Neutrino Decoupling, BBN, & High Precision CMB/CνB

Topics in Cosmic Neutrino Physics

Fermilab

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George M. Fuller

Department of Physics

University of California, San Diego

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

E. Grohs, J. R. Bond, J. Myers, V. Cirigliano, M. Paris, L. Johns, S. Shalgar, D. Blaschke, C. Kishimoto, GMF

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

. . . *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

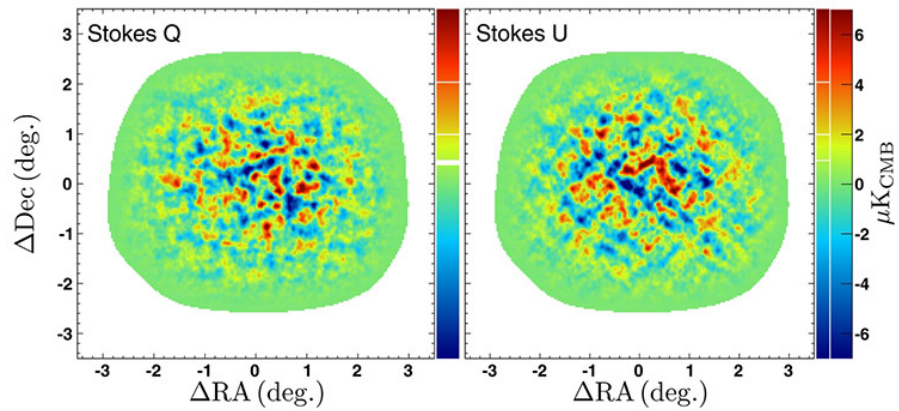
Much of what I will talk about is work in

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

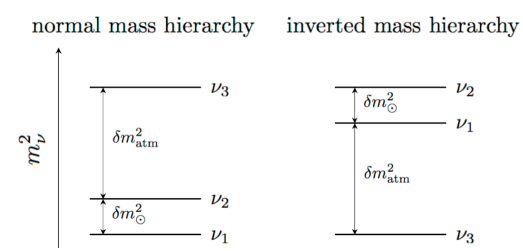
neutrino mass and ***neutrino physics***
will be key science drivers for ***Stage-4 Cosmic Microwave Background***

Simons Observatory



Stage IV CMB ($\sim$ 500,000 detectors):

Neutrino Mass $15\,\mathrm{meV}$ 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*

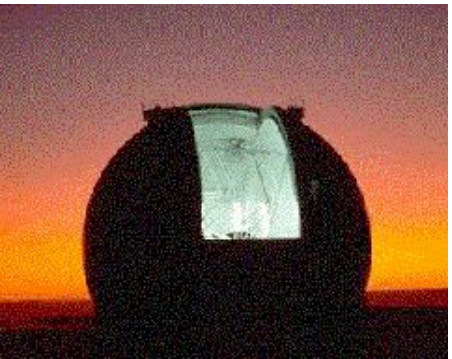
Primordial Deuterium Abundance -- 1% uncertainty?

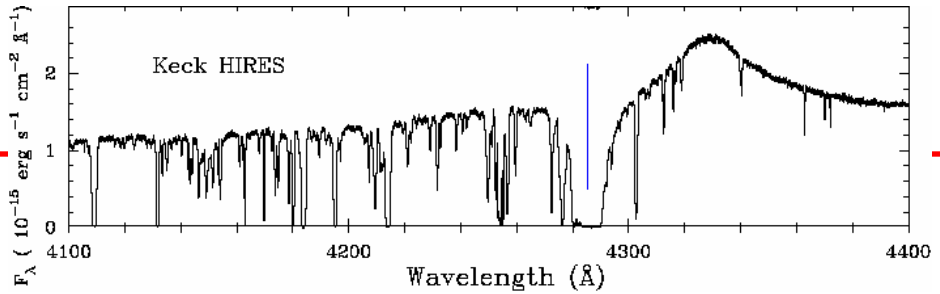
From observations of isotope-shifted Lyman lines in the spectra of high redshift QSO's.

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)





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

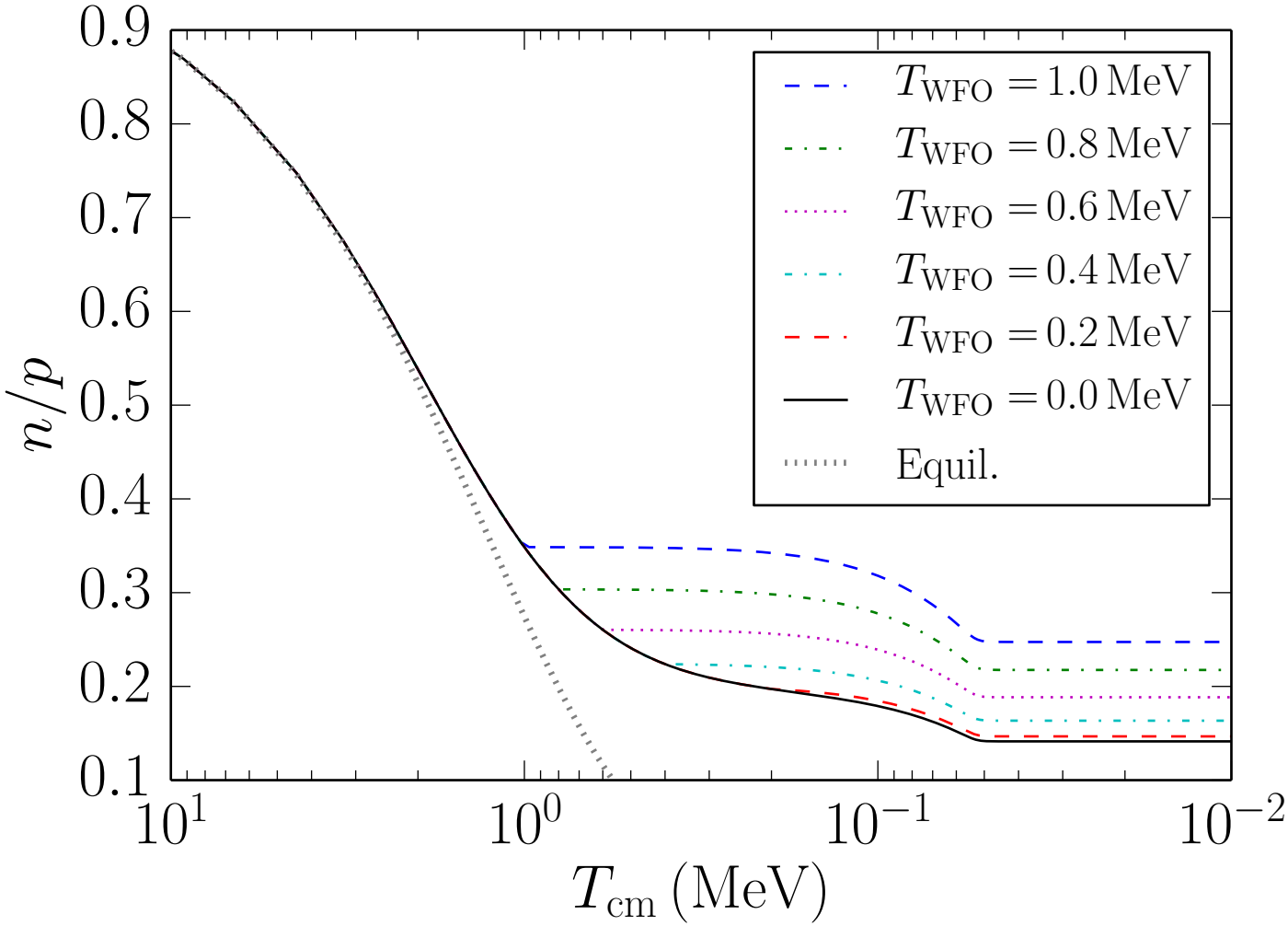
low precision :
connect epochs by using N_{eff}
as the sole determinant of BBN

***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

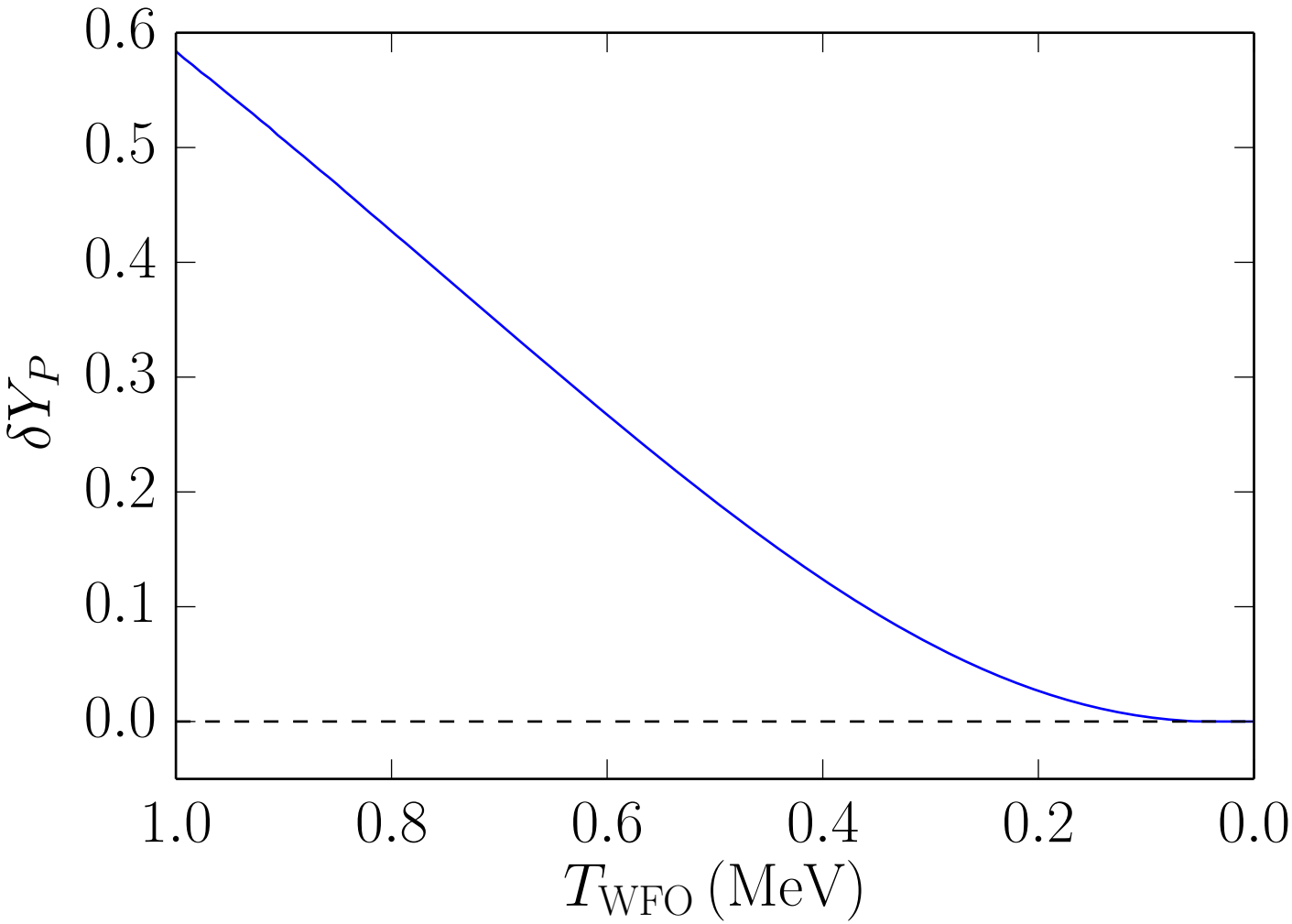
deuterium abundances (*high precision with 30-m class telescopes – Cooke & Petini*)



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).

this serves as a warning!

Going to higher precision means that we will have to model neutrino interactions accurately over the long, protracted decoupling/freeze-out process (> 100 Hubble times)

We need:

(1) Self-consistently coupled neutrino scattering/absorption

(2) Better Plasma/QED physics (e.g., in-medium electron mass)

(3) More reliable nuclear reaction rates (deuterium still an issue); Unitary reaction network

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**

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

© Eve Armstrong

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

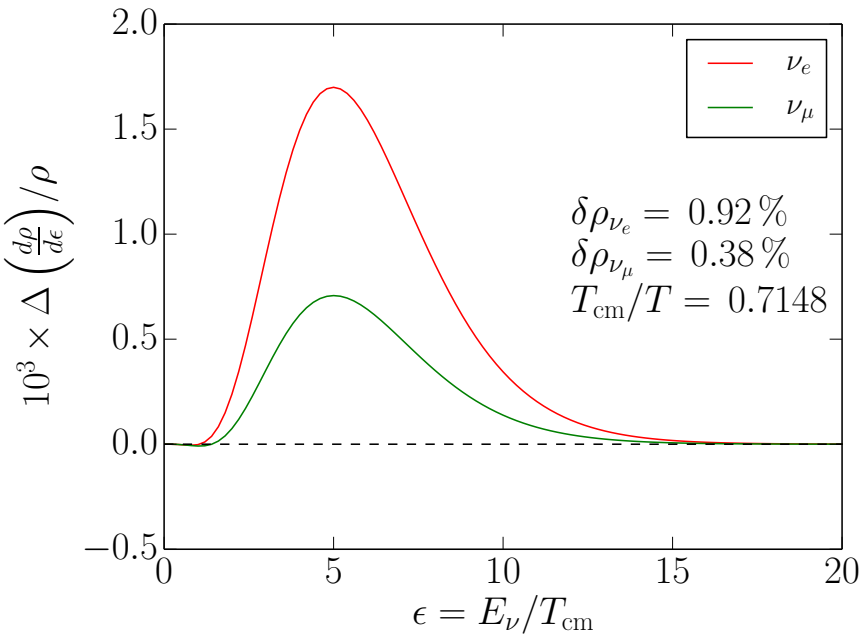
- ➔ Maintain self-consistency over large range of epochs

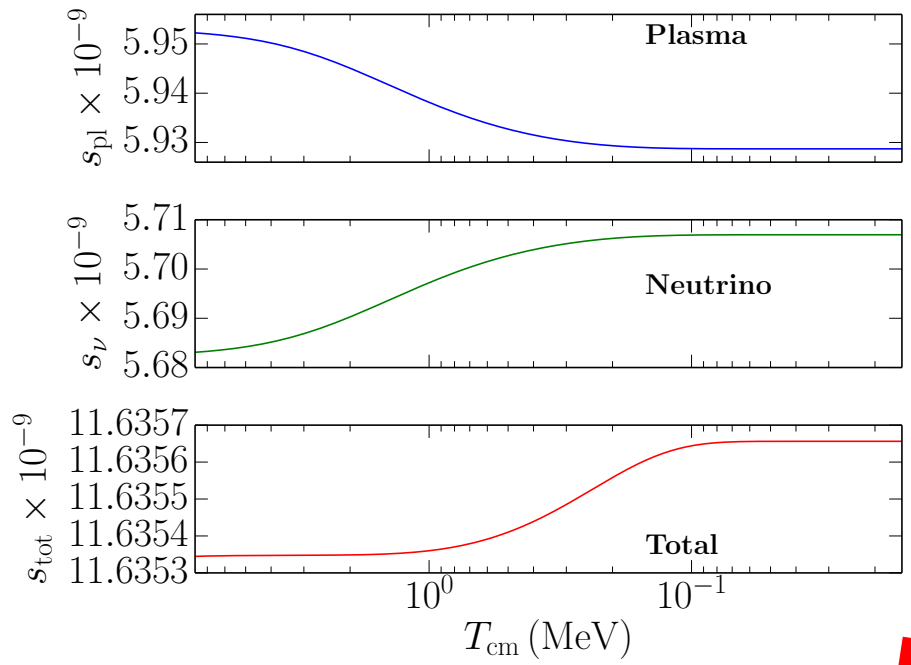
TRANSPORT Boltzmann (classical) and full Quantum Kinetics

- ➔ 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)

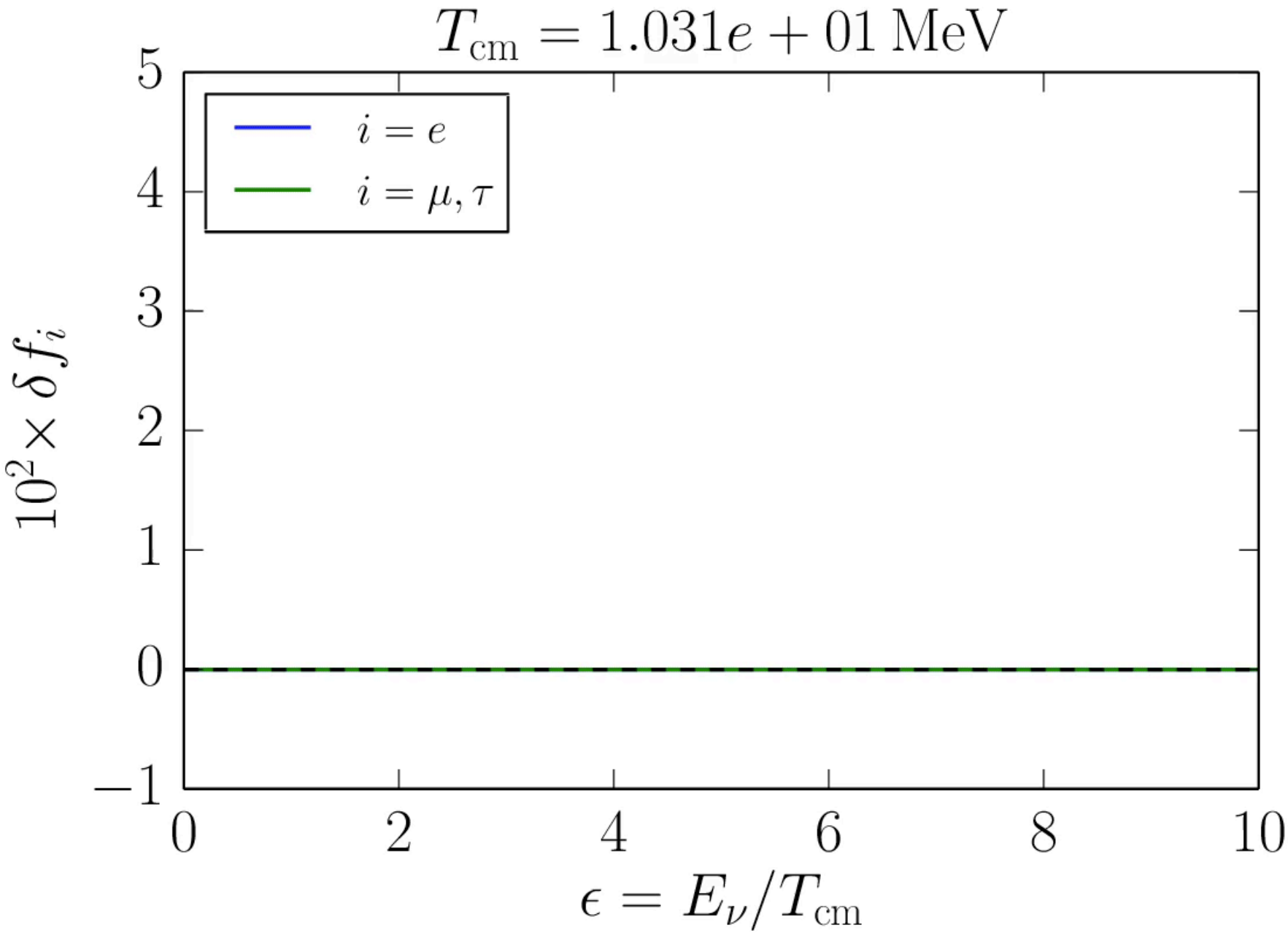
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$
$$n \rightleftharpoons p + e^- + \bar{\nu}_e$$

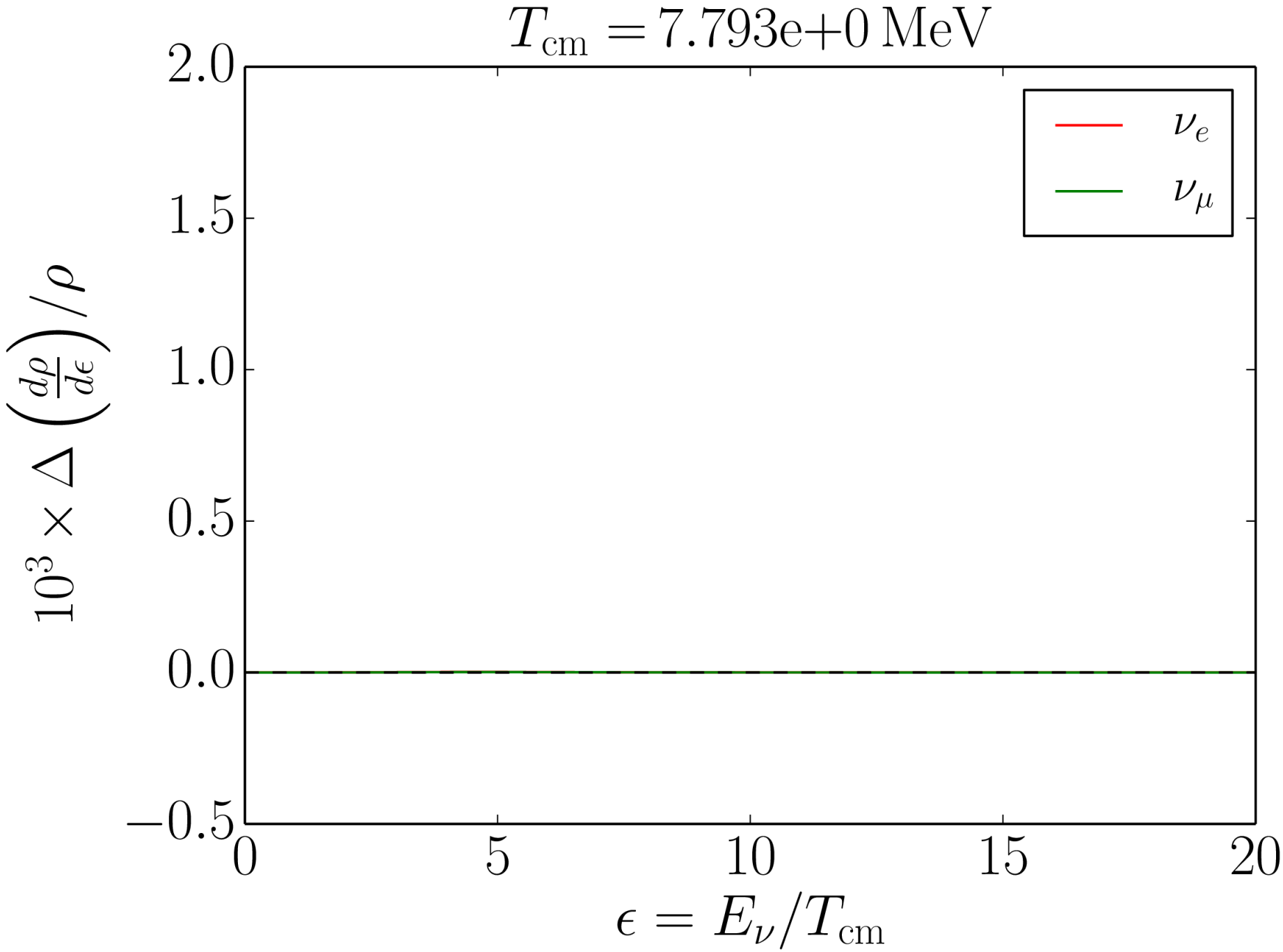
integrated history of the rates of these charged current processes and ***entropy flow*** determine n/p which is key to nucleosynthesis

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

N_{eff}

D, ^{4}He


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



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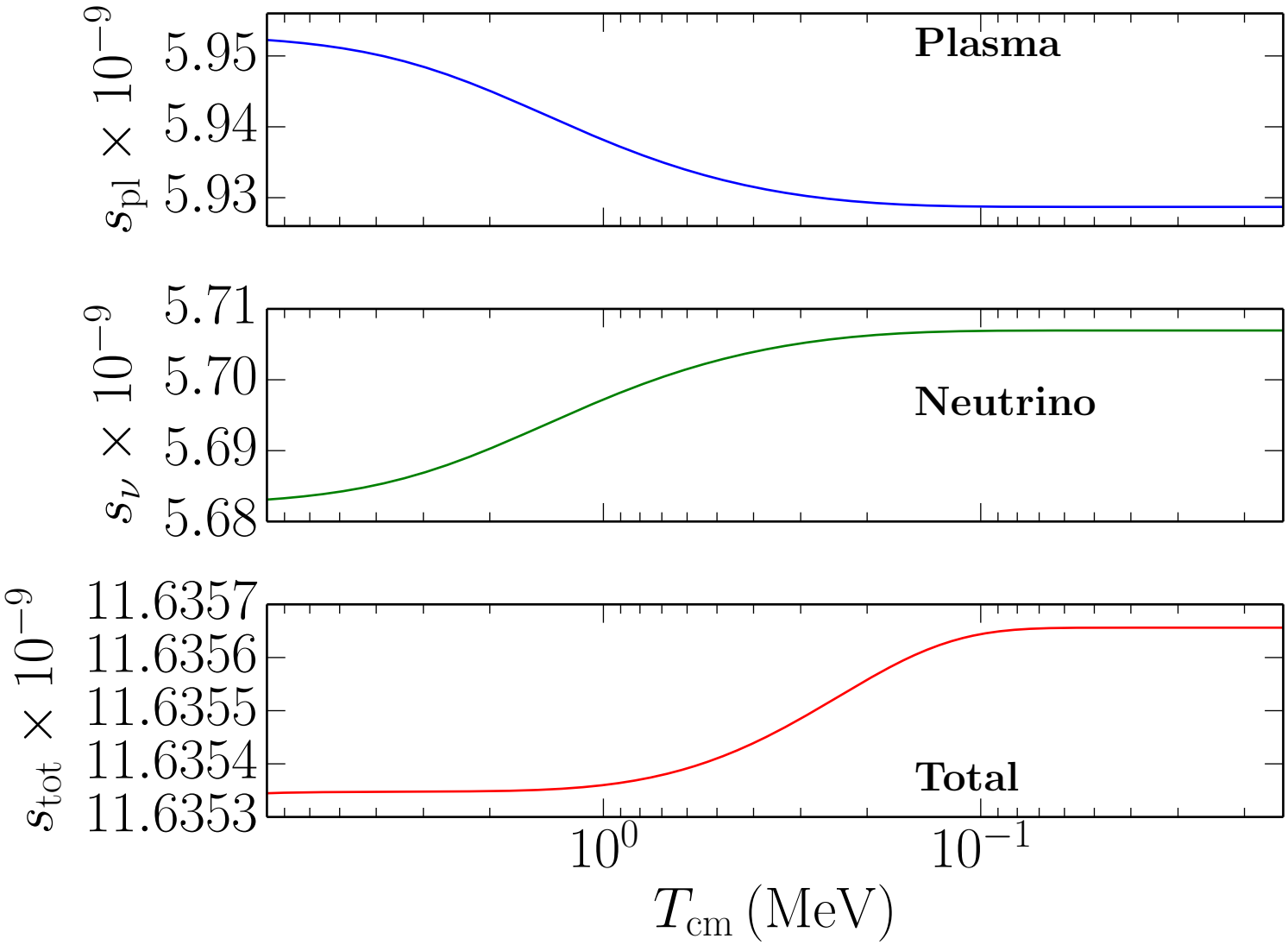
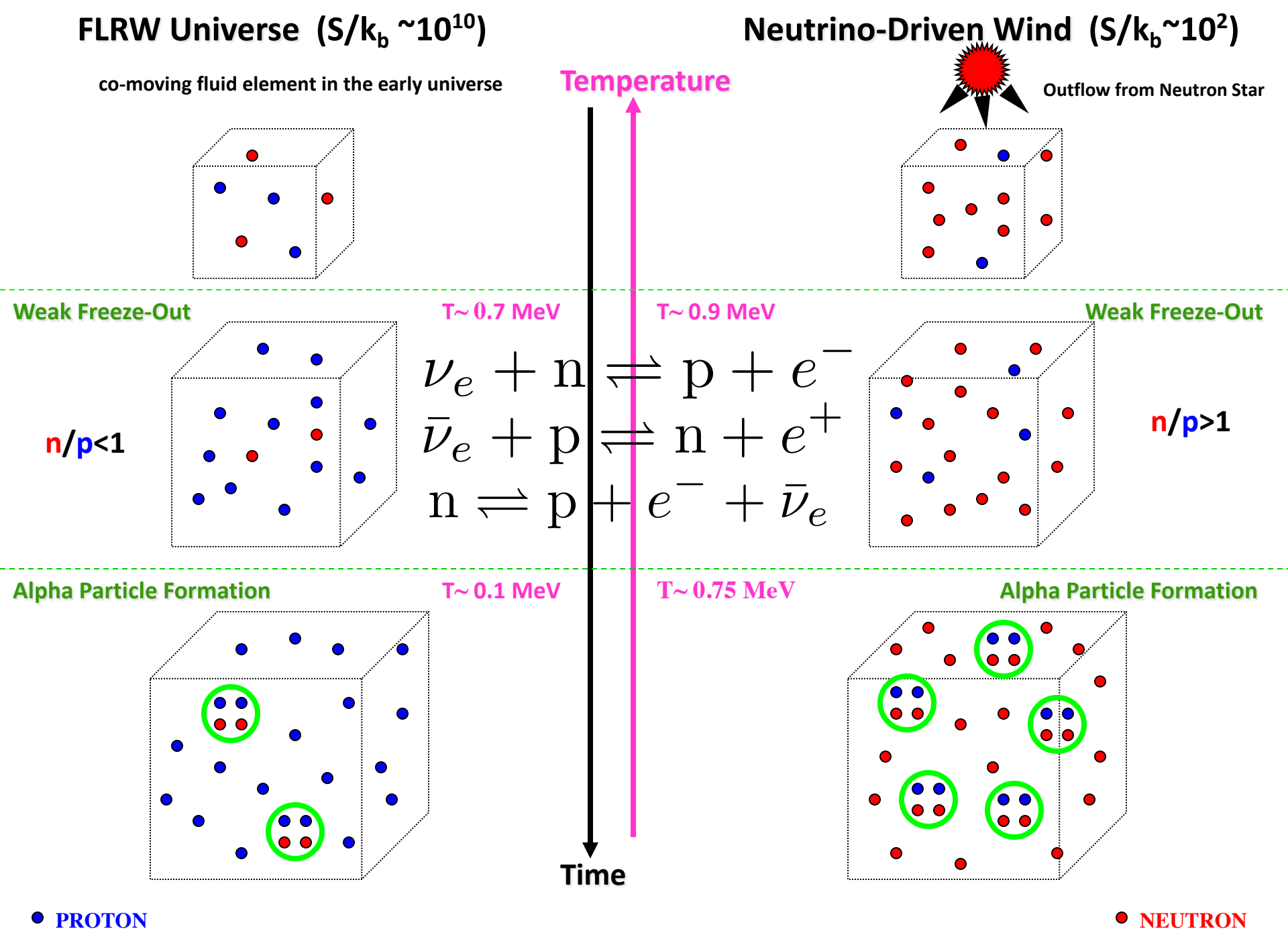
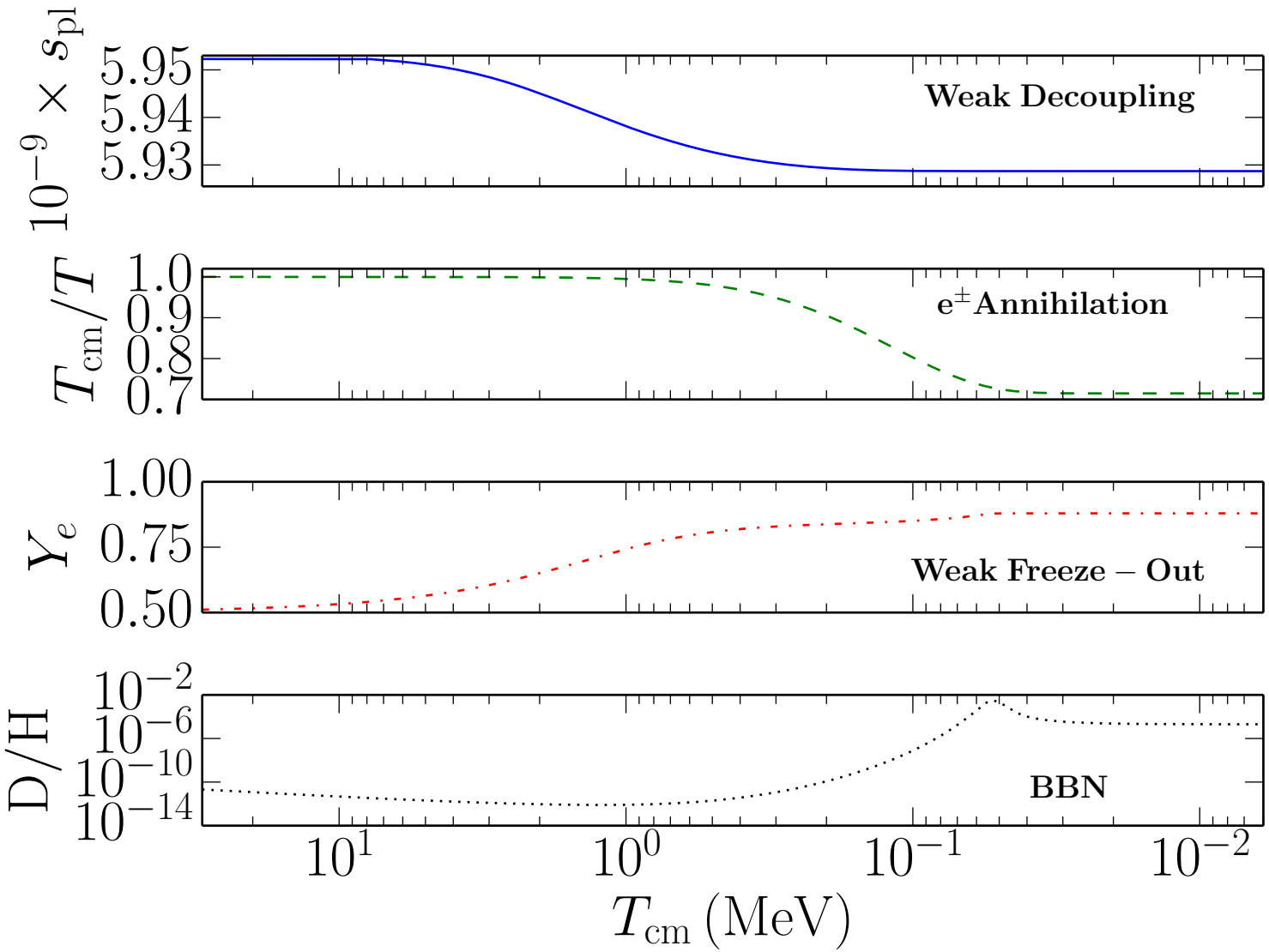


E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205

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}


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
n/p<1
$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$
$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$
$\mathrm{n} \rightleftharpoons \mathrm{p} + e^- + \bar{\nu}_e$
n/p>1
Alpha Particle Formation
T~ 0.1 MeV
T~ 0.75 MeV
Alpha Particle Formation
Time
PROTON
NEUTRON



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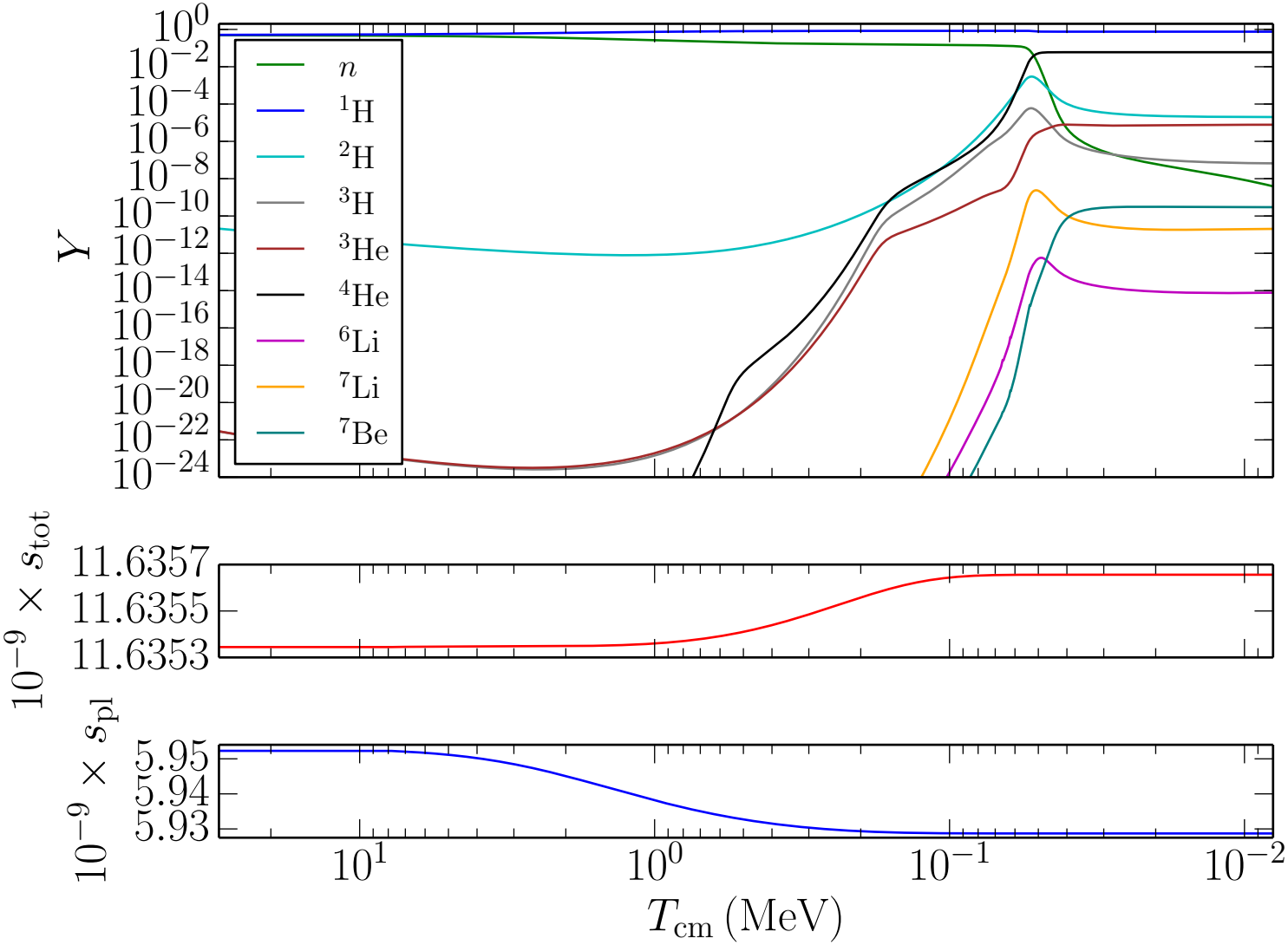


E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205

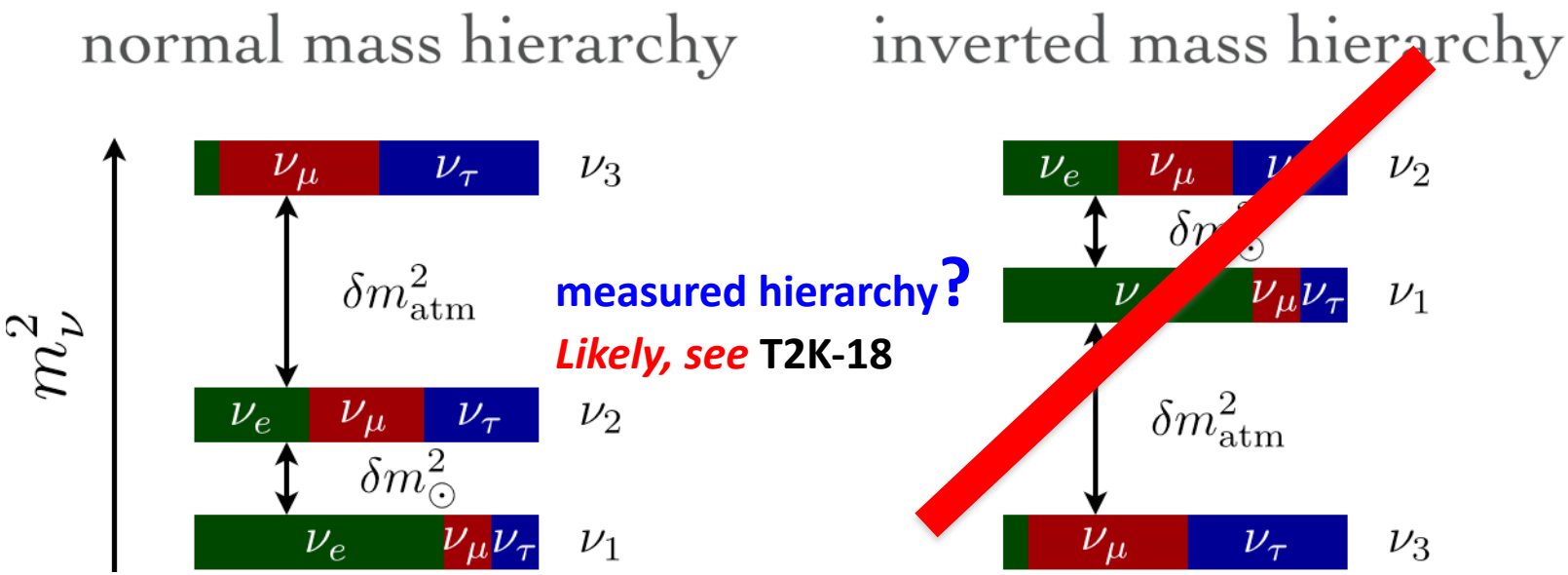
Neutrino Properties

we know the *mass-squared* differences:

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

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

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



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

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 0νββ 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

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

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

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

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

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

more standard model physics . . .

Quantum Kinetic Treatment

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

Our efforts to solve the QKEs for neutrino flavor
in the early universe and in compact objects:

E. Grohs, M. Paris, C. Kishimoto, S. Shalgar, V. Cirigliano, D. Blashke, L. Johns, GMF
and also (in supernovae) Manibrata Sen and Sherwood Richers

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

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

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

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

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**)

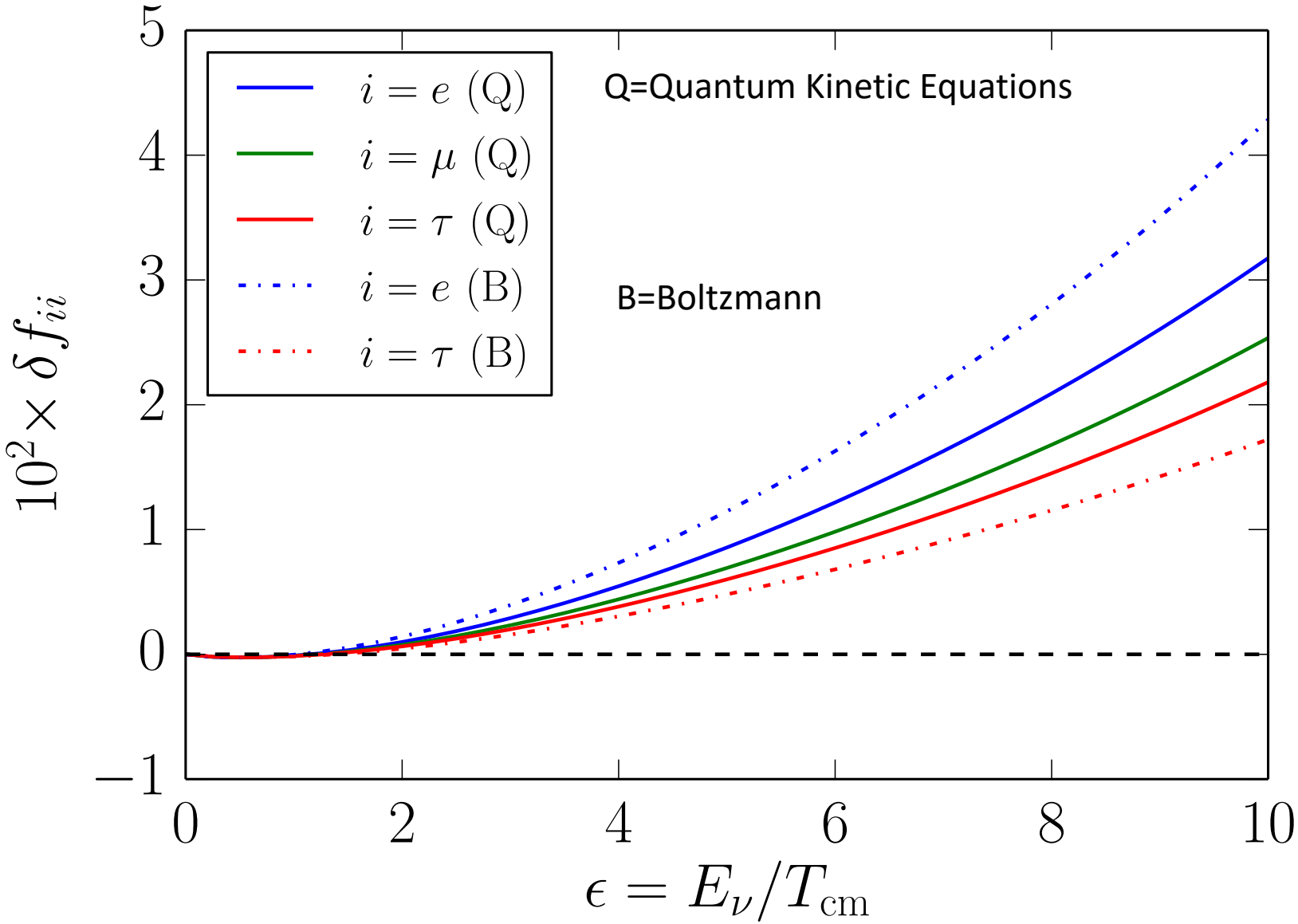
$$\left[\hat{f}\right]_{\text{flavor}} = \begin{pmatrix} f_{\nu_e\nu_e} & f_{\nu_e\nu_\mu} & f_{\nu_e\nu_\tau} \\ f_{\nu_\mu\nu_e} & f_{\nu_\mu\nu_\mu} & f_{\nu_\mu\nu_\tau} \\ f_{\nu_\tau\nu_e} & f_{\nu_\tau\nu_\mu} & f_{\nu_\tau\nu_\tau} \end{pmatrix} \Rightarrow \begin{pmatrix} f_{11} & f_{12} & f_{13}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

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

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



another aspect of neutrino flavor quantum kinetics . . .

"Entanglement Entropy" Flow?

• At high temperature, neutrino flavor amplitudes are thermally, incoherently distributed and unspecified.

• However, as the universe expands and the temperature drops, these amplitudes are set and, for example, neutrinos can be in collective flavor states, i.e., coherent superpositions.

• This represents a *decrease* in entanglement entropy in the neutrino flavor field.

• For example, for 2×2 flavor mixing, this entropy drop is $\sim k_{\rm b}\ \ln 2$ *per neutrino*.

• Since there are $\sim 10^{10}$ neutrinos per baryon, this could be significant.

• The question is: How much of this entanglement entropy drop *is transferred to the plasma* by neutrino scattering? Likely not very much, but only a full 3×3 QKE calculation can say for sure.

Real entanglement? – *efficacy of the mean field treatment*?
See Baha Balantekin, Amol Patwardhan, Michael Cervia

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) low mass/large mixing sterile neutrinos

(2) Neutrino "mass" measurements confront Σm_ν

(3) Dark Photons

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;