Cosmological Measurements of Neutrinos and Other Massive Light Relics

New England Theoretical Cosmology, Gravity and Fields Workshop

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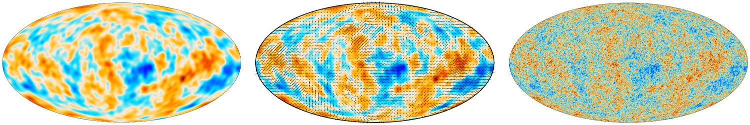
[2006.09395] & [2006.09380]

Harvard University

Introduction



[ESA, Planck Collaboration]

- In the precision era of cosmology
- Lots of data, what questions can be answered?
- Can we answer these questions accurately?

Oppurtunities to find or constrain new physics, e.g. light relics!

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Particles that were in thermal contact with SM at early universe, were relativistic at decoupling, but behaves like matter today.

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- Neutrinos
  - Last piece of the SM
  - Massive, but unresolved
- Not Neutrinos

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  - New particles!
  - Ubiquitous in SM extensions

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- Not Neutrinos (LiMRs)
  - New particles!
  - Ubiquitous in SM extensions

Light Relics & Cosmology

Light relics are important for cosmology:

- Unique imprints on growth of structure
- Degeneracy with other parameters

Cosmology is important for light relics:

- Cosmologically abundant
- Doesn't require present-day interactions

Outline

- Introduction
- Signatures of massive light relics
  - Imprint on the power spectrum
  - Imprint on the bias
- How accurately can we measure light relics?
  - Implement new detailed effects
- How precisely can we measure light relics?
  - Forecast constraints from future experiments

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Massive Light Relics: the Basics

A relic X is characterized by its

- Mass m_X
- (present-day) Temperature $T_X^{(0)}$
- Thermalized* dofs g_X (bosonic or fermionic)

*Higher-spin particles have effective $g_X = 2$

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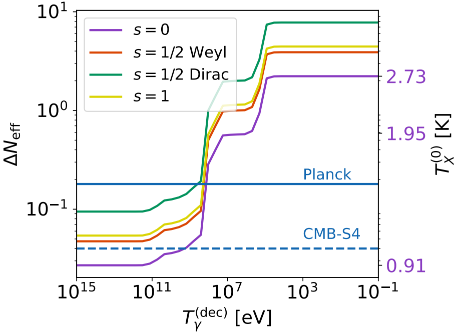
$$m_\nu = ? \quad T_\nu^{(0)} = 1.95 \text{ K} \quad g_\nu = 2$$

Massive Light Relics: the Basics

Relic X is characterized by $\{m_X, T_X^{(0)}, g_X\}$

- $\{T_X, g_X\} \rightarrow \Delta N_{\rm eff}$ (while relativistic), epoch of decoupling

$$\Delta N_{\rm eff} \propto g_X (T_X^0)^4 \qquad g_{*S}^{(dec)} \propto (T_X^0)^{-3}$$



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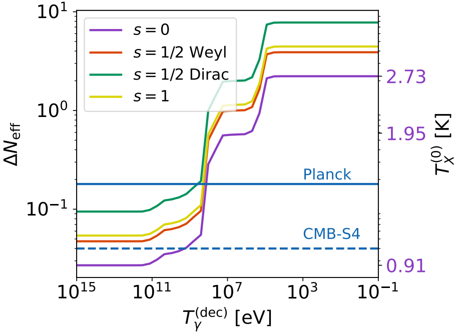
Minimal extensions $\implies T_X^0 \geq 0.91$ K.

Planck $\Delta N_{\rm eff} \leq 0.36$ (95% CL) $\implies T_X^0 \leq 1.5$ K for X Weyl



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- $\{m_X, T_X\} \to$ Free-streaming scale, non-relativistic epoch

$$k_{fs,X}, z_{nr,X} \propto m_X / T_X^{(0)}$$

Non-relativistic today $\Longrightarrow$ $m_X \gtrsim 0.1$ meV

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- $\{m_X, T_X, g_X\} \to$ Present-day abundance

$$\omega_X \propto g_X m_X (T_X^{(0)})^3$$

Overclosure $\omega_X < \omega_{cdm} \implies m_X < 100$ eV for X Weyl

Imprint on Large-scale Structure

Galaxies are biased tracers of matter

$$P_g \propto b P_m(k,z) \qquad \delta_m = \delta_{cb} + \delta_\nu + \delta_X$$

Stuff that clusters $\leftrightarrow$ Stuff that expands

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Neutrinos & LiMRs

Imprint on Large-scale Structure

Galaxies are biased tracers of clustering matter

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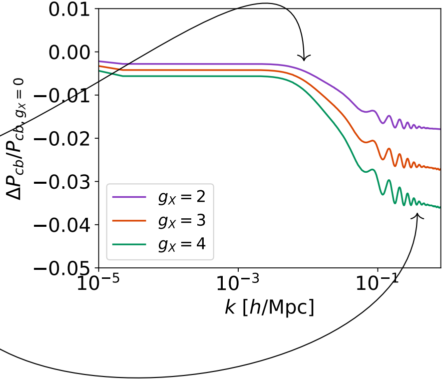
Imprint on Large-scale Structure

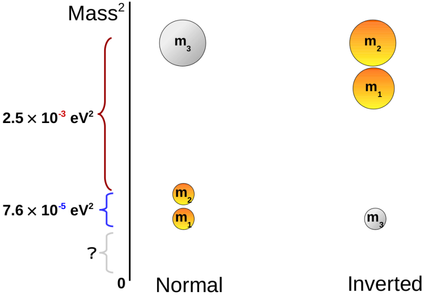
- Structure suppressed at small scales
- Scale set by $k_{fs,X}$
- Amplitude set by ω_X/ω_m



Detail 1: Hierarchical Neutrinos

Neutrinos live in a hierarchy

$$\sum g_\nu = 6, \quad T_\nu^{(0)} = 1.95\text{ K}, \quad \sum m_\nu \geq \begin{cases} 60\text{ meV} & \text{Normal} \\ 100\text{ meV} & \text{Inverted} \end{cases}$$



[Super-Kamiokande]

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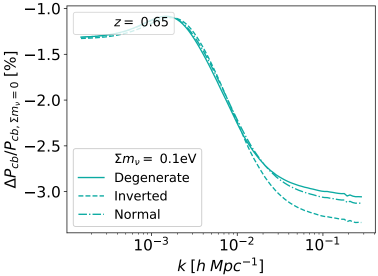
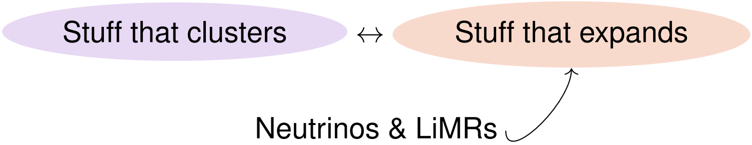
- Heavier ν, more suppression
- Can distinguish in data?
- Will bias results?



Detail 2: Imprint on the halo bias



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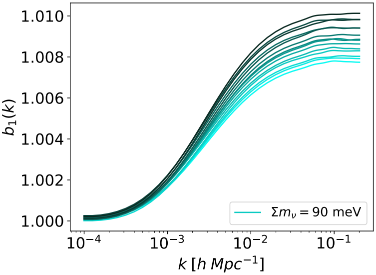
Neutrinos & LiMRs

- Growth-Induced Scale Dependent Bias (GISDB)
- Effect on cosmo results?



[RelicCLASS: github.com/wlxu/RelicClass]

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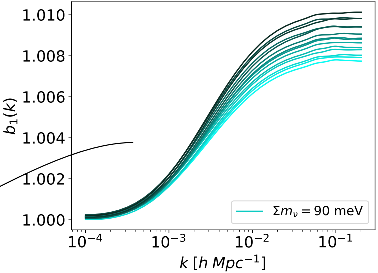

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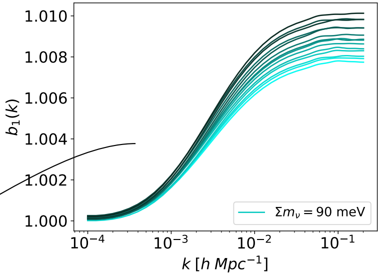

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LSS Data and Parametrization

- Single Tracers:
  - BOSS
    $\mathcal{O}(100)/\Delta z/$deg^2 LRGs
  - DESI
    $\mathcal{O}(1000)/\Delta z/$deg^2 ELGs
  - Euclid
    $\mathcal{O}(5000)/\Delta z/$deg^2 H$\alpha$s

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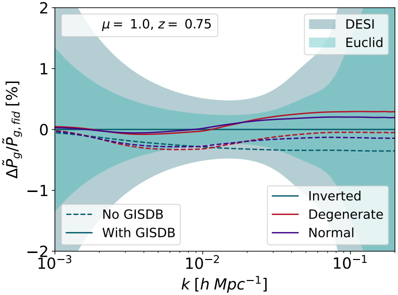

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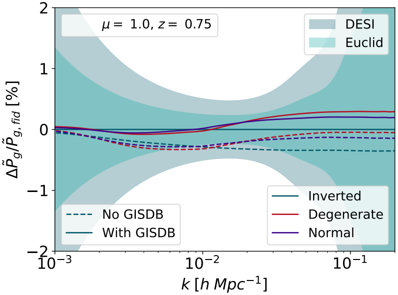
- Follow parametrization of Science Books

$$b_L^{\mathrm{DESI}}(k,z) = \beta_0/D(z) - 1$$
$$b_L^{\mathrm{Euclid}}(k,z) = \beta_0(1+z)^{\beta_1/2} - 1$$



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  - Implement hierarchical neutrinos
  - Account for GISDB
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  - LiMRs

Neutrinos: Set-up

- Markov Chain Monte Carlo
- $\{\omega_b, \omega_{cdm}, h, n_s, A_s, \tau\} + \sum m_\nu$
- CMB-S4 $+\tau$
- DESI ELGs, Euclid Hαs (mock data)

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Neutrinos: Results

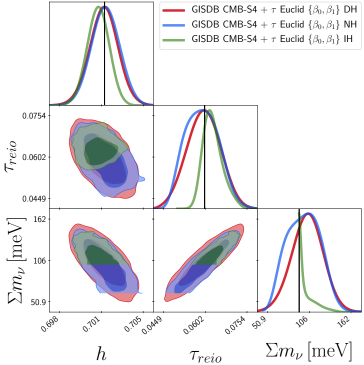
- At least 3σ detection of $\sum m_\nu$, 5σ if IH
- At most 2σ hierarchy differentiation

LSS	CMB	$\sum m_\nu$ [meV]
Euclid	CMB-S4 + τ	103.6 ± 20.1
	CMB-S4	102.9 ± 27.5
DESI	CMB-S4 + τ	107.6 ± 26.7

[All entries assume Deg. hierarchy, include GISDB]

Neutrinos: Results

Data	Model	$-2\Delta \log \mathcal{L}$	$\sum m_\nu$ [meV]	τ
Euclid+ CMB-S4+ τ	Deg.	1.3	103.6 $\pm$ 20.1	5.85e-2 $\pm$ 5.96e-3
	Inv.	0.0	$113.0^{+9.06}_{-0.72}$	6.30e-02 $\pm$ 3.34e-03
	Nor.	0.9	98.90 $\pm$ 21.3	5.89e-2 $\pm$ 6.18e-3



[All entries include GISDB]

- $\Delta\chi^2 = 1$ preference for hierarchy
- No significant shift in parameters

Neutrinos: Results

Data	Model		Mean and error		
	Bias	GISDB	$\sum m_\nu$ [meV]	β_0	β_1
Euclid + CMB-S4 + τ	$\{\beta_0, \beta_1\}$	Yes	103.6 $\pm$ 20.1	1.702 $\pm$ 2.97e-3	1.005 $\pm$ 3.08e-3
		No	104.2 $\pm$ 21.9	1.704 $\pm$ 3.14e-3	1.003 $\pm$ 3.24e-3

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	$\{\beta_0\}$	Yes	102.8 $\pm$ 16.5	1.699 $\pm$ 2.71e-3	-
		No	114.5 $\pm$ 15.6	1.707$\pm$ 2.59e-3	-

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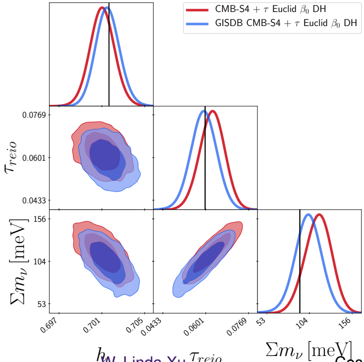

- Include GISDB if want accurate biases
- Marginalize over z-dependence to avoid shift in cosmo parameters

LiMRs: Set-up

- Fisher Forecasts
- $\{\omega_b, \omega_{cdm}, h, n_s, A_s, \tau, \sum m_\nu\}$ $+ g_X$, fixed $\{m_X, T_X^{(0)}\}$
- {Scalar, Weyl, Vector, Dirac}
- 10 meV $\leq m_X \leq 10$ eV, 0.91 K $\leq T_X^{(0)} \leq 1.5$ K

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- 10 meV $\leq m_X \leq 10$ eV, 0.91 K $\leq T_X^{(0)} \leq 1.5$ K
- Planck, CMB-S4 $+\tau$
- BOSS LRGs, DESI ELGs, Euclid Hαs

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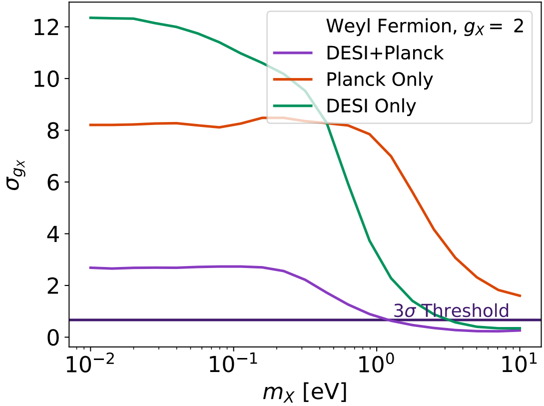

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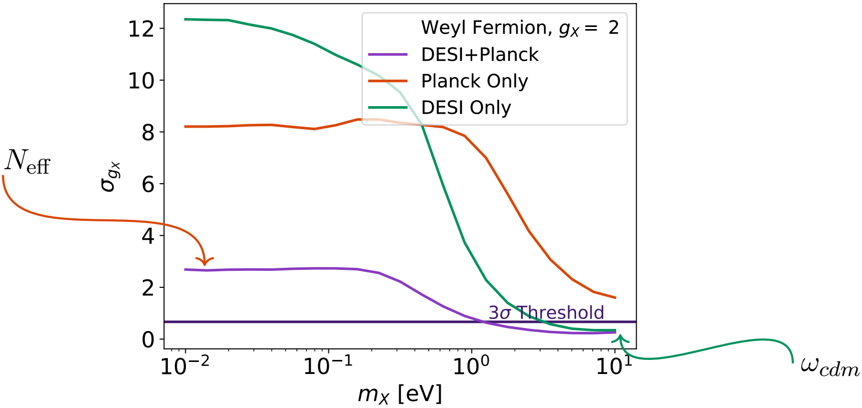

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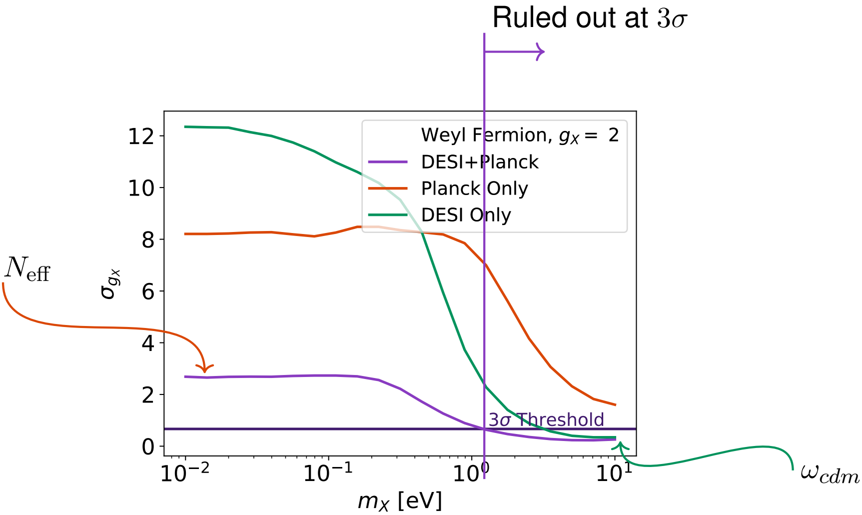
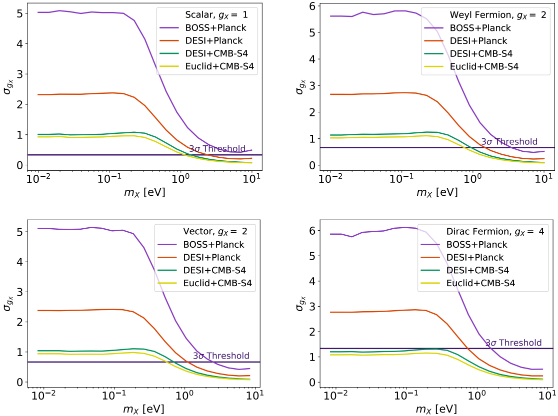


[Minimal temperature $T_X = 0.91$ K]

LiMRs: Results

Data		3σ limits on m_X [eV]			
LSS	CMB	Scalar	Weyl	Vector	Dirac
BOSS	Planck	-	2.85	2.05	1.30
DESI	Planck	1.96	1.20	0.90	1.61
Euclid	CMB-S4	0.93	0.63	0.47	All



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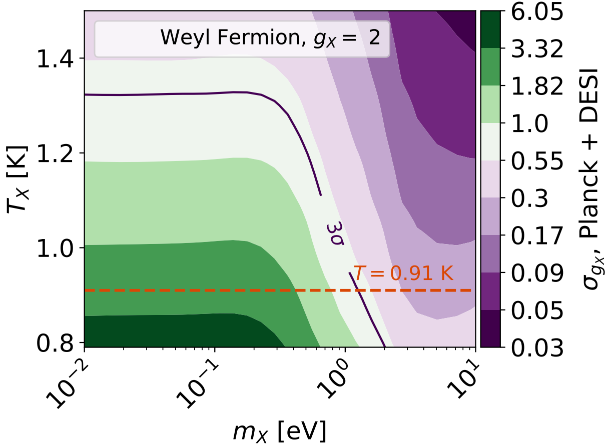

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  - Significant measurements of LiMRs can be expected with DESI/Euclid and S4
    - With Euclid + S4, 3σ measurements on Dirac fermions of any mass, and any particle with eV-scale masses.
    - Currently available BOSS + Planck can constrain/detect any fermion with $m_X \gtrsim 3$ eV at 3σ.

Thank you!