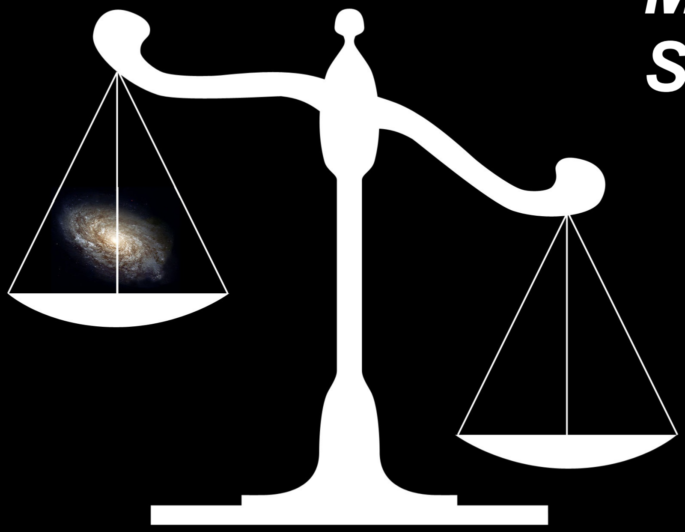
Astrophysical Constraints on Direct Detection:

Multi-Component Dark Matter Scattering and Stability



David Yaylali
University of Hawaii

[ArXiv:1311.xxxx]

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

Argonne National Labs, December 2013

The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*

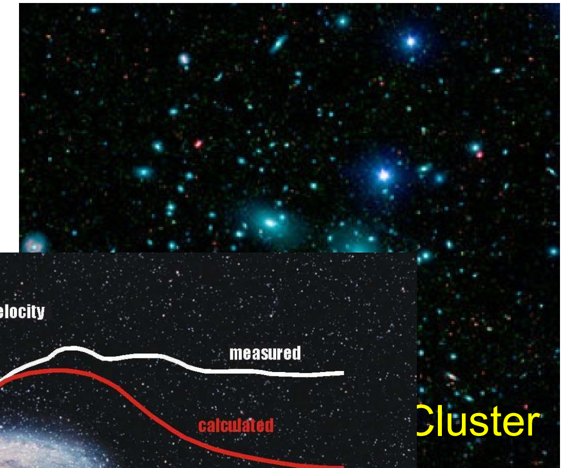
- *Local stellar velocities (Oort, 1932)*

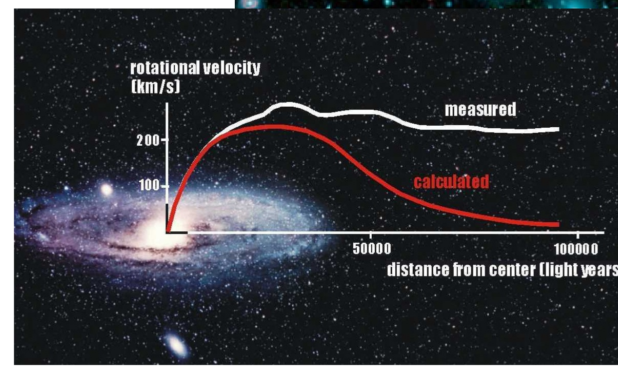
The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*

- *Local stellar velocities (Oort, 1932)*
- *Velocities of galaxies in clusters (Zwicky, 1933)*

The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*

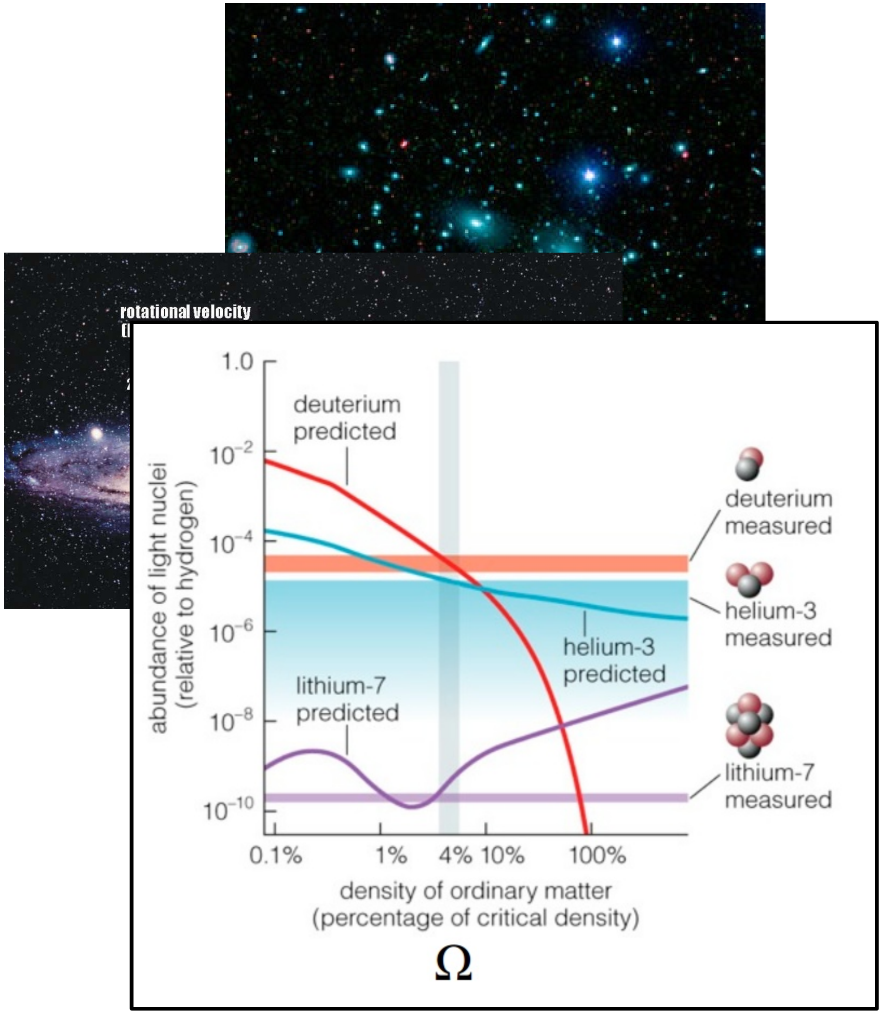
- *Local stellar velocities (Oort, 1932)*
- *Velocities of galaxies in clusters (Zwicky, 1933)*
- *Galactic rotation curves (Rubin, 1960's)*



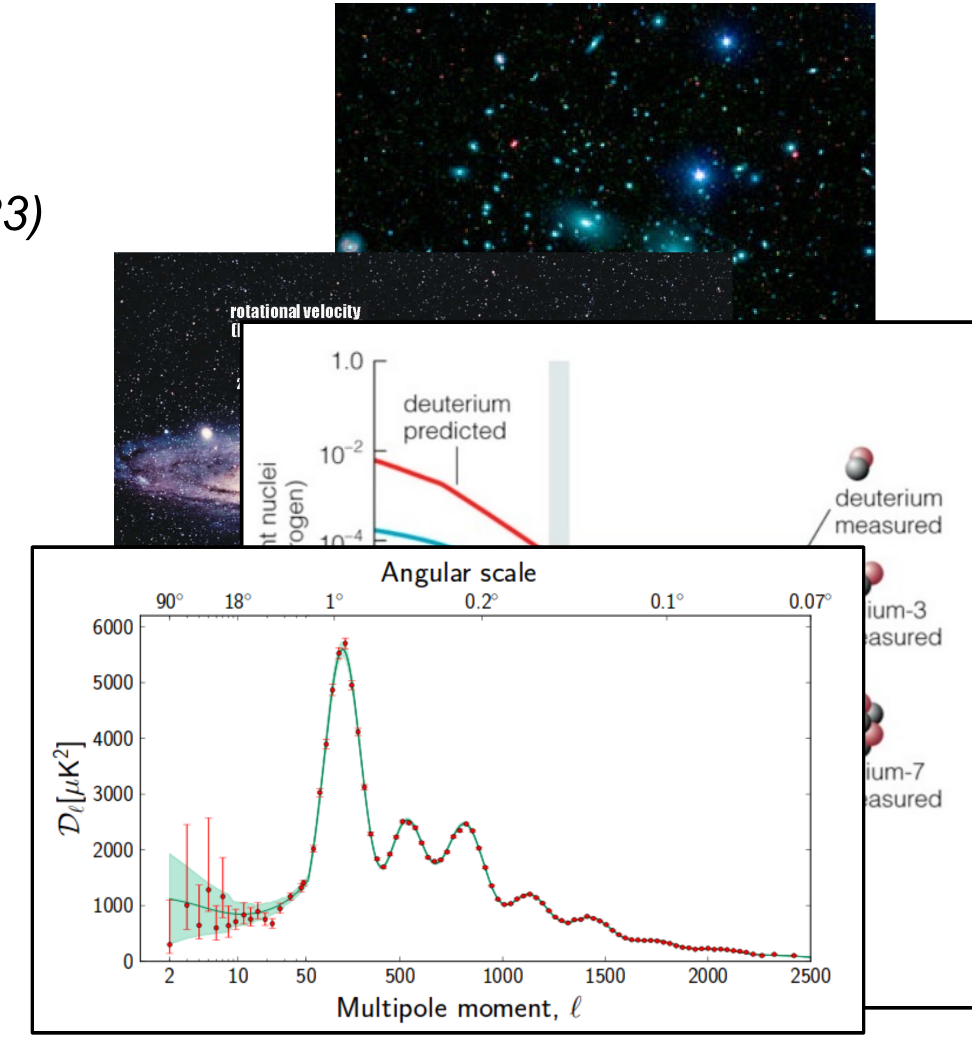


The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*

- *Local stellar velocities (Oort, 1932)*
- *Velocities of galaxies in clusters (Zwicky, 1933)*
- *Galactic rotation curves (Rubin, 1960's)*
- *Big bang neucleosynthesis*



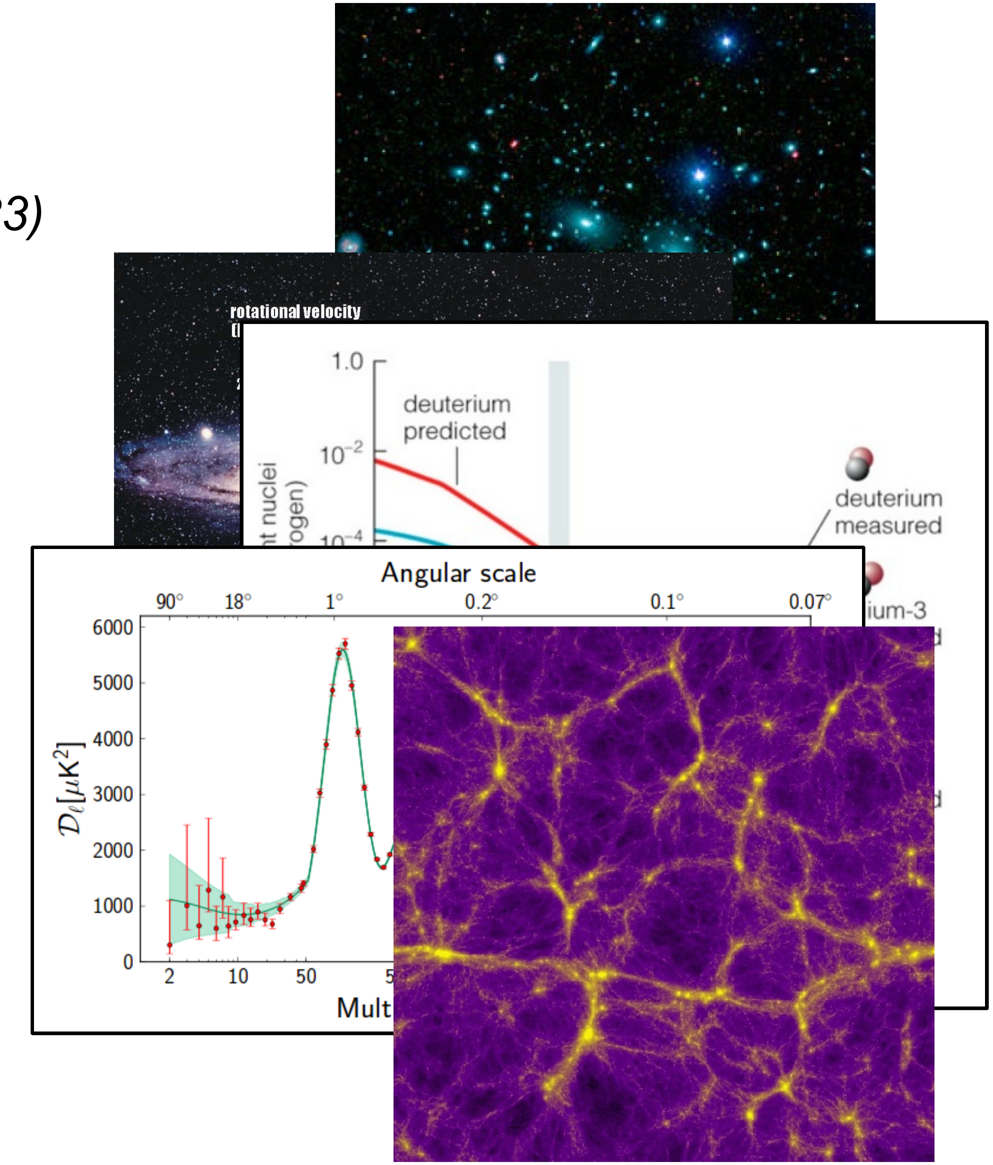
The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*



- *Local stellar velocities (Oort, 1932)*
- *Velocities of galaxies in clusters (Zwicky, 1933)*
- *Galactic rotation curves (Rubin, 1960's)*
- *Big bang neucleosynthesis*
- *Position/ratio of acoustic peaks in the CMB*

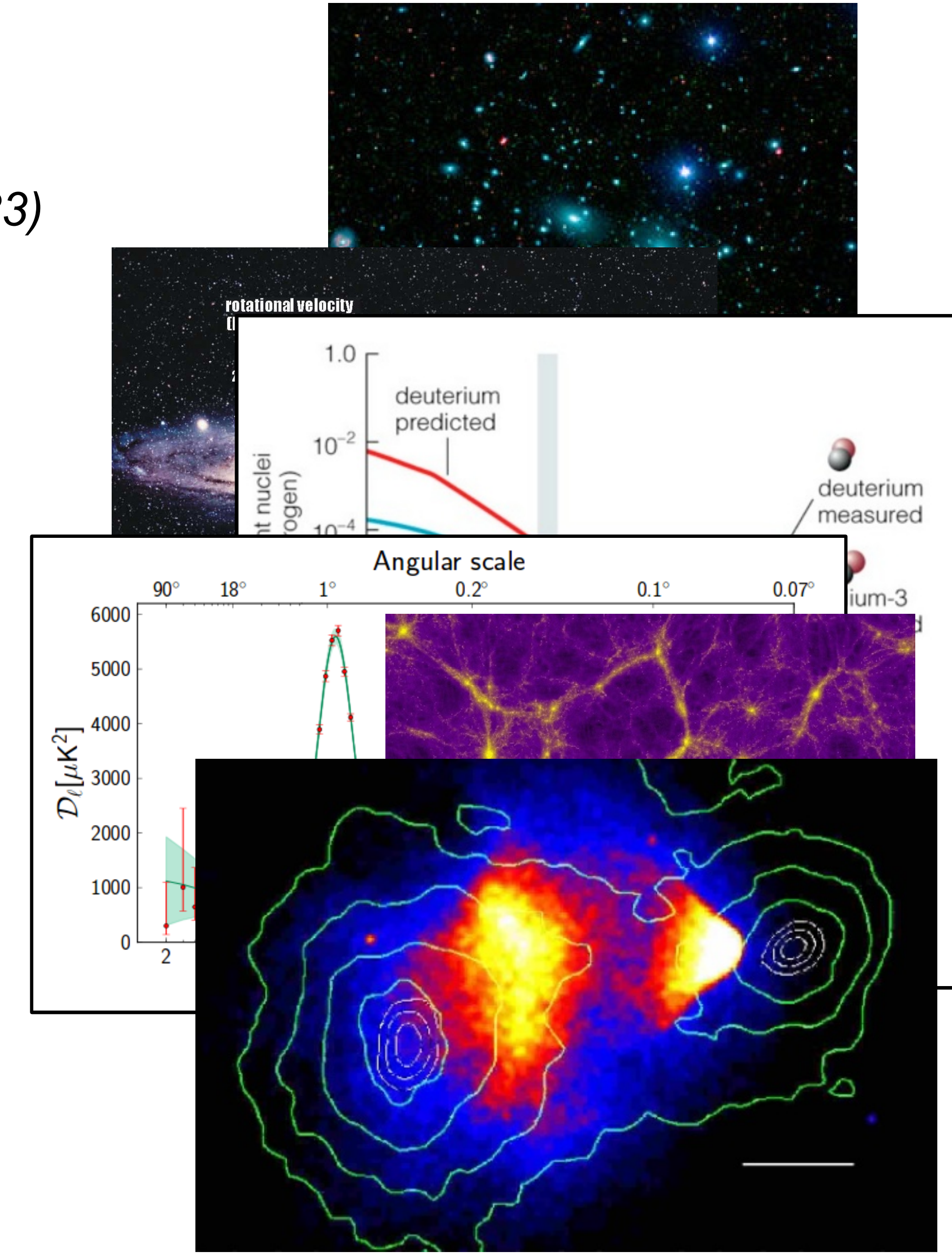
The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*

- *Local stellar velocities (Oort, 1932)*
- *Velocities of galaxies in clusters (Zwicky, 1933)*
- *Galactic rotation curves (Rubin, 1960's)*
- *Big bang neucleosynthesis*
- *Position/ratio of acoustic peaks in the CMB*
- *Large scale structure – N-body simulations*



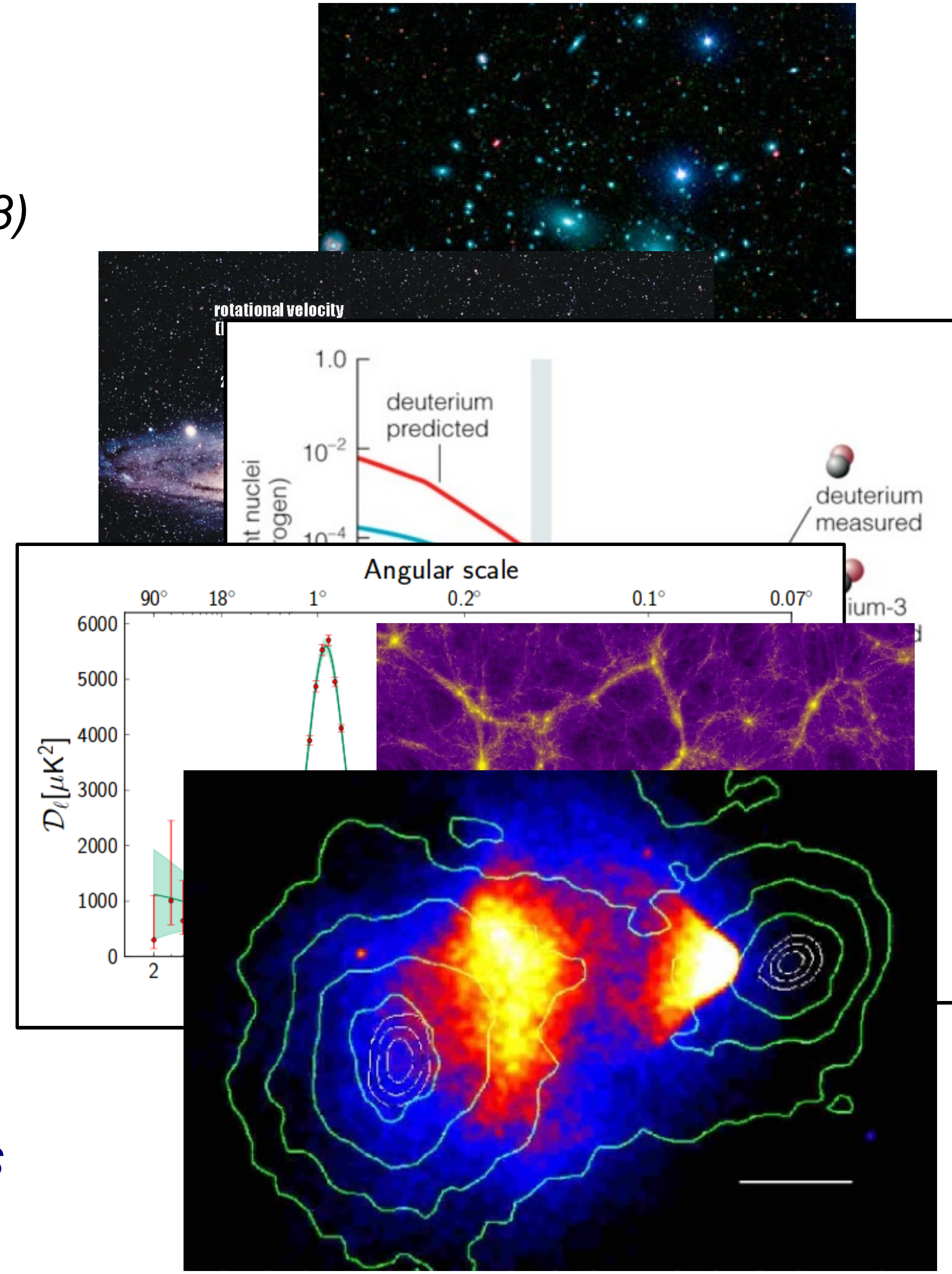
The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*

- *Local stellar velocities (Oort, 1932)*
- *Velocities of galaxies in clusters (Zwicky, 1933)*
- *Galactic rotation curves (Rubin, 1960's)*
- *Big bang neucleosynthesis*
- *Position/ratio of acoustic peaks in the CMB*
- *Large scale structure – N-body simulations*
- *Lensing in the Bullet Cluster*



The existence of dark matter in our universe is at this point very well established. *Let's quickly review why....*

- *Local stellar velocities (Oort, 1932)*
- *Velocities of galaxies in clusters (Zwicky, 1933)*
- *Galactic rotation curves (Rubin, 1960's)*
- *Big bang neucleosynthesis*
- *Position/ratio of acoustic peaks in the CMB*
- *Large scale structure – N-body simulations*
- *Lensing in the Bullet Cluster*

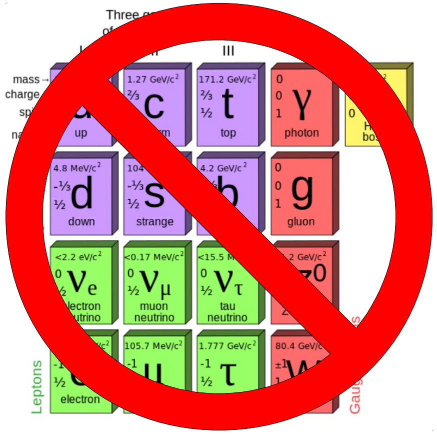


All separate phenomena point to

$$m_{DM}/m_{SM} \approx 5$$

We're pretty damn sure dark matter is really out there!! *(or in here!)*

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



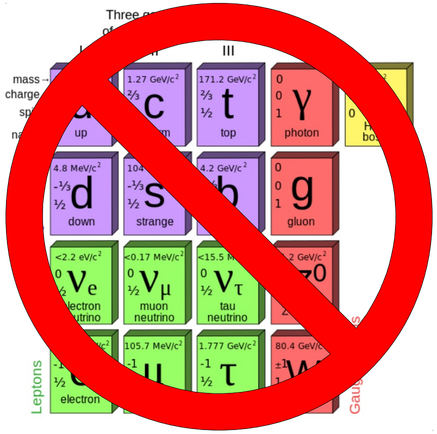
What we know...

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

What we think we know...

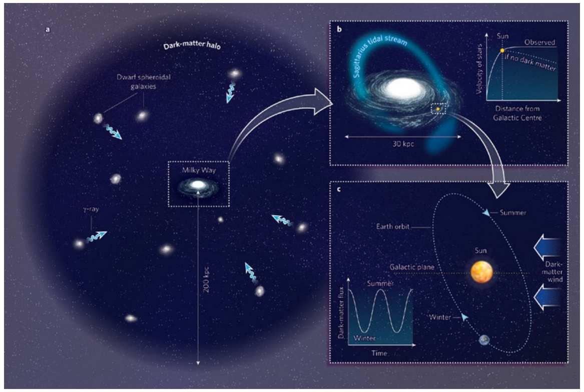
What we don't know...

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...

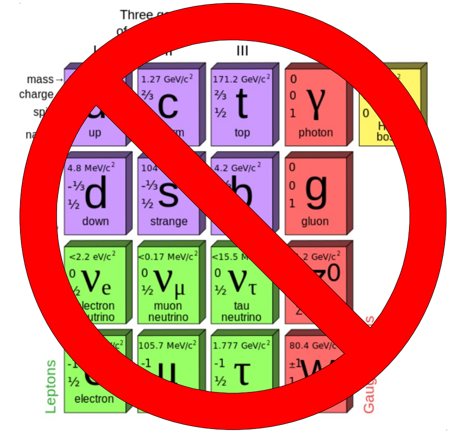
- $\rho_{\rm loc} \sim 0.3 \text{ GeV}/cm^3$
- Local velocity distribution
- Certain DM-SM cross sections/ masses are excluded

What we don't know...

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

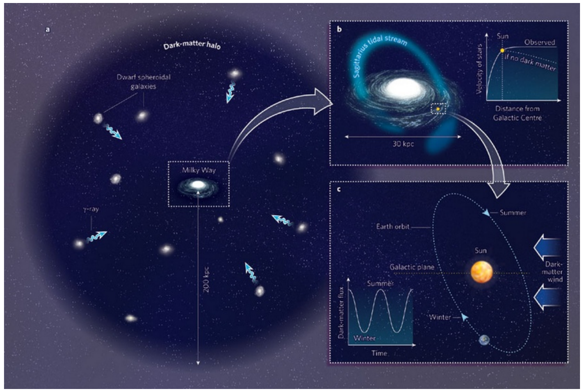
What we know...

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



What we think we know...

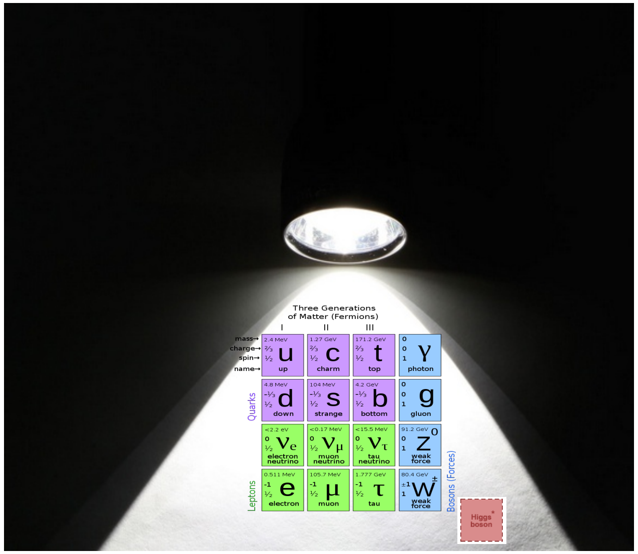
- $\rho_{\rm loc} \sim 0.3\ {\rm GeV}/cm^3$
- Local velocity distribution
- Certain DM-SM cross sections/ masses are excluded



What we don't know...

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

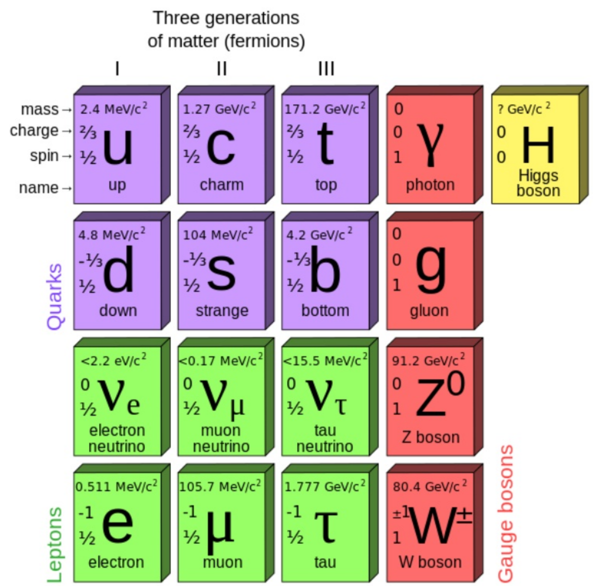
Common Assumptions: Thermally produced, non-zero interactions with SM, *stable*, *single particle*...



Why Consider Multi-Component Dark Matter?

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

SCENARIO I



+

χ

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

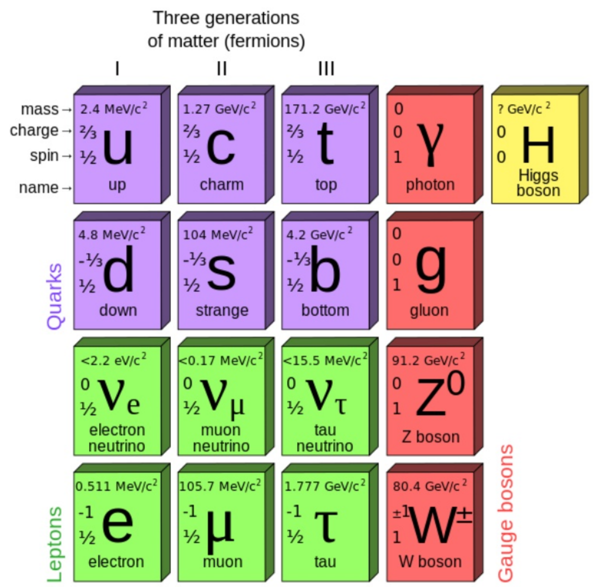
*A **single** extra particle, making up the remaining 80%.*

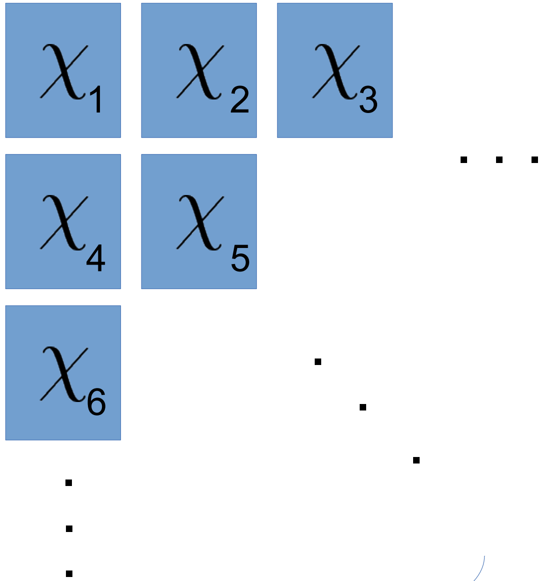
...OR

Why Consider Multi-Component Dark Matter?

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

SCENARIO II





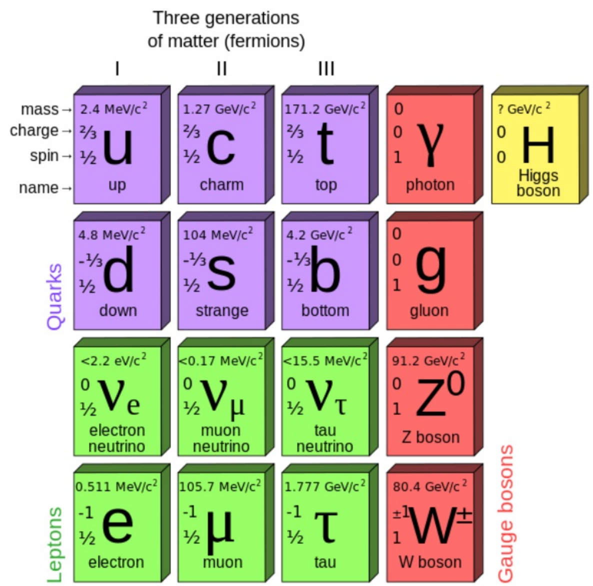
*Everything we **currently** know of... ~20% of the matter in the universe.*

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

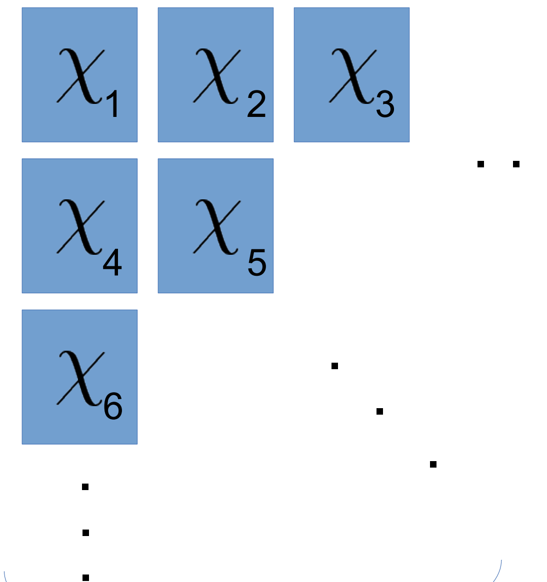
Why Consider Multi-Component Dark Matter?

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

SCENARIO II



+



*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%.*

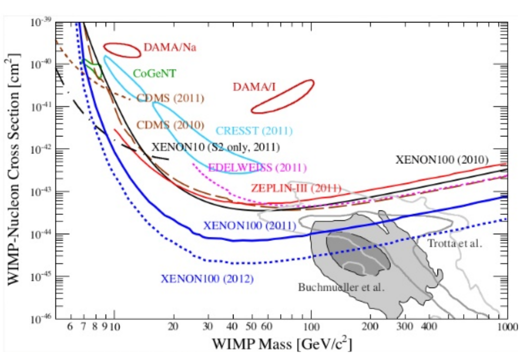
*Given how complicated the standard model is, it is **worth considering** the possibility that the dark sector is complicated as well!*

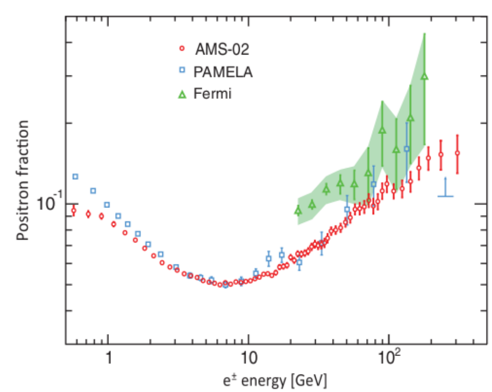
Ok, but what are some more concrete reasons to motivate models of multi-component DM?

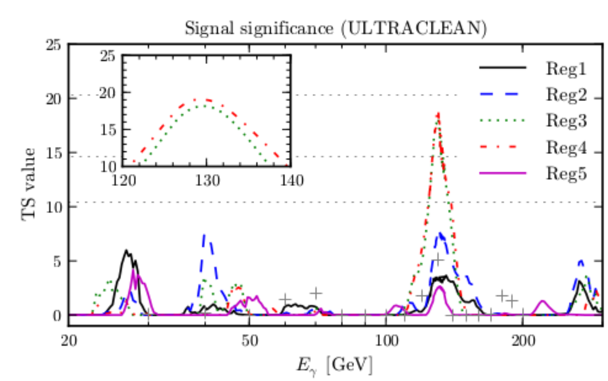
- **DAMA/CoGeNT/CRESST/etc. VS XENON100/COUPP/etc.**
  Reconciling these sets of experiments difficult in vanilla DM models
  - -Inelastic Dark Matter (Smith & Weiner, 2001)
  - -Mirror Matter (Foot, 2004)
  - -Exothermic Dark Matter (Graham, Harnik, et. al., 2010)

- **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)
  - -Dynamical Dark Matter (Dienes, Kumar, Thomas, arXiv:1306.2959)

- **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!)
  Again, hard to reconcile with freeze-out production
  - -Annihilation to other DM particles first (Buckley, Hooper, 2012)
  - -Annihilation to one gamma plus another DM (Eramo, Thaler, 2012)





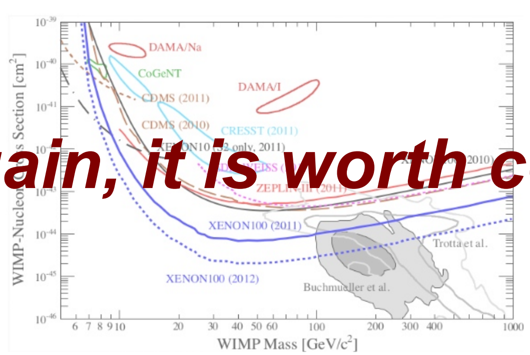


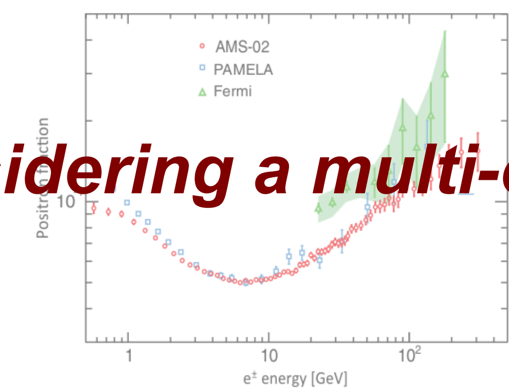
Ok, but what are some more concrete reasons to motivate models of multi-component DM?

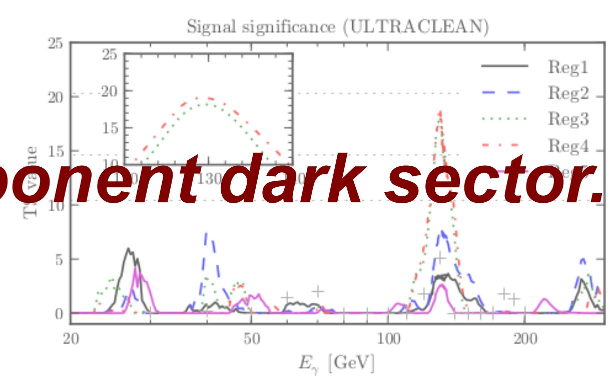
- **DAMA/CoGeNT/CRESST/etc. VS XENON100/COUPP/etc.**
  Reconciling these sets of experiments difficult in vanilla DM models
  - -Inelastic Dark Matter (Smith & Weiner, 2001)
  - -Mirror Matter (Foot, 2004)
  - -Exothermic Dark Matter (Graham, Harnik, et. al., 2010)

- **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)
  - -Dynamical Dark Matter (Dienes, Kumar, Thomas, arXiv:1306.2959)

- **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!)
  Again, hard to reconcile with freeze-out production
  - -Annihilation to other DM particles first (Buckley, Hooper, 2012)
  - -Annihilation to one gamma plus another DM (Eramo, Thaler, 2012)

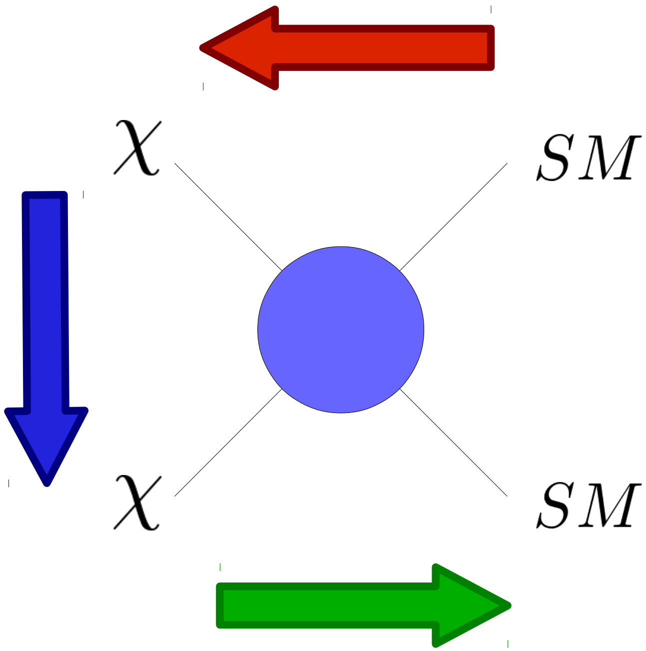






Again, it is worth considering a multi-component dark sector.

Our non-gravitational windows into dark matter...

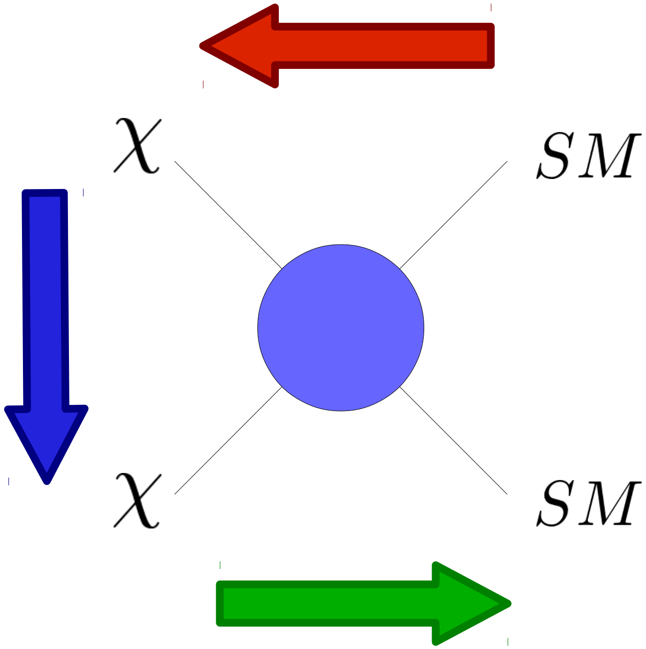


- **DM-SM scattering** – (direct detection)
- **DM annihilation to SM** – (indirect det. + relic density)
- **Collider Production**

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

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

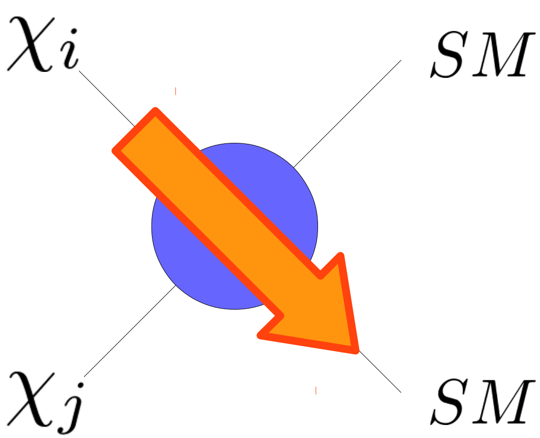
Our non-gravitational windows into dark matter...



- **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...

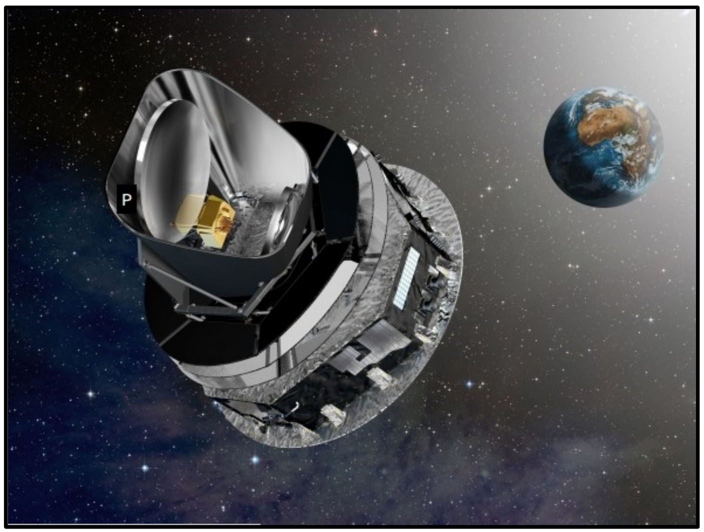


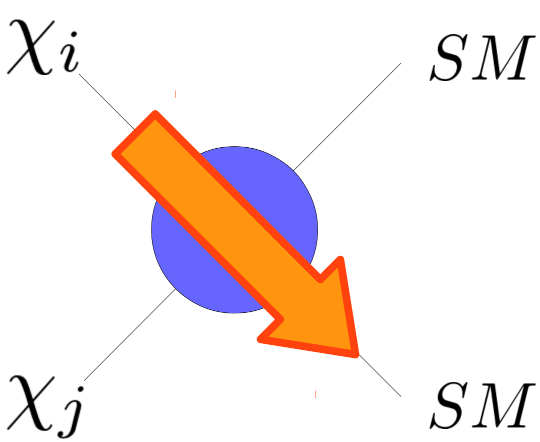
- **DM decay to DM+SM** – (indirect detection!)

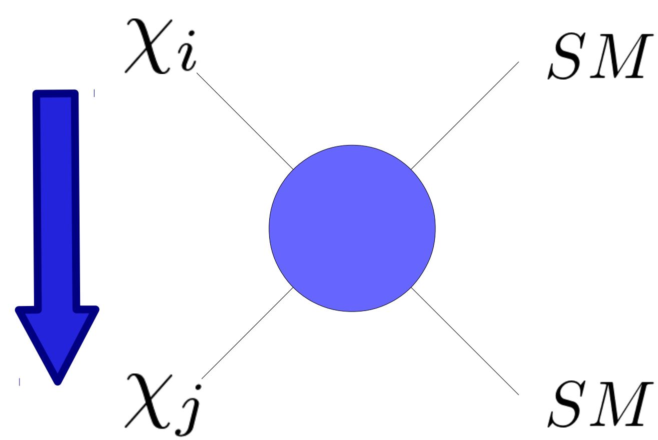
Again, same diagram $\Longrightarrow$ Decay rate **also** correlated with the above cross sections!

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:

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

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

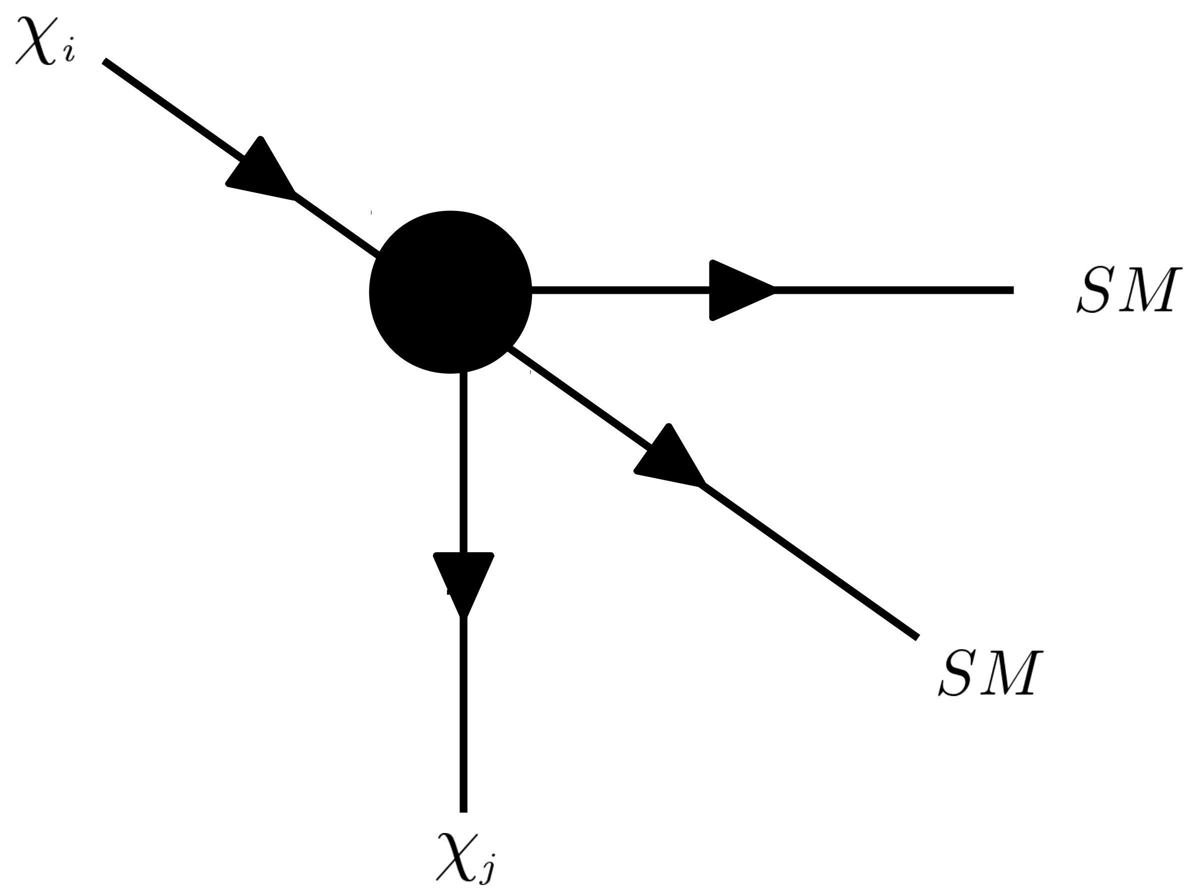
- χ_is uncharged
- Generation independent
- $\Delta m \lesssim \mathcal{O}(100 \text{ kev}) \Rightarrow$ Only light quarks contribute to decay.

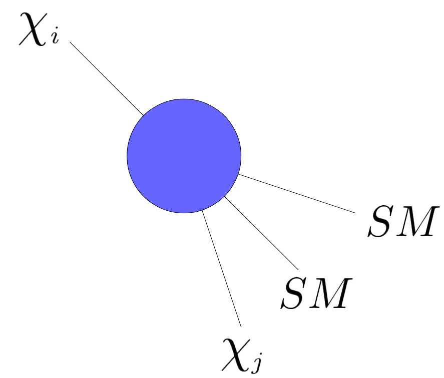
$$c^{(\alpha)}_{ijff'} = \begin{pmatrix} c^{(\alpha)}_{iju} & 0 & 0 \\ 0 & c^{(\alpha)}_{ijd} & 0 \\ 0 & 0 & c^{(\alpha)}_{ijd} \end{pmatrix}$$

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





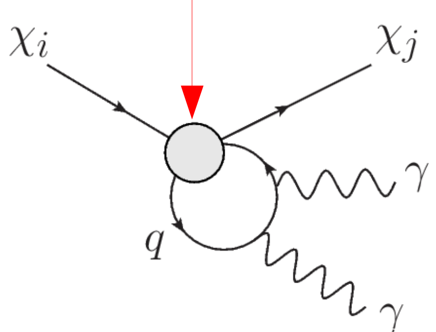
Decay Channels

- 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

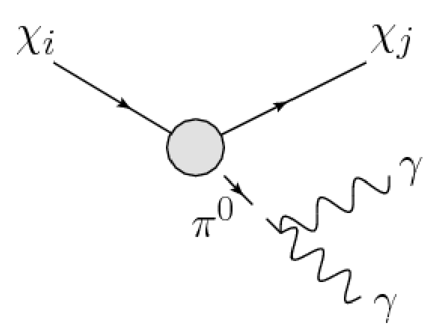
$\Longrightarrow$ Decay of χ_i proceeds through off-shell (loops of) mesons

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

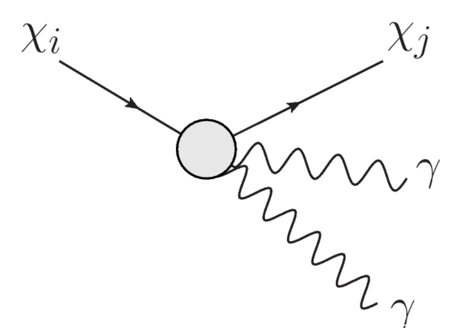
We have this coefficient...



Microscopic Theory



Low Energy EFT

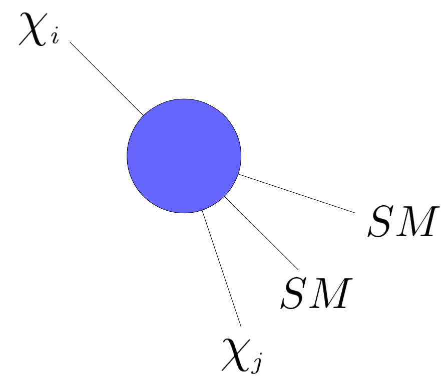


Effective χ-γ couplings

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

...but how do we get here?

Decay Channels

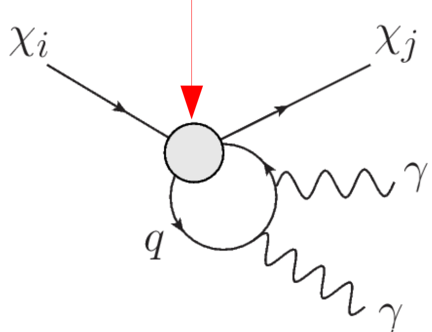


- Since $\Delta m_{ij} \lesssim \mathcal{O}(100 \text{ keV})$, only possible SM decay products are low energy **photons** and **neutrinos**
- χ_i only couples to quarks, which at these low energies are bound as mesons

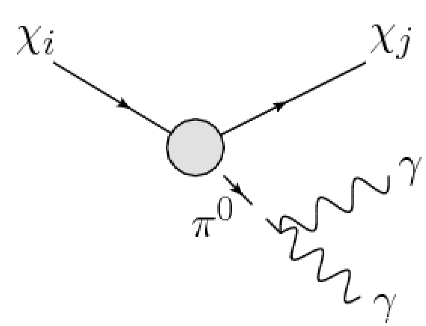
$\Longrightarrow$ Decay of χ_i proceeds through off-shell (loops of) mesons

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

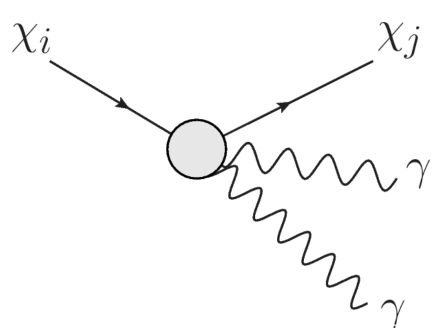
We have this coefficient...



Microscopic Theory



Low Energy EFT



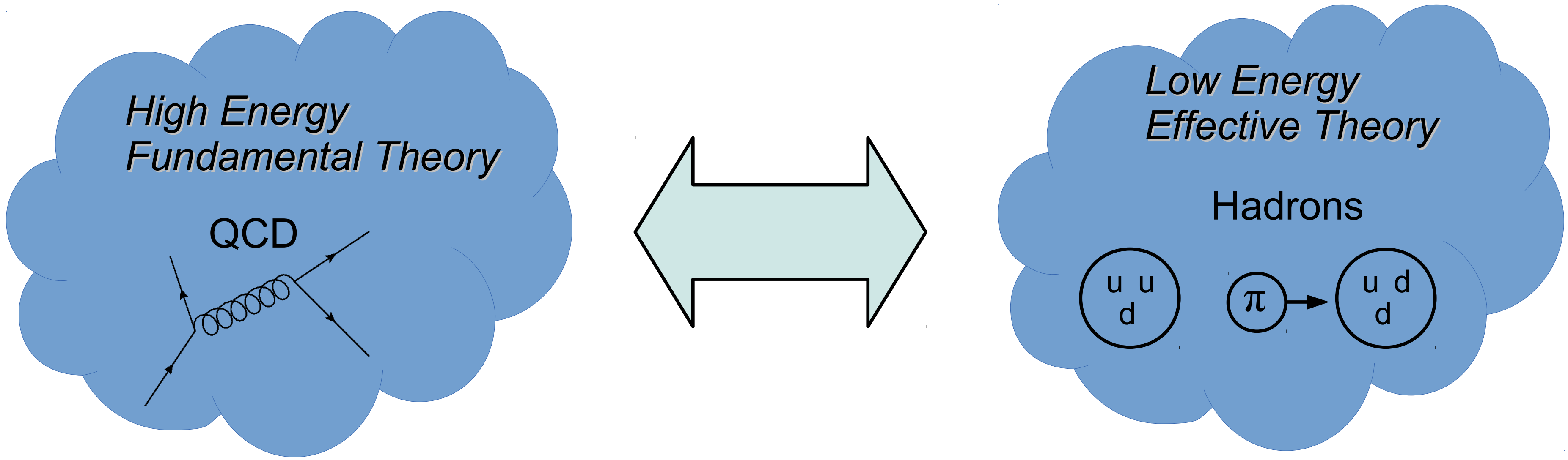
Effective χ-γ couplings

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

...but how do we get here?

Chiral Perturbation Theory

A Brief Outline of Chiral Perturbation Theory (ChPT)



According to a seminal paper by Weinberg (1979), the effective theory should respect all of the symmetries of the fundamental theory. If the fundamental symmetry is broken, the symmetry in the effective theory needs to be broken in the same way.

$$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$$

spontaneously broken
by quark condensate to..

$$\longrightarrow \mathrm{SU}(3)_V$$

Theoretically motivated
(but not proven)

$$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$$

spontaneously broken
by quark condensate to..

$$\longrightarrow \mathrm{SU}(3)_V$$

Phenomenologically motivated
8 light pseudoscalar mesons: $\pi^0,\ \pi^\pm,\ K^0,\ \overline{K}^0,\ K^\pm,\ \eta$

pseudo-Goldstone bosons?

How to build the low energy theory using Weinberg's theorem

- Identify the (approximate) symmetries of the fundamental theory

- Using the fields present in the low energy theory (pions, etc), write all possible terms that
  - Respect Lorentz invariance
  - Respect the chiral symmetry of the original theory (Massless QCD, before explicit symmetry breaking)

- Chiral symmetry is only approximate (quarks have nonzero mass). Break the symmetry in the same way it is broken in the original theory.

- Couple dark matter to the low energy theory – now straightforward in this framework

How to build the low energy theory using Weinberg's theorem

- Identify the (approximate) symmetries of the fundamental theory

- Using the fields present in the low energy theory (pions, etc), write all possible terms that
  - Respect Lorentz invariance
  - Respect the chiral symmetry of the original theory (Massless QCD, before explicit symmetry breaking)

- Chiral symmetry is only approximate (quarks have nonzero mass). Break the symmetry in the same way it is broken in the original theory.

- Couple dark matter to the low energy theory – now straightforward in this framework

Approximate symmetry of QCD

In absence of quark masses, 3-flavor QCD

$$\mathcal{L}^0_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + i\bar{q}_L \gamma^\mu D_\mu q_L + i\bar{q}_R \gamma^\mu D_\mu q_R \qquad q = \mathrm{column}(u, d, s)$$

is invariant under global $G = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ transformations of the left and right-handed quarks:

$$q_R \to g_R q_R \text{ and } q_L \to g_L q_L$$

Generators of $SU(3)_{L/R}$

Approximate symmetry of QCD

In absence of quark masses, 3-flavor QCD

$$\mathcal{L}^0_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + i\bar{q}_L \gamma^\mu D_\mu q_L + i\bar{q}_R \gamma^\mu D_\mu q_R \qquad q = \mathrm{column}(u, d, s)$$

is invariant under global $G = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ transformations of the left and right-handed quarks:

$$q_R \to g_R q_R \text{ and } q_L \to g_L q_L$$

Add terms which will allow symmetry breaking and DM coupling

We are interested in coupling dark matter to the low energy EFT. In order to do so, we *add to massless QCD a general set of external fields...*

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} + \bar{q}\gamma^\mu(v_\mu + \gamma_5 a_\mu)q - \bar{q}(s - i\gamma_5 p)q$$

Massless QCD Lagrangian

External fields

These will eventually be used to

- explicitly break the chiral symmetry
- represent our dark matter bilinears

> We demand this entire construct to be invariant under G, ***so this determines how the external fields*** $s,\ p,\ v_\mu,\ a_\mu$ ***transform***

e.g. $\overline{q}(s - i\gamma^5 p)q = \overline{q}_R(s + ip)q_L + \overline{q}_L(s - ip)q_R \quad \Longrightarrow \quad (s + ip) \to g_R(s + ip)g_L^\dagger$

How to build the low energy theory using Weinberg's theorem

- Identify the (approximate) symmetries of the fundamental theory

- Using the fields present in the low energy theory (pions, etc), write all possible terms that
  - Respect Lorentz invariance
  - Respect the chiral symmetry of the original theory (Massless QCD, before explicit symmetry breaking)

- Chiral symmetry is only approximate (quarks have nonzero mass). Break the symmetry in the same way it is broken in the original theory.

- Couple dark matter to the low energy theory – now straightforward in this framework

Low energy fields

A convenient construct to represent the mesons is given by...

$$\boxed{U \;\equiv\; e^{i\sqrt{2}\Phi/f} \qquad \Phi \;\equiv\; \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \overline{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}}$$

...since U transforms simply under G: $U \to g_R U g_L^\dagger$

Construct the Lagrangian

Since we know how U and the external fields $s,\ p,\ v_\mu,\ a_\mu$ transform, we simply write all possible terms that respect G and Lorentz invariance (up to a certain order in, say, a momentum expansion).

$$\mathcal{L}_{\rm eff}^{(s,p,v,a)} \;=\; \frac{f^2}{4}\mathrm{Tr}\left[D_\mu U^\dagger D^\mu U + U^\dagger \zeta + \zeta^\dagger U\right]$$

where,

$$D_\mu U \equiv \partial_\mu U - i r_\mu U + i U \ell_\mu$$
$$\zeta \equiv 2B_0(s + ip)$$

How to build the low energy theory using Weinberg's theorem

- Identify the (approximate) symmetries of the fundamental theory

- Using the fields present in the low energy theory (pions, etc), write all possible terms that
    - Respect Lorentz invariance
    - Respect the chiral symmetry of the original theory (Massless QCD, before explicit symmetry breaking)

- Chiral symmetry is only approximate (quarks have nonzero mass). Break the symmetry in the same way it is broken in the original theory.

- Couple dark matter to the low energy theory – now straightforward in this framework

"Freezing the Spurions" – Explicit Chiral Symmetry Breaking

By picking specific directions in the external field space ($s,\ p,\ v_\mu,\ a_\mu$), we explicitly break the chiral symmetry. For instance, we can include the quark mass matrix into the scalar external field:

$$s = \mathcal{M} \qquad\qquad \mathcal{M} \equiv \mathrm{diag}(m_u,\ m_d,\ m_s)$$

This breaks the chiral symmetry of QCD, $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} + \bar{q}\gamma^\mu(v_\mu + \gamma^5 a_\mu)q + \bar{q}(s + i\gamma^5 p)q$$

$$\begin{aligned}\mathcal{L}_{QCD} &= \mathcal{L}^0_{QCD} + \bar{q}\mathcal{M}q \\ &= \mathcal{L}^0_{QCD} + (\bar{q}_R\mathcal{M}q_L + \bar{q}_L\mathcal{M}q_R)\end{aligned}$$

"Freezing the Spurions" – Explicit Chiral Symmetry Breaking

By picking specific directions in the external field space ($s,\ p,\ v_\mu,\ a_\mu$), we explicitly break the chiral symmetry. For instance, we can include the quark mass matrix into the scalar external field:

$$s = \mathcal{M} \qquad\qquad \mathcal{M} \equiv \mathrm{diag}(m_u,\ m_d,\ m_s)$$

This breaks the chiral symmetry of QCD, $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} + \overline{q}\gamma^\mu(v_\mu + \gamma^5 a_\mu)q + \overline{q}(s + i\gamma^5 p)q$$

$$\begin{aligned} \mathcal{L}_{QCD} &= \mathcal{L}^0_{QCD} + \overline{q}\mathcal{M}q \\ &= \mathcal{L}^0_{QCD} + (\overline{q}_R\mathcal{M}q_L + \overline{q}_L\mathcal{M}q_R) \end{aligned}$$

Importantly, it breaks the chiral symmetry of our effective theory in ***exactly the same way.***

$$\begin{aligned} \mathcal{L}^{(s,p,v,a)}_{eff} &= \frac{f^2}{4}\mathrm{Tr}[D_\mu U^\dagger D^\mu + U^\dagger \zeta + \zeta^\dagger U] \qquad \zeta \equiv 2B_0(s + ip) \\ &= \frac{f^2}{4}\mathrm{Tr}[D_\mu U^\dagger D^\mu + 2B_0\underbrace{(U^\dagger\mathcal{M} + \mathcal{M}U)}_{\text{Not invariant under } G}] \end{aligned}$$

How to build the low energy theory using Weinberg's theorem

- Identify the (approximate) symmetries of the fundamental theory

- Using the fields present in the low energy theory (pions, etc), write all possible terms that
  - Respect Lorentz invariance
  - Respect the chiral symmetry of the original theory (Massless QCD, before explicit symmetry breaking)

- Chiral symmetry is only approximate (quarks have nonzero mass). Break the symmetry in the same way it is broken in the original theory.

- Couple dark matter to the low energy theory – now straightforward in this framework

Just treat dark matter bilinear as an external field

We can now include dark matter fields (and other things... photons, W's, etc) into the external fields in order to find couplings between the DM and the mesons!

Let's set, for instance, $p = \overline{\chi}\gamma^5\chi$

- Microscopic theory:

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} + \bar{q}\gamma^\mu(v_\mu + \gamma_5 a_\mu)q - \bar{q}(s - i\gamma_5 p)q \quad \ni (\overline{\chi}\gamma^5\chi)(\overline{q}\gamma^5 q)$$

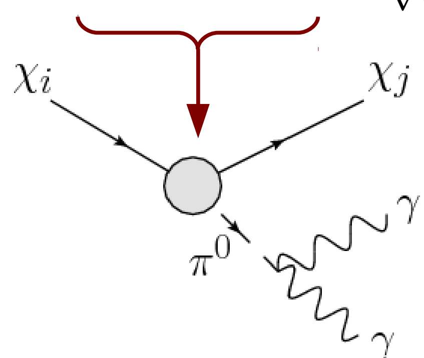
What we started with!

- Macroscopic EFT:

$$\mathcal{L}^{(s,p,v,a)}_{\text{eff}} = \frac{f^2}{4}\text{Tr}\left[D_\mu U^\dagger D^\mu U + U^\dagger\zeta + \zeta^\dagger U\right] \quad \ni iU^\dagger\overline{\chi}\gamma^5\chi$$

…which contains,

$$B_0 f\pi^0\overline{\chi}\gamma^5\chi, \quad \frac{B_0 f}{\sqrt{3}}\eta\overline{\chi}\gamma^5\chi, \quad \frac{B_0}{f\sqrt{2}}K^0K^-\pi^+\overline{\chi}\gamma^5\chi, \quad \cdots$$



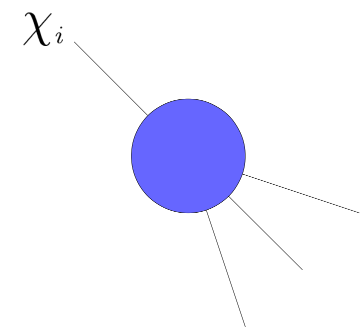
Direct couplings to low energy theory! Coefficients are measurable quantities (e.g. from π-π scattering).

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

Recall...

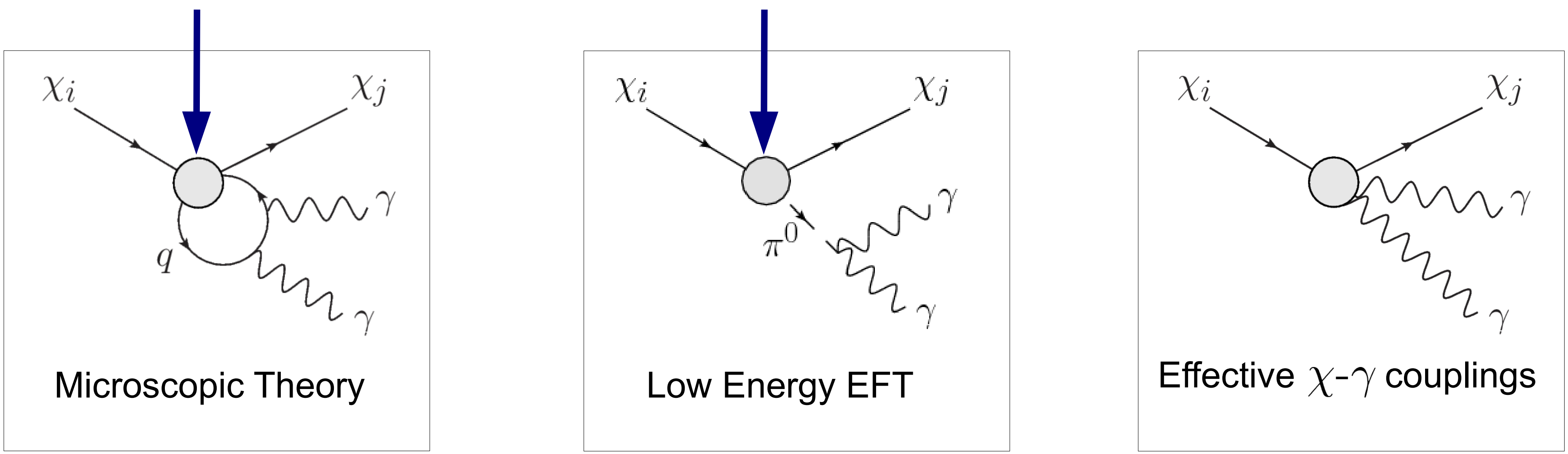
$$U \equiv e^{i\sqrt{2}\Phi/f}$$

$$\Phi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \overline{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$



We now have a direct relationship between the first and second diagrams! It is a simple matter to now calculate the third diagram (π^0 is simply an off-shell mediator)

$$\frac{c_{\pm}^{(p)}}{\Lambda^2} \qquad\qquad \frac{c_{\pm}^{(p)} B_0 f}{\Lambda^2}$$



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

Using ChPT... $\longrightarrow$ ***piece of cake!*** †

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

† not really

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 $\Delta m \ll \{m_j, m_k\}$:

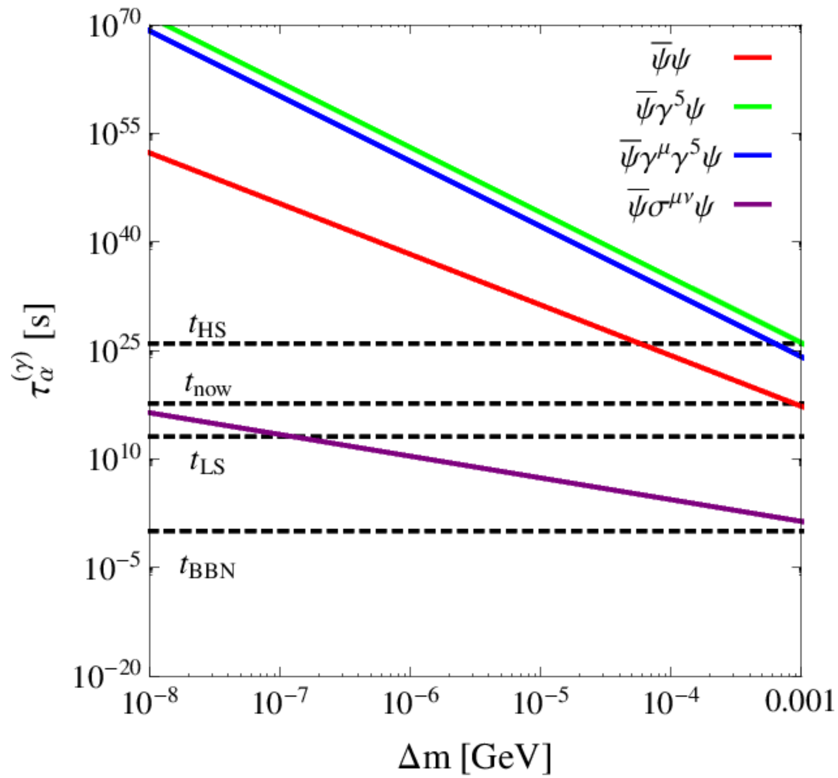
$$\Gamma_S^{(\gamma)} \approx \frac{2c_S^2\Delta m^7}{105\pi^3 f^2\Lambda^4}$$

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

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

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

$$\Gamma_T^{(\gamma)} \approx \frac{4c_T^2\Delta m^3 f^2}{\pi\Lambda^4}$$



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

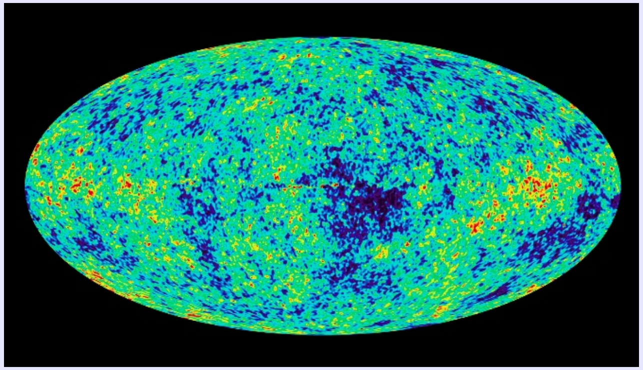
$$\Lambda = 10 \text{ TeV}$$

$$m_i = 100 \text{ GeV}$$

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

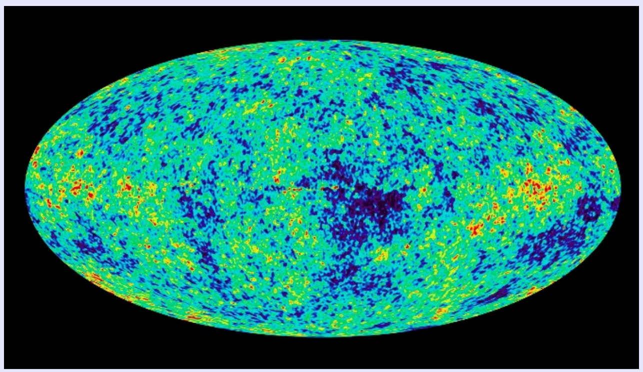
We also require, however, our dark matter particle to be hyperstable..

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]

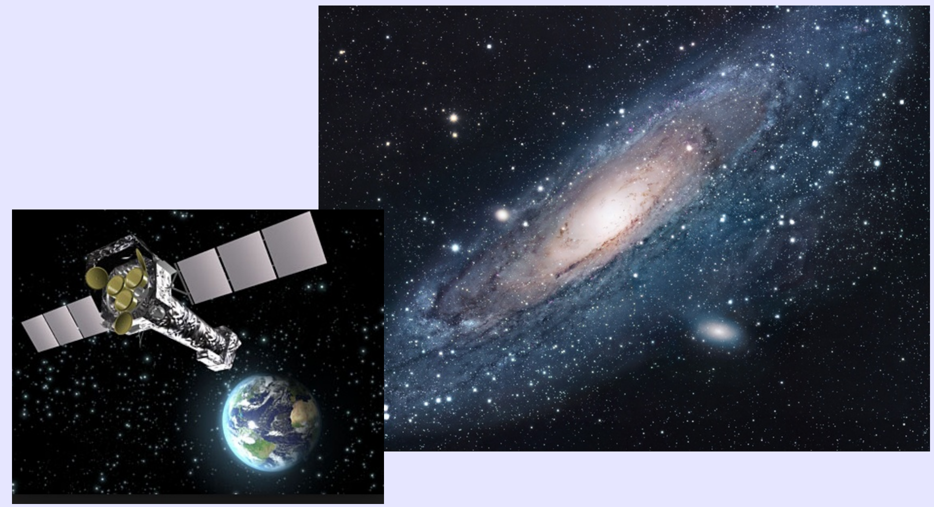


We also require, however, our dark matter particle to be hyperstable..

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]

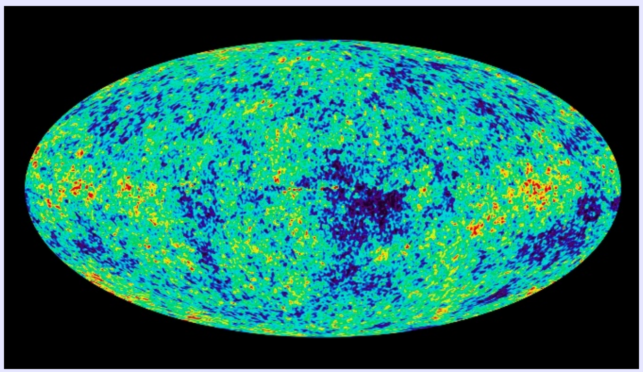


XMM-Newton observations of ***X-ray diffuse background*** of Andromeda constrain lifetime of DM. [Boyarski et. al. 2006]

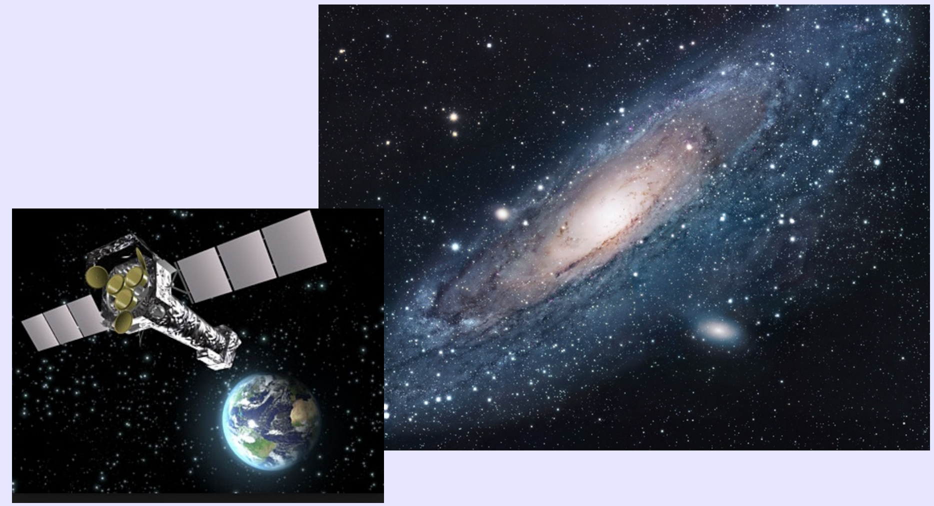


We also require, however, our dark matter particle to be hyperstable..

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]



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



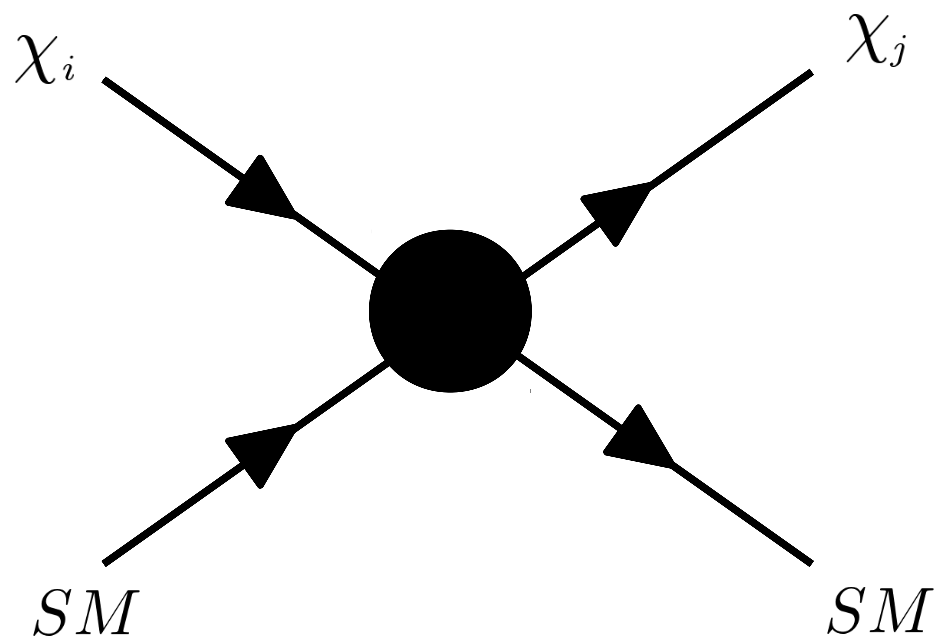
...so this provides us with a constraint on the DM parameter space.

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....

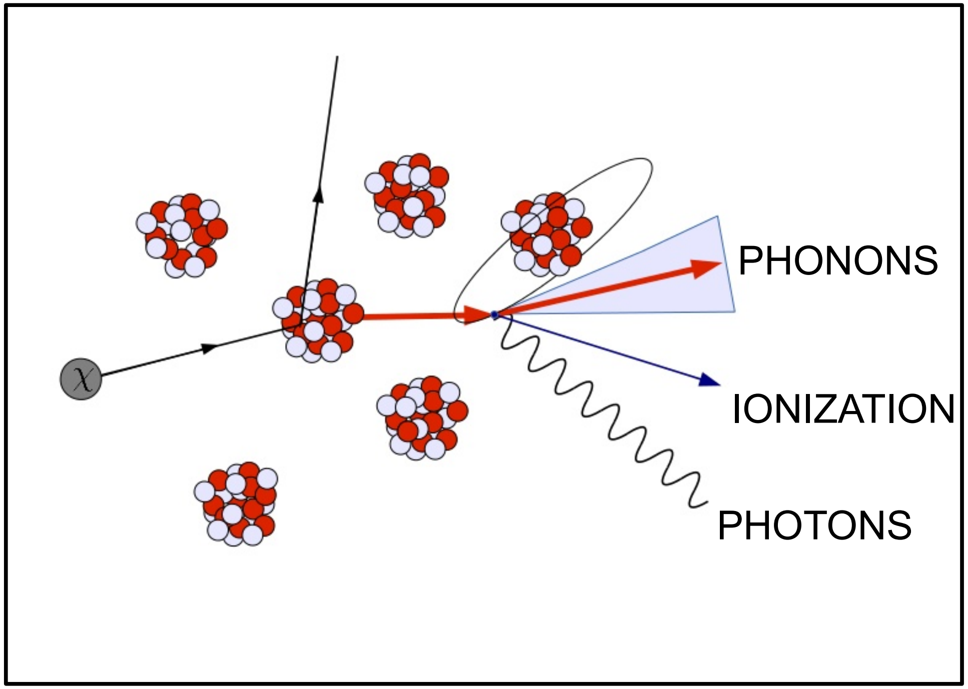
There is some probability that a dark matter particle will scatter off a nucleus within a detector.

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!

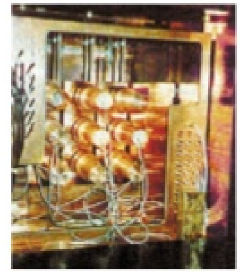
So we better make the most of this limited data!

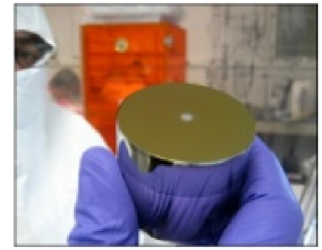
There is no "best" detector type or material!

Each has it's own "sweet spot." Some or more sensitive to specific couplings than others, etc.


CDMS


CRESST


DAMA


CoGeNT


EDELWEISS


XENON100


ZEPLIN III


LUX

Spin Independent:

- Larger the nucleus the better
  (A^2 enhancement)
- Would like $m_{DM} = m_N$ for maximum energy transfer.

Spin Dependent:

- Want an odd number of neutrons or protons.
  (even nucleons tend to anti-align spin)
- Also would like $m_{DM} = m_N$.
- Possibly more sensitive to light DM if low enough threshold. (use light nuclei, such as Fluorine)

Typical operators studied in the context of direct detection...

We are again working in the low energy limit – DM is moving non-relativistically around our galaxy. There is no need for ChPT, however... we have other ways of dealing with nuclear physics (backup slides).

$$\mathcal{O}^{(S)} = (\overline{\chi}\chi)(\overline{q}q)$$
$$\mathcal{O}^{(V)} = (\overline{\chi}\gamma^{\mu}\chi)(\overline{q}\gamma_{\mu}q)$$

in the non-relativistic expansion

Leading order: **spin independent**

$$\sigma \propto A^2$$

Heavier the nucleus the better!

$$\mathcal{O}^{(A)} = (\overline{\chi}\gamma^5\gamma^{\mu}\chi)(\overline{q}\gamma^5\gamma_{\mu}q)$$
$$\mathcal{O}^{(T)} = (\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)$$

Leading order: **spin dependent**

$$\sigma \propto \langle S_n \rangle^2$$

Average spin of the nucleons within the nucleus

$$\mathcal{O}^{(P)} = (\overline{\chi}\gamma^5\chi)(\overline{q}\gamma^5 q)$$

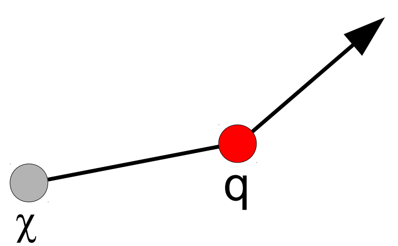
ZERO LEADING ORDER CONTRIBUTIONS

Second order: **spin dependent**
interaction suppressed by $v_{DM}/c \approx 10^{-3}$

Direct Detection Calculations in a Nutshell

A typical direct detection calculation involves three basic steps

- Calculation of the fundamental interaction between DM and quarks/gluons.

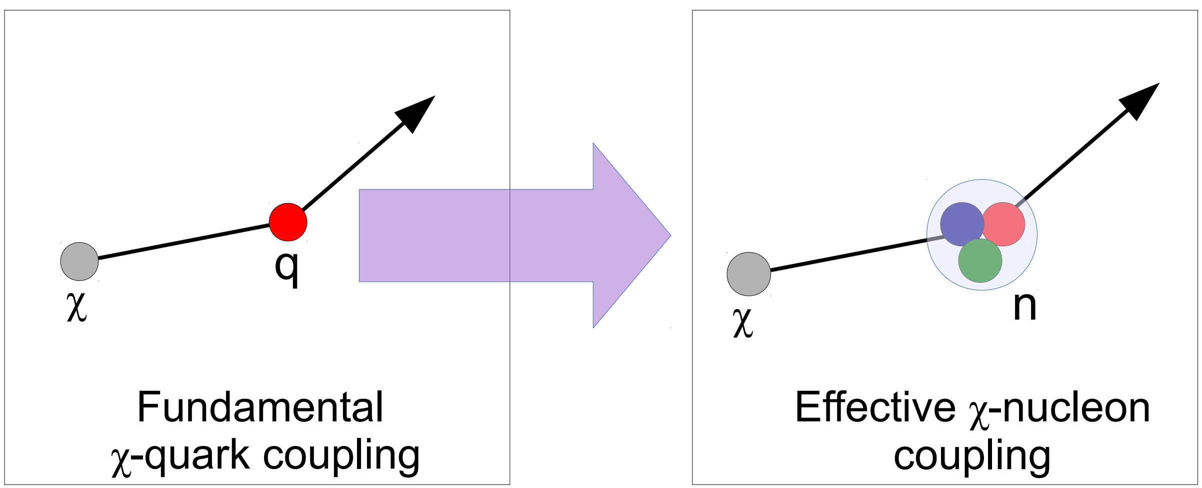


Fundamental
χ-quark coupling

Direct Detection Calculations in a Nutshell

A typical direct detection calculation involves three basic steps

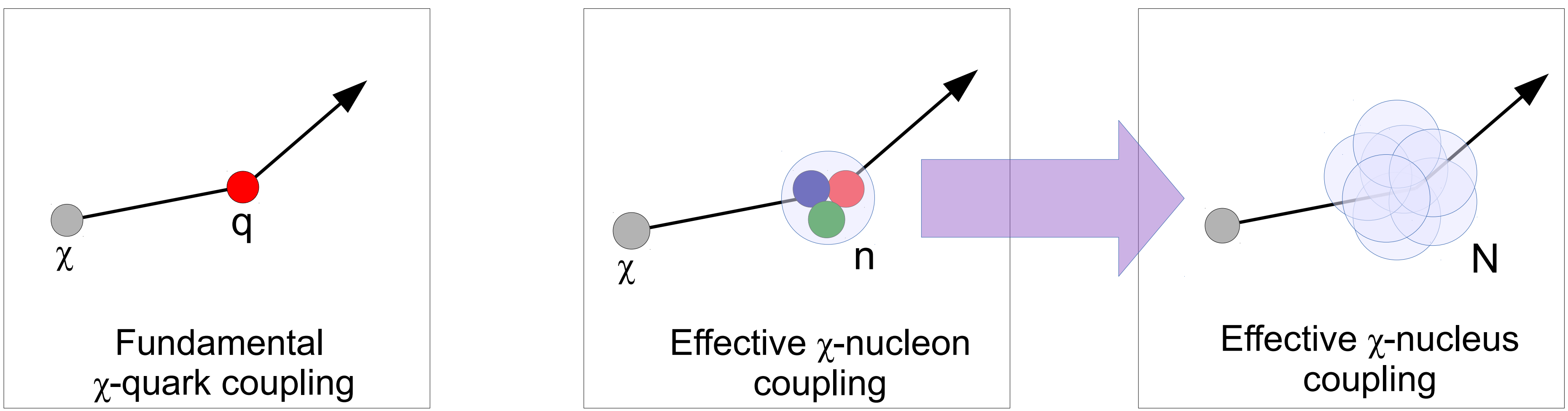
- Calculation of the fundamental interaction between DM and quarks/gluons.
- Translating the above interaction into an interaction between the DM and a nucleon.

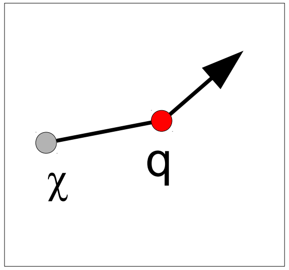


Direct Detection Calculations in a Nutshell

A typical direct detection calculation involves three basic steps

- Calculation of the fundamental interaction between DM and quarks/gluons.
- Translating the above interaction into an interaction between the DM and a nucleon.
- Summing the above interaction over all nucleons in the nucleus, taking into account any effects associated with coherence loss.





Example: Spin Dependent Scattering – quark level

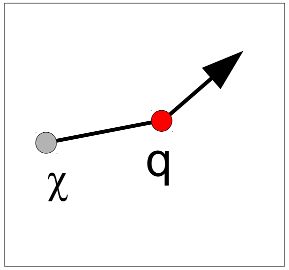
The operator typically studied in the context of spin dependent scattering is

$$\overline{\chi}\gamma^5\gamma^\mu\chi\overline{q}\gamma^5\gamma_\mu q$$

Galactic dark matter is definitely moving ***nonrelativistically***. Lets see what this operator gives in that limit....

$$u^s(p) = \begin{pmatrix} \frac{p_\mu\sigma^\mu + m}{\sqrt{2(p_0+m)}}\xi^s \\ \frac{p_\mu\bar{\sigma}^\mu + m}{\sqrt{2(p_0+m)}}\xi^s \end{pmatrix}$$

$$p_0 = E = \underline{m} + \tfrac{1}{2}mv^2 + \mathcal{O}(v^4)$$
$$p_i = \vec{p} = m\vec{v} + \mathcal{O}(v^3).$$



Example: Spin Dependent Scattering – quark level

The operator typically studied in the context of spin dependent scattering is

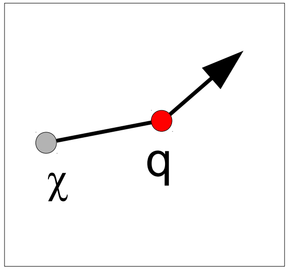
$$\overline{\chi}\gamma^5\gamma^\mu\chi\overline{q}\gamma^5\gamma_\mu q$$

Galactic dark matter is definitely moving ***nonrelativistically***. Lets see what this operator gives in that limit....

$$u^s(p) = \begin{pmatrix} \frac{p_\mu\sigma^\mu + m}{\sqrt{2(p_0+m)}}\xi^s \\ \frac{p_\mu\bar{\sigma}^\mu + m}{\sqrt{2(p_0+m)}}\xi^s \end{pmatrix}$$

$$p_0 = E = \underline{m} + \tfrac{1}{2}mv^2 + \mathcal{O}(v^4)$$
$$p_i = \vec{p} = m\vec{v} + \mathcal{O}(v^3).$$

$$v \sim 10^{-3}$$



Example: Spin Dependent Scattering – quark level

The operator typically studied in the context of spin dependent scattering is

$$\overline{\chi}\gamma^5\gamma^\mu\chi\overline{q}\gamma^5\gamma_\mu q$$

Galactic dark matter is definitely moving ***nonrelativistically***. Lets see what this operator gives in that limit....

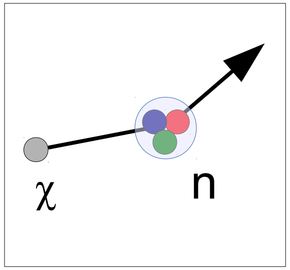
$$u^s(p) = \begin{pmatrix} \frac{p_\mu\sigma^\mu+m}{\sqrt{2(p_0+m)}}\xi^s \\ \frac{p_\mu\bar{\sigma}^\mu+m}{\sqrt{2(p_0+m)}}\xi^s \end{pmatrix}$$

$$p_0 = E = \underline{m} + \tfrac{1}{2}mv^2 + \mathcal{O}(v^4)$$
$$p_i = \vec{p} = m\vec{v} + \mathcal{O}(v^3).$$

$$v \sim 10^{-3}$$

A half a page of matrix algebra gives....

$$\overline{u}^{s'}(p')\gamma^5\gamma^\mu u^s(p) = -2m\underbrace{\xi^{\dagger s'}\sigma^i\xi^s}_{\text{Spin operator}}$$

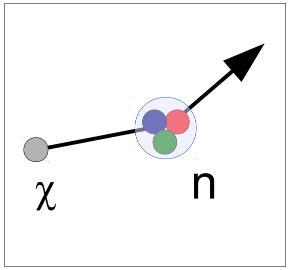


Example: Spin Dependent Scattering – nucleon level

The momentum transfers involved are such that the WIMP never "sees" the quarks. Instead, the "in" and "out" states are the nucleons.

$$\langle \chi_f, n_f | \overline{\chi}\gamma^5\gamma^\mu\chi\overline{q}\gamma^5\gamma_\mu q | \chi_i, n_i\rangle = \langle \chi_f | \overline{\chi}\gamma^\mu\gamma^5\chi | \chi_i\rangle \langle n_f | \overline{q}\gamma^\mu\gamma^5 q | n_i\rangle$$

✓ ?



Example: Spin Dependent Scattering – nucleon level

The momentum transfers involved are such that the WIMP never "sees" the quarks. Instead, the "in" and "out" states are the nucleons.

$$\langle \chi_f, n_f | \overline{\chi}\gamma^5\gamma^\mu\chi\overline{q}\gamma^5\gamma_\mu q | \chi_i, n_i \rangle = \langle \chi_f | \overline{\chi}\gamma^\mu\gamma^5\chi | \chi_i \rangle \langle n_f | \overline{q}\gamma^\mu\gamma^5 q | n_i \rangle$$

We simply parameterize our ignorance of the nuclear physics as the "spin fractions" Δq^n

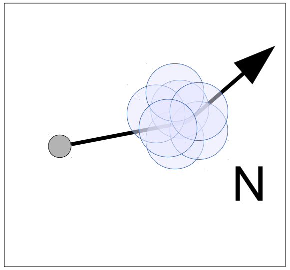
$$\begin{aligned} \langle n | \overline{q}\gamma^5\gamma^\mu q | n \rangle &= \Delta q^n \langle n | \overline{n}\gamma^5\gamma^\mu n | n \rangle \\ &= \Delta q^n (4 m_n \vec{s}_n) \end{aligned}$$

Determined experimentally... i.e., from lepton-proton scattering.

$$\mathcal{L}_{\chi q} = c_q \overline{\chi}\gamma^5\gamma^\mu\chi\overline{q}\gamma^5\gamma_\mu q \quad\Longrightarrow\quad \mathcal{L}_{\chi n} = \Big(\sum_{\mathrm{q=u,d,s}} c_q \Delta q^n \Big) \overline{\chi}\gamma^5\gamma^\mu\chi\overline{n}\gamma^5\gamma_\mu n$$

Interesting note: $\Delta u^{(n)} + \Delta d^{(n)} + \Delta s^{(n)} \approx 0$ "Proton spin crisis" – not well understood.

There is thus enhancement for "isospin violating" cases... i.e., $c_u \neq c_d$



Example: Spin Dependent Scattering – nucleus level

We would think to just sum over the nucleons in the nucleus. However, there are two issues....

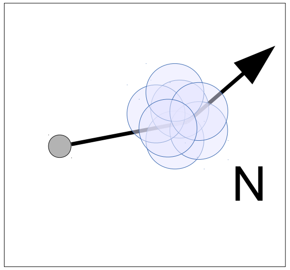
- Nucleons within the nucleus align such that, essentially, spin cancels when possible. The WIMP doesn't really "see" the nucleons... it "see's" the nucleus. So it actually interacts with the *average* spin of the nucleons...

$$\langle S_n \rangle \qquad \langle S_p \rangle$$

For example, in nuclei with an *even* number of protons, $\langle S_p \rangle \approx 0$

For nuclei with an *odd* number of neutrons, $\langle S_n \rangle \approx 0.5$

Thus, for spin-dependent interactions, we choose detector targets accordingly.



Example: Spin Dependent Scattering – nucleus level

We would think to just sum over the nucleons in the nucleus. However, there are two issues....

- Nucleons within the nucleus align such that, essentially, spin cancels when possible. The WIMP doesn't really "see" the nucleons... it "see's" the nucleus. So it actually interacts with the *average* spin of the nucleons...

$$\langle S_n \rangle \qquad \langle S_p \rangle$$

For example, in nuclei with an *even* number of protons, $\langle S_p \rangle \approx 0$

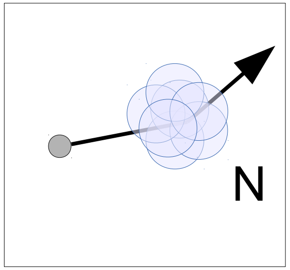
For nuclei with an *odd* number of neutrons, $\langle S_n \rangle \approx 0.5$

Thus, for spin-dependent interactions, we choose detector targets accordingly.

- The above is ***almost*** correct, but not completely. At the momentum transfers relevant for direct detection, the WIMPs can *almost* distinguish the individual nucleons. Thus, we need to include a form factor, $F(q^2)$, to account for this.

Simple choice, for example – a thin shell.

*(but there is **extensive** work done in this area... much more accurate form factors exist!)*



Example: Spin Dependent Scattering – nucleus level

Putting all the pieces together, we find that the differential cross section is given by

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}\frac{J+1}{J}\Big(a_p\langle S_p\rangle + a_n\langle S_n\rangle\Big)^2 F^2(E_R)$$

where,

$$a_n = \sum_{\mathrm{q=u,d,s}} c_q \Delta q^{(n)}$$

This is nothing new... but there *are* some subtleties when dealing with the other operators. (Backup slides)

...but what's different in the multicomponent dark matter scenerio?

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

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

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

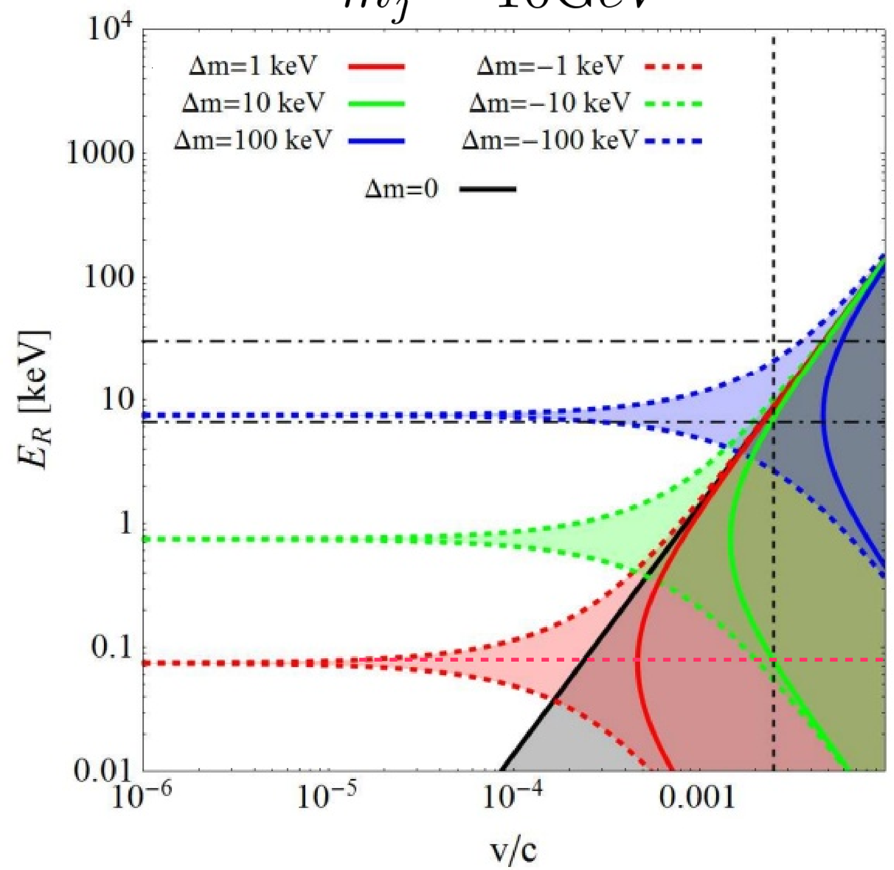
$\Delta m = 0$ ➡ **"Elastic Scattering"**
Typical case studied – single component dark matter.

$\Delta m > 0$ ➡ **"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]

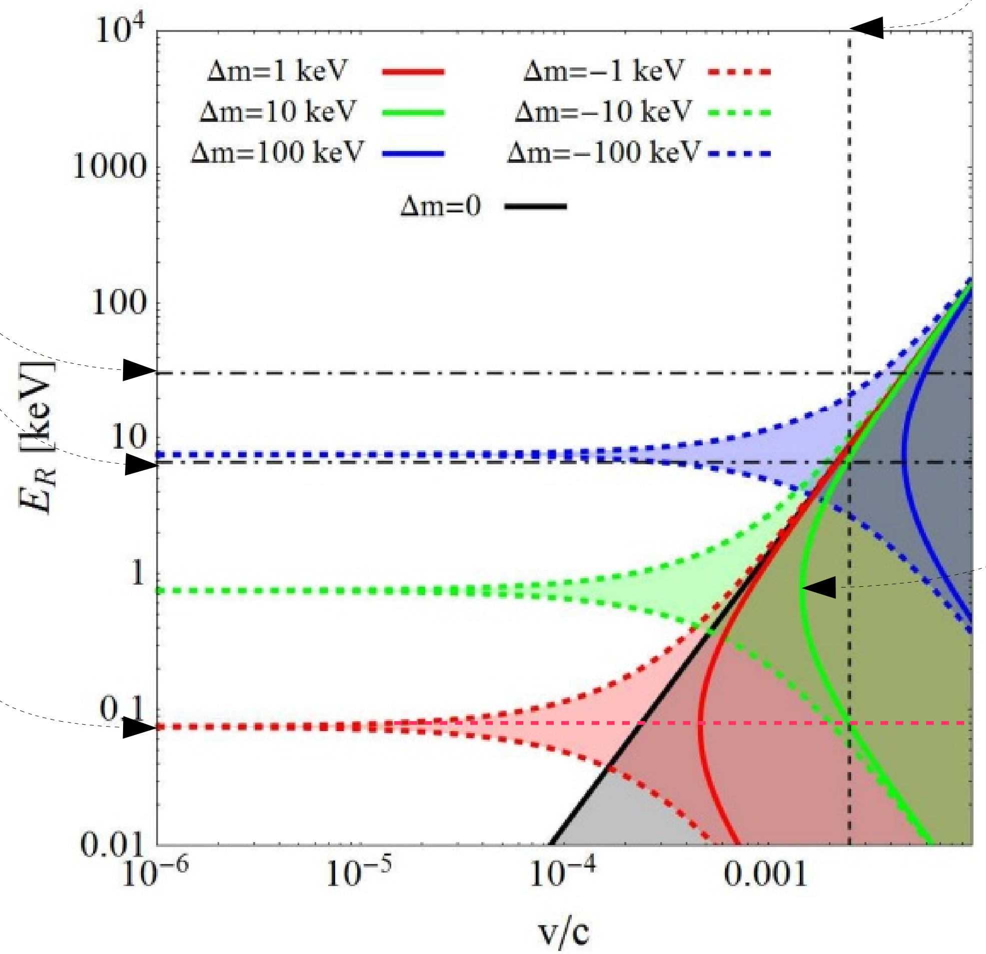
Range of E_R at XENON100

$m_j = 10\text{GeV}$



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

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

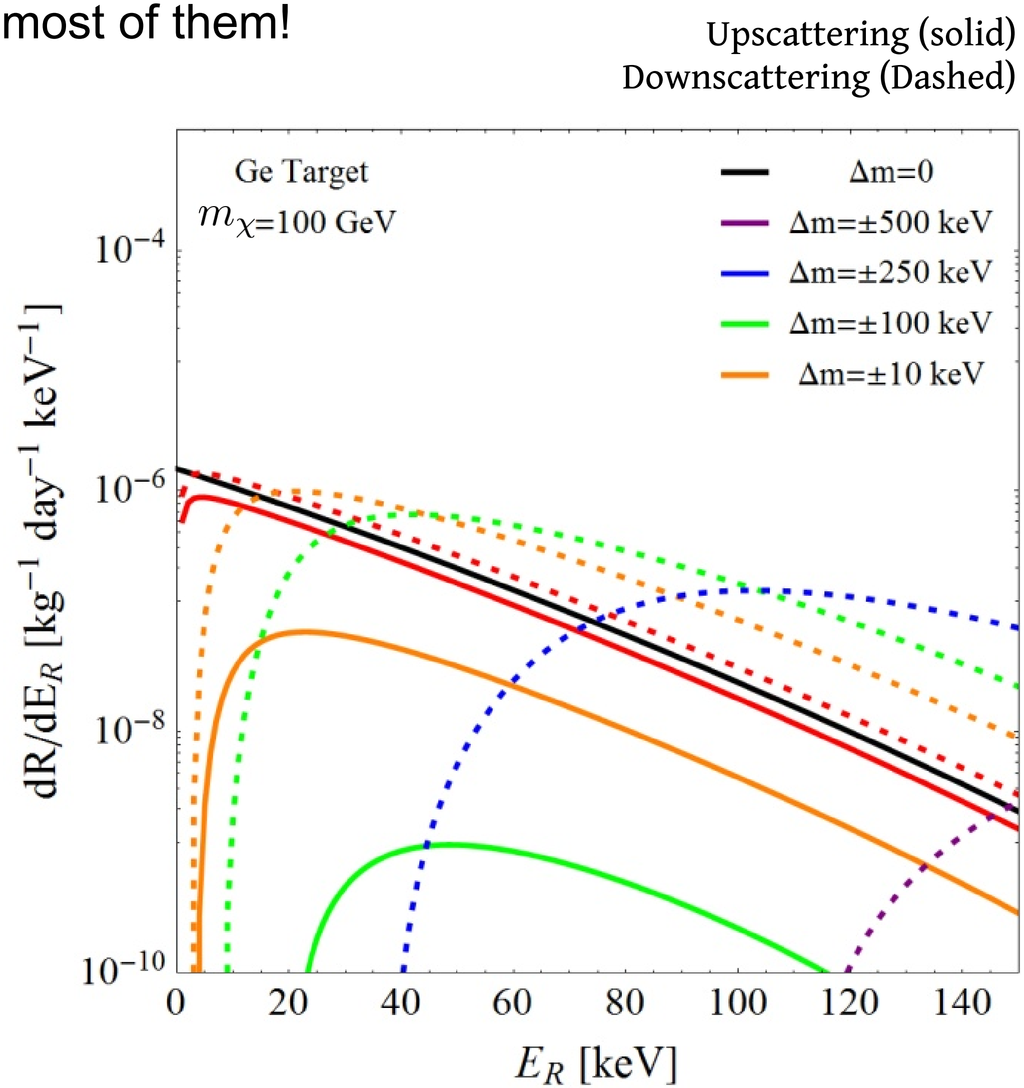
Recoil Energy Spectra

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

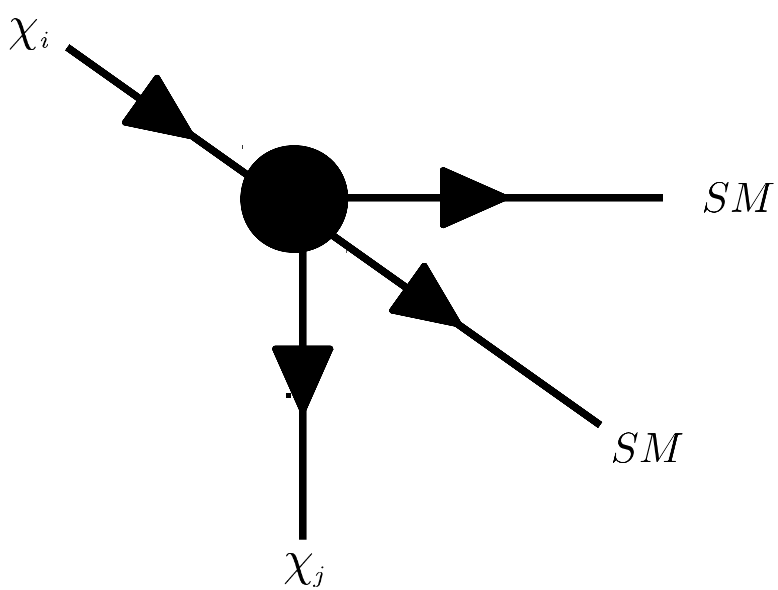
- ***Down/upscattering lead to unique and distinguishable recoil energy spectra***
  (which is our only observable at current direct detection experiments)

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

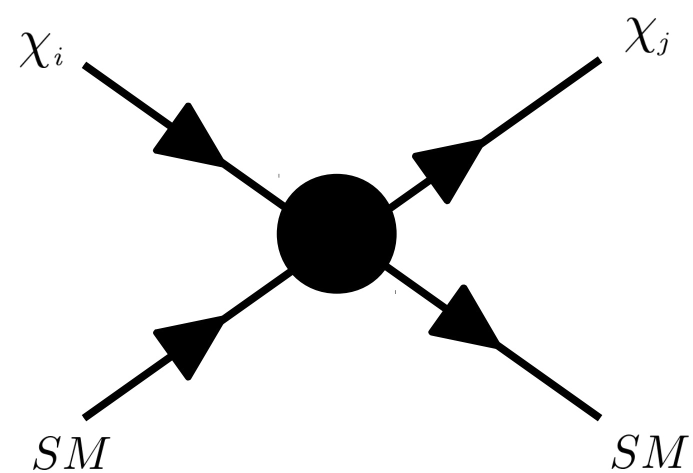
- ***Upscattering becomes undetectable for high*** Δm
  (though bounds from decays become better)



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

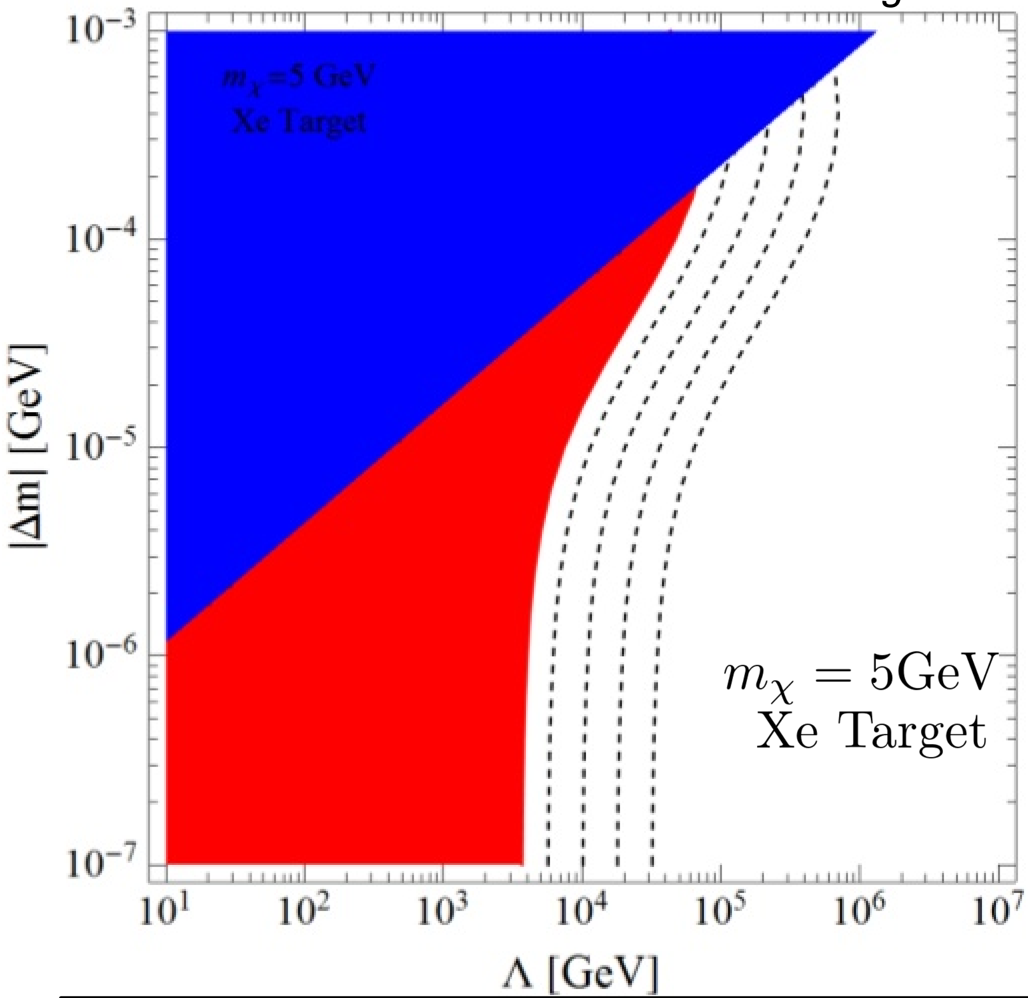
- **Most recent limits** from [arXiv:1207.5988].
- Total event rate for nuclear recoils with
  $6.6 \text{ keV} \leq E_R \leq 30.6 \text{ keV}$
- Most recent limits restrict DM to interact at a rate
  $R \lesssim 5.66 \times 10^{-4} \text{ kg}^{-1} \text{ day}^{-1}$.

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:

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

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:

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

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

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

- What we are interested is the analog for the pseudoscalar bilinear:

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

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

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

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

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:

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

- What we are interested is the analog for the pseudoscalar bilinear:

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

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

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

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

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

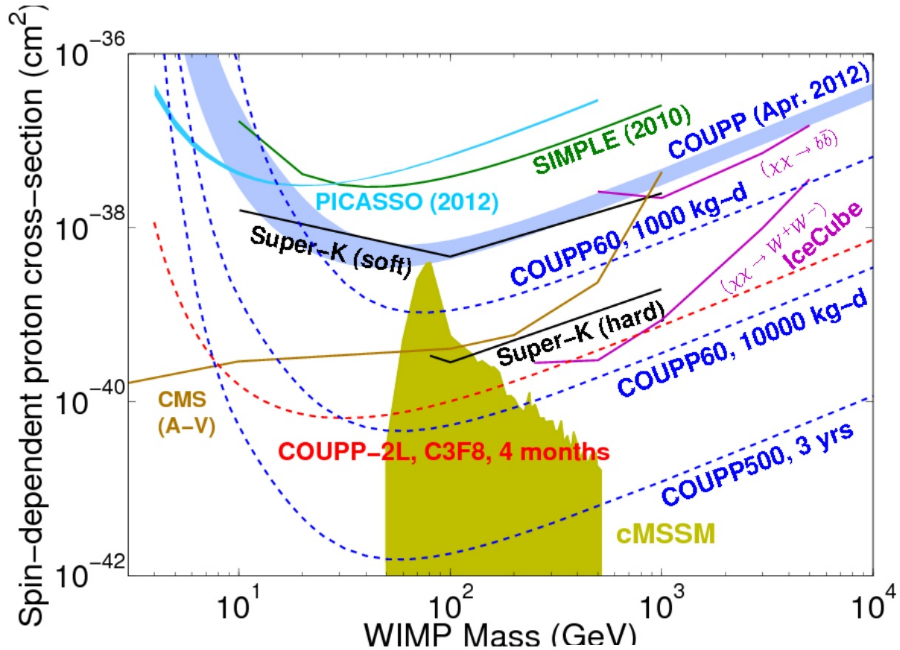
$\mathcal{O}(10^{4})$ enhancement relative to axial-axial coupling

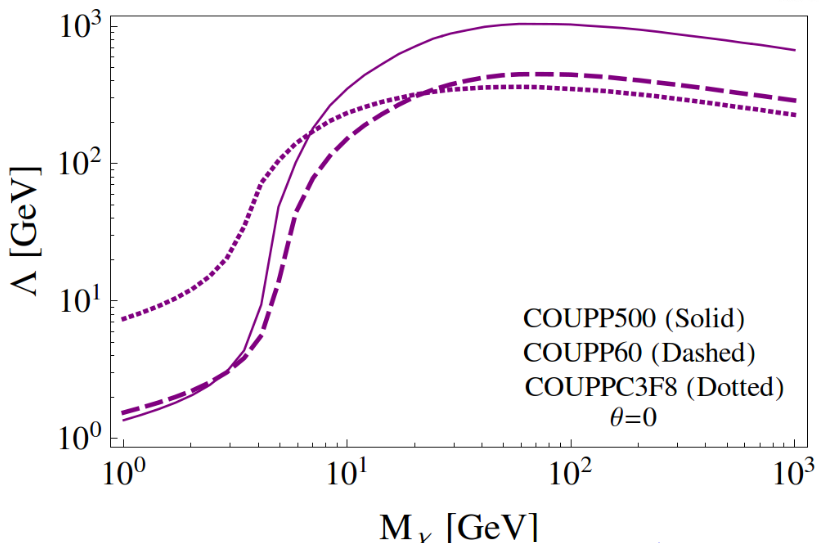
There is also a factor of 6 enhancement to σ_{SP} arising from a difference in the spin structure of the bilinears.

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

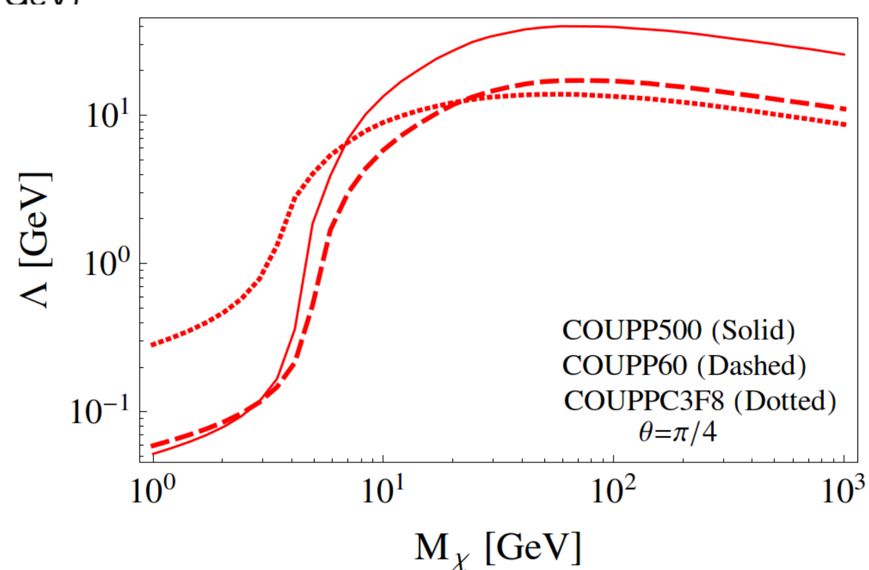
$\mathcal{O}^{(SP)}$ *NOT NEGLIGIBLE*

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





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

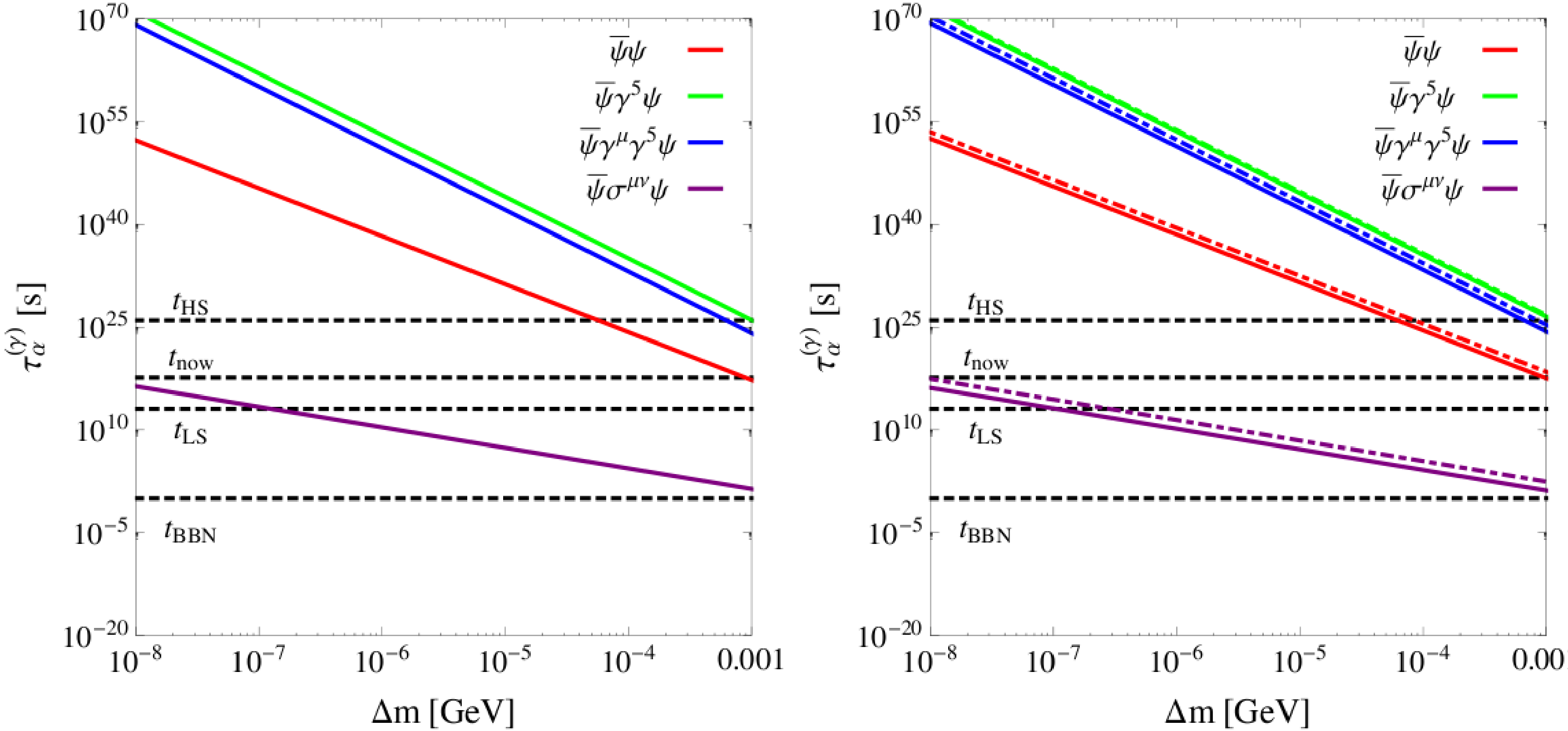


Isospin conserving $g_{\chi u} = g_{\chi d}$

(End of digression)

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

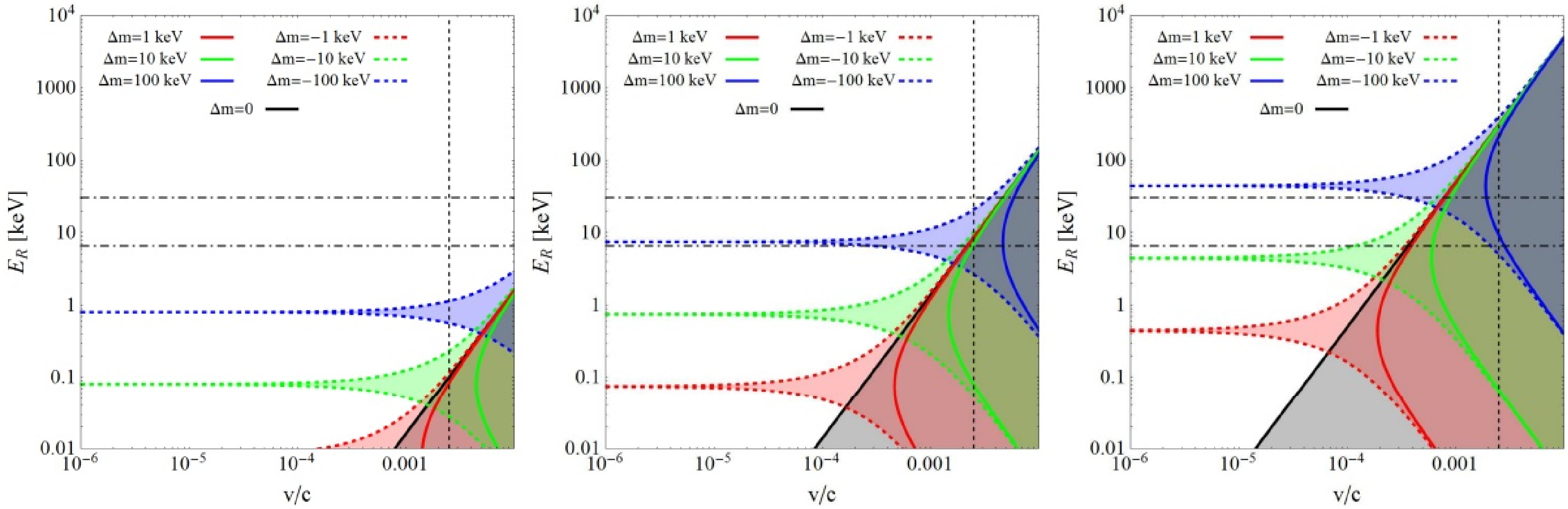
$$c_+^{(\alpha)} = 1, c_-^{(\alpha)} = 0 \quad \text{(solid)}$$
$$c_+^{(\alpha)} = 0, c_-^{(\alpha)} = 1 \quad \text{(dashed)}$$



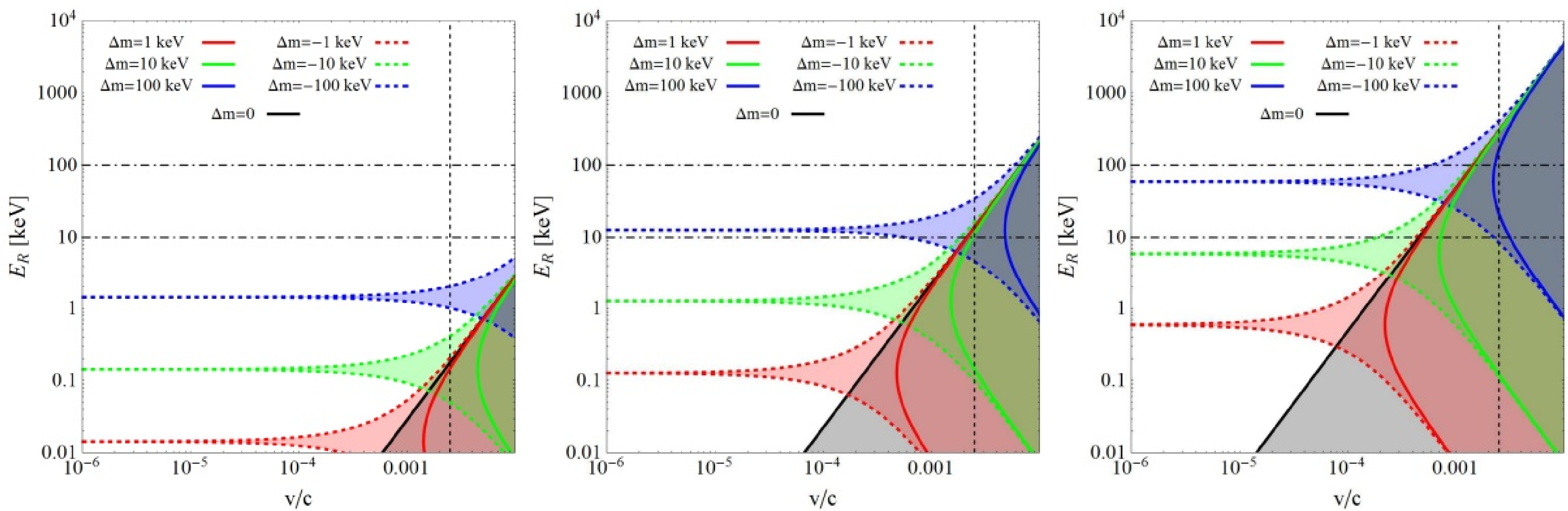
Lifetime of dark fermion which decays via $\chi_j \to \chi_i \gamma$ and $\chi_j \to \chi_i \gamma\gamma$

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

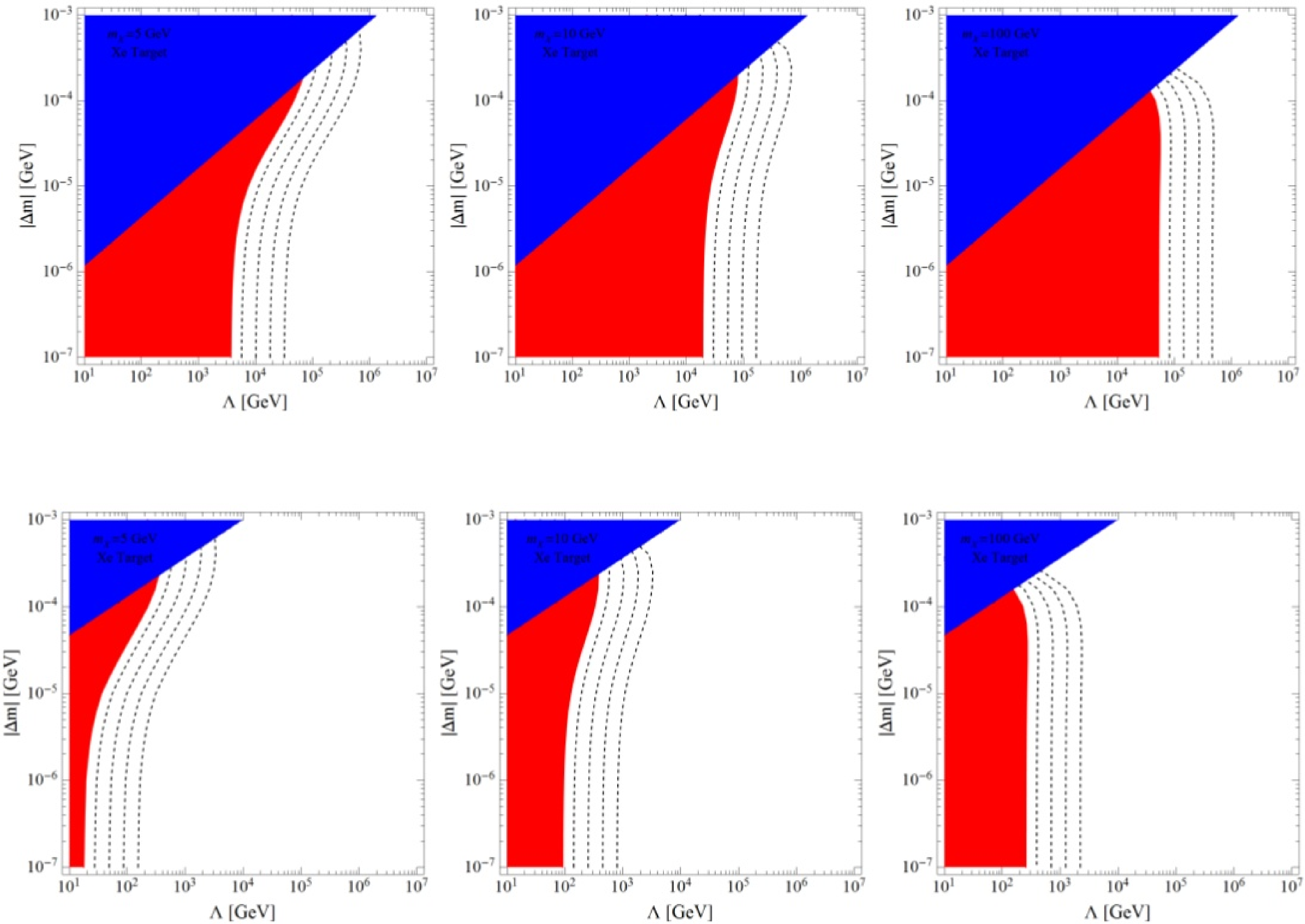
Xenon target --- XENON100



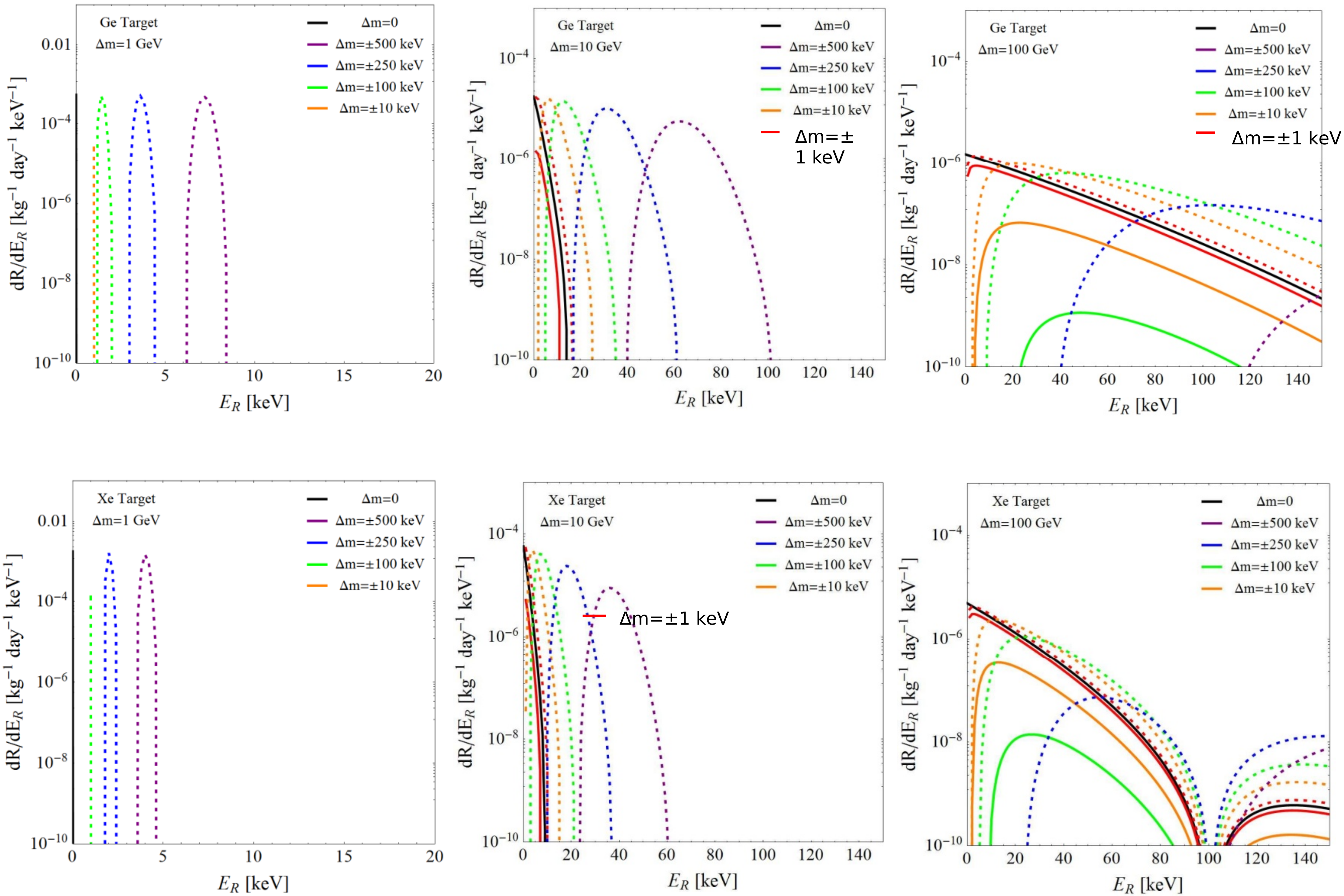
Germanium target --- CDMS II



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



m_χ=5 GeV
Xe Target
m_χ=10 GeV
Xe Target
m_χ=100 GeV
Xe Target
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


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]