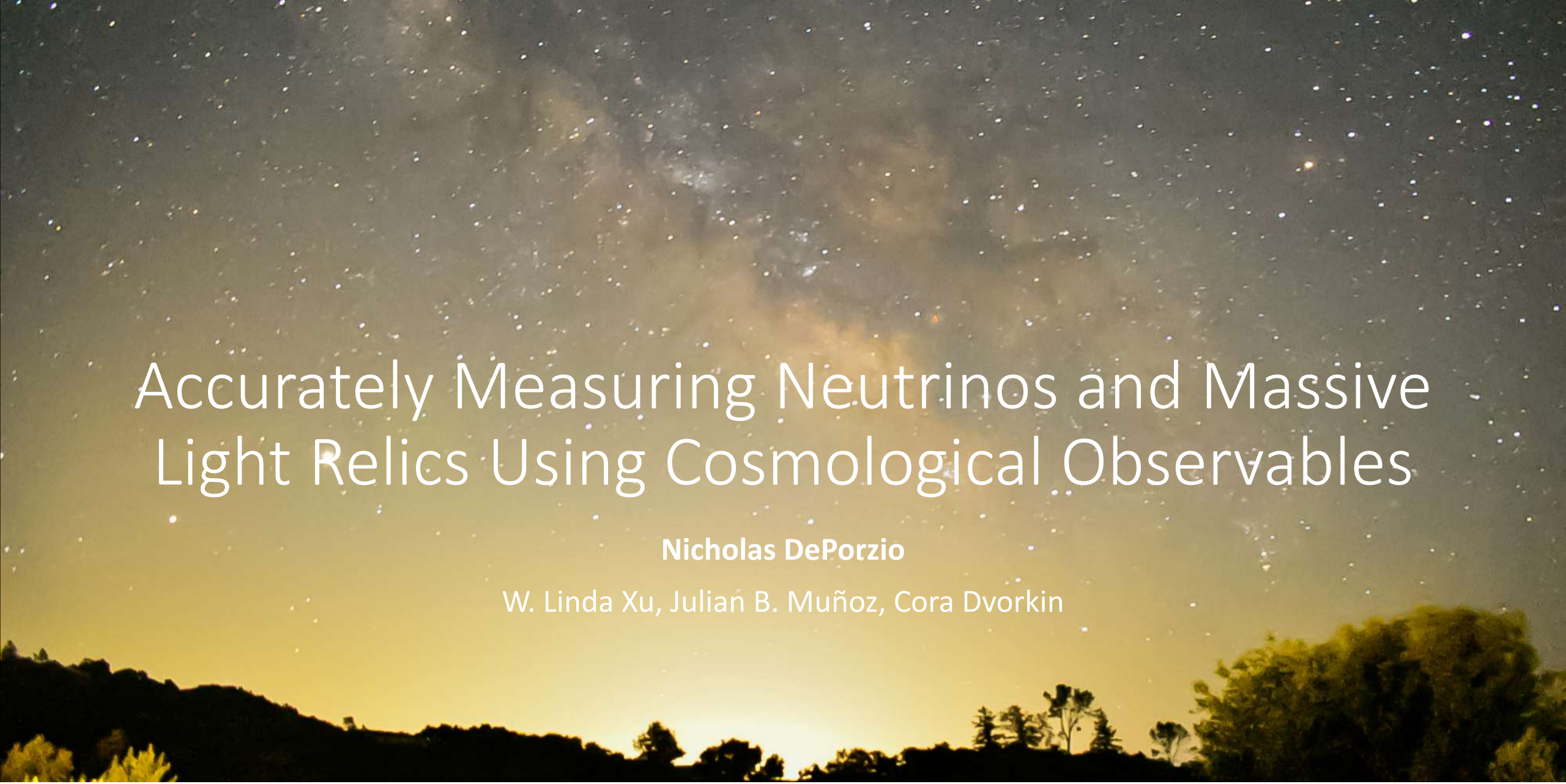


Accurately Measuring Neutrinos and Massive Light Relics Using Cosmological Observables

Nicholas DePorzio

W. Linda Xu, Julian B. Muñoz, Cora Dvorkin

arXiv: 2006.09380
arXiv: 2006.09395

HARVARD UNIVERSITY

Light but Massive Relics (LiMRs)

Abundances via Thermal Equilibrium with Standard Model

Non-zero Mass

Decoupled while relativistic

$M_X, T_X^{(0)}, g_X$

Light but Massive Relics (LiMRs)

Neutrinos

$$\Delta m^2_{21} = 79 \text{ meV}^2$$

$$|\Delta m^2_{31}| = 2.2 \times 10^3 \text{ meV}^2$$

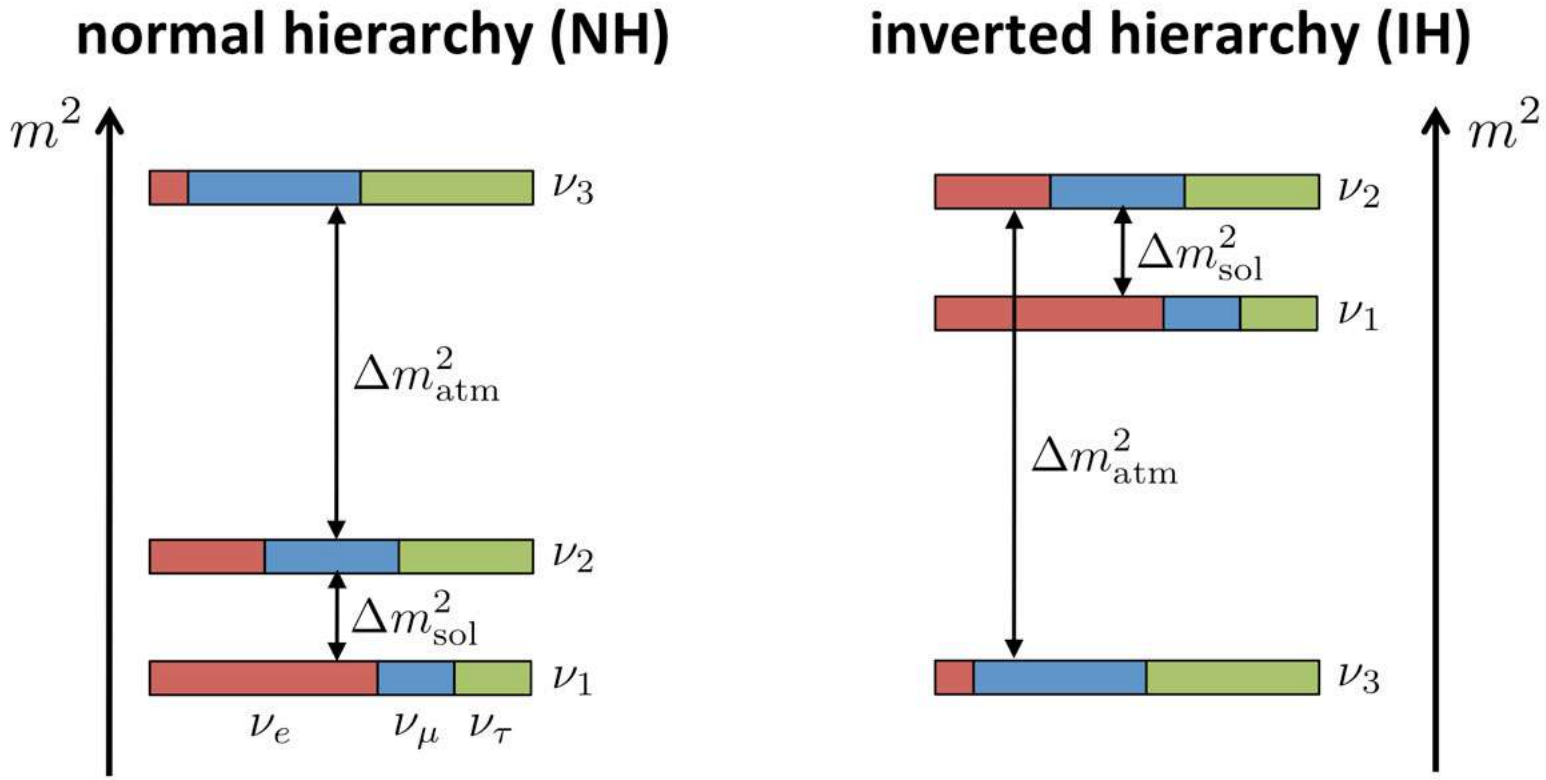
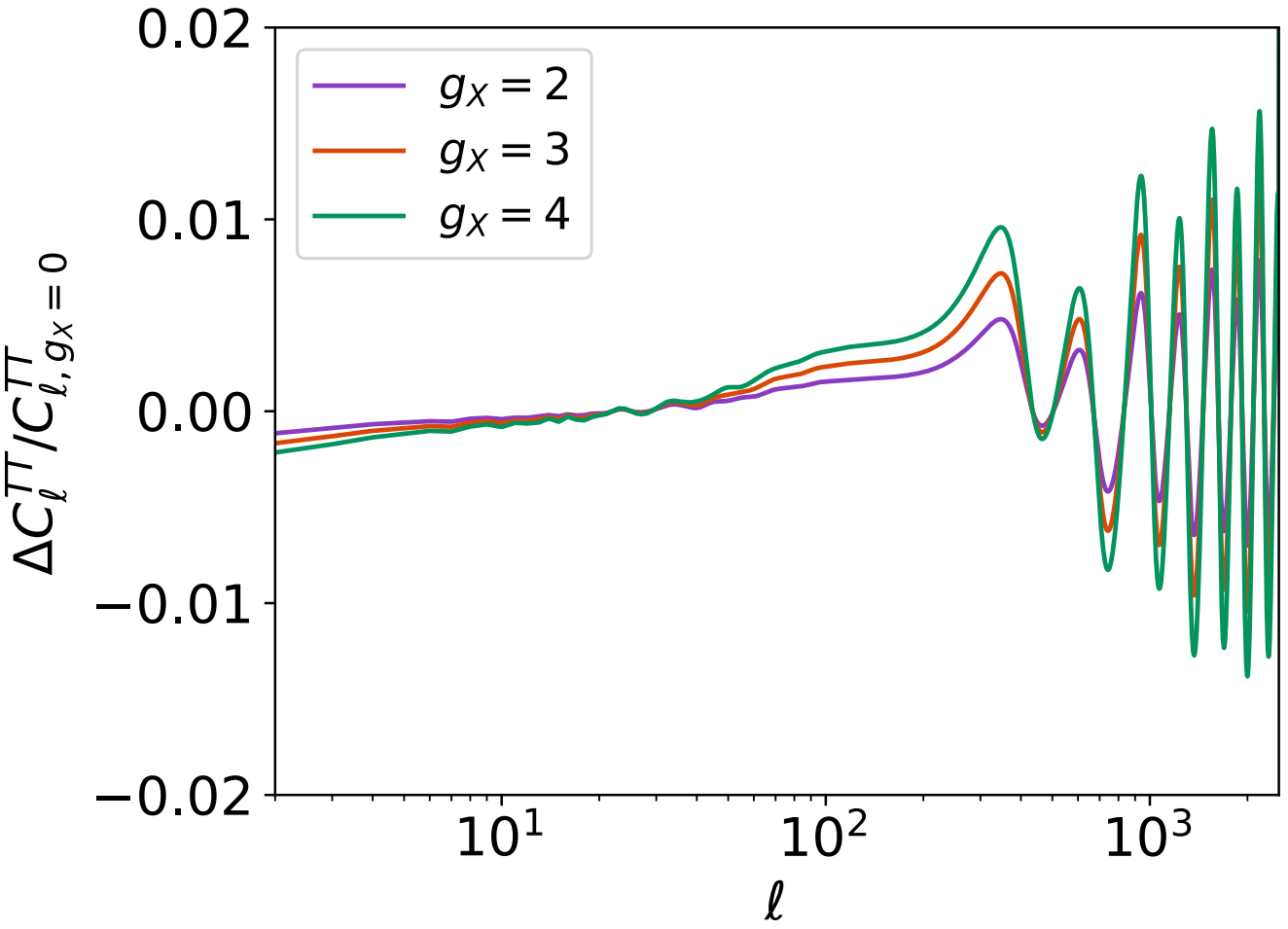


Image Credit: JUNO Collaboration / JGU-Mainz

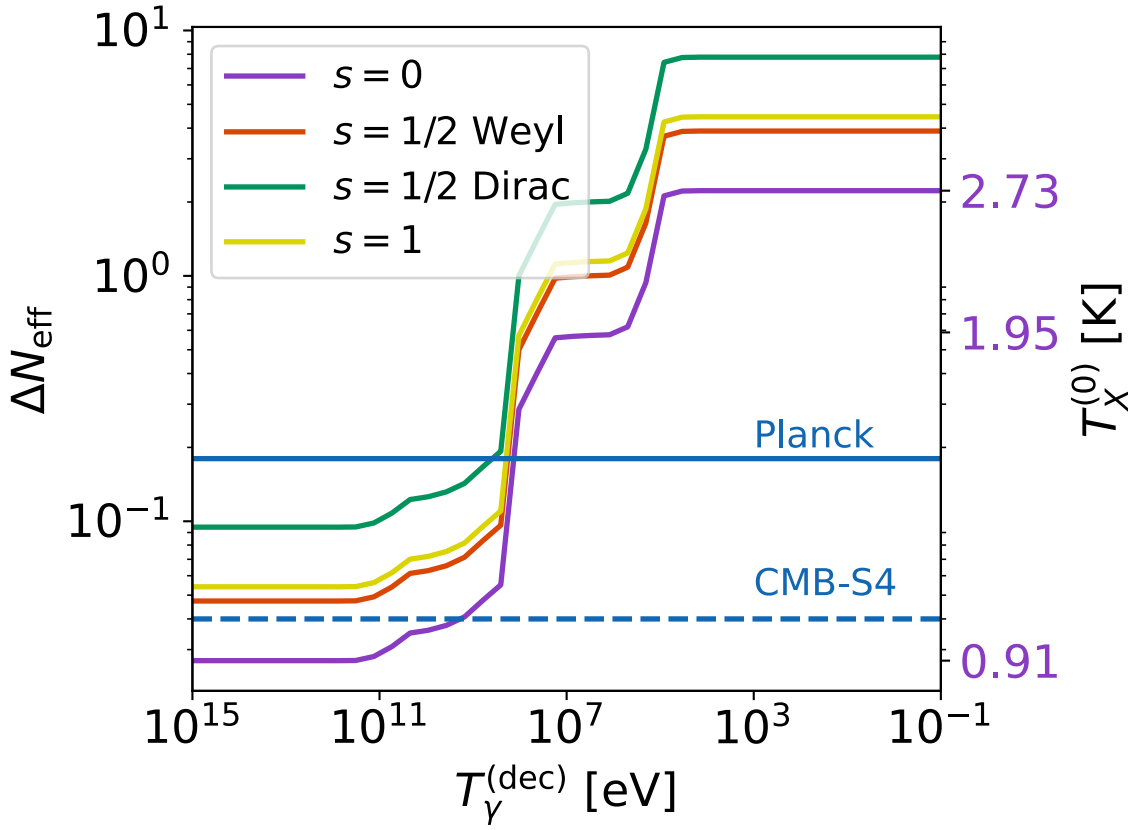
Cosmology of LiMRs
Relativistic Behavior



Cosmology of LiMRs
Relativistic Behavior

$$\rho_{\rm rad}(z) \equiv \frac{\pi^2}{30}\left(2T_\gamma^4(z) + \frac{7}{4}N_{\rm eff}T_\nu^4(z)\right)$$

$$\Delta N_{\rm eff} = c_1^\gamma \left(\frac{g_X}{g_\nu}\right)\left(\frac{T_X^{(0)}}{T_\nu^{(0)}}\right)^4$$



Cosmology of LiMRs
Suppression to P_m

$$\delta_m = f_{cb}\delta_{cb} + \sum_i f_{\nu_i}\delta_{\nu_i} + \sum_j f_{X_j}\delta_{X_j}$$

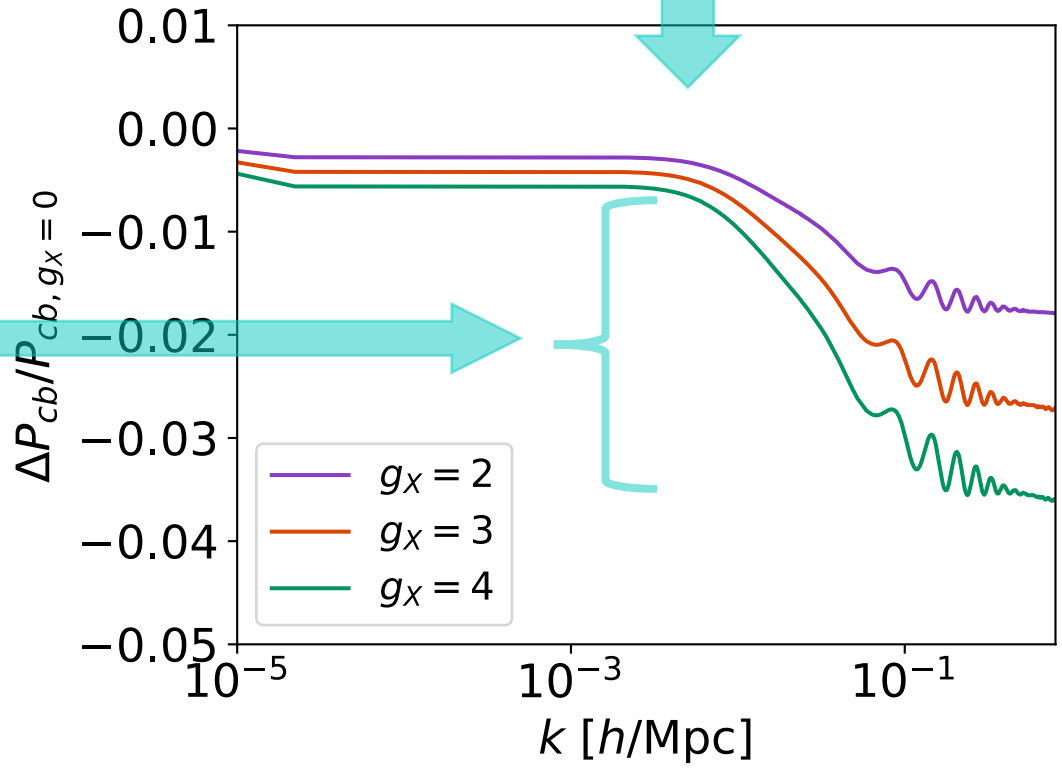
$$k \gg k_{\rm fs} \quad \Rightarrow \quad \delta_X = (k/k_{\rm fs})^{-2}\,\delta_m$$

$$k \ll k_{\rm fs} \quad \Rightarrow \quad \delta_X = \delta_m$$

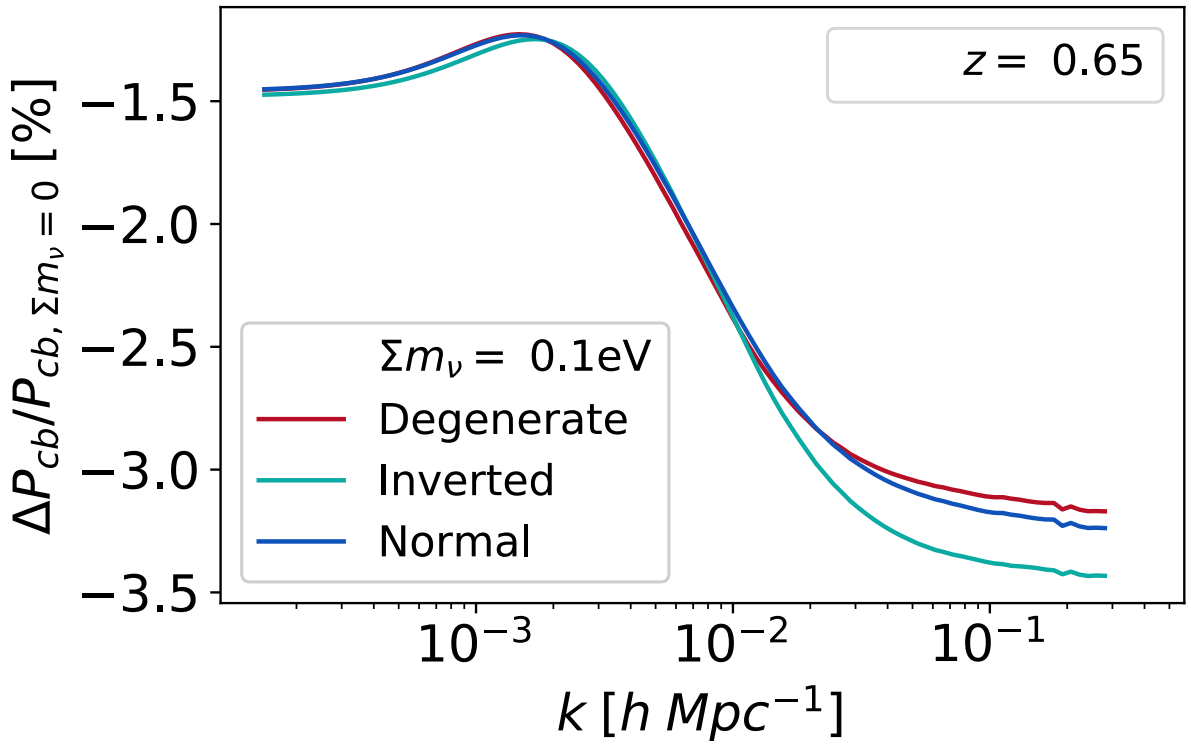
Cosmology of LiMRs
Suppression to P_m

$$k_{\rm fs} = \frac{0.08}{\sqrt{1+z}} \left(\frac{m_X}{0.1{\rm eV}}\right) \left(\frac{T_X^{(0)}}{T_\nu^{(0)}}\right)^{-1} h\,{\rm Mpc}^{-1}$$

$$\Omega_X h^2 = \frac{m_X}{93.14\,{\rm eV}} \frac{g_X}{g_\nu} \left(\frac{T_X^{(0)}}{T_\nu^{(0)}}\right)^3$$



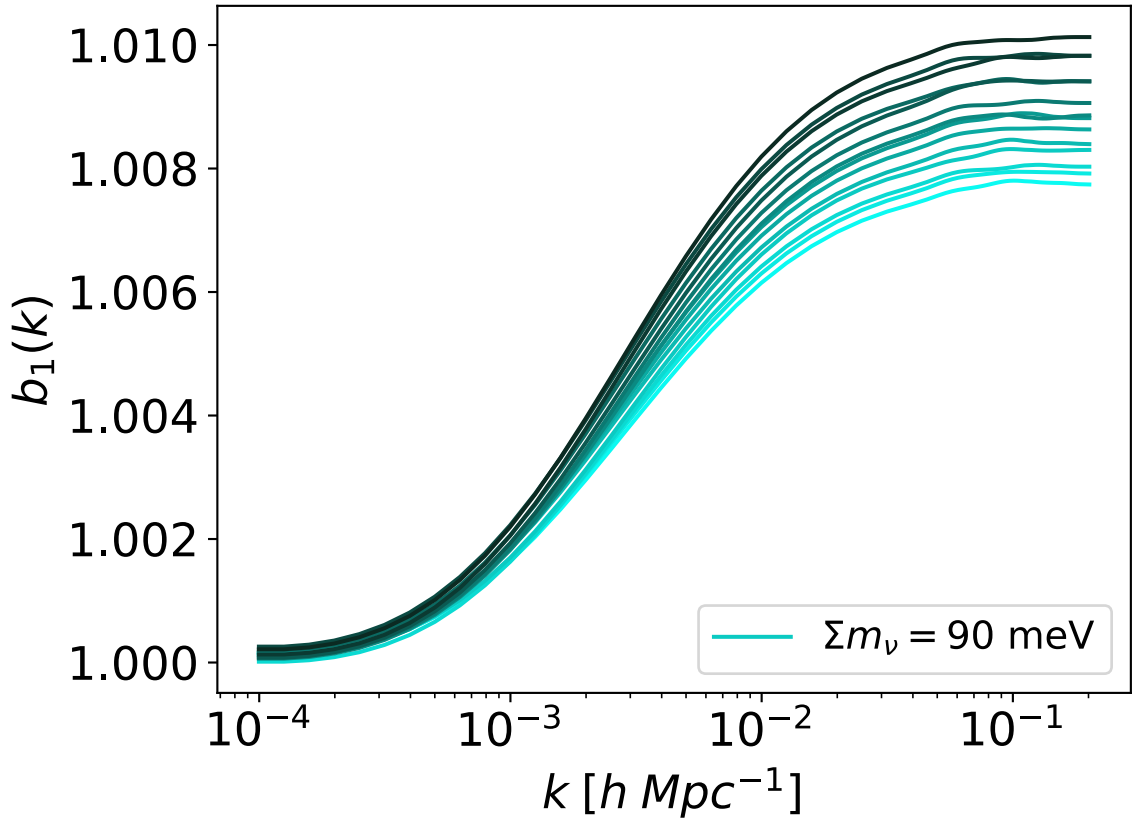
Cosmology of LiMRs
Suppression to P_m



Cosmology of LiMRs
Modifications to Galaxy Bias

$$\delta_h(k,z) = b_1(k,z)\delta_{\rm cb}(k,z)$$

$$b_1(k,z) = 1 + b^{\rm L}(k,z) + \alpha_2 k^2$$



RelicFast: github.com/JulianBMunoz/RelicFast

RelicCLASS: github.com/wlxu/RelicClass

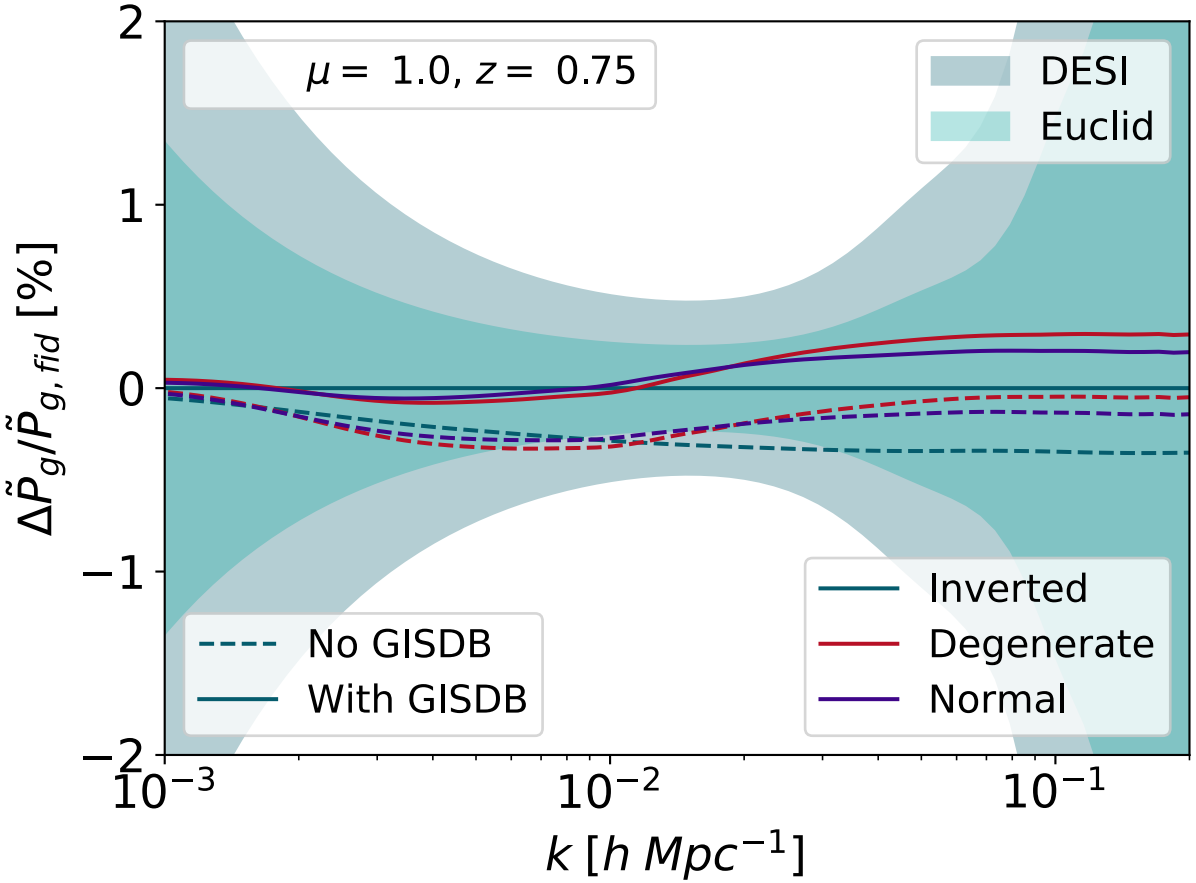
Efficient Computation of Galaxy Bias with Neutrinos and Other Relics
Muñoz and Dvorkin (1805.11623)

Cosmology of LiMRs
Modifications to Galaxy Bias

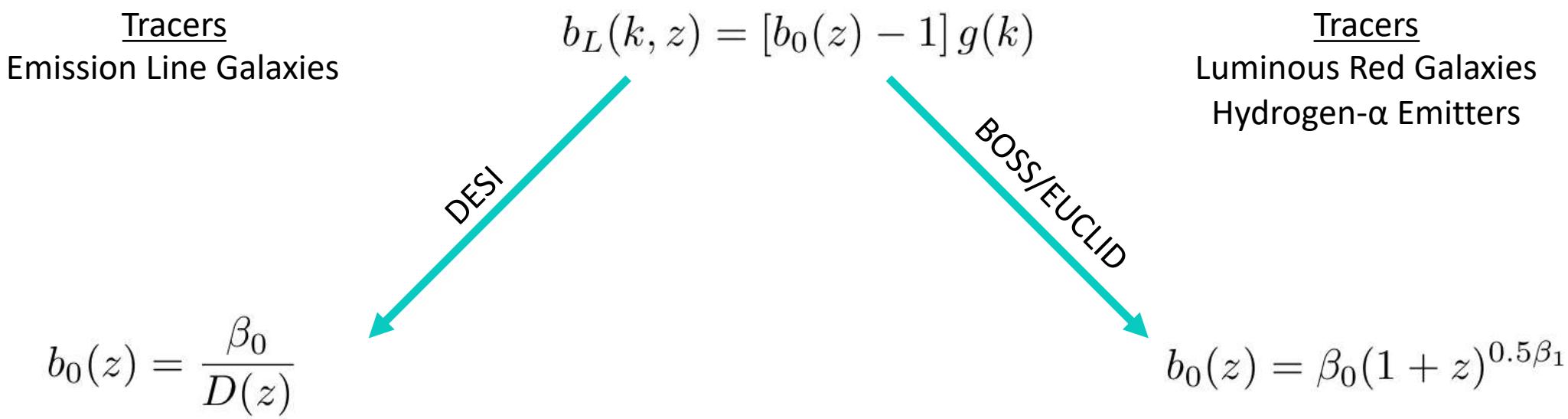
$$b_1(k,z) = \left[1 + b_L(k,z) + \alpha_{k2}k^2\right]$$

$$b_L(k,z) = \left[b_0(z) - 1\right] g(k)$$

$$g(k) = R_L^{\Lambda\mathrm{CDM}}(k) R_L^X(k) R_L^\nu(k)$$



Datasets for Analysis



Datasets for Analysis

Galaxy Surveys

BOSS:	$\frac{\mathcal{O}(100)}{\mathrm{d}z\ \mathrm{ddeg}^2}$	$10,000\ \mathrm{deg}^2$
DESI:	$\frac{\mathcal{O}(1000)}{\mathrm{d}z\ \mathrm{ddeg}^2}$	$14,000\ \mathrm{deg}^2$
Euclid:	$\frac{\mathcal{O}(5000)}{\mathrm{d}z\ \mathrm{ddeg}^2}$	$15,000\ \mathrm{deg}^2$

CMB

Planck:	$\ell = [2 - 2500]$	T, E
CMB-S4:	$\ell = [30 - 5000]$	T, E, lensing

Parameter Space

Thermalized Degrees of Freedom

Scalar:	1
Weyl Fermion:	2
Vector:	2
Dirac Fermion:	4

Temperature

Conservation of Comoving Entropy $\Rightarrow$ $$T_X^{(0)} = \left(\frac{g_{*S}^{(0)}}{g_{*S}^{(\mathrm{dec})}} \right)^{1/3} T_\gamma^{(0)} \quad \Rightarrow \quad T_{X,\mathrm{min}}^{(0)} = 0.91 \text{ K}$$

Weyl Fermion with $\Delta N_{\mathrm{eff}} \leq 0.36$ $\Rightarrow$ $$T_{X,\mathrm{max}}^{(0)} = 1.5 \text{ K}$$

Mass

Non-relativistic today $\Rightarrow$ $$m_X \geq 10 \text{ meV}$$

$$\Omega_{\mathrm{cdm}} h^2 \geq \Omega_X h^2 = \frac{m_X}{93.14\,\mathrm{eV}} \frac{g_X}{g_\nu} \left(\frac{T_X^{(0)}}{T_\nu^{(0)}} \right)^3 \quad \Rightarrow \quad m_X \leq 10 \text{ eV}$$

Effective Relic Parameterization

$$T_X \to T_W^{\rm eq} = T_X \left(\frac{g_X}{g_W}\right)^{1/4} c_1^{\gamma/4}$$

$$m_X \to m_W^{\rm eq} = m_X \left(\frac{g_X}{g_W}\right)^{1/4} c_1^{1/4} c_2^{\gamma}$$

Bosons: $\gamma = 1$

Fermions: $\gamma = 0$

$$c_1 = \frac{8}{7}$$

$$c_2 = \frac{7}{6}$$

Efficient Computation of Galaxy Bias with Neutrinos and Other Relics
Muñoz and Dvorkin (1805.11623)

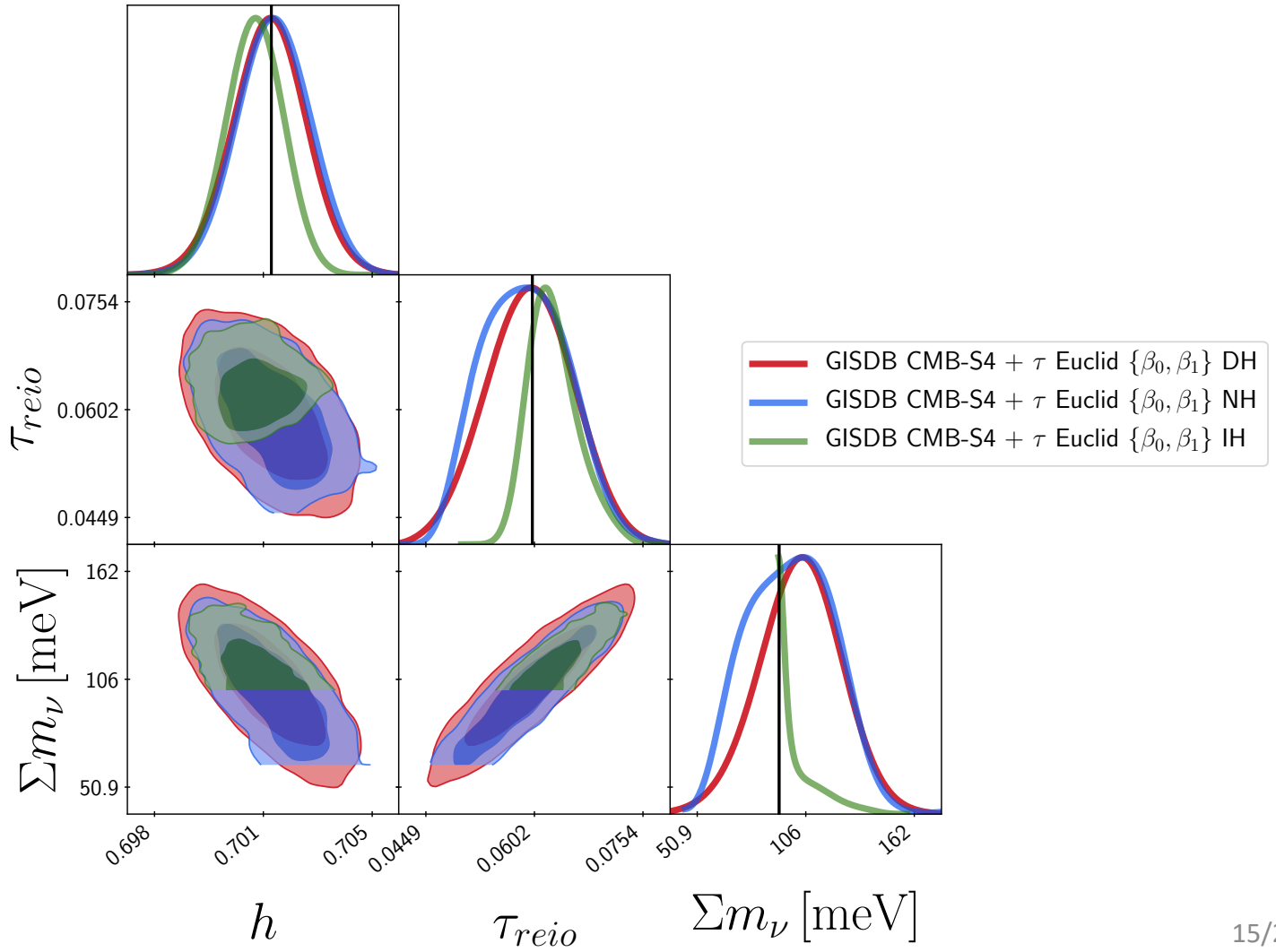
Lyman-α Constraints on Warm and Warm-Plus-Cold Dark Matter Models
Boyarsky, Lesgourgues, Ruchayskiy and Viel (0812.0010)

Results
Neutrino Hierarchy

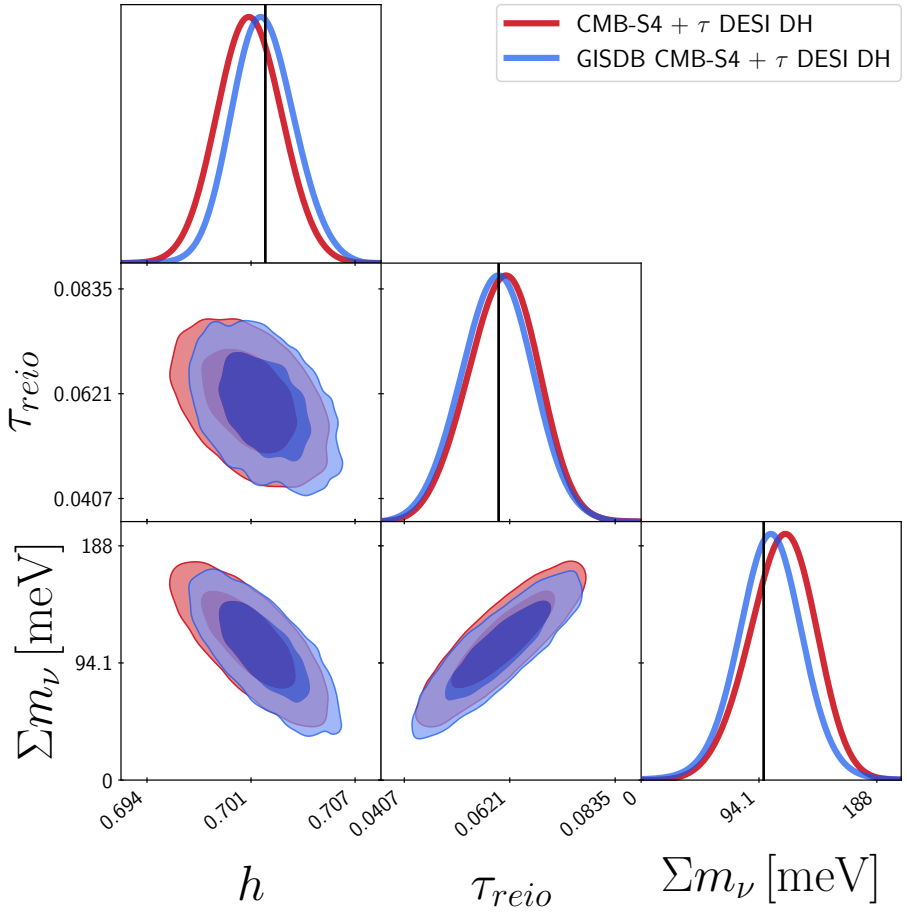
$$\sigma\left(\Sigma m_\nu\right) \approx 20 \text{ meV}$$

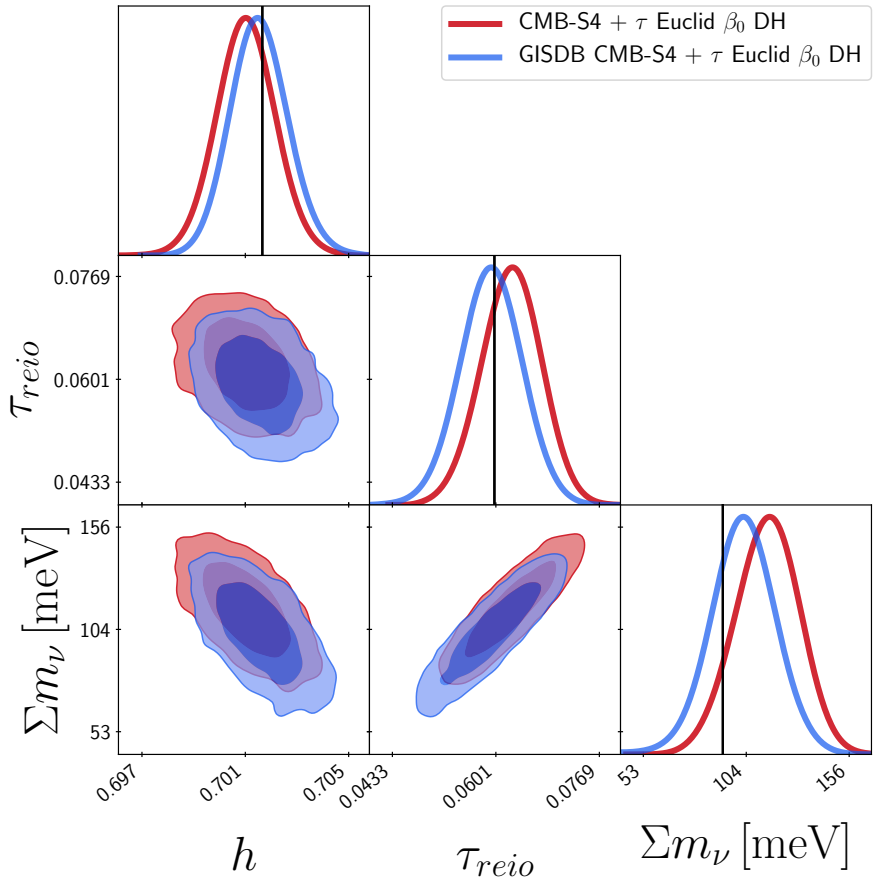
$$\sigma\left(\Sigma m_\nu\right) \neq 0 \text{ at } 5\sigma$$

$$\sigma\left(\Sigma m_\nu\right) \neq 60 \text{ meV at } 2\sigma$$

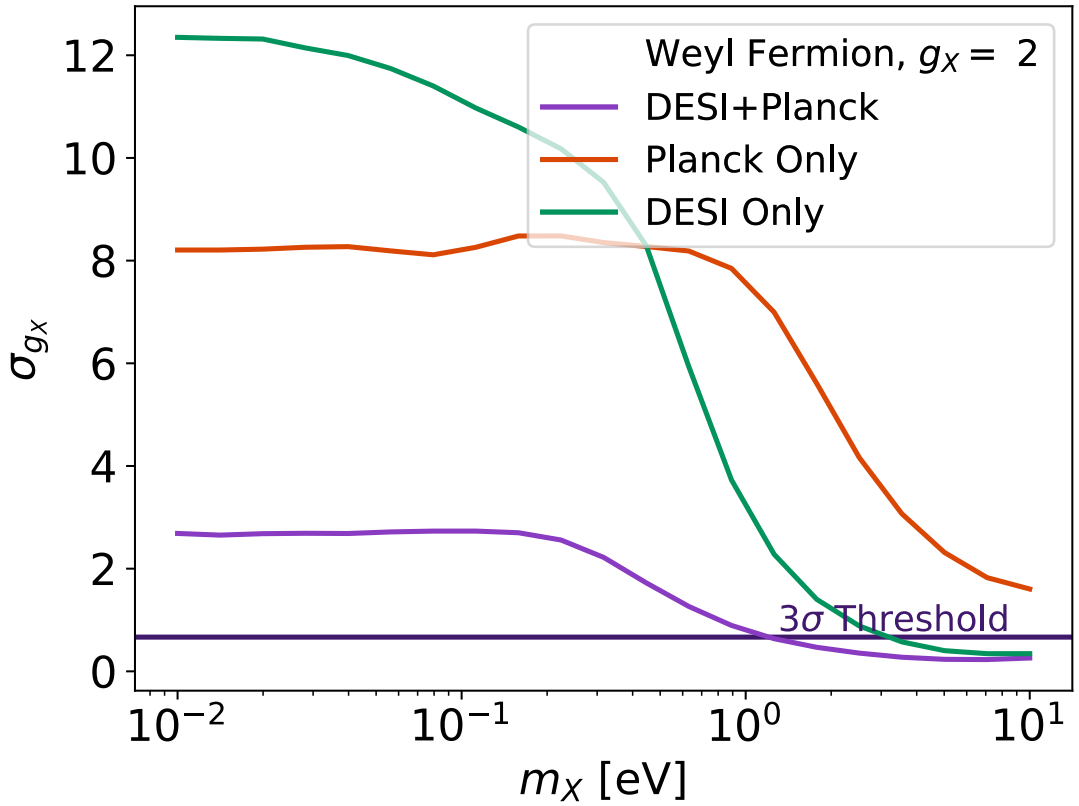


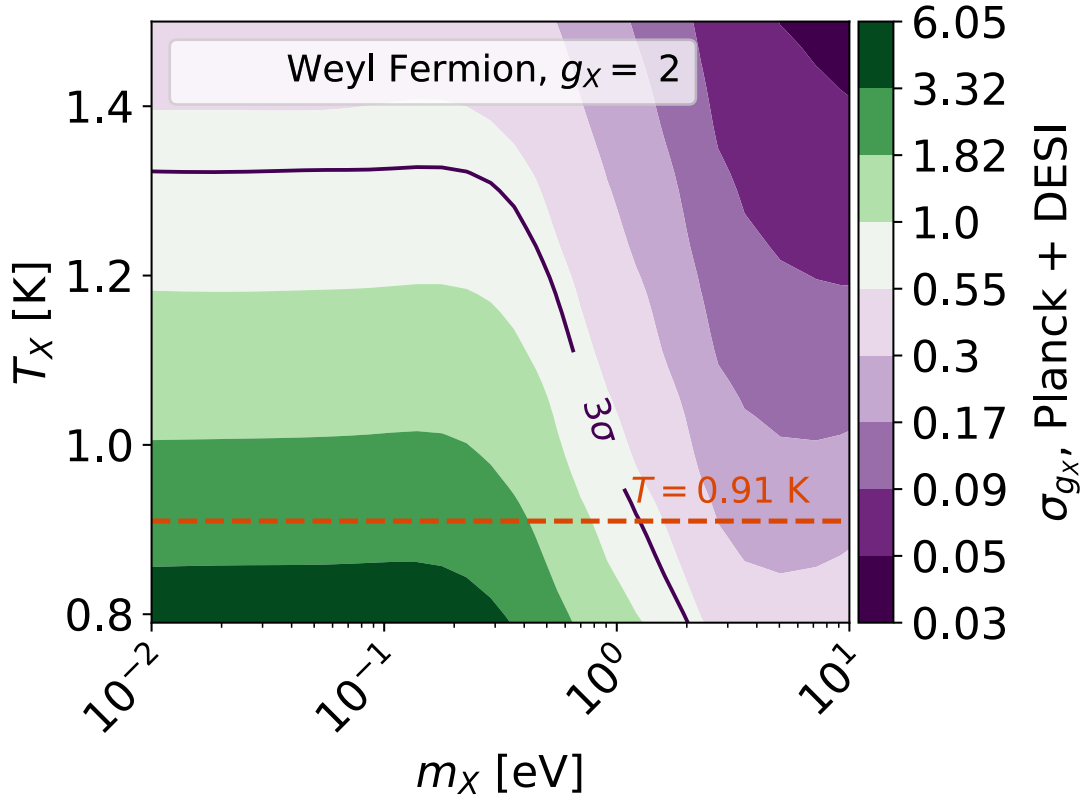
Results
Neutrino GISDB Biasing



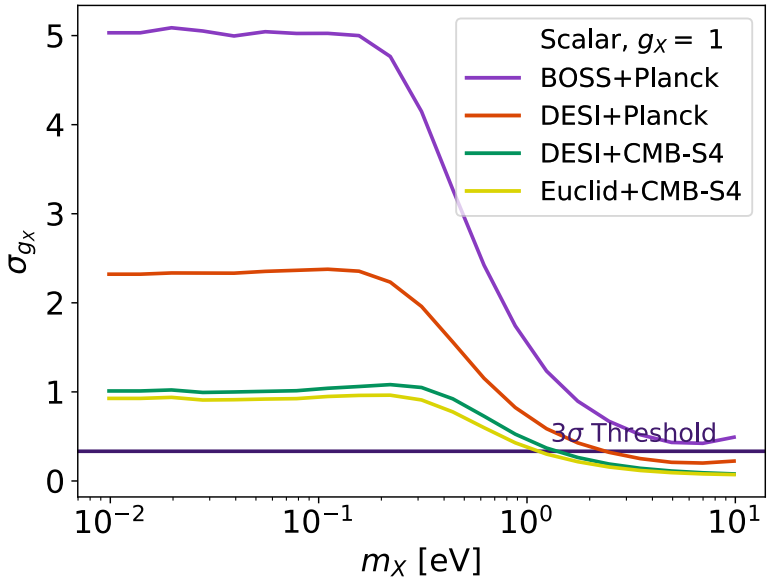


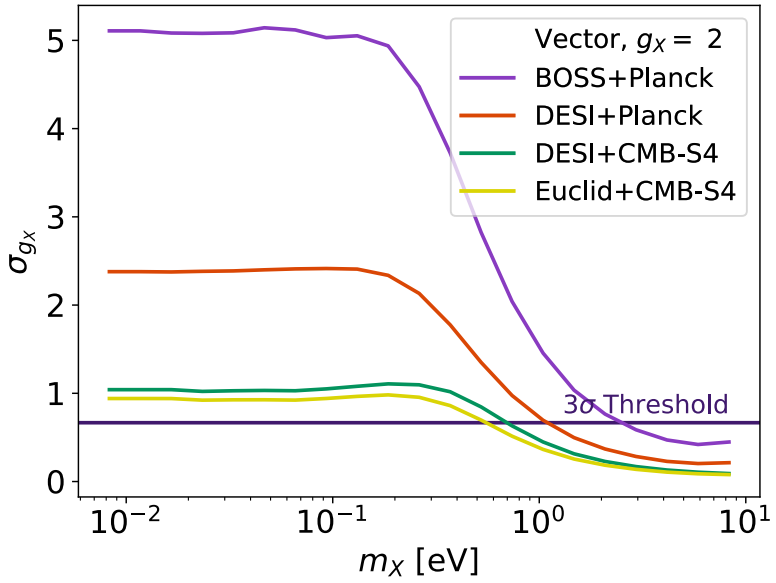
Results
LiMR Weyl Fermion

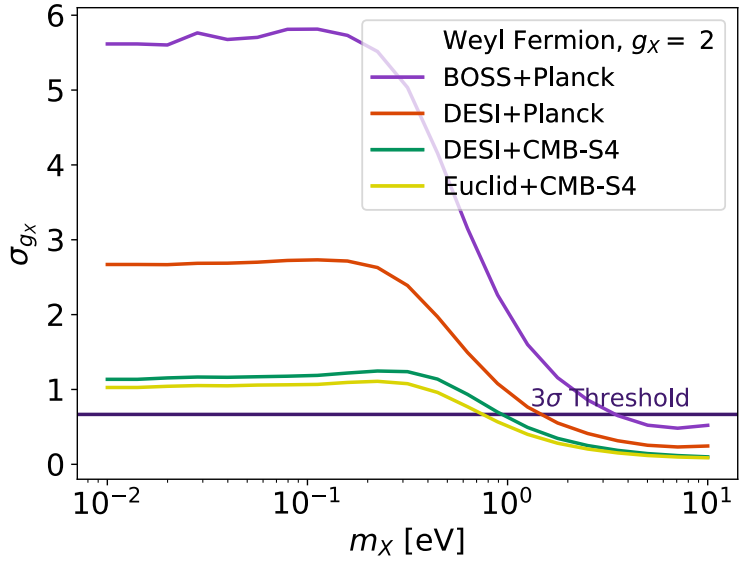


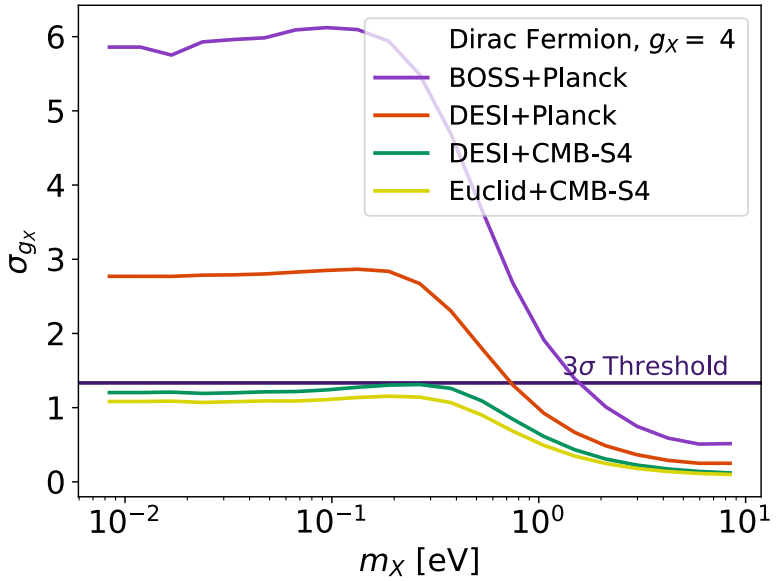


Results

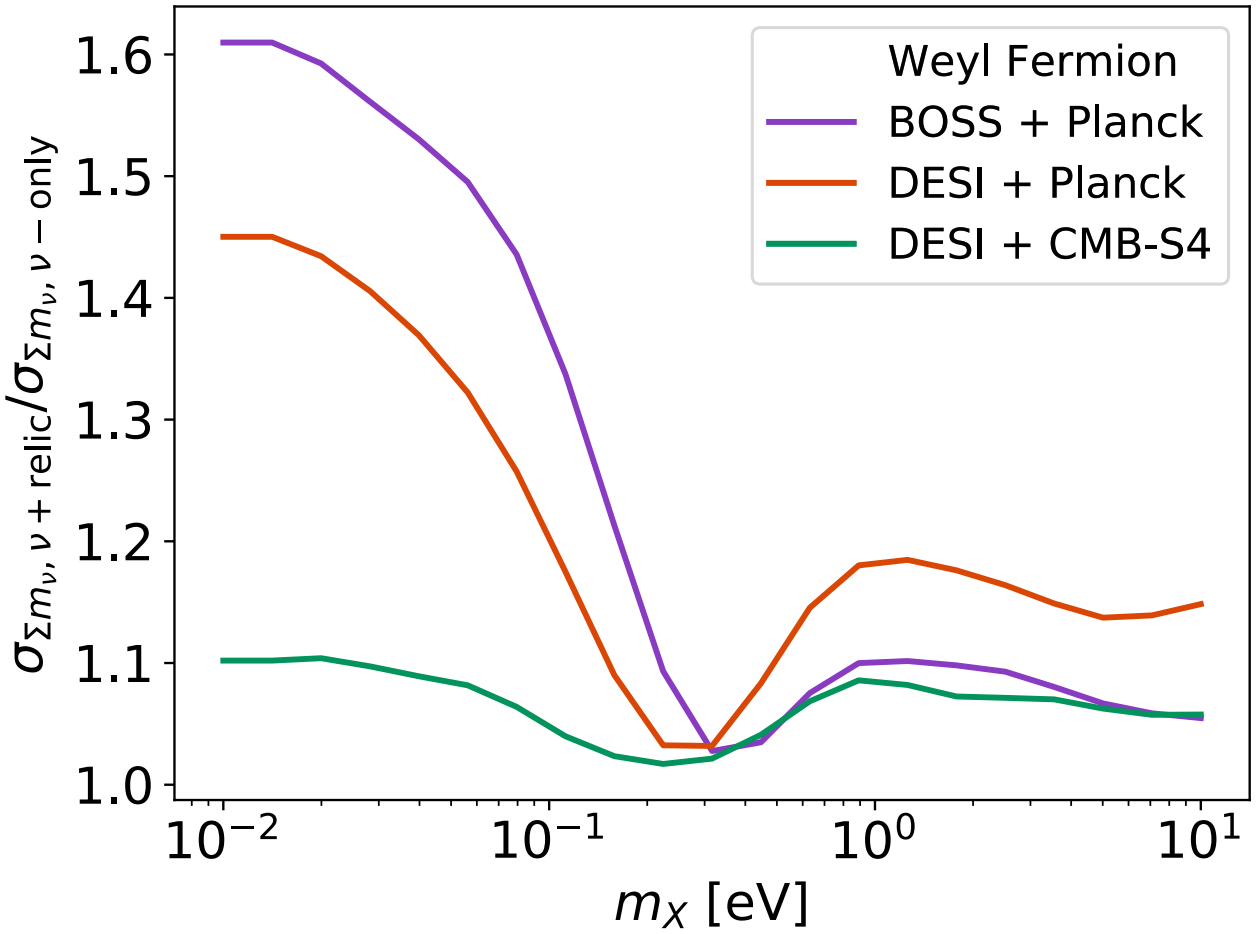

Scalar, $g_X = 1$
BOSS+Planck
DESI+Planck
DESI+CMB-S4
Euclid+CMB-S4
3σ Threshold
σ_{g_X}
m_X [eV]


Vector, $g_X = 2$
BOSS+Planck
DESI+Planck
DESI+CMB-S4
Euclid+CMB-S4
3σ Threshold
σ_{g_X}
m_X [eV]


Weyl Fermion, $g_X = 2$
BOSS+Planck
DESI+Planck
DESI+CMB-S4
Euclid+CMB-S4
3σ Threshold
σ_{g_X}
m_X [eV]


Dirac Fermion, $g_X = 4$
BOSS+Planck
DESI+Planck
DESI+CMB-S4
Euclid+CMB-S4
3σ Threshold
σ_{g_X}
m_X [eV]

Results
LiMR Effect on Neutrino Searches



Conclusions

- LiMR effects on cosmology
  - Suppression to P_m
  - Relativistic contribution
  - Growth induced scale dependent modification to the galaxy bias
- Neglecting GISDB will bias cosmological and neutrino parameters
- Upcoming surveys can constrain large (sometimes all) interesting parameter space of LiMRs

Thank you!

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W. Linda Xu, Julian B. Muñoz, Cora Dvorkin

arXiv: 2006.09380
arXiv: 2006.09395

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