Dark Matter

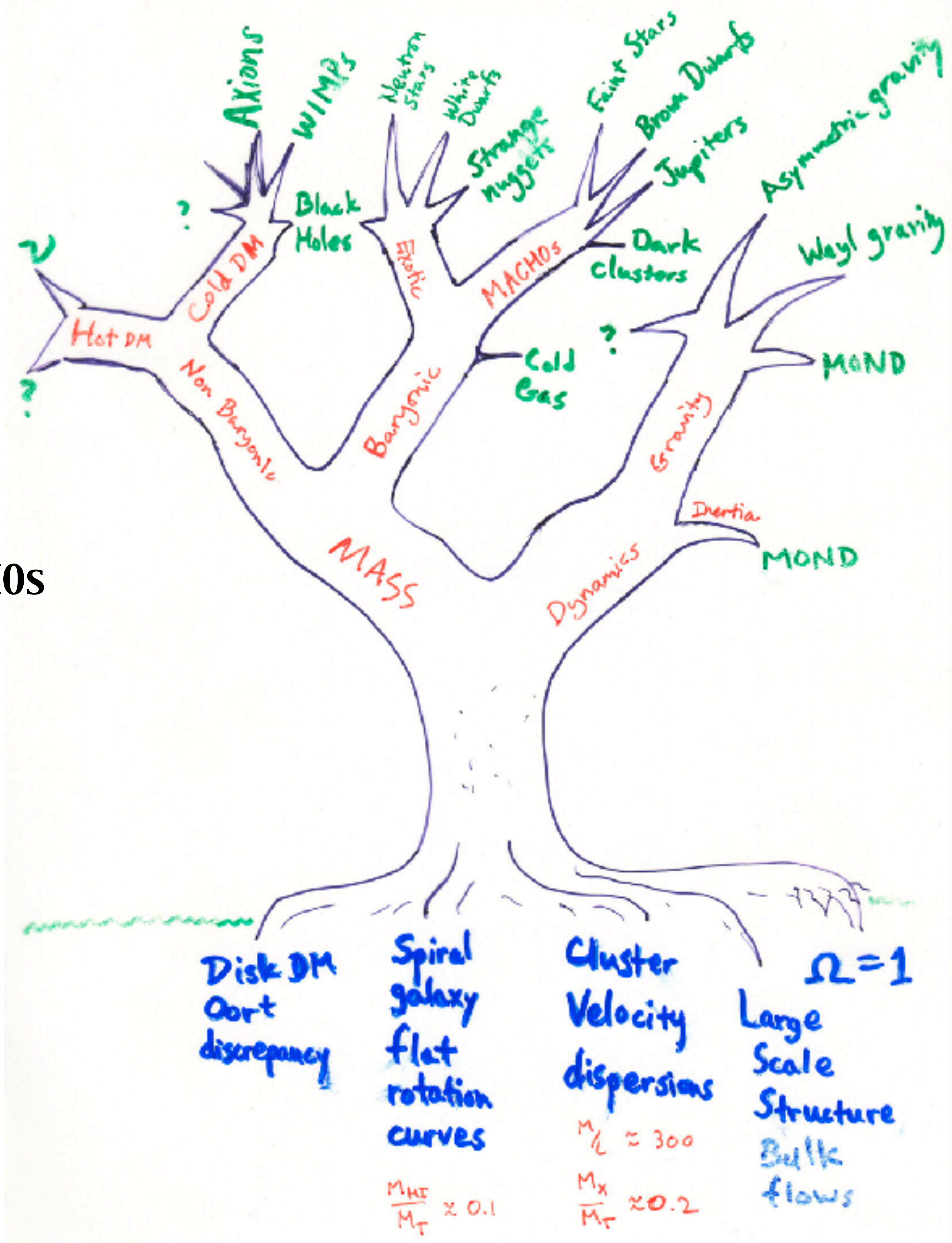
ASTR 333/433

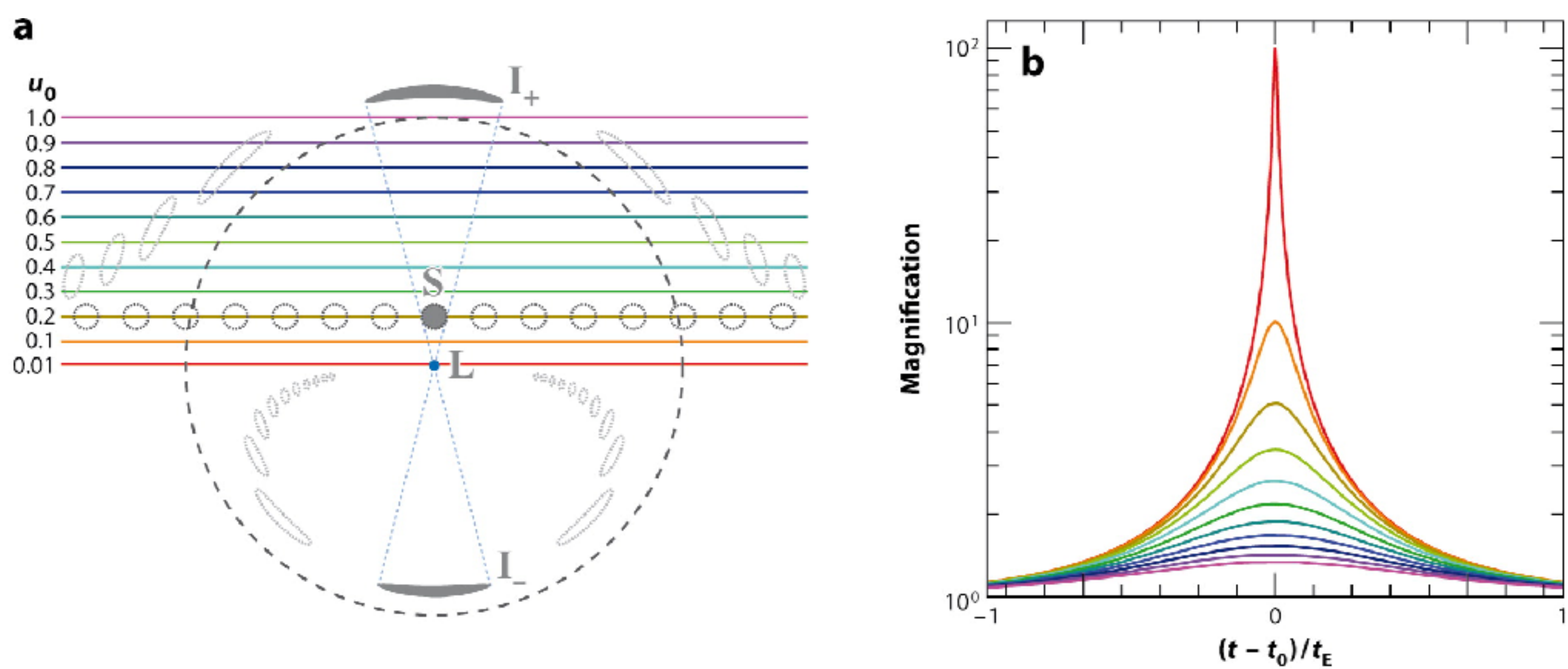
Today

Microlensing constraints on MACHOs
Cosmology

ASTR 433 Projects
4/17: distribute abstracts
4/19: 20 minute talks

4/24: Homework 4 due
4/26: Exam





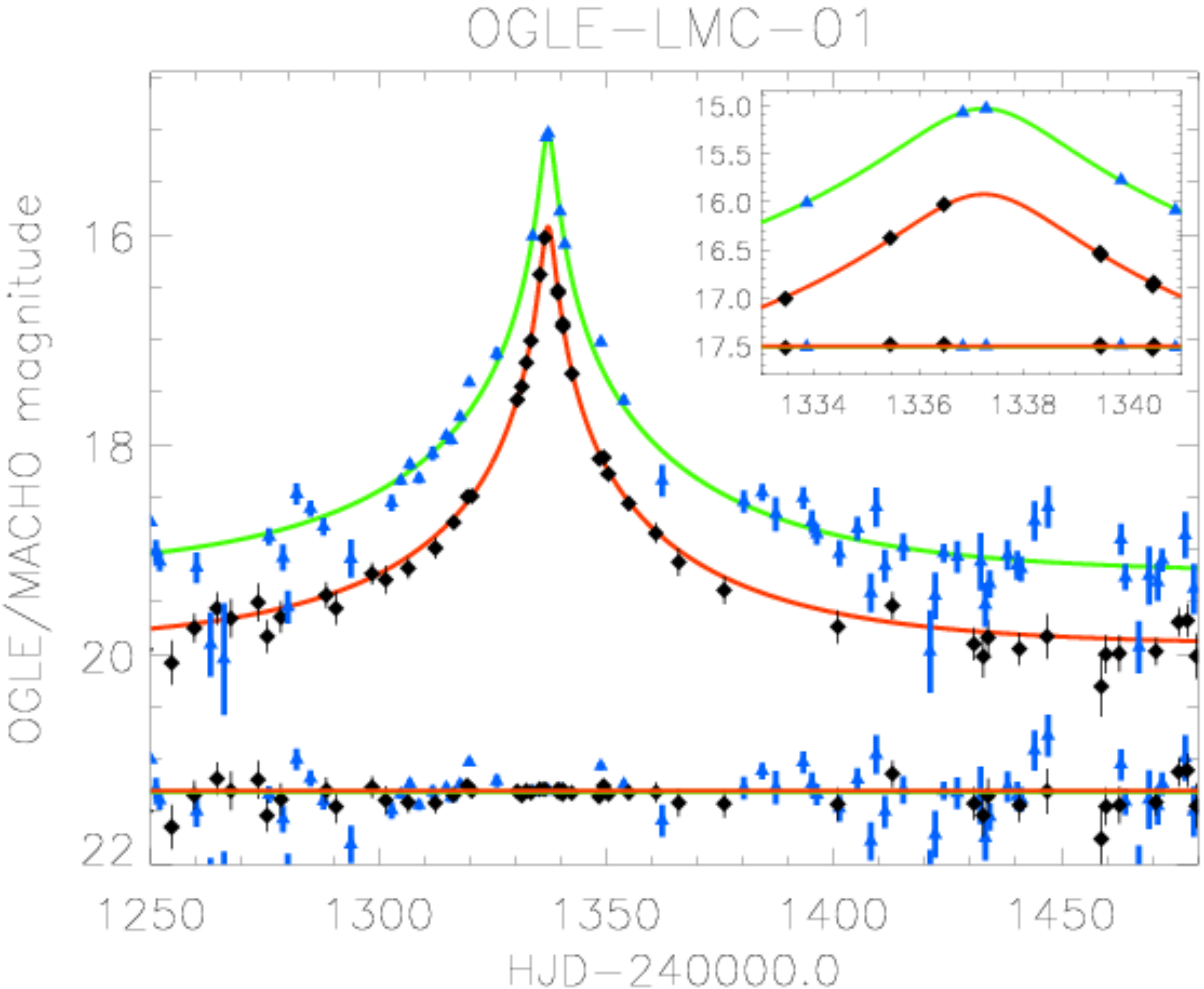
Gaudi BS. 2012.
Annu. Rev. Astron. Astrophys. 50:411–53

$$t_E = \frac{\theta_E}{\mu_{rel}}$$

Einstein crossing time: time to cross Einstein ring.

$$t_E \approx (24.8\ \text{days}) \underbrace{\left(\frac{M}{0.5\ \mathrm{M}_\odot}\right)^{1/2}}_{\textit{lens mass}} \underbrace{\left(\frac{\pi_{rel}}{125\ \mu\text{as}}\right)^{1/2}}_{\textit{parallax}} \underbrace{\left(\frac{\mu_{rel}}{10.5\ \text{mas yr}^{-1}}\right)^{-1}}_{\textit{proper motion}}$$

for lensing events towards the Galactic bulge.



achromatic macho candidate event

Number of microlensing events

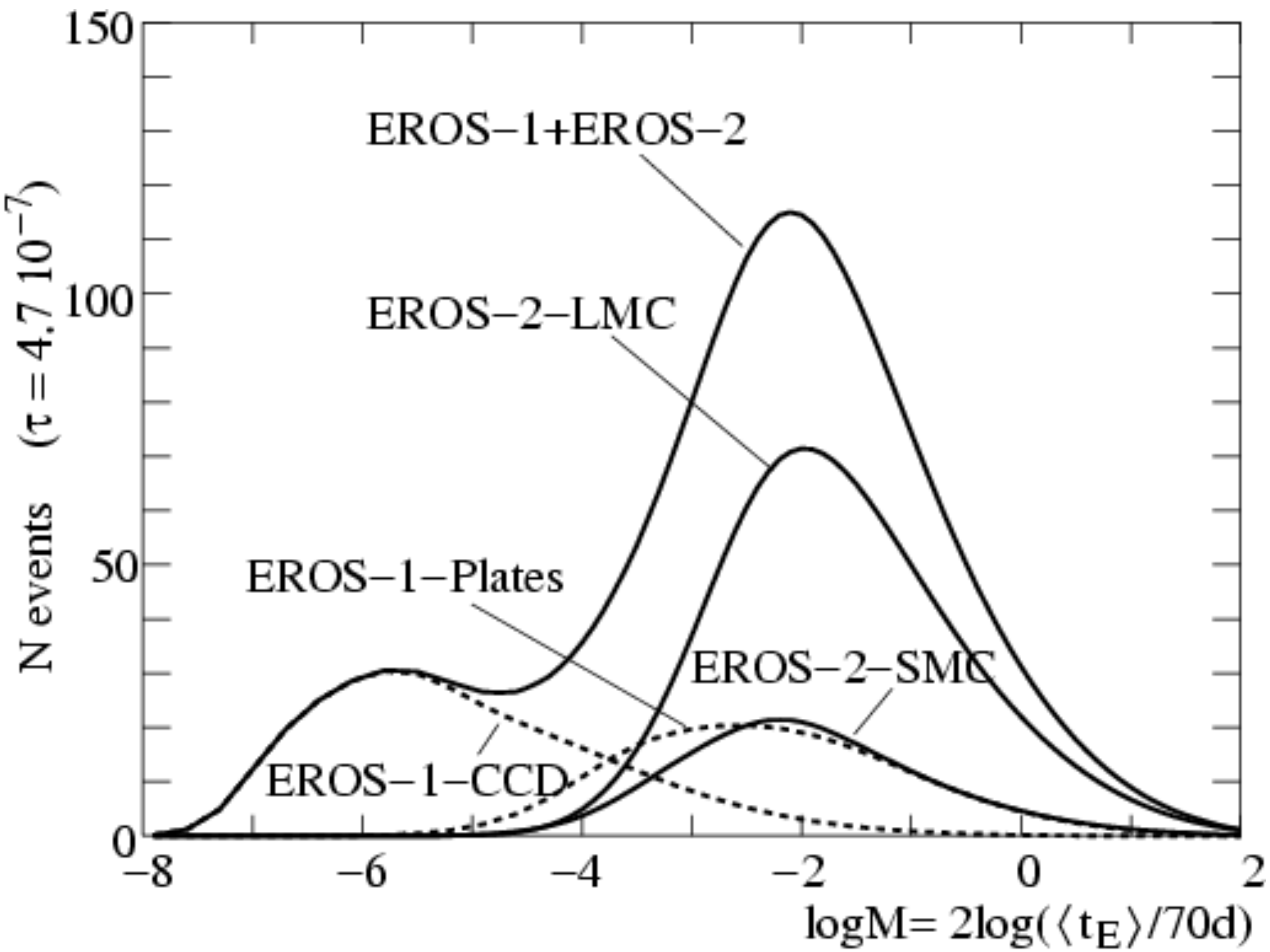
$$N(>A) = \frac{2\tau}{(A^2-1) + A\sqrt{A^2-1}}$$

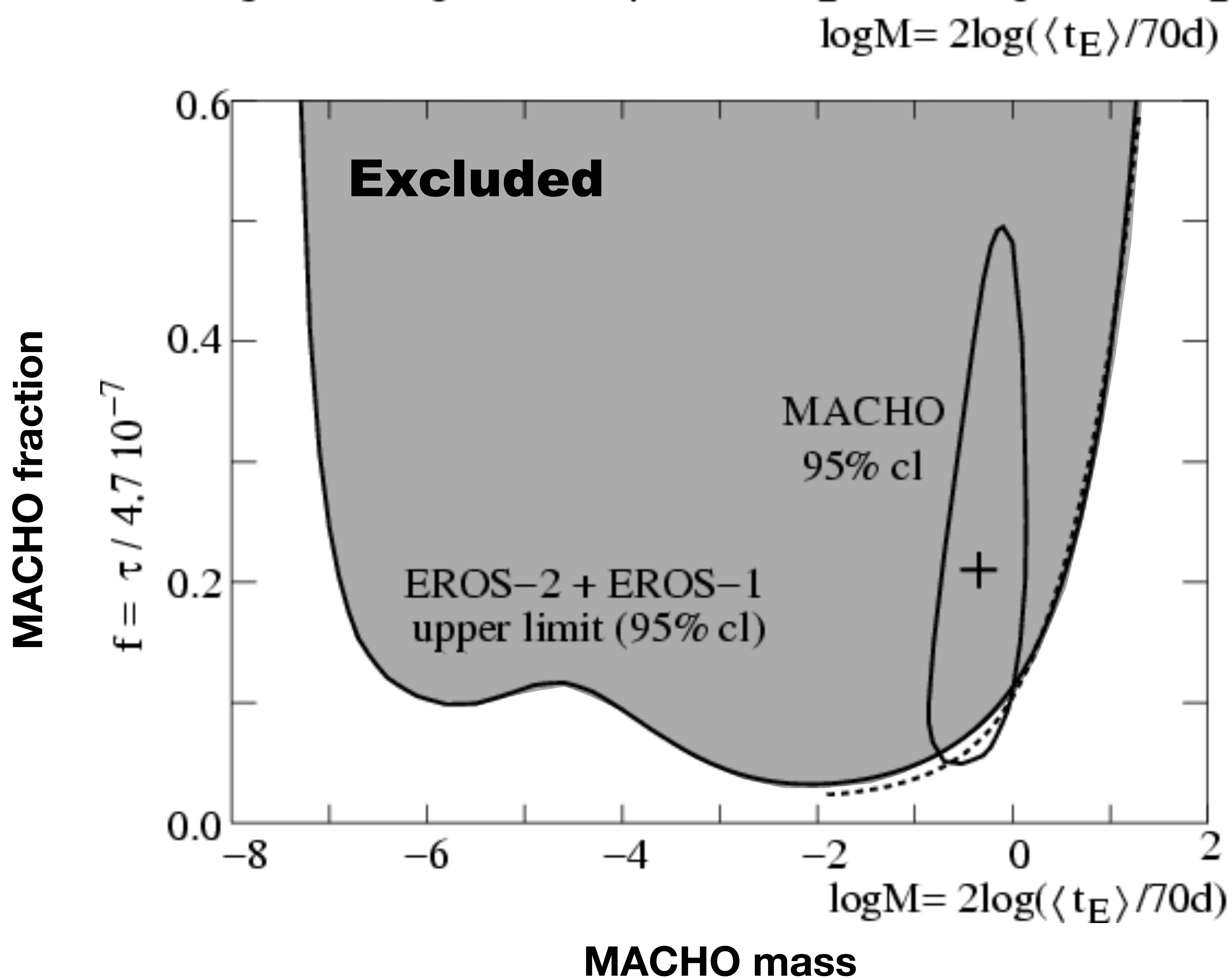
optical depth as a fcn of radius through an isothermal sphere

$$\tau = 2\pi \frac{\sigma_V^2}{c^2} \frac{D_L D_{LS}}{r D_s}$$

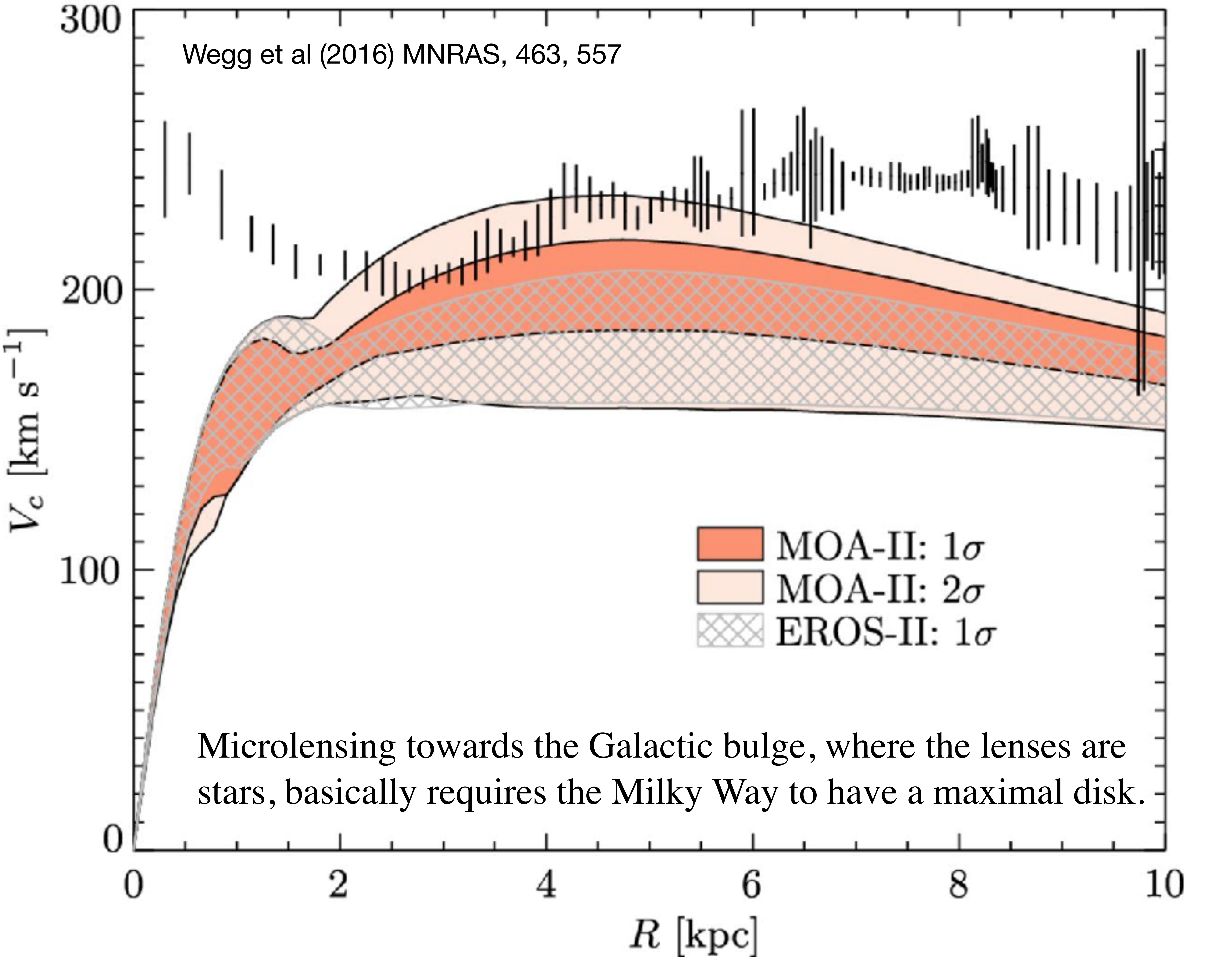
optical depth = fraction of the sky covered by Einstein rings

Number of microlensing events expected if all the halo mass is in MACHOs



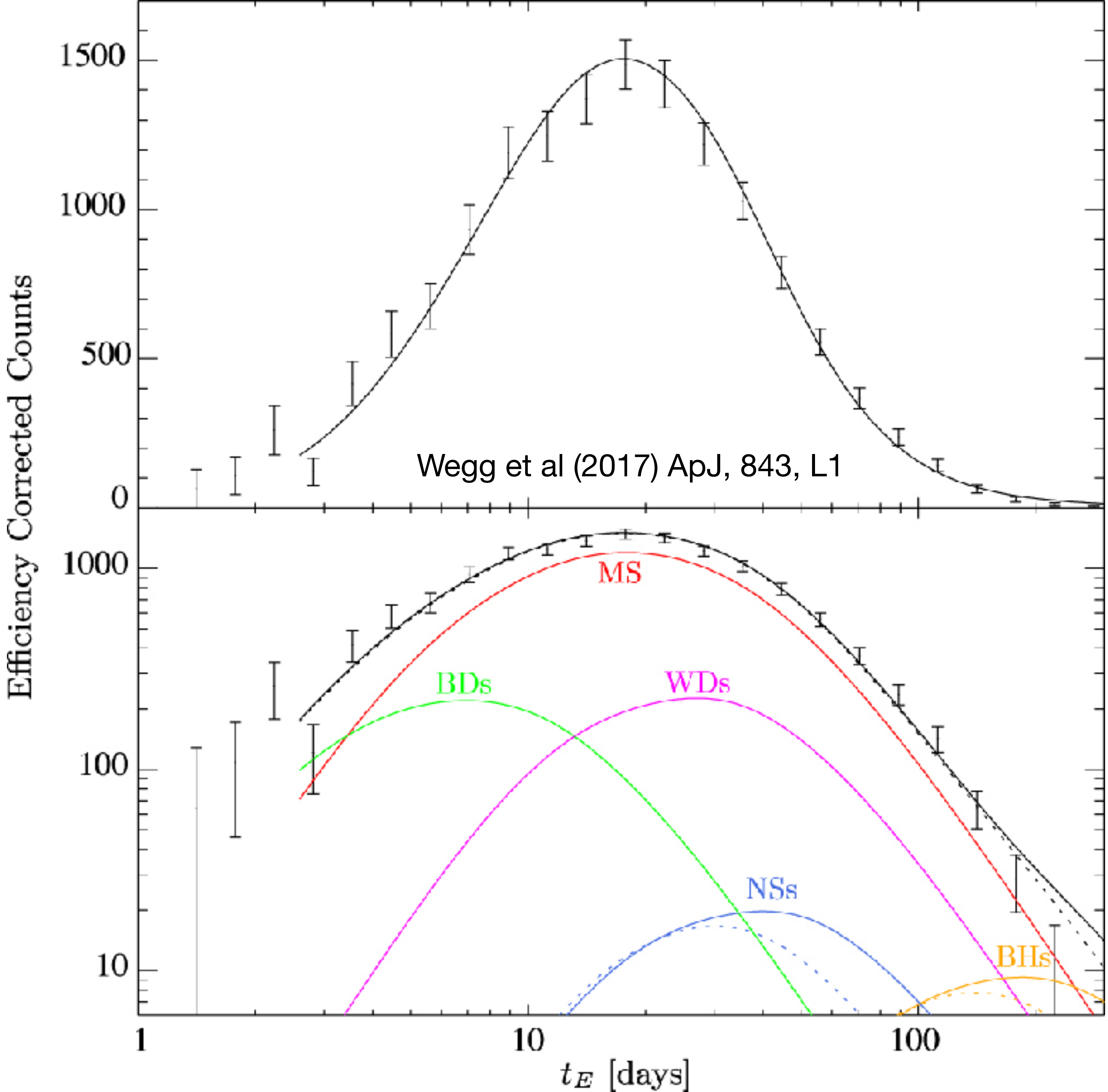


The observed rate of microlensing events leaves no room for the dark matter halo of the Milky Way to be composed of massive compact objects like brown dwarfs or black holes in the mass range $10^{-7} < M < 10$ solar masses.



Microlensing towards the Galactic bulge, where the lenses are stars, basically requires the Milky Way to have a maximal disk.

Also constrains the IMF to be basically the same as seen everywhere else.



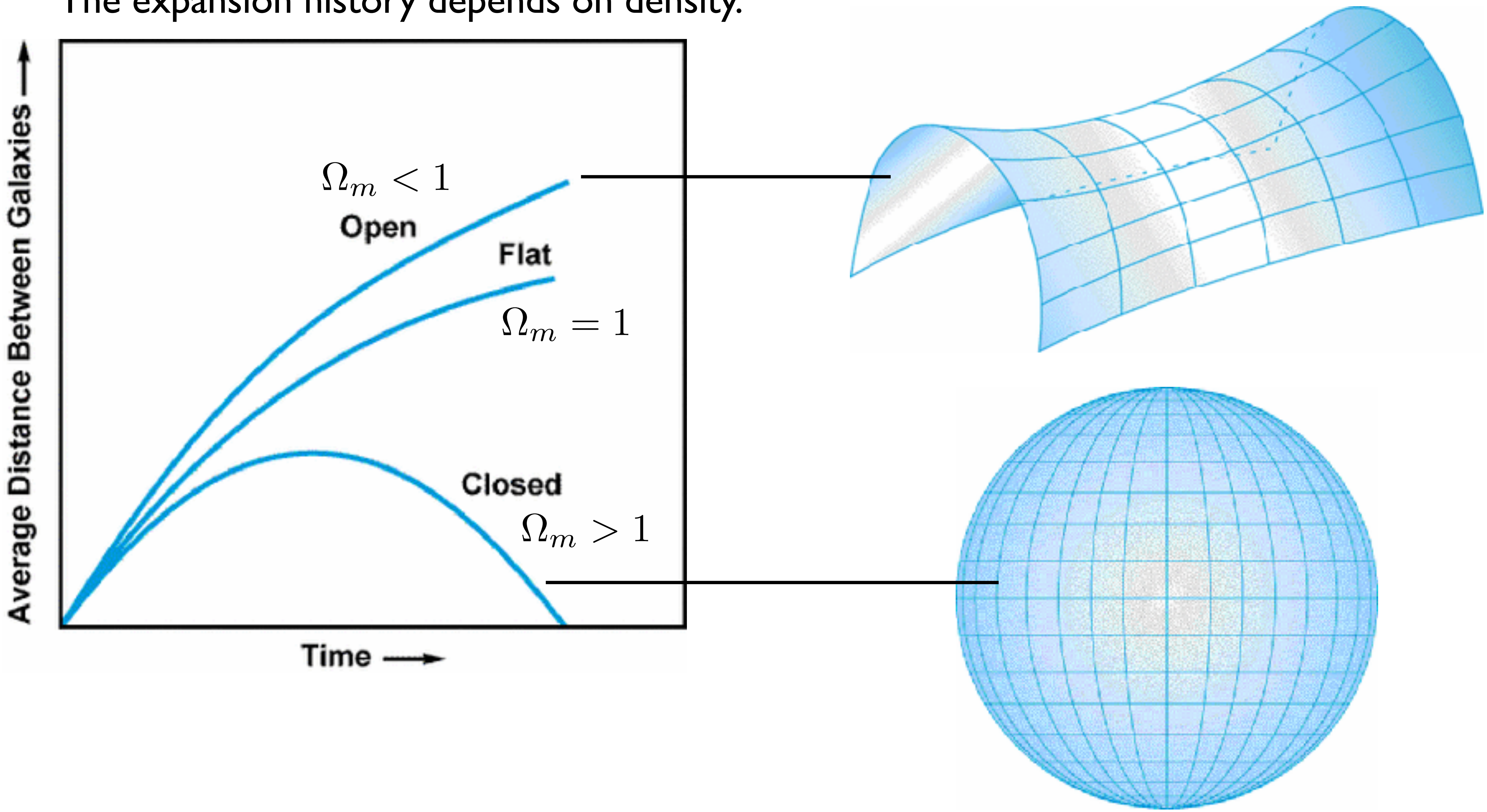
Empirical Pillars of the Hot Big Bang

1. Hubble Expansion
2. Big Bang Nucleosynthesis
3. Cosmic Microwave Background

Auxiliary Hypotheses

- Dark matter
- Dark Energy

The expansion history depends on density.



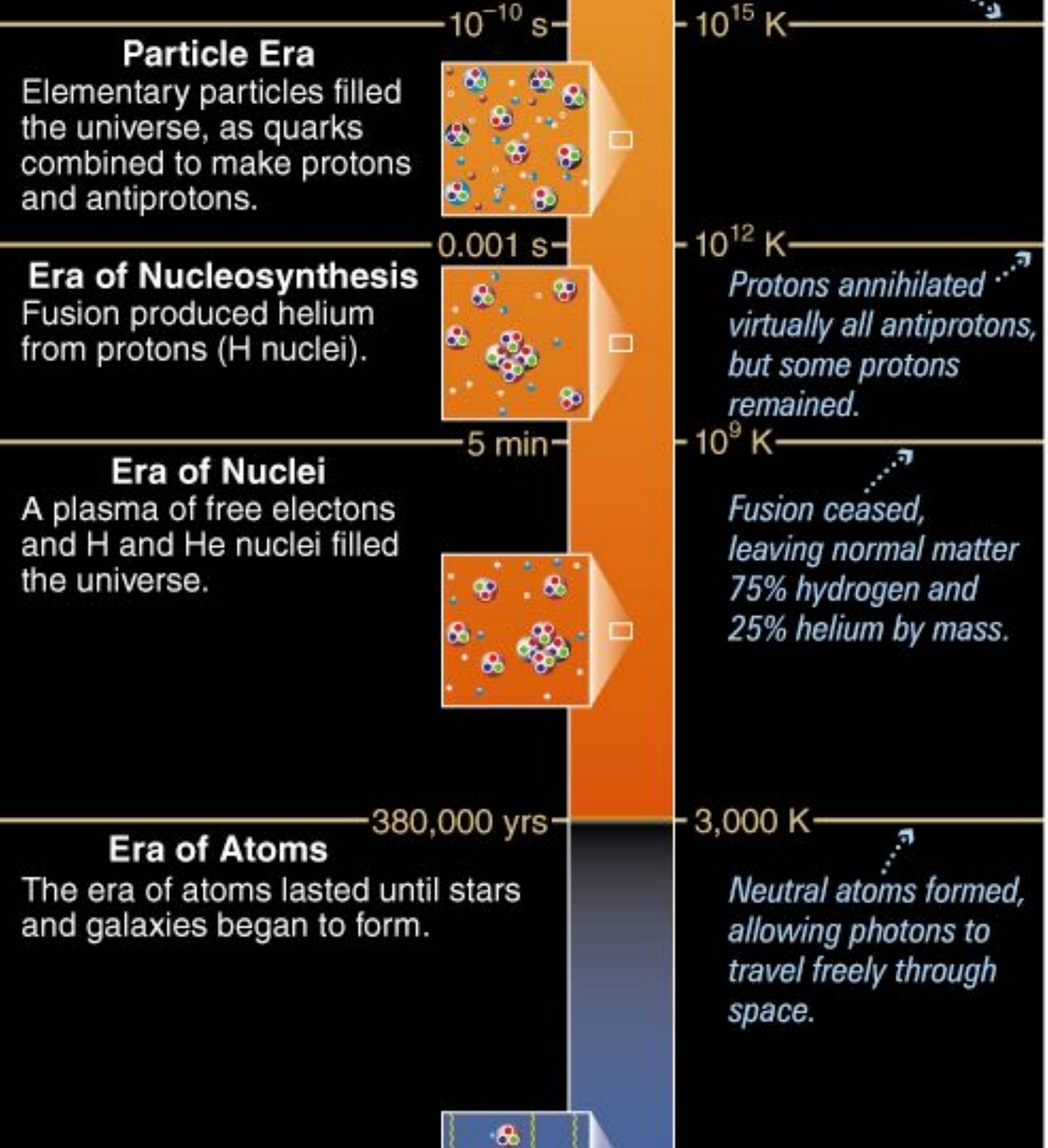
The expansion history and the geometry of the universe are both related to the density.

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

mass density

cosmological constant

curvature



particle soup

< millisecond

$T \sim 10^{14}$ K

nucleosynthesis

~ 3 minutes

$T \sim 10^{10}$ K

recombination

~380,000 year

$T \sim 3000$ K

emission of CMB: surface of last scattering

Basic parameters of cosmology

	H_0	Expansion rate	72 km/s/Mpc	
mass density	Ω_m		0.3	
	Ω_b	0.05		baryons
	Ω_{CDM}	0.25		not baryons
	Ω_Λ		0.7	dark energy
	σ_8	power spectrum	0.8	
	n_s	power spectrum	0.96	

Measurements of the gravitating mass density

- Cluster M/L
  - measure M/L of a cluster, combine with measured luminosity density of universe.
- Weak lensing
  - measure shear over large scales
- Peculiar Velocity Field
  - measure deviations from Hubble flow
- Power spectrum of galaxies
- CMB fits

Virgocentric infall

The Virgo cluster is the largest nearby over-density.
Its gravity distorts the Hubble flow.
We fall towards it so it appears to recede less than
it should by an amount that depends on its mass

682 TONRY AND DAVIS (1981)

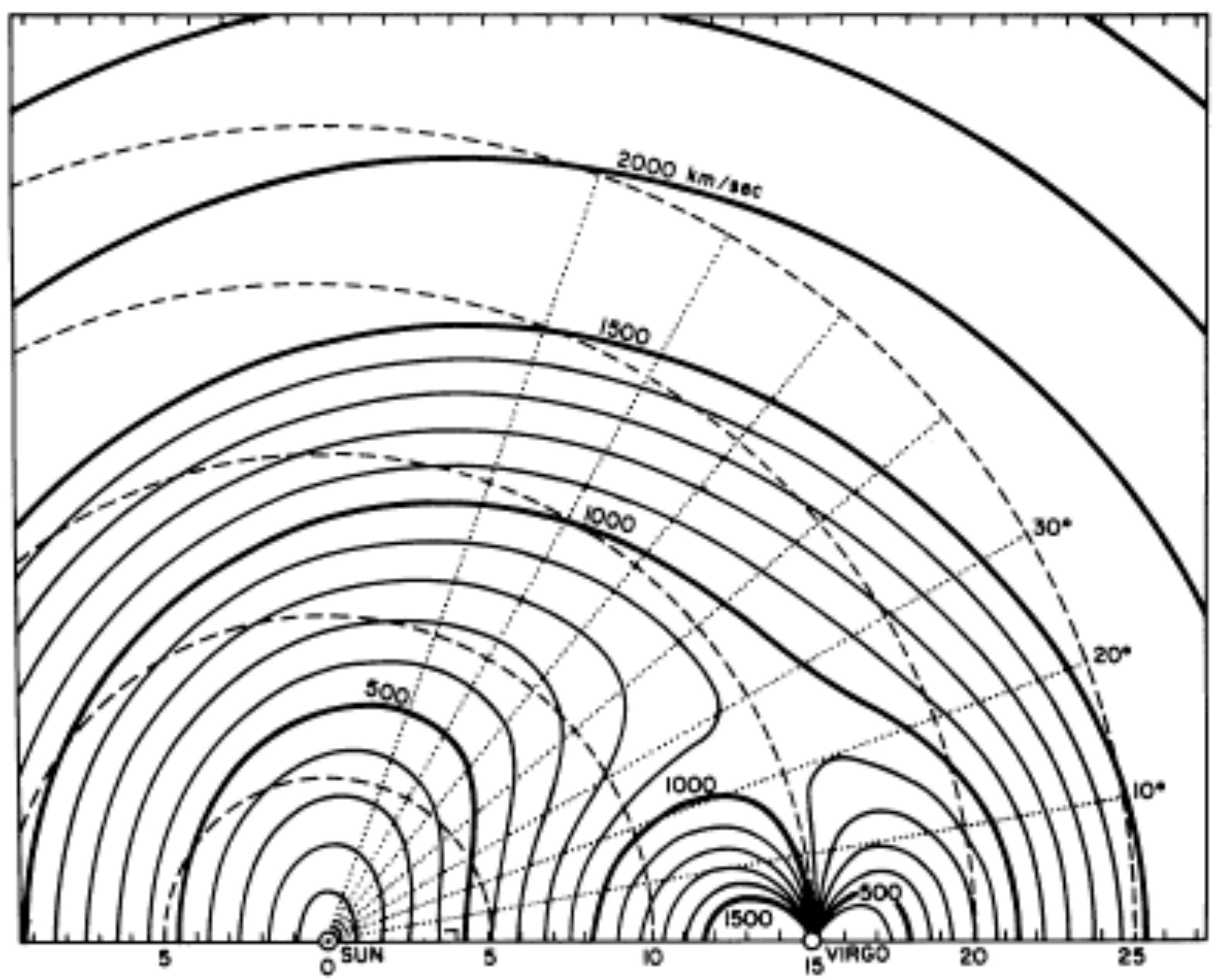


FIG. 1.—On a two-dimensional grid with the Earth and the Virgo cluster on the x axis, redshift contours are plotted for a Hubble flow perturbed by a Virgocentric flow. An infall velocity of 400 km s^{-1} at our position is assumed. A pure Hubble flow would be concentric circles.

Davis et al. (1980) found

$$\Omega_m = 0.4 \pm 0.1$$

with modern distances this becomes

$$\Omega_m = 0.25 \pm 0.05$$

basically unchanged for nearly 40 years

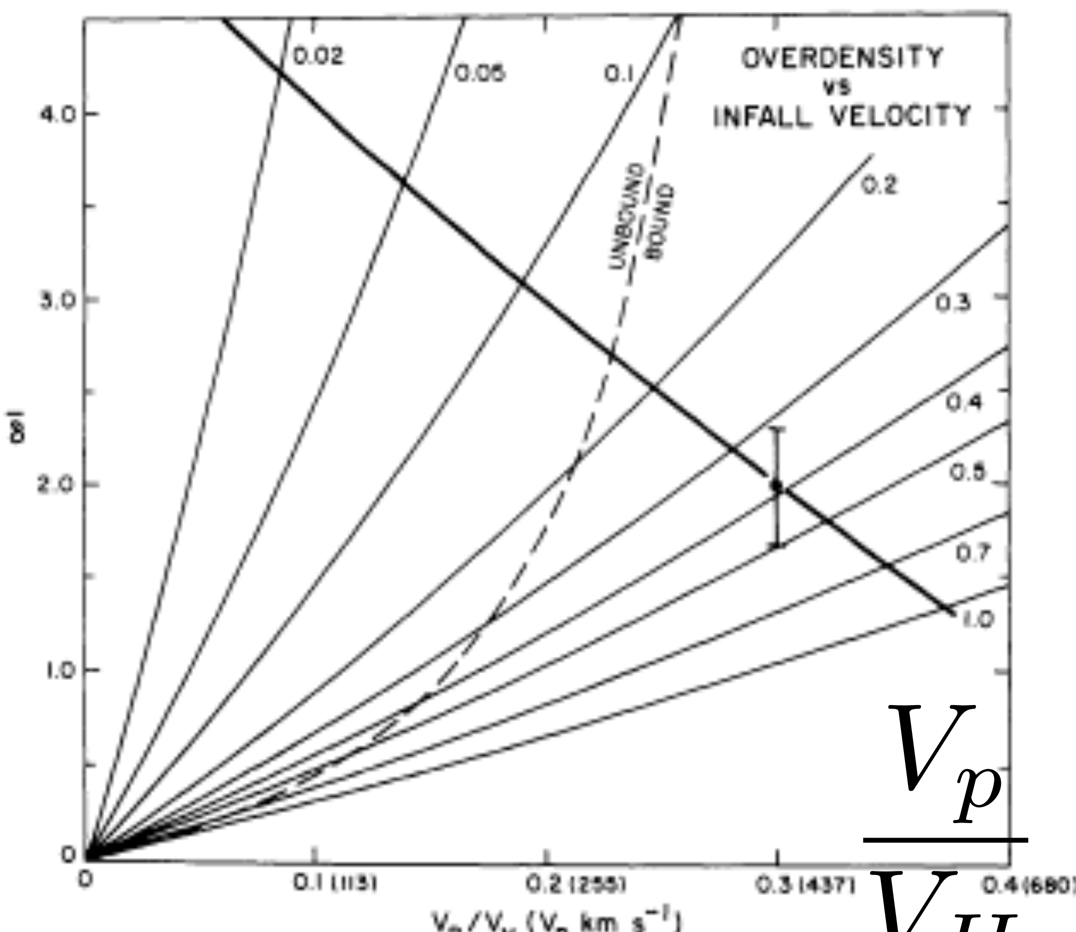
Lines are lines of constant Ω_m

ESTIMATES OF v_p

Velocity	Source
380 ± 75	Smoot and Lubin 1979
480 ± 75	Aaronson *et al*. 1980
350 ± 50	de Vaucouleurs and Bollinger 1979
290 ± 30[a]	Yahil 1980
190 ± 130	Schechter 1968

[a] Calculated with respect to the centroid at the local group as defined by Yahil *et al*. 1977.

$$\frac{\delta\rho}{\rho}$$

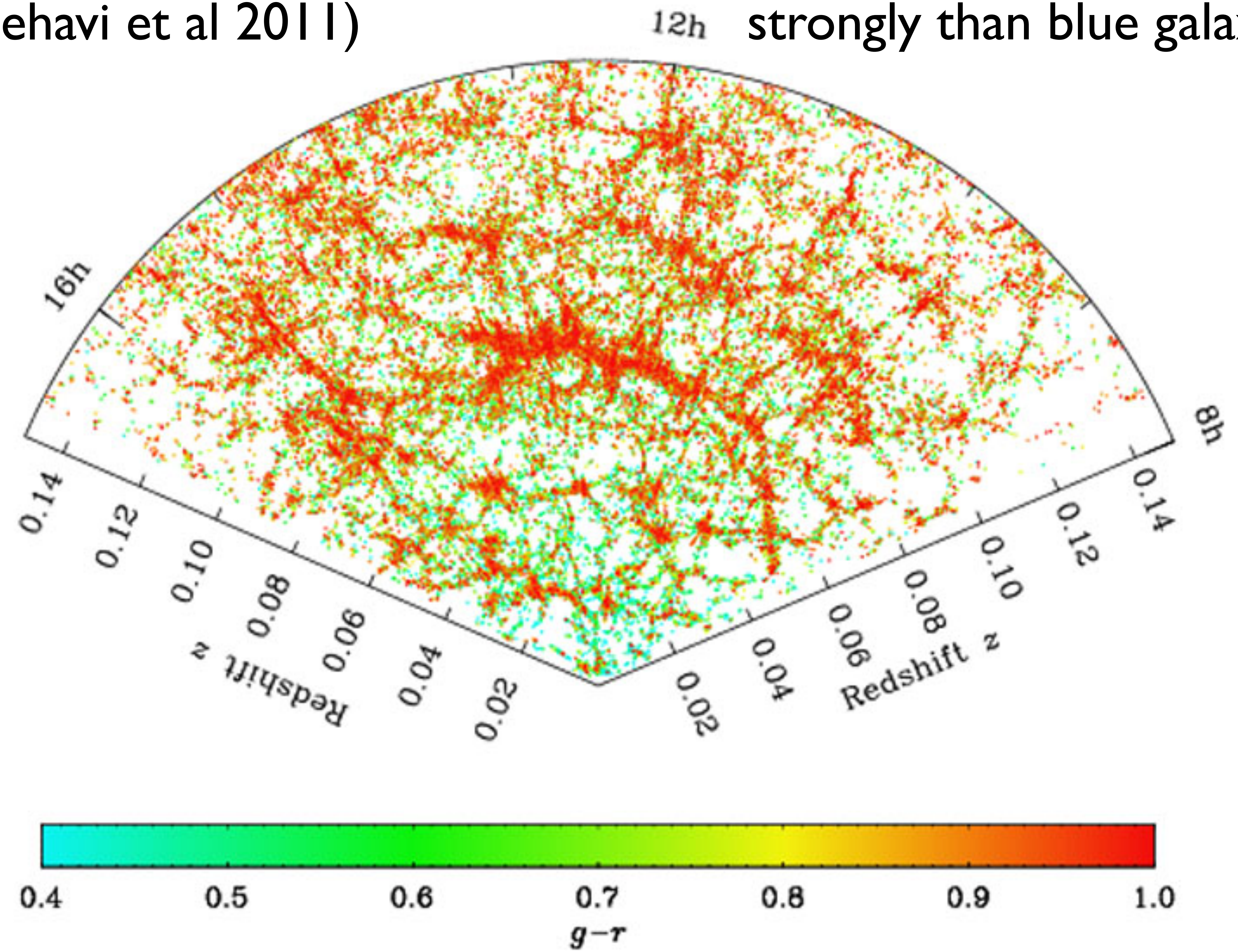


$$\frac{V_p}{V_H}$$

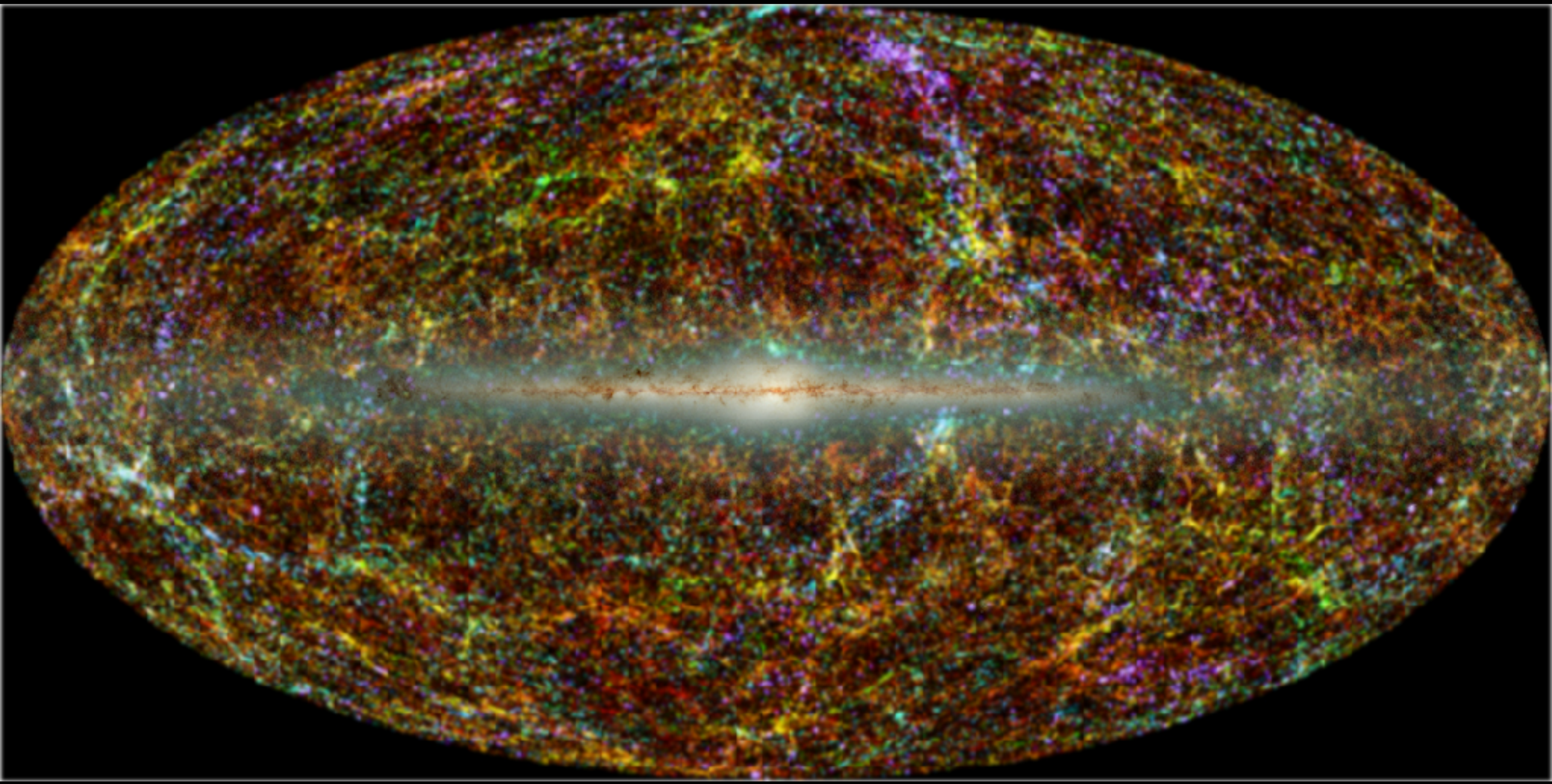
FIG. 1.—The mean overdensity of Virgo vs. v_p/v_H for various values of Ω. The x-axis is also labeled with v_p, using a recessional velocity to Virgo of 1020 km s^{-1}. The measured overdensity is prescribed by the heavy line, and is marked at the favored position as given by the anisotropy of the Hubble flow and microwave background radiation. The error bar is an estimate of the 90% confidence limit of our determination of $\bar{\delta}$. Models to the right of the dotted line are bound to Virgo.

SDSS clustering
(Zehavi et al 2011)

Red galaxies cluster more strongly than blue galaxies



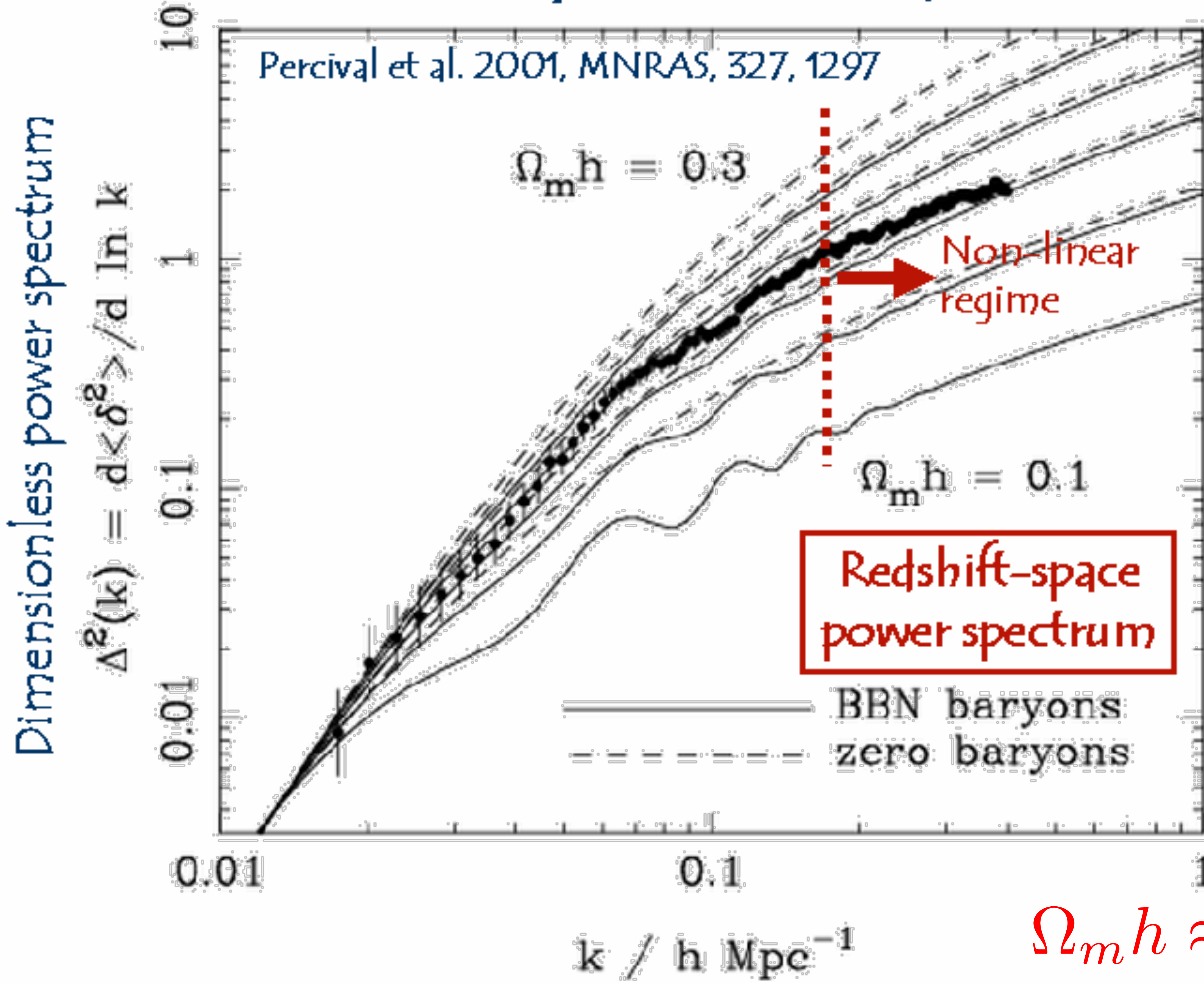
2MASS galaxy distribution on sky in Galactic coordinates



Blue points lower redshift, red points higher redshift

Jarrett et al.

The Galaxy Power Spectrum



$\Omega_m h \approx 0.2$

Basically all data suggest a gravitating mass density

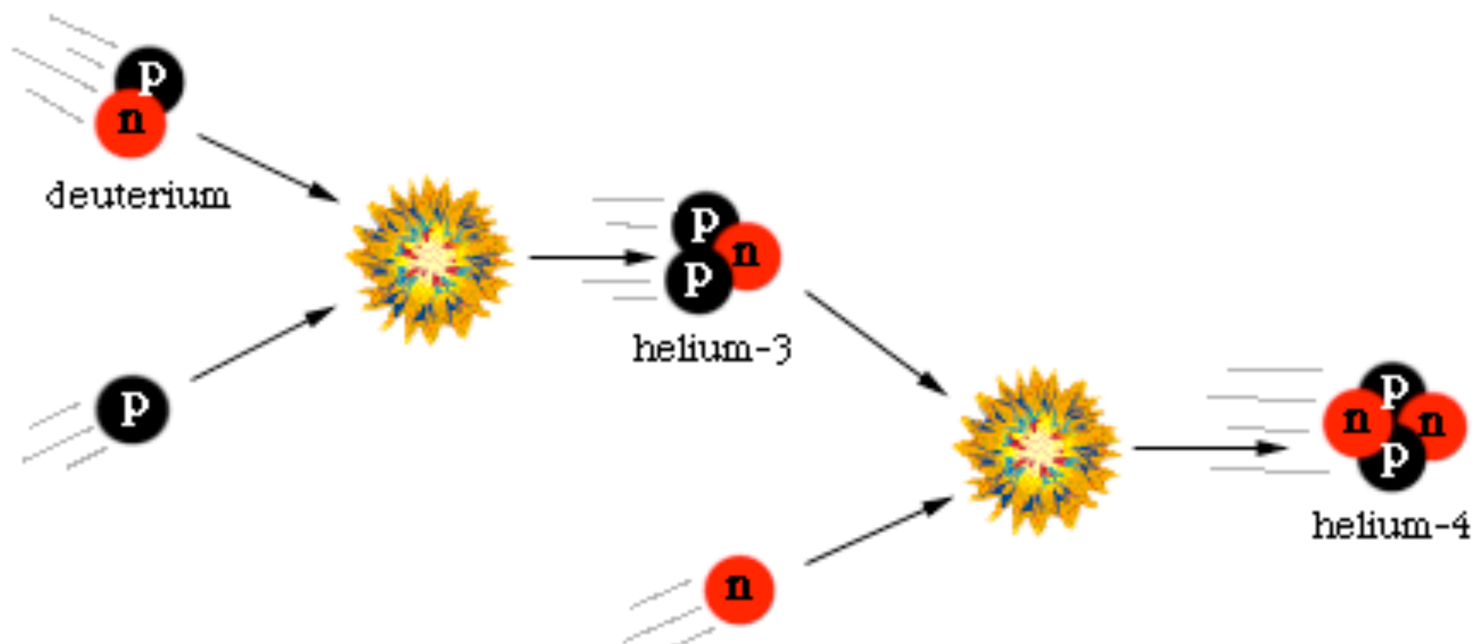
$$\frac{1}{4} < \Omega_m < \frac{1}{3}$$

What about baryons?

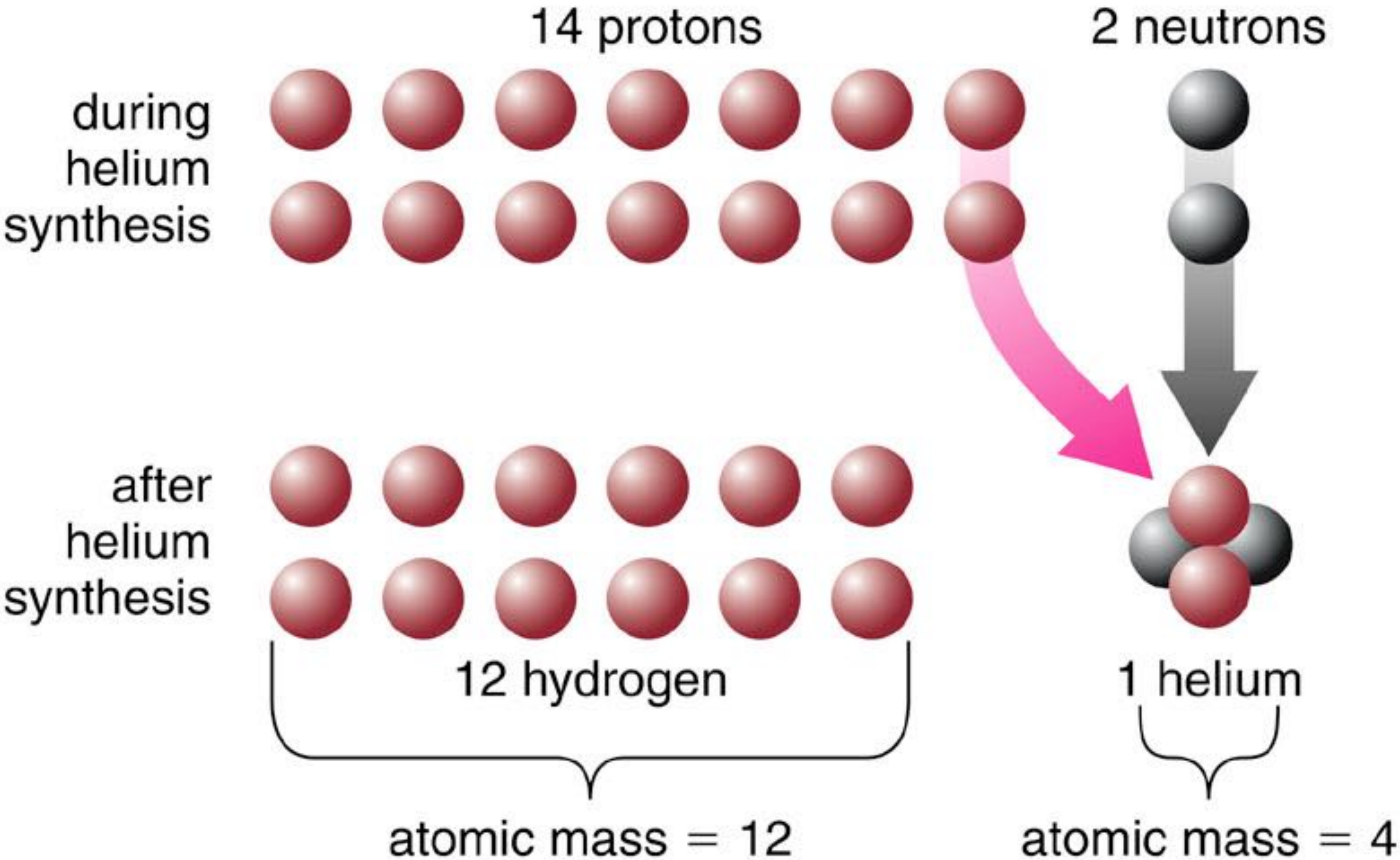
Primordial Nucleosynthesis (BBN):

Gamow

When the universe is just a few minutes old, the Temperature and Density are just right for it to be one Big Nuclear Furnace:

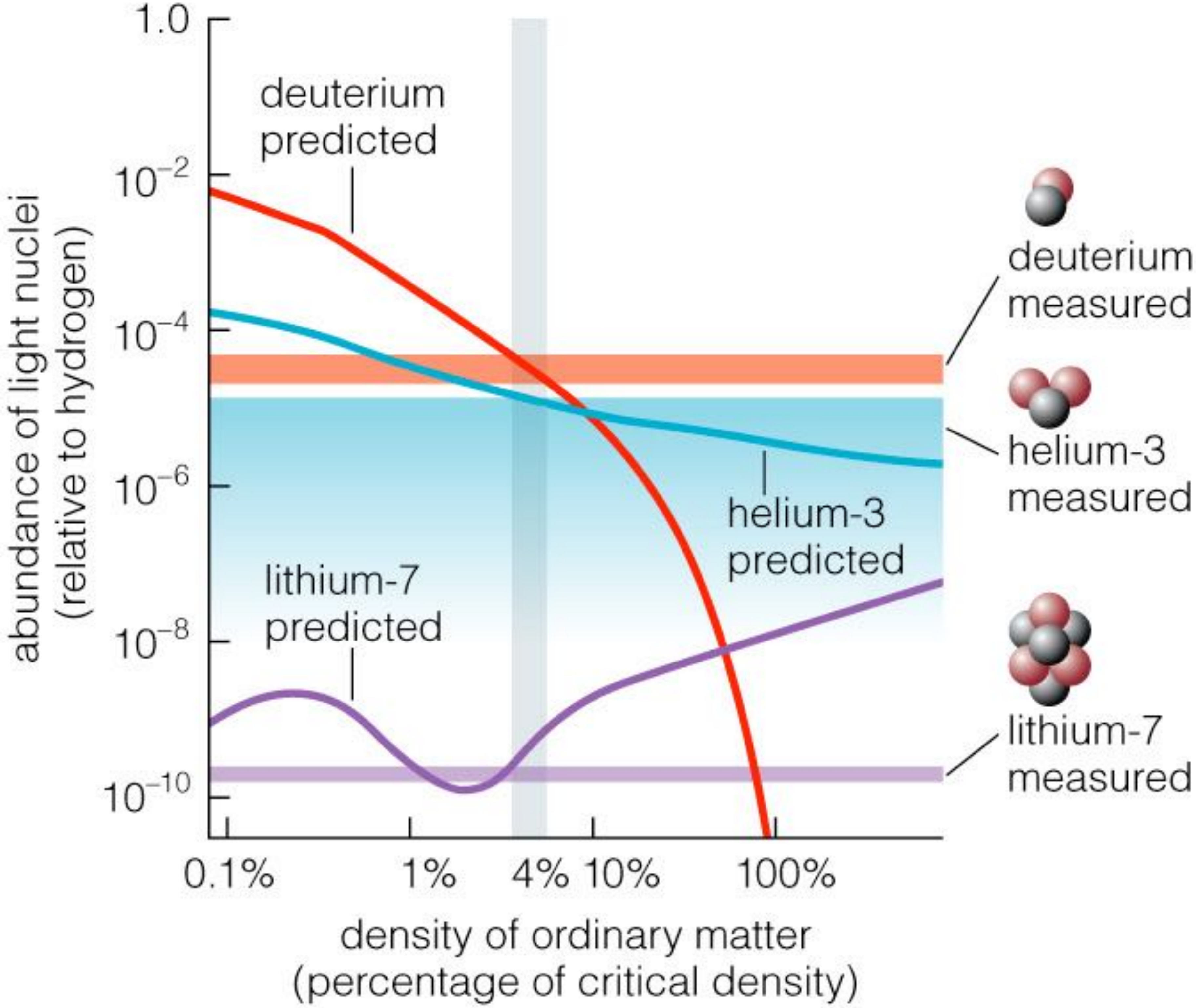


The light elements
Hydrogen, Helium, and Lithium
are made at this time.



Big Bang theory prediction: 75% H, 25% He (by mass)

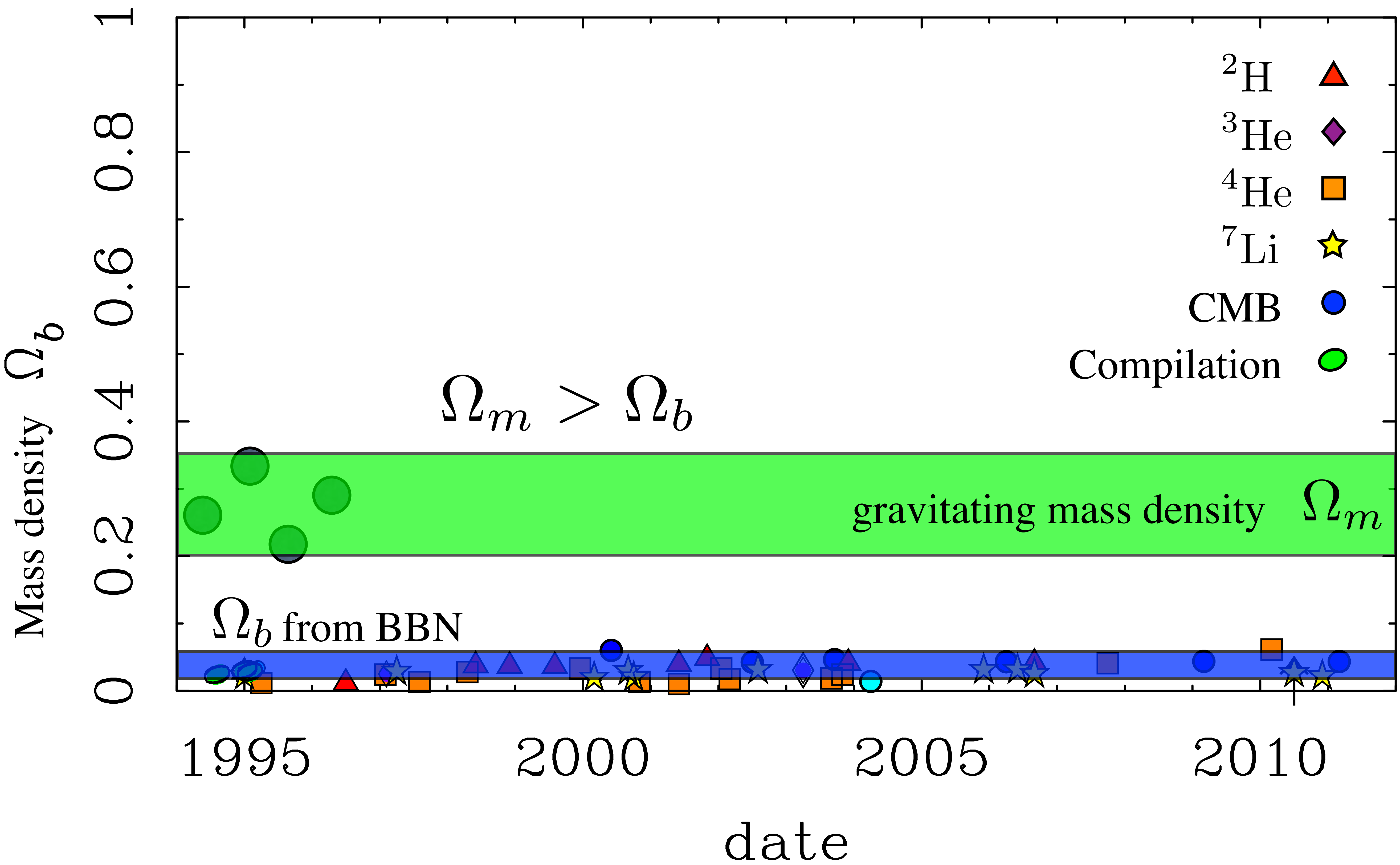
Matches observations of nearly primordial gases



Ω_b

BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.

There's more mass than BBN allows in baryons



$\Omega_b \approx 0.04$ BBN baryon density

$\Omega_m \approx 0.30$ gravitating mass density

<u>There is a hierarchy of missing mass problems</u>

$M_b < f_b M_{200}$ halo missing baryon problem
(not enough baryons in each DM halo)

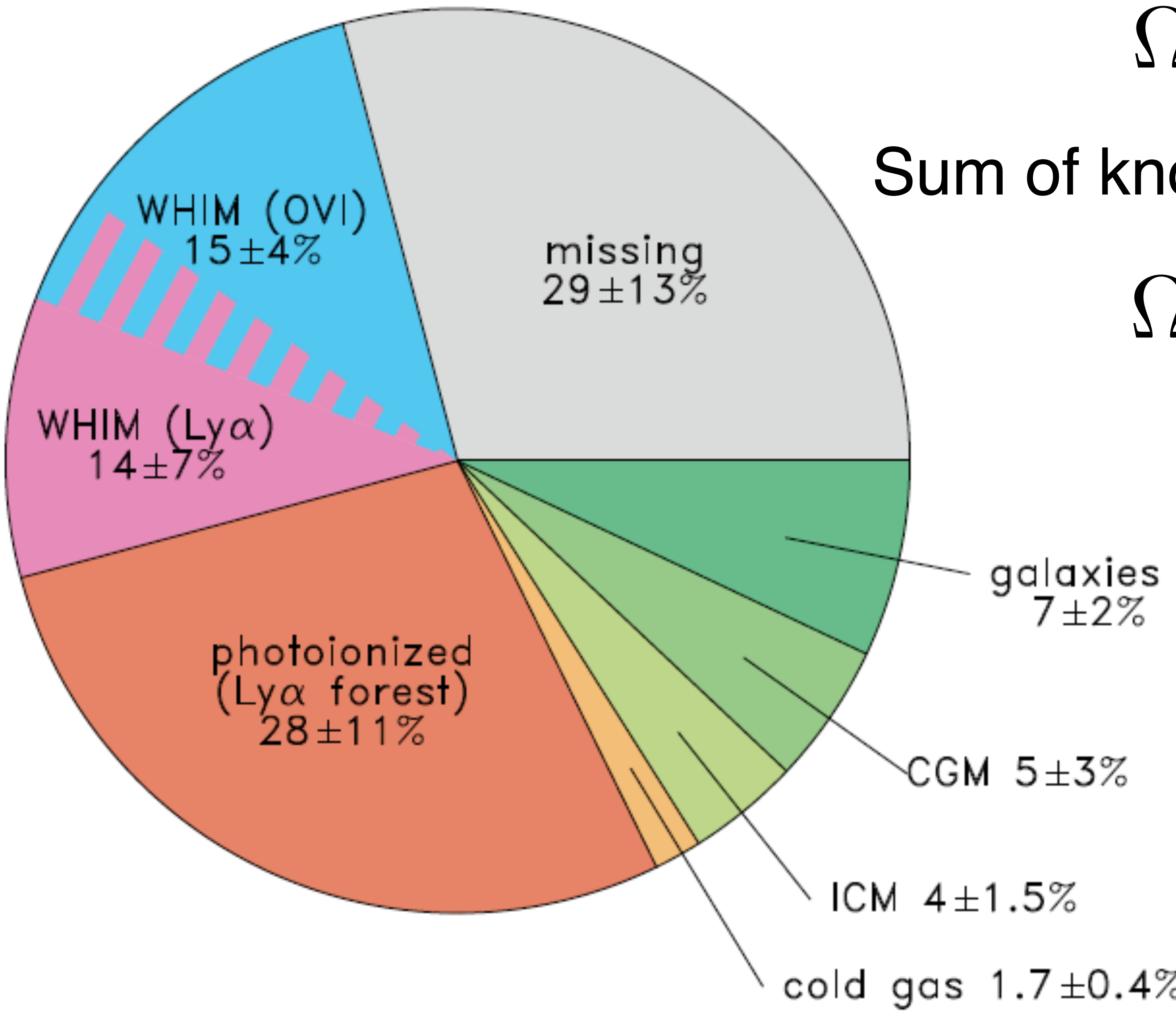
$\sum \Omega_{b,obs} < \Omega_{b,BBN}$ cosmic missing baryon problem
(not enough baryons for BBN)

$\Omega_{b,BBN} < \Omega_m$ cosmic missing mass problem
(not enough BBN baryons to explain all the mass in the Universe)

The global missing baryon problem

Cosmic baryon budget
(Shull et al arXiv:1112.2706)

$@\ z = 0$



Big Bang Nucleosynthesis
CMB fits give

$$\Omega_b h^2 = 0.022$$

Sum of known baryons only

$$\Omega_b h^2 \approx 0.017$$

Total mass density

$$\Omega_m h^2 \approx 0.13$$