The CMB, New Neutrino Physics, and Primordial Nucleosynthesis: A Perfect Storm

47th ESLAB Symposium

The Universe as seen by Planck

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VERY EXCITING FUTURE . . .

. . . because of the advent of . . .

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

(2) 10/30-meter class telescopes, 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!

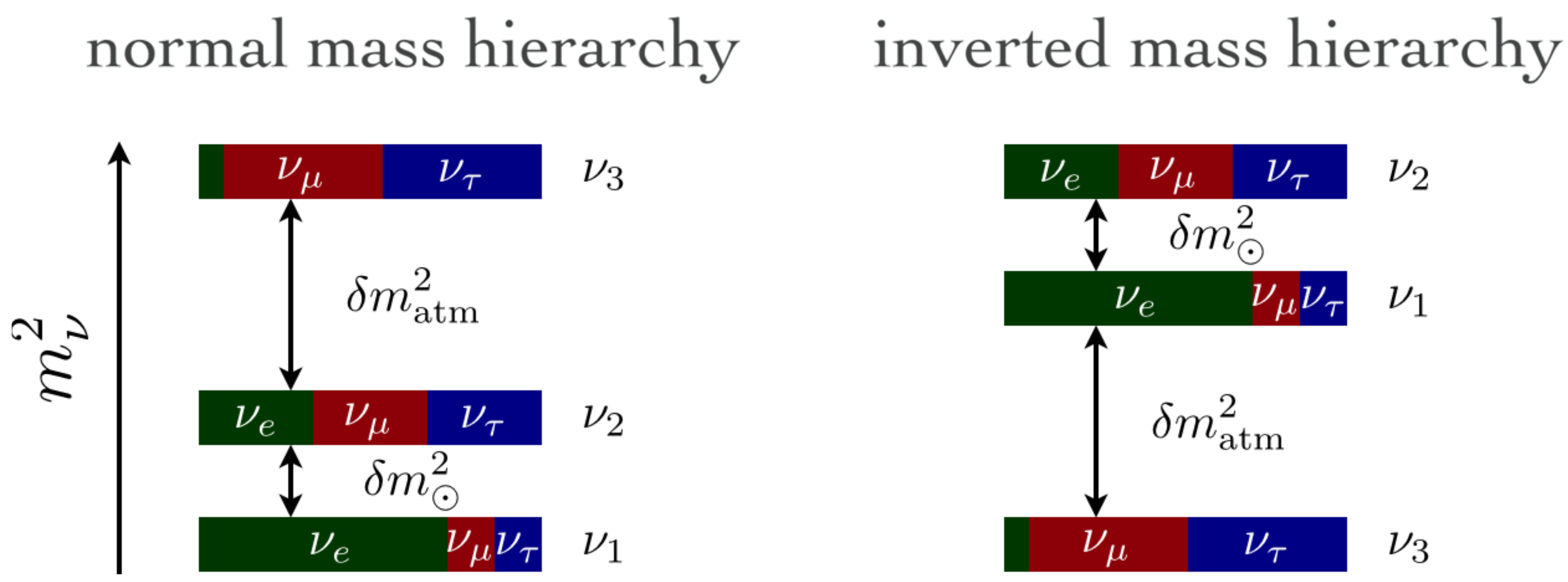
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

$$e.g.,\quad \delta m^2_{21} \equiv m^2_2 - m^2_1$$

$$\begin{cases} \delta m^2_\odot \approx 7.6 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m^2_{\mathrm{atm}} \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

We *do not* know the *absolute masses* or the *mass hierarchy*:



$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

P-Maki-Nakagawa-Sakata matrix

$$U_m = U_{23}\, U_{13}\, U_{12}\, M$$

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4 parameters

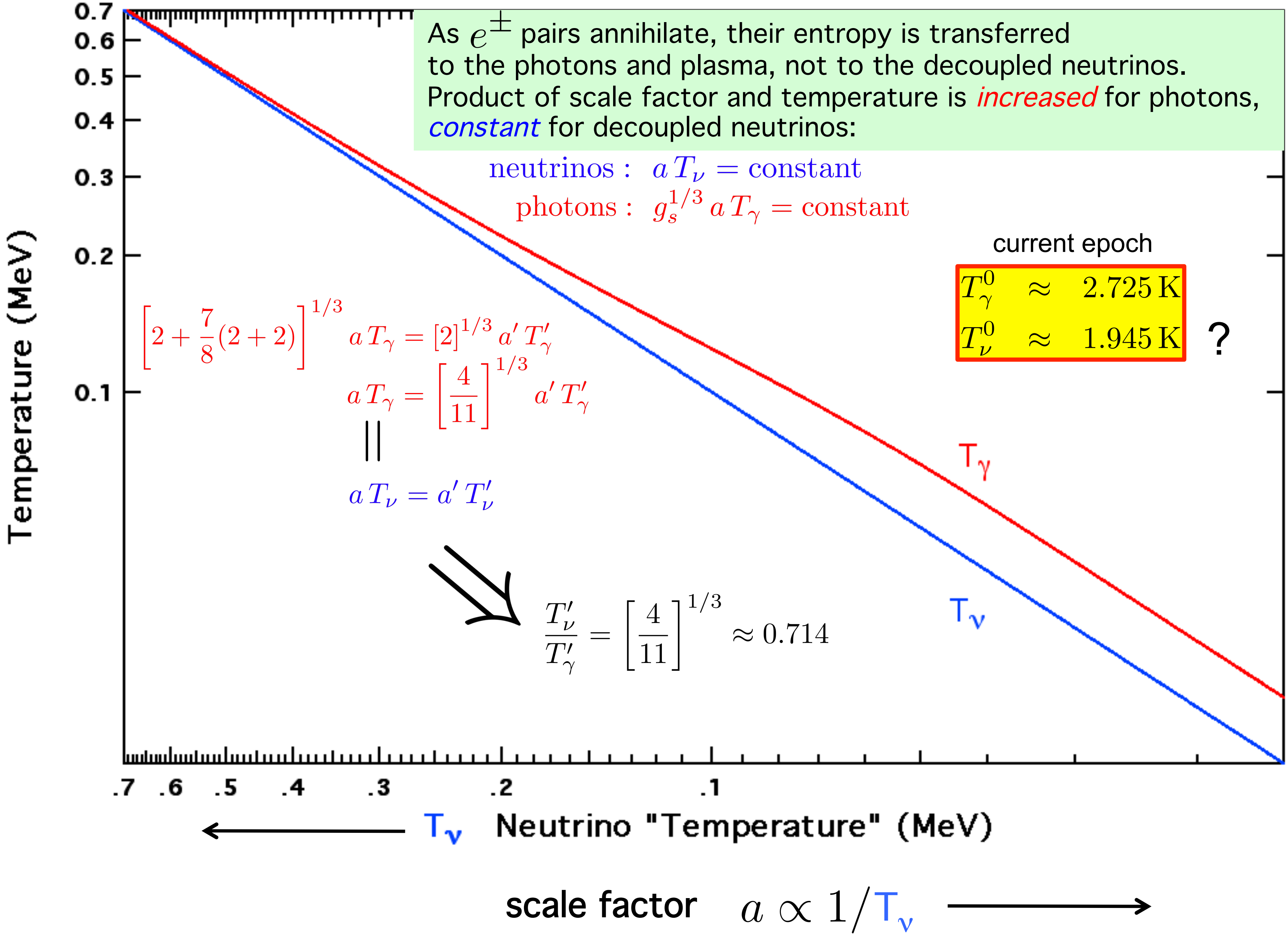
$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$\theta_{12} \approx 0.59^{+0.02}_{-0.015}$$

$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

$$\theta_{13} \approx 0.154^{+0.065}_{-0.065}$$

$\delta = CP$ violating phase $=?$

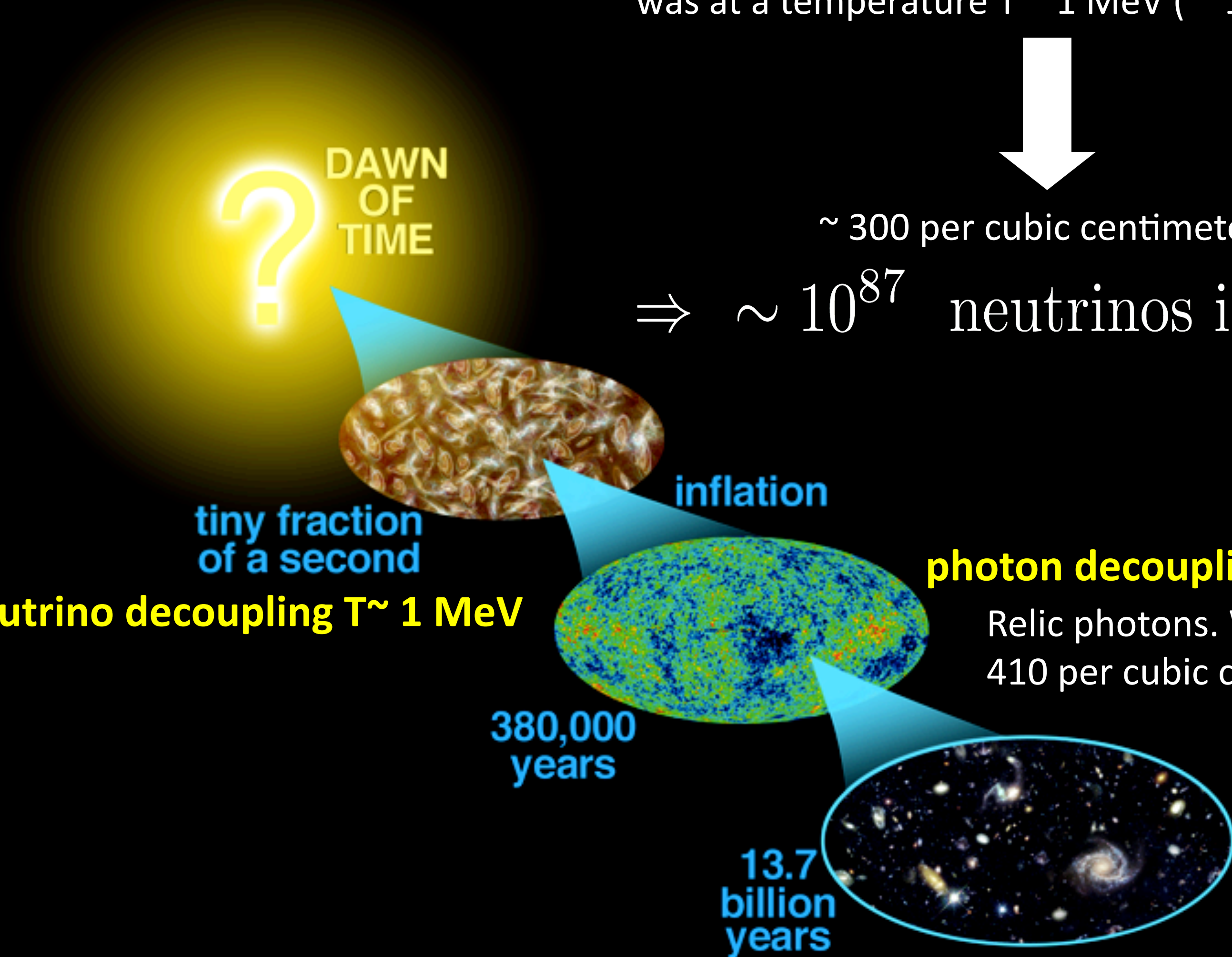


As $e^{\pm}$ pairs annihilate, their entropy is transferred
to the photons and plasma, not to the decoupled neutrinos.
Product of scale factor and temperature is *increased* for photons,
constant for decoupled neutrinos:
$\text{neutrinos}: \; a\,T_\nu = \text{constant}$
$\text{photons}: \; g_s^{1/3}\,a\,T_\gamma = \text{constant}$
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
Temperature (MeV)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
.7
.6
.5
.4
.3
.2
.1
T_ν Neutrino "Temperature" (MeV)
scale factor $a \propto 1/T_\nu$

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

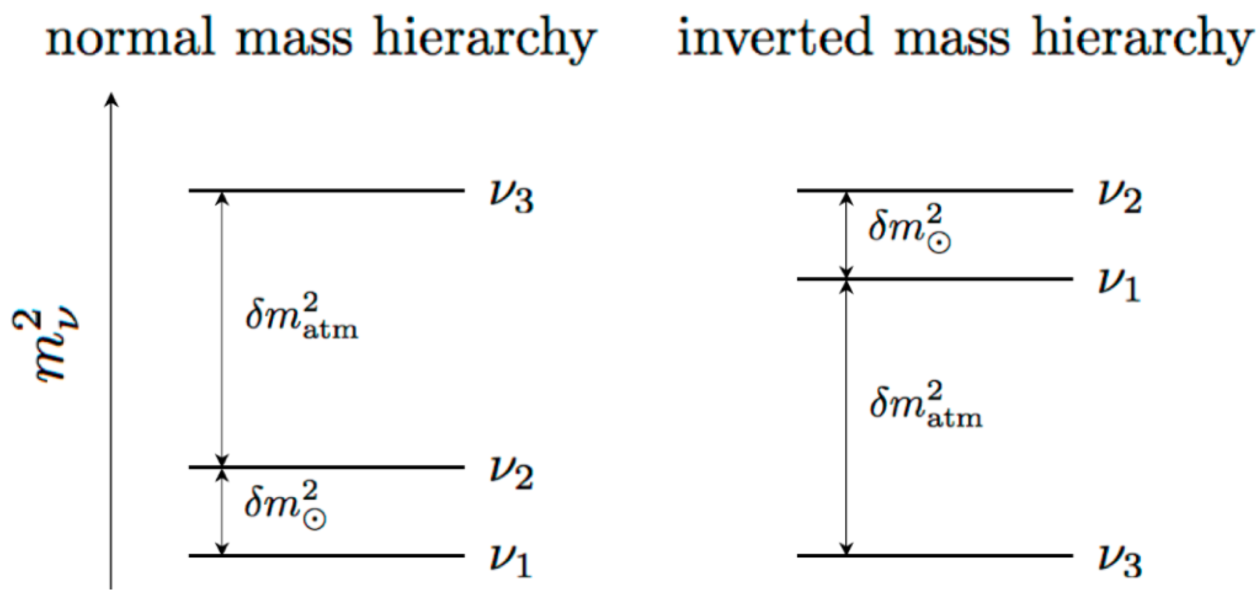
vacuum+matter dominated at current epoch

CMB + large-scale structure observations *do not* actually measure the neutrino rest mass, but rather a convolution of this with the relic neutrino energy spectrum.

It is likely, in my opinion, that we already know the relevant neutrino rest mass, so that a signal for the "sum of the light neutrino masses" is tantamount to a *detection of the relic neutrino background*.

This therefore would give a constraint on the relic neutrino energy spectrum.

at least one of the vacuum neutrino mass eigenvalues satisfies $m_3 \text{ (or } m_2) \geq \sqrt{\delta m^2_{\rm atm}} \approx 0.05\,\mathrm{eV}$



$\Sigma m_\nu \geq 0.05\,\mathrm{eV}$ $\Sigma m_\nu \geq 0.1\,\mathrm{eV}$

$$\sum m_\nu < 0.23\,\mathrm{eV}\ \ (95\ \mathrm{percent\ conf.};\ \mathrm{Planck + WP + highL + BAO})$$

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

The existence of non-zero neutrino rest masses,
as established by the results of neutrino oscillation experiments,
immediately forces us to ponder a question:

Are there right-handed, e.g., so-called "sterile neutrinos" ??

These particles may not really be "sterile" because they can mix in vacuum with ordinary active neutrinos, but their effective coupling strengths may be so tiny that they cannot be probed in the lab . . .

. . . *cosmology is a different matter*.

"Hints" for light sterile neutrinos?

Intriguing, If Not Compelling

mini-BooNE neutrino oscillation experiment at FNAL

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

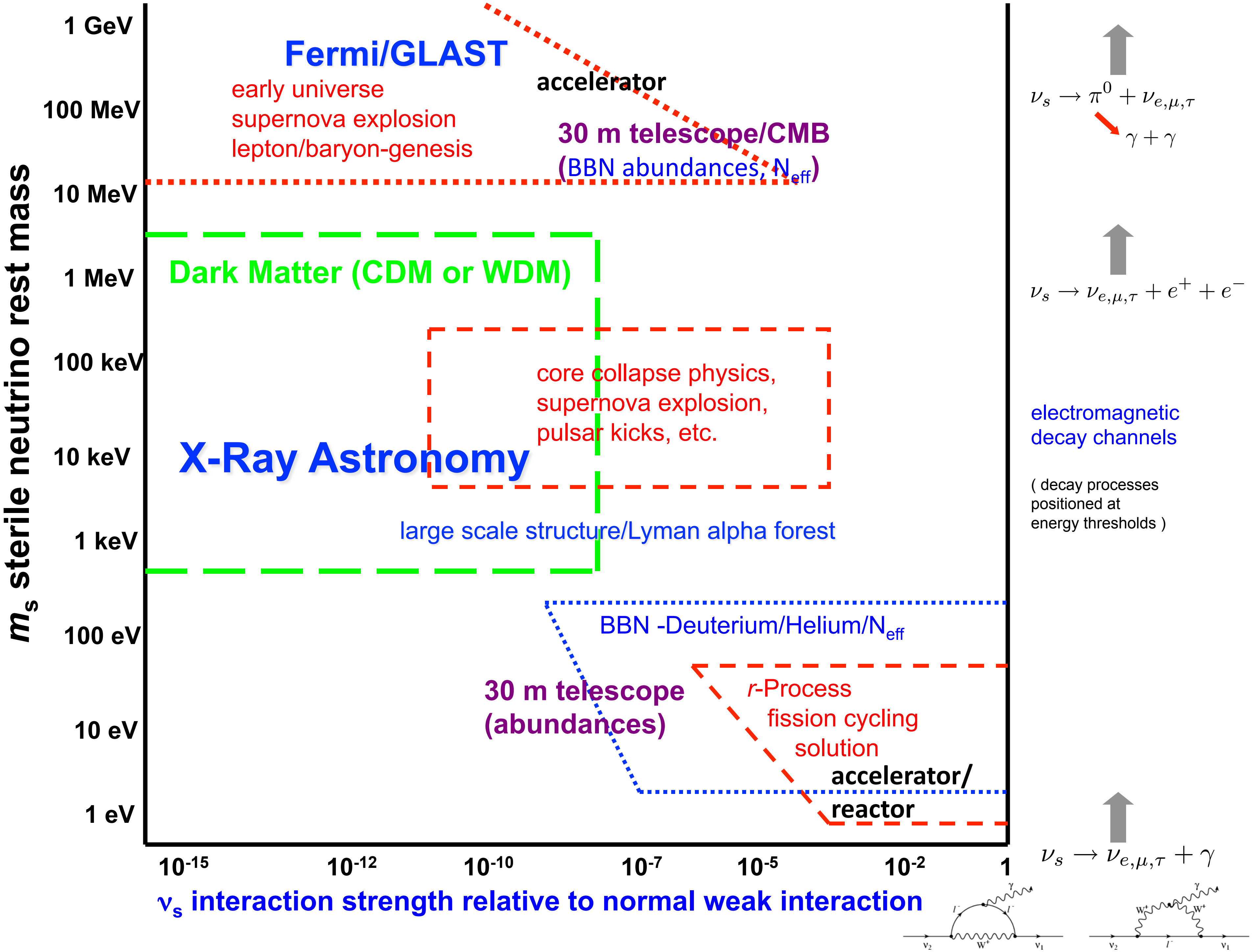
(now 5σ above background)

neutrino reactor anomaly/radioactive source disappearance:

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

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

– Cosmic Microwave Background observations



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/CMB
(BBN abundances; N_{eff})
Dark Matter (CDM or WDM)
core collapse physics,
supernova explosion,
pulsar kicks, etc.
X-Ray Astronomy
large scale structure/Lyman alpha forest
BBN -Deuterium/Helium/N_{eff}
30 m telescope
(abundances)
r-Process
fission cycling
solution
accelerator/
reactor
10^{-15}
10^{-12}
10^{-10}
10^{-7}
10^{-5}
10^{-2}
1
ν_s interaction strength relative to normal weak interaction
$\nu_s \rightarrow \pi^0 + \nu_{e,\mu,\tau}$
$\gamma + \gamma$
$\nu_s \rightarrow \nu_{e,\mu,\tau} + e^+ + e^-$
electromagnetic
decay channels
(decay processes
positioned at
energy thresholds)
$\nu_s \rightarrow \nu_{e,\mu,\tau} + \gamma$

Dark Radiation

N_{eff} as a probe of neutrino sector
and high energy-scale physics

Radiation energy density at γ-decoupling $\left(T_\gamma \approx 0.2\,\mathrm{eV} \right)$
is parameterized by the
so called "*effective number of neutrino degrees of freedom*".

This is a misnomer as it refers to energy density
from ***any and all*** relativistic particles at that epoch.

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

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

$$\mathrm{Nine-year\ WMAP}\quad \mathrm{N_{eff}} = 3.26 \pm 0.35$$

$$\mathrm{ACT}\quad \mathrm{N_{eff}} = 2.78 \pm 0.55$$

$$\mathrm{SPT-SZ\ Survey}\quad \mathrm{N_{eff}} = 3.71 \pm 0.35 \quad (\mathrm{H_0\ and\ BAO\ priors})$$

Planck $\mathrm{N_{eff}} = 3.30^{+0.54}_{-0.51},\ 95\%\ \mathrm{conf.},\ \mathrm{WMAP\ pol.},\ \mathrm{high}\ l,\ \mathrm{BAO}$

analysis with BAO & sterile mass < 10 eV, thermal spectrum $\mathrm{N_{eff}} < 3.80 \ \ \&\ \ m_\nu^{\mathrm{sterile}} < 0.42\,\mathrm{eV},\ \mathrm{at}\ 95\%\ \mathrm{conf.}$

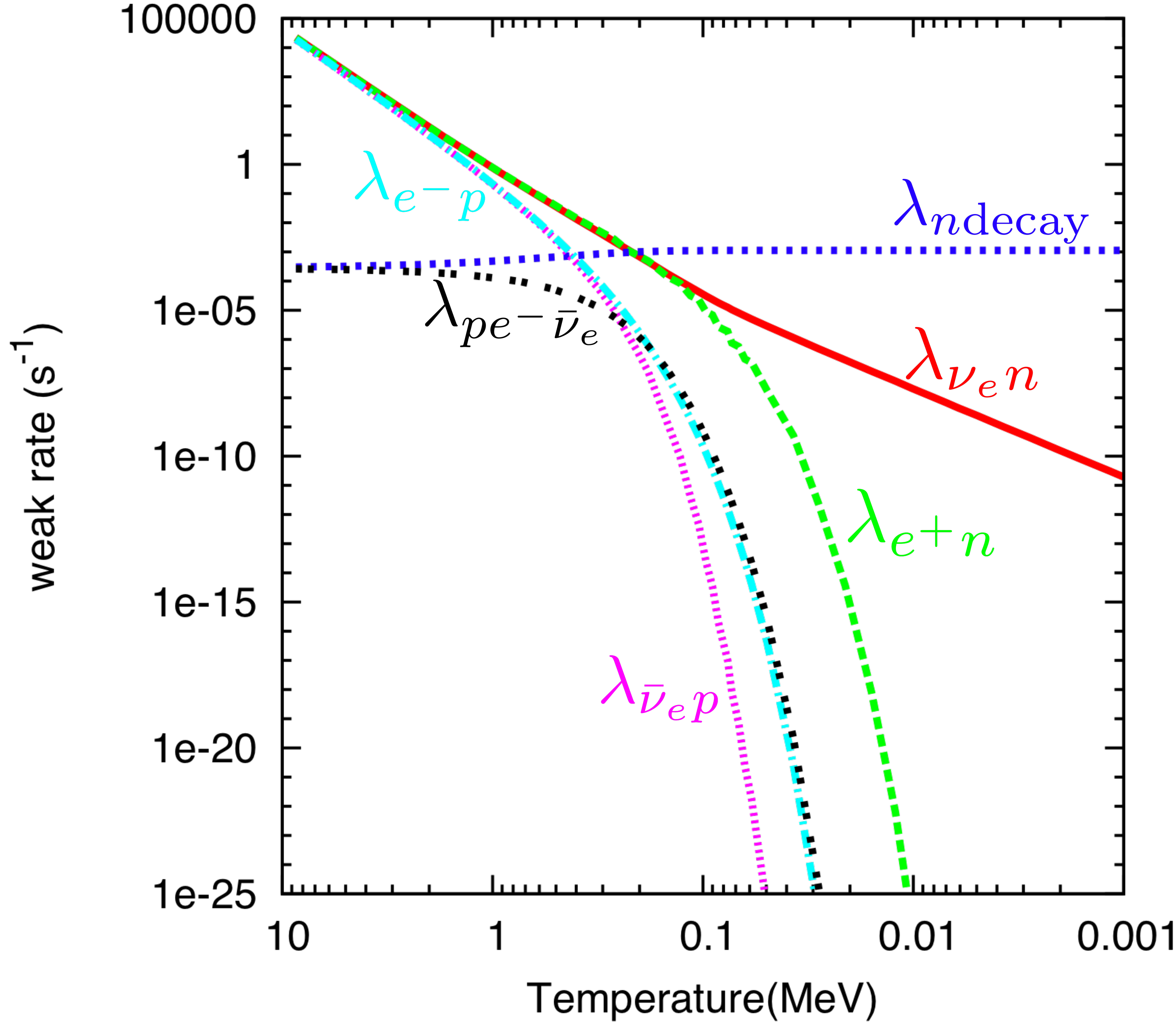
Caveats on CMB as a probe of sterile neutrinos

. . . there are scenarios where *sterile neutrinos*
would **not** have thermal energy spectra/number densities
(sterile neutrinos are sub-weakly interacting!)

. . . be careful with BBN + CMB, especially for ^{4}He.
What we call N_{eff} is **not** what determines the
expansion rate
and *neutron/proton ratio* at T ~ 1 MeV BBN epoch

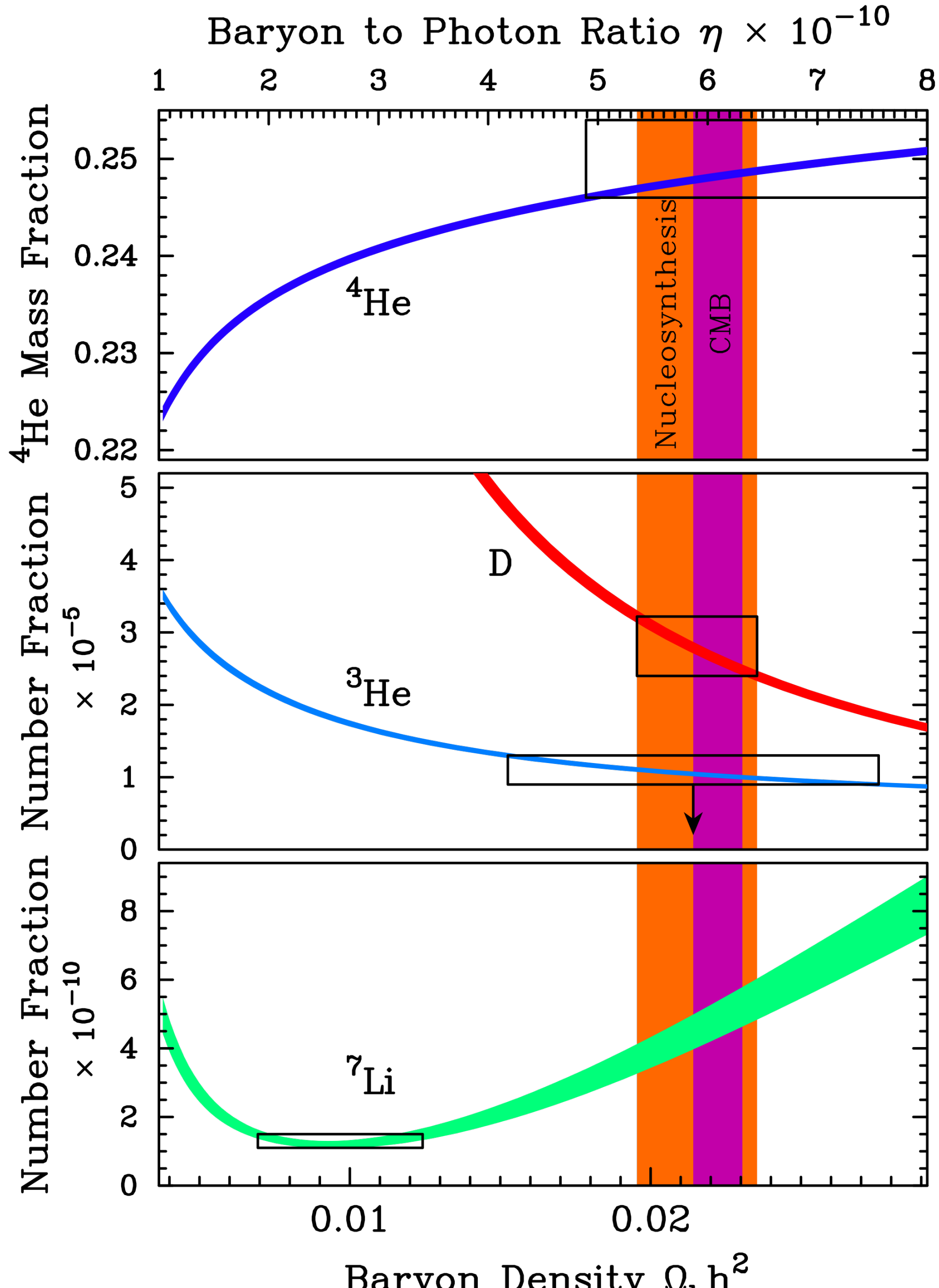
$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$
$$\mathrm{n} \rightleftharpoons \mathrm{p} + e^- + \bar{\nu}_e$$

Rates of these competing processes set ^{4}He
and they are *very* sensitive to
neutrino energy spectra –
active-sterile oscillations can affect these



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}
$\lambda_{\bar{\nu}_e p}$

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 $Y_P = 0.2565 \pm 0.0010\ (\mathrm{stat.}) \pm 0.0050\ (\mathrm{sys.})$

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

$Y_P = 0.2482 \pm 0.0007$ Steigman 1008.476

Best bet may be future CMB determinations via the Silk damping tail,

$Y_p = 0.266 \pm 0.021$ (68 percent conf. Planck + WP + highL)

very tricky – N_{eff} and ^{4}He almost degenerate

(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

Sterile Neutrino Decay

can have effects on

-nucleosythesis

-N_{eff}

these can lead to constraints

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

If so, their number densities will be **comparable to those of photons,** 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

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

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

$\zeta\,(3) \approx 1.20206$

Example: sterile neutrino decay ($m_s <$ a few GeV)

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

$$\nu_s \to \pi^+ + e^- \quad \to 2\gamma + 3\nu$$

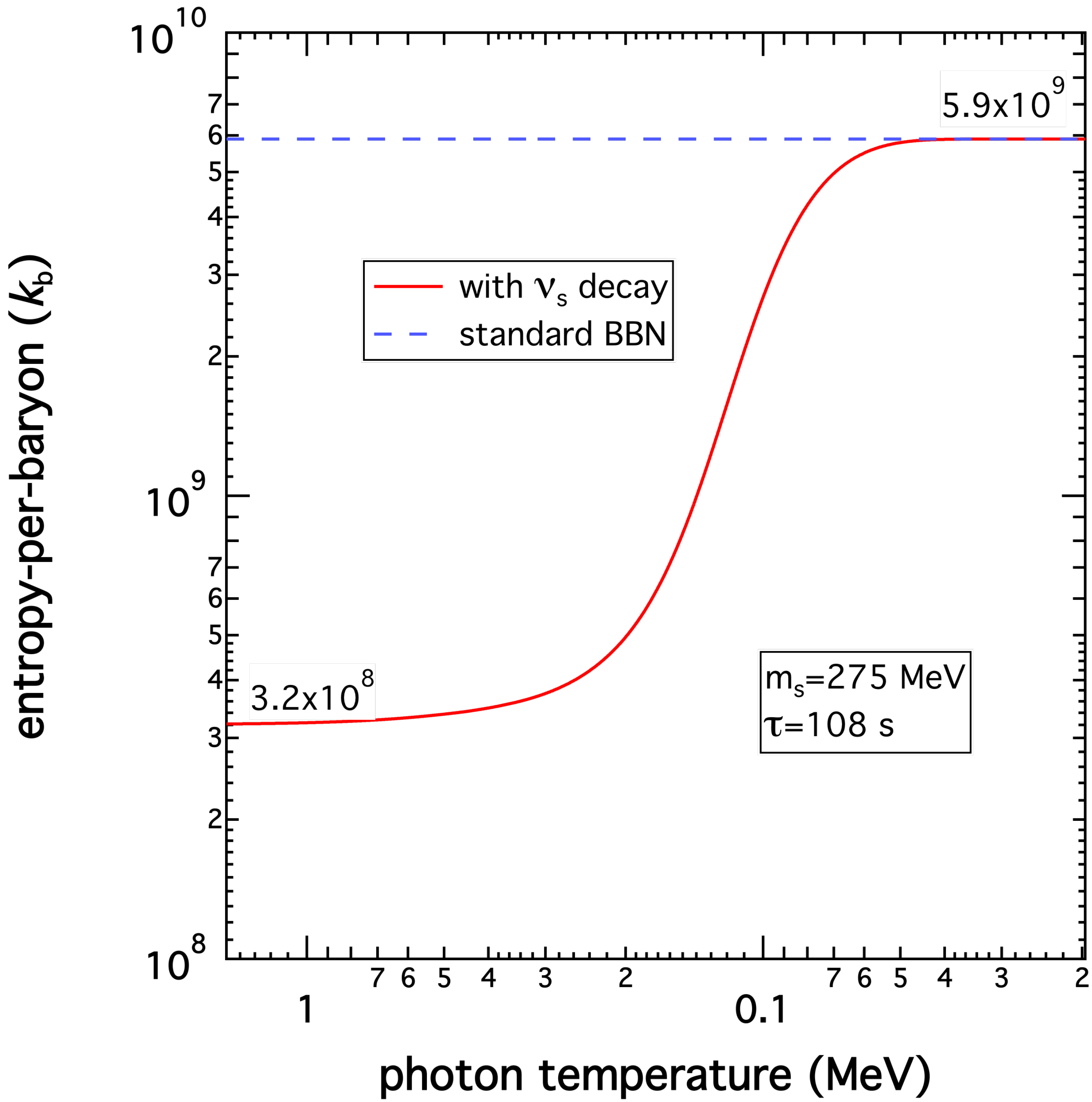
$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

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

Photons thermalize,

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



prodigious entropy production!

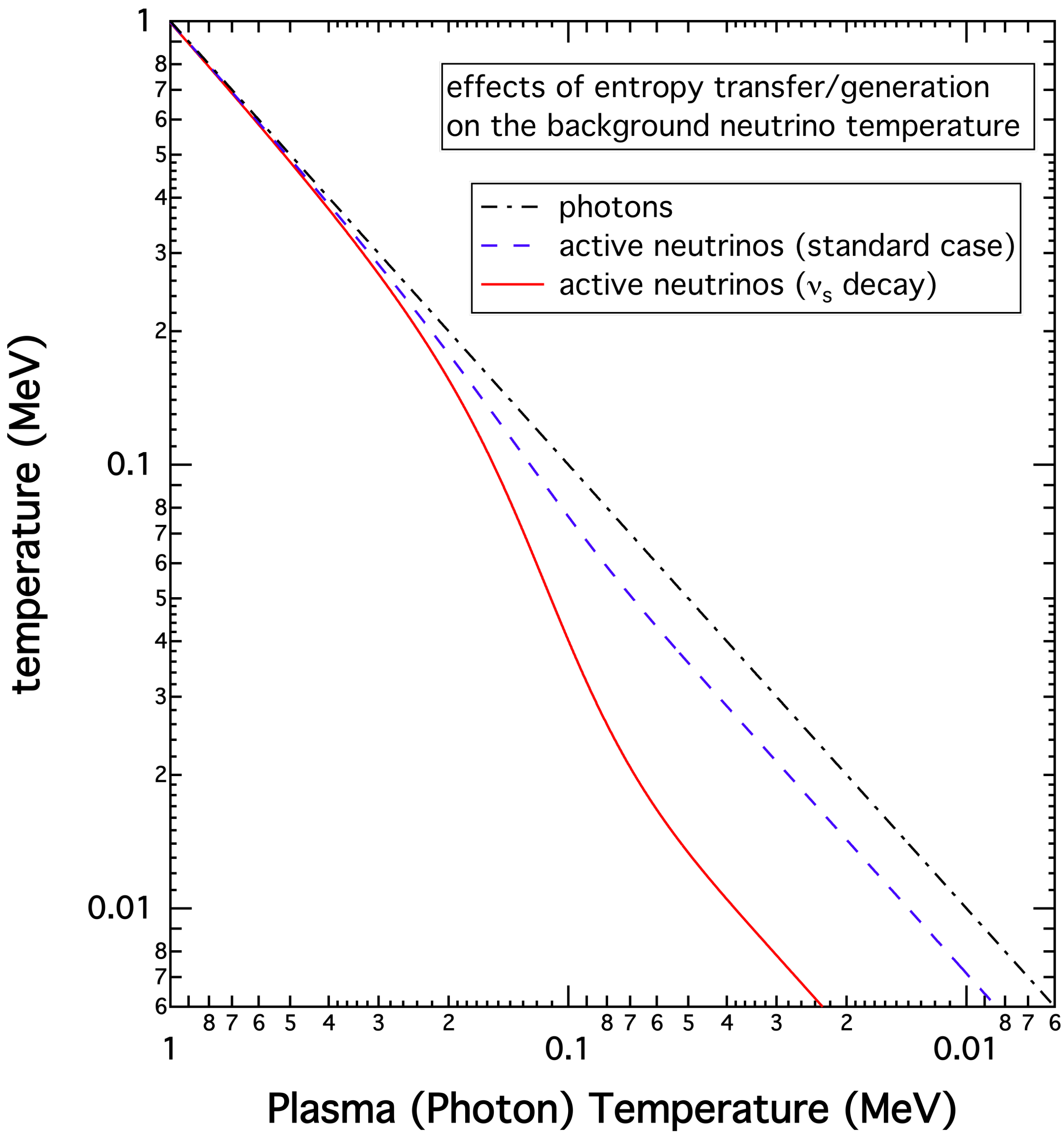
in this case:

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

where entropy-per-baryon is carried by radiation

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

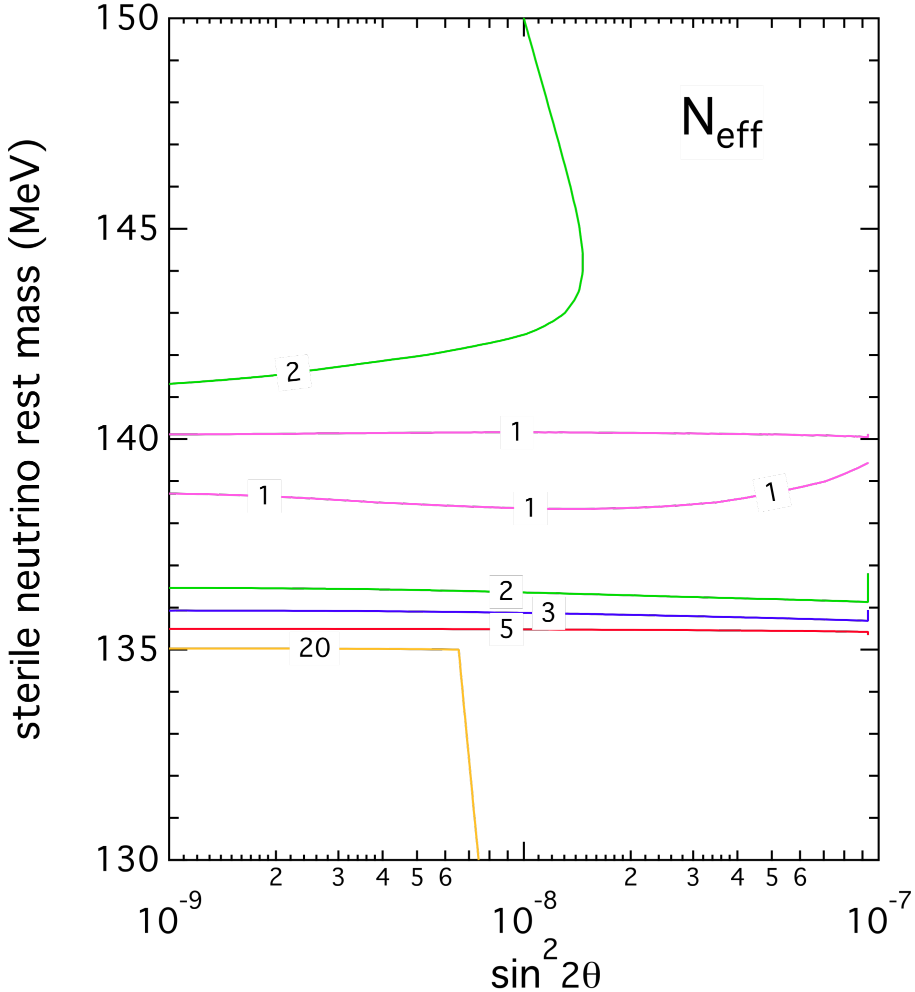
Fuller, Kusenko, Kishimoto

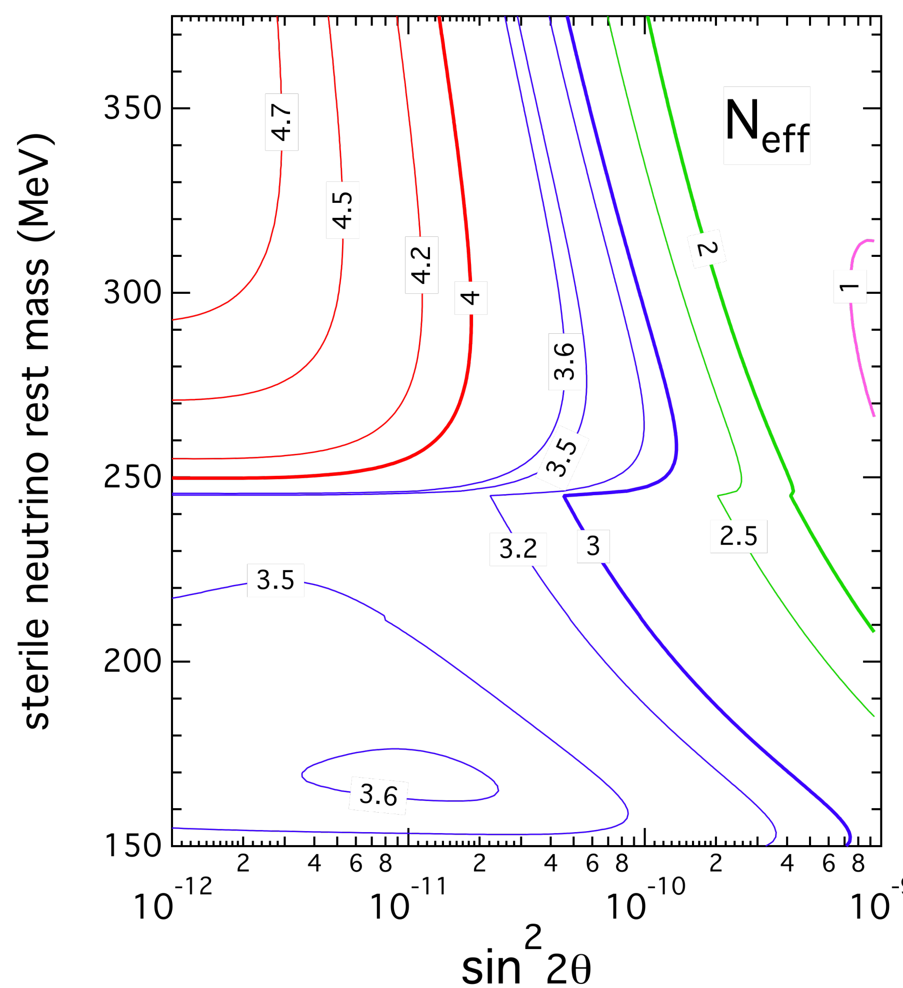

effects of entropy transfer/generation
on the background neutrino temperature
photons
active neutrinos (standard case)
active neutrinos (ν_s decay)
temperature (MeV)
Plasma (Photon) Temperature (MeV)
1
0.1
0.01

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})

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





Summary

N_{eff} constraints from the CMB do not currently completely *rule out* the light sterile neutrinos hinted at by experiments, but they greatly pressure this interpretation of the data

BUT they do ***rule out*** a swath of *heavy sterile neutrino* parameter space, not accessible experimentally

- Do not constrain sterile neutrino dark matter (CDM or WDM)

- **N_{eff}** , together with the "sum of the light neutrino masses", is a fantastic probe of the physics of the early universe and this probe will only get better with time