Self-Interacting Neutrinos in Big Bang Nucleosynthesis

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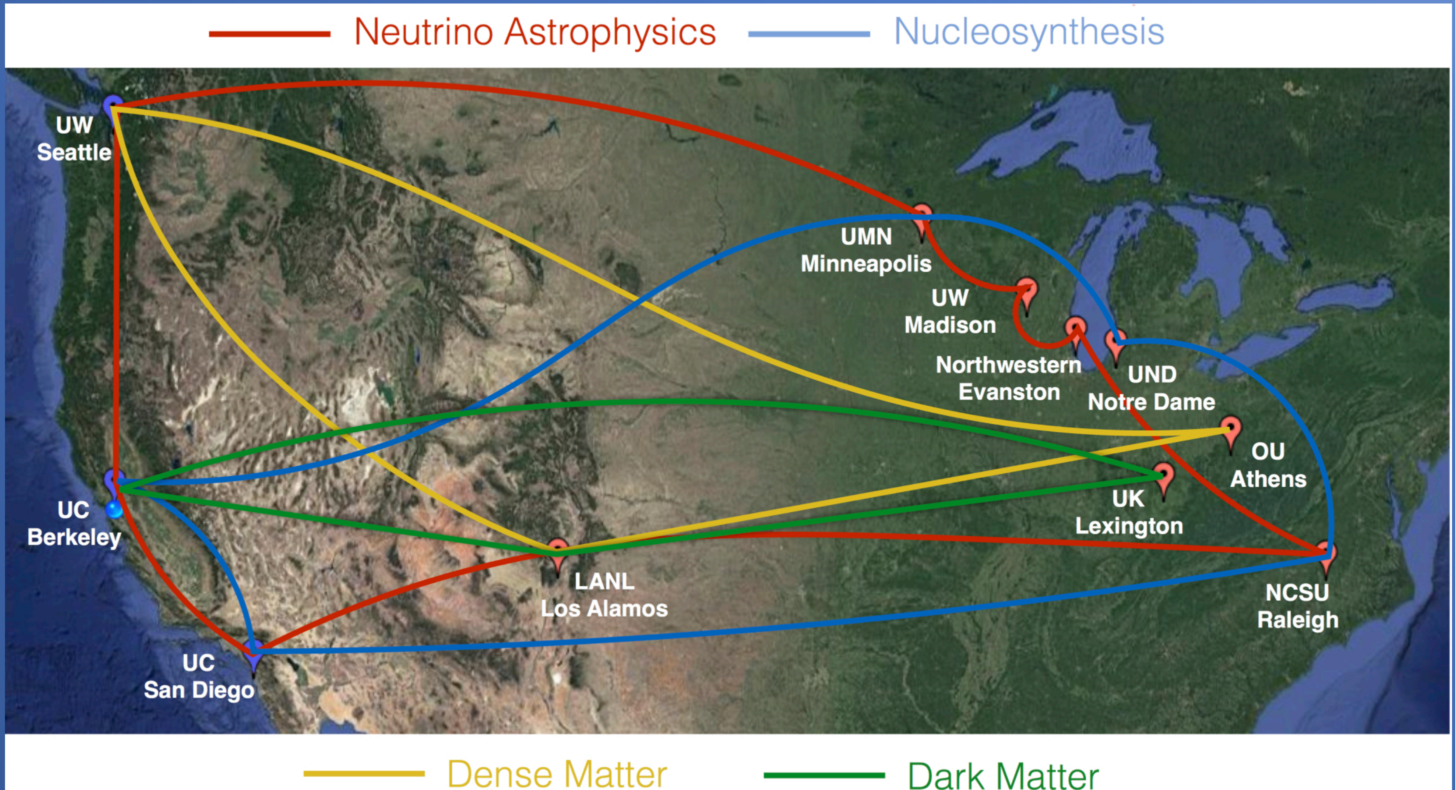
Network for Neutrinos, Nuclear Astrophysics and Symmetries

- Funded by National Science Foundation and Heising-Simons 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



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Outline

1. Motivation for considering Self-Interacting neutrinos (SIν) in BBN

2. Model of SIν with a scalar mediator

3. Implementation into BURST

4. Results
    a. Lepton-symmetric initial conditions
    b. Dark Radiation Addition
    c. Lepton-asymmetric initial conditions

5. Future work and Summary

Motivation for SIν

Sterile neutrino dark matter

Johns & Fuller (2019);

de Gouvea, Sen, Tangarife, Zhang (2019)

Sterile neutrino anomalies for cosmology

Dasgupta & Kopp (2014)

Hubble parameter tension

Kreisch, Cyr-Racine, Dore (2020)

SIν and Hubble Tension (1902.00534)

Hubble Parameter tension (km/s/Mpc)

$$H_0 = 73.0 \pm 1.75 \quad \text{(SNIa)}$$

$$H_0 = 67.36 \pm 0.54 \quad \text{(CMB)}$$

Extend Cosmological Model

$$\Lambda\text{CDM} + \{N_{\text{eff}}, \Sigma m_\nu, G_{\text{eff}}\}$$

$$\sigma_{\nu\nu} \sim G_{\text{eff}}^2 E_\nu^2$$

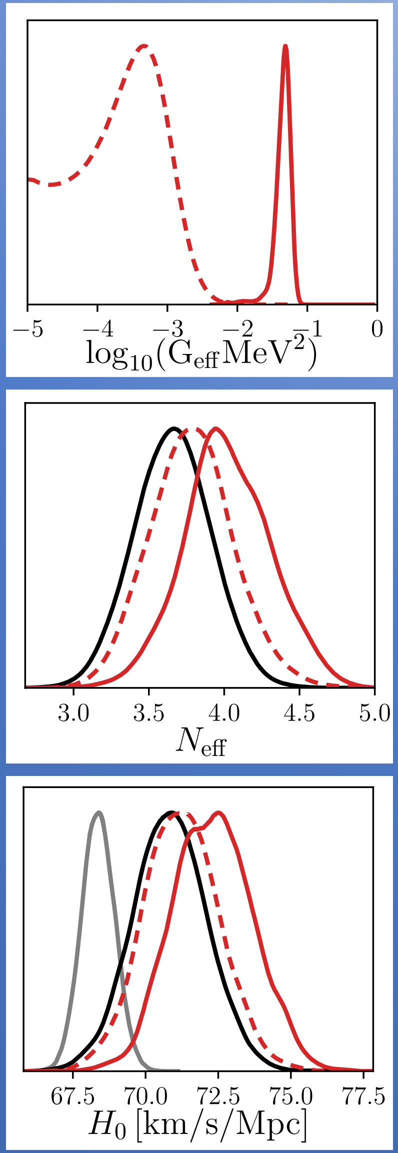
Strongly-Interacting Mode

$$\log_{10}(G_{\text{eff}}\,\text{MeV}^2) = -1.35^{+0.12}_{-0.066}$$

$$N_{\text{eff}} = 4.02 \pm 0.29$$

$$\Sigma m_\nu = 0.42^{+0.17}_{-0.20}\ \text{eV}$$

$$H_0 = 72.3 \pm 1.4$$



Model for SIν

Self-Interacting Lagrangian with a complex mediator

$$\mathcal{L}_{\rm int} = g_{ij}\overline{\nu^c_{iL}}\nu_{jL}\varphi + g_{ij}\overline{\nu_{iL}}\nu^c_{jL}\varphi^* \quad i,j = e,\mu,\tau$$

Scattering Cross Section (massive mediator)

$$\nu + \nu \leftrightarrow \nu + \nu \qquad \sigma_{ij} \sim \left(\frac{g^2_{ij}}{m^2_\varphi}\right)^2 E^2_\nu$$

Flavor-blind couplings

$$[g]_{ij} \rightarrow g \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Implementation for BURST

Parameter relations

$$\left.\begin{aligned} n(T_\nu, \eta_\nu) &= N_\nu \frac{T_\nu^3}{2\pi^2} \int d\epsilon\, \epsilon^2 f^{(\mathrm{eq})}(\epsilon; \eta_\nu) \\ \rho(T_\nu, \eta_\nu) &= N_\nu \frac{T_\nu^4}{2\pi^2} \int d\epsilon\, \epsilon^3 f^{(\mathrm{eq})}(\epsilon; \eta_\nu) \end{aligned}\right\} \implies \begin{cases} T_\nu = T_\nu(n, \rho) \\ \eta_\nu = \eta_\nu(n, \rho) \end{cases}$$

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

Weak interactions

$$\begin{aligned} \nu + e^\pm &\leftrightarrow \nu + e^\pm \\ \nu + \overline{\nu} &\leftrightarrow e^+ + e^- \end{aligned} \implies \left.\frac{\partial n}{\partial t}\right|_a, \left.\frac{\partial \rho}{\partial t}\right|_a$$

Equations of motion

Temperature Parameter

$$\frac{dT_\nu}{dt} = -HT_\nu + T_\nu \frac{n_{,\eta} \left.\frac{\partial \rho}{\partial t}\right|_a - 3T_\nu n \left.\frac{\partial n}{\partial t}\right|_a}{4\rho n_{,\eta} - 9T_\nu n^2}$$

Degeneracy Parameter

$$\frac{d\eta_\nu}{dt} = \frac{4\rho \left.\frac{\partial n}{\partial t}\right|_a - 3n \left.\frac{\partial \rho}{\partial t}\right|_a}{4\rho n_{,\eta} - 9T_\nu n^2}$$

Symbol for above EOM:

$$n_{,\eta} = N_\nu \frac{T_\nu^3}{\pi^2} \int d\epsilon \, \epsilon f^{(\mathrm{eq})}(\epsilon; \eta_\nu)$$

Free-streaming conditions:

$$\frac{dT_\nu}{dt} = -HT_\nu$$

$$\frac{d\eta_\nu}{dt} = 0$$

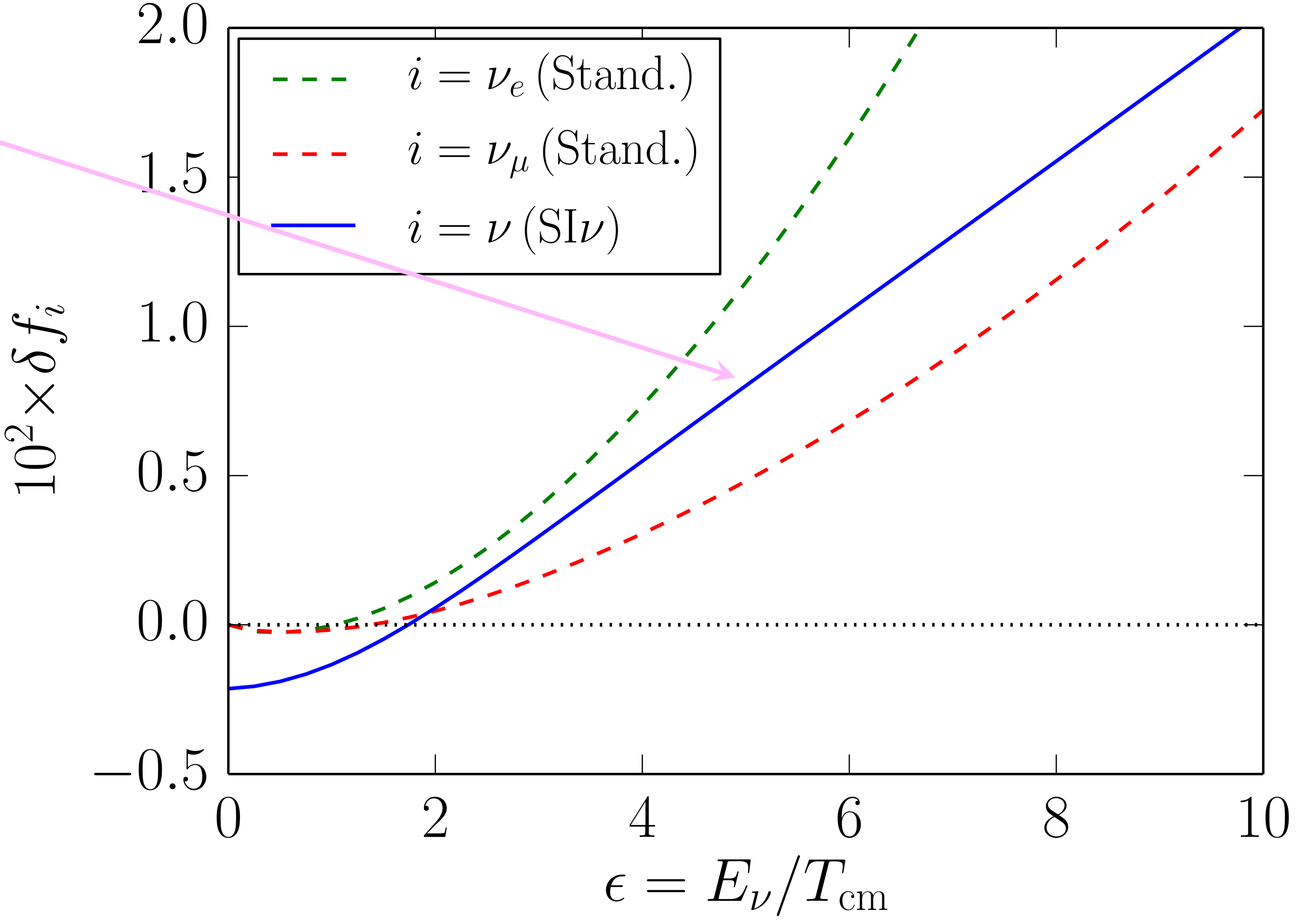
SIν spectra

SIν maintain Fermi-Dirac occupation probabilities

$$N_{\mathrm{eff}} = 3.045 \uparrow$$

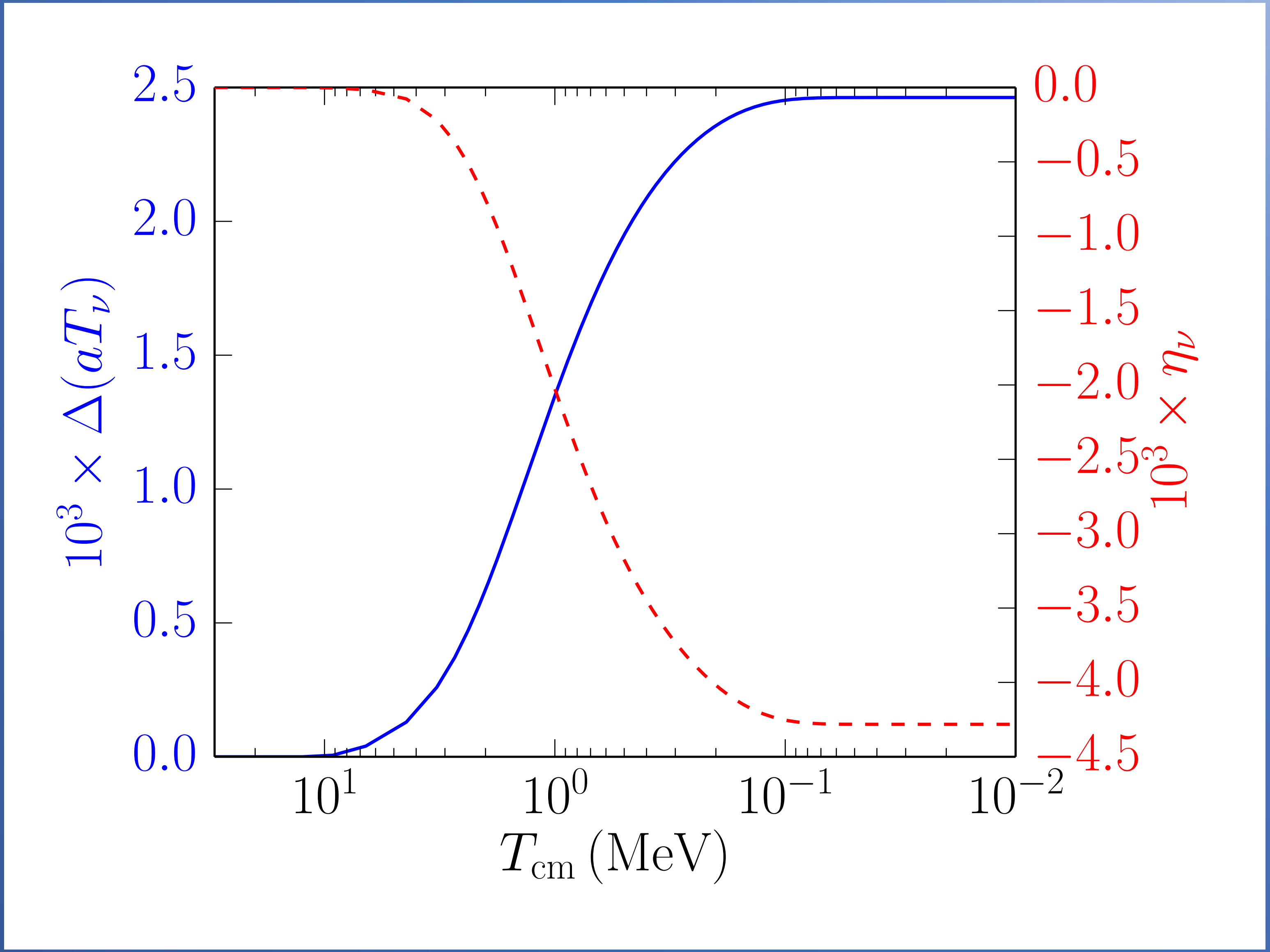
$$\delta Y_{\mathrm{P}} \simeq 4 \times 10^{-4}$$

$$\delta(\mathrm{D/H}) \simeq 2 \times 10^{-4}$$



Sν Parameter Evolution

$$\Delta(aT_\nu) = \frac{T_\nu}{T_{\rm cm}} - 1$$



Dark Radiation Addition

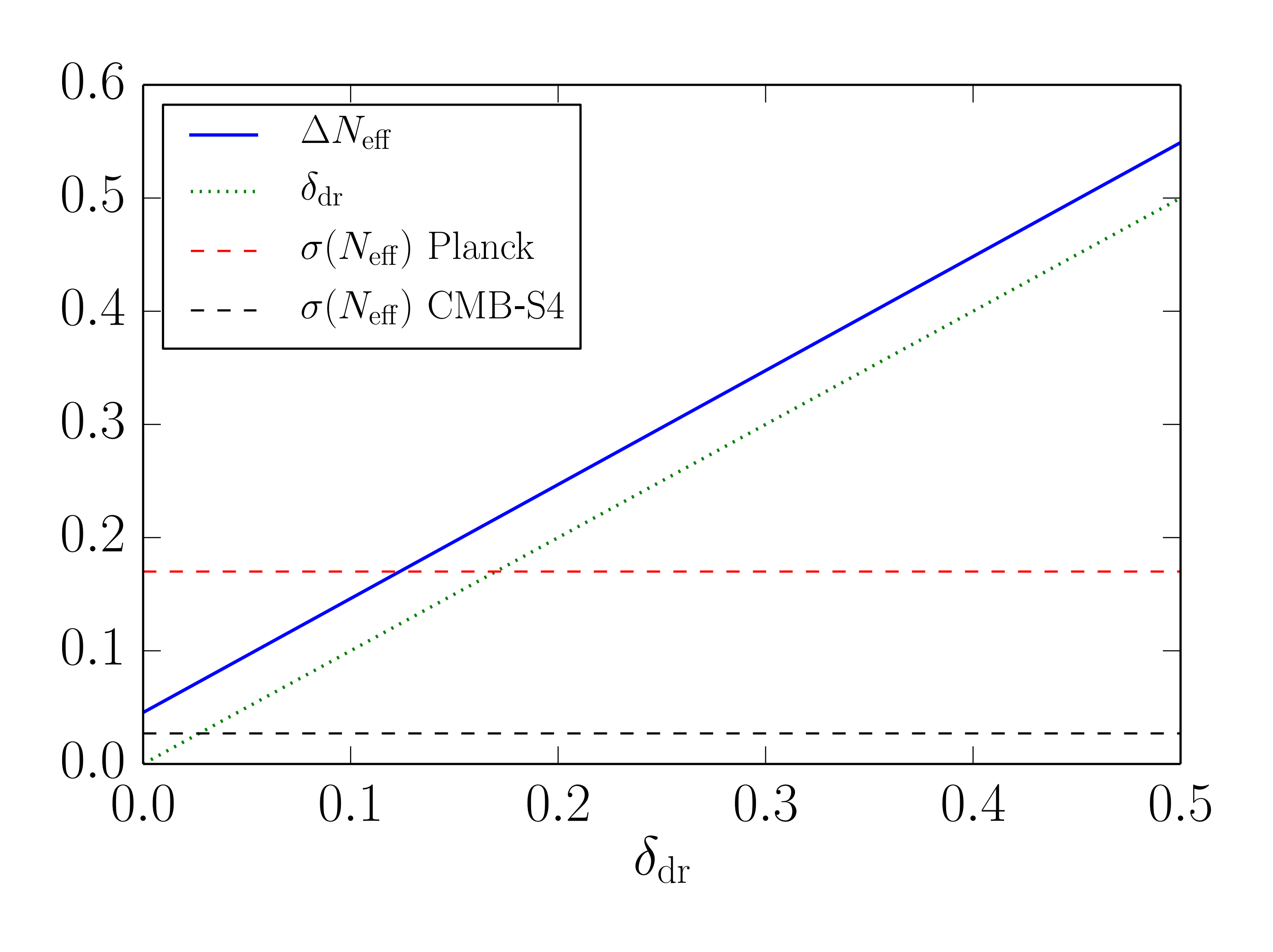
Non-neutrino addition

$$\rho_{\rm dr} = \frac{7\pi^2}{120} T_{\rm cm}^4 \delta_{\rm dr}$$

$$\text{E.g., } \delta_{\rm dr} = 0.4009$$

$$\delta Y_{\rm P} = 2.161\%$$

$$\delta({\rm D/H}) = 5.385\%$$



Lepton Asymmetric Initial Conditions

Comoving Lepton number for 1 species (from non-SIν mechanism)

$$L^\star_\nu \equiv \frac{n_\nu - n_{\overline{\nu}}}{\frac{2\zeta(3)}{\pi^2} T^3_{\mathrm{cm}}}$$

Anti-neutrino degeneracy parameter with t-channel scattering

$$\{T_\nu, \eta_\nu\} \to \{T_\nu, \eta_\nu, \eta_{\overline{\nu}}\}, \; T_{\overline{\nu}} = T_\nu$$

Neutrinos

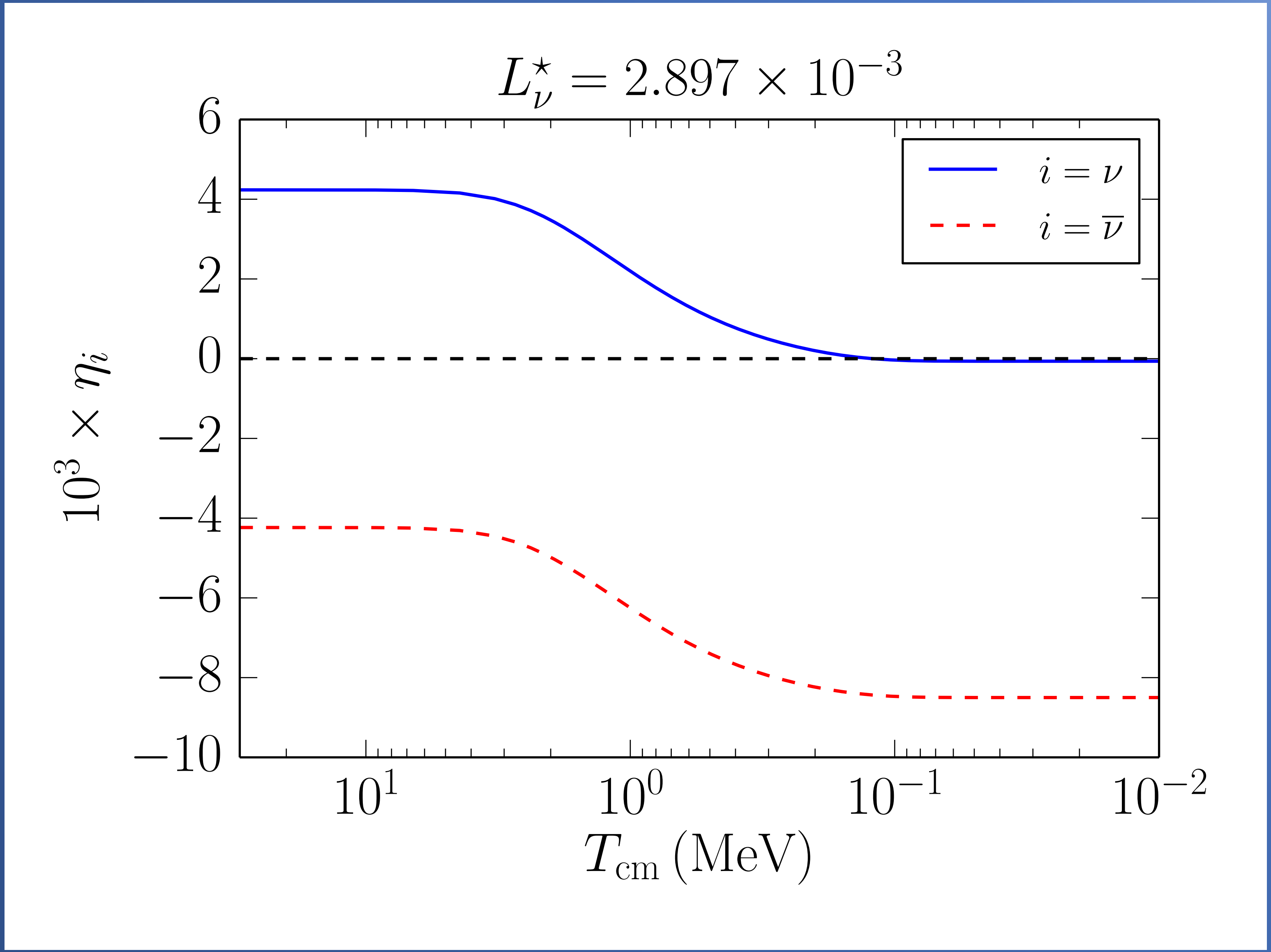
$$\left.\frac{\partial \rho_\nu}{\partial t}\right|_a = \left.\frac{\partial \rho_\nu}{\partial t}\right|_{\mathrm{w}} + \frac{d\mathcal{E}}{dt}$$

Anti-Neutrinos

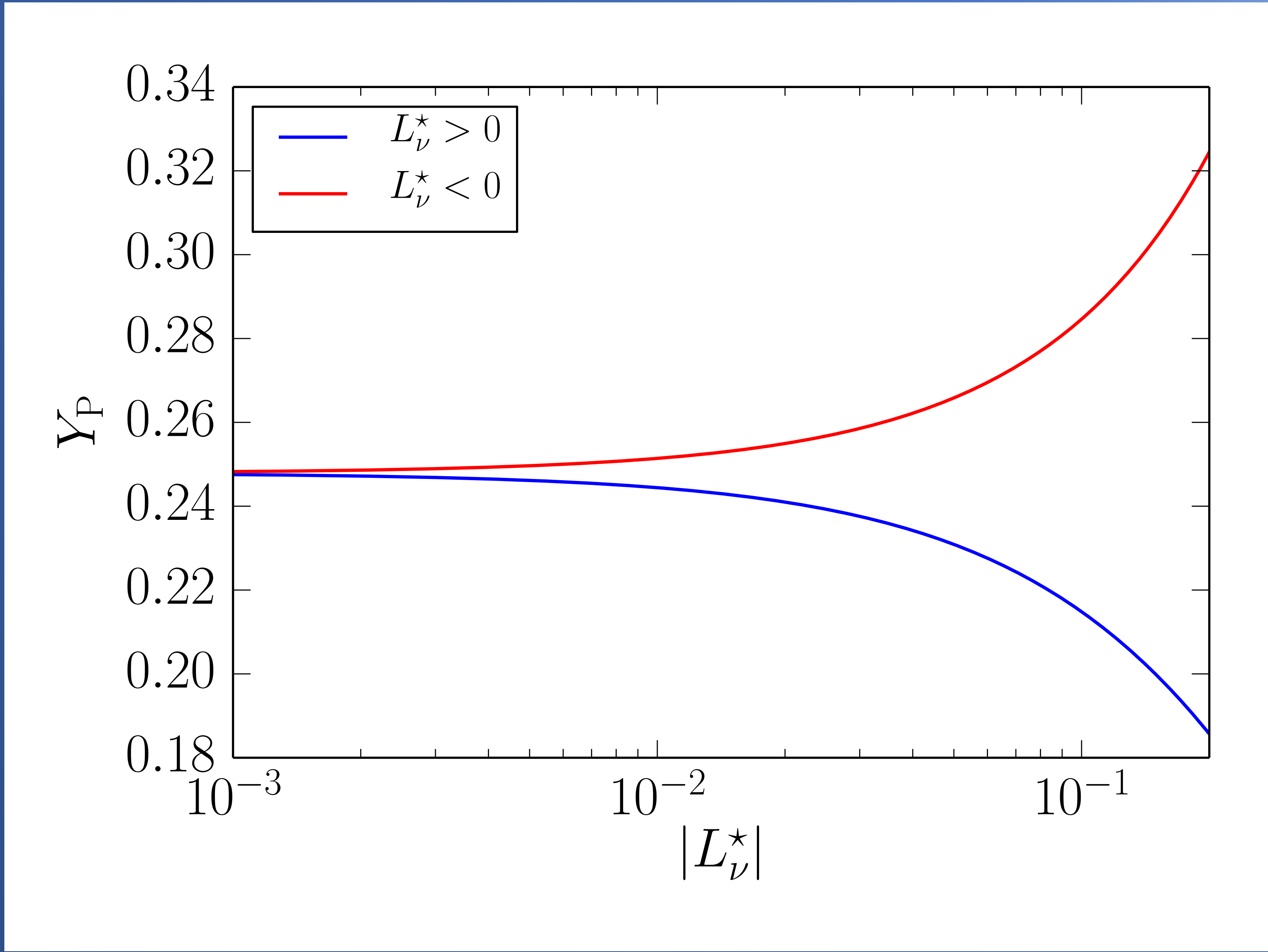
$$\left.\frac{\partial \rho_{\overline{\nu}}}{\partial t}\right|_a = \left.\frac{\partial \rho_{\overline{\nu}}}{\partial t}\right|_{\mathrm{w}} - \frac{d\mathcal{E}}{dt}$$

Equilibration term from t-channel

Evolution of Degeneracy Parameters



Helium Mass Fraction



Future Work

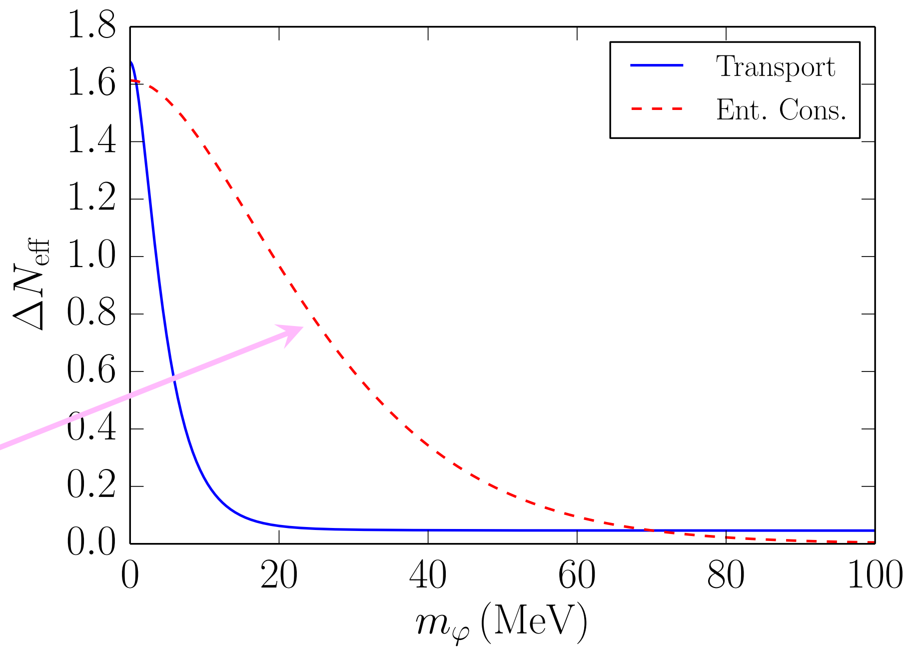
Low-mass mediators provide thermal bath

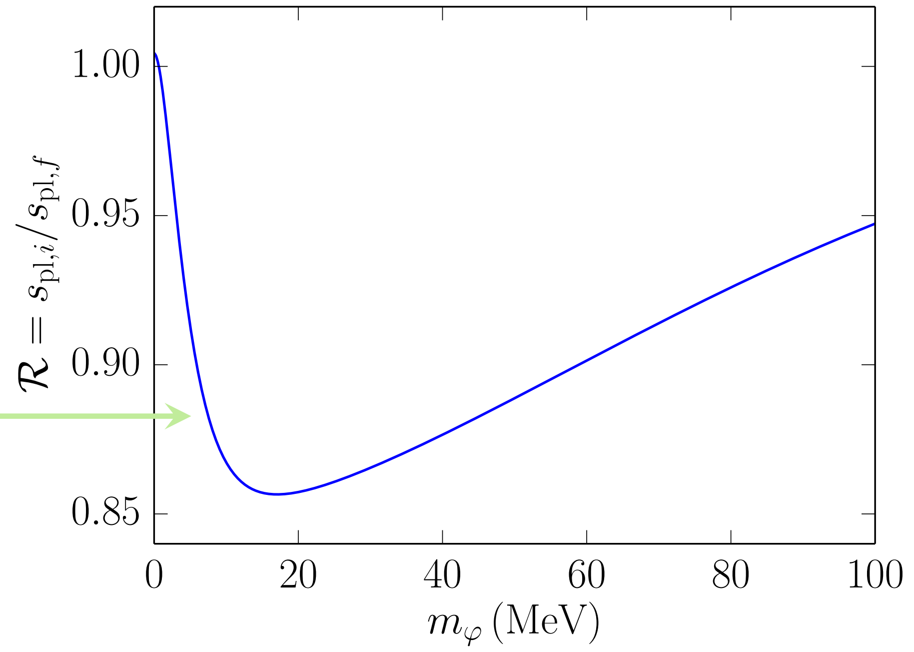
$$\{\varphi, \varphi^*, \nu, \overline{\nu}\} \to T_\nu$$

If ν-sector entropy conserved

$$N_{\rm eff} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T}\right)^4$$

Entropy from mediators dilutes plasma





Summary

1. By themselves, SIν have little effect on N_{eff} and BBN abundances in either the Standard Cosmology or 1-parameter extensions
2. Low-mass mediators have more leverage on changing BBN dynamics
3. Freeze-out of mediators with out-of-equilibrium decay will have effects on BBN
4. Core-collapse dynamics sensitive to neutrino energy transport (Fuller, Mayle, Wilson 1988; Shalgar, Tamborra, Bustamante 2019)
5. Beyond-standard-model scenarios face major constraint: deuterium is measured precisely and influenced by expansion rate