Nuclear Astrophysics Topics:
With Connections to Strong Interaction Physics

I. Introduction: timeline, astrophysics epochs

II. The cosmological inventory

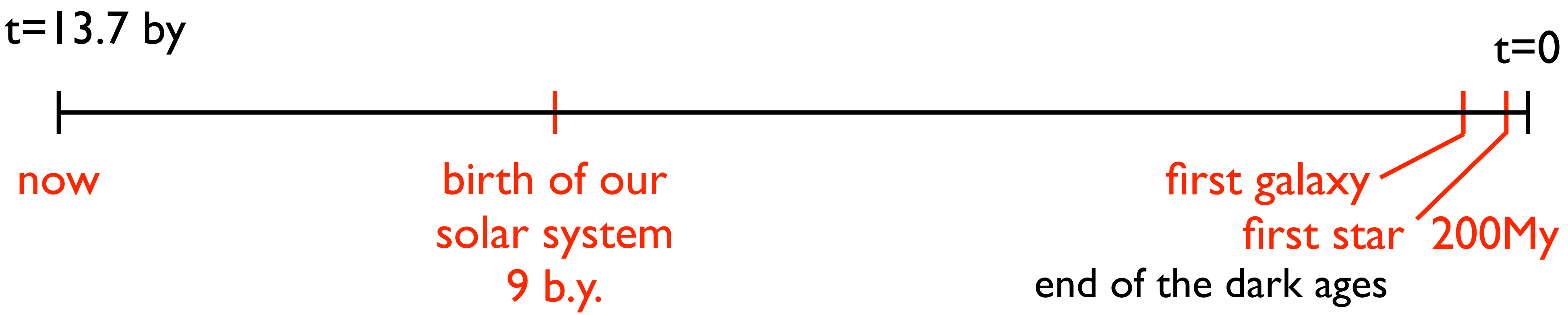
III. BBN and cosmological neutrinos

IV. Solar neutrinos, stellar burning, nucleosynthesis

V. Supernovae and neutron stars

Notes: http://www.int.washington.edu/PHYS554/2011/2011.html

I. Introduction: Time Line and Epochs



The basic strategy in astrophysics is to identify probes -- direct radiation, or some fossil consequence -- of the various interesting epochs along this time line, then exploit these to deduce the underlying physics

Focus here is on the nuclear epochs, $T \leq \Lambda_{QCD}$

1. Epoch of stellar astrophysics: $t \geq 200$ My, $T \leq 20°K$

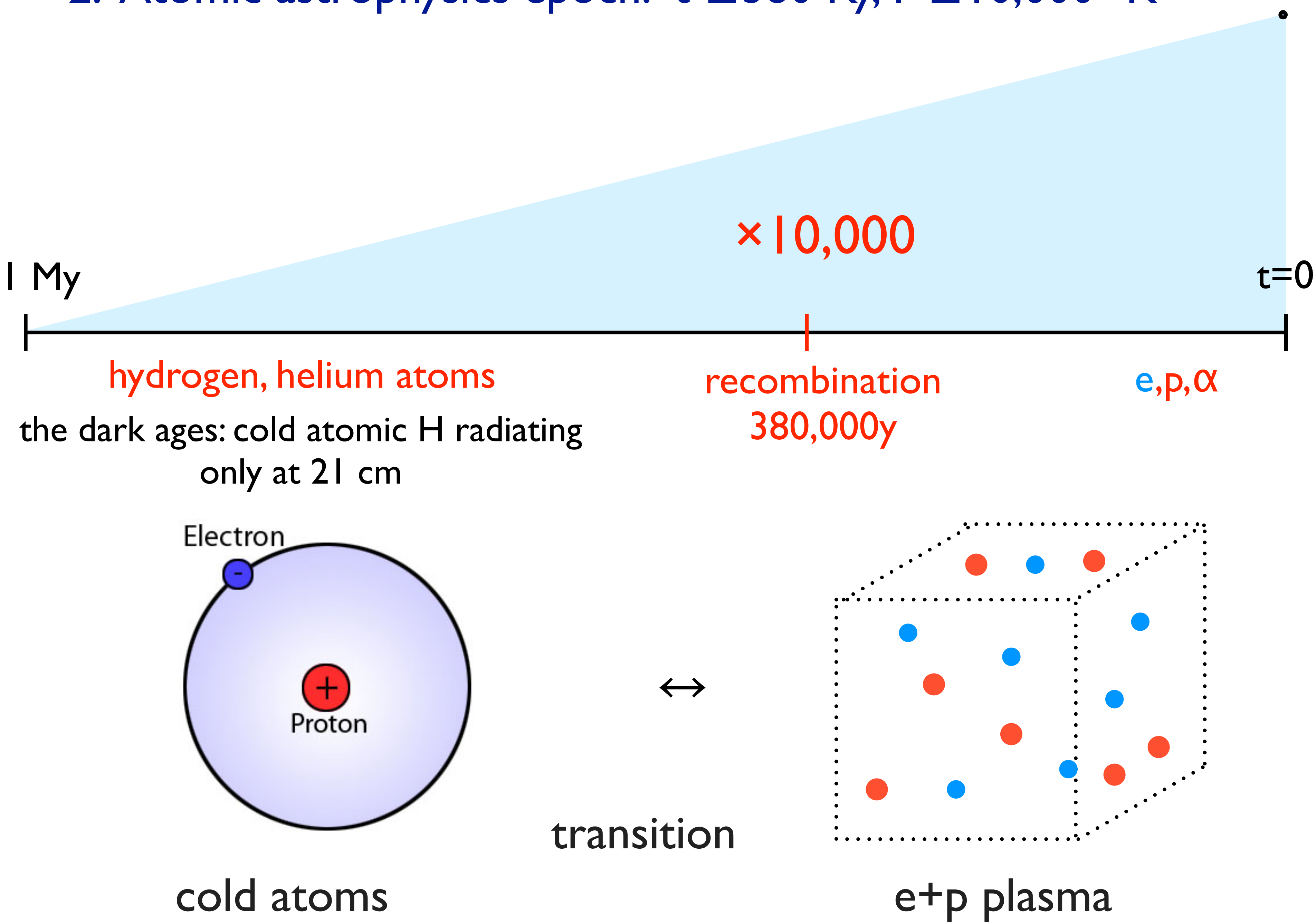
beginning defined by a transition

cold, nonluminous atomic gases contracting under gravity	↔	hot ionized gases in steady-state equilibrium with gravity

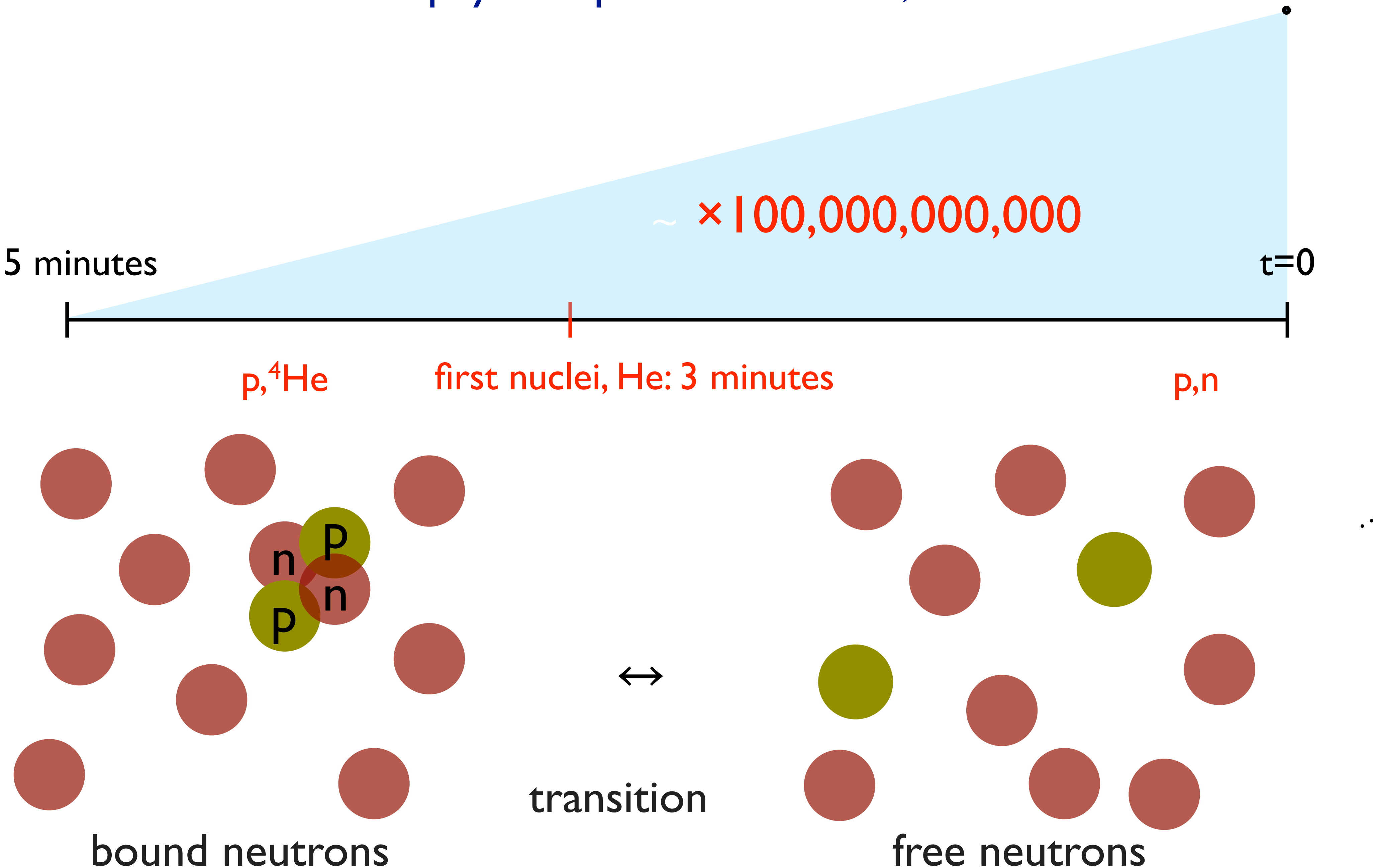
Stars produce

- ionizing UV radiation
- magnetic fields
- shock waves and particle acceleration
- new nuclei ....

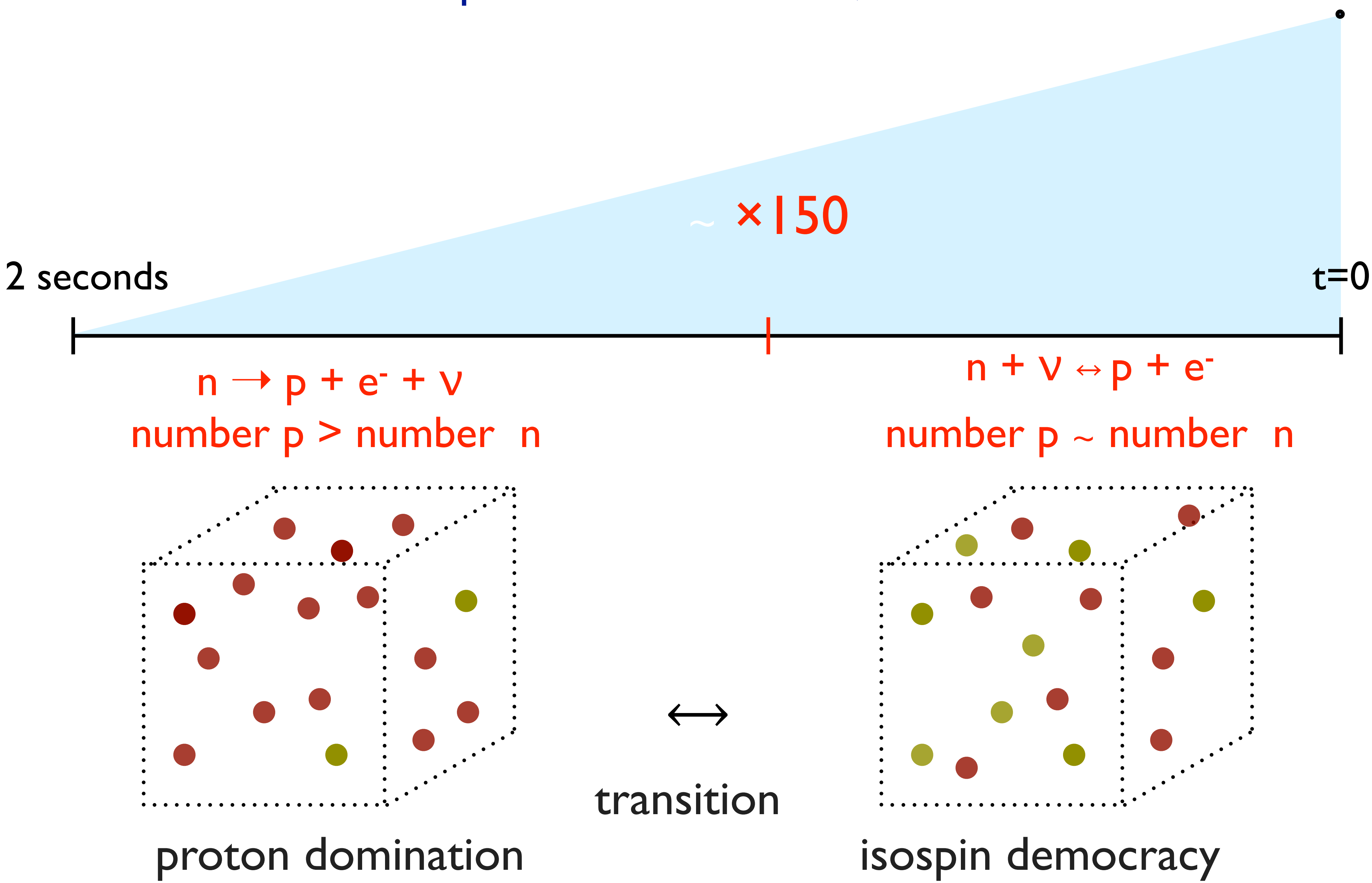
2. Atomic astrophysics epoch: t ≥380 Ky, T ≤10,000 °K



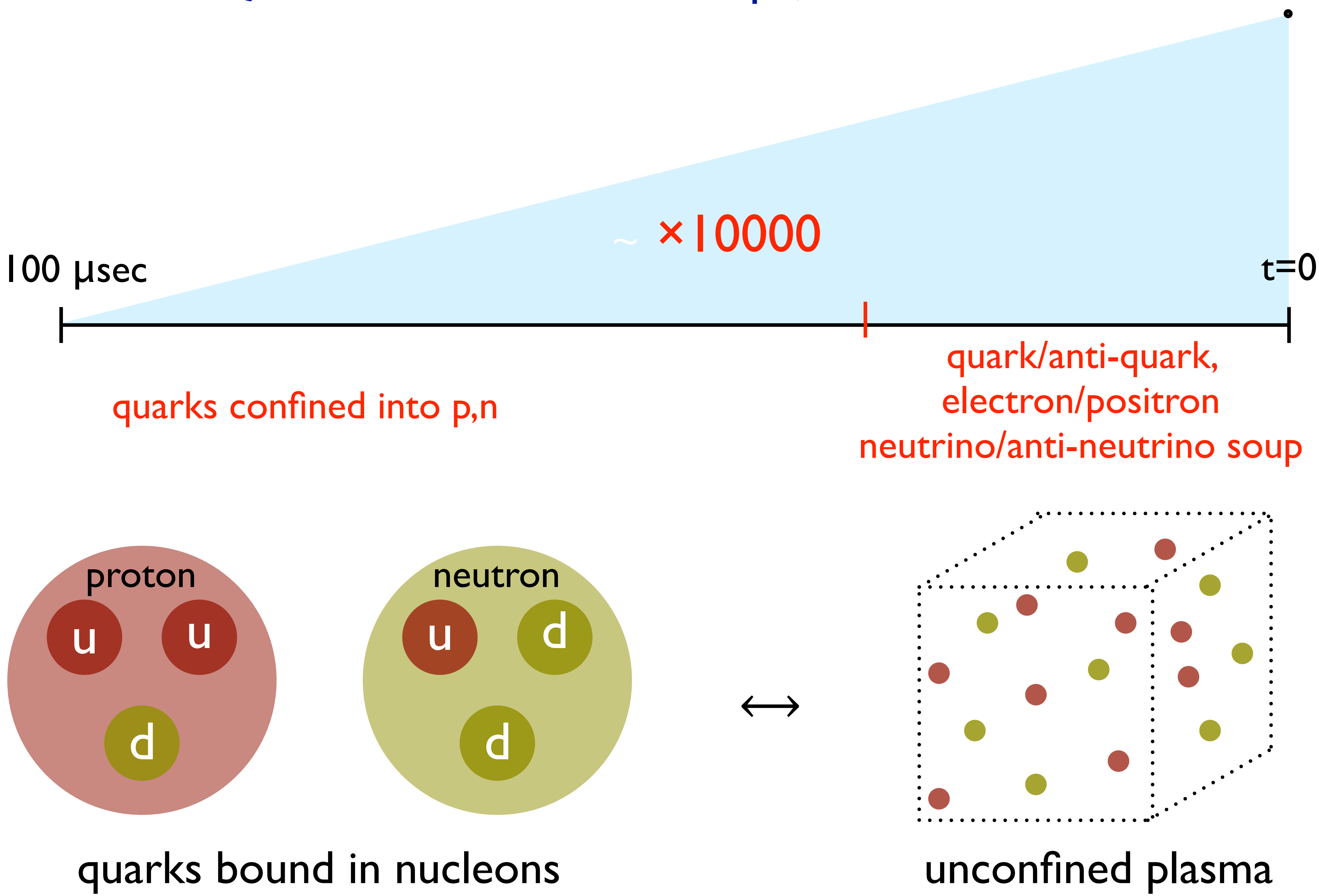
3. Nuclear astrophysics epoch: $t \geq 5$ min, $T \leq 10^9$ °K



4. Weak nonequilibrium: $t \geq 1$ sec, $T \leq 10^{10}$ °K



5. Quark confinement: $t \geq 50\ \mu s$, $T \leq 10^{12}$ °K



Some of the Observables

1. Stellar astrophysics

- Our Sun
  age, mass, radius, luminosity
  photoabsorption lines ↔ surface abundances
  helioseismology and neutrinos (interior)

- Other stars burning in hydrostatic equilibrium
  patterns of colors (surface temperatures) and luminosities (energy production)
  deduced evolutionary paths
  nucleosynthesis, wind ejecta

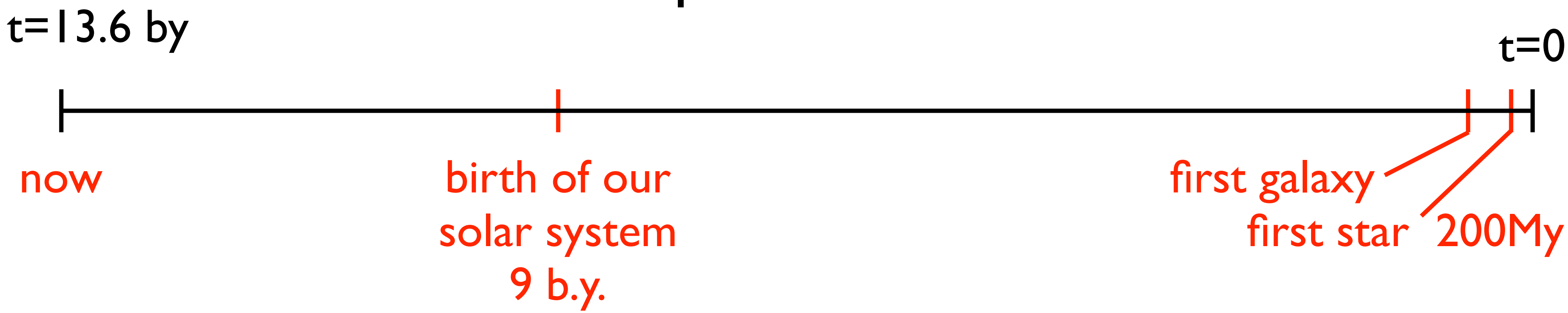
- Core-collapse supernovae
  neutrino fluxes
  nucleosynthetic output ↔ heavy elements
  associated gamma ray bursts (600My post BBN)

- Thermonuclear supernovae
  nuclear-powered light curves are "standard candles" for measuring cosmological expansion

- Neutron stars masses and radii
  cooling
  potentially the gravitational wave signals from their mergers

- Quasars accretion disk surrounding central black holes of galaxies
  absorption-line analysis: "back-lighting" of the absorbing intergalactic medium to 700My

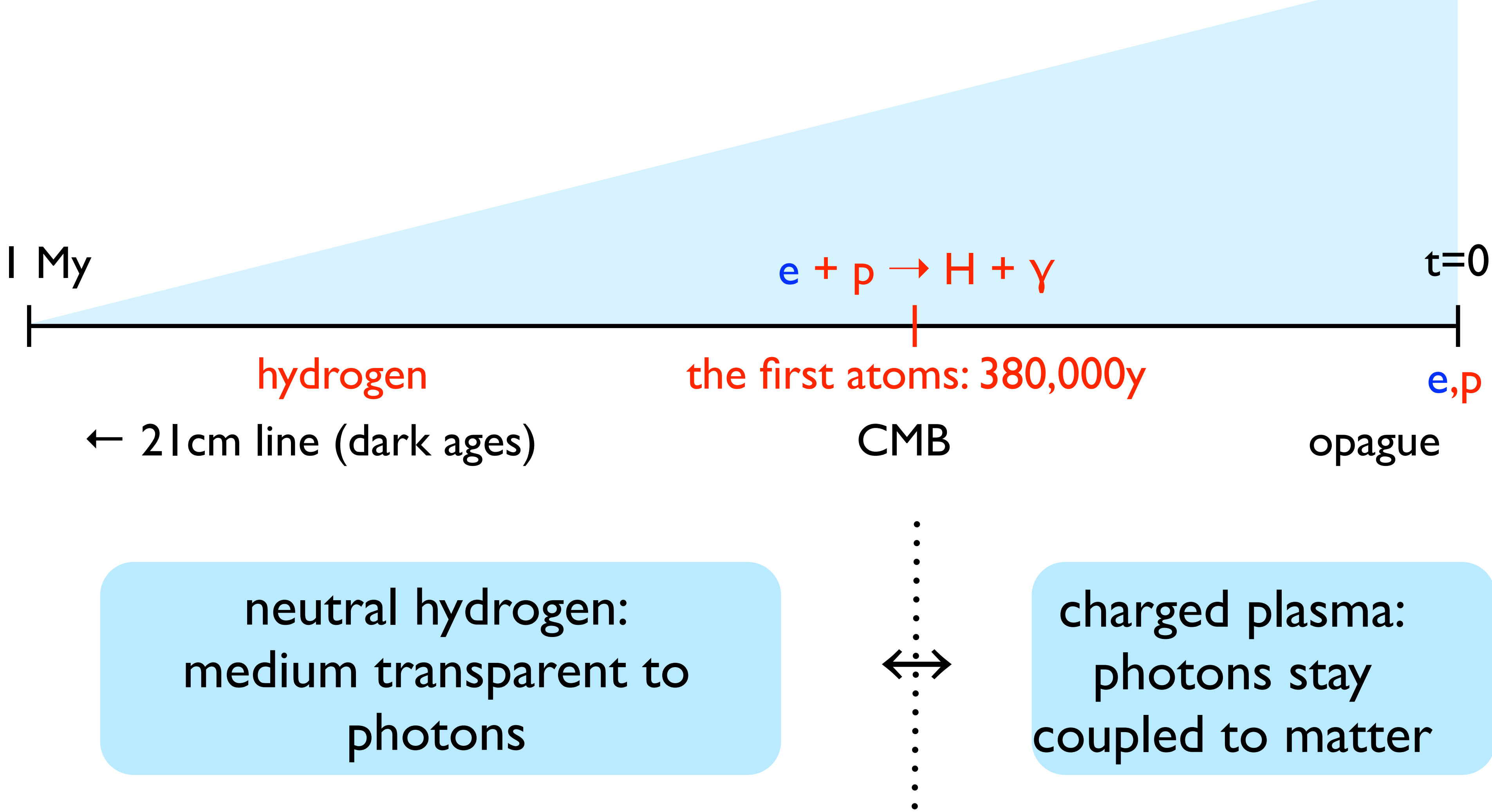
direct optical studies



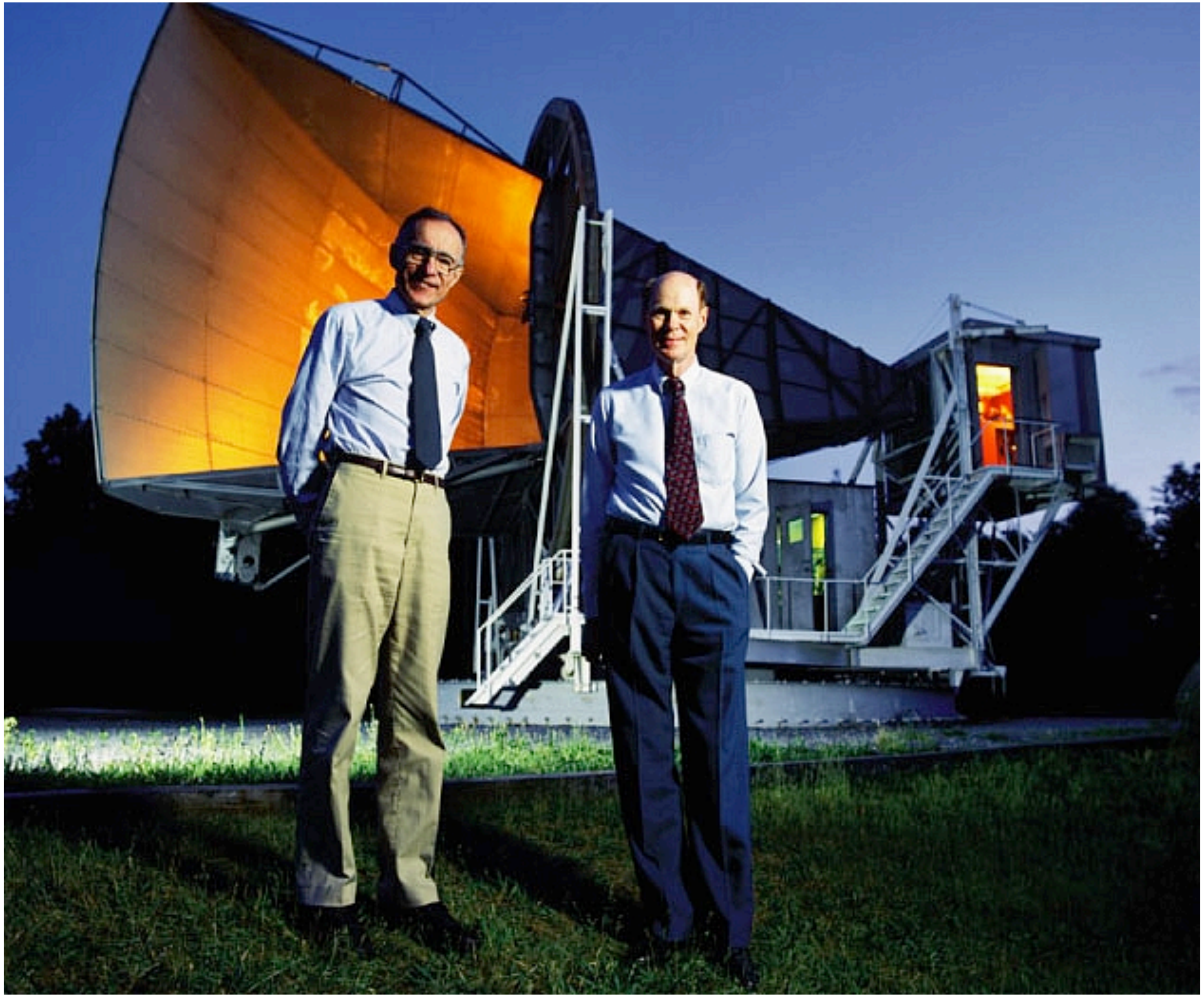
Hubble deep-field, stars from 600My

JWST -- infrared optimized -- will push back to see the first baby galaxies

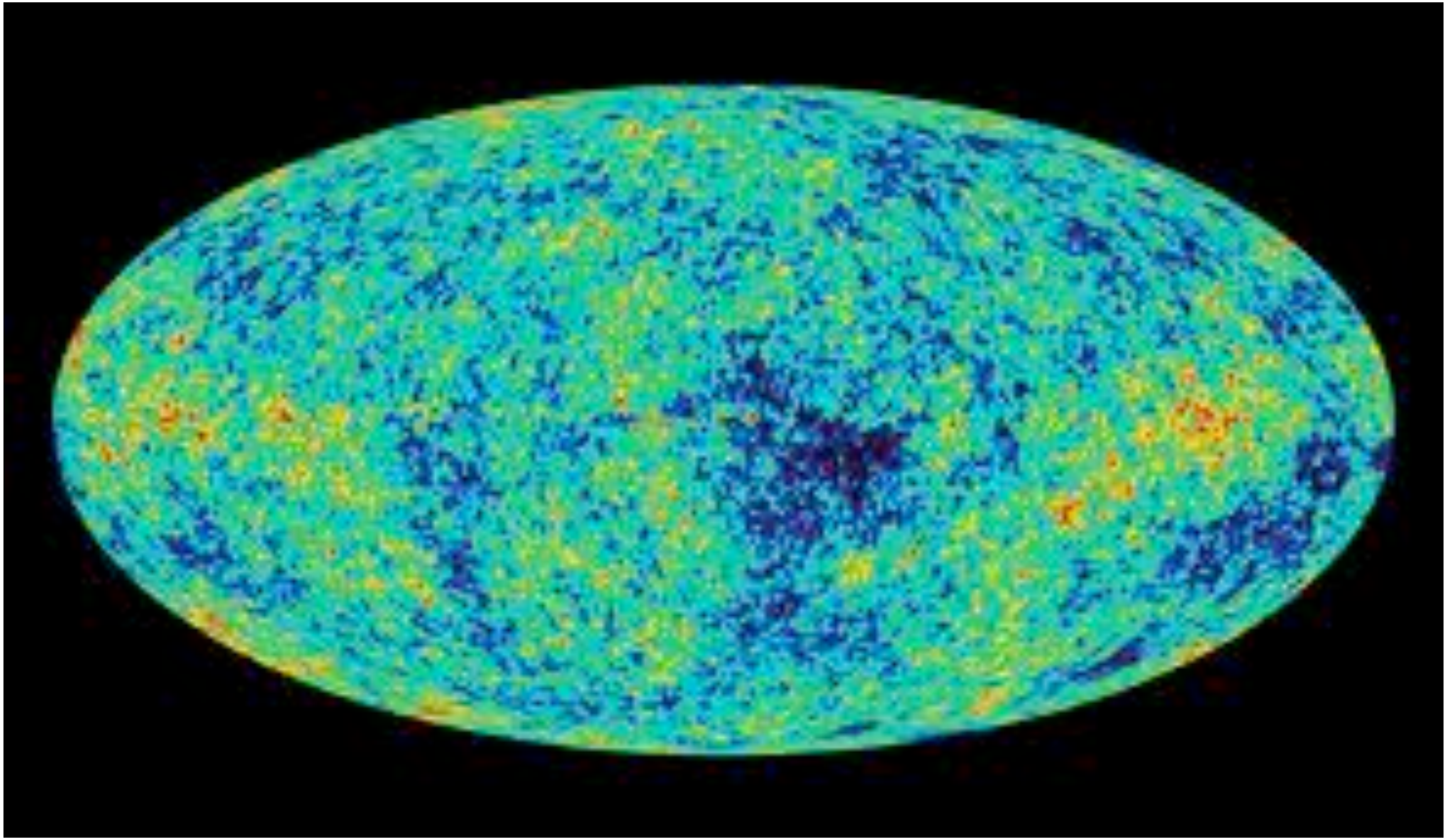
2. Atomic physics: CMB from recombination



photons are released at time of recombination, travel to us from a distance of 13.6 b. light years, their wavelengths stretched as the universe expands



Penzias and Wilson cryogenic cosmic microwave detector of 1964
Nobel prize in 1978 for experimentally verifying the Big Bang



WMAP: tiny temperature fluctuations in the CMB reflecting the dynamics of baryons falling into regions of dark-matter dominated over-density, resisted by the radiative pressure

3. BBN Nucleosynthesis: light-element abundances

- Initial conditions of a nonzero baryon number and a a # abundance of protons ~ # of neutrons at $T \gg m_p - m_n$

- Observables are the fossil records of d, He, Li preserved in the interstellar medium or on the surfaces of old, metal-poor stars

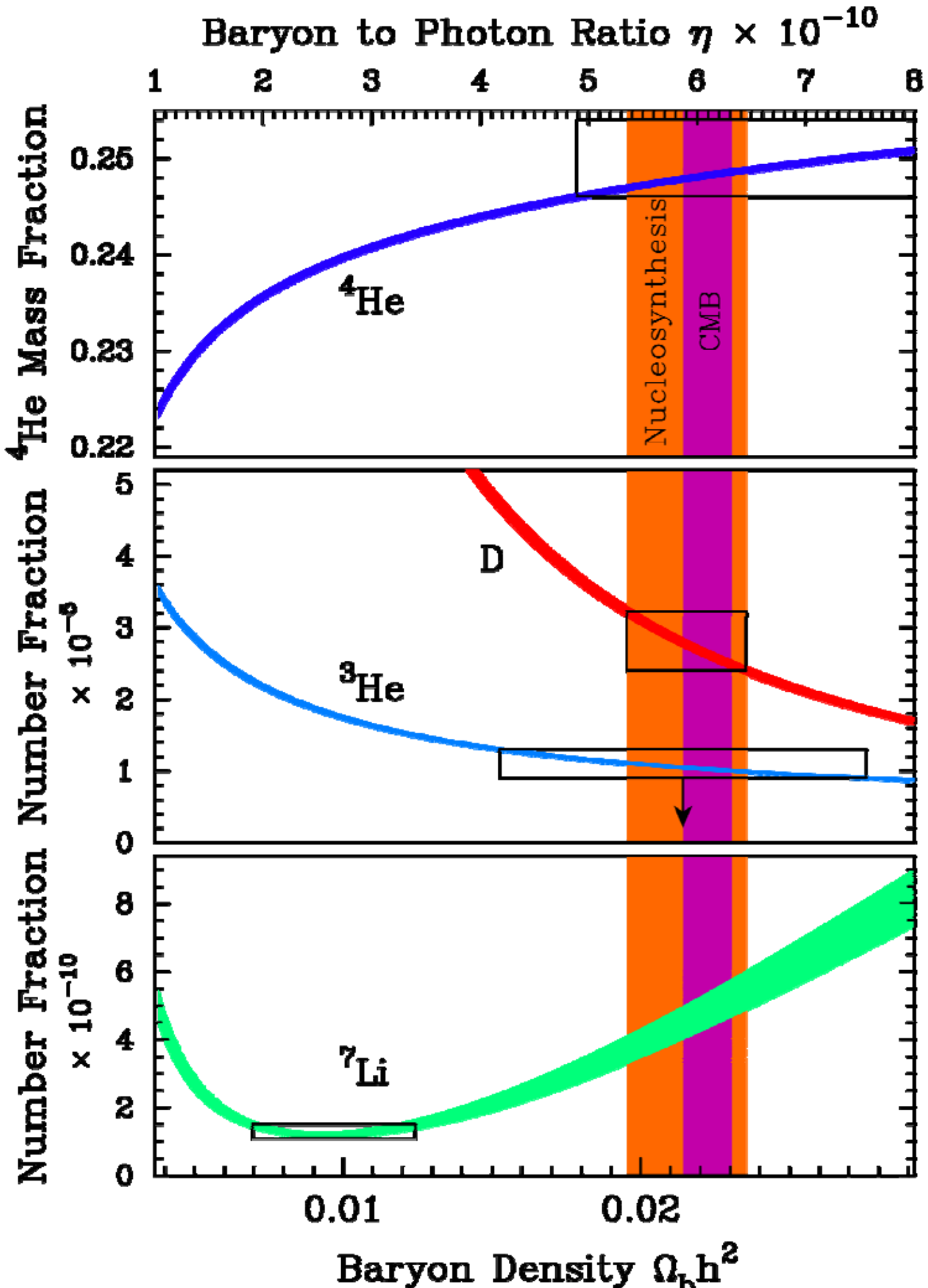
- Connects the surprisingly small binding energy of deuterium to the ratio η of baryons to photons

- η independently and more accurately determined by CMB analyses

The "fossil" data: the abundances of H, He, Li

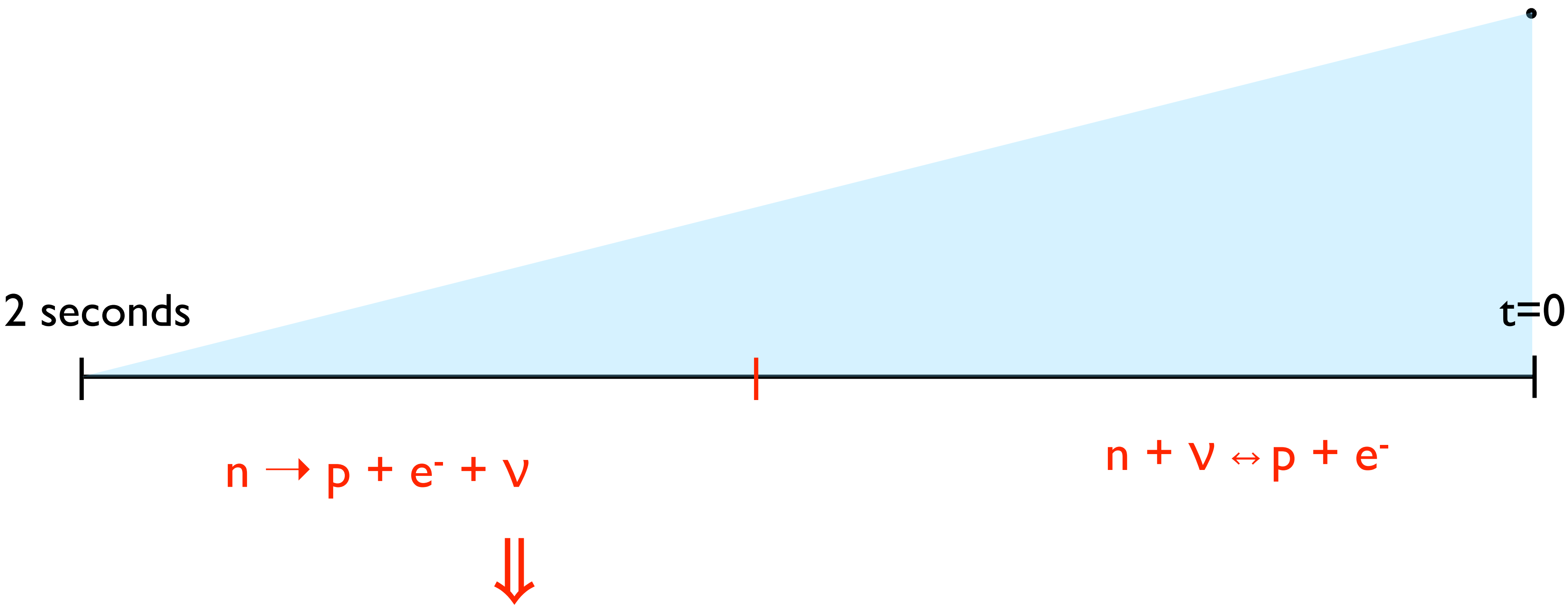
$\eta = 0.6 \times 10^{-9}$ reproduces the needed H/He ratio

few other nuclei are produced



Suzuki (Tytler group) 2006

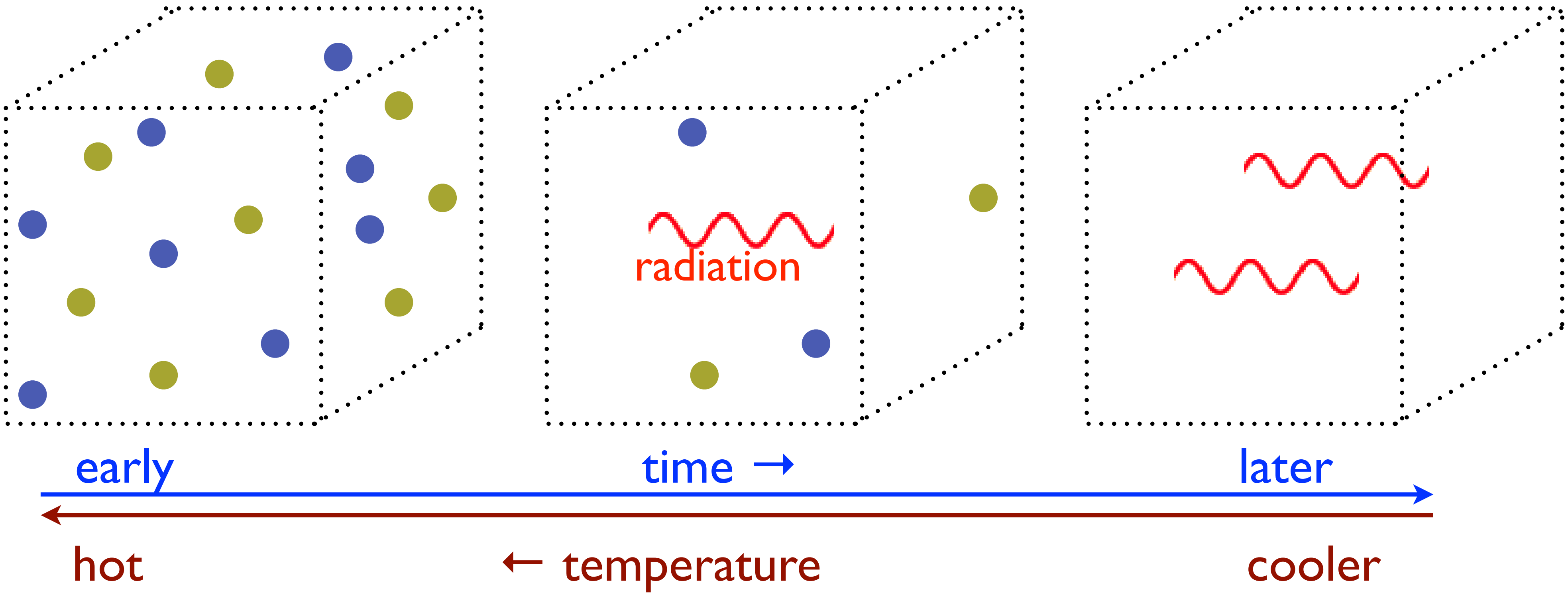
4. Weak decoupling: massive cosmic background neutrinos



- Weak analog of the electromagnetic CMB; ~300/cm^3
- In principle, carry similar information on cosmological structure, though at ~ 1 sec, not 380,000 y
- Neutrino mass: one identified component of the dark matter, detectable through mass affects on growth of structure

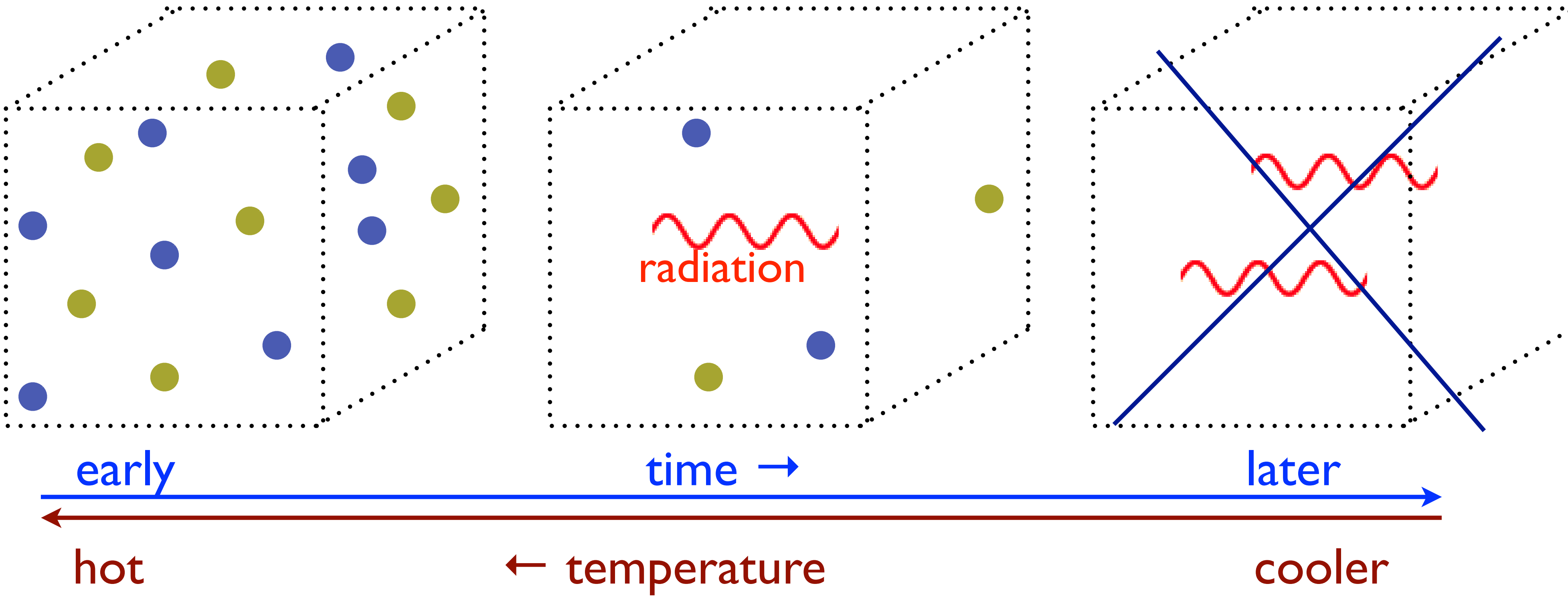
5. QCD phase transition

- The plasma quark/antiquark recombination



5. QCD phase transition

- The plasma quark/antiquark recombination is asymmetric



leaving us with a net nucleon number -- requiring baryon number violation, CP violation, and out-of-equilibrium physics

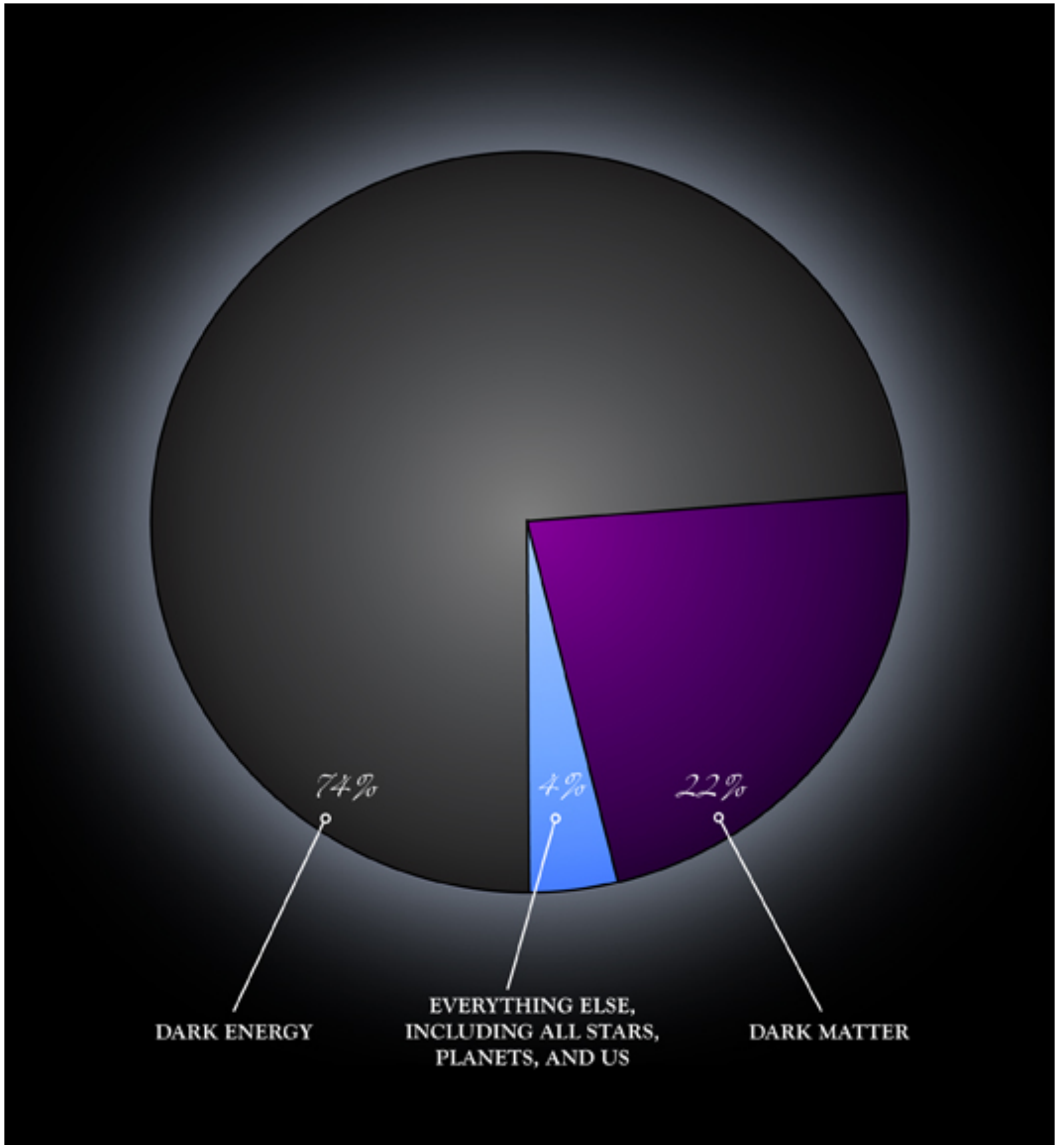
- Introduces a lot of interesting connections to laboratory physics
  - searches from proton decay and $N\bar{N}$ oscillations
  - searches for CP violation in the nucleon and in atomic nuclei

$$\langle gs|H_{\rm edm}|gs\rangle = \langle gs|\vec{E}_{\rm ext}\cdot\vec{s}_N|gs\rangle$$

  - searches for CP violation in LB neutrino experiments

- A sufficiently sharp or violent phase transition can in principle produce density fluctuations that could persist to and affect BBN
  - we will discuss some issues in BBN that might motivate consideration of nonstandard BBN scenarios

II. The Matter/Energy Inventory



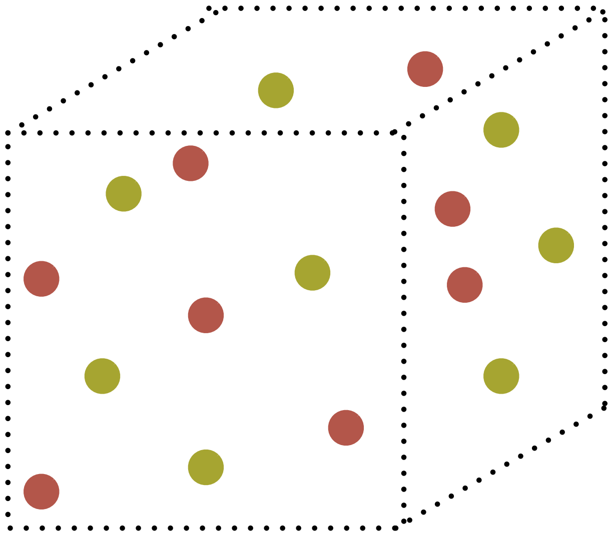
a) The visible matter component, accounted for in the standard model, 98% of which is the interaction energy from QCD: 4% of total

b) The dark matter, 22% of the total, less than 2% of which resides in the standard model (the neutrino component, using the neutrino mass upper bound of 1 eV)

c) The vacuum or dark energy, 74% of the total

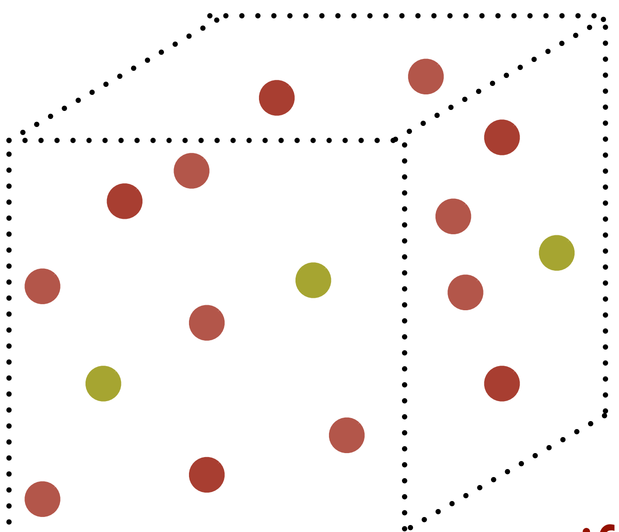
Baryon/photon ratio: Big Bang nucleosynthesis

Wagoner, Fowler, and Hoyle worked out the nuclear and weak interaction physics of Big Bang nucleosynthesis in 1967 -- perhaps the first high-precision result in cosmology



prior to weak decoupling

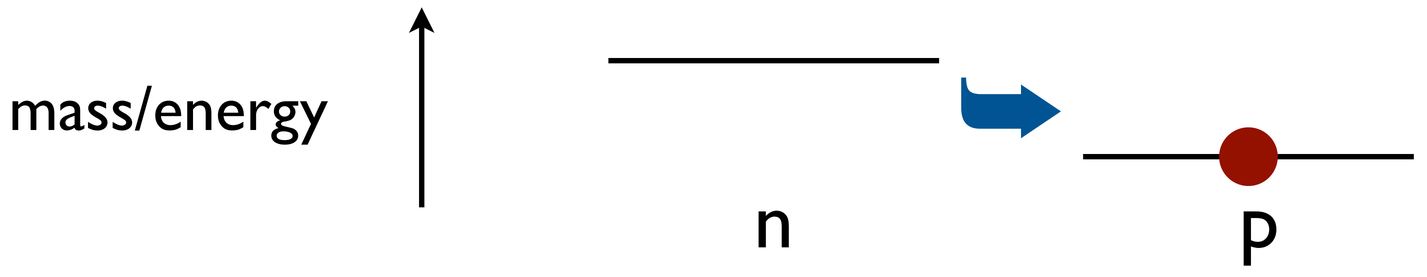
$T > M_n - M_p$



but when the temperature drops below an MeV -- 10^{10}K -- the p → n reaction cannot keep up with the n → p

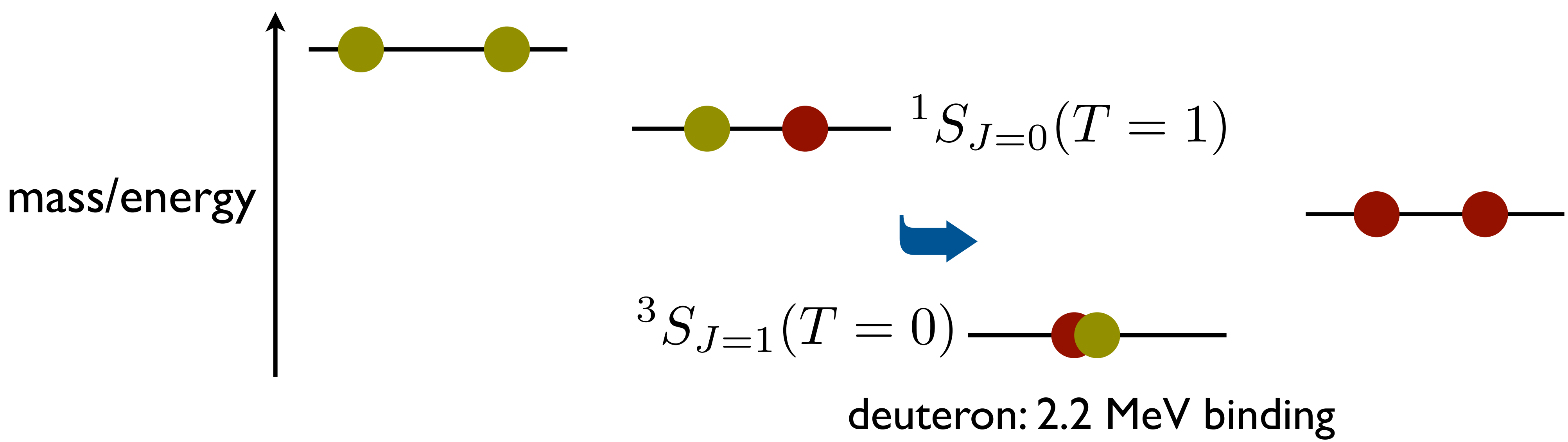
the neutrons start converting to protons

if nothing else were to happen in the next few minutes, our universe would be full of only H when systems cool, they settle into the lowest energy state



which in a nucleon plasma would correspond to protons

But the strong interaction turns on to generate a lower state



In fact the lowest energy state is ^{4}He, but the high entropy and diluteness renders direct reactions such as 2p+2n → ^{4}He + γ too slow to mediate He production: must proceed through the deuteron "bottleneck"

The deuterium "bottleneck"

So we see the basic physics -- can make it more quantitative.

1) The n/p inventory: pick one neutron, calculate dimensionally its decay rate n + $\nu_e \rightarrow$ p + e^-

$$\Lambda(T) \sim \langle \sigma v \rangle n_\nu(T) \qquad \sigma \sim G_F^2 E_\nu^2 \sim G_F^2 (kT)^2$$

$$\#\nu \text{ states/unit volume} \sim (kT)^3 \qquad G_F \sim \frac{10^{-5}}{M_N^2}$$

So dimensionally $\Lambda(T) \sim \frac{0.15}{\mathrm{sec}} \left(\frac{kT}{\mathrm{MeV}} \right)^5$

And with the πs and 2s properly inserted $\Lambda(T) \sim \frac{0.76}{\mathrm{sec}} \left(\frac{kT}{\mathrm{MeV}} \right)^5$

We need to compare to a second rate or clock, the Hubble rate

$$\text{Hubble rate} \equiv \frac{\frac{dR(t)}{dt}}{R(t)} = \sqrt{\frac{8\pi G\rho(t)}{3}}$$

$$\text{(relativistic) energy density} \quad \rho(t) \sim \frac{1}{R(t)^4}$$

$$\frac{\frac{d\rho(t)}{dt}}{\rho} = -4\frac{\frac{dR}{dt}}{R}$$

This can be integrated to give $\rho(t) \sim \dfrac{3}{32\pi G t^2}$

A direct calculation of the relativistic energy density from γ, e^+/e^-, 3 νs $\rho(t) = N\dfrac{\pi^2}{30}T^4 \quad N = 43/4$

$$R \sim T^{-1} \sim \sqrt{t} \qquad \text{Hubble rate} \sim \frac{0.67}{\text{sec}}\left(\frac{kT}{\text{MeV}}\right)^2$$

Bottom line: weak rates ($\sim (kT)^5$) cannot keep up with Hubble expansion ($\sim (kT)^2$) once the temperature reaches

$$kT \sim 1 \text{ MeV}$$

This is the time the n density begins to drop rapidly -- halted only because deuterium forms, preserving neutrons...

2) Deuterium formation constrained experimentally: about 25% of the universe's mass is in He, rest protons ⇒ n/p ~ 1/7. This determines η, the baryon/photon ratio

View n+p and d as two states in contact with a photon bath

$$n + p \leftrightarrow d + \gamma$$

In equilibrium, number density of states is obtained by integrating/summing over all momentum/spin states at temperature T

$$n_A = g_A \left[\frac{m_A T}{2\pi}\right]^{3/2} e^{(\mu_A - M_A)/T}$$

where g_A is the number of available spin states. So

$$\frac{n_d}{n_p n_n} \sim \frac{g_d}{g_p g_n} \left[\frac{A_d}{A_p A_n}\right]^{3/2} \left[\frac{2\pi}{M_N T}\right]^{3/2} e^{B_d/kT}$$

$$A_d = 2,\ A_n = A_p = 1,\ g_d = 3,\ g_n = g_p = 2,$$
$$B_d = m_p + m_n - m_d = 2.22 \text{ MeV}$$

(Saha equation; chemical potentials cancel in equilibrium)

Integrating over states $n_\gamma \sim 0.244T^3$ and using this

$$\frac{n_d/n_N}{(n_p/n_N)(n_n/n_N)} = 8.15\left[\frac{kT}{M_N}\right]^{3/2} \frac{n_N}{n_\gamma}\; e^{B_d/kT}$$

where n_N is the nucleon number and $\eta = n_N/n_\gamma$. Solve for the time of deuterium formation T^d (half of the neutrons free, half bound) using n_n/n_p = 1/7

$$1.72 \times 10^5 = \eta\; (T_9^d)^{3/2} e^{25.8/T_9^d} \qquad (T_9 \text{ units } 10^9 K \sim 86.2 \text{ keV})$$

Relates two parameters, but T^d can be calculated independently by the condition that free neutron decay until that time has yielded n_n/n_p = 1/7: T^d ~ 70 keV

$$\eta \sim 2.4 \times 10^{-9}$$

Deuterium bottleneck breaks when the temperature is 1/32 B_d -- so many photons available to break up deuterium!

Flow then quickly proceeds to ^{4}He, with some production of ^{7}Li

Absence of bound nuclei at A=5, 8 stops further nucleosynthesis

Fixes the baryon number of the cosmos at 4.4% of Ω_{crit}.

Determines the initial isospin -- setting all of the conditions for subsequent stellar evolution, nucleosynthesis.

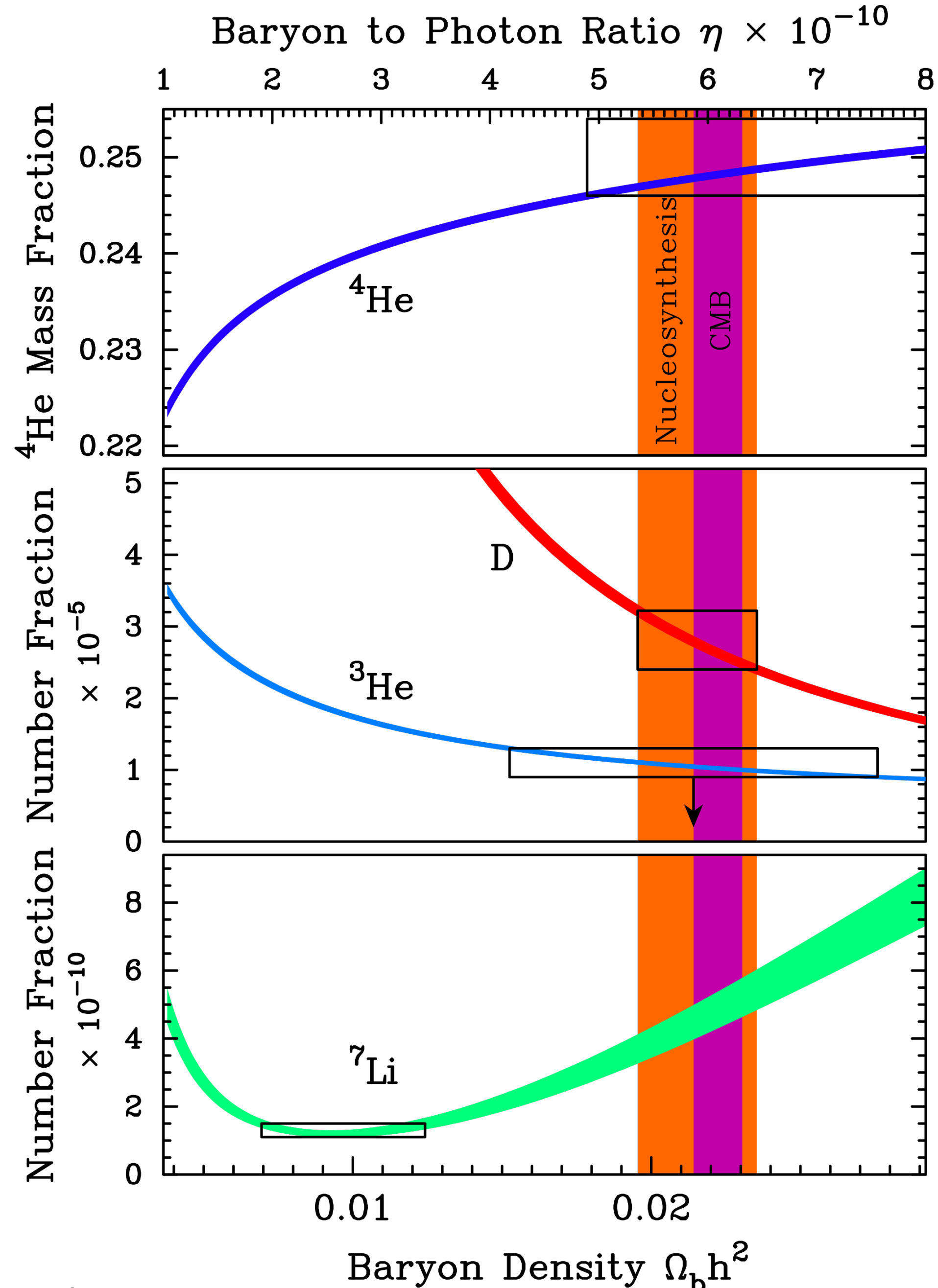
Depends exponentially on $B_d \ll \Lambda_{QCD} \Rightarrow$ small T_d.

One of the interesting questions lattice QCD could answer, how our universe would differ if the standard-model parameters were altered, affecting B_d

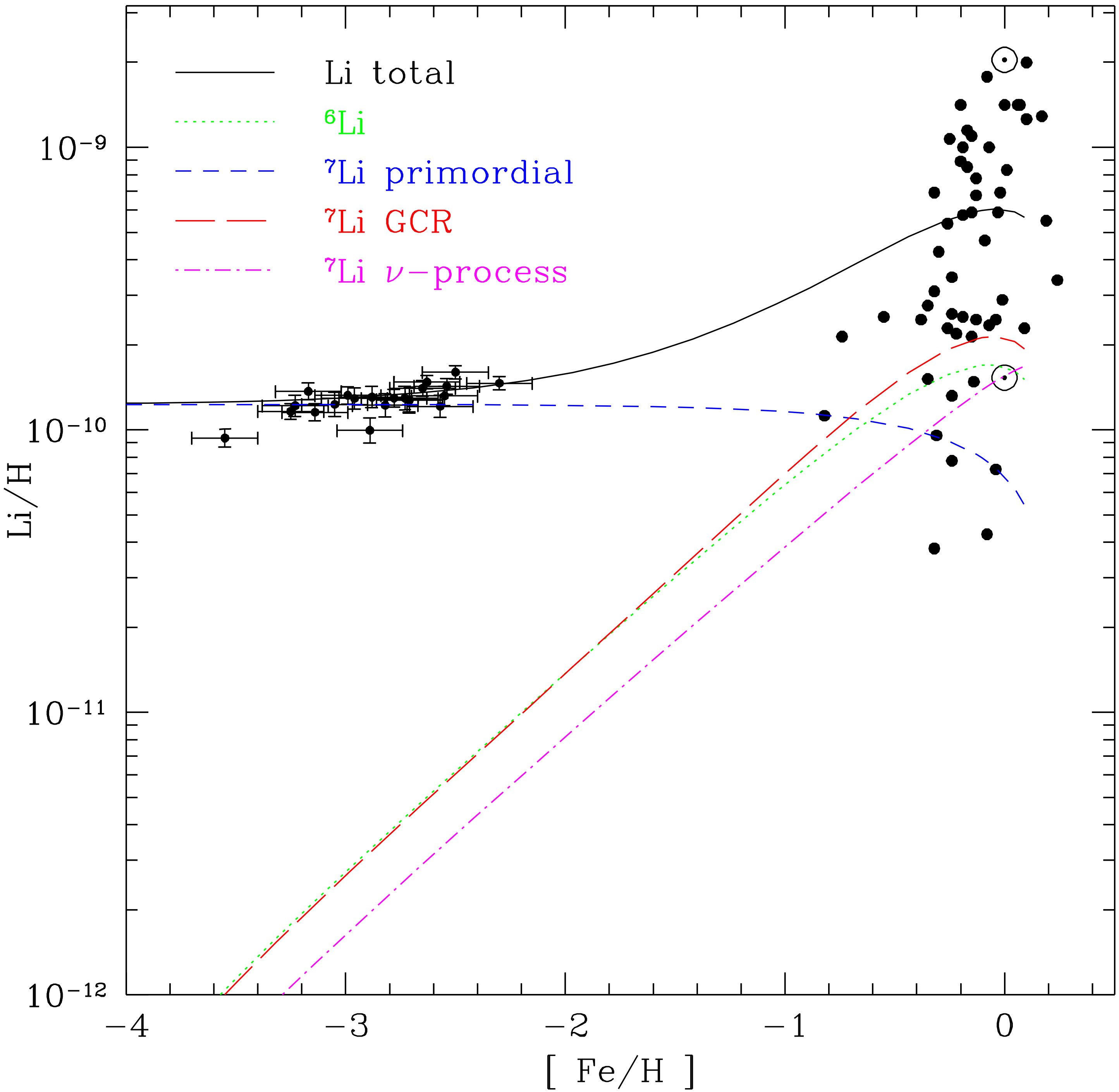
<u>BBN</u>: Issues include $\eta = n_B/n_\gamma$ consistency, the number of relativistic species (e.g., sterile neutrinos), the lepton number asymmetry, and alternatives to conventional abundance determinations

An issue exists with ^{7}Li, which has a well-defined primordial abundance plateau, corresponding to an $\eta \sim \eta_{CMB}$

The tension is ^{7}Li - d, with cosmology indicating that ^{7}Li is the outlier

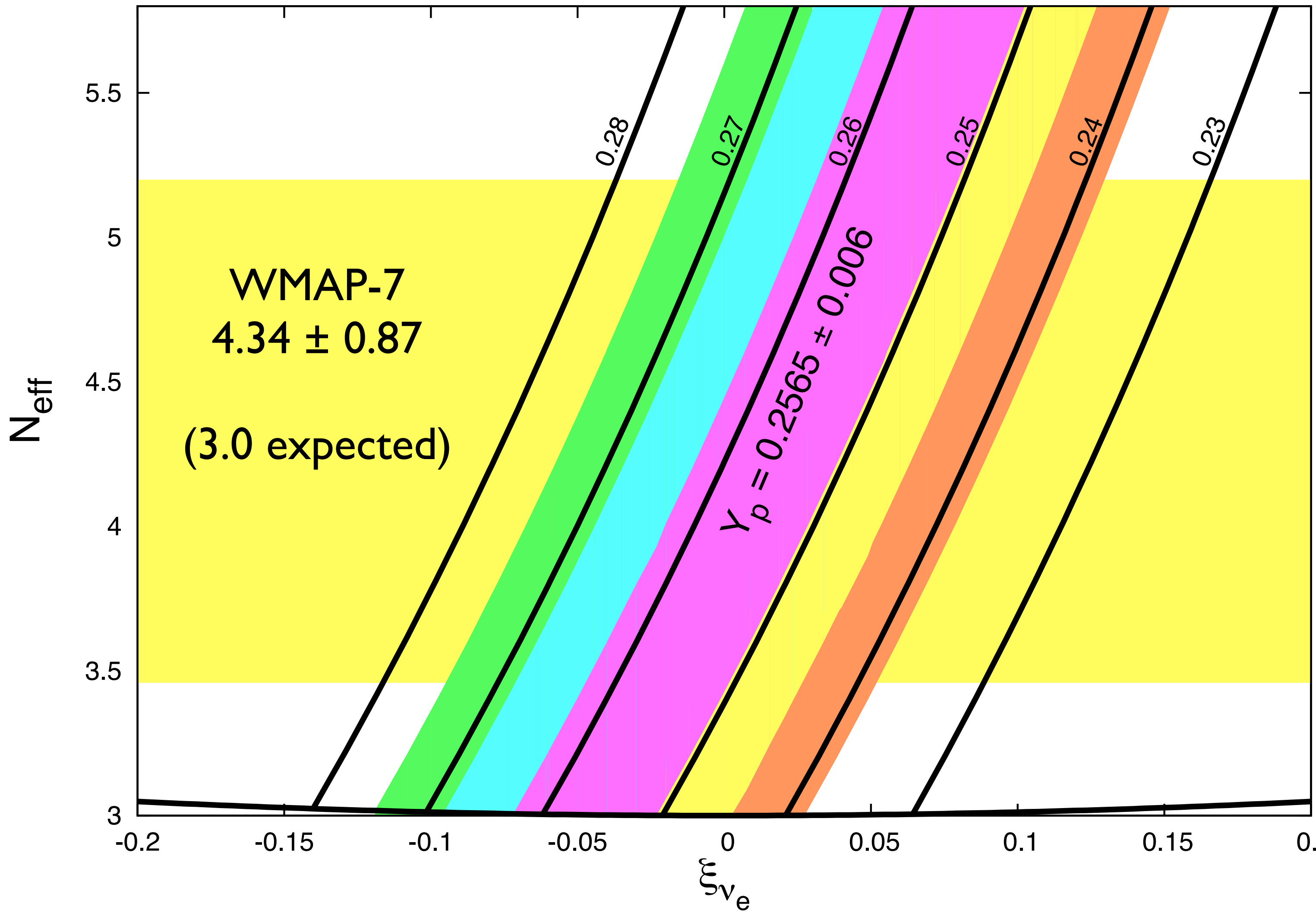


Nao Suzuki (Tytler group) 2006



Li total
6Li
7Li primordial
7Li GCR
7Li ν−process
10−9
10−10
10−11
10−12
Li/H
−4
−3
−2
−1
0
[Fe/H]

Competing clocks: expansion driven by the number N_{eff} of relativistic species versus weak interactions driving n densities downward



Krauss, Lunardini, Smith

BBN and CMB studies constrain the ν number and asymmetry

weak hints that all is not right (Planck results will be VERY interesting)

Cosmological neutrinos and mass

The kinetic and potential energy of a co-moving test particle m outside an expanding sphere of radius R within which the mean energy density is ρ

$$E_{\rm tot} = \frac{1}{2}mv^2 - G\frac{M(R)m}{R} = \frac{1}{2}mR^2(H^2 - \frac{8}{3}\pi\rho G)$$

which defines a critical density separating continually expanding from ultimately contracting universes

$$\rho_{\rm crit} = \frac{3H^2}{8\pi G} \sim 1.9 \times 10^{-29} h^2 \ {\rm g/cm^2}$$

where $h \sim 0.71 \pm 0.04$ is today's Hubble constant in 100 km/s/Mpc

Can calculate the photon number density

$$n_\gamma = 2 \int \frac{d^3q}{(2\pi)^3} \frac{1}{e^{q/T_\gamma} - 1} = 2\zeta(3) T_\gamma^3/\pi^2 \sim 408/\mathrm{cm}^3$$

and the neutrino number density per flavor

$$n_\nu = 2 \int \frac{d^3q}{(2\pi)^3} \frac{1}{e^{q/T_\nu} + 1} = 3\zeta(3) T_\nu^3/(2\pi^2)$$

so that

$$n_\nu = \frac{3}{4} \left(\frac{T_\nu}{T_\gamma} \right)^3 n_\gamma$$

But electrons and positrons annihilate to reheat photons. Throughout this process no energy is exchanged between neutrinos and photons/electrons/positrons. The entropy of each is then unchanged. Equating the entropies before and after annihilation for each (see notes)

$$\frac{T_\nu}{T_\gamma^{\text{after}}} = \left(\frac{4}{11}\right)^{1/3}$$

so if today $T_\gamma \sim 2.72$ K, then $T_\nu \sim 1.92$ K. Thus

$$n_\nu = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma = \frac{3}{4}\frac{4}{11}n_\gamma \quad \Rightarrow \quad \sum_{i=1}^{3} n_\nu = \frac{9}{11}n_\gamma$$

There are about 334 neutrinos/cm^3 today. We can now calculate the energy density due to neutrino mass

$$\rho_\nu = \frac{3}{11}n_\gamma \sum_{i=1}^{3} m_\nu(i) = 0.0106\ \frac{\rho_{\text{crit}}}{h^2}\sum_{i=1}^{3}\frac{m_\nu(i)}{1\ \text{eV}}$$

The mass sum is limited in several ways

oscillations	cosmology	laboratory
> 0.055 eV	< 0.7 eV	< 6.6 eV

Thus $$0.0011 \lesssim \frac{\rho_\nu}{\rho_{\rm crit}} \lesssim \begin{cases} 0.14 & \text{laboratory} \\ 0.015 & \text{cosmology} \end{cases}$$

Suppose neutrinos are light. Similar to what we have done previously, the relativistic energy density is

$$\rho_\gamma + \rho_\nu \sim 4.5 n_\gamma T\gamma$$

Equate to baryon energy density

$$n_{\rm nucleons} M_N = \eta n_\gamma M_N$$

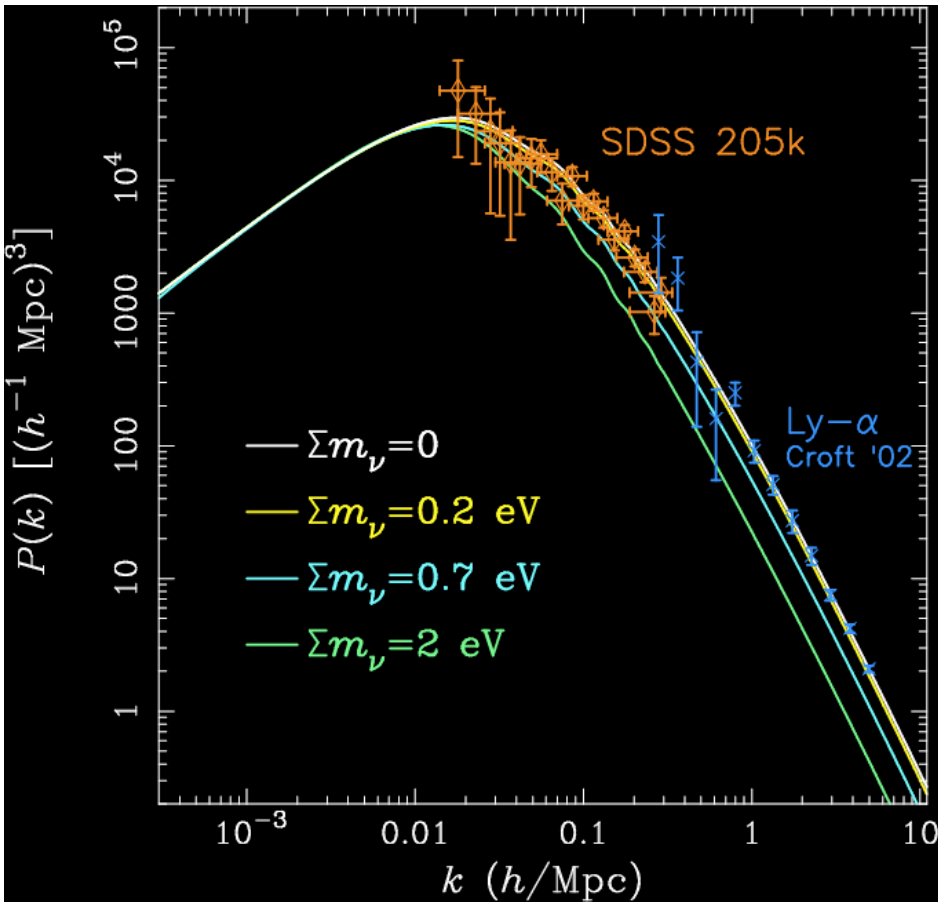
to find $T_\gamma \sim 0.13 \text{ eV}$

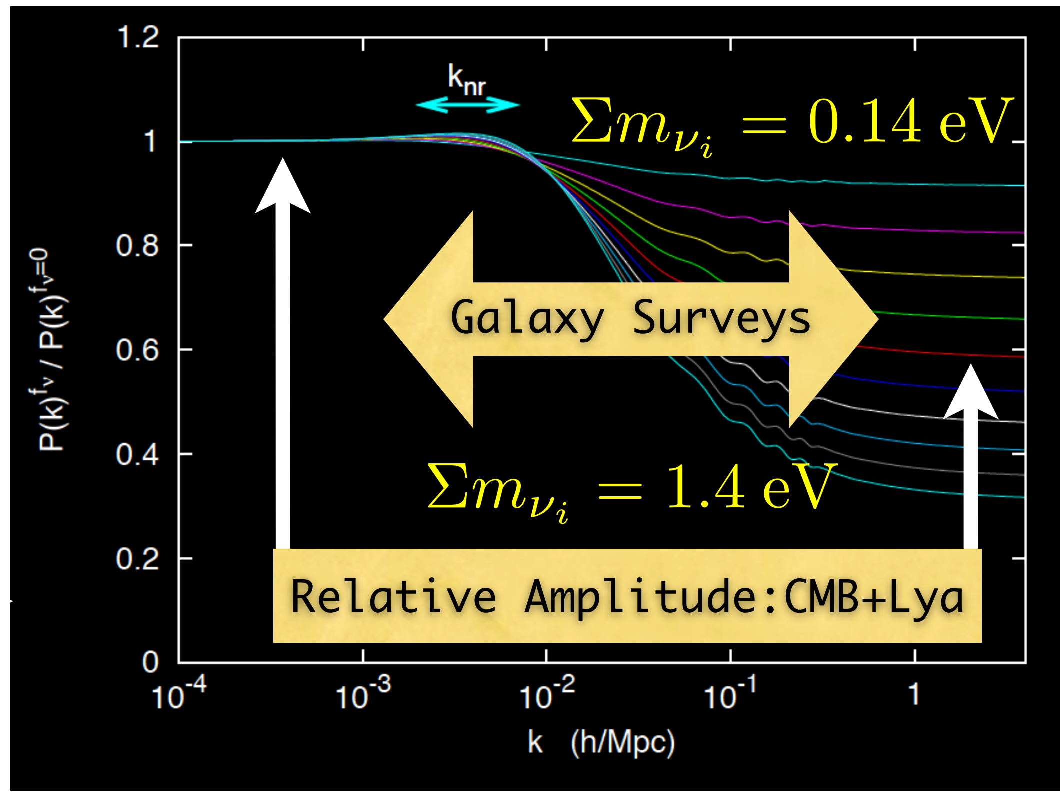
So the standard-model universe is guaranteed to be matter dominated shortly after recombination (~0.35 eV)

And (some of) the νs themselves become nonrelativistic around this time, as the mass range is 0.055-0.70 eV

This is important to cosmological large-scale structure: relativistic neutrinos free-stream and suppress the growth of structure on larger scales

$$k_{\text{free streaming}} \sim 0.004\sqrt{m_\nu/0.05\text{eV}}\ \text{Mpc}^{-1}$$





from Kev Abazajian

Thus ν influences on structure evolve with both redshift Z and spatial scale in a characteristic way:

$$\sum m_\nu \sim 0.05 \text{ eV}, \; z = \begin{pmatrix} 3.5 \\ 3.5 \\ 1.5 \\ 0.0 \end{pmatrix} \Rightarrow \text{ power decrease} \sim \begin{pmatrix} 1.9\% \\ 1.0\% \\ 2.1\% \\ 3.5\% \end{pmatrix} \text{ for } k > \begin{pmatrix} 0.6 \\ 0.03 \\ 0.6 \\ 0.6 \end{pmatrix} \frac{1}{\text{Mpc}}$$

alter baryons + CDM at the ~ % level, when $\Omega_\nu \sim 0.1\%$

One combined analysis using existing data

$$\sum m_{\nu_i} < 0.58 \text{ eV}$$

Komatsu et al. 2010, WMAP7 + SDSS LRG BAO + Ho

$$\left(\frac{\Delta P}{P}\right)_{\text{future}} \sim 1\% \sim -12\frac{\Omega_\nu}{\Omega_m} \Rightarrow \sum m_{\nu_i} \sim 11 \text{ meV}$$

Hu, Eisenstein, & Tegmark 1998; Abazajian & Dodelson 2003

Several anticipated surveys with ~ ×100 increase in statistics

- high redshift galaxy surveys, SDSS-III BOSS 10^5 QSO survey, Planck CMB data, 21-cm radio telescopes with 0.1 km^2 collection, weak lensing
- the statistical power for discovery at 50 meV estimated at 1-7σ, depending on the degree of optimism about systematics

may be the field's only near-term strategy for determining the absolute scale of neutrino mass

could also settle the question of the neutrino hierarchy:
a value < 0.1 eV requires a normal hierarchy
-- topics for next time