# Neutrino Dynamics in Big Bang Nucleosynthesis

Evan Grohs

University of California Berkeley

13 Sep 2019

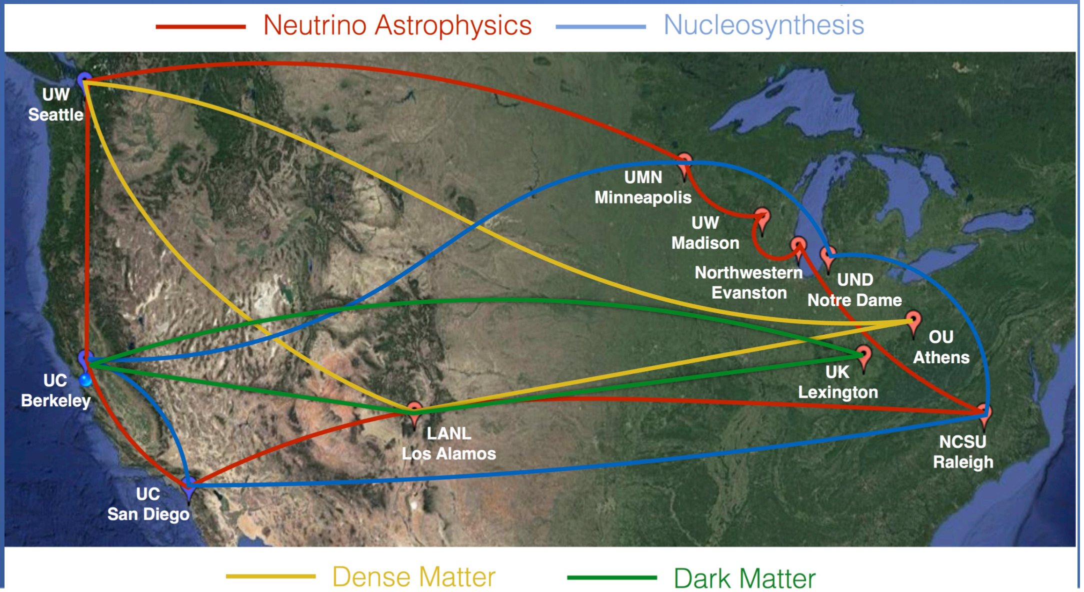
*Extraordinary Seminar: University College London*

Contributors:

George Fuller
Luke Johns
Chad Kishimoto
Alexey Vlasenko
Daniel Blaschke
Vincenzo Cirigliano
Mark Paris
Shashank Shalgar

# Network for Neutrinos, Nuclear Astrophysics and Symmetries

- Funded by National Science Foundation
- 11 Institutions headquartered in Berkeley, CA.
  - 10 Universities
  - 1 National Laboratory
- 8 postdoctoral research fellows
- Research thrusts including
  - Nucleosynthesis and the origin of the elements
  - Neutrinos and fundamental symmetries
  - Dense matter
  - Dark matter



# Outline and preliminaries

- Observational Cosmology
  - The coming era of precision cosmology
  - Neutrino observables
  - Current status and future goals
- Big Bang Nucleosynthesis
  - Overview
  - Weak decoupling
  - Neutron-to-proton rates
  - Neutron life time
- Neutrino Quantum Kinetics
  - Generalized Neutrino Density Matrices
  - Preliminary Calculations
- Summary and future work

Useful constructs:

$$T_{\rm cm} \propto 1/a$$

$$\epsilon \equiv E_\nu / T_{\rm cm}$$

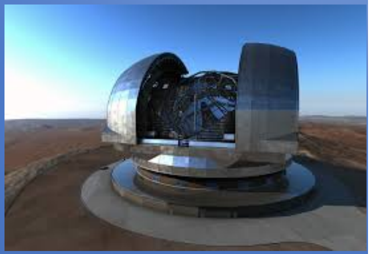
$$dn \sim d^3p\, f(\epsilon)$$

Fermi-Dirac Equilibrium (non-degenerate):

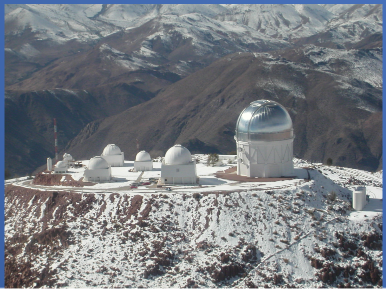
$$f^{(\rm FD)}(\epsilon) = \frac{1}{e^\epsilon + 1}$$

# The coming era of precision cosmology

I. Cosmic Microwave Background Experiments
   A. CMB Stage IV: Simons Observatory & South Pole Observatory
   B. Other Ground-Based CMB experiments: CLASS and QUIET
   C. Future satellites: PICO & LiteBIRD



II. Thirty-meter class telescopes
   A. EELT and GMT - Atacama
   B. TMT – Site to be determined



III. Surveys
   A. DES - Cerro Tololo, Chile
   B. DESI - Kitt Peak, AZ
   C. LSST – Cerro Pachón, Chile

$Y_P$

Primordial Helium Mass Fraction
CMB Polarization data
Simons Observatory/Future Satellites

$\Sigma m_\nu$

Sum of the light neutrino masses
Large Scale Structure/Lensing
CMB Stage-IV & DESI

## *5 Observables in Neutrino Cosmology*

$\mathrm{D/H}$

Deuterium Abundance
QSO Absorption Lines
Thirty-Meter Class Telescopes

$N_{\mathrm{eff}}$

Neutrino Energy Density
High-$\ell$ Temperature Data
SPT & SO

$\omega_b$

Baryon Density
Temperature Power Spectrum
CMB Stage IV

# Cosmological Neutrino Observables: Current Status

Baryon Density, Planck VI, 2018

$$\omega_b = 0.02242 \pm 0.00014\,(1\sigma)$$

Number of relativistic degrees of freedom, Planck VI, 2018

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}\ (2\sigma)$$

Sum of the Neutrino Masses, Planck VI, 2018

$$\Sigma m_\nu < 120\,{\rm meV}\ (2\sigma)$$

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

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

# BBN Epochs of Interest

Equilibrium initial conditions
Nonequilibrium evolution

time

| | | |
|---|---|---|
| $e^{\pm}(\nu_i,\nu_i)e^{\pm} \sim \nu_j(\nu_i,\nu_i)\nu_j \lesssim H$ | (WD) | $T \sim 1\,\mathrm{MeV}$, $t \sim 1\,\mathrm{s}$ |
| $n(\nu_e, e^-)p \lesssim H$ | (WFO) | |
| $e^-(e^+,\gamma)\gamma \lesssim H$ | ($e^{\pm}$A) | |
| $n(p,\gamma)d \lesssim H$ | (NFO) | $T \sim 100\,\mathrm{keV}$, $t \sim 100\,\mathrm{s}$ |

Temp.

# Weak Decoupling: Overview

1. Initially: neutrinos at the same temperature as electrons and positrons
2. Electrons and positrons annihilate to produce photon pairs, slightly raising temperature of plasma
3. Two processes create heat flow between neutrinos and plasma

$$\left.\begin{aligned} \nu_i + e^{\pm} &\leftrightarrow \nu_i + e^{\pm} \\ \nu_i + \overline{\nu}_i &\leftrightarrow e^{-} + e^{+} \end{aligned}\right\}$$

Charged Current $(\nu_e)$

Neutral Current $(\nu_e, \upsilon_\mu, \upsilon_\tau)$

4. Three processes redistribute energy within neutrino seas

$$\nu_i + \nu_j \leftrightarrow \nu_i + \nu_j$$

$$\nu_i + \overline{\nu}_j \leftrightarrow \nu_i + \overline{\nu}_j$$

$$\nu_i + \overline{\nu}_i \leftrightarrow \nu_j + \overline{\nu}_j$$

5. End result: neutrinos cooler than photons

Boltzmann

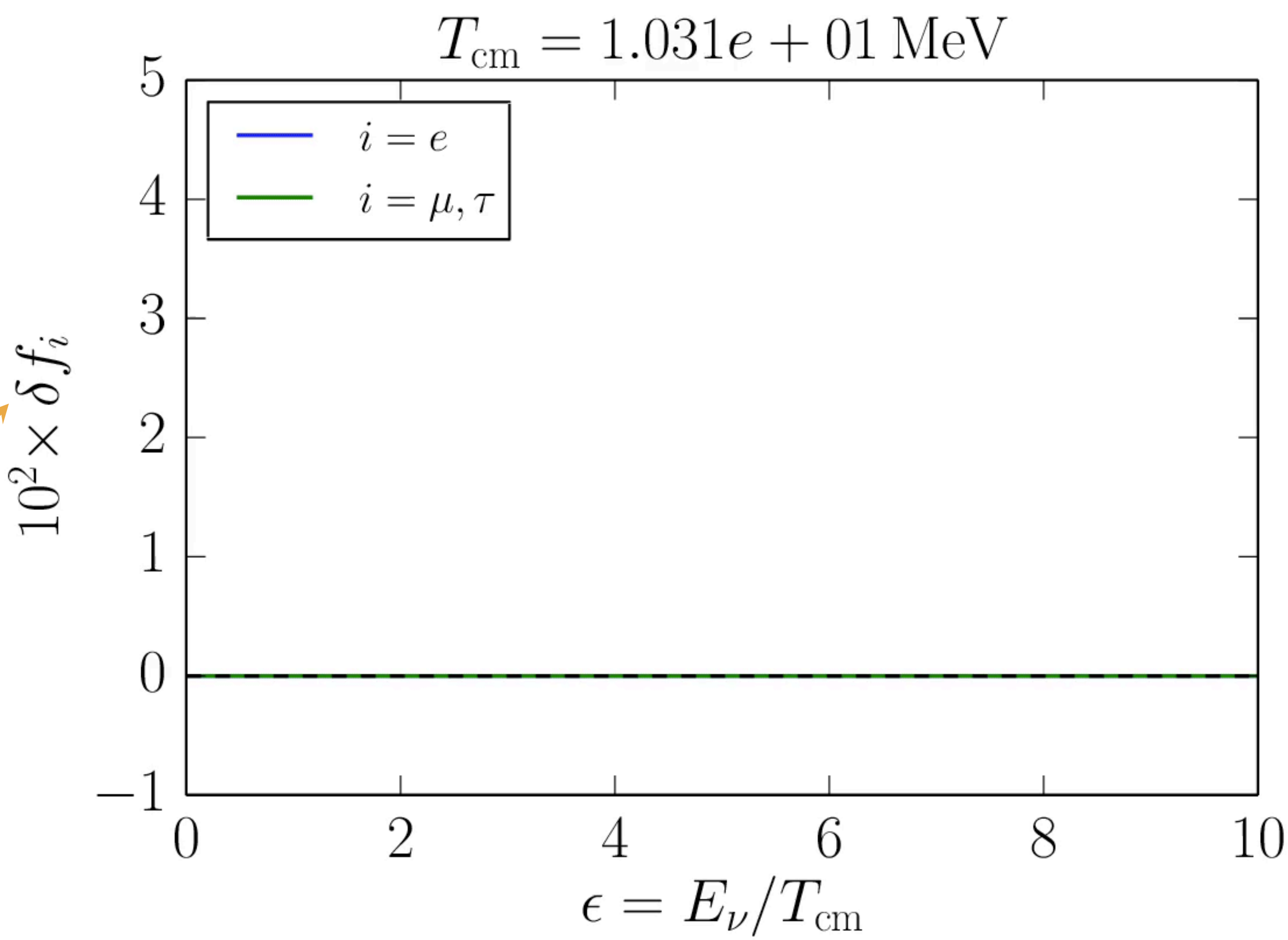
Neutrino

Transport

1-D array for each neutrino flavor; 100 Bins in epsilon $0 \leq \epsilon \leq 25$

Deviation from FD spectra

$N_{\text{eff}} = 3.044$



# Differential Visibility of Neutrino-Electron Scattering

Out-of-Equilibrium Neutrino Transport

$$\nu_i + \overline{\nu}_i \leftrightarrow e^- + e^+$$

$$\nu_i + e^{\pm} \leftrightarrow \nu_i + e^{\pm}$$

Red contours of constant differential visibility for electron flavor

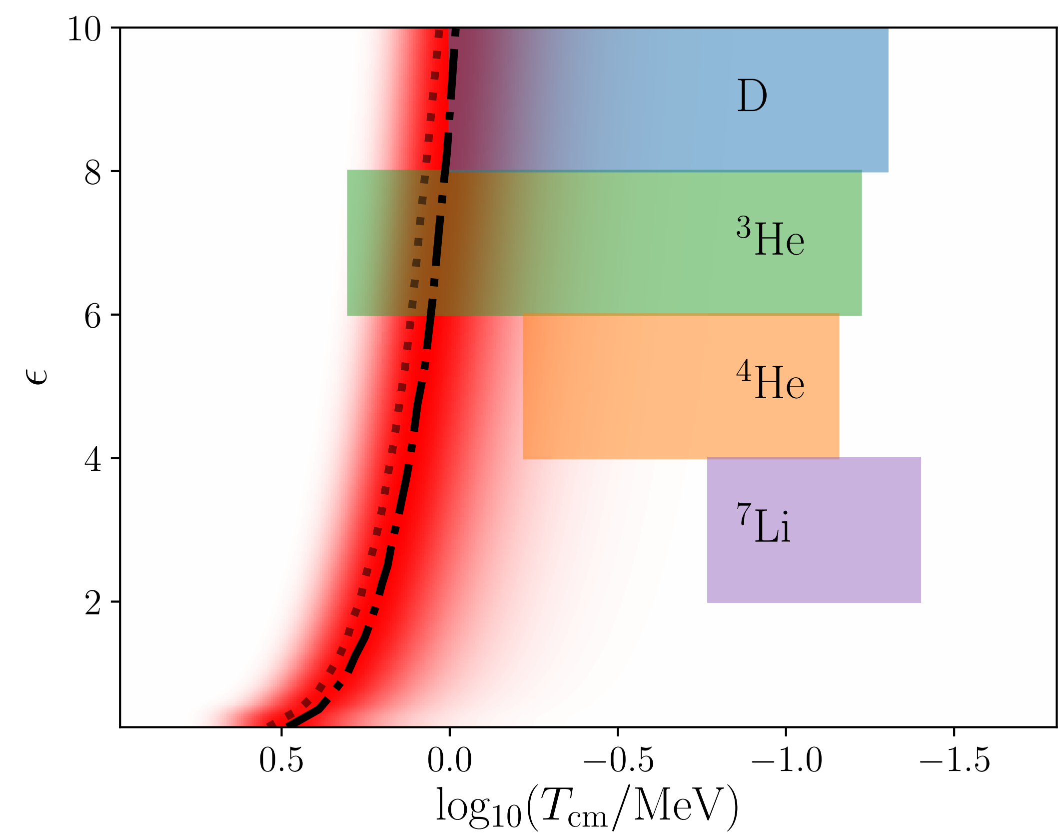
$$\frac{\Gamma'_{\nu_i}}{H} e^{-\tau_{\nu_i}}$$

High $T_{\rm cm}$

$\tau_{\nu_i} >> 1$

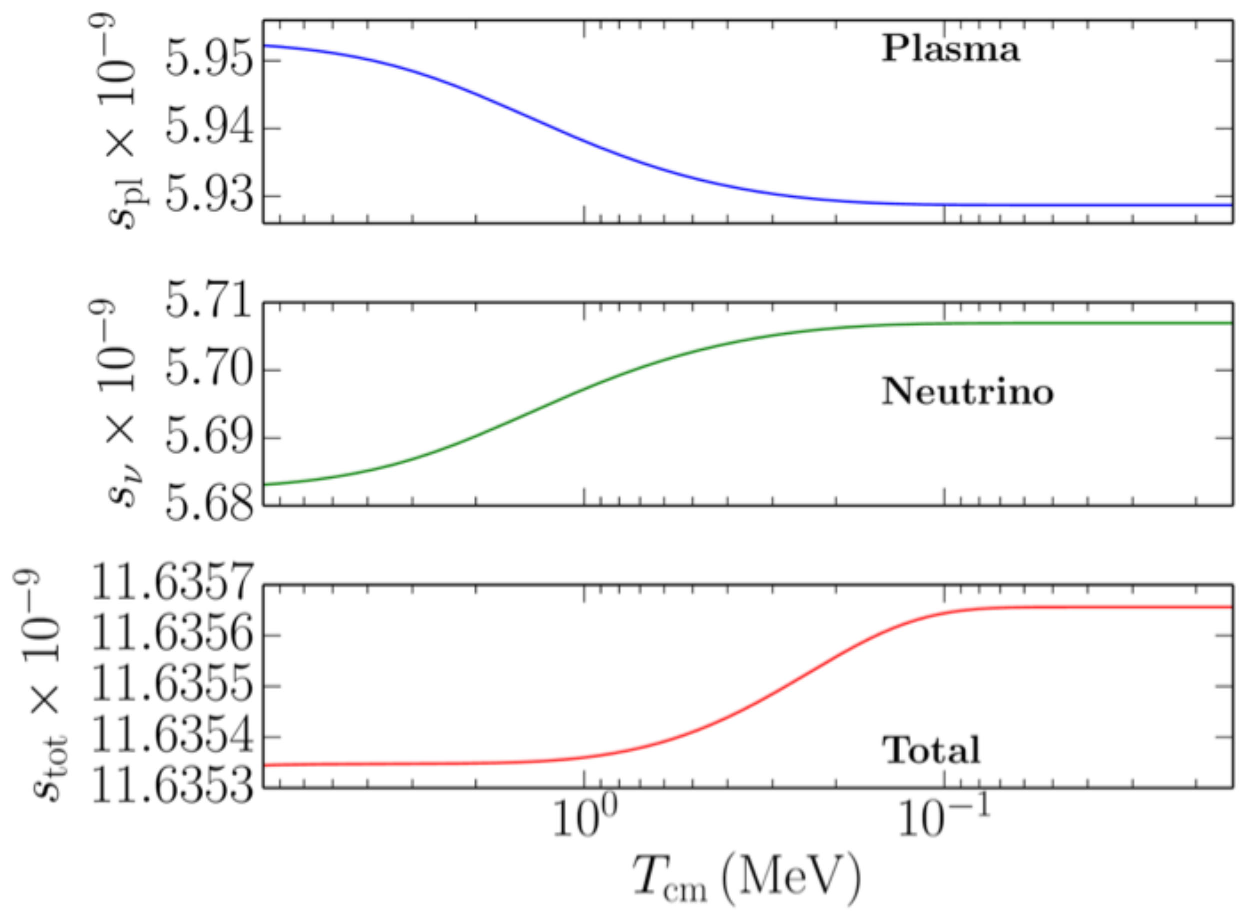
Low $T_{\rm cm}$

$\Gamma'_{\nu_i} << H$




c/o Matthew J. Wilson

# Entropy flows




Entropy flow out of the plasma into the neutrino seas

Charged leptons are hotter than neutrinos

Total entropy in the universe increases

<u>Without Transport:</u>

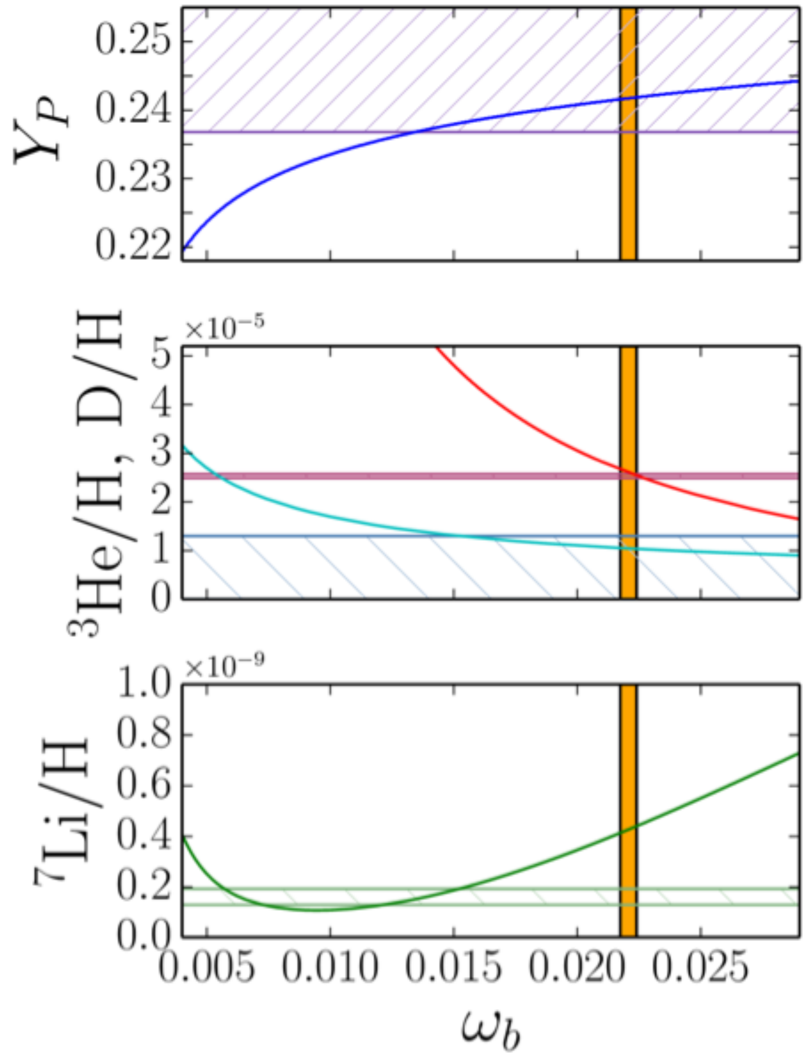
$$Y_P = 0.2478$$
$$\mathrm{D/H} = 2.650 \times 10^{-5}$$

<u>With Transport included:</u>

$$Y_P = 0.2479$$
$$\mathrm{D/H} = 2.659 \times 10^{-5}$$

<u>Relative change:</u>

$$\delta Y_P \sim 4 \times 10^{-4}$$
$$\delta(\mathrm{D/H}) \sim 3 \times 10^{-3}$$



# Neutron to proton rates I

$$\nu_e + n \leftrightarrow p + e^-$$

$$e^+ + n \leftrightarrow p + \overline{\nu}_e$$

$$n \leftrightarrow p + \overline{\nu}_e + e^-$$

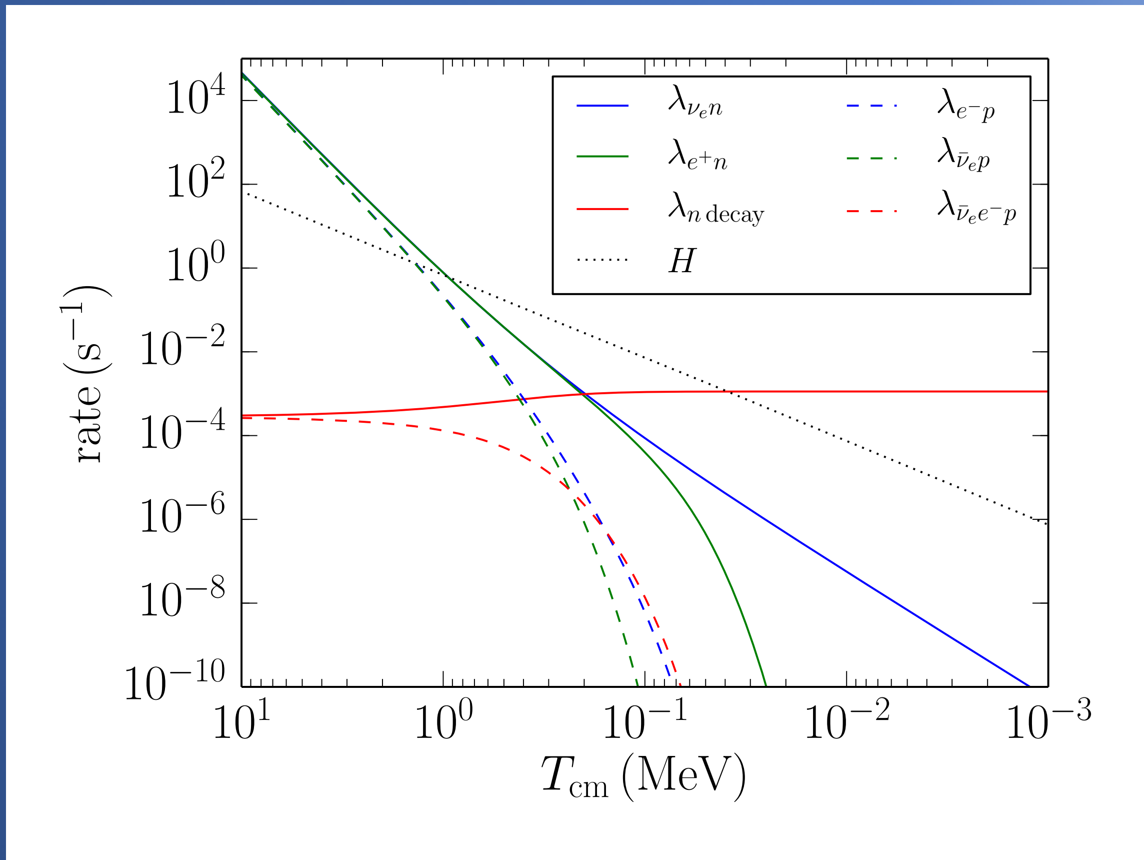
6 Neutron-to-proton rates set n/p

$\nu_e$ capture on neutron, normalized to neutron lifetime

$$\lambda_{\nu_e n \to p e^-} = \frac{G_F^2(1+3g_A^2)}{2\pi^3} \int_0^\infty dE_\nu C(E_\nu + \delta m_{np}) Z(E_\nu + \delta m_{np}, E_\nu) \times E_\nu^2 (E_\nu + \delta m_{np}) \sqrt{(E_\nu + \delta m_{np})^2 - m_e^2} \times [f_{\nu_e}(E_\nu)][1 - g_{e^-}(E_\nu + \delta m_{np})]$$

$$\frac{1}{\tau_n} = \frac{G_F^2(1+3g_A^2)}{2\pi^3} \int_0^{\delta m_{np} - m_e} dE_\nu C(\delta m_{np} - E_\nu) Z(\delta m_{np} - E_\nu, E_\nu) \times E_\nu^2 (\delta m_{np} - E_\nu) \sqrt{(\delta m_{np} - E_\nu)^2 - m_e^2}$$

# Neutron to proton rates II



# Neutron to proton ratio – Primordial Helium

Equilibrium:

$$\mu_{\nu_e} + \mu_n = \mu_p + \mu_{e^-}$$

$$n/p = \exp\left[-\frac{\delta m_{np}}{T} + \phi_e - \xi_{\nu_e}\right]$$

Common Approximation at late times after Weak Freeze-Out (WFO):

$$n/p(t) = e^{-\delta m_{np}/T_{\rm WFO}}\, e^{-(t-t_{\rm WFO})/\tau_n}$$

$T_{\rm WFO} \simeq 0.7$ MeV

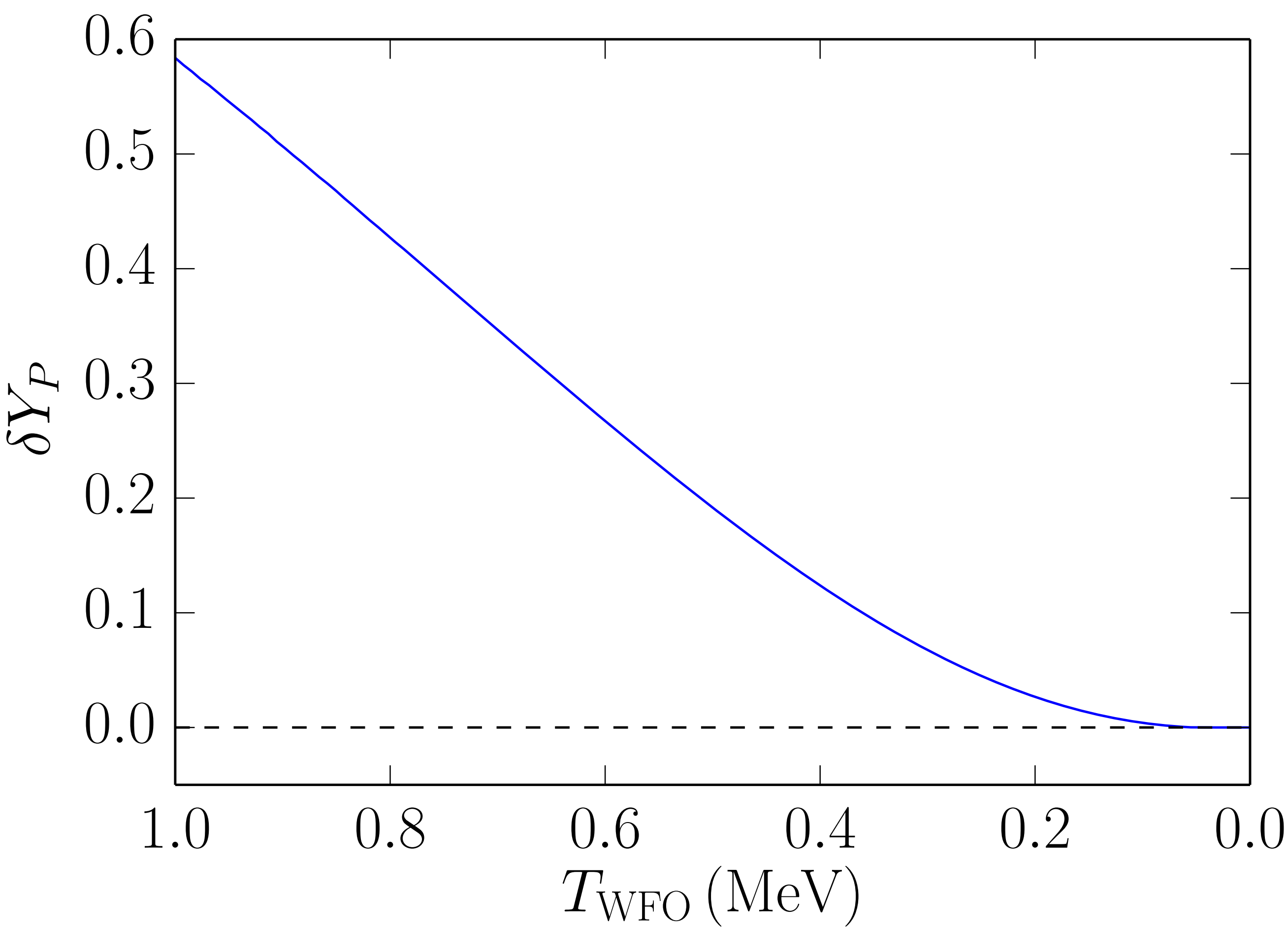
How Accurate is the WFO approximation?

$$Y_{\rm P} \simeq \left.\frac{2n/p}{1+n/p}\right|_{\rm f.o.}$$

Lepton capture rates set to zero at $T_{WFO}$

No Pauli blocking in free neutron decay

Helium-4 Deviation from Baseline



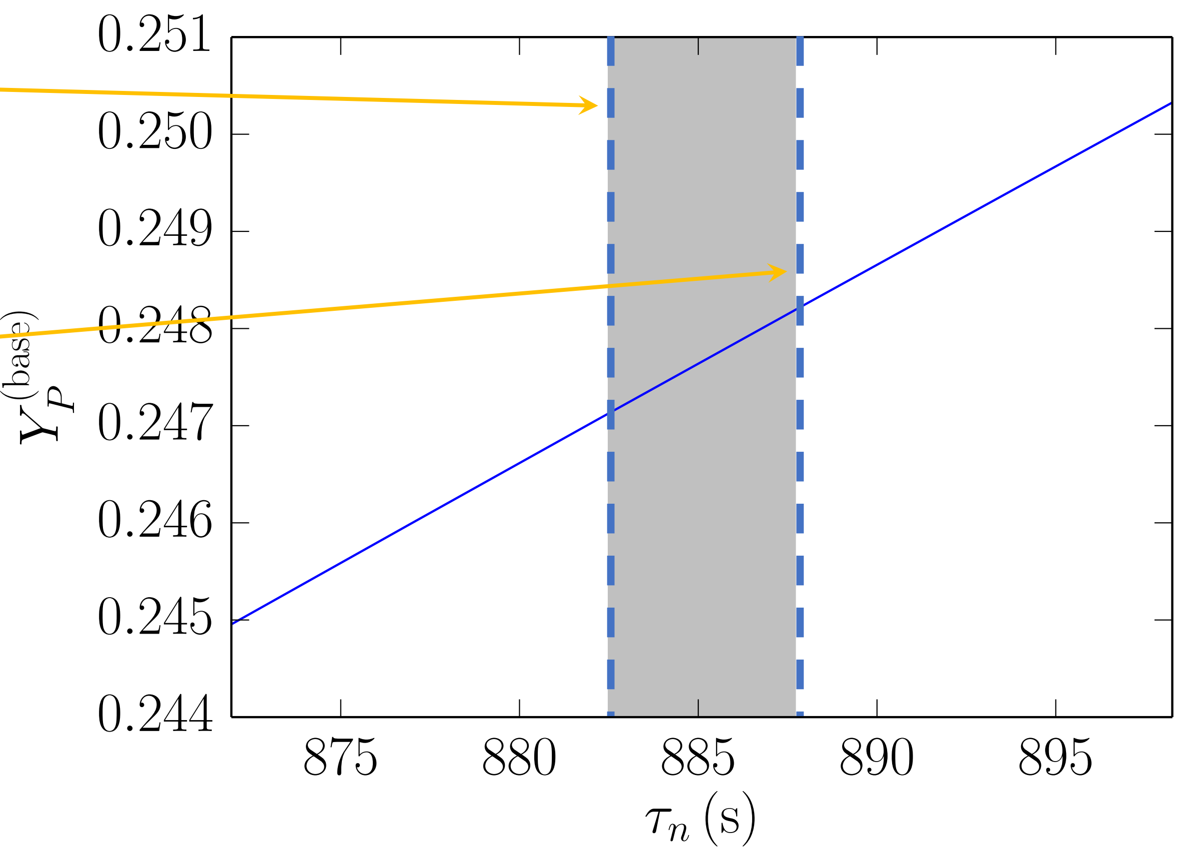

arXiv: 1607.02797

# Helium vs. Neutron lifetime

Bottle expt.
Steyerl et al (2016)
$\tau_n = 882.5 \pm 2.1\,\mathrm{s}$

Beam expt.
(1309.2623)
$\tau_n = 887.7 \pm 3.1\,\mathrm{s}$

UCN$\tau$
(1707.01817)
$\tau_n = 877.7 \pm 1.1\,\mathrm{s}$



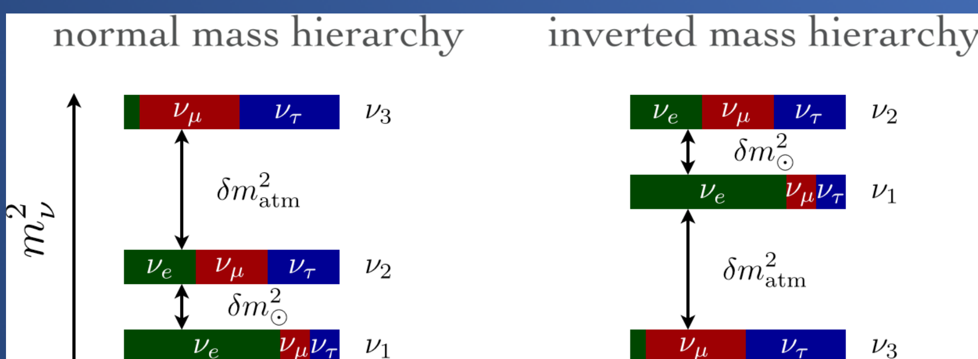
# Beyond the Boltzmann Approach

*Mass* eigenbasis is not coincident with *Weak* eigenbasis

1. Unitary Transformation in vacuum: PMNS matrix
2. Neutrinos oscillate between weak eigenstates
3. Generalized density matrix for neutrino ensemble

$$U = U_{23}U_{13}U_{12} \qquad U_{12} = \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Mixing angles: $\theta_{23}, \theta_{13}, \theta_{12}$




Mass squared differences:

$$\delta m^2_\odot = 7.5 \times 10^{-5}\,{\rm eV}^2$$

$$\delta m^2_{\rm atm} = 2.6 \times 10^{-3}\,{\rm eV}^2$$

c/o George Fuller

# Neutrino Density Matrices

Neutrinos: $$F = F(x, \vec{p})$$

Antineutrinos: $$\overline{F} = \overline{F}(x, \vec{p})$$

Generalized $2n_f \times 2n_f$ density matrices

$n_f$: number of flavors
2 helicity states

$$F = \begin{bmatrix} f_{LL} & f_{LR} \\ f_{LR}^{\dagger} & f_{RR} \end{bmatrix}$$

$f_{LL}^{ii}$ : occupation numbers

$f_{LL}^{ij}$ : flavor coherence

$f_{LR}$ : spin coherence

$f_{RR}$ : opposite helicity

# QKEs in the Early Universe

See Sigl & Raffelt (1993); Vlasenko, Fuller, & Cirigliano (2013); Blaschke & Cirigliano (2016)

Change array dimensions (Majorana or Dirac):

$$\{f_i(\epsilon)\}, \{\overline{f}_i(\epsilon)\} \rightarrow f_{ij}(\epsilon), \overline{f}_{ij}(\epsilon)$$

2 Generalized 3 × 3 density matrices (no spin coherence)

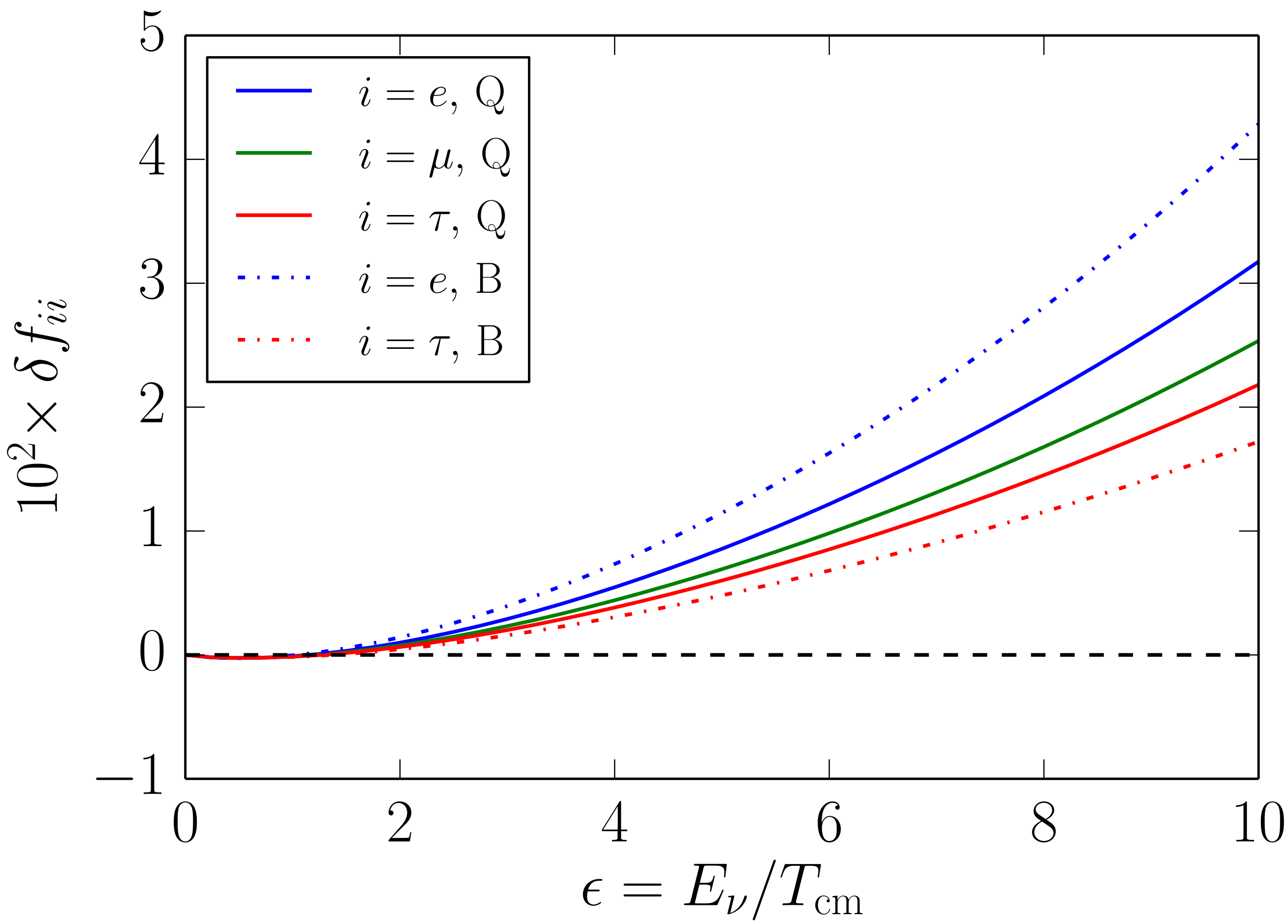
Equations of motion for neutrinos:

$$\frac{df}{dt} = -i[H, f]_- + C[f]$$

*H*: Hamiltonian-like potential (coherent)

$\hat{C}$: Collision term from Blaschke & Cirigliano (2016)

→ Nonlinear coupled ODEs




Freeze-Out

Spectra

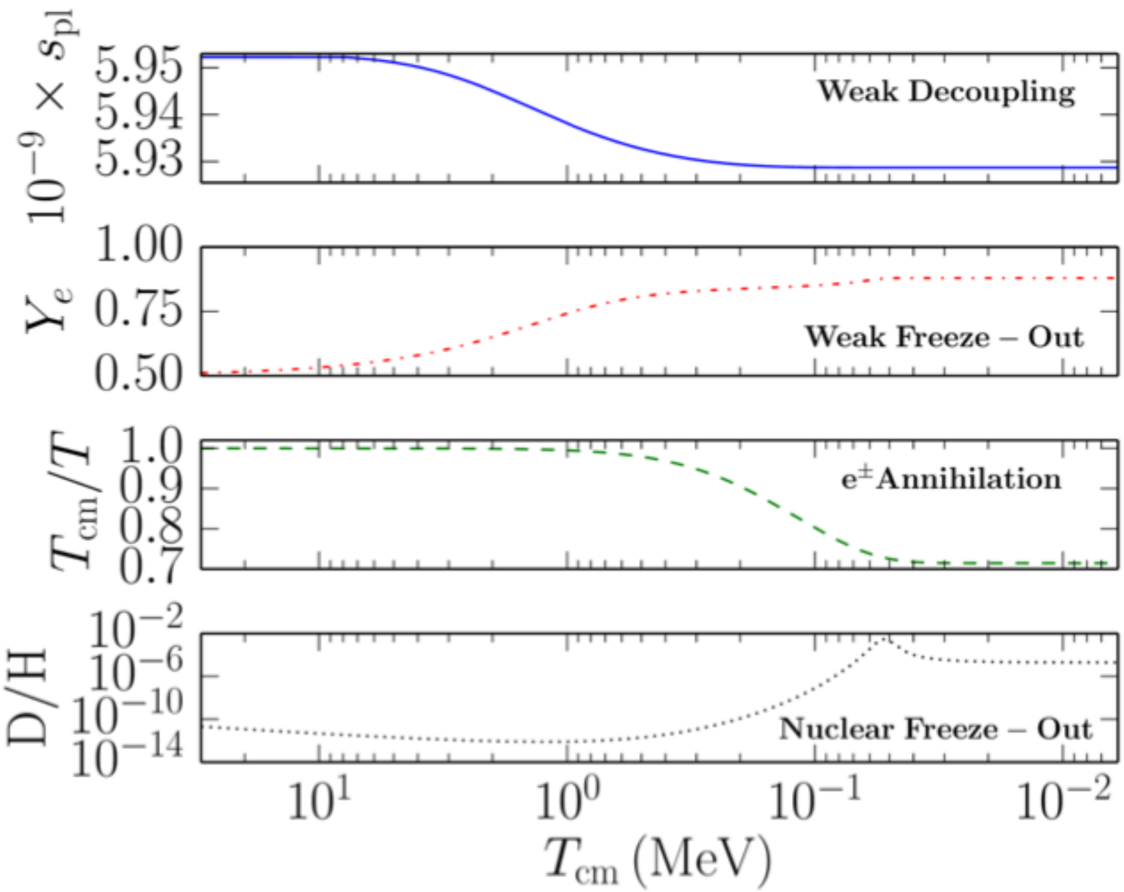
Full collision term, vacuum Potential in QKE calc.

Full collision term in Boltzmann transport calc.

Preliminary Calc.

# Concurrent epochs of BBN

Equilibrium initial conditions
Nonequilibrium evolution




Weak interactions
between leptons

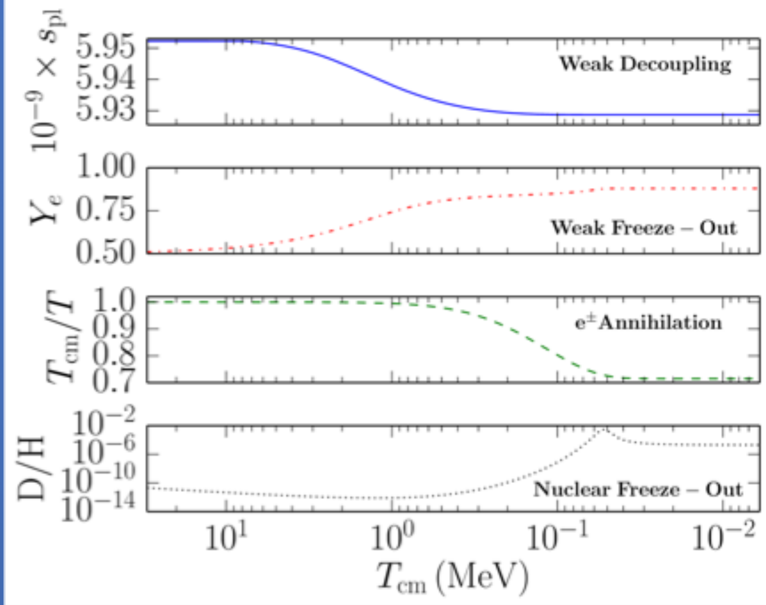
Weak interactions
between leptons
and baryons

EM interactions
between leptons and photons

Strong and EM interactions
between baryons
and photons

# Summary and future work

1. Neutrino cosmology
   a) $N_{\text{eff}}$ and $\Sigma m_\nu$: energy densities
   b) D/H and $Y_P$: convolution in rates
2. Weak Decoupling & Weak Freeze-Out
   a) Neutrino spectra influence $n/p$
   b) Neutron lifetime may be important
3. Quantum Kinetic Equations
   a) Coherent terms up to $G_F^2$
   b) Collisions with $e^{\pm}, \nu, \bar{\nu}$ up to $G_F^2$
4. Future calculations
   a) QKEs for transport: $N_{\text{eff}}$
   b) Charged-Current QKES: Abundances




Observations will drive the Theory!