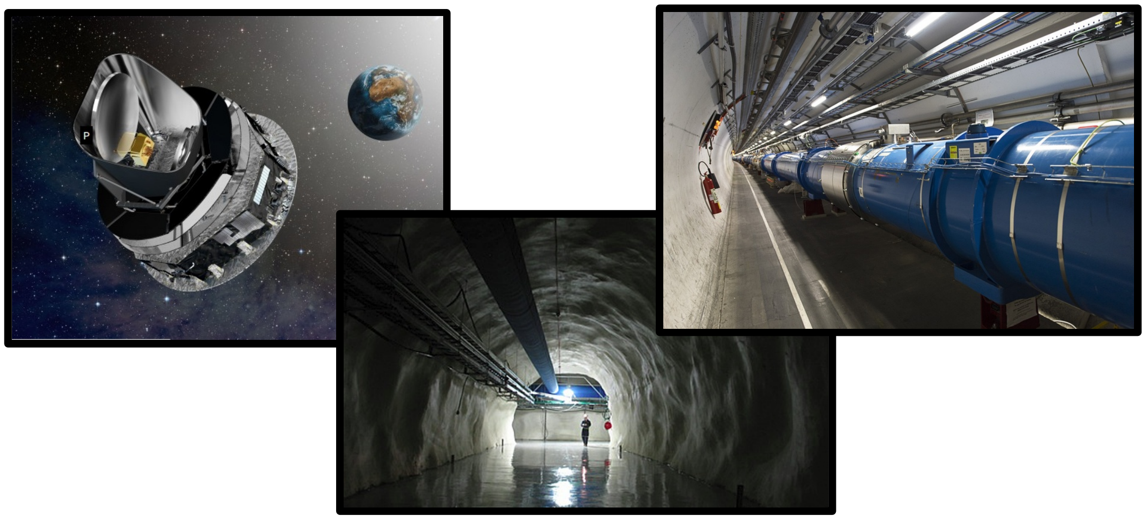
A New Direction in Dark Matter Complementarity



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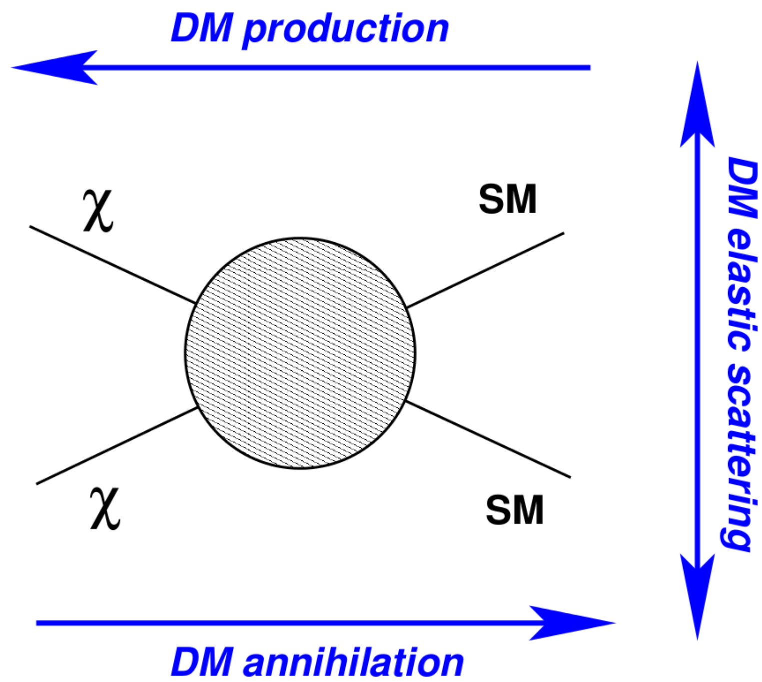
In collaboration with Keith Dienes (UofA), Jason Kumar (UH), and Brooks Thomas (Carleton)

PITT-PACC June 2014 Workshop
Probing Non-Minimal Dark Sectors

Vanilla Dark Matter Complementarity

This figure hardly needs explanation... we've all seen it a million times.

...but the main point is that these different probes are **related** to each other by *crossing symmetry*.



Knowing the rate at one experiment should tell you the rate at another

Different experiments can cover different areas of the same parameter space

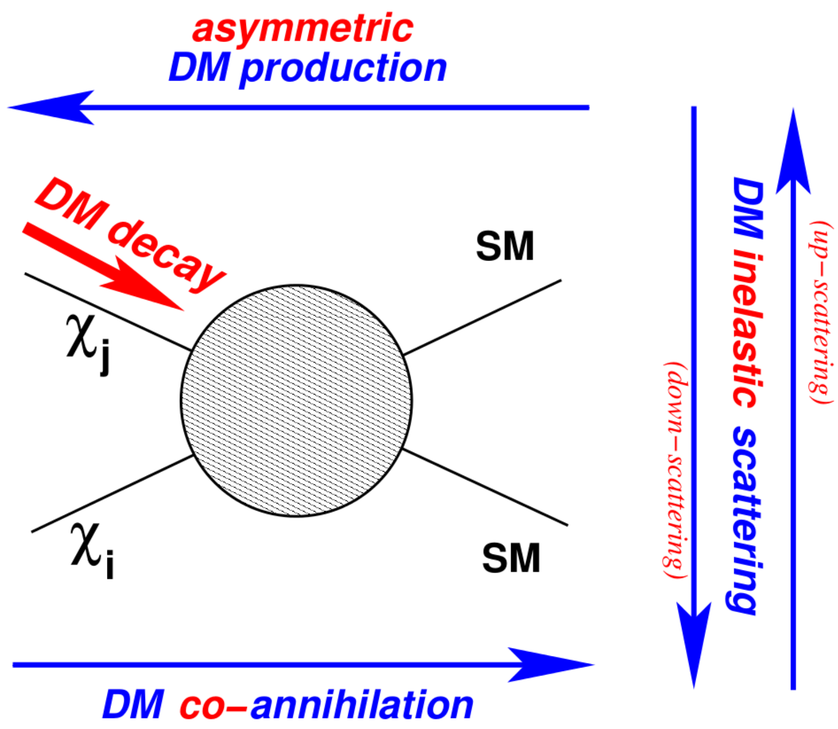
⟷ ***Complementarity***

But what if we have more than one dark matter particle?

Multicomponent Dark Matter Complementarity

If there is more than one dark matter particle, an entirely new direction in this complementarity becomes possible:

Dark Matter Decay



We now have a new probe of dark matter physics

In addition, the new variable $\Delta m_{12} = m_2 - m_1$ adds an entire new dimension to dark matter phenomenology. The complementarity becomes richer.

My goal in this talk is to explore this enhanced complementarity, specifically how scattering and DM decay play off each other.

To Illustrate, we take two example models...

We assume DM-SM interactions are given by a four-fermi effective contact interactions...

$$\mathcal{L}_{\rm int}^{(\rm S)} = \sum_{q=u,d,s,\ldots} \frac{c_q^{(\rm S)}}{\Lambda^2}(\overline{\chi}_2\chi_1)(\overline{q}q)$$

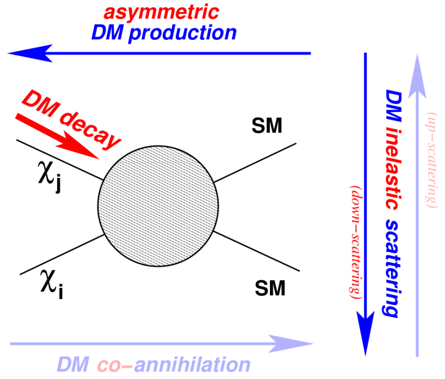
Scalar → *Spin-independent*

$$\mathcal{L}_{\rm int}^{(\rm A)} = \sum_{q=u,d,s,\ldots} \frac{c_q^{(\rm A)}}{\Lambda^2}(\overline{\chi}_2\gamma_\mu\gamma^5\chi_1)(\overline{q}\gamma^\mu\gamma^5 q)$$

Axial → *Spin-dependent*

Assumptions

- $\Delta m_{12} \lesssim \mathcal{O}(1\ \mathrm{MeV})$
  - Leads to most interesting complementarity/phenomenology.
  - Photons and neutrinos are the only SM decay products
- $\Omega_2 = \Omega_{\rm CDM} \approx 0.26,\ \Omega_1 = 0$
  - No need to discuss co-annihilation or up-scattering
  - Maximizes rates for all relevant processes
- $c_u = -c_d = c_c = -c_s = c_t = -c_b \equiv c$
  - Maximizes axial-vector decay rate



Model is now parametrized by three variables: c/Λ^2, m_2, and Δm_{12}.

Inelastic Scattering in Direct Detection

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

$$\chi_j N \to \chi_k N$$

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

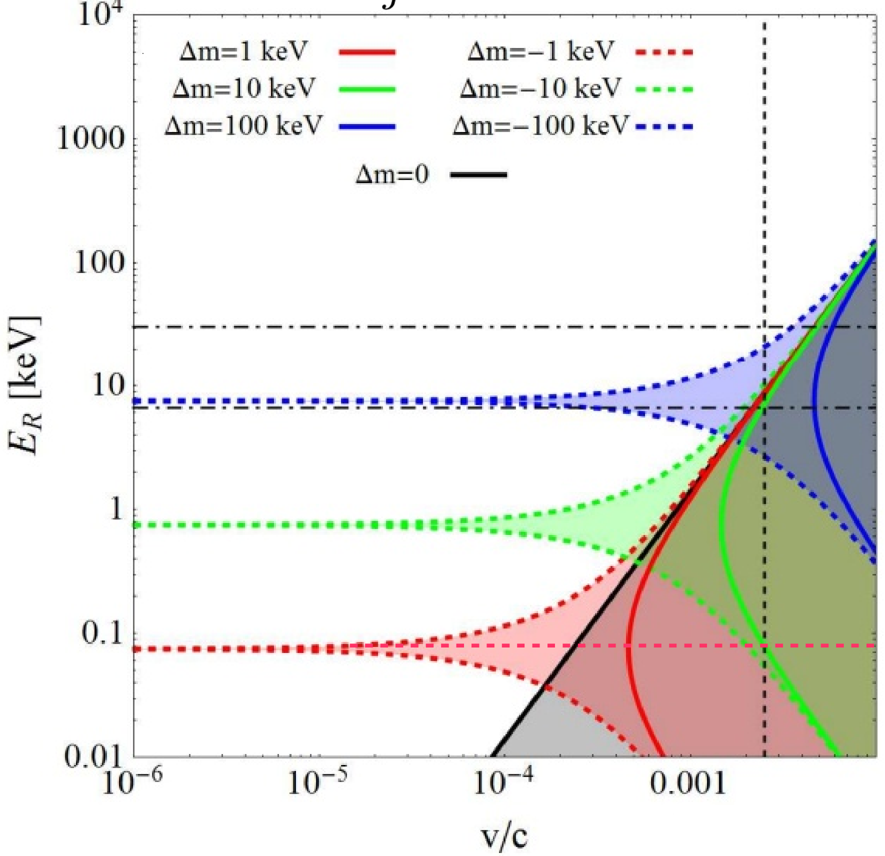
$\Delta m = 0$ ➡ **"Elastic Scattering"**
Typical case studied – single component dark matter.

$\Delta m > 0$ ➡ **"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

$m_j = 10\text{GeV}$



Recoil Energy Spectra

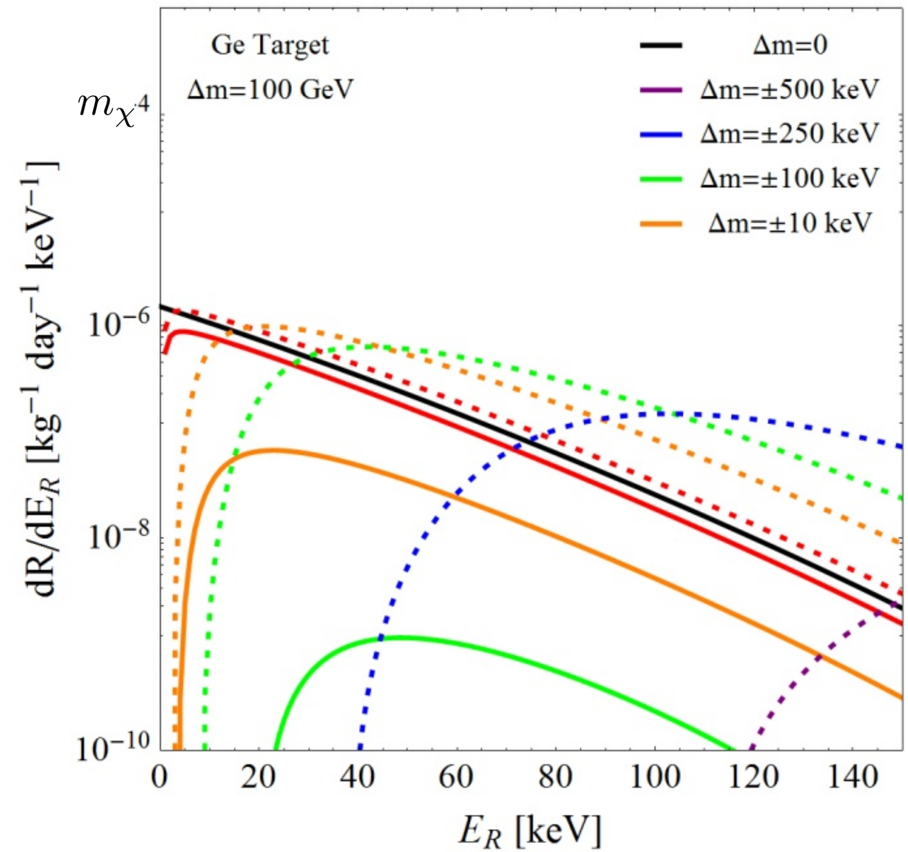
$$\sigma_{n0}^{(SI)} = 10^{-46}\ \mathrm{cm}^{-2}$$

Upscattering (solid)
Downscattering (Dashed)

- ***Down/upscattering lead to unique and distinguishable recoil energy spectra***
  Can be a smoking gun signal for non-minimal dark sector.

- ***Downscattering generally more accessible to direct detection***
  Due to energy released from Δm

- ***We now have minimum and maximum range of recoil energies.***
  This "window" of recoil energies must coincide with the sensitivity of the detector.

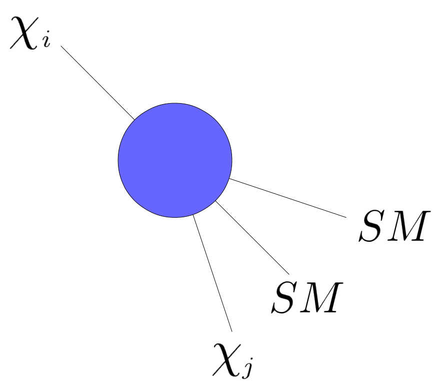


Typically, detectors are sensitive to a certain energy window.... as Δm_{12} increases, the detector can become completely insensitive to down-scattering.

Dark Matter Decay

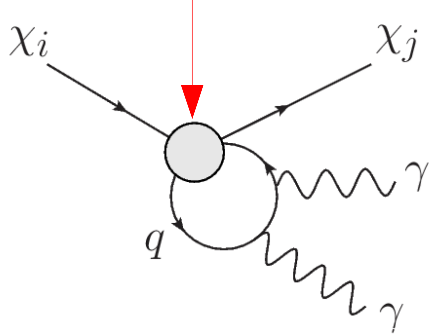
- Since $\Delta m_{ij} \lesssim \mathcal{O}(1\ \mathrm{MeV})$, only possible SM decay products are low energy **photons** and **neutrinos**
- χ_i only couples to quarks, which at these low energies are bound as mesons

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

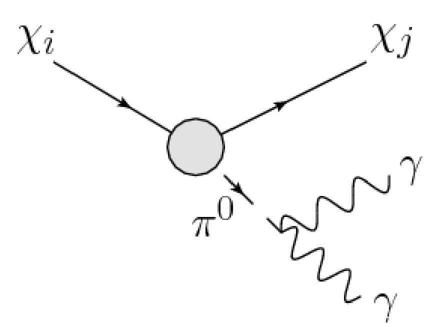


We have this coefficient...

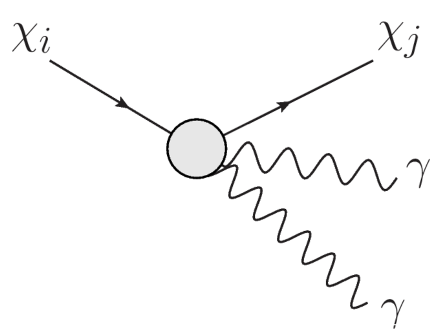
...but how do we get here?



Microscopic Theory



Low Energy EFT



Effective χ-γ couplings

$$\mathcal{L}_{\rm int}^{(\rm fund)} \ni \frac{c^{(A)}}{\Lambda^2}(\overline{\chi}_j\gamma^\mu\gamma^5\chi_i)(\overline{q}\gamma_\mu\gamma^5 q)$$

Chiral Perturbation Theory

$$\mathcal{L}_{\rm int}^{(\rm eff)} \ni C_i(\overline{\chi}_2\gamma^\mu\gamma^5\chi_1)\partial_\mu\pi^0 + \cdots$$

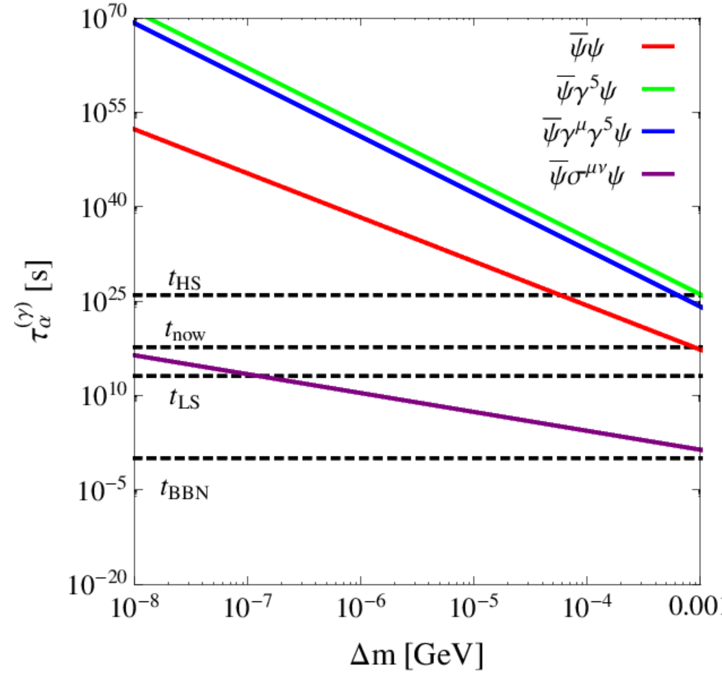
where $C_i = C_i\{c^{(A)}/\Lambda^2, f_\pi, \ldots\}$

...from whence we compute the decay widths.

$$\Gamma^{(\mathrm{S})}_{\gamma\gamma} \approx \frac{B_0^2 \alpha_{\mathrm{EM}}^2 \tilde{\lambda}_2^2 [c^{(\mathrm{S})}]^2}{8(105\pi^5)\Lambda_C^4 \Lambda^4} (\Delta m_{12})^7$$

$$\Gamma^{(\mathrm{A})}_{\gamma\gamma} \approx \frac{\alpha_{\mathrm{EM}}^2 [c^{(\mathrm{A})}]^2}{8(315\pi^5)\Lambda_C^4 \Lambda^4} \left[\tilde{\lambda}_3 + \tilde{\lambda}_4 - \frac{2\Lambda_C^2}{m_\pi^2}\right] (\Delta m_{12})^9$$

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

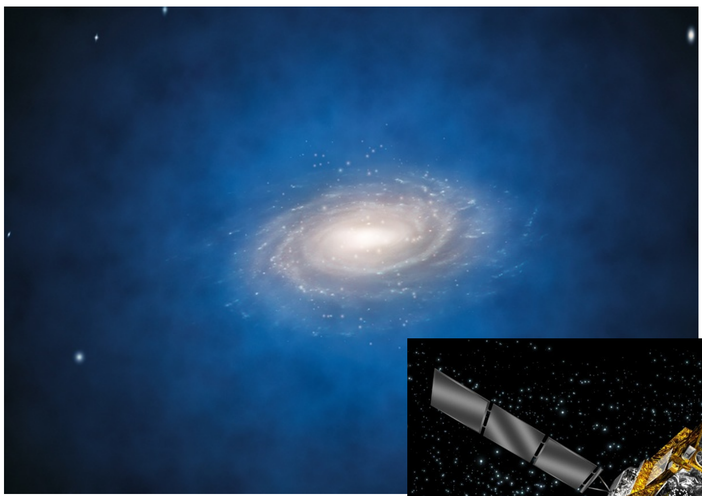


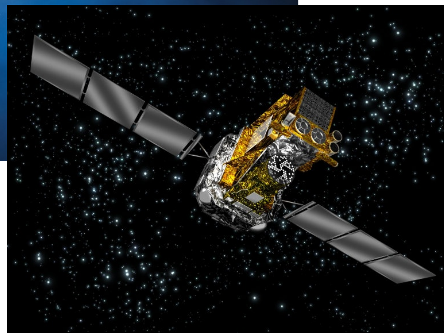
$c_u^{(\alpha)} = c_d^{(\alpha)} = 1$

$\Lambda = 10$ TeV

$m_i = 100$ GeV

Age of Universe





Constraints on excess x-rays from galaxies and clusters **now give us constraints** on our free parameters c/Λ^2, m_2, and Δm_{12}.

(We find our bounds using data from the HEAO-1 and INTEGRAL telescopes, and using the PPPC4DMID software package)

Tying it All Together...

A Picture of the Enhanced Dark Matter Complementarity

Direct Detection Bounds

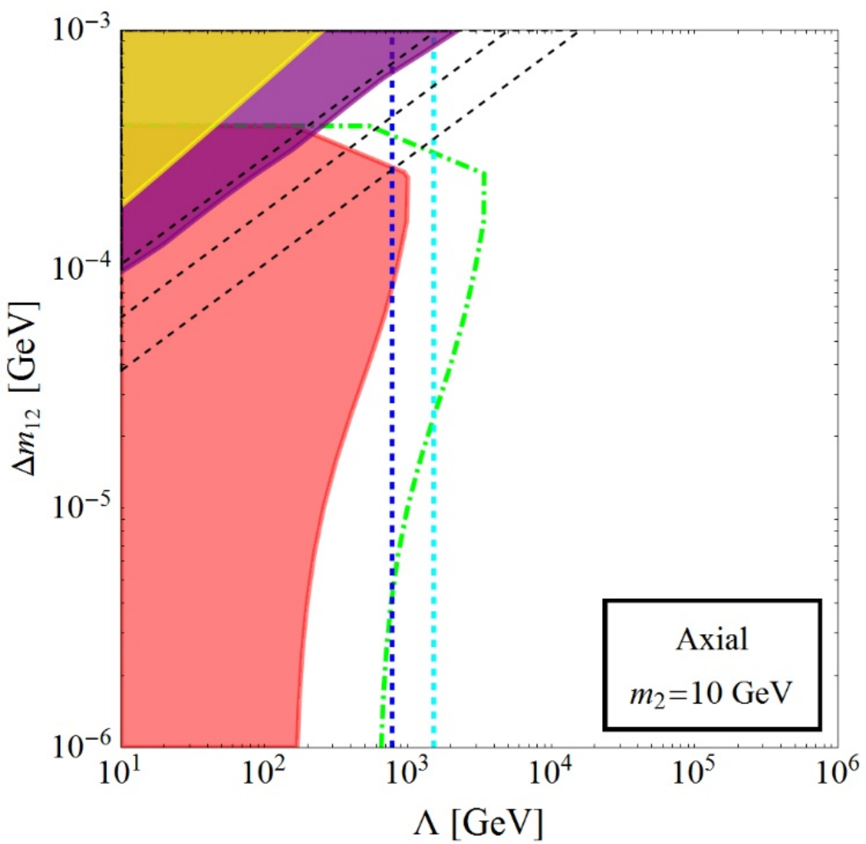
- Red shaded area is excluded by overall event rate expected at detectors.
- Bounds from LUX for scalar operator, COUPP-4 for axial operator.
- Future bounds (LZ 7.2 ton/PICO-250L) shown as green dashed line

Collider Production Bounds

- LHC Mono-jet bounds as blue dashed line
- LHC Mono-W/Z bounds as cyan dashed line
- Assumes EFT is valid at LHC energies, i.e., $\Lambda \gtrsim \mathcal{O}(1\ \text{TeV})$

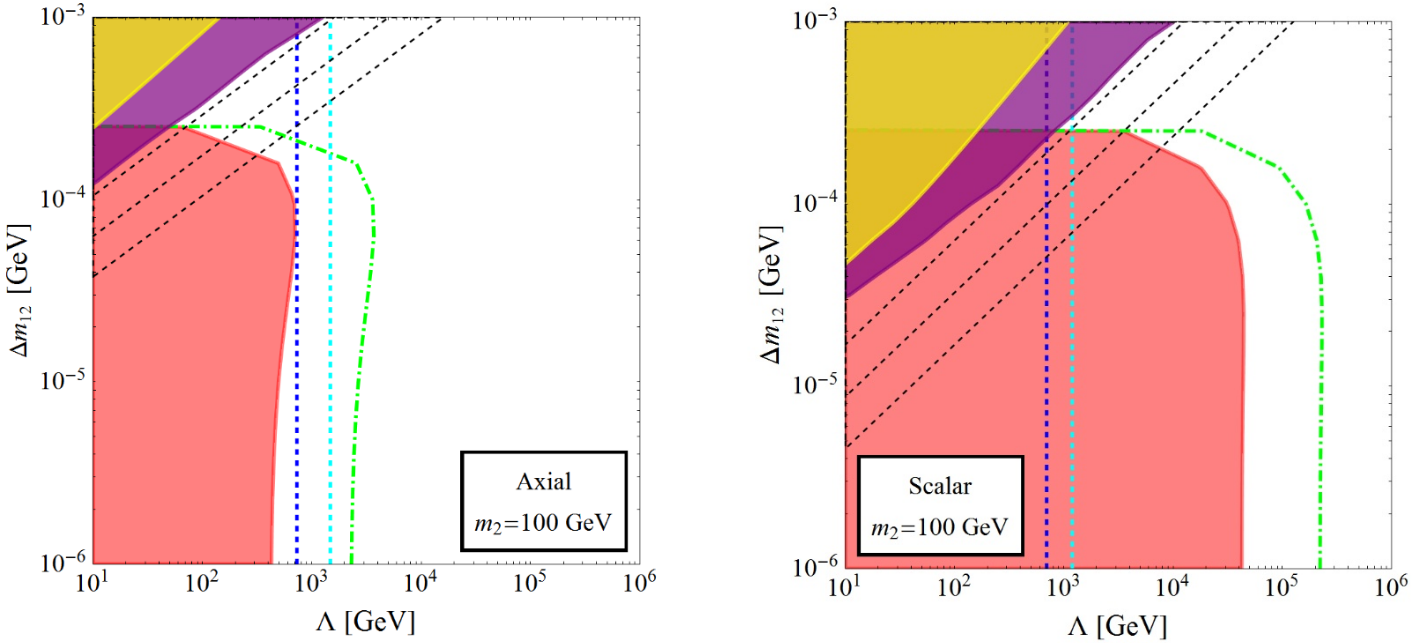
Dark Matter Decay Bounds

- Purple shaded area is excluded by lack of cosmic x-ray excesses.
- HEAO-1 Telescope bounds in yellow
- INTEGRAL bounds in purple
- Diagonal dotted lines represent DM lifetimes $\tau = 10^{22}\ \text{s}, 10^{24}\ \text{s}, 10^{26}\ \text{s}.$

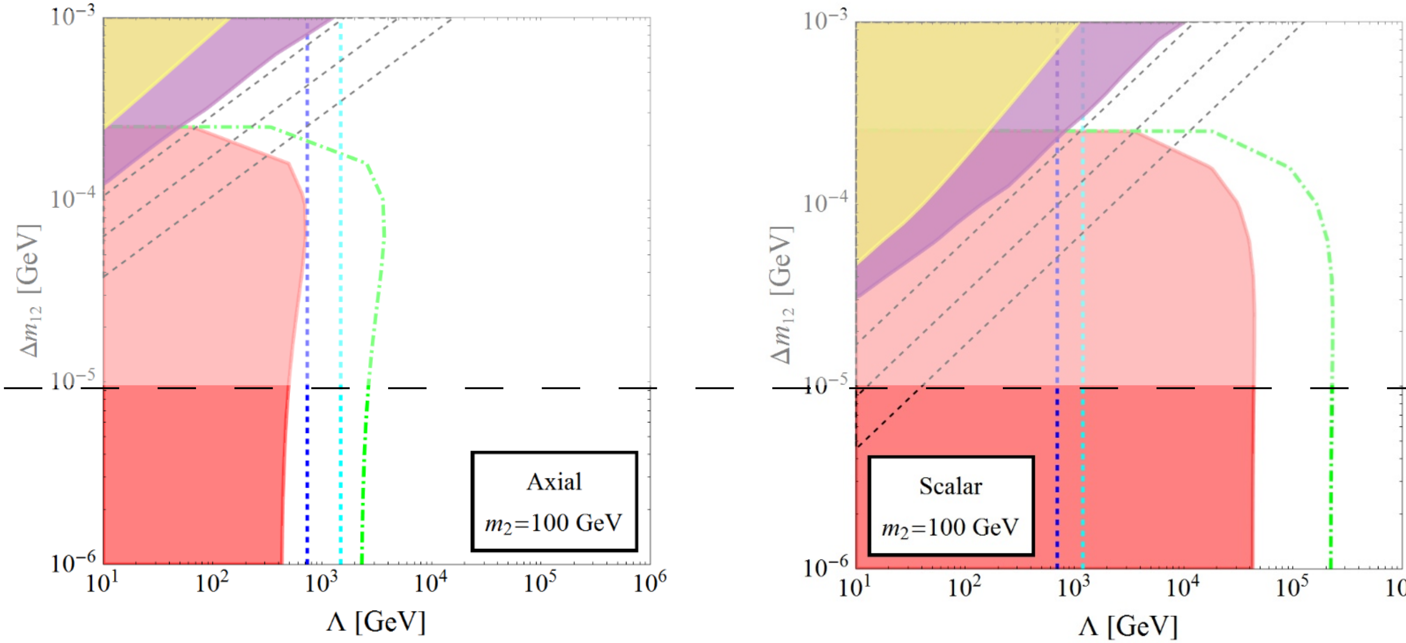


Dienes, Kumar, Thomas, D.Y., [arXiv:1406.xxxx]

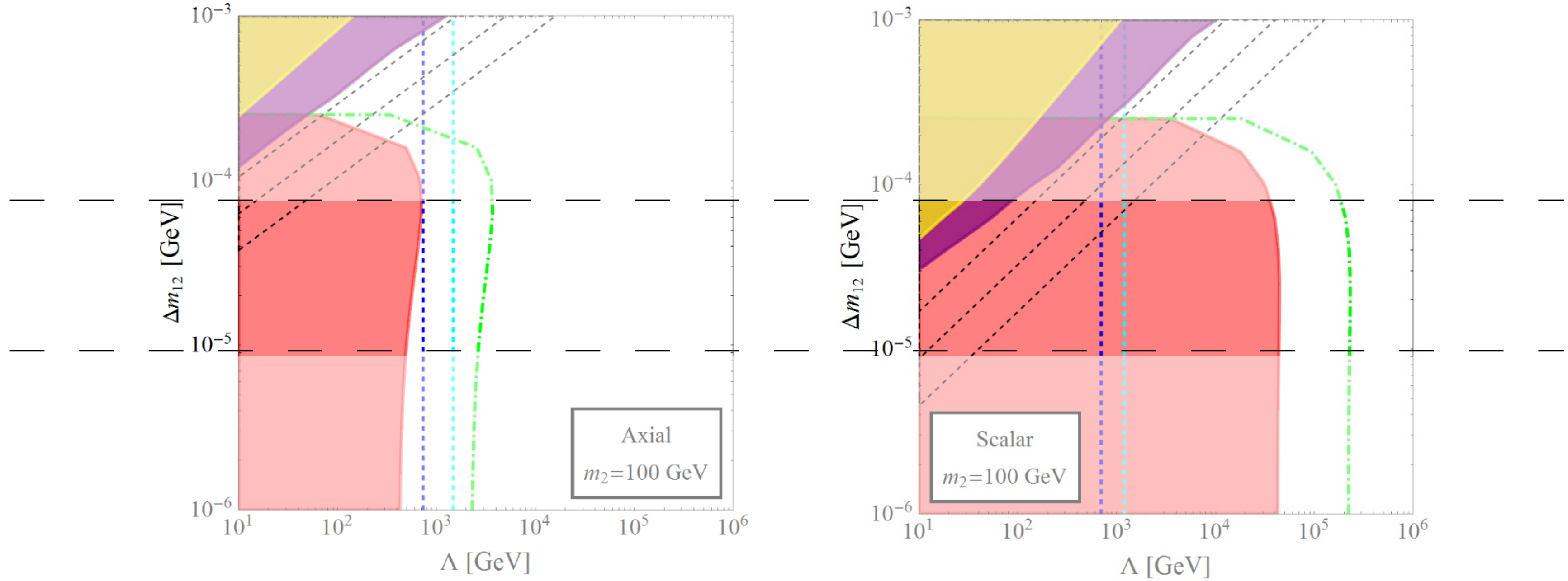
Let us quickly study the new phenomenology emerges as we take $\Delta m_{12} > 0$...



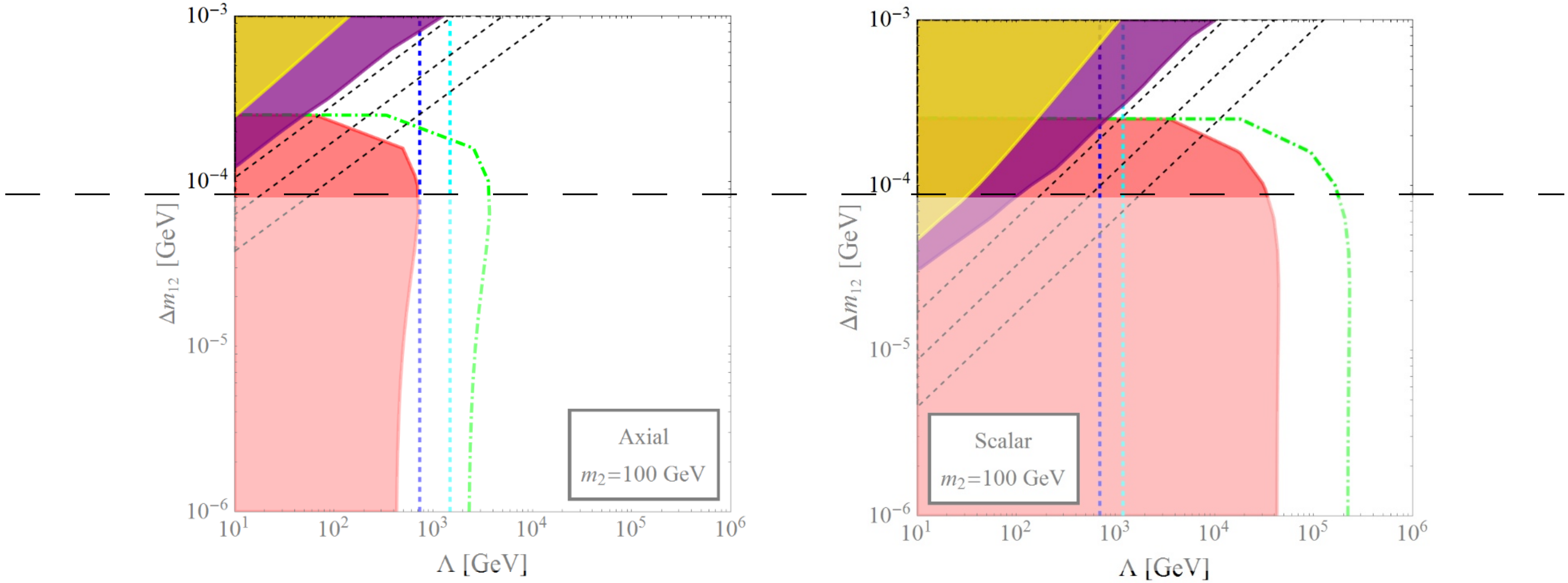
Axial
m_2=100 GeV
Scalar
m_2=100 GeV
Δm_{12} [GeV]
Λ [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^1
10^2
10^3
10^4
10^5
10^6



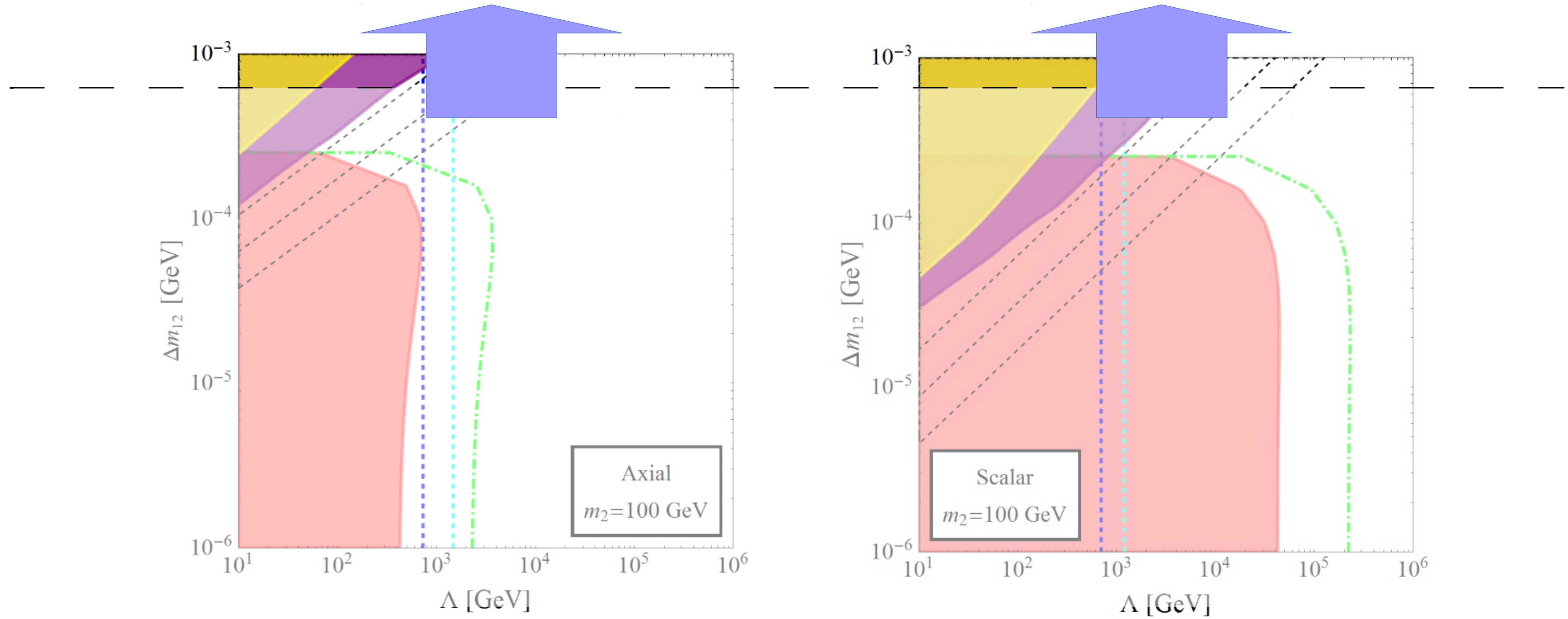
- $\Delta m_{12} \lesssim \mathcal{O}(10 \text{ keV})$
  - Insensitive to Δm_{12}... Virtually indistinguishable from traditional single-component DM with mass m_2



- $\Delta m_{12} \lesssim \mathcal{O}(10 \text{ keV})$
  - Insensitive to Δm_{12}... Virtually indistinguishable from traditional single-component DM with mass m_2
- $\Delta m_{12} \approx \mathcal{O}(10 - 100 \text{ keV})$
  - Bounds from direct detection can strengthen. Mainly due to released energy from down scattering.



- $\Delta m_{12} \lesssim \mathcal{O}(10\ \mathrm{keV})$
  - Insensitive to Δm_{12}... Virtually indistinguishable from traditional single-component DM with mass m_2
- $\Delta m_{12} \approx \mathcal{O}(10 - 100\ \mathrm{keV})$
  - Bounds from direct detection can strengthen. Mainly due to released energy from down scattering.
- $\Delta m_{12} \approx \mathcal{O}(100 - 1000\ \mathrm{keV})$
  - Direct detection loses sensitivity. Again, due to kinematics of down scattering.
  - Dark matter decay now takes over as the main bound on parameter space.



- $\Delta m_{12} \lesssim \mathcal{O}(10\ \text{keV})$
  - Insensitive to Δm_{12}... Virtually indistinguishable from traditional single-component DM with mass m_2
- $\Delta m_{12} \approx \mathcal{O}(10 - 100\ \text{keV})$
  - Bounds from direct detection can strengthen. Mainly due to released energy from down scattering.
- $\Delta m_{12} \approx \mathcal{O}(100 - 1000\ \text{keV})$
  - Direct detection loses sensitivity. Again, due to kinematics of down scattering.
  - Dark matter decay now takes over as the main bound on parameter space.
- $\Delta m_{12} \gtrsim \mathcal{O}(1000\ \text{keV})$
  - New decay channels open, strengthening the DM decay bounds even further.
  - Eventually, our assumption of metastability becomes compromised.

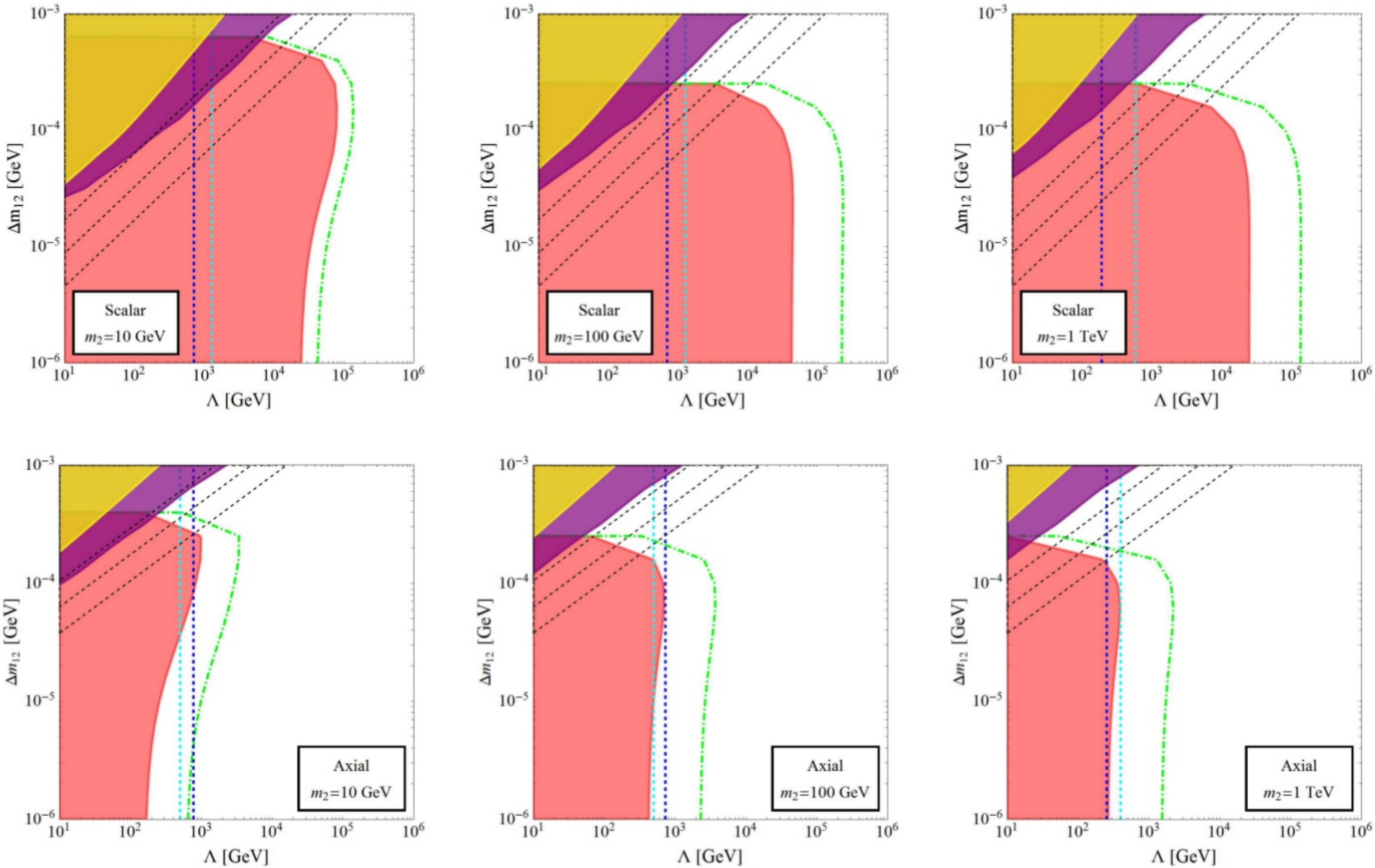
Conclusions

- Complementarity remains a central idea in the hunt for dark matter.
- Consideration of multicomponent dark sectors opens new search channels, namely, dark matter decay.
- Consideration of multi-component DM greatly enhances phenomenology... can lead to unique energy spectra, which can serve as a smoking gun signal.

The interplay between direct-detection experiments and DM decay in non-minimal dark sectors can provide novel constraints on dark matter parameter space.

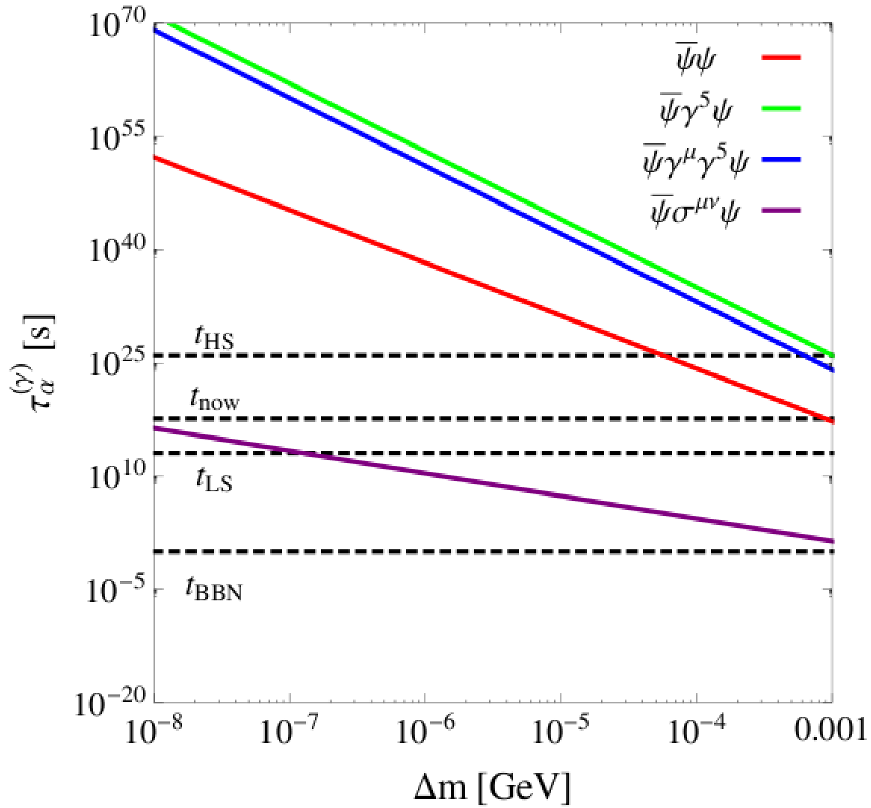
Thanks for your time, and thanks to the organizers!

Backup Slides / Extra Plots

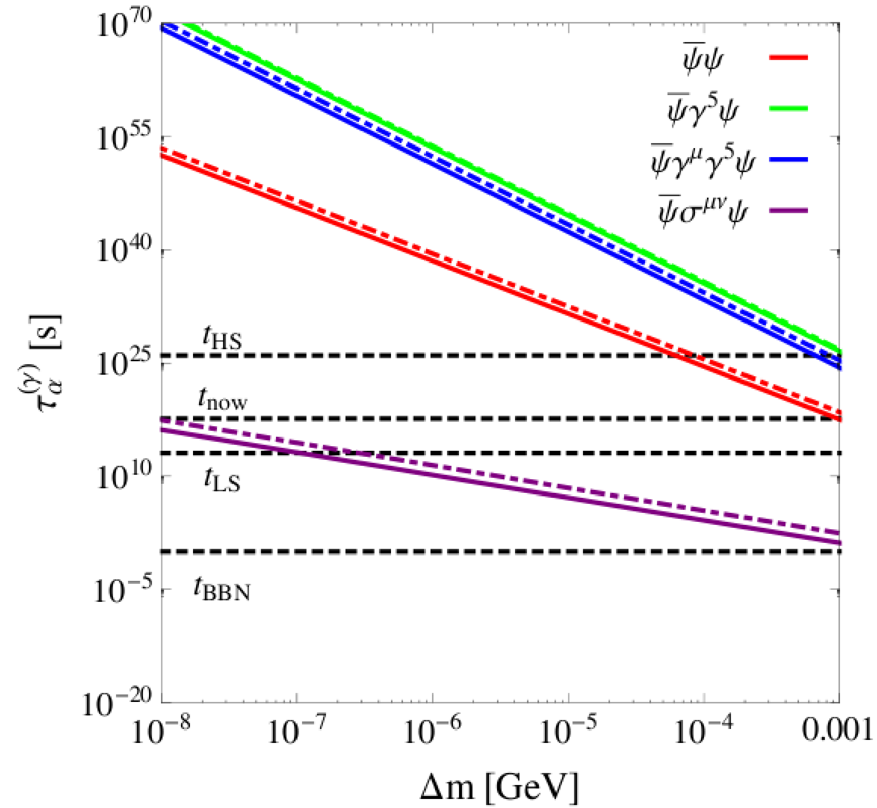


Scalar
m_2=10 GeV
Scalar
m_2=100 GeV
Scalar
m_2=1 TeV
Axial
m_2=10 GeV
Axial
m_2=100 GeV
Axial
m_2=1 TeV
Δm_{12} [GeV]
Λ [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}

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



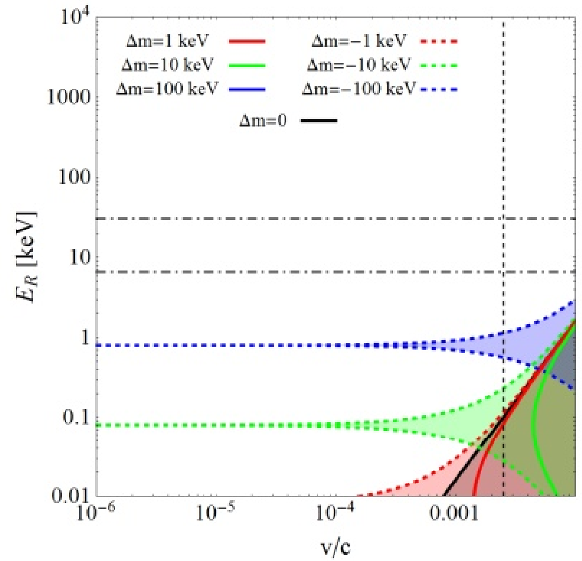
$$c_{+}^{(\alpha)} = 1, c_{-}^{(\alpha)} = 0 \quad \text{(solid)}$$
$$c_{+}^{(\alpha)} = 0, c_{-}^{(\alpha)} = 1 \quad \text{(dashed)}$$



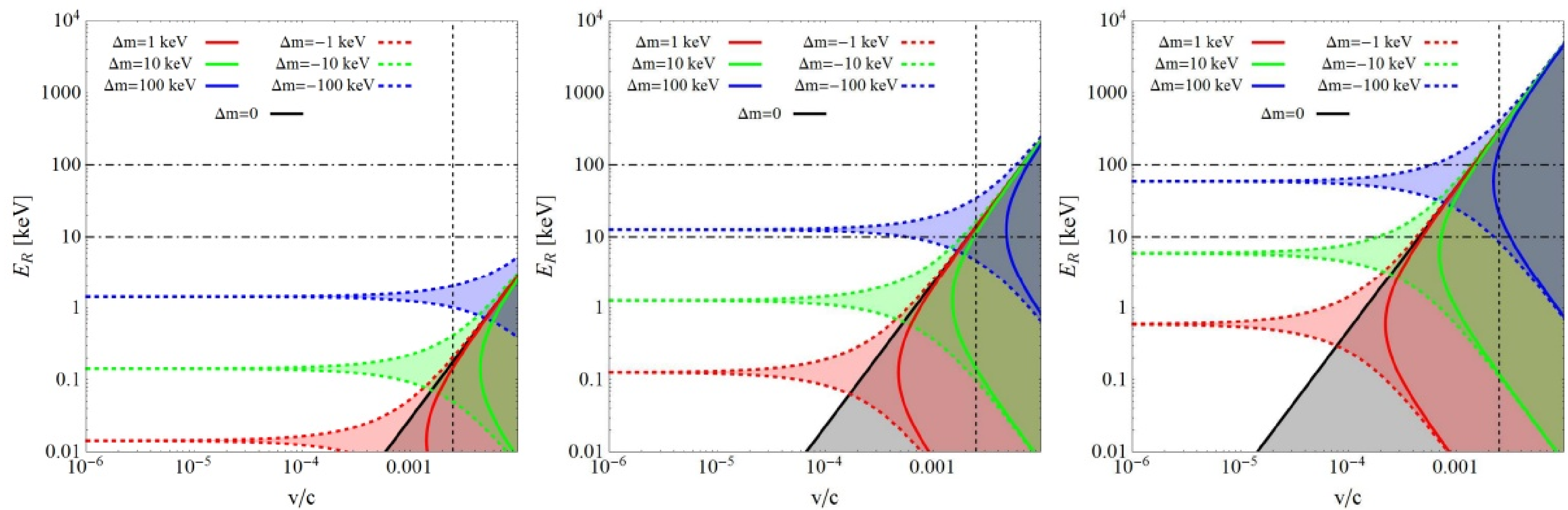
Lifetime of dark fermion which decays via $\chi_j \to \chi_i \gamma$ and $\chi_j \to \chi_i \gamma\gamma$

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

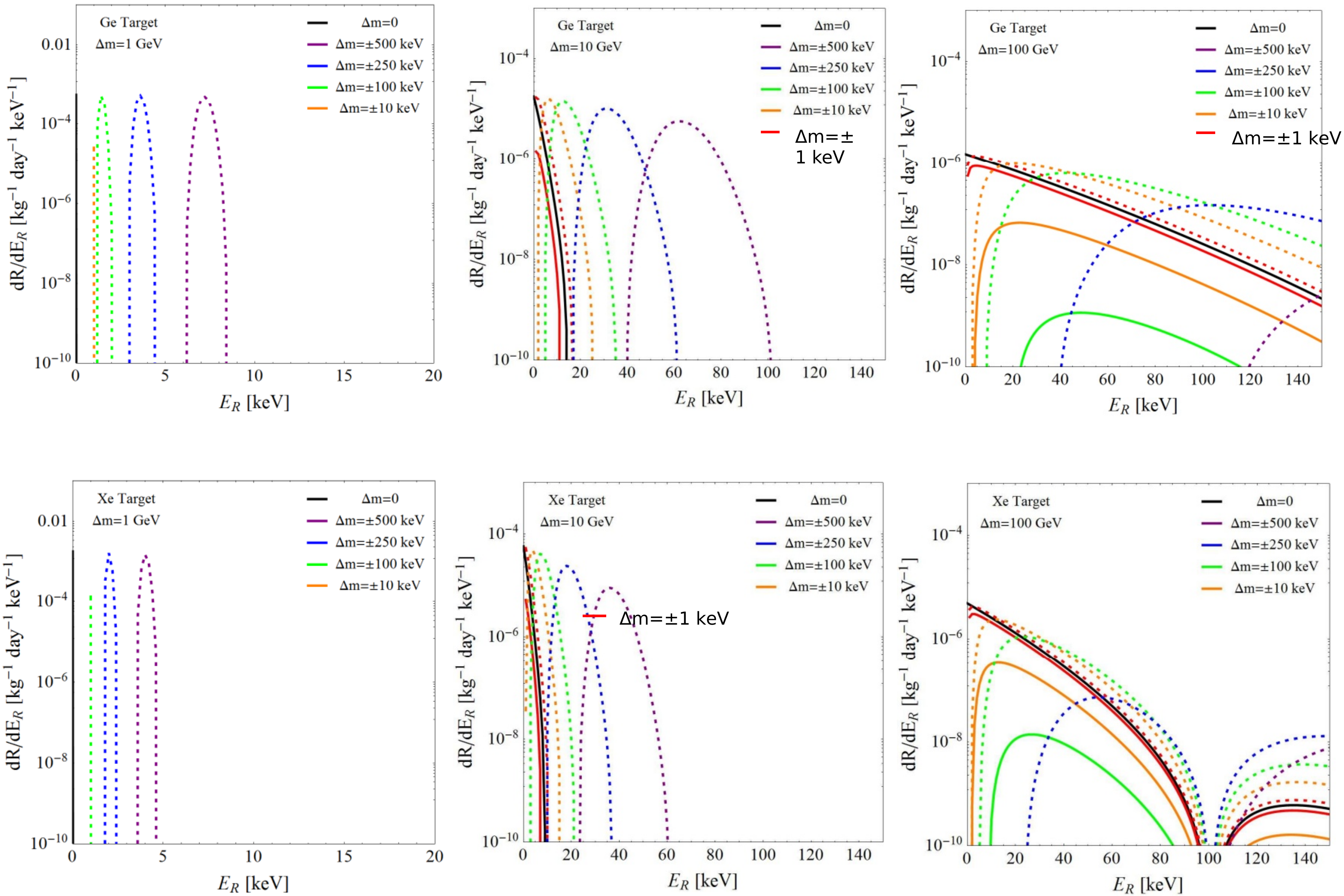
Xenon target --- XENON100



Germanium target --- CDMS II



$m_j = 1$ GeV $\quad m_j = 10$ GeV $\quad m_j = 100$ GeV



Ge Target
Δm=1 GeV
Δm=10 GeV
Δm=100 GeV
Xe Target
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]