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Sommerfeld enhancement and Bound State formation

DM from aeV to ZeV

Durham

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Long range interactions

Long range interactions between DM mediated by a light mediator can induce **Sommerfeld corrections** to annihilation cross-sections and DM can form **Bound States**

Examples of DM models where long range interactions are relevant:

- **TeV scale EW-charged WIMPS**. Here the light mediators are the SM gauge bosons!

e.g. Minimal DM, Higgsino, Wino in SUSY....

Sub-TeV WIMPs when co-annihilating with charged/colored particles.

- Hidden sector DM

.

Simple recipe to get **Self-interacting DM**

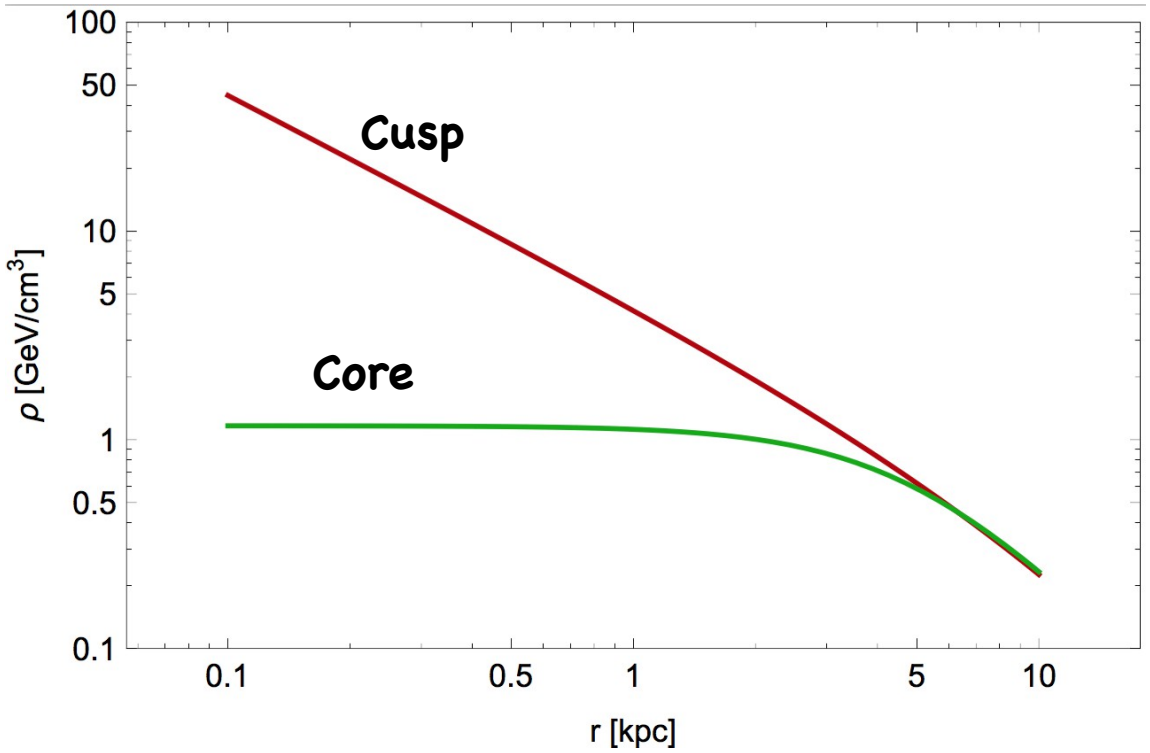
Motivated by astrophysical anomalies

Scenarios with Mirror symmetry, e.g. Twin Higgs models.

Collisionless CDM crisis

Simulations with Collisionless CDM at galactic and sub-galactic scales predict too much DM in the central region

Core vs Cusp problem, "Too big too fail" problem.



Possible solutions

Baryonic physics: large baryonic feedback processes, like SN explosions

Change the DM properties: Warm DM or **Self-Interacting Dark Matter (SIDM)**

The energy exchanged in the collision of SIDM allow to efficiently transfer energy inside the halo. This suppress overdensities

Spergel, Steinhardt (2000)

To solve small scale problems one should have at galactic & sub-galactic scales:

$$\sigma_{\chi\chi}/M_{DM} \sim few \times 0.1 - 1 \ \mathrm{cm}^2/g$$

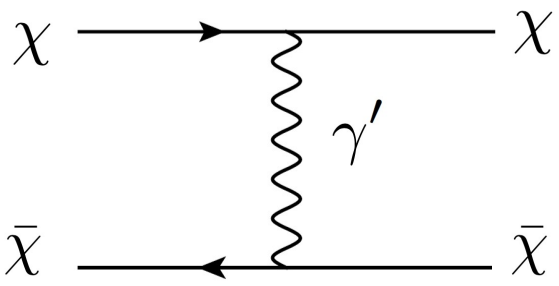
Bounds from ellipticity and merging clusters:

$$\sigma_{\chi\chi}/M_{DM} \lesssim 0.1 - 1 \ \mathrm{cm}^2/g$$

Simulations: Rocha et al. (2012), Peter et al. (2012), Zavala et al. (2012), ….

Dark QED

Get large cross-section with ($\sigma/M \sim$ barn/GeV) in a weakly-coupled model with a light mediator

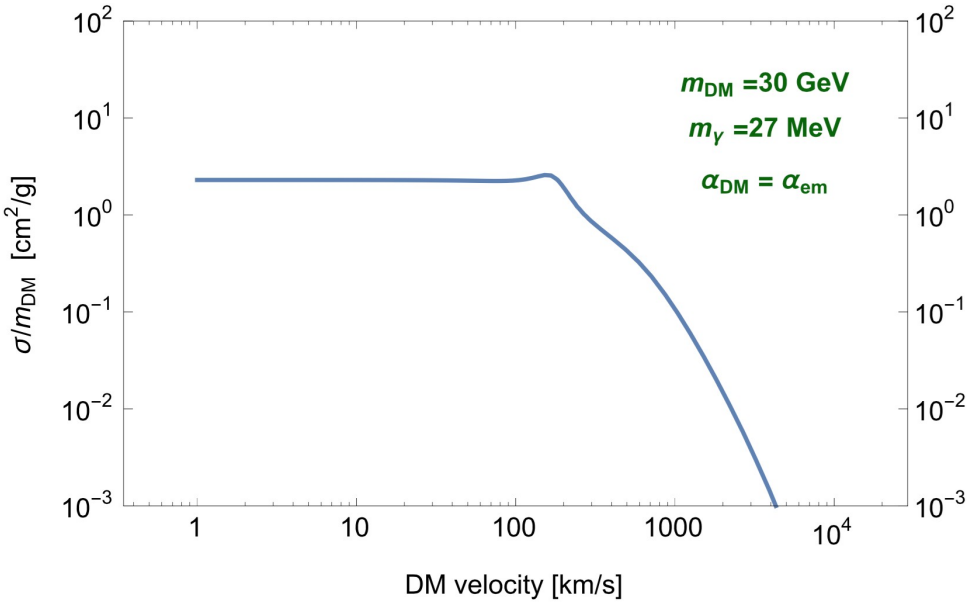


$$V(r) = -\frac{\alpha}{r} e^{-m_{\gamma'} r}$$

Velocity dependent cross-section

M v >> mγ : contact limit and σ is v-independent

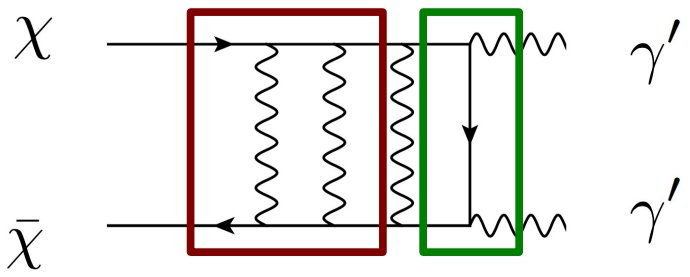
Mv << mγ : Rutherford limit $\sigma \sim 1/v^4$



dwarfs LSB Clusters

Annihilations

Non-relativistic annihilations receive large Sommerfeld corrections.
Re-summation of ladder diagram is needed.
In practice: in NR QM solve Schrodinger equation with suitable boundary conditions



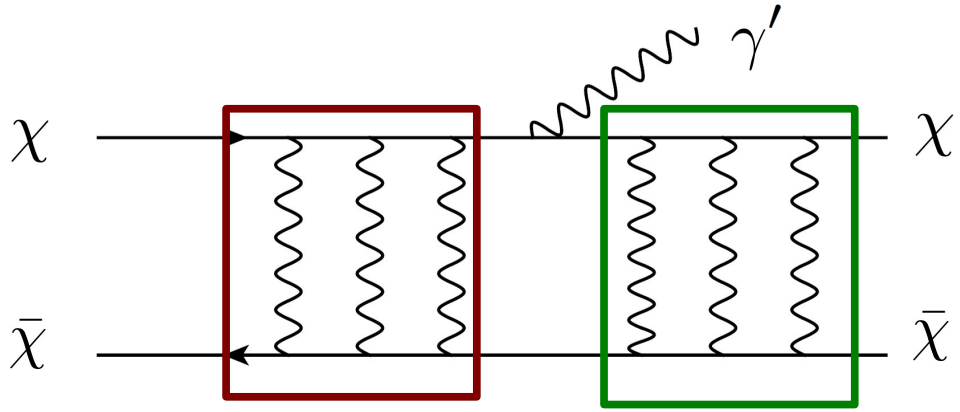
In the Coulomb limit (mass of mediator->0) we get:

$$\sigma v_{ann} = S_{ann}(v)\frac{\pi\alpha^2}{M_{DM}^2}$$

$$S_{ann}(v \to 1) \simeq 1 \qquad\qquad S_{ann}(v << 1) \simeq \frac{2\pi\alpha}{v}$$

Bound state formation

In certain region of the parameter space DM states can form radiatively and then decay



$$\bar{\chi}\chi \to (\bar{\chi}\chi)_{BS} + \gamma' \qquad (\bar{\chi}\chi)_{BS} \to 2\gamma' \text{ or } 3\gamma'$$

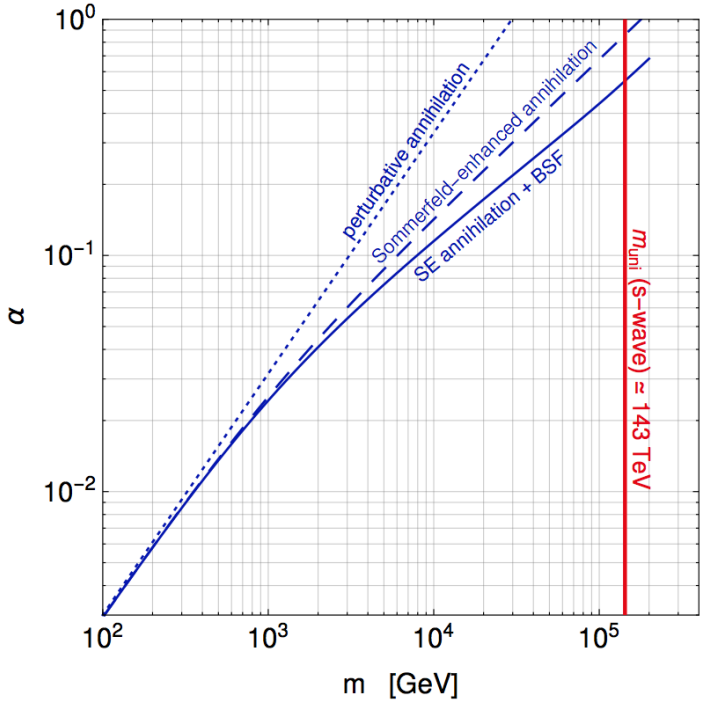
In the Coulomb limit (mass of mediator->0) we get:

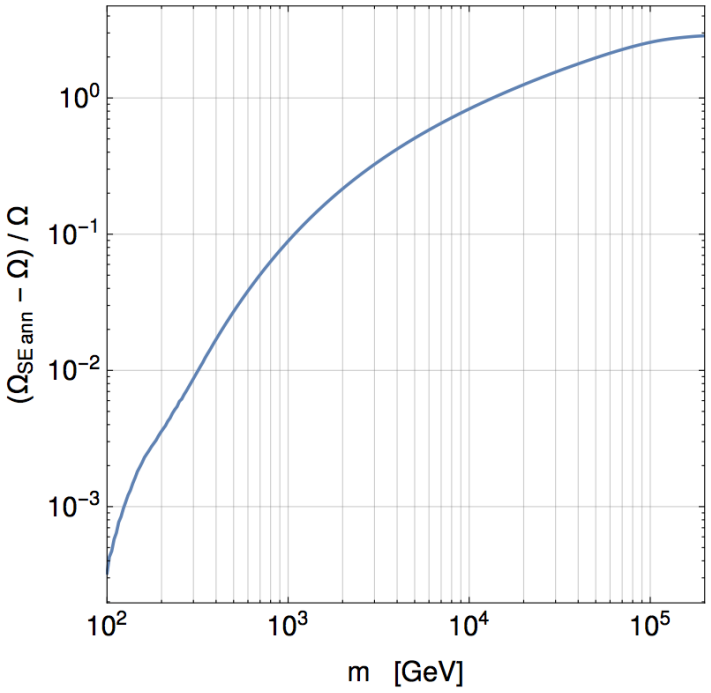
$$\sigma v_{BSF} = S_{BSF}(v)\frac{\pi\alpha^2}{M_{DM}^2} \qquad E_n = \frac{M_{DM}\alpha^2}{4n^2}$$

$$S_{BSF}(v \to 1) << 1 \qquad S_{BSF}^{n=1}(v << 1) \simeq \frac{2^9}{3e^4}\frac{2\pi\alpha}{v} = 3.13 \times S_{ann}(v)$$

Effect on the relic abundance

Relevant processes: Sommerfeld-enhanced annihilations, BS formation and BS desruption.
Solve coupled Boltzmann equations for population of DM and BS.
Bound state processes depend on the balance between their formation and their destruction due to ionization processes and decays



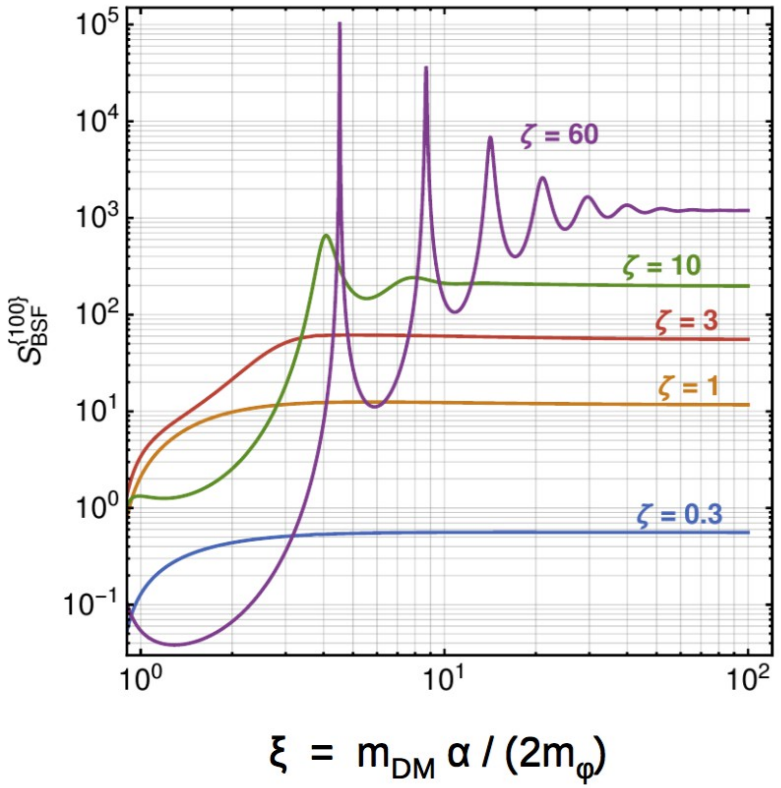


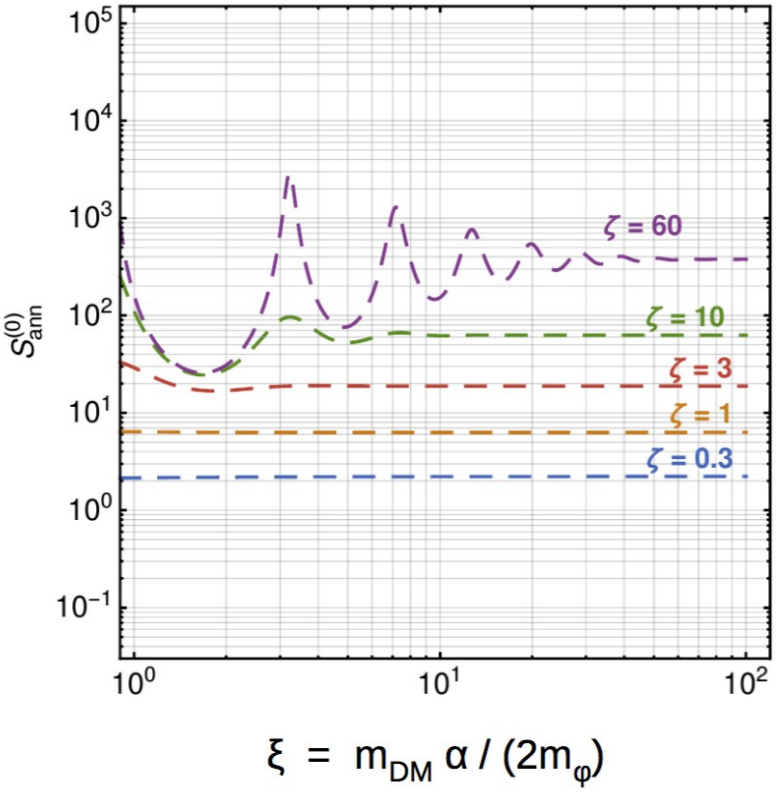
Von Harling, Petraki 1407.7874

Massive mediators

Everything depends on 2 parameters: $\zeta = \frac{\alpha M_{DM}}{2 m_{\gamma'}}$ $\xi = \frac{\alpha}{v}$

Resonances appear at discrete values of ζ



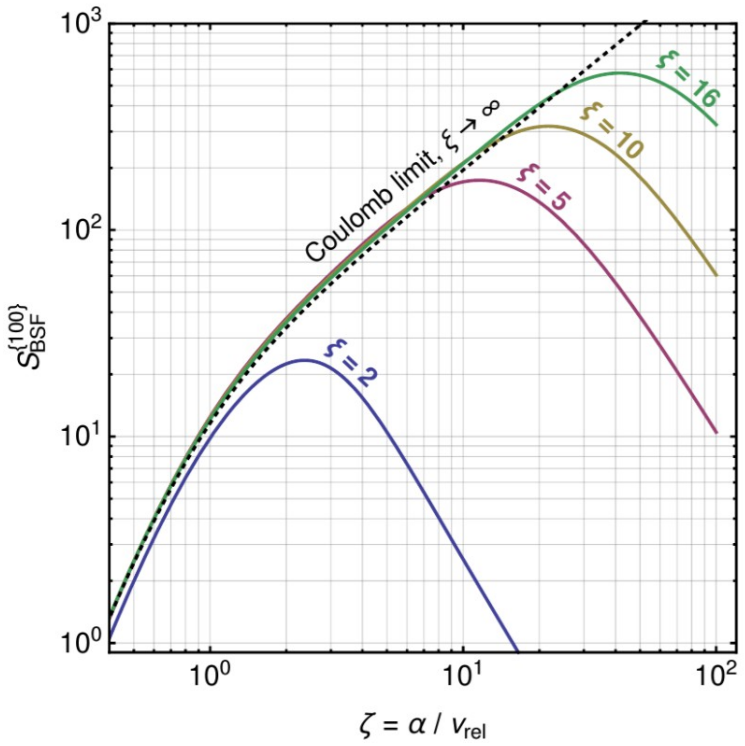


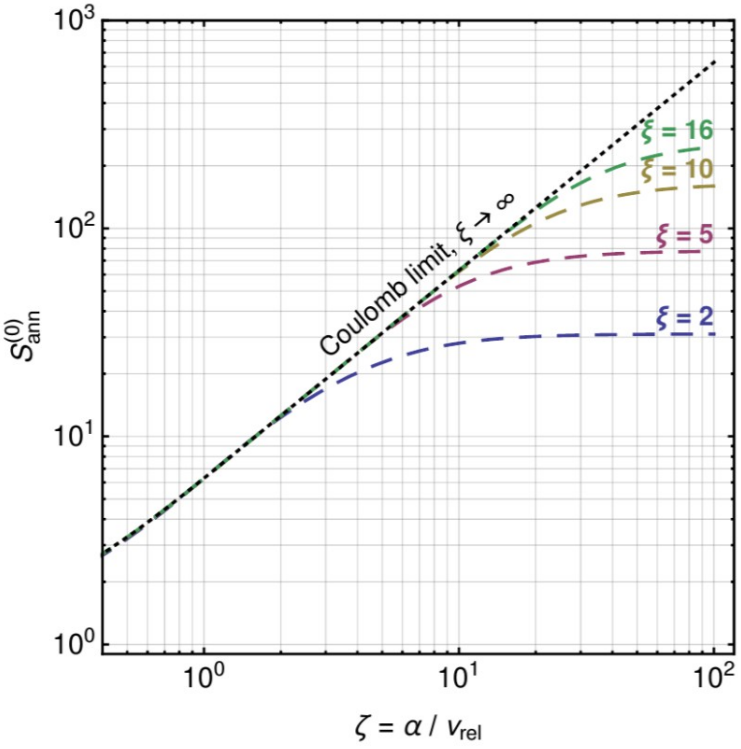
Petraki, Postma, de Vries, 1611.01394

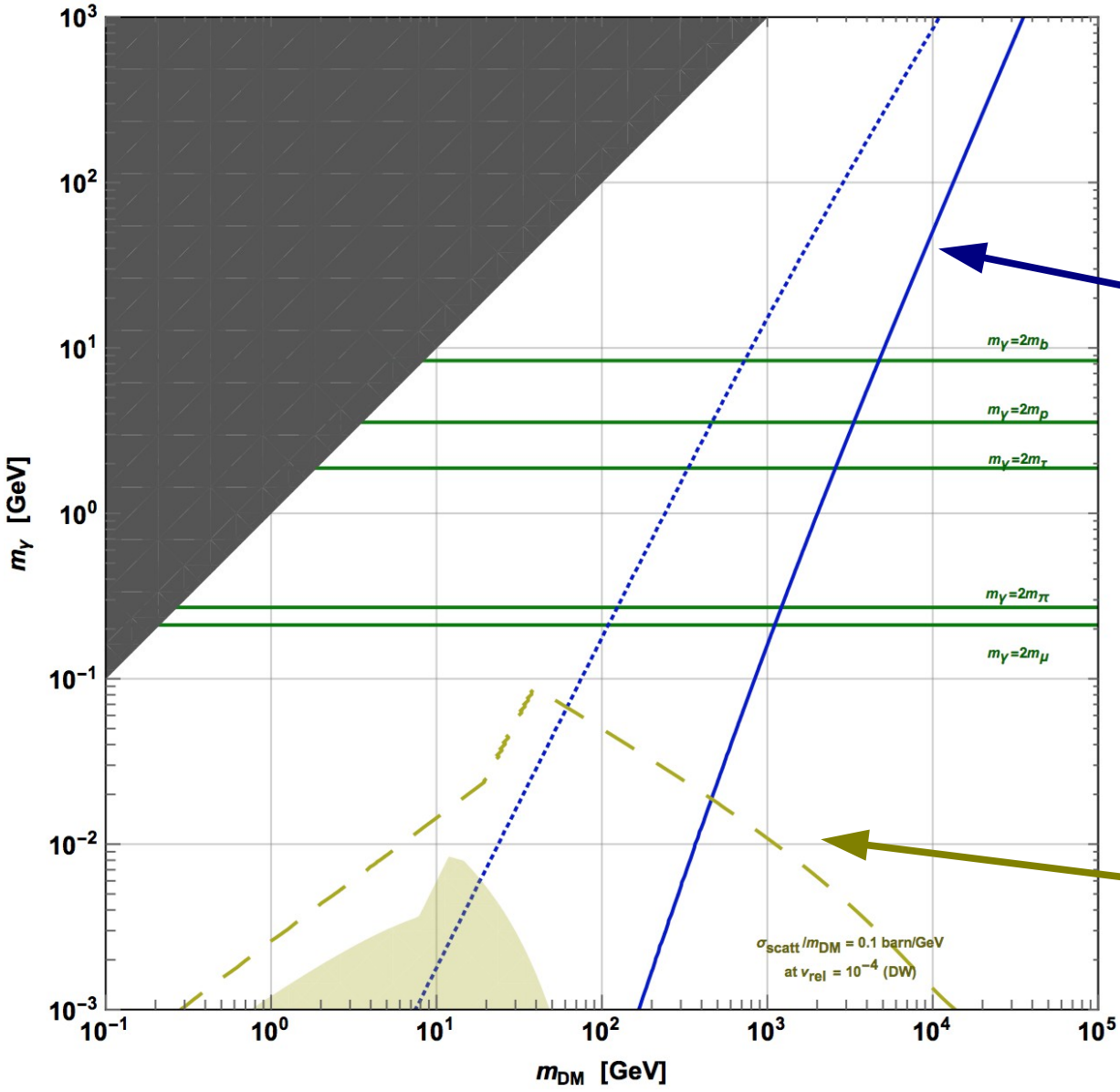
Massive mediators

Everything depends on 2 parameters: $\zeta = \frac{\alpha M_{DM}}{2 m_{\gamma'}}$ $\xi = \frac{\alpha}{v}$

Resonances appear at discrete values of ζ
Sommerfeld saturates at low velocities while BSF on the ground state is suppressed
BSF can be relevant only in finite range of velocities







Below this line
Bound States can
form radiatively

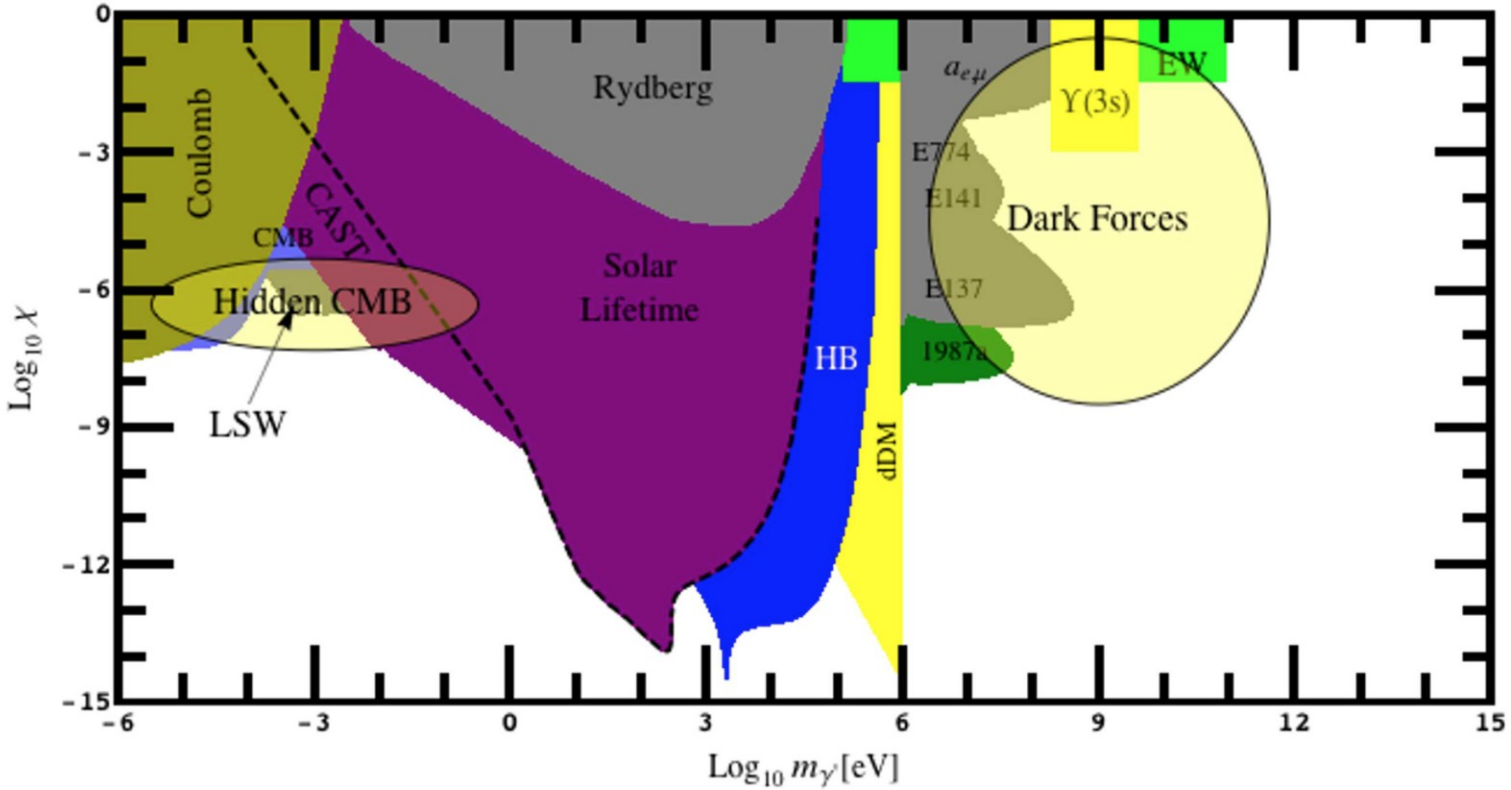
Region of
SIDM

Kinetic mixing

The dark sector can couple with the SM via the kinetic mixing among U(1) and U(1)'

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Dark-QED} + \epsilon \, F^{\mu\nu} F'_{\mu\nu}$$

Diagonalizing one finds that the SM particles have hidden charge ε



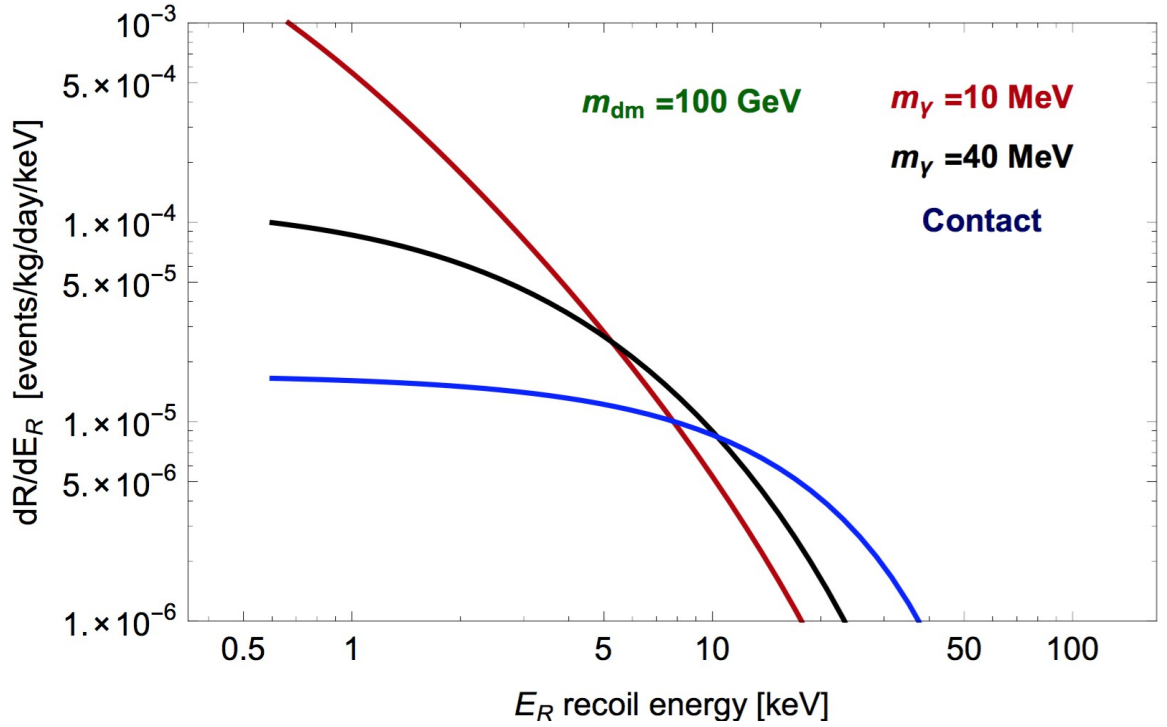
Cicoli, Goodsell, Jaeckel, Ringwald, 1103.3705

Direct detection

The kinetic mixing induce a SI coupling of the DM with the nuclei

Possible way to distinguish from standard SI contact interactions:

since the mediator mass <= of the exchanged momentum the recoil spectrum is more peaked at low recoiled energy

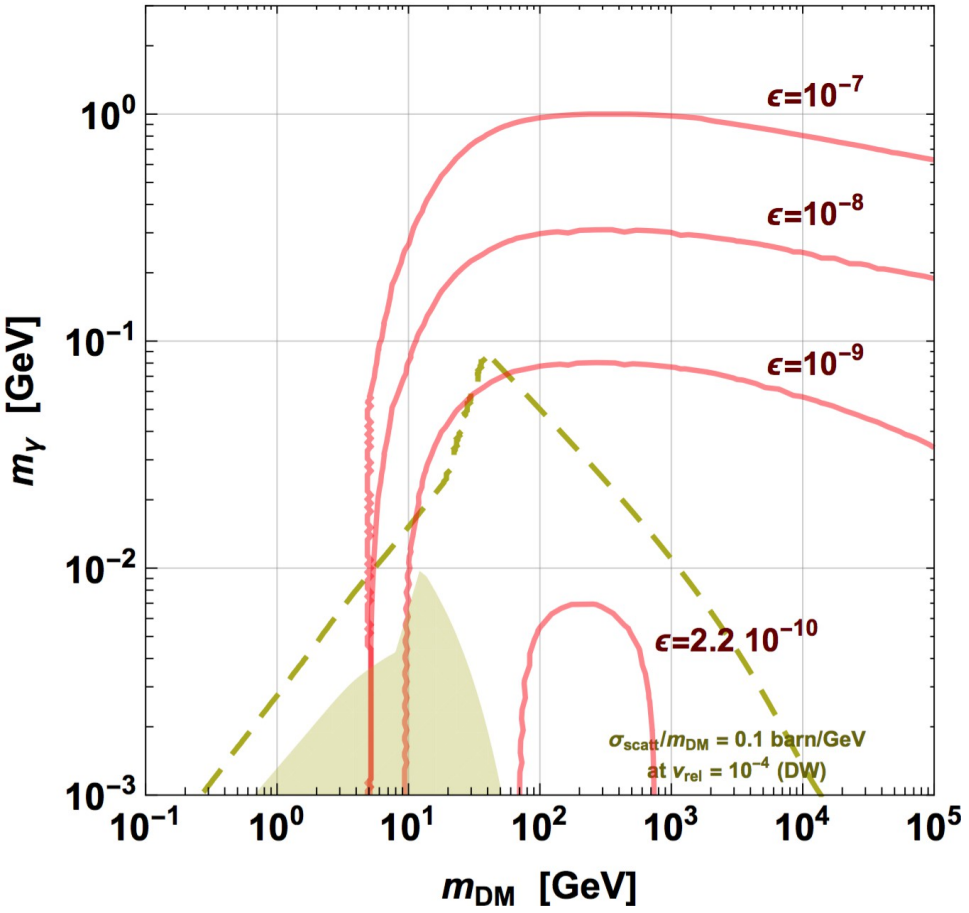


See also Del Nobile, Kaplinghat, Yu, 1507.04007, Kaplinghat, Tulin, Yu 1310.7945

Direct detection

Constrain on the kinetic mixing induced by current direct detection bounds.

Bounds from
LUX-2016

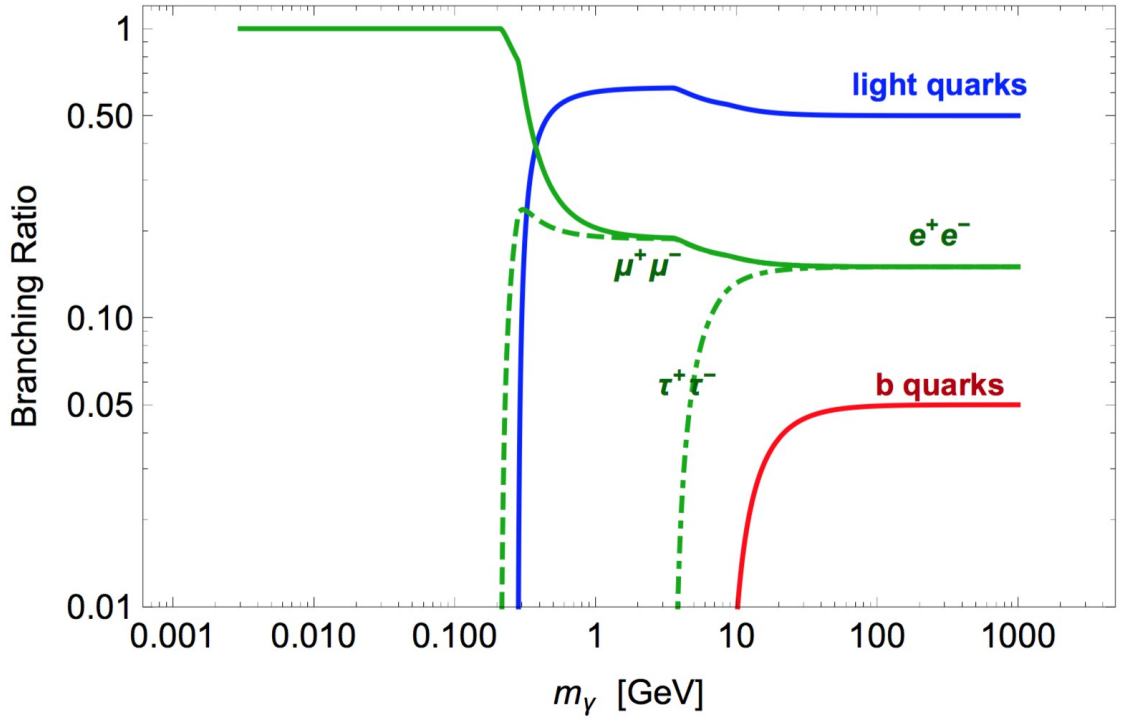


Indirect detection

The decays of the light mediator into SM particles via kinetic mixing can induce indirect detection signals

$$\bar{\chi}\chi \to \gamma'\gamma' \qquad \bar{\chi}\chi \to (\bar{\chi}\chi)_{BS} + \gamma' \qquad (\bar{\chi}\chi)_{BS} \to 2\gamma' \text{ or } 3\gamma'$$

$$\gamma' \to SMSM$$



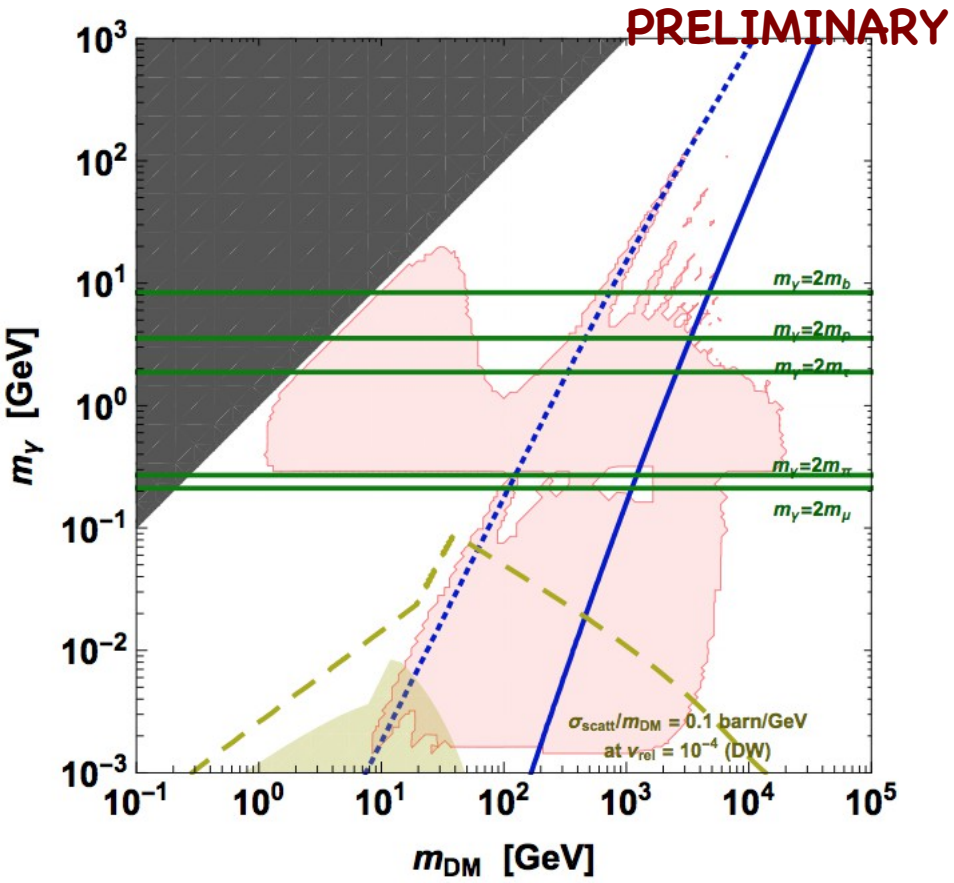
The decay rate is suppressed by the kinetic mixing but they are still prompt for astrophysical scales for kinetic mixing which pass all the constraints

Bounds from dwarfs

Derive bounds from Fermi-LAT stacked analysis of 15 dwarfs
Likelihood functions publicly available Fermi_LAT collaboration 1503.02641

J-factors as in the Fermi-analysis and profiling over J-factors uncertainties.
In all plane: dark coupling α_{DM} fixed to get correct relic abundance

Take typical velocity of DM in dwarfs around 10 km/s



Work in progress with Cirelli, Panci, Petraki, Sala

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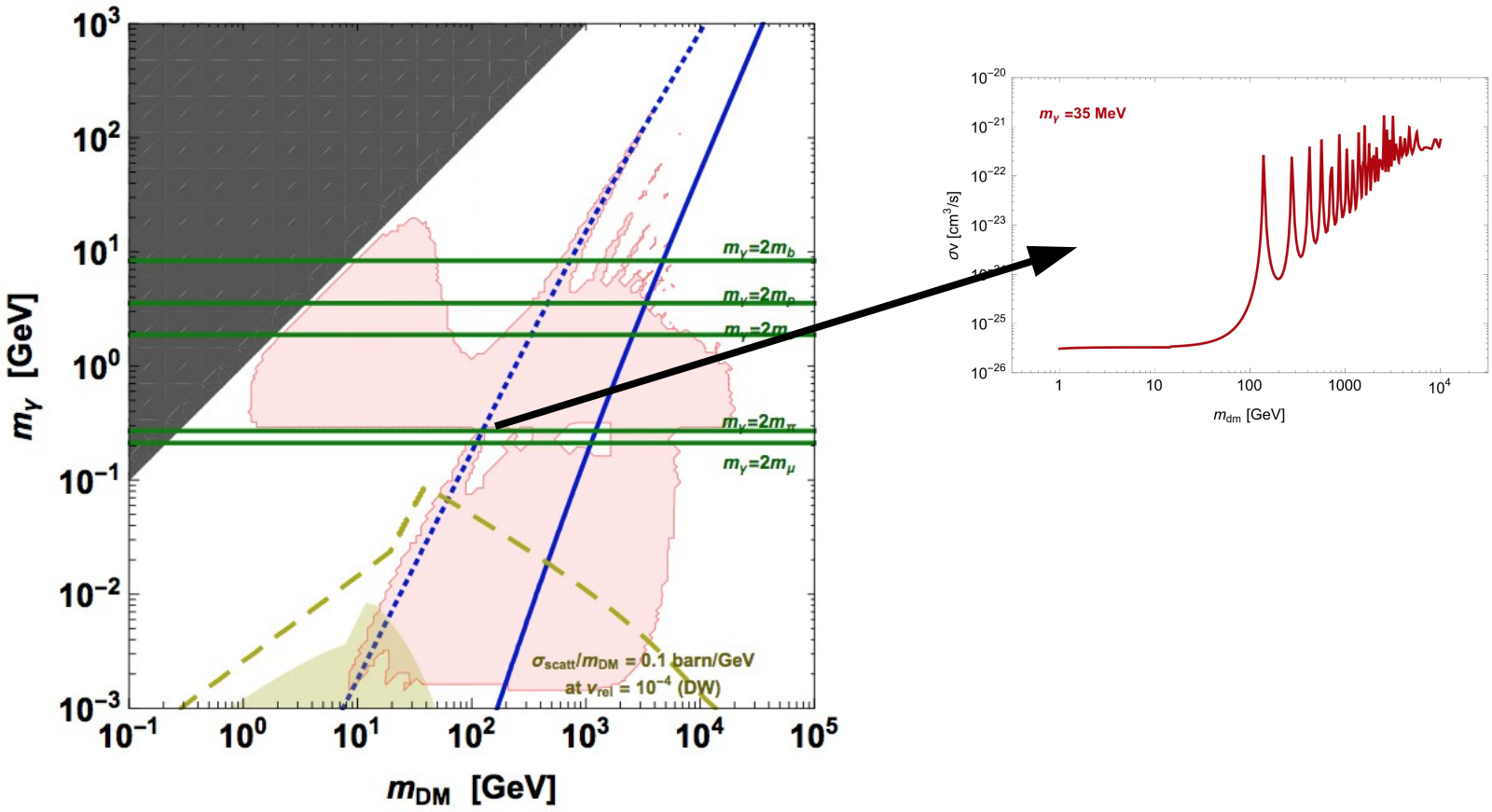

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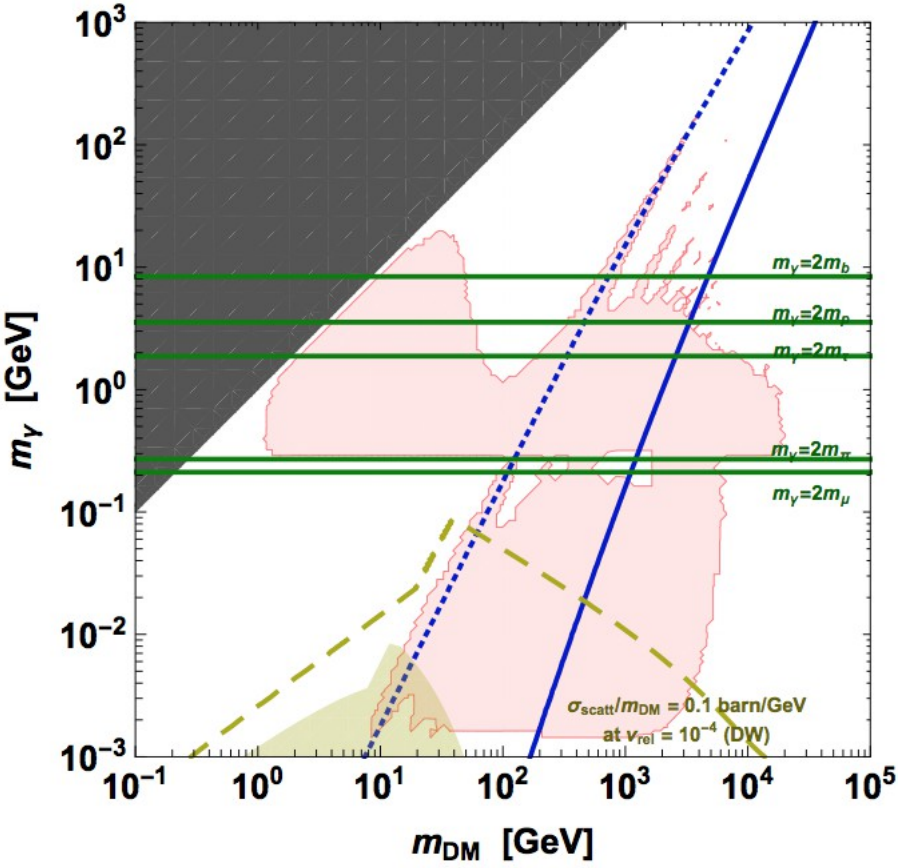
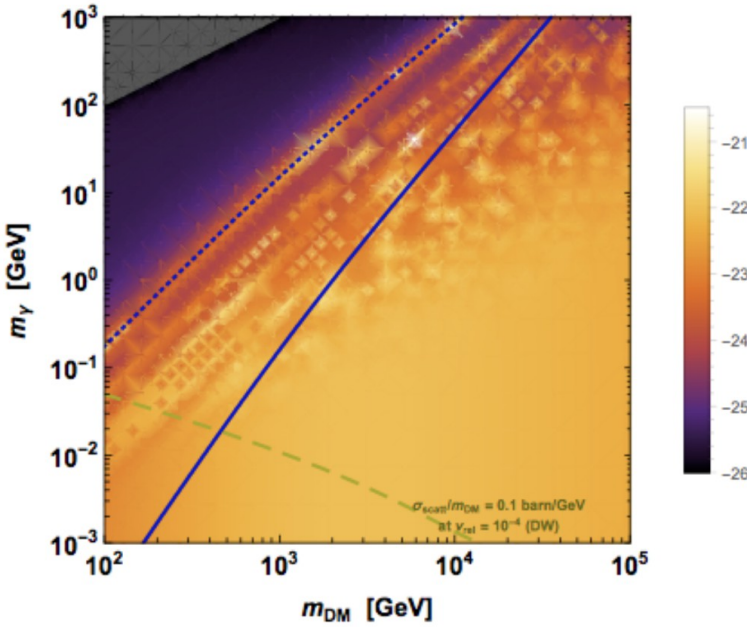
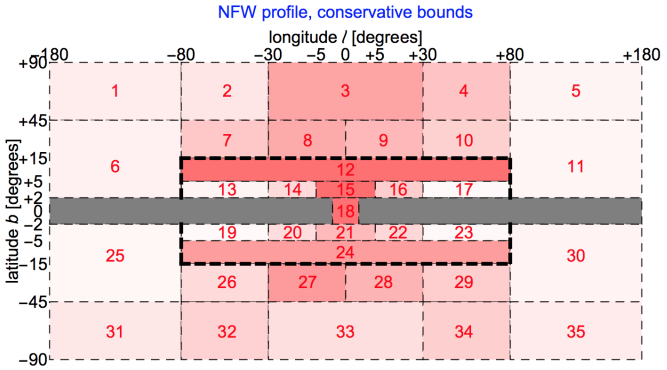
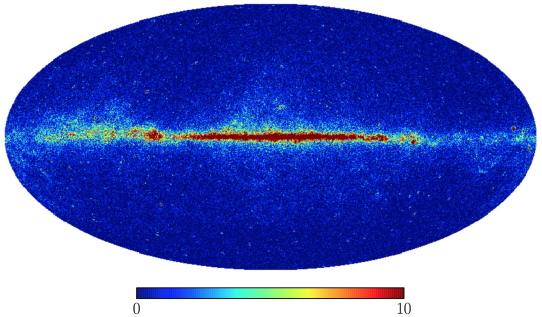


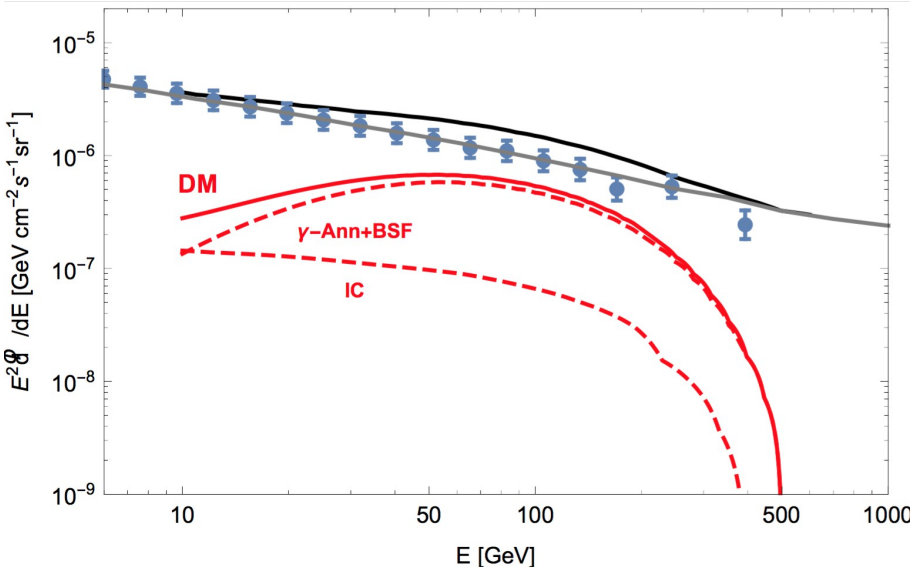


Bounds from diffuse gamma-rays

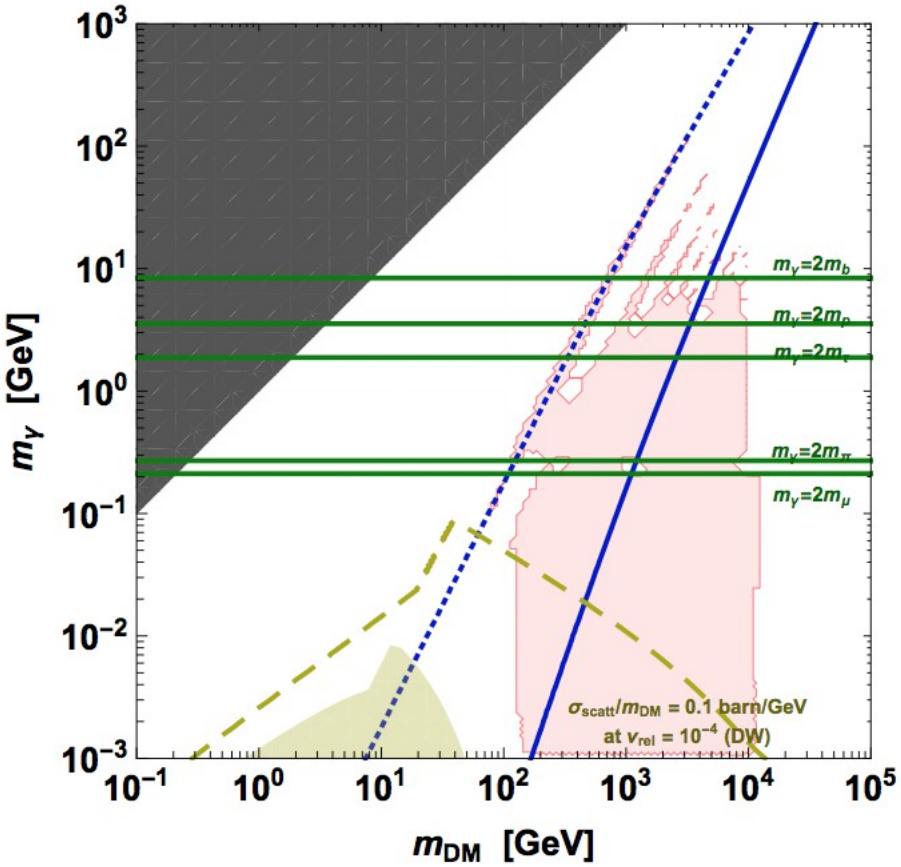
We derive bounds from mid-latitude Fermi-LAT observations 5<|b|<15 and -80<|l|<80
Include different bkg components:
-CRs induced diffuse emission -point-sources -Fermi-bubbles -Isotropic emission



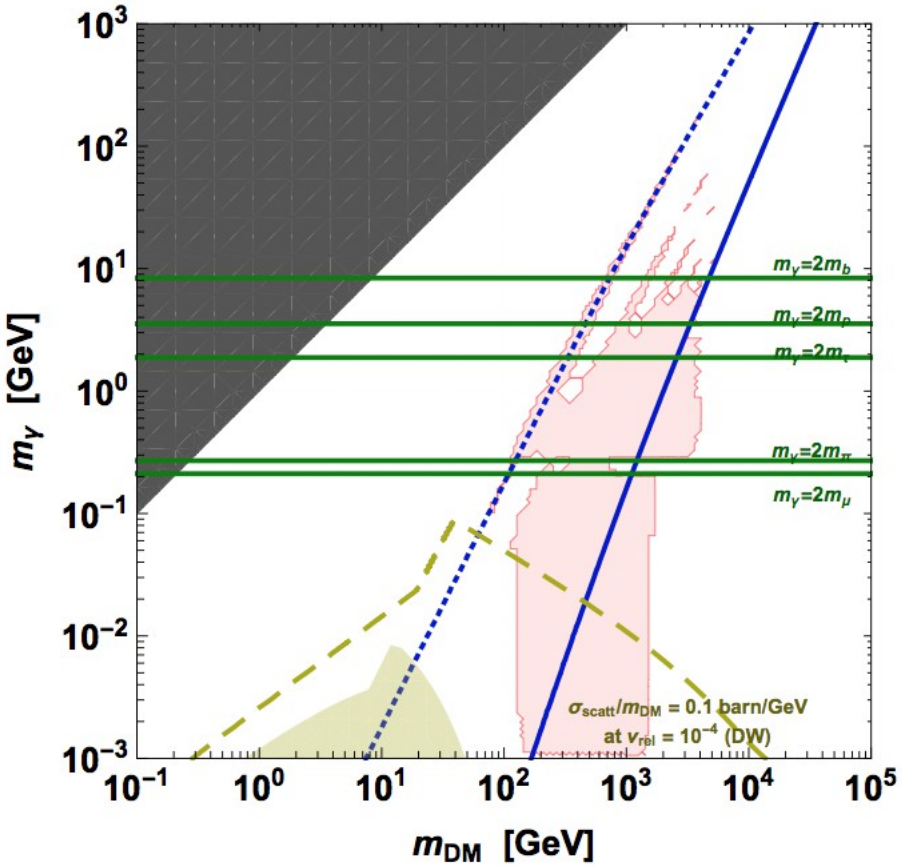




Bounds from diffuse gamma-rays



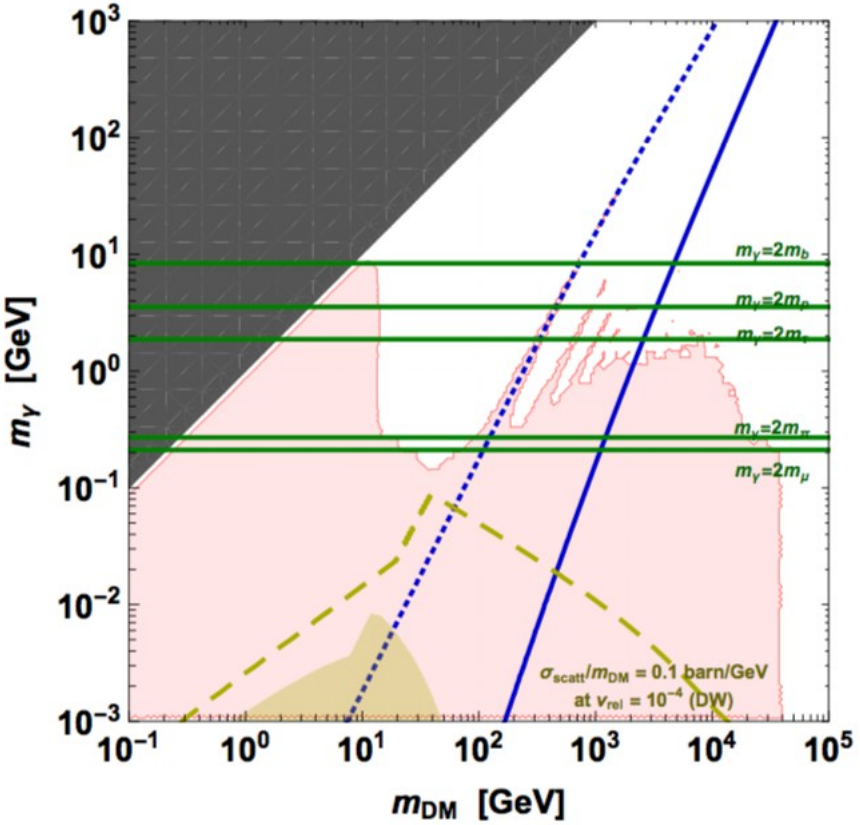
With BSF artificially turned off



PRELIMINARY

Bounds from CMB

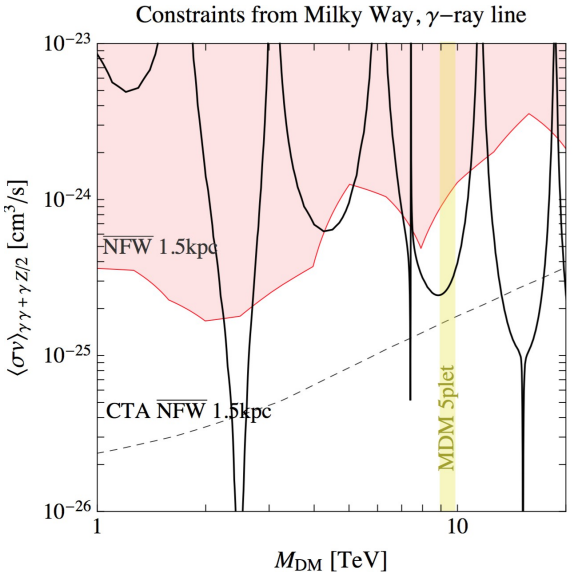
DM annihilations during "dark ages" can modify the ionization of the Universe and modify CMB anisotropies. Bounds are derived from Planck measurements.
The effect involves redshifts where the DM is extremely small thus BSF has no role.

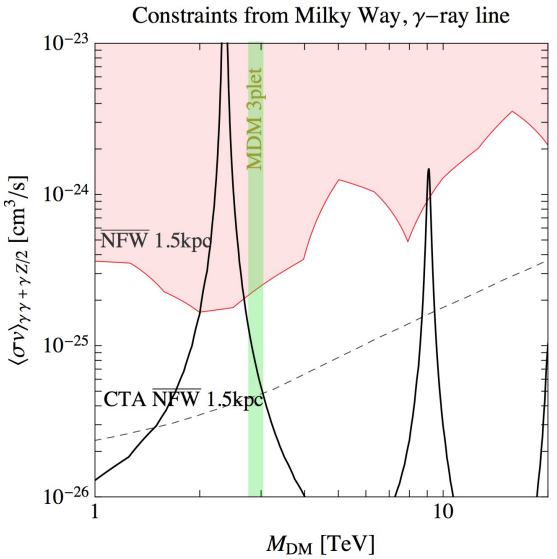


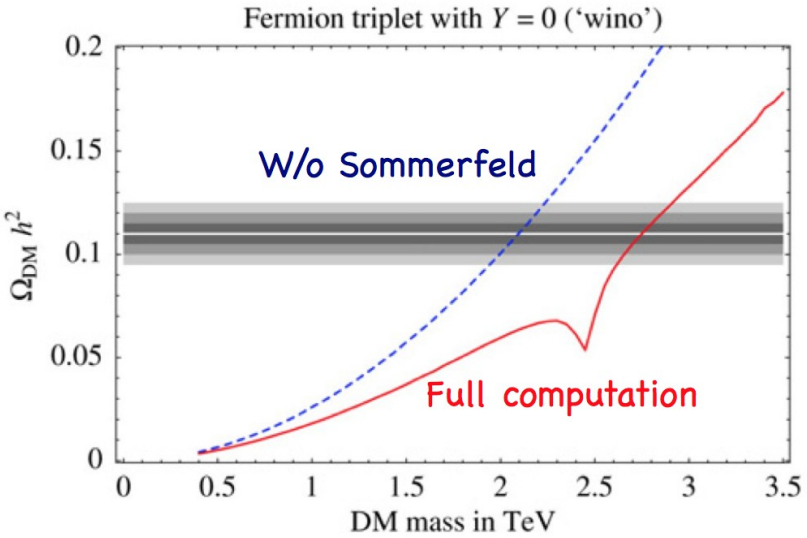
Deposition of energy computed in: Slatyer 1506.03812

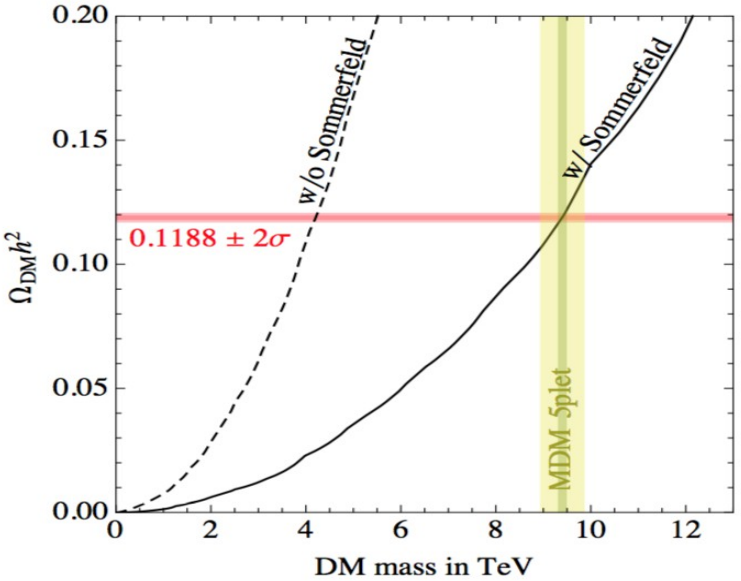
Electroweak multiplets

Examples are Higgsino, Wino and the Minimal DM candidate (5plet)





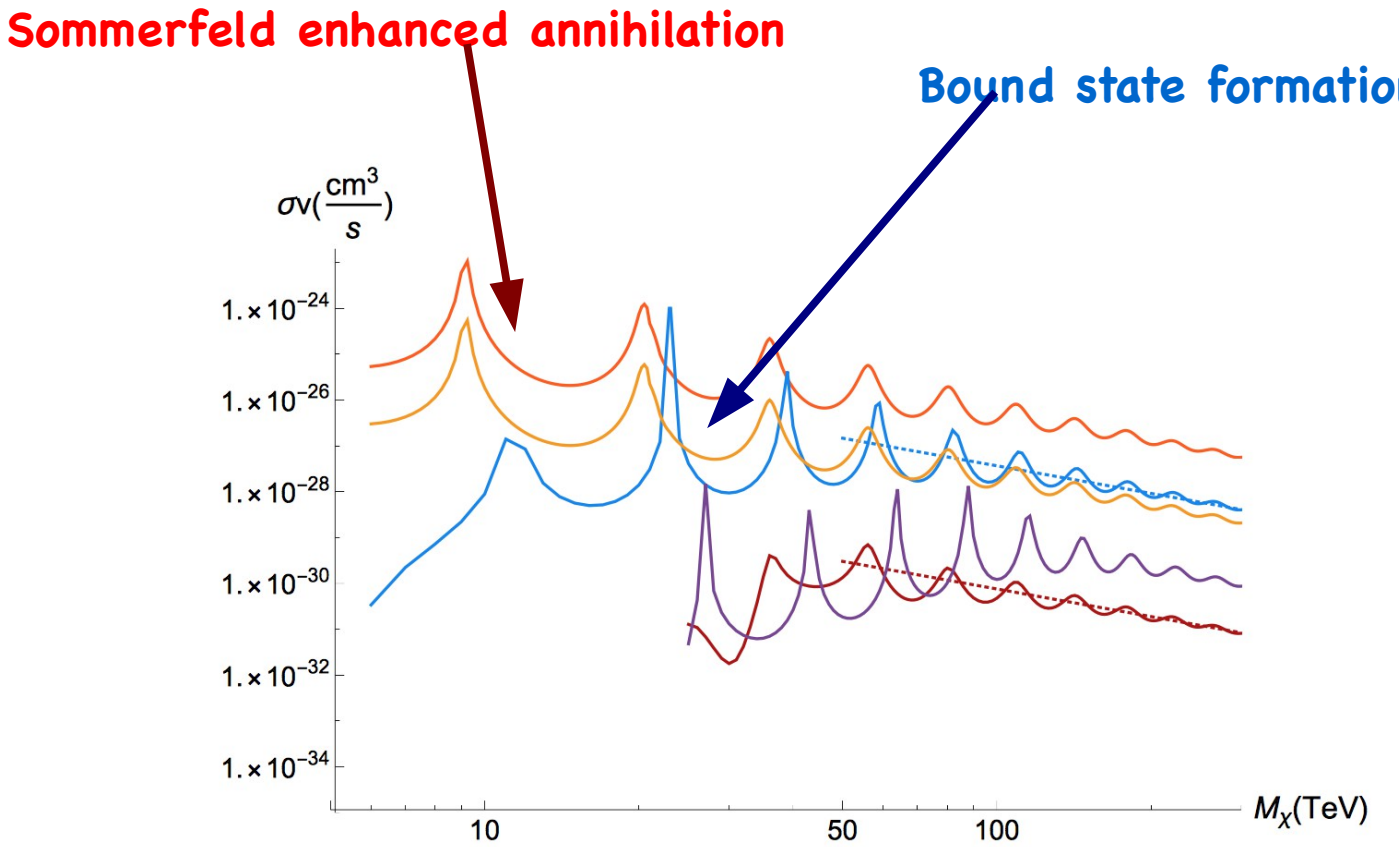




Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

Gamma-ray lines

For EW triplet the BSF is numerically small
Maybe relevant for heavier candidates (Minimal DM?)



Asadi, Baumgart, Fitzpatrick, Krupczak, Slatyer, 1610.07617

Summary

Combination of Sommerfeld effect and Bound state formation give resonant structure and non-trivial dependence of the cross-section on the velocity

This screens the effects in some environments (e.g. small galaxies vs clusters)

Assuming large enough kinetic mixing and not too light mediators indirect detection rules out some portion of the parameter space

Other interesting and different option in presence of a Dark U(1) is asymmetric DM

Thanks!