

Neutrino-genic CMB spectral distortions

李少平

The University of Osaka

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Lisp & Jens Chluba (Manchester U.),
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Outline

- Cosmic observables, N_{eff} and CMB spectral distortions
- CMB spectral distortions from neutrino physics
- Applications in particle physics
- Summary

N_{eff} and CMB spectral distortions

N_{eff} physics

- Cosmic expansion after neutrino decoupling at $T_{\nu,\text{dec}} \simeq 1 \text{ MeV}$ can be characterized by the effective number of neutrino species:

$$N_{\text{eff}} \equiv \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_\nu + \rho_r}{\rho_\gamma} = N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}}$$

$$T > T_{\nu,\text{dec}}, \quad T_\nu = T_\gamma, \quad N_{\text{eff}}^{\text{SM}} = N_\nu = 3$$

$$T < T_{\nu,\text{dec}} \begin{cases} \text{instantaneous} : N_{\text{eff}}^{\text{SM}} = N_\nu = 3 \\ \text{non-instantaneous} : N_{\text{eff}}^{\text{SM}} = 3.043 - 3.046 \end{cases}$$

1812.05605; 1911.04504;
2001.04466; 2402.18481

- Current (future) BBN & CMB sensitivity $\Delta N_{\text{eff}} \simeq 0.1$ (0.01)

- Physics that can induce $\Delta N_{\text{eff}} = \mathcal{O}(0.1)$:
 1. Modification to standard neutrino decoupling
 2. Right-handed Dirac counterpart of SM left-handed neutrinos
 3. Light hidden particles (axions/axion-like particles)
 4. Photon temperature shift ($\Delta N_{\text{eff}} < 0$)
 5.

N_{eff} alone cannot tell apart the physics...

CMB spectral distortions

- Photons in the early universe cannot maintain its perfect blackbody distribution $f_{\text{bb}} = (e^{E/T} - 1)^{-1}$ after $T_{\mu} = 0.47$ keV (redshift $z = 2 \times 10^6$), double Compton scattering/bremsstrahlung $\gamma + e(N) \rightleftharpoons \gamma + \gamma + e(N)$ becomes ineffective

1603.02496

$$12 \text{ eV} \simeq T_{\mu y} < T < T_{\mu} \rightarrow \text{CMB } \mu \text{ distortion, } f_{\gamma} = \frac{1}{e^{(E-\mu)/T} - 1}$$

photons still in kinetic equilibrium with electrons

$$T < T_{\mu y} \rightarrow \text{CMB } y \text{ distortion defined through Compton } y\text{-parameter } \frac{dy}{dt} \equiv n_e \sigma_T \frac{T_e - T_{\gamma}}{m_e}$$

photons not even in kinetic equilibrium with electrons

$T \sim T_{\mu y} \rightarrow$ richer CMB residual distortions, not μ or y , **full numerical analysis required**

- CMB μ distortion is easier to calculate: analytically feasible, proportional to energy injection in the form of electromagnetic species

CMB spectral distortions

- Current bounds date back to 30 years ago from COBE/FIRAS experiment

$$|\mu| < 9 \times 10^{-5}, |y| < 1.5 \times 10^{-5}$$

- Recent re-analysis of COBE/FIRAS data: 2206.02762; 2508.04593

$$|\mu| < 4.7 \times 10^{-5}, |y| < 8.3 \times 10^{-6}$$

- Standard source in Λ CDM model 1603.02496

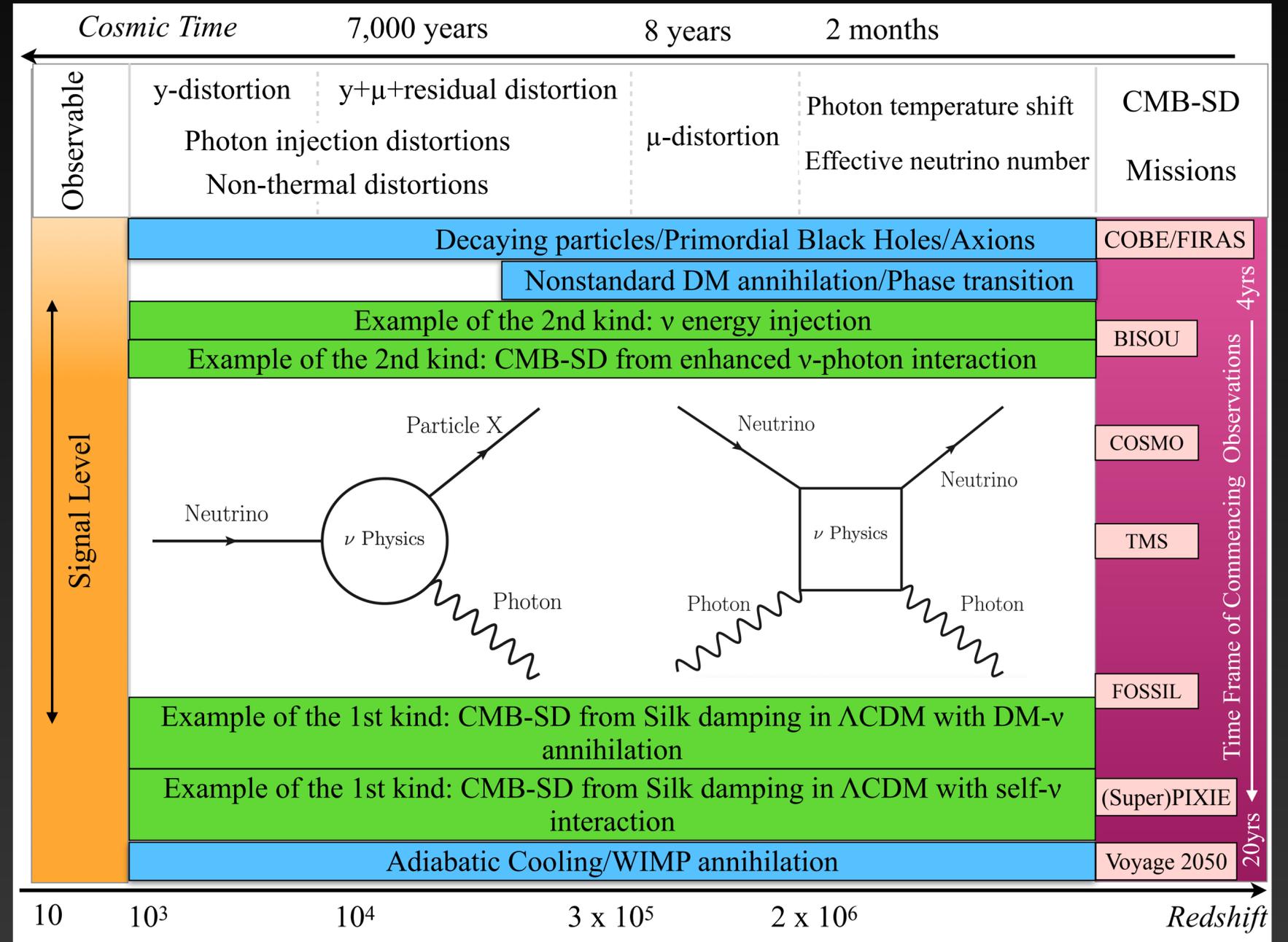
1. Damping of initial density perturbation (likely from inflation): $\mu \approx 2 \times 10^{-8}$
2. Sunyaev-Zeldovich effect (low-energy photons scattering with hot electrons from galaxy clusters):
 $y \approx 10^{-6}$

CMB spectral distortions

- Future targets on spectral distortions: BISO, TMS, COSMO, FOSSIL, SPECTER, aiming at

$$|\mu| \sim 10^{-8}, |y| \sim 10^{-9}$$

- Physics that can induce $|\mu| \sim 10^{-8}, |y| \sim 10^{-9}$



Status of N_{eff} and CMB spectral distortions

- Numerous studies of $\Delta N_{\text{eff}} = \mathcal{O}(0.1)$, a large degeneracy from various physics
- Numerous studies of $|\mu| \sim 10^{-8}$, $|y| \sim 10^{-9}$, mostly from **direct photon energy injection**
- N_{eff} and CMB spectral distortions are deemed different physics and treated separately insofar, but can they actually come from the same source? If positive, we can:
 1. Break the N_{eff} degeneracy to tell apart various physics
 2. Break the degeneracy of CMB spectral distortions to tell apart various physics
 3. Strengthen constraints in particle physics/cosmological scenarios
 4. Open up detection windows

CMB spectral distortions from neutrino energy leakage

Neutrino energy injection & direct N_{eff} excess

- The explanations of neutrino masses bring various possible new processes in the early universe: neutrino-dark matter interactions, neutrino self-interactions, neutrino radiative decay, ...
- Extra neutrino energy may be injected after $T_{\nu,\text{dec}} \simeq 1 \text{ MeV}$, yielding

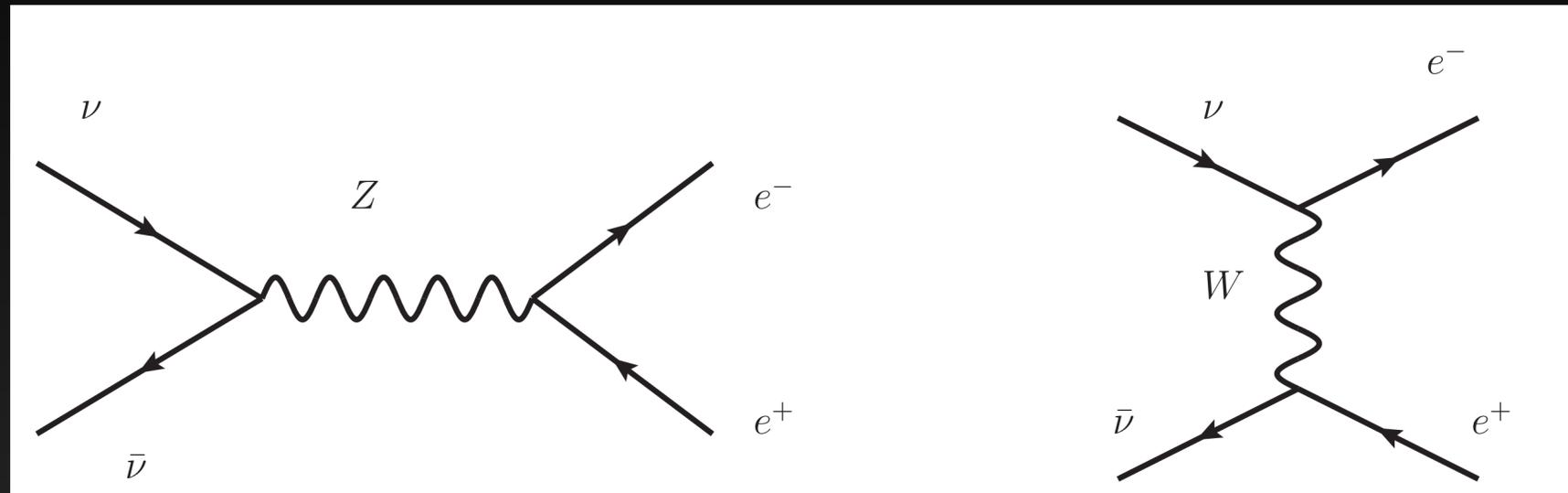
$$\Delta N_{\text{eff}} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \left(\frac{\Delta \rho_\nu}{\rho_\gamma} \right)$$

- For these neutrino-philic energy injection (physics not directly couple to photons), CMB spectral distortions are not induced directly

Neutrino energy leakage $\Delta N_{\text{eff}} \rightarrow \mu, y?$

Inevitable N_{eff} leakage to μ distortion

- The SM electroweak interactions $\nu_{\text{inj}} + \bar{\nu}_{\text{inj}} \rightarrow e^+ + e^-$, $\nu_{\text{inj}} + \bar{\nu}_{\text{bg}} \rightarrow e^+ + e^-$



- The generated electron-positron pairs convert kinetic energy to photons via rapid inverse Compton scattering $e^\pm + \gamma_{\text{bg}} \rightarrow e^\pm + \gamma$, leading to *indirect photon energy injection*
- If e^\pm are relativistic, almost all their kinetic energy will be stored in photon fields at the μ -era $T = T_\mu \approx 4.7$ keV

Neutrino co-annihilation vs pair annihilation

- Co-annihilation: $\nu_{\text{inj}} + \bar{\nu}_{\text{bg}} \rightarrow e^+ + e^-$

Energy threshold: $E_\nu T_\nu > m_e^2$, $\rightarrow E_\nu \gtrsim 500$ MeV after $T_\mu \approx 0.47$ keV

- Pair annihilation: $\nu_{\text{inj}} + \bar{\nu}_{\text{inj}} \rightarrow e^+ + e^-$ Energy threshold: $E_\nu > m_e$

- The injected neutrino number density should in general be smaller than background one unless $E_\nu \ll T_\nu$, because of the N_{eff} constraint

$$\Delta N_{\text{eff}} \propto \frac{\Delta \rho_\nu}{\rho_{\nu,\text{bg}}}, \quad \rightarrow \Delta \rho_\nu \sim E_\nu \Delta n_\nu < \rho_{\nu,\text{bg}} \sim T_\nu n_\nu$$

But $E_\nu < T_\nu < 1$ MeV cannot produce e^\pm , so the only way that pair annihilation can be important is to increase E_ν

Neutrino co-annihilation vs pair annihilation

- Energy transfer rate

$$\frac{d\rho_{e\bar{e}}}{dt} = \int d\Pi \tilde{\delta}^4(p) |\mathcal{M}|_{\nu \rightarrow e}^2 (E_e + E_{\bar{e}}) f_\nu f_{\bar{\nu}}$$

$$d\Pi \equiv \prod_{i=\nu, \bar{\nu}, e, \bar{e}} \frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i}$$

$$\frac{d\rho_\gamma}{dt} \approx \frac{d\rho_{e\bar{e}}}{dt}$$

- Model-independent analytic estimate (COBE/FIRAS bound $\Delta\rho_\gamma/\rho_\gamma \lesssim 6 \times 10^{-5}$ & future detection sensitivity $\Delta\rho_\gamma/\rho_\gamma \sim 10^{-9} - 10^{-8}$)

Co-annihilation

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} \simeq 10^{-9} \left(\frac{E_\nu}{1 \text{ GeV}} \right) \left(\frac{\Delta N_{\text{eff}}}{0.05} \right) \left(\frac{T_i}{0.1 \text{ keV}} \right)^2$$

Pair annihilation

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} \simeq 10^{-10} \left(\frac{E_\nu}{1 \text{ GeV}} \right) \left(\frac{\Delta N_{\text{eff}}}{0.1} \right)^2 \left(\frac{T_i}{0.1 \text{ keV}} \right)^2$$

- μ distortion

$$\mu \approx 1.4 \int_0^\infty \mathcal{J}_\mu(T) \frac{d\rho_\gamma/dt}{\rho_\gamma HT} dT$$

μ distortion visibility function

$$\mathcal{J}_\mu(T) = e^{-(T/T_\mu)^{5/2}} \theta(T - T_{\mu y})$$

Applications in particle physics

Neutrino injection from particle decay

- Precise calculation of energy transfer is particle-physics model dependent

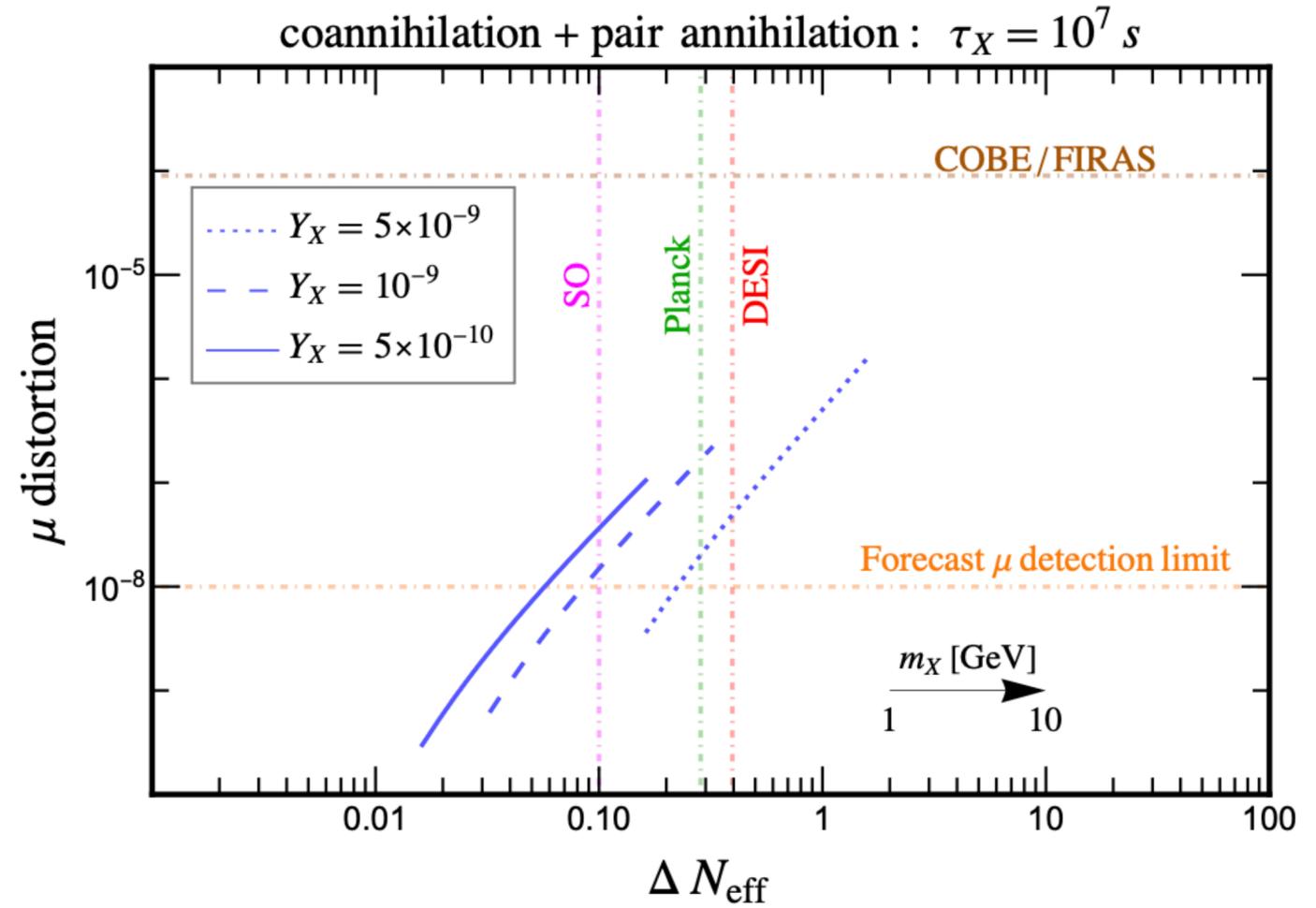
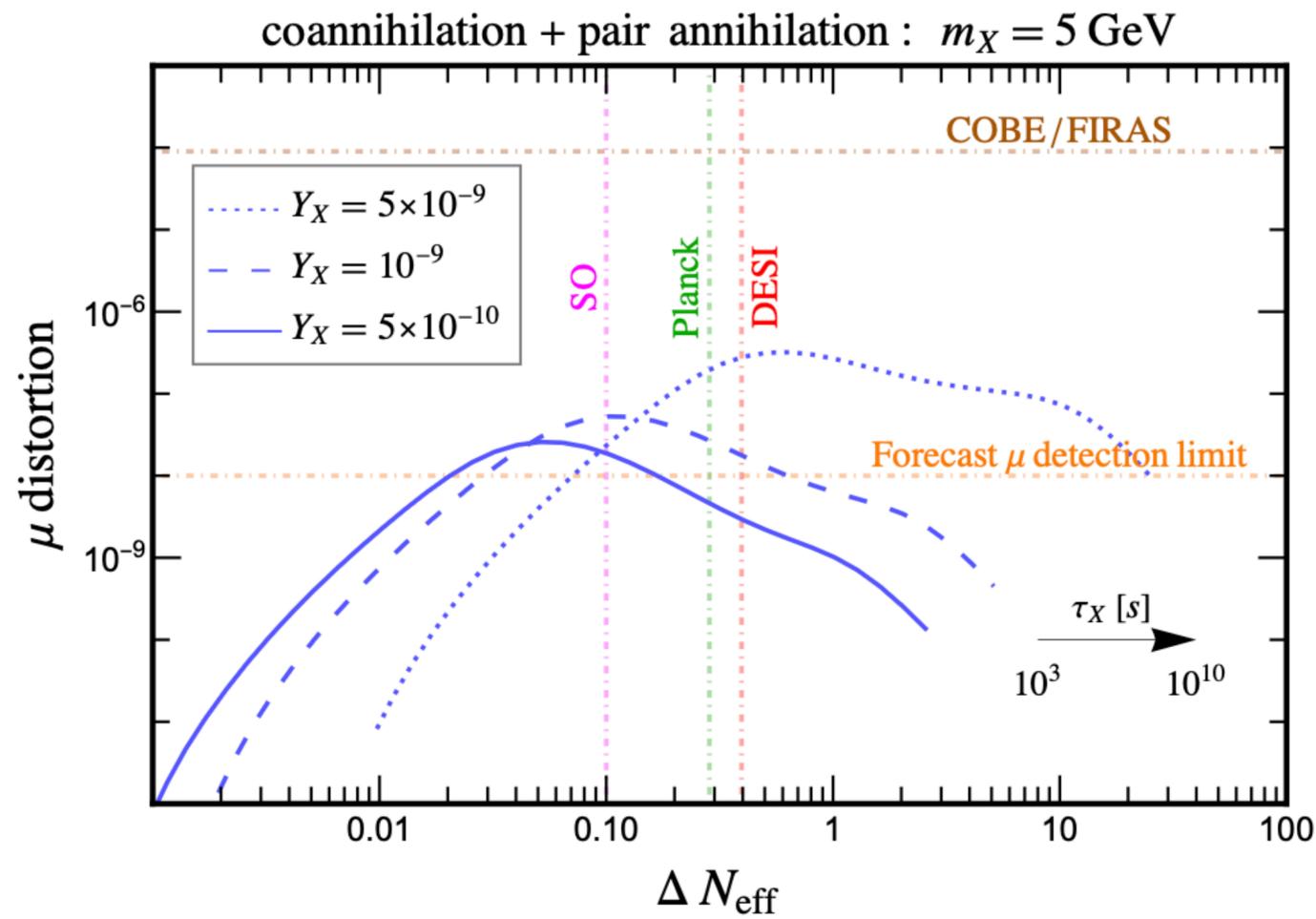
$$\frac{d\rho_{e\bar{e}}}{dt} = \int d\Pi \tilde{\delta}^4(p) |\mathcal{M}|_{\nu \rightarrow e}^2 (E_e + E_{\bar{e}}) f_\nu f_{\bar{\nu}}$$

- Long-lived particle with an initial value $Y_X \equiv n_X/s$ and coupling to neutrinos, $X \rightarrow \nu + \bar{\nu}$
- Injected neutrino spectrum: the Boltzmann equation

$$\frac{\partial f_\nu}{\partial t} - H|\mathbf{p}_\nu| \frac{\partial f_\nu}{\partial |\mathbf{p}_\nu|} = \frac{8\pi\alpha m_X \Gamma_X}{2E_\nu} \int d\Pi \tilde{\delta}^4(p) f_X$$

$f_\nu(t)$ depends on the branching ratio α , lifetime $\tau_X = 1/\Gamma_X$, mass m_X , and initial density Y_X

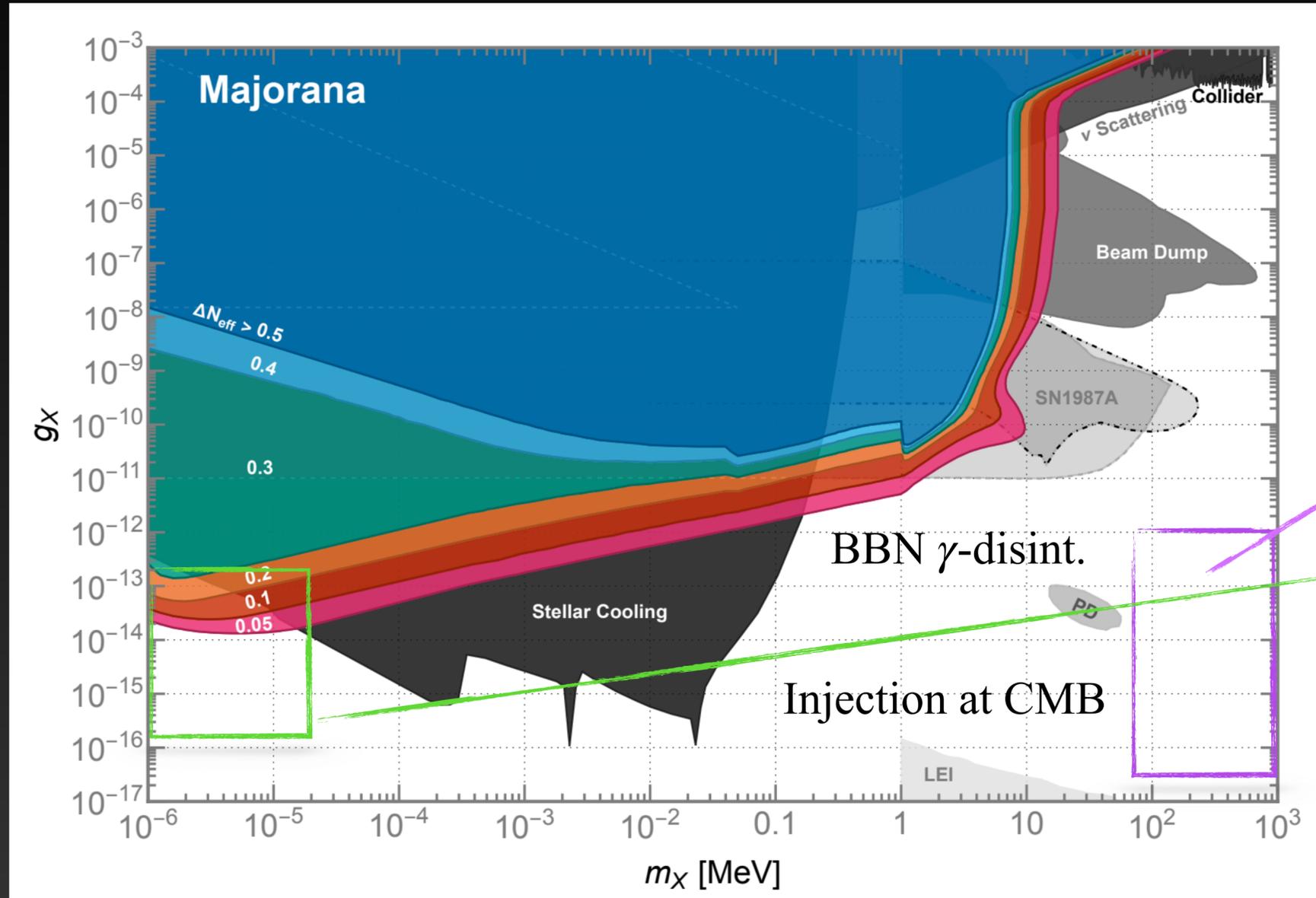
Co-observational window



- A small Y_X can already create the co-observational window, smaller than the current bound $Y_X < 10^{-8}$ from current BBN measurements 2401.00687; 2505.01492

Majorons

- Majoron model, $g_X \nu \gamma_5 \nu X$; Under consideration...



- Co-observational windows for majorons with N_{eff} & μ distortion
- N_{eff} alone cannot tell the mass scale of the majoron, but $N_{\text{eff}} + \mu_{\text{CMB}}$ can

Figure taken from 2308.07955

Summary

- Both N_{eff} and CMB spectral distortions are powerful avenues to probe physics in the early Universe, especially active in particle cosmology
- Synergy of N_{eff} and CMB spectral distortions are feasible to break the observational degeneracy (not complete degeneracy breaking)
- Open up a large parameter space of particle physics models for co-observations

Thank you