Sterile Neutrinos:
Dilution, Dark Radiation, BBN, DM

The 4th NEUTRINO

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but a better title would be . . .

How measurements of *dark radiation*
and cosmological *neutrino mass*
(and *BBN*)
can probe particle physics (heavy sterile ν's)
which is inaccessible in the lab

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!

5 developments mean that new neutrino physics will likely show itself (if it is there):

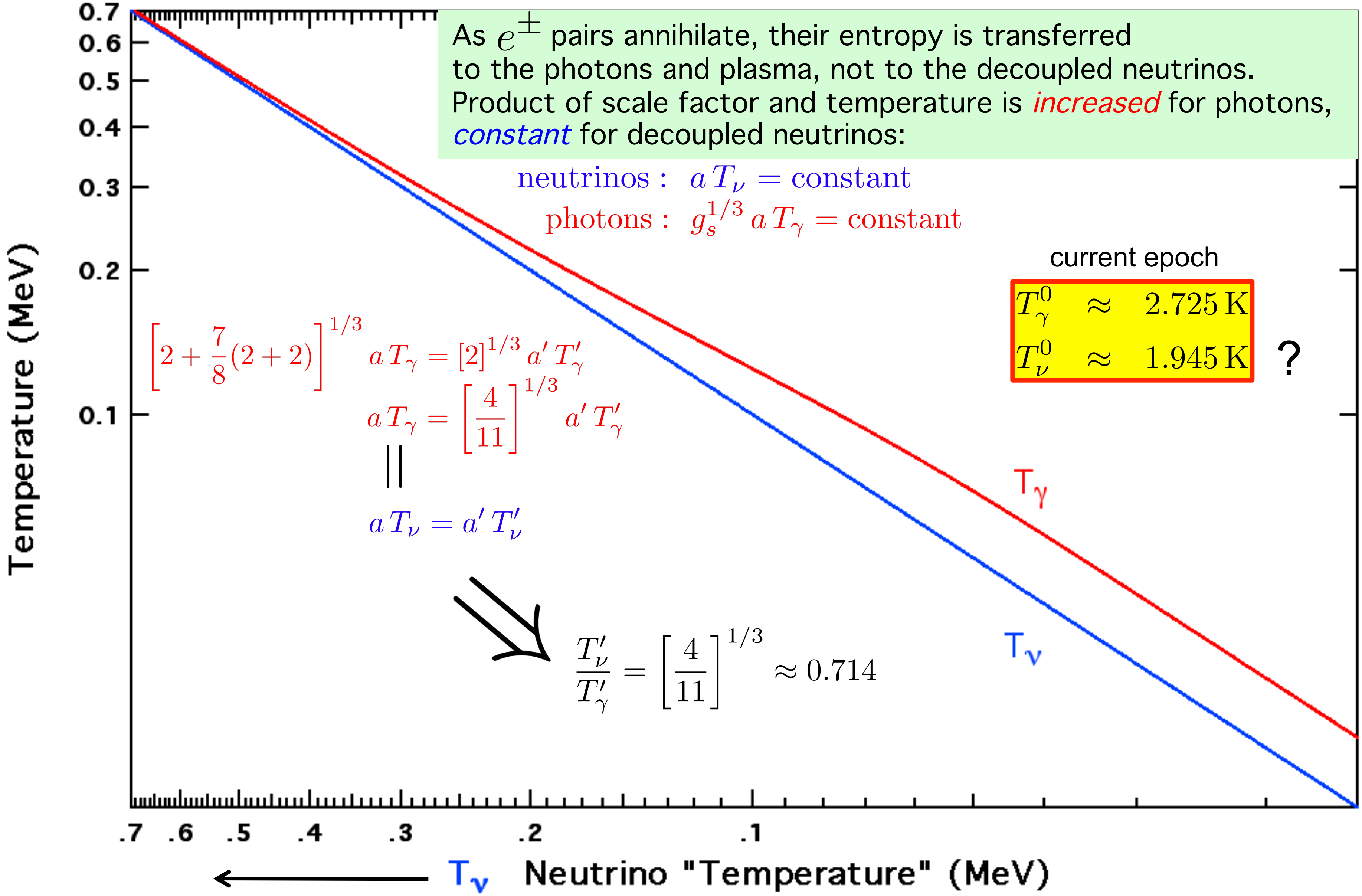
(1) High precision CMB measurements of baryon-to-photon ratio

(2) High precision (*independent*) determination of primordial Deuterium

(3) N_{eff}

(4) Cosmological neutrino mass
(*actually measures convolution of mass and relic energy spectrum*)

(5) ^{4}He – rich interplay with (1) through (4)



scale factor $a \propto 1/T_\nu$ →

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)

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

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

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

light mass (~ 1 eV) sterile neutrinos to influence N_{eff} ????

two lines of laboratory evidence . . . .

- mini-BooNE data

- nuclear reactor neutrino anomaly

Another Way ?

particle decay-induced “dilution” in the early universe

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

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

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

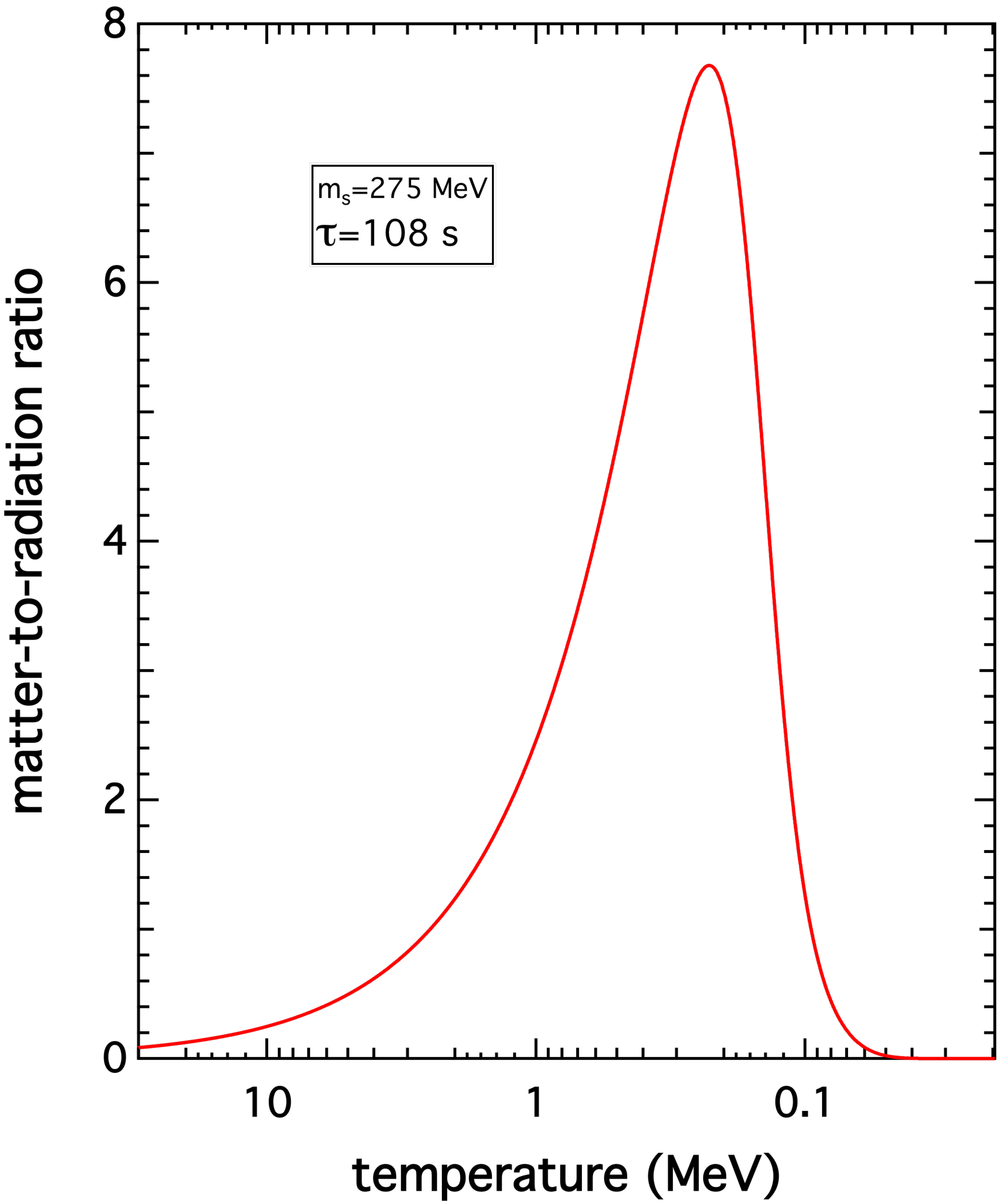
$$T_{\nu_s} \approx T_\gamma/1.79$$

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

heavy “sterile” neutrino decay

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

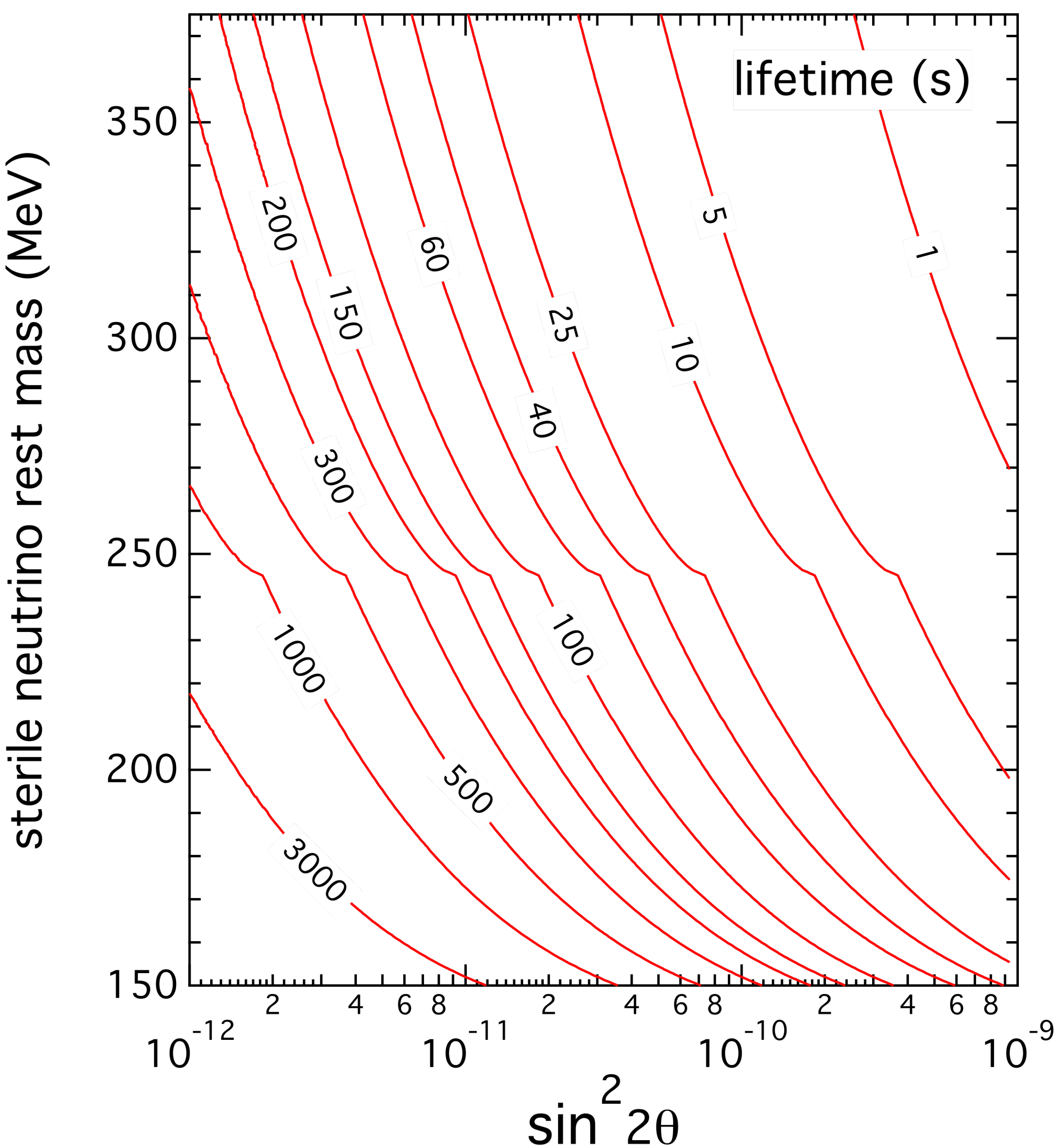
$$\nu_s \to \pi^+ + e^- \quad \to 2\gamma + 3\nu$$

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

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

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

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


lifetime (s)
sterile neutrino rest mass (MeV)
$\sin^2 2\theta$
350
300
250
200
150
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

entropy generation from heavy particle nonequilibrium decay

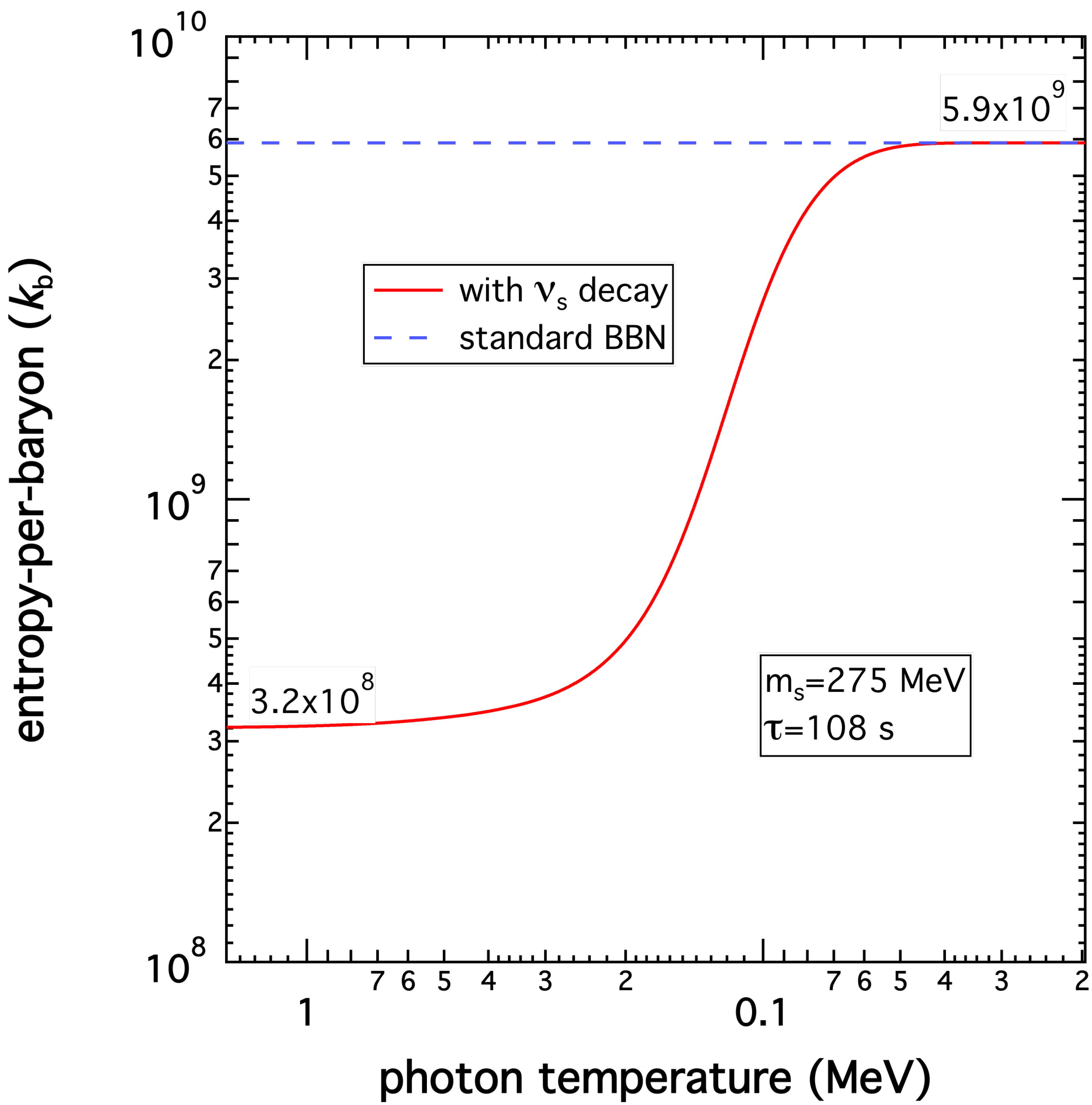
$$\Delta S = \frac{\Delta Q}{T}$$

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



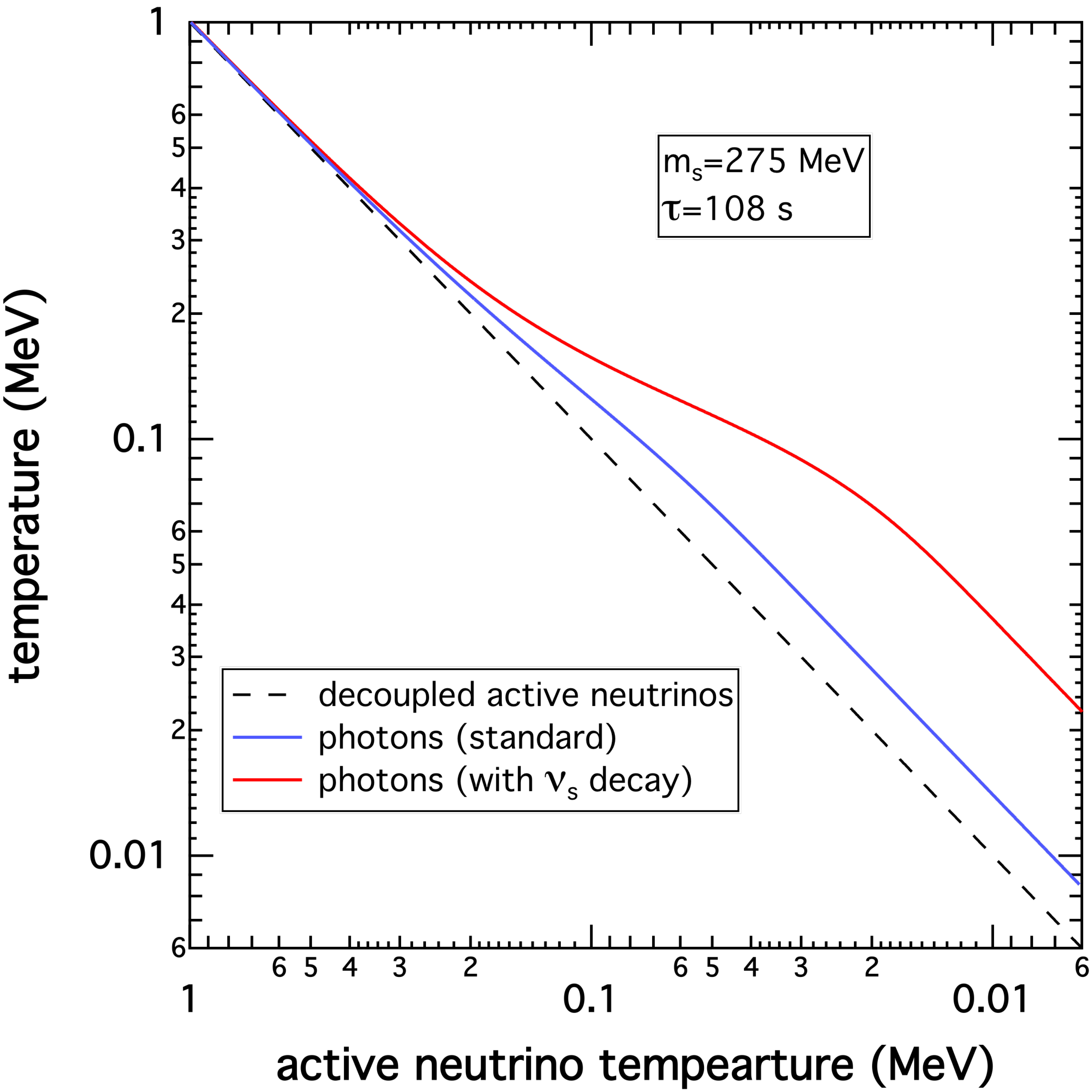
prodigious entropy production!

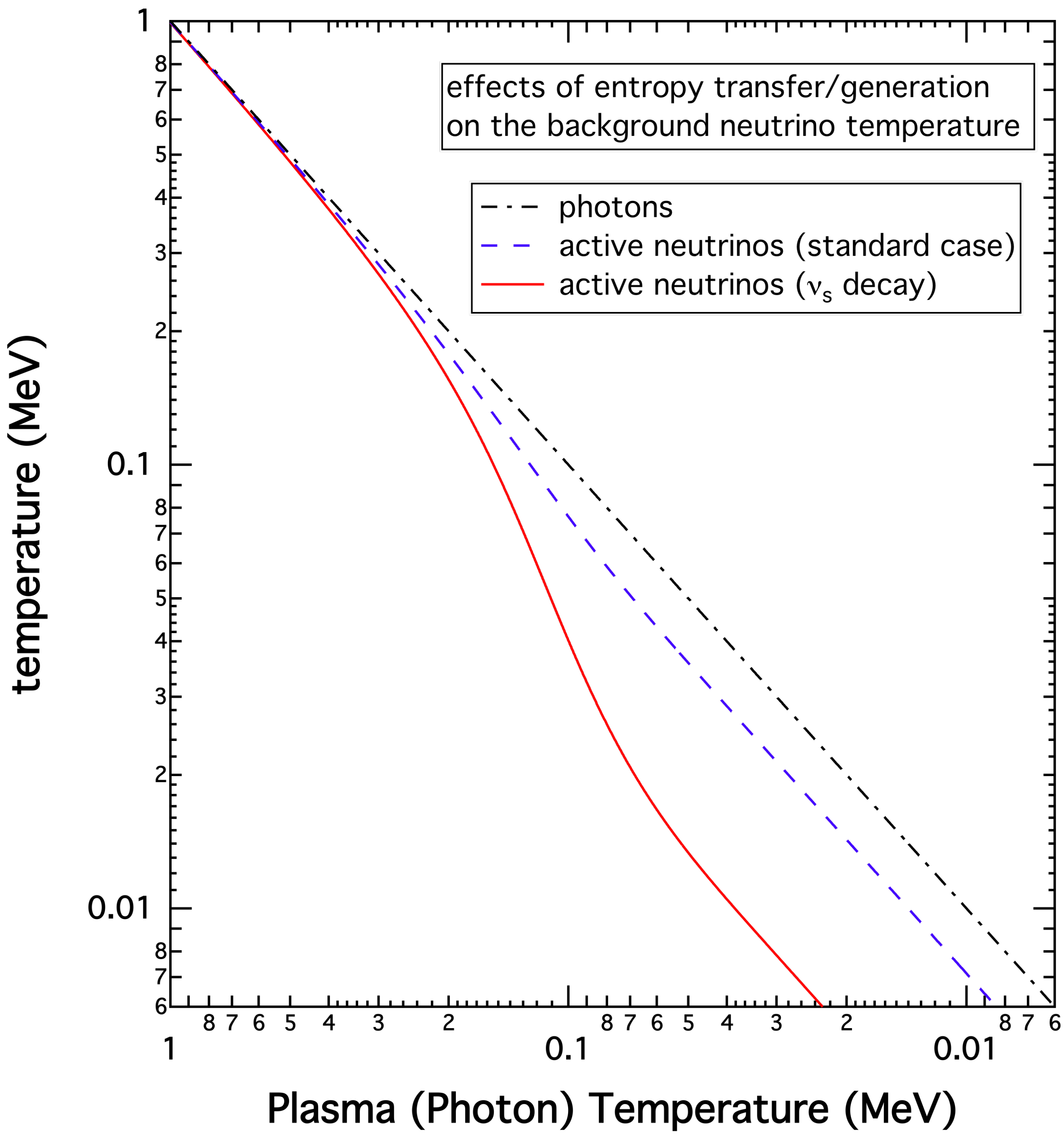
in this case:

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

where entropy-per-baryon is carried by radiation

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


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



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

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

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

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

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

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

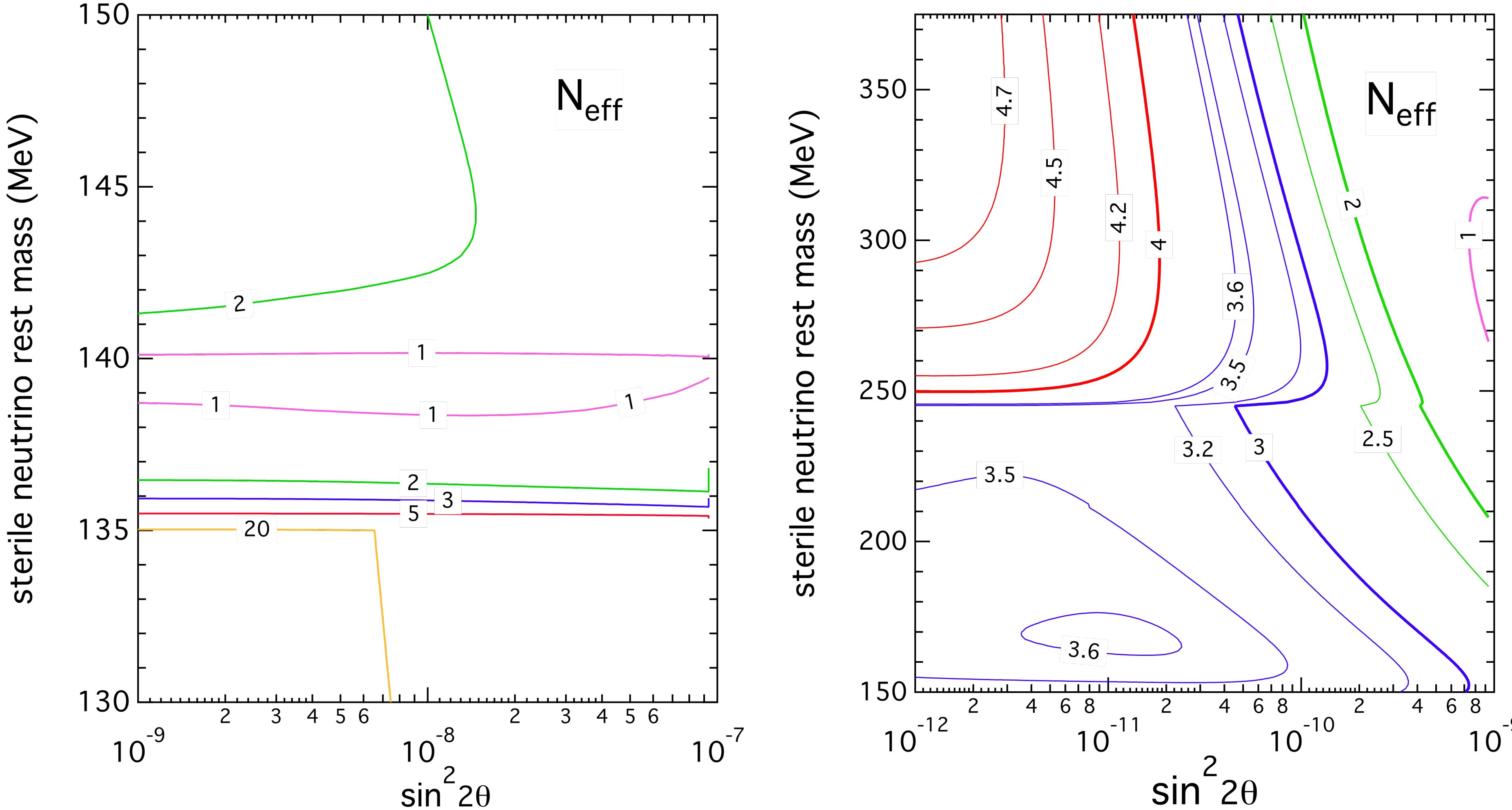
$$\text{contribution to } \mathrm{N_{eff}} \text{ reduced by } \; \frac{T_\nu^4}{(T_\nu^{\rm SBBN})^4} = F^{-4/3}$$

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

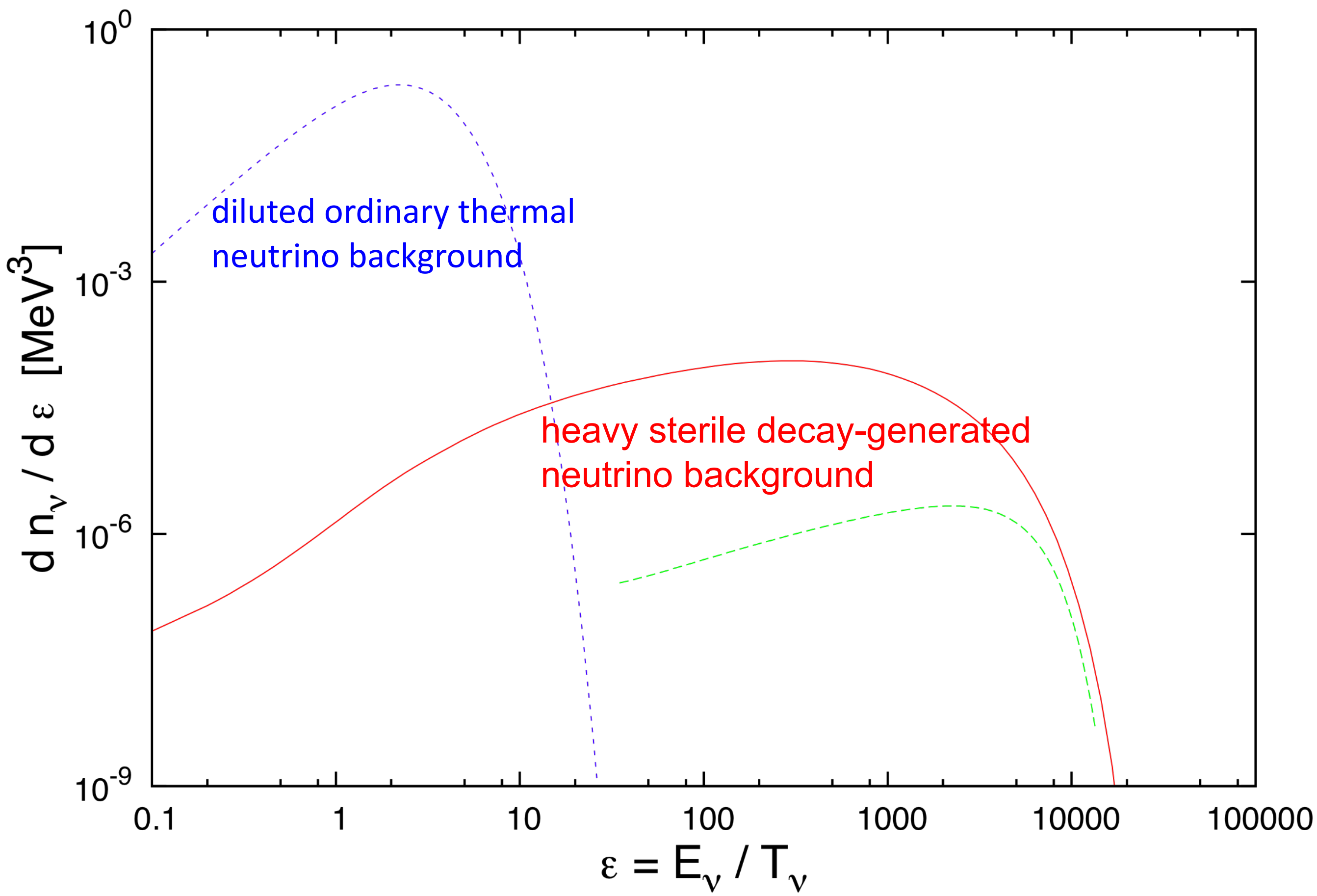
heavy sterile neutrino decay causes dilution of ordinary background neutrinos and generation of radiation energy density (N_{eff})

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



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

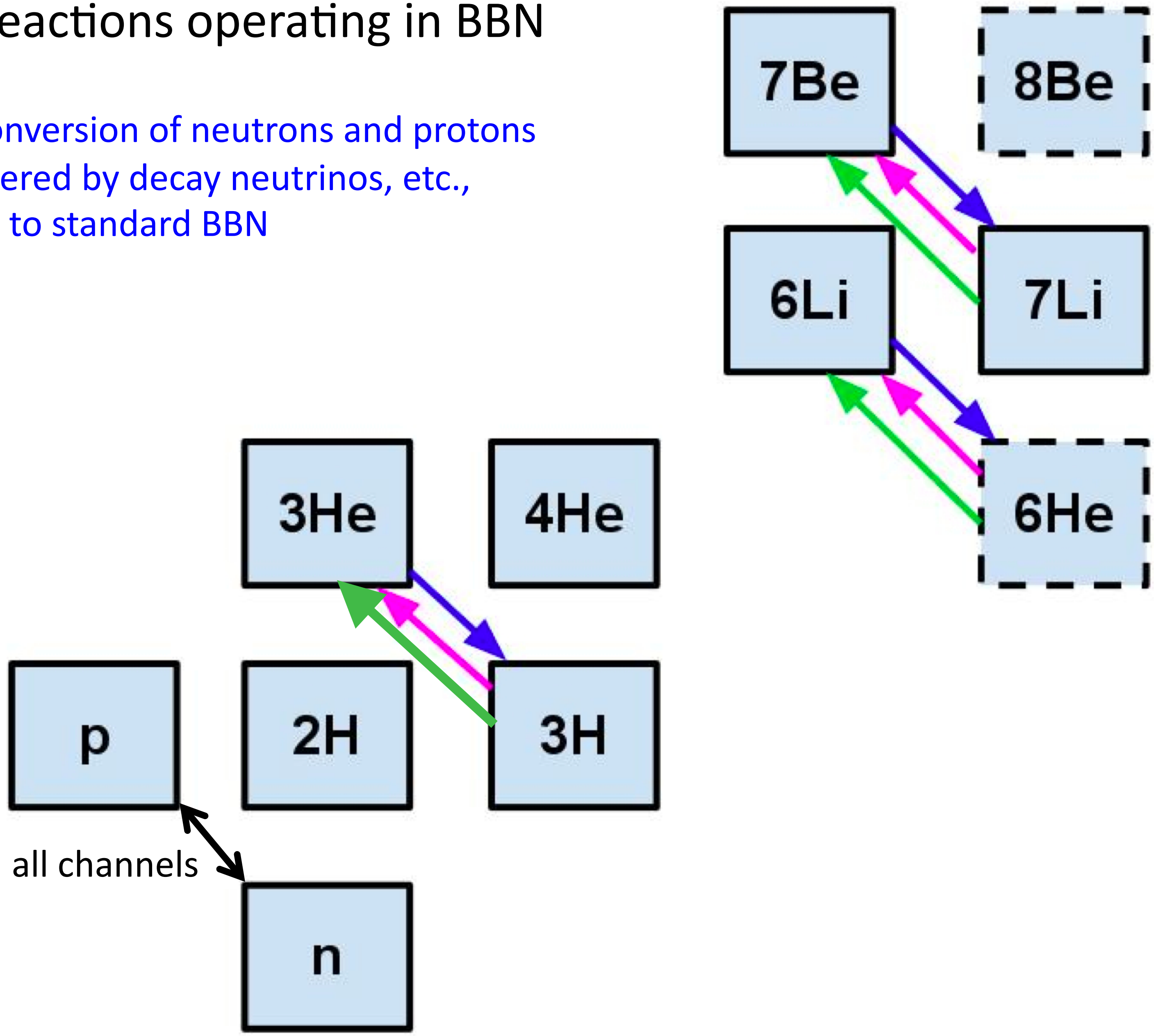
Must *self-consistently* couple all
strong, electromagnetic, and weak nuclear reactions
with the decaying heavy sterile neutrinos and their
energetic active neutrino decay products – GMF, E. Grohs, C. Kishimoto 2012

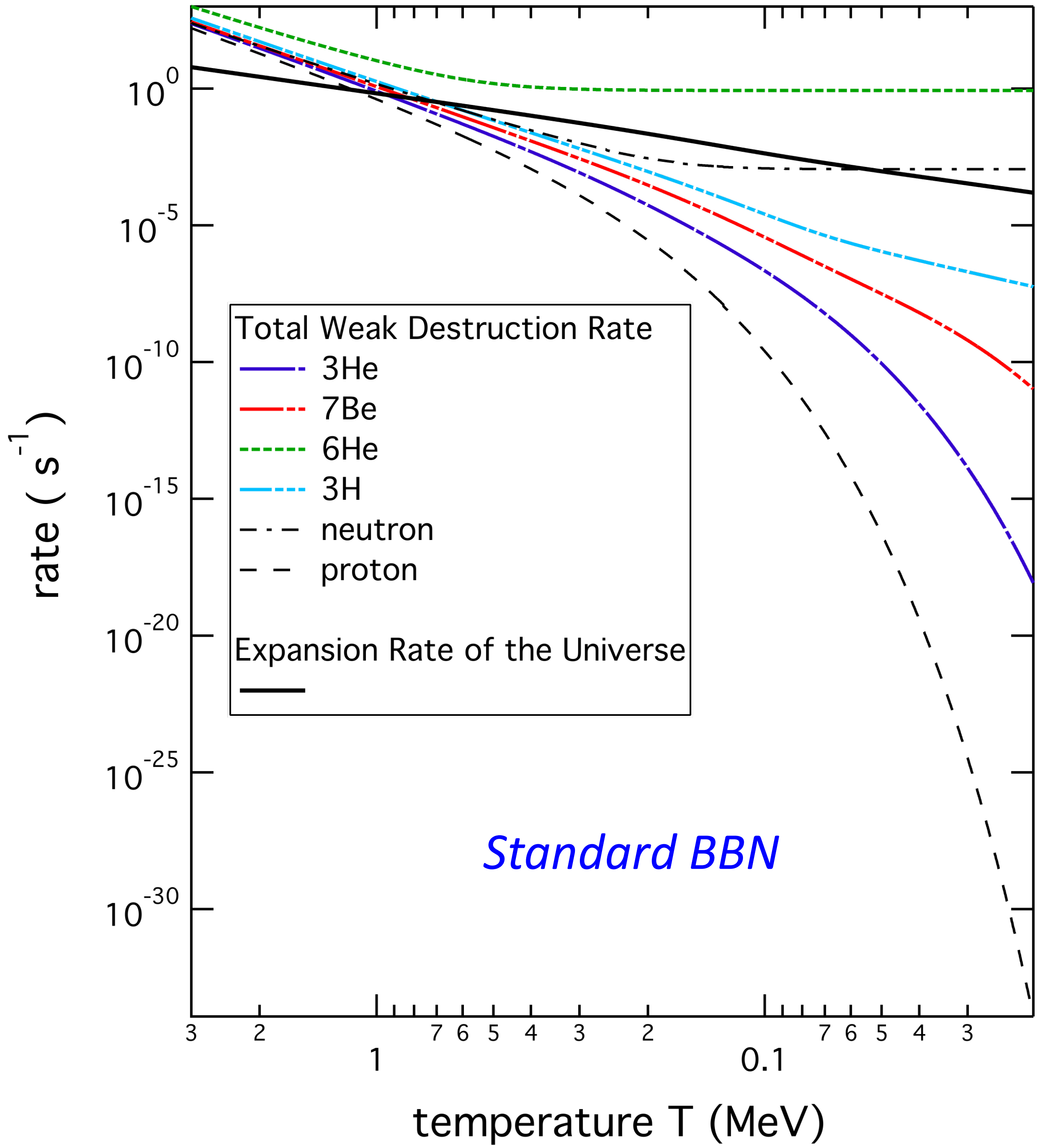
High energy (~ 100 MeV) decay active neutrinos

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

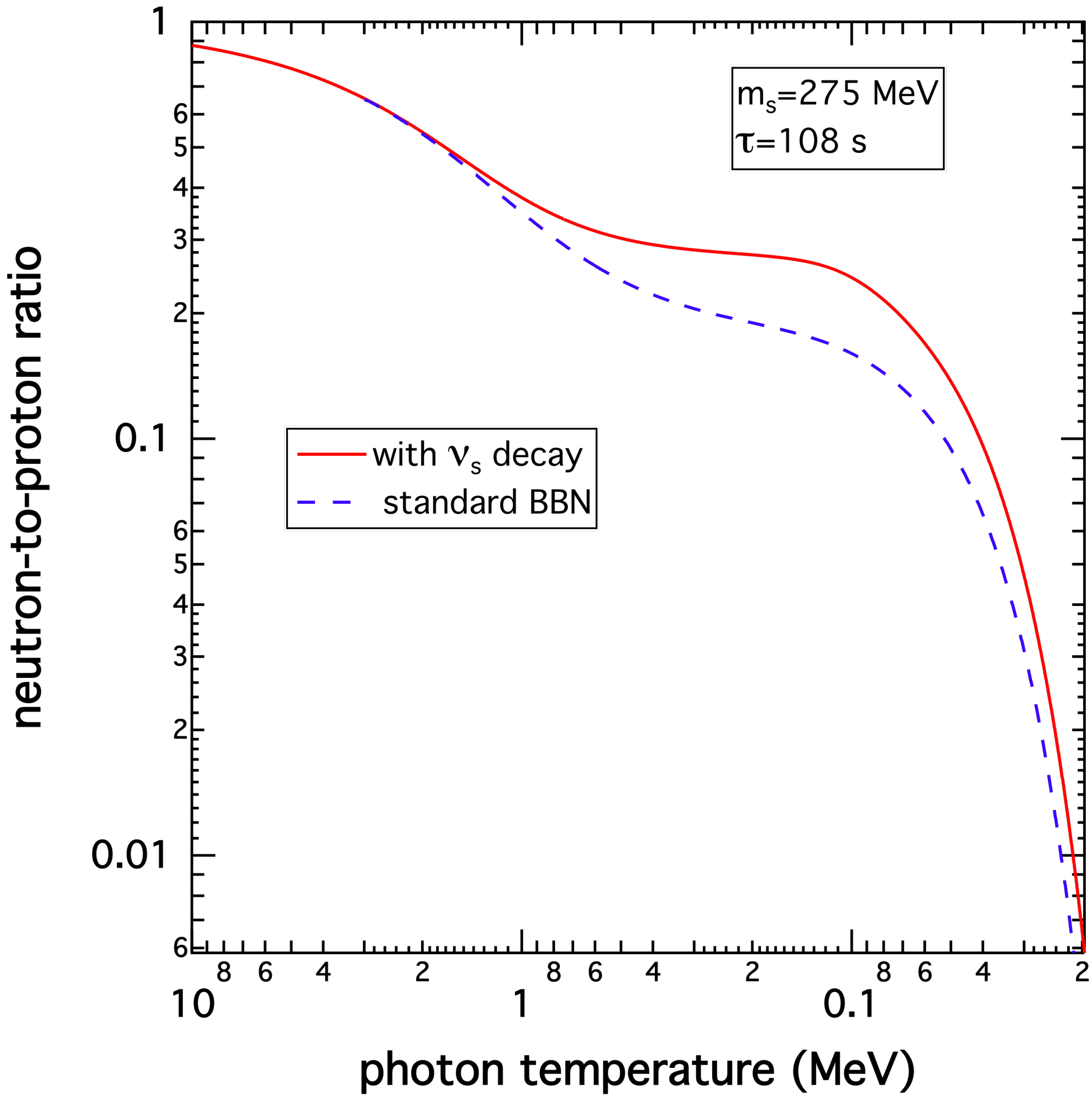
weak reactions operating in BBN

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



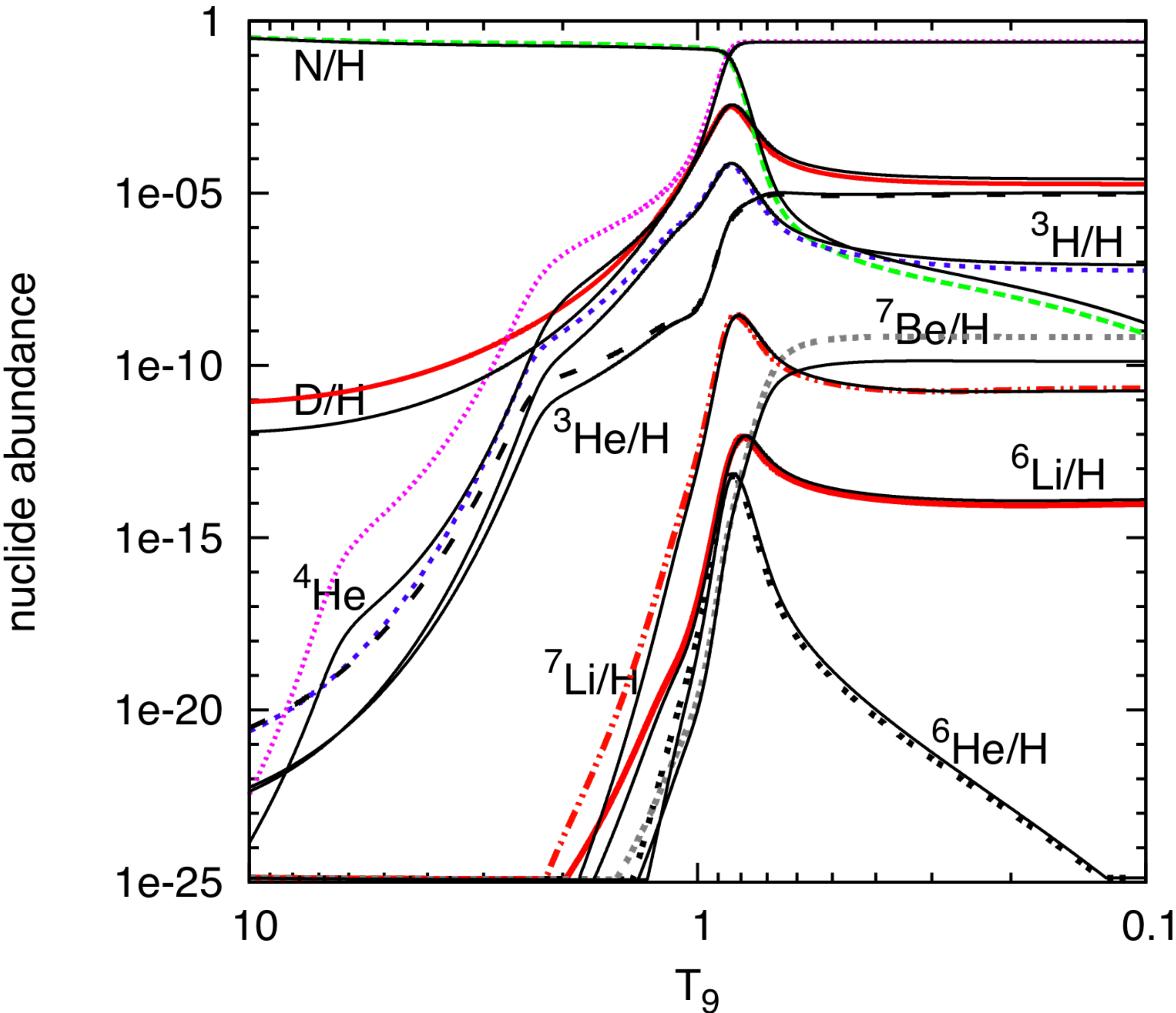


rate (s^{-1})
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
Total Weak Destruction Rate
3He
7Be
6He
3H
neutron
proton
Expansion Rate of the Universe
Standard BBN
3
2
1
7 6 5 4 3 2
0.1
7 6 5 4 3
temperature T (MeV)



neutron-to-proton ratio
photon temperature (MeV)
m_s=275 MeV
τ=108 s
with ν_s decay
standard BBN
1
0.1
0.01
6
5
4
3
2
10
8
6
4
2
1
0.1

Surprisingly subtle changes in BBN abundance yields! Why???



Fuller, Kishimoto, Smith, Grohs 2012

What about these decay scenarios where active neutrinos can be ~ 1000X more energetic than standard background neutrinos?

GMF, Grohs, Haxton, Kishimoto 2012

Note that the ^{7}Li gets made as ^{7}Be

possible enhanced weak reactions include the usual processes on free nucleons and . . .

$$\bar{\nu}_e + {}^7\mathrm{Be} \rightarrow {}^7\mathrm{Li} + e^+$$

$$\nu + \alpha \rightarrow {}^3\mathrm{He} + n + \nu$$

see Haxton & Qian 2011; Haxton et al. 1991

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

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

BBN considerations *will likely*
rule out most of the remaining sterile neutrino
rest mass/lifetime parameter space
that produces N_{eff} in the correct range.

But . . . measurement of:

- a neutrino mass which *exceeds* the cosmological bounds

- N_{eff} not equal to 3

is a smoking gun for Dilution and/or NEW physics!