Cosmological Constraints on Light (but Massive) Relics

New Physics from Galaxy Clustering, 2022

W. Linda Xu

UC Berkeley, LBNL

Λ + CDM

(+ SM + GR
+ SFSR Inflation (-like ICs)
+ ...)

Λ + CDM

(mostly) Cold

(mostly) Dark

(mostly) Matter

Λ + CDM $\rightsquigarrow$ Cold (?) Dark (?) Matter

+ Dark Radiation?
+ (Very) Fuzzy DM?
+ millicharge, SIDM / darkly charged ... ?
+ Massive light relics? + ...

Λ + CDM $\rightsquigarrow$ Cold (?) Dark (?) Matter

+ Dark Radiation?
+ (Very) Fuzzy DM?
+ millicharge, SIDM / darkly charged ... ?
+ massive light relics + ...

1. What
2. Why
3. How

1. What
2. Why
3. How

Light (but Massive) Relics

Particles that were thermalized with SM in early universe, were relativistic at decoupling, but potentially non-relativistic today.

Light (but Massive) Relics

Particles that were thermalized with SM in early universe, were relativistic at decoupling, but potentially non-relativistic today.

Two categories:
- Neutrinos
- Not Neutrinos

Light (but Massive) Relics

Particles that were thermalized with SM in early universe, were relativistic at decoupling, but potentially non-relativistic today.

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

Light (but Massive) Relics

Particles that were thermalized with SM in early universe, were relativistic at decoupling, but potentially non-relativistic today.

Two categories:

- Neutrinos
  - Last piece of the SM
  - Massive, but unresolved
- Not Neutrinos
  - New particles!
  - Ubiquitous in SM extensions

Light (but Massive) Relics

Particles that were thermalized with SM in early universe, were relativistic at decoupling, but potentially non-relativistic today.

Two categories:

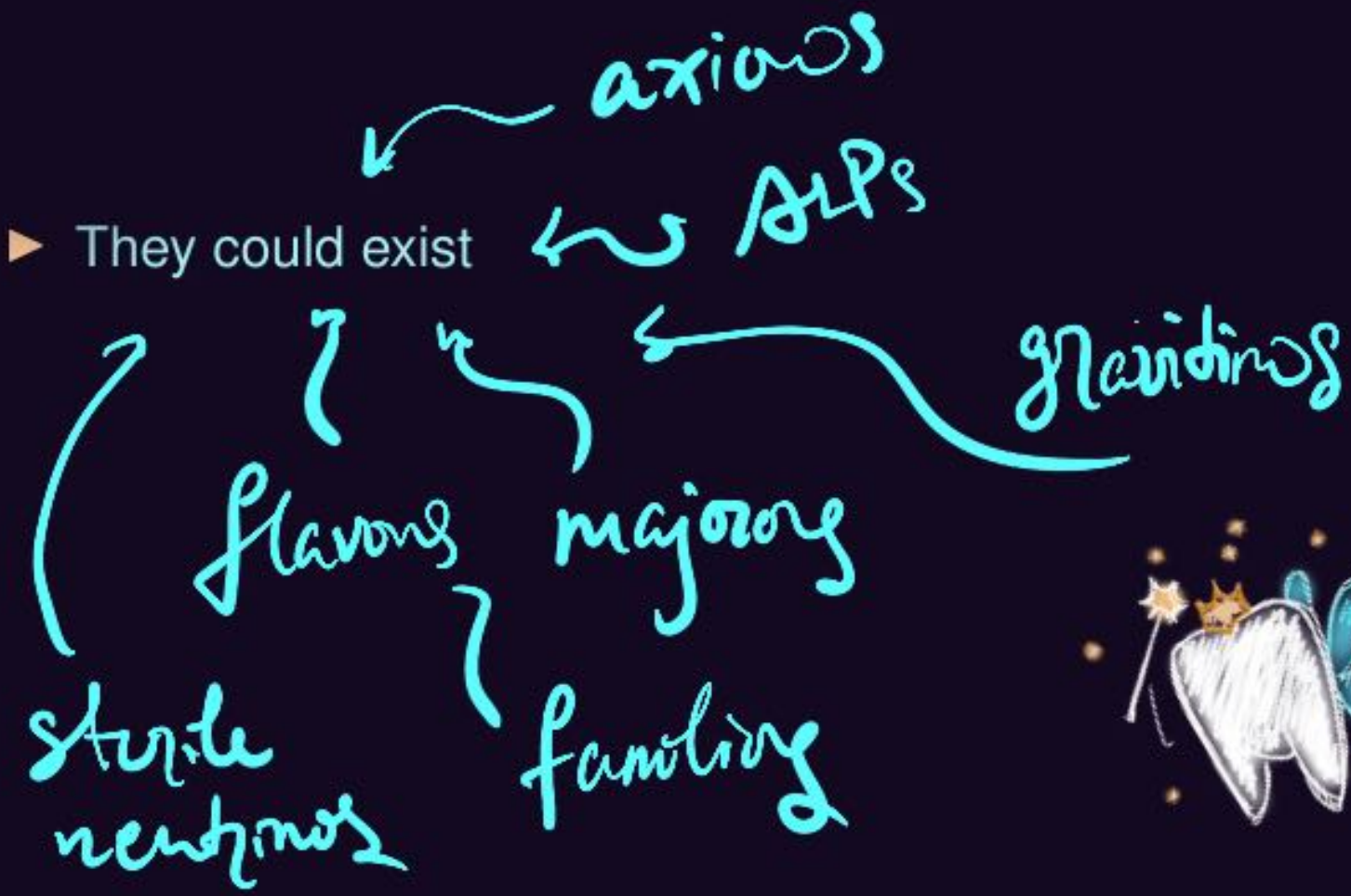
- Neutrinos
  - Last piece of the SM
  - Massive, but unresolved
- Not Neutrinos (LiMRs)
  - New particles!
  - Ubiquitous in SM extensions

Light (but Massive) Relics (LiMRs)

1. What
2. Why
3. How

Why care?

- They could exist

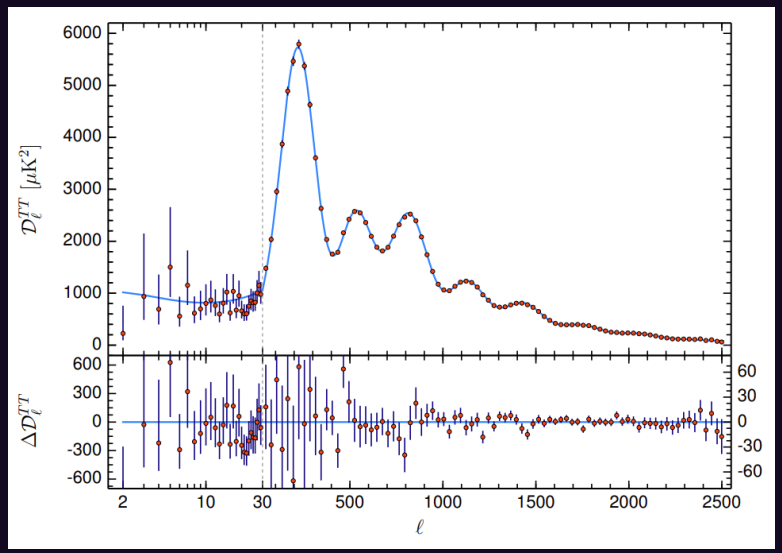


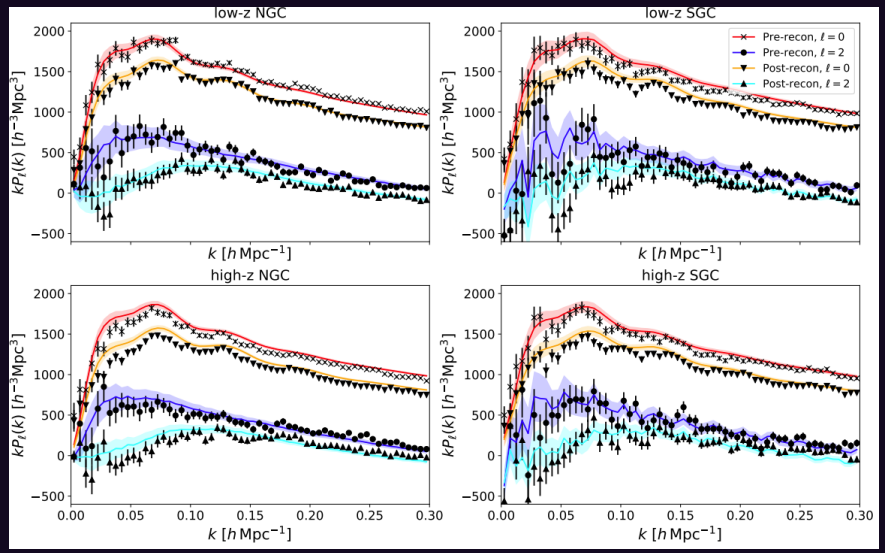
Why care?

- They do exist

Why care?

- They do exist
- We could find them (soon!)





[Planck collaboration 1807.06209; Philcox, Ivanov, Simonović, Zaldarriaga 2002.04035]

[Drinking game: take a shot every time you hear ”precision era of cosmology” in a talk]

Why care?

- They do exist
- We could find them (soon!)
- We might be the only ones who can (for a while)

1. What
2. Why
3. How

To set some intuition

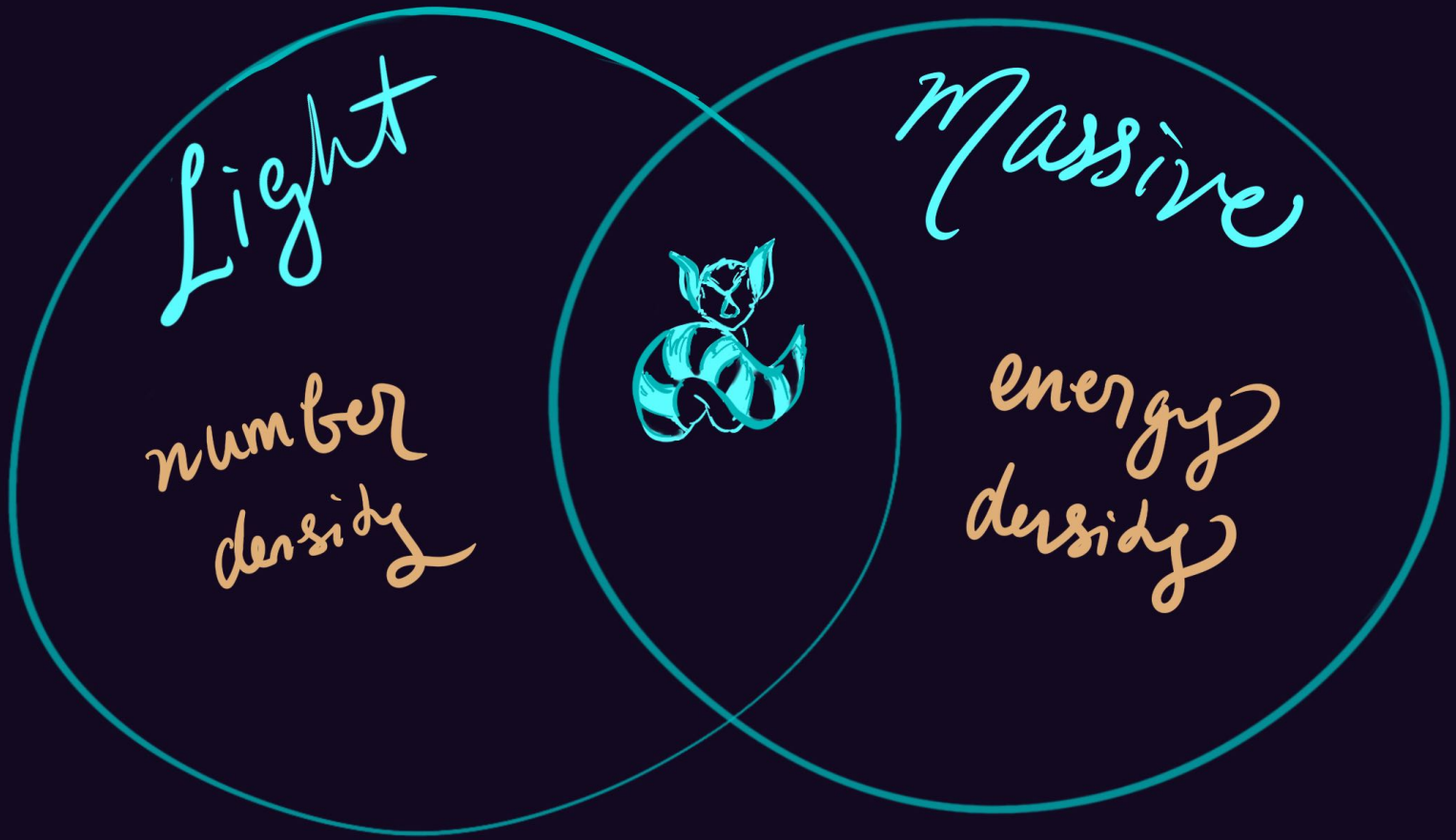
- Mass m_X
- (present-day) Temperature $T_X^{(0)}$
- Thermalized dofs g_X

To set some intuition

- $\lesssim$ eV - scale masses
- $\sim$ 1K temperatures
- % fractions of observed DM abundance
- extremely feeble interactions
- stable, non self-interacting, high reheat temp...

To set some intuition

To set some intuition



The radiation story

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_{LR} \equiv \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

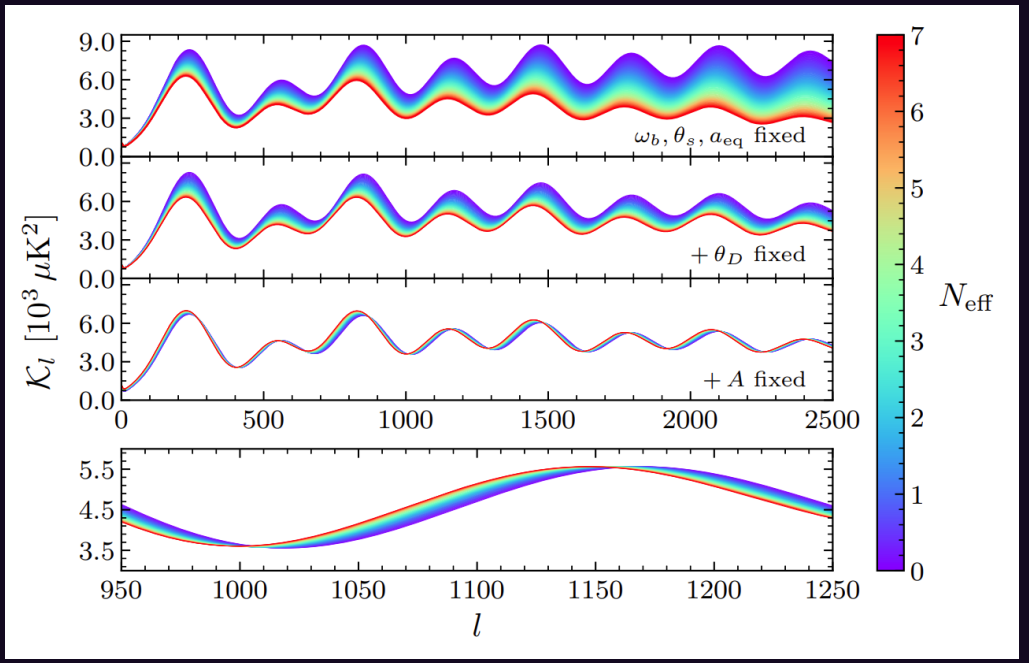
$$\Delta N_{\rm eff} \equiv N_{\rm eff} - 3.044 = \frac{4}{7} g_X \left(\frac{T_X^{(0)}}{T_\nu^{(0)}}\right)^4$$

Adding radiation leads to observable cosmological signatures

The radiation story

LiMRs in the early universe

- Damps small-scale fluctuations
- Shifts scales of acoustic oscillations

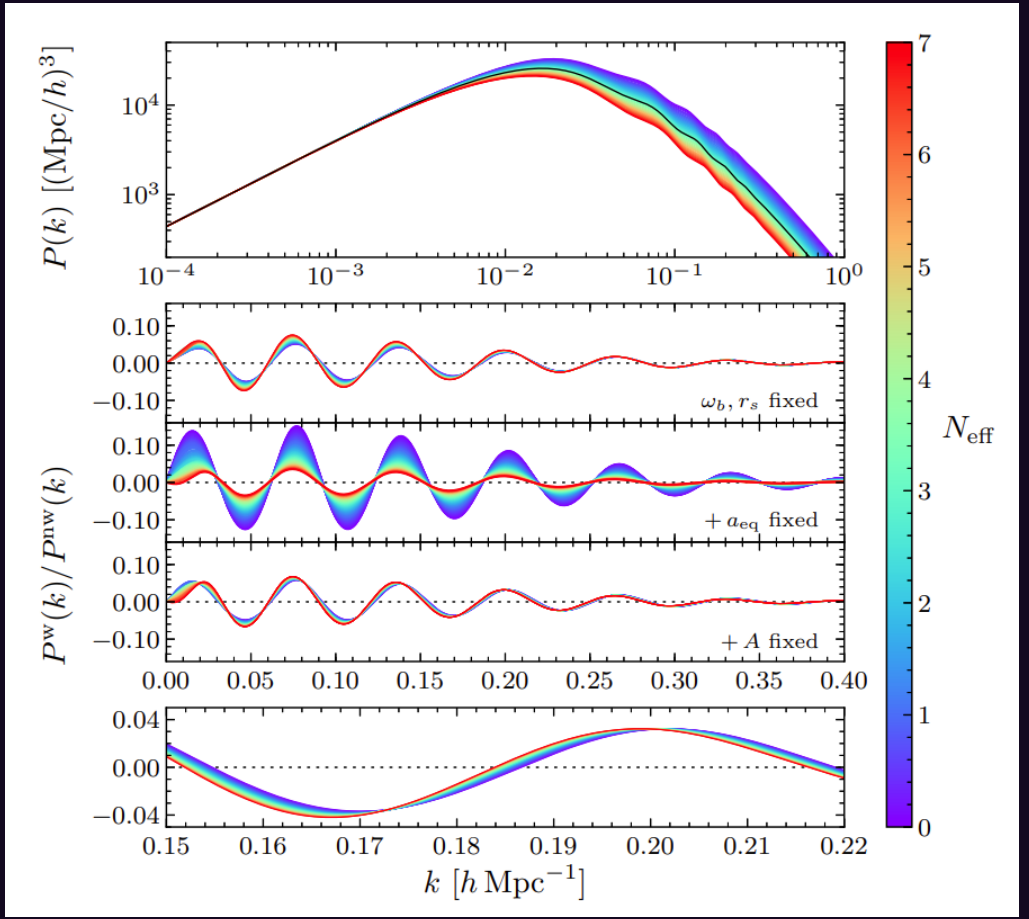


[Baumann, Green & Wallisch, 1712.08067]

The radiation story

LiMRs in the early universe

- Damps small-scale fluctuations
- Shifts scales of acoustic oscillations



[Baumann, Green & Wallisch, 1712.08067]

The radiation story

Planck 18 + BAO	$\Delta N_{\rm eff} \leq 0.28$ [95% CL] $\implies T^0_{\rm Weyl} \leq 1.4$ K
CMB-S4	$\Delta N_{\rm eff} \leq 0.06$ [95% CL] $\implies T^0_{\rm Weyl} \leq 0.96$ K

The radiation story

Planck 18 + BAO $\quad \Delta N_{\rm eff} \leq 0.28$ [95% CL] $\implies T^0_{\rm Weyl} \leq 1.4$ K

CMB-S4 $\quad \Delta N_{\rm eff} \leq 0.06$ [95% CL] $\implies T^0_{\rm Weyl} \leq 0.96$ K

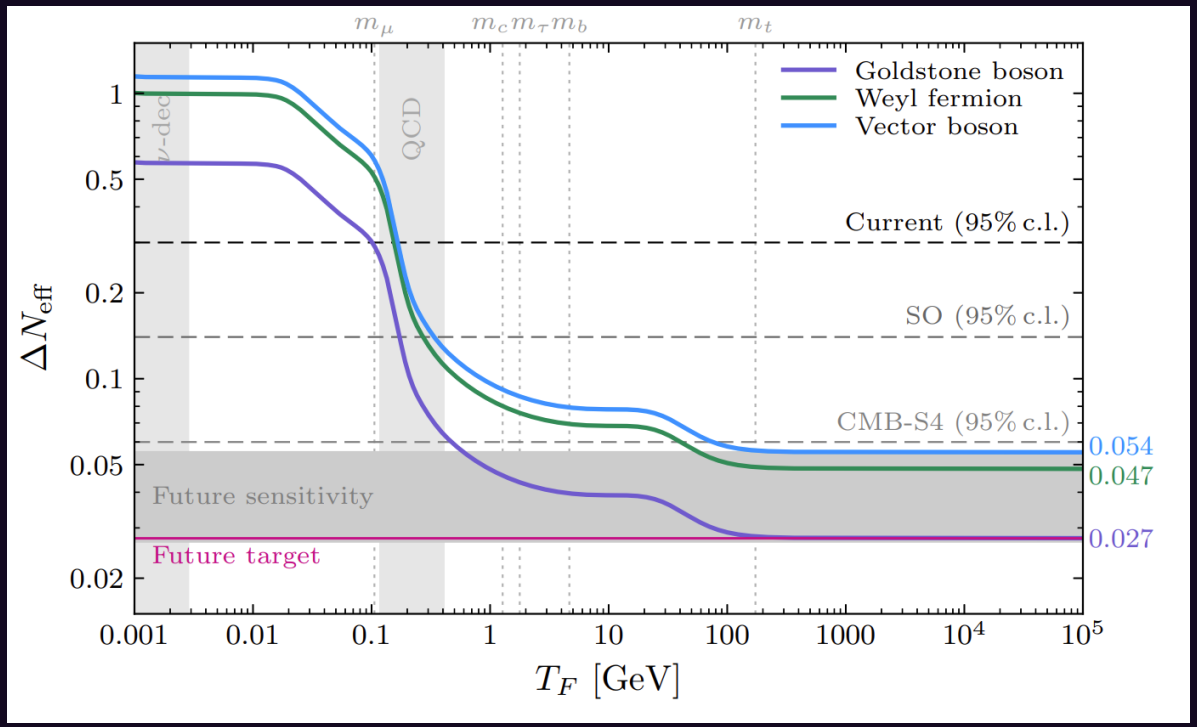
$$\text{Conservation of entropy} \implies T_X^{(0)} = \left(\frac{s^{(0)}}{g_{*S}^{\rm dec}}\right)^{1/3}$$

$$g_{*S}^{\rm SM} \leq 106.75 \implies \text{Minimal SM extensions } T_X^{(0)} \geq 0.91 \text{ K}$$

The radiation story

Planck 18 + BAO $\quad \Delta N_{\rm eff} \leq 0.28 \implies T^{\rm dec}_{\rm Weyl} \lesssim 100$ MeV

CMB-S4 $\quad \Delta N_{\rm eff} \leq 0.06 \implies T^{\rm dec}_{\rm Weyl} \lesssim 100$ GeV (!!)



[Dvorkin, Meyers ... WLX ... et. al; Snowmass study 2203.07943]

The matter story

At $z_{\rm NR} \sim m_X/T_X^{(0)}$, LiMRs transition from radiation to matter ...

$$\rho_X = m_X n_X \qquad \Omega_X h^2 \approx \frac{g_X}{g_\nu} \frac{m_X}{93.14\ \text{eV}} \left(\frac{T_X^{(0)}}{1.95\ \text{K}} \right)^3$$

... but still have significant thermal velocity

The matter story

Significant $v_{\rm th} \implies$ free-streaming at a characteristic scale

$$k_{\rm fs}(z) \sim \frac{H(z)}{v_{\rm th}(z)} = \sqrt{\frac{4\pi G\rho(z)}{v_{\rm th}^2(z)(1+z)^2}}$$

$$\approx \frac{0.1h\ \text{Mpc}^{-1}}{\sqrt{1+z}} \Omega_m^{1/2} \left(\frac{m_X}{0.1\ \text{eV}}\right) \left(\frac{T_X^{(0)}}{1.95\ \text{K}}\right)^{-1} \quad \text{[matter dom]}$$

The matter story

Significant $v_{\rm th} \implies$ free-streaming at a characteristic scale

$$k_{\rm fs}(z) \sim \frac{H(z)}{v_{\rm th}(z)} = \sqrt{\frac{4\pi G\rho(z)}{v_{\rm th}^2(z)(1+z)^2}}$$

$$\approx \frac{0.1h\ \text{Mpc}^{-1}}{\sqrt{1+z}} \Omega_m^{1/2} \left(\frac{m_X}{0.1\ \text{eV}}\right) \left(\frac{T_X^{(0)}}{1.95\ \text{K}}\right)^{-1} \quad \text{[matter dom]}$$

There is a minimum free-streaming mode, $k_{\rm fs}\,(\min[z_{\rm NR}, z_{eq}])$

$$k_{\rm fs}(z) \lesssim \begin{cases} 10^{-3}h\ \text{Mpc}^{-1} \left(\frac{m_X}{0.1\ \text{eV}}\right) \left(\frac{T_X^{(0)}}{1.95\ \text{K}}\right)^{-1} & z_{\rm NR} > z_{eq} \\ 3\times 10^{-3}h\ \text{Mpc}^{-1} \left(\frac{m_X}{0.1\ \text{eV}}\right)^{1/2} \left(\frac{T_X^{(0)}}{1.95\ \text{K}}\right)^{-1/2} & z_{\rm NR} < z_{eq} \end{cases}$$

The matter story

Significant $v_{\rm th} \implies$ free-streaming at a characteristic scale

$$k_{\rm fs}(z) \sim \frac{H(z)}{v_{\rm th}(z)} = \sqrt{\frac{4\pi G\rho(z)}{v_{\rm th}^2(z)(1+z)^2}}$$

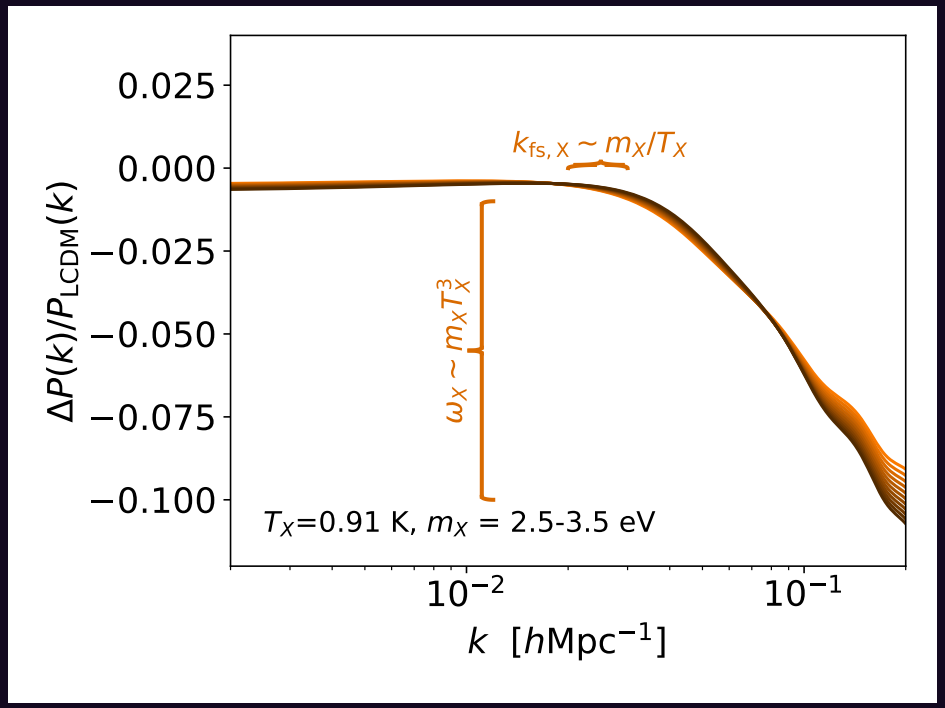
$$\approx \frac{0.1h\ \text{Mpc}^{-1}}{\sqrt{1+z}} \Omega_m^{1/2} \left(\frac{m_X}{0.1\ \text{eV}}\right) \left(\frac{T_X^{(0)}}{1.95\ \text{K}}\right)^{-1} \quad \text{[matter dom]}$$

Adding free-streaming matter leads to observable cosmological signatures

The matter story

LiMRs in the late universe

- free-stream at small scales
- backreact on the metric
- suppress growth of structure

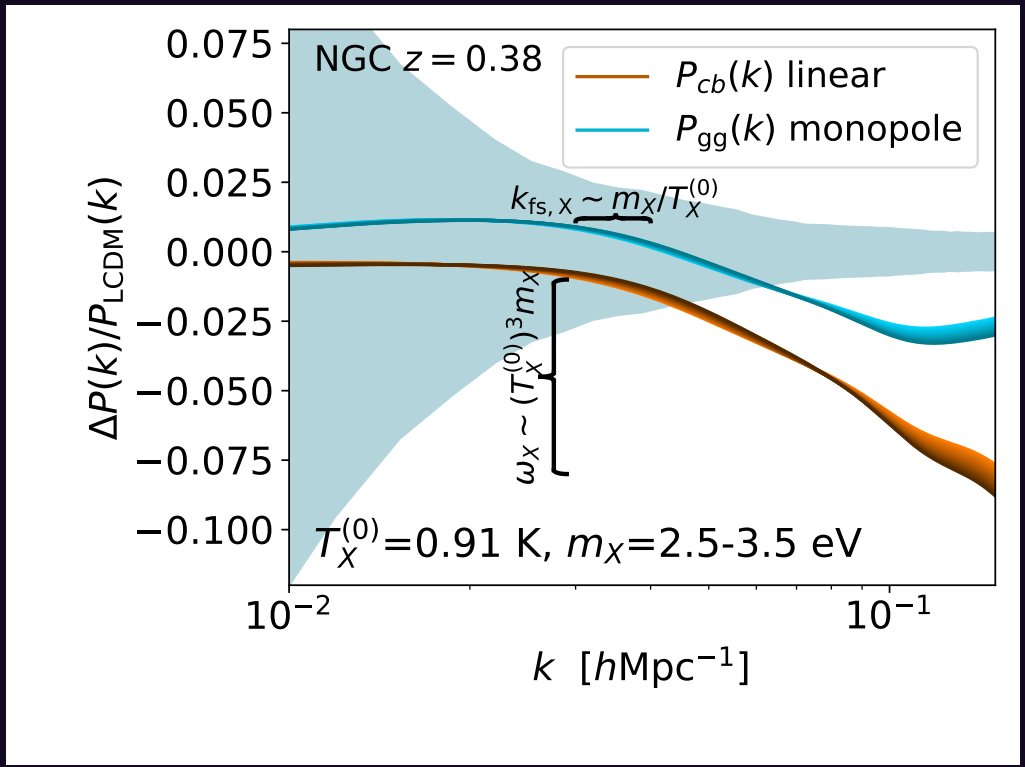


[WLX, Mũnoz, Dvorkin 2107.09664]

The matter story

Observable = clustering statistics of biased tracers

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



[Chudaykin, Ivanov, Philcox, Simonović, 2004.10607; WLX et al 2107.09664]

The matter story

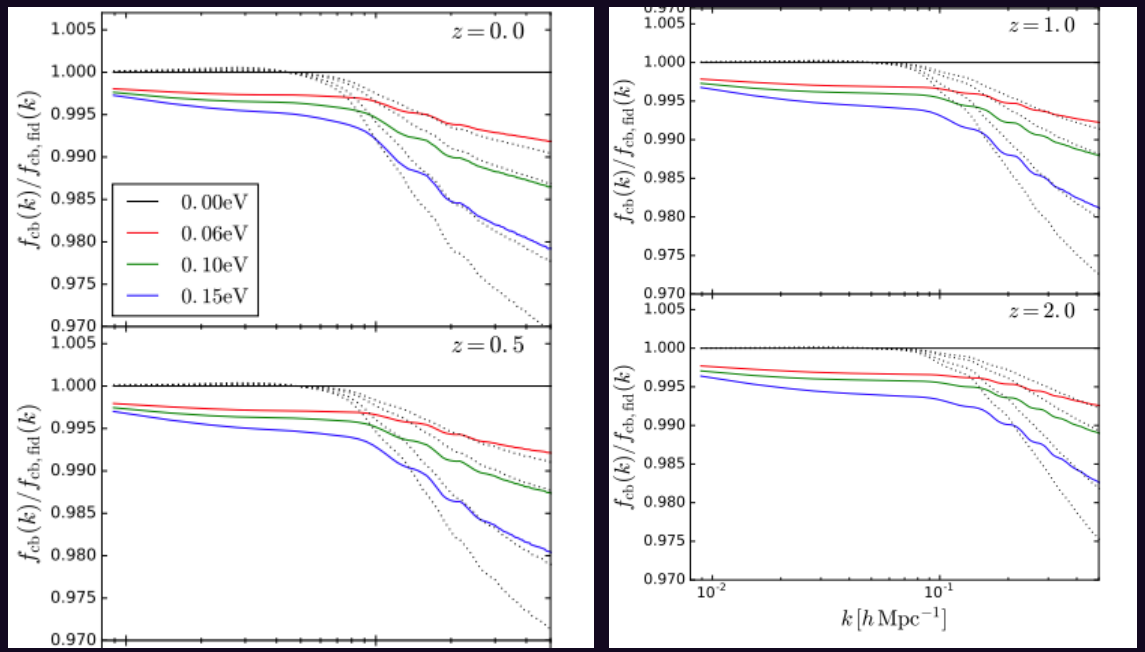
This formalism neglects the nonlinear clustering of light relics

- Neutrinos and LiMRs induce scale-dependent growth

The matter story

This formalism neglects the nonlinear clustering of light relics

- Simulations show this is probably ok for neutrinos



[Villaescusa-Navarro et al 1708.01154]

The matter story

This formalism neglects the nonlinear clustering of light relics

- Neutrinos and LiMRs induce scale-dependent growth
- Simulations show this is probably ok for neutrinos
- ...but might be a problem for heavier relics
- tricky to incorporate into theory, no exact sims to map to

A caveat

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

A caveat

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

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

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

A caveat

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

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

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

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

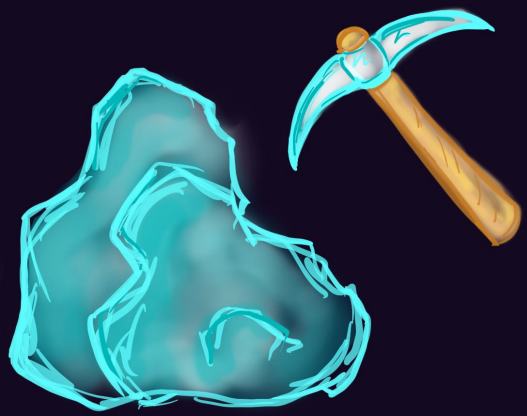
$$c_1 = 8/7, \quad c_2 = 7/6, \quad \gamma = \begin{cases} 0 & \text{fermion} \\ 1 & \text{boson} \end{cases}$$

A caveat

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

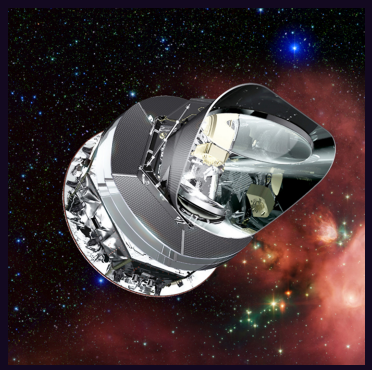
$$\Longrightarrow \text{1 axis of degeneracy within } \{g_X, m_X, T_X^{(0)}\}$$

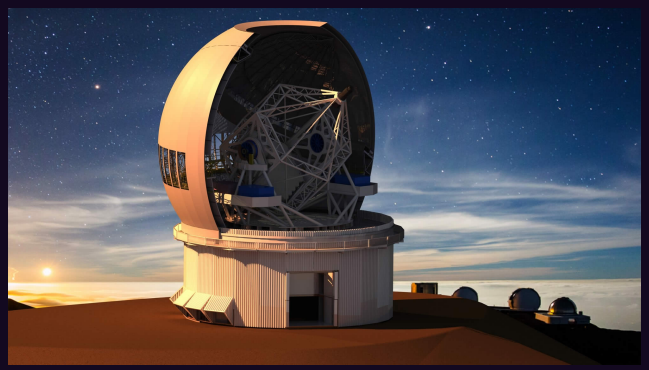
- Easier to search the space
- Harder to interpret detections



Hunting for LiMRs

We've got some pretty impressive data now

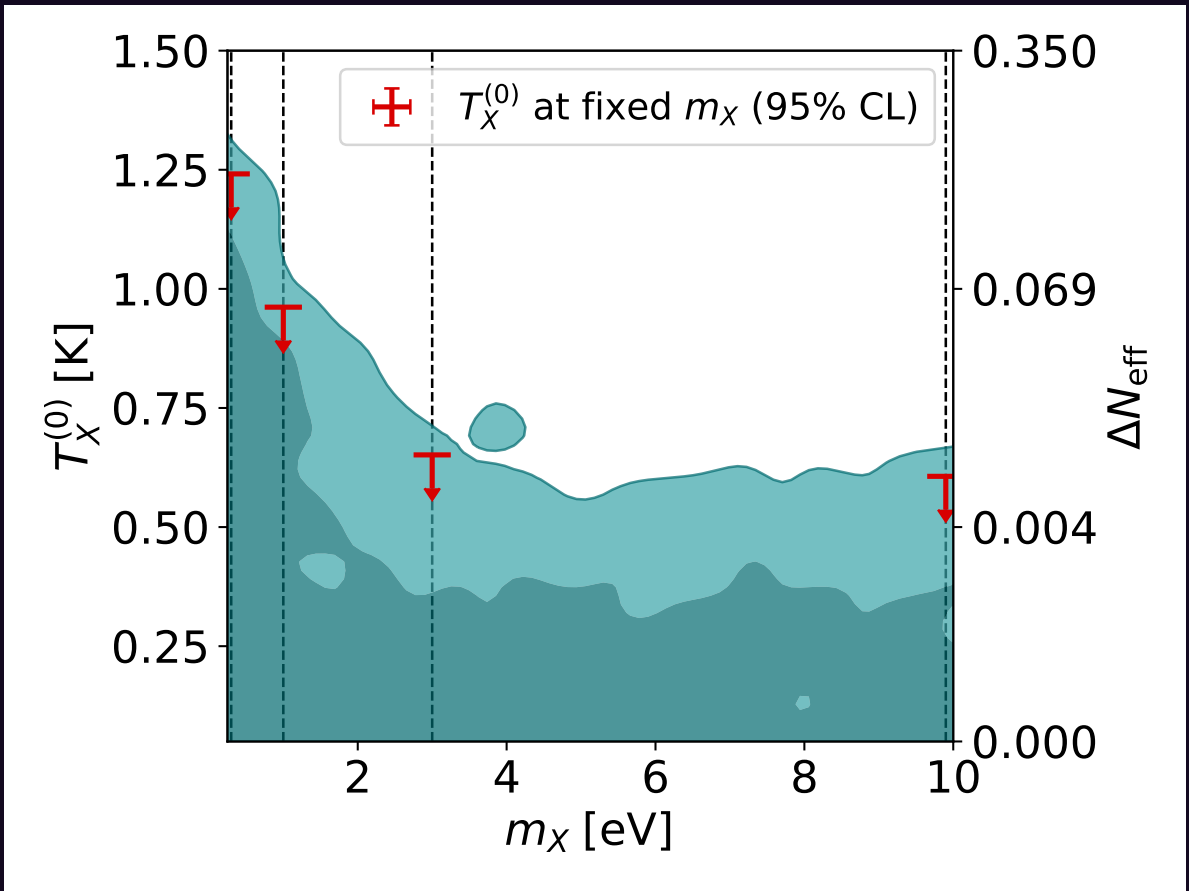




Have we found anything?

Hunting for LiMRs

No(t yet), but...

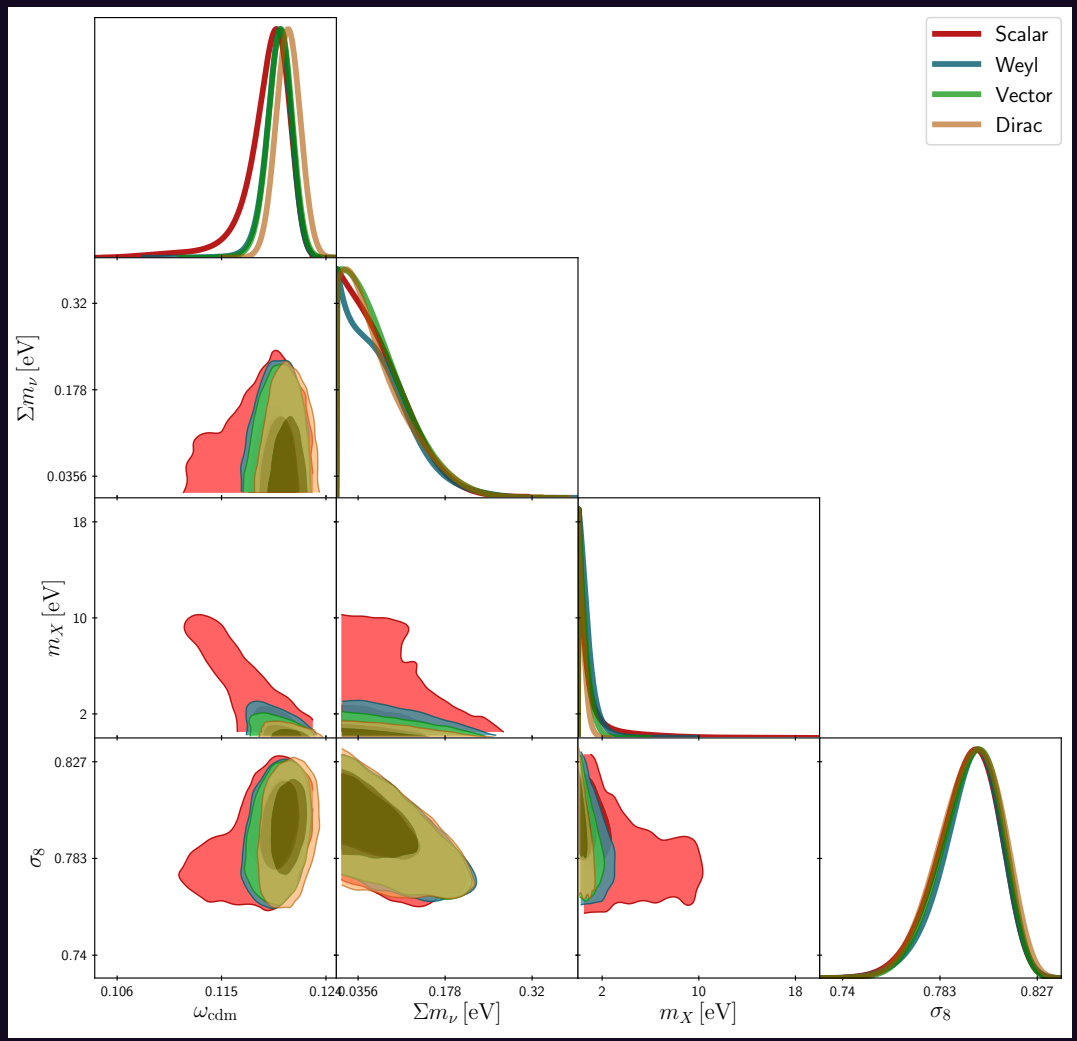


[WLX, Mũnoz, Dvorkin 2107.09664]

Hunting for LiMRs

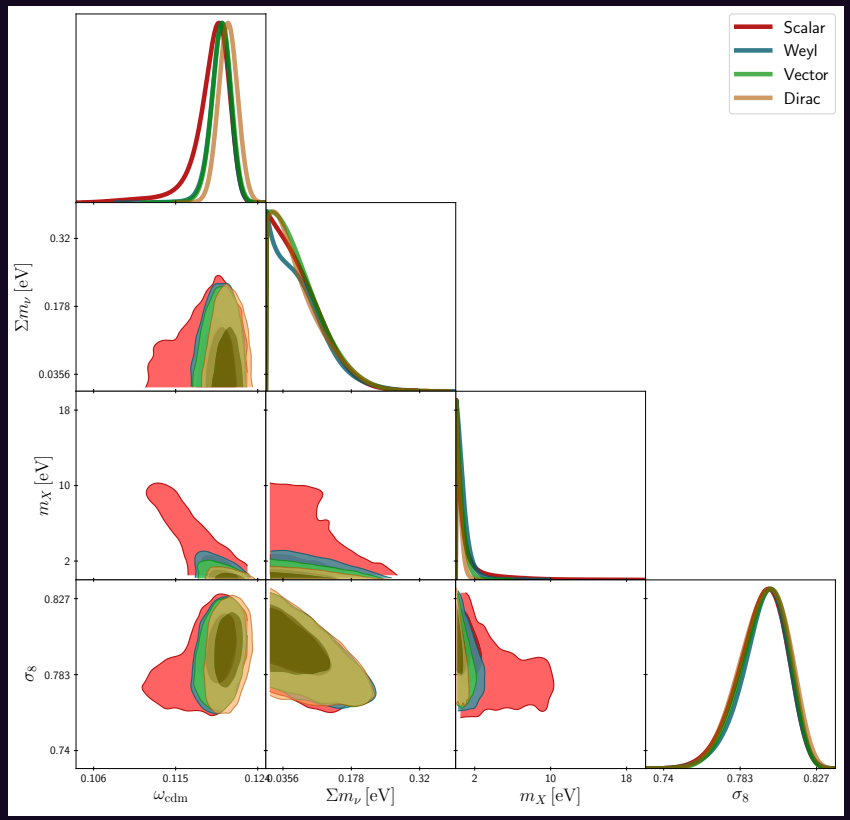
$$T_X = 0.91\ \mathrm{K}$$

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]

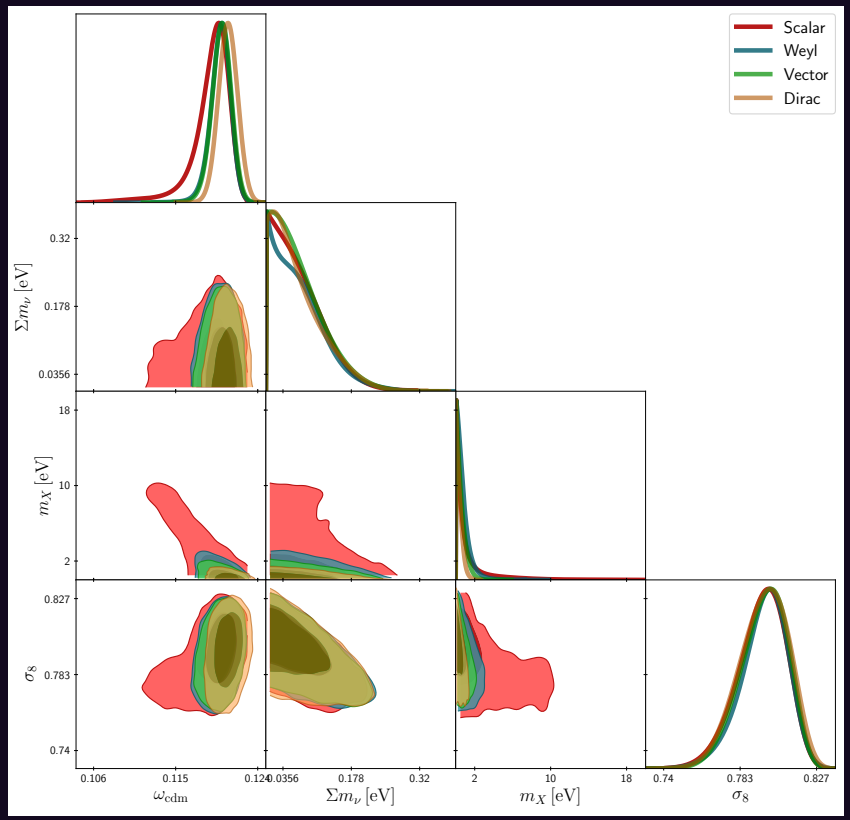
Another caveat



[not pictured]: ΛCDM

[WLX, Mũnoz, Dvorkin 2107.09664]

Another caveat

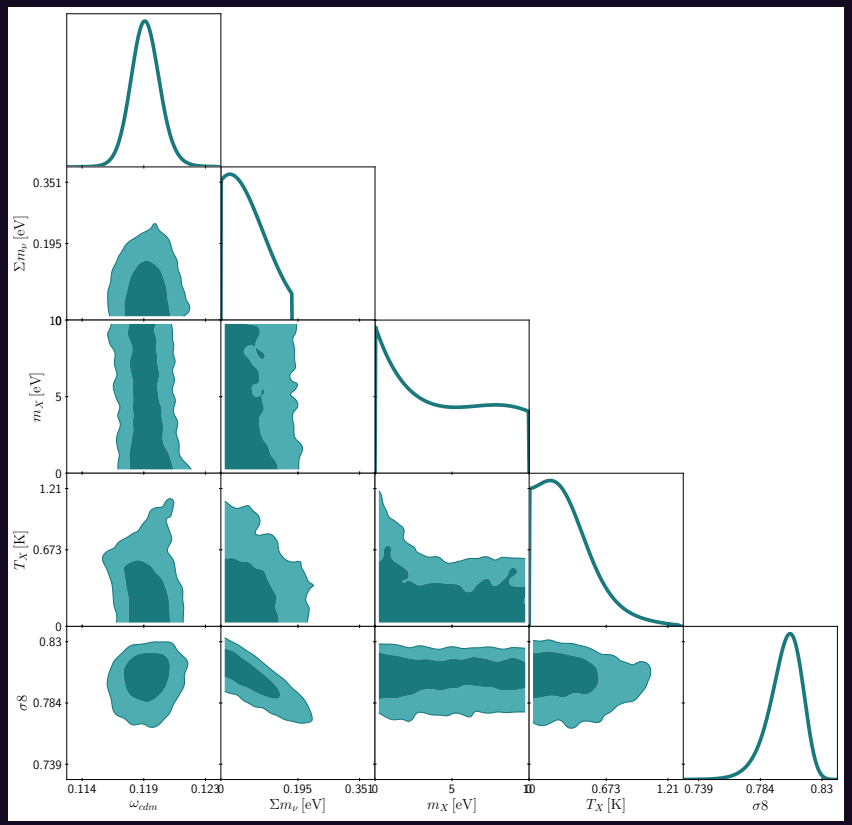


$$\Delta N_{\rm eff}^{\rm max} \sim 0.09 < \sigma_{\Delta N_{\rm eff}}^{\rm P18+BAO}$$

- close enough for now
- but not for long

[WLX, Mũnoz, Dvorkin 2107.09664]

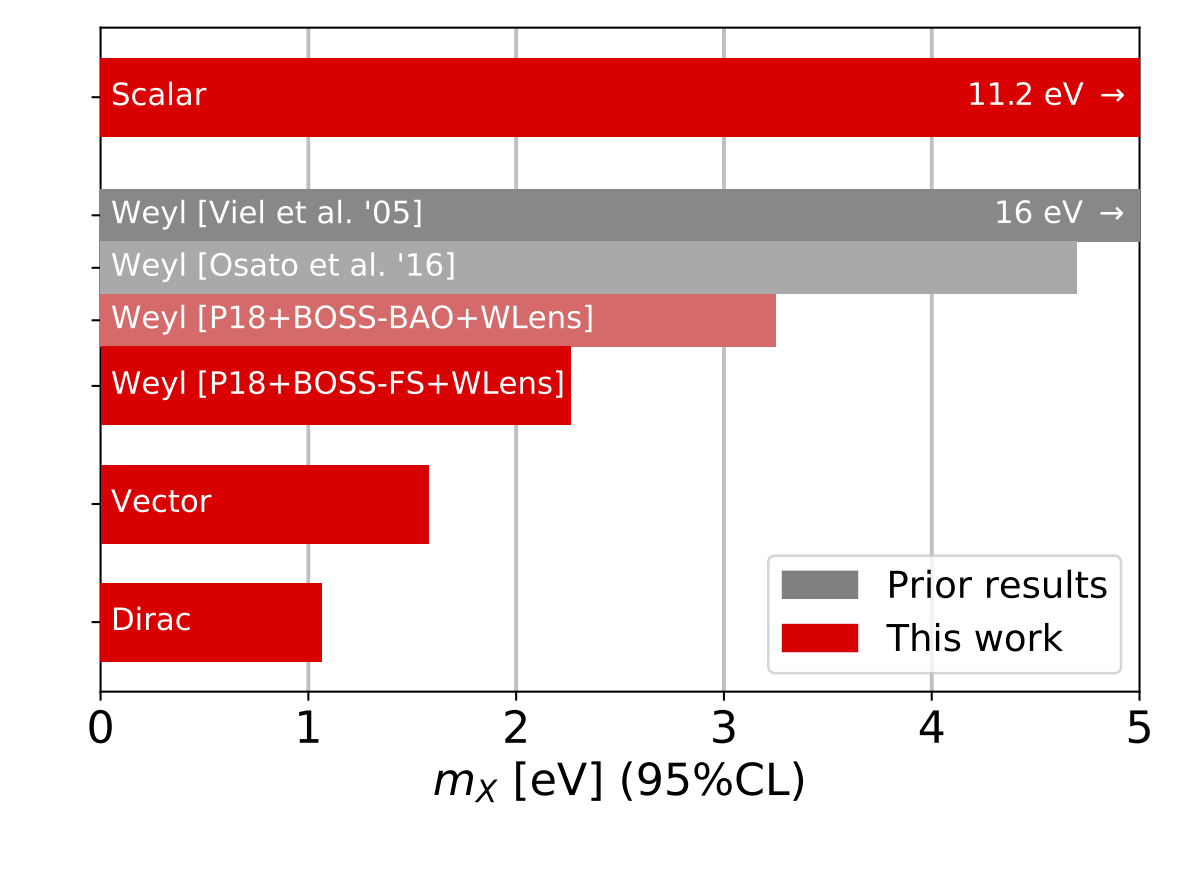
Another caveat



[pictured]: too much ΛCDM

[WLX, Mũnoz, Dvorkin 2107.09664]

Where we're at ...



[WLX, Mũnoz, Dvorkin 2107.09664]

... and what we can learn from it

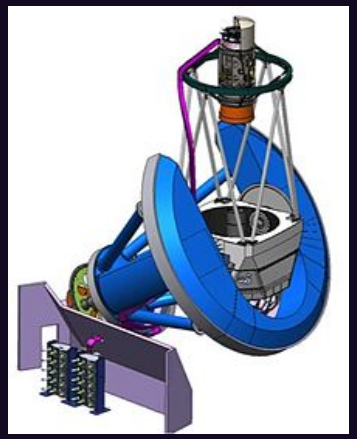
Light gravitinos in gauge-mediated SUSY breaking

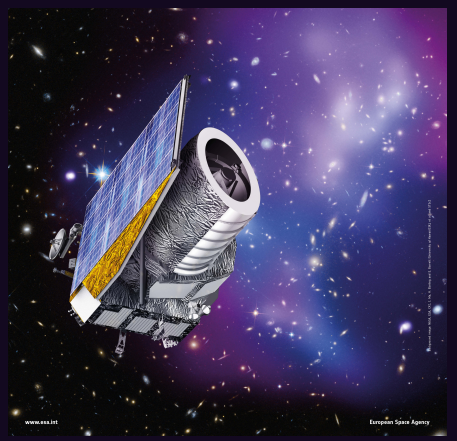
$$m_{3/2} = \frac{\langle F \rangle}{\sqrt{3} M_{pl}}, \quad T_{3/2} \approx 0.95 \text{ K}, \quad g_{3/2,\text{eff}} = 2$$

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

The next hunting season ...

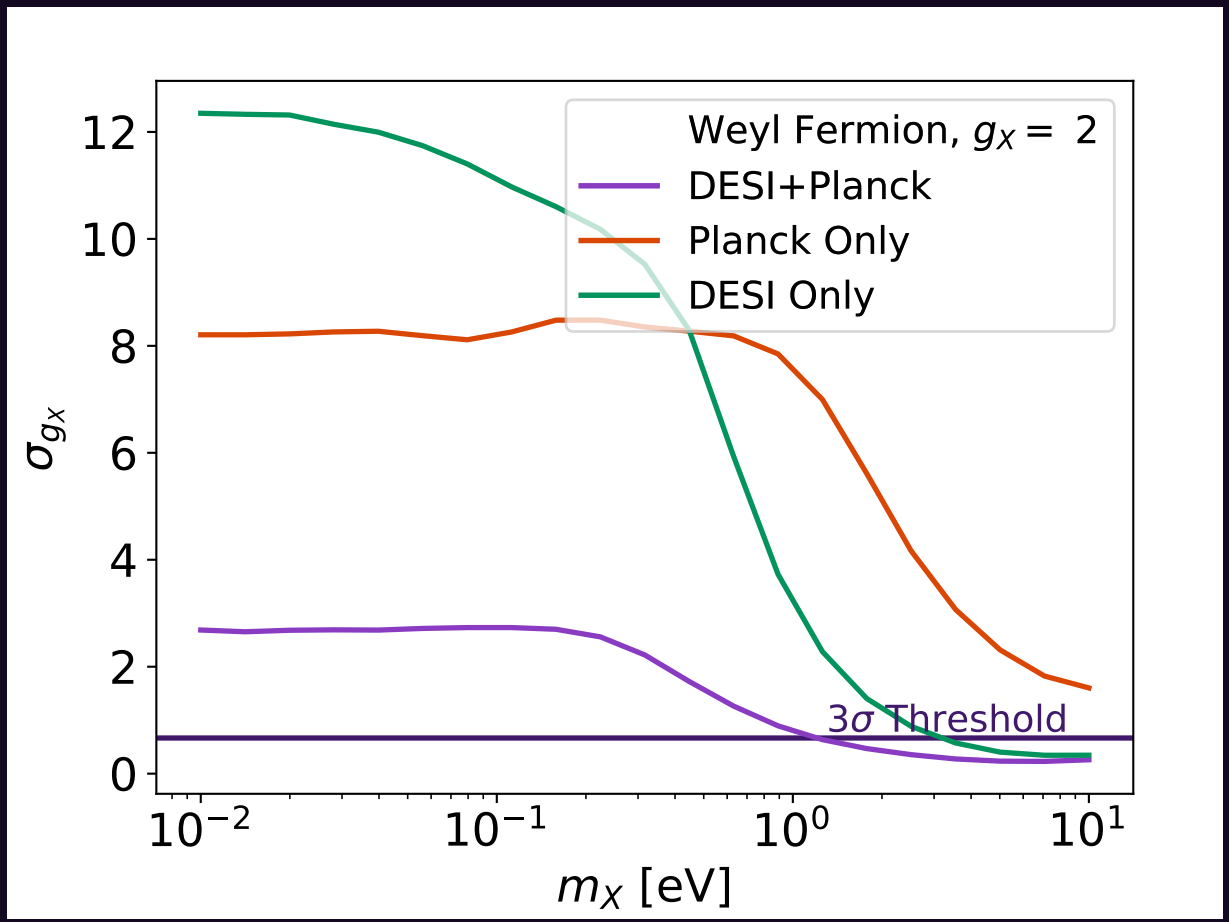
Better data coming soon!





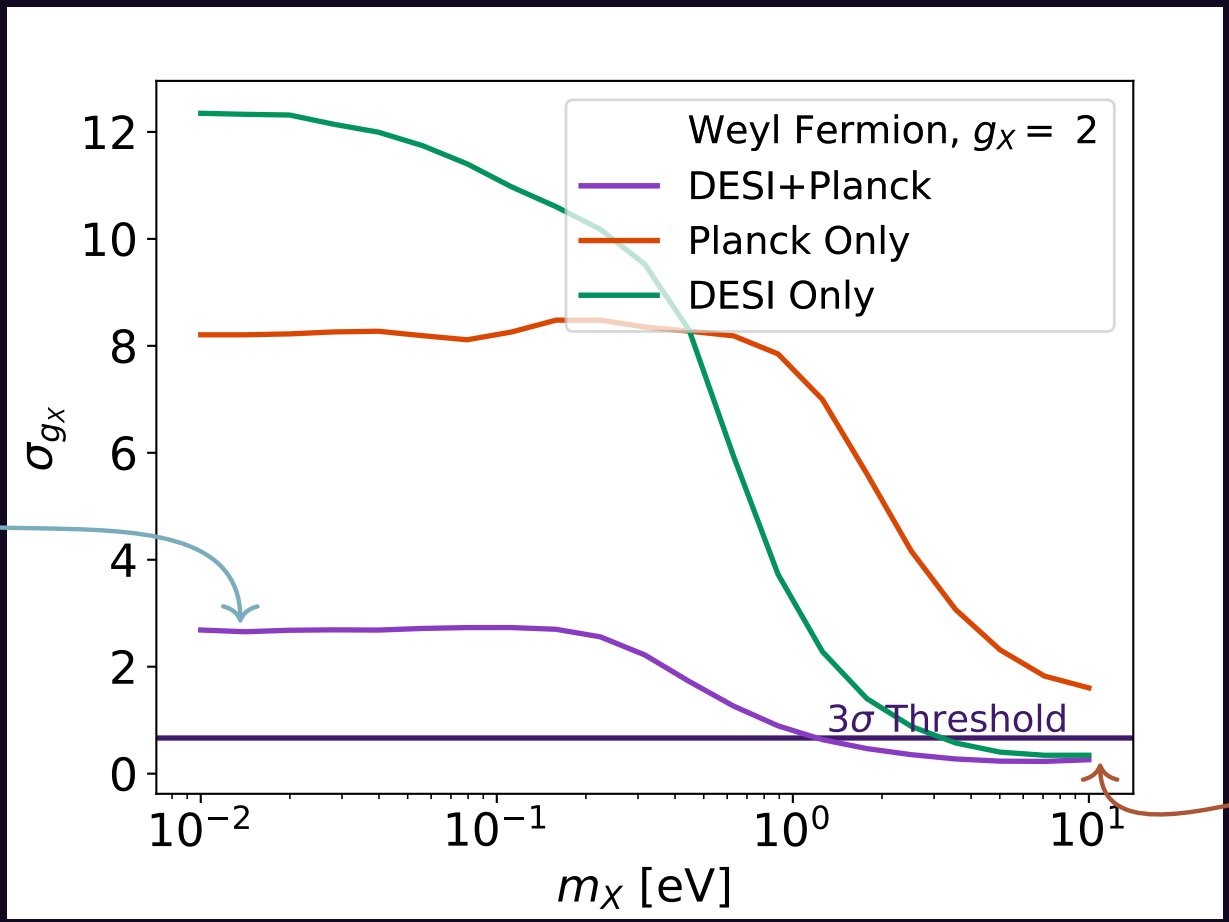
~~Markov Chain Monte Carlo~~ $\rightarrow$ Fisher Forecasts

The next hunting season ...



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

The next hunting season ...

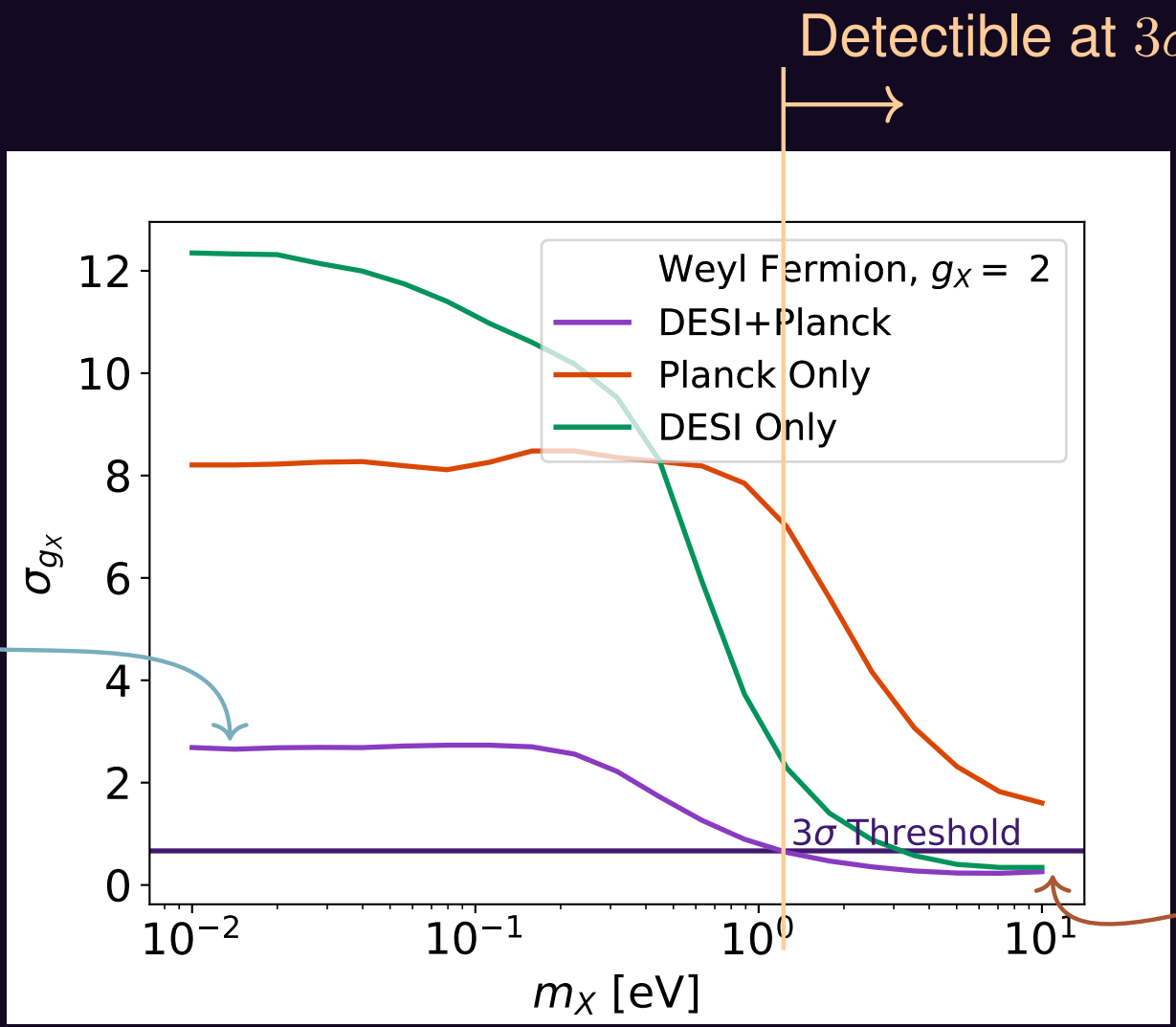


$N_{\rm eff}$

ω_{cdm}

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

The next hunting season ...

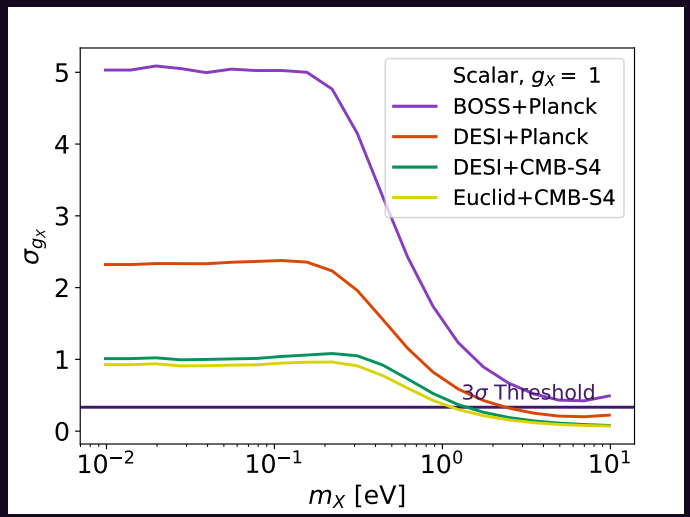


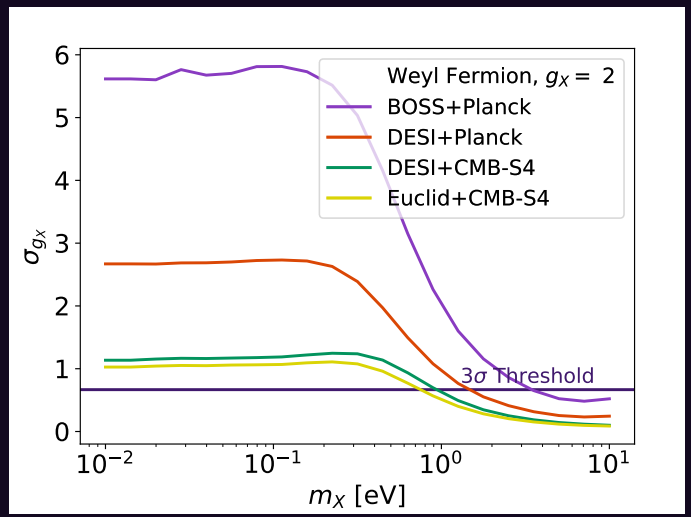
$N_{\rm eff}$

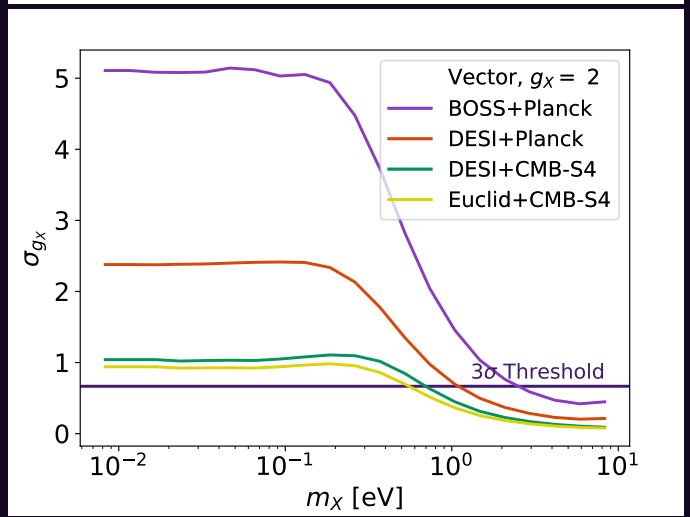
ω_{cdm}

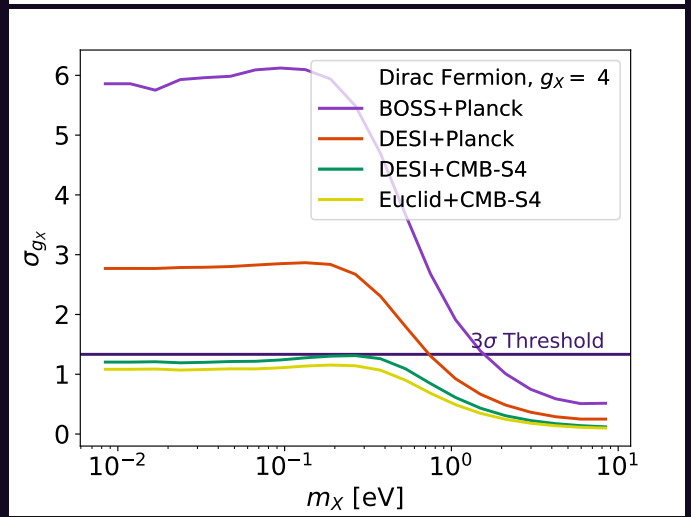
[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380, Minimal temperature $T_X = 0.91$ K]

The next hunting season ...









[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380]

The next hunting season...

A quick sanity check

$$T_X = 0.91 \text{ K}$$

m_X (95% CL)		
BOSS + Planck	Constraints	Forecast
Scalar	11.2 eV	9.6 eV
Weyl	2.26 eV	1.90 eV
Vector	1.58 eV	1.37 eV
Dirac	1.06 eV	0.86 eV

The next hunting season...

$$T_X = 0.91\,\text{K}$$

	m_X (99% CL)	
	DESI + Planck	DESI + CMB-S4
Scalar	1.96 eV	1.14 eV
Weyl	1.20 eV	0.78 eV
Vector	0.90 eV	0.58 eV
Dirac	0.61 eV	All masses

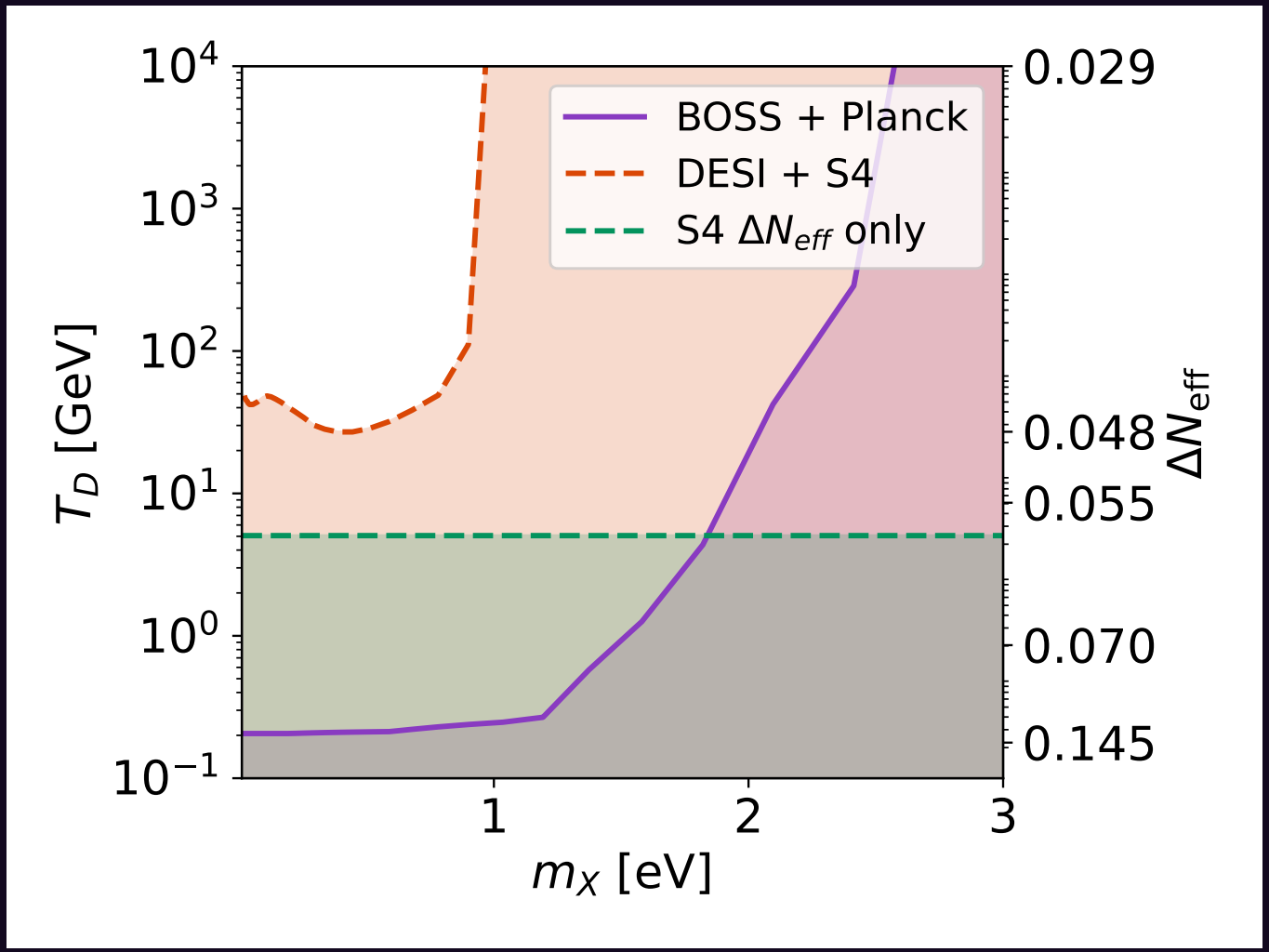
The next hunting season...

$$T_X = 0.91 \text{ K}$$

	m_X (99% CL)	
	DESI + Planck	DESI + CMB-S4
Scalar	1.96 eV	1.14 eV
Weyl	1.20 eV	0.78 eV
Vector	0.90 eV	0.58 eV
Dirac	0.61 eV	All masses

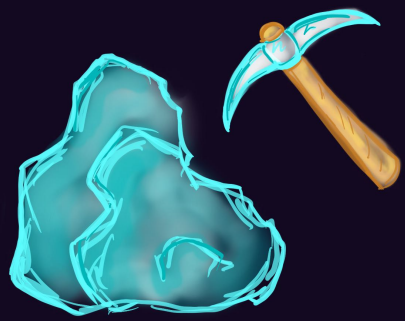
Also: 3σ discovery potential for GMSB gravitinos at
$m_{3/2} \geq 0.77$ eV or $\sqrt{F} \geq 40$ TeV
2σ at *all* masses

Exciting times ahead?



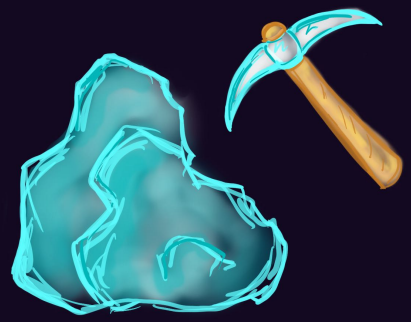
[Deporzio, WLX, Mũnoz, Dvorkin 2006.09380]

What's next?



What's next?



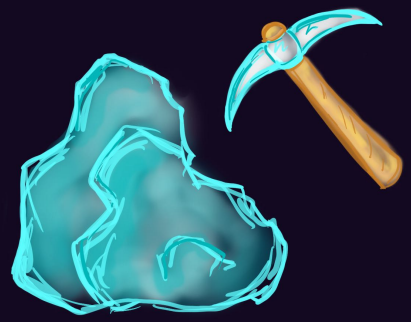


Generalize the framework

- annihilations? decays? self-interactions?
- map out places where we gain/lose sensitivity in the space

What's next?





Solidifying these theory predictions

- Self-consistent incorporation of relics into the PT
- Modeling LiMR nonlinear clustering with simulations

What's next?



Developing a follow-up plan in case of detection

- A good set of benchmark models and places to look next
- Ways to disentangle various degenerate scenarios (equivalent relics, multiple relics ...)
- What does a smoking-gun particle discovery in cosmology look like?

Landing points

Dark sectors are worth studying, in whole or in part

- Compelling reasons to care about LiMRs
- Cosmology very much corners this market
- The first set of comprehensive constraints
  + better things to come

Thank you!

[Estella Lin, 2021]