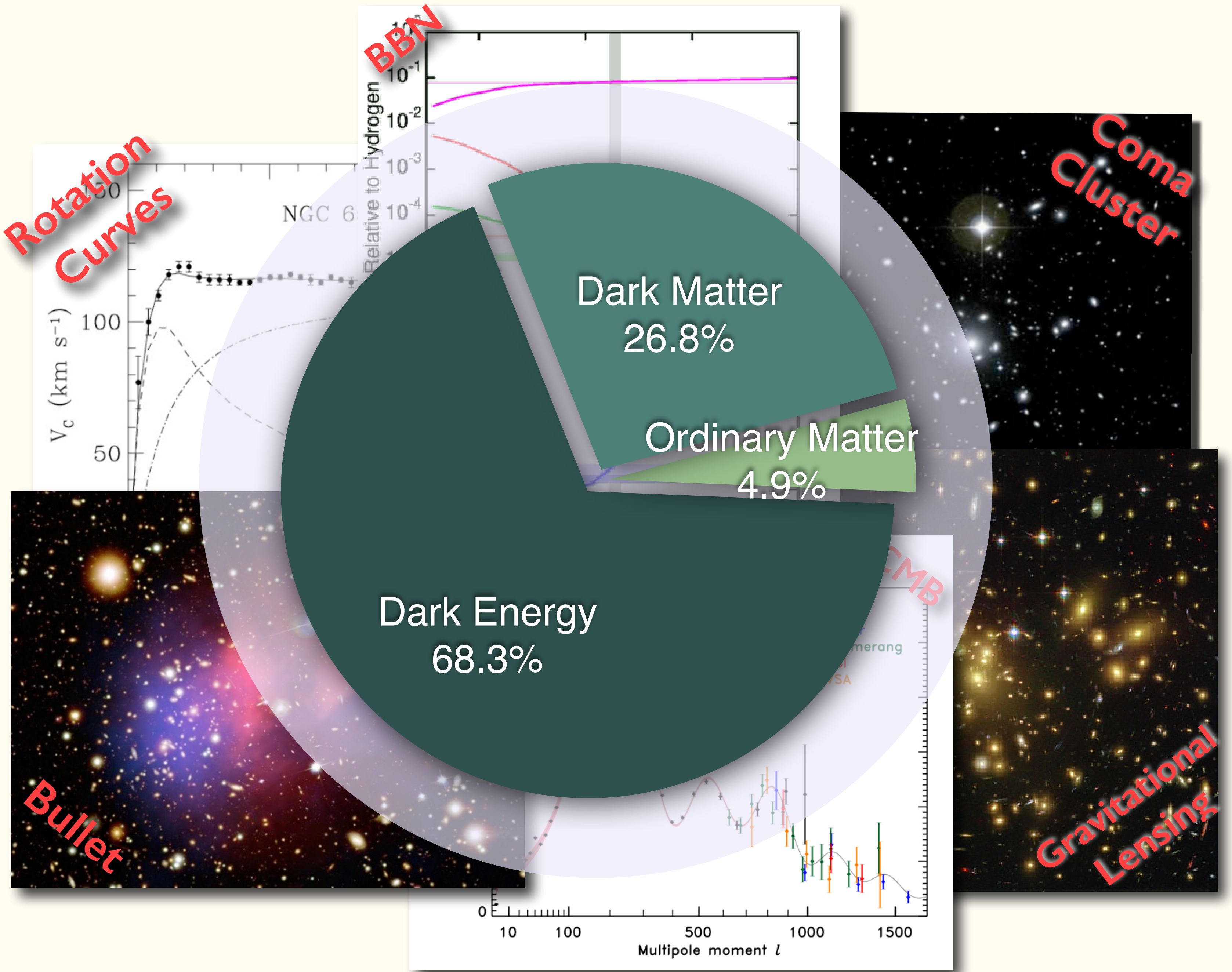
New Paradigms in the Search for Dark Matter

Apr 2015

Tomer Volansky
Tel-Aviv University

Based on collaborations and work in progress with:
A. Abir, R. Budnik, O. Chechnovsky, R. Essig, A. Falkowski, E. Kuflik, Y. Hochberg, N. Levi, P. Manalaysay, J. Mardon, S. McDermott, H. Murayama, P. Sorensen, M. Papucci, O. Slone, J. Wacker, T-T. Yu, Y. Zhong, K. Zurek.

(Gravitational) Evidence for Dark Matter

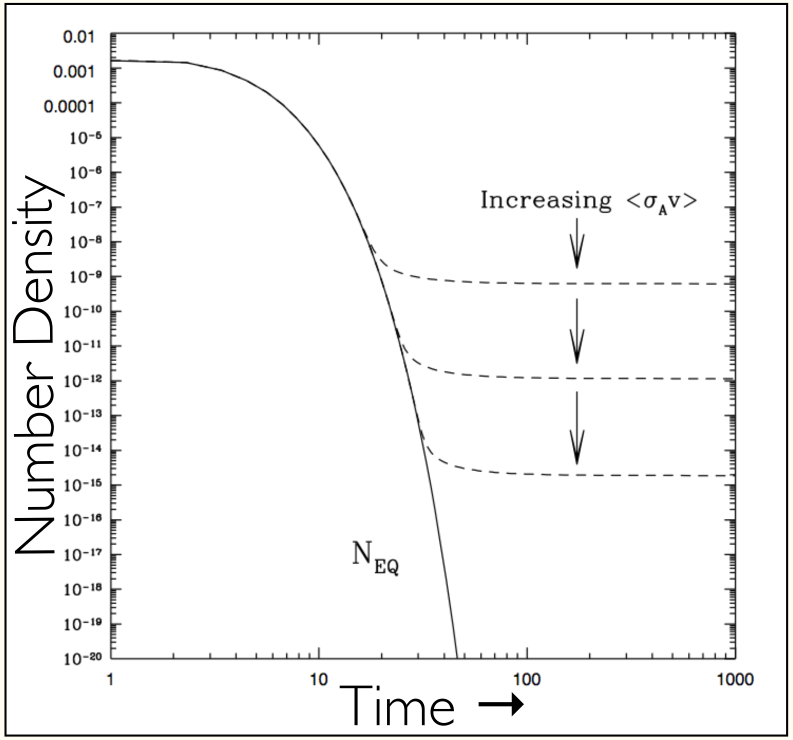


How do we explain the DM abundance?

Thermal WIMP
(Weakly Interacting Massive Particle).

The Thermal WIMP

- Independent of initial conditions.
- Requirements:
  - DM was in thermal equilibrium in early universe.
  - DM stable on cosmological timescales.



- Dynamics described by Boltzmann eqs.
- Result:

$$\langle \sigma v \rangle \simeq \frac{g^4}{m_{\rm DM}^2} \Longrightarrow \boxed{m_{\rm DM} \simeq 100\,{\rm GeV} - 1\,{\rm TeV}}$$

The Thermal WIMP

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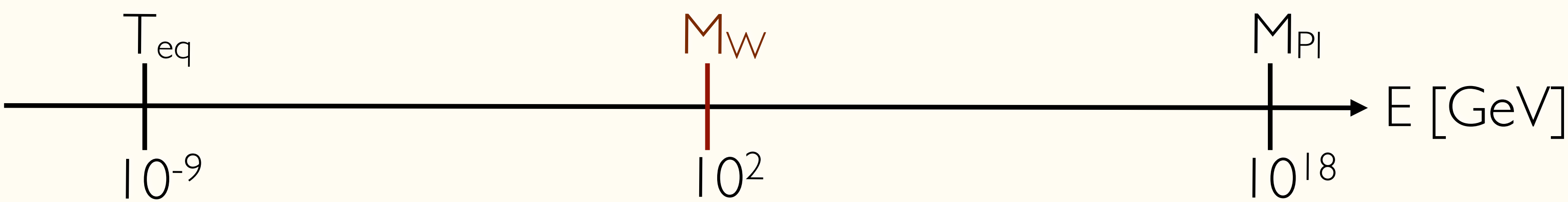
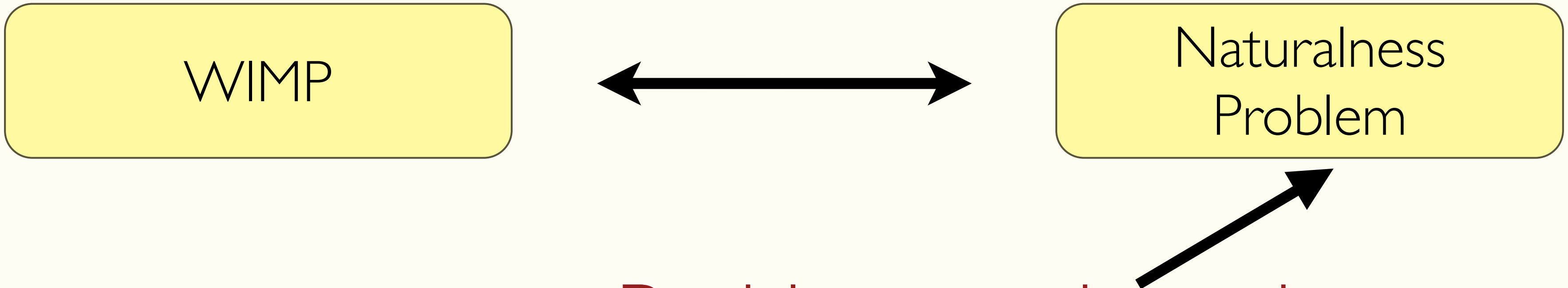
$$m_{\rm DM} \simeq \alpha \sqrt{T_{\rm eq} M_{\rm Pl}}$$



This is the WIMP Miracle

Obsessed with the WIMP...

For the last ~30 years we have been (mostly) focusing on the WIMP scenario



Problem made up by theorists..

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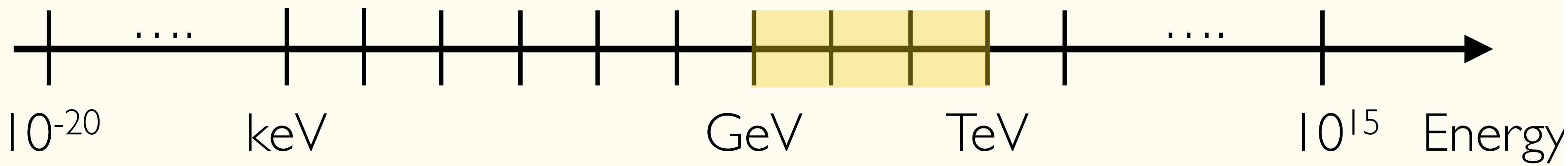
WIMP ⟷ Naturalness Problem

Our experimental effort is strongly focused on the WIMP!



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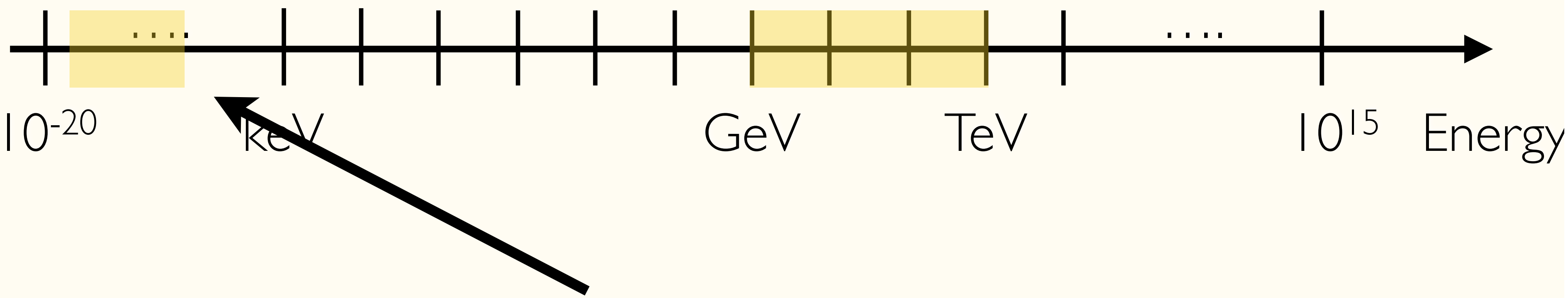

And on the axion…

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Lots more to do!

(repeat everything we did for the WIMP…)

This talk: Focus on keV - GeV mass range

Outline

- Theories of Light DM (Very interesting theoretically…)
- Experimental Probes of DM
  - Direct Detection
  - Indirect Detection
  - Colliders
- Future (…and also detectable)

Theory

Sub-GeV Dark Matter

- Although hasn't been studied systematically, there are numerous models that may accommodate light DM (keV - GeV):
  - WIMPless DM. — Feng Kumar, 2008; Feng, Shadmi, 2011
  - MeV DM (explaining INTEGRAL). — Boehm, Fayet, Silk, Borodachenkova, Pospelov, Ritz, Voloshin, Hooper, Zurek, ...
  - Asymmetric DM. — Nussinov, 1985; Kaplan, Luty, Zurek, 2009; Falkowski, Ruderman, TV, 2011
  - Bosonic Super-WIMP. — Pospelov, Ritz, Voloshin, 2008
  - Axinos — Rajagropal, Turner, Wilczek, 1991; Covi, Kim, Roszkowski 1999; Ellis, Kim, Nanopoulos, 1984
  - Sterile neutrino DM. — Talk by Alexander Merle..
  - Gravitinos. — Ellis, Kim, Nanopoulos; Moroi, Murayama, Yamaguchi; . . .
  - ...

Classifying Theories of DM

Production Mechanism

- Freeze-out
- Freeze-in
- Freeze-out and decay
- Non-thermal
- Asymmetric production
- Misalignment mechanism
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Couplings

- Quarks
- Gluons
- Charged Leptons
- Neutrinos
- Photons
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Direct (Quarks, Gluons)

Colliders (Quarks, Gluons, Charged Leptons)

Indirect (Charged Leptons, Neutrinos, Photons)

Only a small fraction is probed for the WIMP

Asymmetric/Non-Thermal Production

[Kuflik, Falkowski, Levi, TV, in progress]

Asymmetric / Non-thermal

- An intriguing empirical fact:

$$\Omega_{\rm DM} \simeq 5\Omega_b$$

- If we take this as a hint, both densities are related through some joint dynamics.

- The dynamics may relate the baryon asymmetry to a symmetric and/or asymmetric DM density.

[Nussinov, `85; Gelmini, Hall, Lin, `87';
Barr, Chivukula, Farhi, `90'; Kaplan, Luty, Zurek, `09;…]

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- Typical models of Asymmetric DM work as follows:

1. Asymmetry is **created** in one or both sectors. Couplings between the two sectors ensure an asymmetry in both.

2. The two sectors **decouple**.

3. The symmetric component is **annihilated** away.

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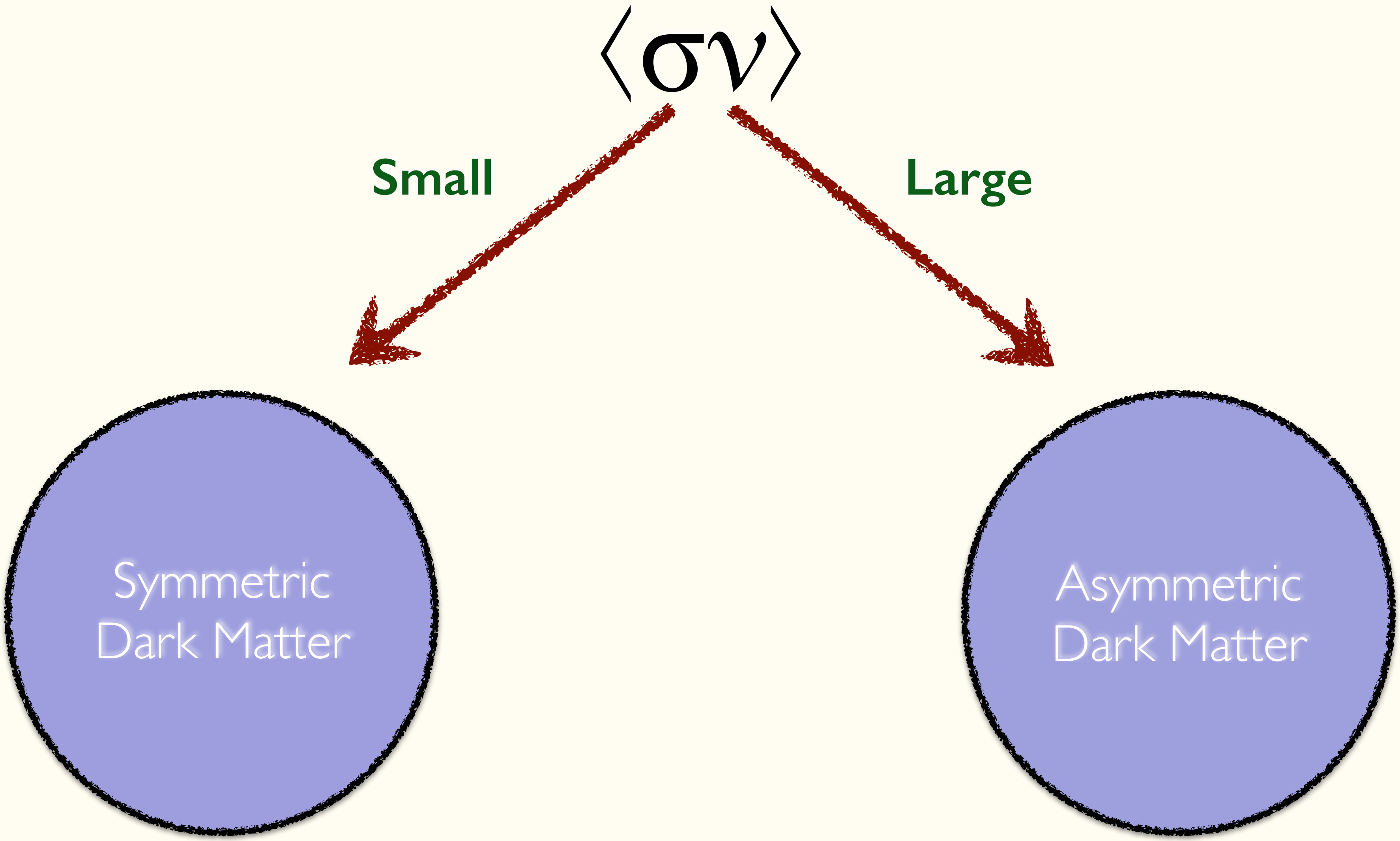
- Whether or not the symmetric component dominates, depends on the the DM annihilation cross-section

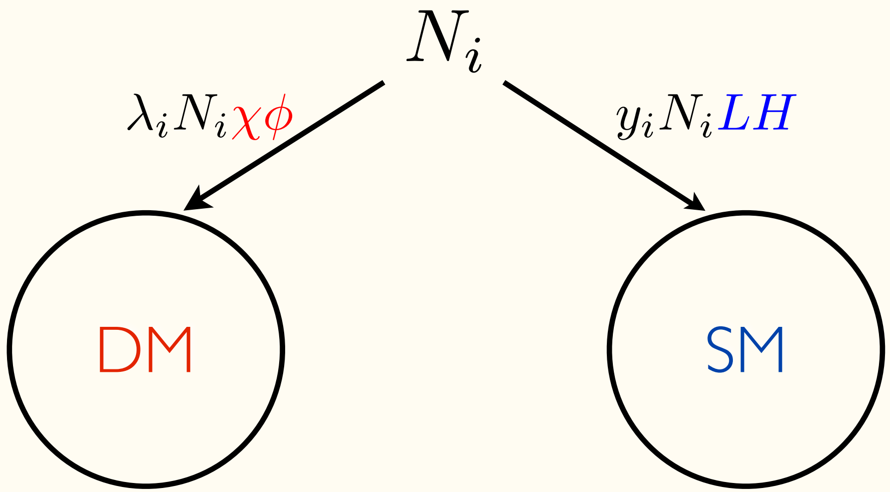
Asymmetric / Non-thermal



Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

[Falkowski,Ruderman,TV, 2011]



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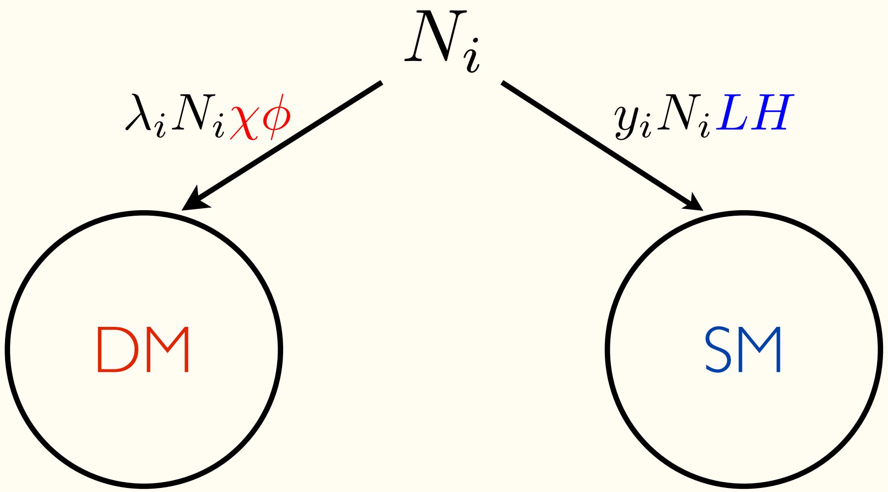
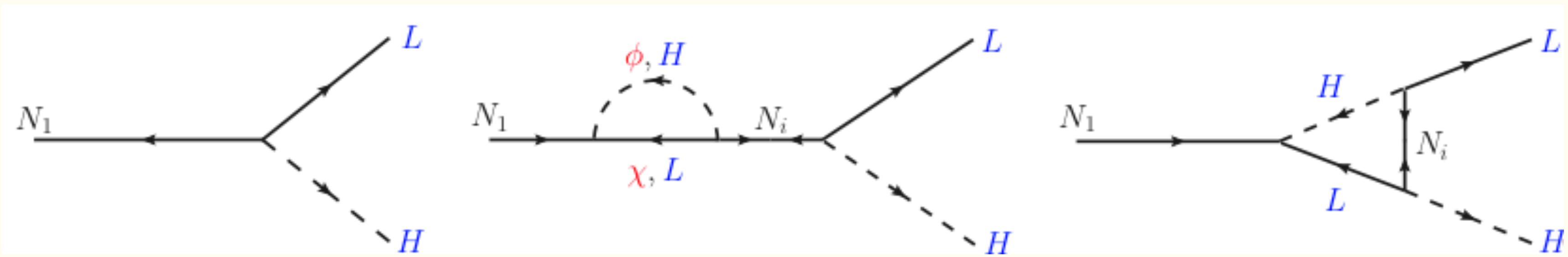


- When N decays it produces the baryon asymmetry through CP violation (loops):



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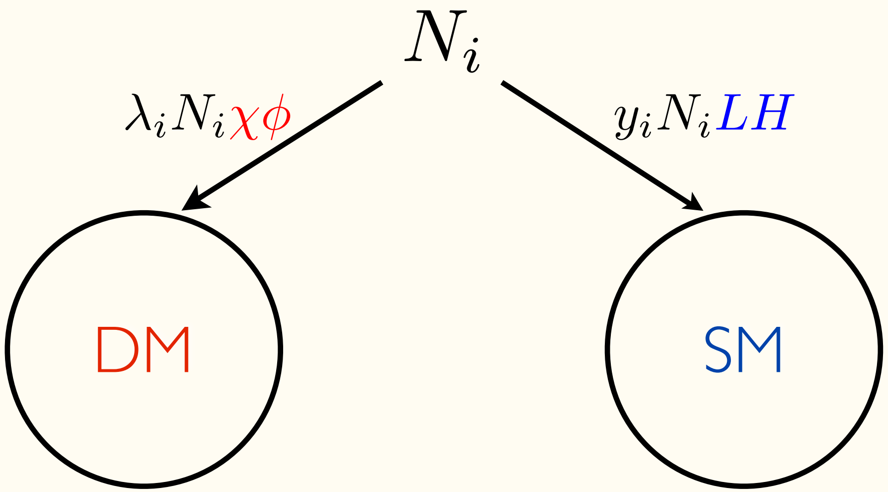

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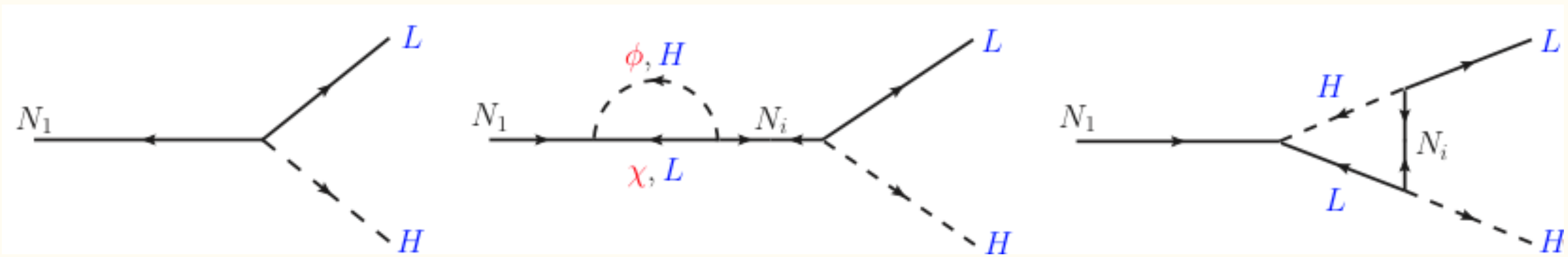
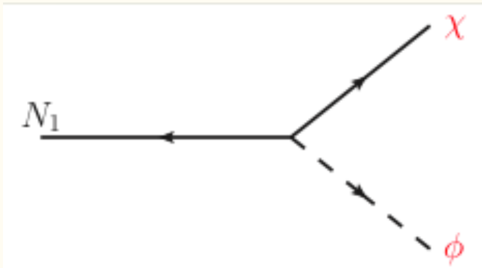


- Symmetric DM produced through tree level:



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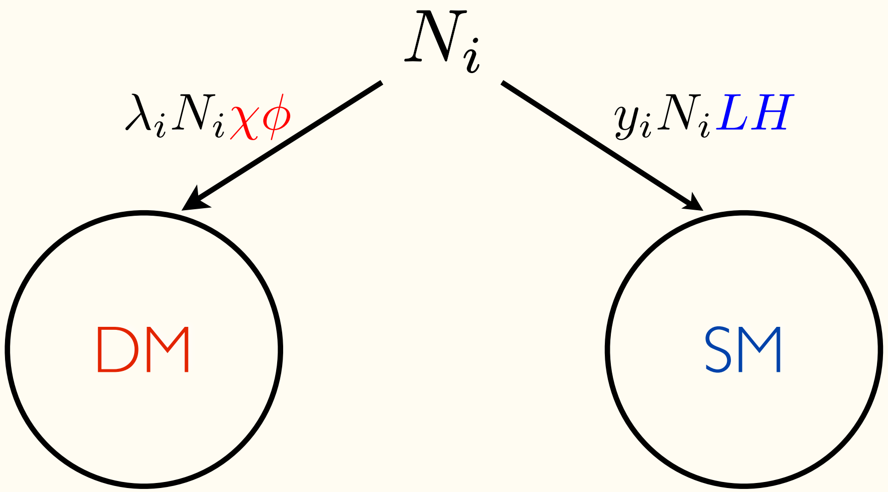


- Consequently, DM number density is generically larger than baryon number density:

$$n_{\rm DM} > n_b$$

- To have the same mass density:

$$m_{\rm DM} n_{\rm DM} = \Omega_{\rm DM} \simeq 5\Omega_b = m_{\rm p} n_b$$

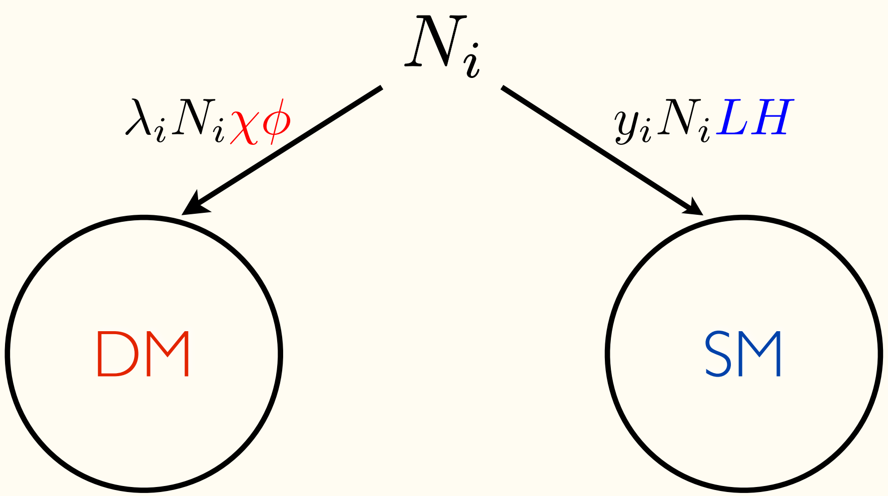
- And hence: $$m_{\rm DM} < m_p \simeq \ {\rm GeV}$$

Light DM

Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

[Falkowski,Ruderman,TV, 2011]



- One typically finds (preliminary):

$$m_{DM} \sim O(\text{keV})$$

$$\mathcal{L}_{\text{eff}} \sim \frac{\chi \phi L H}{M}$$

$$\langle \phi \rangle \neq 0$$

New
Production Mechanism

$$\chi$$

Sterile neutrino
with possible self-interactions

Strongly Interacting Massive Particles

A New Perspective on Freeze Out

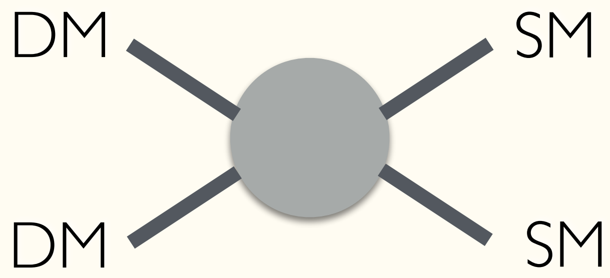
[Kuflik, Hochberg, TV, Wacker, 2014]

[Kuflik, Hochberg, Murayama, TV, Wacker, 2014]

[Kuflik, Hochberg, Murayama, TV, Wacker, in progress]

No 2-2 Annihilations..

- The WIMP paradigm assumes significant 2-2 annihilations (typically to SM) that suppresses the number density.



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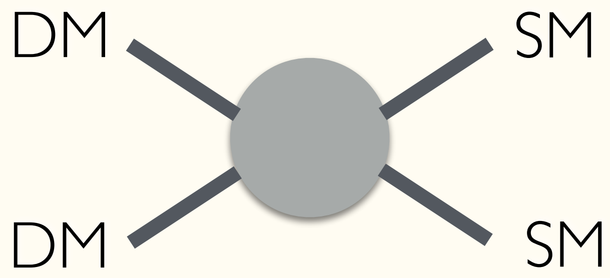
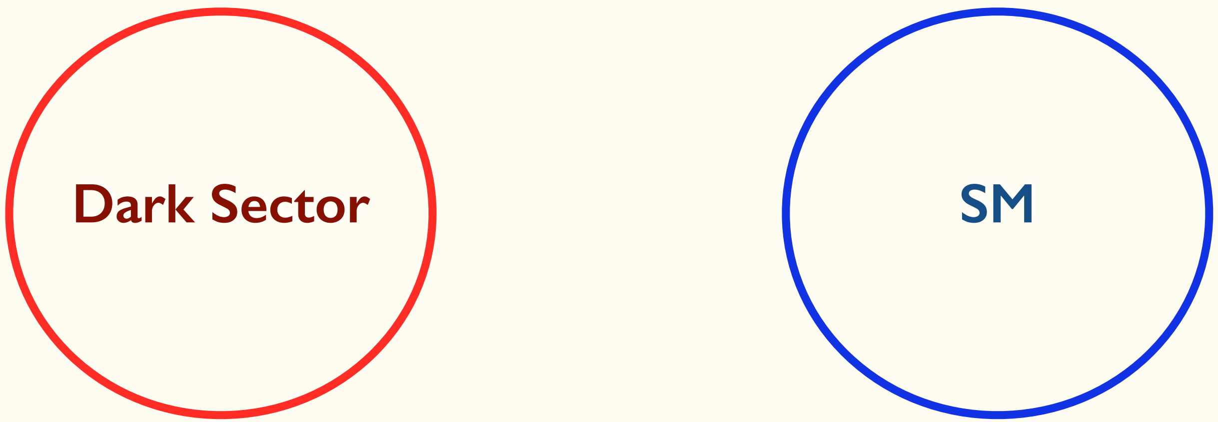


- But what if DM is the lightest state in a hidden (sequestered) sector?



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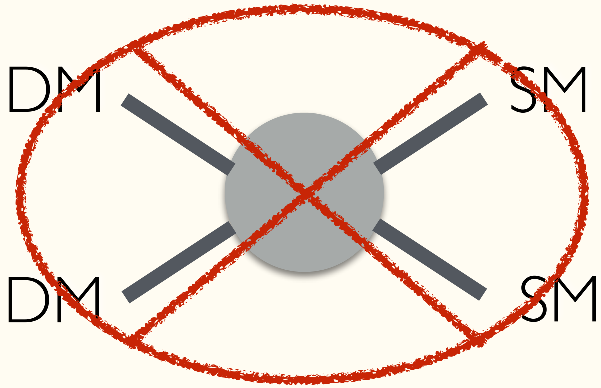

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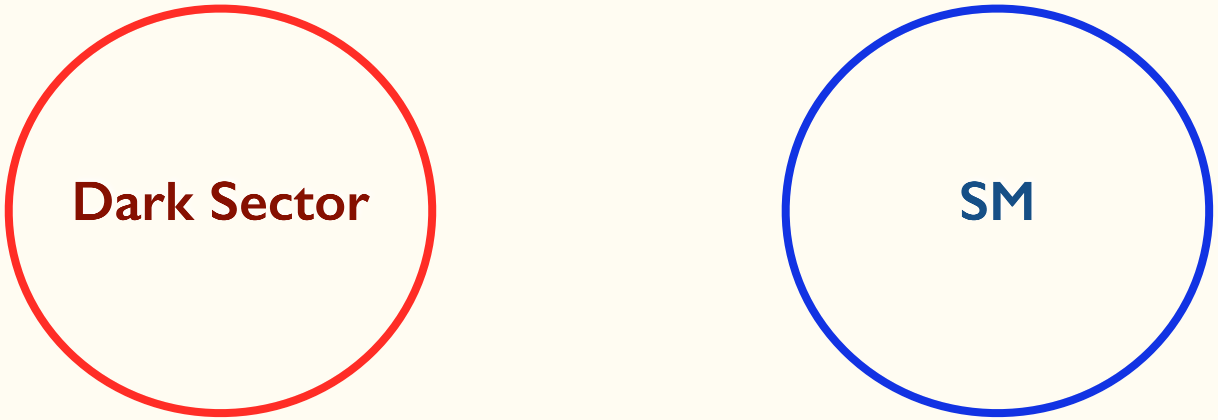
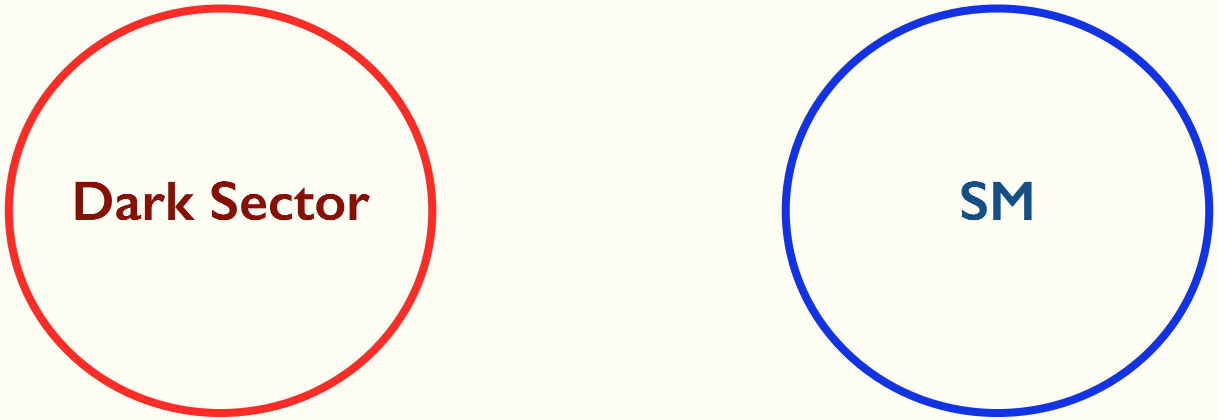


- Then 2-2 annihilations may be highly suppressed

No 2-2 Annihilations..



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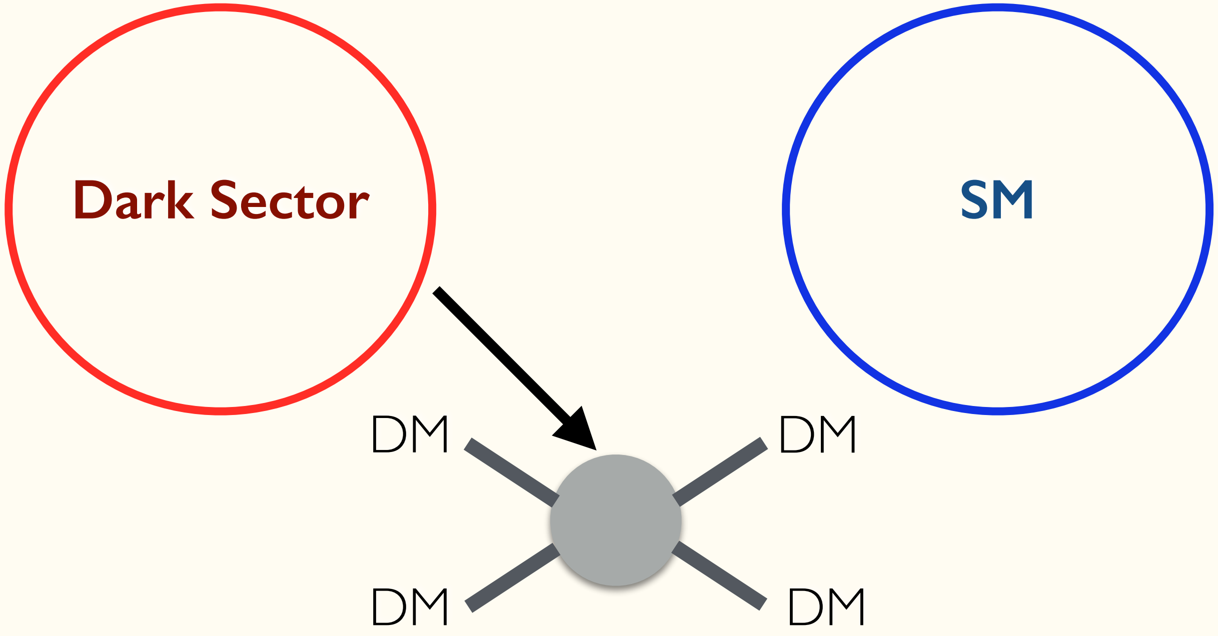
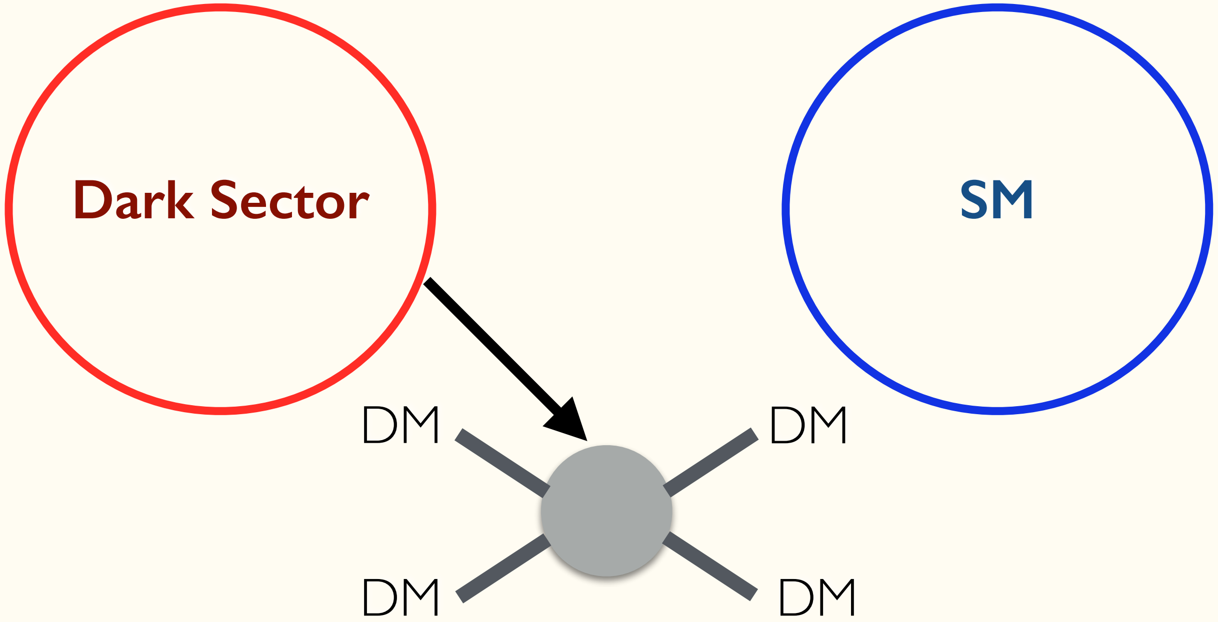


- However, DM can still interact in the hidden sector.
- But this is number-conserving, which implies,

$$\frac{n_{\rm DM}}{s} \sim 1$$

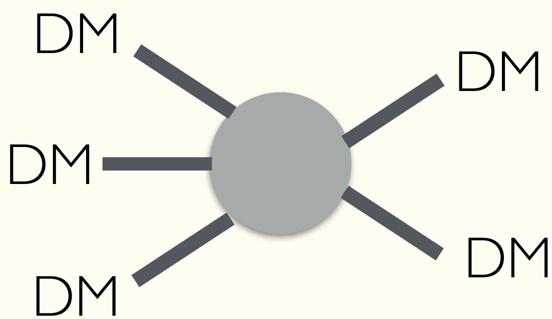
A way out?

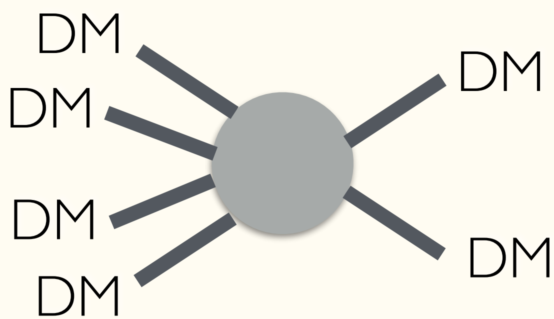
No 2-2 Annihilations..



- More generally, the hidden sector will have additional interactions (especially in a strongly coupled case). **Example**:

$$\mathcal{L}_{\mathrm{DM}} = |\partial\chi|^2 - m_{\mathrm{DM}}^2|\chi|^2 - \frac{\kappa}{6}\chi^3 - \frac{\kappa^\dagger}{6}\chi^{\dagger 3} - \frac{\lambda}{4}|\chi|^4 \,.$$





3-2 Freeze Out

WIMP DM

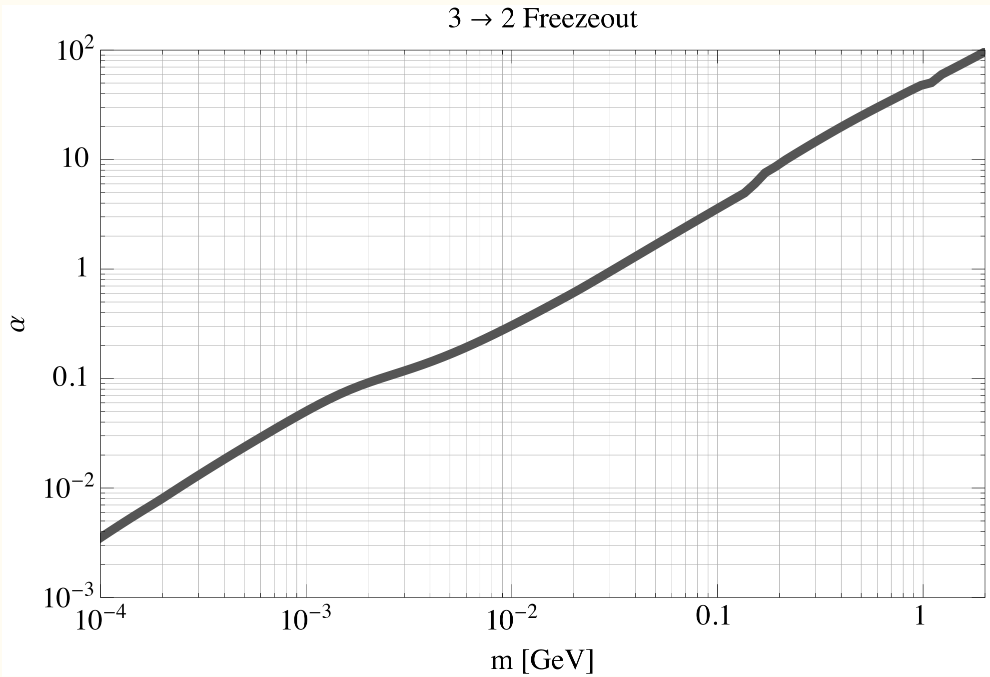
Weak scale emerges for a weak-strength interactions

$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \sim {\rm TeV}$$

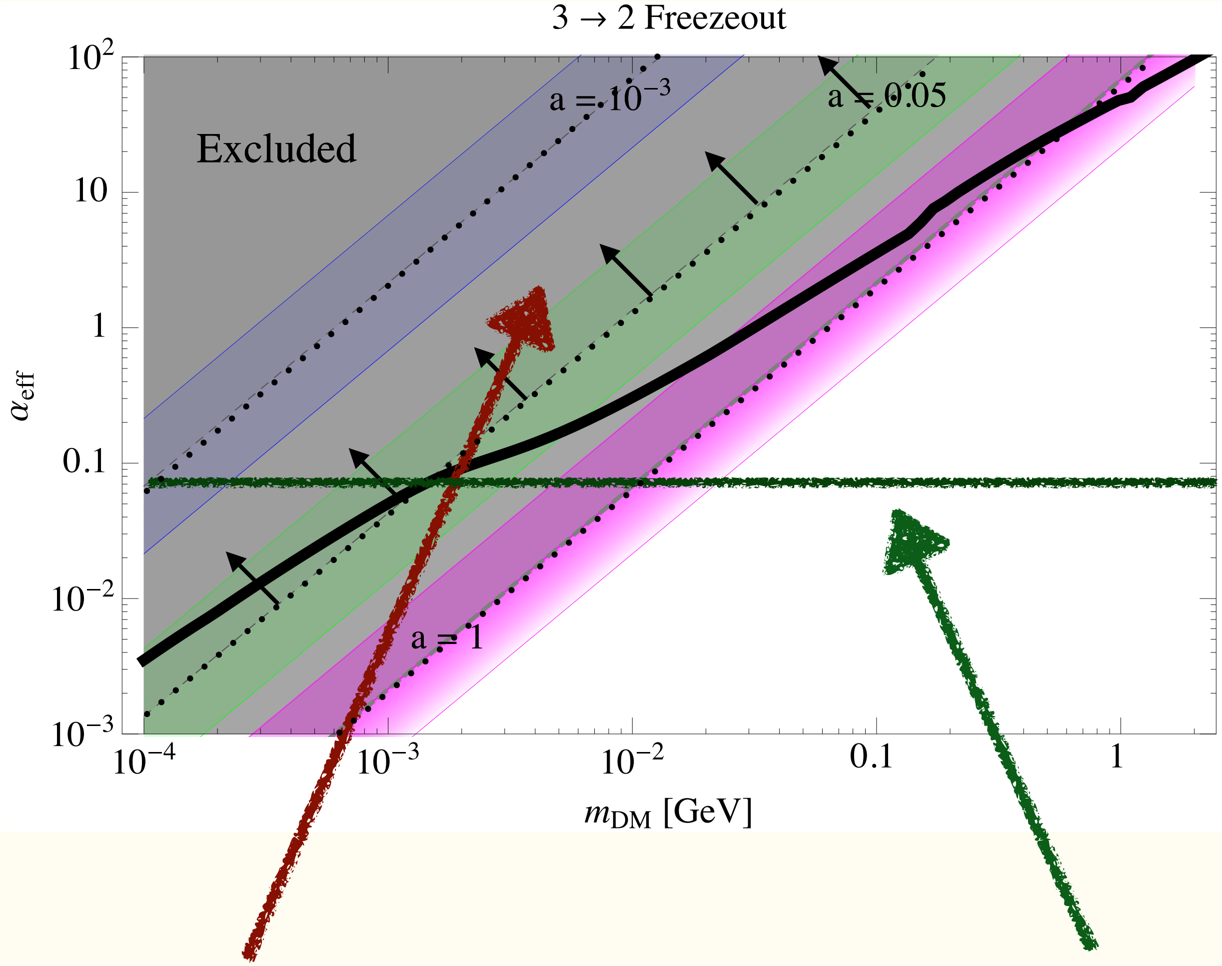
SIMP DM

QCD scale emerges for a strongly-interacting sector.

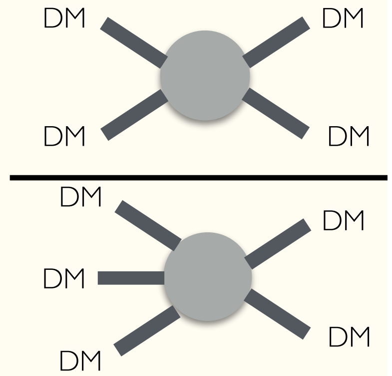
$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100\ {\rm MeV}$$



2-2 Good or Bad?



$$a \equiv \frac{\alpha_{2-2}}{\alpha_{\text{eff}}} =$$



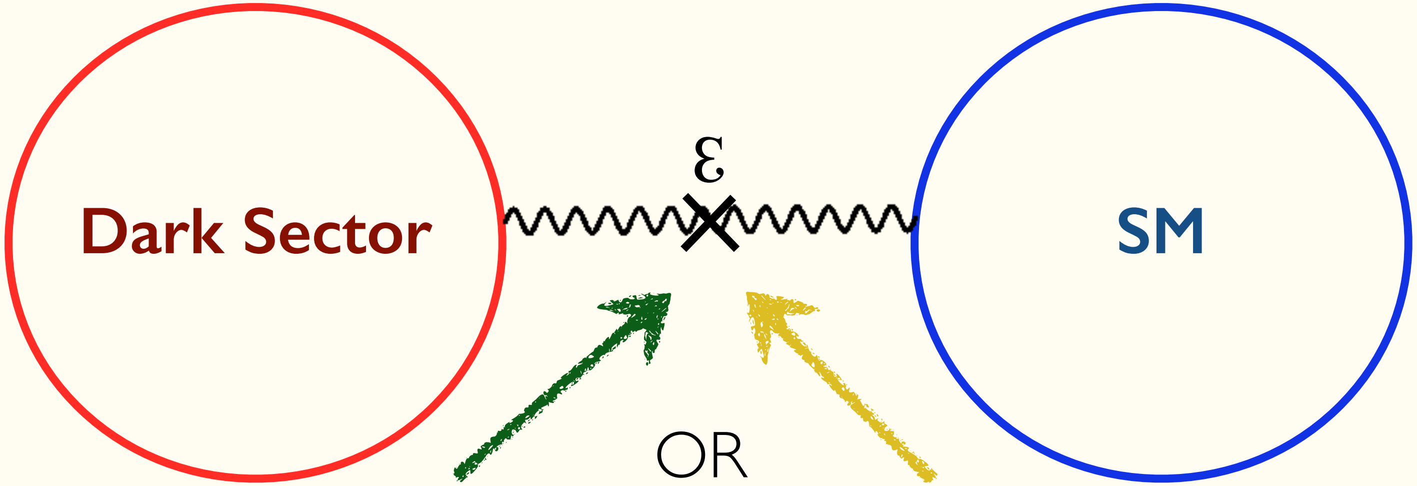
Excluded by
Bullet-cluster and
halo-shape constraints

Constraints
push to strong
regime

→ **SIMP**

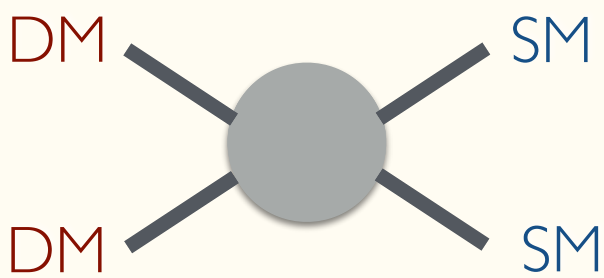
3-2 Freeze Out

- Problem: We implicitly assumed that $\mathbf{T_{dark} = T_{SM}}$. Otherwise DM is hot and excluded.
- To evade limits on hot DM, the dark sector needs to be in thermal equilibrium with SM.

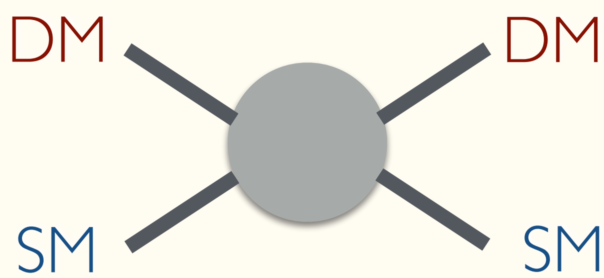


$$\frac{m_f}{\Lambda^2}\chi^\dagger\chi\bar{f}f \qquad\qquad \frac{\alpha_{\rm EM}}{4\pi\Lambda^2}\chi^\dagger\chi F_{\mu\nu}F^{\mu\nu}$$

- Consequently, two more diagrams:



2-2 Annihilations



Thermal Equilibrium

3-2 Freeze Out

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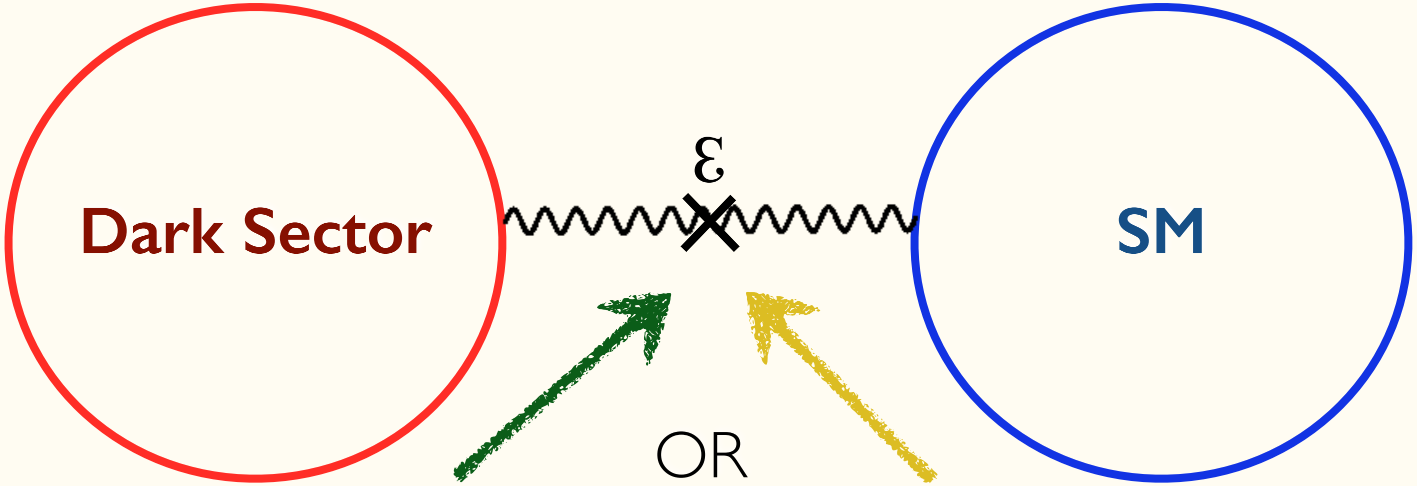

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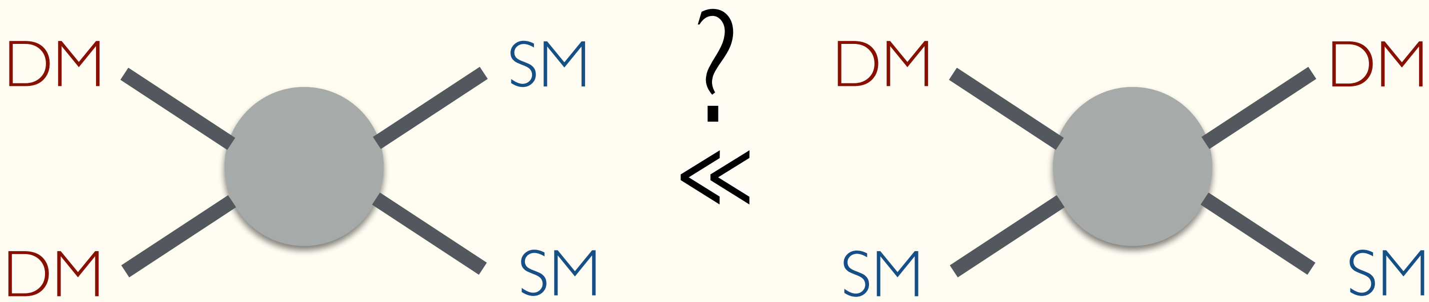
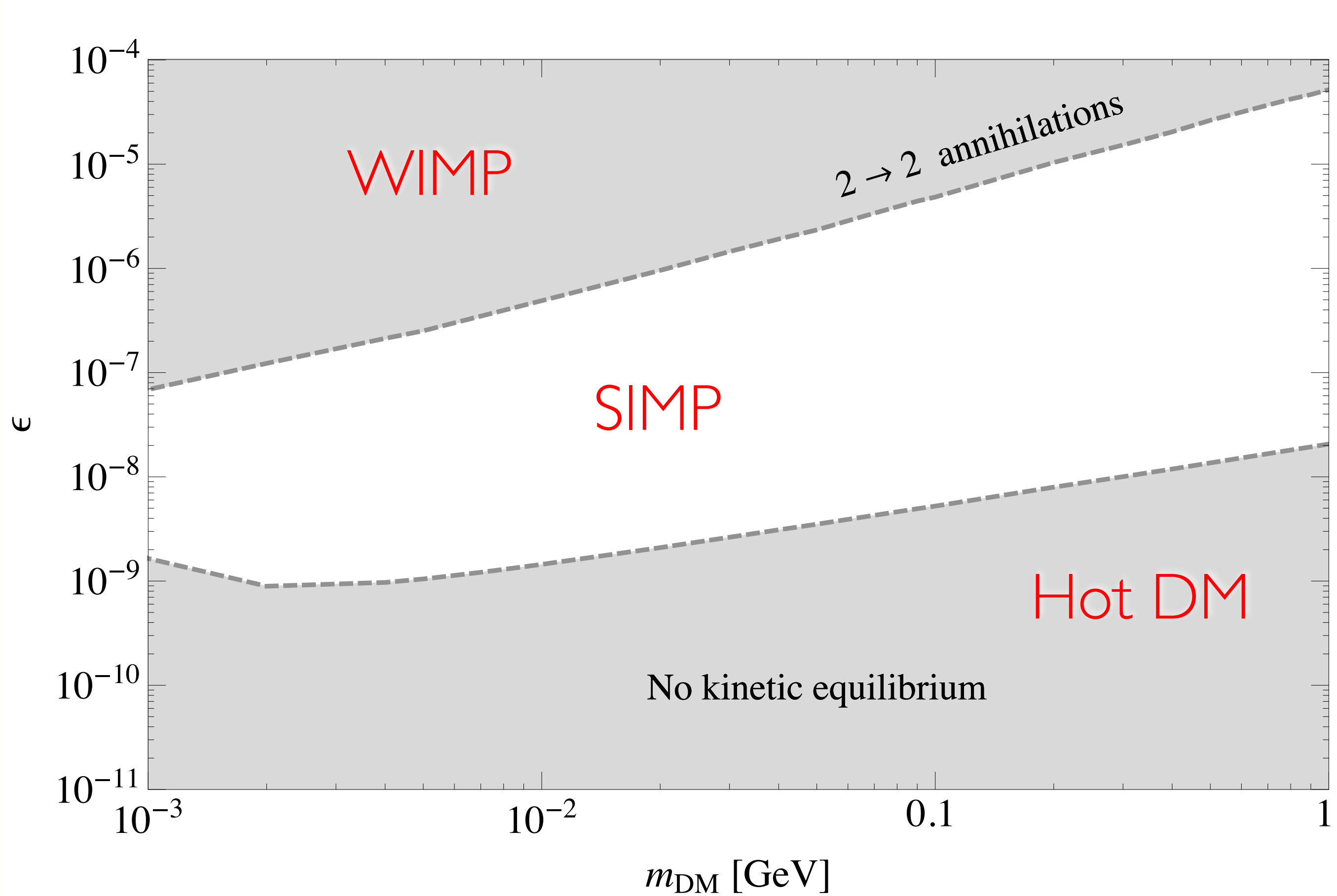


2-2 Annihilations

Thermal Equilibrium

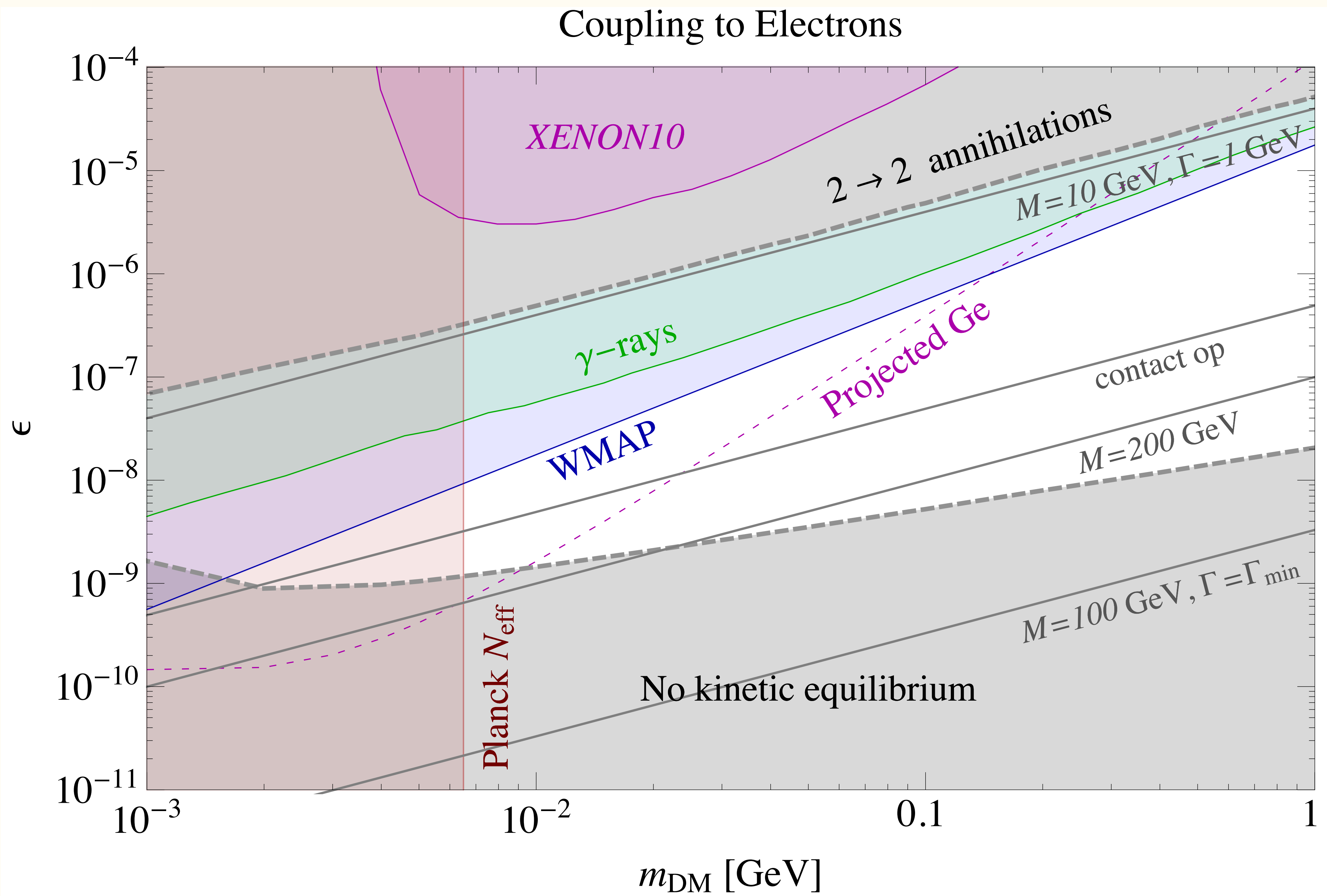
3-2 Freeze Out



Thus, much like the WIMP, the SIMP scenario predicts couplings to SM.

Measurable consequences for all types of experiments

SIMP DM: Experimental Status



SIMP Realization: QCD-like Theories

[Kuflik, Hochberg, Murayama,TV,Wacker, 2014]

- A simple realization: QCD-like theories with a Wess-Zumino-Witten term.

[Wess,Zumino 1971; Witten, 1983]

- Sp(Nc) gauge symmetry with 2Nf Weyl fermions and SU(2Nf) global symmetry.

$$\mathcal{L}_{\rm SIMP} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \bar{q}_i i \not{D} q_i \;, \quad i = 1, \ldots 2N_f$$

$$\mathcal{L}_{\rm mass} = -\frac{1}{2} M^{ij} q_i q_j + c.c., \quad M^{ij} = m_Q \, J^{ij}$$

- In the asymptotically-free range, theory breaks chiral symmetry, SU(2Nf) ⟶ Sp(Nf):

$$\langle q_i q_j \rangle = \mu^3 J_{ij}$$

- At low energy, theory described by the chiral Lagrangian. Pions parametrize the coset space SU(2Nf)/Sp(Nf). Play the role of DM.

- WZW produce 3-2 annihilations:

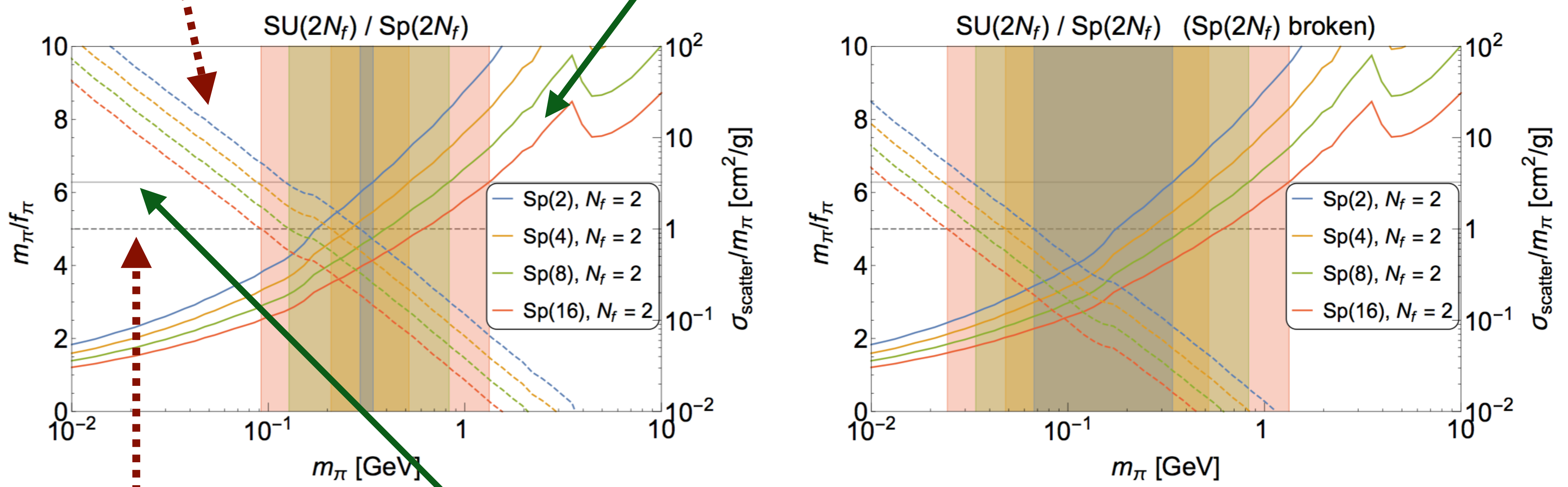
$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} {\rm Tr}\left[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi\right]$$

SIMP Realization: QCD-like Theories

[Kuflik, Hochberg, Murayama, TV, Wacker, 2014]

Predicted Self-Interaction

Solution to BE



Self-interaction bound

Perturbativity limit

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[Kuflik, Hochberg, Murayama, TV, Wacker, 2014]

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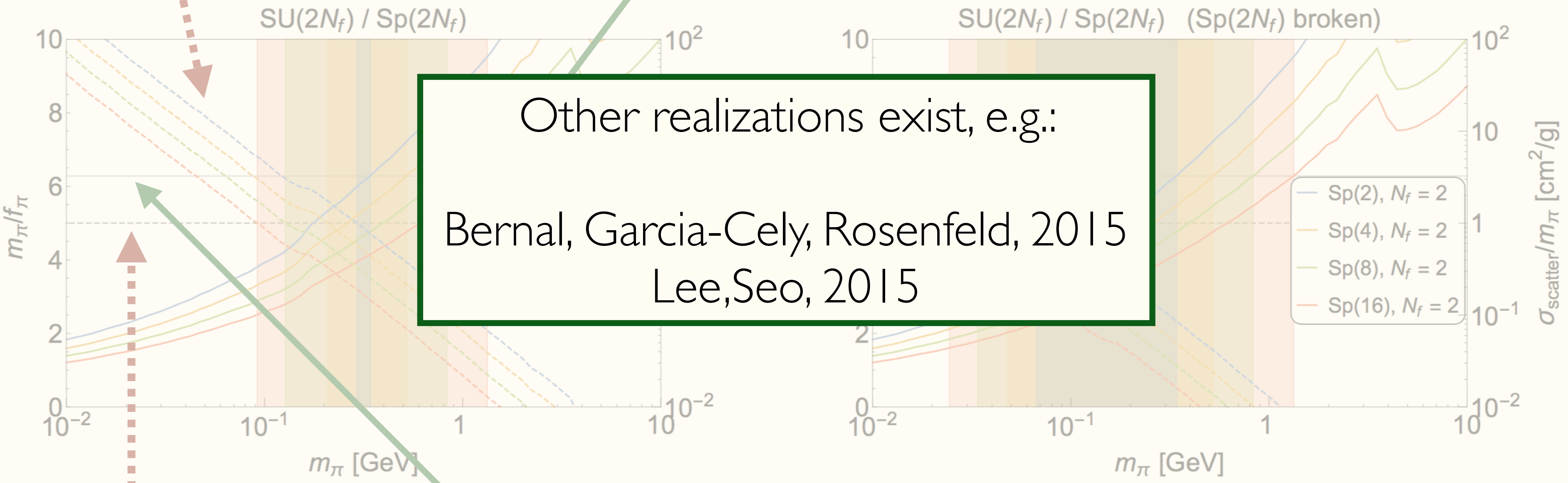


Other realizations exist, e.g.:

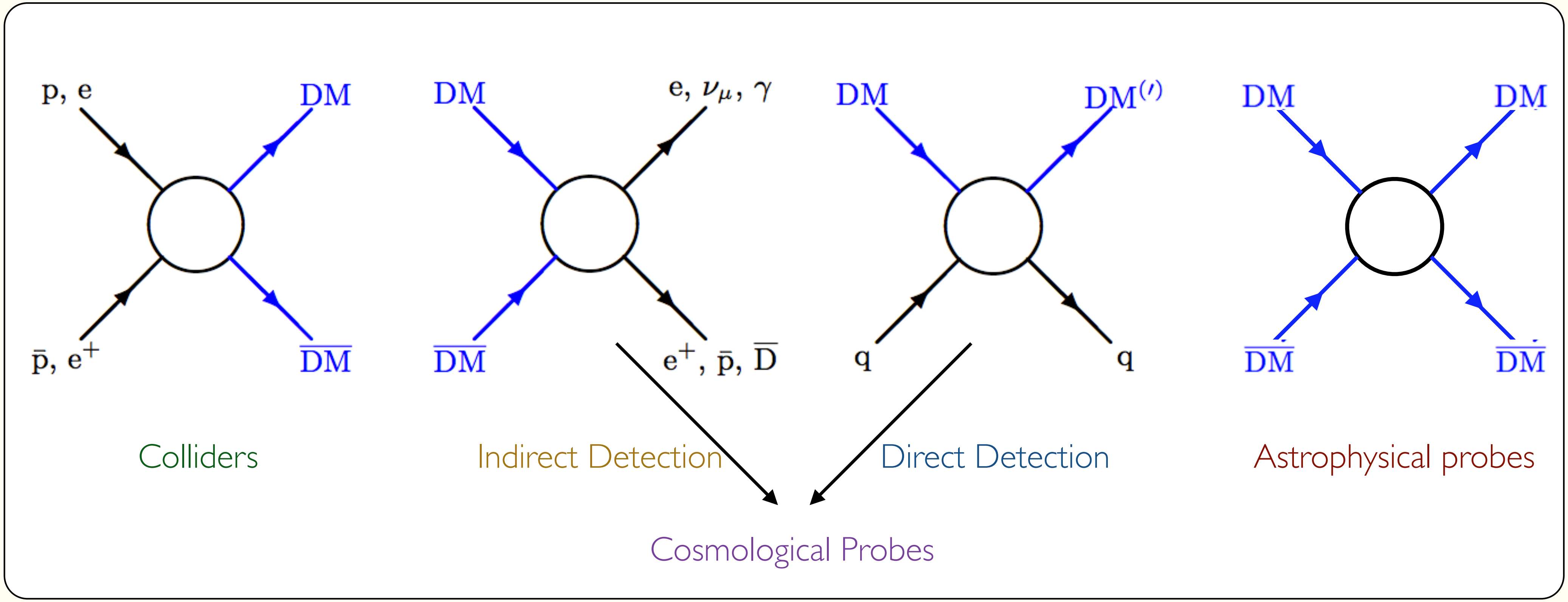
Bernal, Garcia-Cely, Rosenfeld, 2015
Lee, Seo, 2015

Self-interaction bound

Perturbativity limit

Experimental Probes

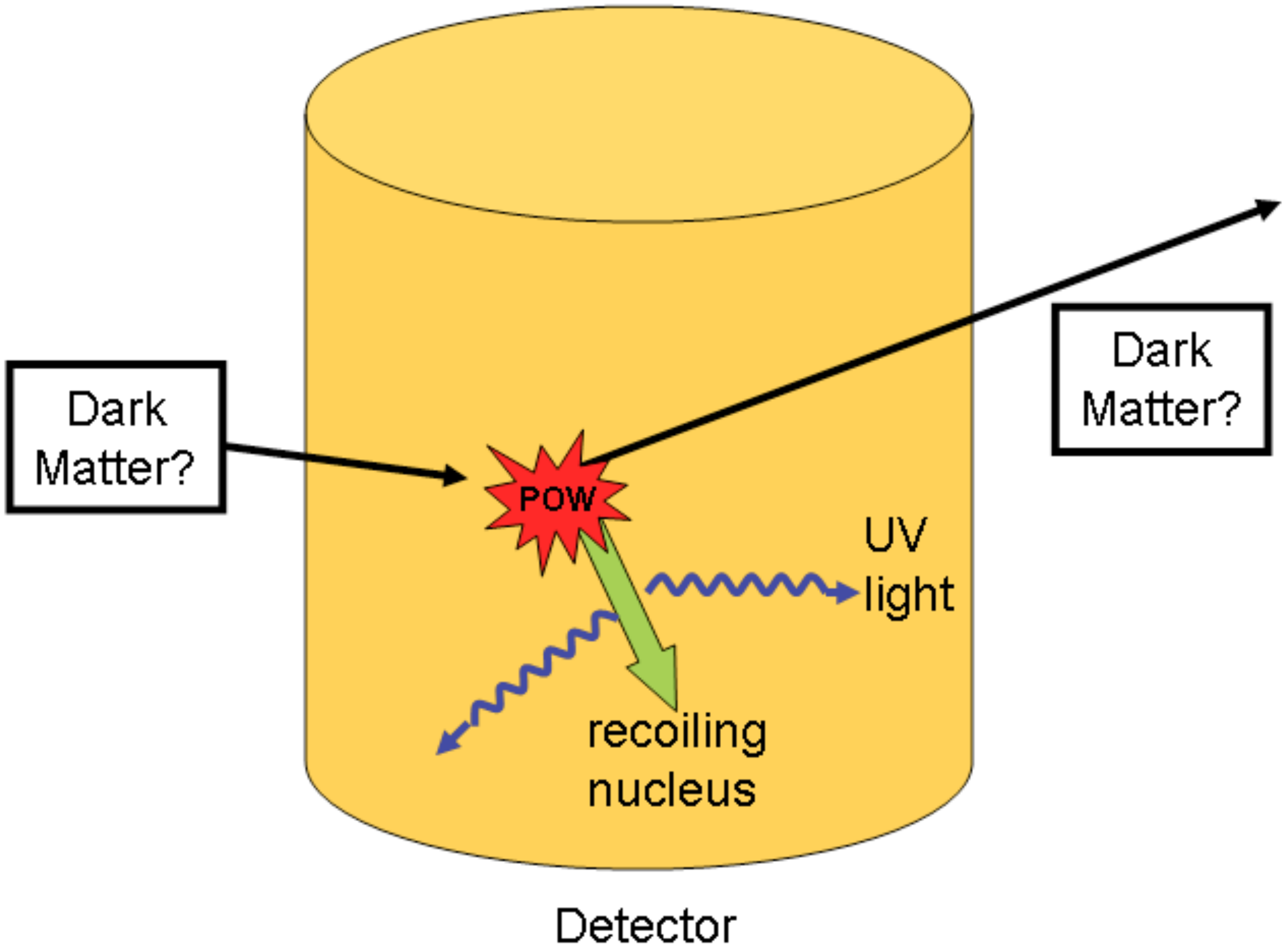
Several ways to search for DM



Experimental Probes

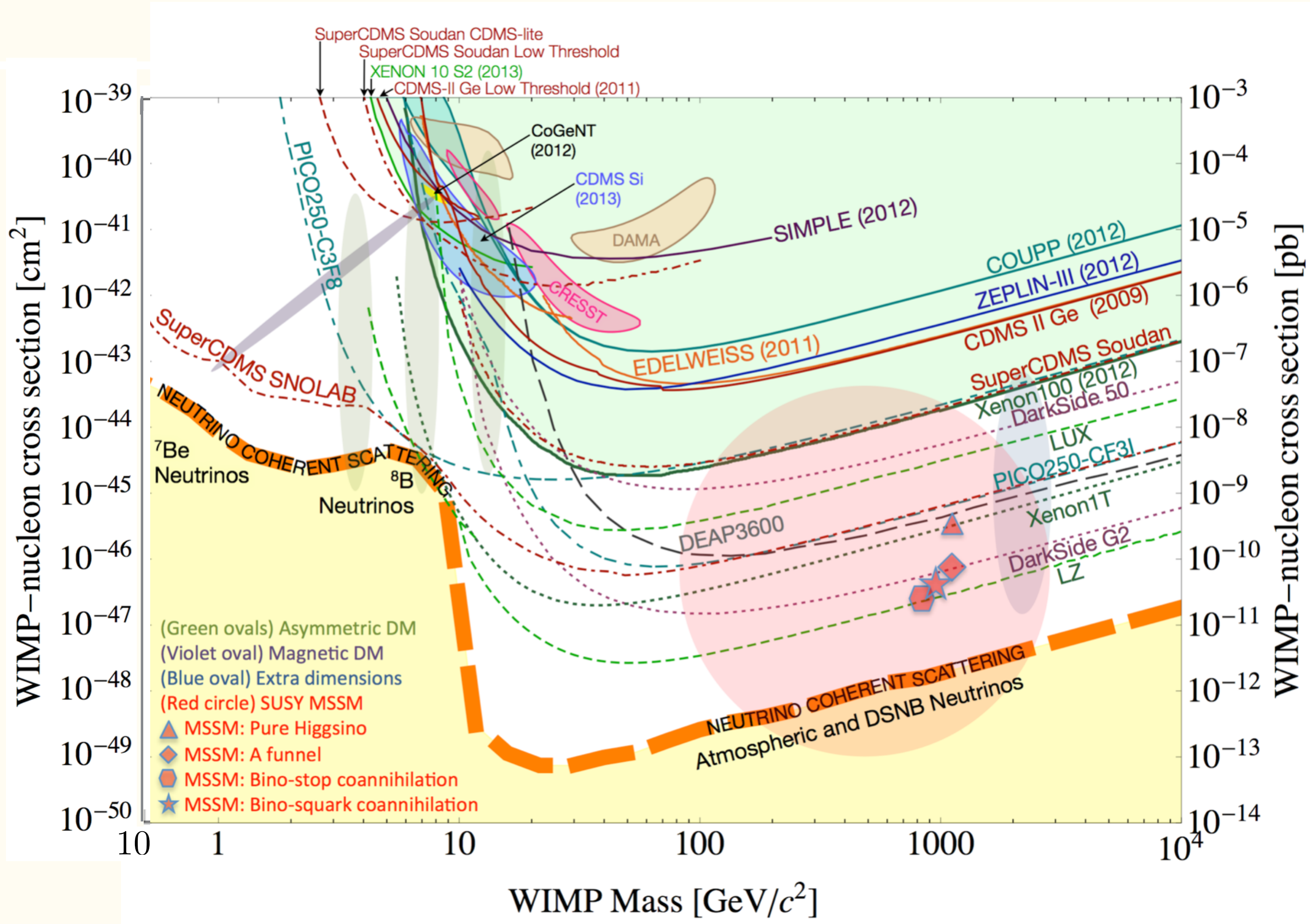
Direct Detection

Basic Idea

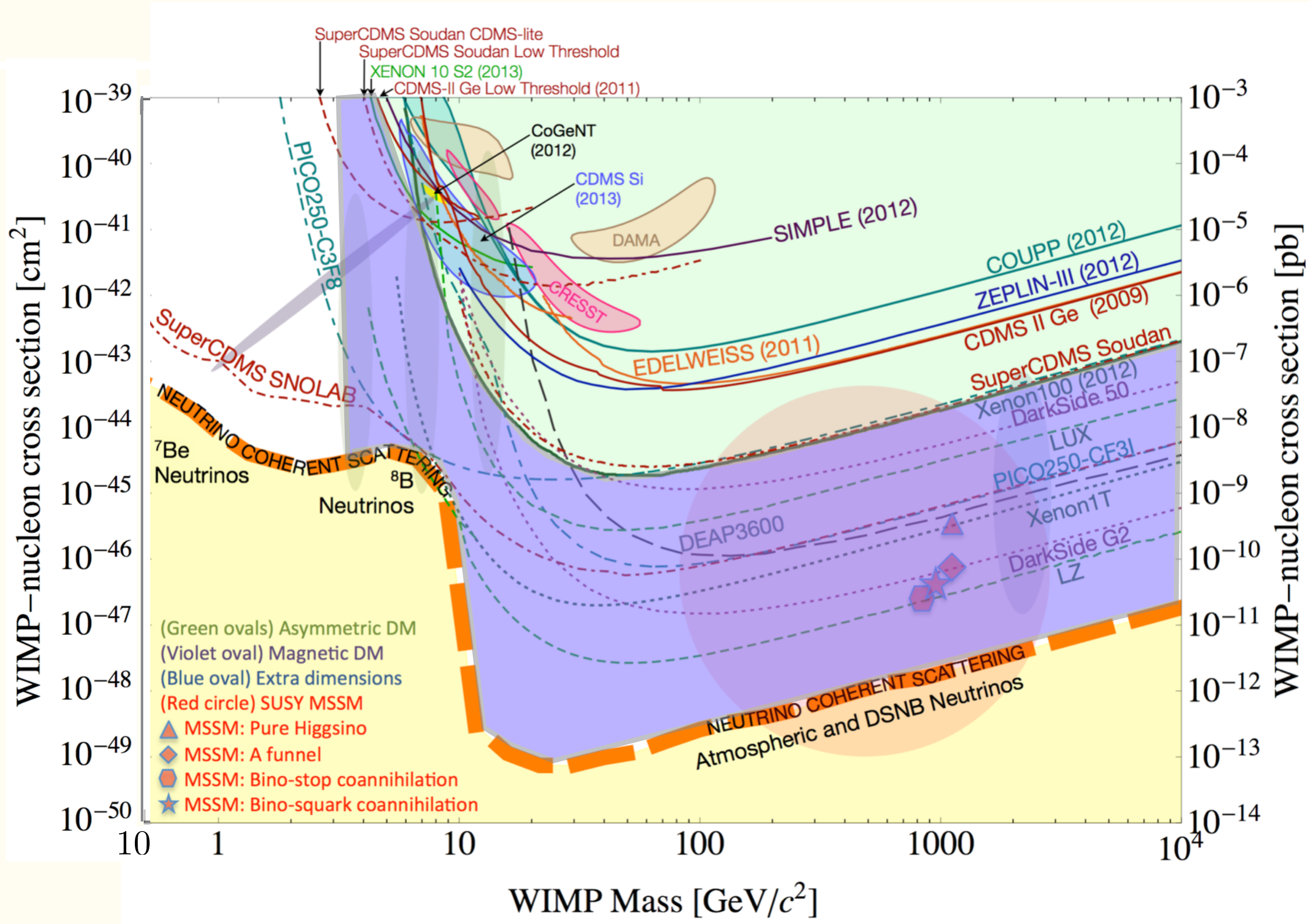


Dark
Matter?
Dark
Matter?
POW
UV
light
recoiling
nucleus
Detector

Prospects for Direct Detection



Prospects for Direct Detection



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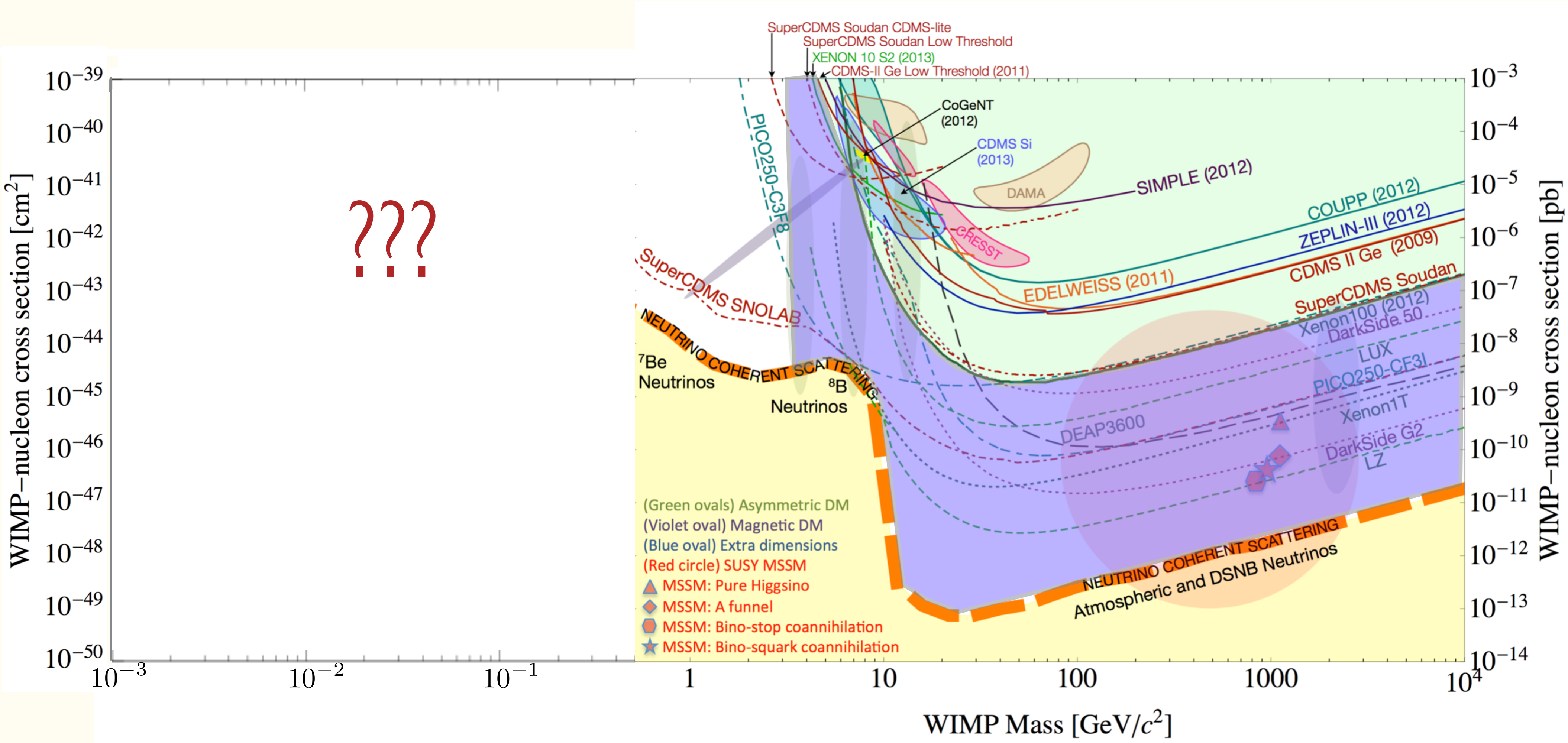

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

$$E_{\rm R} = \frac{q^2}{2m_N} \sim \frac{(m_{\rm DM} v)^2}{2m_N}$$

$$\sim 3 \text{ eV} \times \left(\frac{m_{\rm DM}}{\text{GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

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Recoil energy drops fast

Can't go below ~ GeV

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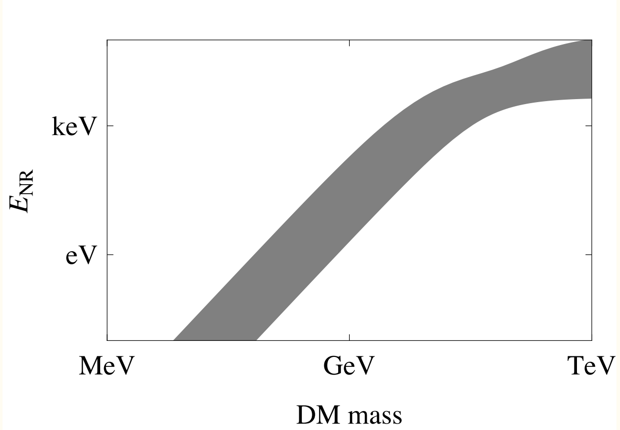

But DM energy is significantly larger:

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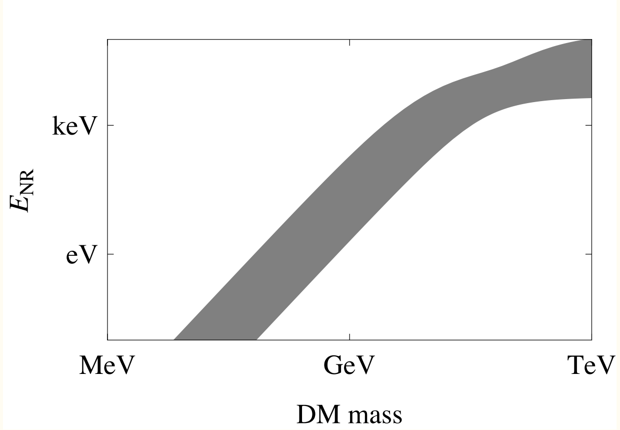

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Enough energy to detect!!

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$$E_{\rm DM} = \frac{1}{2}\mu v_{\rm DM}^2 \simeq 0.3 \text{ keV} \times \left(\frac{m_{\rm DM}}{\rm GeV}\right)$$

Studying elastic recoils is extremely inefficient for light DM

DM energy drops slower

Enough energy to detect!!

Ways to Detect Light DM

- The available energy is sufficient to induce inelastic atomic processes that would lead to visible signals.

[Essig, Mardon, TV, 2011]

- Three possibilities:

  1. Electron ionization

     Threshold: eV - 100's eV
     DM-electron scattering
     Signals: electrons, photons, phonons.

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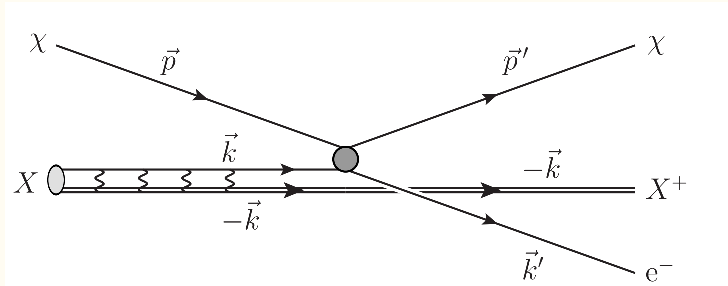

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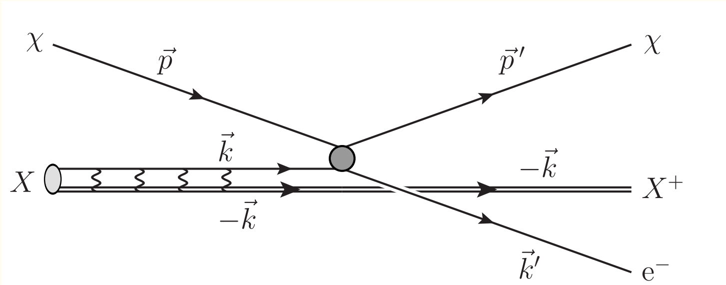

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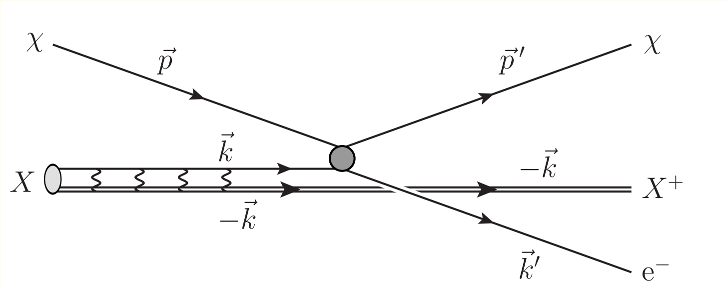

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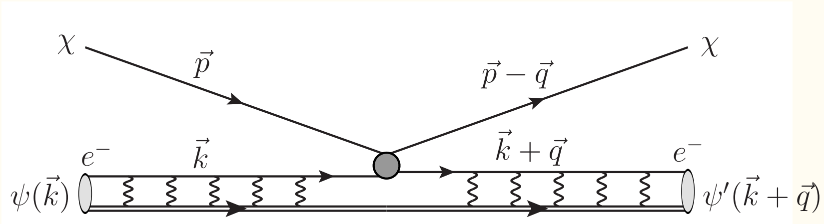

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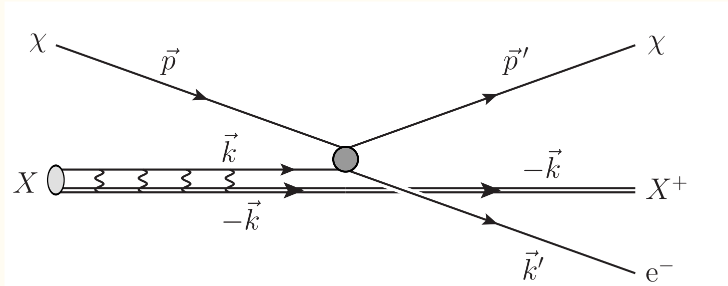

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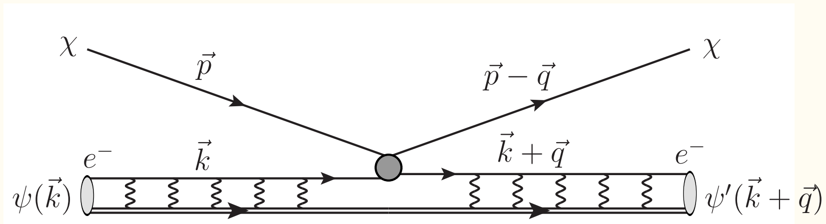

3. Bond Breakage

   Threshold: $\gtrsim$ few eV
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   Signal: ions, photons.

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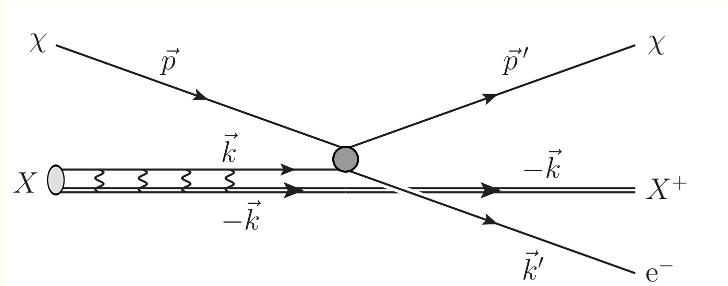

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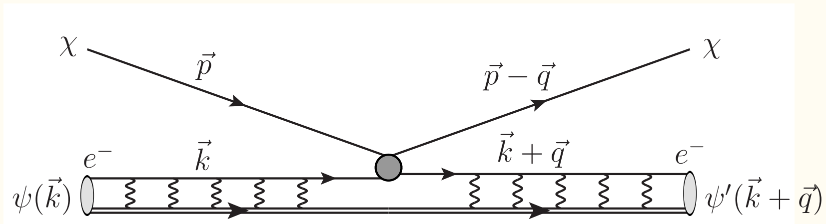

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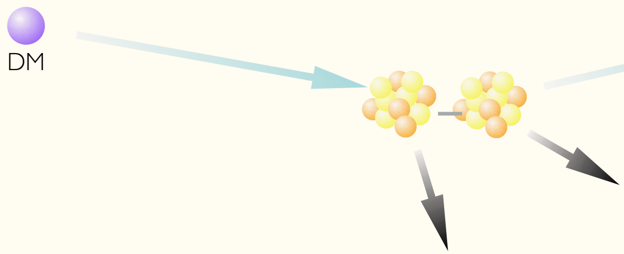
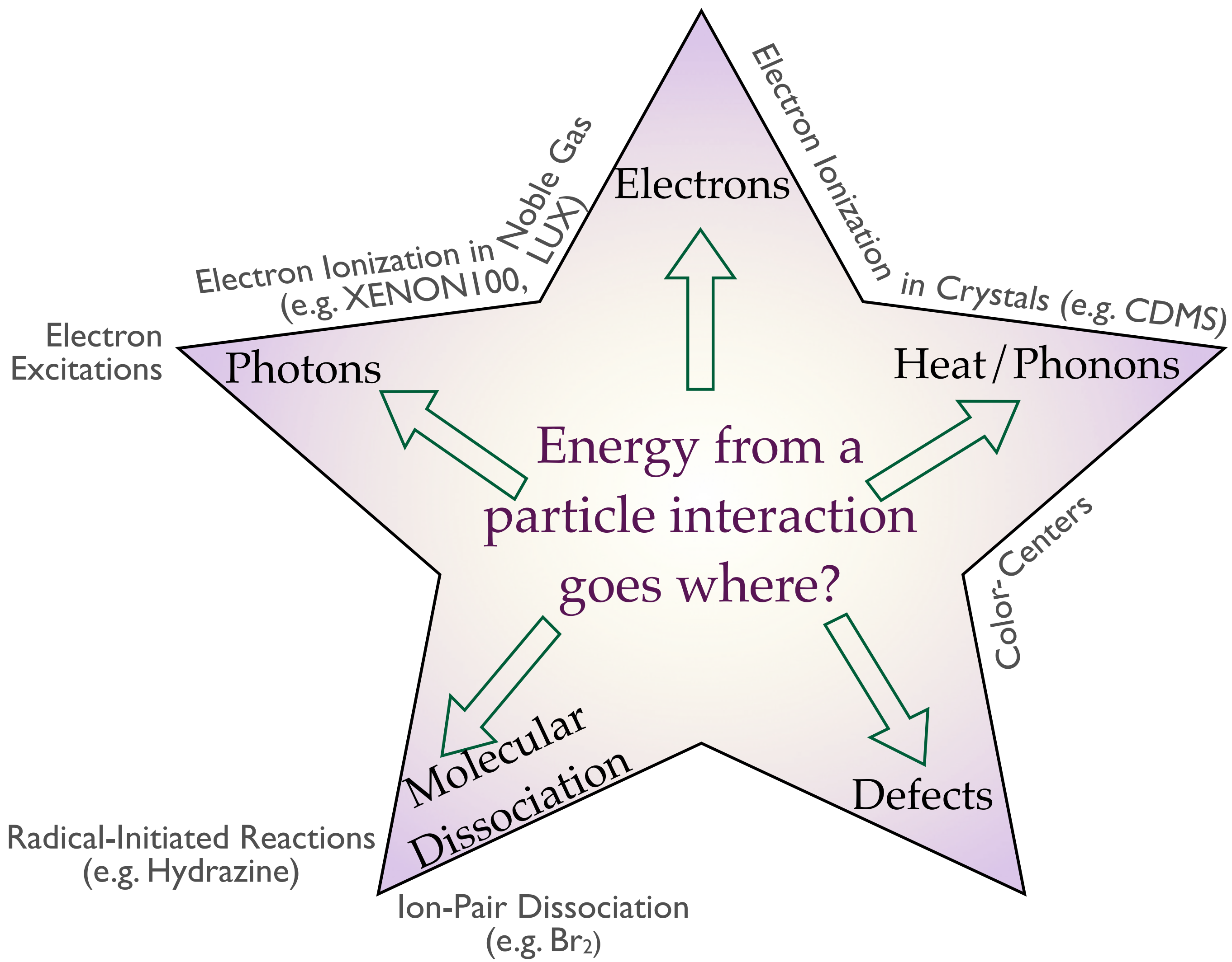


Detectable Signals



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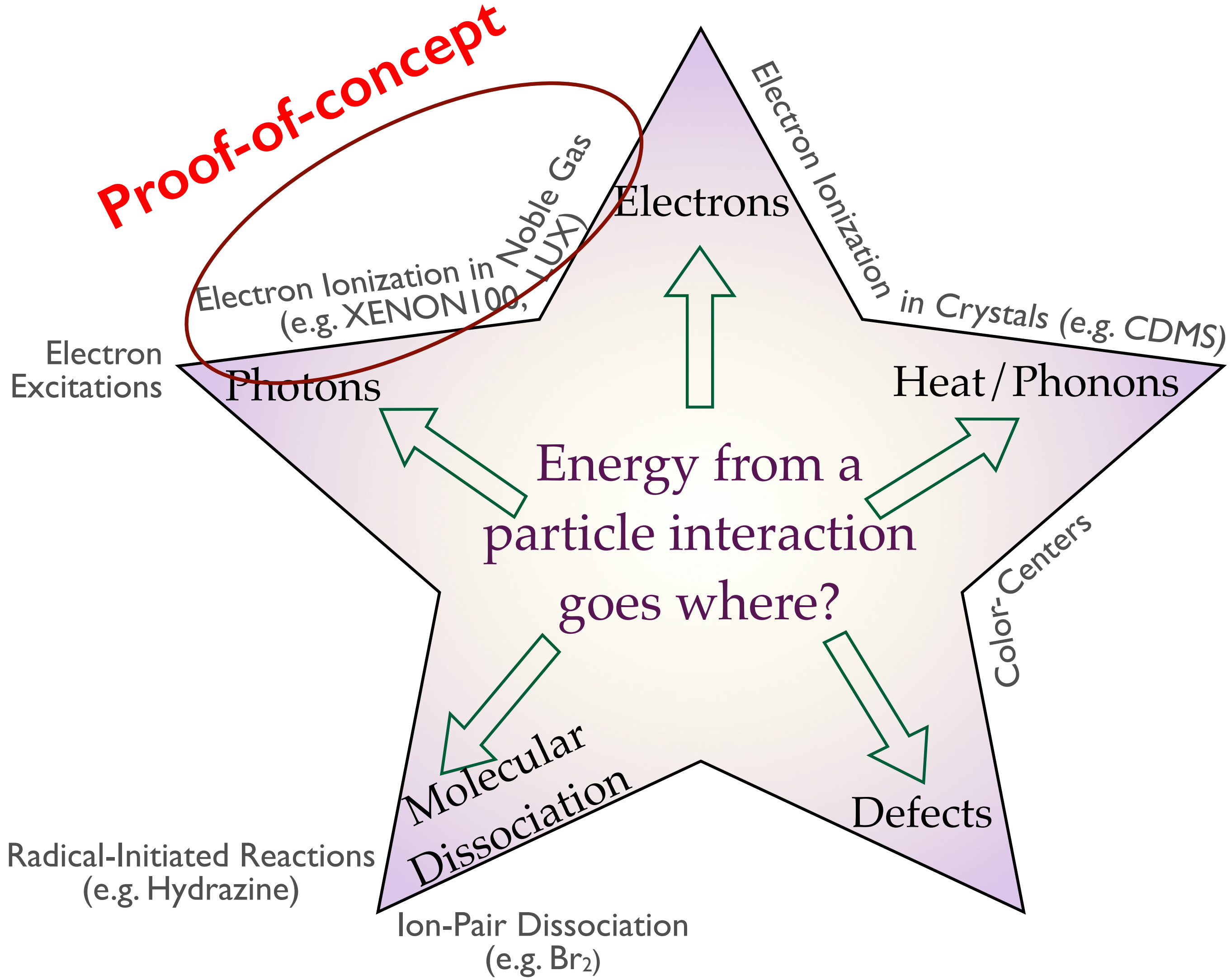

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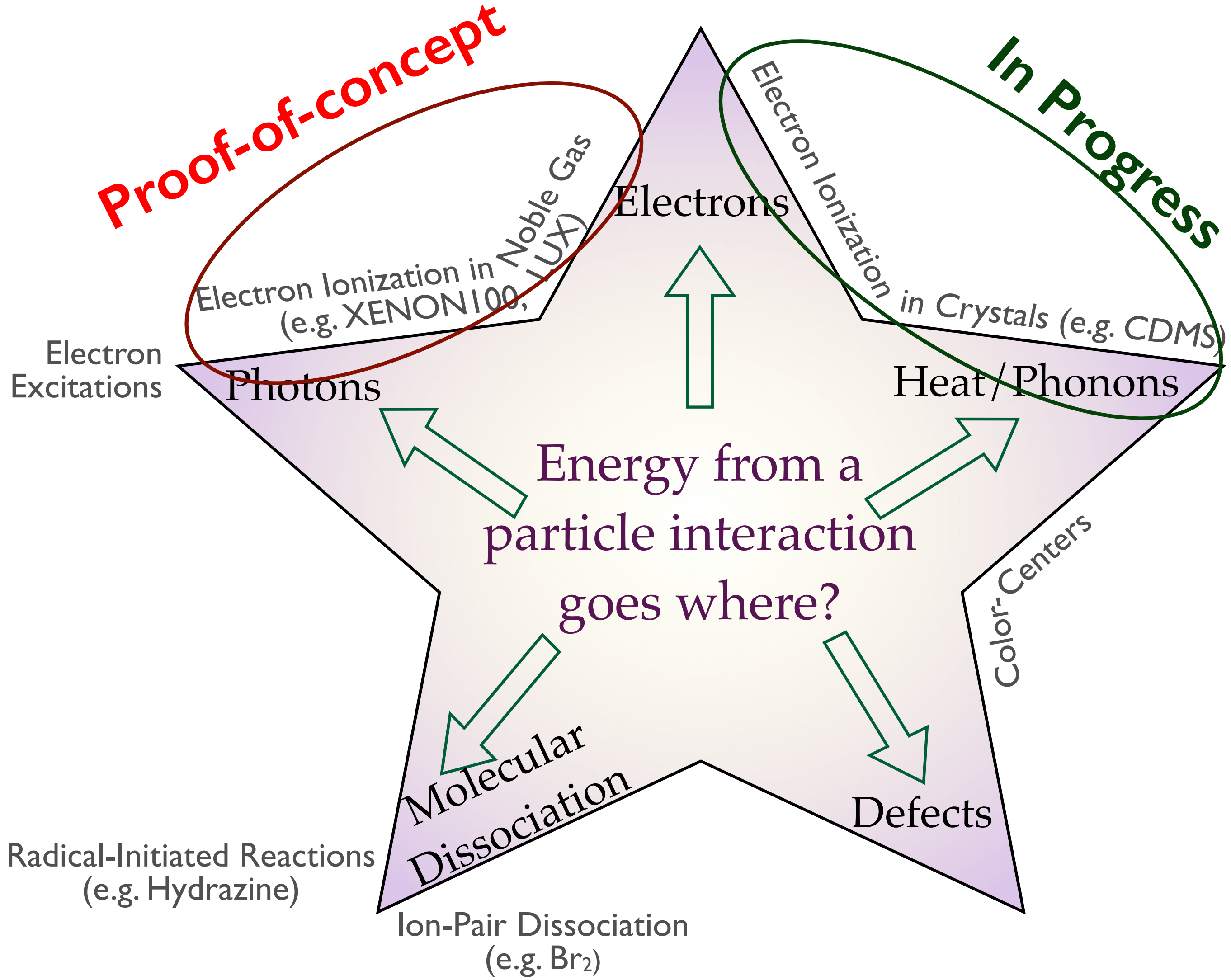

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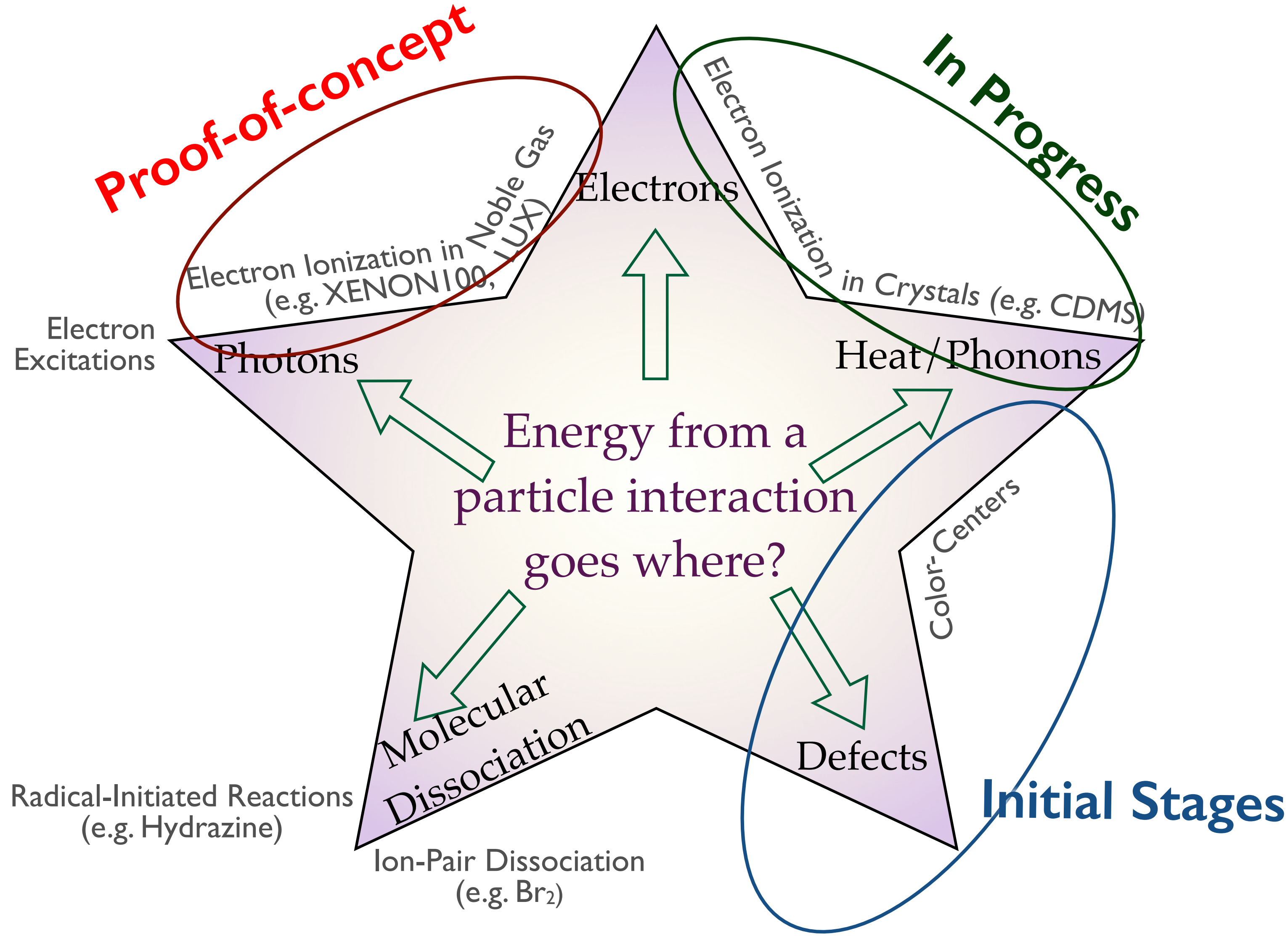

An ongoing program..

Upcoming:

- "Direct Detection of Dark Matter with MeV-to-GeV Masses using Semiconductor Targets",
  Essig, Fernandez-Serra, Mardon, Soto, TV, Yu
- "Search for sub-GeV Dark Matter with XENON100",
  XENON100 Collaboration w/ Essig, Mardon, TV
- "Detection of Weakly Interacting Particles via Molecular Excitations",
  Essig, Mardon, Slone, TV

Additional activities with several collaborations.

Electron Ionization

Proof-of-Concept

Ionization Cross-section

Scattering amplitude = (microscopic amplitude) × (atomic form factor)

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Determined by atomic wave-functions

$$\left|f^i_{ion}(k',q)\right|^2 = \frac{2k'^3}{(2\pi)^3} \sum_{\text{degen. states}} \left| \int d^3x\, \tilde{\psi}^*_{k'l'm'}(\mathbf{x}) \psi_i(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} \right|^2$$

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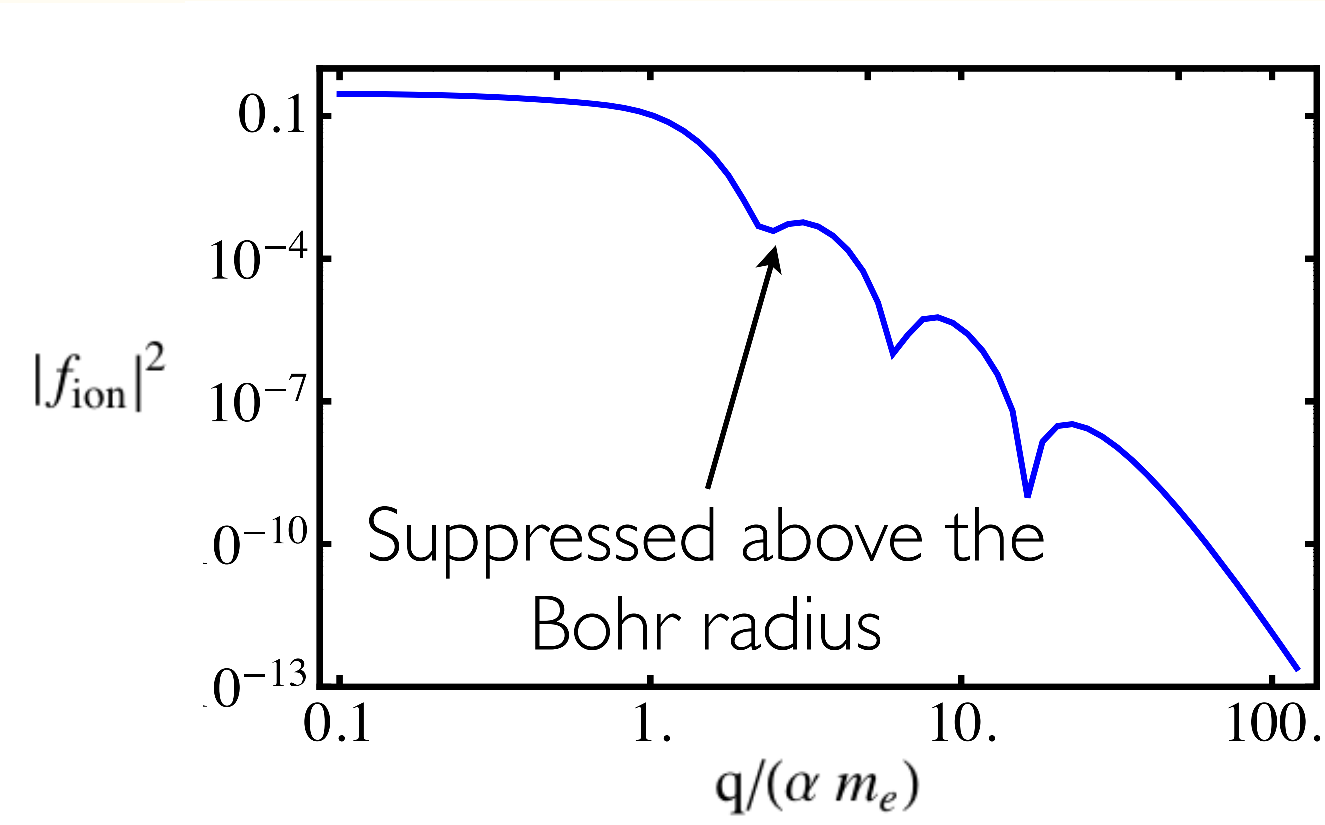

Rates are suppressed for large momentum transfer!

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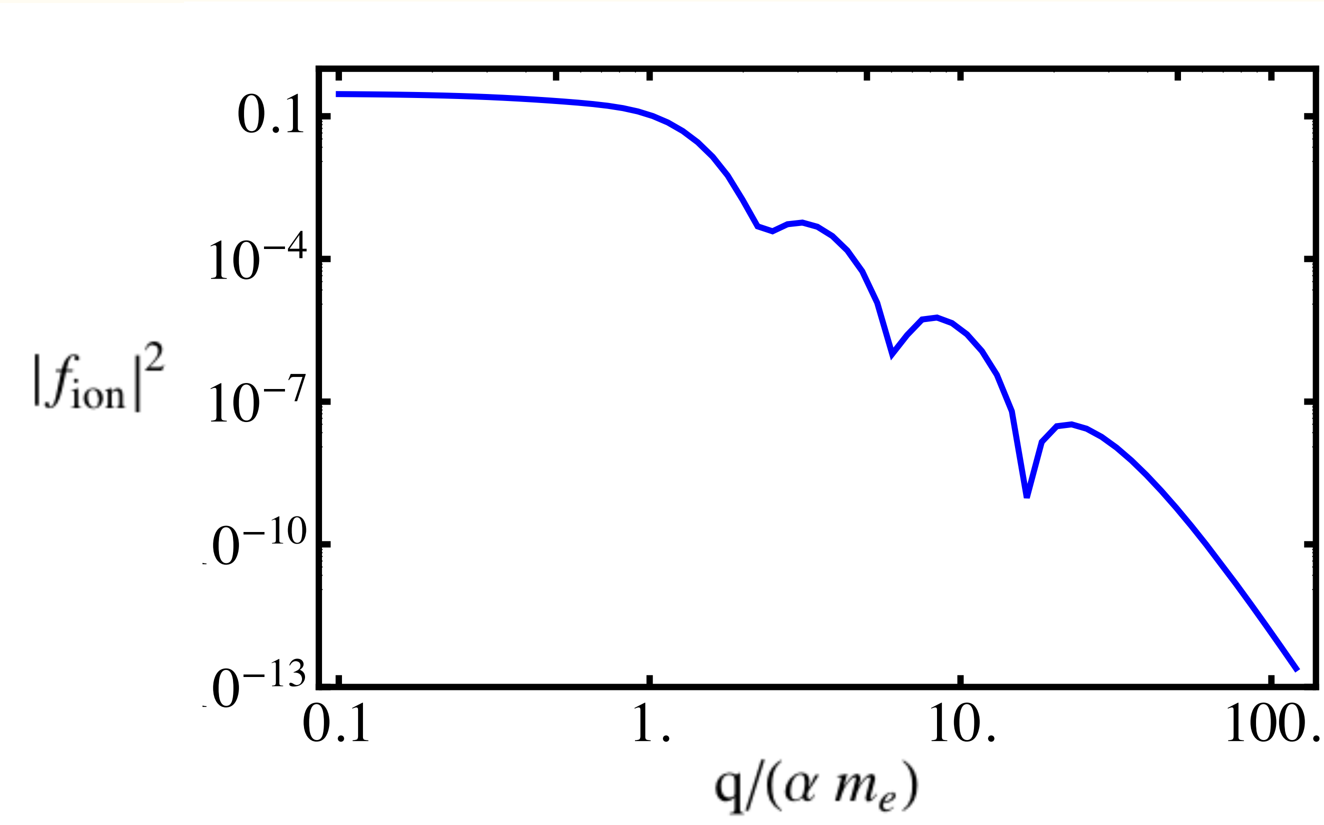

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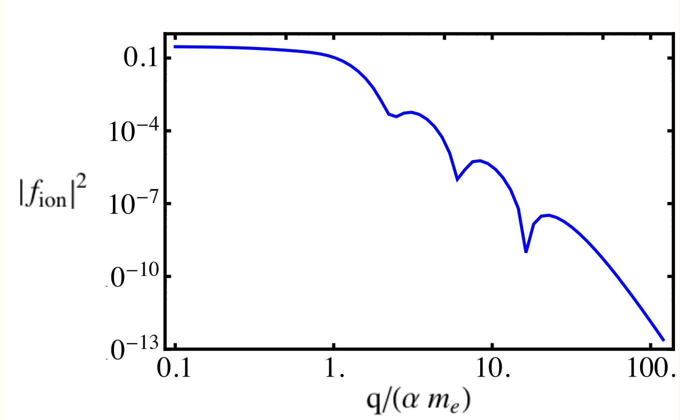


Determined by a specific DM theory

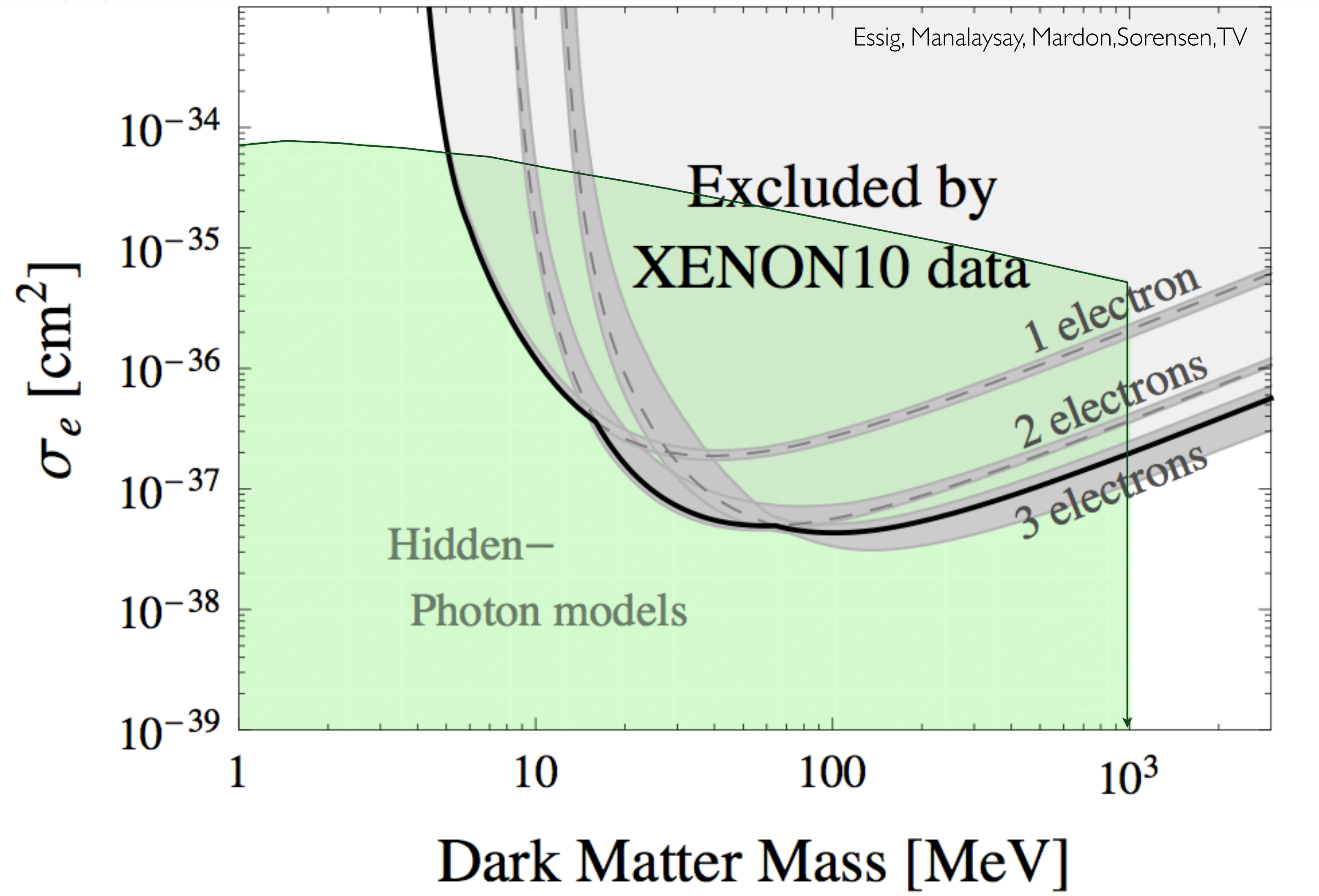
$$\overline{\sigma}_e \equiv \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2} \overline{\left|\mathcal{M}_{\chi e}(q)\right|^2}\Big|_{q^2=\alpha^2 m_e^2}$$

$$\overline{\left|\mathcal{M}_{\chi e}(q)\right|^2} = \overline{\left|\mathcal{M}_{\chi e}(q)\right|^2}\Big|_{q^2=\alpha^2 m_e^2} \times \left|F_{\rm DM}(q)\right|^2$$

$$\frac{d\langle\sigma_{ion}^i v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\,dq \left|f_{ion}^i(k',q)\right|^2 \left|F_{\rm DM}(q)\right|^2 \eta(v_{\rm min}) \qquad \langle\frac{1}{v}\theta(v - v_{\rm min})\rangle$$

Results from XENON10: $F_{DM}=1$

First Direct Detection Bounds for MeV-GeV



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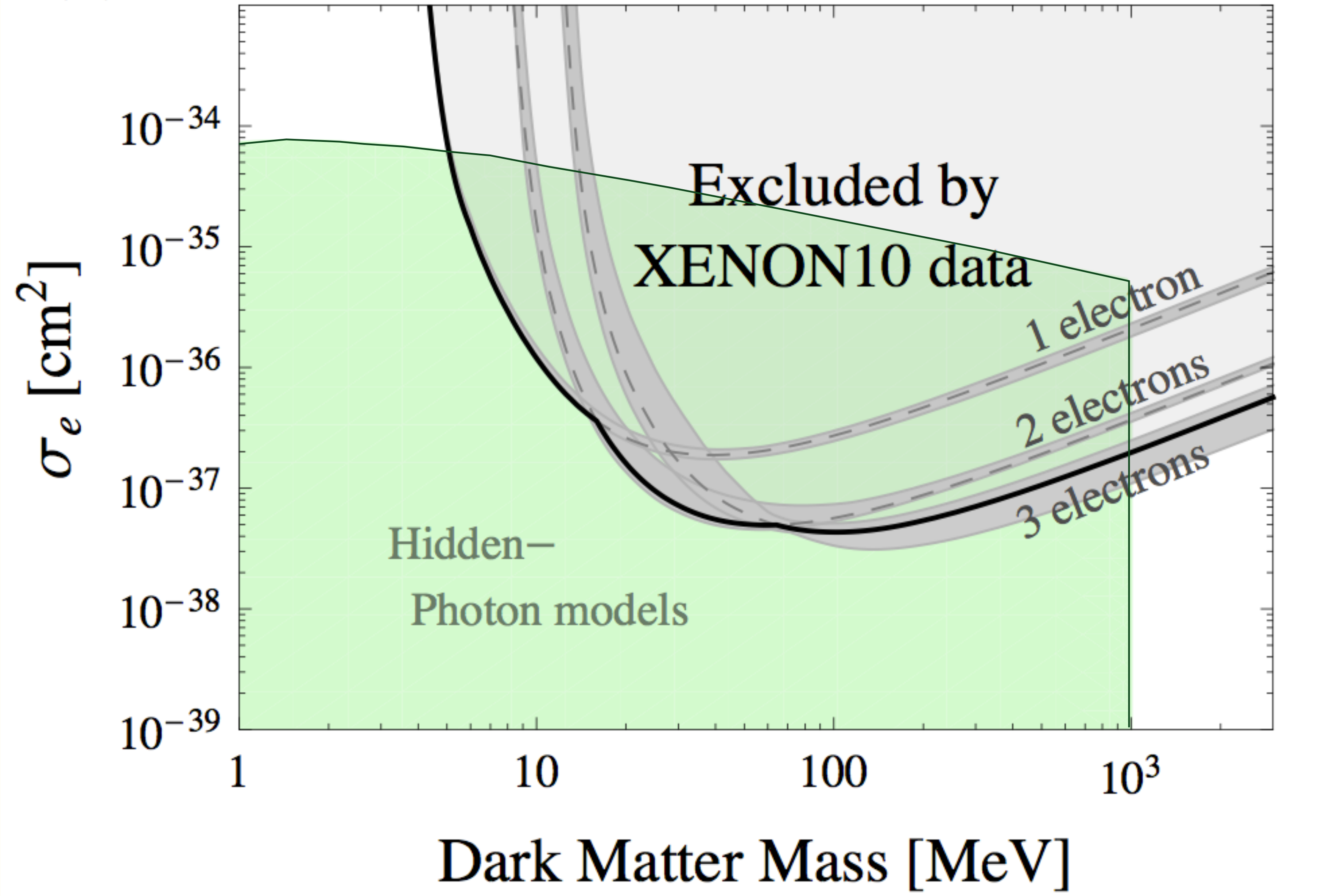
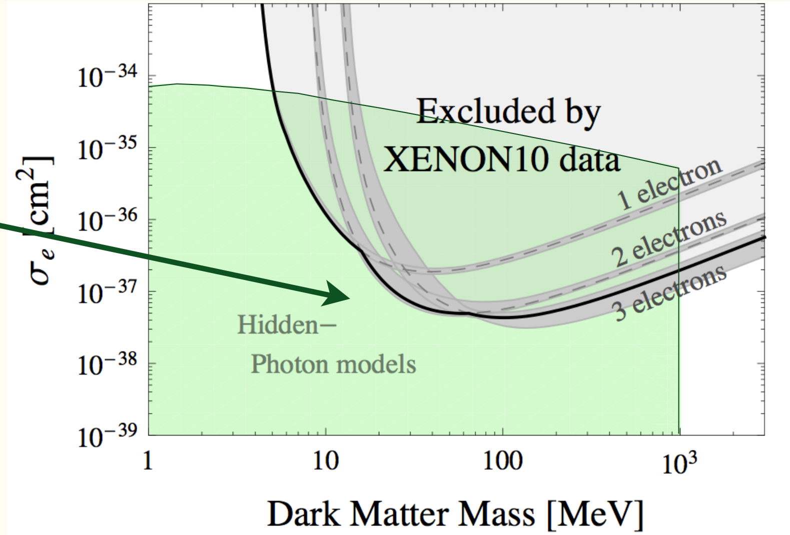
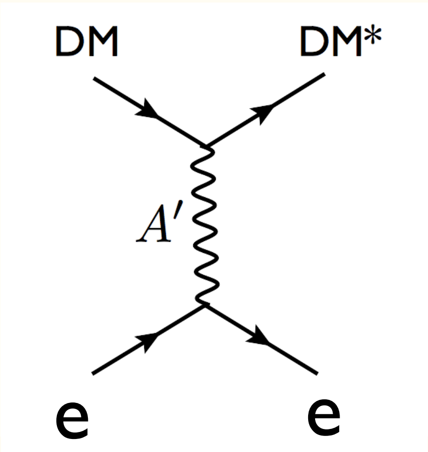


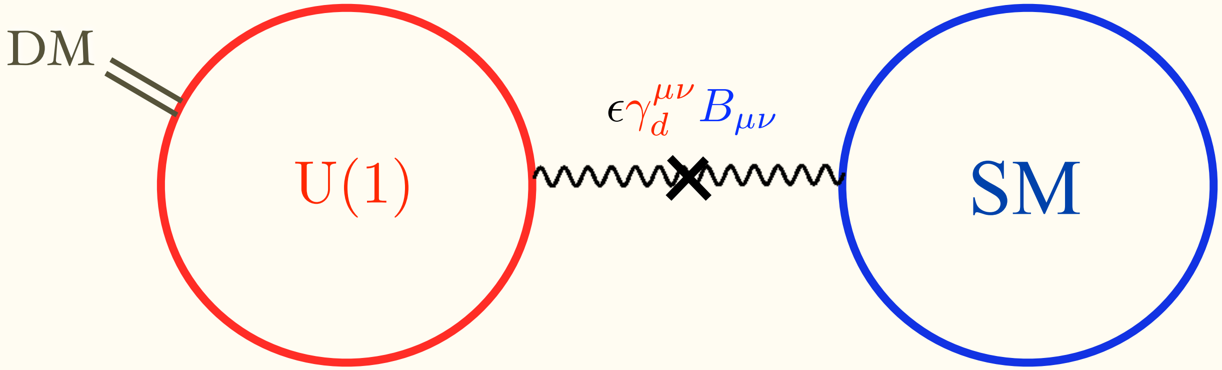
Results from XENON10: $F_{DM}=1$

Model in GREEN



- DM coupled to a hidden photon
- Kinetic mixing induces couplings with SM.





$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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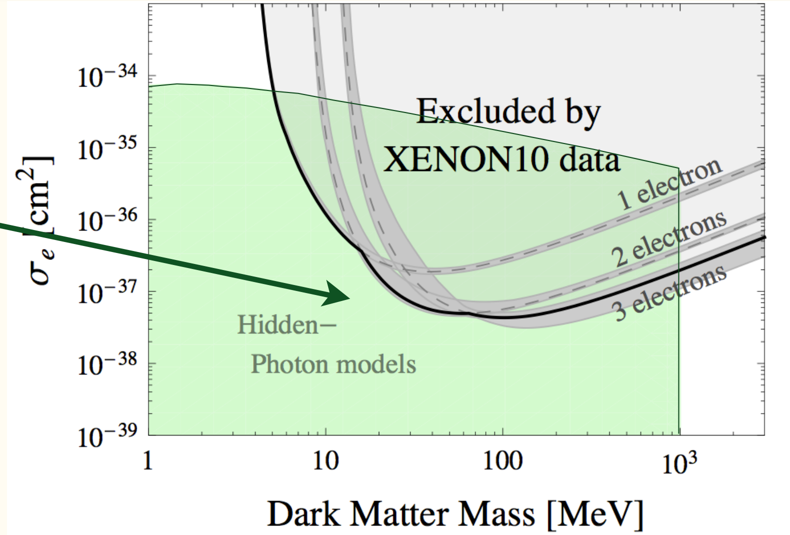

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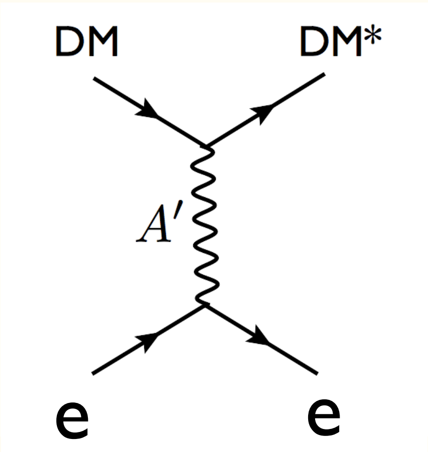
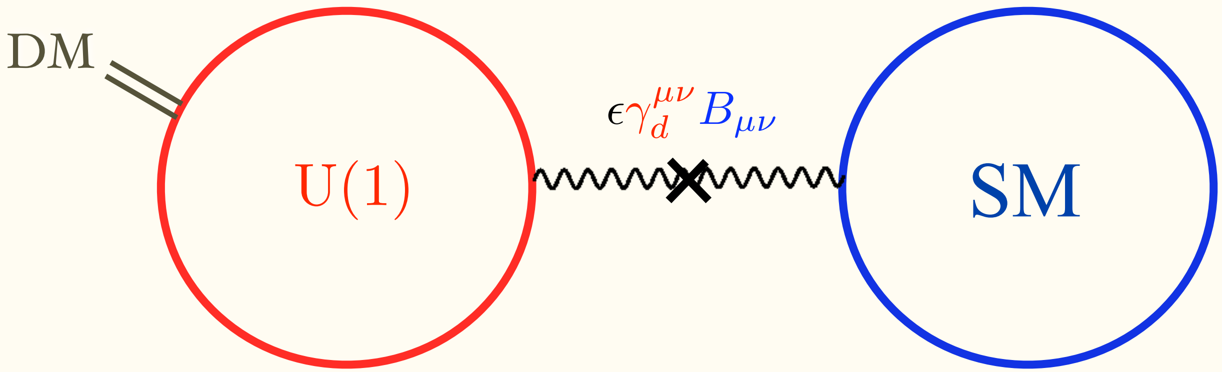
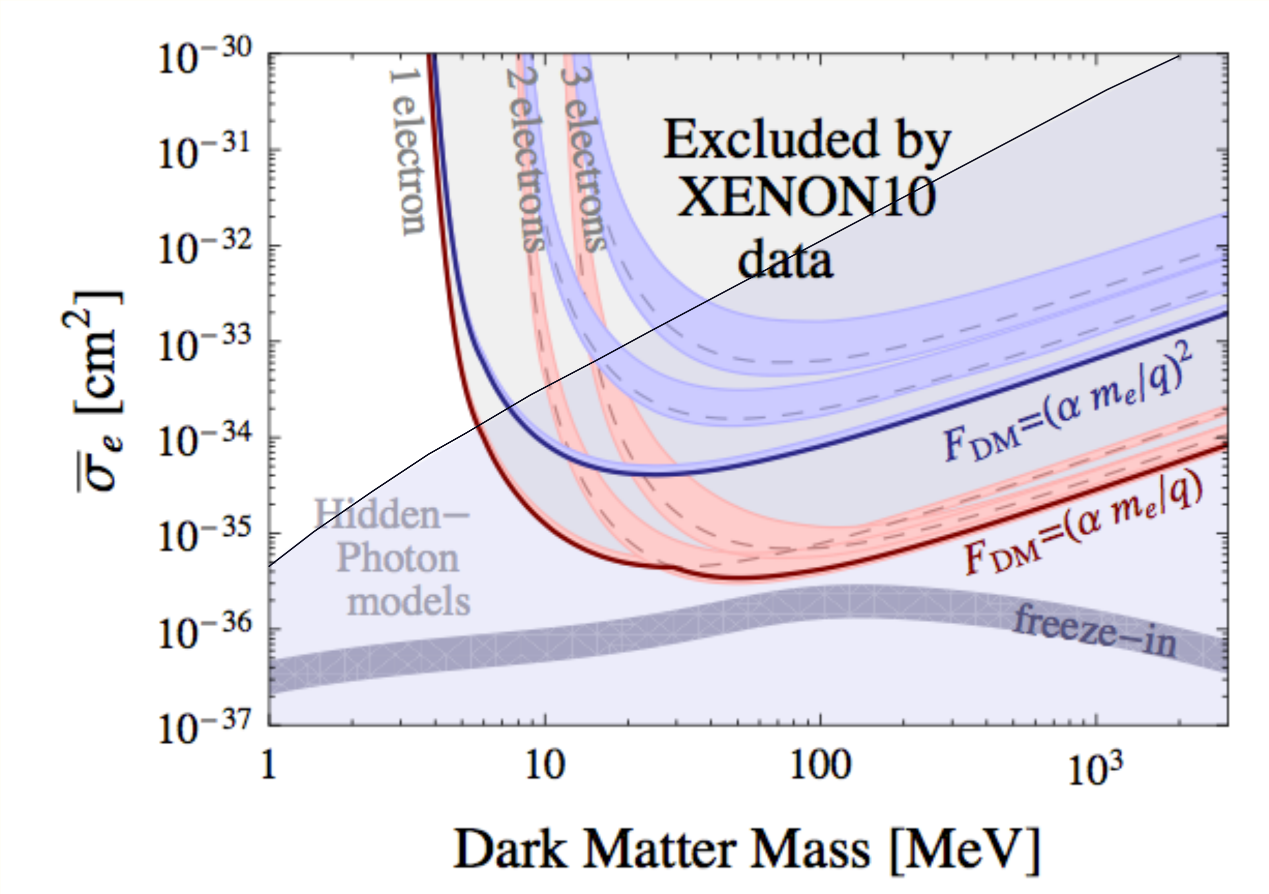




$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

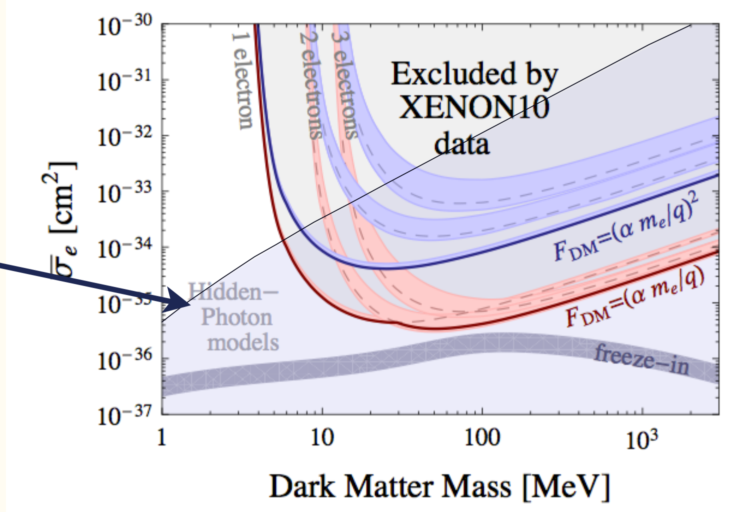
For m_A >MeV hidden photon: $F_{\rm DM} = 1$

Results: Non-trivial form factor

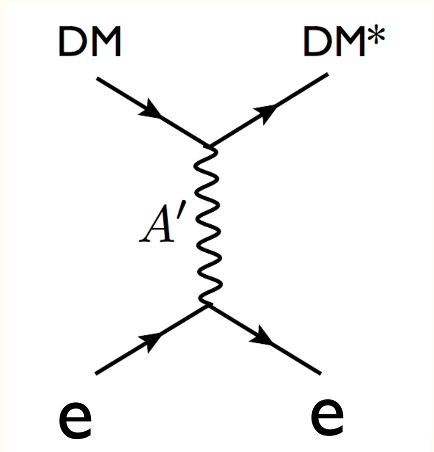


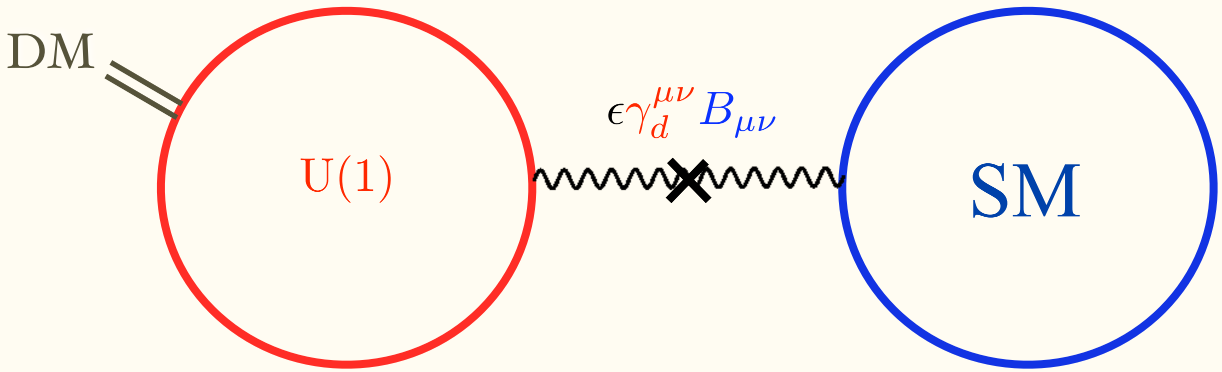
Results: Non-trivial form factor

Model in BLUE



- DM coupled to a hidden photon
- Kinetic mixing induces couplings with SM particles:





$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

For m_A << keV hidden photon: $F_{\rm DM} \propto 1/q^2$

XENON10

These are results for only 15 kg-days with a non-dedicated experiment!

Improvements could be very significant!!!

XENON100 - Work in progress..

Estimated Sensitivity

Essig, Mardon, TV with XENON100

Work in progress with CDMS too.

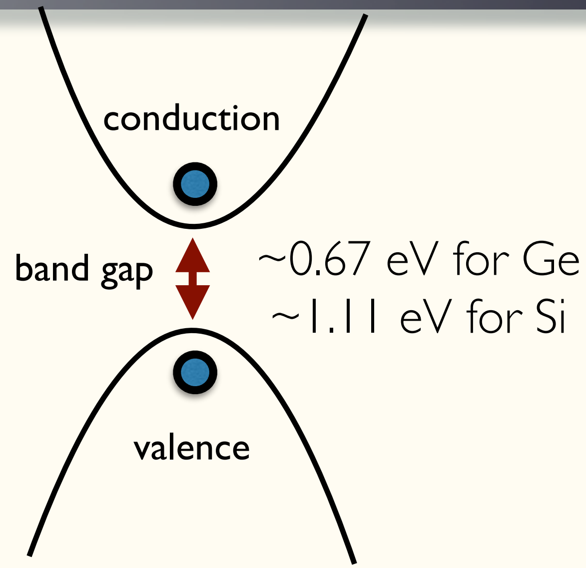
Electron Ionization

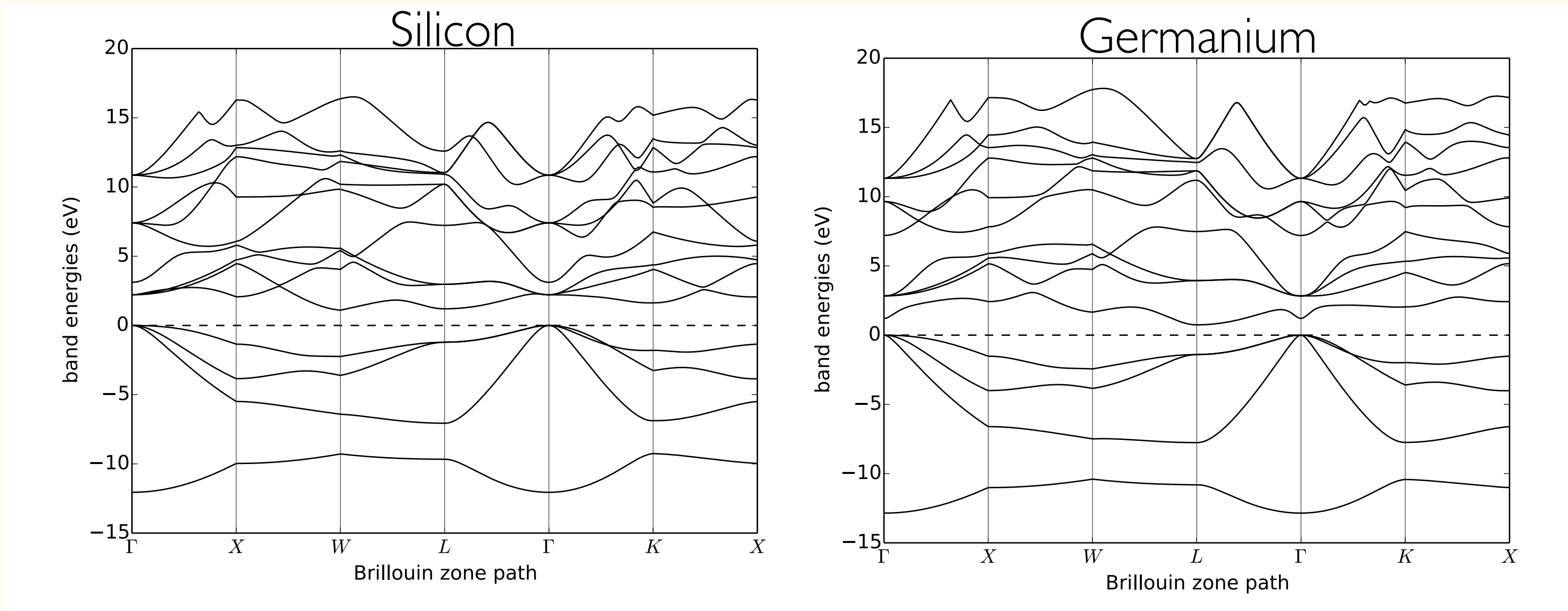
Semiconductors

Essig, Fernandez-Serra, Mardon, Soto, TV, Chiu-Tien Yu (1505.xxxx)

Harder to Compute…

band gap (~1 eV) < atomic ionization energy (~10 eV)

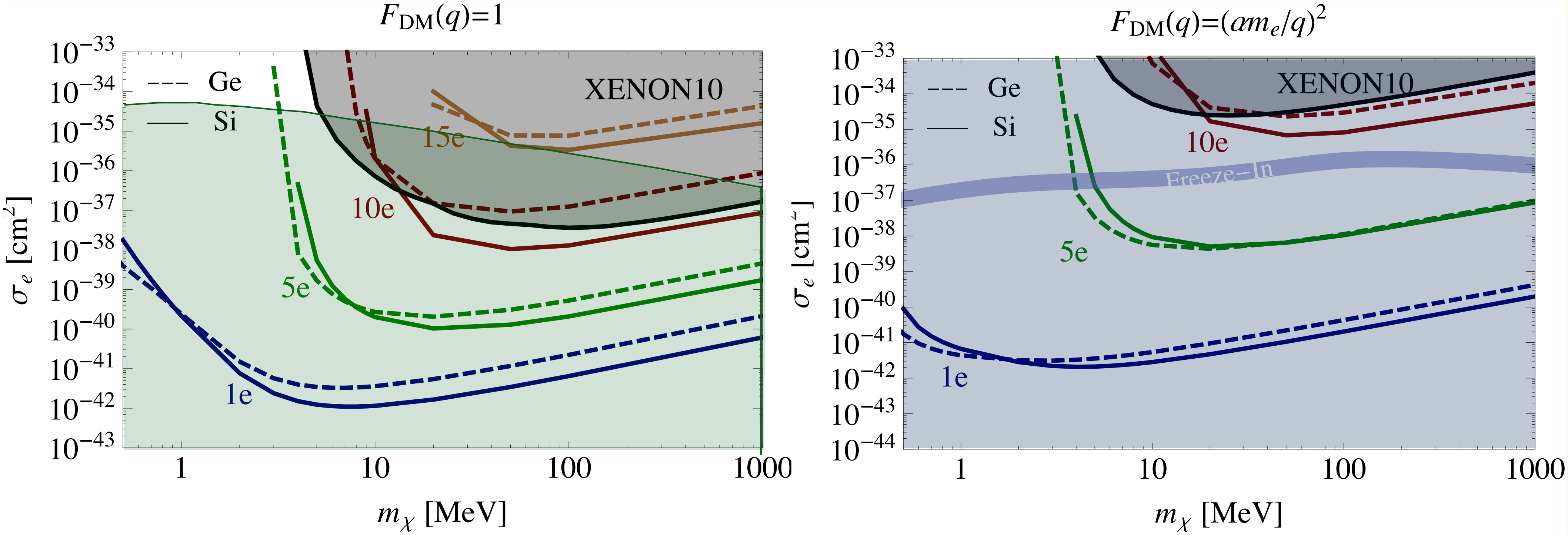




$$f^{\text{crystal}}_{i\vec{k}\to i'\vec{k}'} = \sum_{\vec{G}} u^*_{i'}(\vec{k}' + \vec{G} + \vec{G}')u_i(\vec{k} + \vec{G})$$

$$\psi_{i\vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{G} u_i(\vec{k} + \vec{G})e^{i(\vec{k}+\vec{G})\vec{x}}$$

But very promising..



Essig, Fernandez-Serra, Mardon, Soto, TV, Chiu-Tien Yu (1505.xxxx)

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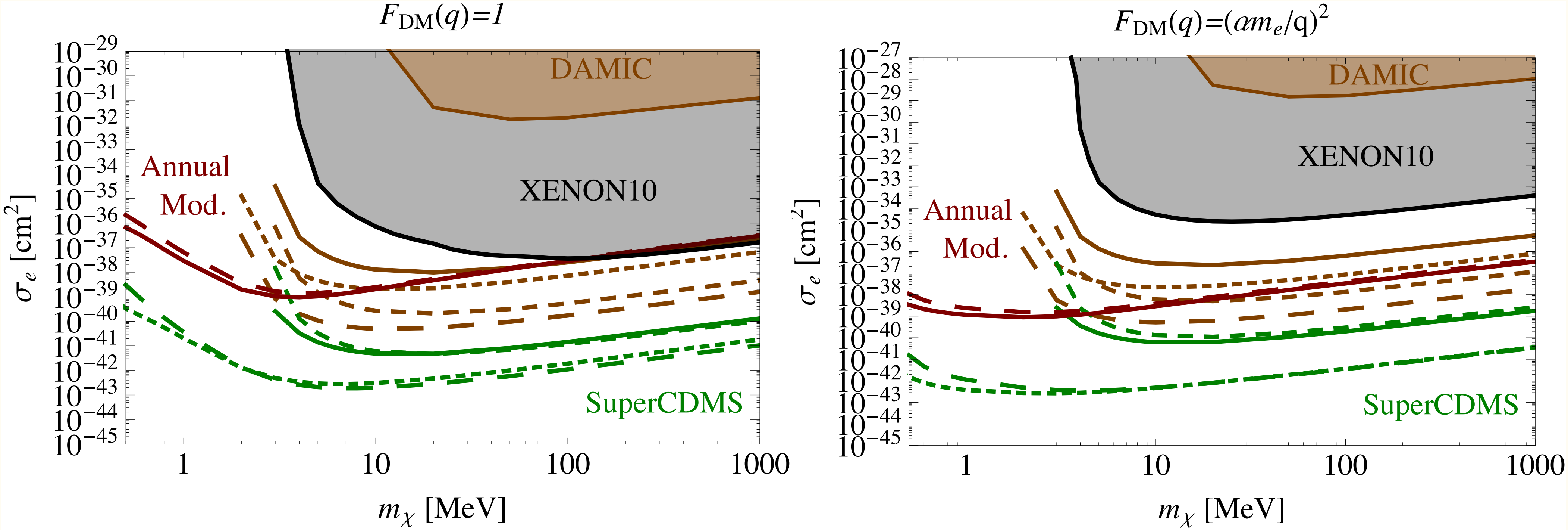

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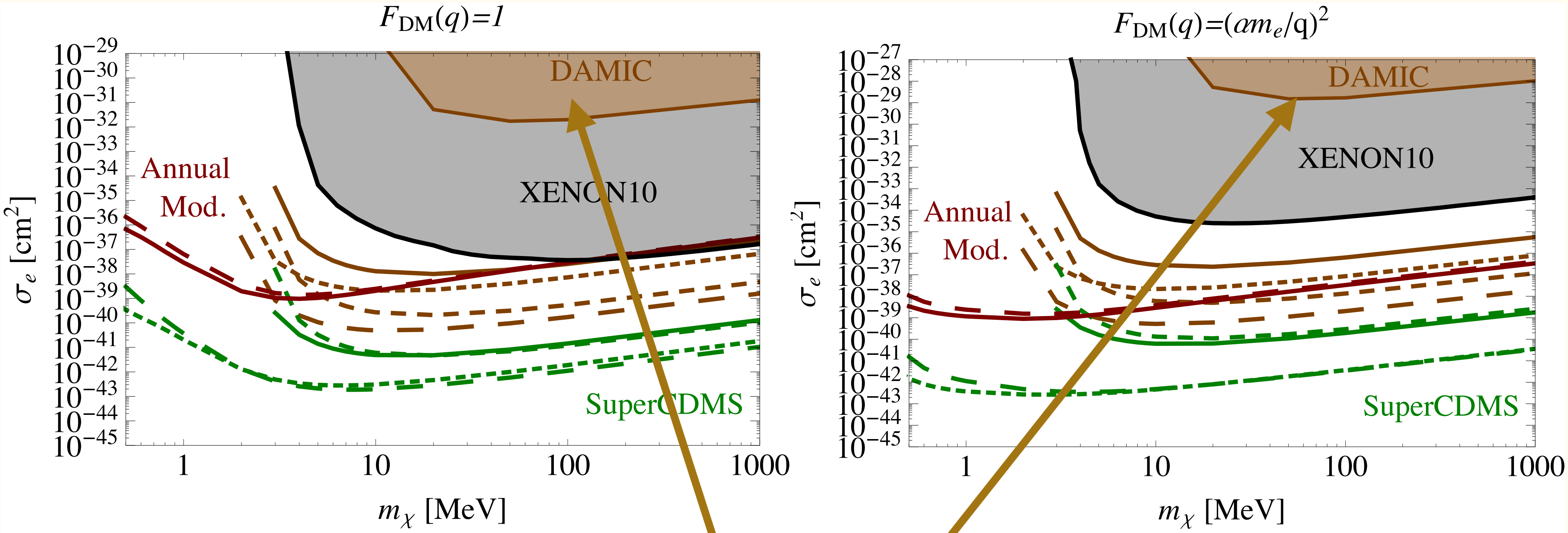
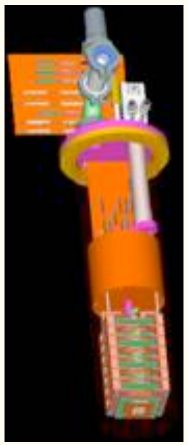


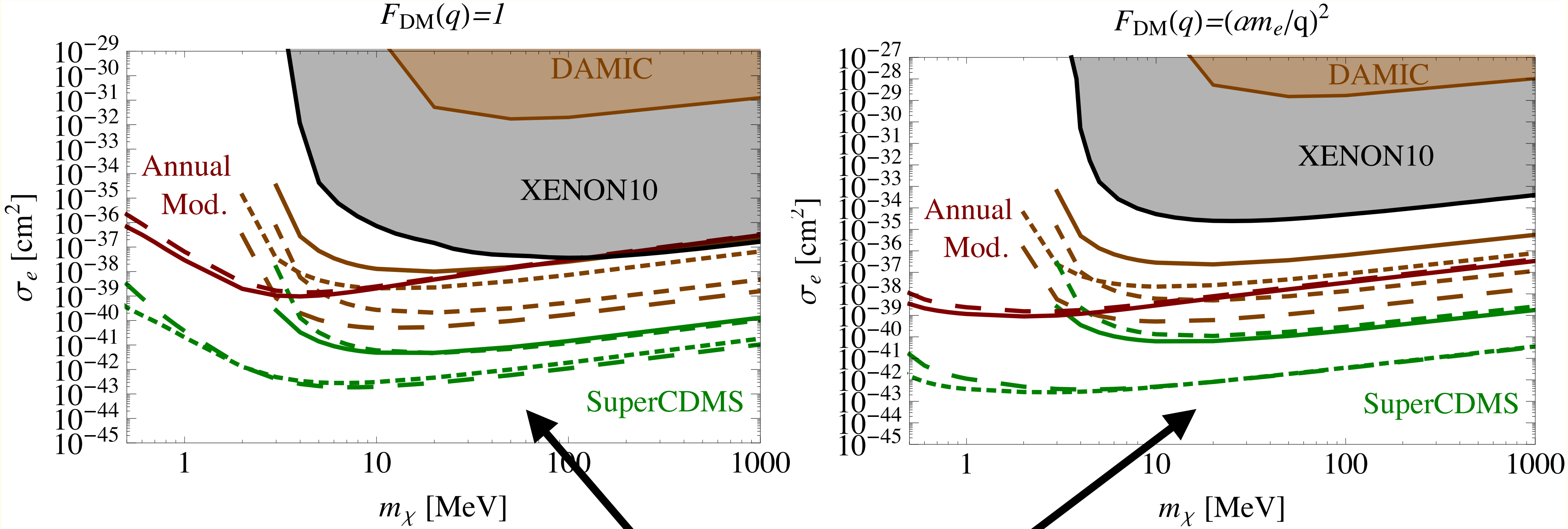
Essig, Fernandez Serra, Mardon, Soto, TV, Chiu-Tien Yu (1505.xxxx)

Silicon
107 g-days
11e threshold



DAMIC - **DA**rk **M**atter **I**n **C**CDs

But very promising..



Essig, Fernandez-Serra, Mardon, Soto, TV, Chiu-Tien Yu (1505.xxxx)

- **DAMIC**:
  1. 1 kg-day, 4e, 0.008=3.6 events
  2. 1 kg-day, 3e, 0.025=3.6 events
  3. 50 kg-days, 4e, 0.4=3.8 events
  4. 50 kg-days, 3e, 1.2=4.3 events
- **SuperCDMS**
  1. 20 kg-years, Ge, 4e, 3.6 events (eff=0.7)
  2. 20 kg-years, Ge, 1e, 3.6 events (eff=0.7)
  3. 10 kg-years, Si, 4e, 3.6 events (eff=0.7)
  4. 10 kg-years, Si, 1e, 3.6 events (eff=0.7)

Future

So we've seen no signal
(we believe in..)

What should we do to continue in the near and far future?

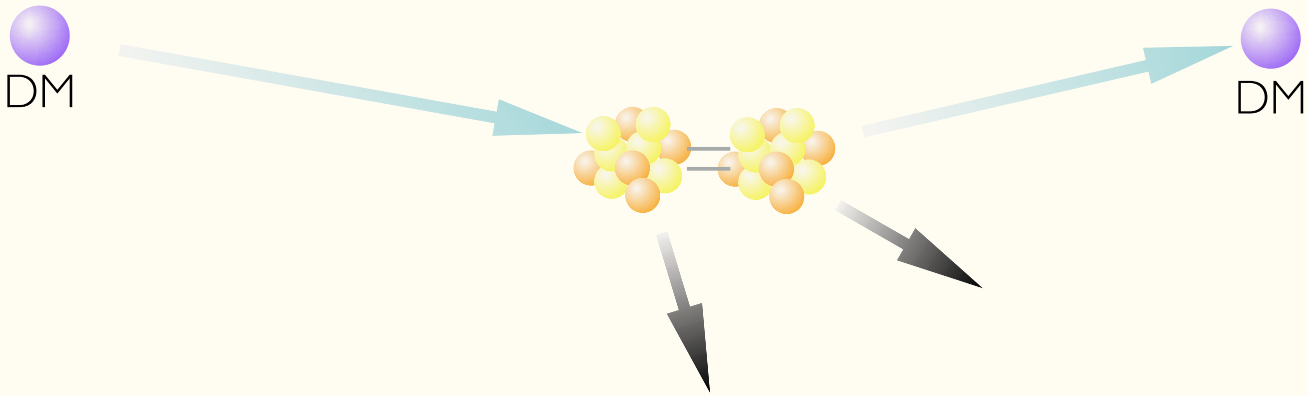
Looking for WIMPs

- In the next ~5-10 years, we'll cover much of the WIMP parameter space (but not all!!)
  - Direct Detection - Will reach the background neutrino limit.
  - Indirect Detection - Will exclude much of the parameter space for a thermal WIMP annihilation cross-section
  - LHC - Will reach its limits in producing DM.

What if we don't find it?

Bond Breakage: New Technologies

Concept



Ultra-low threshold (1eV - 10's of eV)

2-3 orders of magnitude below existing technologies

Detection Method

Spectroscopical measurement of induced chemical change

Bond Breakage: Color Centers

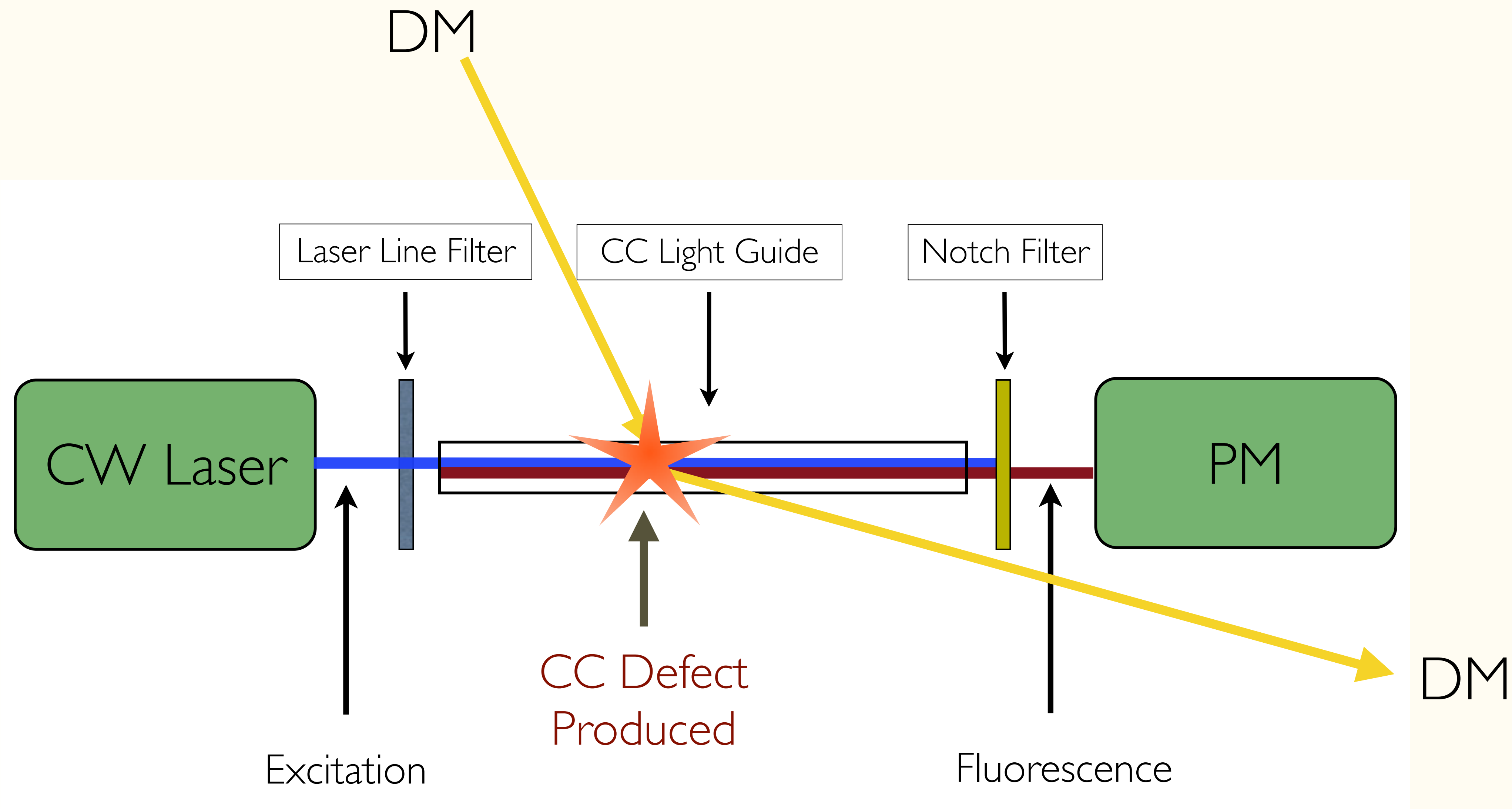
Color Centers

point defects in crystals, due to displacement of an atom into an interstitial position

- Properties fo Color centers:
  - Characterized by their effective charge and feature a strong localization of electrons
  - Produce luminescence light at specific energy.
  - Directional sensitive.
  - Differentiate between electron- and nuclear-recoils.
  - Threshold between 10eV to ~100eV.
- Examples: Sapphire (Al_2O_3), GaN.

Produced only via energetic nuclear collisions (low spontaneous formation rate)

Bond Breakage: Color Centers



Bond Breakage: New Technologies

Growing Theory-Experimental Collaboration

Initial funding granted

Th

- Rouven Essig (Stony Brook)
- Jeremy Mardon (Stanford)
- Oren Slone (TAU)
- Itay Bloch (TAU)
- Amit Abir (TAU)

Exp

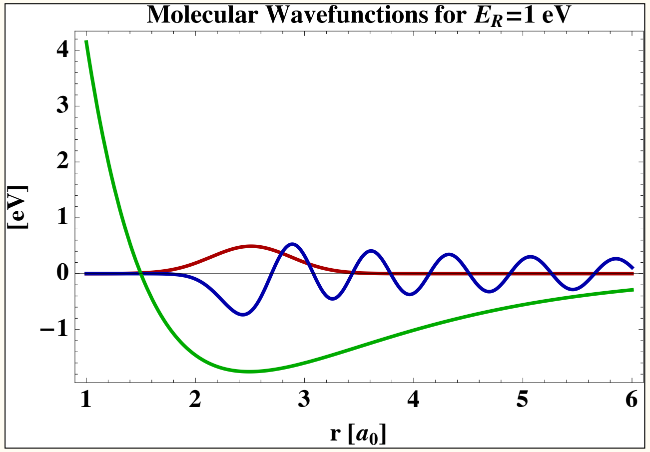
(New lab at Weizmann Institute)

- Ranny Budnik (Weizmann, HEP-Ex)
- Ori Chechnovsky (TAU, Chemistry-Ex)
- Avner Soffer (TAU, HEP-Ex)
- Arik Kreisel (NRC, HEP-Ex)
- Adi Ashkenazi (TAU, HEP-Ex)
- Ilan Sagiv (Weizmann, HEP-Ex)
- Hagar Landsman (Weizmann, HEP-Ex)

Bond Breakage: Theoretical Rates

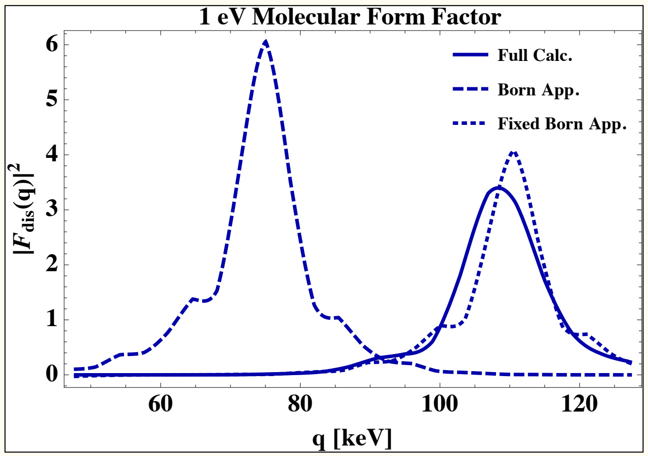
[Essig, Mardon, Slone, TV, in writing]

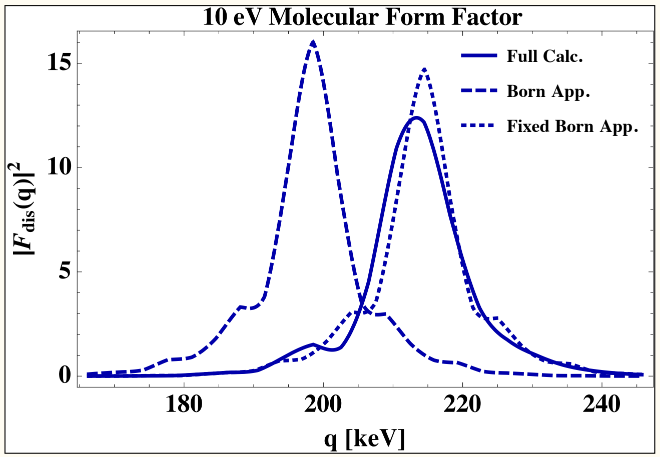
$$
\begin{aligned}
R &= N_m \frac{\rho_\chi}{m_\chi} \int d^3 v f(v) \int d\left\langle \sigma v \right\rangle \\
&= N_m \frac{\rho_\chi}{m_\chi} \frac{\overline{\sigma_p}(m_1+m_\chi)^2}{4 m_\chi^2 m_1^2} \int 4\pi v dv f(v) \int dlnE'_{int} \int qdq |F_{DM}(\mathbf{q})|^2 |F_{dis}(q, E'_{int})|^2 \Theta\left(v - v_{min}(q, E_{int})\right)
\end{aligned}
$$

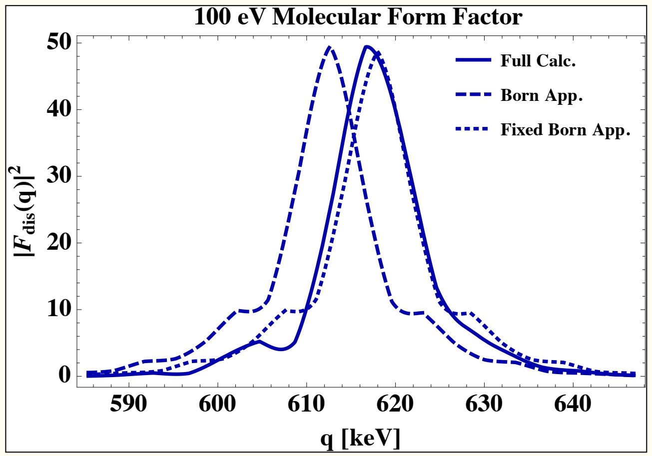


Relatively simple in molecules

Much harder in crystals

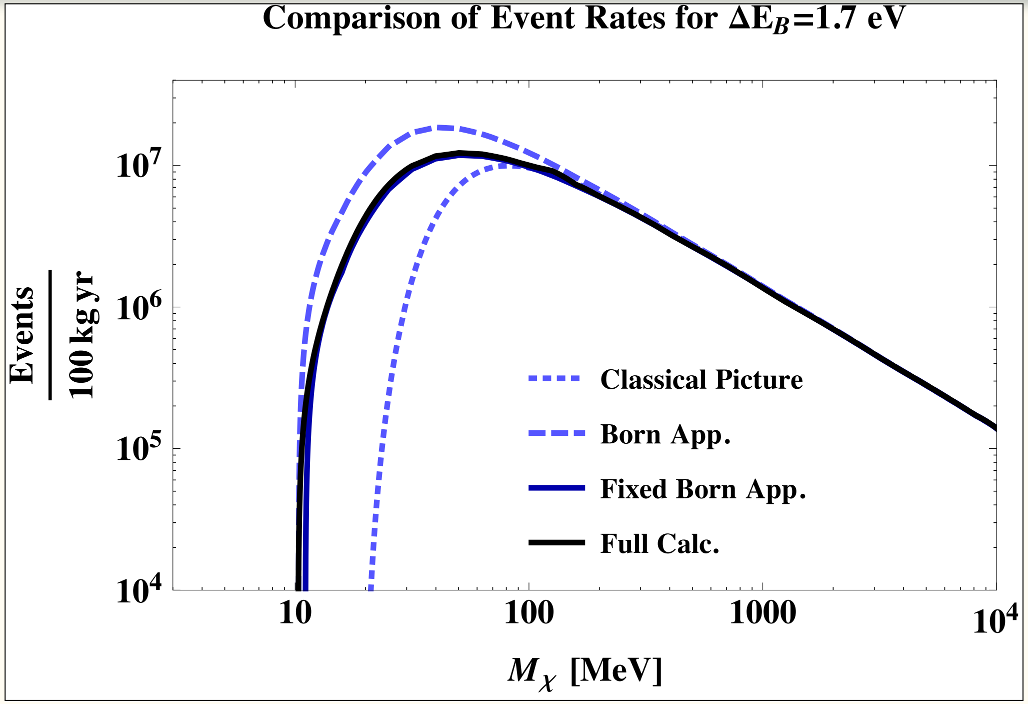


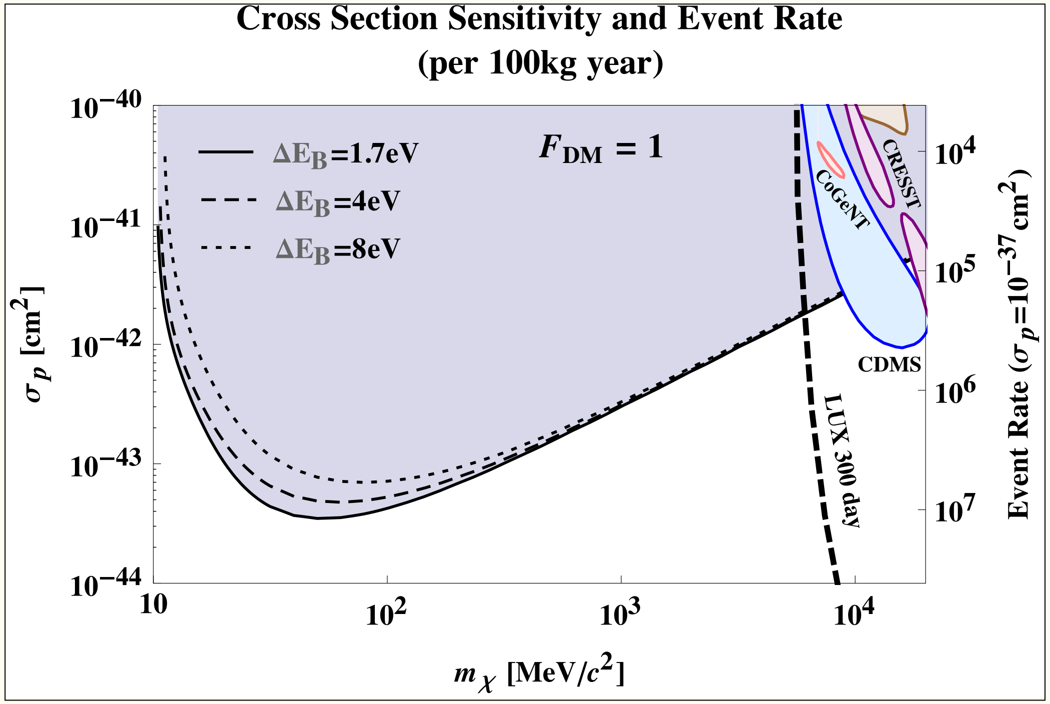


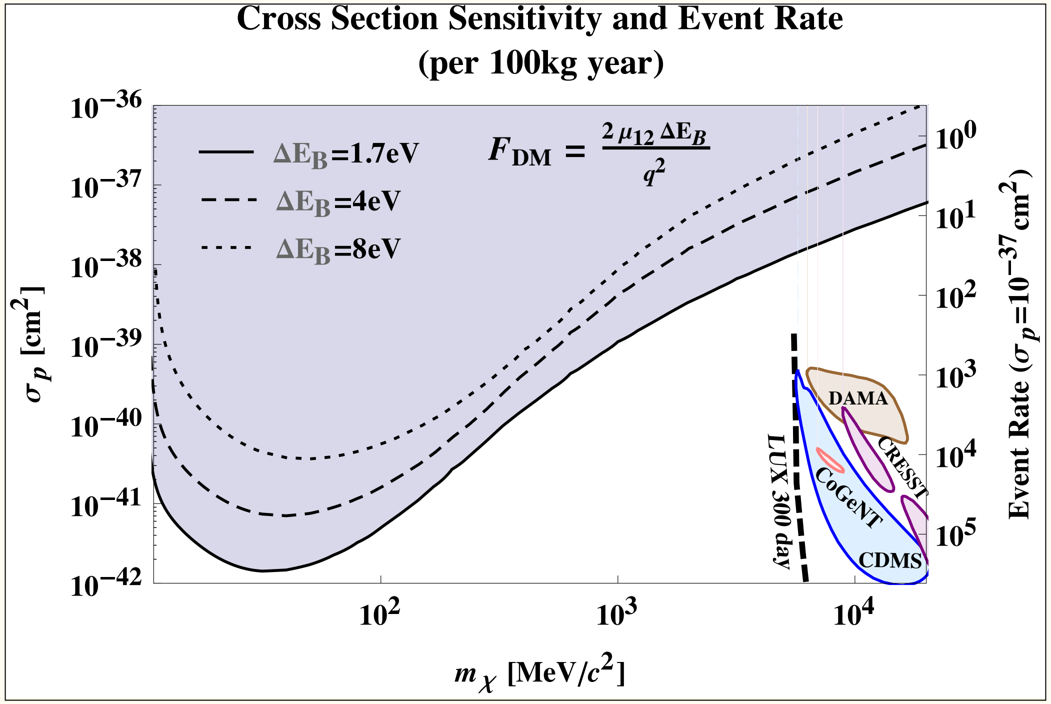


Bond Breakage: light DM Sensitivity

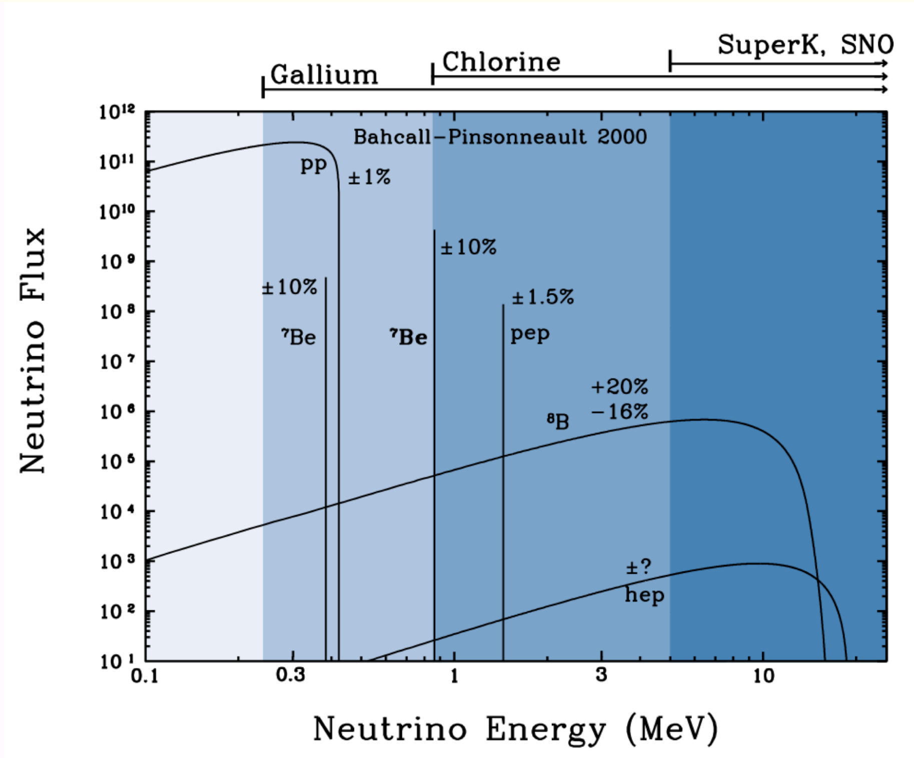
[Essig, Mardon, Slone, TV, in writing]

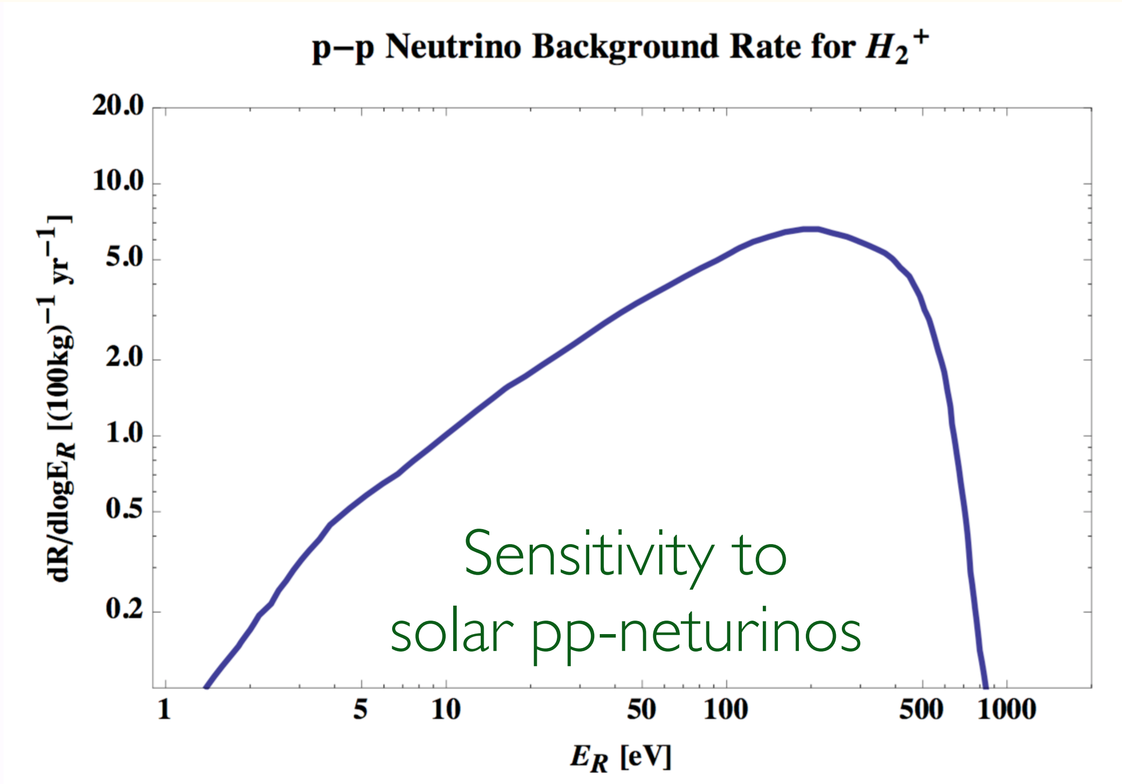






Bond Breakage: Solar Neutrinos





May also be sensitive to eV-scale axions
(in progress)

To Conclude..

The current experimental WIMP DM program will reach its end soon

Everything we did for the WIMP can be repeated again for sub-GeV DM

Many viable models exist that are waiting to be studied

New direct detection bounds are expected

Dedicated indirect searches and collider studies

New technologies are under development

Far too big a mystery to give up.
Can't stop now!

To be continued...

"That isn't dark matter, sir—you just forgot to take off the lens cap."