New Neutrino Physics
in
Astrophysics and Cosmology

Neutrinos and New Physics

TRIUMF, Vancouver, BC, Canada, November 13, 2012

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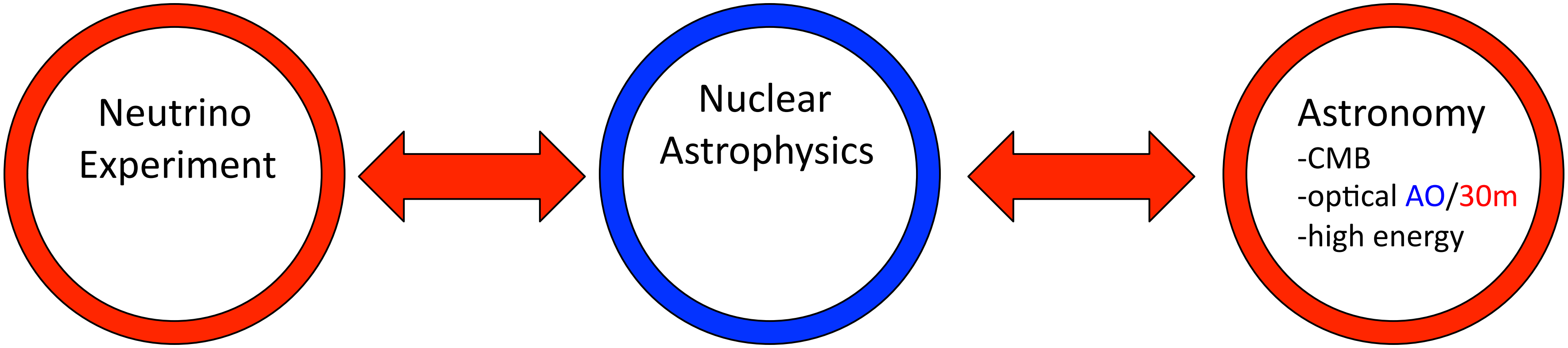
This is the golden age for both
Neutrino Physics *and* Observational Astronomy

discoveries have been coming fast and thick
and, for neutrinos, this is all ***Beyond Standard Model*** physics

Nuclear Astrophysics is right in the middle of all this



Neutrino Experiment

Nuclear Astrophysics

Astronomy
-CMB
-optical AO/30m
-high energy

VERY EXCITING **future** . . . because 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, adaptive optics, and orbiting observatories
(e.g., precision determinations of deuterium abundance, dark energy/matter content, structure history etc.)

(3) Laboratory neutrino mass/mixing measurements

is setting up a nearly over-determined situation where ***new*** Beyond Standard Model neutrino physics likely ***must*** show itself!

The Weak Interaction

- uniquely capable of changing neutrons to protons and *vice versa*

- it is *weak*, so neutrinos can transport energy/entropy from/to dense environments over macroscopic distances (stars, SN)

- neutrinos "remember" the neutron-to-proton ratio of the region where they decoupled, and can transmit this to overlying environments (BBN, SN, compact object mergers)

Early Universe *vs*. **Supernovae/Mergers** as labs for new physics

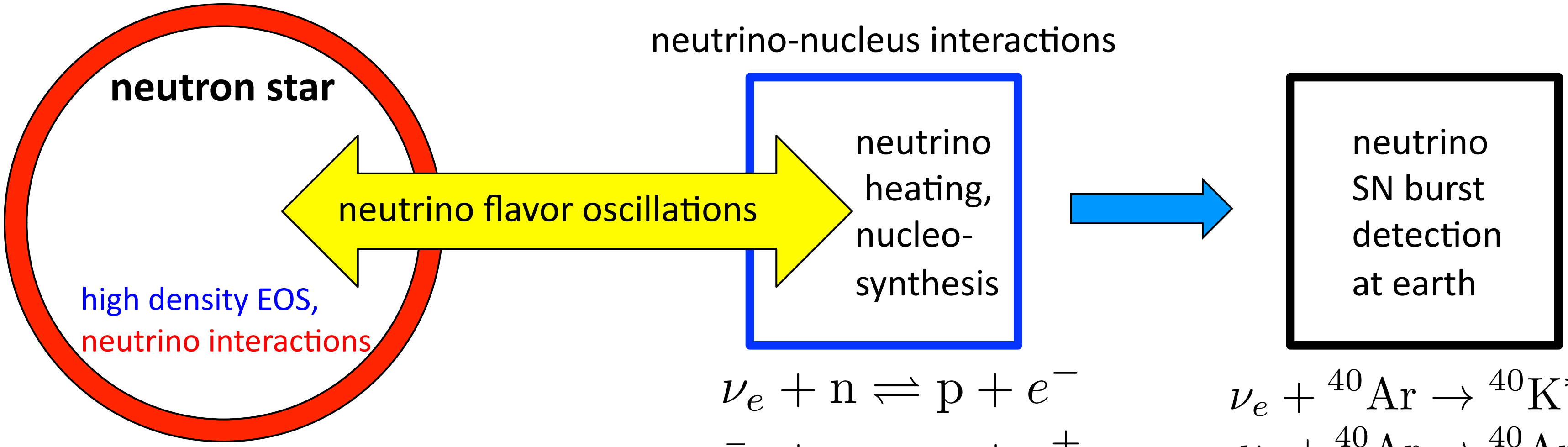
Core collapse supernovae and *compact object mergers*
are fantastic engines for generating neutrinos
(~ 10% of the rest mass into neutrinos)

- neutrino fields are **anisotropic**; complex thermal structure

Early universe and *BBN*: likewise, significant fraction
of energy in neutrinos, but . . .

-**isotropic**, simple geometry, high entropy, no heat flow

Calculating neutrino flavor transformation in the core collapse supernova environment is a vexing problem,
but one whose solution may lie at the heart of many aspects of the nuclear physics of stellar collapse.



neutron star

neutrino flavor oscillations

high density EOS,
neutrino interactions

neutrino-nucleus interactions

neutrino heating, nucleosynthesis

neutrino SN burst detection at earth

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu_x$$

We need the fluxes and energy spectra of each flavor/type of neutrino at all epochs and at all radii.

Calculating neutrino flavor evolution is *not* an optional exercise.

- *measured* neutrino flavor mixing parameters

- neutrinos carry most of the energy/entropy and the way this is transported, deposited, and (may be) detected is *flavor-dependent*

Neutrino Flavor Oscillations

in Medium

Quantum Kinetic Equations

$$i p_\mu \partial^\mu f\,(x,\vec{p}) - [m^2, f\,(x,\vec{p})] - p_\mu[\Sigma_V^\mu(x), f\,(x,\vec{p})] = I_{\mathrm{col}}(f,\bar{f})$$

$$i p_\mu \partial^\mu \bar{f}\,(x,\vec{p}) - [m^2, \bar{f}\,(x,\vec{p})] - p_\mu[\Sigma_V^\mu(x), \bar{f}\,(x,\vec{p})] = \bar{I}_{\mathrm{col}}(f,\bar{f})$$

separation of scales

Schroedinger-like

@ low density where
neutrinos propagate coherently

is it justified

?

Boltzmann equation

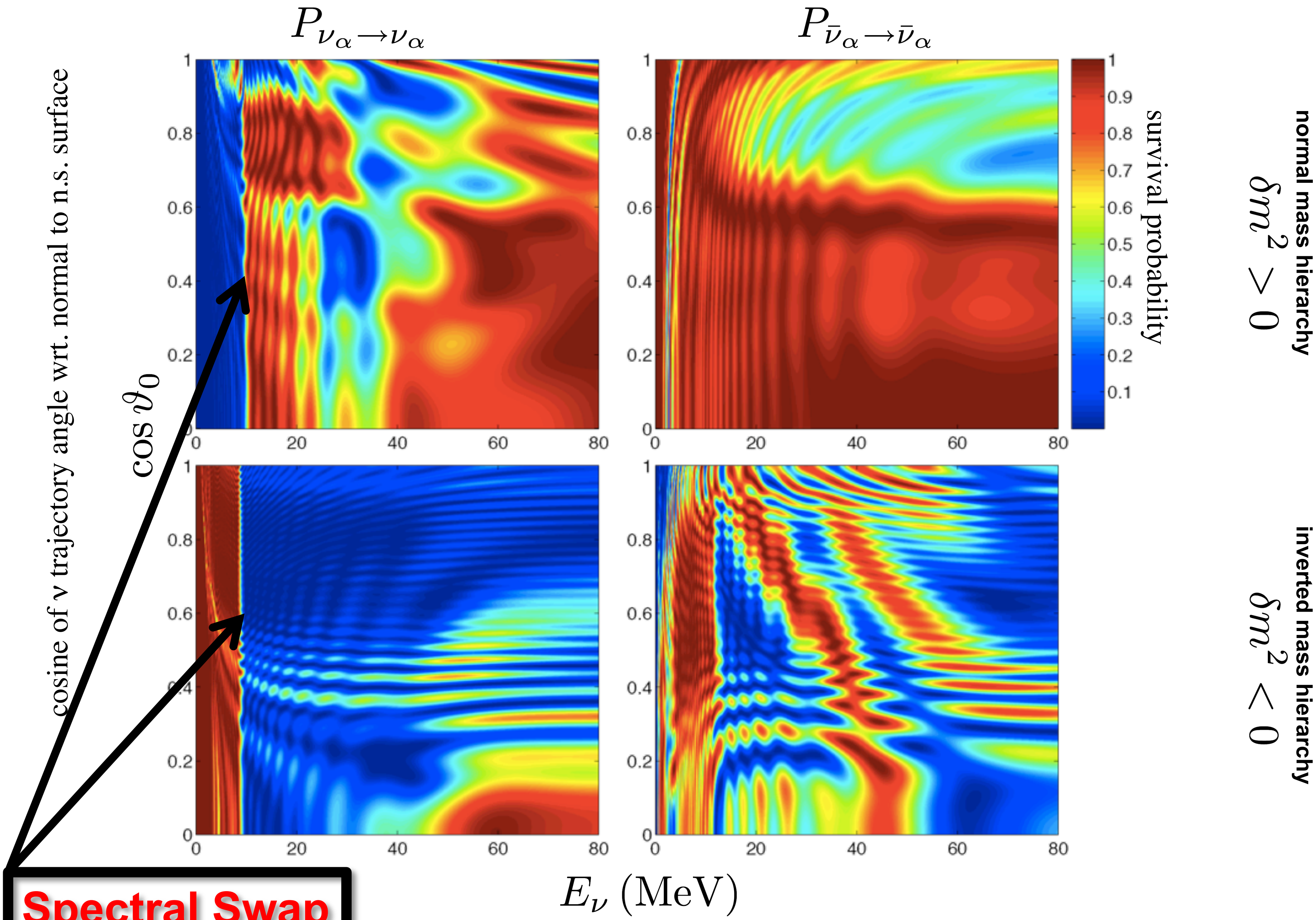
@ high density where
inelastic scattering dominates

A. Vlasenko, V. Cirigliano, G. Fuller 2012

The advent of supercomputers has allowed us in the last few years to follow neutrino flavor transformation in core collapse supernovae, including the first self-consistent treatment of **nonlinearity** stemming from neutrino-neutrino forward scattering.

The results are startling. Despite the small measured neutrino mass-squared differences, **collective** neutrino flavor transformation can take place deep in the supernova envelope

Pushing the frontier of high performance computing with a unique new kind of transport problem



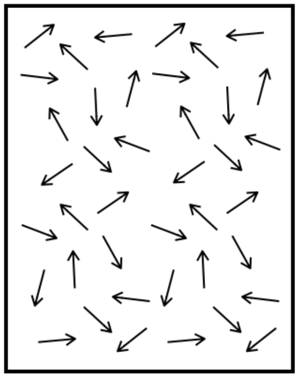
Spectral Swap

consequences of neutrino mass and quantum coherence in supernovae

H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) astro-ph/0606616

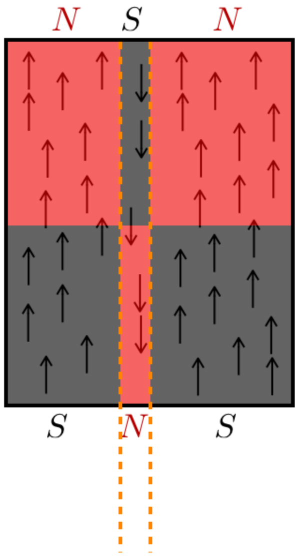
Magnetic Analogy

$T > T_C$



Cooling causes
the magnetic spins
to line up in domains
in space.

$T < T_C$



“Cooling” (moving away
from the neutron star)
causes the neutrino spins
to line up in domains
in energy space.

Baha Balantekin & Shashank Shalgar

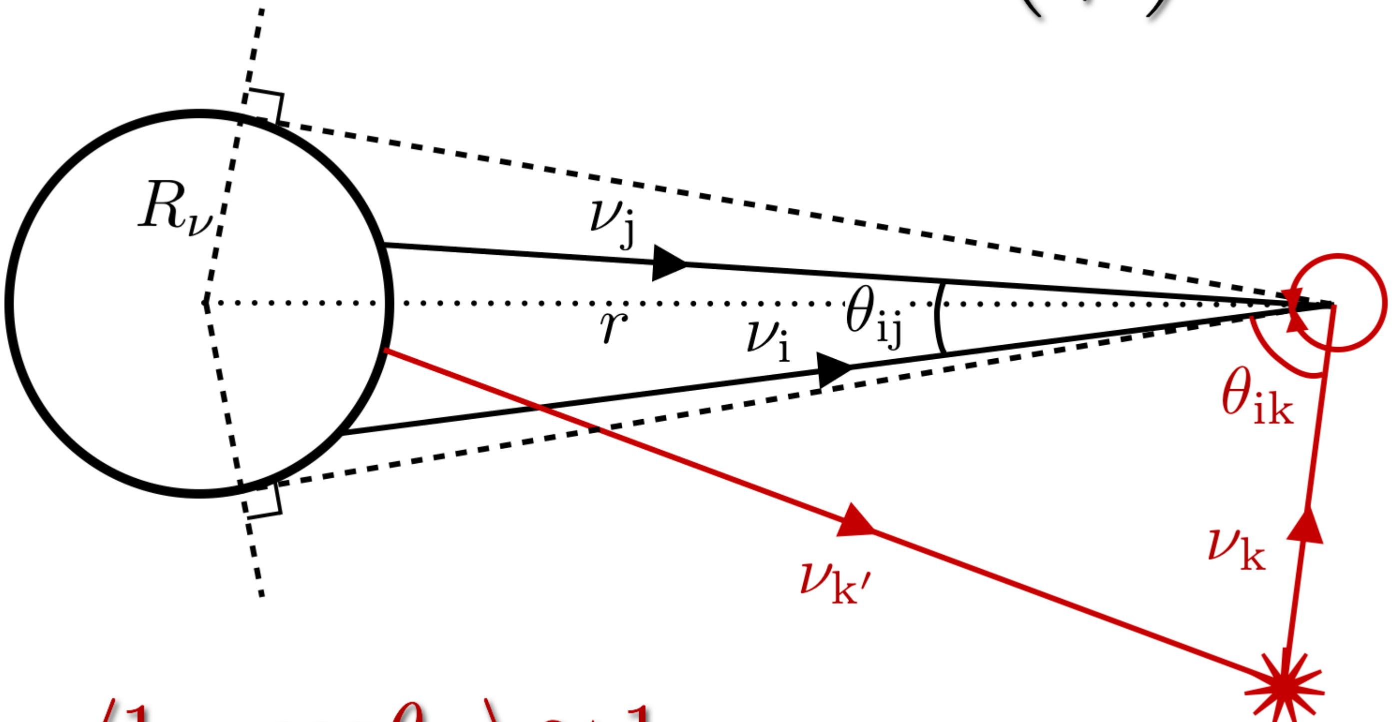
will talk more about collective neutrino oscillations . . .

Toward Quantum Kinetics

i.e., What effect does direction-changing scattering have on the neutrino flavor transformation?

The Neutrino Halo

$$r \gg R_\nu \Rightarrow \langle 1 - \cos\theta_{\mathrm{ij}} \rangle \propto \left(\frac{R_\nu}{r}\right)^2$$

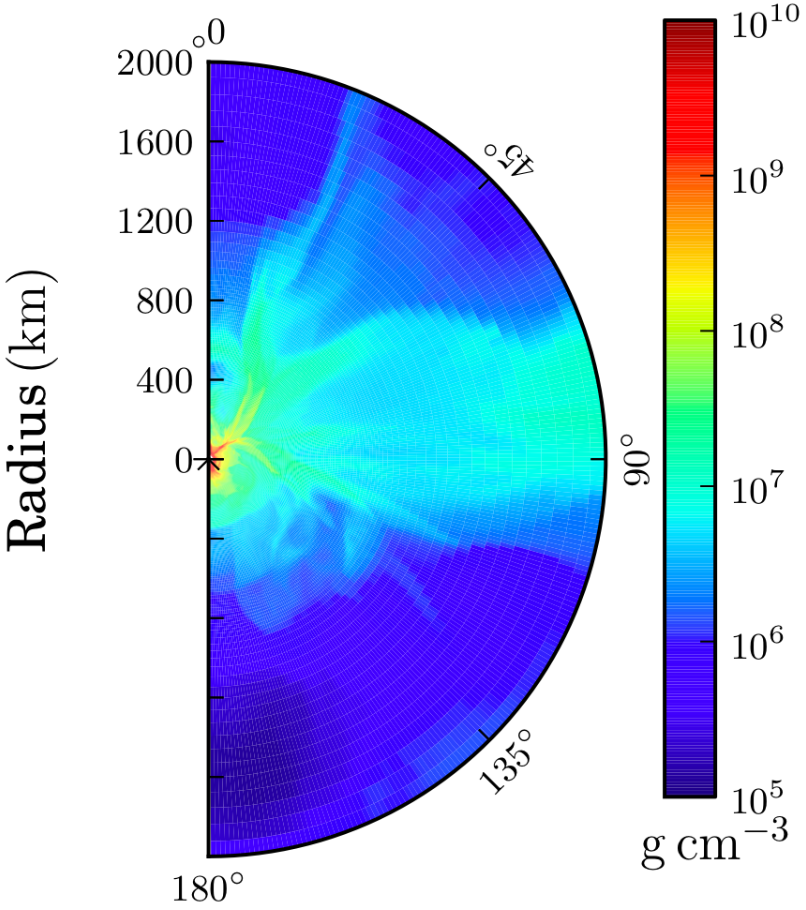


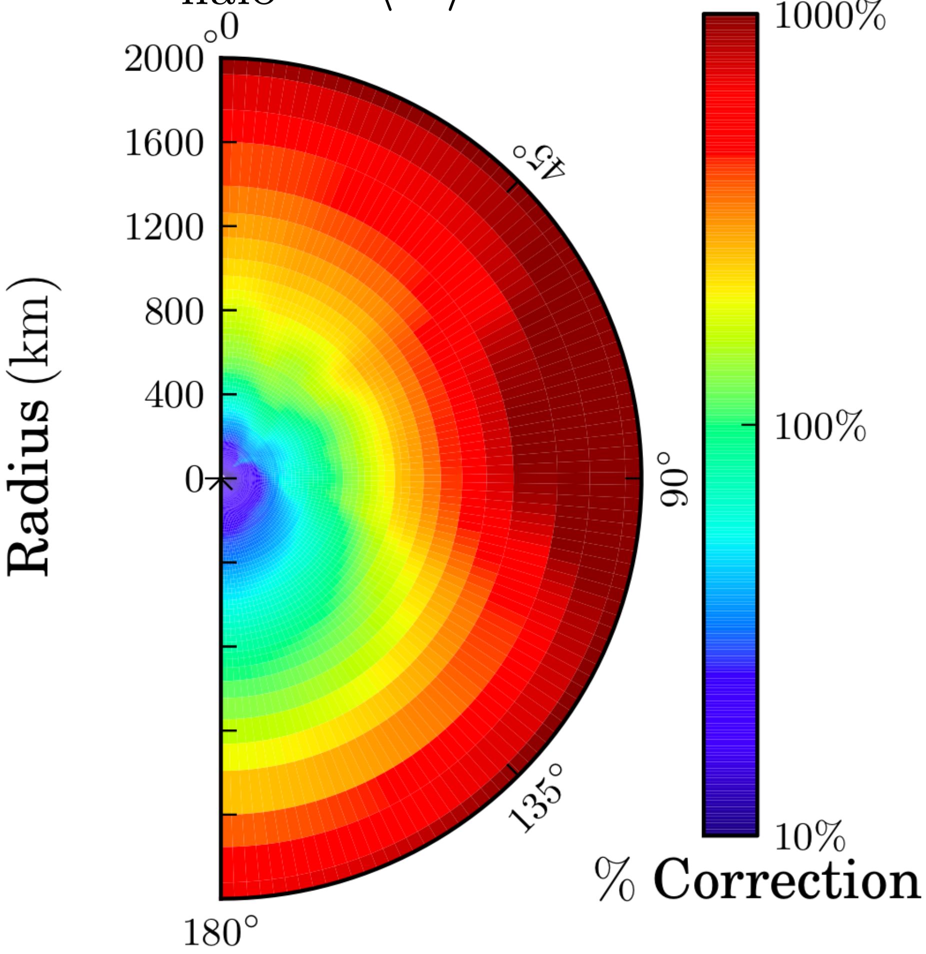
$$\langle 1 - \cos\theta_{\mathrm{ik}} \rangle \approx 1$$

$\sim 10^{-3}$ of all ν's

How large is the Halo effect for free nucleons?

$$\sigma_{\rm coherent} \propto A^2 \;\Rightarrow\; \mathcal{H}_{\rm halo} \propto \langle A \rangle$$

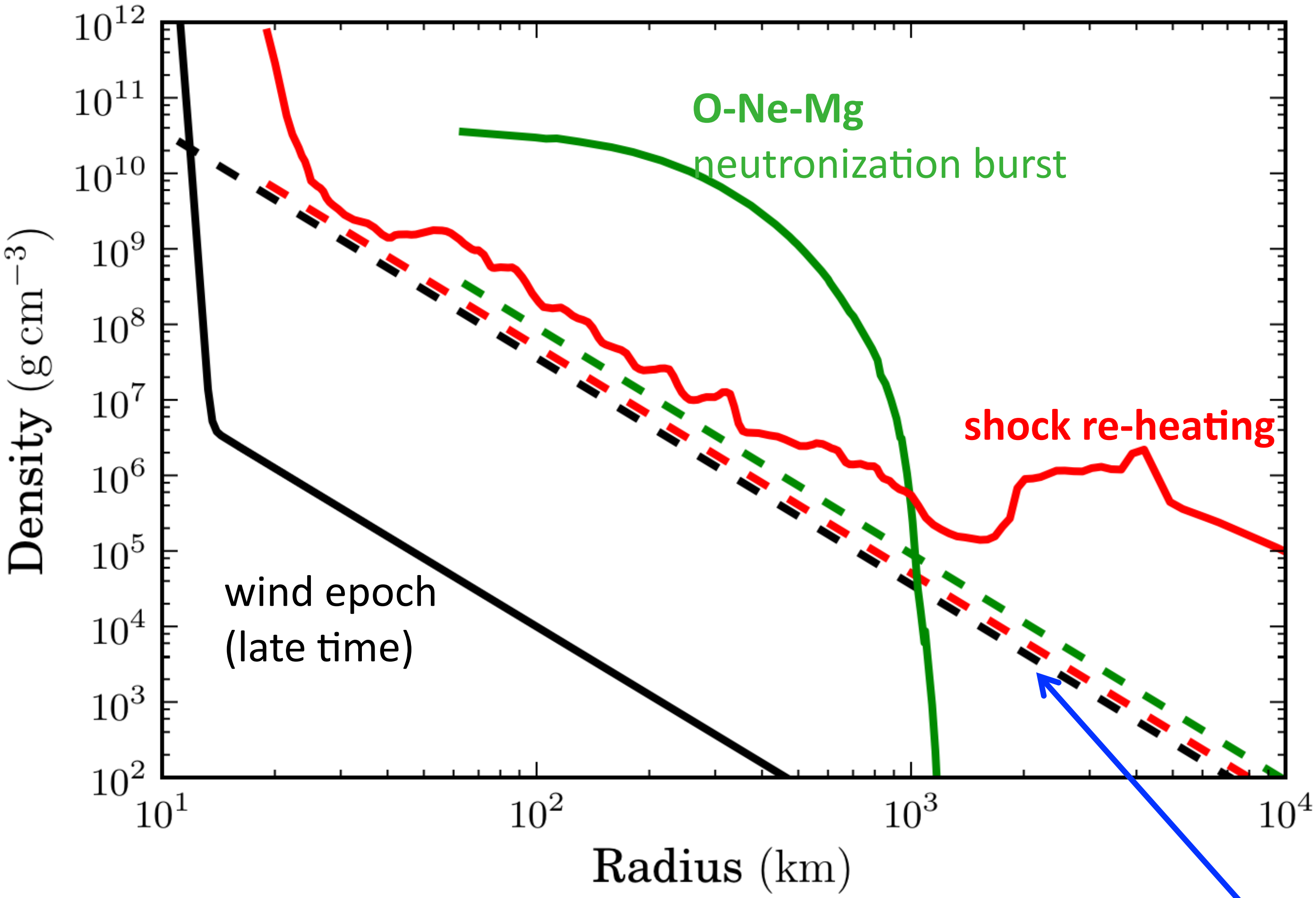




J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012), 1203.1607.

the Halo converts the
neutrino flavor evolution problem
from an *initial value problem* into
a *boundary value problem*
(quantum flavor information coming down from above**)**

and moreover couples in nuclear composition
in a completely new way



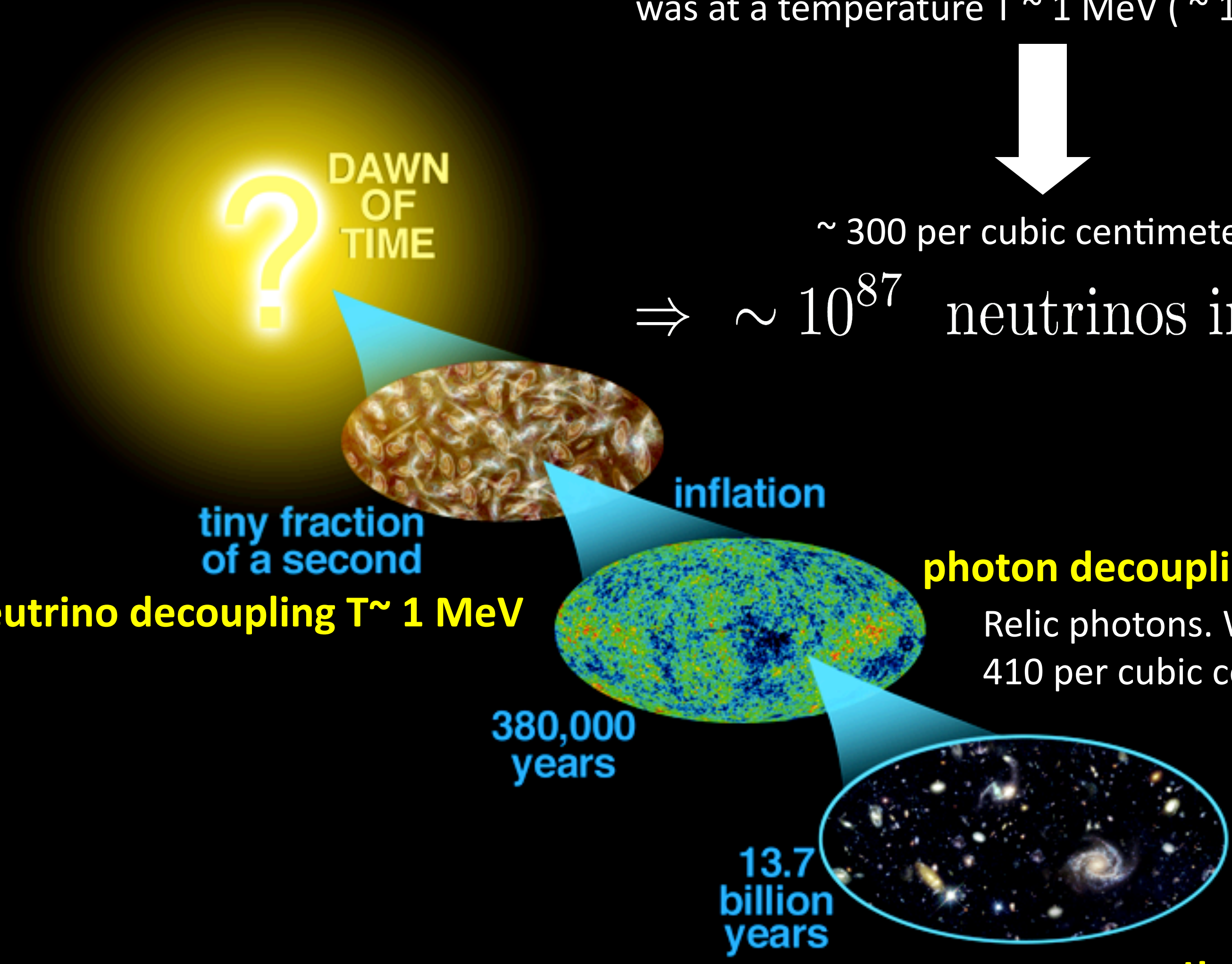
corresponding 1% “safety” criteria

Neutrino Rest Mass

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

~ 300 per cubic centimeter

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

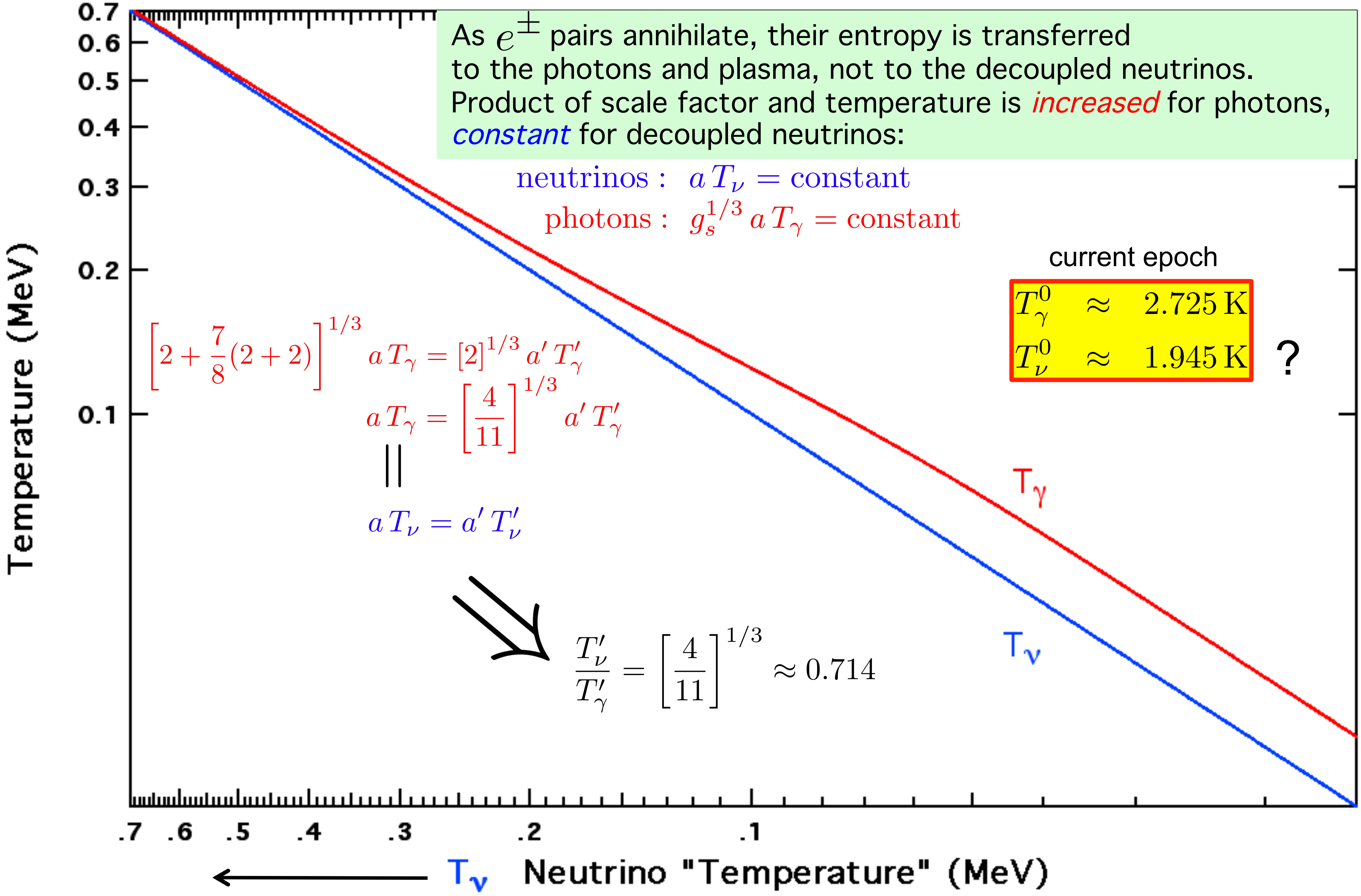


neutrino decoupling T~ 1 MeV

photon decoupling T~ 0. 2 eV

Relic photons. We measure 410 per cubic centimeter

vacuum+matter dominated at current epoch



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:

$$\text{neutrinos}: \quad a\,T_\nu = \text{constant}$$

$$\text{photons}: \quad g_s^{1/3}\,a\,T_\gamma = \text{constant}$$

current epoch

$$\boxed{\begin{aligned} T_\gamma^0 &\approx 2.725\,\mathrm{K} \\ T_\nu^0 &\approx 1.945\,\mathrm{K} \end{aligned}}$$?

$$\left[2+\frac{7}{8}(2+2)\right]^{1/3} a\,T_\gamma = [2]^{1/3}\,a'\,T'_\gamma$$

$$a\,T_\gamma = \left[\frac{4}{11}\right]^{1/3} a'\,T'_\gamma$$

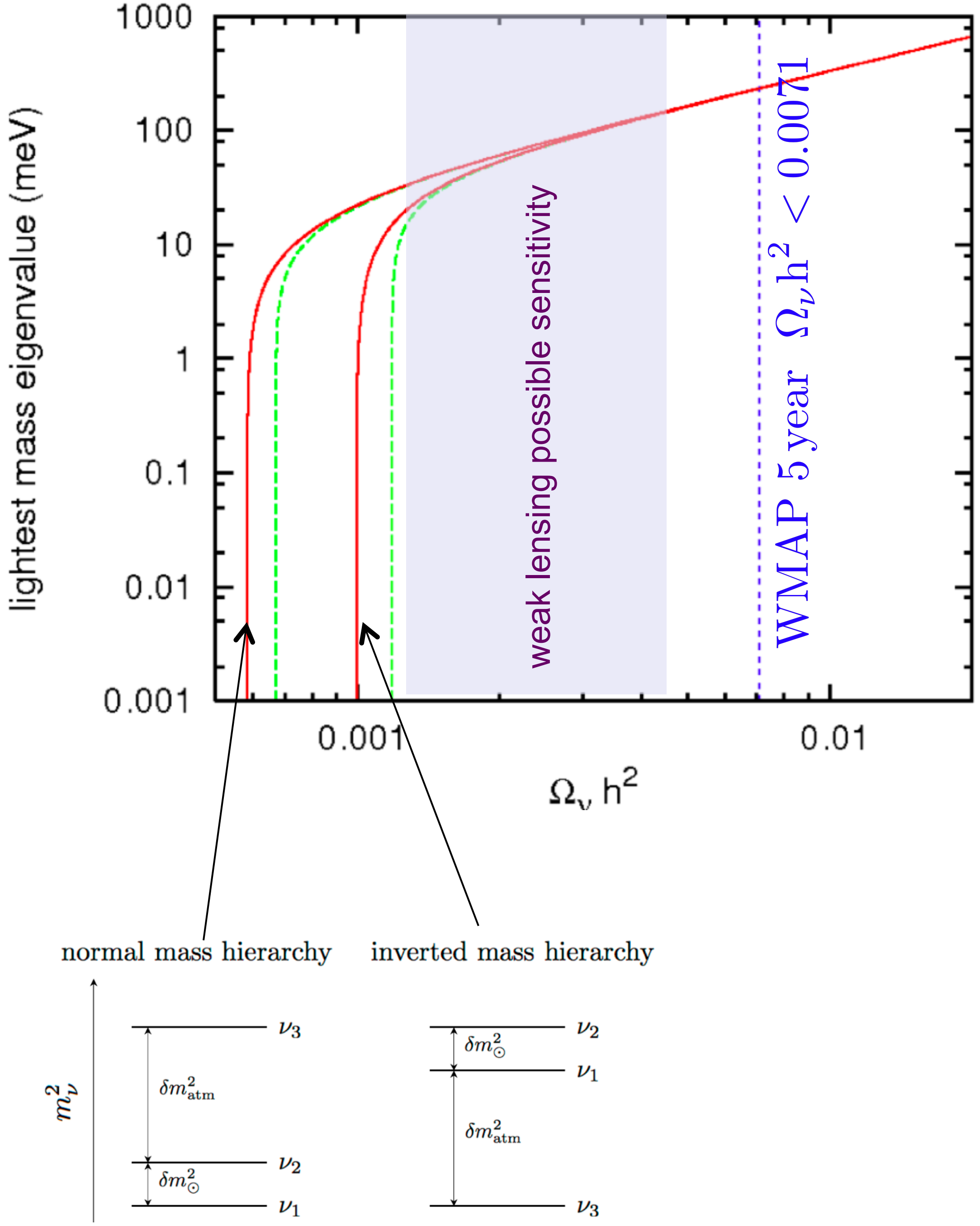
$$\|$$

$$a\,T_\nu = a'\,T'_\nu$$

$$\Rightarrow \quad \frac{T'_\nu}{T'_\gamma} = \left[\frac{4}{11}\right]^{1/3} \approx 0.714$$

← T_ν

scale factor $a \propto 1/T_\nu$ →



Next generation CMB experiments (*e.g.*, Planck; PolarBear) 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]

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], WF-MOS [11], HET-DEX [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

Radiation energy density (relativistic particle) at γ-decoupling
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)

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

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

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

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

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

Planck satellite will measure $\mathrm{N}_{\mathrm{eff}}$ to better than 10% precision

Sterile Neutrinos

Three "hints" for light sterile neutrinos?

mini-BooNE neutrino oscillation experiment at FNAL

$\nu_\mu \to \nu_s \to \nu_e$ appearance with $\delta m^2 \sim 1\,\mathrm{eV}^2$

(now 5σ above background)

neutrino reactor anomaly:

$\bar{\nu}_e$ deficit from $\bar{\nu}_e \to \bar{\nu}_s$ (???) – a disappearance experiment

Extra radiation at photon-decoupling (N_{eff}) ??

– Cosmic Microwave Background observations

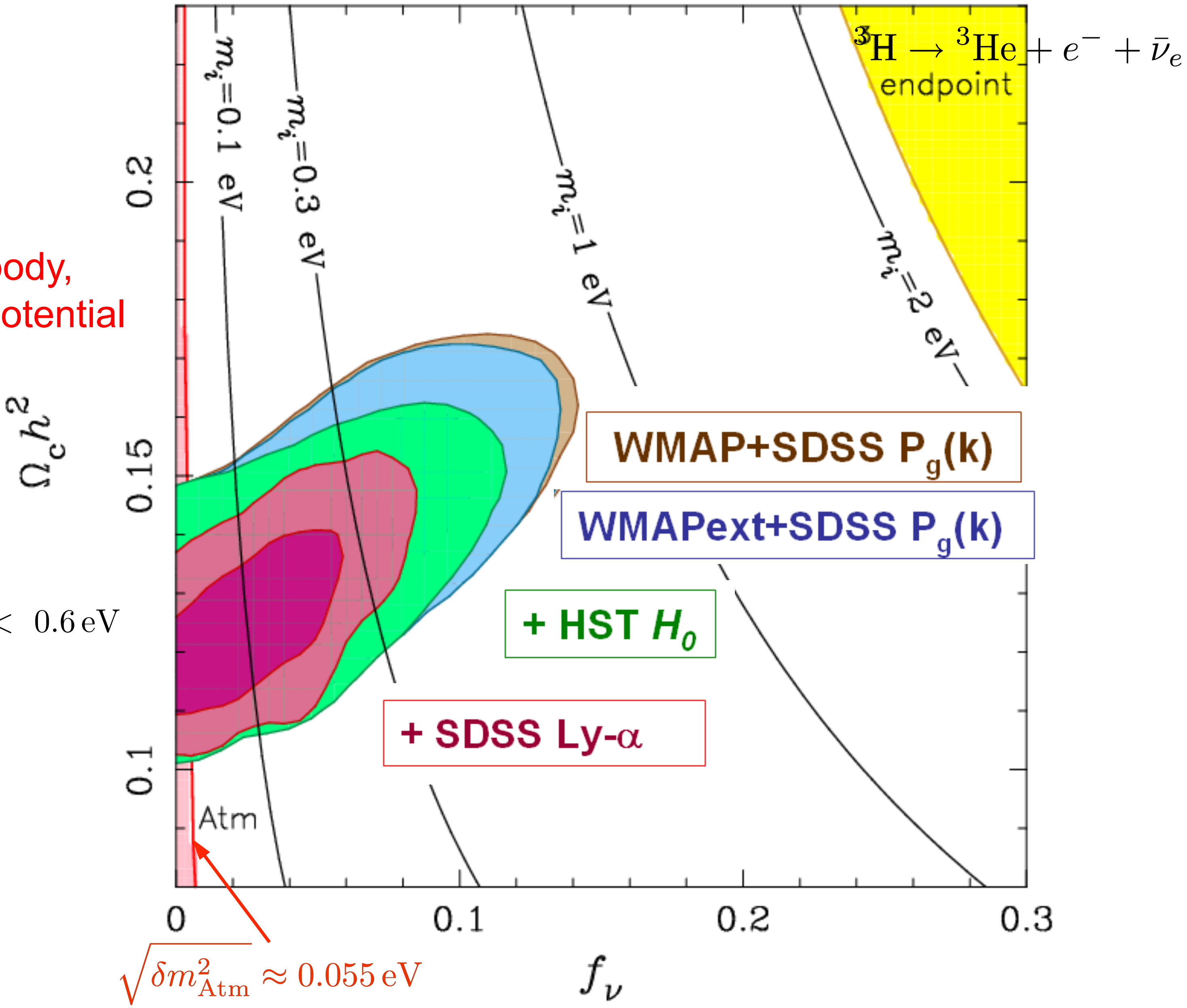
(*e.g.,* PolarBear ; ACT; Planck; *eventually* CMBPol)

cosmological constraints on neutrino rest mass

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

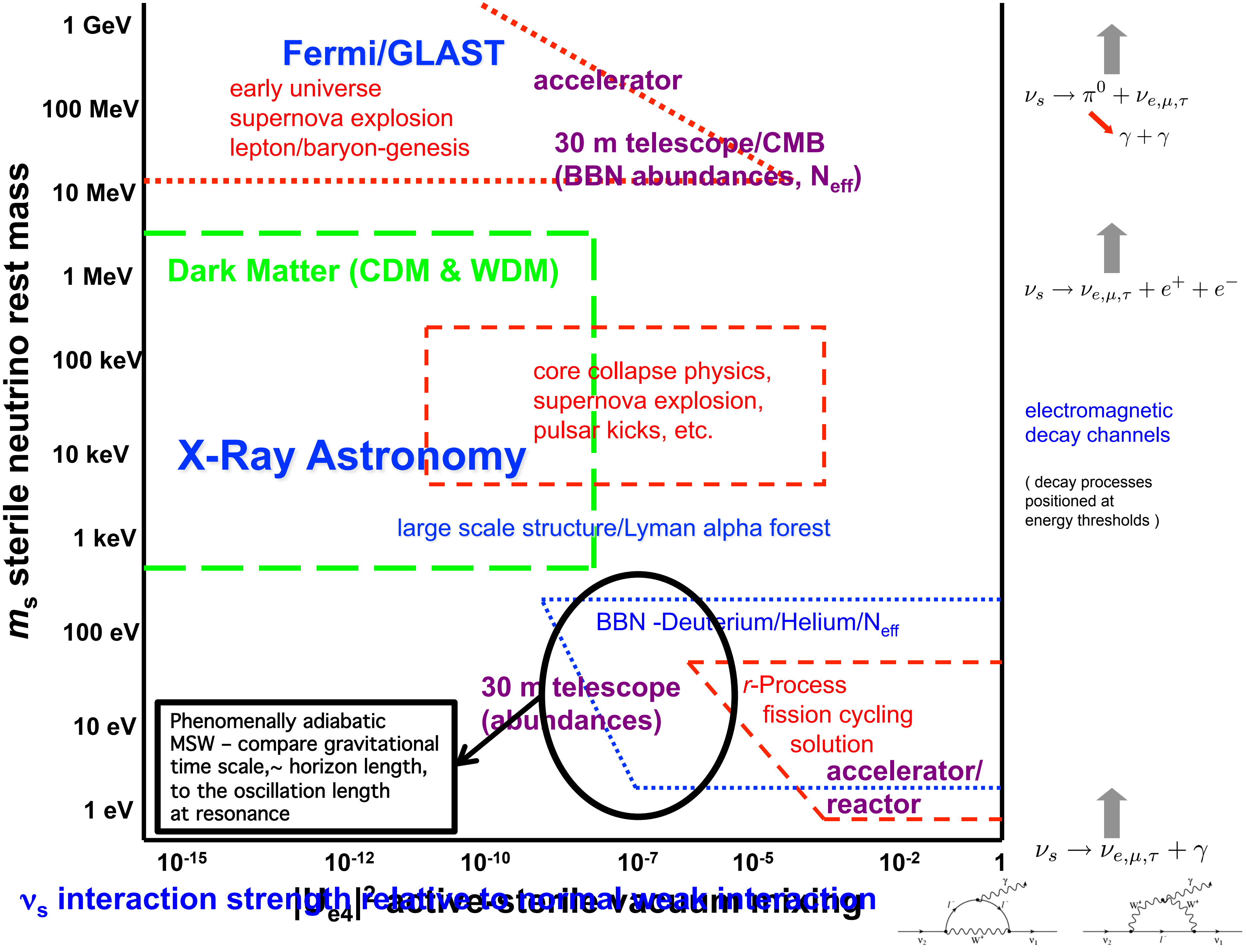
assumes that neutrinos have thermal, black body, zero chemical potential energy spectra

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



$\sqrt{\delta m^2_{\mathrm{Atm}}} \approx 0.055\,\mathrm{eV}$

K. Abazajian



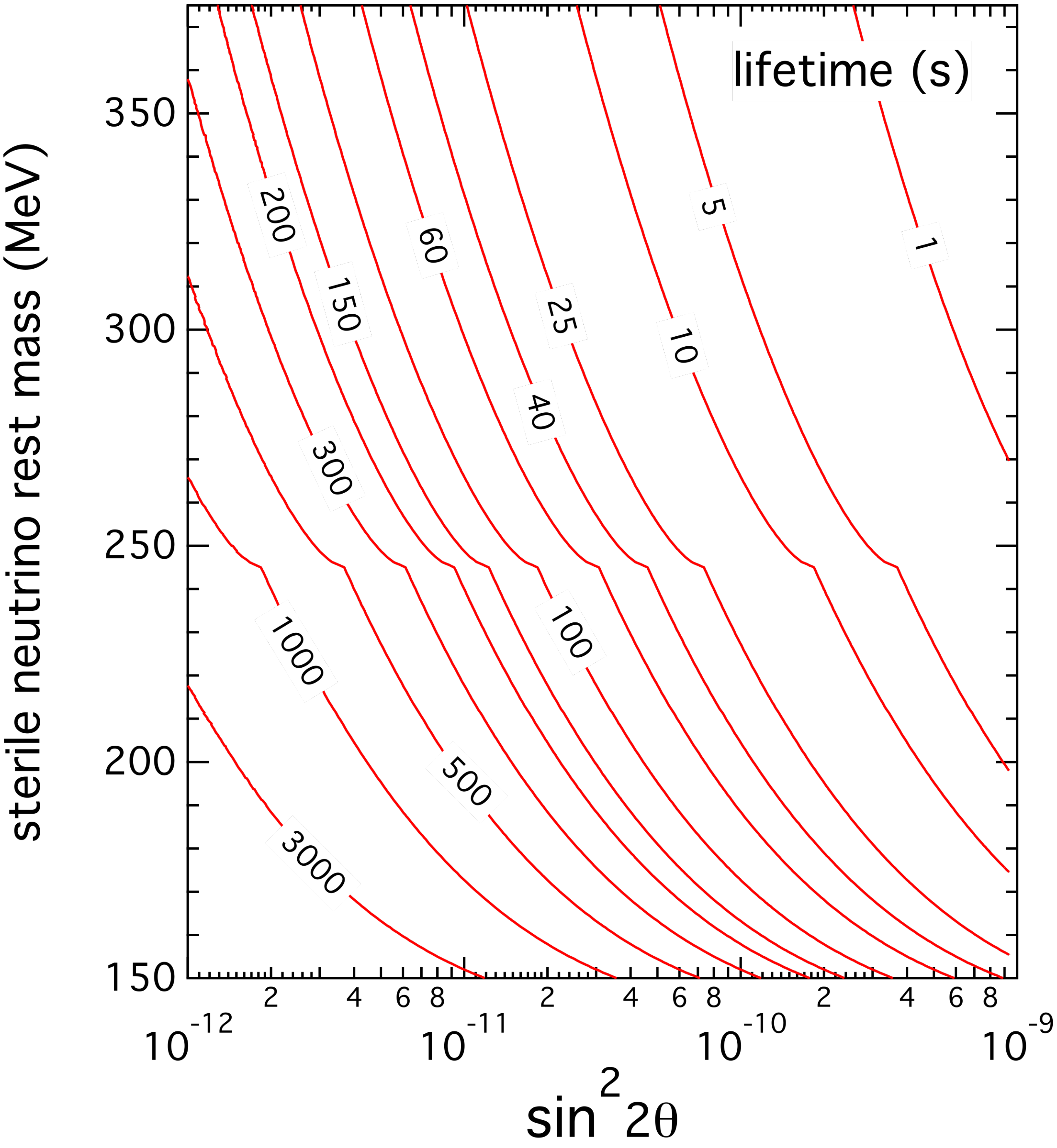
Phenomenally adiabatic MSW – compare gravitational time scale,~ horizon length, to the oscillation length at resonance

(decay processes positioned at energy thresholds)

Consider as an example:

sterile neutrinos with rest masses ~ 1 GeV
and lifetimes ~ seconds

particle decay-induced "dilution" in the early universe


lifetime (s)
sterile neutrino rest mass (MeV)
350
300
250
200
150
sin²2θ
10^-12
10^-11
10^-10
10^-9
2
4
6
8
3000
1000
500
300
200
150
100
60
40
25
10
5
1

Heavy sterile neutrinos with sufficiently large coupling will be in thermal equilibrium at temperatures T >> 1 GeV

This means that their number densities will be **comparable to those of photons** at the BBN epoch, albeit somewhat diluted by loss of degrees of freedom at the QCD epoch.

Nevertheless, their energy spectra will be a "*relativistic Fermi Dirac black body*" just like the decoupled active neutrinos but with a lower "*temperature*"

number density
prior to decay

$$n_{\nu_s} = \frac{3}{4}\frac{\zeta(3)}{\pi^2} T_{\nu_s}^3$$

photon number density

$$n_\gamma = 2\frac{\zeta(3)}{\pi^2} T_\gamma^3$$

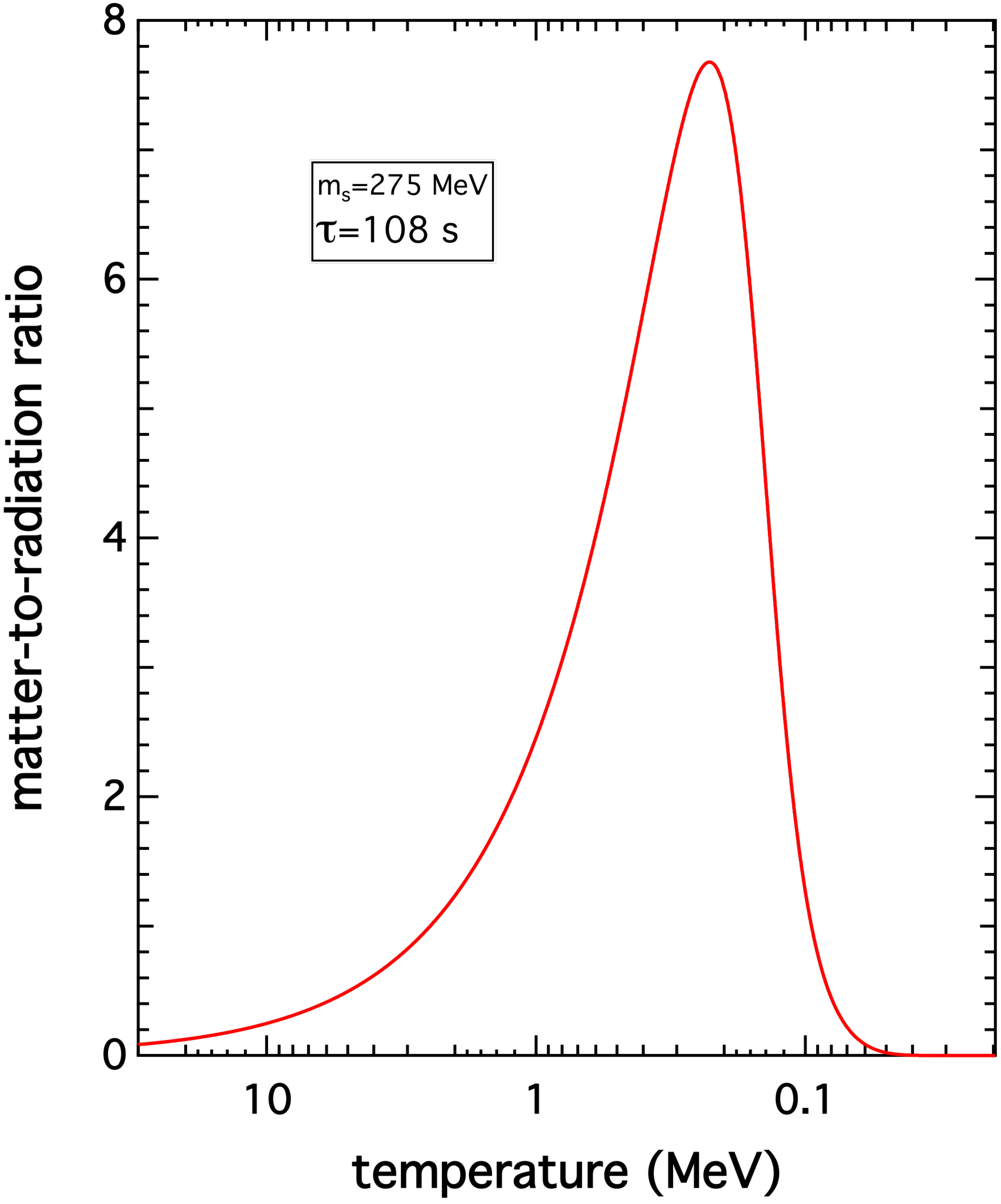
$$T_{\nu_s} \approx T_\gamma / 1.79$$

Fuller, Kishimoto, Kusenko 2011

$\zeta(3) \approx 1.20206$

$$n_{\nu_s} \sim 0.1 \; n_\gamma$$

but the steriles have rest masses ~ GeV   OOPS!



sterile neutrino rest mass density comes to *dominate* over radiation energy density, producing a *matter-dominated* epoch lasting *many* Hubble-times

Decay into 7
possible channels

No threshold:

$$\nu_s \rightarrow 3\nu$$
$$\nu_s \rightarrow \nu + \gamma$$

Non-zero threshold:

$$\nu_s \rightarrow \nu + e^- + e^+$$
$$\nu_s \rightarrow \nu + \mu^- + \mu^+$$
$$\nu_s \rightarrow \nu + \pi^0$$
$$\nu_s \rightarrow \pi^{\pm} + e^{\mp}$$
$$\nu_s \rightarrow \pi^{\pm} + \mu^{\mp}$$

Pions and Muons decay
instantaneously:

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

heavy “sterile” neutrino decay

$$\nu_s \to \pi^0 + \nu_{e,\mu,\tau} \to 2\gamma + \nu_{e,\mu,\tau}$$

$$\begin{tikzcd}[column sep=small]
\nu_s \arrow[r] & \pi^+ + e^- \arrow[d] \arrow[r] & 2\gamma + 3\nu \\
& \mu^+ + \nu_\mu \arrow[d] & \\
& e^+ + \bar{\nu}_\mu + \nu_e &
\end{tikzcd}$$

$$\nu_s \to \pi^+ + \mu^- \quad \to 2\gamma + 5\nu$$

Photons thermalize,
but neutrinos may or may not, depending on their energies and the decay epoch

entropy generation from heavy particle nonequilibrium decay

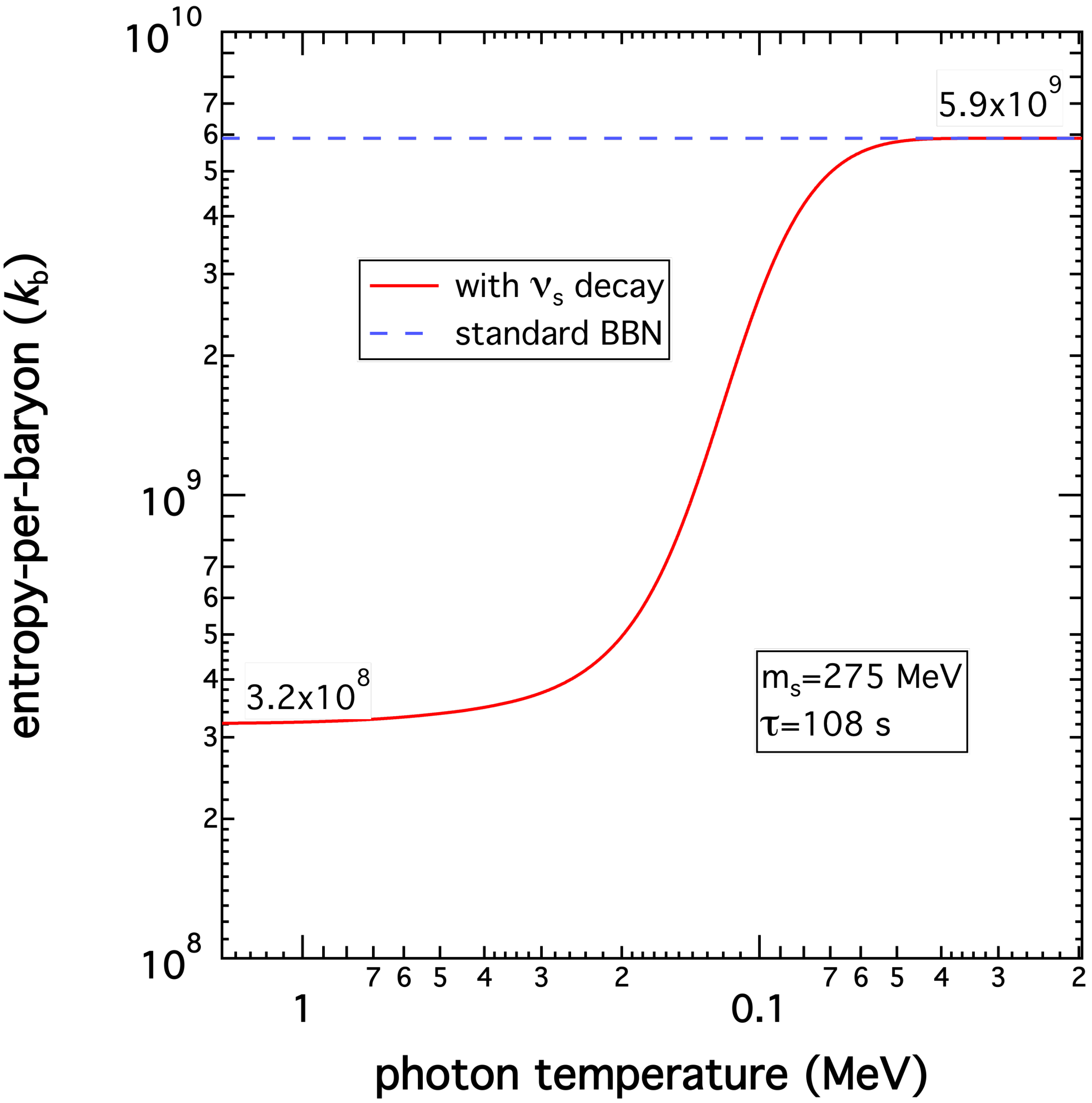
$$\Delta S = \frac{\Delta Q}{T}$$

where the added heat comes from the rest mass of the decaying particle converted into particles which (partially) thermalize

$$\Delta Q = m_s \cdot f$$

Here the fraction of decay product energy which thermalizes is f

m_s is the rest mass of the decaying particle



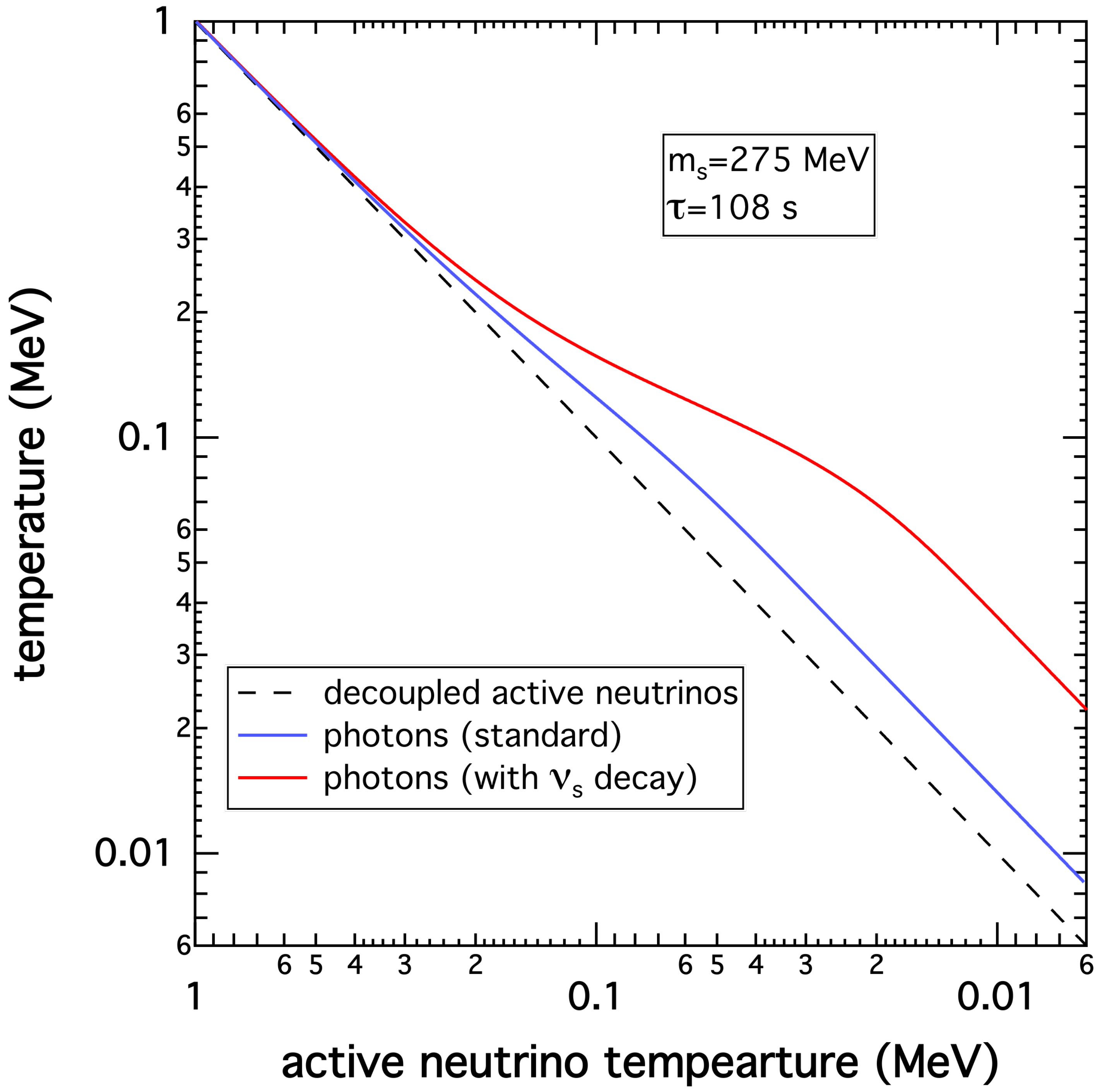
prodigious entropy production!

in this case:

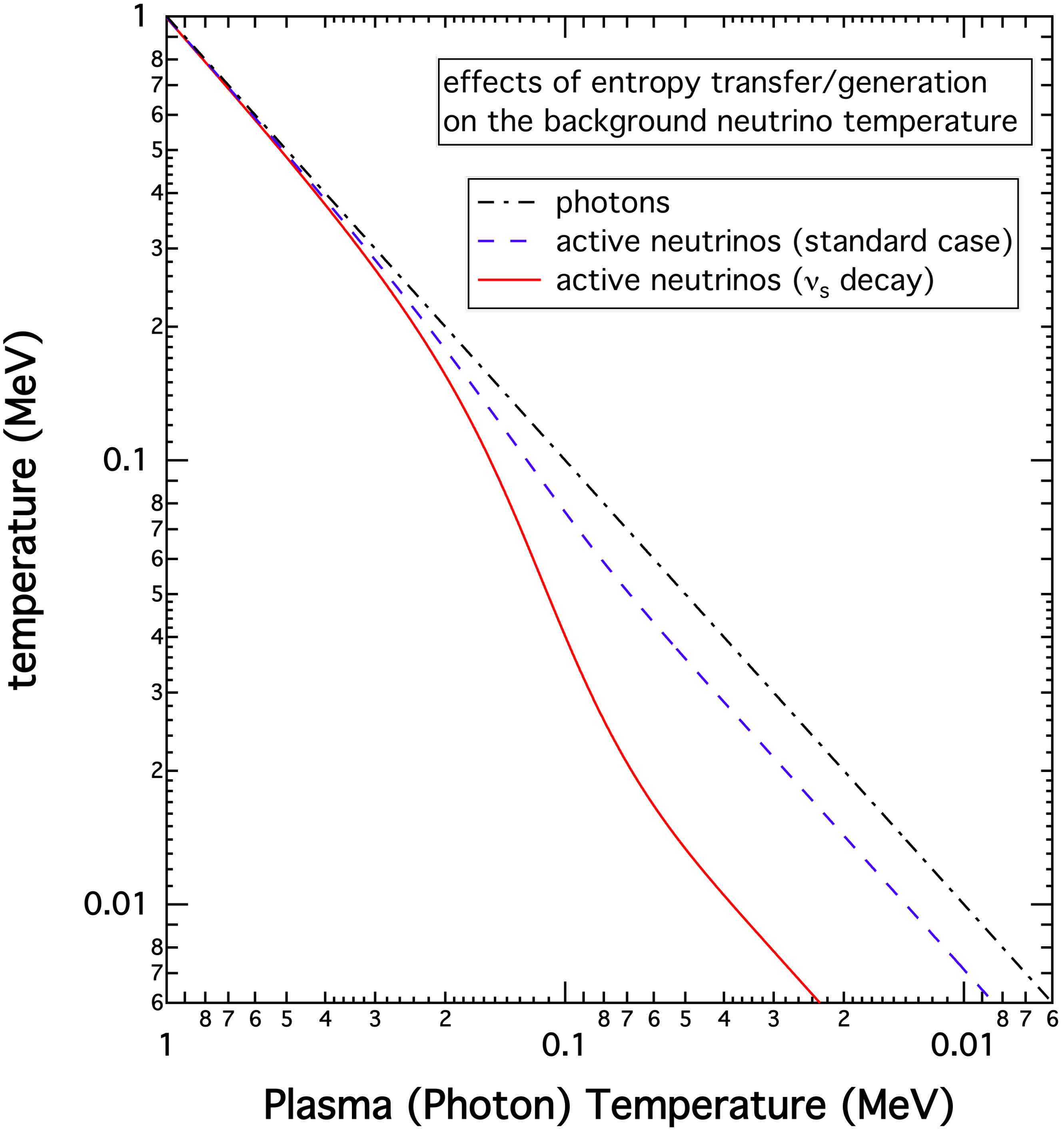
$$F = \frac{s_{\rm final}}{s_{\rm initial}} \approx 18.4$$

where entropy-per-baryon is carried by radiation

$$s = \frac{\left[\frac{2\pi^2}{45}\, g\, T^3\right]}{n_{\rm b}}$$



1
6
5
4
3
2
0.1
6
5
4
3
2
0.01
6
temperature (MeV)
m_s=275 MeV
τ=108 s
decoupled active neutrinos
photons (standard)
photons (with ν_s decay)
1
6 5 4 3 2
0.1
6 5 4 3 2
0.01
6
active neutrino tempearture (MeV)


effects of entropy transfer/generation
on the background neutrino temperature
photons
active neutrinos (standard case)
active neutrinos (ν_s decay)
temperature (MeV)
1
8
7
6
5
4
3
2
0.1
8
7
6
5
4
3
2
0.01
8
7
6
1
8 7 6 5 4 3 2
0.1
8 7 6 5 4 3 2
0.01
8 7 6
Plasma (Photon) Temperature (MeV)

This entropy generation results in “dilution” of the *thermal background neutrinos*

$$F \equiv \frac{s_{\rm final}}{s_{\rm initial}}$$

$$\Rightarrow \qquad \frac{T\,a}{T_0\,a_0} = \left(\frac{g_0}{g}\right)^{1/3} F^{1/3} \quad = \left(\frac{11}{4}\right)^{1/3} F^{1/3}$$

$$T_\nu \; a = T_{\nu 0} \; a_0 \qquad \Rightarrow \qquad \frac{T_\nu}{T} = \left(\frac{4}{11}\right)^{1/3} F^{-1/3}$$

$$\Rightarrow \qquad \frac{T_\nu^{\rm SBBN}}{T} = \left(\frac{4}{11}\right)^{1/3} \qquad \text{and} \qquad \frac{T_\nu}{T_\nu^{\rm SBBN}} = F^{-1/3}$$

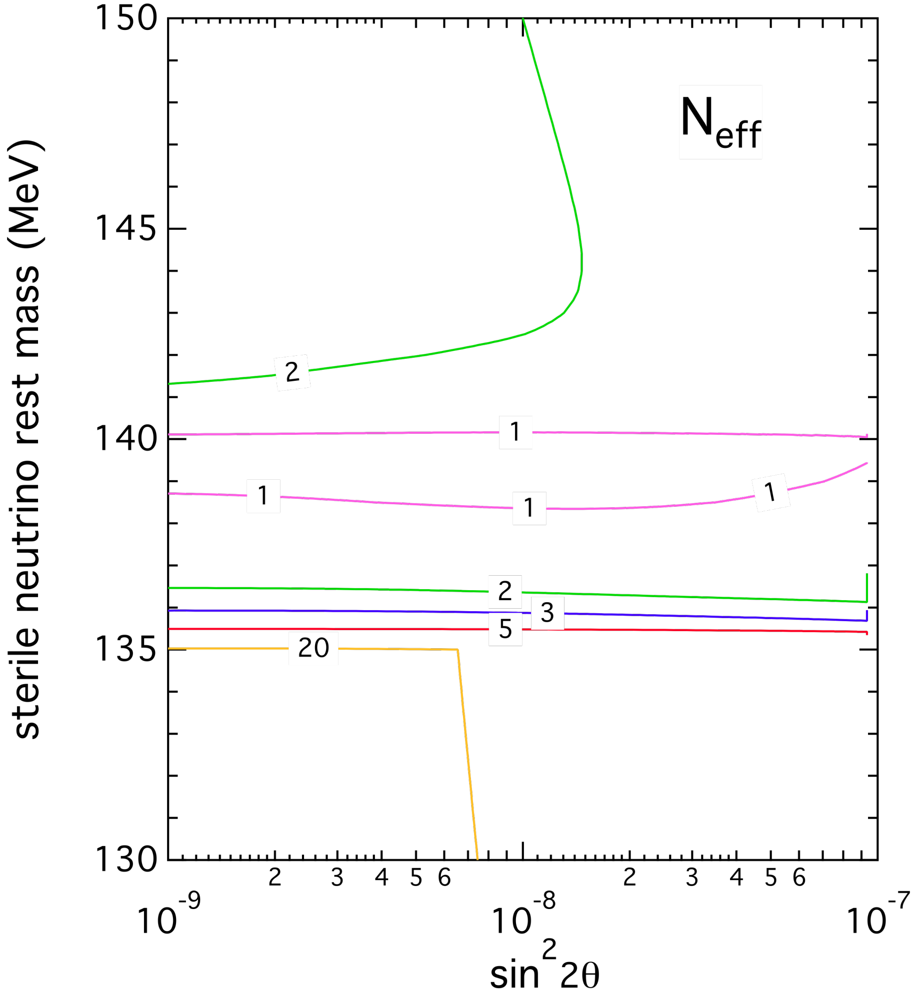
$$\text{contribution to N}_{\rm eff}\text{ reduced by} \quad \frac{T_\nu^4}{(T_\nu^{\rm SBBN})^4} = F^{-4/3}$$

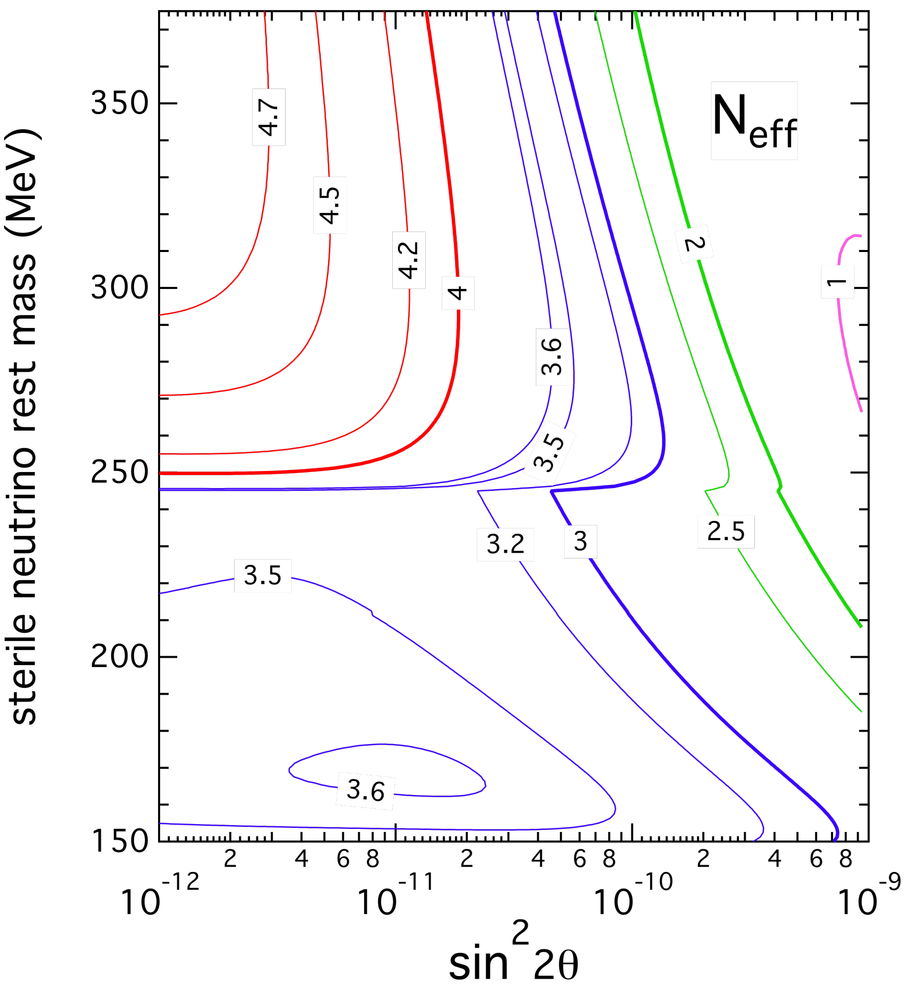
for the above example with F=20 the regular thermal background neutrinos give $N_{\rm eff}$ = 0.055

G.M.F., C. Kishimoto, A. Kusenko arXiv:1110.6479 astro-ph.CO

heavy sterile neutrino decay causes dilution of ordinary background neutrinos and generation of radiation energy density (N_{eff})

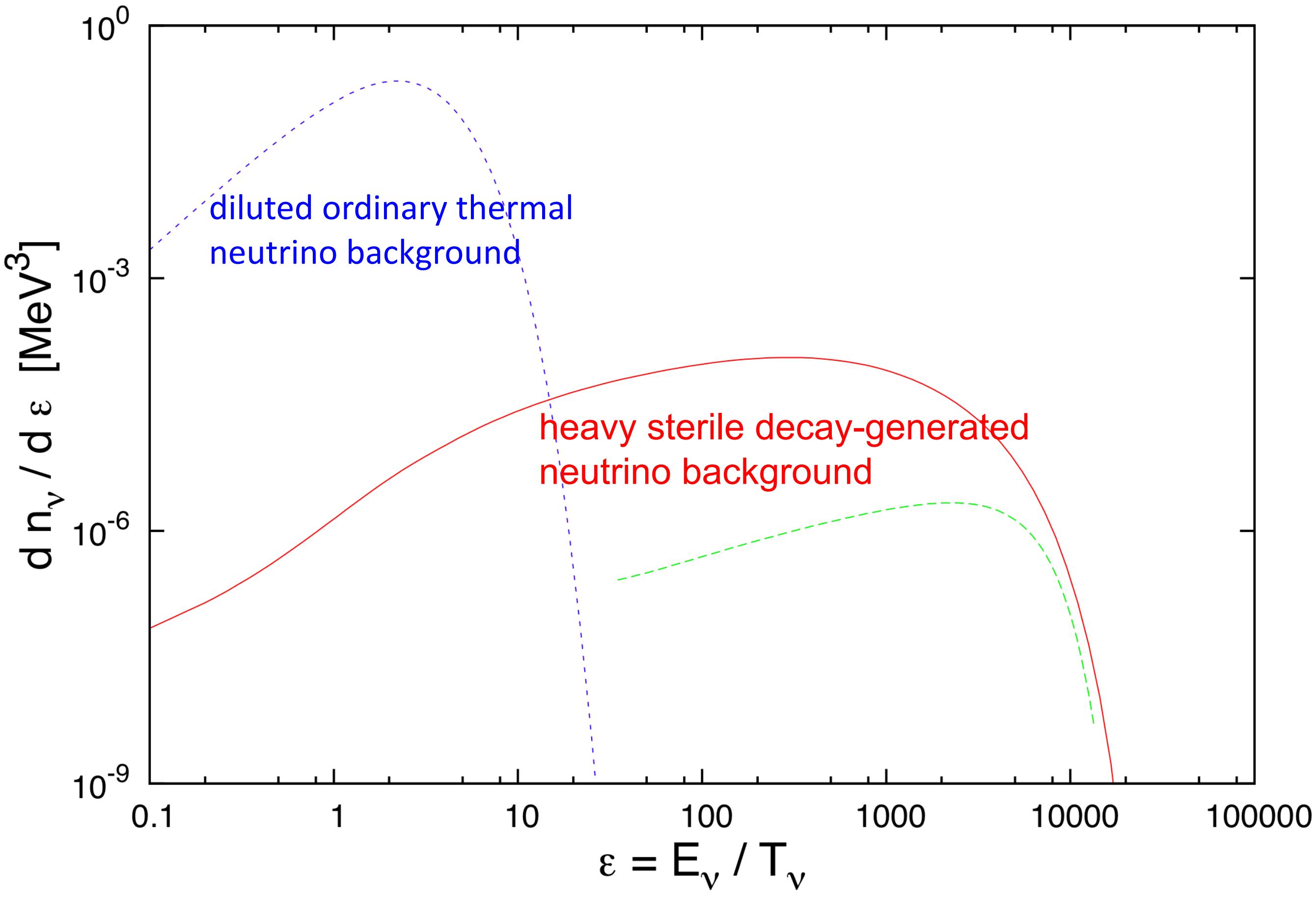
$$\nu_s \rightarrow \underbrace{(\gamma' s)}_{\text{dilution/entropy-generation}} + \underbrace{(\text{decoupled neutrinos})}_{N_{\text{eff}}}$$





heavy sterile decay *dilutes* the “normal” thermal neutrino background,
and leaves a decay-generated neutrino background 1000x as energetic
which *never* becomes nonrelativistic

will not detect neutrino rest mass cosmologically,
even when detection thresholds are below known masses!



Fuller, Kishimoto, Kusenko arXiv:1110.6479 astro-ph.CO

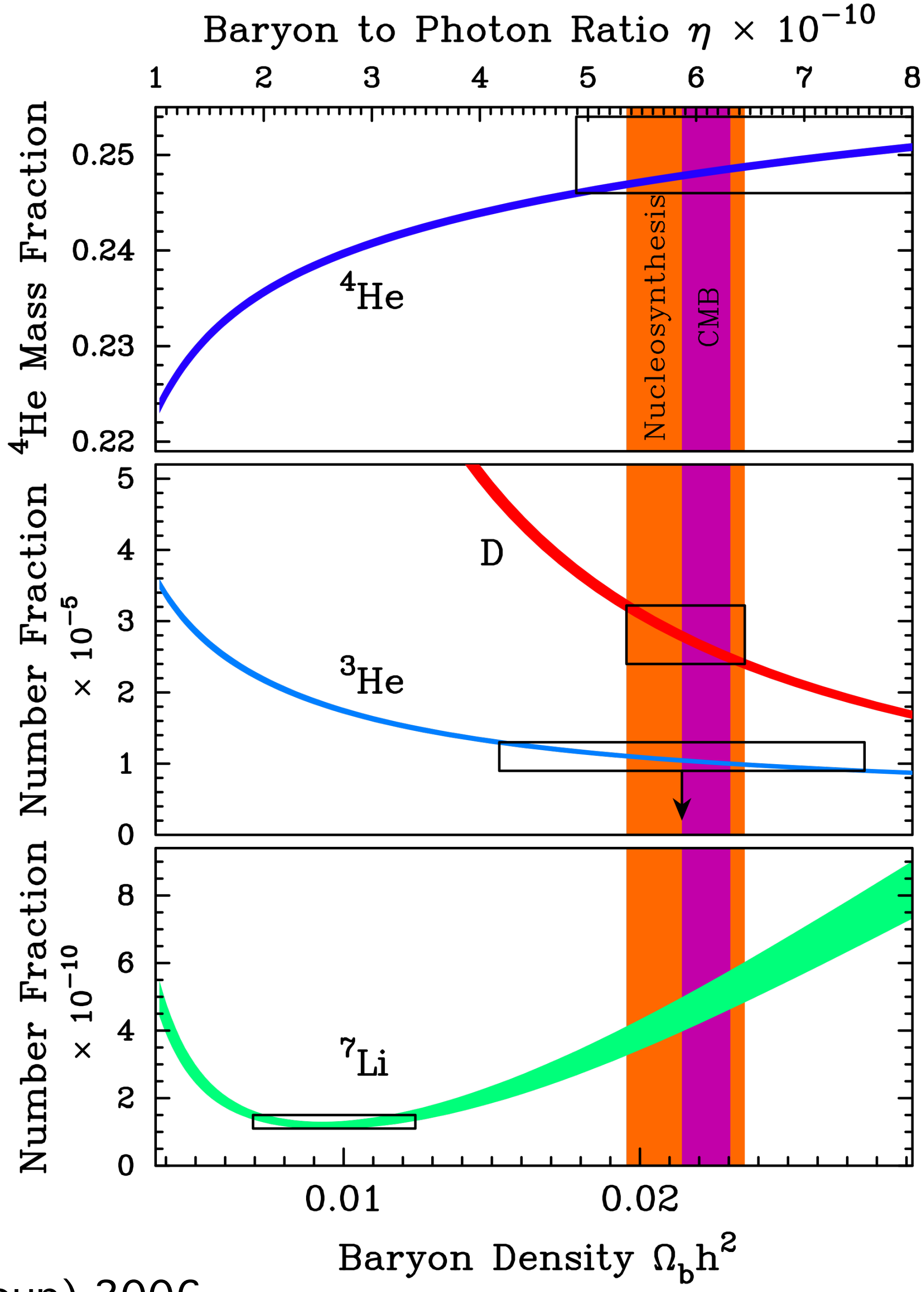
Altered BBN

Must *self-consistently* couple all
strong, electromagnetic, and weak nuclear reactions
with the decaying heavy sterile neutrinos and their
energetic active neutrino decay products – GMF, E. Grohs, C. Kishimoto 2012

High energy (~ 100 MeV) decay active neutrinos

-these can capture on protons and *make neutrons*
(after alpha particle formation = no free neutron targets!)

Standard BBN



Nao Suzuki (Tytler group) 2006

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

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

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

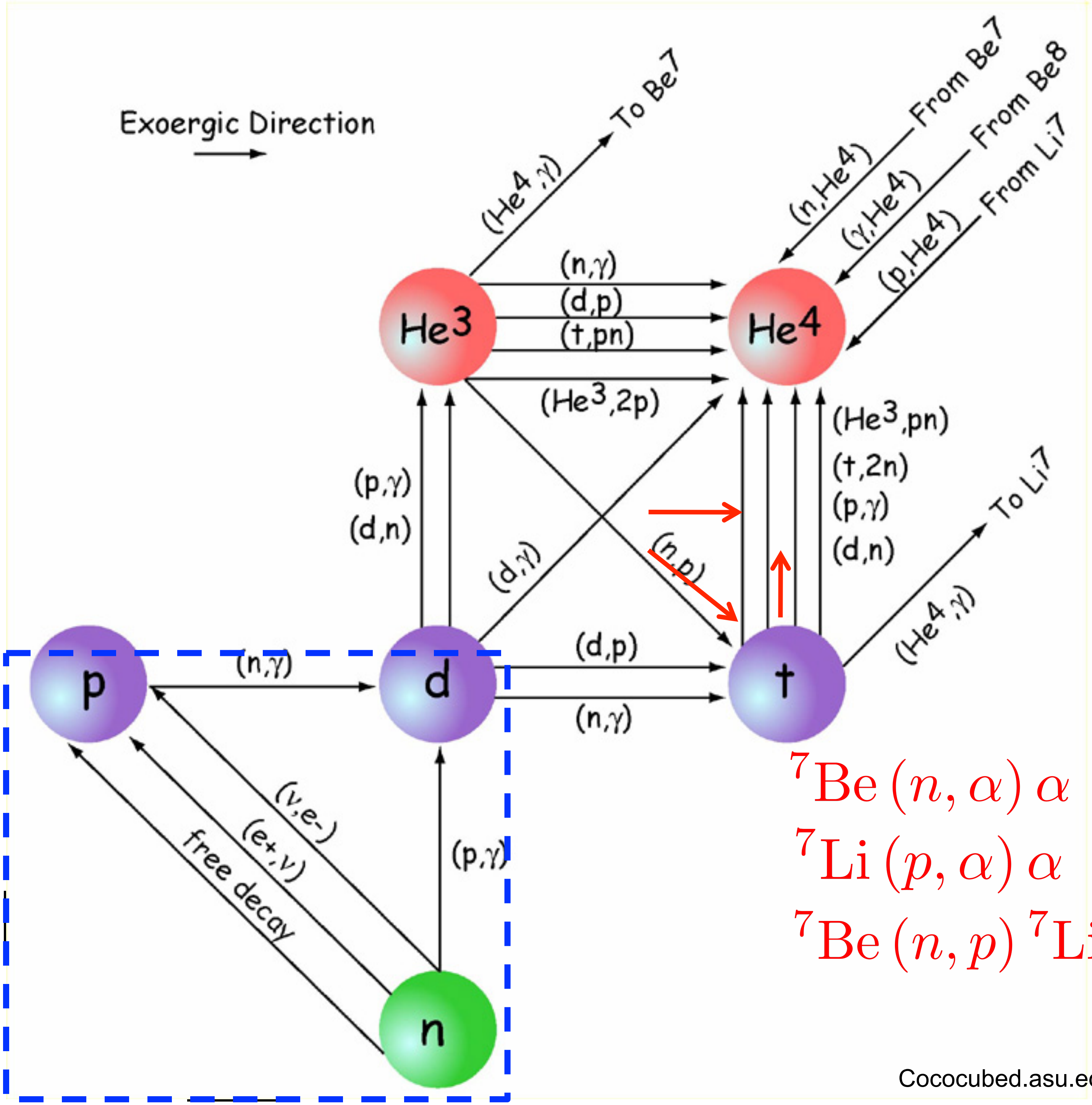
$\mathrm{with\ Planck,\ CMBPol,\ could\ be} \quad \pm 0.004$

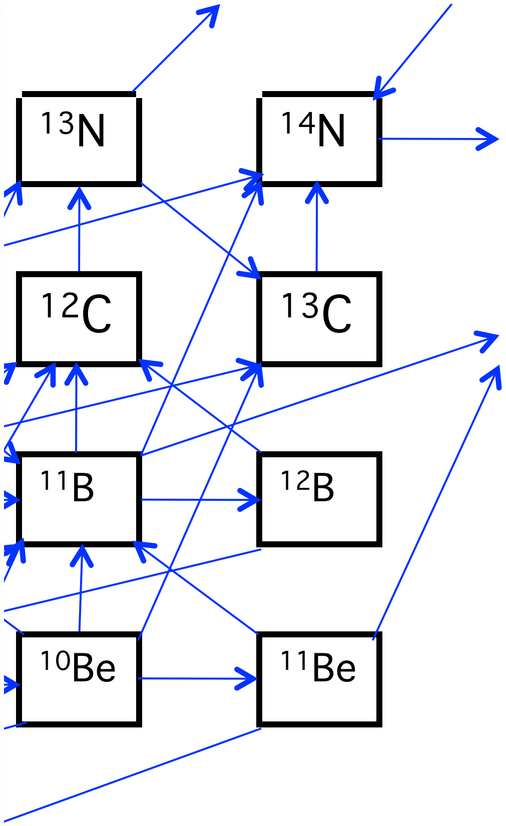
very tricky

(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





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

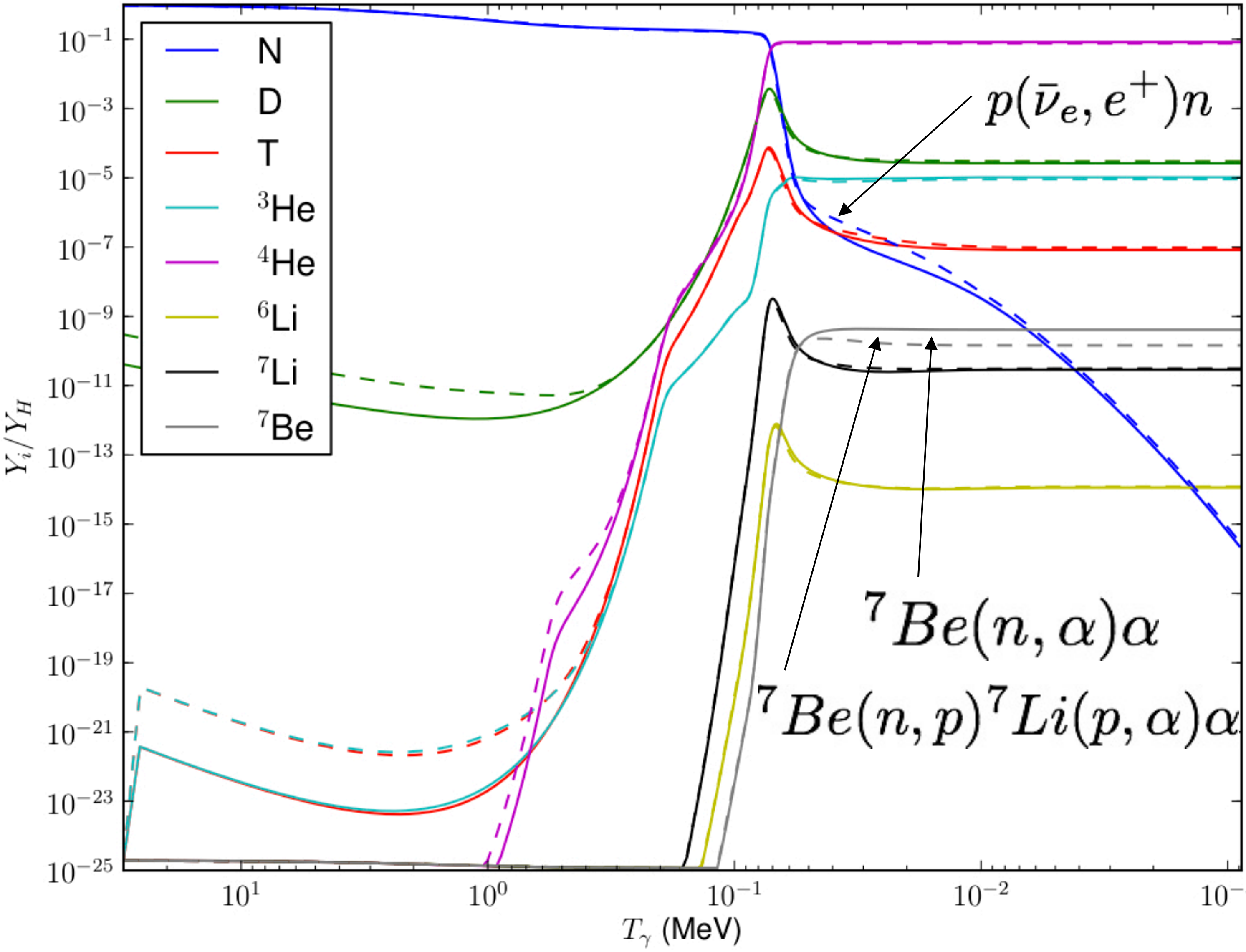
$^{7}\mathrm{Li}\,(p,\alpha)\,\alpha$

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

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

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

Solid Lines: SBBN   Dashed Lines: (m_s,τ_s)=(300 MeV, 4.0 s)



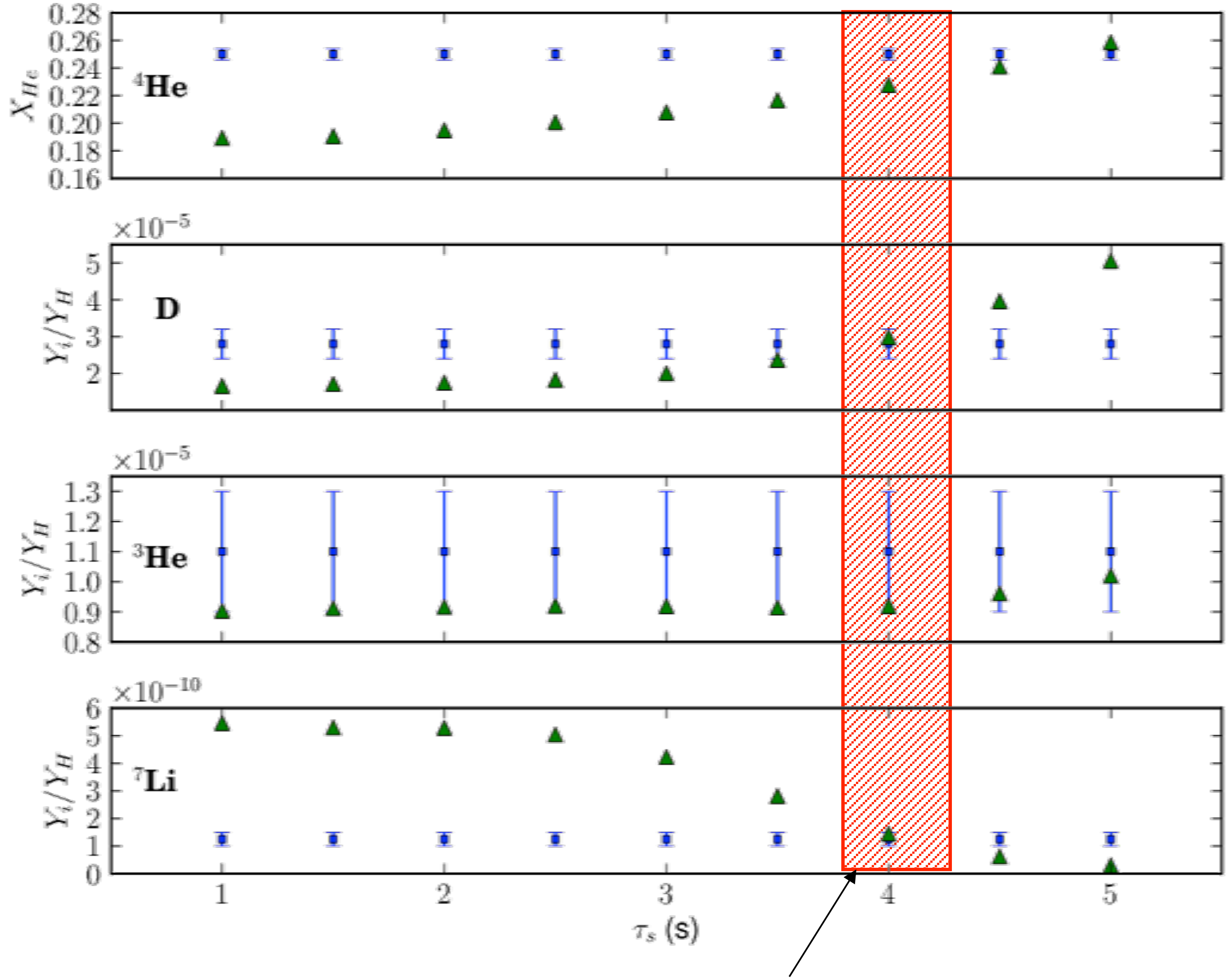
$p(\bar{\nu}_e, e^+)n$

$^7Be(n,\alpha)\alpha$

$^7Be(n,p)^7Li(p,\alpha)\alpha$

$N_{eff} \sim 2.5$

Abundance/Mass Fraction vs. Sterile Lifetime (m_s=300 MeV)



Sweet Spot?

Conclusions

SBBN successfully predicts D abundance, but
has problems with Li and maybe (possibly) N_{eff}

Sterile Neutrino mass/lifetime can be tuned to
preserve primordial abundances
with the exception of Li (Be) and can change N_{eff}

Boltzmann neutrino transport code needed to determine
if sweet-spot solution for Li problem is consistent with
forthcoming constraints on N_{eff}