Cosmological Constraints on Light (but Massive) Relics

UW Institute for Nuclear Theory 2022

W. Linda Xu UC Berkeley/LBNL

with Nick Deporzio, Julian Muñoz, & Cora Dvorkin Harvard

[2006.09395, 2006.09380 & 2107.09664]



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  - Ubiquitous in SM Extensions

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- Not Neutrinos (LiMRs)
  - New particles!
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Light but Massive Relics (LiMRs)

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


LiMRs : but why?

- They could exist

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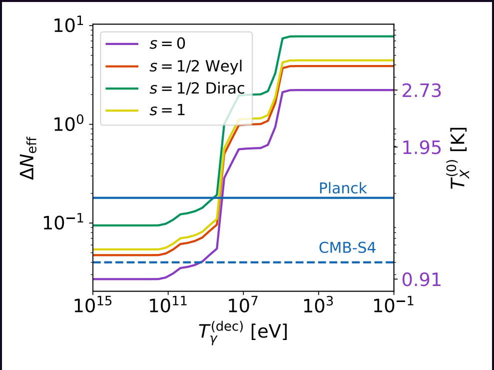
- They could exist
- We could find them

LiMRs : the Light part

$$g_{*S}^{(dec)} \propto (T_X^0)^{-3}$$



[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380]

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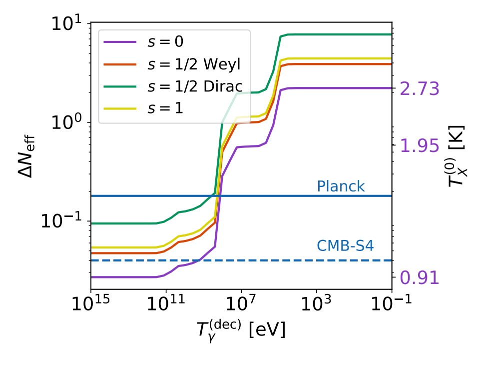
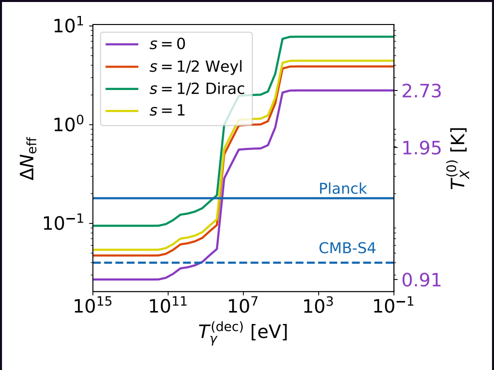


Minimal extensions $\implies T_X^0 \geq 0.91$ K.

[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380]

LiMRs : the Light part

$$\Delta N_{\rm eff} \propto g_X (T_X^0)^4$$



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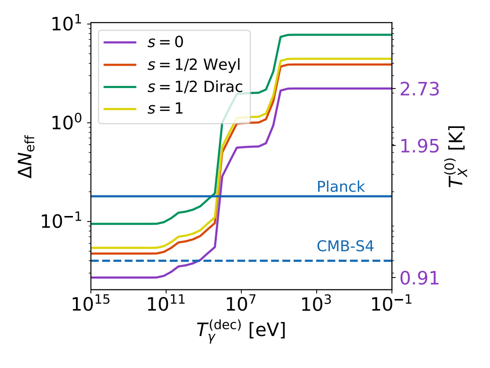


Planck $\Delta N_{\rm eff} \leq 0.36 \implies T^0_{\rm Weyl} \leq 1.5$ K

CMB-S4 $\Delta N_{\rm eff} \leq 0.06 \implies T^0_{\rm Weyl} \leq 0.96$ K

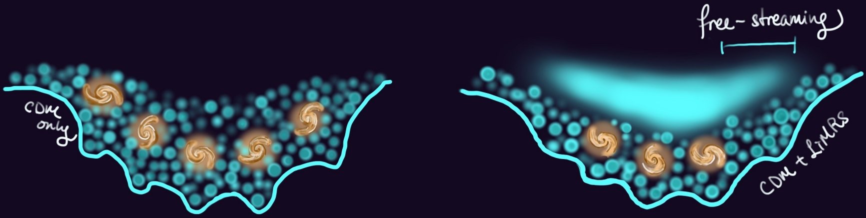
[95% CL]

[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380]

LiMRs : the Massive part

Stuff that clusters ↔ Stuff that expands

Neutrinos & LiMRs



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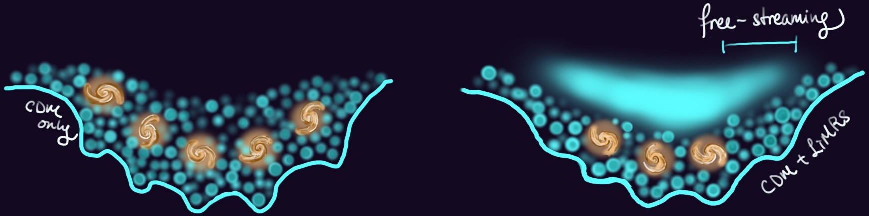

Galaxies are biased tracers

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

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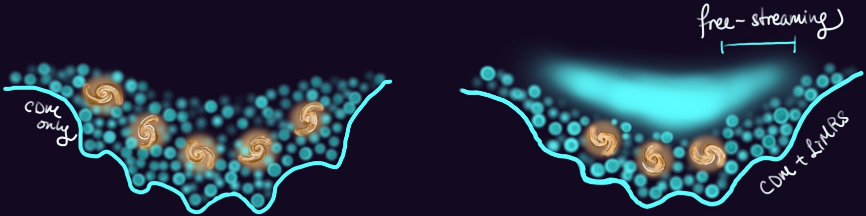
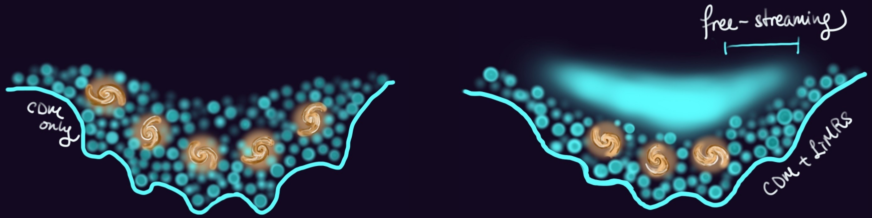


Galaxies are biased tracers of clustering matter

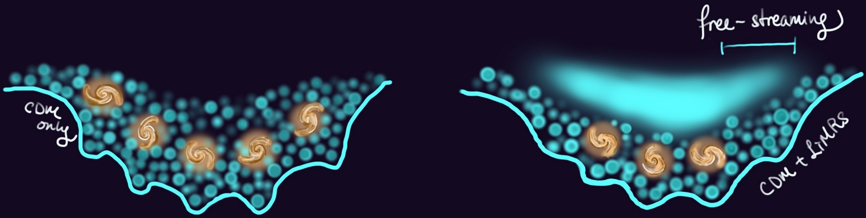
$$P_g \propto b \cancel{P_m} P_{cb}(k, z) \qquad \delta_m = \delta_{cb} + \delta_\nu + \delta_X$$

LiMRs : the Massive part



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

LiMRs : the Massive part



$$\omega_X \propto g_X m_X (T_X^{(0)})^3 \qquad k_{\text{fs},X} \propto \frac{m_X / T_X^{(0)}}{\sqrt{1+z}}$$

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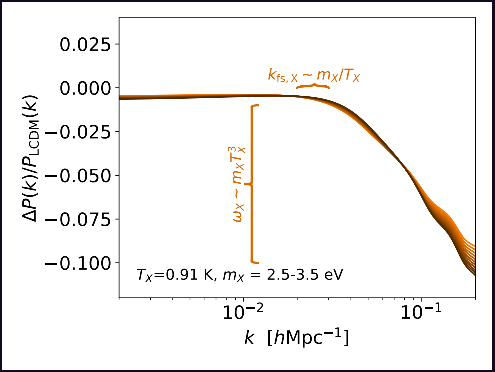
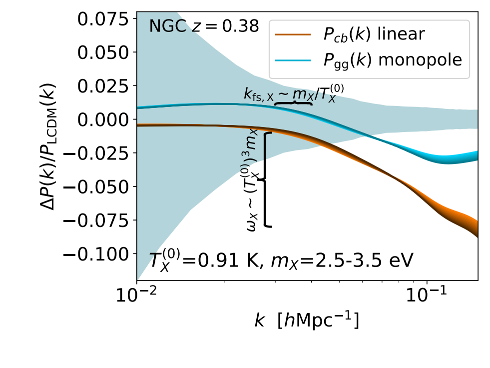


[WLX, Mũnoz, Dvorkin 2107.09664]

LiMRs : the Massive part

$$\delta_g \equiv b_1 \delta_{cb} + b_2 \delta_{cb}^2 + b_{\mathcal{G}_2} \mathcal{G}_2 \qquad \delta_{cb} = (1 - f_\nu - f_X)\delta_m$$



LiMRs : one caveat

$$N_{\rm eff} \propto g_X (T_X^0)^4 \quad k_{fs,X} \propto m_X / T_X^{(0)} \quad \omega_X \propto g_X m_X (T_X^{(0)})^3$$

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$$\omega_X \propto N_{\rm eff} k_{fs,X}$$

$\Longrightarrow$ 1 axis of degeneracy within $\{g_X, m_X, T_X^{(0)}\}$

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$\implies$ 1 axis of degeneracy within $\{g_X, m_X, T_X^{(0)}\}$

Cast to equivalent "neutrinos" $\{m_X, T_X^{(0)}, g_X\} \to \{m_{\text{eq}}, T_{\text{eq}}^{(0)}, 2\}$

$$m_{\text{eq}} = m_X \left(\frac{g_X}{2}\right)^{1/4} c_1^{\gamma/4} c_2^{\gamma} \qquad T_{\text{eq}}^{(0)} = T_X^{(0)} \left(\frac{g_X}{2}\right)^{1/4} c_1^{\gamma/4}$$

$$c_1 = 8/7, \quad c_2 = 7/6, \quad \gamma = \begin{cases} 0 & \text{fermion} \\ 1 & \text{boson} \end{cases}$$

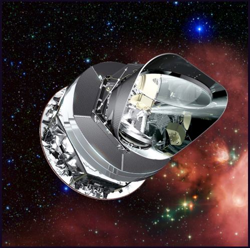
Data/Experiments

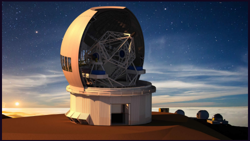
- Markov Chain Monte Carlo

$$\{\omega_b, \omega_{cdm}, h, n_s, A_s, \tau, \sum m_\nu\} + \{m_X, T_X^{(0)}\}$$

- {Scalar, Weyl, Vector, Dirac}

- Planck 2018 TT+TE+EE +Lensing
- CFHTLens
- BOSS DR 12 (CLASS-PT)





[Chudaykin, Ivanov, Philcox, Simonović, 2004.10607]

Results

So, have we found anything?

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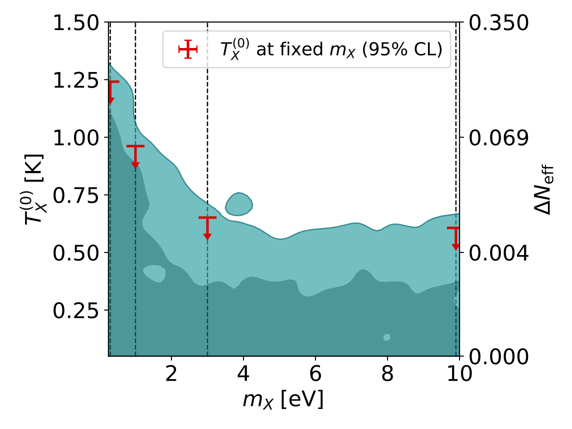
No(t yet), but...

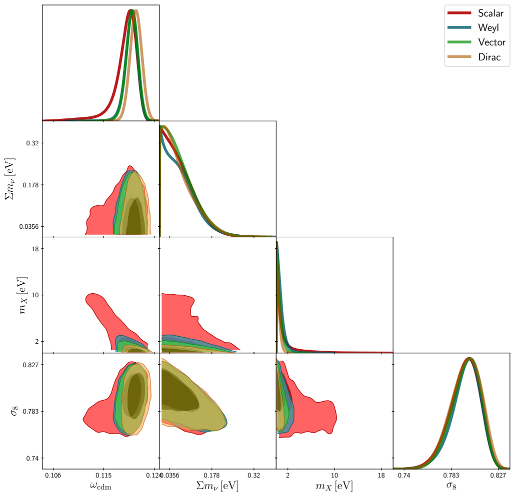


[WLX, Muñoz, Dvorkin 2107.09664]

Results: what we know now

$T_X = 0.91$ K

m_X (95% CL)	
Scalar	11.2 eV
Weyl	2.26 eV
Vector	1.58 eV
Dirac	1.06 eV



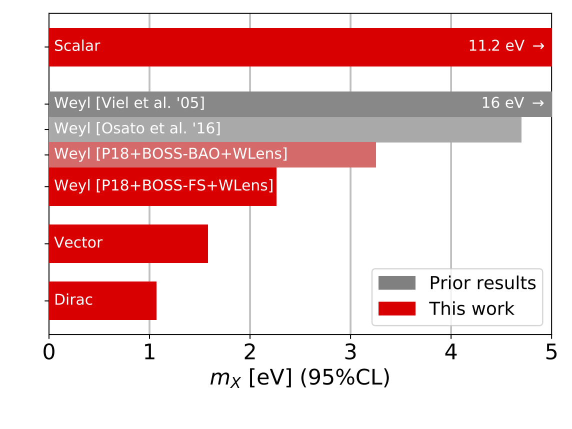
[WLX, Mũnoz, Dvorkin 2107.09664]

Or equivalently...

m_X (95% CL)			
Scalar		Weyl	
0.91 K	11.2 eV	0.79 K	9.55 eV
1.04 K	2.65 eV	0.91 K	2.26 eV
1.08 K	2.23 eV	0.94 K	1.91 eV
1.22 K	1.76 eV	1.08 K	1.50 eV

m_X (95% CL)			
Vector		Dirac	
0.77 K	7.91 eV	0.67 K	6.76 eV
0.88 K	1.87 eV	0.76 K	1.59 eV
0.91 K	1.58 eV	0.79 K	1.34 eV
1.04 K	1.24 eV	0.91 K	1.06 eV

Results: what we know now



[WLX, Mũnoz, Dvorkin 2107.09664]

Results: what we know now & what we can learn from it

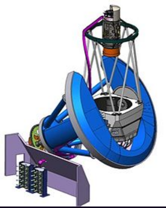
Light gravitinos in gauge-mediated SUSY breaking

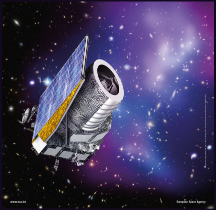
$$m_{3/2} = \frac{\langle F \rangle}{\sqrt{3} M_{pl}}, \quad T_{3/2} \approx 0.95 \text{ K}, \quad g_{3/2,\text{eff}} = 2$$

$$m_{3/2} \leq 1.91 \text{ eV} \implies \sqrt{\langle F \rangle} \leq 63.5 \text{ TeV}$$

Results: where we're going next

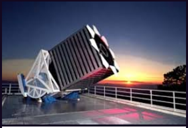
Better data coming soon!

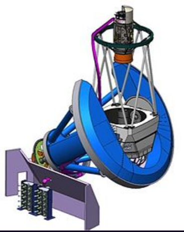


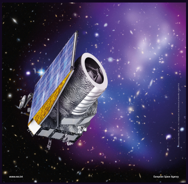


Data/Experiments: Round 2

- Fisher Forecasts

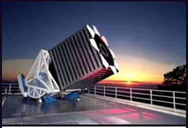


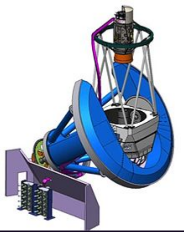


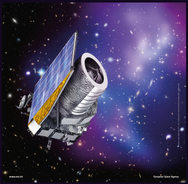


Data/Experiments: Round 2

- Fisher Forecasts
- Planck, CMB-S4 $+\tau$
- LSS Single Tracers:
  - BOSS
    $\mathcal{O}(100)/\Delta z/\text{deg}^2$ LRGs
  - DESI
    $\mathcal{O}(1000)/\Delta z/\text{deg}^2$ ELGs
  - Euclid
    $\mathcal{O}(5000)/\Delta z/\text{deg}^2$ Hαs







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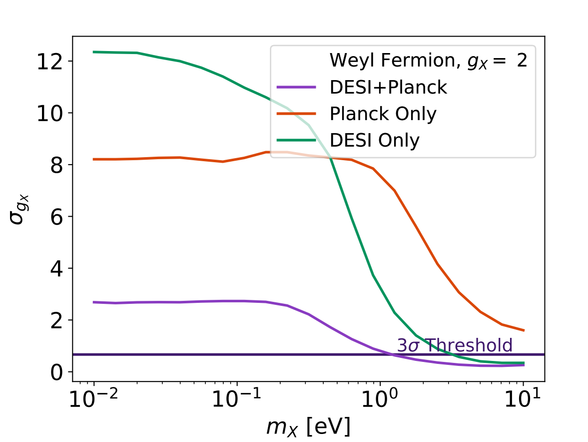

[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380, Minimal temperature $T_X = 0.91$ K]

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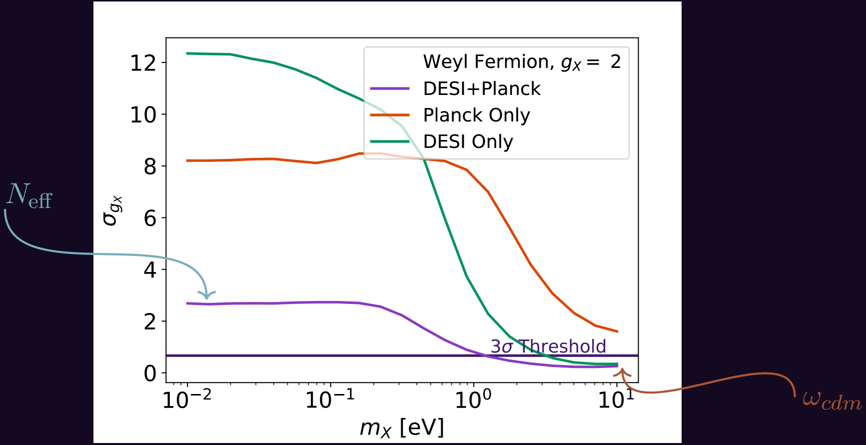

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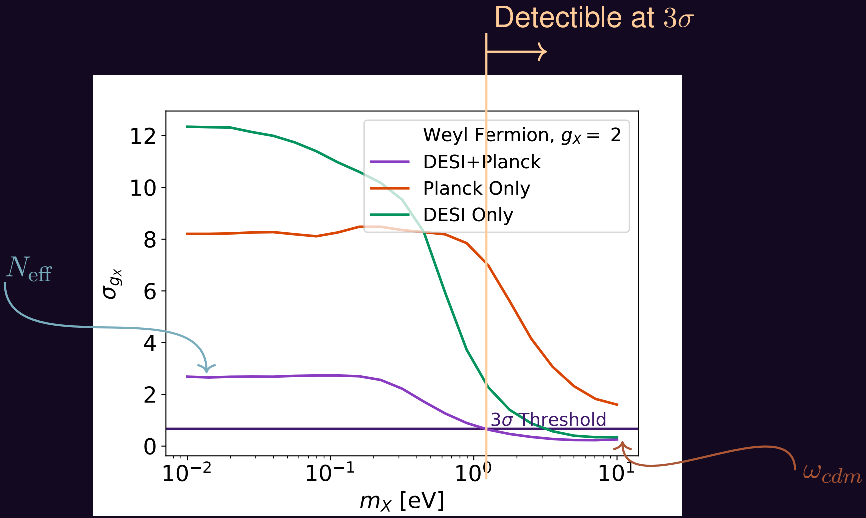

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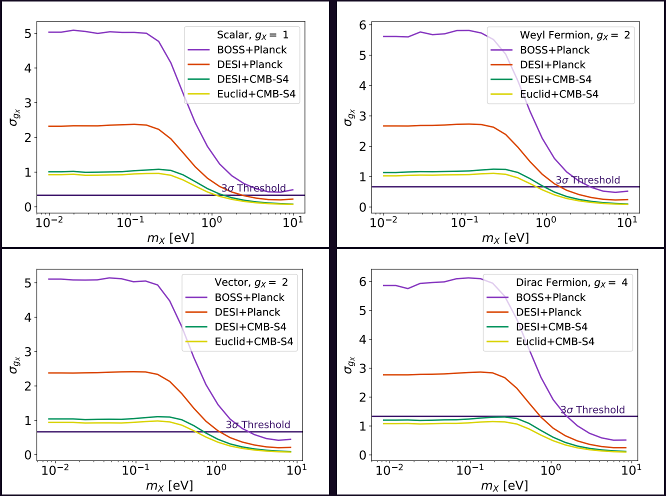
Results: what we can look forward to



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BOSS + Planck	Constraints	Forecast
Scalar	11.2 eV	9.6 eV
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Results: what we can look forward to

$T_X = 0.91$ K

	m_X (**99**% CL)	
	DESI + Planck	DESI + CMB-S4
Scalar	1.96 eV	1.14 eV
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Dirac	0.61 eV	All masses

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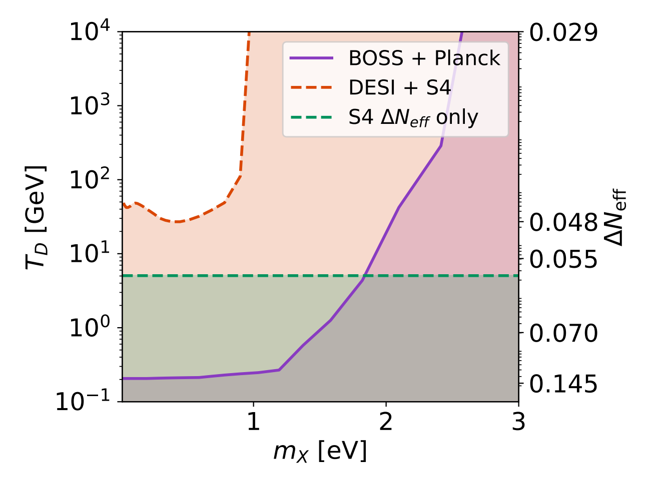
Also: 3σ discovery potential for GMSB gravitinos at
$m_{3/2} \geq 0.77$ eV or $\sqrt{F} \geq 40$ TeV
2σ at *all* masses

Results: what we can look forward to



[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380]

Results
& where we've landed

Dark sectors are worth studying, in whole or in part

- Compelling reasons to care about LiMRs
- If so, cosmological data is uniquely powerful
- The first set of comprehensive constraints
  + better things to come

Results
& where we've landed

Dark sectors are worth studying, in whole or in part

What's next?

- Generalize the framework (+ annihilations, decays...)
- Develop model applications + follow-up plans
  - what are the compelling targets to search for?
  - how do we identify them if we detect something?

Thank you!

[Estella Lin, 2021]