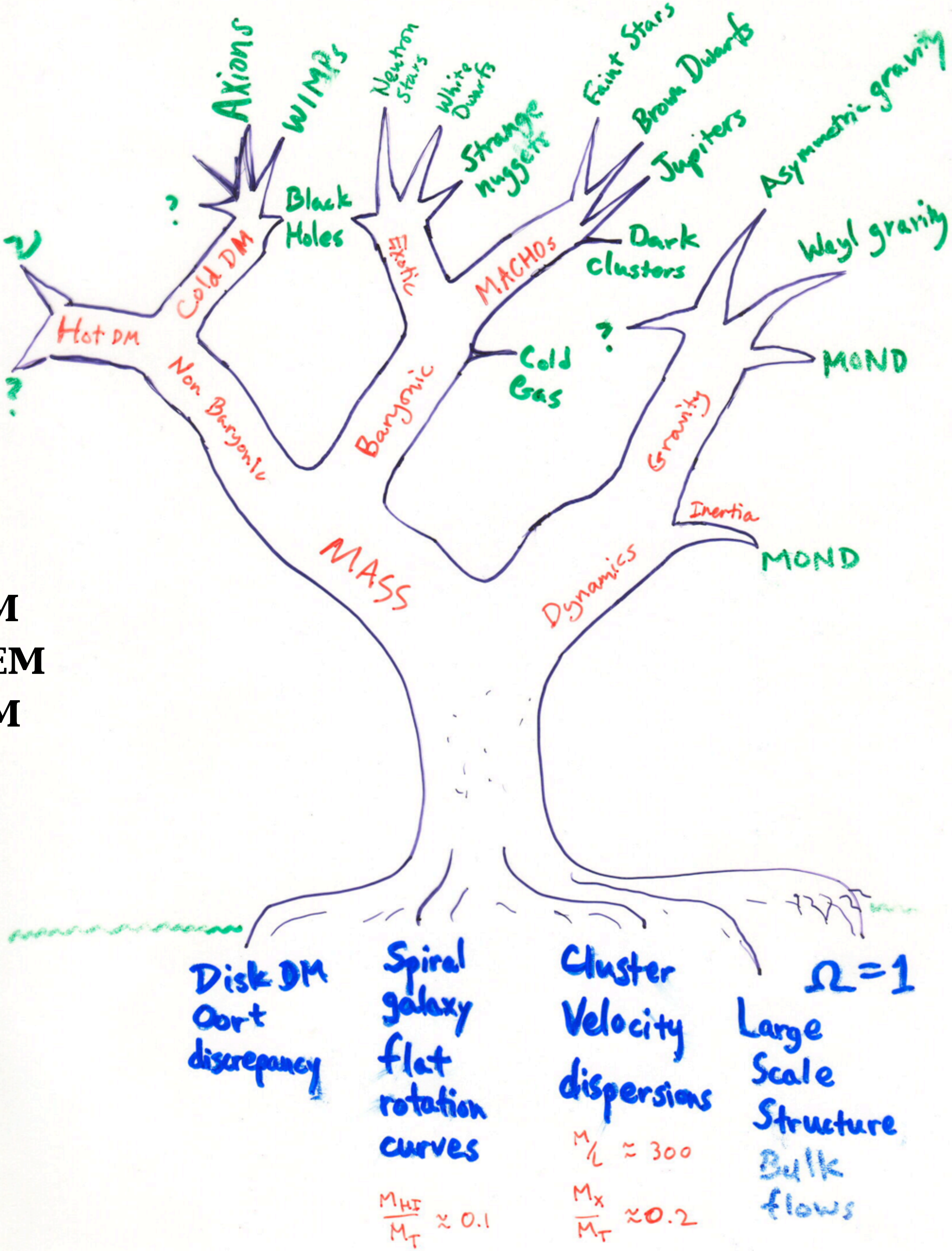
DARK MATTER

ASTR 333/433

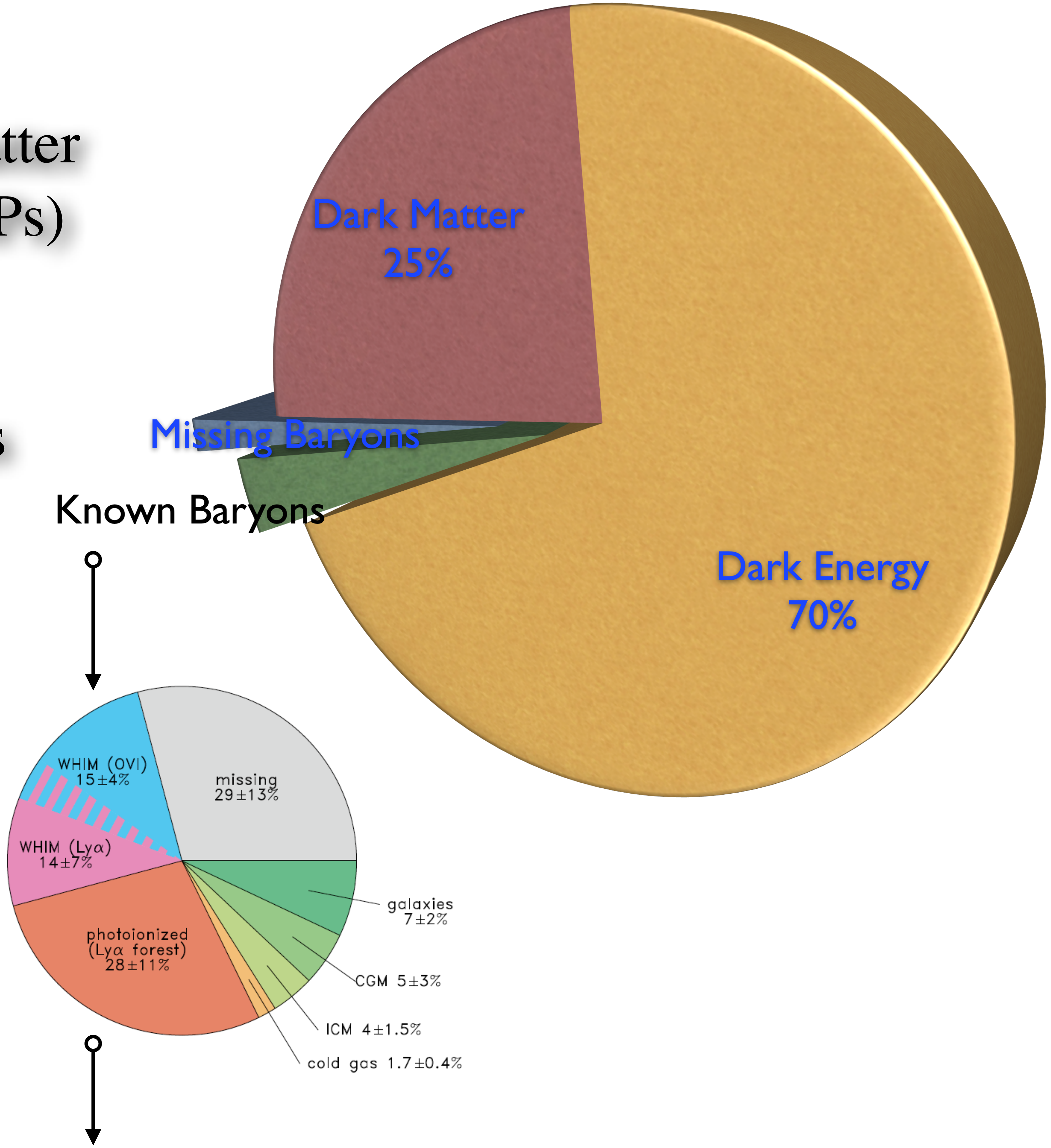
TODAY

COSMIC MISSING MASS PROBLEM
COSMIC MISSING BARYON PROBLEM
HALO MISSING BARYON PROBLEM



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

$$\Omega_x = \frac{\rho_x}{\rho_{crit}} \qquad \rho_{crit} = \frac{3H_0^2}{8\pi G}$$

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

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

$\Omega_b \approx 0.05$	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

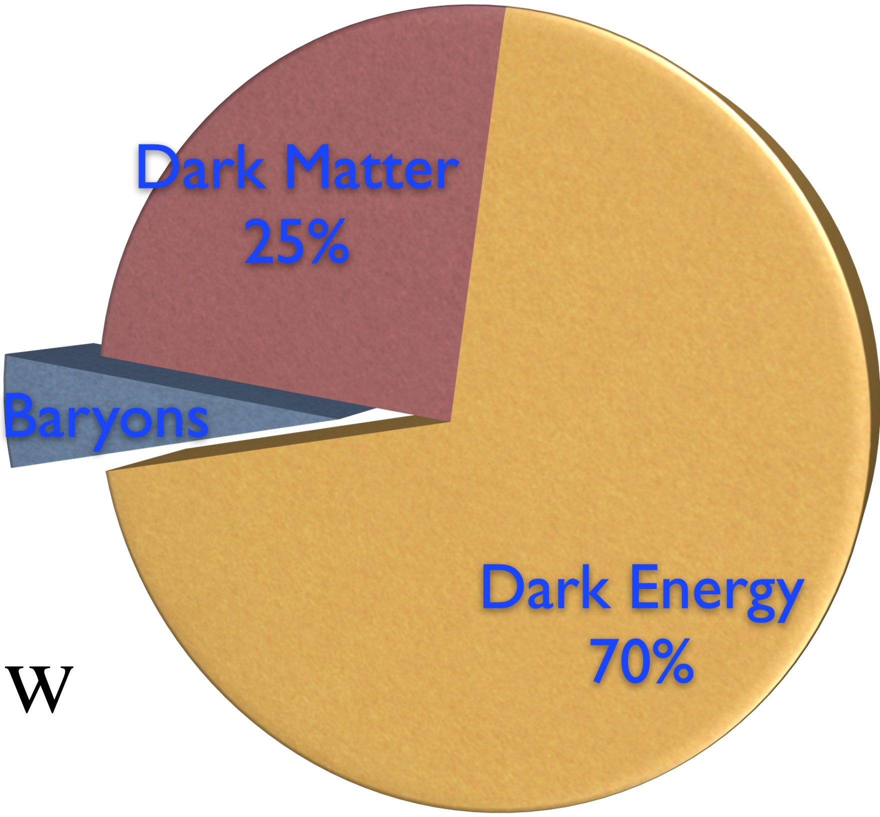
$\Omega_b < \Omega_m$	cosmic missing mass problem (not enough BBN baryons to explain all the gravitating mass in the Universe)
$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$	cosmic missing baryon problem (not enough baryons for BBN)
$M_b < f_b M_{200}$	halo missing baryon problem (not enough baryons in each DM halo)

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



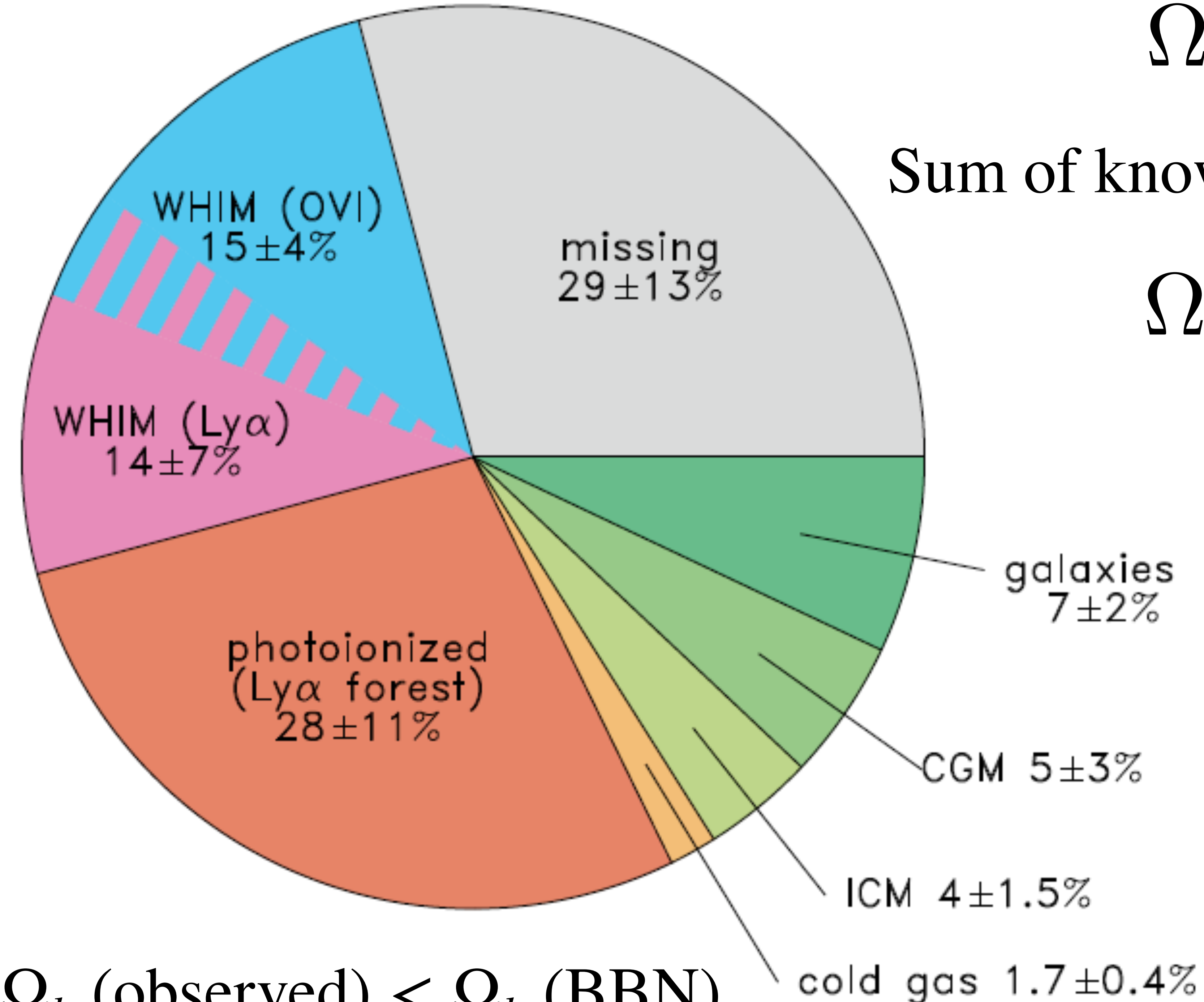
All yield $\Omega_m \approx 0.3$

The cosmic 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

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

$$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$$

Baryon reservoirs

- Galaxies
  - Stars 7% → integrate luminosity function; estimate M*/L
  - cold gas 2% → integrate HI mass function; estimate molecular gas fraction
  - circumgalactic medium (CGM) 5% → absorption of highly ionized gas along sight lines; estimate ionization fraction and covering factor
- Clusters
  - intracluster gas (ICM) 4% → integrate X-ray cluster luminosity function
- Intergalactic Medium (IGM)
  - Warm-Hot IGM 29% → absorption of highly ionized gas along sight lines; estimate ionization fraction
  - Lyman α forest 28% → Lyα absorption lines in QSO spectra

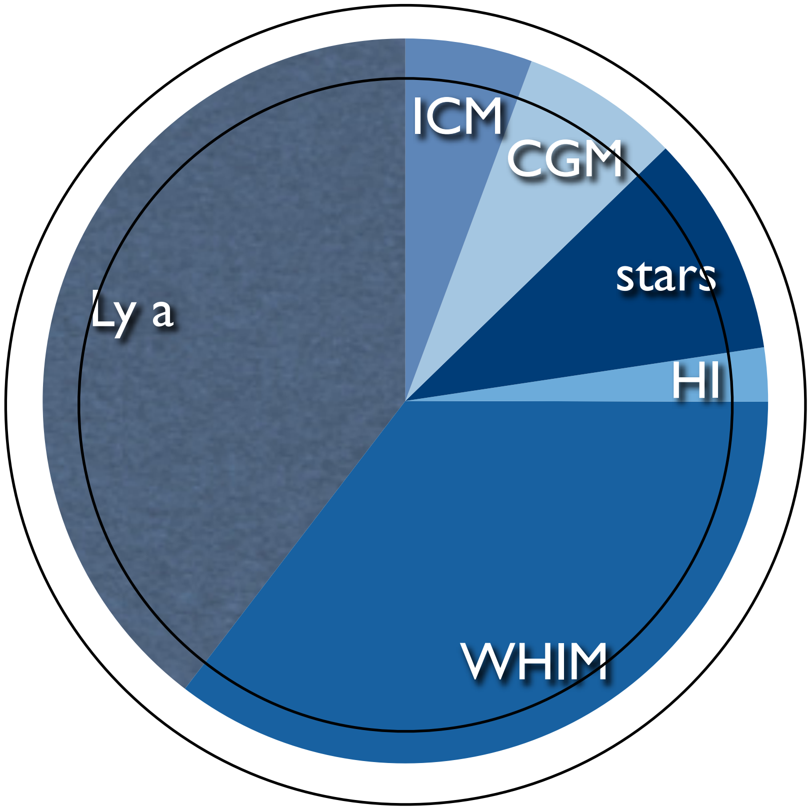
Maybe some extra in large scale filaments?

$$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$$

Percentages are relative to the BBN baryon density.
The uncertainties are large

How many baryons are missing depends on how many BBN predicts

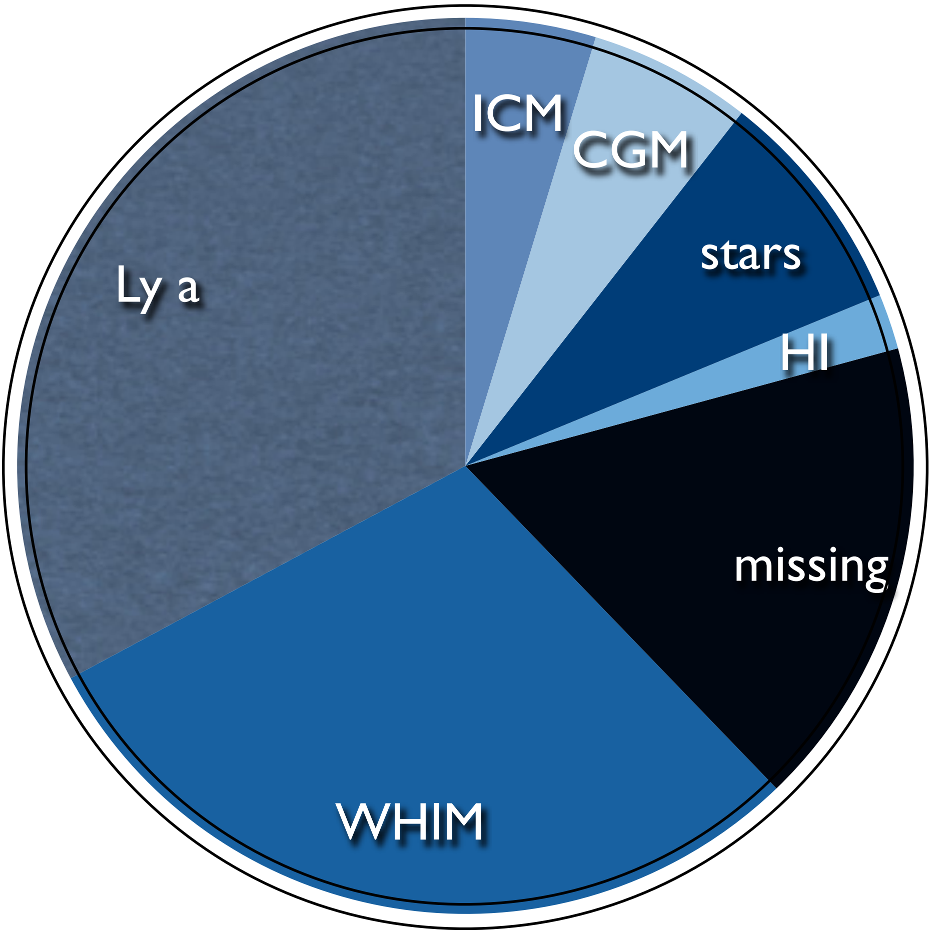
BBN 1991 (Walker et al.)



$\Omega_b h^2 = 0.0125 \pm 0.0025$

$\Omega_b = 0.0255$

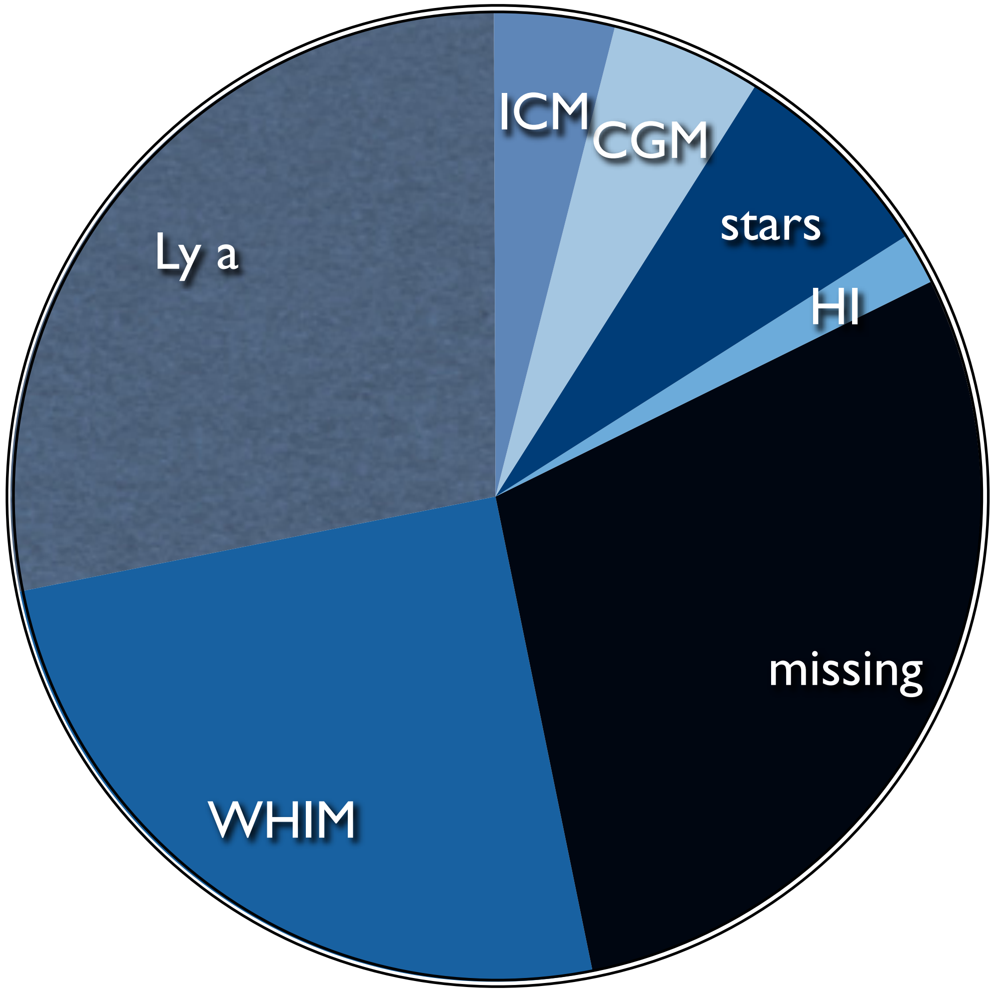
BBN 1999 (pre-CMB D/H)



$\Omega_b h^2 = 0.019 \pm 0.001$

$\Omega_b = 0.0388$

CMB 2015 (Planck)



$\Omega_b h^2 = 0.02230 \pm 0.00023$

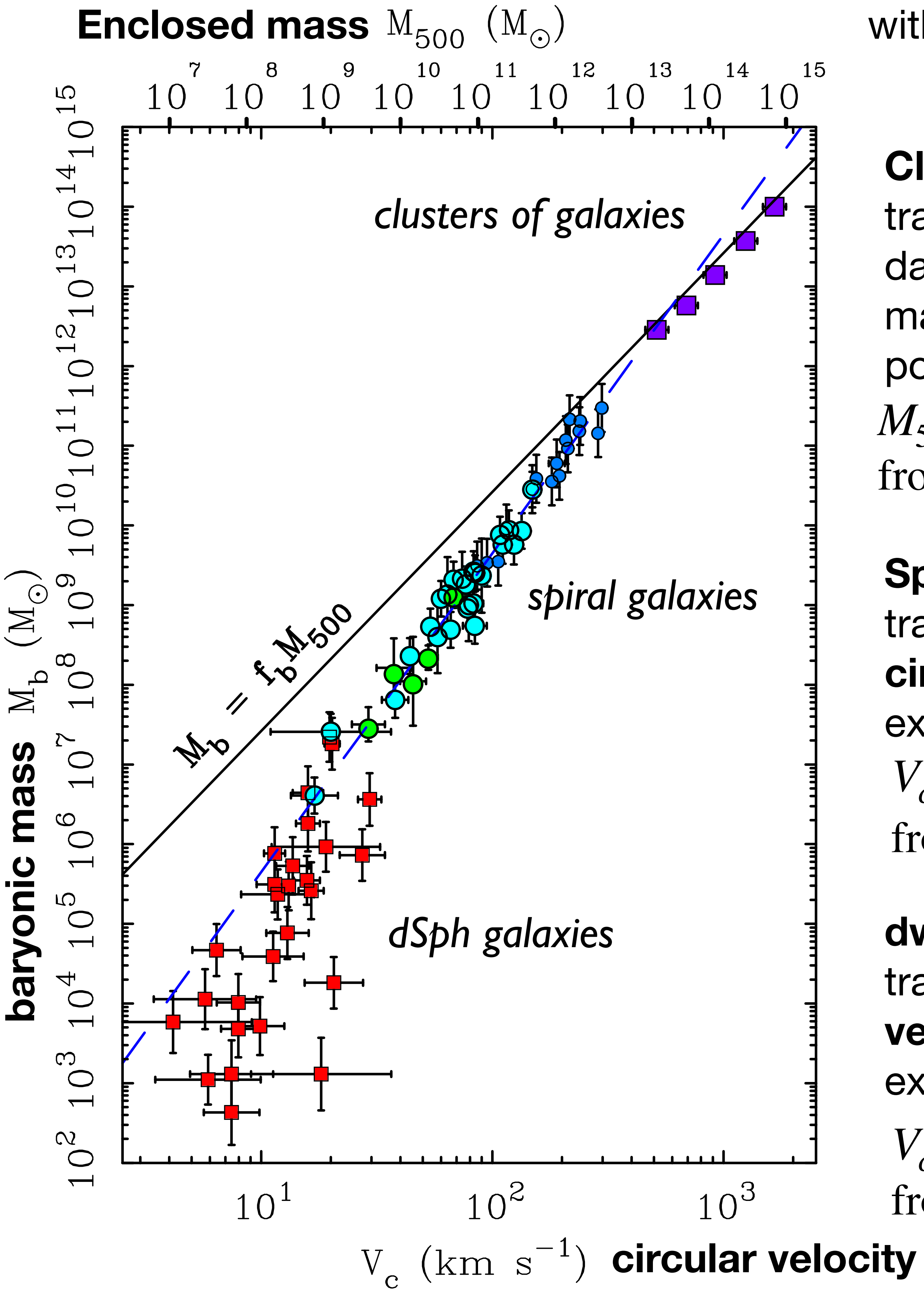
$\Omega_b = 0.0455$ for $H_0 = 70$
$\Omega_b = 0.05$ for $H_0 = 66.8$
$\Omega_b = 0.04$ for $H_0 = 74.7$

Our estimate of the baryon density Ω_b has grown over time.
The first step was in response to improved deuterium data;
the second was due to observation of the CMB acoustic power spectrum.

Extended TF

Mass budget

Basically an accounting exercise: for every object, how much normal matter is there? How much total mass?



within an over-density

$\Delta = 500$

Clusters
traced by **X-rays**
data are binned:
many clusters per
point; hides scatter

M_{500}
from X-ray data

Spirals
traced by
circular velocity
extrapolated to R_{500}

$V_c = V_f$
from rotation curves

dwarf Spheroidals
traced by
velocity dispersion
extrapolated to R_{500}

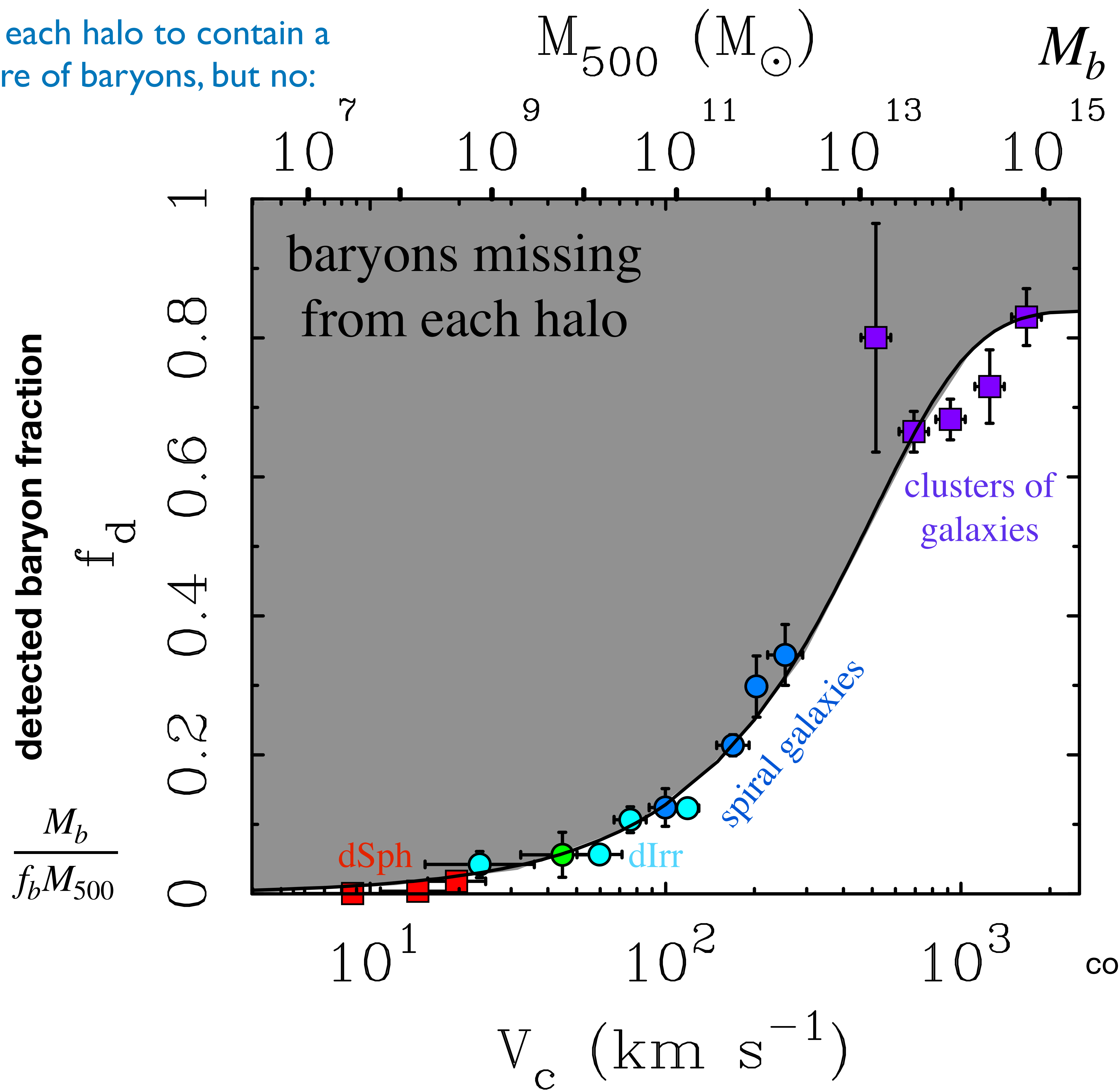
$V_c = \sqrt{3}\sigma$
from rotation curves

McGaugh et al (2010)

The halo missing baryon problem

Expect each halo to contain a fair share of baryons, but no:

$M_b < f_b M_{200}$

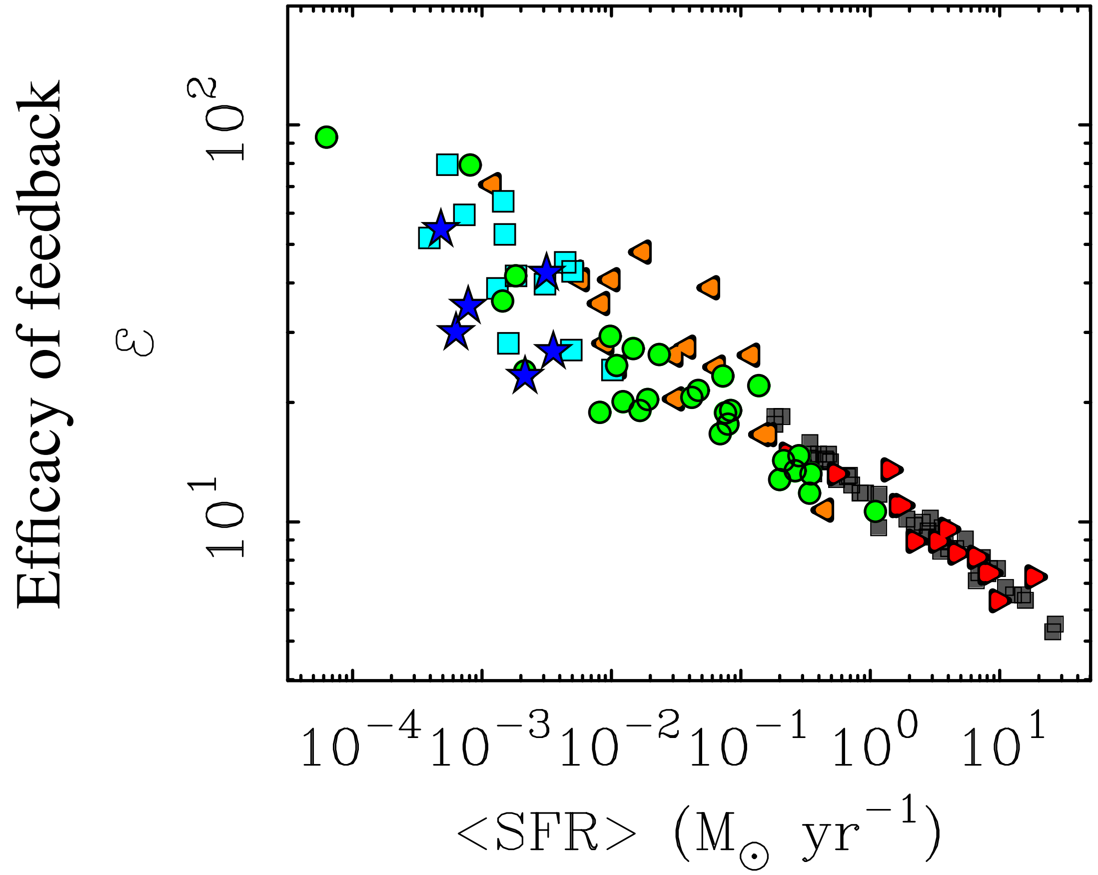


$$f_d = \frac{M_b}{f_b M_{500}}$$

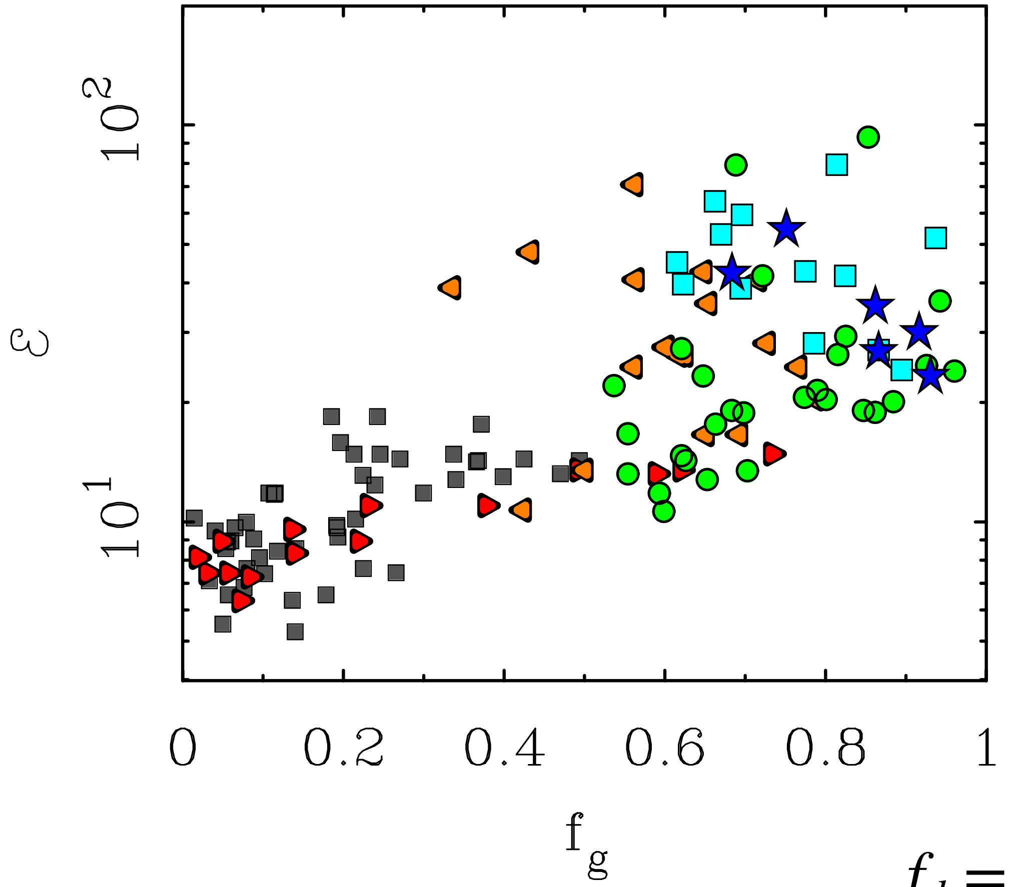
cosmic baryon fraction
$f_b = 0.17$

Feedback

Invoked here to explain the halo missing baryon problem: why aren't the baryons visible?



$$\log \varepsilon = 3 \log f_V - \log f_d$$



Ratio of baryons lost to those retained

$$f_d = \frac{M_b}{f_b M_{200}}$$

$$f_V = \frac{V_f}{V_{200}}$$

The answer is unclear, but it is widely thought that either

(i) supernova feedback blows the excess baryons out of halos, or

(ii) feedback heats baryons so they don't dissipate into the disk

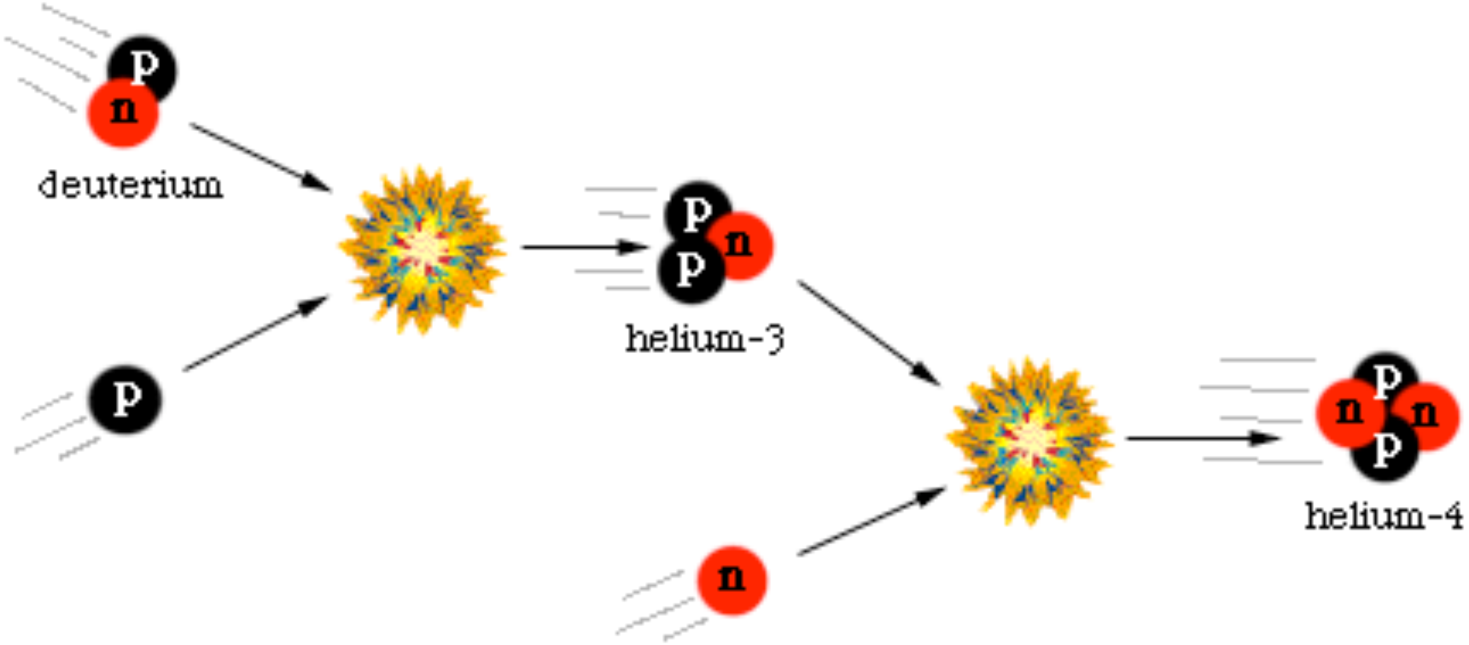
SN feedback is thought to be most effective in low mass galaxies with small potential wells that can't retain material that explodes outwards.

You might expect these processes to be more effective when there is more star formation (more SN, more heating) but the opposite is observed. There is also more gas left over in galaxies that have suffered the most feedback, so it can't blow out 100% of the gas.

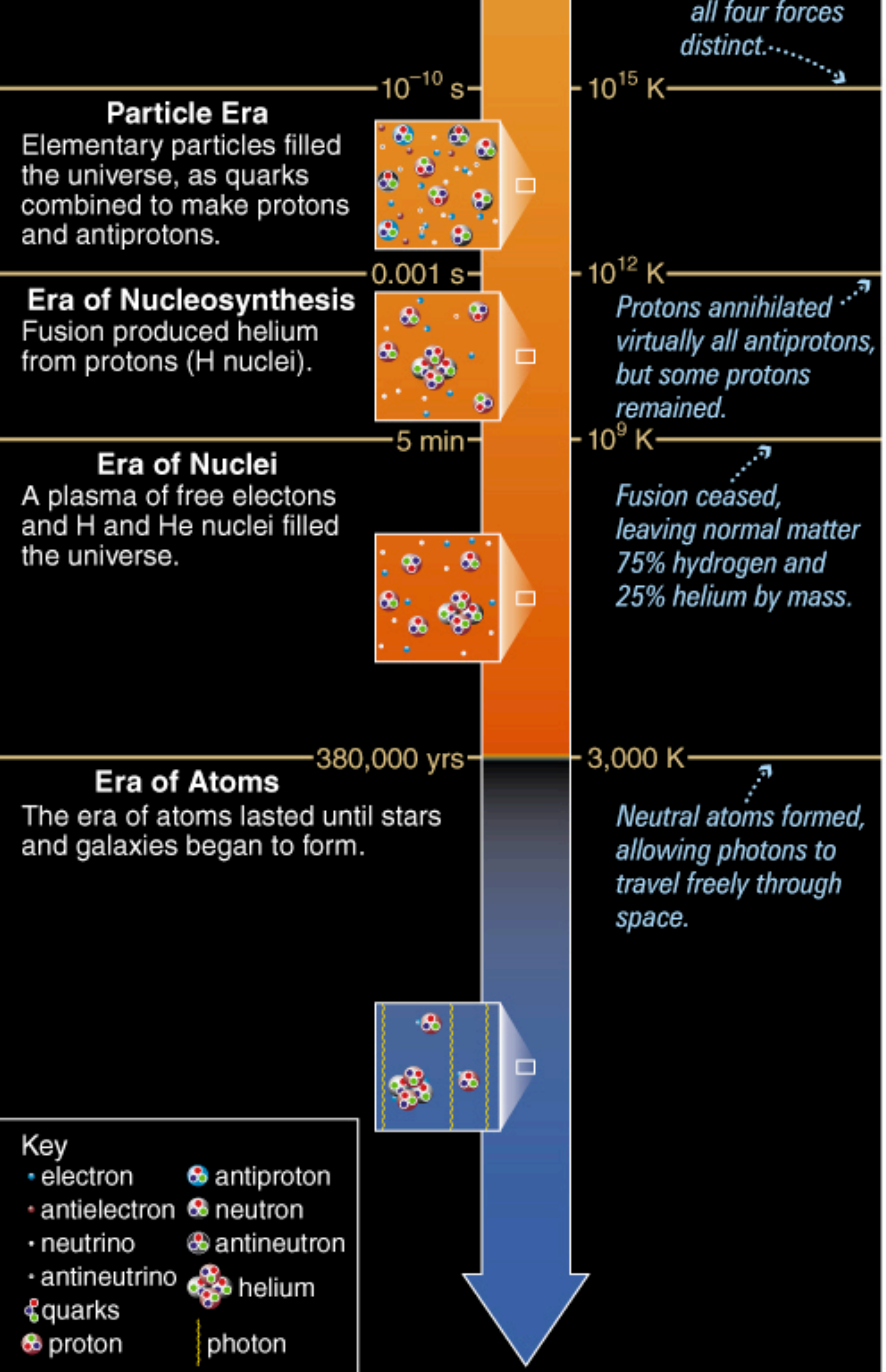
Big Bang Nucleosynthesis (BBN):

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 Era
Elementary particles filled the universe, as quarks combined to make protons and antiprotons.

Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).

Protons annihilated virtually all antiprotons, but some protons remained.

Era of Nuclei
A plasma of free electons and H and He nuclei filled the universe.

Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.

Era of Atoms
The era of atoms lasted until stars and galaxies began to form.

Neutral atoms formed, allowing photons to travel freely through space.

particle soup

< millisecond

T ~ 10^{14} K

nucleosynthesis (BBN)

~ 3 minutes

T ~ 10^{10} K

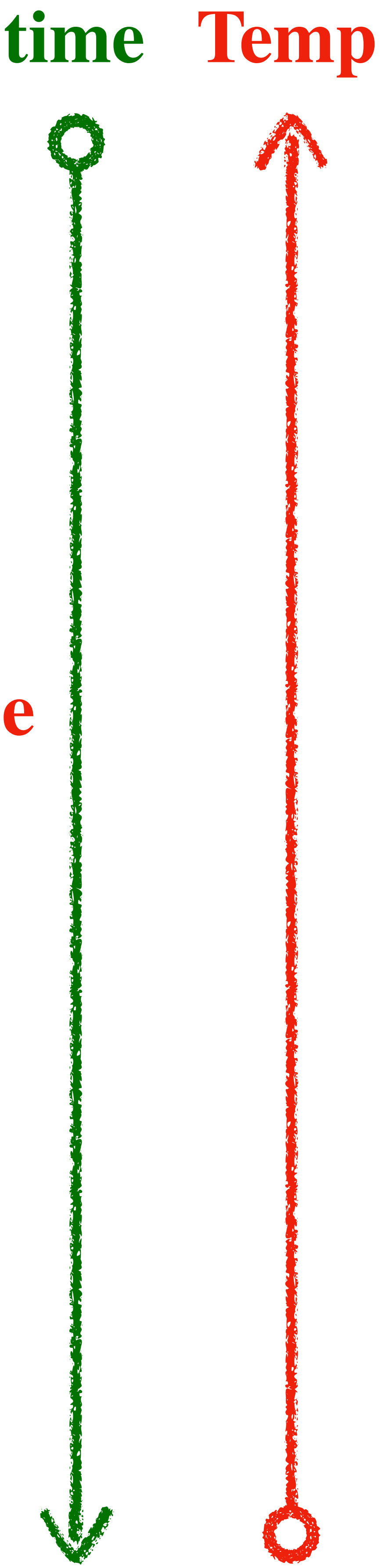
Early Universe

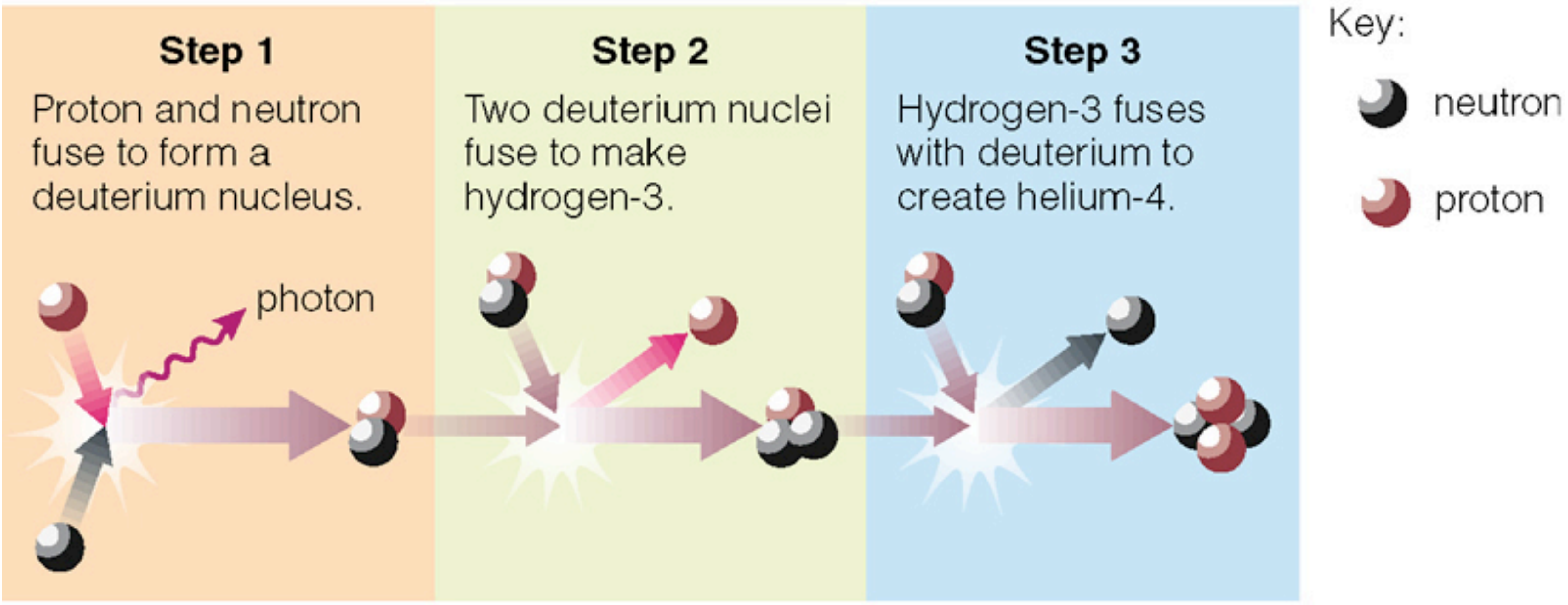
recombination

~380,000 year

T ~ 3000 K

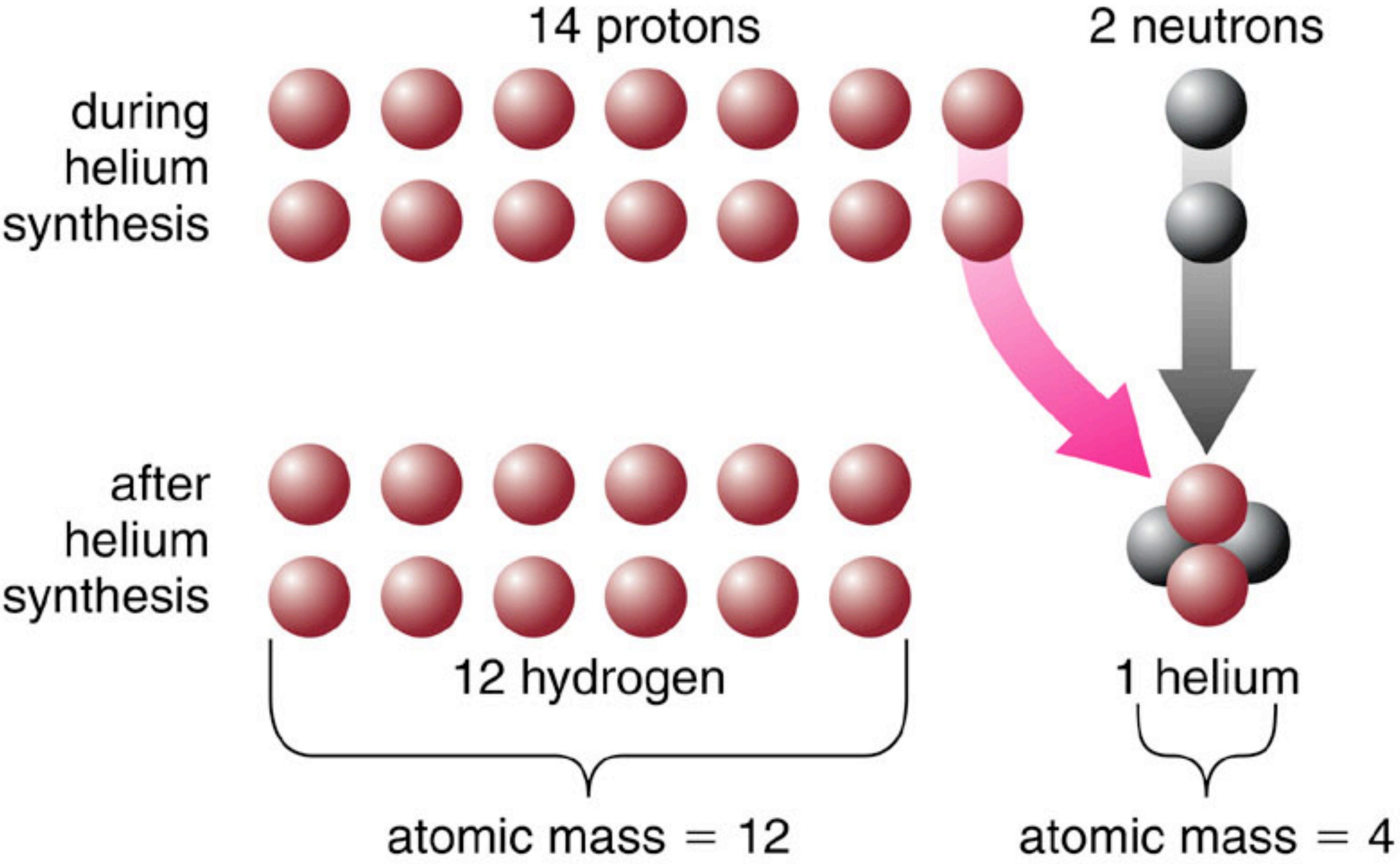
emission of CMB: surface of last scattering





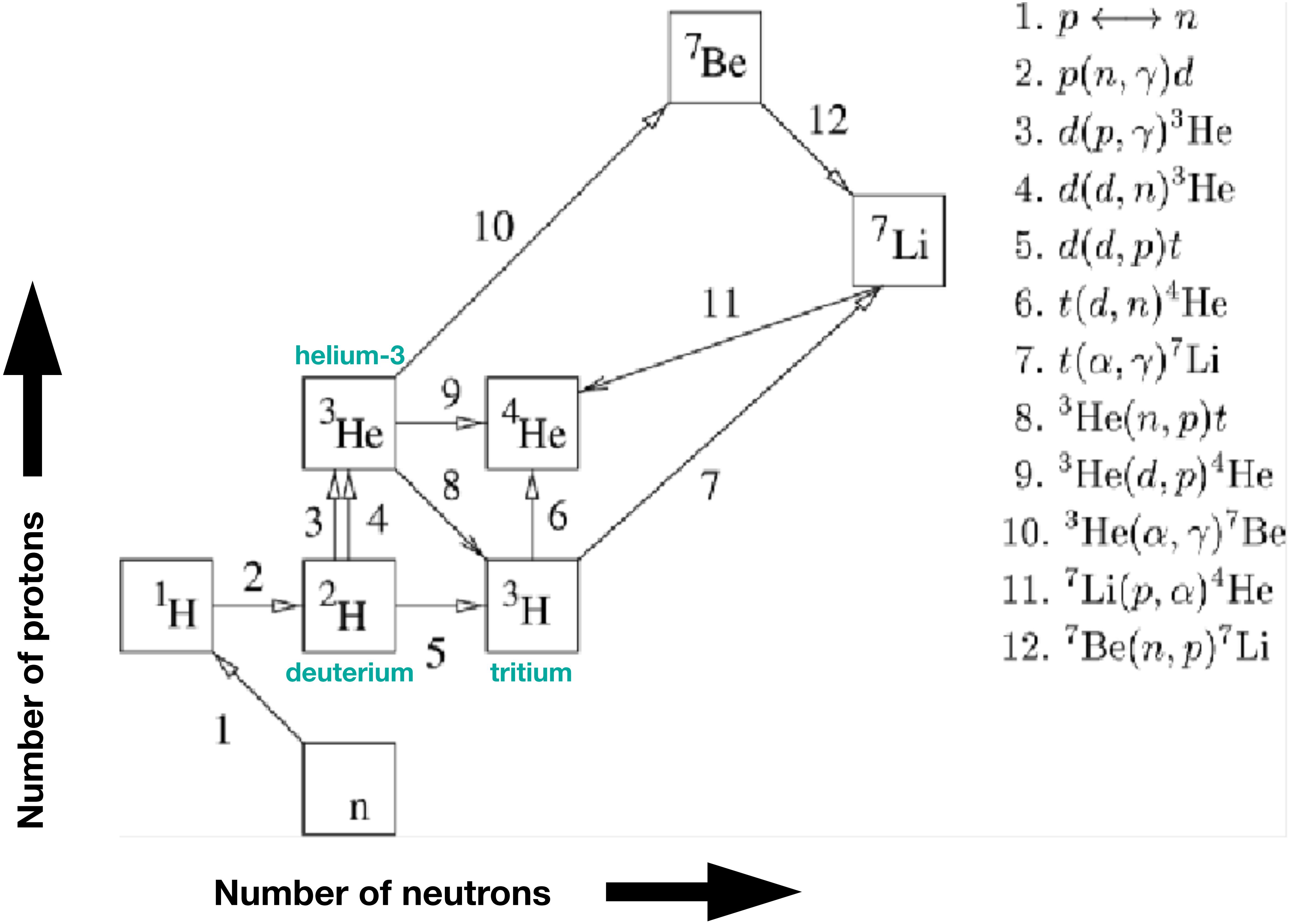
Protons and neutrons combined to make long-lasting helium nuclei when the universe was ~3 minutes old.

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)

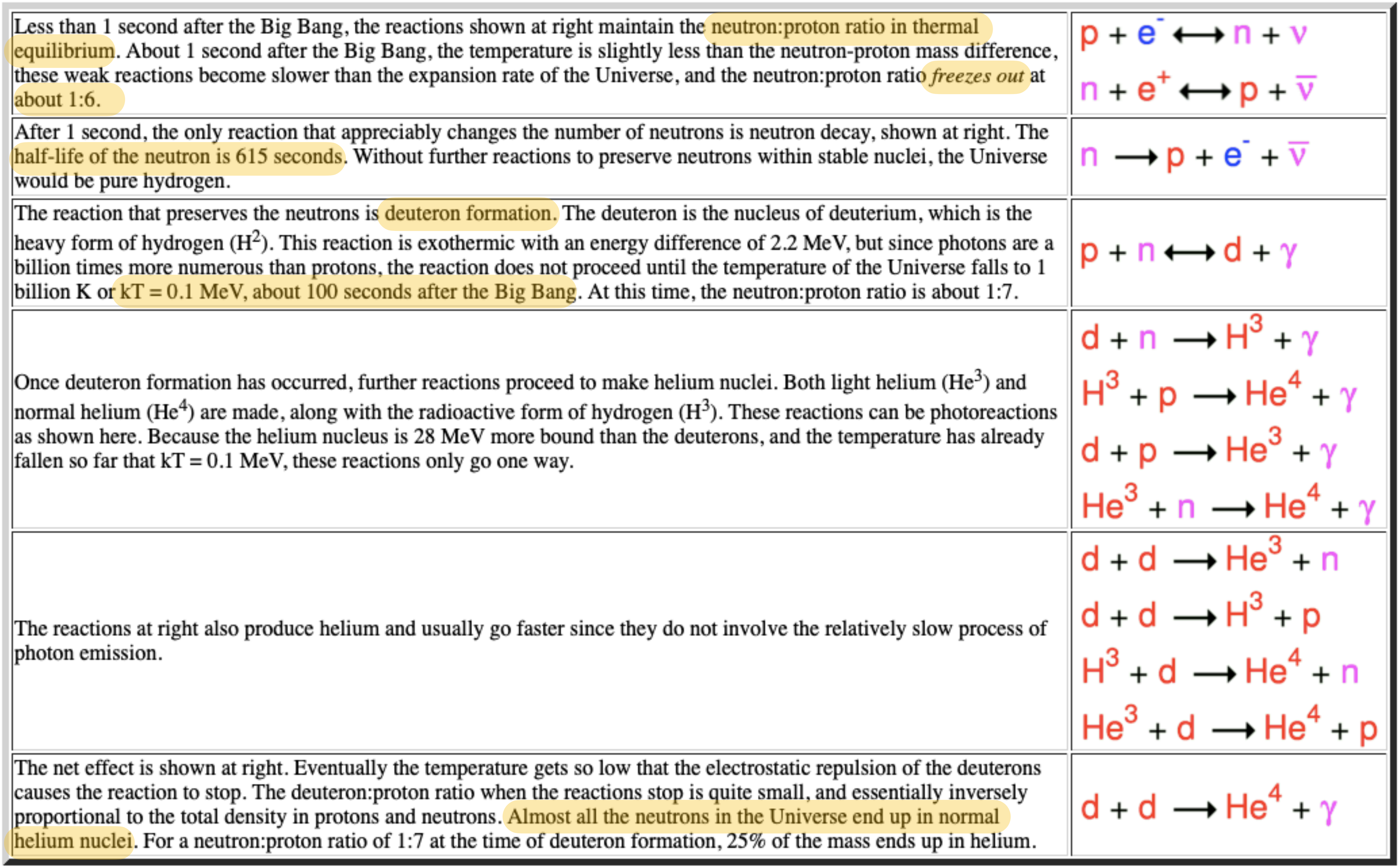
Matches observations of nearly primordial gases



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 reactions

The following stages occur during the first few minutes of the Universe:



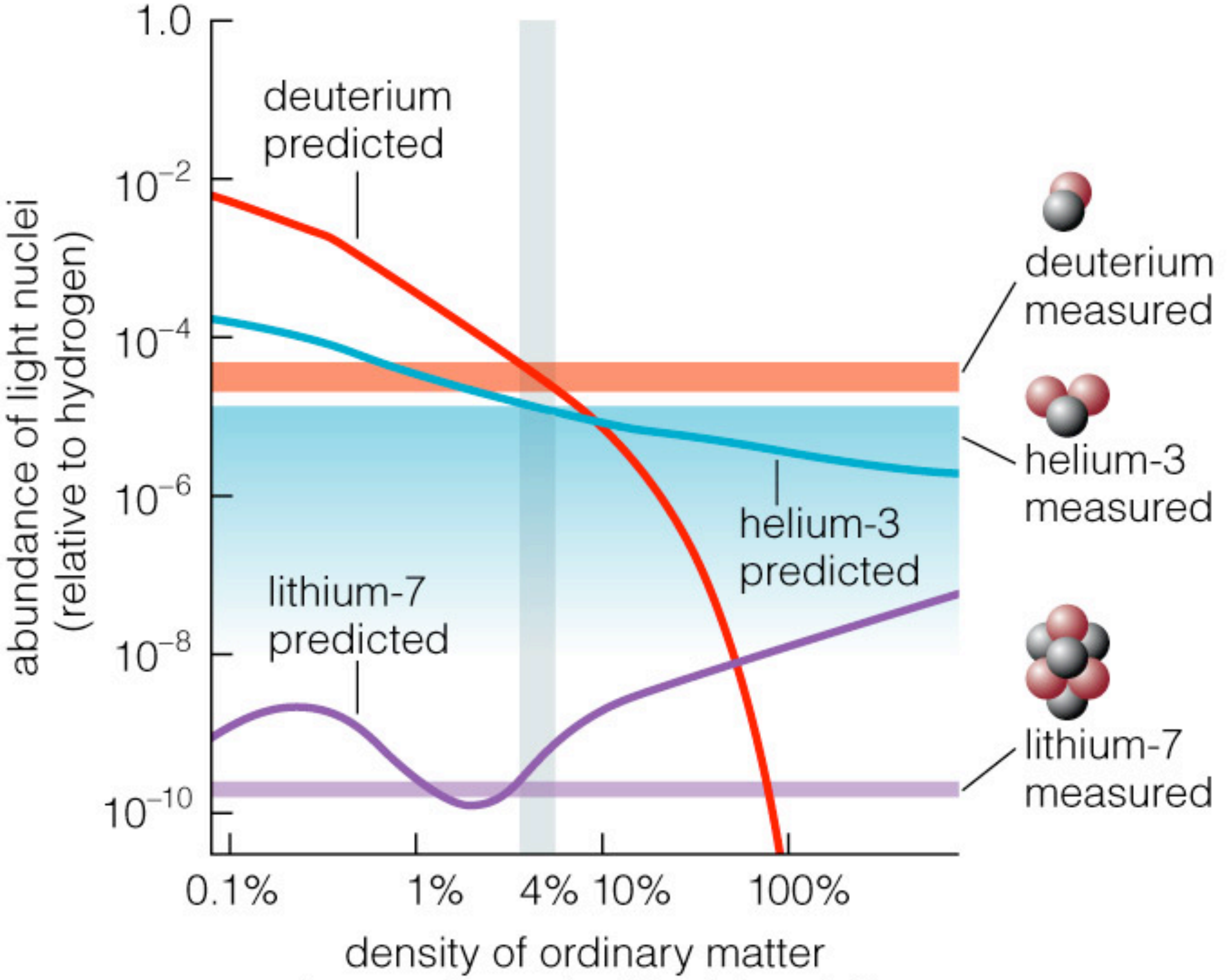
Less than 1 second after the Big Bang, the reactions shown at right maintain the neutron:proton ratio in thermal equilibrium. About 1 second after the Big Bang, the temperature is slightly less than the neutron-proton mass difference, these weak reactions become slower than the expansion rate of the Universe, and the neutron:proton ratio *freezes out* at about 1:6.	$p + e^- \longleftrightarrow n + \nu$ $n + e^+ \longleftrightarrow p + \bar{\nu}$
After 1 second, the only reaction that appreciably changes the number of neutrons is neutron decay, shown at right. The half-life of the neutron is 615 seconds. Without further reactions to preserve neutrons within stable nuclei, the Universe would be pure hydrogen.	$n \longrightarrow p + e^- + \bar{\nu}$
The reaction that preserves the neutrons is deuteron formation. The deuteron is the nucleus of deuterium, which is the heavy form of hydrogen (H^2). This reaction is exothermic with an energy difference of 2.2 MeV, but since photons are a billion times more numerous than protons, the reaction does not proceed until the temperature of the Universe falls to 1 billion K or $kT = 0.1$ MeV, about 100 seconds after the Big Bang. At this time, the neutron:proton ratio is about 1:7.	$p + n \longleftrightarrow d + \gamma$
Once deuteron formation has occurred, further reactions proceed to make helium nuclei. Both light helium (He^3) and normal helium (He^4) are made, along with the radioactive form of hydrogen (H^3). These reactions can be photoreactions as shown here. Because the helium nucleus is 28 MeV more bound than the deuterons, and the temperature has already fallen so far that $kT = 0.1$ MeV, these reactions only go one way.	$d + n \longrightarrow H^3 + \gamma$ $H^3 + p \longrightarrow He^4 + \gamma$ $d + p \longrightarrow He^3 + \gamma$ $He^3 + n \longrightarrow He^4 + \gamma$
The reactions at right also produce helium and usually go faster since they do not involve the relatively slow process of photon emission.	$d + d \longrightarrow He^3 + n$ $d + d \longrightarrow H^3 + p$ $H^3 + d \longrightarrow He^4 + n$ $He^3 + d \longrightarrow He^4 + p$
The net effect is shown at right. Eventually the temperature gets so low that the electrostatic repulsion of the deuterons causes the reaction to stop. The deuteron:proton ratio when the reactions stop is quite small, and essentially inversely proportional to the total density in protons and neutrons. Almost all the neutrons in the Universe end up in normal helium nuclei. For a neutron:proton ratio of 1:7 at the time of deuteron formation, 25% of the mass ends up in helium.	$d + d \longrightarrow He^4 + \gamma$

Source: Ned Wright: http://www.astro.ucla.edu/~wright/BBNS.html

BBN products:

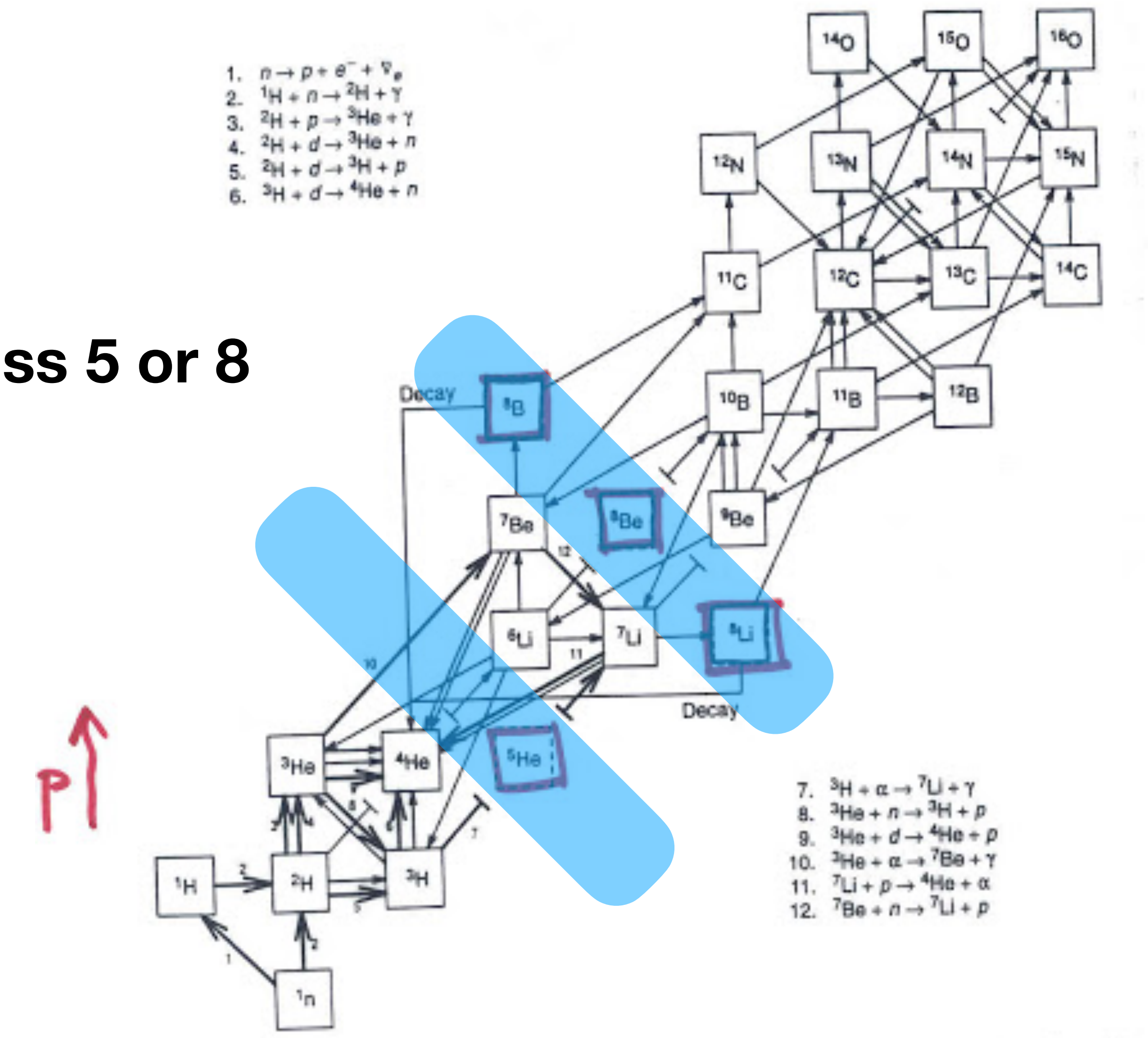
- 3/4 Hydrogen
- 1/4 Helium
- Traces of
  - deuterium
  - tritium
  - helium 3
  - lithium
  - berylium

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



BBN products limited to light isotopes

no stable mass 5 or 8



1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $^1H + n \rightarrow {}^2H + \gamma$
3. $^2H + p \rightarrow {}^3He + \gamma$
4. $^2H + d \rightarrow {}^3He + n$
5. $^2H + d \rightarrow {}^3H + p$
6. $^3H + d \rightarrow {}^4He + n$

7. $^3H + \alpha \rightarrow {}^7Li + \gamma$
8. $^3He + n \rightarrow {}^3H + p$
9. $^3He + d \rightarrow {}^4He + p$
10. $^3He + \alpha \rightarrow {}^7Be + \gamma$
11. $^7Li + p \rightarrow {}^4He + \alpha$
12. $^7Be + n \rightarrow {}^7Li + p$

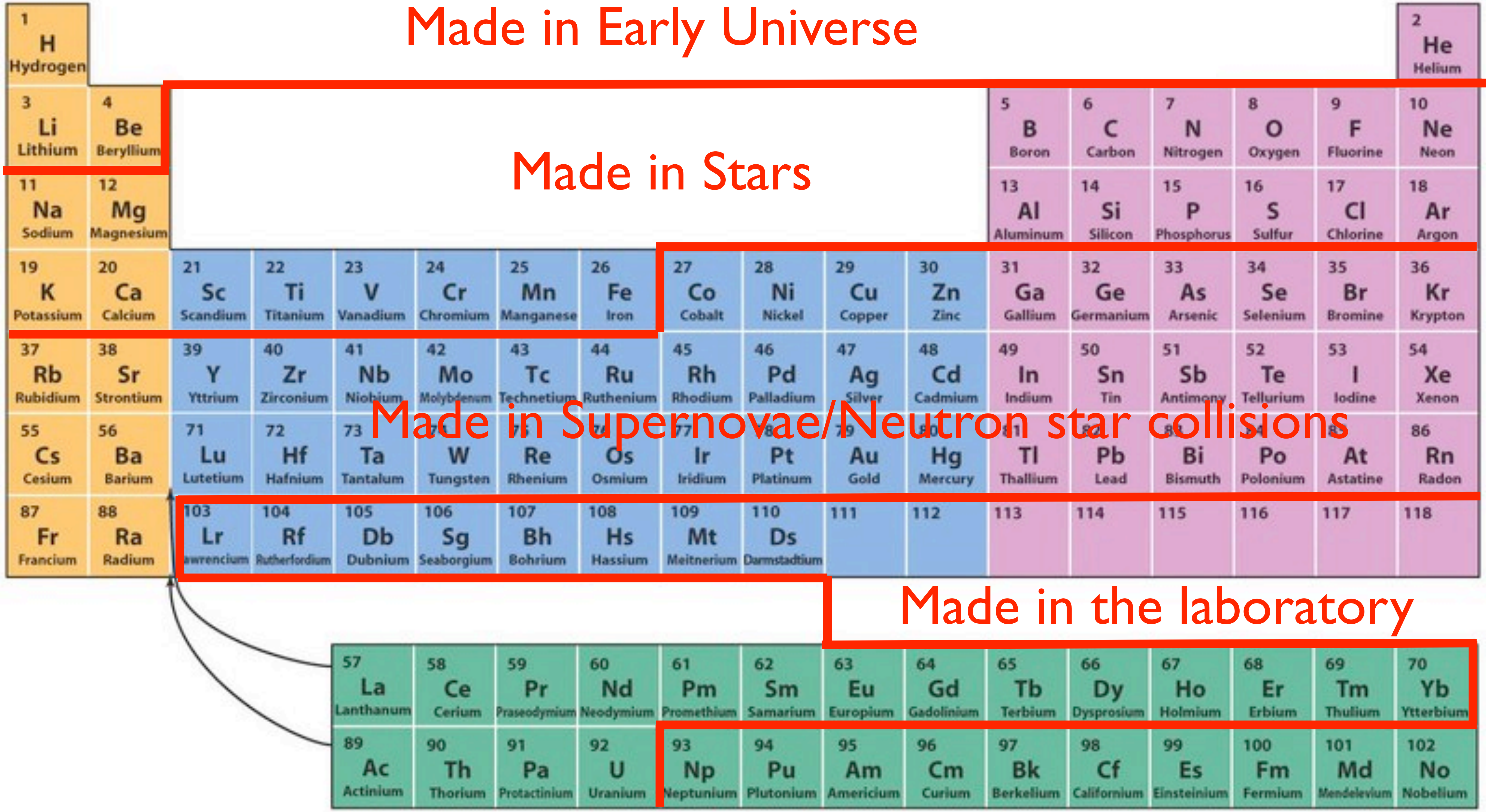
Fig. 2. The nuclear reaction network used for big-bang nucleosynthesis; the most important reactions are numbered and have bold arrows. The broken boxes for mass 5 and 8 indicate that all nuclides of this mass are very unstable.

→ n

BBN restricted to isotopes of the light elements

Stars skip over the mass bottleneck via the triple alpha reaction

$3\ {}^4He \rightarrow {}^{12}C^*$



Made in Early Universe

Made in Stars

Made in Supernovae/Neutron star collisions

Made in the laboratory

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	103 Lr awrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111	112	113	114	115	116	117	118
				57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium
				89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium