos

Including models for baryons in the universe can significantly alter the results from structure formation simulations:

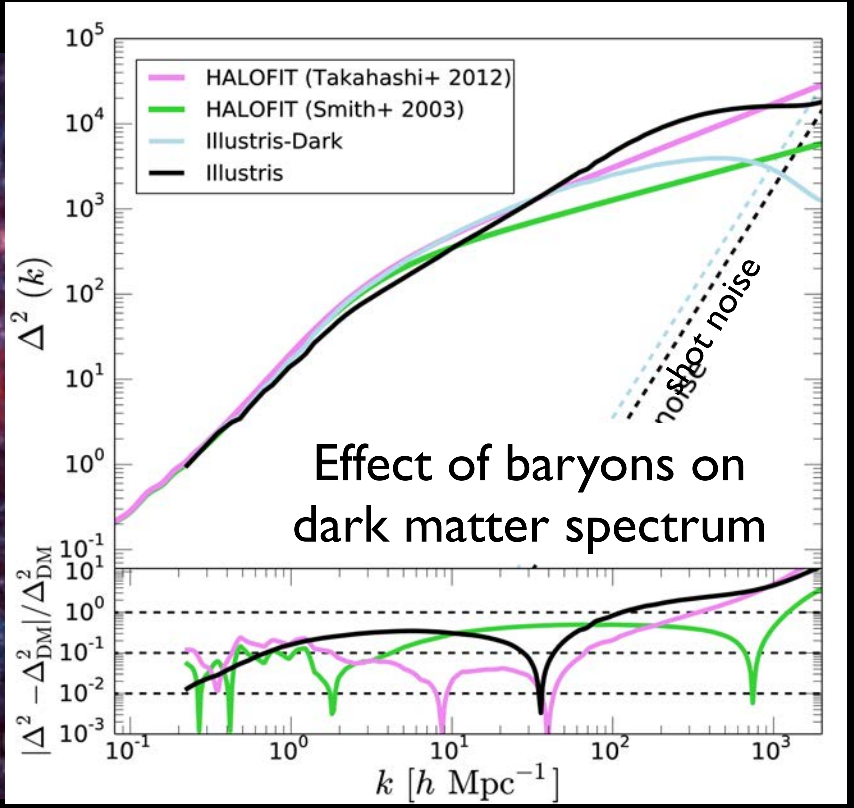
- Triaxial halos ➠ Oblate/round halos.
- Cuspy dark matter profiles ➠ Cored dark matter profiles.
- Cored halos are more easily tidally disrupted ➠ Fewer satellites.
- An existing stellar disk ➠ An accreted dark disk.

# Small galaxies and dark subhalos




## Illustris Simulation

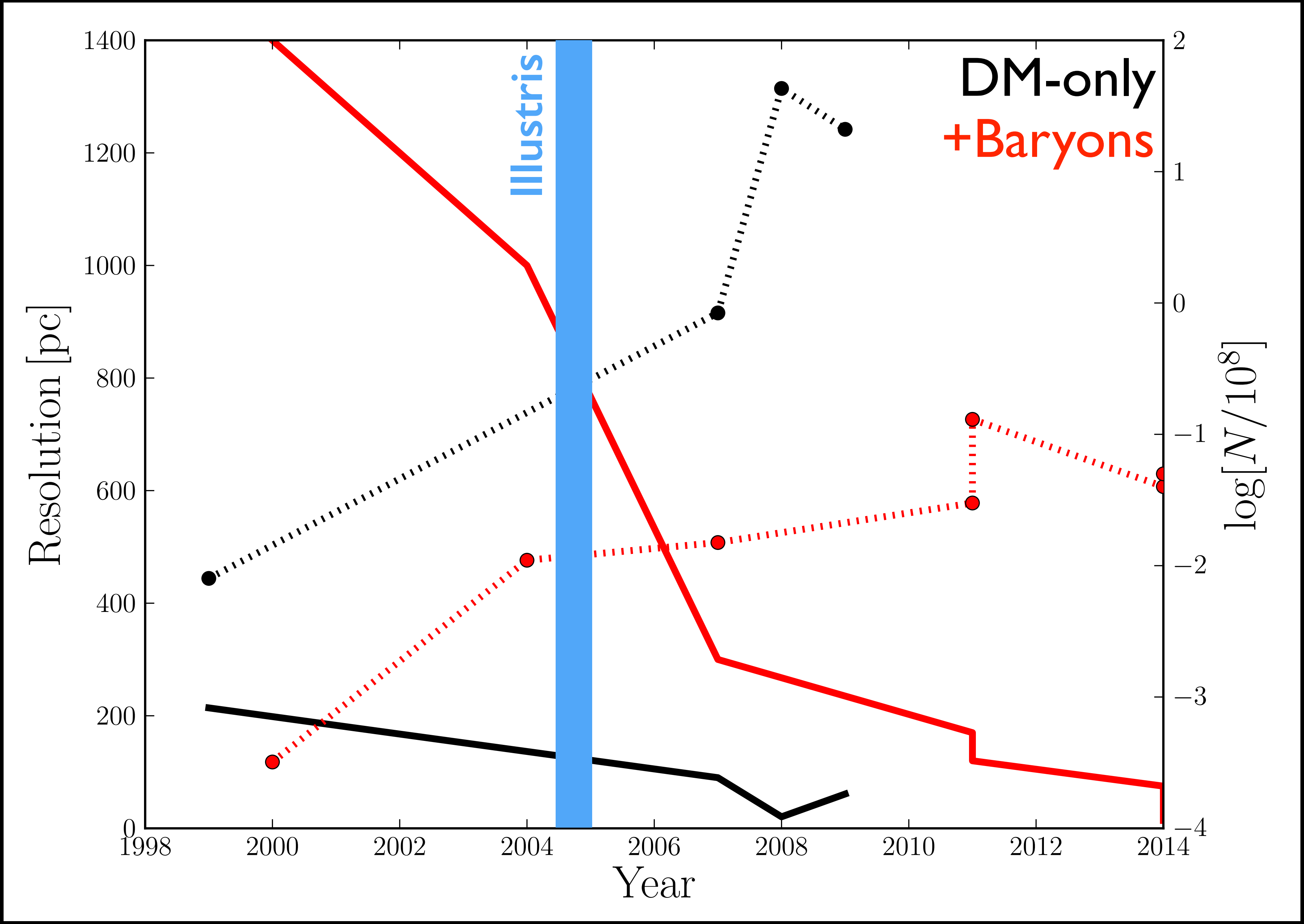
- Hydrodynamical simulation
- Volume: $(106.5\ \mathrm{Mpc})^3$
- Resolution: 710 pc (DM)/48 pc (gas)
- Solves `missing satellite' and `too big-to-fail' problems. Produces observed galaxy shapes and metallicity.




*Illustris Collaboration 2014*

*Vogelsberger et al 2014*

# Small galaxies and dark subhalos

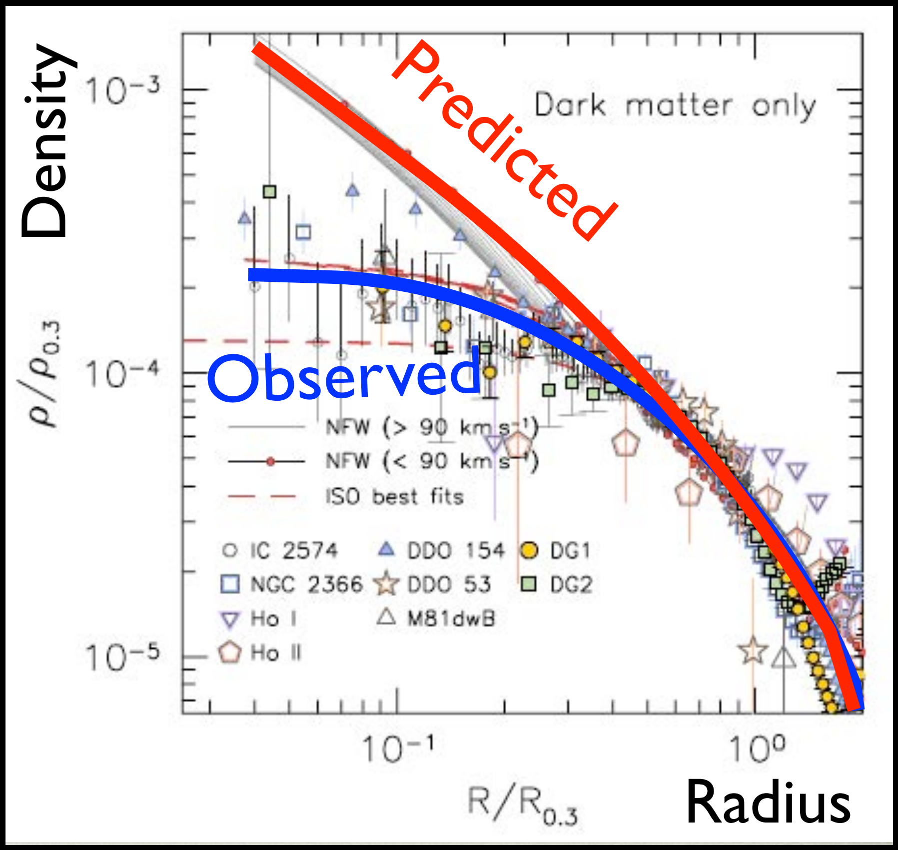



Read 2014

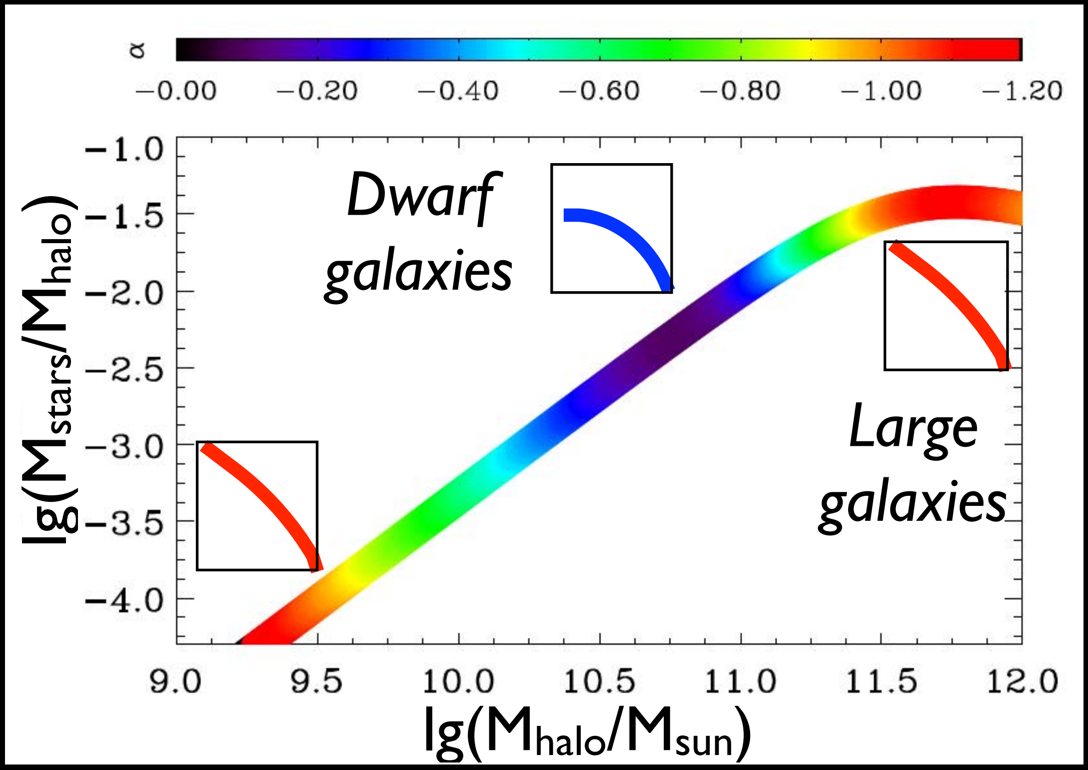
# Small galaxies and dark subhalos

*Cusp/core problem*

Observed density profiles in dwarf galaxies are shallower than predicted with DM only




*Oh et al 2011*




*di Cintio et al 2014*

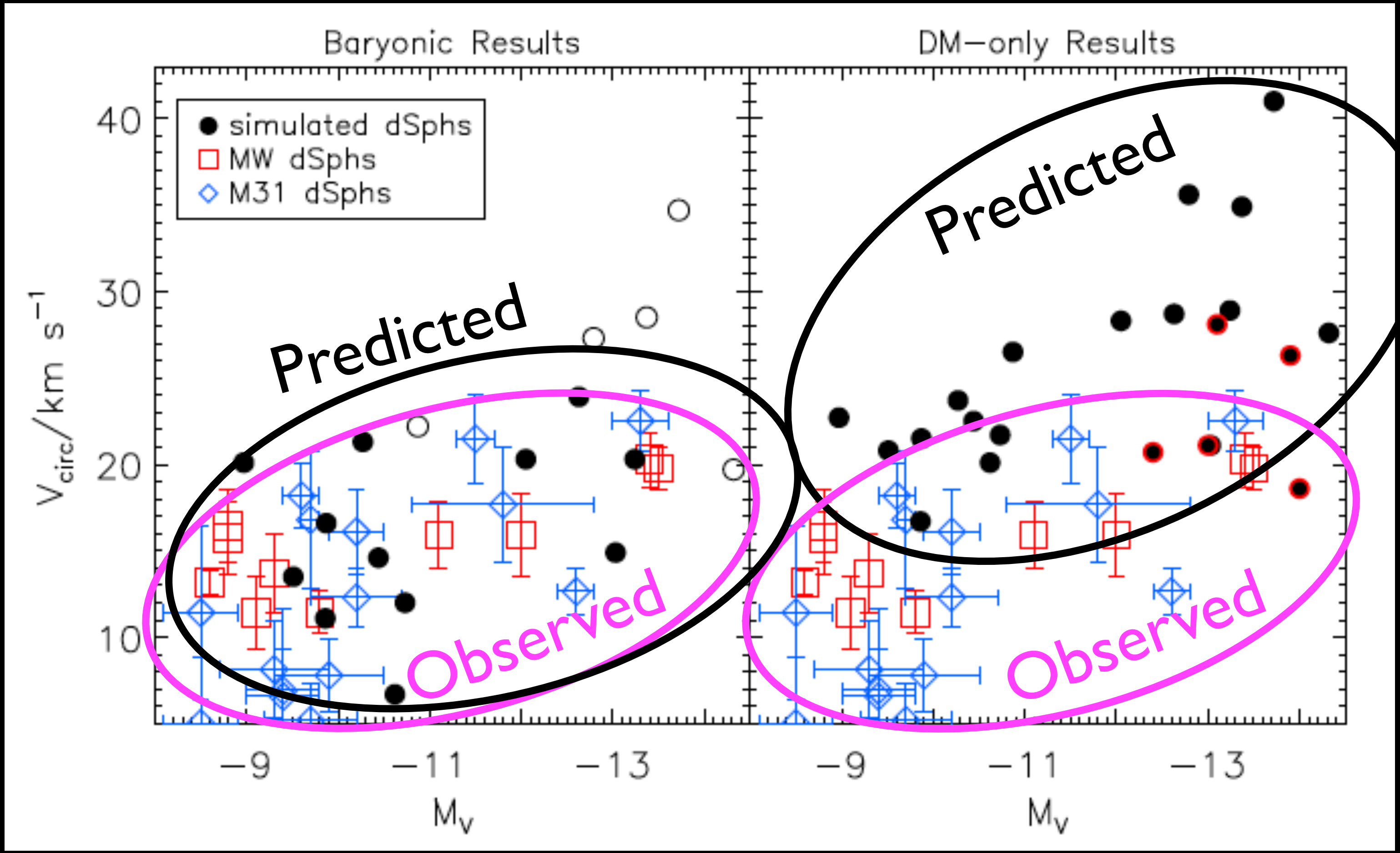
With baryons, density profiles appear to match observations

# Small galaxies and dark subhalos

*"Too big to fail" problem*

With baryons, the predicted satellites match observations

With DM-only, the predicted satellites are too dense



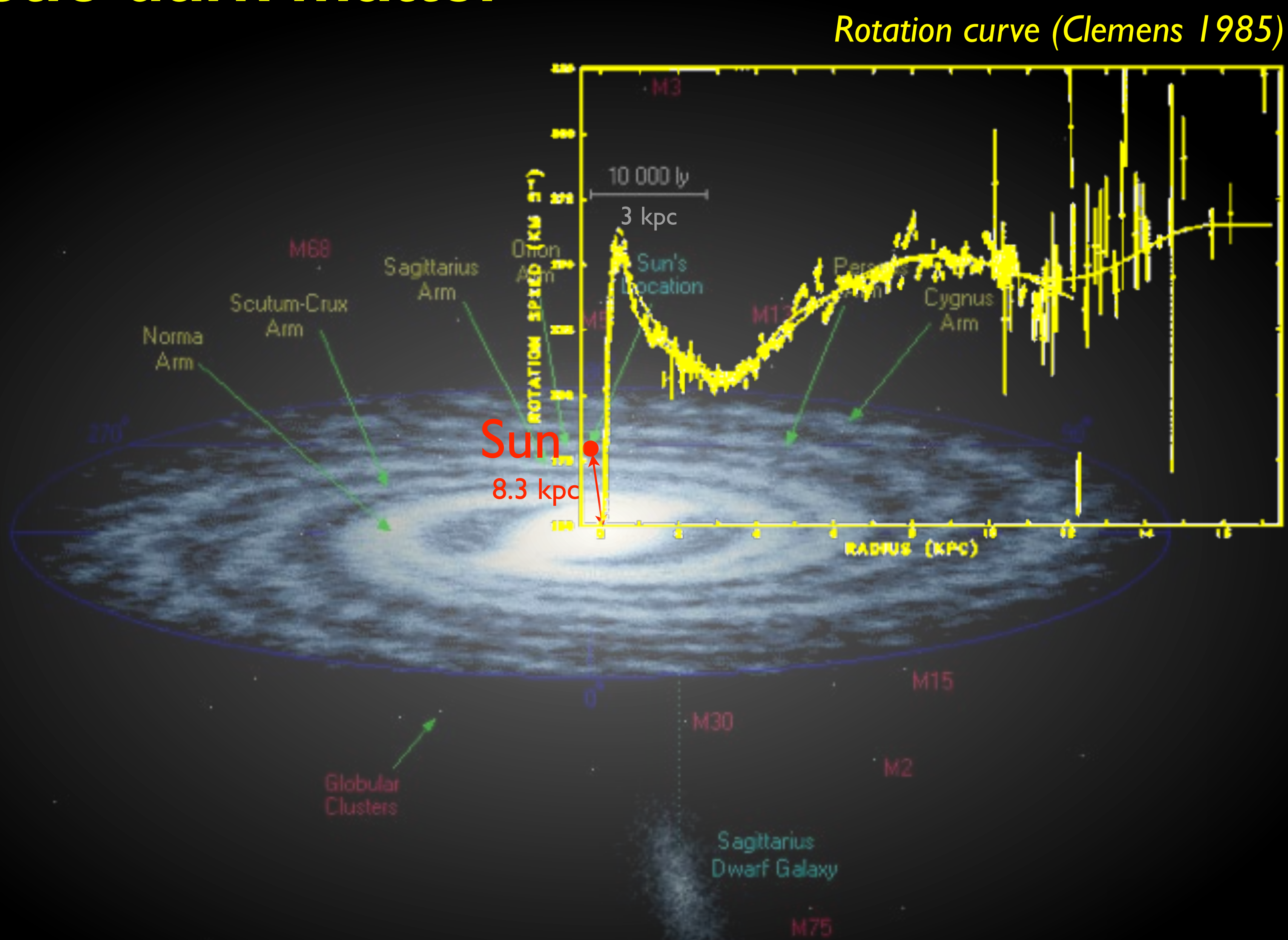

*Brooks, Zolotov 2014*

# Small galaxies and dark subhalos

| | Baryons | WDM | SIDM |
|---|---|---|---|
| Bulge-less disk galaxies | ✓ | | |
| The Cusp/ Core Problem | ✓ | | ✓ |
| Too Big to Fail | ✓ | ✓ | ✓ |
| Missing Satellites | ✓ | ✓ | |

*Brooks 2014*

# Galactic dark matter

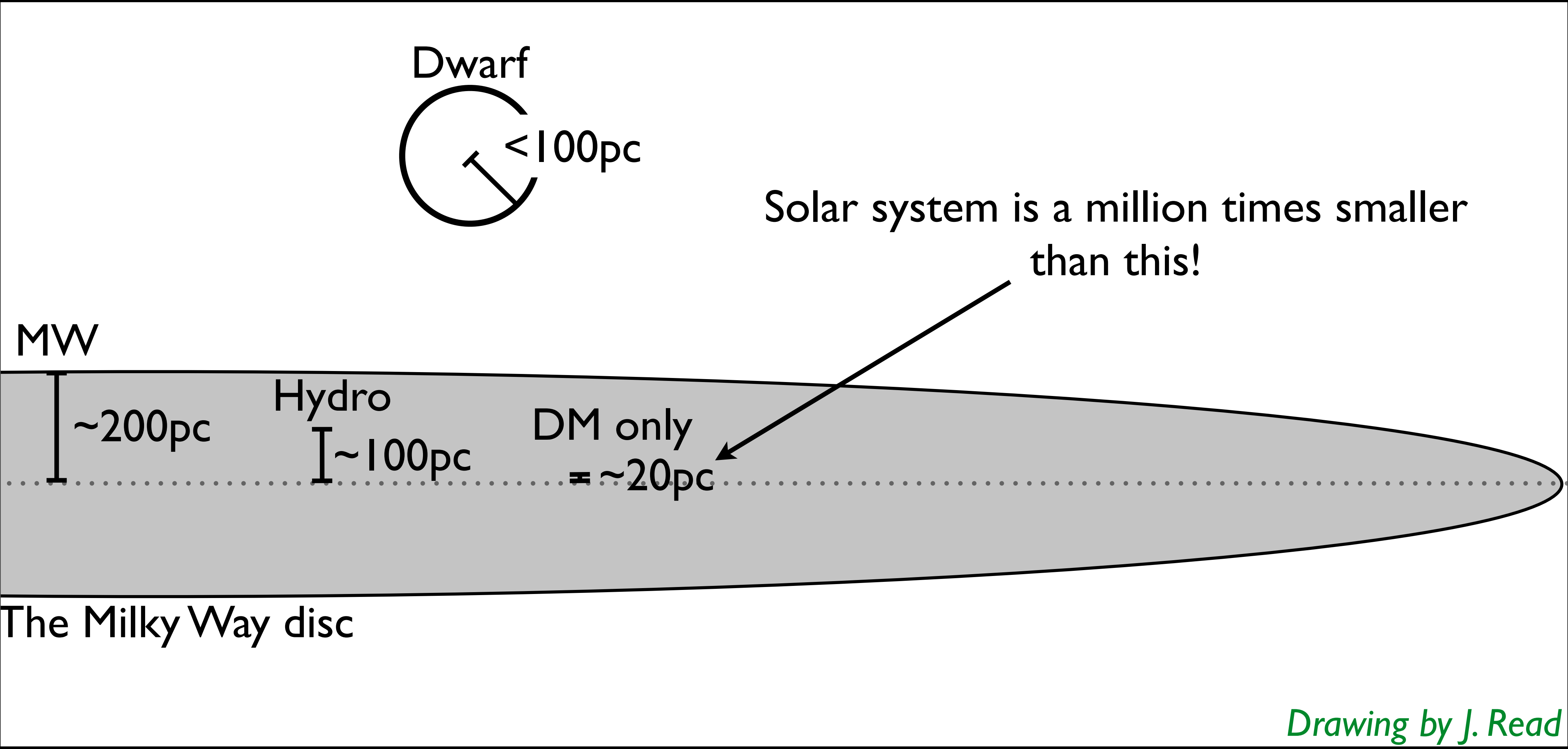



Our galaxy is inside a halo of dark matter particles

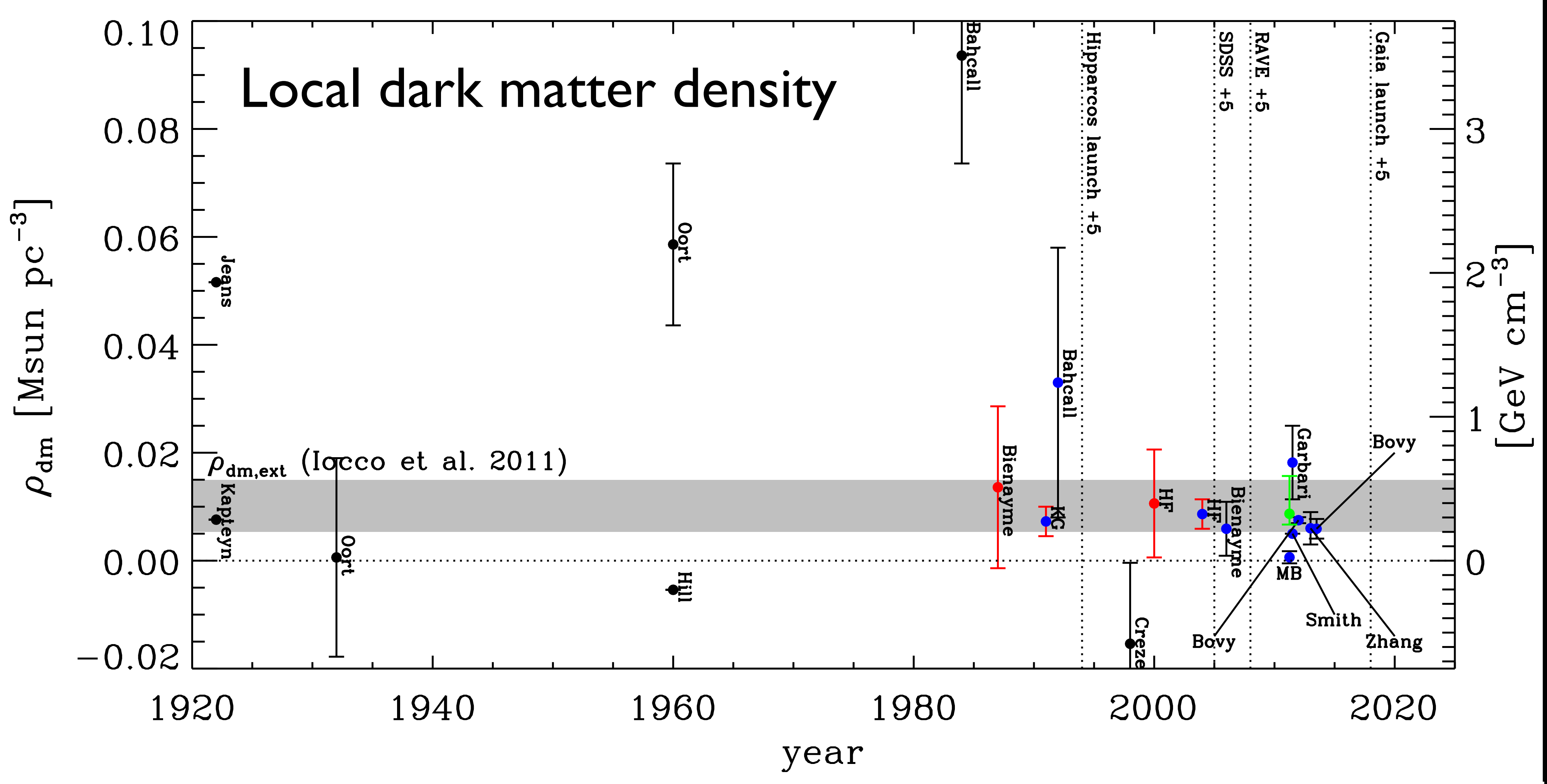
1 kpc = $2.06 \times 10^{11}$ AU

*Image by R. Powell using DSS data*

# Galactic dark matter



# Galactic dark matter




$$\rho_{\rm dm} = 0.33^{+0.26}_{-0.075}\,{\rm GeV\,cm^{-3}}$$

[volume complete; G12*;R14]

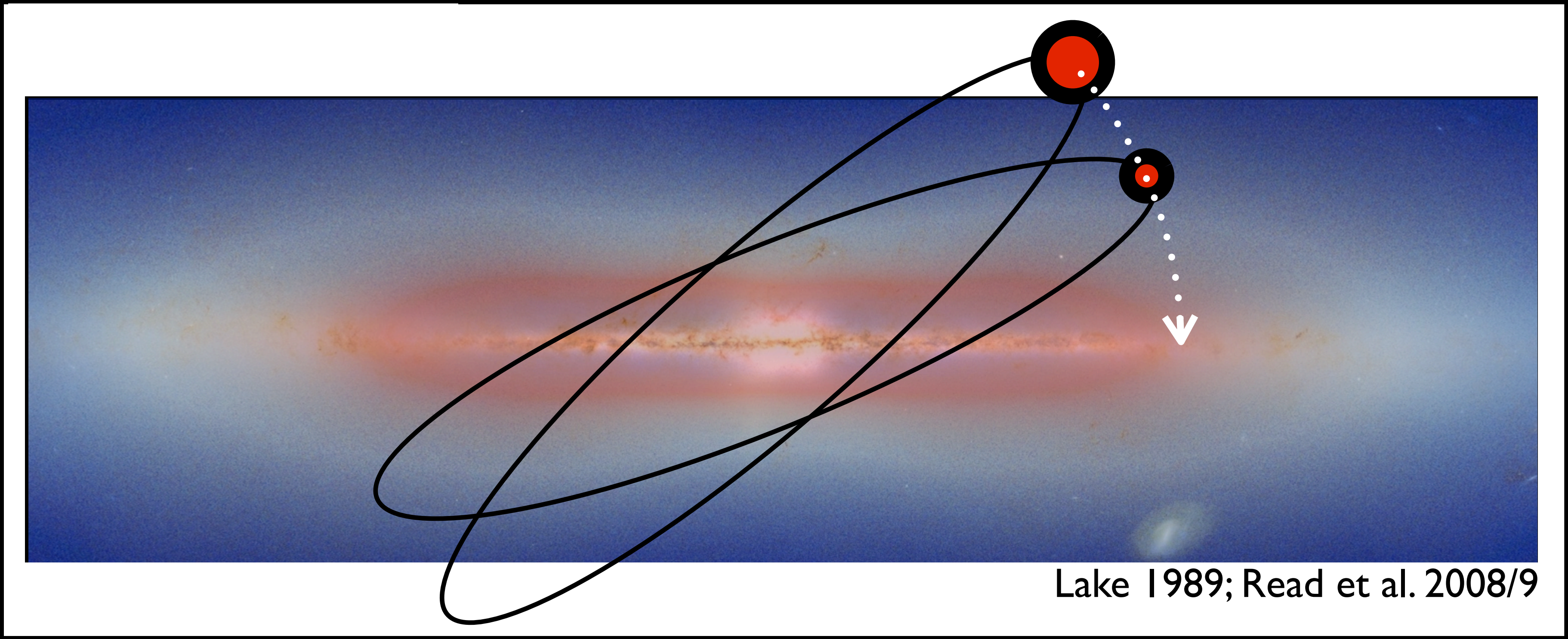
$$\rho_{\rm dm} = 0.25 \pm 0.09\,{\rm GeV\,cm^{-3}}$$

[SDSS; Z13]

*Read at IDM 2014*

# Galactic dark matter

Dark disks arise from dynamical friction on accreted satellites



Lake 1989; Read et al. 2008/9

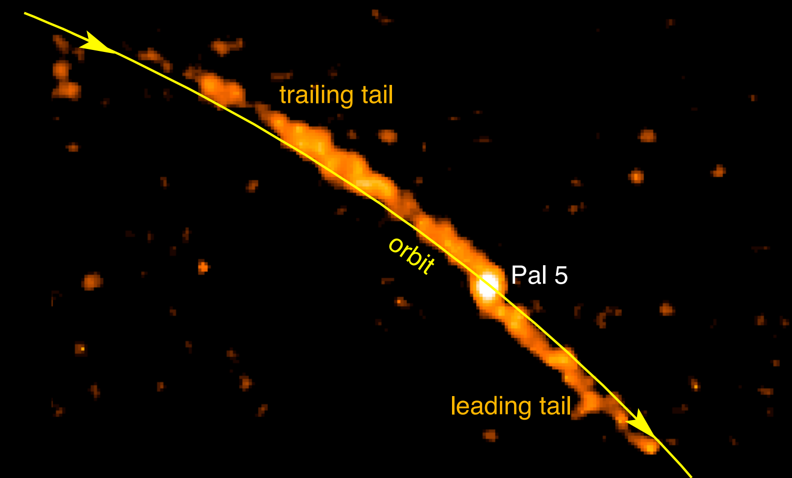
*Our galaxy had no recent major merger, thus no significant dark disk.*

# Galactic dark matter

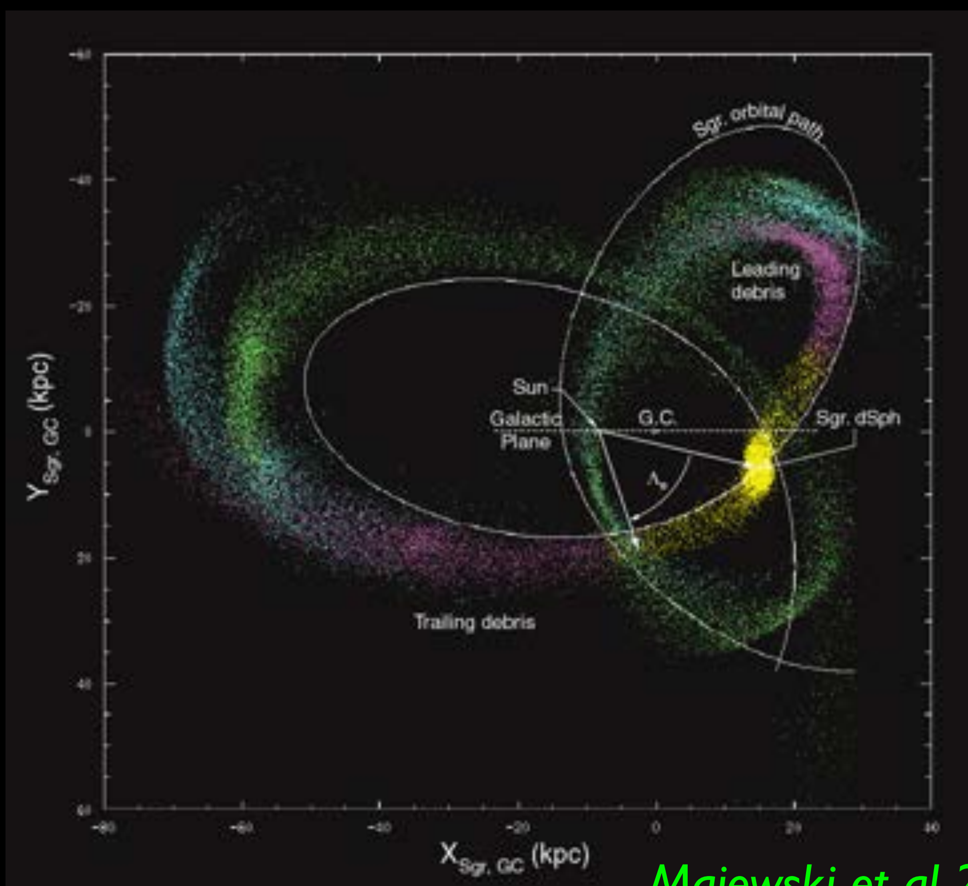
Tidal forces can destroy subhalos and generate tidal streams

*Streams of stars have been observed in the galactic halo*

SDSS, 2MASS, SEGUE,…….



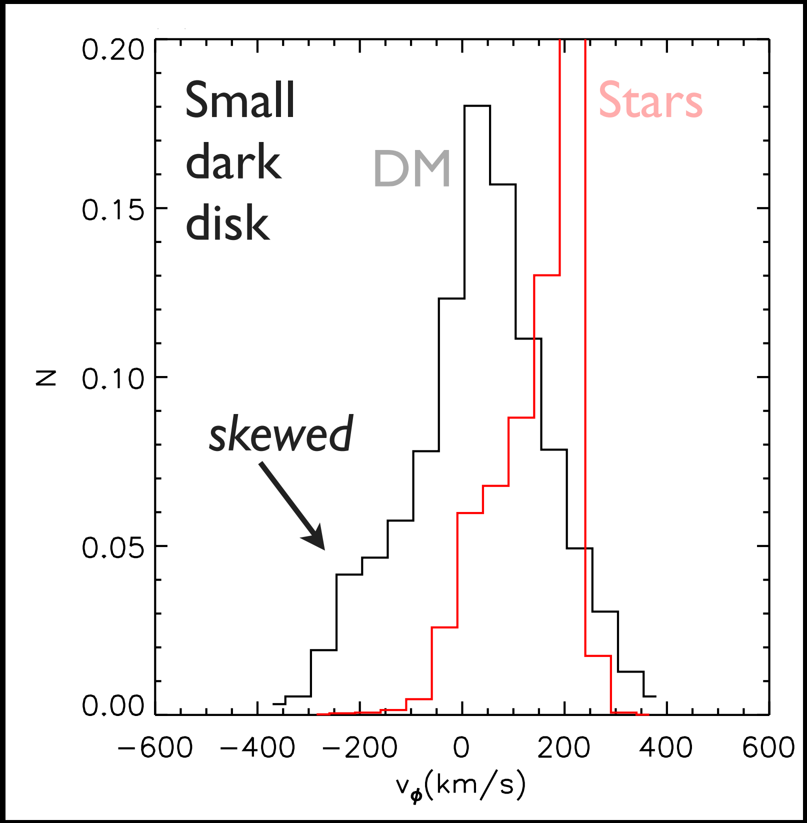

*Odenkirchen et al 2002 (SDSS)*



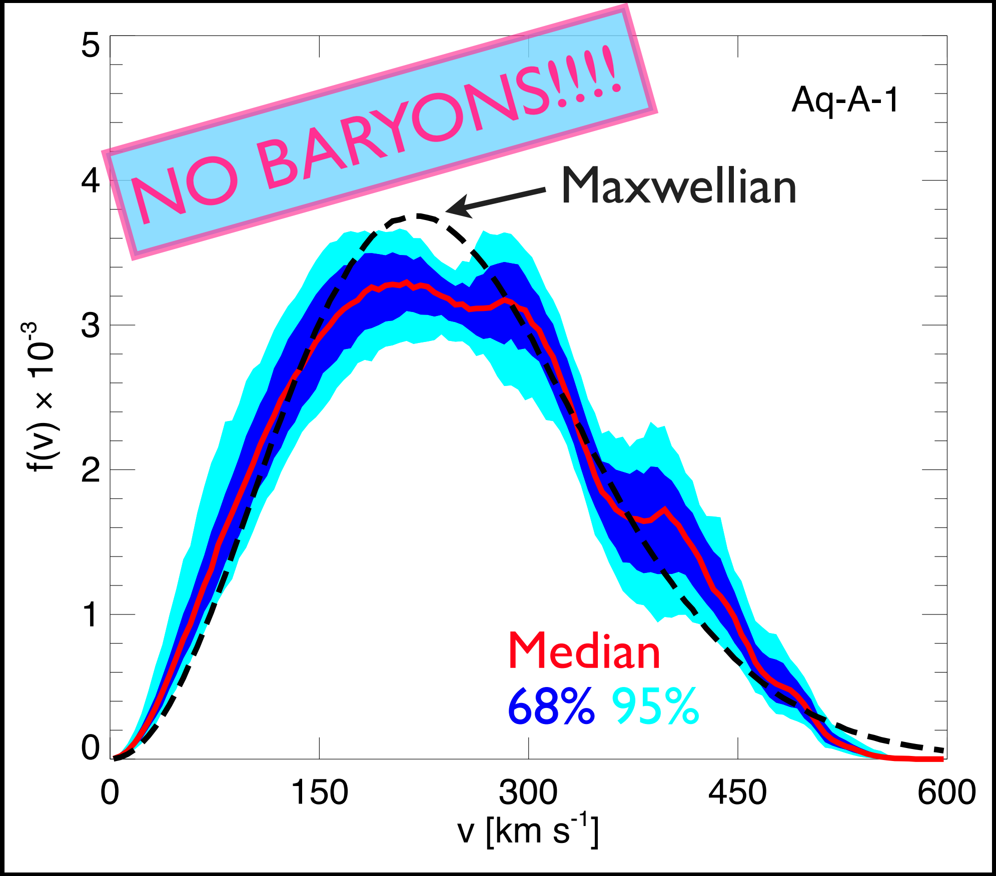

*Majewski et al 2013 (2MASS)*

# Galactic dark matter

We know very little about the dark matter velocity distribution near the Sun




Read et al 2009

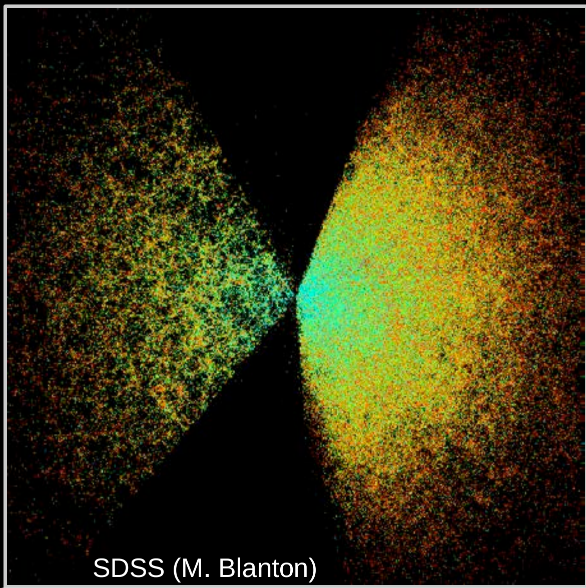


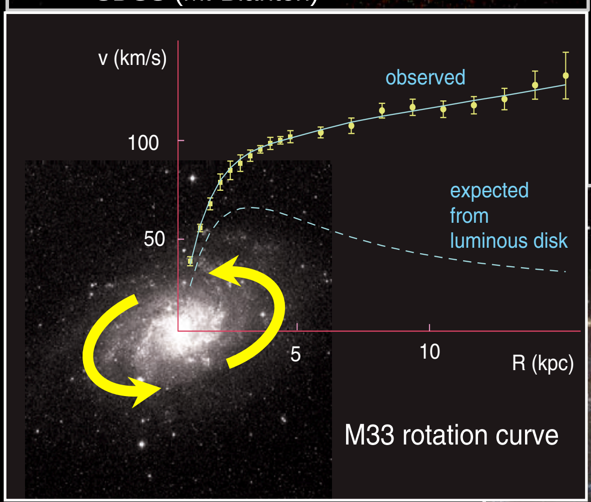

Vogelsberger et al 2009

*Cosmological N-Body simulations including baryons are challenging*

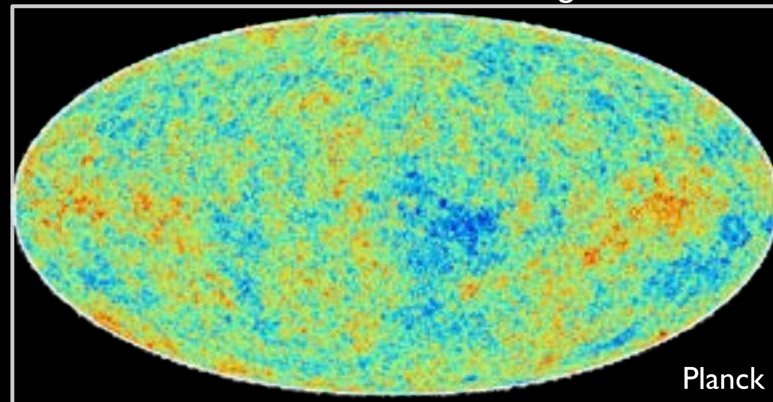
# Evidence for cold dark matter

Large Scale Structure



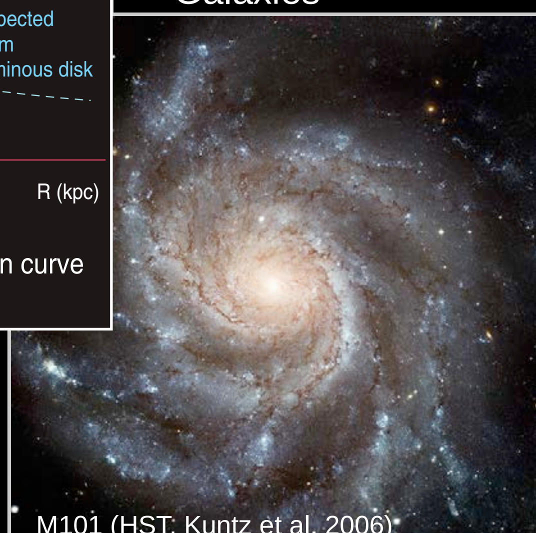




Cosmic Microwave Background

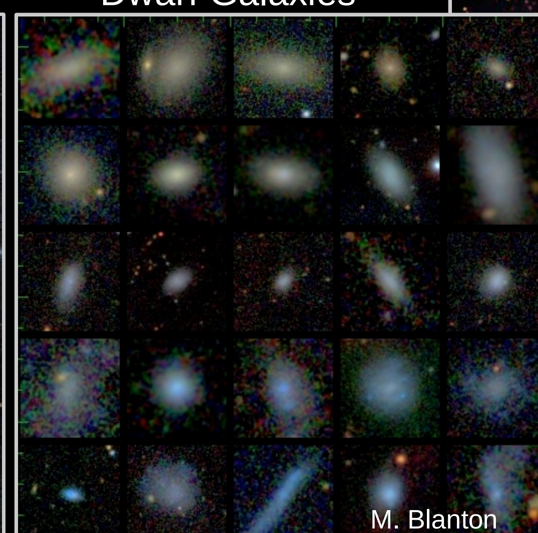



Supernovae

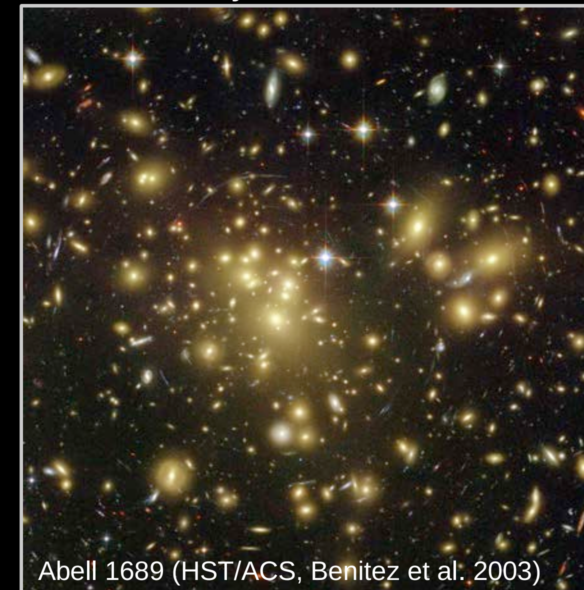

Galaxies

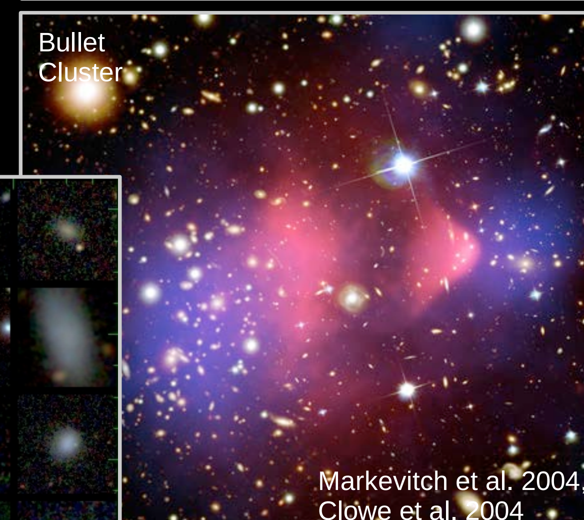



Dwarf Galaxies




Galaxy Clusters



# The warning

"For any complex physical phenomenon there is a simple, elegant, compelling, wrong explanation."

*Thomas Gold, 1920-2004, Austrian-born astronomer at Cambridge University and Cornell University*