Neutrino Physics
and
Nuclear astrophysics

Lecture II – cosmology/BBN

National Nuclear Physics Summer School

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The advent of . . .

(1) comprehensive cosmic microwave background (CMB) observations
(e.g., high precision baryon number and cosmological parameter measurements, N_{eff}, ^{4}He, ν mass limits)

(2) 10-meter class and orbiting optical telescopes
(e.g., precision determinations of deuterium abundance, dark energy/matter content, structure history etc.)

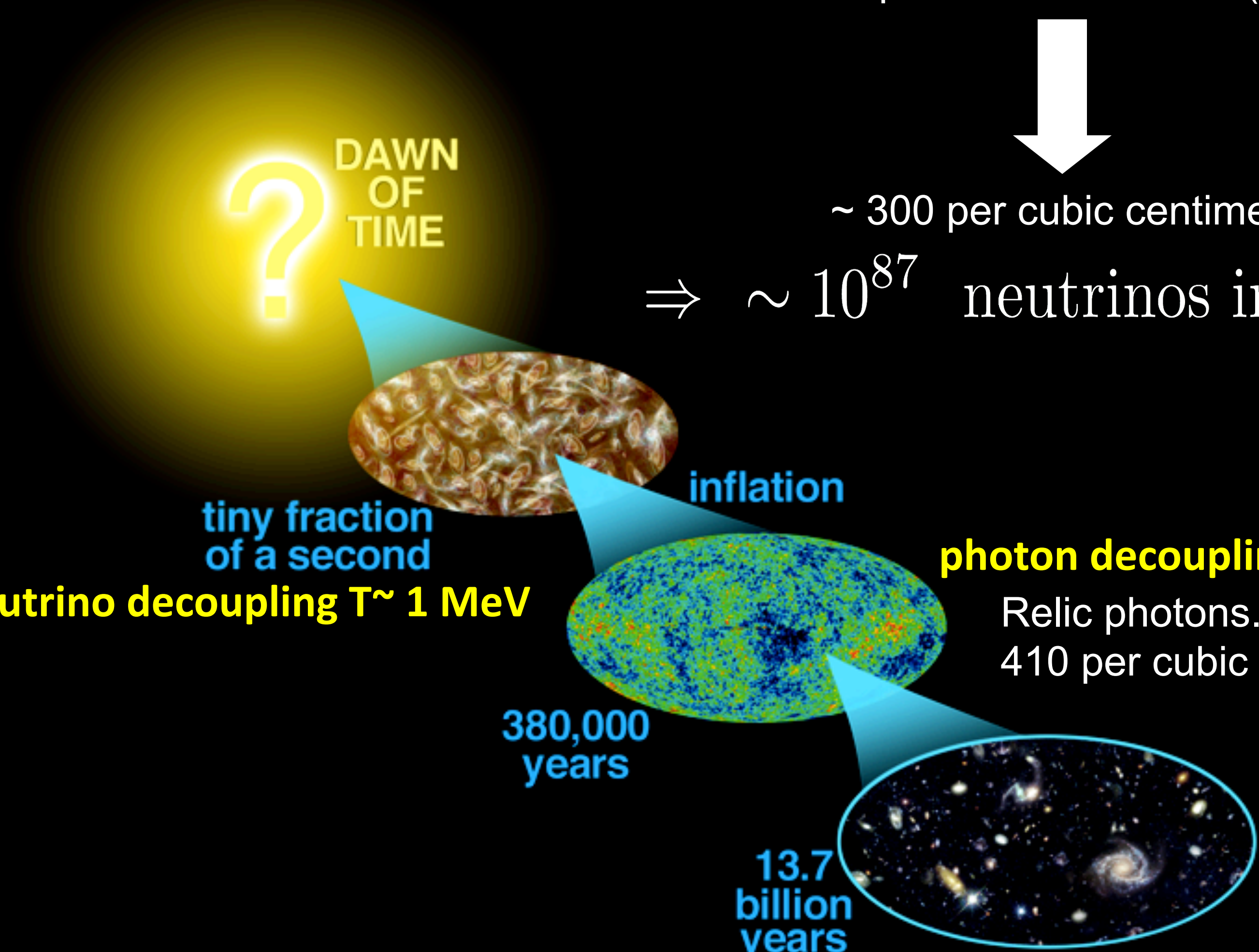
(3) Laboratory neutrino mass/mixing measurements

sets up a nearly over-determined situation where new BSM neutrino physics likely *must* show itself!

Relic neutrinos from the epoch when the universe was at a temperature T ~ 1 MeV (~ 10^{10} K)

~ 300 per cubic centimeter

$$\Rightarrow \; \sim 10^{87} \; \text{neutrinos in universe}$$

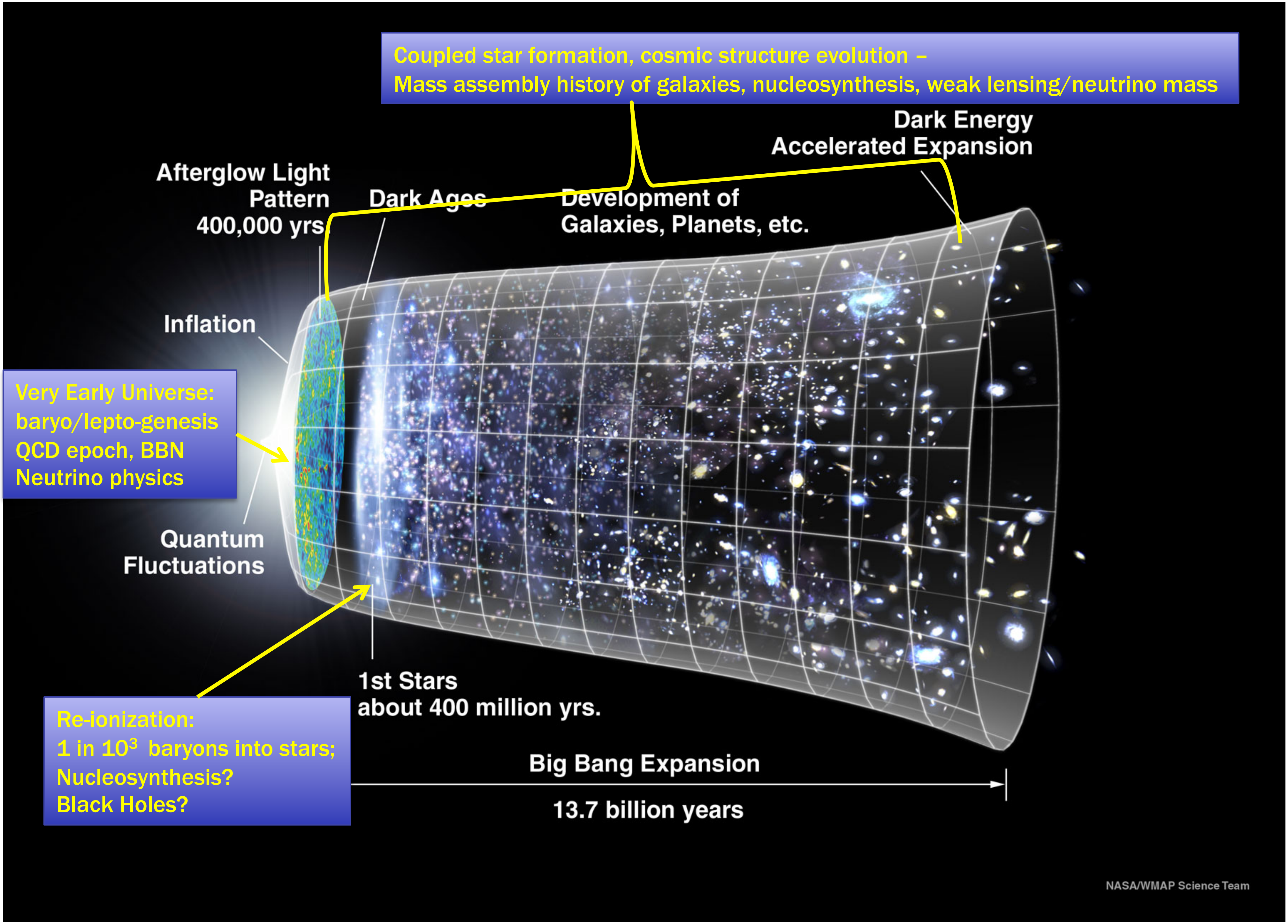


neutrino decoupling T~ 1 MeV

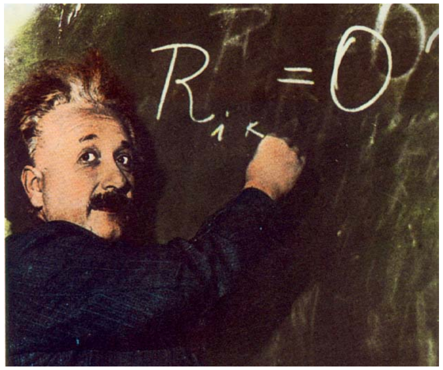
photon decoupling T~ 0. 2 eV

Relic photons. We measure 410 per cubic centimeter

vacuum+matter dominated at current epoch


Coupled star formation, cosmic structure evolution –
Mass assembly history of galaxies, nucleosynthesis, weak lensing/neutrino mass
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Very Early Universe:
baryo/lepto-genesis
QCD epoch, BBN
Neutrino physics
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Re-ionization:
1 in 10³ baryons into stars;
Nucleosynthesis?
Black Holes?
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Spacetime Background



Albert Einstein

George Gamow

A. Friedmann

George LeMaitre

Birkhoff's Theorem

Invoking this requires symmetry:
specifically, a homogeneous and isotropic distribution of mass and energy!

What evidence is there that this is true?

Look around you. This is manifestly NOT true on small scales. The Cosmic Microwave Background Radiation (CMB) represents our best evidence that matter is smoothly and homogeneously distributed on the largest scales.

Homogeneity and isotropy of the universe:
implies that *total energy* inside a co-moving spherical surface is constant with time.

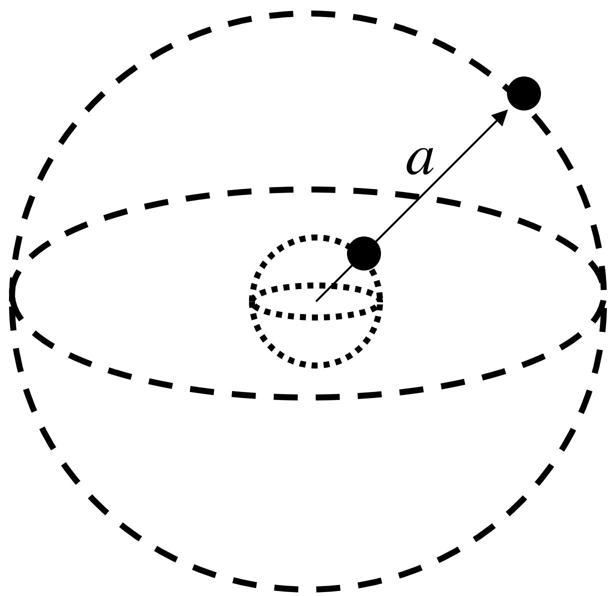
total energy **= (kinetic energy of expansion) + (gravitational potential energy)**

mass-energy density = ρ

test mass = *m*

$$\approx \tfrac{1}{2} m \dot{a}^2$$

$$\approx -\frac{G\left[\frac{4}{3}\pi a^3 \rho\right] m}{a}$$

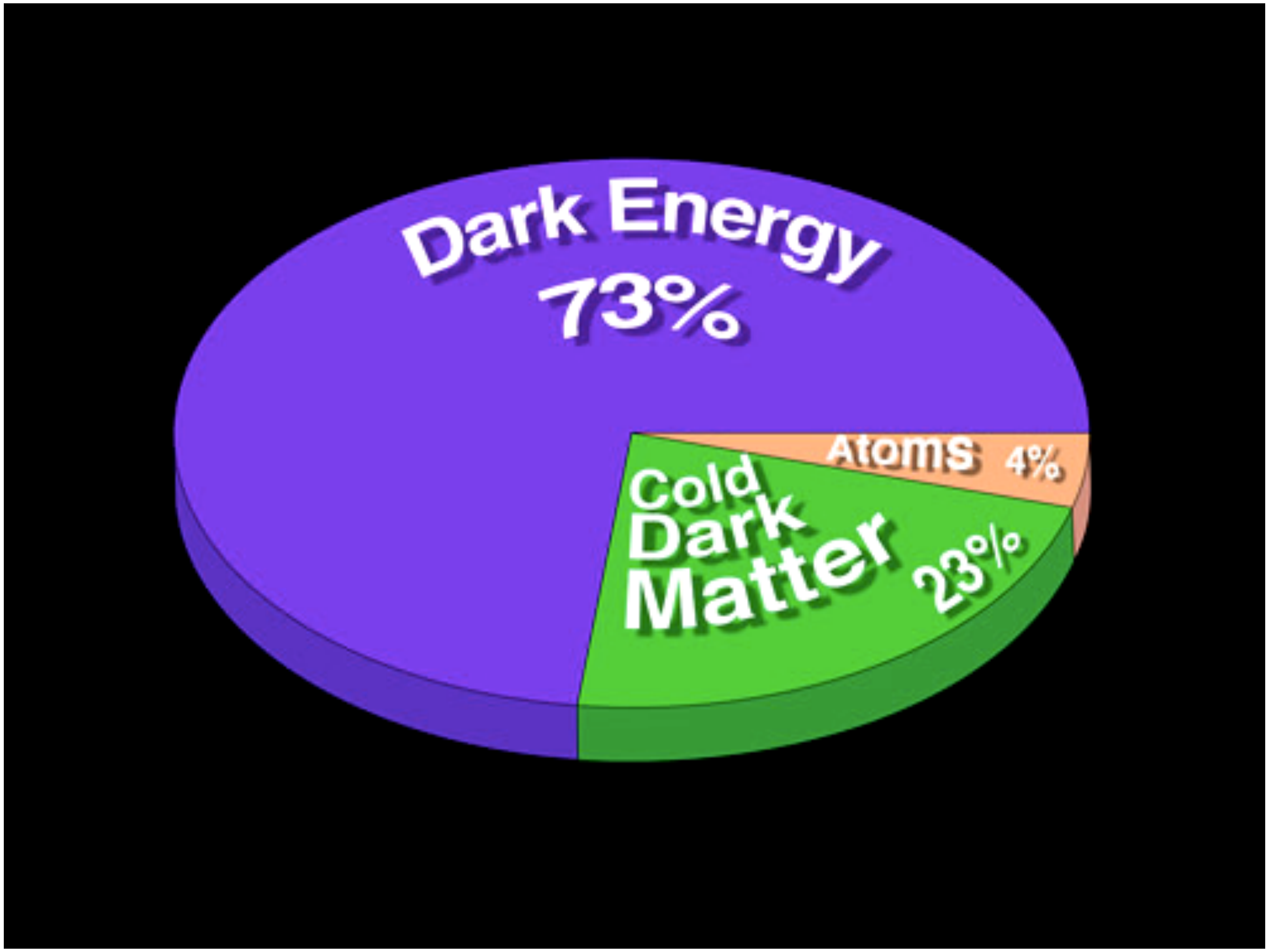


$$\dot{a}^2 + k = \frac{8}{3}\pi G \rho\, a^2$$

total energy **> 0**	**expand forever**	**k = -1**
total energy **= 0 for** $\rho = \rho_{crit}$		**k = 0**
total energy **< 0**	**re-collapse**	**k = +1**

$$\Omega = \rho/\rho_{crit} = \Omega_\gamma + \Omega_\nu + \underbrace{\Omega_{baryon} + \Omega_{dark\ matter}}_{\approx 0.27} + \Omega_{vacuum} \approx 1 \quad \textbf{(k=0)}$$

We live in a k = 0, critically closed universe.



number density for fermions (+) and bosons (-)

$$dn \approx g \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{e^{E/T-\eta} \pm 1} \approx \frac{g}{2\pi^2} \left(\frac{d\Omega}{4\pi} \right) \frac{E^2 dE}{e^{E/T-\eta} \pm 1}$$

where the pencil of directions is $d\Omega = \sin\theta \, d\theta \, d\phi$

The energy density is then

$$d\varepsilon \approx \frac{g}{2\pi^2} \left(\frac{d\Omega}{4\pi} \right) \frac{E \cdot E^2 dE}{e^{E/T-\eta} \pm 1}$$

now get the total energy density by integrating over all energies and directions (relativistic kinematics limit)

$$\rho \approx \frac{T^4}{2\pi^2} \int_0^\infty \frac{x^3 \, dx}{e^{x-\eta} \pm 1}$$

degeneracy parameter (chemical potential/temperature)

$$\eta \equiv \frac{\mu}{T}$$

in extreme relativistic limit

$\eta \to 0$

$$\int_0^\infty \frac{x^3 \, dx}{e^x - 1} = \frac{\pi^4}{15} \quad \text{and} \quad \int_0^\infty \frac{x^3 \, dx}{e^x + 1} = \frac{7\pi^4}{120}$$

bosons $\rho \approx g_b \frac{\pi^2}{30} T^4$ and fermions $\rho \approx \left(\frac{7}{8} g_f \right) \frac{\pi^2}{30} T^4$

Statistical weight in all relativistic particles:

$$g_{\text{eff}} = \sum_i g_i^b \left(\frac{T_i}{T}\right)^3 + \frac{7}{8}\sum_j g_j^f \left(\frac{T_j}{T}\right)^3$$

e.g., statistical weight in photons, electrons/positrons and six thermal, zero chemical potential (zero lepton number) neutrinos, e.g., BBN:

$$g_{\text{eff}} = 2 + \tfrac{7}{8}\left(2 + 2 + 6\right) = 10.75$$

$\nu_e \ \bar{\nu}_e \ \nu_\mu \ \bar{\nu}_\mu \ \nu_\tau \ \bar{\nu}_\tau$

Friedmann equation is $\dot{a}^2 + k = \frac{8}{3}\pi G\rho\, a^2$ and

$G = \frac{1}{m_{\rm PL}^2}$ where $\hbar = c = 1$ and the Planck Mass is $m_{\rm PL} \approx 1.22 \times 10^{22}$ MeV

radiation dominated $\rho \approx \frac{\pi^2}{30} g_{\rm eff} T^4 \sim \frac{1}{a^4}$

$\Rightarrow$ horizon is $d_{\rm H}(t) \approx 2t \approx H^{-1}$

where the Hubble parameter, or expansion rate is

$$H = \frac{\dot{a}}{a} \approx \left(\frac{8\pi^3}{90}\right)^{1/2} g_{\rm eff}^{1/2} \frac{T^2}{m_{\rm PL}}$$

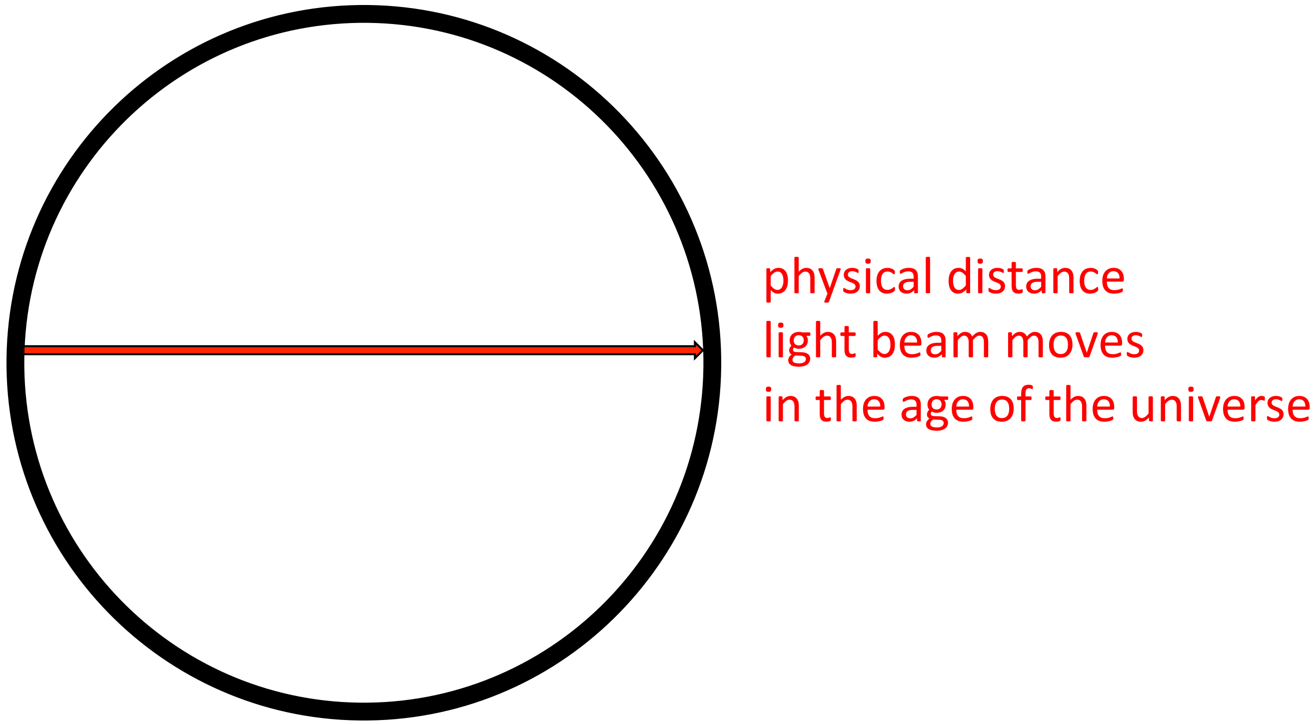
$$t \approx (0.74\ {\rm s})\left(\frac{10.75}{g_{\rm eff}}\right)^{1/2} \left[\frac{\rm MeV}{T}\right]^2$$

The entropy in a co-moving volume is conserved

$\Rightarrow$ $g_{\rm eff}^{1/3} aT = g_{\rm eff}'^{1/3} a'T'$ so that if the number of relativistic degrees of freedom is constant

$\Rightarrow$ $T \sim \frac{1}{a}$

Causal Horizon



$$\text{radiation dominated} \quad \Rightarrow \quad d\,(t) = 2t$$

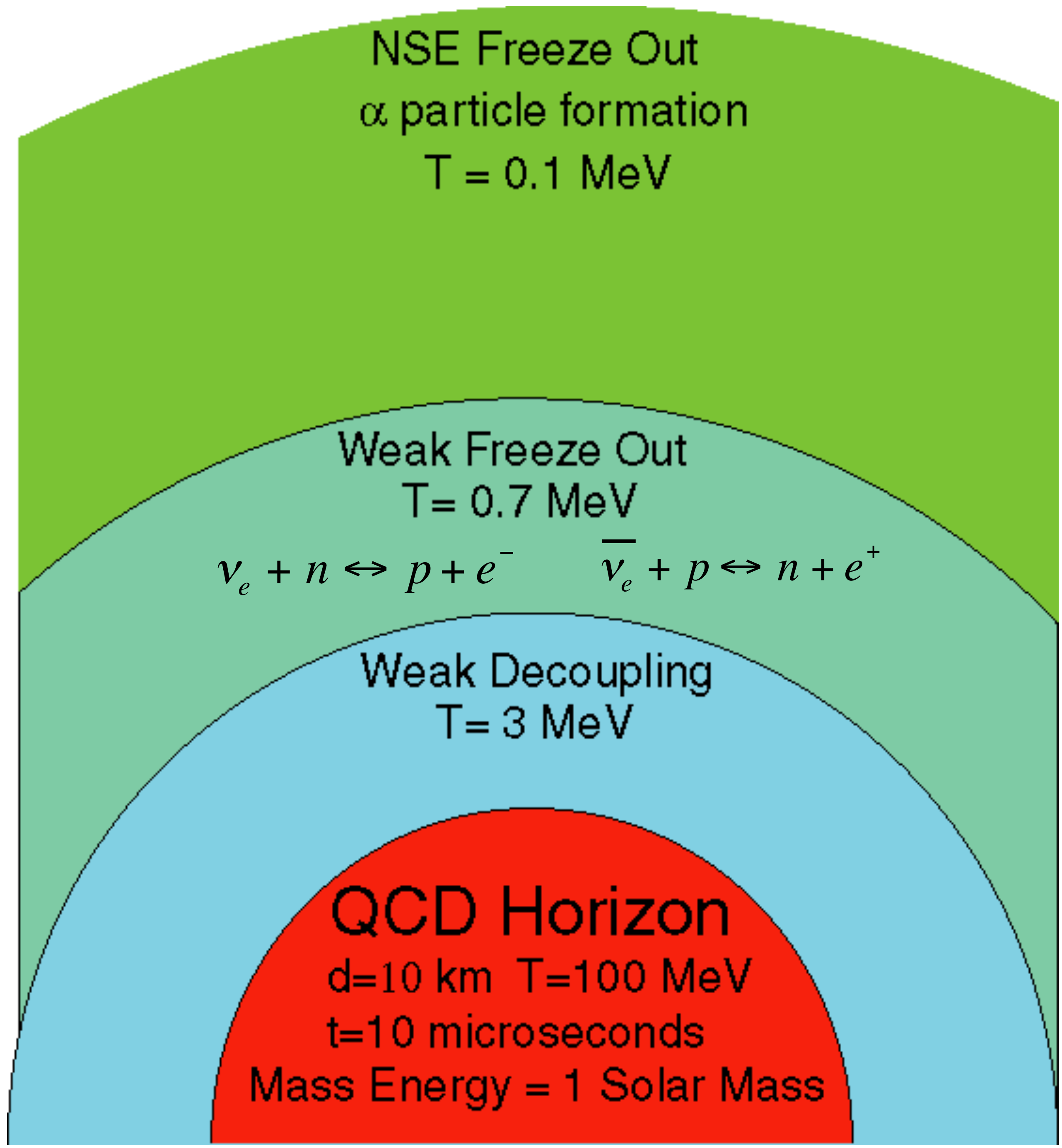
some significant events/epochs in the early universe

Epoch	T	g_{eff}	Horizon Length	Mass-Energy (solar masses)	Baryon Mass (solar masses)
Electroweak phase transition	100 GeV	~100	~ 1 cm	$\sim 10^{-6}$ (~ earth mass)	$\sim 10^{-18}$
QCD	100 MeV	51 - 62	20 km	~ 1	$\sim 10^{-9}$
weak decoupling	2 MeV	10.75	$\sim 10^{10}$ cm	$\sim 10^{4}$	$\sim 10^{-3}$
weak freeze out	0.7 MeV	10.75	$\sim 10^{11}$ cm	$\sim 10^{5}$	$\sim 10^{-2}$
BBN	100 keV	10.75	$\sim 10^{13}$ cm (~ 1 A.U.)	$\sim 10^{6}$	~ 1
e^-/e^+ annihilation	~ 20 keV	3.36	$\sim 10^{14}$ cm	$\sim 10^{8}$	~ 100
photon decoupling	0. 2 eV	-	~ 350 kpc	$\sim 10^{18}$ dark matter	$\sim 10^{17}$

$1 \text{ solar mass } \approx 2 \times 10^{33} \text{ g } \approx 10^{60} \text{ MeV}$

The History of
The Early Universe:

(shown are a succession of temperature and causal horizon scales)



The QCD horizon is essentially an ultra-high entropy Neutron Star

Another consequence of
homogeneity & isotropy + Birkhoff's theorem:

Cannot be any net heat flow – i.e., adiabatic so the **entropy** in a co-moving volume is conserved.

The Entropy of the Universe is Huge

We know the entropy-per-baryon of the universe because we measure the cosmic microwave background temperature and we measure the baryon density through the deuterium abundance and/or CMB acoustic peak amplitude ratios.

$$S/k_b = 5.9 \times 10^9$$

Neglecting relatively small contributions from black holes, SN, shocks, nuclear burning, etc., S/k_b has been constant throughout the history of the universe.

S/k_b is a (roughly) co-moving invariant.

entropy per baryon in radiation-dominated conditions

entropy per unit proper volume

$$S \approx \frac{2\pi^2}{45} g_s \, T^3$$

proper number density of baryons $n_b = \eta \, n_\gamma$

entropy per baryon $s \approx \dfrac{S}{n_b}$

baryon number of universe → $$\eta \equiv \frac{n_{\rm b} - n_{\bar{\rm b}}}{n_\gamma}$$

From CMB acoustic peaks, and/or observationally-inferred primordial D/H:

$$\eta \approx 6.11 \times 10^{-10}$$

three lepton numbers →

$$\begin{cases} L_{\nu_e} \approx \dfrac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \\ L_{\nu_\mu} = \dfrac{n_{\nu_\mu} - n_{\bar{\nu}_\mu}}{n_\gamma} \\ L_{\nu_\tau} = \dfrac{n_{\nu_\tau} - n_{\bar{\nu}_\tau}}{n_\gamma} \end{cases}$$

From observationally-inferred ^{4}He and large scale structure and using *collective (synchronized) active-active neutrino oscillations* (Abazajian, Beacom, Bell 03; Dolgov et al. 03; Wong 2003):

$$|L_{\nu_{\mu,\tau}}| \sim L_{\nu_e} < 0.15$$

Baryon Number

(from CMB acoustic peak amplitudes)

3 year WMAP $\eta \approx (6.11 \pm 0.22) \times 10^{-10}$

$\sim \pm 3.6\%$ uncertainty

4 year WMAP $\sim \pm 1.9\%$ uncertainty

Planck $\sim \pm 0.74\%$ uncertainty

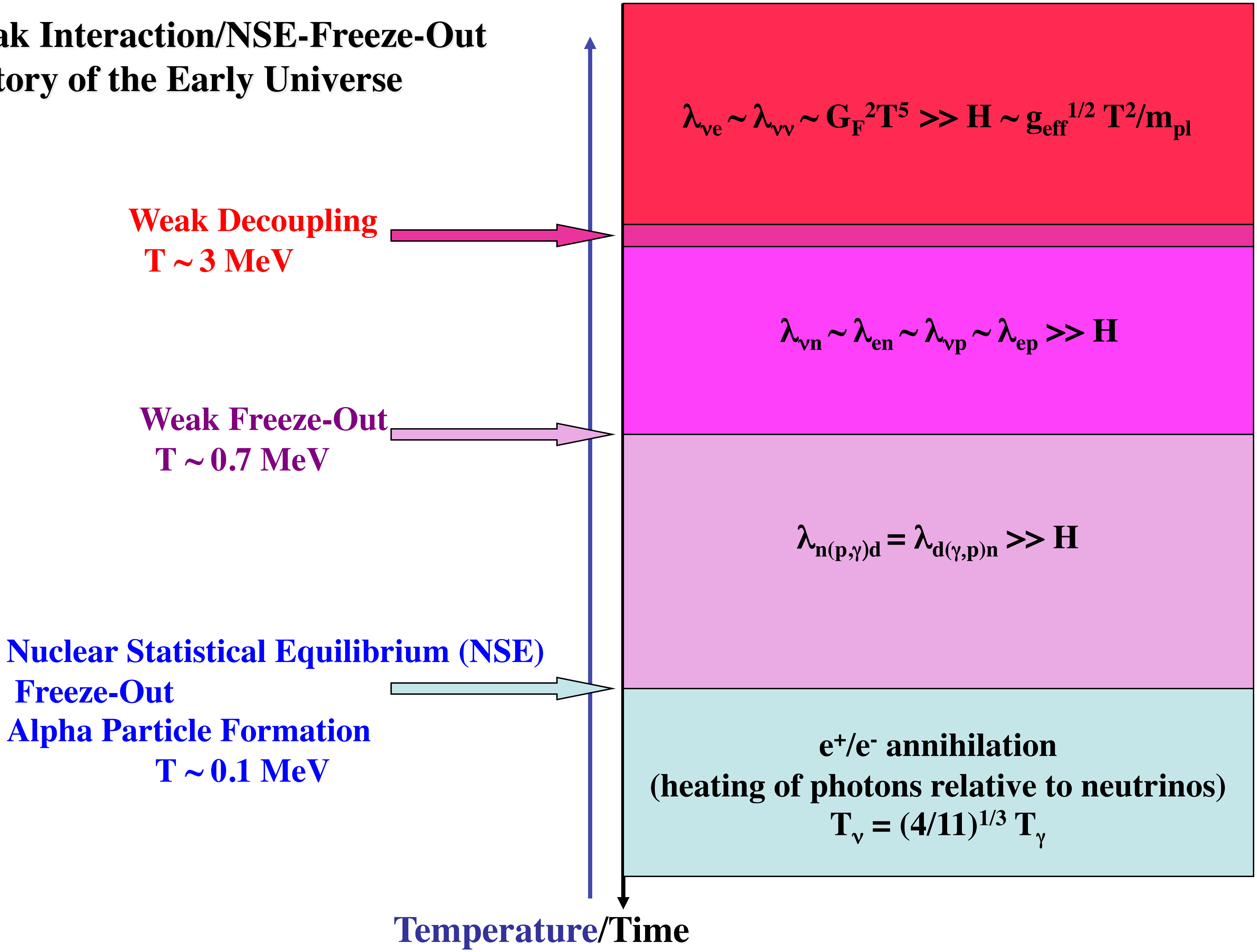
The "baryon number"
is defined to be the ratio of the net number of baryons to the number of photons:

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

The "baryon number," or baryon-to-photon ratio, η is a kind of "inverse entropy per baryon," but it is not a co-moving invariant.

$$\eta \approx \frac{2\pi^4}{45} \frac{1}{\zeta(3)} \frac{g_{total}}{g_\gamma} S^{-1}$$

Weak Interaction/NSE-Freeze-Out
History of the Early Universe



Weak Decoupling

This occurs when the rates of neutrino scattering reactions on electrons/positrons drop below the expansion rate.

After this epoch the neutrino gas ceases to efficiently exchange energy with the photon-electron plasma.

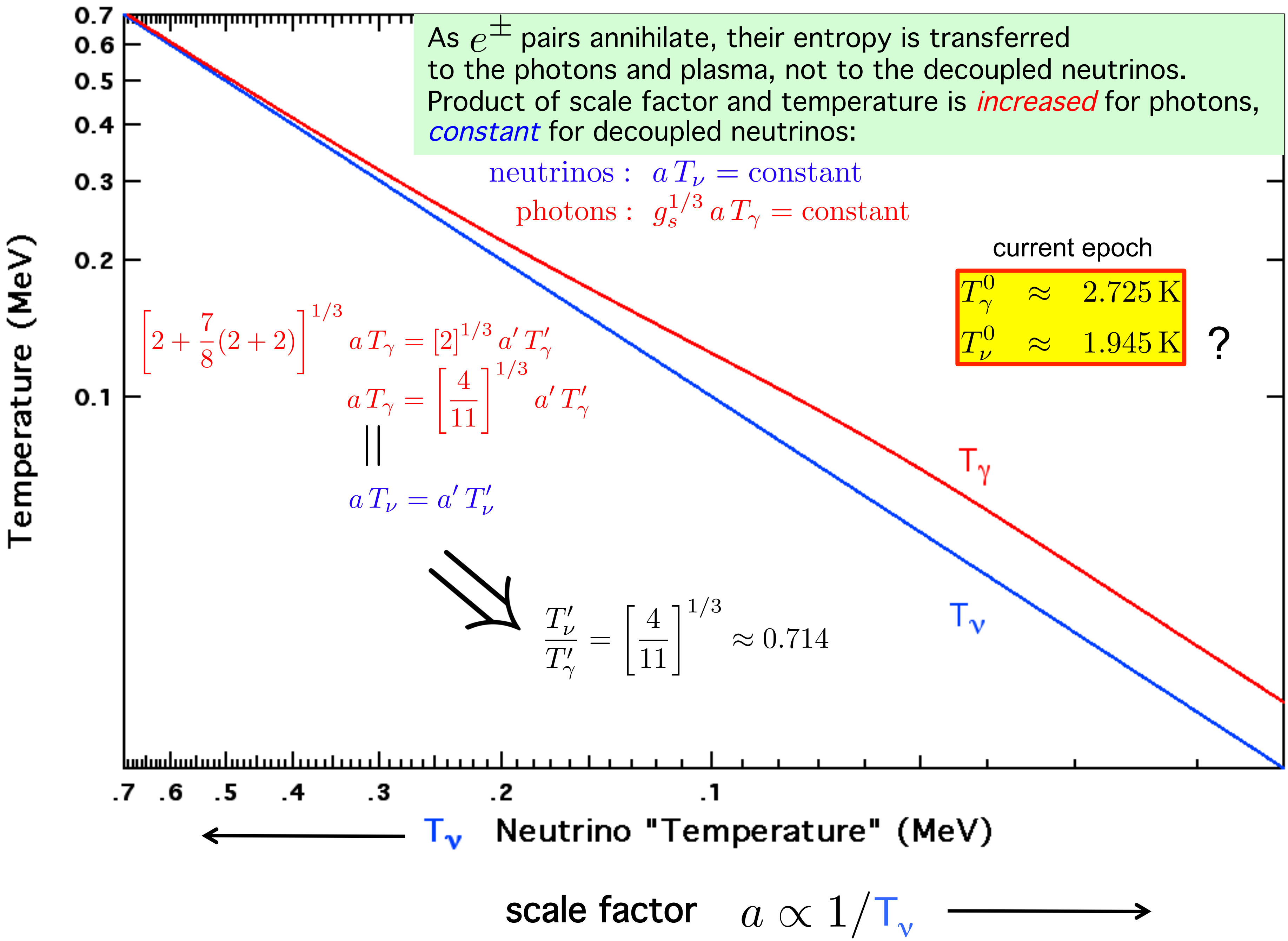
neutrino scattering rate $\lambda_\nu \sim \left(\mathrm{G}_\mathrm{F}^2\, T^2\right)\left(T^3\right) = \mathrm{G}_\mathrm{F}^2\, T^5$

where the Fermi constant is $\mathrm{G}_\mathrm{F} \approx 1.166 \times 10^{-11}\ \mathrm{MeV}^{-2}$

expansion rate $H \approx \left(\dfrac{8\pi^3}{90}\right)^{1/2} g_\mathrm{eff}^{1/2}\, \dfrac{T^2}{m_\mathrm{PL}}$

weak decoupling temperature

$$T_\mathrm{WD} \approx \left(\frac{8\pi^3}{90}\right)^{1/6} \frac{g_\mathrm{eff}^{1/6}}{\left(\mathrm{G}_\mathrm{F}^2\, m_\mathrm{PL}\right)^{1/3}} \approx 1.5\ \mathrm{MeV} \left(\frac{g_\mathrm{eff}}{10.75}\right)^{1/6}$$



0.7
0.6
0.5
0.4
0.3
0.2
0.1
Temperature (MeV)
As $e^{\pm}$ pairs annihilate, their entropy is transferred to the photons and plasma, not to the decoupled neutrinos. Product of scale factor and temperature is *increased* for photons, *constant* for decoupled neutrinos:
$\text{neutrinos}: \; a\,T_\nu = \text{constant}$
$\text{photons}: \; g_s^{1/3}\,a\,T_\gamma = \text{constant}$
current epoch
$T_\gamma^0 \approx 2.725\,\text{K}$
$T_\nu^0 \approx 1.945\,\text{K}$
?
$\left[2+\frac{7}{8}(2+2)\right]^{1/3} a\,T_\gamma = [2]^{1/3}\,a'\,T'_\gamma$
$a\,T_\gamma = \left[\frac{4}{11}\right]^{1/3} a'\,T'_\gamma$
||
$a\,T_\nu = a'\,T'_\nu$
$\frac{T'_\nu}{T'_\gamma} = \left[\frac{4}{11}\right]^{1/3} \approx 0.714$
T_γ
T_ν
.7
.6
.5
.4
.3
.2
.1
T_ν Neutrino "Temperature" (MeV)
scale factor $a \propto 1/T_\nu$

Weak Freeze Out

- Even though neutrinos are *thermally* decoupled, there are still $\sim 10^{10}$ of them per nucleon.

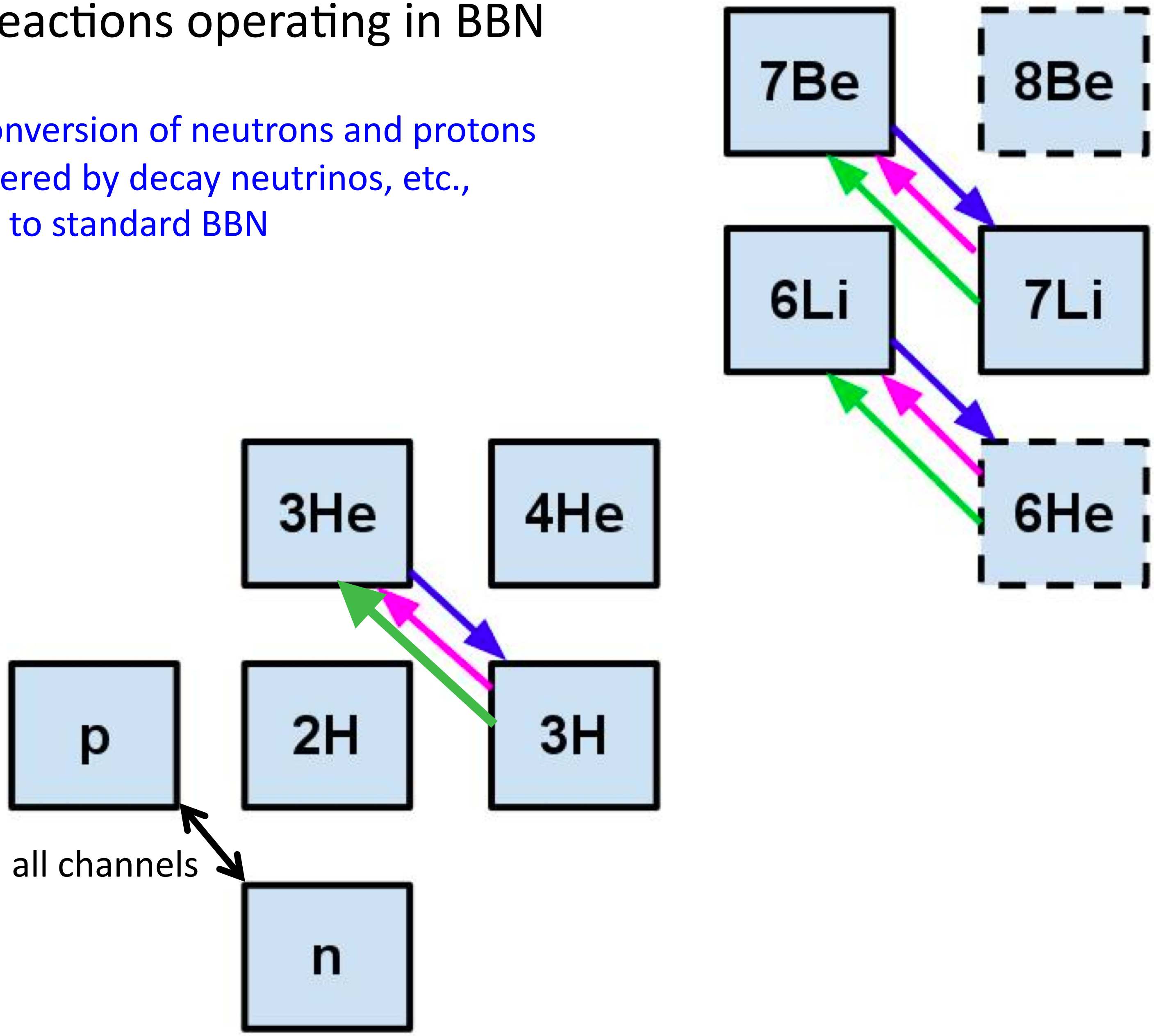
- Weak charged current lepton-nucleon processes flip nucleon isospins from neutron to proton to neutron to proton . . .

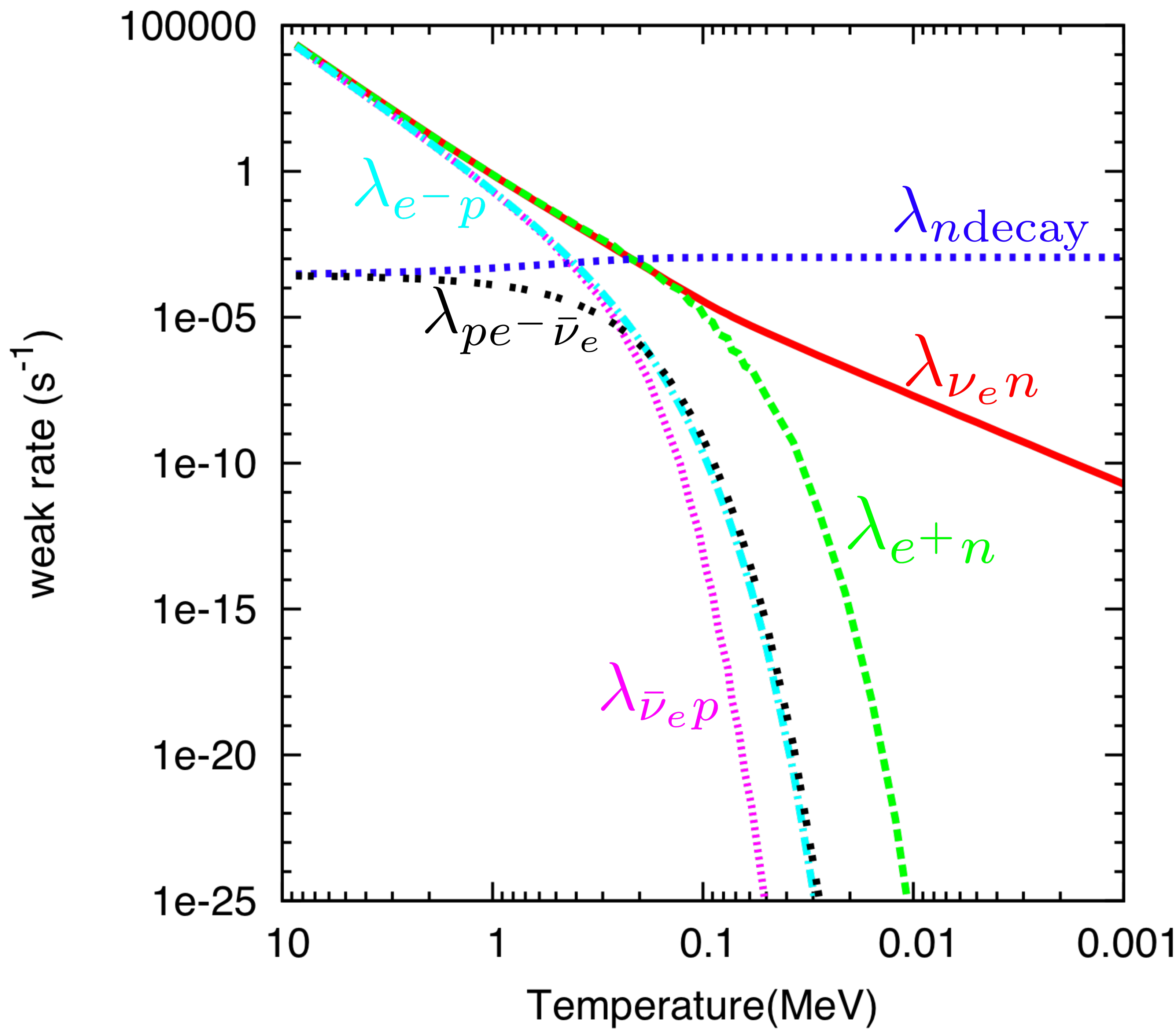
- If this isospin flip rate is large compared to the expansion rate, then steady state, chemical equilibrium can be maintained between leptons and nucleons.

- Eventually, weak interaction-driven isospin flip rate falls below expansion rate, neutron/proton ratio “frozen in,” ------- this is **Weak Freeze Out**

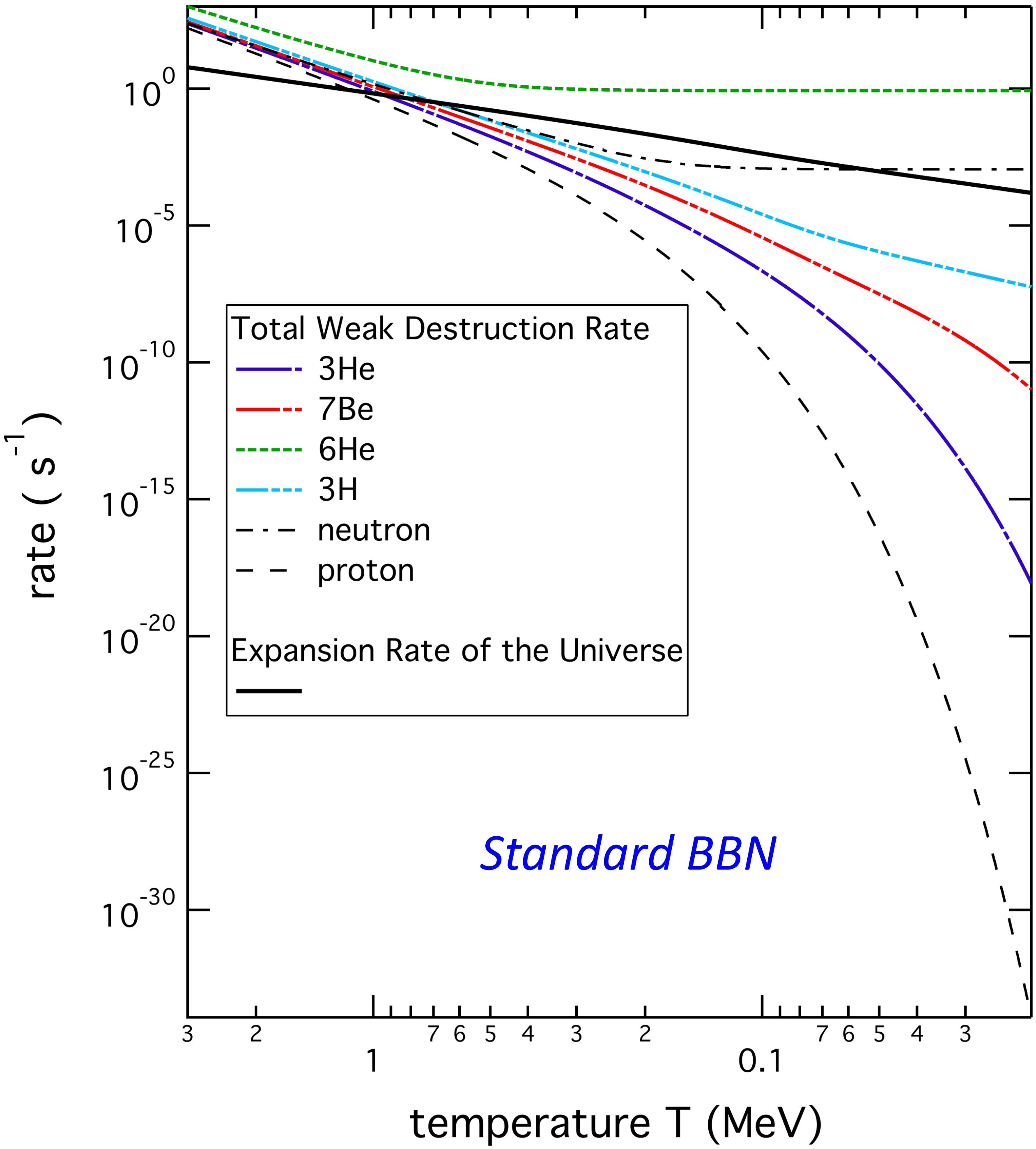
weak reactions operating in BBN

inter-conversion of neutrons and protons
now altered by decay neutrinos, etc.,
relative to standard BBN

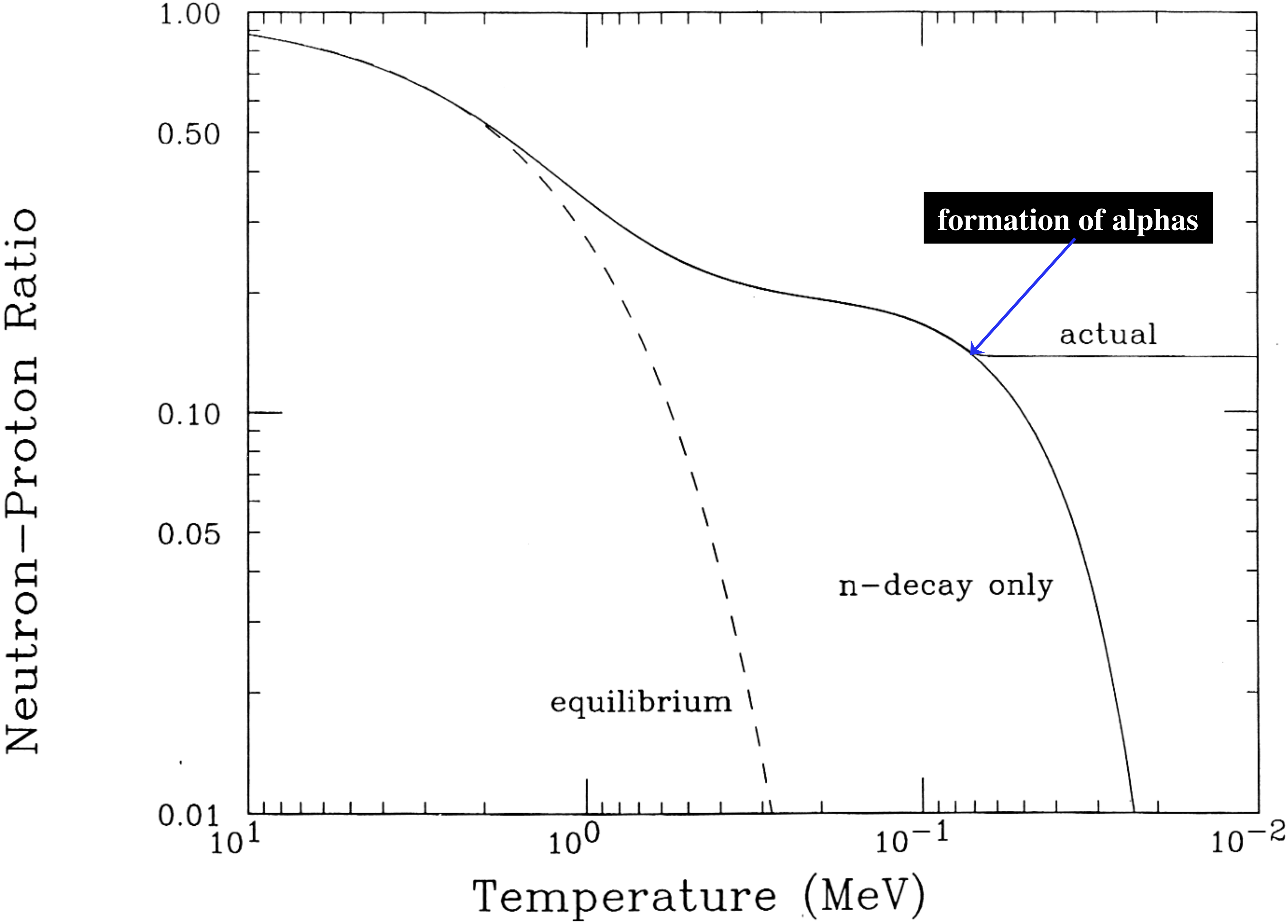




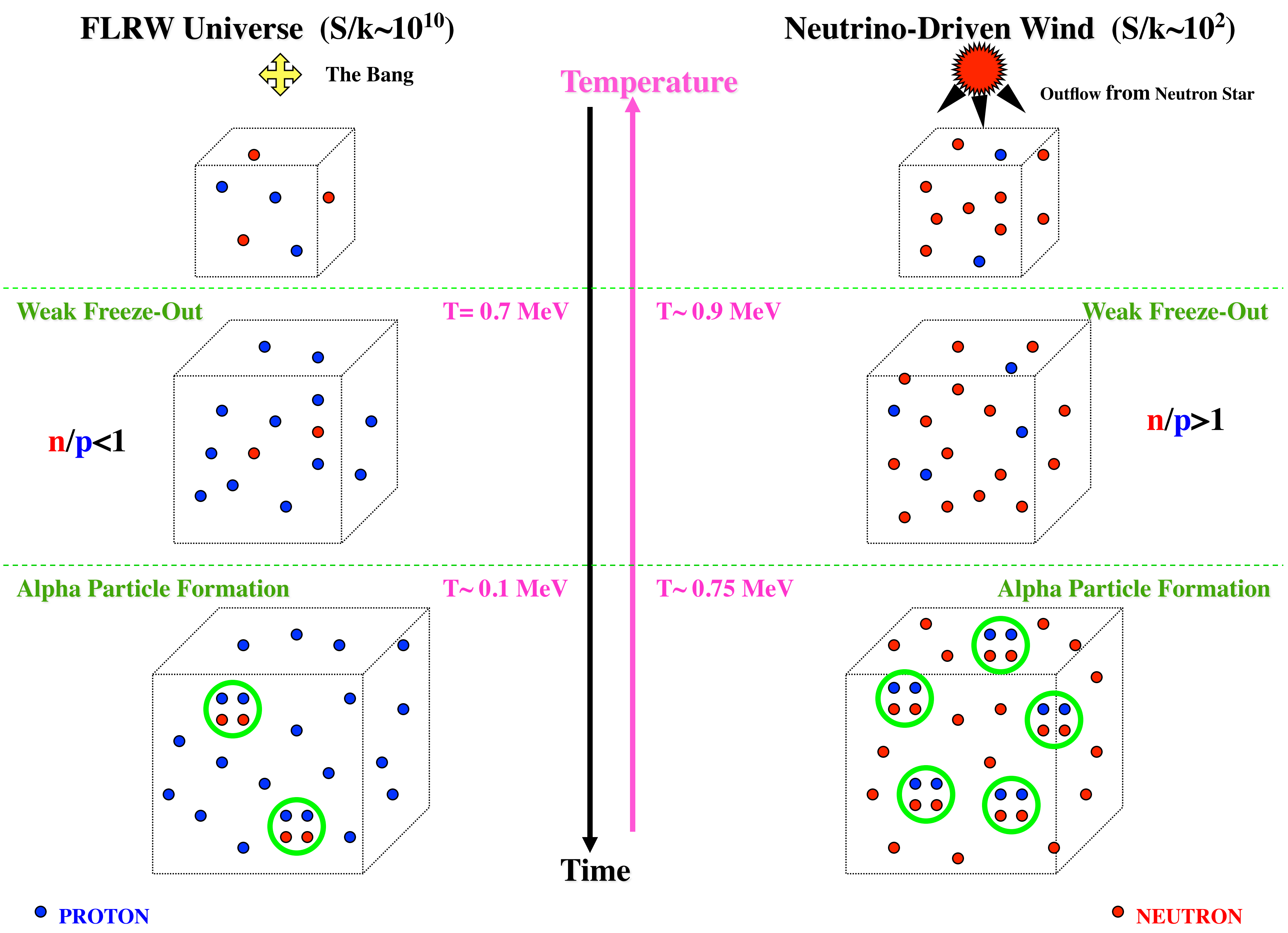
100000
1
1e-05
1e-10
1e-15
1e-20
1e-25
10
1
0.1
0.01
0.001
weak rate (s^{-1})
Temperature(MeV)
λ_{e^-p}
$\lambda_{n\mathrm{decay}}$
$\lambda_{pe^-\bar{\nu}_e}$
$\lambda_{\nu_e n}$
λ_{e^+n}
$\lambda_{\bar{\nu}_e p}$



rate (s^{-1})
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
Total Weak Destruction Rate
3He
7Be
6He
3H
neutron
proton
Expansion Rate of the Universe
Standard BBN
3
2
1
7 6 5 4 3 2
0.1
7 6 5 4 3
temperature T (MeV)



formation of alphas
actual
n−decay only
equilibrium
1.00
0.50
0.10
0.05
0.01
10^1
10^0
10^{-1}
10^{-2}
Neutron−Proton Ratio
Temperature (MeV)



FLRW Universe (S/k~10^10)
The Bang
Temperature
Neutrino-Driven Wind (S/k~10^2)
Outflow from Neutron Star
Weak Freeze-Out
T= 0.7 MeV
T~ 0.9 MeV
Weak Freeze-Out
n/p<1
n/p>1
Alpha Particle Formation
T~ 0.1 MeV
T~ 0.75 MeV
Alpha Particle Formation
Time
PROTON
NEUTRON

Freeze-Out from Nuclear Statistical Equilibrium (NSE)

In NSE the reactions which build up and tear down nuclei have equal rates, and these rates are large compared to the local expansion rate.

$$Z\,p + N\,n \longleftrightarrow A(Z,N) + \gamma$$

nuclear mass A is the sum of protons and neutrons A=Z+N

$$Z\,\mu_p + N\,\mu_n = \mu_A + Q_A$$

Binding Energy of Nucleus A

Saha Equation

$$Y_{A(Z,N)} \approx \left[S^{1-A}\right] G \pi^{\frac{7}{2}(A-1)} 2^{\frac{1}{2}(A-3)} A^{3/2} \left(\frac{T}{m_b}\right)^{\frac{3}{2}(A-1)} Y_p^Z Y_n^N e^{Q_A/T}$$

Typically, each nucleon is bound in a nucleus by ~ 8 MeV.

For alpha particles the binding per nucleon is
more like 7 MeV.

But alpha particles have mass number A=4,
and they have almost the same
binding energy per nucleon as heavier nuclei
so they are favored whenever there is a competition
between binding energy and disorder (high entropy).

There are two neutrons for every alpha particle, so in the limit where *every* neutron gets incorporated into an alpha particle the abundance of alpha's will be

$$Y_\alpha \approx \frac{1}{2} Y_n = \frac{1}{2} X_n \quad \text{where } Y_\alpha = X_\alpha / 4$$

number density is $n_{\mathrm{A}} = n_{\mathrm{b}} Y_{\mathrm{A}}$
and abundance is $Y_{\mathrm{A}} = X_{\mathrm{A}} / \mathrm{A}$
where mass fraction is X_{A}
and A is nuclear mass number
and baryon number density is n_{b}

The alpha mass fraction at the α formation epoch, T ~ 100 keV, is then

$$X_\alpha = 4Y_\alpha \approx 2Y_n \approx \frac{2n_n}{(n_n + n_p)} = \frac{2(n_n/n_p)}{(1 + n_n/n_p)}$$

$$\approx \frac{2(1/7)}{(1+1/7)} = \frac{2/7}{8/7} = \frac{2}{8} = 0.25$$

where we have used $\frac{n_n}{n_p} \approx \frac{1}{7}$ at the time the alpha particles form

Remember that at Weak Freeze Out, $T \approx 0.7$ MeV,
the neutron to proton ratio for zero lepton number is

$$\frac{n_n}{n_p} \approx \frac{1}{6}$$

Dave Schramm pioneered the use of primordial nucleosynthesis considerations as a probe of particle physics and cosmology.

In particular, he and his co-workers pushed to use the observationally-inferred helium abundance to determine the number of flavors of neutrinos.

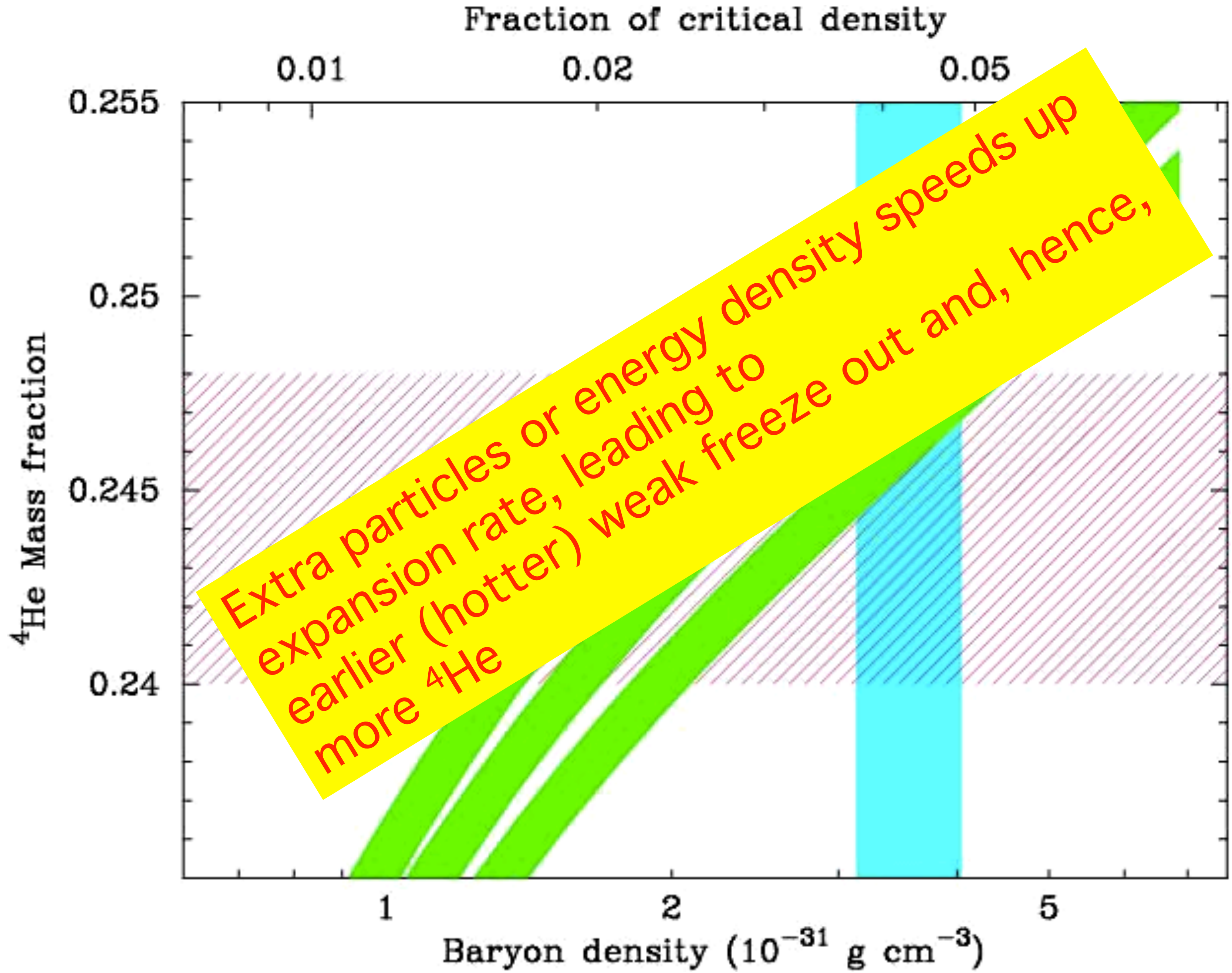
David N. Schramm

very crudely:

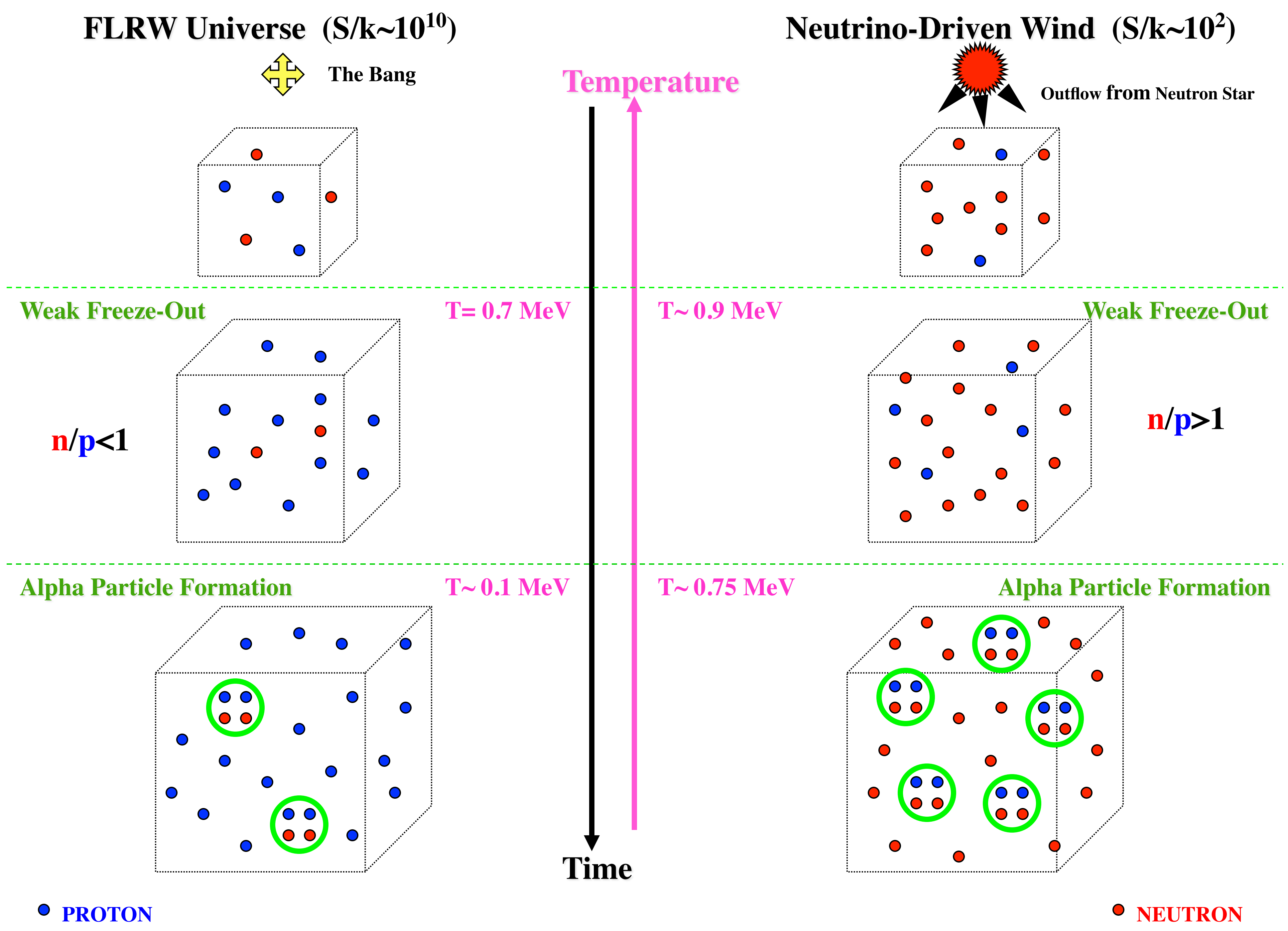
^{4}He yield sensitive to expansion rate

^{2}H sensitive to baryon density

Actually, helium *does* depend on baryon density, and deuterium *does* depend on the n/p ratio and the expansion rate.



Fraction of critical density
0.01
0.02
0.05
0.255
0.25
0.245
0.24
4He Mass fraction
1
2
5
Baryon density (10^-31 g cm^-3)
Extra particles or energy density speeds up expansion rate, leading to earlier (hotter) weak freeze out and, hence, more 4He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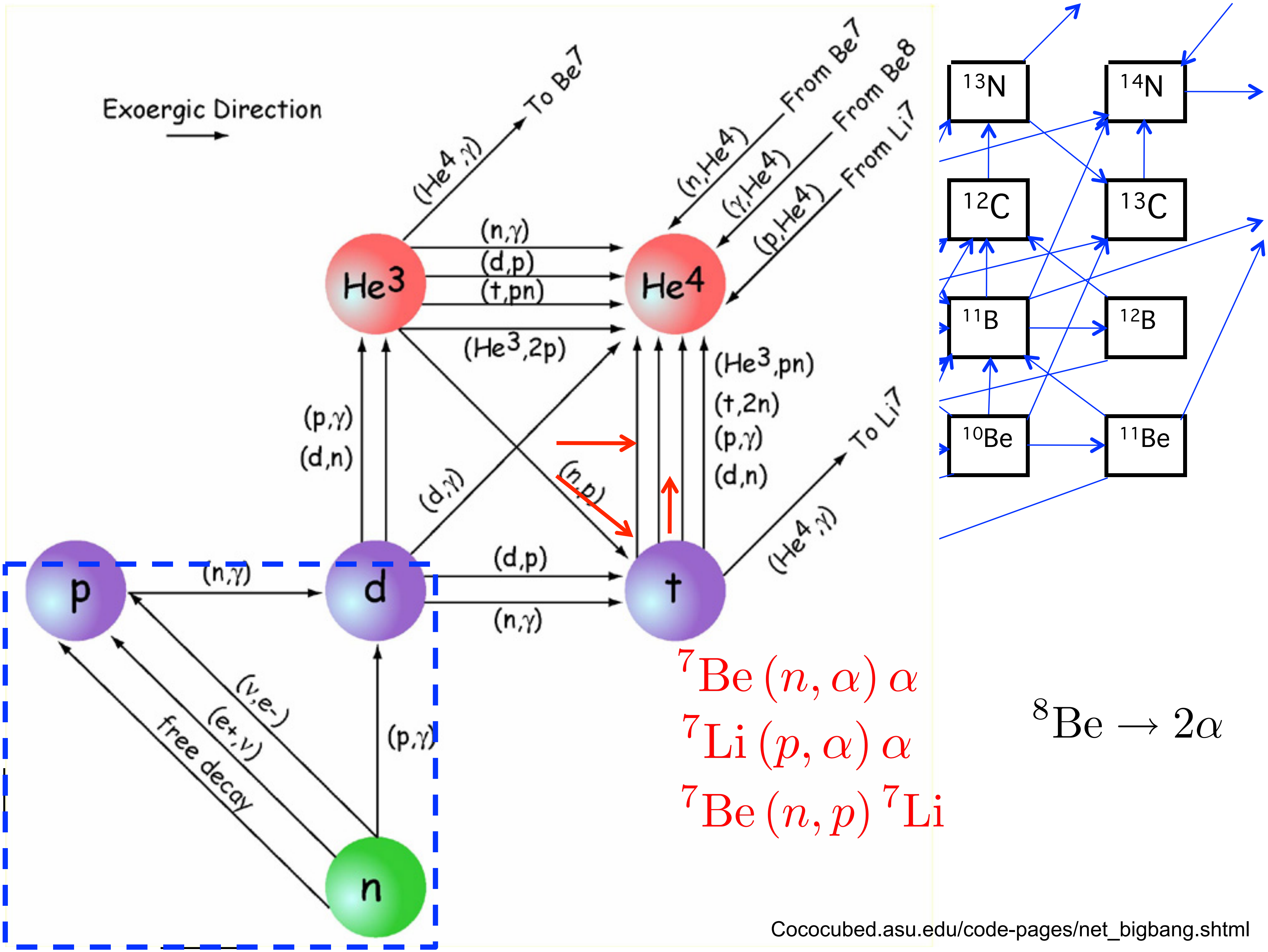


$$^{7}\mathrm{Be}\,(n,\alpha)\,\alpha$$

$$^{7}\mathrm{Li}\,(p,\alpha)\,\alpha$$

$$^{7}\mathrm{Be}\,(n,p)\,^{7}\mathrm{Li}$$

$$^{8}\mathrm{Be} \rightarrow 2\alpha$$

Cococubed.asu.edu/code-pages/net_bigbang.shtml

Nuclear Abundance Evolution – nuclear reactions

$$\text{nucleus } i,\ A_i(Z_i) \ \Rightarrow\ A_i = Z_i + N_i$$

$$n_i\, A_i(Zi) + n_j\, A_j(Z_j) \ldots$$

Wagoner-Kawano Code

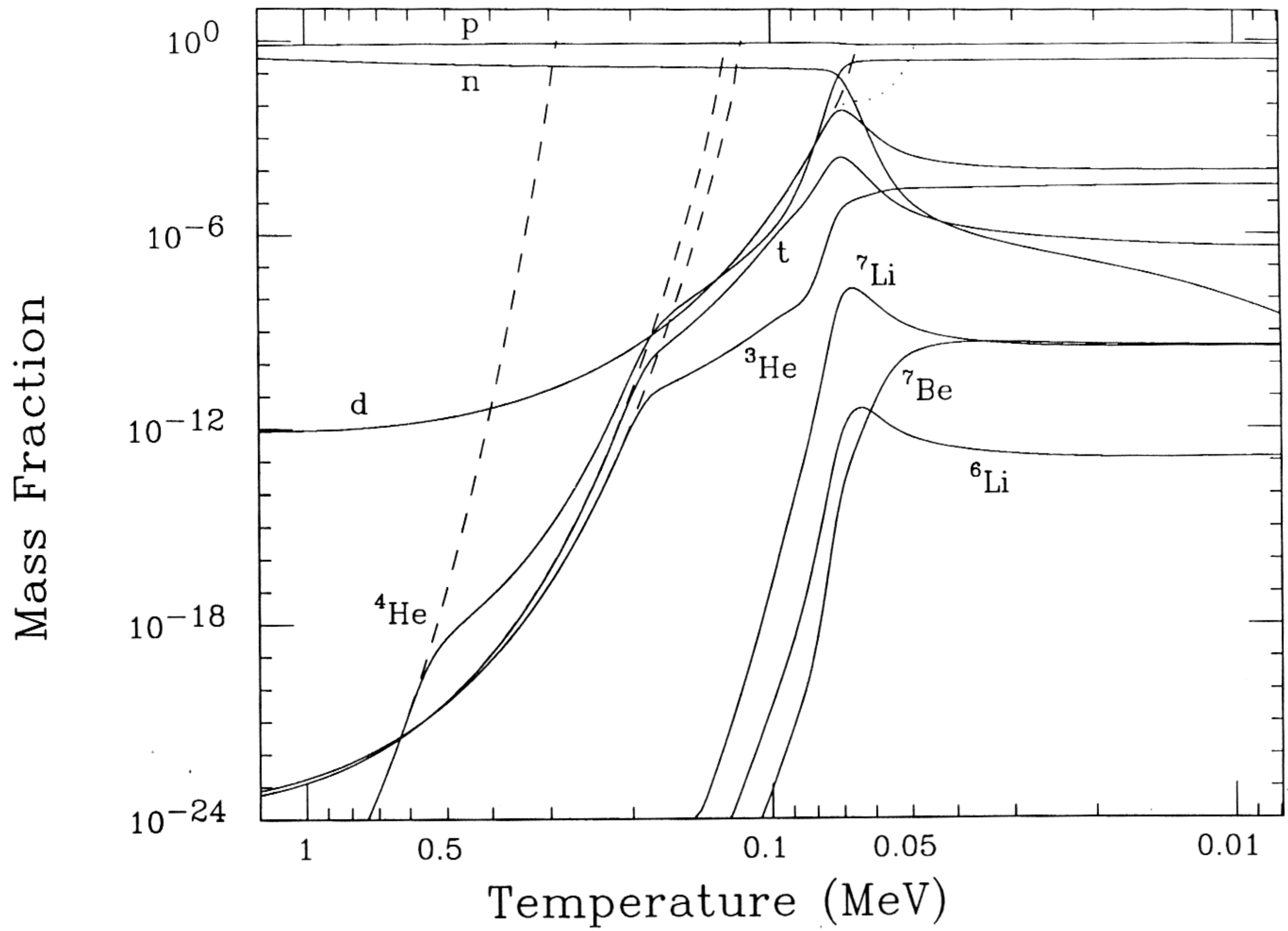
2nd order Runga-Kutta integration

many variants with different integrators and weak rate prescriptions

See bigbangonline.org hosted and led by Michael Smith at ORNL

…interaction,
…the example above,

$$[ij]_k = n_b\langle\sigma v\rangle$$
$$= \rho_b N_A \langle\sigma v\rangle$$



Full network BBN

What NSE and the
Saha equation would have given

M. Smith, L. Kawano, R. Malaney

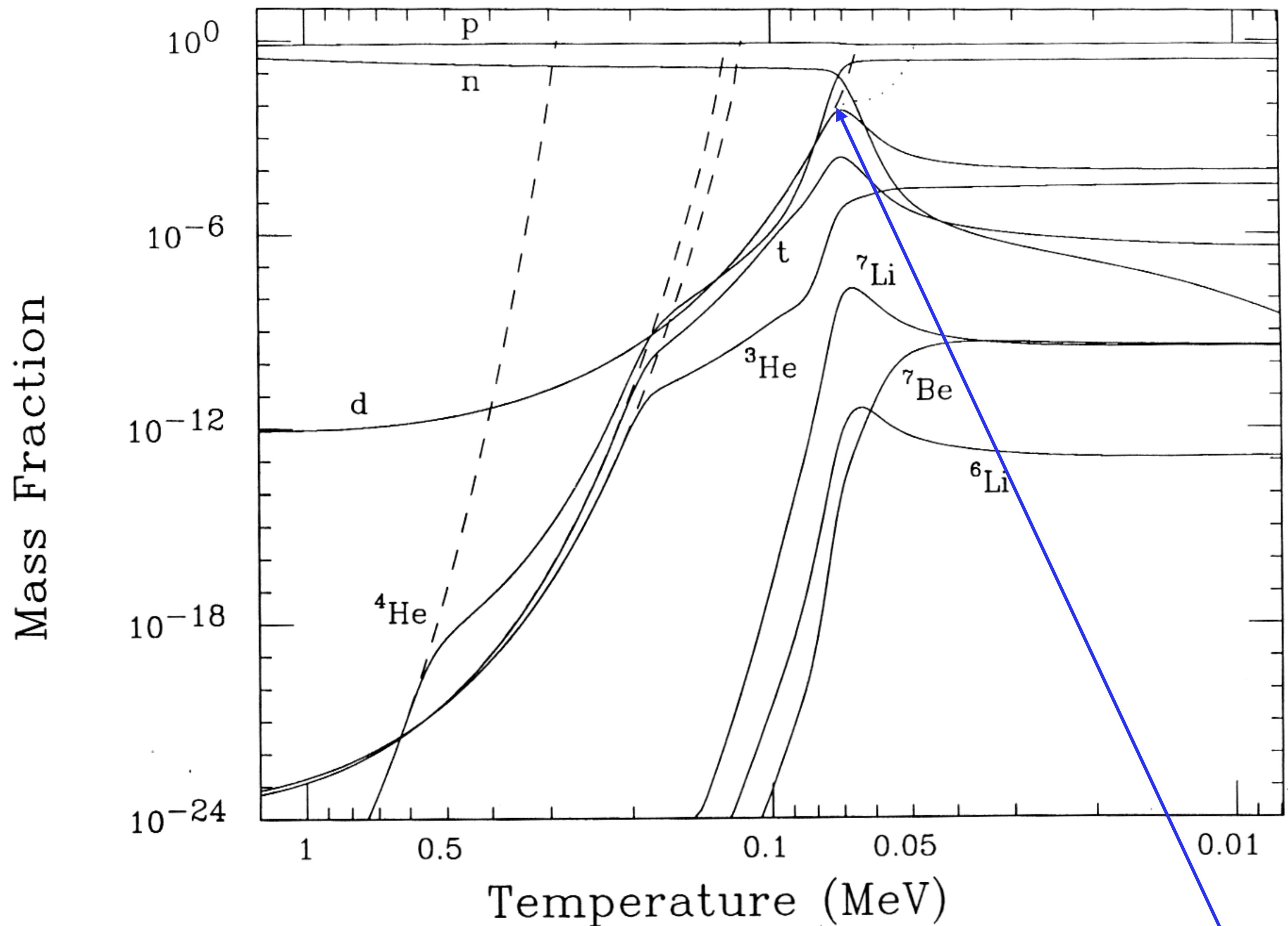
NSE Freeze-Out for the Deuteron

deuteron is very fragile, with a binding energy of only 2.2 MeV

In Nuclear Statistical Equilibrium (NSE), the rate of assembly of deuterons matches the destruction rate, and both of these are large compared to the expansion rate . . .

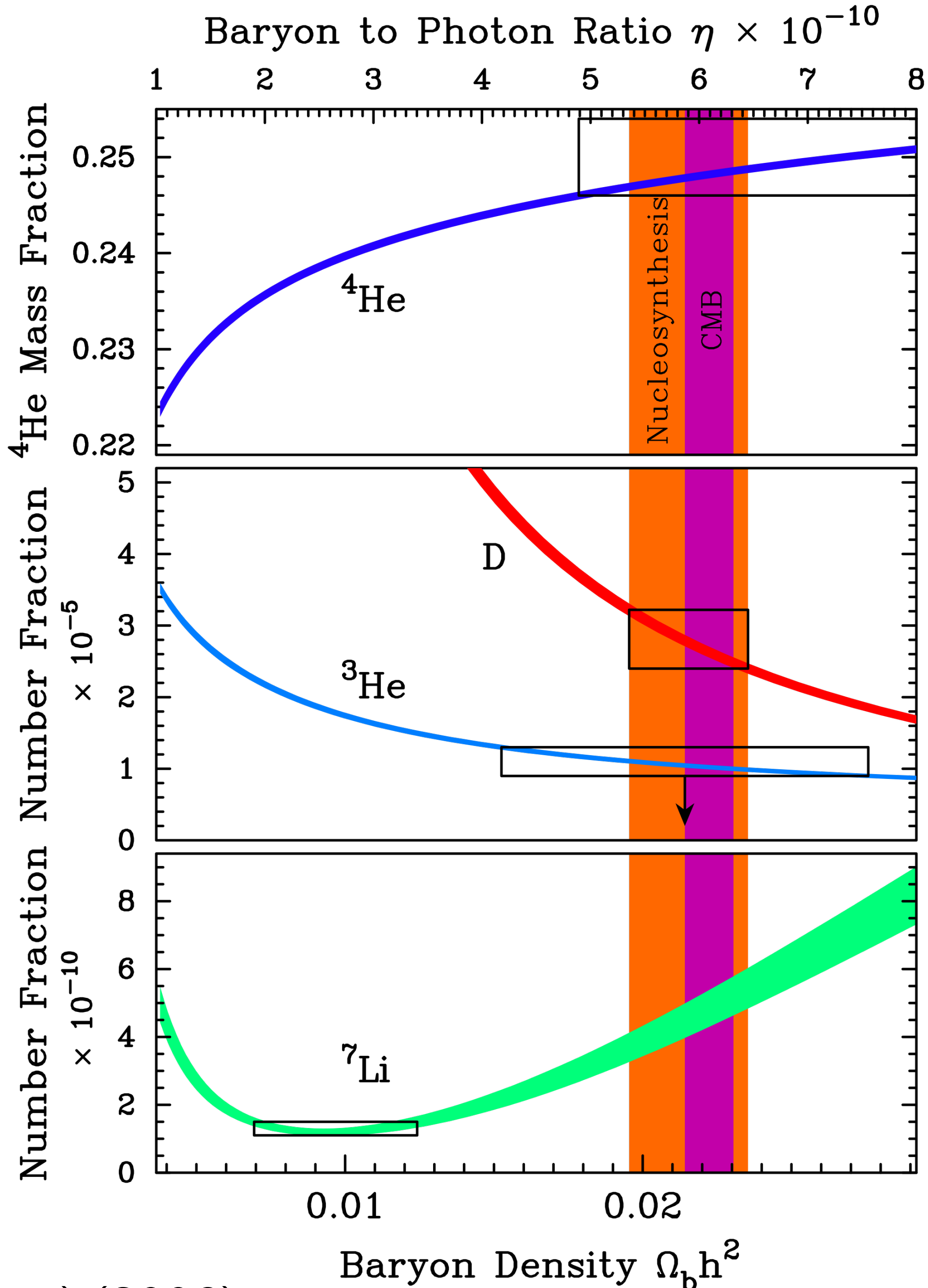
$$\mathrm{n} + \mathrm{p} \rightleftharpoons \mathrm{d} + \gamma$$

In NSE, abundance relative to baryons is $Y_{\mathrm{d}} \propto e^{\mathrm{B.E.}/T} = e^{2.2\,\mathrm{MeV}/T}$



$n + p \Leftrightarrow {}^2\text{H} + \gamma$

Deuteron production reaction deprived of neutrons because of alpha formation: goes out of NSE



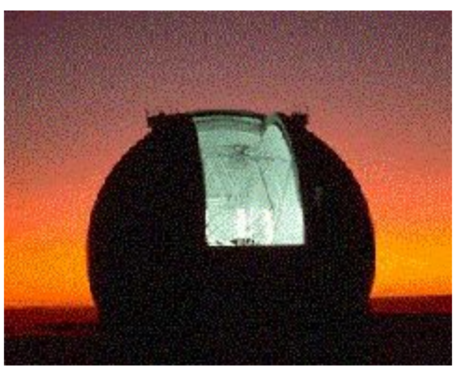
N. Suzuki (Tytler group) (2006)

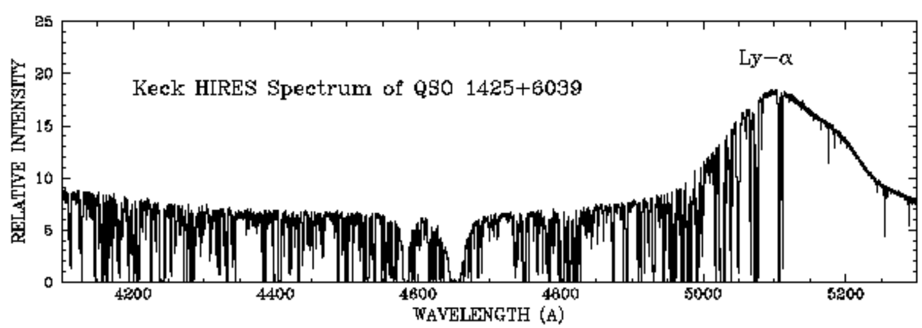
Primordial Deuterium Abundance

From observations of isotope-shifted Lyman lines in the spectra of high redshift QSO's.

See for example: J.M. O'Meara, D. Tytler, D. Kirkman, N. Suzuki, J.X. Prochaska, D. Lubin, & A.M. Wolfe
Astrophys. J. **552,** 718 (2001)

D. Kirkman, D. Tytler, N. Suzuki, J.M. O'Meara, & D. Lubin
Astrophys. J. Suppl. Ser. **149,** 1 (2003)





So, where do we stand in comparing the observationally-determined light element abundances with BBN predictions ??

(1) only really complete success is deuterium

– and this is very good! (Tytler's measurement confirmed by CMB)

(2) Helium is historically problematic, but promising with CMB

From compact blue galaxy linear regression, extrapolation to zero metallicity

Izotov & Thuan (2010) get helium mass fraction $\mathrm{Y_P} = 0.2565 \pm 0.0010\ (\mathrm{stat.}) \pm 0.0050\ (\mathrm{sys.})$

Using the CMB-determined baryon-to-photon ratio the standard BBN prediction is

$\mathrm{Y_P} = 0.2482 \pm 0.0007$ Steigman 1008.476

Best bet may be future CMB determinations via the Silk damping tail, currently this isn't great $\mathrm{Y_P} = 0.326 \pm 0.075$ Komatsu *et al.* 2010

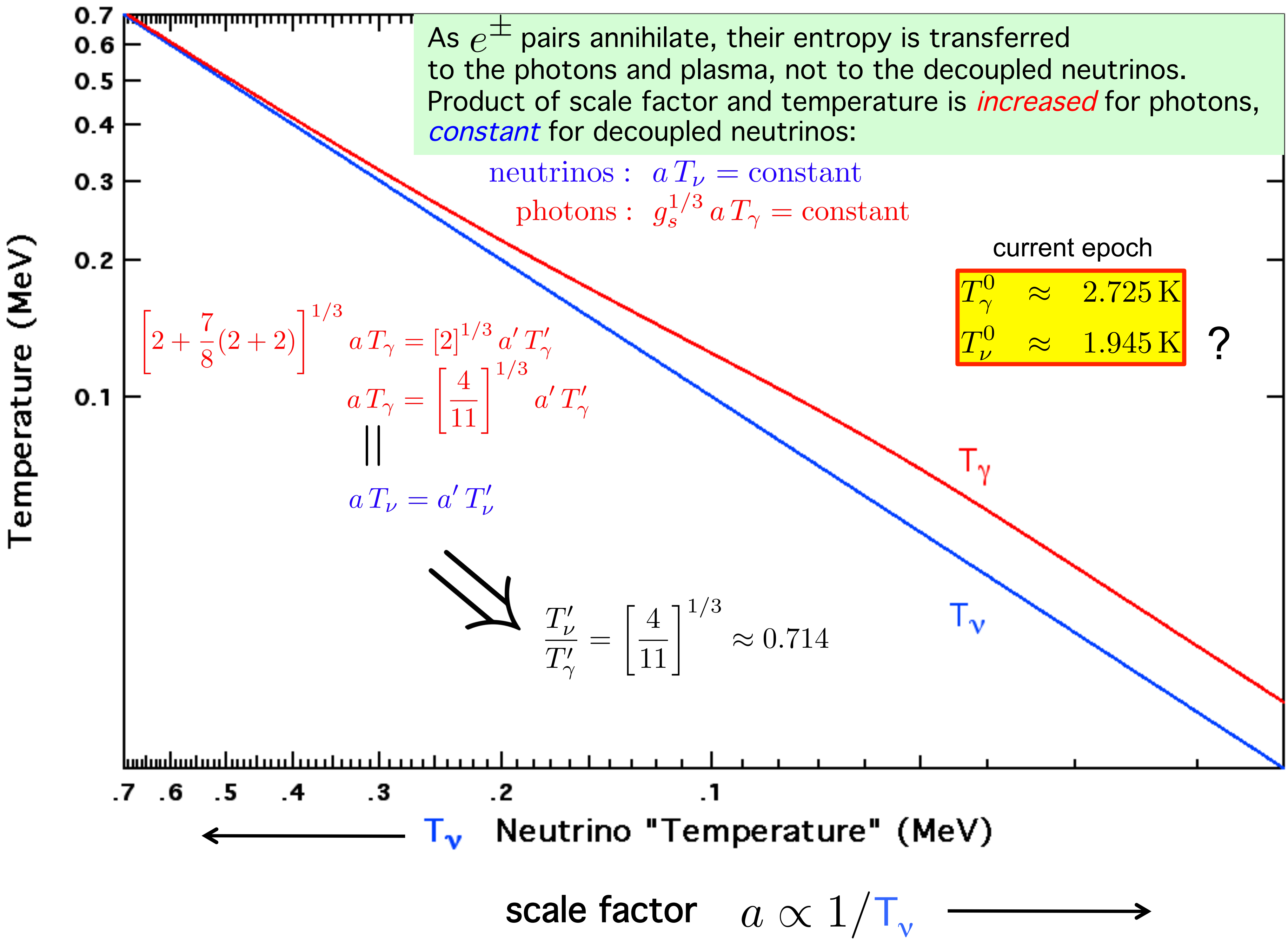
with Planck, CMBPol, could be ± 0.004

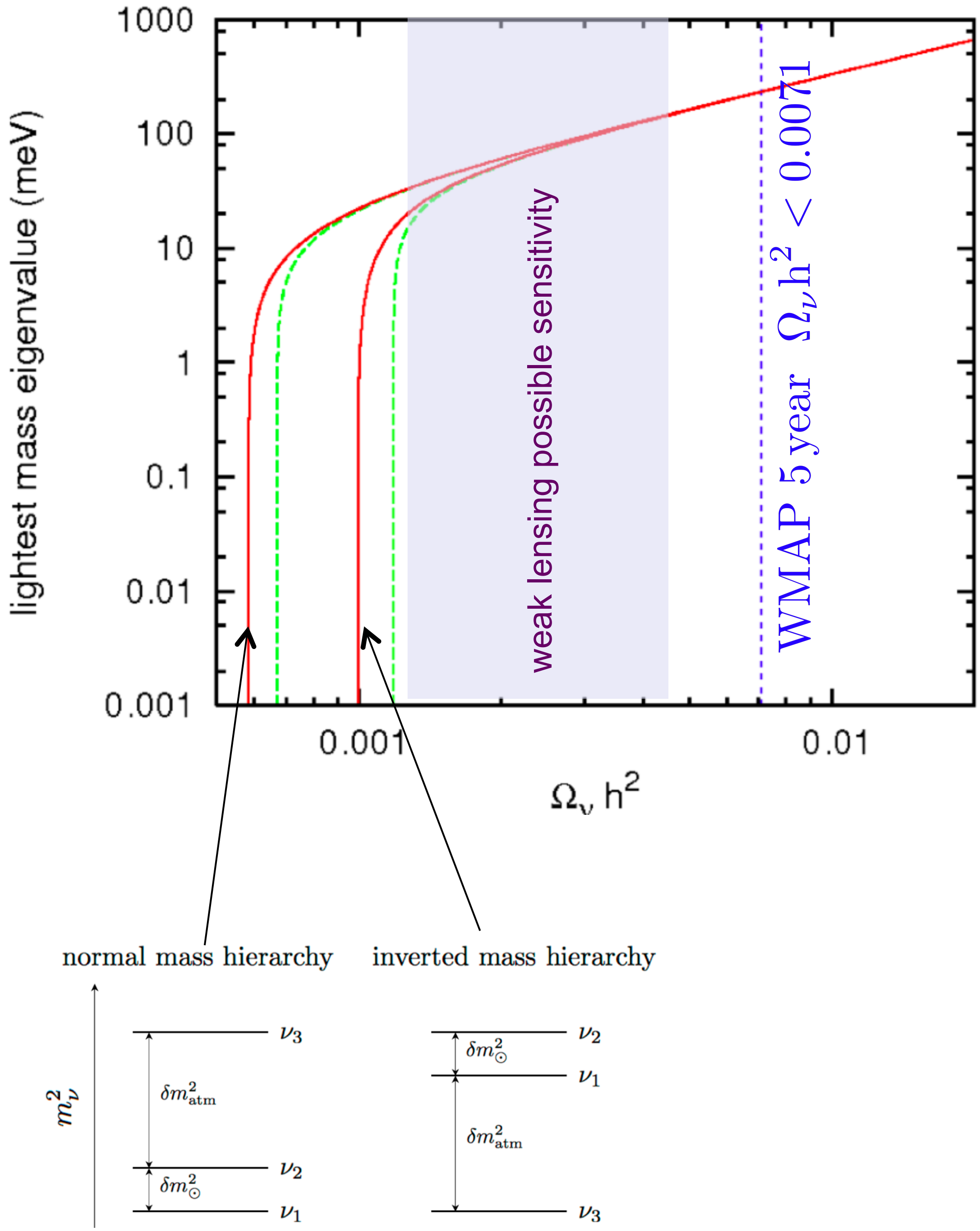
very tricky

(3) Lithium is a mess:

observed ^{7}Li low relative to BBN prediction by factor of 3

claimed observation of ^{6}Li high relative to BBN prediction by three orders of magnitude


As $e^{\pm}$ pairs annihilate, their entropy is transferred
to the photons and plasma, not to the decoupled neutrinos.
Product of scale factor and temperature is *increased* for photons,
constant for decoupled neutrinos:
$\text{neutrinos}: \; a\,T_\nu = \text{constant}$
$\text{photons}: \; g_s^{1/3}\,a\,T_\gamma = \text{constant}$
current epoch
$T_\gamma^0 \approx 2.725\,\text{K}$
$T_\nu^0 \approx 1.945\,\text{K}$?
$\left[2 + \frac{7}{8}(2+2)\right]^{1/3} a\,T_\gamma = [2]^{1/3}\,a'\,T'_\gamma$
$a\,T_\gamma = \left[\frac{4}{11}\right]^{1/3} a'\,T'_\gamma$
||
$a\,T_\nu = a'\,T'_\nu$
$\frac{T'_\nu}{T'_\gamma} = \left[\frac{4}{11}\right]^{1/3} \approx 0.714$
Tγ
Tν
Temperature (MeV)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
.7 .6 .5 .4 .3 .2 .1
Tν Neutrino "Temperature" (MeV)
scale factor $a \propto 1/T_\nu$



Next generation CMB experiments (*e.g.,* Planck; Polar Bear) will be sensitive to weak lensing and this will provide the best sensitivity to neutrino mass.

See for example
Kaplinghat, Knox, Song PRL **91**, 241301 (2003)

But the neutrino mass hierarchy will be one of the chief determinants of whether we can infer the absolute neutrino masses

G. M. Fuller & C. T. Kishimoto, *Phys. Rev. Lett.* **102**, 201303 (2009) [arXiv:astro-ph/0811.4370]

“Measuring” neutrino mass with cosmological considerations

Basic idea is that neutrinos “free stream” (move at ~ c) early on and so can remove energy density from structures, making their gravitational potential wells less deep, so they don’t grow as fast!

$$\text{density contrast in potential well} \quad \frac{\delta\rho}{\rho} \propto \Omega_{\mathrm{CDM}}$$

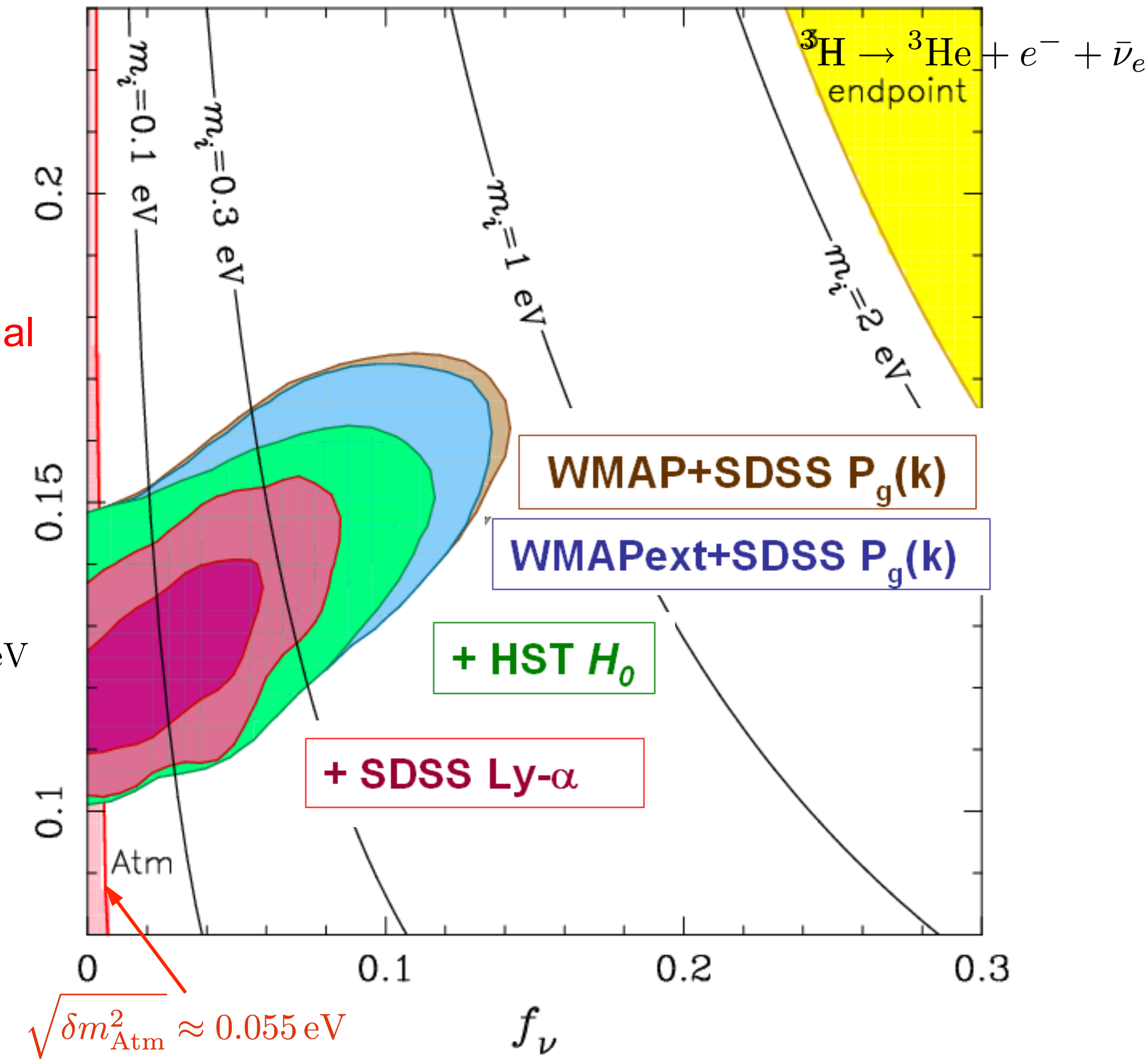
If neutrinos are massive they may be non-relativistic now,
so they contribute to cold dark matter (CDM). But they were relativistic at early epochs, meaning the CDM closure fraction earlier was *smaller*, so fluctuation density contrast grows more slowly with time.

cosmological constraints on neutrino rest mass

$\mathrm{WMAP}_{+\mathrm{ACBAR+CBI}}$ + SDSS + HST: ν Dark Matter

assumes that neutrinos have thermal, black body, zero chemical potential energy spectra

$\mathrm{WMAP} \quad \sum m_\nu \ < \ 0.6\,\mathrm{eV}$



K. Abazajian

Astrophysical Probes of Neutrino Rest Mass

(Abazajian et al., arXiv:1103.5083)

Probe	Current/Reach $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3/0.6	Recombination	WMAP, Planck	None
CMB Primordial w/ Distance	0.58/0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞/0.2-0.05	NG of Secondary anisotropies	Planck, ACT [47], SPT, PolarBear, EBEX, QUIET II [48]	CMBPol [44]
Galaxy Distribution	0.6/0.1	Nonlinearities, Bias	SDSS [9, 10], DES [43], BOSS [15]	LSST [17], WFMOS [11], HETDEX [12]
Lensing of Galaxies	0.6/0.07	Baryons, NL, Photo-z	CFHT-LS [42],DES [43], HyperSuprime	LSST, Euclid [57], DUNE [58]
Lyman α	0.2-?/0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS [59]
21 cm	∞/0.1-0.006	Foregrounds	Lofar [46], MWA [49], Paper, GMRT	SKA [50], FFTT [38]
Galaxy Clusters	0.3-?/0.1	Mass Function, Mass Calibration	SDSS, SPT, DES, Chandra	LSST
Core-Collapse Supernovae	NH (If $\theta_{13} > 10^{-3}$) IH (Any θ_{13})	Emergent ν spectra	SuperK, ICECube	Noble Liquids, Gadzooks

Table I: Cosmological probes of neutrino mass. "Current" denotes published (although in some cases controversial, hence the range) 95% C.L/ upper bound on $\sum m_\nu$ obtained from currently operating surveys, while "Reach" indicates the forecasted 95% sensitivity on $\sum m_\nu$ from future observations. These numbers have been derived for a minimal 7-parameter vanilla+m_ν model. The six other parameters are: the amplitude of fluctuations, the slope of the spectral index of the primordial fluctuations, the baryon density, the matter density, the epoch of reionization, and the Hubble constant.

Each of these probes faces technological, observational, and theoretical challenges in its quest to extract a few percent level signal. Table I highlights the key theoretical systematics each probe will have to overcome to obtain a reliable constraint on neutrino masses.

1. Primordial Cosmic Microwave Background

Dark Radiation*

*Evan Grohs will talk about models for this which involve “dilution” (entropy generation)

Radiation (relativistic particle) energy density beyond that contributed by photons is parameterized by the so called "effective number of neutrino degrees of freedom".

This is a dangerous misnomer as it may refer to energy density from ***any*** relativistic particles (e.g., super-WIMP decay products)

$$\rho_{\text{radiation}} = \left[2 + \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} \mathrm{N}_{\text{eff}}\right] \frac{\pi^2}{30} T_\gamma^4$$

The standard model predicts $N_{\text{eff}} = 3.046$ Calabrese *et al*. PRD **83**, 123504 (2011)

$$\text{WMAP7} \quad \mathrm{N}_{\text{eff}} = 4.34 + 0.86 - 0.88 \quad \text{(68\% confidence limit)}$$

$$\text{SPT} \quad \mathrm{N}_{\text{eff}} = 3.86 \pm 0.42 \quad \text{(with H}_0 \text{ \& BAO priors)}$$

$$\text{Archidiacono, Calabrese, Melchiori, ArXiv : 1109.2767} \quad N_{\text{eff}} = 4.08 + 0.71 - 0.68$$

another CMB observable?

N_{eff}

The implications of N_{eff} being greater or less than 3 are huge:

(1) from oscillations/ direct limits we have strict bounds on all light neutrino masses

(2) most ways you can think to do this hurt BBN agreement with observation

$$\mathrm{WMAP7} \quad \mathrm{N_{eff}} = 4.34 + 0.86 - 0.88 \quad (68\%\ \text{confidence limit})$$

Are light mass (~ 1 eV) sterile neutrinos increasing N_{eff} above its standard model value???

two lines of *laboratory* evidence . . . .

- mini-BooNE data

- nuclear reactor neutrino anomaly

If you are invoking a sterile neutrino

(e.g., ~ 1 eV for expt/N_{eff}, ~ 1 keV for dark matter, etc.)

WATCH OUT!

There may be more than one!

“Sterile” neutrinos are *not sterile* by virtue of their vacuum mixing with active neutrinos

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

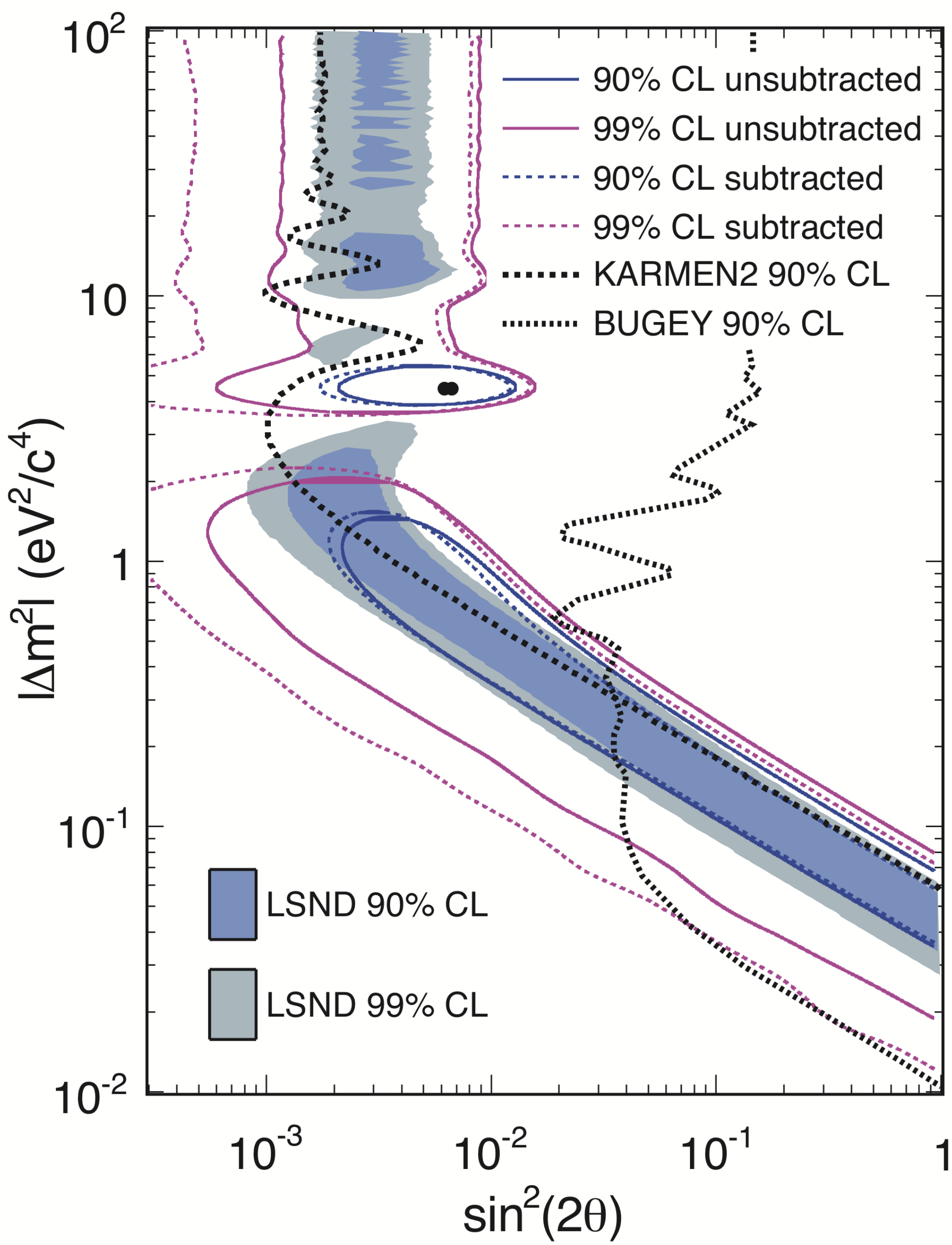
$\sin^2 2\theta$ { Gives effective interaction strength of the sterile neutrino relative to the standard ***Weak Interaction***

It is by virtue of these tiny interactions that sterile neutrinos can be produced in the early universe or in supernovae

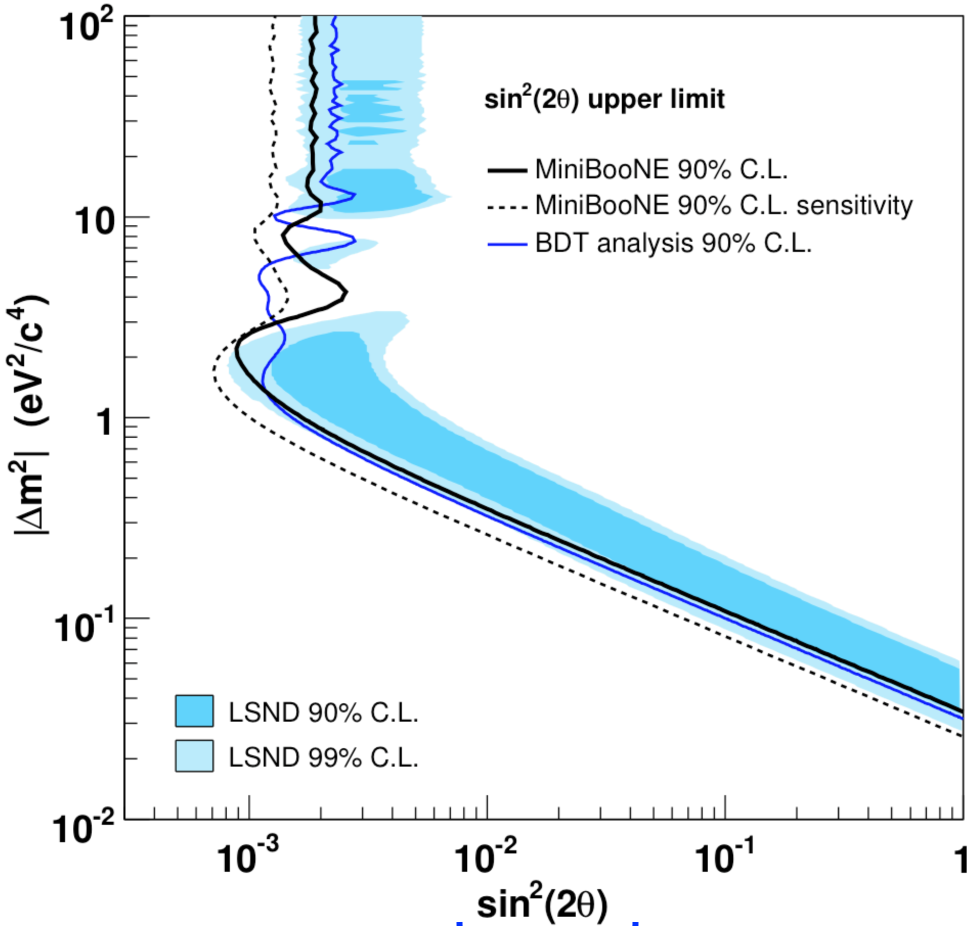
MiniBooNE Oscillation Fit

E>200 MeV

$\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed



MiniBooNE



Now consistent with the LSND signal.

If you take this as a constraint on active-sterile mixing, it does not eliminate much of the astrophysically interesting parameter space.

Why?

Watch out! This refers to an effective 2X2 vacuum mixing angle satisfying (for, *e.g.,* "3+1")

$$\sin^2 2\theta \approx 4|U_{e4}|^2|U_{\mu 4}|^2$$

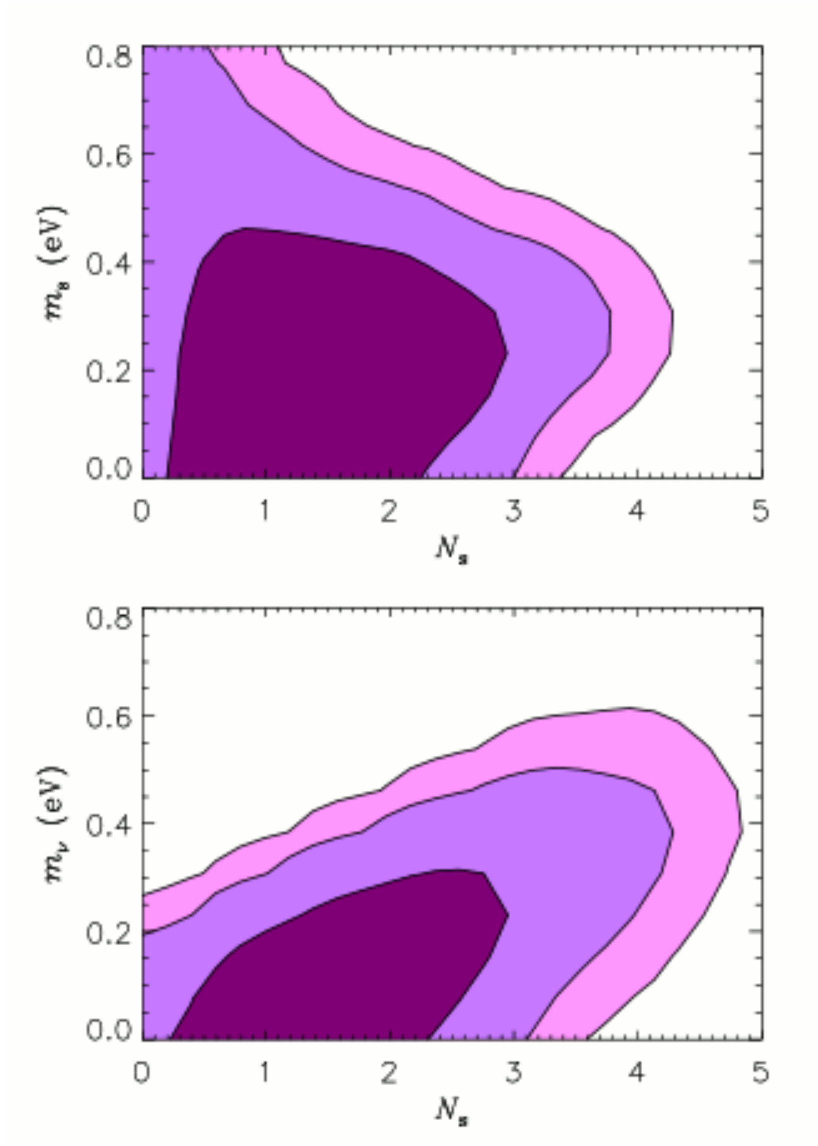
$$\nu_\mu \longrightarrow \nu_s \longrightarrow \nu_e$$

But for astrophysics we want , *e.g.,* just

$$\nu_e \rightarrow \nu_s \quad \& \quad |U_{e4}|^2$$

OK, if sterile neutrinos with masses ~ 1 eV
are there, shouldn’t they be there in the early universe,
and what about the cosmological mass constraints?

some claim that a light sterile neutrino is not ruled out by observations – but with big caveats
Hamann, Hannestad, Raffelt, Wong JCAP **9**, 34 (2011)



$3 + N_s$
$m_\nu = 0$

$3 + N_s$
$m_s = 0$

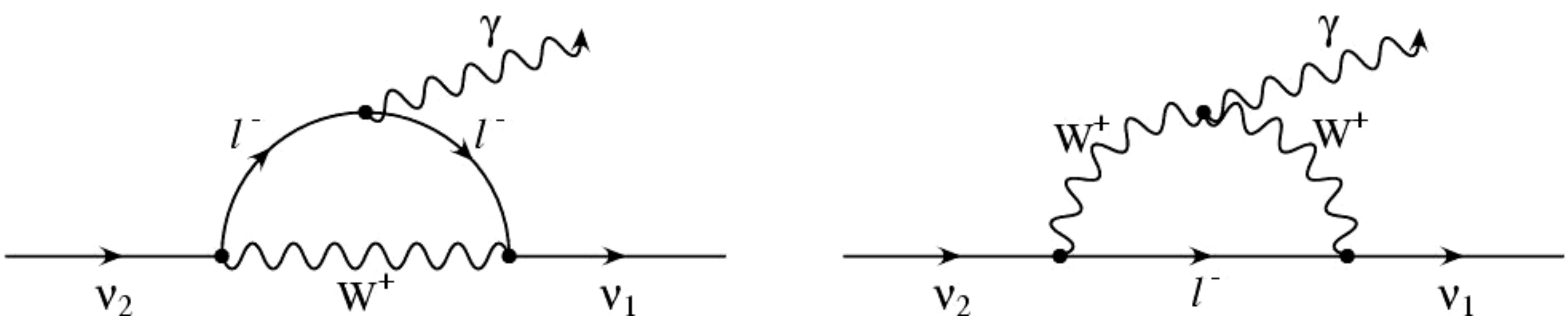
OK, what about heavier sterile neutrinos perhaps with tiny mixing with active neutrinos so they never thermalize in the early universe?

Live by the sword . . .

Die by the sword!

A heavy "sterile" neutrino can decay into a light "active" neutrino and a photon.

The final state light neutrino and the photon *equally share* the rest mass energy of the initial heavy neutrino.



$$\nu_s \longrightarrow \nu_{e,\mu,\tau} + \gamma$$

photon line $E_\gamma = m_s/2$

Singlet Neutrino Radiative Decay Rate

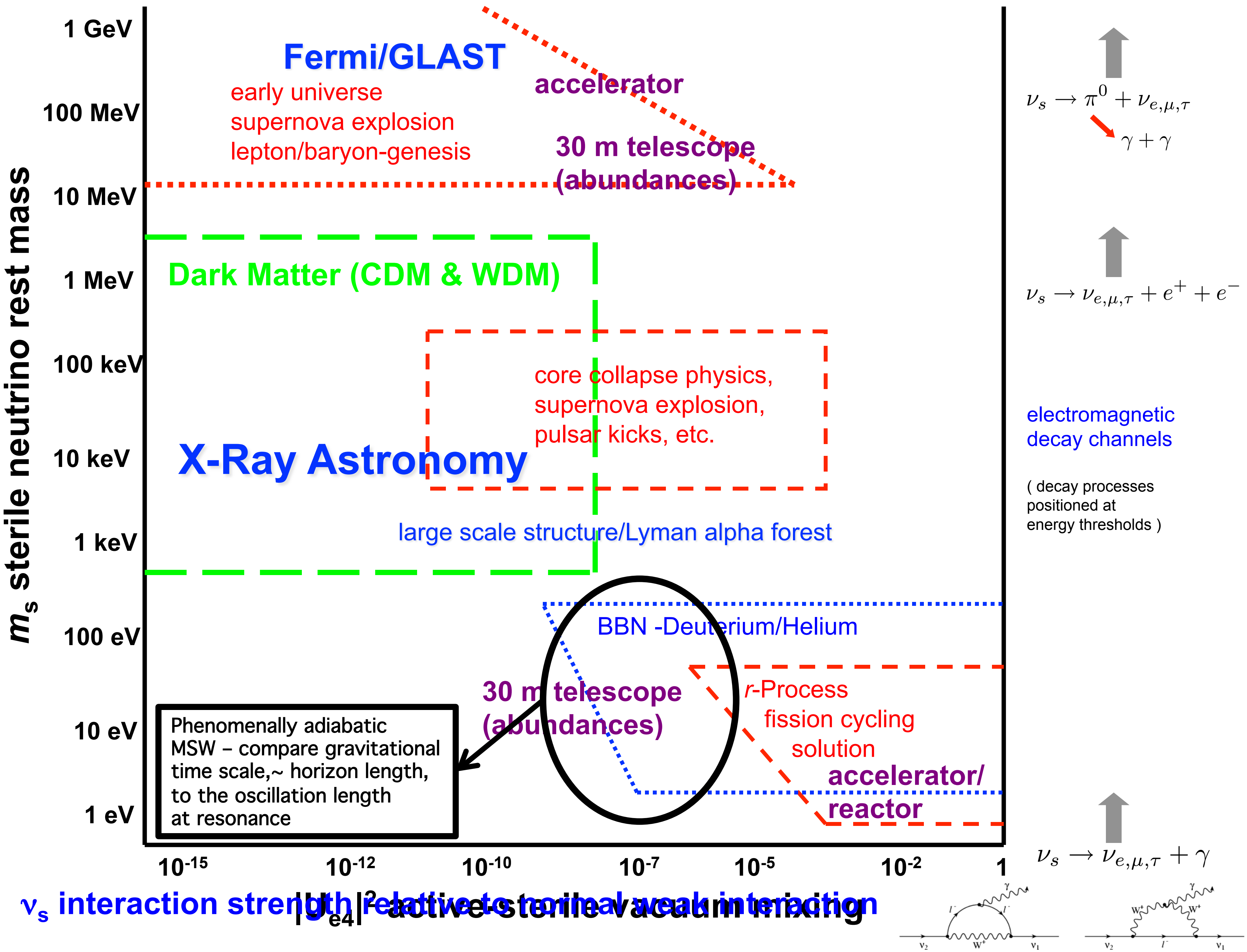
$$\Gamma_\gamma \approx \frac{\alpha G_F^2}{64\pi^4} m_2^5 \left[\sum_\beta U_{1\beta} U_{2\beta} F(r_\beta)\right]^2$$

$$\approx 6.8 \times 10^{-33}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5$$

no GIM suppression for sterile neutrinos

$$F(r_\beta) \approx -\tfrac{3}{2} + \tfrac{3}{4} r_\beta$$

$$r_\beta = \left(M_\beta^{lep} / M_W\right)^2$$



1 GeV
100 MeV
10 MeV
1 MeV
100 keV
10 keV
1 keV
100 eV
10 eV
1 eV
m_s sterile neutrino rest mass
Fermi/GLAST
early universe
supernova explosion
lepton/baryon-genesis
accelerator
30 m telescope
(abundances)
Dark Matter (CDM & WDM)
core collapse physics,
supernova explosion,
pulsar kicks, etc.
X-Ray Astronomy
large scale structure/Lyman alpha forest
BBN -Deuterium/Helium
30 m telescope
(abundances)
r-Process
fission cycling
solution
accelerator/
reactor
Phenomenally adiabatic MSW – compare gravitational time scale,~ horizon length, to the oscillation length at resonance
10^{-15}
10^{-12}
10^{-10}
10^{-7}
10^{-5}
10^{-2}
1
ν_s interaction strength relative to normal weak interaction
$|U_{e4}|^2$ active-sterile vacuum mixing
$\nu_s \rightarrow \pi^0 + \nu_{e,\mu,\tau}$
$\gamma + \gamma$
$\nu_s \rightarrow \nu_{e,\mu,\tau} + e^+ + e^-$
electromagnetic
decay channels
(decay processes
positioned at
energy thresholds)
$\nu_s \rightarrow \nu_{e,\mu,\tau} + \gamma$

Sterile Neutrino Dark Matter?

Singlet ("sterile") neutrinos which have tiny vacuum mixing with active neutrinos can be produced in the early universe and in supernova cores via coherent MSW processes and via de-coherence associated with collisions.

These singlets make interesting Warm and Cold Dark Matter candidates. They are not "WIMPS," as their interaction strengths are typically 10 to 15 orders of magnitude weaker than the Weak Interaction and they were never in equilibrium in the early universe.

However, they are eminently constrainable/detectable with existing and proposed X-Ray observatories.

Sterile Neutrino Dark Matter ???

active-active neutrino scattering-induced decoherence

S. Dodelson & L. M. Widrow, Phys. Rev. Lett. **72**, 17 (1994)

A. D. Dolgov & S. H. Hansen, Astropart. Phys. **16**, 339 (2002)

→ Largely eliminated by the X-ray observations

But Some Models Are Still Viable . . .

low temperature inflation

M. Shaposhnikov & I. Tkachev, Phys. Lett. B **639**, 414 (2006)

Higgs decay

A. Kusenko, Phys. Rev. Lett. **97**, 241301 (2006)

K. Petraki & A. Kusenko (2007), arXiv:0711.4646

K. Petraki (20008), arXiv:0801.3470

lepton number-enhanced decoherence

X. Shi & G. M. Fuller, Phys. Rev. Lett. **83**, 3120 (1999)

K. Abazajian, G.M. Fuller, M. Patel, Phys. Rev. D **64**, 023501 (2001)

C. Kishimoto & G.M. Fuller, Phys. Rev. D **78**, 023524 (2008) arXiv:0802.3377

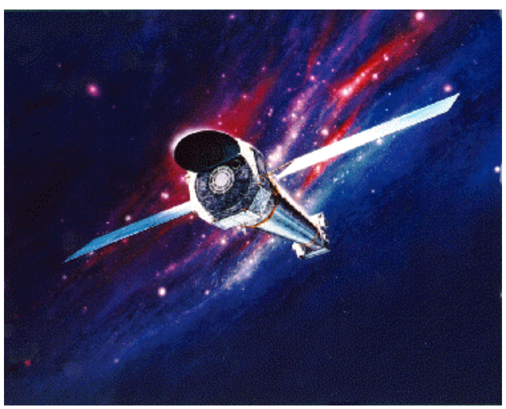
M. Shaposhnikov, Nucl. Phys. B **763**, 49 (2007)

A serendipitous coincidence:

XMM-Newton and Chandra have greatest sensitivity for photons with energies between about 1 keV to 10 keV, serendipitously coincident with the expected photon energies from decaying Dark Matter “sterile” neutrinos.

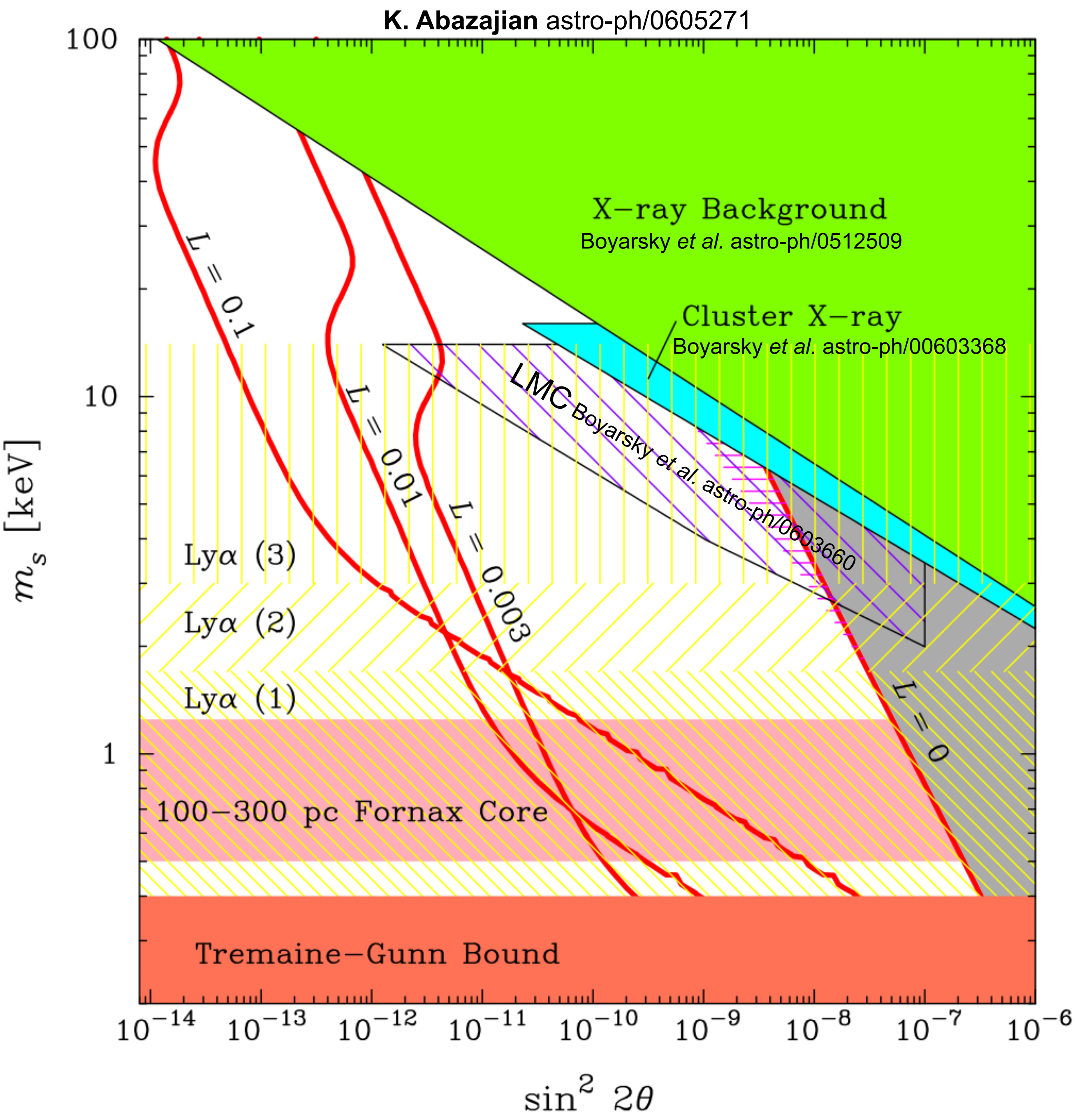
Typical lifetimes against radiative decay are some $\sim 10^{16}$ times the age of the universe! However, if steriles are the Dark Matter, then in a typical cluster of galaxies there could be $\sim 10^{79}$ of these particles.

This could allow x-ray observatories to probe physics at interaction strengths some 10-14 orders of magnitude smaller than the Weak Interaction.



Chandra X-Ray Observatory

XMM-Newton X-Ray Observatory



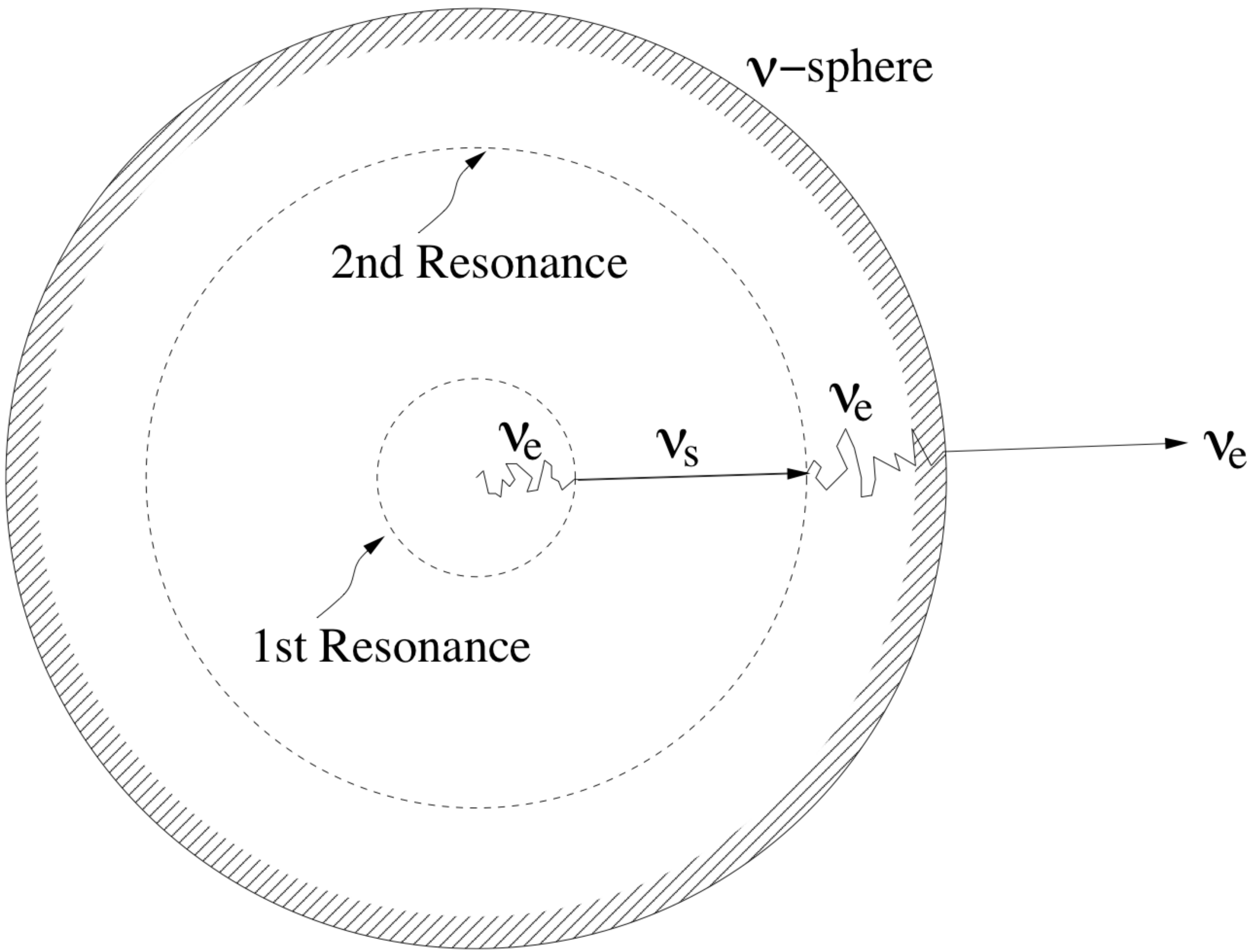
K. Abazajian astro-ph/0605271
X−ray Background
Boyarsky et al. astro-ph/0512509
Cluster X−ray
Boyarsky et al. astro-ph/00603368
LMC Boyarsky et al. astro-ph/0603660
L = 0.1
L = 0.01
L = 0.003
L = 0
Lyα (3)
Lyα (2)
Lyα (1)
100−300 pc Fornax Core
Tremaine−Gunn Bound
m_s [keV]
sin^2 2θ

Fun with Compact Objects and ~ keV Rest Mass Sterile Neutrinos

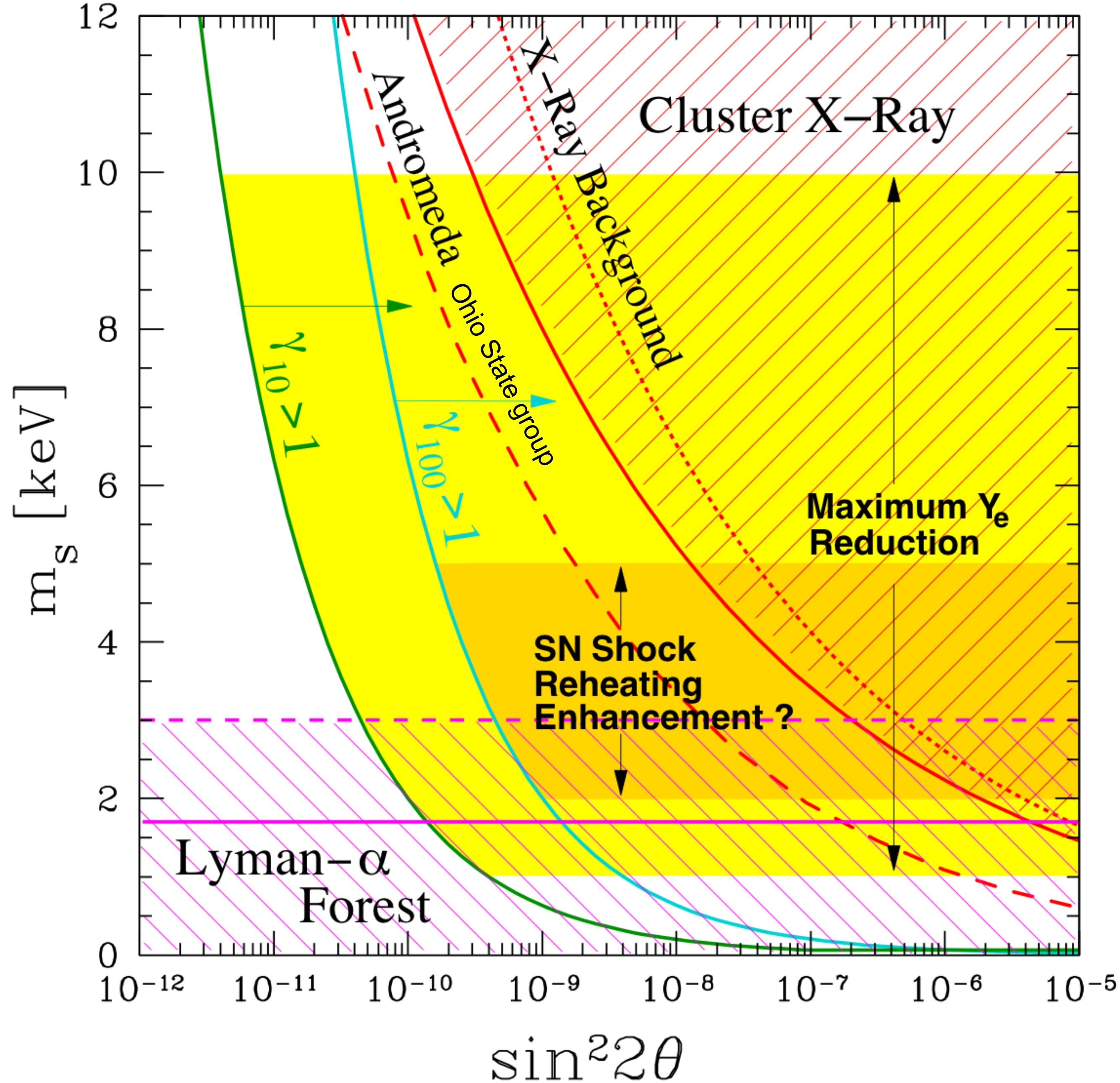
Pulsar "Kicks"
A. Kusenko & G. Segre, PRD 59, 061302 (1999);
G. M. Fuller, A. Kusenko, I. Mocioiu, and S. Pascoli PRD **68**, 103002 (2003).

Proto-neutron star "kick"-aided hydrodynamic supernova shock enhancement
C. Fryer & A. Kusenko, Astrophys. J. (Suppl) **163**, 335 (2006).

Active-sterile-active neutrino matter-enhanced alteration of collapse physics and enhanced shock re-heating
J. Hidaka & G. M. Fuller, Phys. Rev. D **74,** 125015 (2006)



J. Hidaka & G. M. Fuller, Phys. Rev. D **74**, 125015 (2006) J. Hidaka & G. M. Fuller, Phys. Rev. D **76**, 085013 (2007)



J. Hidaka & G. M. Fuller, Phys. Rev. D **74**, 125015 (2006)

J. Hidaka & G. M. Fuller, Phys. Rev. D **76**, 085013 (2007)