Going Beyond the WIMPs

New Avenues for Direct Detection of DM

GGI 2012

Tomer Volansky

Based on:

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

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, TV [arXiv:1206.2644].

More work in progress...

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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]

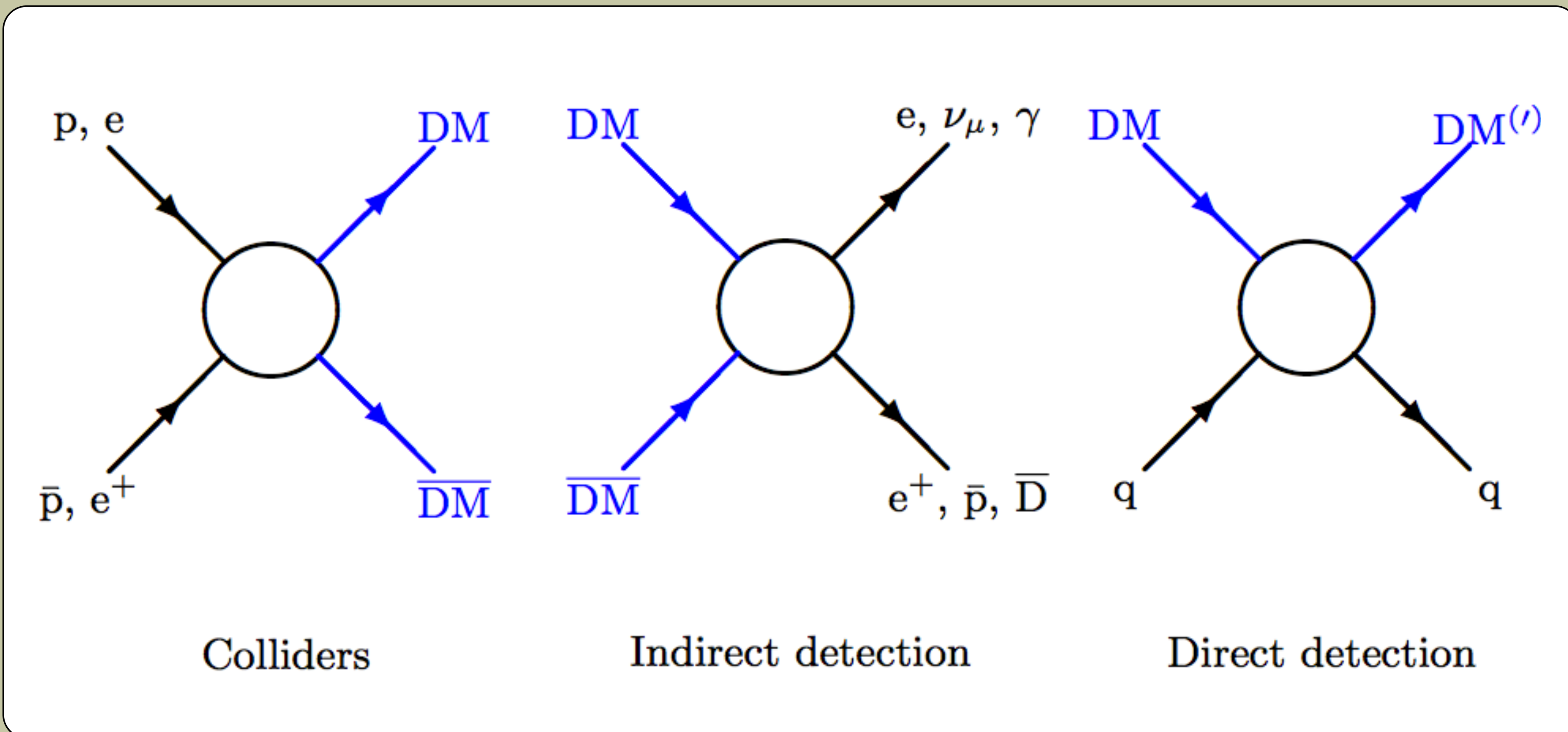
$$\langle \sigma v \rangle \sim 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$$

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

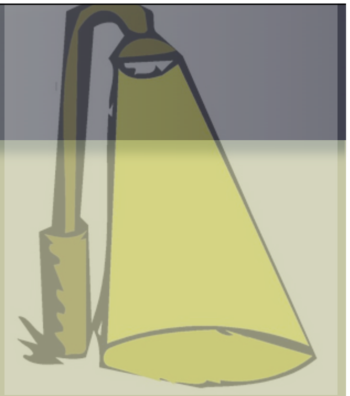
$$\langle \sigma v \rangle \simeq \frac{g^4}{m_{\mathrm{DM}}^2} \Longrightarrow \boxed{m_{\mathrm{DM}} \simeq 100\,\mathrm{GeV} - 1\,\mathrm{TeV}}$$

Detection of DM

- Three ways to detect DM:



Looking Under the Lamppost..



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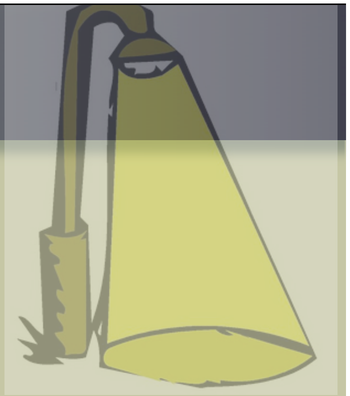

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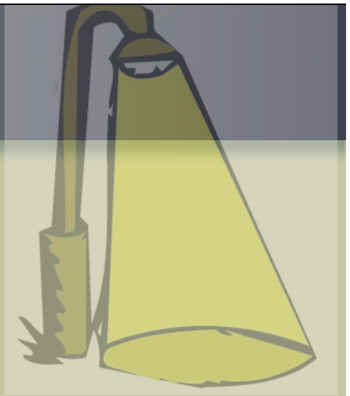

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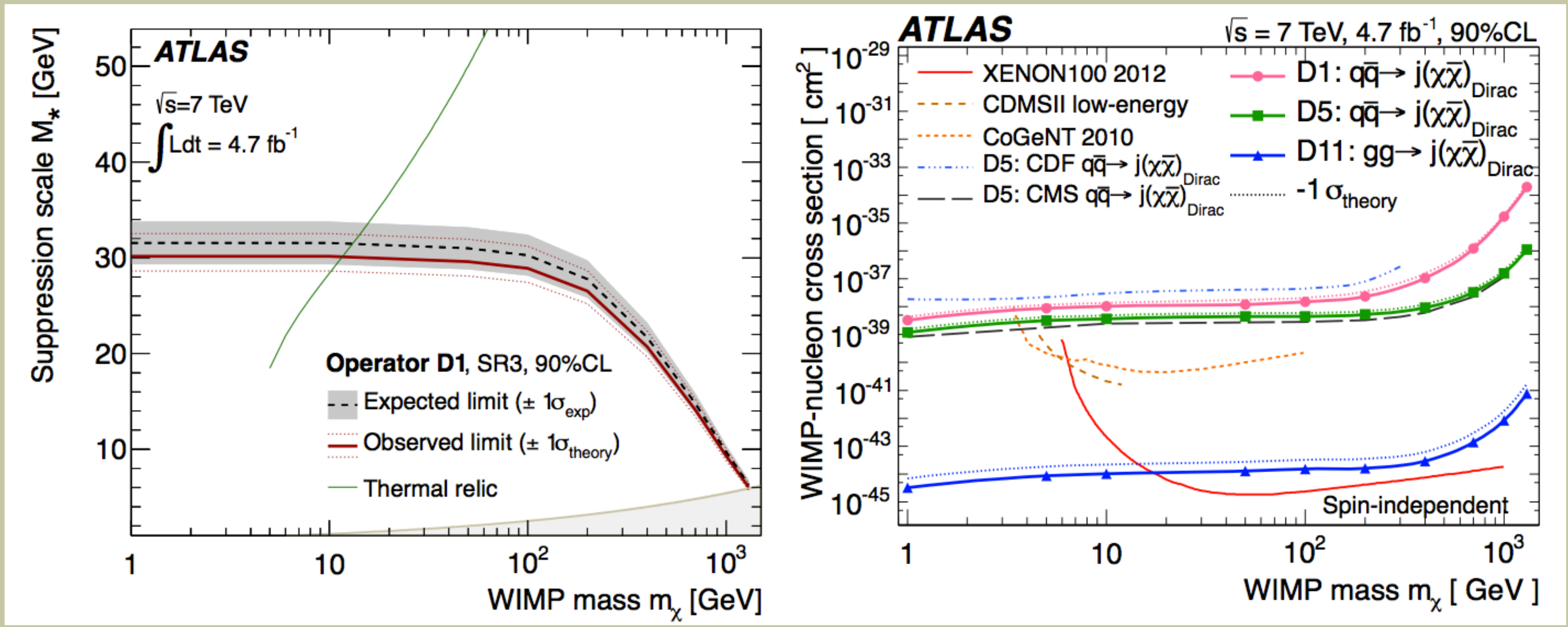

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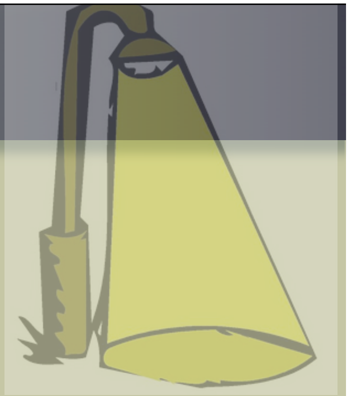

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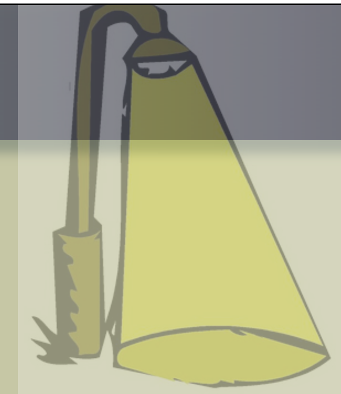

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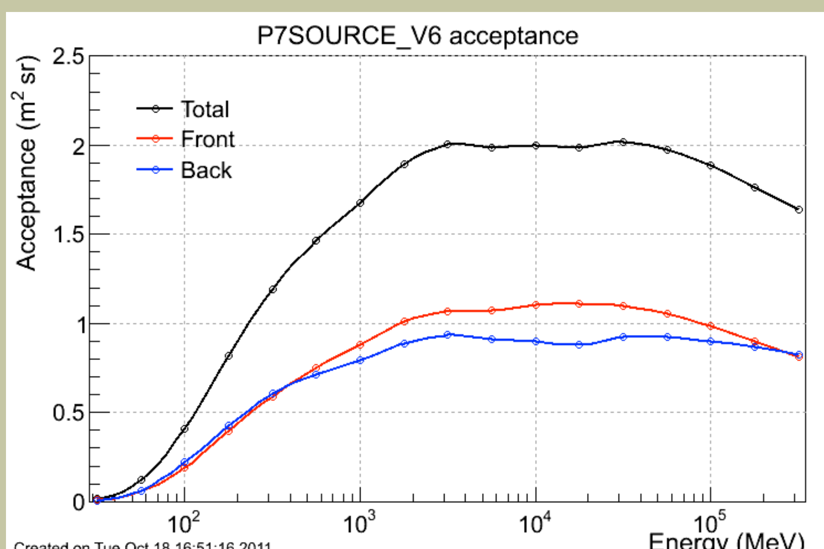

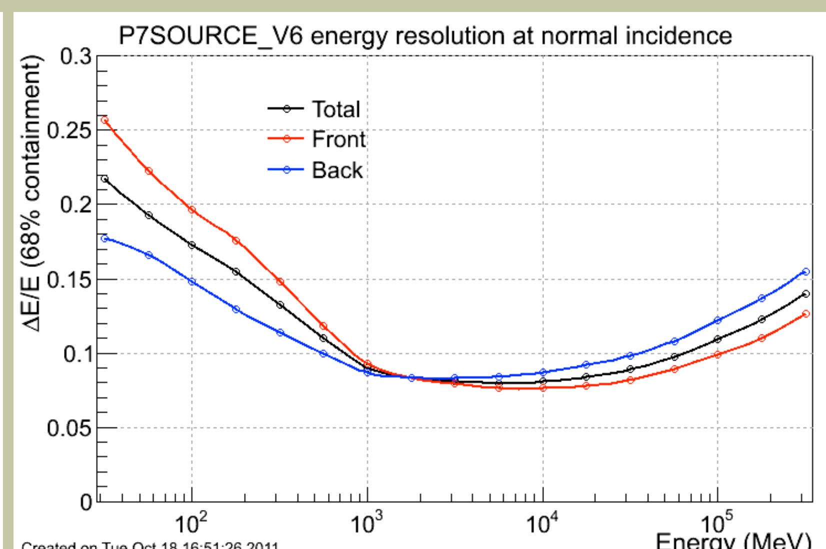

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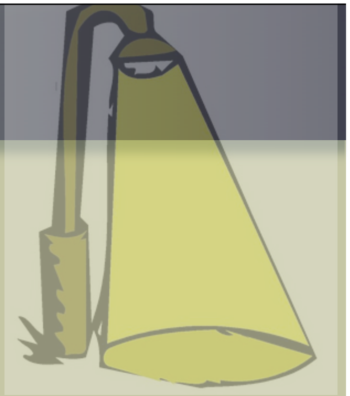

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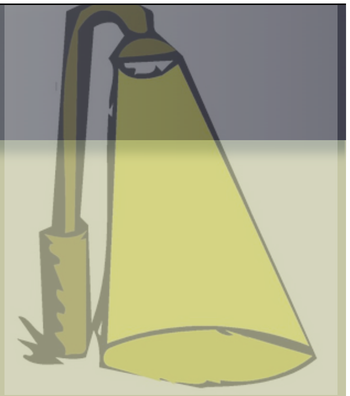

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  - Indirect Detection: Large CR BG at low energy ($E^{-2.8}$) and effective area limit low scale, while at high energy particle identification and energy resolution deteriorates quickly.
  - Direct Detection: Kinematically, rate of elastic DM-nucleon scattering is maximized when $m_{DM} \sim m_{nucleon} \sim 100$ GeV.

$$E_{nr} = \frac{q^2}{2m_N} \qquad q^2 = 2\mu^2 v_{\rm DM}^2 (1 - \cos\theta^*)$$

Obsessed with the WIMP..

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

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"We will see it as soon as the LHC turns on..."

Our experimental effort is strongly focused on the WIMP!

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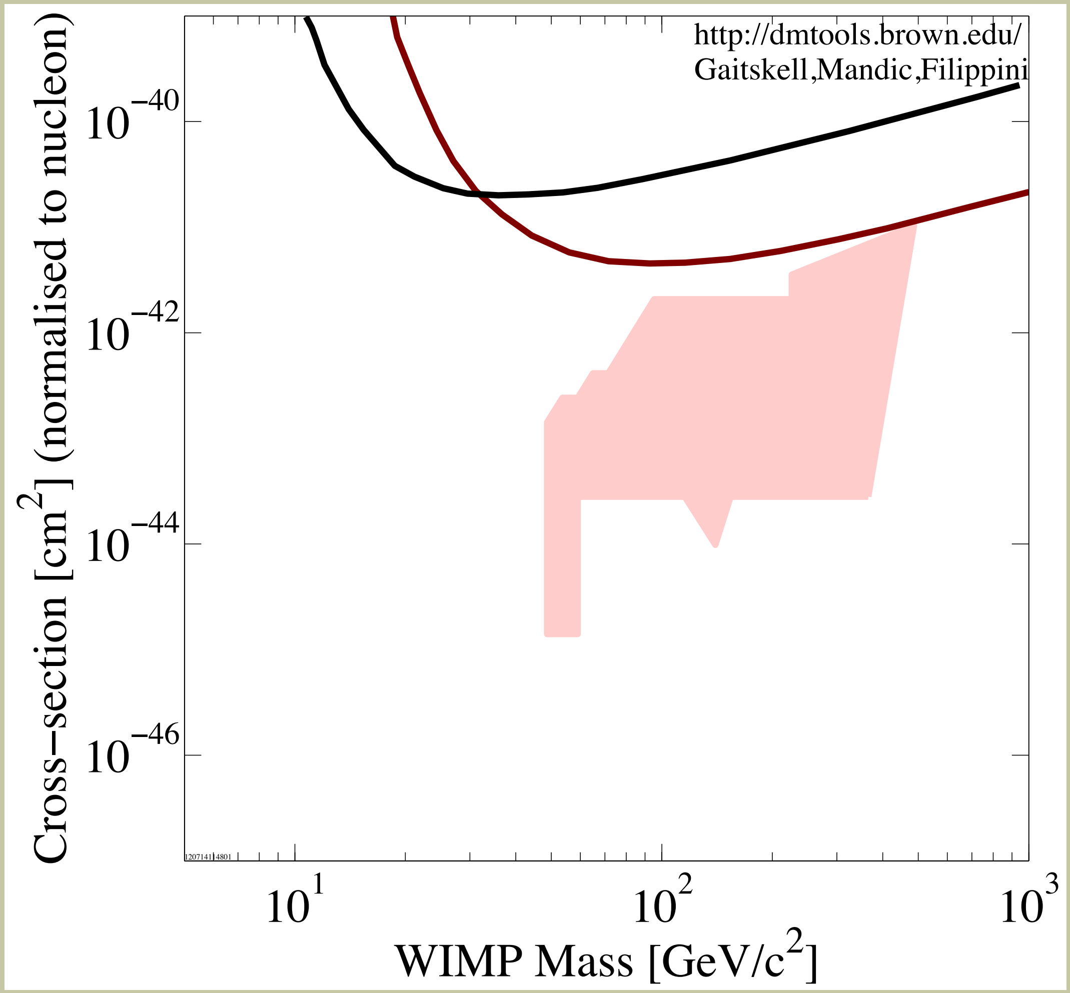
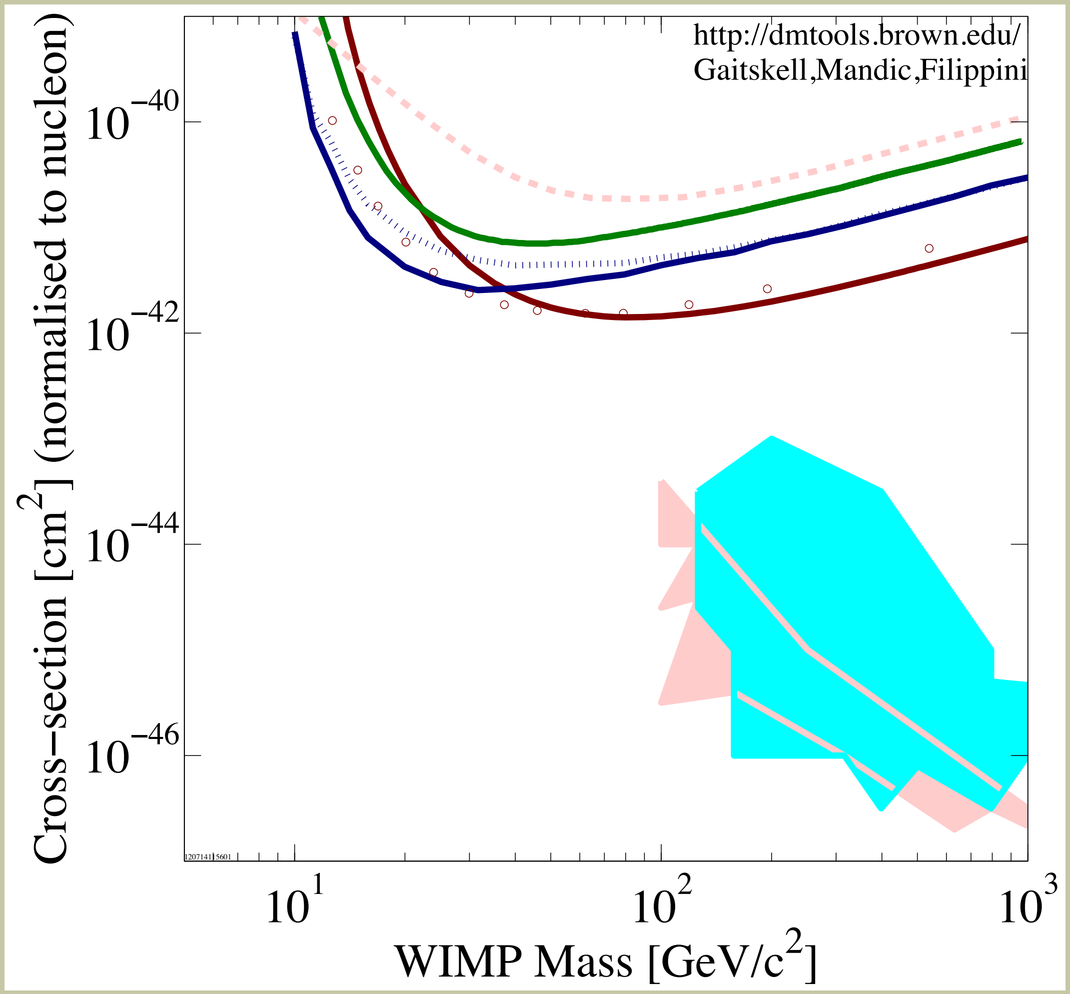
So how confident are we???

30 Seconds on the progress of direct detection...

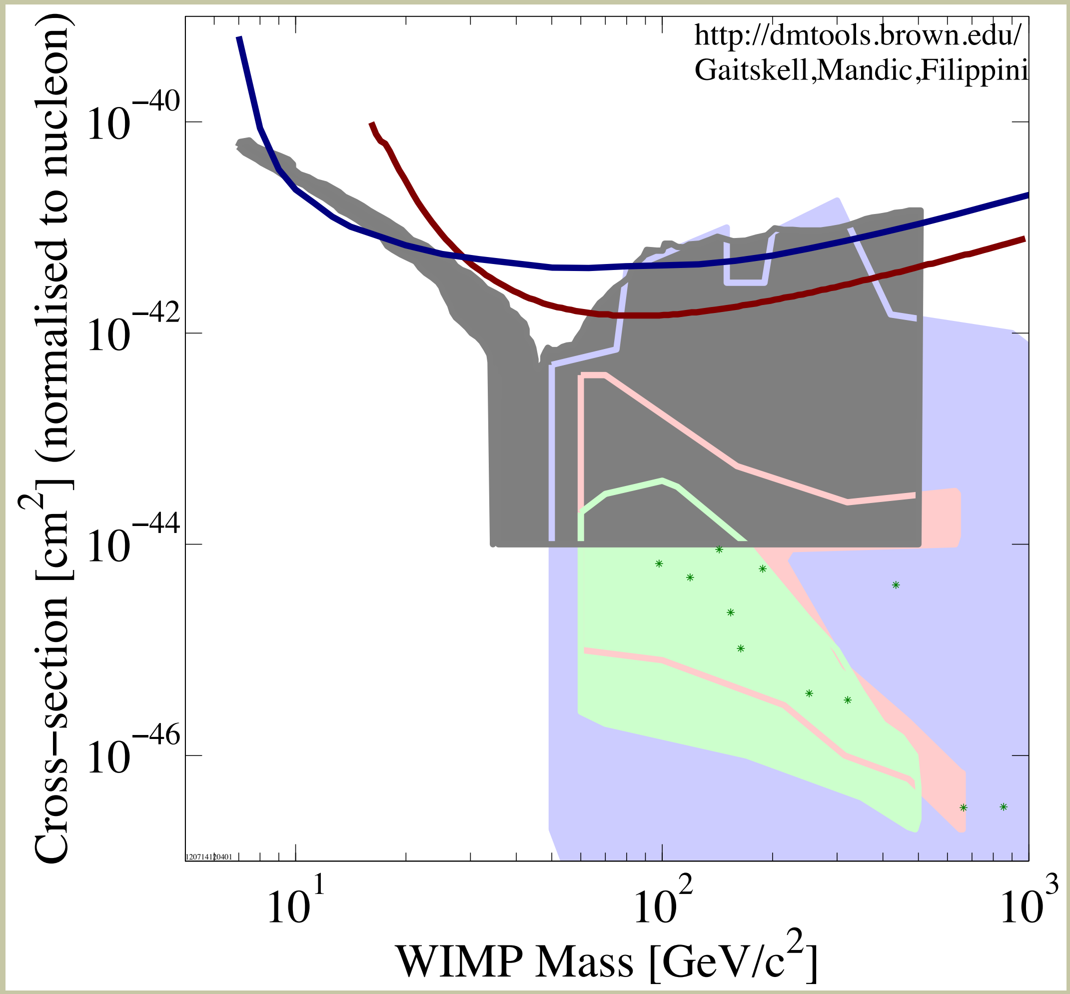
Direct Detection Limits: 2001



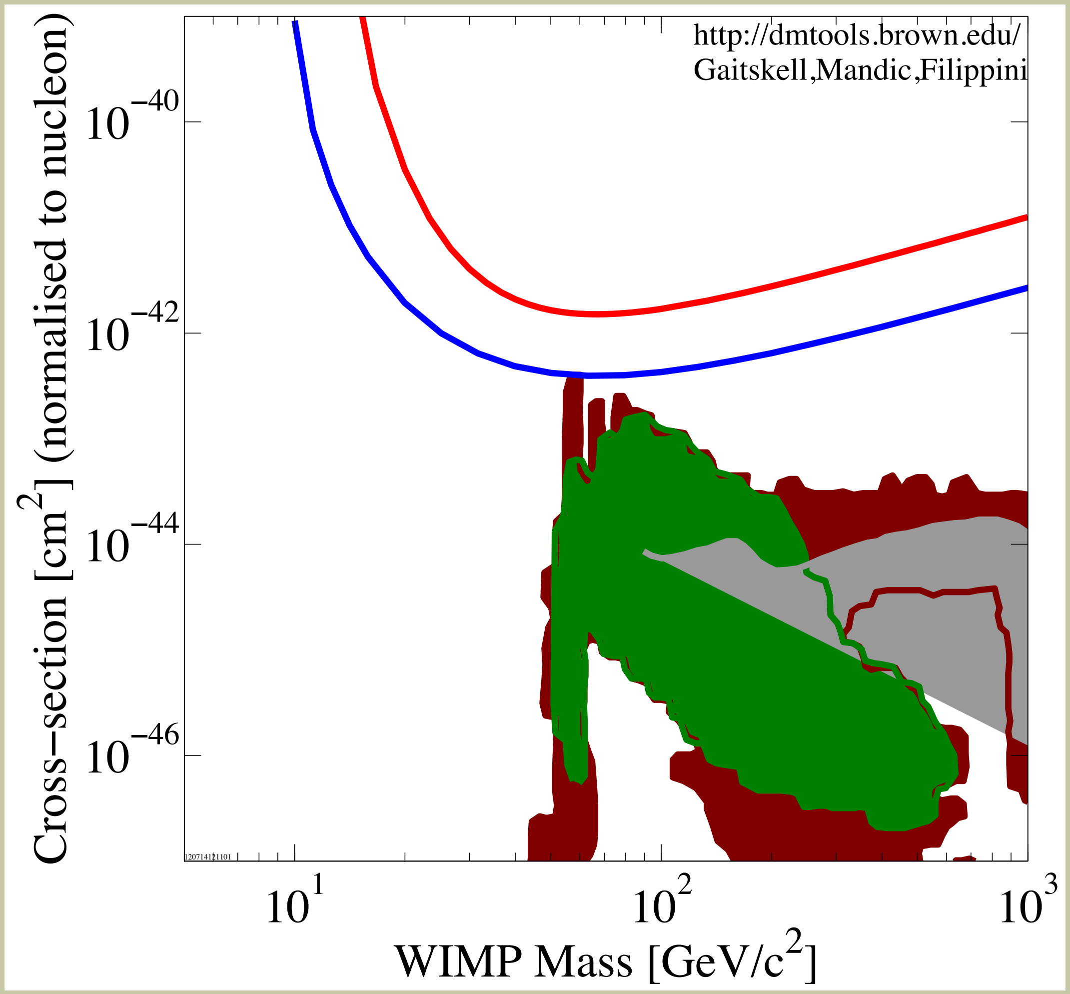
Direct Detection Limits: 2002



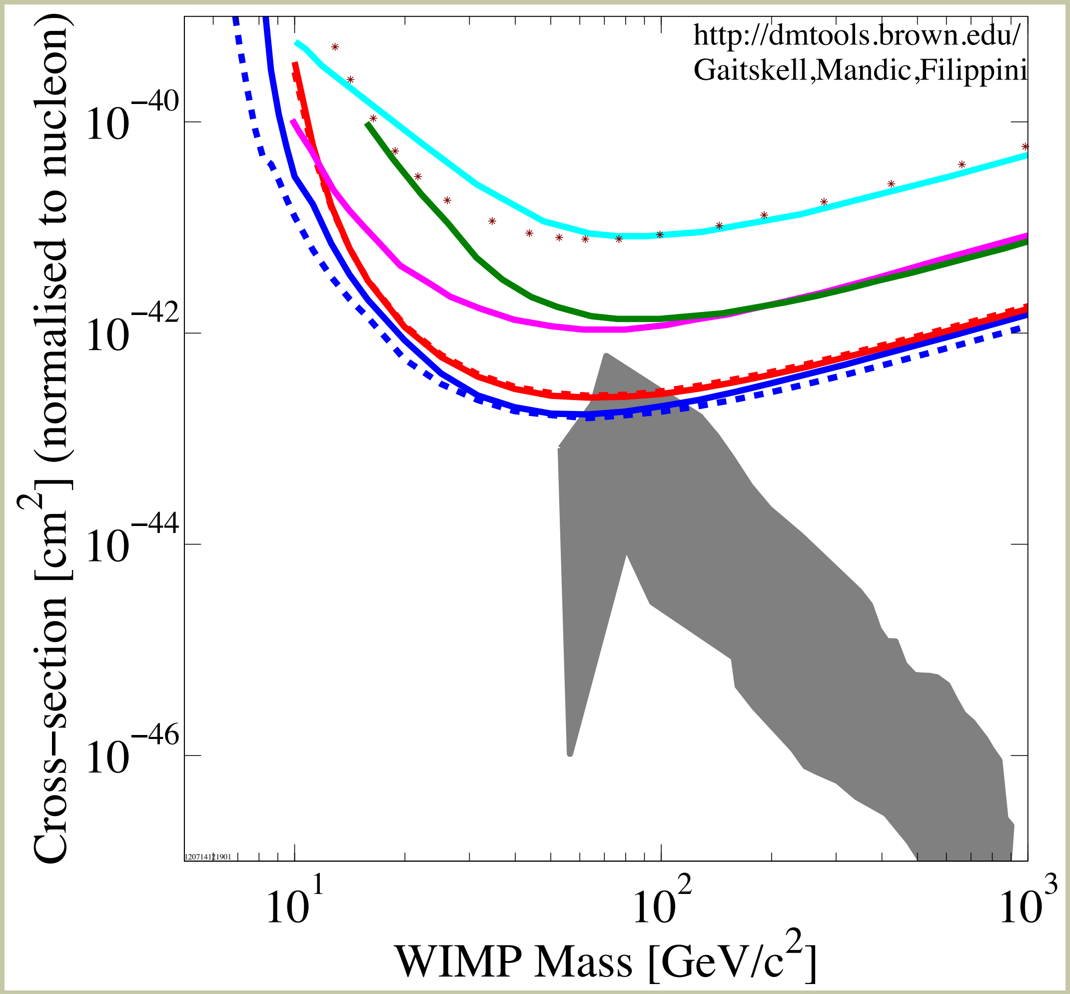
Direct Detection Limits: 2003



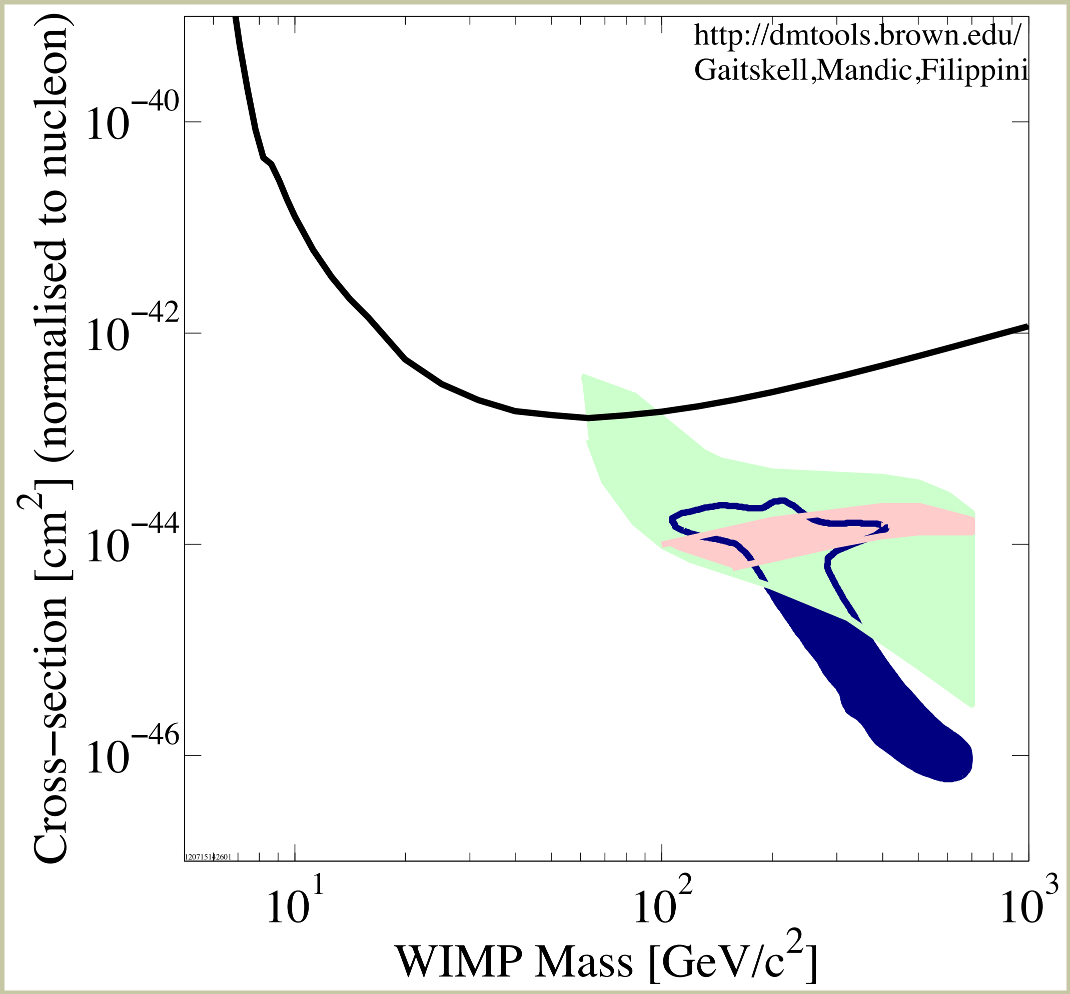
Direct Detection Limits: 2004



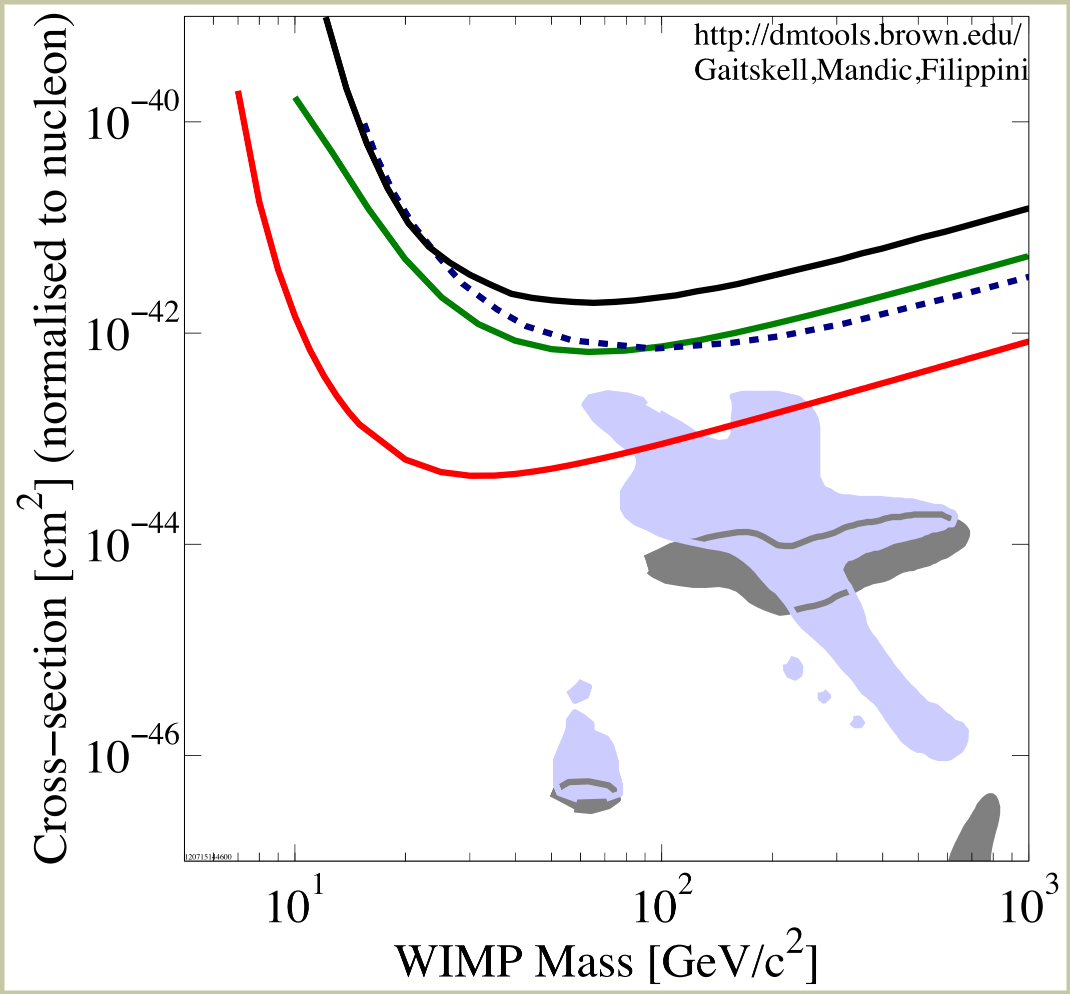
Direct Detection Limits: 2005



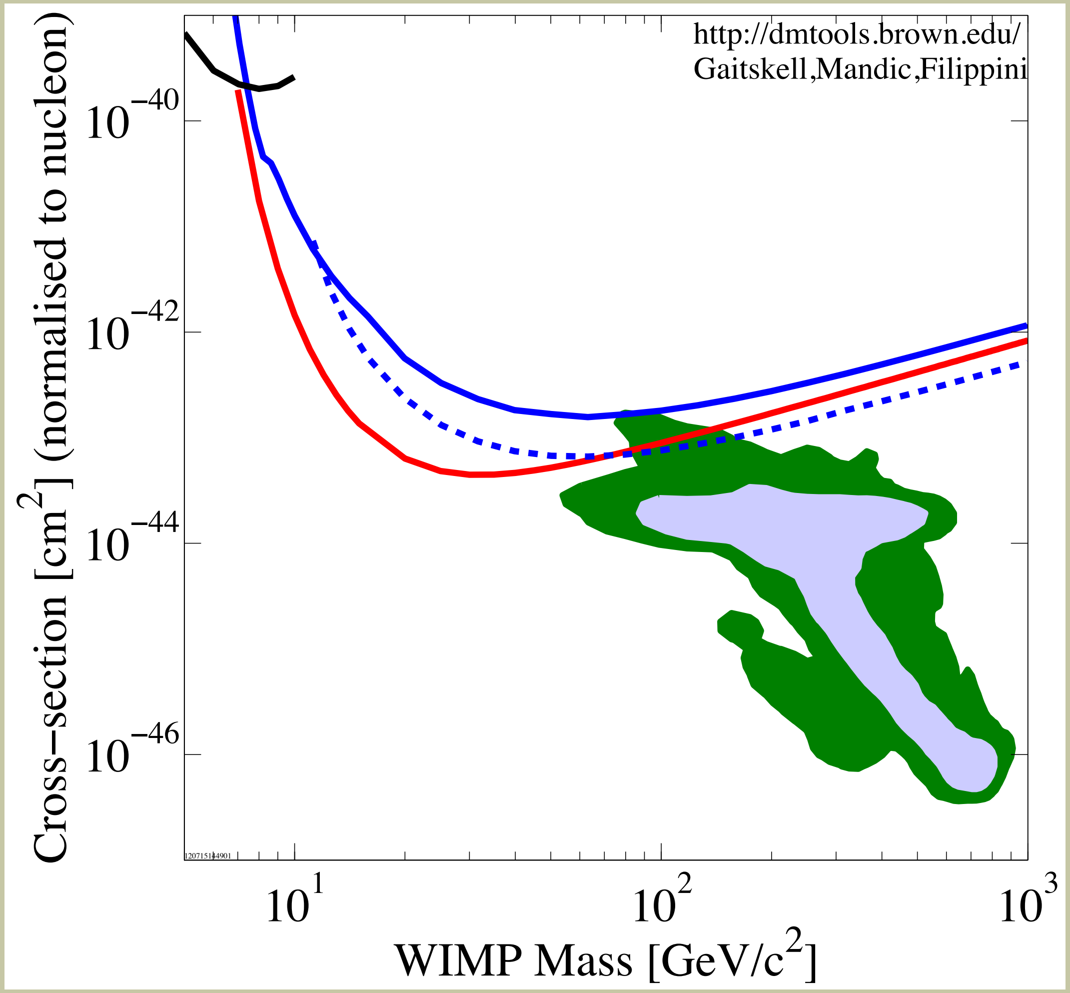
Direct Detection Limits: 2006



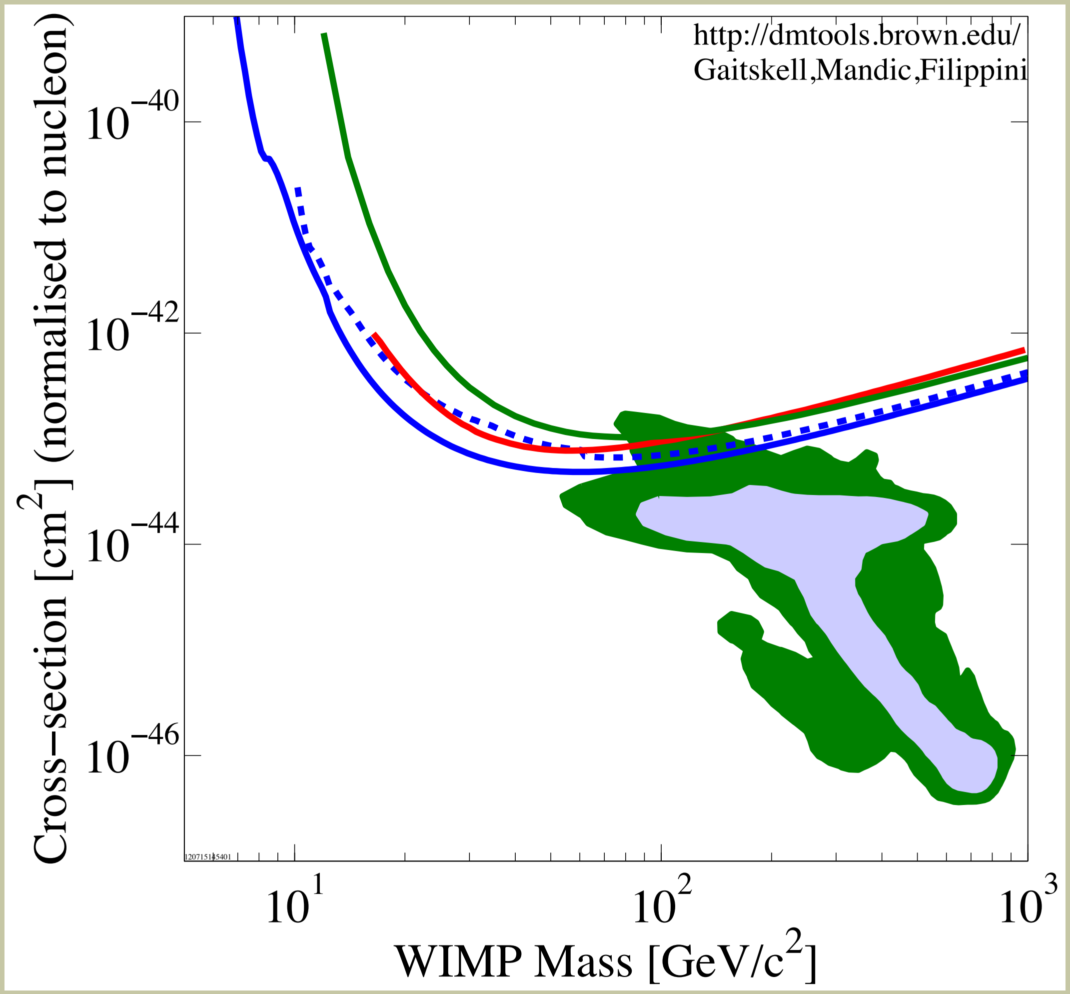
Direct Detection Limits: 2007



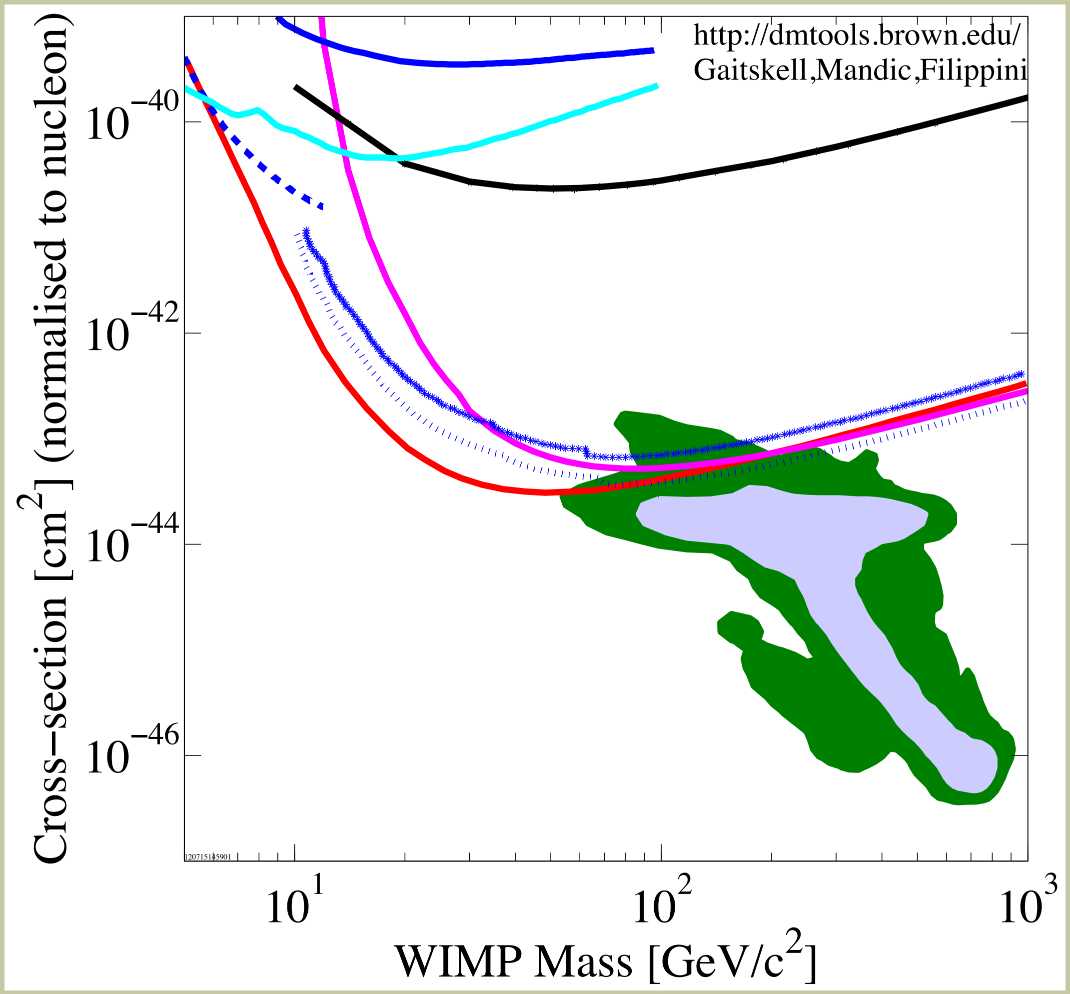
Direct Detection Limits: 2008



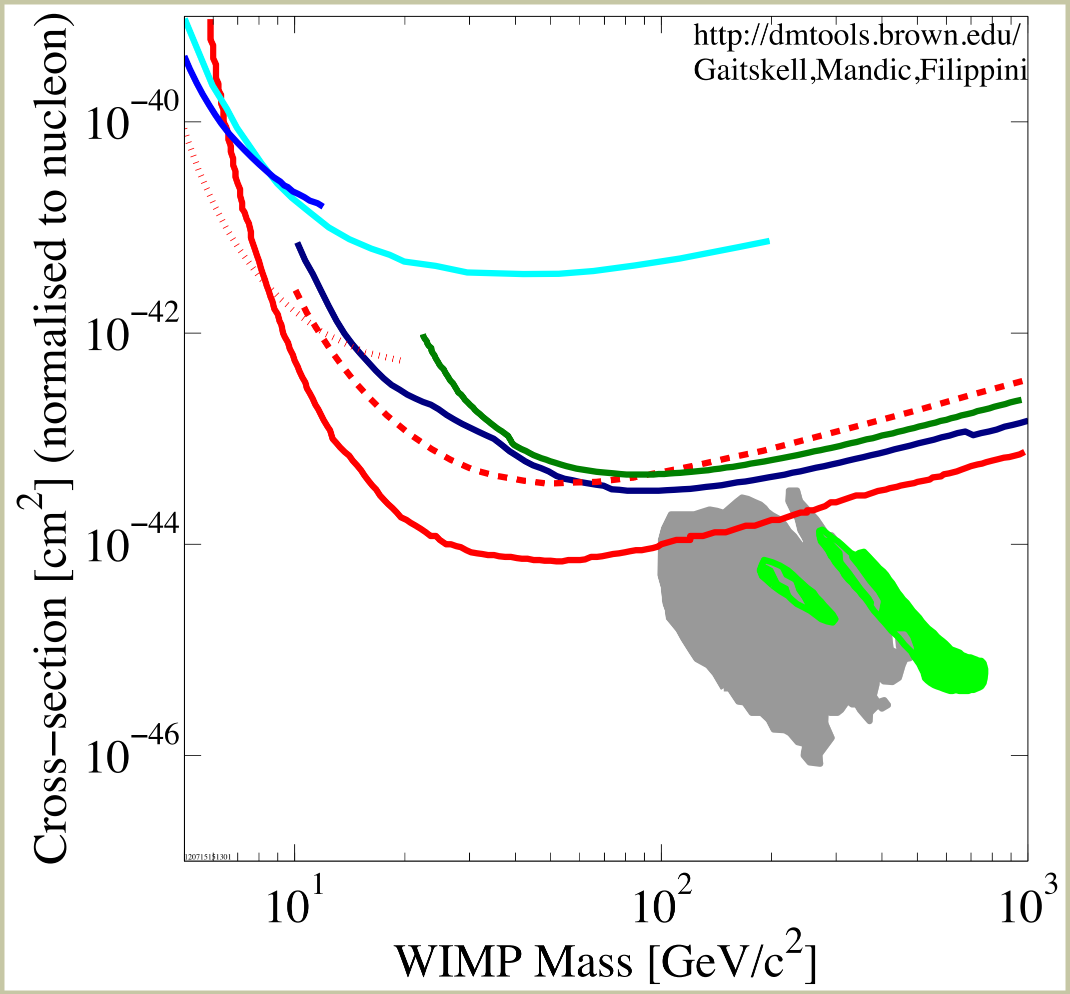
Direct Detection Limits: 2009



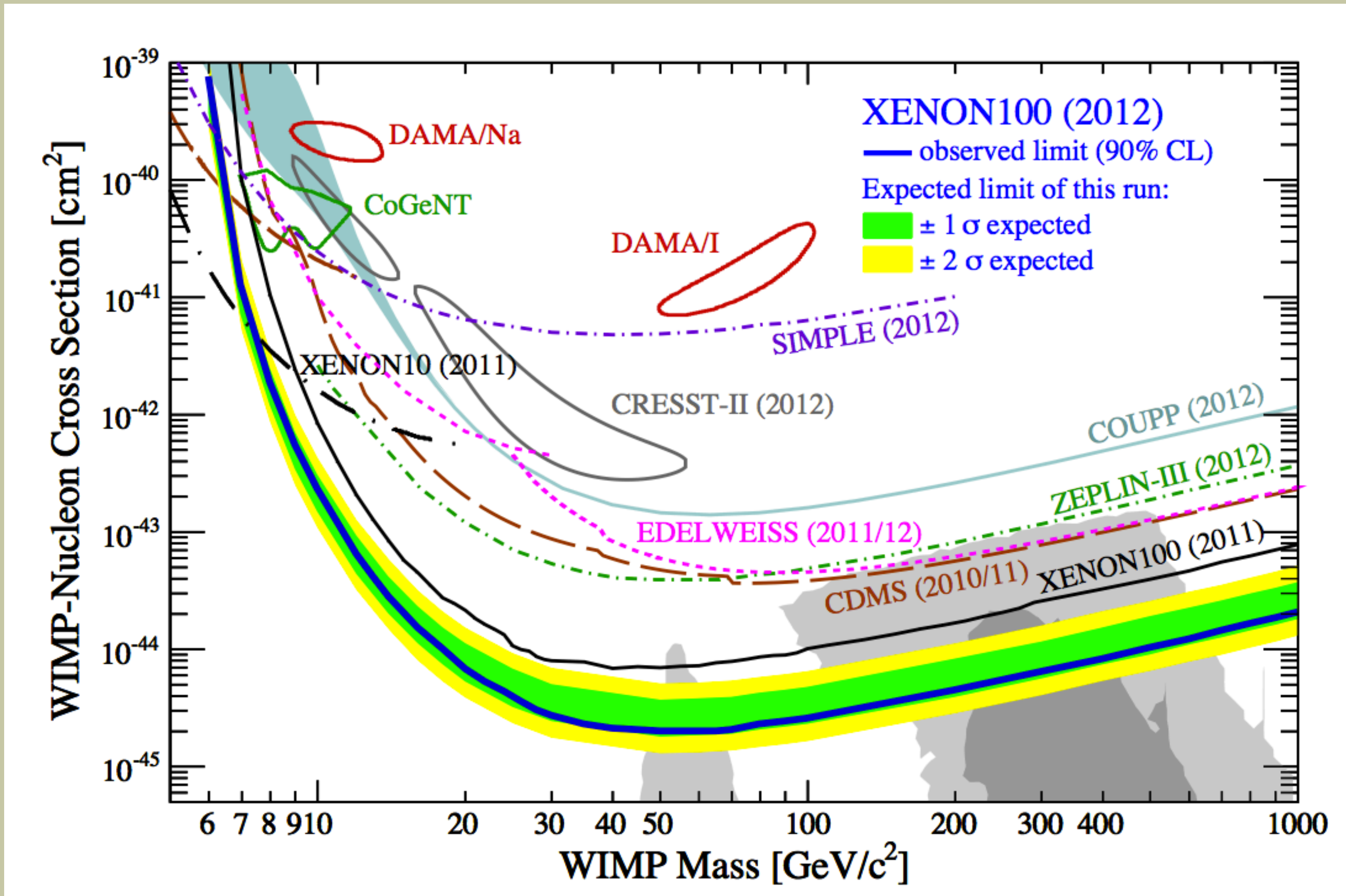
Direct Detection Limits: 2010



Direct Detection Limits: 2011



Direct Detection Limits: 2012



Strongest bound at 55 GeV: 2×10^{-45} cm^2 @ 90% CL

The Fun Part of Direct Detection...

XENON100: Basics

detector
schematic

two-phase xenon time projection chamber

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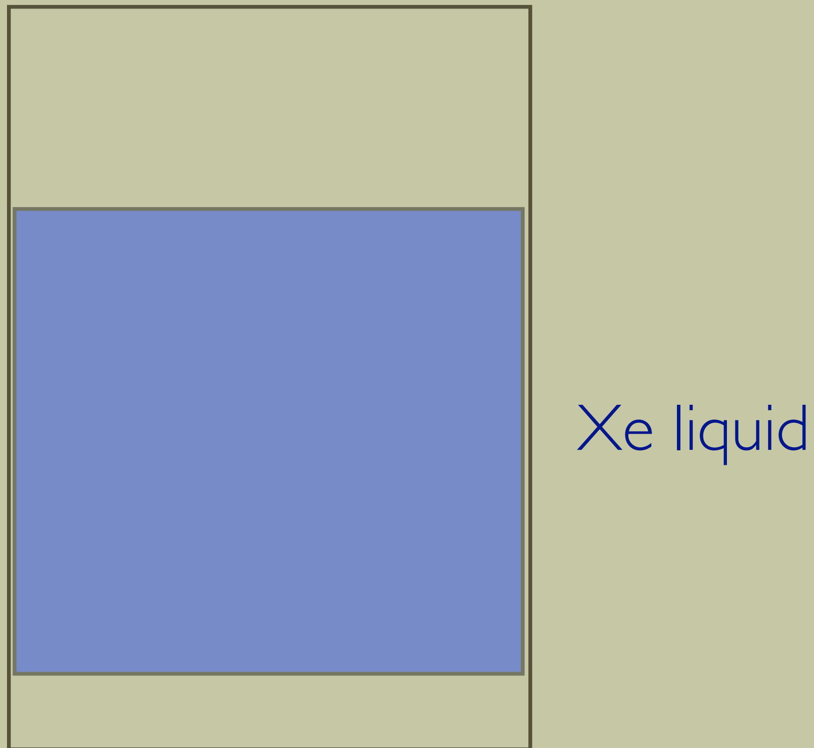
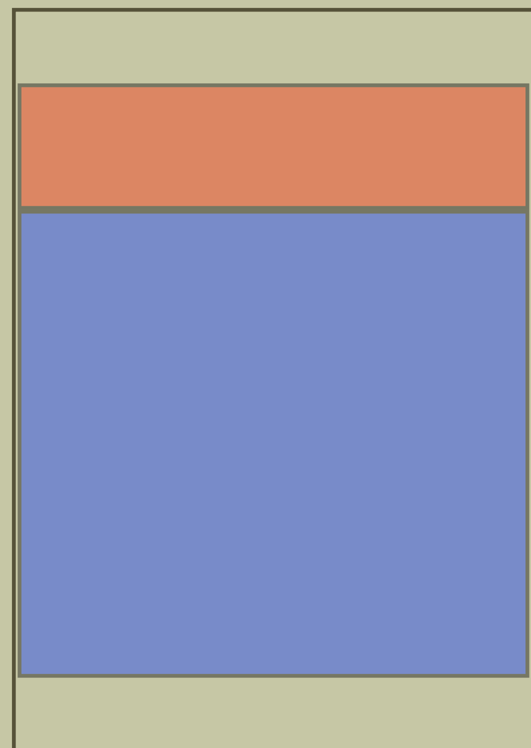


two-phase xenon time projection chamber

XENON100: Basics

detector schematic



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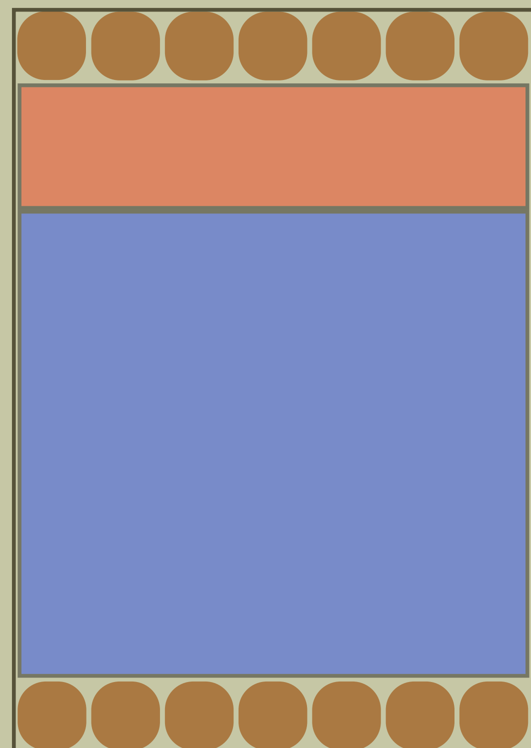

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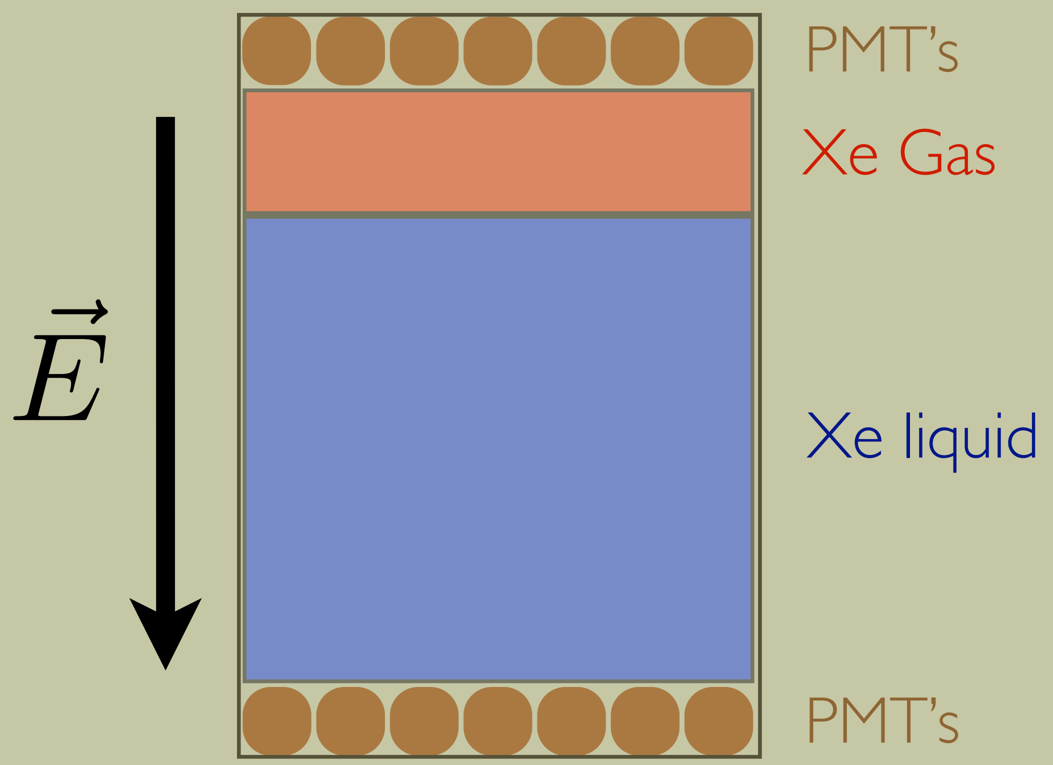
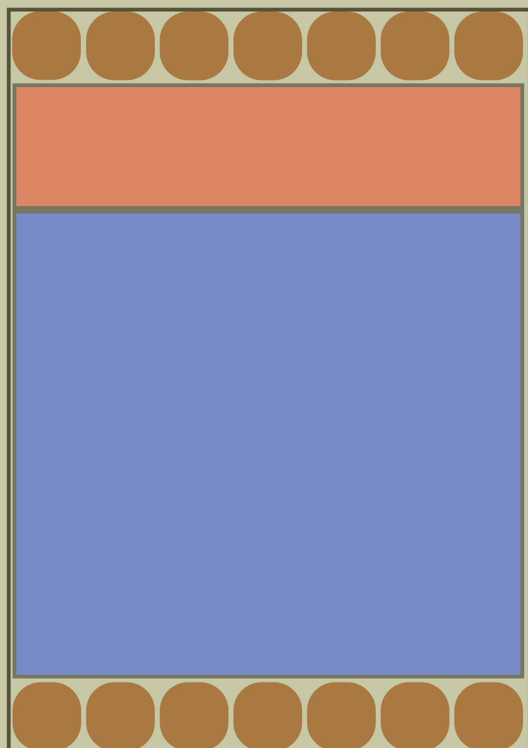


two-phase xenon time projection chamber

XENON100: Basics

Heavy DM



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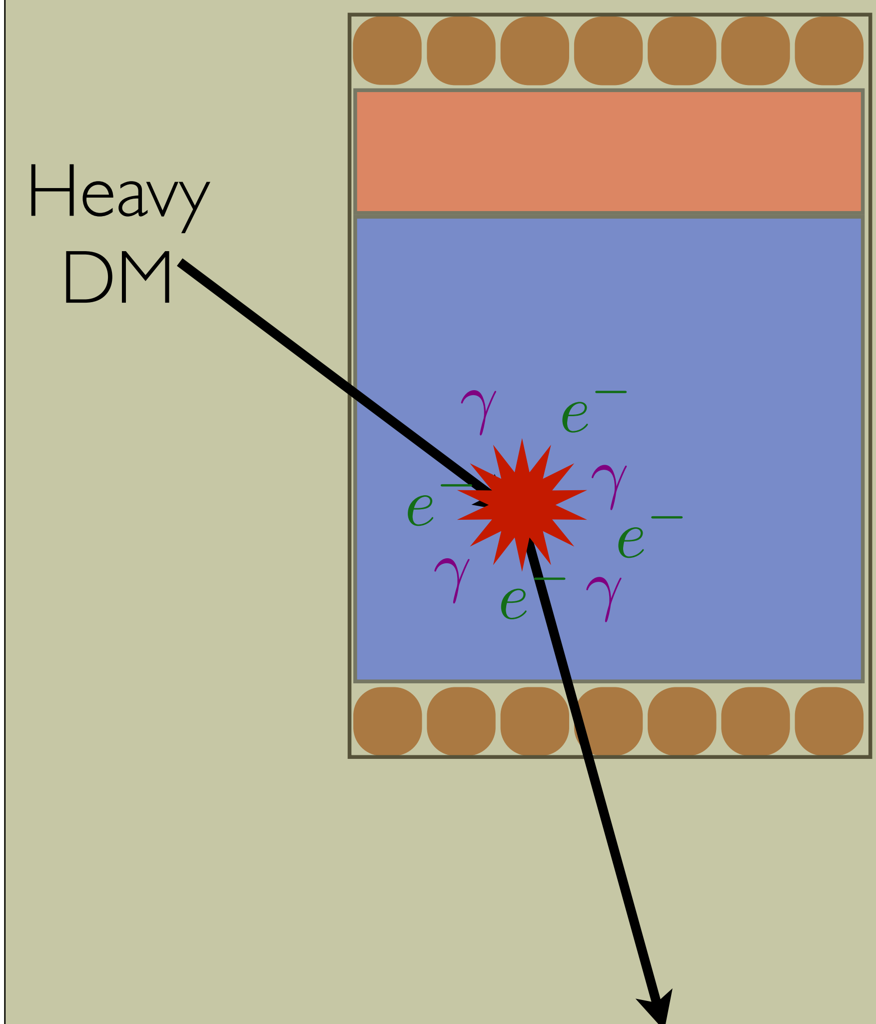

$$\mathrm{Xe} \rightarrow \mathrm{Xe}^*, \mathrm{Xe}^+$$

produces photons and electrons

Two types of signal:

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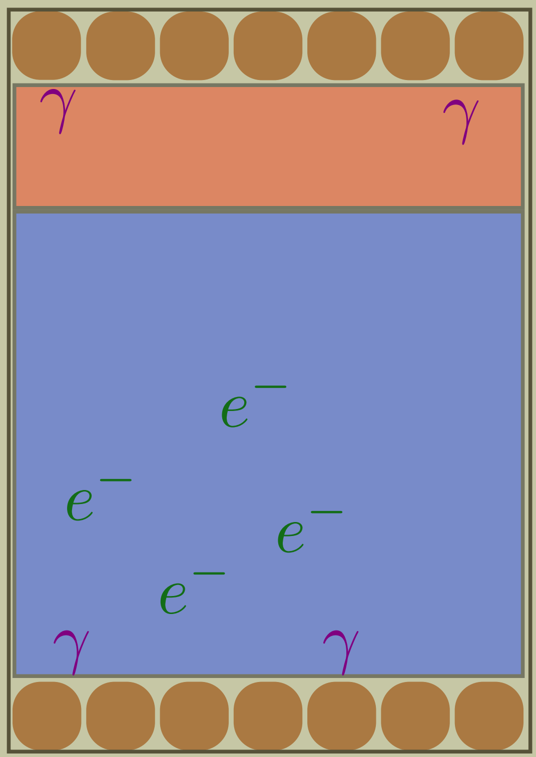

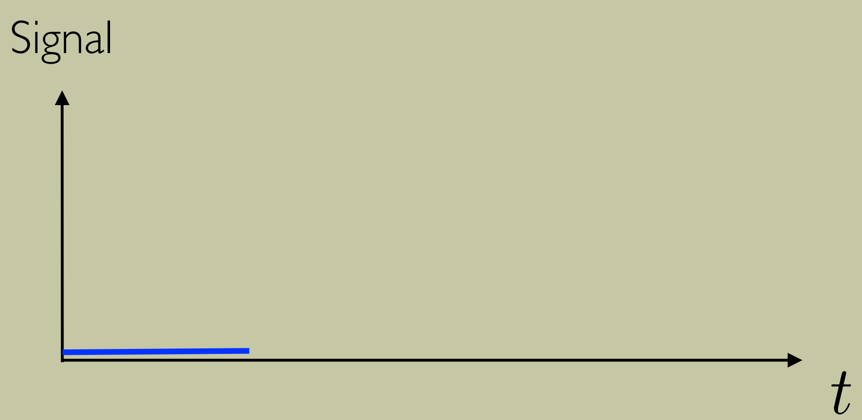

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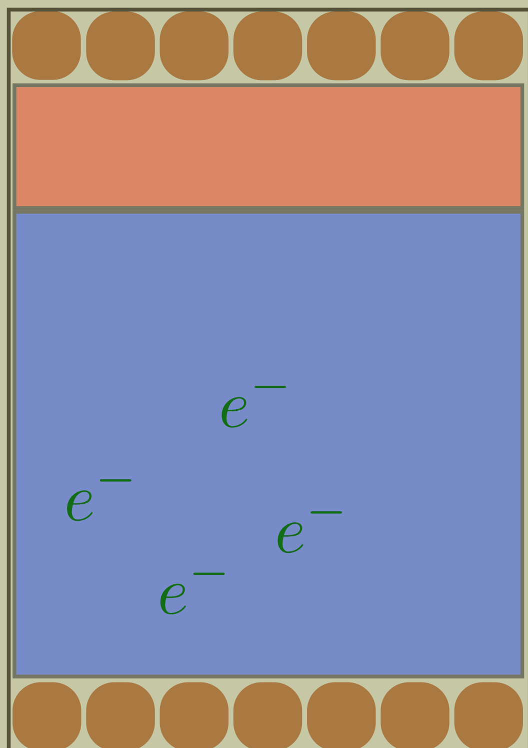
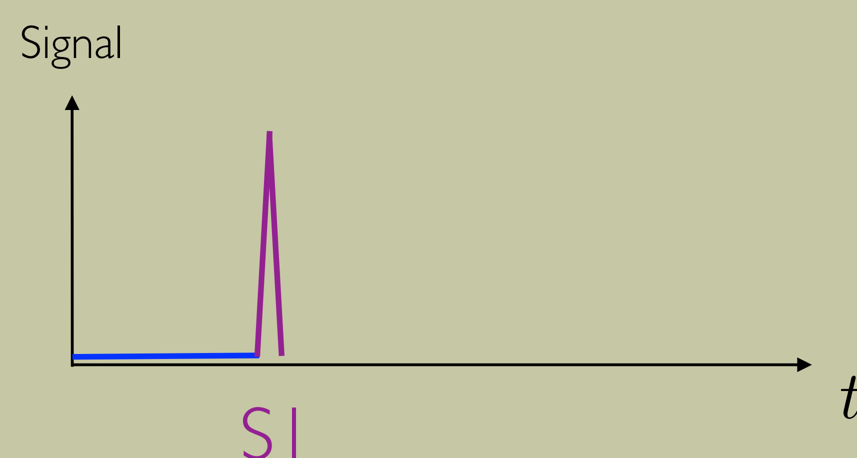


Two types of signal:

S1: prompt scintillation



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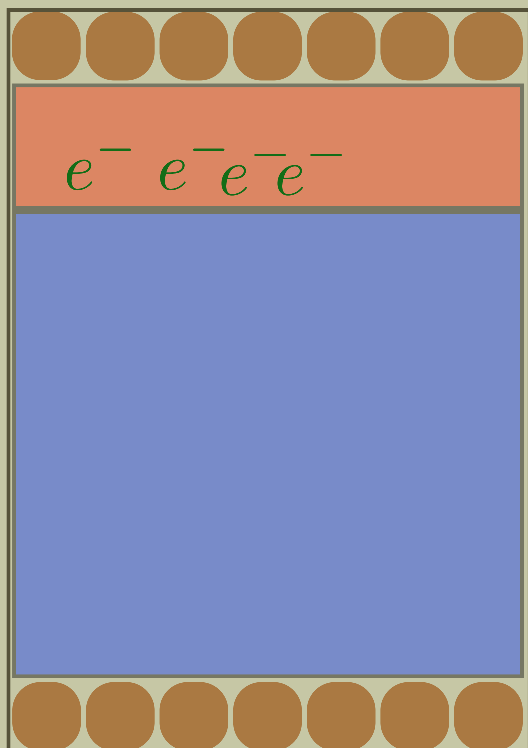

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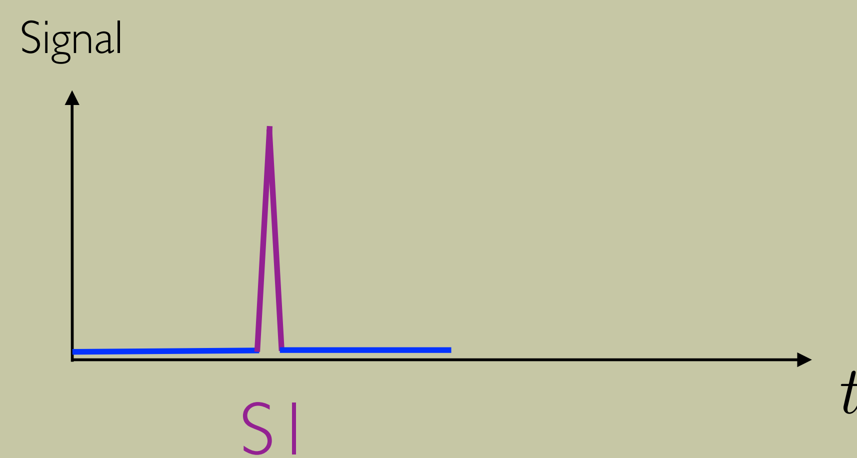

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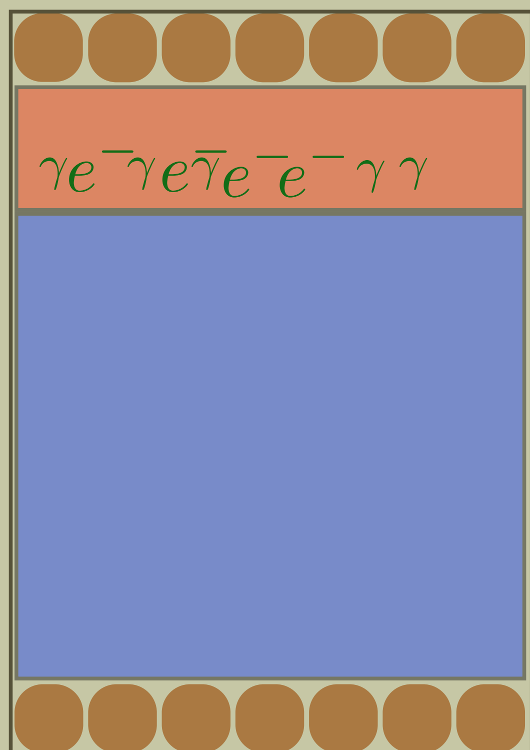

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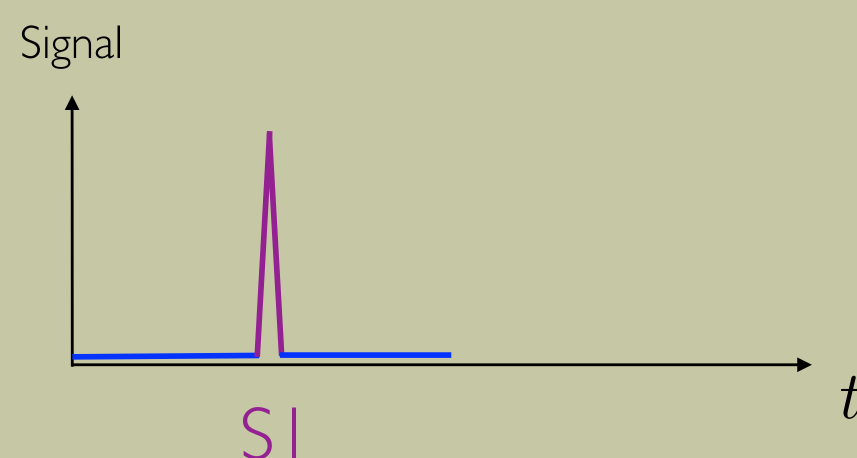

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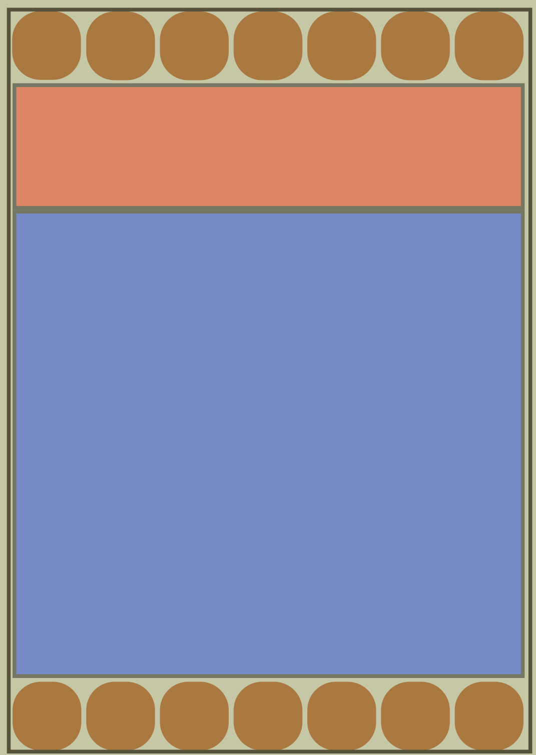

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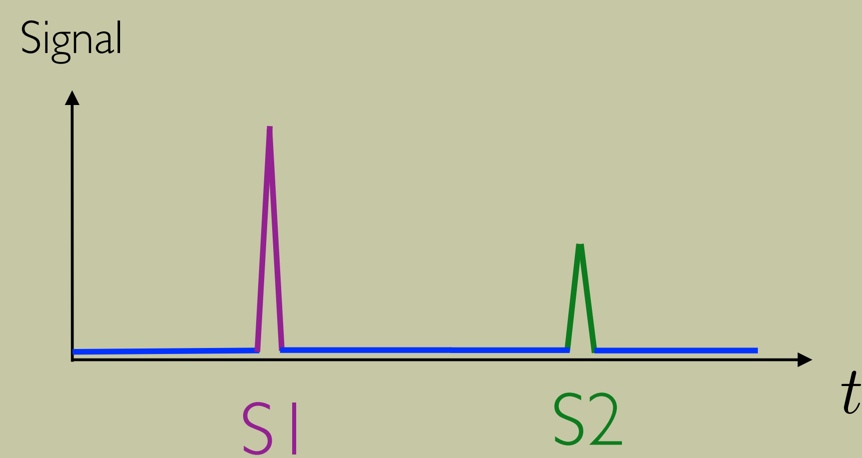
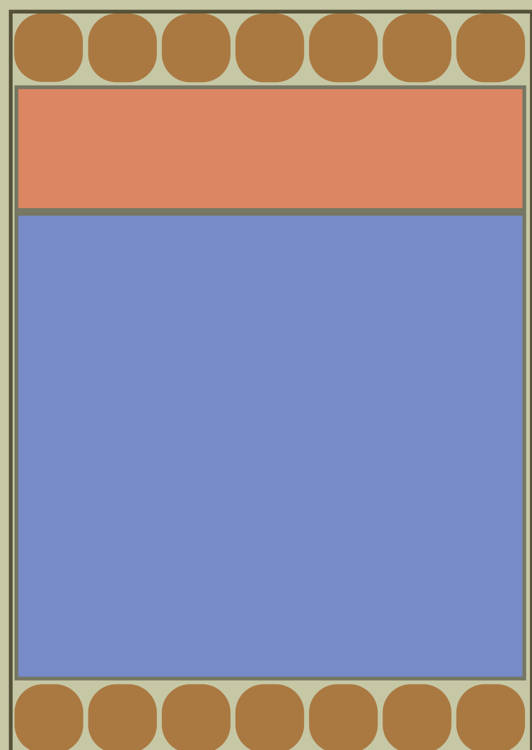
S2: proportional scintillation (from ionization)



XENON100: Basics

e^-, γ



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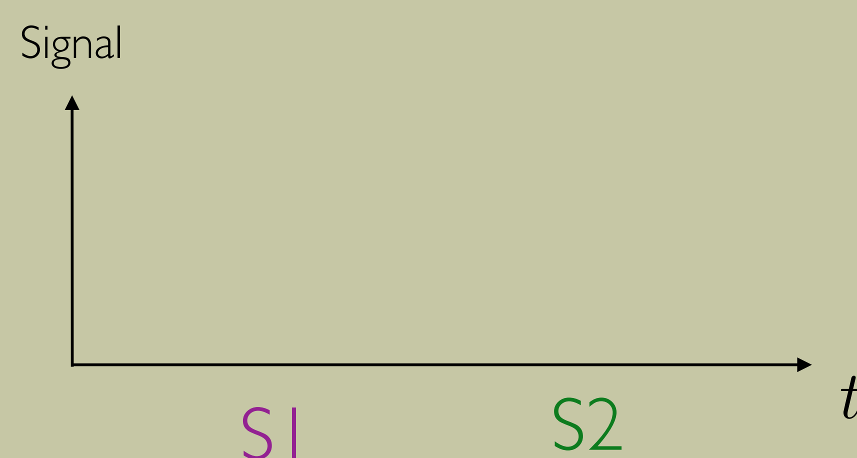

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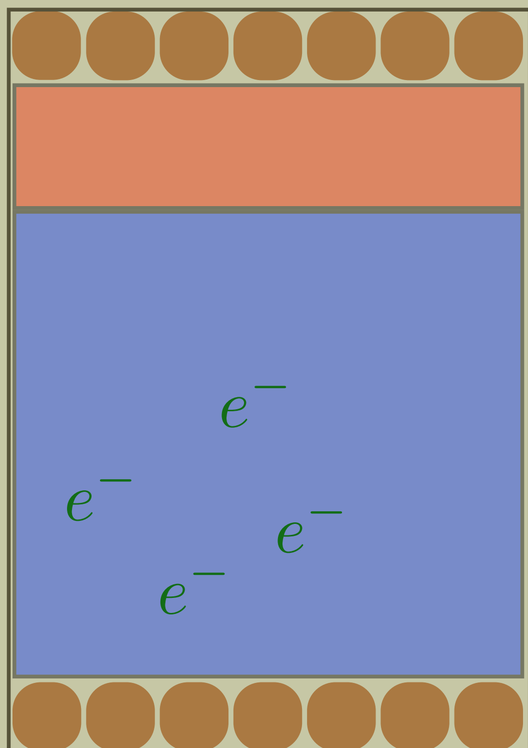

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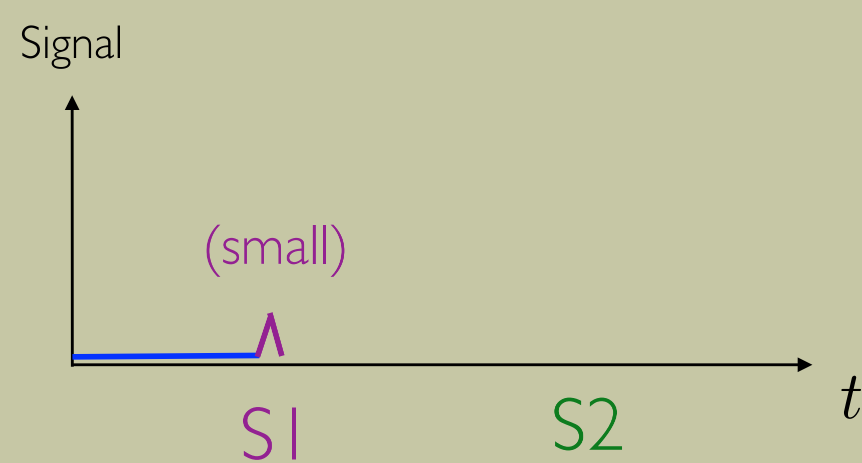
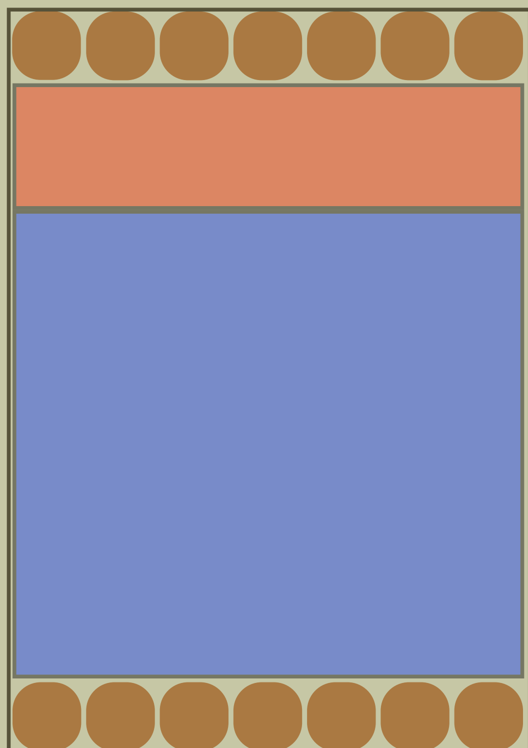


XENON100: Basics



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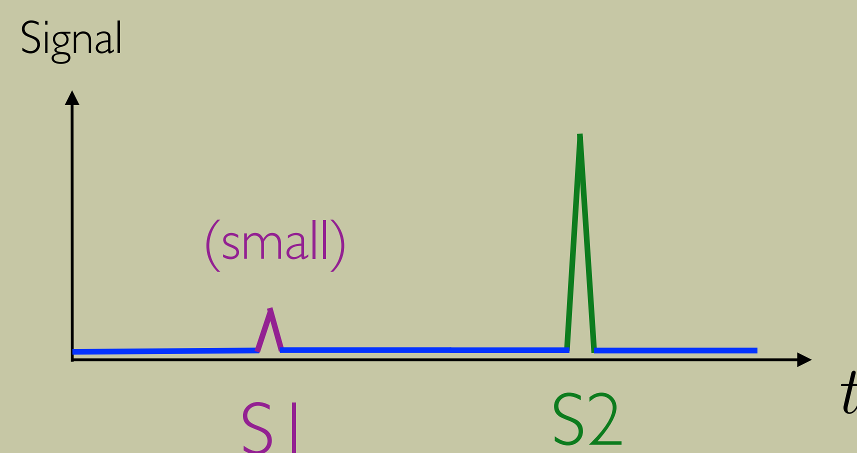
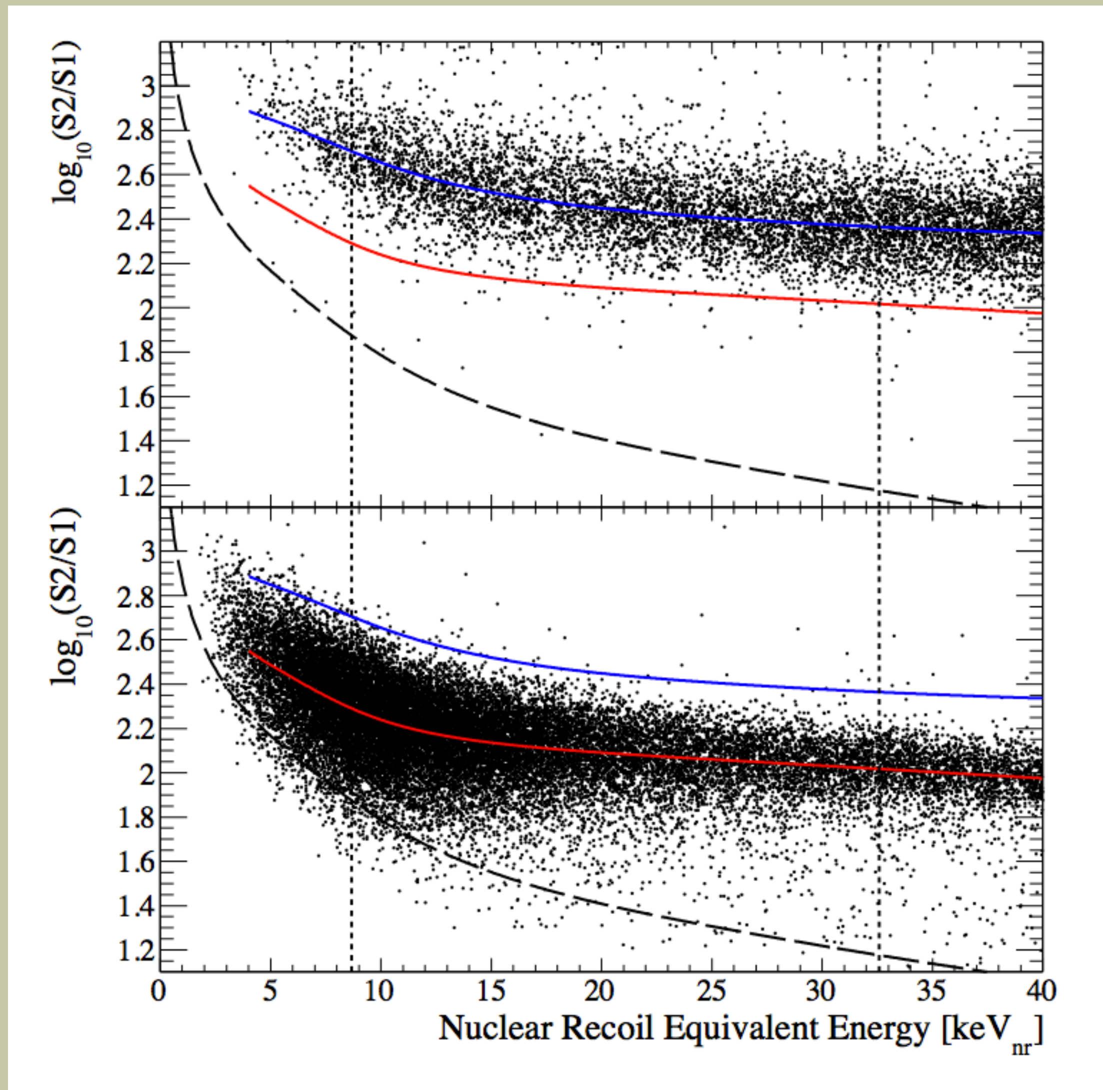
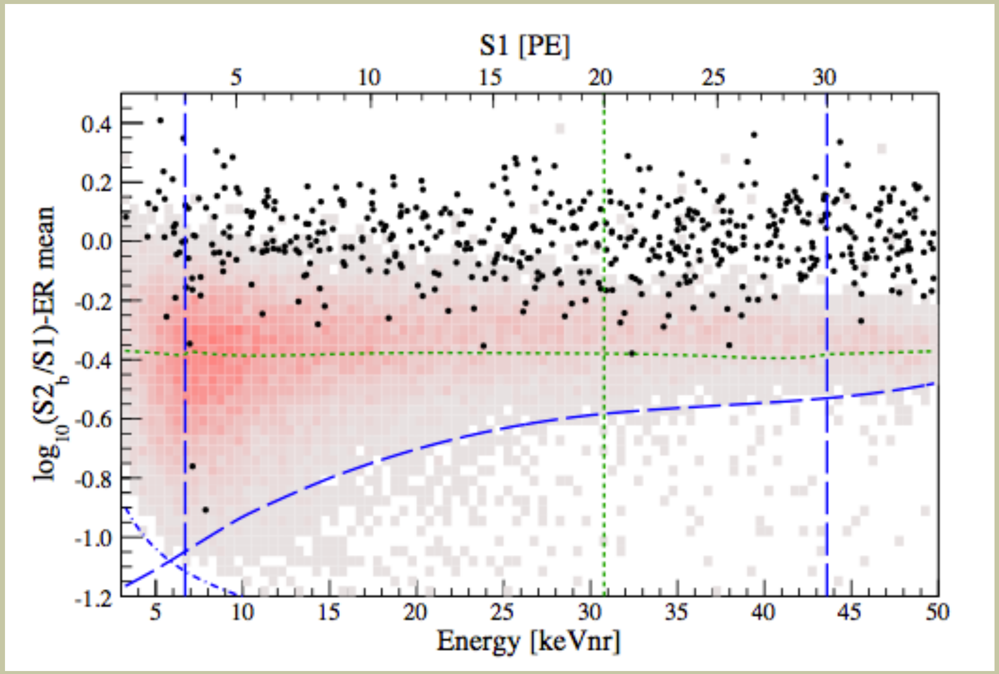


XENON100: Basics



XENON100

- New results from 225 live days.
- 34kg fiducial volume.
- See 2 events:



XENON100: Seeing DM?

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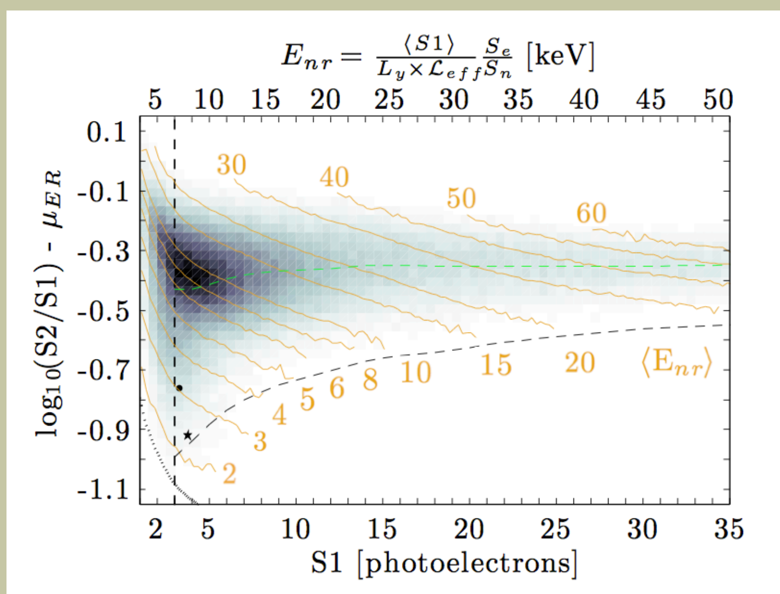
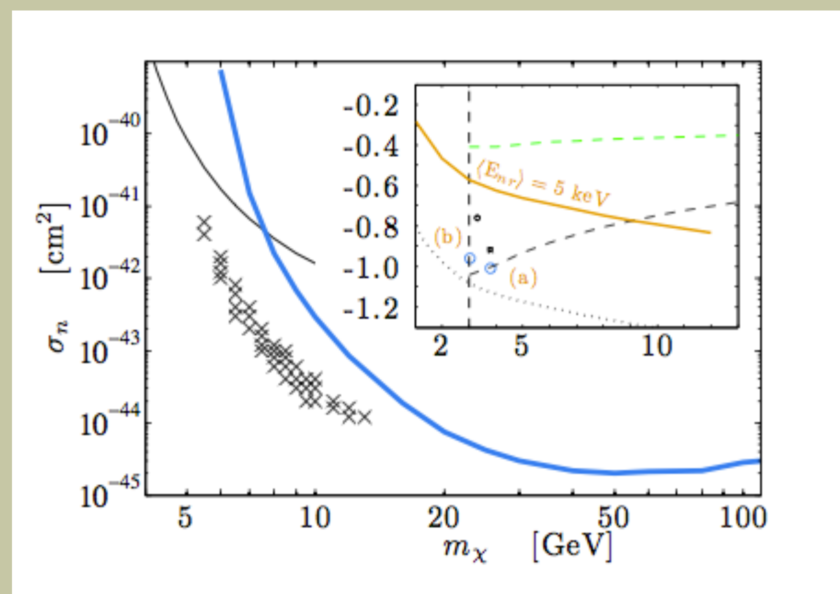
Subtleties of searching for dark matter with liquid xenon detectors

Peter Sorensen[1,*]

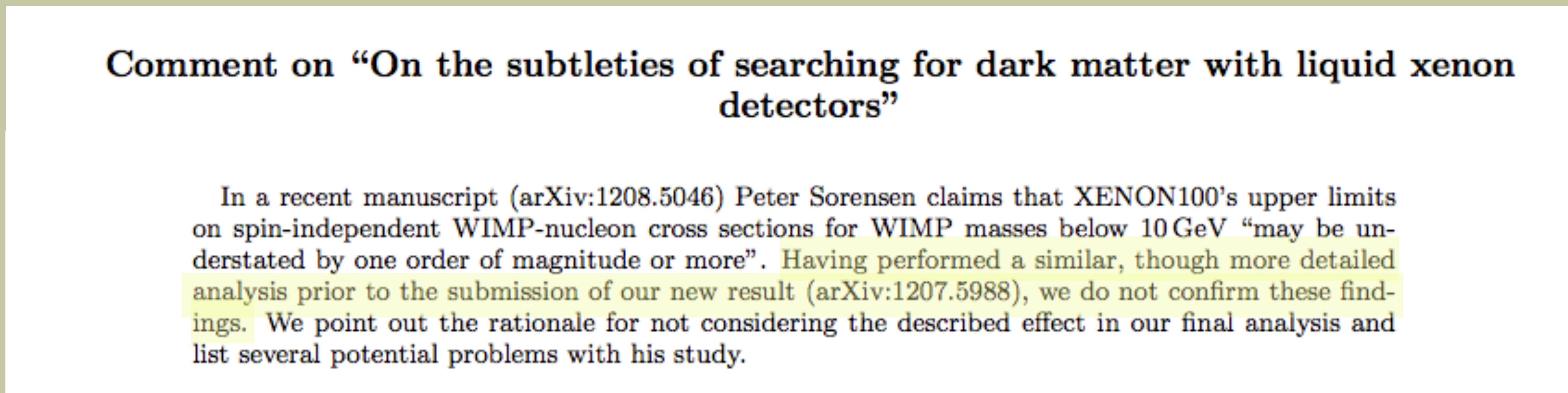
[1] *Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550, USA*

We examine the recent XENON100 dark matter search results, and show how the usual energy scale employed by this and similar experiments may lead to incorrect conclusions. For dark matter particle masses $m_\chi \lesssim 10$ GeV, a nuclear recoil from a scattering event in a liquid xenon detector is more likely to be observed in the lower left corner of the typical search box, rather than near the nuclear recoil calibration centroid. In this region of the typical acceptance box, the actual nuclear recoil energies are smaller than the usual energy scale suggests, by about a factor $\times 2$. As a result, low-mass exclusion limits may be understated.





XENON100: "We're good.."



Comment on "On the subtleties of searching for dark matter with liquid xenon detectors"

In a recent manuscript (arXiv:1208.5046) Peter Sorensen claims that XENON100's upper limits on spin-independent WIMP-nucleon cross sections for WIMP masses below 10 GeV "may be understated by one order of magnitude or more". Having performed a similar, though more detailed analysis prior to the submission of our new result (arXiv:1207.5988), we do not confirm these findings. We point out the rationale for not considering the described effect in our final analysis and list several potential problems with his study.

What's going on?

- Roughly speaking - Peter correctly points out that the extraction of the recoil energy should be done with the information from S1($\simeq n_\gamma$) and S2($\simeq n_e$) jointly. Using only S1 information for low mass WIMPs can be very wrong.

- XENON100 claims that (my version...):
  - Sorensen does not have sufficient information to simulate their detector.
  - Effect is much smaller when the precise detector simulation is used.
  - Not enough experimental data (Q_y=S2/E_{nr}) to use Sorensen's method yet.
  - Sorensen is really right about his point - they'll use it in the future..

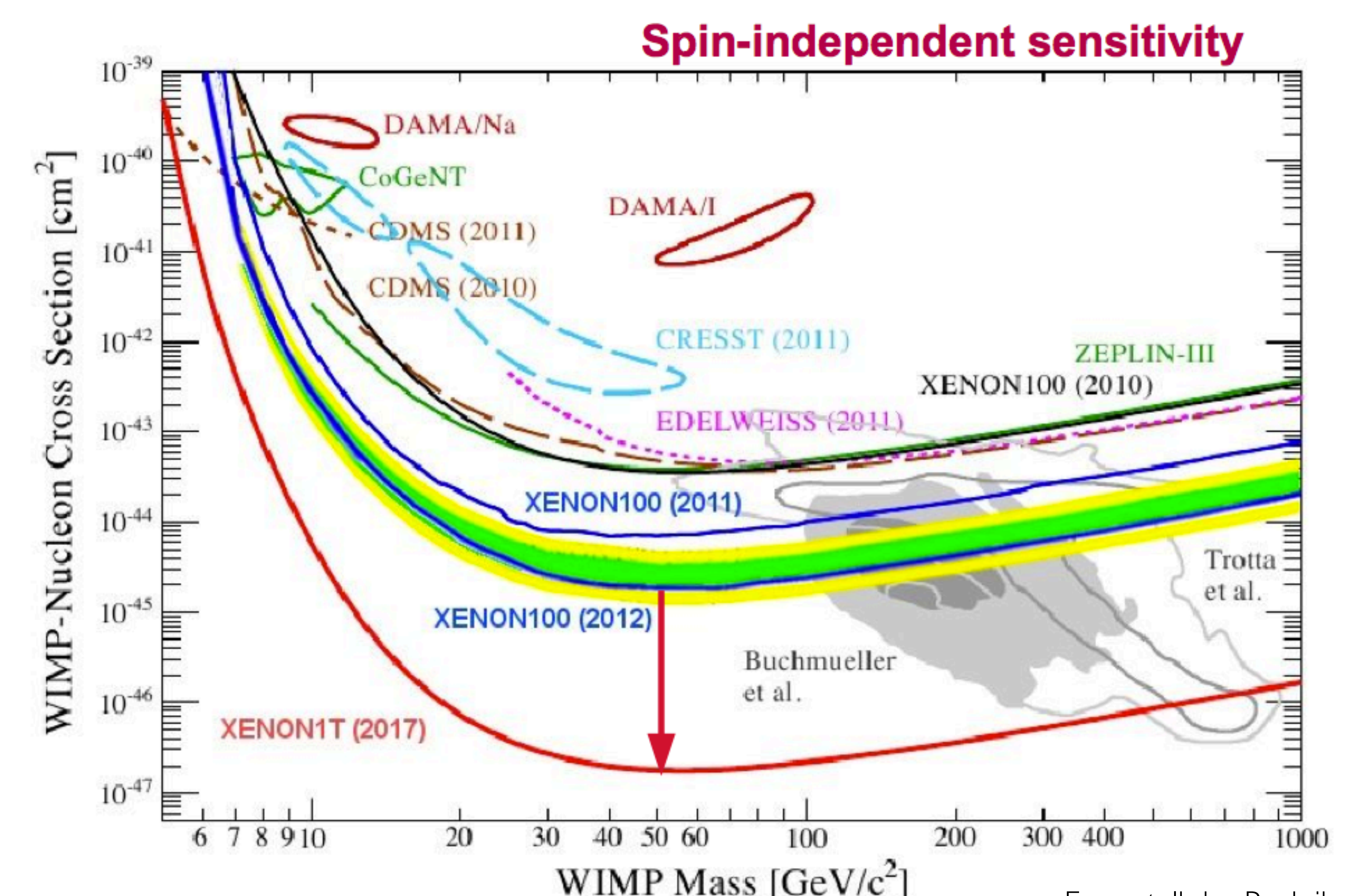
- The key point is: While statistically insignificant for now, these events are what you expect from DM with mass 5-10 GeV.

Who should we believe?

No one right now.

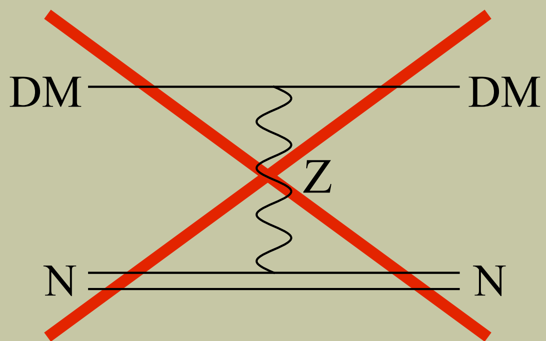
Interesting to think about but more data is needed.

Direct Detection - Future

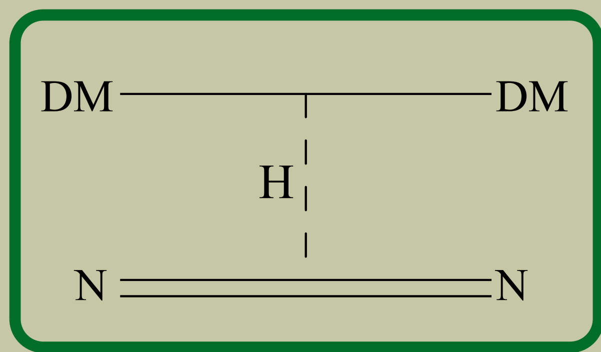


From talk by Budnik

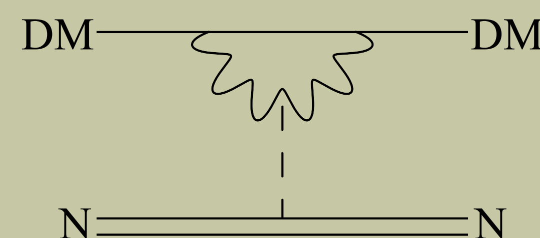
Experimental Status of DM



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



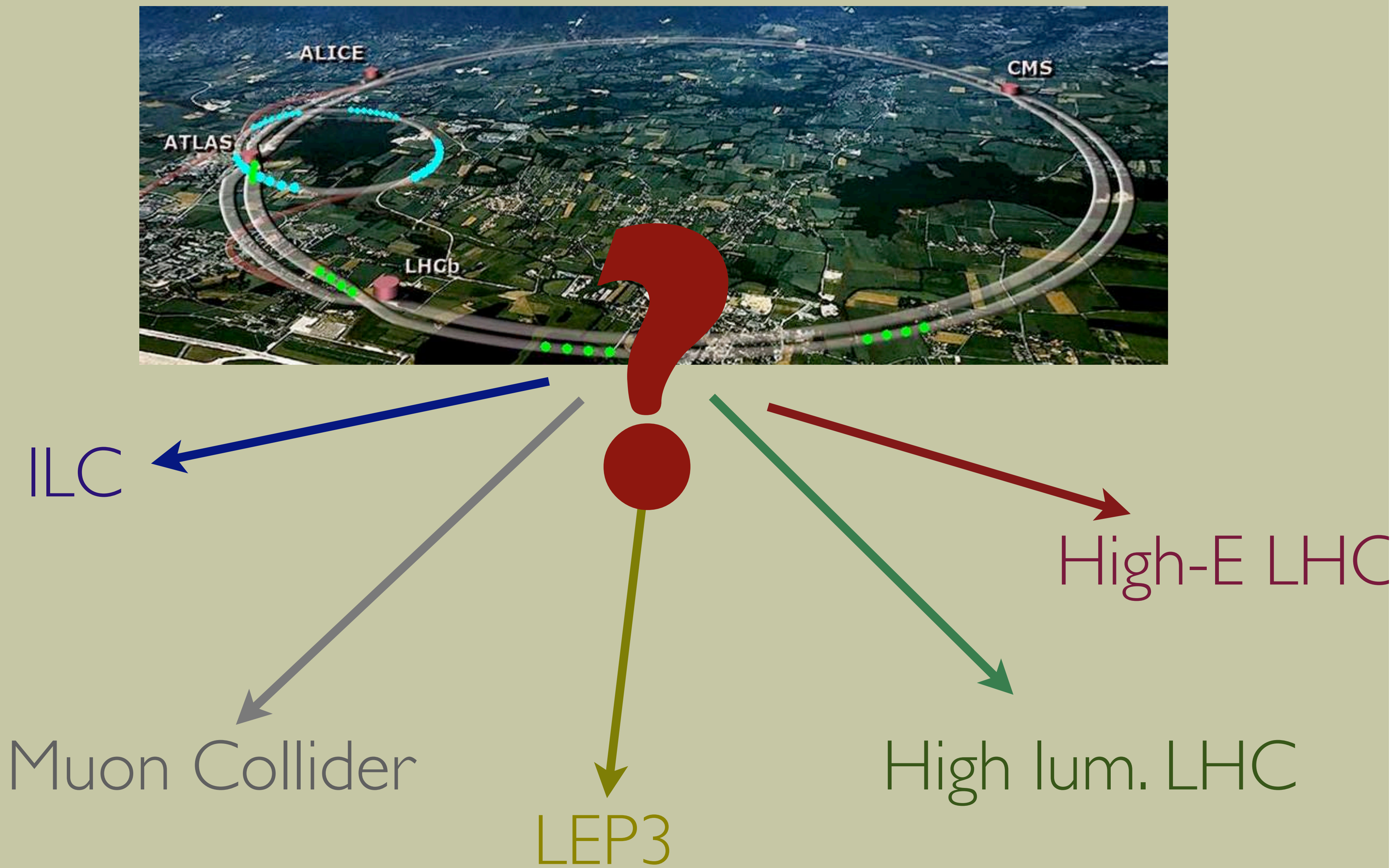
$\sigma_{\chi N} \sim 10^{-44-47}\ \mathrm{cm}^2$



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

XENON100
LUX
CDMS
...

At a Crossroad...



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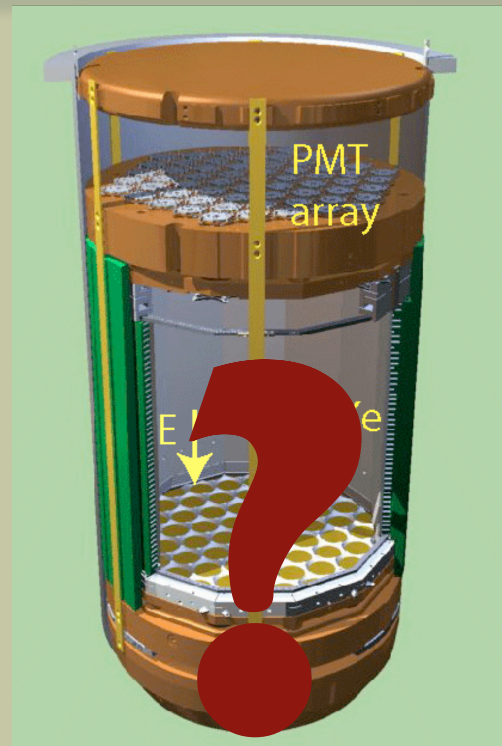


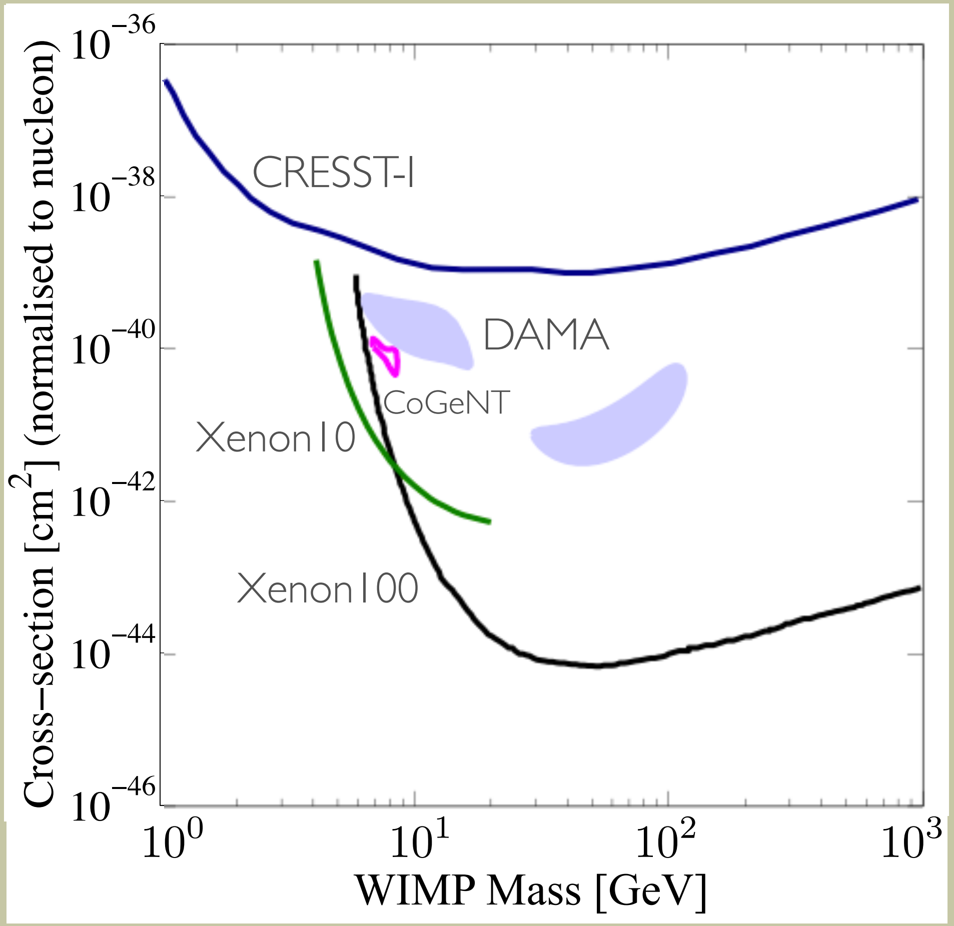
Axion
Searches

...

Ultra low-threshold
Cryogenic Detectors

Capabilities for
Directionality

Direct Detection Status



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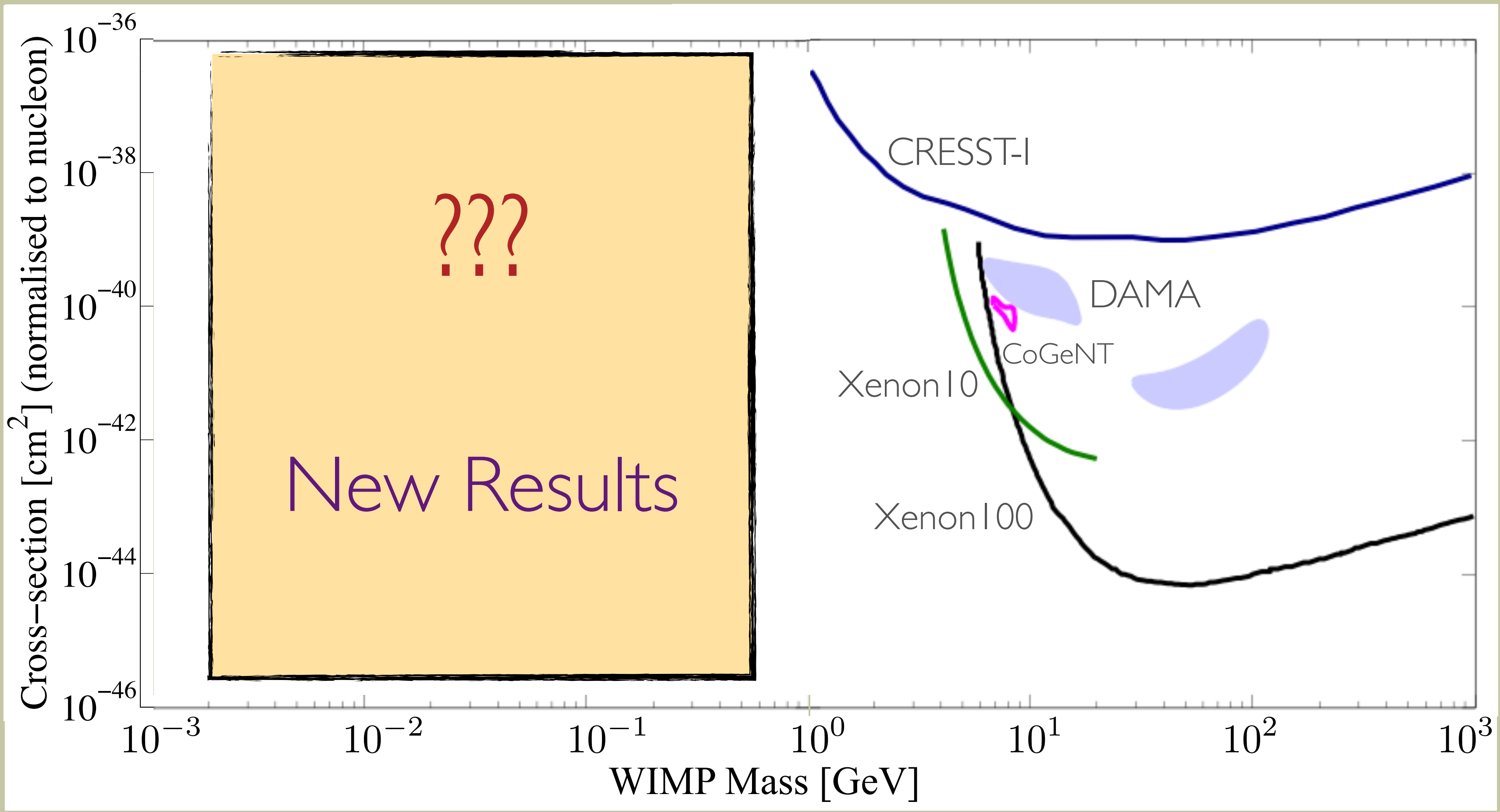


Outline

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

Models of Sub-GeV Dark Matter

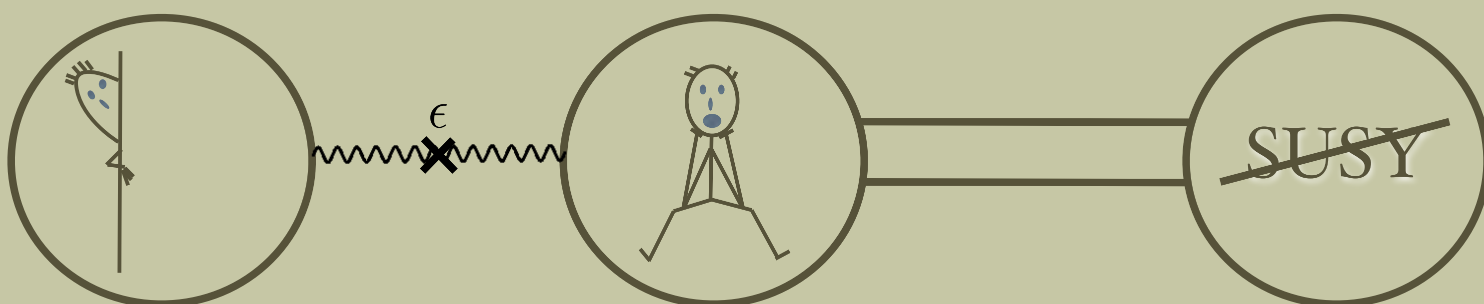
Sub-GeV Dark Matter

- 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.
  - ...

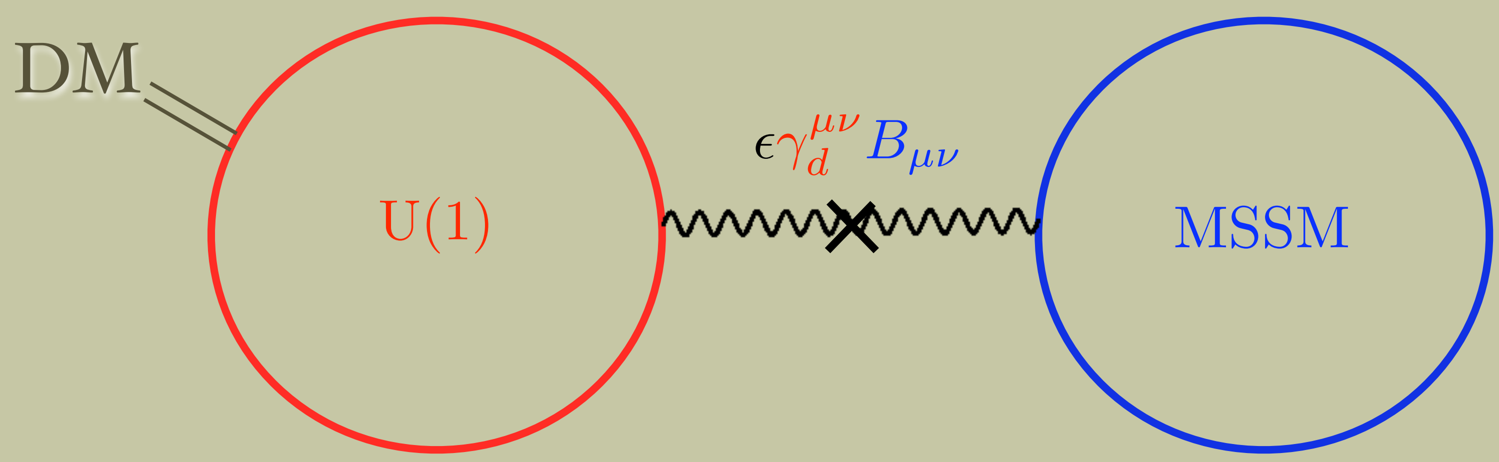
Sub-GeV?

- 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,

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



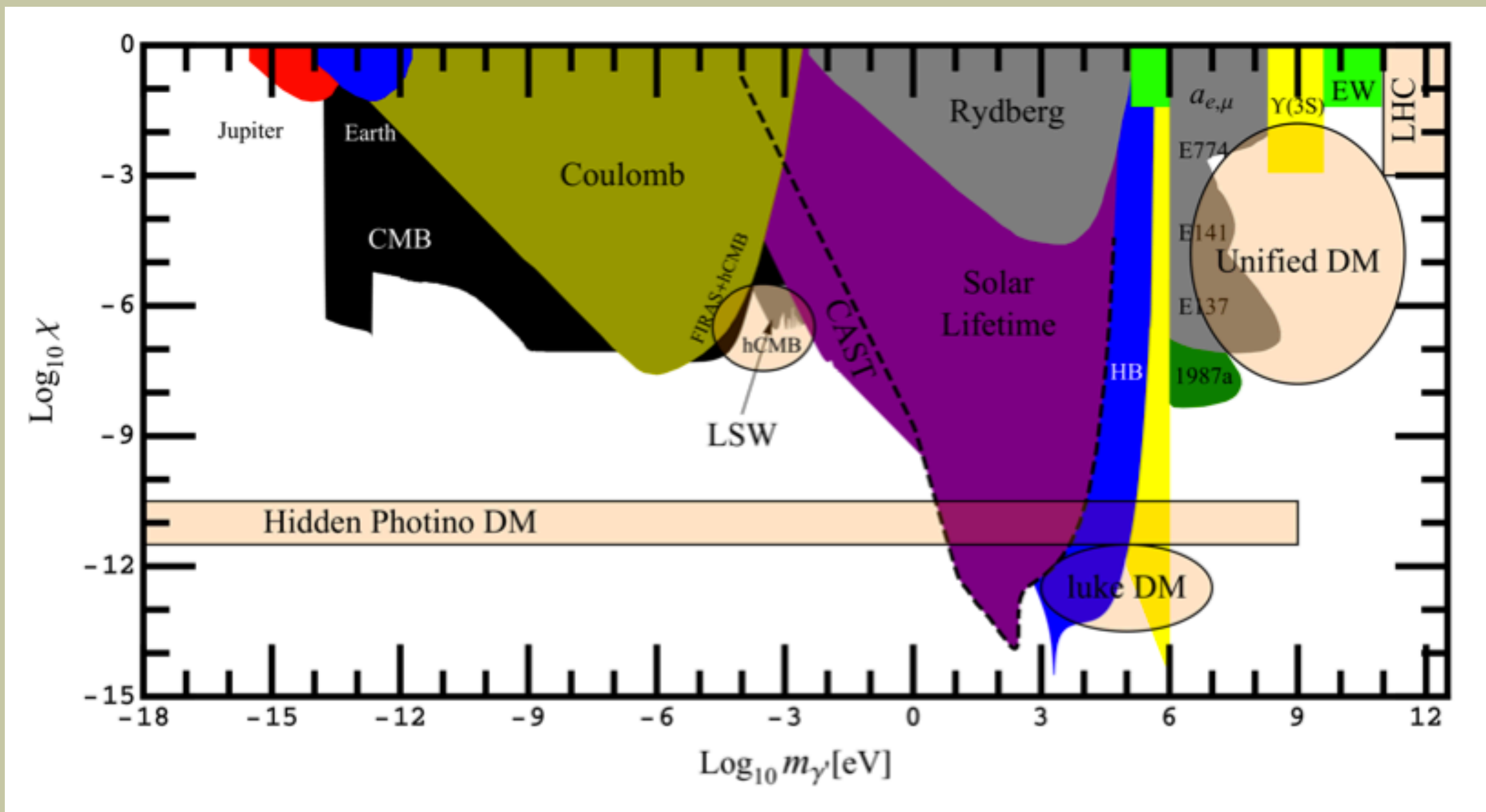
Simple Realization



- 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.



Relic Abundance?

- Several options:
    - Freeze-out
    - Freeze-in
    - Non-thermal production
    - Asymmetric
    - Freeze-out and Decay (superWIMP)
    - ...

Relic Abundance?

- Several options:
  - Freeze-out ← Production for the WIMP
  - Freeze-in
  - Non-thermal production
  - Asymmetric
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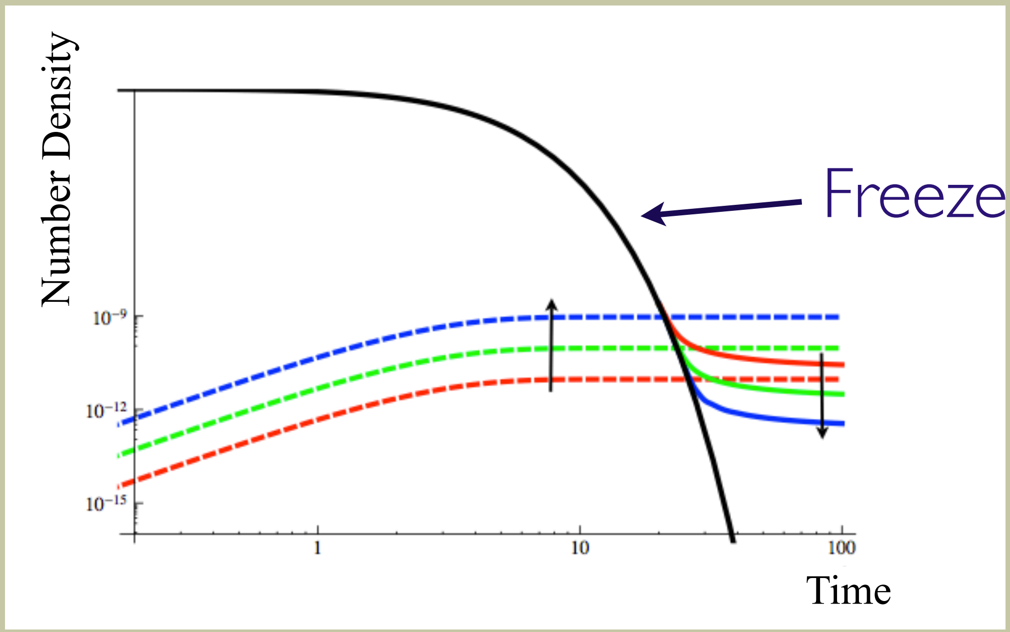
  - ...

Freeze-In

[Hall et al. 2009]

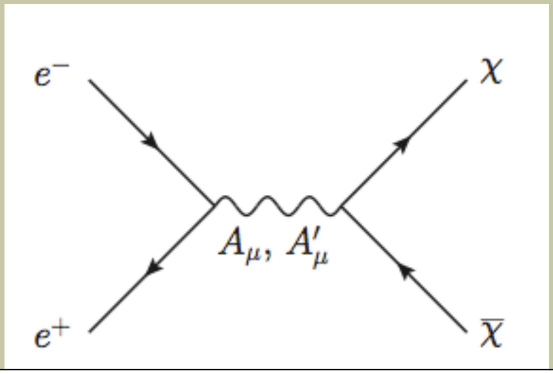
- DM may couple very weakly to thermal bath, in which case it never reaches thermal equilibrium.



Freeze-out of WIMP

- 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.



Relic Abundance: Asymmetric /Non-thermal

- Another motivation is the empirical fact:

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

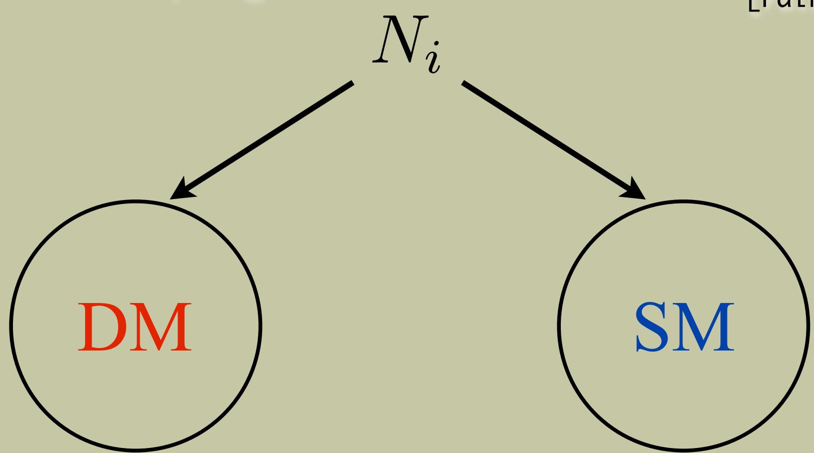
- If we take this as a hint, both densities are related through some joint dynamics.
- The dynamics may relate the baryon asymmetry to a symmetric and/or asymmetric DM density.
- Whether or not the symmetric component dominates, depends on the the DM annihilation cross-section:

  - Large $\sigma_{\rm ann}$: Asymmetric DM
  - Small $\sigma_{\rm ann}$: Symmetric DM

Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

[Falkowski,Kuflik,TV, work in progress]
[Falkowski,Ruderman,TV, 2011]



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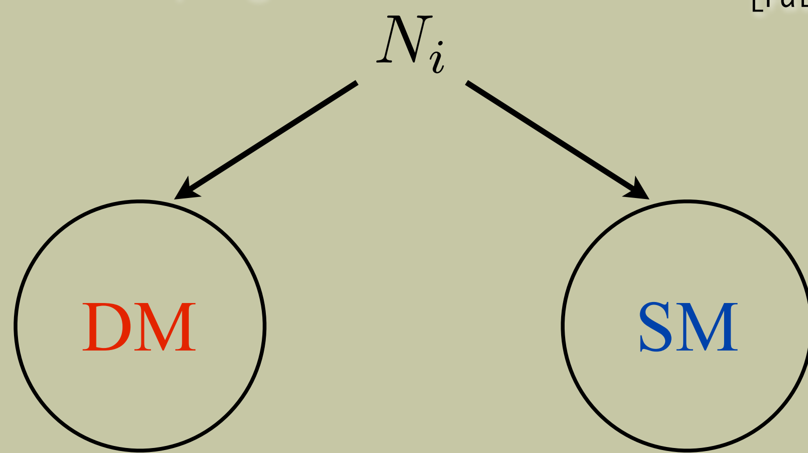
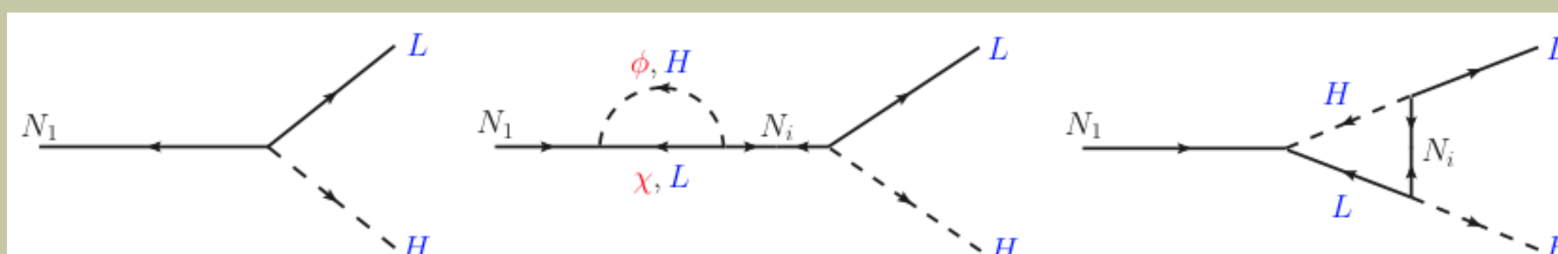


- When N decays it produces the baryon asymmetry through CP violation (loops):



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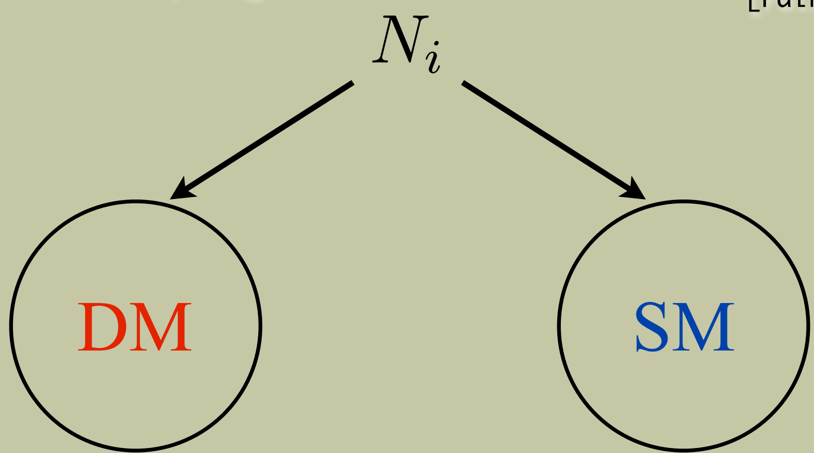

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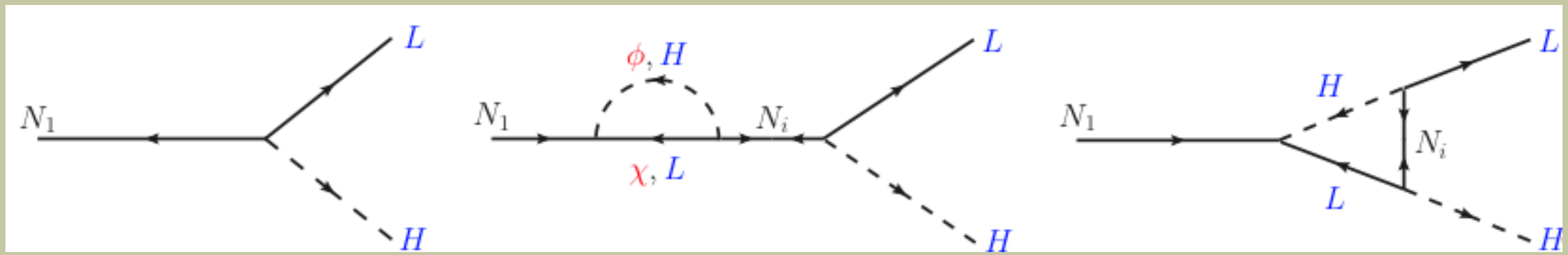
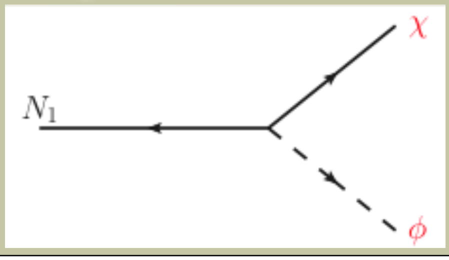


- Symmetric DM produced through tree level:



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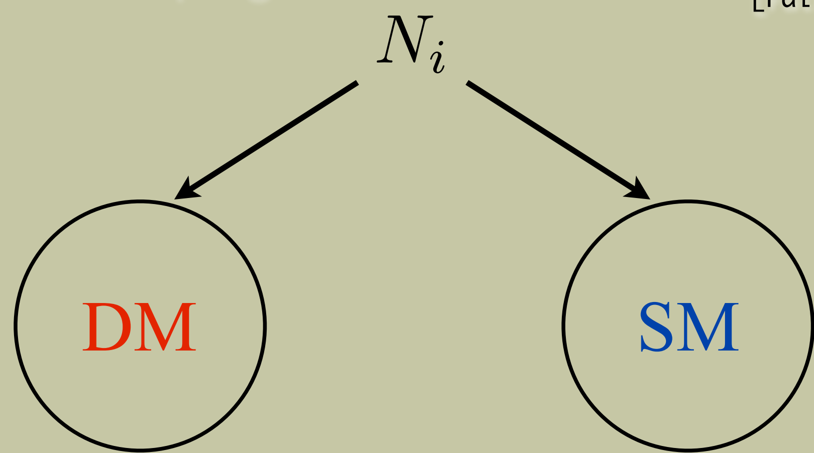

- Consequently, DM number density is generically larger than baryon number density.

- To have the same mass density, $\Omega_i \propto m_i n_i$, this requires $m_{DM} < m_{proton}$

Light DM.

Is Sub-GeV DM Allowed?

- 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

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

[Finkbeiner et al. 2009]

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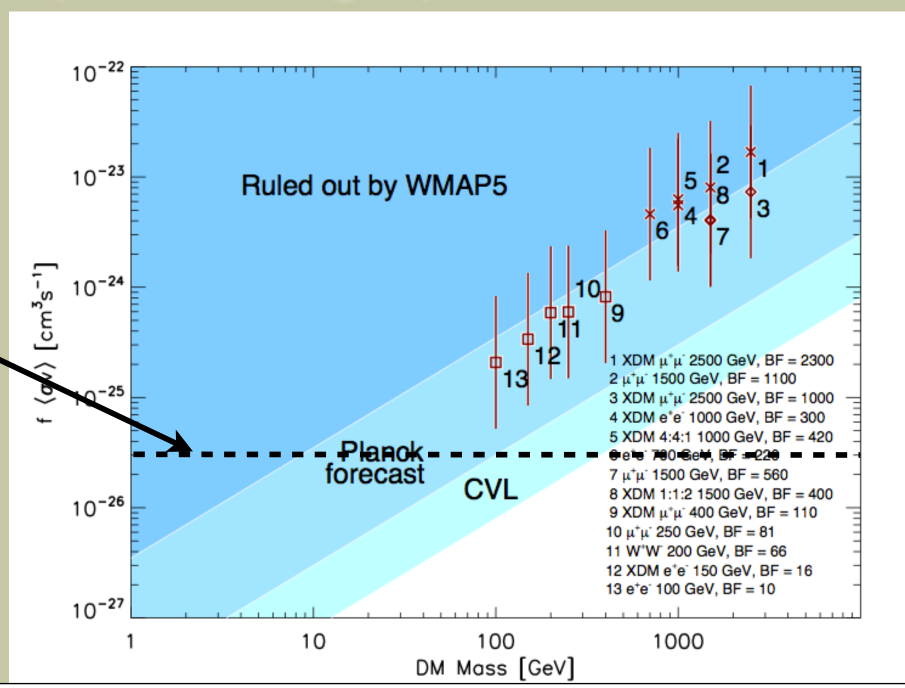
Standard Thermal WIMP



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

Halo ellipticity: $$\frac{\sigma_{\rm self}}{m_{\rm DM}} < 0.02\ {\rm cm}^2/{\rm g}$$ [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!!

[Cohen,Essig,Kuflik,Mardon,TV, work in progress]

Has not received enough attention
More studies are needed.

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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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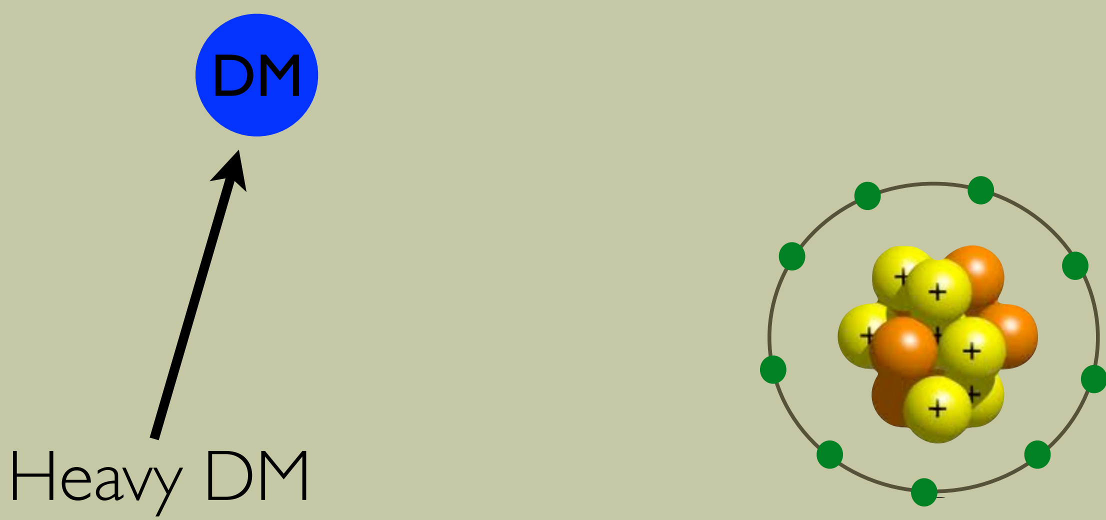

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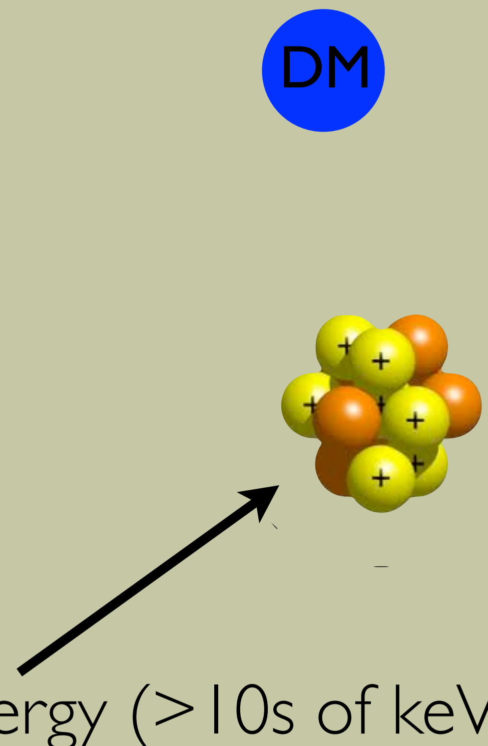

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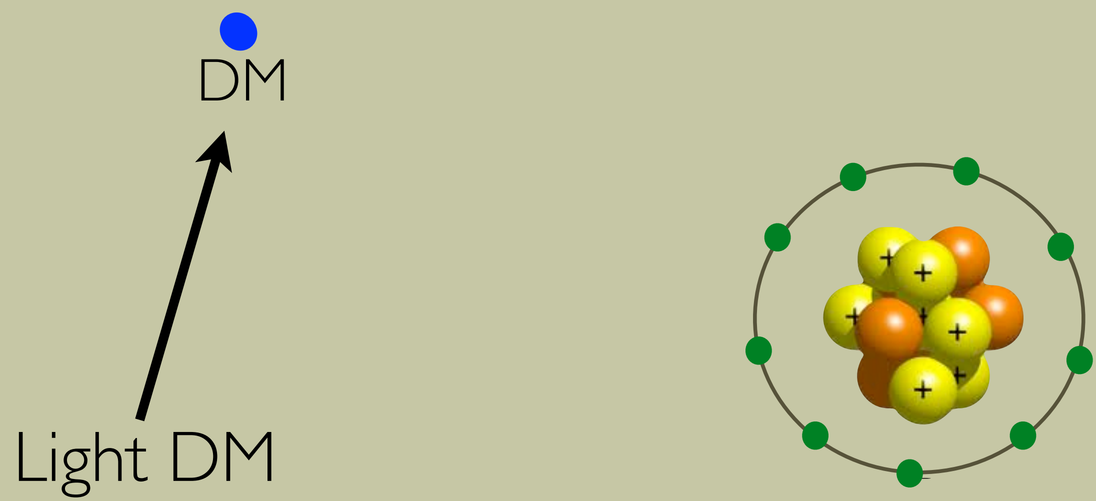

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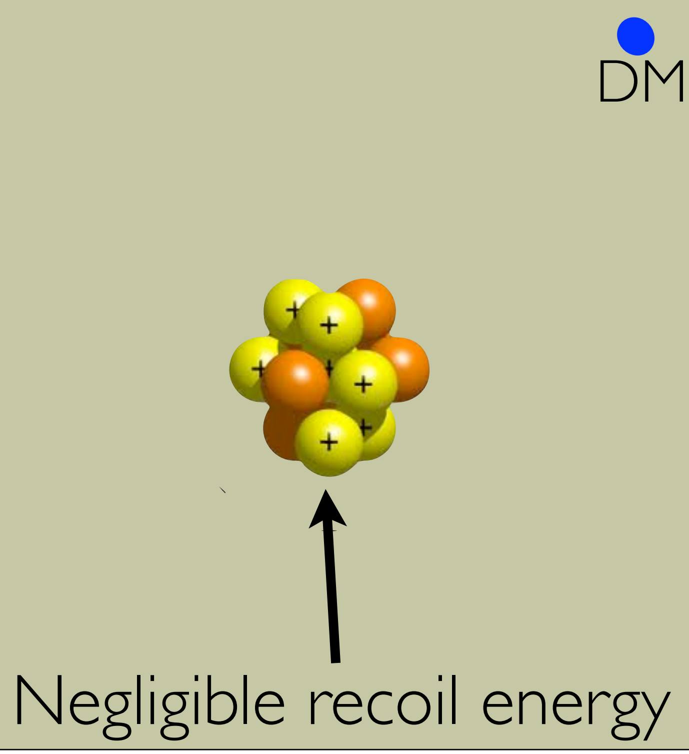

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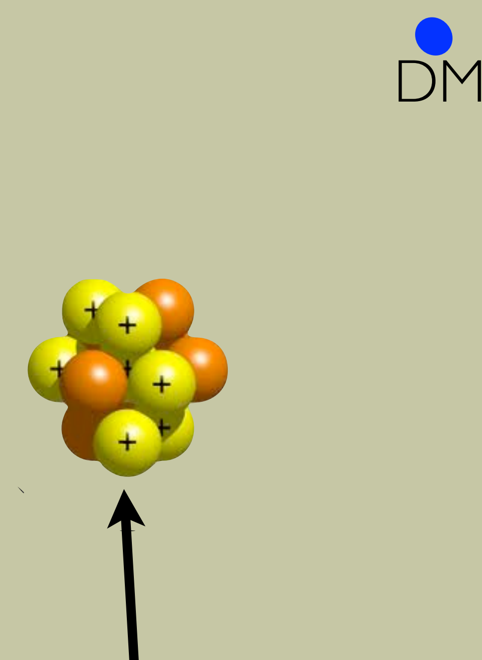

$$E_{\mathrm{R}} = \frac{q^2}{2m_N}$$

Negligible recoil energy

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

DM

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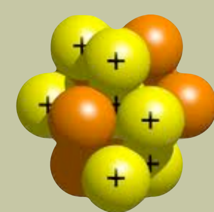

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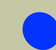
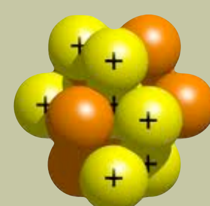


DM

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

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



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Recoil energy drops fast

Can't go below ~ GeV

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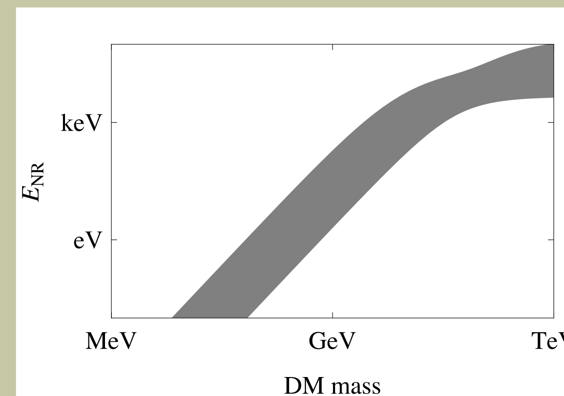

But DM energy is significantly larger:

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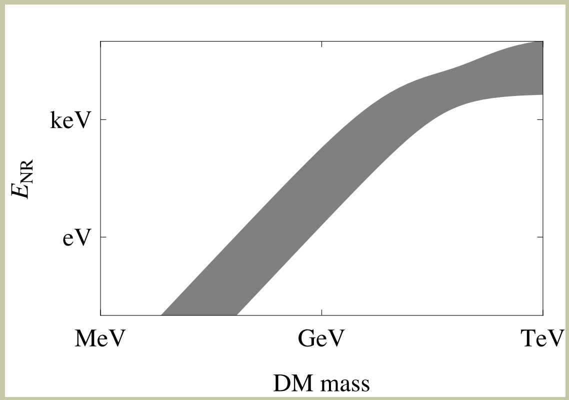

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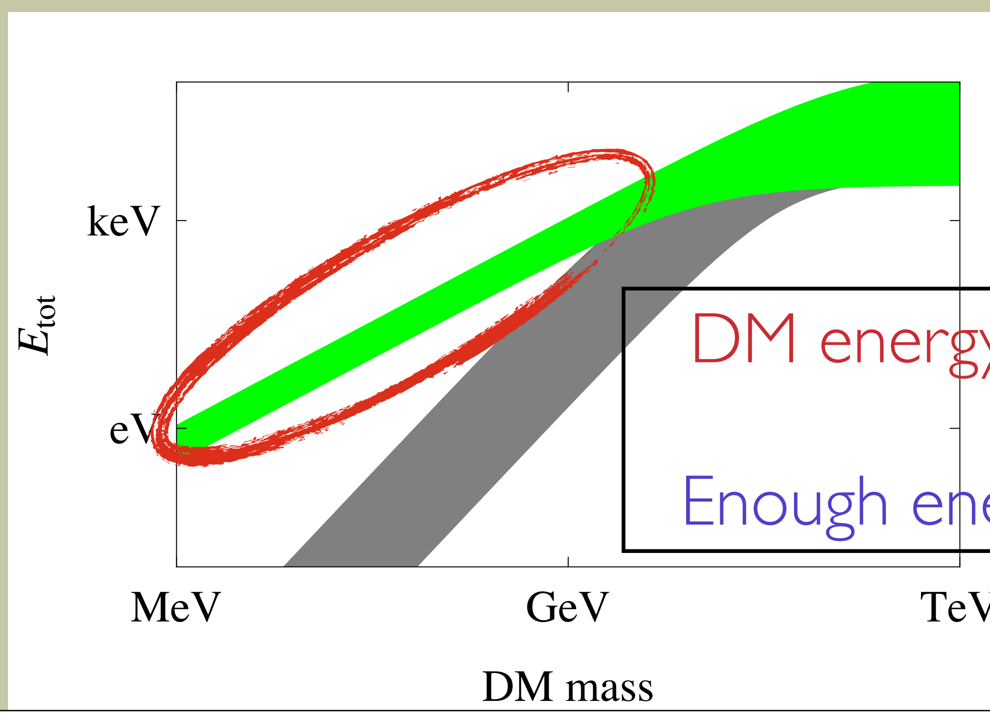

DM energy drops slower

Enough energy to detect!!

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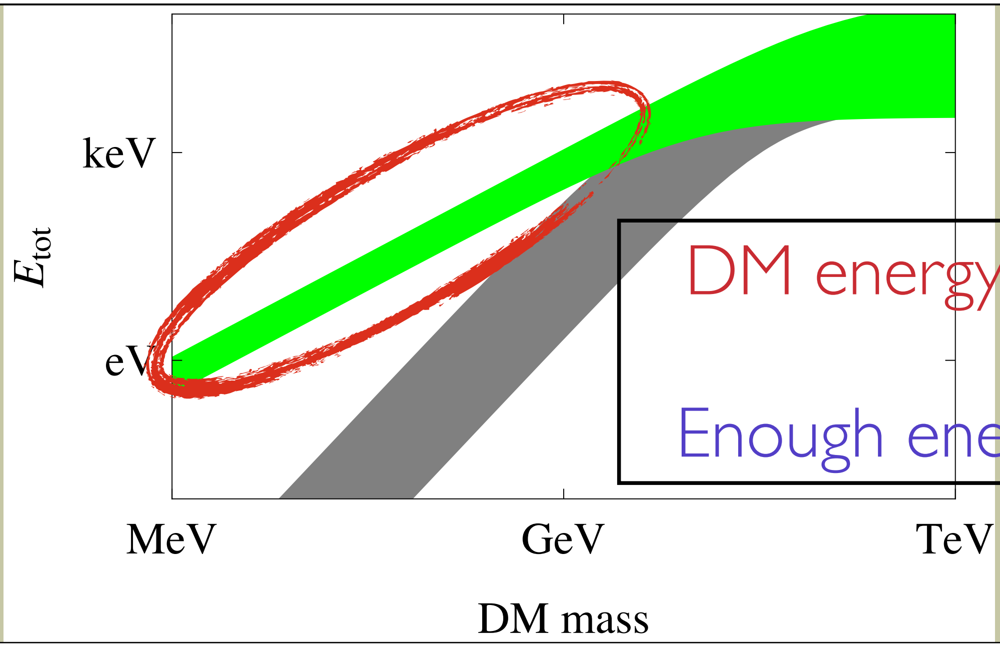
Studying nuclear recoils is extremely inefficient for light DM



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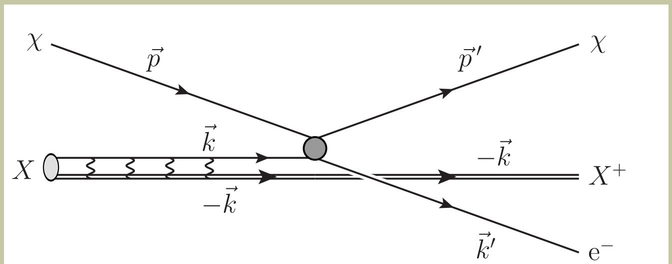
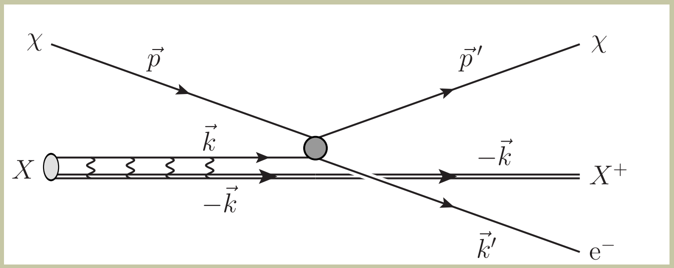
  1. Electron ionization

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



Ways to Detect Light DM



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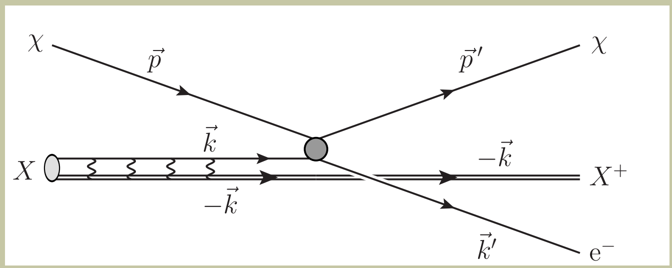

2. Electronic excitation

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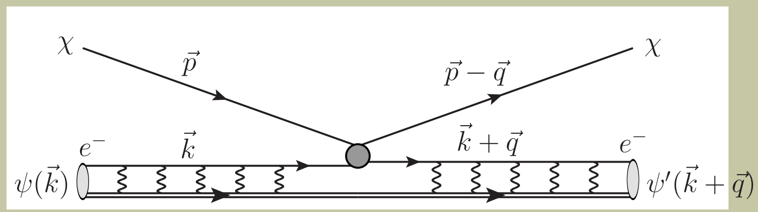
   Signal: photons, phonons.



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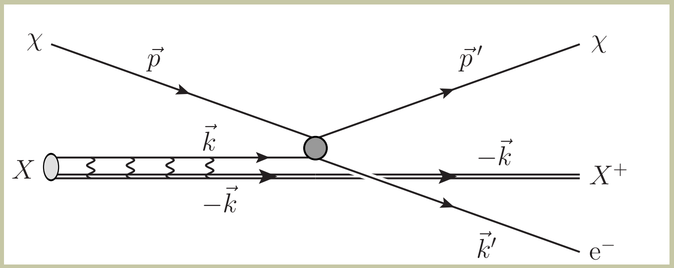

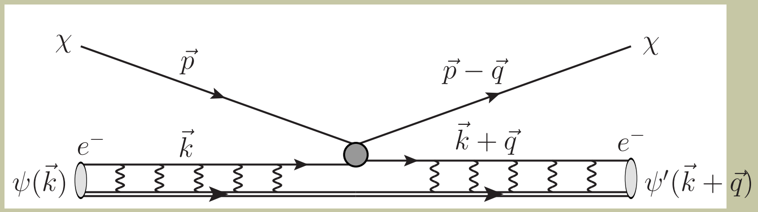

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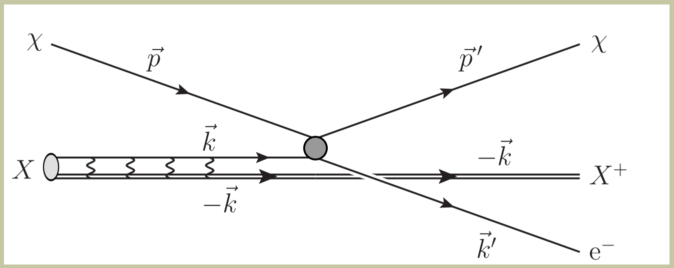

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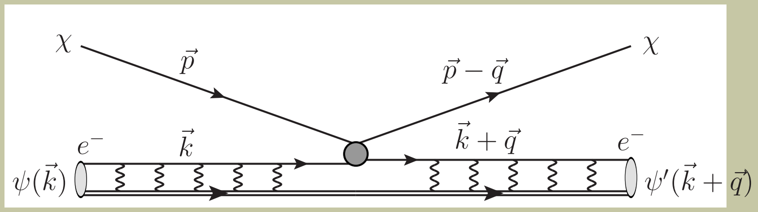
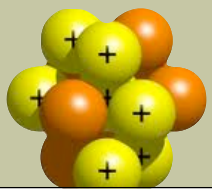
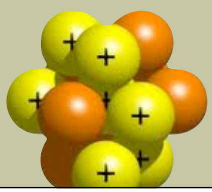


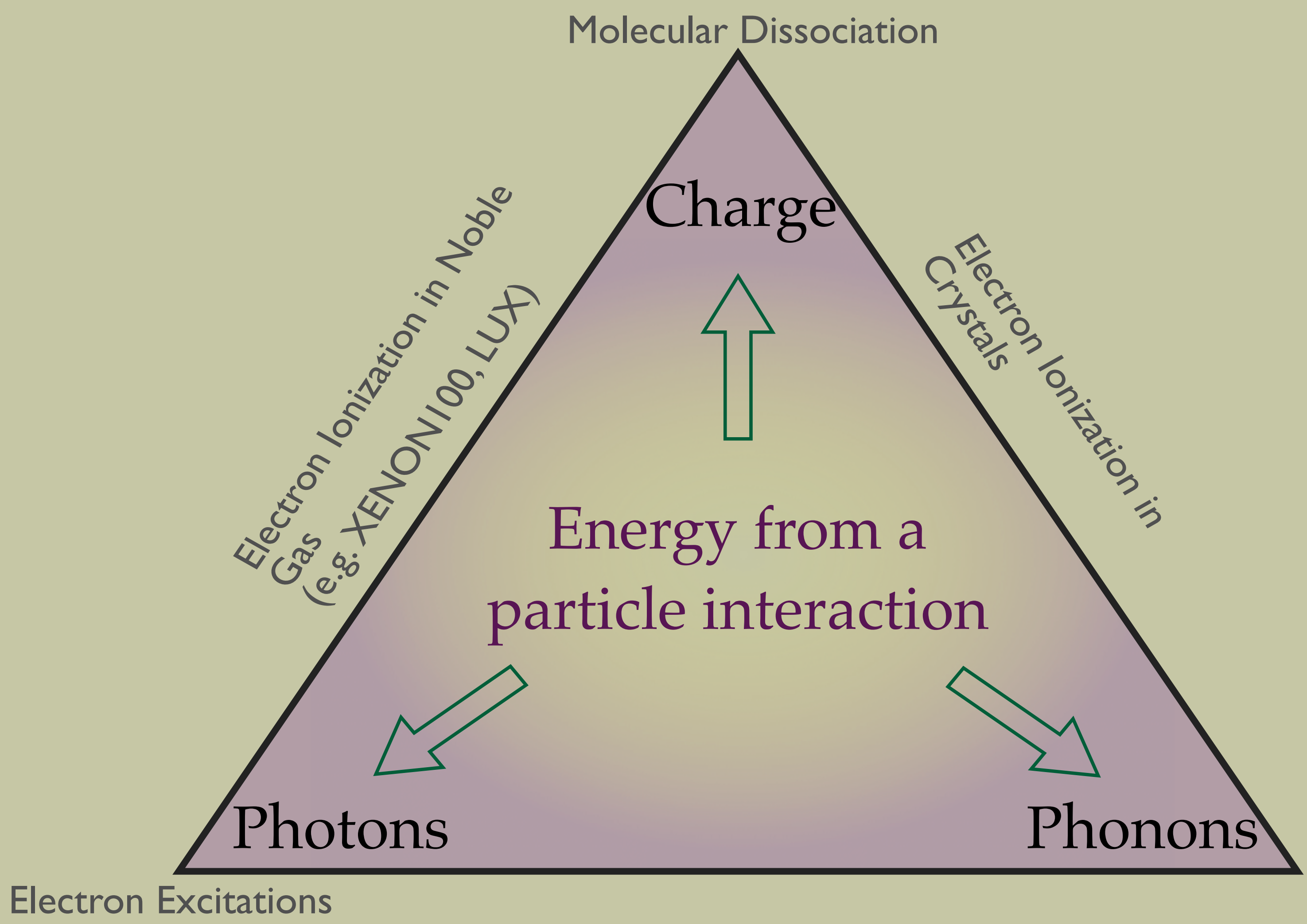
3. Molecular dissociation

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





Detectable Signals



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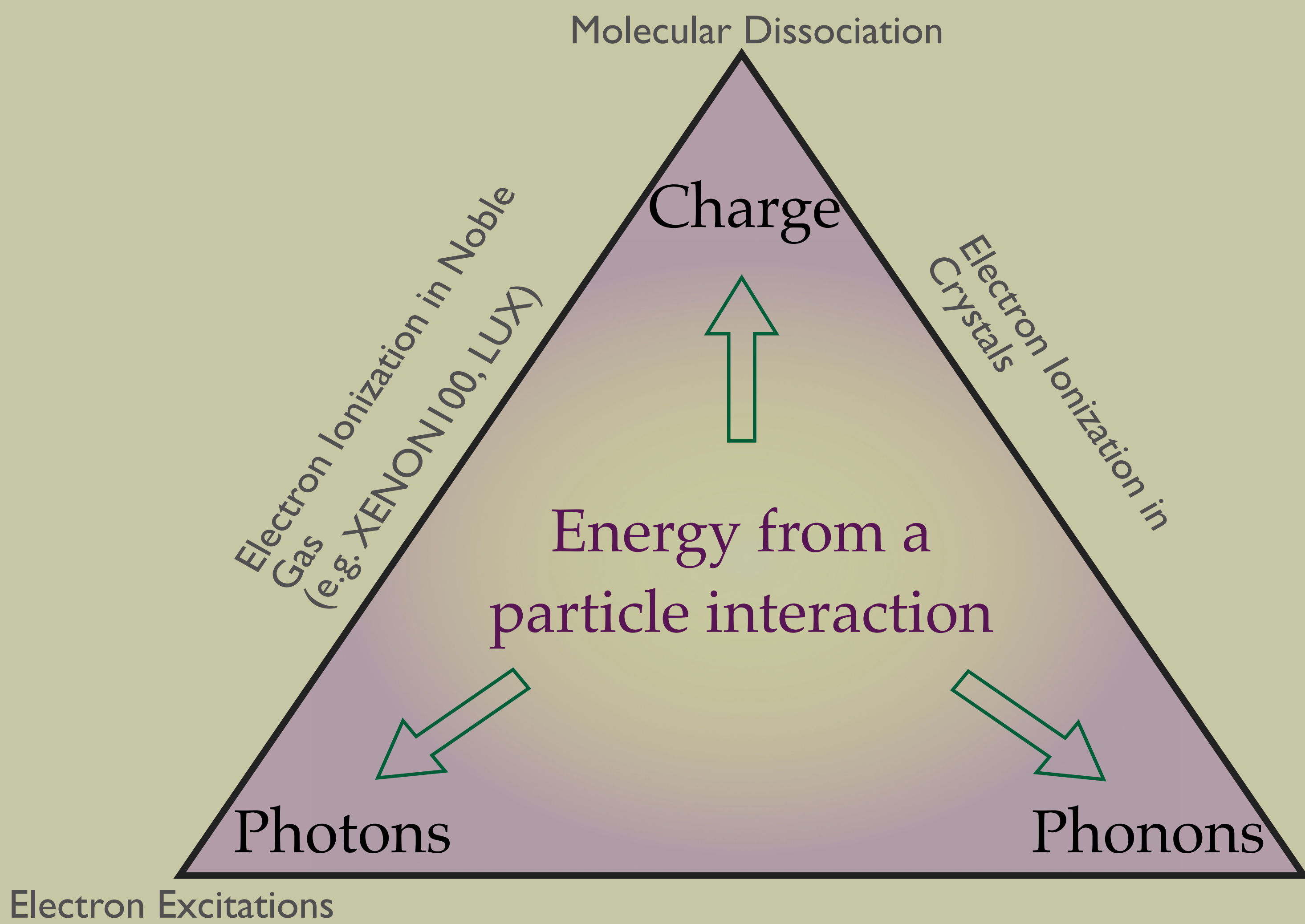

Discovery already possible with one type of signal only - search for annual modulation

For the rest of this talk:

Focus on electron ionization through electron-DM scattering

Computing Rates

Ionization Cross-section

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

Ionization Cross-section

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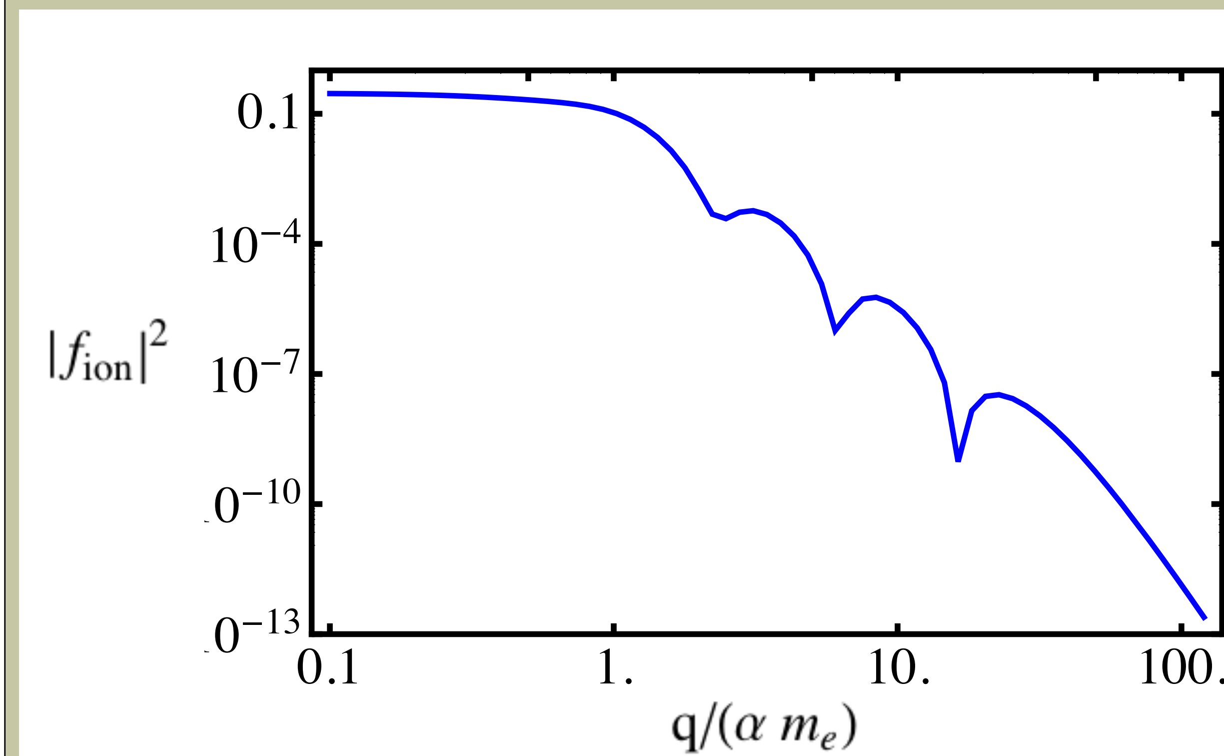
Determined by atomic wave-functions

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

Ionization Cross-section

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



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Ionization Cross-section

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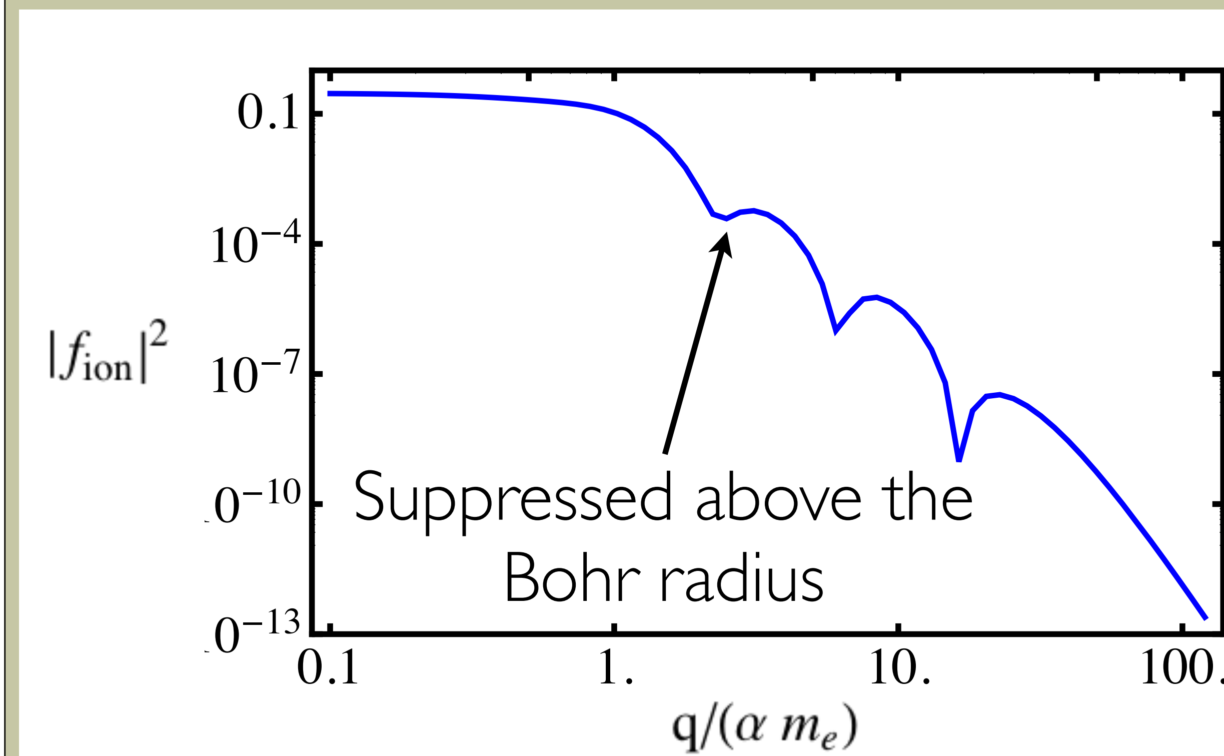

Rates are suppressed for large momentum transfer!

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

Ionization Cross-section

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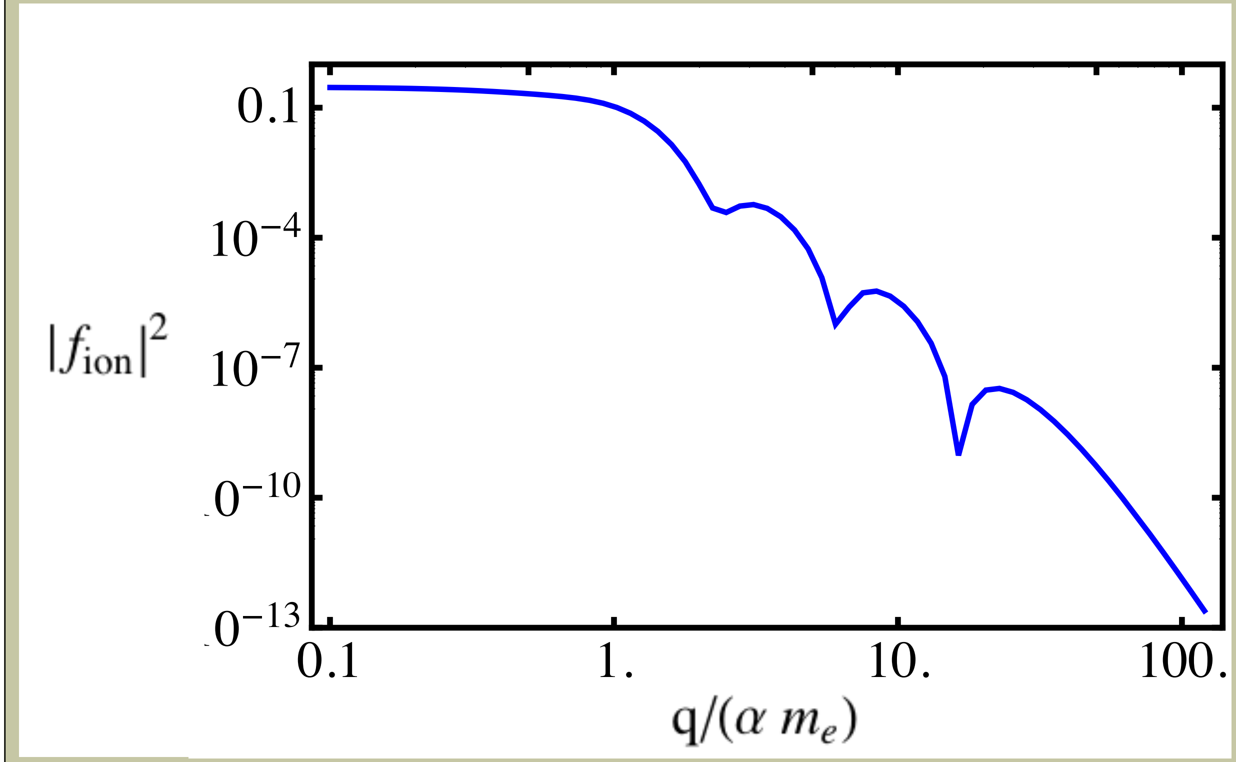
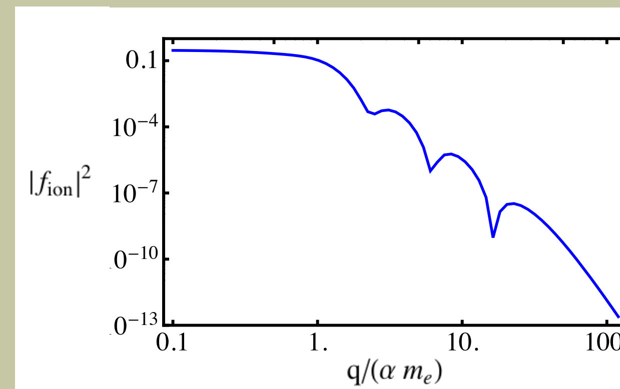


Ionization Cross-section

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

Determined by a specific DM theory



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

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

Rates: Electron-Hole Pair Production

- Similar computation can be done in crystals. The form factor takes a similar form,

$$f_{cryst}^{i\to i'}(\mathbf{q},\mathbf{k}) = \sum_G \psi_{i'}^*(\mathbf{k}+\mathbf{G}+\mathbf{q})\psi_i(\mathbf{k}+\mathbf{G})\,.$$

- Wavefunctions are more complicated to compute. Can use available codes to do that (e.g. `Quantum ESPRESSO`).

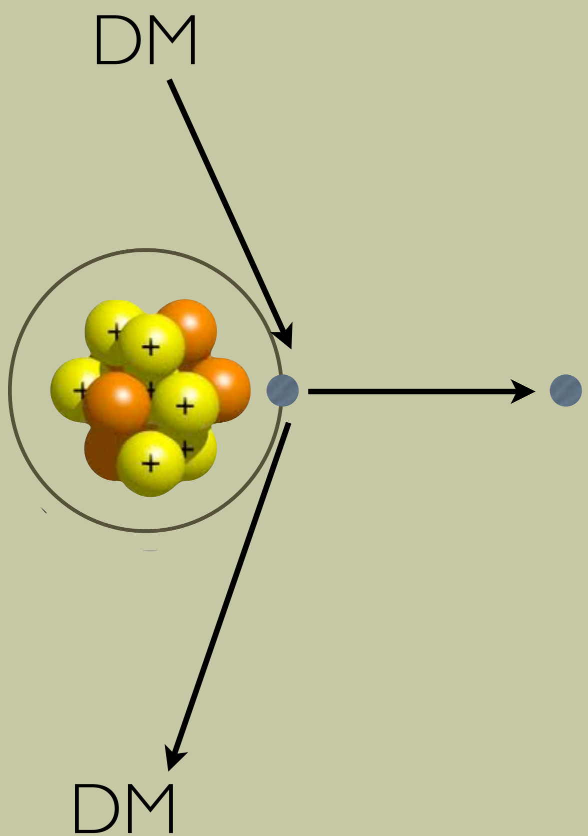
- Two interesting differences:

  1. Energy gap can be significantly smaller than in liquids. Significant improvement of sensitivity.

  2. Lattice axis defines direction. Rates depends on DM direction. May be used to improve background subtraction (work in progress).

Secondary Interactions

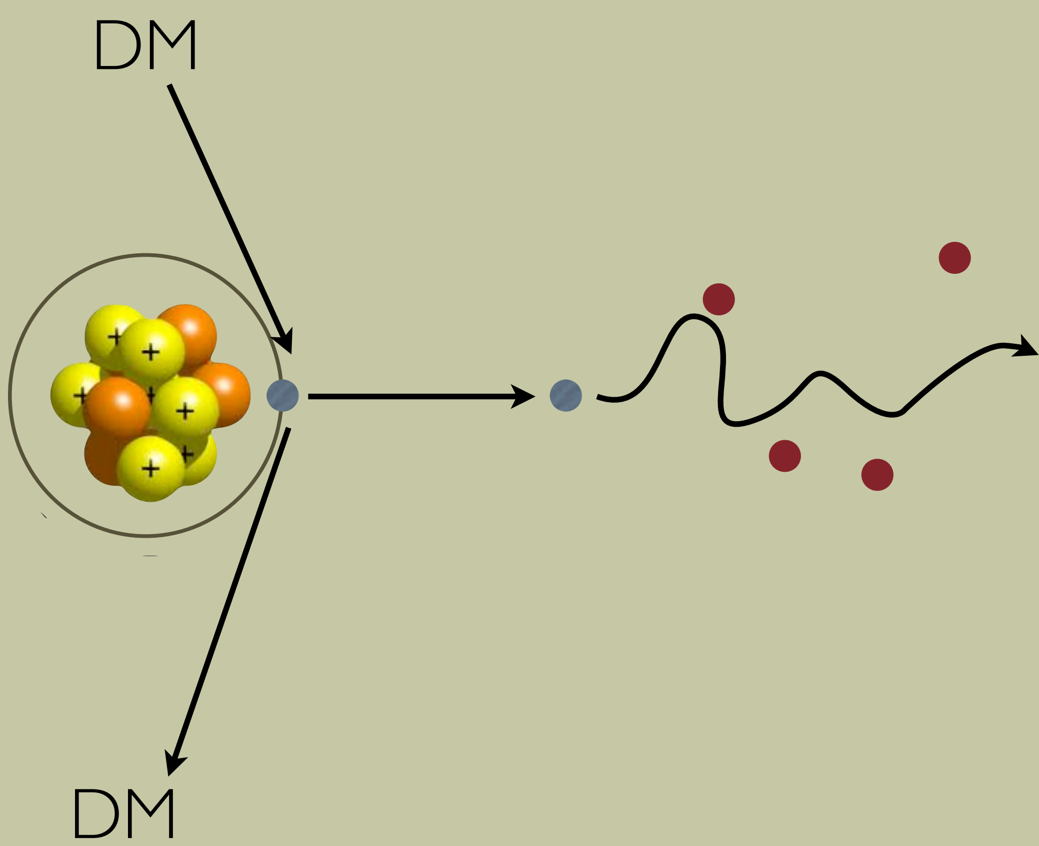
- Given a cross-section, the scattering rate is straightforward.



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

Secondary Interactions

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



Electron number depends on:

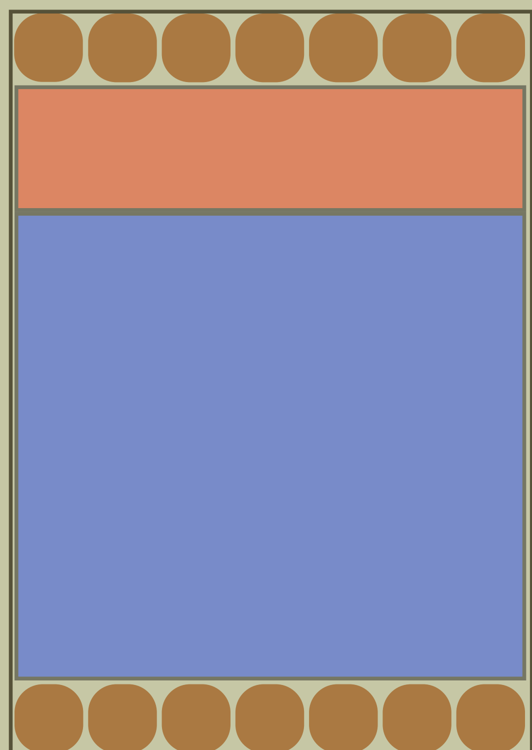
- W - average energy of observable quanta.
- f_R - electron-ion recombination probability.
- N_{ex}/N_{ion} - The excited to ion ratio

XENON10
New Results

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, TV

XENON10

Light
DM



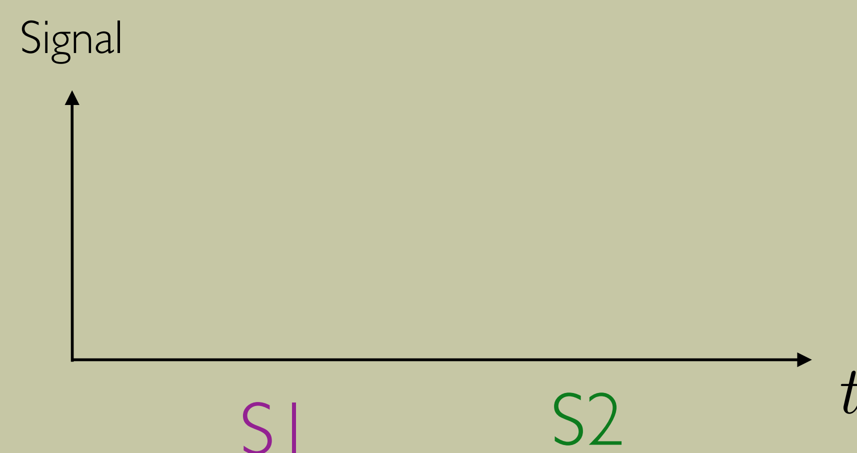
$$\mathrm{Xe} \rightarrow \mathrm{Xe}^{*}\,,\ \mathrm{Xe}^{+}$$

produces photons and electrons

Two types of signal:

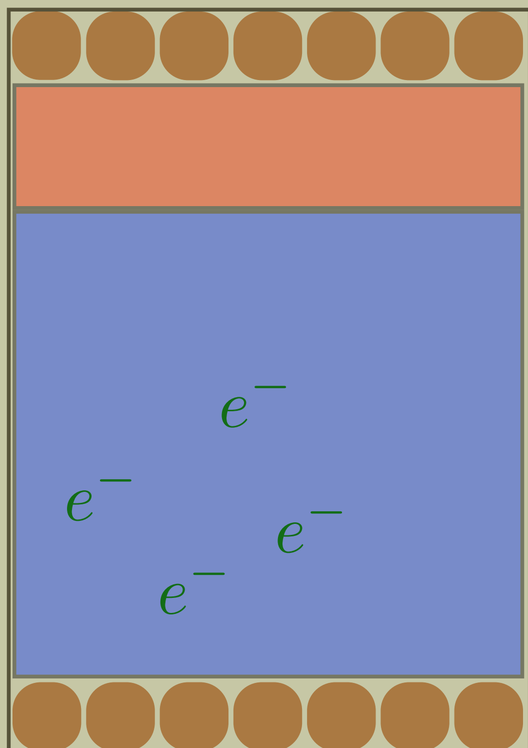
S1: prompt scintillation

S2: proportional scintillation
(from ionization)



XENON10

Light DM



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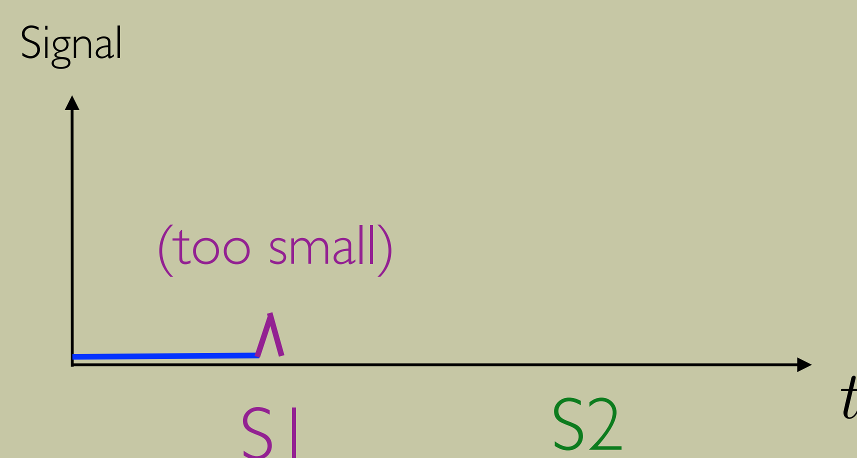
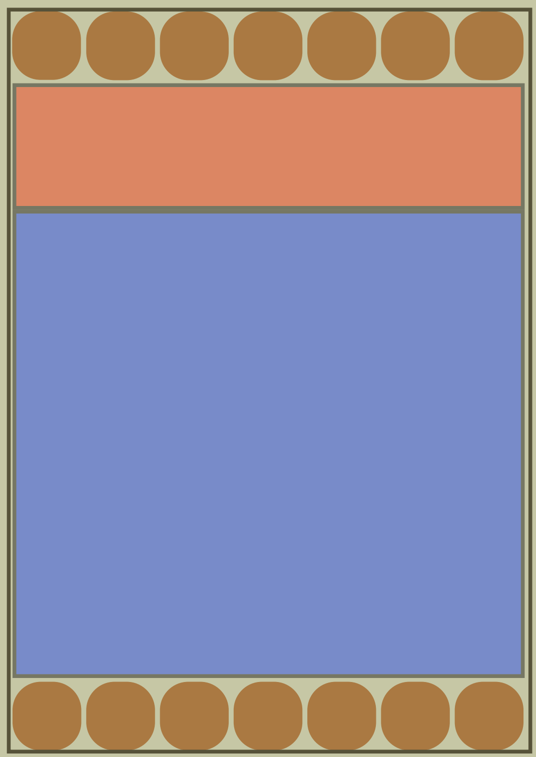


XENON10



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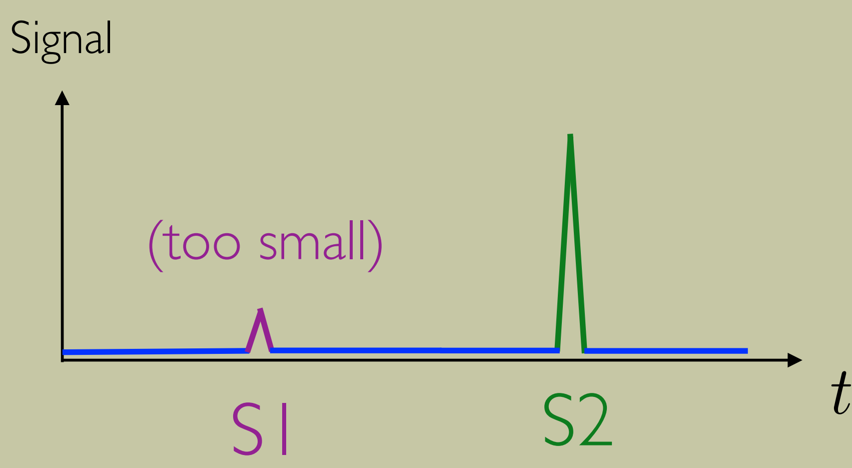
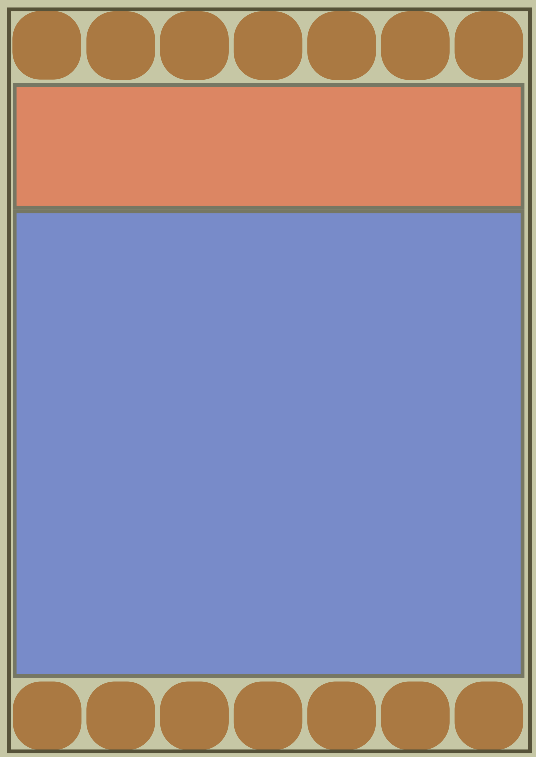
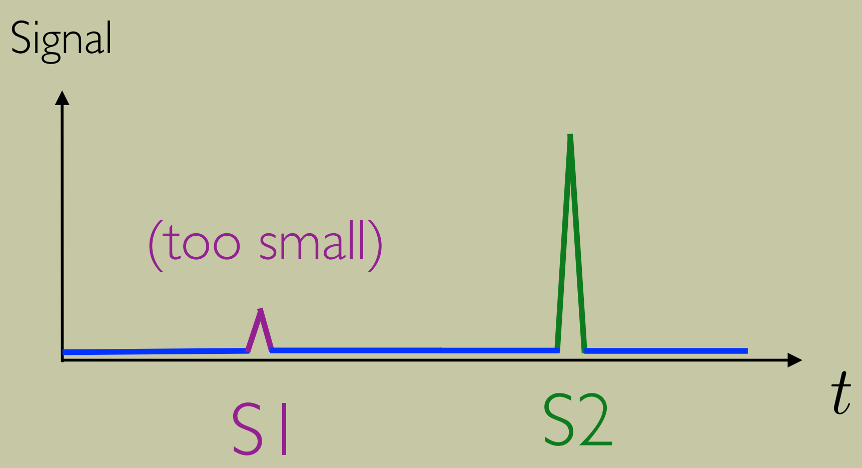


XENON10

For LDM, S1 is too small!



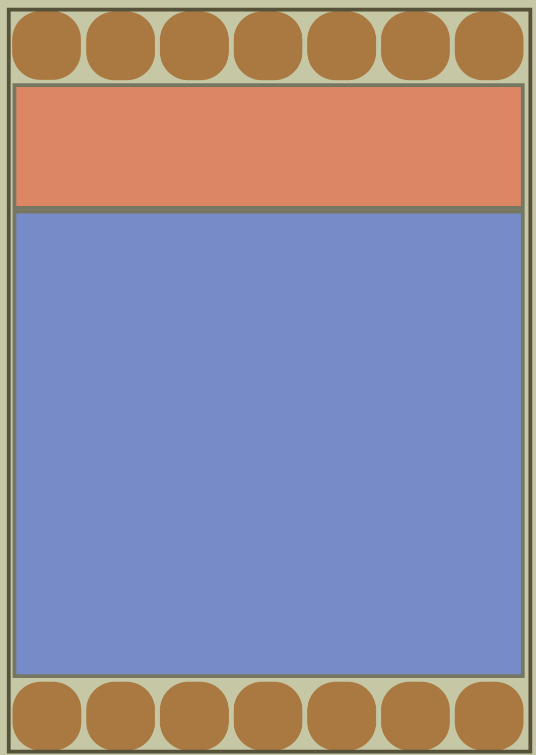


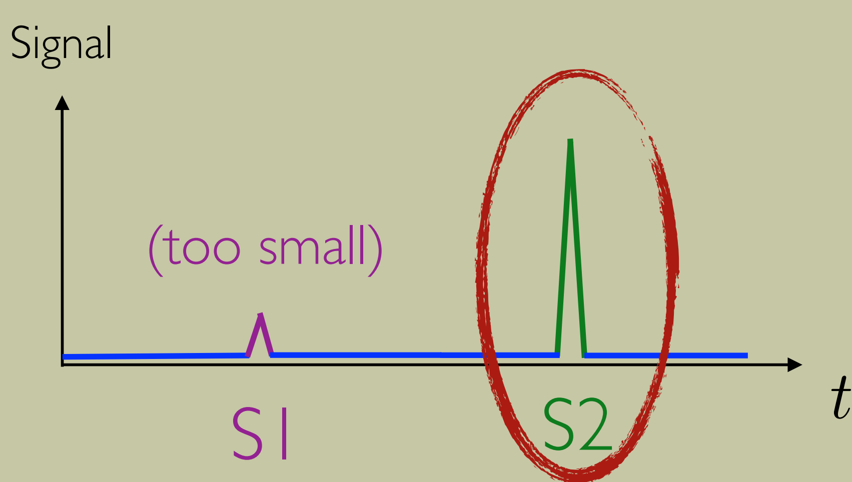
XENON10

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!

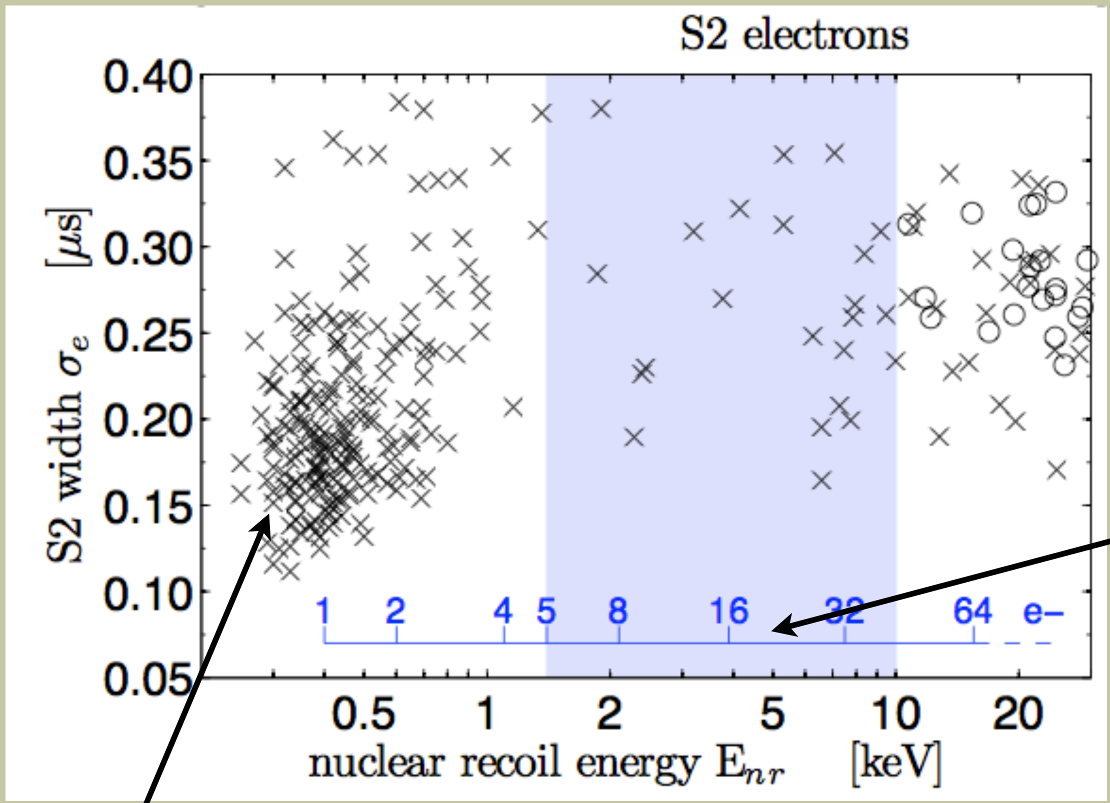
Instead can use S2 Only

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

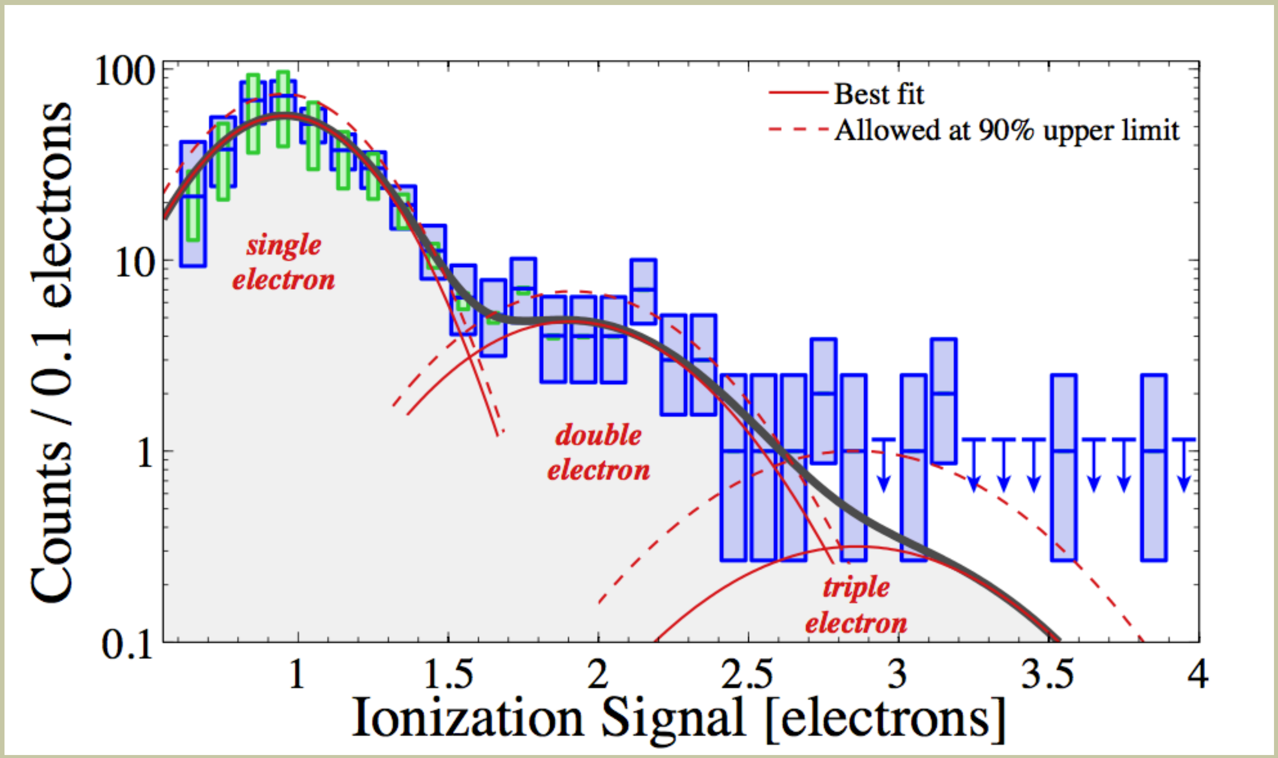


Number of electrons

Large population of single electrons.

Data Sample

- After correcting for triggering efficiency we get,

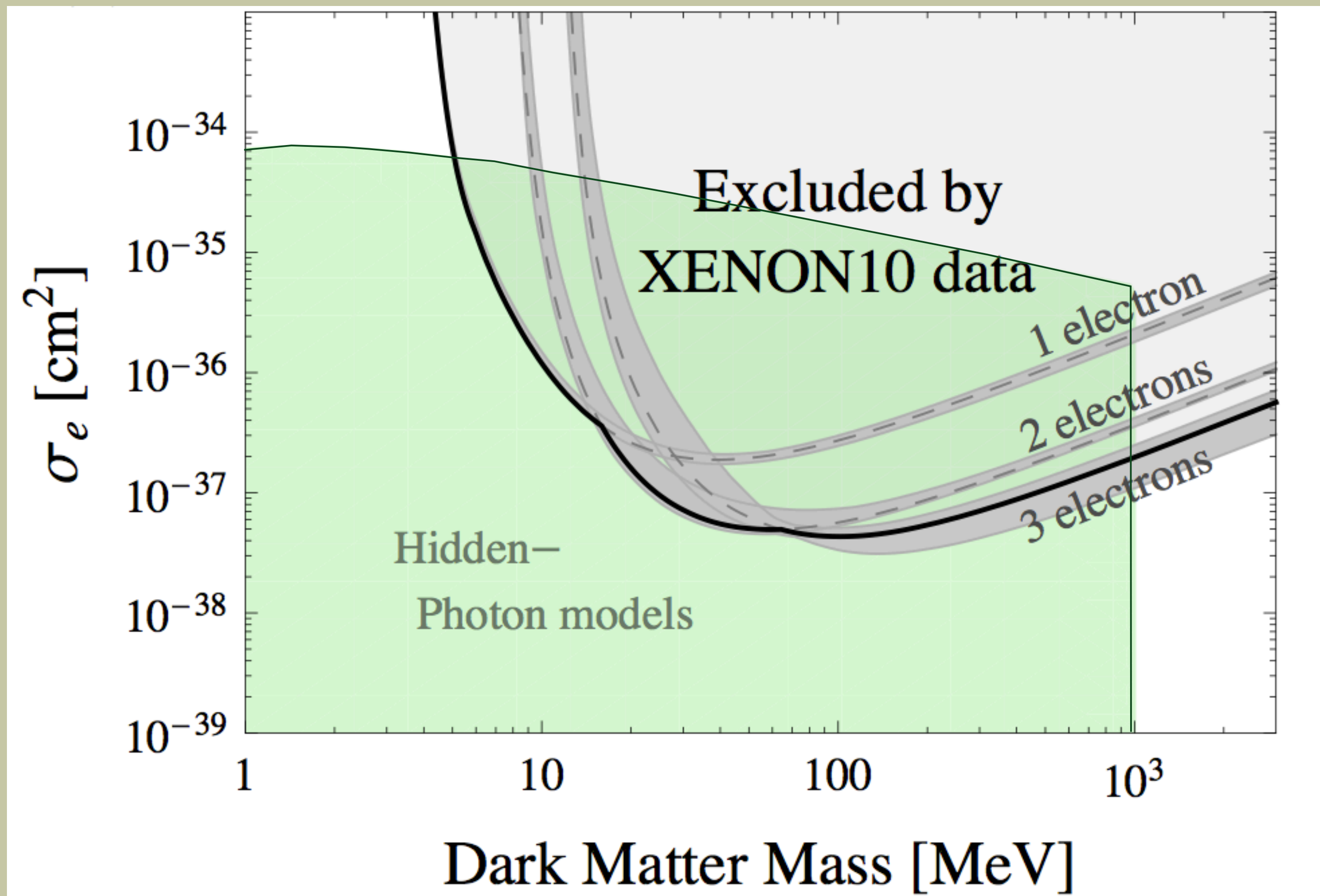


- The result of the fit (dark-gray curve) gives a 90% upper confidence bound (counts/kg/day):

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

Results: $F_{DM}=1$

First Direct Detection Bounds for MeV-GeV



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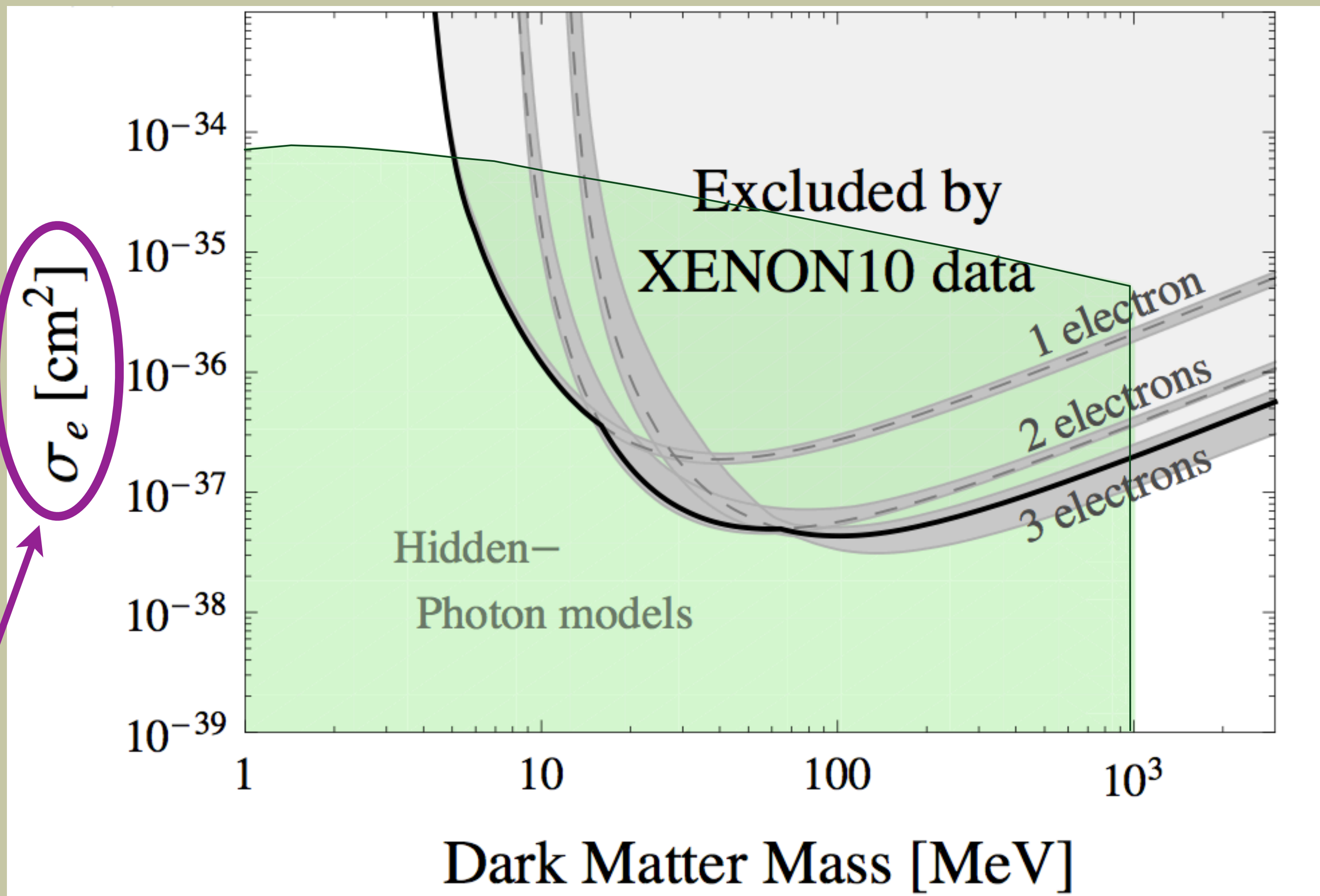
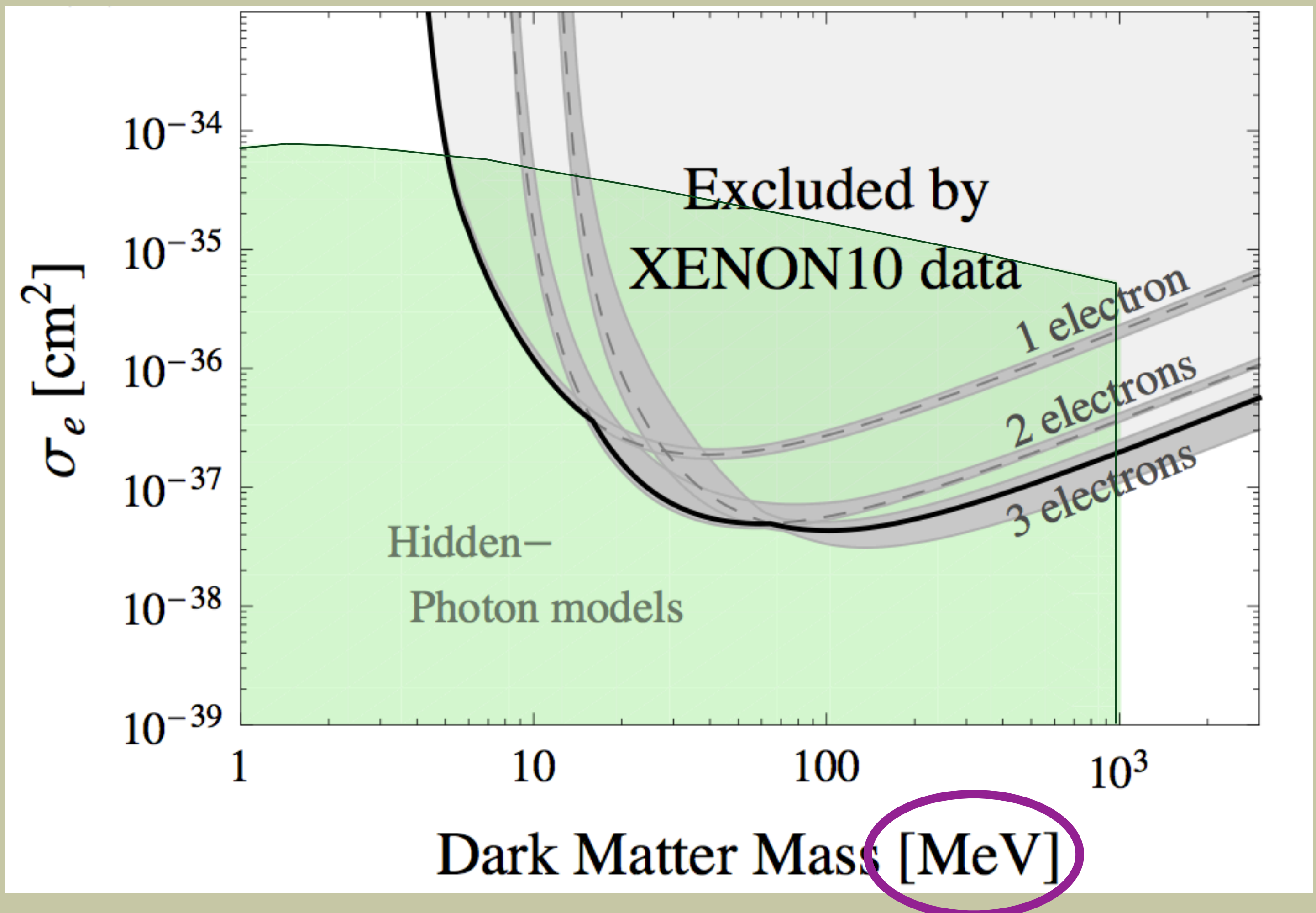


free electron-DM cross-section.

Results: $F_{DM}=1$

First Direct Detection Bounds for MeV-GeV



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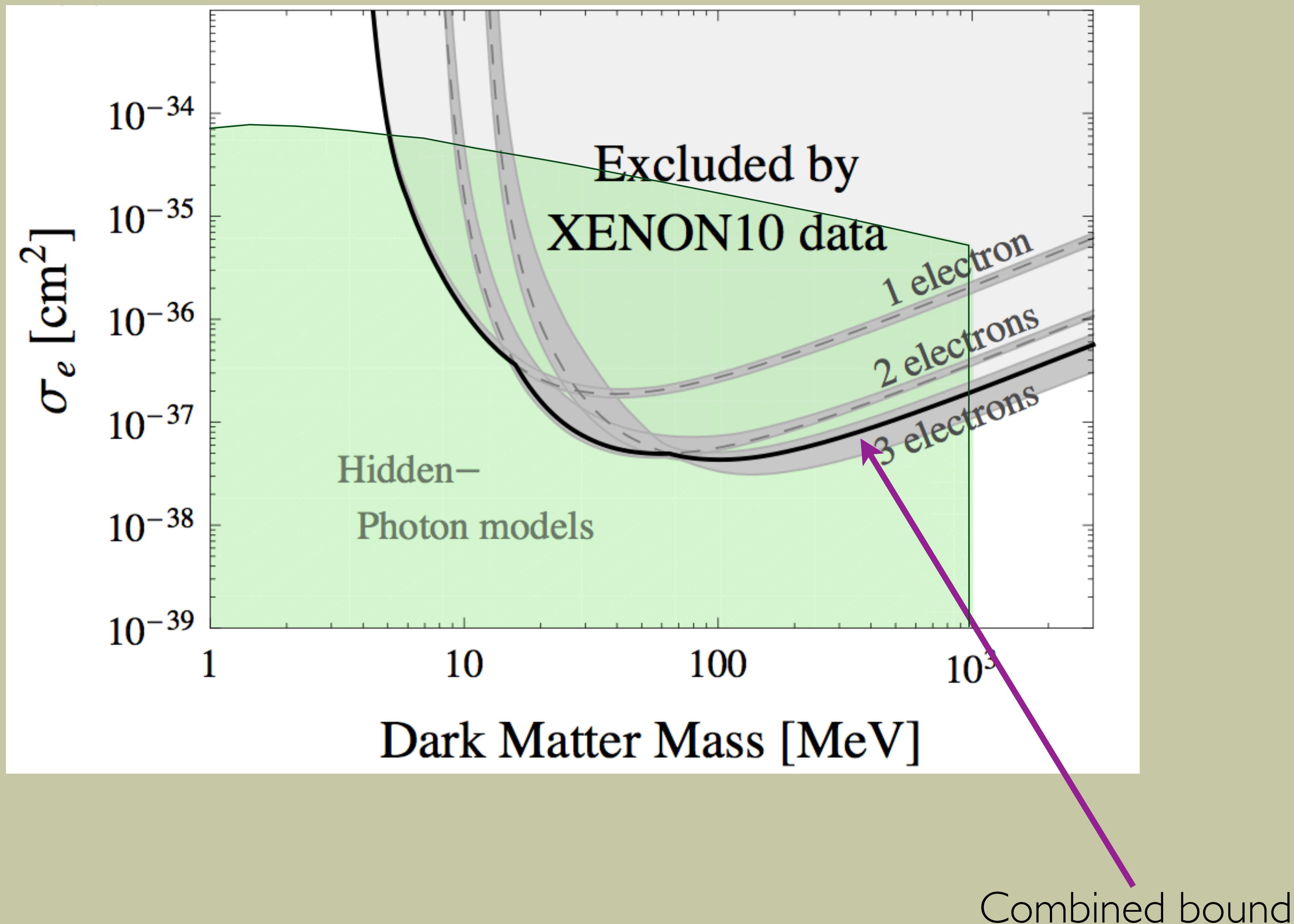

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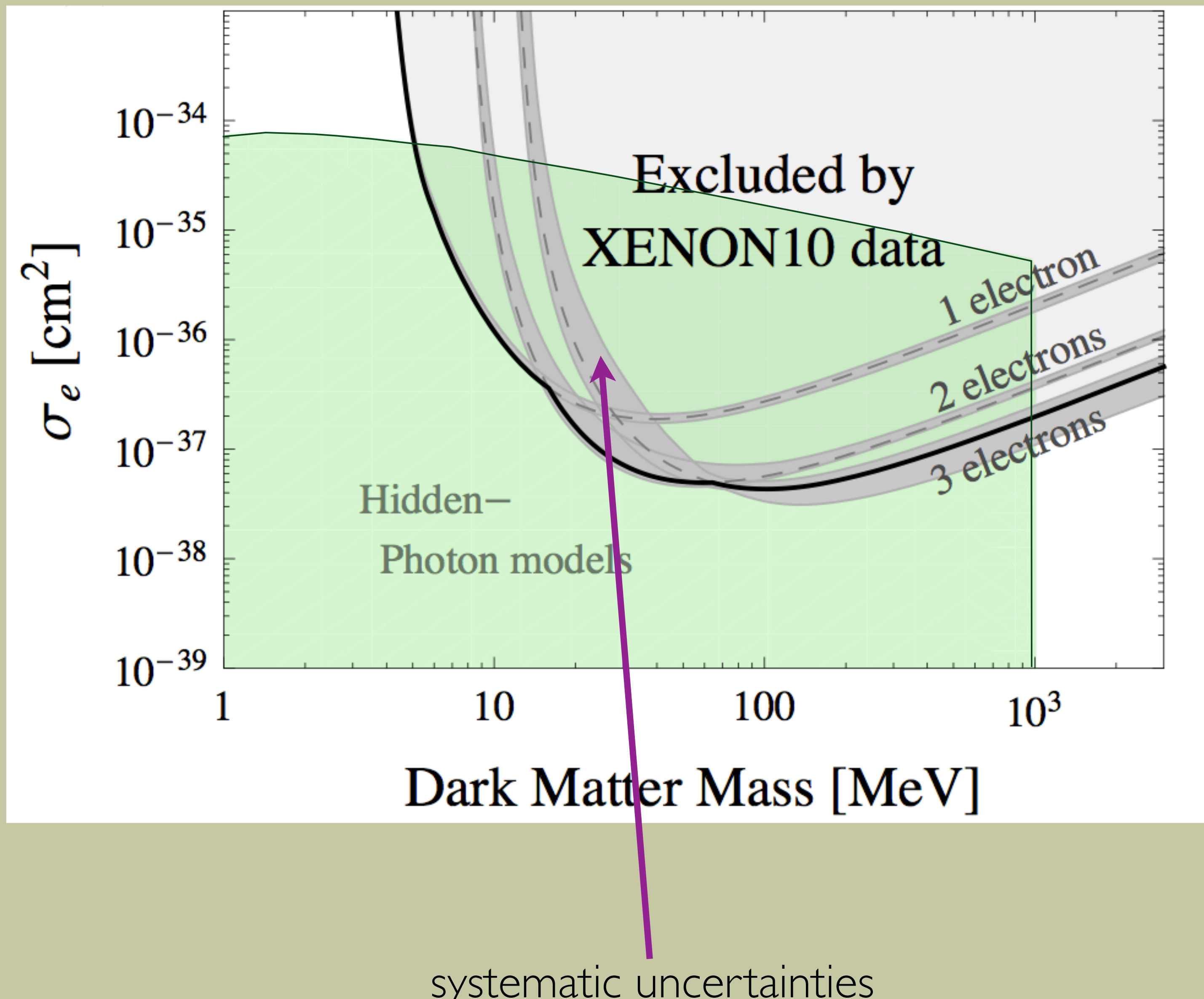

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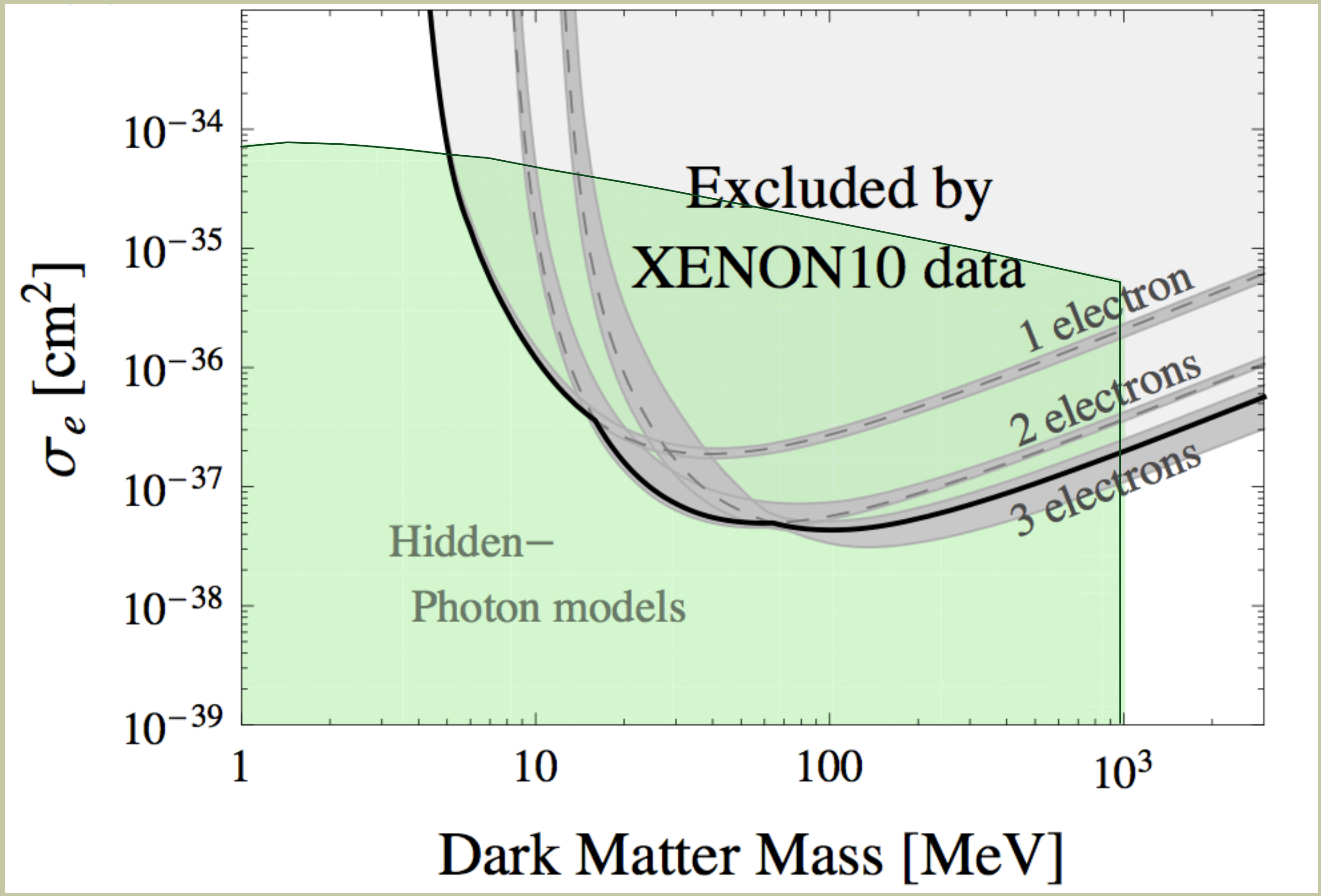
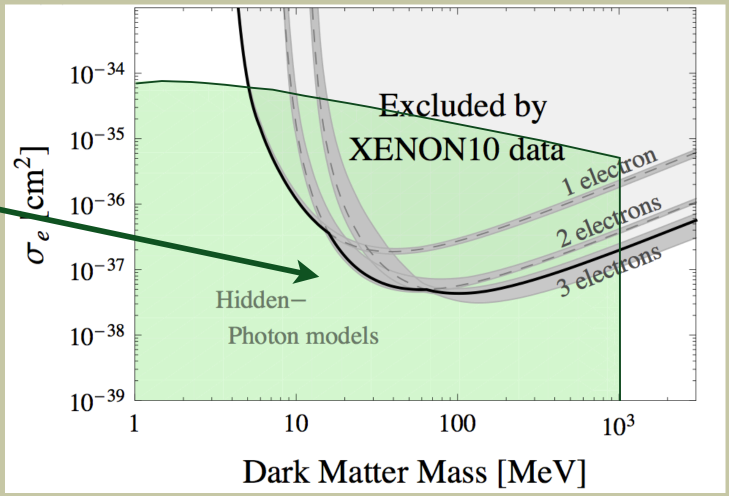
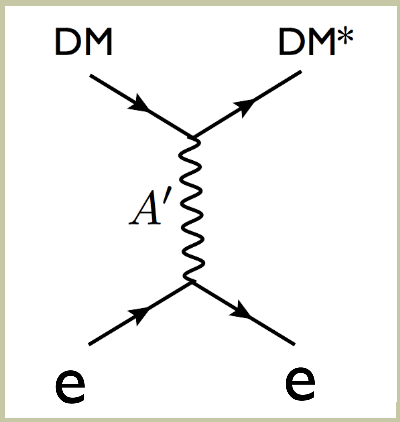


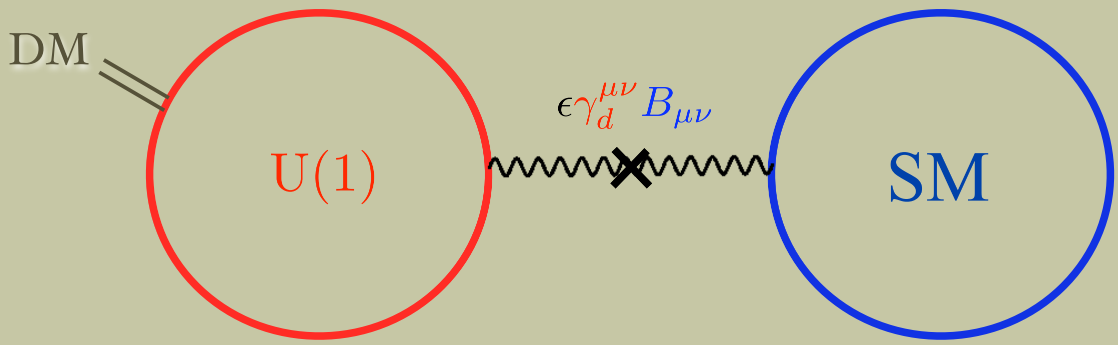
Results: $F_{DM}=1$

Model in GREEN



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

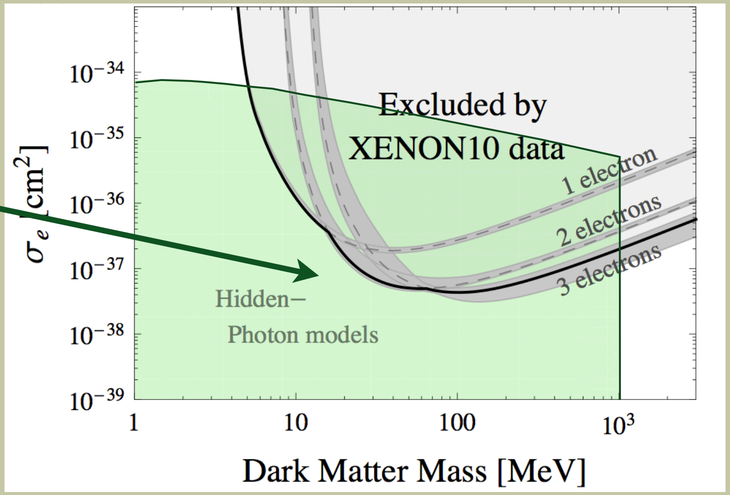




$$\sigma = \frac{16\,\pi\,m_e^2\,\alpha\,\alpha'\,\epsilon^2}{(m_{A'}^2+q^2)^2}$$

Results: $F_{DM}=1$

Model in GREEN



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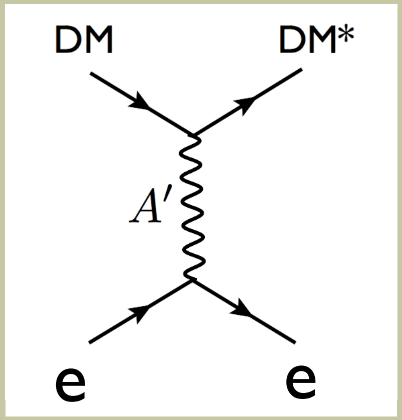
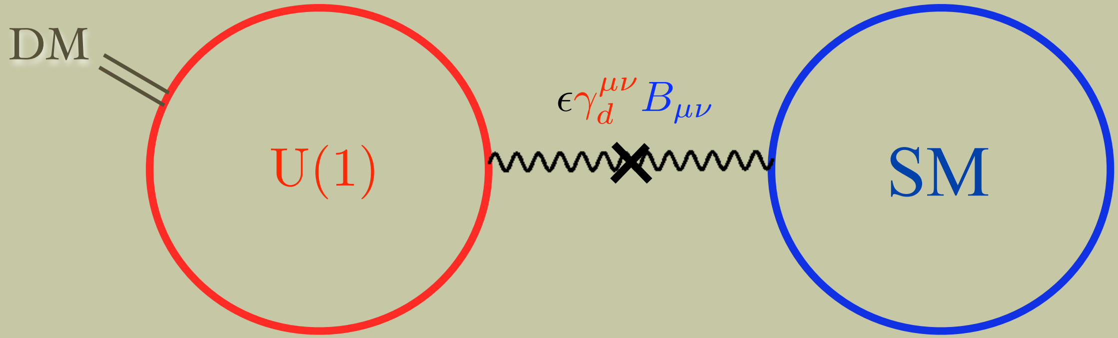
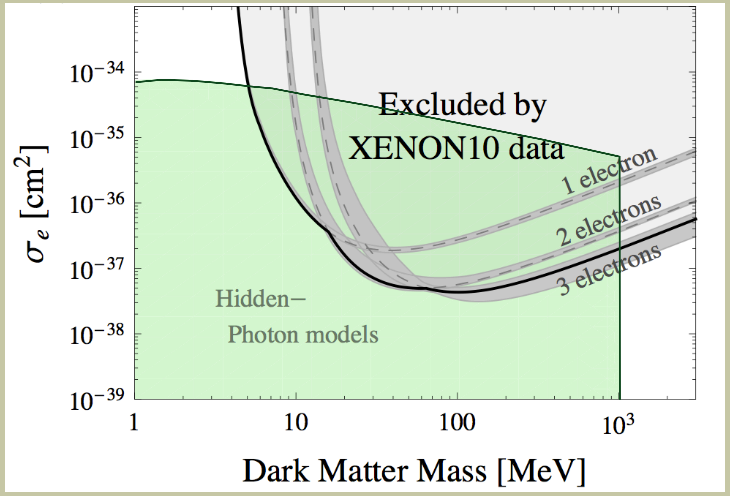


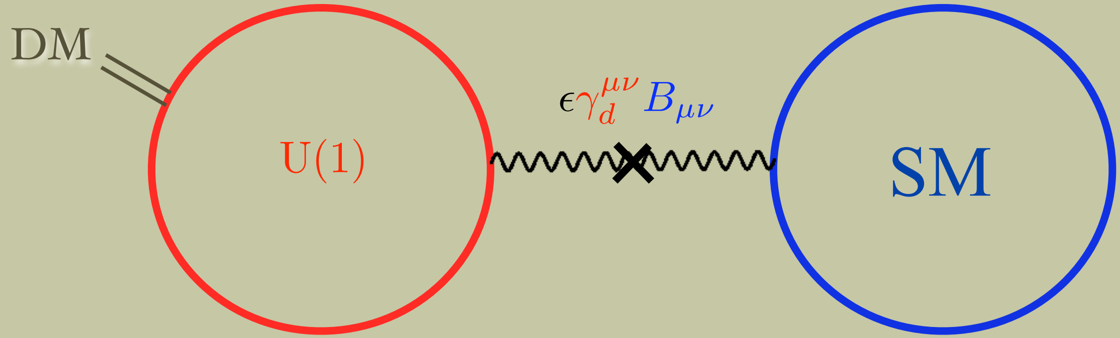


$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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

Results: $F_{DM}=1$





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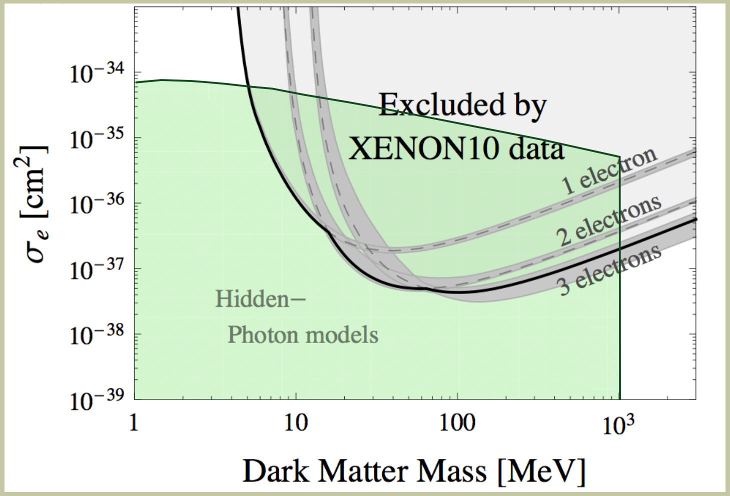
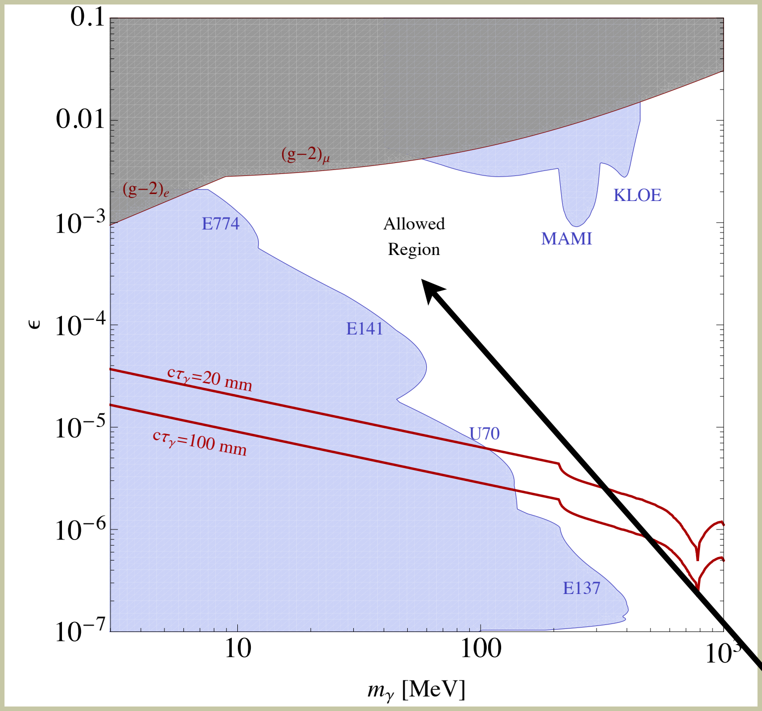
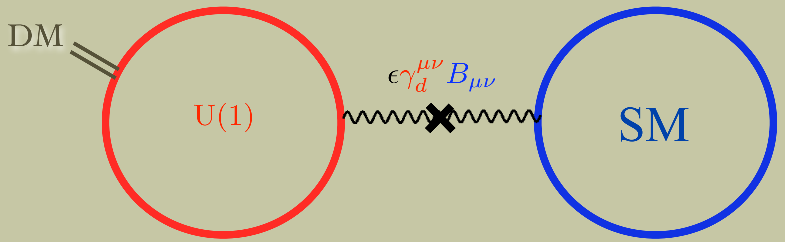


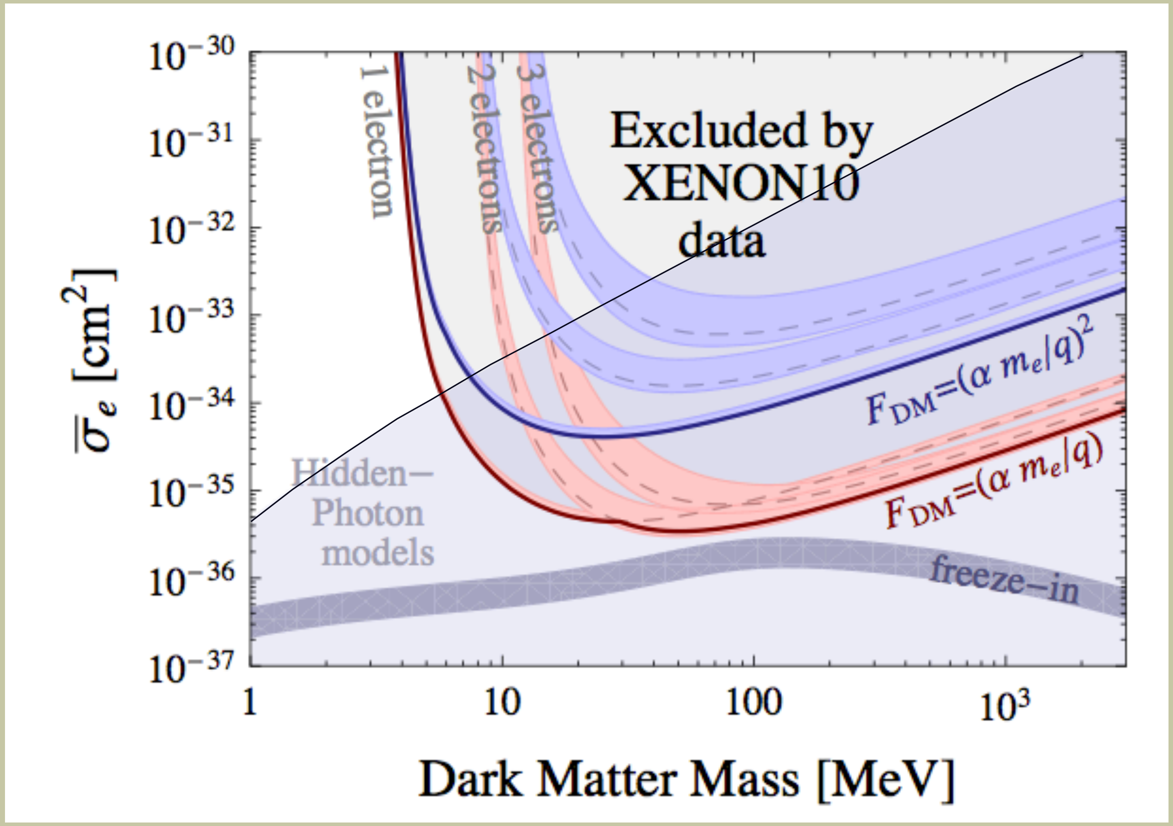


[Bjorken, Essig, Schuster, Toro 2009;
Blumlein, Brunner 2011]



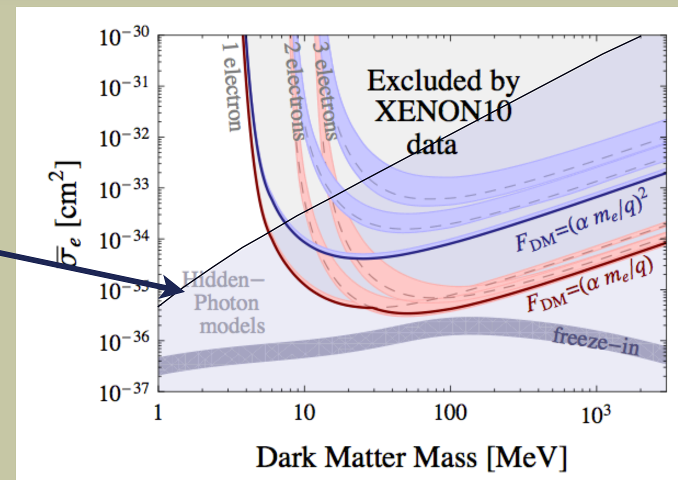
For m_A >MeV hidden photon: $F_{\rm DM} = 1$

Results: Non-trivial form factor

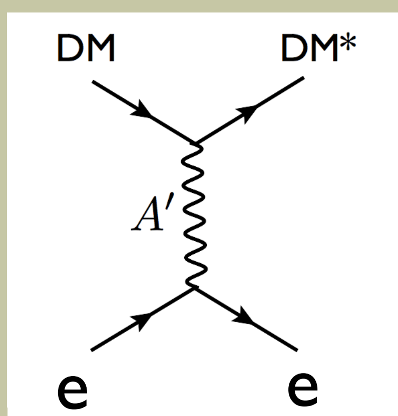


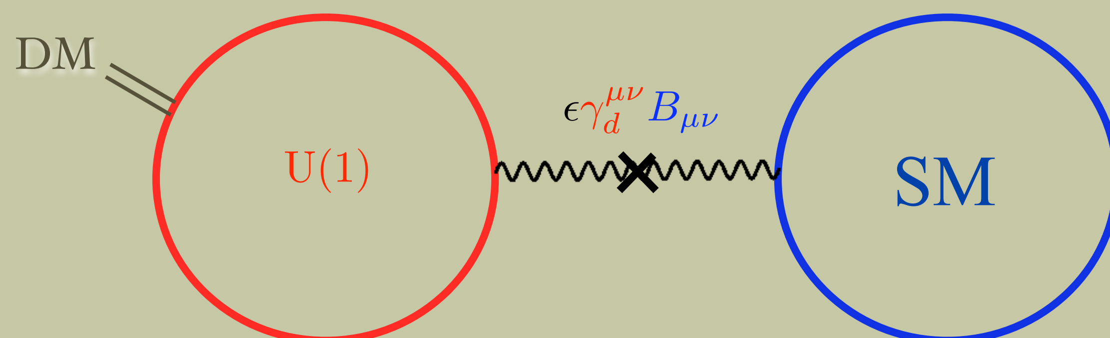
Results: Non-trivial form factor

Model in BLUE



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

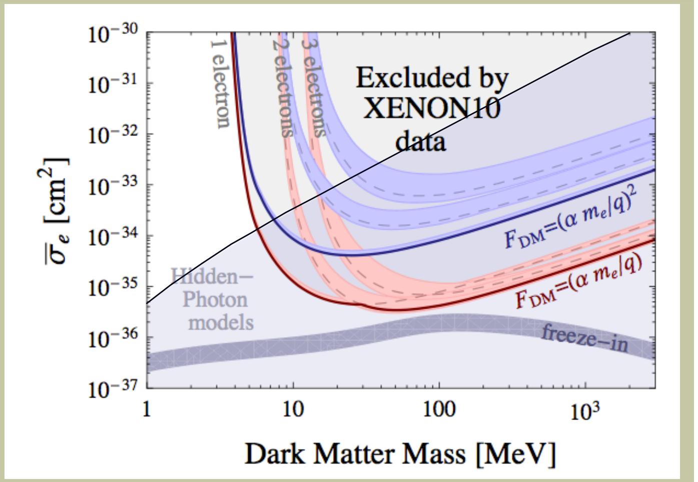




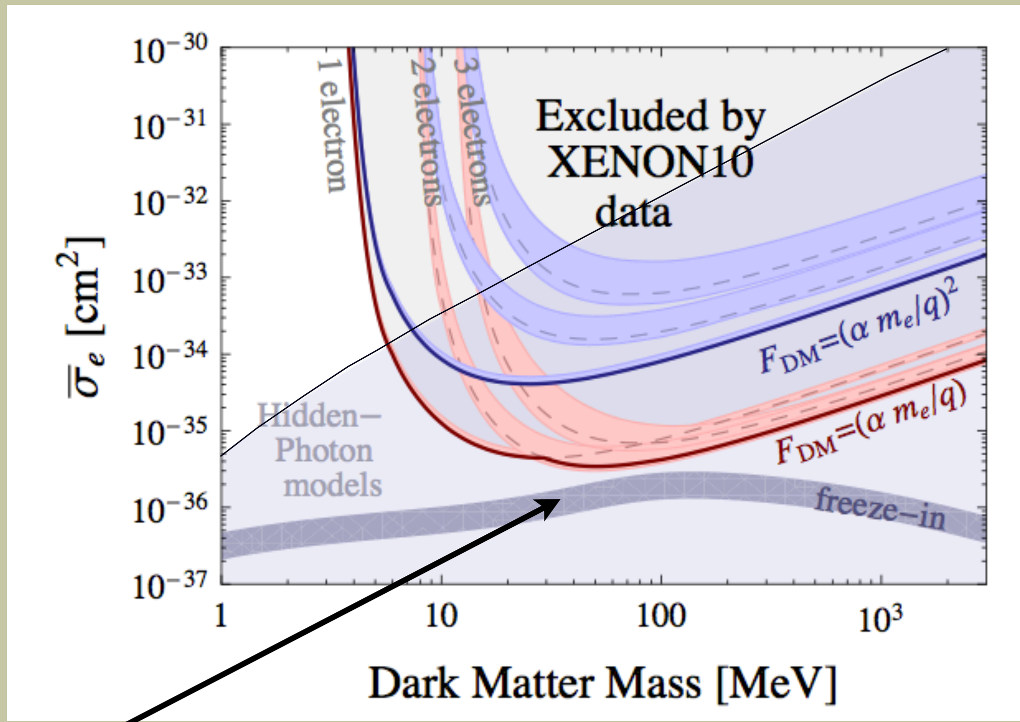
$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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

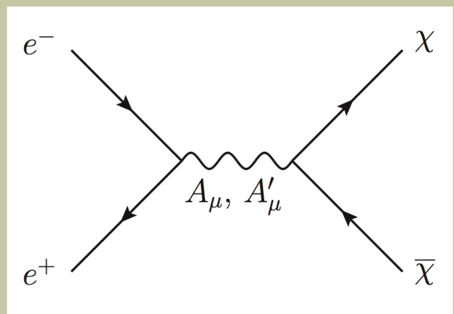
Results: $F_{DM} \sim 1/q^2$



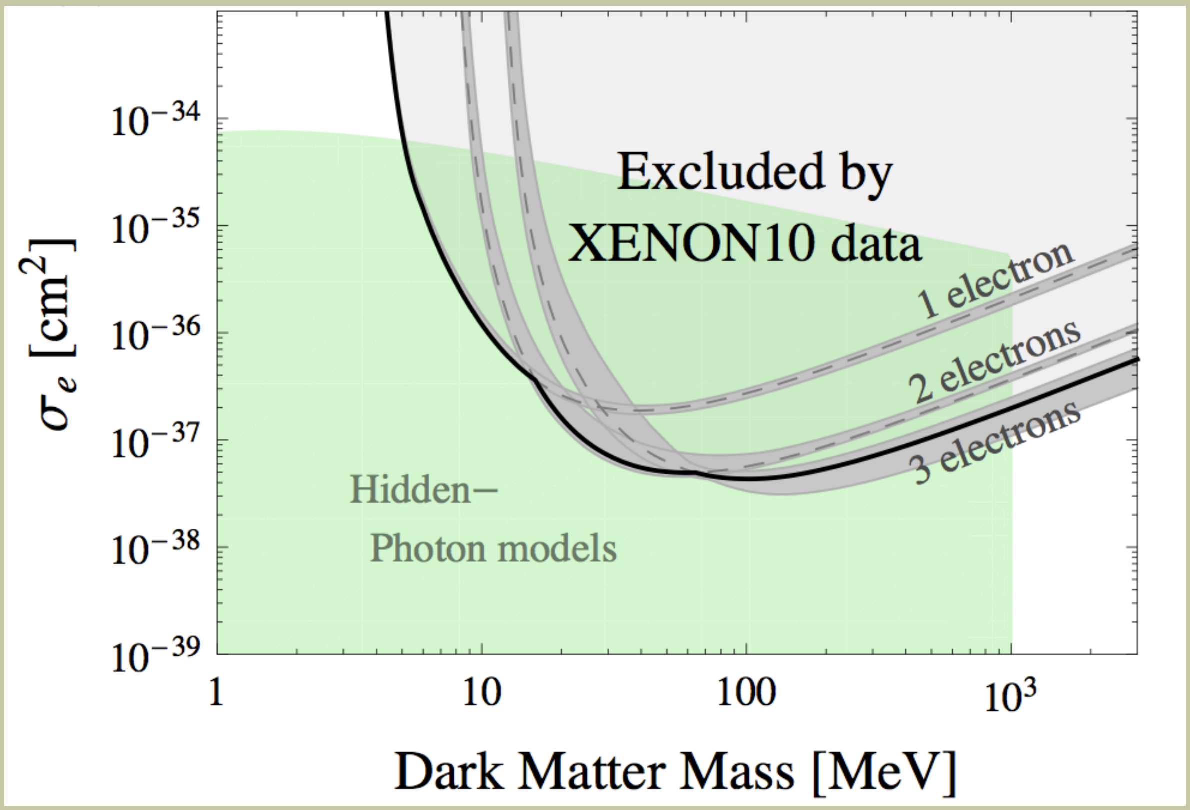
Results: $F_{DM} \sim 1/q^2$



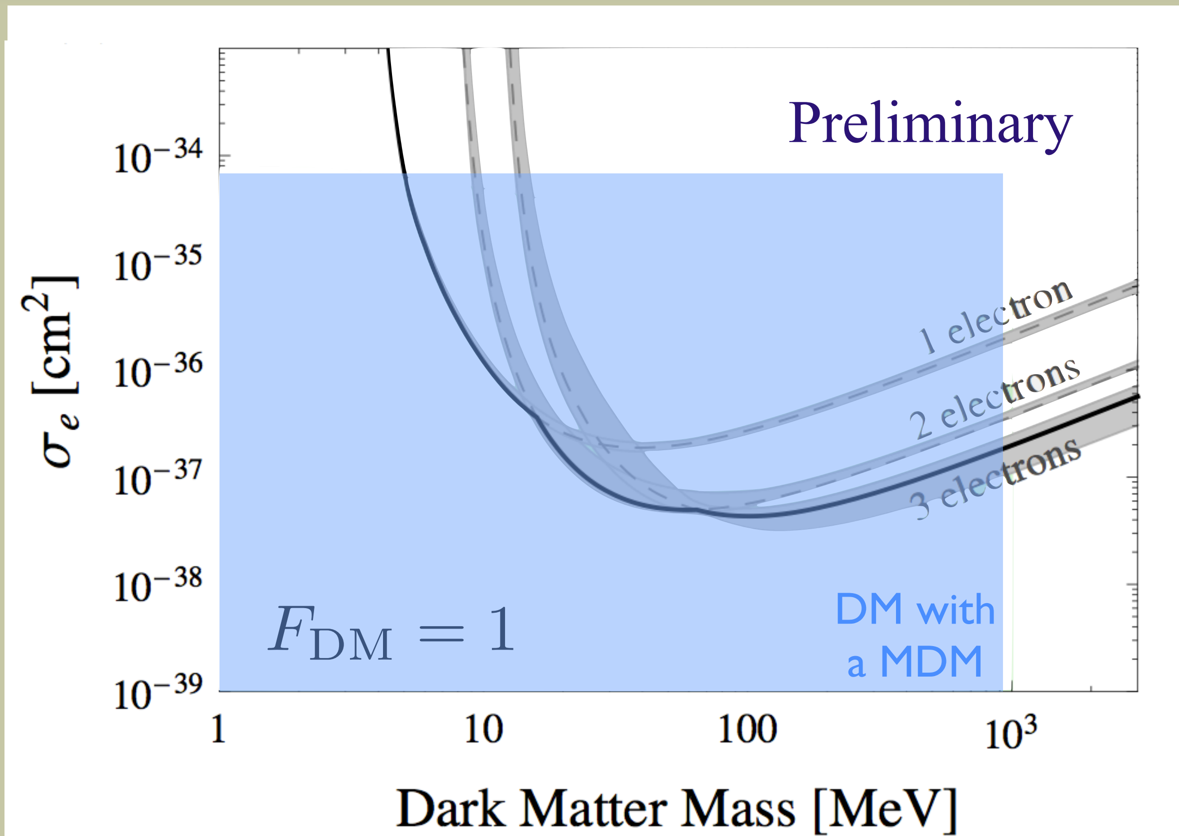
Almost sensitive to Freeze-in region: DM is naturally produced by SM production.



More Interesting Models



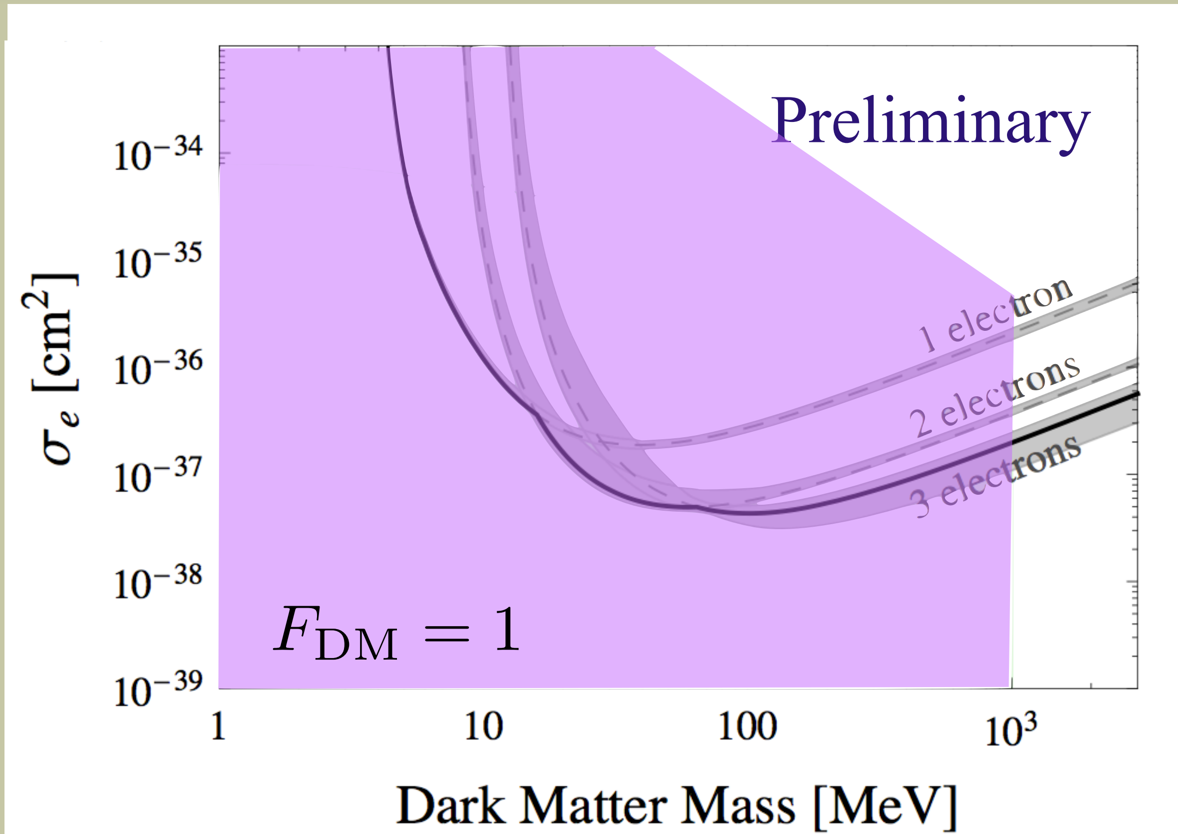
More Interesting Models

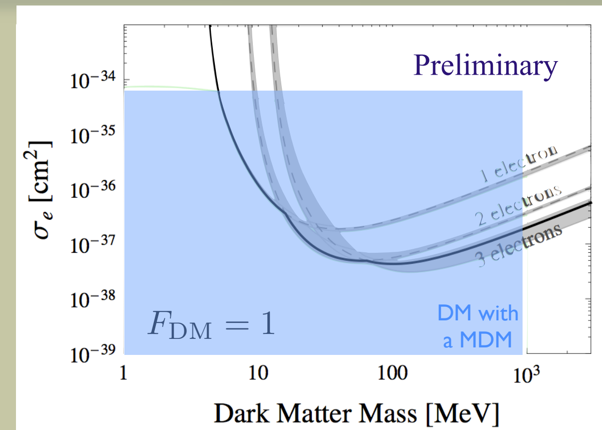


DM with magnetic dipole moment

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

More Interesting Models

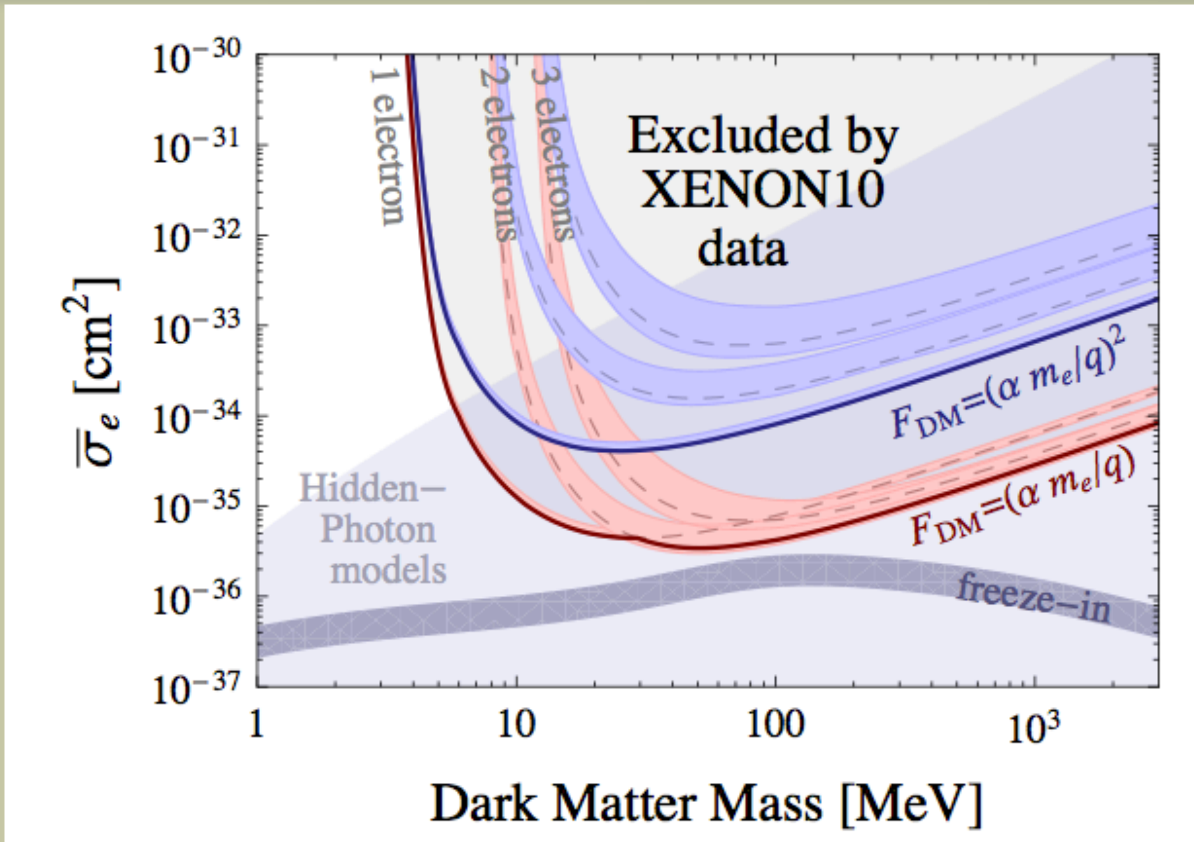


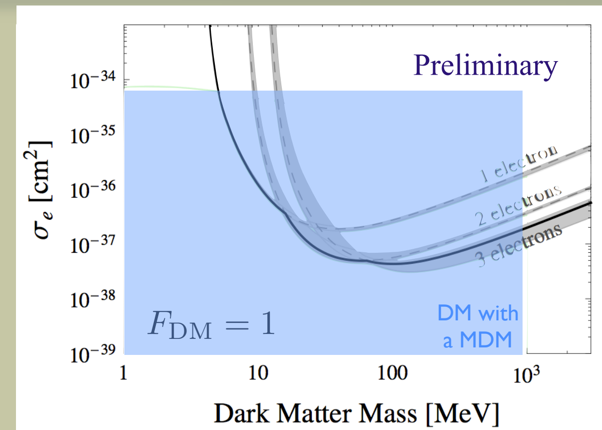


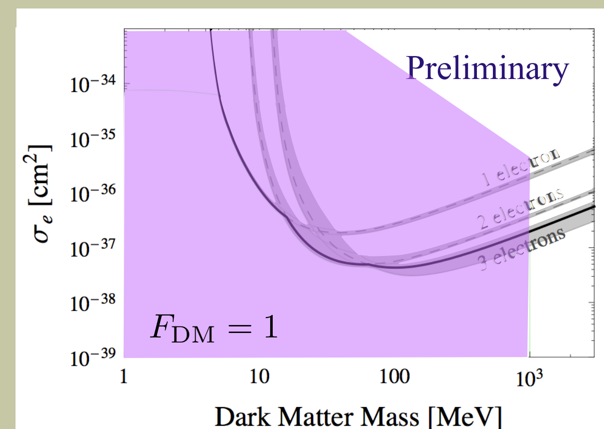
Scalar DM operator

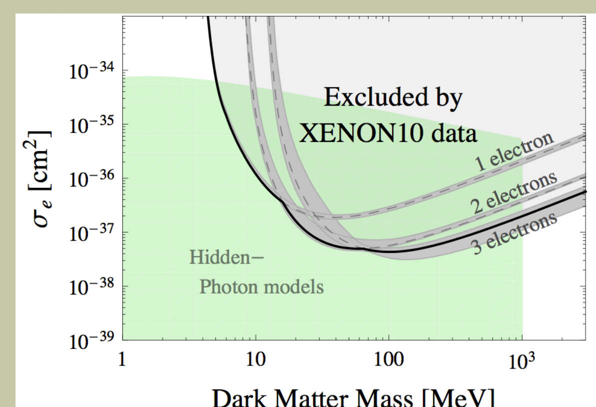
$$\frac{1}{\Lambda}\bar{\phi}^{\dagger}\phi\bar{e}e$$

More Interesting Models

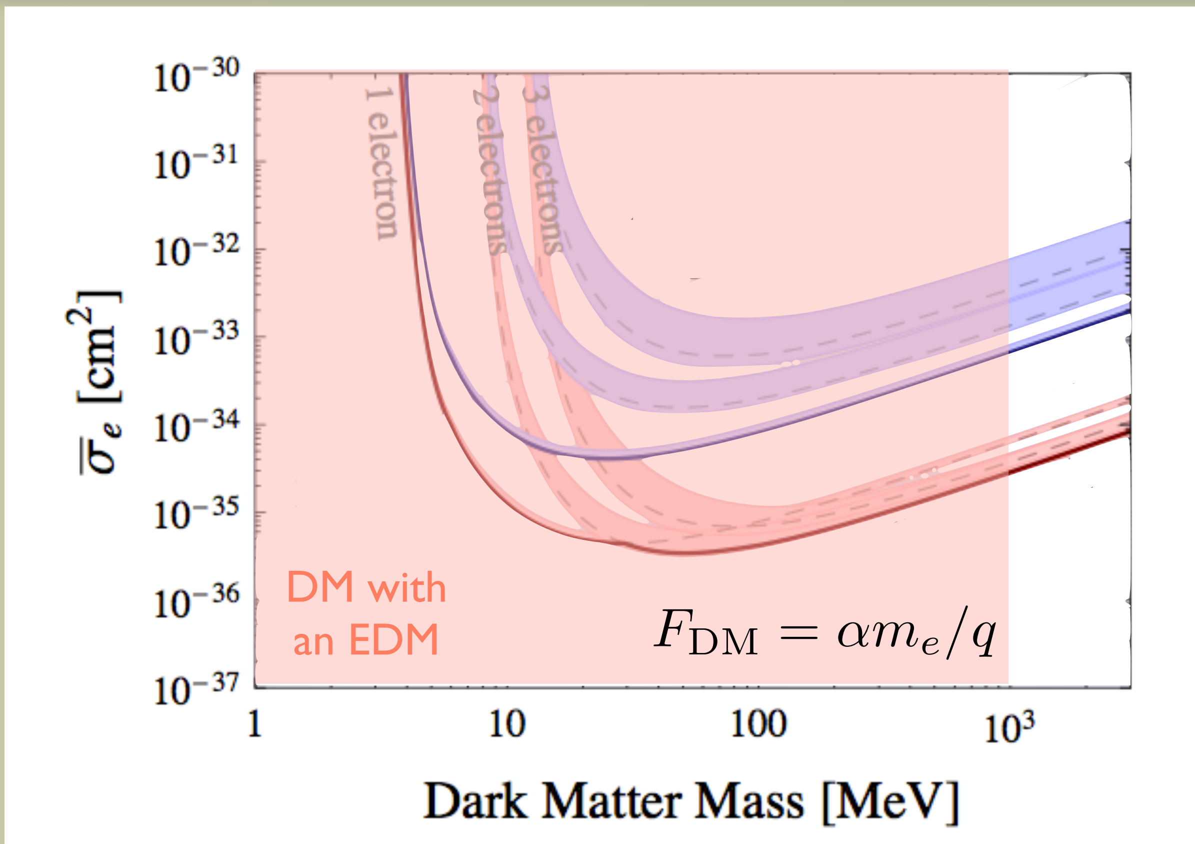


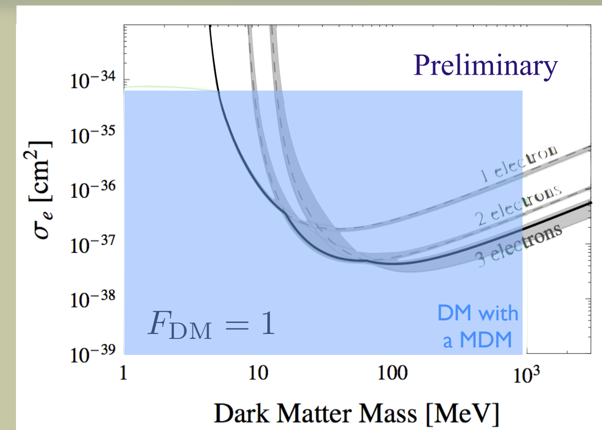


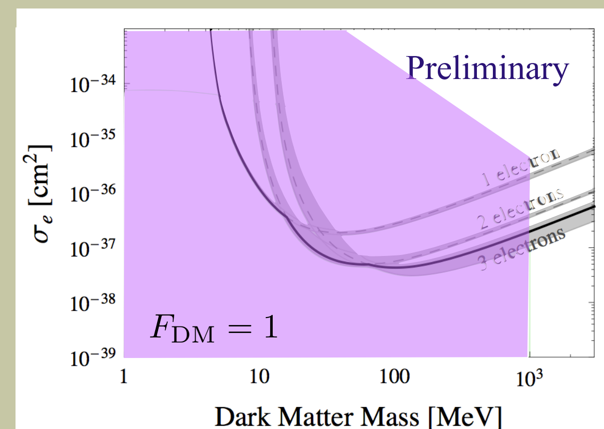


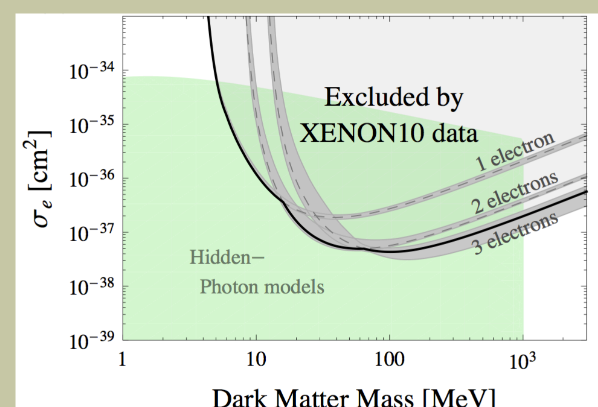


More Interesting Models





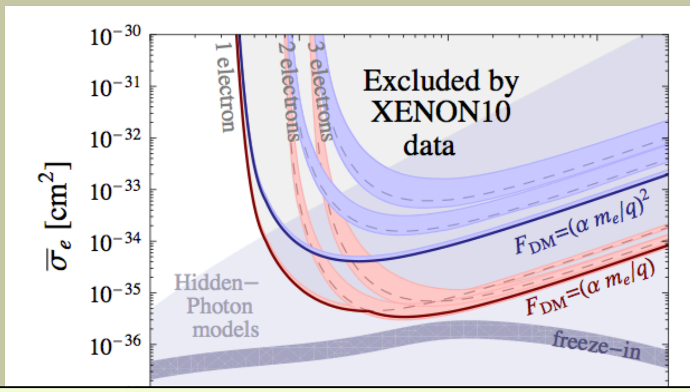


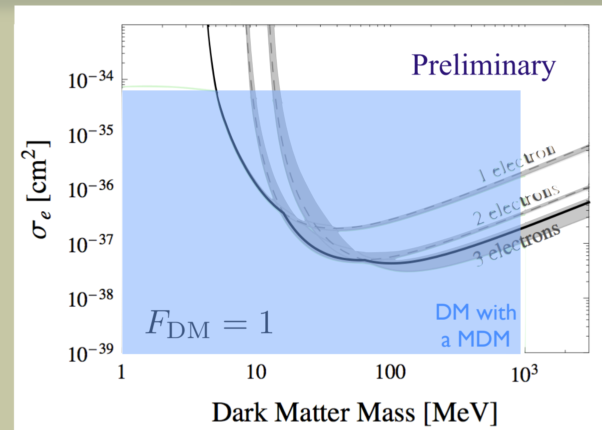


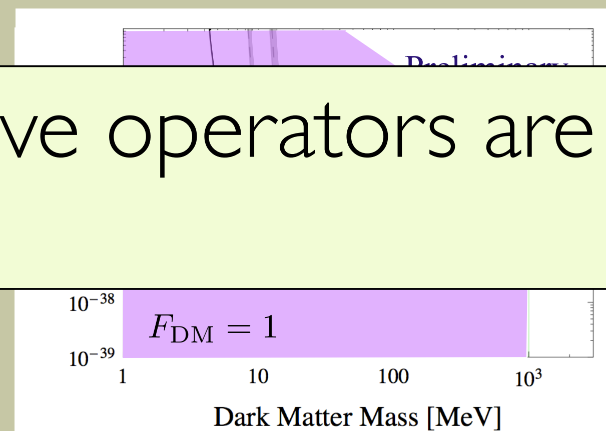
DM with electric dipole moment

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

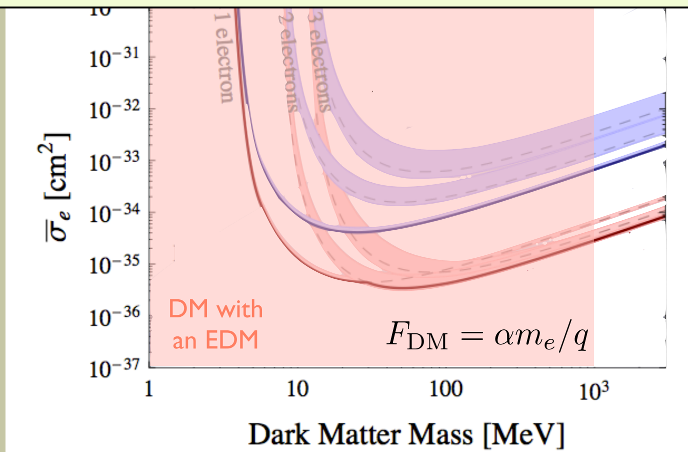
More Interesting Models

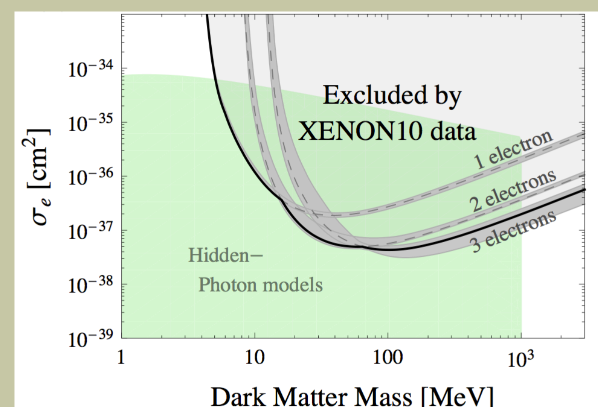






Many interesting models and effective operators are already probed





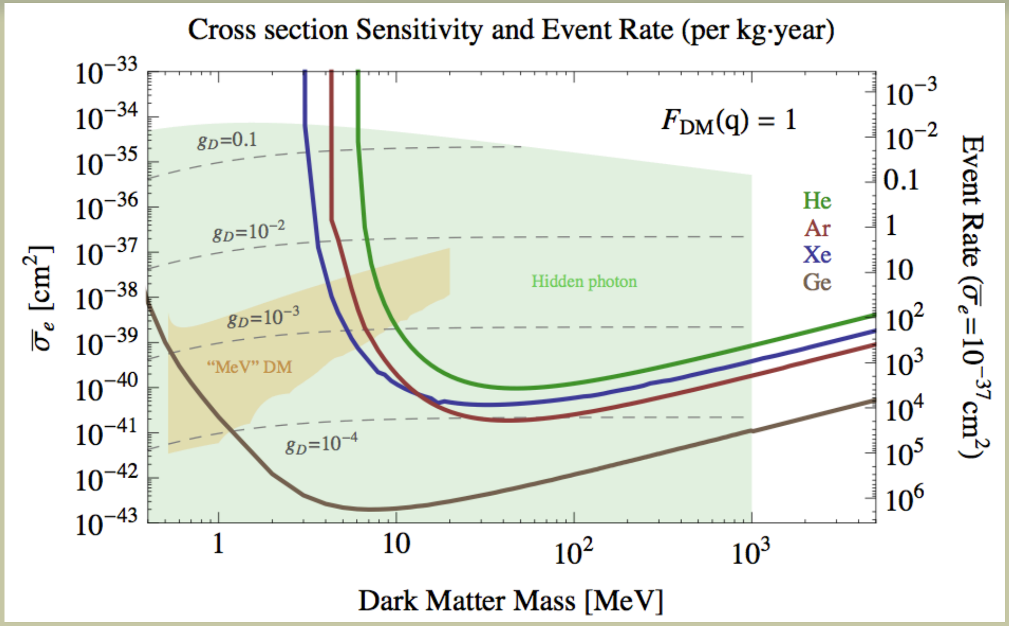
Results

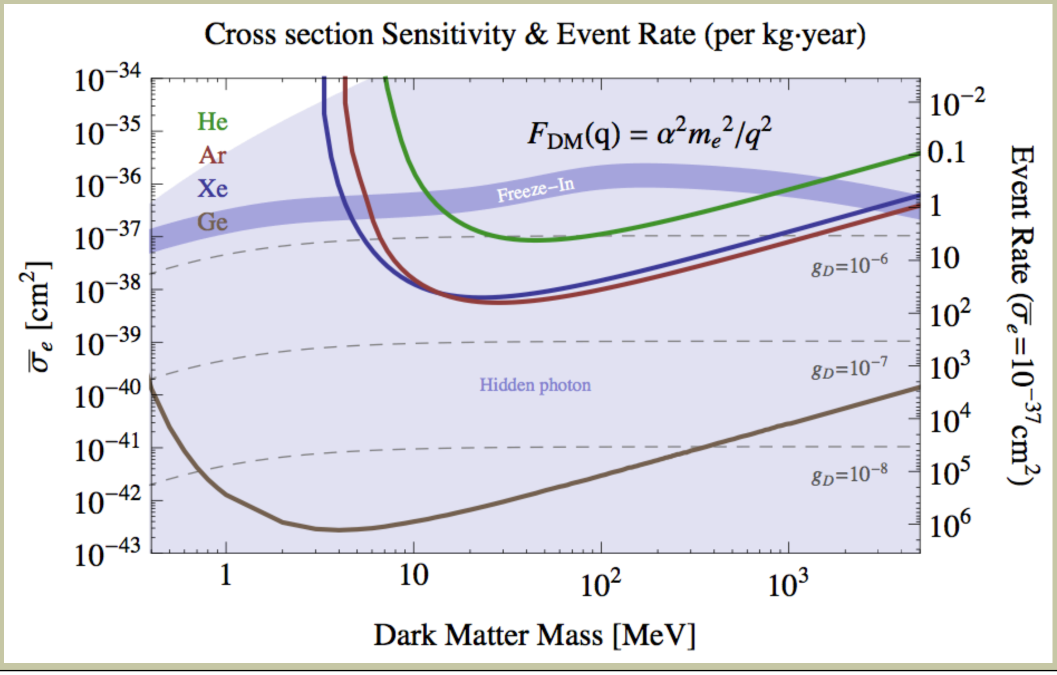
These are results for only 15 kg-days with a non-dedicated experiment!

Improvements could be very significant!!!

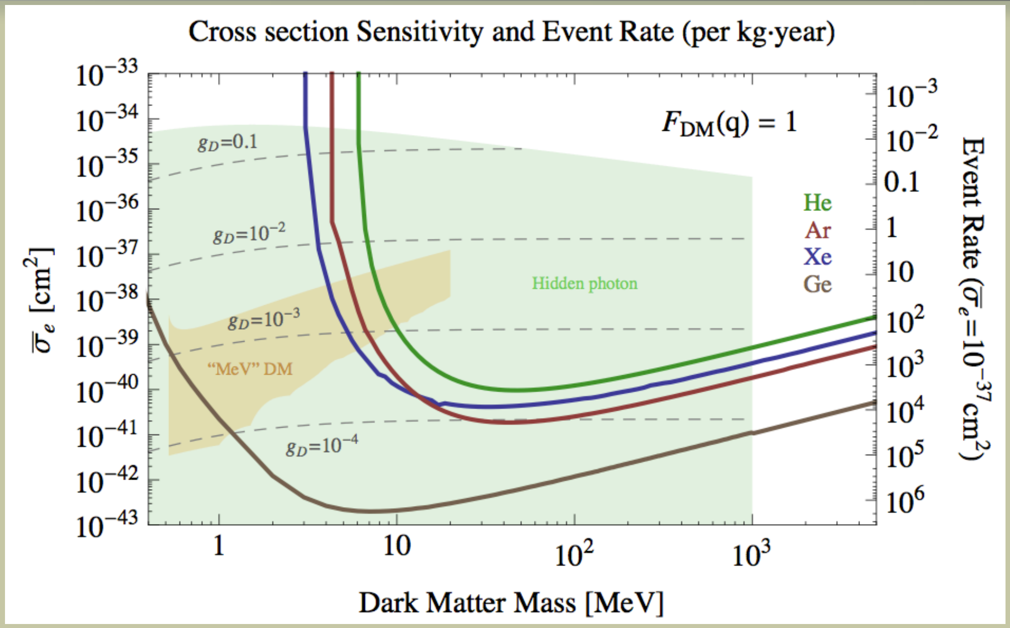
So What Can We Expect?

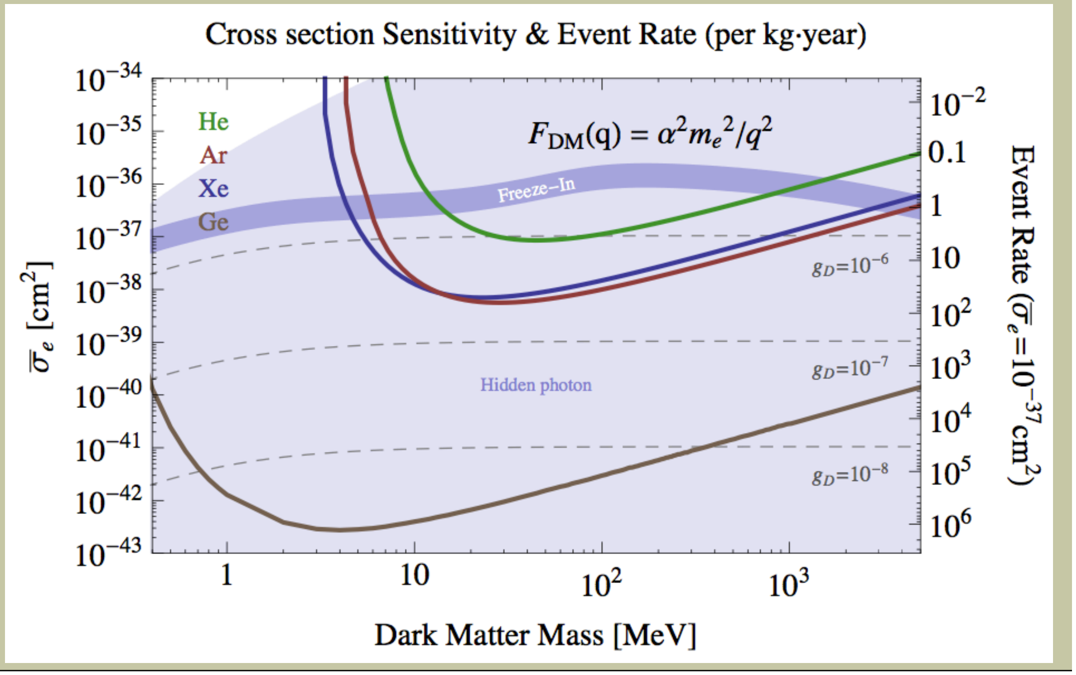
Projected Sensitivity





Projected Sensitivity





Can we discover light DM without a dedicated experiment?

YES. Search for annual modulation.

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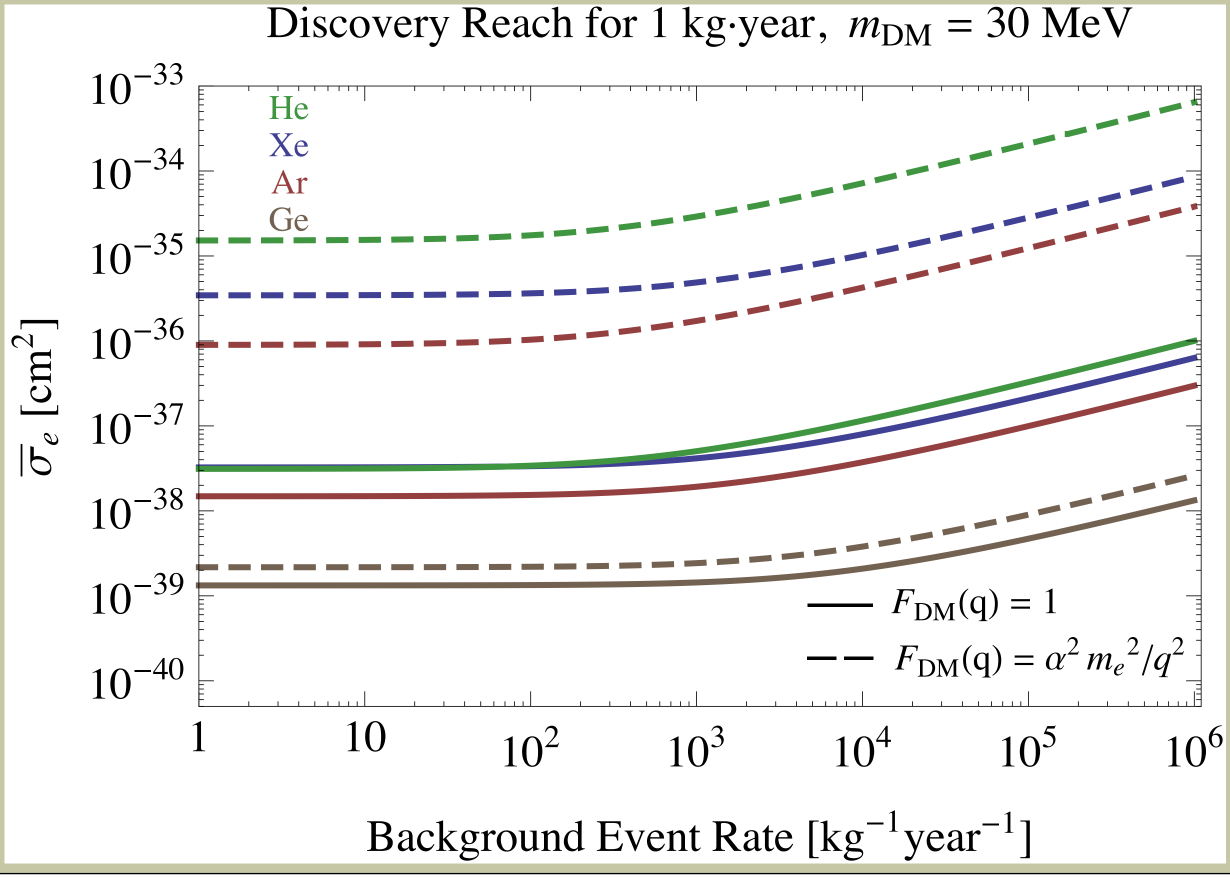
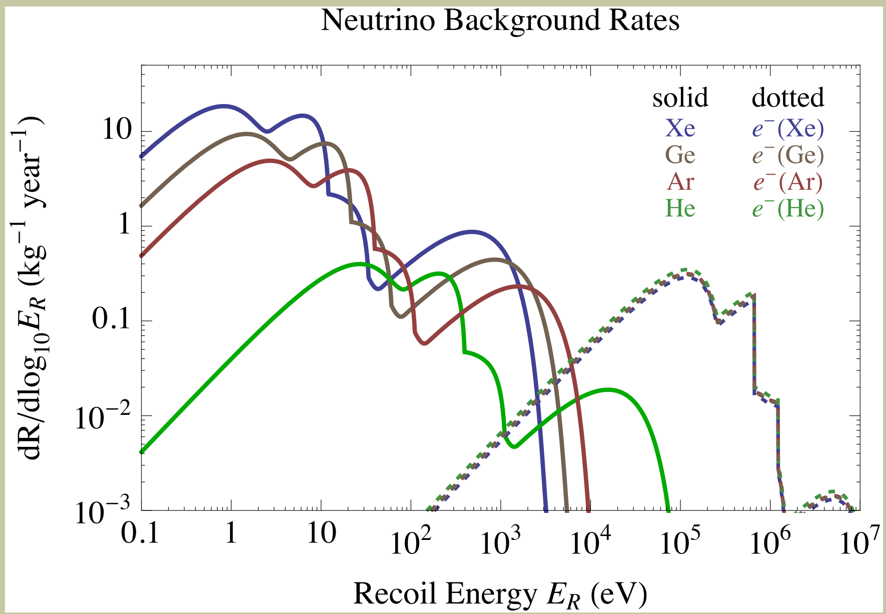


Backgrounds

- 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.

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
    - New generation @ CDMS:

New results likely in the near future..

Stay Tuned

Ultra-High Resolution Athermal Phonon Detectors

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.

Outlook

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  [Essig, Mardon, Papucci, TV, Zhong, *in writing*]
- Direct Detection: Ongoing experiments and dedicated ones.

Extras

Technological Directions

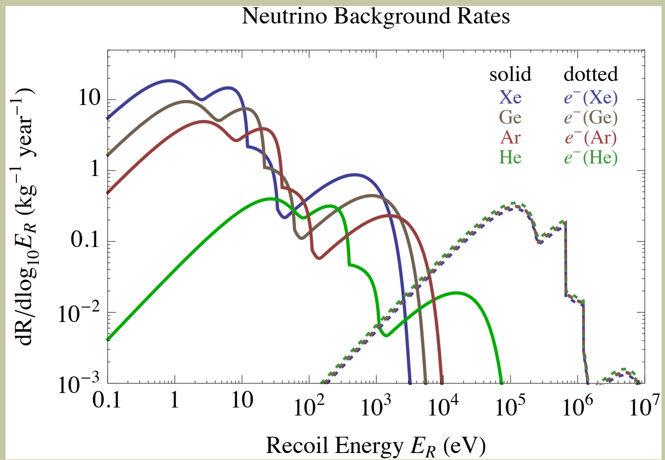
R&D needed in direct detection experiments

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

- Photon 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.

[Essig,Grossman,Mardon,TV, work in progress]



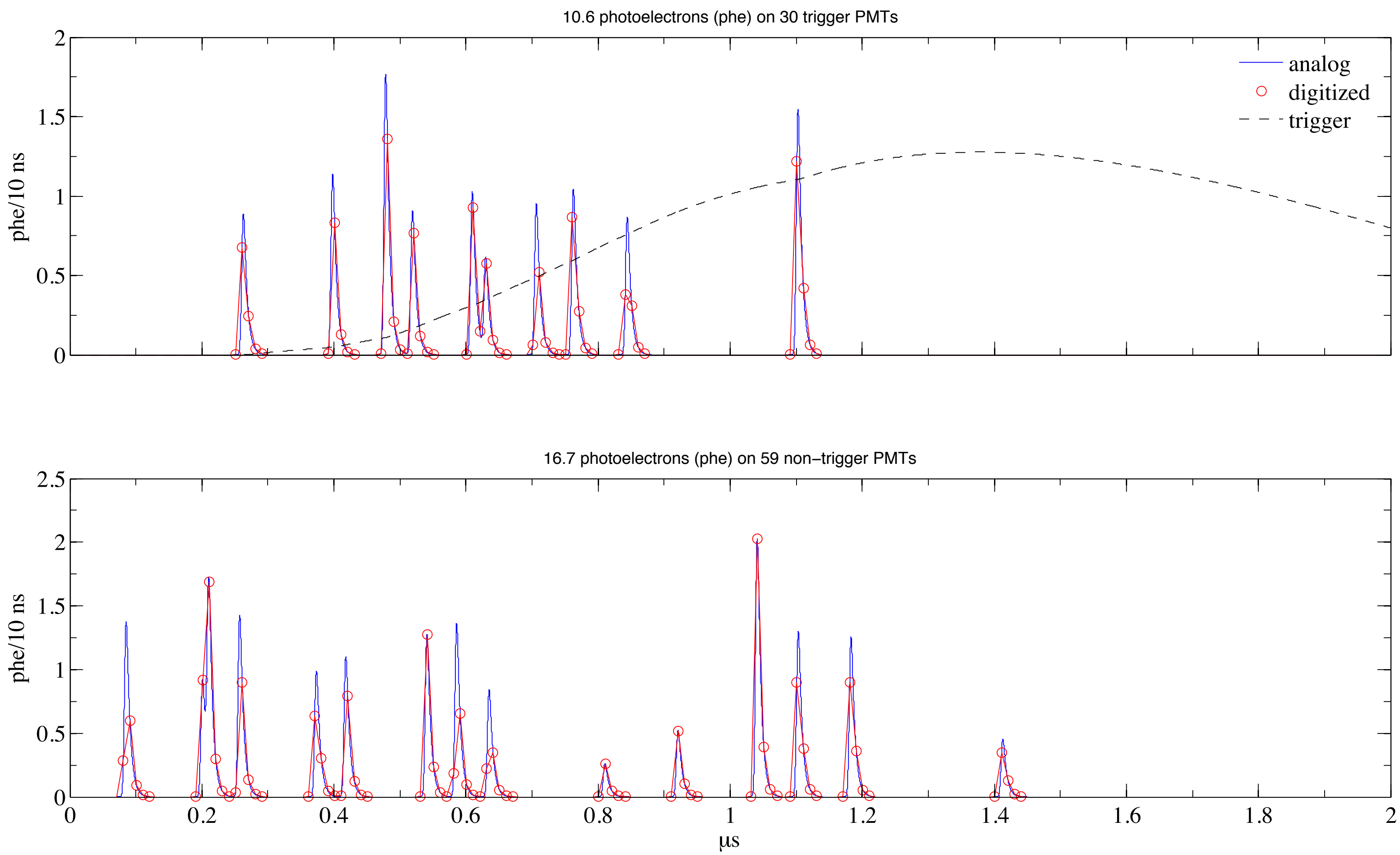
XENON10 Cuts

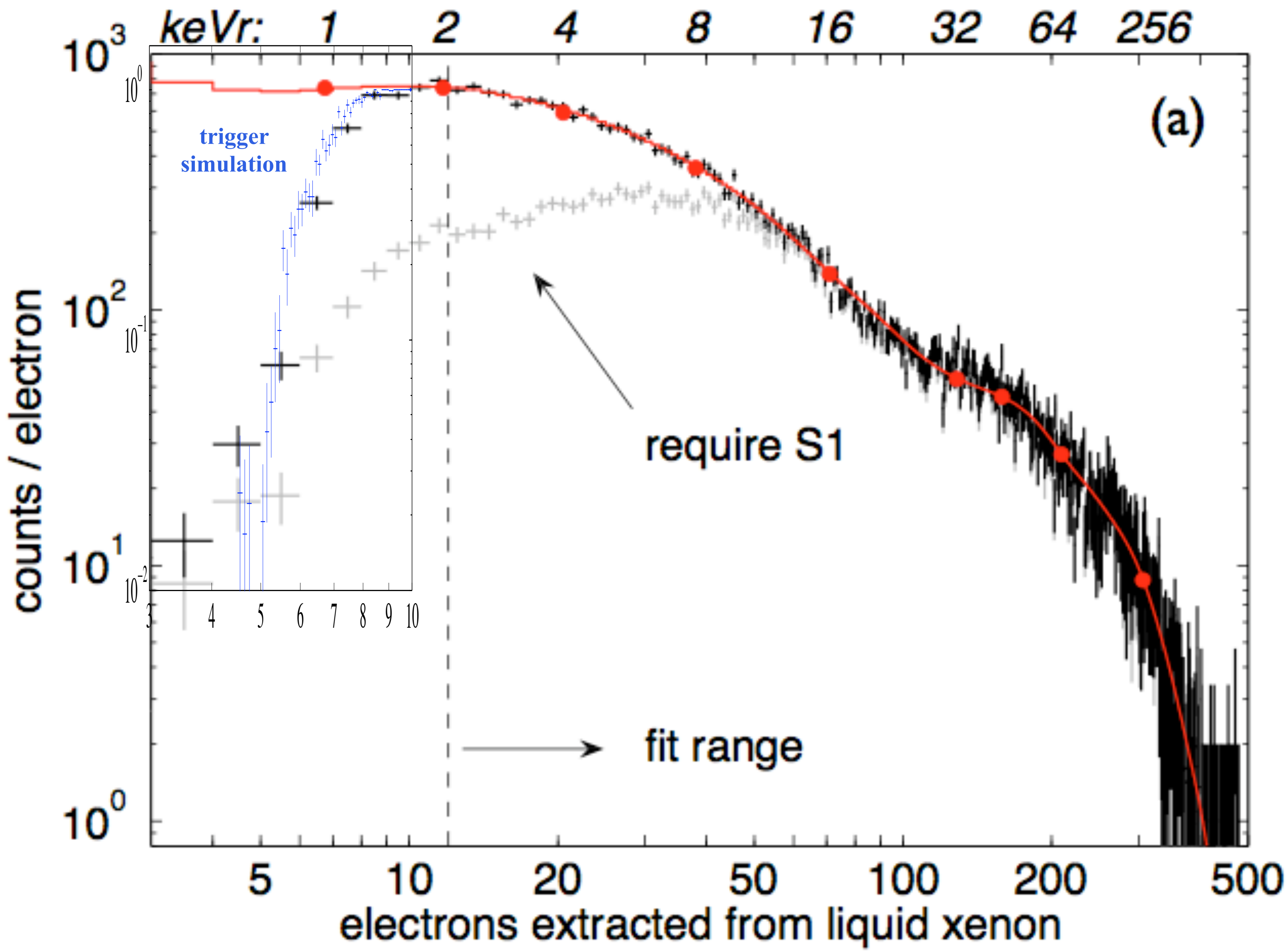
TABLE I. Summary of cuts applied to 15 kg-days of dark matter search data, corresponding acceptance for nuclear recoils ε_c and number of events remaining in the range $1.4 < E_{nr} \leq 10$ keV.

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

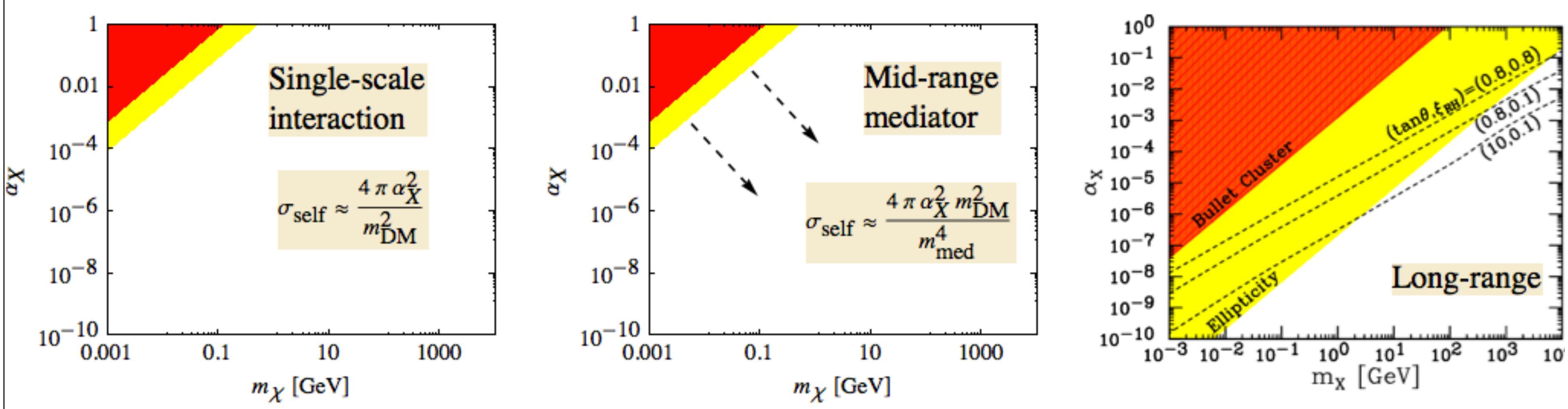
[b] differential acceptance shown in Fig. 1


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
0
0.5
1
1.5
2
2.5
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8



keVr: 1 2 4 8 16 32 64 256
(a)
trigger
simulation
require S1
fit range
counts / electron
electrons extracted from liquid xenon
10^3
10^2
10^1
10^0
5 10 20 50 100 200 500

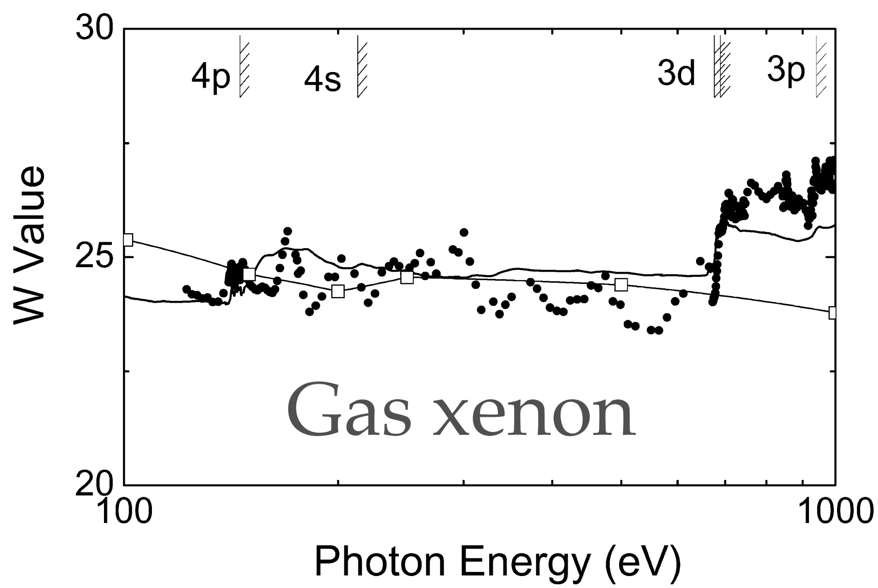
DM Self Interactions



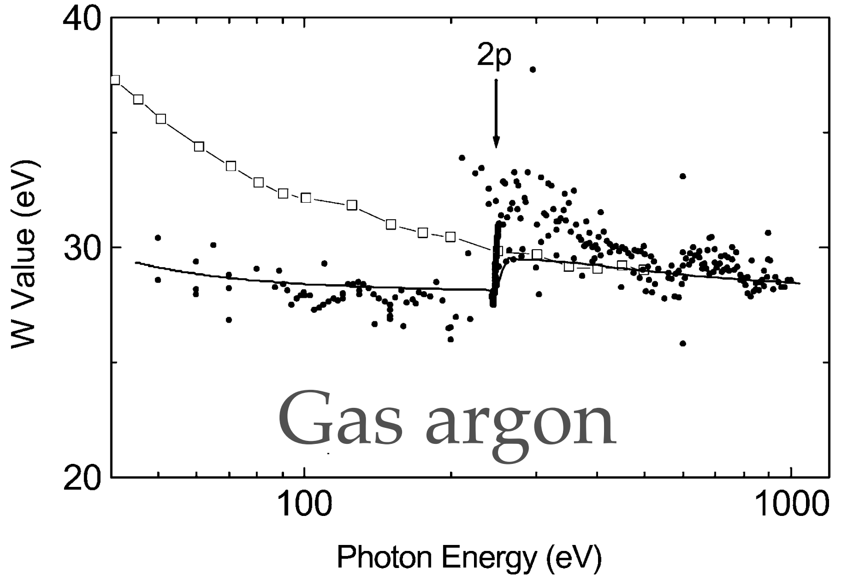
(approximate)

Feng et al 0905.3039

W value



30
25
20
W Value
4p
4s
3d
3p
Gas xenon
100
1000
Photon Energy (eV)



40
30
20
W Value (eV)
2p
Gas argon
100
1000
Photon Energy (eV)