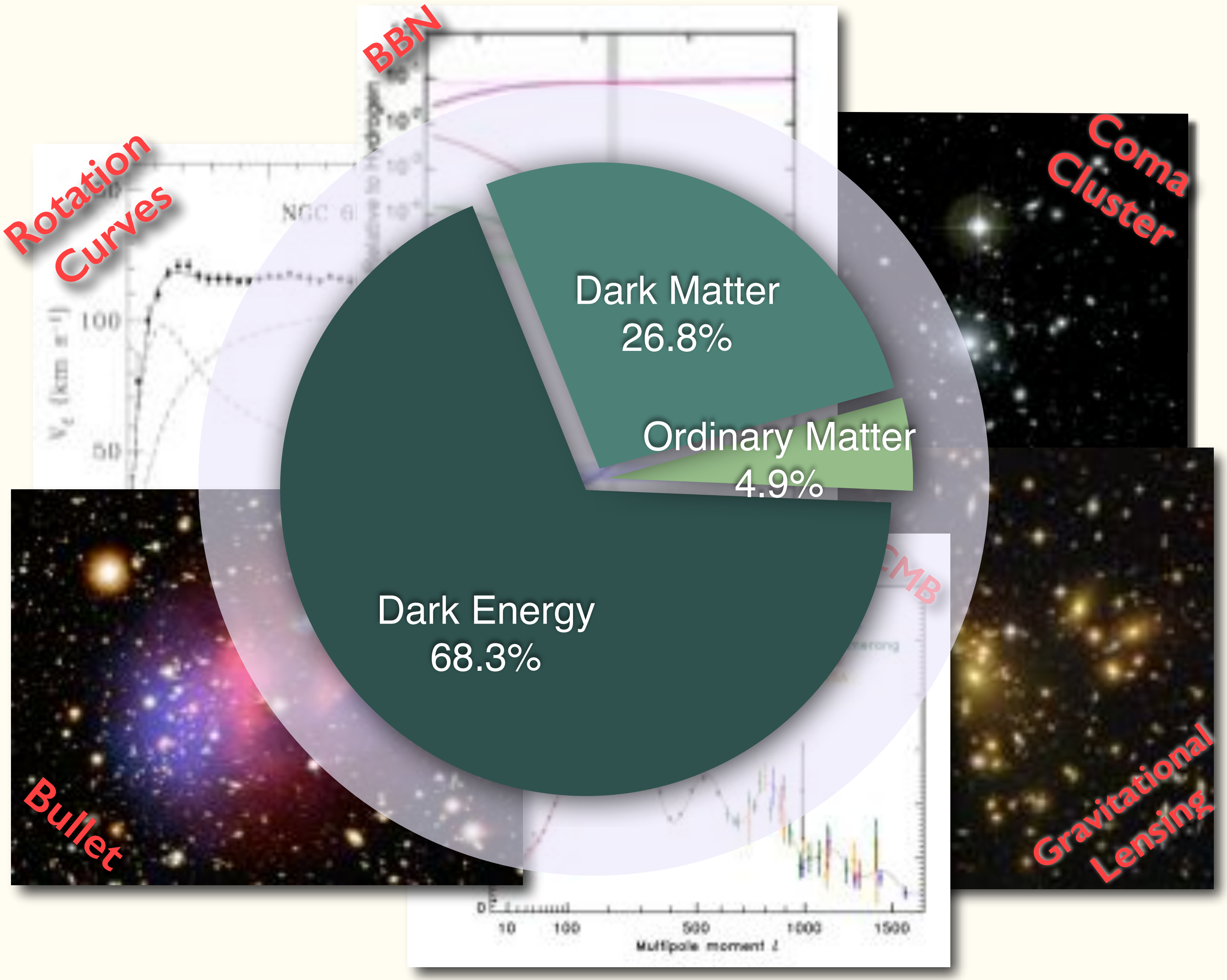
New Paradigms in the Search for Dark Matter

September 2014

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, C-T. Yu, Y. Zhong, K. Zurek.

(Gravitational) Evidence for Dark Matter



What is DM?

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

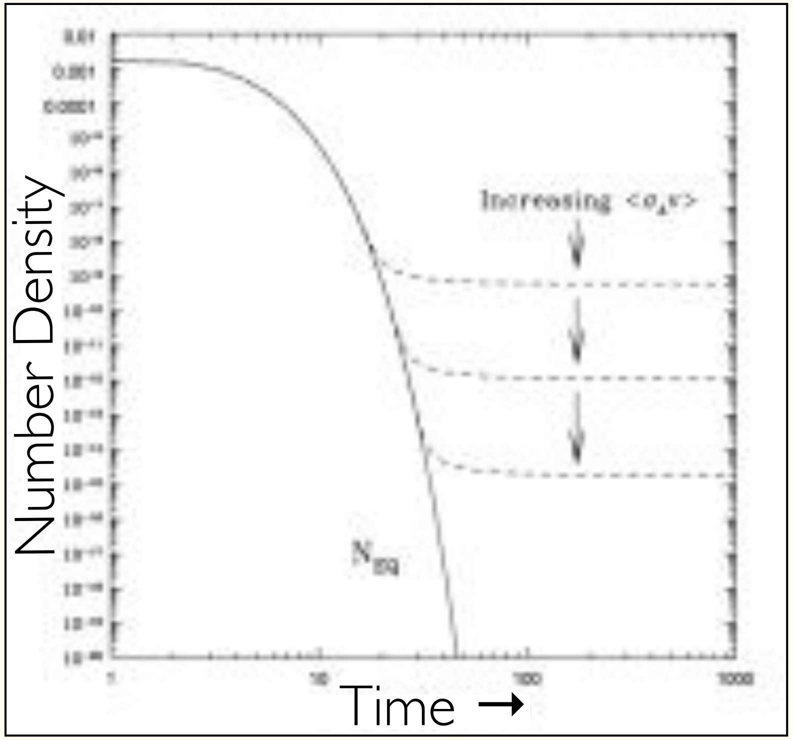
- We don't know this particle(s) identity. But we know a little:
  - Comprises 85% of the matter in our universe.
  - Non-baryonic.
  - Massive.
  - Stable on cosmological timescales.
  - Doesn't interact with EM or QCD (at leading order).
  - Doesn't interact very strongly with itself.
  - …

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.
    - DM stable on cosmological timescales.



- Dynamics described by Boltzmann eqs.

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v \rangle (n_\chi^2 - n_{\chi,\mathrm{eq}}^2)$$

The Thermal WIMP

- 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:

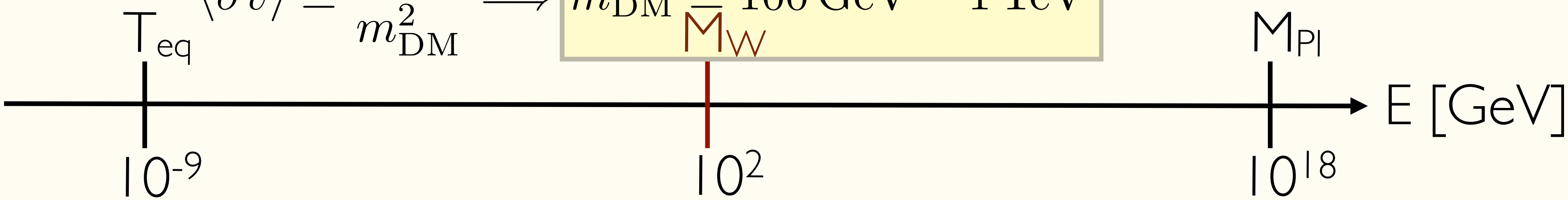
$$\langle \sigma v \rangle \simeq \frac{g^4}{m_{\mathrm{DM}}^2} \Longrightarrow m_{\mathrm{DM}} \simeq 100\, \mathrm{GeV} - 1\, \mathrm{TeV}$$

Same mass-scale we are now probing at the LHC

The Thermal WIMP

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

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



This is the WIMP Miracle

Obsessed with the WIMP...

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

WIMP ⟷ Naturalness Problem

Problem made up by theorists..

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!

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

(…but 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. — 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
- Asymmetric production
- Misalignment mechanism
- …

Mediation Scheme

- Gravity
- Weak-scale Mediator
- Light Hidden photon
- Axion portal
- Higgs portal
- …

Couplings

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

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:

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

- 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.

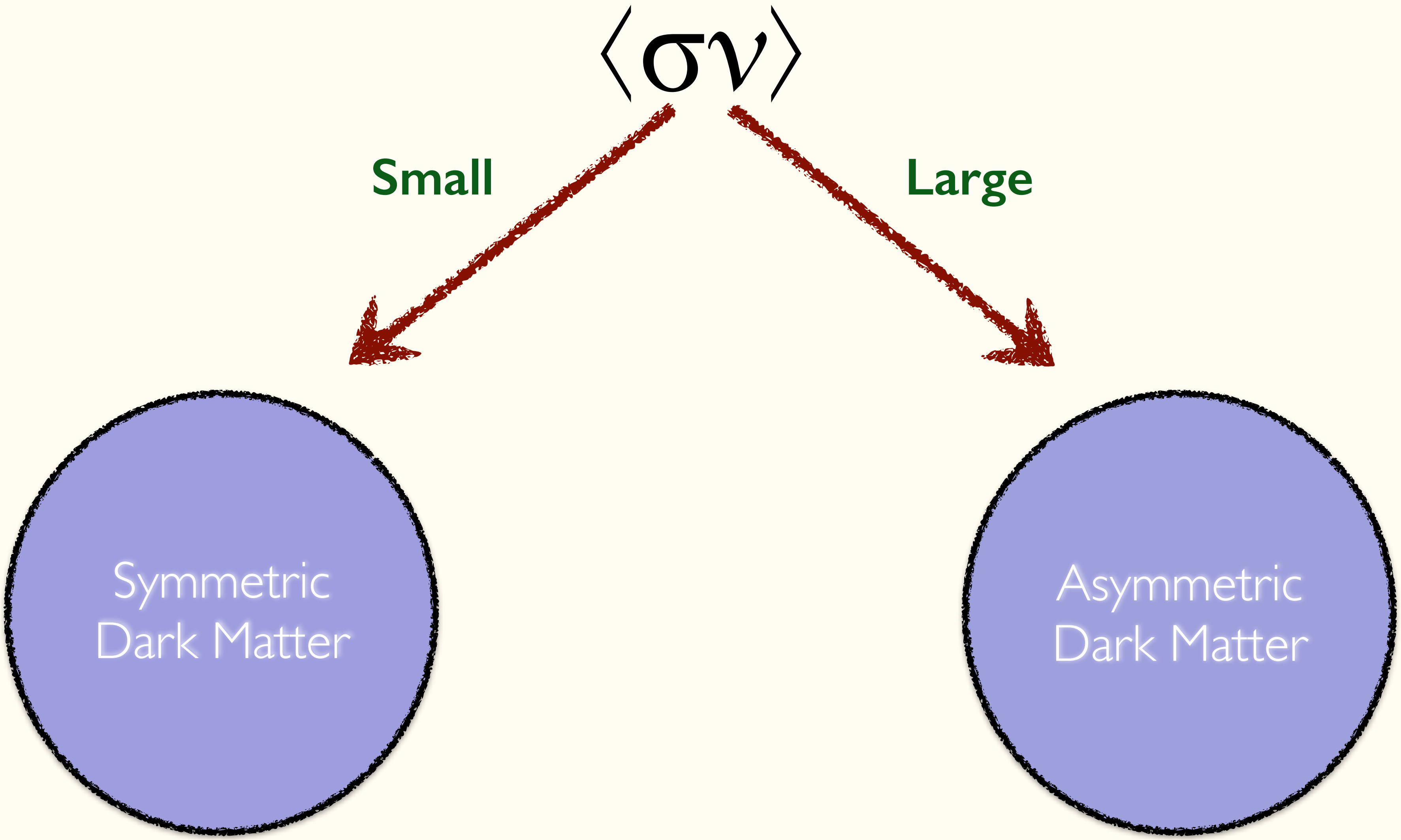
[Nussinov, `85; Gelmini, Hall, Lin, `87'; Barr, Chivukula, Farhi, `90'; Kaplan, Luty, Zurek, `09;...]

- 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.

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

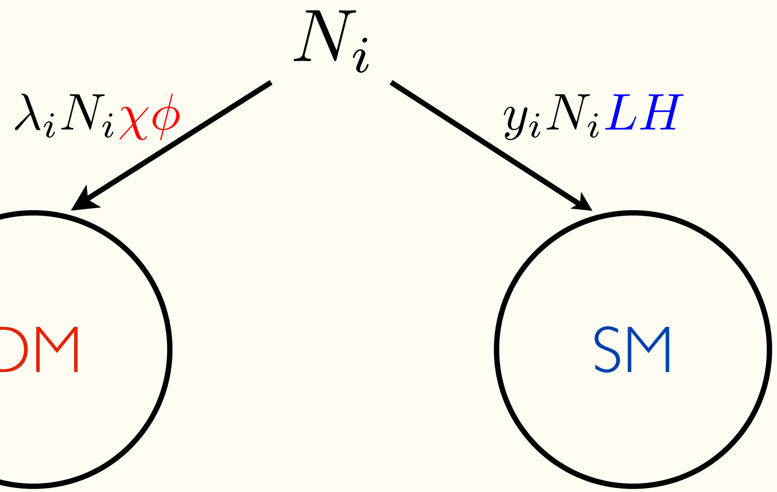
Asymmetric / Non-thermal



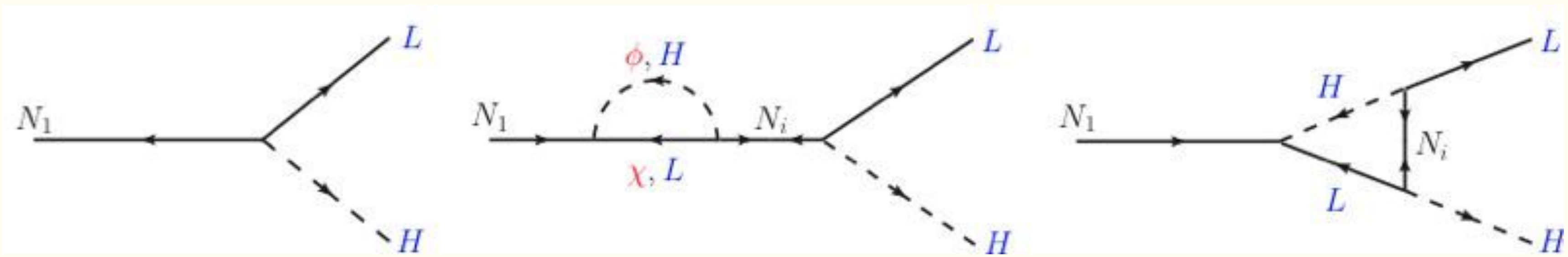
Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

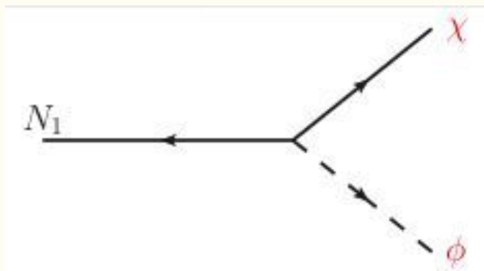
[Falkowski,Ruderman,TV, 2011]



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



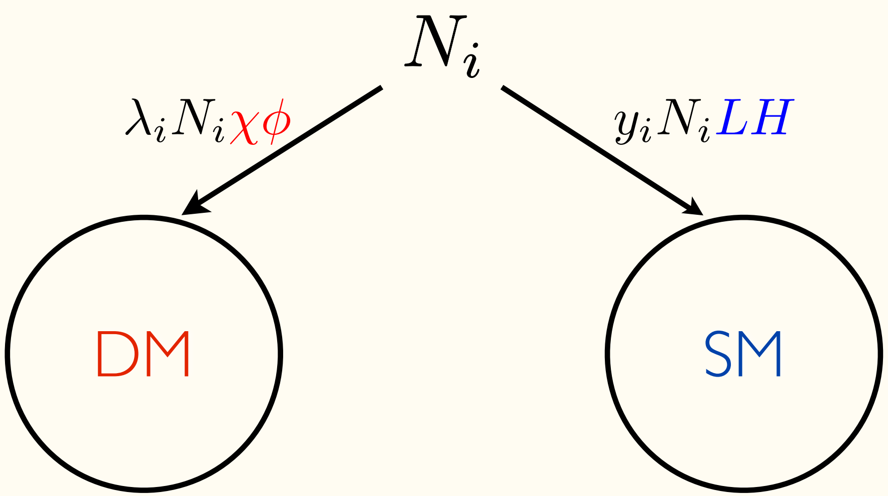
- Symmetric DM produced through tree level:



Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

[Falkowski,Ruderman,TV, 2011]



- 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

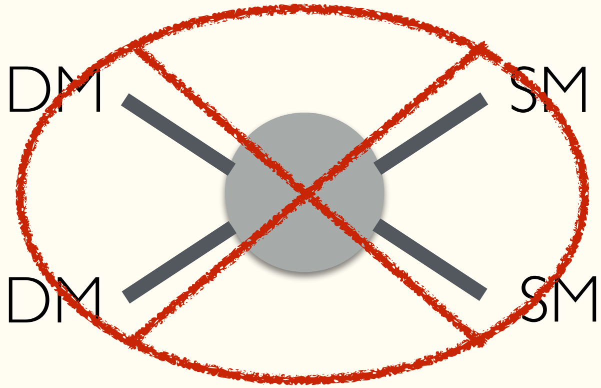
A New Perspective on Freeze Out

[Kuflik, Hochberg, TV, Wacker, 2014]

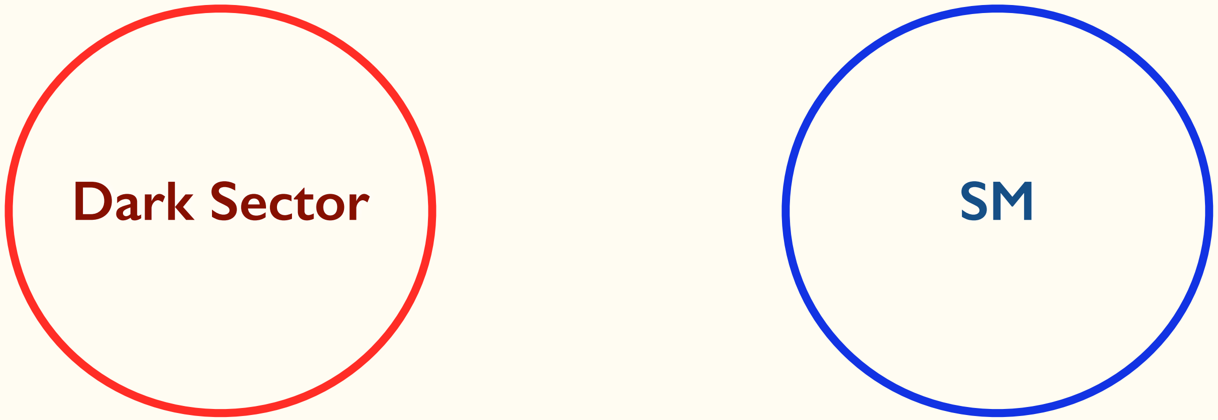
[Kuflik, Hochberg, Murayama, TV, Wacker, in progress]

No 2-2 Annihilations..

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

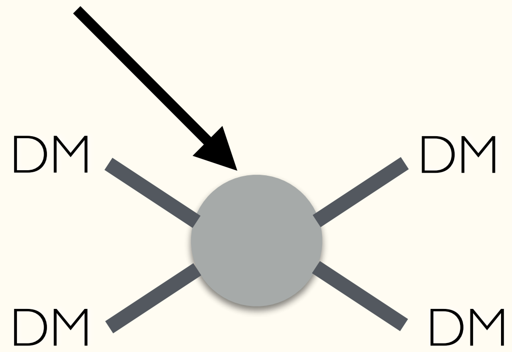


- But what if DM is the lightest state in a hidden (sequestered) sector?

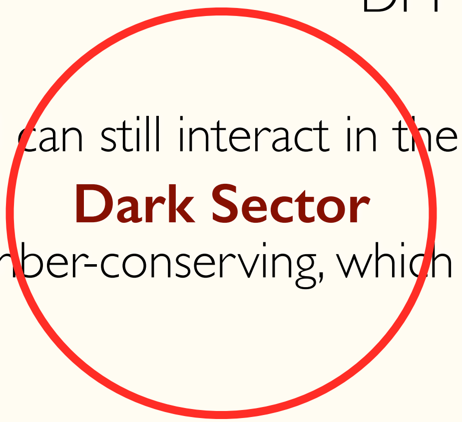


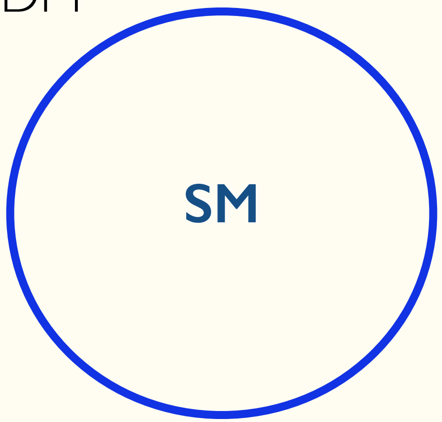
- Then 2-2 annihilations may be highly suppressed

No 2-2 Annihilations..



- However, DM can still interact in the hidden sector.



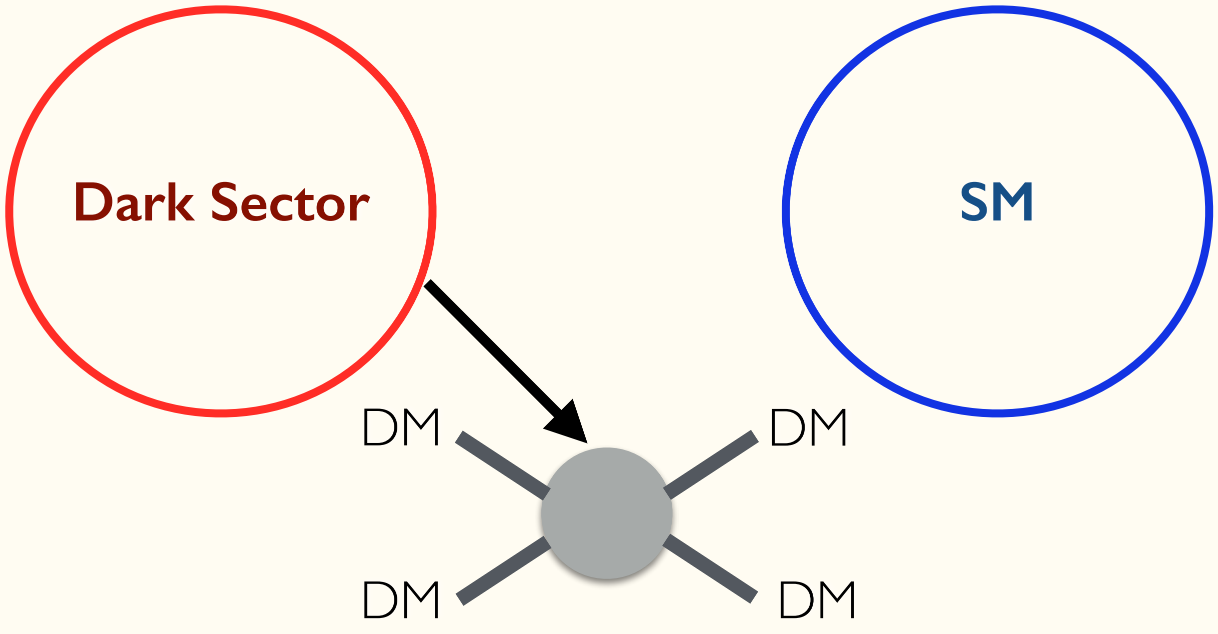


- But this is number-conserving, which implies,

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

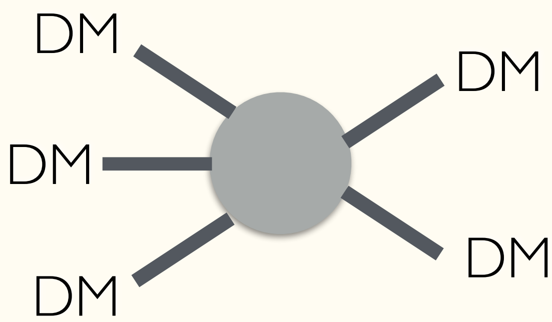
A way out?

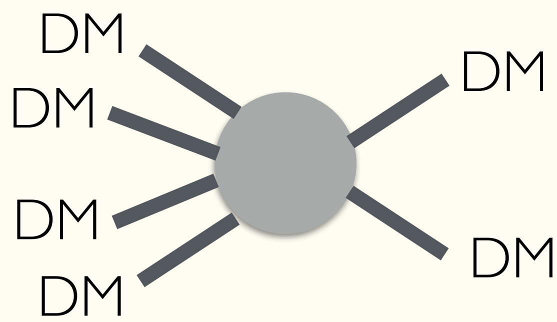
No 2-2 Annihilations..



- 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

WIMP
DM

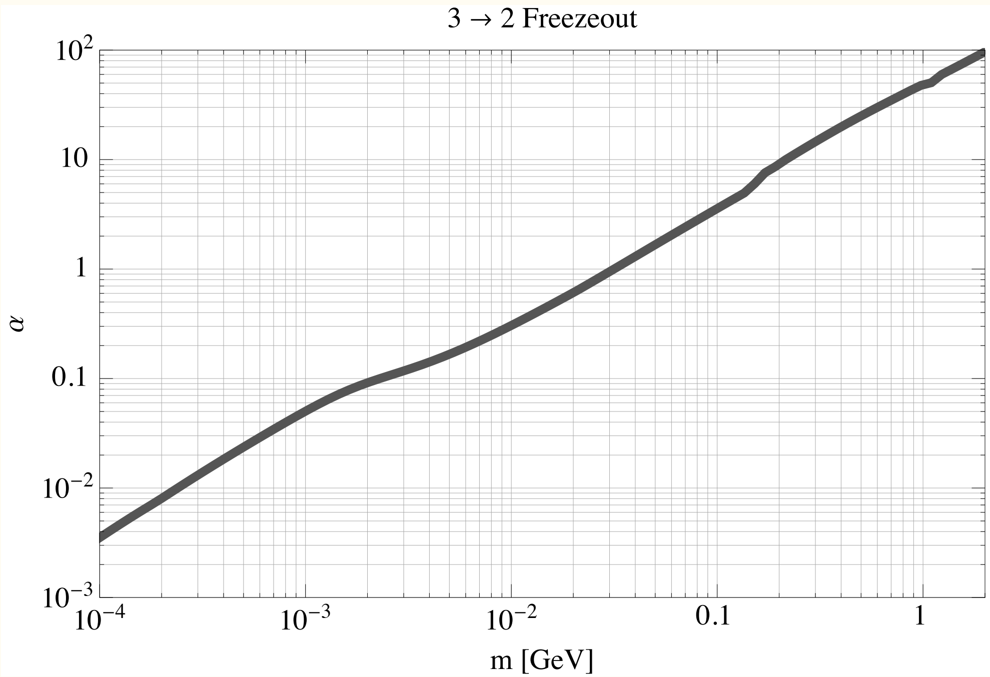
Weak scale emerges for a weak-strength interactions

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

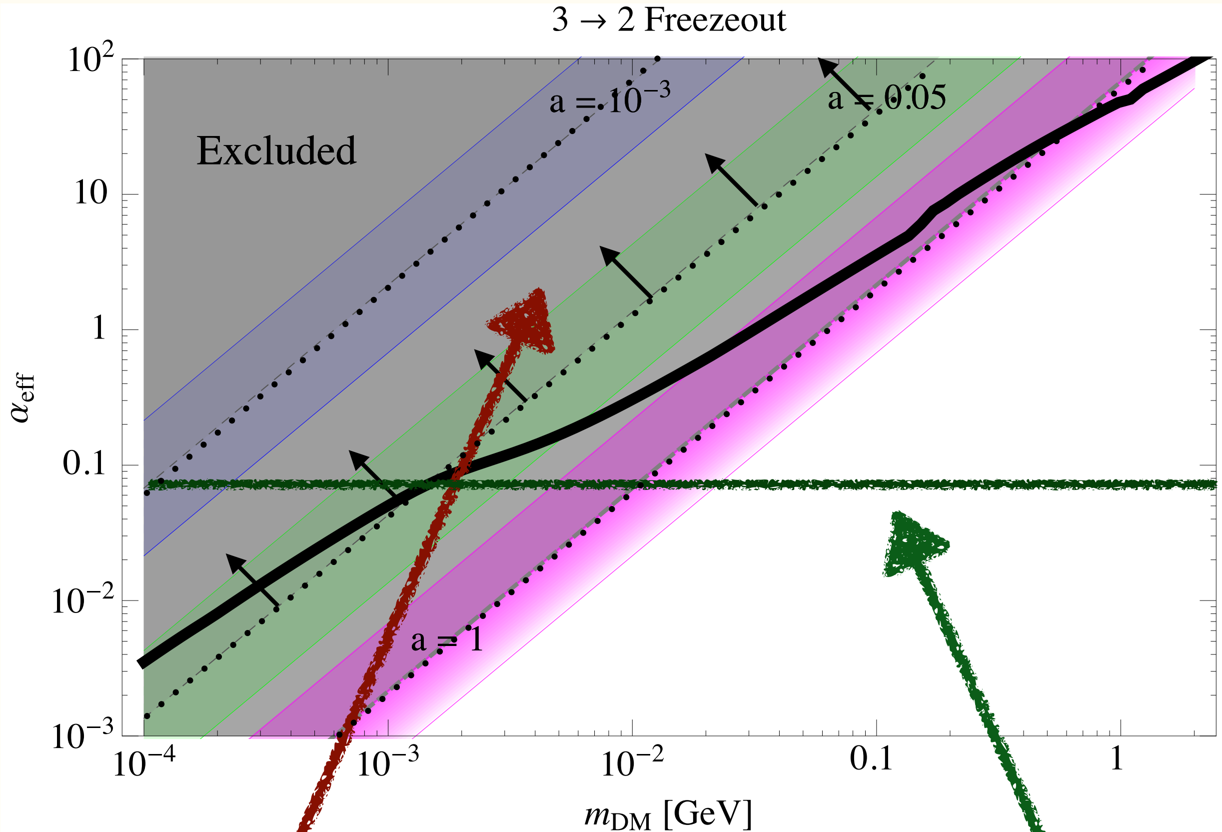
SIMP
DM

QCD scale emerges for a strongly-interacting sector.

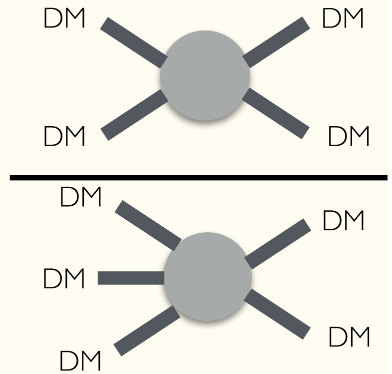
$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100~{\rm MeV}$$



2-2 Good or Bad?



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

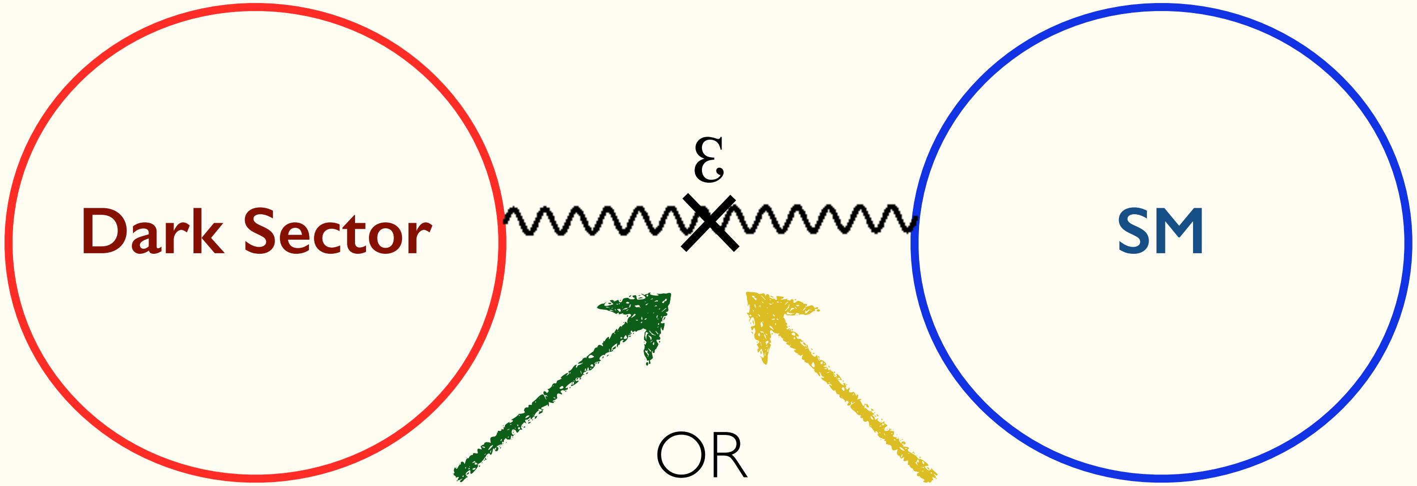


Excluded by Bullet-cluster and halo-shape constraints

Constraints push to strong regime → **SIMP**

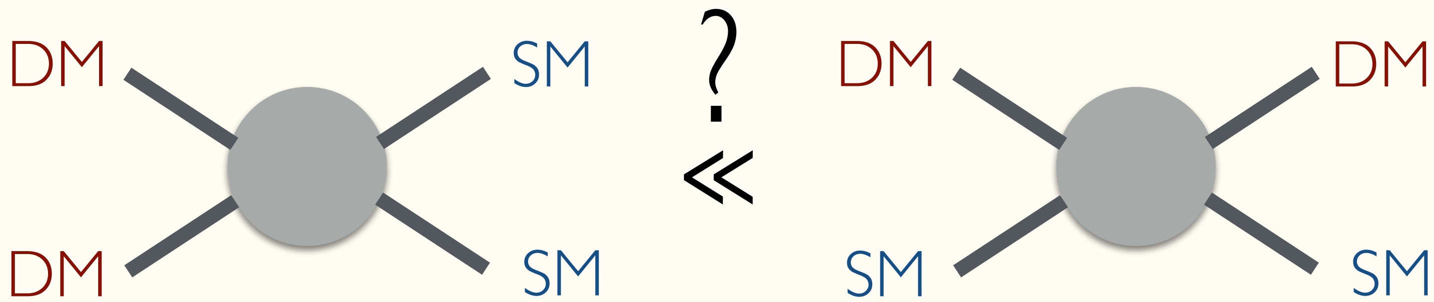
3-2 Freeze Out

- 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.



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

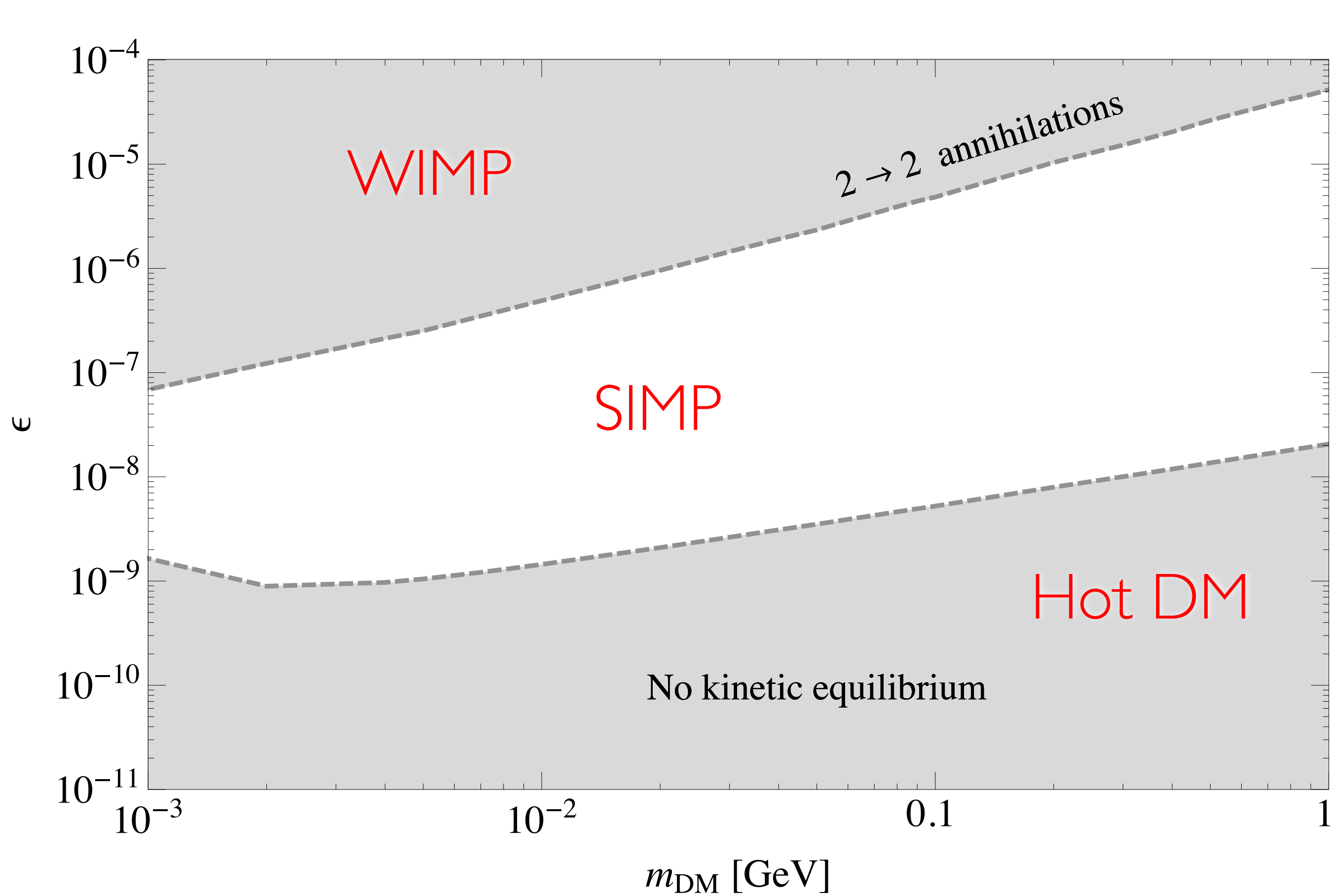
- Consequently, two more diagrams:



2-2 Annihilations

Thermal Equilibrium

3-2 Freeze Out

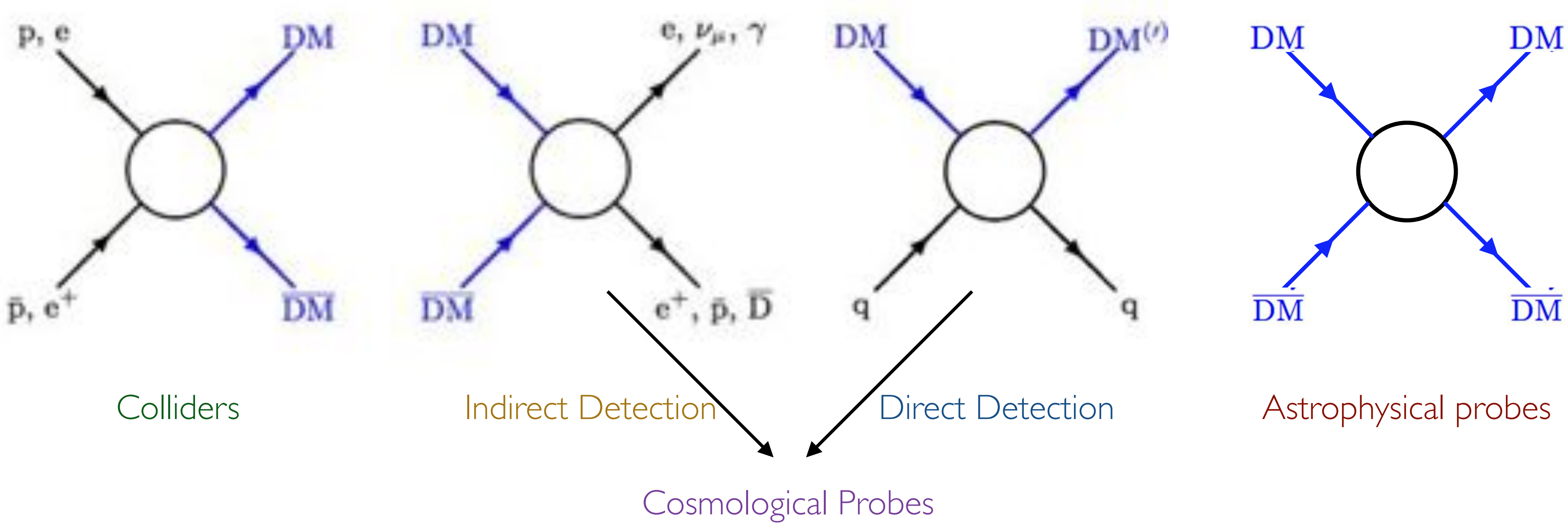


Thus, much like the WIMP, the SIMP scenario predicts couplings to SM. Thus:

Measurable consequences for all types of experiments

Experimental Probes

Several ways to search for DM

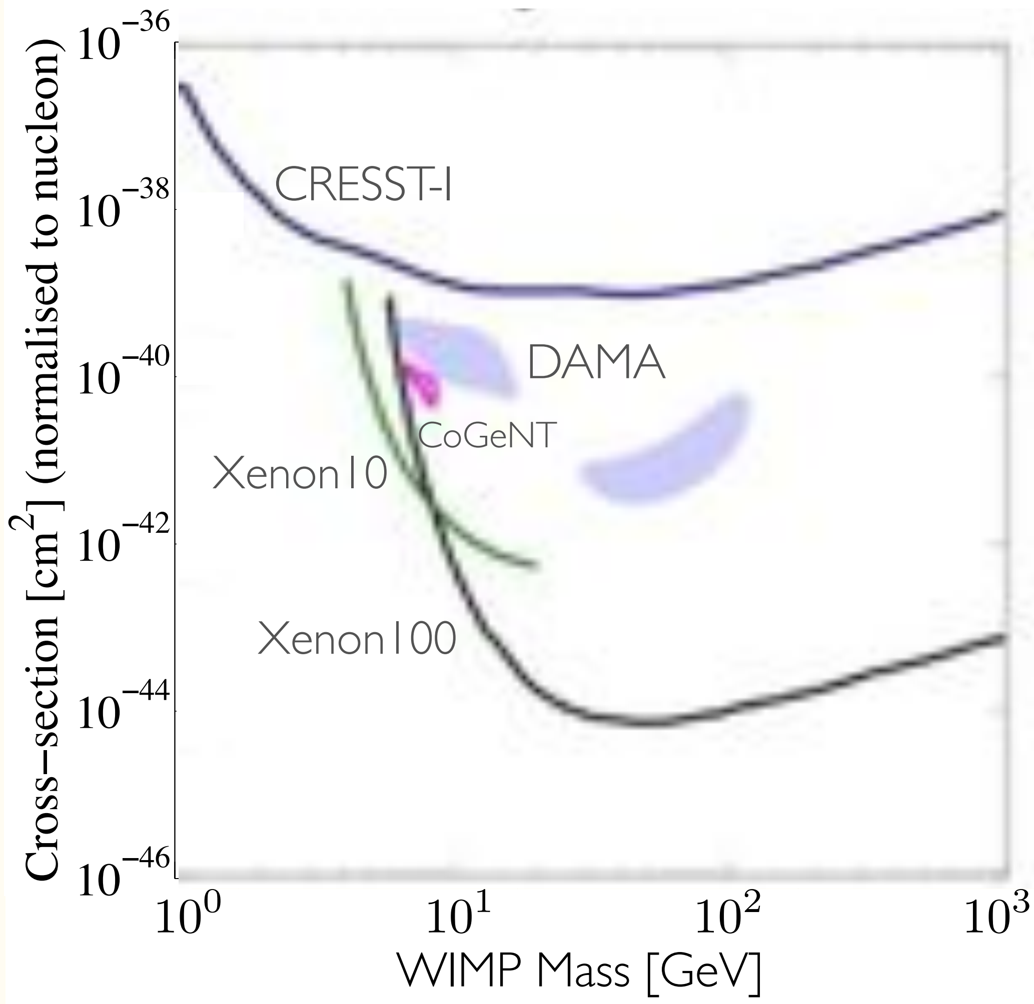


Experimental Probes

Direct Detection

A New Direction: Light Dark Matter

???



Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

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

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

Recoil energy drops fast

Can't go below ~ GeV

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

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

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

But DM energy is significantly larger:

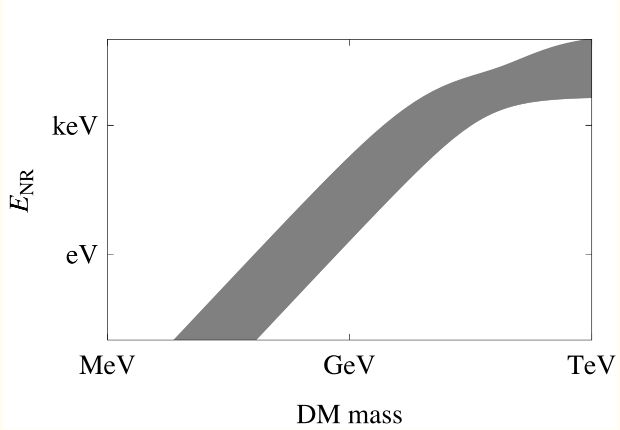
$$E_{\rm DM} = \frac{1}{2}\mu v_{\rm DM}^2 \simeq 0.3 \text{ keV} \times \left(\frac{m_{\rm DM}}{\rm GeV}\right)$$

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

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

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



Studying elastic recoils is extremely inefficient for light DM

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

DM energy drops slower

Enough energy to detect!!

Ways to Detect Light DM

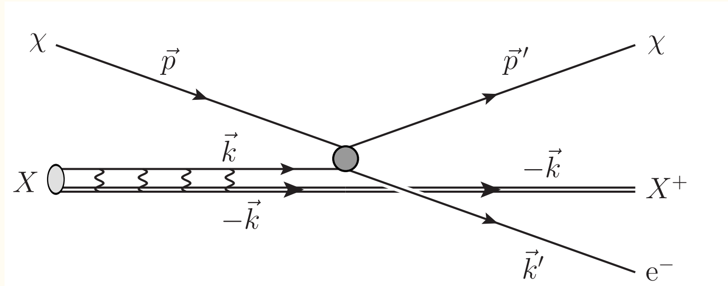
- The available energy is sufficient to induce inelastic atomic processes that would lead to visible signals.

[Essig, Mardon, TV, 2011]

- Three possibilities:

1. Electron ionization

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



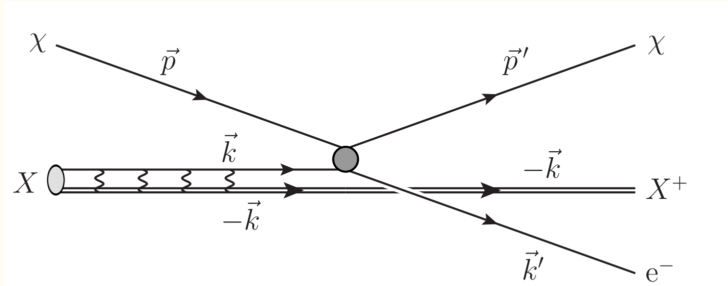
Ways to Detect Light DM

- The available energy is sufficient to induce inelastic atomic processes that would lead to visible signals. [Essig, Mardon, TV, 2011]

- Three possibilities:

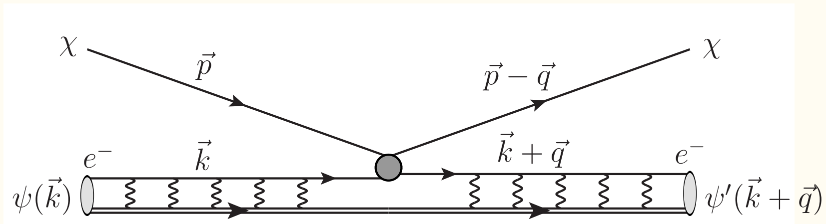
1. Electron ionization

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



2. Electronic excitation

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



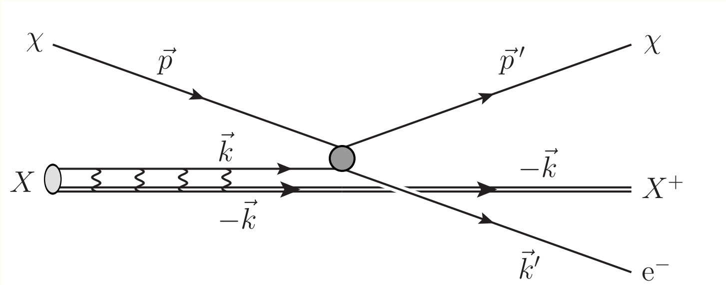
Ways to Detect Light DM

- The available energy is sufficient to induce inelastic atomic processes that would lead to visible signals. [Essig, Mardon, TV, 2011]

- Three possibilities:

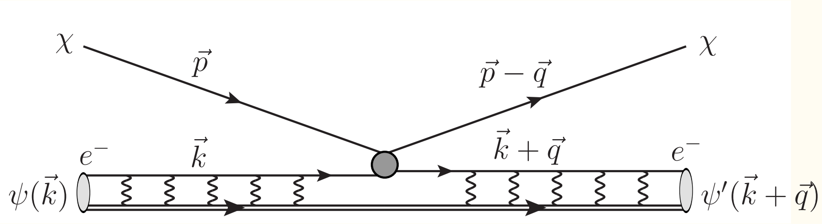
1. Electron ionization

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



2. Electronic excitation

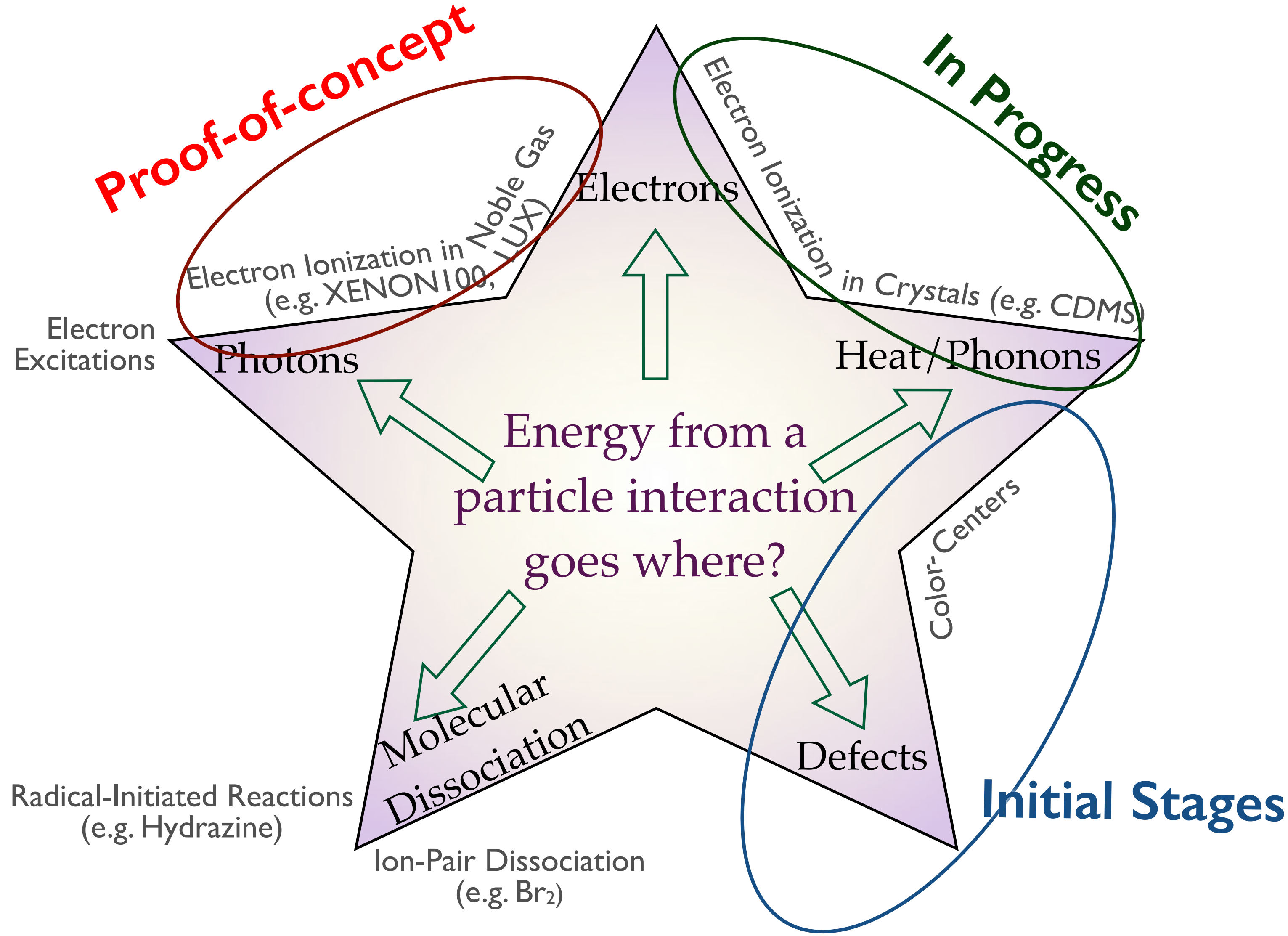
   Threshold: eV - 100's eV
   DM-electron scattering
   Signal: photons, phonons.



3. Bond Breakage

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

Detectable Signals



An ongoing program..

Upcoming:

- "Prospects for sub-GeV DM Detection with Semiconductor Targets",
  Essig, Fernandez-Serra, Mardon, Soto, TV, Chiu-Tien 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.

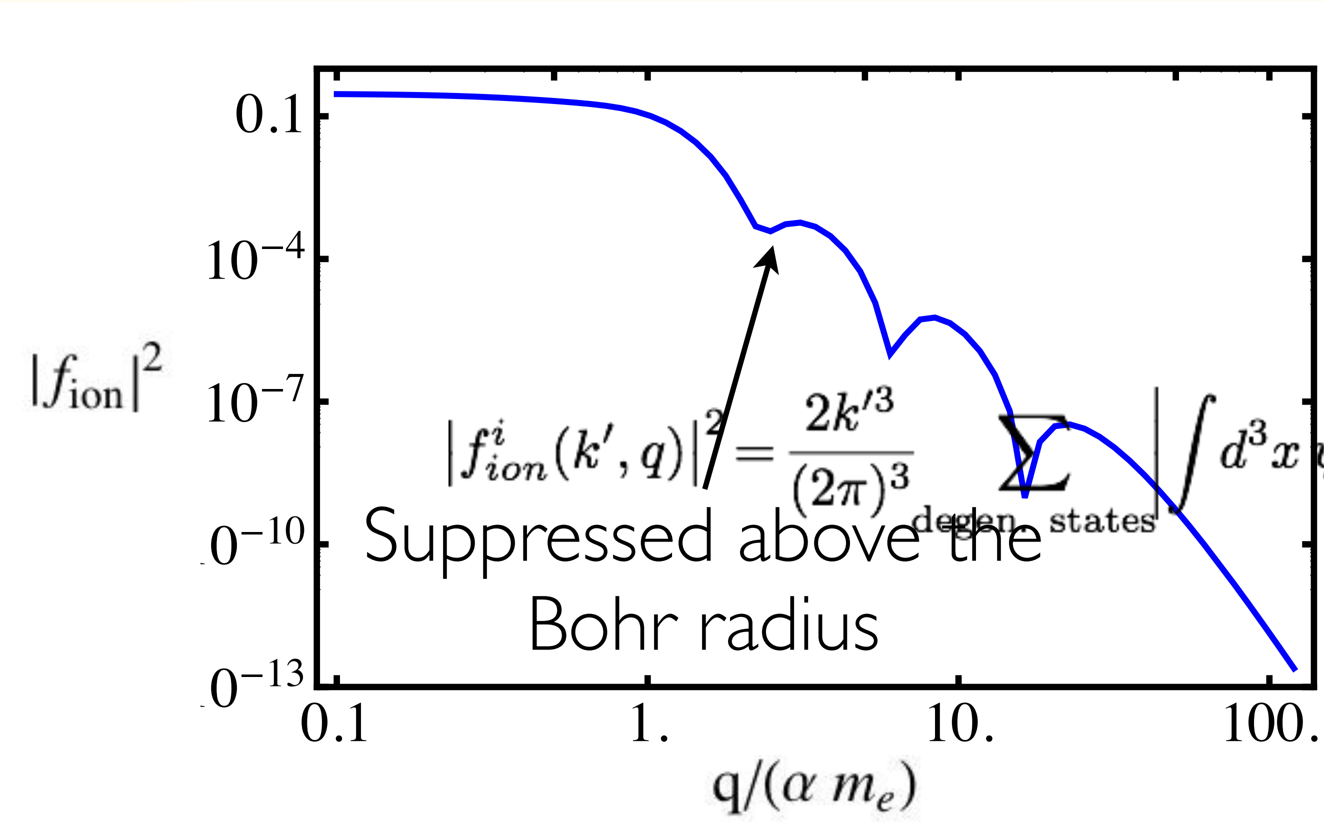
Electron Ionization

Proof-of-Concept

Ionization Cross-section

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

Determined by atomic wave-functions



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

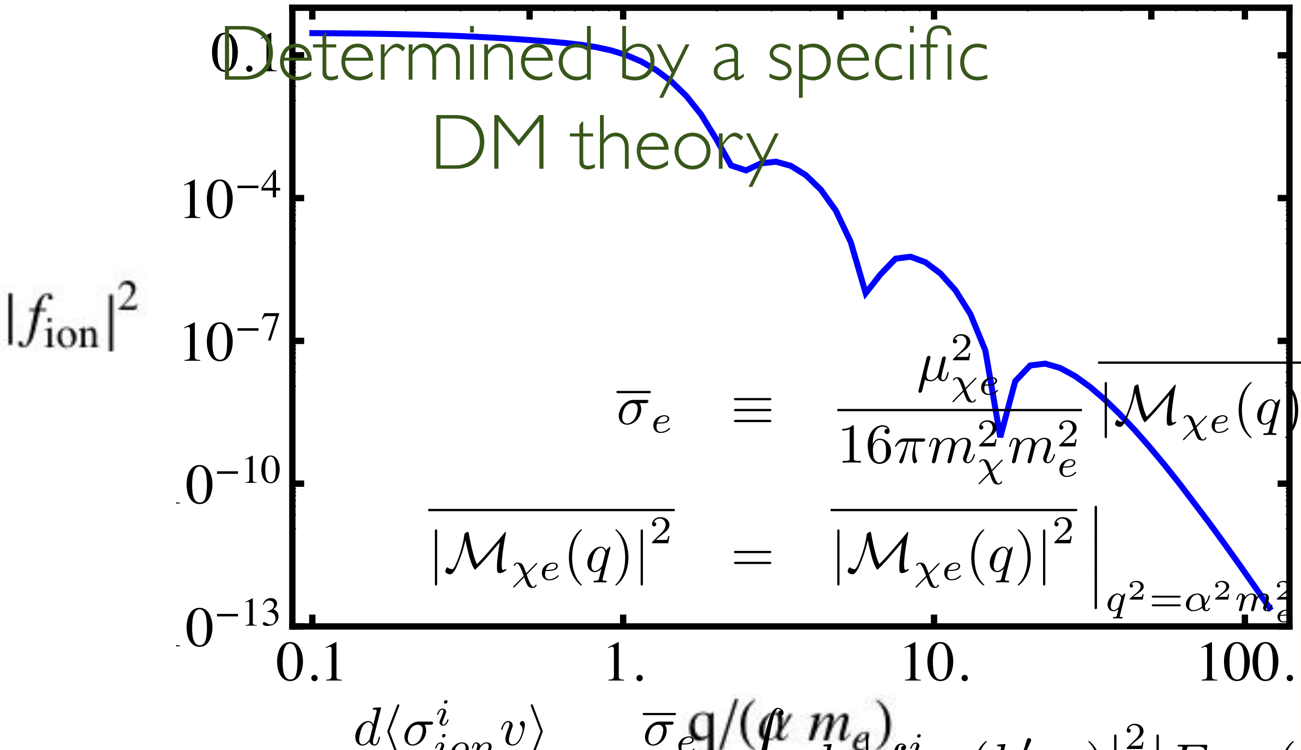
Suppressed above the Bohr radius

Rates are suppressed for large momentum transfer!

Ionization Cross-section

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

Determined by a specific DM theory



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

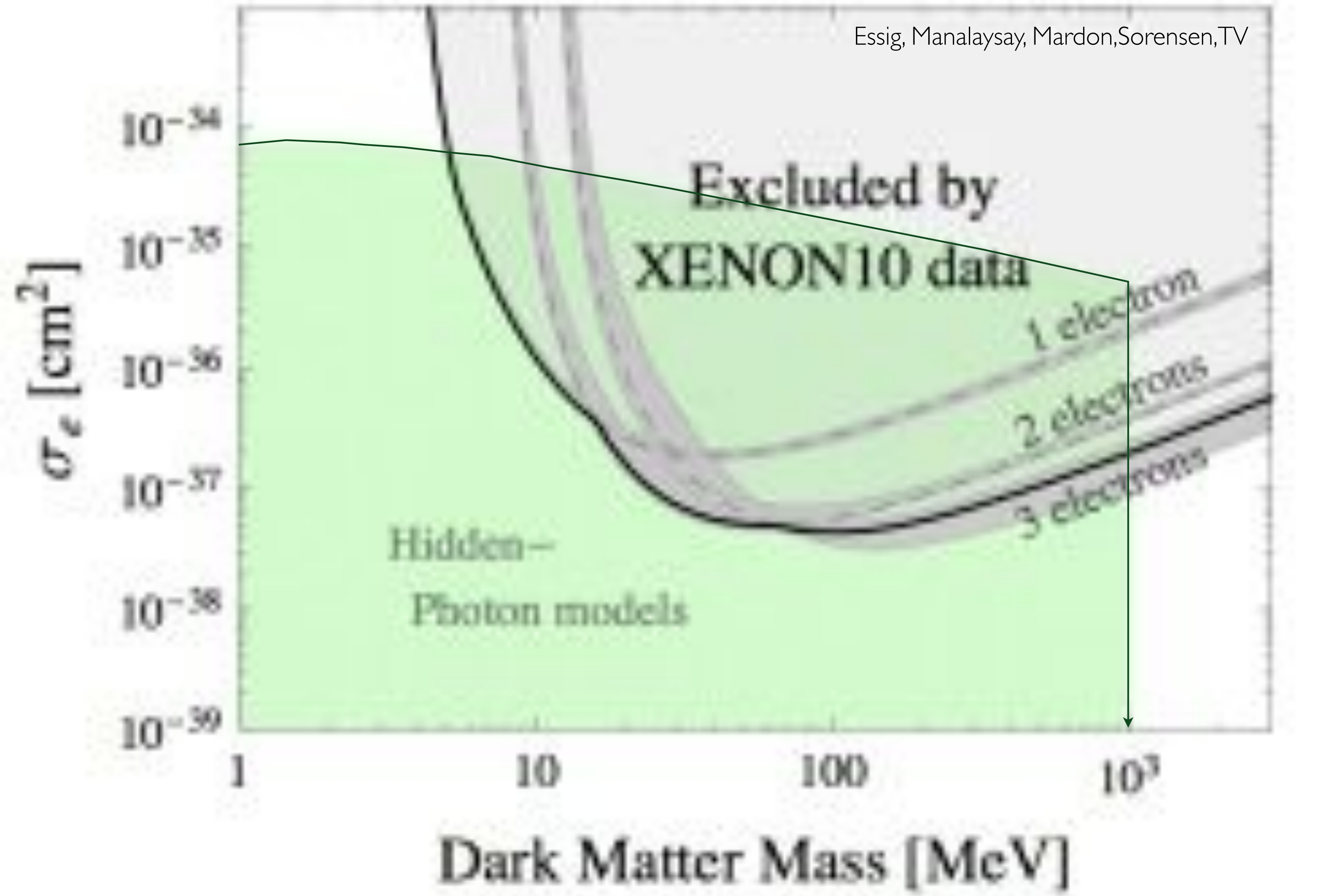
$$\overline{|\mathcal{M}_{\chi e}(q)|^2} = \overline{|\mathcal{M}_{\chi e}(q)|^2}\Big|_{q^2=\alpha^2 m_e^2} \times |F_{\rm DM}(q)|^2$$

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

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

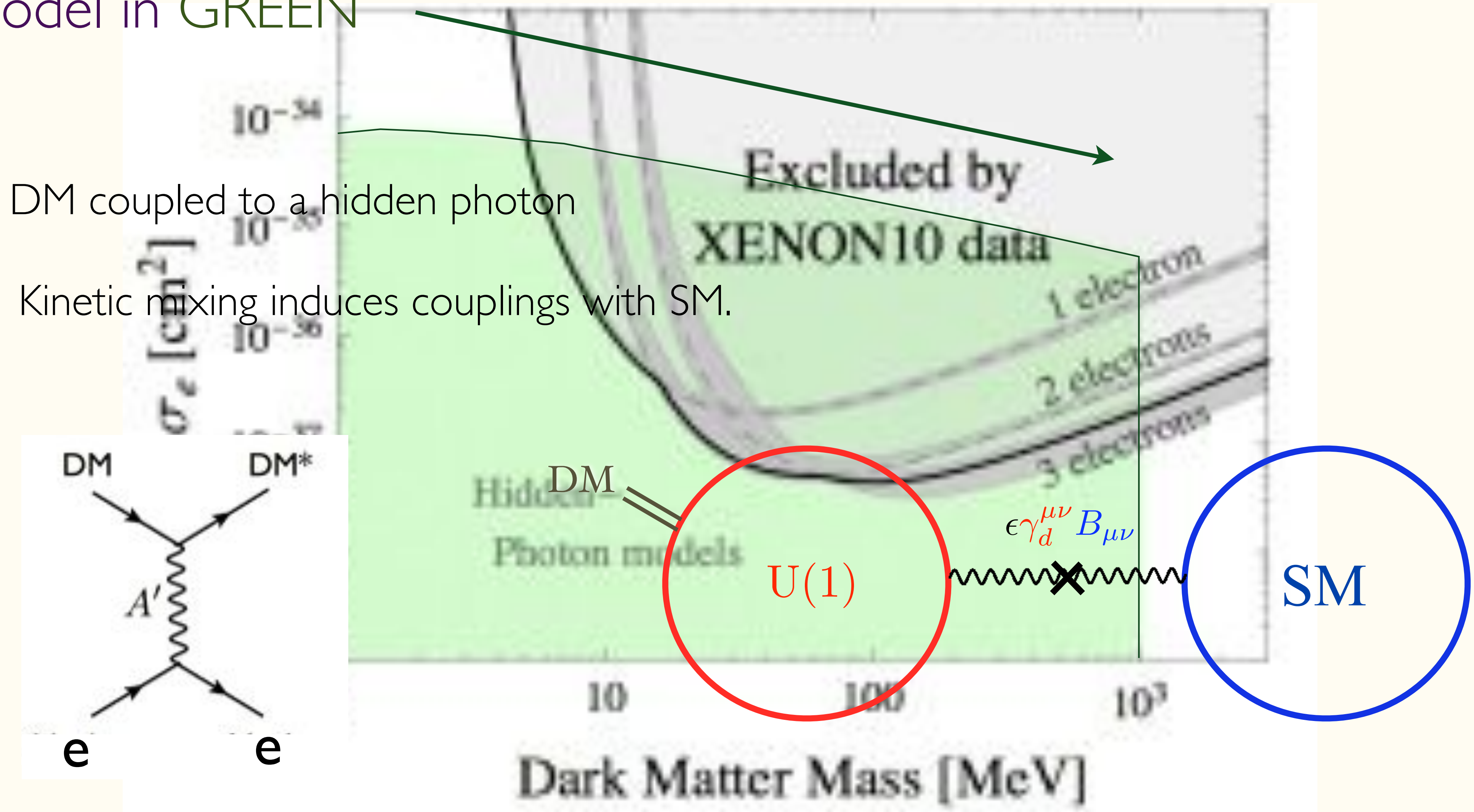
Results from XENON10: $F_{DM}=1$

First Direct Detection Bounds for MeV-GeV



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

Model in GREEN



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

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

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

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

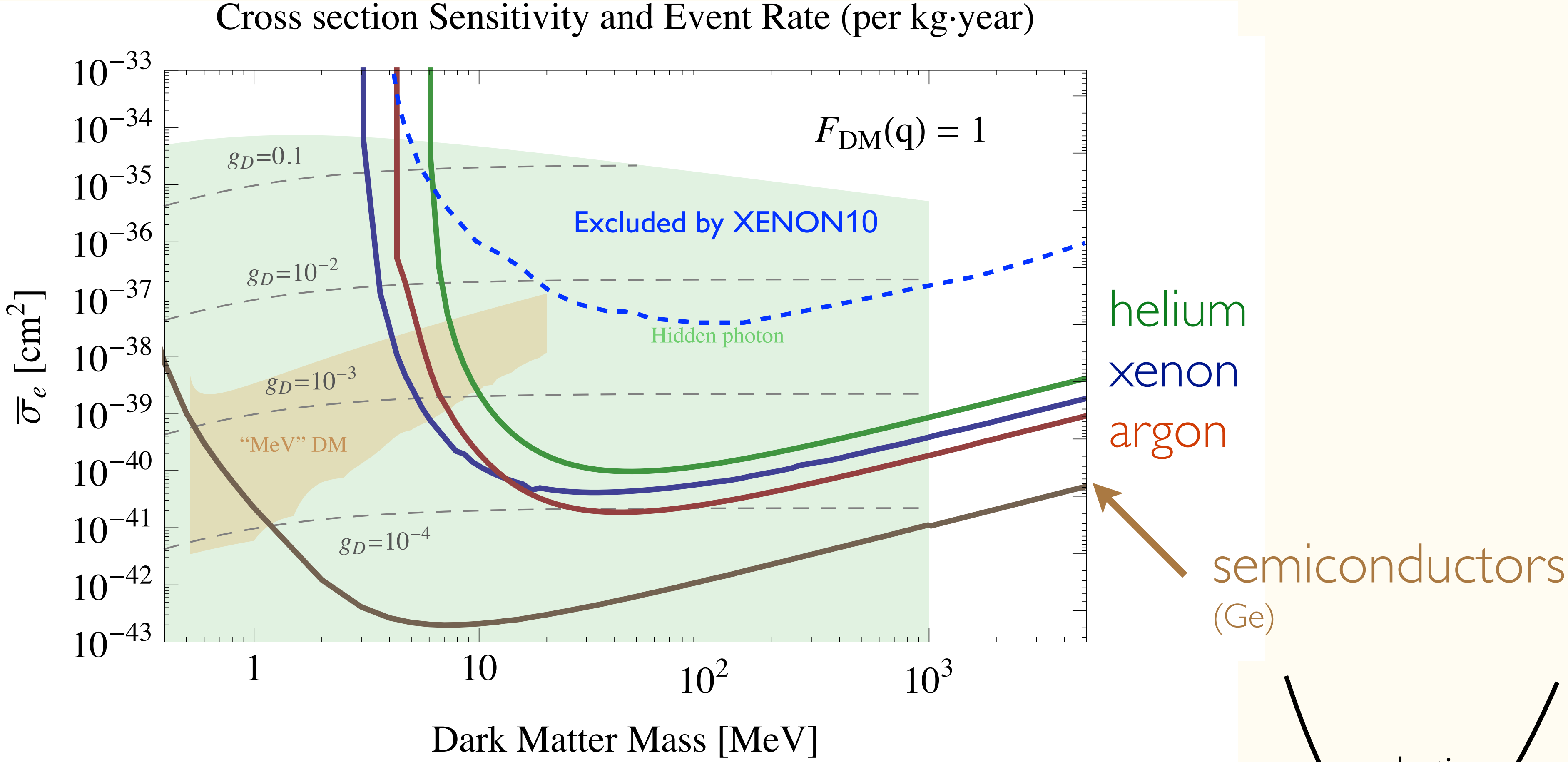
Essig, Mardon, TV with XENON100

Work in progress with CDMS too.

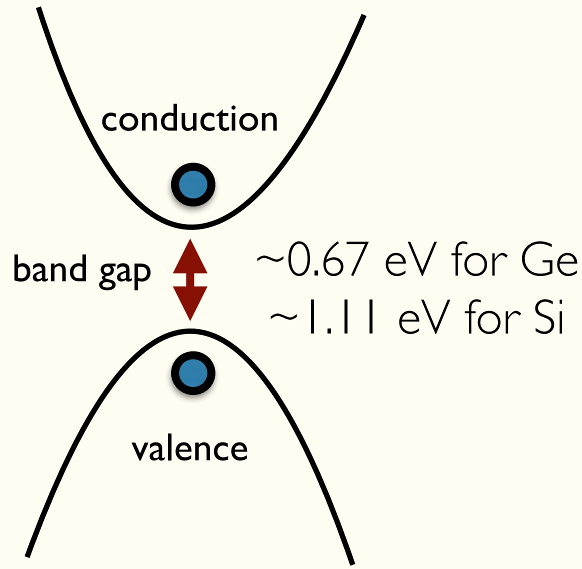
Electron Ionization

Semiconductors

Very promising..



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



Essig, Fernandez-Serra, Mardon, Soto, TV, Chiu-Tien Yu (in progress)

Experimental Probes

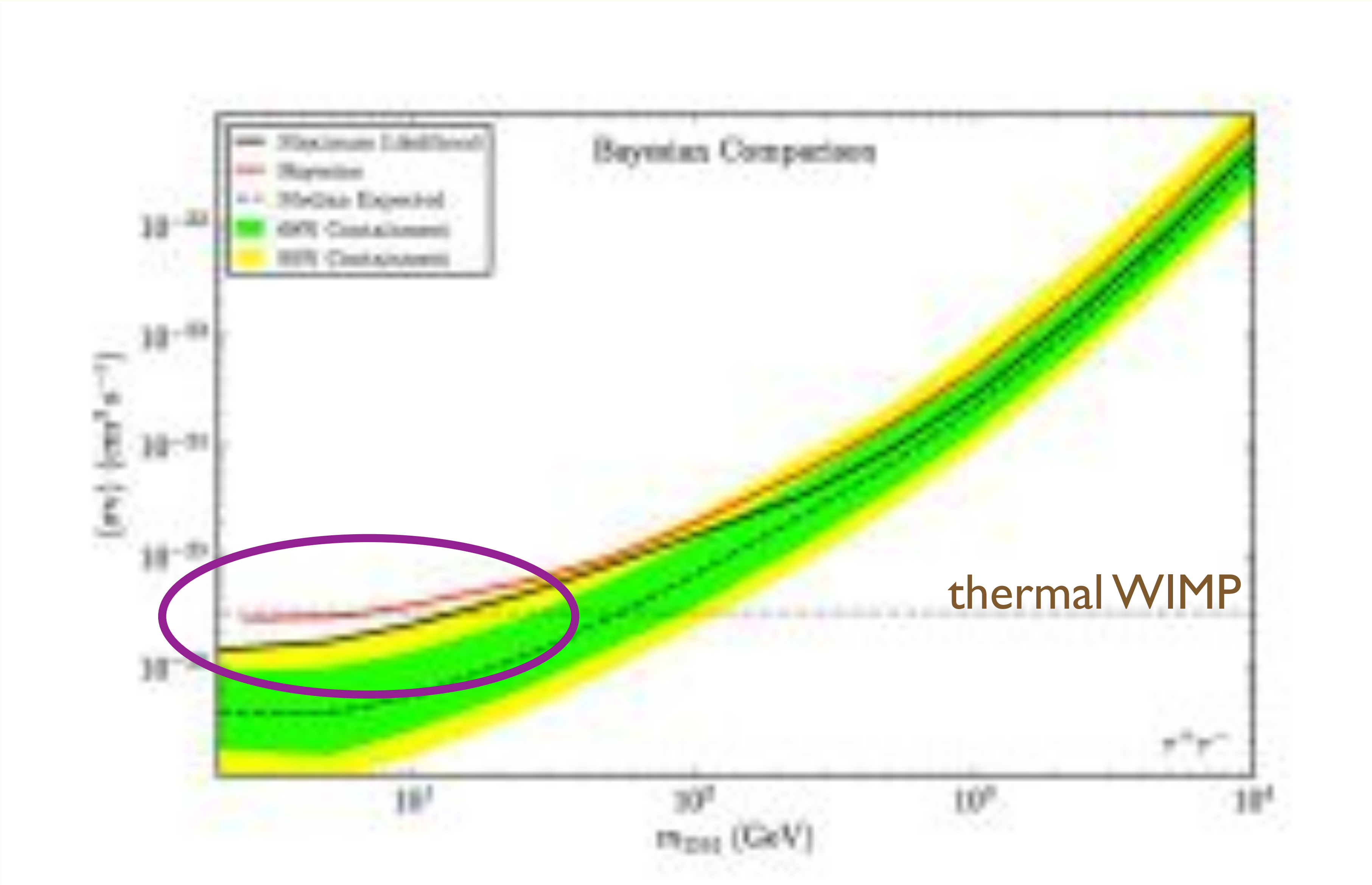
Indirect Detection

Skip

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

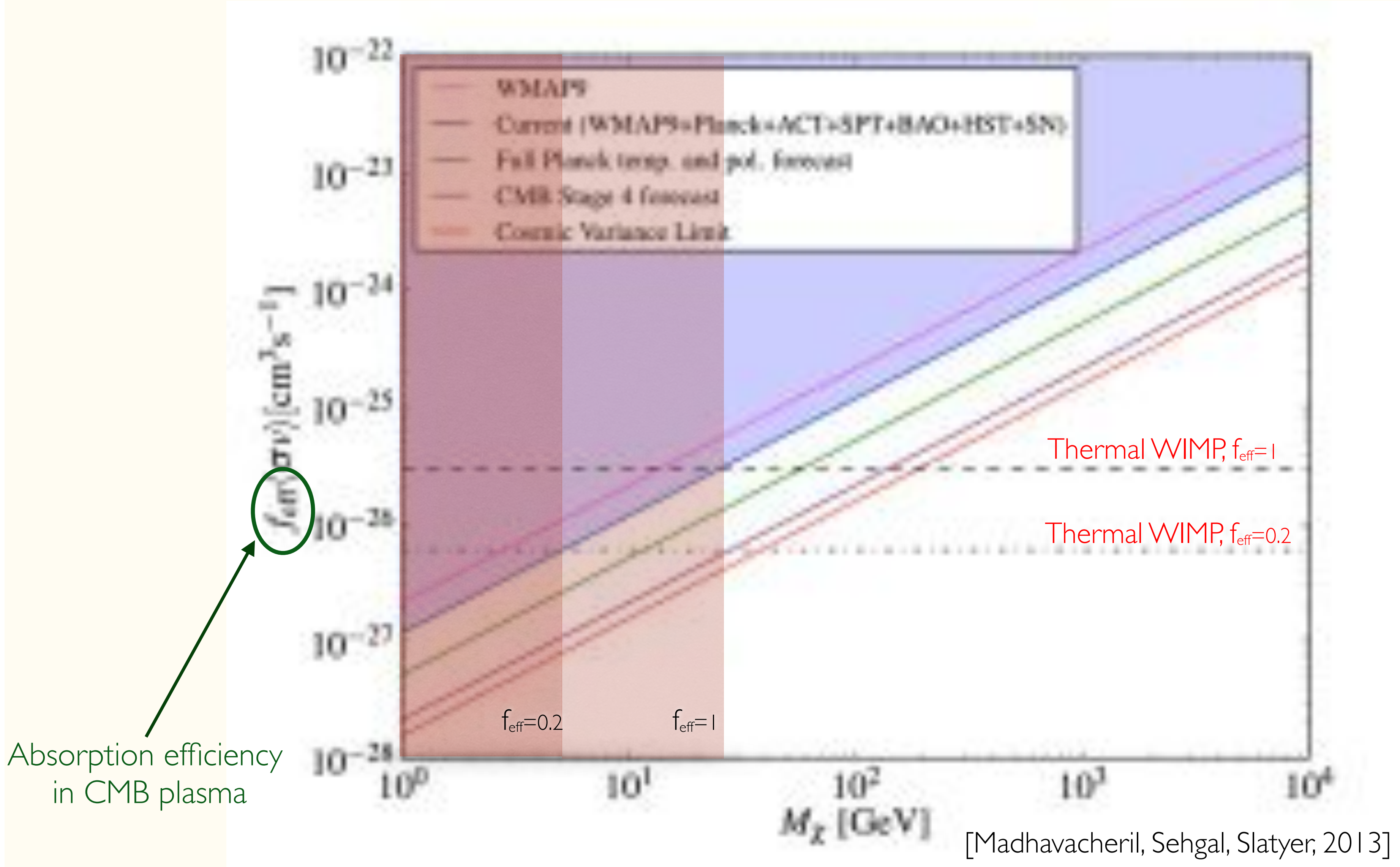
Strong Constraints

- E.g.: Dwarf galaxies



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:

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

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

Hope for indirect detection?

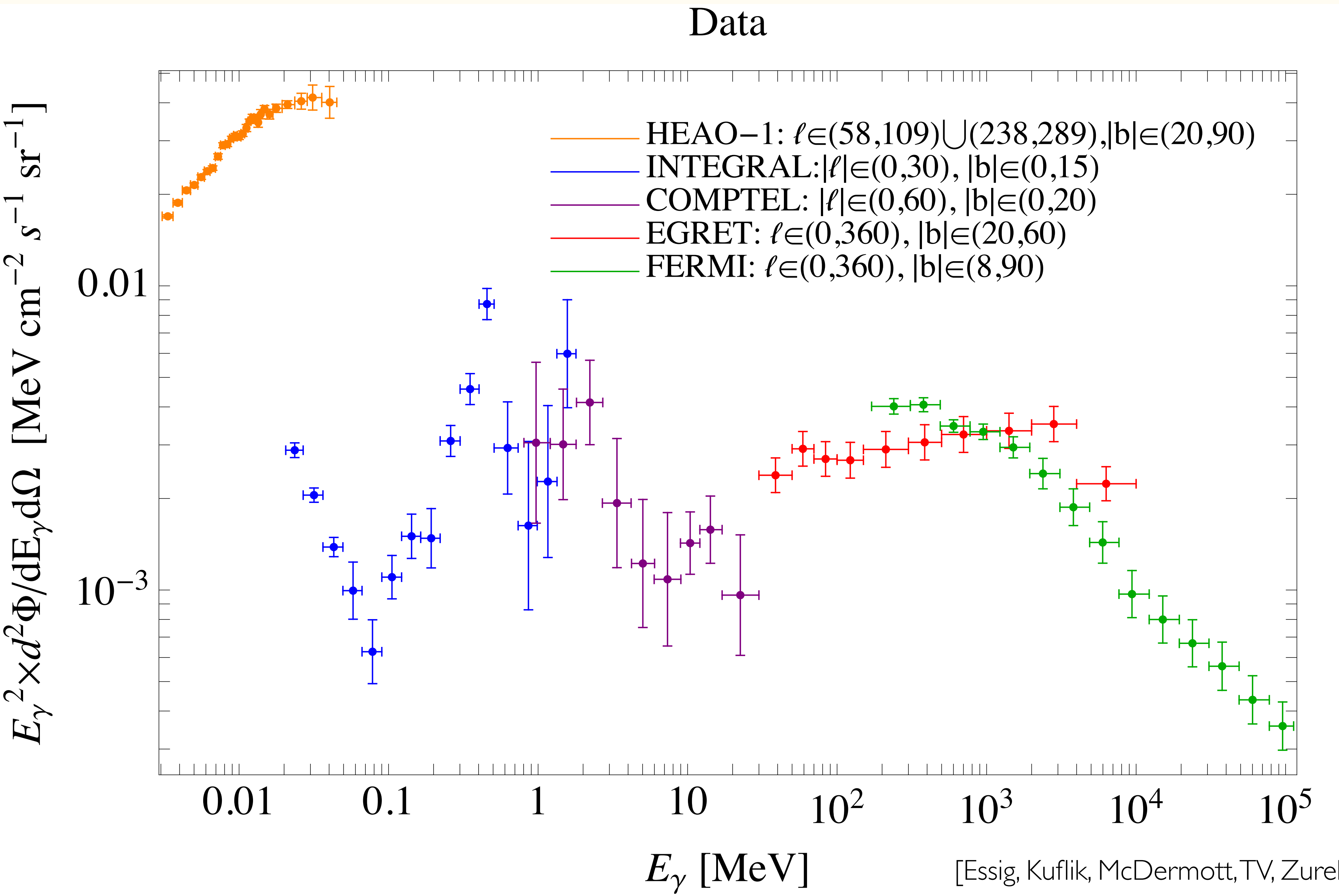
YES

Velocity dependent annihilations

Decaying DM

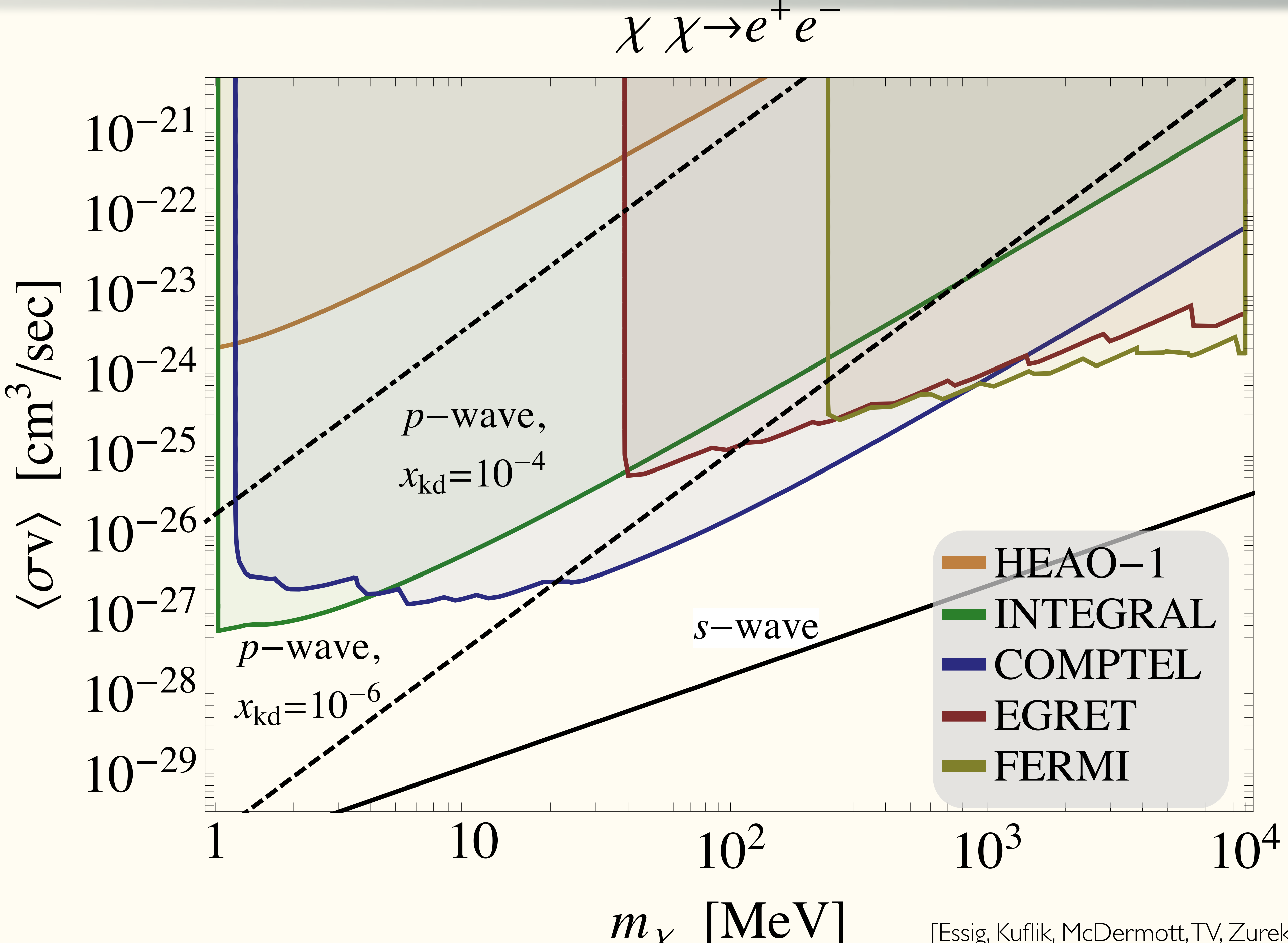
- Annihilation rate $\propto \rho^2$
- Decay rate $\propto \rho$
- Evades limits from CMB

Data



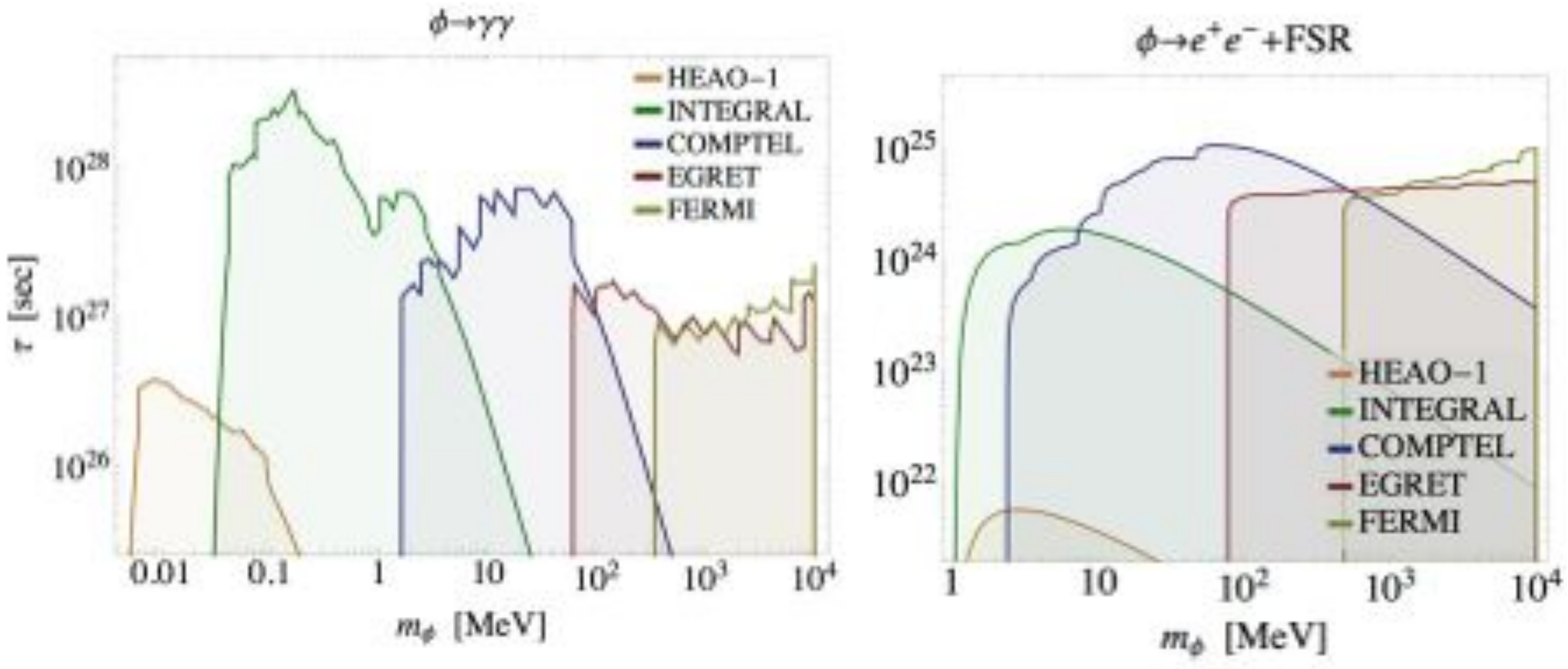
[Essig, Kuflik, McDermott, TV, Zurek, 2013]

Annihilating Light DM



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

Decaying Light DM



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

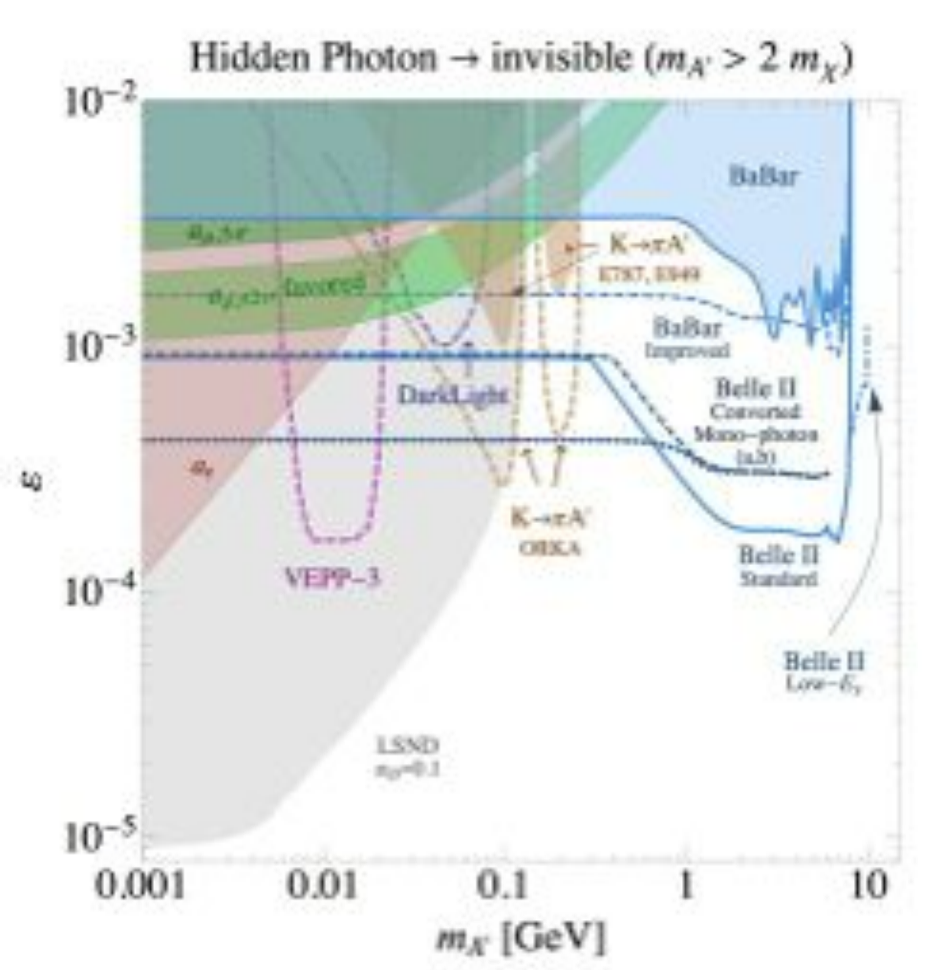
Experimental Probes

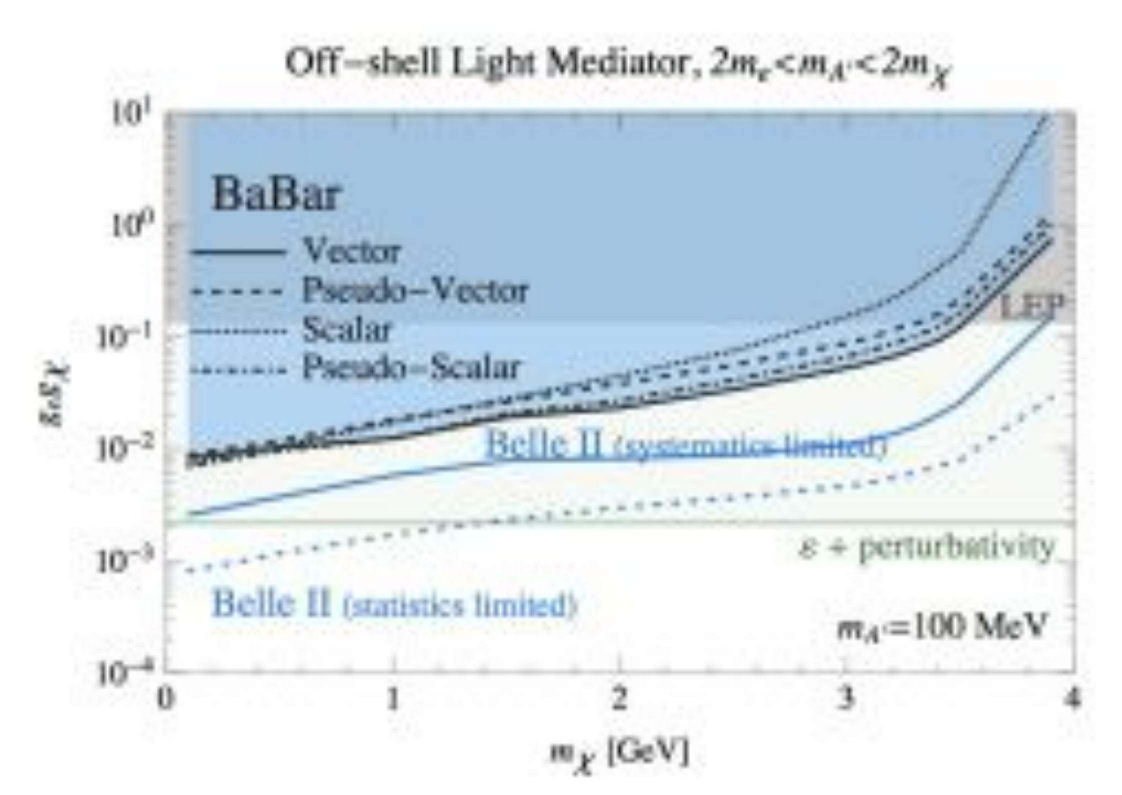
Colliders

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?

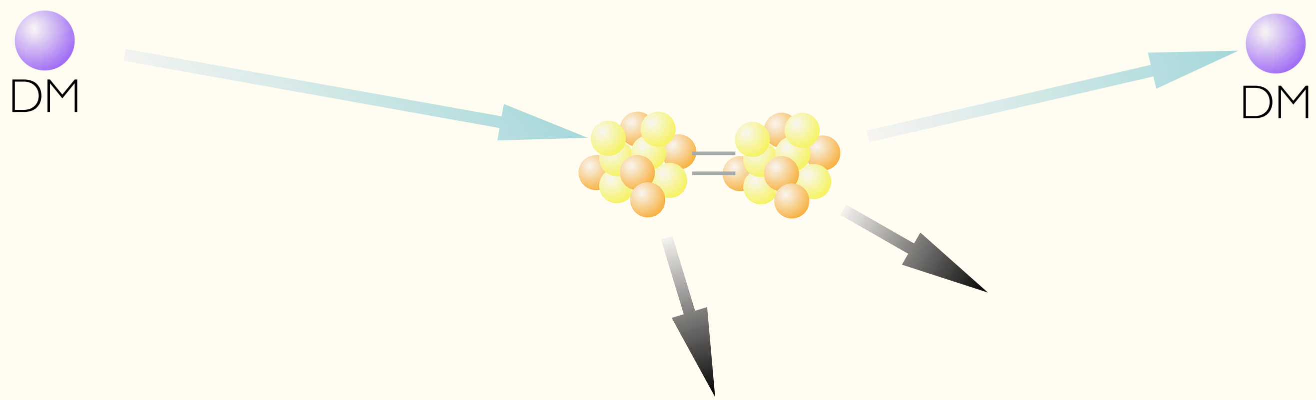
Looking for WIMPs

- 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

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

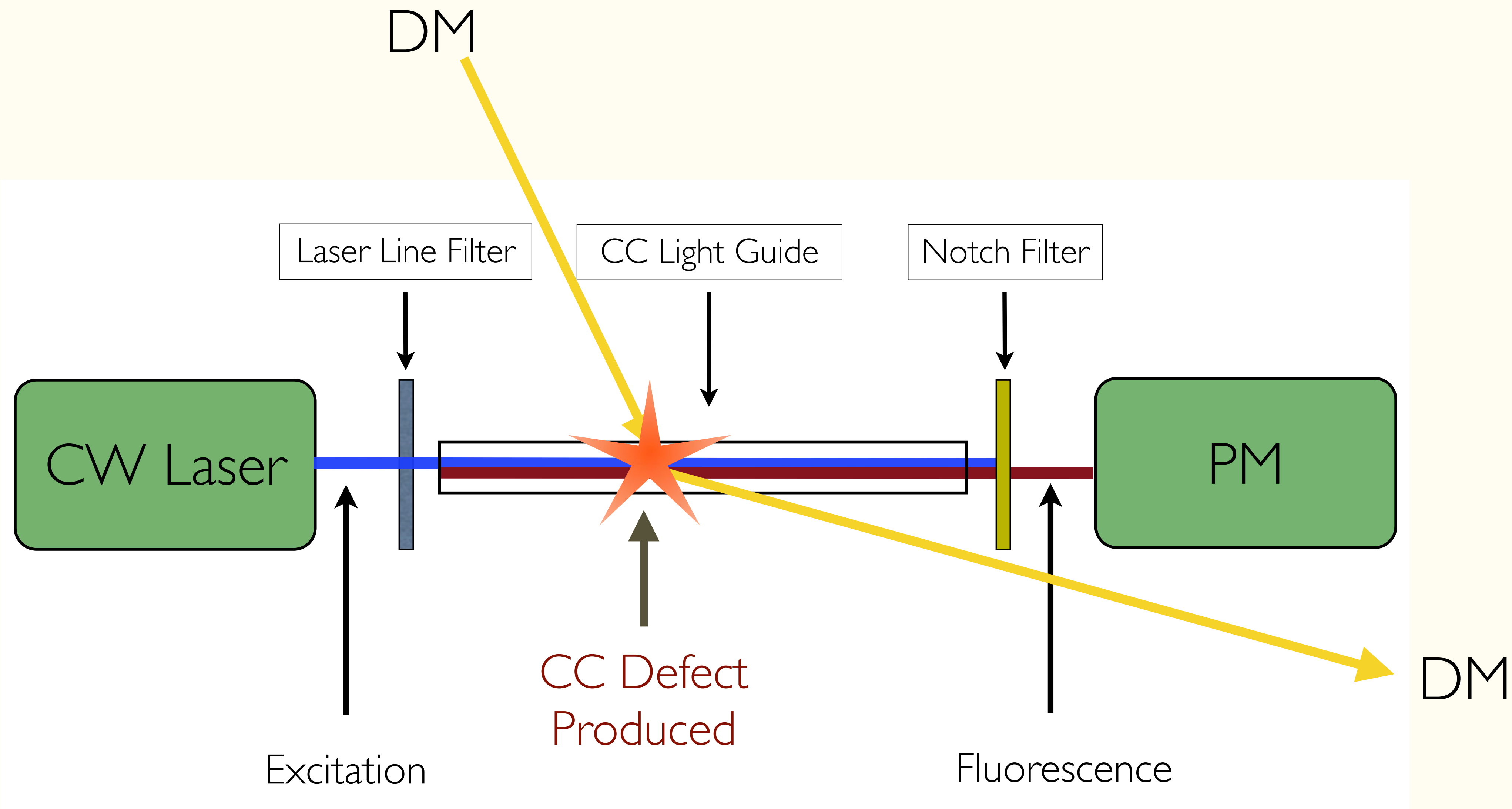
Color Centers

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

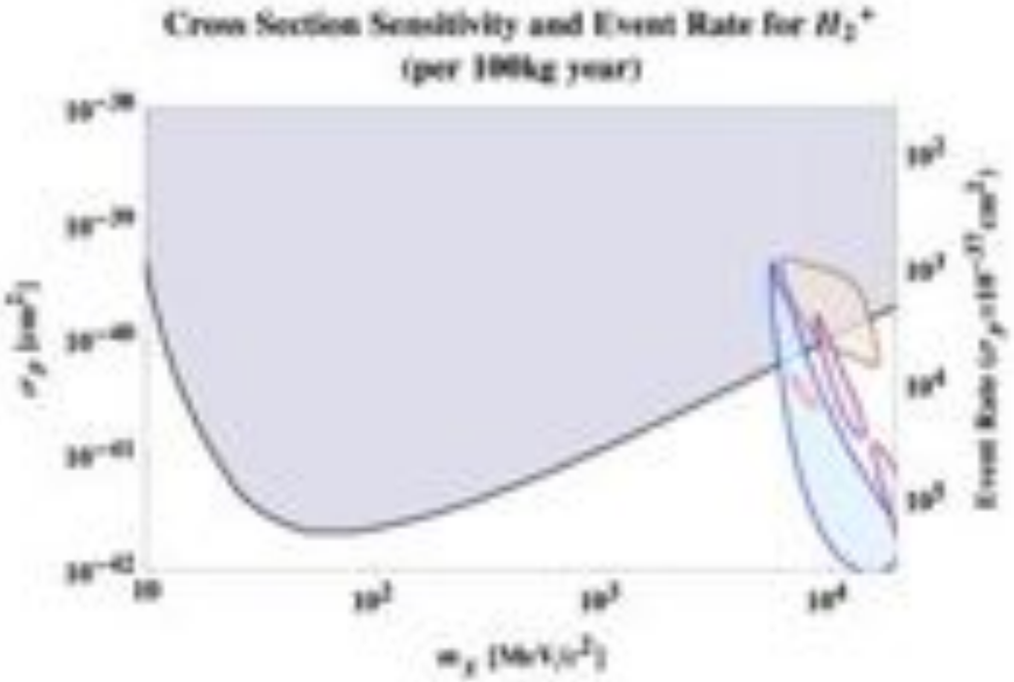
Th

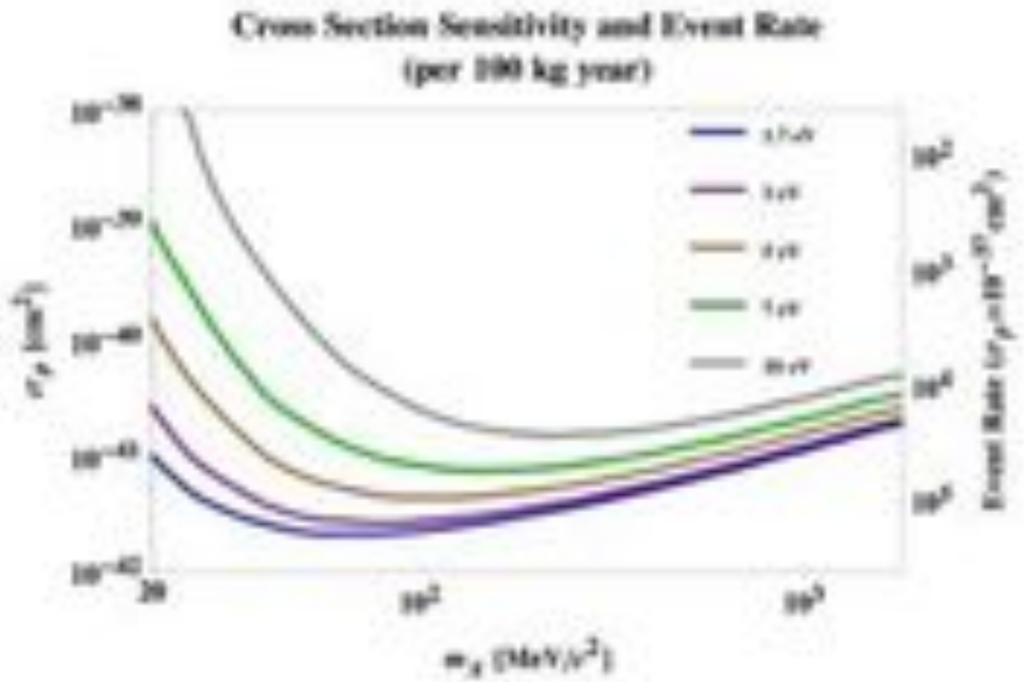
- Rouven Essig (Stony Brook)
- Jeremy Mardon (Stanford)
- Oren Slone (TAU)
- Itay Bloch (TAU)
- Amit Abir (TAU)

Exp
(New lab at Weizmann Institute)

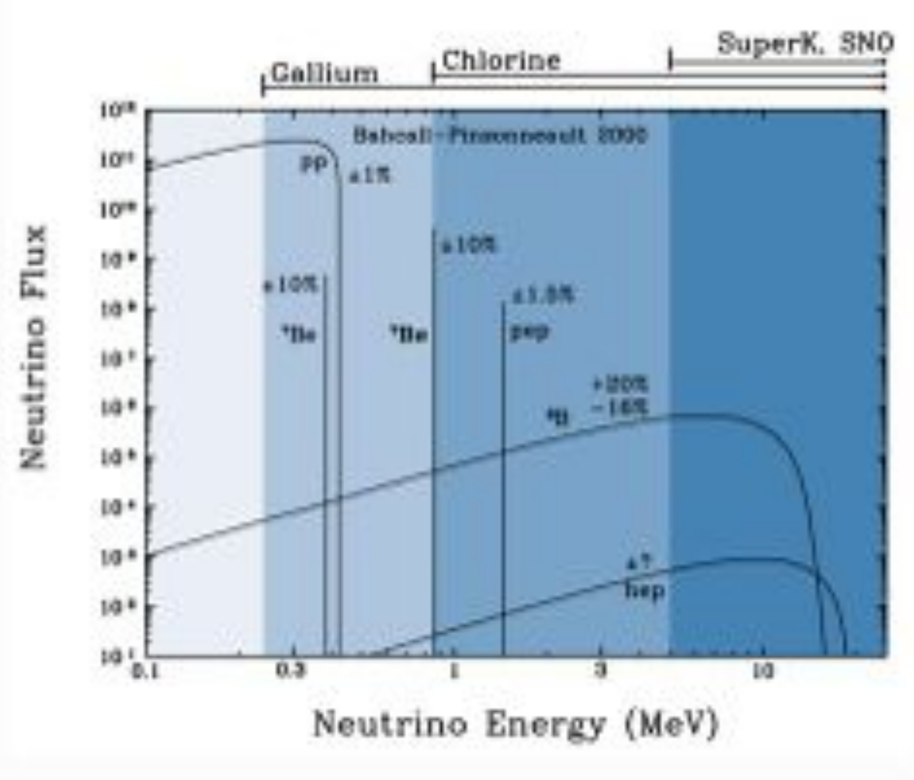
- **Ranny Budnik (Weizmann, HEP-Ex)**
- **Ori Chechnovsky (TAU, Chemistry-Ex)**
- **Avner Soffer (TAU, HEP-Ex)**
- Arik Kreisel (NRC, HEP-Ex)
- Adi Ashkenazi (TAU, HEP-Ex)
- Ilan Sagiv (Weizmann, HEP-Ex)
- Hagar Landsman (Weizmann, HEP-Ex)

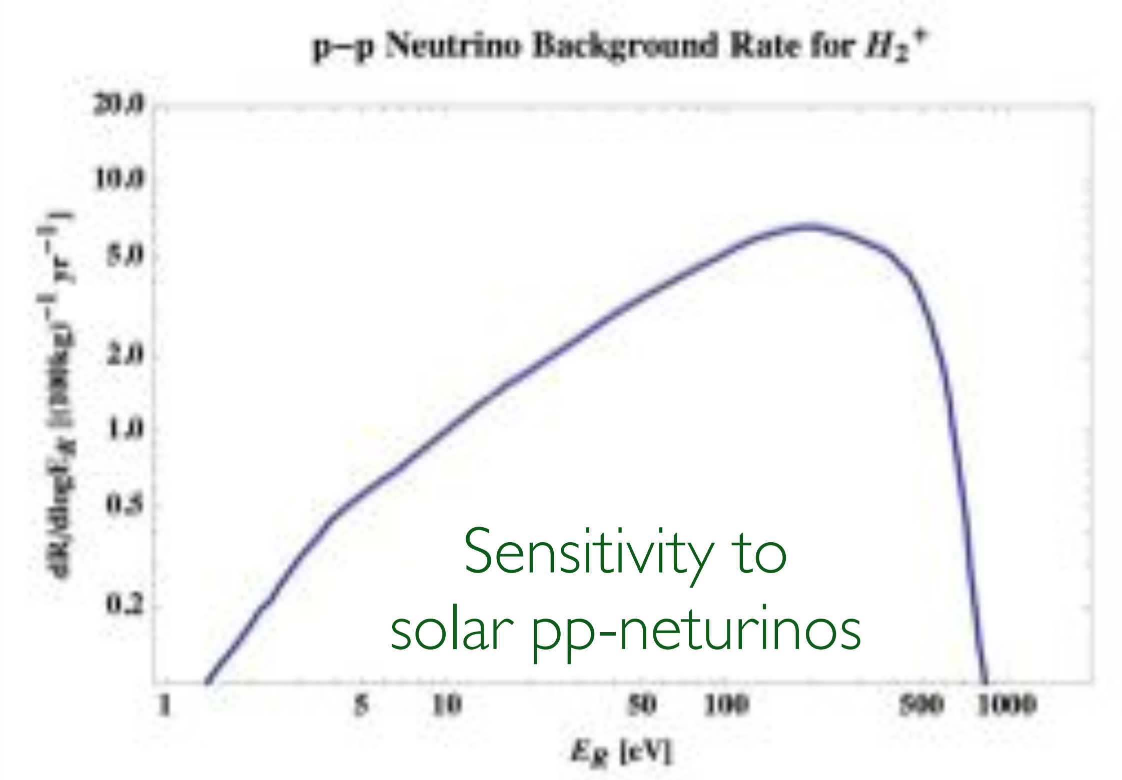
Bond Breakage: light DM Sensitivity





Bond Breakage: Solar Neutrinos





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...