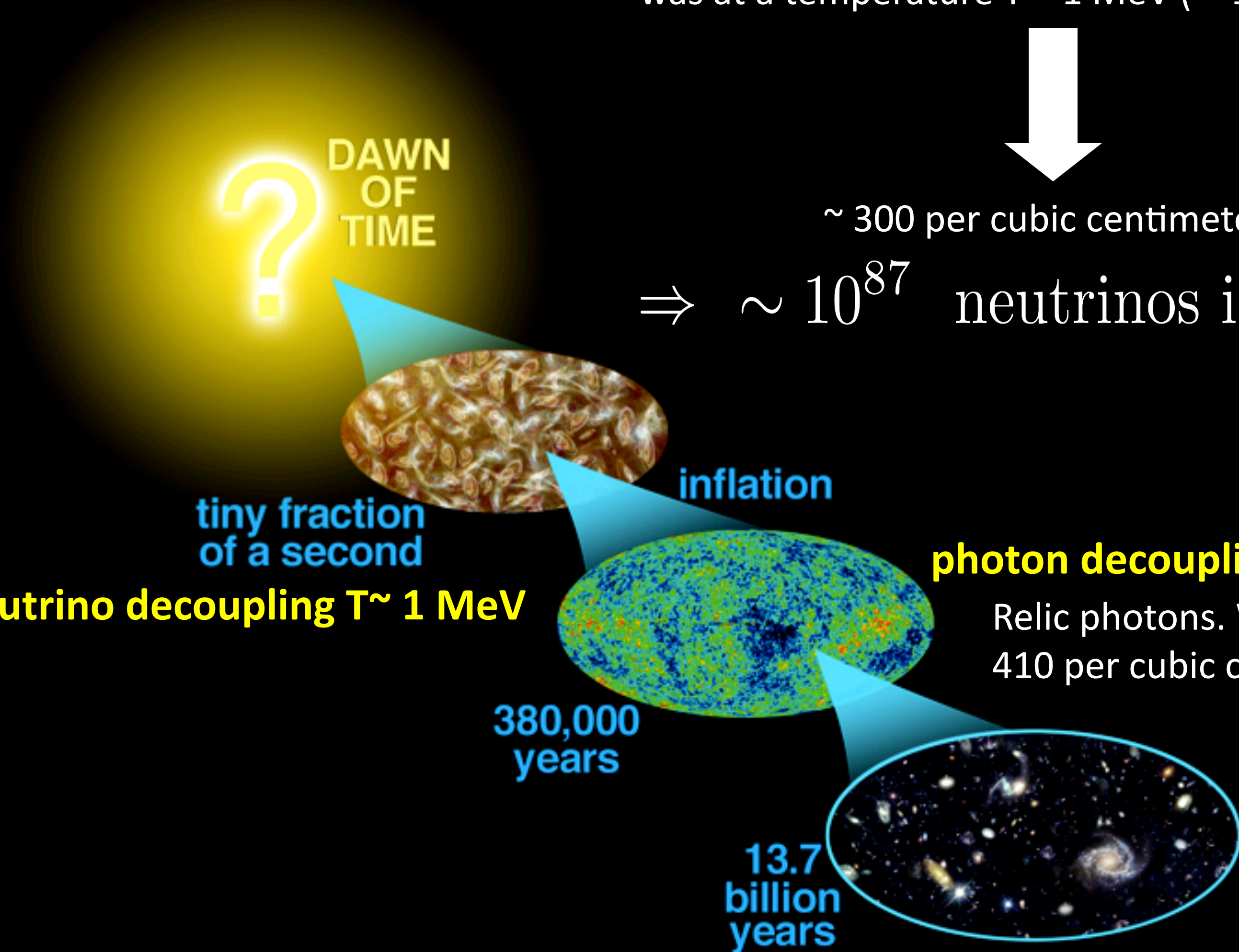
Neutrinos in **COSMOLOGY**

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

So what is unique about the
cosmic neutrino background (CνB)
as a lab for studying neutrinos?

In a nutshell:

There are a ***huge*** number of these neutrinos.
They make themselves felt in Big Bang Nucleosynthesis
and by their gravitational effects.

Moreover, the relic density of these neutrinos
and their energy spectra could give unique insights
into the physics of the very early universe

Weak interaction decoupling, after which the neutrinos no longer scatter and exchange energy with the electron/positron/photon/baryon medium, occurs at T_{weak} where the scale factor is a_{weak}.

$$T_{\text{weak}} \approx 3\,\text{MeV to } 1\,\text{MeV} \;\gg m \;\text{ the mass of the neutrino}$$

$$E_\nu = \left(p^2 + m^2\right)^{1/2} \approx p \quad \text{at } \; T_{\text{weak}}$$

Therefore, the energy distribution function for neutrino flavor α with degeneracy parameter η_{ν_α} (a co-moving invariant) is

$$dn_{\nu_\alpha} \;\approx\; \frac{1}{2\,\pi^2} \cdot \frac{p^2\;dp}{e^{(p/T_{\text{weak}}-\eta_{\nu_\alpha})}+1}$$

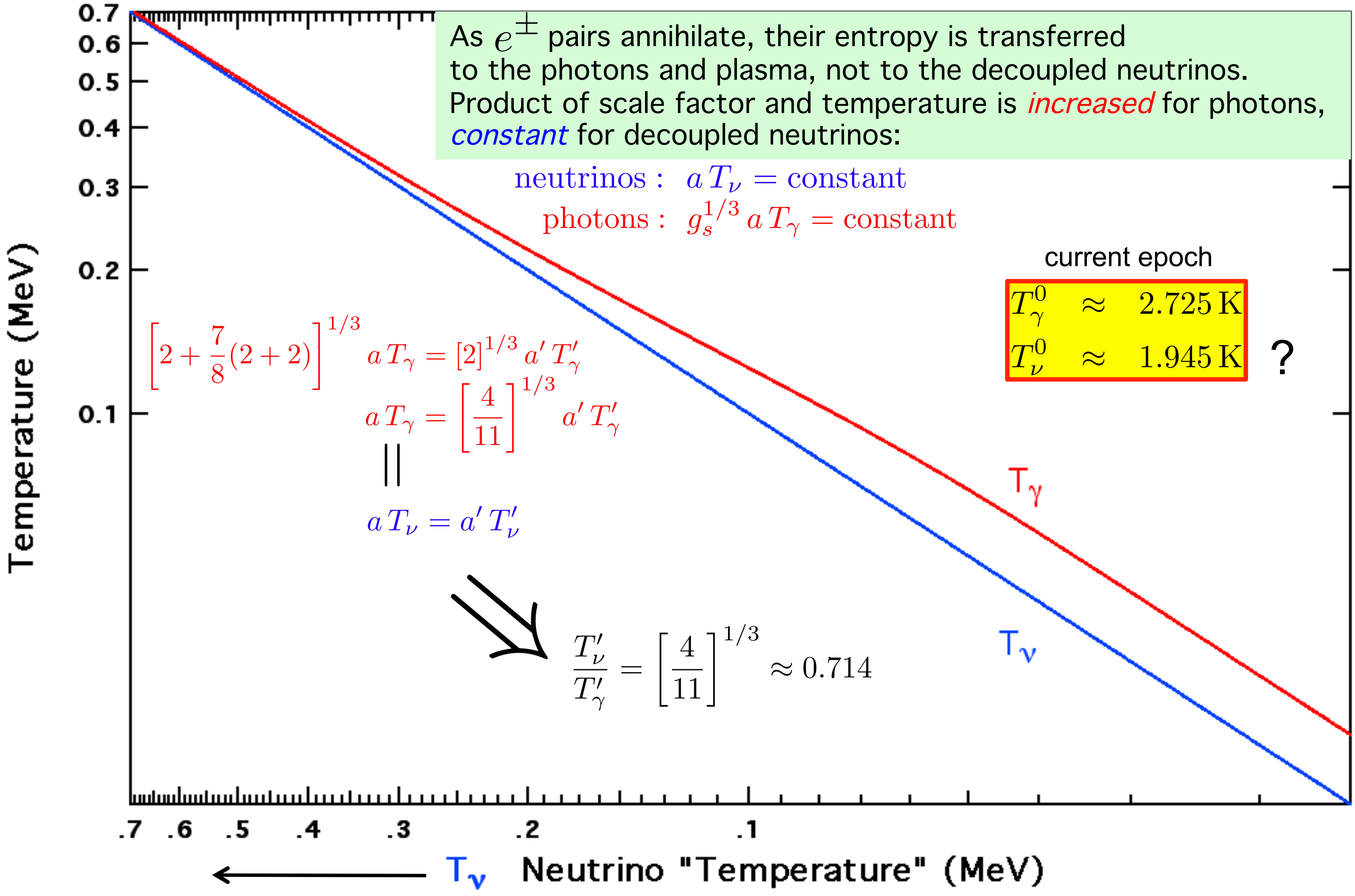
Subsequent to weak decoupling, the neutrinos simply free-fall through a Friedman-LeMâitre-Robertson-Walker spacetime, and their momenta redshift with scale factor like $p \propto a^{-1}$.

So *define* a neutrino "temperature" $T_{\nu_\alpha} \equiv T_{\text{weak}} \cdot (a_{\text{weak}}/a)$

then for $T_{\nu_\alpha} < T_{\text{weak}}$ the neutrino energy distribution is $dn_{\nu_\alpha} \approx \dfrac{1}{2\,\pi^2} \cdot \dfrac{p^2\;dp}{e^{(p/T_{\nu_\alpha}-\eta_{\nu_\alpha})}+1}$

The corresponding number density is

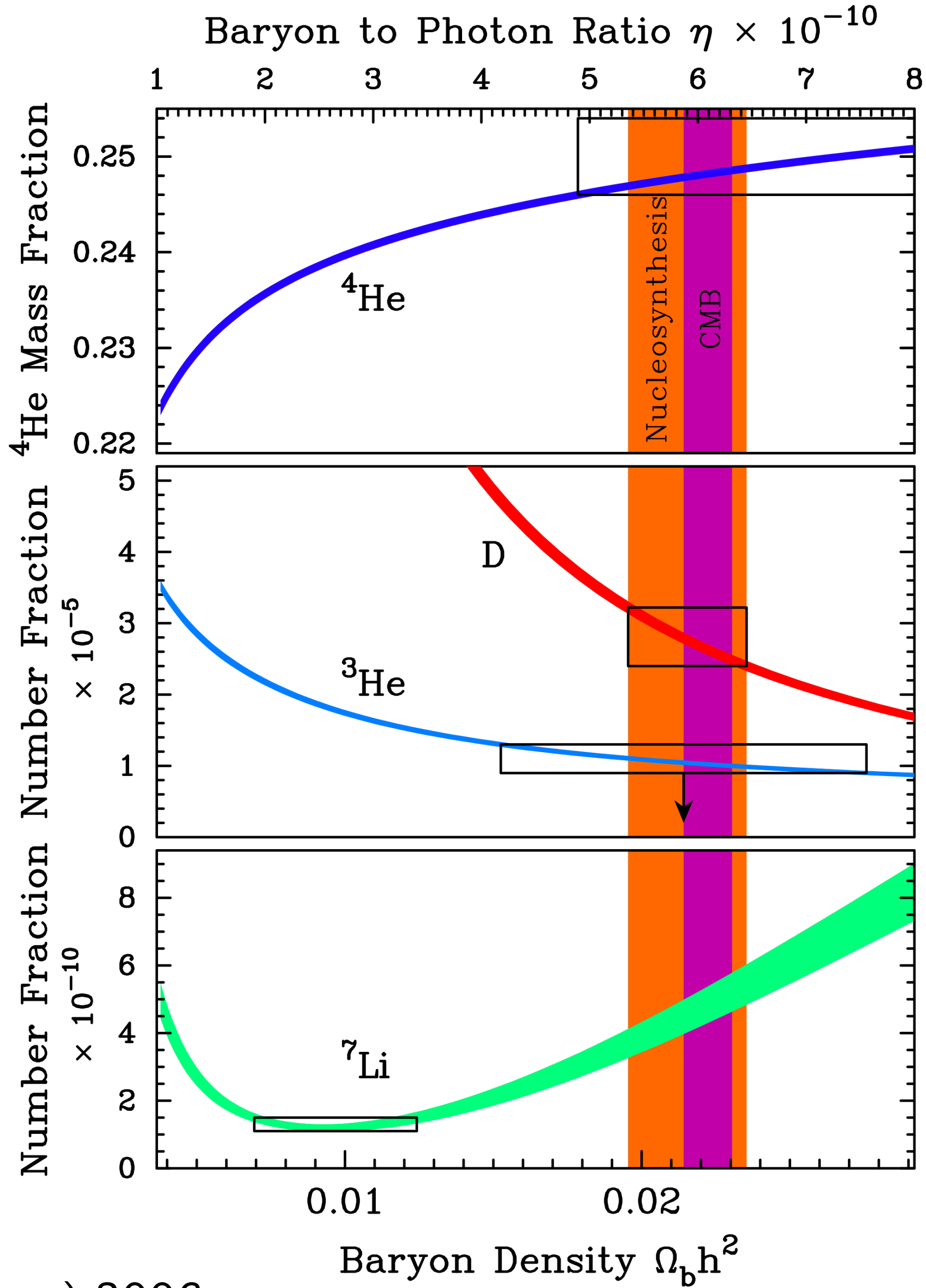
$$n_{\nu_\alpha} = \frac{T_{\nu_\alpha}^3}{2\,\pi^2}\,F_2\left(\eta_{\nu_\alpha}\right) \;\propto\; a^{-3} \;\text{ and for }\; \eta_{\nu_\alpha} = 0 \text{ we have } n_{\nu_\alpha} = \frac{3}{4} \cdot \frac{\zeta\,(3)}{\pi^2} \cdot T_{\nu_\alpha}^3$$



scale factor $a \propto 1/T_\nu$

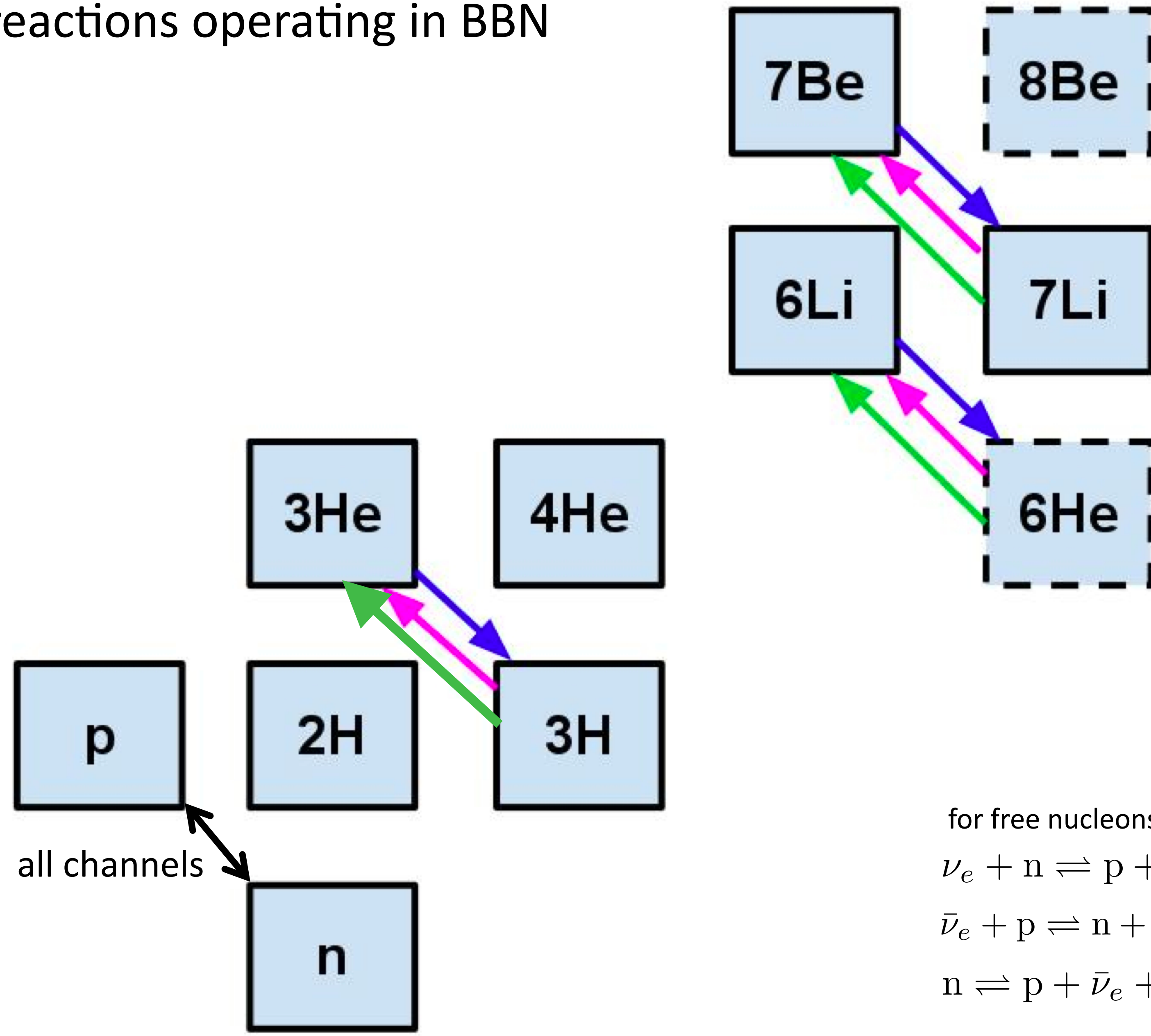
We know that this
neutrino background
is there at the the **BBN Epoch**

Standard BBN



Nao Suzuki (Tytler group) 2006

weak reactions operating in BBN

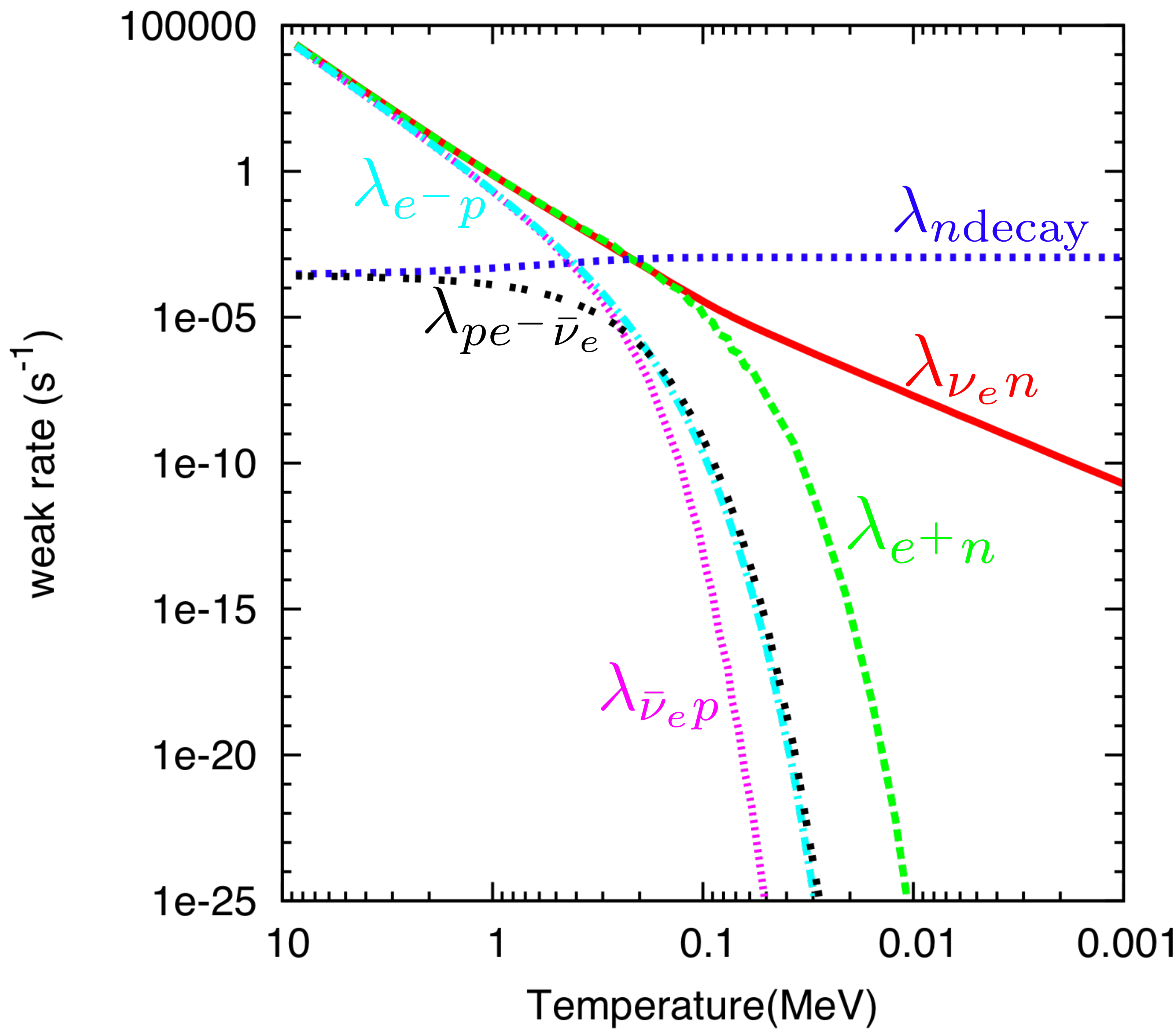


for free nucleons:

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

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

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



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}
$\lambda_{n\text{decay}}$
$\lambda_{pe^-\bar{\nu}_e}$
$\lambda_{\nu_e n}$
λ_{e^+n}
$\lambda_{\bar{\nu}_e p}$

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

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.

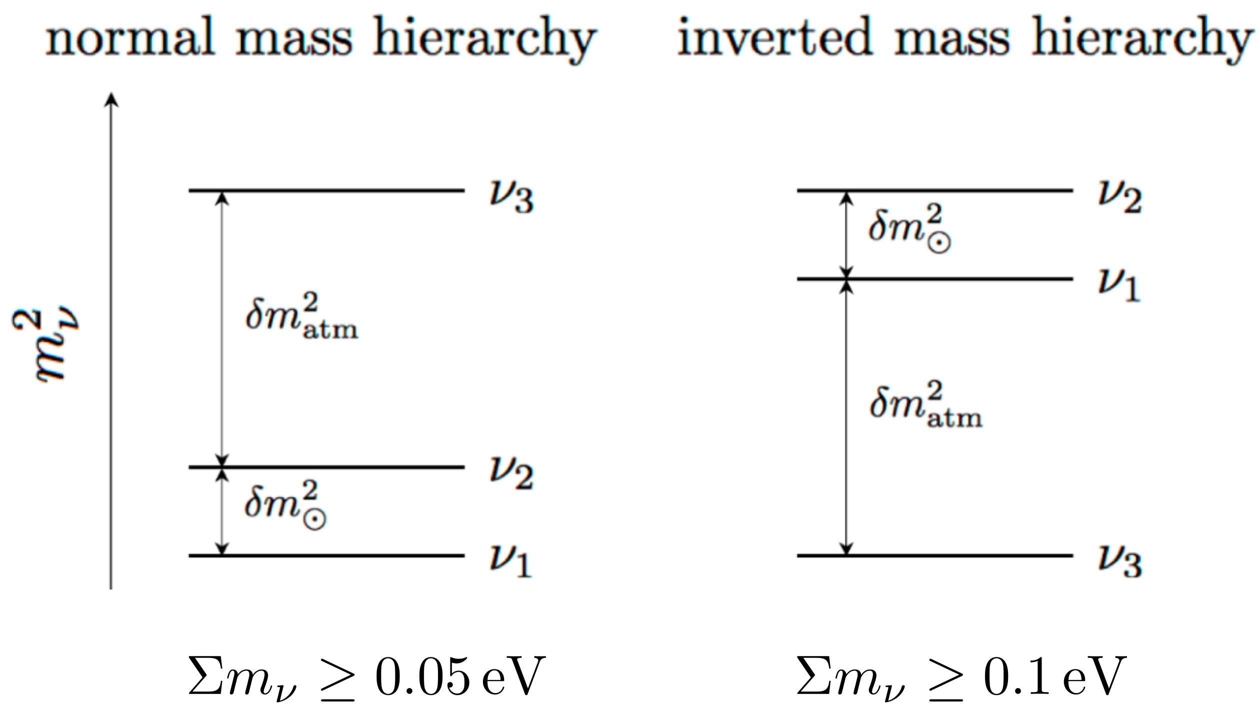
It is likely, in my opinion, that we already know the relevant neutrino rest mass,
so that a signal for the "sum of the light neutrino masses" is tantamount to
a *detection of the relic neutrino background*.

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

The Relic Neutrino Energy Spectrum
encodes all beyond standard model particle physics
which affects entropy generation, energy density, *etc.*

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

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



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

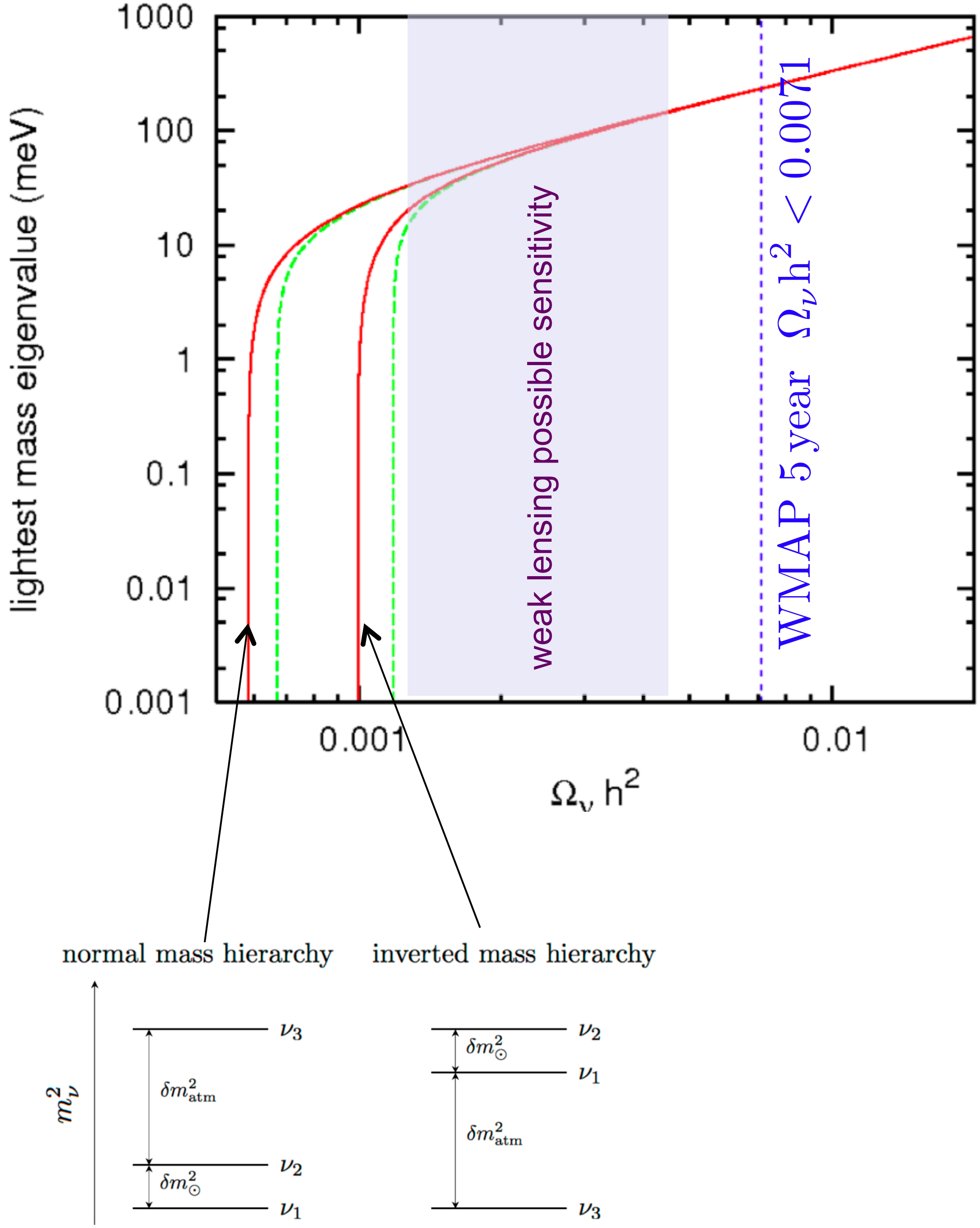
Contribution to closure of all neutrino species with thermal (black body, BB) energy spectra. A thermal energy spectrum is characterized by a temperature and a degeneracy parameter (chemical potential divided by temperature).

$$\Omega_{\nu_{\text{tot}}} \text{h}^2 \approx \left(5.31 \times 10^{-3}\right) \left(\frac{T_\gamma}{2.725 \text{ K}} \right)^3 \left[\sum_{i_{\text{BB}}} \left(\frac{\text{F}_2\left(\eta_{\nu_i}\right)}{\frac{3}{2}\zeta(3)} \right) \left(\frac{T_{\nu_i}}{\left(\frac{4}{11}\right)^{1/3} T_\gamma} \right)^3 \left(\frac{"m_{\nu_i}"}{1 \text{ eV}} \right) \right]$$

$e.g.$, a neutrino and antineutrino with mass

$$m_{\nu_3} \approx \sqrt{\delta m^2_{\text{atm}}} \approx 0.055 \text{ eV}$$

$$\Rightarrow \quad \Omega_{\nu_{\text{tot}}} \approx (0.0012) \left(\frac{0.7}{\text{h}} \right)^2 \quad \Rightarrow \quad \sim 3\% \text{ of baryon rest mass}$$



Next generation CMB experiments (*e.g.*, 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

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.

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

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

$$\text{Nine} - \text{year WMAP} \quad \mathrm{N}_{\mathrm{eff}} = 3.26 \pm 0.35$$
$$\text{ACT} \quad \mathrm{N}_{\mathrm{eff}} = 2.78 \pm 0.55$$
$$\text{SPT} - \text{SZ Survey} \quad \mathrm{N}_{\mathrm{eff}} = 3.71 \pm 0.35 \quad (\mathrm{H}_0 \text{ and BAO priors})$$

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

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

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*.

Sterile Neutrinos ---models can produce these with non-thermal energy spectra

so you can be fooled by the rest mass into thinking that sterile neutrinos are warm dark matter,

but in some models they are CDM, even for rest masses ~ 1 keV

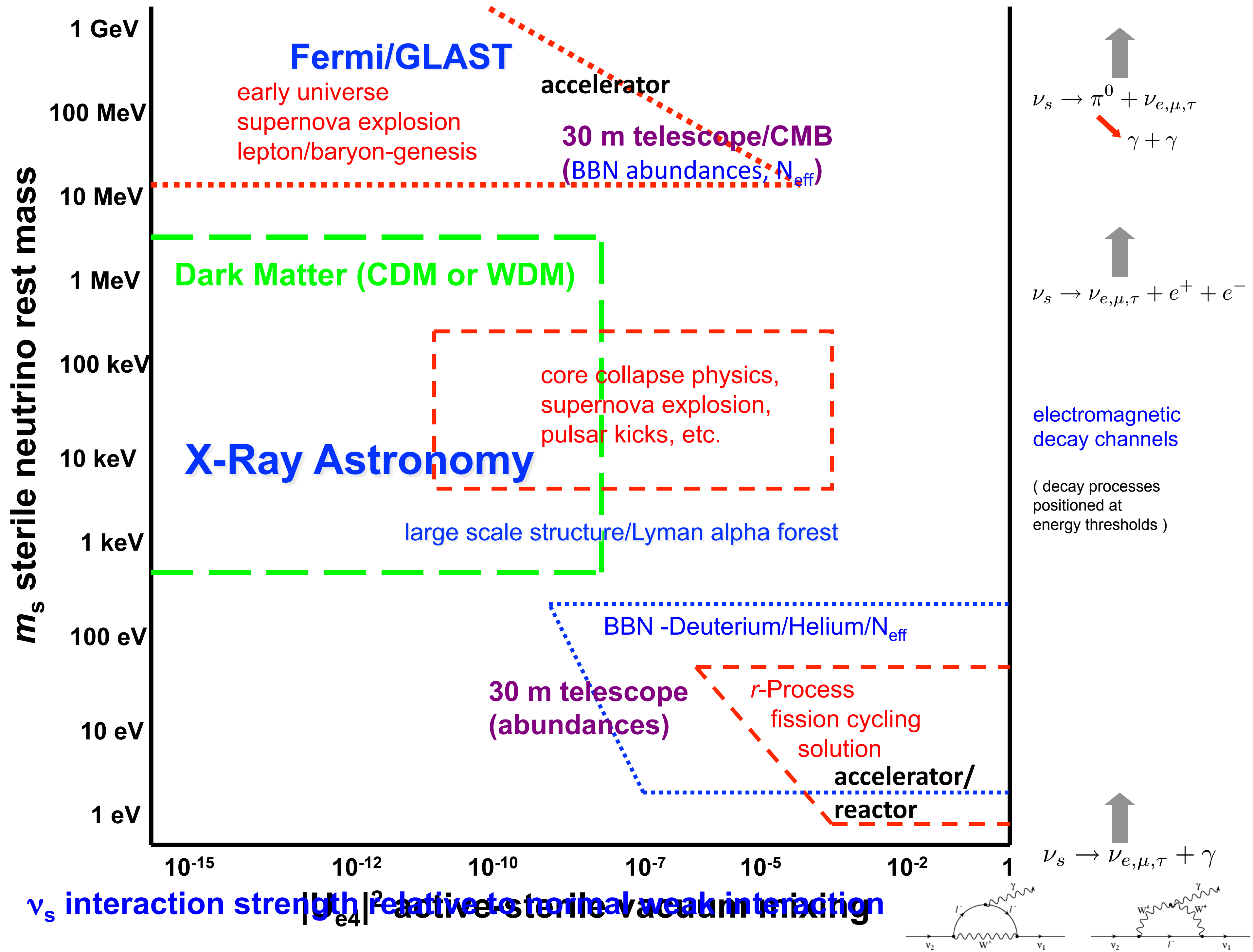
Summary

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



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
$|U_{e4}|^2$ 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)
$\nu_s \rightarrow \nu_{e,\mu,\tau} + \gamma$

"Hints" for light sterile neutrinos?

mini-BooNE neutrino oscillation experiment at FNAL

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

(now 6σ above background)

neutrino reactor anomaly/radioactive source disappearance:

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

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

– Cosmic Microwave Background observations

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

Intriguing, If Not Compelling

Does finding one sterile neutrino bolster the case for others ?

I call this "**The Cockroach Principle**"

- *where there is one there are bound to be others!*

. . . but Alex Kusenko would rather call this . . . "**The Mushroom Principle**"

you find mushrooms where there are other mushrooms

And you actually want to find mushrooms!