But What If It's Not a WIMP??

New Avenues for Direct Detection of DM

Planck 2012

Tomer Volansky

Based on:

R. Essig, J. Mardon, TV [arXiv:1108.5383].

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, TV (submitted to PRL).

More work in progress...

First Direct Detection Limits on Sub-GeV Dark Matter from XENON10

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Obsessed with the WIMP..

- Dark Matter is all around us, but we still know very little about it.
- For the last ~30 years we've been focusing mainly on the WIMP scenario.
- Two theoretical reasons for obsessing over the WIMP

1. Cosmological abundance: simple and predictive (independent of initial condition and is controlled by a single parameter).

[Lee, Weinberg, 1977]

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

2. Fine tuning problem: DM is natural in many solutions.

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

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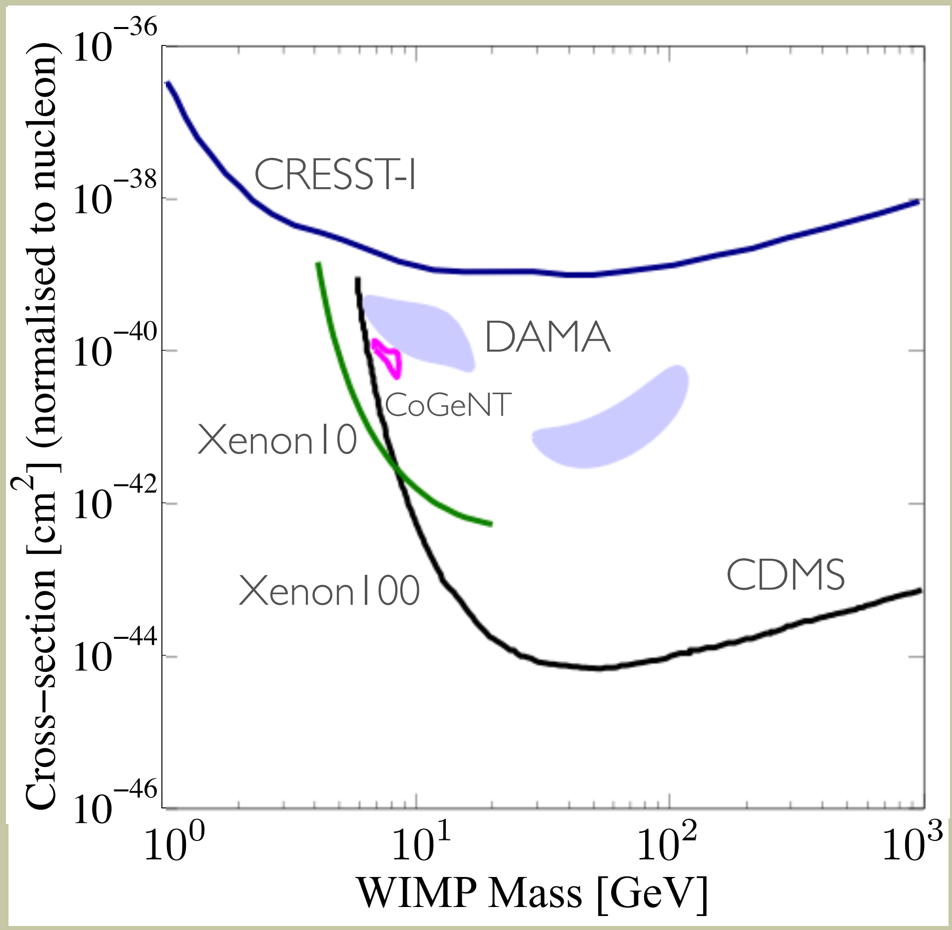
So how confident are we???

Direct Detection Status



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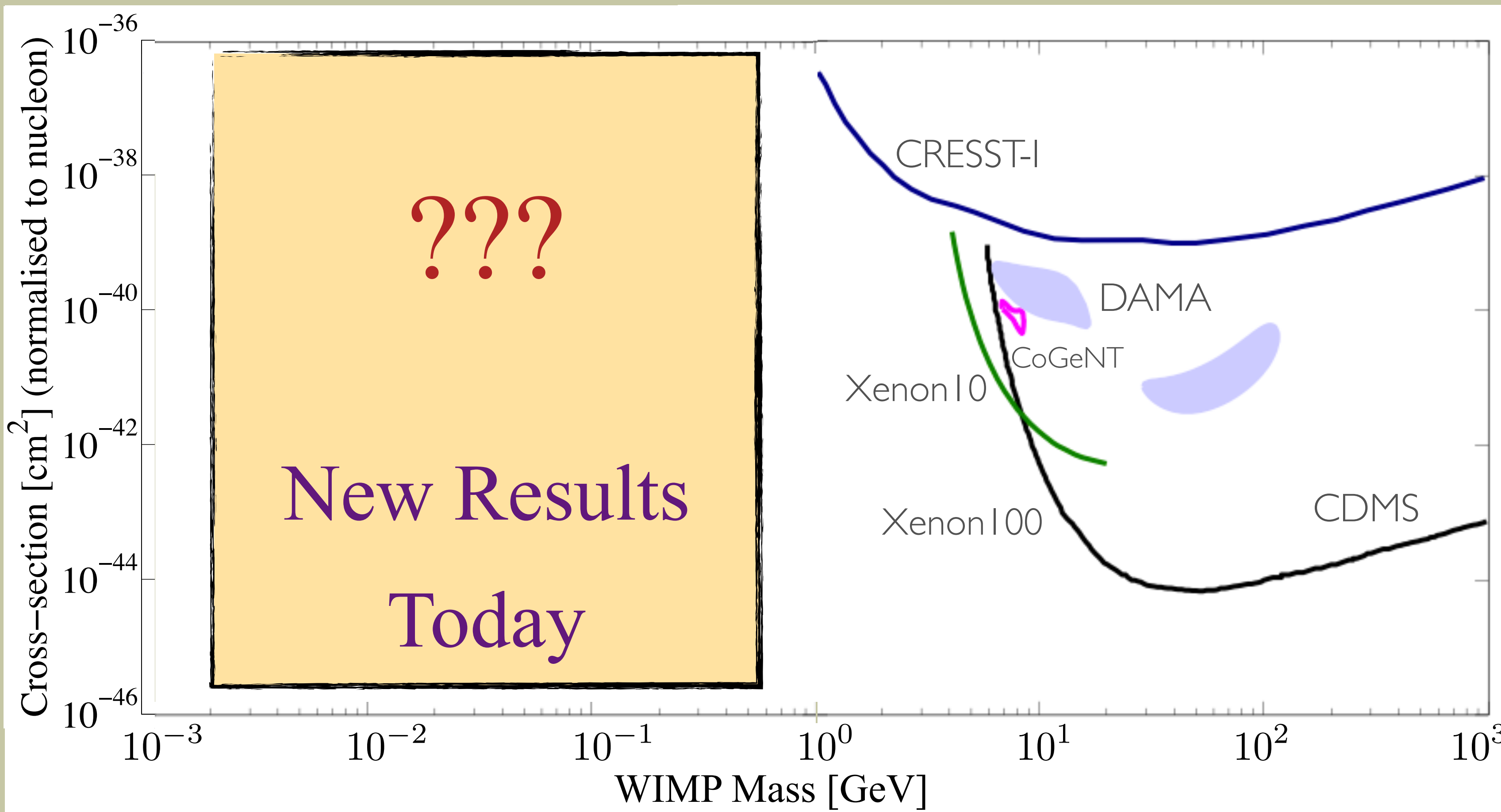

Outline

- Sub-GeV Dark Matter
- Direct Detection of Sub-GeV Dark Matter
  - Idea
  - Rates
- First Direct Detection Limits from XENON10
- Outlook

Sub-GeV Dark Matter

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.
  - ...

Is Sub-GeV DM Allowed?

- There are several constraints for light DM:
  - Free streaming. If DM is too light, it interferes with structure formation. Constraints are typically of the order

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

[Finkbeiner et al. 2009]

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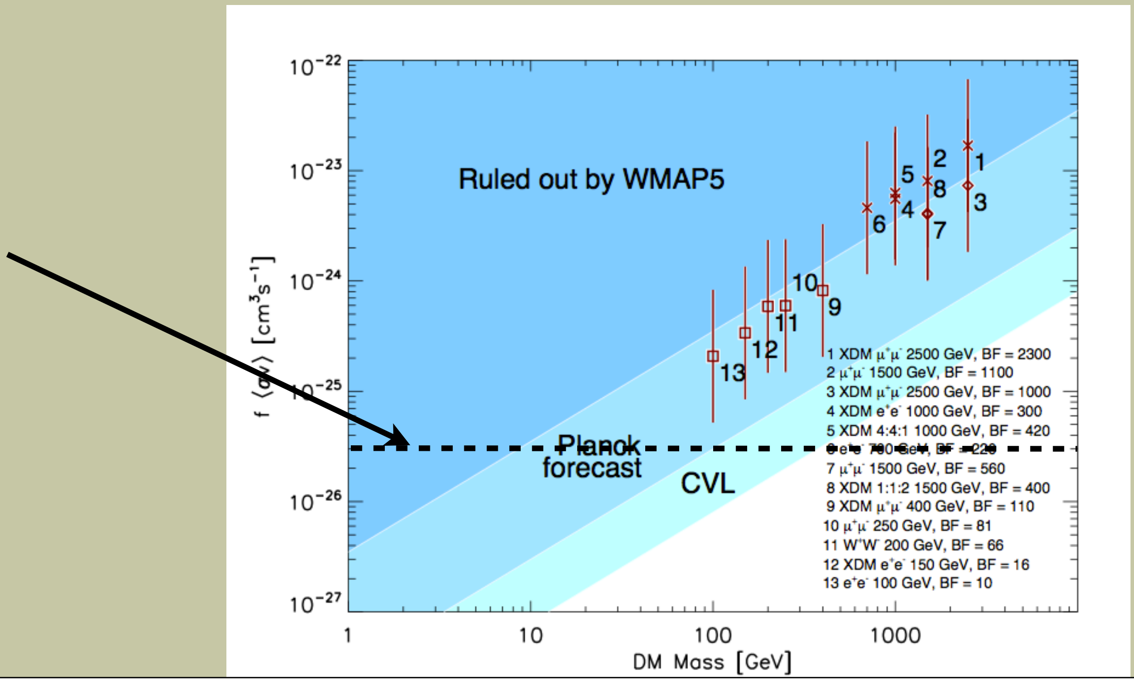
Standard Thermal WIMP



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  - Annihilations during CMB. Significant DM annihilations may re-ionize the photon-baryon plasma, leaving imprints in the CMB.
  - DM self interactions. Self interactions distort the dynamics in DM halos.

Bullet cluster: $\frac{\sigma_{\text{self}}}{m_{\text{DM}}} < 1 \text{ cm}^2/\text{g}$ [Markevitch et al. 2003]

Halo ellipticity: $\frac{\sigma_{\text{self}}}{m_{\text{DM}}} < 0.02 \text{ cm}^2/\text{g}$ [Miralda-Escude, 2000]

Models Status

- There are several constraints on light DM, but situation is not worse than the WIMP models we know.

- Some constraints are model-dependent.

Large class of viable models exist!!

[Essig,Mardon,TV, work in progress]

Has not received enough attention
More studies are needed.

- Key question: Can we probe these models?

Basic Idea

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

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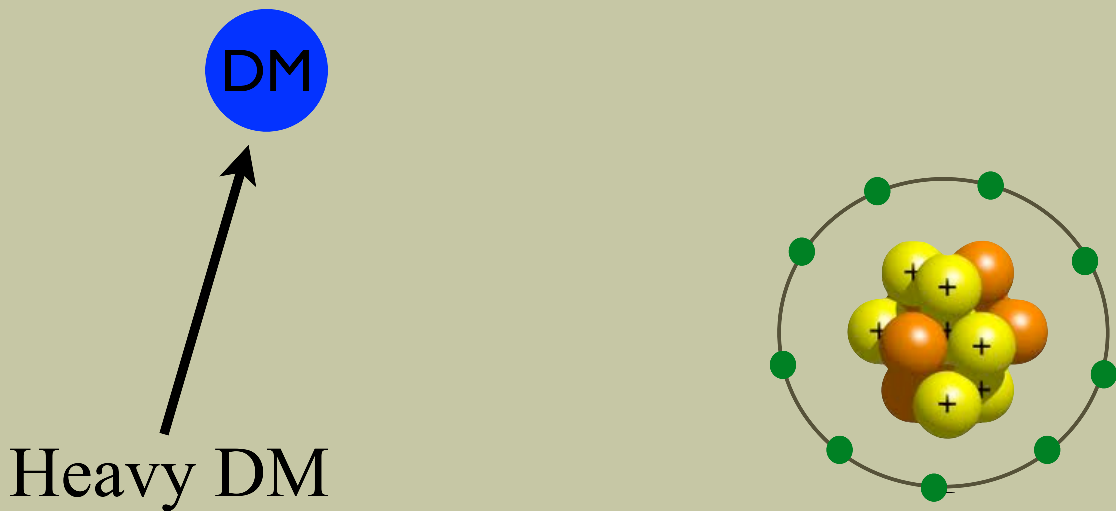

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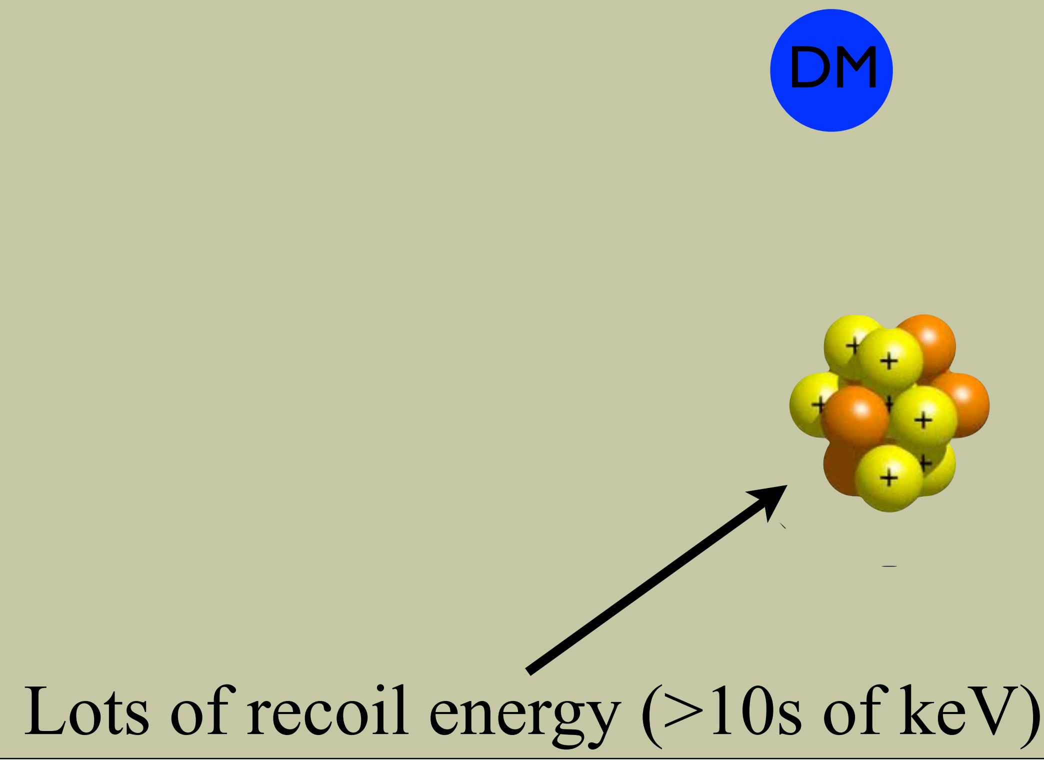

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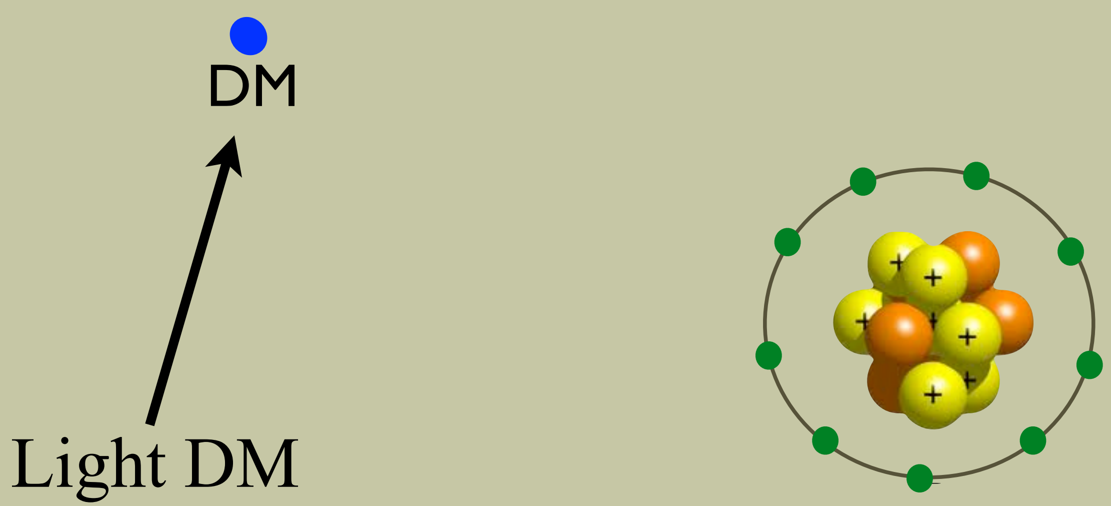

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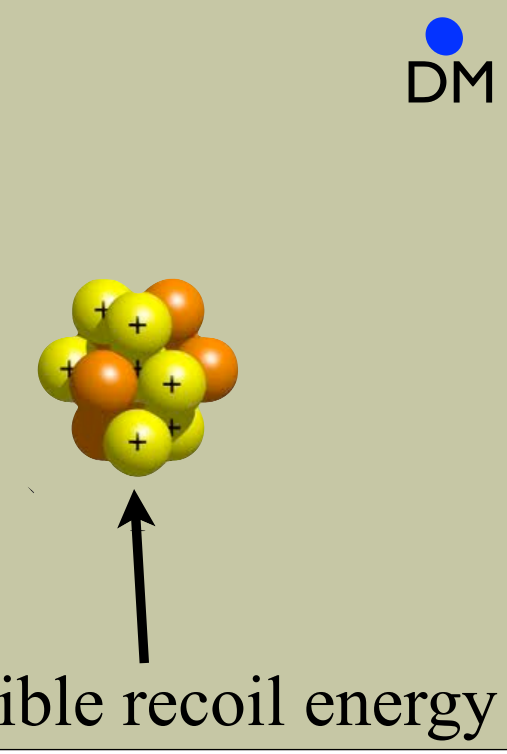

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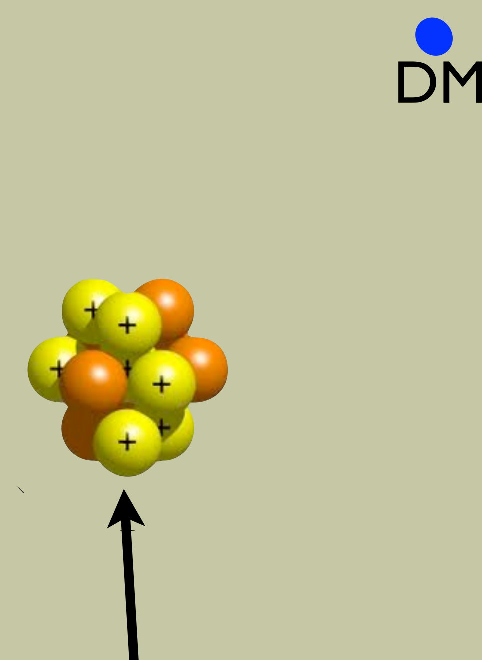
$$E_{\mathrm{R}} = \frac{q^2}{2m_N}$$



Negligible recoil energy

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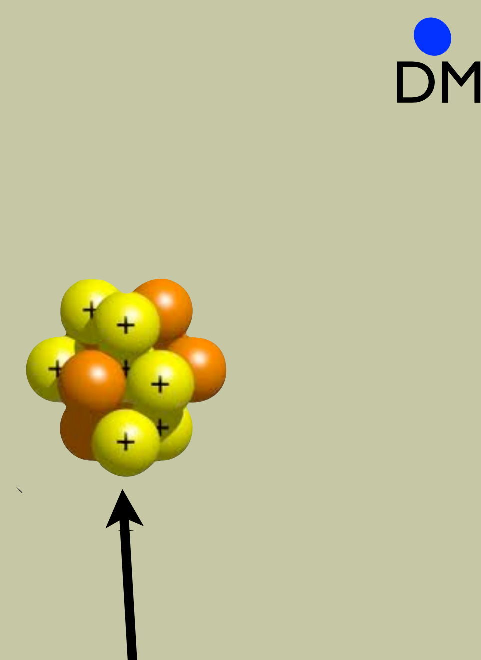

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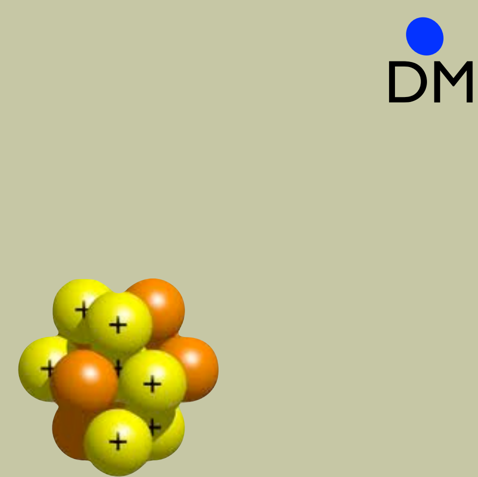

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$$\sim 3 \text{ eV} \times \left(\frac{m_{\rm DM}}{\rm GeV}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

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Recoil energy drops fast

Can't go below ~ GeV

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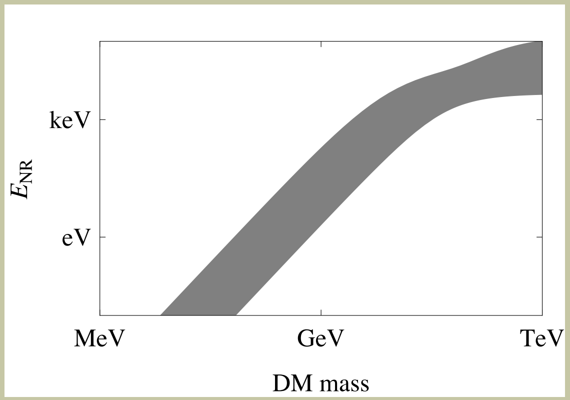

But DM energy is significantly larger:

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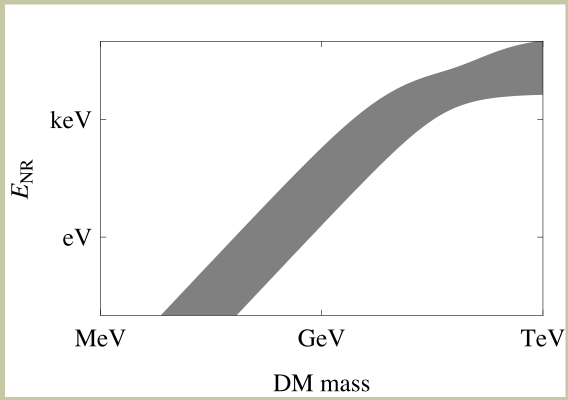

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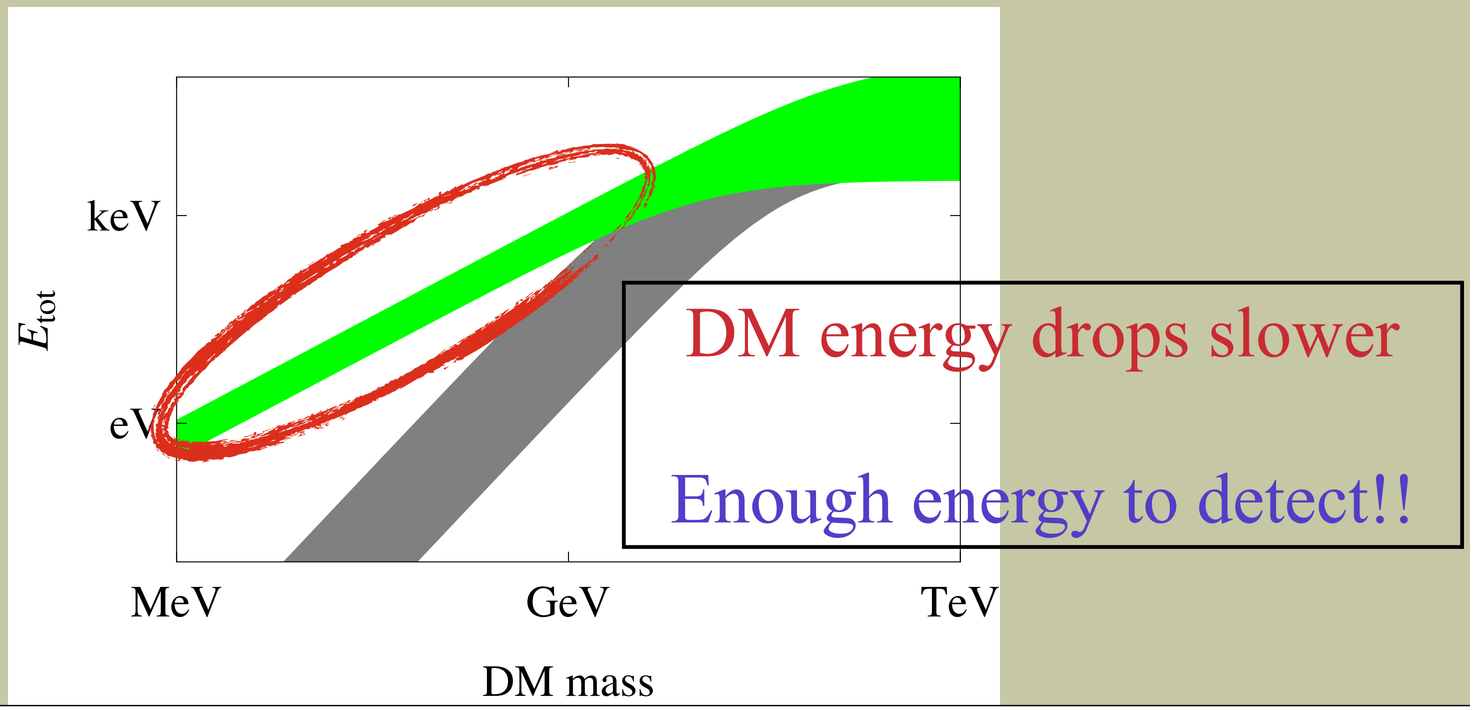

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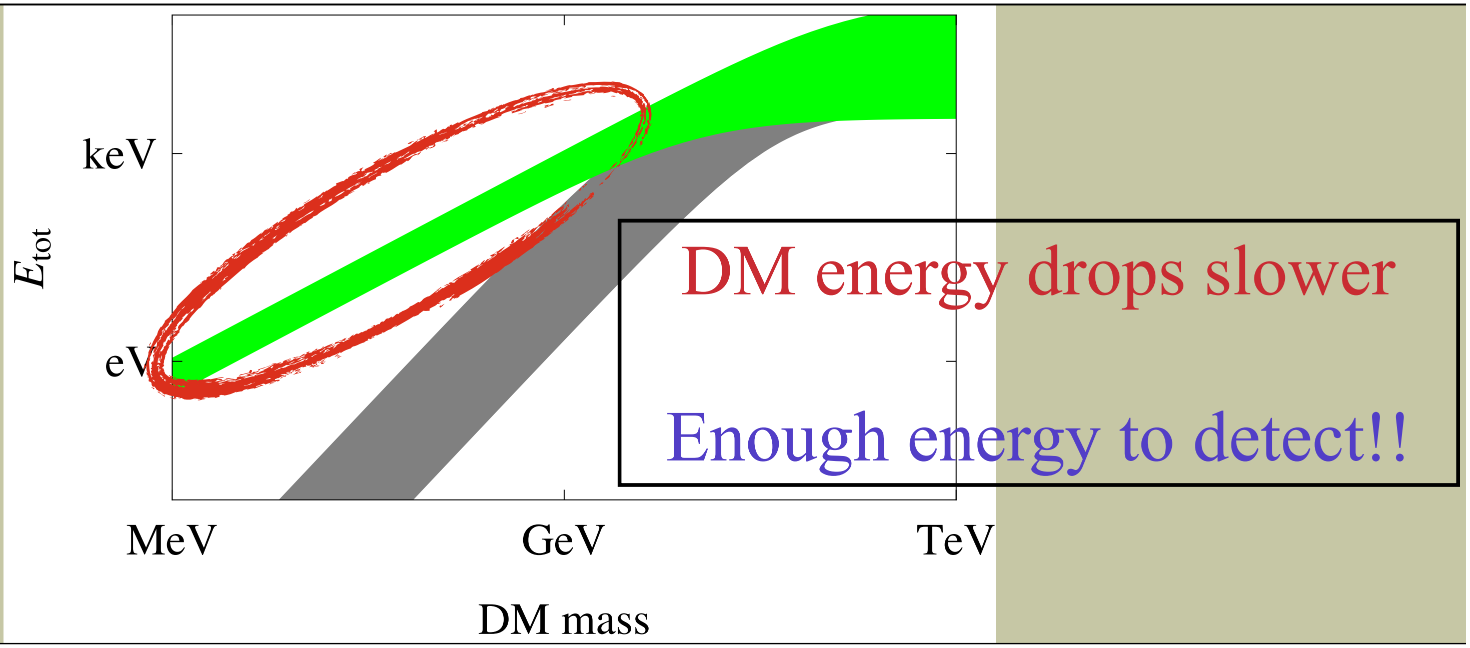
Studying nuclear recoils is extremely inefficient for light DM



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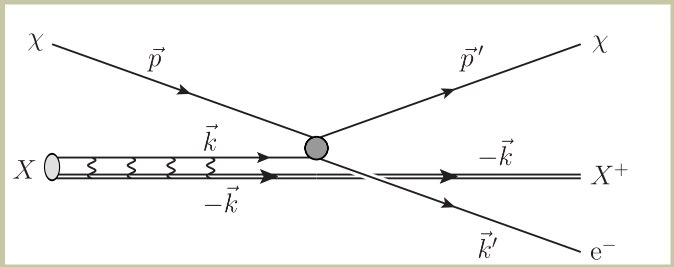
  1. Electron ionization

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



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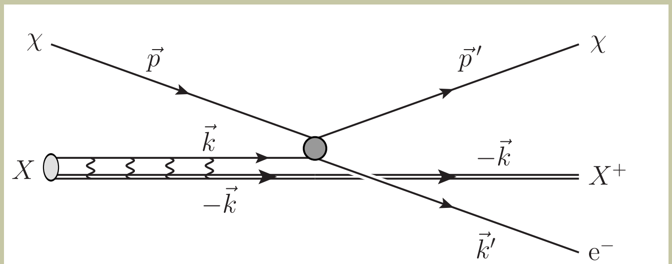

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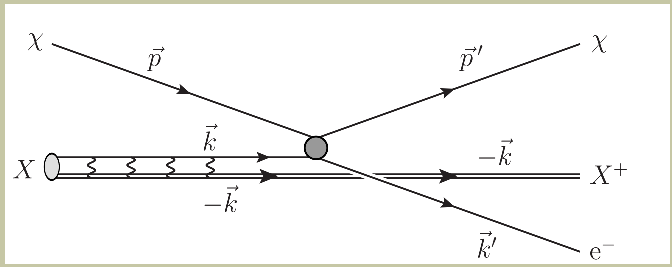

2. Electronic excitation

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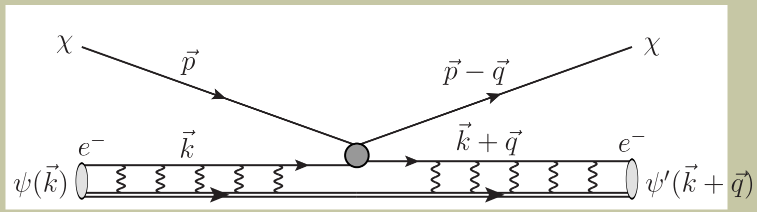

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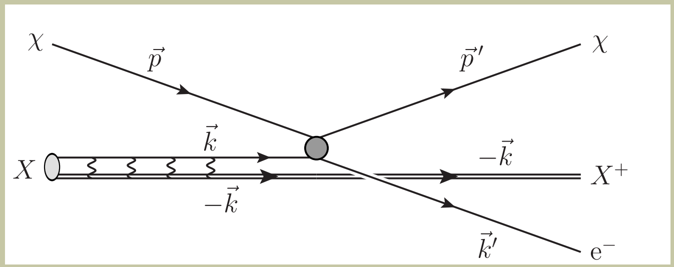

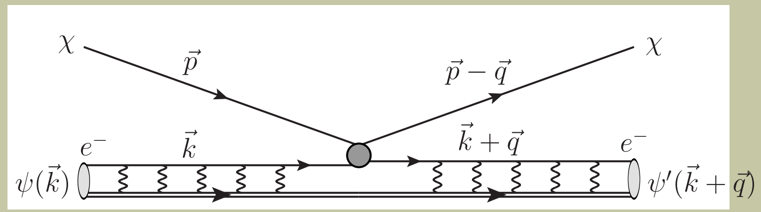

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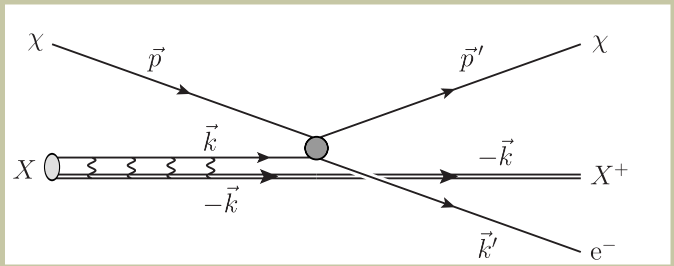

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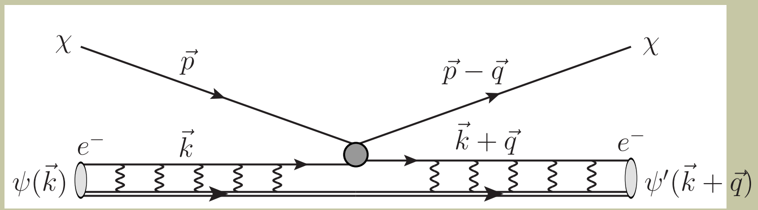
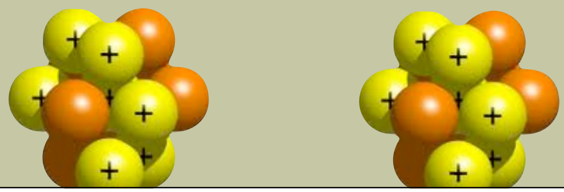


3. Molecular dissociation

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



Ways to Detect Light DM

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

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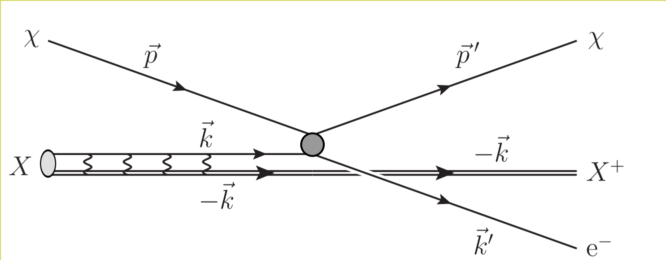

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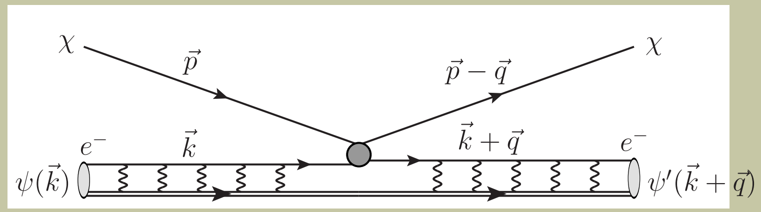

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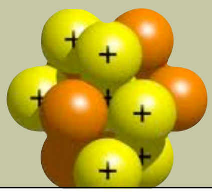
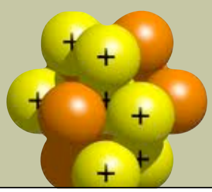

For the rest of this talk:

Focus on electron ionization through electron-DM scattering

Computing Rates

Ionization Rate

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

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Determined by atomic wave-functions

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

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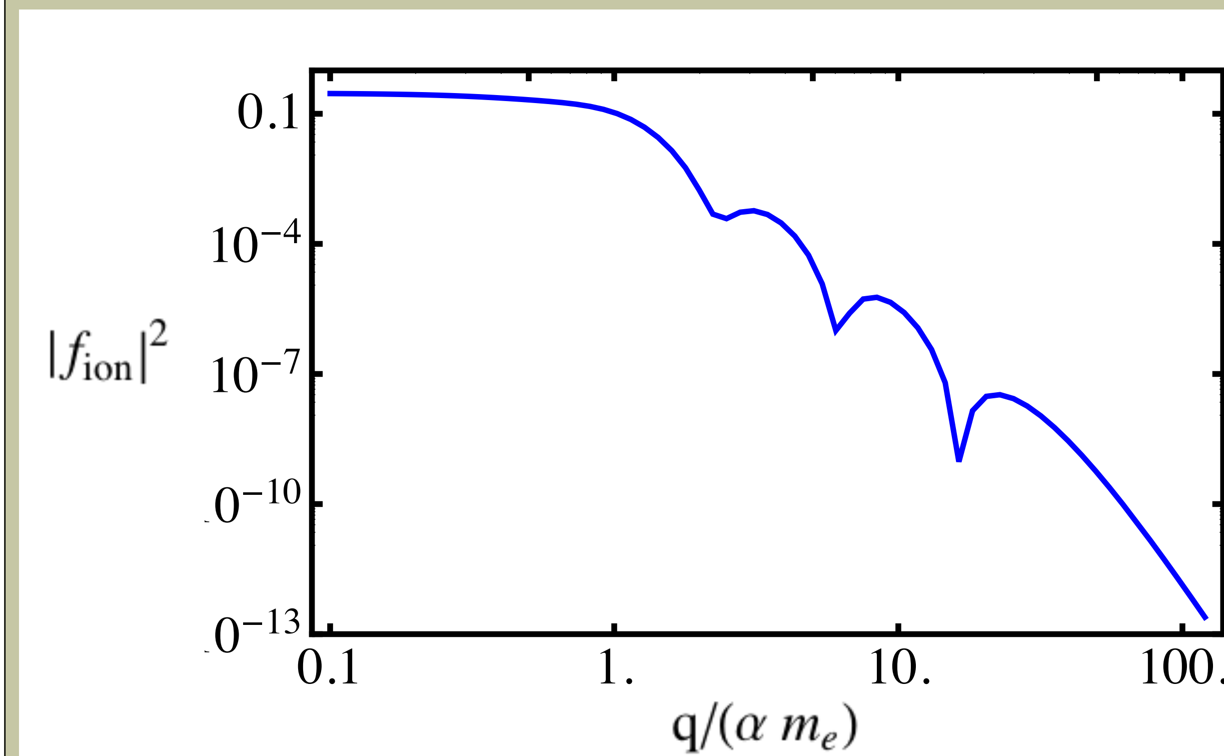

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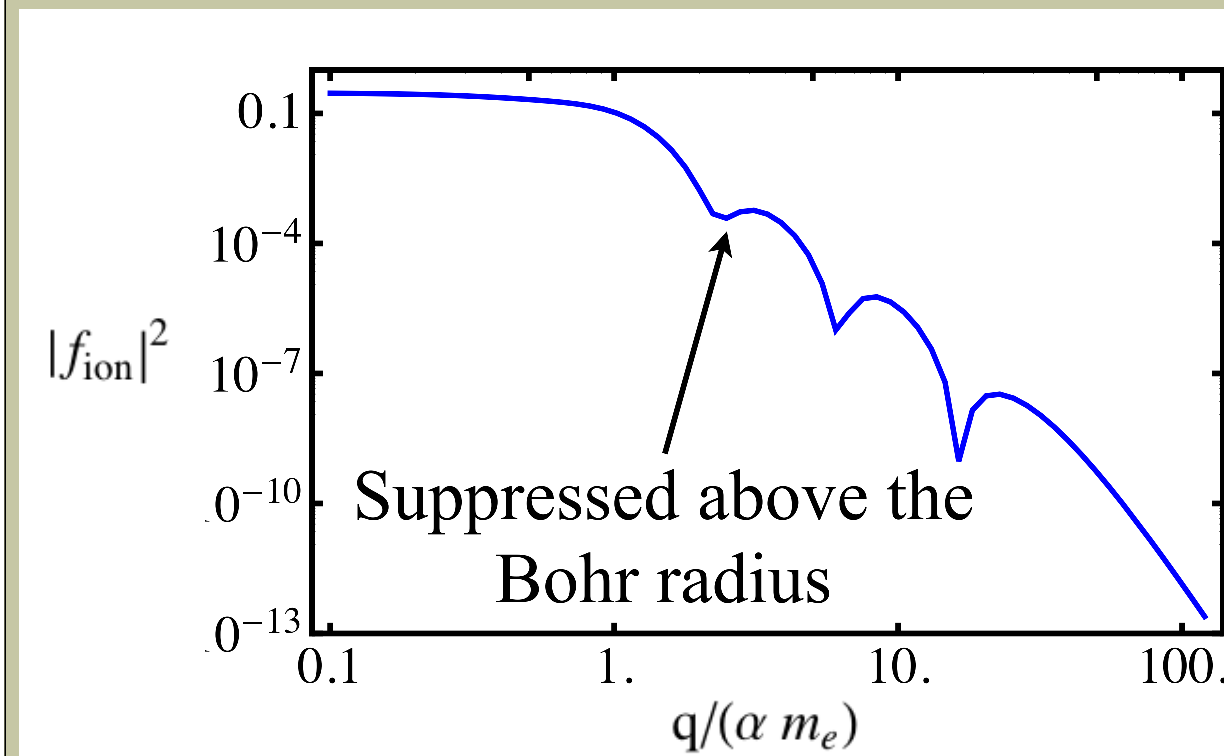

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Rates are suppressed for large momentum transfer!

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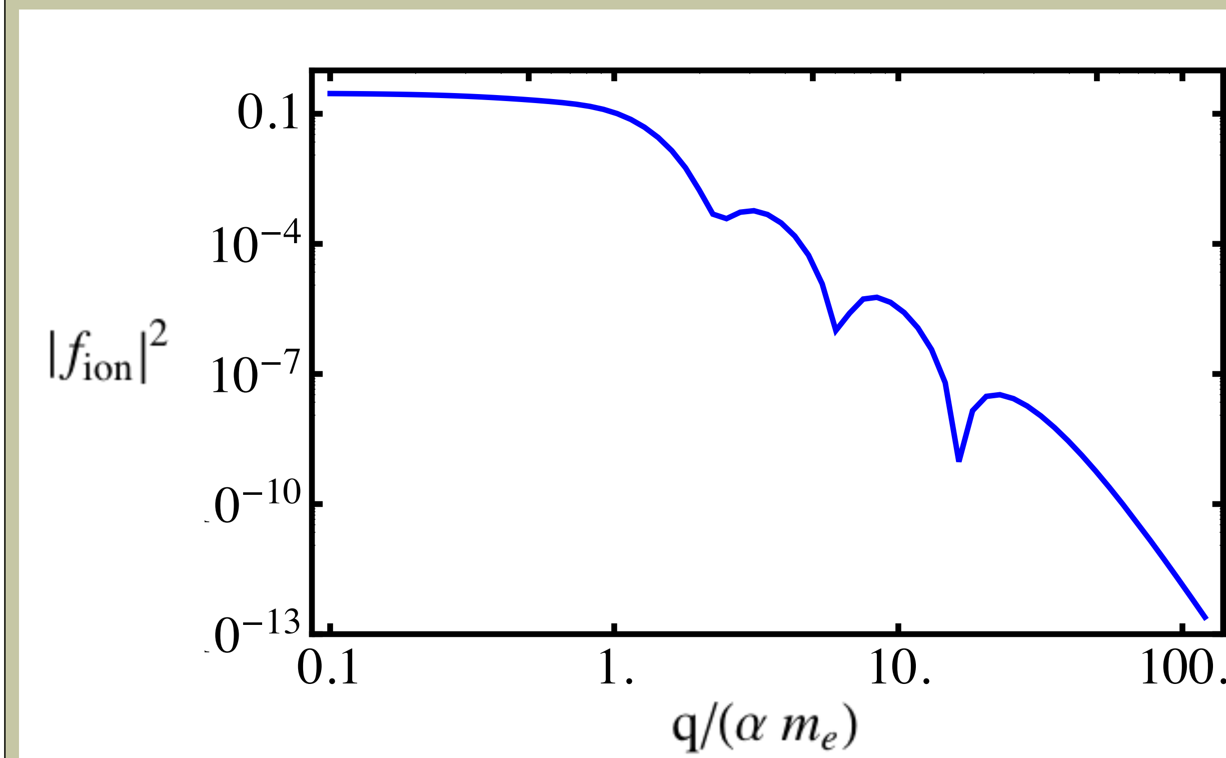

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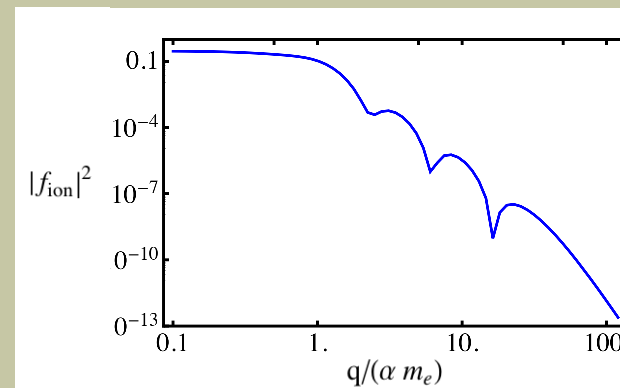

Determined by a specific DM theory

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

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

Kinematics

- Kinematics dictates the minimal velocity to ionize:

$$v_{\rm DM} \geq v_{\rm min} = \frac{E_B + E_R}{q} + \frac{q}{2m_{\rm DM}} \geq \sqrt{\frac{2(E_B + E_R)}{m_{\rm DM}}}$$

- Thus given that v_{DM}~10^{-3}, we find the a bound on the mass

$$m_{\rm DM} \geq {\rm MeV} \times \left(\frac{E_B}{5\ \rm eV}\right)$$

  - Kinematics requires: $q \geq 10^{-3} E_B$ (satisfied for larger masses)
  - Form factor prefers small q.

Tension between kinematics and form factor.

XENON10
New Results

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, TV (to appear soon)

Xenon10

detector
schematic

two-phase xenon time projection chamber

Xenon10

detector
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Xenon10

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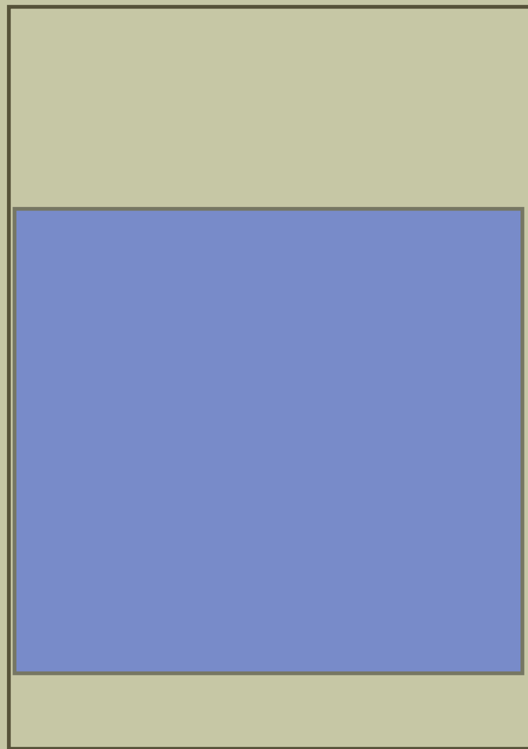
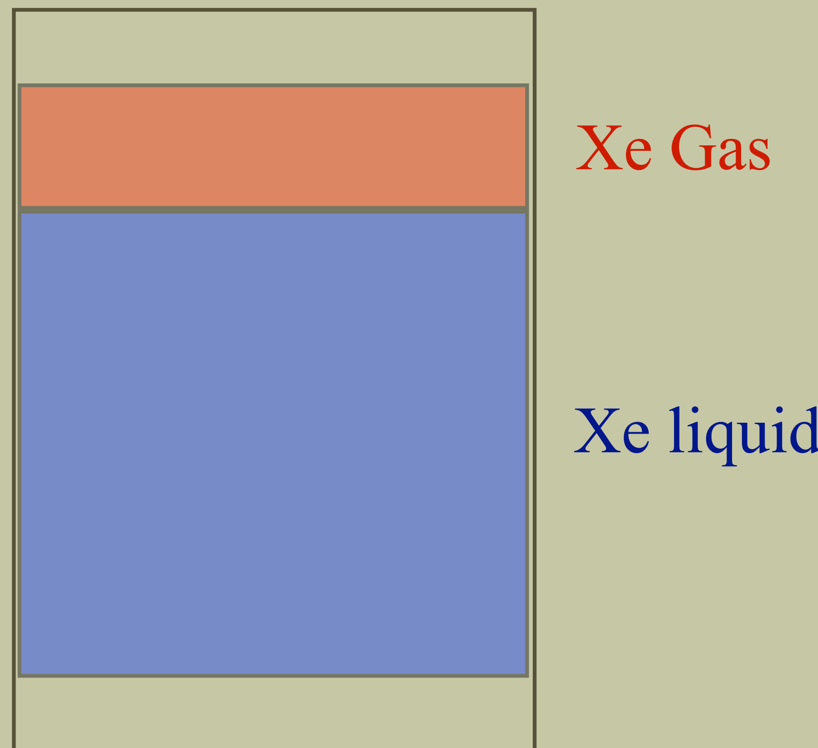


Xe liquid

two-phase xenon time projection chamber

Xenon10

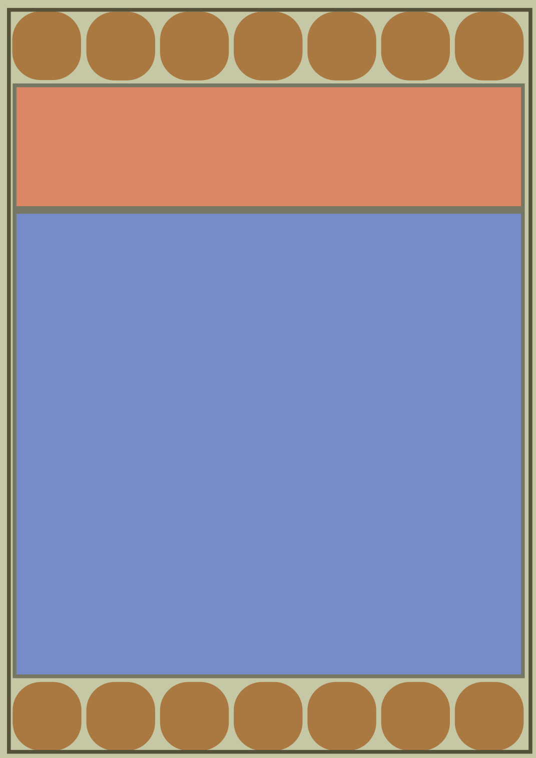
detector schematic



two-phase xenon time projection chamber

Xenon10

detector schematic



two-phase xenon time projection chamber

Xenon10

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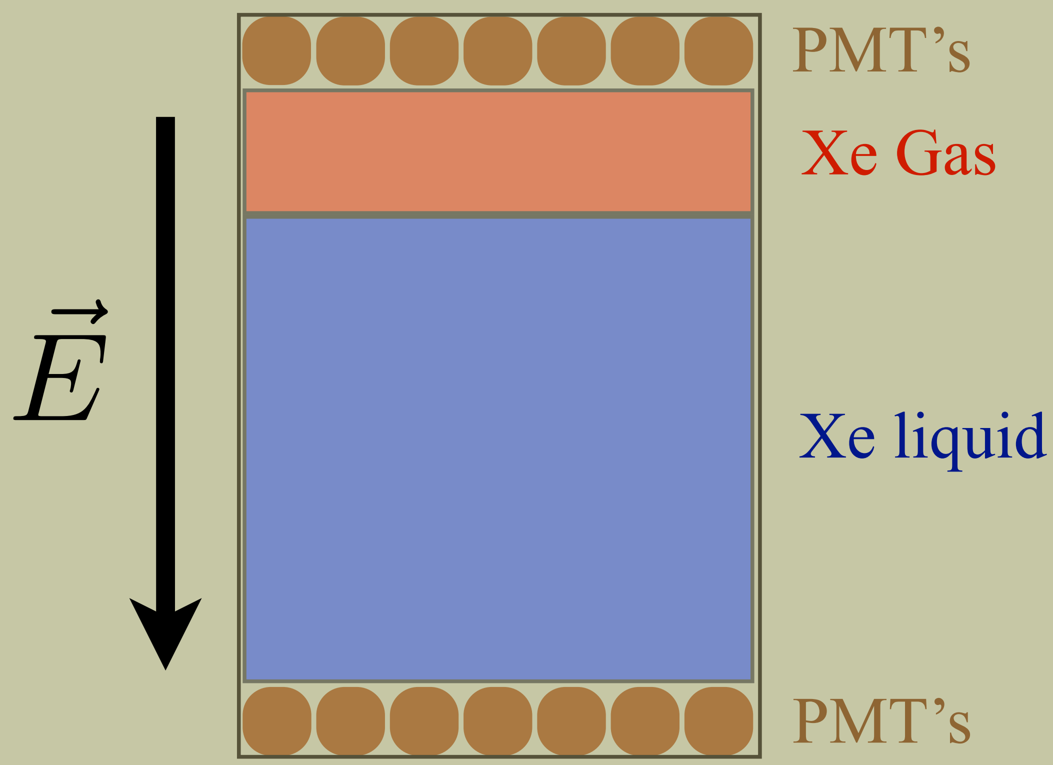
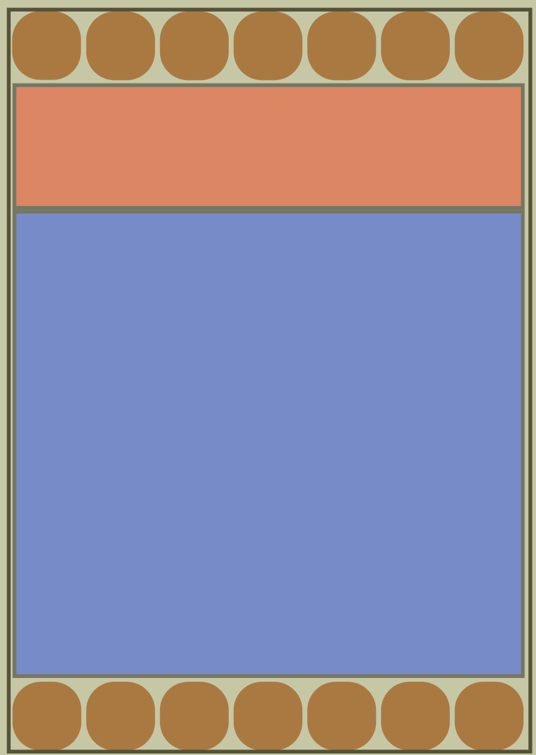


two-phase xenon time projection chamber

Xenon10

Heavy DM

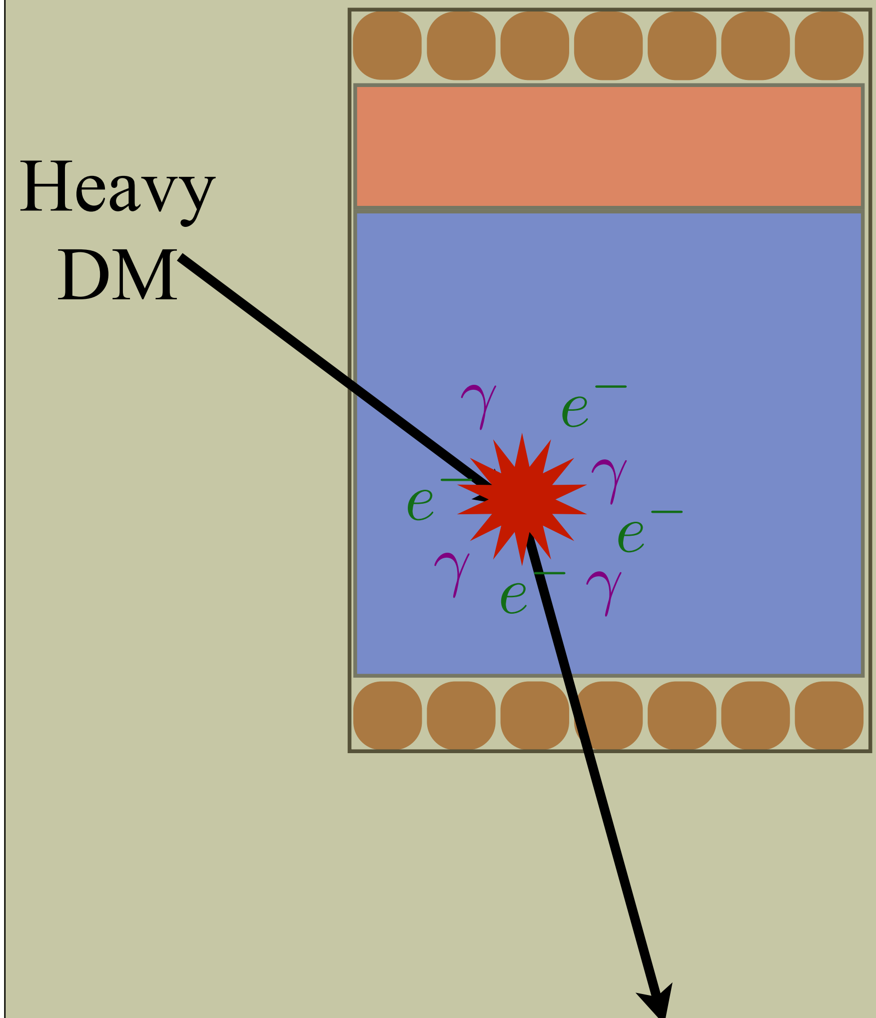


Xenon10

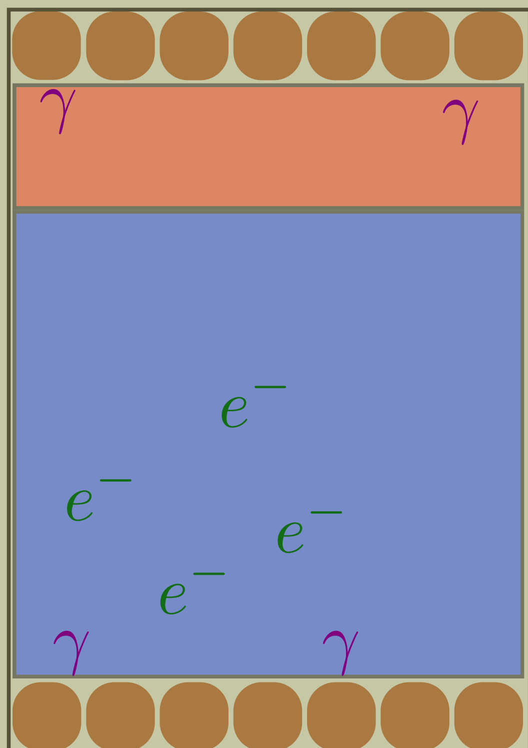
$$\text{Xe} \rightarrow \text{Xe}^*, \; \text{Xe}^+$$

produces photons and electrons

Two types of signal:



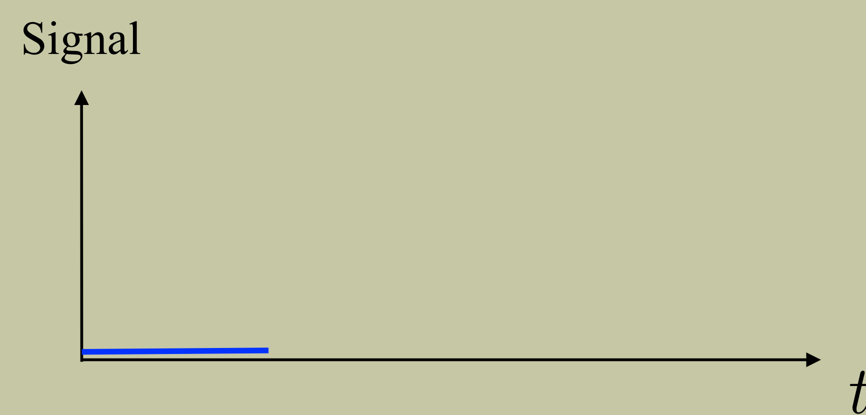
Xenon10



$$\text{Xe} \rightarrow \text{Xe}^*,\ \text{Xe}^+$$

produces photons and electrons

Two types of signal:



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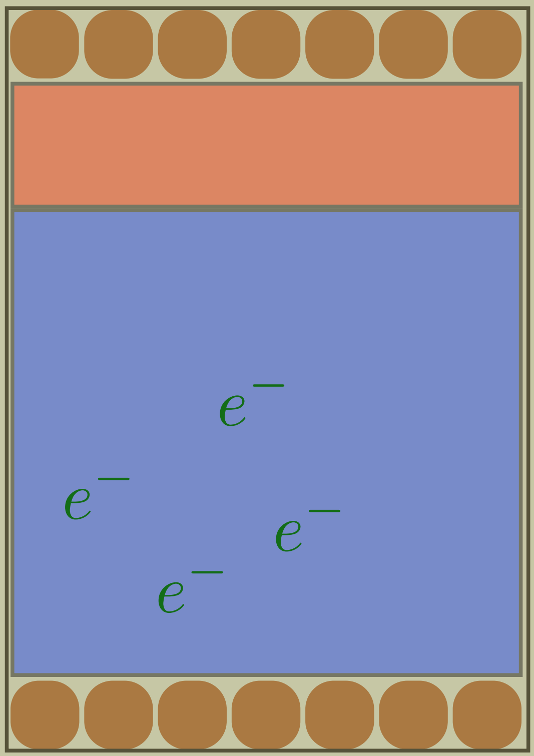
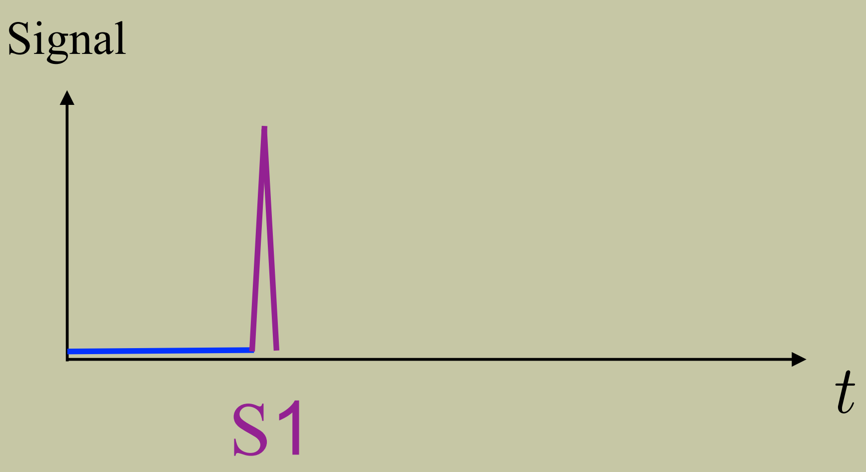
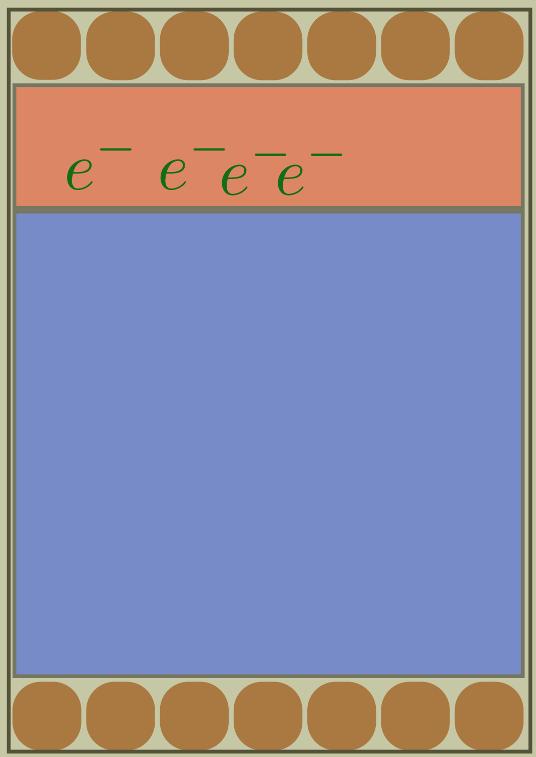
S1: prompt scintillation





Xenon10



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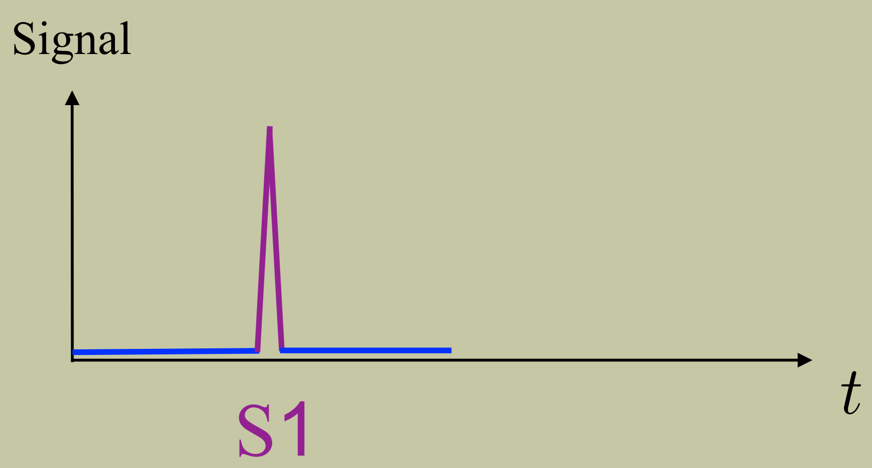

Xenon10

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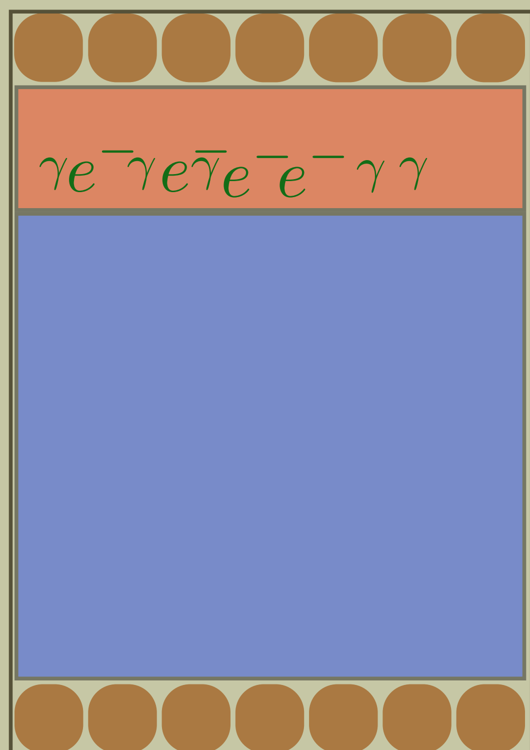
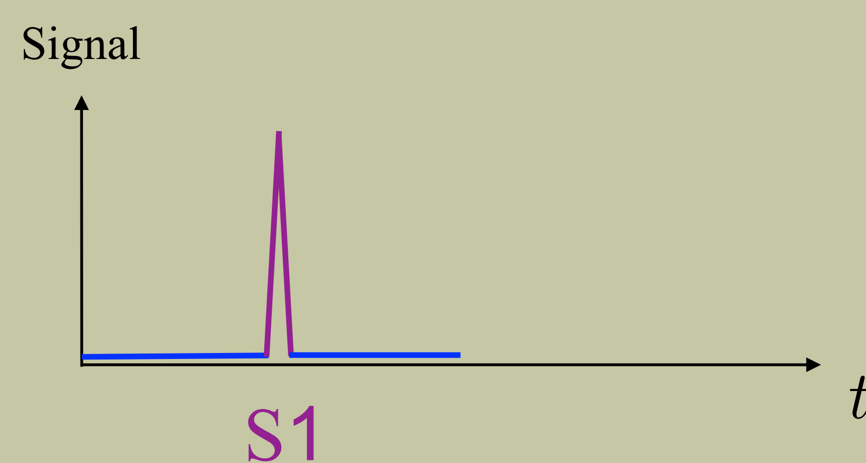
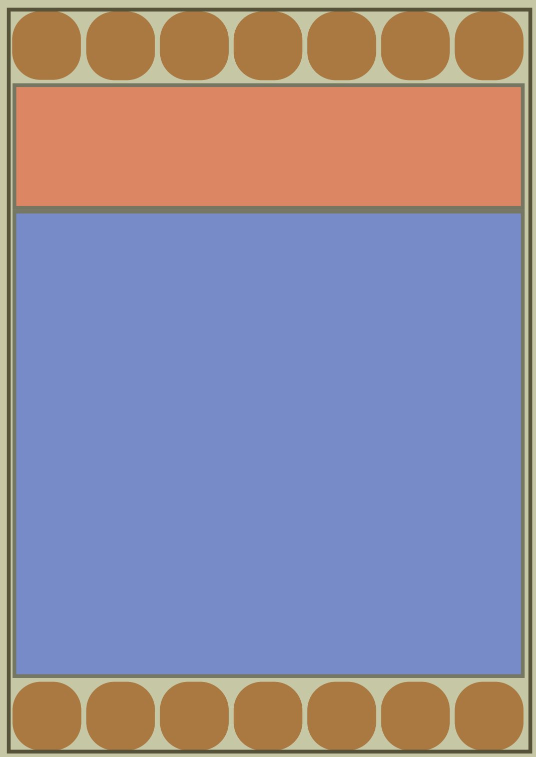




Xenon10



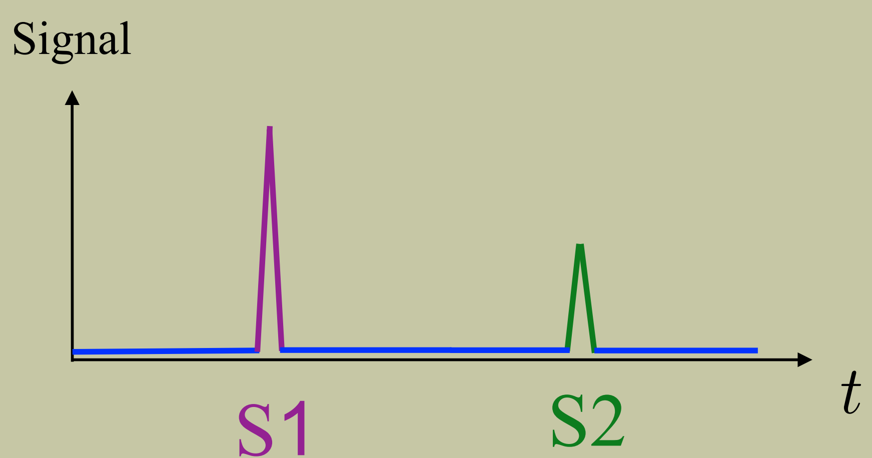
$$\mathrm{Xe} \rightarrow \mathrm{Xe}^*,\ \mathrm{Xe}^+$$

produces photons and electrons

Two types of signal:

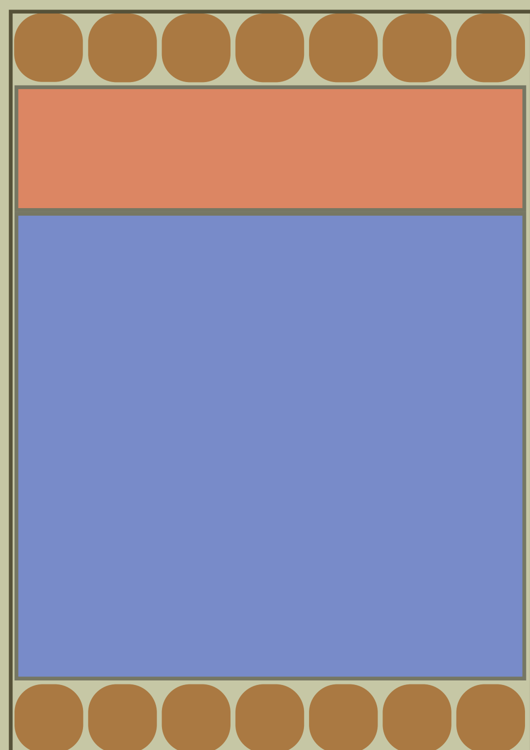
S1: prompt scintillation

S2: proportional scintillation (from ionization)



Xenon10

Light
DM



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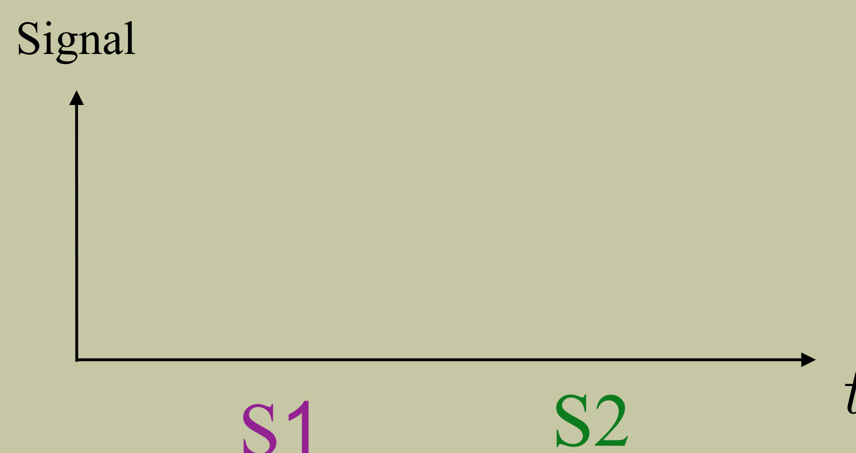
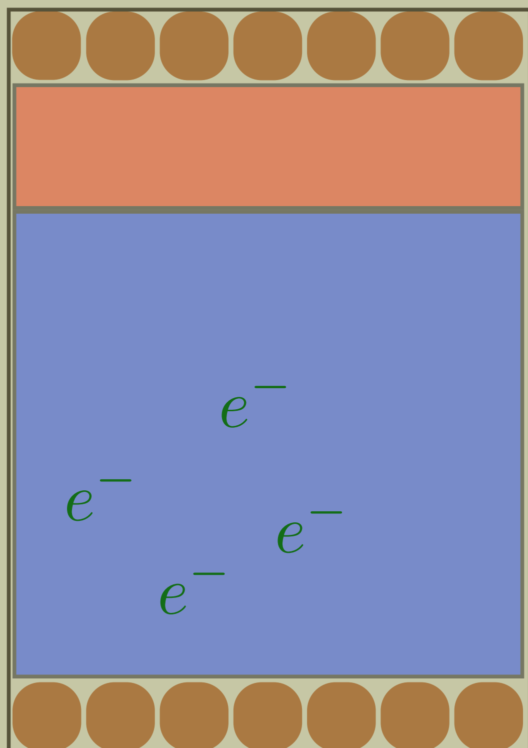


Xenon10

Light
DM



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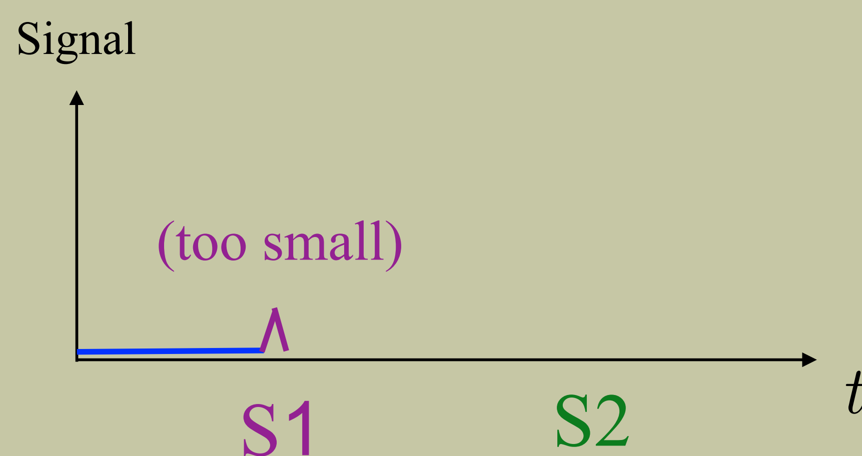
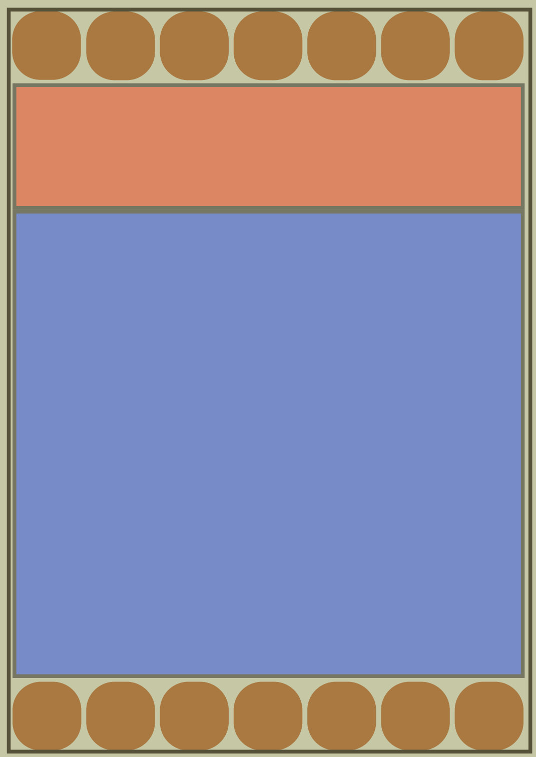


Xenon10



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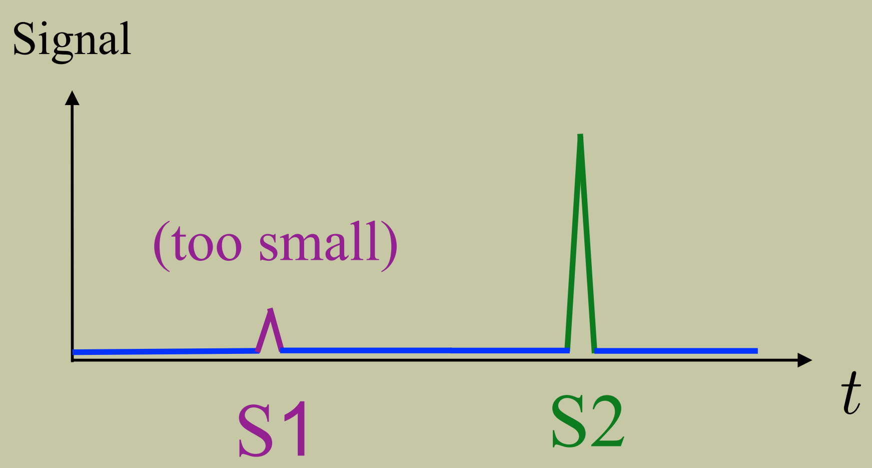
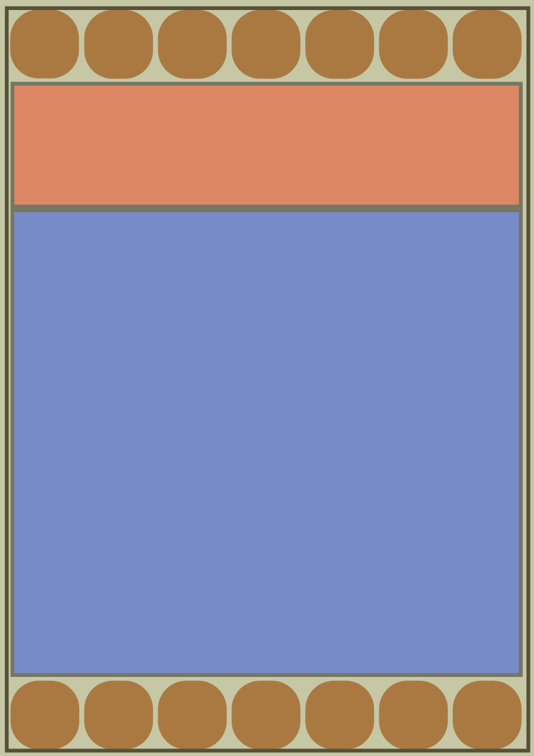
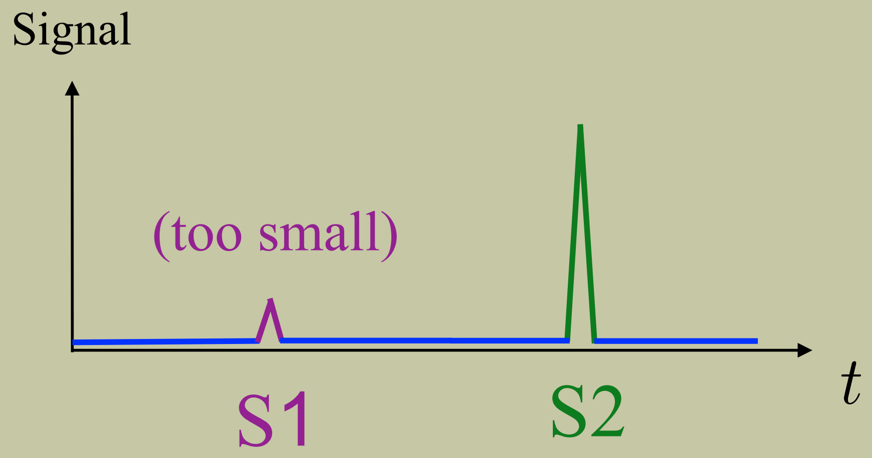


Xenon10

For LDM, S1 is too small!



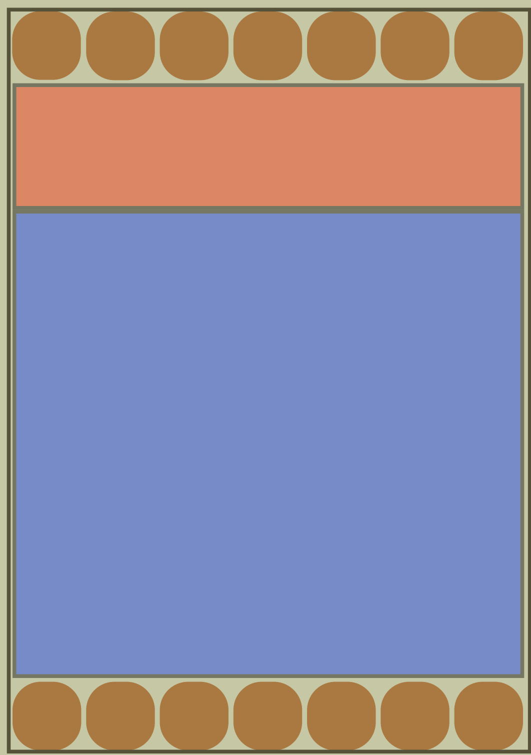


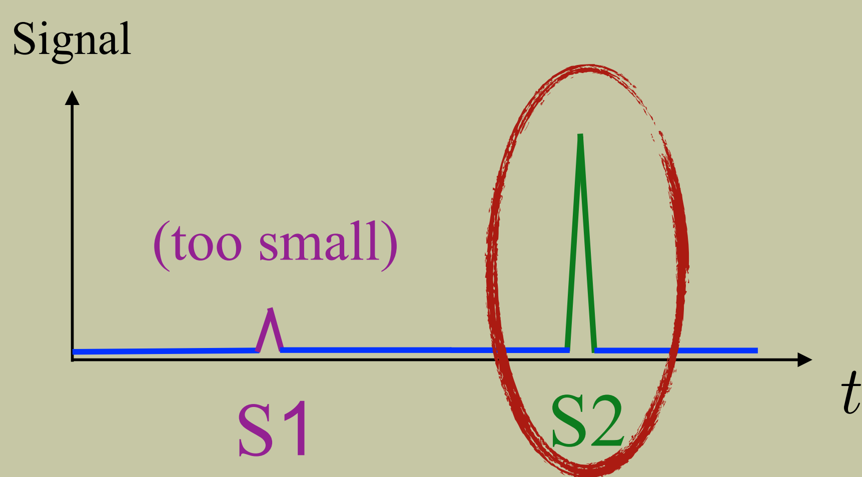
Xenon10

For LDM, S1 is too small!

Instead can use S2 Only

Every electron produces 27 photoelectrons.
Sufficient for triggering.





Xenon10

For LDM, S1 is too small!

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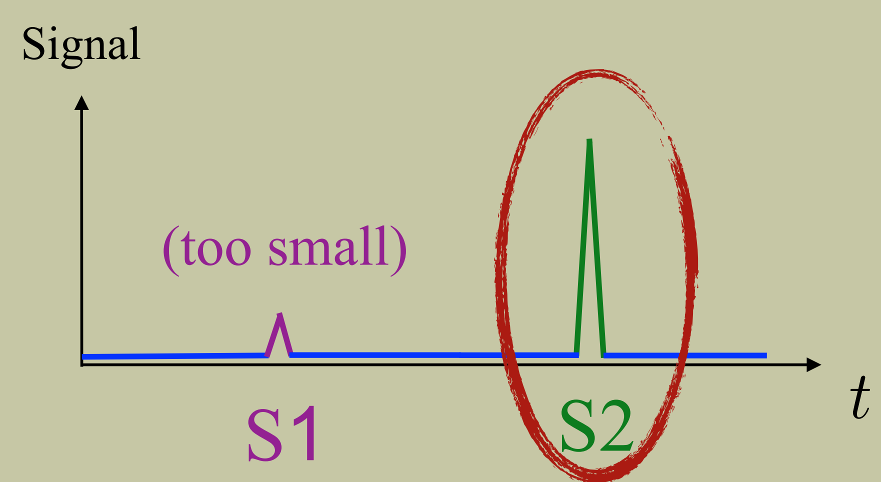
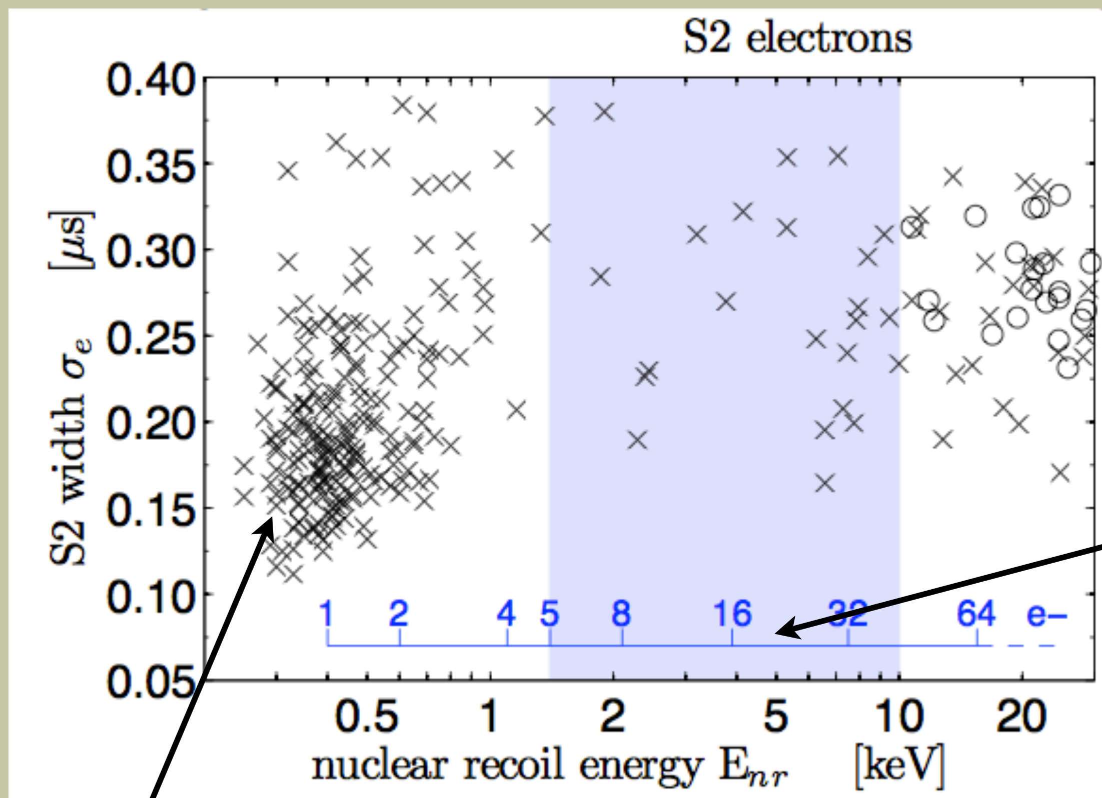
Every electron produces 27 photoelectrons.
Sufficient for triggering.

Xenon10 had a 12.5-day run (corresponding to 15 kg-days) with a single electron trigger.



Data Sample

"A search for light dark matter in XENON10 data"
1104.3088

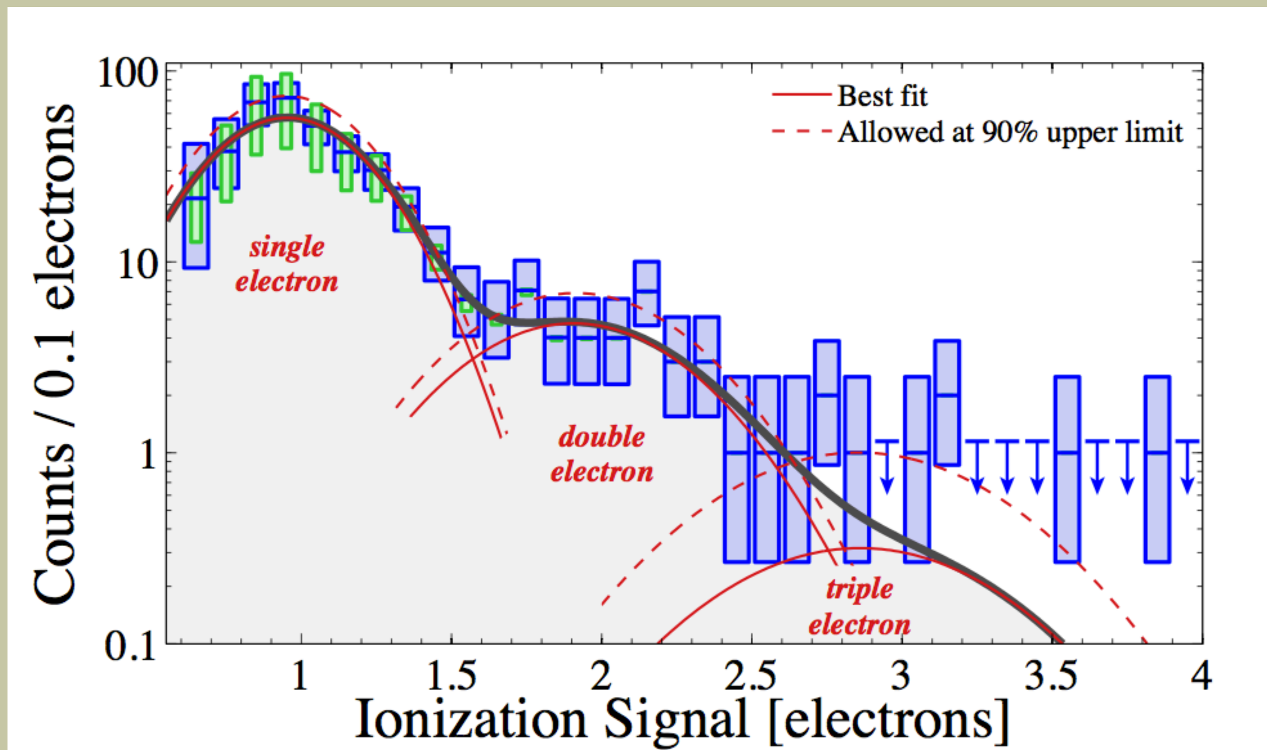


Number of electrons

Large population of single electrons.

Data Sample

- After correcting for triggering efficiency we get,

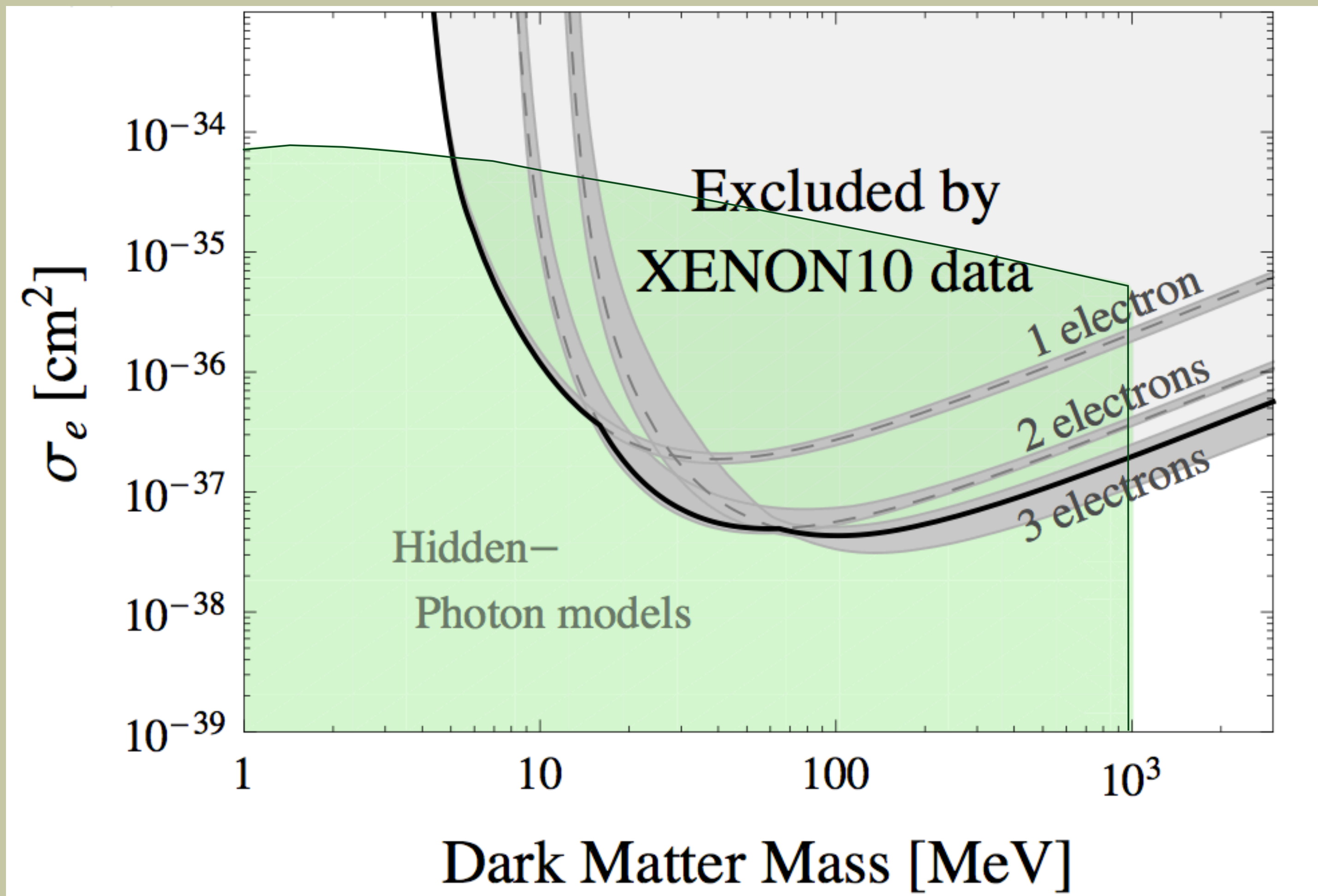


- The result of the fit (dark-gray curve) gives a 90% upper confidence bound (counts/kg/day):

$$R_1 < 39 \qquad R_2 < 4.7 \qquad R_3 < 1.1$$

Results: $F_{DM}=1$

First Direct Detection Bounds for MeV-GeV



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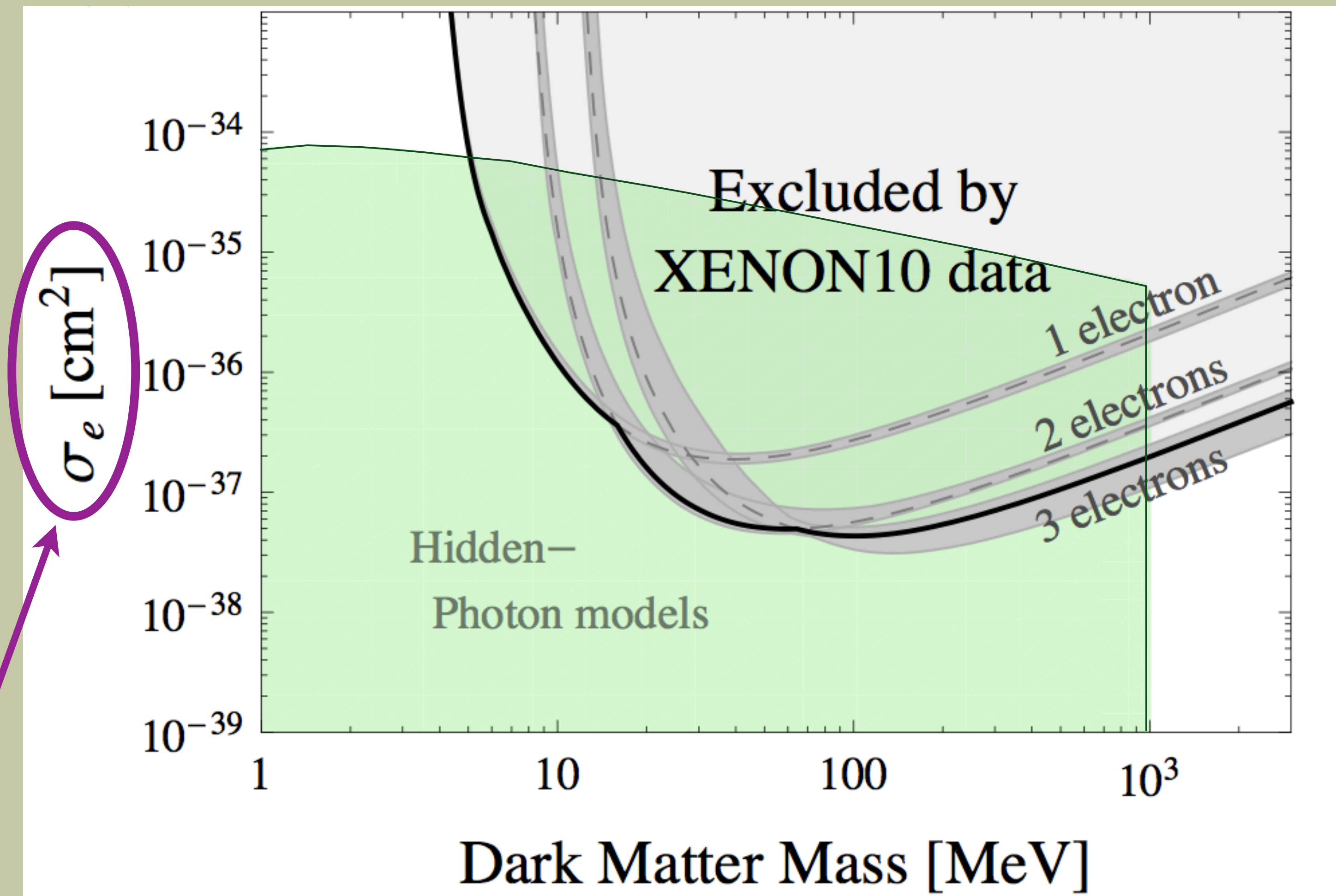
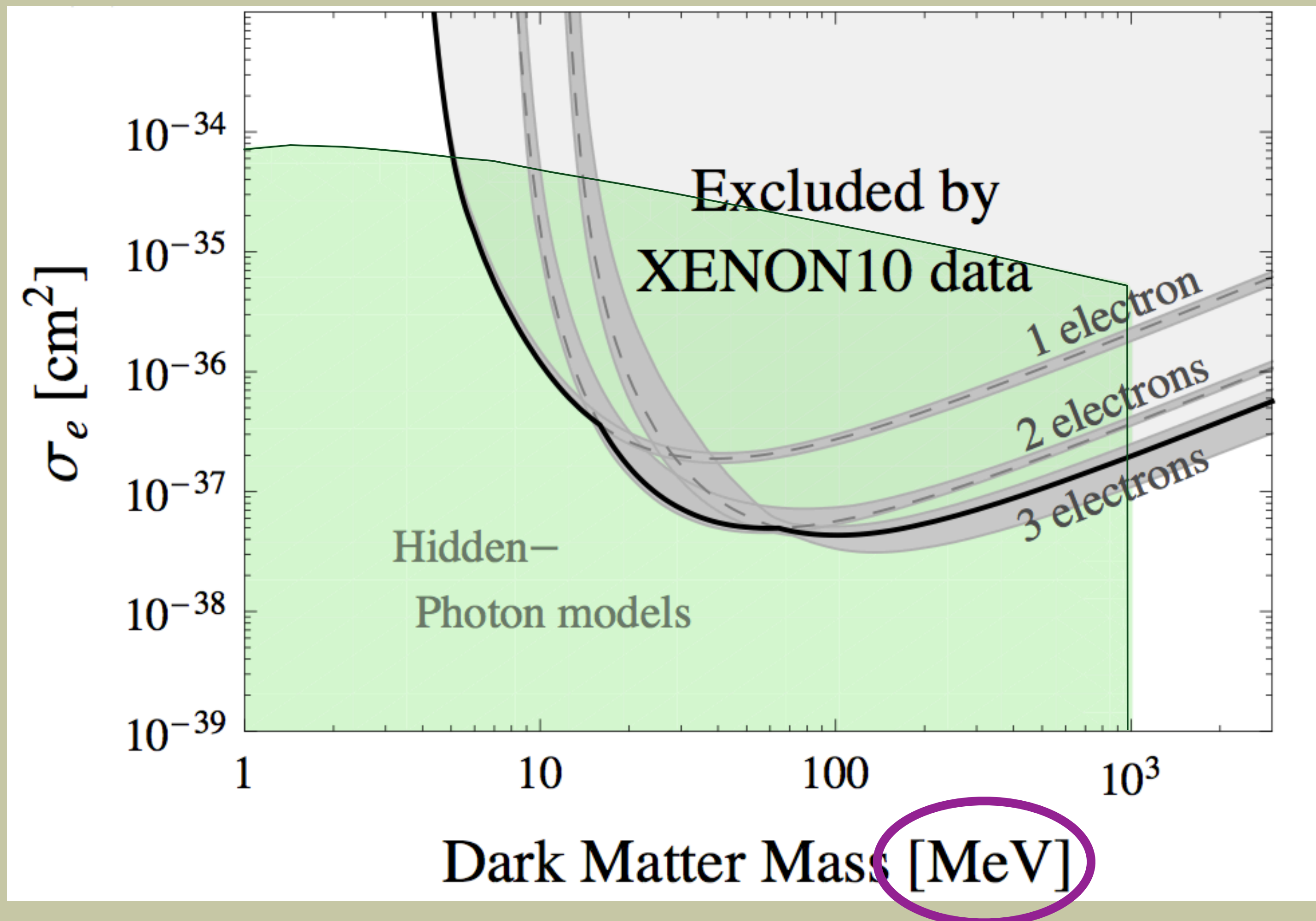
First Direct Detection Bounds for MeV-GeV



free electron-DM
cross-section.

Results: $F_{DM}=1$

First Direct Detection Bounds for MeV-GeV



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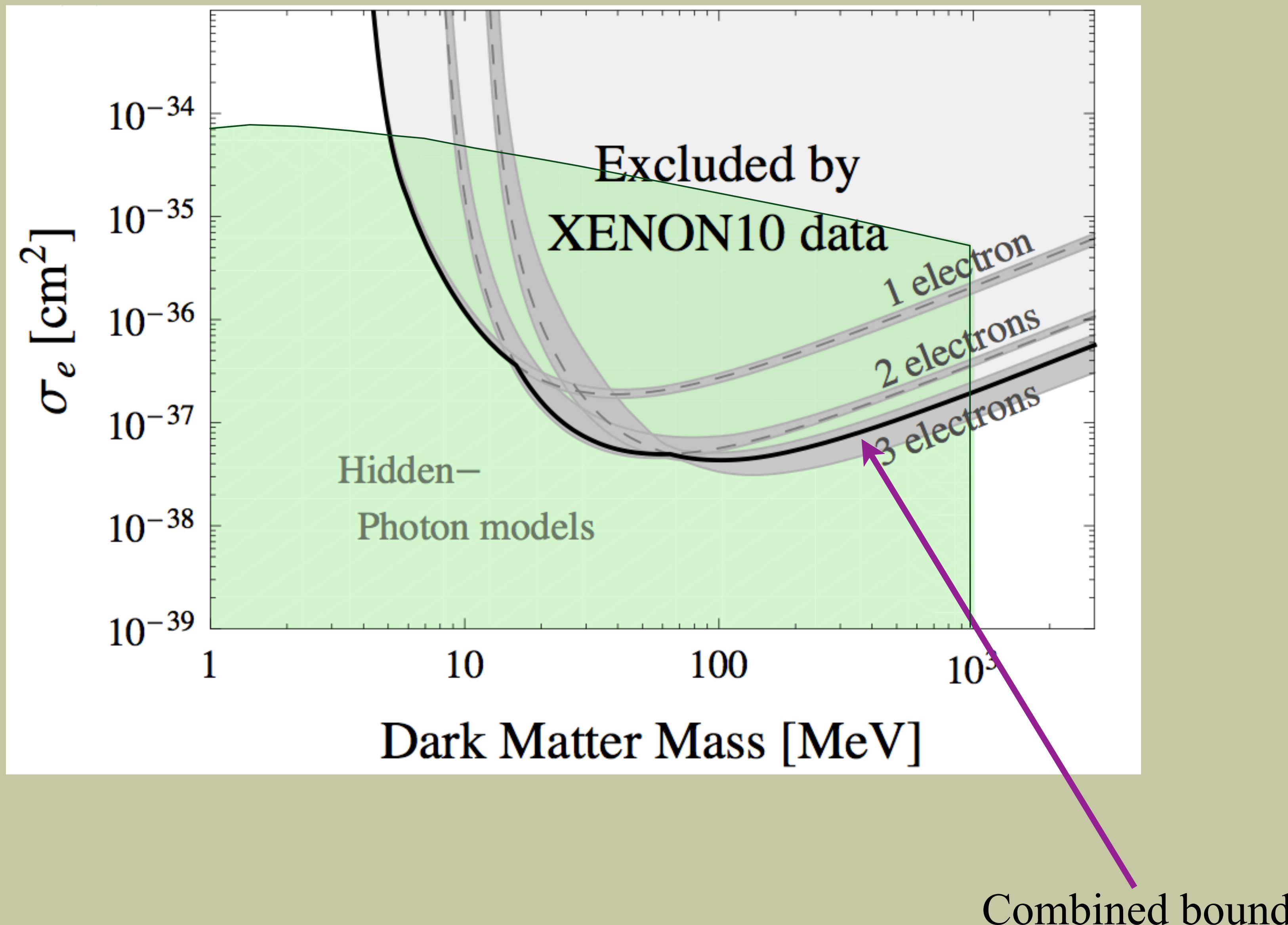

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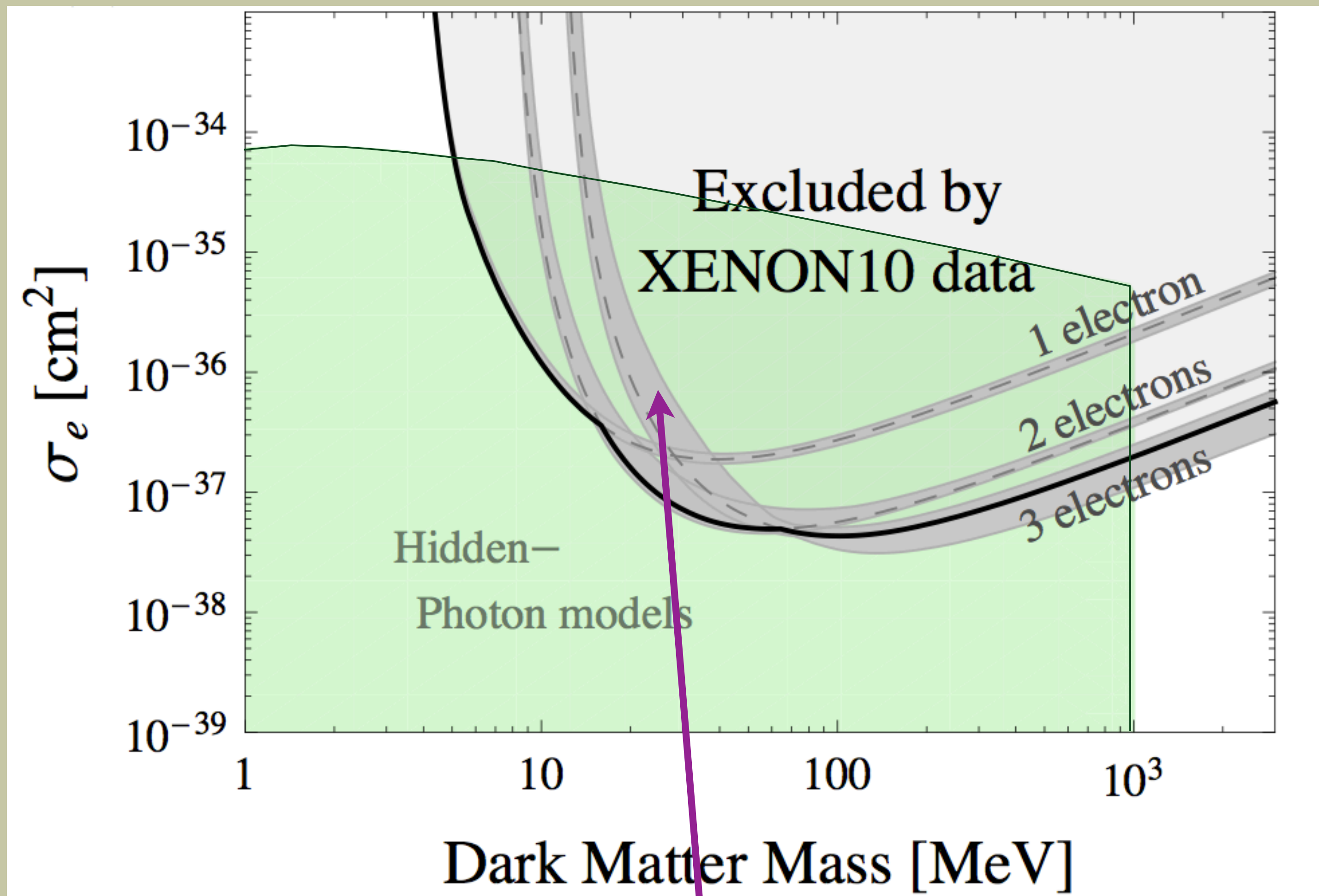
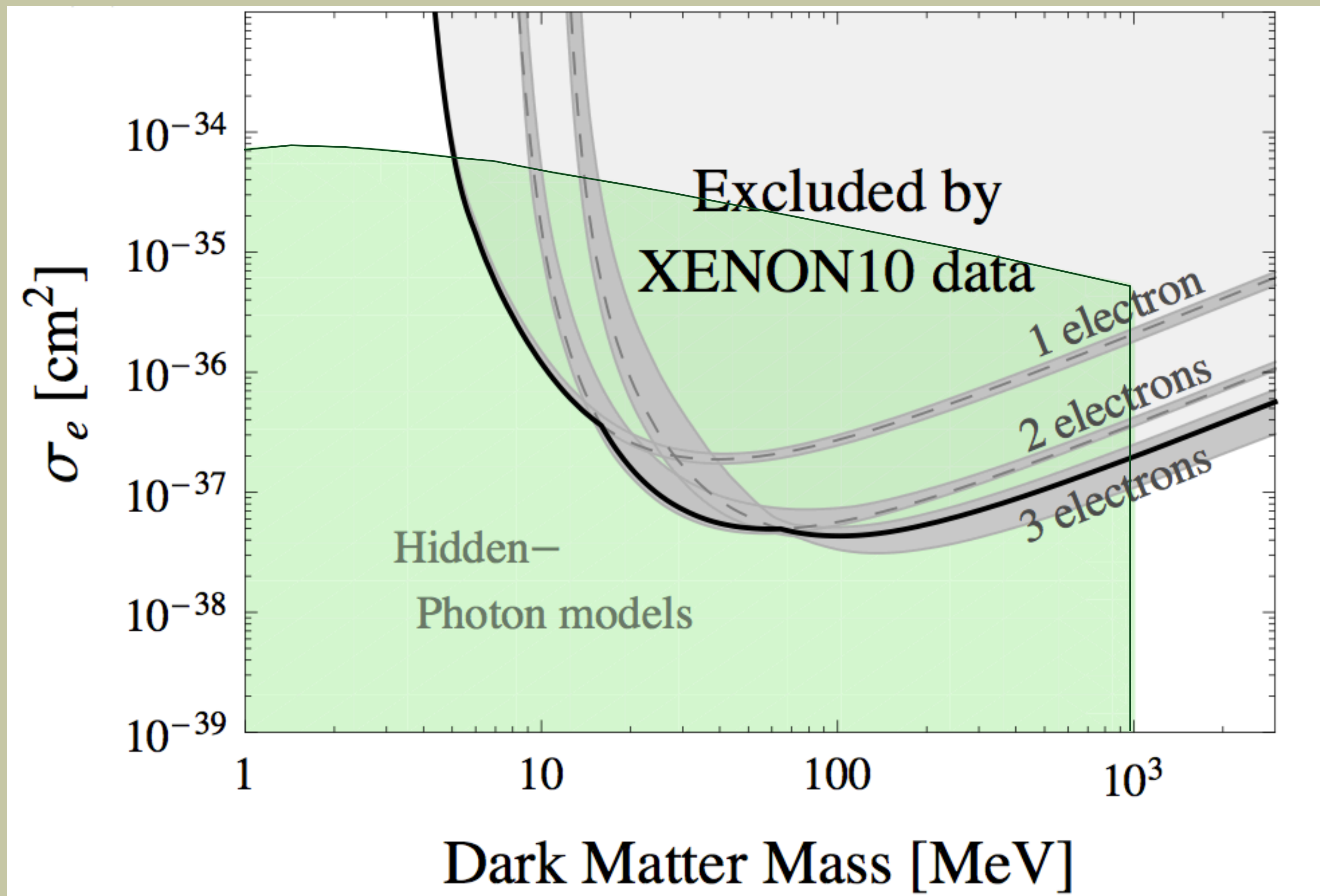
First Direct Detection Bounds for MeV-GeV



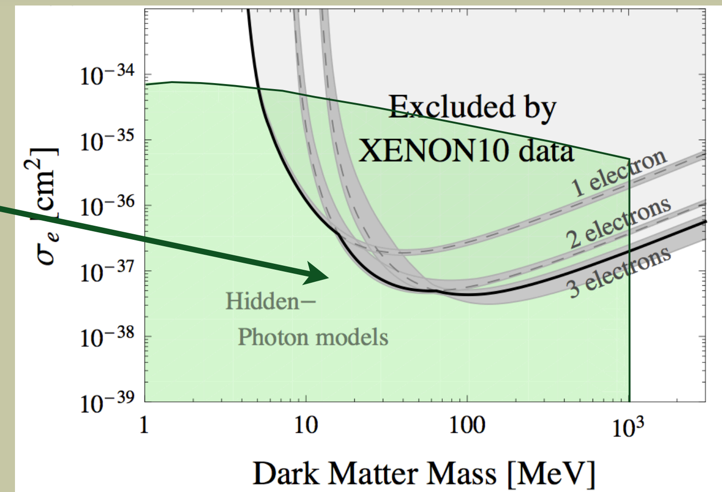
systematic uncertainties

Results: F_{DM}=1

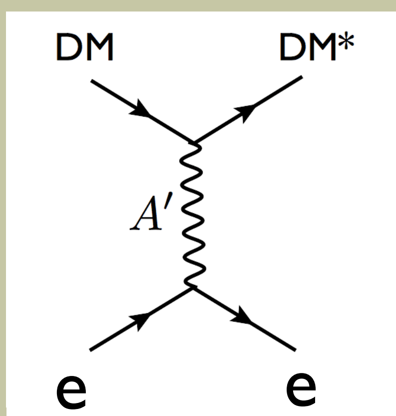


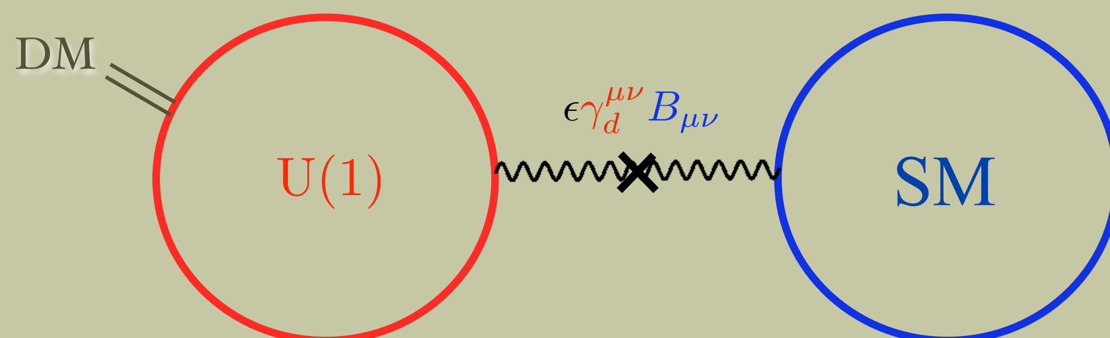
Results: F_{DM}=1

Model in **GREEN**



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

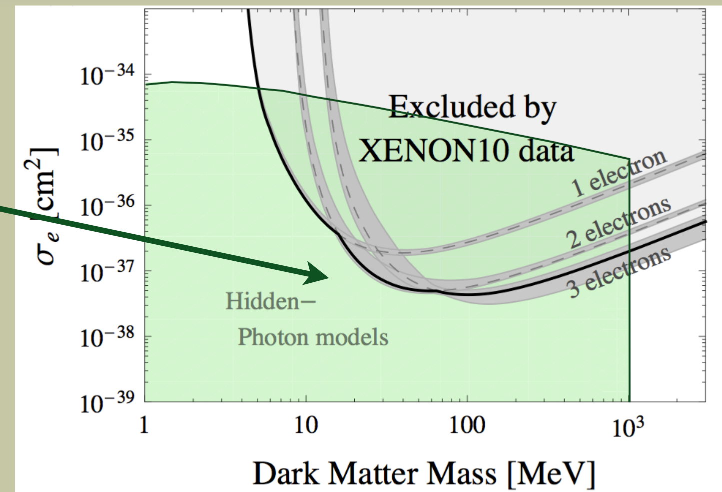




$$\sigma = \frac{16\,\pi\,m_e^2\,\alpha\,\alpha'\,\epsilon^2}{(m_{A'}^2 + q^2)^2}$$

Results: F_{DM}=1

Model in **GREEN**



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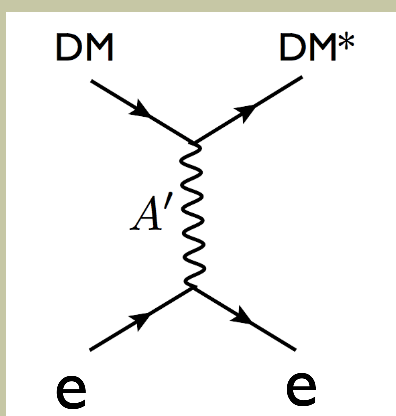
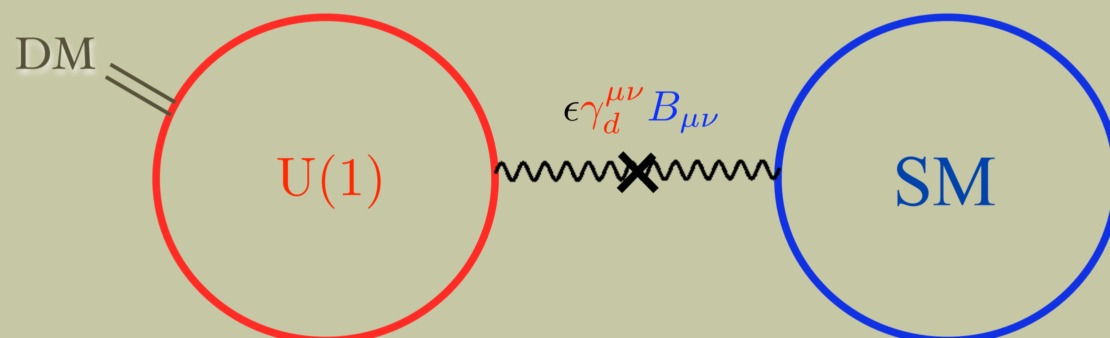
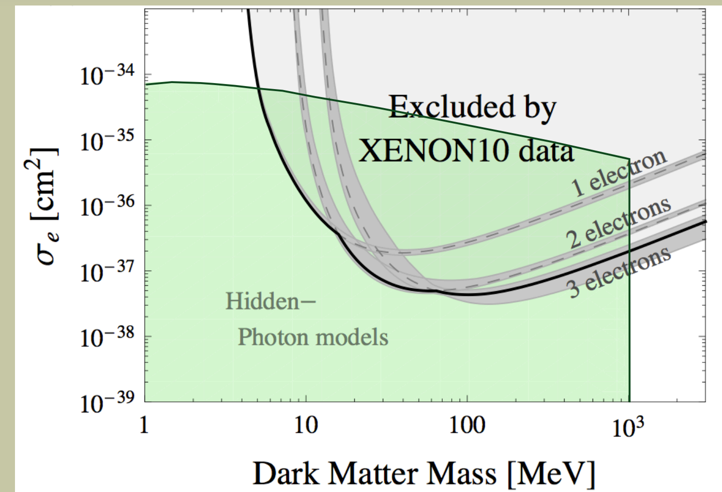


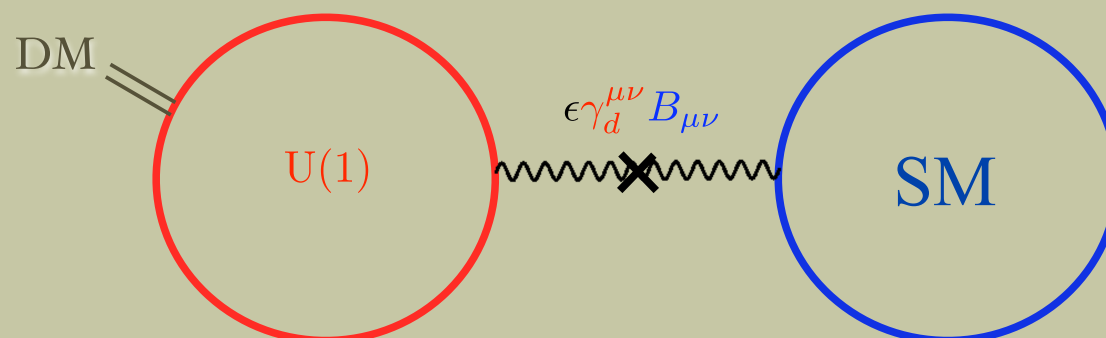


$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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

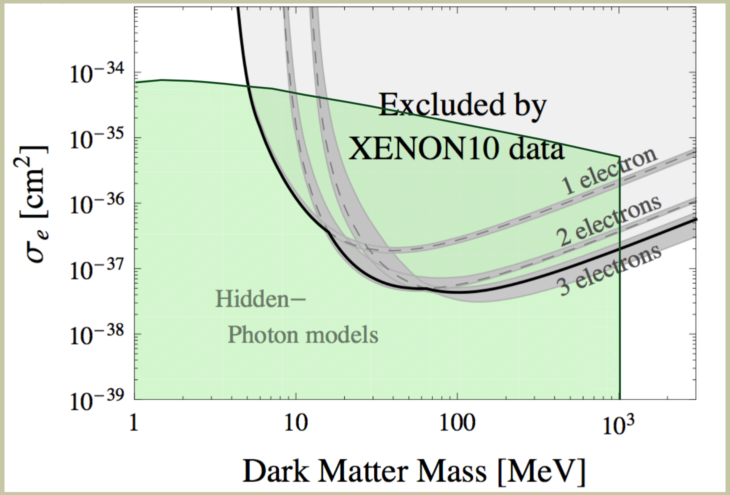
Results: $F_{DM}=1$

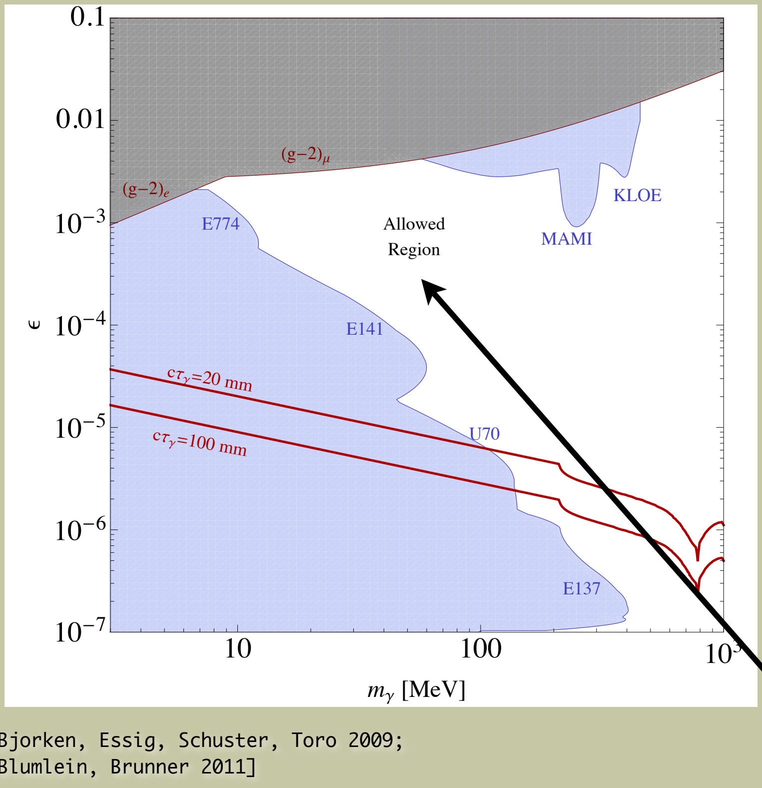




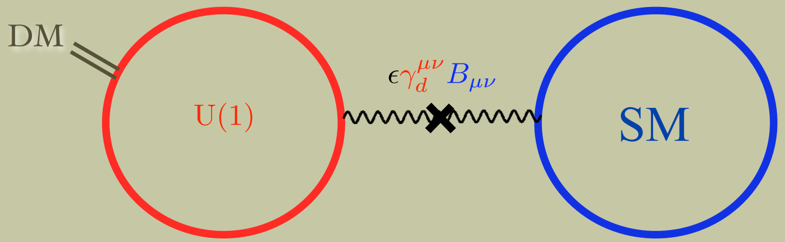
For m_A >MeV hidden photon: $F_{\rm DM} = 1$

Results: F_{DM}=1



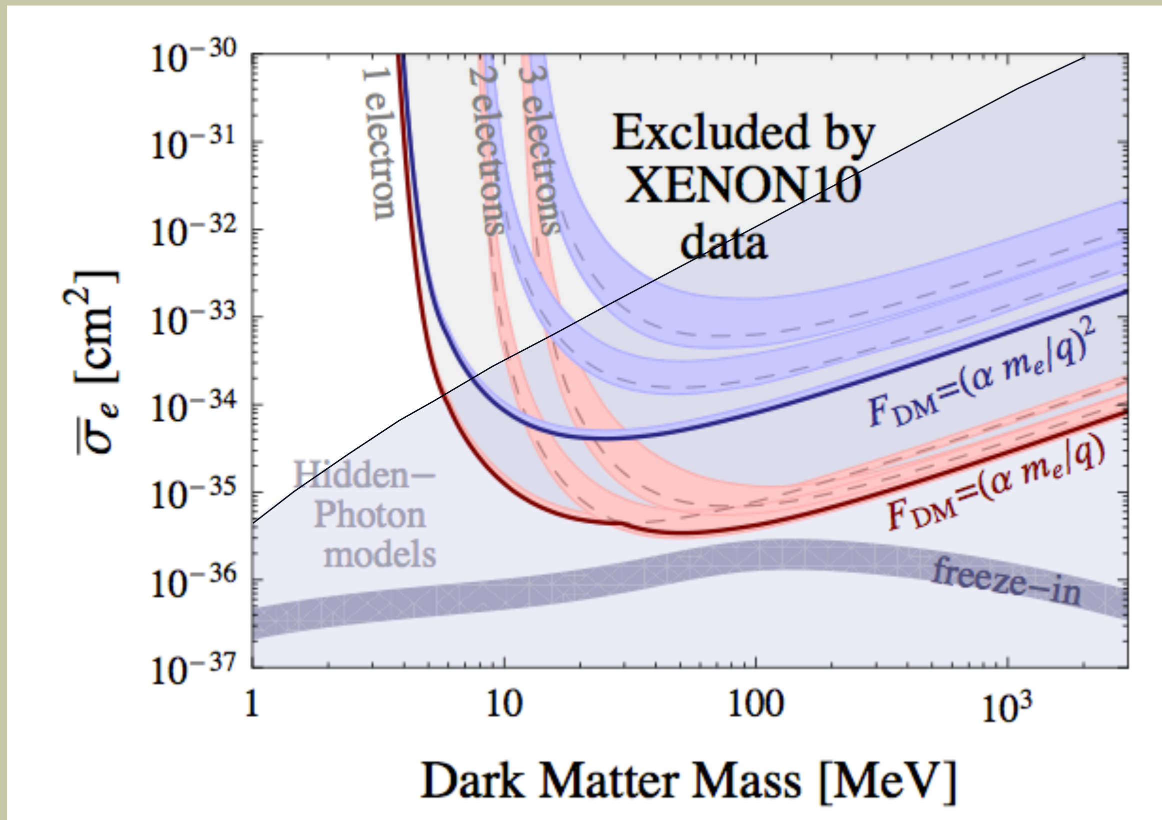


[Bjorken, Essig, Schuster, Toro 2009;
Blumlein, Brunner 2011]



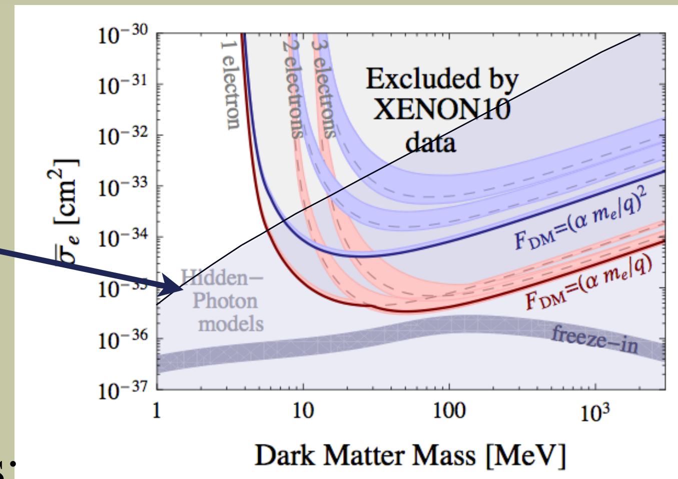
For m_A >MeV hidden photon: $F_{\rm DM} = 1$

Results: Non-trivial form factor

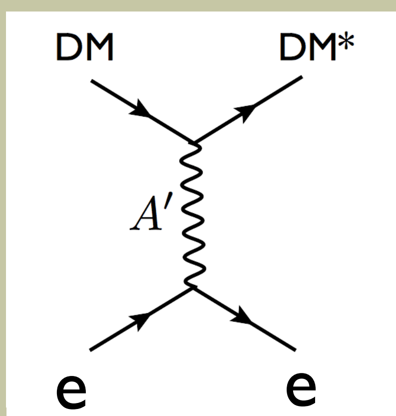


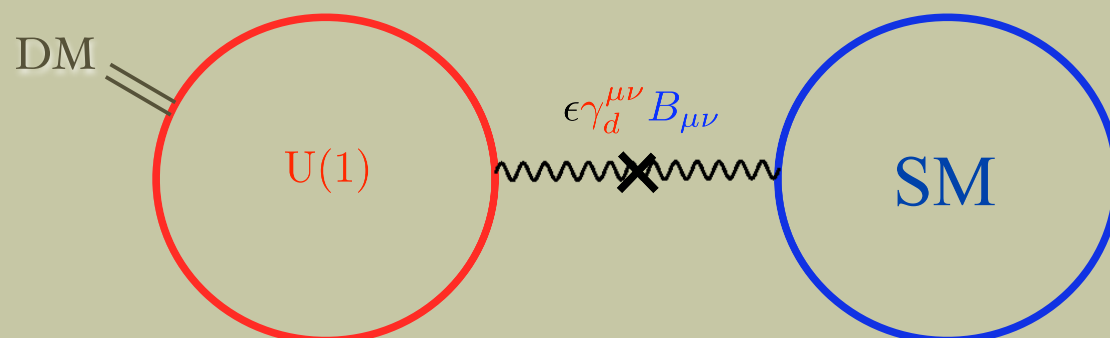
Results: Non-trivial form factor

Model in **BLUE**



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

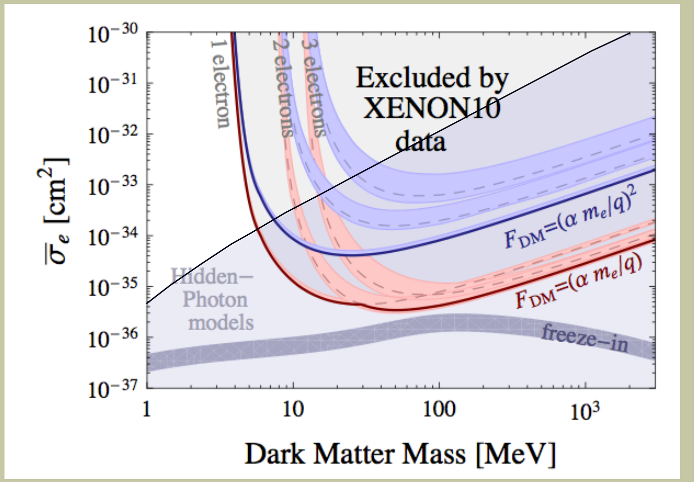




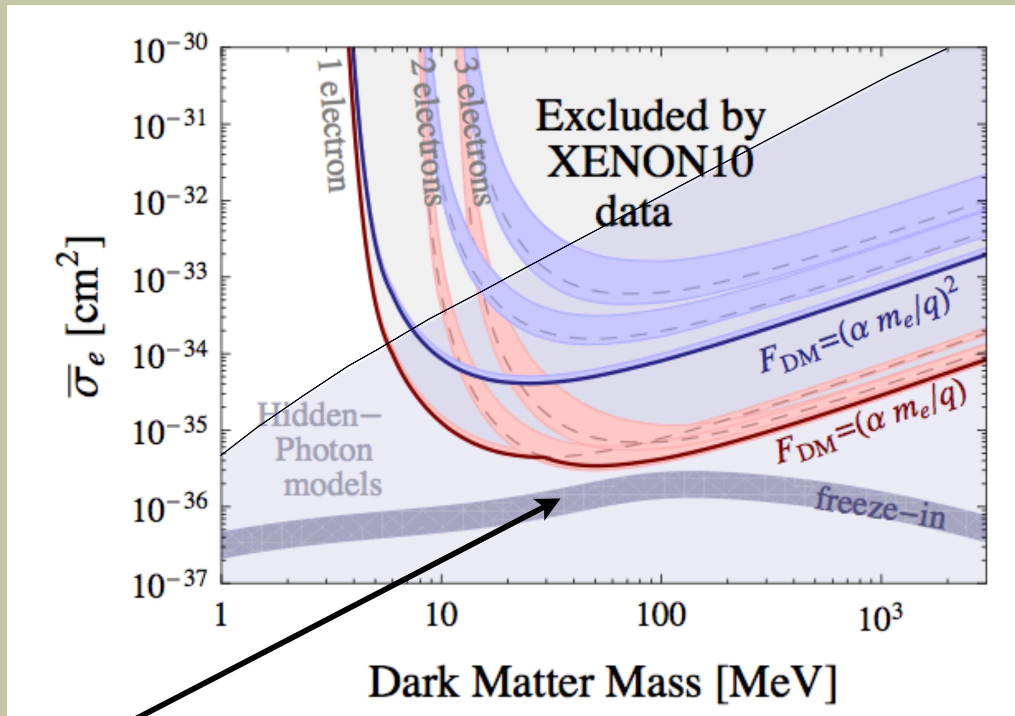
$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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

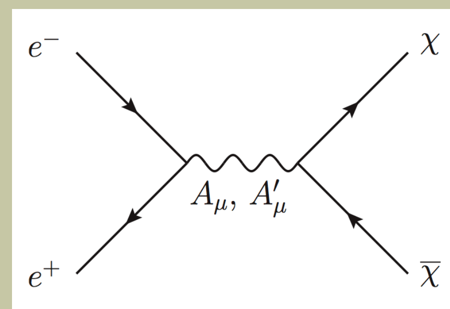
Results: $F_{DM} \sim 1/q^2$



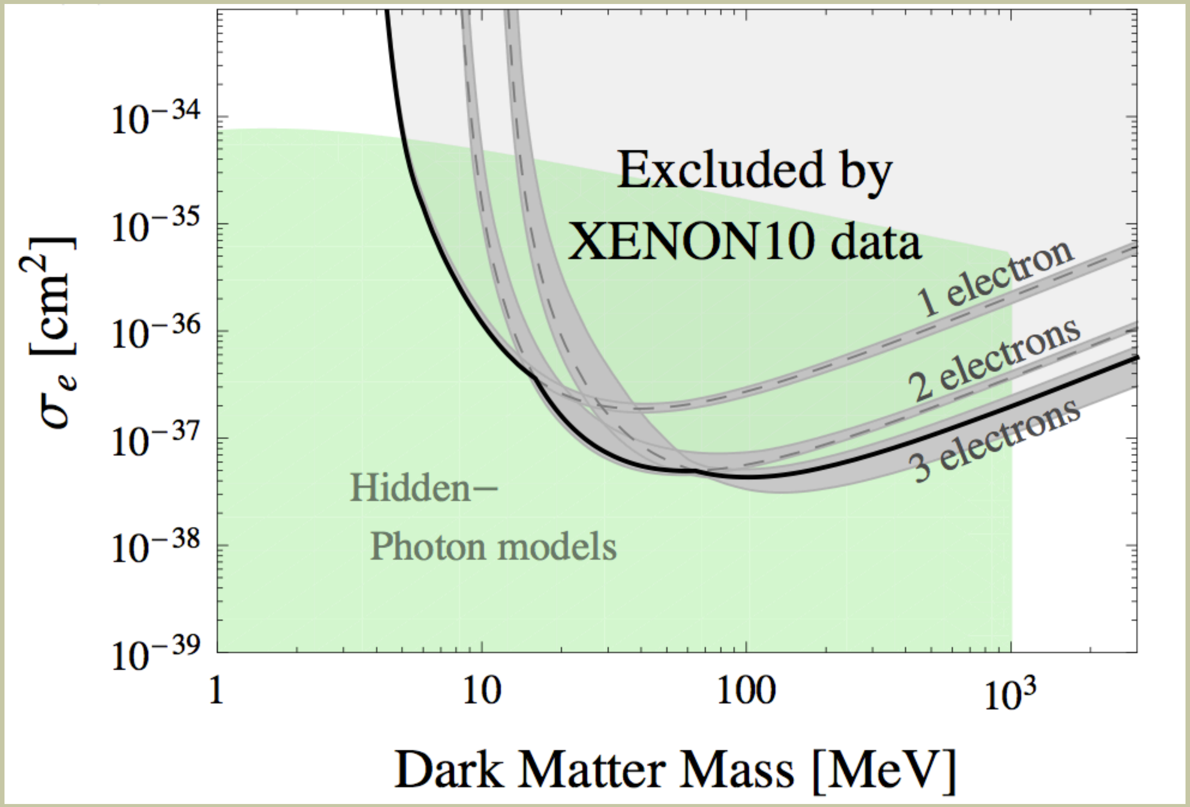
Results: $F_{DM} \sim 1/q^2$



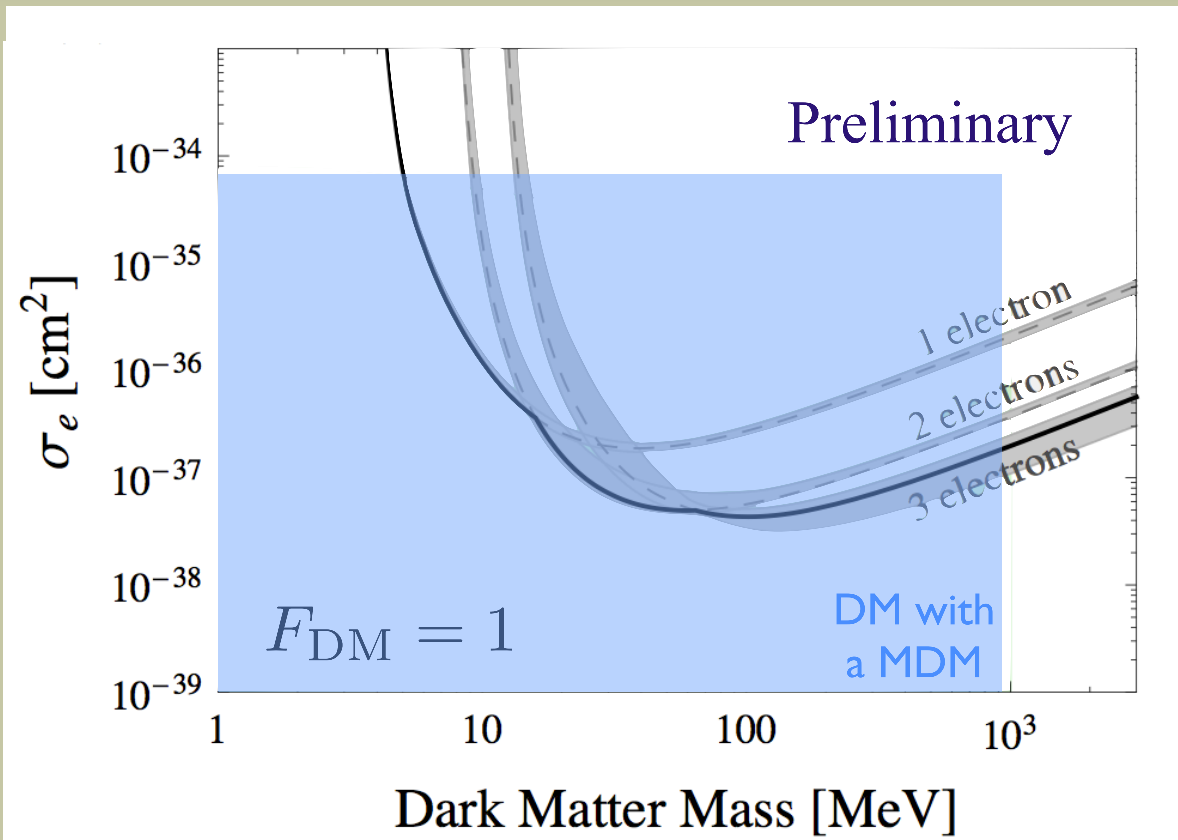
Almost sensitive to Freeze-in region: DM is naturally produced by SM production.



More Interesting Models



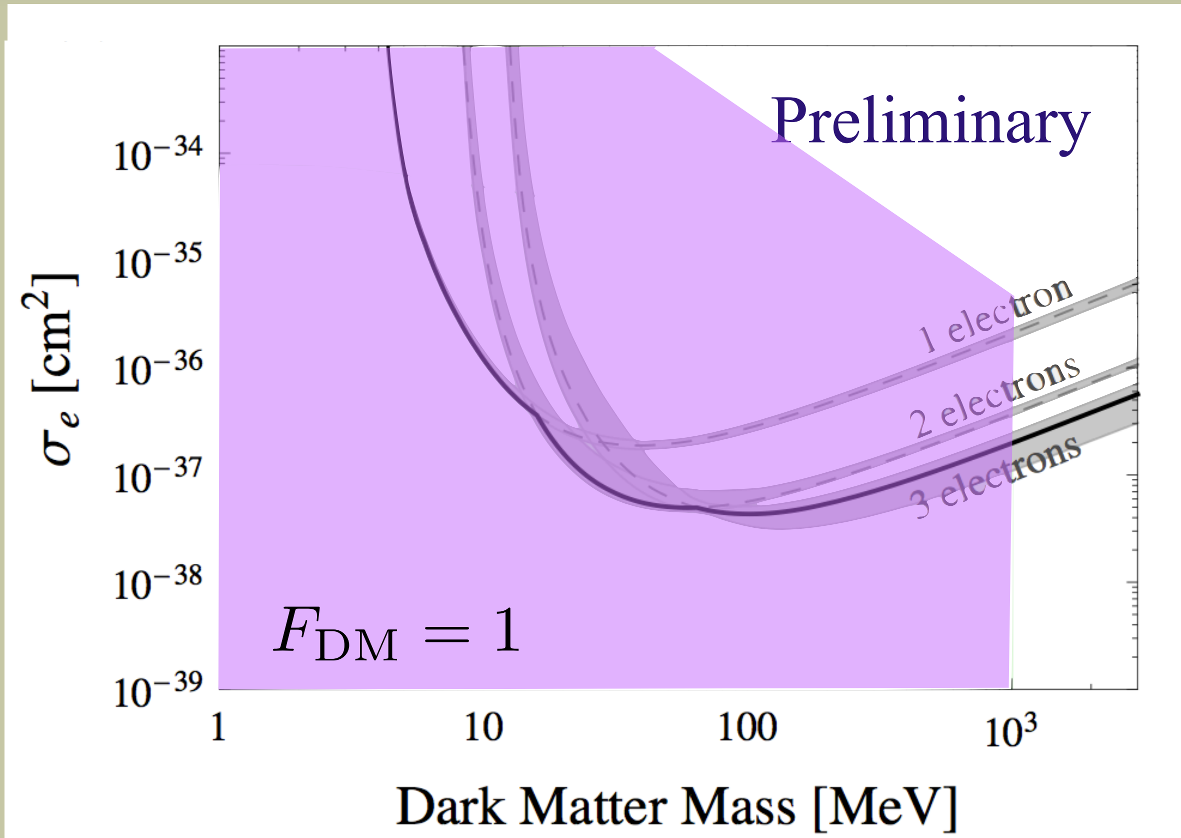
More Interesting Models

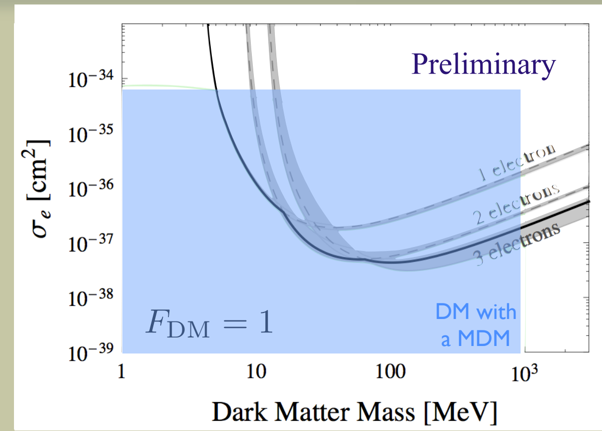


DM with magnetic dipole moment

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

More Interesting Models

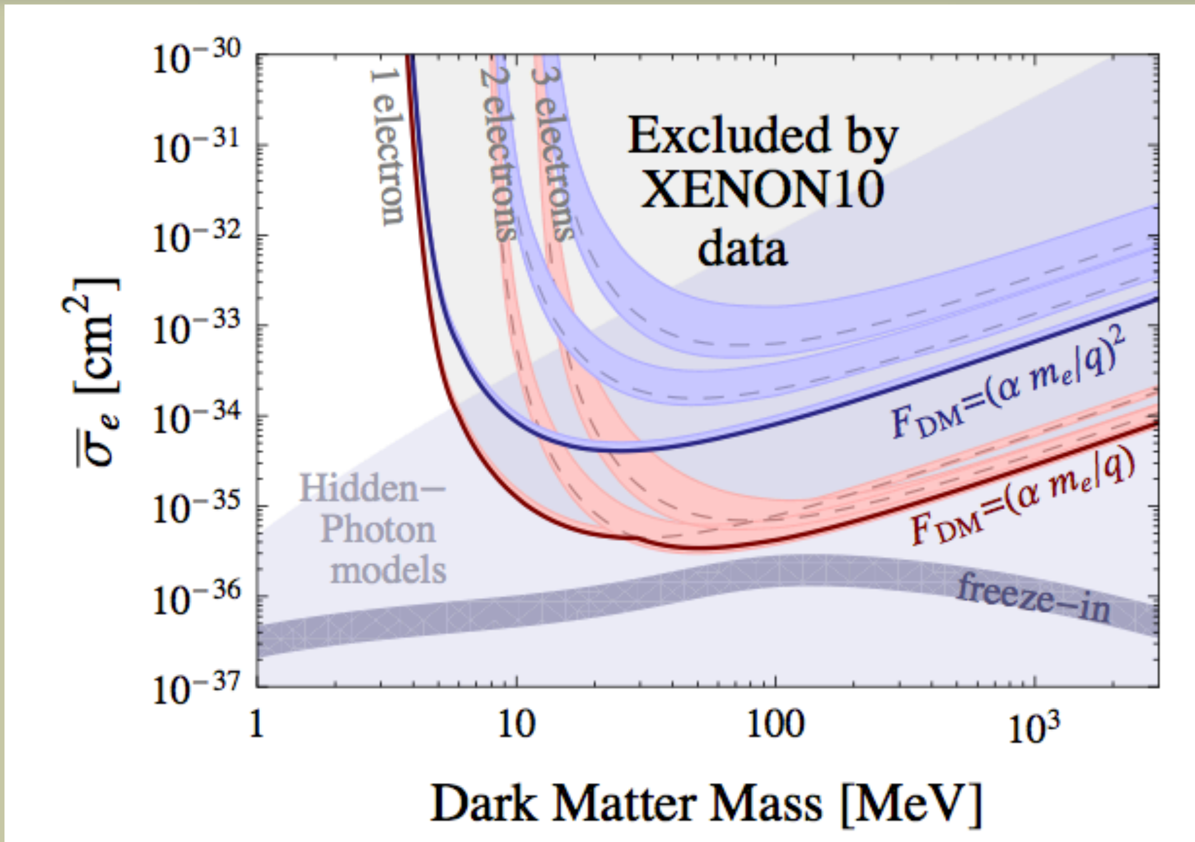


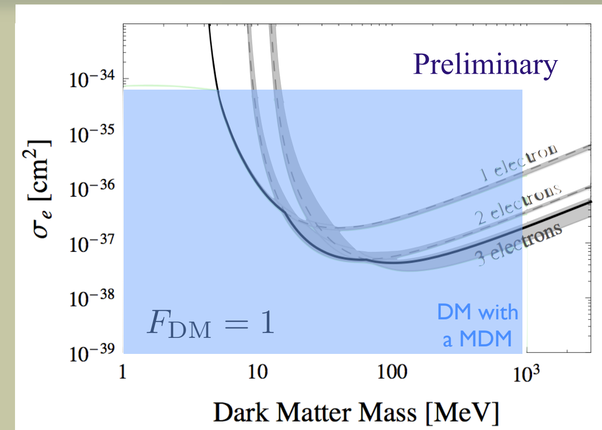


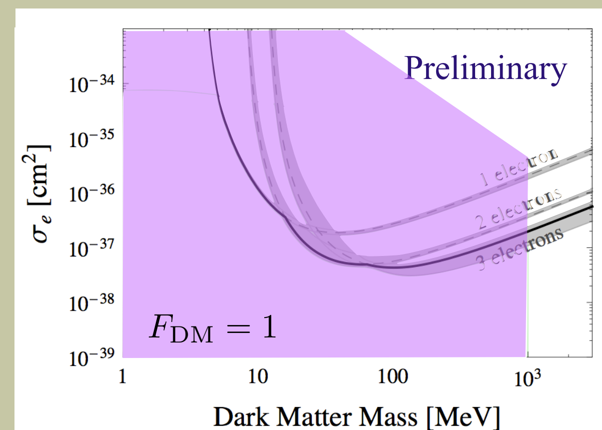
Scalar DM operator

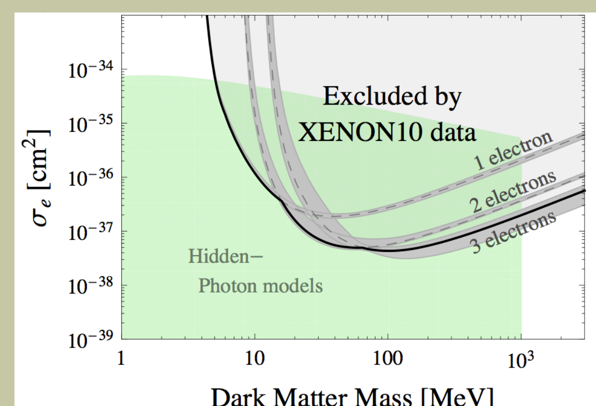
$$\frac{1}{\Lambda}\bar{\phi}^\dagger \phi \bar{e} e$$

More Interesting Models

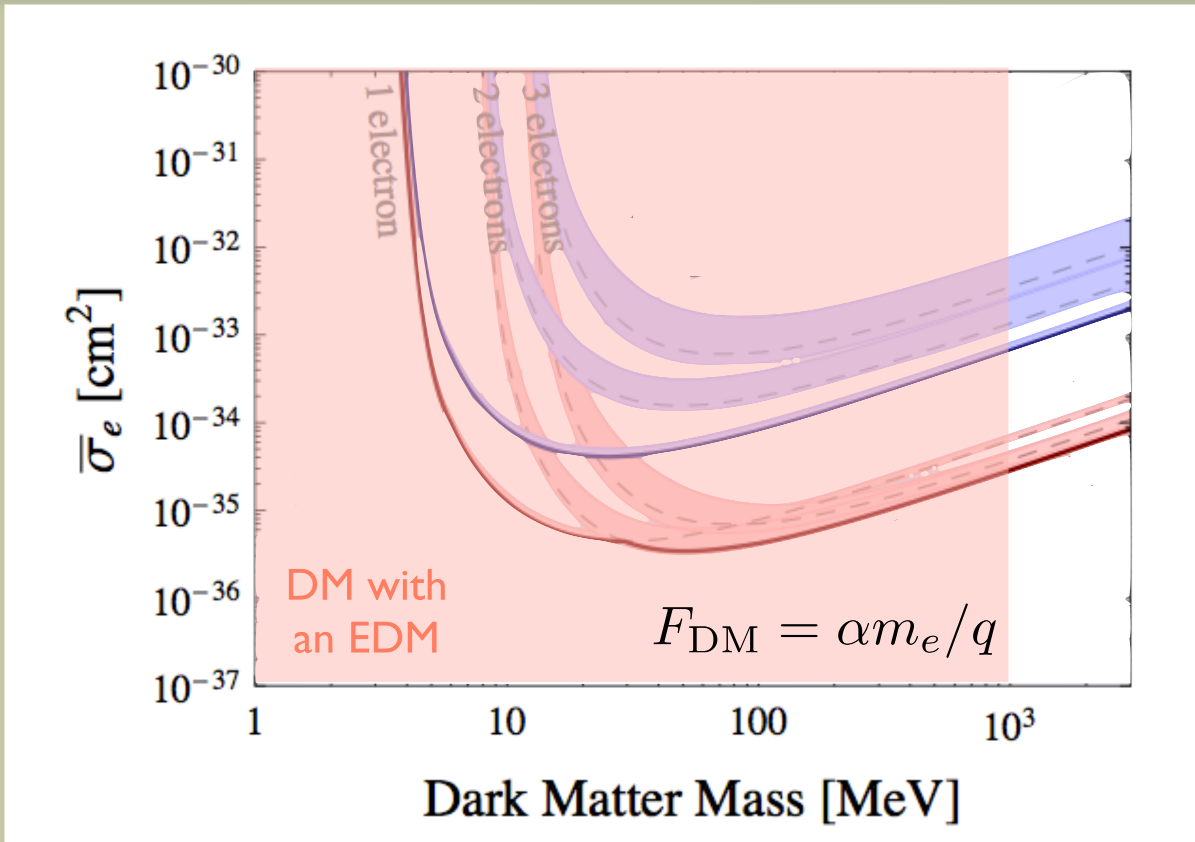


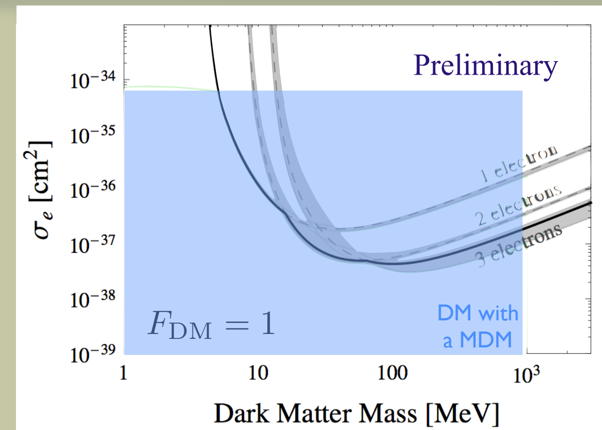


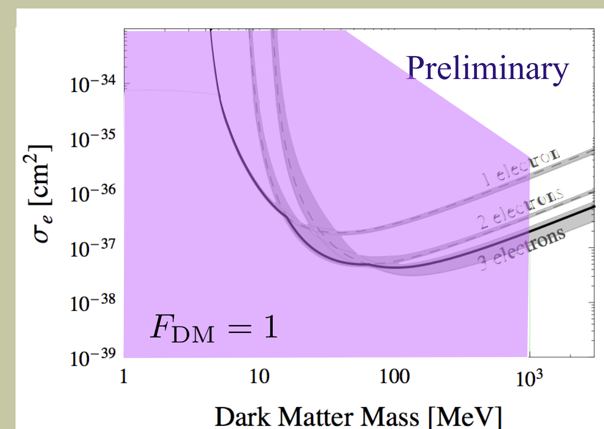


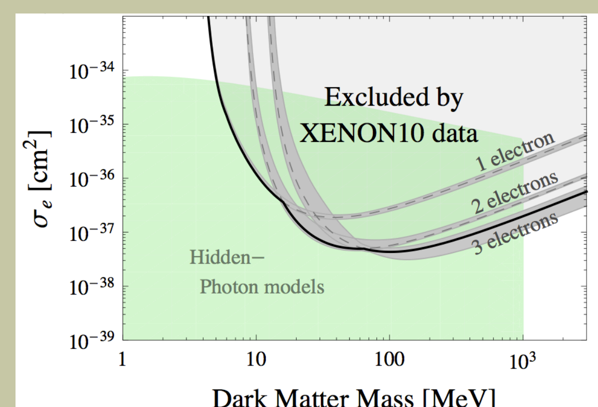


More Interesting Models





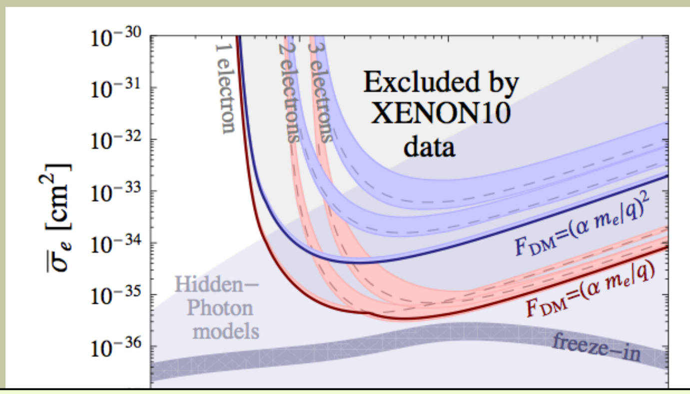


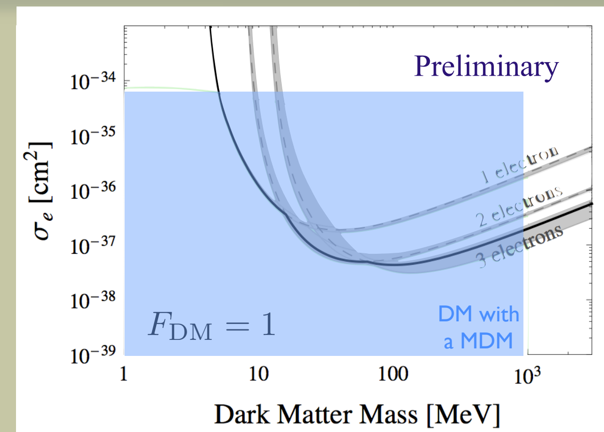


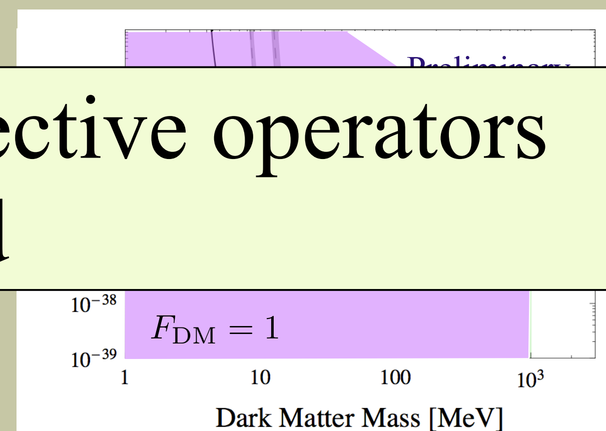
DM with electric dipole moment

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

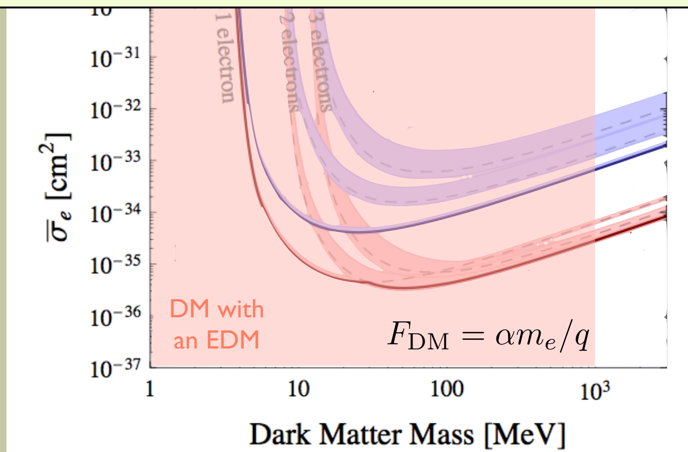
More Interesting Models

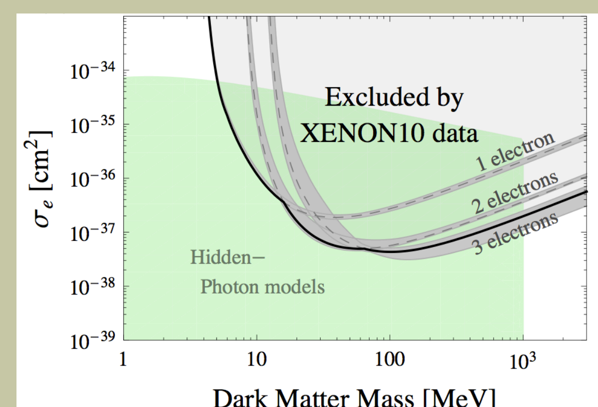






Many interesting models and effective operators are already probed





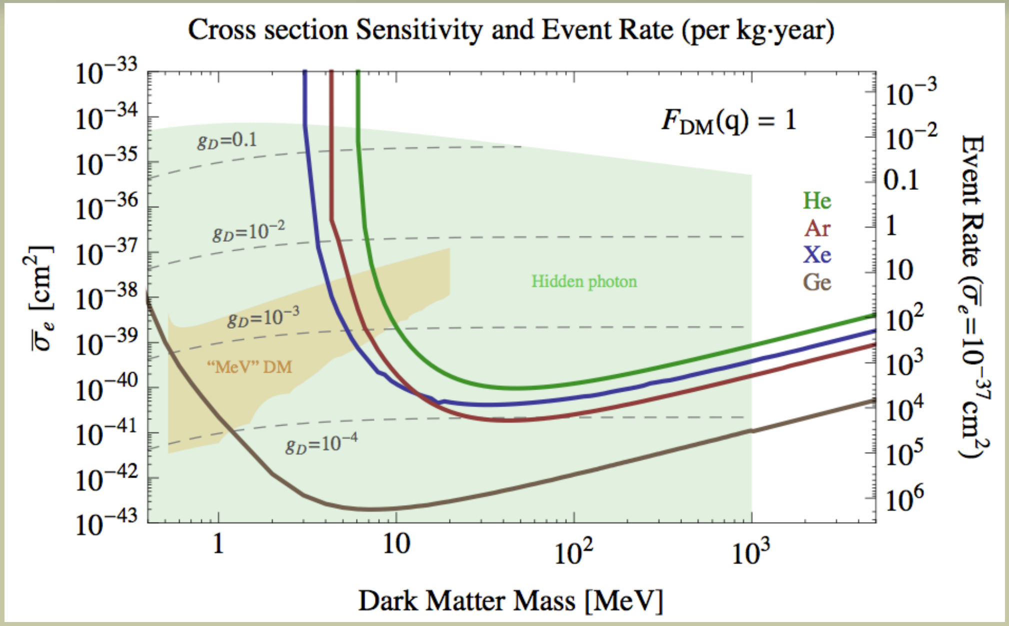
Results

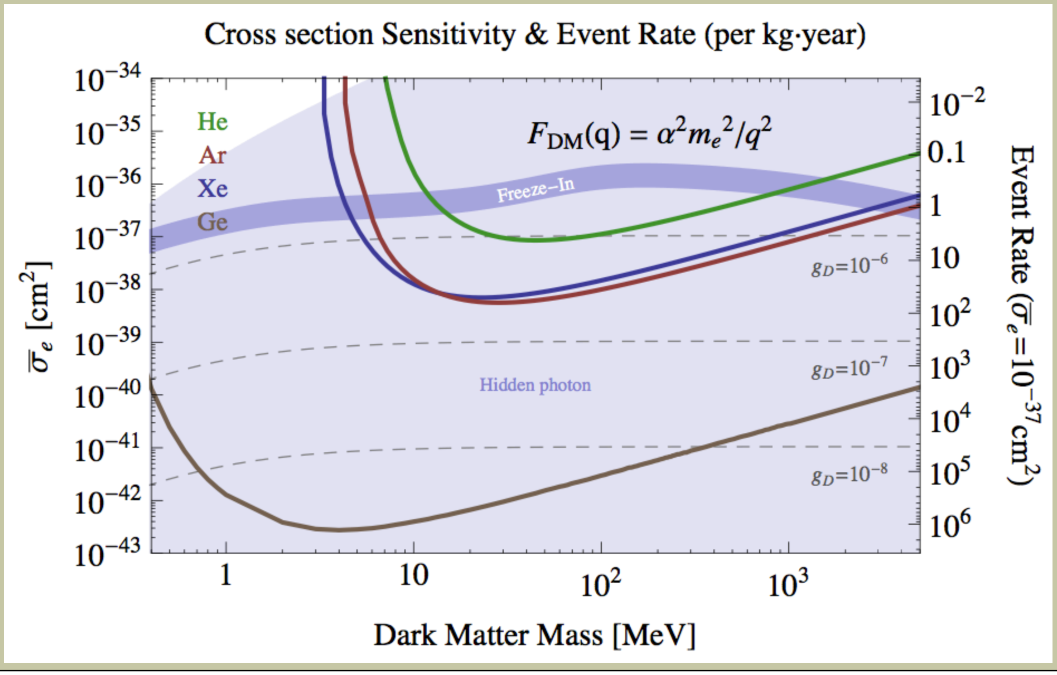
These are results for only 15 kg-days with a non-dedicated experiment!

Improvements could be very significant!!!

So What Can We Expect?

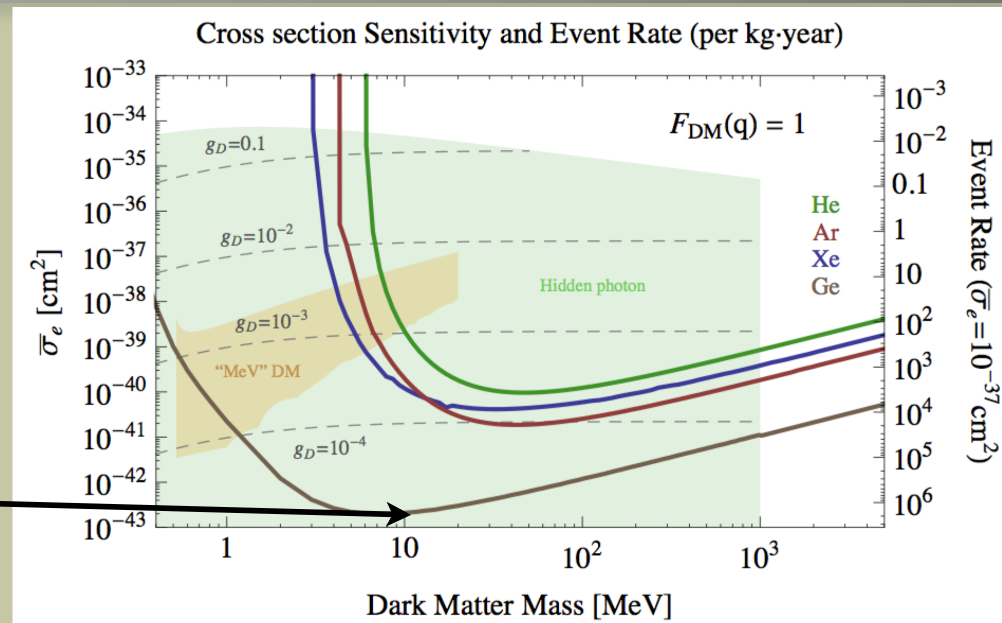
Projected Sensitivity

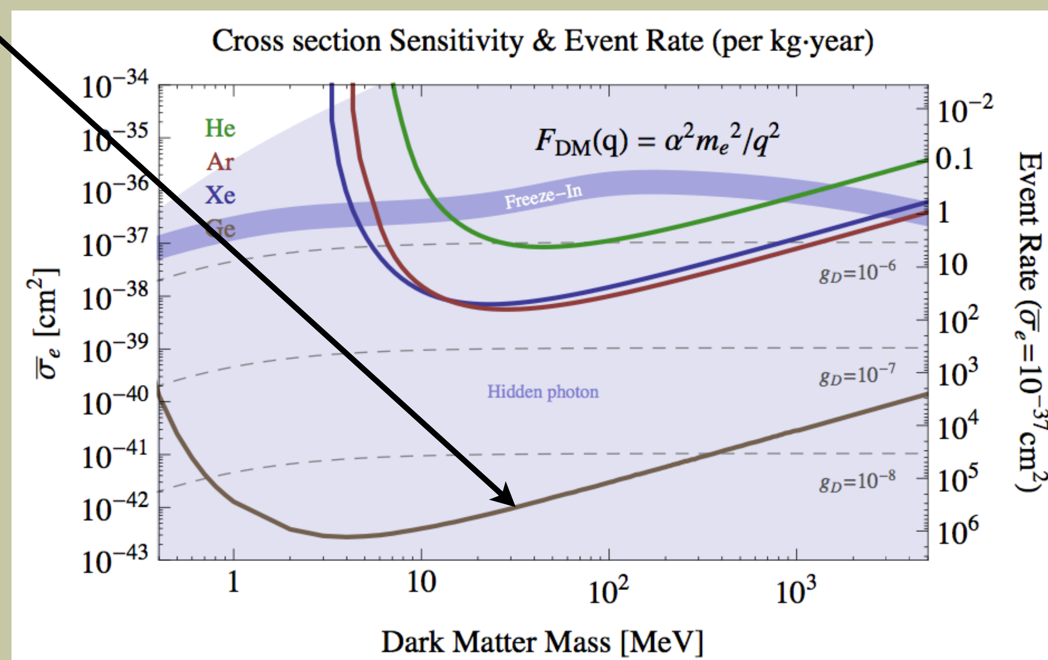




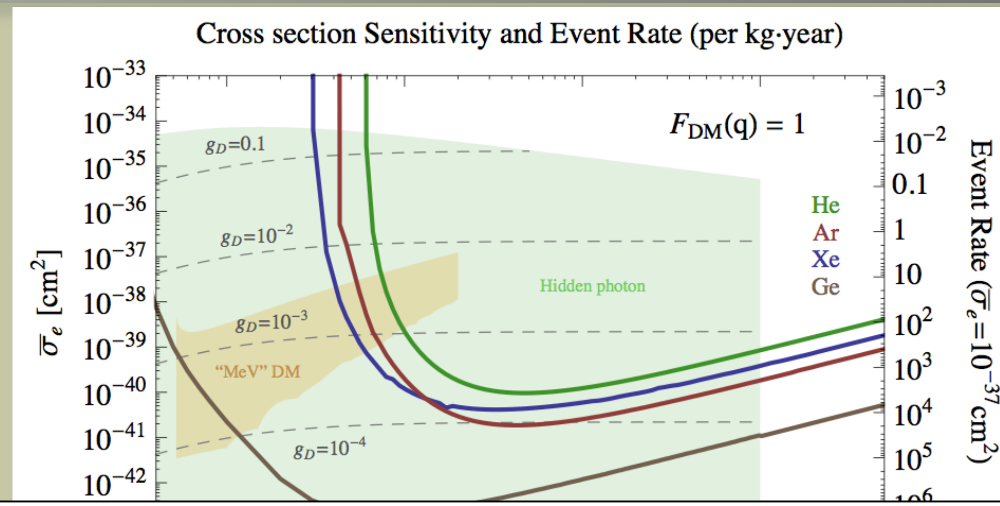
Projected Sensitivity

Crystals can do much better due to small band gap!

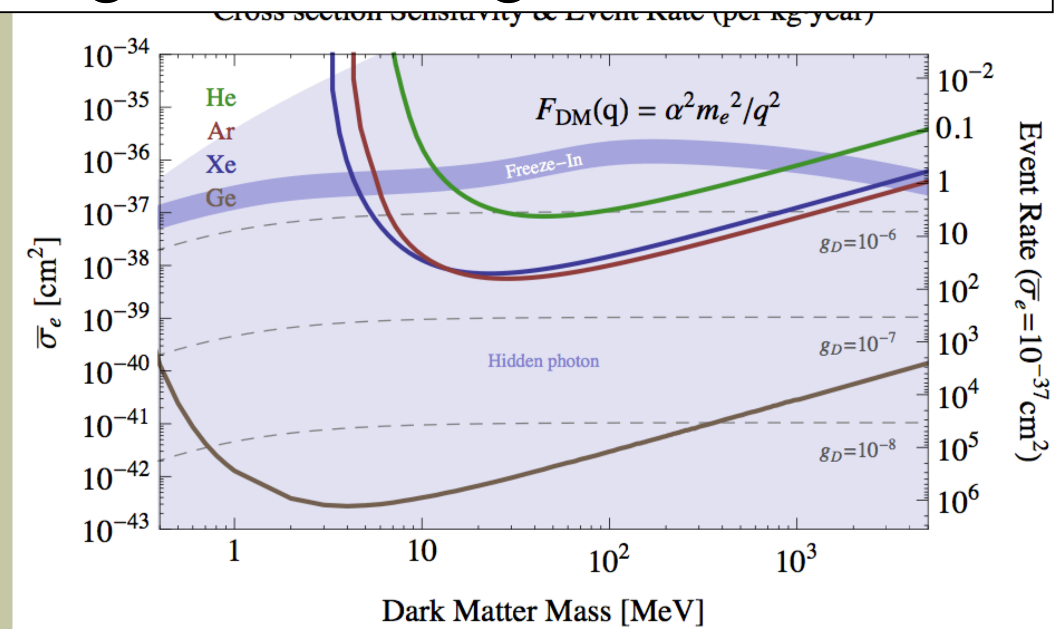




Projected Sensitivity



Annual modulation will allow for a discovery even with nothing more than the single electron signal.



Backgrounds

- Obviously, controlling backgrounds is crucial for a successful LDM search.
- In the past ~20 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.

Outlook

- The WIMP scenario may turn out wrong.
- Contrary to the lore, direct detection experiments may probe significantly lower mass scales.
- 15 kg-days of data were enough to place meaningful bounds! Dedicated search will do much more.
- Several ongoing and future experiments:
  - Xenon100
  - LUX
  - CDMS-light
  - Interesting proposal: Low-threshold bolometers.

Stay Tuned

} New results likely in the near future..

Sterile Neutrinos, Coherent Scattering and Oscillometry Measurements with Low-temperature Bolometers

Joseph A. Formaggio, E. Figueroa-Feliciano, and A.J. Anderson
Massachusetts Institute of Technology,
Cambridge, MA 02139
(Dated: July 25, 2011)

Outlook

Lots more to be done with light DM.

In fact, everything that was done for the WIMP in the last 30 years, can be repeated:

- Theory: Understand more systematically models of LDM and their constraints.
- Indirect Detection: Can LDM be probed? Requires low threshold (INTEGRAL).
- Collider: More promising at the intensity frontier (e.g. SuperB factories)
- Direct Detection: Ongoing experiments and dedicated ones.

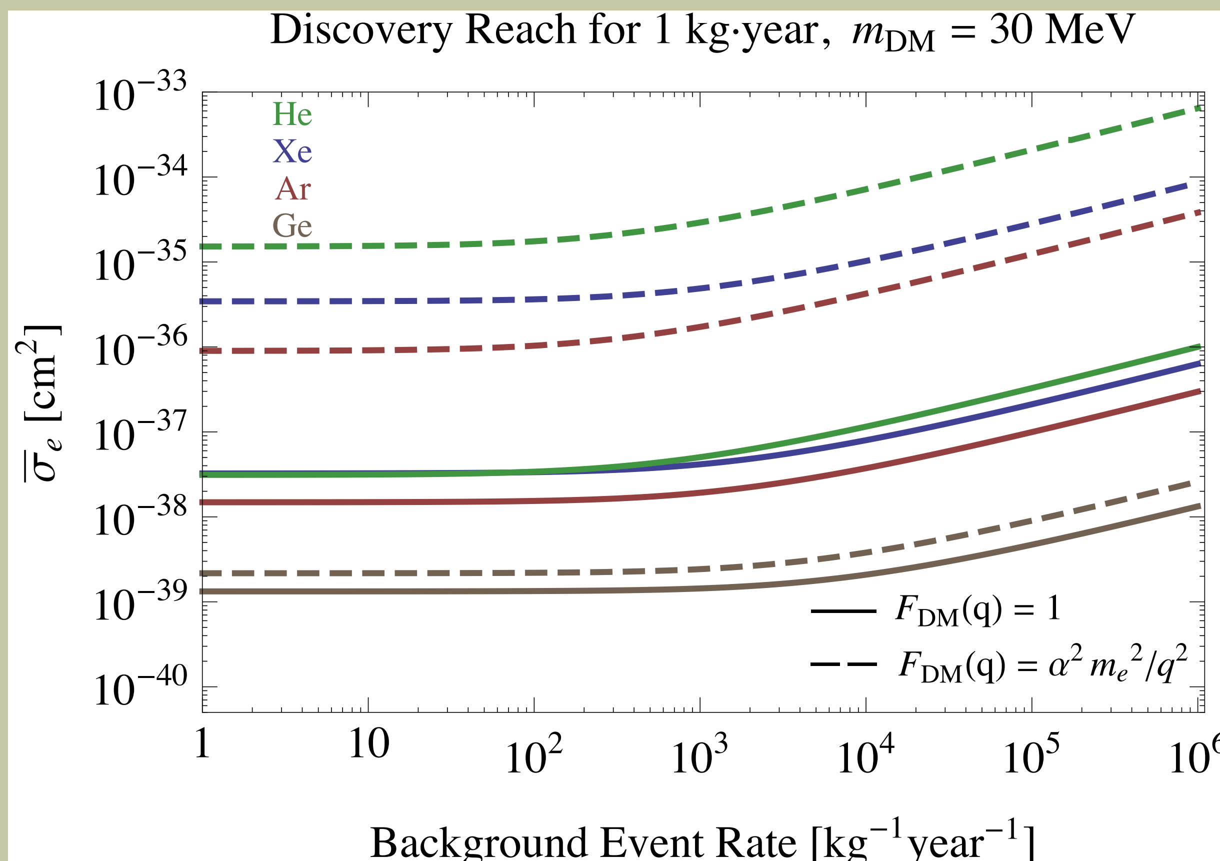
Extras

Can we discover light DM without a dedicated experiment?

YES. Search for annual modulation.

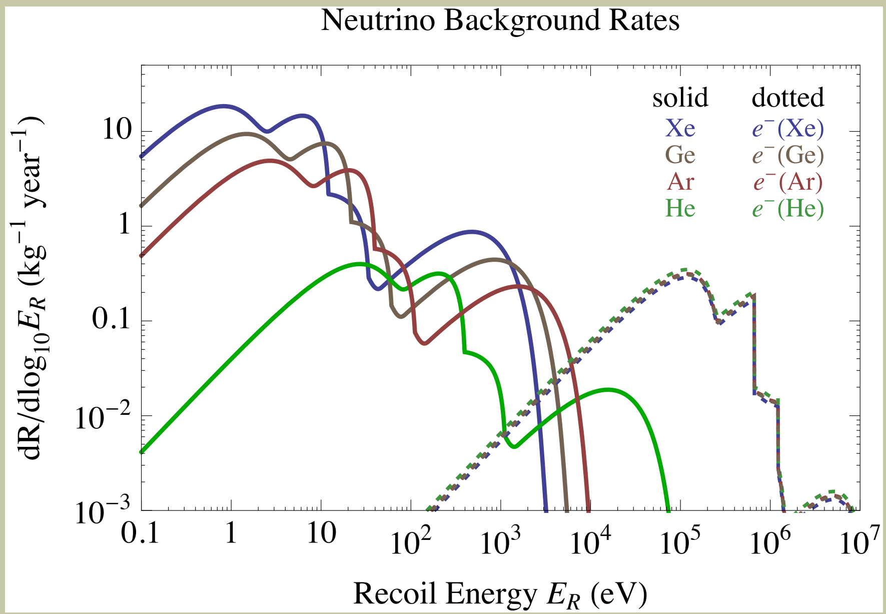
Can we discover light DM without a dedicated experiment?

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.

Technological Directions

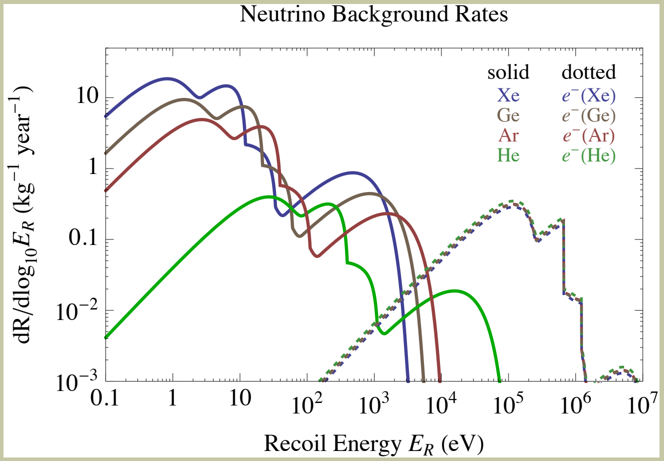
R&D needed in direct detection experiments

- Phonons Detectors: New studies claim 10 eV threshold with cryogenic solid state bolometers! Maybe possible in the near future. [Anderson et al. 2011]

- Photons Detectors: Current detectors have too large dark current (CCDs: 1 count/hour, PMTs: 1 count/sec). Could imply a higher threshold (few electrons), but still interesting.

- Molecular dissociation: Very interesting direction. Probes DM-nuclear interactions!!
  Problem is purification. No one knows...
  Might be a promising direction to measure the pp neutrino spectrum from the sun.

  [Work in progress with Tim Nelson, SLAC]
  [Essig,Grossman,Mardon,TV, work in progress]



XENON10 Cuts

TABLE I. Summary of cuts applied to 15 kg-days of dark matter search data, corresponding acceptance for nuclear recoils ε_c and number of events remaining in the range $1.4 < E_{nr} \leq 10$ keV.

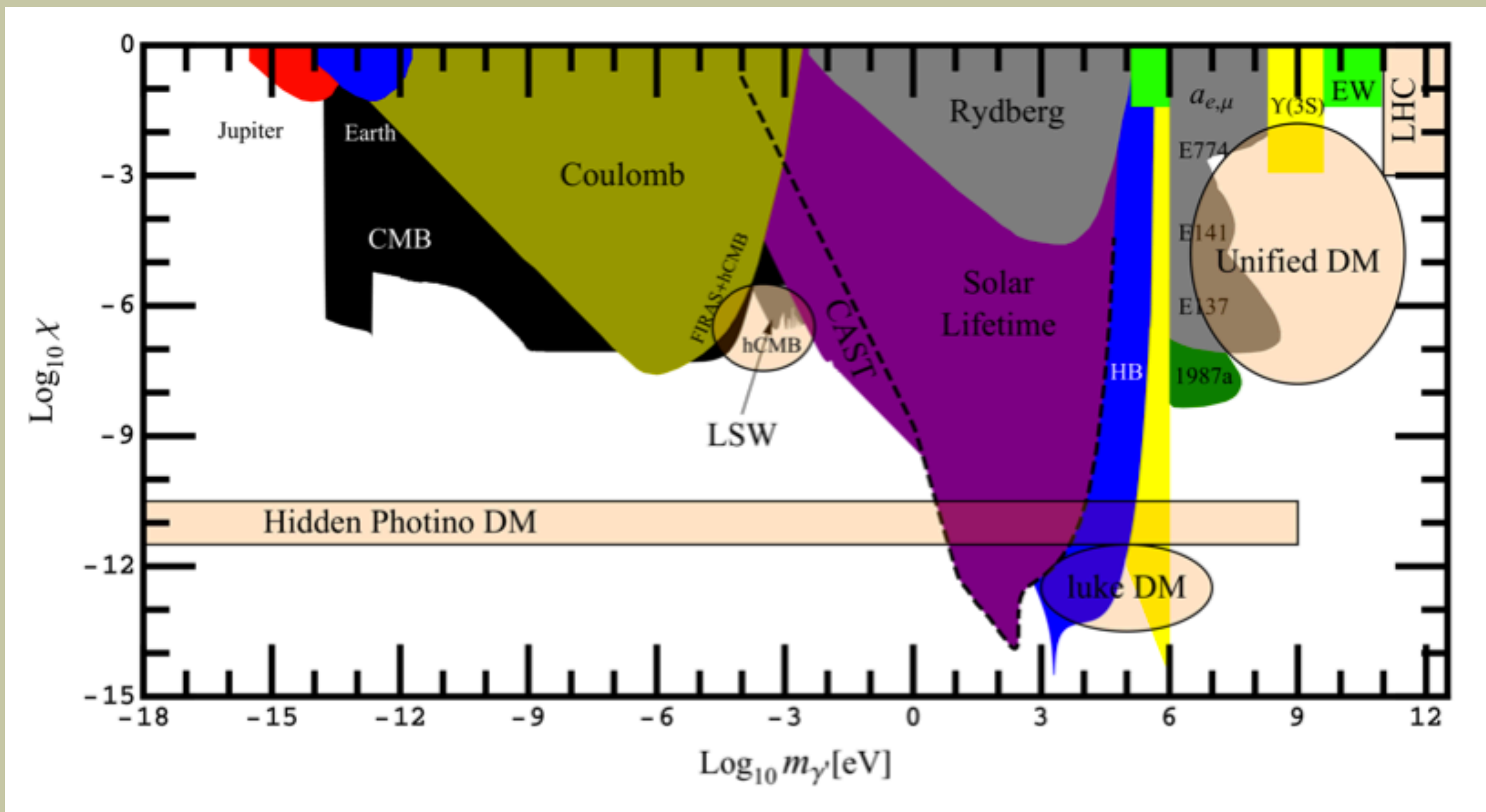
Cut description	ε_c	N_{evts}
1. event localization $r < 3$ cm	1.00^a	125
2. signal-to-noise	> 0.94	57
3. single scatter (single S2)	> 0.99	37
4. $\pm 3\sigma$ nuclear recoil band	> 0.99	22
5. edge (in z) event rejection	0.41^b	7

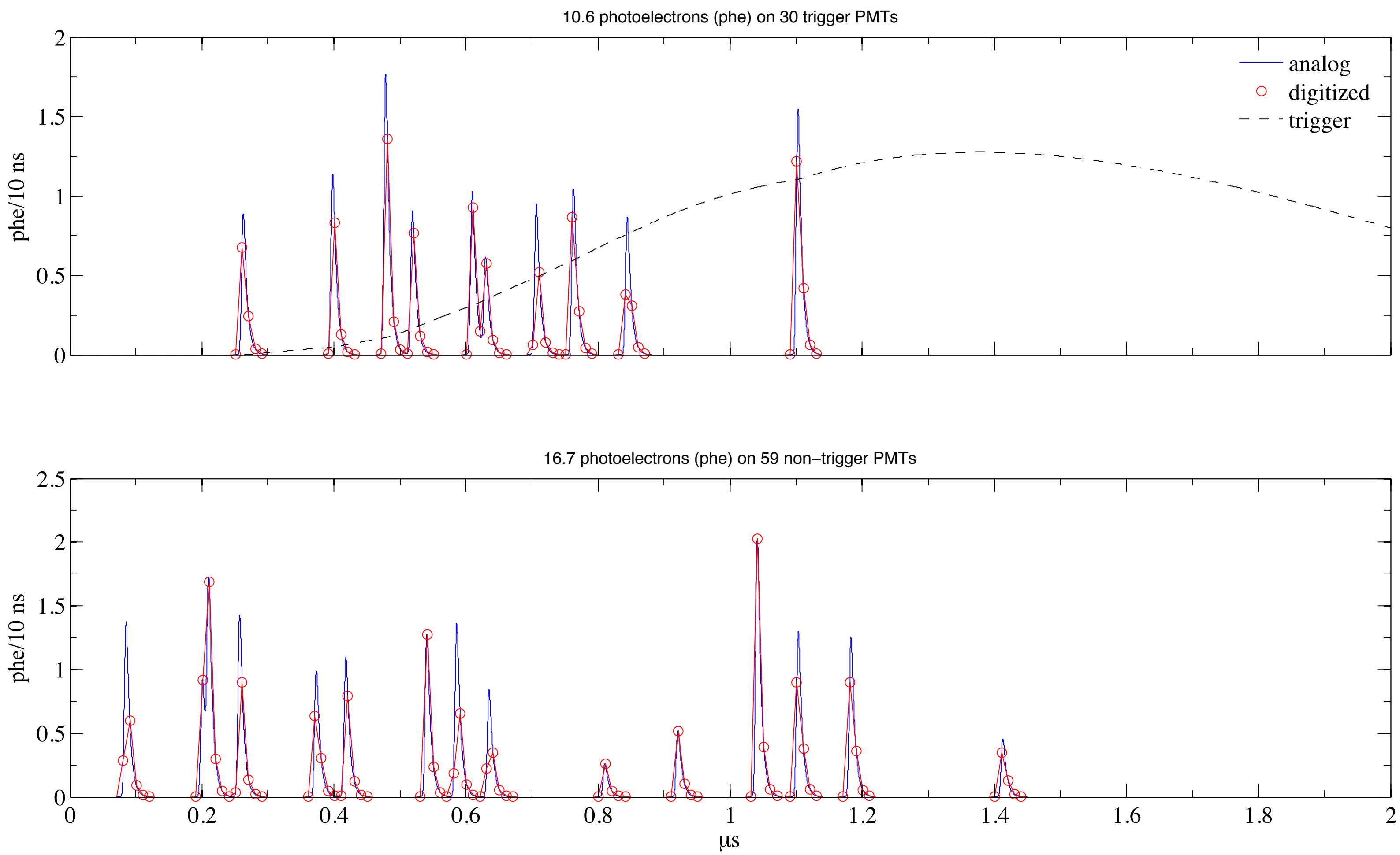
[a] limits effective target mass to 1.2 kg

[b] differential acceptance shown in Fig. 1

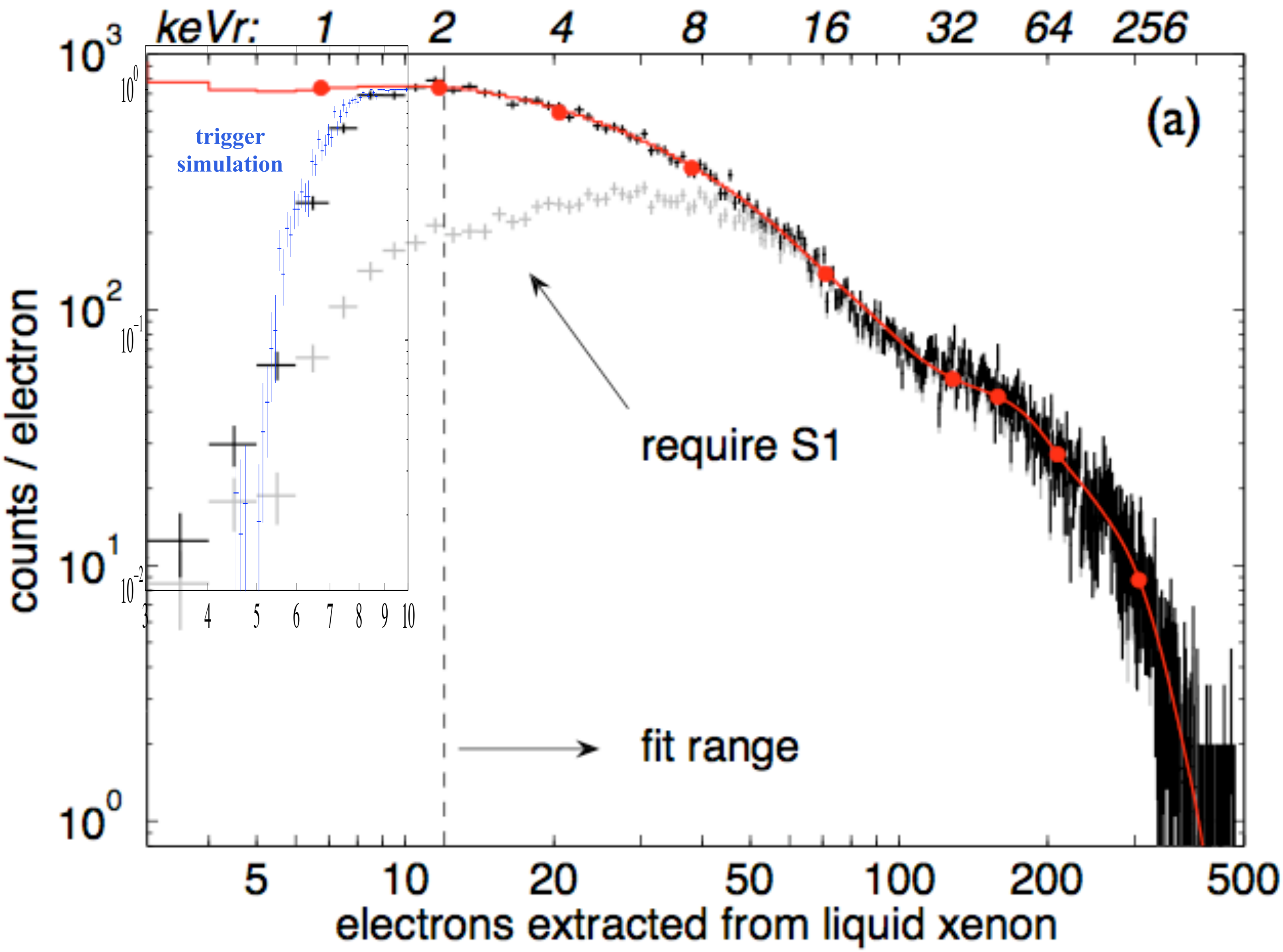
Hidden Photon Constraints

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



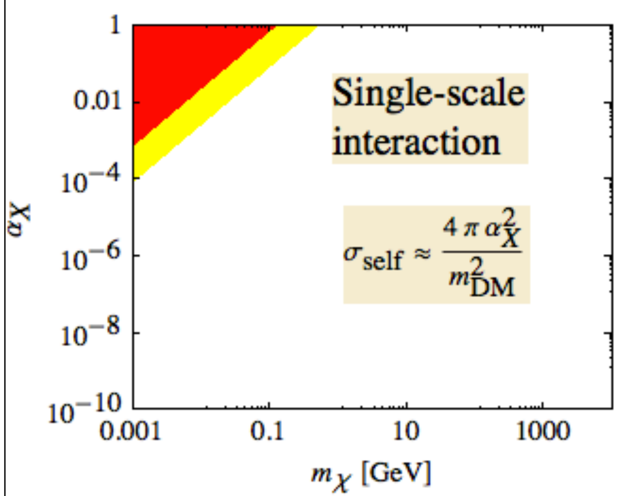


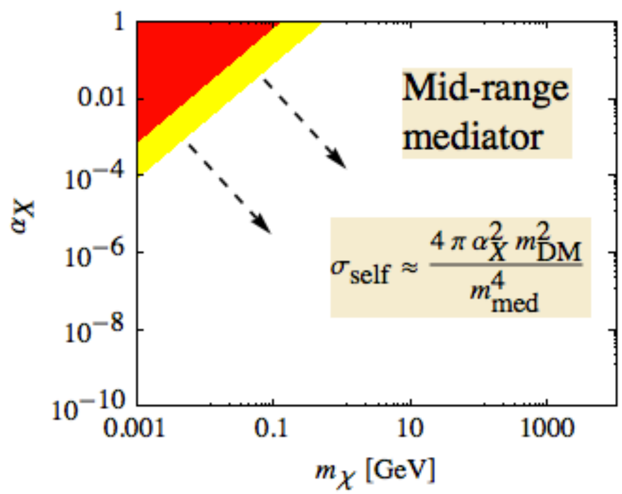
10.6 photoelectrons (phe) on 30 trigger PMTs
phe/10 ns
analog
digitized
trigger
16.7 photoelectrons (phe) on 59 non−trigger PMTs
phe/10 ns
μs

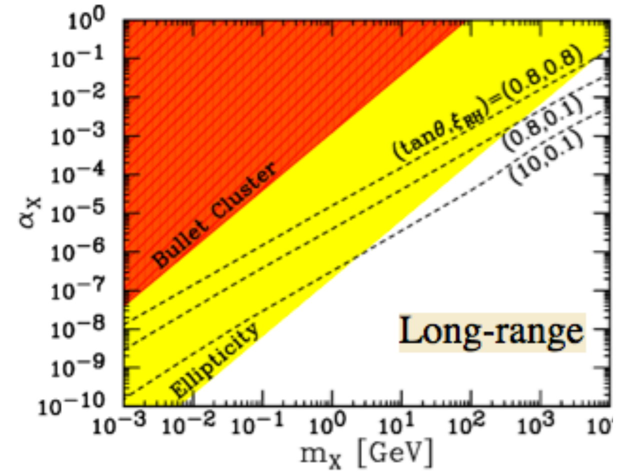


keVr:
1
2
4
8
16
32
64
256
(a)
trigger
simulation
require S1
fit range
counts / electron
electrons extracted from liquid xenon

DM Self Interactions







(approximate)

Feng et al 0905.3039