Title: The Direct Detection of sub-GeV Dark Matter: First Limits and Future Prospects

Date: Apr 17, 2012 01:00 PM

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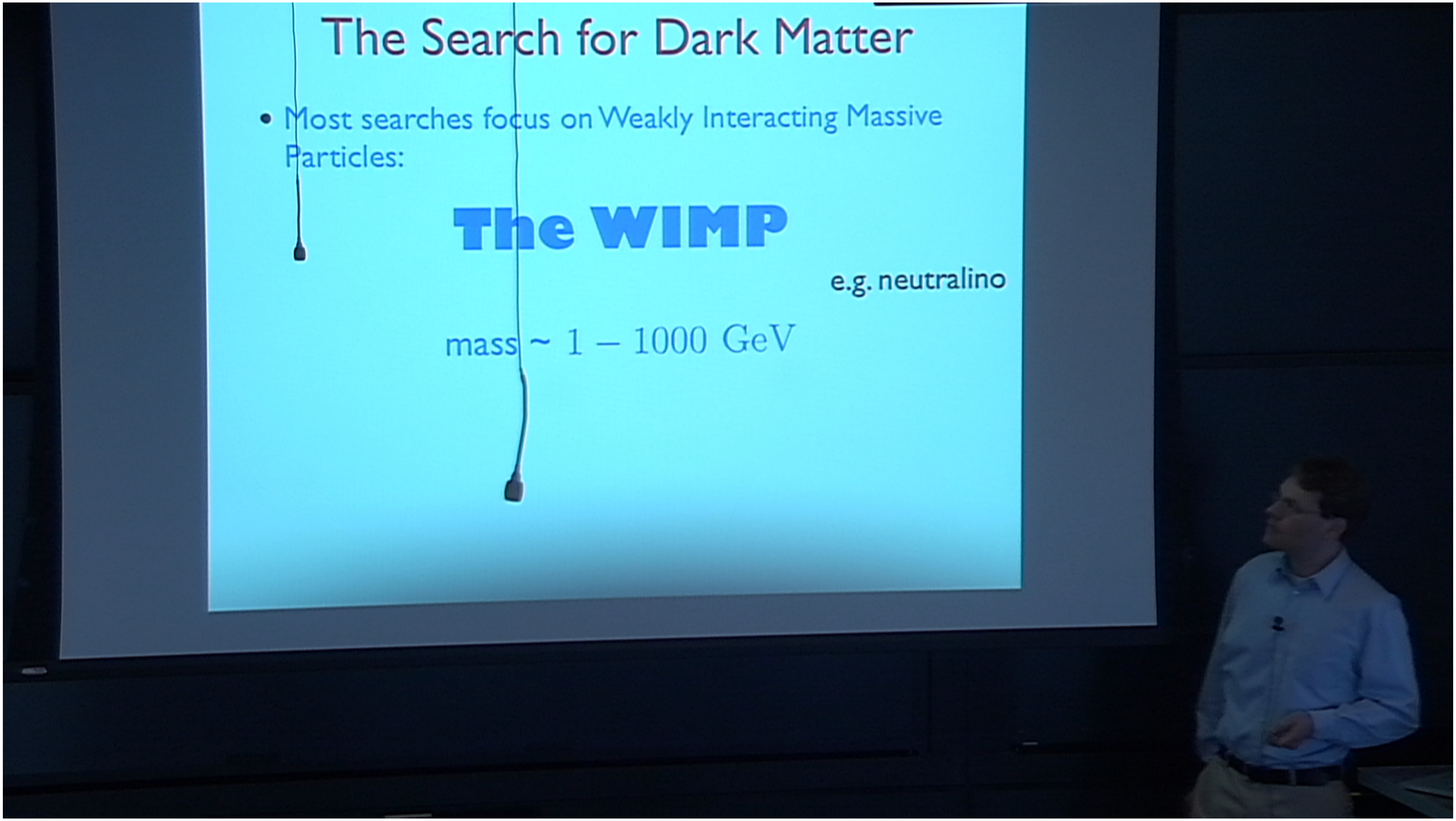
Abstract: Direct dark matter (DM) detection experiments almost always focus on Weakly Interacting Massive Particles (WIMPs), which have a mass in the 1--1000 GeV range. However, what if DM is not a WIMP? In this talk, new direct detection strategies for DM particles with MeV to GeV mass will be presented. In this largely unexplored mass range, DM can scatter with electrons, causing ionization of atoms in a detector target material and leading to single- or few-electron events. I will present the first direct detection limits on DM as light as a few MeV, using XENON10 data. Theoretically interesting models can already be probed. Significant improvements in sensitivity should be possible with dedicated experiments, opening up a window to new regions in DM parameter space.


The Search for Dark Matter
• Most searches focus on Weakly Interacting Massive Particles:
The WIMP
e.g. neutralino
mass ~ 1 – 1000 GeV

The Direct Detection of sub-GeV Dark Matter

Rouven Essig

YITP, Stony Brook

Perimeter Institute, April 17, 2012

with:

J. Mardon, T. Volansky (1108.5383)

A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky (submitted to PRL)

+ work in progress

The Direct Detection of sub-GeV Dark Matter

(yes, it is possible)

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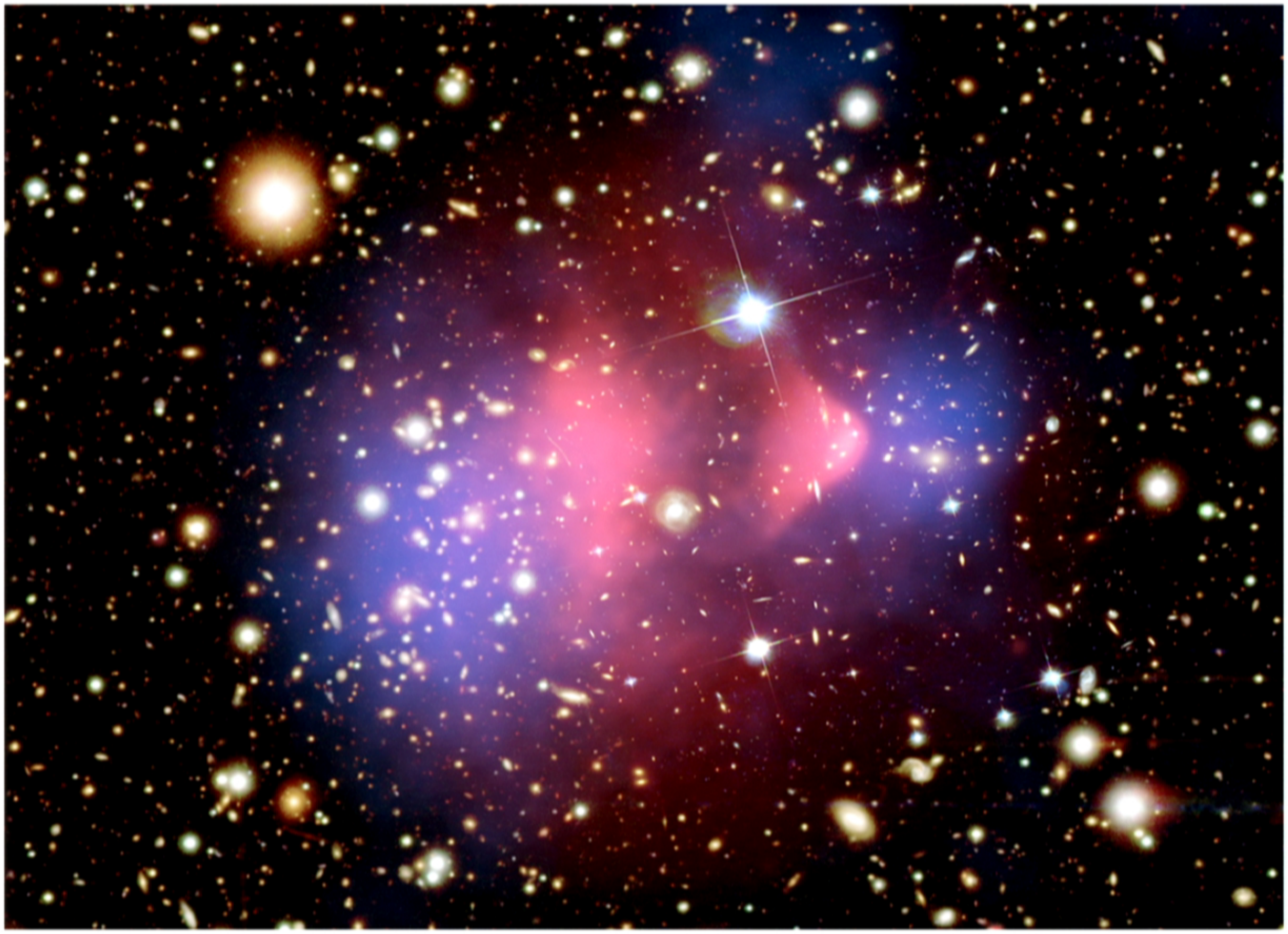
Lots of evidence for dark matter



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

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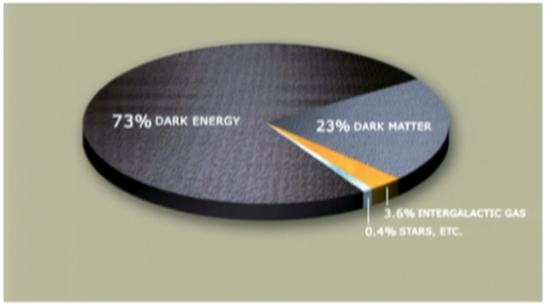
  $\Longrightarrow$ clearly, an important question…



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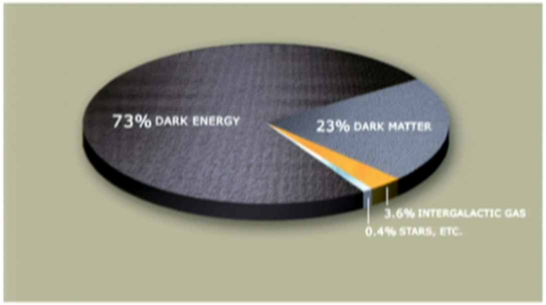

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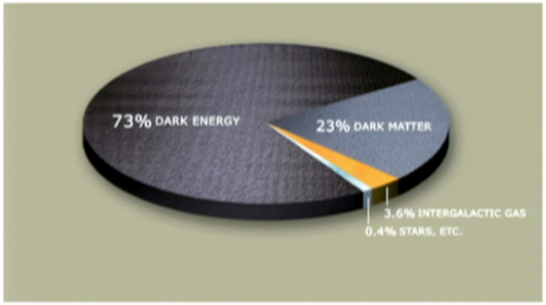

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But are we looking everywhere we can and should?

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But what if DM is lighter than this??

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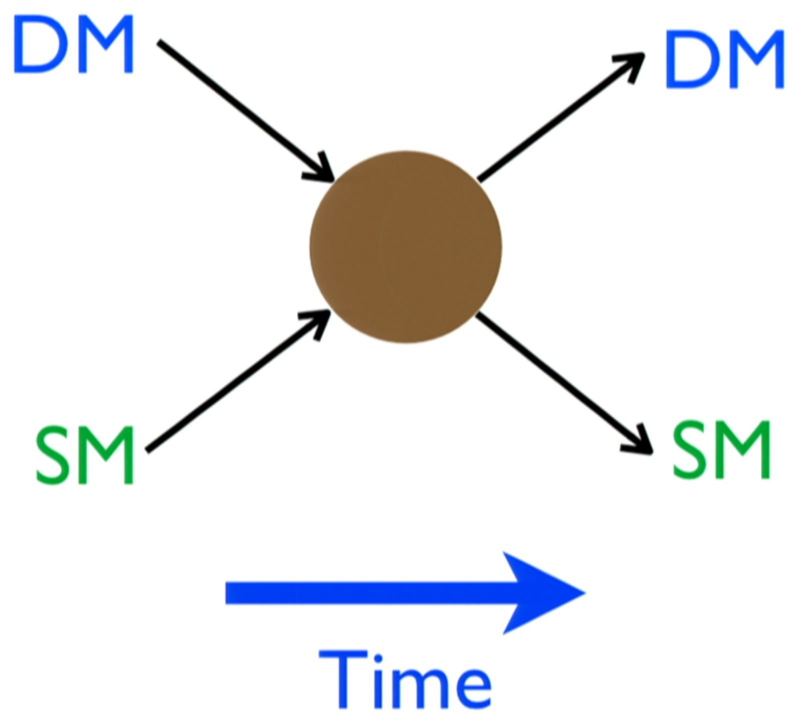
- eminently testable:
  - indirect detection
  - colliders
  - direct detection

This Talk

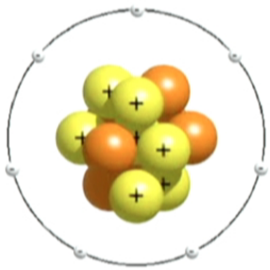
Focus on
Direct Detection

“Direct” Detection



How does this work?

Take a detector with lots of nuclei
(e.g. Germanium, Xenon, NaI, …)



Atom

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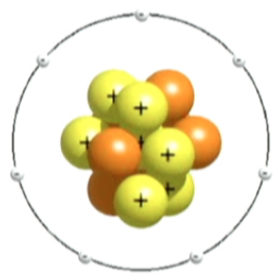

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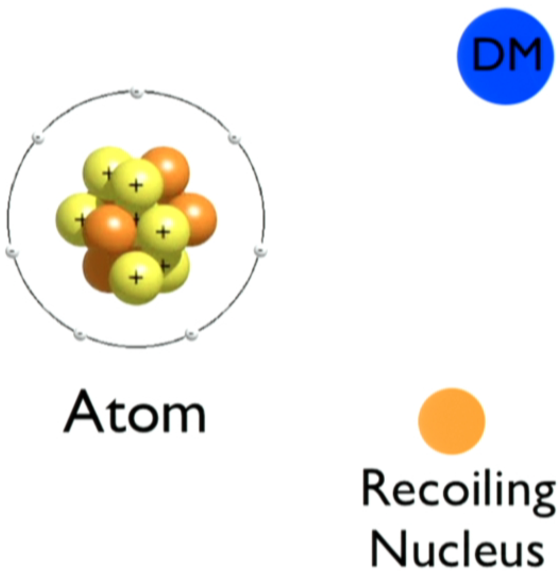

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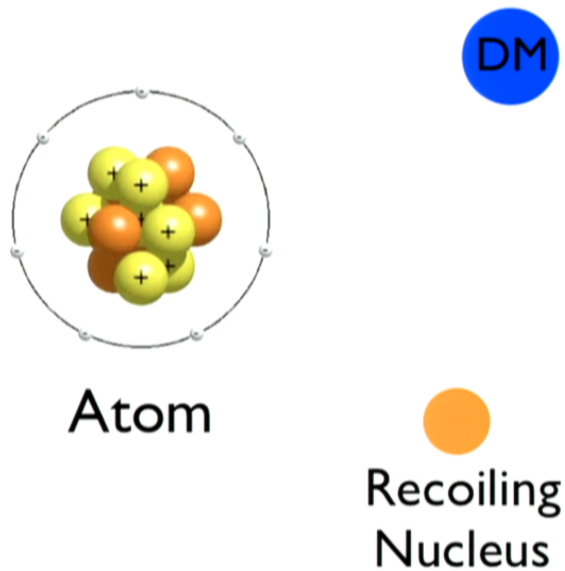
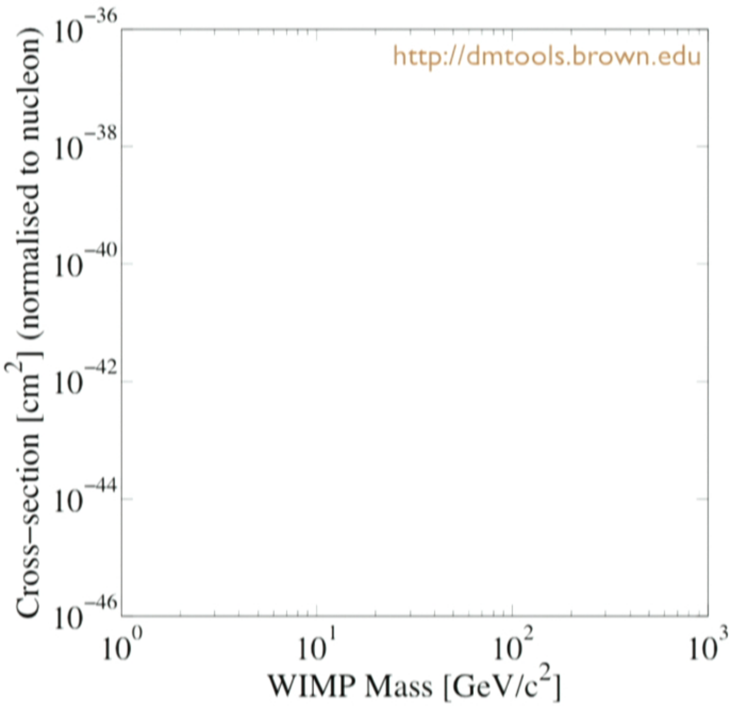
depending on material, recoil can produce:
phonons
scintillation
ionization



Current Direct Detection Situation

(it's very confusing…)



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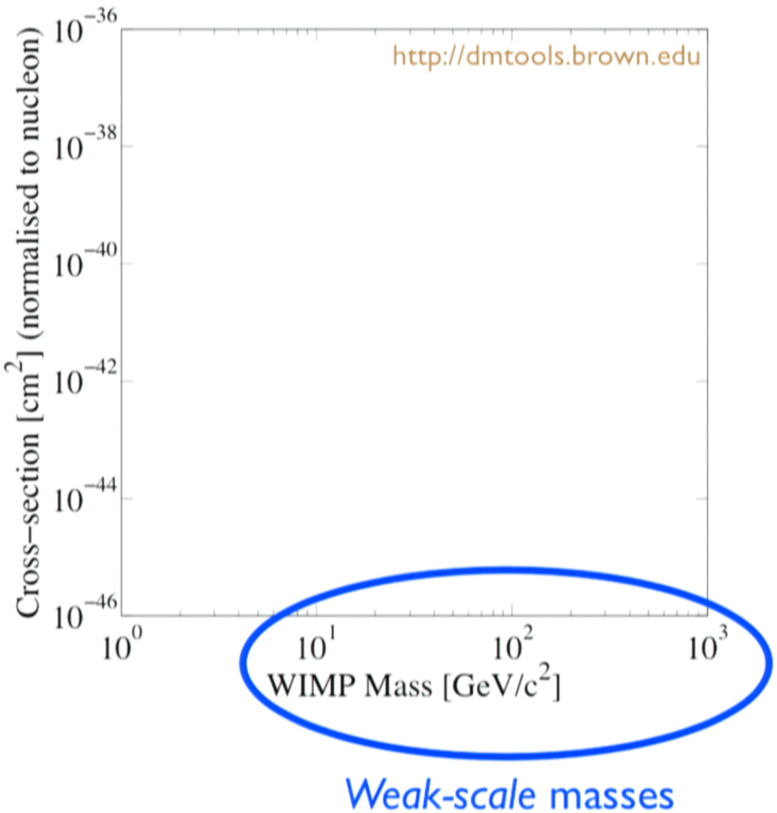

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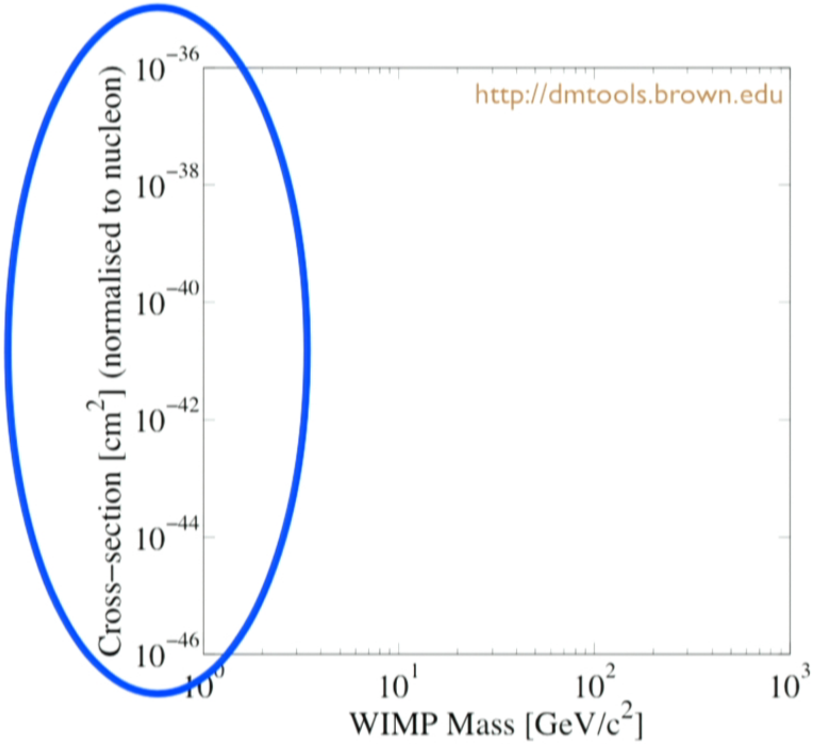

Cross section to scatter off nucleons

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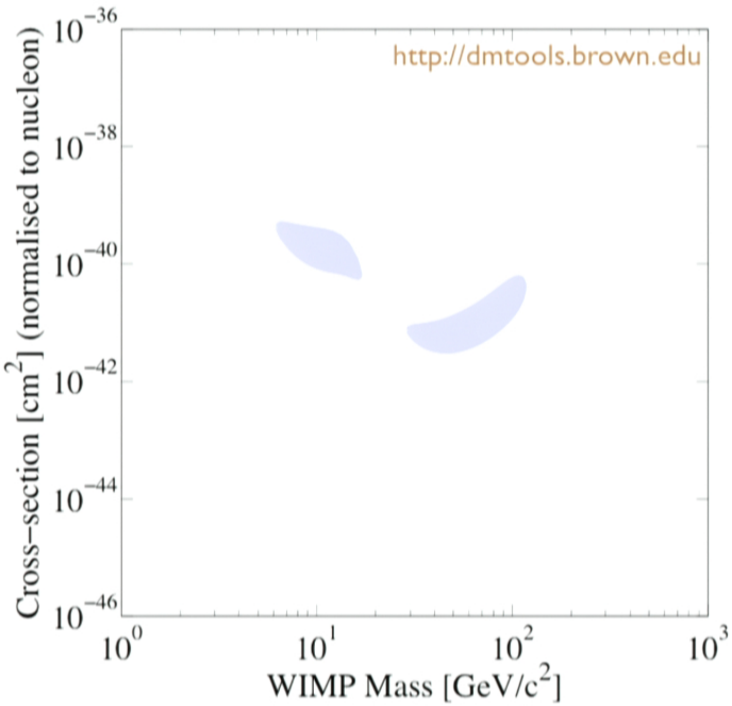

DAMA/LIBRA (NaI)

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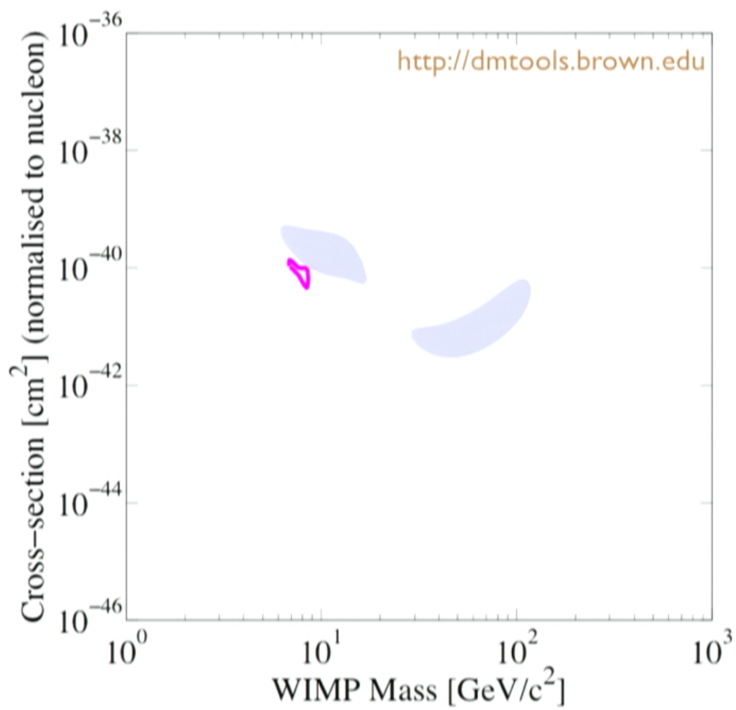

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CoGeNT (Ge)

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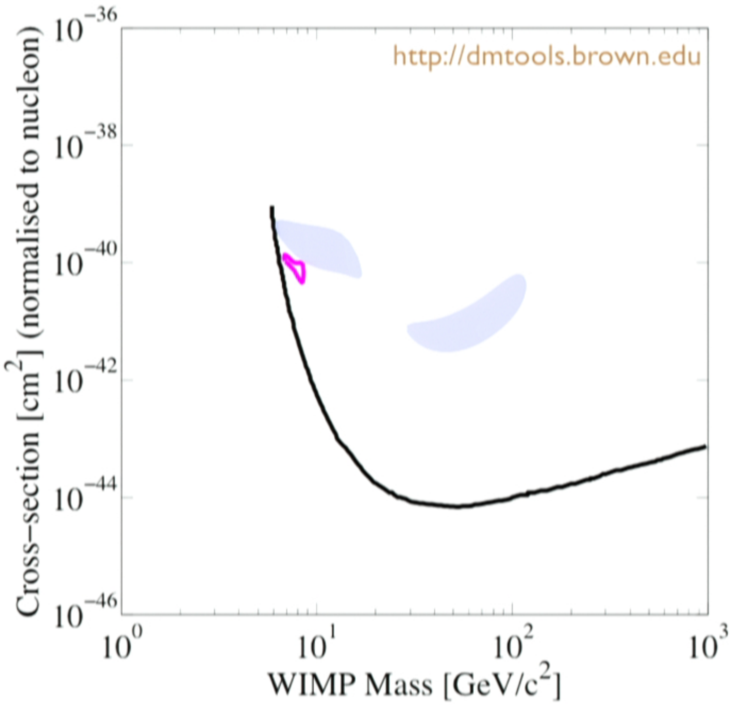

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XENON-100 (Xe)

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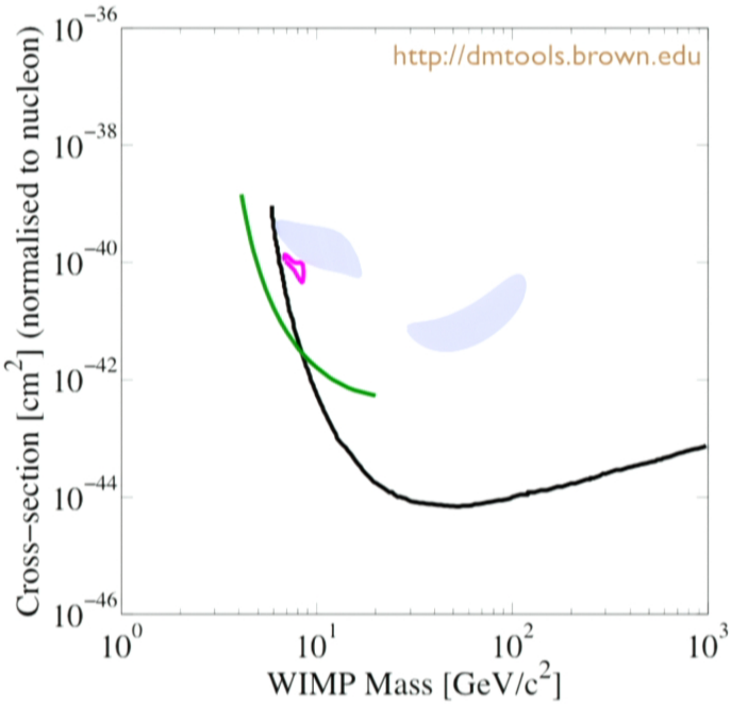

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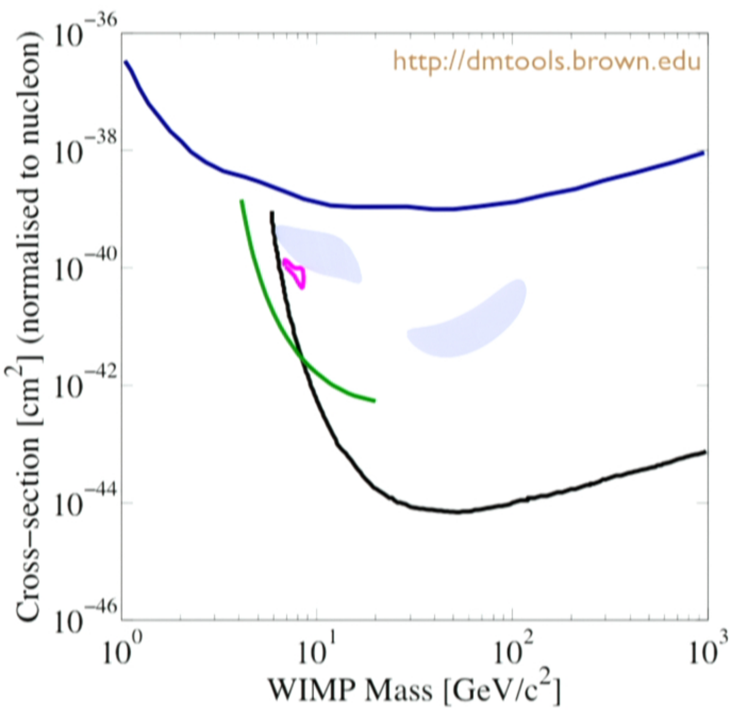

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CRESST-1 ($CaWO_4$)

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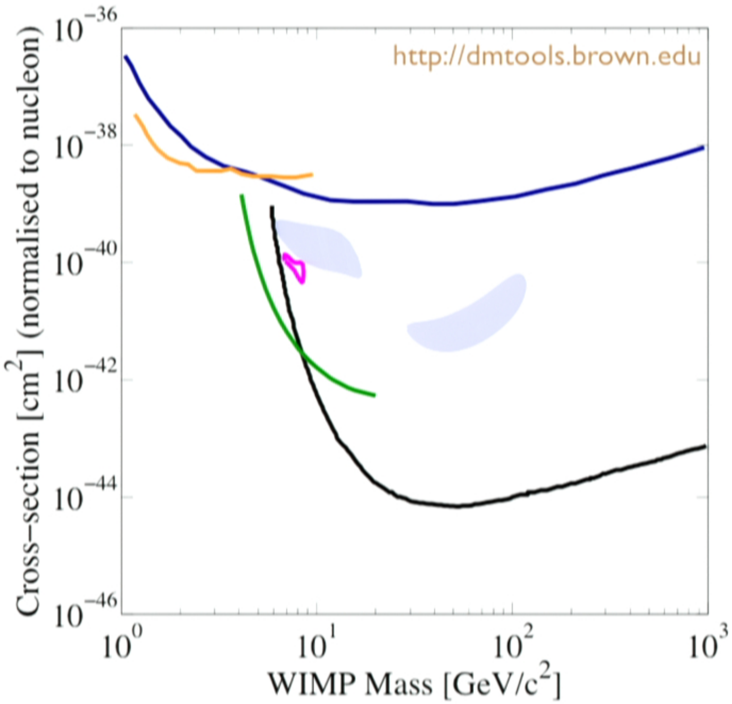

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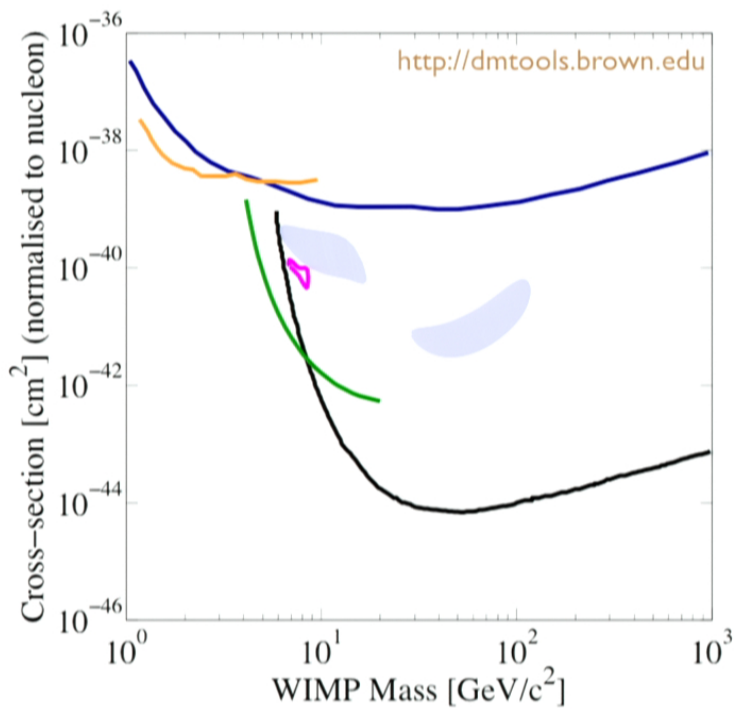

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+ many more experiments

Experiments are optimized for WIMPs

nuclear recoil energy

$$E_{\rm nr} \sim \frac{1}{2}\,\mu\,v^2$$

$\mu =$ reduced WIMP-nucleus mass

$v =$ WIMP velocity

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$$\sim \frac{1}{2}\,(50\ {\rm GeV})(10^{-3})^2$$

$$\sim 25\ {\rm keV}$$

"easy" to detect

But…

But…

What if it's not a WIMP ???

Why it's ok to pick on WIMPs

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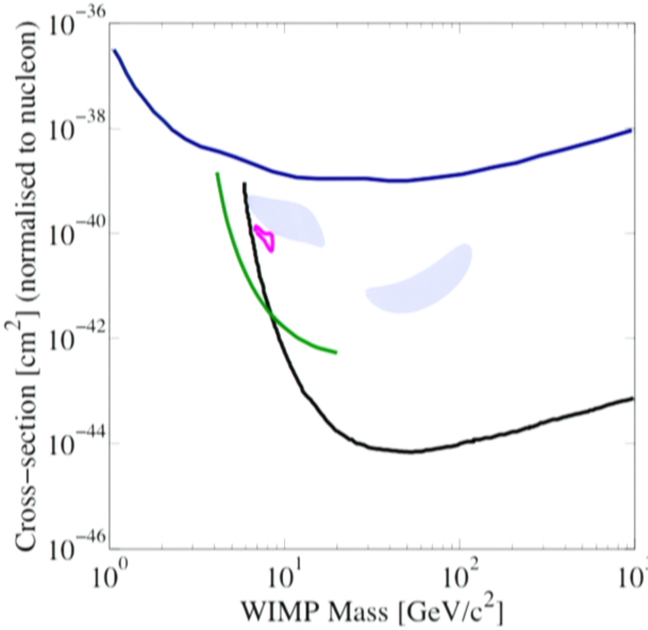
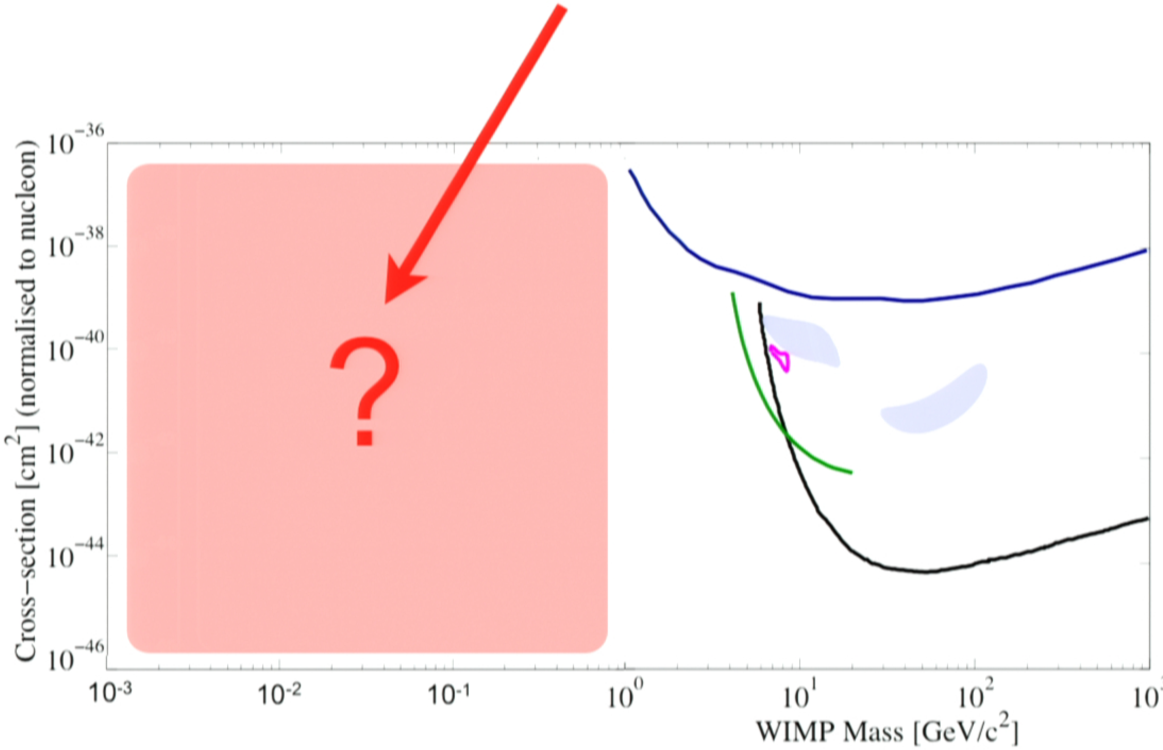
don't let a paradigm blind you
to other experimental opportunities !

So instead of considering only this…



What if DM is here?



mass ~ MeV - GeV

Outline

Direct Detection of sub-GeV DM

- constraints
- direct detection
- future

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- free streaming

light DM can wash out small-scale structure

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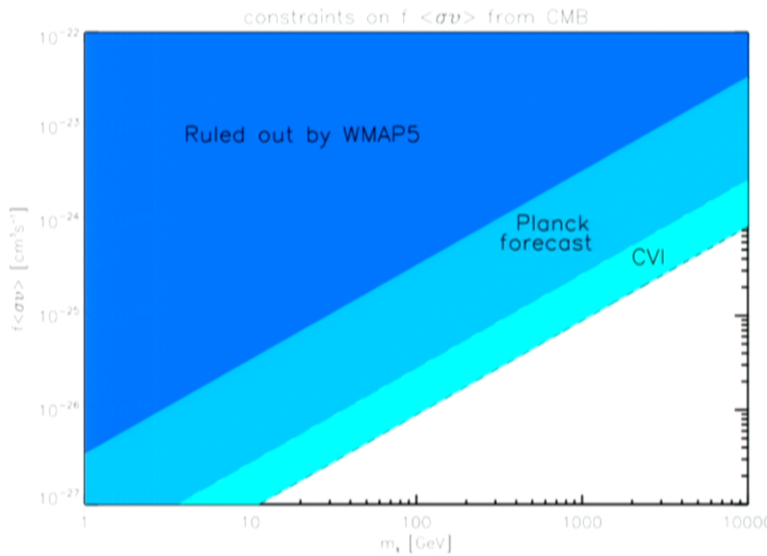

Galli et.al.
Slatyer, Padmanabhan, Finkbeiner

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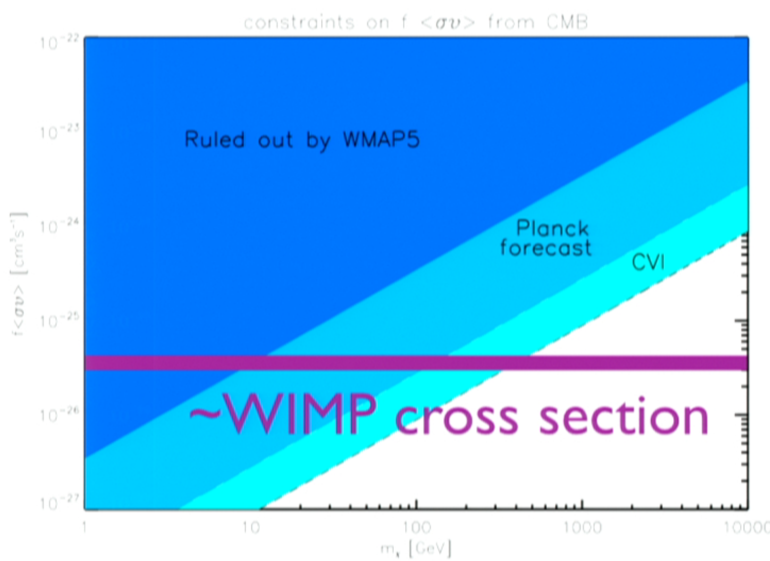

disfavors standard freeze-out below ~10 GeV

Galli et.al.
Slatyer, Padmanabhan, Finkbeiner

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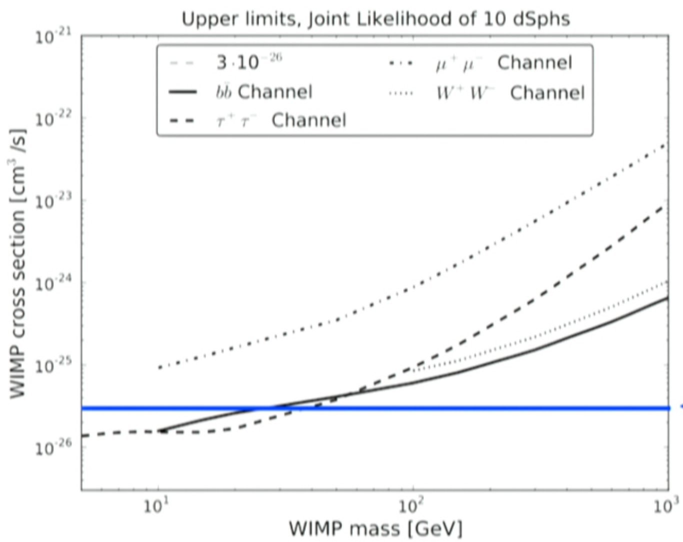
+ other indirect constraints (e.g. dwarf galaxies)

see also Deniverville, Pospelov, Ritz (2011)



thermal WIMP cross section

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Examples:

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e.g. Kaplan et.al. (2009), Falkowski et.al. (2011)

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- light asymmetric DM — e.g. Kaplan et.al. (2009), Falkowski et.al. (2011)
- freeze-out within a hidden sector (WIMPless DM) — e.g. Feng & Kumar (2008)
- freeze-in — e.g. Hall et.al. (2009)

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Bullet cluster: $\frac{\sigma}{m_{\rm DM}} \lesssim 1\ {\rm cm}^2/{\rm g}$ Markevitch et.al. (2003)

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Halo shapes: $\frac{\sigma}{m_{\rm DM}} \lesssim 0.02 \ {\rm cm}^2/{\rm g}$ Miralda-Escude (2000)

Is sub-GeV Dark Matter allowed?

Answer:

Yes!

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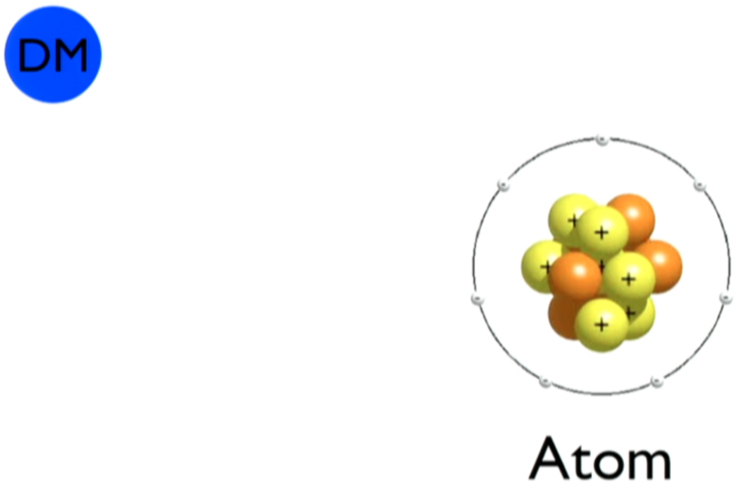
- constraints
- → direct detection
- future

Elastic nuclear recoils don't work

Recall: Heavy DM



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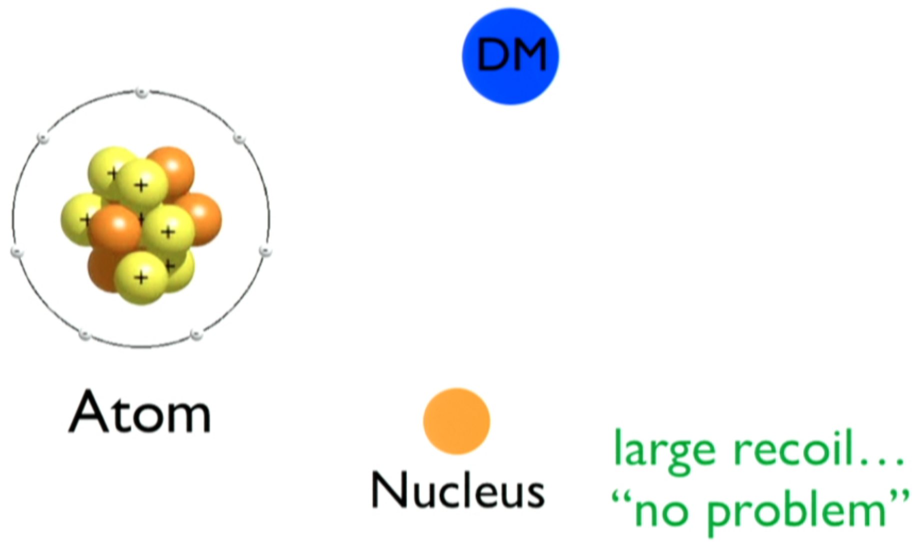

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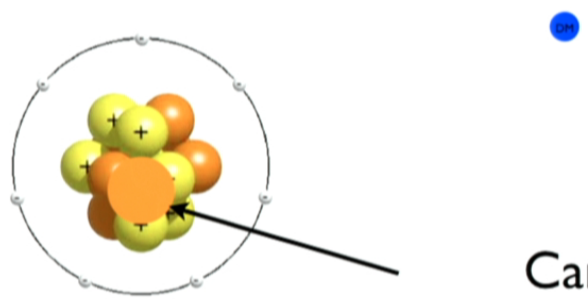
Light DM $\lesssim 1\ \text{GeV}$



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nuclear
recoil
energy

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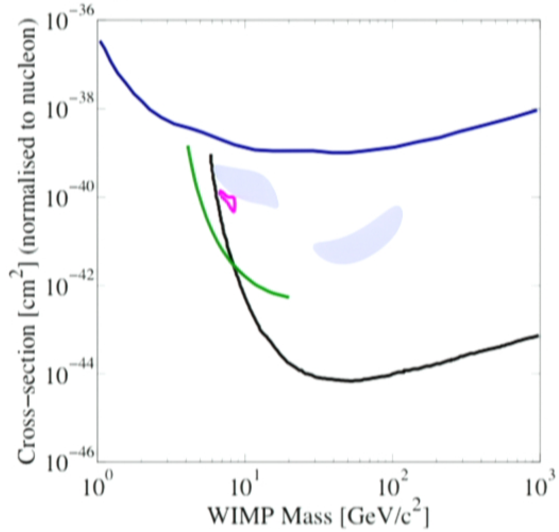

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But, total energy available is much larger!

$$E_{\rm tot} \sim \frac{1}{2} m_{\rm DM} v^2 \sim 50 \text{ eV} \left(\frac{m_{\rm DM}}{100 \text{ MeV}}\right) \left(\frac{v}{300 \text{ km/s}}\right)^2$$

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enough energy to excite or ionize an atom,
or dissociate molecules !

How to detect sub-GeV DM

- ionization
- excitation
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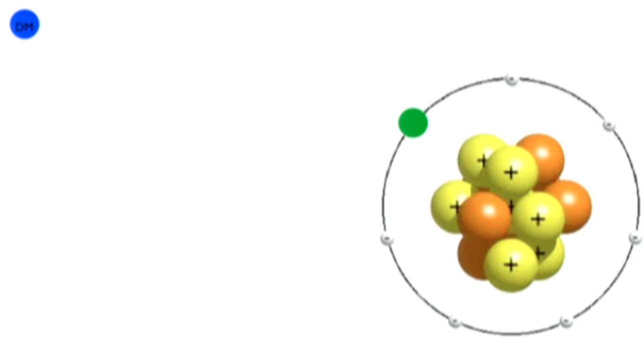
DM scattering off an electron: 1



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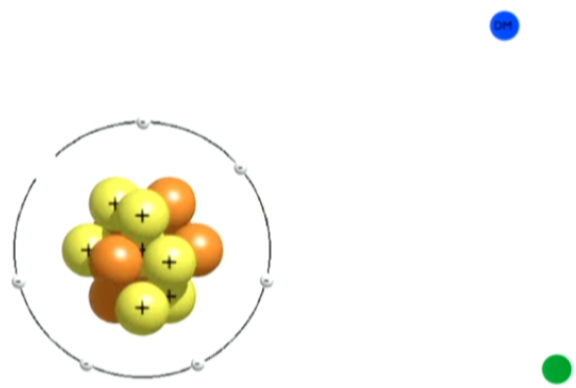
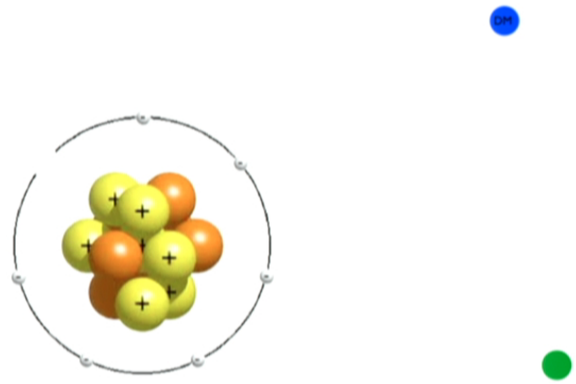


Ionization

Signal: single (or few) electron events

DM scattering off an electron: 1



Atom

Ionization

threshold ~ 1-100 eV

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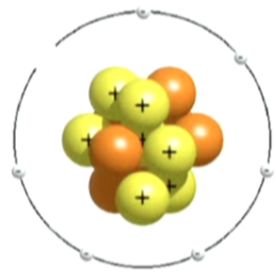

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<u>existing</u> technologies can measure ionization,
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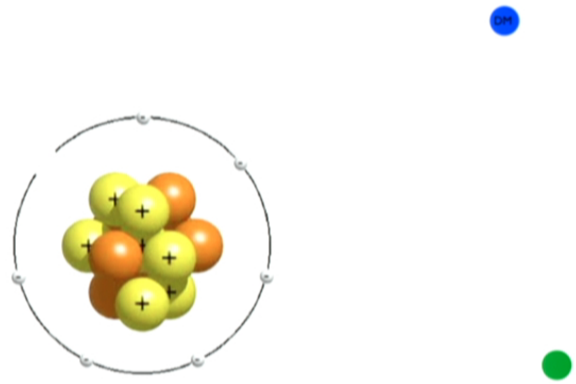
Focus on this today



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How to detect sub-GeV DM

- ionization
- excitation
- molecular dissociation

(brief)

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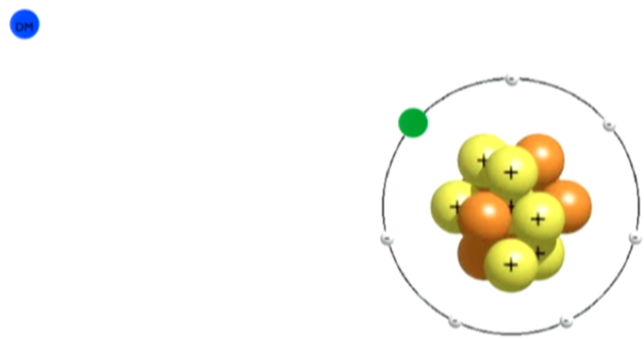

Atom

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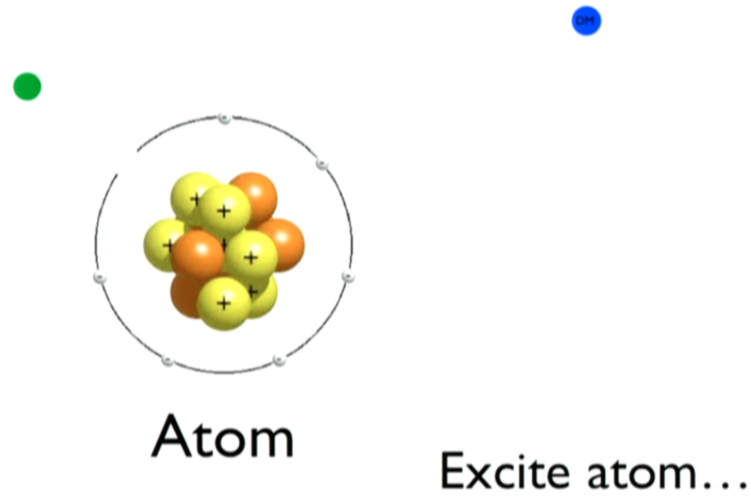

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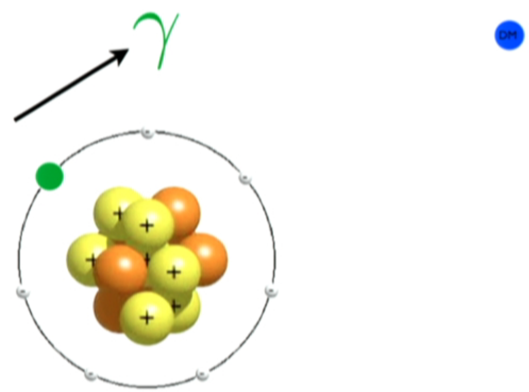

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Excitation

Excite atom…& look for de-excitation photon

Signal: photons

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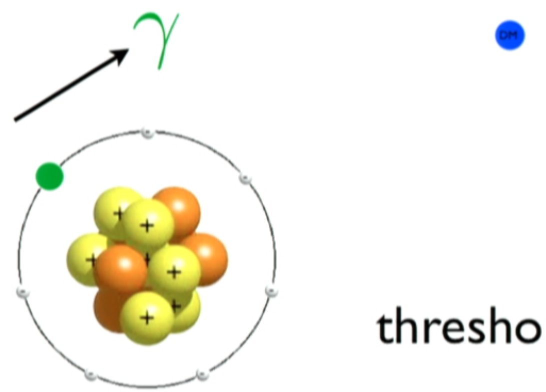

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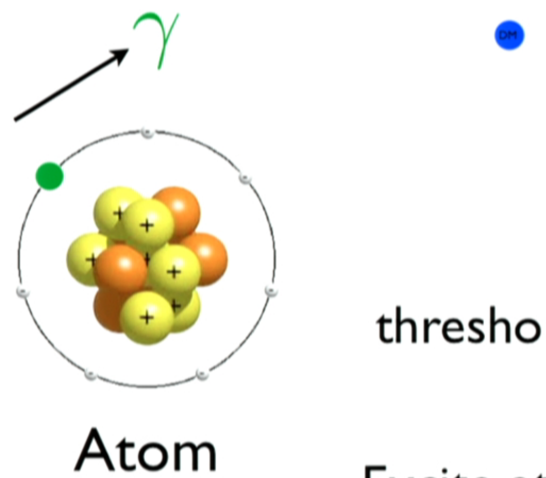

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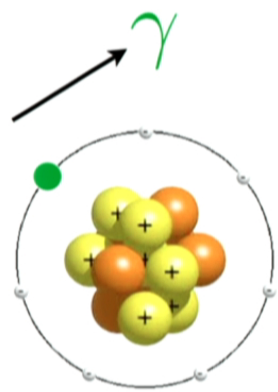

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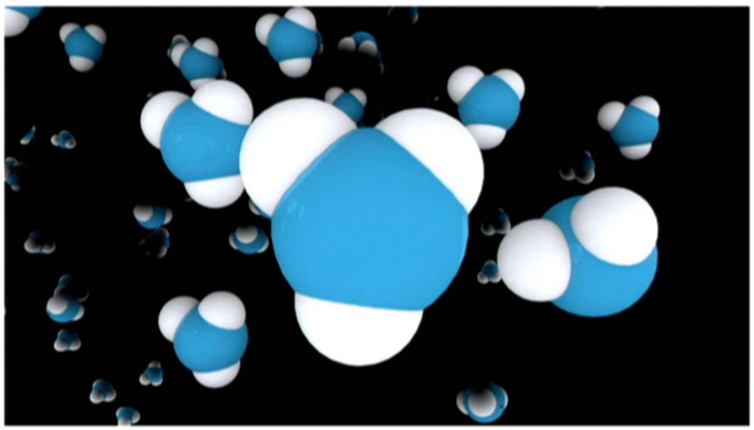
(brief)

DM scattering off nuclei

Break apart molecules



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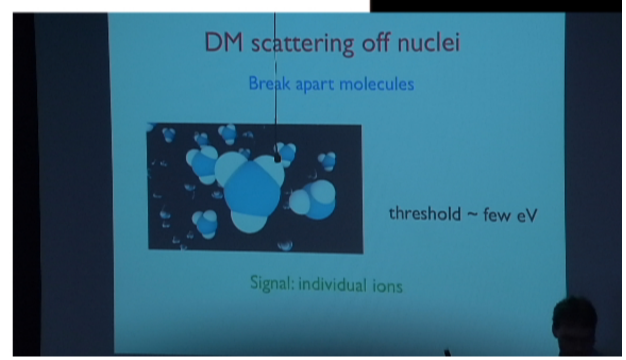

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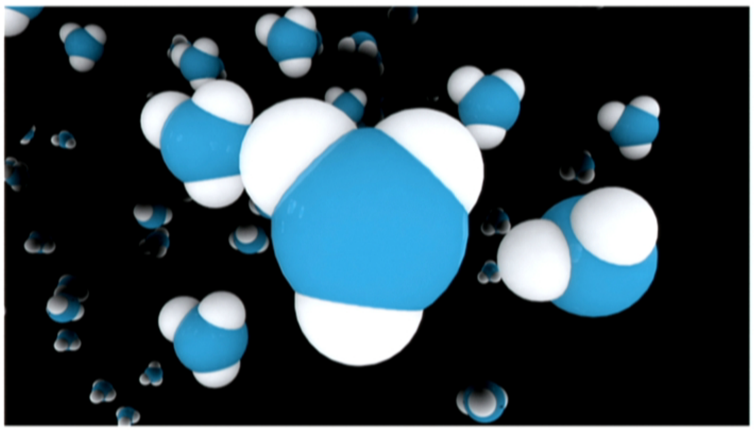

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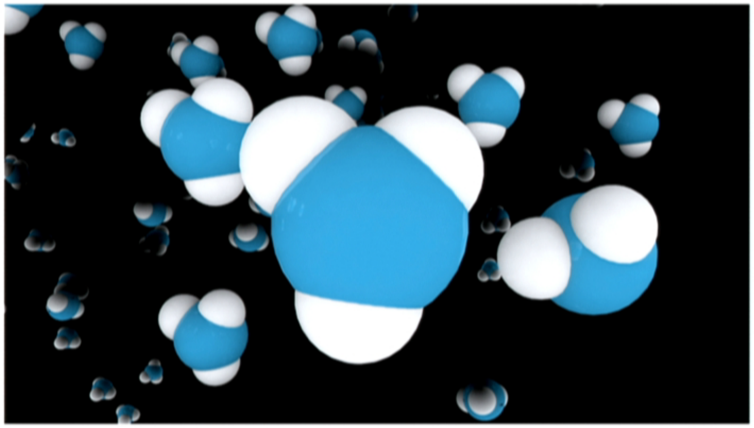

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Signal: individual ions

still requires more work to see if feasible…

In this talk, we focus on ionization signal

A Proof of Principle

(for ionization signal)

A Proof of Principle

(for ionization signal)

"First direct detection limits on sub-GeV Dark Matter from XENON10"

RE, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky
(submitted to PRL)

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e^- bound in atom, w/ binding energy: ΔE

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So in principle we can probe DM as light as a few MeV !

The XENON10 experiment

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detector
schematic

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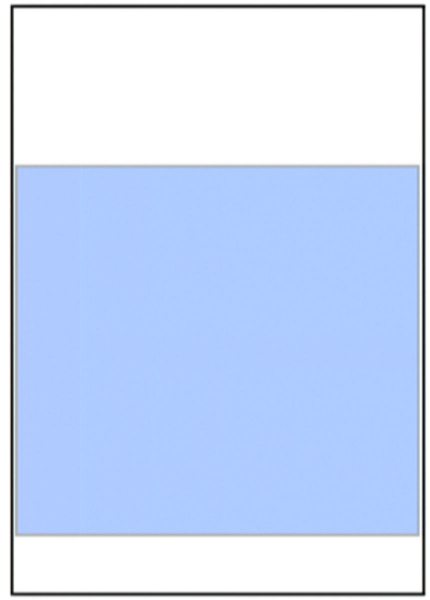
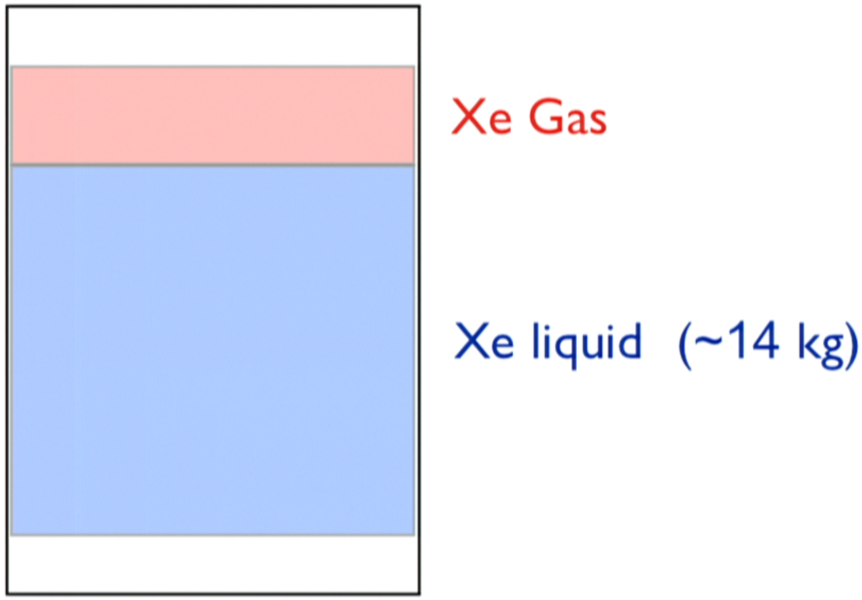


Xe liquid (~14 kg)

The XENON10 experiment

detector schematic



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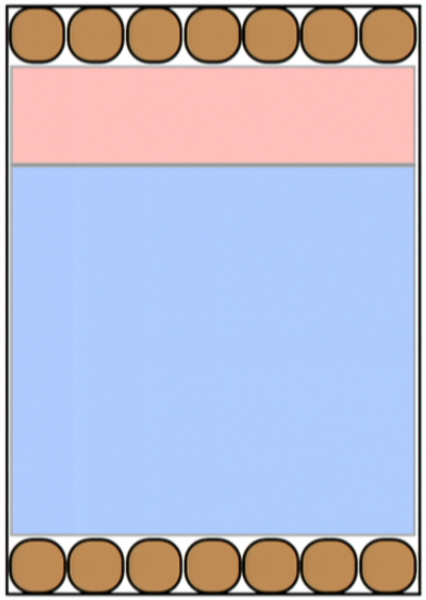

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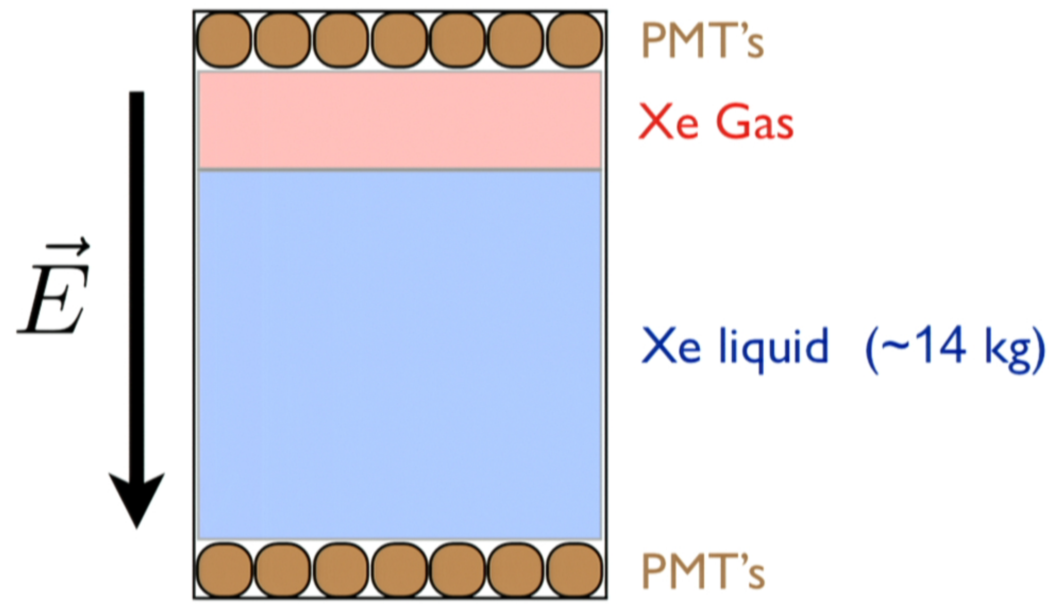

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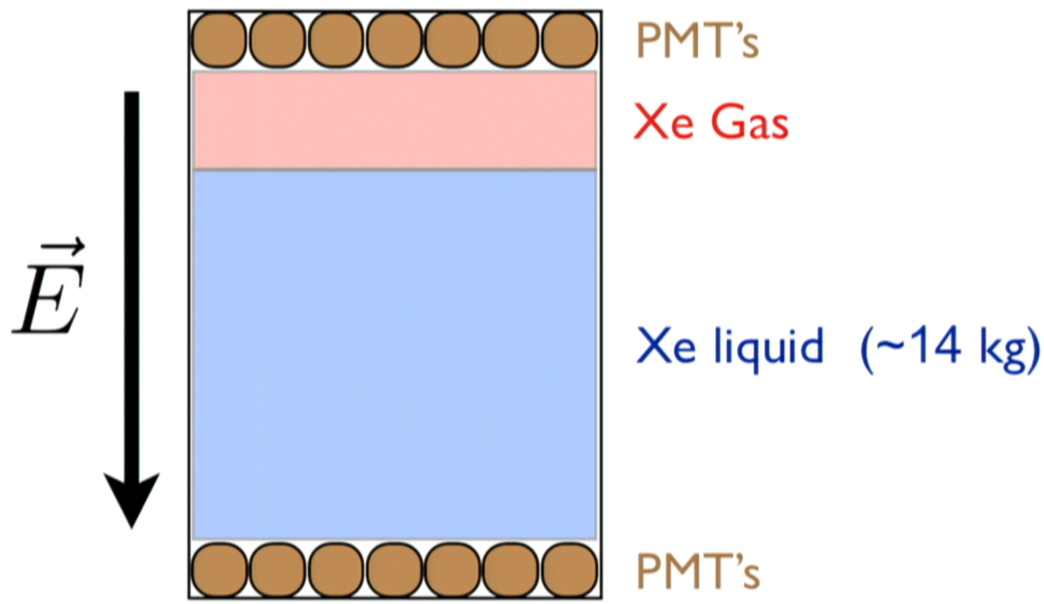

two-phase xenon time projection chamber

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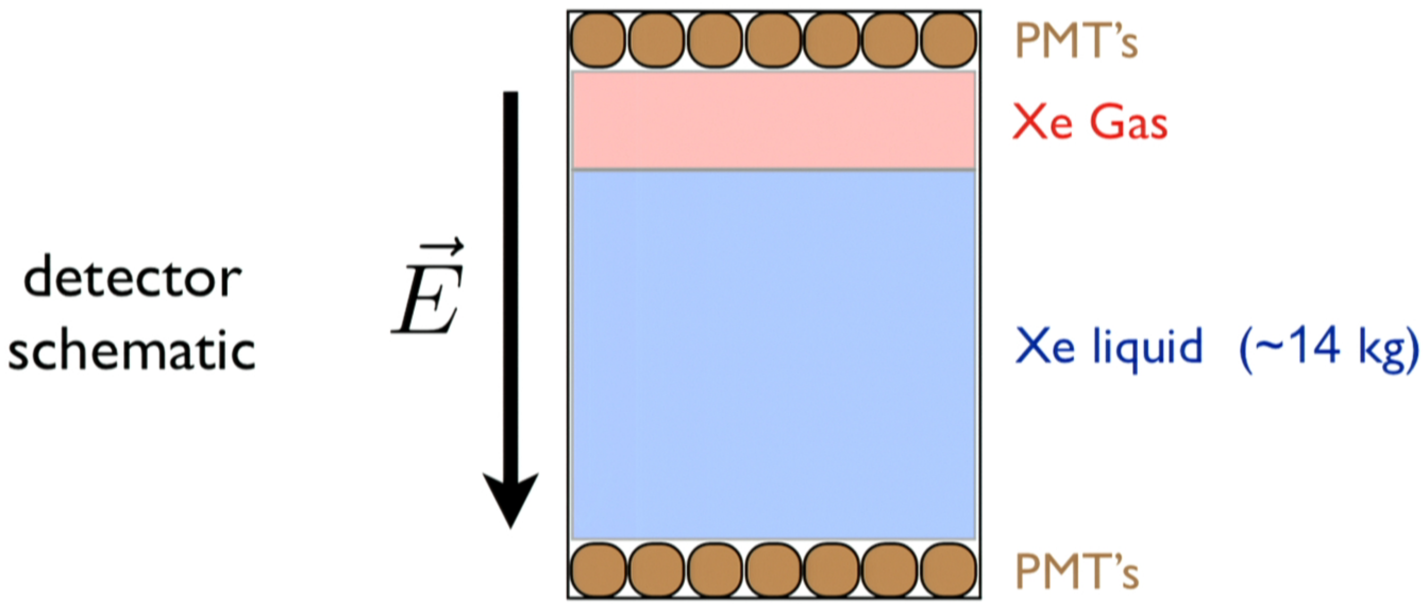
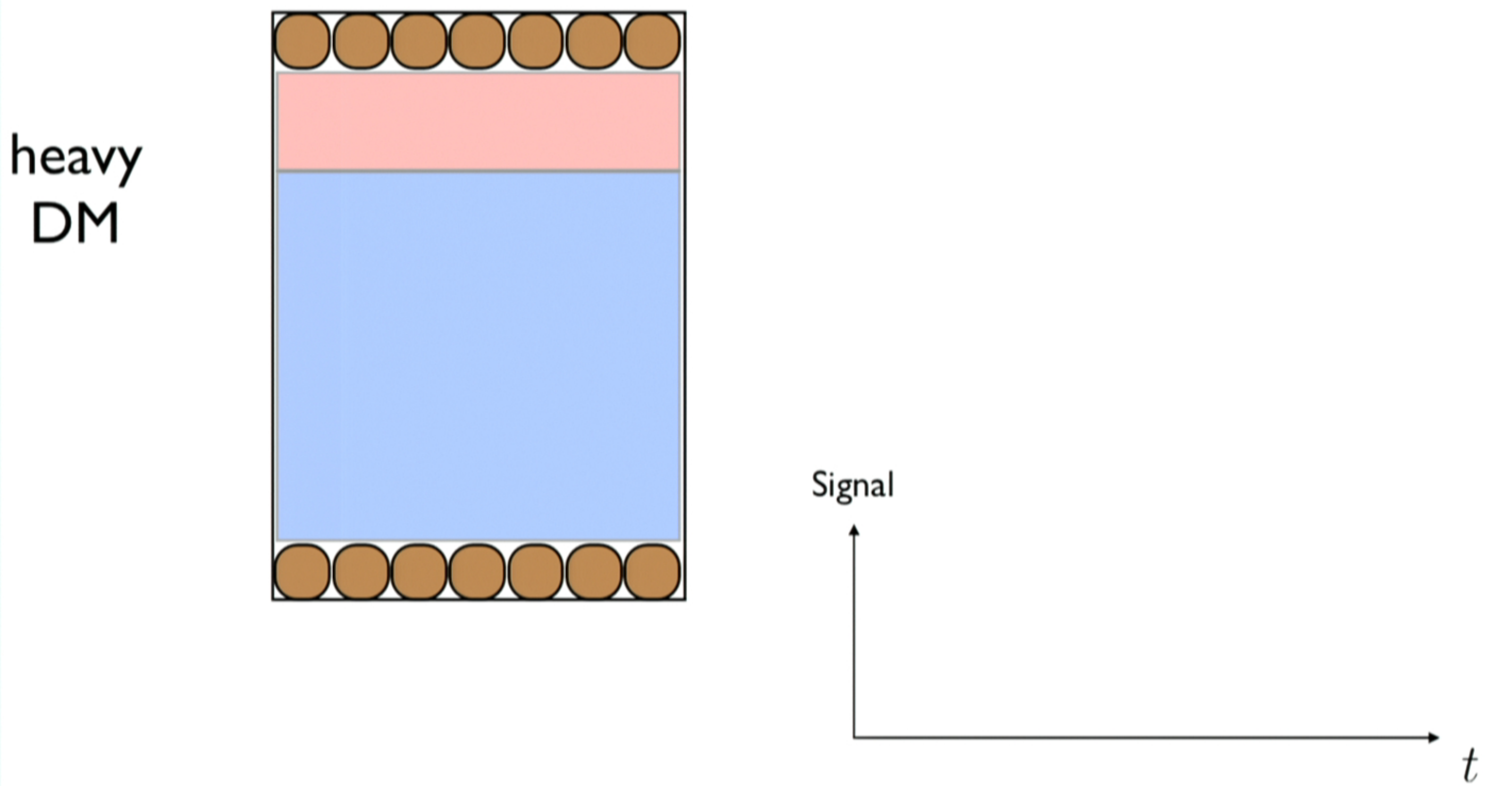


two-phase xenon time projection chamber

operated for ~1 year in 2006/2007

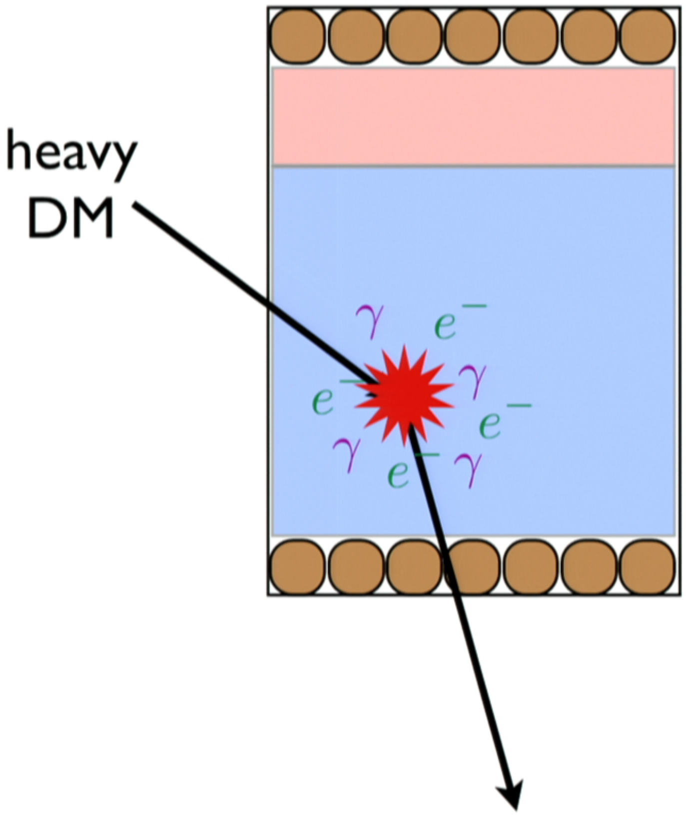
How to detect nuclear recoils from DM



How to detect nuclear recoils from DM

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

produces photons and electrons



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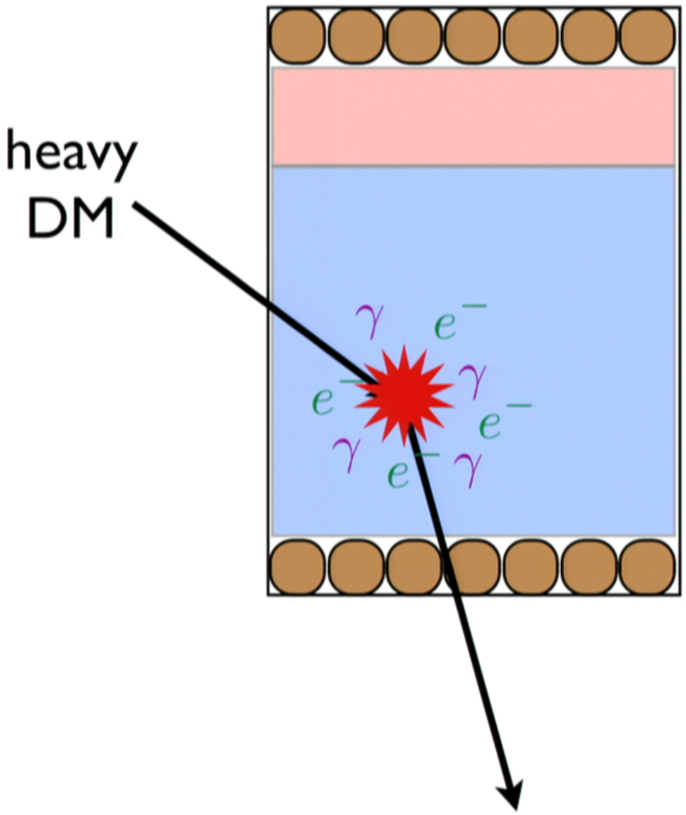

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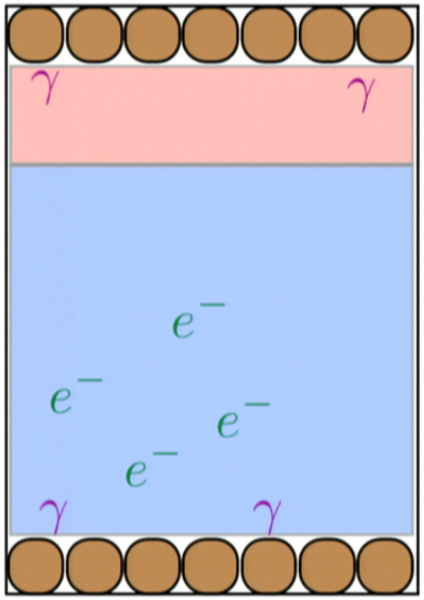

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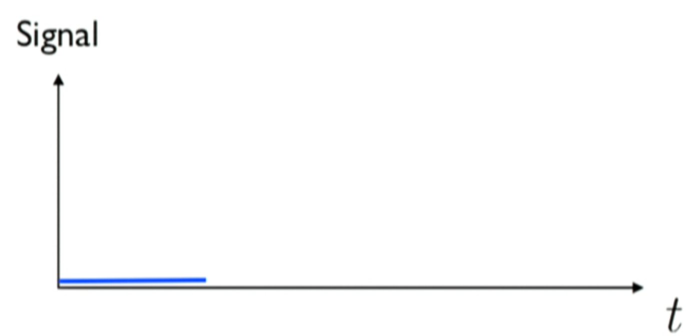

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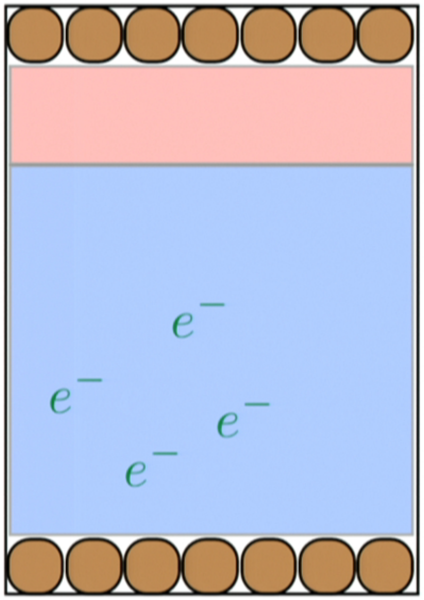

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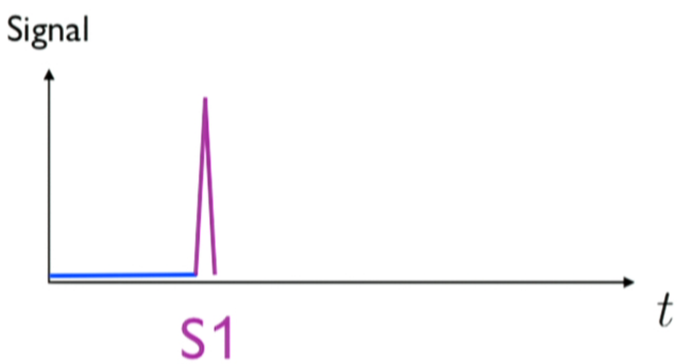

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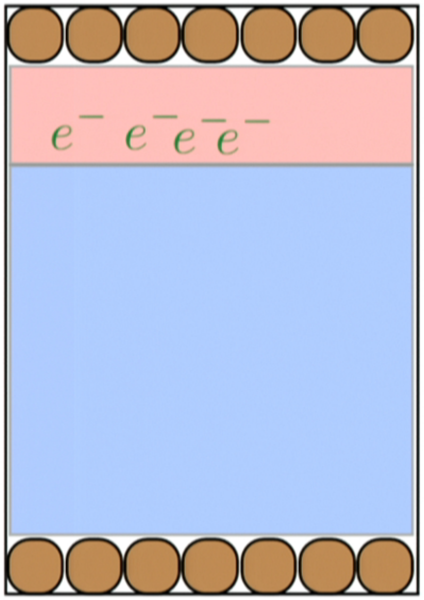

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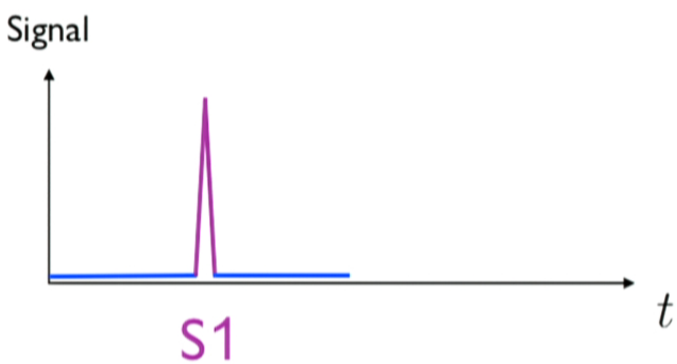

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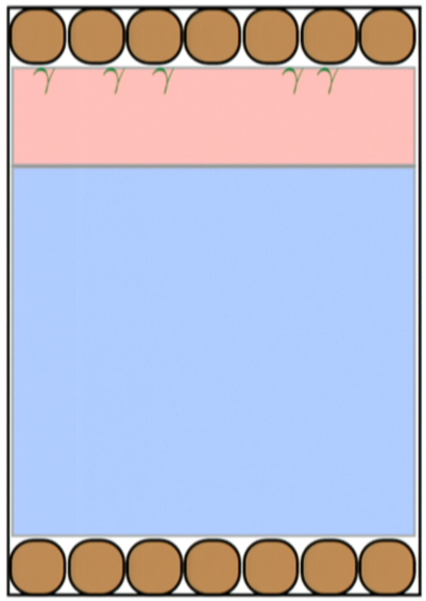

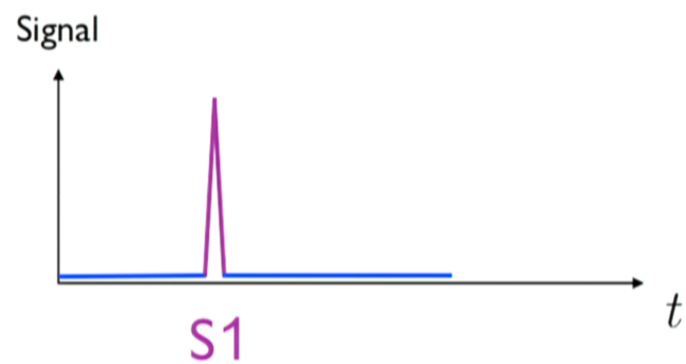

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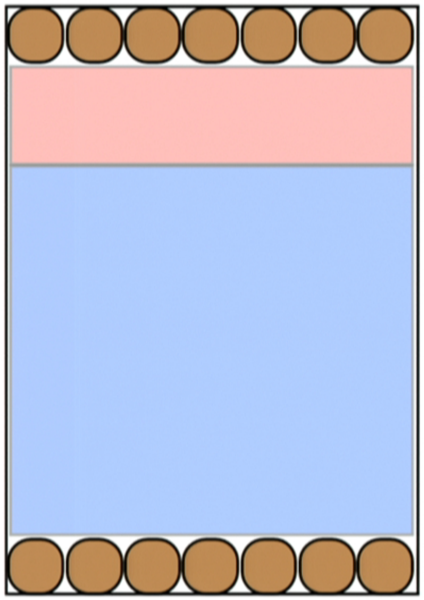

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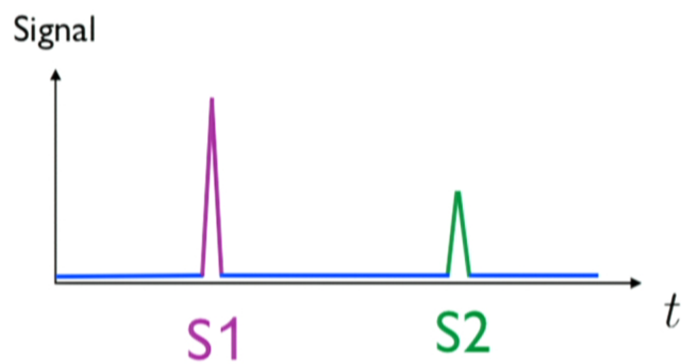
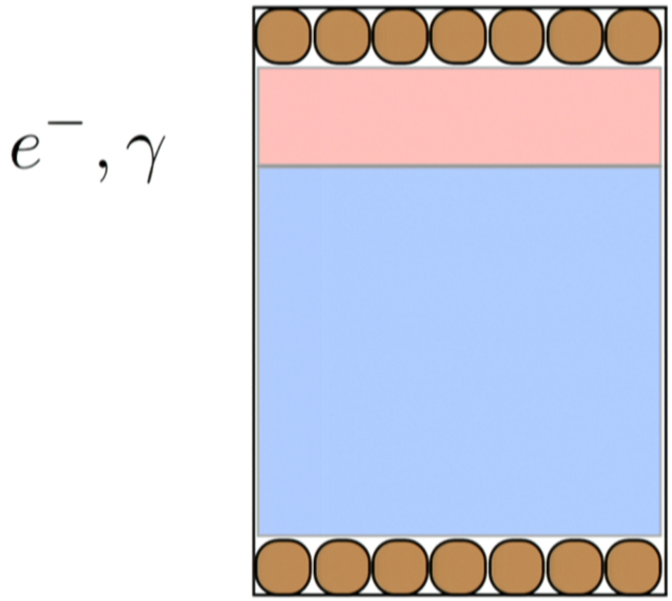


Background events



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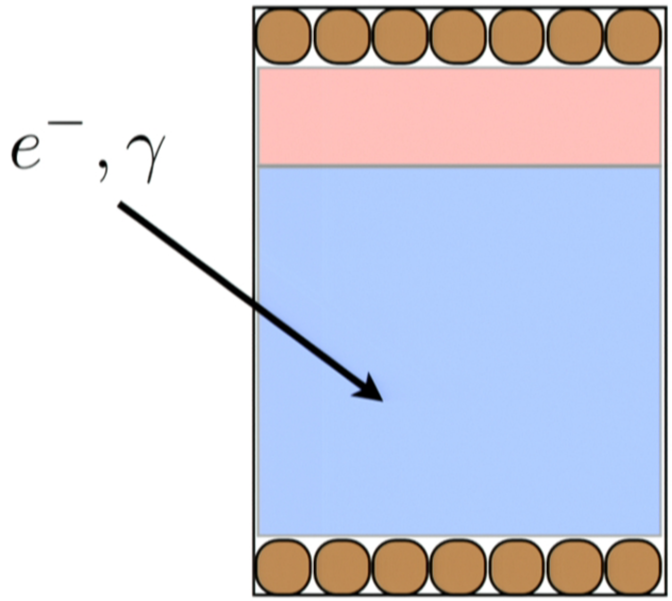

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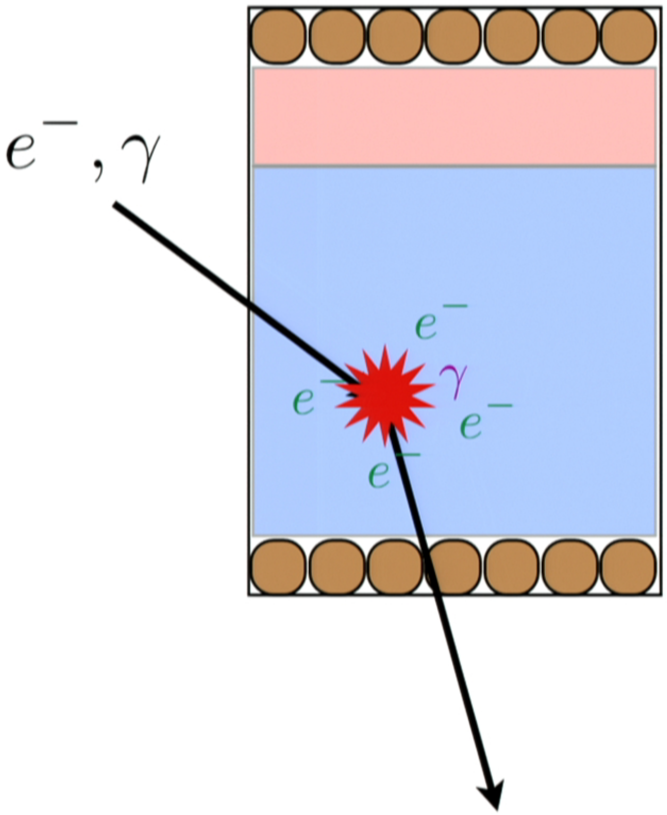

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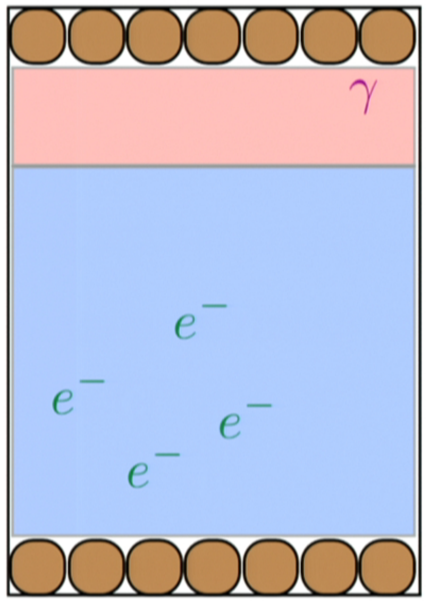

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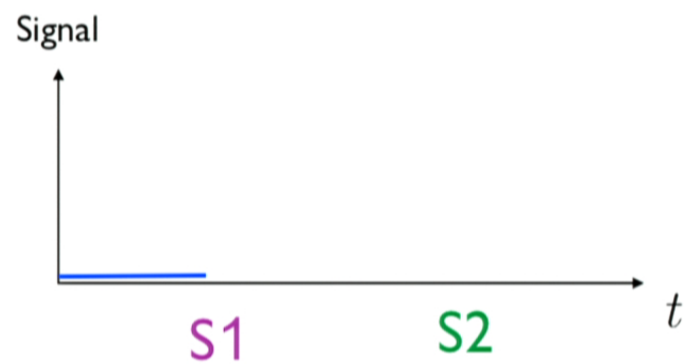

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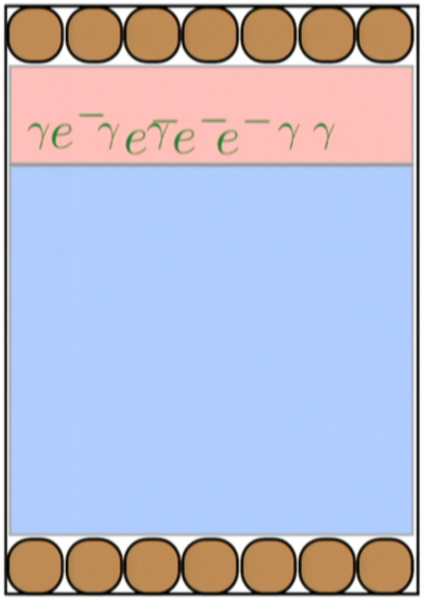

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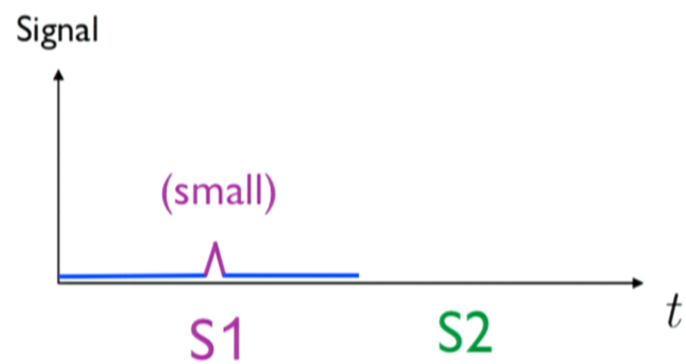
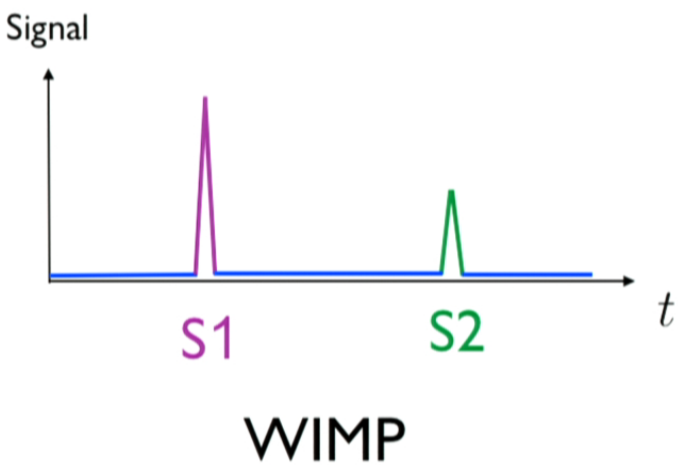
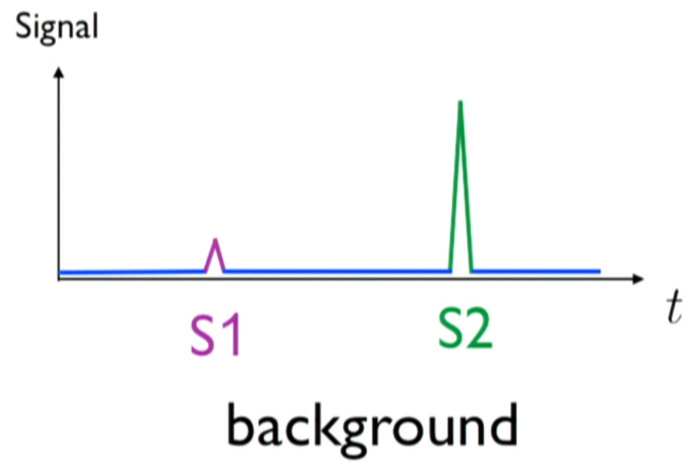


Usual WIMP searches





$$\left(\frac{S_2}{S_1}\right)_{\text{WIMP}} \ll \left(\frac{S_2}{S_1}\right)_{\gamma}$$

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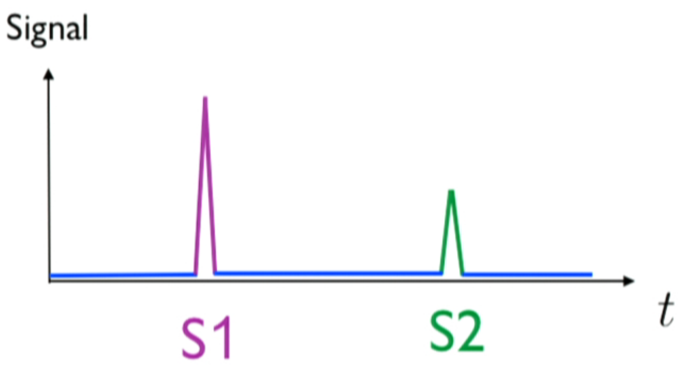

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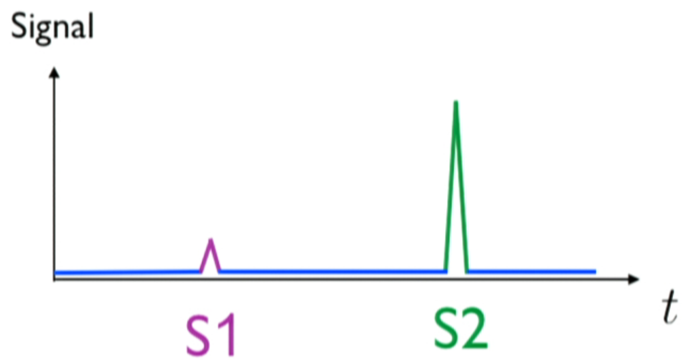

background

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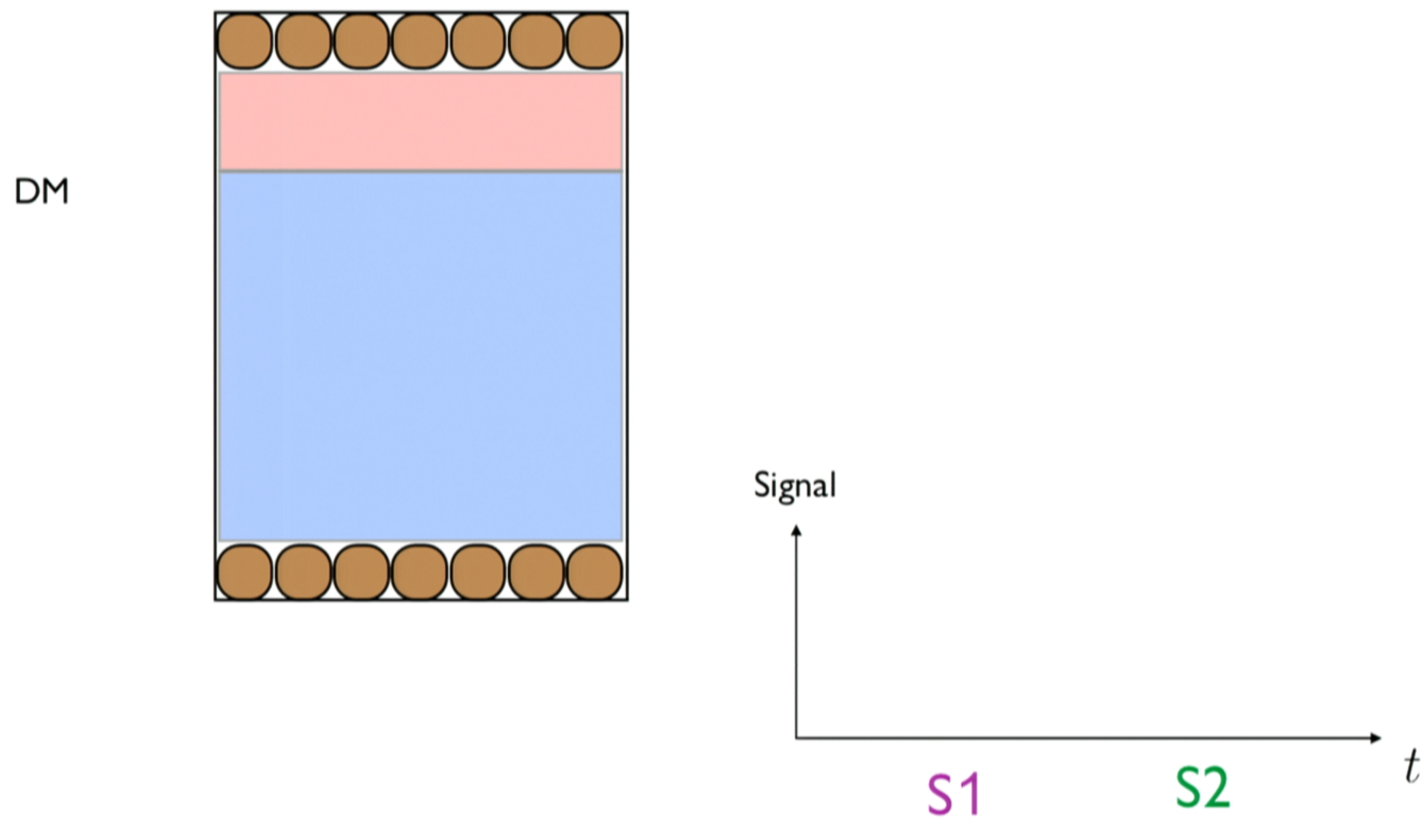
What about light DM ?

Light Dark Matter hitting an electron



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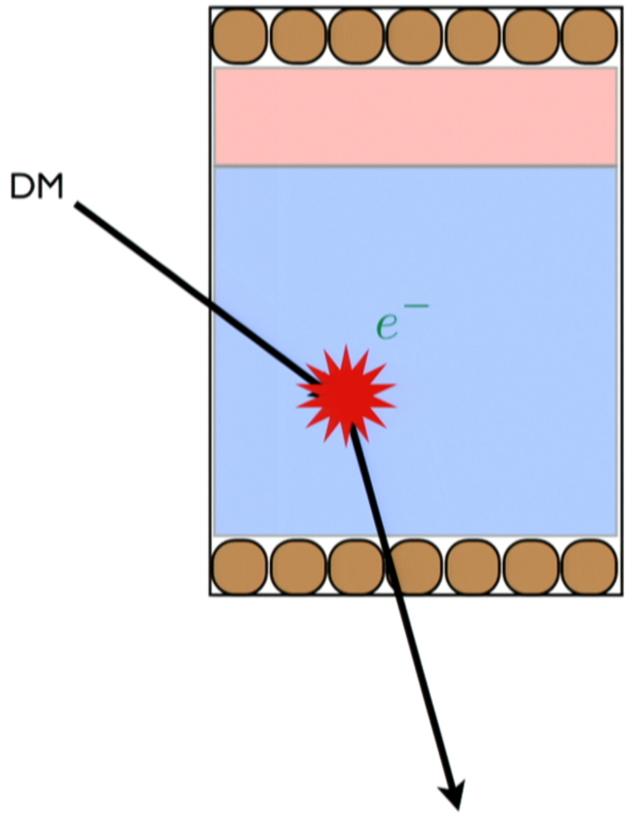
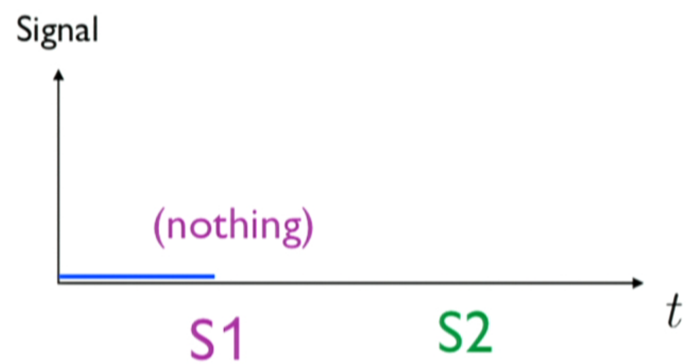


S1: not measurable



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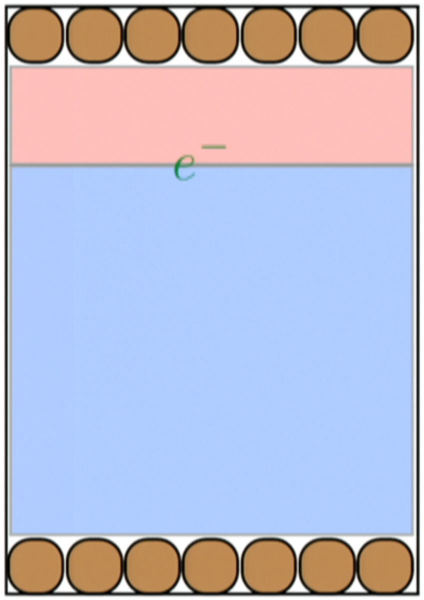

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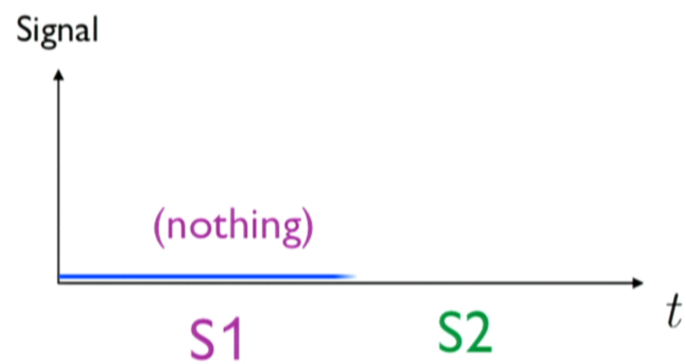

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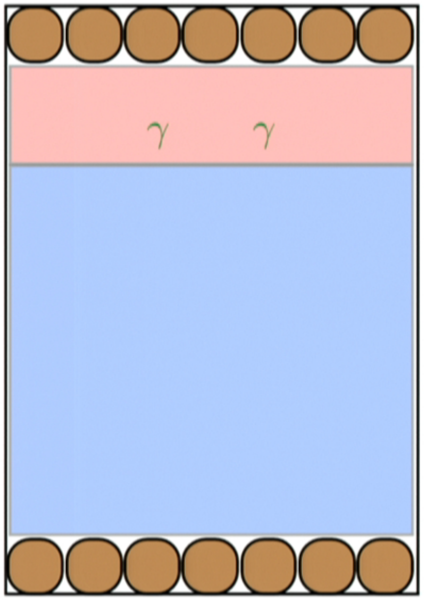

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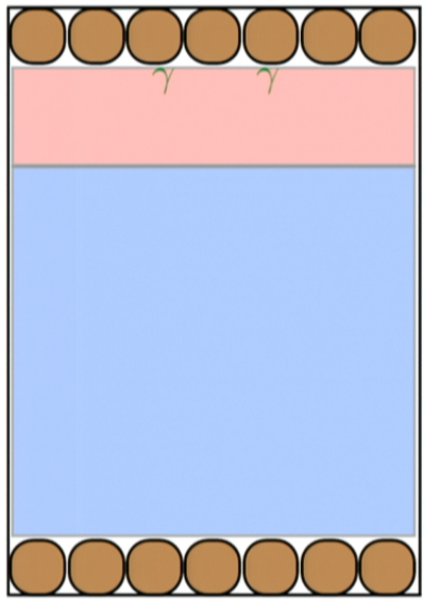

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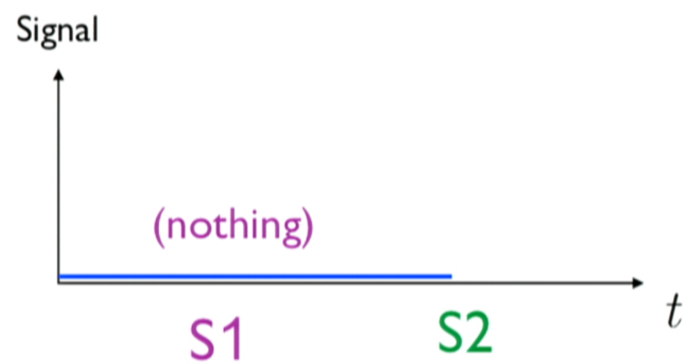

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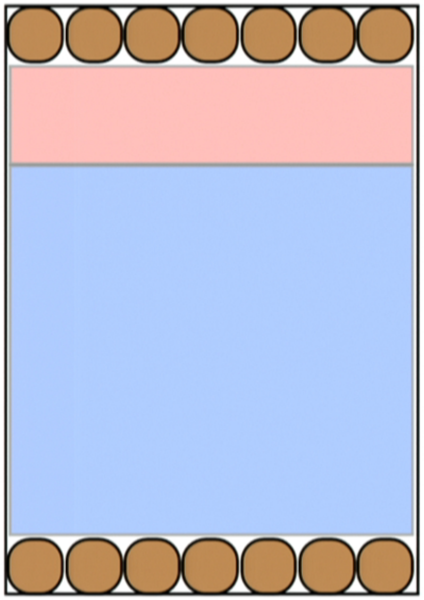
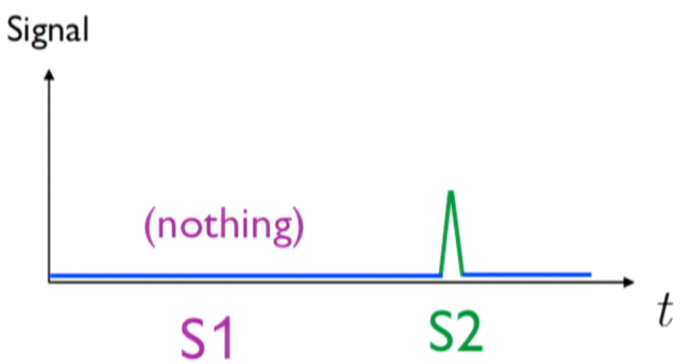


S1: not measurable

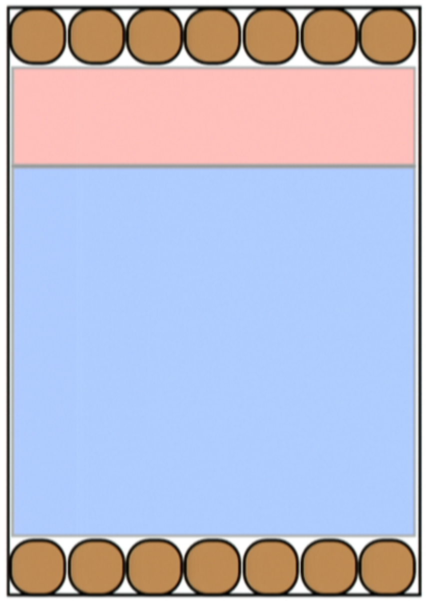
S2: small signal



The XENON10 data

on average, a single electron
produces about 27 photo-electrons

Light Dark Matter hitting an electron



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S2: small signal

The XENON10 data

on average, a single electron
produces about 27 photo-electrons

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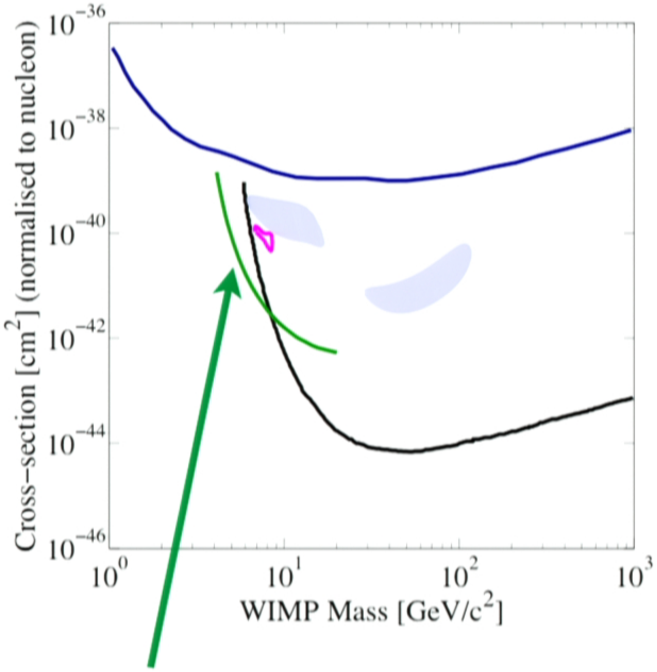

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(2011)

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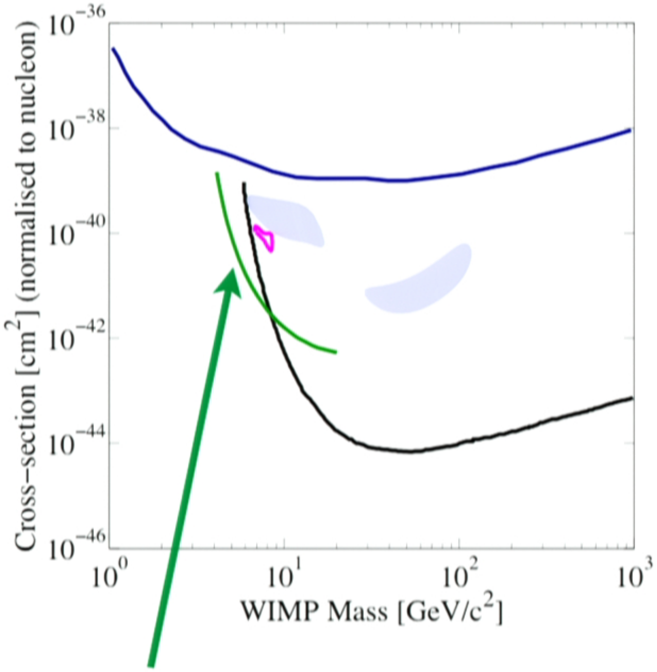

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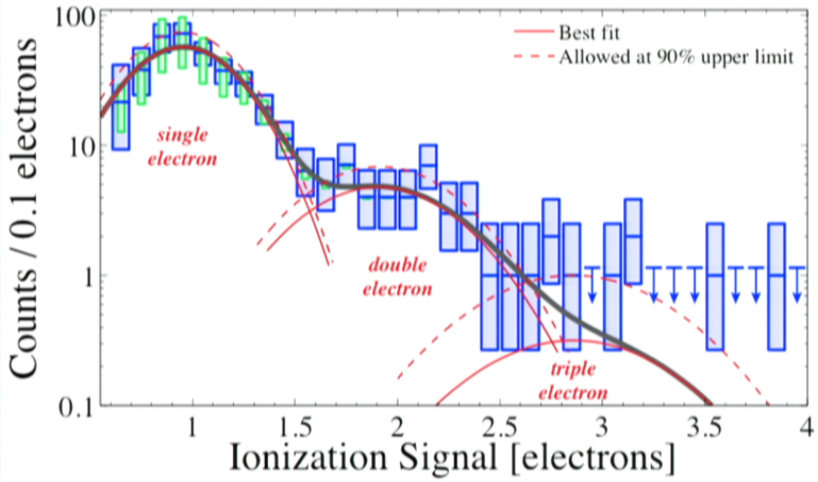

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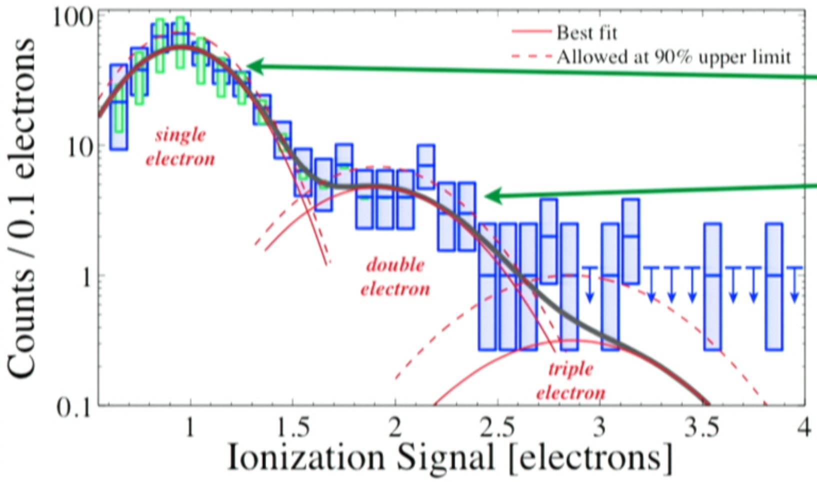

1-electron events

2-electron events

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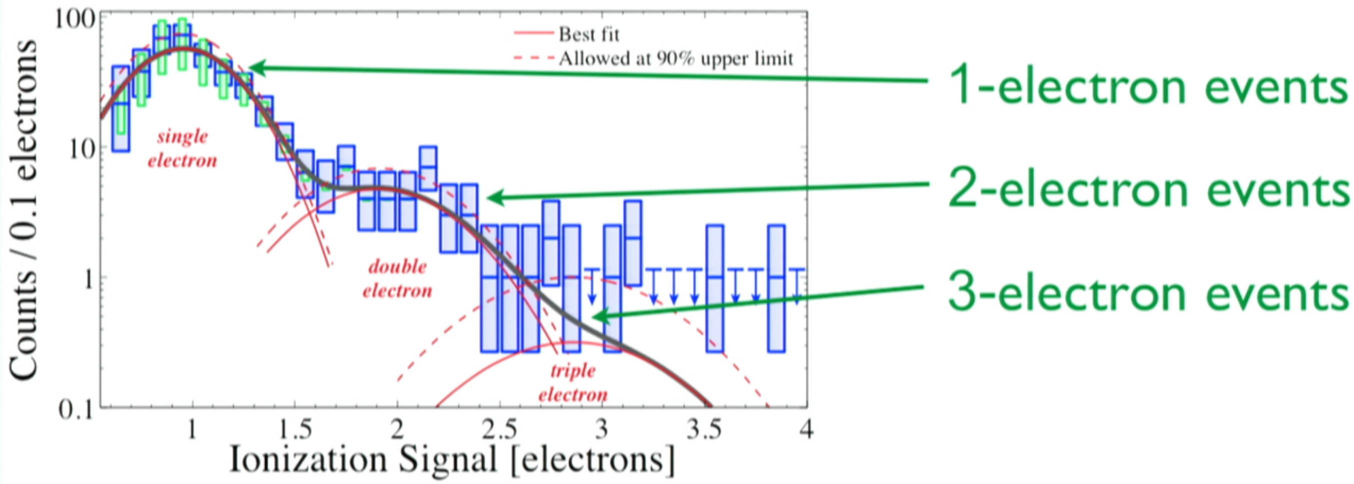

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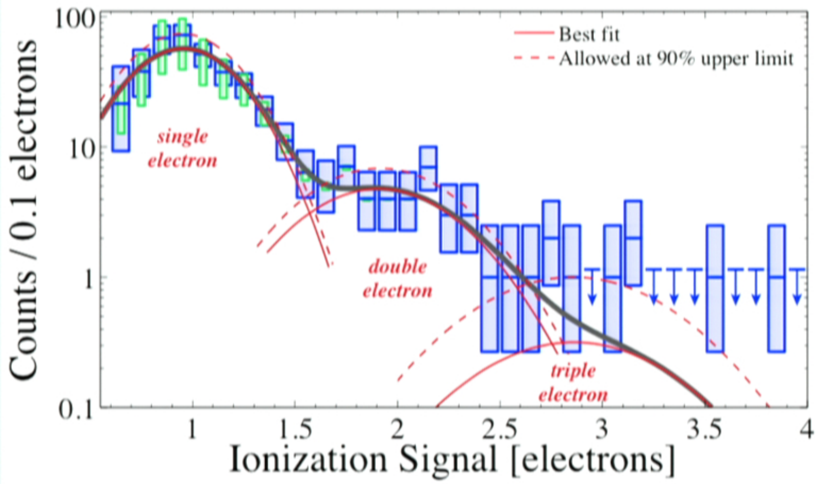

blue bands:
statistical uncertainty

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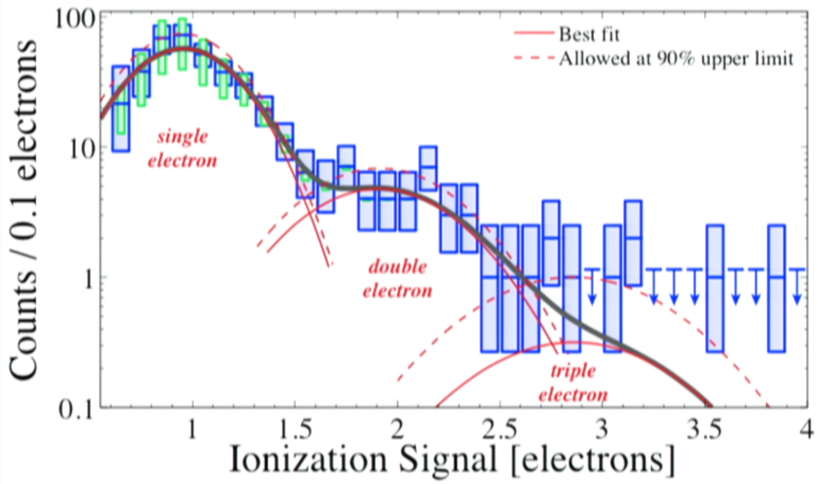

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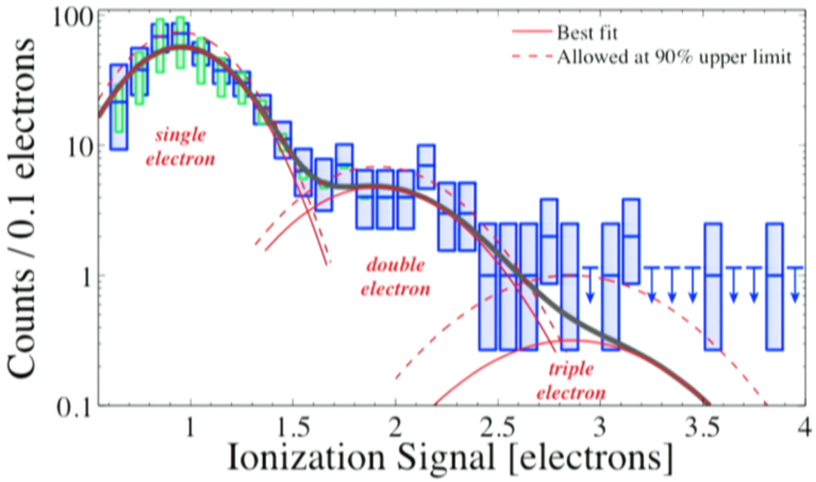

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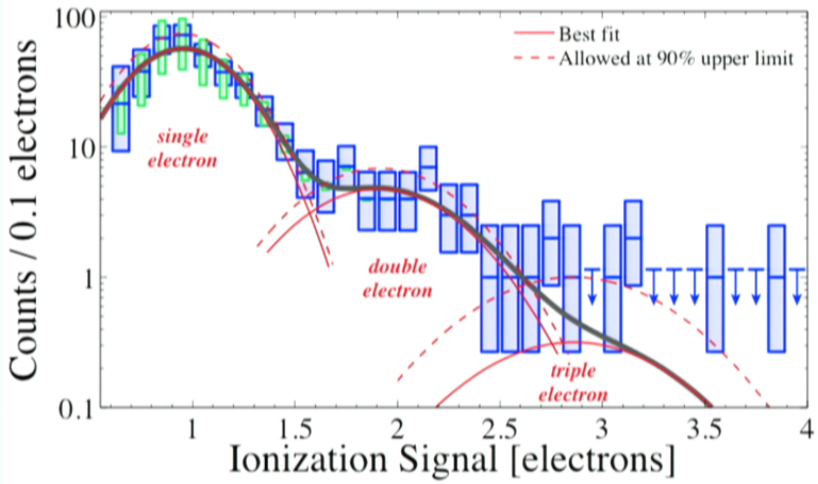

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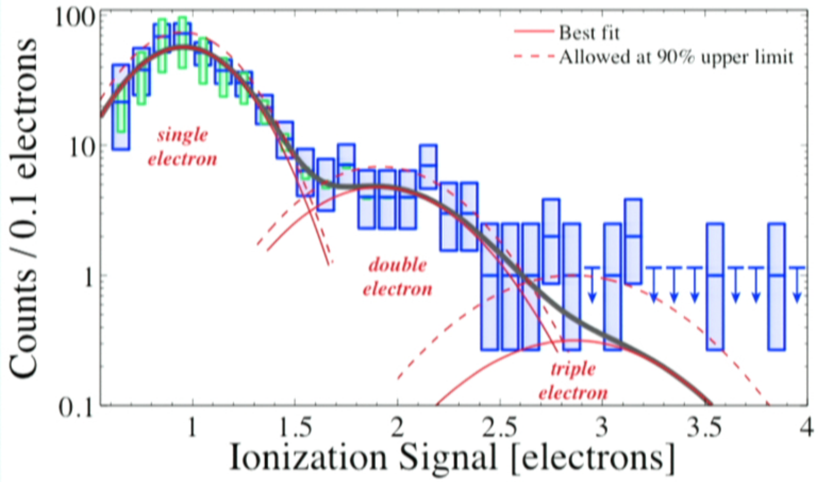

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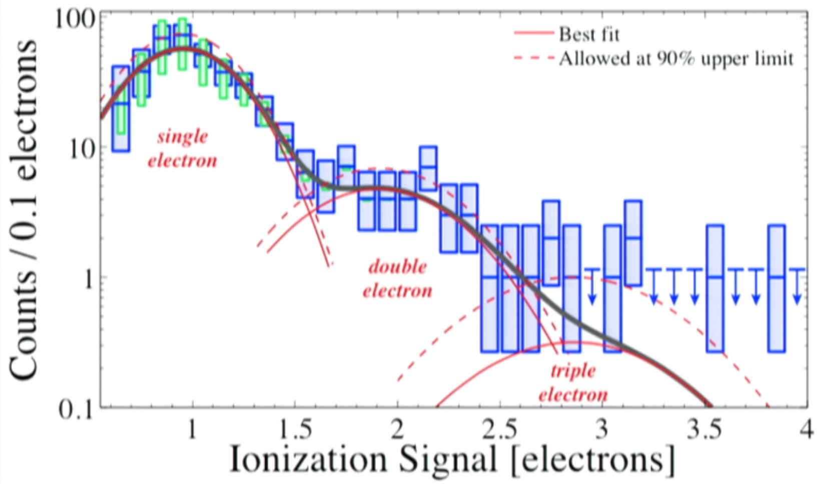

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- spontaneous emission of e^- trapped in potential barrier at liquid-gas interface

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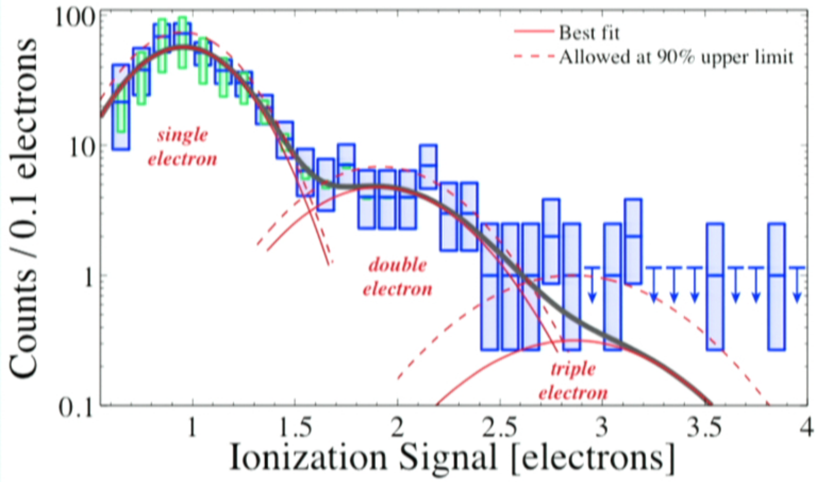

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virtually no attempt has been made to understand origin of these events!

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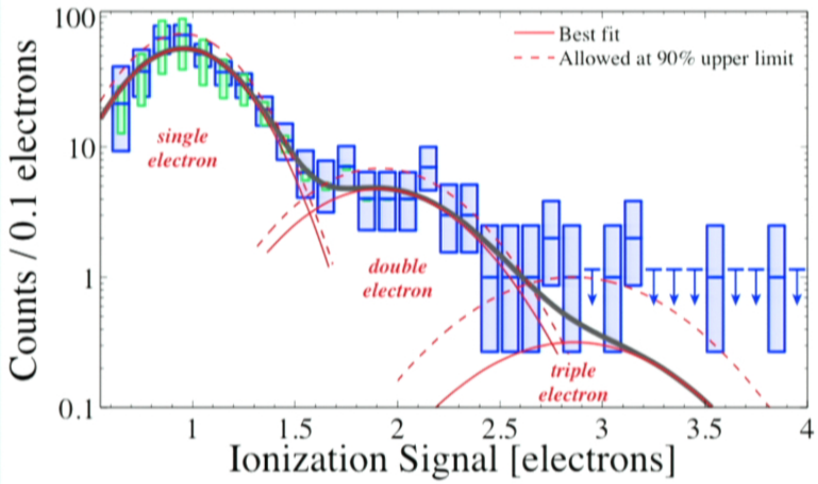

90% c.l. upper bounds on rates:

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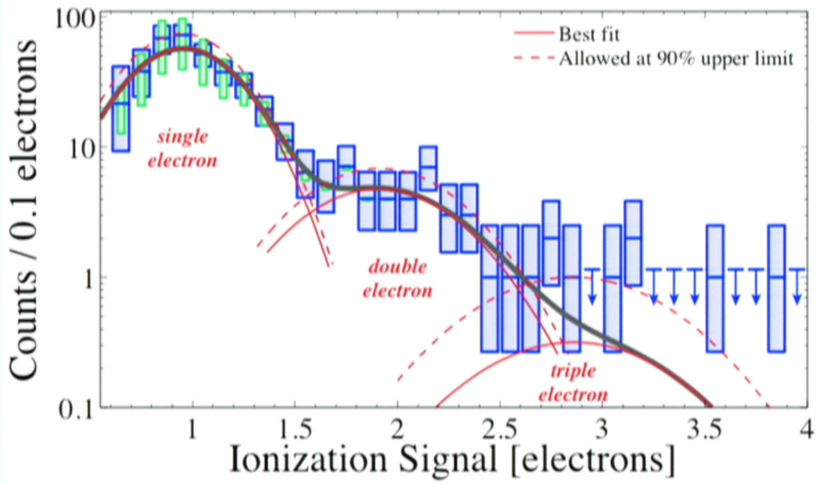

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1 e^-: 34.5 counts/kg/day

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To set limits on DM, must calculate DM-induced ionization rates

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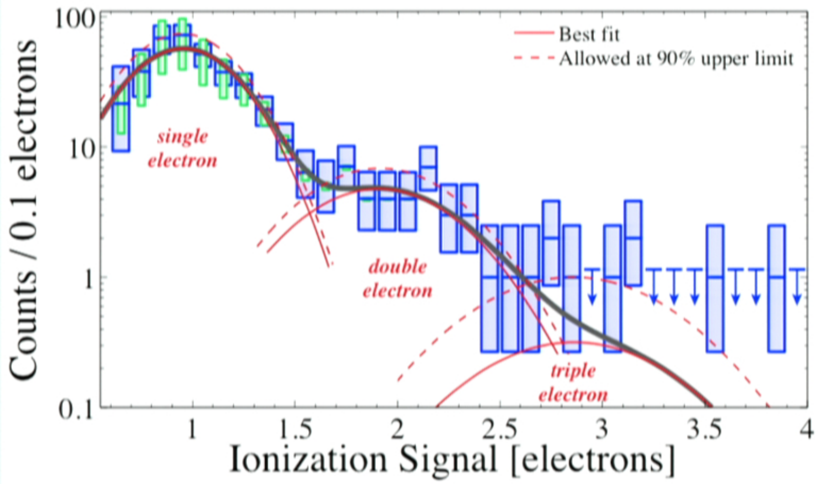

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Scattering Rate $\propto$

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Scattering Rate $\propto$ atomic form-factor $\times$ DM form-factor $\times$ σ_e

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[Bunge, Barrientos, Bunge]

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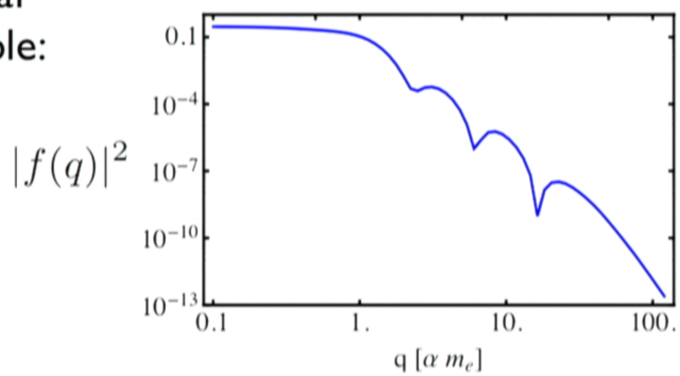

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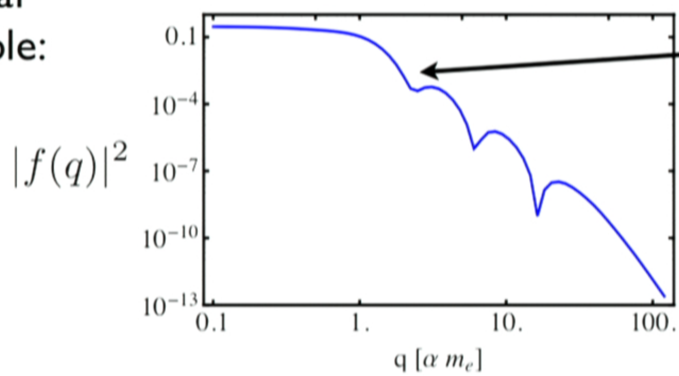
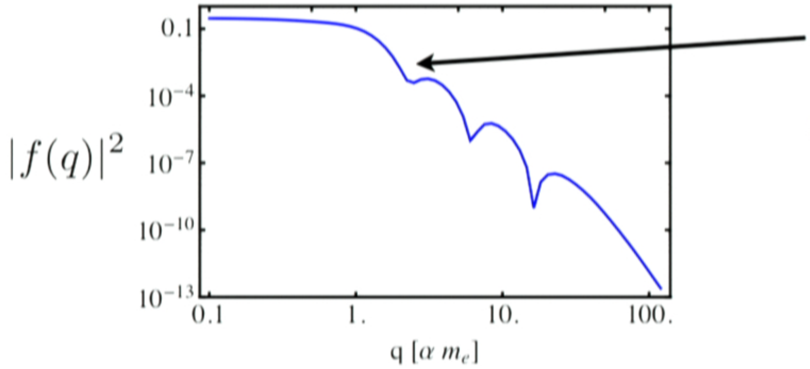


Drops sharply for

$q \gtrsim \alpha\, m_e \sim$ few keV

i.e. for large q, rates are small !



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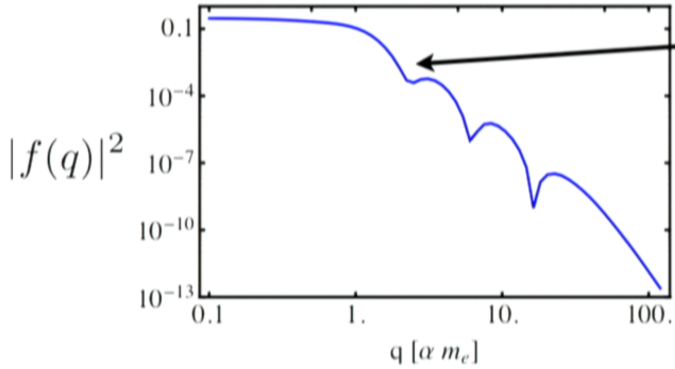

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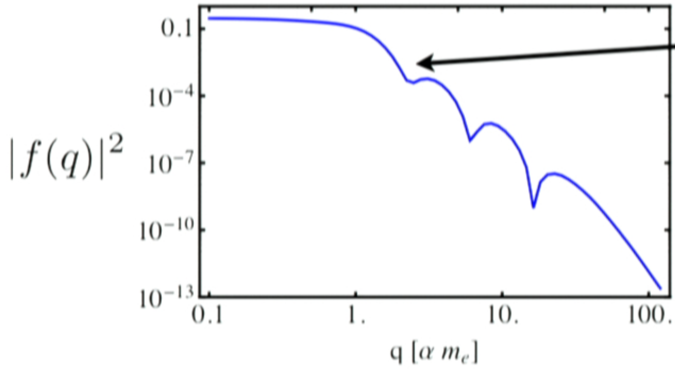

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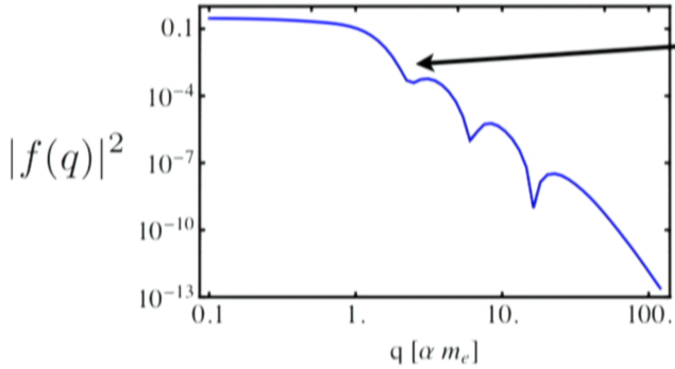

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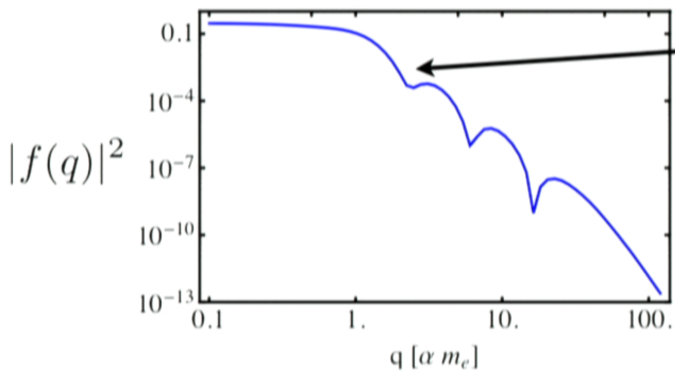
recoil energy $E_R \sim$10 keV $\Longrightarrow$ $q \sim$ 1 MeV $\sim 250\, \alpha\, m_e$

Negligible !

[Kopp, Niro, Schwetz, Zupan (2009)]



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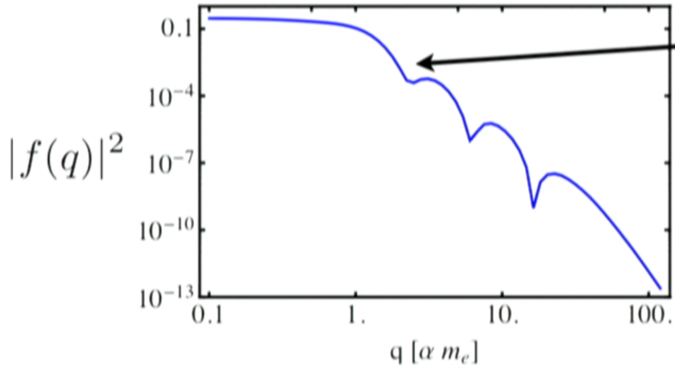

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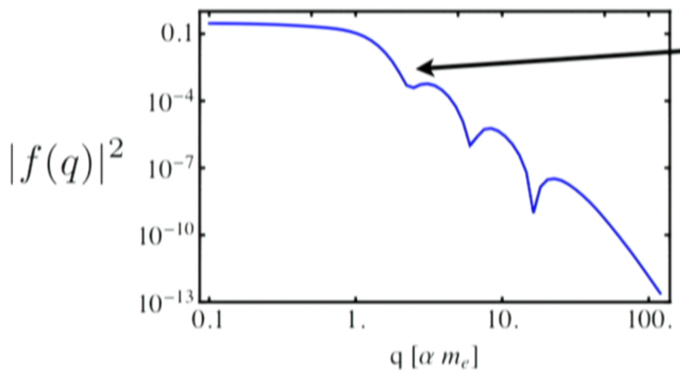

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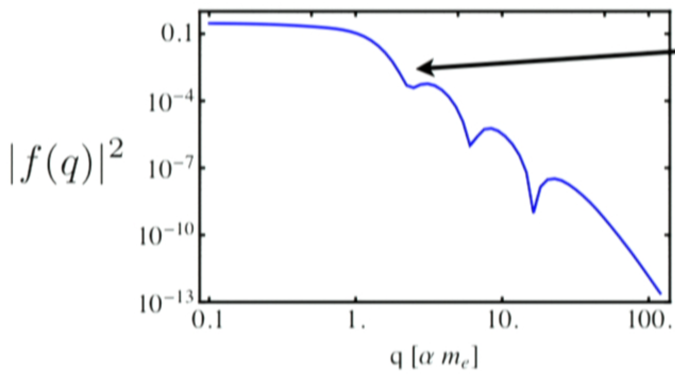

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For sub-GeV DM-e$^-$ scattering with

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Ok !

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cross section to scatter off *free* electron

Calculating Ionization Rates

And one more point…

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In addition to single-electron events, we can also get events with 2, 3, etc. electrons !

How ?

- outgoing e^- can ionize further electrons

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$\Longrightarrow$ can give stronger constraints than pure single electron events

Results

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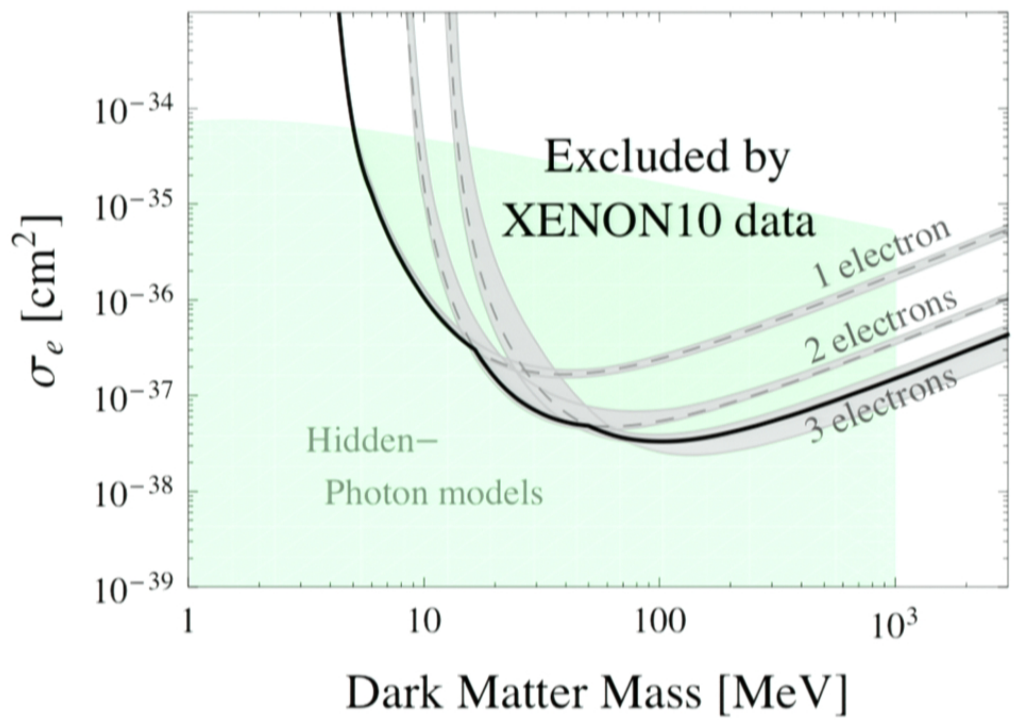
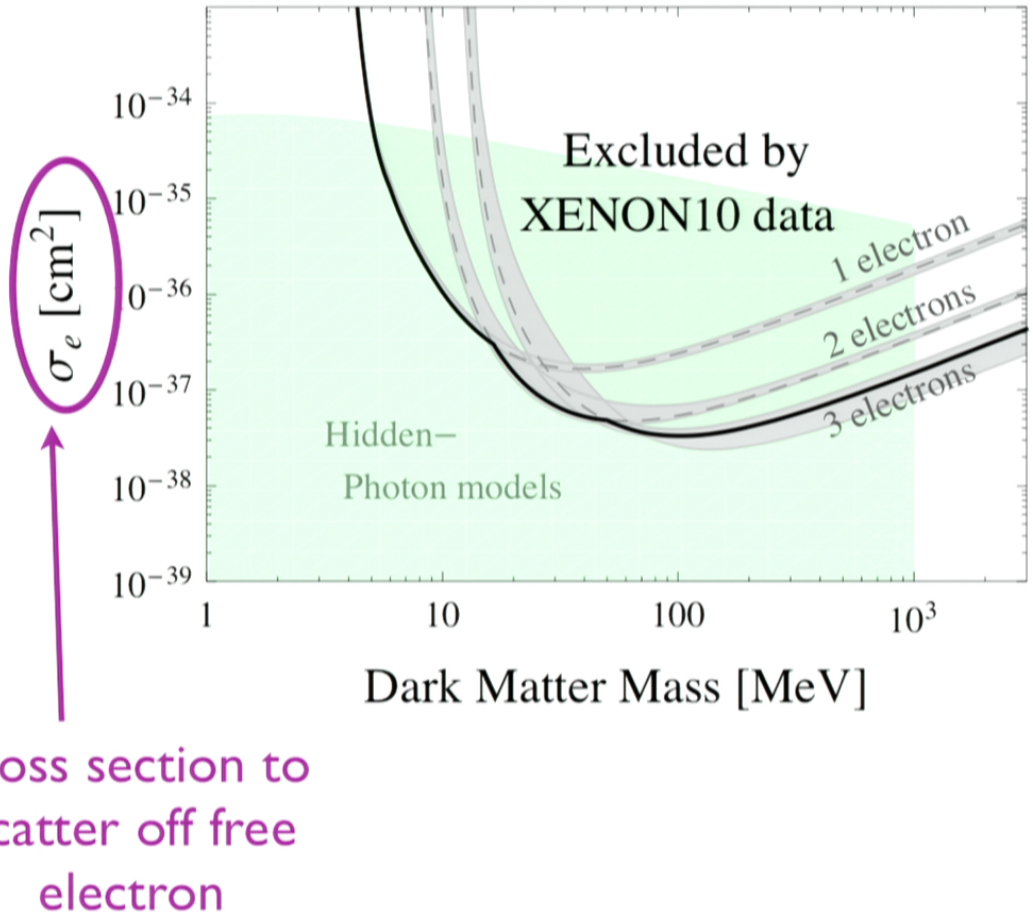


Excluded by XENON10 data
1 electron
2 electrons
3 electrons
Hidden–
Photon models
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
σ_e [cm^2]
1
10
100
10^3
Dark Matter Mass [MeV]

Results



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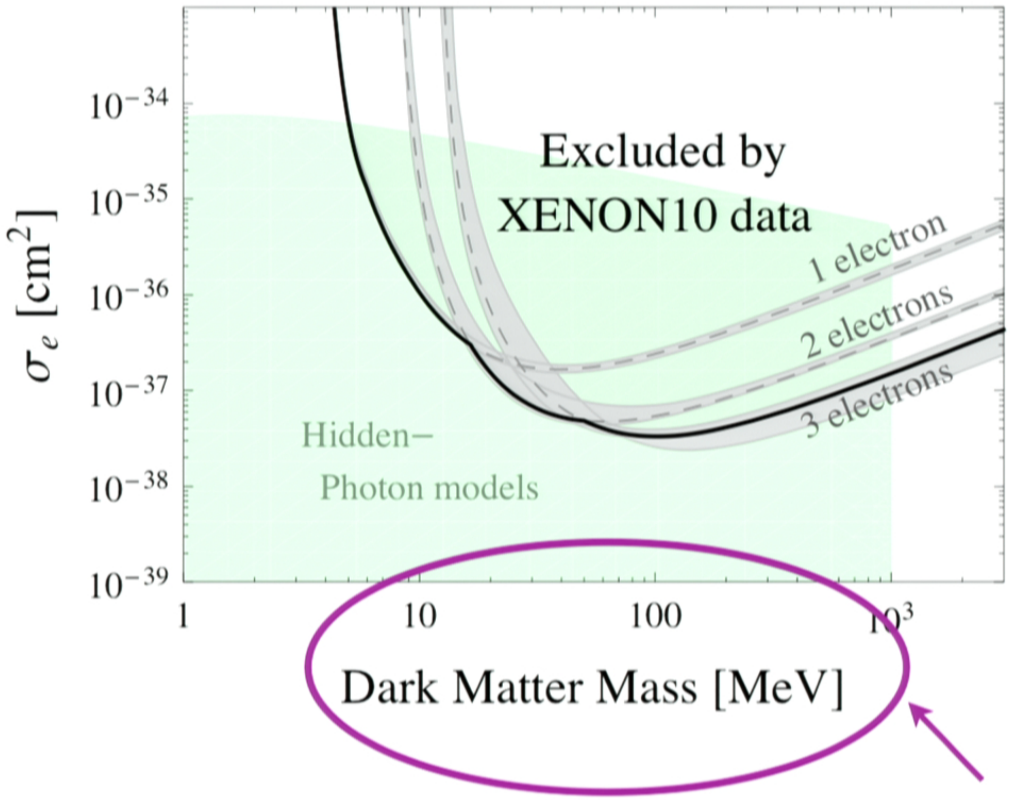
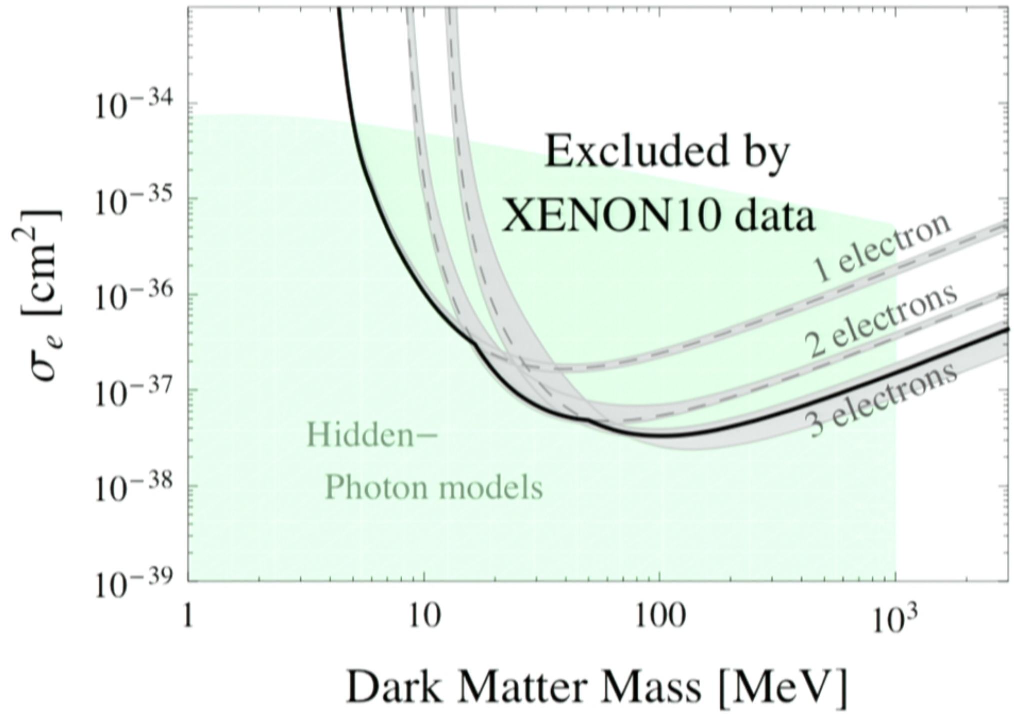
Results



DM mass
(notice MeV scale !!!)

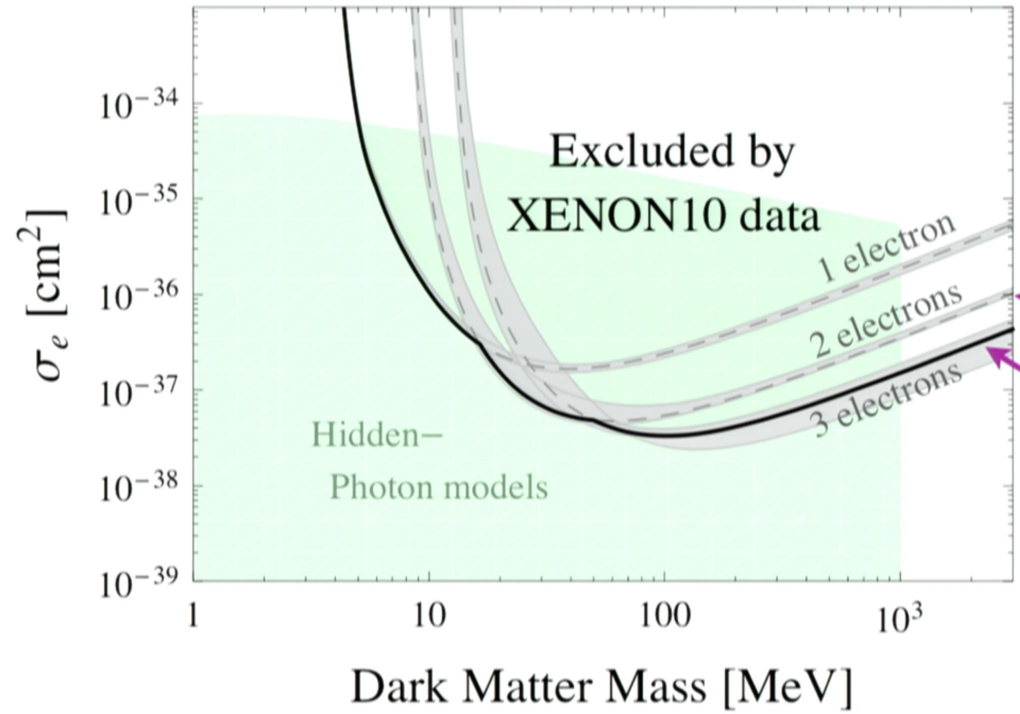
Results



Momentum-independent
DM interaction

$$F_{\rm DM} = 1$$

Results



Constraints from

1 e⁻ - events

2 e⁻ - events

3 e⁻ - events

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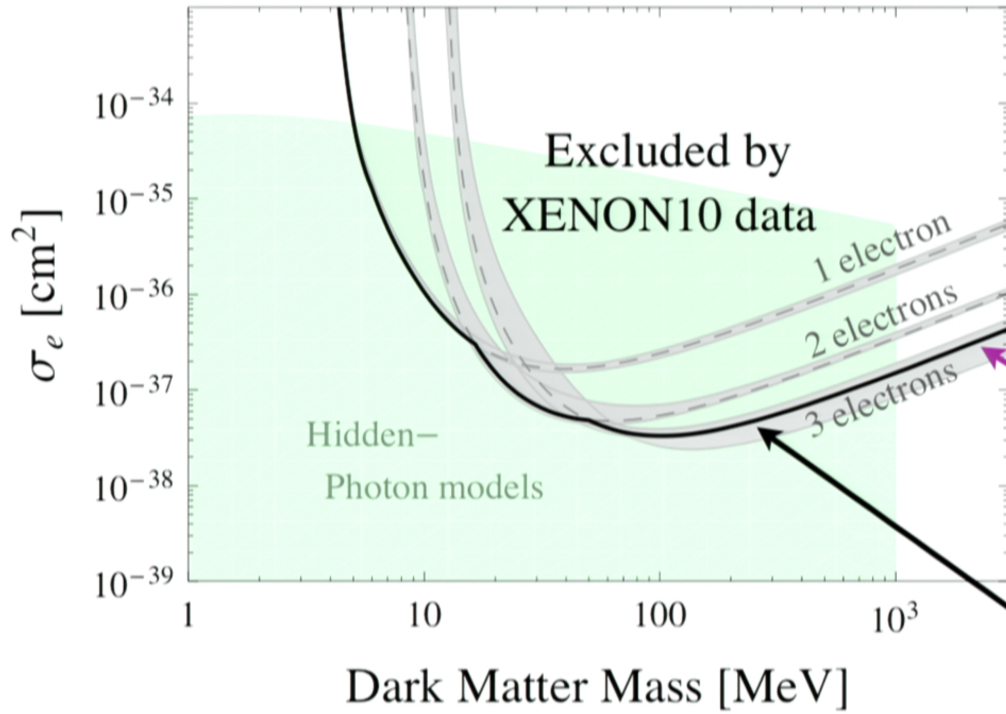

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black line: combined limit

Momentum-independent DM interaction

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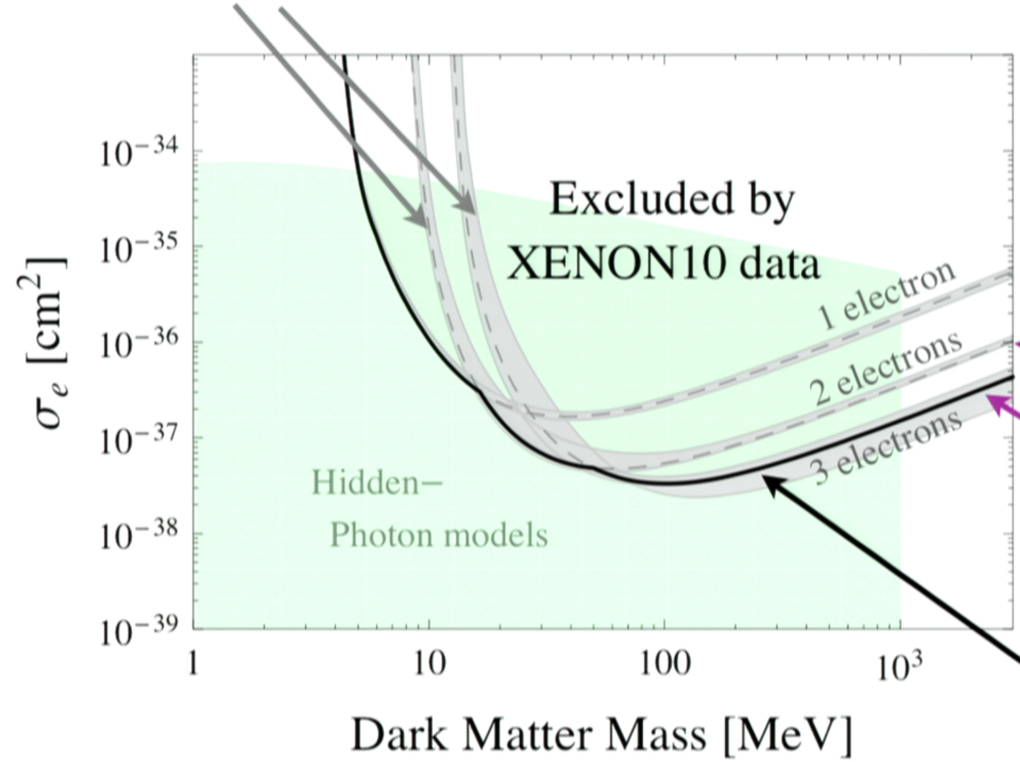
Results

gray bands:
systematic uncertainty



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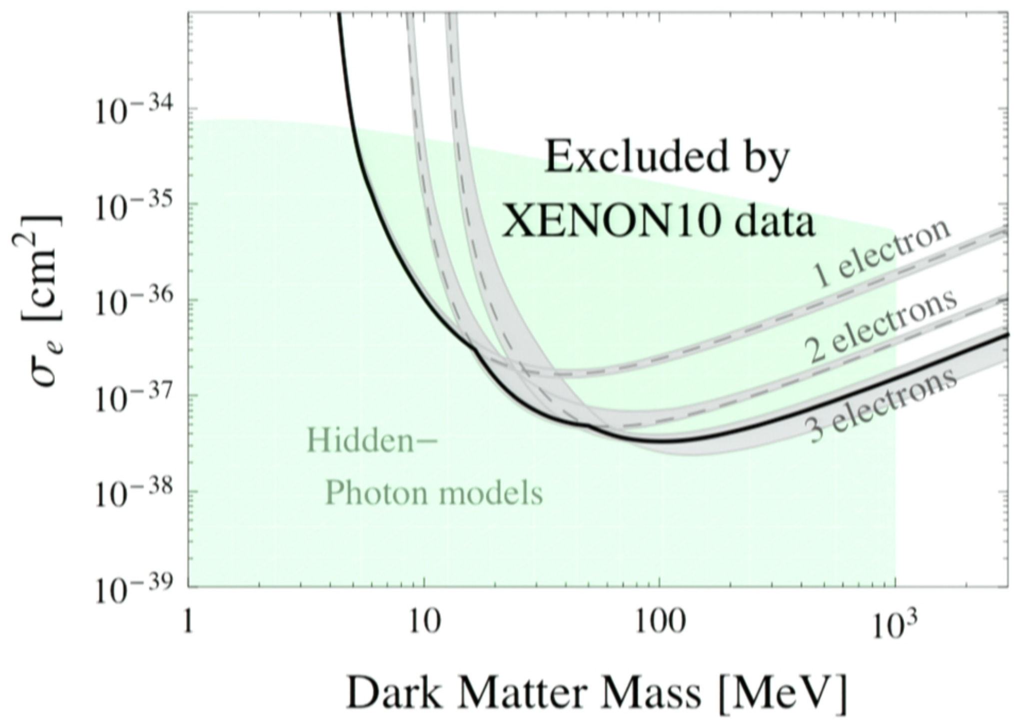
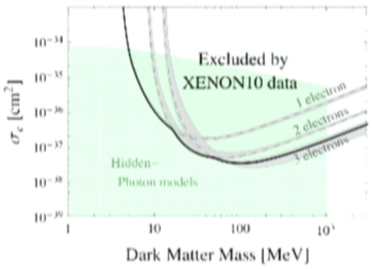
strongest constraint
at high masses from 3 e⁻

Results

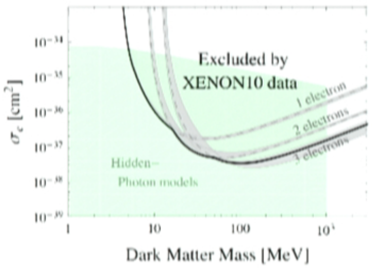


What is the green region ?



Assume DM charged under *U(1)'*,
which couples to hypercharge *U(1)*$_Y$
via *kinetic mixing*

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$



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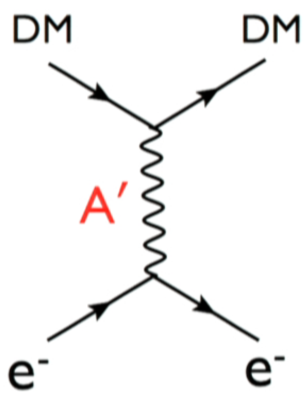
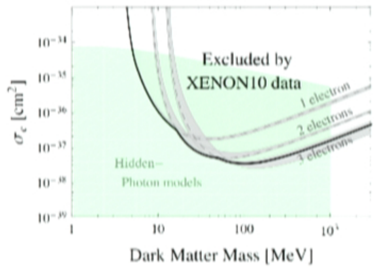
DM-electron scattering mediated by hidden-photon A′



(too many people to cite)



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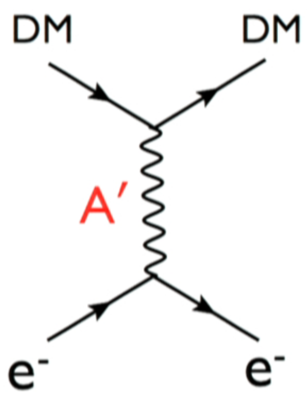

DM-electron scattering mediated by hidden-photon A′

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

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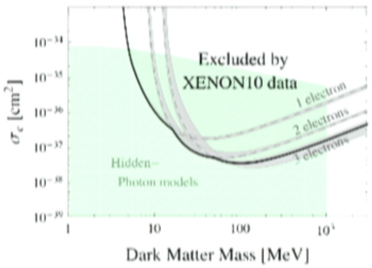

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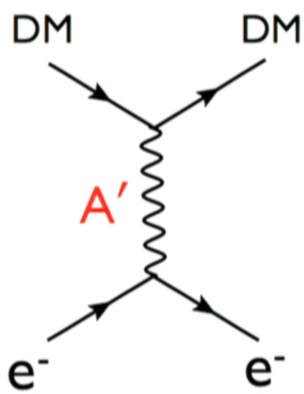

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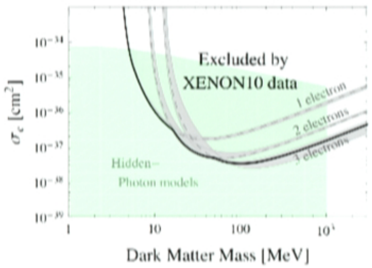

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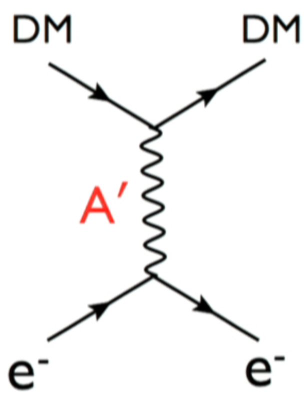

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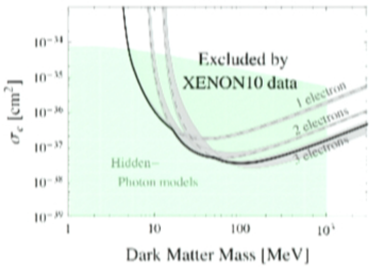

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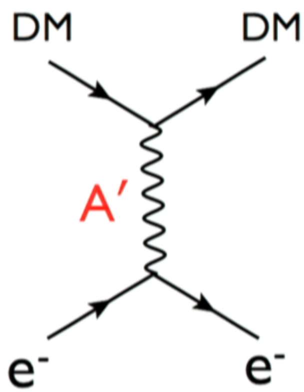

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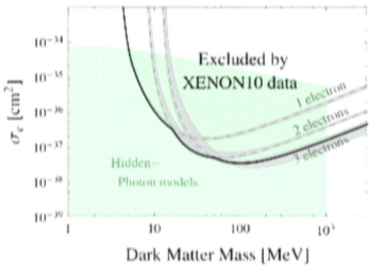

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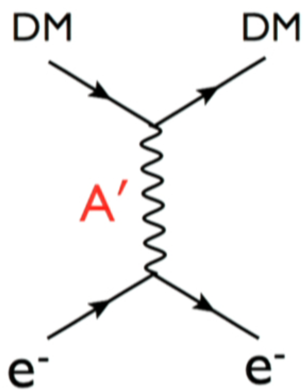

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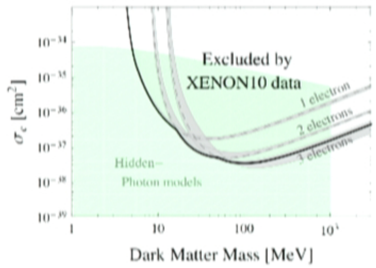
Green region:

- DM self-interaction cross section consistent with observations
- $m_{A'} > 1$ MeV consistent with all constraints
- (to avoid CMB constraints, need e.g. asymmetric DM)

see also Lin, Yu, Zurek (2011)



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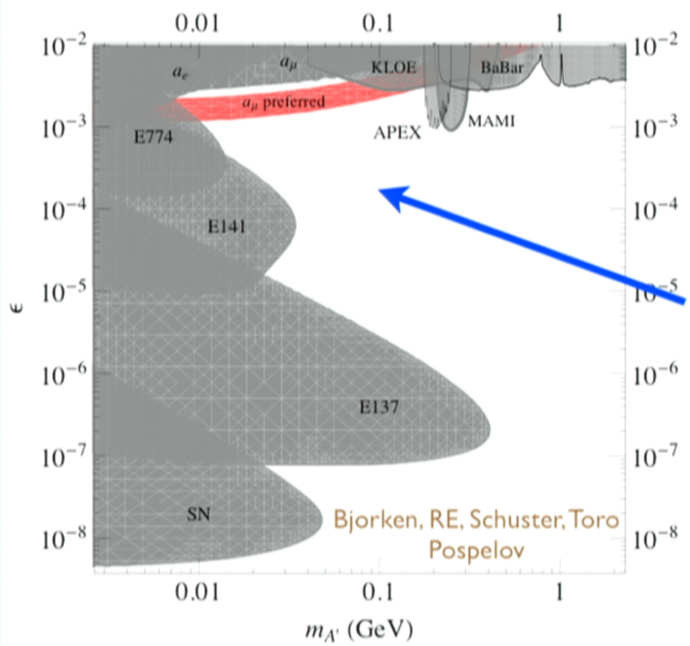

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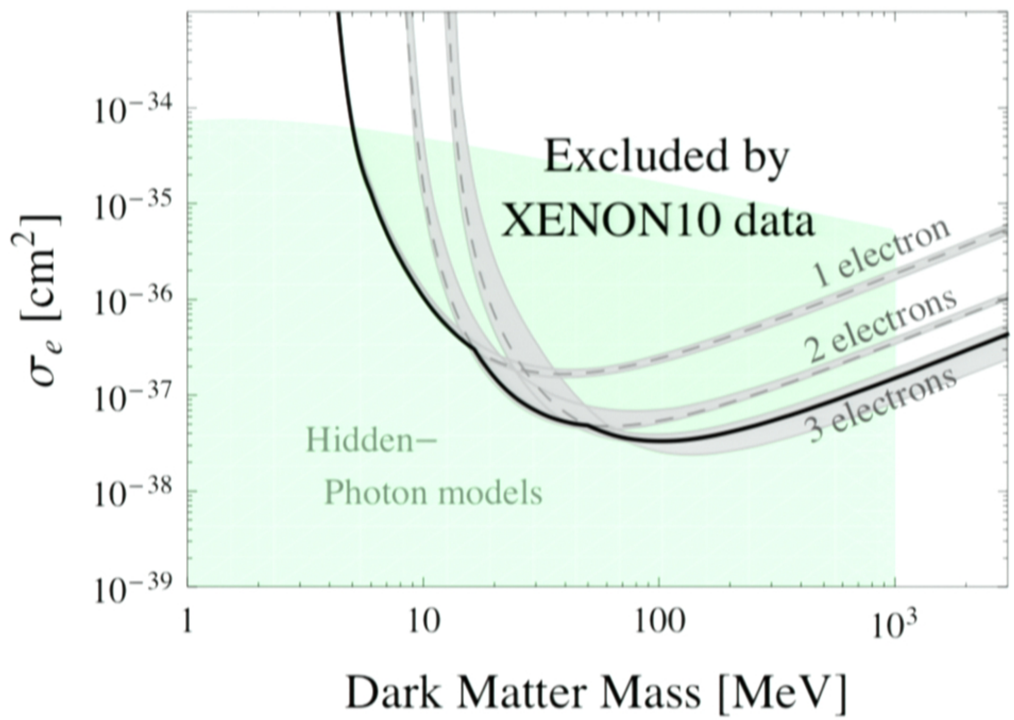

Excluded by XENON10 data
1 electron
2 electrons
3 electrons
Hidden–
Photon models
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
σ_e [cm^2]
1
10
100
10^3
Dark Matter Mass [MeV]

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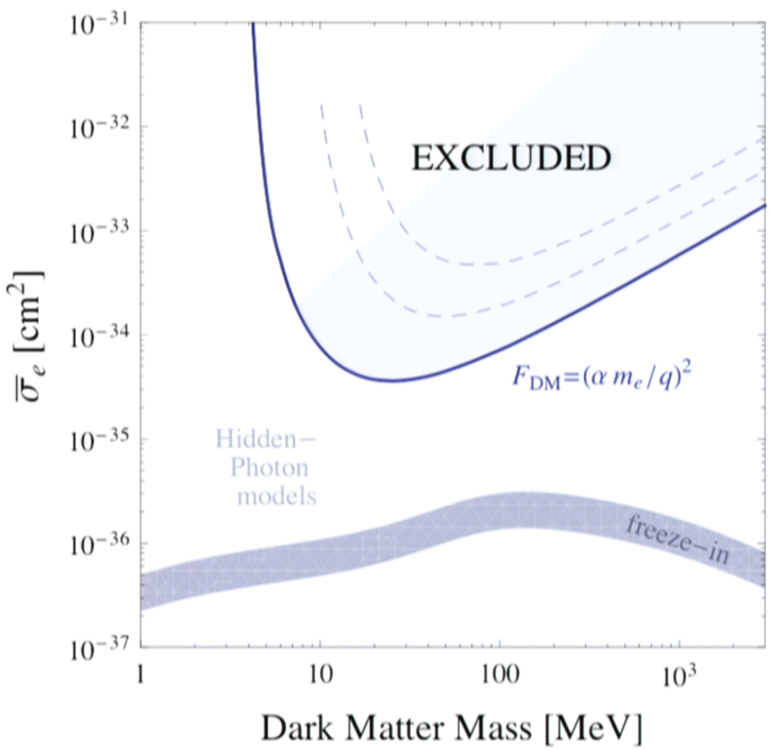

Momentum-dependent DM interaction: $F_{\rm DM} \propto 1/q^2$

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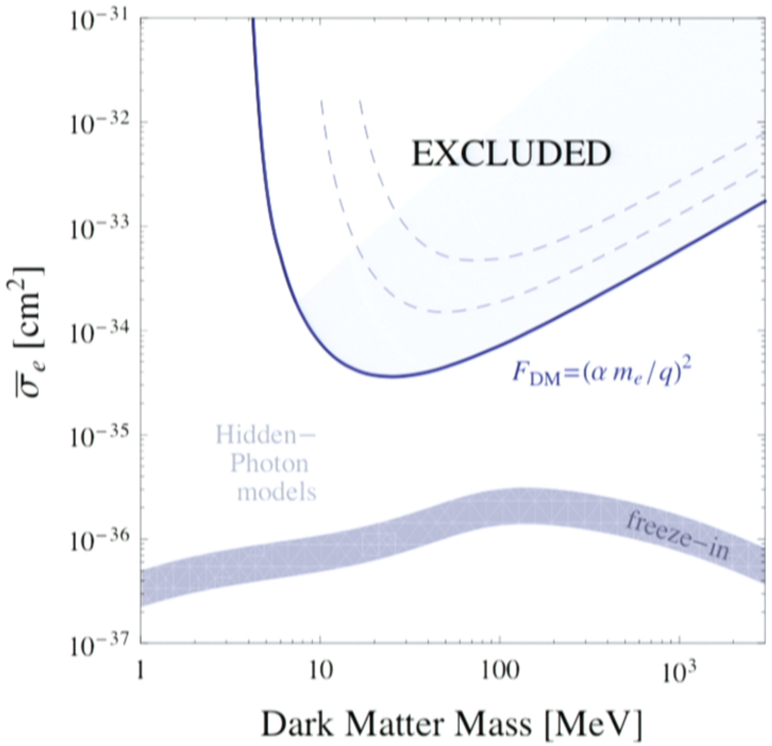

Constraints from

3 e$^-$ - events

2 e$^-$ - events

1 e$^-$ - events

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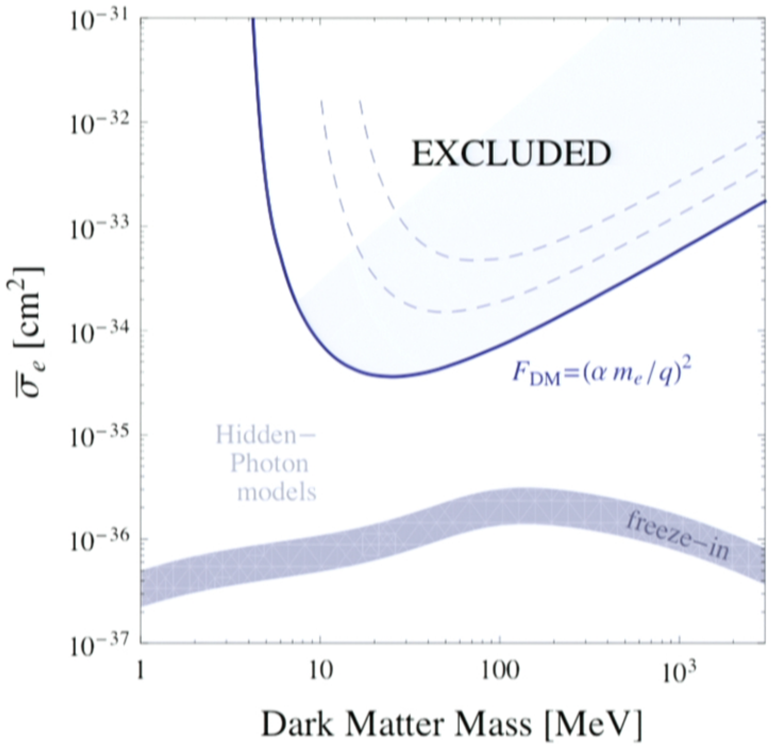

Constraints from

3 e⁻ - events

2 e⁻ - events

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What is the blue region ?

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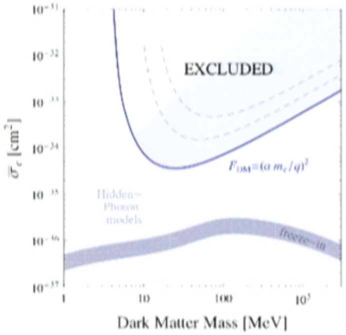

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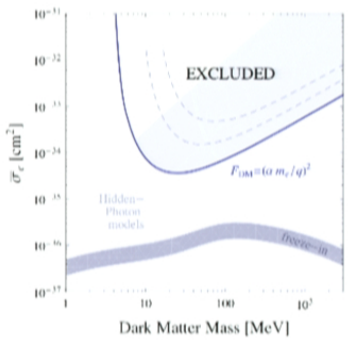

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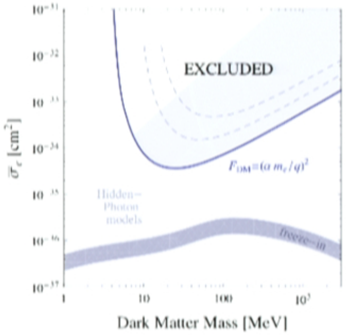

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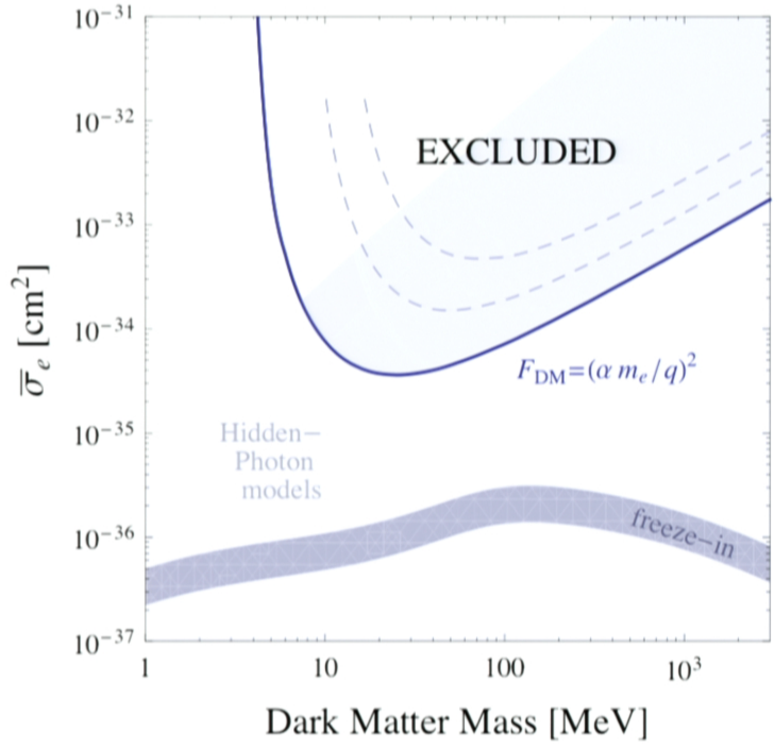

EXCLUDED
$F_{DM}=(\alpha m_e/q)^2$
Hidden−
Photon
models
freeze−in
10^{-31}
10^{-32}
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10^{-34}
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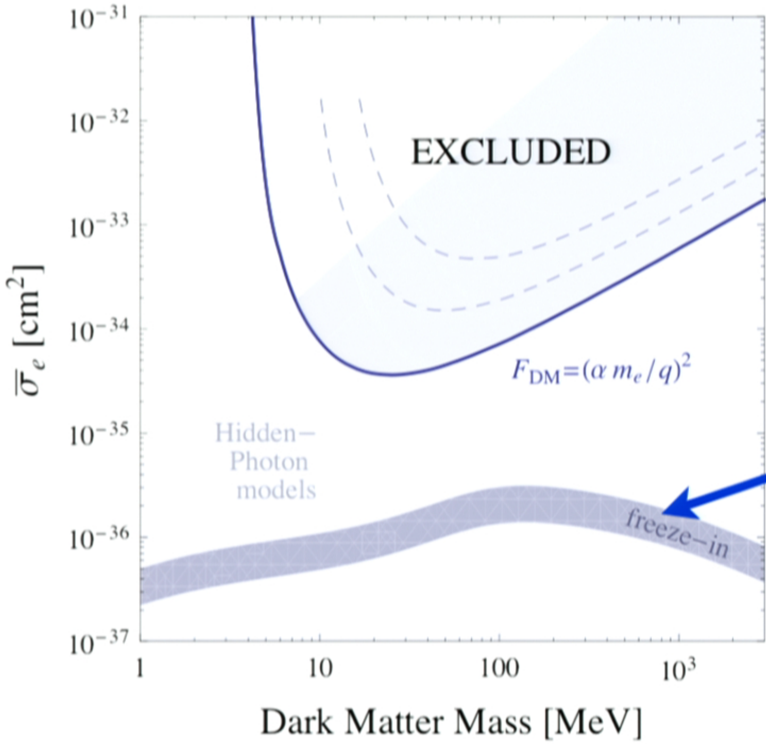

in addition,
in dark blue region
correct DM abundance is
obtained from *freeze-in*

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

$$e^+ + e^- \to \mathrm{DM} + \mathrm{DM}$$
$$Z \to \mathrm{DM} + \mathrm{DM}$$

[see also Chu, Hambye, Tytgat (2011)]

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"accidentally" already sets meaningful limits on DM-electron recoils

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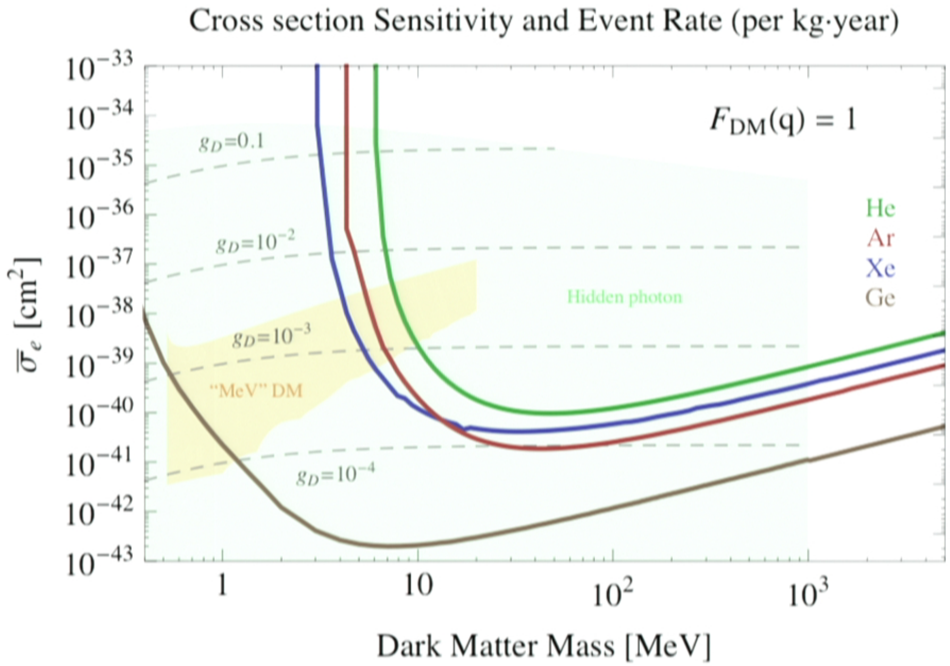
How well can an experiment do that purposefully looks for sub-GeV DM ?

Projected reach for various elements



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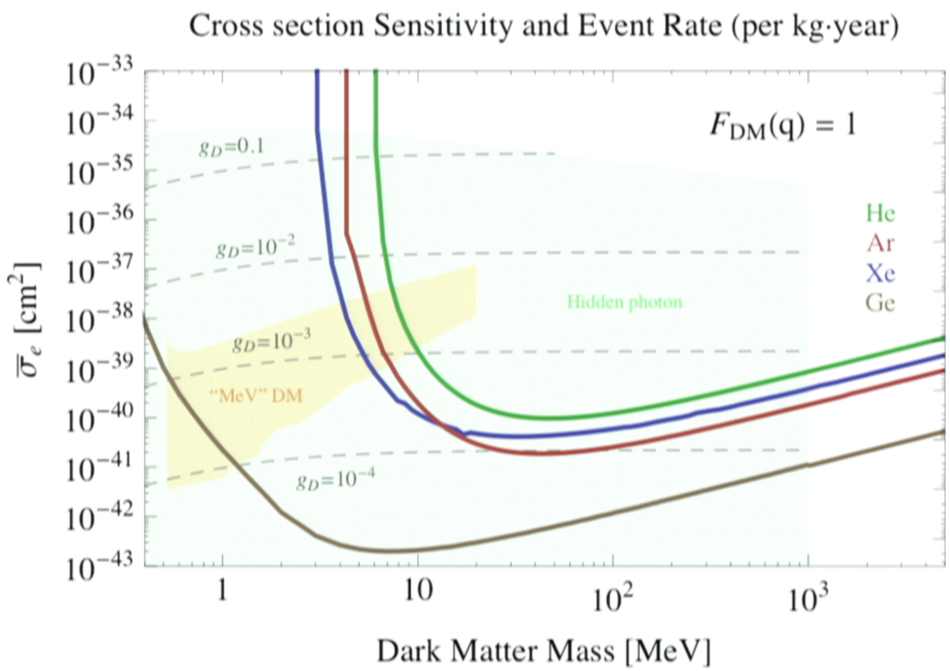

1 kg-year

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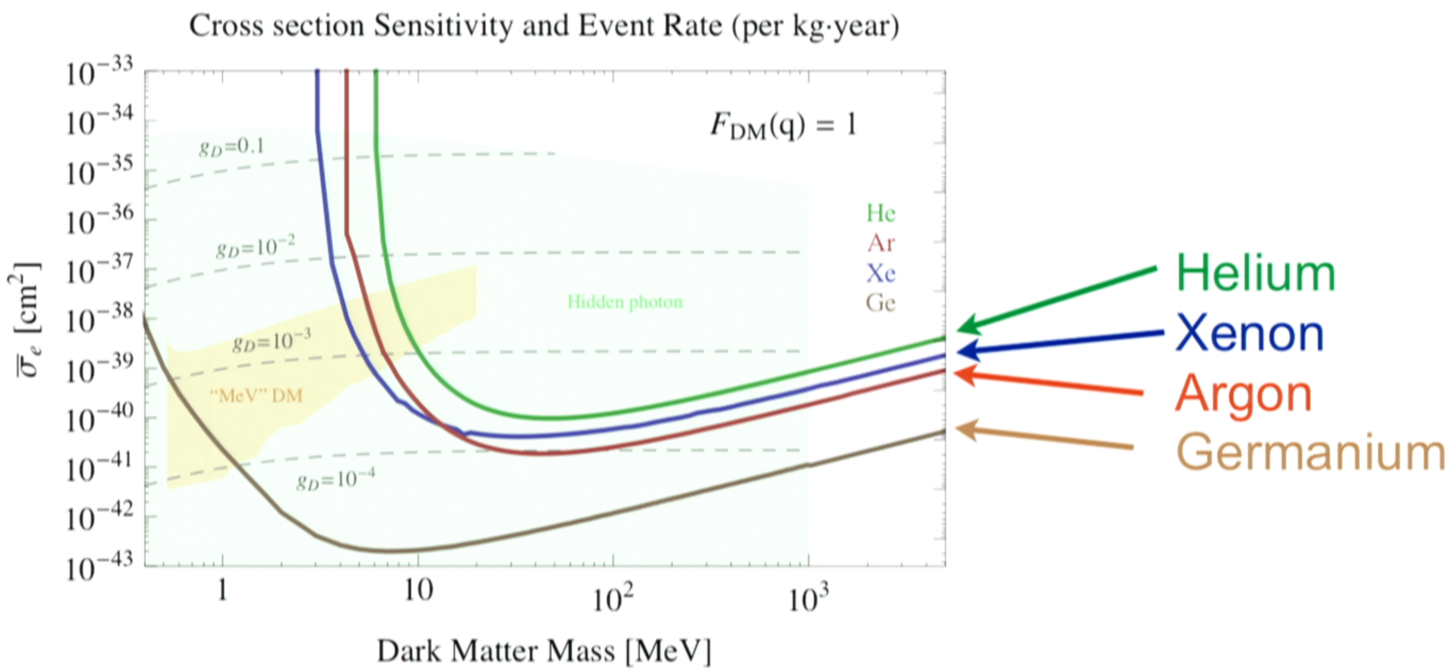

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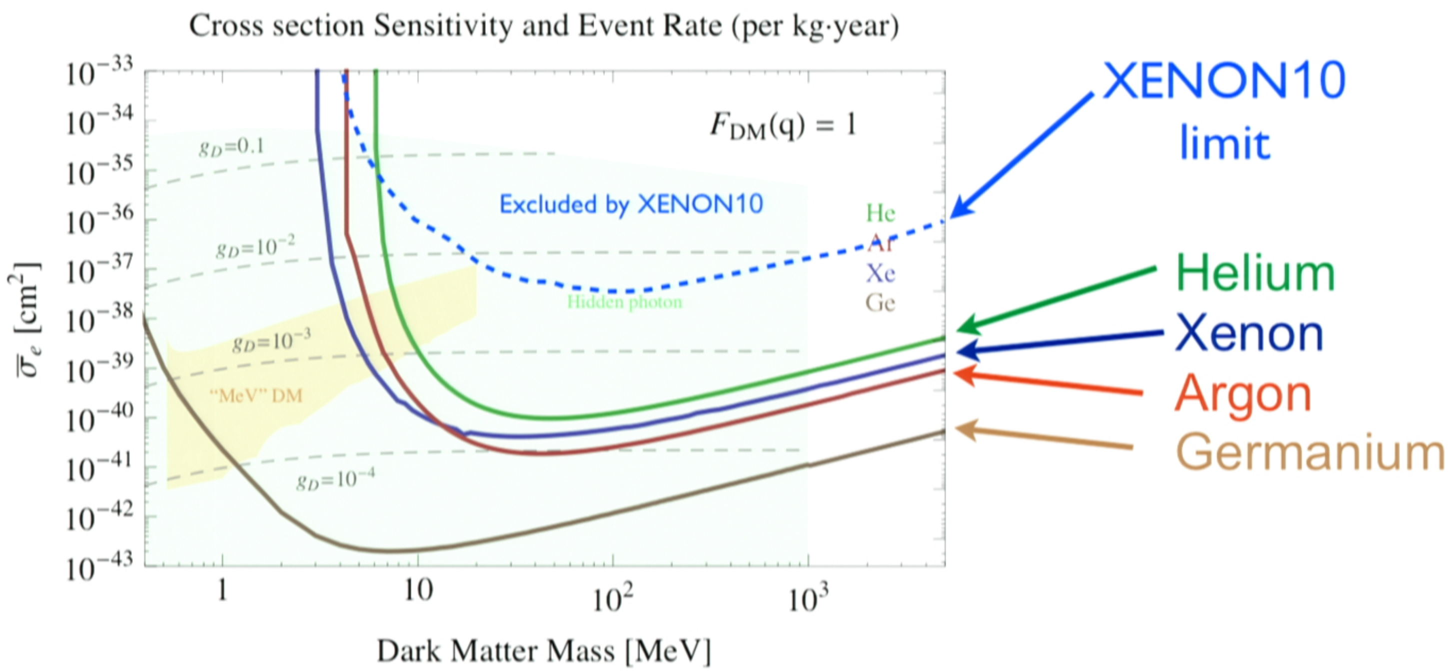

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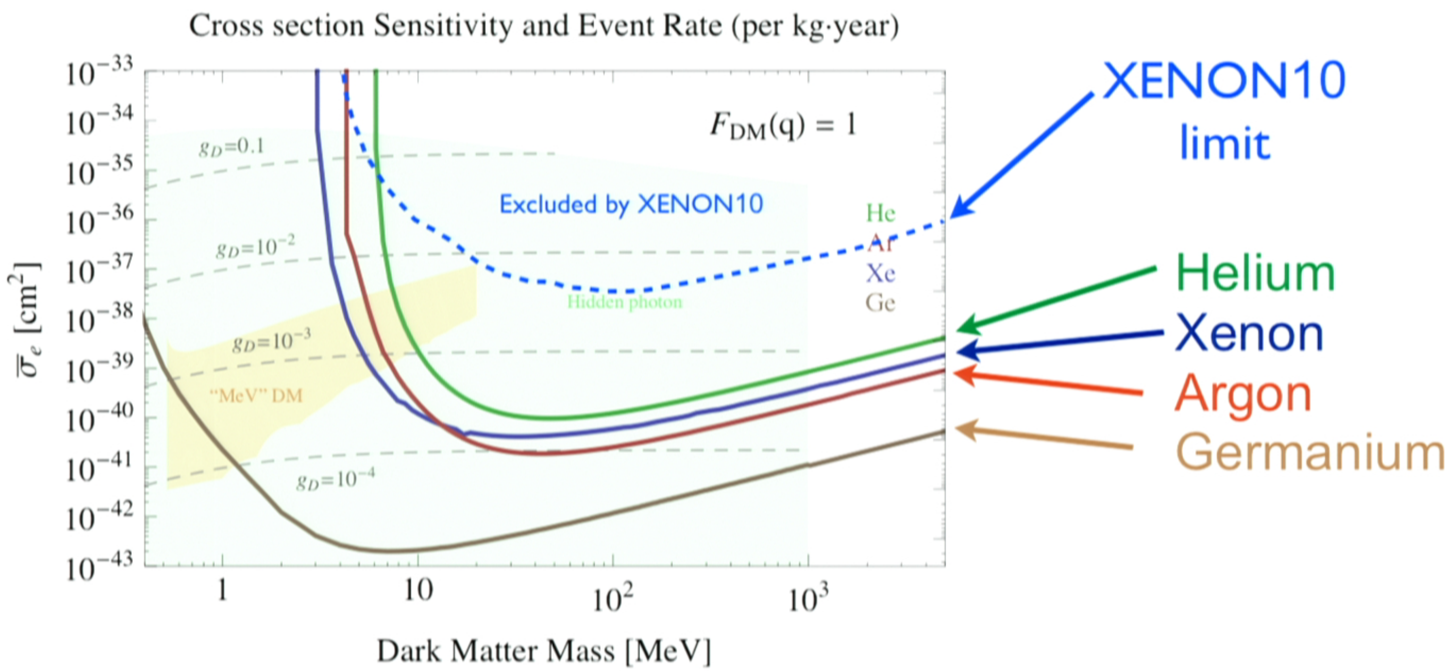

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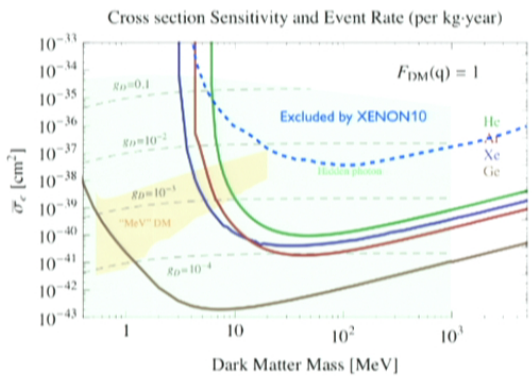

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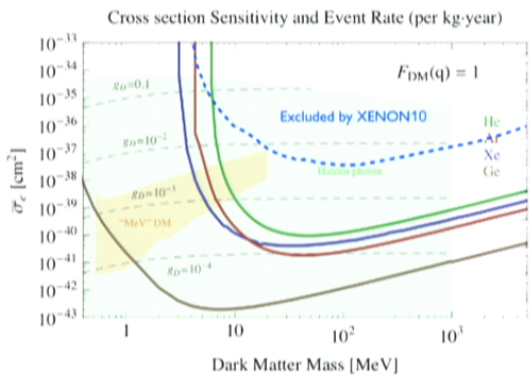

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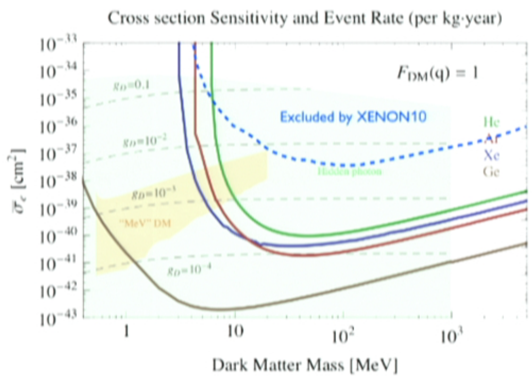

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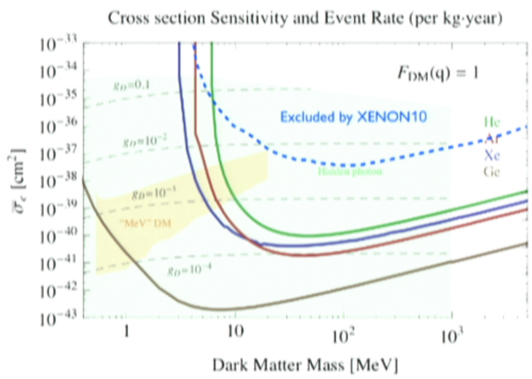

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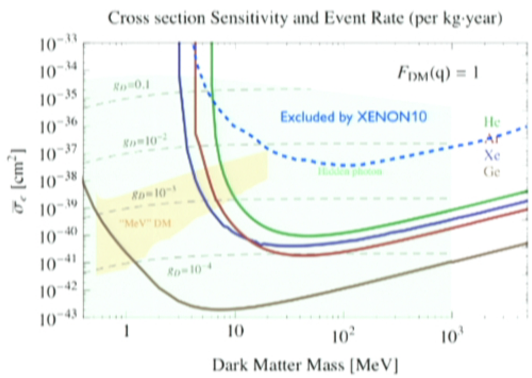

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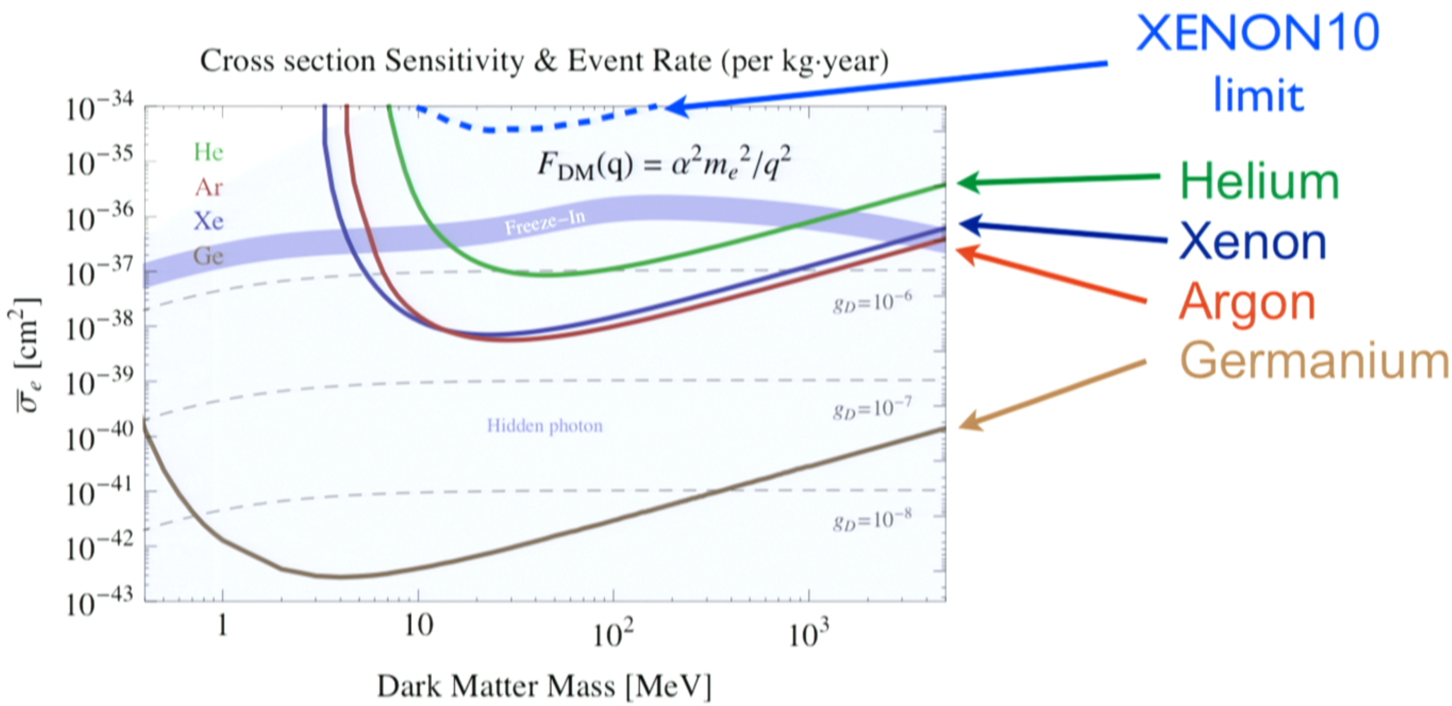

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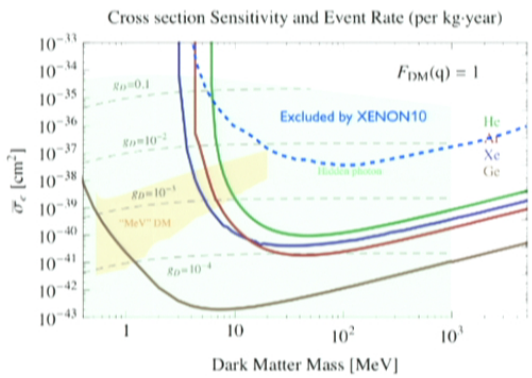

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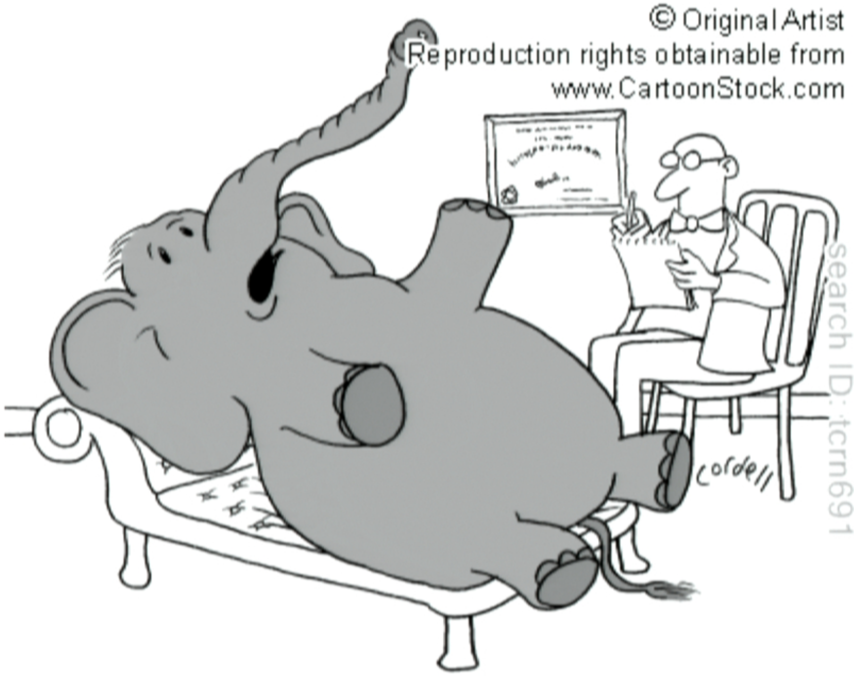

"Whenever I walk in a room, everyone ignores me."

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- Neutrinos
- Radioactive impurities
- Surface events
- Secondary events
- + stuff we haven't thought about …

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Can always use *annual modulation* of DM signal rate

- larger for light DM (~10%) than for WIMPs !
- perhaps not as convincing as once thought (remember DAMA?)
- but still a powerful signal for DM

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