Cosmological Measurements of Light but Massive Relics

Nick DePorzio

Based on work with: W. Linda Xu, Julian B. Muñoz, Cora Dvorkin

arXiv: 2006.09380 (**ND**, Xu, Muñoz, Dvorkin)
arXiv: 2006.09395 (Xu, **ND**, Muñoz, Dvorkin)

HARVARD UNIVERSITY

Light but Massive Relics (LiMRs)

Abundances via Thermal Equilibrium with Standard Model

Decoupled while relativistic

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

Light but Massive Relics (LiMRs)

Neutrinos

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

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

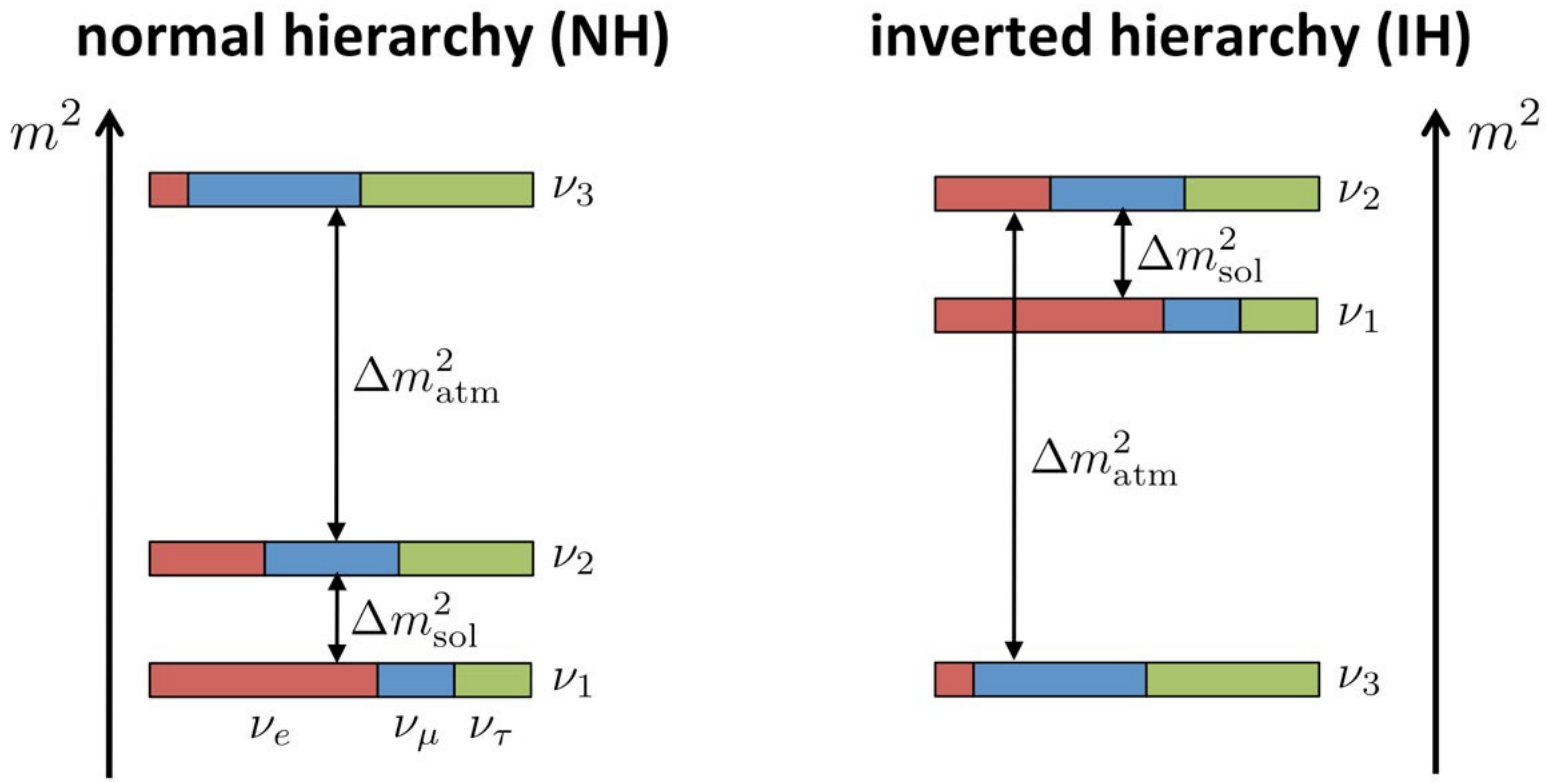
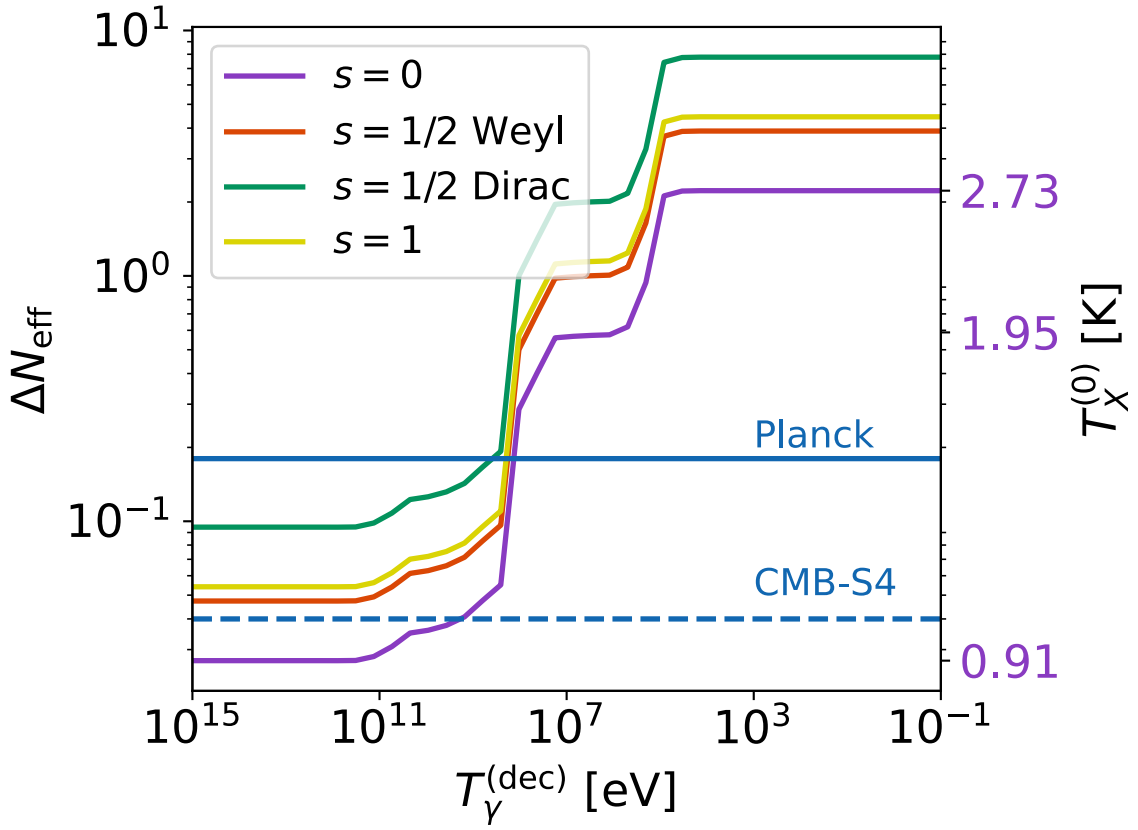


Image Credit: JUNO Collaboration / JGU-Mainz

Cosmology of LiMRs
Relativistic Behavior

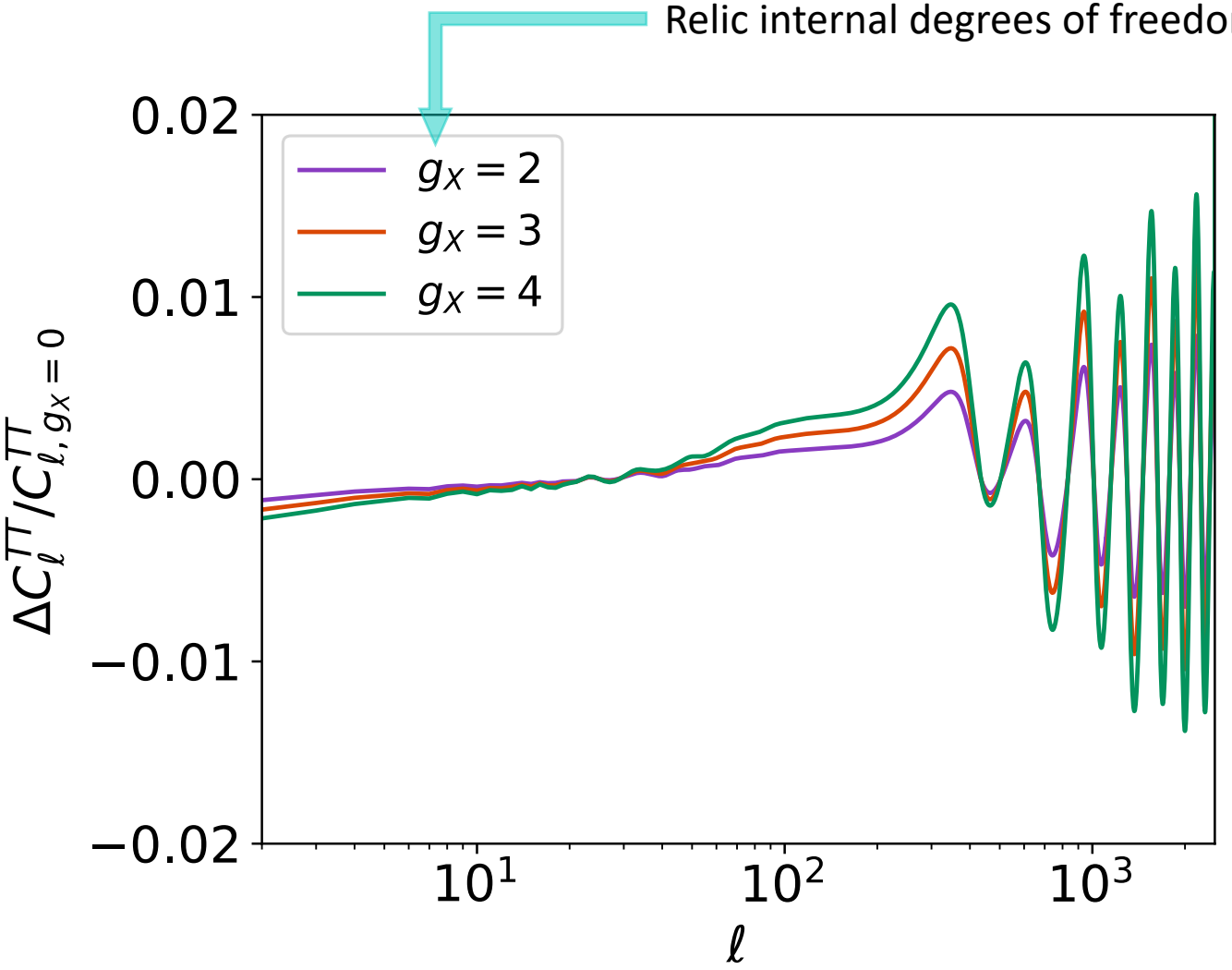
$$\rho_{\rm rad}(z) \equiv \frac{\pi^2}{30}\left(2T_\gamma^4(z) + \frac{7}{4}N_{\rm eff}T_\nu^4(z)\right)$$

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



Cosmology of LiMRs
Relativistic Behavior

$$H_0, \omega_{\rm b}, \omega_{\rm cdm}, n_{\rm s}, A_{\rm s}, \tau_{\rm reio}$$



Cosmology of LiMRs
Suppression to P_m

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

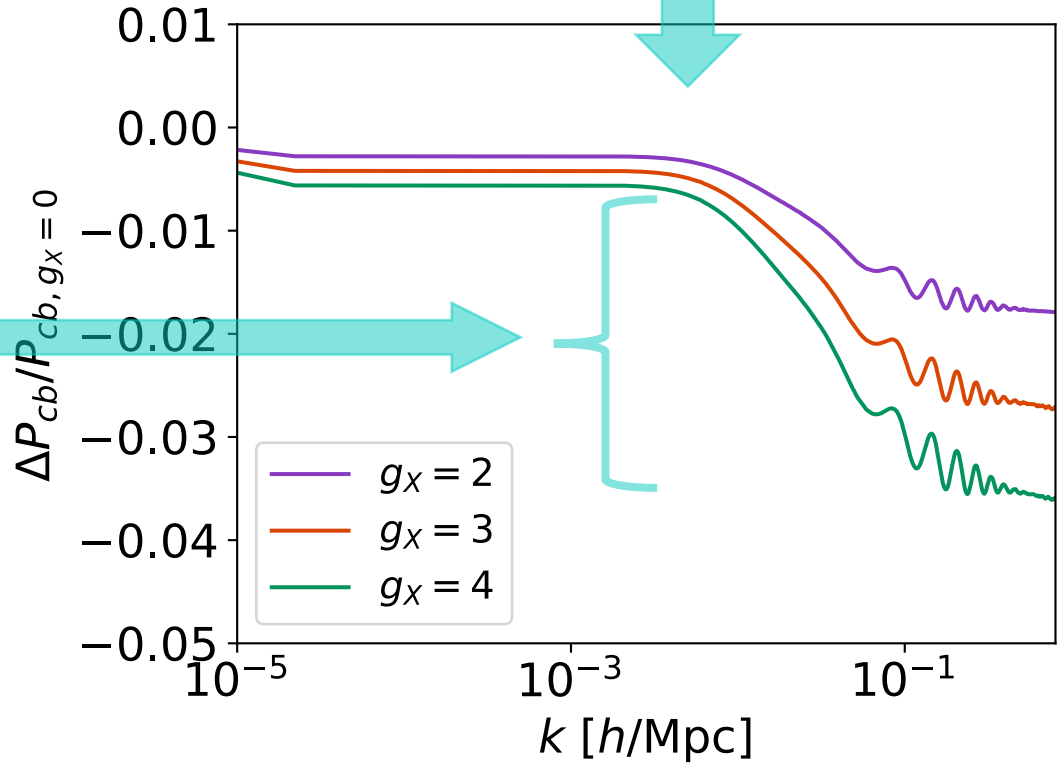
$$k \gg k_{\rm fs} \quad \Rightarrow \quad \delta_X = (k/k_{\rm fs})^{-2}\,\delta_m$$

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

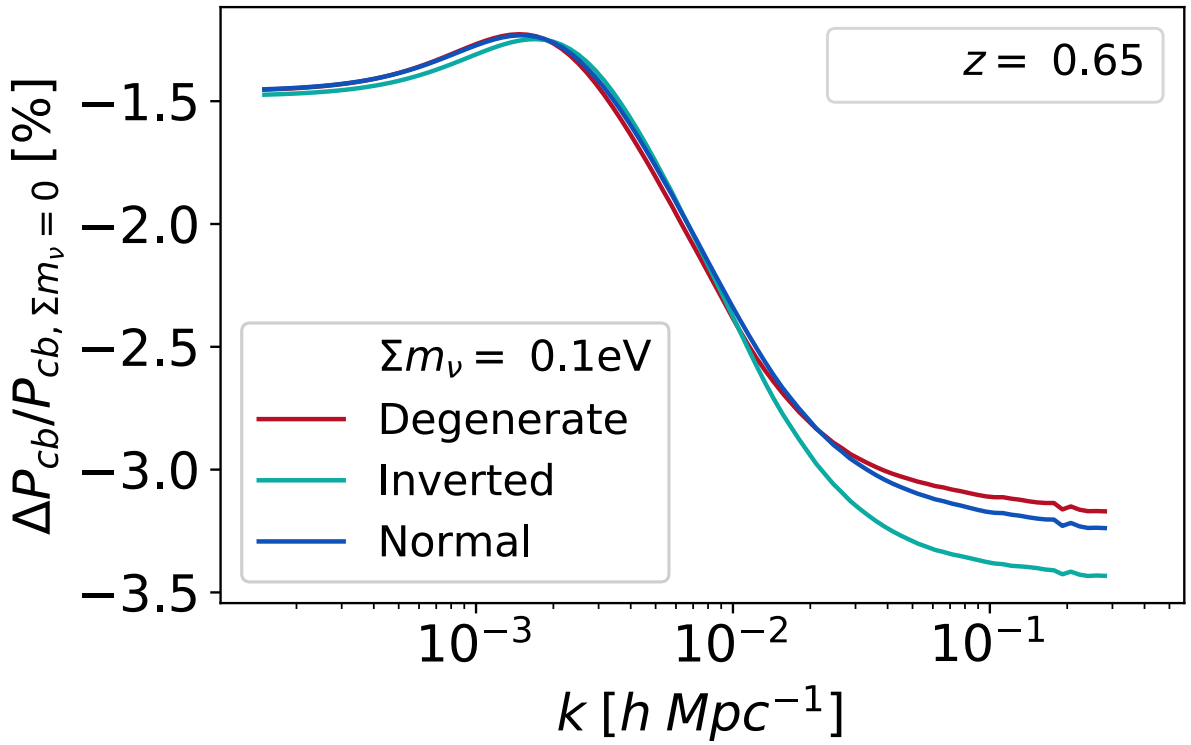
Cosmology of LiMRs
Suppression to P_m

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

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



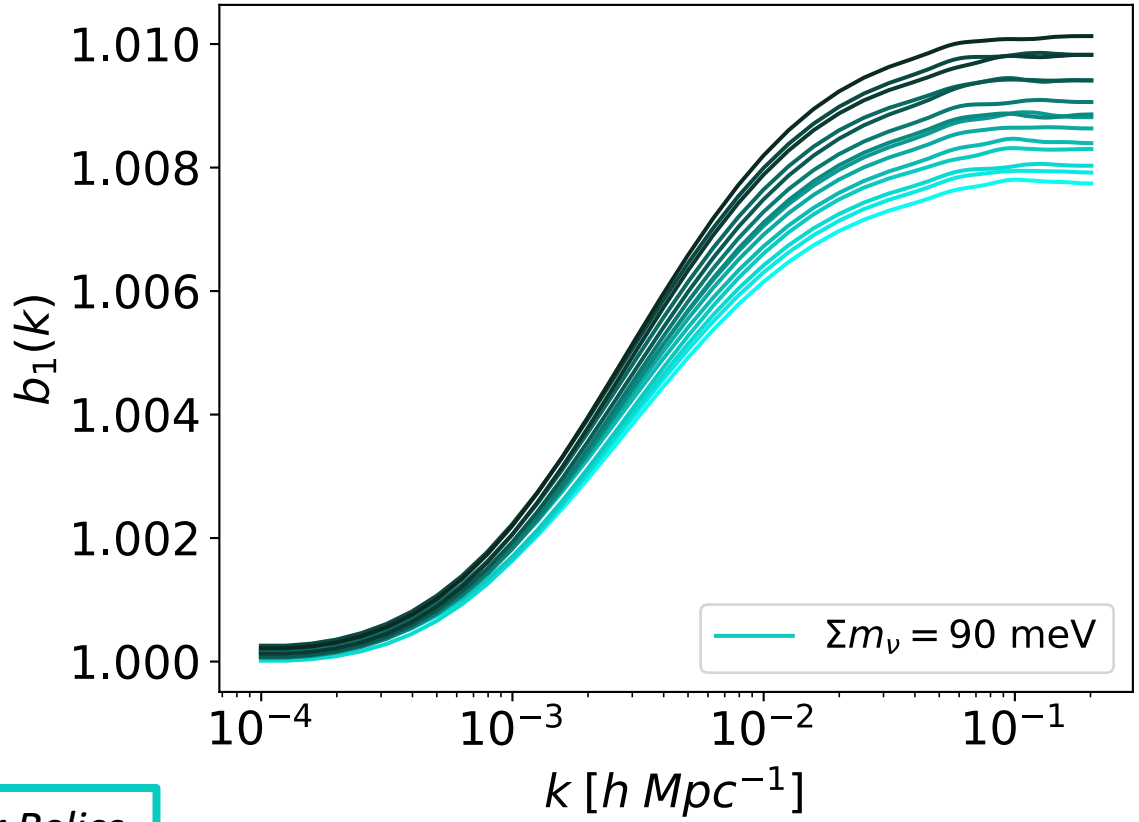
Cosmology of LiMRs
Suppression to P_m



Cosmology of LiMRs
Modifications to Galaxy Bias

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

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



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

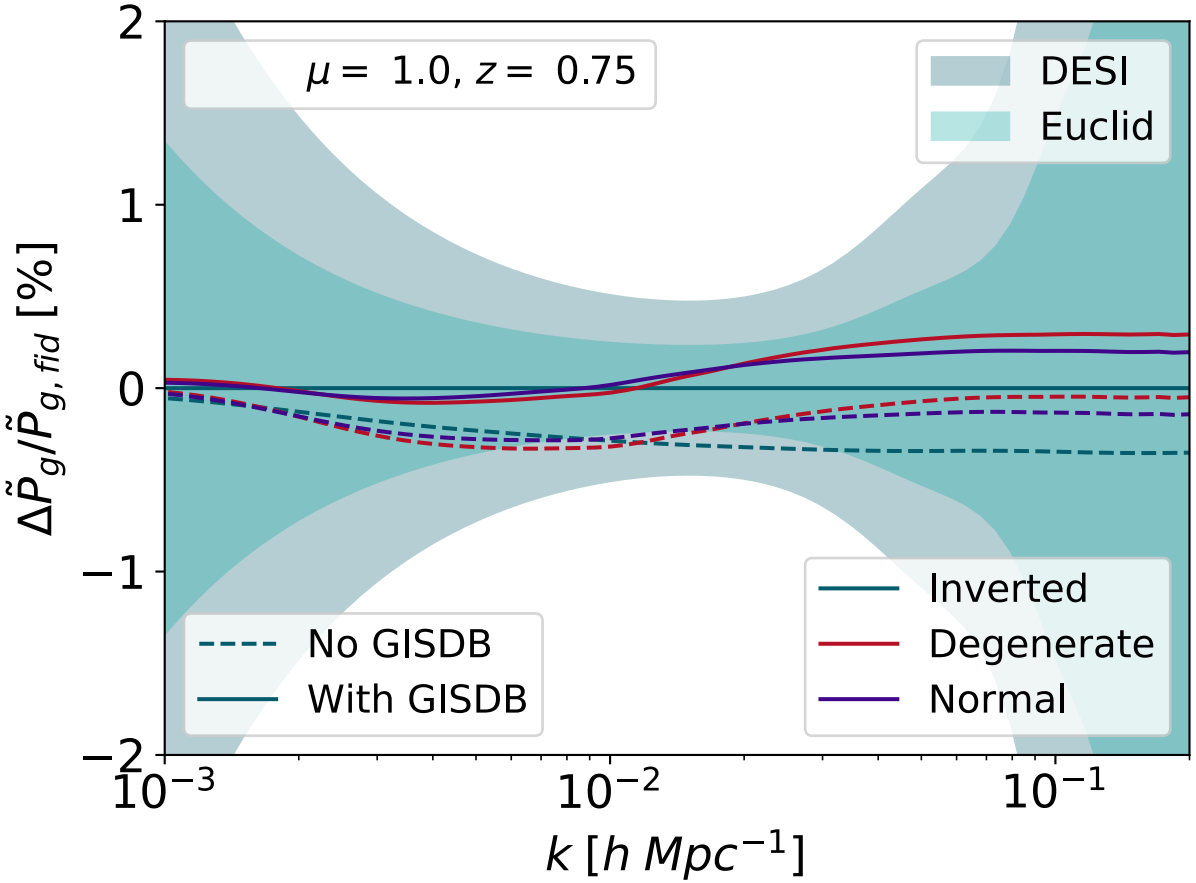
Cosmology of LiMRs
Modifications to Galaxy Bias

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

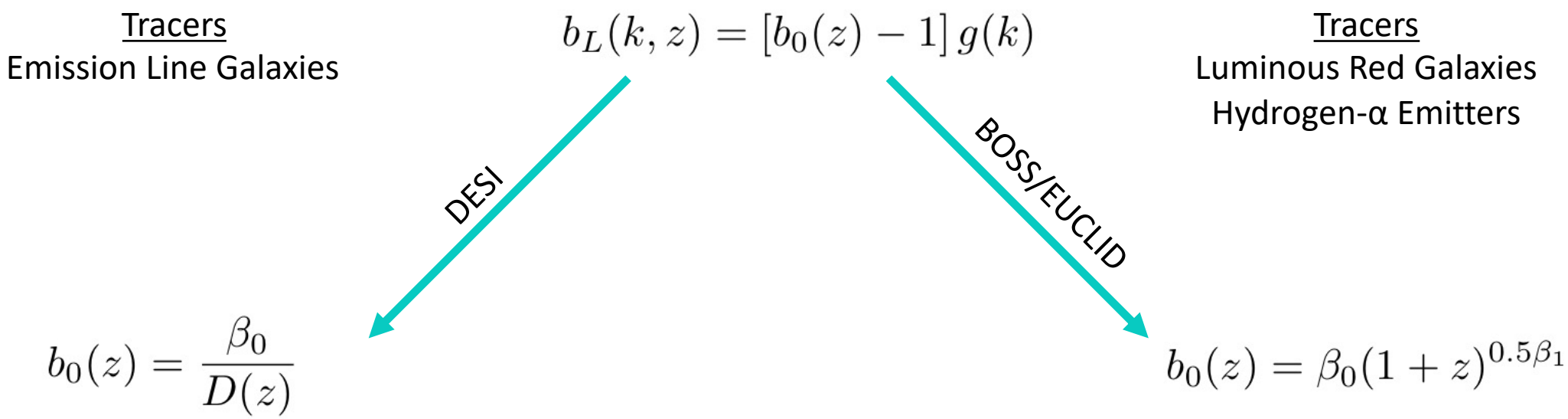
$$b_L(k,z) = \left[b_0(z) - 1\right] g(k)$$

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

$$\frac{b_1^{L,\mathrm{fit}}(k)}{b_1^L(k_{\mathrm{ref}})} = R_L^{\Lambda\mathrm{CDM}} \left[1 + \frac{\Delta_L}{2}\left(\tanh\left[\frac{\log(q)}{\Delta_q}\right] + 1\right)\right]$$



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

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

Weyl Fermion with $\Delta N_{\mathrm{eff}} \leq 0.36$

$$\Rightarrow \quad T_{X,\mathrm{max}}^{(0)} = 1.5\ \mathrm{K}$$

Mass

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

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

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)

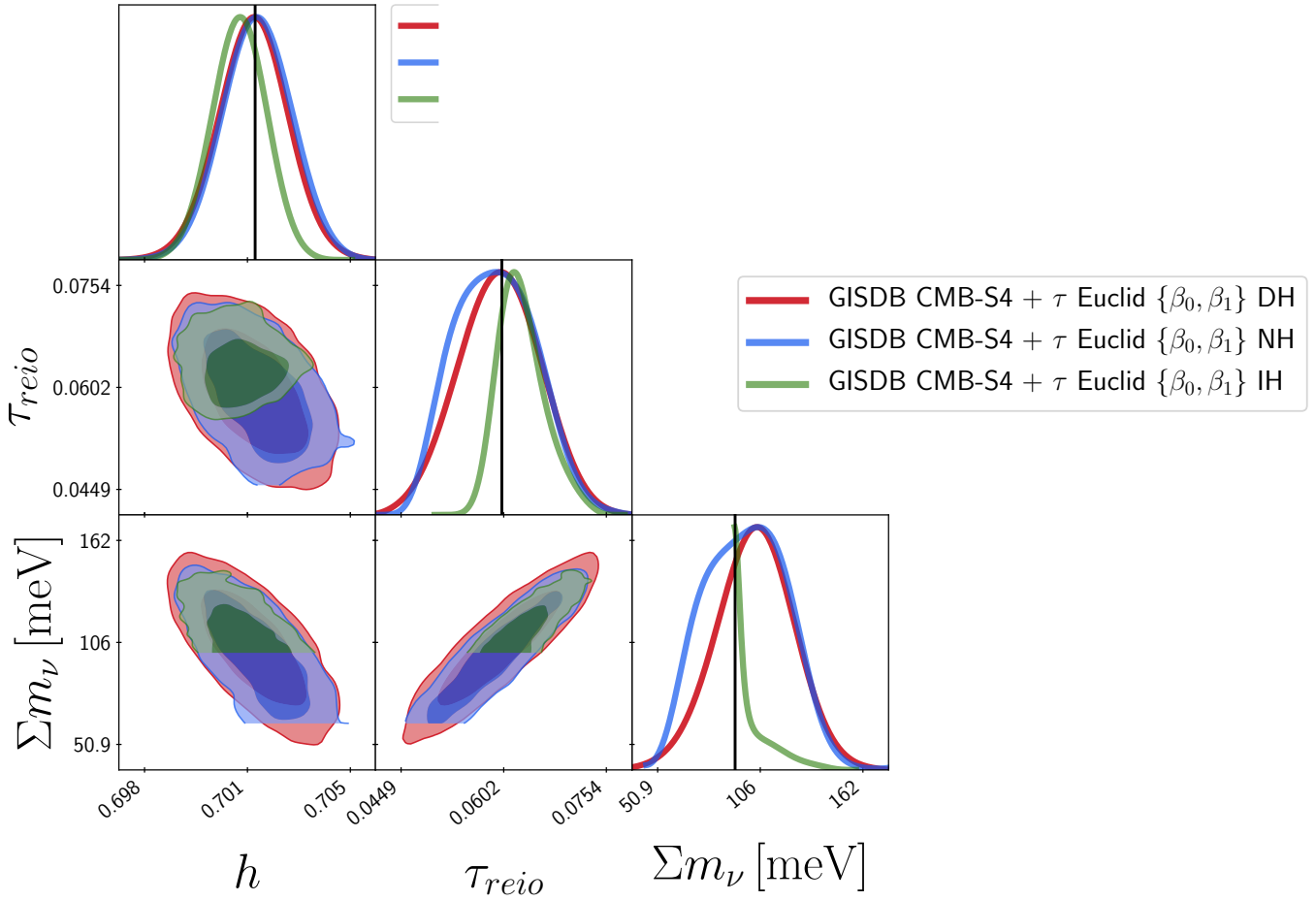
Lyman-α Constraints on Warm and Warm-Plus-Cold Dark Matter Models
Boyarsky, Lesgourgues, Ruchayskiy and Viel (0812.0010)

Results
Neutrinos

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

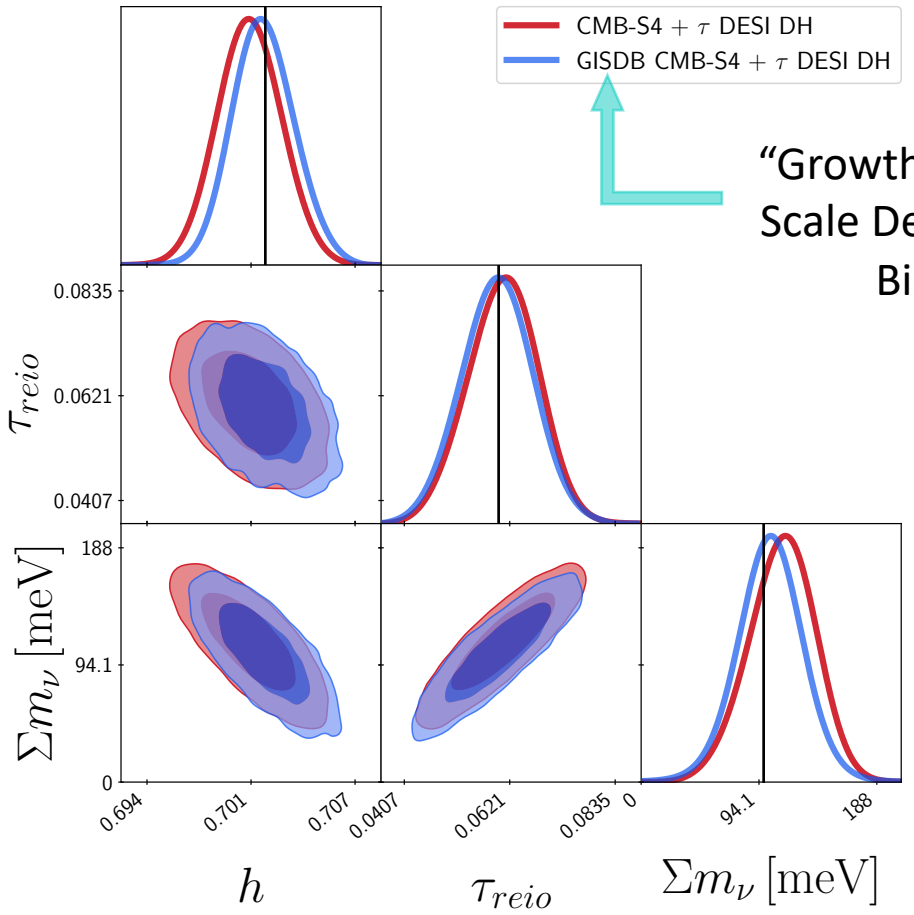
$$\sigma\left(\Sigma m_\nu\right) \neq 0 \text{ at } 5\sigma$$

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

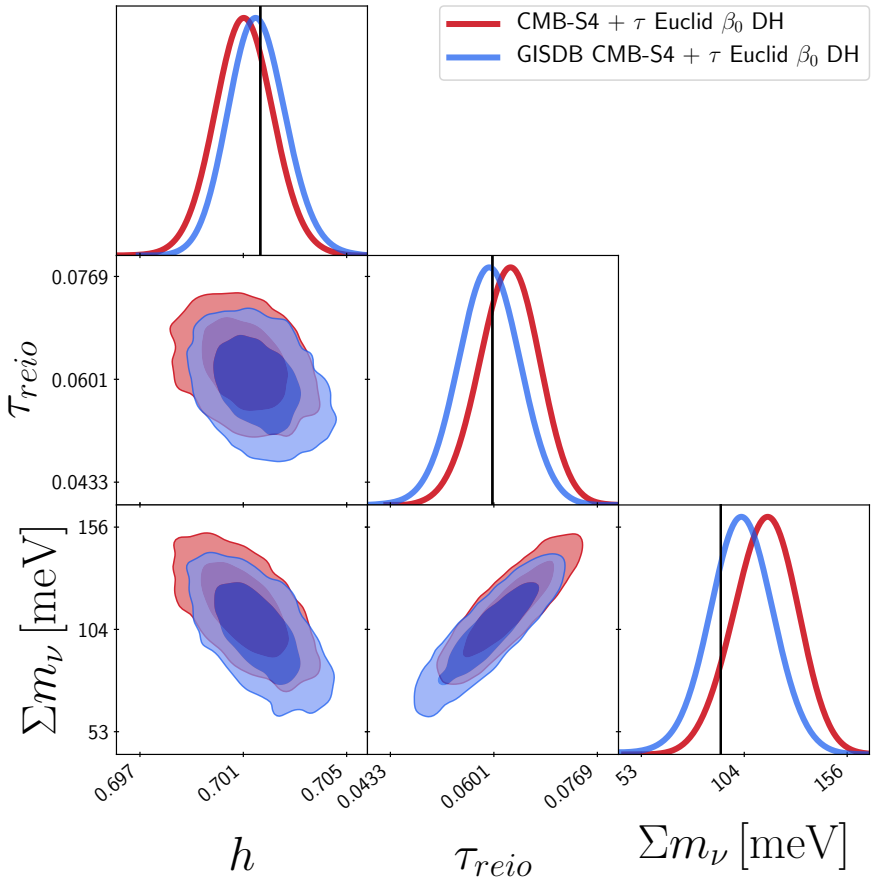


Accurately Weighing Neutrinos with Cosmological Surveys
Xu, **DePorzio**, Muñoz, Dvorkin (2006.09395)

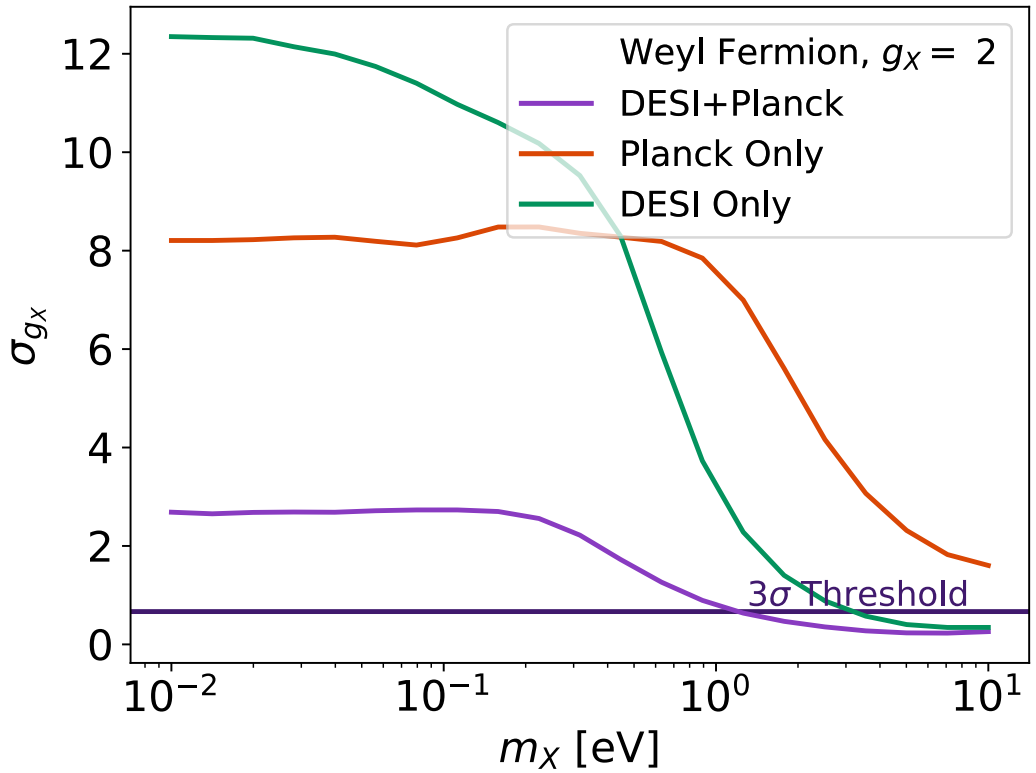
Results
Neutrino GISDB Biasing

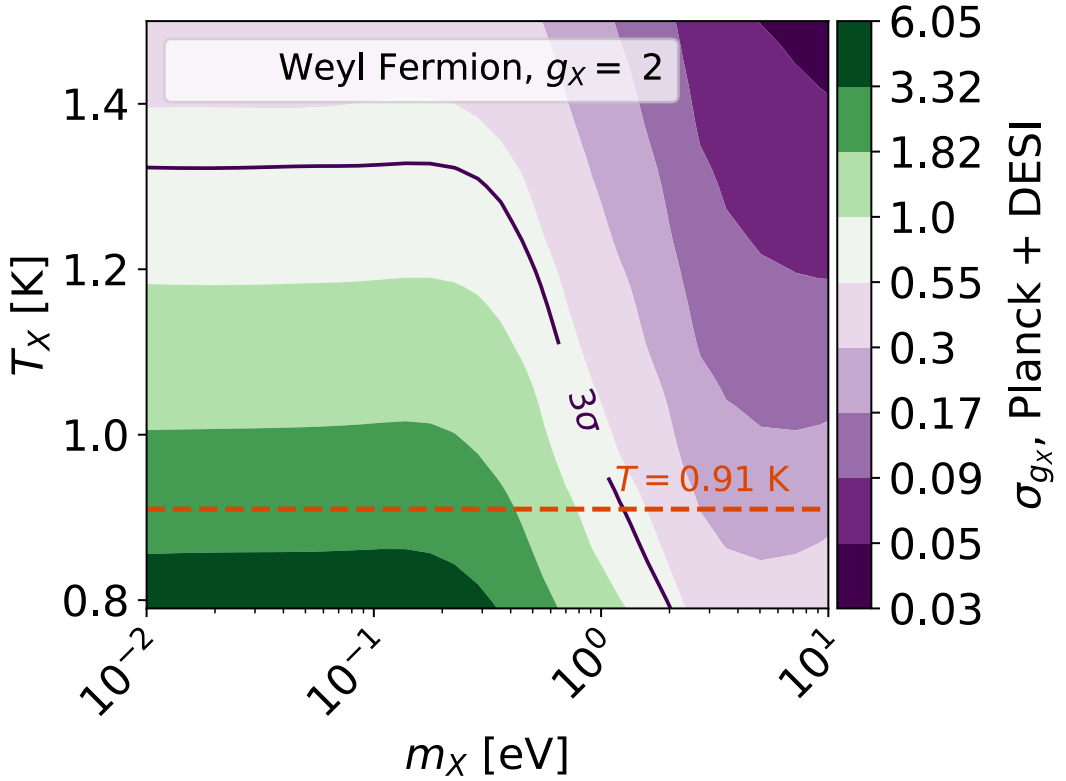


"Growth Induced Scale Dependent Bias"



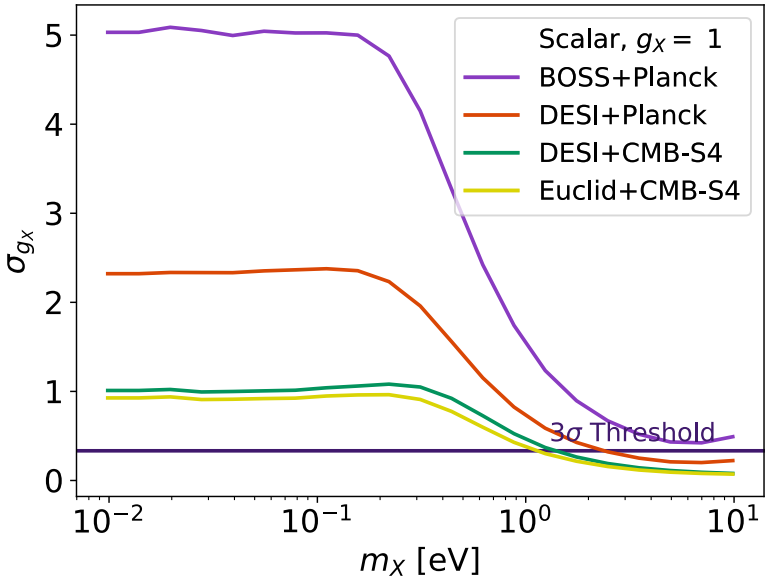
Results
LiMR Weyl Fermion

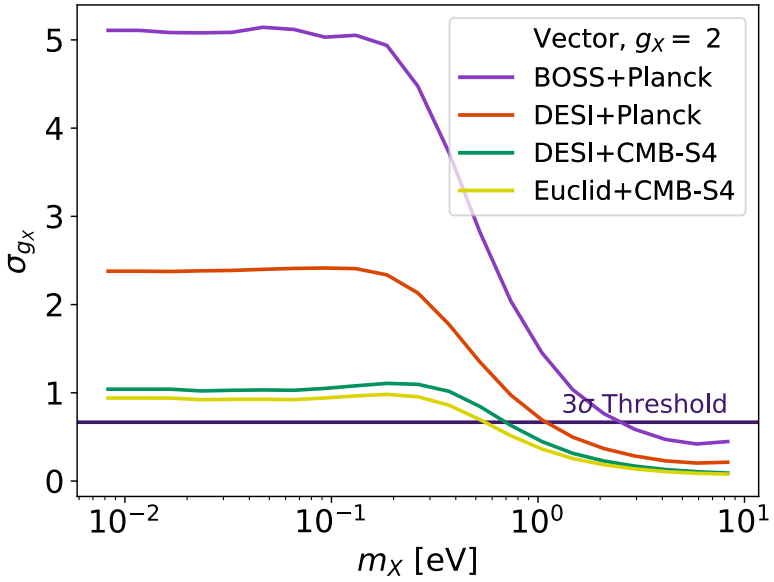


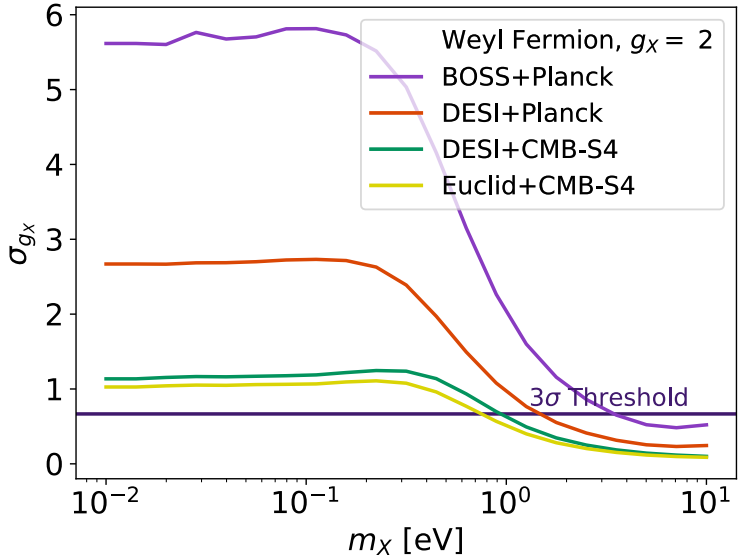


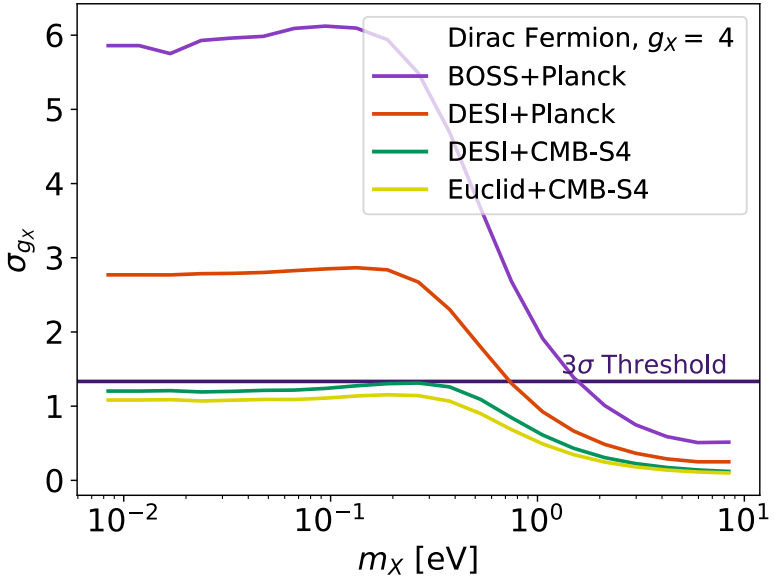
Finding eV-scale Light Relics with Cosmological Surveys
DePorzio, Xu, Muñoz, Dvorkin (2006.09380)

Results

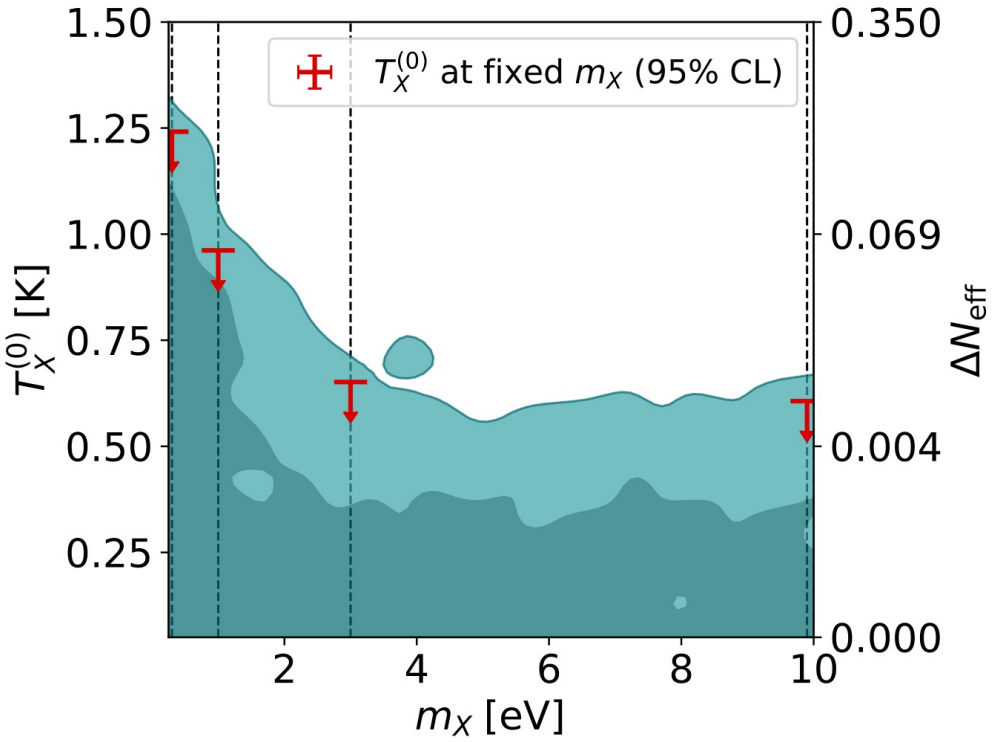

Scalar, $g_X = 1$
BOSS+Planck
DESI+Planck
DESI+CMB-S4
Euclid+CMB-S4
3σ Threshold
σ_{g_X}
m_X [eV]

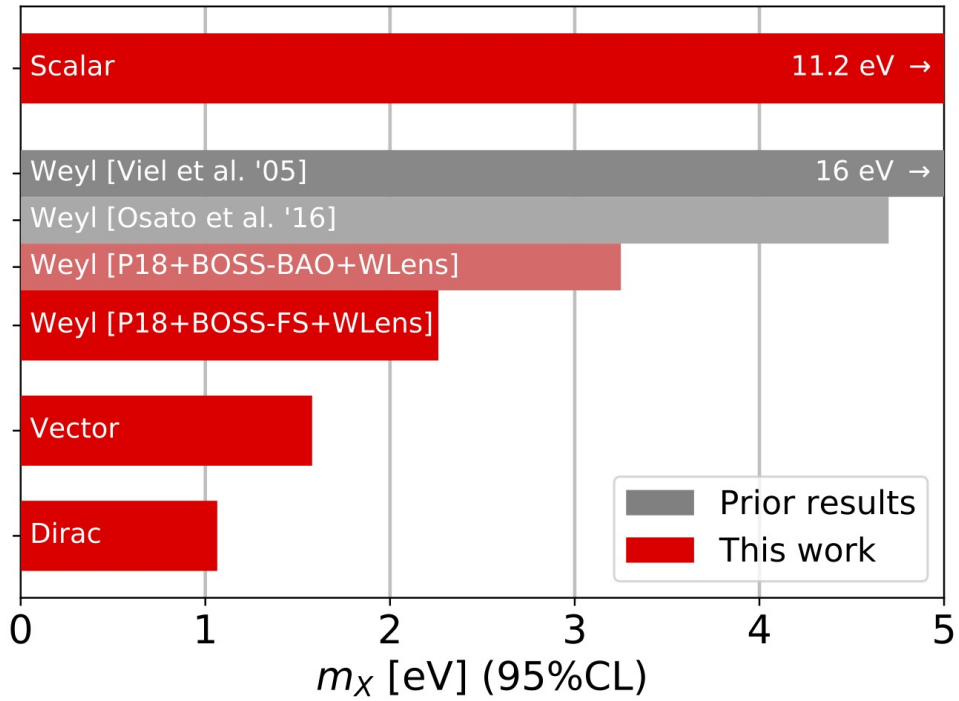

Vector, $g_X = 2$
BOSS+Planck
DESI+Planck
DESI+CMB-S4
Euclid+CMB-S4
3σ Threshold
σ_{g_X}
m_X [eV]


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]

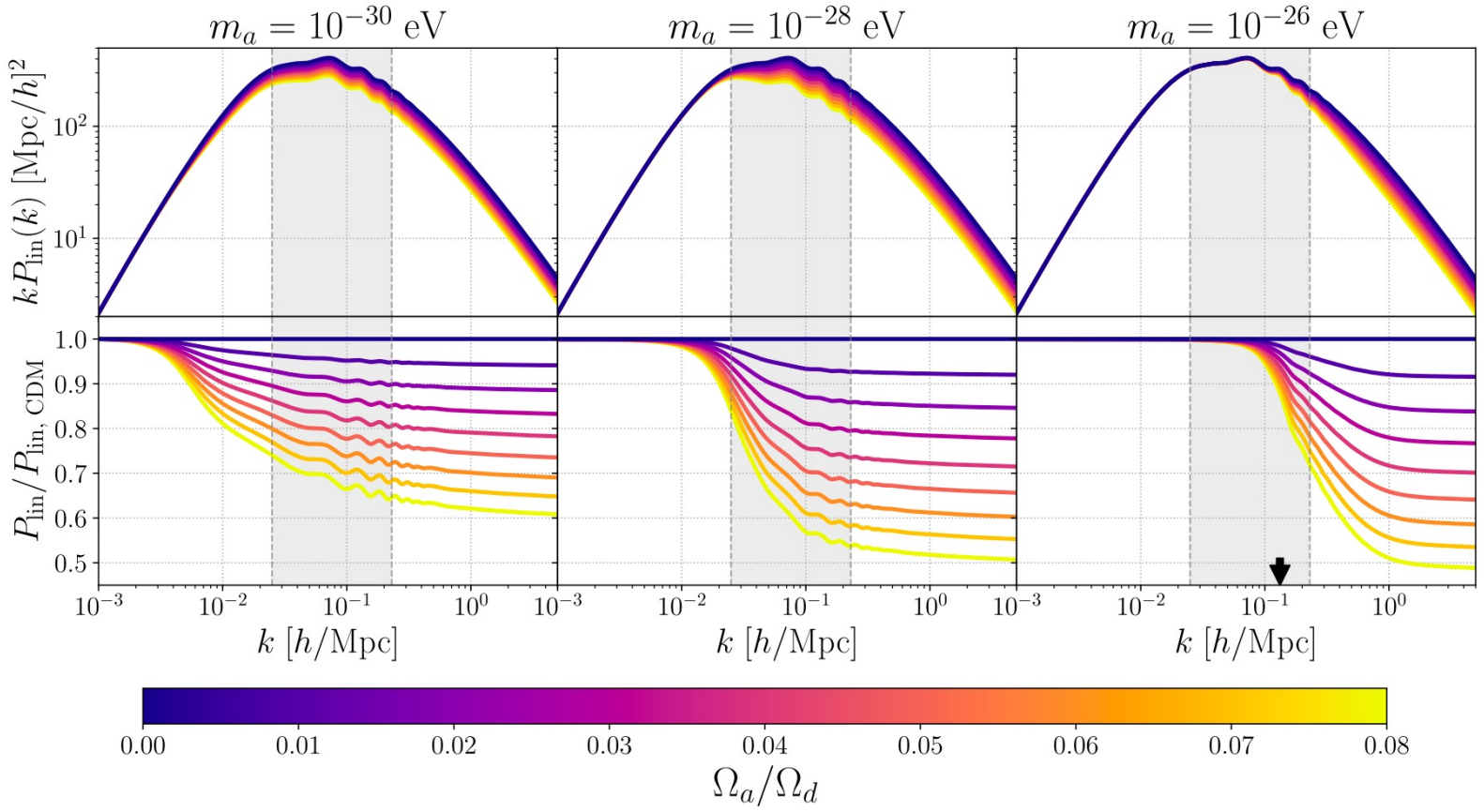
Real Data Constraints





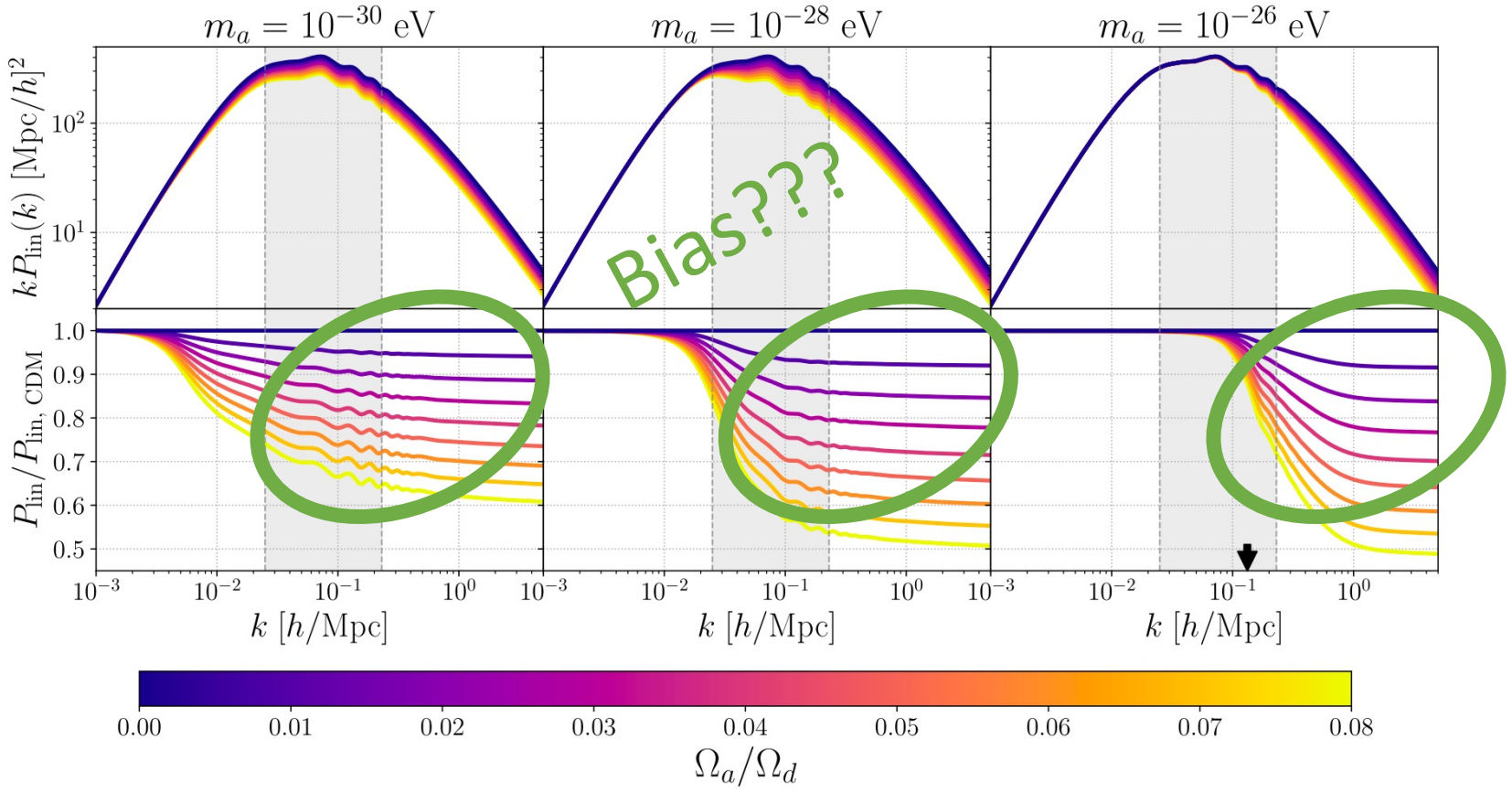
Planck 2018 CMB Data + BOSS Full Shape + CFHT Lensing Datasets
Xu, Muñoz, Dvorkin 2107.09664

Outlook: Ultralight Axions



Credit: Laguë+ 2021

Outlook: Ultralight Axions



Credit: Laguë+ 2021

Conclusions

1. LiMR effects cosmology through:
   - Relativistic suppression to P_m
   - Relativistic contribution to N_{eff}
   - Growth induced scale dependent modification to the galaxy bias

2. Neglecting GISDB will bias cosmological and neutrino parameters

3. Upcoming surveys can constrain large (sometimes all) interesting parameter space of LiMRs (ultralight axions?)

Thank you!

Nick DePorzio

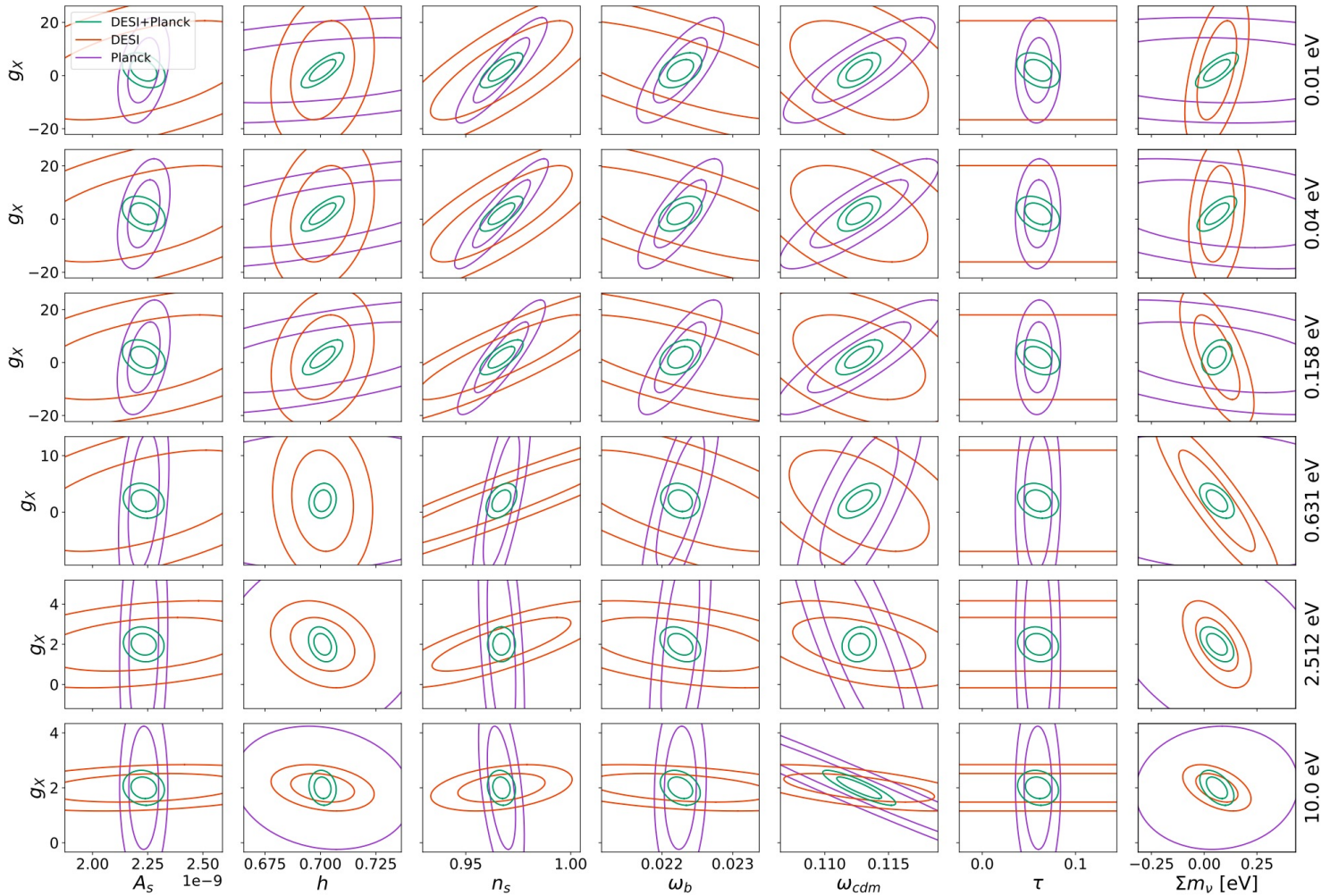
NicholasDePorzio@g.harvard.edu

arXiv: 2006.09380
arXiv: 2006.09395

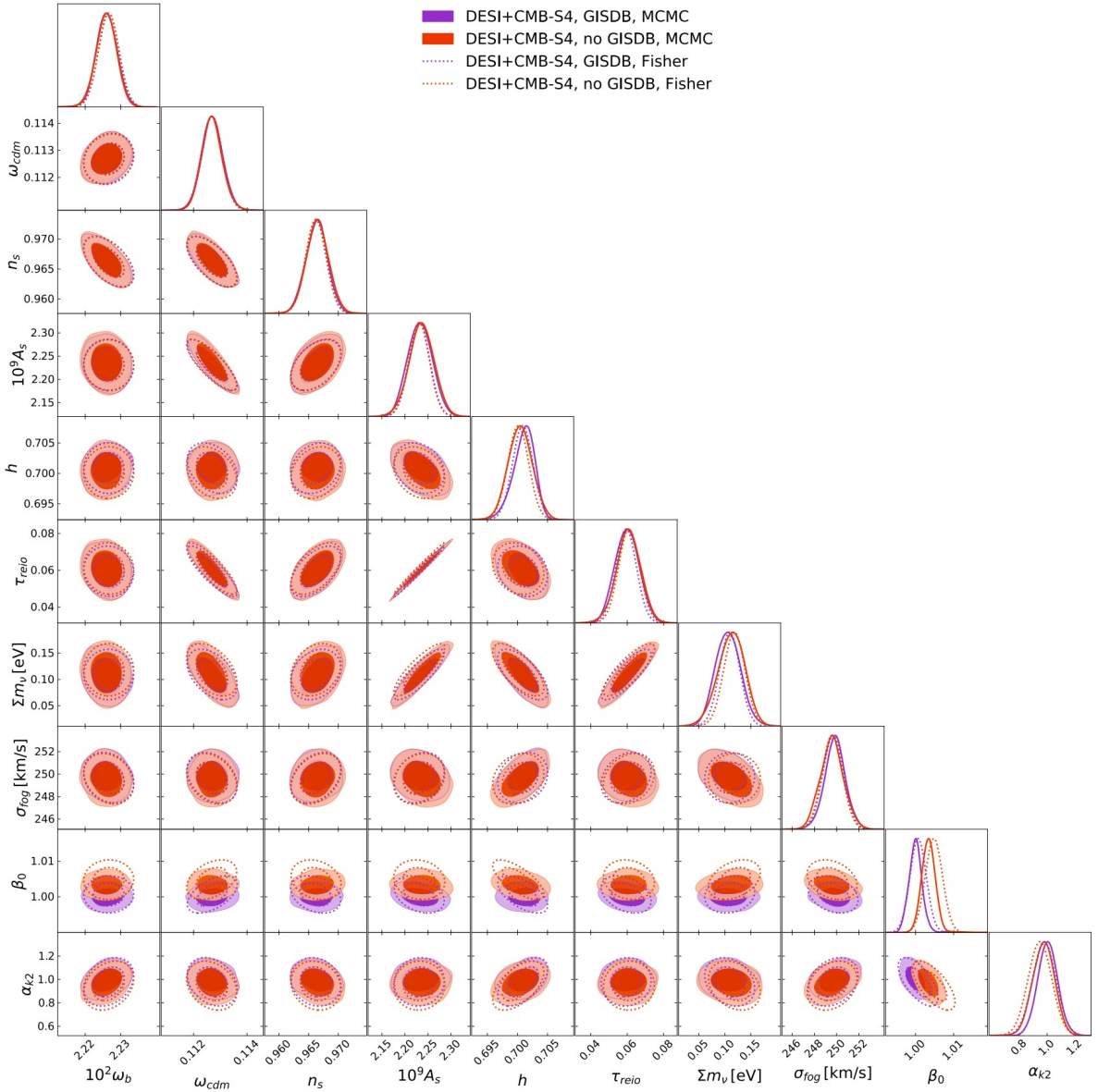
RelicFast: github.com/JulianBMunoz/RelicFast
RelicCLASS: github.com/wlxu/RelicClass

HARVARD UNIVERSITY

Backup: Degeneracy Breaking



Backup:
Fisher Validation



Backup:
Full Posteriors