The BURST Code

Evan Grohs
University of Michigan
QuEPCO Workshop
23 Aug 2017

Outline and preliminaries

- Introduction to BURST
  - Self-Consistency in the early universe
- Previous work done with BURST
  - BBN with neutrino transport
  - Entropy Flow from plasma to neutrinos
  - Weak Freeze-Out sensitivity to n↔p rates
  - Lepton asymmetry in BBN
  - Electron mass effects in BBN
  - νMR effect
- Quantum Kinetic Equations
  - Hamiltonian-like potential
  - Slab testing
- Summary and future work

Useful constructs:

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

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

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

BURST

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

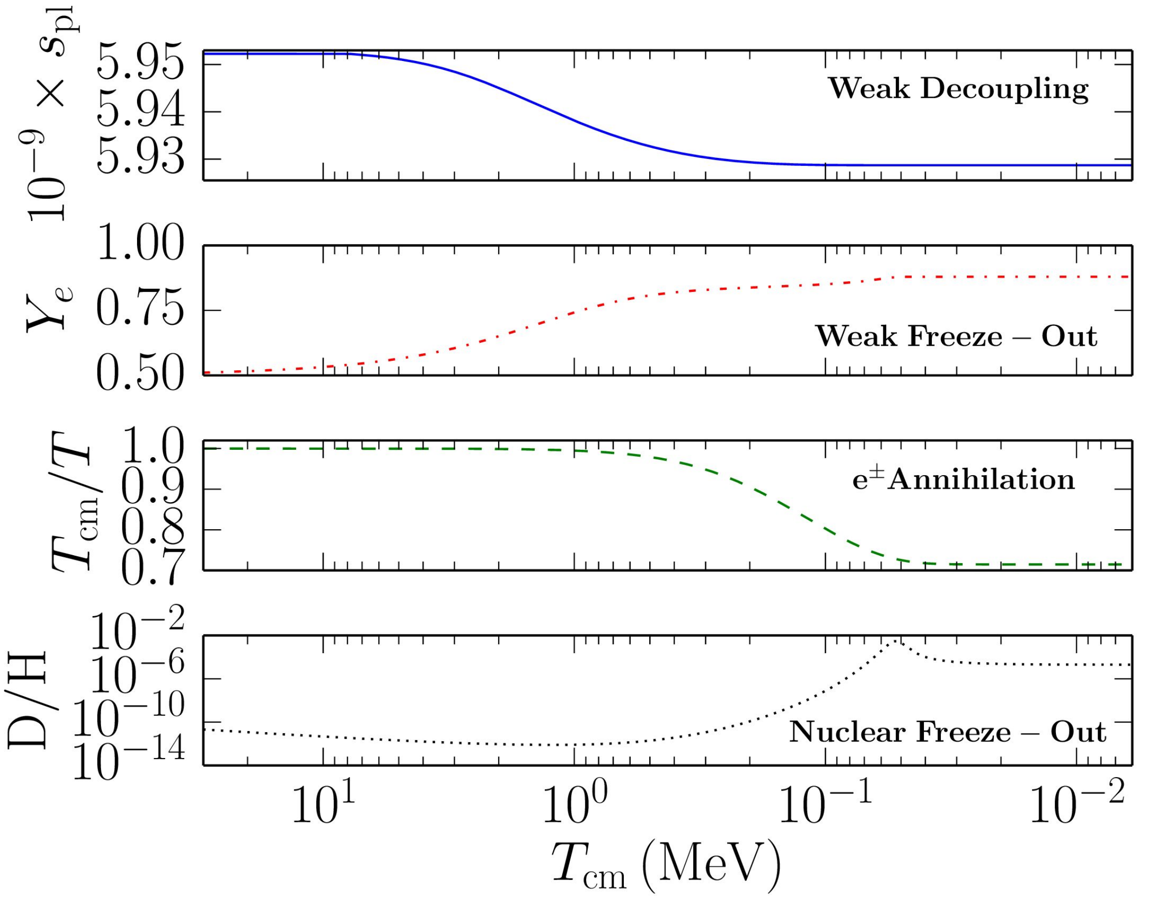
- ➔ Maintain self-consistency over large range of epochs

TRANSPORT

- ➔ Follow evolution of neutrino spectra

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

Weak Decoupling: Instantaneous vs. Boltzmann Transport

Neutrinos have identical temperature to plasma particles at early times

$$T_{\rm cm} = T = 10\,{\rm MeV}$$

Unperturbed Fermi-Dirac (FD) occupation numbers

$$f(E;T_{\rm cm}) = \frac{1}{e^{E/T_{\rm cm}}+1}$$

Ratio of temperature-parameter scales

$$\left.\frac{T_{\rm cm}}{T}\right|_{\rm f.o.} = \left(\frac{4}{11}\right)^{1/3}$$

Neutrinos decouple over many Hubble times

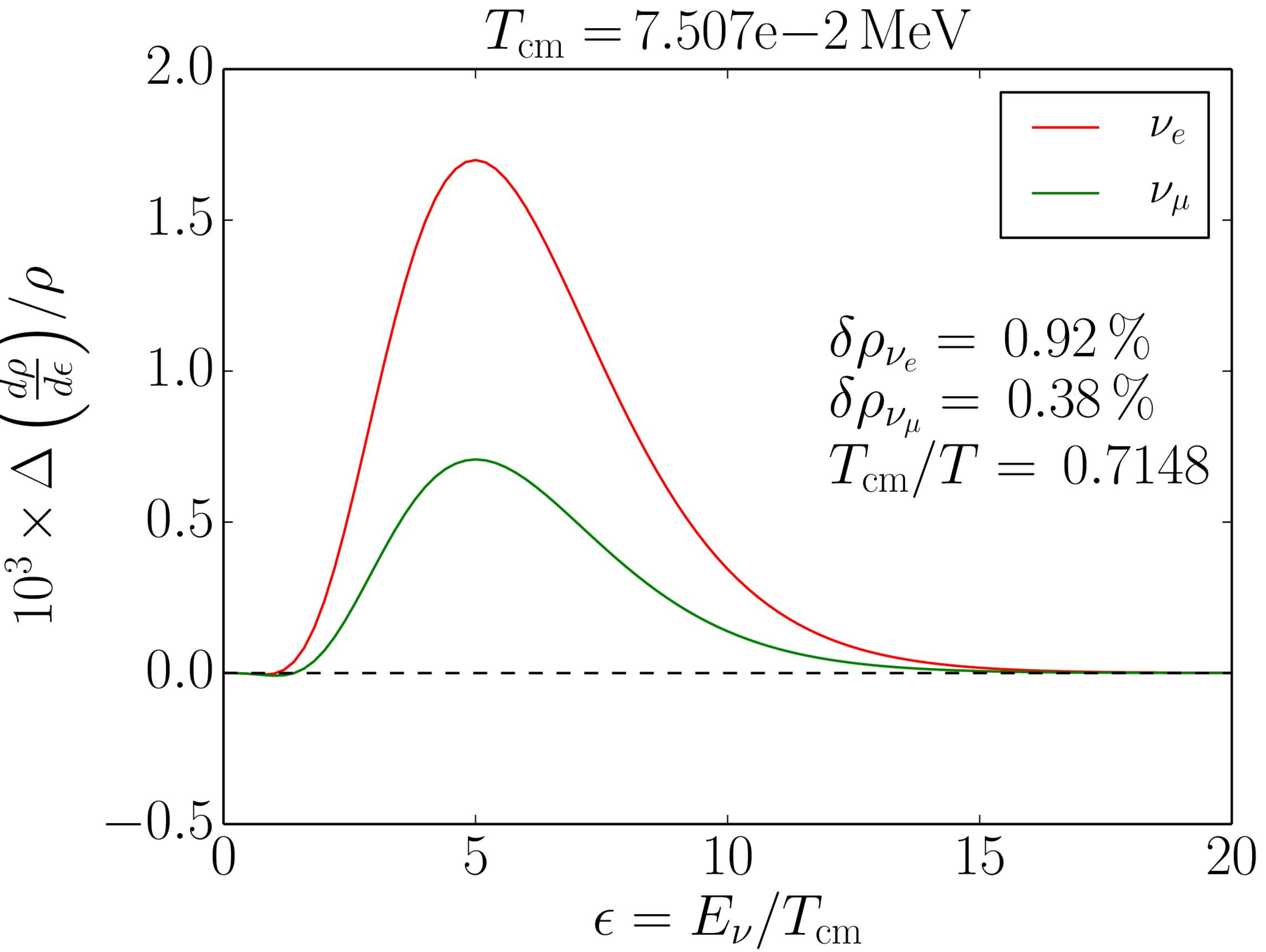
$$\begin{gathered}\nu+\nu \leftrightarrow \nu+\nu \\ \nu+\overline{\nu} \leftrightarrow \nu+\overline{\nu} \\ \nu+e \leftrightarrow \nu+e \\ \nu+\overline{\nu} \leftrightarrow e^- + e^+\end{gathered}$$

Derivatives are functions of comoving temperature and occupation numbers

$$\frac{df}{dt} \sim T_{\rm cm}^5 \int\int \langle|\mathcal{M}|^2\rangle F$$

Heat flow from plasma to neutrino seas

$$\left(\frac{d\rho_\nu}{dt}\right)_T > 0 \implies \frac{ds_{\rm pl}}{dt} < 0$$

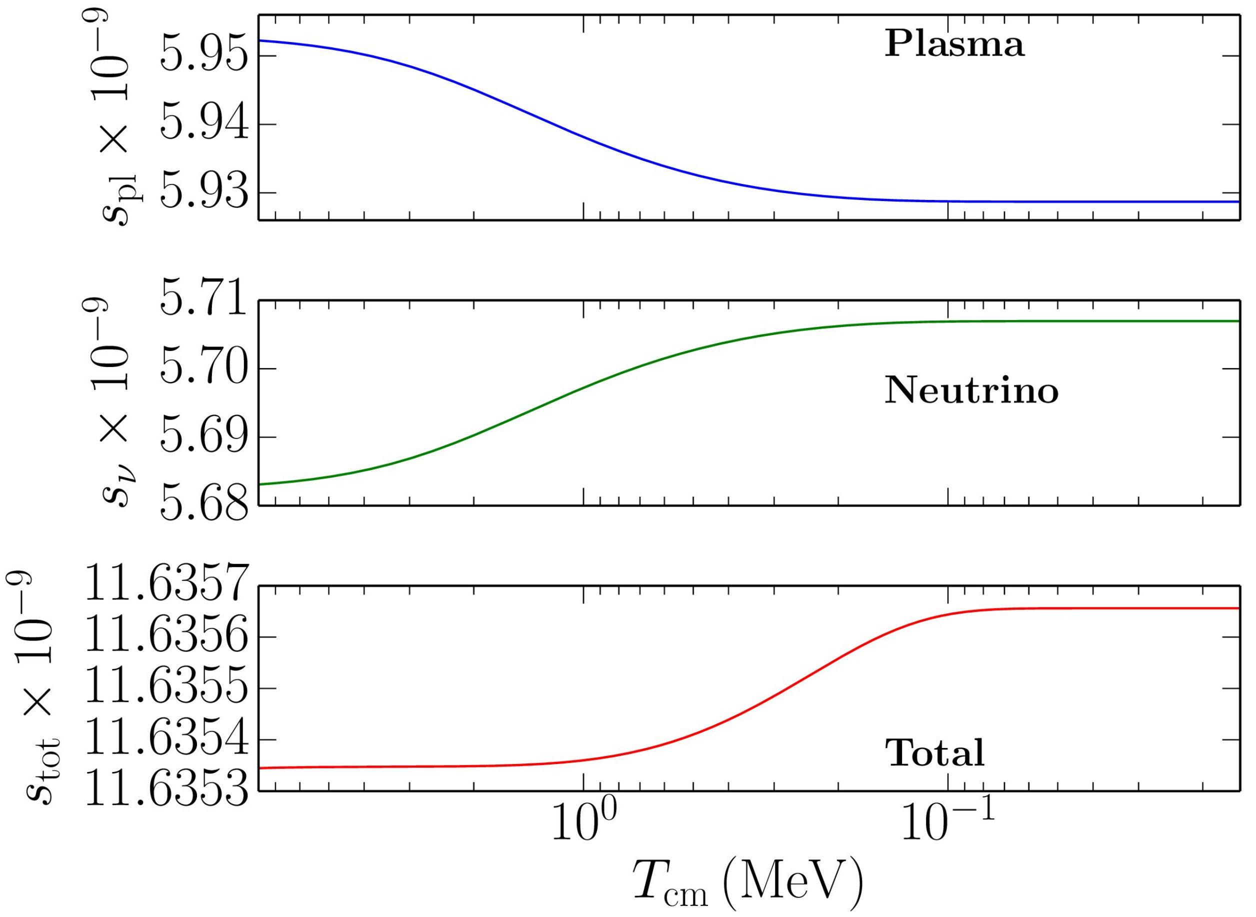


Standard Cosmology, Neutrino transport w/o oscillations

μ and τ flavor degenerate

Neutrinos and antineutrinos degenerate

Entropy flows



Entropy flow out of the plasma into the neutrino seas

Charged leptons are hotter than neutrinos

Total entropy in the universe increases

Weak Freeze-Out: Equilibrium vs. Boltzmann

Neutron to proton reactions:

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

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

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

Neutrinos keep neutron-to-proton ratio in equilibrium at high temperatures

$$\mu_{\nu_e} + \mu_n = \mu_p + \mu_e$$

n/p ratio and electron fraction:

$$n/p = e^{-(\delta m_{np}/T) - \xi_{\nu_e} + \phi_e}$$

$$Y_e = \frac{1}{1 + n/p}$$

Neutron to proton rate coefficients:

$$\lambda_{\nu_e n},\ \lambda_{e^- p}$$

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

$$\lambda_{n\,\mathrm{decay}},\ \lambda_{\overline{\nu}_e e^- p}$$

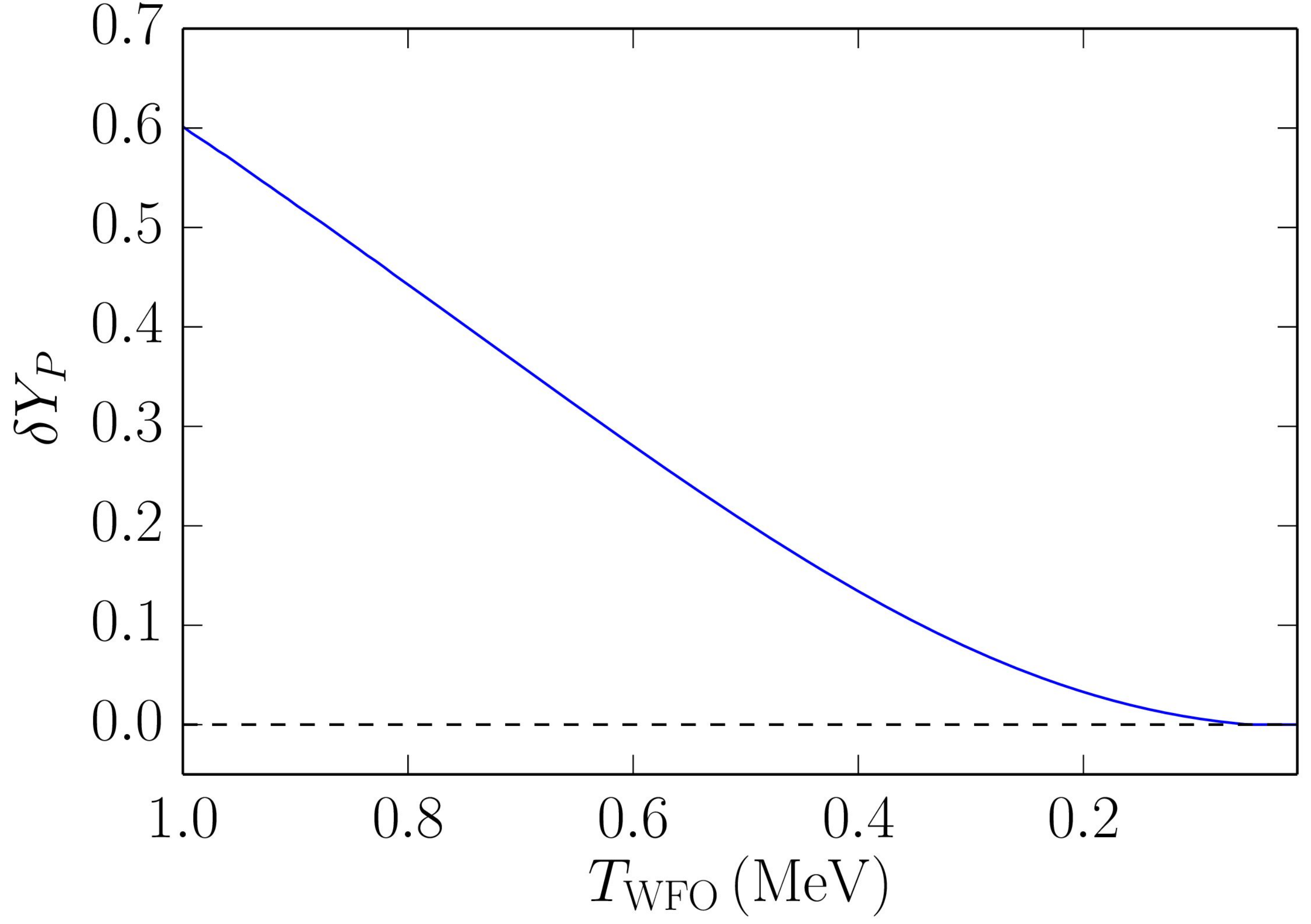
Rates functions of comoving temperature and occupation numbers

$$\lambda \sim G_F^2 T_{\mathrm{cm}}^5 \int d\epsilon\, f_{\nu_e}(\epsilon)$$

Leverage on helium mass fraction:

$$Y_P \simeq \frac{2n/p}{1 + n/p}$$

Equilibrium initial conditions
Nonequilibrium evolution



What if we assume the *np* rates freeze-out instantaneously?

Artificial scenario of WFO:
Set all lepton capture rates to zero at T_{WFO}

$$\lambda_{e^-p},\ \lambda_{\overline{\nu}_e p} \rightarrow 0$$
$$\lambda_{\nu_e n},\ \lambda_{e^+n} \rightarrow 0$$

Lepton asymmetry in BBN

Posit that universe has an asymmetry in the lepton sector different than the baryon number:

$$L_i \equiv \frac{n_{\nu_i} - n_{\overline{\nu}_i}}{n_\gamma}$$

Comoving lepton number (same in all flavors)

$$L_\nu^\star = \frac{1}{4\zeta(3)} \int_0^\infty d\epsilon\, \epsilon^2 [f_\nu(\epsilon) - f_{\overline{\nu}}(\epsilon)]$$

Motivated by:

- →Sterile neutrinos [Matter enhanced MSW resonance(s)]
- →Primordial abundances [Sensitivity of helium]
- →Leptogenesis/Baryogenesis

Degenerate Fermi–Dirac Equilibrium initial conditions:

$$f^{(\mathrm{eq})}(\epsilon;\xi) = \frac{1}{e^{\epsilon-\xi}+1}$$

Helium mass fraction suggests $L_\nu \lesssim 0.1$ (Kneller & Steigman 2004)

Primordial Abundances

Solid Lines: Dark radiation model to "mock up" transport effects

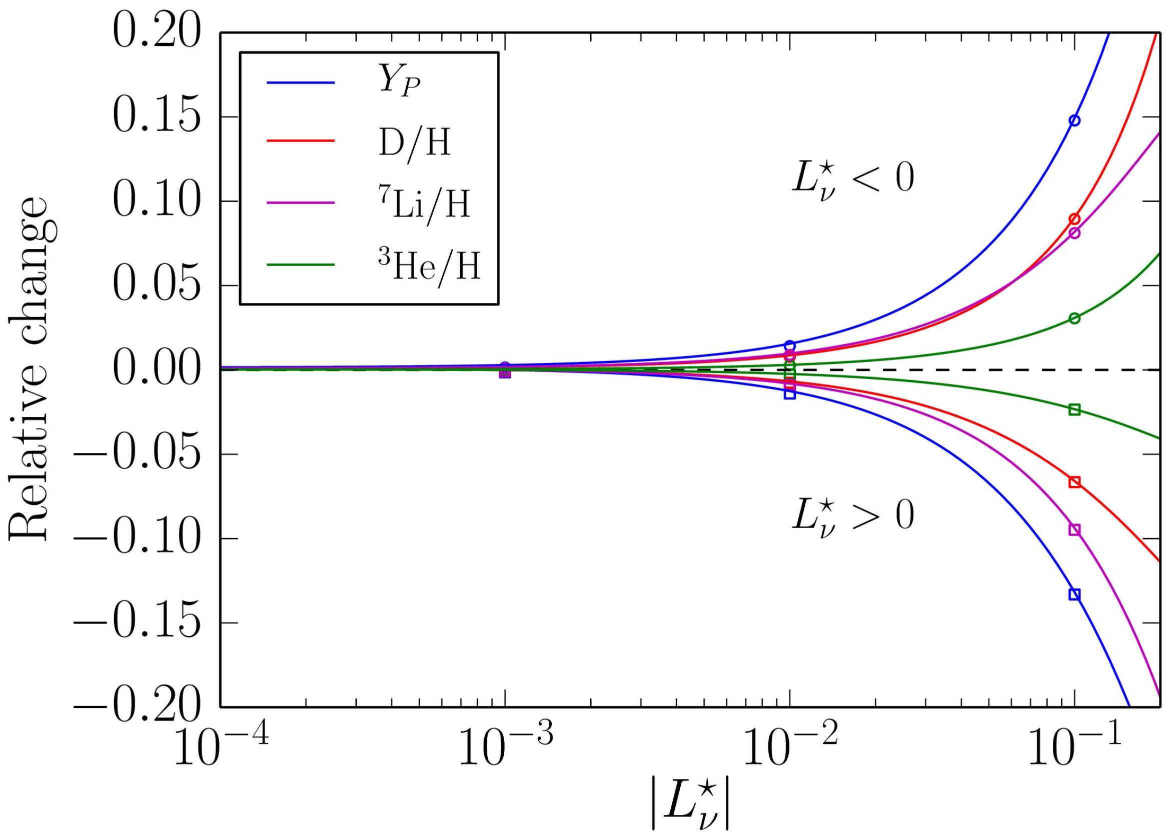
Squares and circles: full Boltzmann calculation

1% changes in ^{4}He and D:

$$L_\nu^\star \simeq 7 \times 10^{-3} \quad (Y_P)$$

$$L_\nu^\star \simeq 1.5 \times 10^{-2} \quad (\mathrm{D/H})$$

All nuclides more sensitive to negative asymmetry (except ^{7}Li)



Electron mass effects in BBN

Definition of N_{eff}:

Three flavors of neutrinos

Nondegenerate spectra

Canonical value of temperature

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

Example of sharp decoupling: Temperature-parameter ratio at freeze-out

$$\left.\frac{T_{\rm cm}}{T}\right|_{\rm f.o.} = \left(\frac{4}{11}\right)^{1/3}\left[1 + \frac{5}{22\pi^2}\left(\frac{m_e}{T_{\rm dec}}\right)^2 + \frac{25\alpha}{66\pi}\right]$$

Nonzero electron mass

Finite temperature QED

Solve for N_{eff} due to $\boldsymbol{\nu}$ and $e^{\pm}$

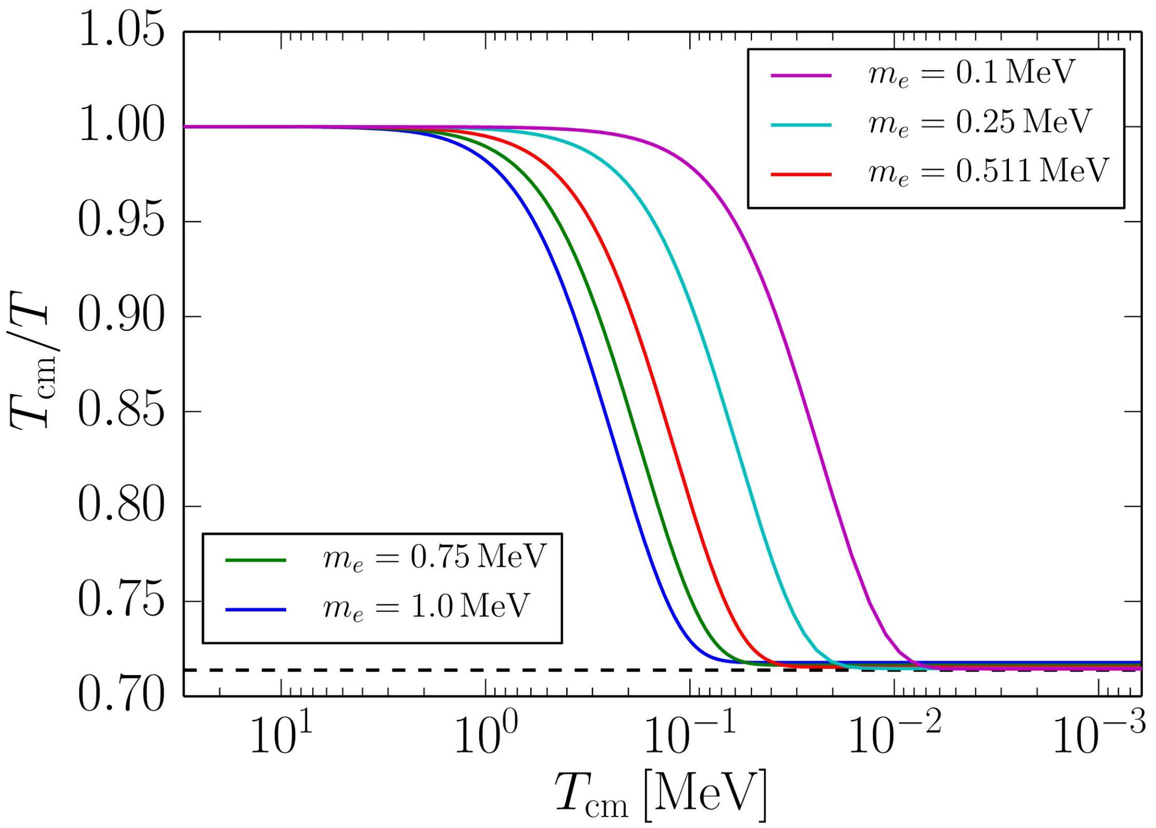
$$N_{\rm eff} = [1 + \delta(T_{\rm cm}/T)_{\rm f.o.}]^4 \times \left[3 + \frac{1}{2}\sum_{i=1}^{6}\delta\rho_{\nu_i}\right]$$

Ratio of T_{cm}/T versus T_{cm}

Full transport calculation with different electron vacuum masses

Larger mass implies larger N_{eff}

Dashed line identical to $(4/11)^{1/3}$



Neutrino Mass Recombination (νMR) Effect

Neutrinos free stream after weak decoupling

$$\rho_\nu(m \neq 0) = \int_0^\infty dp \, \frac{p^2\sqrt{p^2+m^2}}{e^{p/T_{\mathrm{cm}}}+1} > \int_0^\infty dp \, \frac{p^3}{e^{p/T_{\mathrm{cm}}}+1} = \rho_\nu(m=0)$$

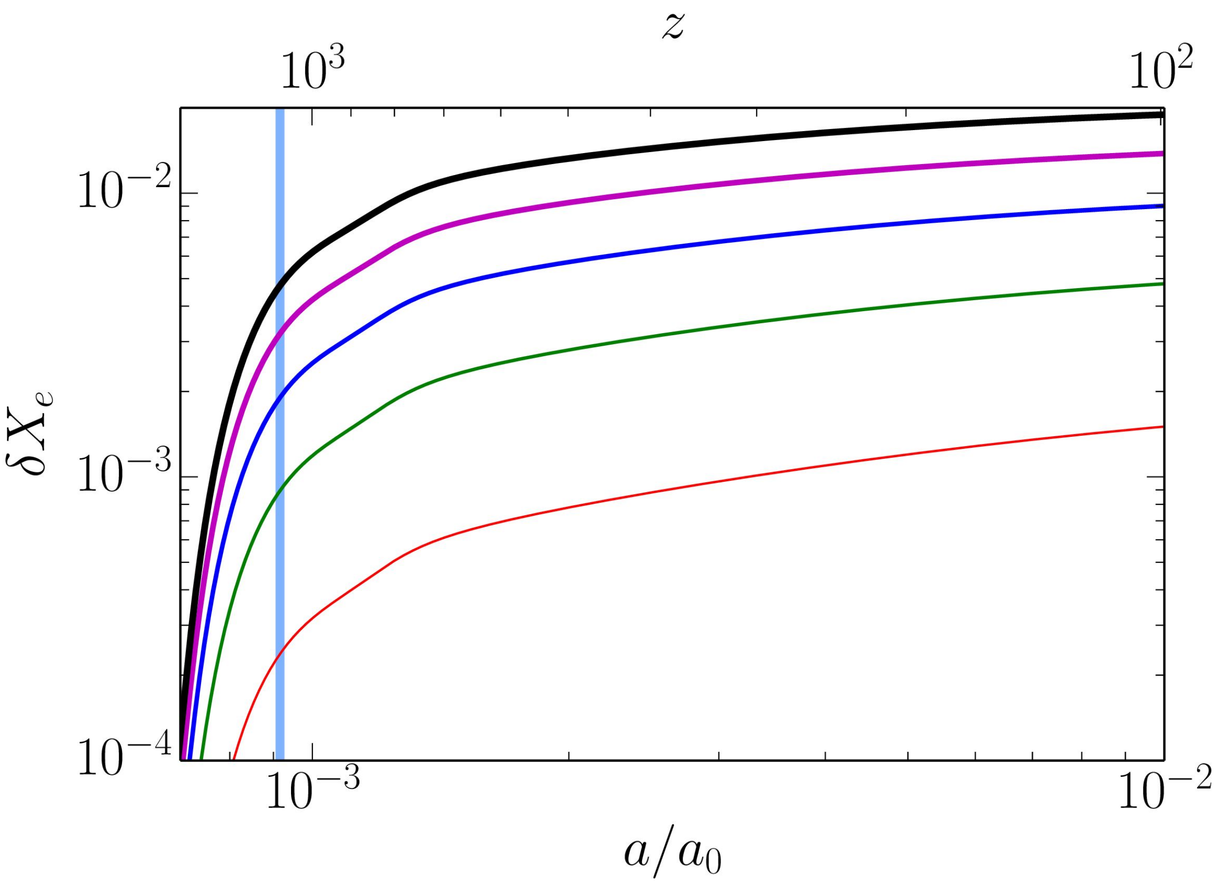
Sound Horizon and Photon Diffusion Length (comoving)

$$r_s = \int_0^{a_{\gamma d}} da \, \frac{1}{a^2 H\sqrt{3(1+R)}} \qquad r_d^2 = \pi^2 \int_0^{a_{\gamma d}} da \, \frac{1}{a^3 H n_e(a)\sigma_T} \frac{R^2 + \frac{16}{15}(1+R)}{6(1+R)^2}$$

The ratio r_s/r_d can be used to infer the evolution of the Hubble expansion rate

Photon diffusion length also has dependence on free-electron fraction X_e

Relative change in free-electron fraction



Equilibrium initial conditions
Nonequilibrium evolution

Relative changes with respect to massless neutrinos

Dark radiation affects these curves differently

Increasing neutrino mass sum (Σm_ν) in increments of 0.2 eV for normal hierarchy

Quantum Kinetic Equations (QKEs)

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

Equations of motion (early universe):

$$\frac{df}{dt} = -i[H, f] + \hat{C}(f, \overline{f})$$

H: Hamiltonian-like potential (coherent)

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

Nonlinear coupled ODEs

Coherent term in the early universe

$$H = H_V + H_D + H_T$$

$$H_V = \frac{1}{2p} U M^2 U^\dagger$$

Vacuum Oscillations

$$H_D = \sqrt{2} G_F (L + \widetilde{L})$$

Density Term (proportional to asymmetry)

$$H_T = -\frac{8\sqrt{2} G_F p}{3 m_W^2} (E + \cos^2\theta_W \widetilde{E})$$

Thermal term (proportional to energy density)

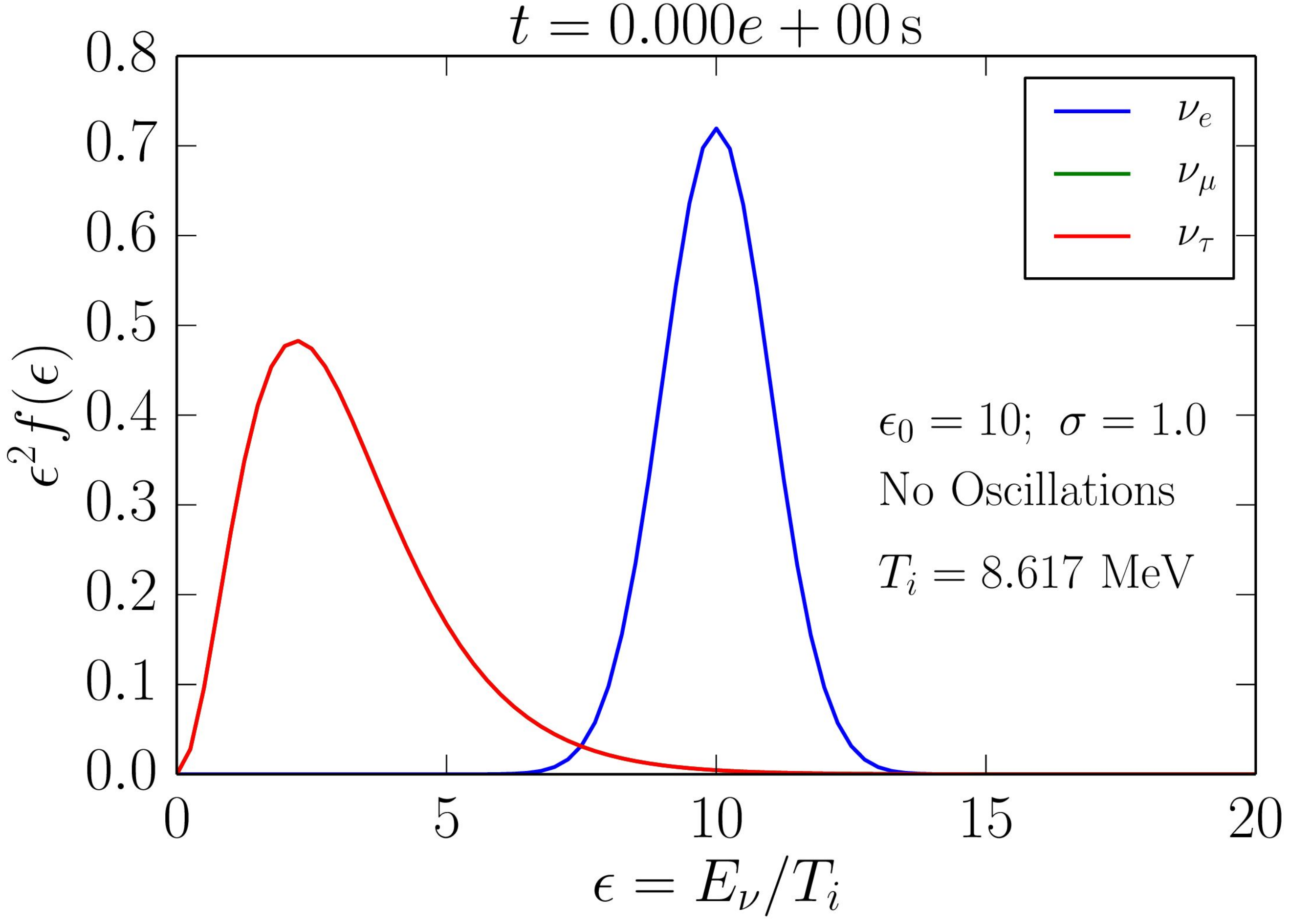
Slab Testing

Infinite slab - no geometric boundary conditions

Only neutrinos and antineutrinos exist

Normalized differential number density

$$\frac{1}{T_i^2}\frac{dn}{dE} = \epsilon^2 f(\epsilon)$$



Infinite Slab at time = 0

electron flavor in Gaussian distribution

μ and τ flavor in FD equilibrium at T_i

Neutrinos and antineutrinos degenerate

Summary and Future Work

- BURST
  - ➢ Use the neutrino spectra
    - Evolve through weak-decoupling-nucleosynthesis epoch
    - Link to other periods of cosmological history
  - ➢ Collaboration between ~UCSD and ~LANL
    - G. Fuller, L. Johns, C. Kishimoto, A. Vlasenko
    - M. Paris, D. Blaschke, V. Cirigliano, S. Shalgar
  - ➢ Public release version in the future

- Slab Calculations ⇨ Early Universe
  - ➢ Integrate QKEs into expanding medium
  - ➢ Couple density matrices to nuclear reaction network
  - ➢ Charged Current neutron-to-proton rates QKEs