New Directions in Dark-Matter Complementarity

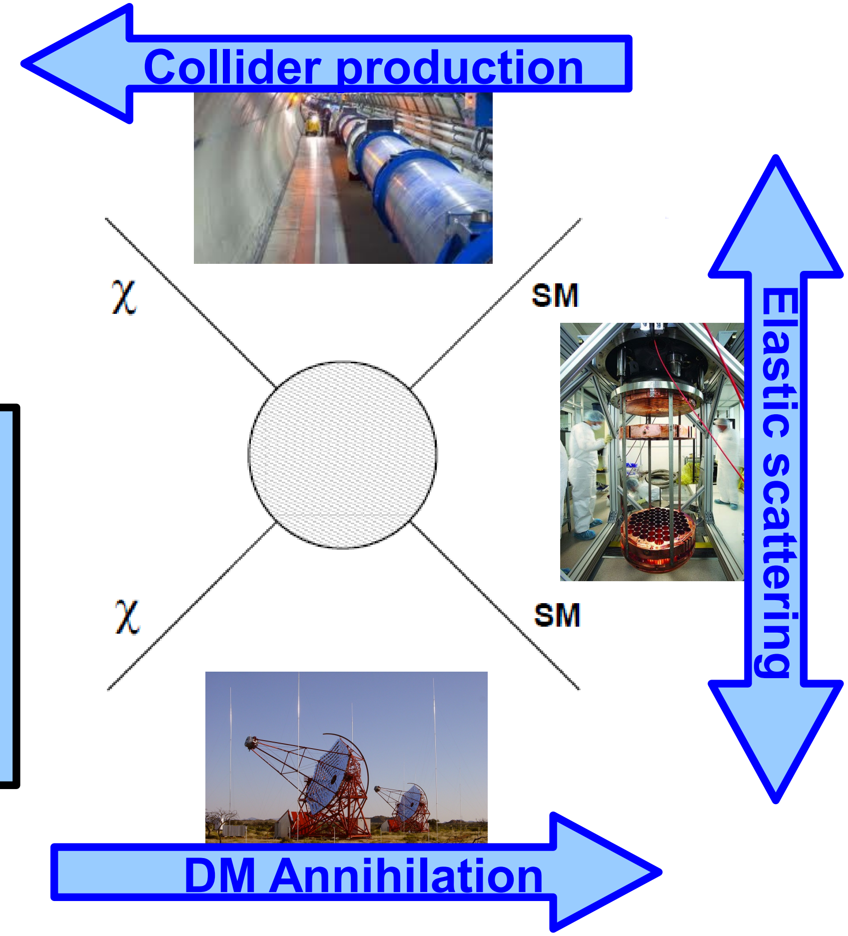
Brooks Thomas
Carleton University

Based on work done in collaboration with Keith Dienes, Jason Kumar, and David Yaylali [arXiv:1405.xxxx]

Complementarity: The Standard Picture

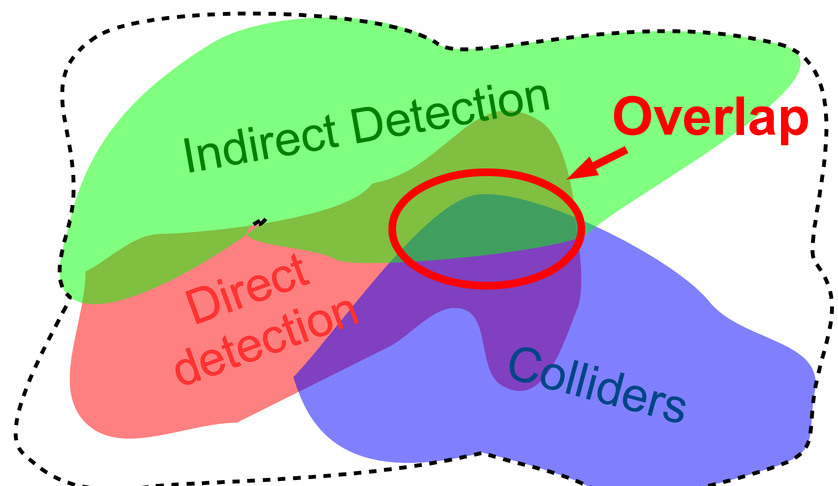
The Underlying Principle:

A single operator which couples DM particles to SM particles generically contributes to a variety of different physical processes.



Two facets of complementarity:

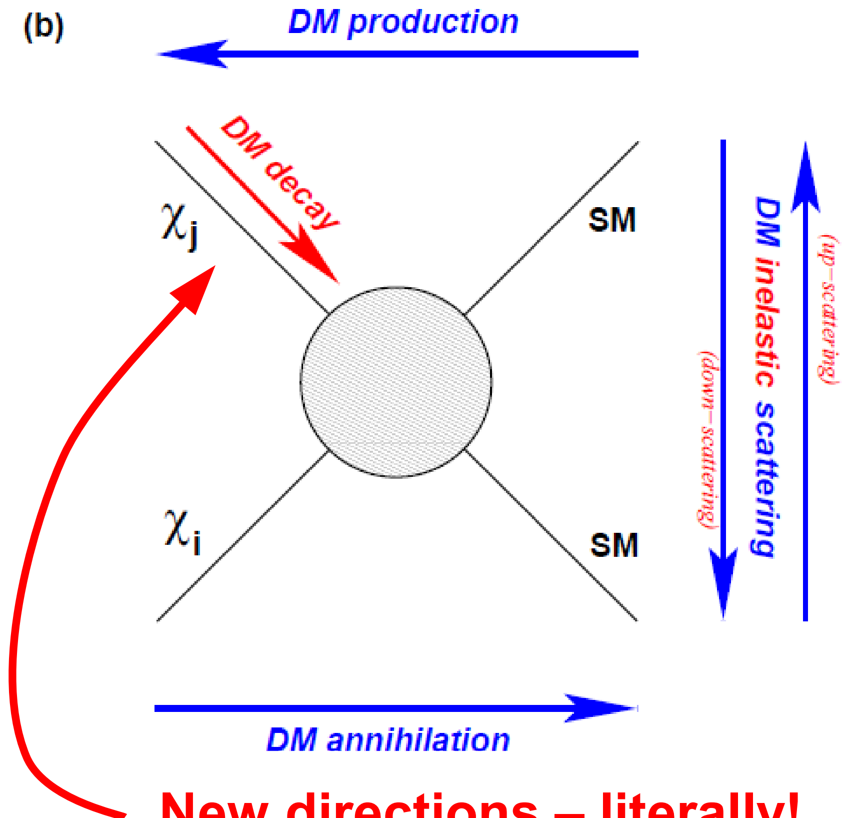
- **Coverage**: Different detection channels are sensitive in different regions of the parameter space of dark-matter models.
- **Correlations**: Observing signals in multiple channels with regions of that parameter space in which sensitivities overlap.



DM Parameter Space

Complementarity: A More General Picture

In **multi-component** theories of dark matter, additional physical processes are possible. These include...



New directions – literally!

① Dark-matter decay

- Heavier χ_i can decay into lighter ones even in the case in which the lightest χ_i is stable due to a symmetry.

② Inelastic scattering of dark matter off with atomic nuclei

- **Upscattering** of a ligher χ_i into a heavier χ_j (prototypical inelastic DM)
  [Hall, Moroi, Murayama, '97; 'Weiner, Tucker-Smith, '01]
- **Downscattering** of a heavier, metastable χ_i into a lighter χ_j ("exothermic" DM).
  [Finkbein er, Slatyer, Weiner, Yavin, '09; Batell, Pospelov, Ritz, '09; Graham,Harnik, Rajendran, Saraswat, '11]

③ Asymmetric pair-production of χ_i and χ_j at colliders

④ Coannihilation of χ_i and χ_j (both in the early universe *and* today)

The Fundamental Interactions

- At the energy scales $|\vec{q}| \lesssim O(100\text{ MeV})$ relevant for direct detection, interactions between the dark and visible sectors in a wide variety of theories can be modeled as **effective contact interactions**.

[See, e.g., Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu '10]

- As an example, consider a dark sector comprising two Dirac fermions χ_1 and χ_2, with $m_2 > m_1$, whose dominant couplings to the visible sector are to SM quarks:

$$\boxed{\mathcal{O}_{ij}^{(XY)} = \sum_{q=u,d,s,\ldots} \frac{c_{qij}^{(XY)}}{\Lambda^2}(\overline{\chi}_i \Gamma^X \chi_j)(\overline{q}\Gamma^Y q)}$$

for $i, j = 1, 2$, with $\Gamma = \{1, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$

Moreover, for purposes of illustration let's focus on the case in which:

- A single operator with $i \neq j$ dominates and $c_{qij}^{(XY)} \approx 0$ for all operators with $i = j$.
- The majority of the dark matter is in the metastable state χ_2 – i.e, $\Omega_{CDM} \approx \Omega_2$.
- The $c_{qij}^{(XY)}$ are O(1) and flavor-universal up to an overall ratio between up- and down-type quarks.

And define: $\boxed{\Delta m_{12} \equiv m_2 - m_1}$ $\boxed{c_{u12}^{(XY)} = \cos\theta \,, \quad c_{d12}^{(XY)} = \sin\theta}$

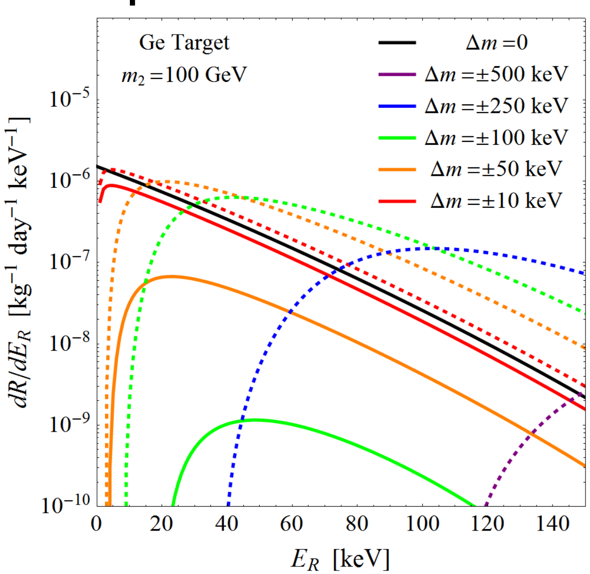
Inelastic Scattering and Direct Detection

- In multi-component scenarios, a variety of processes can contribute to the overall scattering rate at direct-detection experiments:

- **Inelastic scattering** can have a significant impact on direct detection signals when Δm_{12} is similar the range of recoil energies to which these experiments are sensitive:

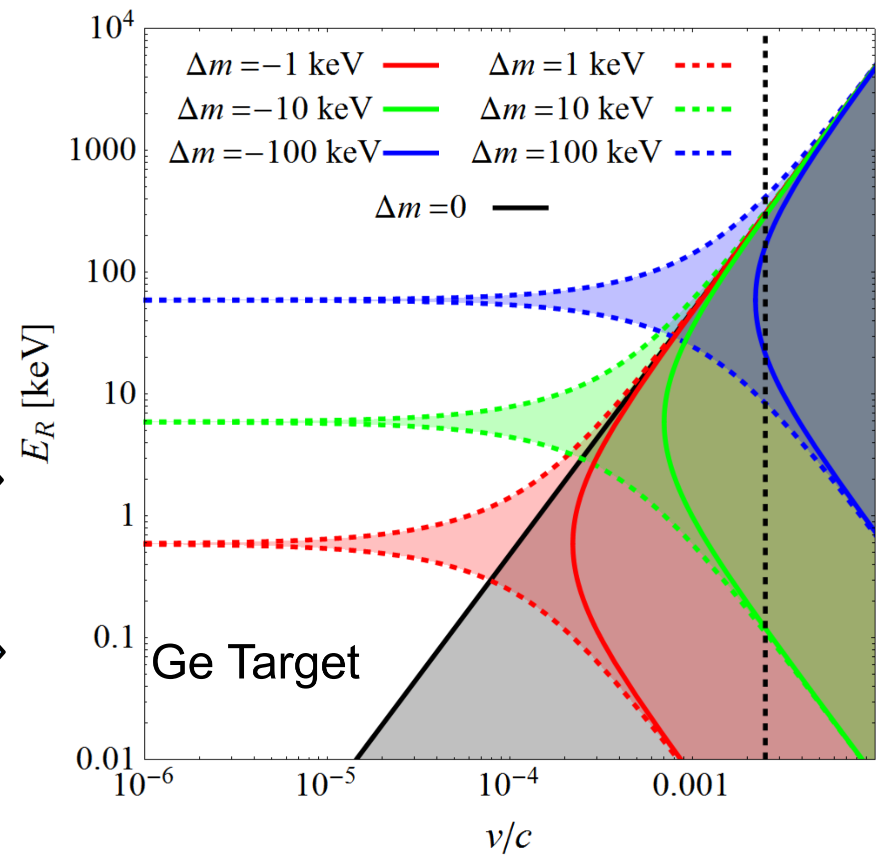
$$1\ \mathrm{keV} \lesssim E_R \lesssim 100\ \mathrm{keV}$$

Elastic scattering, upscattering, and downscattering have their own **distinctive kinematics** and contribute to the total recoil-energy spectrum in different ways.



Solid lines: upscattering

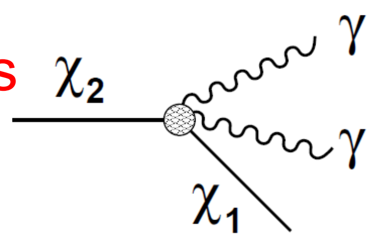
Dashed lines: downscattering



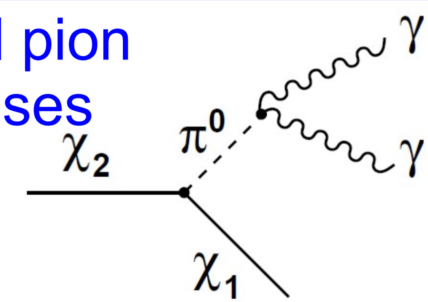
Decays and Indirect Detection

- In the Δm_{12} regime relevant for inelastic DM scattering off nuclei, only photons and neutrinos are accessible in $\chi_2 \rightarrow \chi_1$ + SM decays.
- Even when χ_1 and χ_2 couple primarily to quarks, contributions to the decay width of χ_2 generically arise from diagrams involving virtual quarks/hadrons:

Contact operators



Off-shell pion processes



These contributions can be evaluated, e.g., in Chiral Perturbation theory.

- For example, for scalar (SS) and axial-vector (AA) interactions, we find:

$$\mathcal{L}_{\rm int}^{(\rm S)} = \frac{B_0 \alpha_{\rm EM} \tilde{\lambda}_2 c^{(\rm S)}}{4\pi\Lambda_C^2\Lambda^2} \underline{(\overline{\chi}_2 \chi_1) F_{\mu\nu} F^{\mu\nu}} + \ldots , \quad \Rightarrow \quad \Gamma_{\gamma\gamma}^{(\rm S)} \approx \frac{B_0^2 \alpha_{\rm EM}^2 \tilde{\lambda}_2^2 [c^{(\rm S)}]^2}{8(105\pi^5)\Lambda_C^4\Lambda^4} (\Delta m_{12})^7$$

Decay-Width Contributions

$$\mathcal{L}_{\rm int}^{(\rm A)} = -\frac{2 f_\pi c^{(\rm A)}}{\Lambda^2} \left[1 + \frac{m_\pi^2}{32\pi^2 f_\pi^2} \tilde{\lambda}_3\right] \underline{(\overline{\chi}_2 \gamma^\mu \gamma^5 \chi_1)(\partial_\mu \pi^0)} + \frac{\alpha_{\rm EM} \tilde{\lambda}_4 c^{(\rm A)}}{4\pi\Lambda_C^2\Lambda^2} \underline{(\overline{\chi}_2 \gamma^\mu \gamma^5 \chi_1)(\partial_\mu F^{\nu\rho}) \tilde{F}_{\nu\rho}} + \ldots$$

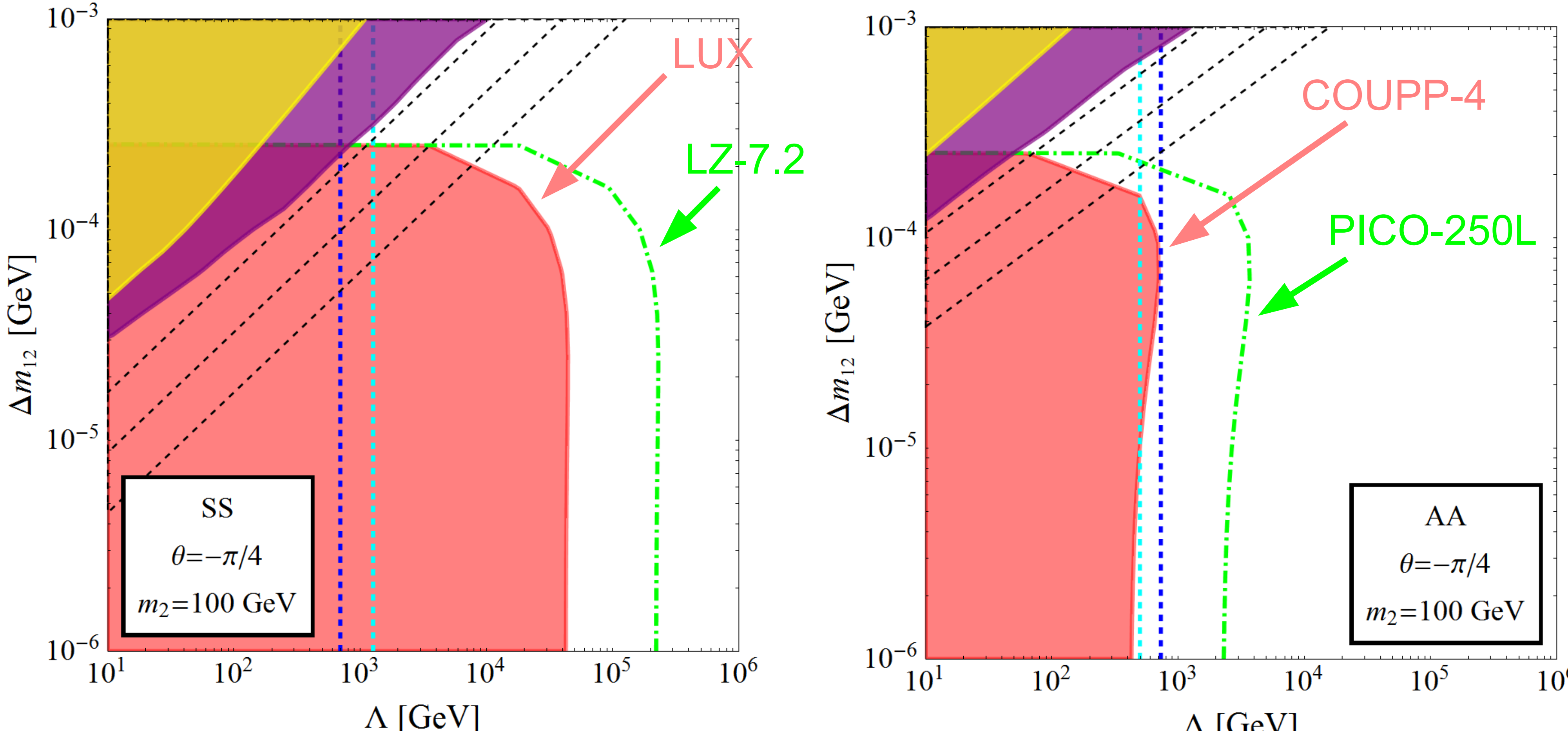
$$\Rightarrow \quad \Gamma_{\gamma\gamma}^{(\rm A)} \approx \frac{\alpha_{\rm EM}^2 [c^{(\rm A)}]^2 (\Delta m_{12})^9}{8(315\pi^5)\Lambda_C^4\Lambda^4} \left[\tilde{\lambda}_3 + \tilde{\lambda}_4 - \frac{2\Lambda_C^2}{m_\pi^2}\right]$$

Spectrum peaked in the X-ray for Δm_{12} ~ O(1-100 keV). Widths constrained by diffuse X-ray data from COMPTEL, HEAO-1, etc.

Interplay Between Detection Channels: Results

(Preliminary)

(Spin-independent) (Spin-dependent)



- Current direct-detection limits
- Diffuse XRB limit (HEAO-1)
- Diffuse XRB limit (COMPTEL)
- ATLAS/CMS monojet limit
- ATLAS mono-W/Z limit
- Future direct-detection reach

Summary

- In multi-component theories of dark matter, **new complementarity relations** exist between processes absent in single-component theories.
- In particular, a single interaction between DM and SM particles can contribute to:

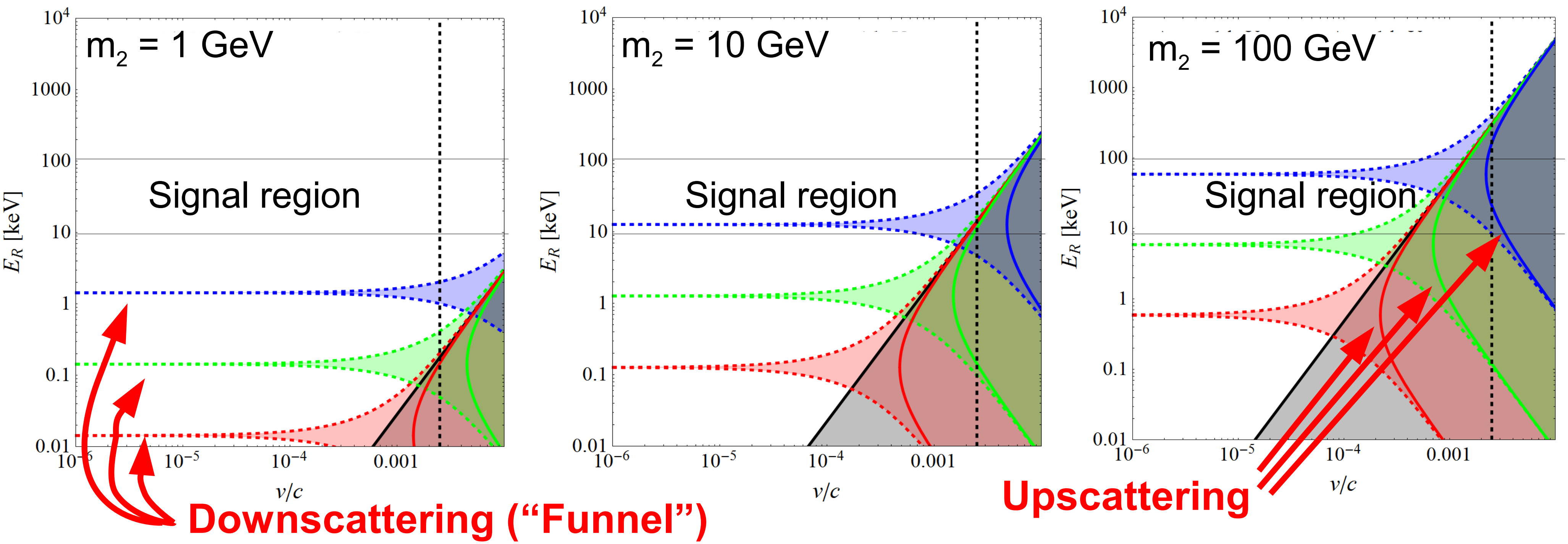
> - **Inelastic scattering** at direct-detection experiments
> - **Asymmetric** dark-matter production at colliders
> - Indirect-detection signals due to **dark-matter decay**
>
> Absent in single-component theories!

- We have also demonstrated the power of these complementarity relations in covering the parameter space of a toy two-component dark sector.
- In the small-coupling/large-Λ regime, there is significant overlap between the regions excluded by direct- and indirect-detection limits. Together, these complementary probes of the dark sector provide **complete coverage of the relevant parameter space** in this regime.
- By contrast, in the large-coupling/small-Λ regime, a range of Δm_{12} opens up for which the dark sector escapes detection. Motivates new detection strategies to “fill the gap.”

Backup Slides

Inelastic Dark Matter: Scattering Kinematics

$$E_R \approx \frac{\mu_{N2}^2 v^2}{m_N}\left[1 + \frac{\Delta m}{\mu_{N2} v^2} + \left(1 + \frac{2\Delta m}{\mu_{N2} v^2}\right)^{1/2} \cos\theta\right] , \qquad \mu_{N2} \equiv \frac{m_2 m_N}{m_2 + m_N}$$



Downscattering

- - - Δm_{12} = 1 keV
- - - Δm_{12} = 10 keV
- - - Δm_{12} = 100 keV

Upscattering

— Δm_{12} = -1 keV
— Δm_{12} = -10 keV
— Δm_{12} = -100 keV