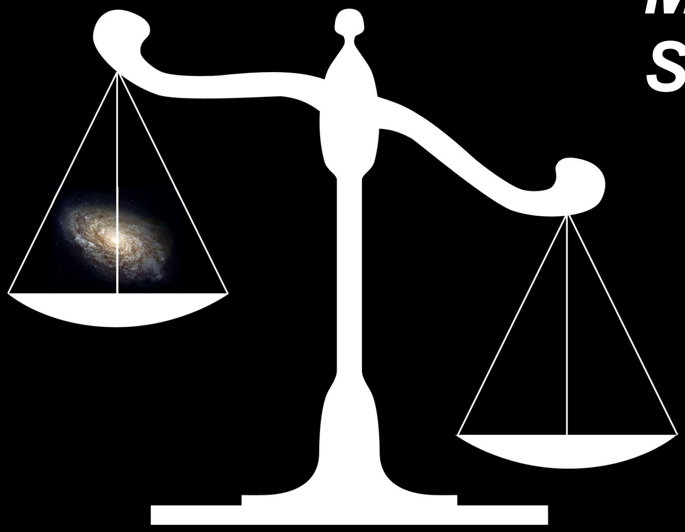
Astrophysical Constraints on Direct Detection:

Multi-Component Dark Matter Scattering and Stability



David Yaylali
University of Hawaii

In collaboration with Keith Dienes (UofA), Jason Kumar (UH), and Brooks Thomas (Carleton).

[ArXiv:1311.xxxx]

Dark Matter: What we do, and do not, know

What we know...

- It is at least one new non-relatavistic particle
- Uncharged
- $\Omega_{DM} \sim 0.25$

What we think we know...

What we don't know...

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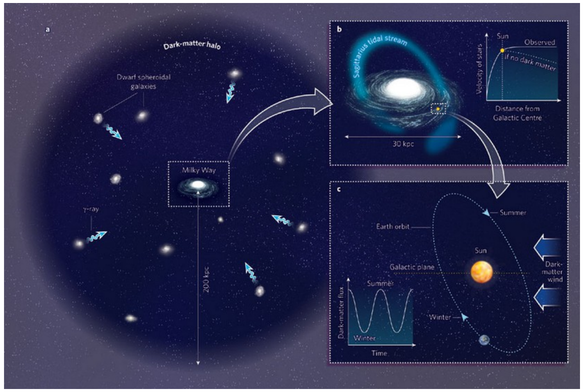

☀ *What we think we know...*

- $\rho_{\text{loc}} \sim 0.3 \text{ GeV}/cm^3$
- Local velocity distribution
- Certain DM-SM cross sections/ masses are excluded

☀ *What we don't know...*

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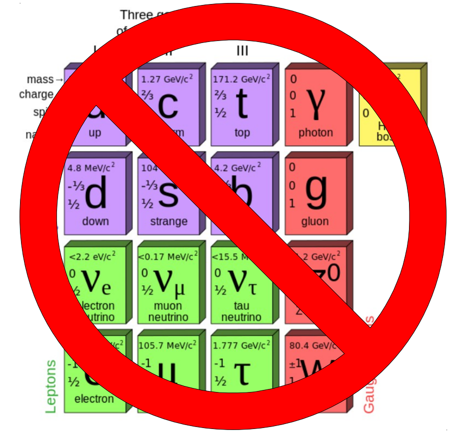

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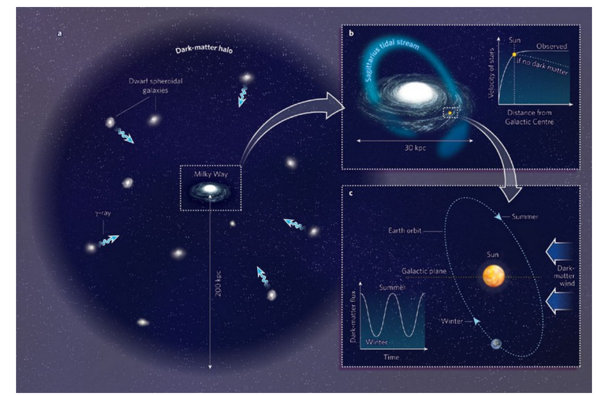

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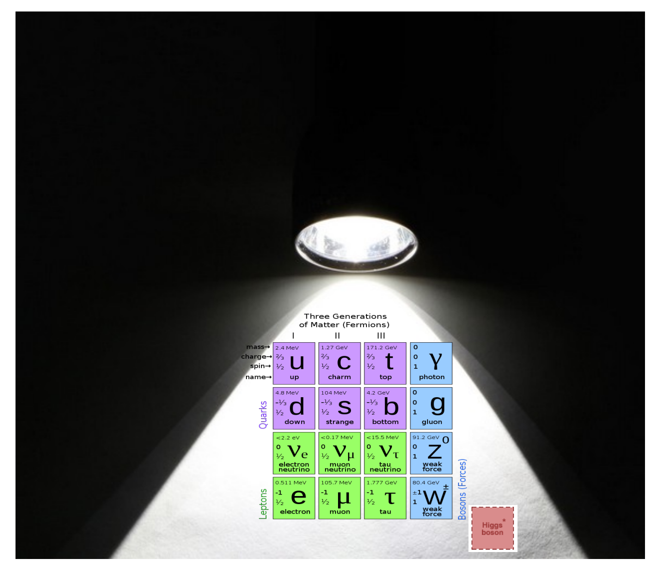


What we don't know...

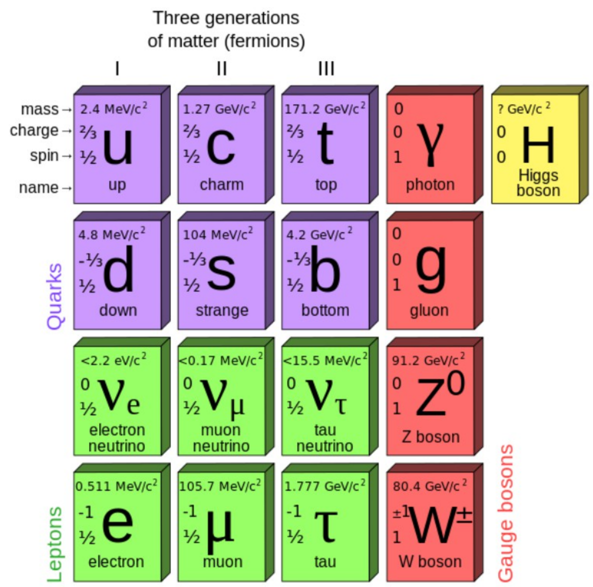
...well, there's more than one reason why it's called "dark" matter.

Common Assumptions: Thermally produced, non-zero interactions with SM, *stable*, *single particle*...

Why Consider Multi-Component Dark Matter?

Given that one accepts the hypothesis of dark matter, there are two scenarios...

SCENARIO I



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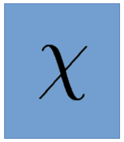

*Everything we **currently** know of... ~20% of the matter in the universe.*

*A **single** extra particle, making up the remaining 80%.*

...OR

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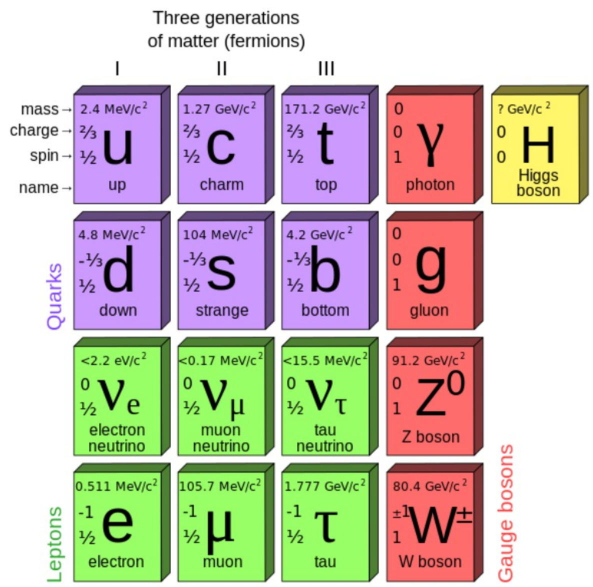

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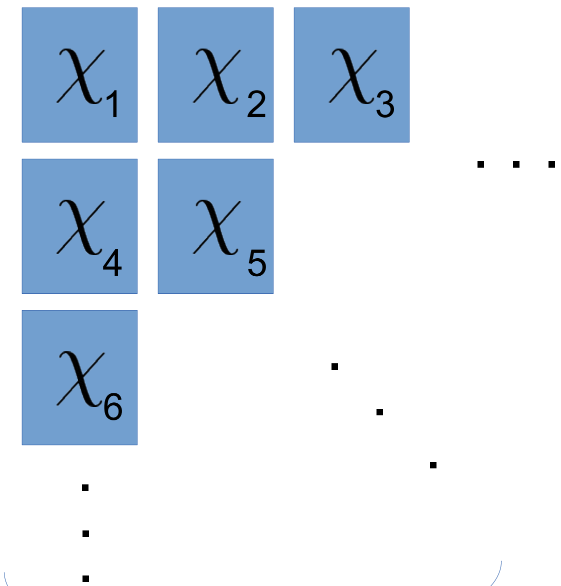

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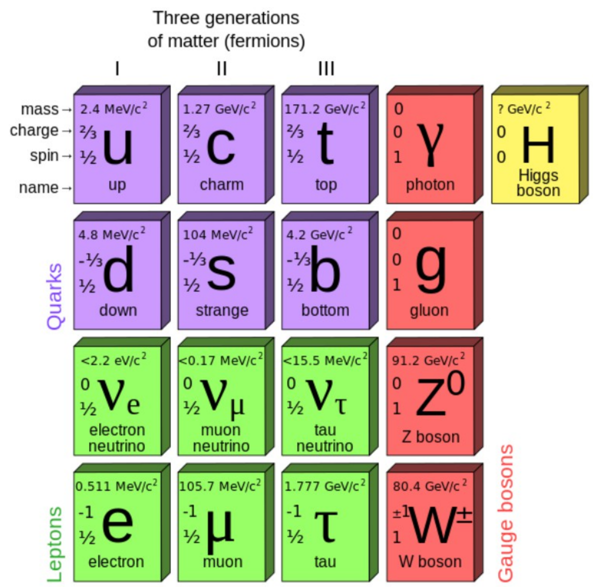

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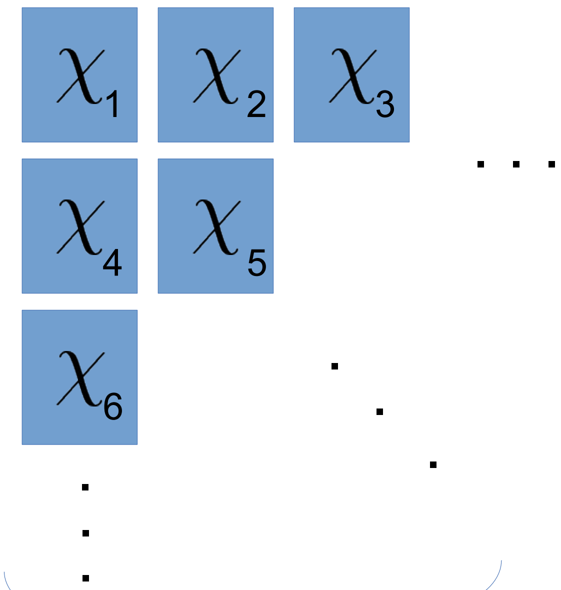

*Everything we **currently** know of... ~20% of the matter in the universe.*

*A **dark sector**, consisting of many different particles which make up the remaining 80%.*

*Given how complicated the standard model is, it is **worth considering** the possibility that the dark sector is complicated as well!*

Ok, but what are some more concrete reasons to motivate models of multi-component DM?

- **DAMA/CoGeNT/CRESST/etc. VS XENON100/COUPP/etc.**
  Reconciling these sets of experiments difficult in vanilla DM models
  - -Inelastic Dark Matter (Smith & Weiner, 2001)
  - -Mirror Matter (Foot, 2004)
  - -Exothermic Dark Matter (Graham, Harnik, et. al., 2010)

- **Positron excess – Pamela, FERMI, AMS-II**
  Similar excess not observed in antiprotons
  Excess too big for thermal freezeout production
  - -Multiple DM particles (Zurek et. al., 2008; Feldman, et. al., 2010)

- **Gamma ray line at 130 GeV (FERMI)** *(...or just "earth limb" photons?)*
  DM typically annihilates to other particles at much larger rate (DM is dark!)
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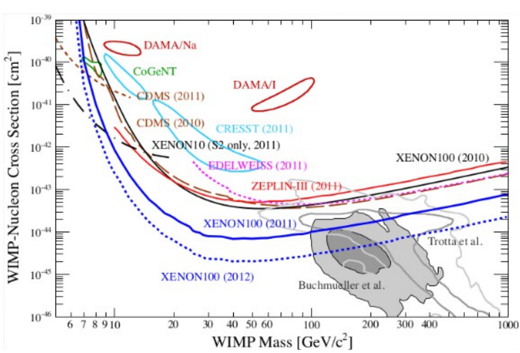

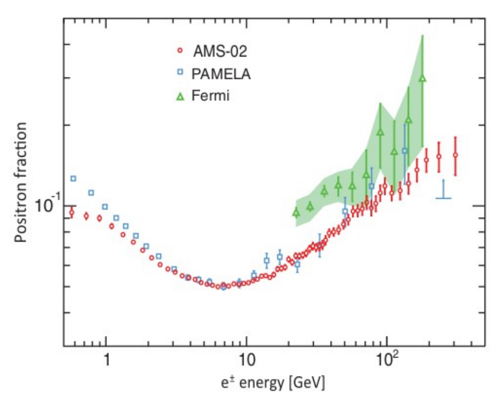

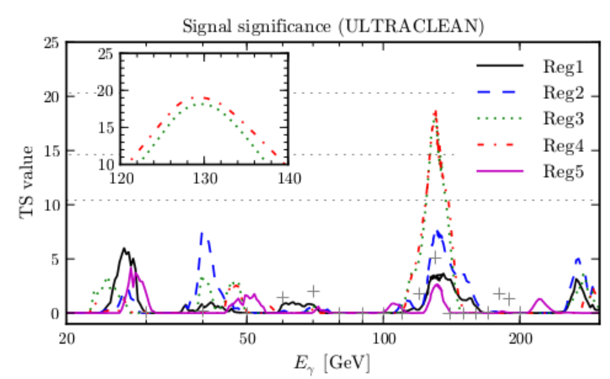

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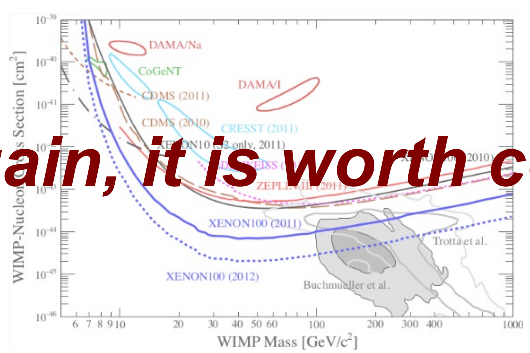
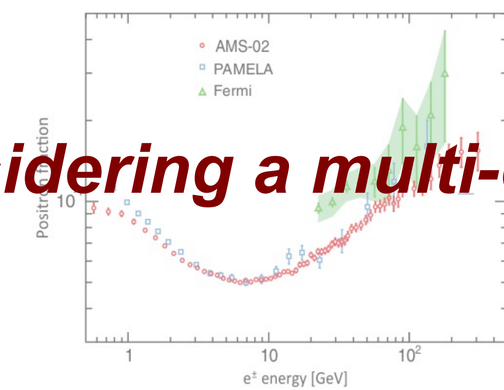
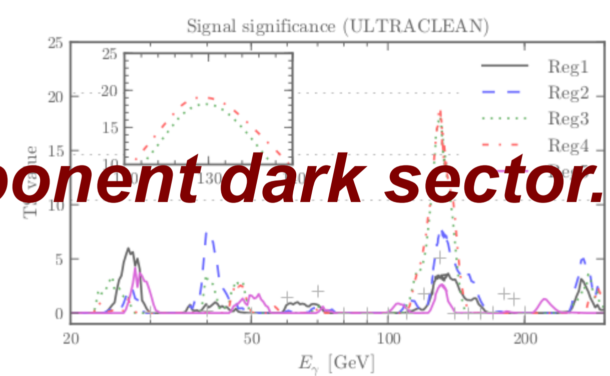
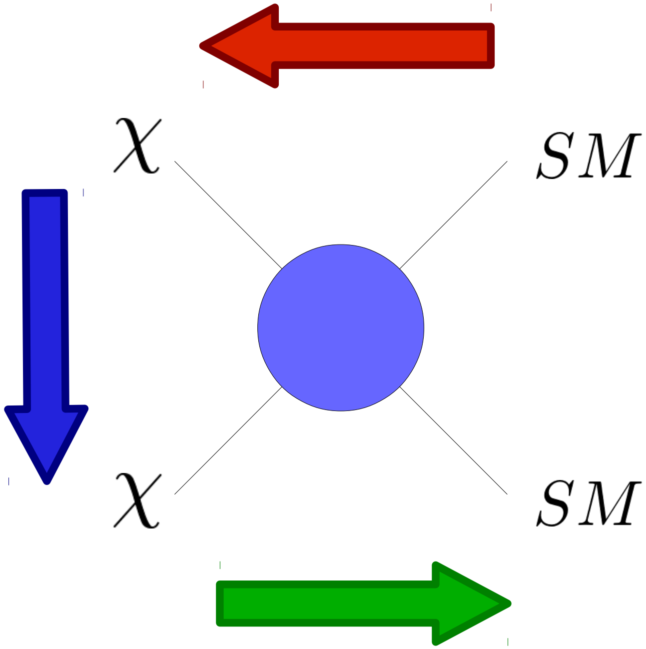






Again, it is worth considering a multi-component dark sector.

Our non-gravitational windows into dark matter...



- **DM-SM scattering** – (direct detection)
- **DM annihilation to SM** – (indirect det. + relic density)
- **Collider Production**

Same diagram $\Longrightarrow$ Processes related by "crossing symmetry"

If there are two or more species of dark matter, we also have...

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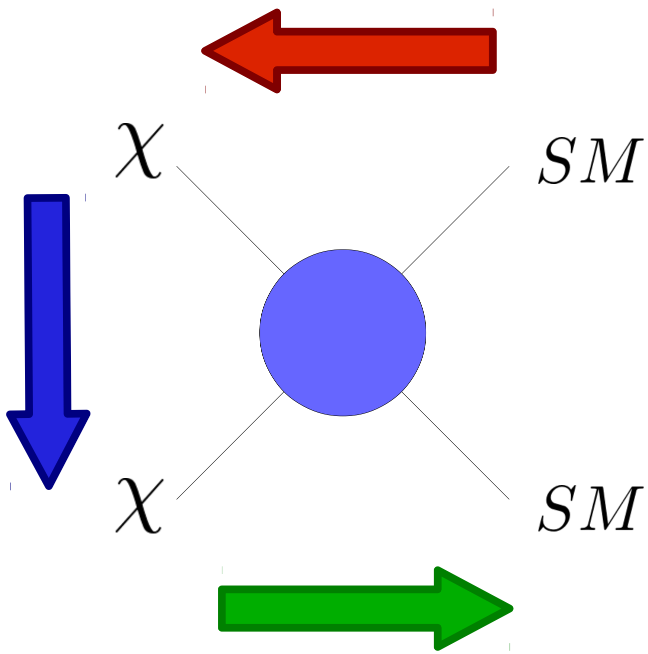

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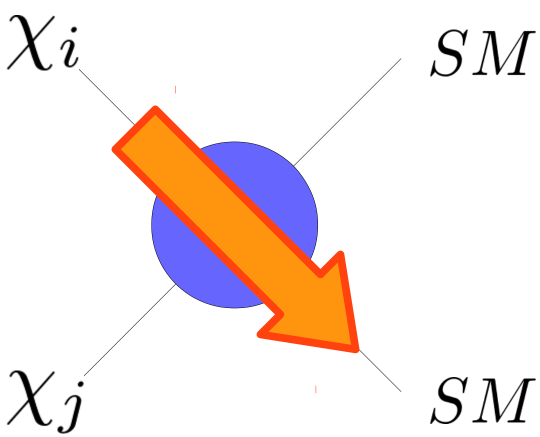
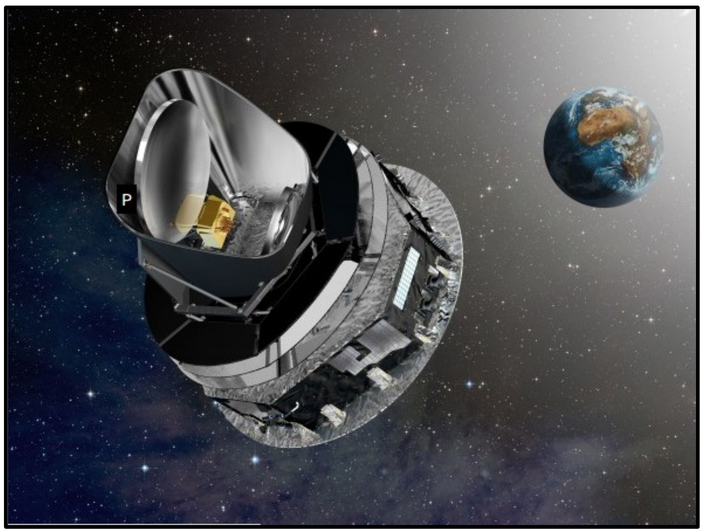


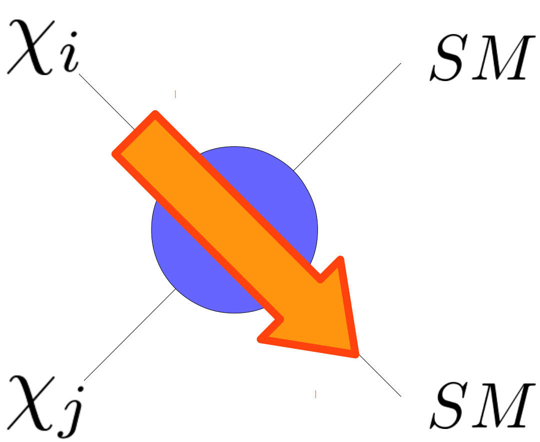
- **DM decay to DM+SM** – (indirect detection!)

Again, same diagram $\Longrightarrow$ Decay rate **also** correlated with the above cross sections!

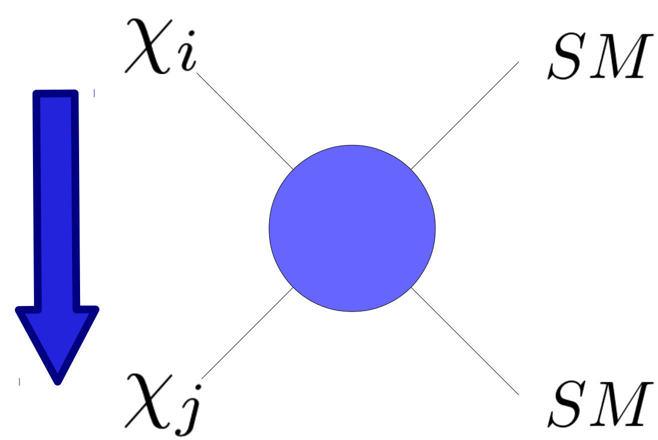
We now have a new relationship at our disposal...

The Final Frontier...





Dante's Inner Circles...



The Framework

To see how this works, we study an illustrative and general model:

- Two fermionic DM particles, χ_i and χ_j
- Mass difference of order $\Delta m_{ij} \equiv m_j - m_i \lesssim \mathcal{O}(100 \text{ keV})$
  (Thus these operators are relevant for direct detection)
- Effective contact couplings between DM particles and quarks:

$$\mathcal{L}_{\text{int}}^{(\text{fund})} = \sum_{\alpha} \sum_{ijff'} \frac{c^{\alpha}_{ijff'}}{\Lambda^2} \mathcal{O}^{(\alpha)}_{ijff'}$$

$$\begin{aligned}
\mathcal{O}^{(S)}_{ijff'} &= (\overline{\chi}_i \chi_j)(\overline{q}_f q_{f'}) \\
\mathcal{O}^{(P)}_{ijff'} &= (\overline{\chi}_i \gamma^5 \chi_j)(\overline{q}_f \gamma^5 q_{f'}) \\
\mathcal{O}^{(V)}_{ijff'} &= (\overline{\chi}_i \gamma^\mu \chi_j)(\overline{q}_f \gamma_\mu q_{f'}) \\
\mathcal{O}^{(A)}_{ijff'} &= (\overline{\chi}_i \gamma^\mu \gamma^5 \chi_j)(\overline{q}_f \gamma_\mu \gamma^5 q_{f'}) \\
\mathcal{O}^{(T)}_{ijff'} &= (\overline{\chi}_i \sigma^{\mu\nu} \chi_j)(\overline{q}_f \sigma_{\mu\nu} q_{f'})
\end{aligned}$$

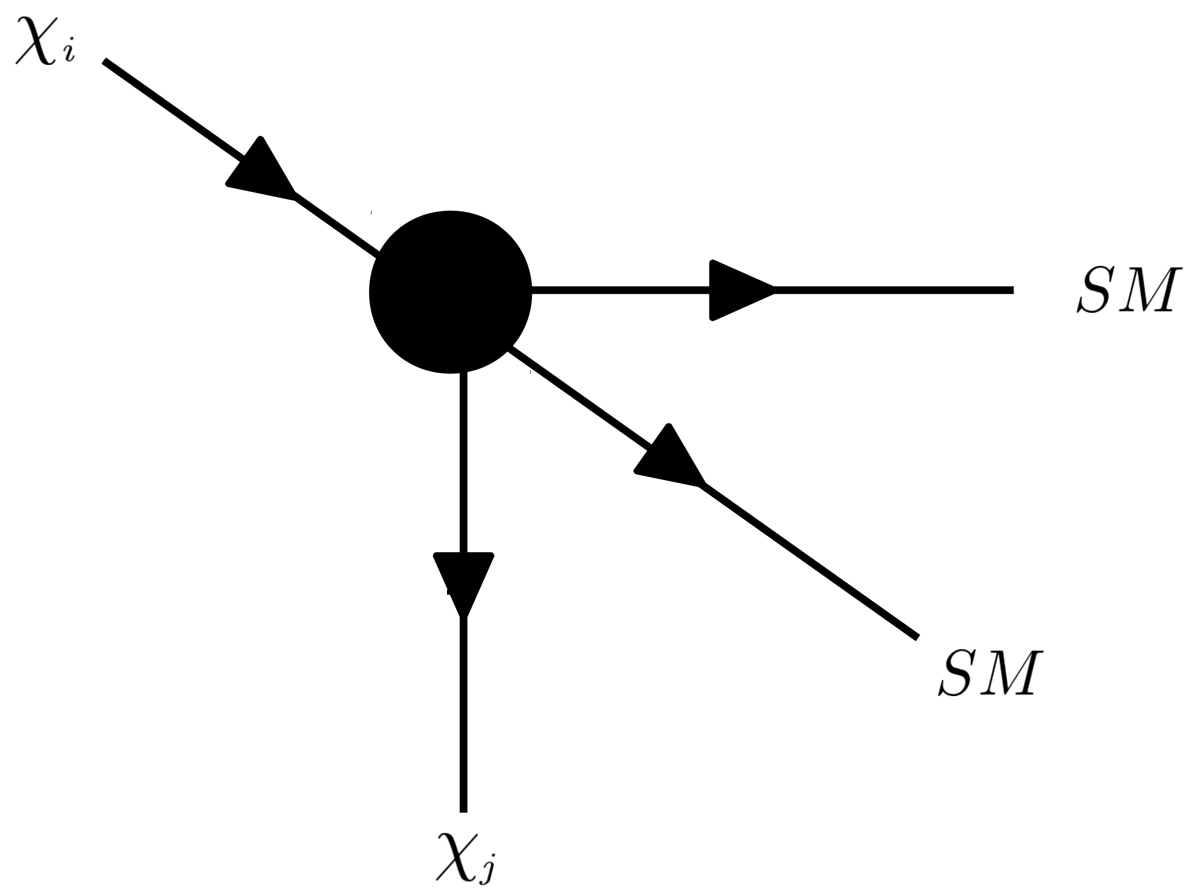
- χ_is uncharged
- Generation independent
- $\Delta m \lesssim \mathcal{O}(100 \text{ kev}) \Rightarrow$ Only light quarks contribute to decay.

$$c^{(\alpha)}_{ijff'} = \begin{pmatrix} c^{(\alpha)}_{iju} & 0 & 0 \\ 0 & c^{(\alpha)}_{ijd} & 0 \\ 0 & 0 & c^{(\alpha)}_{ijd} \end{pmatrix}$$

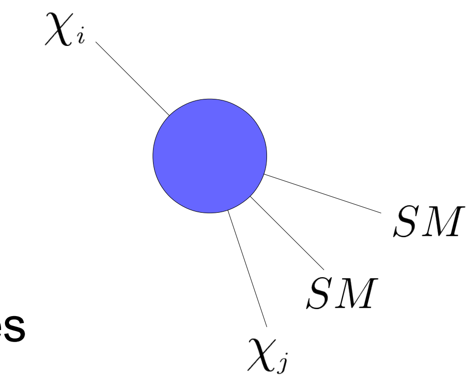
In what follows we choose to express results in terms of the coefficients

$$c^{(\alpha)}_{\pm} = c^{(\alpha)}_u \pm c^{(\alpha)}_d$$

Decaying Dark Matter



Decay Channels

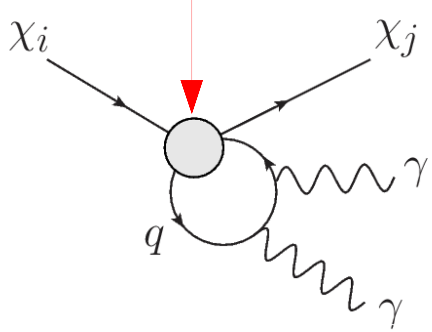


- Since $\Delta m_{ij} \lesssim \mathcal{O}(100\ \mathrm{keV})$, only possible SM decay products are low energy **photons** and **neutrinos**
- χ_i only couples to quarks, which at these low energies are bound as mesons

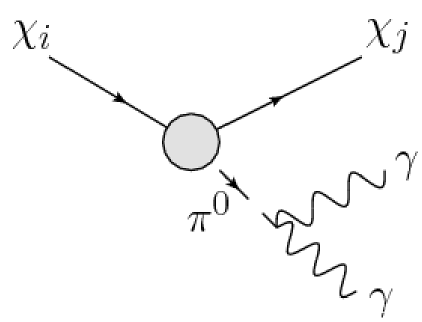
$\Longrightarrow$ Decay of χ_i proceeds through off-shell (loops of) mesons

$\Rightarrow$ Decay widths highly suppressed (this is good, as we shall see)

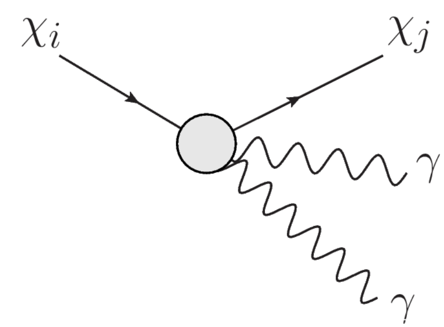
We have this coefficient... *...but how do we get here?*



Microscopic Theory



Low Energy EFT



Effective χ-γ couplings

$$\mathcal{L}_{\mathrm{int}}^{(\mathrm{fund})} \ni \frac{c_{\pm}^{(p)}}{\Lambda^2} (\overline{\chi}_j \gamma^5 \chi_i)(\overline{q} \gamma^5 q)$$

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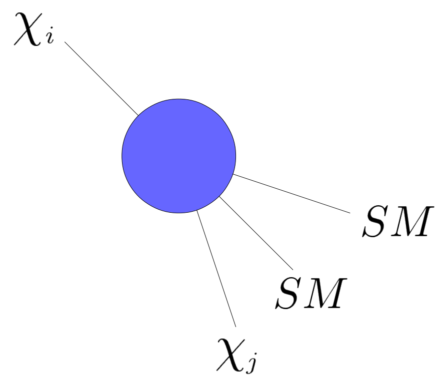

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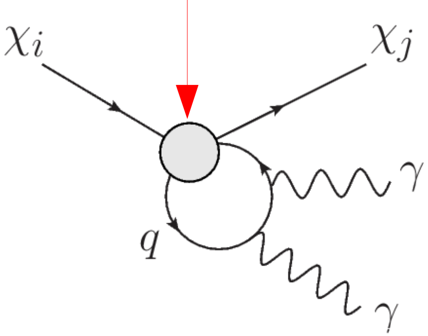

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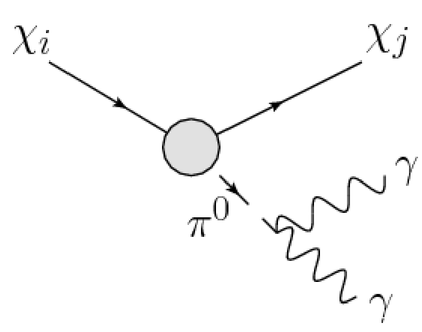

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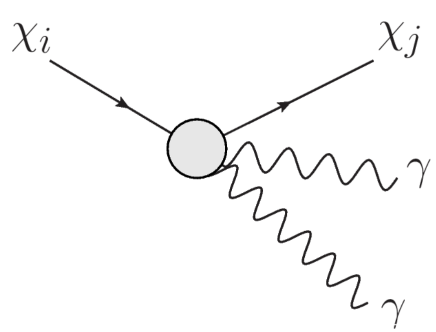

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Chiral Perturbation Theory $\longrightarrow$

$$\mathcal{L}_{\rm int}^{\rm (eff)} \ni \frac{C_P}{\Lambda^2}(\overline{\chi}_j\gamma^5\chi_i)F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

where $C_P = C_P\{c_\pm^{(p)}, B_0, f_\pi, \dots\}$

Decay Widths

We now have the entire effective Lagrangian for the interactions $\chi_j \to \chi_k \gamma$ and $\chi_j \to \chi_k \gamma\gamma$, in terms of our original high energy coefficients:

$$\mathcal{L}_{\rm eff} = \frac{c_S}{f\Lambda^2}(\overline{\chi}\chi)F_{\mu\nu}F^{\mu\nu} + \frac{c_P}{f\Lambda^2}i(\overline{\chi}\gamma^5\chi)F_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{c_V}{\Lambda^2}(\overline{\chi}\gamma^\mu\chi)\partial^\nu F_{\mu\nu} + \frac{c_{V'}}{f^2\Lambda^2}(\overline{\chi}\gamma^\mu\chi)\partial_\rho\partial^\rho\partial^\nu F_{\mu\nu} + \cdots$$

...from whence we compute the decay widths. Things are **NOT PRETTY**, but simplify considerably with the approximation $\Delta m \ll \{m_j, m_k\}$:

$$\Gamma_S^{(\gamma)} \approx \frac{2c_S^2\Delta m^7}{105\pi^3 f^2\Lambda^4}$$

$$\Gamma_P^{(\gamma)} \approx \frac{2c_P^2\Delta m^9}{315\pi^3 f^2\Lambda^4 m_j^2}$$

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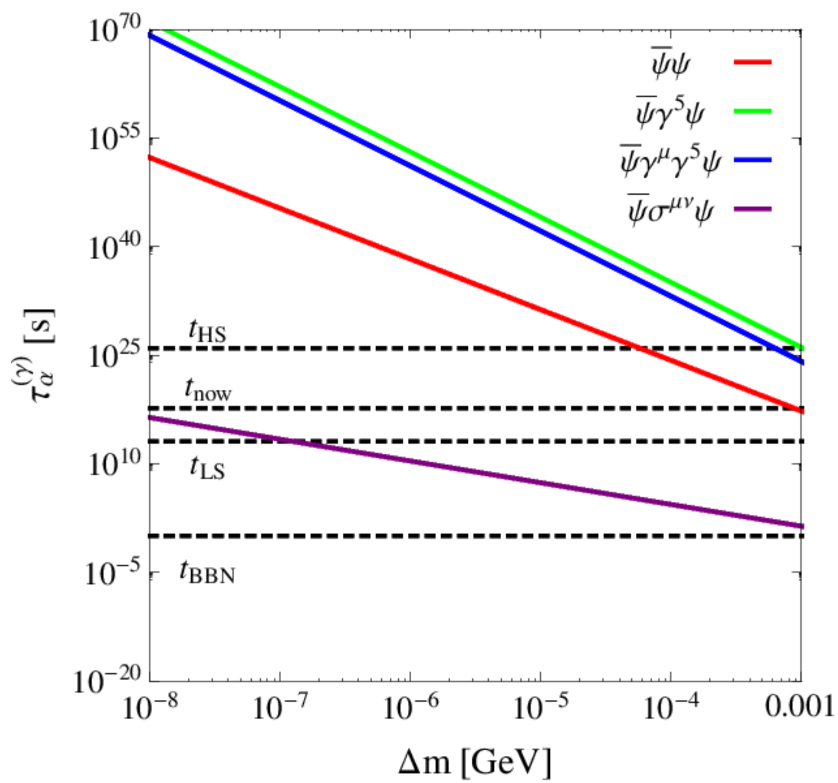

$c_+^{(\alpha)} = c_-^{(\alpha)} = 1$

$\Lambda = 10$ TeV

$m_i = 100$ GeV

Dienes, Kumar, Thomas, D.Y., [arXiv:1311.xxxx]

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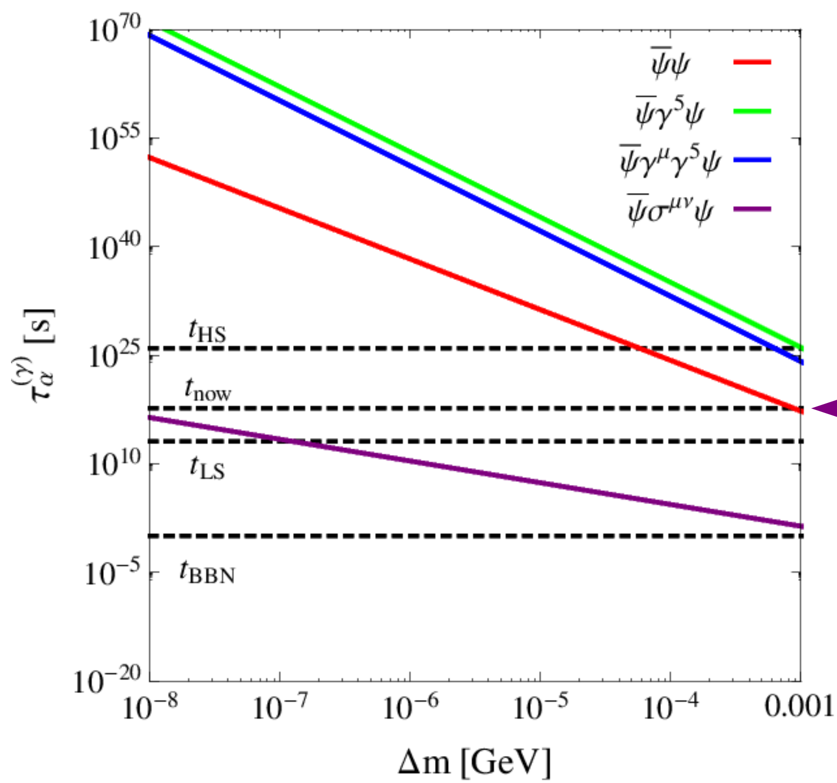


Age of the Universe

$c_u^{(\alpha)} = c_d^{(\alpha)} = 1$

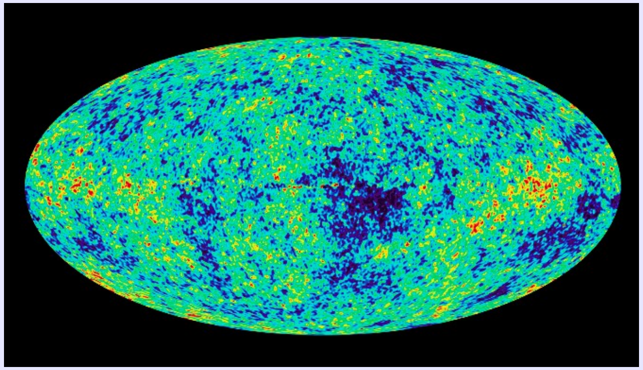
$\Lambda = 10$ TeV

$m_i = 100$ GeV

We can clearly achieve models where the heavier DM component remains undecayed to this day

We also require, however, our dark matter particle to be hyperstable..

Dark matter decaying to x-rays can affect the ***reionization history*** of our universe. This history is *precisely imprinted in the CMB anisotropies*. This constrains Δm and lifetime. [arXiv:1206.4114]



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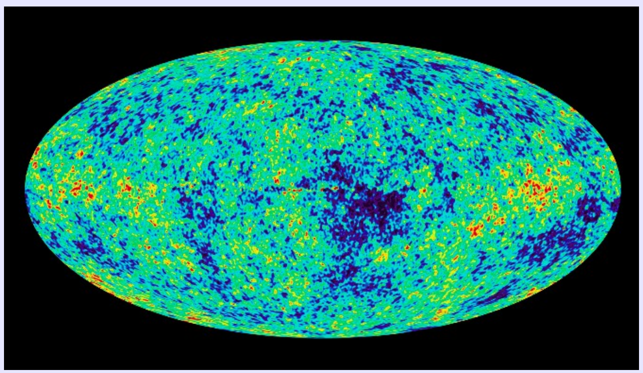

XMM-Newton observations of ***X-ray diffuse background*** of Andromeda constrain lifetime of DM. [Boyarski et. al. 2006]

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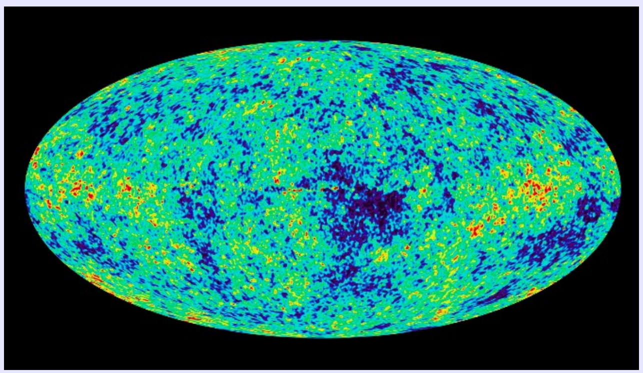

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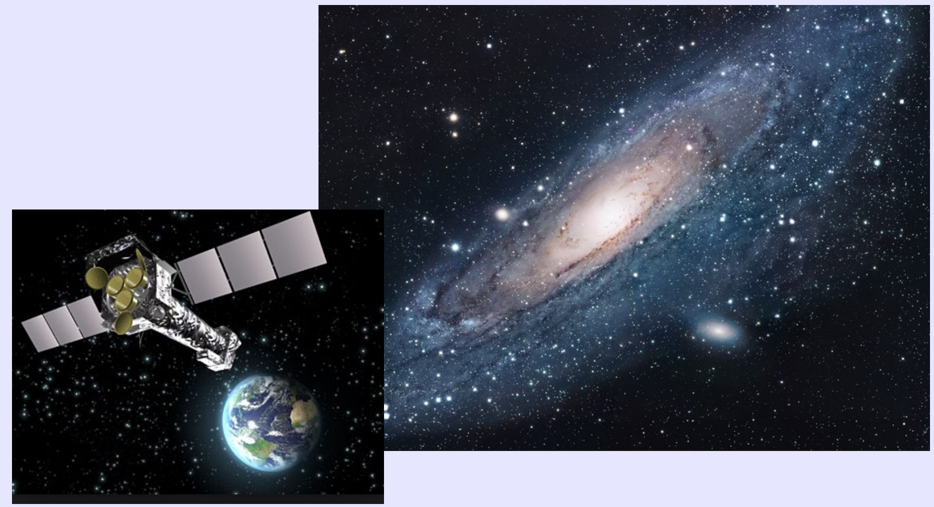


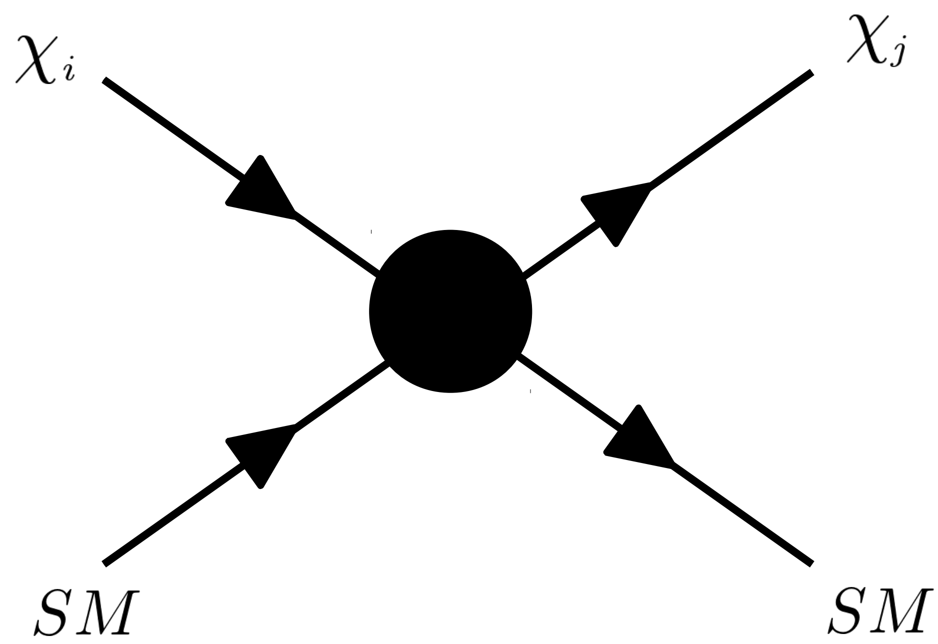
...so this provides us with a constraint on the DM parameter space.

Dark matter decaying to x-ray photons must be ***hyperstable***:

$$\tau_{DM} \geq 10^{26}\mathrm{s}$$

This constrains $\Lambda,\ c_{u/d},\ m_i,\ \Delta m$

Inelastic Dark Matter Direct Detection



Direct detection experiments all function on the same basic principle....

There is some probability that a dark matter particle will scatter off a nucleus within a detector.

Detection Mechanisms

As the nucleus recoils, it will either

- Excite phonons
- Ionize other nuclei
- Emit photons

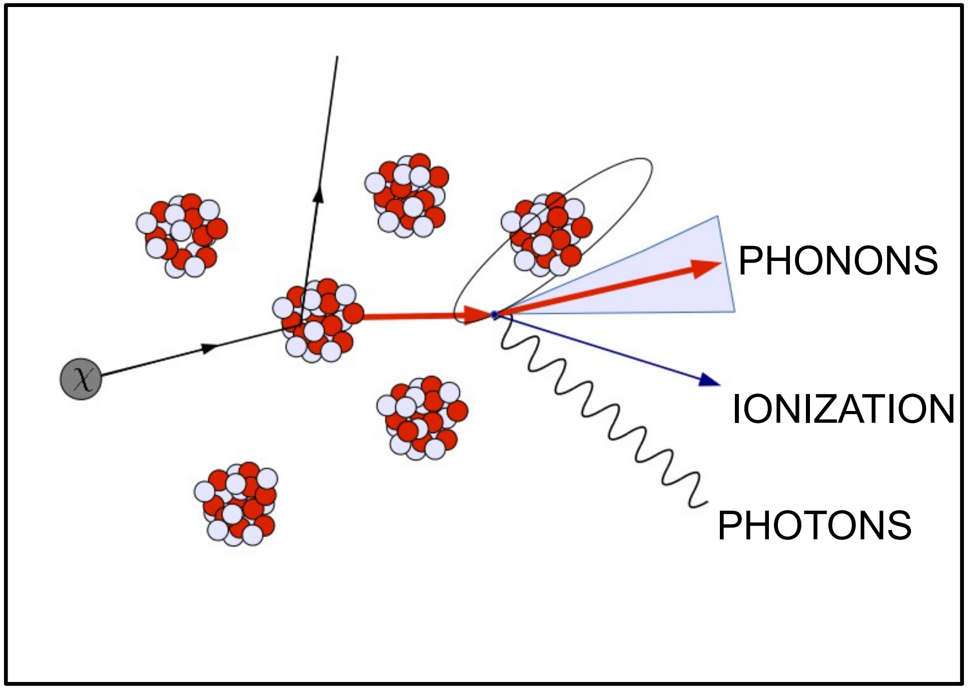
Each mechanism has it's advantages and disadvantages (backgrounds).

Observables

- Event rate (and modulation)
- Recoil Energy Spectra
- Directionality

That's it!

So we better make the most of this limited data!



Scattering Kinematics for $\chi_j N \to \chi_k N$

In multi-component dark matter models, we have three different regimes which lead to unique recoil energy spectra.

$$\Delta m \equiv m_k - m_j$$

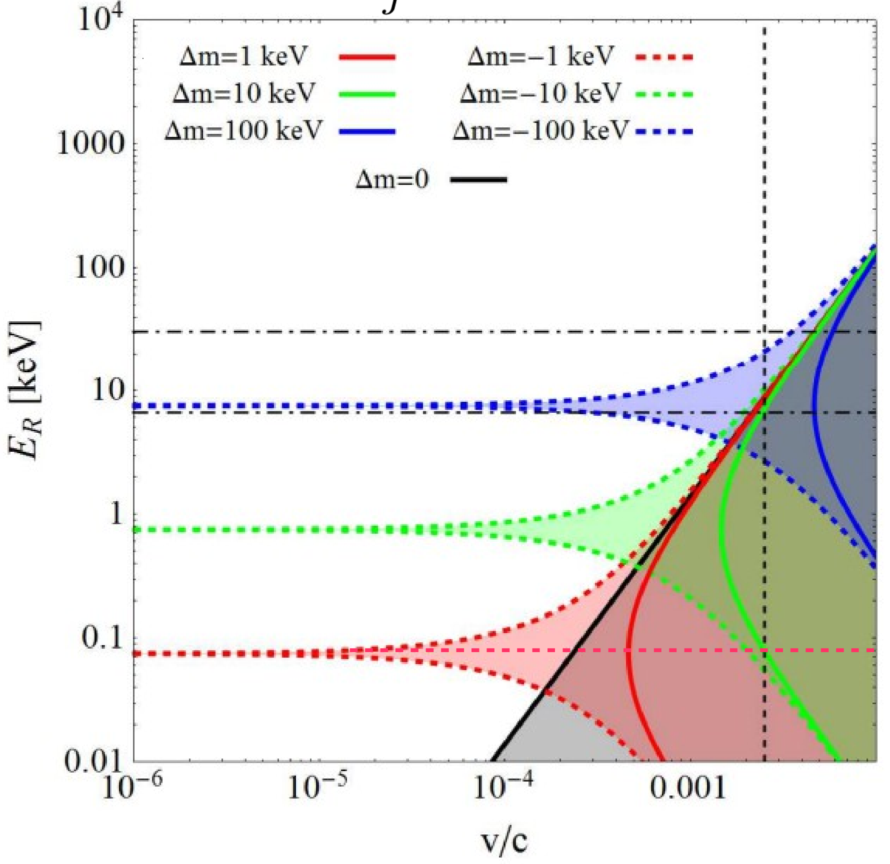
$\Delta m = 0$ ➡ **"Elastic Scattering"**
Typical case studied – single component dark matter.

$\Delta m > 0$ ➡ **"Upscattering"**
Typical case studied in *inelastic* DM scenarios. DM scatters off nucleus into higher mass "excited" state.
[Inelastic DM – Smith, Weiner, 2001]

$\Delta m < 0$ ➡ **"Downscattering"**
DM scatters off nucleus into lower mass state. Δm released as kinetic energy
[Exothermic DM – Graham, Harnick, et. al. 2010]

Range of E_R at XENON100

$m_j = 10\text{GeV}$



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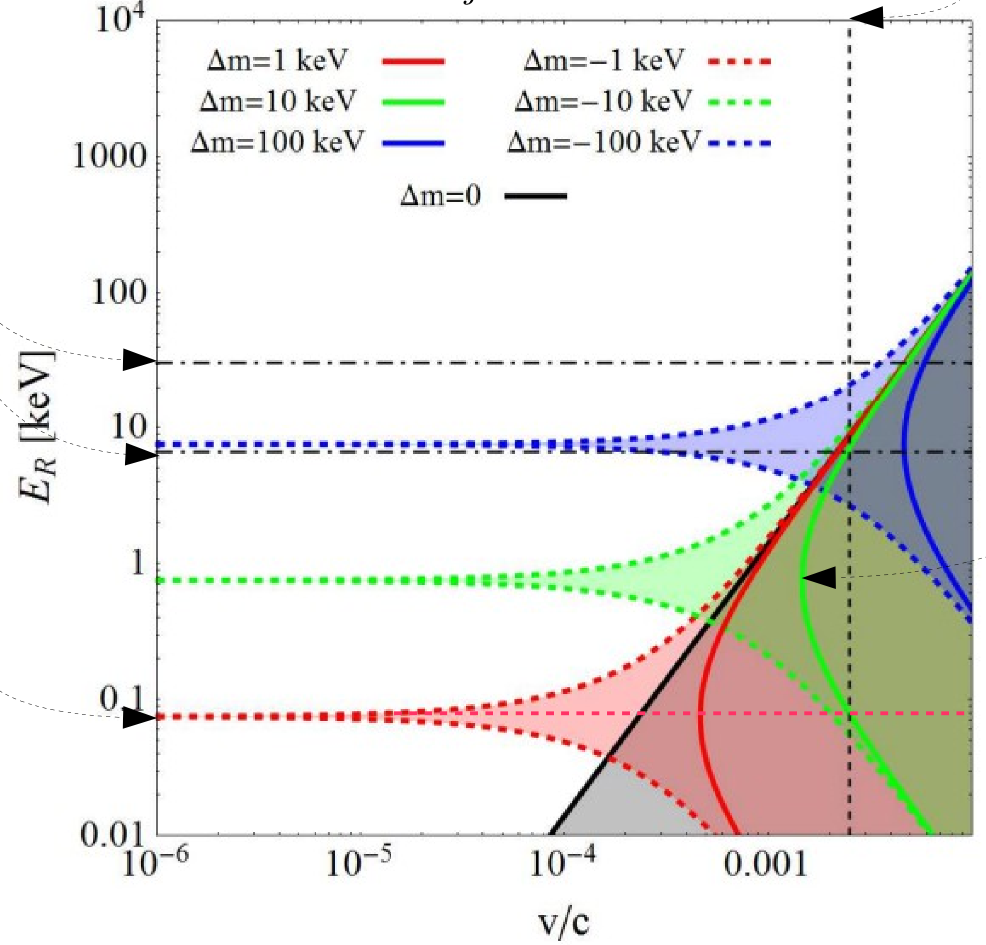


- Expected velocity cutoff v_{esc}
- Min/max recoil energies used by XENON100 analysis
- Energy threshold for upscattering: $v > \sqrt{m/\mu_{Nj}}$
- "Stationary" particles: Energy Δm given to χ_k and N

$$E_R = \frac{-\mu_{Nk}\Delta m}{m_N}$$

- Scattering assumed isotropic in CM frame

$$E_R \approx \frac{\mu_{Nj}^2 v^2}{m_N}\left[1 - \frac{\Delta m}{\mu_{Nj} v^2} + \left(1 - \frac{2\Delta m}{\mu_{Nj} v^2}\right)^{1/2} \cos\theta\right]$$

Recoil Energy Spectra

Remember, recoil energy spectra are one of our very few observables... and so we better make the most of them!

- ***Down/upscattering lead to unique and distinguishable recoil energy spectra***
  (which is our only observable at current direct detection experiments)

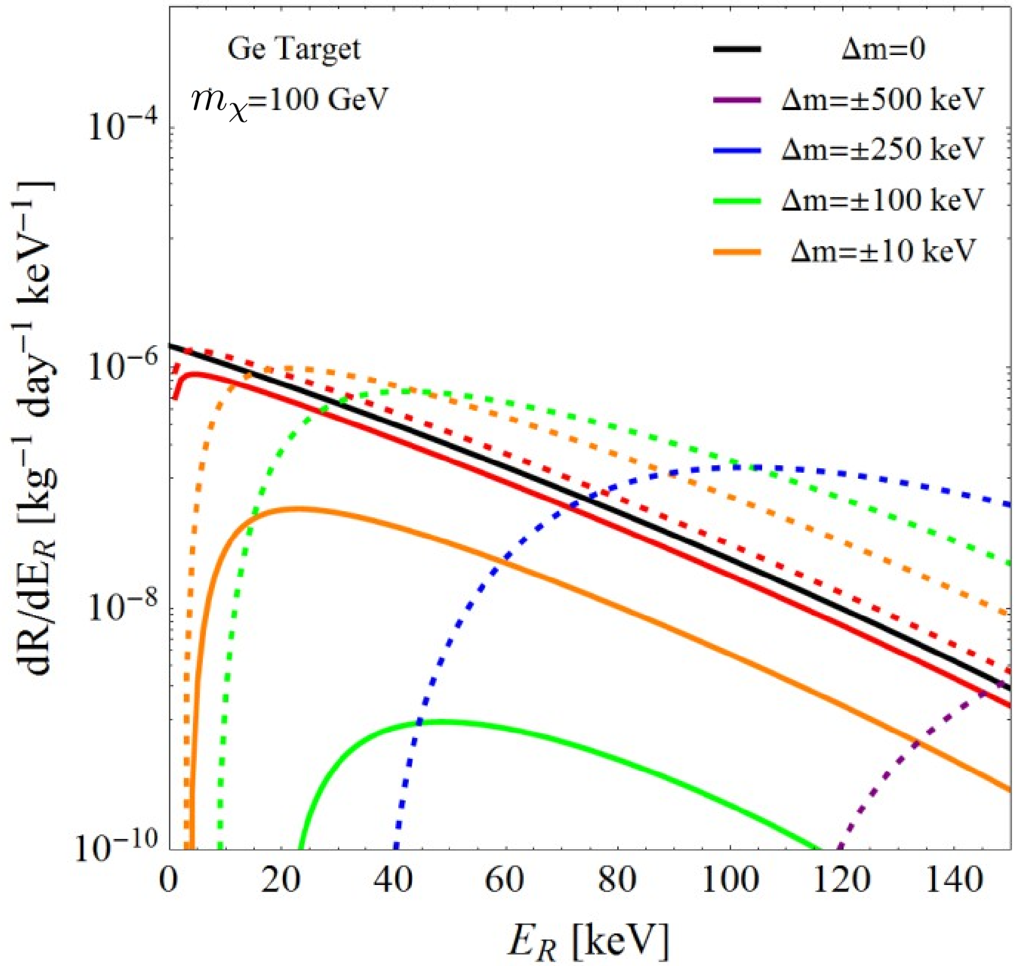
- ***Downscattering generally more accessible to direct detection***
  (due to energy released from Δm)

- ***Upscattering becomes undetectable for high Δm***
  (though bounds from decays become better)

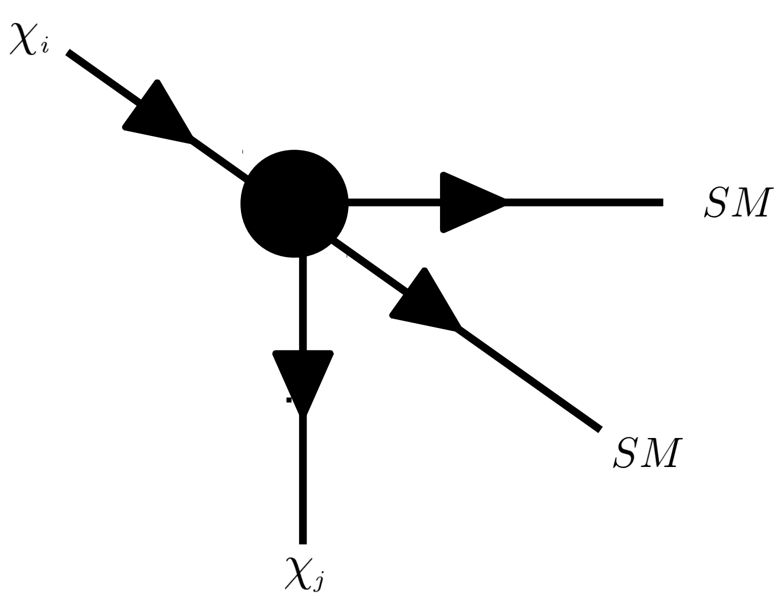
Here, we have chosen $c_{\pm}$ *such that*

$$\sigma_{n0}^{(SI)} = 10^{-46}\ \mathrm{cm}^{-2}$$

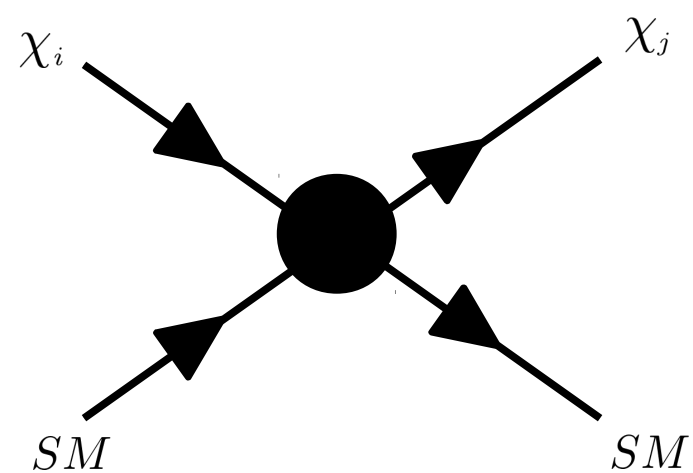
Upscattering (solid)
Downscattering (Dashed)



These spectra would be a *smoking gun* signal for multi-component dark matter.



Finally, Tying it all Together...



Now combine constraints from scattering and decay

Excluded by XENON100

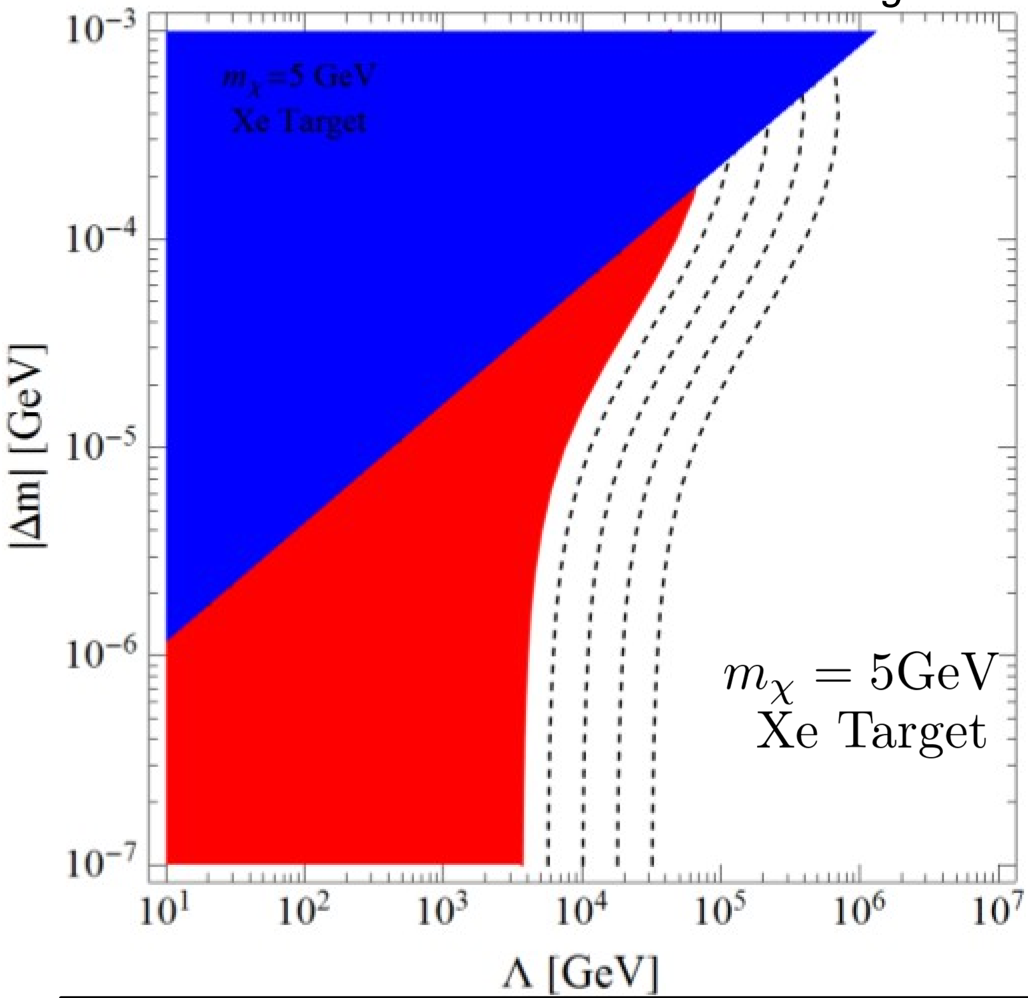
- **Most recent limits** from [arXiv:1207.5988].
- Total event rate for nuclear recoils with
  $6.6\ \text{keV} \leq E_R \leq 30.6\ \text{keV}$
- Most recent limits restrict DM to interact at a rate
  $R \lesssim 5.66 \times 10^{-4}\ \text{kg}^{-1}\ \text{day}^{-1}$.

Excluded by astrophysical (CMB) constraints on decays to photons

- **Largely model independent**... follow directly from existence of operators allowing downscattering.
- **Region does not include current/future Planck data,** which may eat further into parameter space
- **Region does not include other operators** (e.g., tensor), which may have substantially more stringent bounds.

Dienes, Kumar, Thomas, D.Y., [arXiv:1311.xxxx]

"French Flag Plot"



- Scalar operator: $\mathcal{O}^s = \frac{c^{(s)}}{\Lambda^2}(\overline{\chi}_i \chi_j)(\overline{q} q)$
- Dashed lines represent event direct detection event rate of
  $R = \{10^{-4},\ 10^{-5},\ 10^{-6},\ 10^{-7}\}\ \text{kg}^{-1}\ \text{day}^{-1}$

Conclusions

- It is almost a certainty that the majority of matter in our universe is something unknown to the standard model.
- Multicomponent dark matter models are **well motivated** theoretically and experimentally.
- This scenario naturally leads to the possibility of DM decay, and decay rates can be reliably calculated using ChPT.
- Multicomponent DM leads to **unique recoil energy spectra**.

The interplay between direct detection experiments and DM decay provide a novel constraint on dark matter parameter space.

Thanks for coming!

Backup Slides

A Short Digression: Dispensing with the Common Lore...

- To calculate direct detection rates, a necessary step is to take nucleonic matrix elements of these operators:

$$\langle n|\overline{q}\gamma^\mu\gamma^5 q|n\rangle \to \Delta q^{(n)}\langle n|\overline{n}\gamma^\mu\gamma^5 n|n\rangle$$

$\Delta q^{(n)}$ are *spin fractions*, determined both experimentally and on the lattice:

$\Delta u^{(p)} = 0.78$ $\Delta d^{(p)} = -0.48$ $\Delta s^{(p)} = -0.15$

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$$\langle n|\overline{q}\gamma^5 q|n\rangle \to \Delta q'^{(n)}\langle n|\overline{n}\gamma^5 n|n\rangle$$

We can find the Δq' coefficients from the Δq coefficients using a Goldberger-Treiman type argument...

$$\partial_\mu\langle n|\overline{q}\gamma^\mu\gamma^5 q|n\rangle = 2m_q\langle n|\overline{q}\gamma^5 q|n\rangle + \frac{\alpha_s}{4\pi}\langle n|G_{\mu\nu}\widetilde{G}^{\mu\nu}|n\rangle$$

$\Delta u'^{(p)} = 170$ $\Delta d^{(p)} = -165$ $\Delta s^{(p)} = -5.07$

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⇒ $\Delta u'^{(p)} = 170$ $\Delta d^{(p)} = -165$ $\Delta s^{(p)} = -5.07$

So couplings are enhanced by $\Delta q^{(n)}/\Delta q'^{(n)} = \mathcal{O}(10^2)$

A Short Digression: Dispensing with the Common Lore...

- Typical (axial-axial) spin dependent interaction:

$$\sigma_{AA} \propto \left(\Delta q^{(n)} \langle S_n \rangle\right)^2$$

- Previously neglected scalar-pseudoscalar spin dependent interaction:

$$\sigma_{SP} \propto \left(\frac{v_{DM}}{c} \times \Delta q'^{(n)}\right)^2 \langle S_n \rangle^2$$

$\mathcal{O}(10^{-6})$ velocity suppression relative to axial-axial coupling

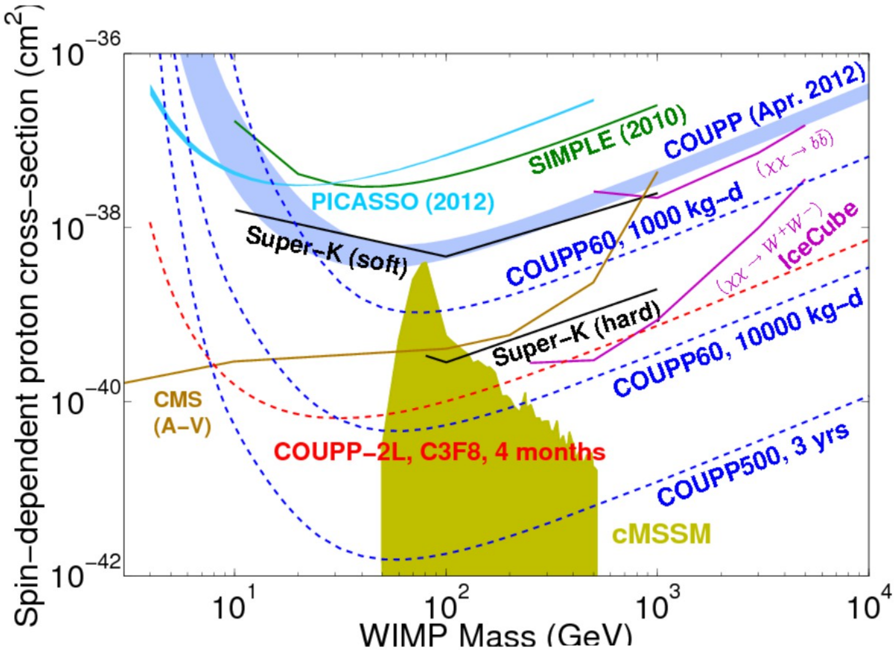
$\mathcal{O}(10^{4})$ enhancement relative to axial-axial coupling

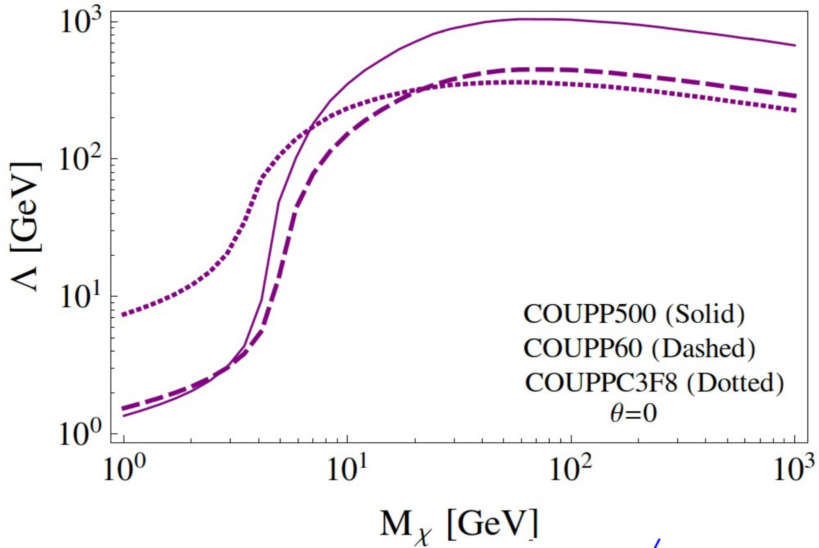
There is also a factor of 6 enhancement to σ_{SP} arising from a difference in the spin structure of the bilinears.

Pseudoscalar event rates only suppressed by a factor of 10, NOT 10^6!

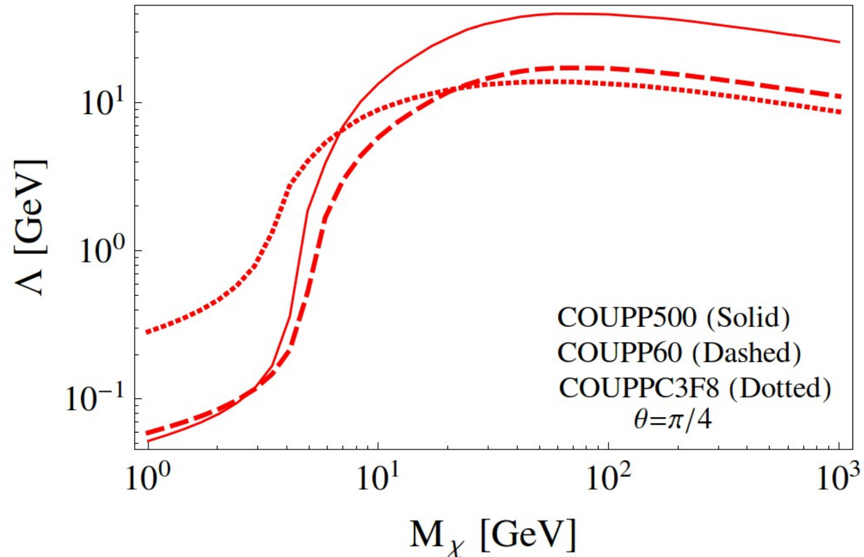
$\mathcal{O}^{(SP)}$ *NOT NEGLIGIBLE*

A Short Digression: Dispensing with the Common Lore...





Isospin violating $g_{\chi u} \neq g_{\chi d}$



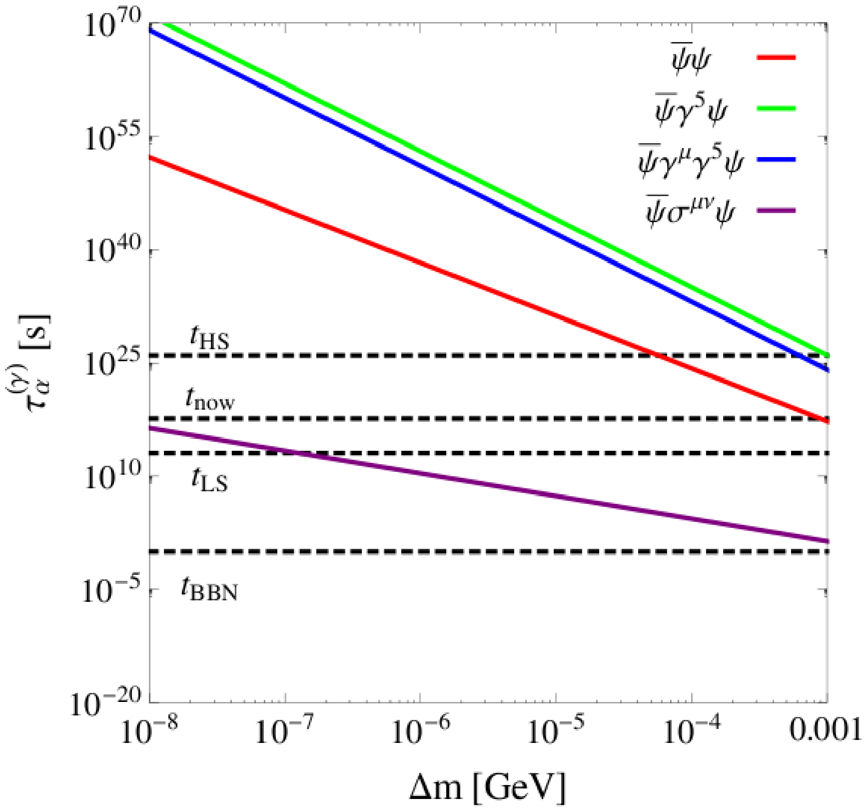
Isospin conserving $g_{\chi u} = g_{\chi d}$

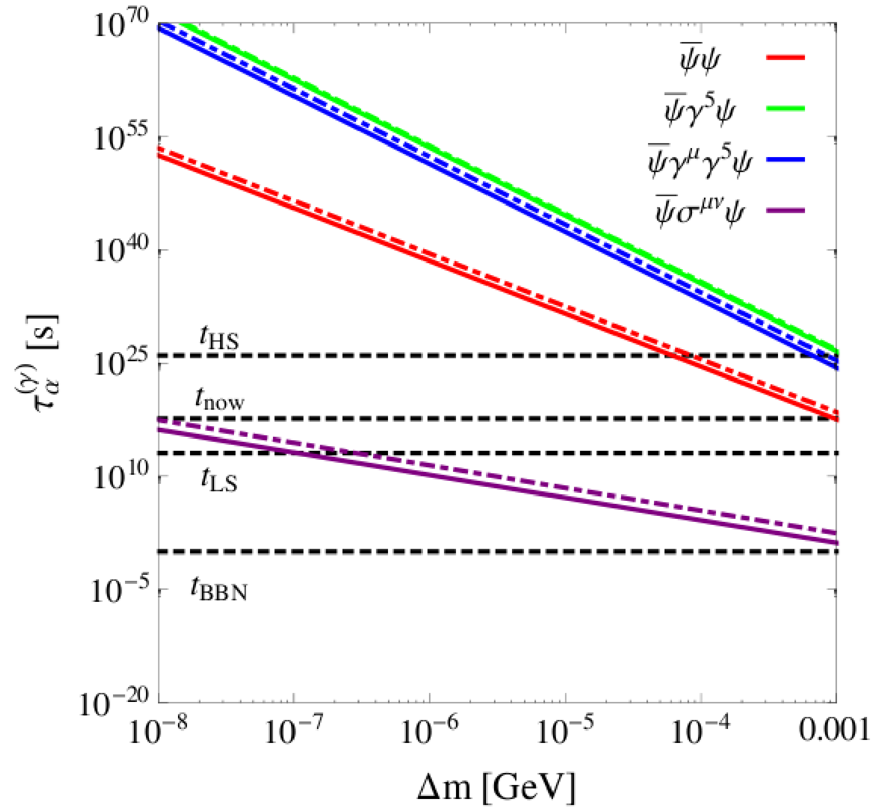
(End of digression)

$c_+^{(\alpha)} = c_-^{(\alpha)} = 1$

$c_+^{(\alpha)} = 1, c_-^{(\alpha)} = 0$ (solid)

$c_+^{(\alpha)} = 0, c_-^{(\alpha)} = 1$ (dashed)

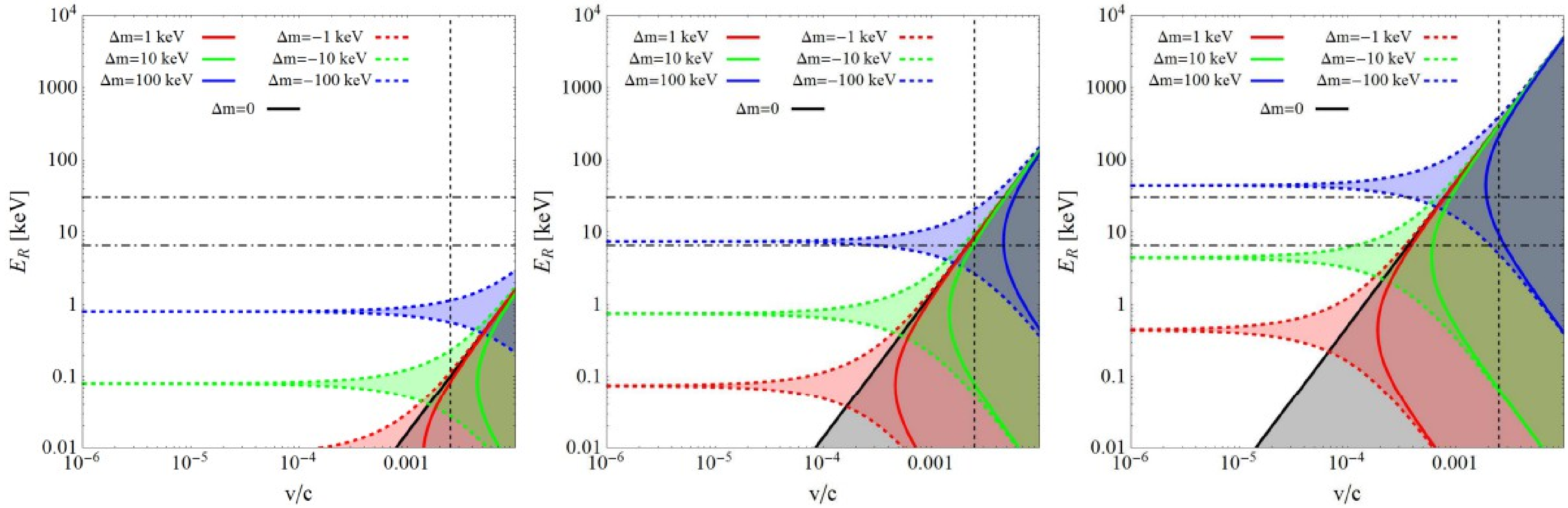




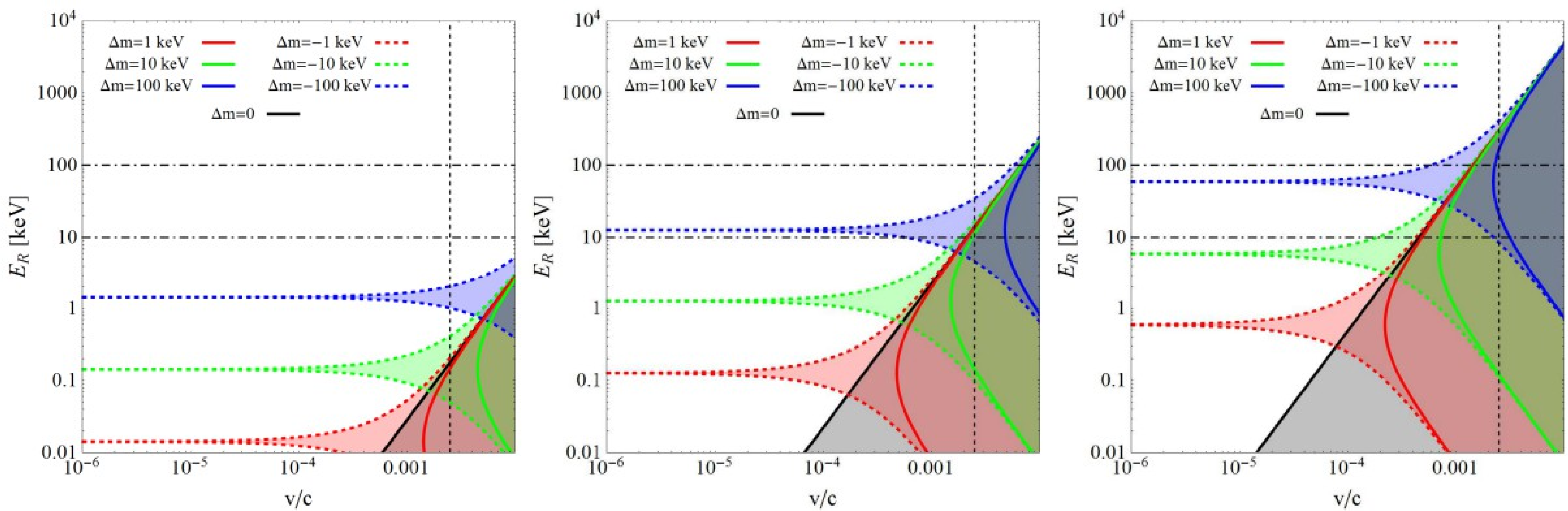
Lifetime of dark fermion which decays via $\chi_j \to \chi_i \gamma$ and $\chi_j \to \chi_i \gamma\gamma$

$\Lambda = 10\ \mathrm{TeV}$ $\qquad m_i = 100\ \mathrm{GeV}$

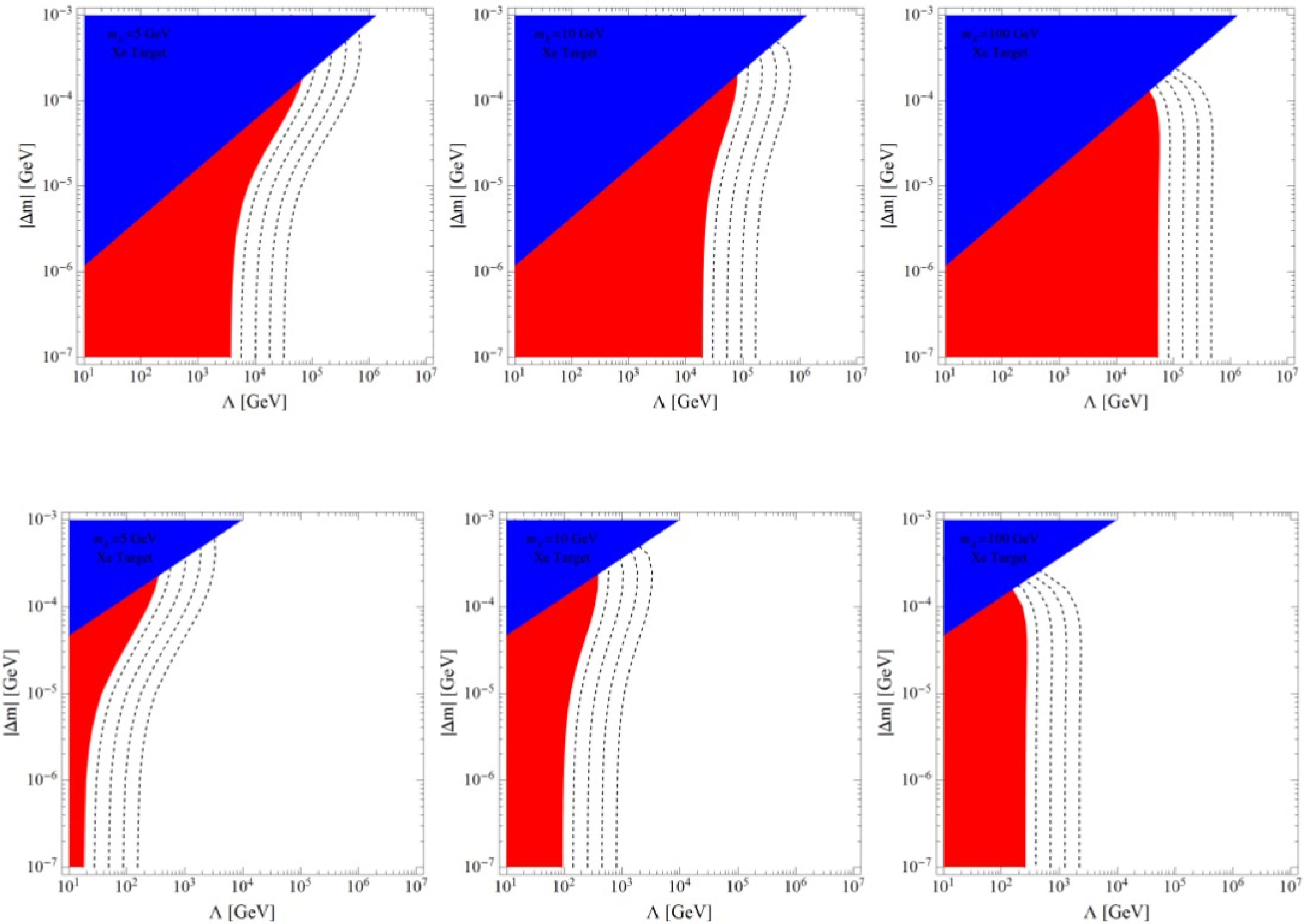
Xenon target --- XENON100



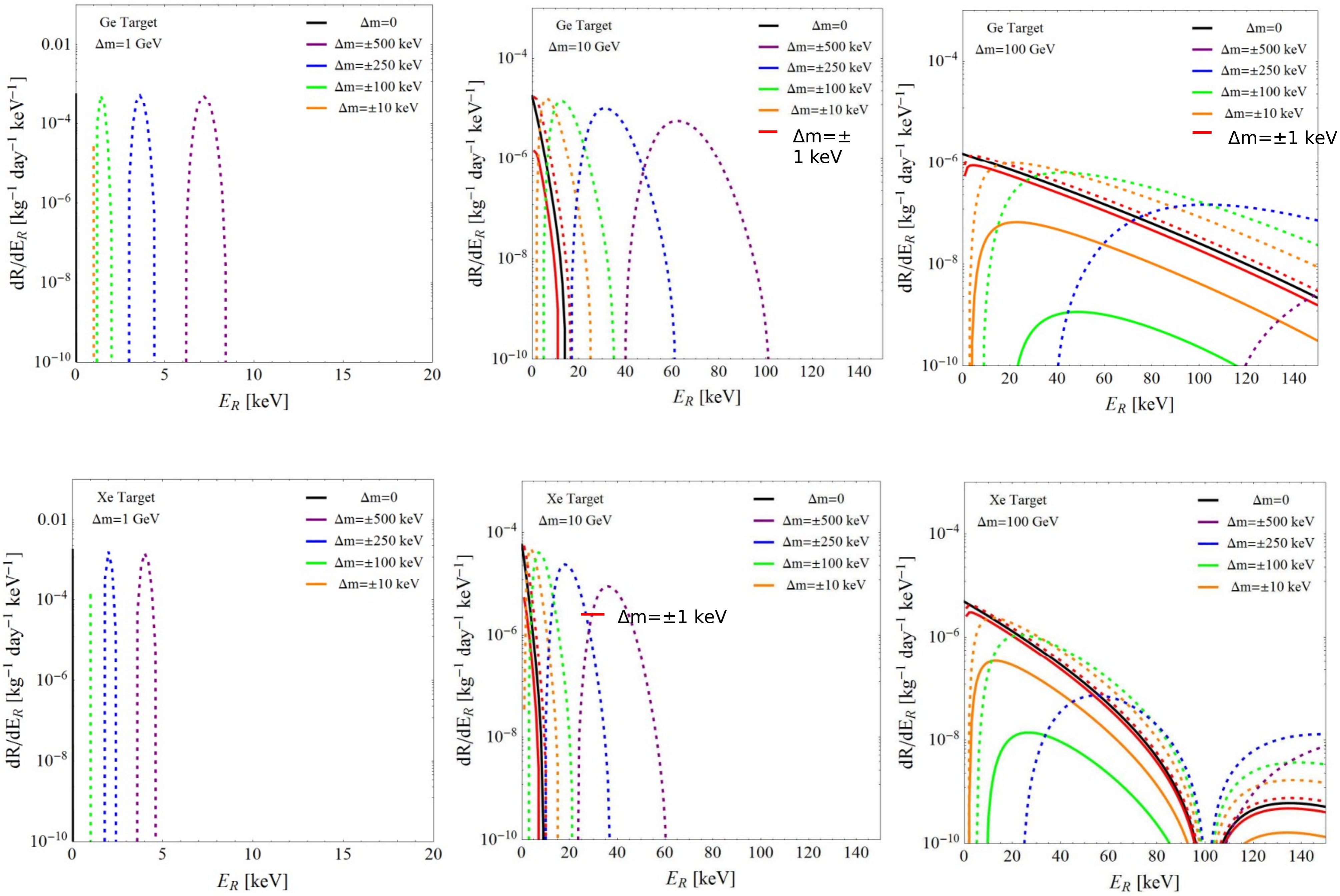
Germanium target --- CDMS II



$m_j = 1$ GeV $m_j = 10$ GeV $m_j = 100$ GeV



m_χ=5 GeV
Xe Target
m_χ=10 GeV
Xe Target
m_χ=100 GeV
Xe Target
|Δm| [GeV]
Λ [GeV]
10^-3
10^-4
10^-5
10^-6
10^-7
10^1
10^2
10^3
10^4
10^5
10^6
10^7
m_χ=5 GeV
Xe Target
m_χ=10 GeV
Xe Target
m_χ=100 GeV
Xe Target
|Δm| [GeV]
Λ [GeV]


Ge Target
Δm=1 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]
Ge Target
Δm=10 GeV
Δm=0
Δm=±500 keV
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
Δm=± 1 keV
dR/dE_R [kg^-1 day^-1 keV^-1]
E_R [keV]
Ge Target
Δm=100 GeV
Δm=0
Δm=±500 keV
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