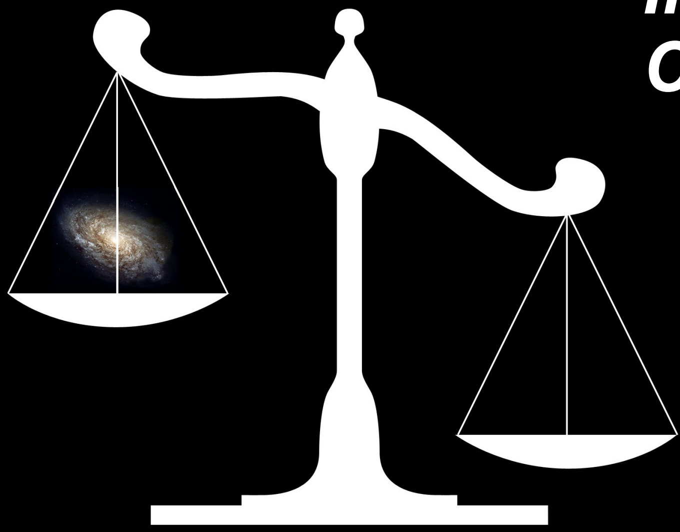
Correlating Direct and Indirect Detection:

Inelastic Scattering Rates and Constraints on Dark-Sector Instability



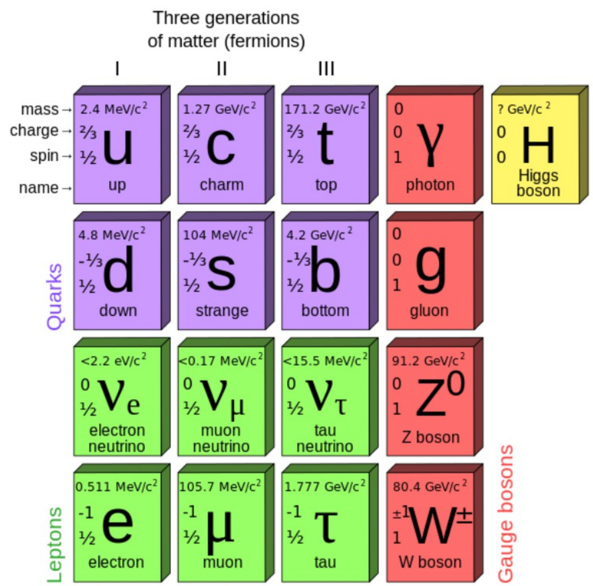
David Yaylali
University of Hawaii

[ArXiv:1305.xxxx]

In collaboration with Keith Dienes, Jason Kumar, and Brooks Thomas.

Why Consider Multi-Component Dark Matter?

What seems more likely?



+

χ

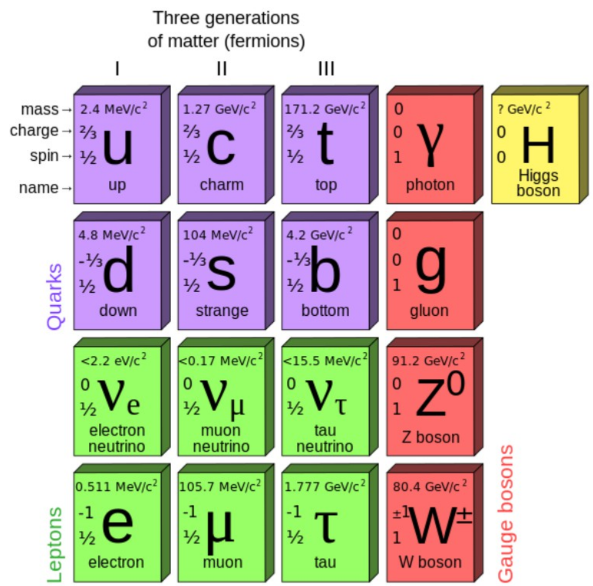
*Everything we **currently** know of... ~20% of the matter in the universe.*

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

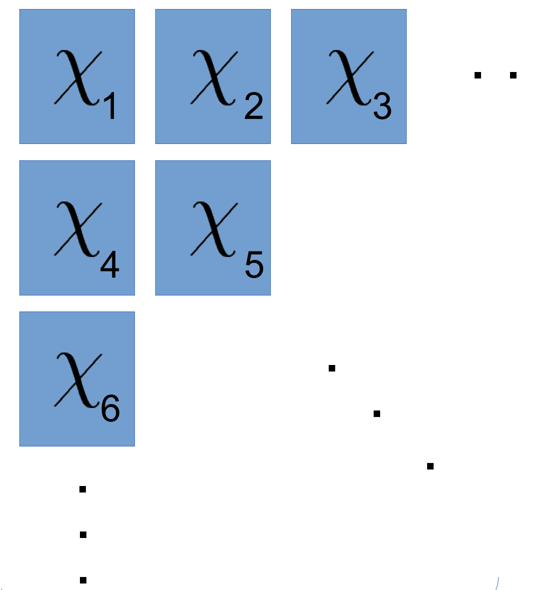
…OR

Why Consider Multi-Component Dark Matter?

What seems more likely?



+



*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%.*

*Note: There **are** mechanisms of generating a single DM particle (SUSY w/ R-parity), but this is **not the general case**.*

Ok, but what are some more concrete reasons to consider 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

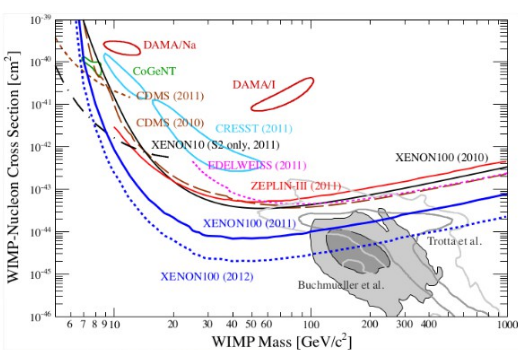
Similar excess not observed in antiprotons
Excess too big for thermal freezeout production

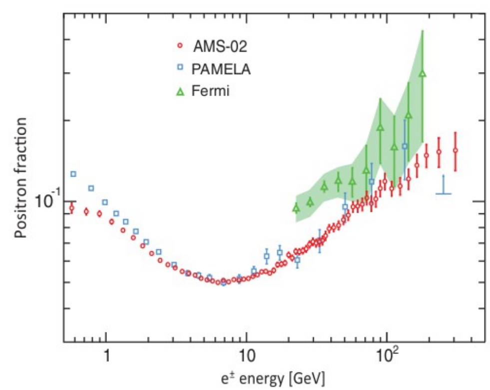
-Multiple DM particles (Zurek et. al., 2008; Feldman, et. al., 2010)

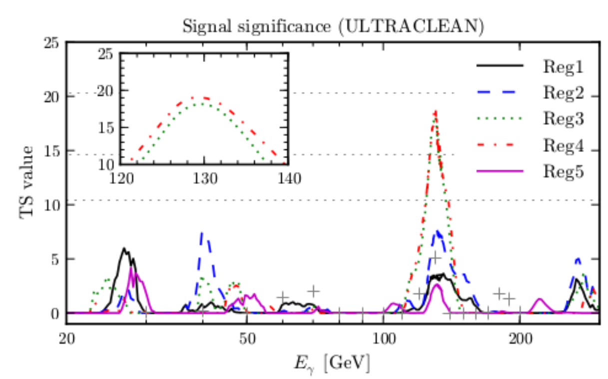
Gamma ray line at 130 GeV (FERMI) (???)

DM typically annihilates to other particles at much larger rate (DM is dark!)
Again, hard to reconcile with freeze-out production

-Multiple DM particles
Annihilation to other DM particles first (Buckley, Hooper, 2012)
Annihilation to one gamma plus another DM (Eramo, Thaler, 2012)







Ok, but what are some more concrete reasons to consider 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

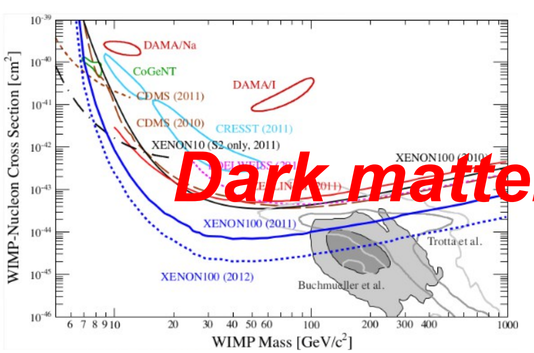
- -Multiple DM particles (Zurek et. al., 2008; Feldman, et. al., 2010)

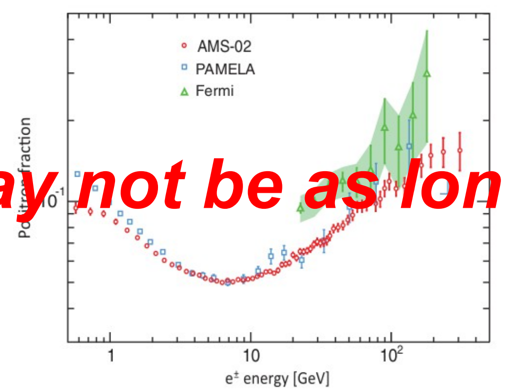
Gamma ray line at 130 GeV (FERMI) (???)

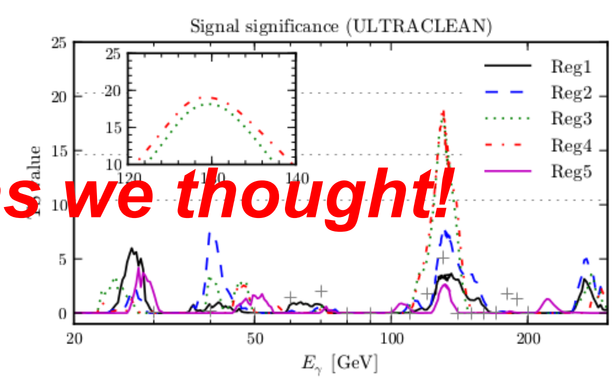
DM typically annihilates to other particles at much larger rate (DM is dark!)

Again, hard to reconcile with freeze-out production

- -Multiple DM particles
  - Annihilation to other DM particles first (Buckley, Hooper, 2012)
  - Annihilation to one gamma plus another DM (Eramo, Thaler, 2012)





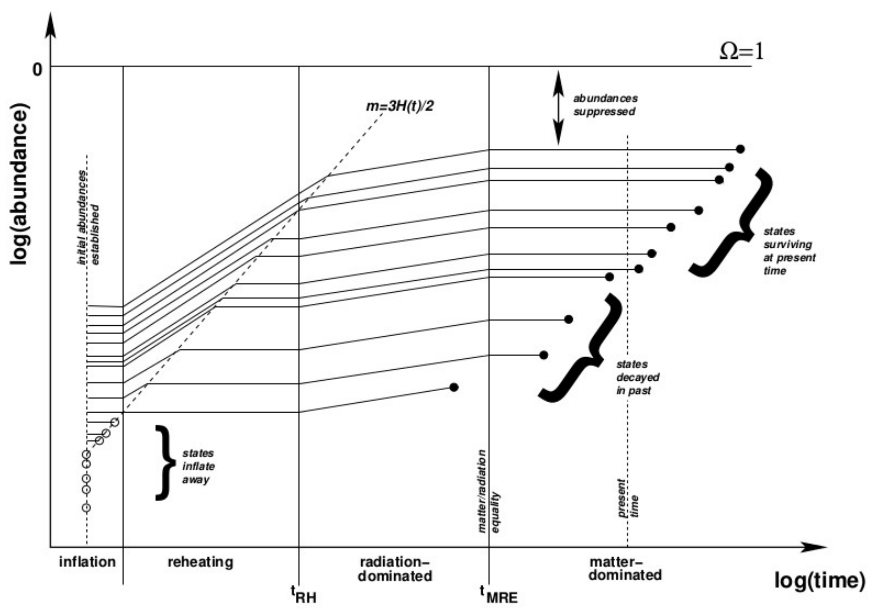


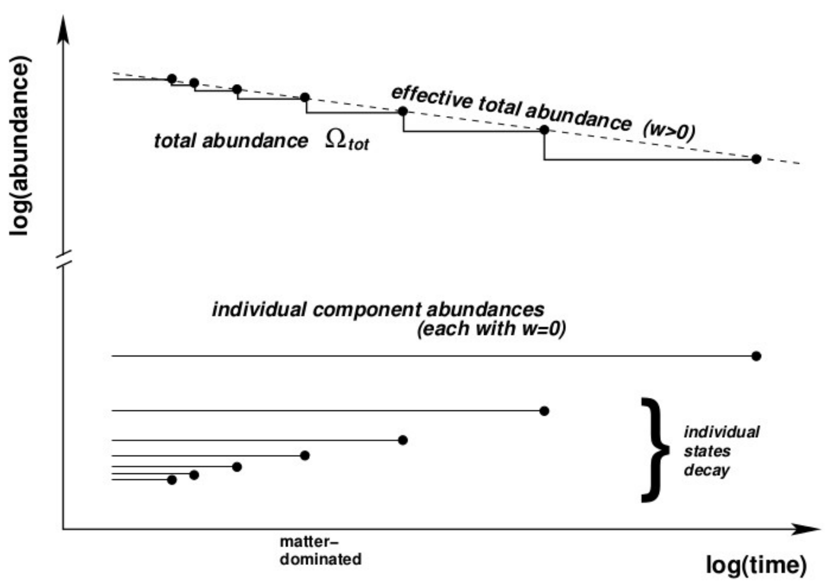
Dark matter may not be as lonely as we thought!

$$\Omega_{\text{tot}} \equiv \sum_i \Omega_i$$

Dynamical Dark Matter (DDM)

(Dienes & Thomas, 2011)



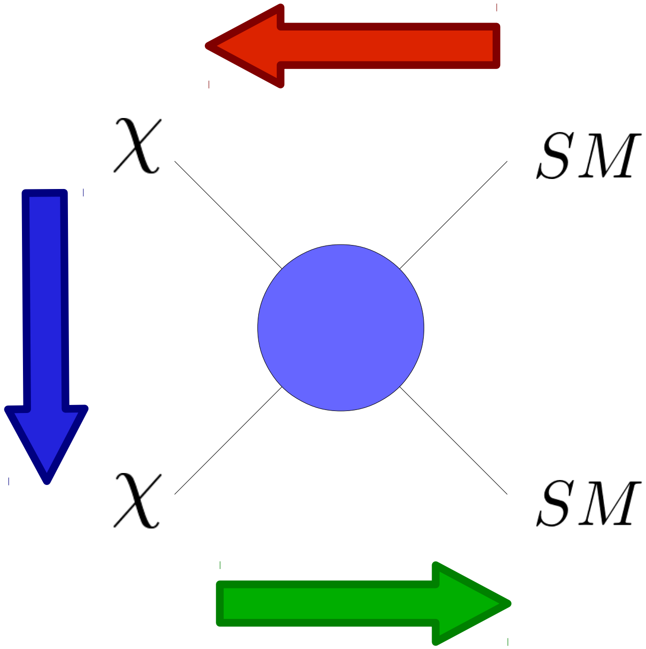


- Dark matter can be an *ensemble* of different (semi-stable) states, each with their own abundances, masses, lifetimes.
- Total DM abundance can change in time.
- Single component *vanilla* DM is **a limiting case of DDM.**
- Viable models exist (e.g., Kaluza-Klein axions) which exhibit the unique phenomenology of DDM.
- **Dark matter is not necessarily stable.** Rather, there exists a balance between lifetimes and abundances.

***MUCH MORE** to be said about DDM!*
Stick around for Brooks Thomas's talk!

*DDM is a nice framework for discussing multi-component dark matter, and **opens up a new window** into dark matter physics...*

Our non-gravitational windows into dark matter...

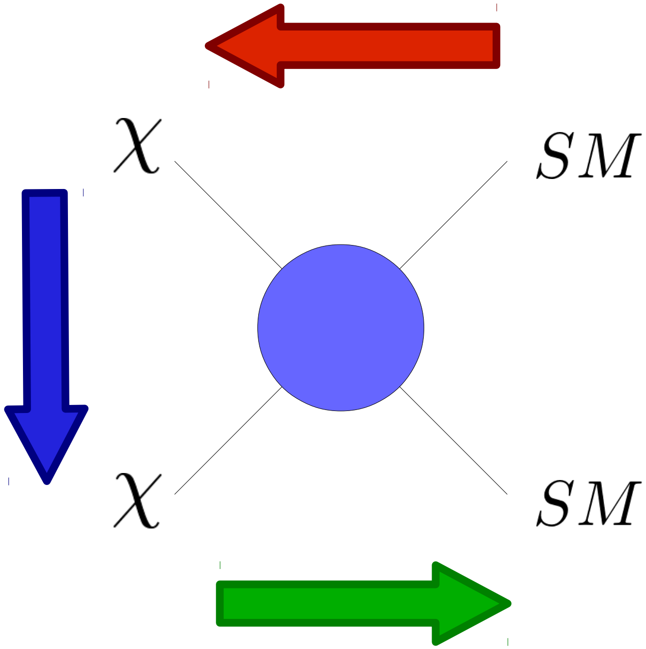


- **DM-SM scattering** – (direct detection)
- **DM annihilation to SM** – (indirect detection)
- **Collider Production**

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

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

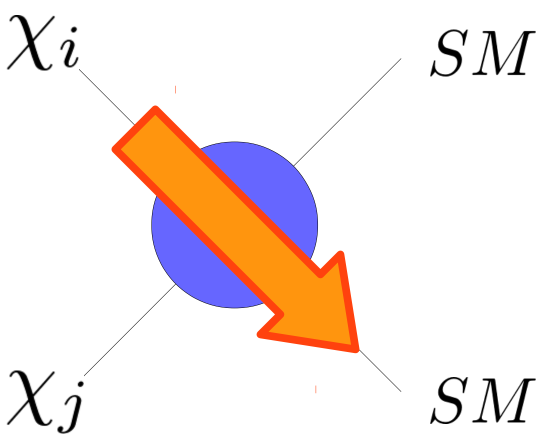
Our non-gravitational windows into dark matter...



- **DM-SM scattering** – (direct detection)
- **DM annihilation to SM** – (indirect detection)
- **Collider Production**

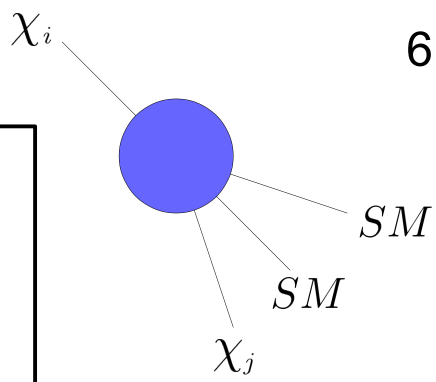
Same diagram $\Longrightarrow$ Processes related by "crossing symmetry"

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



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

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



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 $\Delta m_{ij} \equiv m_j - m_i \lesssim \mathcal{O}(100\ \mathrm{keV})$
- Effective contact couplings between DM particles and quarks:

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

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

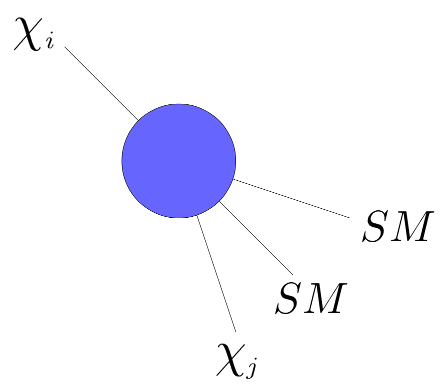
- χ_is uncharged
- Generation independent
- $\Delta m \lesssim \mathcal{O}(100\ \mathrm{kev}) \Rightarrow$ Only light quarks contribute to decay.

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

We choose to express results in terms of isospin violating/conserving coefficients

$$c^{(\alpha)}_{\pm} = c^{(\alpha)}_{u} \pm c^{(\alpha)}_{d}$$

Decay Channels

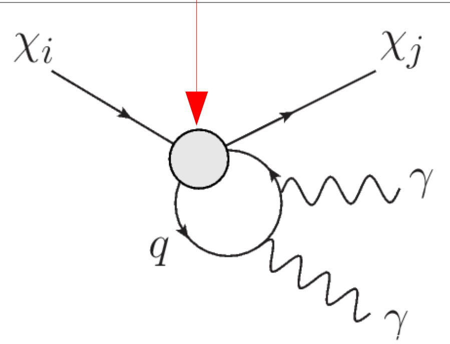


- Since $\Delta m_{ij} \lesssim \mathcal{O}(100\ \mathrm{keV})$, only possible SM decay products are low energy **photons** and **neutrinos**
- χ_i only couples to quarks, which at these low energies are bound as mesons

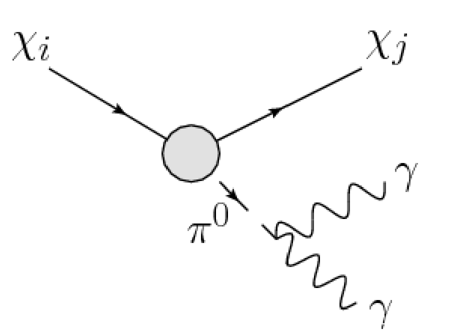
$\Longrightarrow$ Decay of χ_i proceeds through off-shell (loops of) mesons

$\Rightarrow$ Decay widths highly suppressed

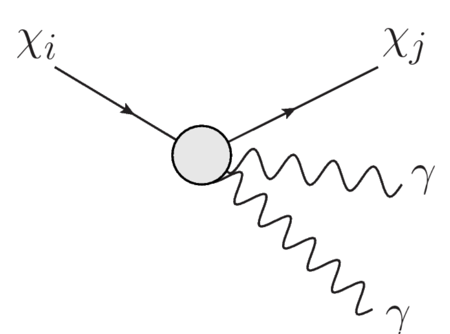
We have this coefficient... ...*but how do we get here?*



Microscopic Theory



Low Energy EFT



Effective χ-γ couplings

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

Chiral Perturbation Theory $\Longrightarrow$

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

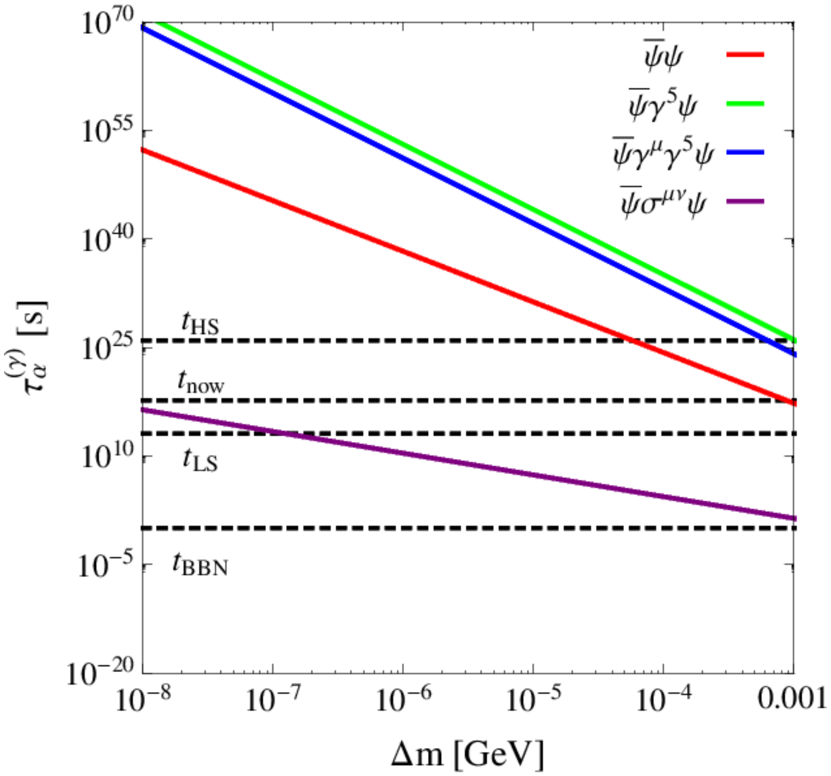
Decay Widths

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:

$$\mathcal{L}_{\rm eff} = \frac{c_S}{f\Lambda^2}(\overline{\chi}\chi)F_{\mu\nu}F^{\mu\nu} + \frac{c_P}{f\Lambda^2}i(\overline{\chi}\gamma^5\chi)F_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{c_V}{\Lambda^2}(\overline{\chi}\gamma^\mu\chi)\partial^\nu F_{\mu\nu} + \frac{c_{V'}}{f^2\Lambda^2}(\overline{\chi}\gamma^\mu\chi)\partial_\rho\partial^\rho\partial^\nu F_{\mu\nu}$$
$$+\frac{c_A}{f^2\Lambda^2}(\overline{\chi}\gamma^\mu\gamma^5\chi)(\partial_\mu F^{\nu\rho})\widetilde{F}_{\nu\rho} + \frac{c_T f}{\Lambda^2}(\overline{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu} + \frac{c_{T'}}{f\Lambda^2}(\overline{\chi}\sigma^{\mu\nu}\chi)\partial_\mu\partial^\rho F_{\nu\rho}$$

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

$$\Gamma_S^{(\gamma)} \approx \frac{2c_S^2\Delta m^7}{105\pi^3 f^2\Lambda^4}$$
$$\Gamma_P^{(\gamma)} \approx \frac{2c_P^2\Delta m^9}{315\pi^3 f^2\Lambda^4 m_j^2}$$
$$\Gamma_A^{(\gamma)} \approx \frac{4c_A^2\Delta m^9}{315\pi^3 f^4\Lambda^4}$$
$$\Gamma_{PA}^{(\gamma)} \approx \frac{2c_P c_A\Delta m^9}{315\pi^3 f^3\Lambda^4 m_j}$$
$$\Gamma_T^{(\gamma)} \approx \frac{4c_T^2\Delta m^3 f^2}{\pi\Lambda^4}$$



$$c_+^{(\alpha)} = c_-^{(\alpha)} = 1$$
$$\Lambda = 10\ \text{TeV}$$
$$m_i = 100\ \text{GeV}$$

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

$\Delta m > 0$ ➡ **“Upscattering”**
Typical case studied in *inelastic* DM scenarios. DM scatters off nucleus into higher mass “excited” state.

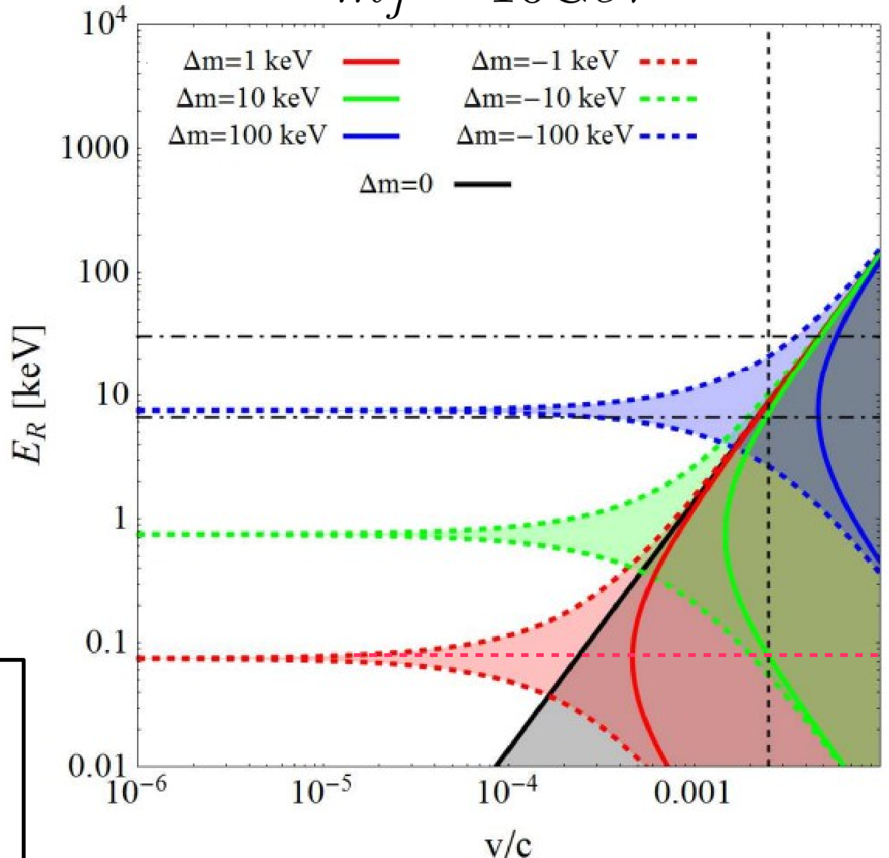
$\Delta m < 0$ ➡ **“Downscattering”**
DM scatters off nucleus into lower mass state. Δm released as kinetic energy

For $\Delta m \ll \{m_i, m_j\}$,

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

where, $\Delta m \equiv m_k - m_j$
$\mu_{Nj} = m_N m_j/(m_N + m_j)$

Range of E_R at XENON100
$m_j = 10\mathrm{GeV}$



Recoil Energy Spectra

$$\frac{dR}{dE_R} = N_N \sum_j \sum_k \frac{\rho_j^{\rm loc}}{m_j} \int_{v > v_{\rm min}^{(jk)}} v \mathcal{F}_j(\vec{v}) \left(\frac{d\sigma_{jk}}{dE_R} \right) d^3 v$$

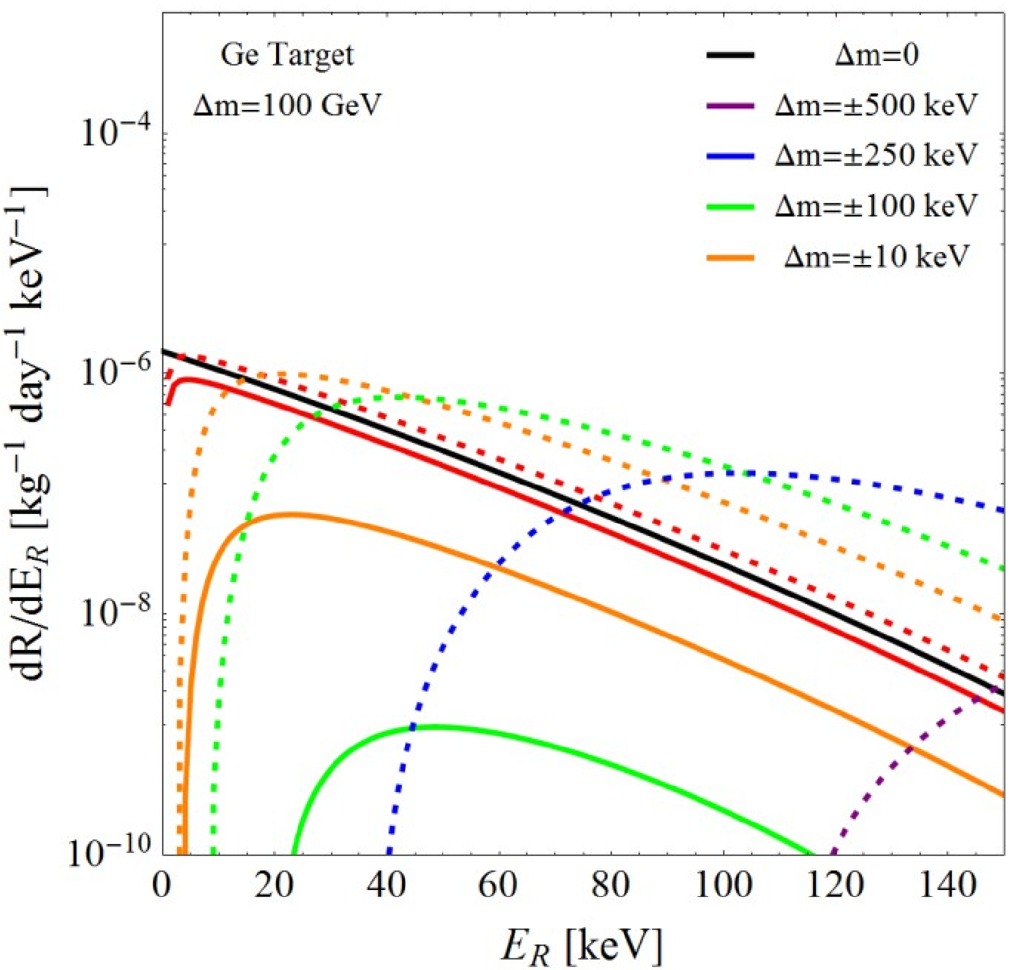
- ***Down/upscattering lead to unique and distinguishable recoil energy spectra***
  (which is our only observable at current direct detection experiments)

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

Recoil Energy Spectrum



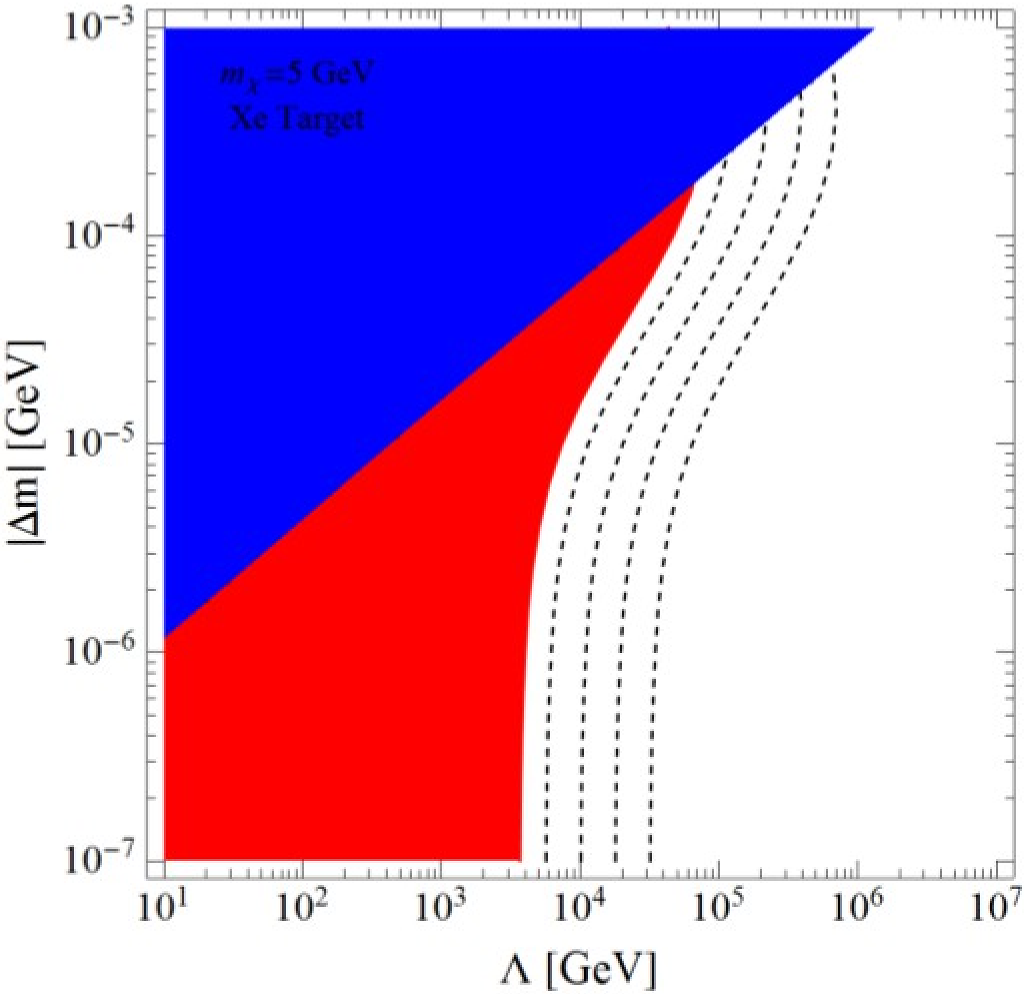
Now combine constraints from scattering and decay

Excluded by XENON100

- **Most recent limits** from [arXiv:1207.5988].
- Total event rate for nuclear recoils with $6.6\ \mathrm{keV} \leq E_R \leq 30.6\ \mathrm{keV}$

Excluded by astrophysical 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.



- Scalar operator: $\mathcal{O}^s = \dfrac{c^{(s)}}{\Lambda^2}(\overline{\chi}_i\chi_j)(\overline{q}q)$
- Dashed lines represent:

$R = \{10^{-4},\ 10^{-5},\ 10^{-6},\ 10^{-7}\}\ \mathrm{kg}^{-1}\ \mathrm{day}^{-1}$

Conclusions

- Multicomponent dark matter models are **well motivated** theoretically and experimentally.
- These models open up the possibility of *upscattering* and *downscattering*, which lead to **unique recoil energy spectra**.
- Dark matter decay in these models **opens up a new window** into the properties of the dark sector.
- Decay is characterized by the **same operators** as those governing scattering rates.

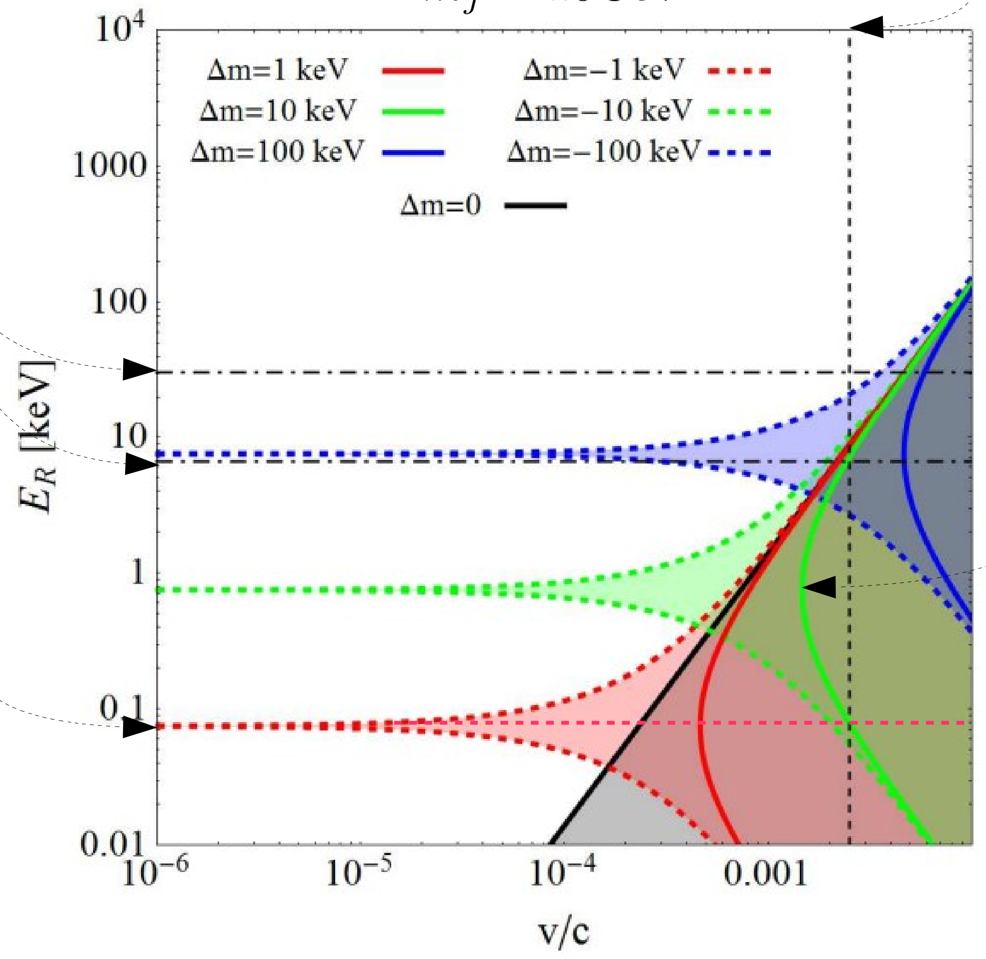
The interplay between direct detection experiments and DM decay provide a novel constraint on dark matter parameter space.

Thanks for coming!

Backup Slides

Range of E_R at XENON100

$m_j = 10\mathrm{GeV}$



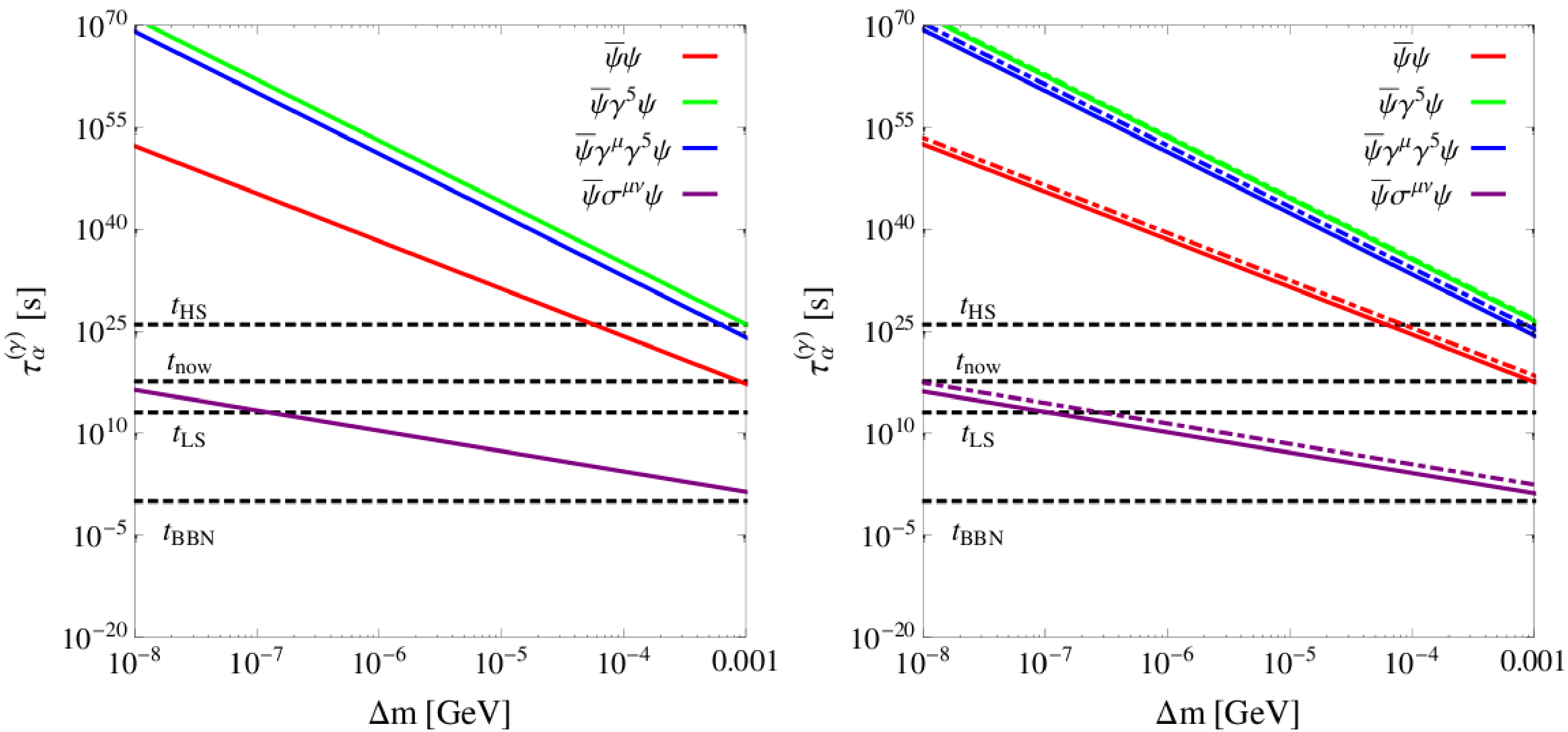
- Expected velocity cutoff v_{esc}
- Min/max recoil energies used by XENON100 analysis
- Energy threshold for upscattering: $v > \sqrt{m/\mu_{Nj}}$
- "Stationary" particles: Energy Δm given to χ_k and N $$E_R = \frac{-\mu_{Nk}\Delta m}{m_N}$$
- Scattering assumed isotropic in CM frame

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

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

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

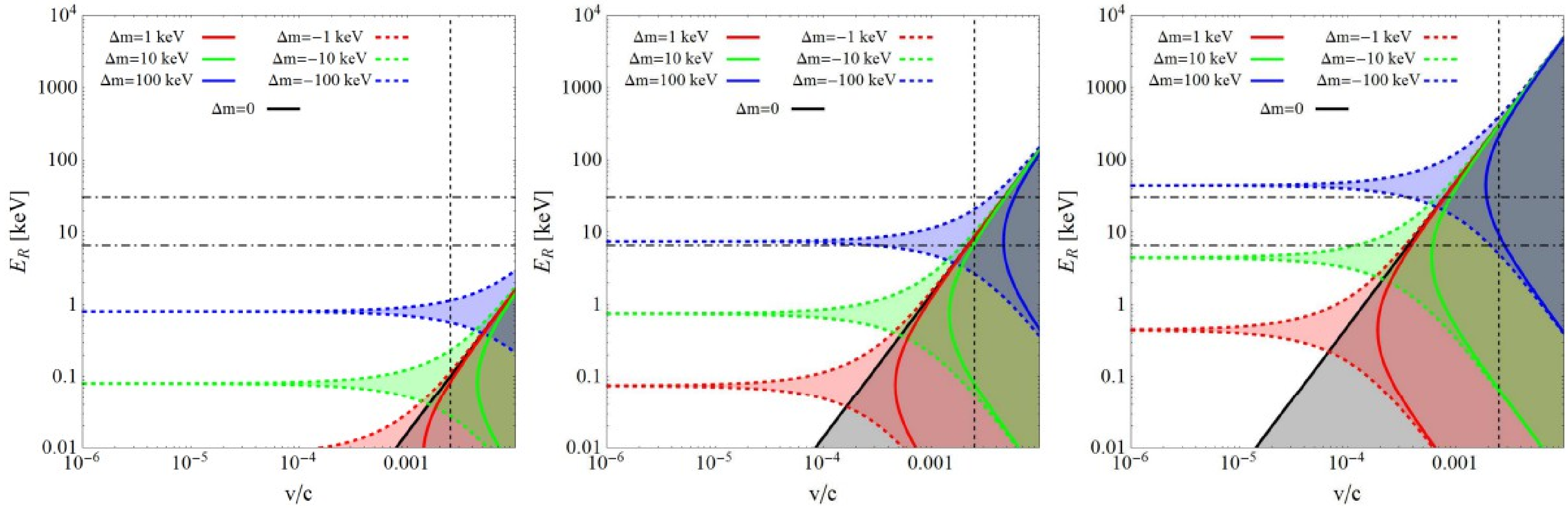
$$c_+^{(\alpha)} = 0, c_-^{(\alpha)} = 1$$ (dashed)



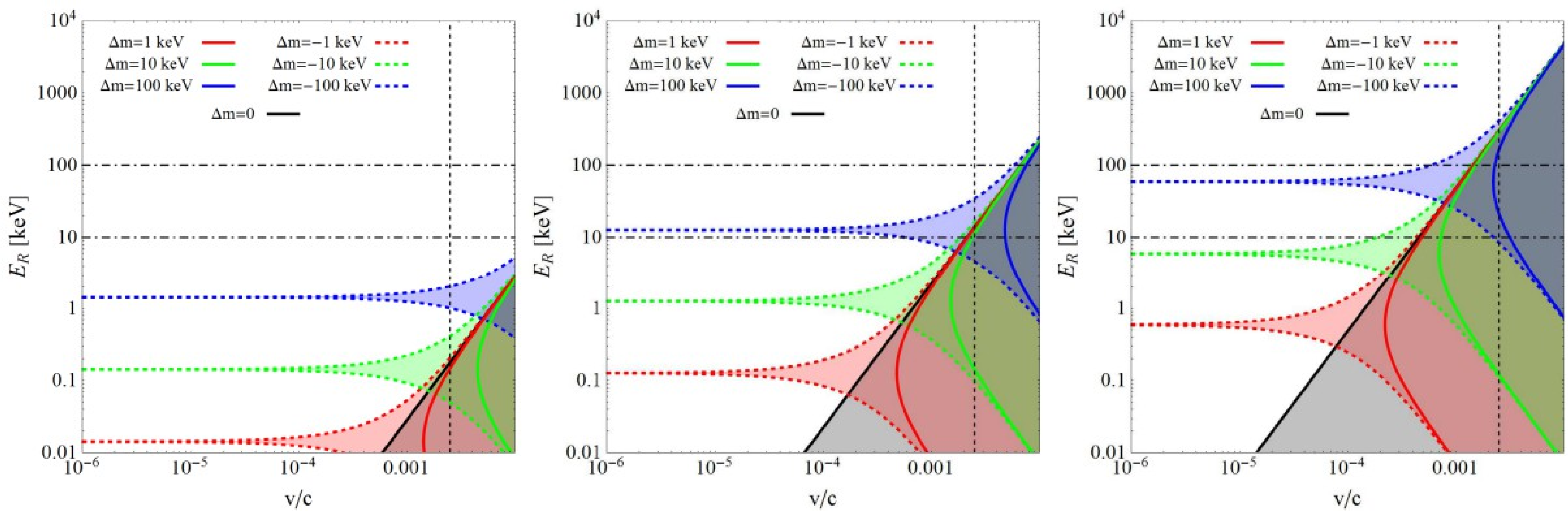
Lifetime of dark fermion which decays via $\chi_j \to \chi_i \gamma$ and $\chi_j \to \chi_i \gamma\gamma$

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

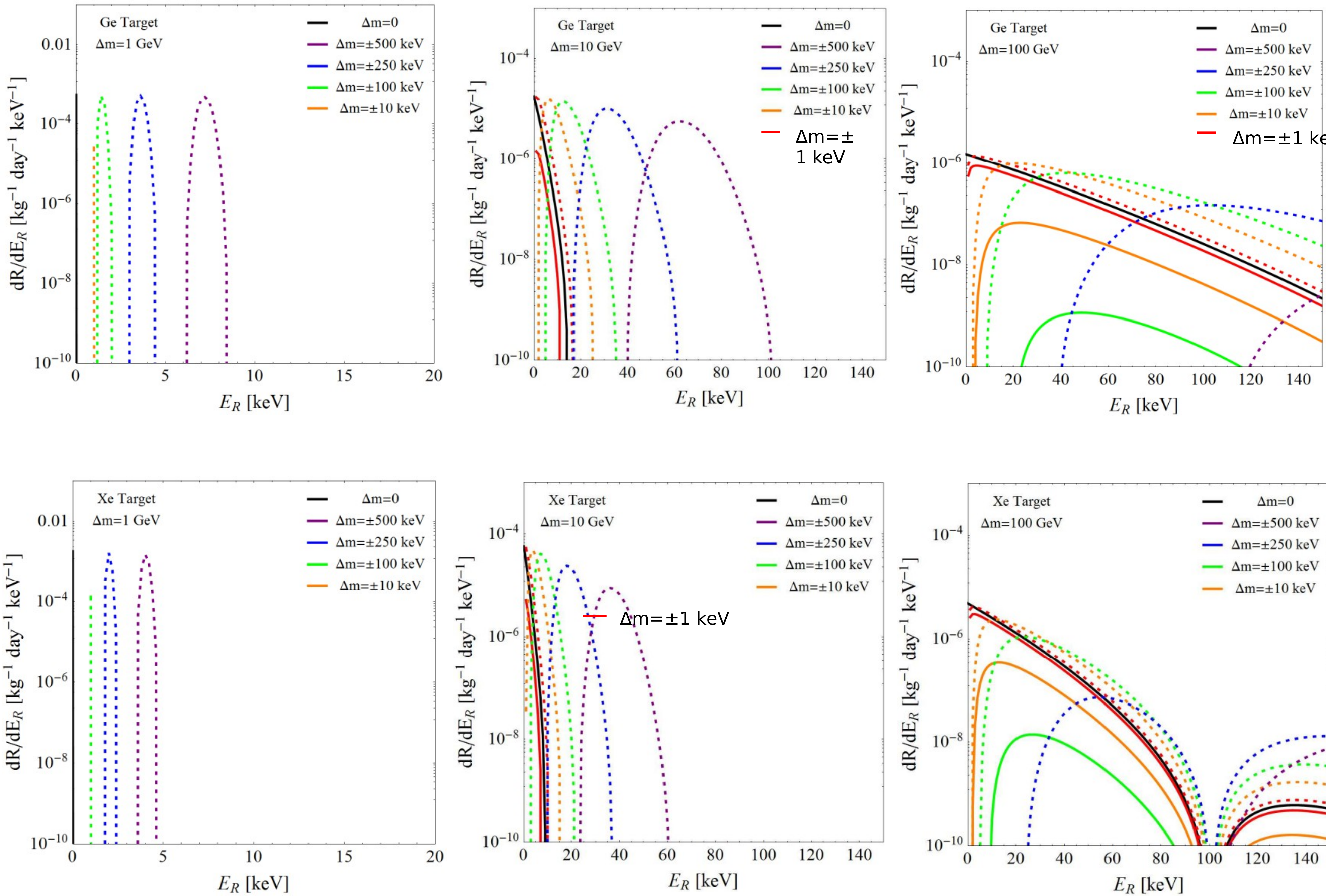
Xenon target --- XENON100



Germanium target --- CDMS II



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



Ge Target
Δm=1 GeV
Δm=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
Δm=±250 keV
Δm=±100 keV
Δm=±10 keV
Δm=±1 keV
dR/dE$_R$ [kg^{-1} day^{-1} keV^{-1}]
E_R [keV]
Xe 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]
Xe 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]
Xe Target
Δm=100 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]