# Neutrino Cosmology with Nucleosynthesis

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# Outline and preliminaries

- Early Universe review
  - Five observables
  - The BURST code
- Weak Decoupling in the standard cosmology
  - Neutrinos decouple from plasma of electrons/positrons/photons
- Quantum Kinetic Equations
  - Hamiltonian-like potential
  - Slab testing
- Summary and future work

Useful constructs:

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

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

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

# Summary of BBN

Equilibrium initial conditions
Nonequilibrium evolution

time

Temp.

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

# Standard BBN - Physics and Computation

Synthesis of nine light element nuclei using abundances:

$$Y_i \equiv n_i / n_b$$

High entropy per baryon in the plasma:

$$s_{\rm pl} \sim 10^9$$

Relativistic components:

| Bosons | Fermions |
|---|---|
| $\gamma$ | $e^\pm$ |
| | $\nu_e, \nu_\mu, \nu_\tau$ |
| | $\overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$ |

After weak decoupling: $\gamma, e^\pm$

After $e^\pm$ annihilation: $\gamma$

Numerical treatments: Wagoner, Fowler, Hoyle (1967); Smith, Kawano, Malaney (1993)

Isotropic and Homogeneous geometry

Evolution of three thermodynamic/ cosmological variables:

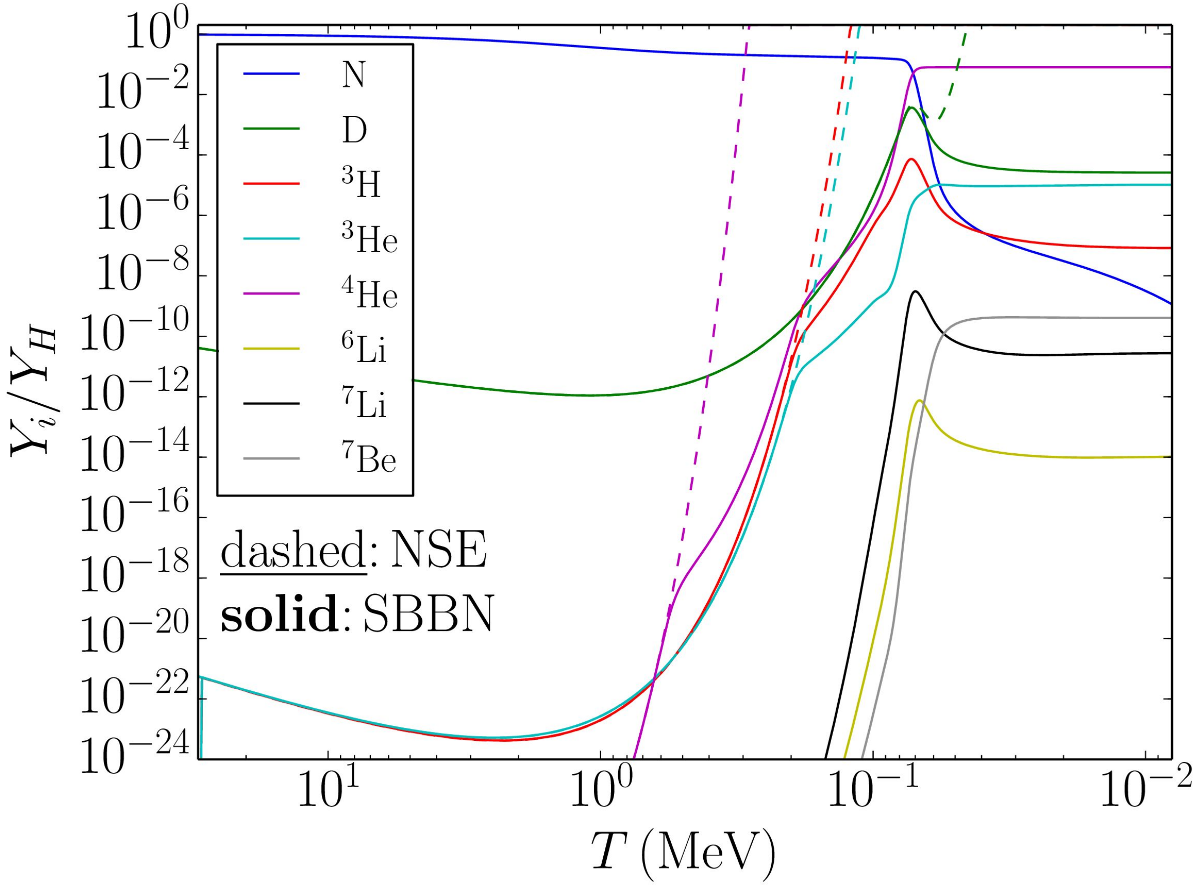
$$\begin{cases} T & : \text{Photon (plasma) temperature} \\ h_v & : \text{Ratio of baryon energy density to } T^3 \\ \phi_e & : \text{electron degeneracy parameter} \end{cases}$$

34 Nuclear Reactions:

$$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left( -\frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!} [ij]_k + \frac{Y_k^{N_k} Y_l^{N_l}}{N_k! N_l!} [kl]_j \right)$$

Neutrinos preserve Fermi-Dirac shape

# Freeze out from NSE




Equilibrium initial conditions
Nonequilibrium evolution

$$\omega_b = 0.022068$$

$$s_{\rm pl} = 5.9288 \times 10^9$$

$$\eta \equiv n_b/n_\gamma$$
$$= 6.0756 \times 10^{-10}$$

Aver et al (2013):

$$Y_P = 0.2465 \pm 0.0097$$

Cooke et al (2014)

$$\mathrm{D/H} = (2.53 \pm 0.04) \times 10^{-5}$$

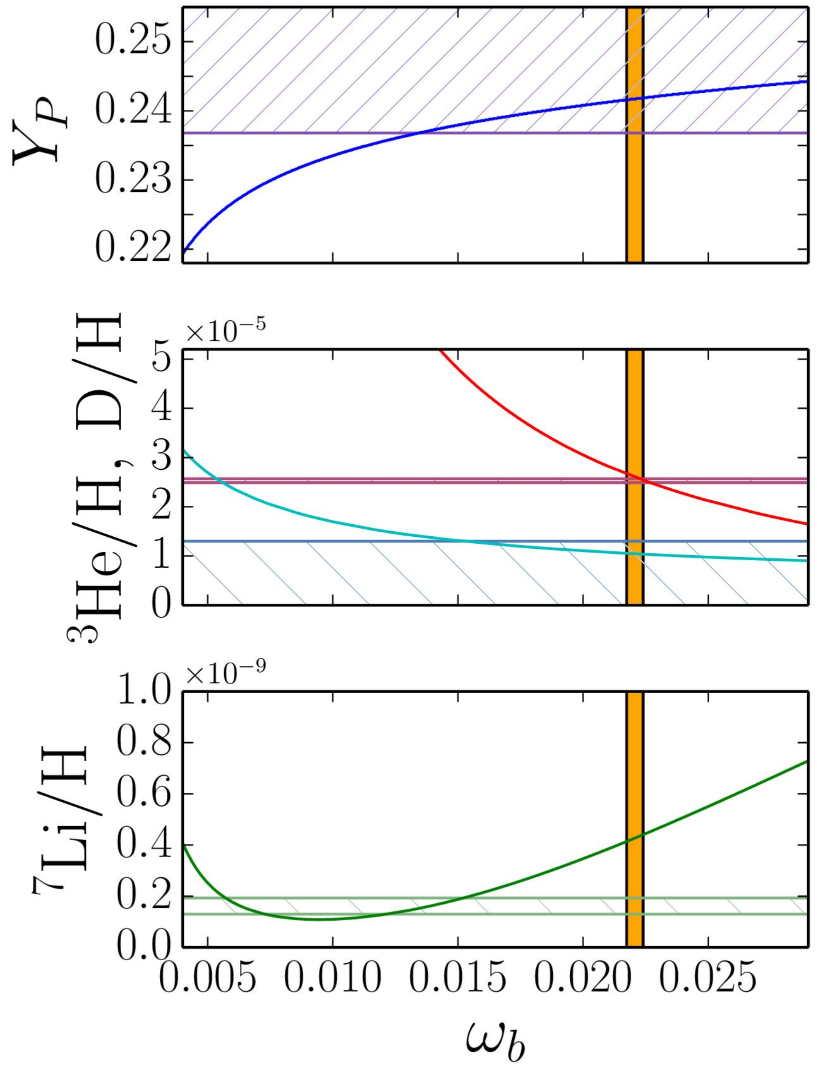
Bania, Rood, Balser (2002)

$$^3\mathrm{He/H} = (1.1 \pm 0.2) \times 10^{-5}$$

Sbordone et al (2010)

$$^7\mathrm{Li/H} = 1.58^{+0.35}_{-0.28} \times 10^{-10}$$

"Lithium Problem"



# The coming era of precision cosmology

I. CMB Stage-IV
   A. Simons Array - Atacama Desert, Chile
   B. SPT and Keck Array - South Pole
   C. Other experiments - CLASS and QUIET
II. Thirty-meter class telescopes
   A. EELT and GMT - Atacama
   B. TMT - Site TBD
III. Surveys
   A. DES - Cerro Tololo, Chile
   B. DESI - Kitt Peak, AZ

Precision of <1% for CMB neutrino quantities

Precision of ~1% for primordial helium and deuterium

$$Y_P$$

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

$$\Sigma m_\nu$$

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

# *5 Observables in Neutrino Cosmology*

$$\mathrm{D}/\mathrm{H}$$

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

# 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

- ➔ Follow evolution of neutrino spectra

# Weak Interactions for neutrino energy transport

Channels:

$$\nu_i + \nu_j \leftrightarrow \nu_i + \nu_j$$
$$\nu_i + \bar{\nu}_j \leftrightarrow \nu_i + \bar{\nu}_j$$
$$\nu_i + \bar{\nu}_i \leftrightarrow \nu_j + \bar{\nu}_j$$
$$\nu_i + e^{\pm} \leftrightarrow \nu_i + e^{\pm}$$
$$\bar{\nu}_i + e^{\pm} \leftrightarrow \bar{\nu}_i + e^{\pm}$$
$$\nu_i + \bar{\nu}_i \leftrightarrow e^- + e^+$$

Summed-Squared Amplitude examples:

$$\nu_e(1) + \nu_e(2) \leftrightarrow \nu_e(3) + \nu_e(4)$$
$$\langle|\mathcal{M}|^2\rangle = 2^7 G_F^2 (P_1 \cdot P_2)^2$$

$$\nu_e(1) + e^-(2) \leftrightarrow e^-(3) + \nu_e(4)$$
$$\begin{aligned}\langle|\mathcal{M}|^2\rangle = 2^5 G_F^2 [&(1 + 2\sin^2\theta_W)^2 (P_1 \cdot Q_2)(Q_3 \cdot P_4) \\ &+ 4\sin^4\theta_W (P_1 \cdot Q_3)(Q_2 \cdot P_4) \\ &- 2\sin^2\theta_W (1 + 2\sin^2\theta_W) m_e^2 (P_1 \cdot P_4)]\end{aligned}$$

# Collision Term Reduction (no oscillations)

1. Nine-dimensional integral over phase space of particles 2, 3, and 4
2. Conservation of four-momentum – Five-dimensional integral
3. Isotropy – Three-dimensional integral
4. Integration Limits Trick – Two-dimensional integral
5. Example, neutrinos scattering on neutrinos:

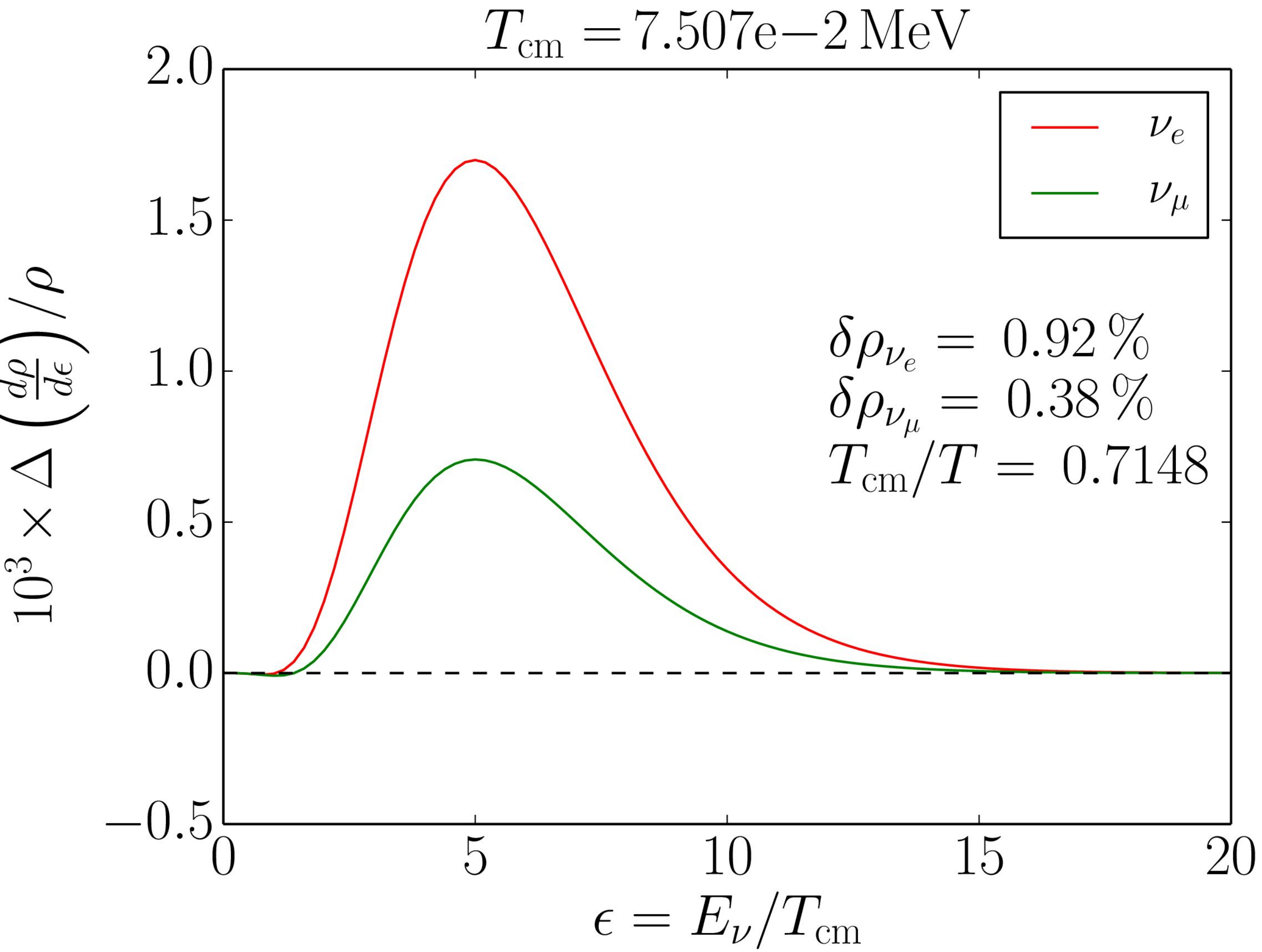
Parallelize the Computation of Df/Dt in BURST

$$\frac{Df_1}{Dt} = \frac{\kappa}{32(2\pi)^3} \int_0^\infty dp_2\, p_1 p_2^3 \int_0^{p_1+p_2} dp_3 W(p_1, p_2, p_3) F(p_1, p_2, p_3, p_1 + p_2 - p_3)$$

$$W(p_1, p_2, p_3) = \int_{x_0}^{1} dx \frac{(1-x)^2}{\sqrt{p_1^2 + p_2^2 + 2p_1 p_2 x}}$$

$$x_0 = \max\left(-1, 1 - \frac{2p_3(p_1 + p_2 - p_3)}{p_1 p_2}\right)$$

$$F = f_3 f_4 (1 - f_1)(1 - f_2) - f_1 f_2 (1 - f_3)(1 - f_4)$$




*Standard Cosmology, No oscillations*

$\boldsymbol{\mu}$ and $\boldsymbol{\tau}$ flavor degenerate

Neutrinos and antineutrinos degenerate

## Without Transport:

$$Y_P = 0.2478$$

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

## With Transport included:

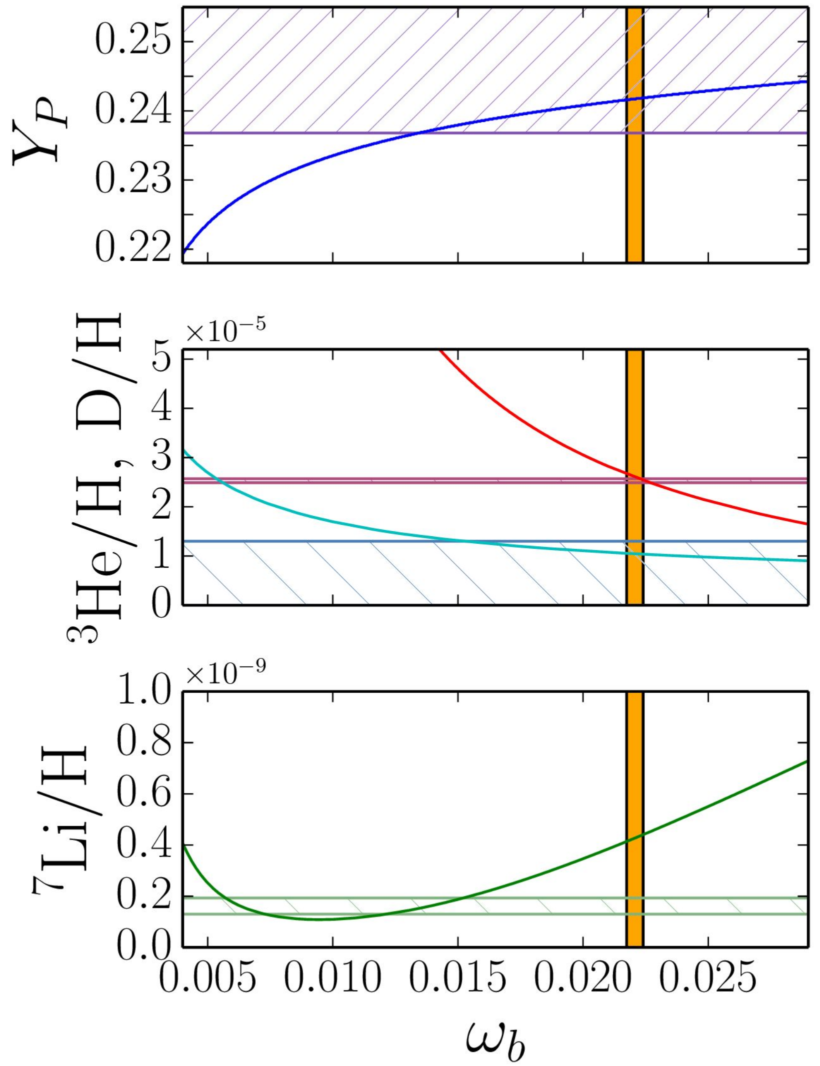
$$Y_P = 0.2479$$

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

## Relative change:

$$\delta Y_P \sim 4 \times 10^{-4}$$

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



# Quantum Kinetic Equations (QKEs)

Change array dimensions (Majorana):

$$f_i(\epsilon), \overline{f}_j(\epsilon) \to \widehat{F}(\epsilon)$$

Generalized $6 \times 6$ density matrix

Equations of motion (early universe):

$$\frac{d\widehat{F}}{dt} = -i[H, \widehat{F}] + \widehat{C}$$

*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

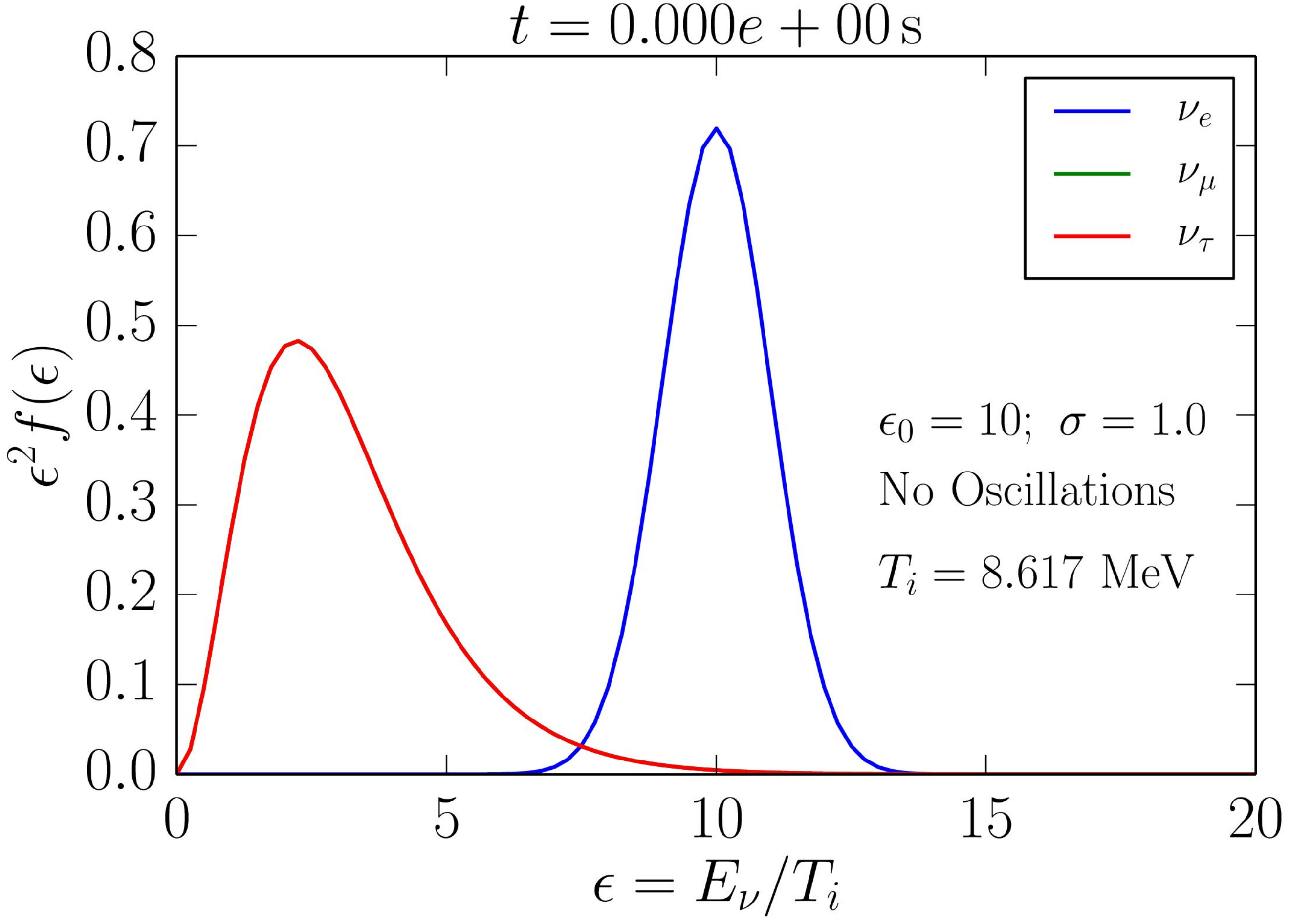
Equilibrium initial conditions
Nonequilibrium evolution

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

$\mu$ and $\tau$ flavor in FD equilibrium at $T_i$

Neutrinos and antineutrinos degenerate

# Summary and Future Work

- ❑ BURST
  - ➣ Follow neutrino spectra through weak-decoupling-nucleosynthesis epoch
  - ➣ 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

- ❑ Forging Connections
  - ➣ Neutrino Physics
  - ➣ Exotic particles
  - ➣ Advanced reaction networks
  - ➣ Neutrino transport in challenging environments