Sterile Neutrinos:
Dark Matter and Supernovae

Cosmic Frontier

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VERY EXCITING **future** . . . because 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}, ^{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!

Three "hints" for light sterile neutrinos?

Intriguing, If Not Yet 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

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

Dark Radiation

Radiation energy density (relativistic particle) at γ-decoupling is parameterized by the so called "effective number of neutrino degrees of freedom".

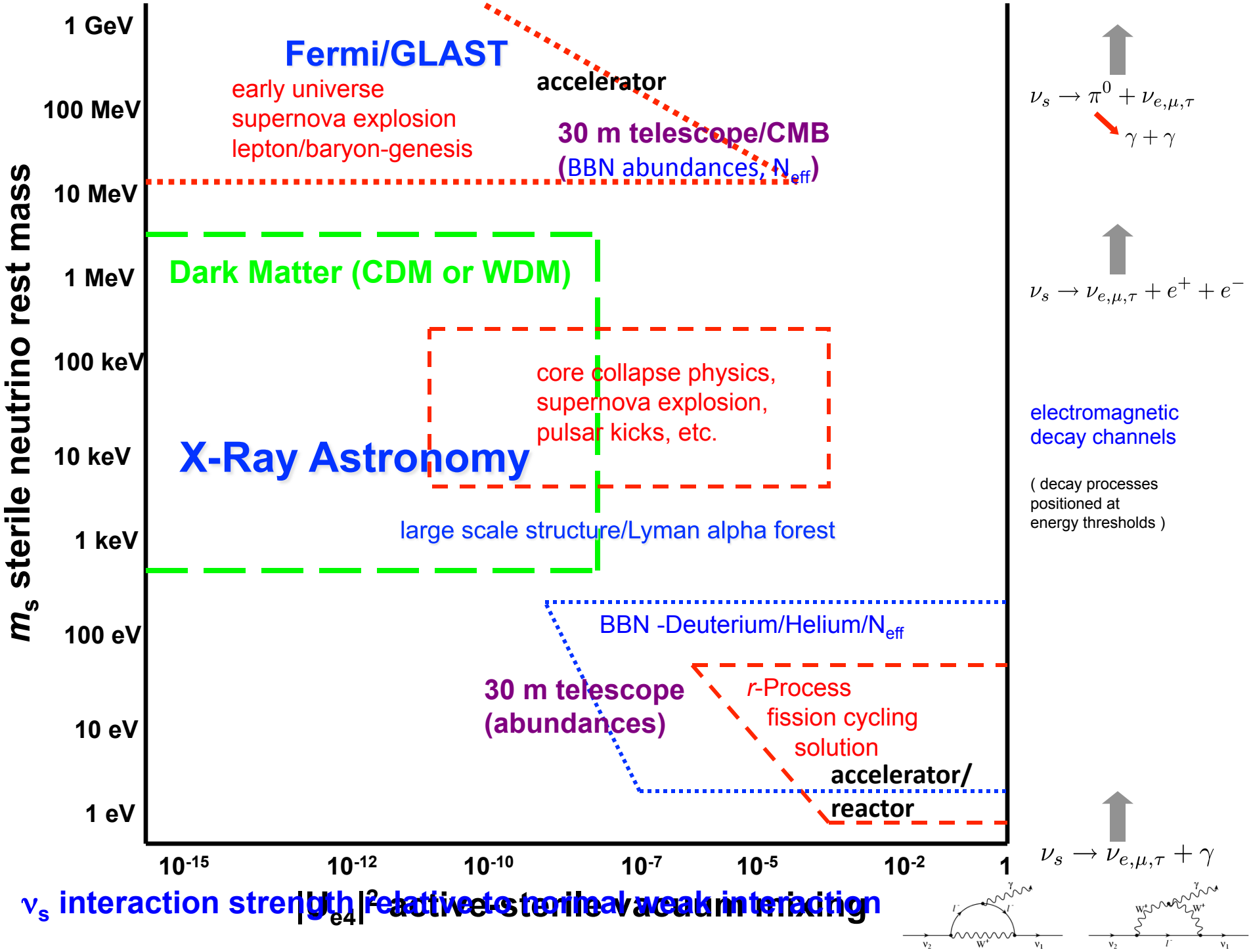
This is a dangerous misnomer as it may refer to energy density from ***any*** relativistic particles (e.g., super-WIMP decay products)

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

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

$$\begin{aligned} \text{Nine} - \text{year WMAP} \quad & {\rm N_{eff}} = 3.26 \pm 0.35 \\ \text{ACT} \quad & {\rm N_{eff}} = 2.78 \pm 0.55 \\ \text{SPT} - \text{SZ Survey} \quad & {\rm N_{eff}} = 3.71 \pm 0.35 \quad ({\rm H_0} \text{ and BAO priors}) \end{aligned}$$

Planck satellite will measure N_{eff} to better than 10% precision


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
$|U_{e4}|^2$ active-sterile vacuum mixing
ν_s interaction strength relative to normal weak interaction
$\nu_s \to \pi^0 + \nu_{e,\mu,\tau}$
$\gamma + \gamma$
$\nu_s \to \nu_{e,\mu,\tau} + e^+ + e^-$
electromagnetic
decay channels
(decay processes
positioned at
energy thresholds)
$\nu_s \to \nu_{e,\mu,\tau} + \gamma$

Decay into 7
possible channels

No threshold:

$$\nu_s \to 3\nu$$
$$\nu_s \to \nu + \gamma$$

Non-zero threshold:

$$\nu_s \to \nu + e^- + e^+$$
$$\nu_s \to \nu + \mu^- + \mu^+$$
$$\nu_s \to \nu + \pi^0$$
$$\nu_s \to \pi^\pm + e^\mp$$
$$\nu_s \to \pi^\pm + \mu^\mp$$

Pions and Muons decay instantaneously:

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

heavy "sterile" neutrino decay

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

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

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

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

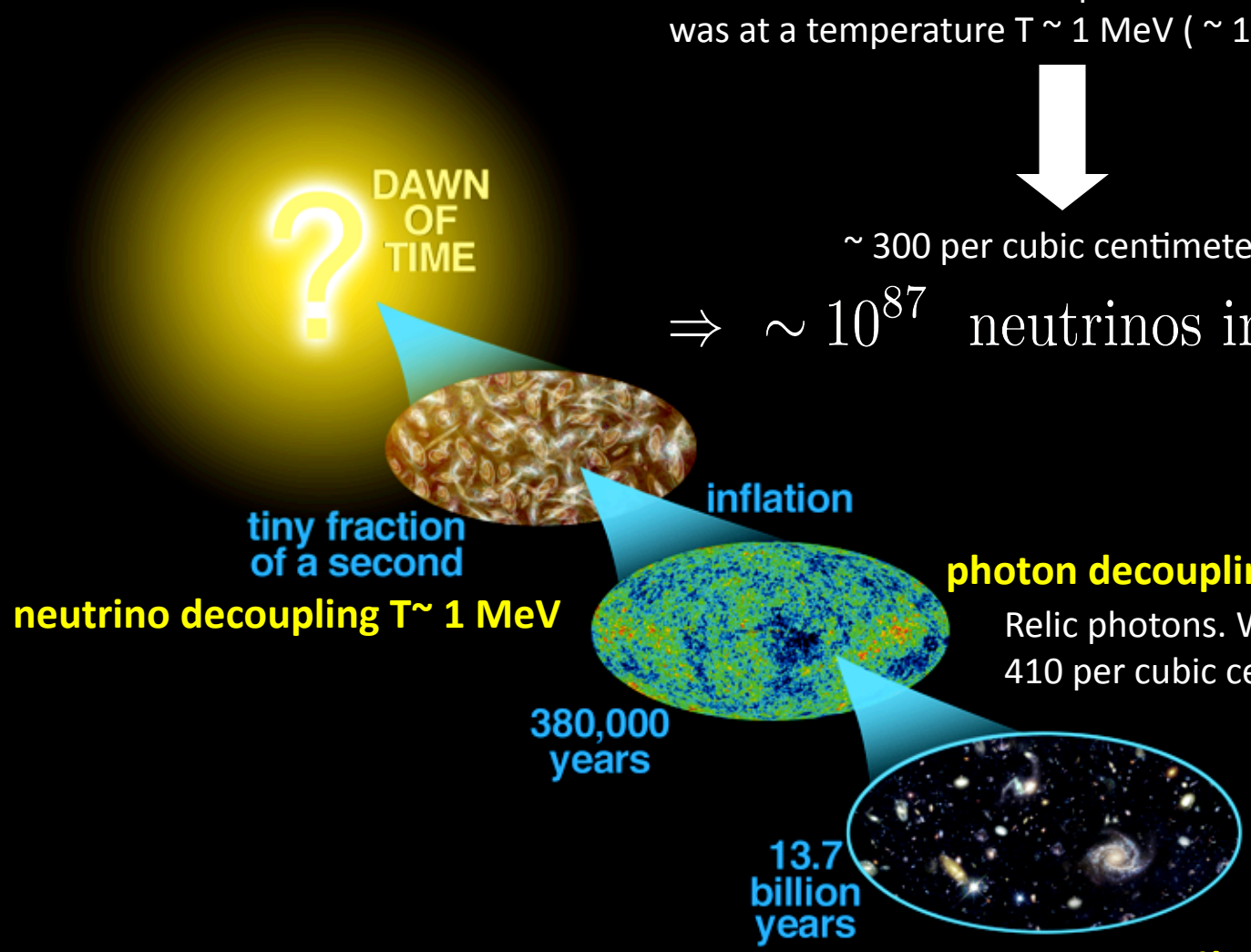
$$\nu_s \to \pi^+ + \mu^- \quad \to 2\gamma + 5\nu$$

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

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

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*

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 30 orders of magnitude weaker than the Weak Interaction.

However, they may be constrainable/detectable with existing and proposed X-Ray and Gamma-Ray observatories.

Sterile Neutrino Dark Matter ???

see review by Alex Kusenko: *Physics Reports* **481**, 1 (2009)

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
T. Asaka, S. Blanchet, M. Shaposhnikov, Phys. Lett. B **631**, 151 (2005)

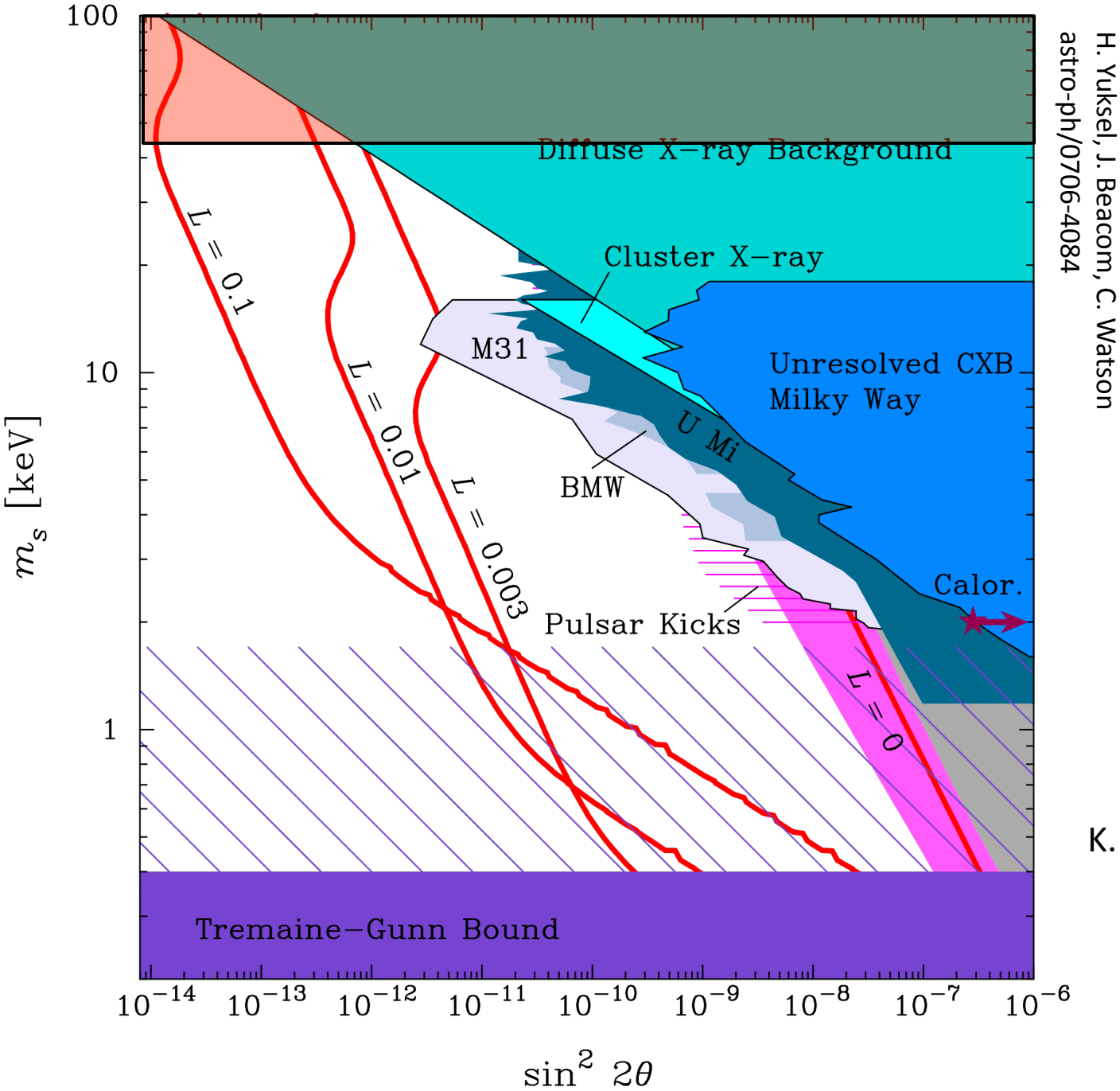
lepton number-enhanced decoherence

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)



H. Yuksel, J. Beacom, C. Watson
astro-ph/0706-4084

K. Abazajian 2012

Sterile Neutrinos --- many models 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 many models they are CDM, even for rest masses ~ 1 keV

Fuller, Kusenko, Kishimoto

Dilution-Generated Sterile Neutrino Dark Matter

Use *two* particles (perhaps two sterile neutrinos):

-both in thermal/chemical equilibrium at very high temperature

-both decouple at very high temperature (T > 100 GeV)

-the heavier particle, the **DILUTON** (dilution generator), decays prior to weak decoupling

-the lighter particle has its relic density diluted down to a range where it can be dark matter

(The dilution event "cools" the particle's energy spectrum, making it **COLDER** than its rest mass might lead you to believe!)

$\nu_s^{\rm DM}$, $\nu_s^{\rm diluton}$ decoupling, $T \gg 100\,{\rm GeV}$

$\nu_s^{\rm diluton}$ decay epoch

$e.g.,\ T \sim 1\,{\rm GeV},\ \tau \sim 10^{-7}\,{\rm s}$

dilution $= F_1$

Diluton decay prior to T ~ 1 MeV does not affect BBN or $N_{\rm eff}$

One or more very heavy sterile neutrino "dilutons" decay and dilute the relic density of a previously decoupled lighter sterile neutrino species

ν_e, ν_μ, ν_τ decoupling $T \sim 1\,{\rm MeV}$

$\nu_s^{\rm diluton}$ decay epoch

dilution $= F_2$

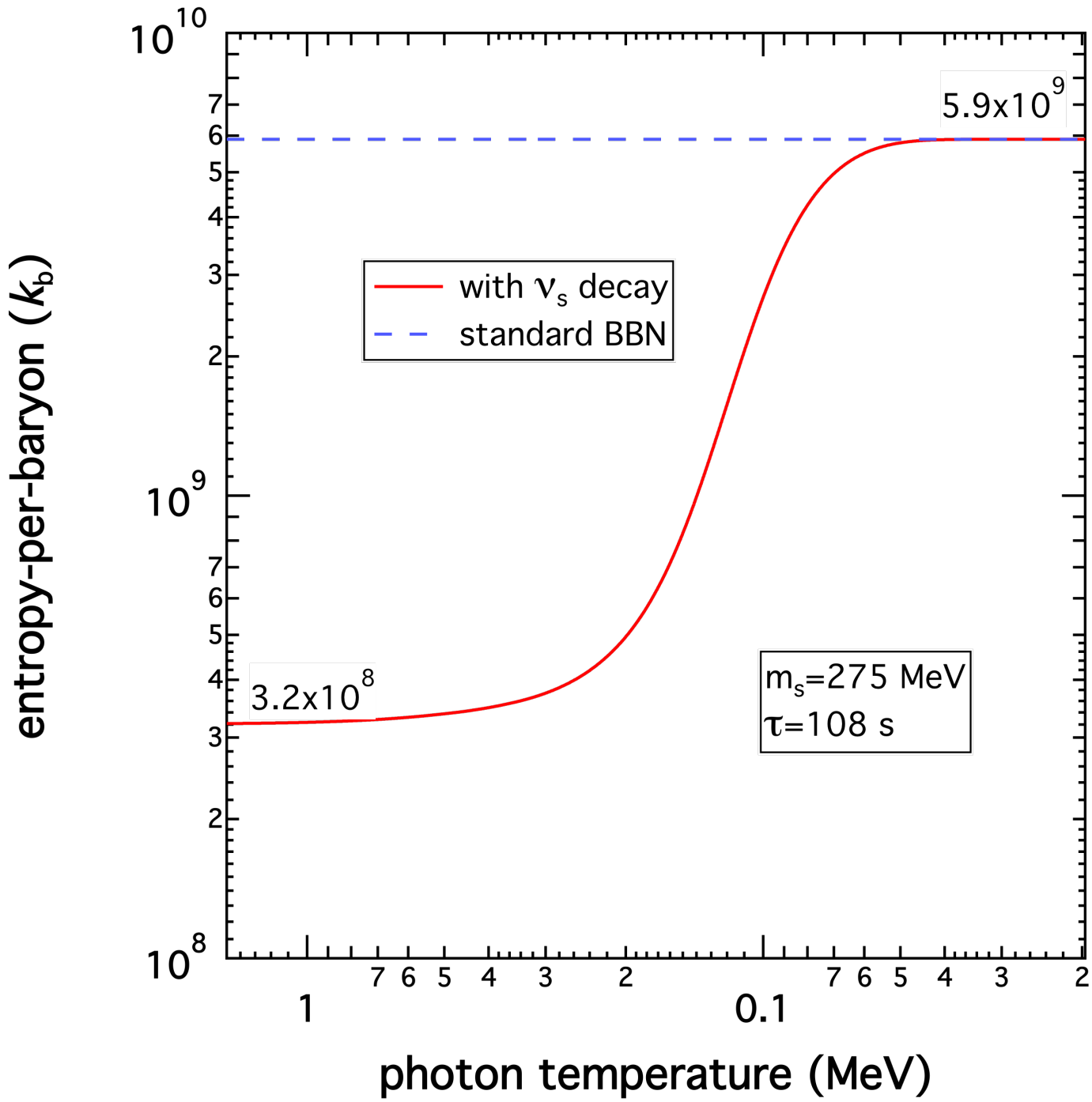
thermal BBN

$T \sim 10\,{\rm keV}$

$$F = \frac{\text{final } \textbf{entropy}}{\text{initial } \textbf{entropy}}$$

$\gamma -$ decoupling, $T \approx 0.2\,{\rm eV}$

cumulative decay dilution $\Rightarrow\ F = F_1 \cdot F_2$



prodigious entropy production!

in this case:

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

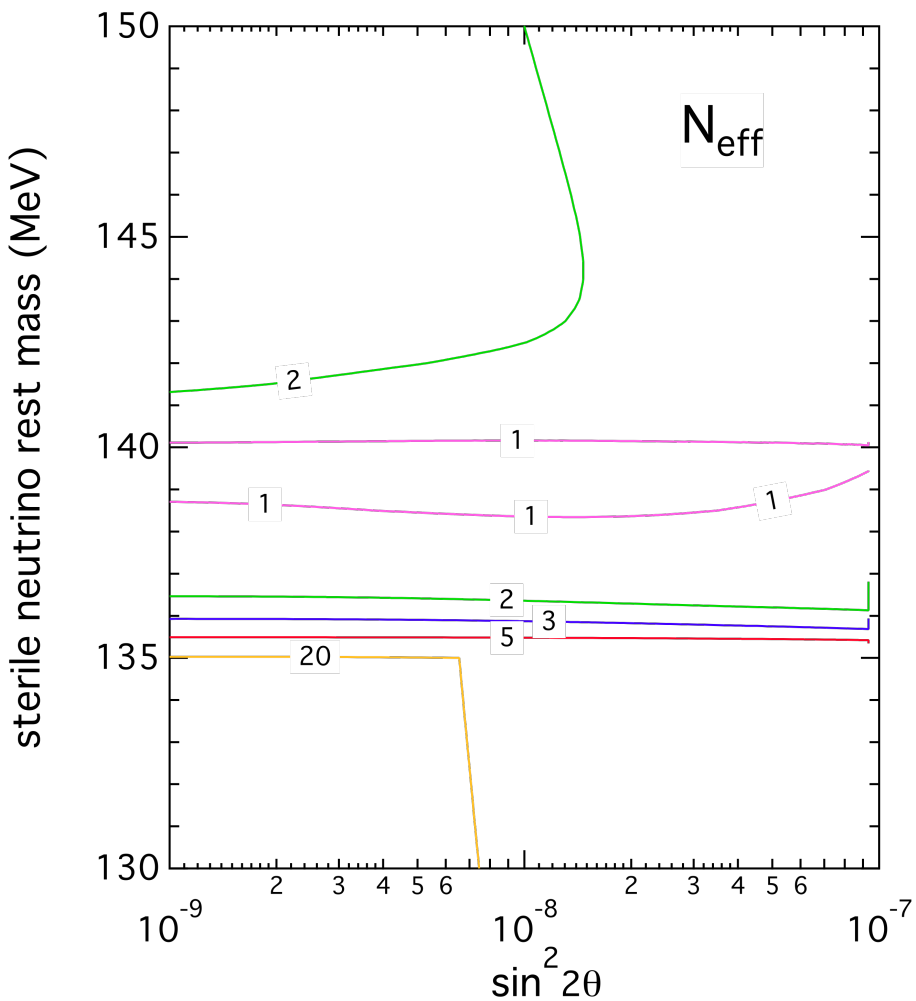
where entropy-per-baryon is carried by radiation

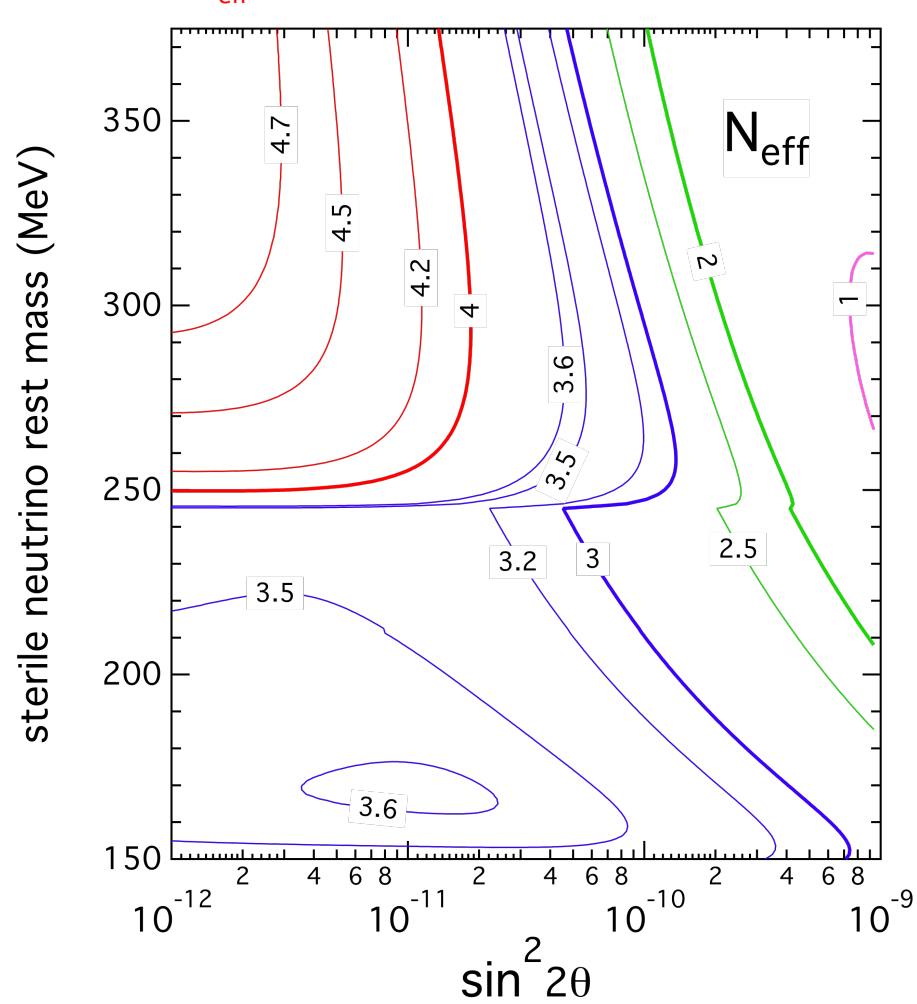
$$s = \frac{\left[\frac{2\pi^2}{45}\, g\, T^3\right]}{n_{\rm b}}$$

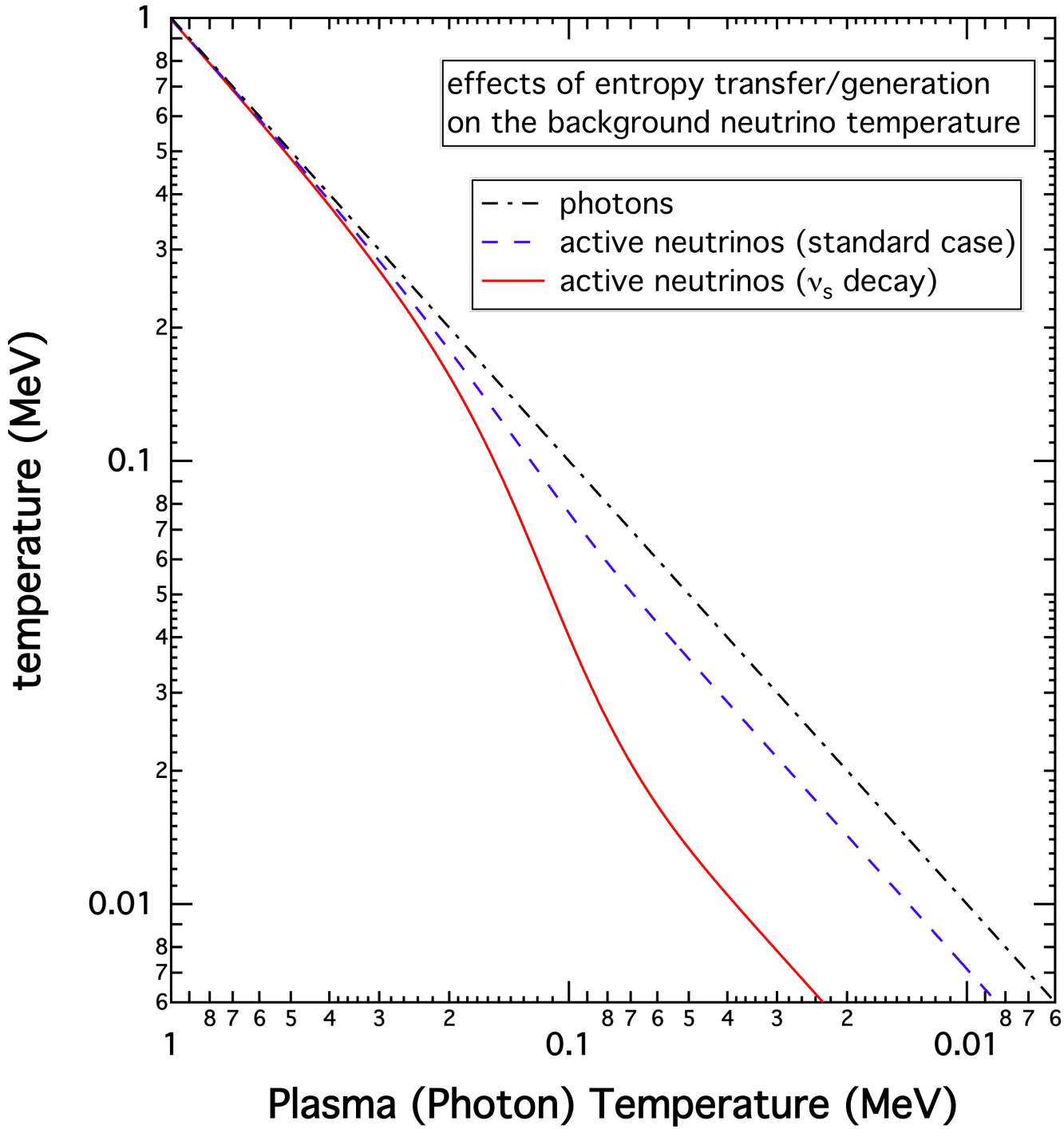
G.M.F., C. Kishimoto, A. Kusenko arXiv:1110.6479 astro-ph.CO

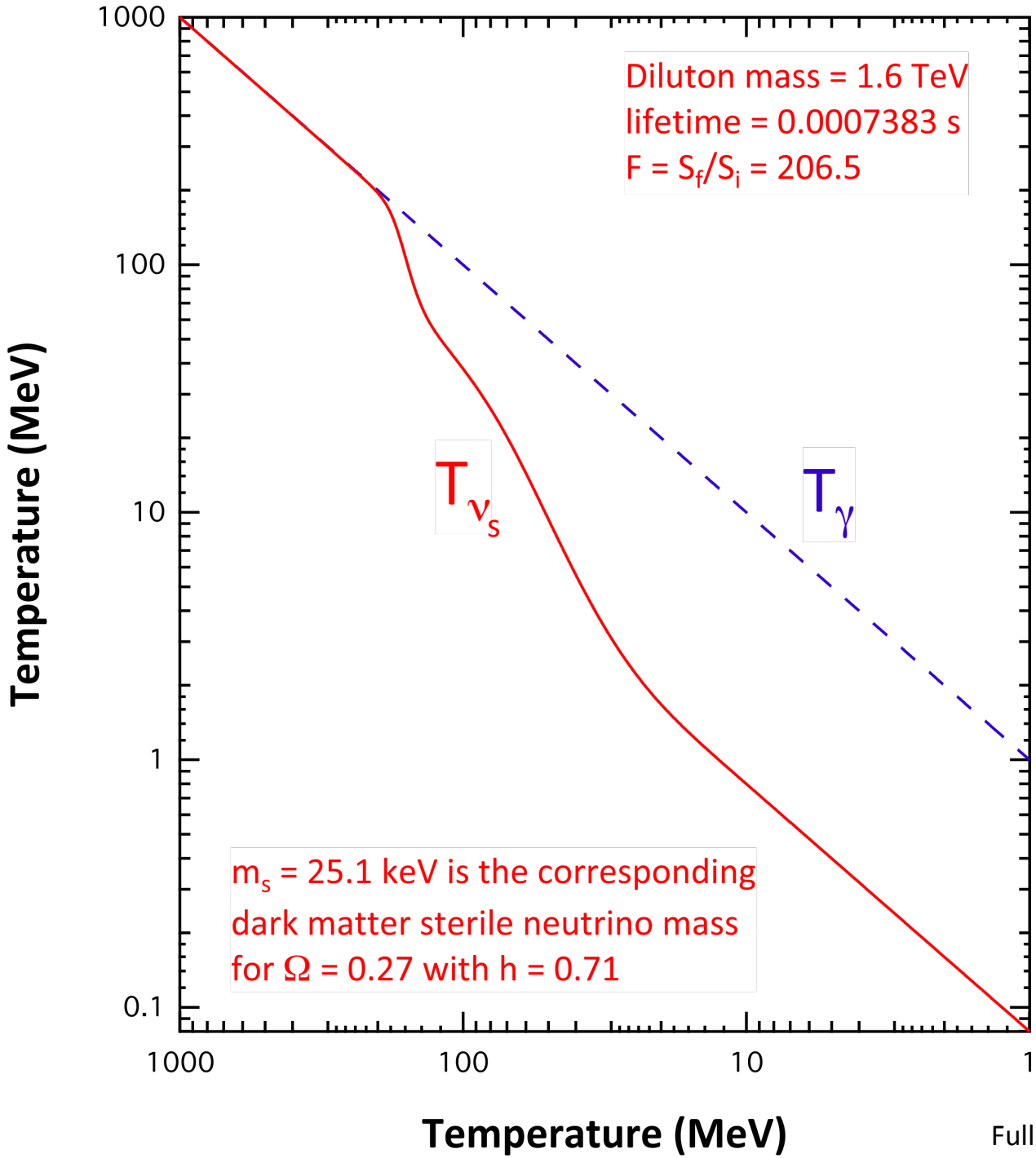
heavy sterile neutrino decay causes dilution of ordinary background neutrinos and generation of radiation energy density (N_{eff})

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






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

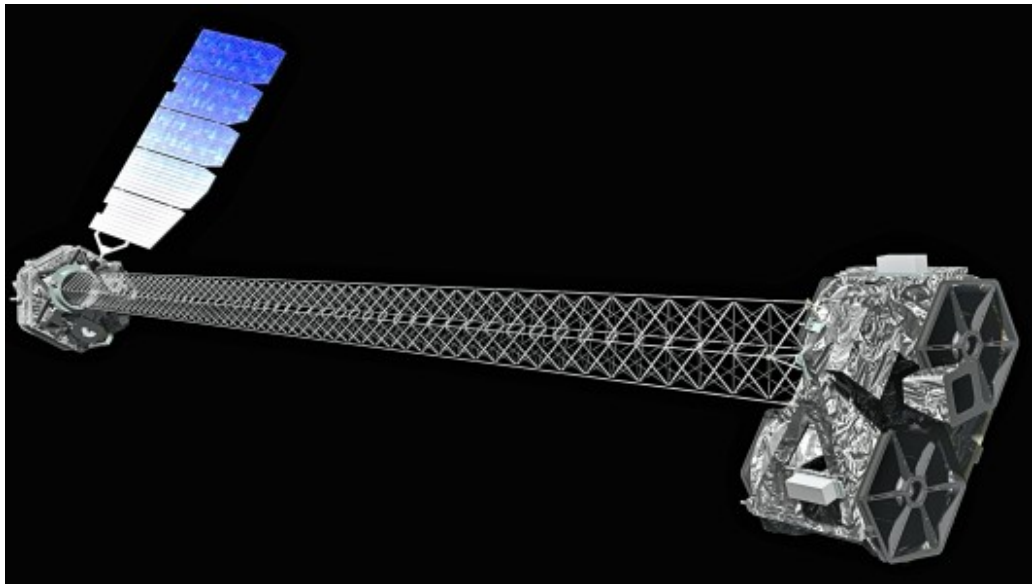


Fuller, Kusenko, Kishimoto

Heavy diluton-generated sterile neutrino dark matter:

rest masses m_s = ~ 10 keV to ~ 300 keV (*maybe higher*)

$$E_\gamma = \frac{m_s}{2}$$

Produce X-ray lines in a perfect range for **NuStar** (6 keV to 79 keV)

at higher X-ray energy, galaxy clusters become good targets for searching for sterile neutrino dark matter decay X-ray lines:
lots of dark matter in field of view; no expected higher energy atomic lines.