Dark Matter

ASTR 333/433
Spring 2026
TR 11:30am-12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

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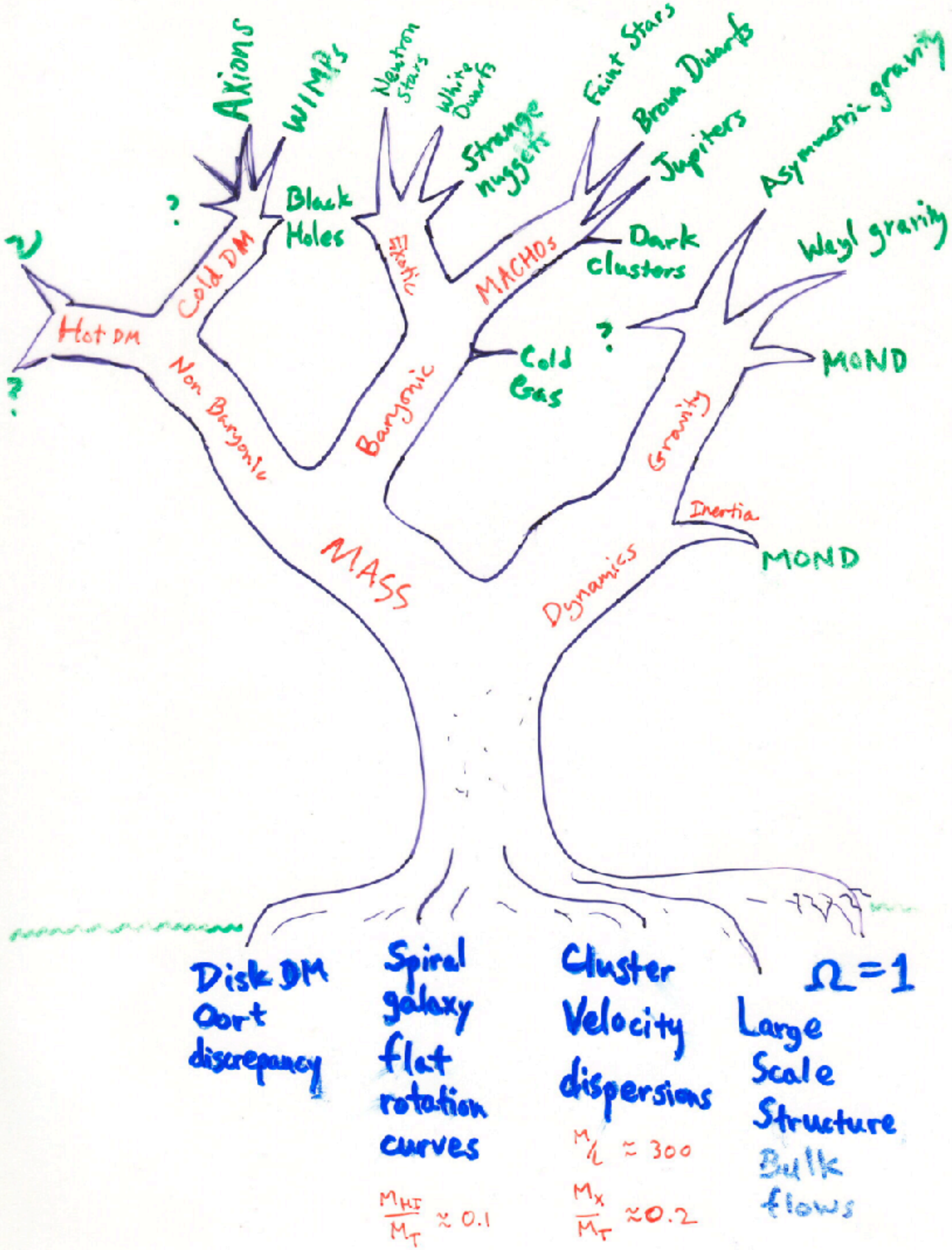
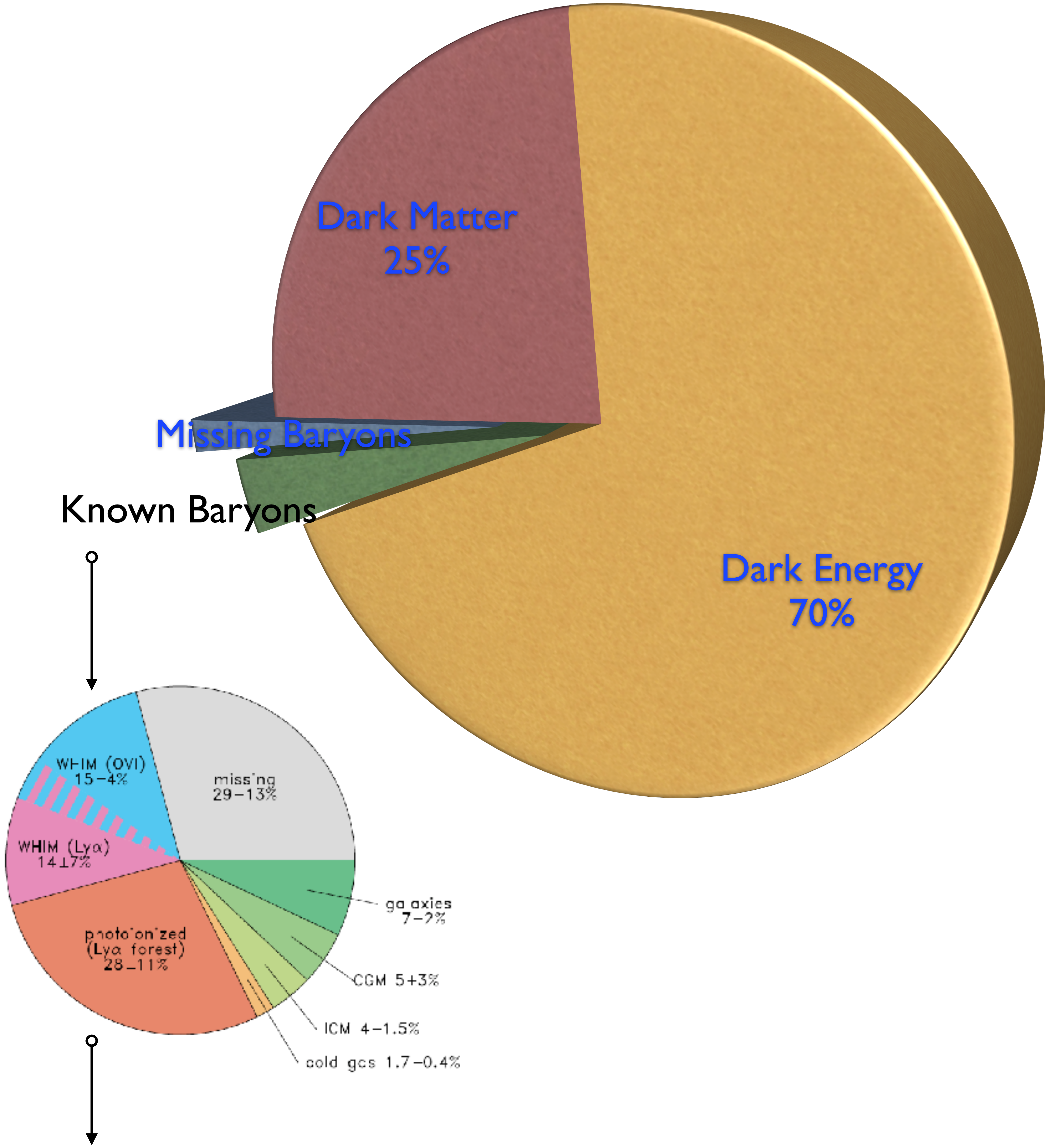
Homework due a week from today



Cosmological Dark Matter

ΛCDM Cosmology

- non-baryonic cold dark matter
  - whatever it is (e.g., WIMPs)
- dark energy
  - whatever that even means
- dark baryons
  - 29% not accounted for



We have direct knowledge of < 5% of the total mass-energy density of the universe

Current mass-energy content of the universe

mass density Ω_m		0.30	give or take a bit
normal matter	Ω_b	0.05	baryons - from BBN
mass that is *not* normal matter	Ω_{CDM}	0.25	cold dark matter
cosmic background radiation	Ω_r	5×10^{-5}	photons
neutrinos	$0.001 < \Omega_\nu < 0.002$		for 3 neutrino flavors with $0.06 < \sum_{i=1}^{3} m_{\nu_i} < 0.12$ eV
dark energy Ω_Λ		0.70	energy density of vacuum

e.g, $\Omega_\nu = \dfrac{\sum m_\nu}{93 \text{ eV}}$

definitions: $\Omega_x = \dfrac{\rho_x}{\rho_{crit}}$ $\rho_{crit} = \dfrac{3H_0^2}{8\pi G}$

since $n_\nu = \dfrac{9}{11} n_\gamma$

$\Omega_b \approx 0.05$ BBN baryon density

$\Omega_m \approx 0.30$ gravitating mass density

$f_b = \dfrac{\Omega_b}{\Omega_m}$ baryon fraction

There is a hierarchy of missing mass problems

$\Omega_b < \Omega_m$ cosmic missing mass problem
(not enough BBN baryons to explain all the gravitating mass in the Universe)

$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$ cosmic missing baryon problem
(not enough baryons for BBN)

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

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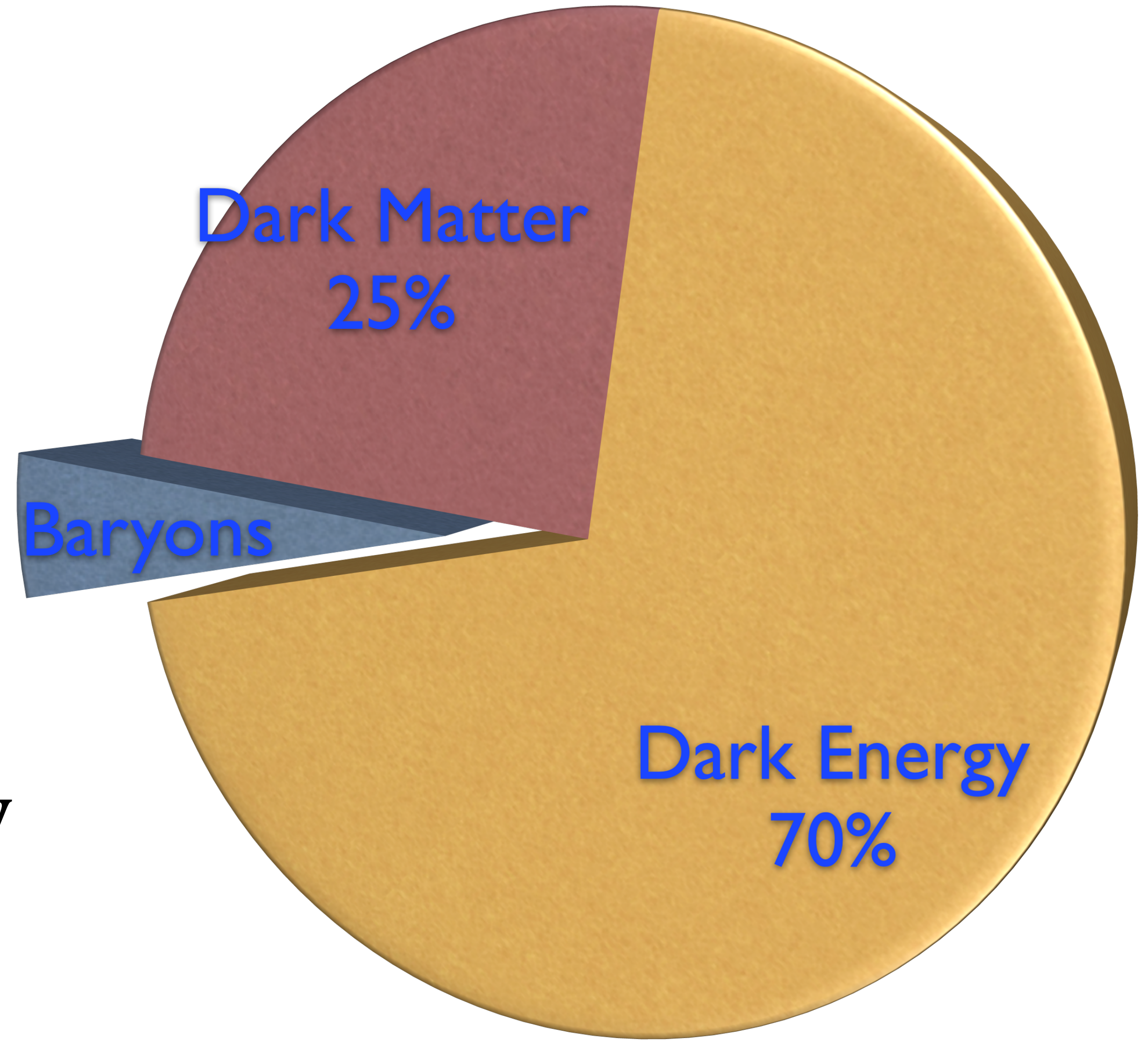
The cosmic missing baryon problem

This is usually what people mean when the say "dark matter" or "missing mass"

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
- Acoustic power spectrum of the CMB



All yield $\Omega_m \approx 0.3$

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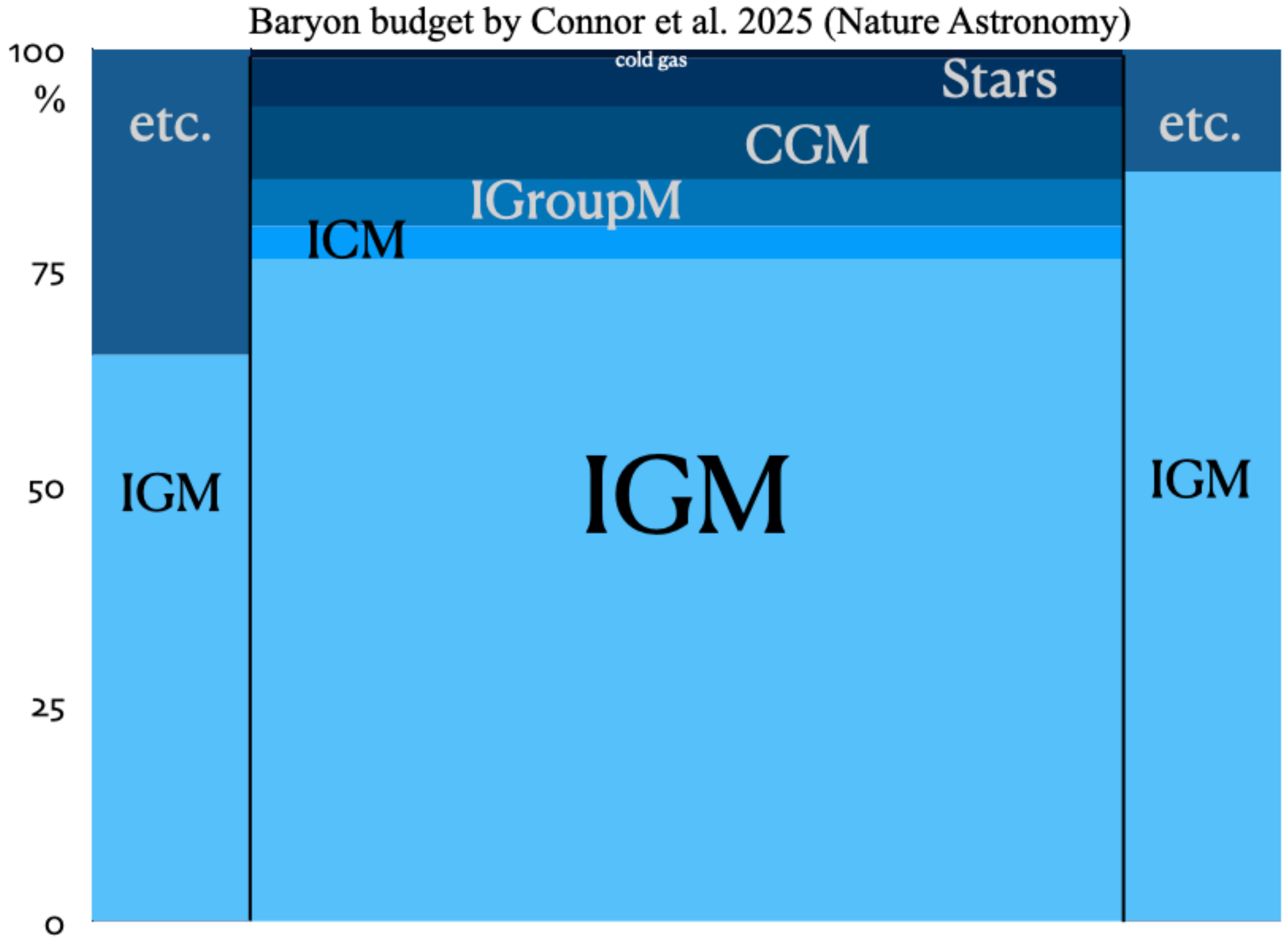
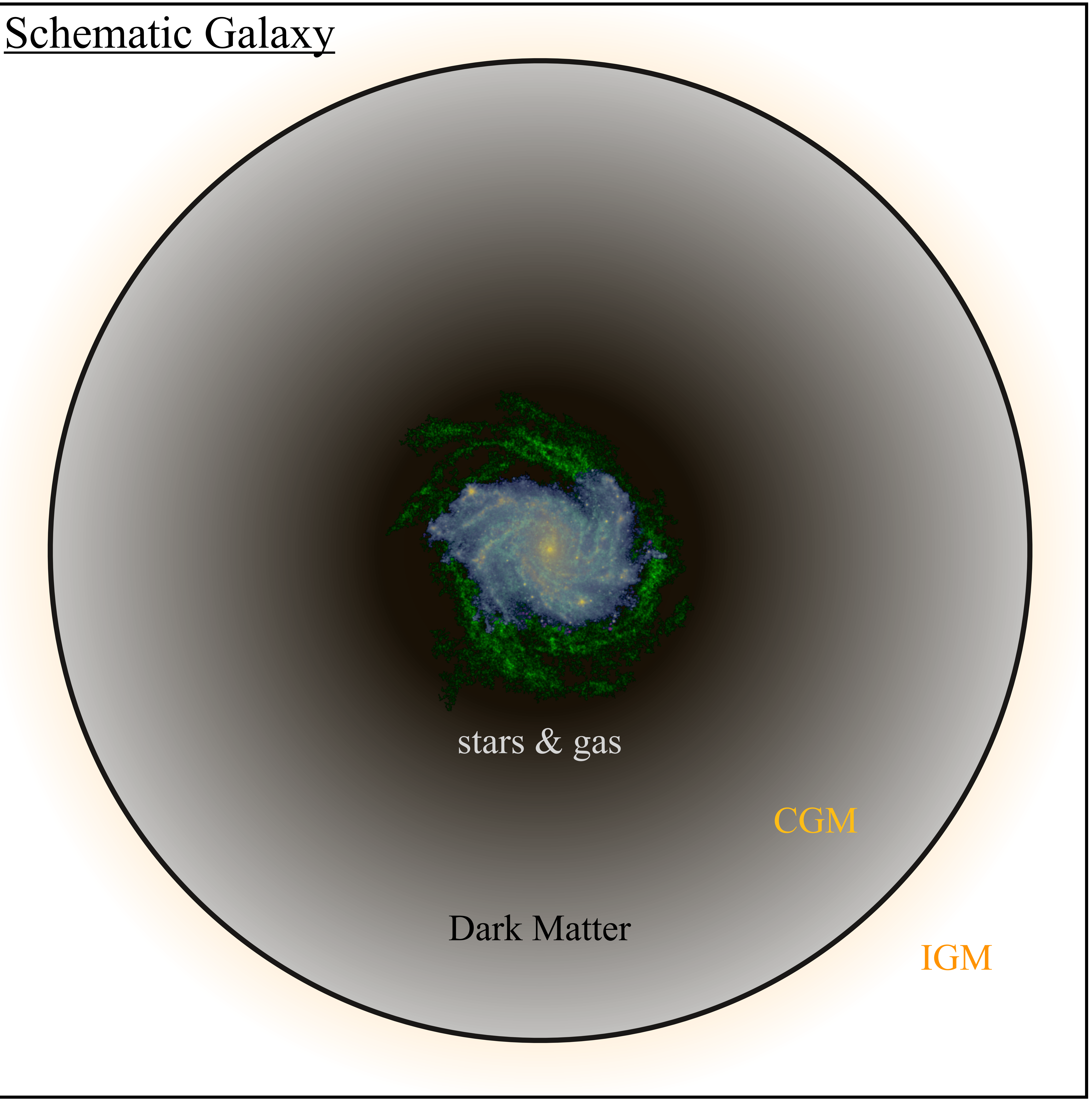
Solved

$\sum \Omega_b$ (observed) < Ω_b (BBN)

cosmic missing baryon problem
(not enough baryons for BBN)



most baryons in the intergalactic medium



cold gas: atomic & molecular gas in galaxies

stars in galaxies

ICM: intracluster medum - hot gas in clusters

IGroupM: gas in groups outside individual galaxies

Baryon budget by Connor et al. 2025 (Nature Astronomy)

IGM: intergalactic medium

diffuse gas between galaxies

CGM: circumgalactic medium

coronal gas outside of galaxies but inside their DM halos

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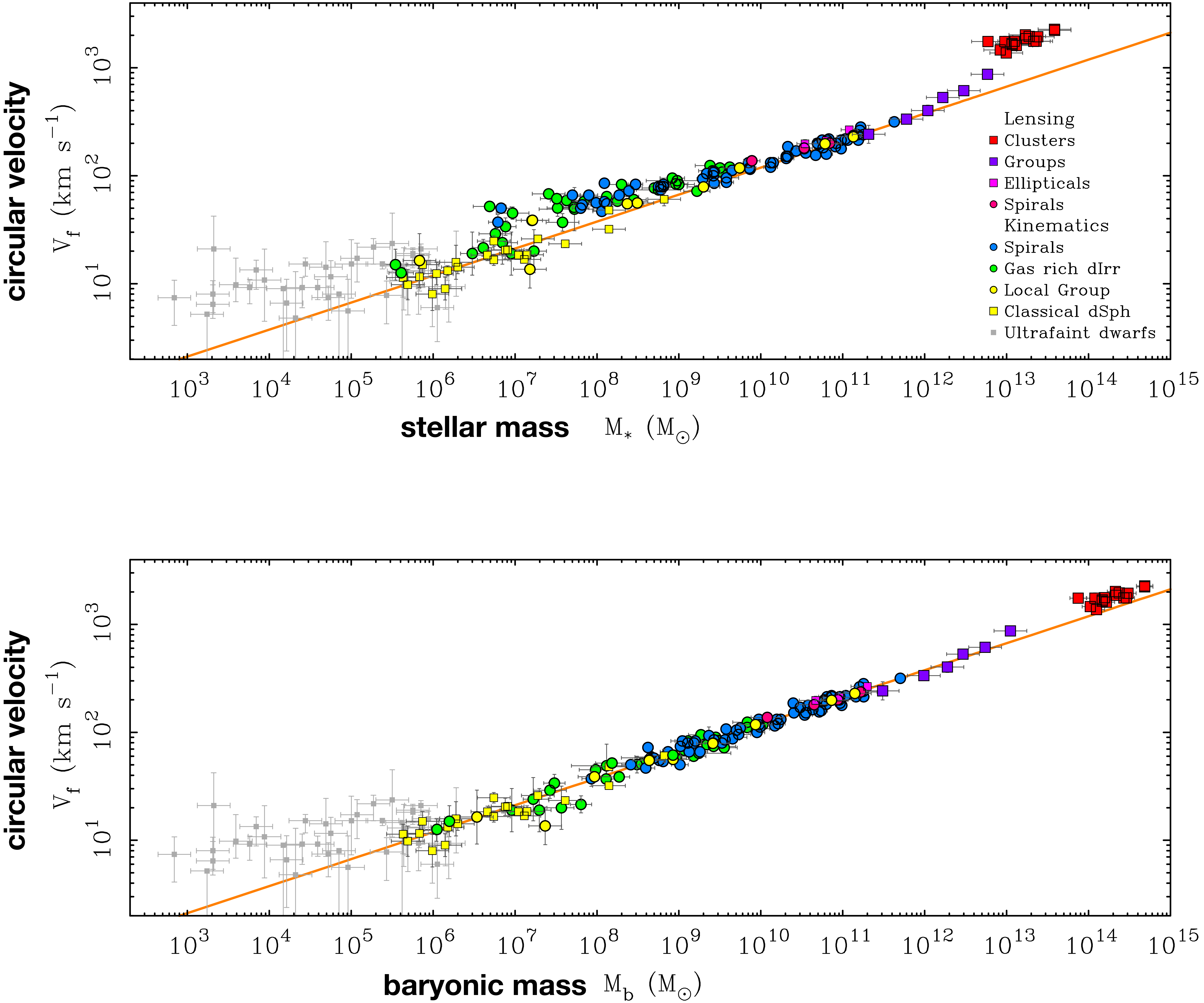
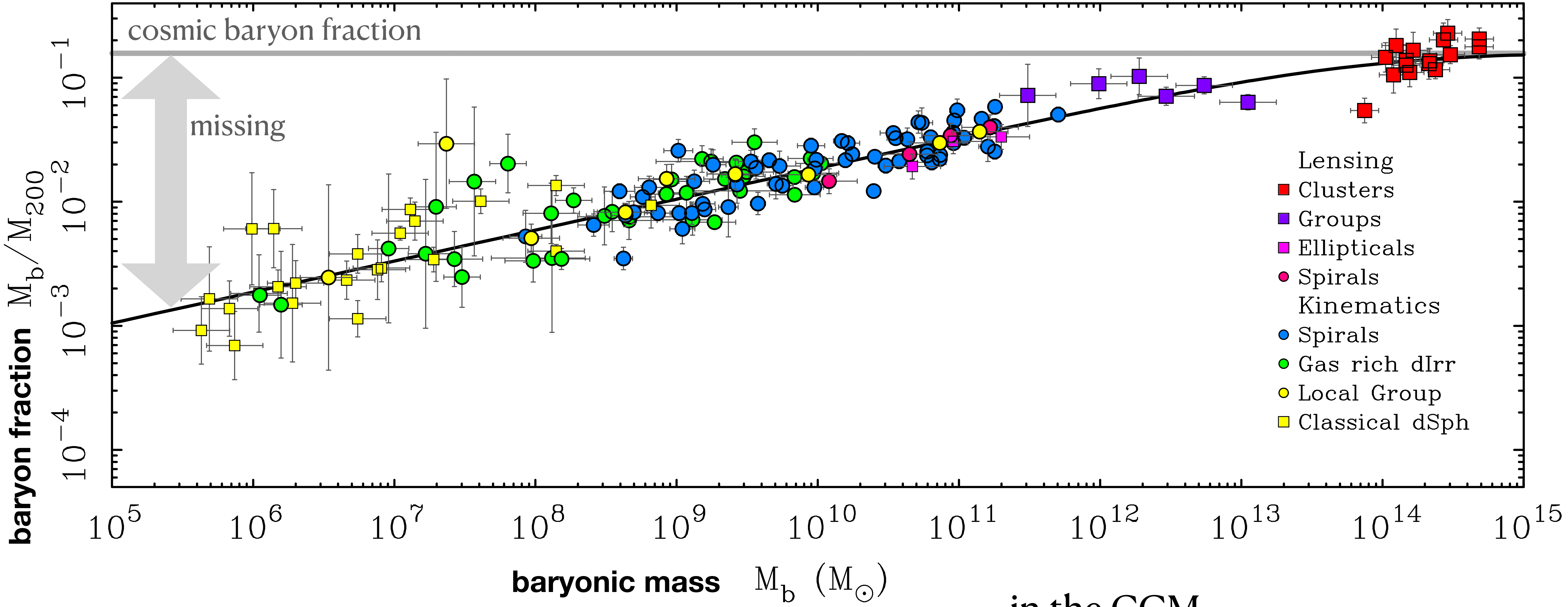
Extended TF



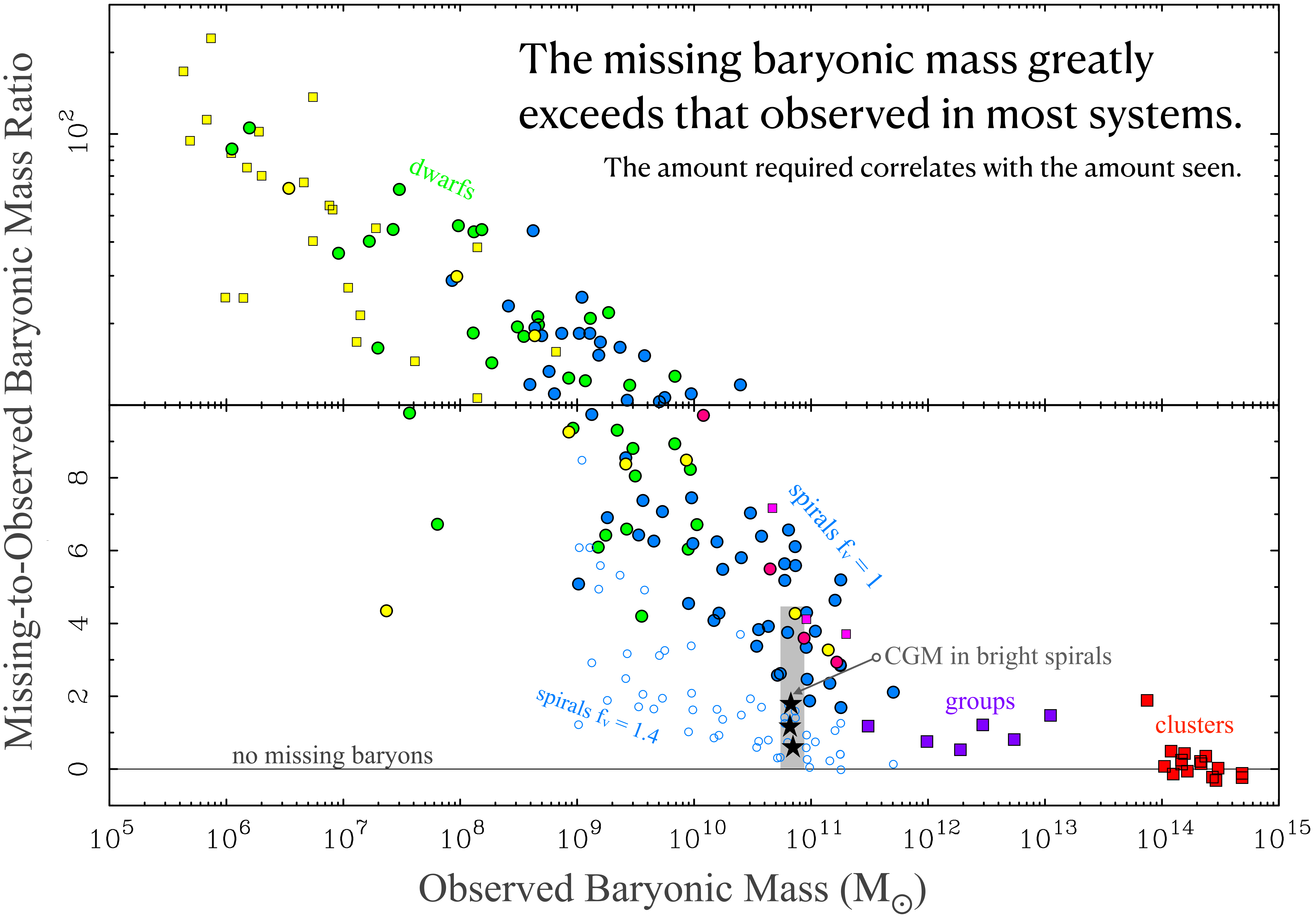
McGaugh et al. (2026)

Mass budget

Basically an accounting exercise: for every object,
how much normal matter is there? $M_b = M_* + M_g$
How much total mass? M_{200} total mass within an over-density $\Delta = 200$

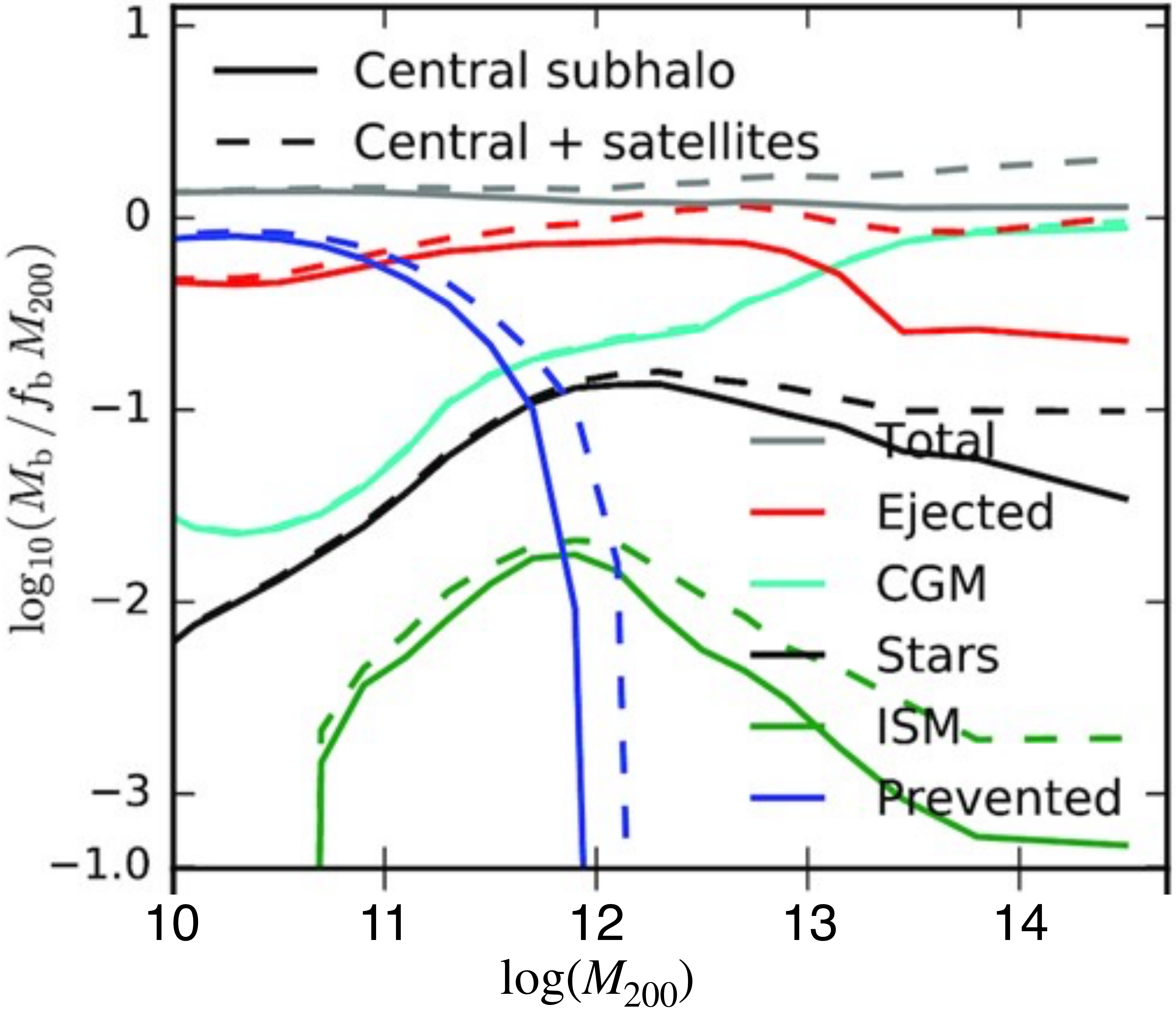


Possible locations of missing baryons: { in the CGM; ejected to the IGM; something wrong with the accounting



The missing baryonic mass greatly exceeds that observed in most systems.
The amount required correlates with the amount seen.
dwarfs
spirals $f_v = 1$
CGM in bright spirals
spirals $f_v = 1.4$
groups
clusters
no missing baryons
Missing-to-Observed Baryonic Mass Ratio
10^2
8
6
4
2
0
10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}
Observed Baryonic Mass ($M_\odot$)

Simulations model the distribution of baryons between stars, cold gas, CGM, and ejected/rejected baryons but are no where near to getting it right.



EAGLE simulation

Mitchell & Schaye (2022)

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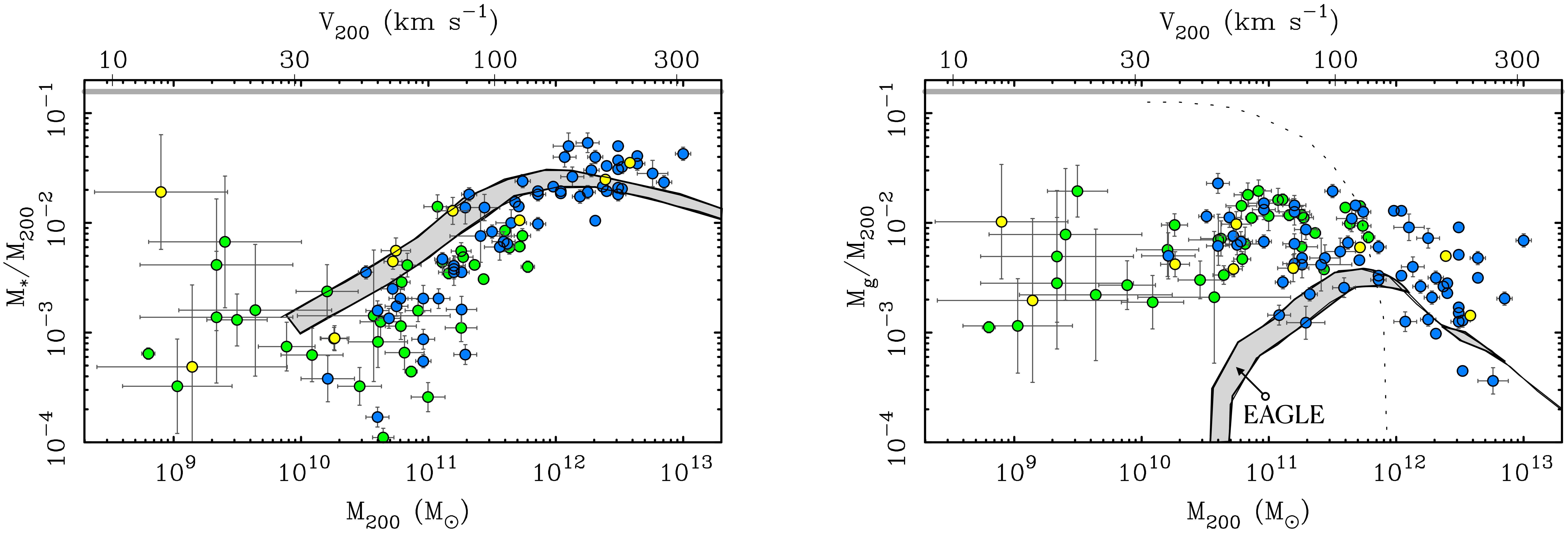

$M_b < f_b M_{200}$

halo missing baryon problem
(not enough baryons in each DM halo)

remains unsolved

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

$\Omega_b < \Omega_m$ cosmic missing mass problem (not enough BBN baryons to explain all the gravitating mass in the Universe)

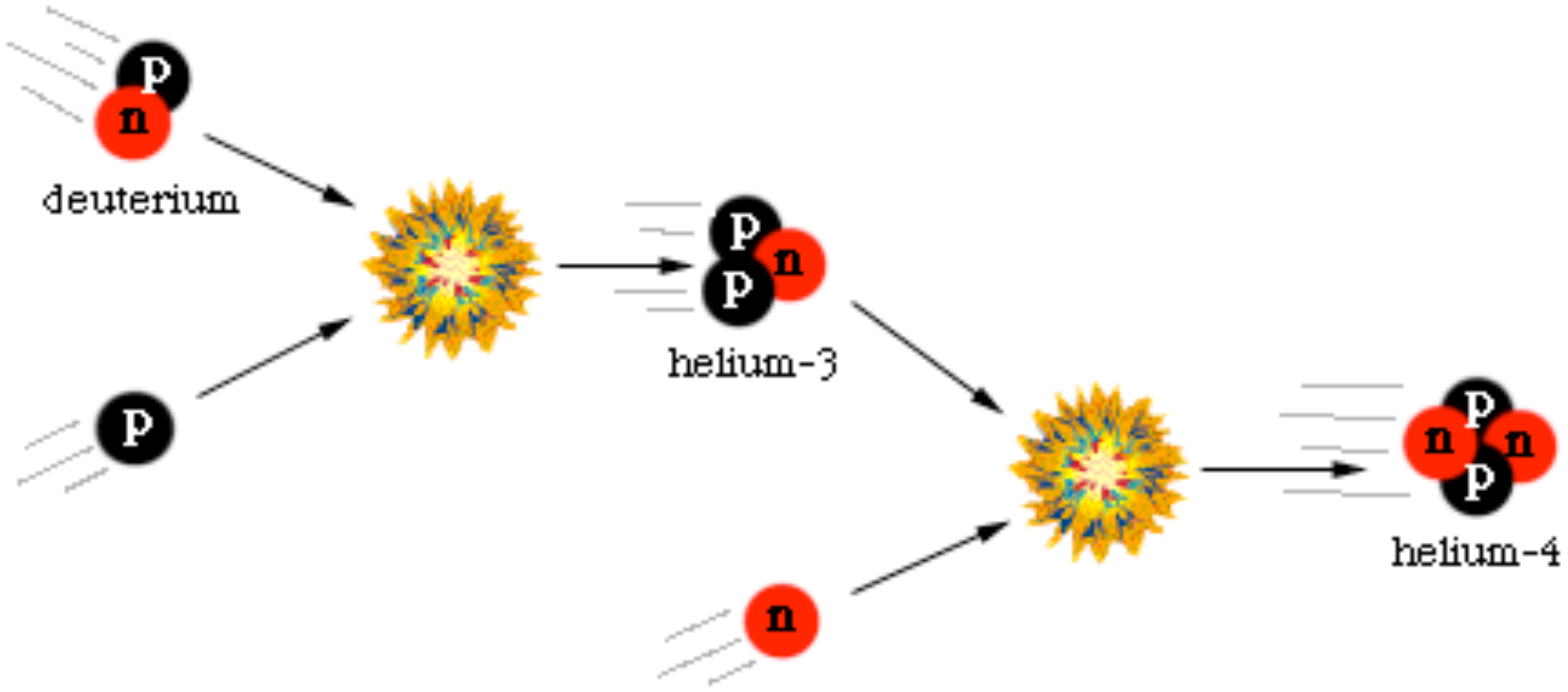
The cosmic missing mass problem also remains unsolved

But how do we know what the baryon density should be?

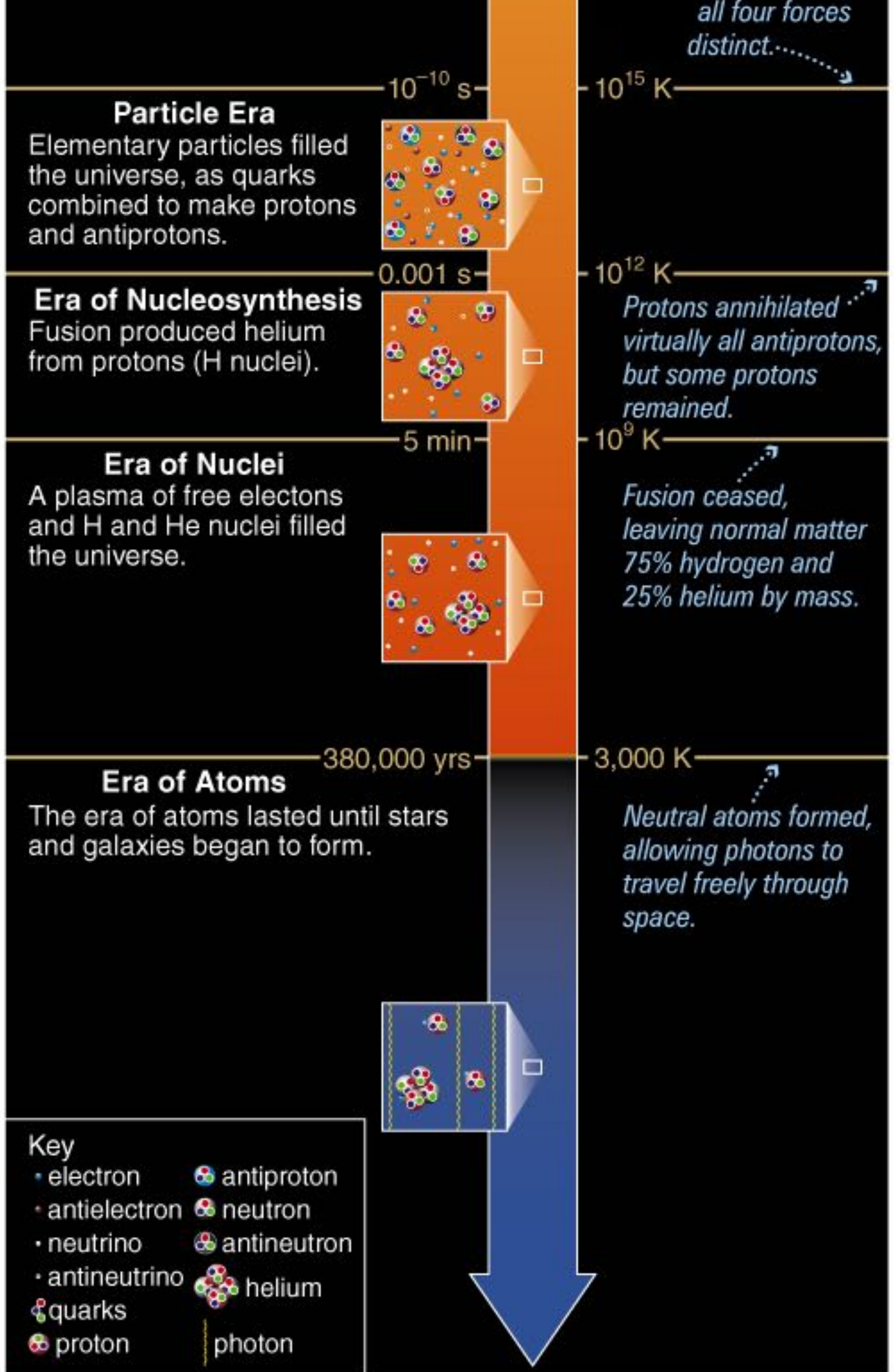
Big Bang Nucleosynthesis (BBN):

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.



particle soup

< millisecond

T ~ 10^{14} K

nucleosynthesis (BBN)

~ 3 minutes

T ~ 10^{10} K

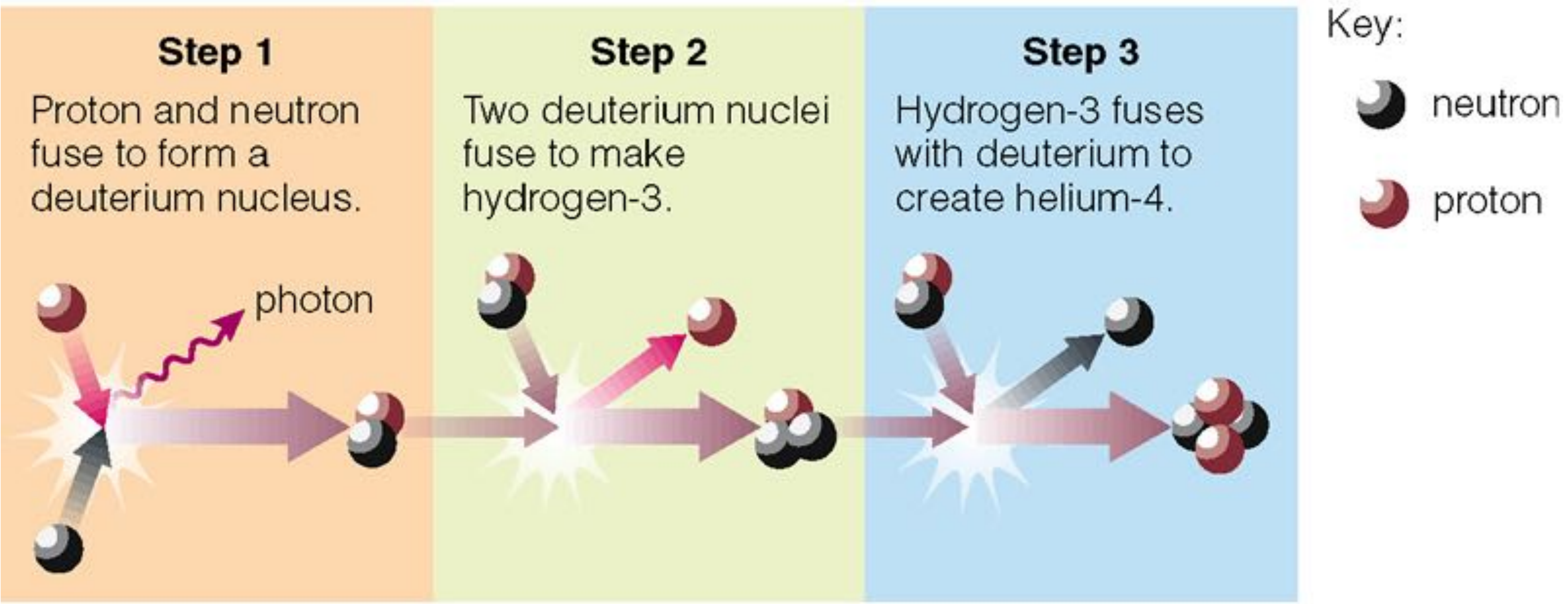
Early Universe

recombination

~380,000 year

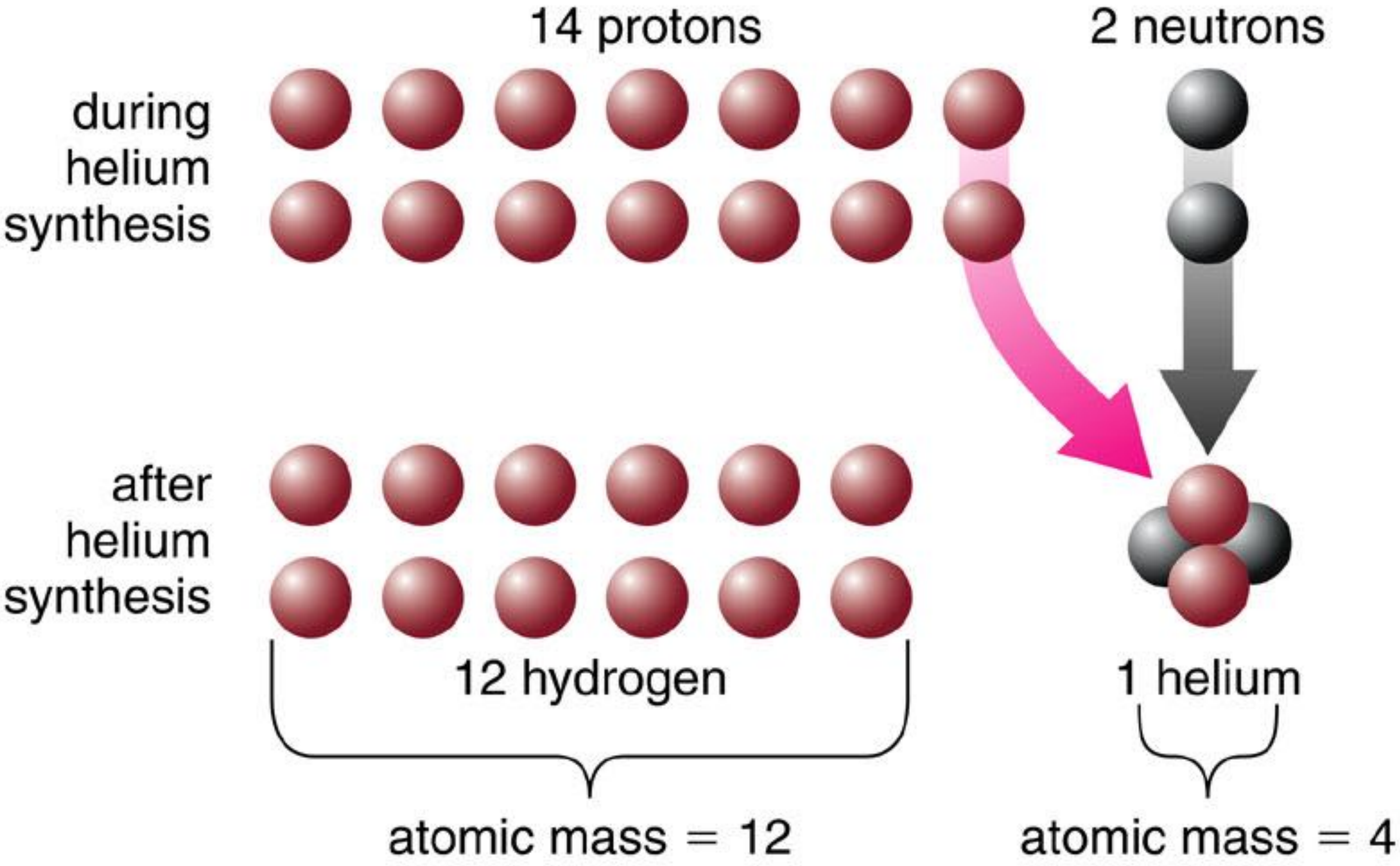
T ~ 3000 K

emission of CMB: surface of last scattering



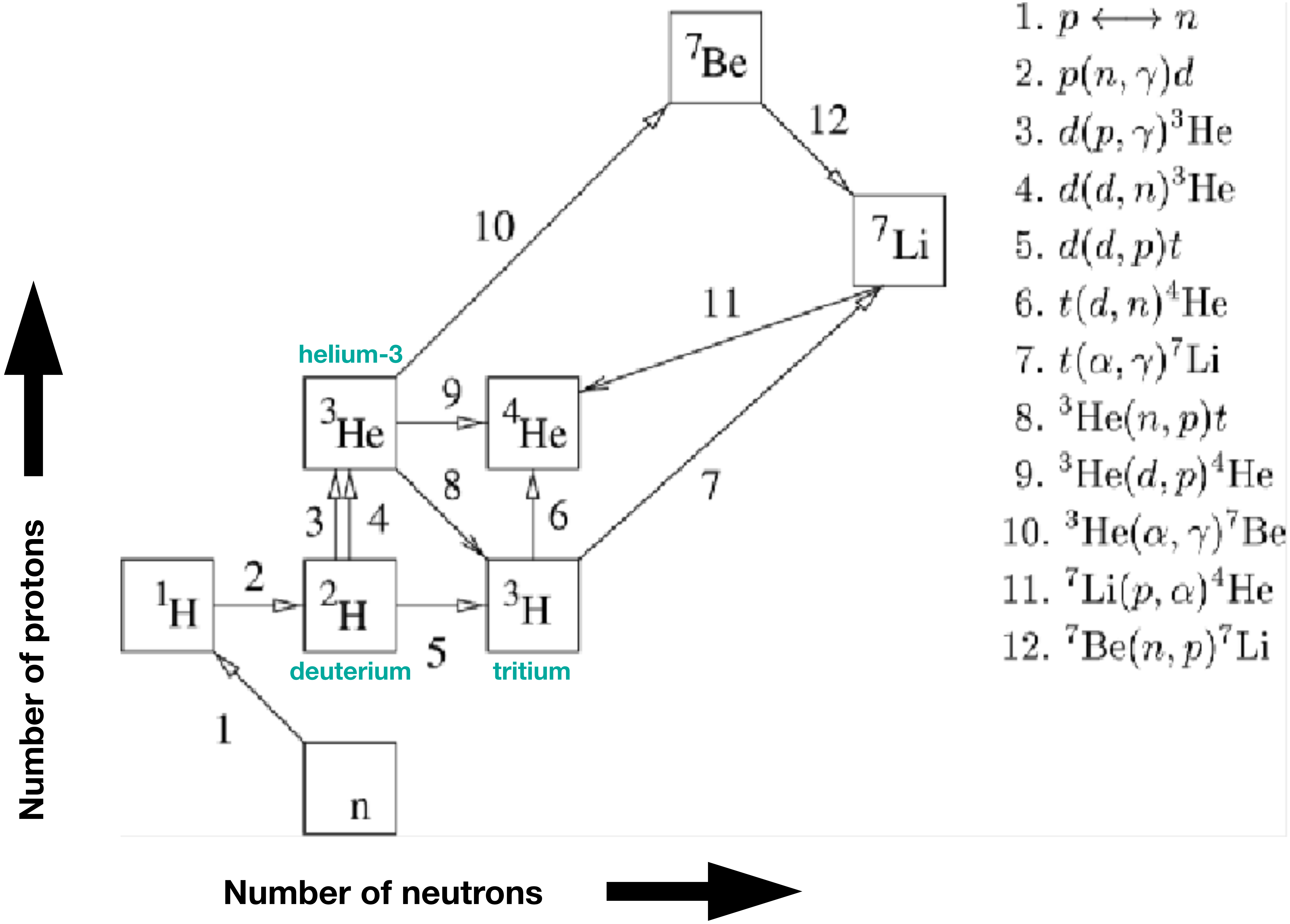
Protons and neutrons combined to make long-lasting helium nuclei when the universe was ~3 minutes old.

The proton-proton chain was enhanced by the presence of free neutrons, making the creation of deuterium easier.



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

Matches observations of nearly primordial gases



7Be
7Li
10
12
11
helium-3
3He
4He
9
8
3
4
6
7
1H
2
2H
5
3H
deuterium
tritium
1
n
Number of protons
Number of neutrons
1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

BBN products:

- 3/4 Hydrogen
- 1/4 Helium
- Traces of
  - deuterium
  - tritium
  - helium 3
  - lithium
  - berylium

Abundances depend on the density of matter. The higher the density parameter (Ω_b), the more helium.