Cosmological imprints of non-thermalized dark matter

in collaboration with
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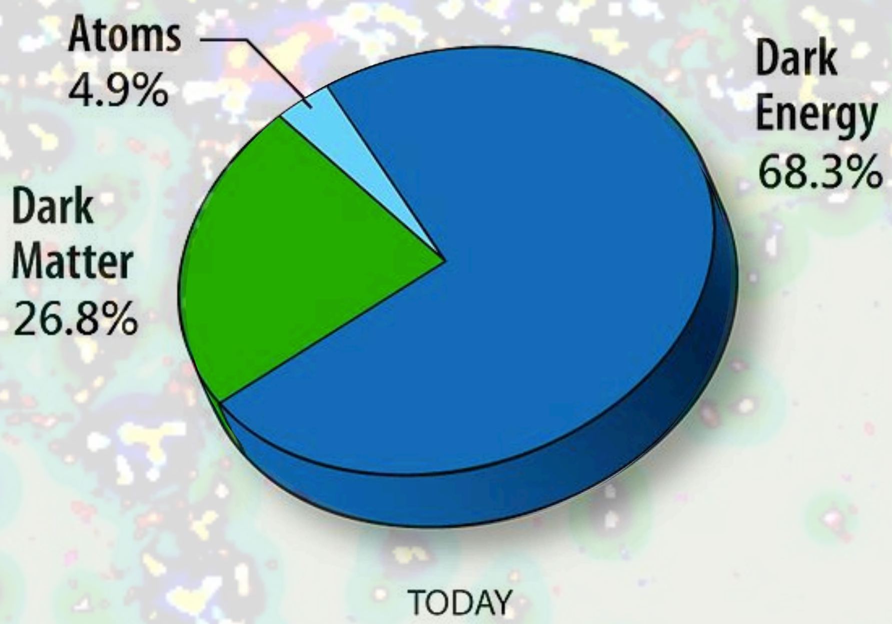
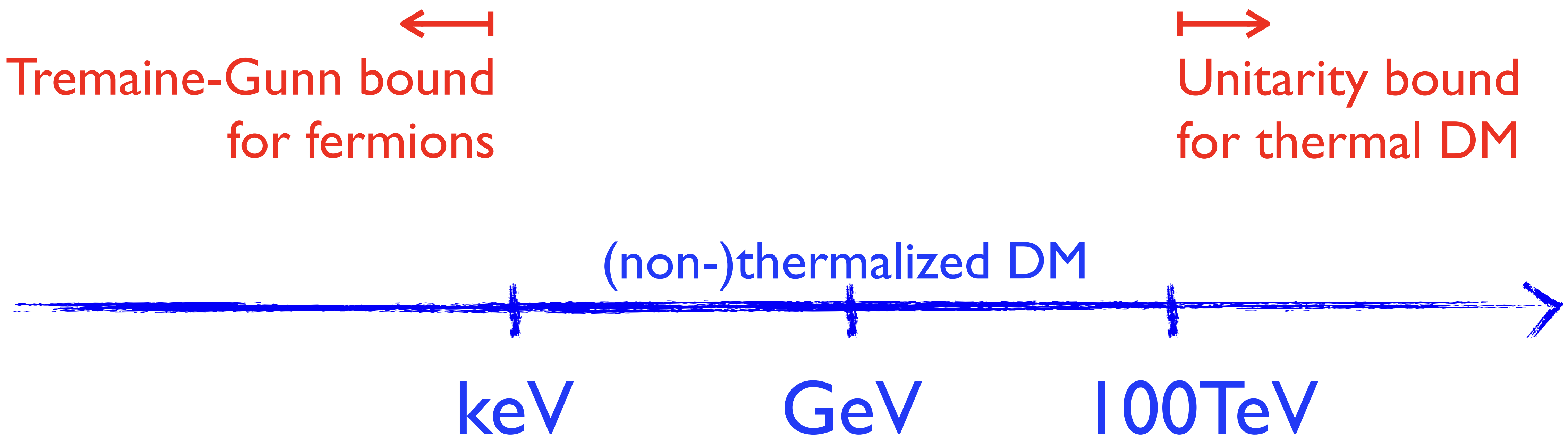
VIRTUAL EDITION

“Invisible threads are the strongest ties.”

Friedrich Nietzsche (1844-1900)



Dark matter: What is it?



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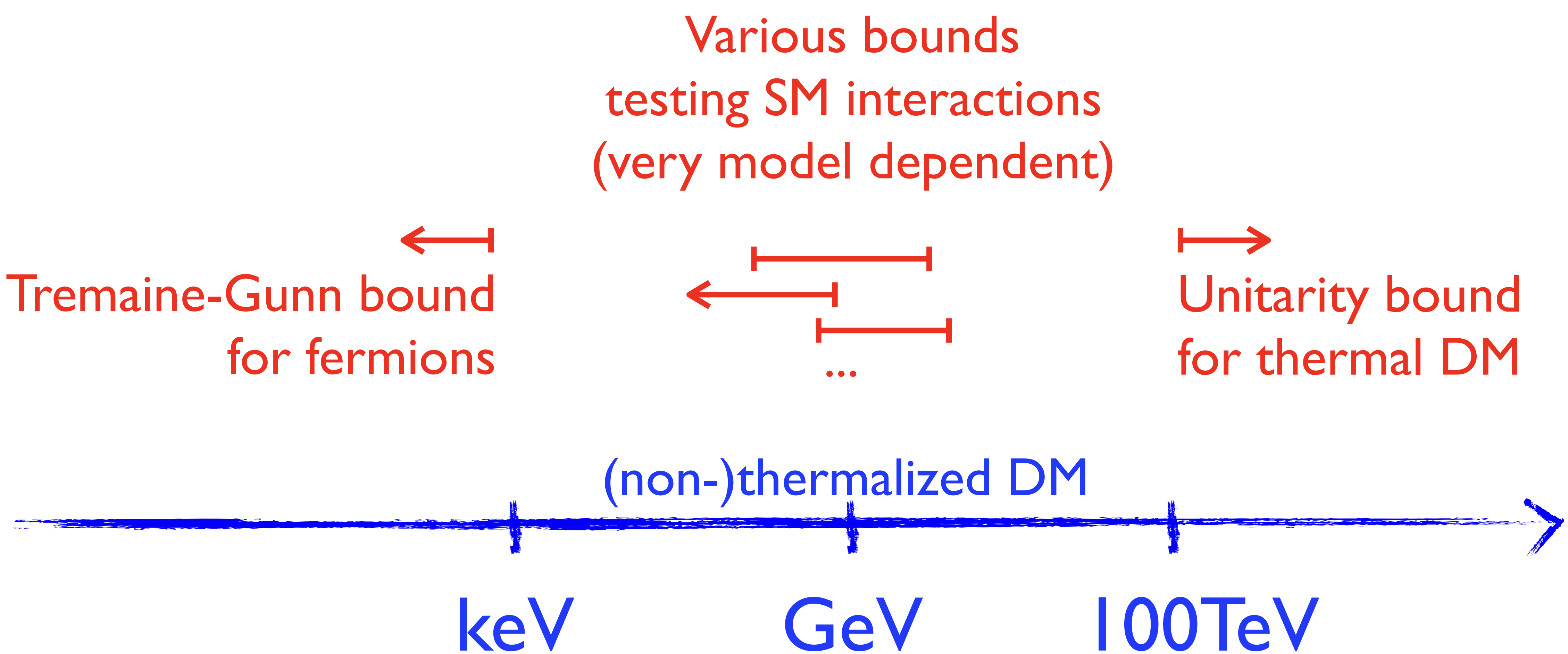
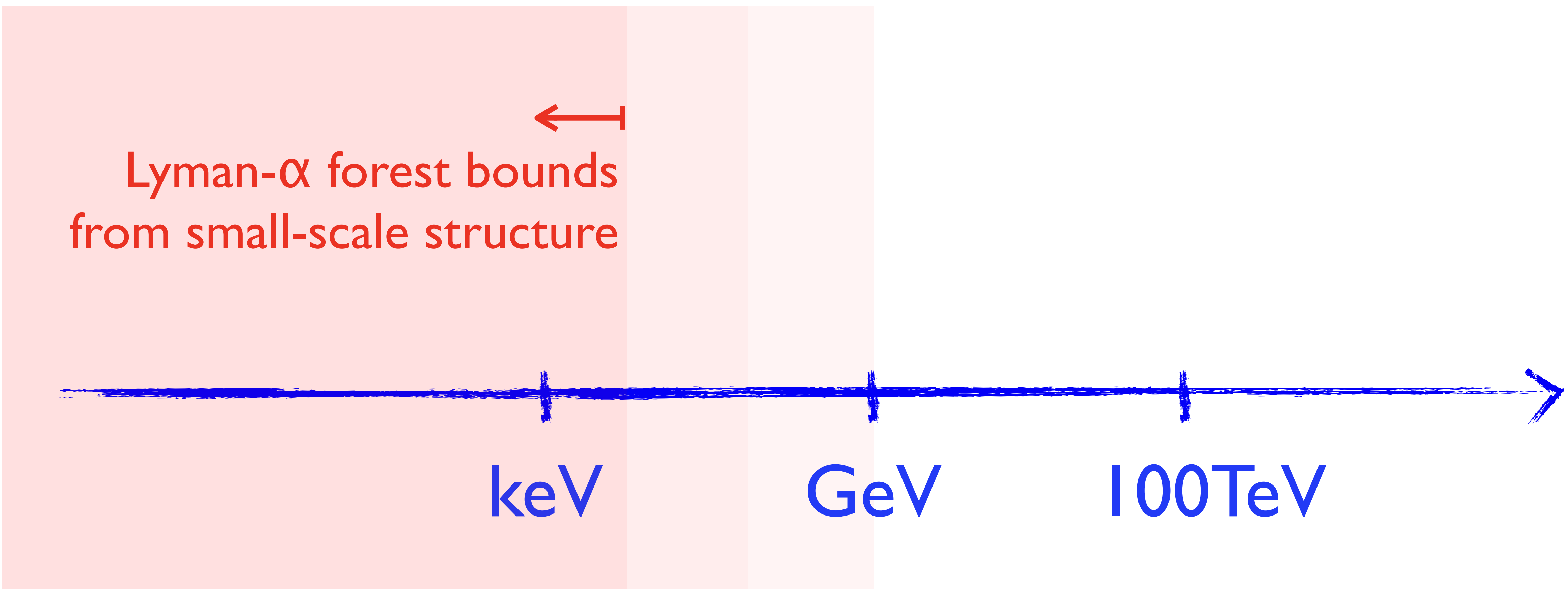


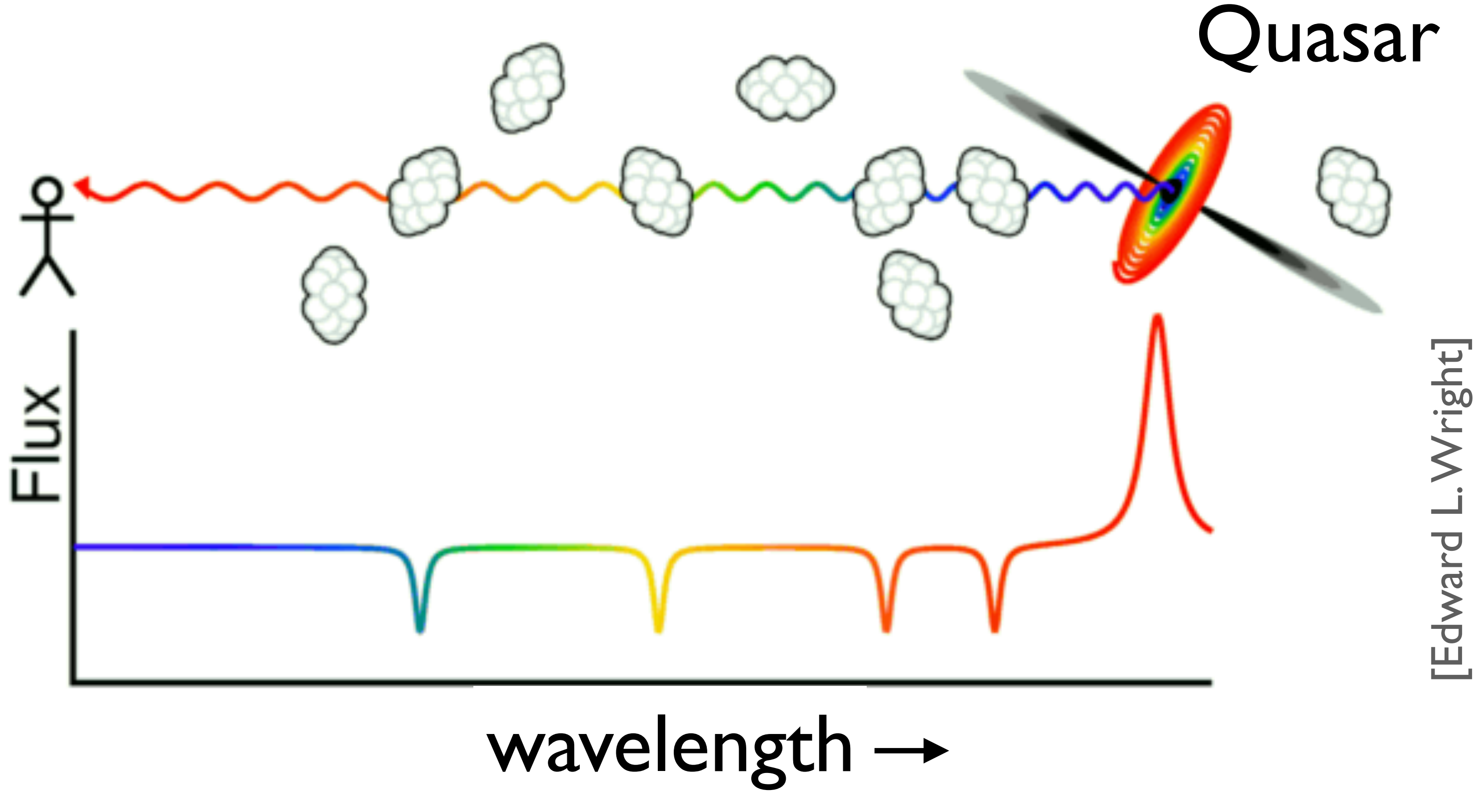
Dark matter: What is it?

Considered here:



Lyman-α forest observations

$2 \lesssim z \lesssim 6$



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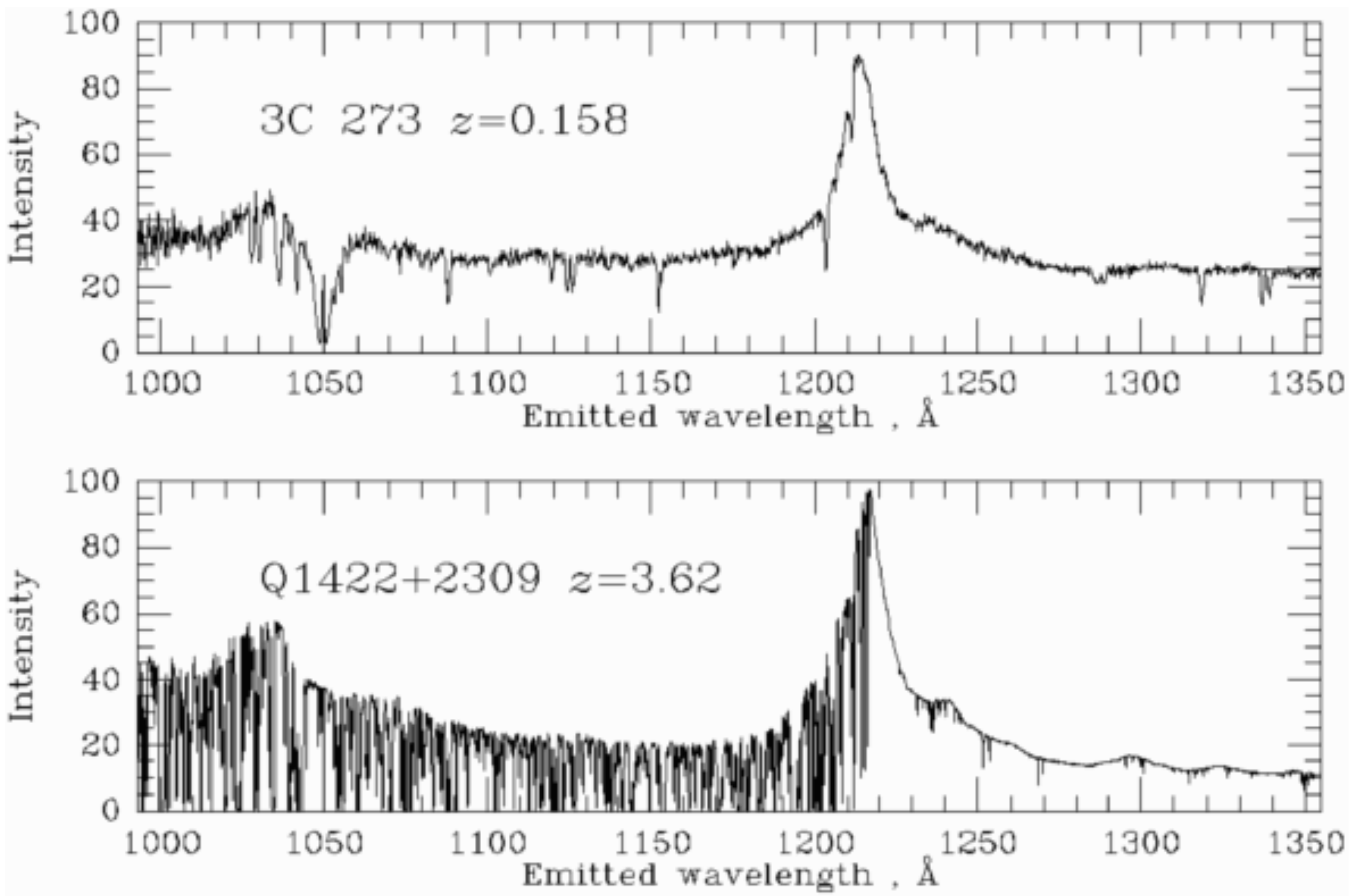
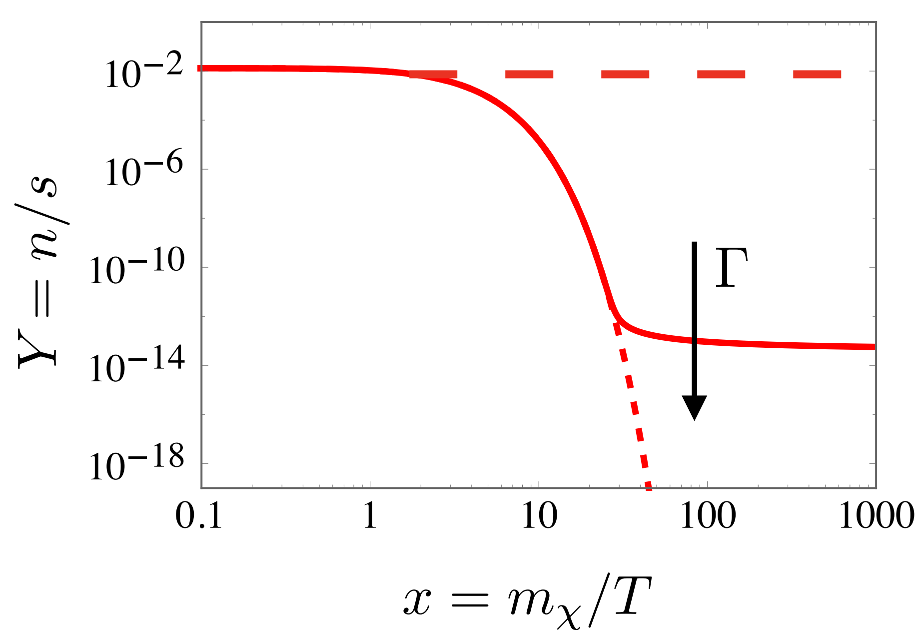


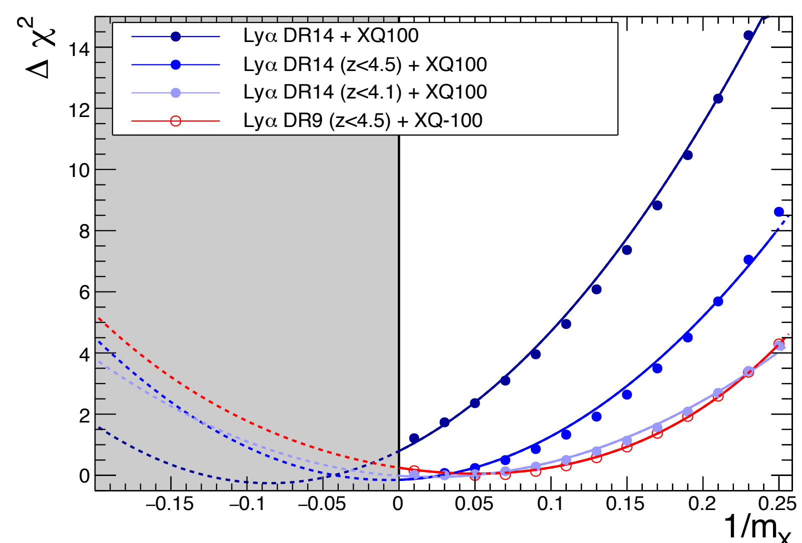
[Bill Keel]

Lyman-α constraints on dark matter

[Palanque-Delabrouille *et al.* 1911.09073]

- Recent analysis of 1D Lyman-α flux power spectrum based on SDSS DR14 BOSS/ BOSS data
- Hydrodynamical simulation based on [Baur et al.1512.01981]
- Interpreted in thermal dark matter or 'warm dark matter' (WDM)





$$\Rightarrow m_{\mathrm{WDM}} > 5.3\,\mathrm{keV}$$

[*but see also* Garzilli, Ruchayskiy, Magalich, Boyarsky, 1912.09397]

Non-thermalized dark matter

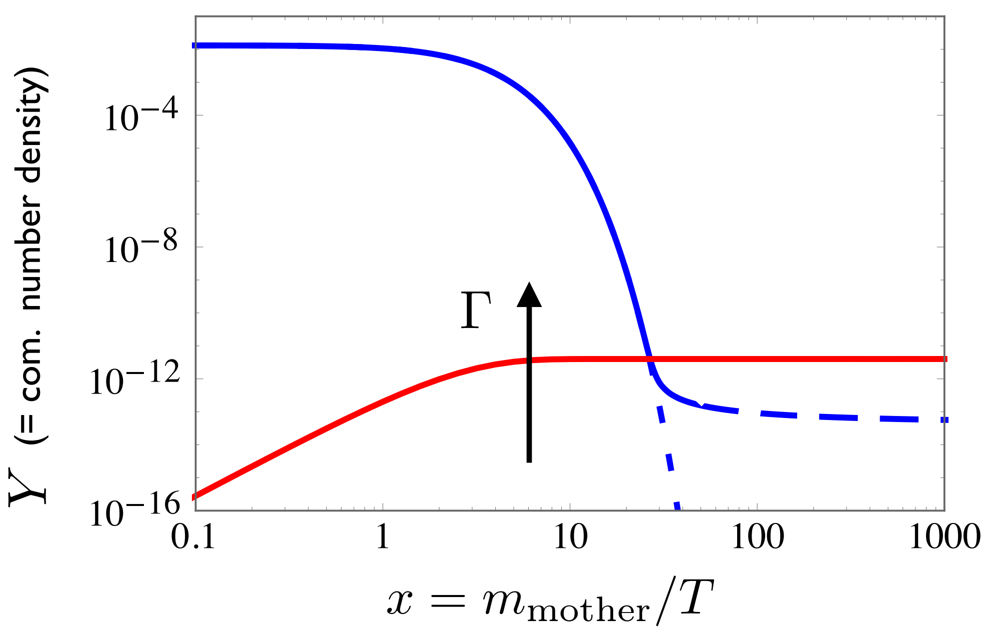
or Feebly Interacting Massive Particles (FIMPs)

- Only production, no annihilation
- Dependence on initial conditions (inflation/reheating)
- Additional assumptions to be made, here:
  Vanishing initial abundance

Freeze-in production

- Occasional production from thermal bath
- Here: IR-sensitive scenario:
  (renormalizable operators)

[Bolz, Buchmüller, Plümacher 1998;
Bolz, Brandenburg, Buchmüller 2001;
Pradler, Steffen 2006]



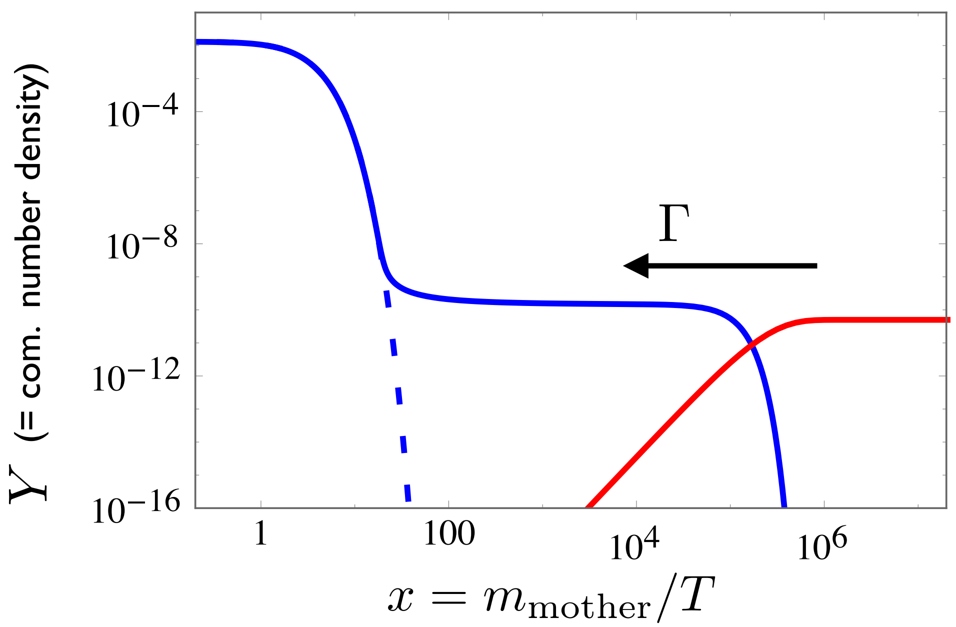
[McDonald 2002;
Covi, Roszkowski, Small 2002;
Choi, Roszkowski 2005;
Asaka, Ishiwata, Moroi 2006;
Petraki, Kusenko 2008;
Hall, Jedamzik, March-Russell, West, 2009]

SuperWIMP production

- Late decay of frozen-out particle

[Covi, Kim, Roszkowski 1999; Feng, Rajaraman, Takayama 2003]

- DM density independent of DM coupling



$$(\Omega h^2)_\chi = m_\chi / m_{\mathrm{mother}} \, (\Omega h^2)_{\mathrm{mother}}$$

<u>Only</u> if M ➔ SM SM forbidden (Z_2 symmetry)

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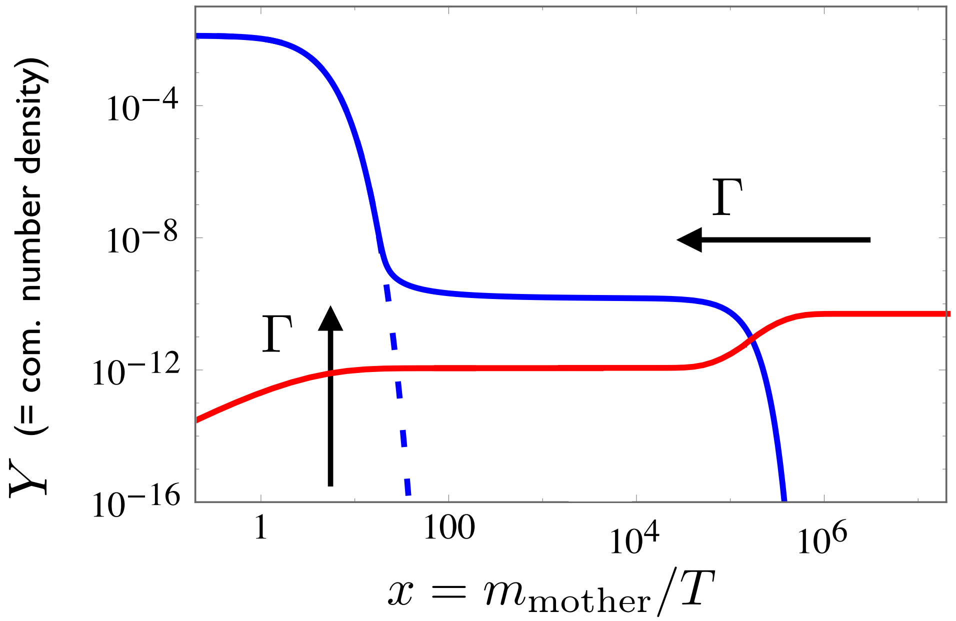

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Freeze-in in general <u>always</u> present!

Lyman-alpha constraints

- Three ways of using the WDM results for non-thermal dark matter:

1) Free streaming length:

$$\lambda_{\rm fs} = \int_0^{z_{\rm prod}} {\rm d}z \, \frac{\langle v \rangle (z)}{H(z)}$$

- Consider characteristic mean velocity or velocity dispersion
- Compare WDM to non-thermal DM, we obtain:

$$m_\chi^{\rm FI} \gtrsim 16\,{\rm keV} \times \delta \qquad \text{for FI through decays,}$$

$$m_\chi^{\rm SW} \gtrsim 3.8\,{\rm keV} \times \delta \left(R_\Gamma^{\rm SW}\right)^{-1/2} \qquad \text{for SW,}$$

$$\delta = \frac{m_B^2 - m_A^2}{m_B^2}$$

$$R_\Gamma = \frac{M_0 \Gamma_{B \to A\chi}}{m_B^2}$$

- Difficult for mixed superWIMP-freeze-in scenario

[*see also* Bae, Kamada, Liew, Yanagi, 2018; Ballesteros, Garcia, Pierre, 2021; ...]

Lyman-alpha constraints

2) Parametrization of the transfer function

[Bode, Ostriker, Turok, 2001; Viel, Lesgourgues, Haehnelt, Matarrese Riotto, 2005]

- Consider transfer function, computed with CLASS [Lesgourgues *et al.* 2011]

$$T_X^2(k) = \frac{P_X(k)}{P_{\rm CDM}(k)}$$ where $P(k)$ = power spectrum

- Fit transfer function with

$$T_X(k) = \left(1 + (\alpha_X k)^{2\mu}\right)^{-5/\mu}$$

- Freeze-in and superWIMP well fitted with $\mu = 1.12$ and

$$\alpha_{\rm FI} \propto \left(\frac{m_\chi}{\delta}\right)^{-0.833}, \ \ \alpha_{\rm SW} \propto R_\Gamma^{-0.416} \left(\frac{m_\chi}{\delta}\right)^{-0.833}$$

- Compare to WDM bounds, for freeze-in ($\delta = 1$):

$$m_{\rm FI} > 15.2\,{\rm keV}$$

Lyman-alpha constraints

3) Area criterium [Schneider 2016, Murgia, Merle, Viel, Totzauer, Schneider 2017]

- Consider ratio of 1D power spectra, computed with CLASS

$$r(k) = \frac{P_{1D}^{X}(k)}{P_{1D}^{\mathrm{CDM}}(k)} \quad \text{with} \quad P_{1D}^{X}(k) = \int_k^\infty dk'\, k'\, P_X(k')\,,$$

- Compute area under the curve

$$A_X = \int_{\mathrm{k_{min}}}^{k_{\max}} dk'\, r(k')$$

and

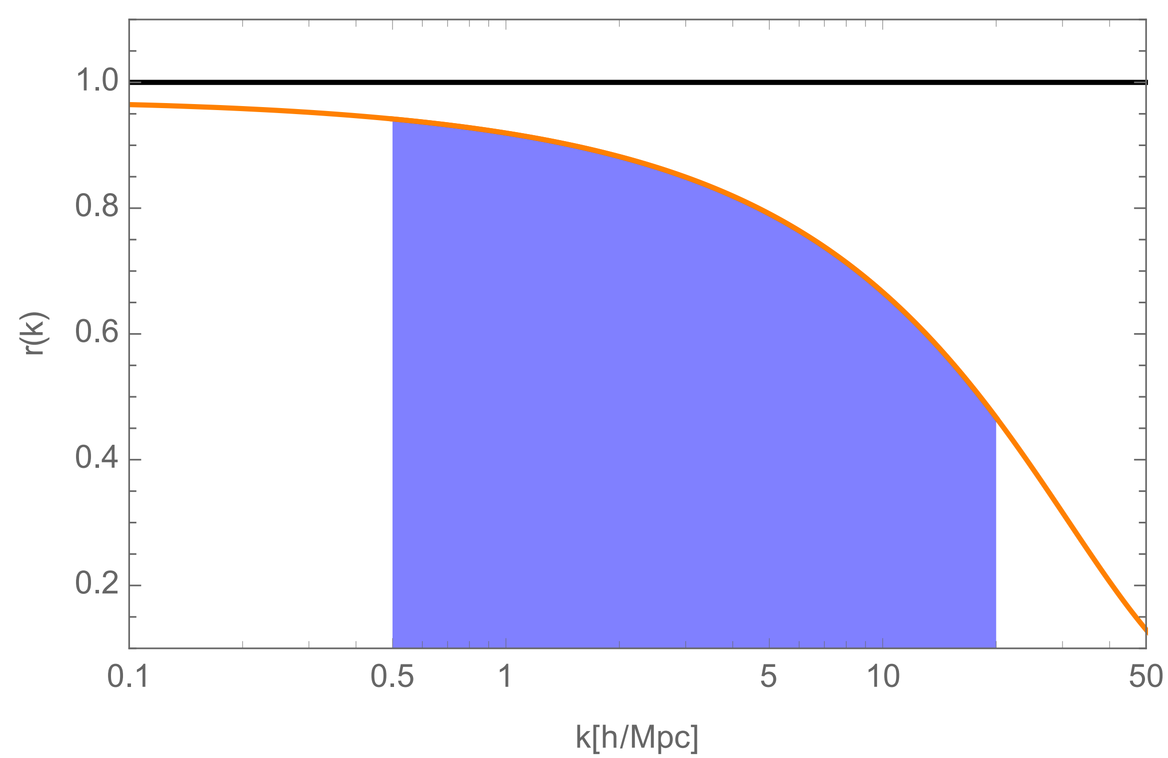
$$\delta A_X = \frac{A_{\mathrm{CDM}} - A_X}{A_{\mathrm{CDM}}}$$

- For freeze-in ($\delta = 1$):

$$m_{\mathrm{FI}} > 15.3\,\mathrm{keV}$$

- Suitable for mixed scenario

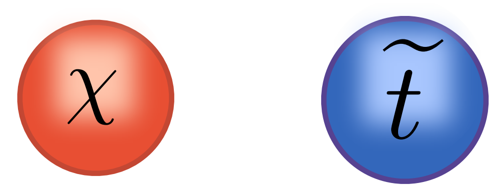
$$\delta A_{\mathrm{WDM}} = 0.33 \quad \text{for} \quad m_{\mathrm{WDM}} = 5.3\,\mathrm{keV}$$



[*see also* D'Eramo, Lenoci, 2020; Egana-Ugrinovic, Essig, Gift, LoVerde 2021]

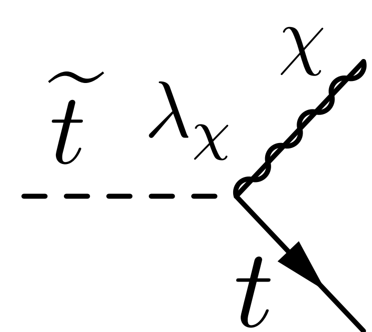
Explicit Example: Top-philic model

- Specific model: $\mathcal{L}_{\mathrm{int}} = |D_\mu \widetilde{q}|^2 - \lambda_\chi \widetilde{q}\bar{q}\frac{1-\gamma_5}{2}\chi + \mathrm{h.c.}$
- SUSY-inspired simplified model:
  Choose Majorana DM and scalar top-partner



[Provides rich phenomenology, see Garny, JH, Hufnagel, Lülf 1802.00814]

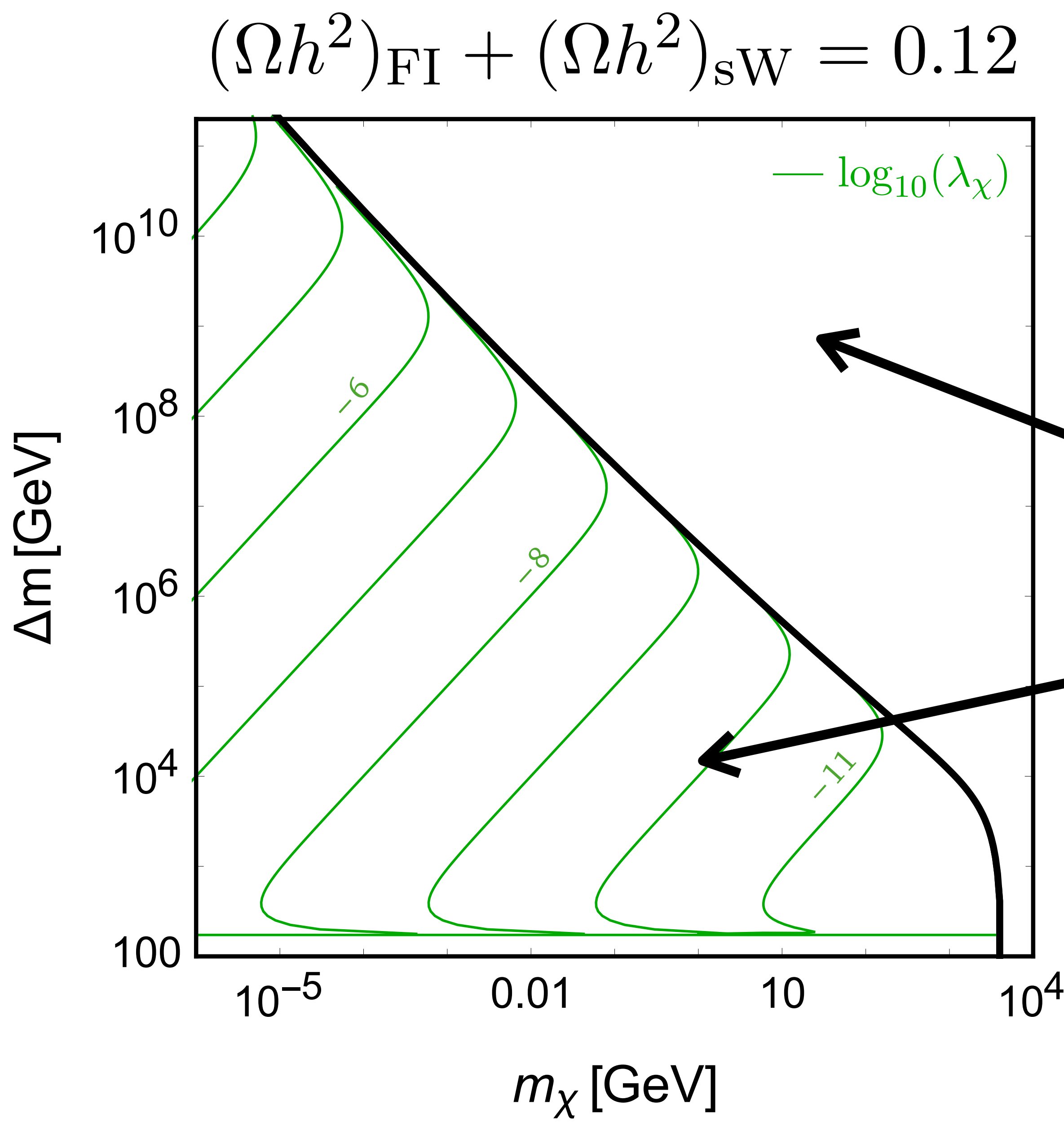
- Yukawa-type interaction:



λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

Top-philic model: viable parameter space

[*see also* Garny, JH, 1809.10135]



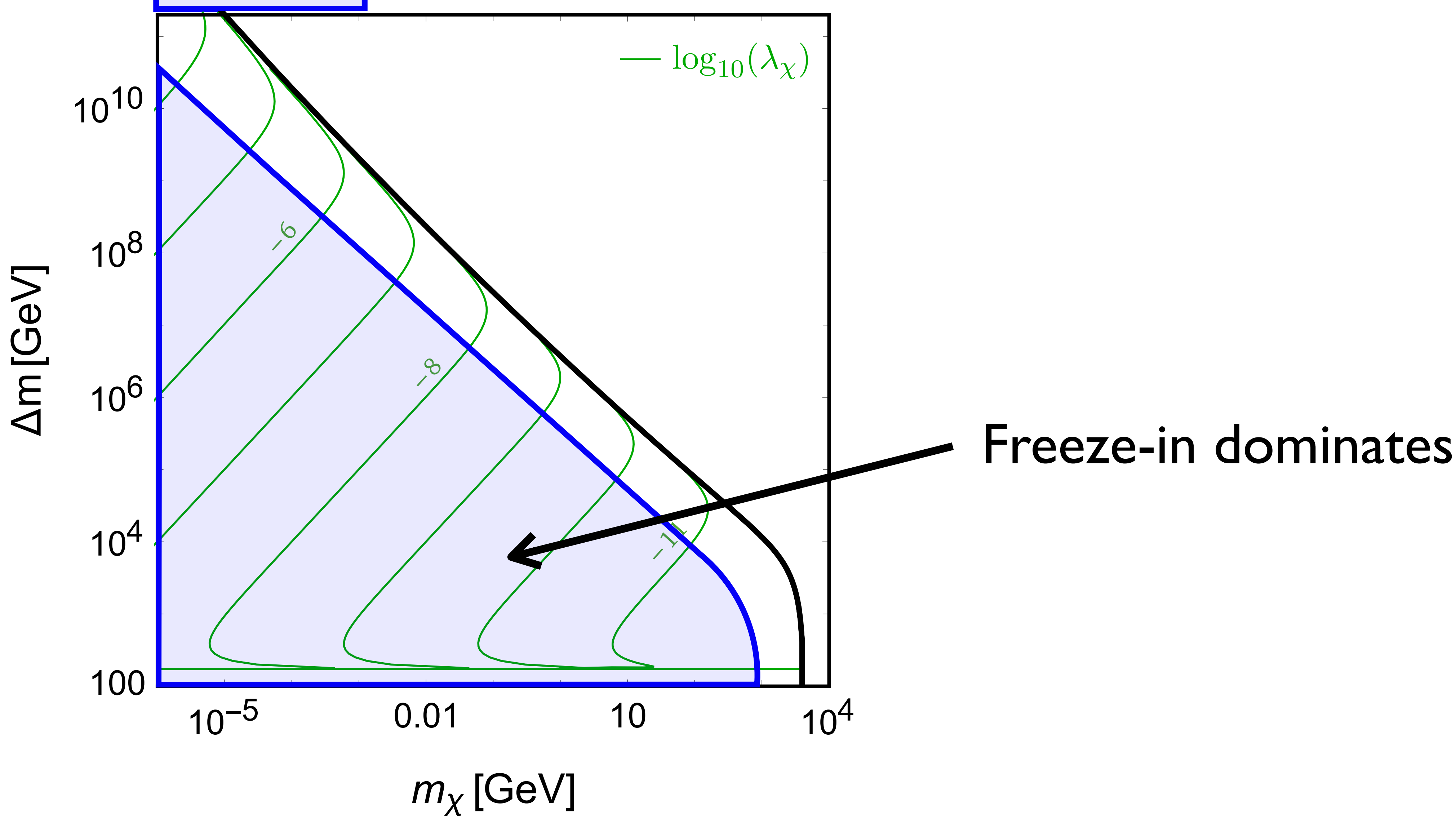
Over-abundant

Cosmological viable parameter space

Top-philic model: viable parameter space

[*see also* Garny, JH, 1809.10135]

$\boxed{(\Omega h^2)_{\rm FI}} + (\Omega h^2)_{\rm sW} = 0.12$



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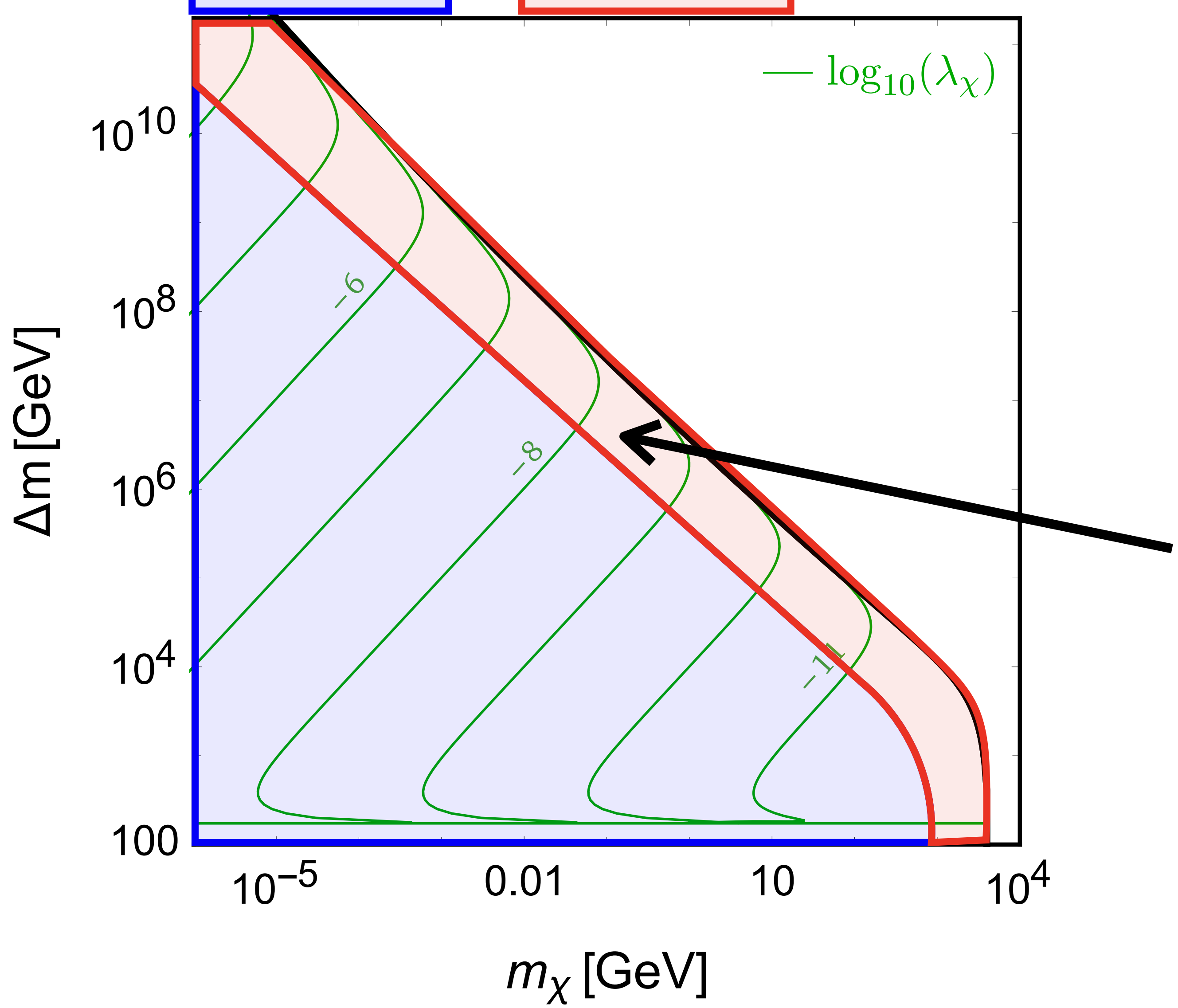

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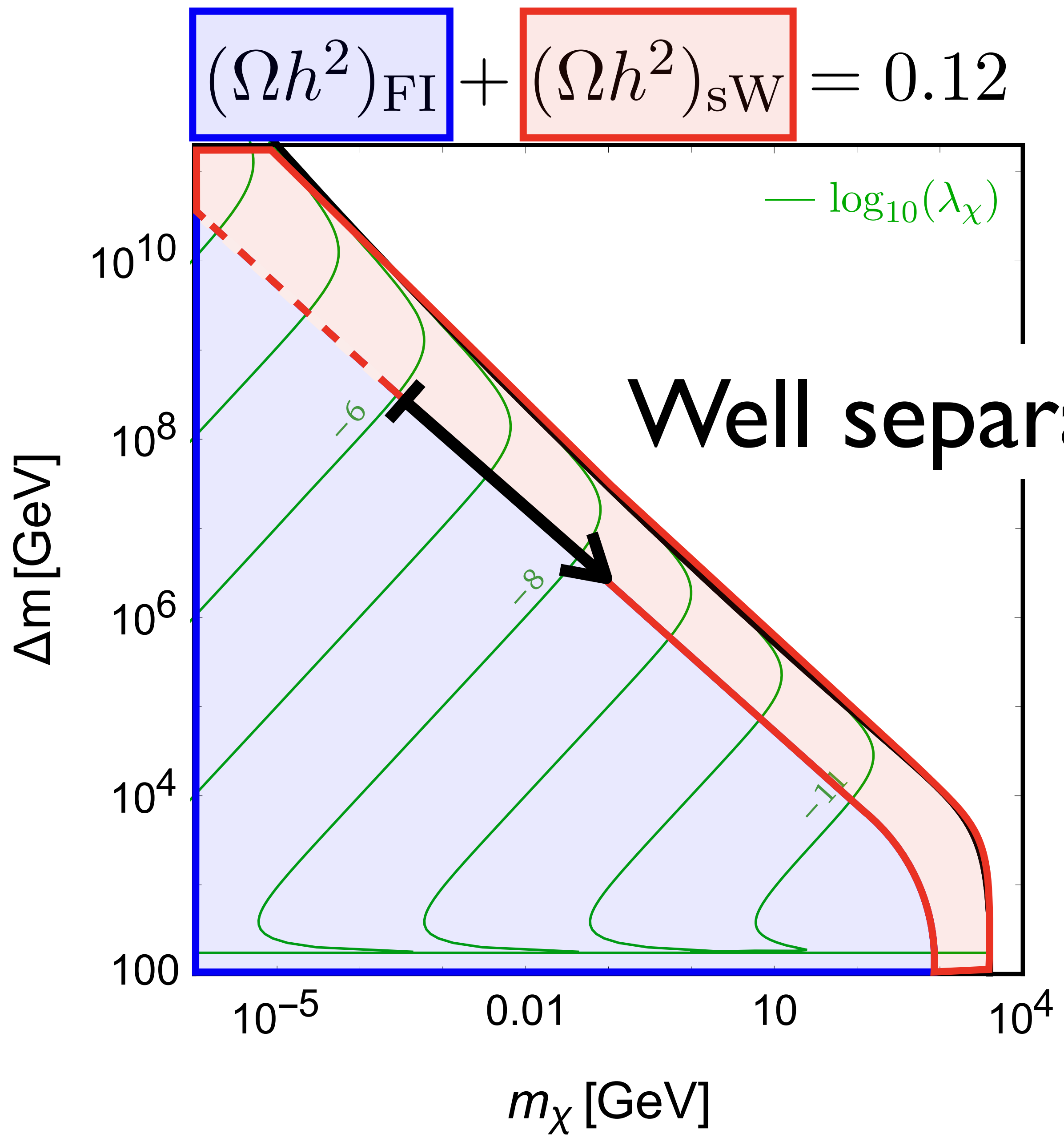
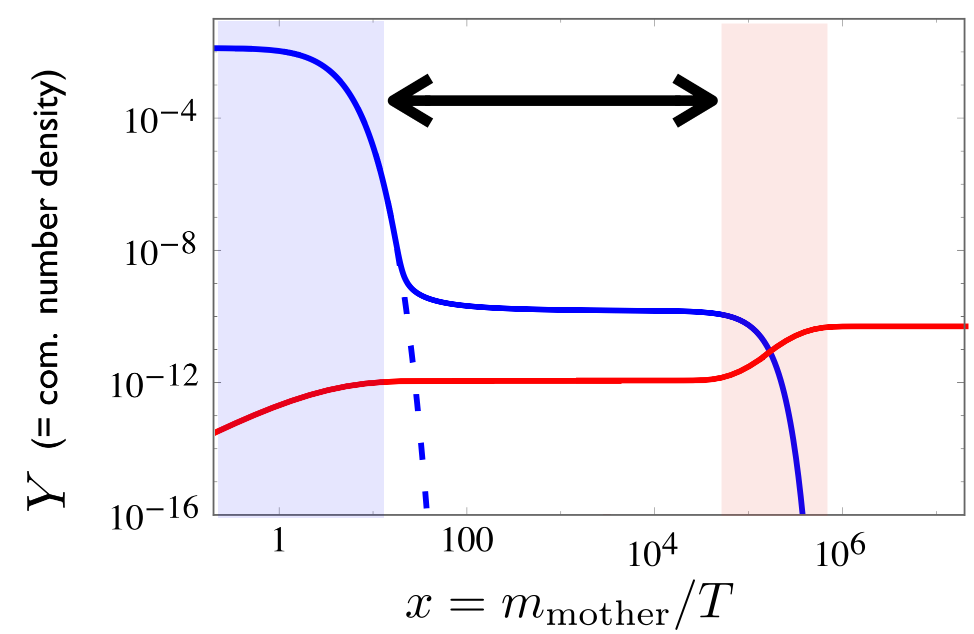


Well separated for small couplings



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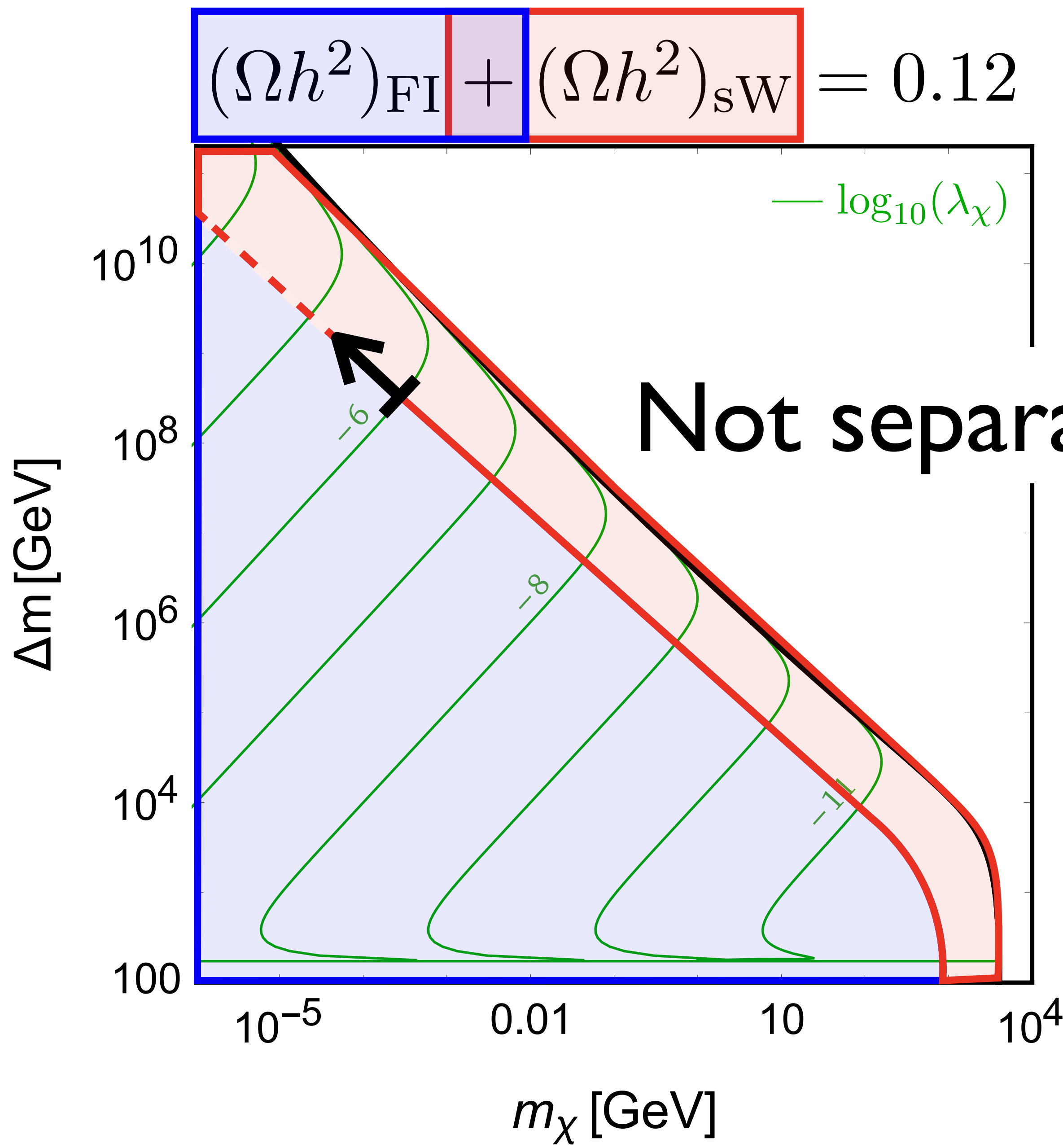
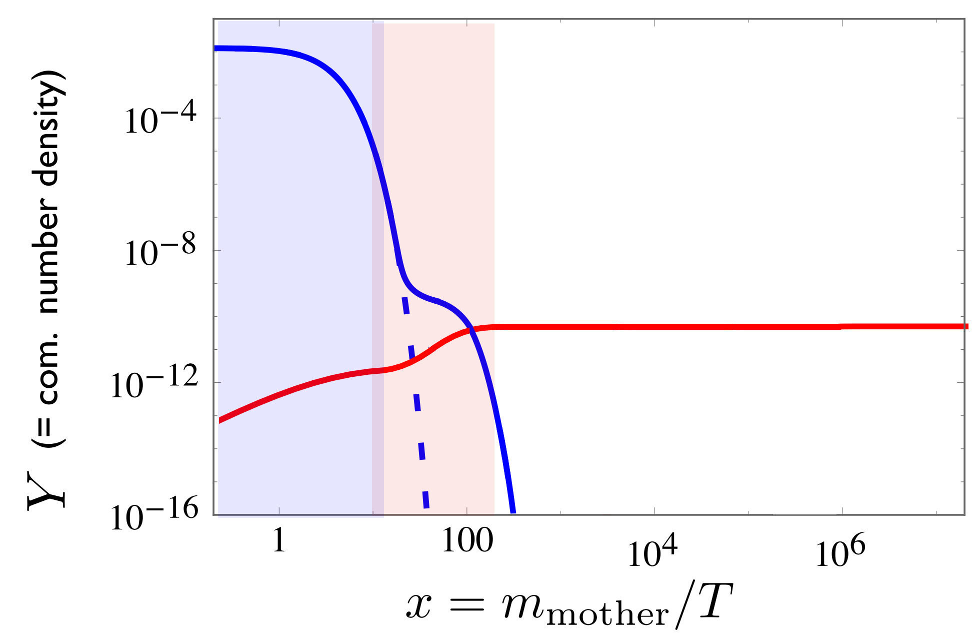
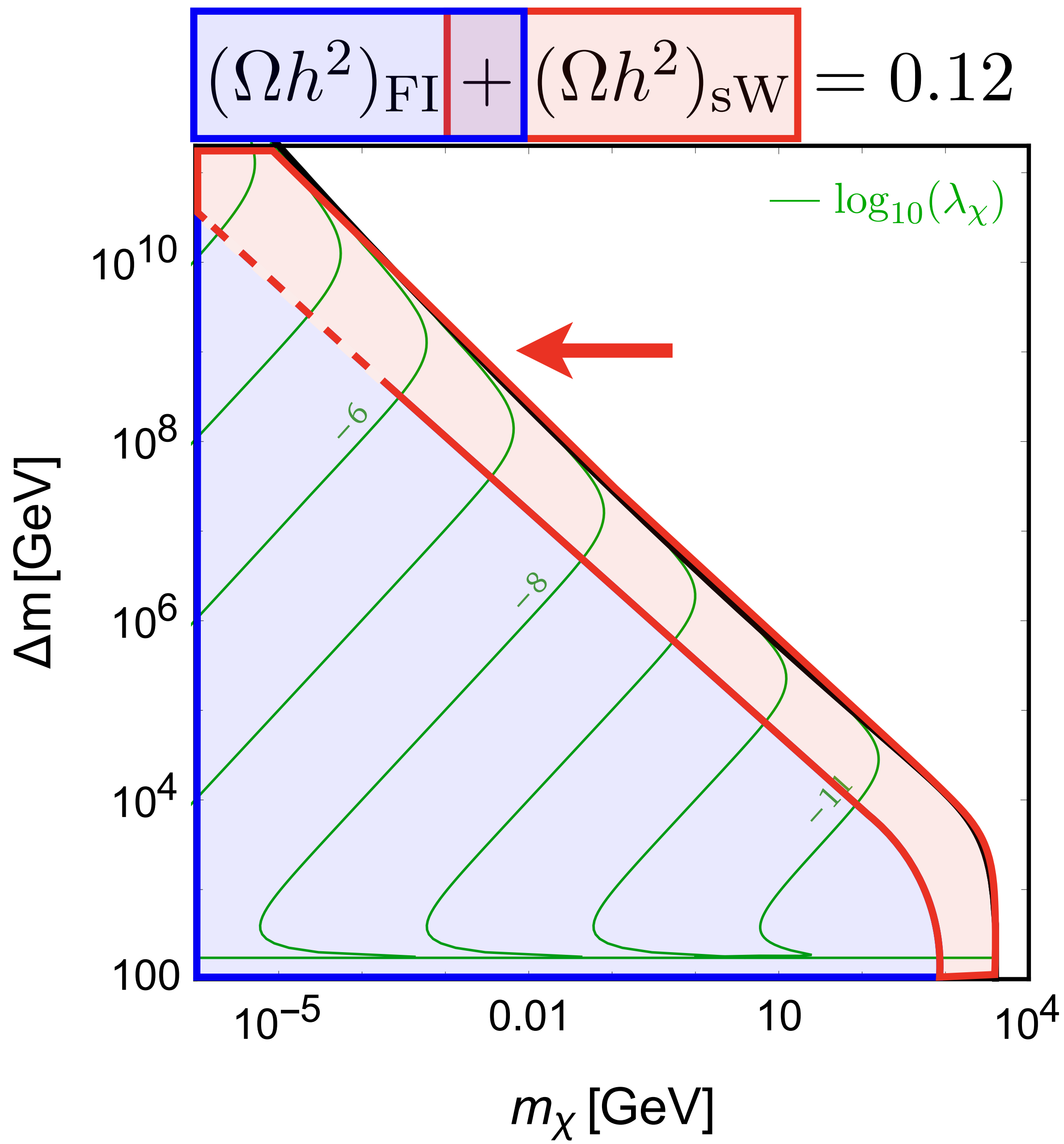


Not separated for large couplings

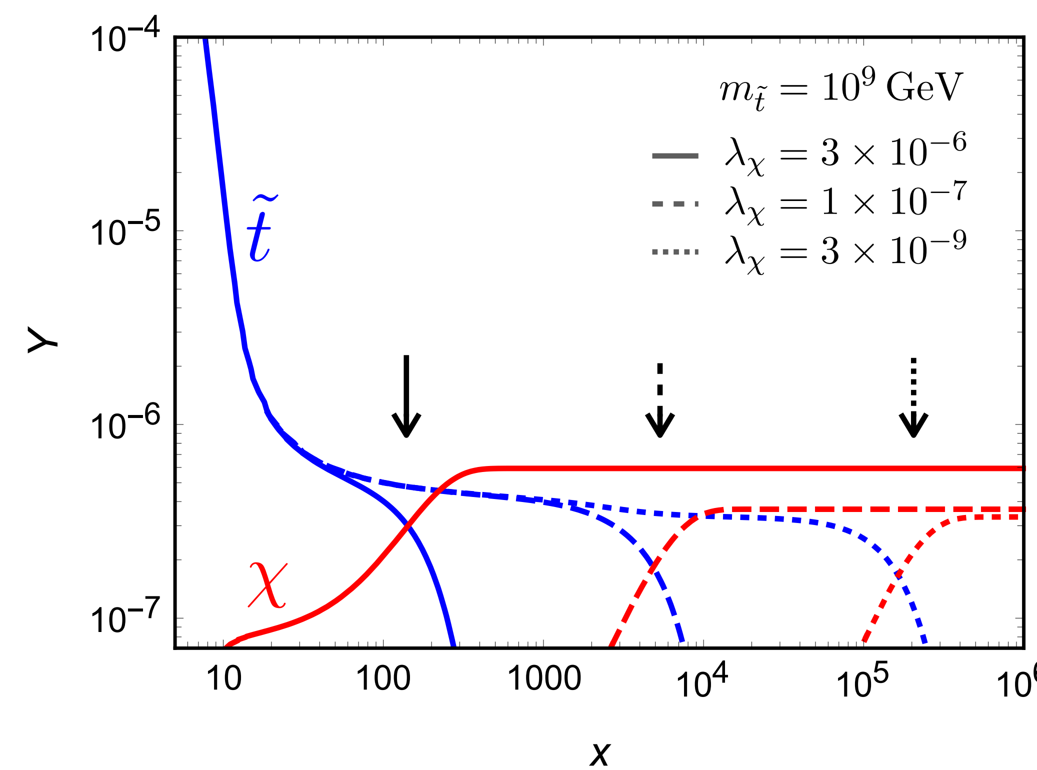


Top-philic model: viable parameter space

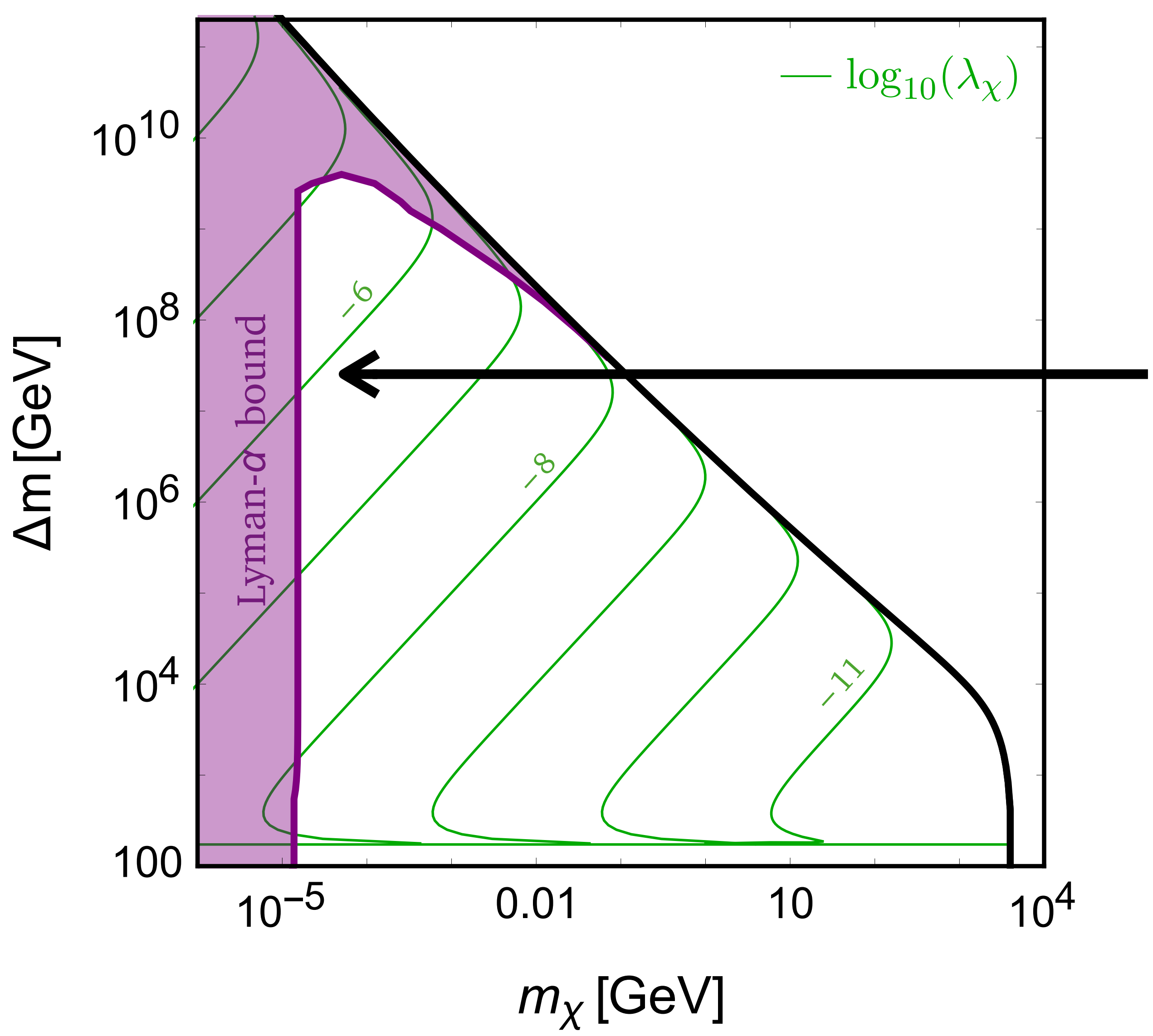


Prolonged freeze-out due to bound state formation effects:

[*following* Harz, Petraki, 1805.01200]



Lyman-alpha constraints

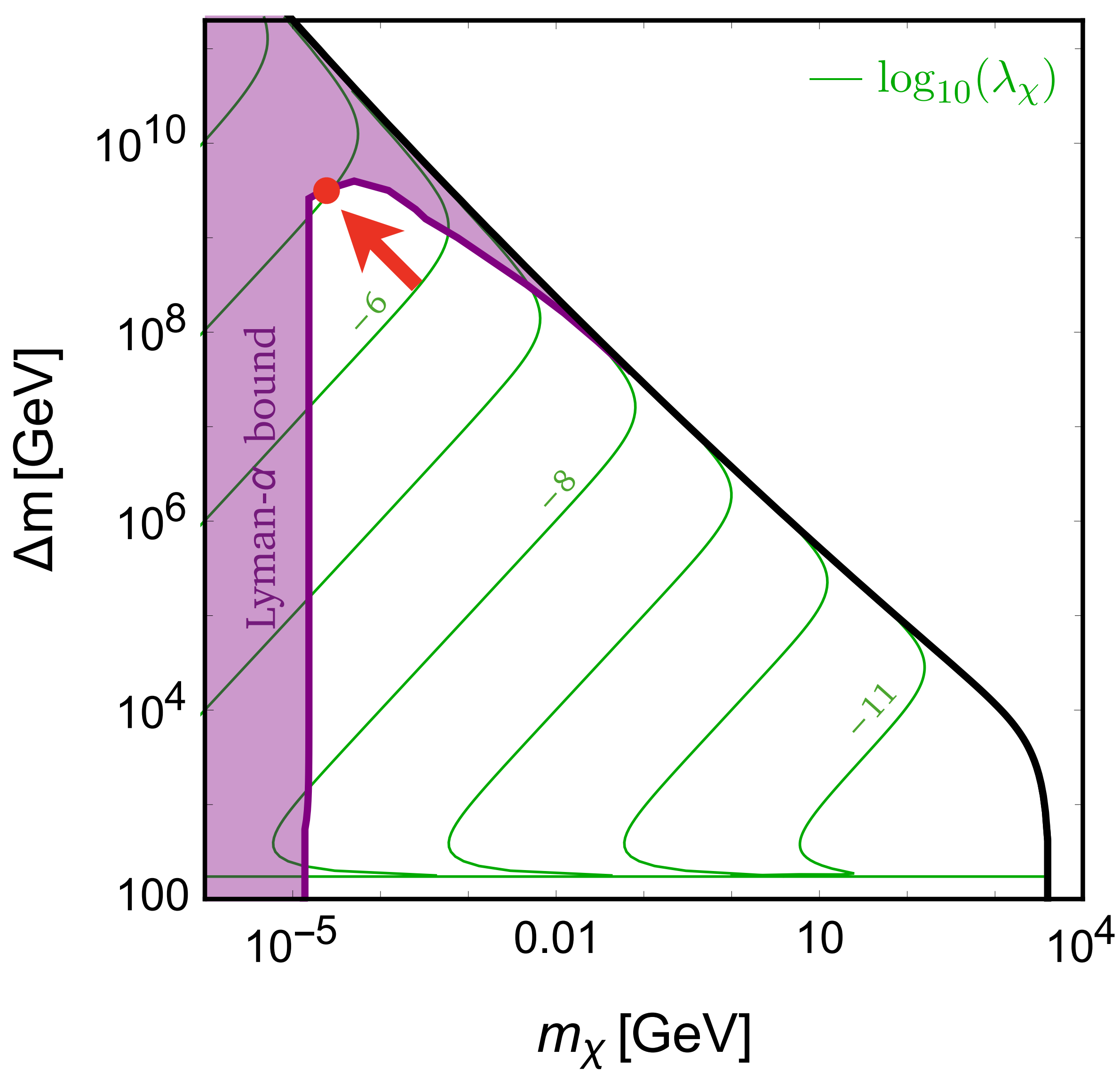


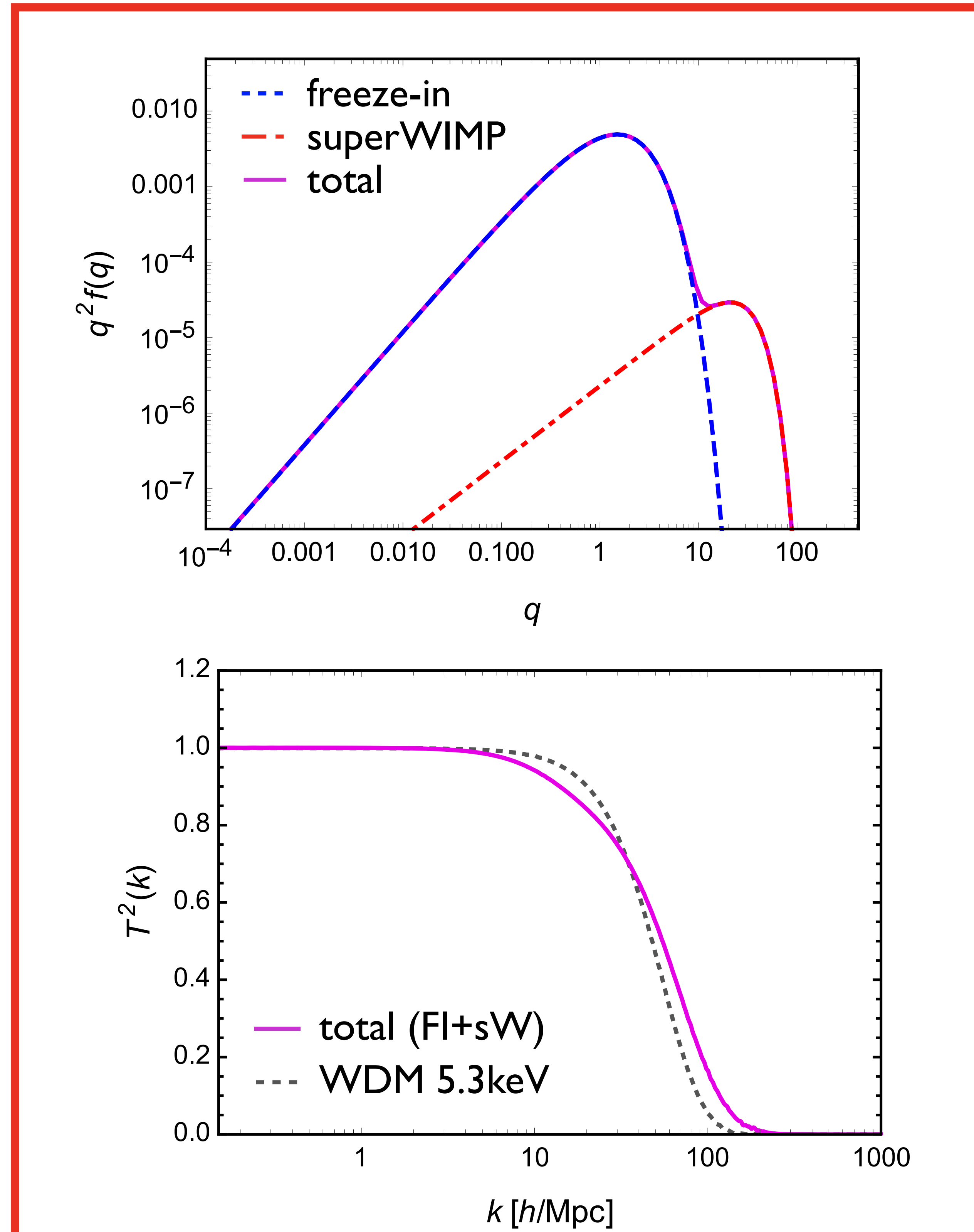
Lyman-alpha constraints from area criterium

Lyman-alpha constraints

$m_\chi \simeq 22\text{keV}$

$\Omega_{sW}/\Omega_{tot} \simeq 12\%$

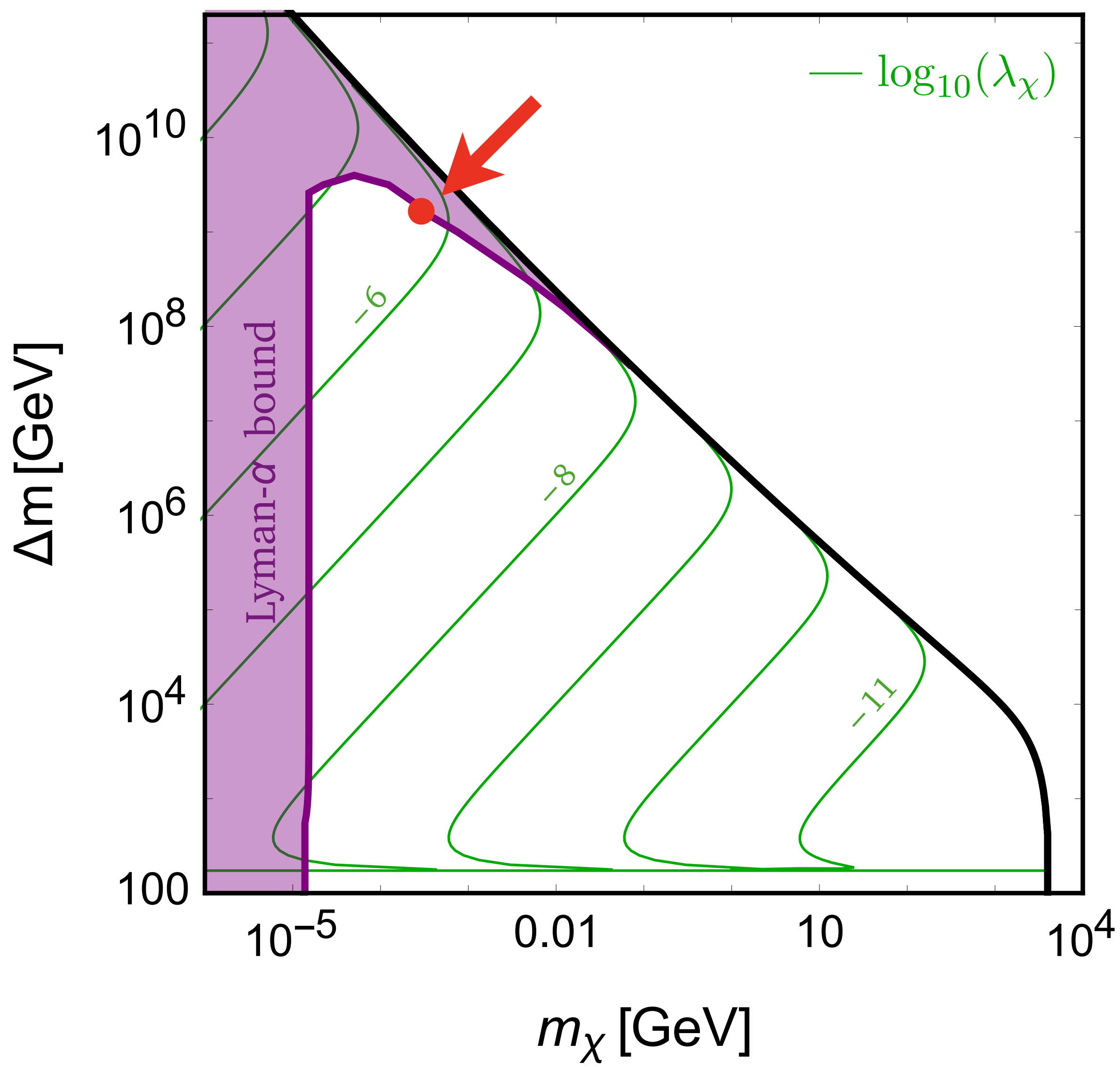


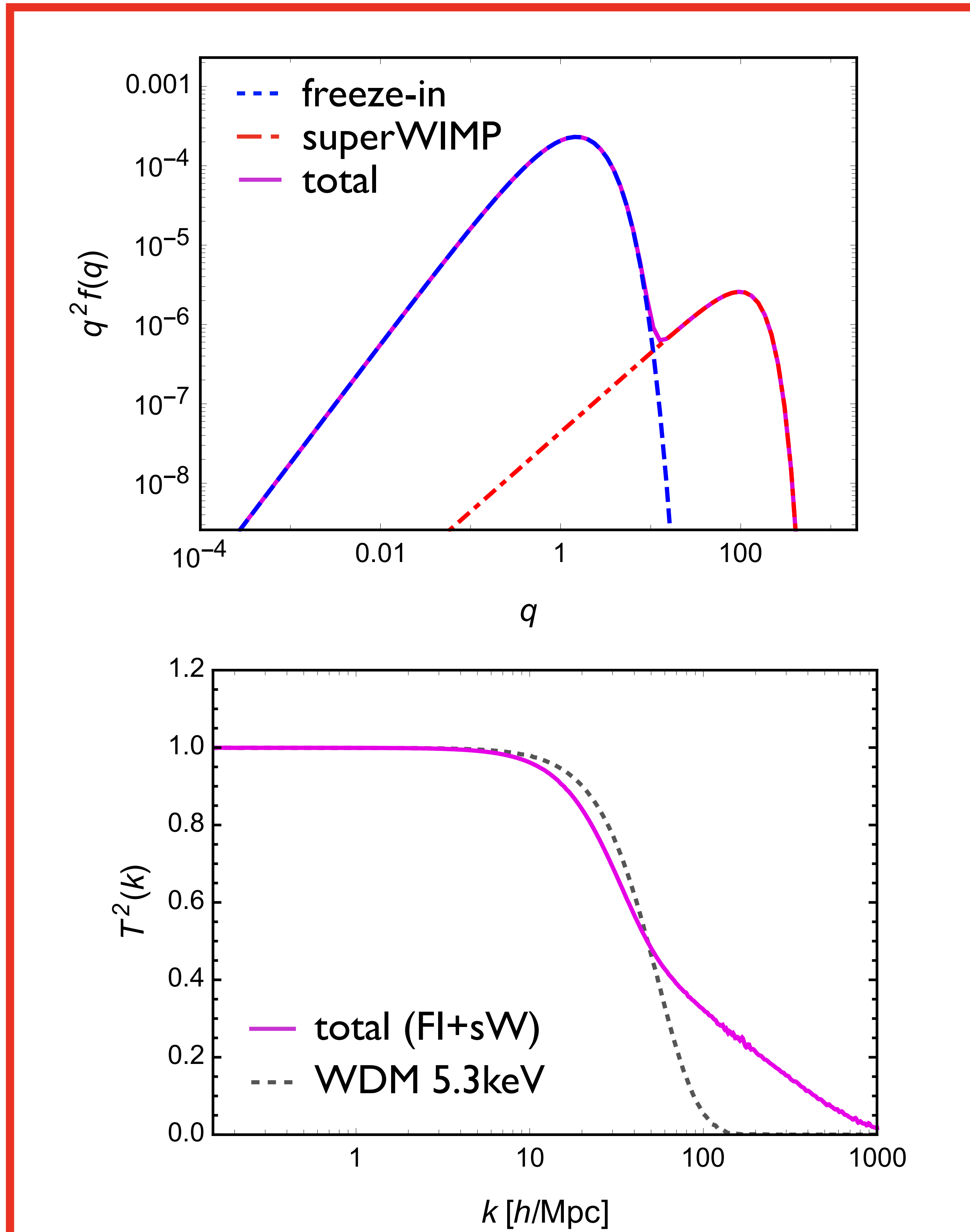


Lyman-alpha constraints

$m_\chi \simeq 0.3\mathrm{MeV}$

$\Omega_{\mathrm{sW}}/\Omega_{\mathrm{tot}} \simeq 40\%$

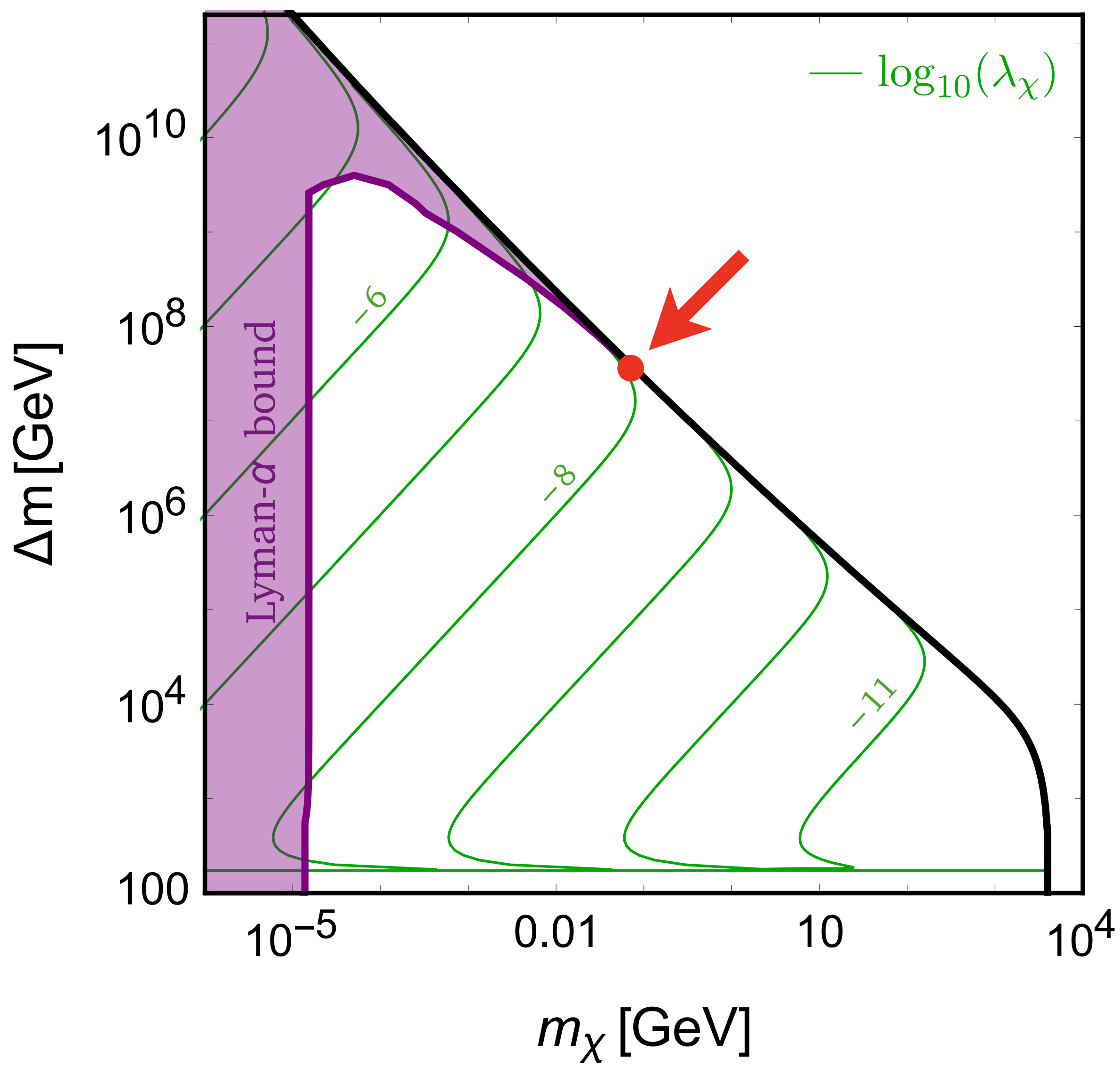


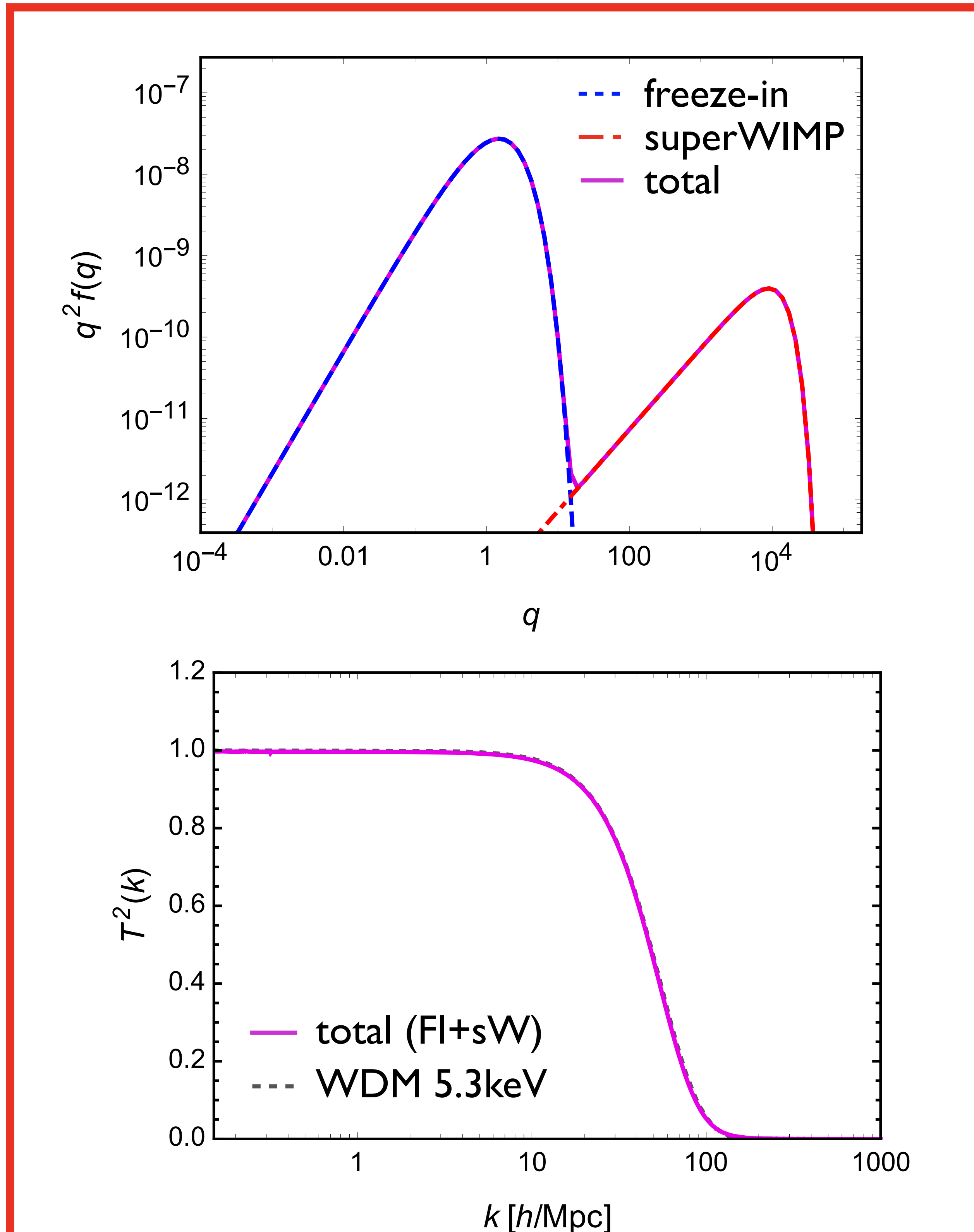


Lyman-alpha constraints

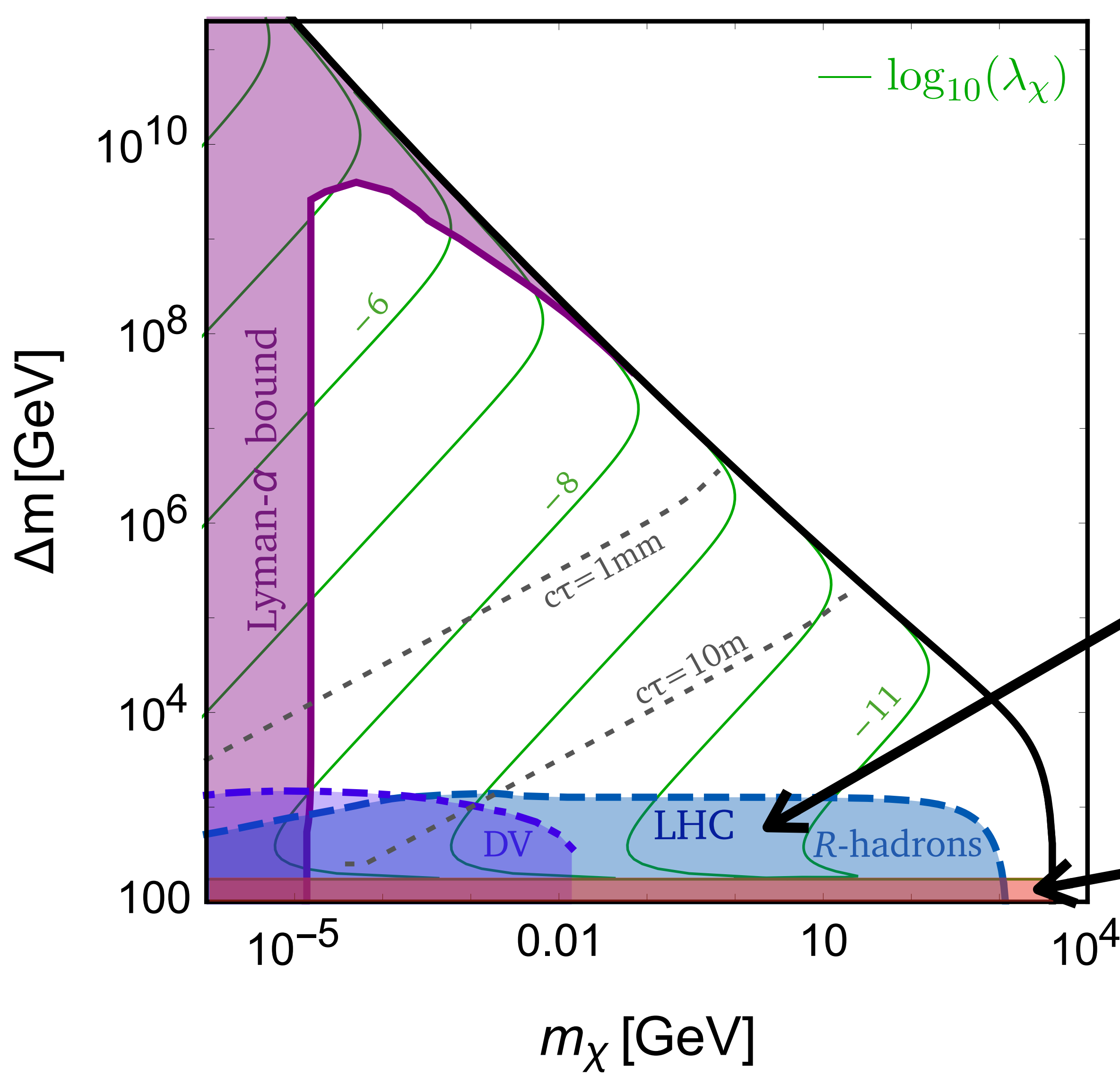
$m_\chi \simeq 70\text{MeV}$

$\Omega_{sW}/\Omega_{tot} \simeq 99\%$





Other constraints



Low masses constraint by long-lived particle searches at the LHC

Small mass splittings constraint by BBN

Summary

- Lyman-α forest probes dark-matter momentum distribution
- Reinterpreted WDM bound for freeze-in, superWIMP and mixed scenario
- Analytic expressions for pure freeze-in and superWIMP
- Mixed scenario implemented in CLASS, area criterium
- Application to top-philic model
- Cornered by Lyman-α, LHC bounds, BBN