# **Cosmological Constraints on SuperWIMPs**

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## BSM and DM at the LHC

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#### ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2018



\*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

#### ATLAS Preliminary

0 10 T-W

√s = 8, 13 TeV Reference	ATLAS SUSY Searches* - 95% CL Lower Limits								
1711.03301		Model	S	Signatu	e j	<i>L dt</i> [fb <sup>-</sup>	Mass limit	Reference	
1707.04147 1703.09127 1606.02265 1512.02596 1707.04147 CERN-EP-2018-179 1804.10823 1803.09678 1707.02424 1709.07242 1805.09299 1804.10823 ATLAS-CONF-2018-017 1801.06992 ATLAS-CONF-2018-016 1712.06518 CERN-EP-2018-142	ې ک	$ ilde{q} ilde{q}, ilde{q} ightarrow q ilde{\chi}_1^0$	0 <i>e</i> , µ mono-jet	2-6 jets 1-3 jets	$E_T^{ m miss} \ E_T^{ m miss}$	36.1 36.1	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	1712.02332 1711.03301	
	arche	$\tilde{g}\tilde{g},\tilde{g}\! ightarrow\!q ilde{q} ilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jets	$E_T^{\rm miss}$	36.1	2.0         m(𝔅̃ <sup>0</sup> <sub>1</sub> )<200 GeV           Forbidden         0.95-1.6         m(𝔅̃ <sup>0</sup> <sub>1</sub> )=900 GeV	1712.02332 1712.02332	
	ie Se	$\tilde{g}\tilde{g},  \tilde{g}  ightarrow q \bar{q}(\ell \ell) \tilde{\chi}_1^0$	3 e,μ ee,μμ	4 jets 2 jets	$E_T^{ m miss}$	36.1 36.1	1.85         m(𝔅̃1)<800 GeV           1.2         m(𝔅̃1) <sup>0</sup> )=50 GeV	1706.03731 1805.11381	
	nclusi	$\tilde{g}\tilde{g},  \tilde{g} \rightarrow qq WZ \tilde{\chi}_1^0$	0 e,μ SS e,μ	7-11 jets 6 jets	$E_T^{\rm miss}$	36.1 139	1.8 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ 1.15 $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	1708.02794 ATLAS-CONF-2019-015	
	h	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 <i>e</i> ,μ SS <i>e</i> ,μ	3 <i>b</i> 6 jets	$E_T^{\rm miss}$	79.8 139	2.25         m( $\tilde{k}_1^0$ )<200 GeV           1.25         m( $\tilde{g}$ )-m( $\tilde{k}_1^0$ )=300 GeV	ATLAS-CONF-2018-041 ATLAS-CONF-2019-015	
		$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$		Multiple Multiple Multiple		36.1 36.1 139	Forbidden         0.9 $m(\tilde{\chi}_1^0)=300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_1^0)=1$ Forbidden         0.58-0.82 $m(\tilde{\chi}_1^0)=300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_1^0)=0.5$ Forbidden         0.74 $m(\tilde{\chi}_1^0)=200 \text{ GeV}, m(\tilde{\chi}_1^\pm)=300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_1^\pm)=1$	1708.09266, 1711.03301 1708.09266 ATLAS-CONF-2019-015	
	arks tion	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	6 <i>b</i>	$E_T^{\rm miss}$	139	Forbidden         0.23-1.35 $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ 0.23-0.48 $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	SUSY-2018-31 SUSY-2018-31	
	<sup>4</sup> gen. squa rect produc	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0 \text{ or } t\tilde{\chi}_1^0$ $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$ $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	0-2 $e, \mu$ 1 $e, \mu$ 1 $\tau$ + 1 $e, \mu$ ; 0 $e, \mu$	0-2 jets/1-2 3 jets/1 <i>b</i> $\tau$ 2 jets/1 <i>b</i>	$b E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$	36.1 139 36.1 36.1	1.0 $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 0.44-0.59 $m(\tilde{\chi}_1^0)=400 \text{ GeV}$ 1.16 $m(\tilde{\tau}_1)=800 \text{ GeV}$ 0.85 $m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520 ATLAS-CONF-2019-017 1803.10178 1805.01649	
1703.09127 1707.02424 CERN-EP-2018-174	3 <sup>7</sup> di	$i_1i_1, i_1 \rightarrow i_1 \neq i_2, i \rightarrow i_1$	0 e,μ	mono-jet	$E_T^{\text{miss}}$	36.1	$\begin{array}{c} 0.46 \\ 0.43 \end{array} \qquad $	1805.01649 1711.03301	
		$ \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h  \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z $	1-2 e,μ 3 e,μ	4 <i>b</i> 1 <i>b</i>	$E_T^{ m miss}$ $E_T^{ m miss}$	36.1 139	0.32-0.88 $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\iota}_1)-m(\tilde{\chi}_1^0)=180 \text{ GeV}$ Forbidden         0.86 $m(\tilde{\chi}_1^0)=360 \text{ GeV}, m(\tilde{\iota}_1)-m(\tilde{\chi}_1^0)=40 \text{ GeV}$	1706.03986 ATLAS-CONF-2019-016	
1711.03301 1711.03301 1608.02372 1605.06035 1605.06035 1605.06035 1508.04735		$ ilde{\chi}_1^{\pm}  ilde{\chi}_2^0$ via $WZ$	2-3 e,μ ee,μμ	≥ 1	$E_T^{ m miss} \ E_T^{ m miss}$	36.1 139	$\begin{array}{c c} & & & & \\ & & & & \\ &$	1403.5294, 1806.02293 ATLAS-CONF-2019-014	
		$ ilde{\chi}_1^{\pm}  ilde{\chi}_1^{\mp}$ via WW $ ilde{\chi}_1^{\pm}  ilde{\chi}_2^{0}$ via Wh	2 <i>e</i> ,μ 0-1 <i>e</i> ,μ	2 <i>b</i> /2 γ	$E_T^{ m miss}$ $E_T^{ m miss}$	139 139	<b>0.42</b> $m(\tilde{\chi}_{1}^{0})=0$ $I\tilde{\chi}_{1}^{0}$ <b>Forbidden 0.74</b> $m(\tilde{\chi}_{1}^{0})=70$ GeV	ATLAS-CONF-2019-008 ATLAS-CONF-2019-019, ATLAS-CONF-2019-	
	EW direct	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp} \text{ via } \tilde{\ell}_{L}/\tilde{\nu}$ $\tilde{\tau}\tilde{\tau}, \tilde{\tau} \to \tau \tilde{\chi}_{1}^{0}$	2 e,μ 2 τ		$E_T^{miss}$ $E_T^{miss}$	139 139	<b>1.0</b> $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$ $[\tilde{\tau}_L, \tilde{\tau}_{R,L}]$ <b>0.16-0.3 0.12-0.39</b> $m(\tilde{\chi}_1^0)=0$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-018	
		$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, μ 2 e, μ	$\begin{array}{l} \textbf{0 jets} \\ \geq 1 \end{array}$	$E_T^{miss}$ $E_T^{miss}$	139 139	<b>0.7</b> <b>0.256</b> <b>0.7</b> $m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=10 \text{ GeV}$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-014	
ATLAS-CONF-2018-032 ATLAS-CONF-2018-032 CERN-EP-2018-171 ATLAS-CONF-2016-072 ATLAS-CONF-2016-024 1509.04261		$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	0 e,μ 4 e,μ	$\geq 3 b$ 0 jets	$\begin{array}{c} E_T^{\rm miss} \\ E_T^{\rm miss} \end{array}$	36.1 36.1	0.13-0.23         0.29-0.88 $BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$ 0.3 $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602	
	Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	c 1 jet	$E_T^{\rm miss}$	36.1	0.46 Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019	
		Stable $\tilde{g}$ R-hadron Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple Multiple		36.1 36.1	[ $\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.4 m( $\tilde{\chi}_1^0$ )=100 GeV	1902.01636,1808.04095 1710.04901,1808.04095	
1703.09127 1709.10440 1805.09299 1411.2921 1411.2921	RPV	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$ $\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$ $\tilde{t}, \tilde{t}, \tilde{t} \rightarrow bs$	eμ,eτ,μτ 4 e,μ	0 jets 4-5 large- <i>R</i> j Multiple Multiple 2 jets + 2	$E_T^{\text{miss}}$ ets	3.2 36.1 36.1 36.1 36.1 36.1	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	1607.08079 1804.03602 1804.03568 ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 1710.07171	
ATLAS-CONF-2018-020 1506.06020 1710.09748 1411.2921 1410.5404 1504.04188		$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q \ell$	2 <i>e</i> ,μ 1 μ	2 b DV		36.1 136	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	1710.05544 ATLAS-CONF-2019-006	
	*Only phe	a selection of the available ma nomena is shown. Many of the	ss limits on limits are ba	new state ased on	es or	1	1 Mass scale [TeV]		

1504.04188

1509.08059

simplified models, c.f. refs. for the assumptions made.

What if BSM was very weakly coupled : Decay lengths upto ~ 100 m

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BSM lepton 📕 quark photon anything

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lepton Beyond Colliders n 📕 quark Coupling strength ⇒ Log<sub>\*</sub> g/M<sub>mediator</sub> [GeV LHC photon anything SHiP NA62++ NA62++ IAXO NA64++ LDMX JURA REDTOP **KLEVER** FASER EDM CODEX-B MATHUSLA oEDM MilliQan Planck Scale -21 -24 -21 -18 -15 -12 12 -9 -6 -3 n 9 6 Mass of BSM state  $\Rightarrow Log_{10} m_X[eV]$ 









### An Almost Perfect Blackbody



### An Almost Perfect Blackbody



#### CMB Anisotropy measured by COBE/Firas

Small temperature fluctuations left over from Big Bang

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**CMB Spectral Distortions** 

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- Small departures of the CMB frequency spectrum compared to a perfect black body
- Typically at redshifts of  $Z: 10^4 10^6$
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Chemical potential  $\mu$  distortion



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Due to inefficient photon number changing processes photons gain a net non-zero chemical potential

Compton y distortion

- Z < 10<sup>4</sup> : Compton scattering becomes inefficient,
- CMB photons boosted via non-relativistic scattering



#### **COBE/Firas measurement**

$$|\mu| < 9 \times 10^{-5} \quad |y| < 1.5 \times 10^{-5}$$

Constrains Cosmological models with exotic energy injection at the level

Any excess EM energy dumped by late decaying particles will be severely constrained by the above observations

**Energy Injection rates** 

Decay

$$\dot{\mathcal{Q}} = \rho_{\rm cdm} f_{\rm frac} f_{\rm eff} \Gamma_{\rm dec} e^{-\Gamma_{\rm dec} t}$$

Annihilation

$$\dot{\mathcal{Q}} = \rho_{\rm cdm}^2 f_{\rm frac} f_{\rm eff} \frac{\langle \sigma v \rangle}{M_{\chi}} \equiv \rho_{\rm cdm}^2 p_{\rm ann}$$

 $\Delta \rho_{\gamma} / \rho_{\gamma} < 6 \times 10^{-5}$
### Can Cosmology tell us more about BSM/Dark Matter

CMB Spectral distortions

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# Can Cosmological that era

#### CMB Spectral distortions

Within 
$$\Lambda {\rm CDM}$$
  $\mu \sim 2 \times 10^{-8}$   $y \sim {\rm few} \times 10^{-6}$  
$$\begin{array}{c} {\rm COBE/Firas\ measurement}} & \mu & g \\ \Lambda \\ |\mu| < 9 \times 10^{-5} & |y| < 1.5 \times 10^{-5} \end{array}$$

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 $\mu$  $\boldsymbol{y}$ 

Y

$$rac{\Delta I}{I}\sim 10^{-5}-10^{-4}$$

#### CMB Spectral distortions

**COBE/Firas measurement** 

Within 
$$\Lambda$$
CDM  $\mu \sim 2 imes 10^{-8} \, 10^{-8} \, y \sim y {
m few}{
m few}$ 

 $\begin{array}{ccc} \Lambda & \Lambda \\ |\mu| < 9 \times 10^{-5} & |y| < 1.5 \times 10^{-5} \end{array}$ 

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Can Costae processes during the state of the

$$\|\mu\| \mu \not\in \mathcal{S}_{10}^{-10^{-5}} \|y\| < |y| \le 10^{-5} \times 10^{-5}$$

УY ffl ¥

### $\Delta \rho_{\gamma} / \rho_{\gamma} < 6 \times 10^{-5}$

$$rac{\Delta I}{I}\sim 10^{-5}-10^{-4}$$

$$rac{\Delta I}{I} \sim 10^{-5} - 10^{-4}$$

#### CMB Spectral distortions

**COBE/Firas measurement** 

Within 
$$\Lambda$$
CDY $\mu$   $\sim$   $\mu 2 \sim 2101 8^{-8}$   $_{10}$   $y \sim {
m few} imes 10^{-6}$   $_{6}$ 

 $|\mu|^{\Lambda} < \frac{\Lambda}{9 \times 10^{-5}} \quad |y| < 1.5 \times 10^{-5}$ 

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**Energy Injection rates** 

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Can Cost and the state of the s

### $|\mu| \mu || \mathbf{y} ||_{10} = 0.0^{-5} ||_{0} ||_{5} ||_{5} ||_{5} ||_{5} ||_{5} ||_{5} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{5} ||_{5} ||_{10} = 10^{-5} ||_{10} ||_{10} ||_{10} ||_{10} = 10^{-5} ||_{10} ||_{10} ||_{10} ||_{10} = 10^{-5} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} = 10^{-5} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{10} ||_{$

μμ<sup>yy</sup>y Yy

 $\Delta \rho_{\gamma} / \rho_{\gamma} < 6 \times 10^{-5}$ 

$$rac{\Delta I}{I}\sim 10^{-5}-10^{-4}$$

$$rac{\Delta I}{I} \sim 10^{-5} - 10^{-4}$$

# Can Cosmology tell us more about BSM/Dark Matter

### **BBN Constraints**

Production of light elements D, He-3/4, Li-7 A small amount of Be-9, B-10/11 via CNO processes

**Characterized by the Baryon-Photon ratio** 

 $\eta_{\rm CMB} = 6.10 \pm 0.04$  $\eta = n_b/n_\gamma$ (Ade et al., 2016)

Measurements of Abundances of other light elements

D/H = (2)	.527±0.03)	$10^{-5}$
``	, ,	

(Cooke et al., 2017) High Redshift low metallicty H clouds Any excess energy injection at late times can alter the predictions of BBN, primarily by photodissociation of light elements Population II stars in the spheroid of the galaxy :



(Sbordone et al. (2010)) factor 3 off from standard estimates

 $Y_p = 0,245 \pm 0,003$ 

He-4 primordial mass fraction (Particle Data group 2019))

Lyman-alpha Constraints blished under licence by IOP Publishing Ltd

If a relativistic relic is produced deep in the dependent of the vertex perturbations of these particles suppressed for scales below 3.0 lider the defines of these particles suppressed for scales below 3.0 lider the defines of the vertex of Published under licence by IOP Publishing Ltd

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Feng, Rajaraman, Takayama 2003, Feng++ 2004, 2005 Pospelov, Ritz, Voloshin 2008 +many more



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Example 1 : Gravitinos

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Spin-3/2 Superpartners of gravitons

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 $\langle F \rangle / m_{\rm pl}$  $|m_{\tilde{G}}| \simeq$ 

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$$\Gamma(\chi_1^0 \to \tilde{G}\gamma) = \frac{m_{\chi_1^0}^5 \cos^2 \theta_{\rm W}}{48\pi m_{\rm Pl}^2 m_{\tilde{G}}^2} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right)^3 \left(1 + 3\frac{1}{2}\right)^3 \left(1 + 3\frac{1}{2}\right$$

$$m_{\tilde{G}} \simeq \langle F \rangle / m_{\rm pl}$$

## SuperWIMPS







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 $\Omega_{\rm LSP}h^2 = \Omega_{\rm LSP}^{\rm thermal}h^2 + \Omega_{\rm LSP}^{\rm non-thermal}h^2$ 



Decay width depends only on Planck scale and masses





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Decay width depends only on Planck scale and masses

$$E_{\gamma} = (m_{\chi_1^0}^2 - m_{\tilde{G}}^2) / (2m_{\chi_1^0})$$





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 $A = (s + ia)/\sqrt{2} + \sqrt{2}\theta a + \theta^2 F$ 



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Axino-gaugino-gauge boson interactions



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Axino-gaugino-gauge boson interactions

 $\left| \mathcal{L}_{\tilde{a}\lambda A} = i \frac{\alpha_Y C_{aYY}}{16\pi \left( f_a/N \right)} \bar{\tilde{a}} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{B} B_{\mu\nu} + i \frac{\alpha_s}{16\pi \left( f_a/N \right)} \bar{\tilde{a}} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{g}^b F^b_{\mu\nu} \right|$ 



$$A = (s + ia)/\sqrt{2} + \sqrt{2}\theta a + \theta^2 F$$

Axino-gaugino-gauge boson interactions

$$\mathcal{L}_{\tilde{a}\lambda A} = i \frac{\alpha_Y}{16\pi}$$

$$\Gamma\left(\chi_{1}^{0} \to \tilde{a}\gamma\right) \simeq \left(\frac{\alpha^{2}}{4\pi}\right) C_{aYY}^{2} \frac{m_{\chi_{1}^{0}}^{3}}{32\pi^{2} f_{a}^{\prime \, 2} \cos^{2} \theta_{W}} \left(1 - \frac{m_{\tilde{a}}^{2}}{m_{\chi_{1}^{0}}^{2}}\right)^{3}$$
$$= \left(\frac{\alpha^{2}}{4\pi}\right) C_{aYY}^{2} \frac{m_{\chi_{1}^{0}}^{3}}{4\pi^{2} f_{a}^{\prime \, 2} \cos^{2} \theta_{W}} \epsilon_{SM}^{3}$$

 $\frac{\gamma C_{aYY}}{\pi (f_a/N)} \bar{\tilde{a}} \gamma_5 [\gamma^{\mu}, \gamma^{\nu}] \tilde{B} B_{\mu\nu} + i \frac{\alpha_s}{16\pi (f_a/N)} \bar{\tilde{a}} \gamma_5 [\gamma^{\mu}, \gamma^{\nu}] \tilde{g}^b F^b_{\mu\nu}$ 



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## SuperWIMPS

 $\frac{\partial Y C_{aYY}}{\pi (f_a/N)} \bar{\tilde{a}} \gamma_5 [\gamma^{\mu}, \gamma^{\nu}] \tilde{B} B_{\mu\nu} + i \frac{\alpha_s}{16\pi (f_a/N)} \bar{\tilde{a}} \gamma_5 [\gamma^{\mu}, \gamma^{\nu}] \tilde{g}^b F^b_{\mu\nu}$ 

### Additional freedom in the Peccei-Quinn scale



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$$L = c\tau \simeq = \frac{14.15}{\epsilon_{sm}^3} \left( \frac{f'_a}{10^8 \text{ GeV}} \right)^2 \left( \frac{100 \text{ GeV}}{m_{\chi_1^0}} \right)^3 \text{m}$$

## SuperWIMPS

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## SuperWIMPS

 $\frac{{}_{Y}C_{aYY}}{\pi \left(f_{a}/N\right)}\bar{\tilde{a}}\gamma_{5}[\gamma^{\mu},\gamma^{\nu}]\tilde{B}B_{\mu\nu}+i\frac{\alpha_{s}}{16\pi \left(f_{a}/N\right)}\bar{\tilde{a}}\gamma_{5}[\gamma^{\mu},\gamma^{\nu}]\tilde{g}^{b}F_{\mu\nu}^{b}$ 

### Additional freedom in the Peccei-Quinn scale

Low PQ scales constrained by colliders while PQ scales constrained by cosmology

A slightly modified version of Exoclass 6+2 extension of the standard  $\Lambda CDM$  $\{h, \omega_{\rm b}, \omega_{\rm cdm}, n_s, A_s, z_{\rm reio}\} + \{\log_{10} f_{\rm frac}, \log_{10} \tau_{\rm dec}\}$ Slow Monte-Carlo Convergence Spectral distortion dominated exclusion region

 $10^5 \mathrm{s} < \tau_{\mathrm{dec}} < 10^{13} \mathrm{s}$ 

CMB anisotropy dominated exclusion region >  $10^{12}$  s

**BBN most sensitive upto**  $10^{12}$  s

Needs CMBS<sub>4</sub> + Prism to extend the reach









Used Exoclass [Stocker, Kramer, Lesgourgues, Poulin 2018], a tool to analyze spectral distortion Present within the current Class [Lesgourgues 2011] version 3.





Used Exoclass [Stocker, Kramer, Lesgourgues, Poulin 2018], a tool to analyze spectral distortion Present within the current Class [Lesgourgues 2011] version 3.

Result consistent with Hooper, Lucca, Lesgorugues, Schoneberg: 1910.04619



# Combined constraints

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$$2.8 \times 10^{22} \left(\frac{\text{GeV}}{m_{\chi_1^0}}\right)^3 \frac{(1 - 2\epsilon_{SM})}{\epsilon_{SM}^3 (1 + 3(1 - 2\epsilon_{SM}))} m$$



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LLP Searches for non pointing photons





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LLP Searches for non pointing photons

## Constraints depend on the PQ scale f<sub>a</sub>

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#### $f_a = 10^{12} \text{ GeV}$

### f<sub>a</sub> = 10<sup>8</sup> GeV : Dominated by Collider

,

## Constraints depend on the PQ scale f<sub>a</sub>





# Conclusions



- The hunt for BSM physics is not just limited to collider physics
- Cosmology can probe a larger parameter space in well-motivated BSM models
- SuperWIMPS are heavily constrained by Cosmology
- Previous constraints primarily have focussed on BBN constraints
- Spectral Distortions and CMB anisotropies constrain a large part of the SuperWIMP parameter space • Future CMB experiments can push the envelop further

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## Conclusions

## Kompaneets equation and PPSD

Modification of photon bath by Compton scattering

$$C[f]|_{\rm CS} = \dot{\tau} \frac{T_e}{m_e} \frac{1}{x^2} \frac{\partial}{\partial x} \left( x^4 \left[ \frac{\partial f}{\partial x} + \frac{T_z}{T_e} f(1+f) \right] \right) \qquad \dot{\tau} = n_e \sigma_T \\ T_z \equiv T_0 (1+f) = T_z = T_0 (1+f)$$

If CS is efficient, above moves towards an equillibrium solution

$$0 = \left[\frac{\partial f}{\partial x} + \frac{T_z}{T_e}f(1+f)\right] \longrightarrow f(x) = \frac{1}{\exp(\tilde{x}+C) - 1} \quad \text{BE equation with} \quad \tilde{x} = x T_z/T_e = p/T_e$$

Compton Scaterring conserves the number of photons in the bath and generates a non-zero chemical potential

Double Compton Scaterring + Brehmstralung generates a zero chemical potential  $n\gamma \leftrightarrow m\gamma$  with  $n \neq m$ 

$$\frac{\partial f}{\partial \tau} = \frac{T_e}{m_e} \frac{1}{x^2} \frac{\partial}{\partial x} \left( x^4 \left[ \frac{\partial f}{\partial x} + \frac{T_z}{T_e} f(1+f) \right] \right) + \frac{K_{\rm BR} e^{-\widetilde{x}}}{\widetilde{x}^3} \mathcal{F} + \frac{K_{\rm DC} e^{-2x}}{x^3} \mathcal{F} \right] \quad \mathbf{d}\tau$$

-z)

 $\tau = \sigma_T n_e \mathrm{d}t$ 



#### See ... Hooper, Lucca, Lesgorugues, Schoneberg : 1910.04619 Chluba, Lesgourgues 2011



#### **Temperature Shifts**

$$f(t,x) = B(x) + \Delta f(t,x) \qquad \Delta f(t,x) \quad \text{a distortion of the spec}$$

$$\Delta f(x) = G(x) \frac{\Delta T}{T_z} \qquad G(x) = -x \frac{\partial B(x)}{\partial x} = \frac{xe^x}{(e^x - 1)^2}$$

Chemical potential  $\mu$  distortion

$$f(x) = B(x+\mu) = \frac{1}{e^{x+\mu} - 1} \approx \frac{1}{e^x - 1} - \mu \frac{G(x)}{x} = B(x) - \mu \frac{G(x)}{x}$$

$$\Delta f(x) = -$$

#### Compton y distortion

Kompaneets eqn without equillibrium

$$\left[\frac{\Delta f}{\Delta \tau} \approx \frac{T_e}{m_e} \frac{1}{x^2} \frac{\partial}{\partial x} \left( x^4 \left[ \frac{\partial B(x)}{\partial x} + \frac{T_z}{T_e} B(x) (1 + B(x)) \right] \right) = \frac{T_z - T_e}{m_e} \frac{\partial}{\partial x} (x^3 G(x))}{x^2} \right] \qquad \Delta f(x) \approx \Delta \tau^2$$

## Spectral Distortions

ctrum

$$\mu \frac{G(x)}{x}$$

$$\frac{T_e - T_z}{m_e} Y(x) \qquad \qquad Y(x) \equiv -\frac{\frac{\partial}{\partial x} (x^3 G(x))}{x^2} = G(x) \left[ x \frac{e^x + 1}{e^x - 1} - 4 \right]$$

#### Injection and deposition

**Energy Injection into IGM** 

deposition function  $f_c(z)$ 

Fraction of injected energy in channel c at redshift z

$$\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\Big|_{\mathrm{dep,c}} = \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\Big|_{\mathrm{inj}} f_{\mathrm{c}} = \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\Big|_{\mathrm{inj}} f_{\mathrm{eff}} \chi_{c} \equiv \dot{\mathcal{Q}}\chi_{c}$$

$$\left| \dot{Q} = \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V} \right|_{\mathrm{dep},h} + \dot{Q}_{\mathrm{non-inj}} = \dot{\mathcal{Q}}\chi_h + \dot{Q}_{\mathrm{non-inj}} \quad \text{Energy Deposition}$$



Use on-the spot approximation

sition into heat



Estimate the Co-moving Free Streaming Scale

$$\lambda_{\rm FS}(t) \simeq \int_{t_{\rm prod}}^t \frac{\mathrm{d}t'}{a(t')} v(t')$$

Depends on the particle mass and cosmological parameters

Value at z=0 should correspond to the thermal (WDM) transfer function

$$T(k) = \left[1 + (\alpha k)^{2\nu}\right]^{-5\nu}$$

Found by fitting the function to the actual transfer function from CLASS or CAMB

$$\alpha = am_X^b \left(\frac{\omega_X}{0.12}\right)^\eta \left(\frac{h}{0.6736}\right)^\theta h^{-1} \operatorname{Mpc} \qquad \left[\alpha = 0.24 \left(\frac{m_x/T_x}{1 \text{ keV}/T_\nu}\right)^\theta h^{-1} \operatorname{Mpc} \right]$$

With for a thermal WDM

$$\omega_x = \left(\frac{T_x}{T_\nu}\right)^3 \left(\frac{m_x}{94 \text{ eV}}\right),$$

# Lyman alpha

$$\lambda_{\rm FS,WDM}(z=2) \simeq \int_0^t \frac{\mathrm{d}t'}{a(t')} \frac{p}{E}(t'),$$
$$\simeq \frac{1}{H_0} \sqrt{\frac{a_{\rm eq}}{\Omega_m}} \int_0^{a/a_{\rm eq}} \frac{\mathrm{d}y}{\sqrt{(1+y)(1+b^2y^2)}},$$

$$\left(\frac{\omega_x}{0.12}\right)^{-0.16}$$
 Mpc