Beyond WIMP:
From Theory to Detection of Sub-GeV Dark Matter

March 2014

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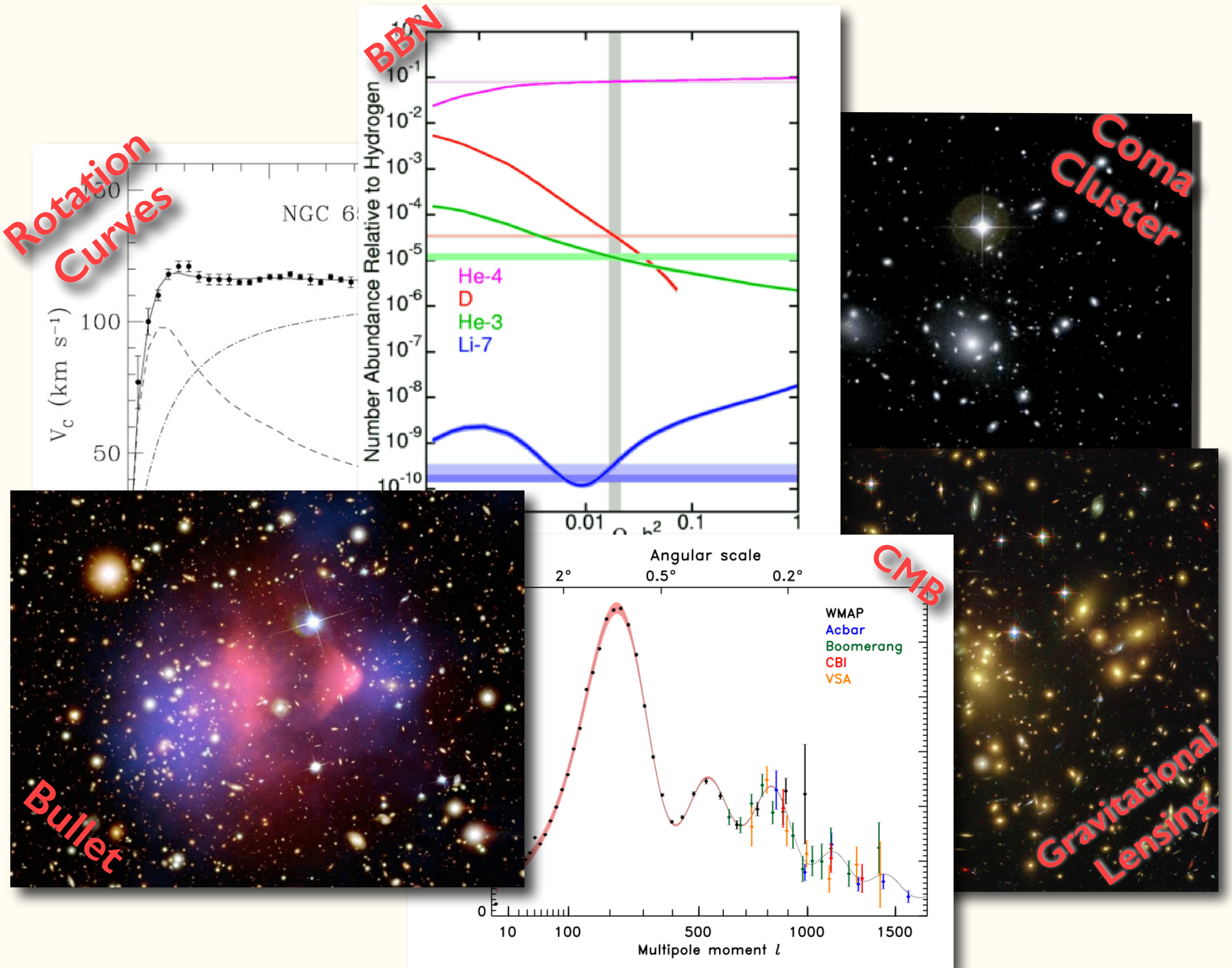
Tel-Aviv University

(Gravitational) Evidence for Dark Matter



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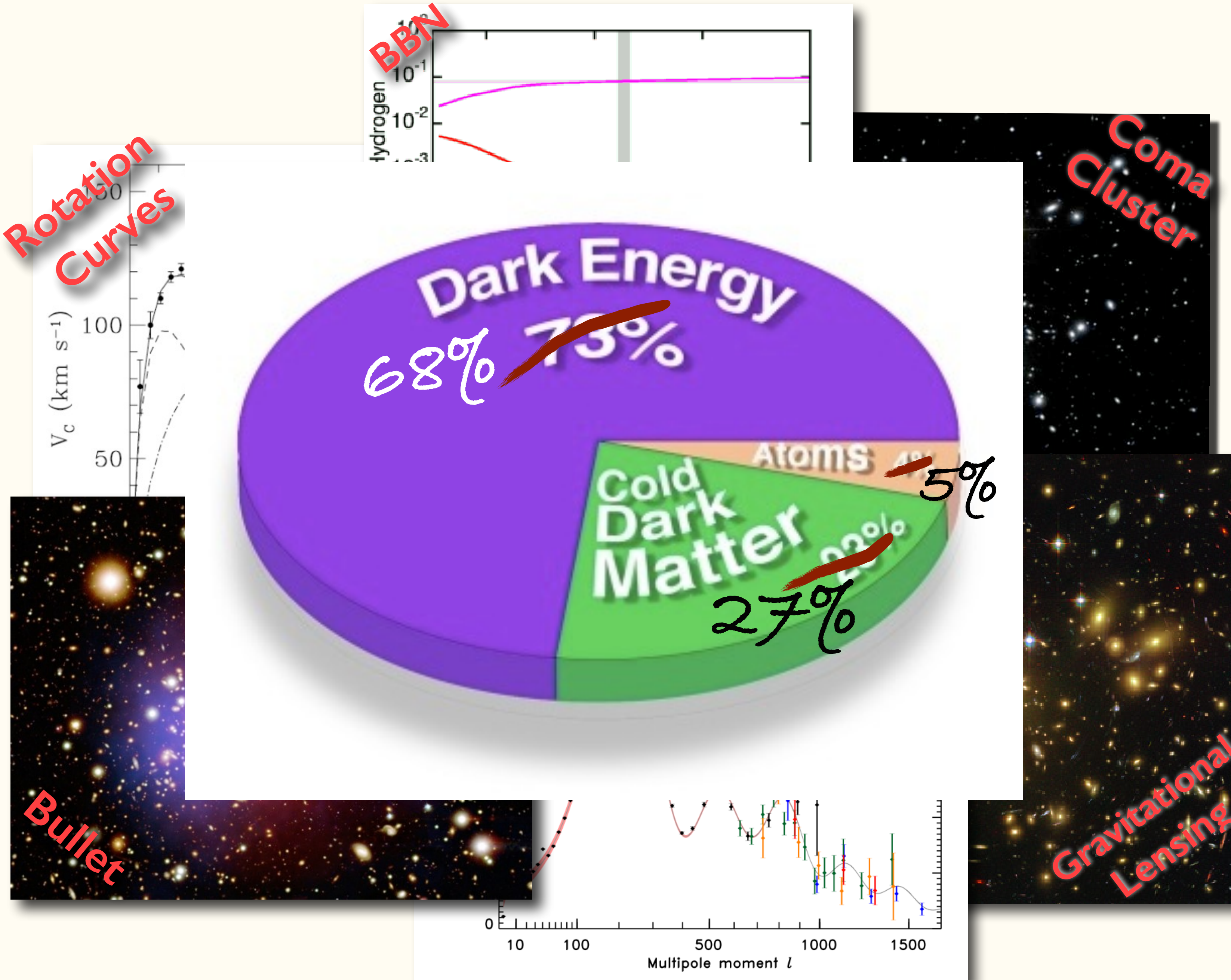

What is DM?

Clearly one of the biggest mysteries in Beyond the Standard Model!

- We don't know this particle(s) identity. But we know a little:
    - Comprises 85% of the matter in our universe.
    - Non-baryonic.
    - Massive.
    - Stable on cosmological timescales.
    - Doesn't interact with EM or QCD (at leading order).
    - Doesn't interact very strongly with itself.
    - …

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.
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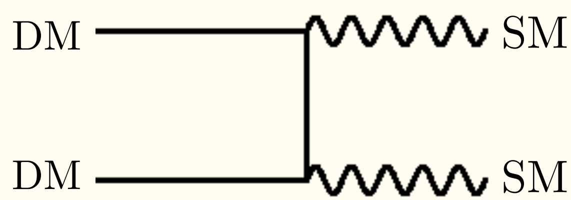

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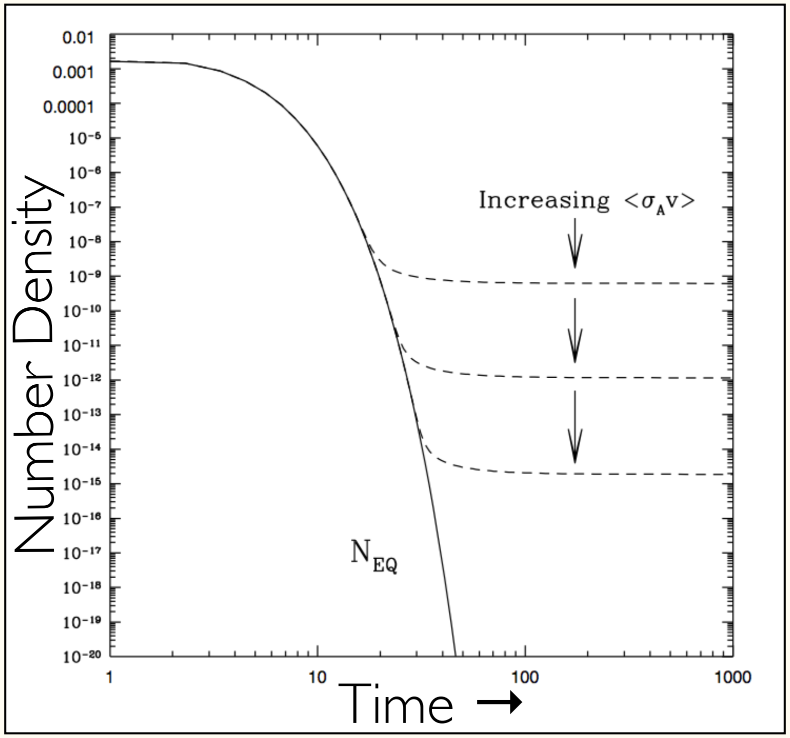

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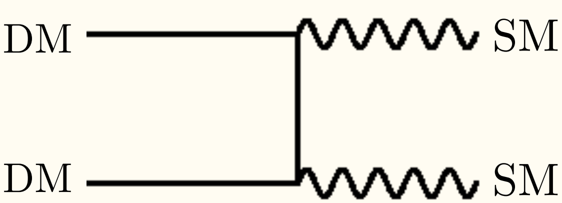

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The Thermal WIMP

- Evolution described by the Boltzamann eq.: $$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma v\rangle(n_\chi^2 - n_{\chi,\mathrm{eq}}^2)$$
- Solution can be approximated by solving:

$$\Gamma = n_\chi \langle\sigma v\rangle = H$$

- As expected, solution depends (strongly) on a single parameter: $\langle\sigma v\rangle$.
- One finds:

$$\langle\sigma v\rangle \sim 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$$

- For standard annihilation cross-section:

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

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Same mass-scale we are now probing at the LHC

The Thermal WIMP

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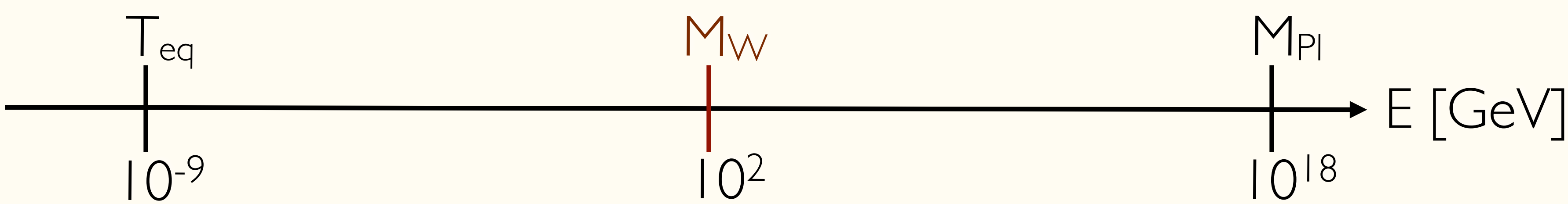
$$m_{\rm DM} \simeq \alpha \sqrt{T_{\rm eq} M_{\rm Pl}}$$

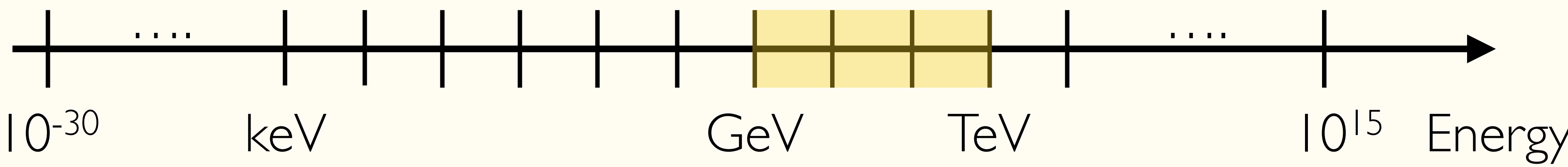


This is the WIMP Miracle

Obsessed with the WIMP...

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

Our experimental effort is strongly focused on the WIMP!



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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
- Experimental Probes of DM
  - Direct Detection
  - Indirect Detection
  - Cosmological and Astrophysical Probes
  - Colliders
- Future

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. — Kusenko 2006 (review)
  - Gravitinos. — Ellis,Kim,Nanopoulos; Moroi,Murayama,Yamaguchi;. . .
  - ...

Classifying Theories of DM

Production Mechanism

- Freeze-out
- Freeze-in
- Freeze-out and decay
- Non-thermal
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Couplings

- Quarks
- Gluons
- Charged Leptons
- Neutrinos
- Photons
- …

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• Non-thermal	• Axion portal	• Neutrinos
• Asymmetric production	• Higgs portal	• Photons
• Misalignment mechanism	• …	• …
• …		

Couplings: Quarks, Gluons } Direct; Quarks, Gluons, Charged Leptons } Colliders; Charged Leptons, Neutrinos, Photons } Indirect

Only a small fraction is probed for the WIMP

Asymmetric/Non-Thermal Production

[Kuflik, Levi, Merdler, 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.

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- Typical models of Asymmetric DM work as follows:

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

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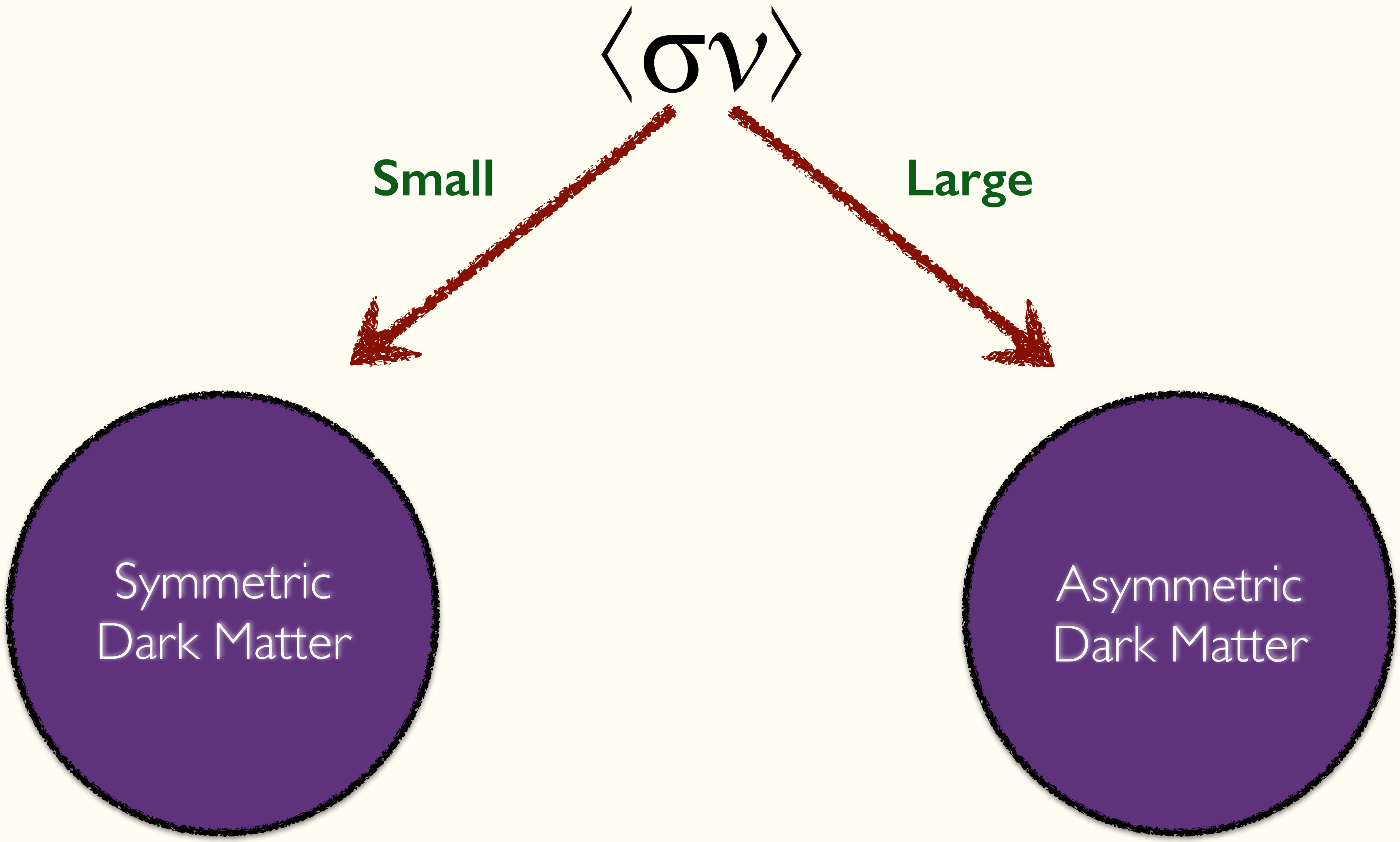
- Whether or not the symmetric component dominates, depends on the the DM annihilation cross-section

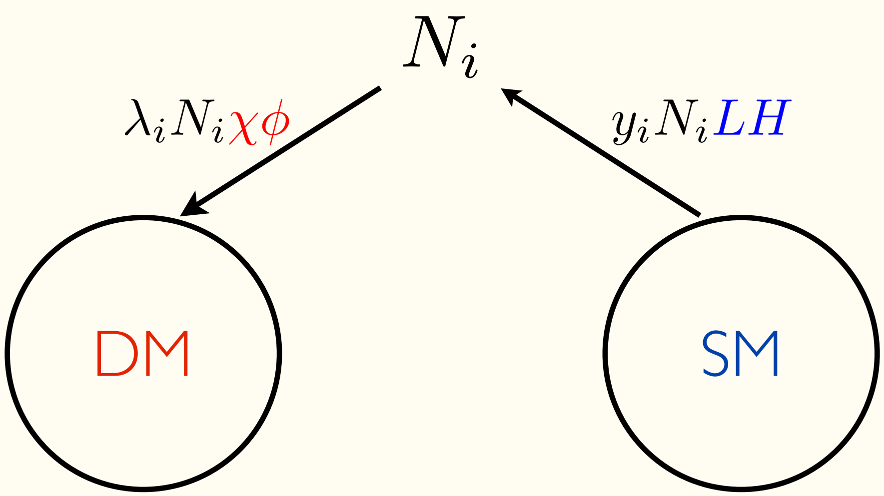
Asymmetric / Non-thermal



Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

[Falkowski,Ruderman,TV, 2011]



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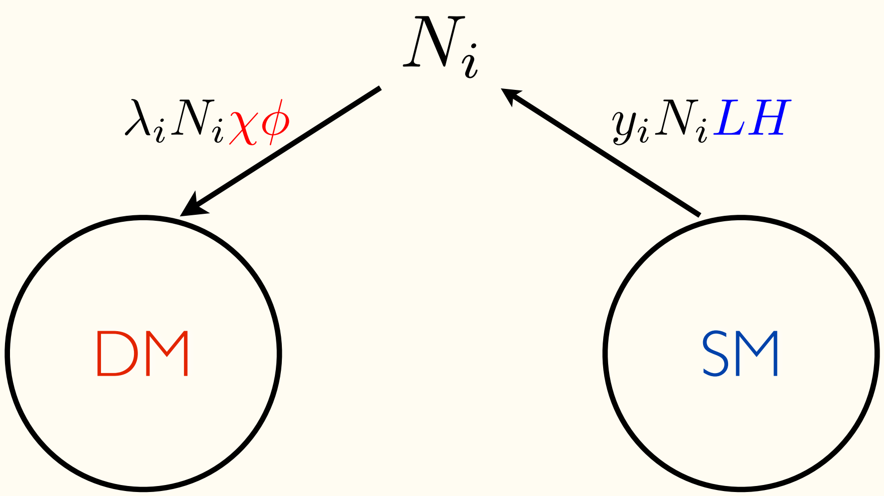
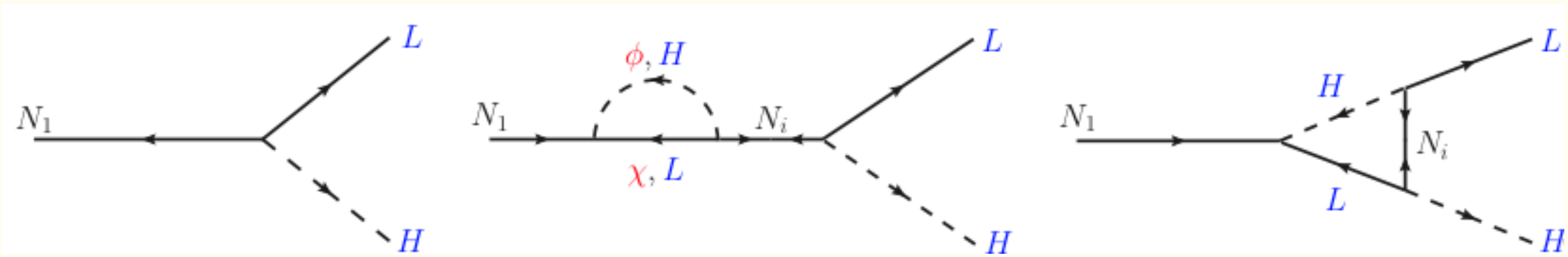


- When N decays it produces the baryon asymmetry through CP violation (loops):



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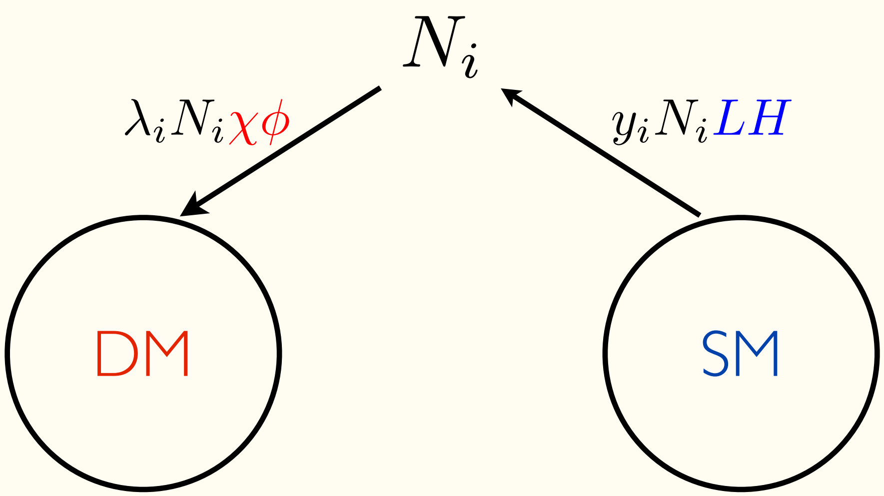

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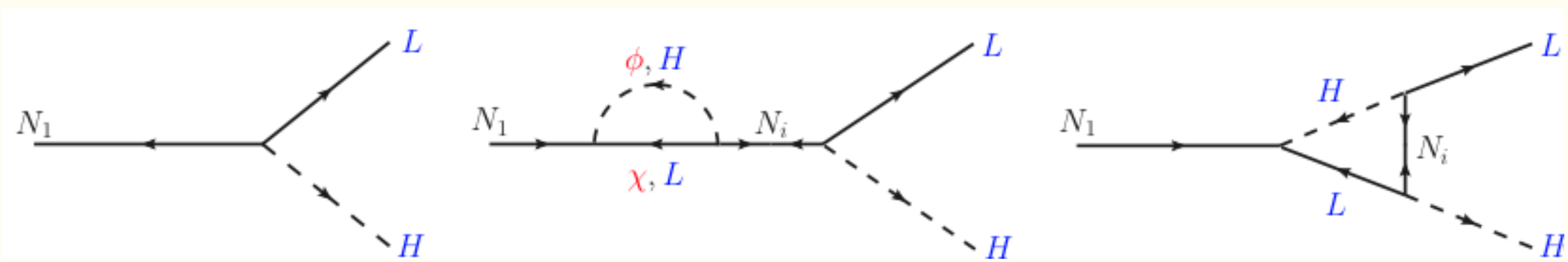
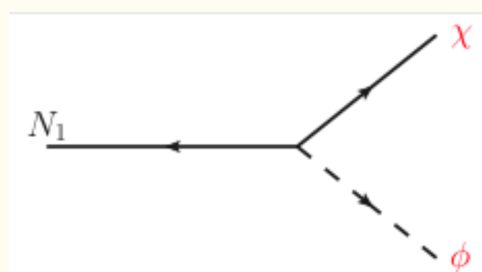


- Symmetric DM produced through tree level:



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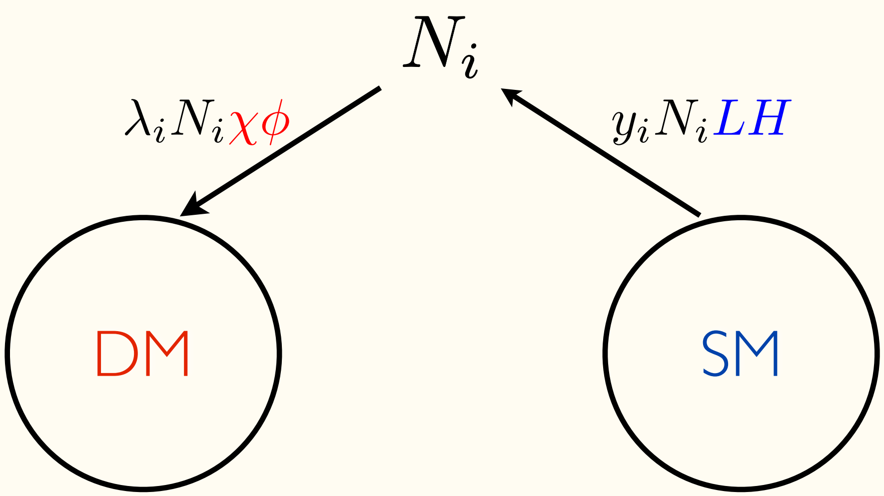


- Consequently, DM number density is generically larger than baryon number density:

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

- 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

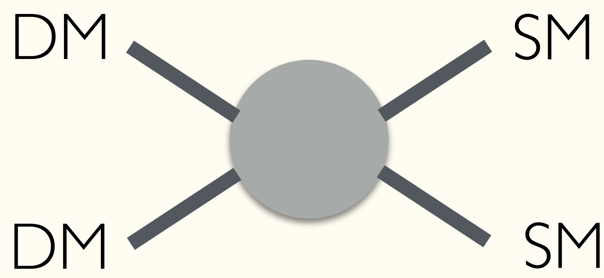
Strongly Interacting Massive Particles

A New Perspective on Freeze Out

[Kuflik, Hochberg, TV, Wacker, 2014]

No 2-2 Annihilations..

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



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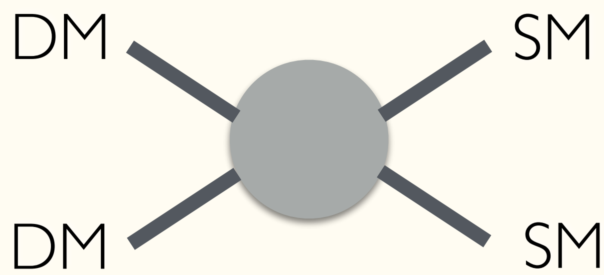
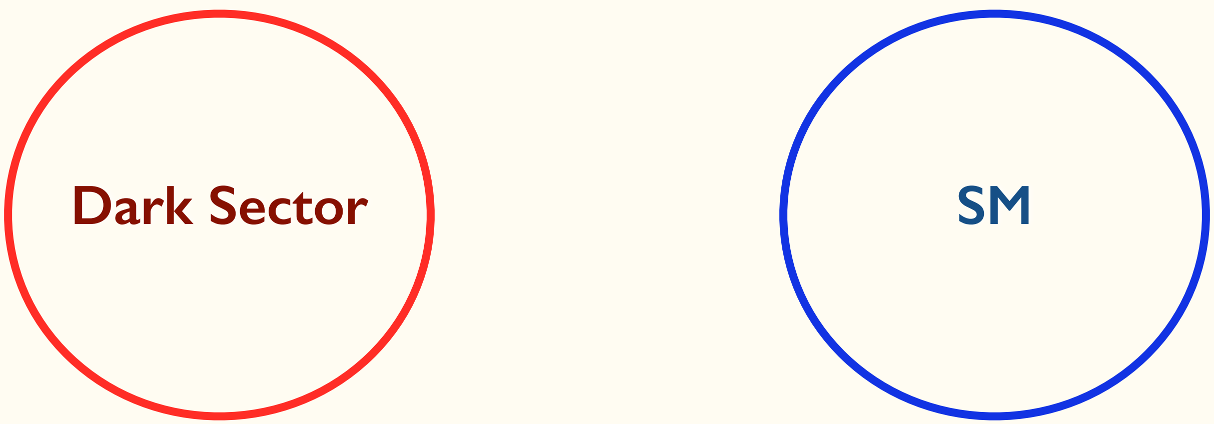


- But what if DM is the lightest state in a hidden (sequestered) sector?



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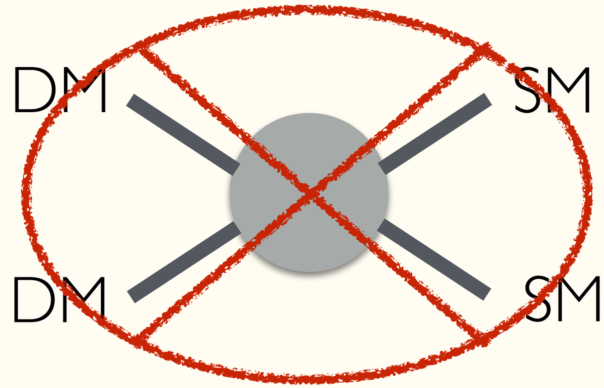

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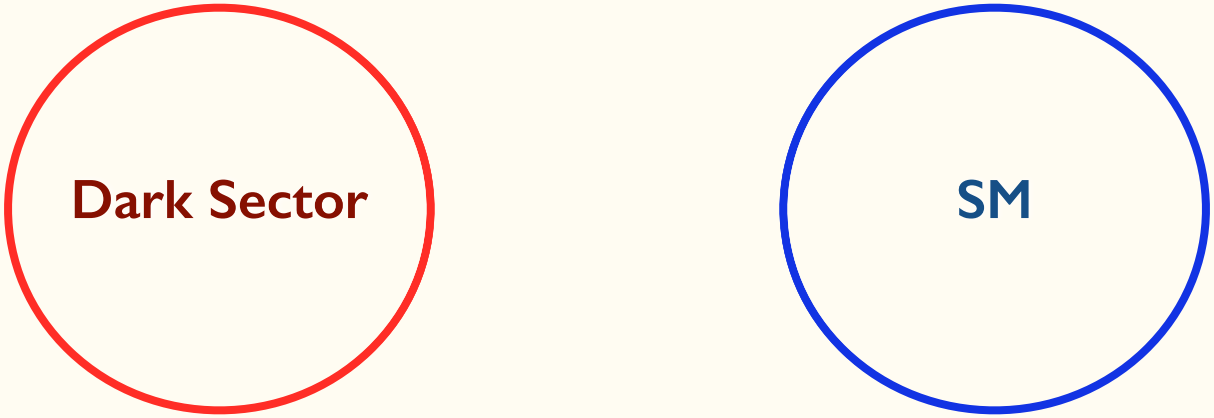
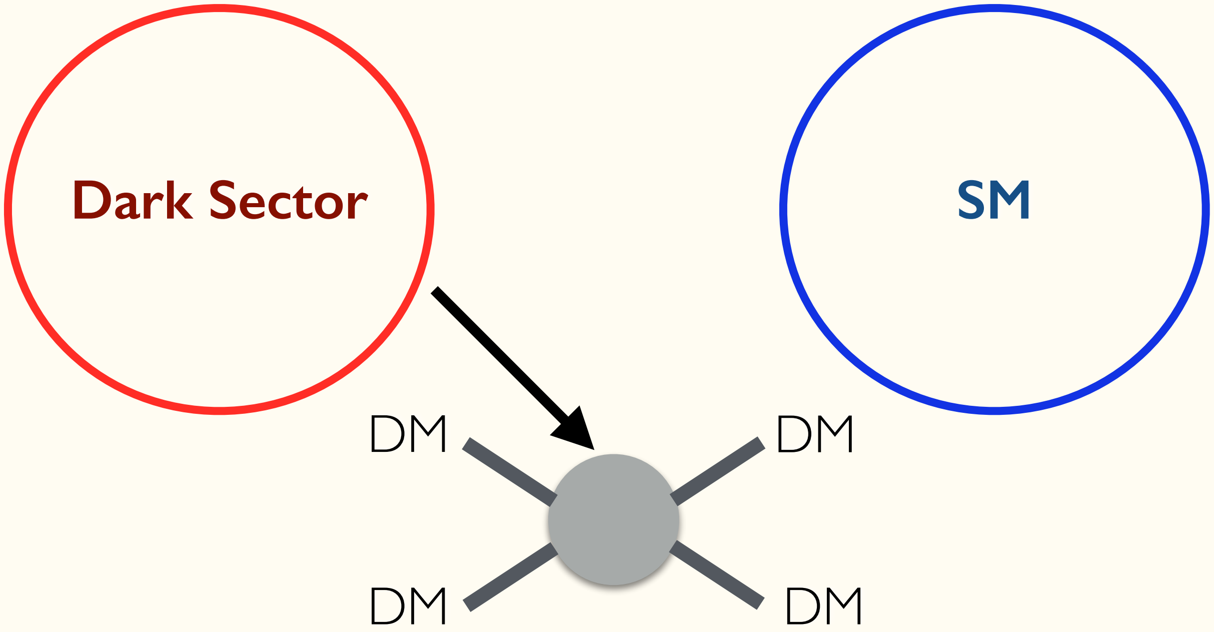


- Then 2-2 annihilations may be highly suppressed

No 2-2 Annihilations..

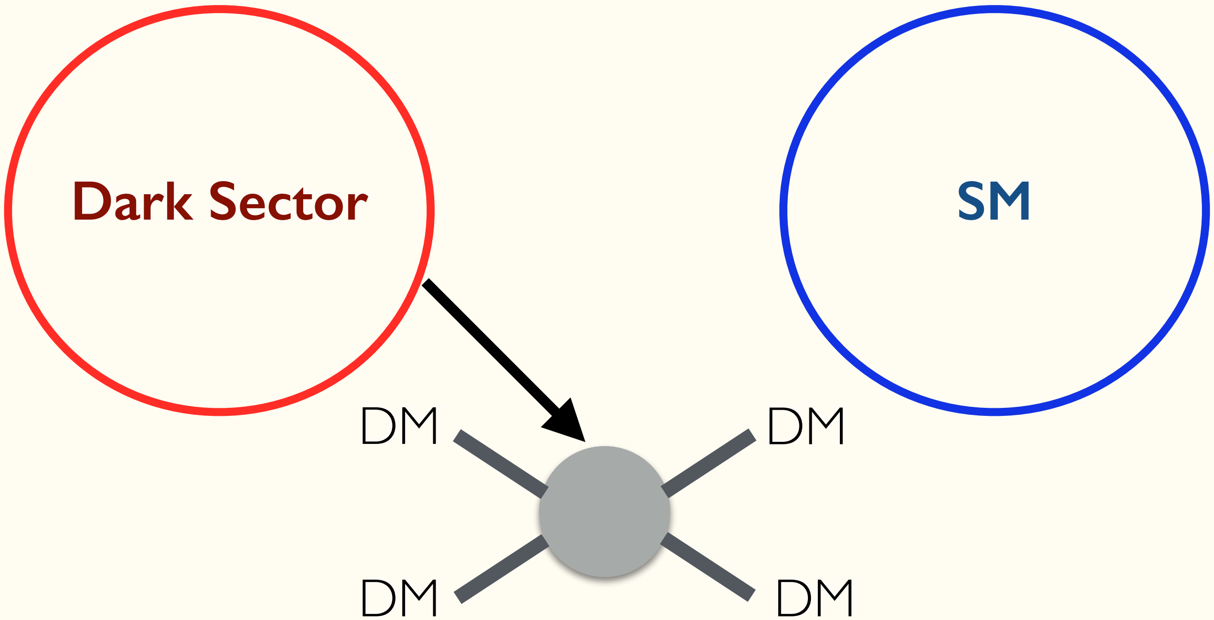


- However, DM can still interact in the hidden sector.
- But this is number-conserving, which implies,

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

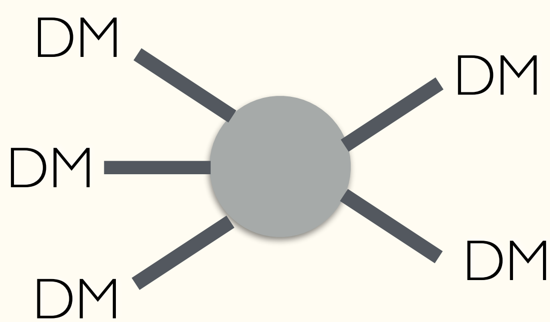
A way out?

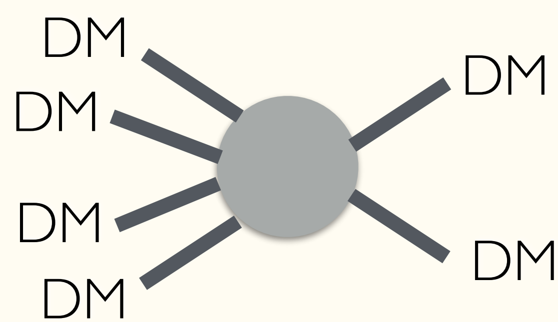
No 2-2 Annihilations..



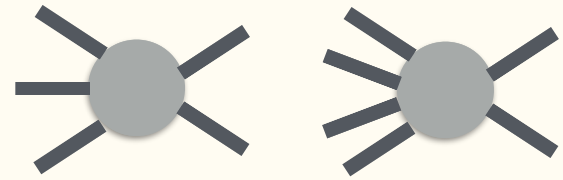
- More generally, the hidden sector will have additional interactions (especially in a strongly coupled case). **Example**:

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





3-2 Freeze Out



- Such interactions can significantly alter the relic density.
- At freeze out:

$$\Gamma_{3\to 2} = H$$

$$\Gamma_{3\to 2} = n_{\rm DM}^2 \langle \sigma v^2 \rangle_{3\to 2} \qquad \langle \sigma v \rangle_{3\to 2} = \frac{\alpha_{\rm eff}^2}{m_{\rm DM}^5}$$

$$n_{\rm DM} = \frac{\xi m_p \eta_b s}{m_{\rm DM}} = \frac{c T_{\rm eq} s}{m_{\rm DM}} \qquad \xi = \frac{\Omega_{\rm DM}}{\Omega_b}$$

$$s \sim T^3$$

$$H \simeq \sqrt{g_*} \frac{T^2}{M_{\rm Pl}}$$

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

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.

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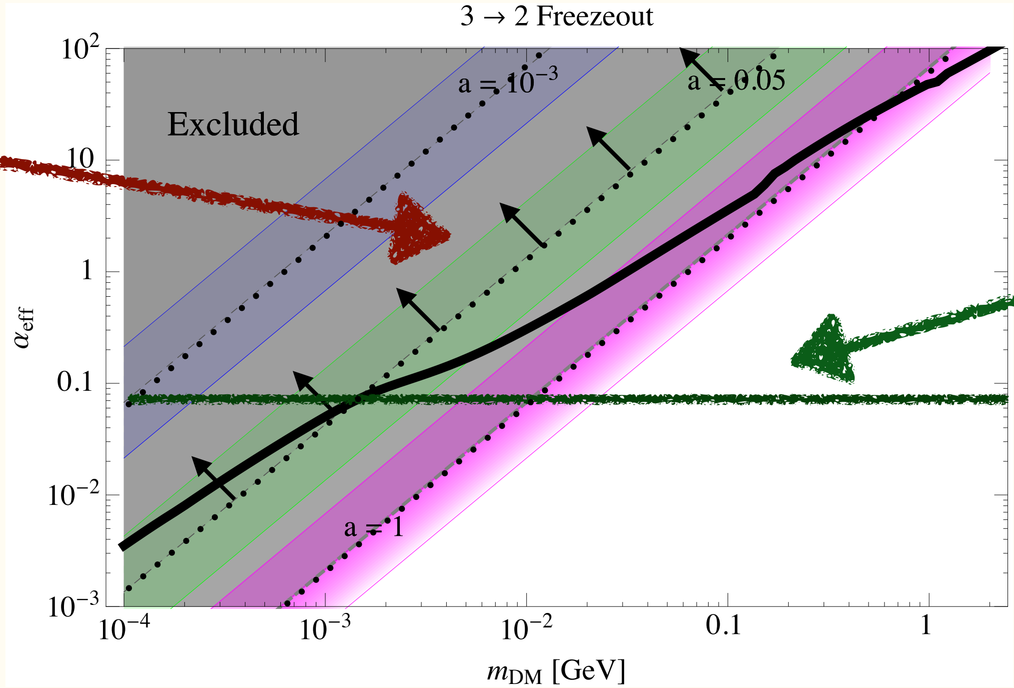
Excluded by Bullet-cluster and halo-shape constraints

$$a \equiv \frac{\alpha_{2-2}}{\alpha_{\rm eff}}$$



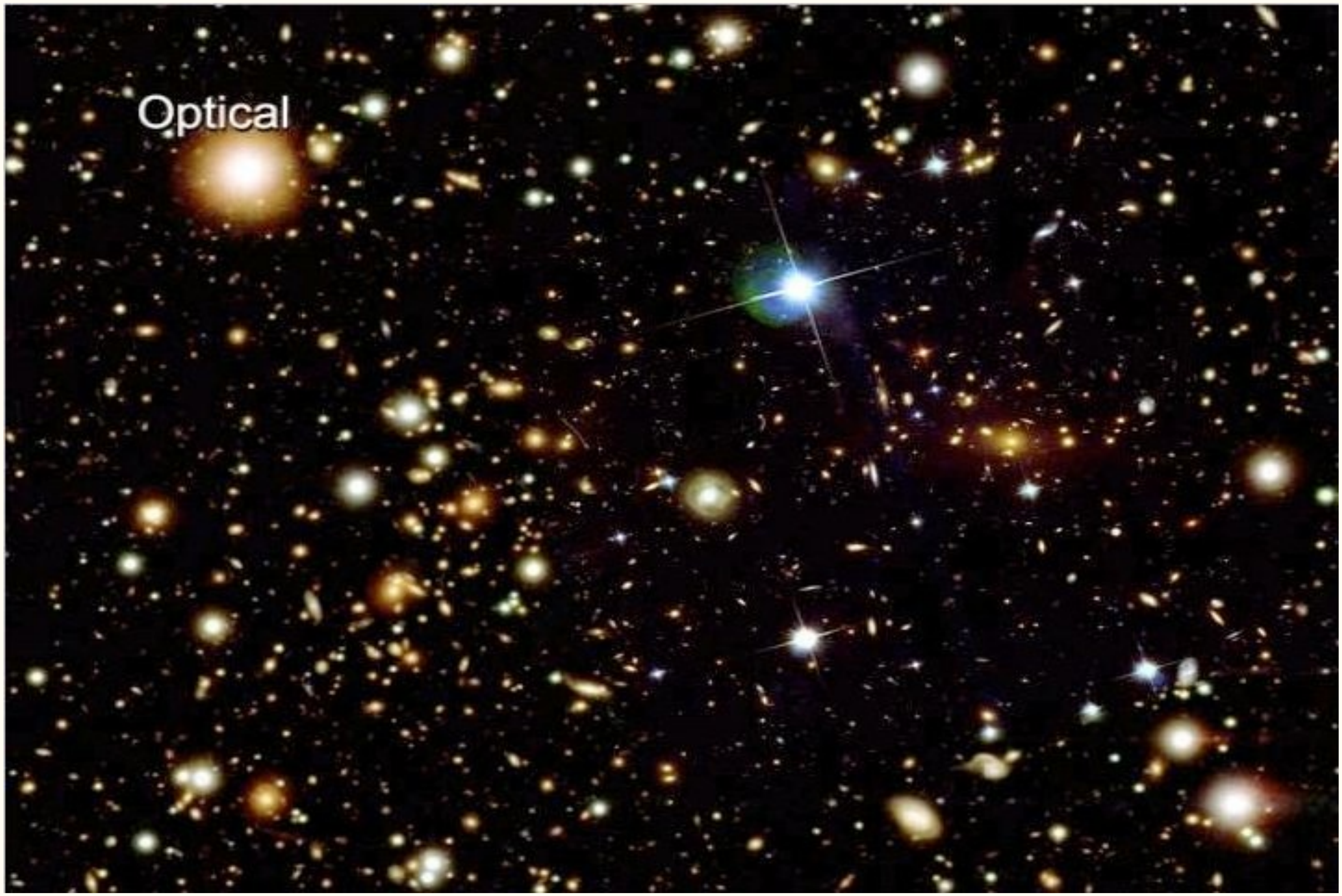
Constraints push to strong regime

$\Downarrow$

SIMP

The Bullet Cluster

90% of ordinary matter is in gas, not in galaxies



X-ray: NASA/CXC/CfA/M.Markevitch et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al. Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

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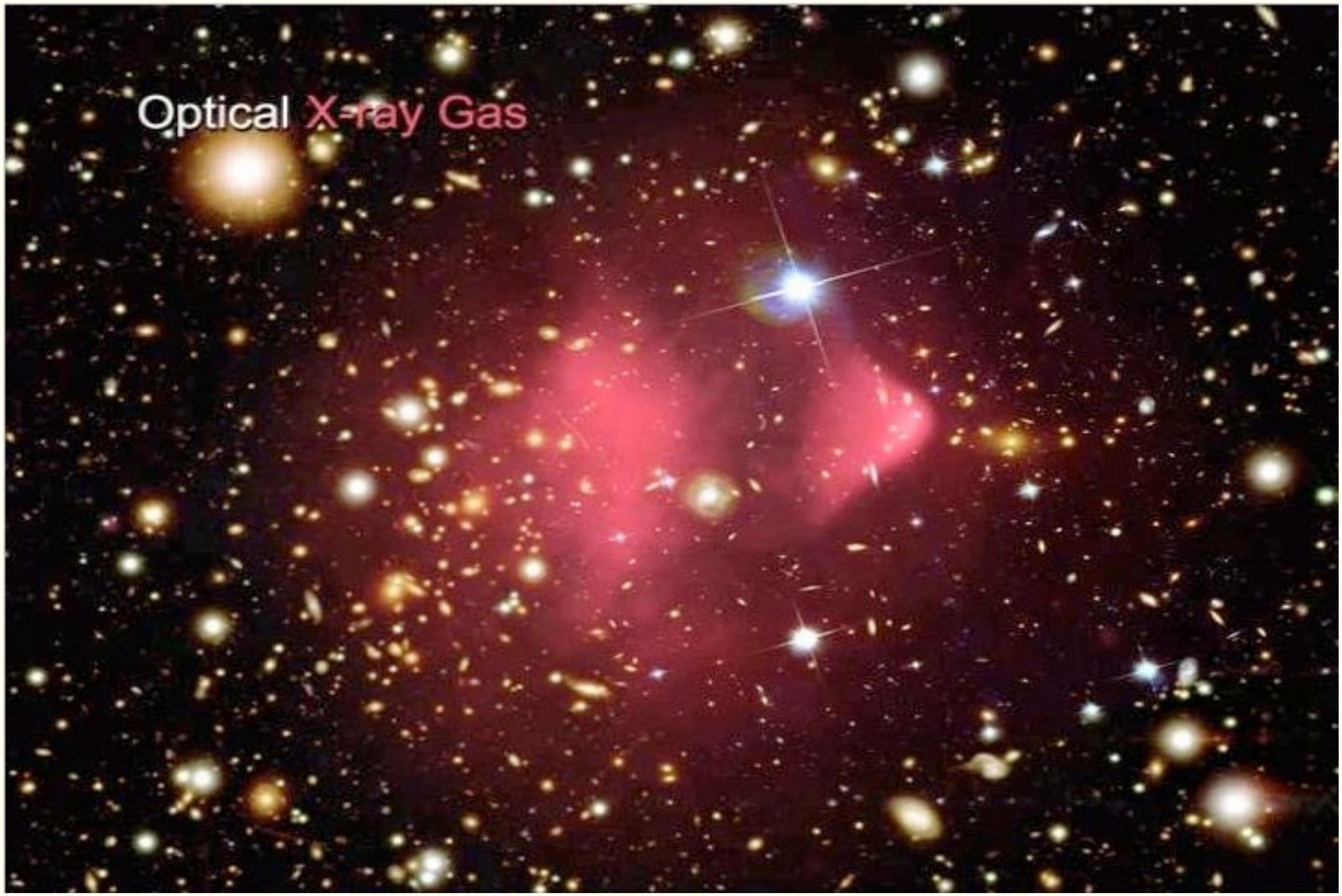

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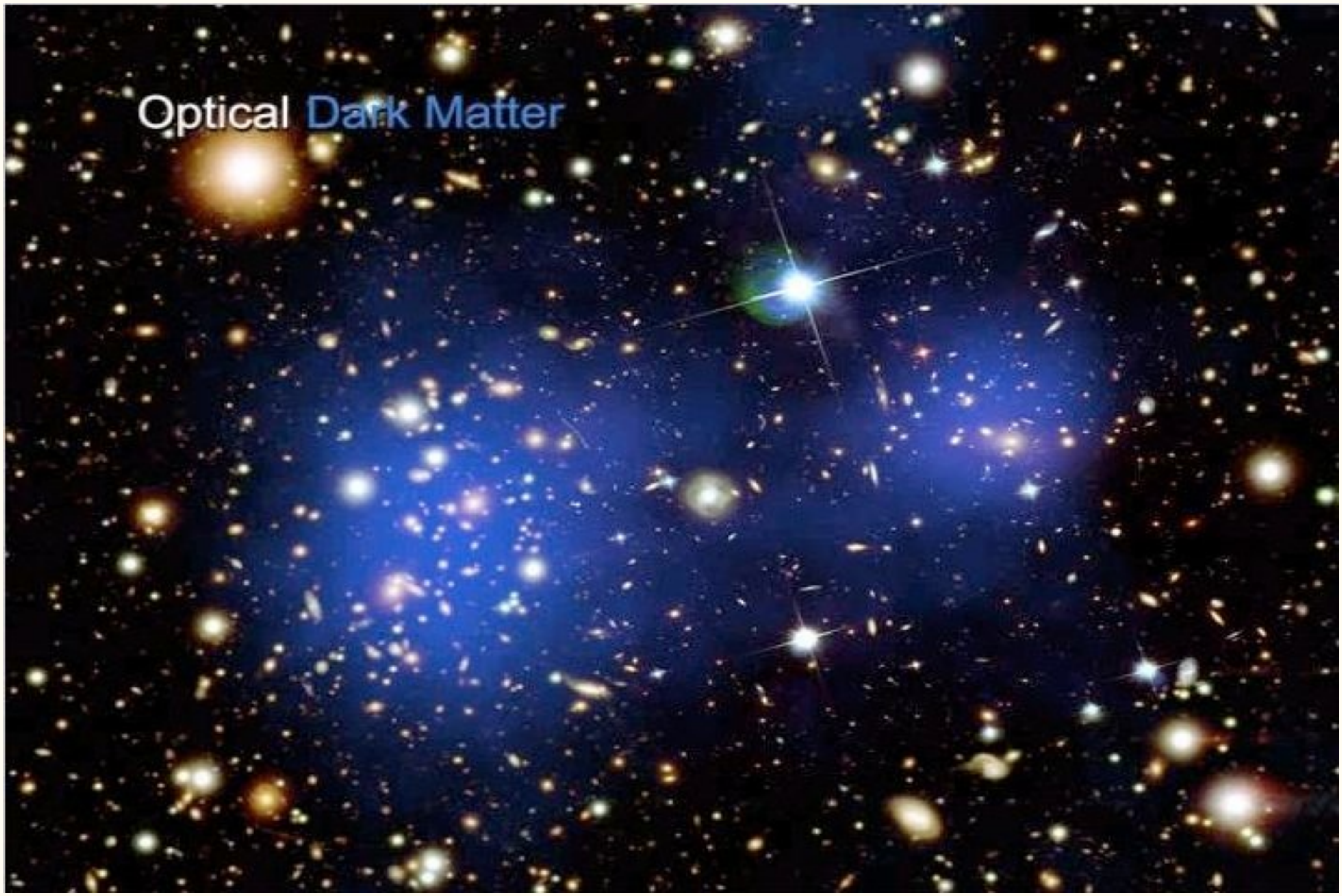
The Bullet Cluster

Determine location of mass with weak-lensing



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The Bullet Cluster

Composite image: ordinary + dark matter

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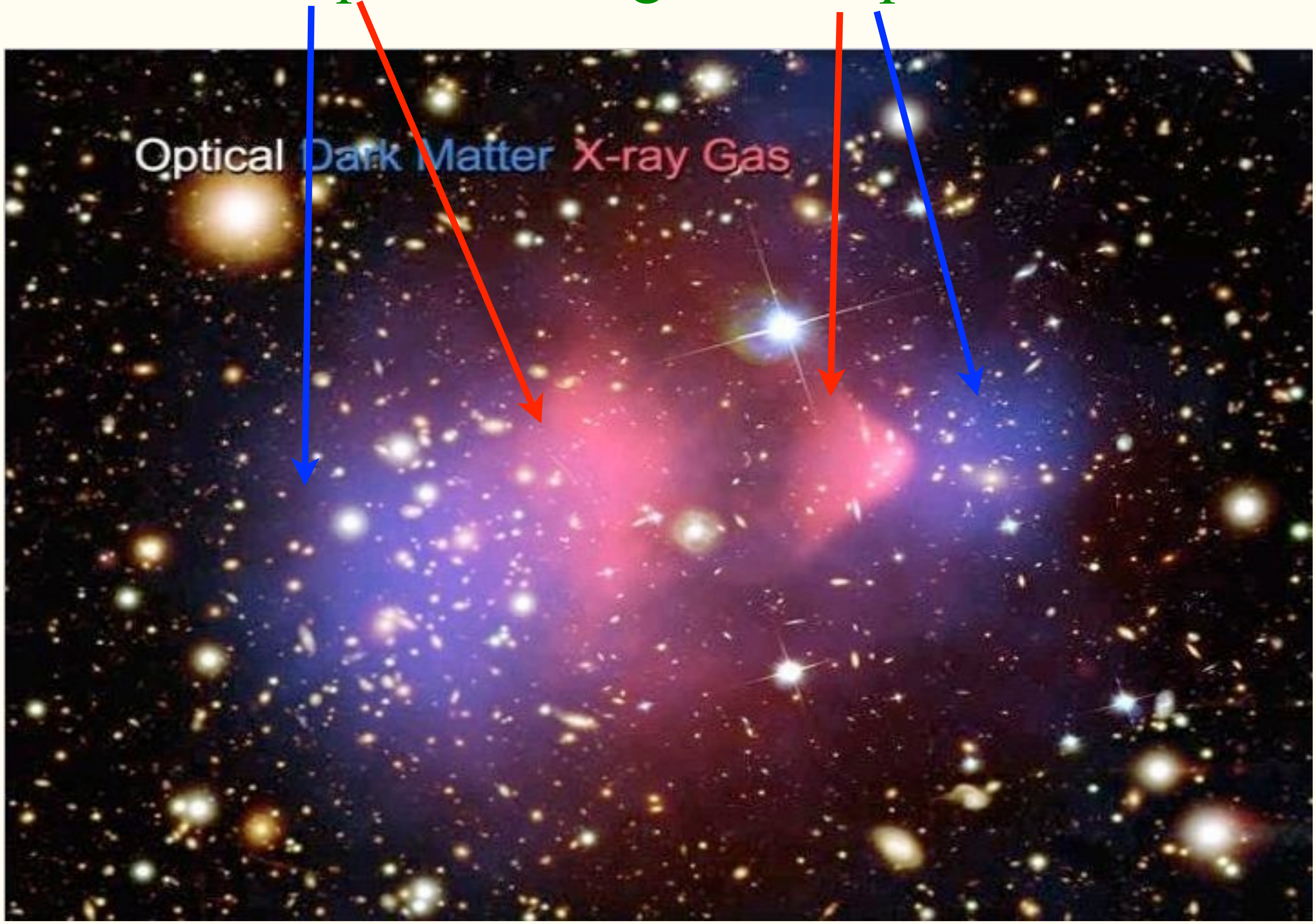
clear separation of gas/mass peaks



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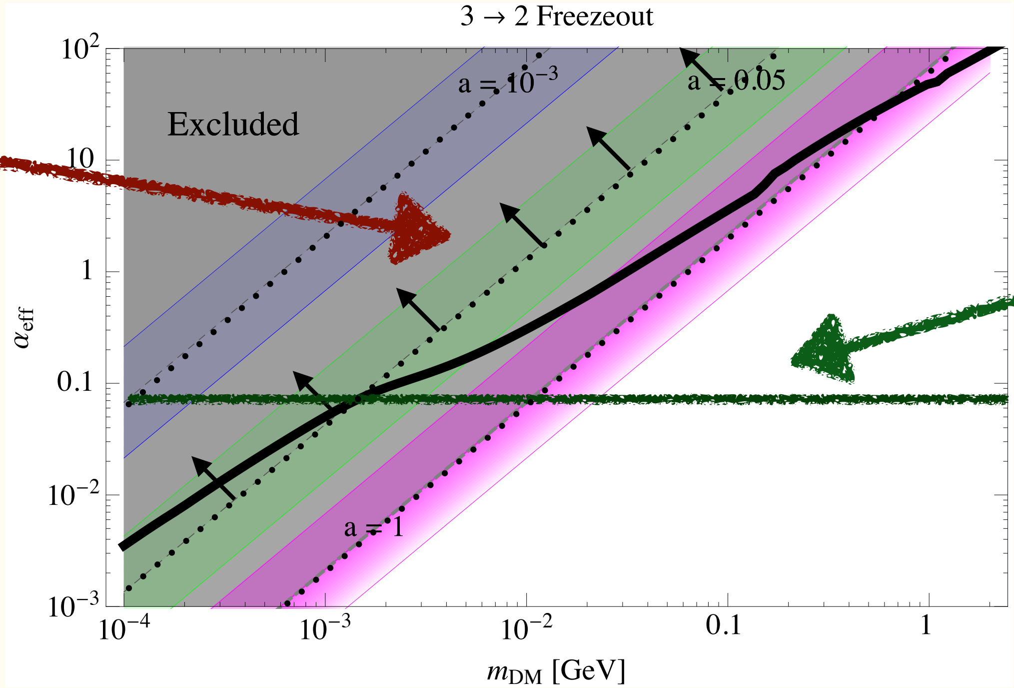


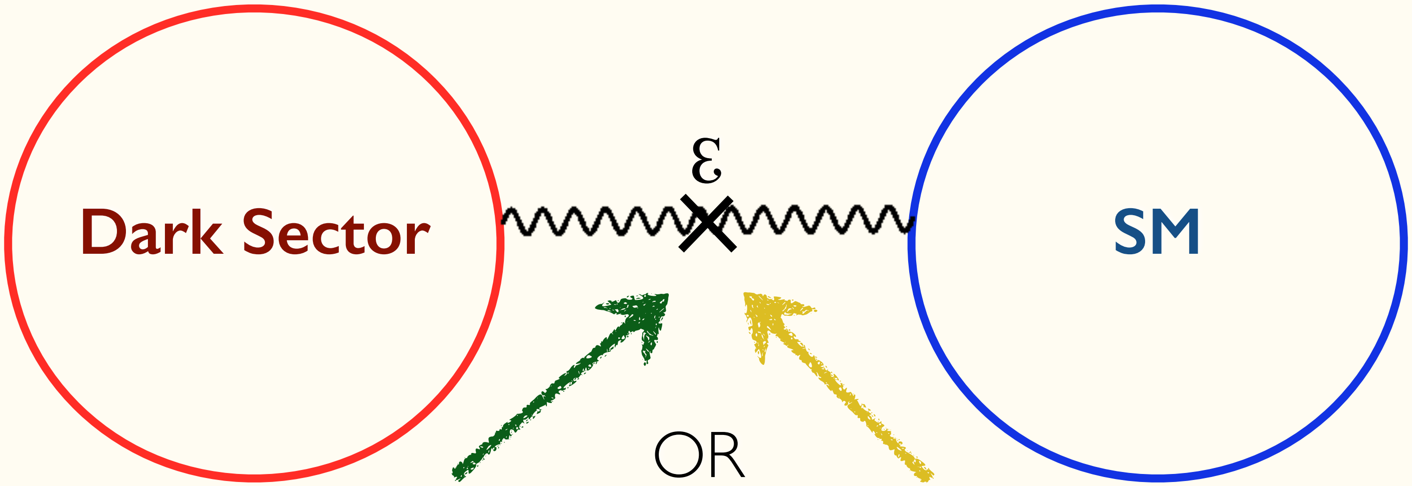
Constraints push to strong regime

⇓

SIMP

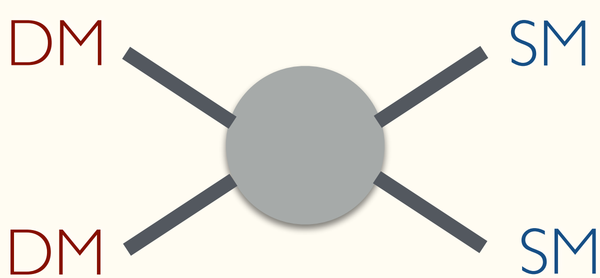
3-2 Freeze Out

- Problem: We implicitly assumed that **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.

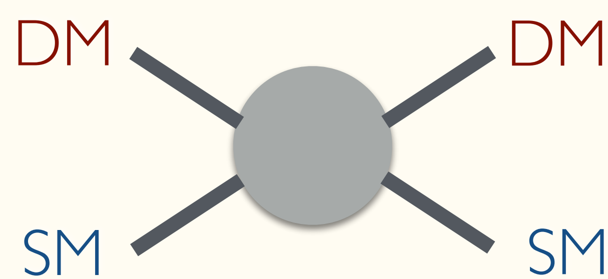


$$\frac{m_f}{\Lambda^2}\chi^\dagger\chi\bar{f}f \qquad \frac{\alpha_{\rm EM}}{4\pi\Lambda^2}\chi^\dagger\chi F_{\mu\nu}F^{\mu\nu}$$

- Consequently, two more diagrams:



2-2 Annihilations



Thermal Equilibrium

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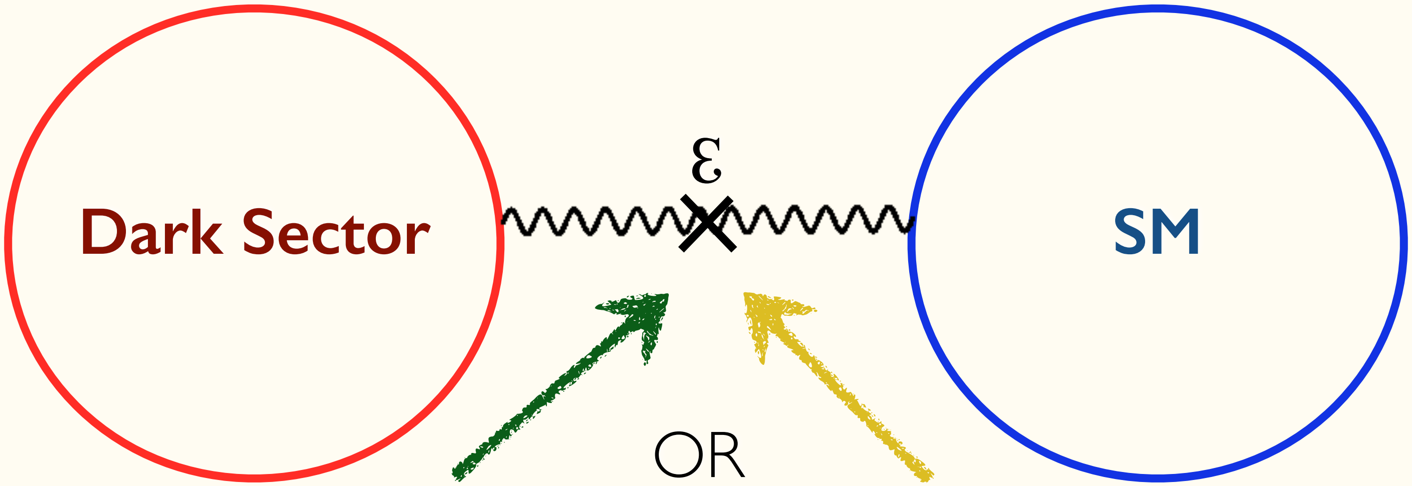

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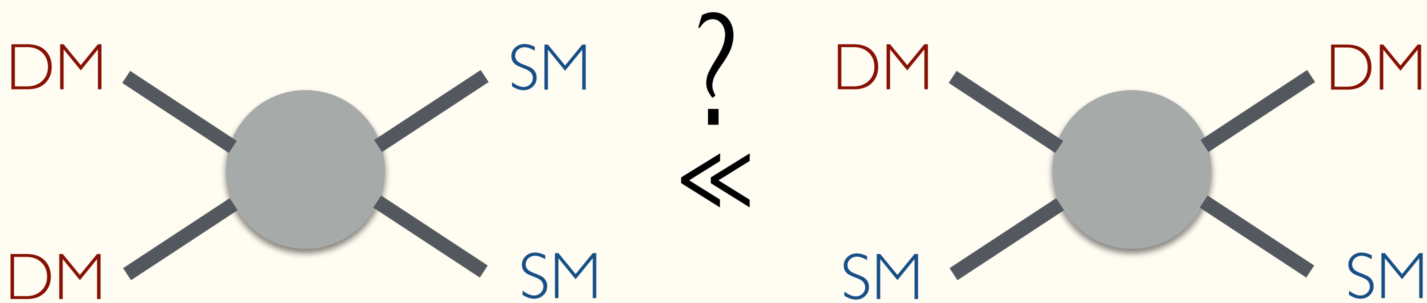

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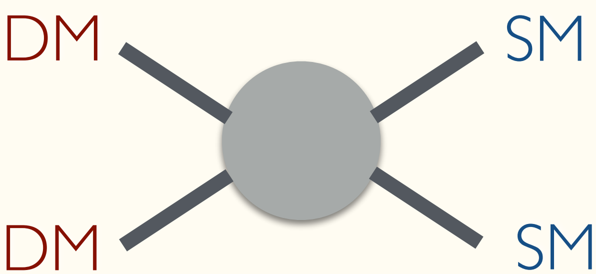
Thermal Equilibrium

3-2 Freeze Out

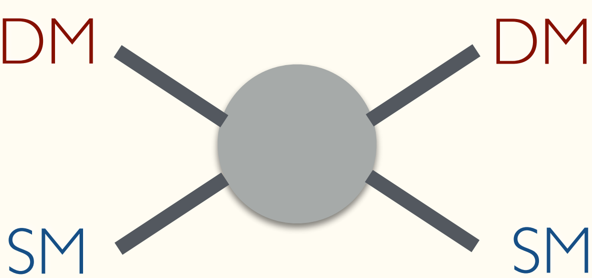
Taking:

$$\langle \sigma v \rangle_{\rm kin} \sim \langle \sigma v \rangle_{\rm ann} \equiv \frac{\epsilon^2}{m_{\rm DM}^2}$$

$$\Longrightarrow \qquad \frac{\Gamma_{\rm ann}}{\Gamma_{\rm kin}} \sim \frac{n_{\rm DM}}{n_{\rm SM}} \sim e^{-m_{\rm DM}/T} \sim 2 \times 10^{-7}$$

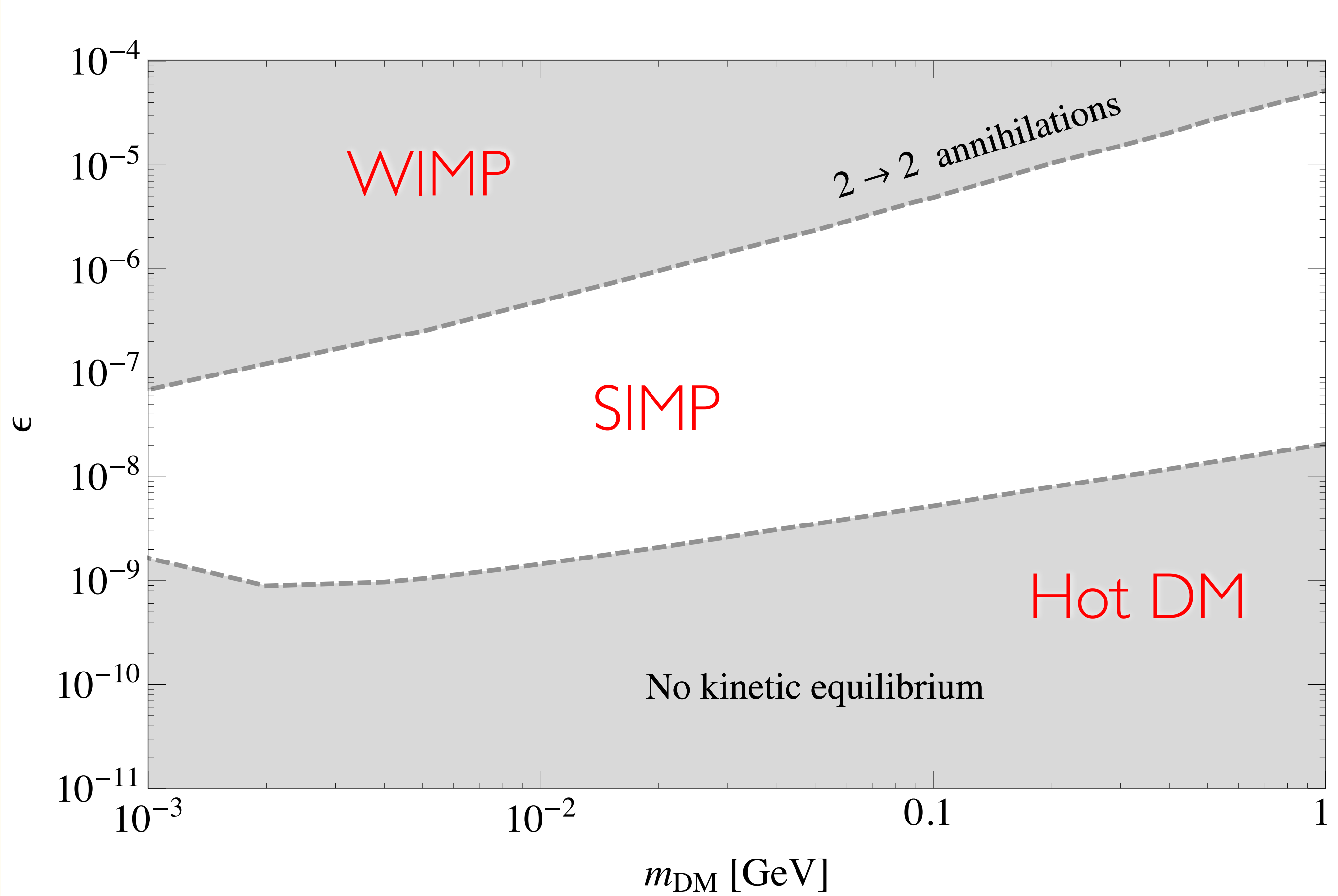


$$\left.\frac{\Gamma_{\rm ann}}{\Gamma_{3\to 2}}\right|_{T=T_F} \lesssim 1 \Longrightarrow \epsilon \lesssim \epsilon_{\rm max} \equiv 0.1\ \alpha_{\rm eff} \left(\frac{T_{\rm eq}}{M_{\rm Pl}}\right)^{1/6} \simeq 3 \times 10^{-6}$$



$$\left.\frac{\Gamma_{\rm kin}}{\Gamma_{3\to 2}}\right|_{T=T_F} \gtrsim 1 \Longrightarrow \epsilon \gtrsim \epsilon_{\rm min} \equiv 2\ \alpha_{\rm eff}^{1/2} \left(\frac{T_{\rm eq}}{M_{\rm Pl}}\right)^{1/3} \simeq 1 \times 10^{-9}$$

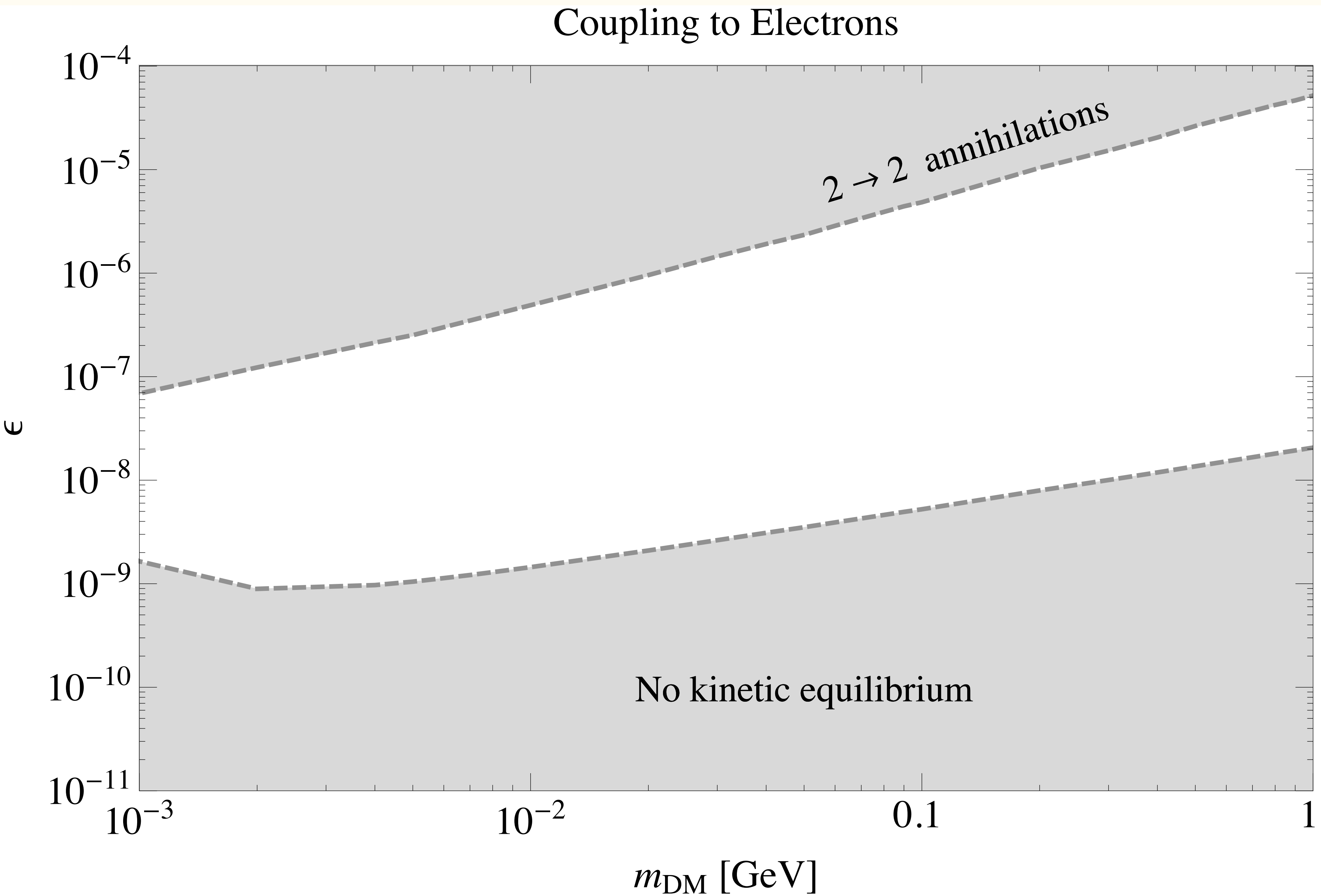
3-2 Freeze Out



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

Measurable consequences for all types of experiments

SIMP DM: Experimental Status



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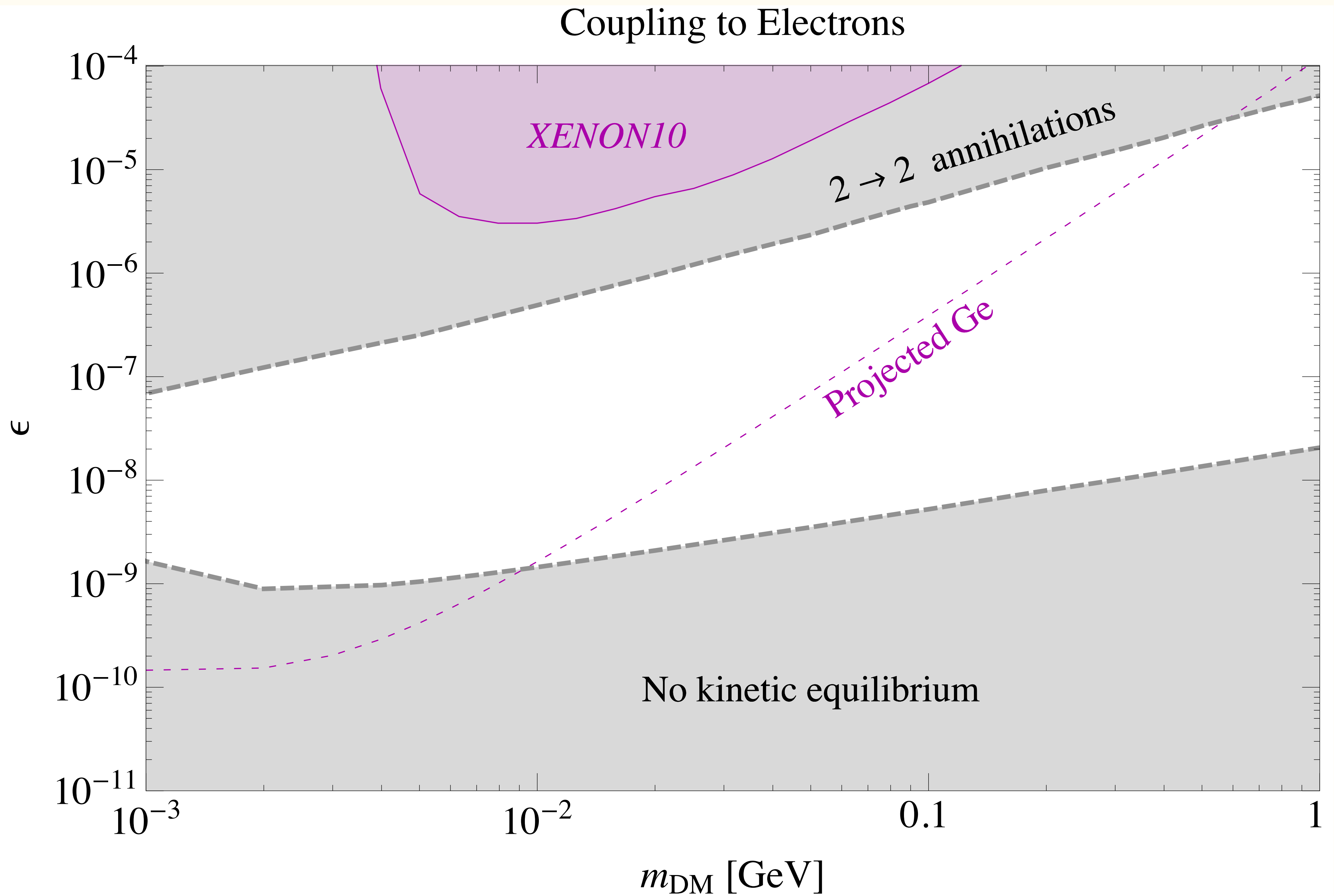

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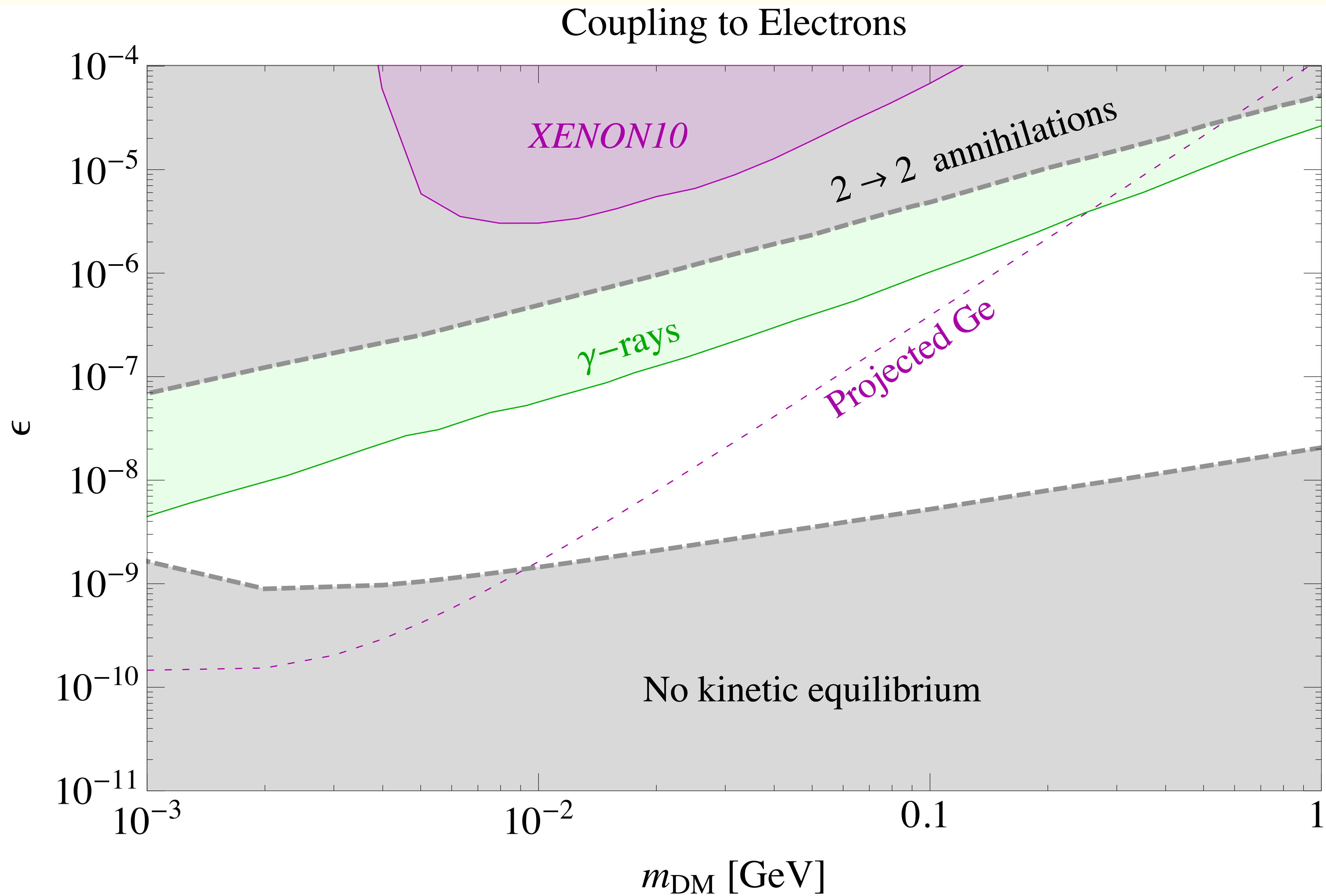
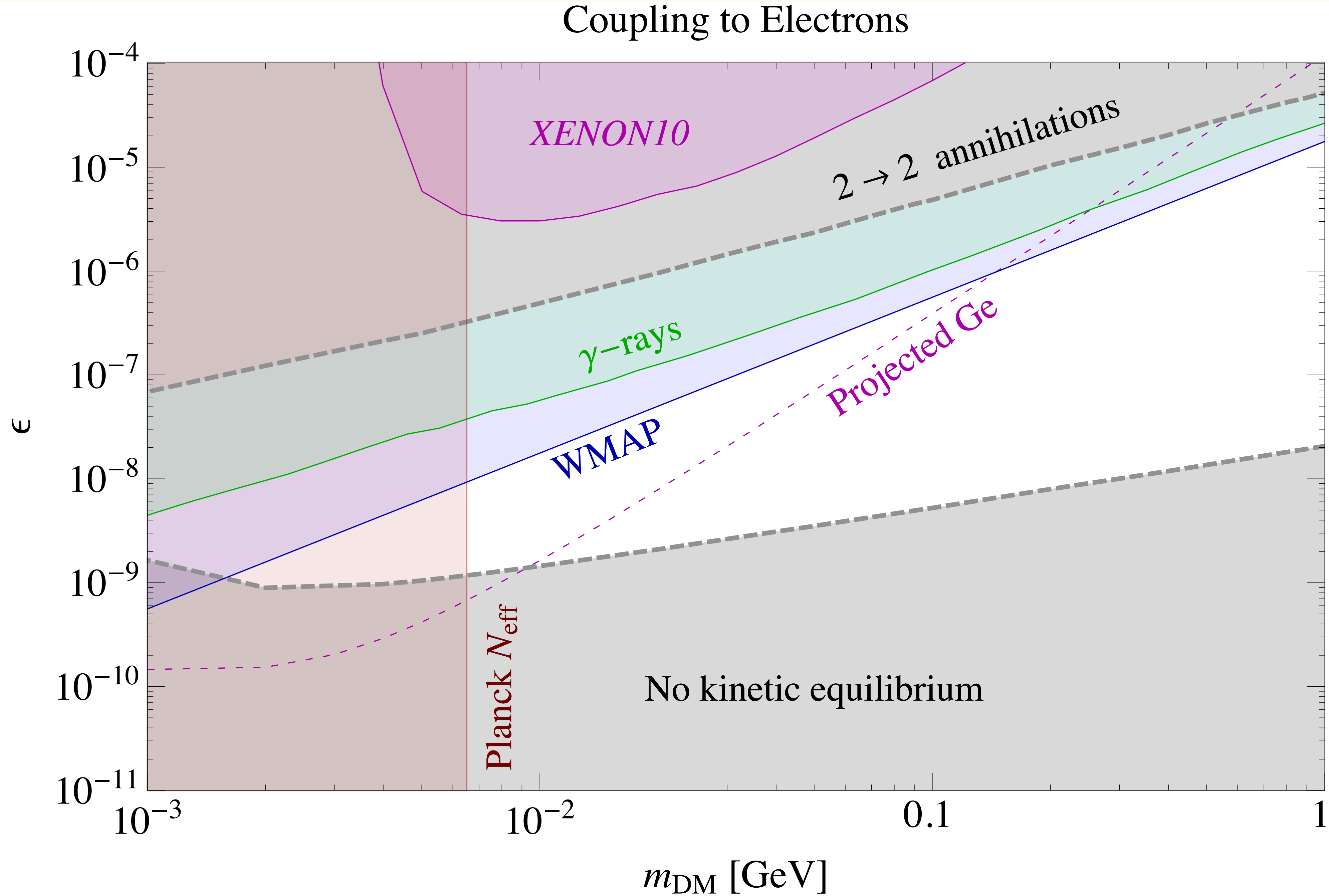
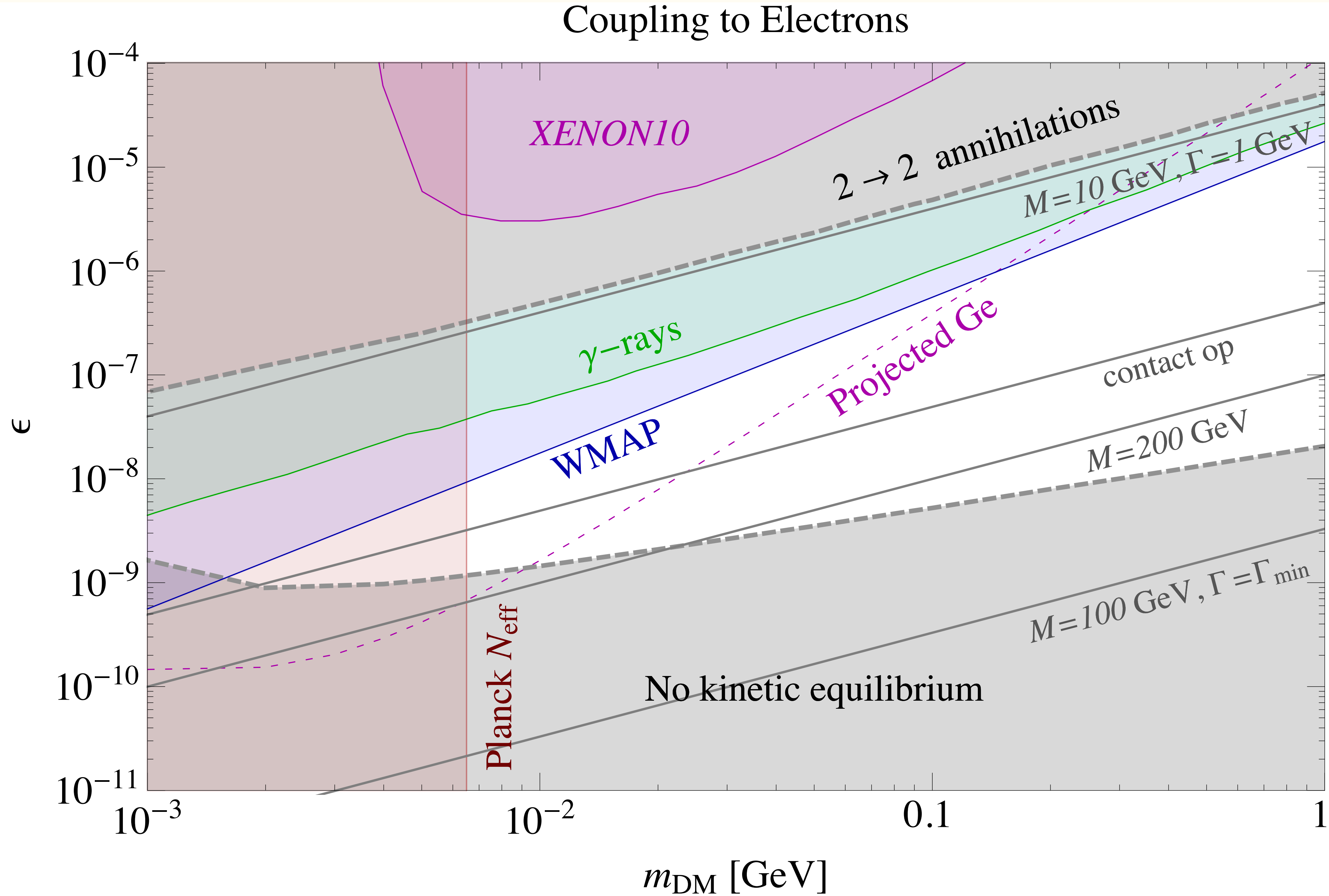


SIMP DM: Experimental Status

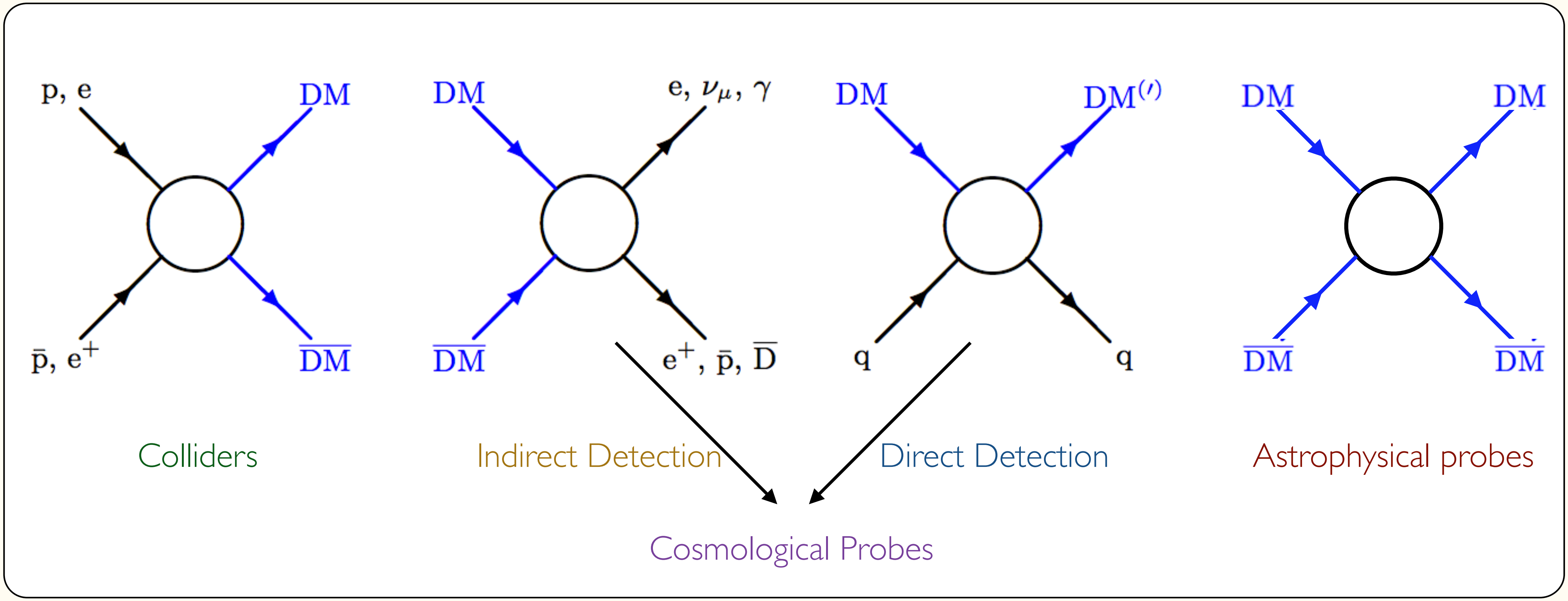


SIMP DM: Experimental Status



Experimental Probes

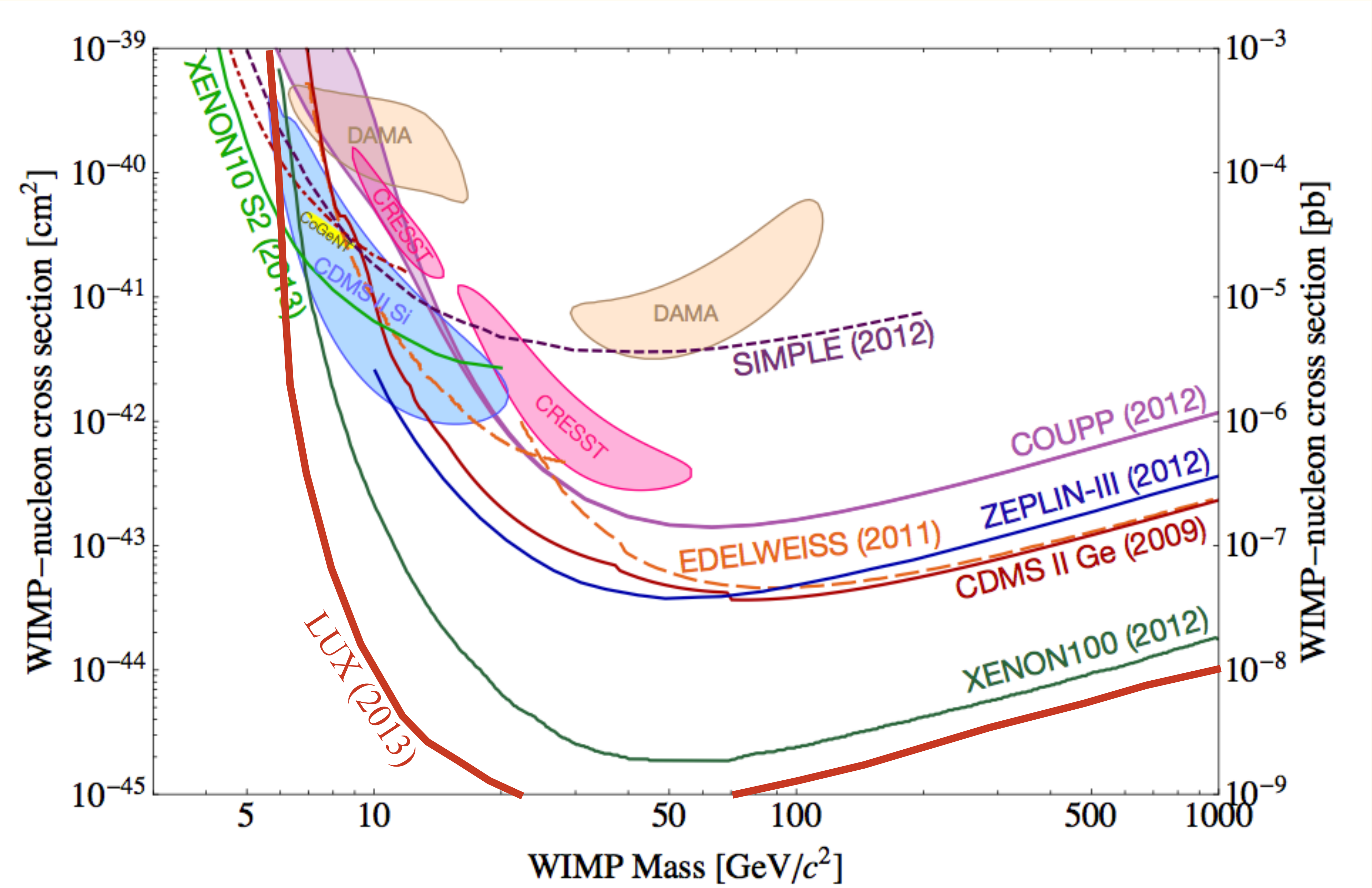
Several ways to search for DM



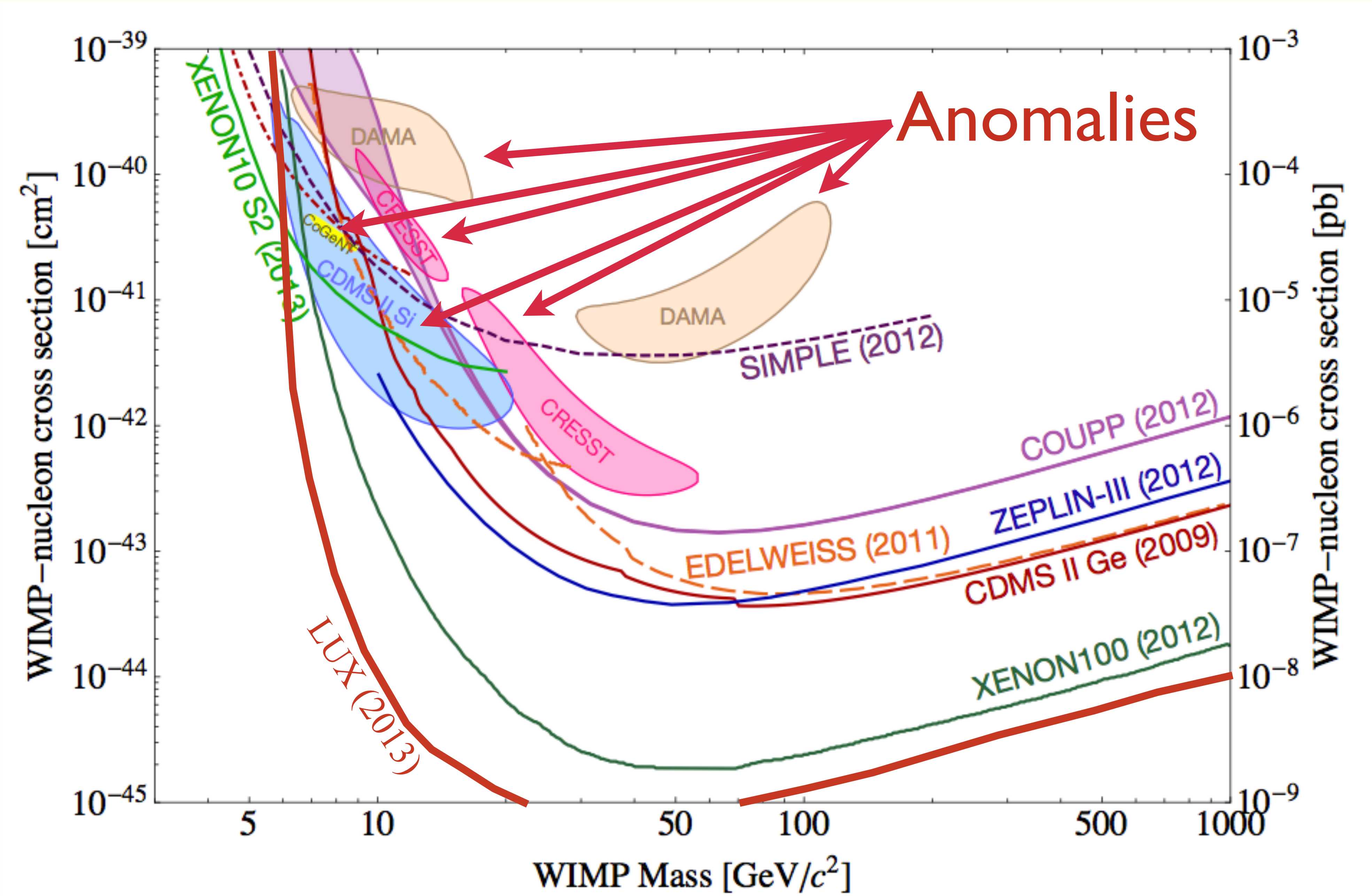
Experimental Probes

Direct Detection

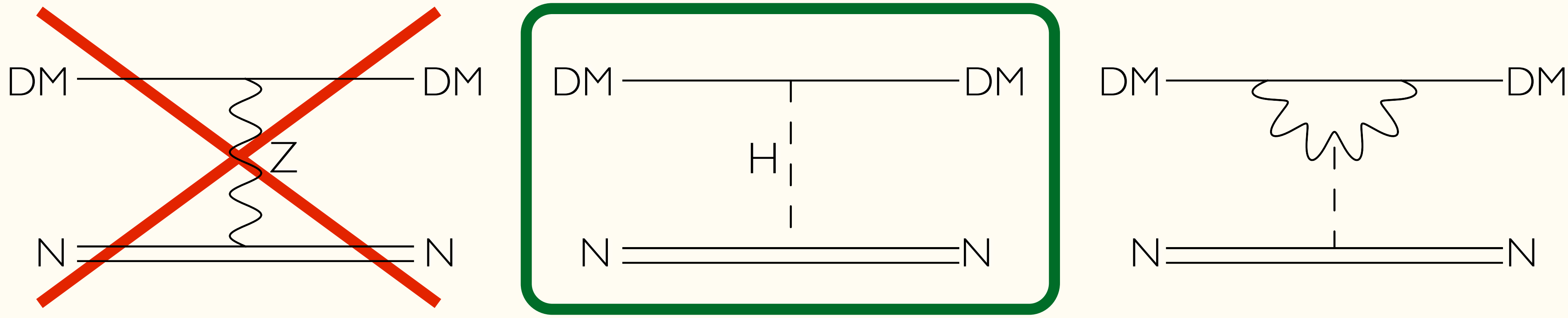
Direct Detection Limits



Direct Detection Limits



What do we learn?



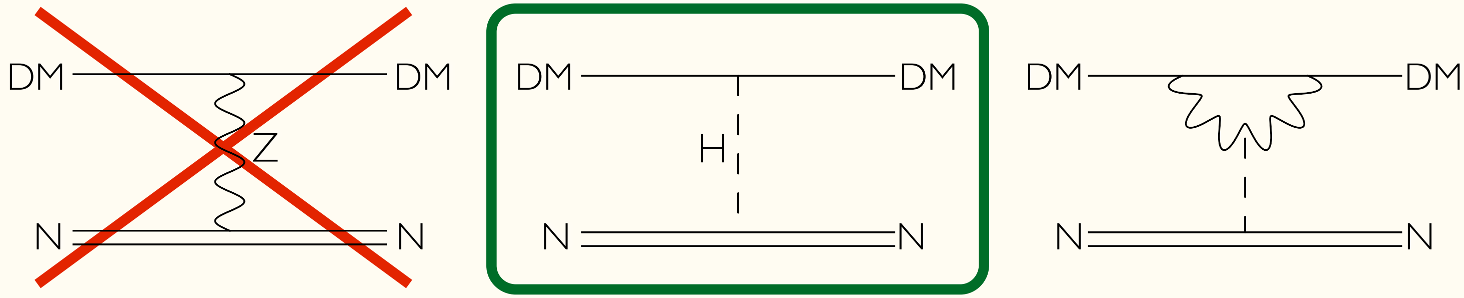
$\sigma_{\chi N} \sim 10^{-39}\ \mathrm{cm}^2$

$\sigma_{\chi N} \sim 10^{-44-47}\ \mathrm{cm}^2$

$\sigma_{\chi N} \lesssim 10^{-46}\ \mathrm{cm}^2$

XENON100
LUX
CDMS
...

What do we learn?



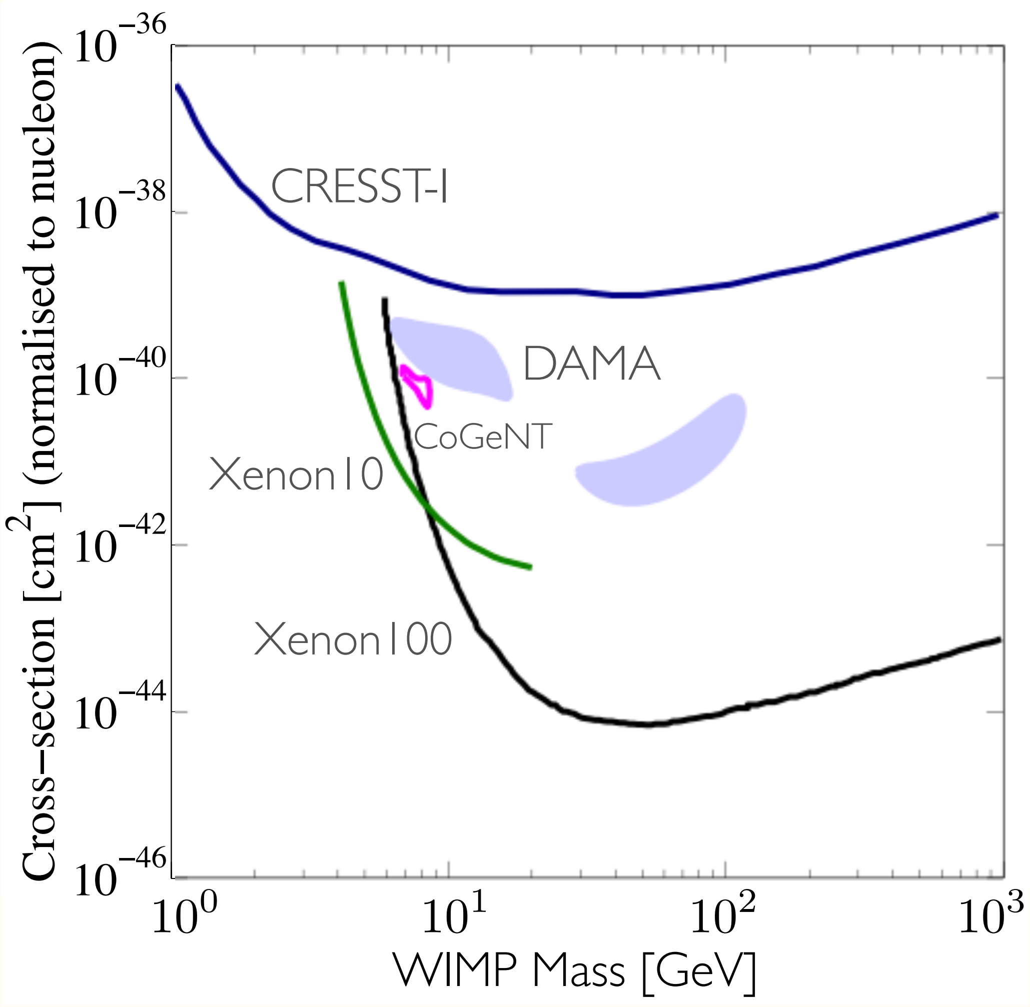
$\sigma_{\chi N} \sim 10^{-39}\ \mathrm{cm}^2$ $\sigma_{\chi N} \sim 10^{-44-47}\ \mathrm{cm}^2$ $\sigma_{\chi N} \lesssim 10^{-46}\ \mathrm{cm}^2$

XENON100
LUX
CDMS
...

Current technologies will only be able to reach $\sim 10^{-48}\ \mathrm{cm}^2$ due to irreducible backgrounds

Significant fraction probed possibly before 2020

A New Direction: Light Dark Matter



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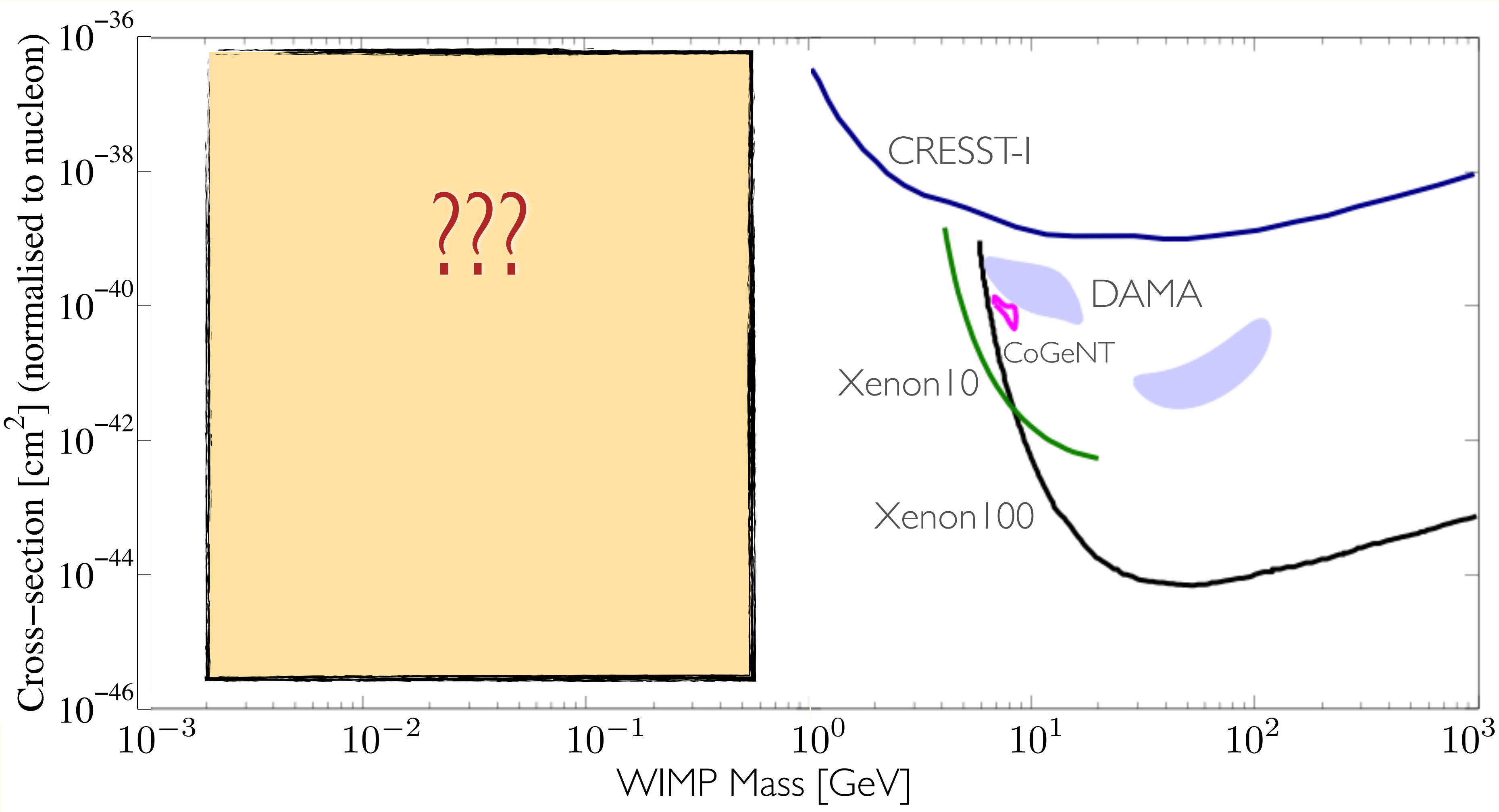

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

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

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

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Recoil energy drops fast

Can't go below ~ GeV

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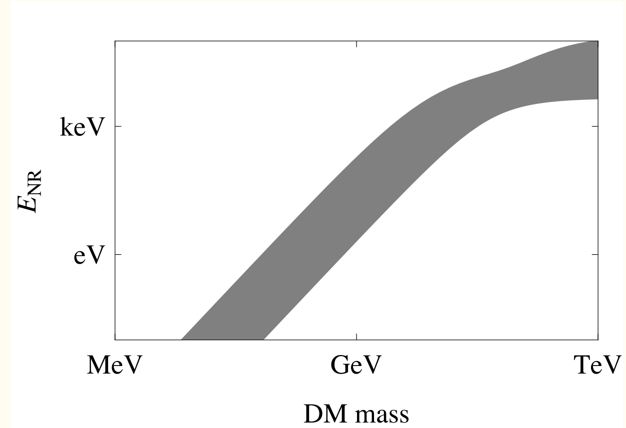

But DM energy is significantly larger:

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

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DM energy drops slower

Enough energy to detect!!

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Studying nuclear recoils is extremely inefficient for light DM

DM energy drops slower

Enough energy to detect!!

Ways to Detect Light DM

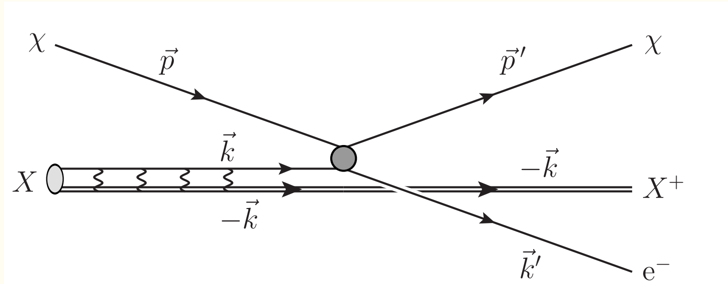
- The available energy is sufficient to induce inelastic atomic processes that would lead to visible signals.

[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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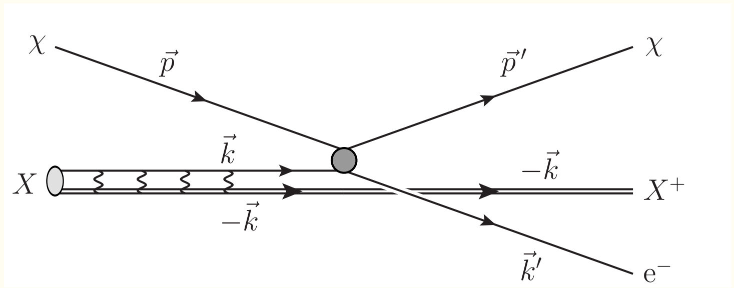

2. Electronic excitation

   Threshold: eV - 100's eV
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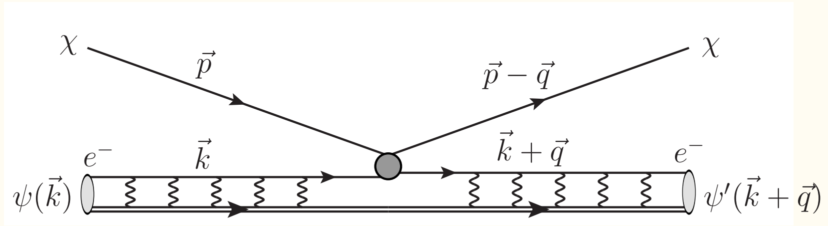

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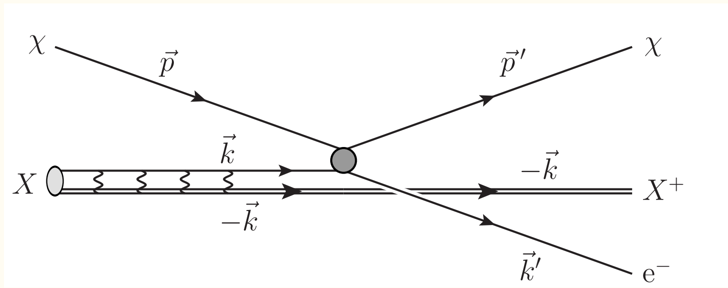

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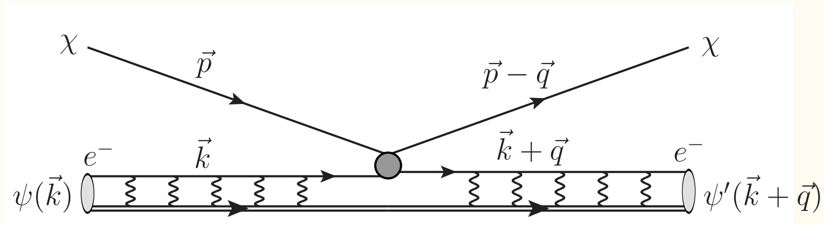
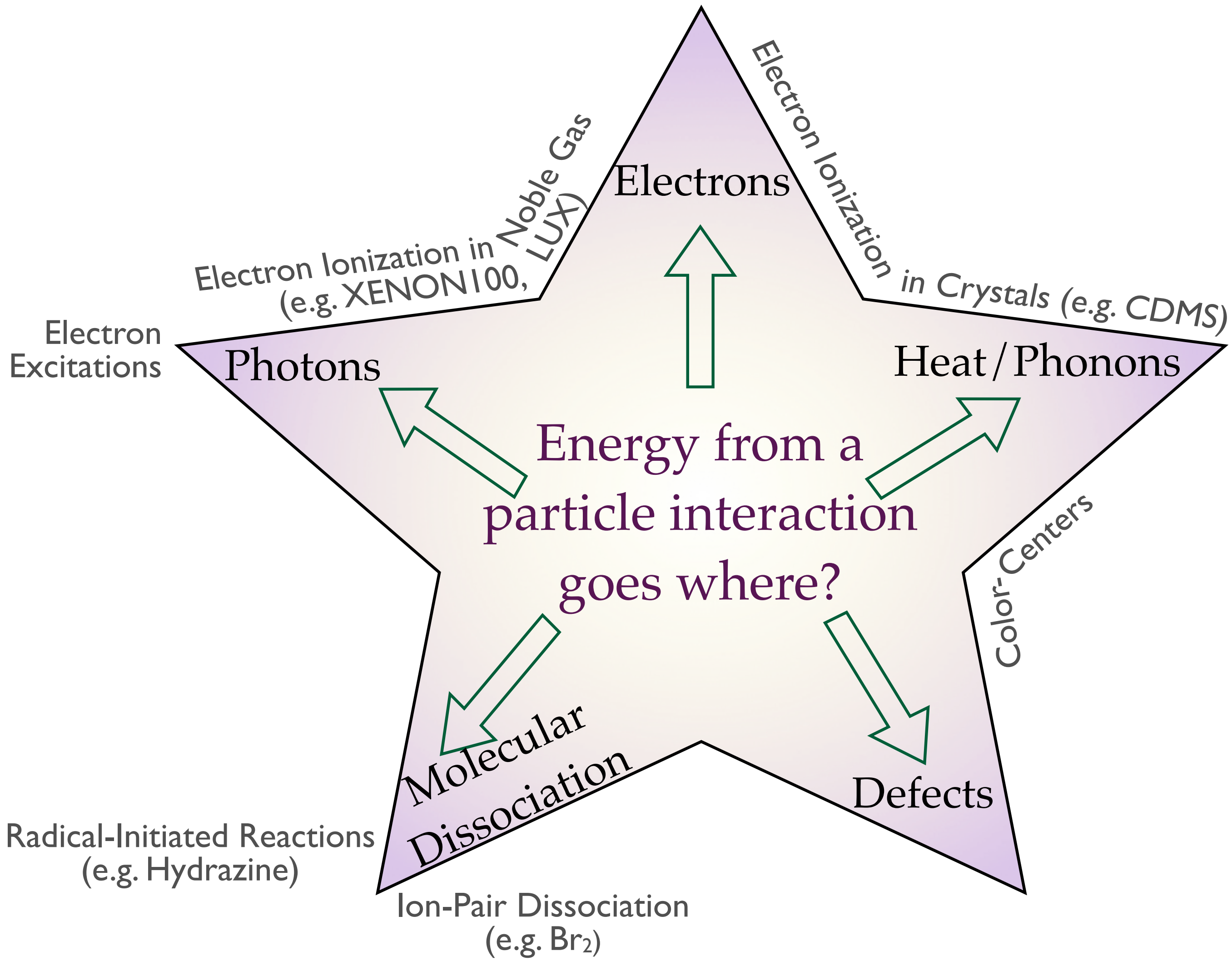


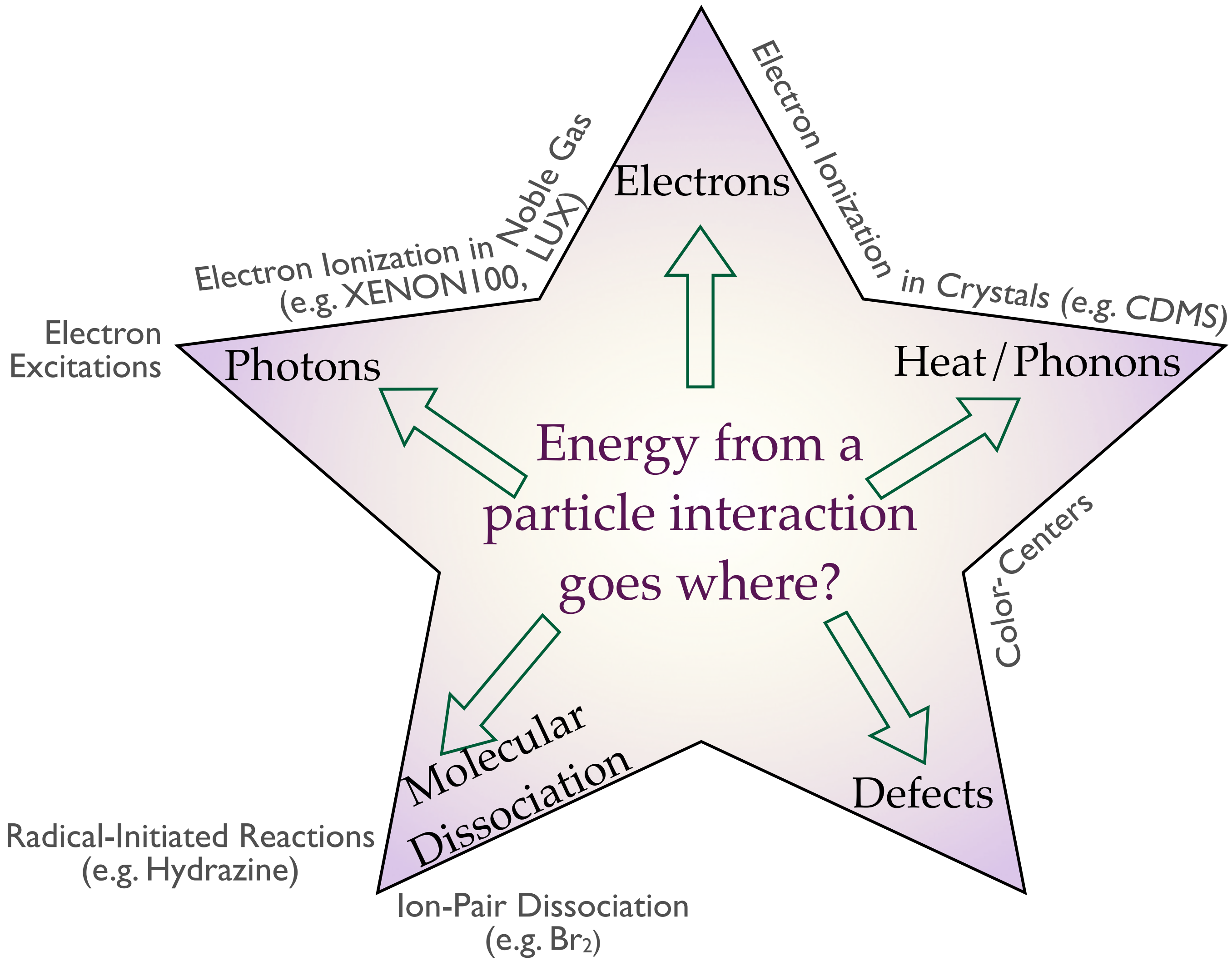
3. Bond Breakage

   Threshold: ≳ few eV
   DM-nucleon scattering
   Signal: ions, photons.

Detectable Signals

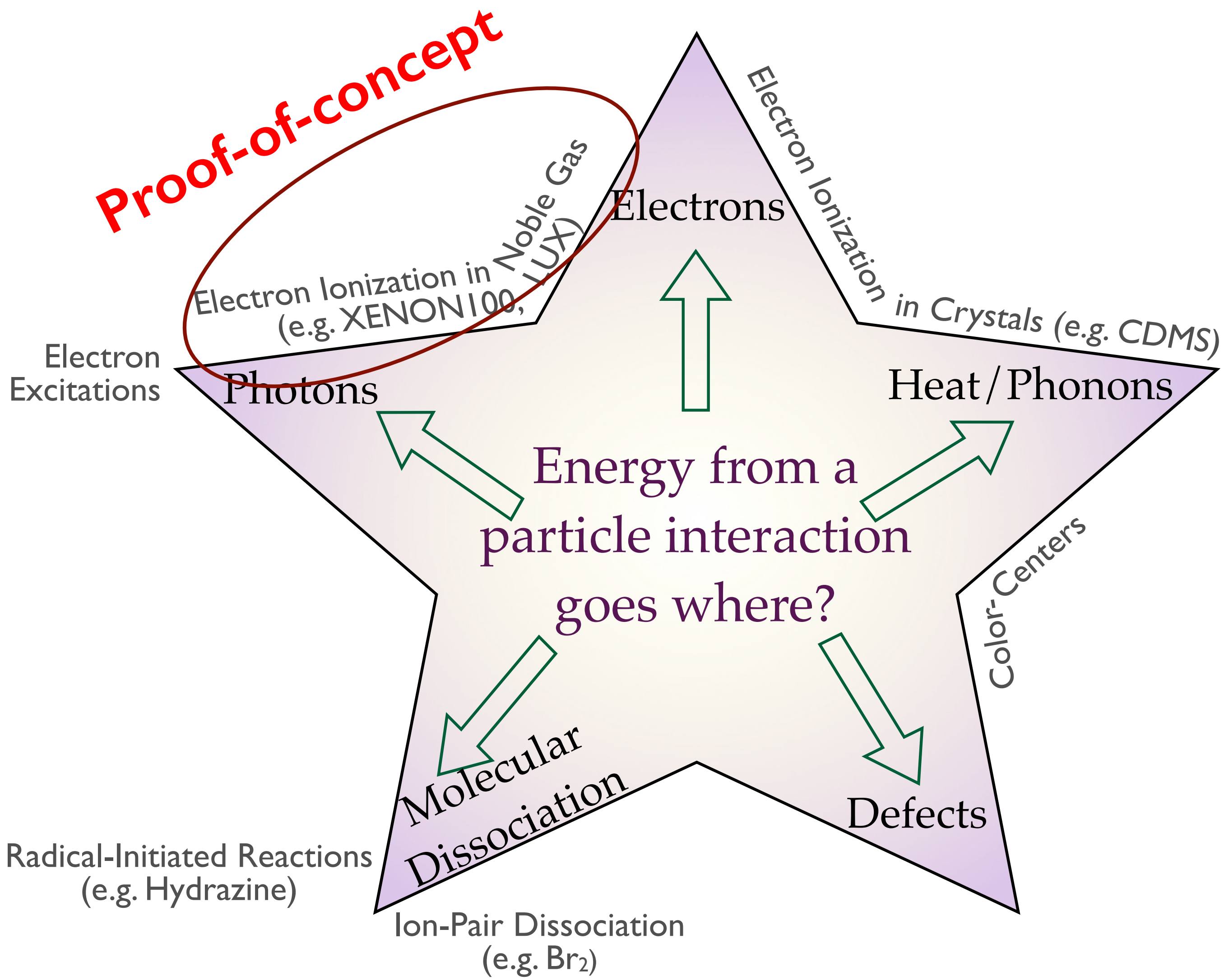


Detectable Signals



Discovery already possible with one type of signal only - search for annual modulation

Detectable Signals



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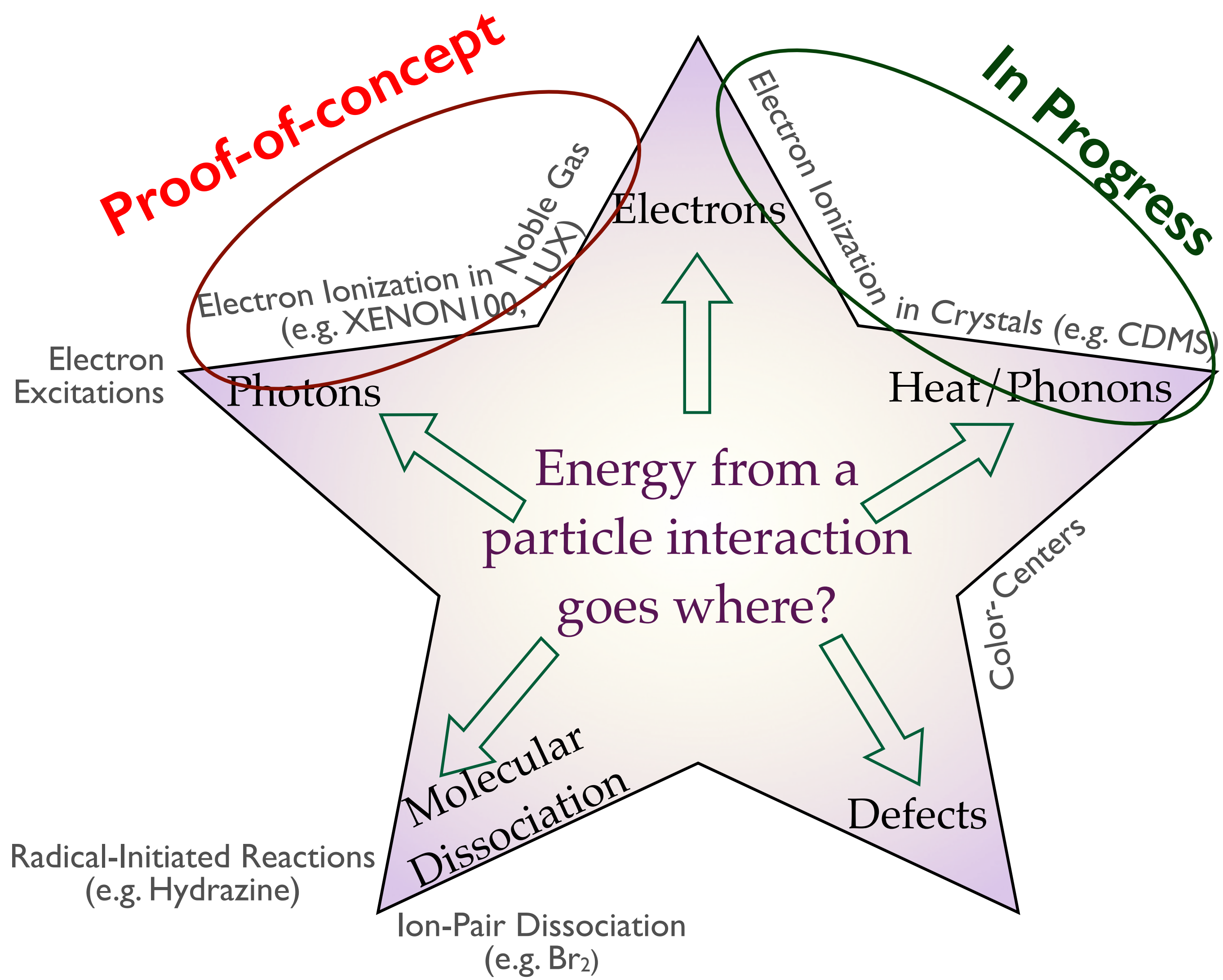
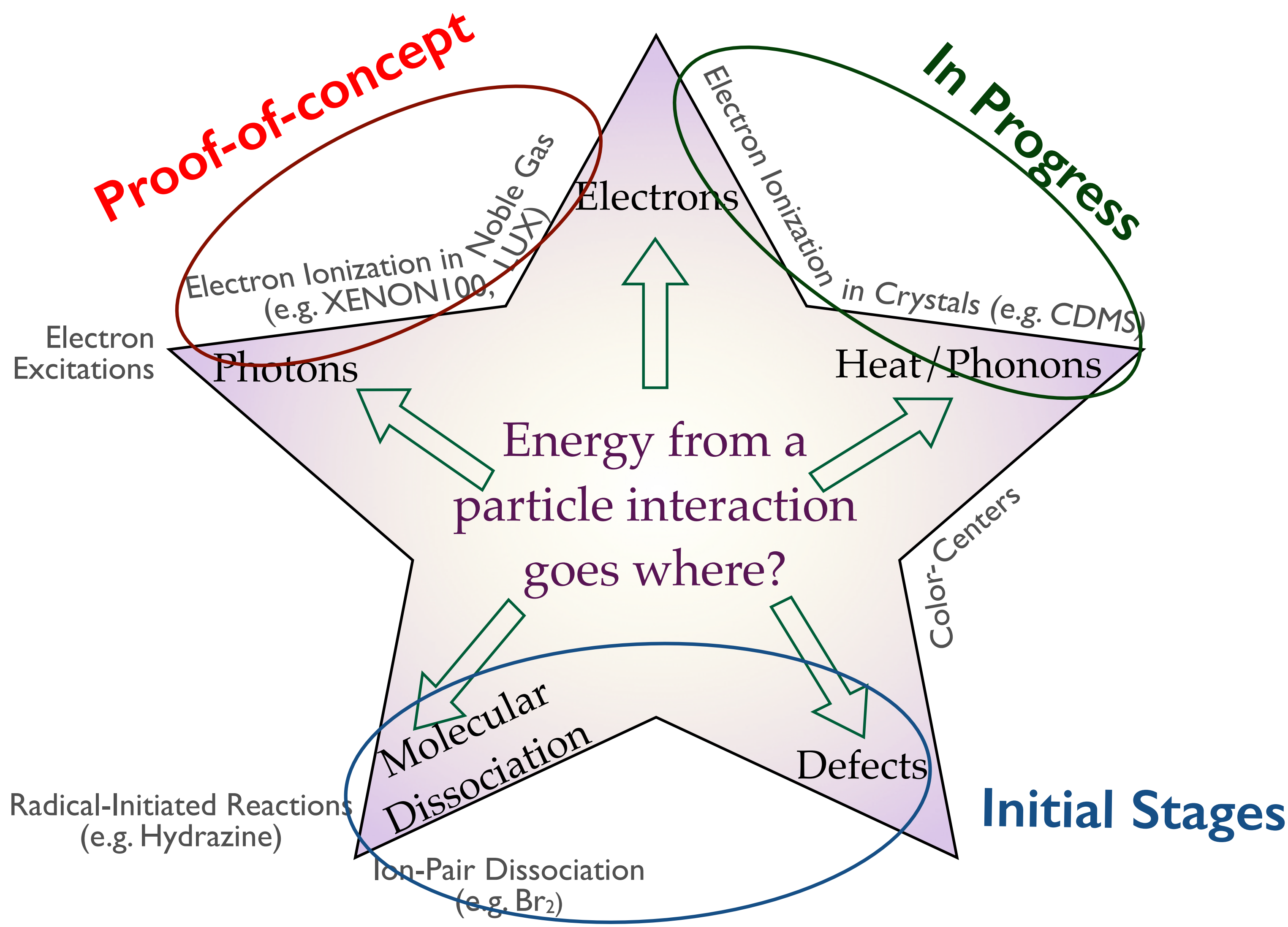


Discovery already possible with one type of signal only - search for annual modulation

Detectable Signals



Discovery already possible with one type of signal only - search for annual modulation

Electron Ionization

Proof-of-Concept

Ionization Cross-section

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

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

Determined by atomic wave-functions

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

Ionization Cross-section

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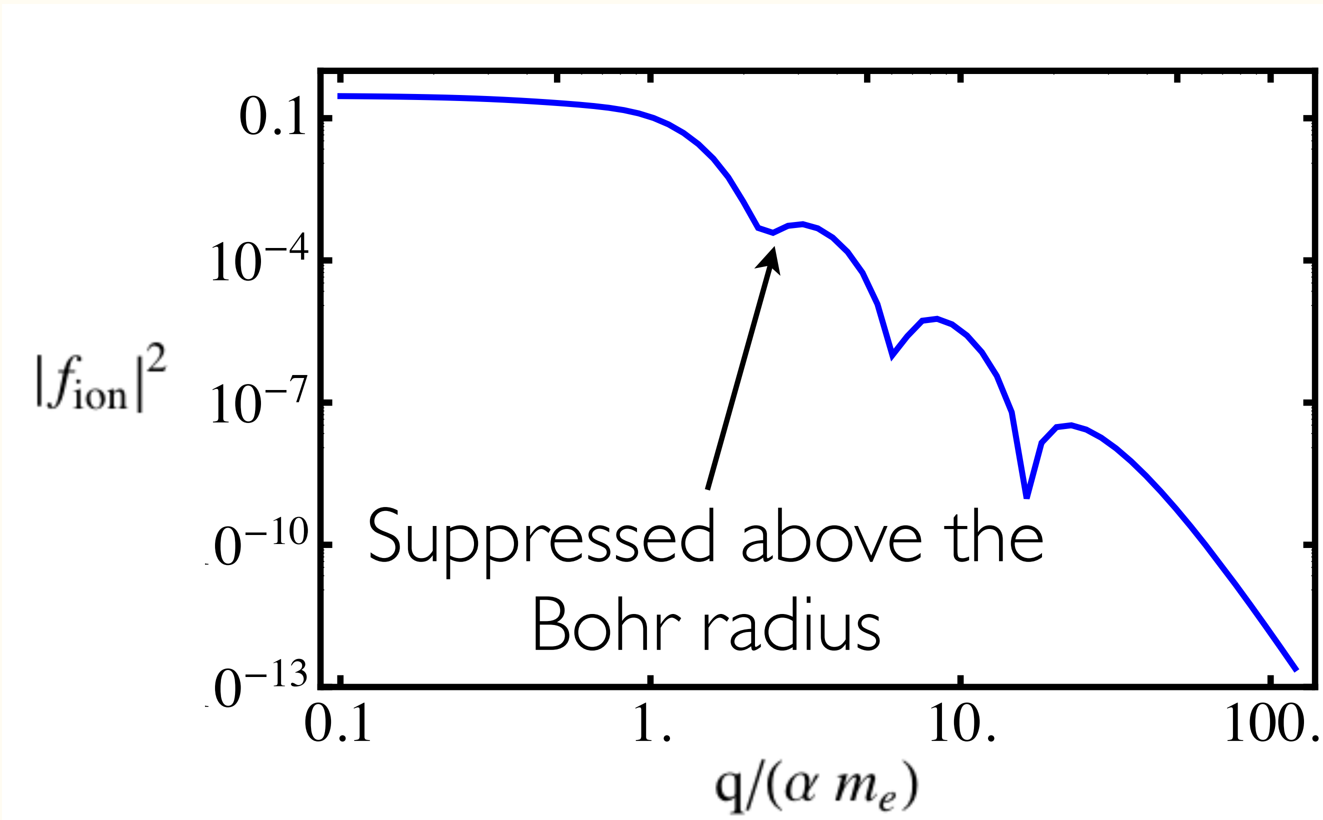
Determined by atomic wave-functions



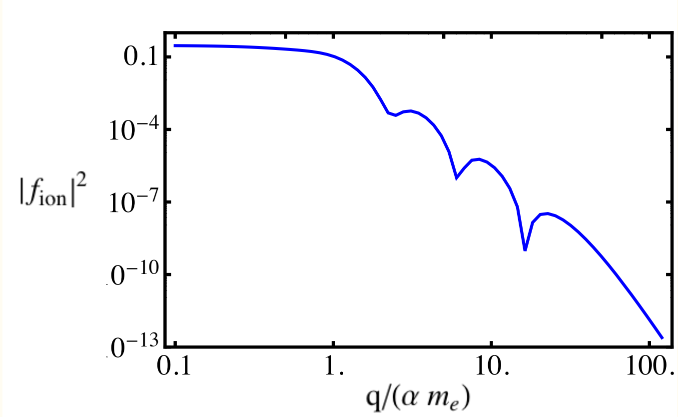
Rates are suppressed for large momentum transfer!

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

Ionization Cross-section

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

Determined by a specific DM theory



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

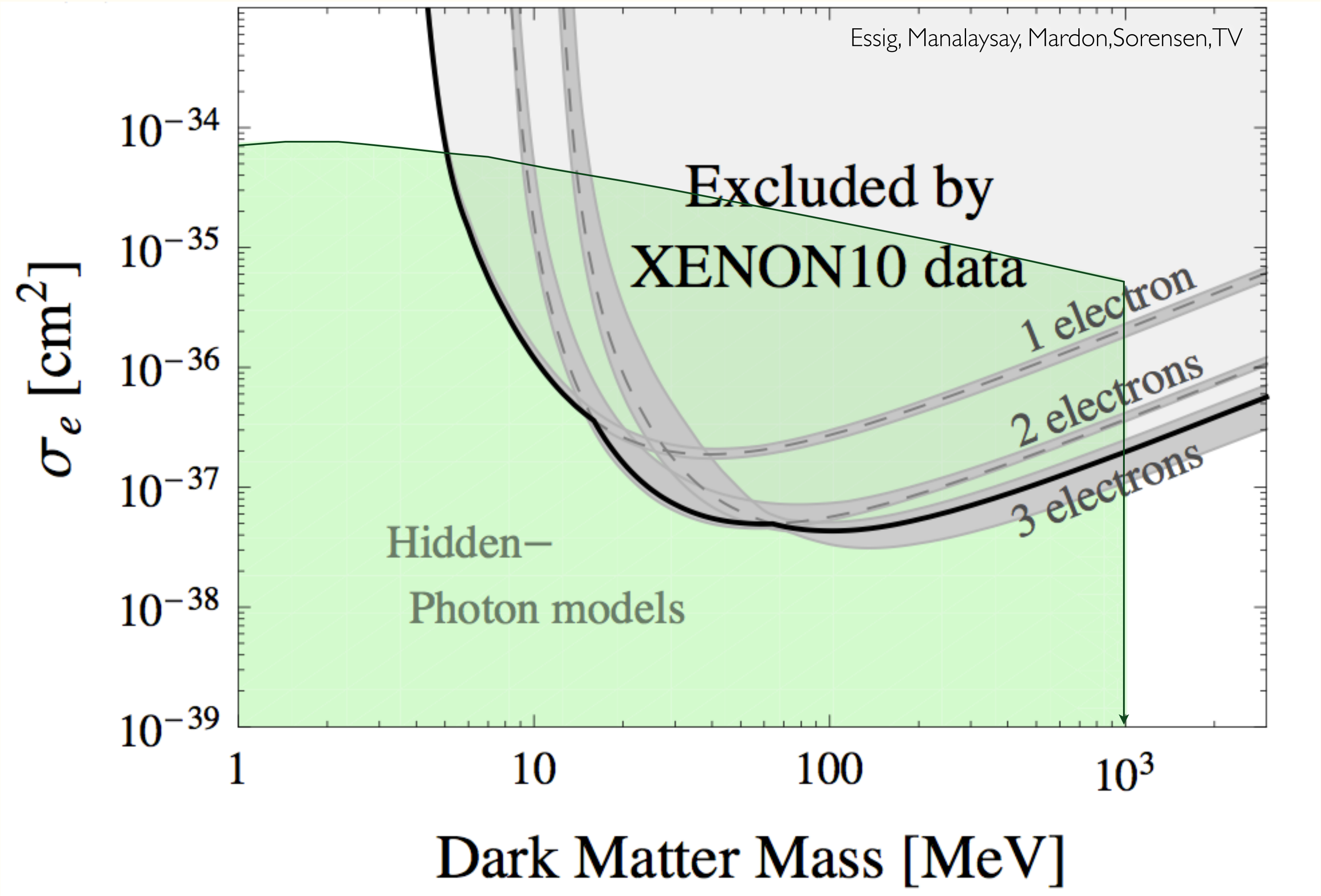
$$\overline{|\mathcal{M}_{\chi e}(q)|^2} = \overline{|\mathcal{M}_{\chi e}(q)|^2}\Big|_{q^2=\alpha^2 m_e^2} \times |F_{\rm DM}(q)|^2$$

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

$$\langle \frac{1}{v}\theta(v - v_{\rm min})\rangle$$

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

First Direct Detection Bounds for MeV-GeV



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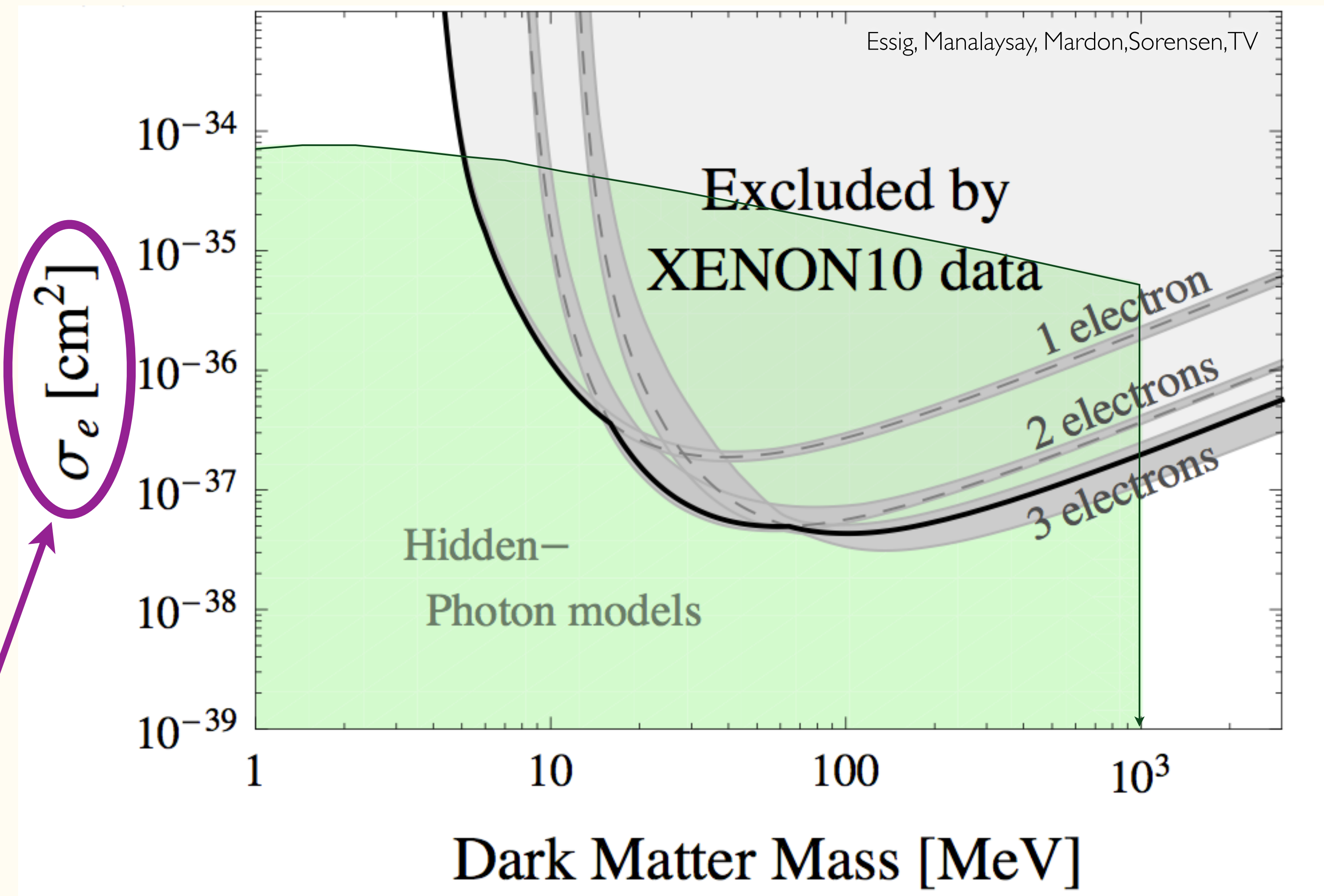
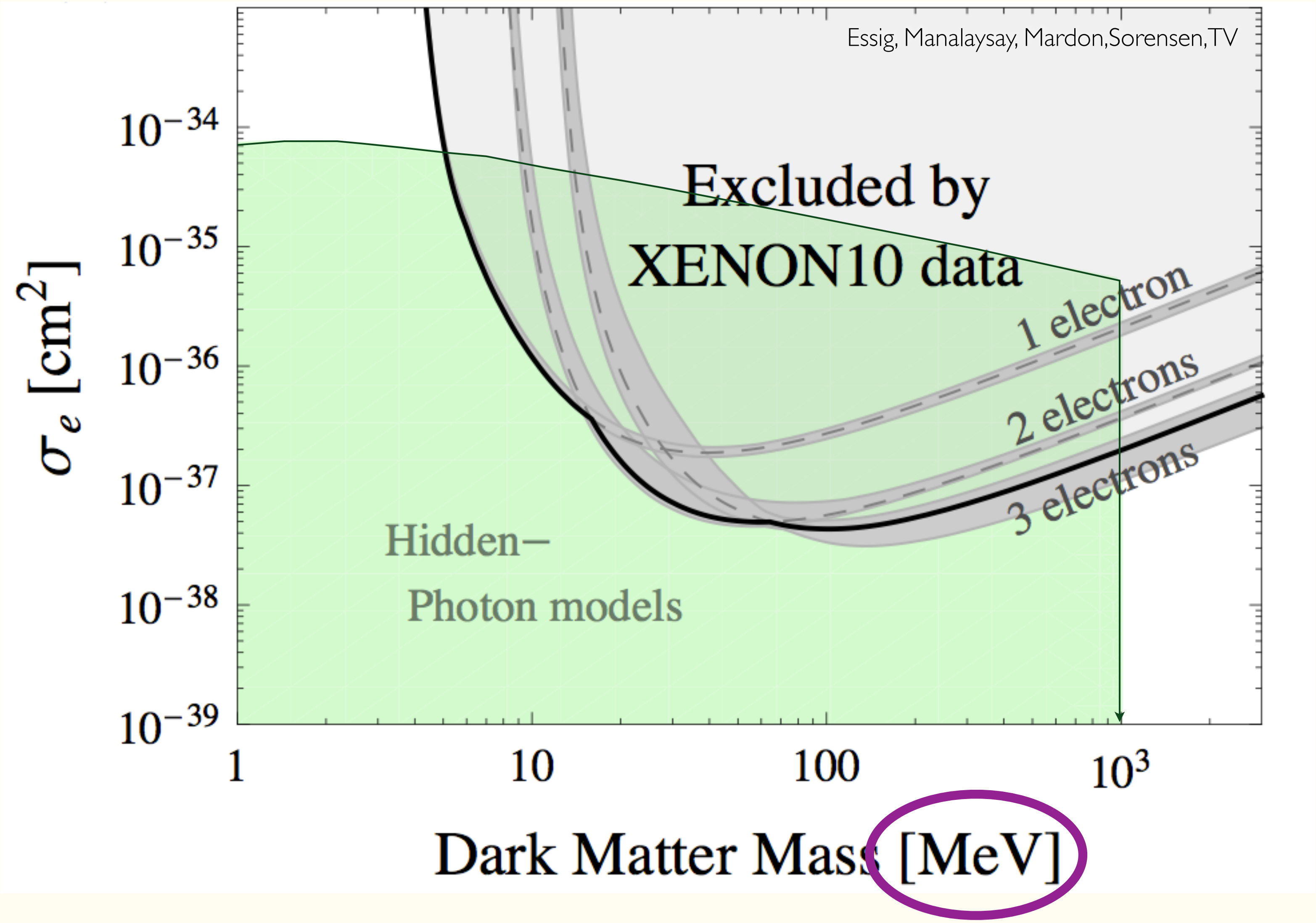


free electron-DM cross-section.

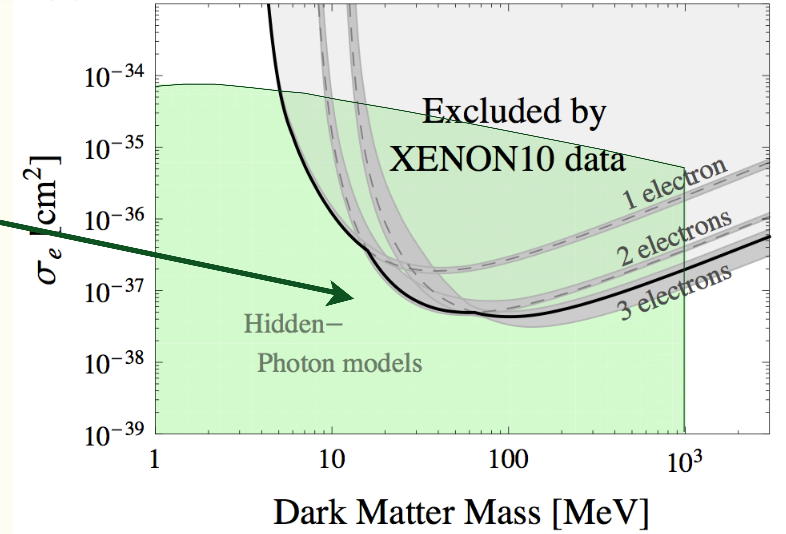
Results from XENON10: $F_{DM}=1$

First Direct Detection Bounds for MeV-GeV

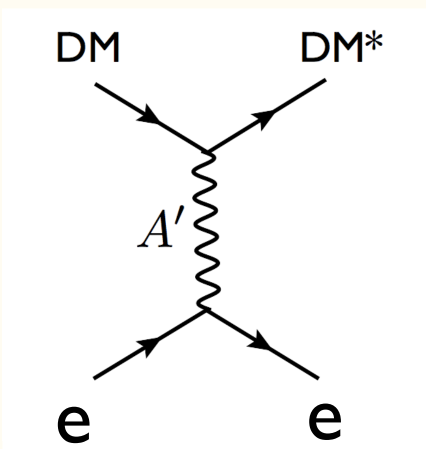


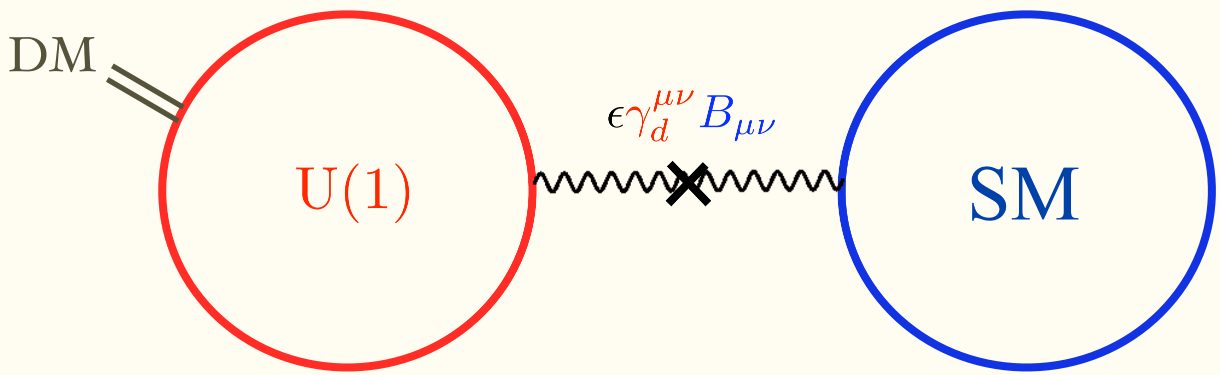
Results from XENON10: $F_{DM}=1$

Model in GREEN



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

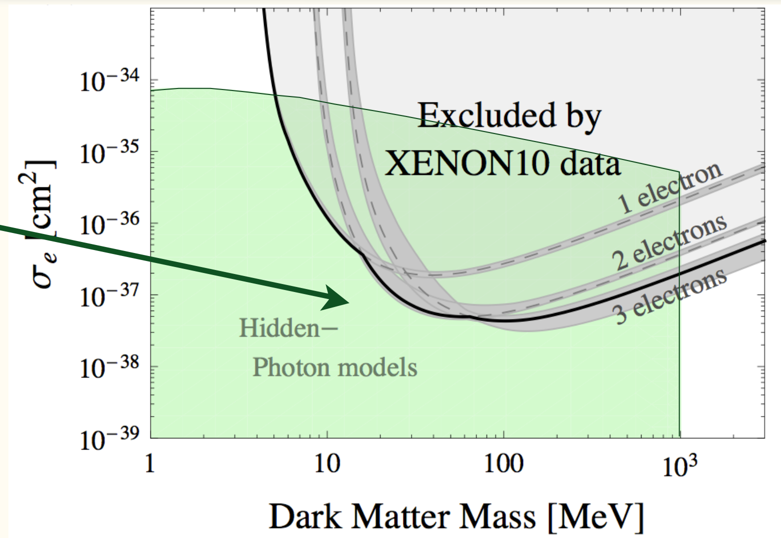




$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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

Model in GREEN



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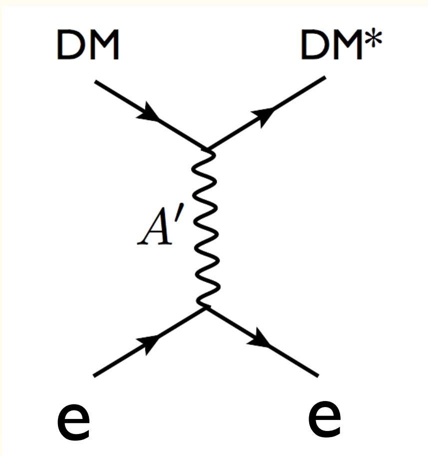
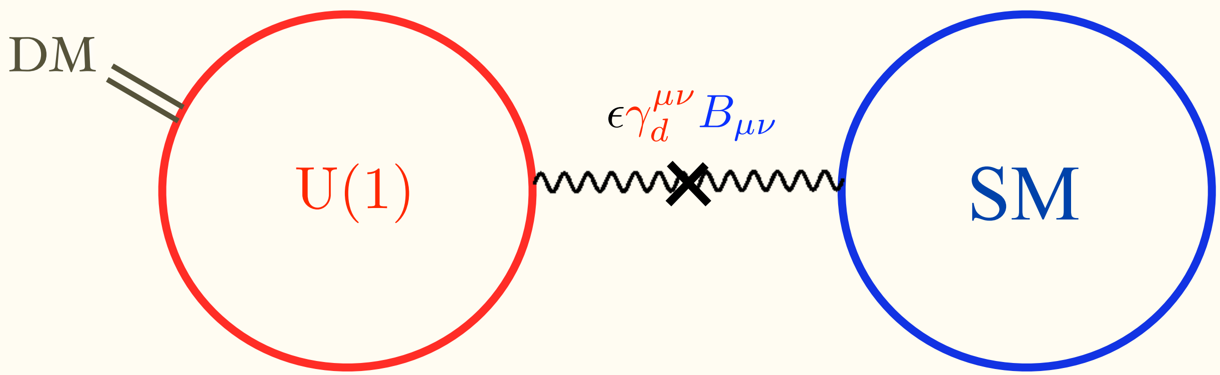
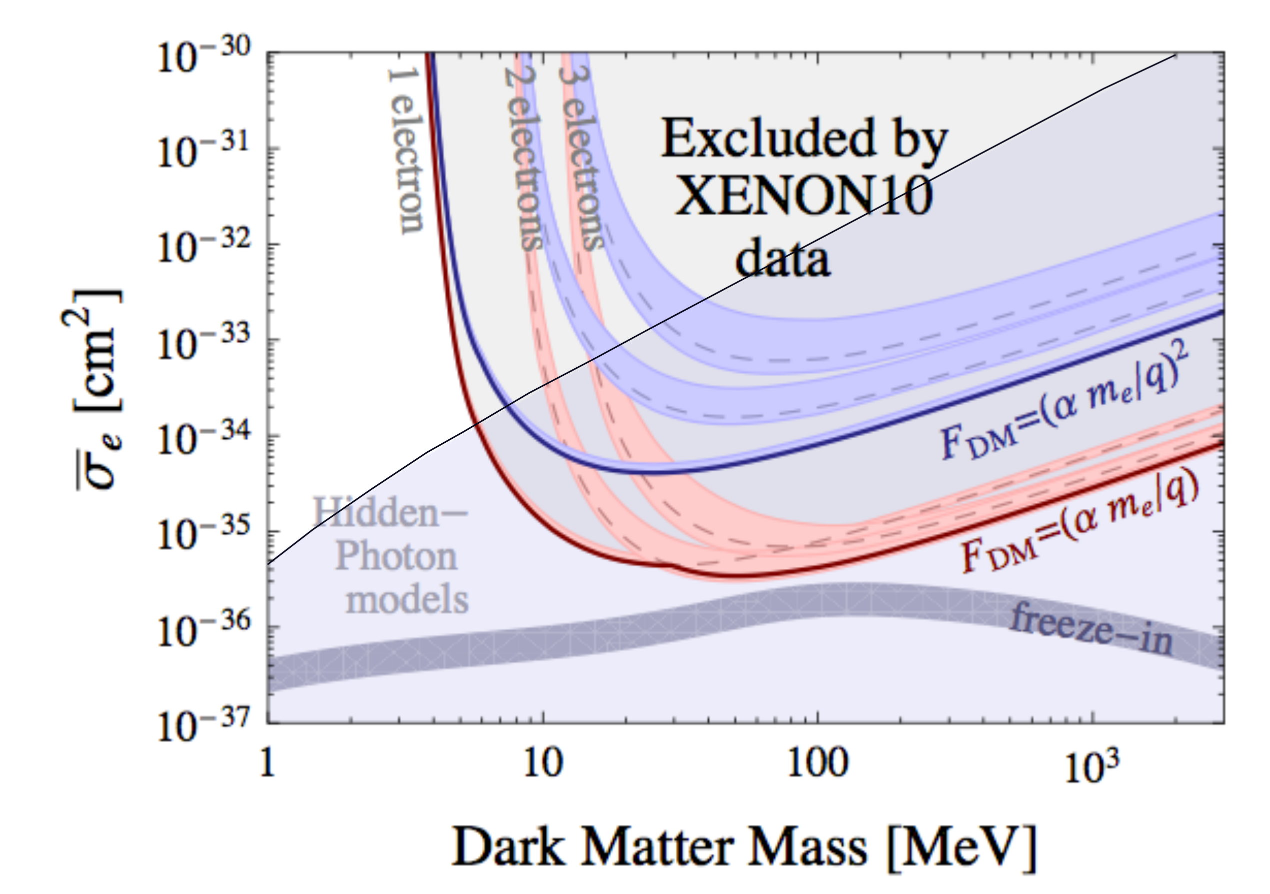




$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

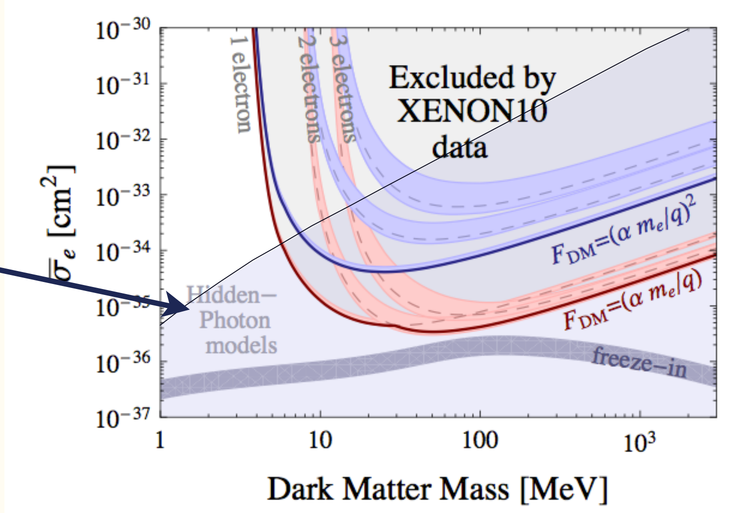
For m_A >MeV hidden photon: $F_{\rm DM} = 1$

Results: Non-trivial form factor

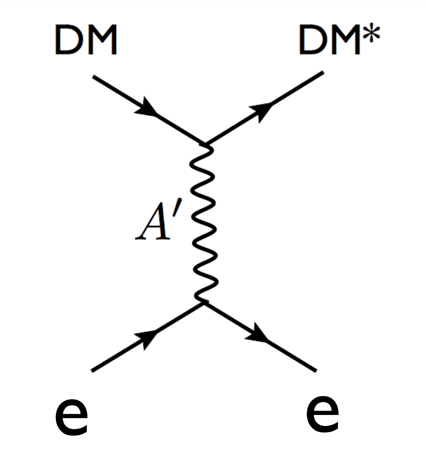


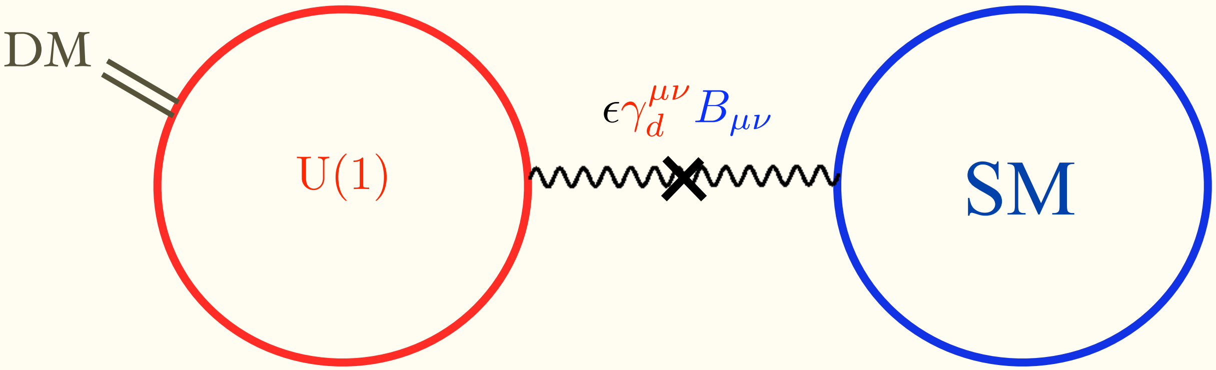
Results: Non-trivial form factor

Model in BLUE



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

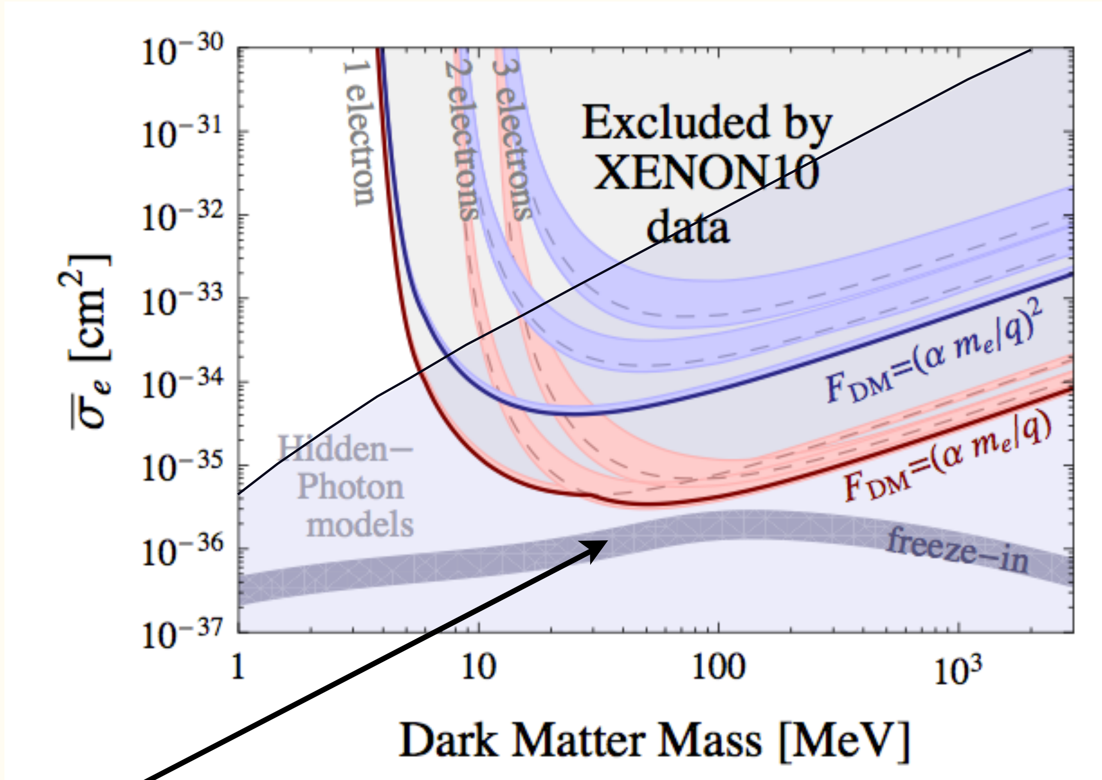




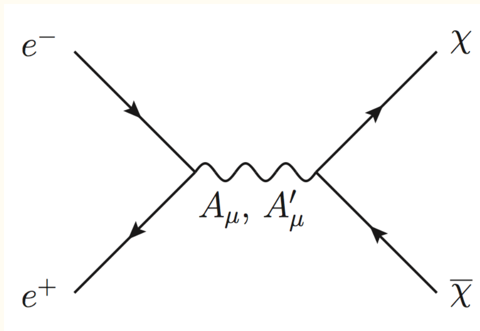
$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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

Results: $F_{DM} \sim 1/q^2$



Almost sensitive to Freeze-in region: DM is naturally produced by SM production.



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

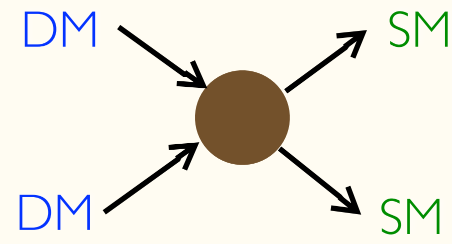
Work in progress with CDMS too.

Experimental Probes

Indirect Detection

Skip

[Essig, Kuflik, McDermott, TV, Zurek, 2013]

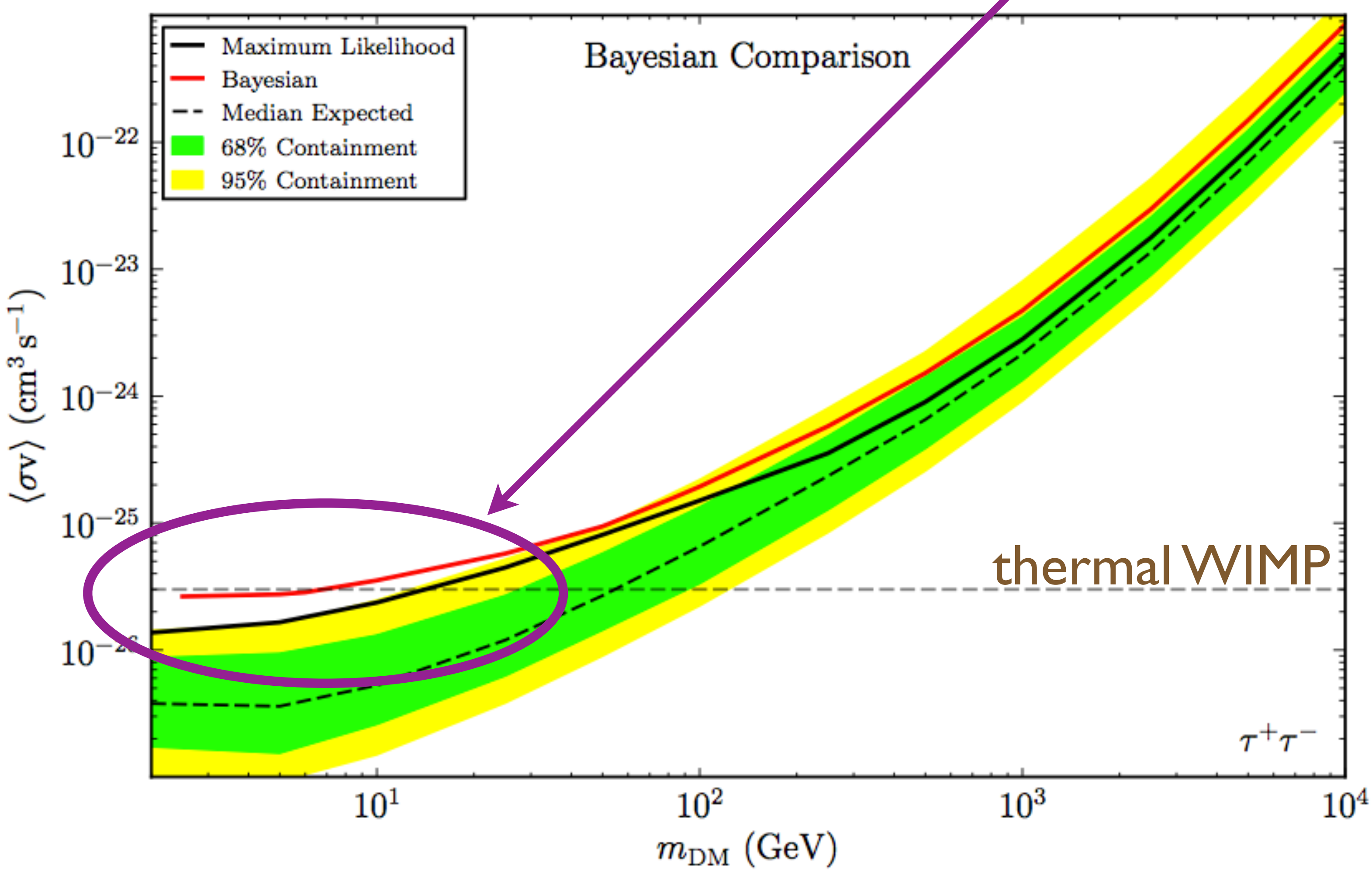


Annihilation products	Experiment
photons	Fermi, INTEGRAL, . . .
electrons, positrons	PAMELA, Fermi, AMS-02, CREST, . . .
antiprotons	PAMELA, AMS-02, ...
neutrinos	IceCube, Super-K, . . .
. . .	

Strong Constraints

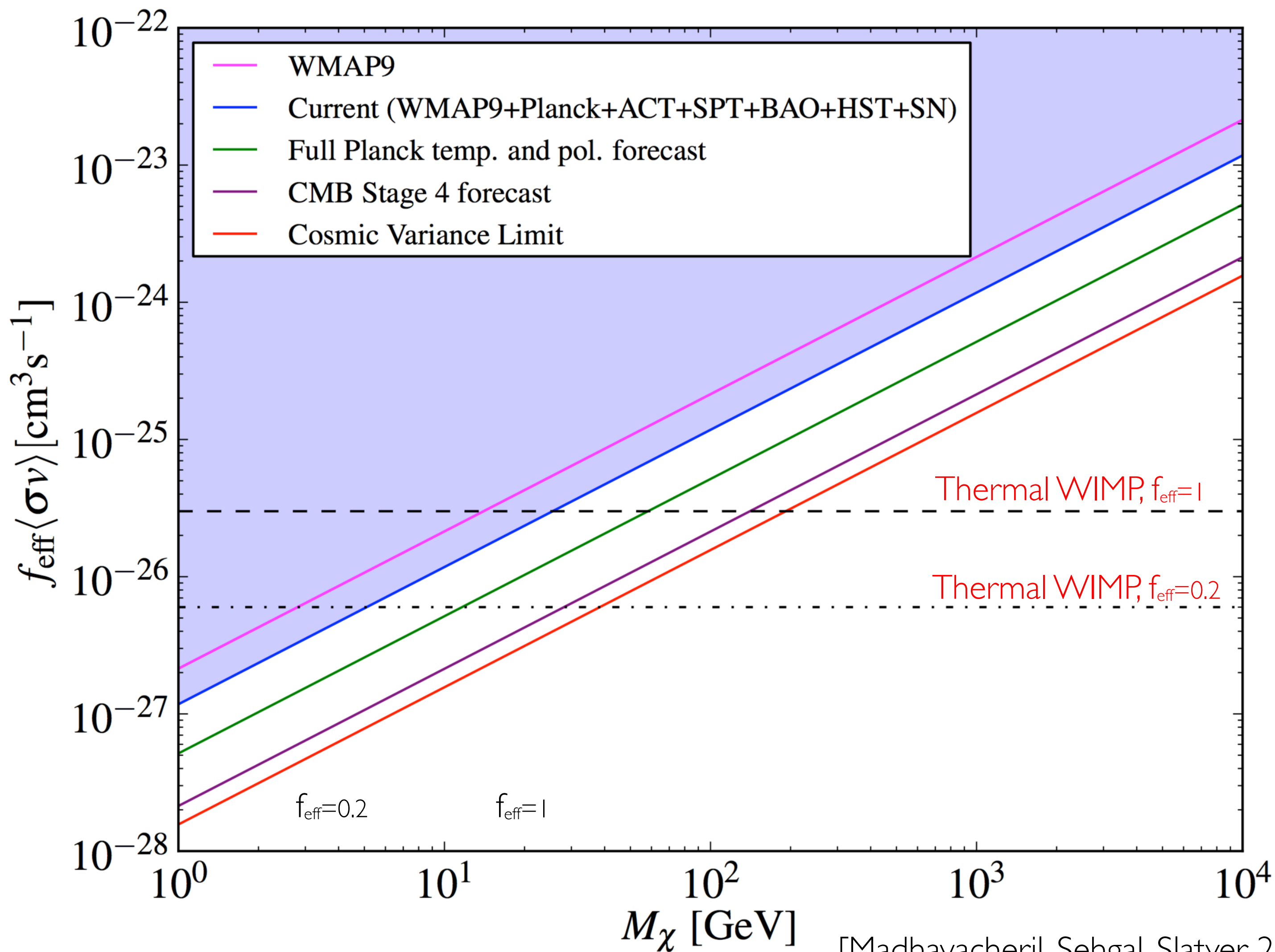
- E.g.: 15 Dwarf galaxies

low-mass thermal WIMPs disfavored!



CMB Constraints

Limits from ionization at recombination epoch. Strongly constrain annihilations of light DM.



[Madhavacheril, Sehgal, Slatyer, 2013]

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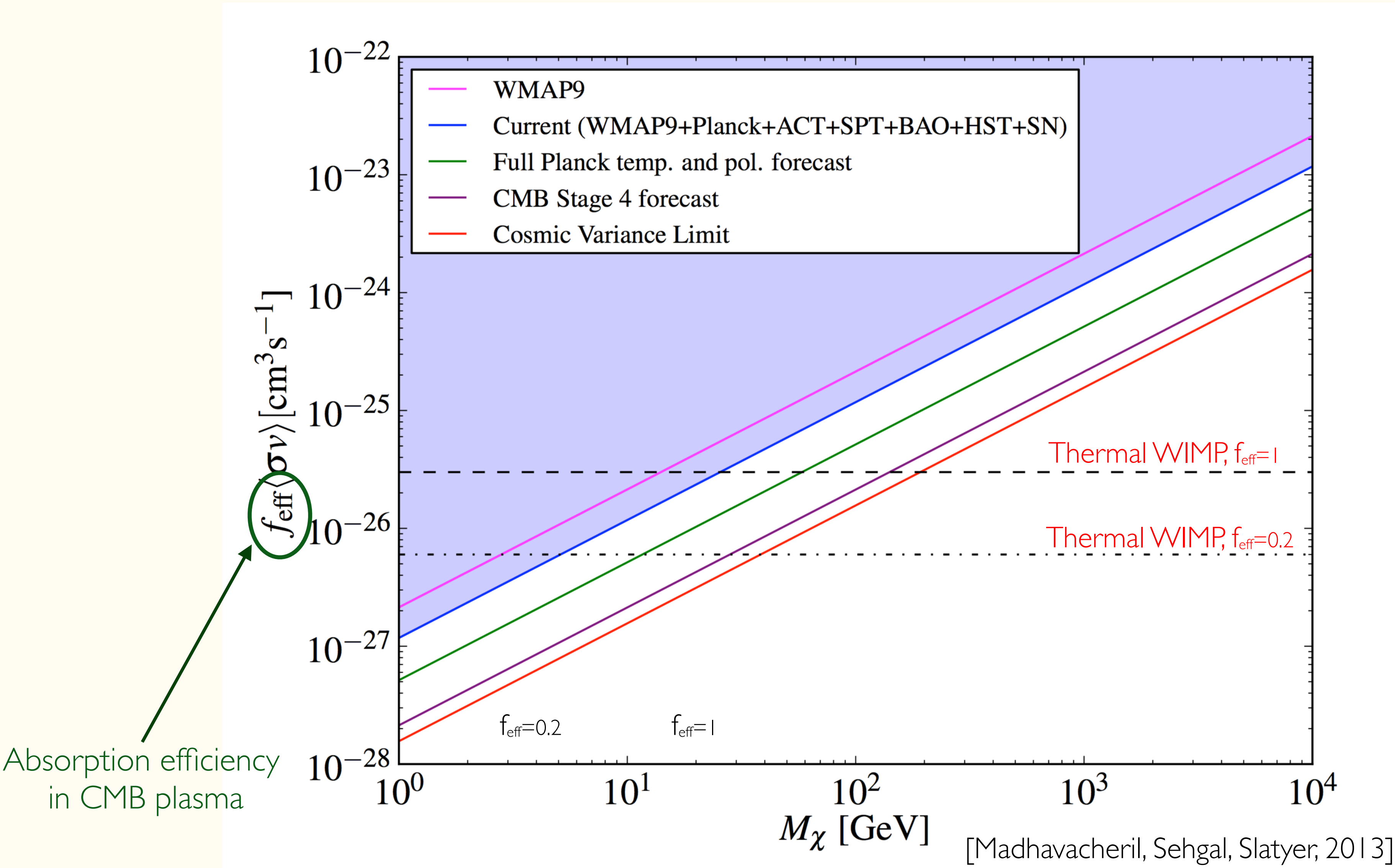
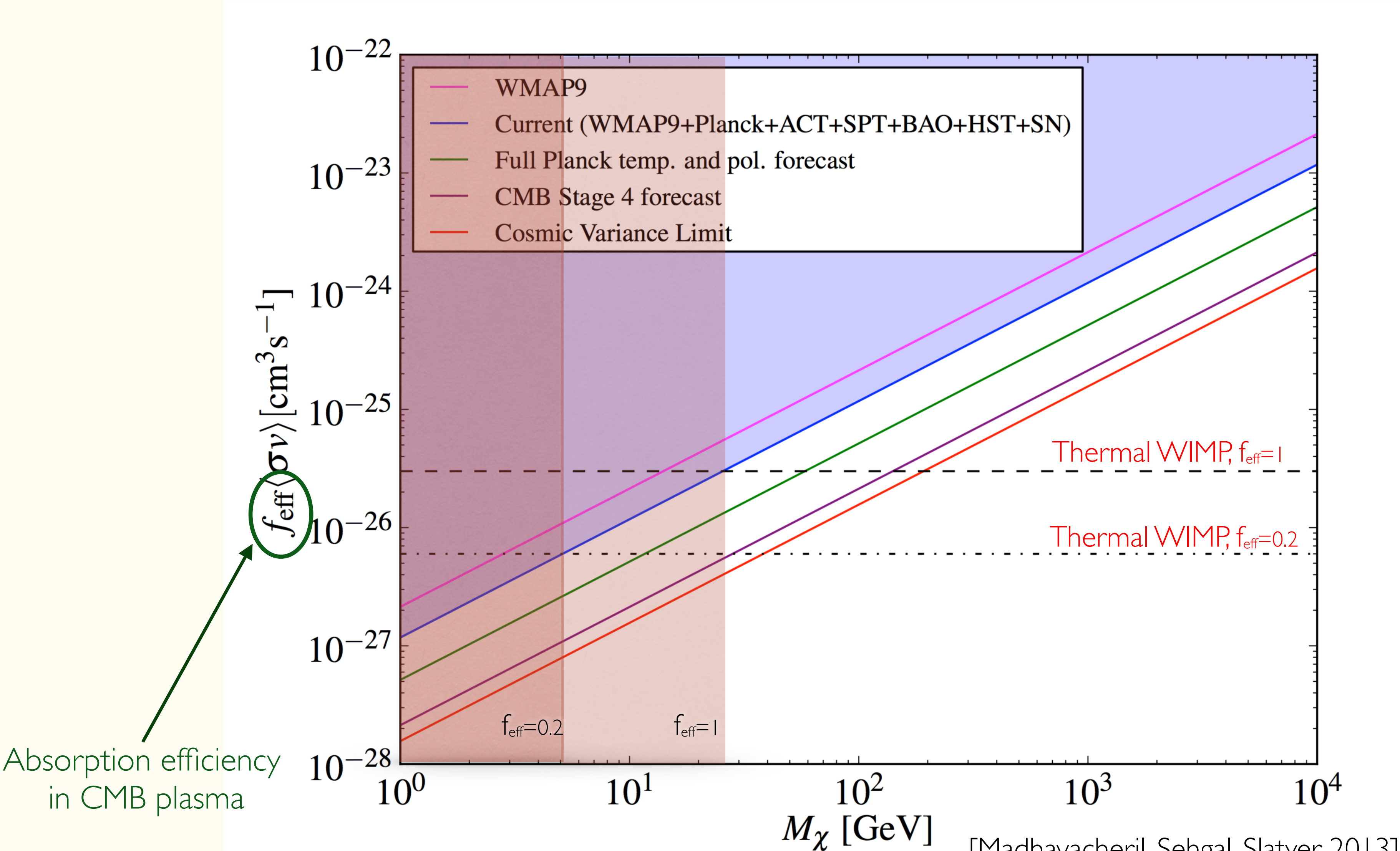


[Madhavacheril, Sehgal, Slatyer, 2013]

CMB Constraints

Limits from ionization at recombination epoch.   Strongly constrain annihilations of light DM.



[Madhavacheril, Sehgal, Slatyer, 2013]

Hope for indirect detection of Sub-GeV DM?

YES

Velocity dependent annihilations

- DM may have velocity suppressed annihilations: $\langle \sigma v \rangle \simeq \sigma_0 v^{2(n-1)}$
- DM velocity depends on when it kinetically decoupled from thermal bath:

$$T_{\rm DM} = T_{\rm kd} \left(\frac{z}{z_{\rm kd}} \right)^2$$

- So DM velocity at CMB is:

$$\begin{aligned} v_{\rm DM} &= \sqrt{3 T_{\rm DM}/m_{\rm DM}} = \sqrt{3} x_\gamma \, x_{\rm kd}^{-1/2} \\ &\simeq 2 \times 10^{-4} \left(\frac{T_\gamma}{1 \text{ eV}} \right) \left(\frac{1 \text{ MeV}}{m_{\rm DM}} \right) \left(\frac{10^{-4}}{x_{\rm kd}} \right)^{1/2} , \qquad x_i \equiv \frac{T_i}{m_{\rm DM}} \end{aligned}$$

vs. today: $v_{\rm DM,0} \simeq 10^{-3}$

Hope for indirect detection?

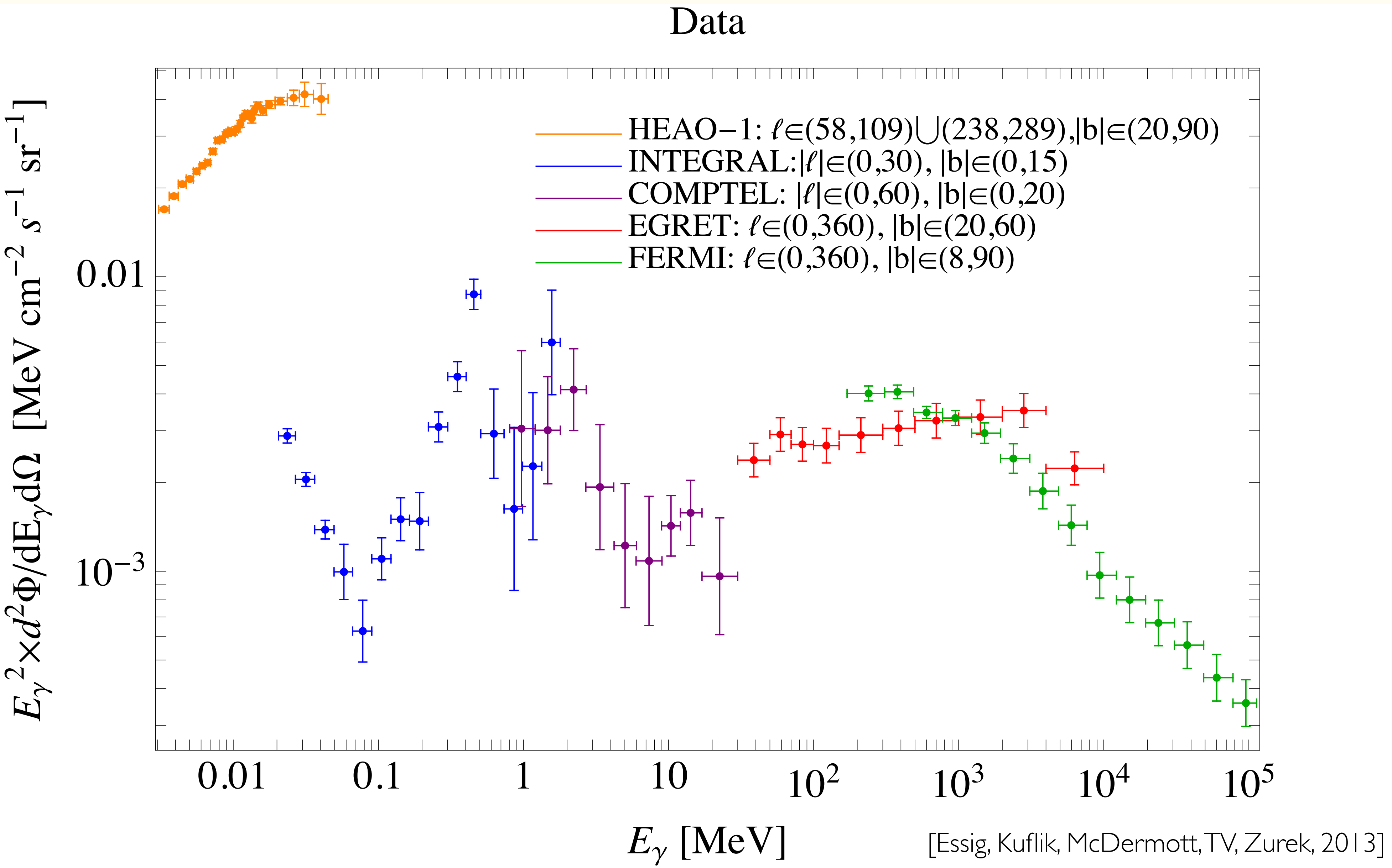
YES

Velocity dependent annihilations

Decaying DM

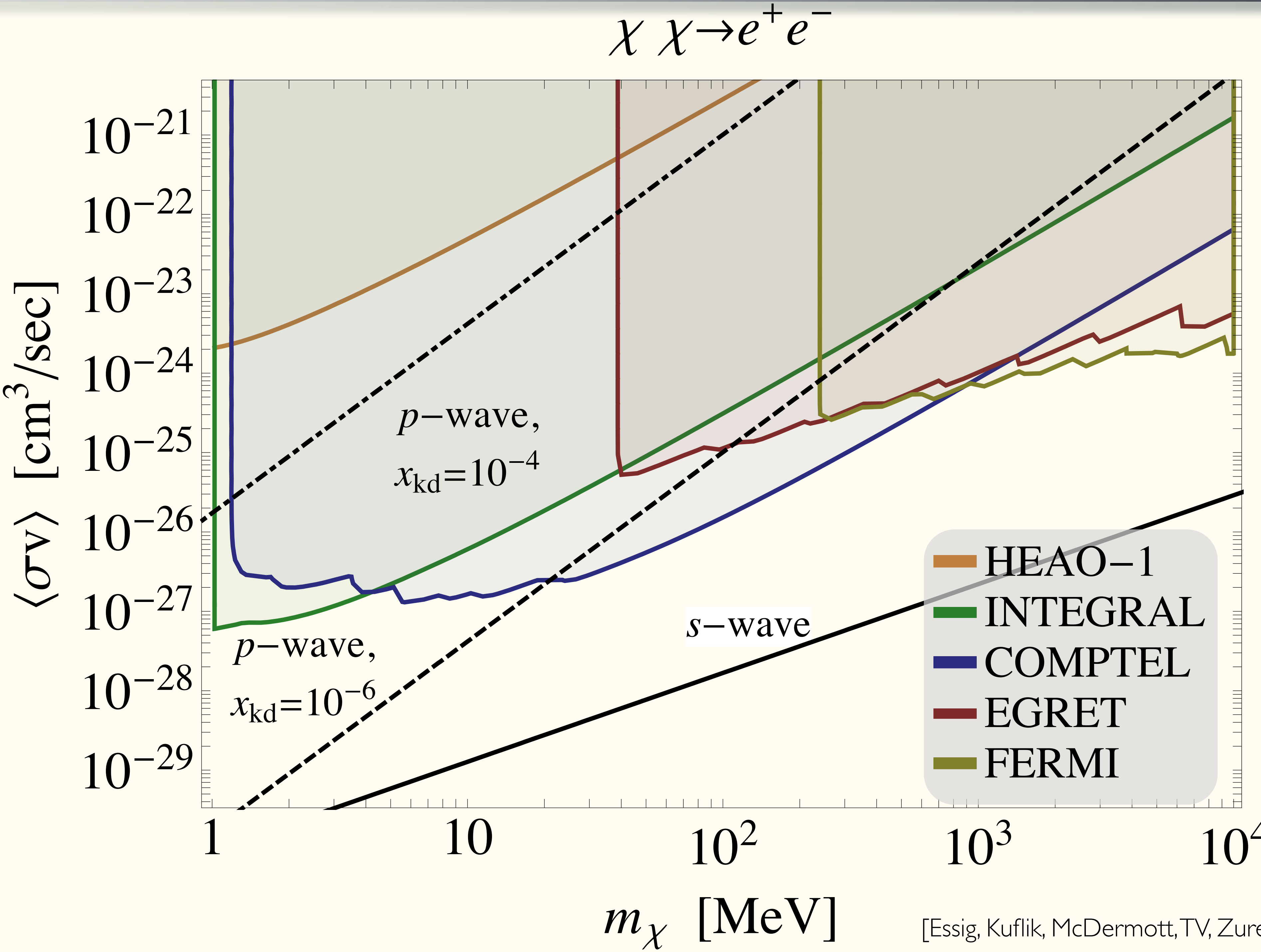
- Annihilation rate $\propto \rho^2$
- Decay rate $\propto \rho$
- Evades limits from CMB

Data



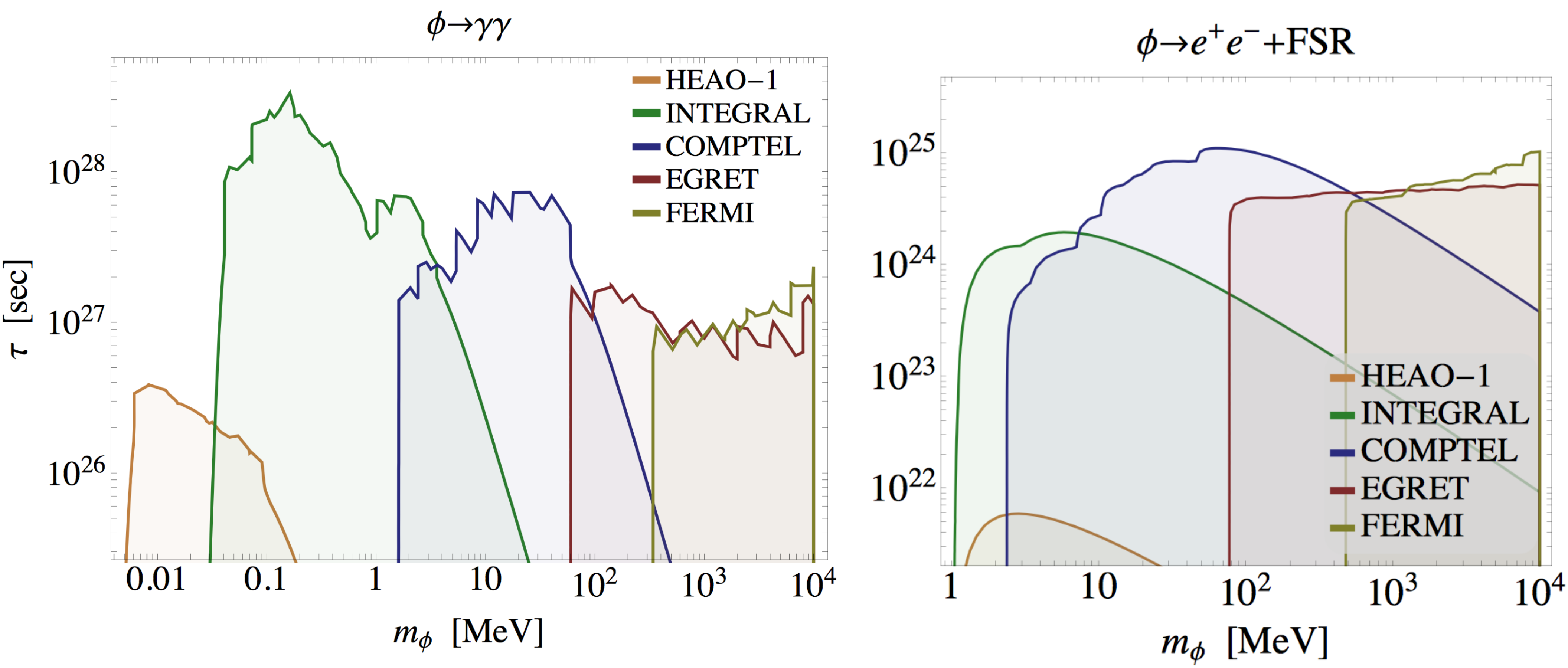
[Essig, Kuflik, McDermott, TV, Zurek, 2013]

Annihilating Light DM



[Essig, Kuflik, McDermott, TV, Zurek, 2013]

Decaying Light DM



[Essig, Kuflik, McDermott, TV, Zurek, 2013]

Experimental Probes

Astrophysical and Cosmological Probes

Skip

Structure Formation

- There are several constraints for light DM:
  - Free streaming. If DM is too light, it washes out small scale structure. Constraints are typically of the order

$$m_{DM} \gtrsim 10 \text{ keV}$$

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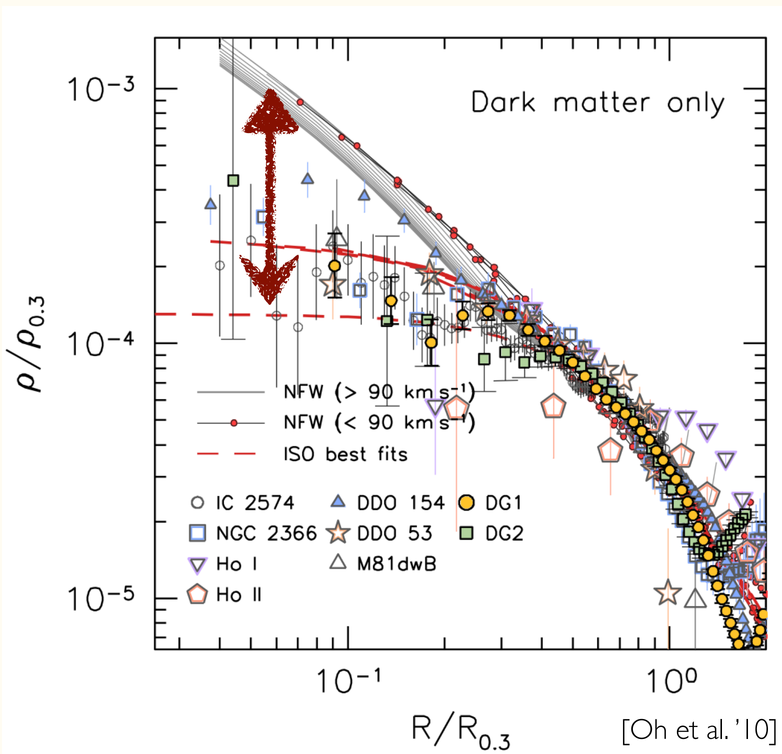
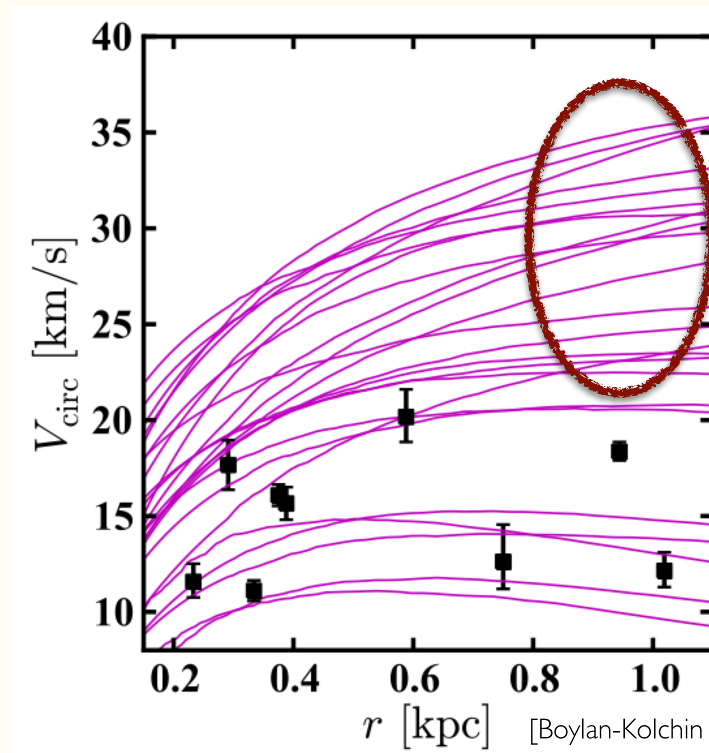
    [Boylan-Kolchin et al. '11, '12; Vogelsberger, '12; Rocha et al. '13; Zavala et al. '13; Peter et al. '12]
    [Spergel, Steinhardt, '00]



[Oh et al. '10]



[Boylan-Kolchin et al. '11]

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$$\left(\frac{\sigma_{\rm scatter}}{m_{\rm DM}}\right)_{\rm obs} = (0.1 - 10)\ {\rm cm}^2/{\rm g}$$

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$$\left(\frac{\sigma_{\text{scatter}}}{m_{\text{DM}}}\right)_{\text{obs}} = (0.1 - 10)\ \text{cm}^2/\text{g}$$

  - Self interactions. Distort the dynamics in DM halos. Significant uncertainty.

Bullet cluster:
[Clowe et al., '04; Markevitch et al. '04; Randall et al. '08]

Halo ellipticity:
[Miralda-Escude, '00; Rocha et al. '13; Peter et al. '12]

$$\frac{\sigma_{\text{scatter}}}{m_{\text{DM}}} \leq 1\ \text{cm}^2/\text{g}$$

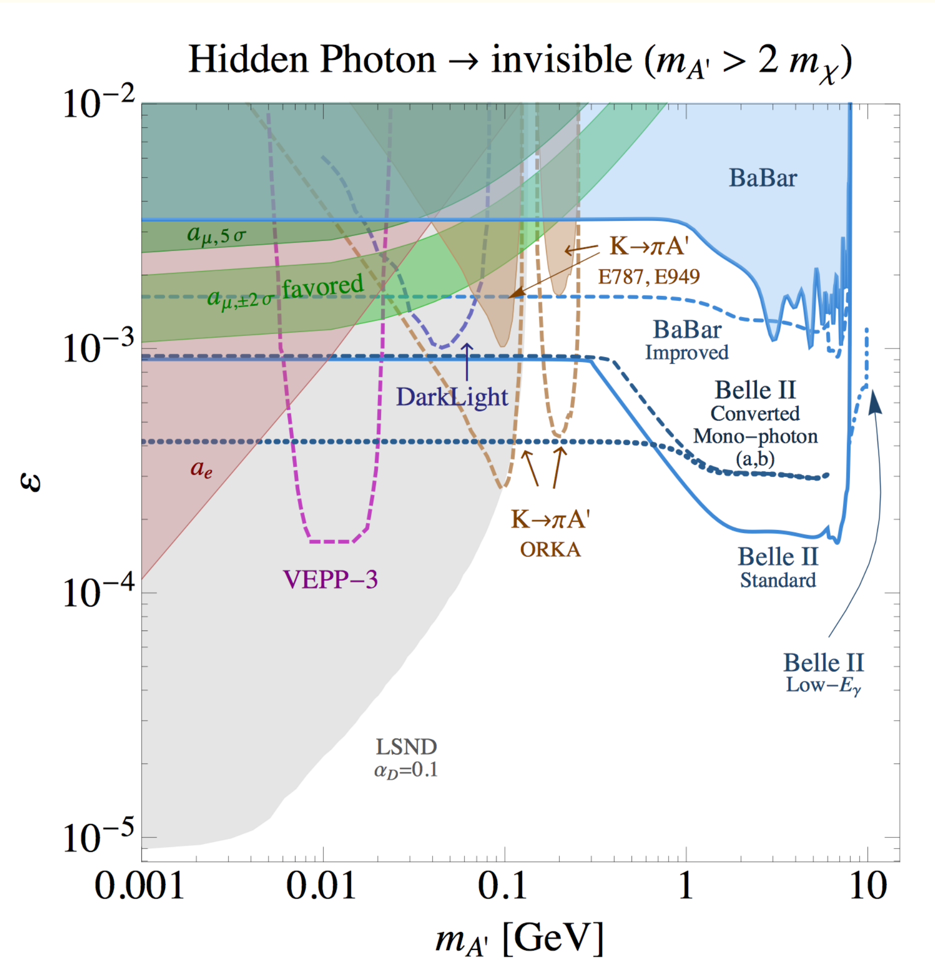
Experimental Probes

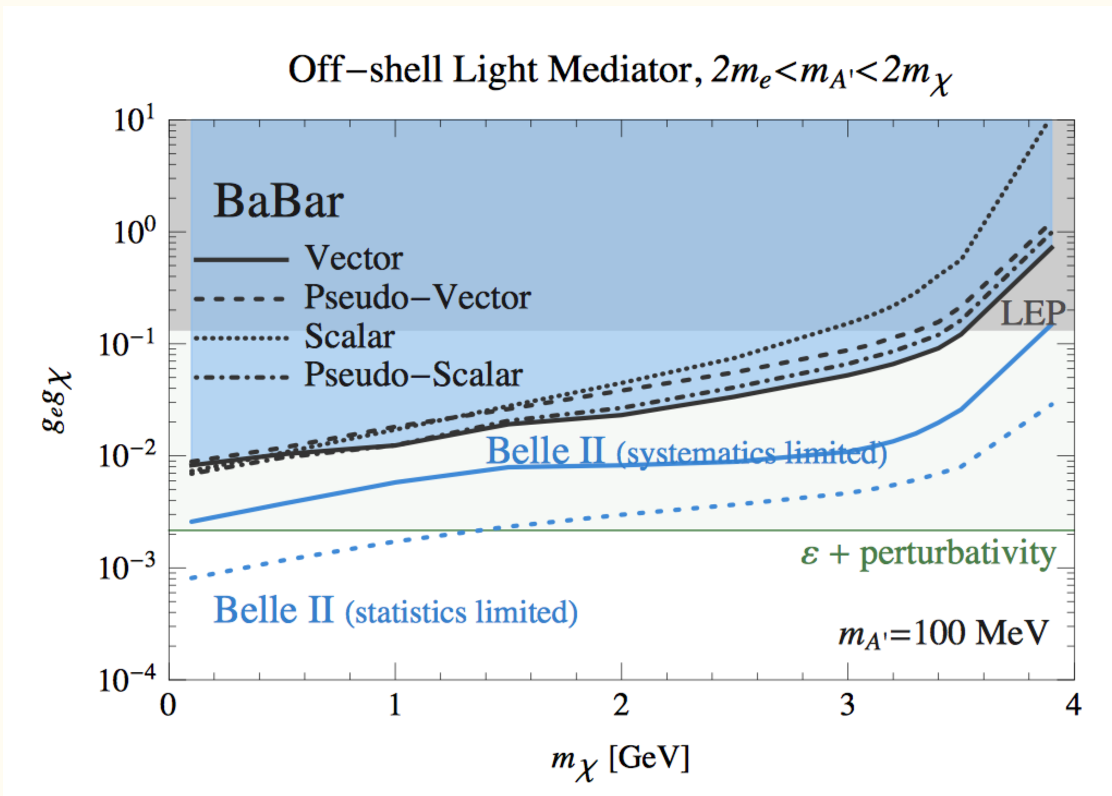
Colliders

Light DM at B-factories

[Essig, Mardon, Papucci, TV, Zhong, 2013]

- B-factories are ideal to search for light DM.





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

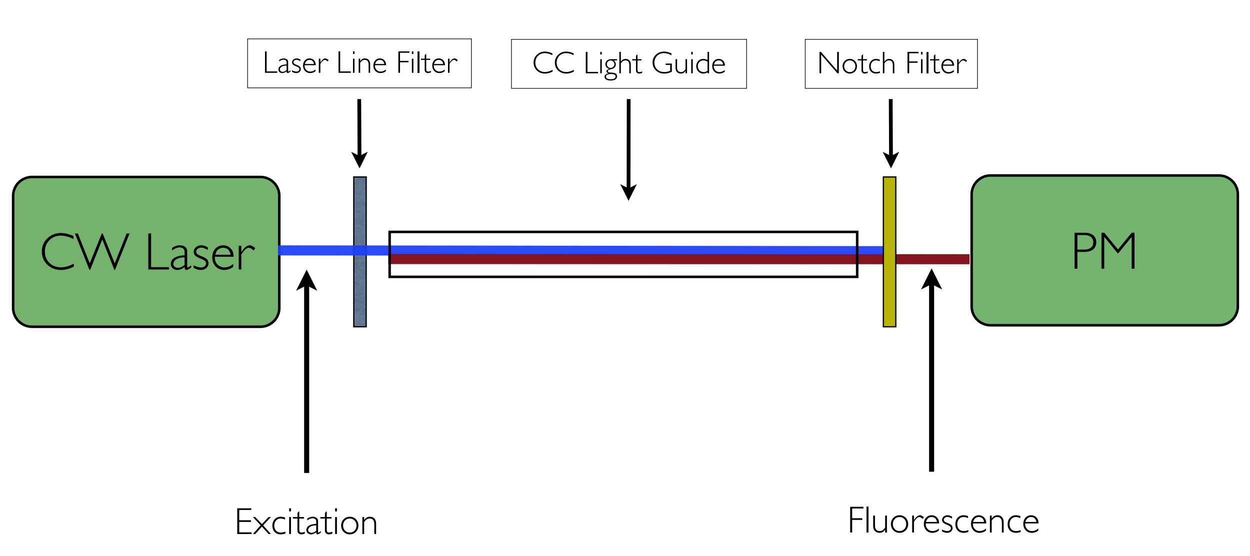
- In the next ~5-10 years, we'll cover much of the WIMP parameter space (but not all!!)
  - Direct Detection - Will reach the background neutrino limit.
  - Indirect Detection - Will exclude much of the parameter space for a thermal WIMP annihilation cross-section
  - LHC - Will reach its limits in producing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

What if we don't find it?

Bond Breakage: New Technologies

- To lower the threshold in DM-Nucleon scattering, one needs to study inelastic processes.
- Bonds in molecules and crystals provide an opportunity. However, signal must be amplified.
- One way: Optical enhancement, which utilizes spectroscopy of chemical change in material.
- 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.

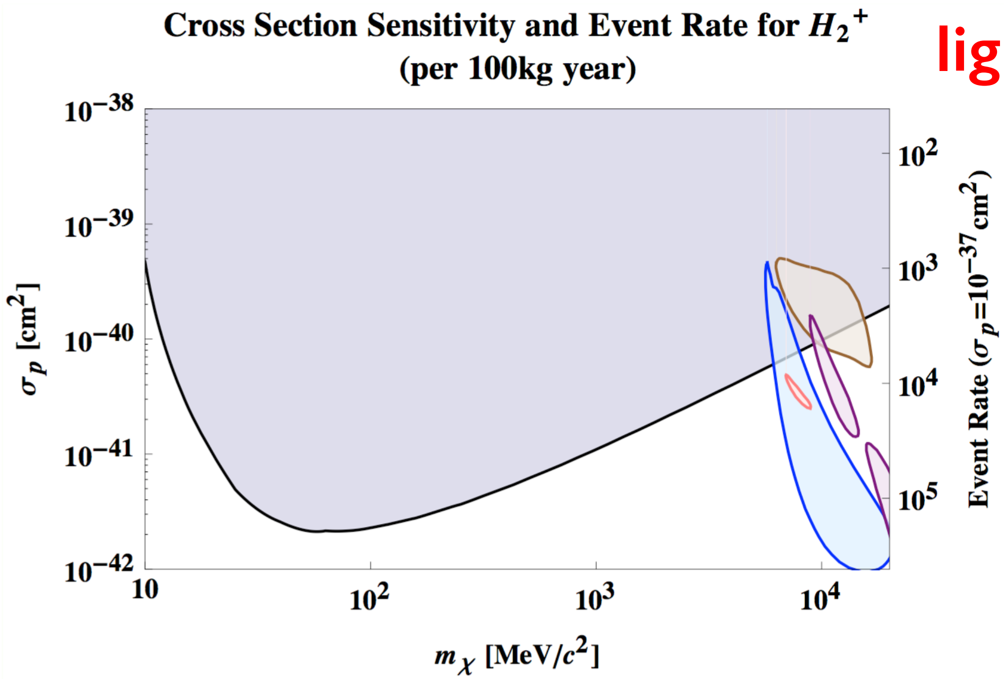
Bond Breakage: New Technologies

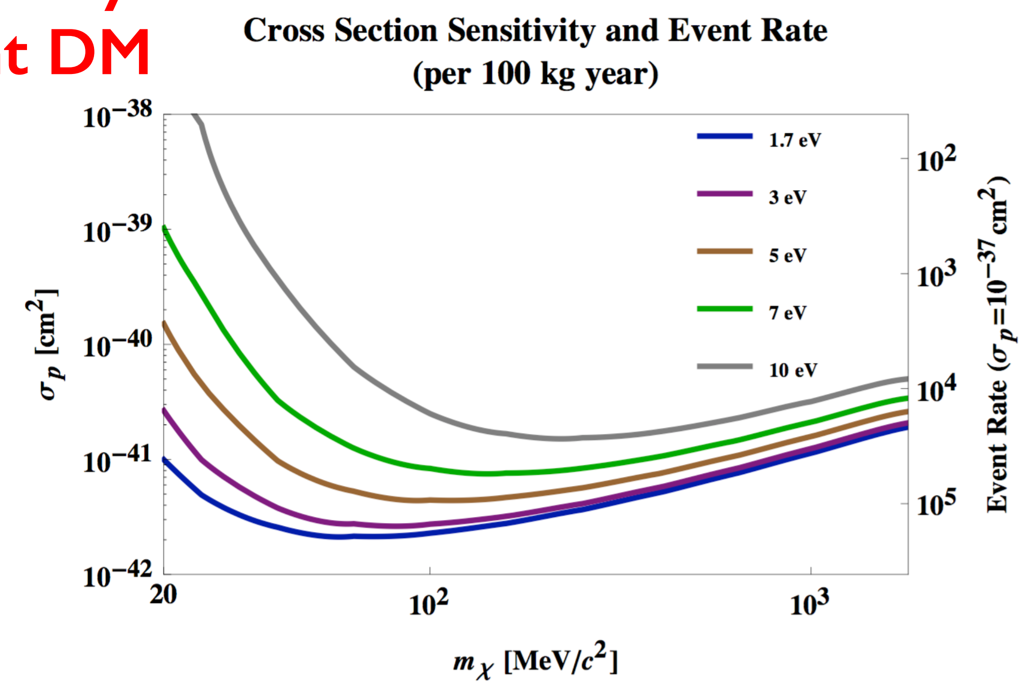


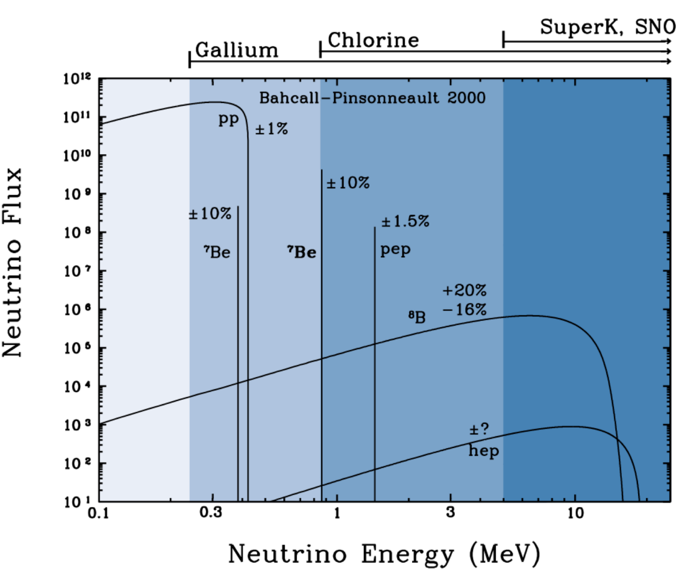
- Technology is under development.
- An on-going Theory-Experimental collaboration with:
  - Rouven Essig (Stony Brook, HEP-Ph)
  - Jeremy Mardon (Stanford, HEP-Ph)
  - Oren Slone (TAU, HEP-Ph)
  - Itay Bloch (TAU, HEP-Ph)
  - Ranny Budnik (Weizmann, HEP-Ex)
  - Ori Chechnovsky (TAU, Chemistry-Ex)
  - Arik Kreisel (NRC, HEP-Ex)
  - Avner Soffer (TAU, HEP-Ex)

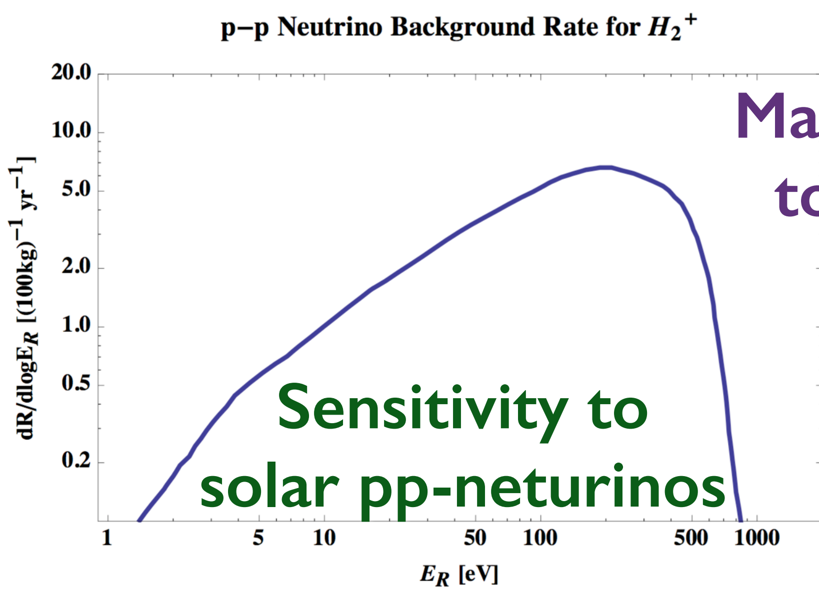
Bond Breakage: New Technologies

Sensitivity to light DM









Sensitivity to solar pp-neturinos

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

To Conclude..

The current experimental 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

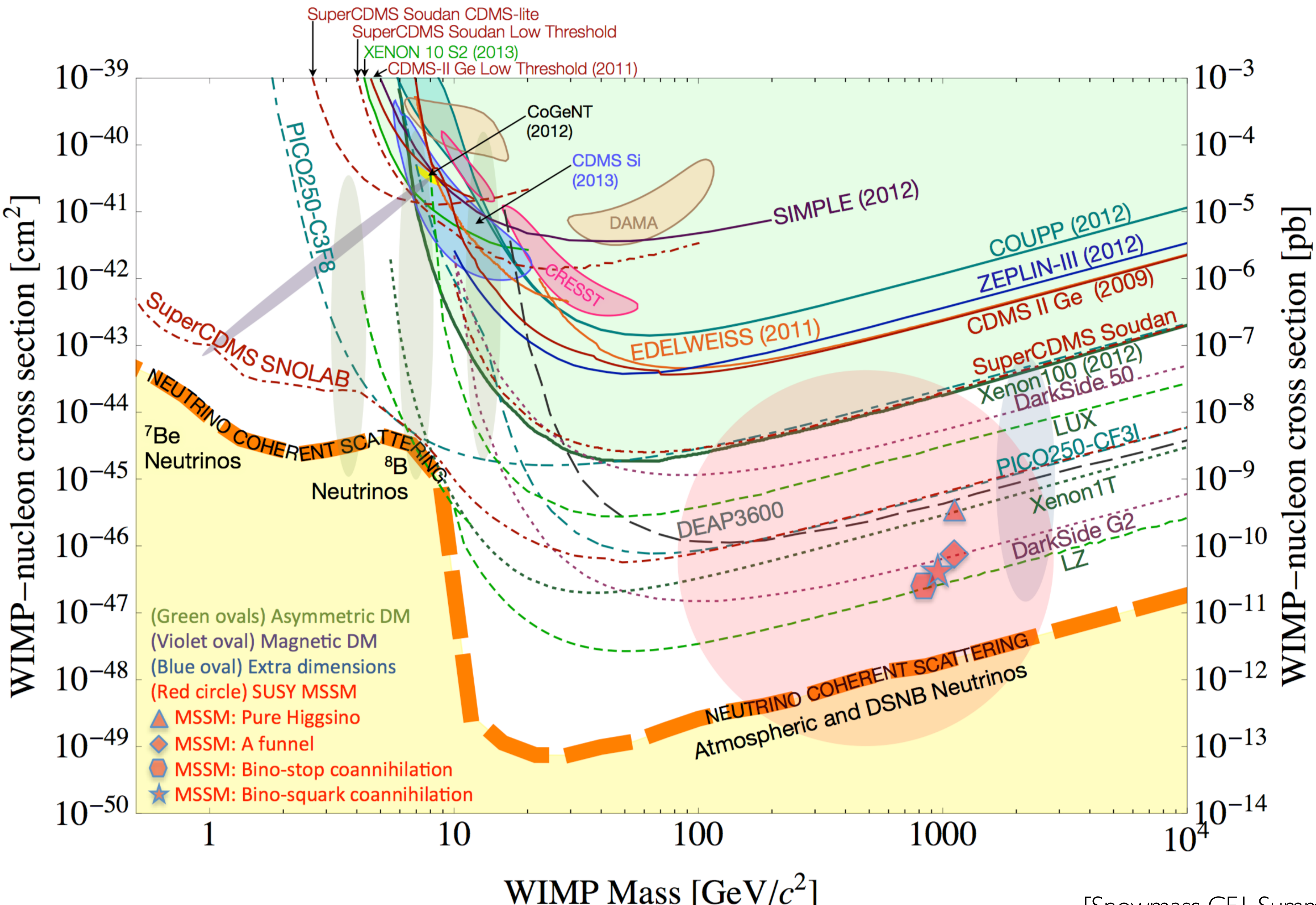
Far too big a mystery to give up. Can't stop now!

To be continued...

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

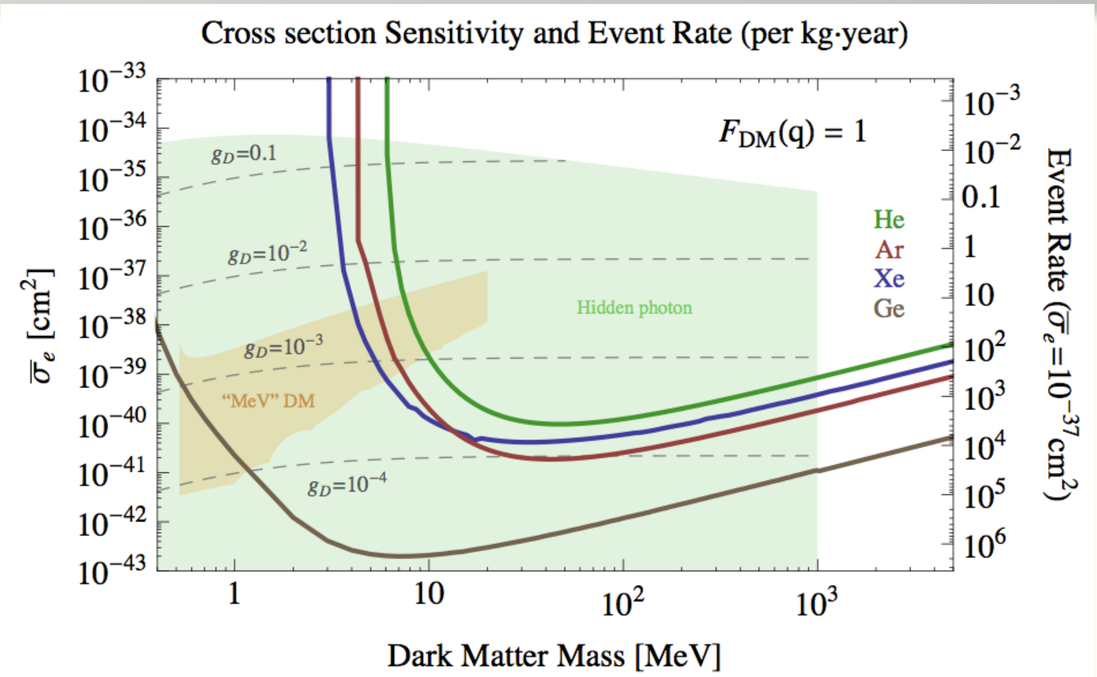
Extras...

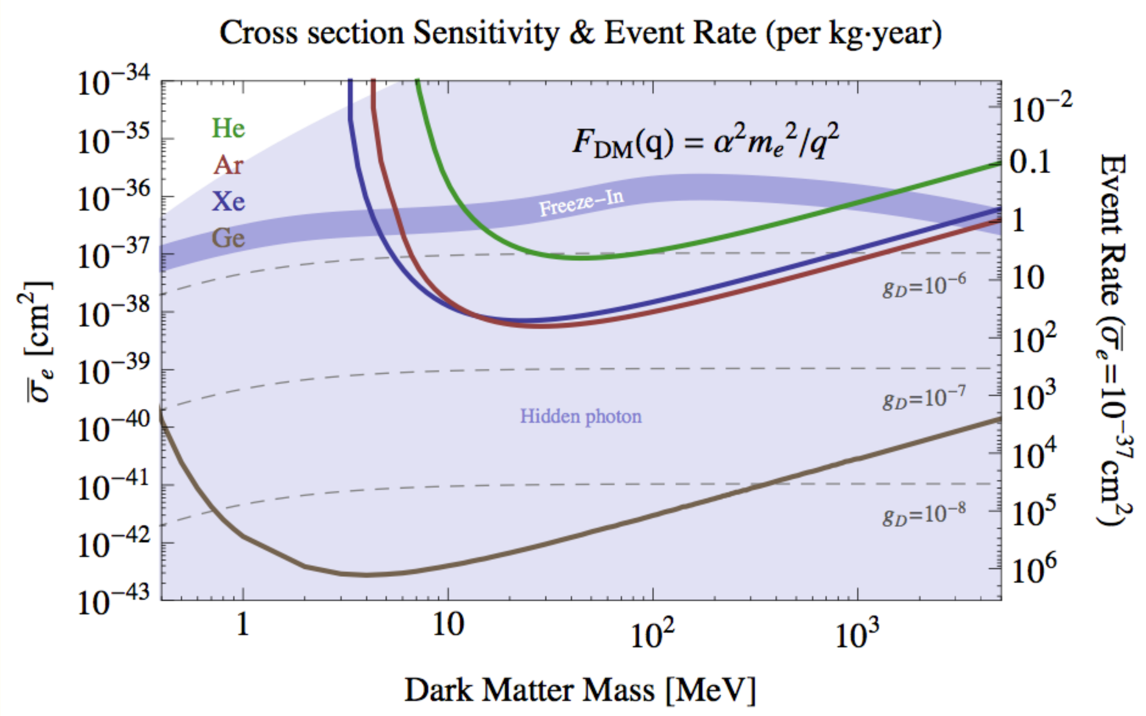
Direct Detection Limits: Future



[Snowmass CF1 Summary]

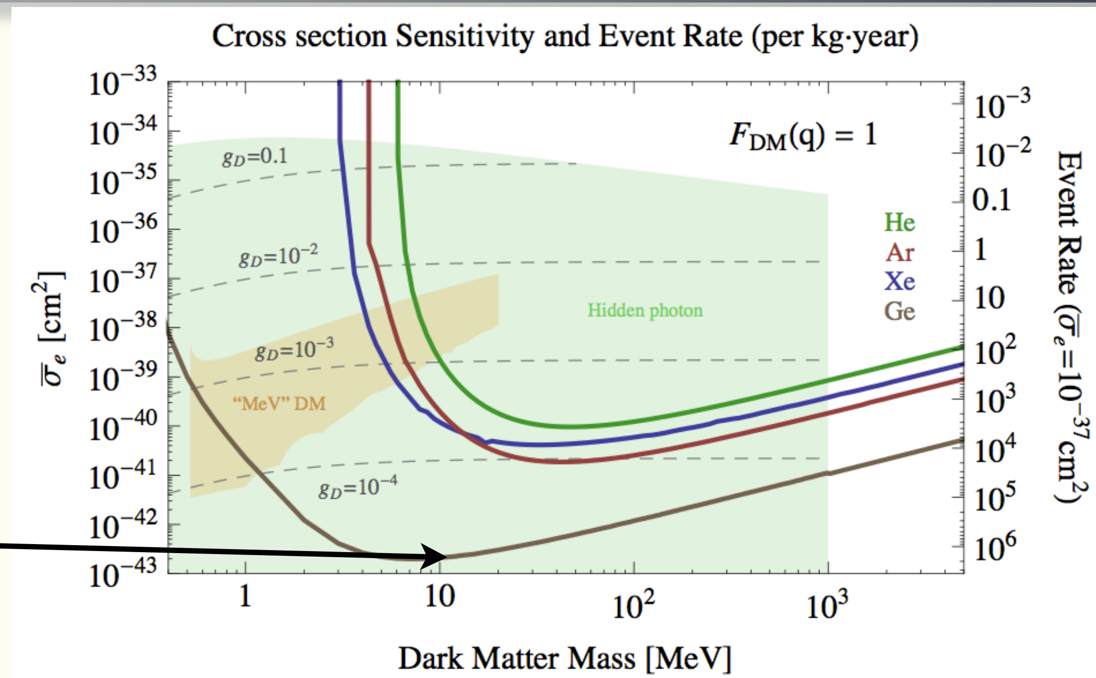
Projected Sensitivity

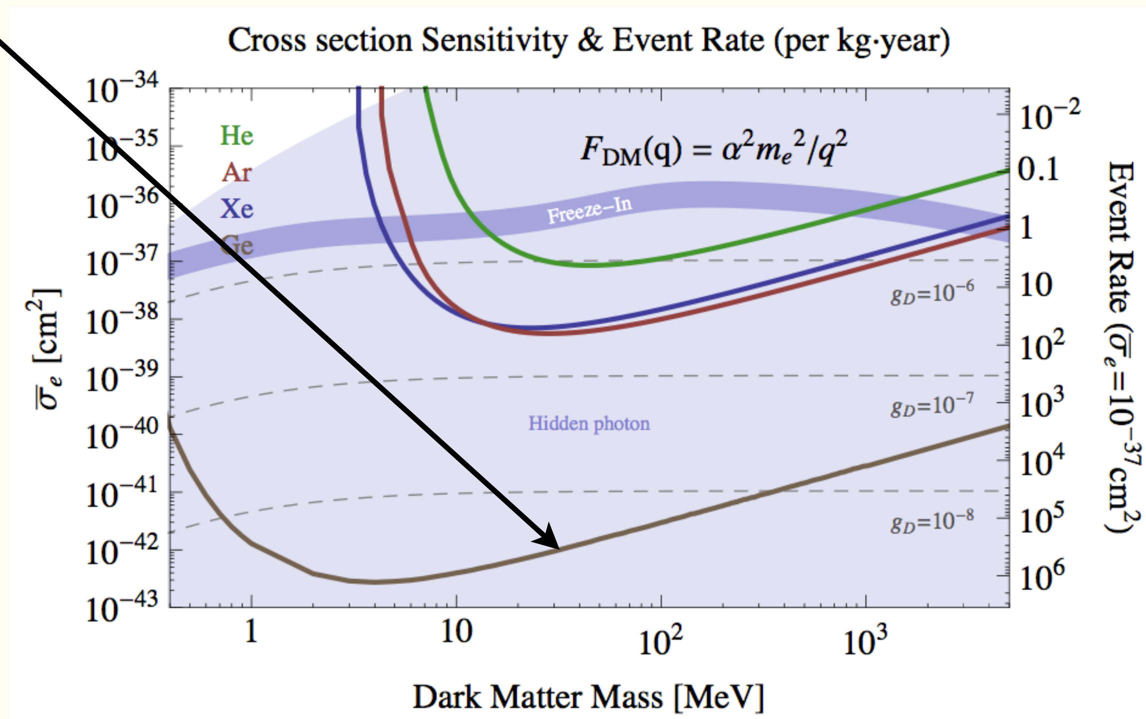




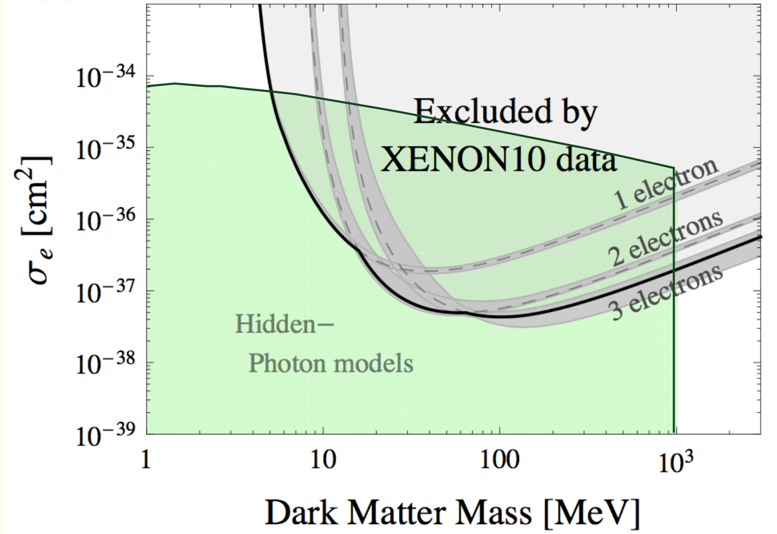
Projected Sensitivity

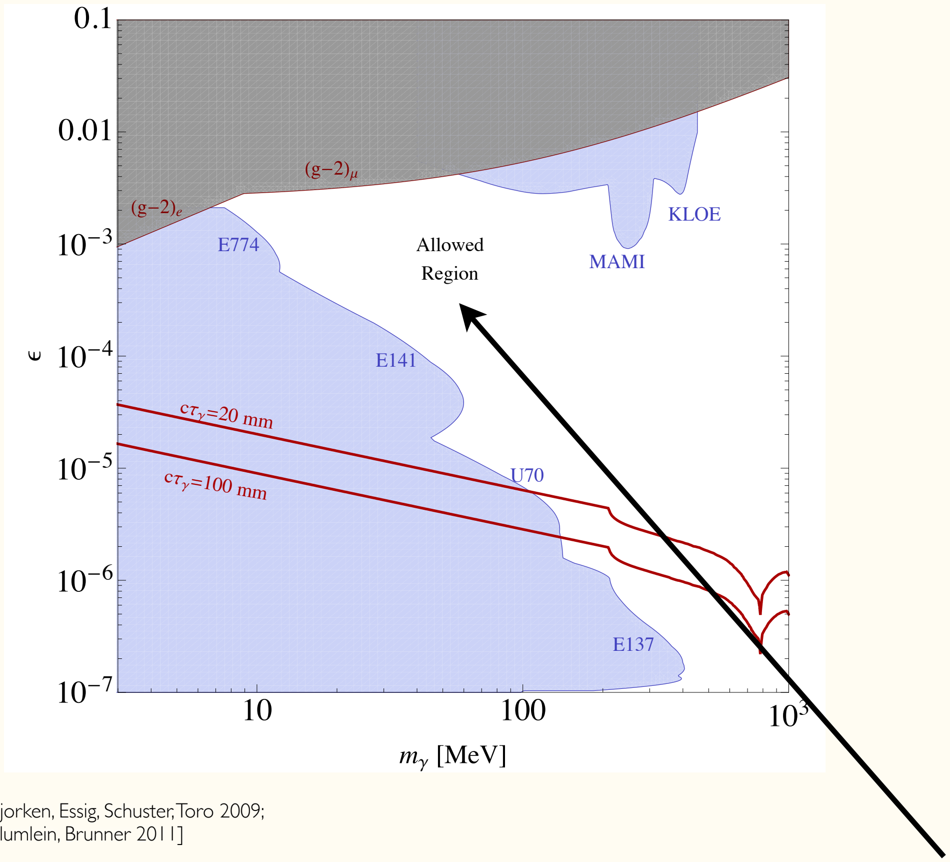
Crystals can do much better due to small band gap!



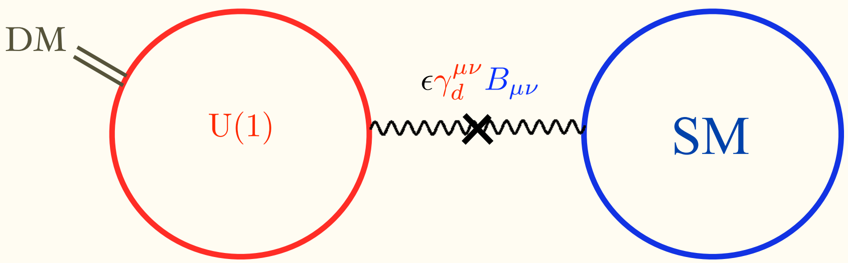


Results from XENON10: $F_{DM}=1$





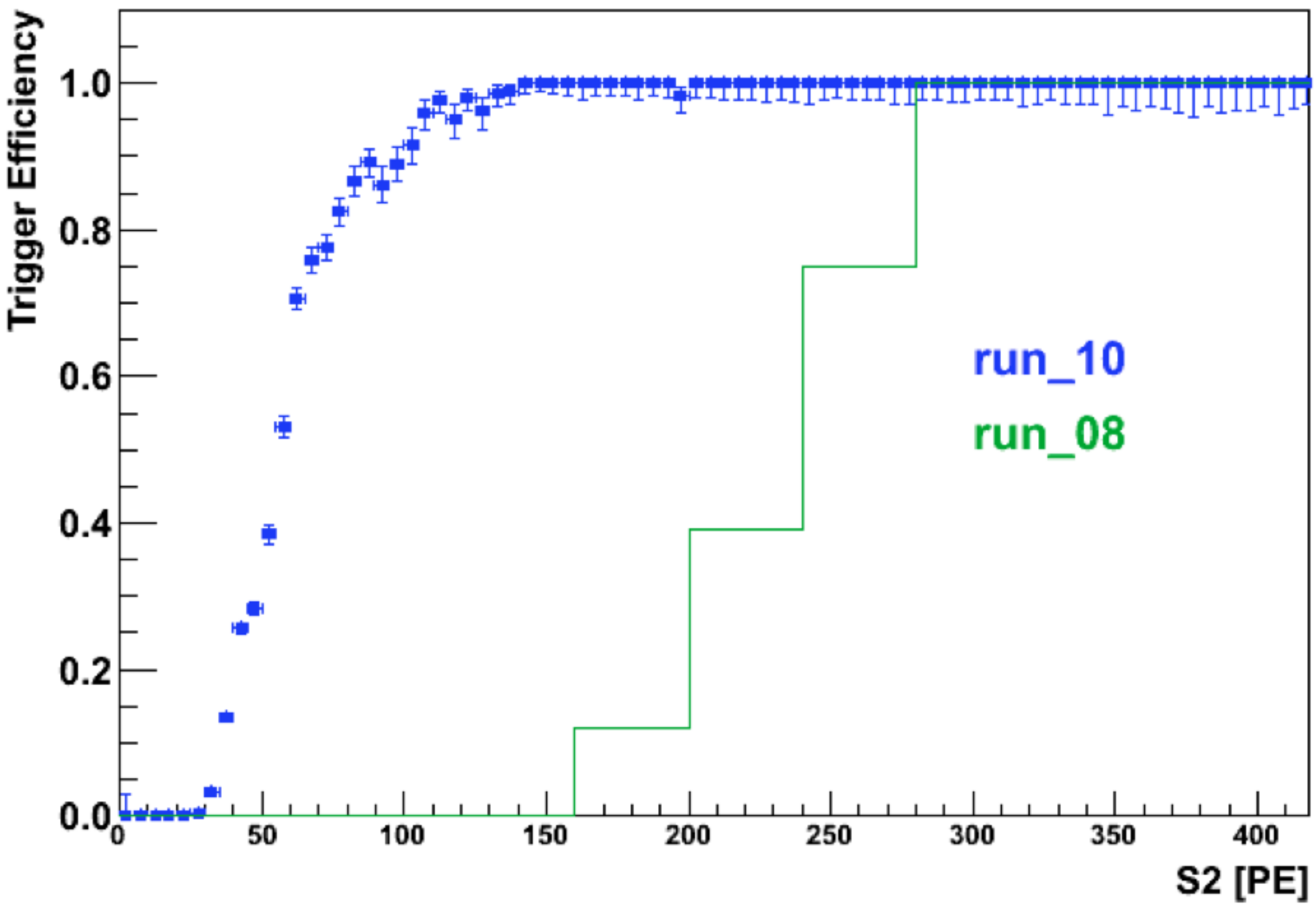
[Bjorken, Essig, Schuster, Toro 2009;
Blumlein, Brunner 2011]



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

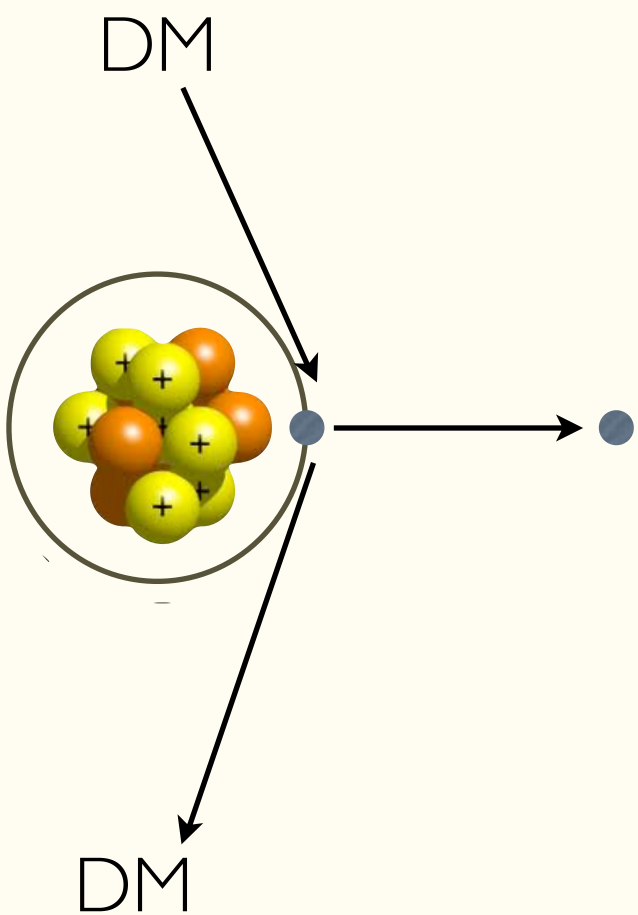
XENON100 proposal

Trigger efficiency



Secondary Interactions

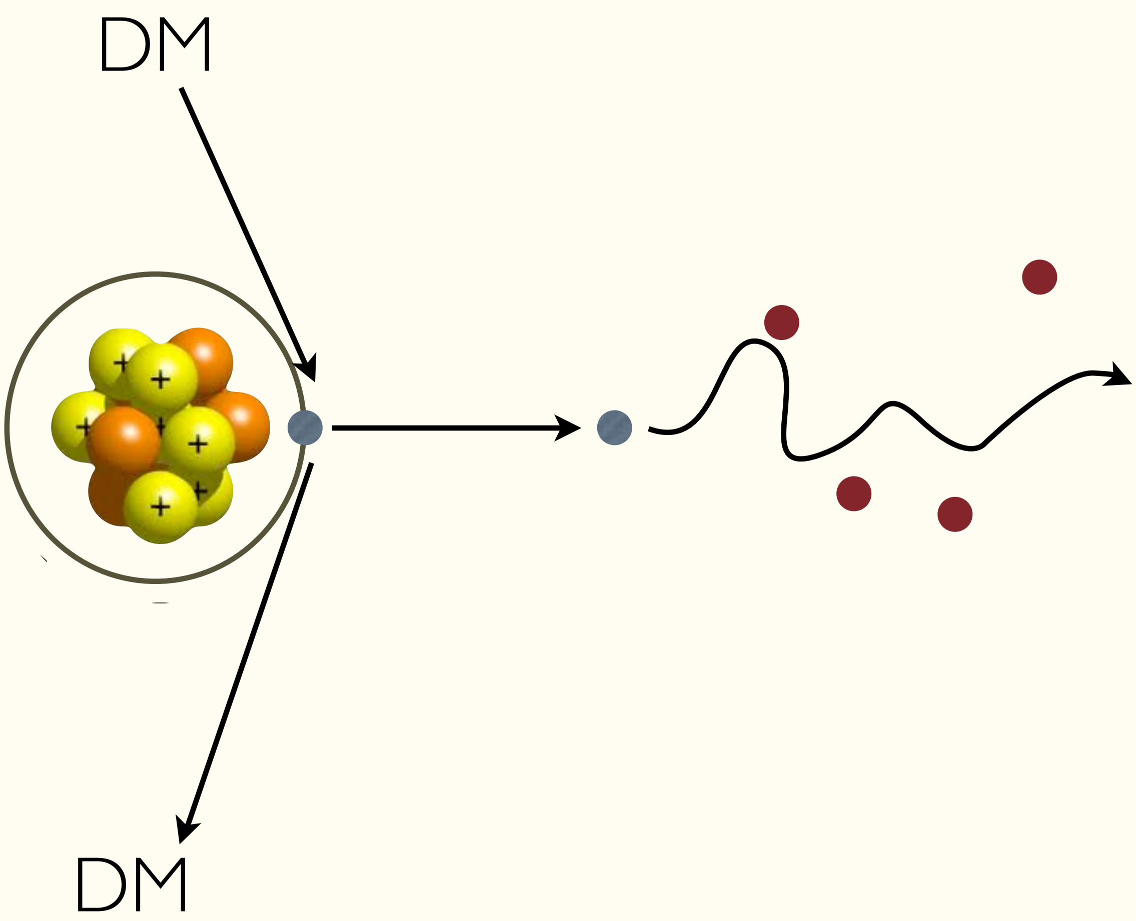
- Given a cross-section, the scattering rate is straightforward.



$$\frac{dR}{d\ln E_R} = N_{\rm T}\frac{\rho_{\rm DM}}{m_{\rm DM}}\frac{d\langle\sigma_{\rm ion}v\rangle}{d\ln E_R}$$

Secondary Interactions

- But in non-gaseous targets, the ionized electron hits other atoms which can be ionized and excited.



Electron number depends on:

- W - average energy of observable quanta.
- f_R - electron-ion recombination probability.
- N_{ex}/N_{ion} - The excited to ion ratio

Can we discover light DM without a dedicated experiment?

YES. Search for annual modulation.

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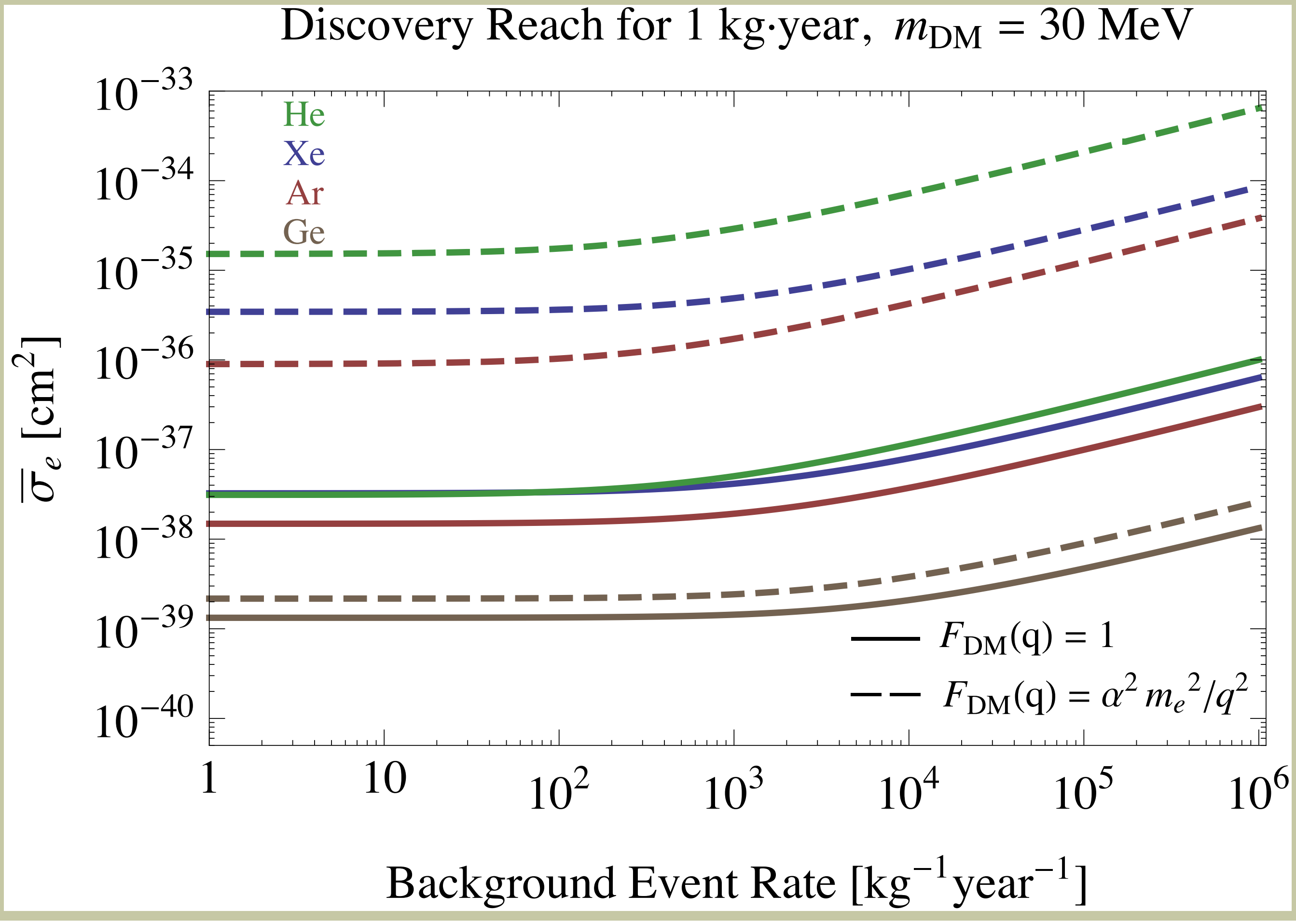
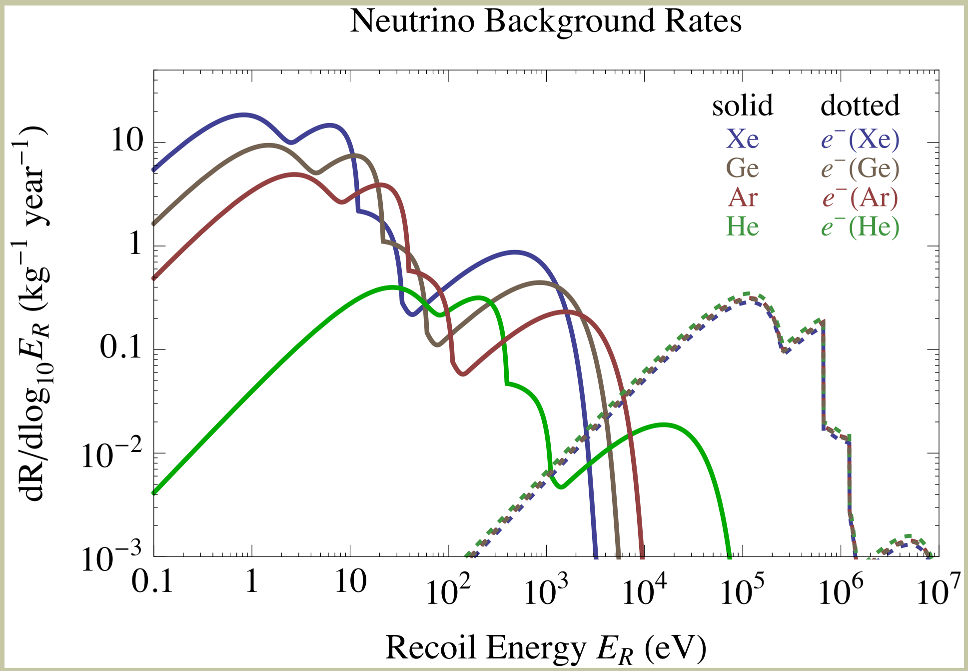
YES. Search for annual modulation.



Backgrounds

- Several possible backgrounds are identified:
  - Neutrinos.
    - Neutrino scattering with electrons and nuclei generates a small but irreducible background.
    - Dominated by solar neutrinos.
    - Typical energies between 100 keV - 20 MeV.
    - Electron recoils have energies well above signal. Nuclear recoils have too low energies.
    - No more that 1 event/kg-year.



Backgrounds

- Several possible backgrounds are identified:
  - Neutrinos.
  - Radioactive impurities.
    - Typically deposits energy well above keV.
    - Occasional low-energy events occur (e.g. low-energy tail of beta-decay spectra).
    - Low energy events are highly suppressed, thus no expected significant background.

Backgrounds

- Several possible backgrounds are identified:
  - Neutrinos.
  - Radioactive impurities.
  - Surface events.
    - As in conventional DD experiments, higher-energy surface events may appear to have low energy, due to partial signal collection.
    - Rejection requires new designs since current detectors cannot reconstruct z-position of low energy events.

Backgrounds

- Several possible backgrounds are identified:
  - Neutrinos.
  - Radioactive impurities.
  - Surface events.
  - Secondary events.
    - Possibly the main background.
    - Primary high-E signal may be accompanied by a few low-E events.
    - Effect observed in ZEPLIN-II and XENON10.
    - Possible explanation - secondary ionization of impurities (e.g. oxygen) or of xenon atoms by primary scintillation photons.
    - Could be reduced by vetoing events occurring too close in time to large event.
    - Another explanation - electrons captured by impurities are eventually released much later.
    - Long impurities lifetime (e.g. O^-_2 ion) implies a need for improved purification.

Backgrounds

- Several possible backgrounds are identified:
  - Neutrinos.
  - Radioactive impurities.
  - Surface events.
  - Secondary events.
  - Neutrons.
    - Current direct detection experiments are effective at shielding against neutron backgrounds.
    - Modification of existing designs to minimize the very low energy neutron scattering relevant for LDM detection could yield further improvements.

Backgrounds

- Obviously, controlling backgrounds is crucial for a successful LDM search.

- In the past ~30 years, incredible progress has been made in understanding and discriminating background from signal events at current direct detection experiments (this is why we call them "background-free" experiments..).

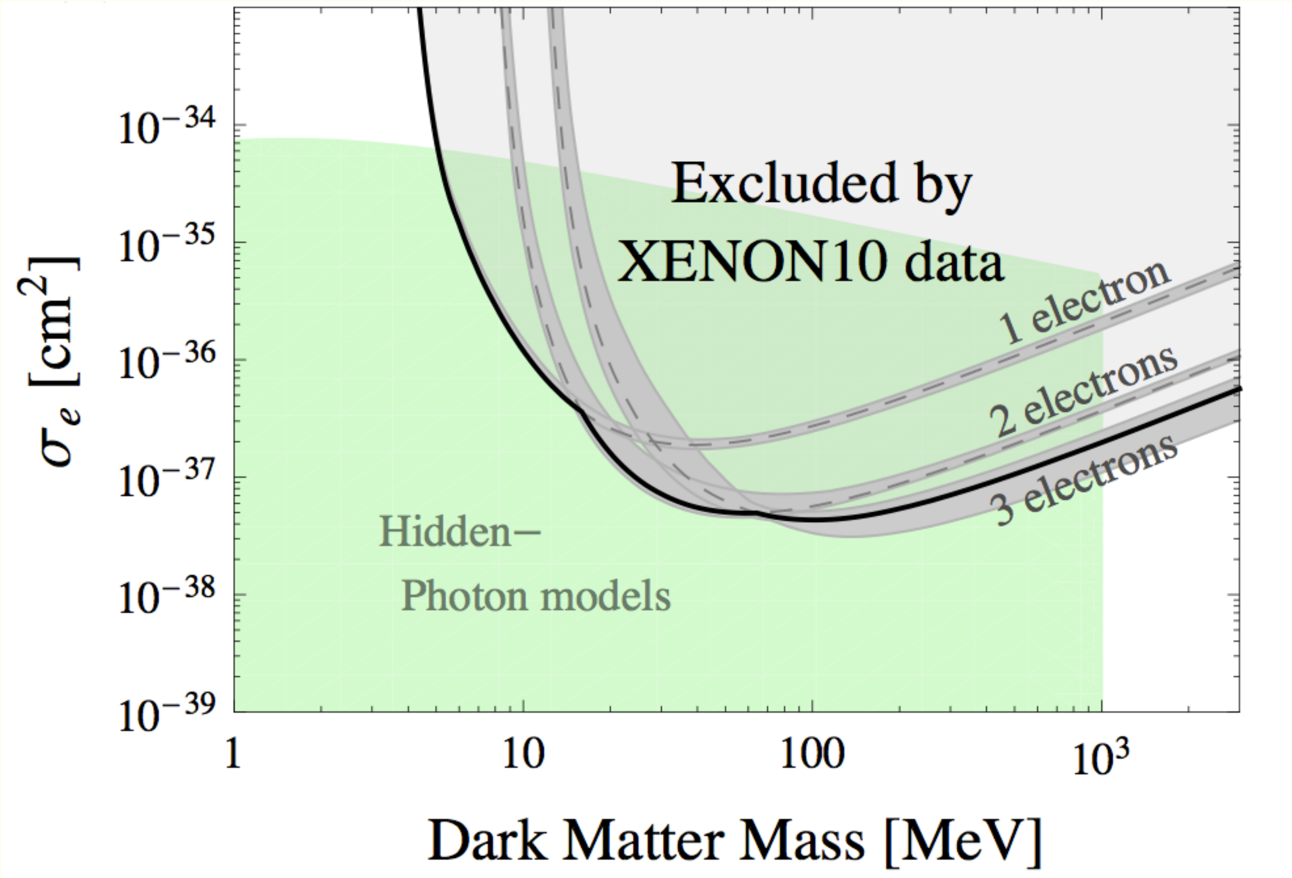
- Backgrounds to very low energy signals are neither well measured nor well understood. Some initial studies:

ZEPLIN-II & III: 0708.0778 & 1110:3056
XENON10: P. Sorensen, PhD thesis & 1104.3088

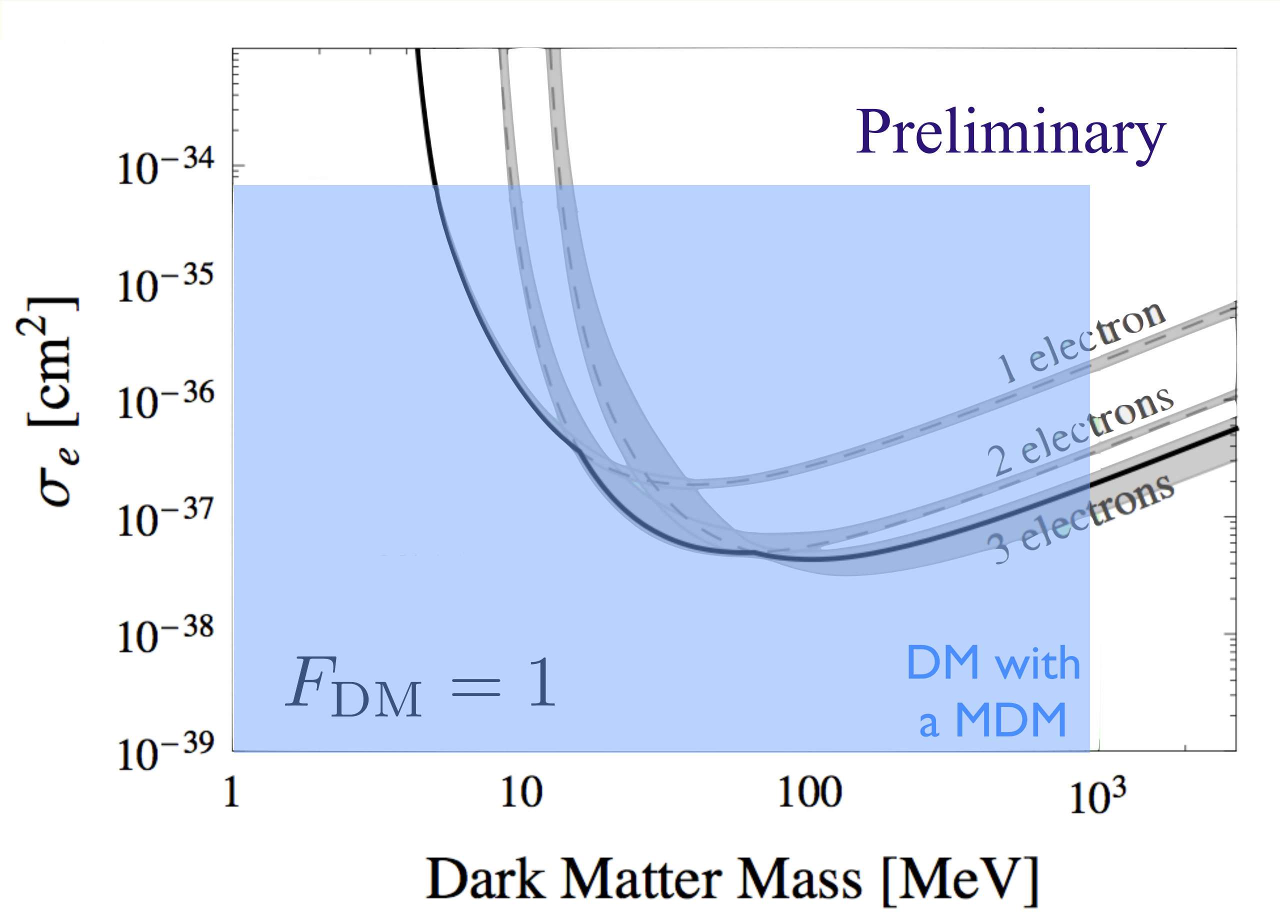
- Current direct detection experiments have not attempted to mitigate them.

Dedicated studies and detector designs would allow for significant improvements.

More Interesting Models



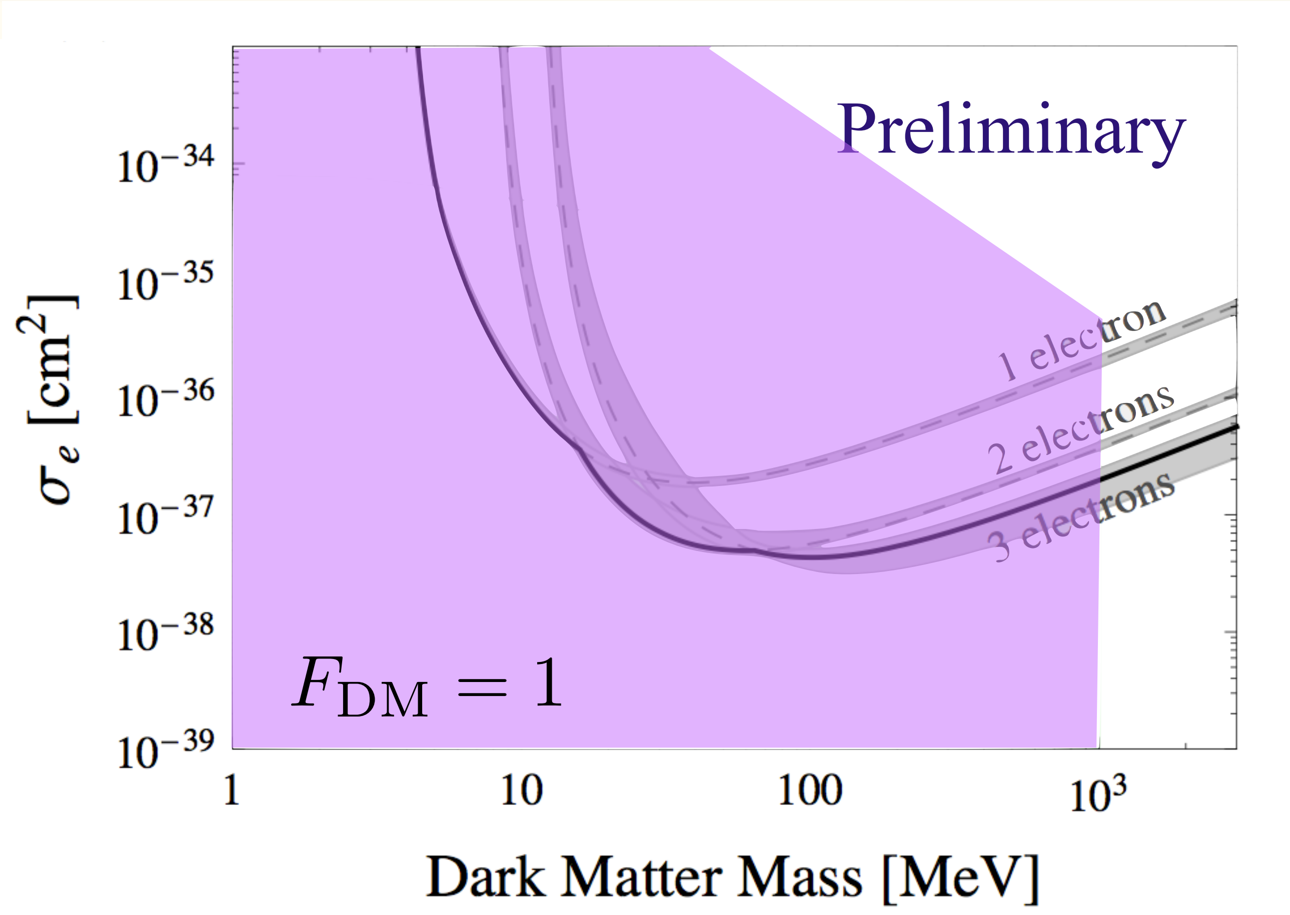
More Interesting Models

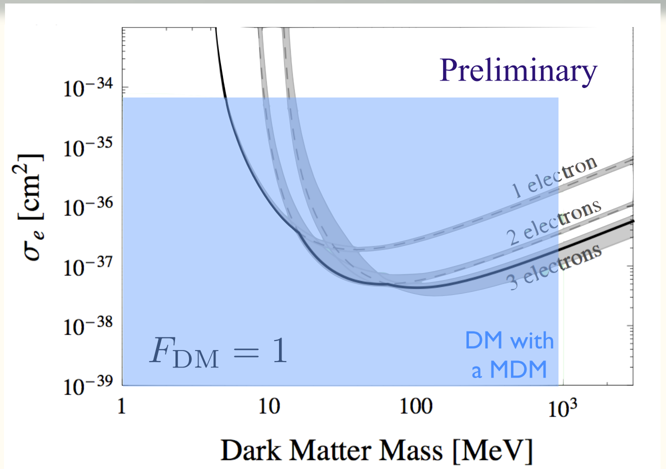


DM with magnetic dipole moment

$$-\frac{i}{2\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$$

More Interesting Models

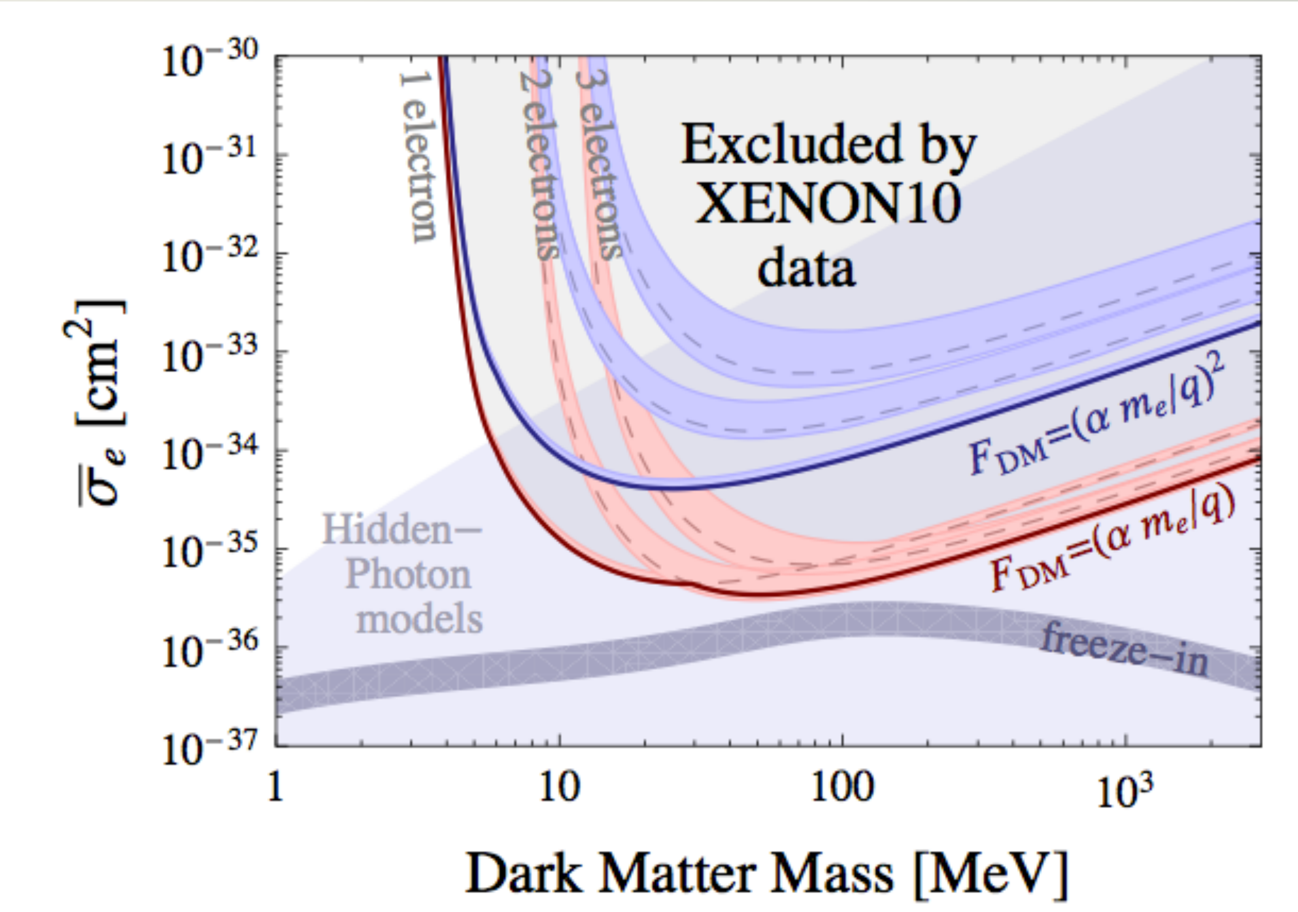


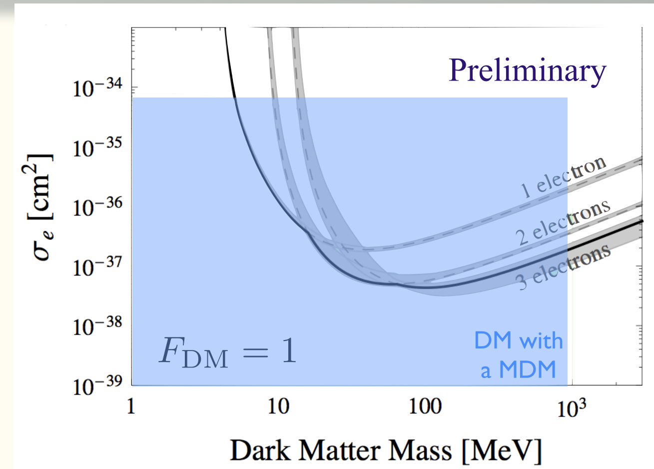


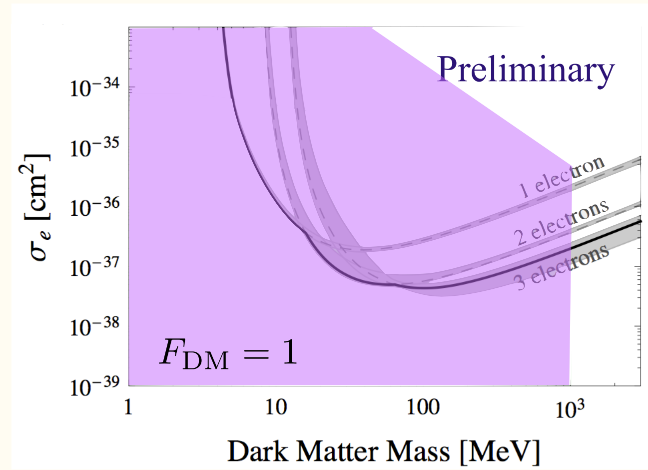
Scalar DM operator

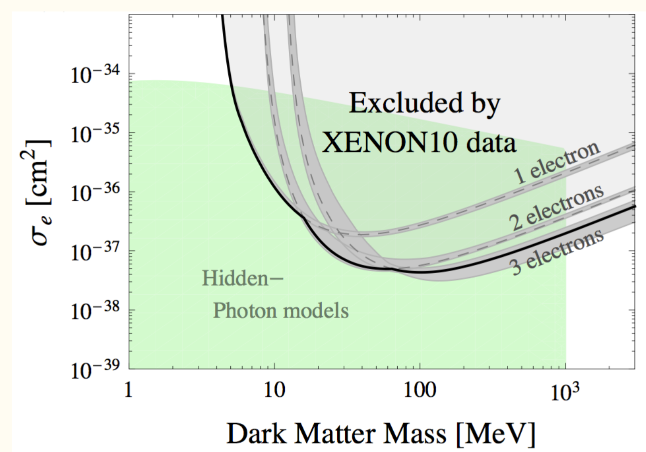
$$\frac{1}{\Lambda}\bar{\phi}^\dagger \phi \bar{e} e$$

More Interesting Models

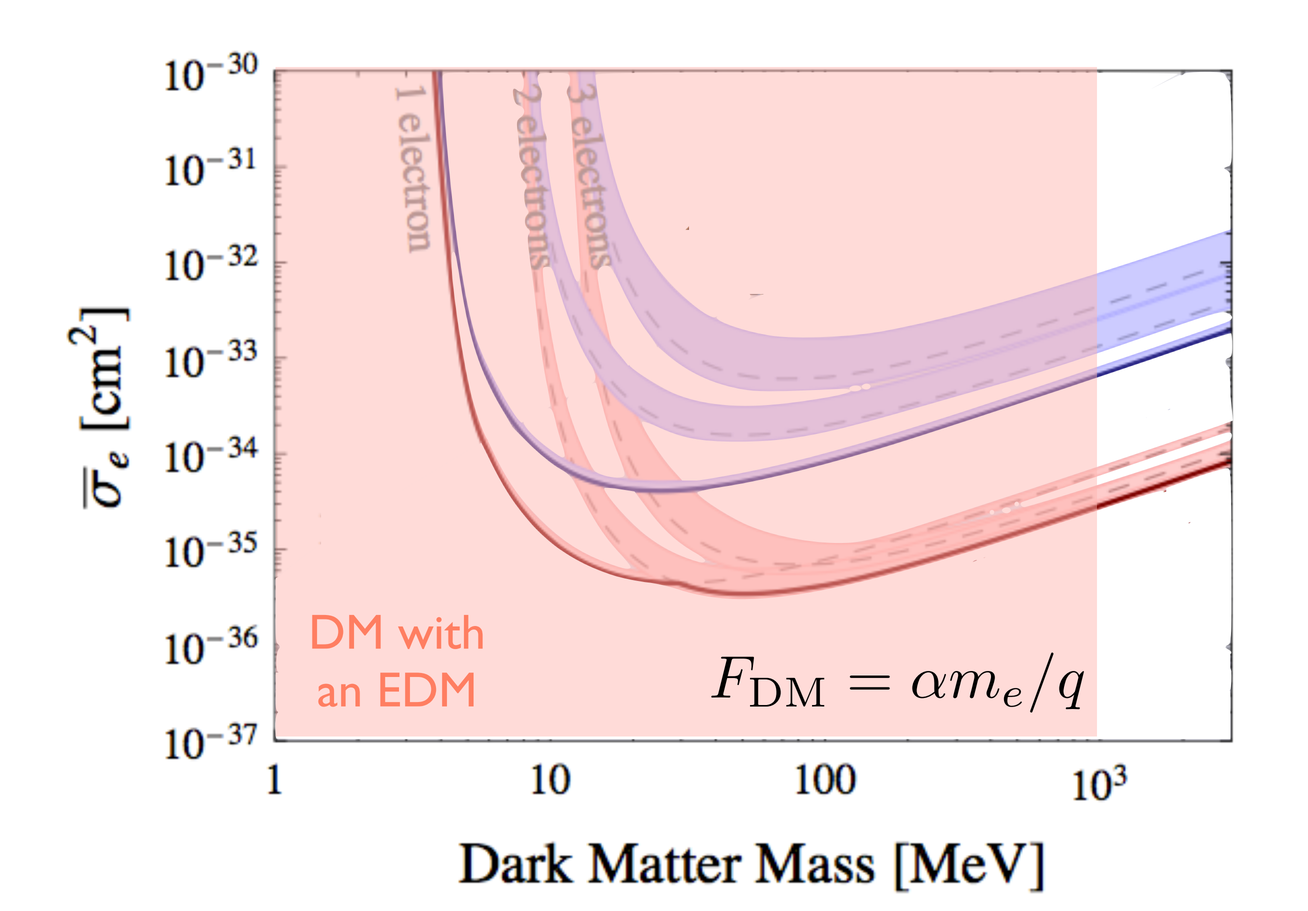


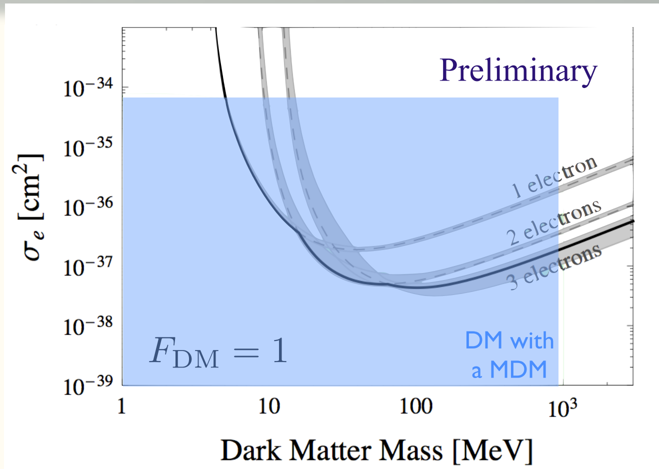


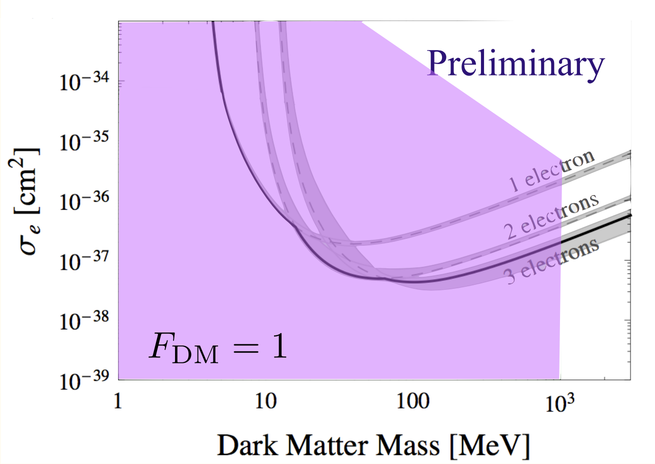


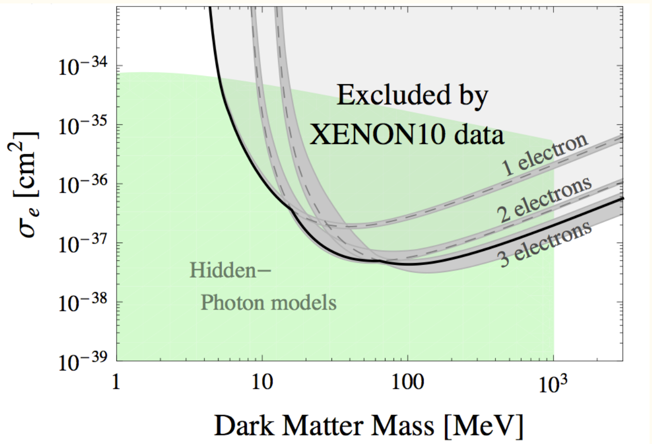


More Interesting Models





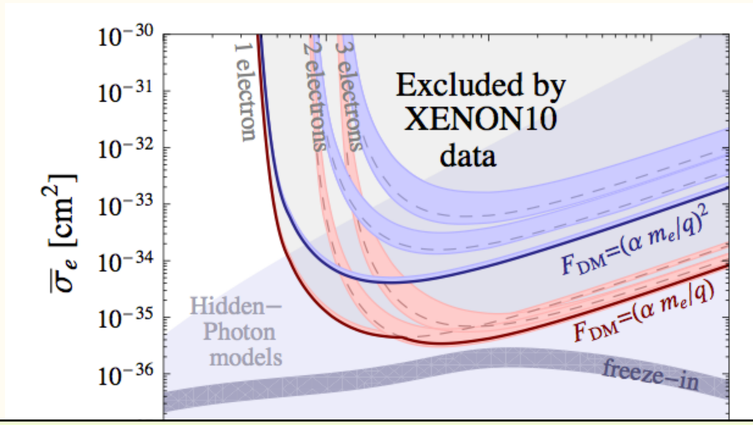




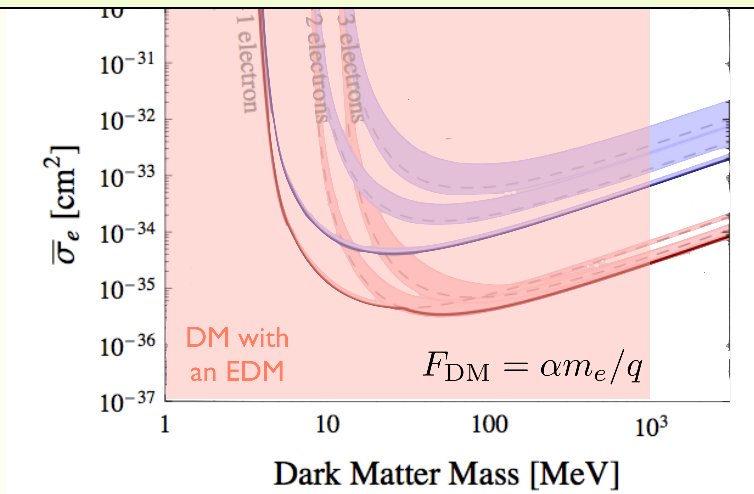
DM with electric dipole moment

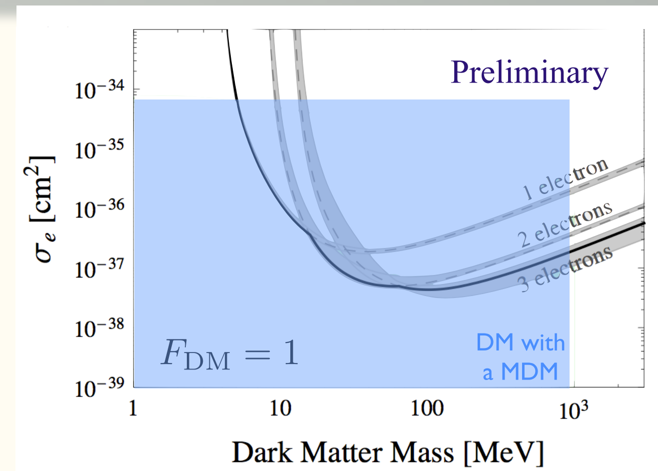
$$-\frac{i}{2\Lambda}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$$

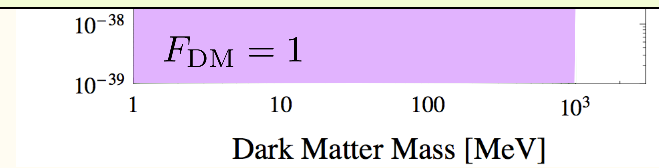
More Interesting Models

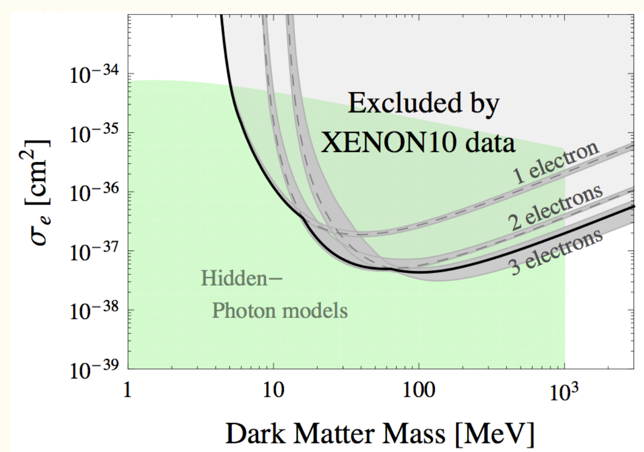


Many interesting models and effective operators are already probed









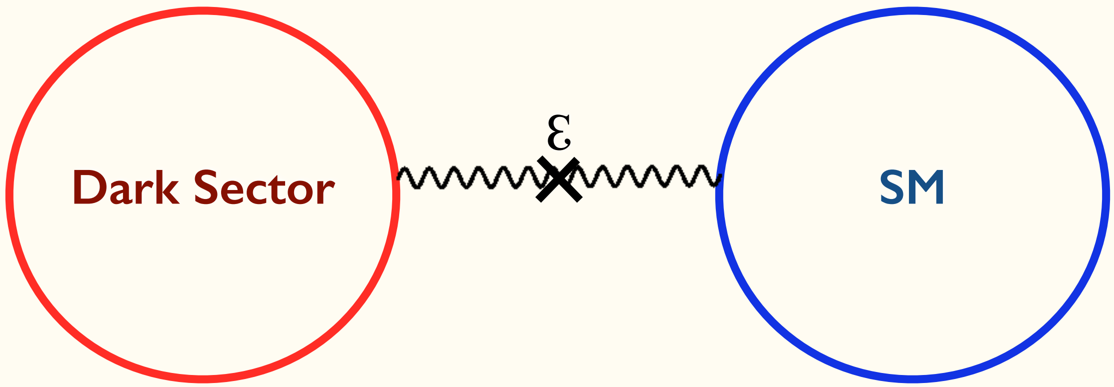
Freeze In

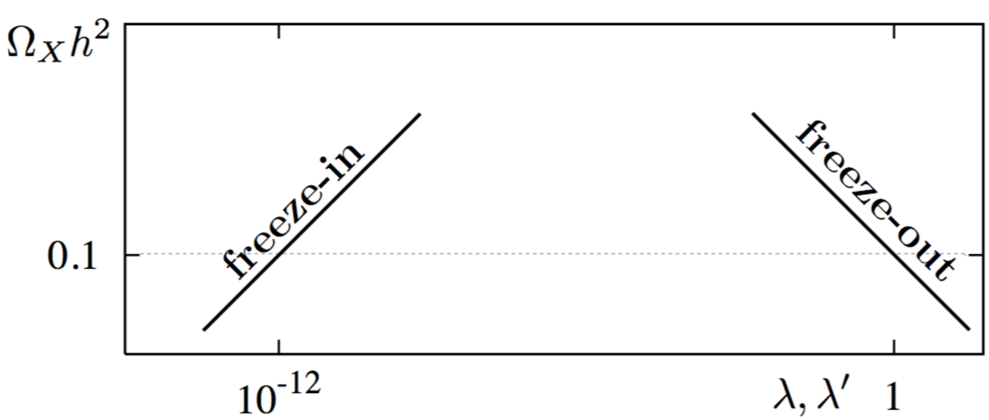
[Hall, Jedamzik, March-Russell, West, 2009]

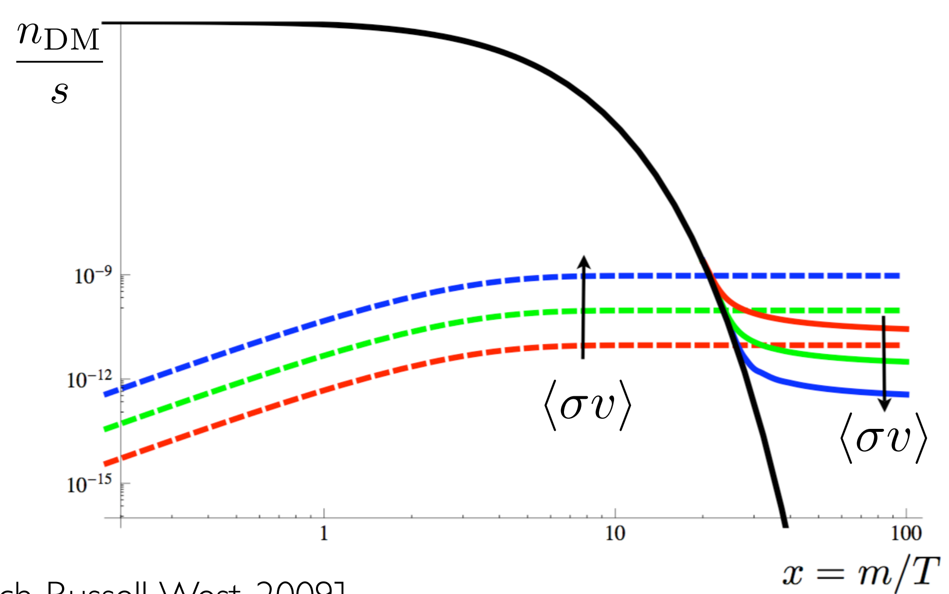
[Essig, Mardon, TV, 2011]

Concept

- A (typically) UV-insensitive, irreducible mechanism that produces DM.
- Relevant for dark sectors weakly coupled to the SM:





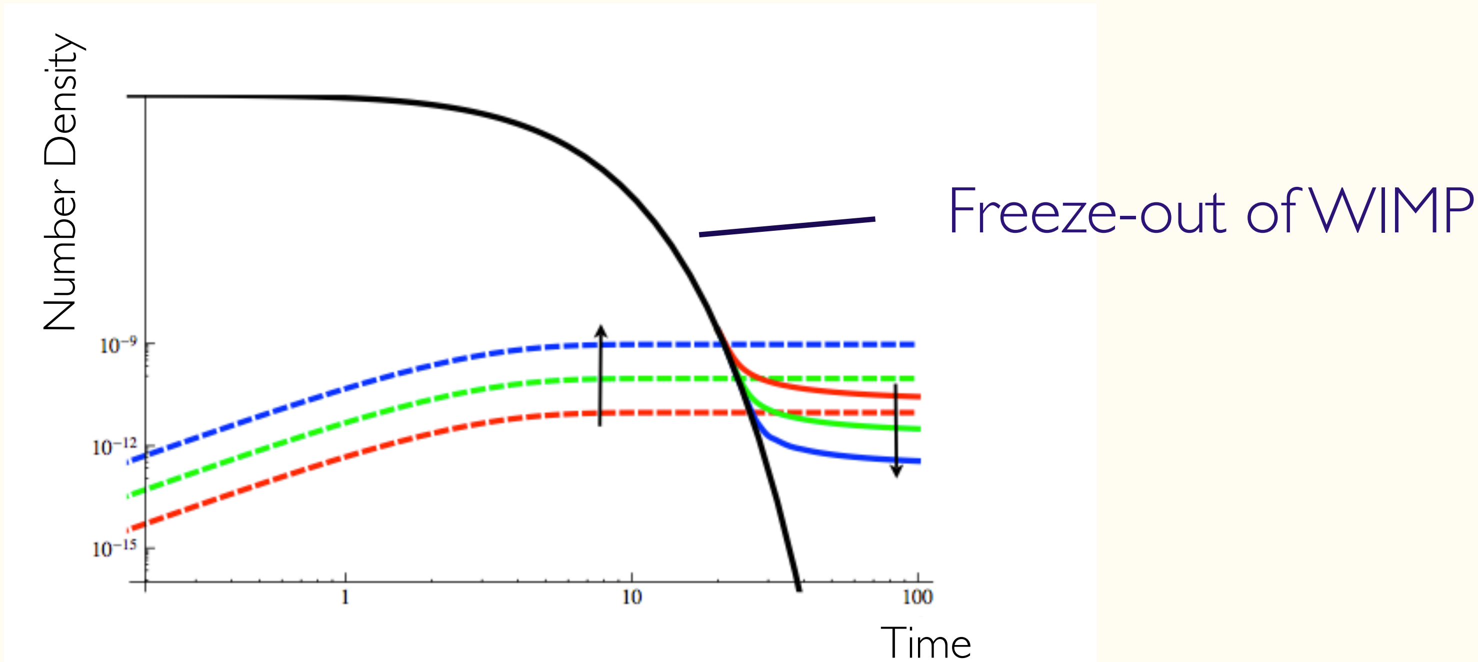


[Hall, Jedamzik, March-Russell, West, 2009]

Freeze-In

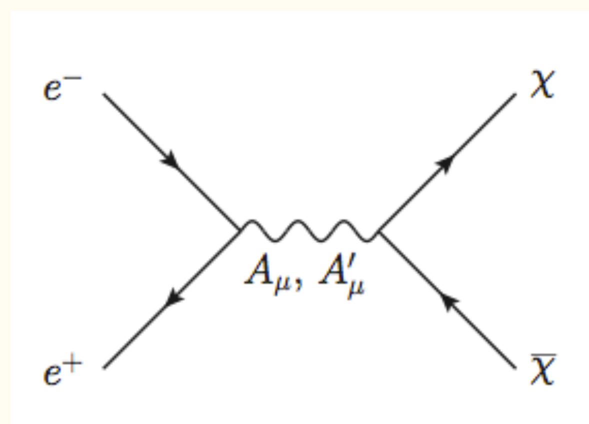
[Hall et al. 2009]

- DM may couple very weakly to thermal bath, in which case it never reaches thermal equilibrium.



- Production is IR dominated. Independent of initial conditions (and UV quantities) much like in freeze-out.

- Freeze-in could be responsible for DM density in hidden sector.



Decaying Light DM - Sterile Neutrinos

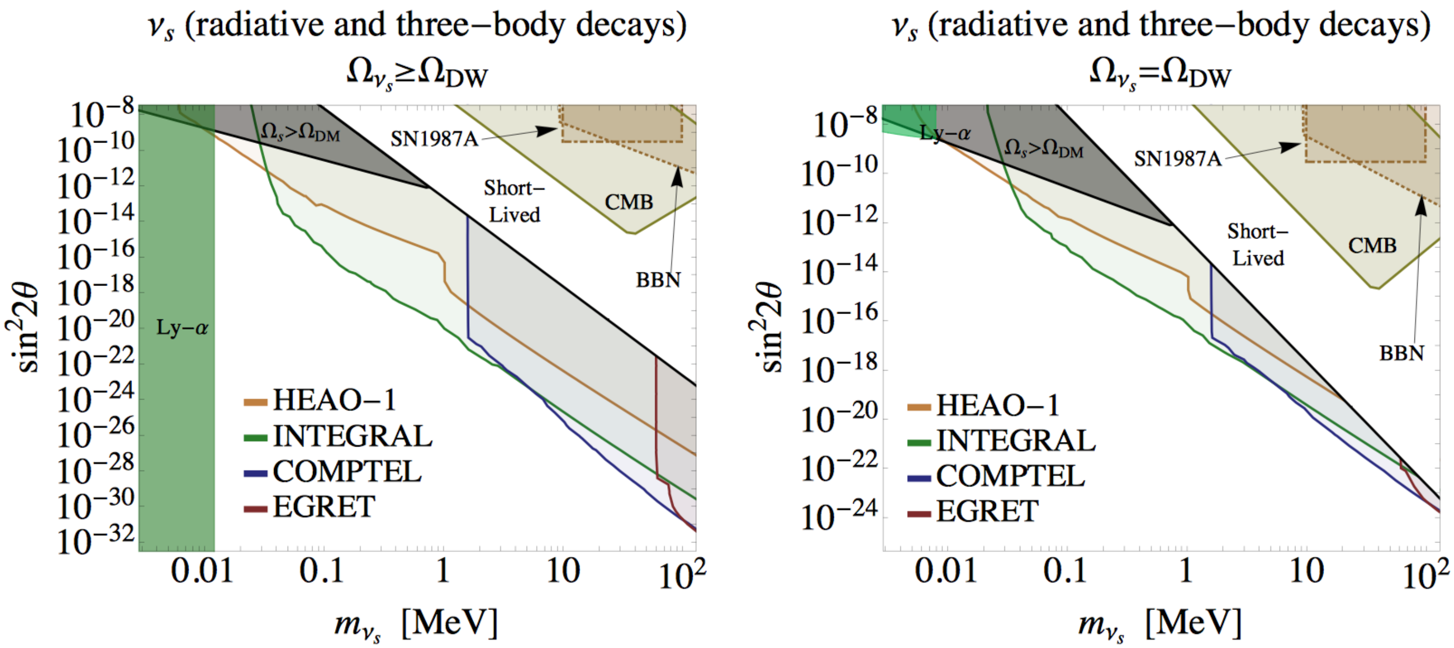


FIG. 5. Constraints on the sum of sterile-neutrino decay to $\gamma\nu$ and $\nu e^+ e^-$ using the decay widths in Eqs. (11) and (12). The constraints from the diffuse gamma- and X-ray data are HEAO-1 (orange), INTEGRAL (green), COMPTEL (blue), and EGRET (red). Within the solid black region, the neutrino energy density must be greater than the observed DM density. Above (below) the black solid line, the neutrino lifetime is shorter (longer) than the age of the Universe. Within the green boundaries, the sterile neutrino is ruled out by Ly-α forest data [48, 49]. Two cases for the sterile-neutrino energy density are assumed. In the **left** plot, the density is assumed to precisely equal the DM energy density everywhere below the dark and light gray regions. In the **right** plot, the density is determined by the (irreducible) DW mechanism.

Decaying Light DM - Hidden Photino

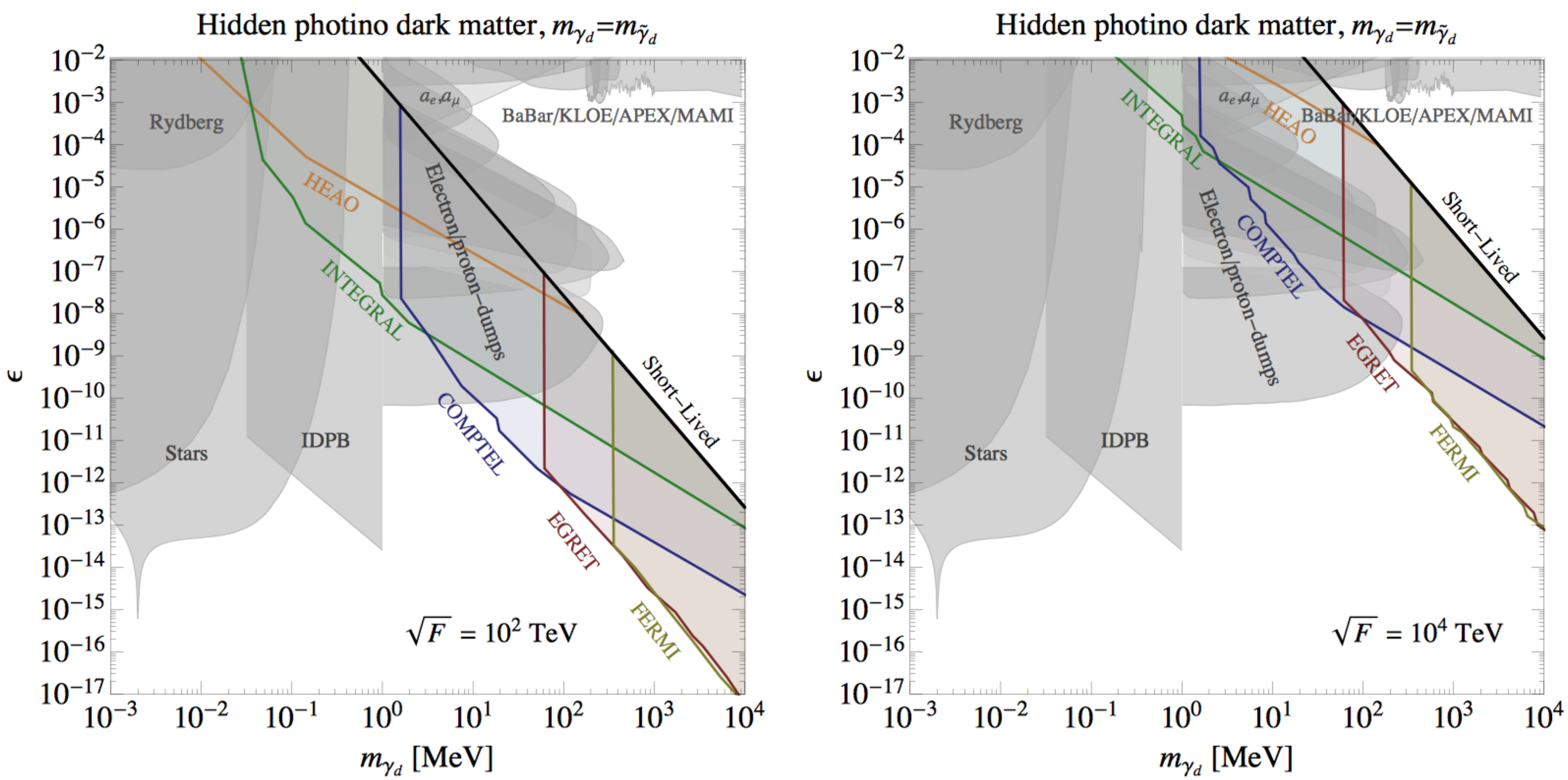


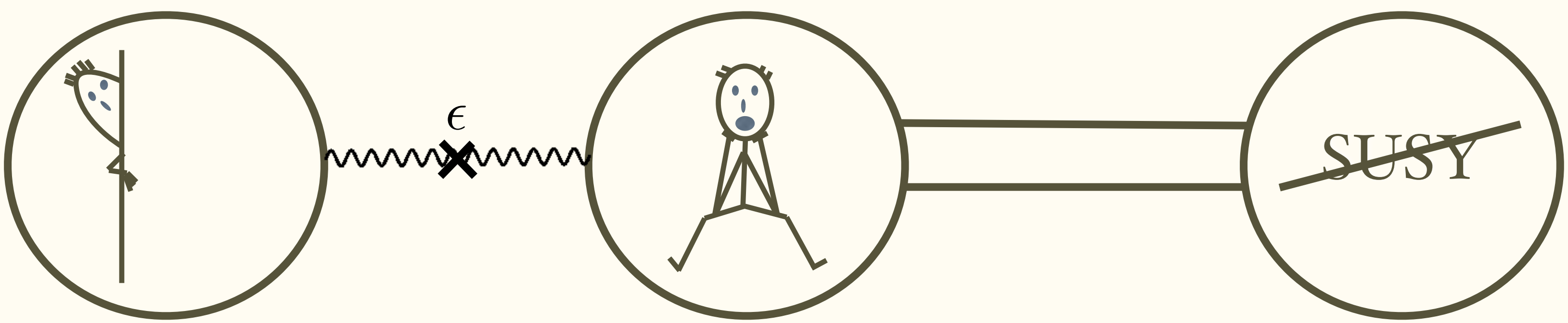
FIG. 3. Constraints on a hidden photon in the hidden photino DM model for the case where the hidden photino decays to a photon and a gravitino, $\tilde{\gamma}_d \to \gamma\tilde{G}$, and with $\sqrt{F} = 100\,\text{TeV}$ (**left**) or $\sqrt{F} = 10^4\,\text{TeV}$ (**right**). Gray shaded regions indicate constraints from beam-dump, fixed-target, and colliding beam experiments, stars, precision measurements, and from the intergalactic diffuse photon background (IDPB), while the colored regions show the gamma- or X-ray constraints as in Fig. 2. In the "Short-Lived" region the DM lifetime is shorter than the age of Universe. See text for more details.

Models of Sub-GeV Dark Matter

Sub-GeV?

- Sub-GeV scale is easy to explain.
- DM may obtain its mass scale from same dynamics as EWSB.
- If it is also weakly coupled to us, it's mass would be suppressed by the small couplings,

$$m_{\rm hid} \sim \epsilon m_W$$

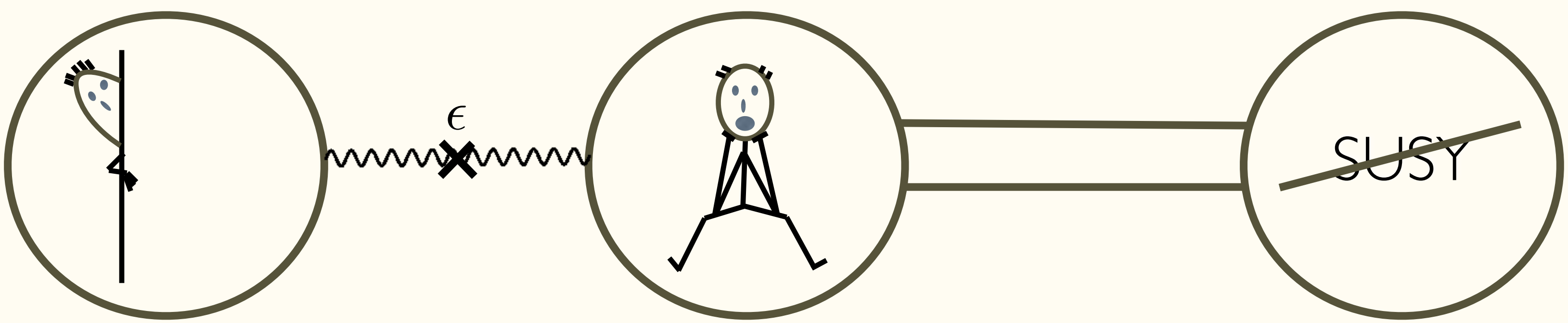


Sub-GeV?

- The sub-GeV scale is easy to motivate.
- Typically there is a mechanism to explain the stability of the electroweak scale (e.g. SUSY).
- If the generation of the weak scale is communicated to the hidden sector only through couplings to the SM, the natural scale there is

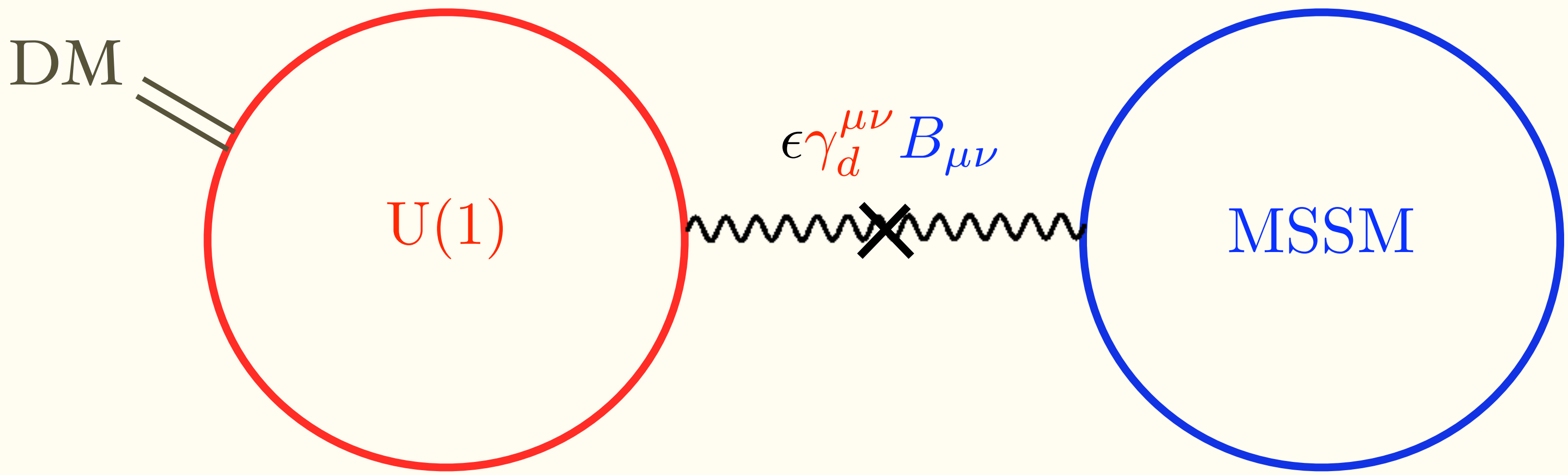
$$\epsilon m_W \qquad \text{or} \qquad \frac{\alpha}{4\pi} m_W$$

which can naturally be $\lesssim$ GeV.



[Essig,Mardon,TV, work in progress]

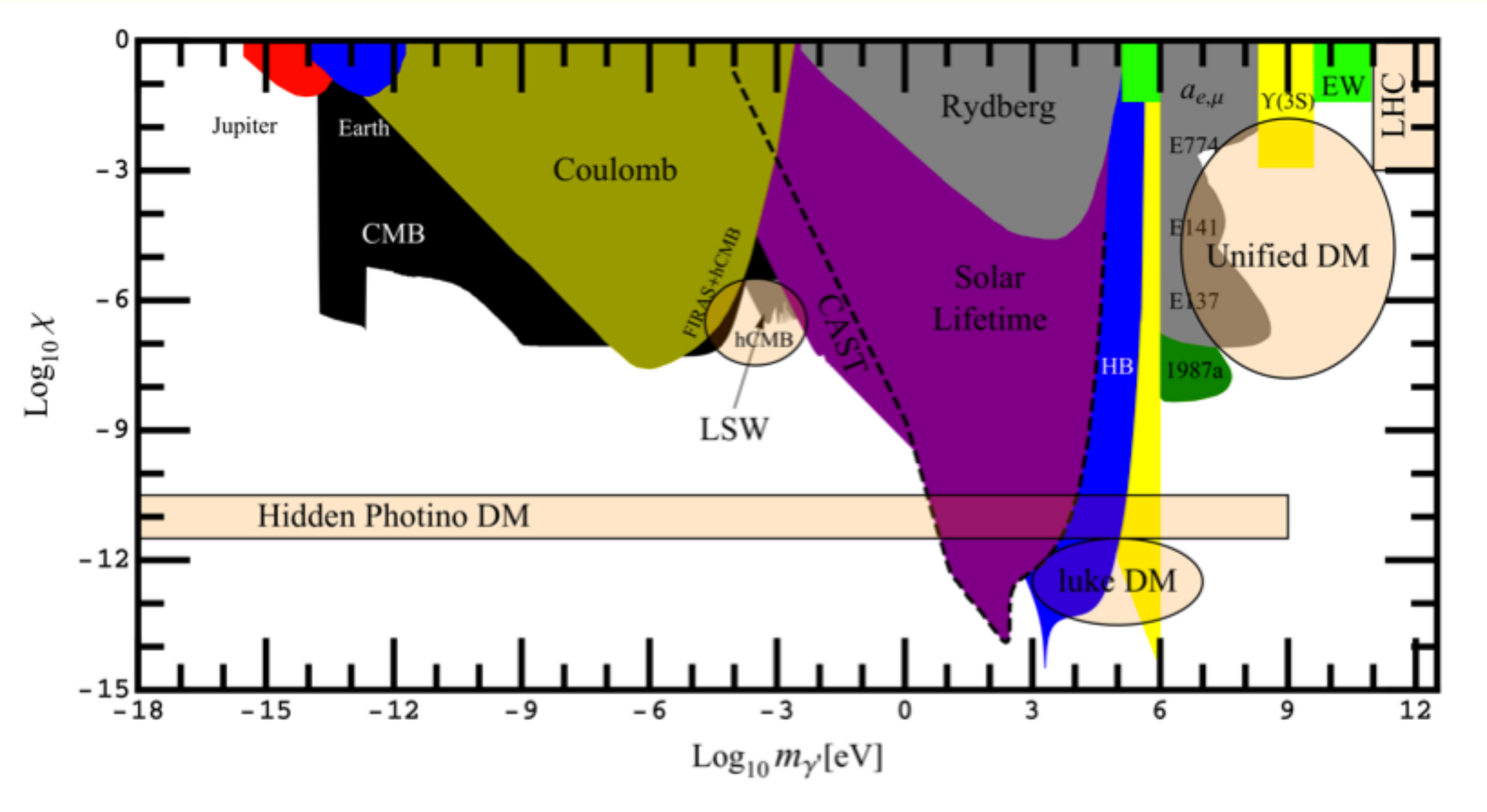
Simple Realization



- DM is charged under a new massive U(1) (hidden photon).
- Hidden photon mixes with the SM hypercharge.
- Thermal history of the hidden sector depends on **ε** and mass of hidden photon.

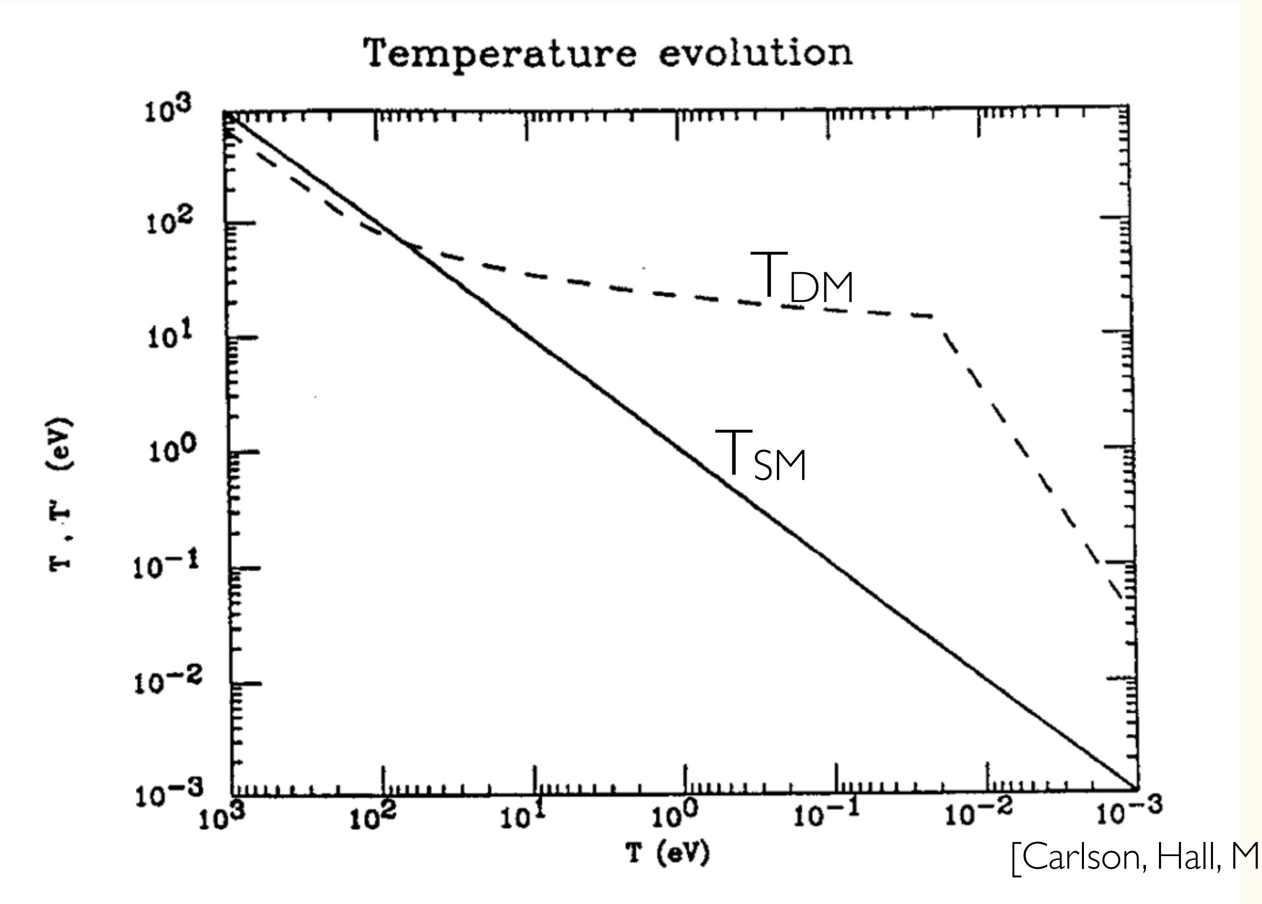
Hidden Photon Constraints

- Some of the constraints are model-dependent, but generally couplings are constrained.



3-2 Freeze Out

- Problem: We implicitly assumed that $\mathbf{T_{dark} = T_{SM}}$.
- Otherwise, 3-2 annihilations heat up DM



[Carlson, Hall, Machacek, 1992]

3-2 Freeze Out

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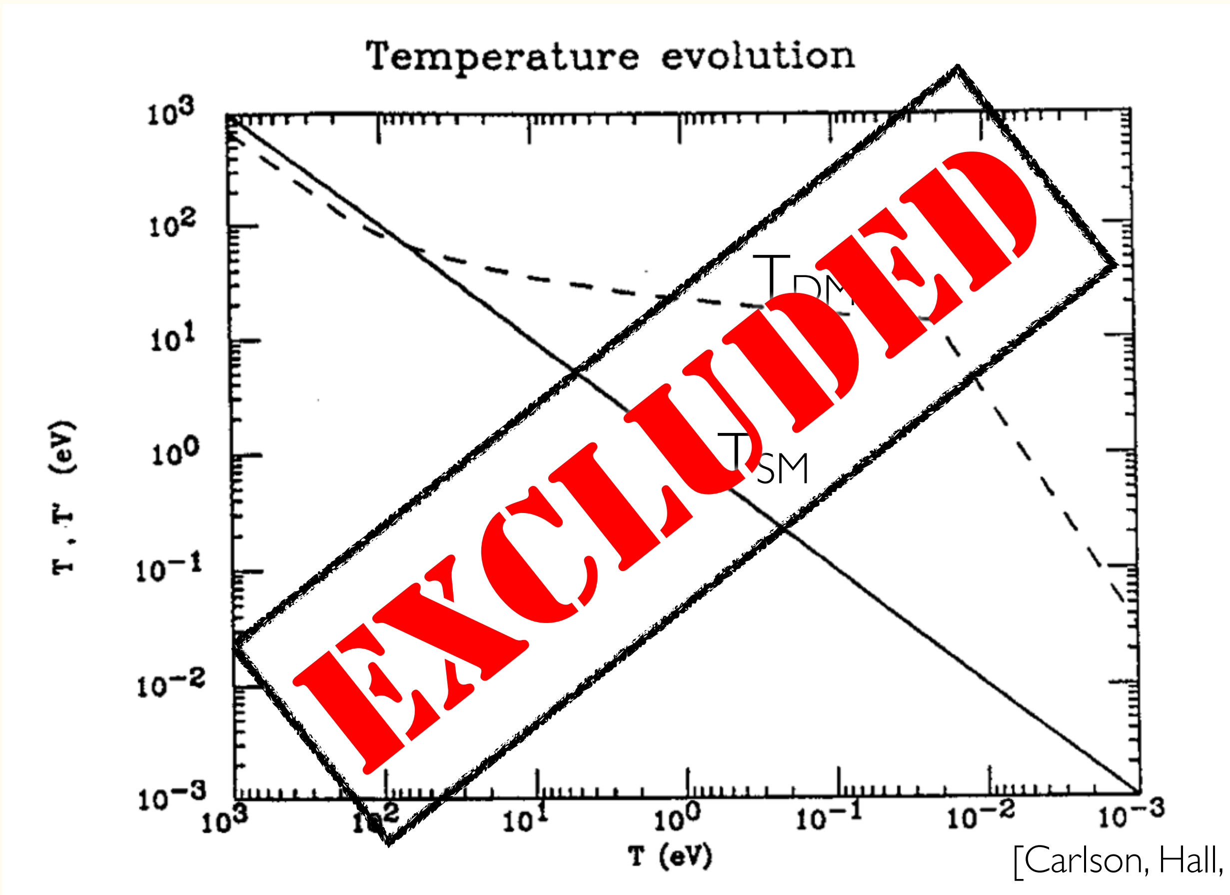
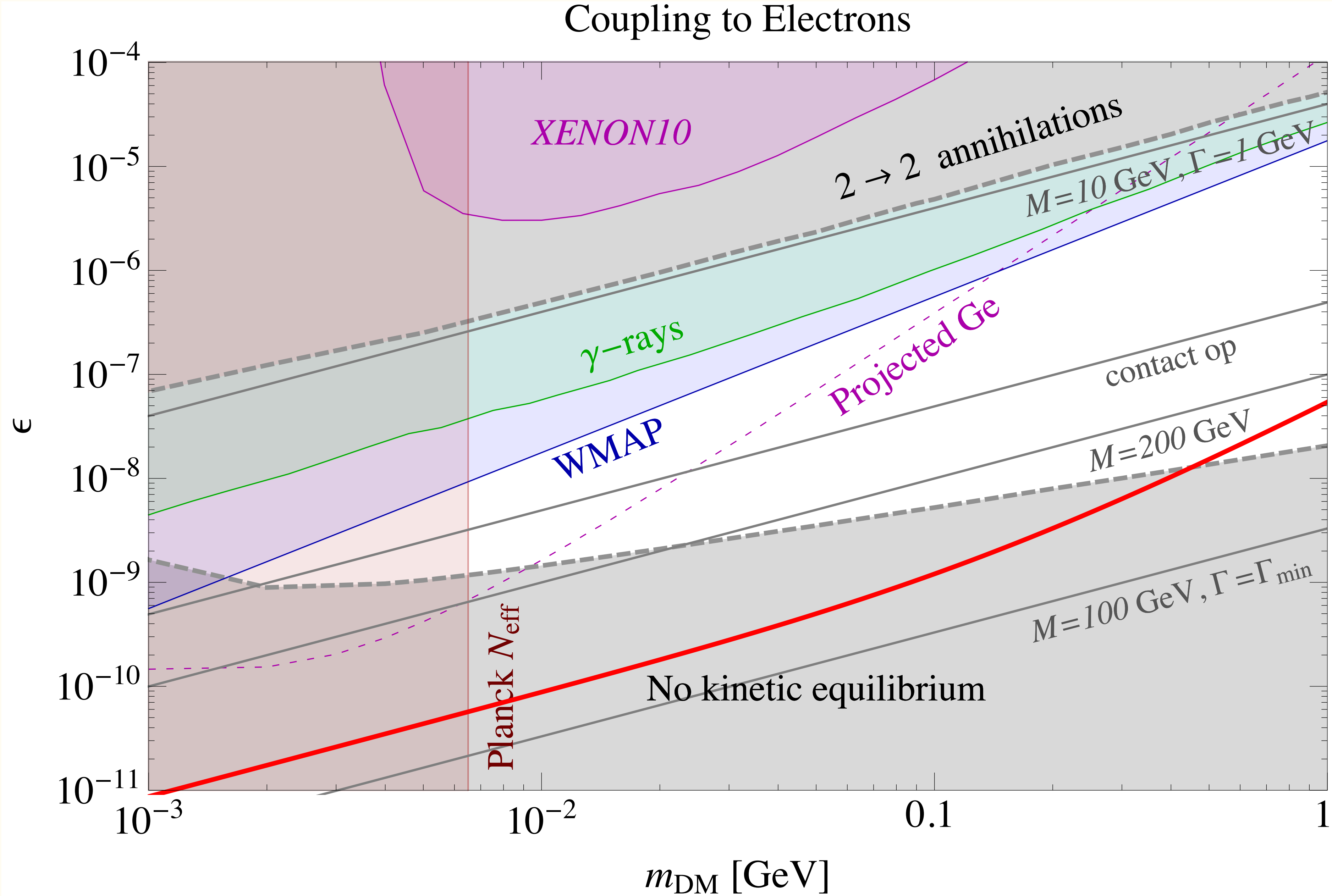


[Carlson, Hall, Machacek, 1992]

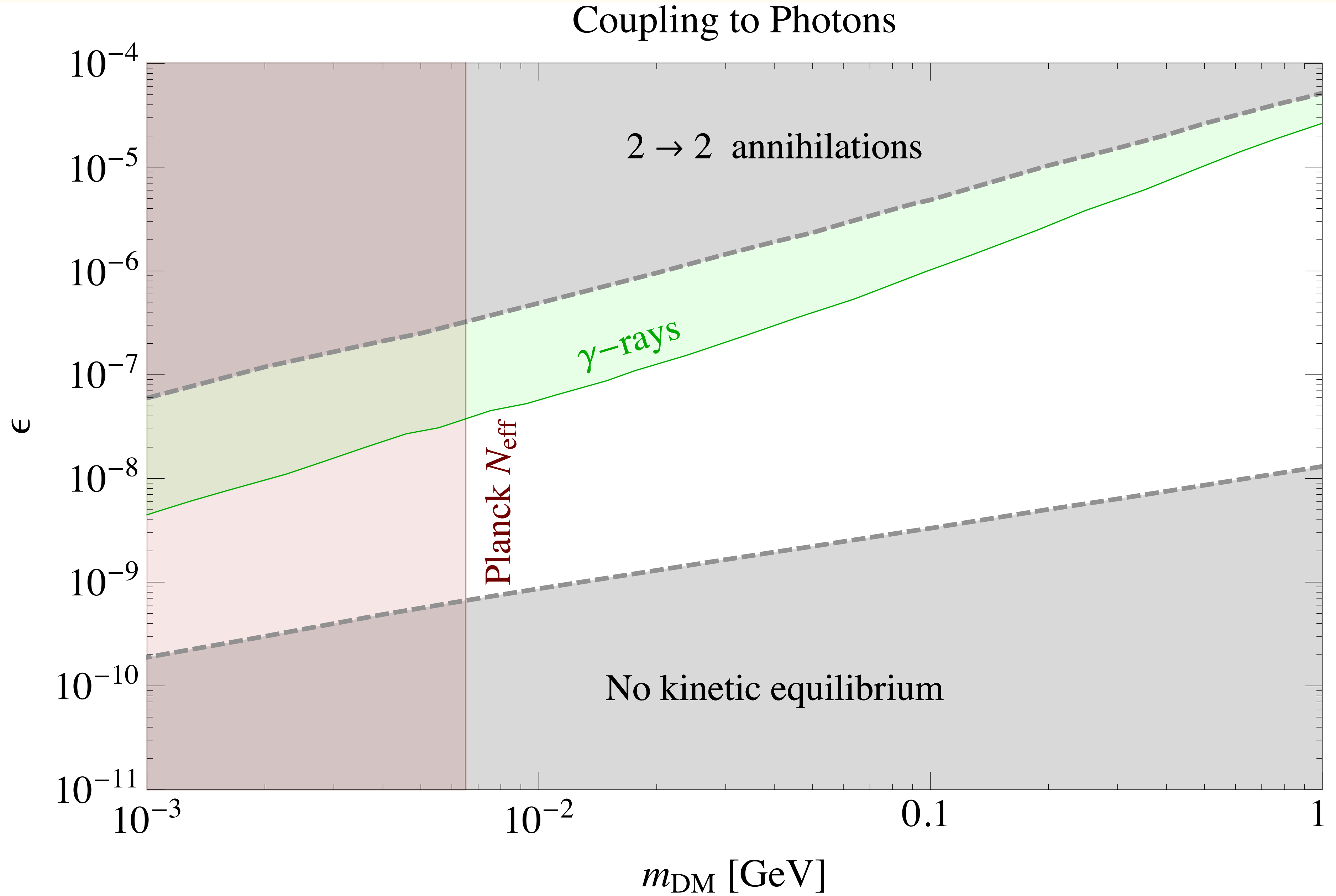
[de Laix, Scherrer and Schaefer, 1995]

Light Hot Dark Matter

SIMP DM: Experimental Status



SIMP DM: Experimental Status



Solar Neutrino Spectrum