Neutrino Physics in Cosmology

NBIA-LANL Neutrino Quantum Kinetics in Dense Environments

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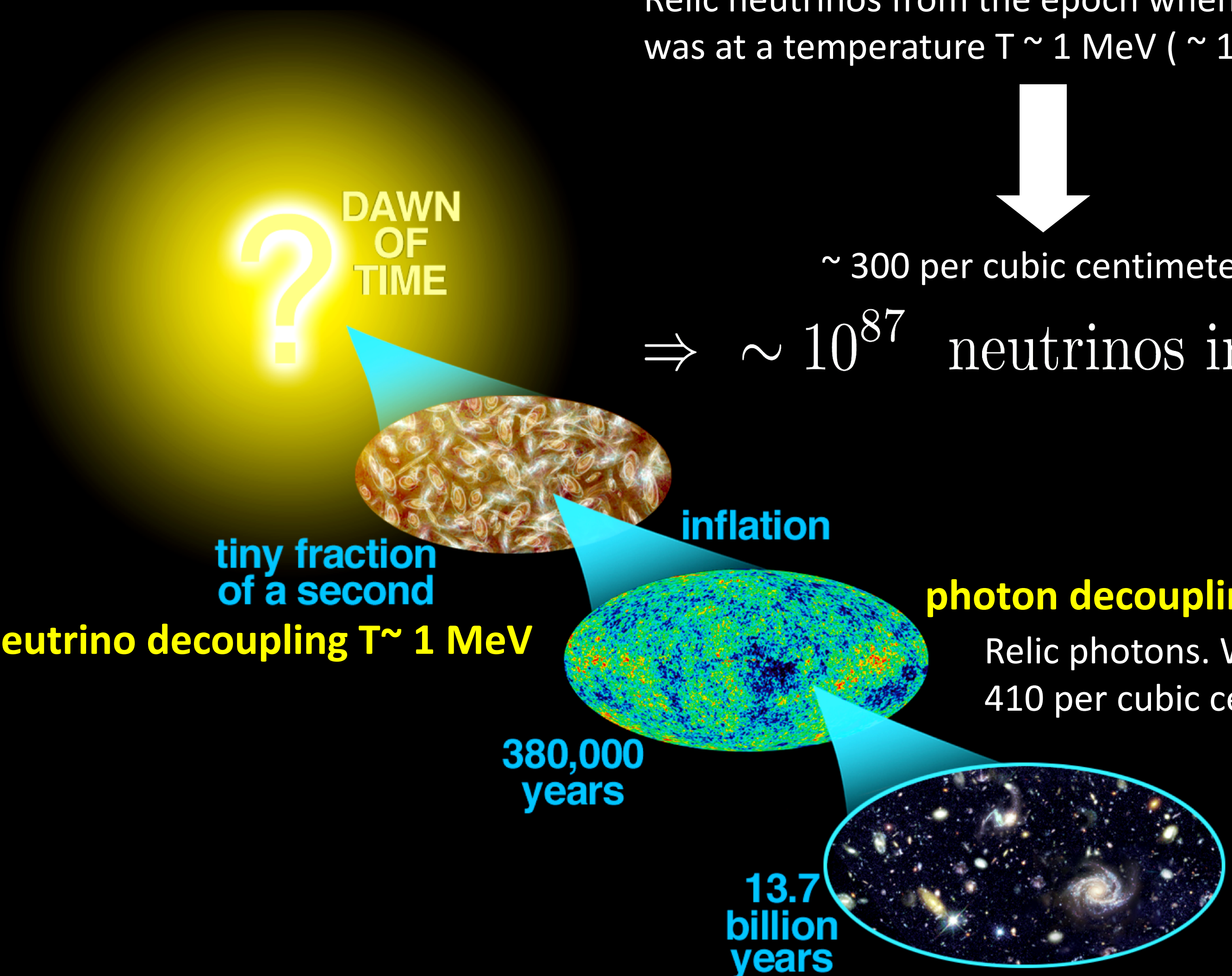
Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS)

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

~ 300 per cubic centimeter

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



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

Gravitation is weak

Gravitation governs the expansion of the universe

Consequently, the expansion rate is *SLOW*, and this allows *very weakly interacting particles* to affect the physics of the early universe

Neutrinos and Lepton Number Violation in Astrophysics

Leptogenesis/Baryogenesis:

Baryon Number: $\eta = (n_{\mathrm{b}} - n_{\bar{\mathrm{b}}})/n_\gamma \approx 6.1 \times 10^{-10}$ (measured in CMB)

Lepton numbers: $L_{\nu_e,\nu_\mu,\nu_\tau} \leq 0.1$ (He or D plus neutrino mixing parameters)

Compact Object Physics is ***exquisitely sensitive*** to *lepton number violating processes* and neutrino flavor/spin physics:

Nucleosynthesis (e.g., the **r-process**) is sensitive to neutrino flavor/spin/sterile
- role of neutrinos in core collapse SN and compact object mergers?

Cosmology/BSM neutrino sector physics/Dark Matter

Will approach a nearly over-determined situation with advent of

-Stage IV CMB polarization: N_{eff}, He, baryon-number, Σm_ν

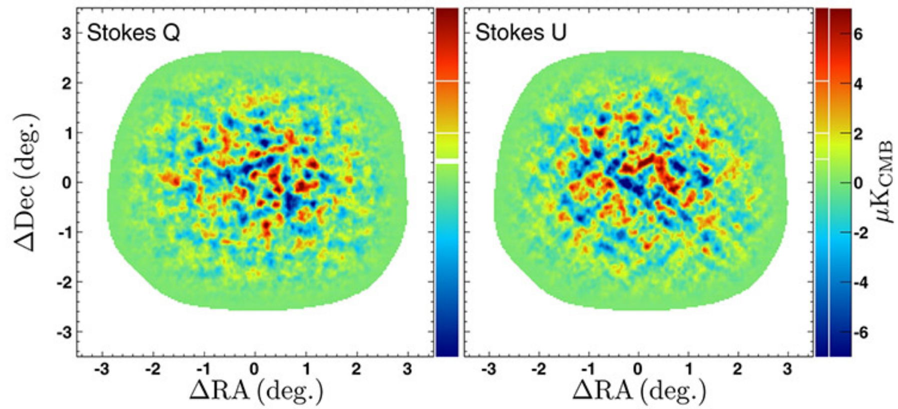
-30m-class telescopes: Primordial Deuterium to 2%

- X-ray (successor to Hitomi?) and gamma-ray observatories (Fermi)

Weak Decoupling/BBN = very sensitive to any alteration of the phasing of *scale factor/temperature/time*

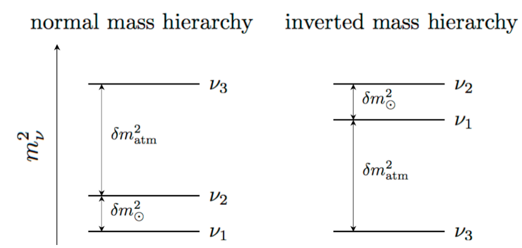
neutrino mass and *neutrino physics* will be key science drivers for ***Stage IV Cosmic Microwave Background***

Simons Observatory



Stage IV CMB (∼ 500,000 detectors):

Neutrino Mass — 15 meV sensitivity for Σm_ν at 1σ.



Radiation Energy Density – Neutrino energy spectrum — 0.02 sensitivity for $N_{\rm eff}$ at 1σ.

0.027 in Stage 4 *Science Book*

0.01 ?? See N. Sehgal et al. 2019 *Astro2020*

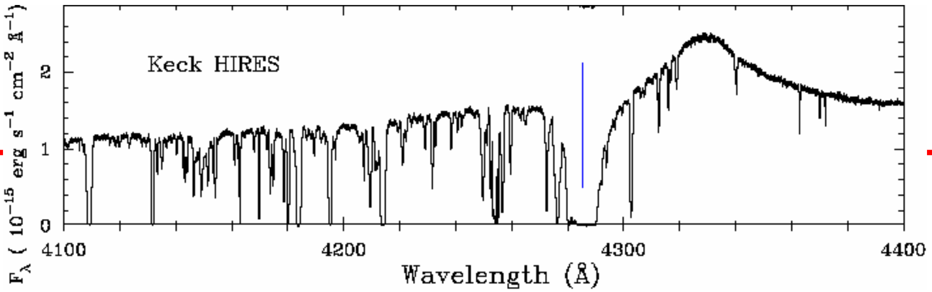
Primordial Deuterium Abundance

From observations of isotope-shifted Lyman lines in the spectra of high redshift QSO's.

See for example: J.M. O'Meara, D. Tytler, D. Kirkman, N. Suzuki, J.X. Prochaska, D. Lubin, & A.M. Wolfe
Astrophys. J. **552,** 718 (2001)

D. Kirkman, D. Tytler, N. Suzuki, J.M. O'Meara, & D. Lubin
Astrophys. J. Suppl. Ser. **149,** 1 (2003)

M. Pettini & R. Cooke, *MNRAS* **425**, 2477-2486 (2012)
R. Cooke et al. (2018)



E. Grohs' slide

CURRENT STATE OF COSMOLOGICAL NEUTRINO OBSERVABLES

Number of Relativistic DOF, Planck XIII, 2015

$$N_{\rm eff} = 3.04 \pm 0.33 \;\; (2\sigma)$$

Sum of the Neutrino Masses, Planck XIII, 2015

$$\Sigma m_\nu < 0.194\,{\rm eV} \;\; (2\sigma)$$

Primordial Mass Fraction of Helium, Aver et al, 2015

$$Y_{\rm P} = 0.2449 \pm 0.0040 \;\; (1\sigma)$$

Primordial Abundance of Deuterium, Cooke et al, 2018

$$10^5({\rm D/H}) = 2.527 \pm 0.030 \;\; (1\sigma)$$

turning precision measurements of the

CMB + Nuclear Abundances

into probes of the

CνB and BSM physics

The "tool" we are developing will help leverage an *increased space for discovery*[*]
from a combined analysis of the cosmological observables and laboratory experiments, e.g., tritium endpoint, $0\nu\beta\beta$-decay,
short baseline and reactor-based neutrino oscillation studies, dark sector physics probes.

[*]Roger Blandford's terminology

history of the early universe through *weak decoupling*/*freeze-out*, BBN, γ-decoupling

$T \sim 1\,\mathrm{MeV};\;\; t \approx 1\,\mathrm{s}$

$T \sim 10\,\mathrm{keV}; t \sim 3\,\mathrm{hours}$

$T_\gamma \approx 0.2\,\mathrm{eV};\;\; t \sim 3\times 10^5\,\mathrm{yrs}$
$z \approx 1100$

$z \sim 3 \qquad t \sim 2\,\mathrm{Gyr}$

energy exchange between ν's, plasma

$\nu - \nu/e^{\pm}$ scattering

+

n/p-ratio

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

$\Longrightarrow$

nuclear reactions

$$Z\,p + N\,n \rightleftharpoons A\,(Z,N) + \gamma$$

freeze-out from NSE

low precision :
connect epochs by using N_{eff}
as the sole determinant of BBN

***high precision* Stage 4**
connect epochs by using N_{eff}, primordial D, He
with transport/QKE-derived
neutrino energy distribution functions
and consistent evolution of n/p

measure N_{eff}, primordial helium (*break the degeneracy between He & N_{eff}*)

and

deuterium abundances (*high precision with 30-m class telescopes – Cooke & Petini*)

. . . *an alluring feature of the early universe*
ripe for exploitation!

Any physics operating in the early universe which
alters the scale factor–time-temperature relationship, *a(t),*
during the weak decoupling/BBN epoch (T ~ 30 MeV to T ~ 20 keV)
will manifest as an altered neutrino spectral history which, in turn,
alters deuterium and helium production and N_{eff}

Can we find the fingerprints of BSM physics on D, ^{4}He, and N_{eff} (and Σm_ν) ?

The anticipated higher precision of CMB S4 (for helium and N_{eff})
and 30-m class telescopes (for deuterium) means we have to "***raise our game***"
in modeling the Standard Model + neutrino physics
in the weak decoupling/BBN epoch

Much of what I will talk about is work in

E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko
"Neutrino energy transport in weak decoupling and big bang nucleosynthesis"
Physical Review D **93**, 083522 (2016)

Other collaborators on this work : S. Shalgar, V. Cirigliano, L. Johns, D. Blaschke, M. Mina,
J. R. Bond, J. Myers, J.T. Li

Homogeneity and isotropy of the universe:

implies that *total energy* inside a co-moving spherical surface is constant with time.

total energy **= (kinetic energy of expansion) + (gravitational potential energy)**

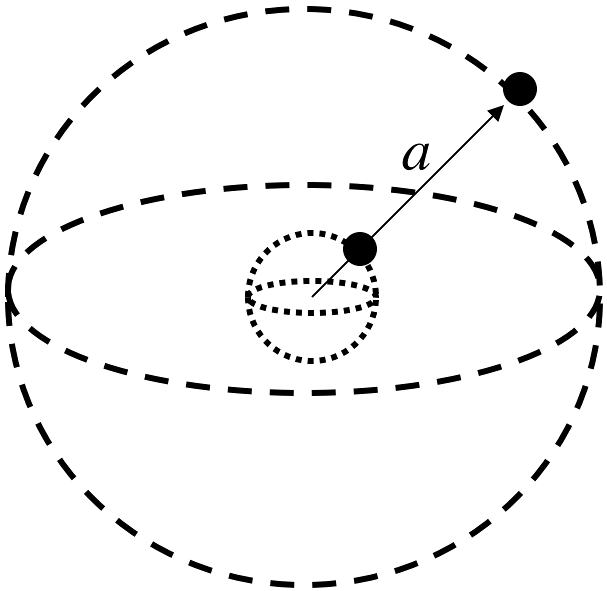
mass-energy density = ρ

test mass = m

$$\approx \tfrac{1}{2} m\dot{a}^2$$

$$\approx -\frac{G\left[\tfrac{4}{3}\pi a^3 \rho\right] m}{a}$$

$$\dot{a}^2 + k = \frac{8}{3}\pi G \rho\, a^2$$



total energy > 0 **expand forever** k = -1

total energy $= 0$ **for** $\rho = \rho_{crit}$ k = 0

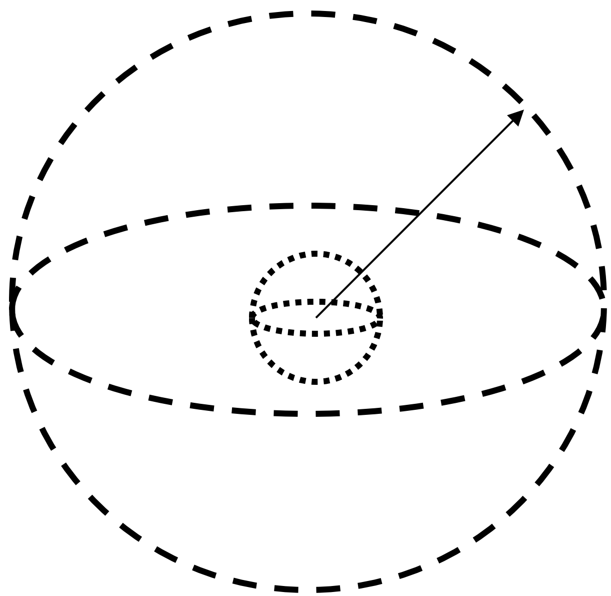
total energy < 0 **re-collapse** k = +1

$$\Omega = \rho/\rho_{crit} = \Omega_{\gamma} + \Omega_{\nu} + \Omega_{\text{baryon}} + \Omega_{\text{dark matter}} + \Omega_{\text{vacuum}} \approx 1 \quad (\mathbf{k=0})$$

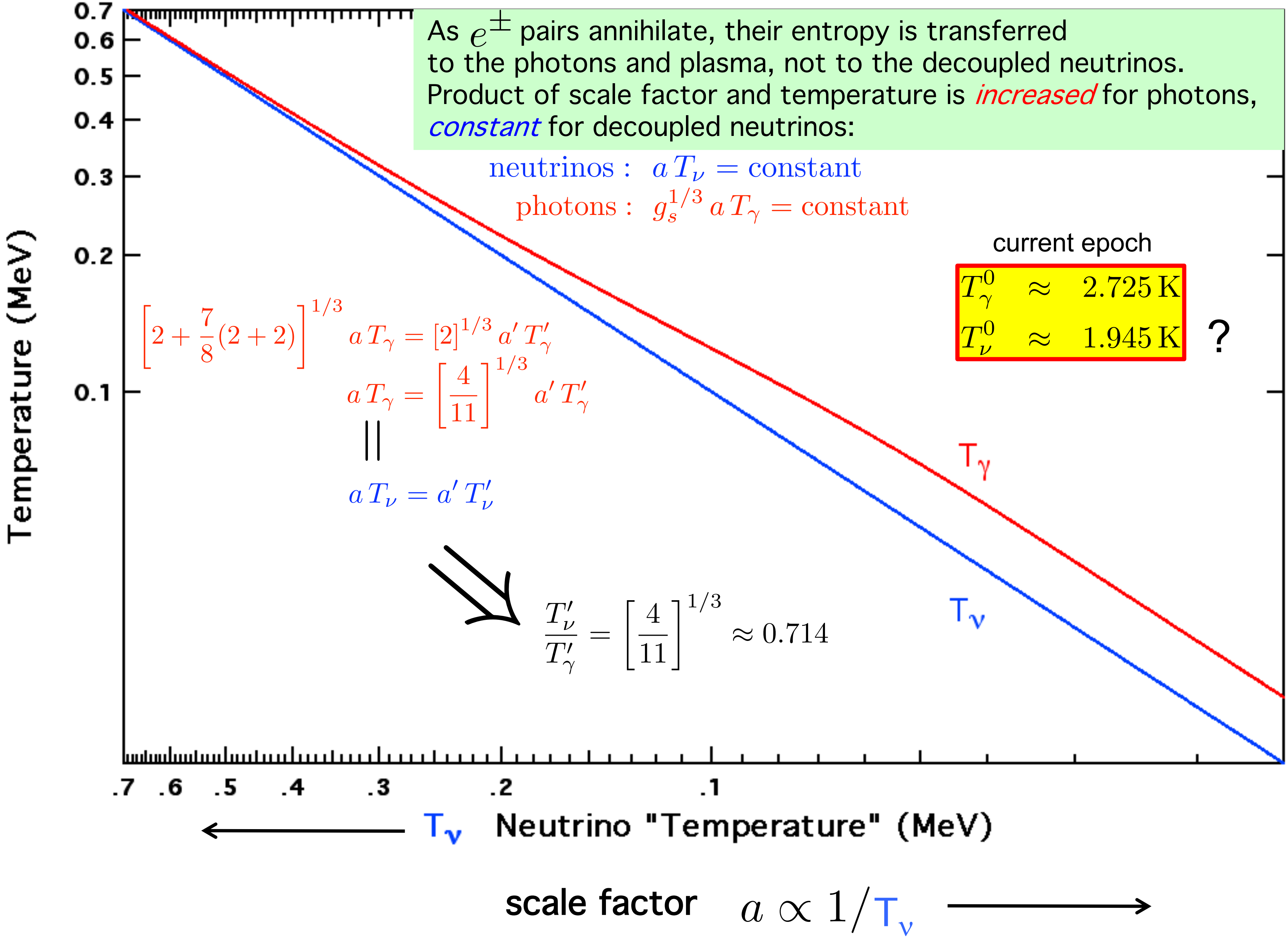
Symmetry is (nearly) everything in General Relativity

homogeneity and *isotropy* of this FLRW spacetime dictates that there be ***no spacelike heat flow*** or non-uniform heat sources: evolution is ***adiabatic***

entropy in a co-moving volume is conserved*



***Symmetry does not preclude *timelike* heat flows, e.g., from decaying particles *or* from non-equilibrium processes like decoupling ν's scattering on e^-/e^+**



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:
neutrinos : $a\,T_\nu = \text{constant}$
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
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Temperature (MeV)
.7 .6 .5 .4 .3 .2 .1
T_ν Neutrino "Temperature" (MeV)
scale factor $a \propto 1/T_\nu$

radiation energy density at the photon decoupling epoch

$N_{\rm eff}$ defined through

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

$$N_{\rm eff}^{\rm theory} = 3.046$$

e.g., Mangano et al. 2012

Polarization release Planck XIII (2015)

$N_{\rm eff} = 3.15 \pm 0.23$ (Planck TT+ low P + BAO)

$\sum m_\nu < 0.23\,{\rm eV}$ (Planck TT+ low P + lensing + BAO + JLA + H_0))

Claimed eventual 2% precision from CMB polarization data
– but don't actually measure N_{eff}

But cosmological neutrinos **cannot** be described by $N_{\rm eft}$ and $\sum m_\nu$ alone - see E. Grohs *et al.* (2014, 2015)

baryon number of universe → $$\eta \equiv \frac{n_{\rm b} - n_{\bar{\rm b}}}{n_\gamma}$$

From CMB acoustic peaks, and/or observationally-inferred primordial D/H:

$$\eta = 6.11 \times 10^{-10}$$

three lepton numbers →

$$\begin{cases} L_{\nu_e} \approx \dfrac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \\ L_{\nu_\mu} = \dfrac{n_{\nu_\mu} - n_{\bar{\nu}_\mu}}{n_\gamma} \\ L_{\nu_\tau} = \dfrac{n_{\nu_\tau} - n_{\bar{\nu}_\tau}}{n_\gamma} \end{cases}$$

From observationally-inferred ^{4}He and large scale structure and using *collective (synchronized) active-active neutrino oscillations* (Abazajian, Beacom, Bell 03; Dolgov et al. 03):

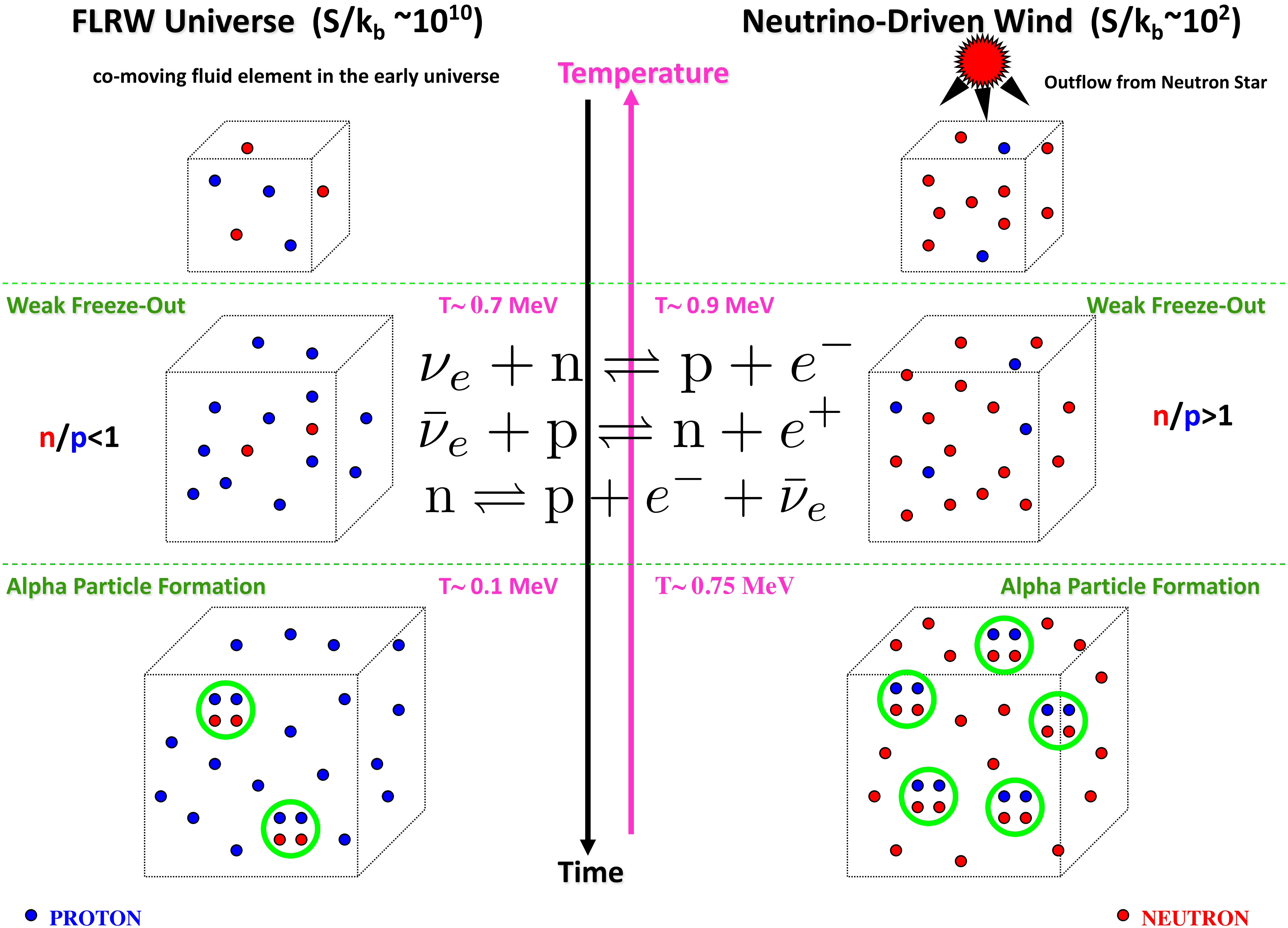
$$|L_{\nu_{\mu,\tau}}| \sim L_{\nu_e} < 0.15$$

In the words of Serpico & Raffelt (PRD 2005)…

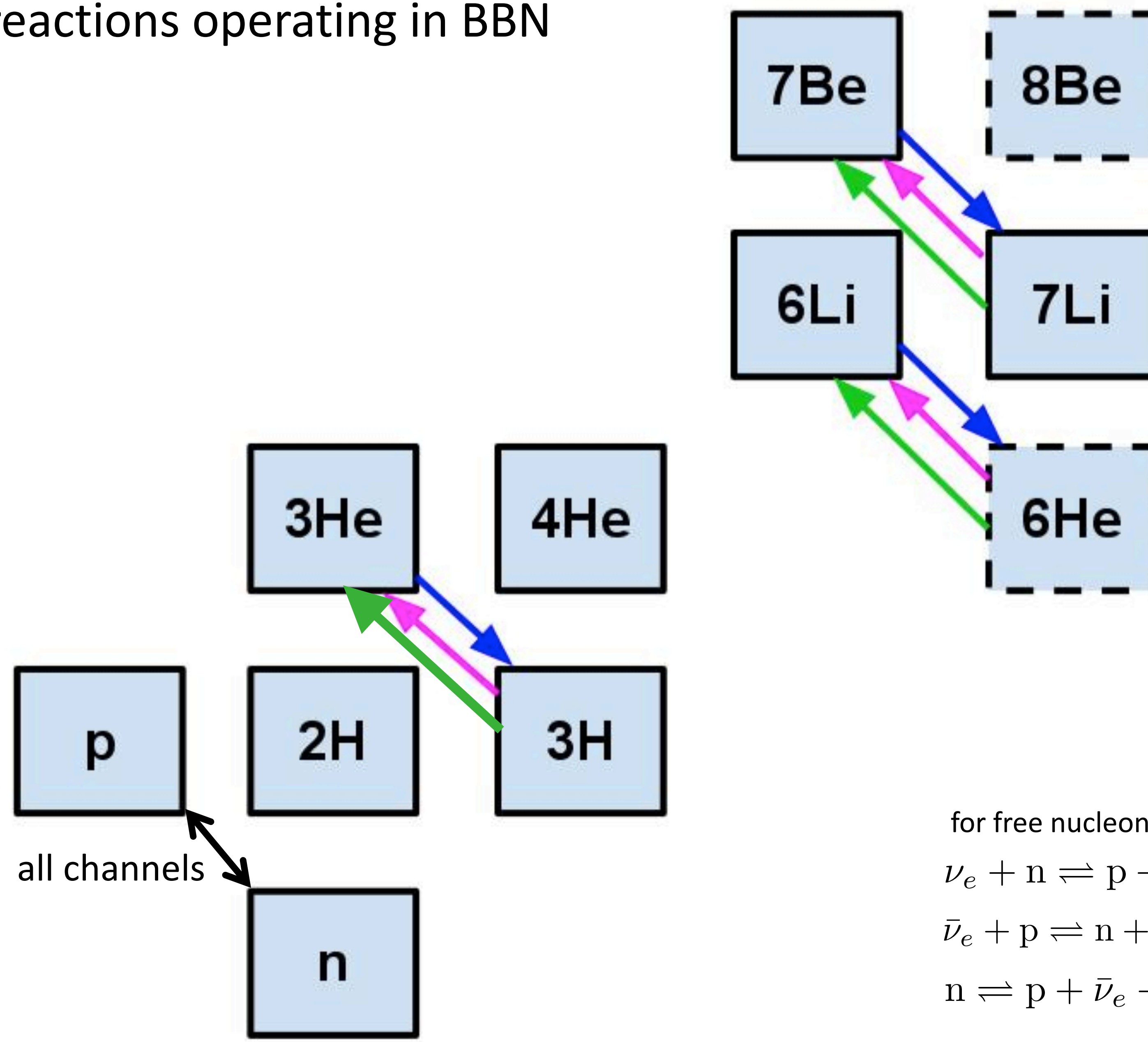
In summary, now that the cosmic baryon abundance has been extremely well determined by CMB observations and now that much about neutrino properties has been learnt by experiments, the role of BBN as a baryometer has shifted to that of the best available cosmic leptometer. Therefore, a more reliable $Y_{\rm p}$ determination is of much greater fundamental interest than the next round of more precise CMB baryon determinations.

So, for all we know right now . . .

L_ν may be several orders of magnitude larger than η


FLRW Universe (S/k$_b$ ~10^{10})
Neutrino-Driven Wind (S/k$_b$~10^2)
co-moving fluid element in the early universe
Temperature
Outflow from Neutron Star
Weak Freeze-Out
T~ 0.7 MeV
T~ 0.9 MeV
Weak Freeze-Out
$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$
$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$
$\mathrm{n} \rightleftharpoons \mathrm{p} + e^- + \bar{\nu}_e$
n/p<1
n/p>1
Alpha Particle Formation
T~ 0.1 MeV
T~ 0.75 MeV
Alpha Particle Formation
Time
PROTON
NEUTRON

weak reactions operating in BBN

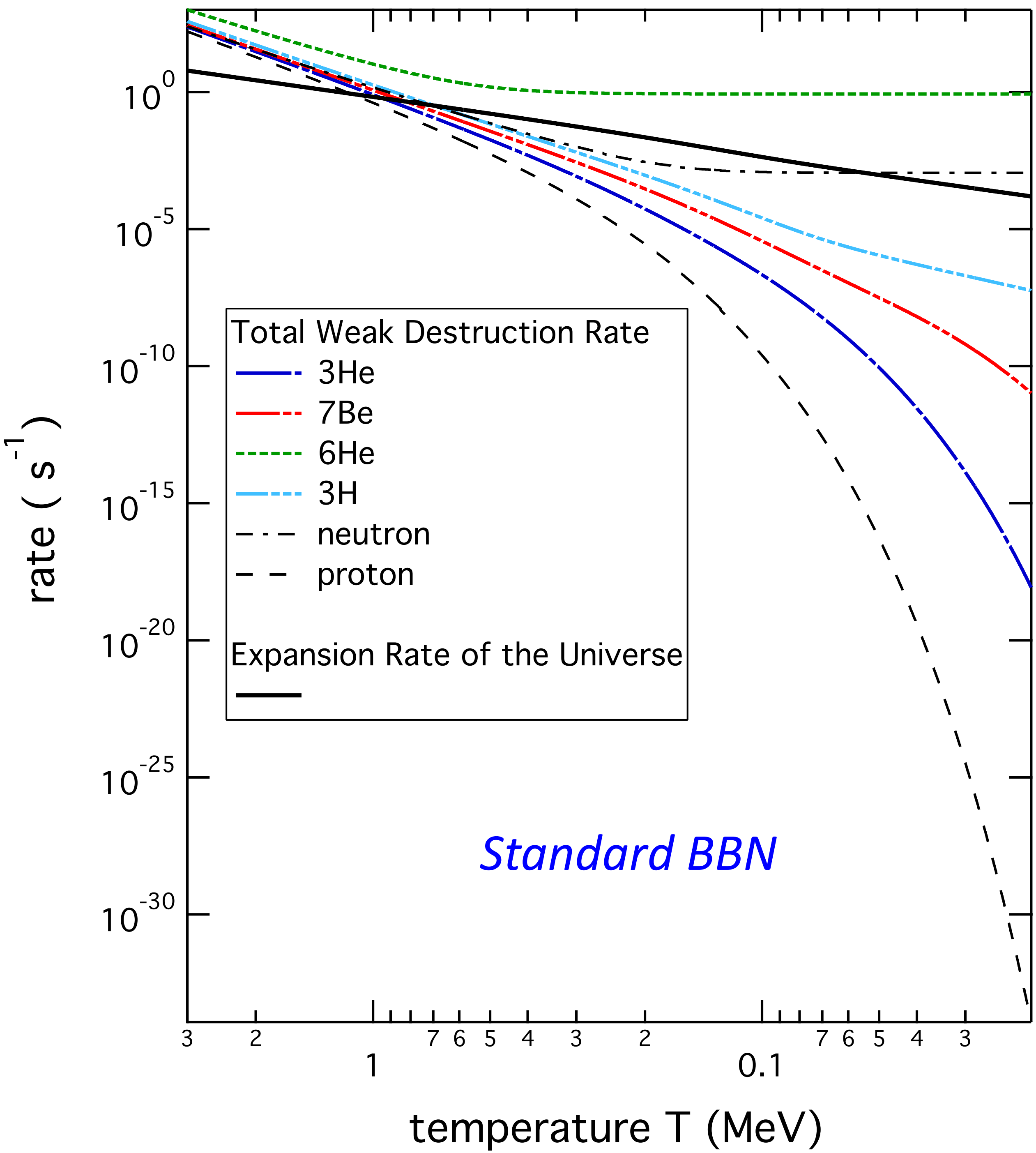


for free nucleons:

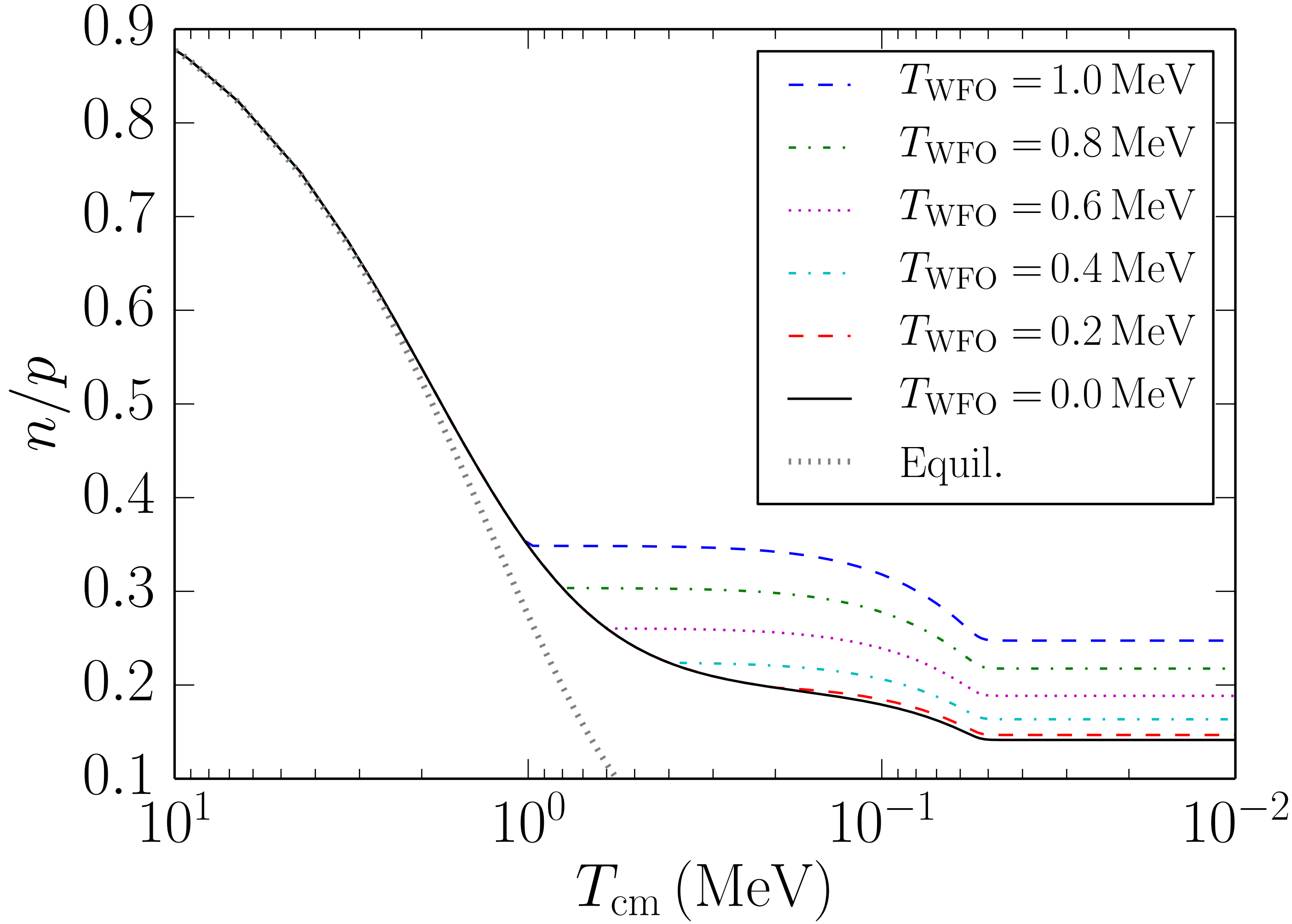
$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$

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

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



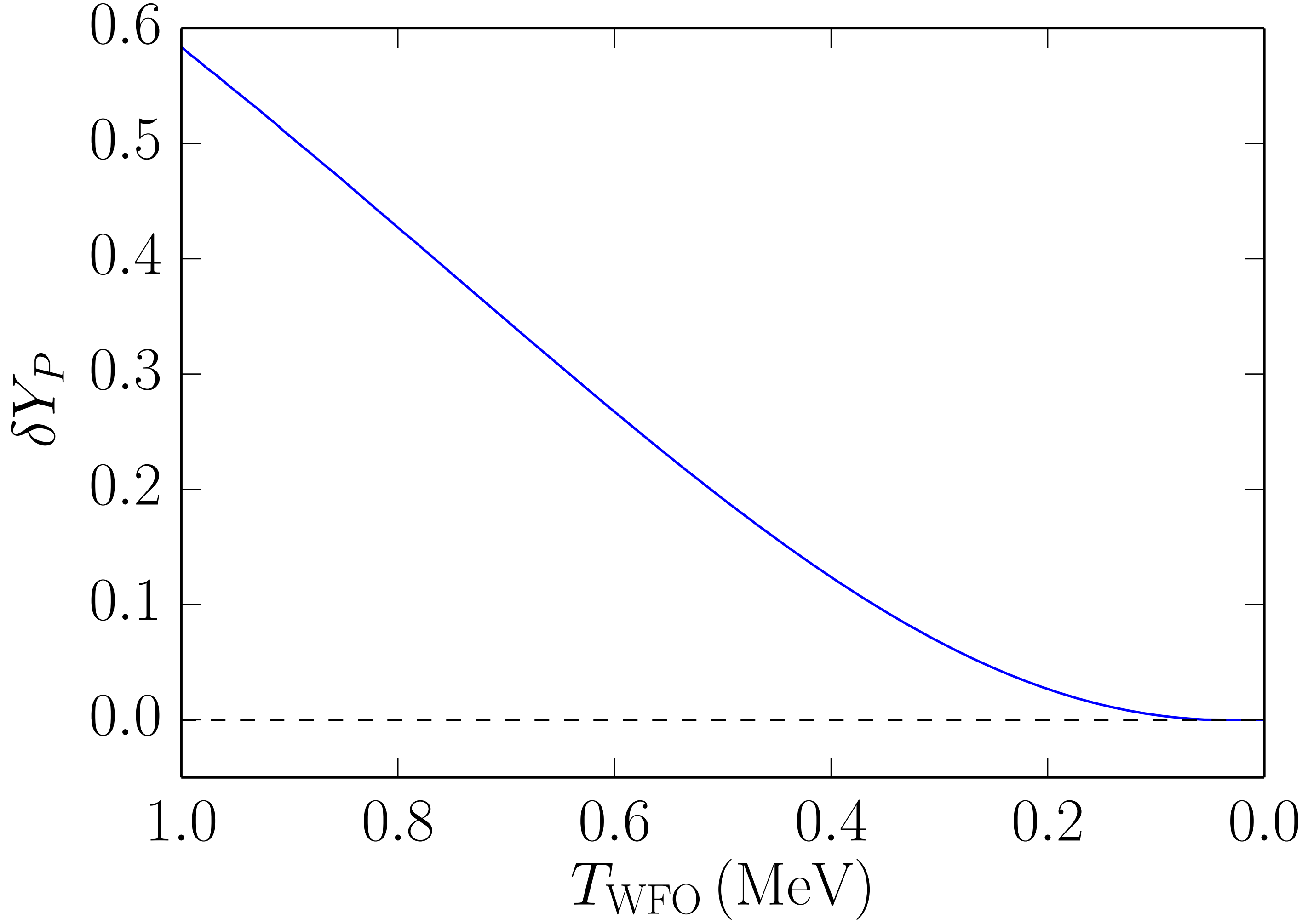
Total Weak Destruction Rate
3He
7Be
6He
3H
neutron
proton
Expansion Rate of the Universe
Standard BBN
rate (s⁻¹)
temperature T (MeV)
10^0
10^-5
10^-10
10^-15
10^-20
10^-25
10^-30
3
2
1
7
6
5
4
3
2
0.1
7
6
5
4
3



The usual description of BBN: neutrinos decouple at T_{WFO} ,
then free neutron decay dominates n/p, 4He, etc.

is grossly **WRONG** !

E. Grohs & G. M. Fuller, "The surprising influence of late charged current weak interactions on Big Bang Nucleosynthesis" *Nuclear Physics B* **911**, 955 (2016).



E. Grohs & G. M. Fuller, "The surprising influence of late charged current weak interactions on Big Bang Nucleosynthesis" *Nuclear Physics B* **911**, 955 (2016).

HIGH ENTROPY

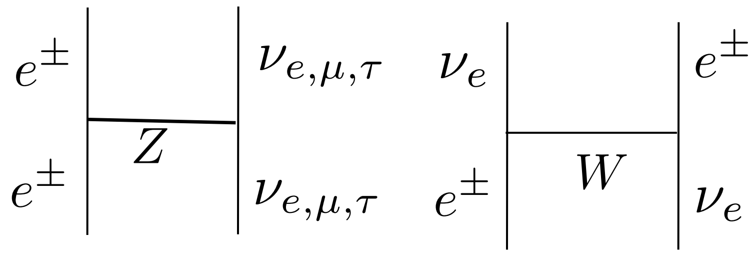
The entropy is high, $s \sim 10^{10}$ units of Boltzmann's constant per baryon, and that means $\sim 10^{10}$ photons per baryon, and $\sim 10^{10}$ neutrinos per baryon!

Even down to temperatures $\sim 10\,\mathrm{keV}$ there will be plenty of photons on the tail of the Planck distribution with enough energy to make $e^{\pm}$-pairs. We have a pair-dominated plasma all the way through weak decoupling/freeze-out and BBN!

. . . and lots of neutrinos per baryon, so even when the neutrinos have decoupled thermally, they still "have purchase" on neutron-to-proton inter-conversion!

. . . and the decoupling neutrinos will suffer out-of-equilibrium scattering and energy exchange with these electrons and positrons **= ν spectral distortions**

neutral- and (*and for electron flavor*) **charged-current** neutrino scattering on electrons and positrons couples the neutrinos to the electron/positron/photon plasma



+ neutral current **neutrino-neutrino scattering**

Follow the Boltzmann evolution of the (binned) energy distribution functions *f* of the of the active neutrinos

$$\frac{df(p,t)}{dt} = C[f(p,t)] \quad \Rightarrow \quad \left(\frac{\partial}{\partial t} - H\,p\,\frac{\partial}{\partial p}\right) f\,(p,t) = C\,(f)$$

$f\,(p,t)$ = occupation probabilities for a neutrino with momentum p at FLRW time coordinate t.

If all neutrino/antineutrino scattering rates fast compared to the expansion rate of the universe H, then we attain thermal, chemical equilibrium

$\Rightarrow f\,(p,t) = \frac{1}{e^{p/T-\eta}+1}$

A. Dolgov, S. Hansen, D. V. Semikoz, NP B 503, 426 (1997) arXiv:9712199
S. Esposito et al. NP 590, 539 (2000), arXiv:0005973

"Neutrino energy transport in weak decoupling and big bang nucleosynthesis"
E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205

Plasma/QED corrections critical:

D. Dicus, E. W. Kolb et al, PRD 26, 2649 (1982)
S. Dodelson & M. S. Turner PRD 46, 3372 (1992)
R. Lopez & M. S. Turner, PRD 59, 103502 (1999)

Evan Grohs et al.

The BURST Code

BBN

- ➔ Predict primordial nuclear abundances

UNITARY

- ➔ Preserve unitarity in nuclear reaction network
- ➔ Quantify errors

RECOMBINATION

- ➔ Treat recombination with three-level atom similar to recfast
- ➔ Isolate neutrino signatures in cosmological power spectra

SELF-CONSISTENT

- ➔ Maintain self-consistency over large range of epochs

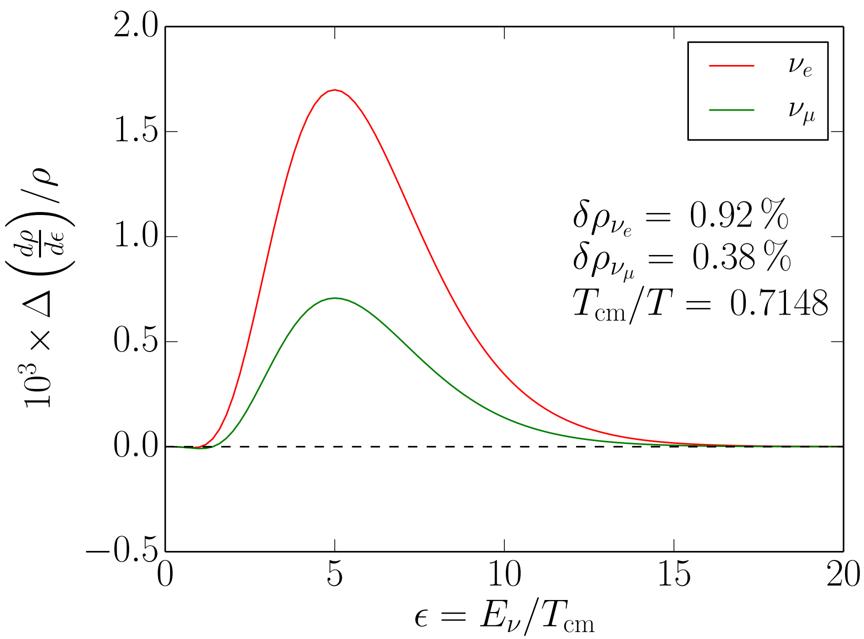
TRANSPORT

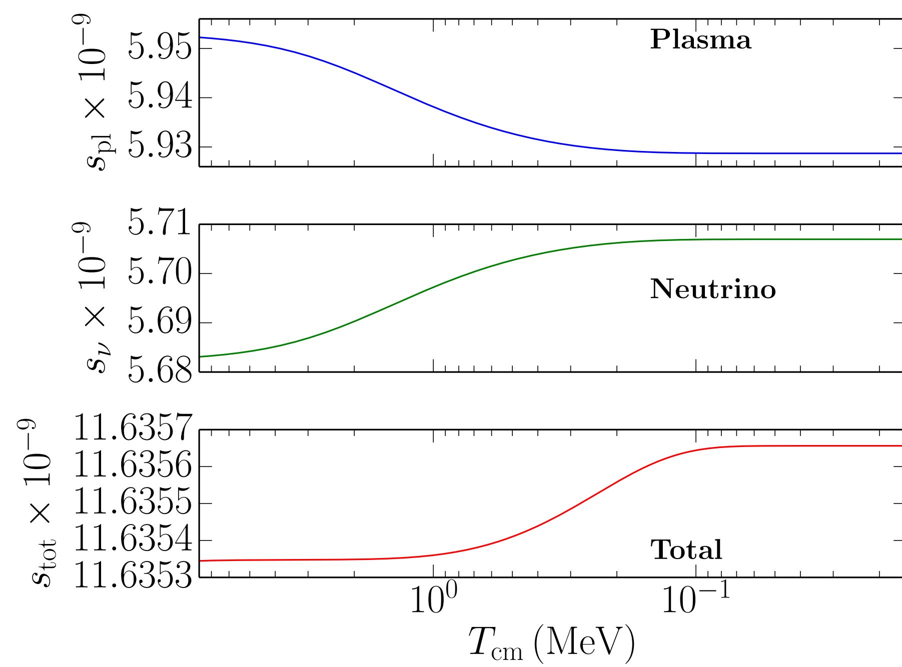
Boltzmann (classical) and full Quantum Kinetics

- ➔ Follow evolution of neutrino spectra

out-of-equilibrium neutrino scattering leads to ***neutrino spectral distortions*** and timelike ***entropy flow/generation***

$$\nu - \nu / e^{\pm} \text{ scattering}$$





"Neutrino energy transport in weak decoupling and big bang nucleosynthesis". E.Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko Phys. Rev. D **93**, 083522 (2016)

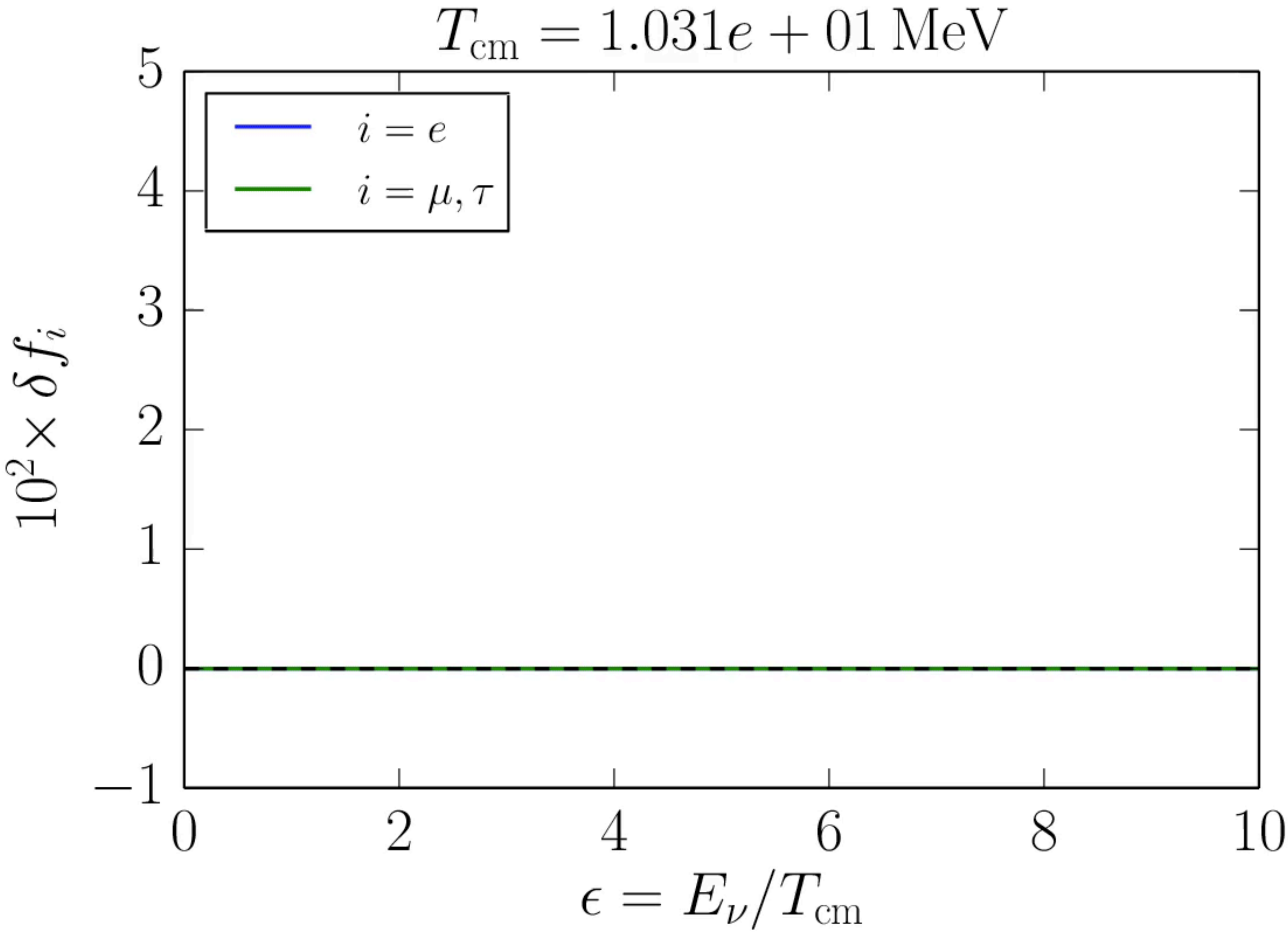
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$
$$n \rightleftharpoons p + e^- + \bar{\nu}_e$$

integrated history of the rates of these charged current processes and ***entropy flow*** determine n/p which is key to nucleosynthesis

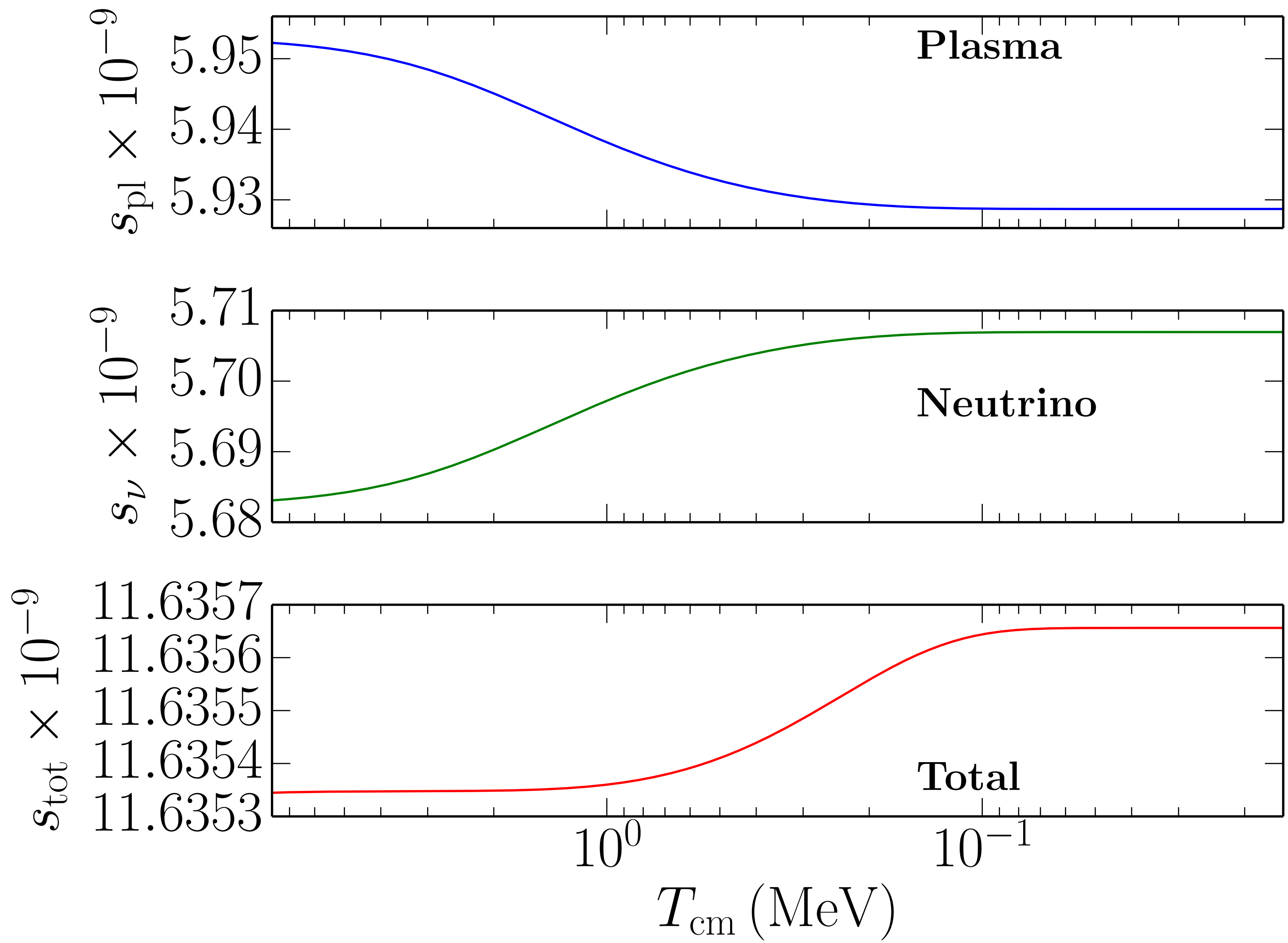
$$Z\,p + N\,n \rightleftharpoons A\,(Z,N) + \gamma$$

$N_{\rm eff}$

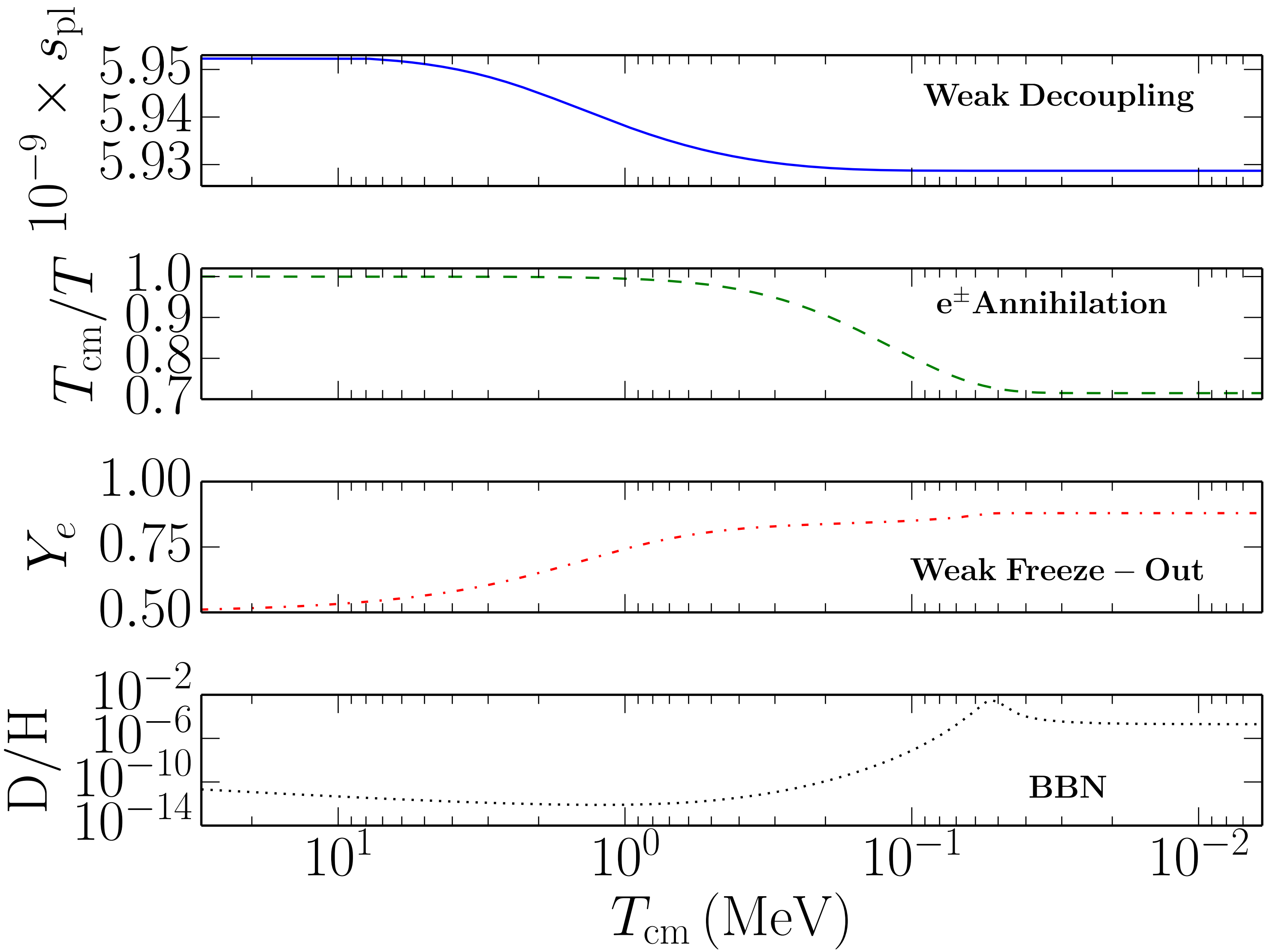
D, ^{4}He



$T_{\rm cm} = 1.031e + 01\,{\rm MeV}$
$i = e$
$i = \mu, \tau$
$10^2 \times \delta f_i$
5
4
3
2
1
0
−1
0
2
4
6
8
10
$\epsilon = E_\nu / T_{\rm cm}$

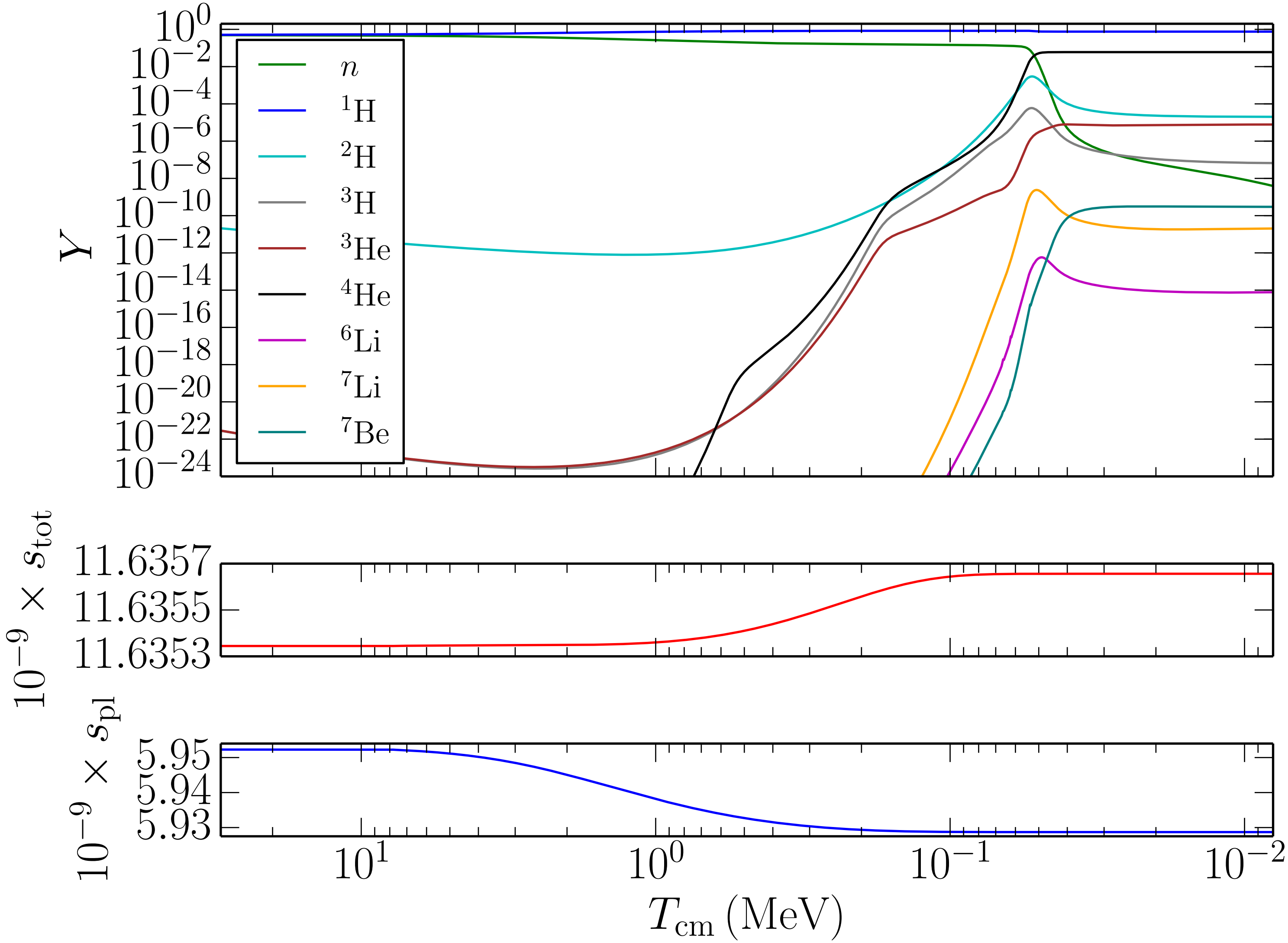


E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205



E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205

Out-of-equilibrium entropy transfer (timelike heat flow)
alters the phasing between
time, temperature, and scale factor
which, in turn, alters weak freeze-out and hence light element abundances and dark relic energy as parameterized by N_{eff}



E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205

"Neutrino energy transport and big bang nucleosynthesis"
E. Grohs, G.M. Fuller, C.T. Kishimoto, M. Paris, A. Vlasenko, arXiv:1512.02205

Transport-derived alterations in BBN light element abundance yields
Relative to a standard no-transport baseline calculation

Deuterium *increases by* +0.4%

Helium *unchanged*

Lithium *decreases* by roughly -0.4%

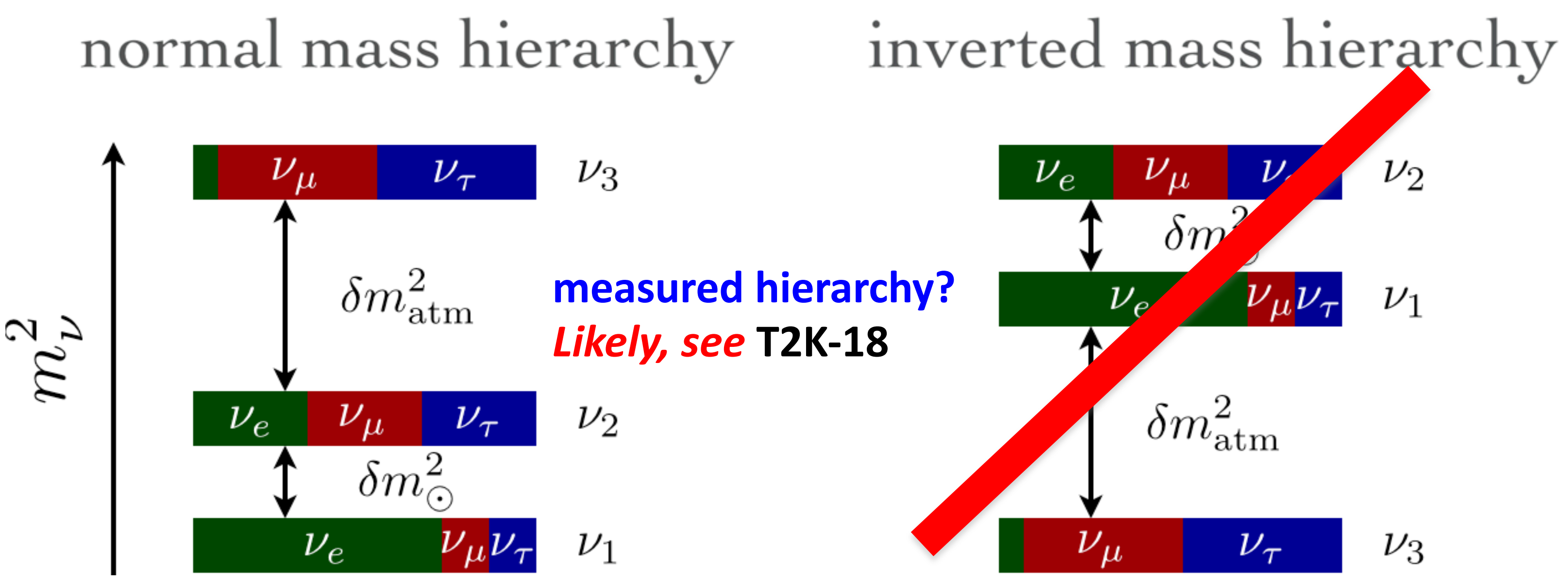
Neutrino Properties

we know the *mass-squared* differences:

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

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

we *do not* know the *absolute masses*,
but likely we do know the *mass hierarchy*:



measured hierarchy?
***Likely, see* T2K-18**

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

Pontecorvo-Maki-Nakagawa-Sakata matrix

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

If Neutrinos are Majorana . . .

$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{bmatrix}$$

unknown:

Majorana phases α_1, α_2

Hints in $0\nu\beta\beta$ or supernovae?

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

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

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

4 parameters

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

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

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

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

$$\delta = CP \text{ violating phase} = ?$$

The Key Computational Challenge which makes incorporating neutrino mass/oscillation physics different from conventional astrophysical (Boltzmann) neutrino transport:

high frequency quantum amplitudes/phases

Quantum Kinetic Treatment

Now include the flavor off-diagonal neutrino interactions,
i.e., the *coherent oscillation* **and** *collision* terms
which can change neutrino flavor

Toward Neutrino Flavor Quantum Kinetics

G. Sigl & G. Raffelt, Nucl. Phys. B **406**, 423 (1993)

B.H.J. McKellar and M.J. Thomson, Phys. Rev. D **49**, 2710 (1994)

K. Enqvist, K. Kainulainen, J. Maalami, Nucl. Phys. B **349**, 743 (1991)

R. F. Sawyer, Phys. Rev. D**79**,, 105003 (2009).

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Grohs, Paris, Kishimoto, Shalgar, Cirigliano, Blashke, Johns, GMF

Quantum Kinetic Equations

$$i\frac{D\hat{f}(p,t)}{D\lambda} - \left[\hat{H}, \hat{f}(p,t)\right] = iC\left[\hat{f}(p,t)\right]$$

$$i\left(\frac{\partial}{\partial t} - H\,p\,\frac{\partial}{\partial p}\right)\,f\,(p,t) = \left[\Sigma_R^\kappa\left(f,\hat{f}\right) + \frac{m^\dagger\,m}{2p}\,,\,f\right] + i\,\mathcal{C}\,(f,\bar{f})$$

$$i\left(\frac{\partial}{\partial t} - H\,p\,\frac{\partial}{\partial p}\right)\,\bar{f}\,(p,t) = \left[\Sigma_R^\kappa\,(f,\bar{f}) - \frac{m^\dagger\,m}{2p}\,,\,\bar{f}\right] + i\,\mathcal{C}\,(f,\bar{f})$$

Where now the occupation probability we had in the Boltzmann equation is replaced by density matrices *f* and, likewise, the collision operator becomes a matrix with flavor off-diagonal components (see **Blaschke & Cirigliano 2016**)

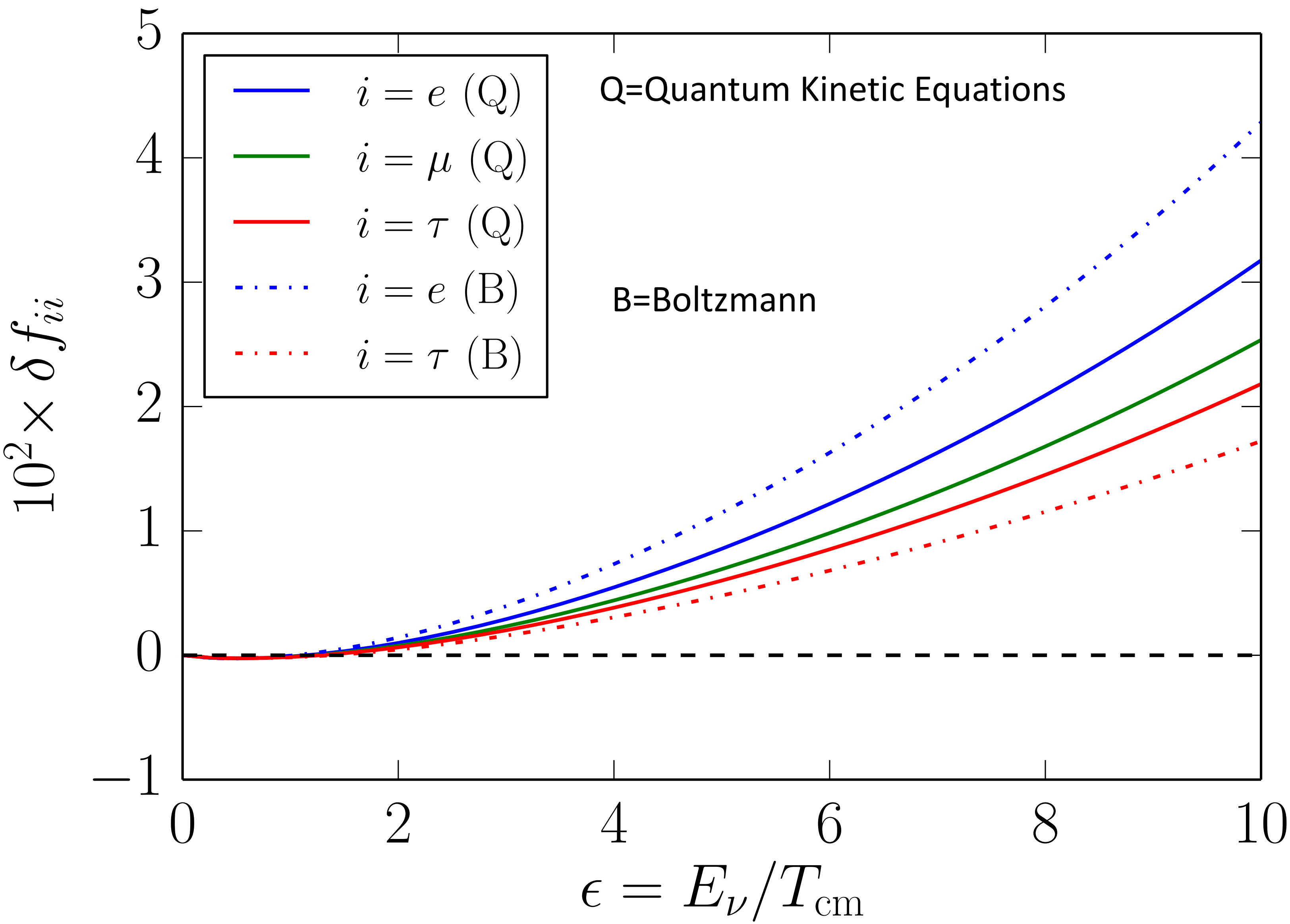
$$\left[\hat{f}\right]_{\rm flavor} = \begin{pmatrix} f_{\nu_e\nu_e} & f_{\nu_e\nu_\mu} & f_{\nu_e\nu_\tau} \\ f_{\nu_\mu\nu_e} & f_{\nu_\mu\nu_\mu} & f_{\nu_\mu\nu_\tau} \\ f_{\nu_\tau\nu_e} & f_{\nu_\tau\nu_\mu} & f_{\nu_\tau\nu_\tau} \end{pmatrix} \Rightarrow \begin{pmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{pmatrix}$$

likewise for antineutrino density matrix $\hat{\bar{f}}$

Number densities of neutrinos are related to the flavor-diagonal matrix elements of the density operator by

$$n_{\nu_\alpha}\,(t) = \int \frac{d^3p}{(2\pi)^3}\,f_{\nu_\alpha\nu_\alpha}$$

E. Grohs et al. 2019 -- preliminary



more issues . . .

(1) Add capability to handle nonzero and “large” lepton number:

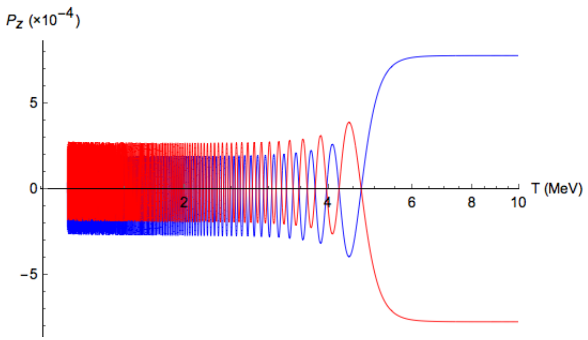
Baryon number $\equiv \eta = \frac{n_{\rm b} - n_{\bar{\rm b}}}{n_\gamma} \approx 6.1 \times 10^{-10}$ (CMB measurement)

Lepton number in ν_α neutrino sea $L_{\nu_\alpha} = \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma} < 0.1$ (bound from primordial helium or deuterium)

We have studied the effects of coherent neutrino oscillations:

L. Johns, M. Mina, V. Cirigliano, M. Paris, GMF, "Neutrino flavor transformation in the lepton-asymmetric universe", Physical Review D **94**, 083505 (2016).

Objective is to extend to a full QKE treatment for *some* cases.



(2) Explore specific BSM physics issues with QKE + BBN codes:
New dark photon parameter space; Light nuclear reaction physics and unitarity; out-of-equilibrium particle decay; non-thermal relics, etc.

(3) Explore adapting QKE codes to treat the neutrino decoupling region (vicinity of the neutrino sphere) in compact object environments (core collapse supernovae, binary neutron star mergers) – see M. Sen’s talk

Any New Physics which alters the
time, ***temperature***, ***scale factor*** phasing
during weak decoupling
can show up as alterations in ^{4}He, D, N_{eff}

Weak Decoupling/BBN is a protracted process, spanning > 100 Hubble times, with neutrino-electron/positron scattering causing entropy transfer from the plasma to the decoupling neutrinos, *even down to temperatures well below the electron rest mass*

= development of neutrino spectral distortions

= alterations in the phasing of time, temperature, scale factor

} alterations in ^{4}He, D, N_{eff}

these alterations are at the ~ 1% level for *standard model physics*

they could be much larger for *BSM physics*

Any New Physics which alters the ***time***, ***temperature***, ***scale factor phasing*** during weak decoupling can show up as further alterations in ^{4}He, D, N_{eff} -- these can be more dramatic

- Some BSM physics will move each of ^{4}He, D, N_{eff} in separate "directions" – telltale fingerprints?

The alterations that originate from otherwise standard model neutrino mass/mixing physics are *small* compared to the anticipated precision of the observations, though potentially detectable in an overall assessment of deuterium and helium abundances and N_{eff}

Some BSM physics can result in dramatic alterations. But we are after more subtle "fingerprints".

Some BSM examples . . .

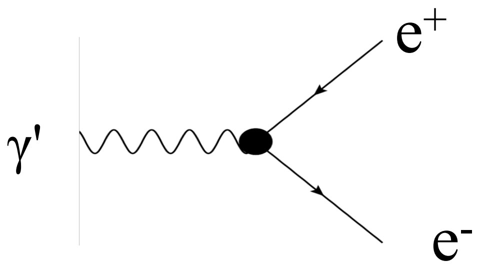
(1) The sterile neutrino from **HELL**

(2) Neutrino "mass" measurements confront Σm_ν

(3) Dark Photons

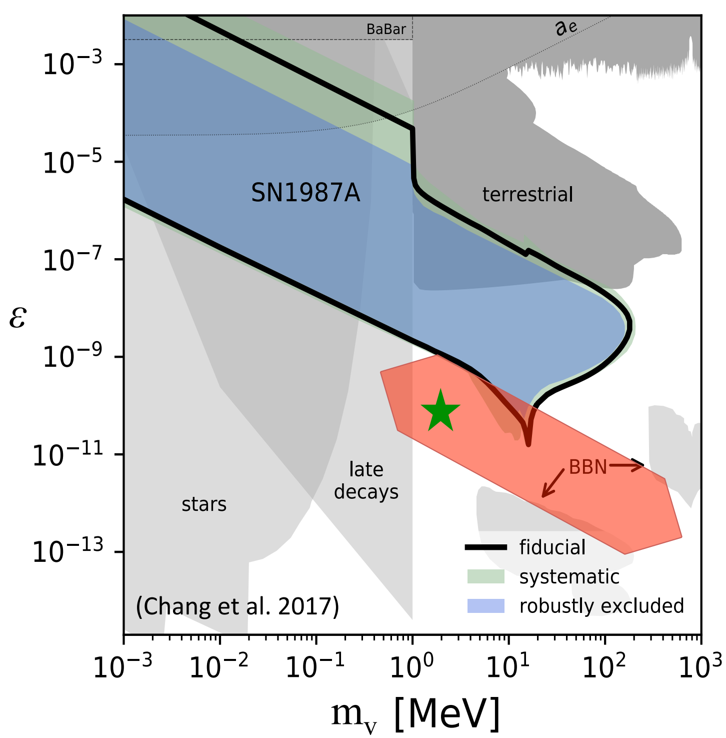
EXAMPLE: *Dark photons* γ' *with mass* m_V *mix* (ε) *with Standard Model photons* γ

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_{\rm v}^2 V_\mu^2 + eJ^\mu_{\rm em}(A_\mu - \epsilon V_\mu)$$



Can decay **during** weak decoupling/BBN

$$\Gamma(\gamma' \to e^+e^-) = \frac{\alpha}{3}\epsilon^2 m_{\rm v}\left(1-\frac{4m_e^2}{m_{\rm v}^2}\right)^{1/2}\left(1+\frac{2m_e^2}{m_{\rm v}^2}\right)\frac{m_{\rm v}}{E_{\gamma'}}$$
$$\sim \epsilon^2 m_{\rm v}$$



J.-T. Li, E. Grohs, GMF 2019

- Entropy generation/dilution

$$\Delta s = \Delta t \cdot \frac{m_{\rm v}}{T} \cdot \left(\frac{n_{\gamma'}}{n_b}\right) \cdot e^{-\Delta t/\tau} \cdot \Gamma$$
$$\sim t \cdot \frac{m_{\rm v}}{t^{-1/2}} \cdot \epsilon^2 \cdot 1 \cdot \epsilon^2 m_{\rm v}$$
$$\sim \epsilon\sqrt{m_{\rm v}}$$

- Diagonal band (new)

Pushing to/below $\sim 1\%$ errors on $N_{\rm eff}$ gets us new constraints (roughly the red diagonal band)

Bruno Pontecorvo

recognized that the handedness of the weak interaction meant that non-zero neutrino rest mass could enable neutrino spin flip from active, left-handed states, to **sterile**, right-handed states.

Soviet Physics – JETP **26**, 984 (1968)

A take-away message from the experiments is that neutrinos have *non-zero rest masses*

This fact begs the question: Are there sterile neutrino states?

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle\; + \;\sin\theta\,|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle\; + \;\cos\theta\,|\nu_2\rangle$$

If sterile neutrinos mix with active neutrinos in vacuum like this, then they are not really ***sterile*** !!

active neutrino cross section $\sigma \sim G_{\rm F}^2\, E_\nu^2$

"sterile" neutrino cross section $\sigma \sim (G_{\rm F}^2\, \sin^2\theta)\, E_\nu^2$

EXAMPLE:

miniBooNE: near maximal active-sterile neutrino mixing at mass-squared difference $\delta m^2 \sim 1\ eV^2$

The Sterile Neutrino from **HELL**

The possible ways out of this dilemma are intriguing!

- A net lepton number $L_{\nu_\alpha} \geq 10^{-4}$ residing in any of the active neutrino species (Abazajian, Bell, Fuller, Wong 2006; Chu & Cirelli 2006)

  — interestingly in the range of what we would need to drive resonant sterile neutrino dark matter production for a sterile neutrino with rest mass $m_s \sim 10\,\mathrm{keV}$.

  But possible troubles with BBN, N_{eff}, $\sum m_\nu$ for $m_s > 0.6\,\mathrm{eV}^2$ – see N. Saviano et al. 2017 – but need full 4X4 analysis

- Low inflation re-heat temperature (e.g., Gabriel, Palmerez-Reiz, Pascoli 2004)

- Non-standard ("secret") sterile neutrino interactions
  Hannestad et al. 2013; Mirizzi et al. 2013; others

  see especially B. Dasgupta & J. Kopp "Cosmologically safe eV-scale sterile neutrinos and improved dark matter structures" Phys. Rev. Lett. **112**, 031803 (2014).

- A whole new sterile neutrino self-interacting sector? Other steriles? Interaction with dark matter, whatever that is?

see also L. Johns & G. M. Fuller PRD **100**, 023533 (2019)

See J. Cherry, A. Friedland, I. Shoemaker arXiv:1411.1071 – opacity for PeV/ICECUBE neutrinos, engineers dark matter self-interaction;

(1) Quantum Mechanical Limit: Dodelson & Widrow 1994

active neutrino scattering-induced de-coherence produces a relic density of sterile neutrinos -- *picks out keV scale rest masses, small vacuum mixing angles*

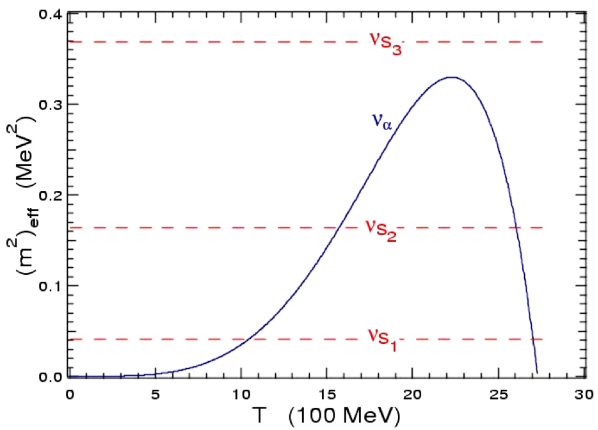
(2) Lepton number-driven resonant production: Shi & Fuller 1998; Abazajian, Fuller, Patel 2001; Abazajian ’14, Abazajian & GMF 2002; Kishimoto & GMF 2008; T. Venumadhav, F. Cyr-Racine, K. Abazajian, C. Hirata arXiv150706655

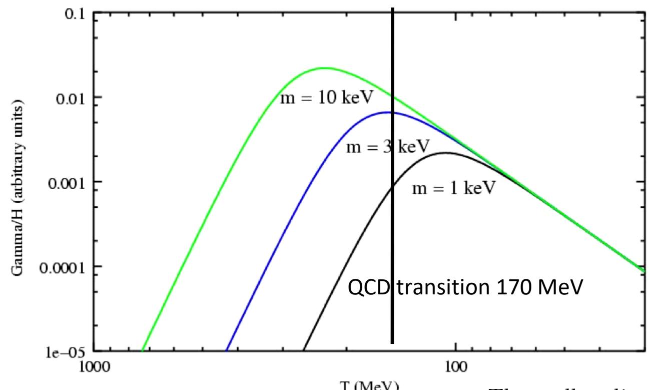
Like MSW: initial lepton number partially converted to a relic sterile neutrino population

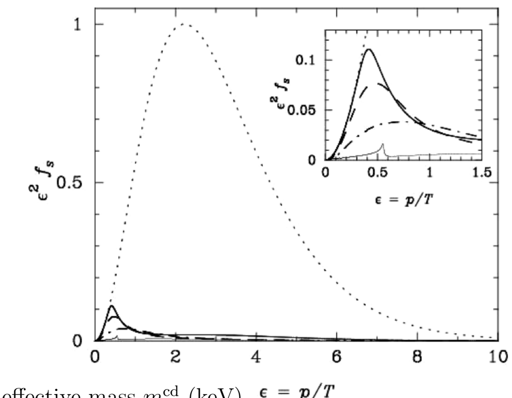
-- *can work for smaller mixing angles, larger (1-10 keV) masses, with colder sterile neutrino relic energy spectrum*

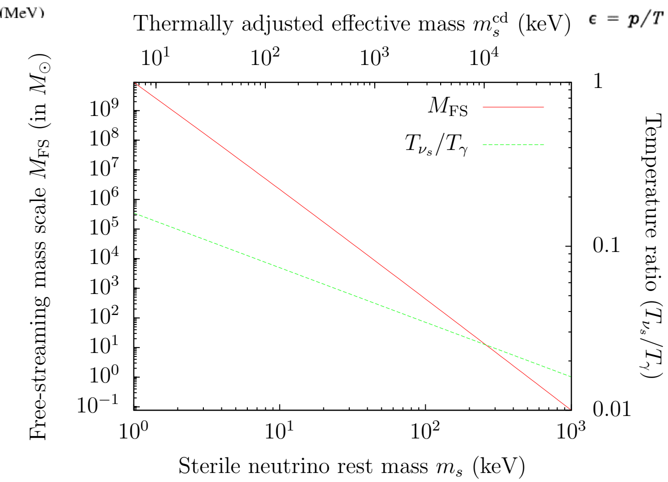
-- *sterile neutrinos may allow you to make the lepton number:*

*e.g., Asaka & Shaposhnikov , “The nuMSM, dark matter, and baryon asymmetry”, PLB **620**, 17 (2005)*









(3) Higgs decay and/or Dilution:

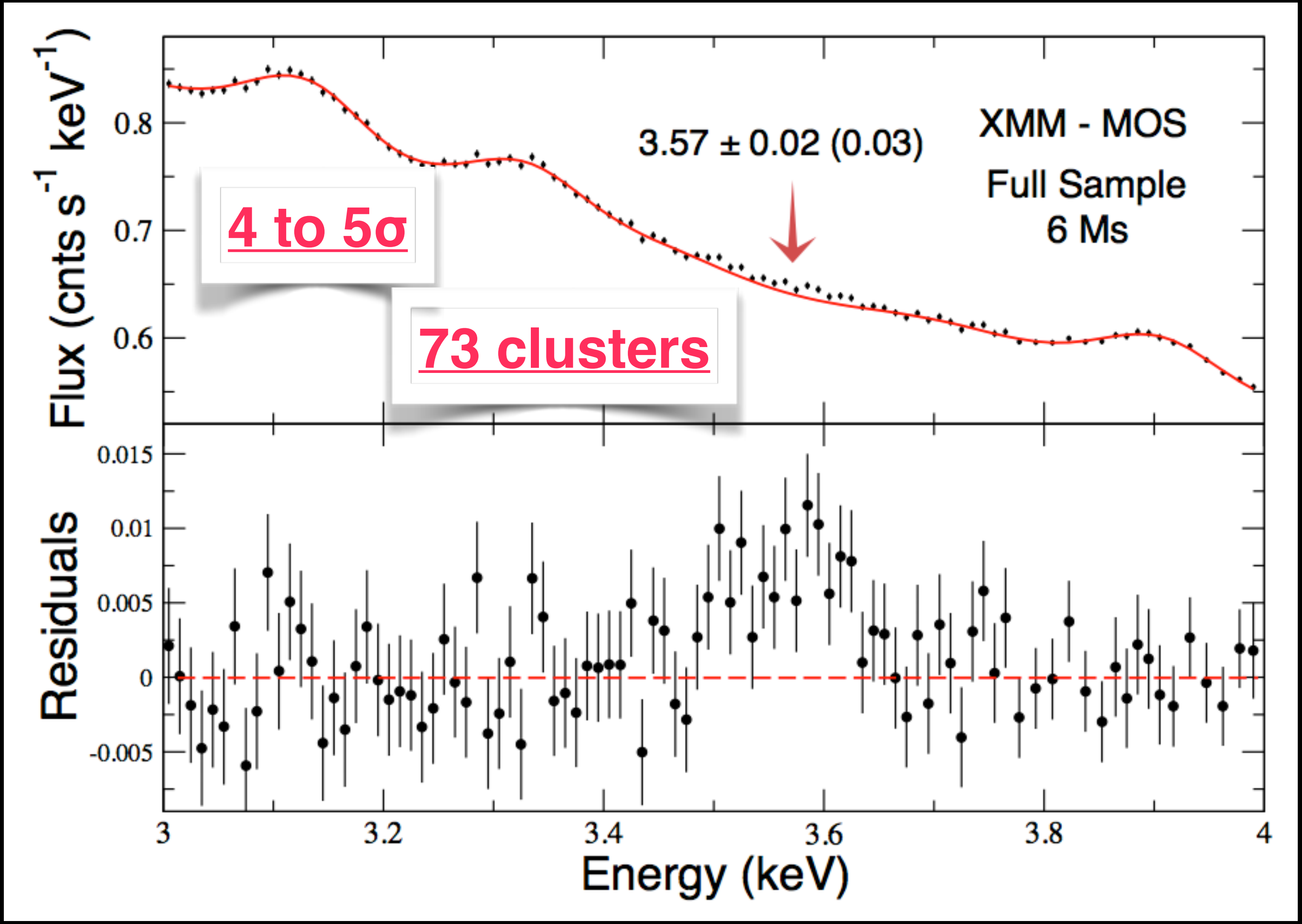
e.g., Kusenko (2006); Asaka, Shaposhnikov, Kusenko (2006);
F. Bezrukov, D. Gorbunov arXiv:1403.4638
Patwardhan, GMF, Kishimoto, Kusenko (2015)

thermalize or partially thermalize steriles very early, QKE calculations with scattering/decay then resonant or dilution production

Dilution can produce CDM/evade constraints

Patwardhan, GMF, C. Kishimoto, A. Kusenko PRD **92**, 103509 (2015)

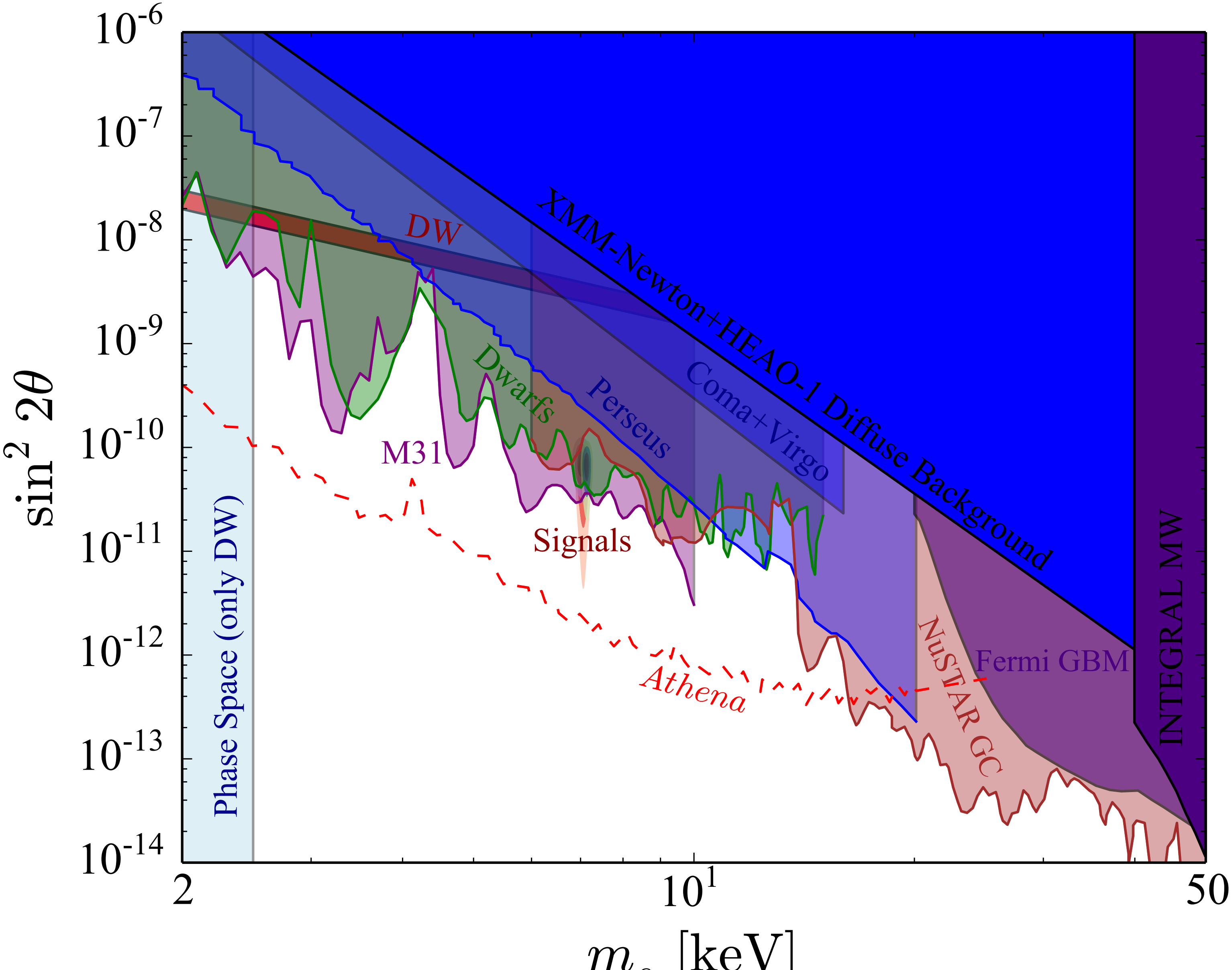
The Detection of an Unidentified Line



Kev Abazajian's slide

Bulbul et al. ApJ 2014

Sterile Neutrino Dark Matter: Parameter Space Summary



Abazajian *Physics Reports* arXiv:1705.01837

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.
- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, at s cutoff scale of great interest in galaxy formation of the local group of galaxies,

Kev Abazajian's slide

4 ways to get at "*neutrino mass*"

neutrino vacuum mass eigenvalues m_i

Beta Decay endpoint:

PMNS matrix element-weighted sum of mass eigenvalues (squared) $m_{\nu_e}^2 \equiv \sum_i \left(|U_{ei}|^2_{\mathrm{PMNS}} \right) m_i^2$

e.g., tritium endpoint $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$

$\mathrm{KATRIN\ sensitivity}: m_{\nu_e} = 200\,\mathrm{meV}$

$\mathrm{RF/Project8\ sensitivity}: m_{\nu_e} = 100\,\mathrm{meV}$

Cosmology/collisionless damping scale

Neutrino relic spectrum-weighted sum of mass eigenvalues $\sum m_\nu \equiv \sum_{\alpha=e,\mu,\tau,s} W_{\nu_\alpha} \cdot \text{“}m_{\nu_\alpha}\text{”}$

$$\text{“}m_{\nu_\alpha}\text{”} \equiv \sum_i \left(|U_{\alpha i}|^2 \right) m_i \qquad W_{\nu_\alpha} \equiv \frac{1}{2\, n_{\nu_\alpha}^{\mathrm{FD,BB},\eta_\alpha=0}} \cdot \left[\int_0^\infty \frac{dn_{\nu_\alpha}}{dp}\, dp + \int_0^\infty \frac{dn_{\bar{\nu}_\alpha}}{dp}\, dp \right]$$

$\mathrm{Stage\ IV\ CMB\ sensitivity\ at}\ 1\,\sigma: \ m_{\nu_e} \geq 10\,\mathrm{meV}$

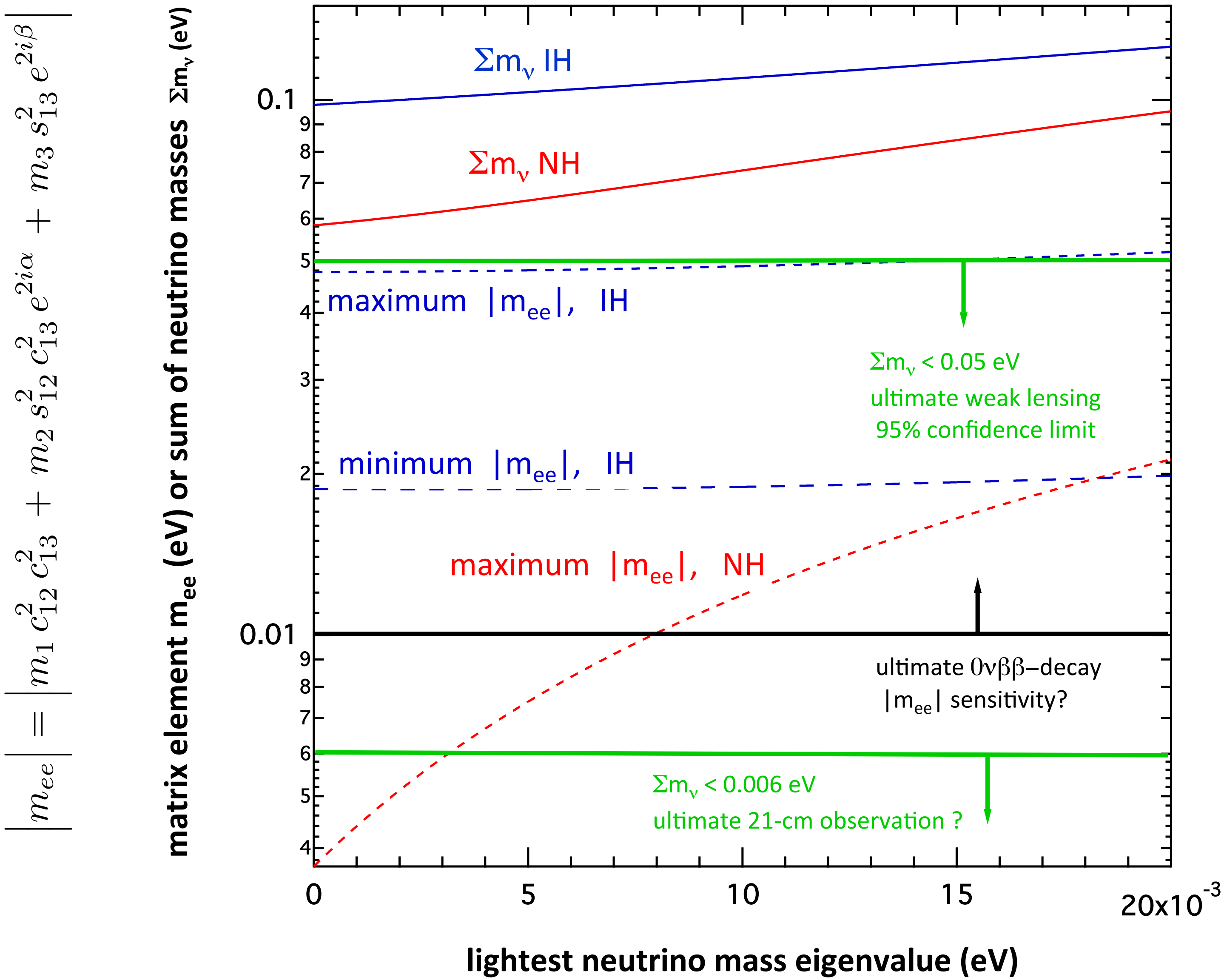
Spin Flip: zero-neutrino-double-beta-decay

coherent (with phases) matrix element-weighted sum of mass eigenvalues

$$\left| m_{ee} \right| = \left| m_1\, c_{12}^2\, c_{13}^2 + m_2\, s_{12}^2\, c_{13}^2\, e^{2i\alpha} + m_3\, s_{13}^2\, e^{2i\beta} \right| \qquad \mathrm{ton-scale\ sensitivity}: |m_{ee}| \sim 10\,\mathrm{meV}$$

Spin Flip: supernova neutrino-antineutrino transformation ????

coherent (w/phases) matrix element-weighted sum of mass eigenvalues


$|m_{ee}| = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta}|$
matrix element m_{ee} (eV) or sum of neutrino masses Σm_ν (eV)
Σm_ν IH
Σm_ν NH
maximum $|m_{ee}|$, IH
$\Sigma m_\nu < 0.05$ eV
ultimate weak lensing
95% confidence limit
minimum $|m_{ee}|$, IH
maximum $|m_{ee}|$, NH
ultimate 0νββ–decay
$|m_{ee}|$ sensitivity?
$\Sigma m_\nu < 0.006$ eV
ultimate 21-cm observation ?
0.1
9
8
7
6
5
4
3
2
0.01
9
8
7
6
5
4
0
5
10
15
20x10^{-3}
lightest neutrino mass eigenvalue (eV)

Suppose the following situation arises . . .

We know the neutrino mass hierarchy from reactor or long baseline experiments, and it is the ***Normal Mass Hierarchy***

A ton-scale **0νββ–decay** (*zero neutrino double beta decay*) experiment **sees a signal**

CMB S4 (and/or 21-cm or weak lensing observations) conclude that the "*sum of the light neutrino masses*" is $\Sigma m_\nu < 0.06$ eV = 60 meV

↓

The neutrino spin flip that occurred in the **0νββ–decay** events
was not mediated by neutrino mass,
but rather (high energy scale) BSM physics (e.g., right-handed W)

BUT . . . (1) Did Σm_ν really measure mass? (Lyman alpha forest?)
(2) Nuclear matrix elements larger than theory calculations?
if so . . . This is probably also an indication of BSM physics.