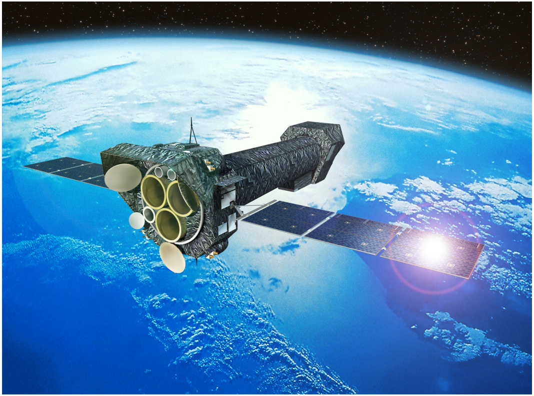
Generating X-ray lines from annihilating dark matter

Lucien Heurtier

Heidelberg, GDR Terascale, September 2014

hep-ph 1404.1927 : E. Dudas, L. H., Y. Mambrini



- XMN- Newton telescope : Xray spectrum from galaxy clusters

Claims from two different analysis :

- Bulbul *et al.*

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DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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- Boyarsky *et al.*

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

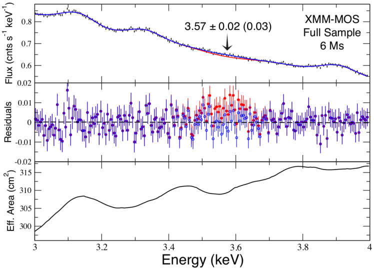
A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

Datas coming from several astrophysical sources

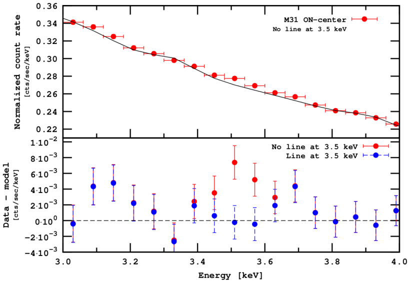
XMN-Newton telescope
Chandra telescope

Bulbul *et al.*	Boyarski *et al.*
73 clusters (centers only)	M31 galaxy (center and outskirts)
Perseus cluster (center only)	Perseus cluster (outskirts only)
Virgo cluster (center only)	blank sky

$\longrightarrow$ γ-ray line at 3.5 keV (>3 σ significance)

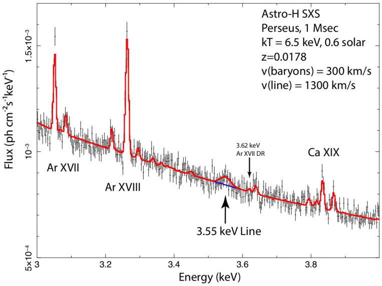


Bulbul *et al.*



Boyarski *et al.*rray

Good agreement for the Perseus cluster



Flux :

$$\phi_{Perseus} \sim 5.2 \times 10^{-5} ph.cm^{-2}.s^{-1}$$

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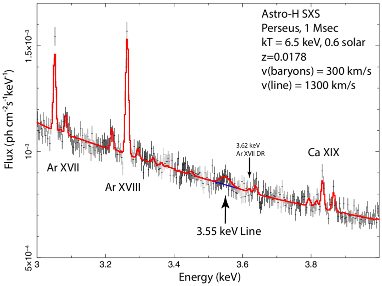

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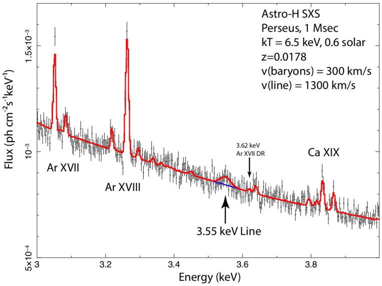

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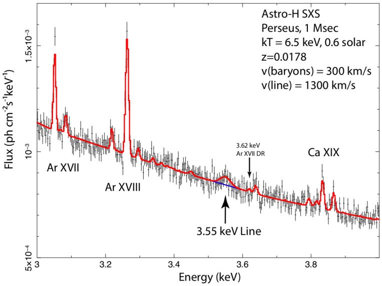
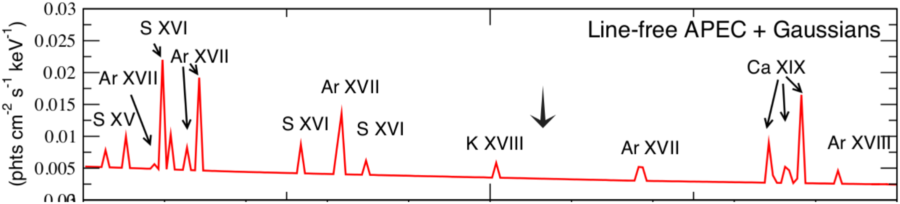


Flux :

$$\phi_{Perseus} \sim 5.2 \times 10^{-5} ph.cm^{-2}.s^{-1}$$

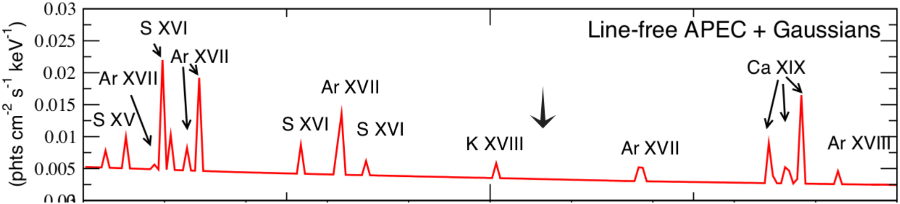
- Detected in 4 different detectors
- Line redshifts correctly with sources
- Not detected in blank sky dataset

Challenging background substraction



$\longrightarrow$ Many atomic transitions lines around...

Challenging background substraction



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Jeltema and Profumo : *"Dark matter searches going bananas : the contribution of Potassium (and Chlorine) to the 3.5 keV line"*

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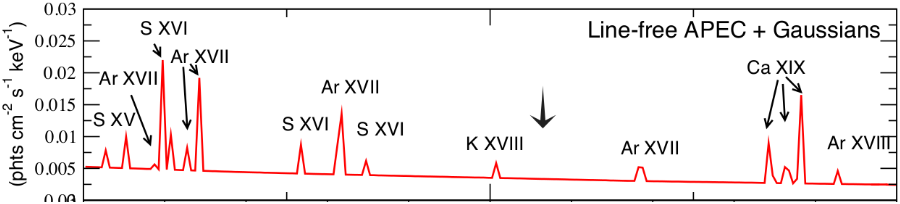

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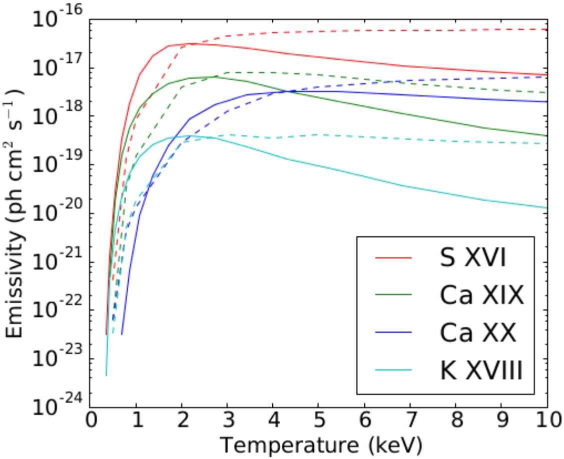
Bulbul et al.'s reaction :

Challenging background substraction

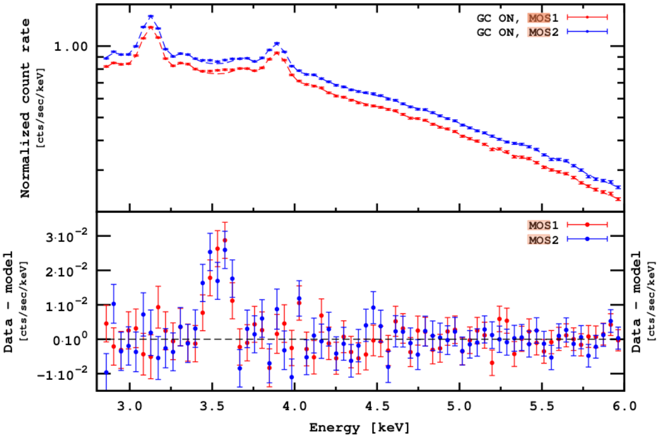
Indeed, Jeltema and Profumo : $\epsilon(T) = \epsilon(T_{peak})N(T)/N(T_{peak})$

Overestimation of emissivity :



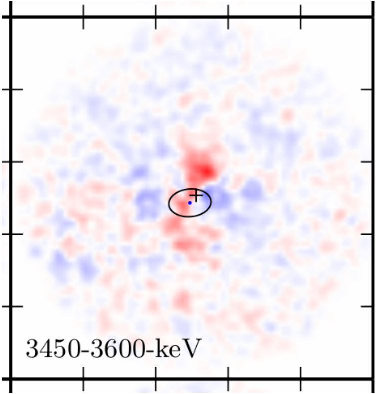
What's up in our Galaxy ?

Boyarsky *et al.* (August 2014) :



Problems of profile...

Carlson, Jeltema, Profumo : profile of emission not compatible with an annihilating or decaying scenario



Known astrophysical interpretation ?

A priori no ... but many dark matter candidates !

- Decaying DM (Sterile neutrino, gravitino, ALP, axinos,...)
- State transitions (EXciting DM, dark atoms, ...)
- ...

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↪ Annihilating dark matter ?

Conventional wisdom :

Main ingredient : $\phi_{\gamma\gamma}^{exp} \sim 5.2 \times 10^{-5}\ \mathrm{ph.cm^{-2}.s^{-1}}$ [Boyarski et al.]

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To compare with

$$\phi_{\gamma\gamma} = \frac{L}{(4\pi D_{Pe}^2)}$$

where

$$L = \int_0^{R_{Pe}} 4\pi r^2 n_{DM}^2 \langle \sigma v \rangle_{\gamma\gamma} = \int_0^{R_{Pe}} 4\pi r^2 \left(\frac{\rho(r)}{m_s} \right)^2 \langle \sigma v \rangle_{\gamma\gamma}$$

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Simplest profile :

$$L \simeq 1.2 \times 10^{55} \left(\frac{3.5\ \mathrm{keV}}{m_s} \right)^2 \left(\frac{\langle \sigma v \rangle_{\gamma\gamma}}{10^{-26}\mathrm{cm^3 s^{-1}}} \right)\ \mathrm{ph.s^{-1}}$$

Flux condition : $\phi^{th}_{\gamma\gamma} \;=\; \phi^{exp}_{\gamma\gamma}$

where

$$\phi^{th}_{\gamma\gamma} = 1.7\times 10^{-5}\left(\frac{3.5\ \mathrm{keV}}{m_s}\right)^2\left(\frac{\langle\sigma v\rangle_{\gamma\gamma}}{10^{-32}\mathrm{cm}^3\mathrm{s}^{-1}}\right)\ \mathrm{ph.cm}^{-2}.\mathrm{s}^{-1}$$

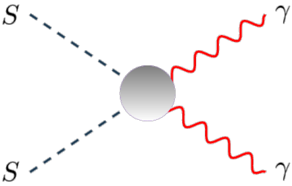
$$\phi^{exp}_{\gamma\gamma} = 5.2^{+3.70}_{-2.13}\times 10^{-5}\ \mathrm{ph.cm}^{-2}.\mathrm{s}^{-1}$$

$$\hookrightarrow \quad \langle\sigma v\rangle_{\gamma\gamma} \simeq (2\times 10^{-33} - 4\times 10^{-32})\ \mathrm{cm}^3\mathrm{s}^{-1}$$

+ CMB constraints :

$$\longrightarrow \quad \boxed{2\times 10^{-33}\ \mathrm{cm}^3\mathrm{s}^{-1} \;<\; \langle\sigma v\rangle_{\gamma\gamma} \;<\; 8.5\times 10^{-33}\ \mathrm{cm}^3\mathrm{s}^{-1}}$$

Usual effective approach :



$$\frac{S^2}{\Lambda^2} F_{\mu\nu} F^{\mu\nu}$$

$$\longrightarrow \qquad \langle \sigma v \rangle^{eff}_{\gamma\gamma} = \frac{2 m_s^2}{\pi \Lambda^4}$$

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{exp} \quad \Rightarrow \quad \Lambda \in [10 - 15]\mathrm{GeV} \ \ldots$$

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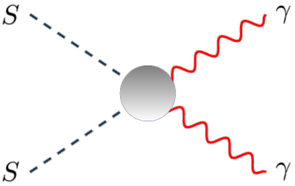

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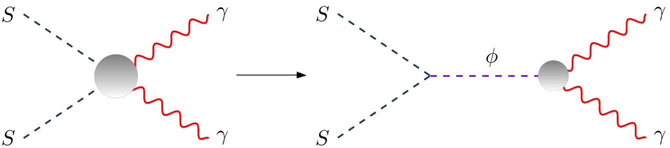
WRONG APPROACH : light fields can be involved in the game !

Introduce a mediator ϕ



$$\mathcal{L}_{eff} \supset -\frac{m_s^2}{2} S^2 - \frac{m_\phi^2}{2}\phi^2 - \tilde{m}\,\phi\, S^2 + \frac{\phi}{\Lambda} F_{\mu\nu} F^{\mu\nu}$$

↪ $m_s = 3.5\ \mathrm{keV}$, and $(m_\phi,\ \tilde{m},\ \Lambda)$ free parameters ?

An explicit UV model

$$\mathcal{L} = \mathcal{L}_{kin} + \frac{\mu^2}{2}(\sigma^2 + S^2) - \frac{\lambda}{4}(\sigma^2 + S^2)^2 - \bar{\psi}(h_1\sigma + ih_2 S\gamma_5)\psi + \frac{\sigma}{\Lambda}F_{\mu\nu}F^{\mu\nu}$$

↪ ψ : hidden sector, SM singlets

With $\Phi \equiv \frac{1}{\sqrt{2}}(\sigma + iS)$

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 \text{ , where}$$
$$\mathcal{L}_0 = \mathcal{L}_{kin} + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 - (h_1\bar{\psi}_L\Phi\psi_R + \text{h.c.}) \ ,$$
$$\mathcal{L}_1 = i(h_1 - h_2)\ S\ \bar{\psi}\gamma_5\psi + \frac{\sigma}{\Lambda}F_{\mu\nu}F^{\mu\nu} \ .$$

⟶ Look at the symmetries...

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$\mathcal{L}$ invariant under

$$U(1)_V \quad : \quad \psi \to e^{i\alpha}\psi \quad , \quad \Phi \to \Phi \ ,$$

whereas only $\mathcal{L}_0$ invariant under

$$U(1)_A \quad : \quad \psi \to e^{i\beta\gamma_5}\psi \quad , \quad \Phi \to e^{-2i\beta}\Phi \ .$$

$\longrightarrow$ Exact symmetry if $h_1 = h_2$

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Theoretical expectation : $\tilde{m} \lesssim m_\phi$

The model

$$\mathcal{L}_{eff} \supset -\frac{m_s^2}{2} S^2 - \frac{m_\phi^2}{2} \phi^2 - \tilde{m}\, \phi\, S^2 + \frac{\phi}{\Lambda} F_{\mu\nu} F^{\mu\nu}$$

- $m_s = 3.5\ \mathrm{keV}$
- $\tilde{m} \lesssim m_\phi$
- $\Lambda \gtrsim 5 - 50\ \mathrm{TeV}$

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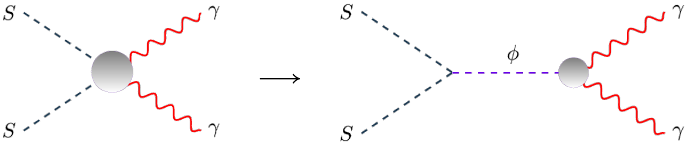


$$\langle \sigma v \rangle_{\gamma\gamma}^{eff} = \frac{2m_s^2}{\pi\Lambda^4} \quad \longrightarrow \quad \langle \sigma v \rangle_{\gamma\gamma}^{micro} = \frac{1}{\Lambda^2}\underbrace{\left(\frac{4m_s^2\tilde{m}^2}{\pi(4m_s^2 - m_\phi^2)^2}\right)}_{\text{can be big!}}$$

Two cases :

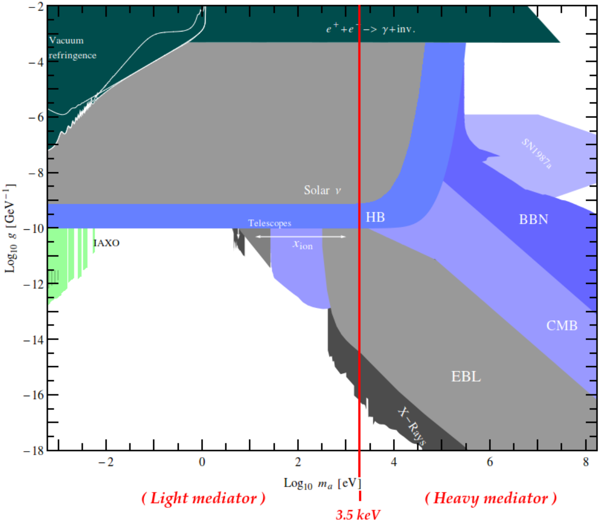
◇ Heavy mediator : $m_\phi \gtrsim m_s$

$$\hookrightarrow \quad m_\phi \simeq (12.3 - 17.6)\sqrt{\frac{m_s}{3.5\ \text{keV}}}\sqrt{\frac{\tilde{m}}{\Lambda}}\ \text{GeV}$$

◇ Light mediator : $m_\phi \lesssim m_s$

$$\hookrightarrow \quad \frac{\tilde{m}}{\Lambda} \sim (1.63 - 3.36) \times 10^{-13}$$

Constraints on scalar particle coupling to photons :



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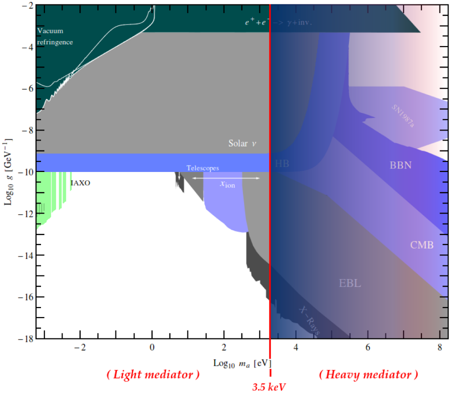

Light mediator : $\Lambda \gtrsim 10^{10}$ GeV $\Rightarrow$ $\tilde{m} \gtrsim$ MeV $\gg m_\phi$ ... Excluded

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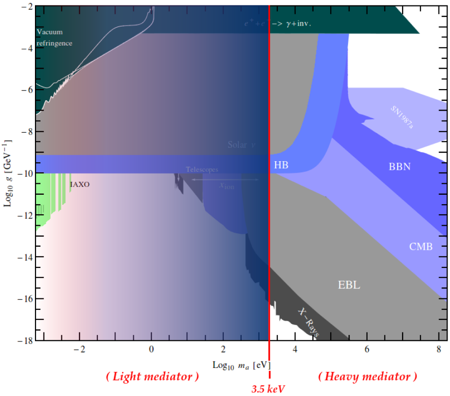

Heavy mediator :

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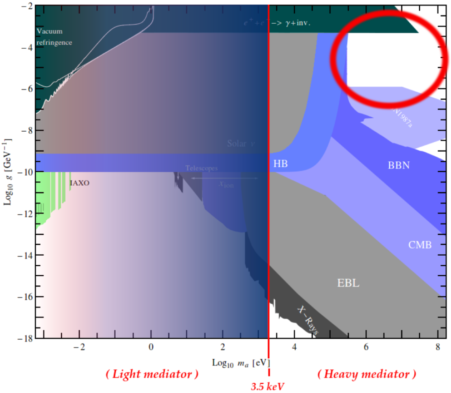

Heavy mediator : $[\Lambda \gtrsim 3\text{TeV}, m_\phi \gtrsim 300\text{keV}]$

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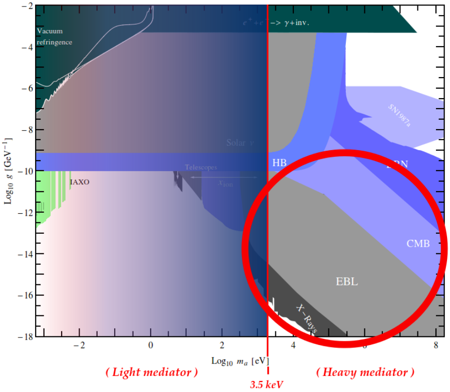
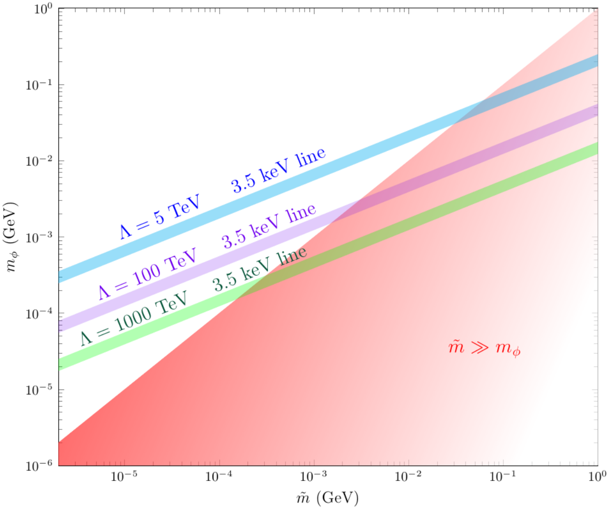


Heavy mediator : $[\Lambda \gtrsim 3\text{TeV}, m_\phi \gtrsim 300\text{keV}]$

or $[\Lambda \gtrsim 10^{8-10}\text{GeV}, \tilde{m} \gg m_\phi] \to$ ... Excluded


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
m_ϕ (GeV)
$\Lambda = 5$ TeV
3.5 keV line
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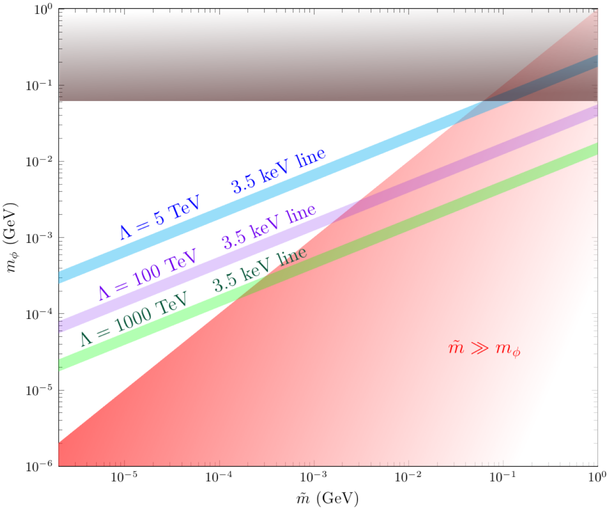
$\tilde{m} \gg m_\phi$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$\tilde{m}$ (GeV)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10^{-1}
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10^{-4}
10^{-5}
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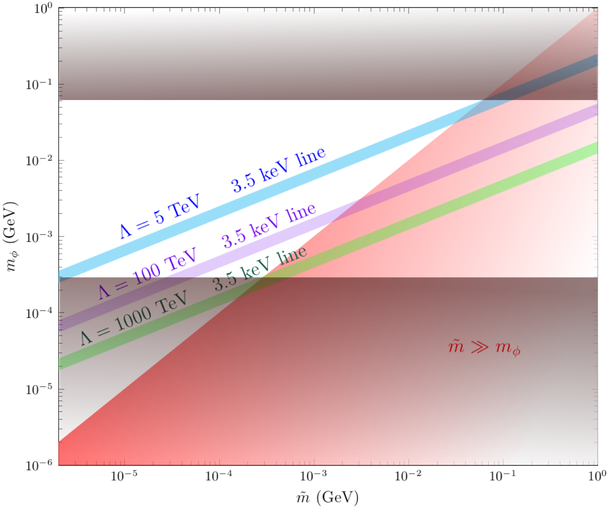

$m_\phi \gtrsim 300$ keV and $\Lambda \gtrsim 5$ TeV $\longrightarrow m_\phi \in [300\text{keV} - 50\text{MeV}]$

A lack of production...

Flux : $\langle \sigma v \rangle_{\gamma\gamma} \sim 10^{-33}\ \mathrm{cm^3 s^{-1}}$

Relic abundance : $\langle \sigma v \rangle_{\gamma\gamma} \sim 10^{-26}\ \mathrm{cm^3 s^{-1}}$ needed...

↪ Hot scenario ?
↪ FIMP scenario ?
↪ Alternative channels of annihilation required.

For instance : Sterile neutrino production

$$-\mathcal{L}_\nu = \frac{M}{2}\nu_R \nu_R + m_D \nu_L \nu_R + \lambda_\nu \phi \nu_R \nu_R + h.c.$$

Assuming $M \ll m_s$:

$$\langle \sigma v \rangle_{\nu\nu} \sim \frac{\lambda_\nu^2}{8\pi^2}\left(\frac{\tilde{m}}{m_s}\right)^2 \frac{m_s^2}{(4m_s^2 - m_\phi^2)^2}$$

Hidden temperature ?

Scalar DM, Sterile neutrinos $\longrightarrow$ a hidden bath at $T_h = \xi(t)\, T_v$

$\hookrightarrow$ New ranges of relic density allowed [Das et al., Feng et al.]

$$0.015\, \langle \sigma v \rangle_0 \lesssim \langle \sigma v \rangle \lesssim 0.045\, \langle \sigma v \rangle_0$$

- Tremaine-Gun bound : Hidden temperature cannot be too low
- Free streaming length : High temperature $\rightarrow$ high velocities, can destroy large scale structures..

Hidden temperature ?

Scalar DM, Sterile neutrinos $\longrightarrow$ a hidden bath at $T_h = \xi(t)\, T_\nu$

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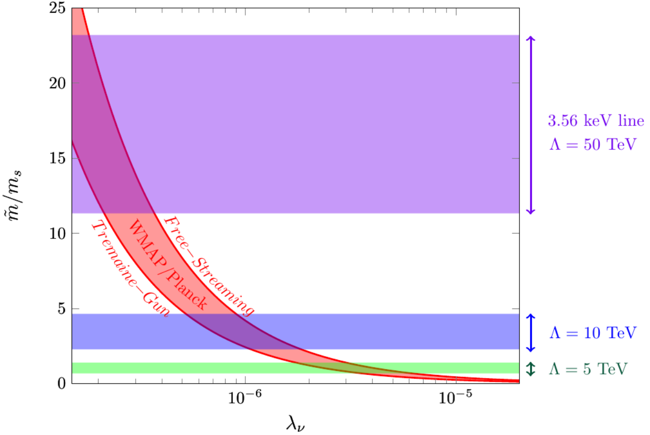

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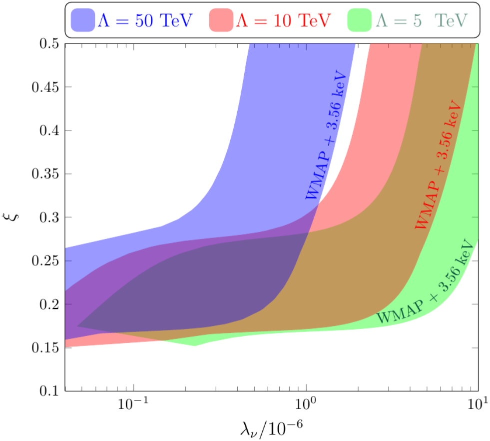

Conclusions and outlooks

- Annihilating DM hard to handle but still possible to achieve with light intermediate fields,
- Prediction of a light scalar particle coupling to photons of mass $m_\phi \in [300\mathrm{keV} - 50\mathrm{MeV}]$,
- Possible to fit relic density constraints with hidden channels such as sterile neutrinos, other channels can be investigated,
- Hidden thermal baths features give freedom on the relic density to match with, which should be studied in more evolved dynamical simulations...

Thanks !