Hunting Down Dark Matter

Cracow School of Theoretical Physics

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Tomer Volansky

(An optimistic) Outline

- Evidence for DM
- The WIMP Miracle
- The Hunt for DM: Experimental Status
    - Collider Bounds
    - Direct Detection
    - Indirect Detection (covered by Alejandro Ibarra)
- Models of DM - Going Beyond the WIMP Scenario
- Direct Detection of sub-GeV DM
- First Direct Detection Limits on sub-GeV DM
- Outlook: Where are we heading?

Evidence for DM

"Facts" for my mother in law..

- It comprises 85% of the matter in our Universe.
- It is made of special, non-baryonic matter.
- It is massive and interacts gravitationally. Can be detected indirectly.
- Stable on cosmological time scales.
- DM does not interact with light, hence "dark".
- It is slow and cold.
- There is one DM particle in a milk box.
- 10^5 DM particles go through us every second.
- ...
- (My mother in law usually falls asleep at this point..)

The Beginning - Coma Cluster

- First observation by Jan Oort in 1932 and then by Fritz Zwicky in 1933.

- Zwicky used the viral theorem:

$$2\langle E_k \rangle = -\langle V_{\text{tot}} \rangle$$

to measure the total gravitational potential and hence the mass in the Coma cluster:

$$2\frac{v^2}{2} \sim \frac{G_N M}{R}$$

$$\Downarrow$$

$$M = \frac{v^2 R}{G_N}$$

- Comparing to the visible light, he found a factor of 400 discrepancy.

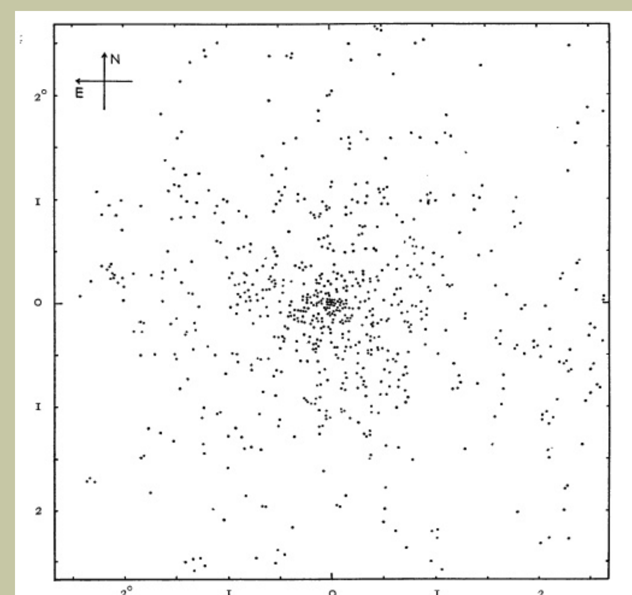


FIG. 3.—The Coma cluster of nebulae

Rotation Curves

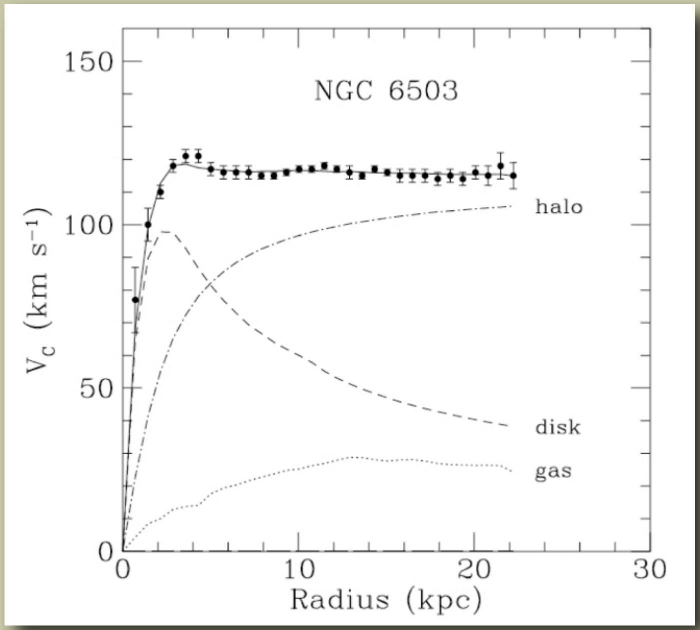
- In the late 60's Vera Rubin studied rotation curves.

- Far from the center, the velocity is expected to drop with the distance:

$$\frac{mv^2}{r} = \frac{G_N m M}{r^2}$$

$$\Downarrow$$

$$v \propto r^{-1/2}$$



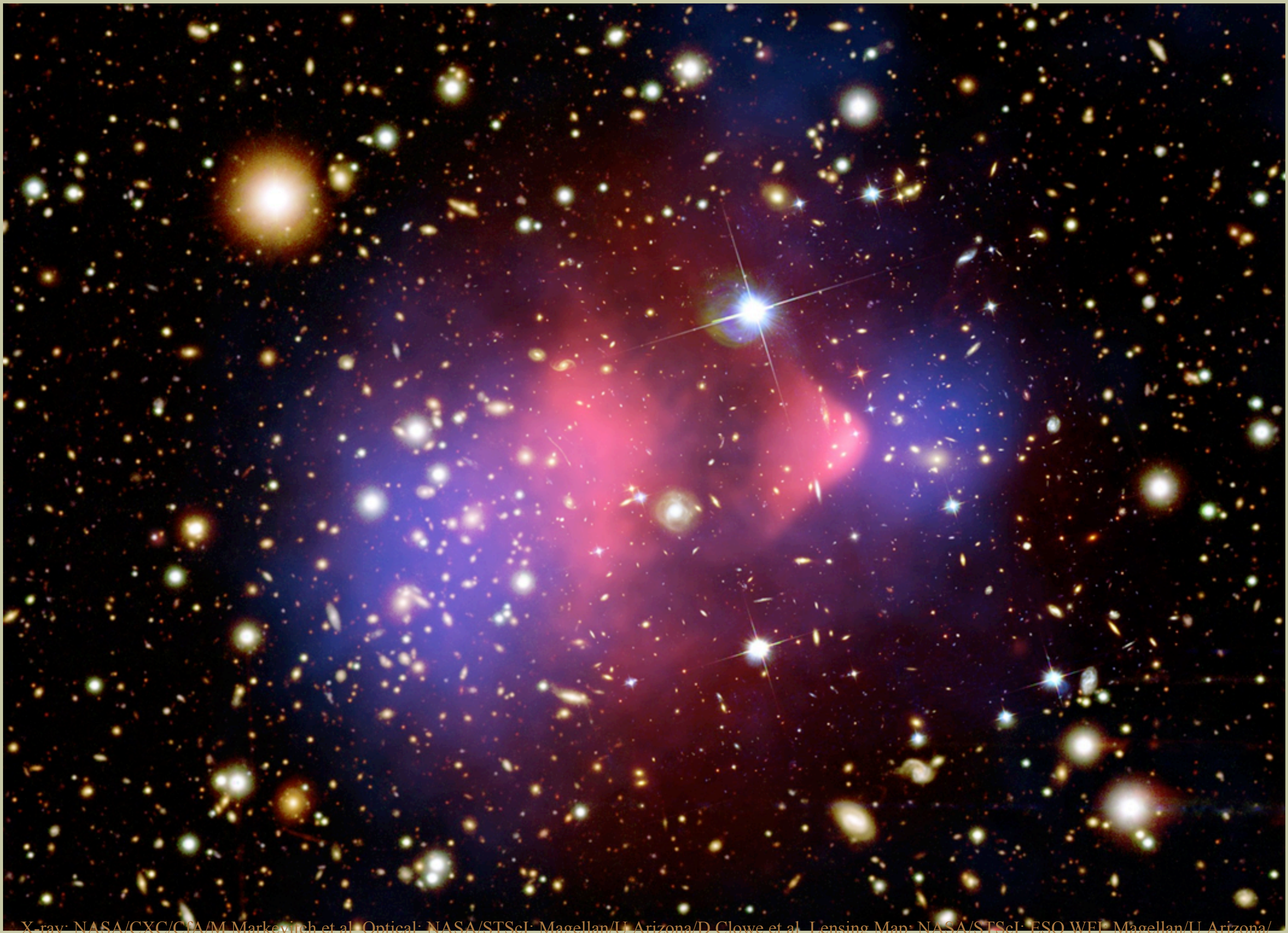
- Rubin found that the velocity is constant so M ∝ r and therefore,

$$M = \int d^3 r \rho(r) \sim \int dr r^2 \rho(r)$$

$$\Downarrow$$

$$\rho(r) \propto r^{-2}$$

The Bullet Cluster



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/

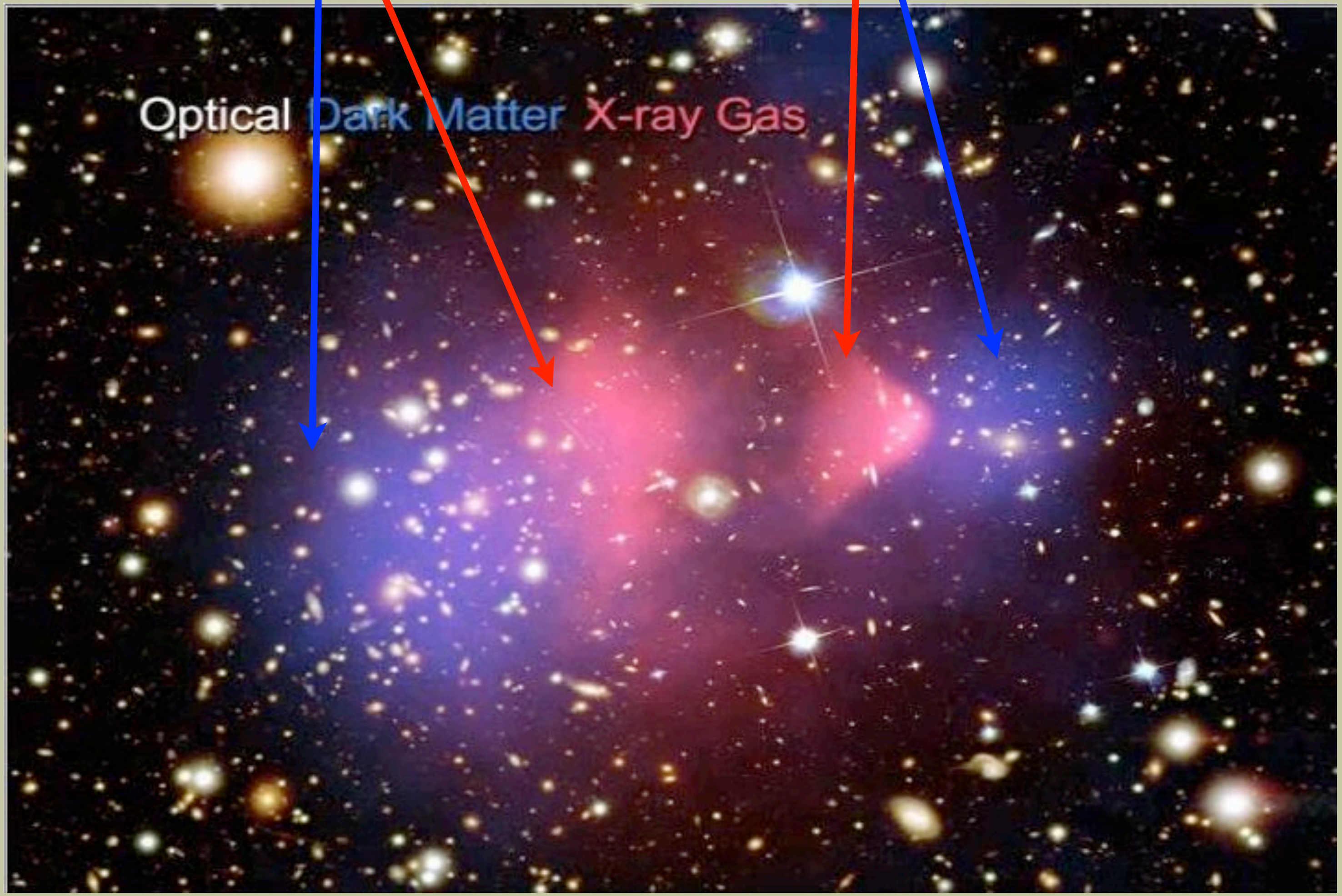
The Bullet Cluster

Composite image: +

90% of ordinary matter is gas, not in galaxies

Determination of mass with weak lensing

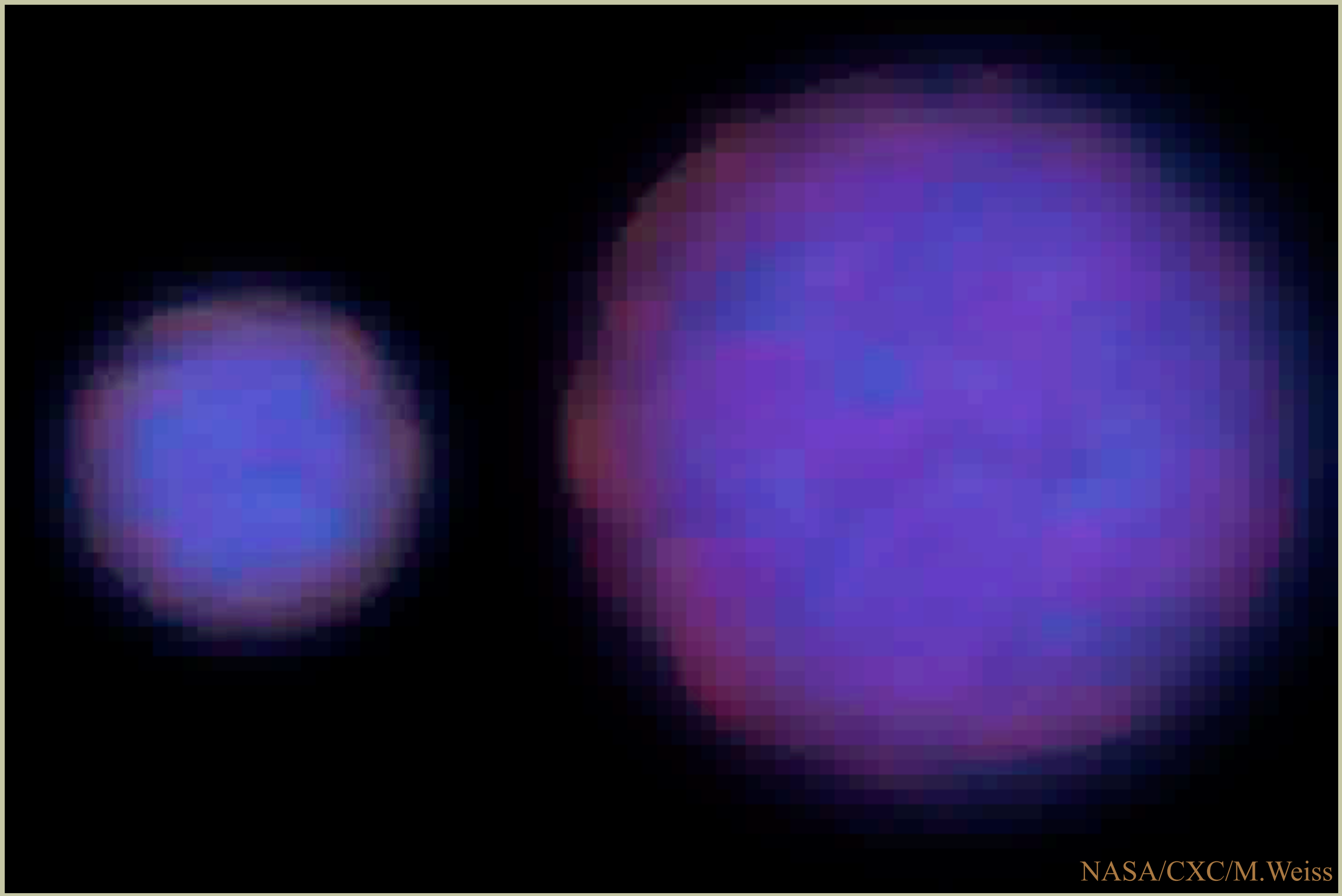
clear separation of gas/mass peaks



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.

The Bullet Cluster

Simulation: visible + dark matter

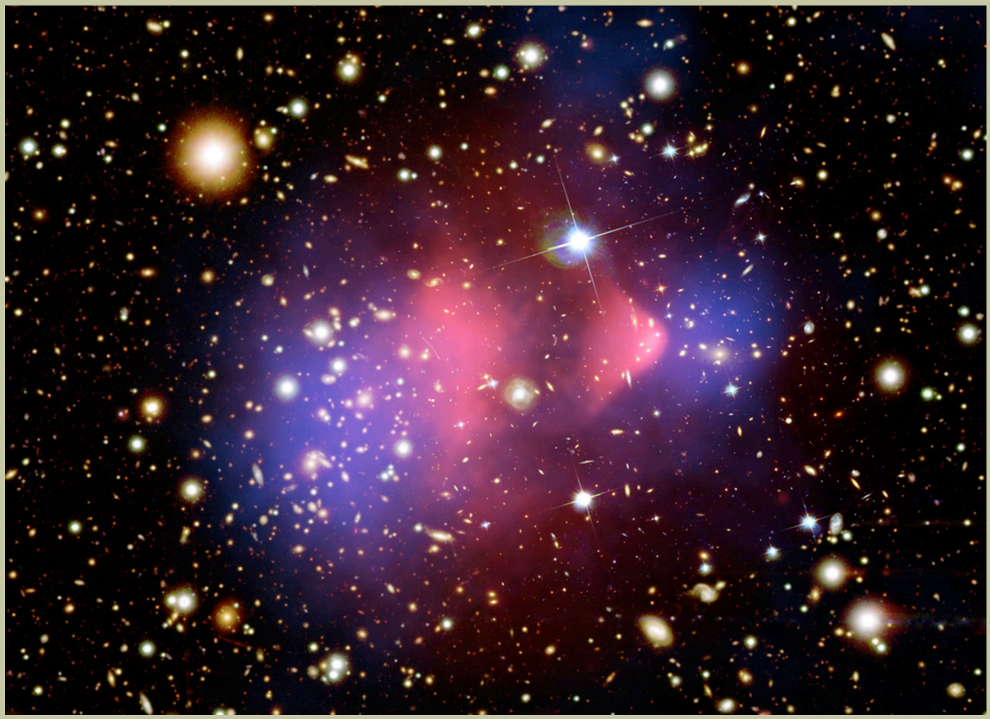


Evidence for DM?

Bullet Cluster

- Always wise to be skeptical..

- Could lensing be affected by unobserved objects along the line of sight? (recent optical spectroscopic surveys of galaxies in the field of the bullet cluster reveal the presence of two smaller systems). [Lazar,Perez,Waxman, in progress]



Big Bang Nucleosynthesis

- The density of light elements is determined during nucleosynthesis at around T~0.1 MeV.

- Elements abundance strongly depend on two things:

    - Baryon density:

$$\eta = \frac{n_b}{n_\gamma} \simeq 6 \times 10^{-10}$$

    - Decoupling temperature between neutrons and protons.

- Imply only 4% baryons in the universe

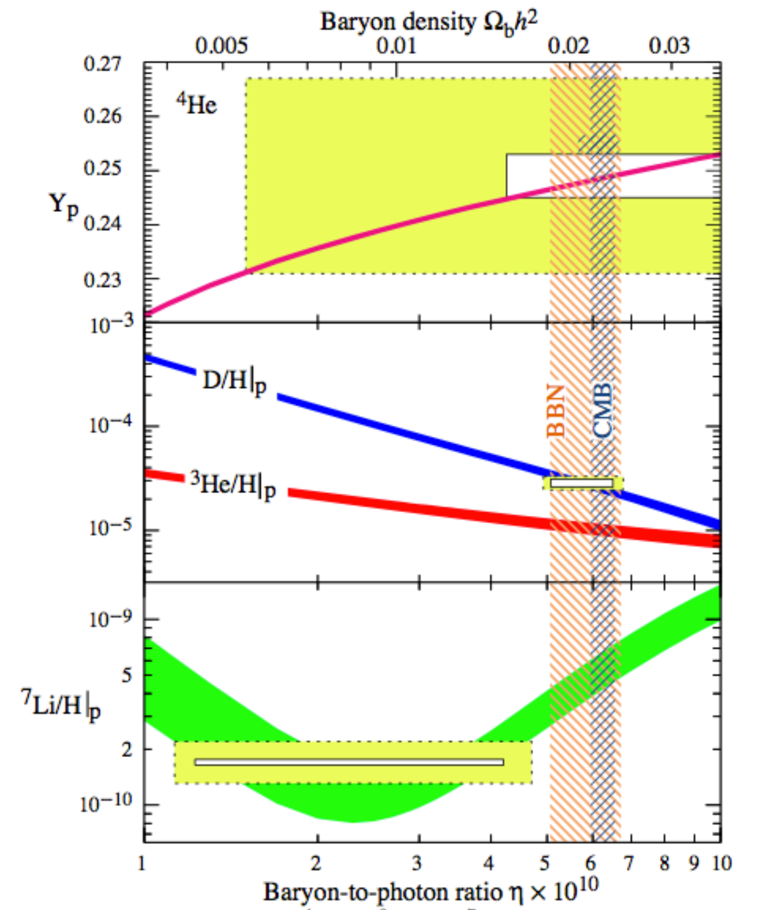
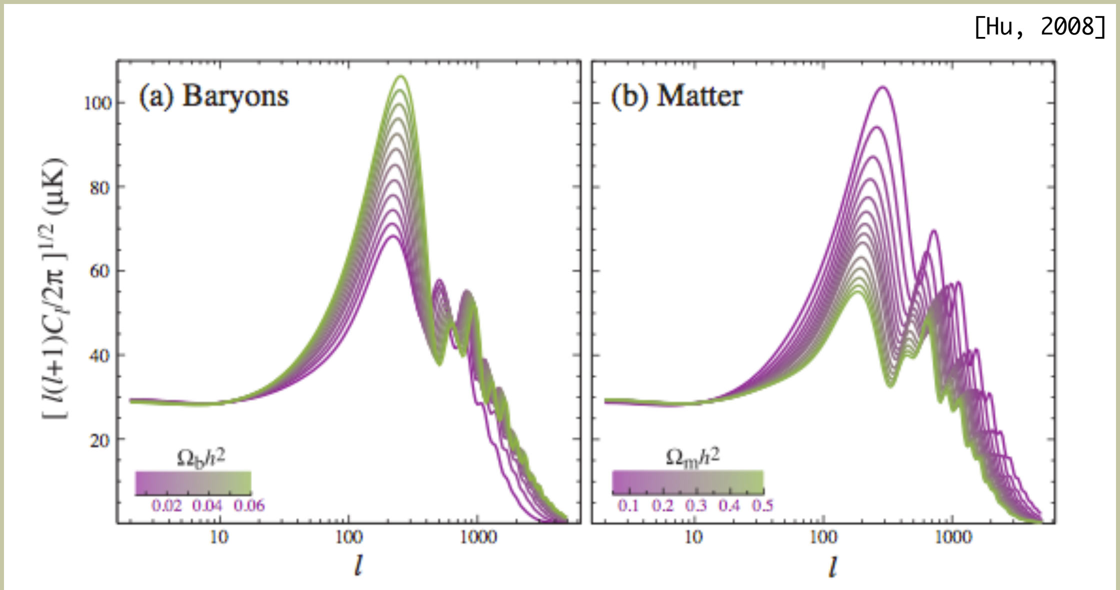
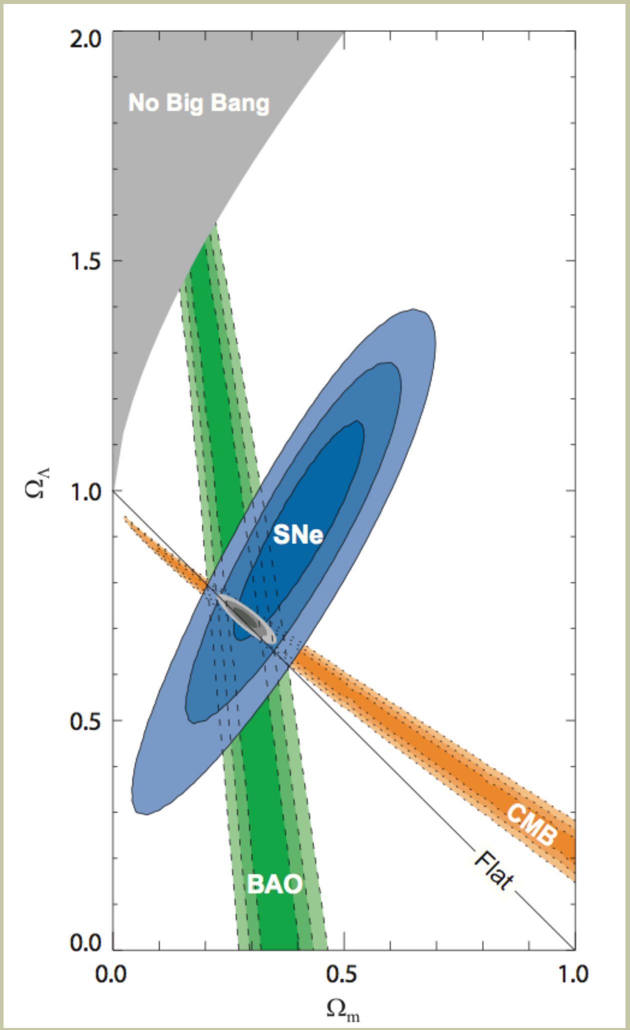


Figure 20.1: The abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis [11] – the bands show the 95% CL range. Boxes indicate the observed light element abundances (smaller boxes: $\pm 2\sigma$ statistical errors; larger boxes: $\pm 2\sigma$ statistical *and* systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% CL). Color version at end of book.

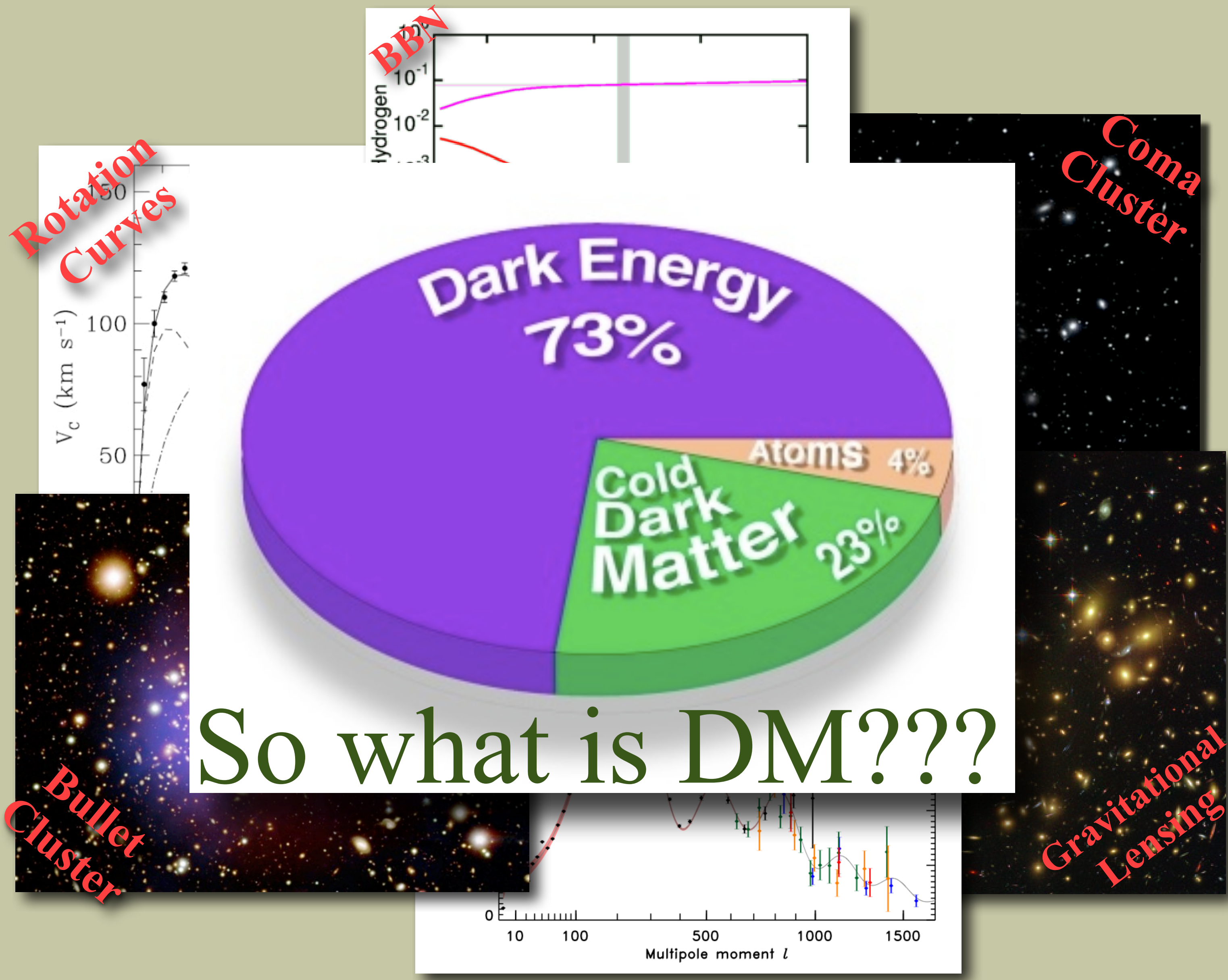
CMB

- Temperature fluctuations in the CMB encodes information about the evolution since recombination (z~1100).
- Fluctuations determine the dark energy, baryonic matter and total matter.





Bottom Line



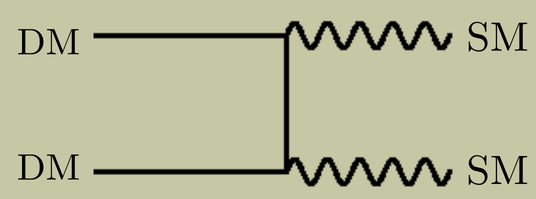
BBN
Rotation Curves
Coma Cluster
Dark Energy 73%
Atoms 4%
Cold Dark Matter 23%
So what is DM???
Bullet Cluster
Gravitational Lensing
Multipole moment l

The WIMP Miracle

The Idea

- Extremely predictive scenario.
- Independent of initial conditions.
- Requirements:
  - DM was in thermal equilibrium in early universe.
  - DM stable on cosmological timescales.
- Annihilations reduce DM density in our Universe:

$$\chi\chi \rightarrow \bar{f}f$$



- Once annihilation rate is slower than Universe expansion rate, DM density freezes out.

A Walkthrough: WIMP Thermal Abundance

- To compute the number density, we use the Boltzmann Equation:

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

Dilution from expansion
$n \propto a^{-3}$

Annihilations

- Dilution behaves the same as dilution of entropy. Indeed assuming an adiabatic expansion:

$$\begin{aligned} & \frac{d}{dt}(a^3 s) = 0 \\ \Rightarrow \quad & a^3 \frac{ds}{dt} + 3\dot{a}a^2 s = 0 \\ \Rightarrow \quad & \frac{ds}{dt} + 3Hs = 0 \end{aligned}$$

- Thus, defining:

$$x = \frac{m_\chi}{T} \qquad\qquad Y = \frac{n_\chi}{s}$$

We can eliminate the dilution due to the expansion. [Recall: $t \simeq \frac{1}{2}H^{-1} \simeq 0.3 g_*^{-1/2} \frac{M_{\mathrm{Pl}}}{T^2}$]

A Walkthrough: WIMP Thermal Abundance

- So the BE:

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

$$\Downarrow$$

becomes:

$$\frac{x}{Y_{\mathrm{eq}}}\frac{dY}{dx} = -\frac{\langle\sigma v\rangle n_{\chi,\mathrm{eq}}}{H}\left(\frac{Y^2}{Y_{\mathrm{eq}}^2} - 1\right)$$

- Two relevant limits:

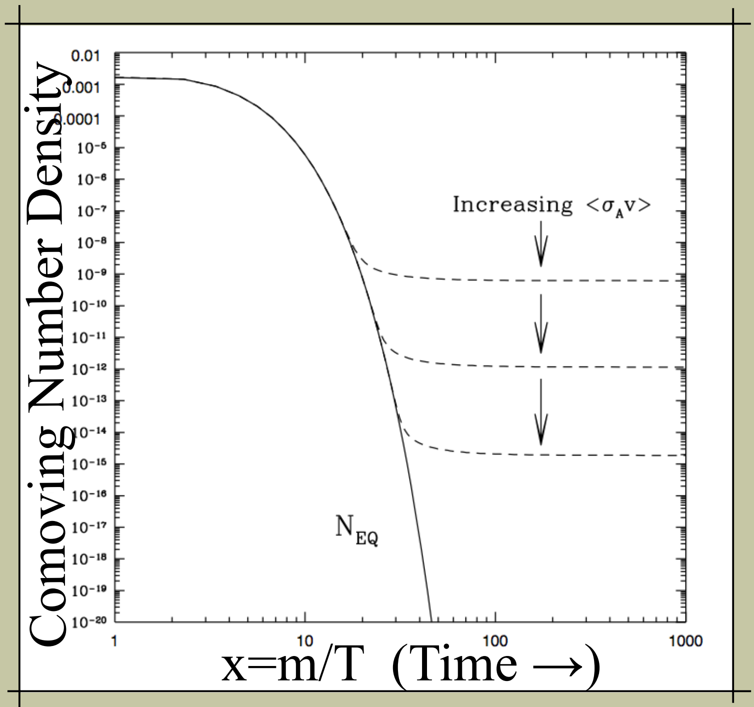
$$n_{\chi,\mathrm{eq}}\langle\sigma v\rangle \ll H \qquad Y \sim Y_{\mathrm{eq}}$$

$$n_{\chi,\mathrm{eq}}\langle\sigma v\rangle \ll H \qquad Y \sim \text{ const}$$

- The constant depends on when the decoupling:

$$n_{\chi,\mathrm{eq}}\langle\sigma v\rangle = H$$

occurs.



A Walkthrough: WIMP Thermal Abundance

- So we can approximate the solution to the BE by solving

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

- Use:

$$n_{\rm eq} \simeq g \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T} = \frac{g m_\chi^3}{(2\pi)^{3/2}} x^{-3/2} e^{-x}$$

$$H \simeq 1.66\sqrt{g_*}\frac{T^2}{M_{\rm Pl}} = 1.66\sqrt{g_*}x^{-2}\frac{m_\chi^2}{M_{\rm Pl}}$$

$$\langle \sigma v \rangle = \sigma_0 x^{-n}$$

- Plugging in:

$$x_f^{\frac{1}{2}-n} e^{-x_f} \simeq 1.66 (2\pi)^{3/2} \frac{g_*^{1/2}}{g} \frac{1}{M_{\rm Pl}\sigma_0 m_\chi}$$

$$\Longrightarrow \qquad x_f \simeq \ln\left[\frac{g}{g_*^{1/2}} M_{\rm Pl}\sigma_0 m_\chi\right] \simeq 25$$

- Freeze-out temperature only weekly dependent on the cross-section or the DM mass.

A Walkthrough: WIMP Thermal Abundance

- Since $mv^2 = 3\ k_B\ T$, the above implies v_f~0.3. So DM decouples non-relativistically, when it's cold.

- Going back to the BE, we can derive the DM number density at freeze-out:

$$n_f = \frac{H(x = x_f)}{\langle \sigma v \rangle} = 1.66 \sqrt{g_*} x_f^{n-2} \frac{m_\chi^2}{\sigma_0 M_{\rm Pl}}$$

And today:

$$n_0 = n_f \frac{T_0^3}{T^3} = n_f \frac{s_0}{c g_{*s}} \frac{x_f^3}{m_\chi^3} \simeq 3.8 \frac{\sqrt{g_*}}{g_{*s}} x_f^{n+1} \frac{s_0}{m_\chi \sigma_0 M_{\rm Pl}} \qquad c = \frac{2\pi^2}{45}$$

- Using for non-relativistic species:

$$\Longrightarrow x_f \simeq \ln \left[\frac{g}{g_*^{1/2}} M_{\rm Pl} \sigma_0 m_\chi \right] \simeq 25$$

The mass density today is therefore

$$\Omega_\chi \propto \frac{\sqrt{g_*}}{g_{*s}} x_f^{n+1} \frac{s_0}{\sigma_0 M_{\rm Pl} \rho_c}$$

The Thermal WIMP

- There are only a few parameters: $m_{\rm DM},\ \langle\sigma v\rangle,\ M_{\rm Pl}$

- A simple analysis shows,

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

- For standard annihilation cross-section:

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

The LHC may therefore produce the WIMP

Why TeV? The Fine Tuning Problem

Why is gravity so weak?

=

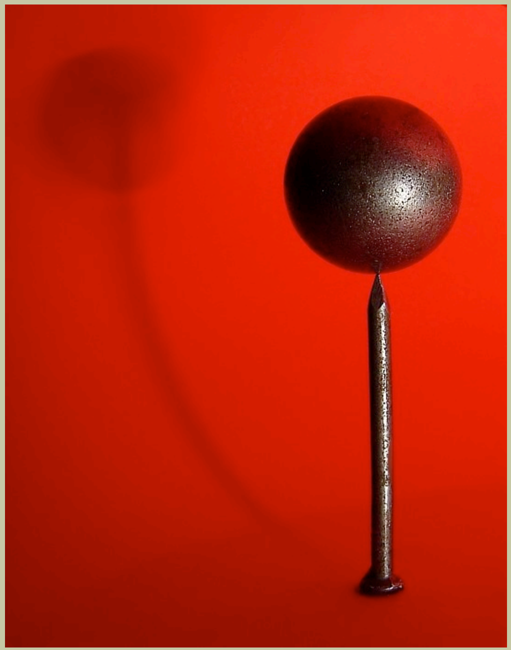
Why is the electron so light?

Weak Force	$\sim 10^{-5}$
Gravitational Force	$\sim 10^{-38}$

Why TeV? The Fine Tuning Problem

- The quantum prediction for the mass of the elementary particles is

$$m_W \sim M_p \sim 10^{19}\ \text{GeV}$$



Within the SM, the parameters must be tuned to one part in 10^{32}!

Where do WIMPs come from?

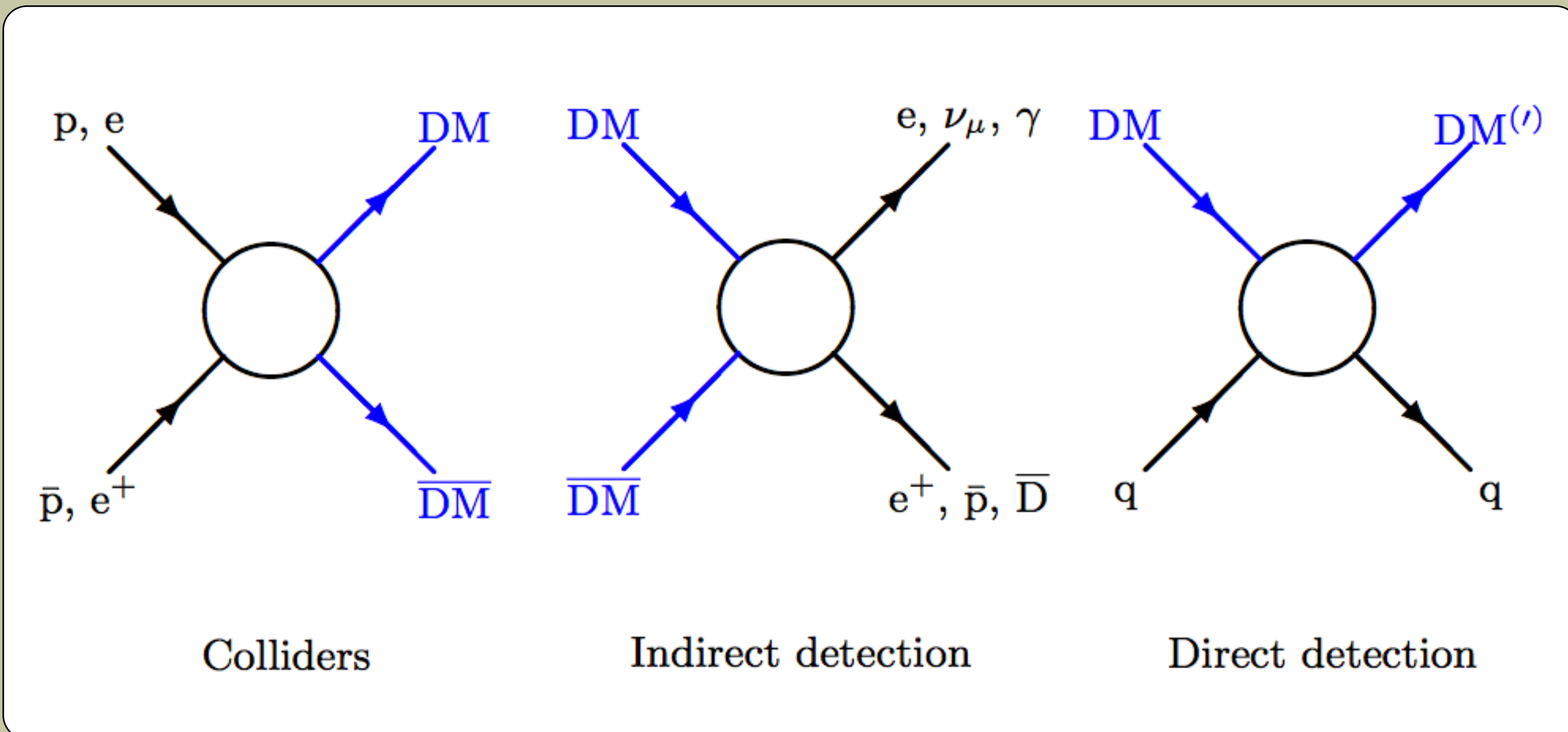
WIMPs are predicted by theories beyond the SM that address the fine tuning problem.

- For example, in SUSY:
  - Lightest superpartner is stable ⇒ Dark Matter.
  - It is in thermal equilibrium with SM at early Universe.
  - Same Weak-scale mass required to resolve fine tuning, produces correct relic abundance.

Experimental Status
Bounds from Colliders

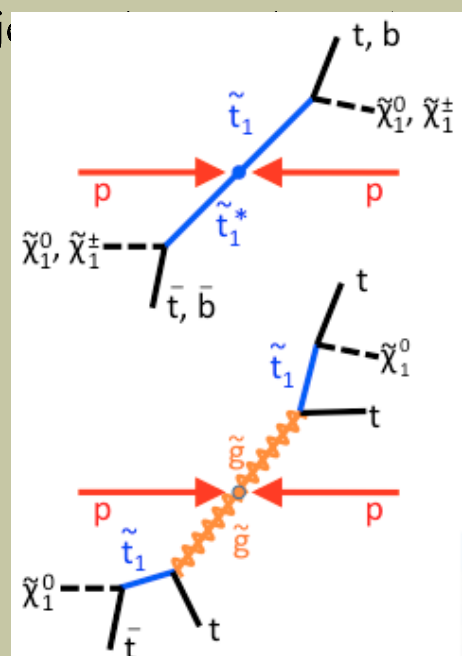
Detecting DM

- Three ways to detect DM:



DM at the Tevatron and LHC

- If DM is light enough and interacts strongly enough with ordinary matter, it can be produced at colliders.
- As we mentioned, solutions to the fine tuning problem predict, in many cases, a dark matter particle, which will be produced.
- Searches may be implemented in two ways:
  - Model dependent (e.g. search for cascade events with MET).
  - Model independent (monoj



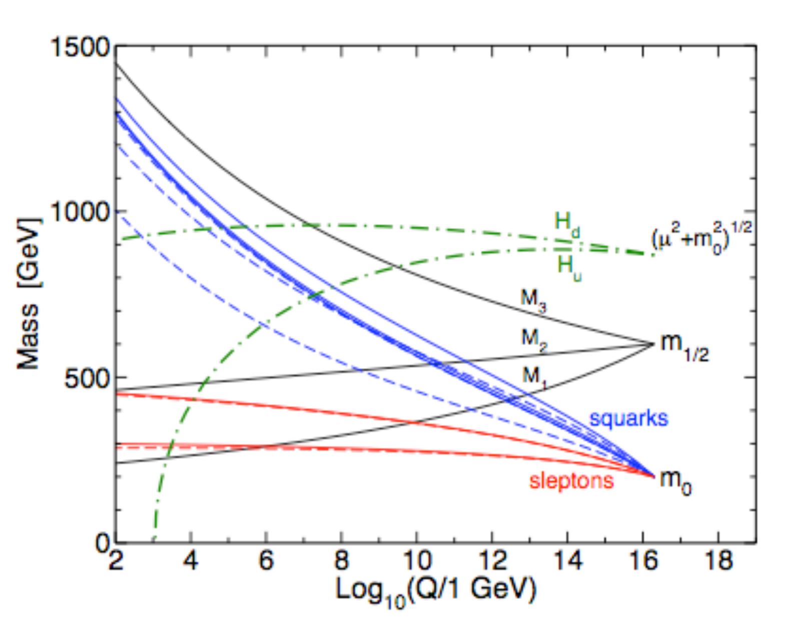
Collider Constraints: SUSY DM

- There are many model-dependent bounds from the LHC.
- To demonstrate, let's choose one of the **least** motivated, but **most** studied scenario: mSUGRA.
- The model is defined by five parameters:

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$$

- Spectrum is determined by RGEs
- DM can be one of the neutralinos:

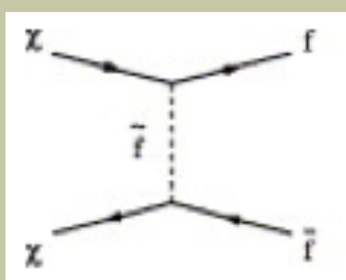
$$(\tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d)$$

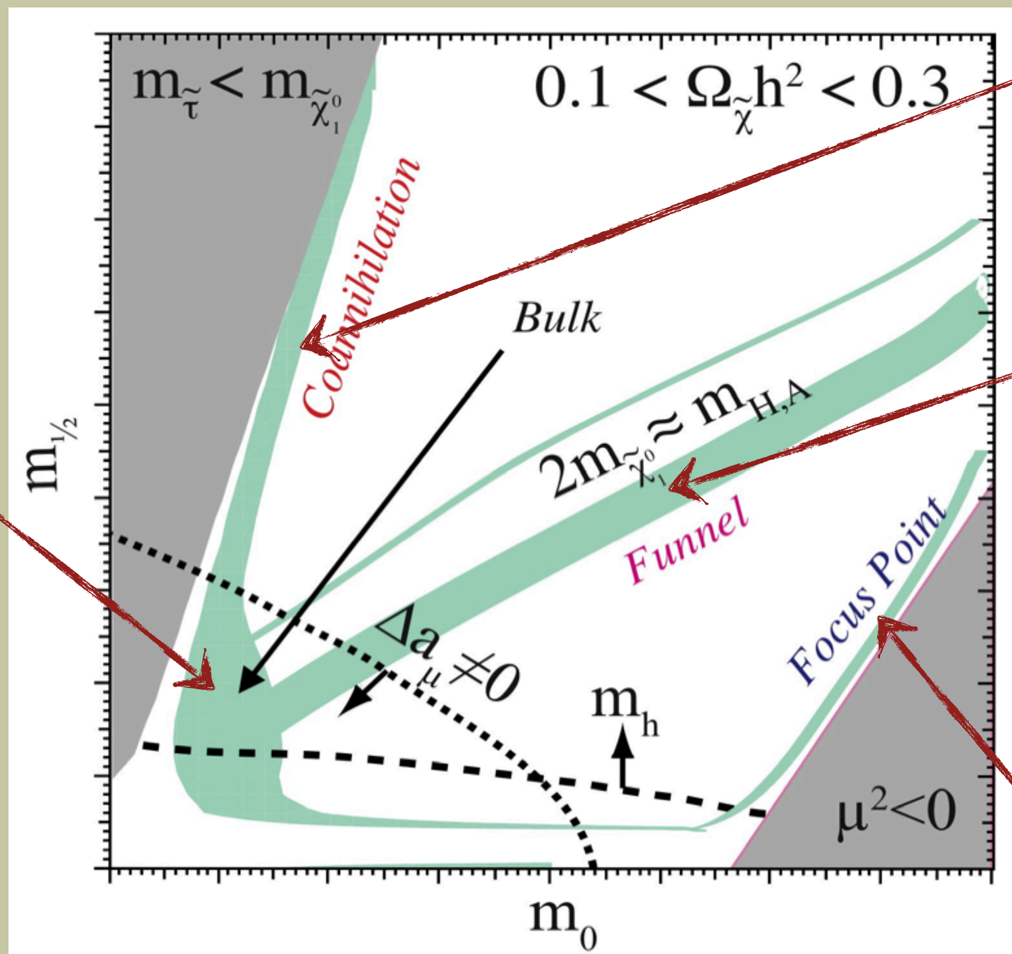


Collider Constraints: SUSY DM

- The correct relic abundance is obtained in several regions with enhanced annihilations.

Mostly Bino which annihilates through a slepton. Requires light slepton excluded by LEP long ago.





Degenerate neutralino and stau. Annihilation rate enhanced.

Annihilation enhanced via intermediate heavy CP-odd Higgs [large tan(beta)]

Relative large mixture of Higgsino-Bino. Annihilation enhanced through a charged Higgs.

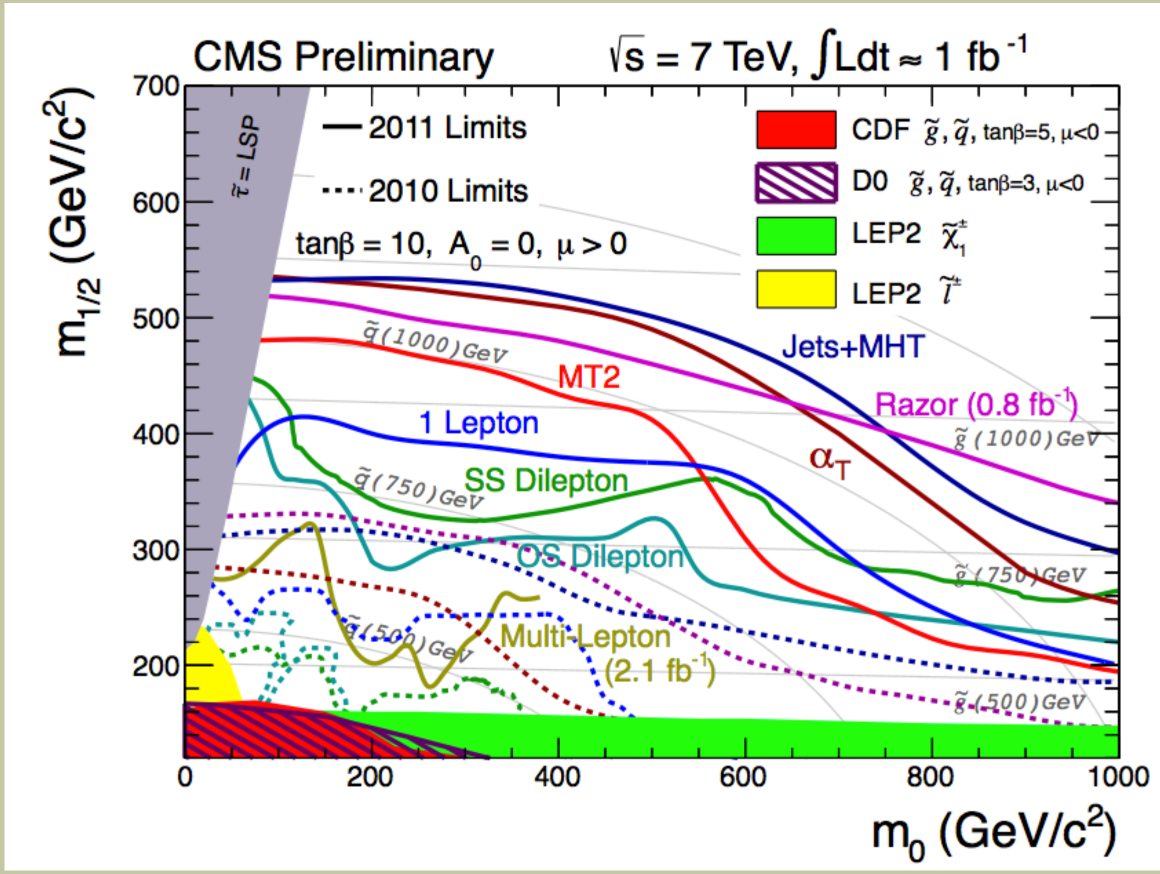
Most of the mSUGRA parameter lies outside the preferred region!

Collider Constraints: SUSY DM

- Recent LHC constraints on the mSUGRA parameter space imply that most of the neutralino-only DM scenario is excluded.

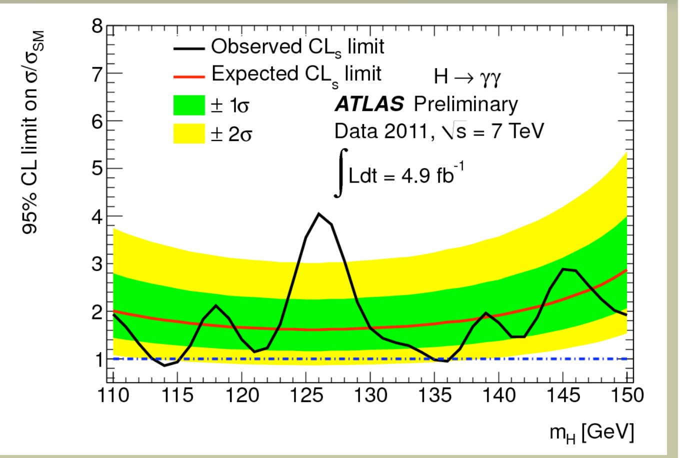
- Coannihilation and funnel regions pushed to more tuned regions.

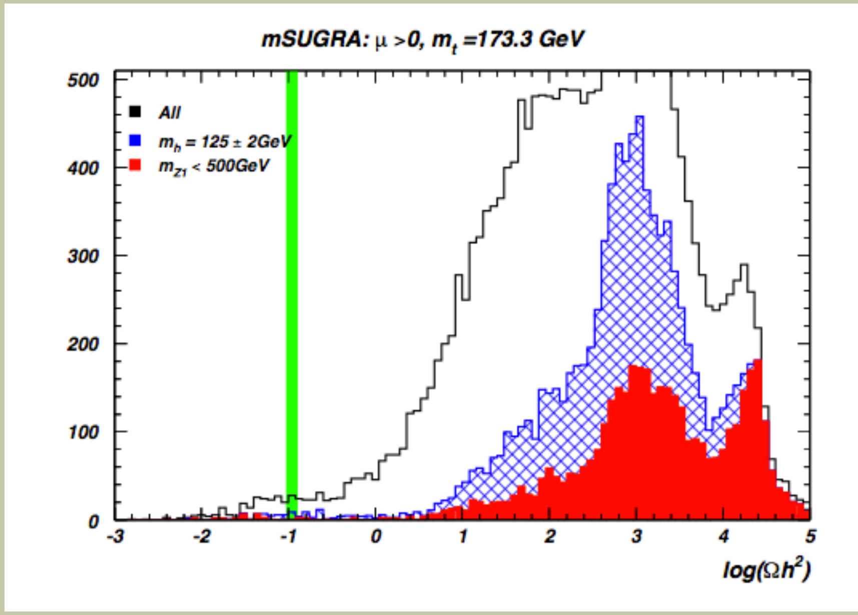
- Focus point relatively untouched due to large squark masses.

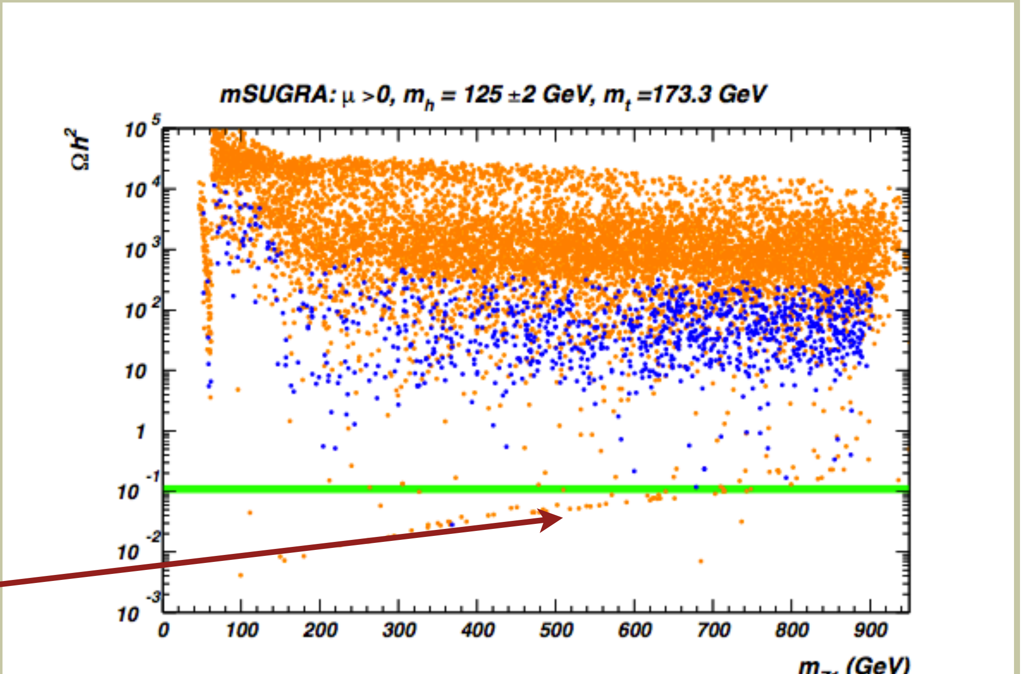


Collider Constraints: SUSY DM

- The hints for a 125 GeV Higgs place additional sever constraints, leaving more or less only the focus points and very little coannihilations.







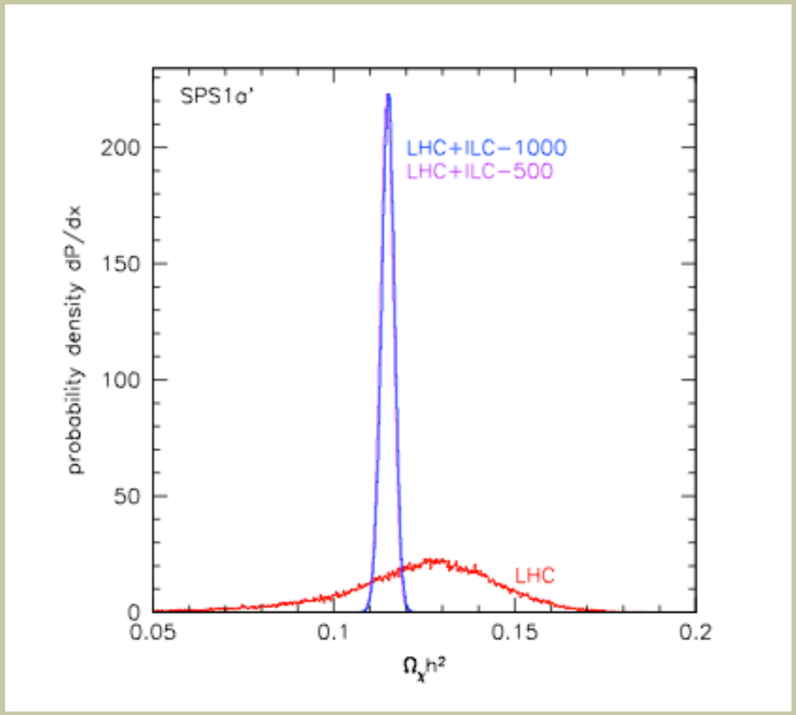
[Baer et al., 2012]

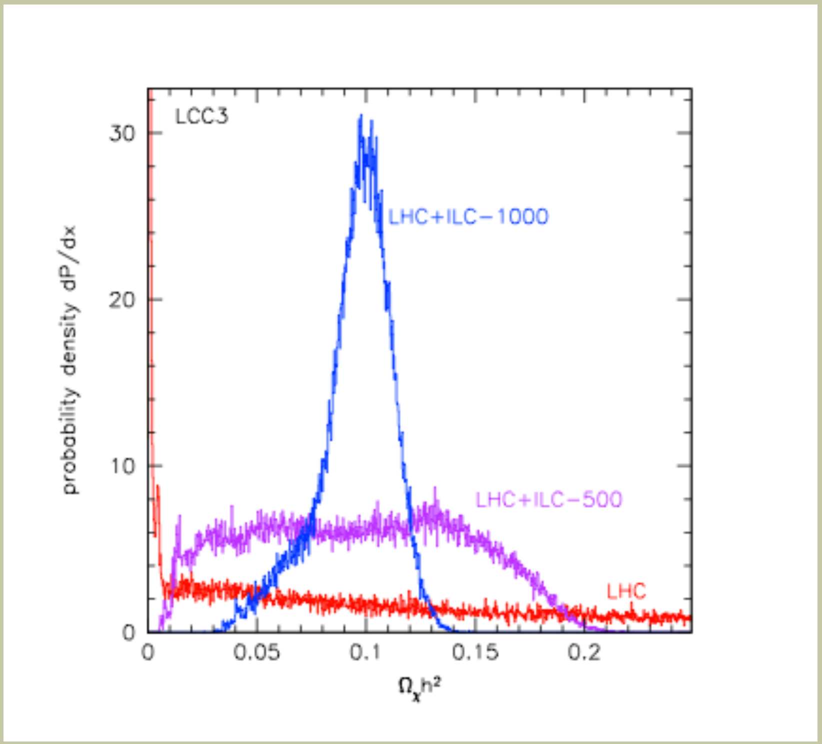
Focus points with m_0>5 TeV

Can We Discover DM at Colliders?

- One should remember that if excess of MET events is to be found at the LHC, it would still not allow us to draw clear conclusions as to the identity of DM.

- Assuming a given spectrum, one can ask how well will we be able to conclude that DM is seen.





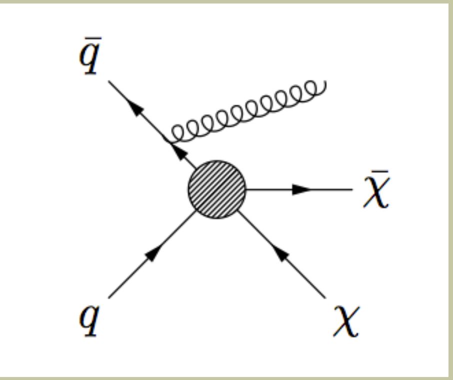
[Baltz,Battaglia,Peskin,Wizansky. 2006]

So should we care about mSUGRA?
(or any specific model-dependent bound..)

Model Independent Constraints

[Cao et al.; Agrawal et al.; Goodman et al.; Bai et al.; Kopp; Rajaraman et al.; Birkedal et al.; Borodatchenkova; Fox et al.; Gershtein et al;...]

- If DM couples to SM particles, it can, in principle, be produced directly. The only guaranteed type of events are those with MET + something.
- DM may couple to:
  - Leptons: monophotons @ LEP and B-factories.
  - Light quarks: monojets @ LHC and Tevatron.
  - Heavy flavor: Upsilon decay @ B-factories.
  - Higgs: Invisible Higgs decay @ LHC.



- B-factories can only probe light DM, but the luminosity is huge!
- Idea: Use effective field theory to constrain possible operators.

Model Independent Constraints

- The virtue of searching for monophotons and monojets is that they allow for an (almost) model-independent analysis, using Effective Field Theory (EFT).
- Consider as an example DM couplings to quarks and/or gluons.
- Some of these operators would induce spin-dependent couplings and velocity- or momentum-suppressed at direct detection, however this does not affect strongly the production at colliders.
- Small inelastic splittings between DM states is also unimportant here as opposed to direct detection.
- Finally, colliders can probe the light mass region, below the capabilities of direct detection.

Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\mu\nu}q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar\chi\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar\chi\chi\bar q q$	$m_q/2M_*^3$
M2	$\bar\chi\gamma^5\chi\bar q q$	$im_q/2M_*^3$

Name	Operator	Coefficient
M3	$\bar\chi\chi\bar q\gamma^5 q$	$im_q/2M_*^3$
M4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	$m_q/2M_*^3$
M5	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/2M_*^2$
M6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/8M_*^3$
C1	$\chi^\dagger\chi\bar q q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar q\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar q q$	$m_q/2M_*^2$
R2	$\chi^2\bar q\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^2$

[Goodman et al., 2010]

Model Independent Constraints

- Focus on a few channels.
- In UV theory: $\Lambda = \dfrac{M}{\sqrt{g_f g_\chi}}$
- Procedure:
  - Simulate events for a given operator and background.
  - Compare to data
  - Set limits.

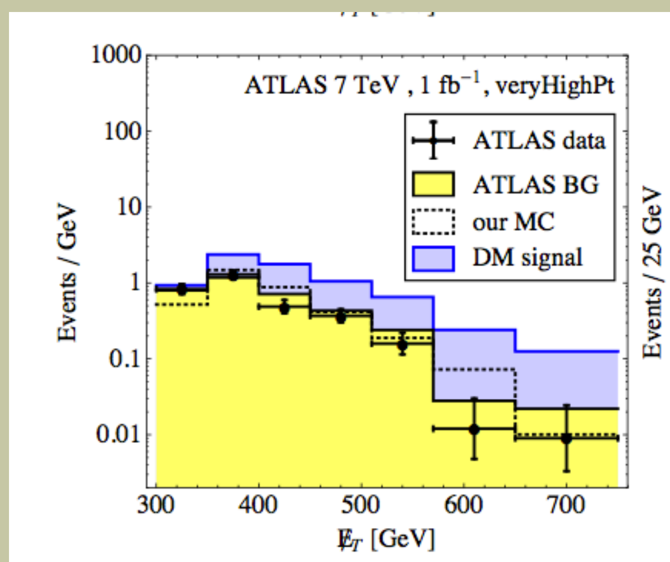
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{f}\gamma^\mu f)}{\Lambda^2},$$

$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{f}f)}{\Lambda^2}$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu\gamma_5 f)}{\Lambda^2}$$

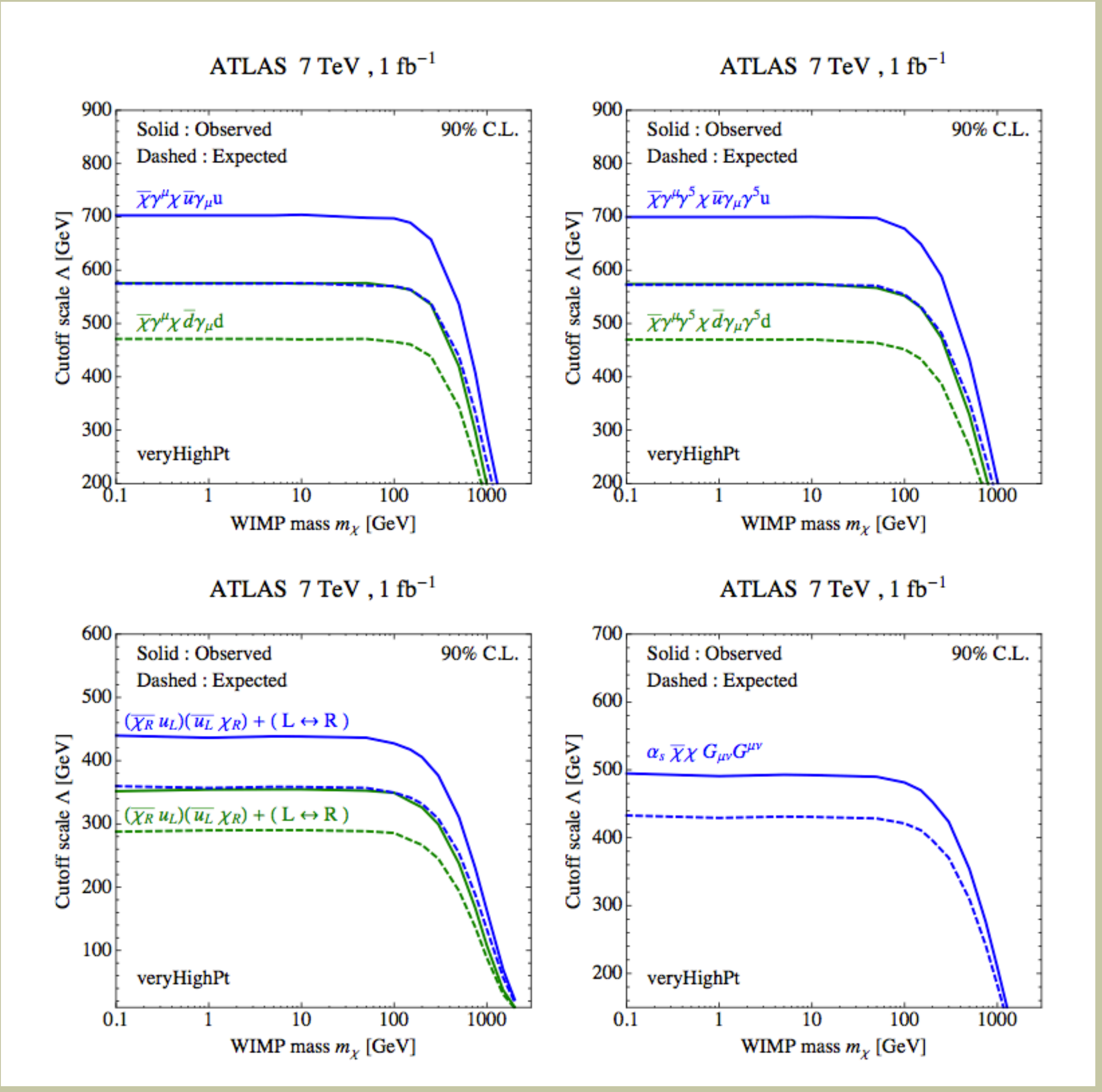
$$\mathcal{O}_t = \frac{(\bar{\chi}P_L f)(\bar{f}P_R\chi)}{\Lambda^2} + (L \leftrightarrow R),$$

$$\mathcal{O}_g = \frac{\alpha_s(\bar{\chi}\chi)(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^2}$$



[Fox et al., 2011]

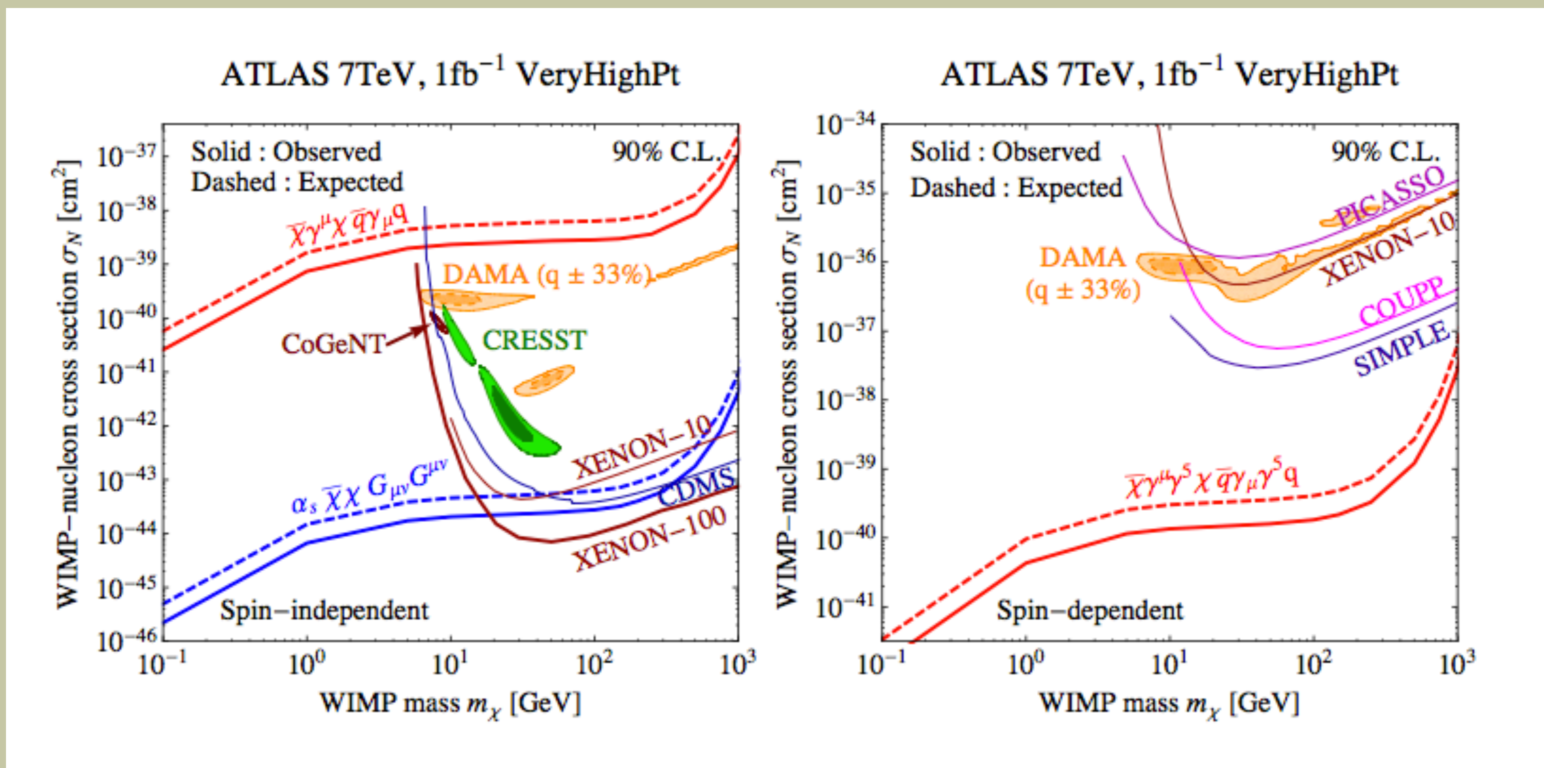
Model Independent Constraints



[Fox et al., 2011]

Model Independent Constraints

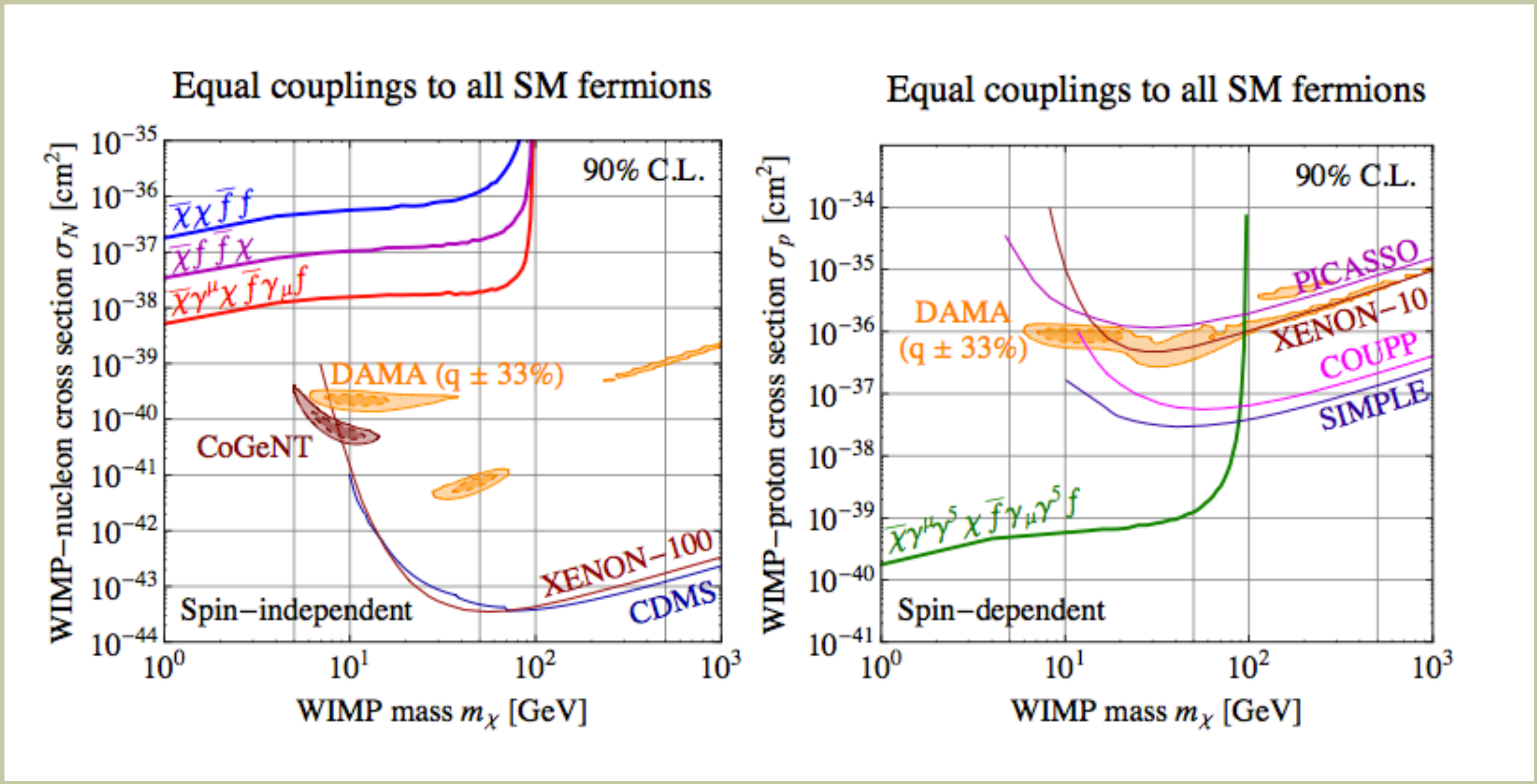
- Given an operator, one can compute the DM-nucleon cross-section, and compare the constraints to those from direct detection (to be discussed soon..).



[Fox et al., 2011]

Model Independent Constraints

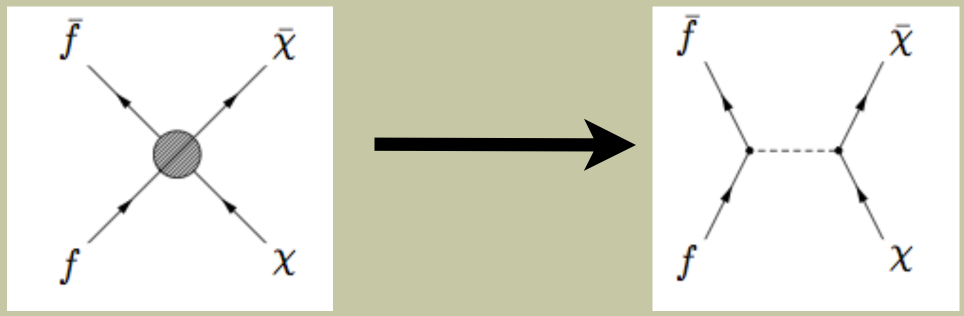
- Similar results from LEP, with couplings to leptons.



[Fox et al., 2011]

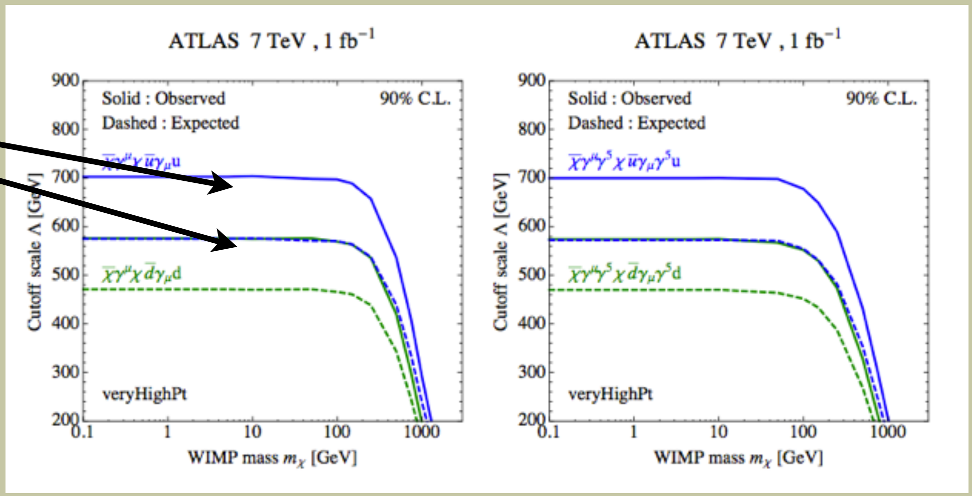
Model Independent Constraints??

- When does the EFT breaks down? If the particles integrated out to produce the effective theory are too light, they would be directly produced and the bounds deteriorate.



- Typical bounds are of order Λ~500 GeV, while center of mass energy is s~(7 TeV)² so for M> 5 TeV one requires g>~5-10. $(\Lambda = \frac{M}{\sqrt{g_f g_\chi}})$

- So really, there should be a band here:



Model Independent Constraints??

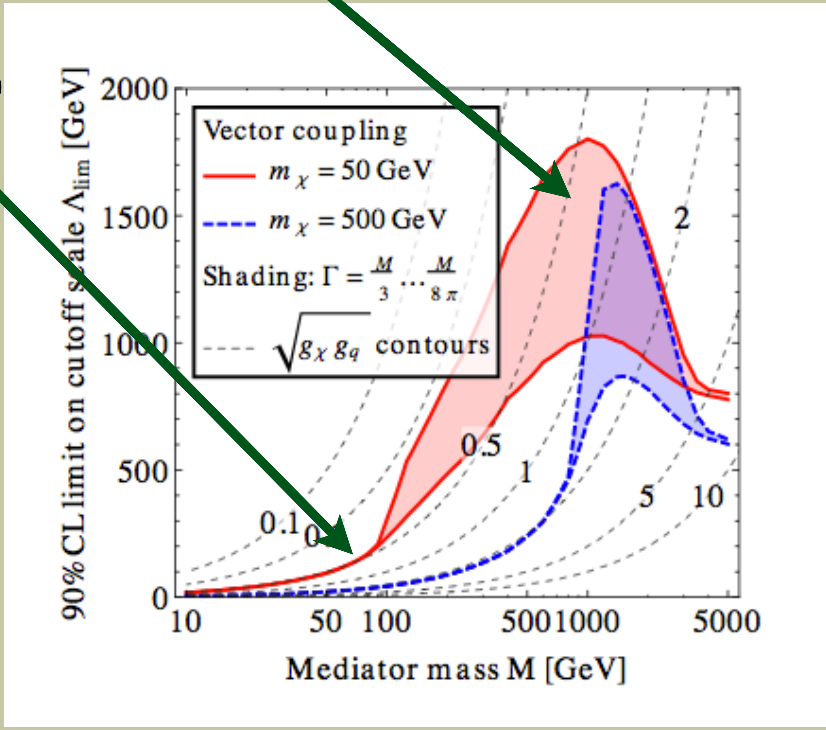
- However bounds on model dependence could be stronger:

$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$

- For M~q (~100's of GeV at LHC) production is enhanced.

- At low mediator mass, M, there's no bound since mediator does not decay to DM (MET)

  In that case, need to go back to model-dependent searches.

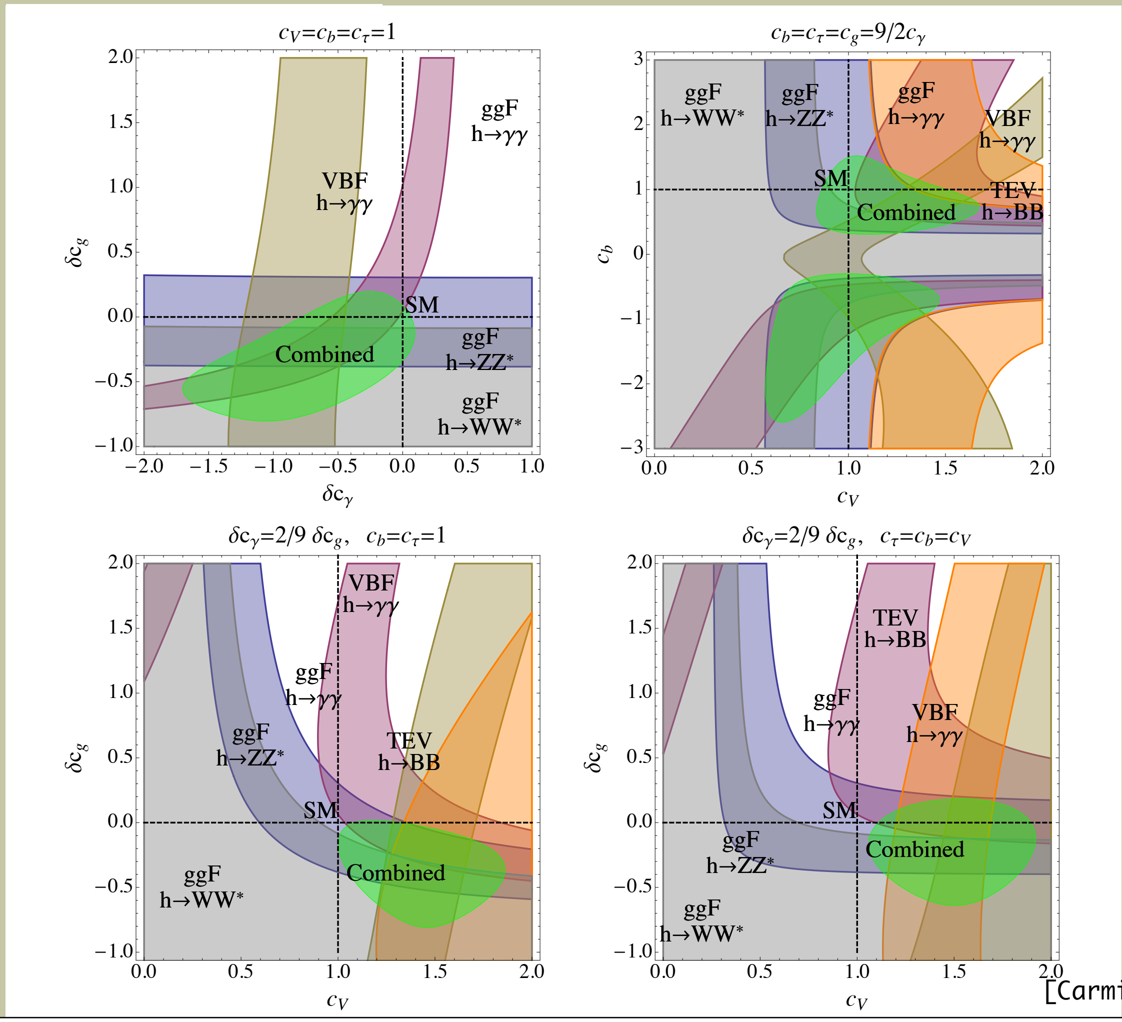


Still lots of work for us model builders...

Invisible Higgs Decays

- Typical SM searches for the Higgs place stringent bounds on the effective Higgs couplings,

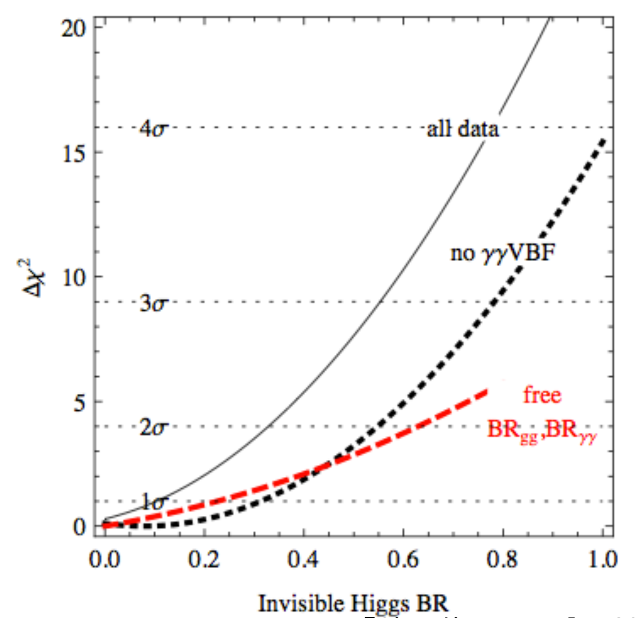
$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h Z_\mu Z_\mu - c_b \frac{m_b}{v} h\bar{b}b - c_\tau \frac{m_\tau}{v} h\bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h A_{\mu\nu} A_{\mu\nu} + c_{\rm inv} \frac{m_\chi}{v} h\bar{\chi}\chi + \ldots$$



[Carmi,Falkowski,Kuflik,TV, 2012]

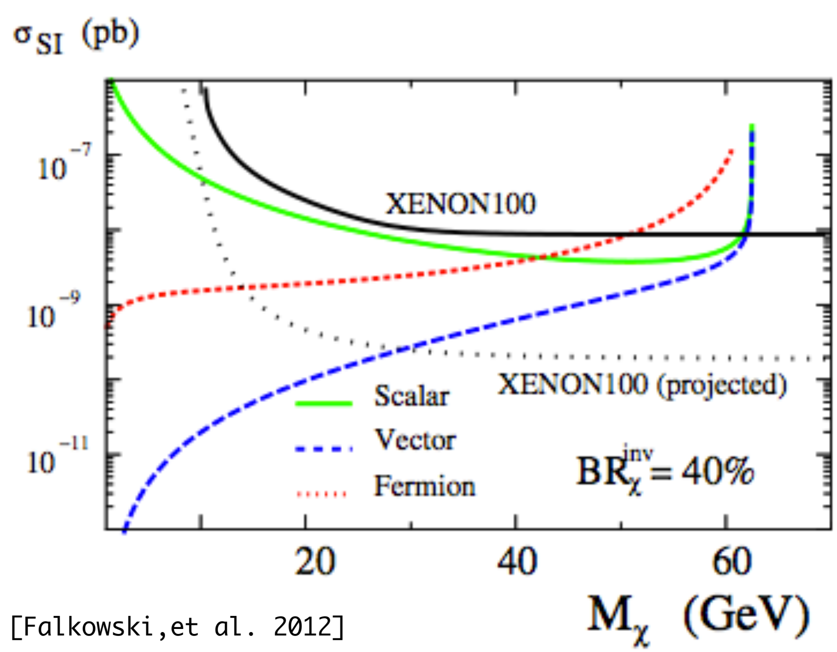
Invisible Higgs Decays

- One can also constrain c_{inv}. A global fit gives:



[Giardino,et al. 2012]

- Relating the invisible to direct detection one finds



[Falkowski,et al. 2012]

$$BR_S^{inv} \simeq \frac{\left(\frac{\sigma_{Sp}^{SI}}{10^{-9}\mathrm{pb}}\right)}{400\left(\frac{10\ \mathrm{GeV}}{M_S}\right)^2 + \left(\frac{\sigma_{Sp}^{SI}}{10^{-9}\mathrm{pb}}\right)}$$

$$BR_V^{inv} \simeq \frac{\left(\frac{\sigma_{Vp}^{SI}}{10^{-9}\mathrm{pb}}\right)}{4\times 10^{-2}\left(\frac{M_V}{10\ \mathrm{GeV}}\right)^2 + \left(\frac{\sigma_{Vp}^{SI}}{10^{-9}\mathrm{pb}}\right)}$$

$$BR_f^{inv} \simeq \frac{\left(\frac{\sigma_{fp}^{SI}}{10^{-9}\mathrm{pb}}\right)}{3.47 + \left(\frac{\sigma_{fp}^{SI}}{10^{-9}\mathrm{pb}}\right)}$$

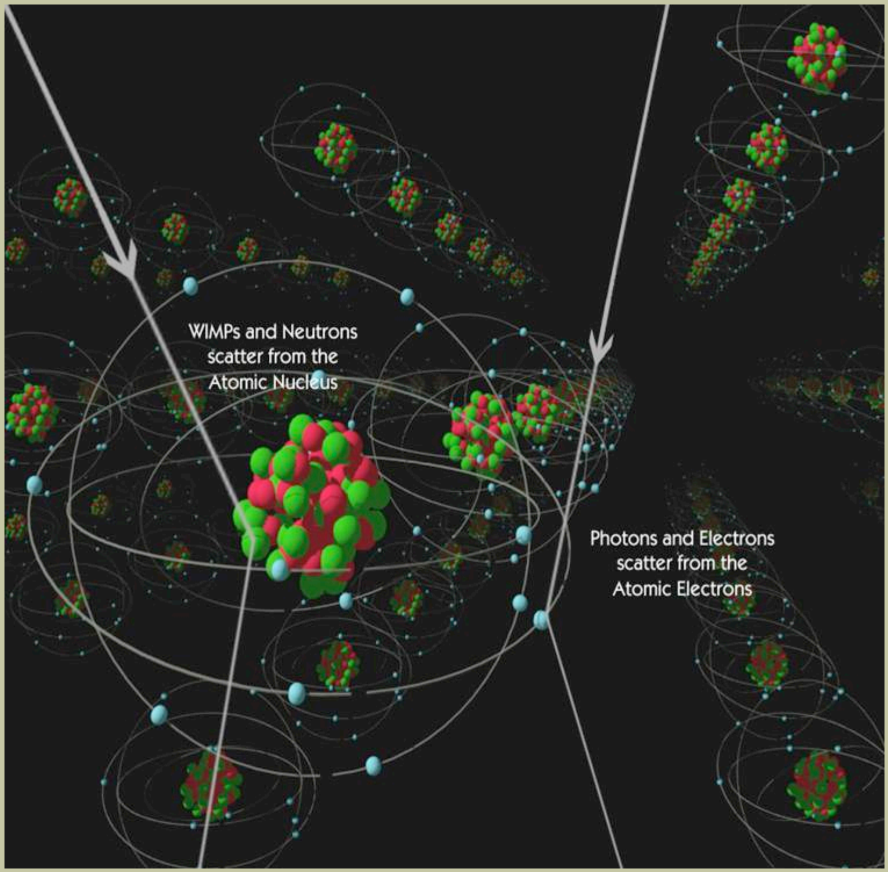
Experimental Status
Direct Detection

Principles of Direct Detection

- Movement with respect to the galactic frame imply DM flux,

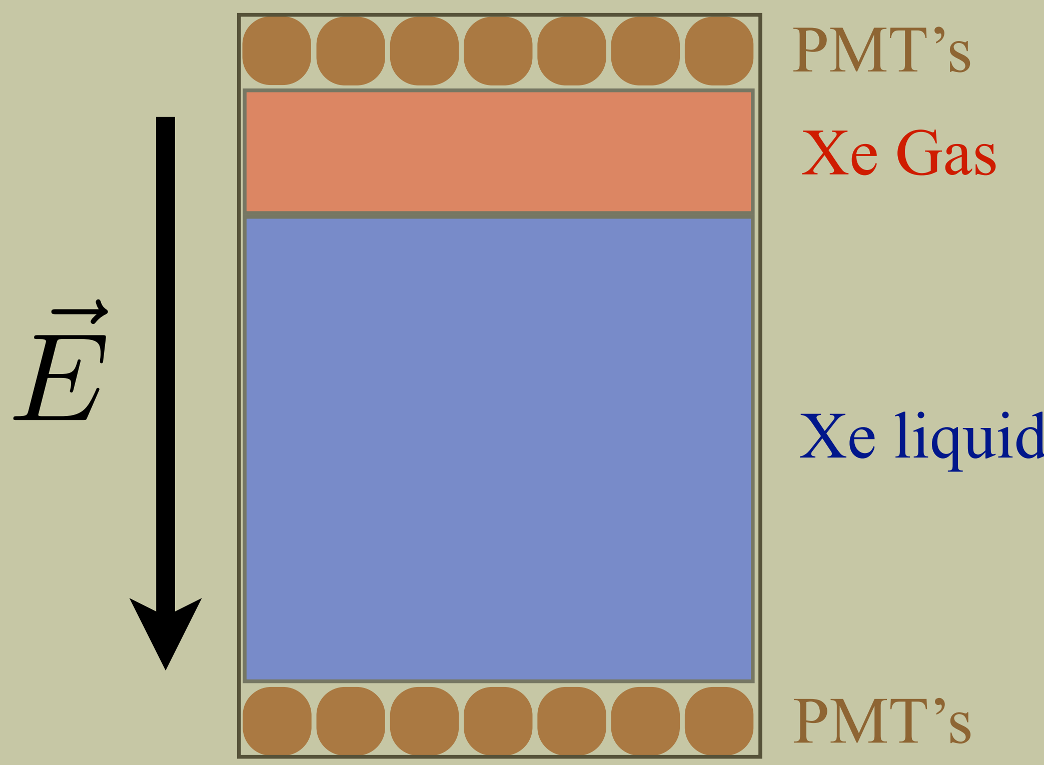
$$\Phi \simeq 7.5 \times 10^4 \text{ particles/cm}^2\text{/sec}$$

- DM recoils off a target material, leaving some energy in the form of:
  - Ionized electrons.
  - Scintillation light.
  - Heat/phonons.
- Signal is collected and the recoil energy is extracted.



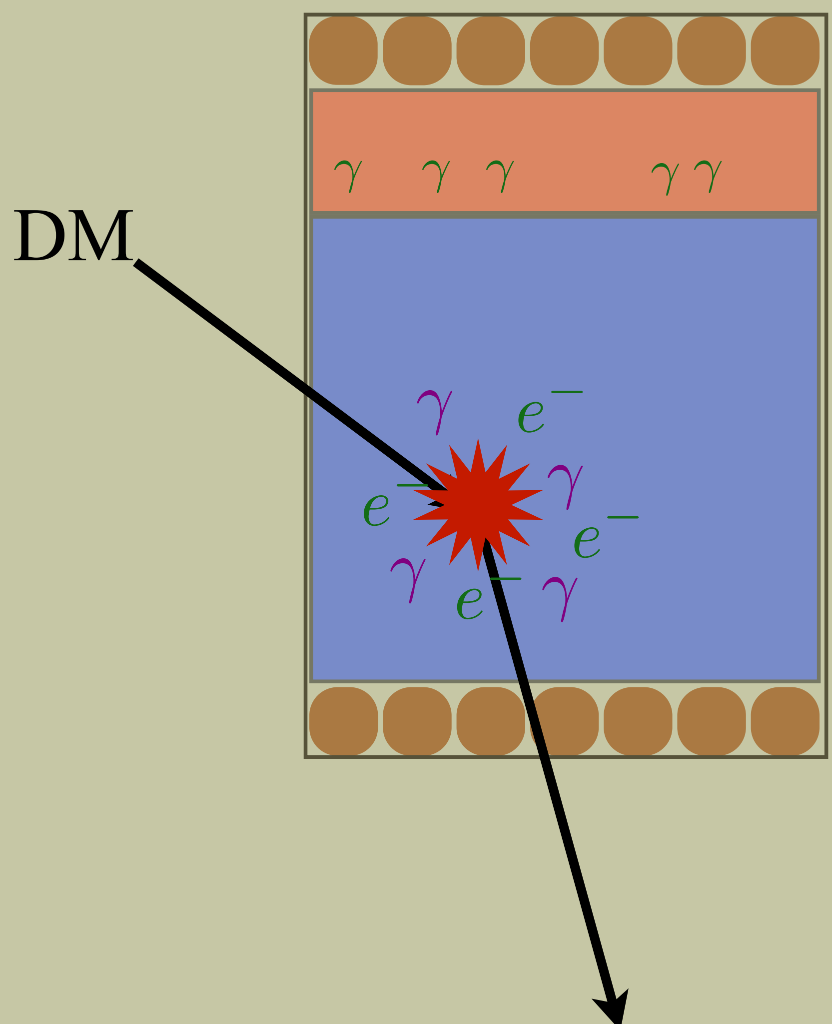
Example: Two-Phase Xenon Detector

detector
schematic



two-phase xenon time projection chamber

Example: Two-Phase Xenon Detector



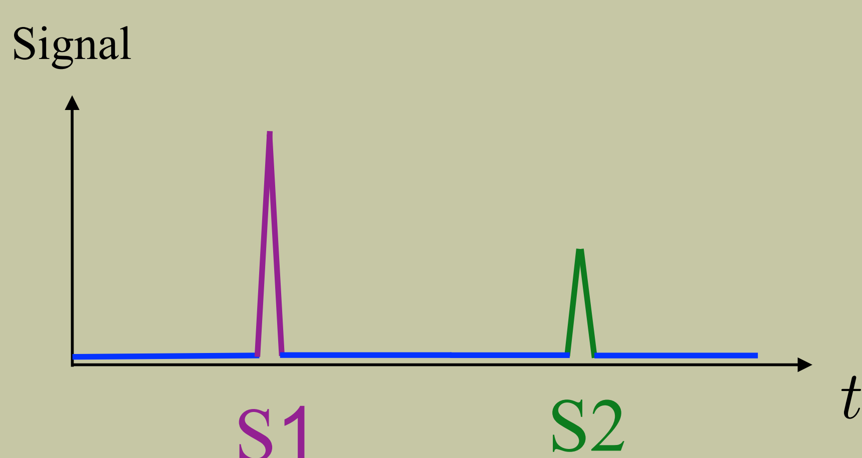
$$\mathrm{Xe} \rightarrow \mathrm{Xe}^*,\ \mathrm{Xe}^+$$

produces photons and electrons

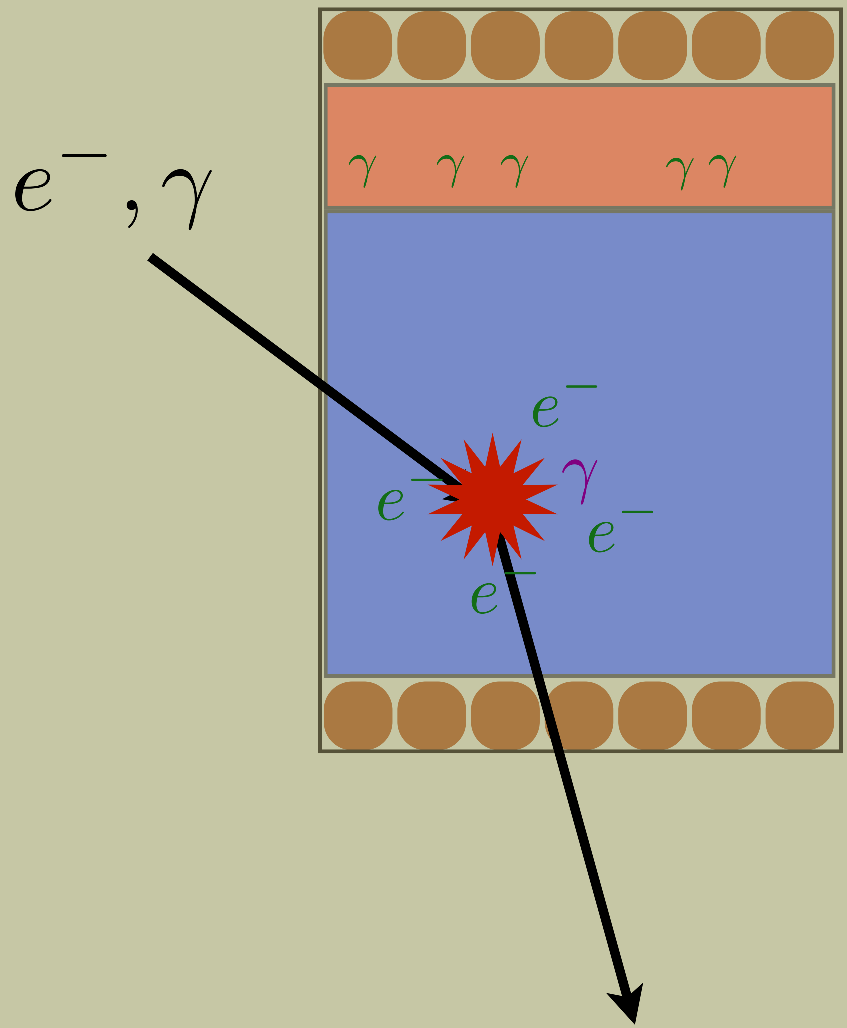
Two types of signal:

S1: prompt scintillation

S2: proportional scintillation (from ionization)



Example: Two-Phase Xenon Detector



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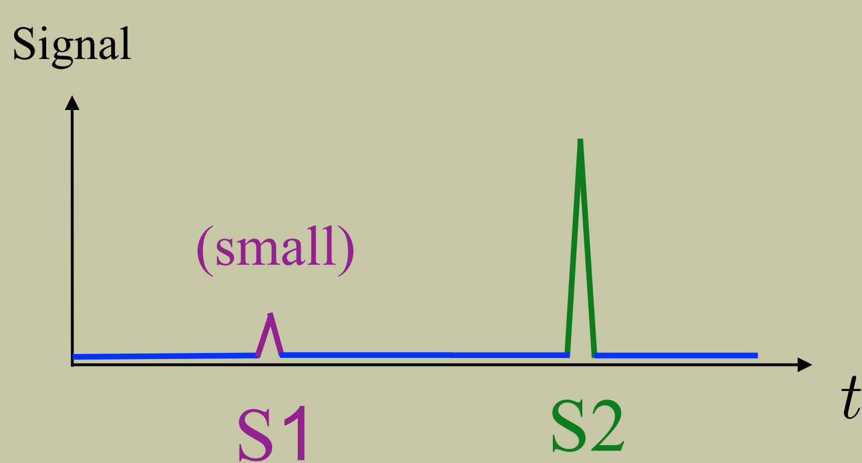
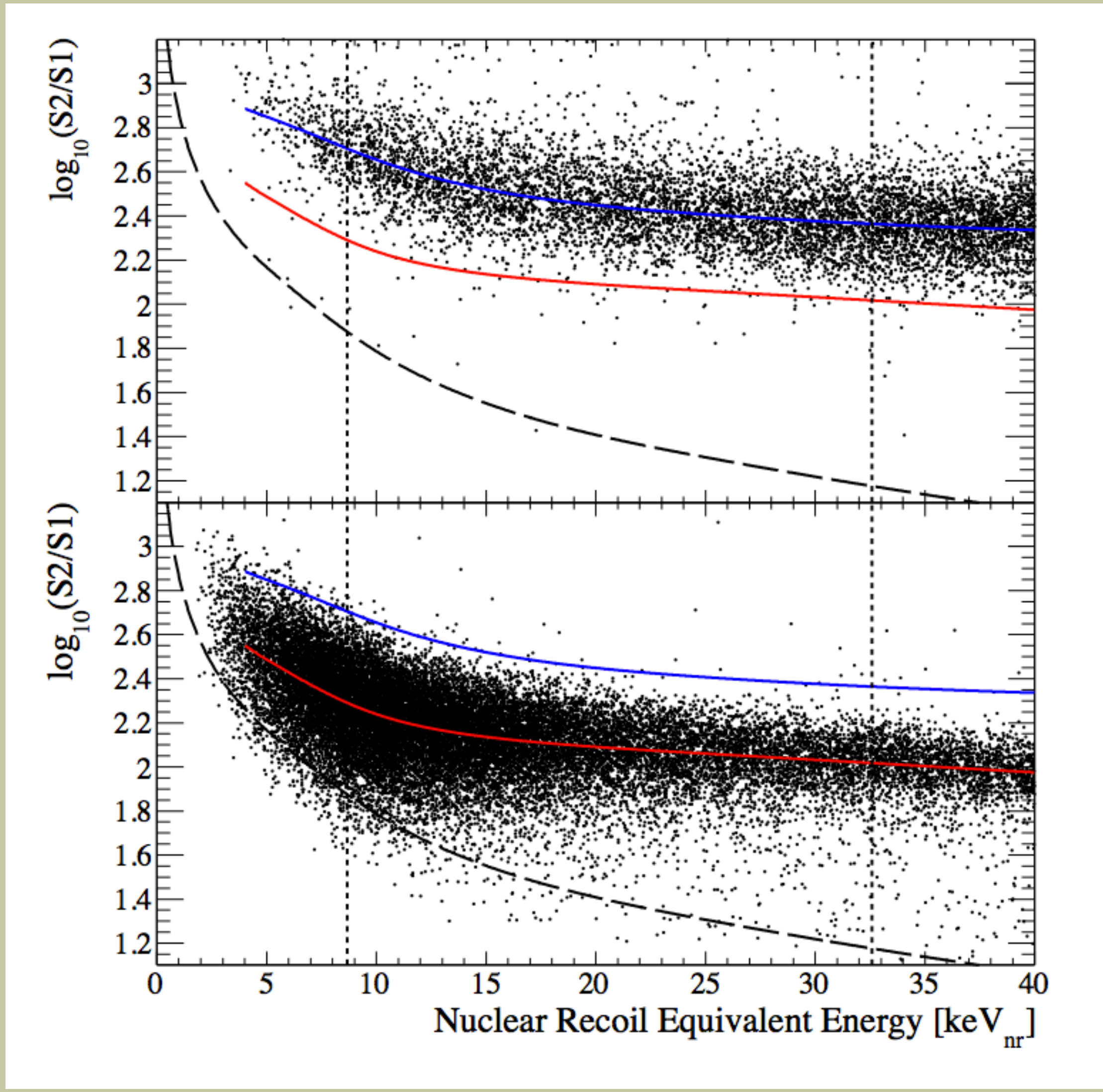


Example: Two-Phase Xenon Detector

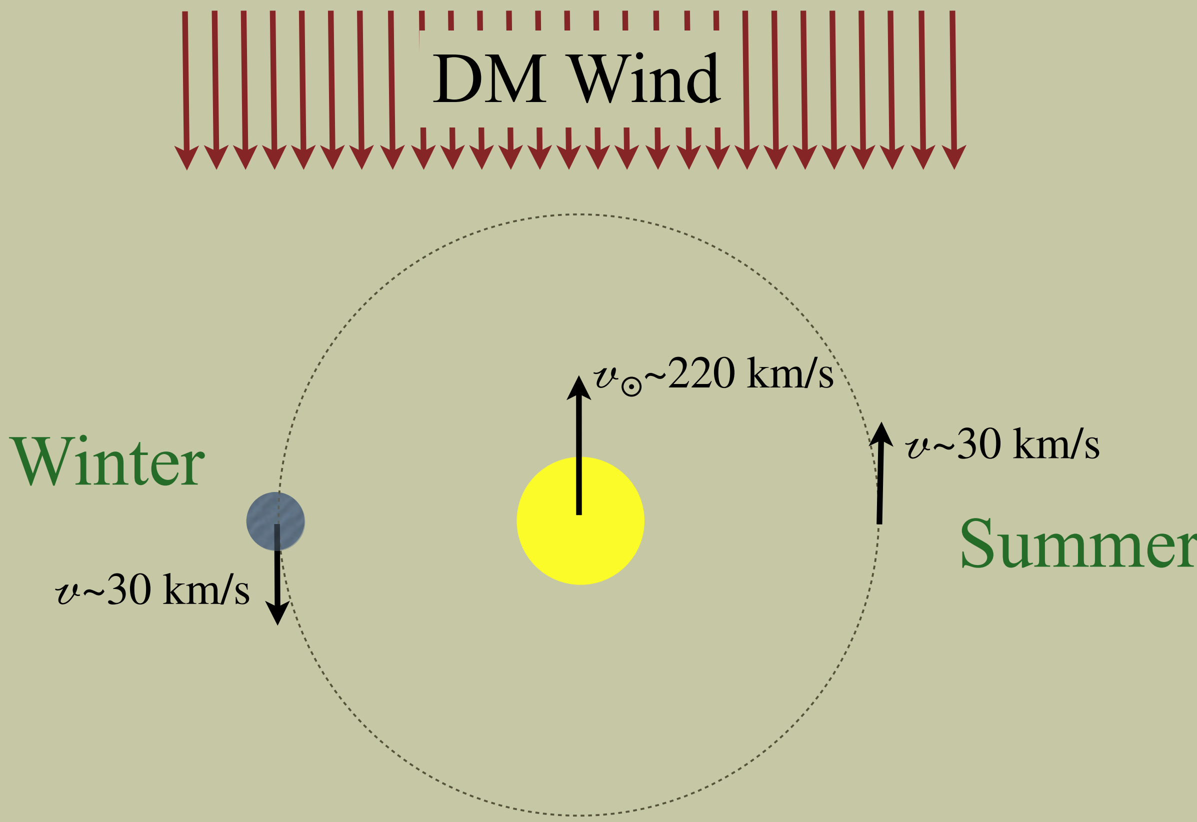


Principles of Direct Detection

- The scattering rate depends on several (often uncertain) factors:
  - What does DM interact with? (protons/neutrons/electrons/..)
  - DM number density
  - DM velocity distribution
  - Type of interaction (elastic/inelastic/spin dependent/velocity suppressed/...)
  - Target material
  - Size of the detector

Velocity Distributions

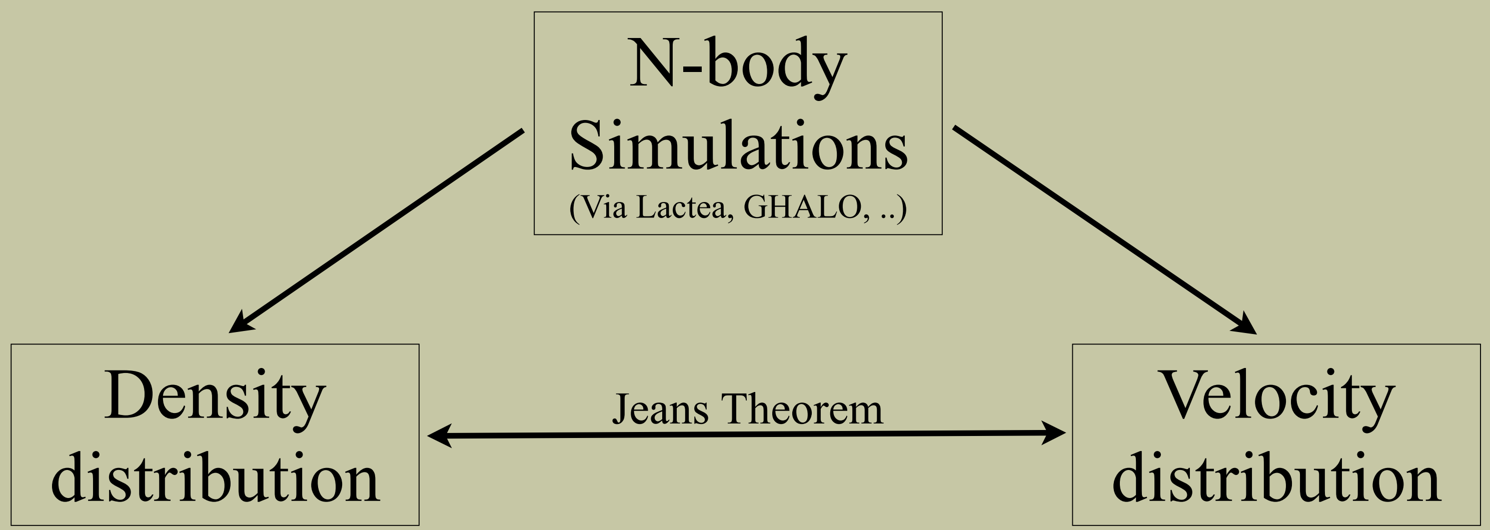
- To calculate the rate of interaction with DM, we need to know the DM velocity distribution and local density.



- The rotation around the Sun implies an annual modulation of the flux.

Velocity Distributions

- We don’t really know the velocity distribution or the local density
- One typically extracts the information from N-body simulations:



- There are very large uncertainties (due to e.g. non-inclusion of baryons, possible streams, sub-halos, etc..).
- Uncertainties are larger at large velocities, and may have significant effects on the direct detection rate.

Density Distributions

- The density is often taken to be of the form:

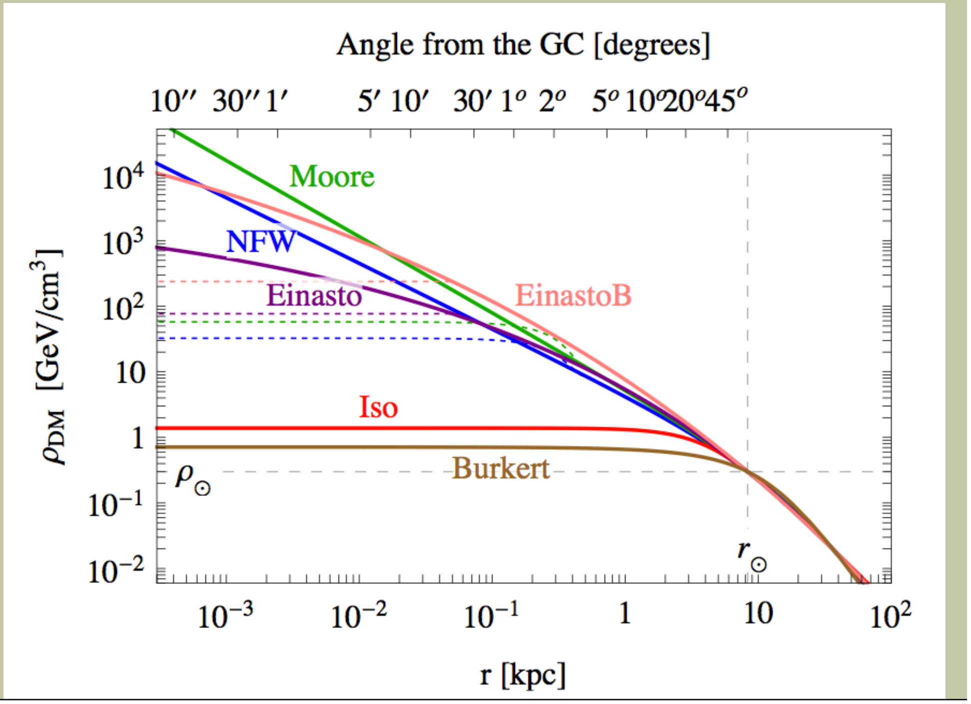
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Profile Name	α	β	γ	r_s (kpc)
NFW	1	3	1	20
Moore	1	3	1.16	30
Isothermal	2	2	0	5

or the Einasto profile:

$$\rho(r) = \rho_\odot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right] \qquad \alpha = 0.12 - 0.20$$

- The different profiles differ mostly in their distribution close to the galactic center.



Velocity Distributions

- The velocity distribution is almost always taken to be the Maxwell-Boltzmann, with a sharp cutoff at the escape velocity,

$$\tilde{f}_{\rm MB}(v; v_0, v_{\rm esc}) = \frac{1}{N_E} e^{-v^2/v_0^2} \Theta(v_{\rm esc} - v)\,,$$

$$220 < v_0 < 270 \text{ km/s}$$
$$450 < v_{\rm esc} < 650 \text{ km/s}$$

- The MB is, however, inconsistent with the more realistic solutions to the density. Better fits are obtained by

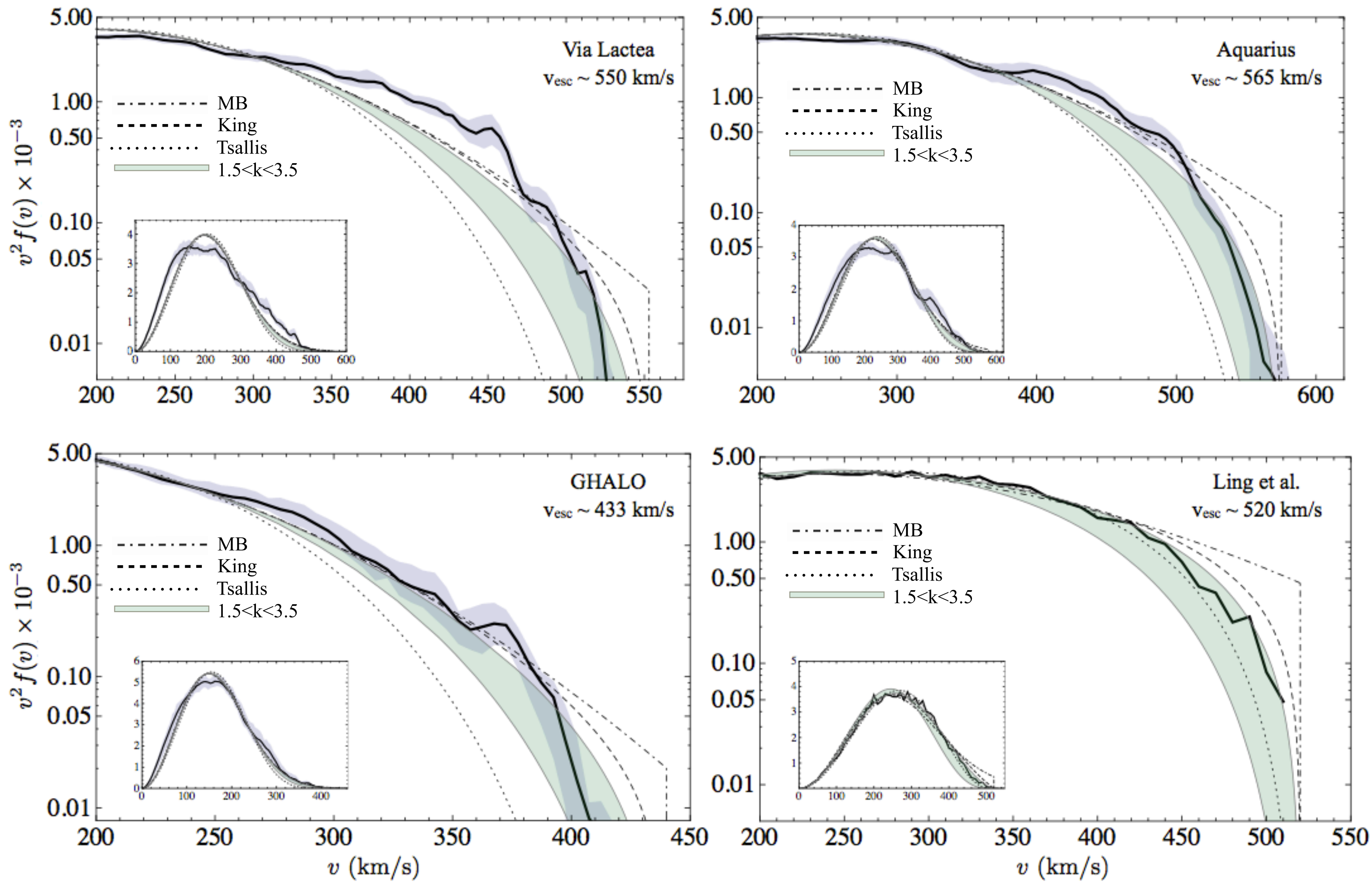
$$\tilde{f}_k(v; v_0, v_{\rm esc}) \propto \left[\exp\left(\frac{v_{\rm esc}^2 - v^2}{k v_0^2}\right) - 1\right]^k \Theta(v_{\rm esc} - v)$$

[Lisanti et al., 2010]

- The velocity in the Earth frame is then related to the above distributions given in the halo frame,

$$f_\oplus(v, t) = \tilde{f}(v + v_\odot + v_\oplus(t); v_0, v_{\rm esc})$$

Uncertainties in Velocity Distributions



[Lisanti et al., 2010]

Local Density

- It is hard to extract the local density from N-body simulations, since they don't include baryons.
- A given density determines the r-dependent circular velocity

$$\rho(r) = \frac{1}{4\pi G r^2} \frac{d}{dr}[r v^2(r)]$$

- It can be shown that at large distances the velocity is the most likely velocity, v_0, obtained from the velocity distribution.
- The above allows to determine the local density, in terms of the local velocity (obtained from rotation curves or simulations) and v_0.
- Typical values used:

$$\rho_\odot = 0.4 \text{ GeV/cm}^3$$

Local Density: Recent News

On the local dark matter density

Jo Bovy[1] and Scott Tremaine

Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA

ABSTRACT

An analysis of the kinematics of 412 stars at 1–4 kpc from the Galactic mid-plane by Moni Bidin et al. (2012) has claimed to derive a local density of dark matter that is an order of magnitude below standard expectations. We show that this result is incorrect and that it arises from the invalid assumption that the mean azimuthal velocity of the stellar tracers is independent of Galactocentric radius at all heights; the correct assumption—that is, the one supported by data—is that the circular speed is independent of radius in the mid-plane. We demonstrate that the assumption of constant mean azimuthal velocity is physically implausible by showing that it requires the circular velocity to drop more steeply than allowed by any plausible mass model, with or without dark matter, at large heights above the mid-plane. Using the correct approximation that the circular velocity curve is flat in the mid-plane, we find that the data imply a local dark-matter density of $0.008 \pm 0.002\, M_\odot\, \mathrm{pc}^{-3} = 0.3 \pm 0.1\, \mathrm{Gev\ cm}^{-3}$, fully consistent with standard estimates of this quantity. This is the most robust direct measurement of the local dark-matter density to date.

The Master Formula

- The DM-nucleon scattering rate for is straightforward to compute,

$$\frac{dR}{dE_R} = N_{\rm T} \int_{v>v_{\rm min}} \frac{d\sigma}{dE_R} v \frac{\rho_\odot}{m_{\rm DM}} f_\oplus(v,t) d^3v$$

Number of target nuclei per unit mass

$$N_{\rm T} = 10^3 \frac{N_A}{A} \text{ kg}^{-1}$$

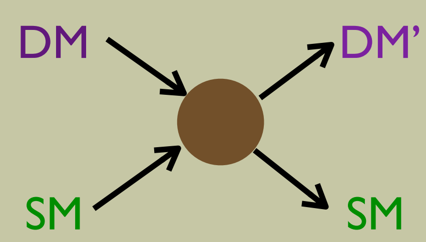
$dn_{\rm DM}$ - differential number density for a given velocity.

- The minimal velocity, $v_{\rm min}$, follows from kinematics which determines the relation between the latter and the recoil energy.

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

$$v_{\rm min} = \frac{1}{\sqrt{2m_N E_R}} \left| \frac{m_N E_R}{\mu} + \delta \right| .$$

$\delta = m_{\rm DM} - m'_{\rm DM}$ vanishes for elastic scattering and may have a large effect on rate, especially for annual modulation.



The Master Formula

- The DM-nucleon cross-section is model dependent,

$$\frac{dR}{dE_R} = \frac{m_N \sigma_n}{2v^2\mu_n^2}\int_{v>v_{\min}} \frac{[f_p Z + f_n (A-Z)]^2}{f_n^2} F_N^2(q) F_{\rm DM}^2(q,v)$$

$$\frac{d\sigma}{dE_R} = N_T \int \frac{d\sigma}{dE_R}\, v\, \frac{\rho_\odot}{m_{\rm DM}} f_\oplus(v,t)\, d^3v$$

- Usually $f_p = f_n$ is assumed. Easy to write models with different couplings to protons and neutrons.

- The spin-independent cross-section is enhanced by $\sim A^2$. DM may couple to the spin of the nucleus, in which case there's no enhancement.

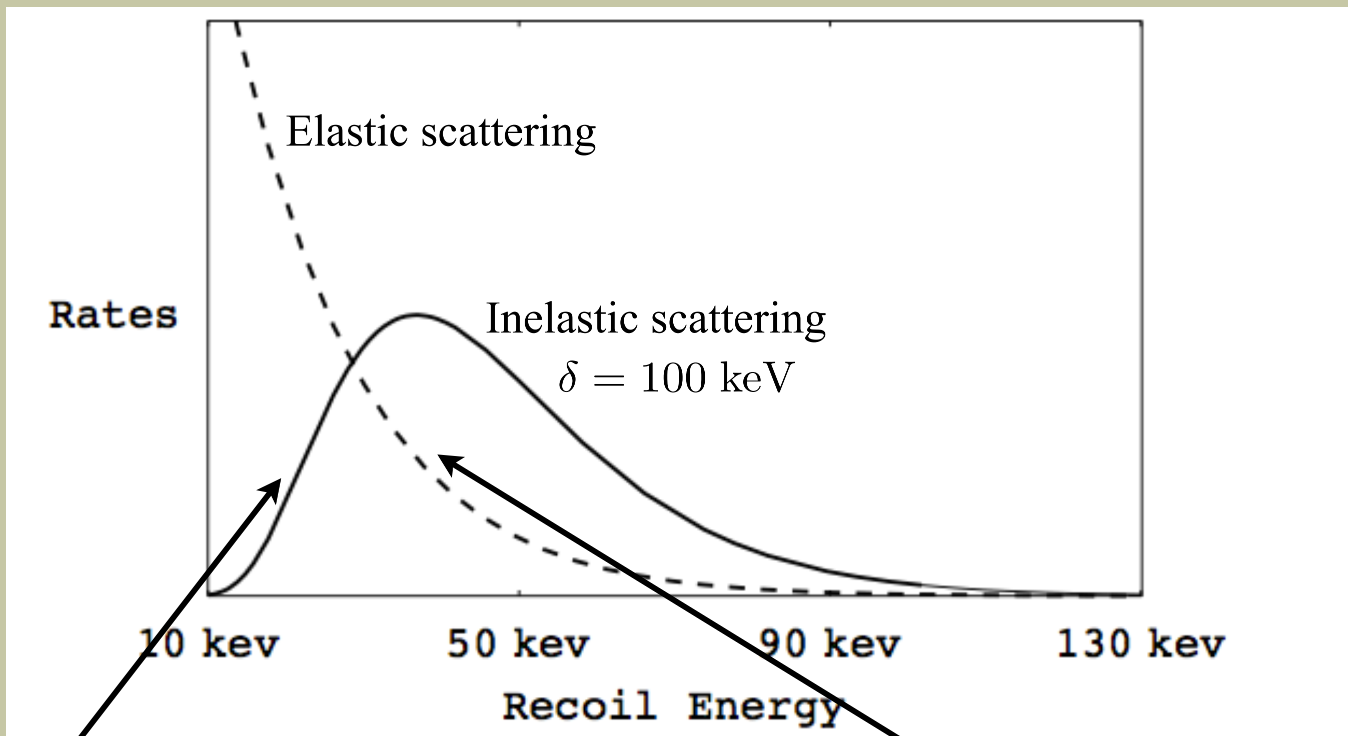
- $F_N(q) \propto e^{-q/q_0}$ is the nucleus form factor which depends on the momentum transfer.

- The DM form-factor can be both velocity and momentum dependent

$$\begin{aligned} \mathcal{A}_1 &\propto 1, & \sigma &\propto 1 \\ \mathcal{A}_2 &\propto \vec{s}_{\rm DM}\cdot\vec{q}, & \sigma &\propto q^2 \\ \mathcal{A}_3 &\propto \vec{s}_{\rm DM}\cdot\vec{v}, & \sigma &\propto v^2 \\ \mathcal{A}_4 &\propto \vec{s}\cdot\vec{q}\times\vec{v}, & \sigma &\propto q^2 v^2 \end{aligned}$$

Spectrum

- Show scattering rate plot with elastic and inelastic.

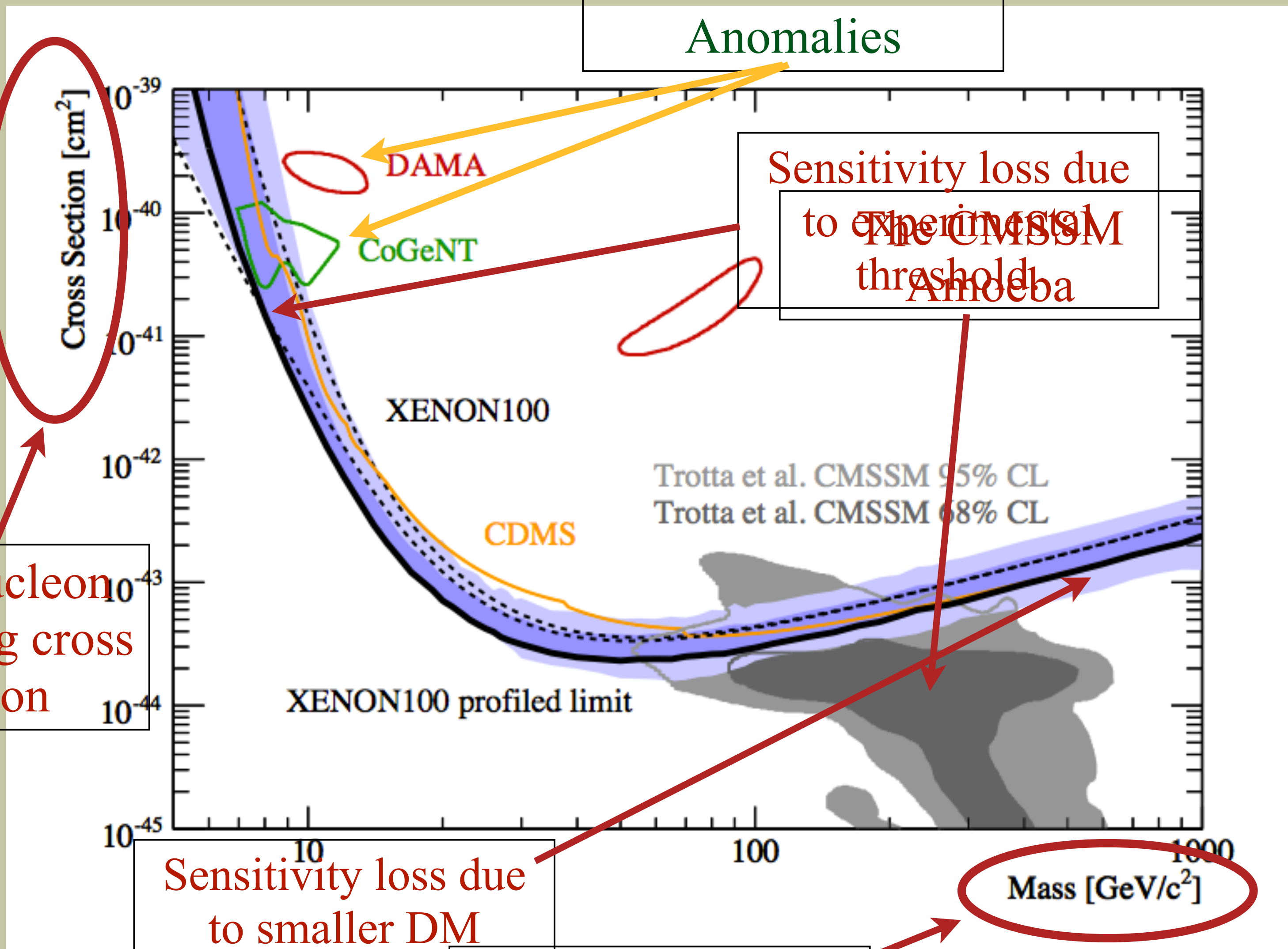


Drop at low energy for inelastic scattering

Exponential fall due to nucleus form-factor and velocity distribution

$$v_{\min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu} + \delta \right| .$$

What Do The Results Look Like?



Some Claimed Anomalies

Sensitivity loss due to experimental threshold

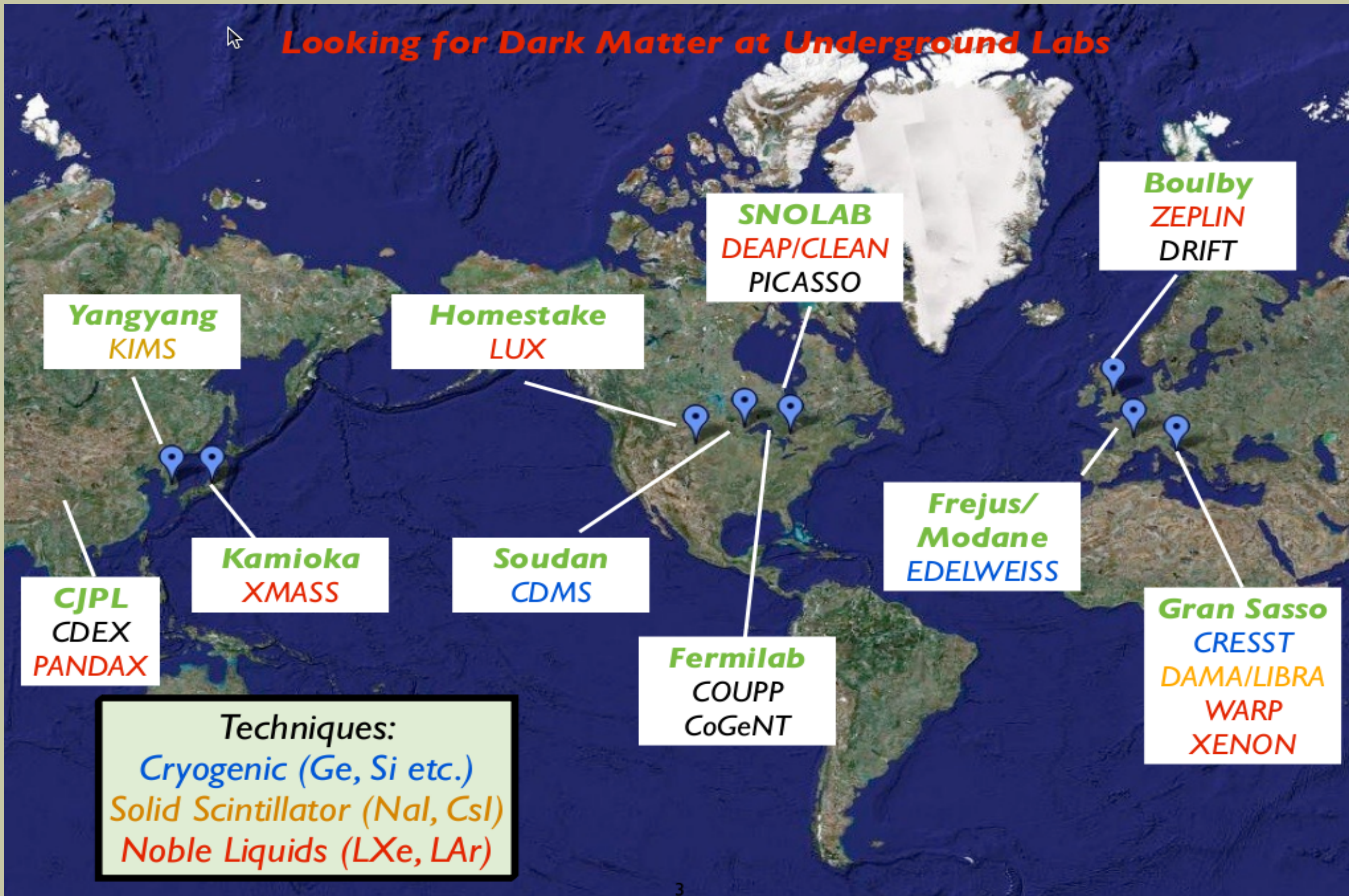
The CMSSM Amoeba

DM-Nucleon scattering cross section

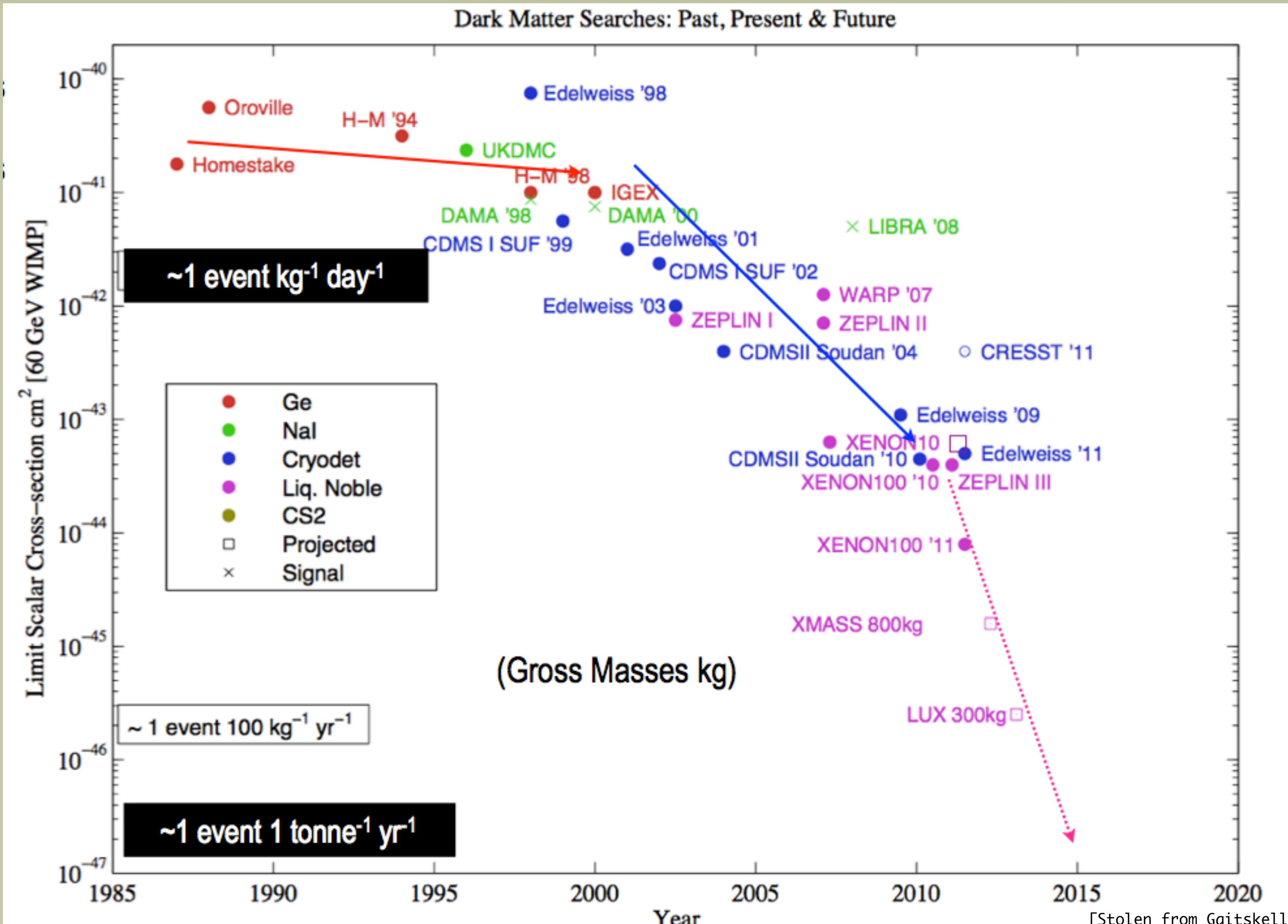
Sensitivity loss due to smaller DM number density ~$1/m_{DM}$

WIMP Mass

Direct Detection Progress

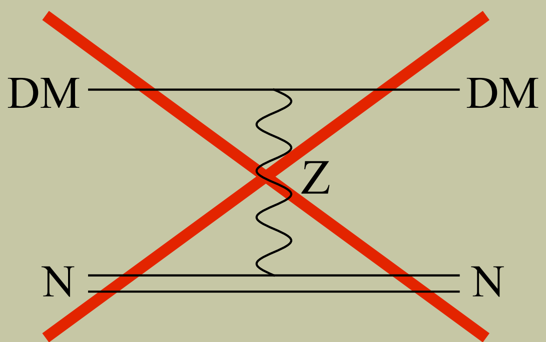


Direct Detection Progress

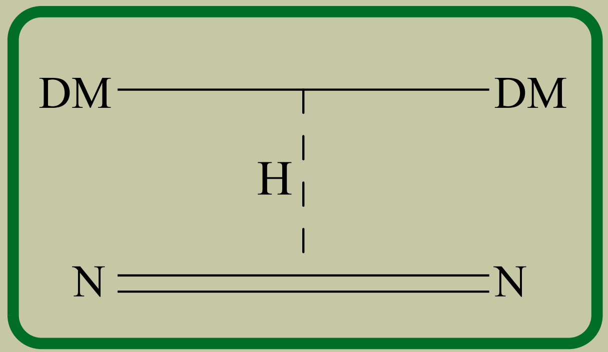


[Stolen from Gaitskell]

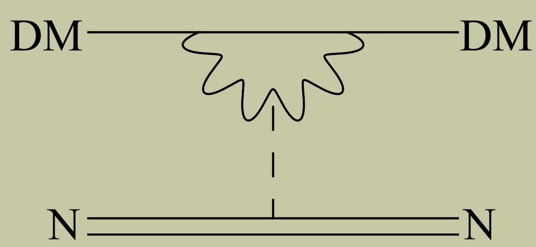
What Are We Probing?



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



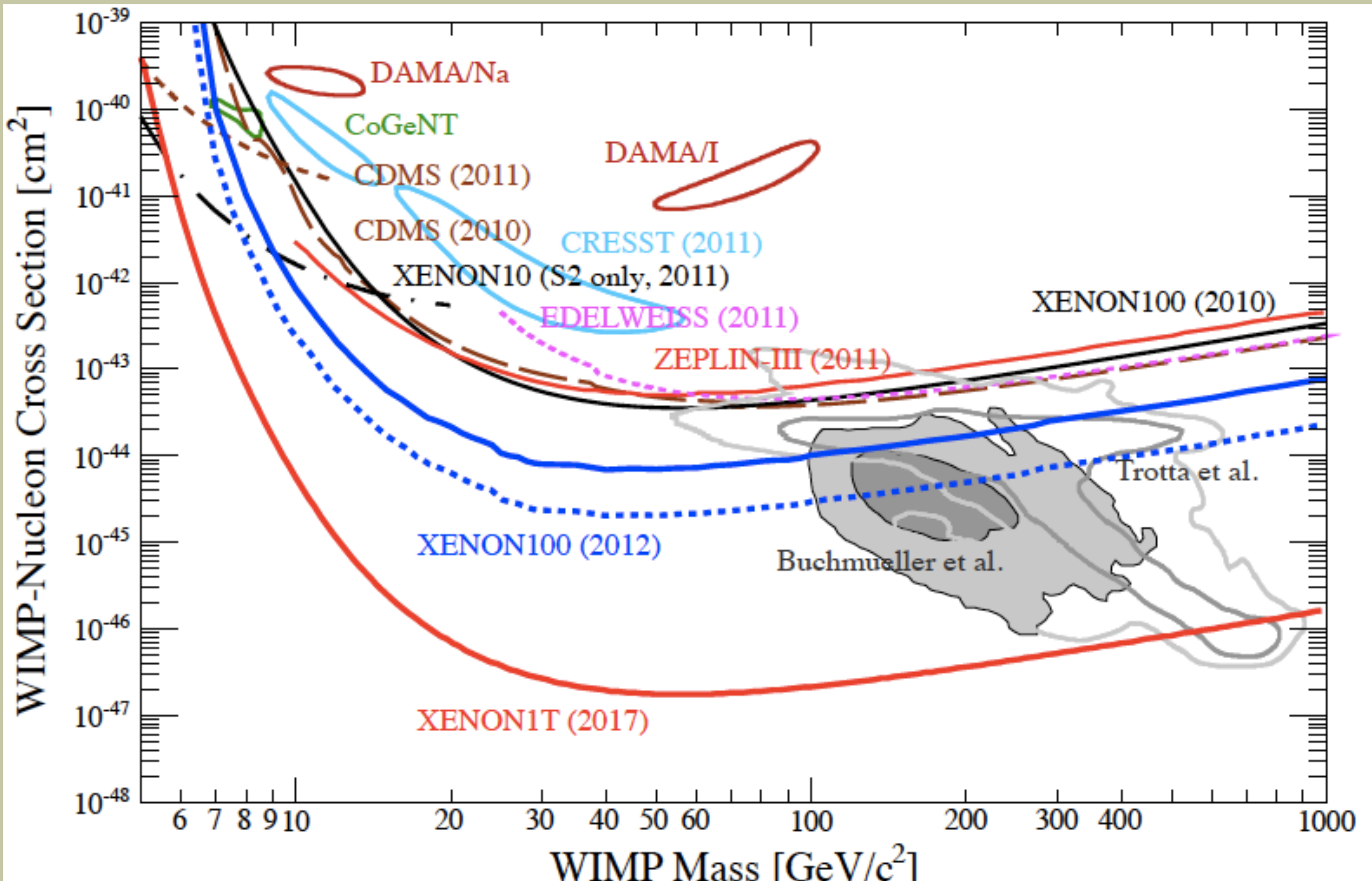
$\sigma_{\chi N} \sim 10^{-44-46}$ cm^2



$\sigma_{\chi N} \sim 10^{-46-48}$ cm^2

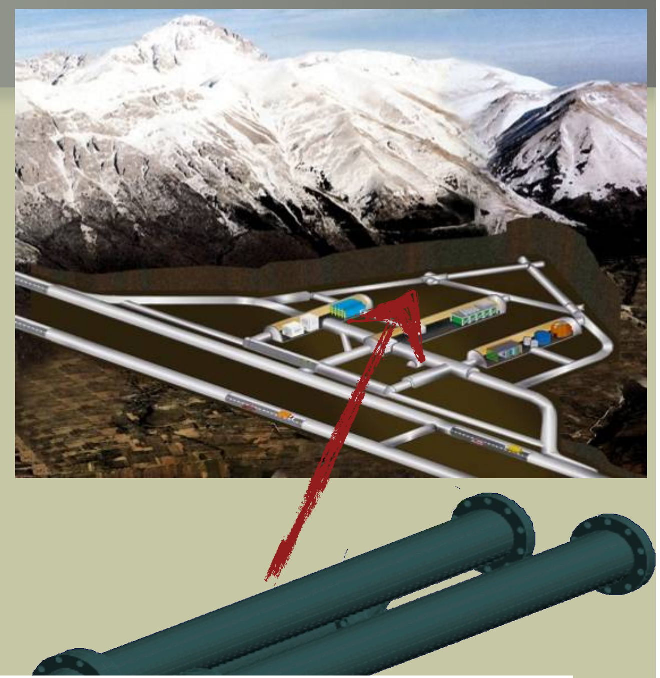
Current Sensitivity

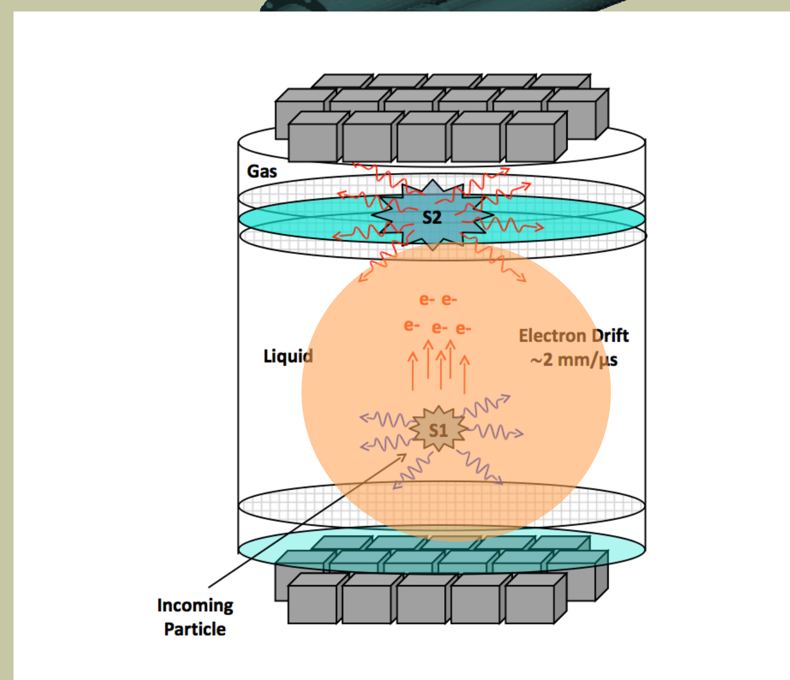
Projected Sensitivity



Xenon100

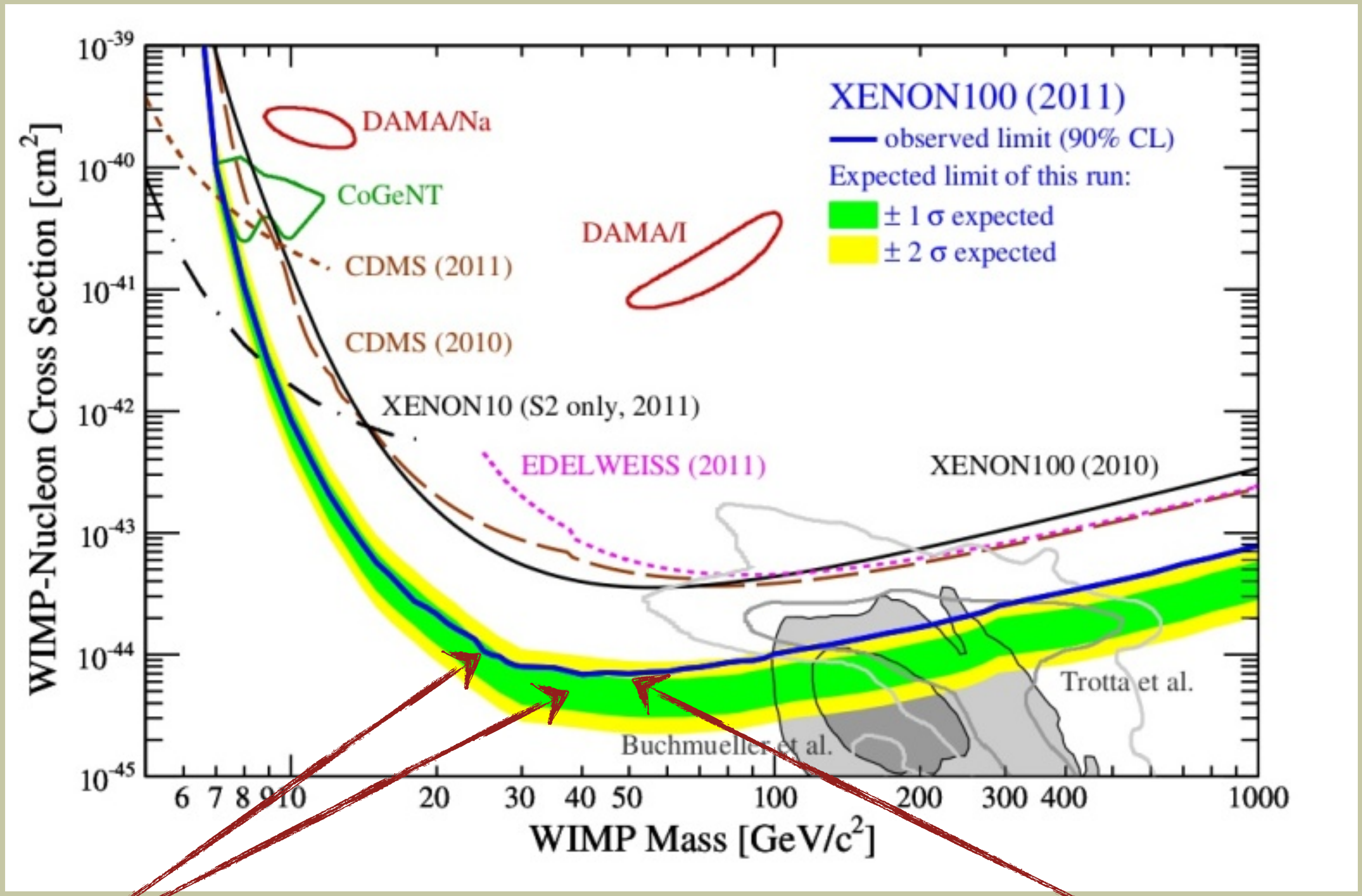
- Located at Gran Sasso under 1400m of rock.
- 2-phase xenon detector.
- Scintillation light is collected and the recoiling energy is extracted.
- $E_{collected} = q\ E_R$, so need to know the quenching factor, $q<1$.
- To get rid of significant background events, only the central part of the detector is used.
  The fiducial mass used: 48kg.





Xenon100

- 2010 Results - 100 live days corresponding to 1471 kg-days.

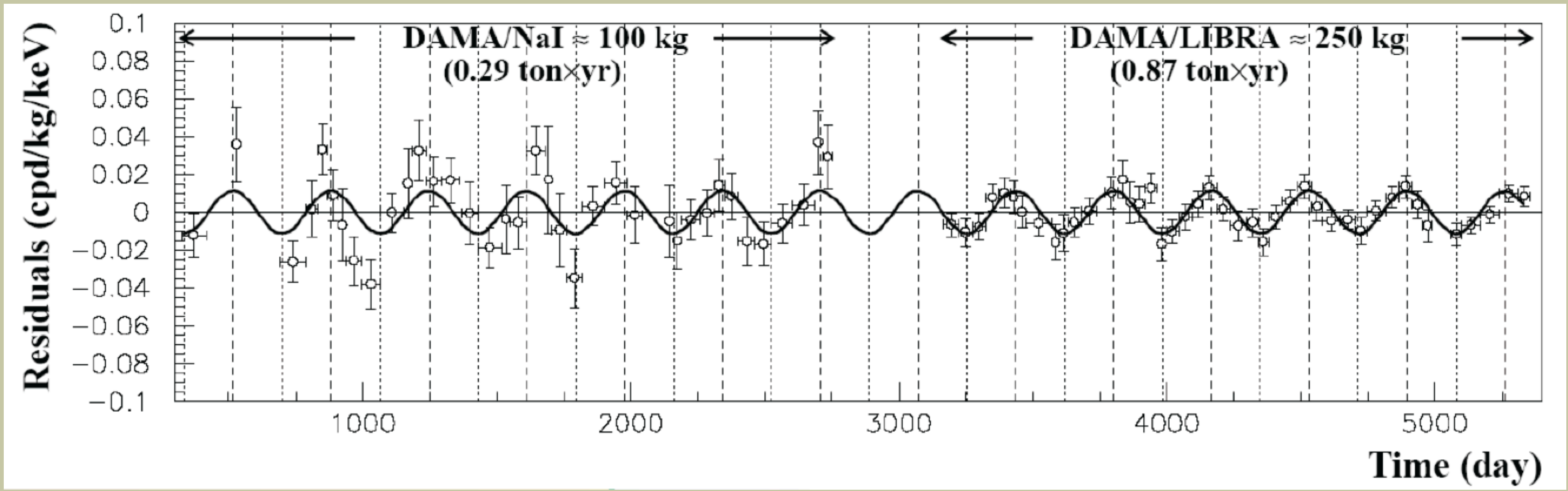


Bound worse than expected due to 3 seen events.

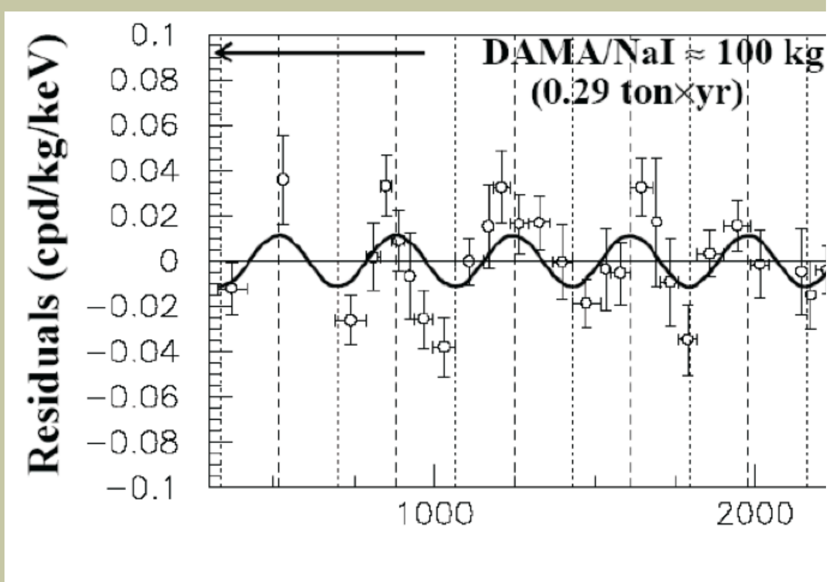
7×10^{-45} cm^2 @ 50 GeV

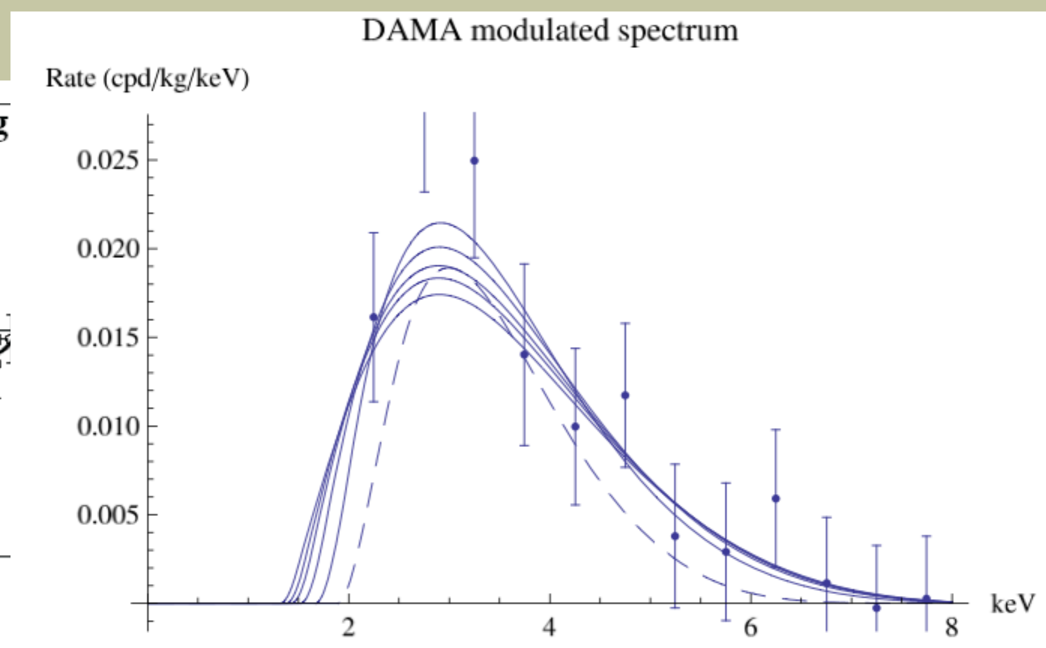
DAMA

- Long standing measurement (first positive result in 1989).
- Uses NaI crystals (250 kg in second DAMA/LIBRA phase).
- No background/signal discrimination. Searches for annual modulation.
- Results in 0.87 ton-year of data, and 8.9σ evidence for modulation (13 cycles)!
- Phase is correct - peak at June 2 ± week.



DAMA


DAMA/NaI ≈ 100 kg
(0.29 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
1000
2000


DAMA modulated spectrum
Rate (cpd/kg/keV)
0.025
0.020
0.015
0.010
0.005
2
4
6
8
keV

DAMA - Is it Background?

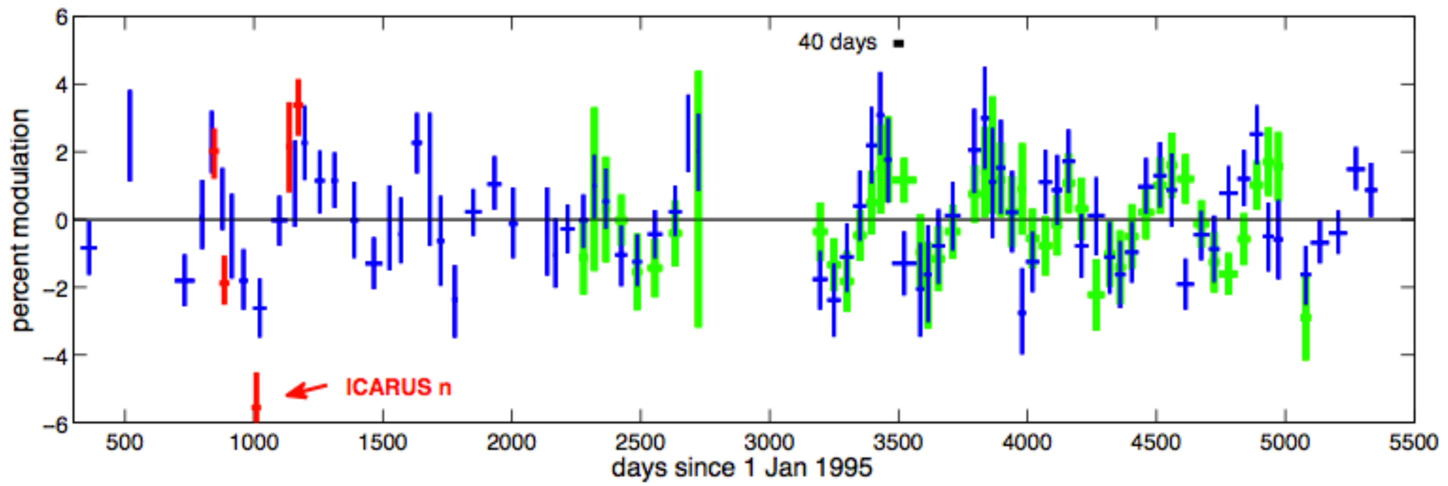
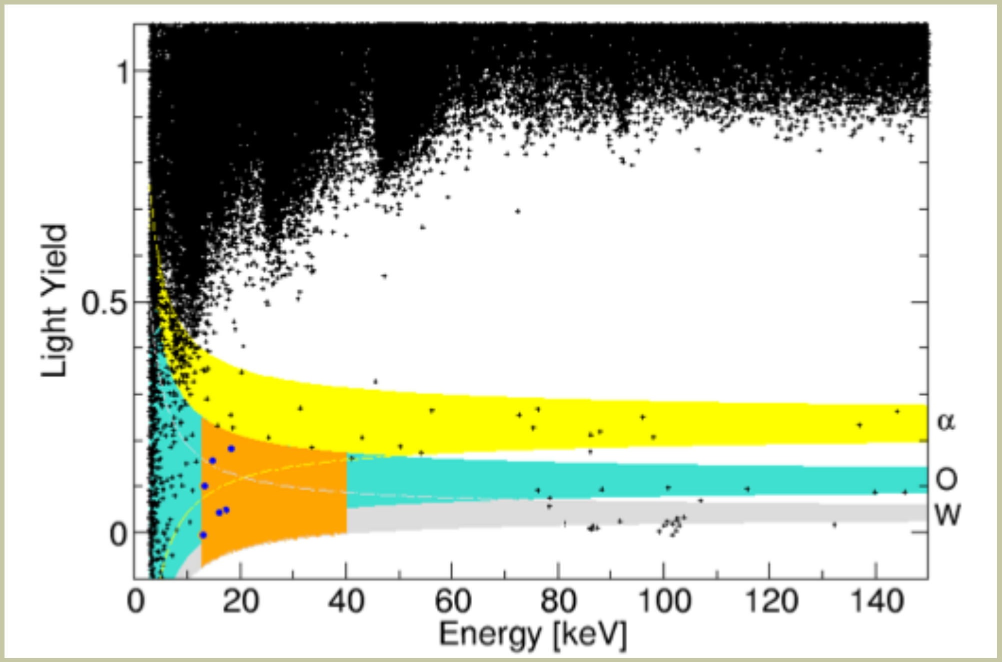


Figure 2: DAMA residuals (blue) and binned muon intensity residuals (green). ICARUS neutron measurements during 1997-1998 are added (red).

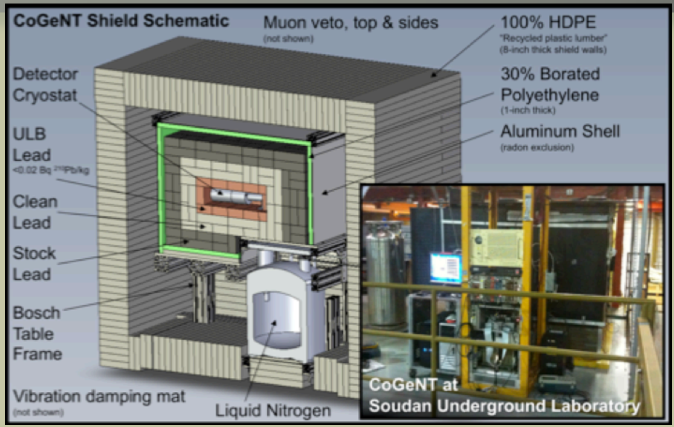
- Could it be muons?
  - Nygren: Maybe...
  - Blum: Maybe...
  - Chang et al.: No!
- Don't know!! Need to repeat experiment on the other side of the world. DAMA won't let anyone do that!

CRESST II

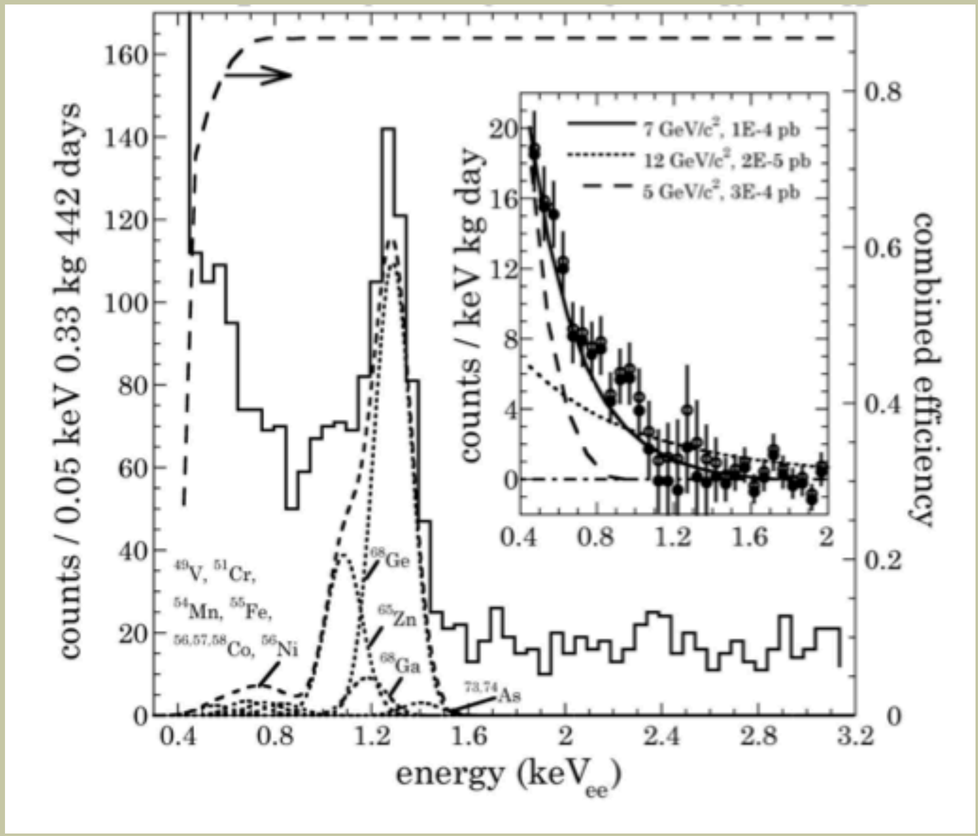
- Cryogenic calorimeter. Collects phonons and scintillation light.
- Target: $CaWO_4$
- First analysis:
  - 730 kg-days
  - Found 67 events
  - 4.2σ-4.7σ
- A new analysis:
  - 572 kg-days
  - Found 52 events.
  - 1.9σ-2.5σ



CoGeNT (Coherent Germanium Neutrino Technology)

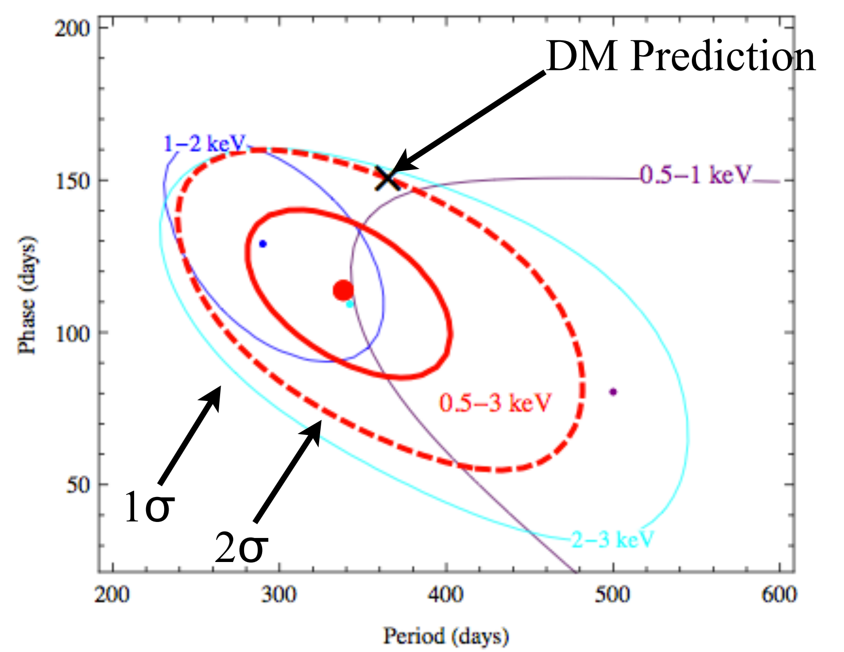


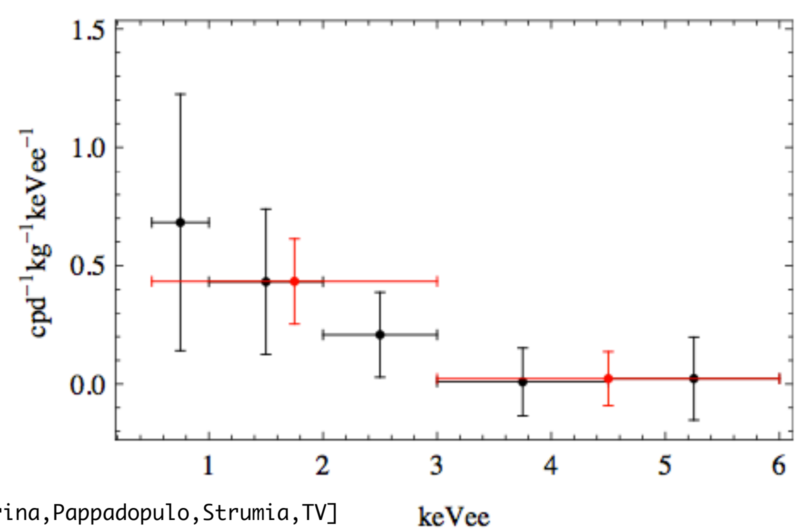
- Germanium detector in Soudan Underground Lab.
- 0.5 keV threshold. No signal/background discrimination.
- Started taking data 2009. Fire broke in Mar. 2011. Resumed July 2011.
- Reported 442 live days on a 0.33kg Ge detector.
- CoGeNT's first release claimed an exponentially falling set of events, unexplained by background.



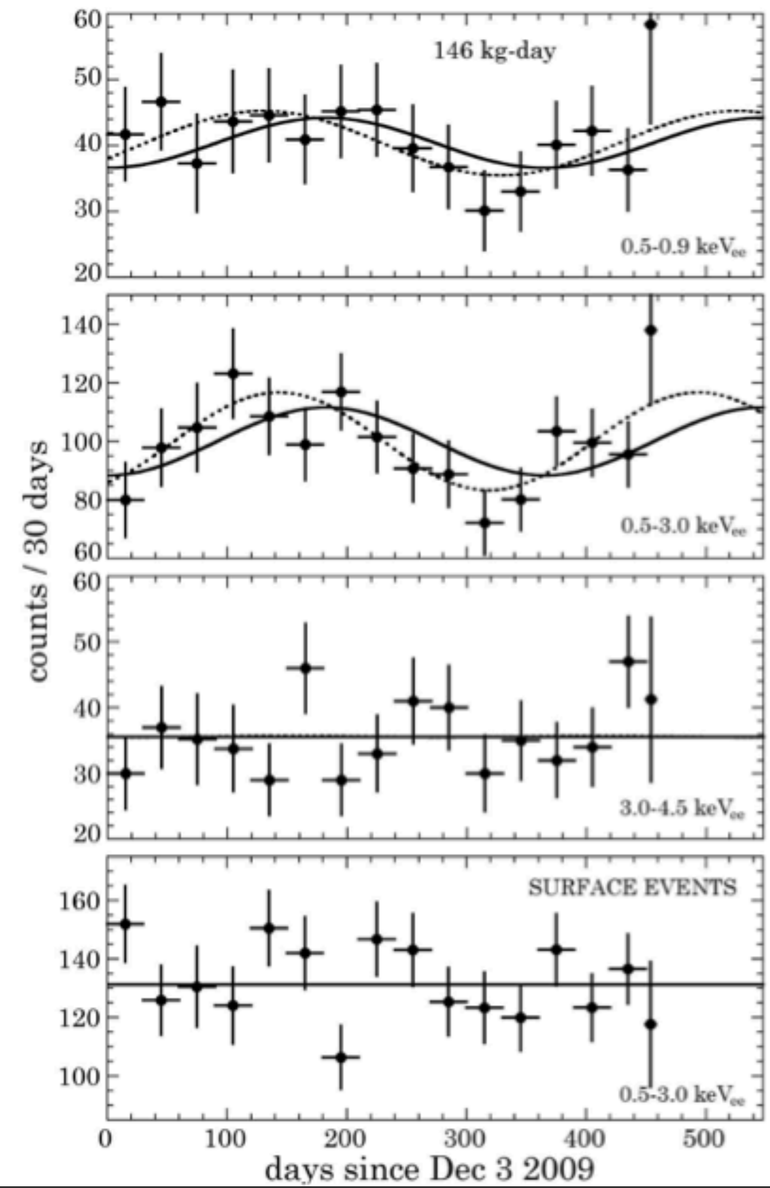
CoGeNT (Coherent Germanium Neutrino Technology)

- Events found to modulate!! Agrees with DM within 2σ. Excludes no-modulation by 3σ.



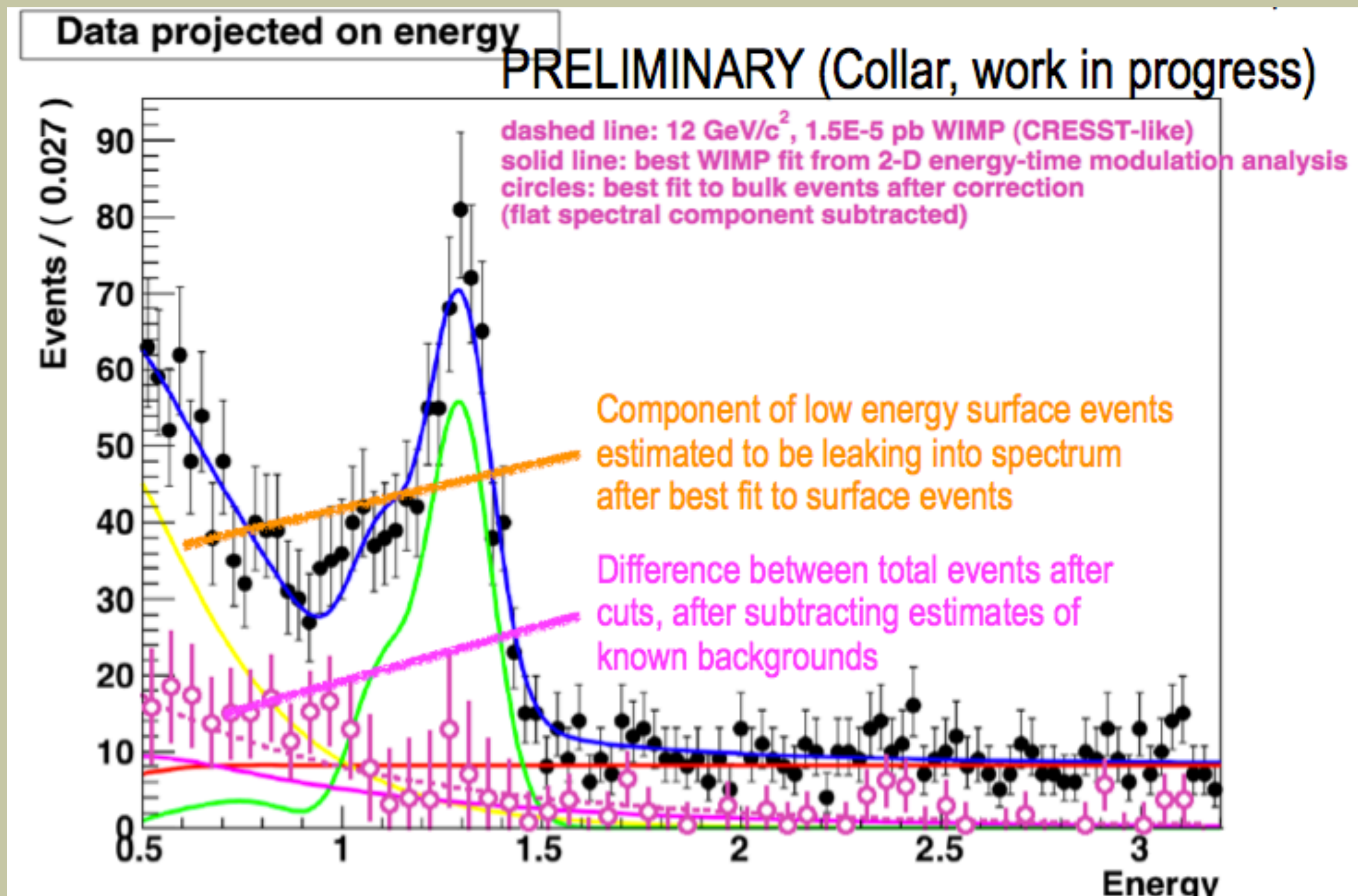


[Farina,Pappadopulo,Strumia,TV]



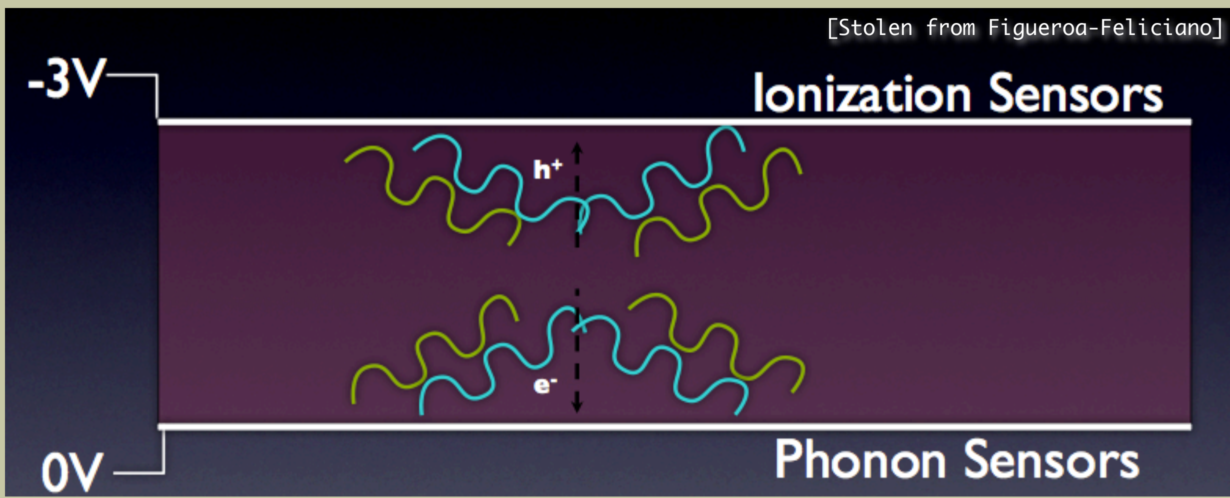
CoGeNT (Coherent Germanium Neutrino Technology)

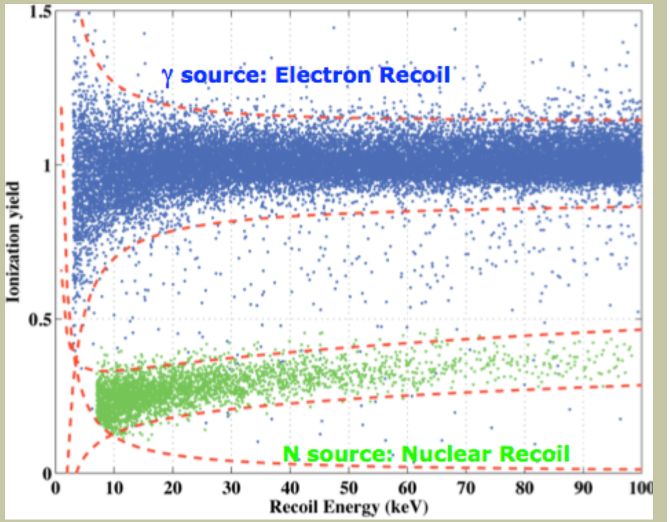
- Later more surface (background) events were found.



CDMS (Cryogenic Dark Matter Search)

- CDMS is also a Germanium (and Silicon) detector in Soudan Underground Lab.
- Measures phonons and ionization so is able to distinguish signal from background.





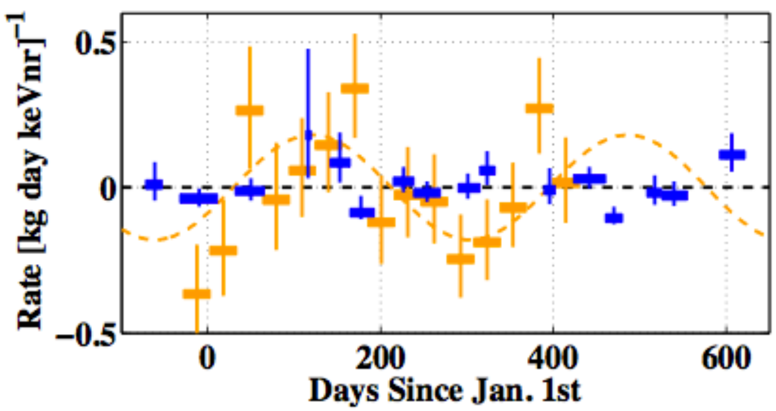
- Threshold is higher however, 10 keV. Low threshold analysis allows lowering the threshold to 2 keV.

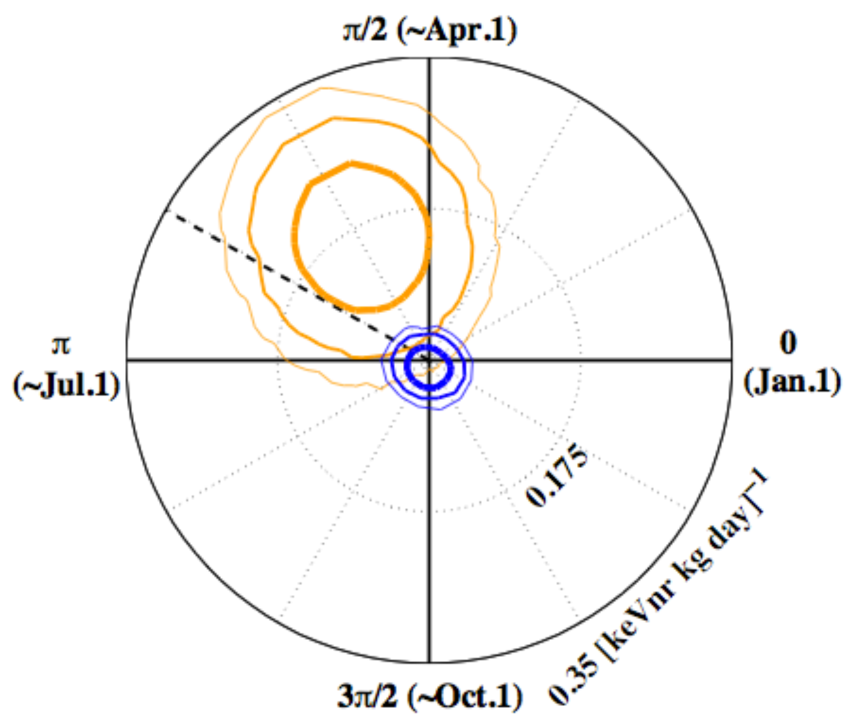
CDMS sees no excess of events!

(or so they claim..)

CDMS (Cryogenic Dark Matter Search)

- Also checking for annual modulation (preliminary)





CDMS sees no sign of modulation! (from nuclear recoils)
(or so they claim..)

CDMS (Cryogenic Dark Matter Search)

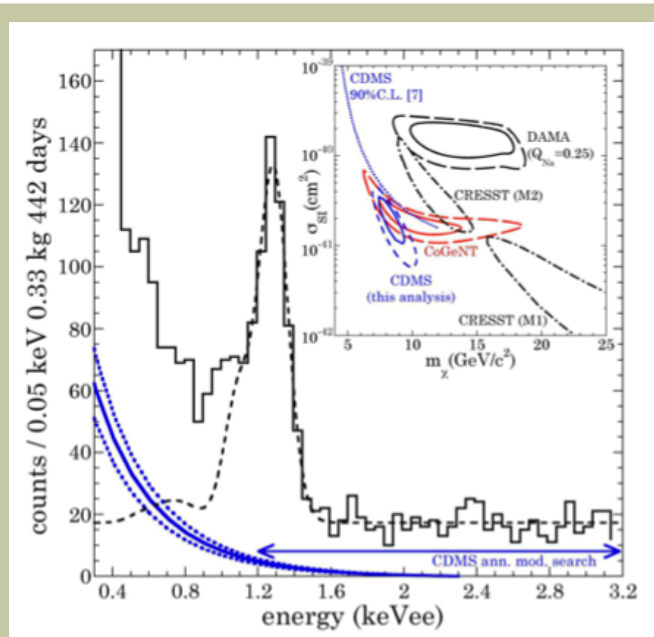
- A month ago, Collar and Fields (from CoGeNT) reanalyzed the CDMS data.

A Maximum Likelihood Analysis of Low-Energy CDMS Data

J.I. Collar and N.E. Fields[1]

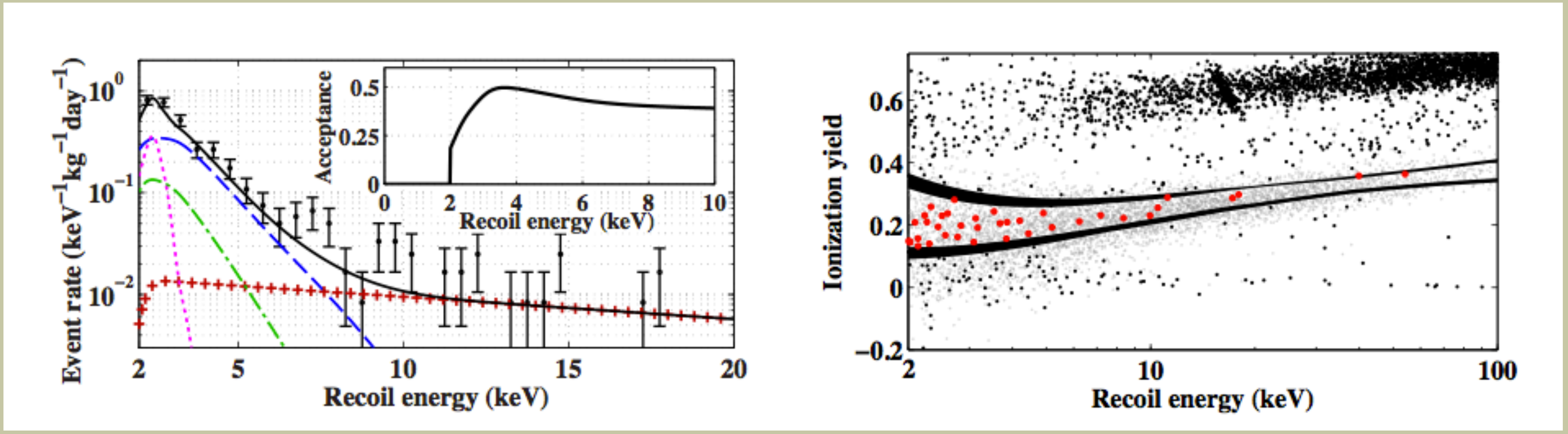
[1] *Enrico Fermi Institute, Kavli Institute for Cosmological Physics and Department of Physics, University of Chicago, Chicago, IL 60637*

An unbinned maximum likelihood analysis of CDMS low-energy data reveals a strong preference (5.7σ C.L.) for a model containing an exponential excess of events in the nuclear recoil band, when compared to the null hypothesis. We comment on the possible origin of such an excess, establishing a comparison with anomalies in other dark matter experiments. A recent annual modulation search in CDMS data is shown to be insufficiently sensitive to test a dark matter origin for this excess.



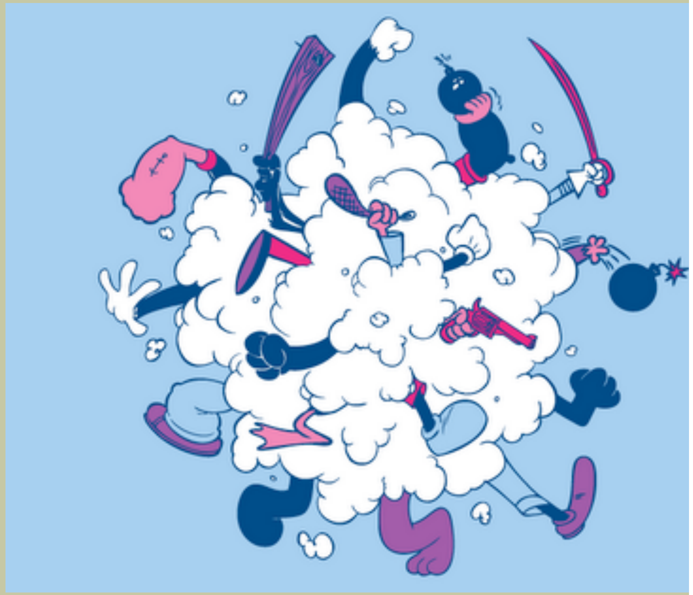
What's going on?

- Roughly speaking - to place constraints CDMS "counts" the number of electrons (ionization energy) and compares those to the total recoil energy (from phonon energy). This distinguishes electron-recoils from nuclear recoils.



- Collar claims that
  - CDMS's energy calibration is wrong (large systematics).
  - Wrong estimation of BG (which CDMS conservatively doesn't subtract).
  - No sensitivity to modulation when BG is subtracted.

Who should we believe?



No one right now.

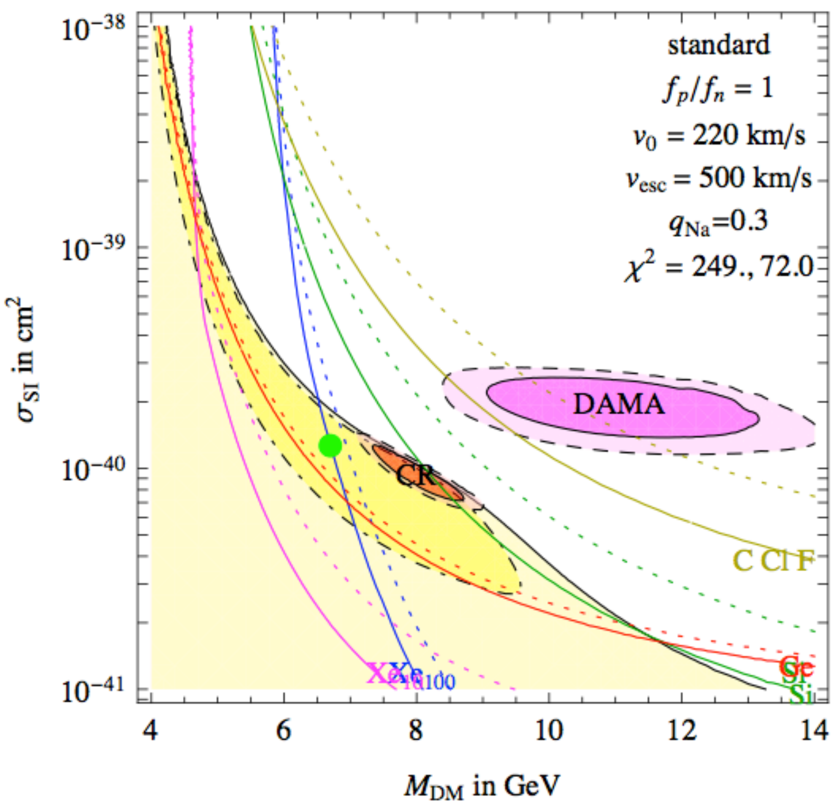
Interesting to think about but more data is needed.

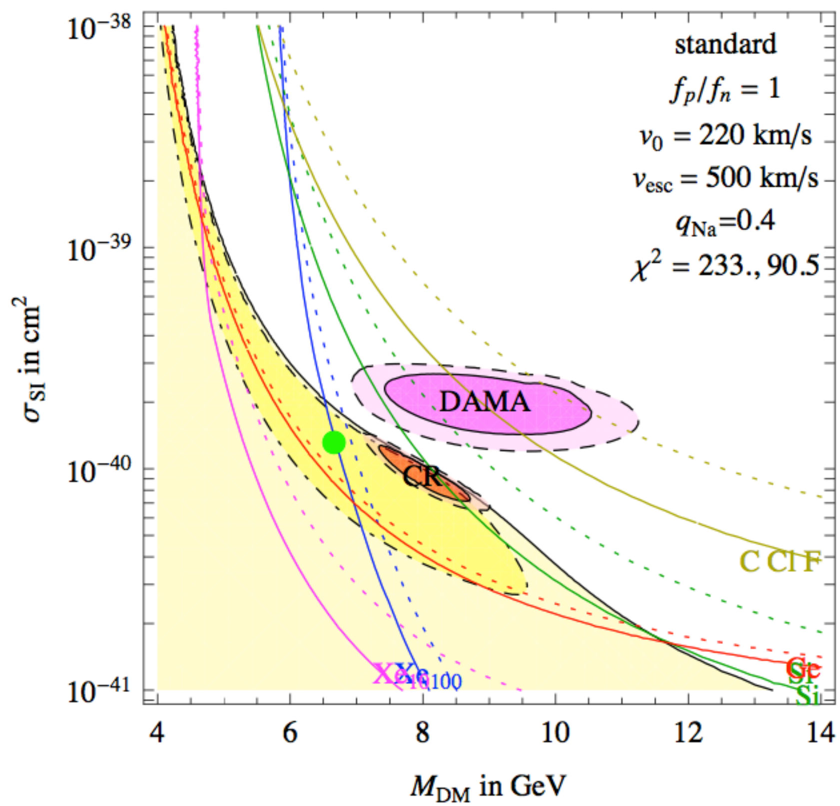
(Xenon100 is out very soon, superCDMS is on it's way...)

Explaining the Anomalies..

- What can the positive signals be given the null experiments?
- Lots of trials:
  - Inelastic DM [Tucker-Smith,Weiner, 2001]
  - Form-factor DM [Feldstein,Fitzpatrick,Katz, 2009]
  - Resonant DM [Bai,Fox, 2009]
  - Luminous DM [Feldstein,Graham,Rajendran, 2010]
  - Isospin violating DM [Chang et al., Kang et al., Feng et al.]
  - Exothermic DM [Graham,Harnik,Rajendran,Saraswat, 2010]
  - ...

DM Fits: Standard Fit





- DAMA and CoGeNT do not overlap.
- DAMA and CoGeNT are disfavored.
- DAMA quenching factors shift the mass.

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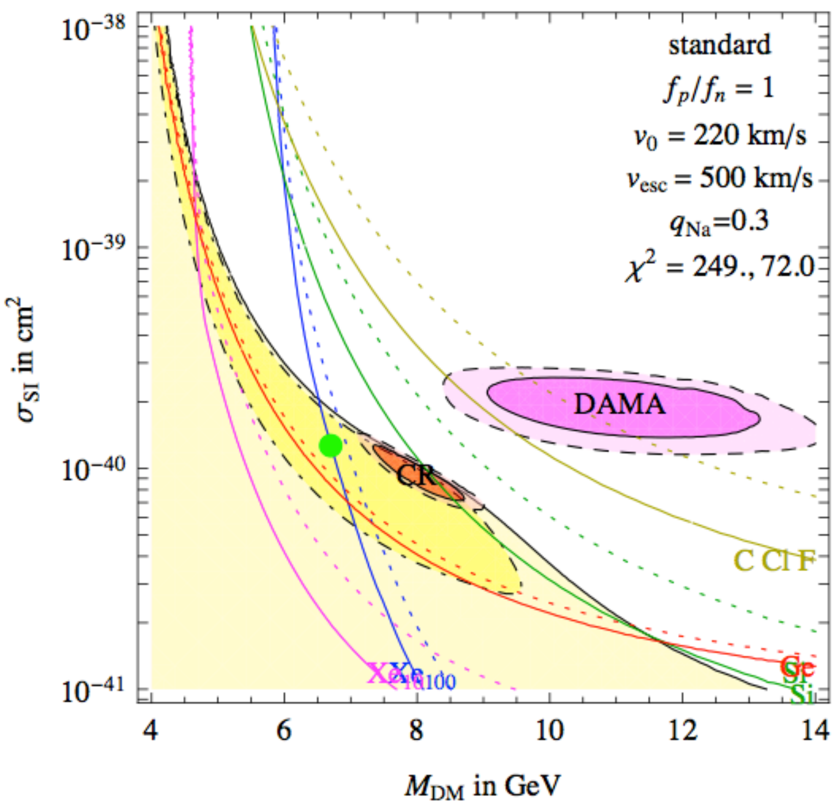

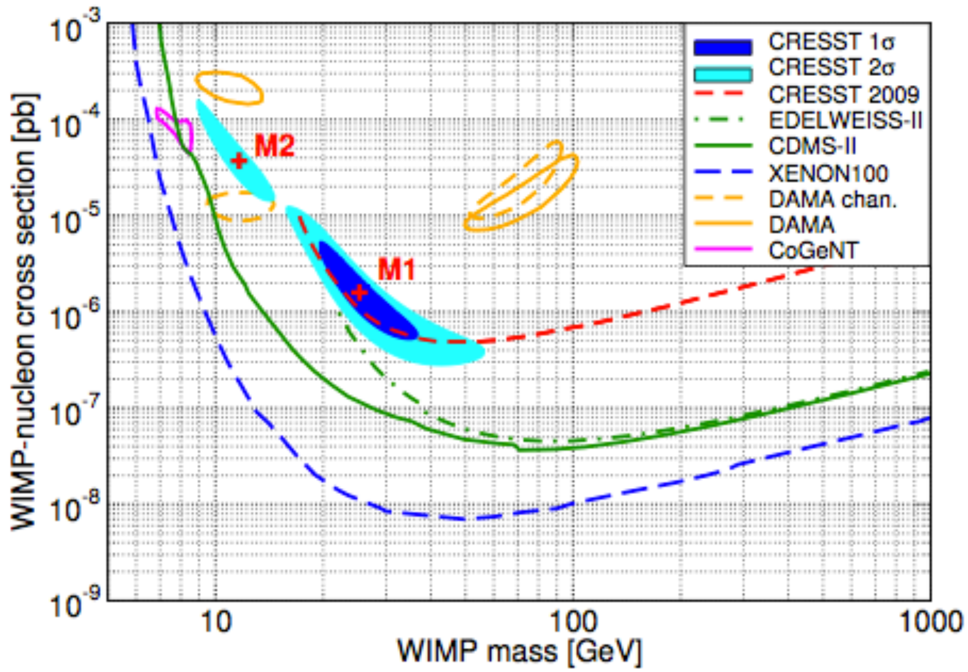

- DAMA and CoGeNT do not overlap.
- DAMA and CoGeNT are disfavored.
- DAMA quenching factors shift the mass.

DM Fits: Isospin Violation

- May improve agreement in DAMA and CoGeNT.
- Can evade one bound tuning: $f_p Z + f_n(A-Z) \sim 0$ so that,

$$\frac{d\sigma_{\rm SI}}{dE_{\rm R}} = \frac{m_N \sigma_n}{2v^2\mu_n^2}\frac{[f_p Z + f_n(A-Z)]^2}{f_n^2} F_N^2(q) F_{\rm DM}^2(q,v) \sim 0$$

- Easy to accommodate isospin violation in a microscopic theory:

$$W = \sum_i (\lambda_q^i X Y_{q_L} q_L^i + \lambda_u^i X Y_{u_R} u_R^i + \lambda_d^i X Y_{d_R} d_R^i)$$

$$\mathcal{O}_i = \lambda_q^i \lambda_u^i X X \bar{u}^i u^i / m_Y + \lambda_q^i \lambda_d^i X X \bar{d}^i d^i / m_Y$$

[Feng et al., 2011]

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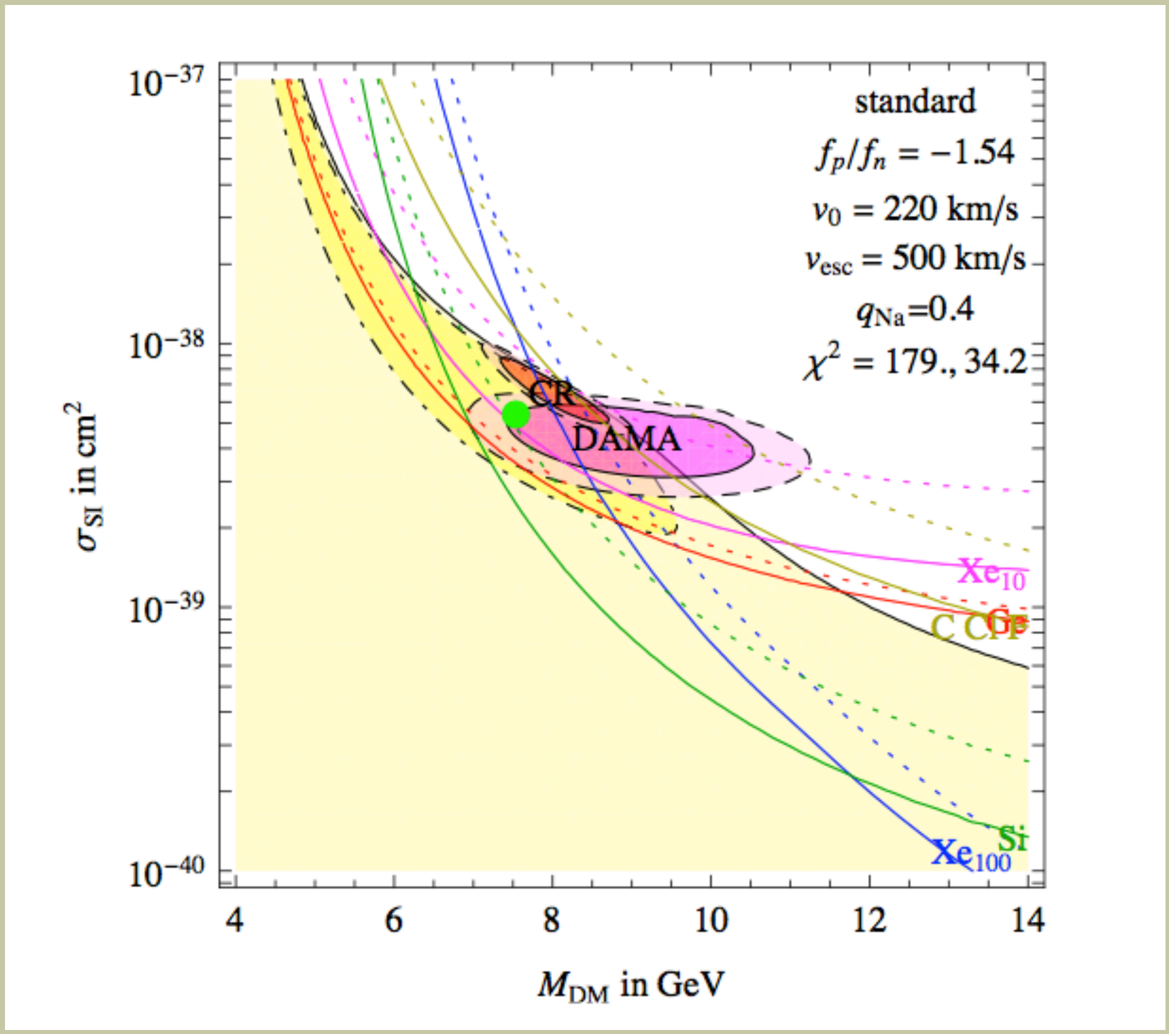
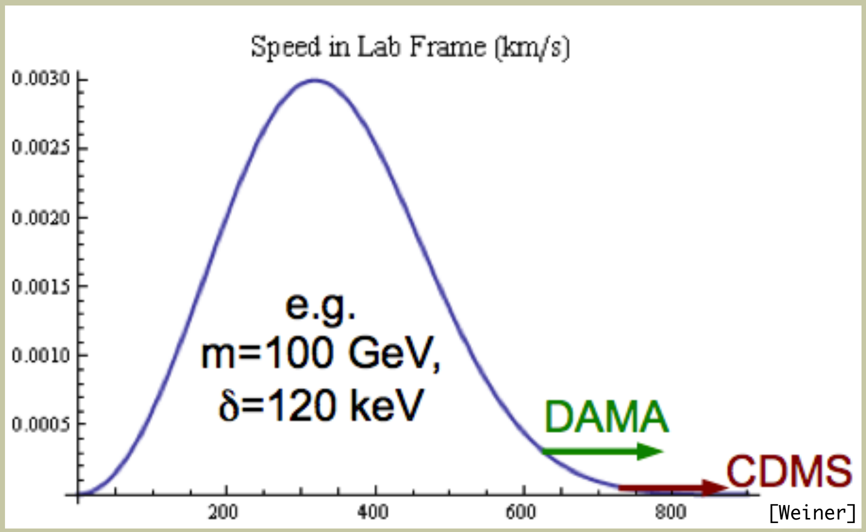
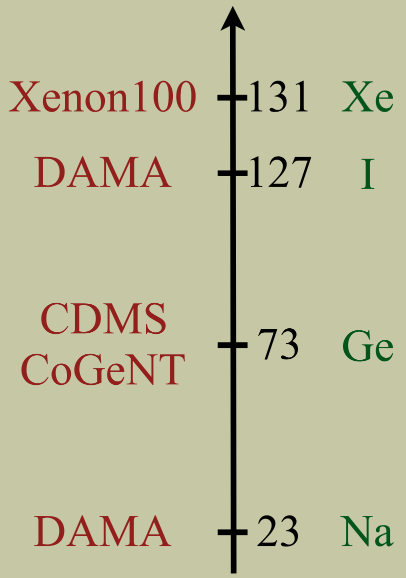


DM Fits: Inelastic Scattering

- It is possible that DM scattering is inelastic, $\delta = m_{\rm DM} - m'_{\rm DM}$
- Up-scattering of the lighter DM state requires it to have enough energy, thereby suppressing the rate for small values of the recoil energy.
- iDM favors heavy targets: $$v_{\rm min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu} + \delta \right| .$$
- Originally suggested to ameliorate between (the heavier) DAMA and other null experiments. Worked for $m_{\rm DM} \sim 100$ GeV, $\delta \sim 100$ keV. Now excluded by Xenon100.





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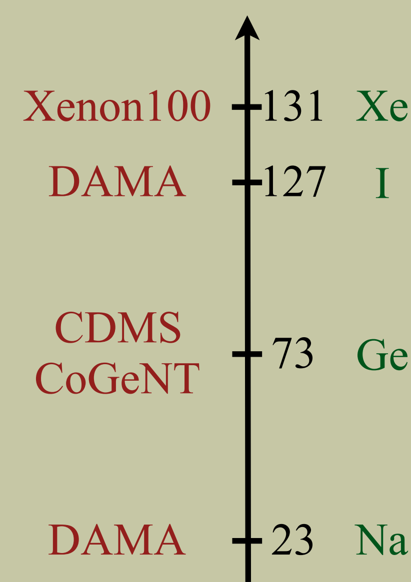
- Originally suggested to ameliorate between (the heavier) DAMA and other null experiments. Worked for $m_{\mathrm{DM}} \sim 100$ GeV, $\delta \sim 100$ keV. Now excluded by Xenon100.

- For the light DM case, endothermic inelasticity doesn't make a big difference.

- However, the heavier DM can be long lived and have a significant density.

- Then DM can down-scatter - exothermic DM ($\delta<0$).

- Minimal velocity is minimized for $E_R \sim \mu\delta/m_N$ hence lighter targets are more sensitive.



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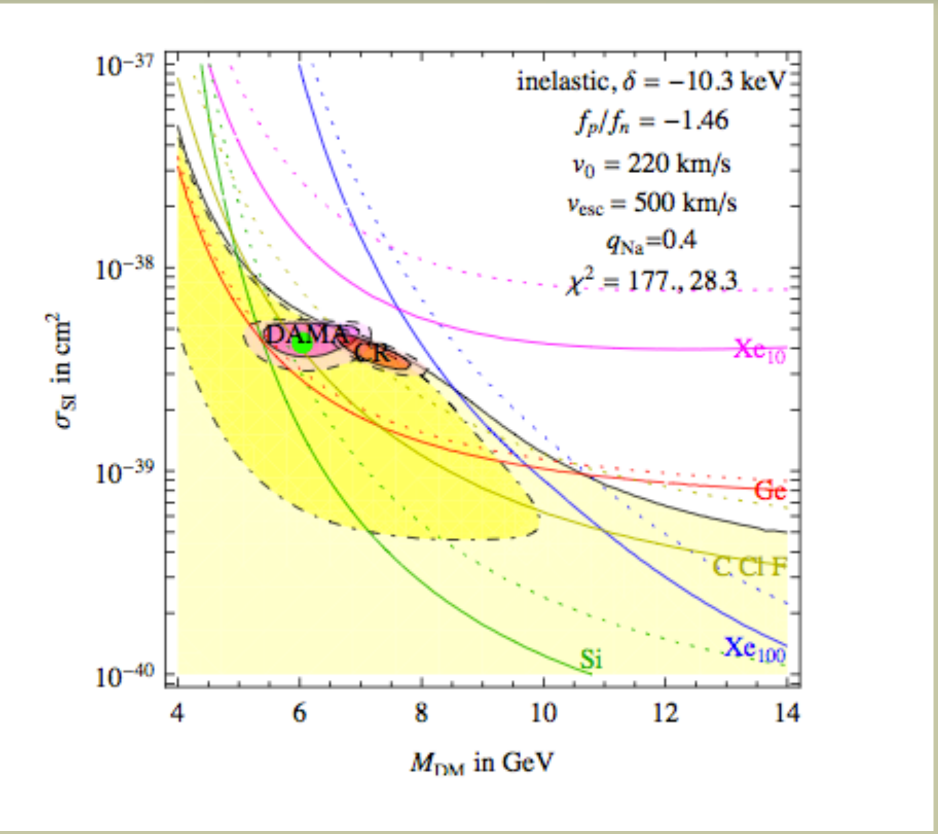

- However, the heavier DM can be long lived and have a significant density.

- Then DM can down-scatter - exothermic DM (δ<0).

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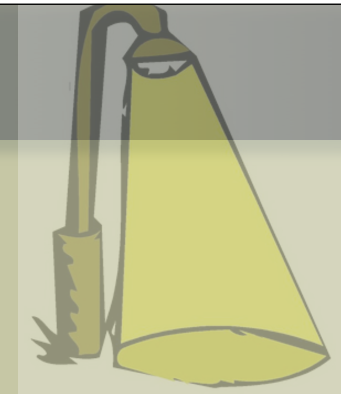
What's the Take-home Message?

- Prior to the new BG source in CoGeNT, nothing seemed to work well.
- No new analysis yet has been reported but it seems that after removing the surface events, CoGeNT does not agree with DAMA and should have far too large modulation.

We (the theorists) issue a call for new anomalies...

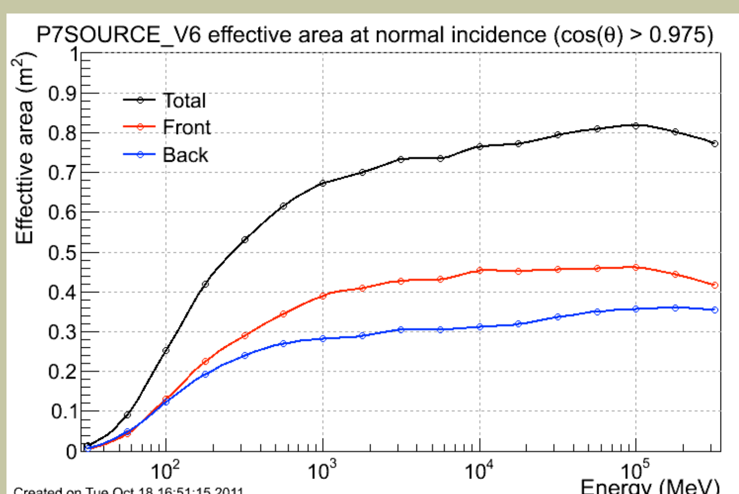
Going Beyond the WIMP Scenario

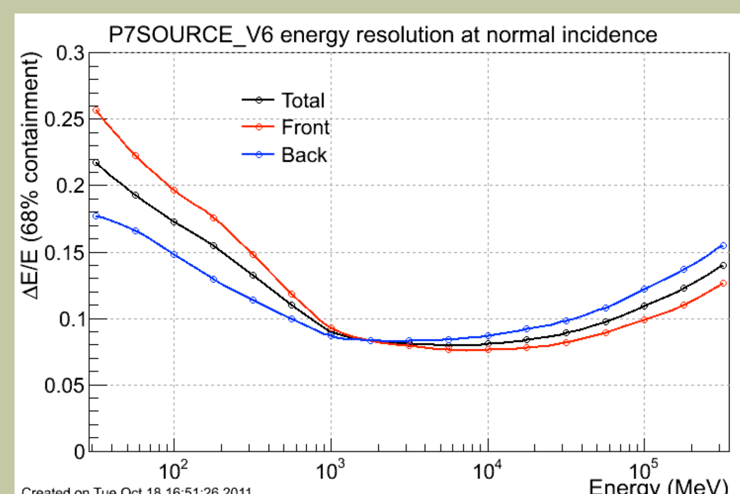
Looking Under the Lamppost..



We’ve been obsessed with WIMPs

- By and large, most of our current experimental searches for DM are “tuned” for the WIMP:
  - Collider Searches: Search for TeV physics and are therefore most sensitive to Weak scale DM.
  - 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.





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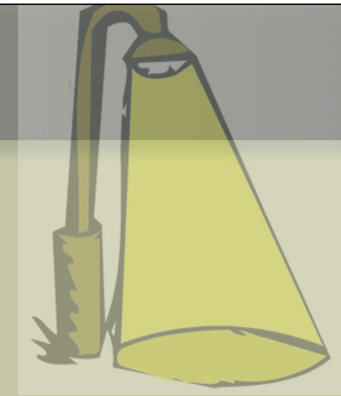

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- By and large, most of our current experimental searches for DM are "tuned" for the WIMP:
  - Collider Searches: Search for TeV physics and are therefore most sensitive to Weak scale DM.
  - Indirect Detection: Large CR BG at low energy ($E^{-2.8}$) 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.

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

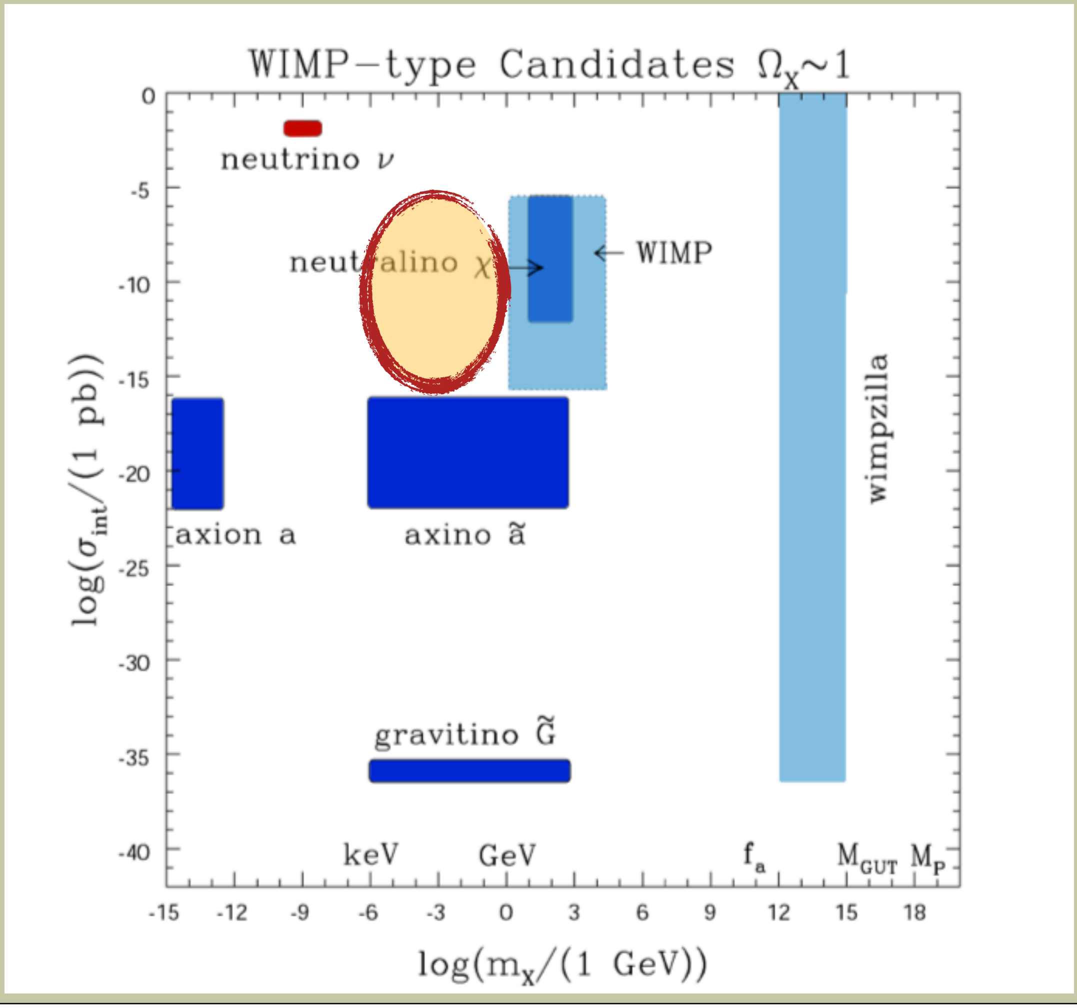
A WIMP?

No convincing e   related to the
hierarchy prol   rved so far.

Our experime   the WIMP.

But what if it's not a WIMP???

We'll focus here on the case of light (sub-GeV) DM



Sub-GeV Dark Matter

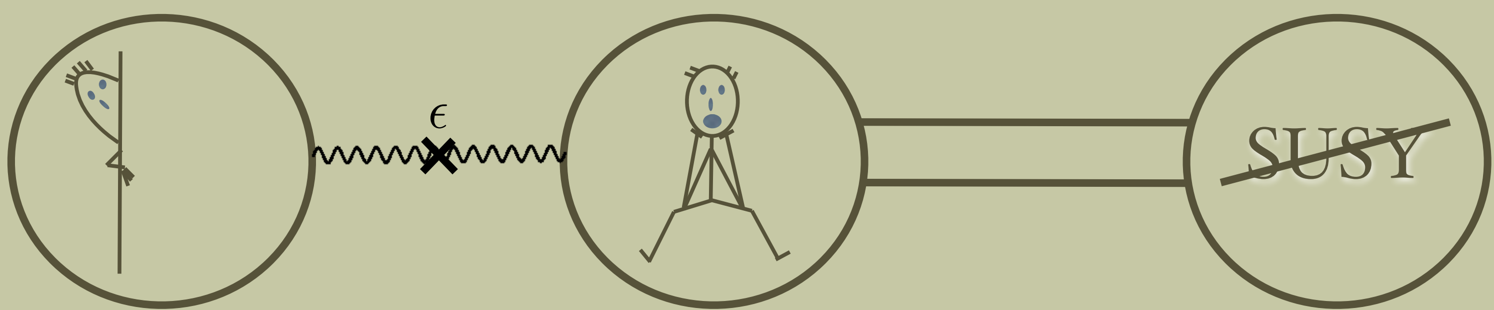
- Although hasn't been studied systematically, there are numerous models that may accommodate light DM (keV - GeV):
  - WIMPless DM. [Feng Kumar, 2008 Feng, Shadmi, 2011]
  - MeV DM (explaining INTEGRAL). [Boehm, Fayet,Silk,Borodachenkova, Pospelov,Ritz,Voloshin,Hooper,Zurek,...]
  - Asymmetric DM. [Nussinov, 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?

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

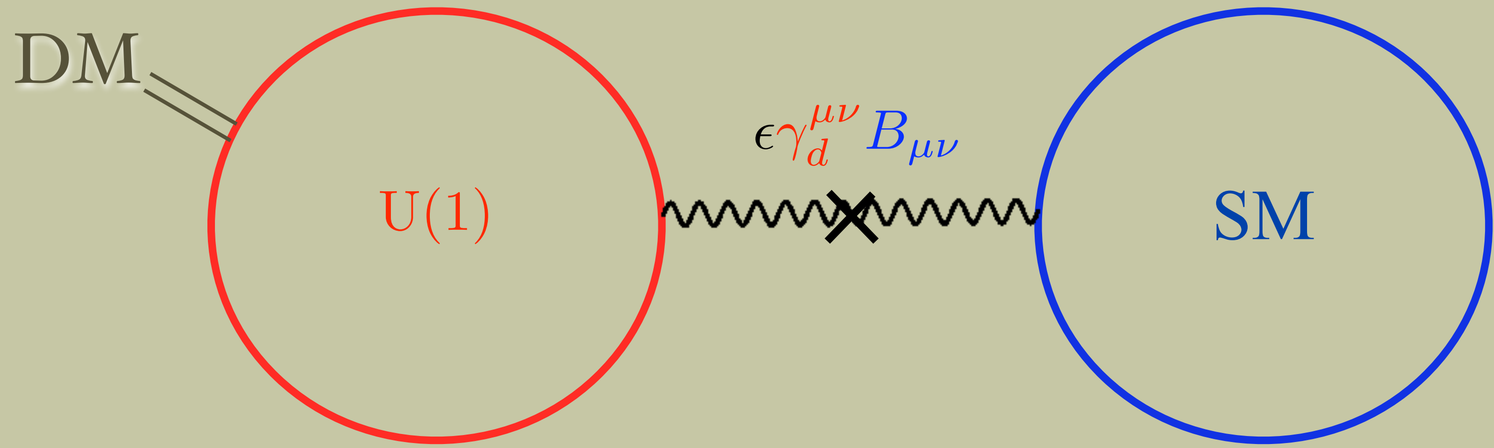
$$\epsilon m_W \qquad \text{or} \qquad \frac{\alpha}{4\pi} m_W$$

which can naturally be $\lesssim$ GeV.

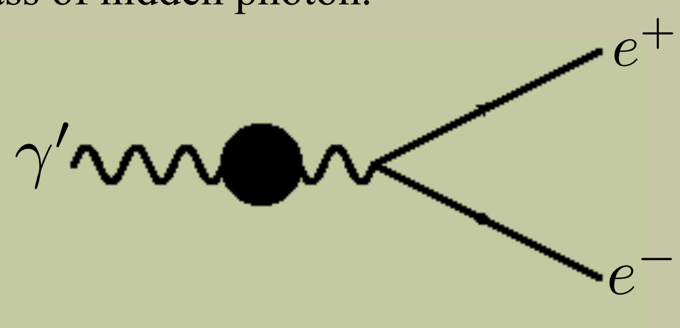


[Essig,Mardon,TV, work in progress]

Simple Realization



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



$$A_\mu \to A_\mu + \epsilon \cos\theta_W \gamma_{d\mu}$$

$$A_\mu J^\mu_{\rm SM} \to A_\mu J^\mu_{\rm SM} + \epsilon \cos\theta_W \gamma_{d\mu} J^\mu_{\rm SM}$$

- Therefore the SM fields are millicharges under the new photon.

Asymmetric DM

[Nussinov, 1985; , Kaplan, 1992]

Experimental fact:

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

Main idea:

Relate the DM abundance to the baryon abundance.

Asymmetric DM

[Nussinov, 1985; , Kaplan, 1992]

- DM carries a conserved charge.
- A finite $n_{\Delta\chi} = n_\chi - n_{\bar{\chi}}$ is generated in the early universe.

Example:

- $B - L$ asymmetry is generated at high scale.
- Asymmetry is transferred to DM through an operator, e.g. $\chi^2 HL$.

[Kaplan, Luty, Zurek, 2009]

- Depending on when the operator decouples,

$$n_\chi = n_b \quad \text{or} \quad n_\chi = n_b e^{-m_\chi/T_d}$$

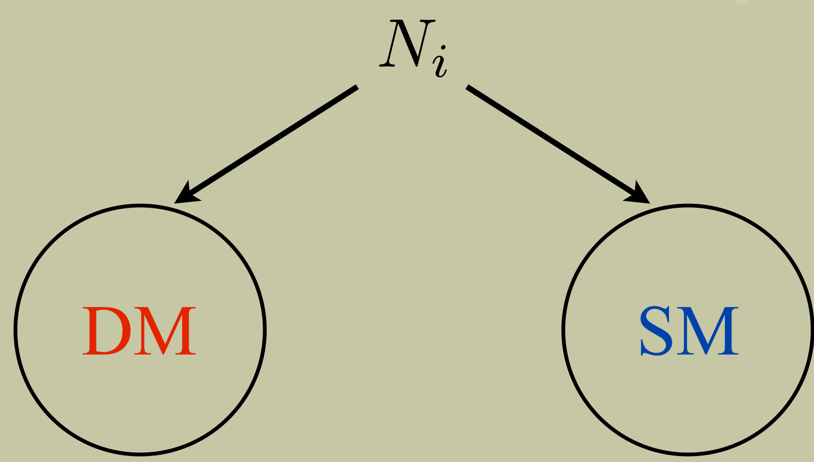
$$m_\chi \sim \text{GeV} \qquad\qquad m_\chi \sim \text{TeV}$$

- Meanwhile, the symmetric component is annihilated away.
- DM density is controlled by the asymmetric component.

2-sector Leptogenesis

- Simple scenario: 2-sector leptogenesis.

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



- The ratio number densities in the two sectors depend on the ratio of branching fractions.

- If the asymmetric component dominates the DM density (fast annihilations), one can obtain a wide range of DM number densities, and therefore a wide rate of DM masses: keV - 100 TeV.

Asymmetric or Symmetric?

Experimental fact:

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

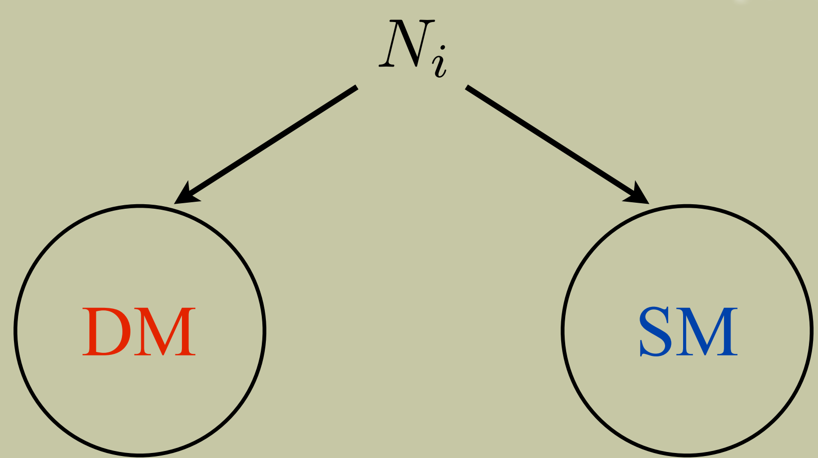
- If we take this as a hint, both densities are related through some joint dynamics.
- The dynamics may relate the baryon asymmetry to a symmetric and/or asymmetric DM density.
- Whether or not the symmetric component dominates, depends on the the DM annihilation cross-section:
  - Large $\sigma_{\rm ann}$: Asymmetric DM
  - Small $\sigma_{\rm ann}$: Symmetric DM

What is the generic expectation in the Symmetric case?

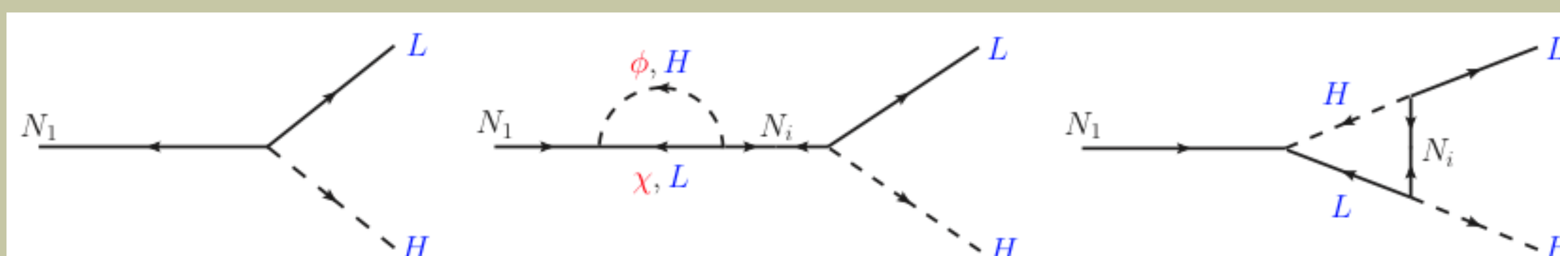
Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

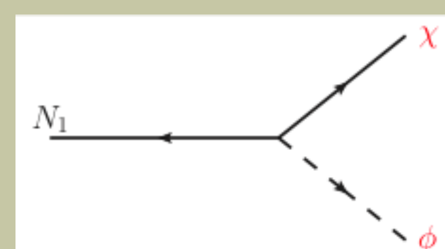
[Falkowski,Kuflik,TV, work in progress]
[Falkowski,Ruderman,TV, 2011]



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



- Symmetric DM produced through tree level:



Sub-GeV?

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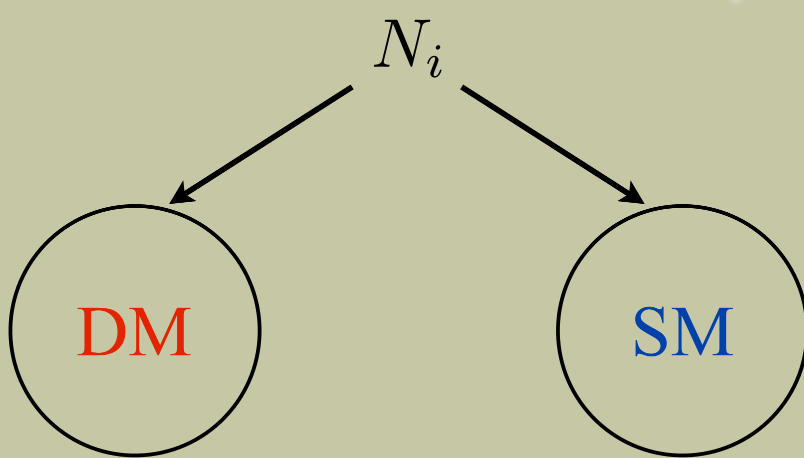

- Consequently, DM number density is generically larger than number baryon density.
- To have the same mass density, $\Omega_i \propto m_i n_i$, this requires $m_{DM} < m_{proton}$

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

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

[Finkbeiner et al. 2009]

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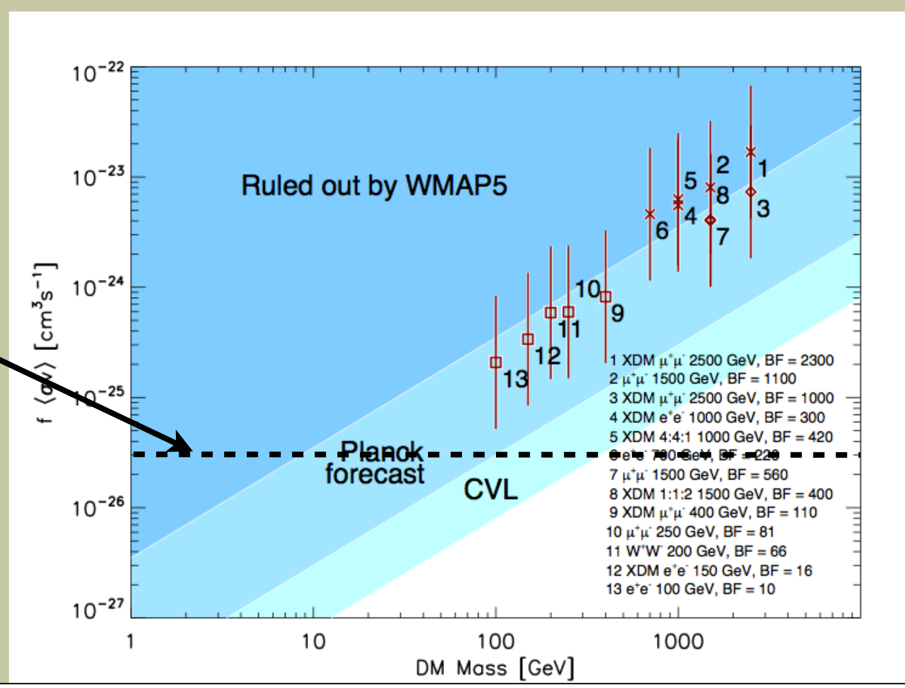
  - Annihilations during CMB. Significant DM annihilations may re-ionize the photon-baryon plasma, leaving imprints in the CMB.

Standard Thermal WIMP



[Finkbeiner et al. 2009]

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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]

Model Summary

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

- Some constraints are model-dependent.

Large class of viable models exist!!

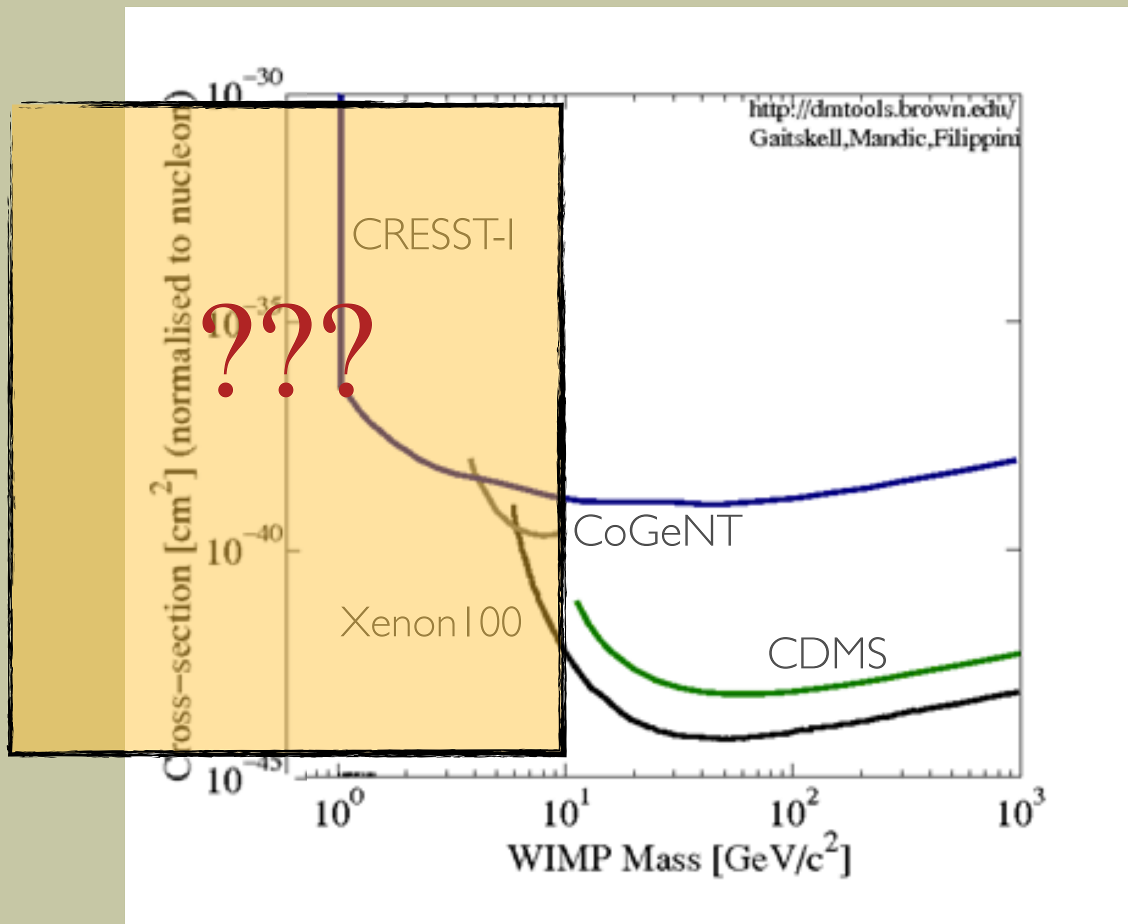
[Essig,Mardon,TV, work in progress]

- Key question: Can we probe these models?

Direct Detection of Light Dark Matter

Based on:
R. Essig, J. Mardon, TV [arXiv:1108.5383].
R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, TV (submitted to PRL).
More work in progress...

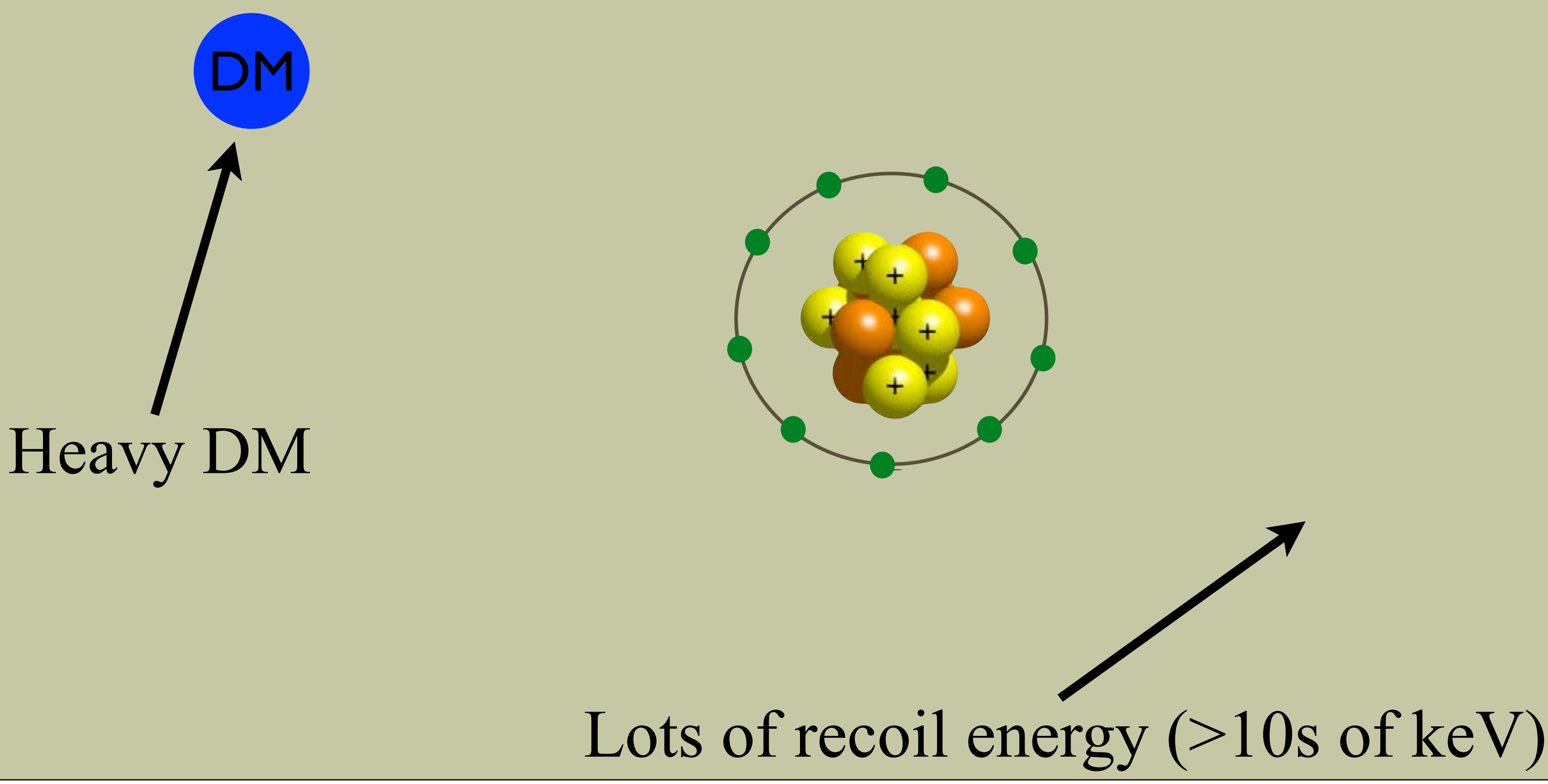
Where is DM?



http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
CRESST-I
???
CoGeNT
Xenon100
CDMS
Cross−section [cm^2] (normalised to nucleon)
WIMP Mass [GeV/c^2]

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:



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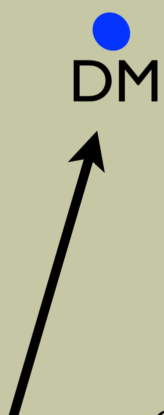
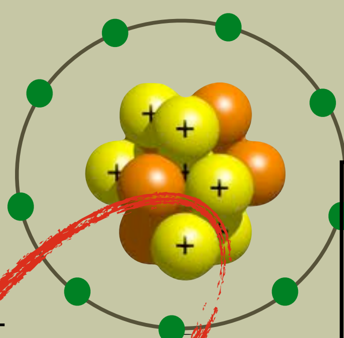


Light DM

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

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



Recoil energy drops fast

Can't go below ~ GeV

Negligible recoil energy

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

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

But DM energy is significantly larger:

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

Elastic Scattering of LDM

Current direct detection experiments search for elastic scattering off nuclei:

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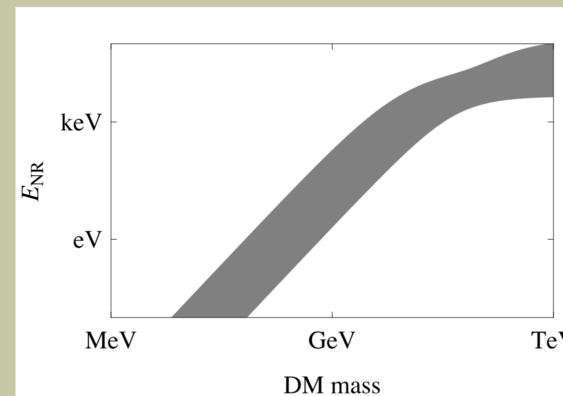
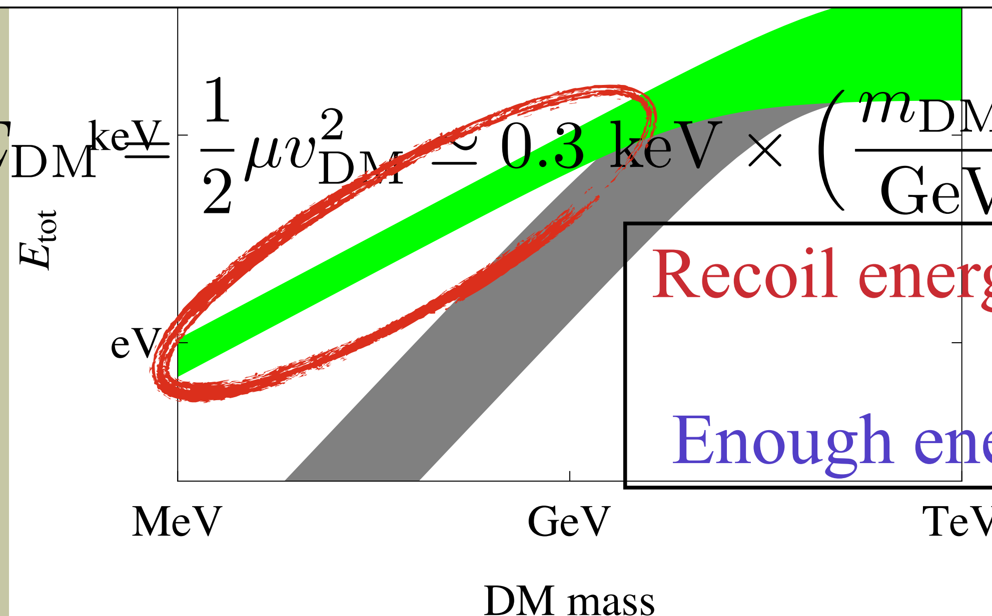
$$\sim 3 \text{ eV} \times \left(\frac{m_{\rm DM}}{\rm GeV}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$



Studying nuclear recoils is extremely inefficient for light DM

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



Recoil energy drops slower

Enough energy to detect!!

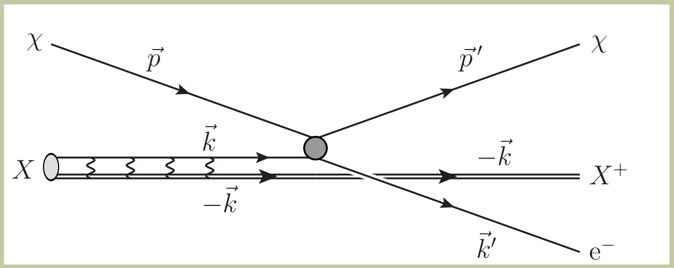
Ways to Detect Light DM

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

- Three possibilities:

  1. Electron ionization

Threshold: eV - 100's eV
DM-electron scattering



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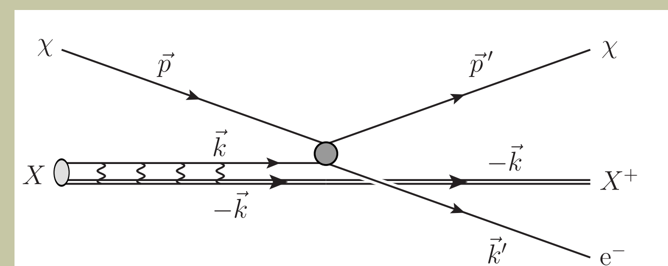
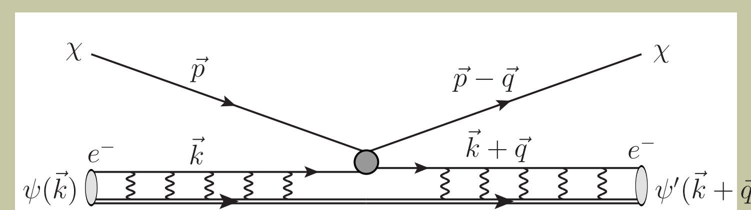
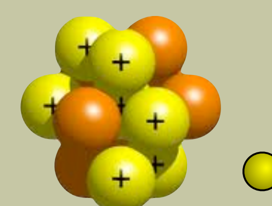


2. Electronic excitation

   Threshold: eV - 100's eV
   DM-electron scattering





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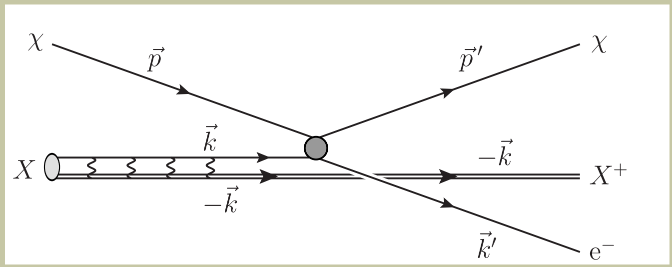

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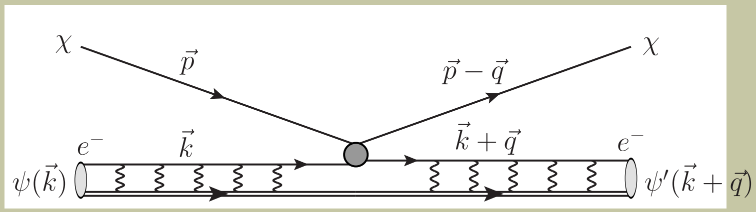
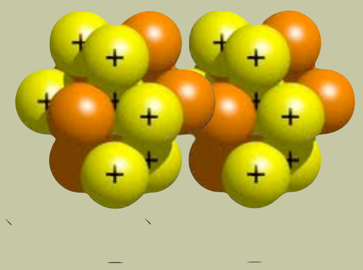


3. Molecular dissociation

   Threshold: ≳ few eV
   DM-nucleon scattering



Detectable Signals

There are several detectable signals, depending on the experimental setup:

- Individual electrons. An electron may be ionized (or, in semiconductors, excited to a conduction band).
  Signal amplification can be achieved by drifting the electron in an applied electric field.

- Individual photons. Following excitation, de-excitation may produce photons. Photons could escape the target and be detected if not efficiently reabsorbed. Current technologies are too noisy. Requires more R&D.

- Individual ions. Could be produced by ionizing electrons, or due to molecular dissociation.

- Heat/phonons. Energy deposited may emerge as phonons or heat, especially if any charge carriers produced are not drifted away from the interaction site by an electic field.

Discovery can be made using one or more of the signals above, depending on BG reduction.

Annual modulation an additional available tool.

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Discovery can be made using one or more of the signals above, depending on BG reduction.

Annual modulation an additional available tool.

For the rest of this talk:

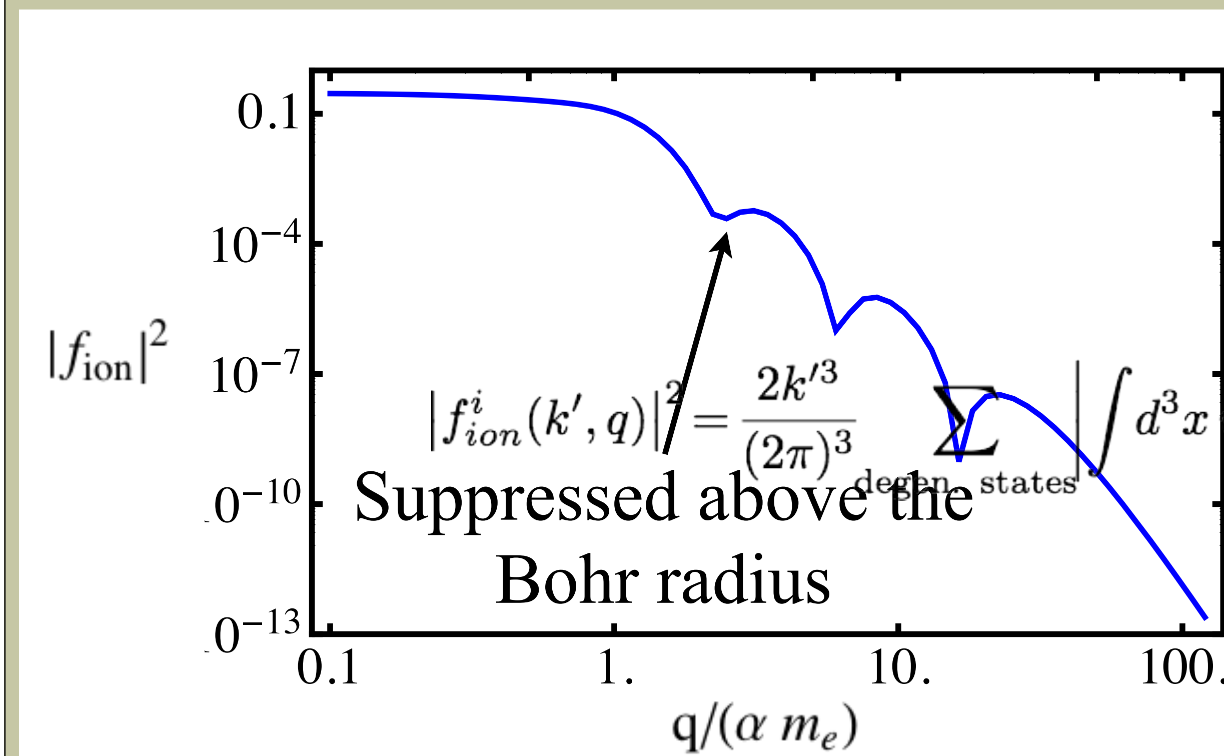
focus on electron ionization
through electron-DM scattering

Computing Rates

Ionization Rate

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

Determined by atomic wave-functions



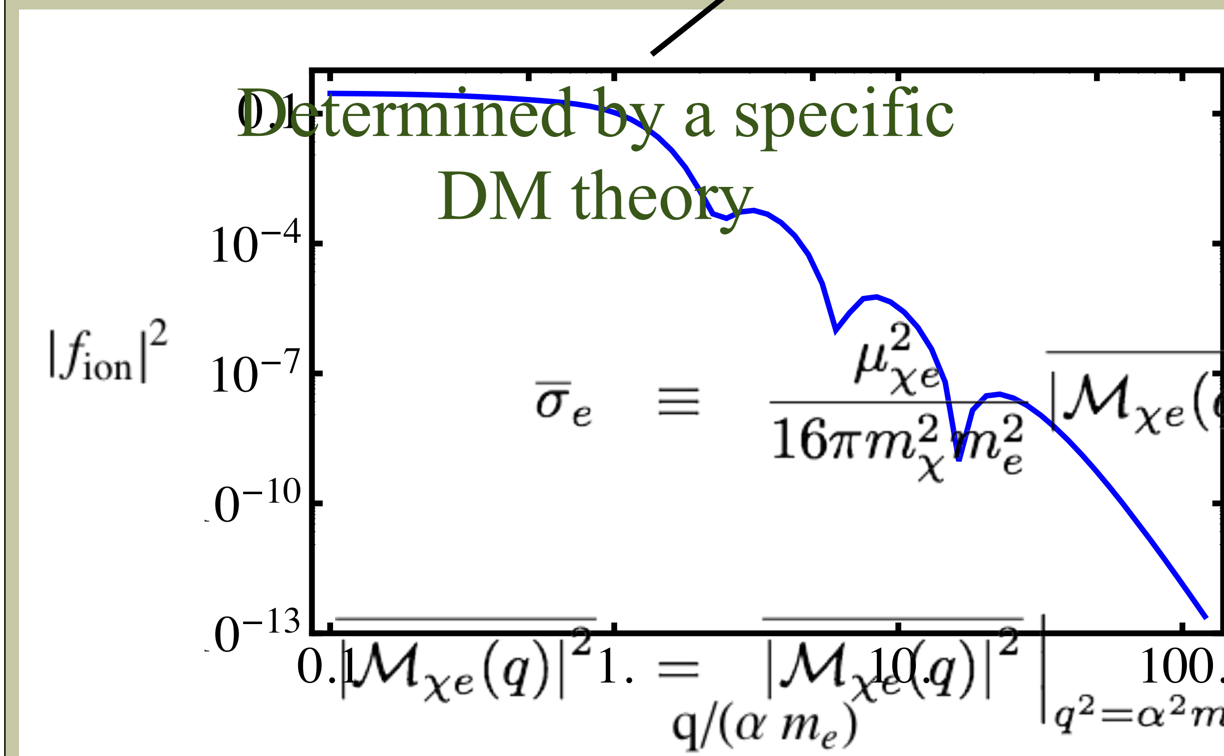
$$|f^i_{ion}(k',q)|^2 = \frac{2k'^3}{(2\pi)^3} \sum_{\text{degen. states}} \left| \int d^3x\, \tilde{\psi}^*_{k'l'm'}(\mathbf{x})\psi_i(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} \right|^2$$

Rates are suppressed for large momentum transfer!

Ionization Rate

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

Determined by a specific DM theory



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

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

Kinematics

- Kinematics dictates the minimal velocity to ionize:

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

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

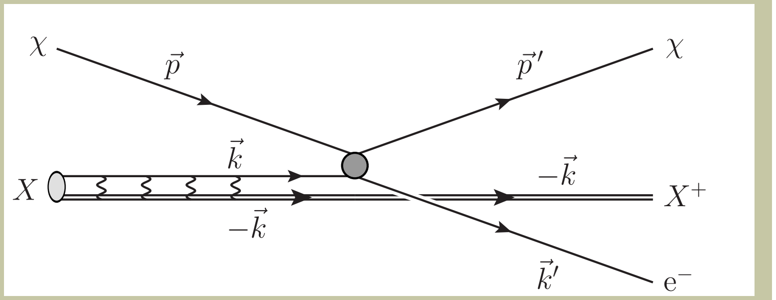
$$m_{\rm DM} \geq \text{MeV} \times \left(\frac{\Delta E_B}{5 \text{ eV}}\right)$$

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

Tension between kinematics and form factor.

Ionization Rate

- The velocity-averaged differential cross-section:



$$\frac{d\langle\sigma^i_{ion}v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}}\int q\,dq\left|f^i_{ion}(k',q)\right|^2\left|F_{\rm DM}(q)\right|^2\eta(v_{\rm min})$$

$$\eta(v_{\rm min},t) = \int_{v_{\rm min}}^{\infty} d^3v\,\frac{f(\vec{v},t)}{v}$$

$f(\vec{v},t)$ – DM velocity distribution

$$v_{min} = \frac{\Delta E_B + E_R}{q} + \frac{q}{2m_\chi}$$

Ionization Rate: Multiple Electrons

- Electron-DM scattering can result in more than a single electron.
- An energetic primary electron can ionize additional electrons and excite atoms.
- Ionized inner-shall electrons cause a de-excitation which in turn produce photons that can ionize additional electrons.

One can end up with 2-4 electrons

Bounds can be significantly stronger!

How to Compute Form Factor?

- For the form factor, we need to know the wave functions.
- In practice, the correct unbounded wave functions are tedious to compute. Approximate the outgoing electron as a free plane wave.
- Near origin wave function is modified by the presence of the ion from which it escaped.
- What is the effect of the distortion on the form factor? The escaping electron with momentum p far from atom, had to have momentum p_0>p near the origin (energy conservation):

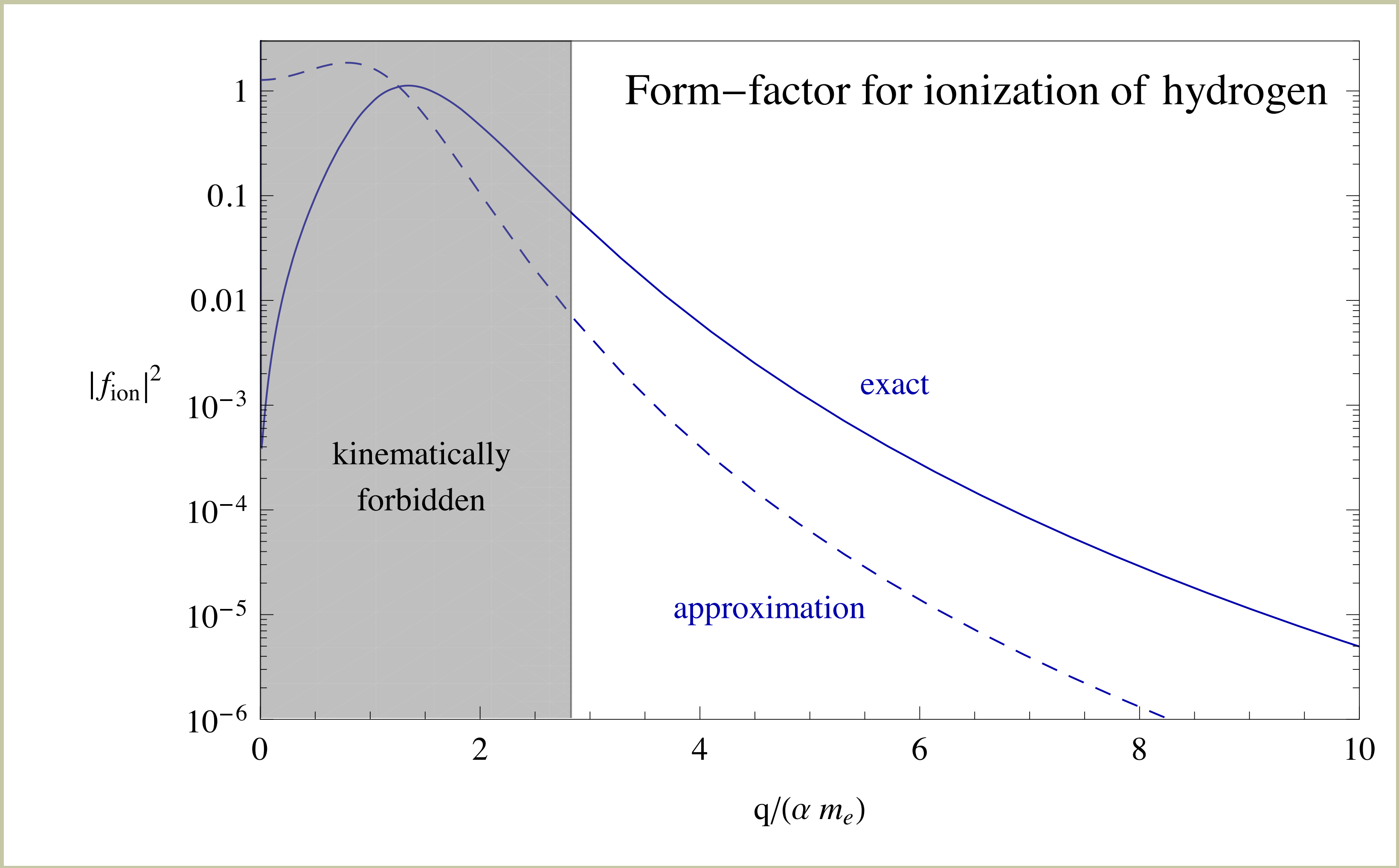
$$\frac{p^2}{2m_e} = \frac{p_0^2}{2m_e} - V(r) = \frac{p_0^2}{2m_e} - \frac{Z\alpha_{\rm EM}}{r}$$

$$p_0 \sim 2Z\alpha_{\rm EM}m_e - \frac{1}{2}\frac{p^2}{Z\alpha_{\rm EM}m_e}$$

$$p_0^2 dp_0 \sim \frac{Z\alpha_{\rm EM}m_e}{p} p^2 dp$$

So exact phase-space is enhanced compared to free wave functions.
Larger Z is better.

How to Compute Form Factor?

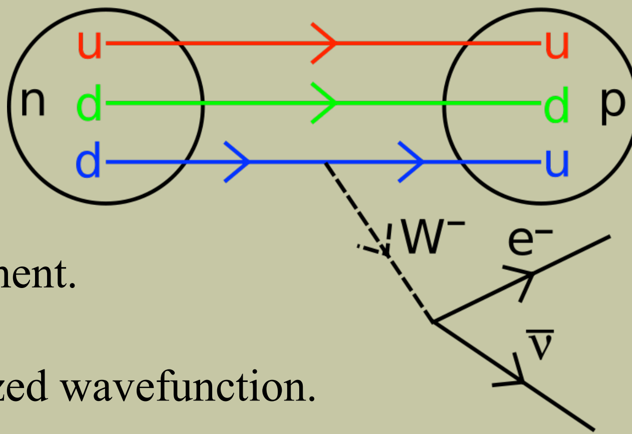


How to Compute Form Factor?

- This is in fact a well known effect in beta-decays.

- The enhancement of the wavefunction at the origin is given by the Fermi function:

$$F(p, Z_{\text{eff}}) = \left| \frac{\psi_{\text{exact}}(0)}{\psi_{\text{free}}(0)} \right|^2 = \frac{2\pi\eta}{1 - e^{-2\pi\eta}} , \qquad \eta = Z_{\text{eff}} \frac{\alpha m_e}{p} ,$$



- Similar parametrics shows up in the Zommerfeld enhancement.

- In our case, correction is a little different due to non-localized wavefunction.

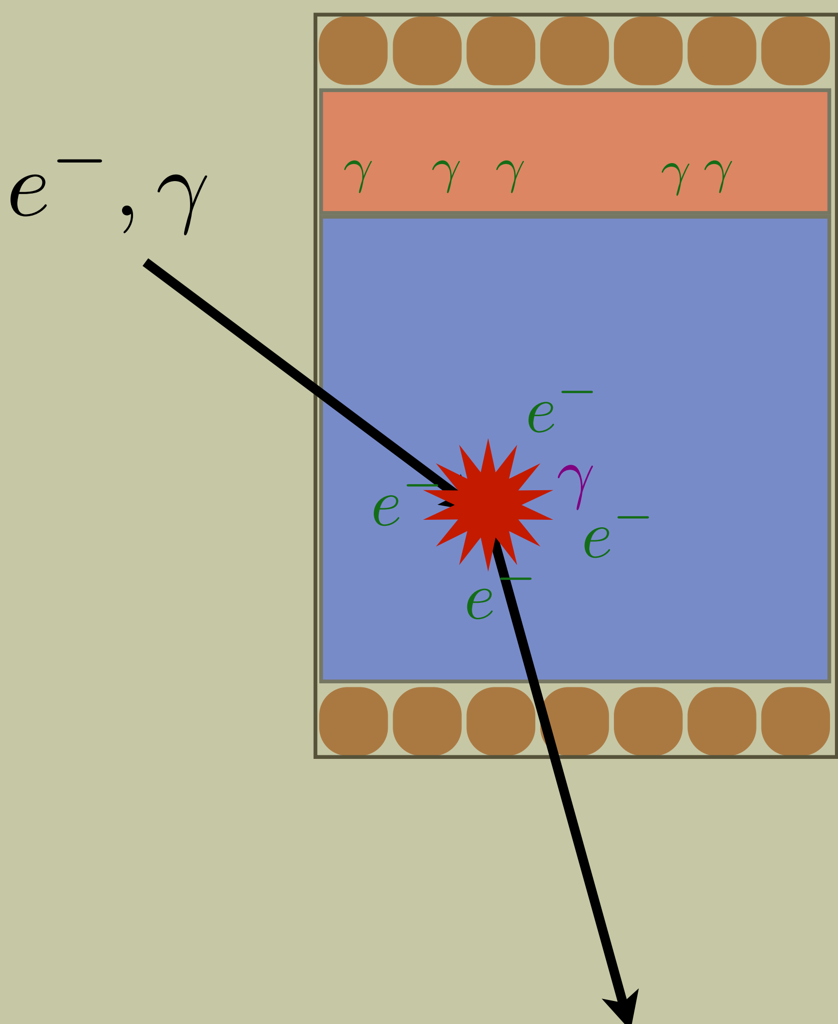
- This description is good to about 30%.

- To get more precise results, one can solve numerically the wave functions (which we do).

XENON10
Proof of Principle

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

Xenon10



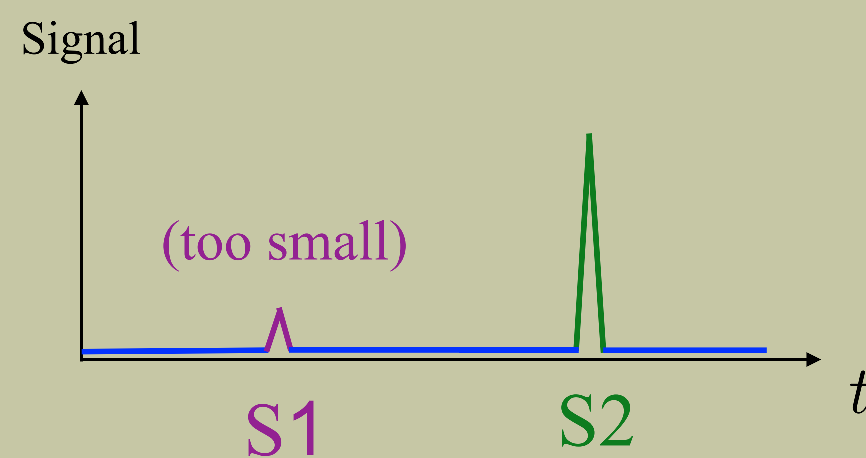
$$\mathrm{Xe} \rightarrow \; \mathrm{Xe}^*, \; \mathrm{Xe}^+$$

produces photons and electrons

Two types of signal:

S1: prompt scintillation

S2: proportional scintillation (from ionization)

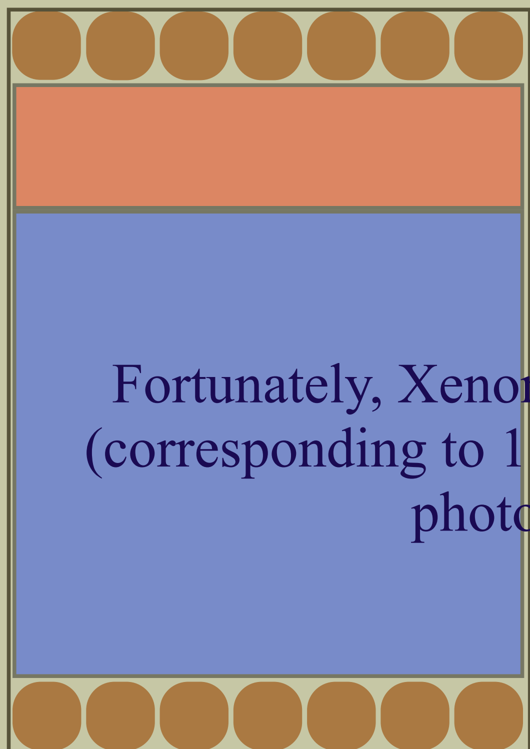


Xenon10

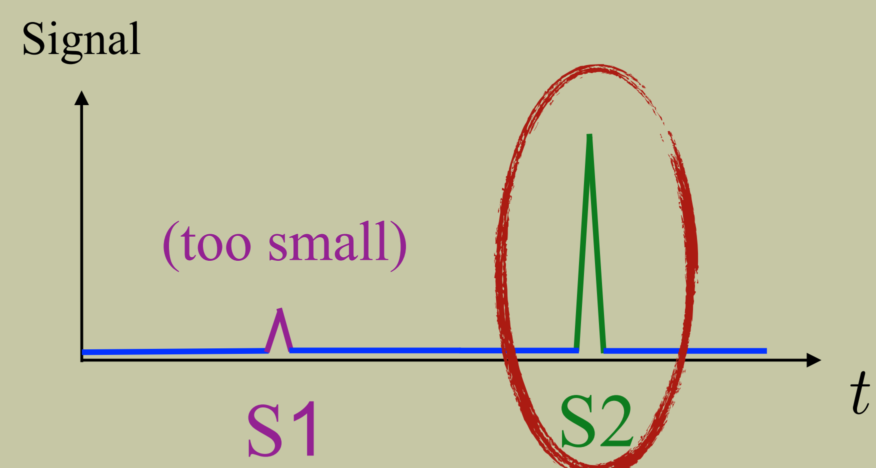
For LDM, S1 is too small!

Instead can use S2 Only

Every electron produced 27 photoelectrons
- sufficient for triggering.

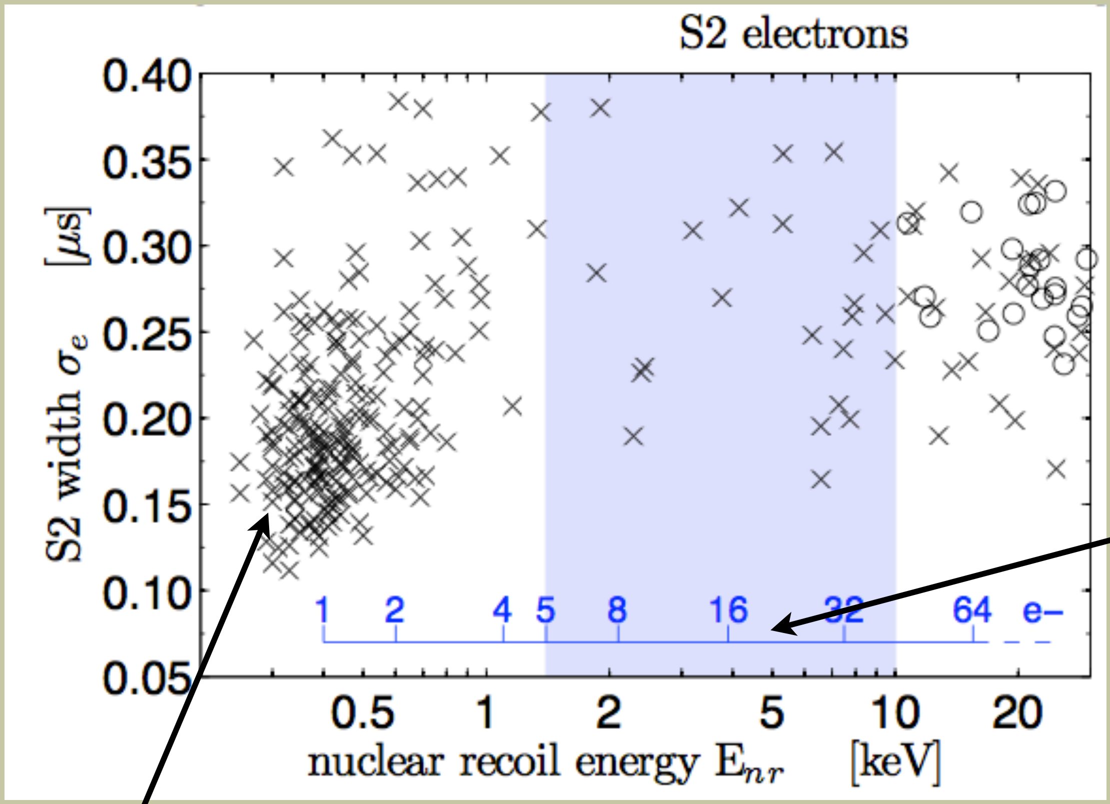


Fortunately, Xenon10 had a 12.5-day run (corresponding to 15 kg-days) with a single photon trigger.



Data Sample

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

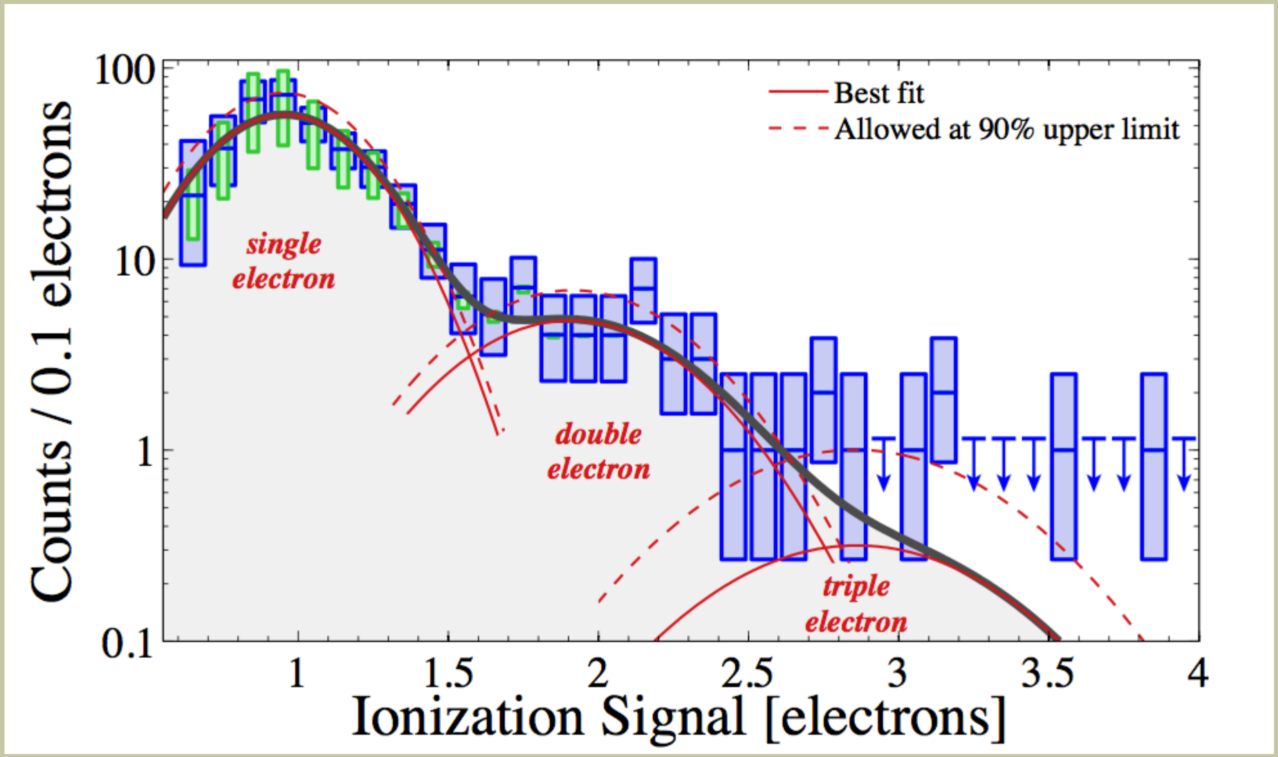


Number of electrons

Large population of single electrons.

Data Sample

- After correcting for triggering efficiency we get,

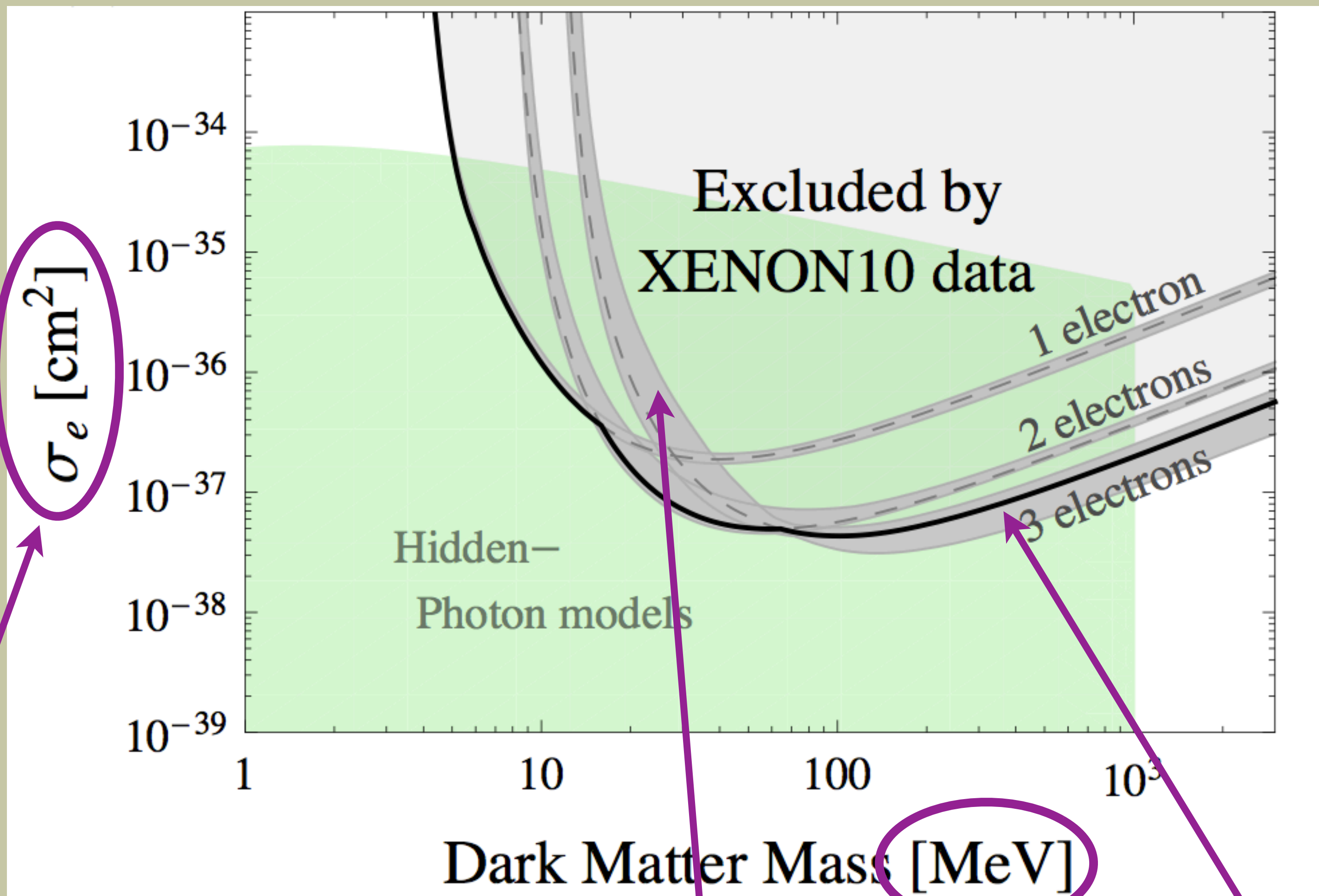


- The result of the fit (dark-gray curve) gives a 90% upper confidence bound (counts/kg/day):

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

Results: F_{DM}=1

First Direct Detection Bounds for MeV-GeV



free electron-DM cross-section.

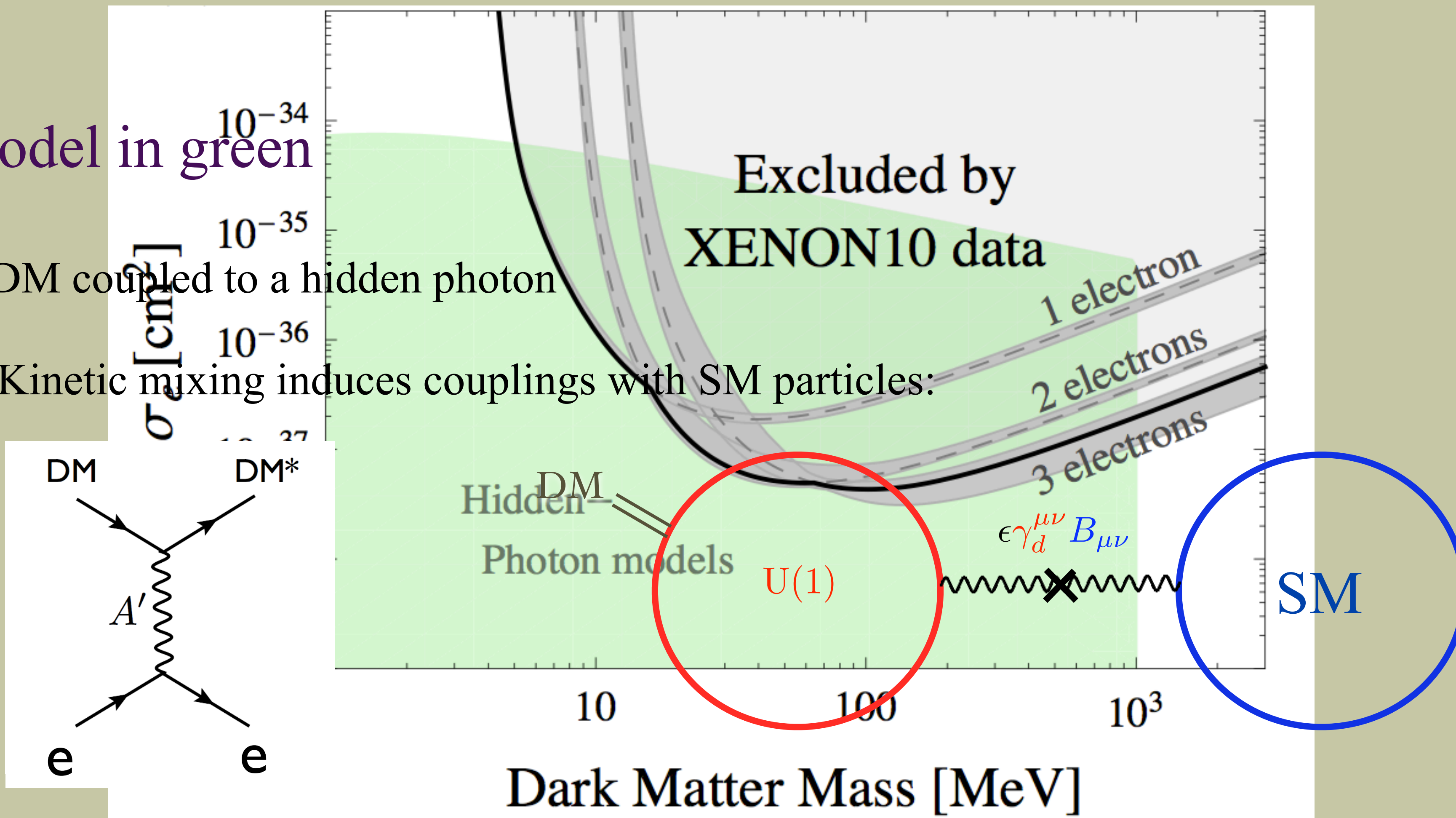
systematic uncertainties

Combined bound

Results: $F_{DM}=1$

Model in green

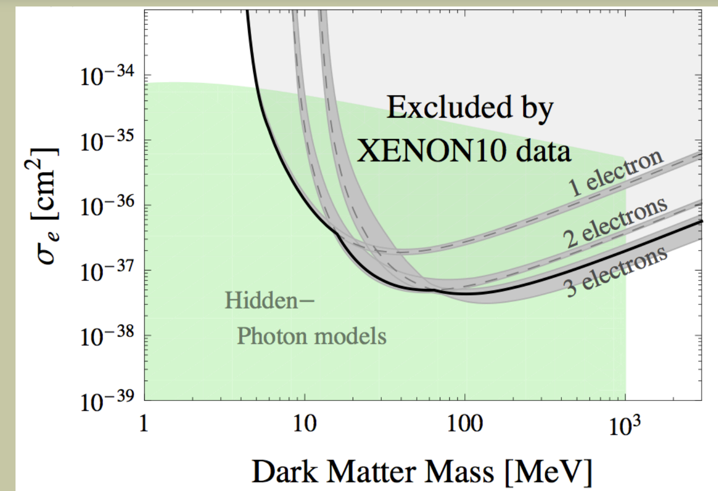
- DM coupled to a hidden photon
- Kinetic mixing induces couplings with SM particles:

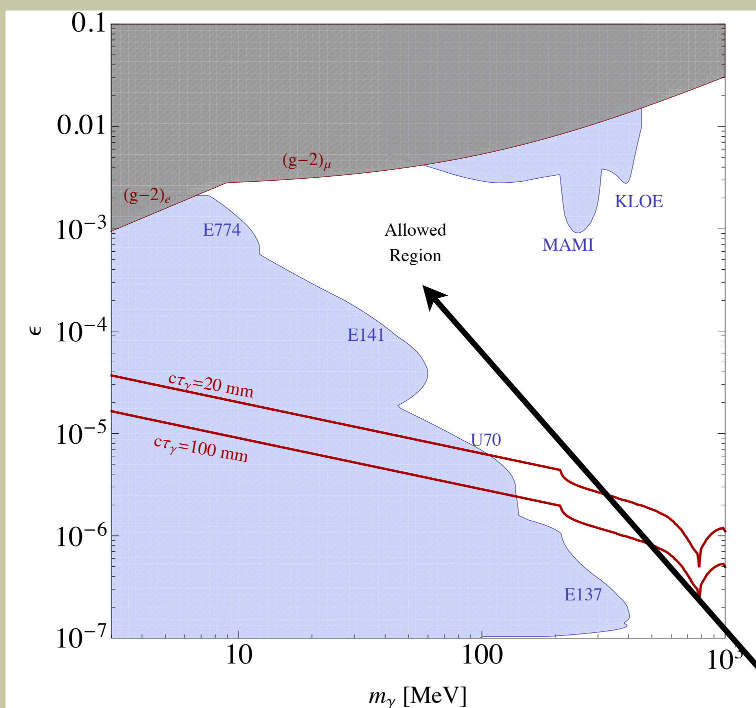


$$\sigma = \frac{16\,\pi\,m_e^2\,\alpha\,\alpha'\,\epsilon^2}{(m_{A'}^2+q^2)^2}$$

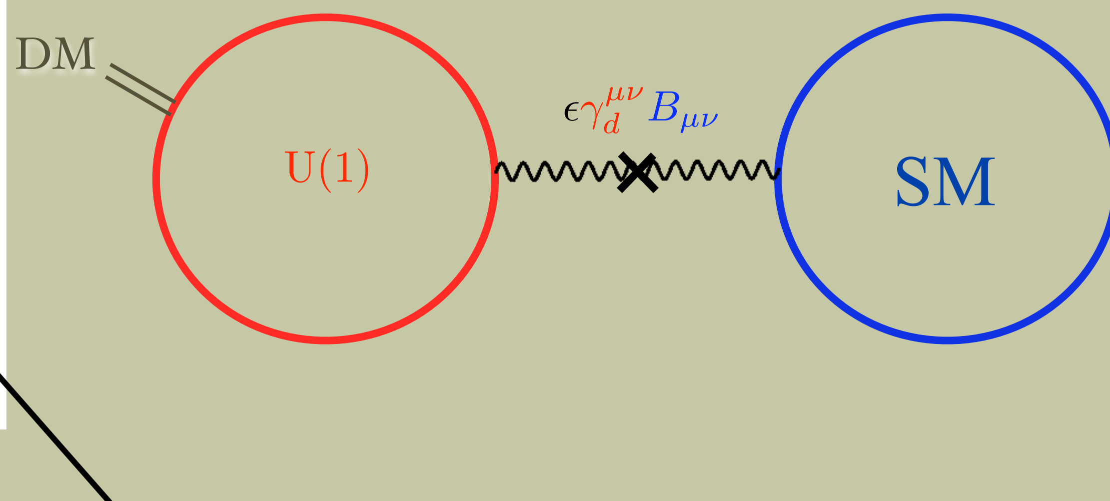
For m_A >MeV hidden photon: $F_{\mathrm{DM}} = 1$

Results: $F_{DM}=1$



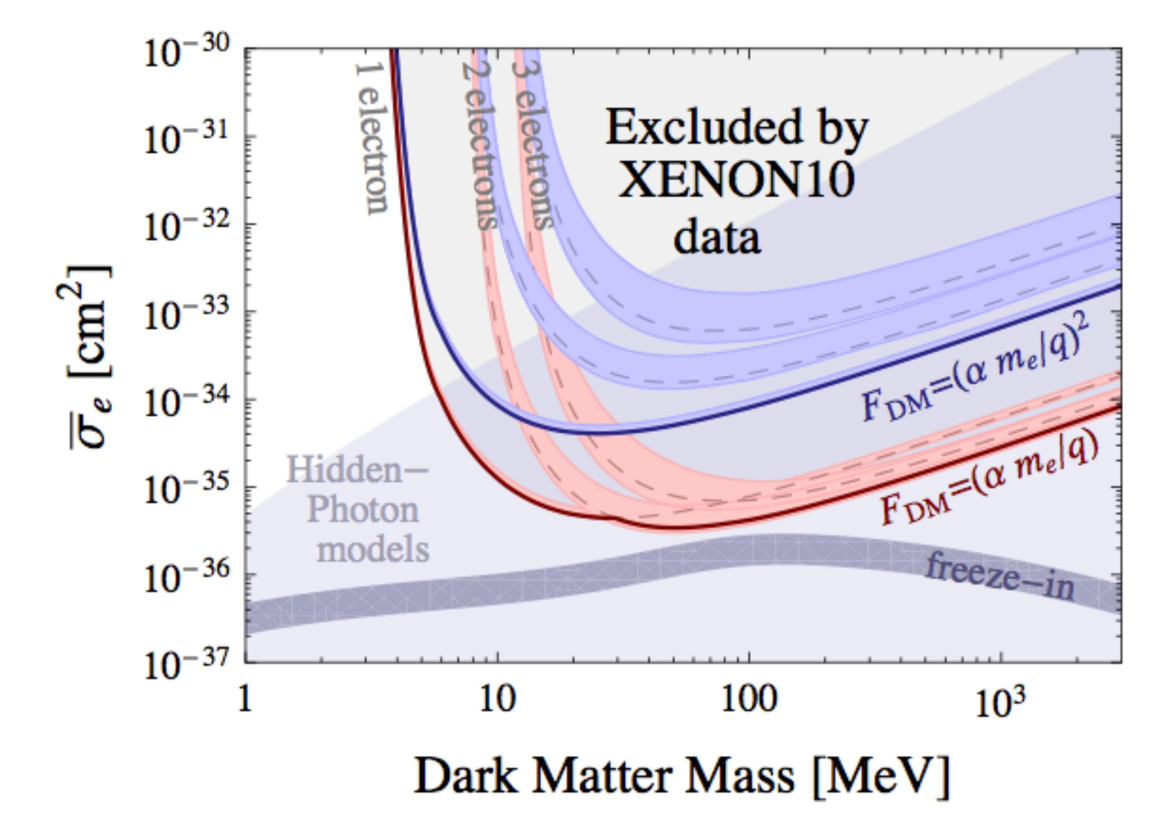


[Bjorken, Essig, Schuster, Toro 2009;
Blumlein, Brunner 2011]



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

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



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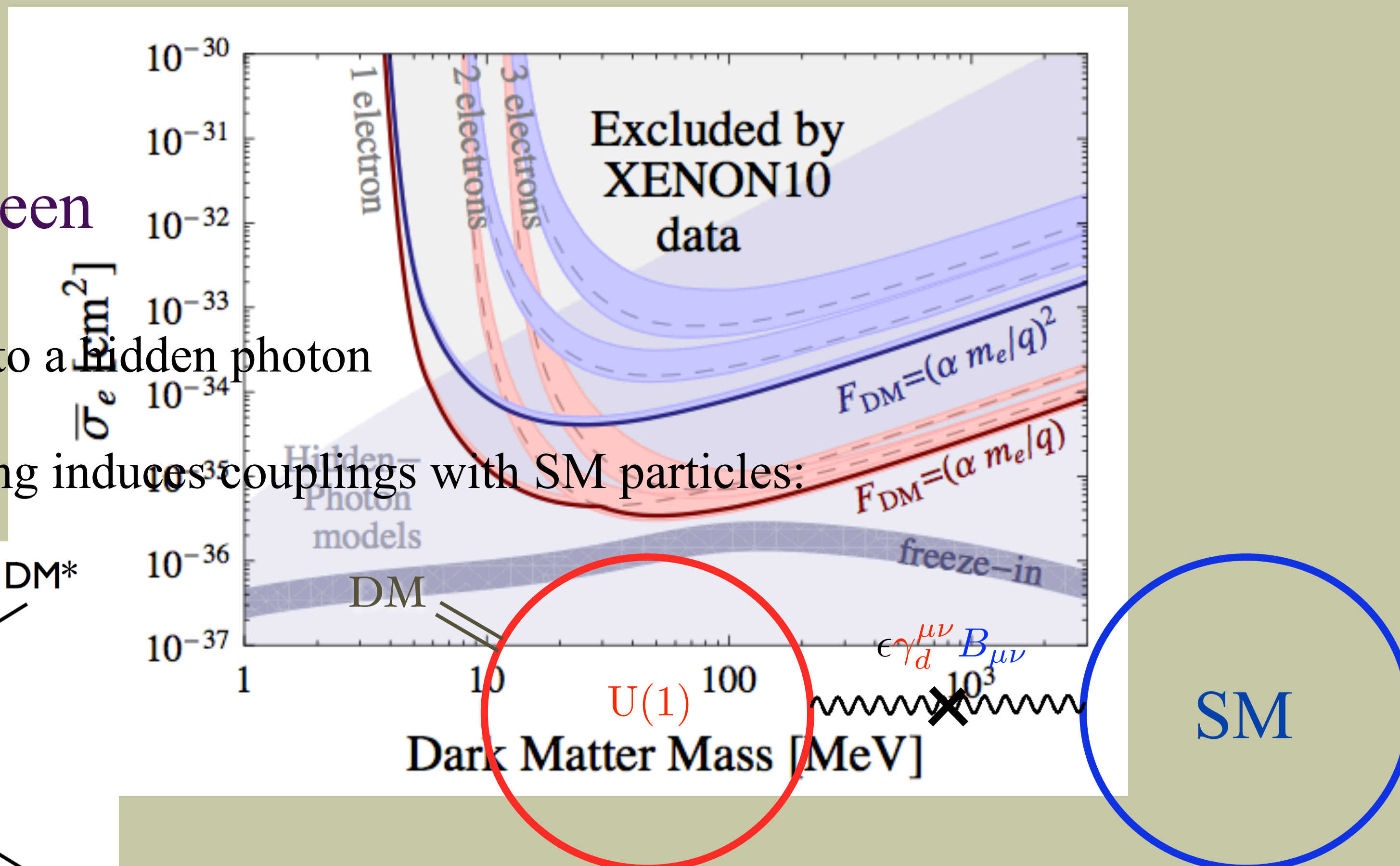
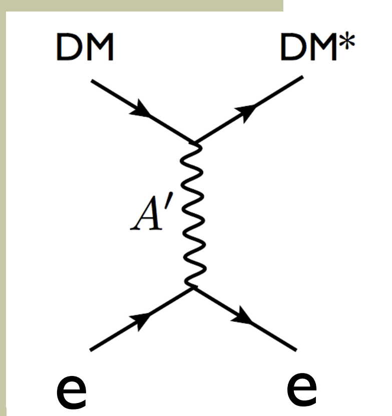
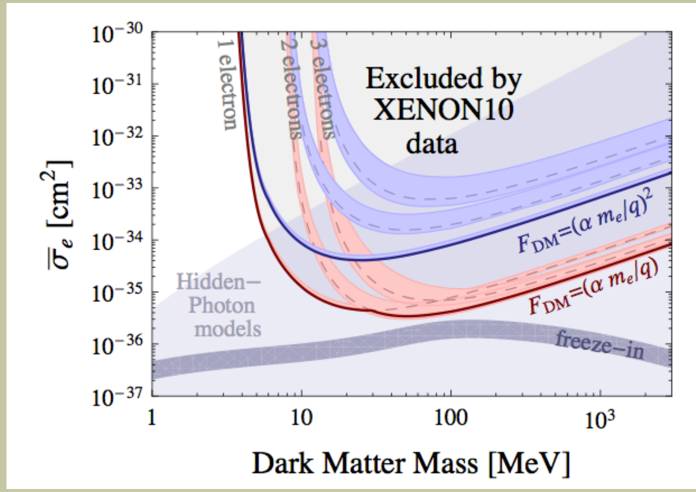


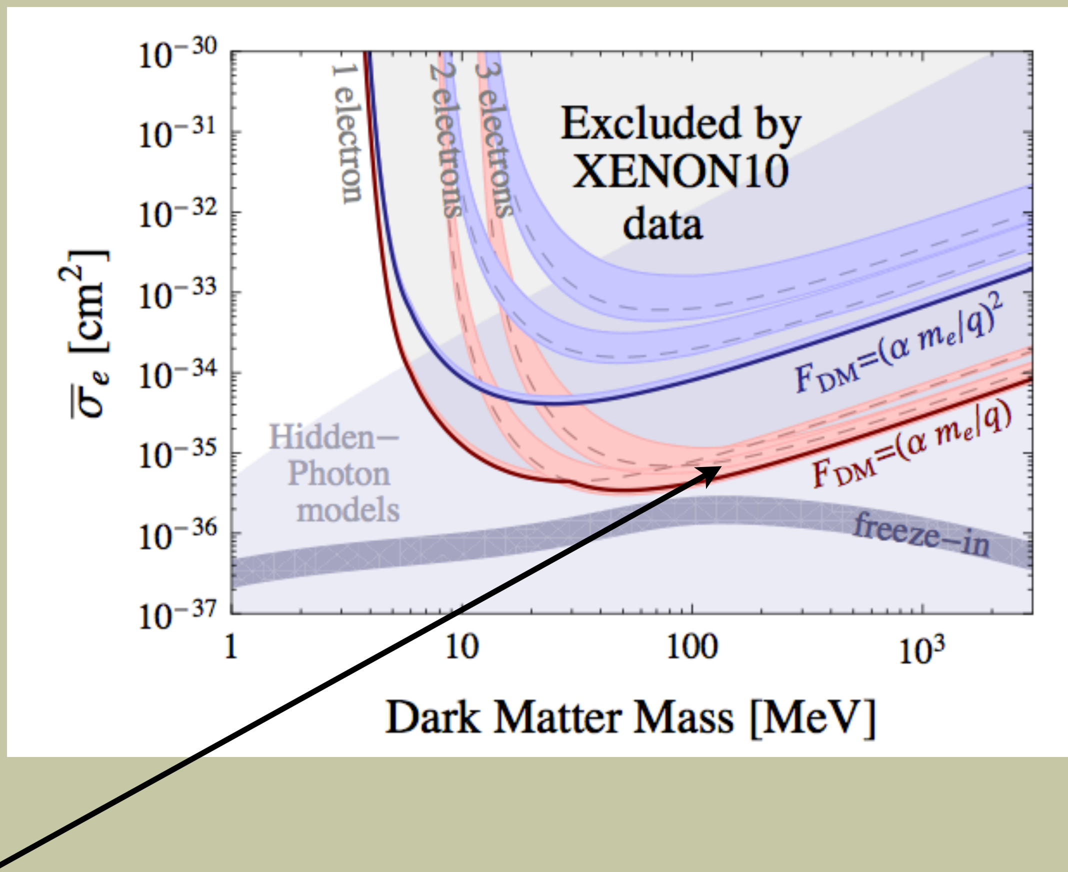


$$\sigma = \frac{16\,\pi\, m_e^2\, \alpha\, \alpha'\, \epsilon^2}{(m_{A'}^2 + q^2)^2}$$

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



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



1/q form factor is obtained for DM coupled with electric dipole moment

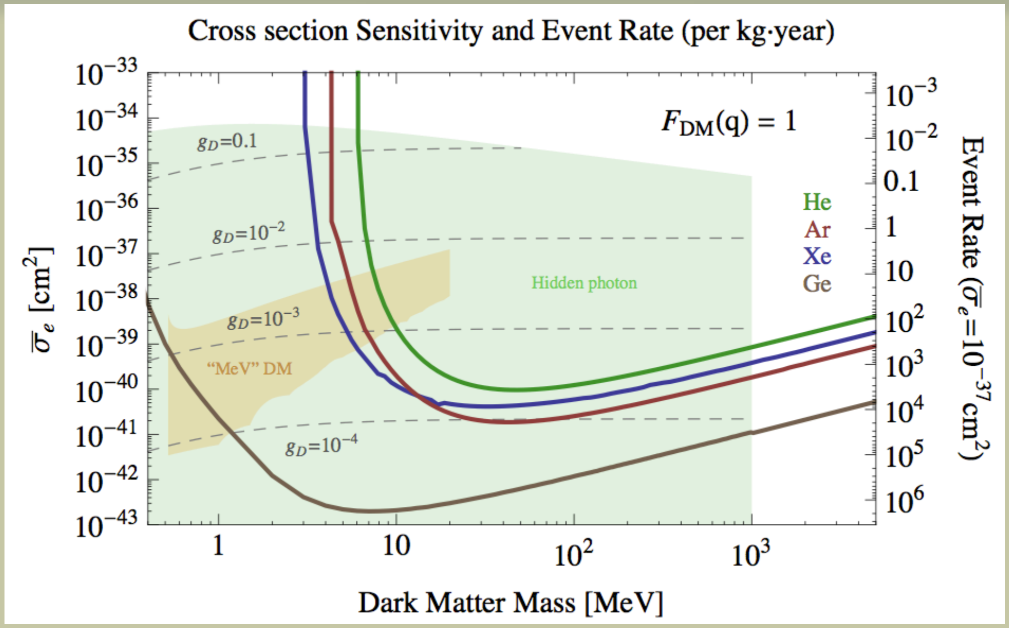
Results

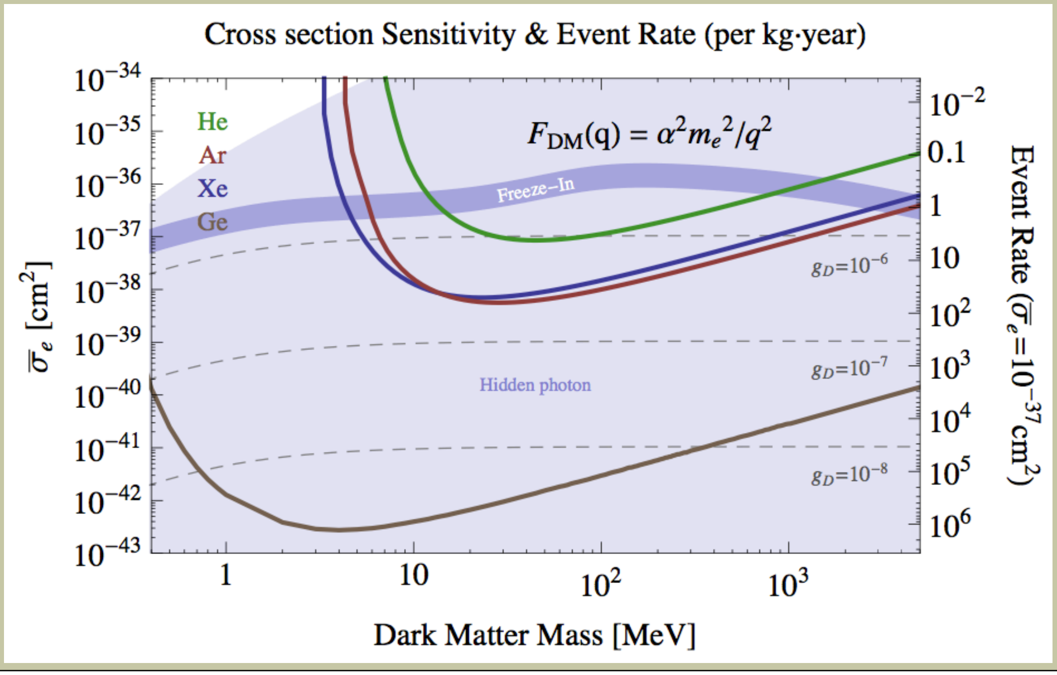
These are results for only 15 kg-days with a non-dedicated experiment!

Improvements could be very significant!!!

So What Can We Expect?

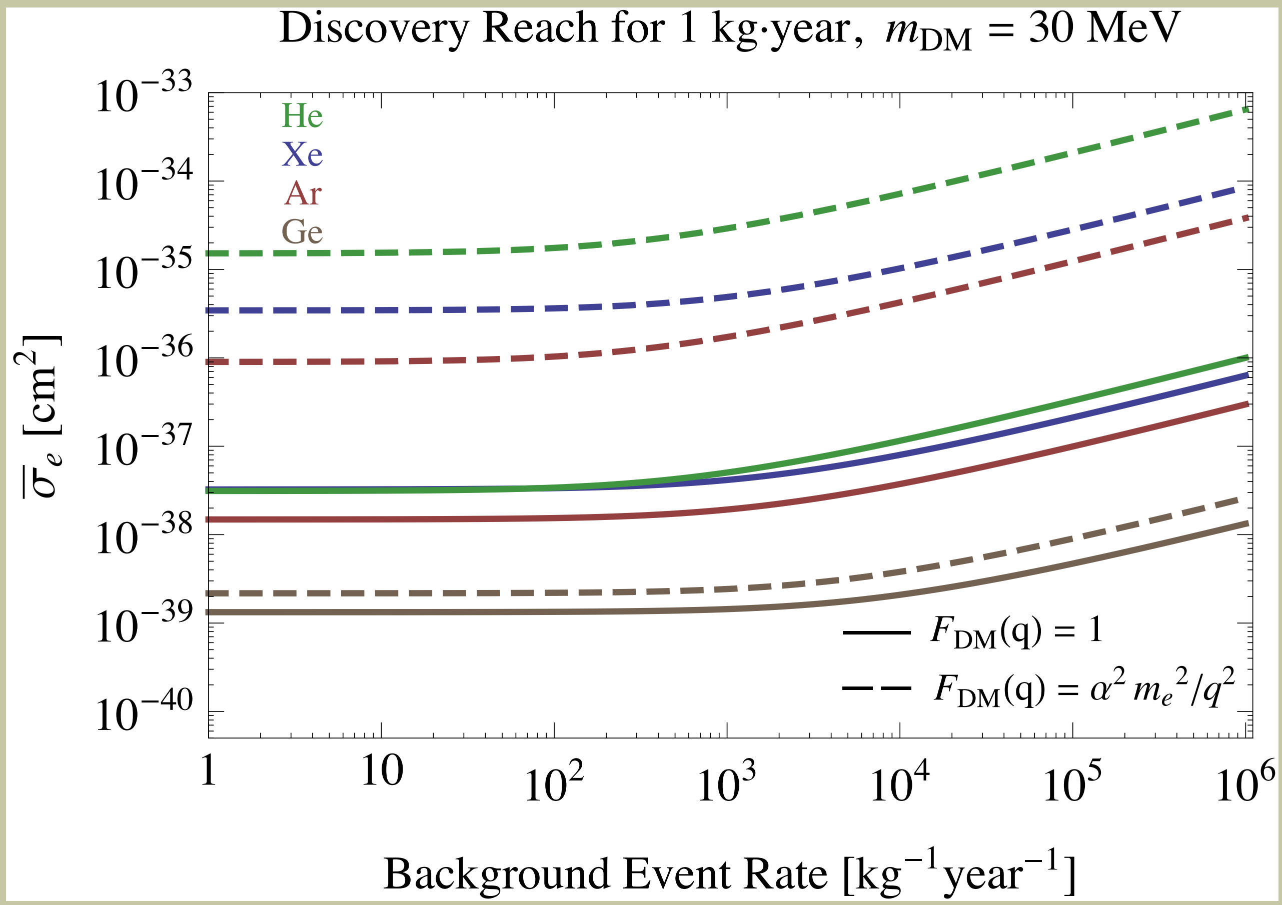
Projected Sensitivity





Discovery Reach

- Discovery can be made with only electrons, by studying annual modulations (10%).



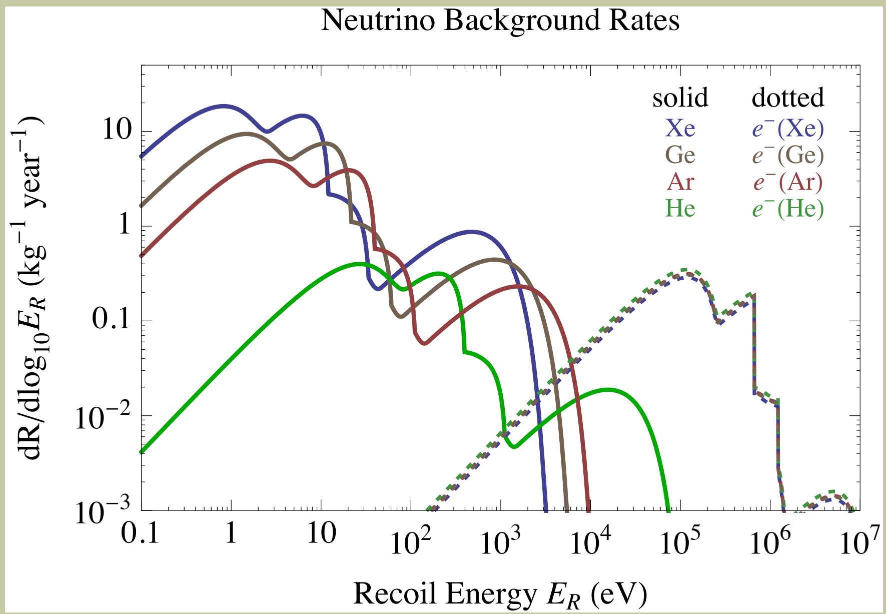
How Can We Improve Further?

Backgrounds

- Obviously, controlling backgrounds is crucial for a successful LDM search.
- In the past ~20 years, incredible progress has been made in understanding and discriminating background from signal events at current direct detection experiments (this is why we call them "background-free" experiments..).
- Backgrounds to very low energy signals are neither well measured nor well understood.
- Current direct detection experiments have not attempted to mitigate them.
- Dedicated studies and detector designs would allow for a significant improvements.

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

- Several possible backgrounds are identified:
  - Neutrinos.
  - Radioactive impurities.
  - Surface events.
  - Secondary events.
  - Neutrons.

Significant BG studies at low energy are required.

OUTLOOK

Relevant Questions

Lots more to be done with DM in general and light DM in particular!

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.

Existing Experiments

- Several ongoing and upcoming experiments may be able to do better than XENON10 for LDM.
- Need to understand density of impurities and sensitivity to single electron triggers.
- Relevant experiments:
    - CDMS-light (still too-high threshold)
    - XENON100 (electronic noise??)
    - ZEPLIN
    - LUX (very promising)

Technological Directions

R&D needed in direct detection experiments

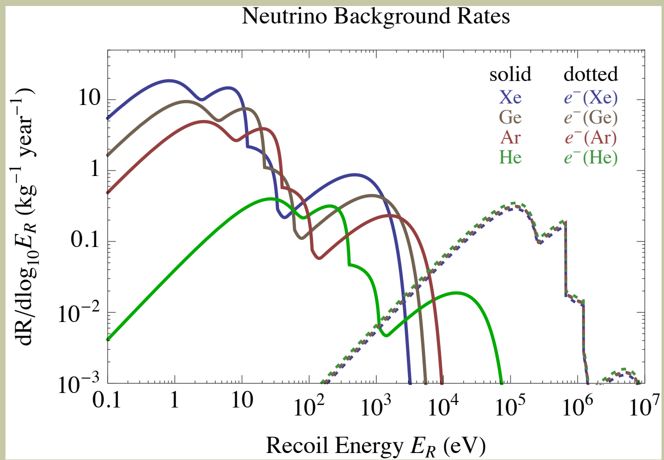
- Phonons Detectors: New studies claim 10 eV threshold with cryogenic solid state bolometers! Maybe possible in the near future.

[Anderson et al. 2011]

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

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

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



Extras

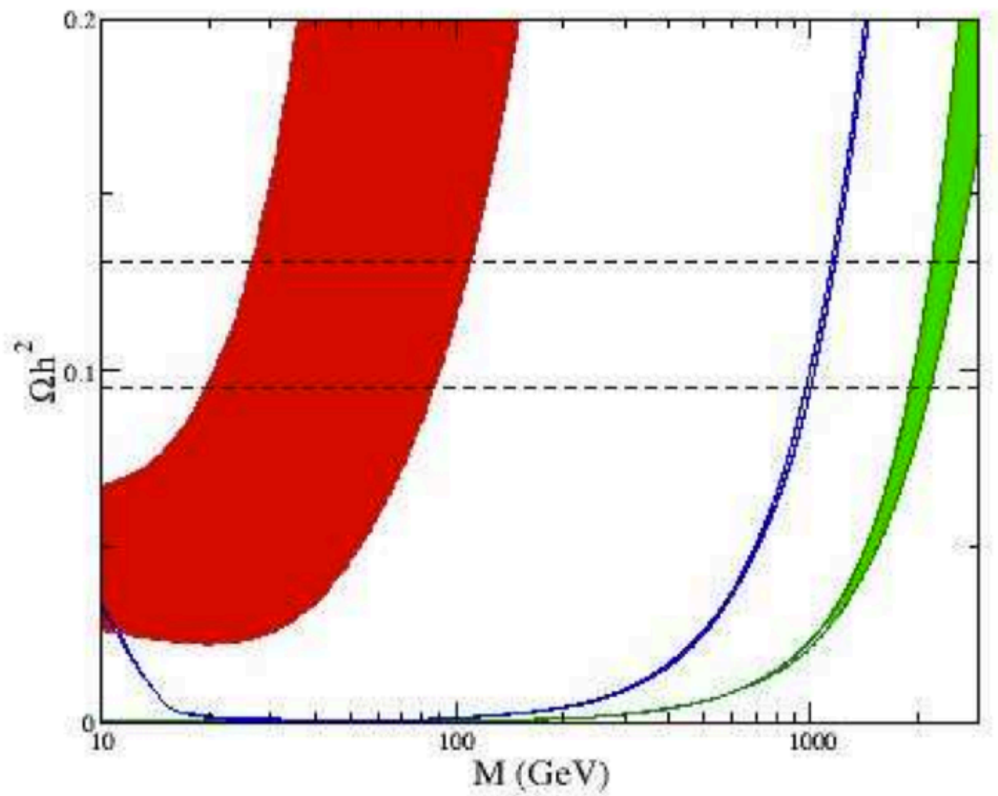


Figure 1: The three bands show the contribution to Ωh^2 from pure Bino LSP with $0.3 < M_1/m_{\tilde{e}_R} < 0.9$ (red band), Higgsino LSP with $1.5 < m_{\tilde{t}}/\mu < \infty$ (blue band) and Wino LSP with $1.5 < m_{\tilde{\ell}_L}/M_2 < \infty$ (green band).

XENON10 Cuts

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

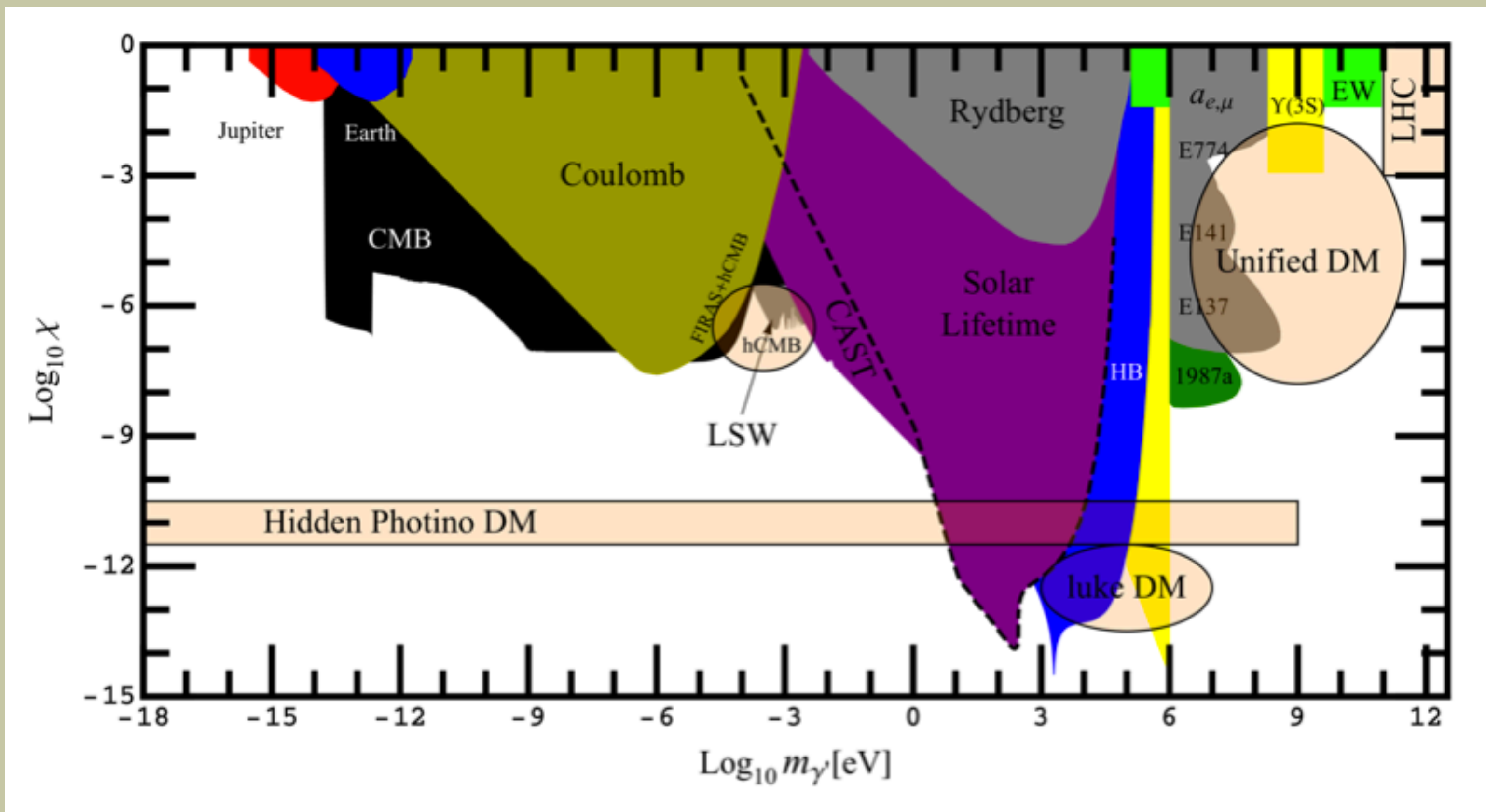
Cut description	ε_c	N_{evts}
1. event localization $r < 3$ cm	1.00[a]	125
2. signal-to-noise	> 0.94	57
3. single scatter (single S2)	> 0.99	37
4. $\pm 3\sigma$ nuclear recoil band	> 0.99	22
5. edge (in z) event rejection	0.41[b]	7

[a] limits effective target mass to 1.2 kg

[b] differential acceptance shown in Fig. 1

Hidden Photon Constraints

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



Circular Velocities from N-Body

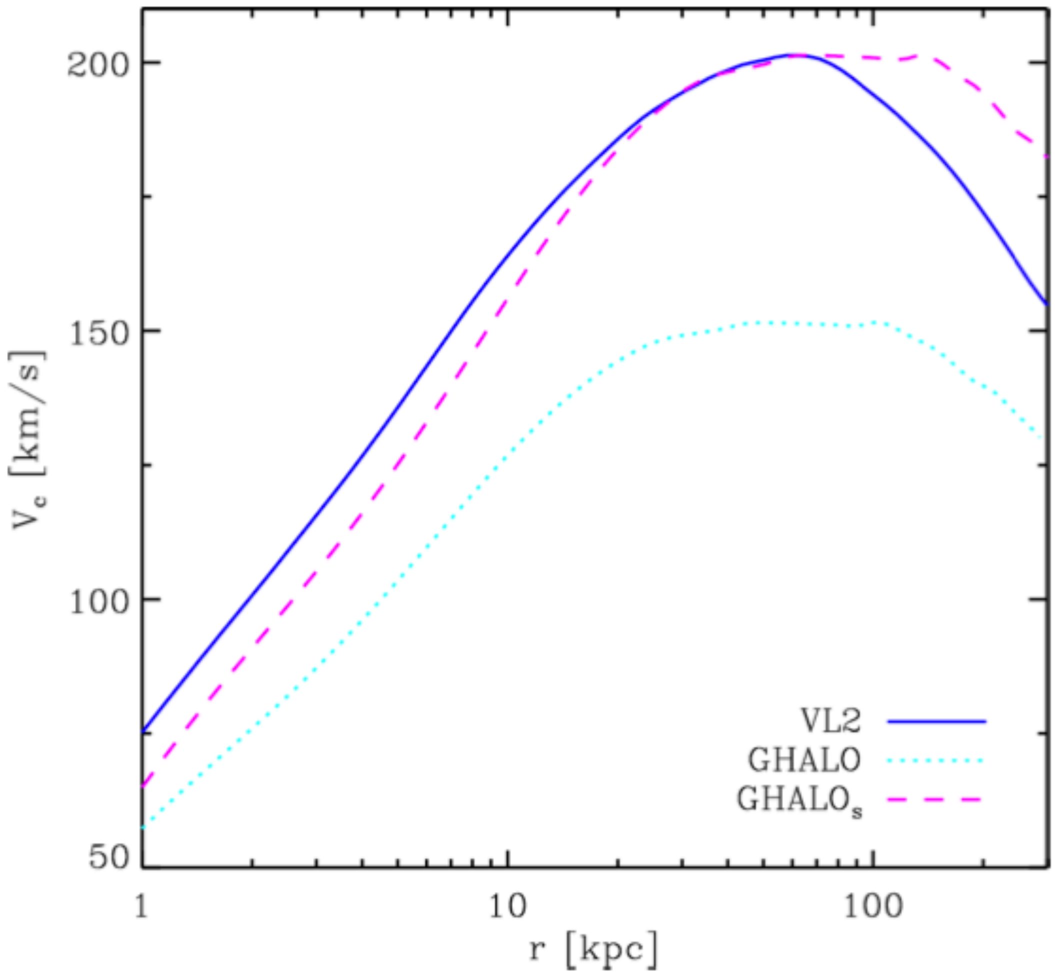


Figure 1: Circular velocity profiles of the VL2, GHALO, and $GHALO_s$ host halos.

Velocity Distribution Effect on Rate

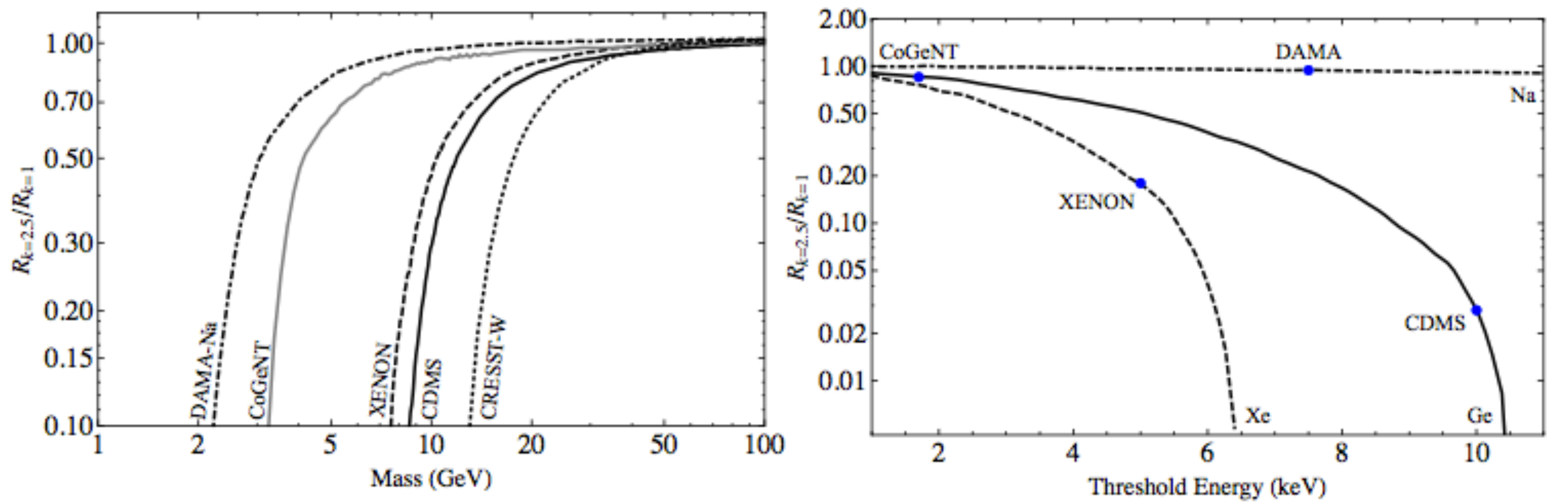
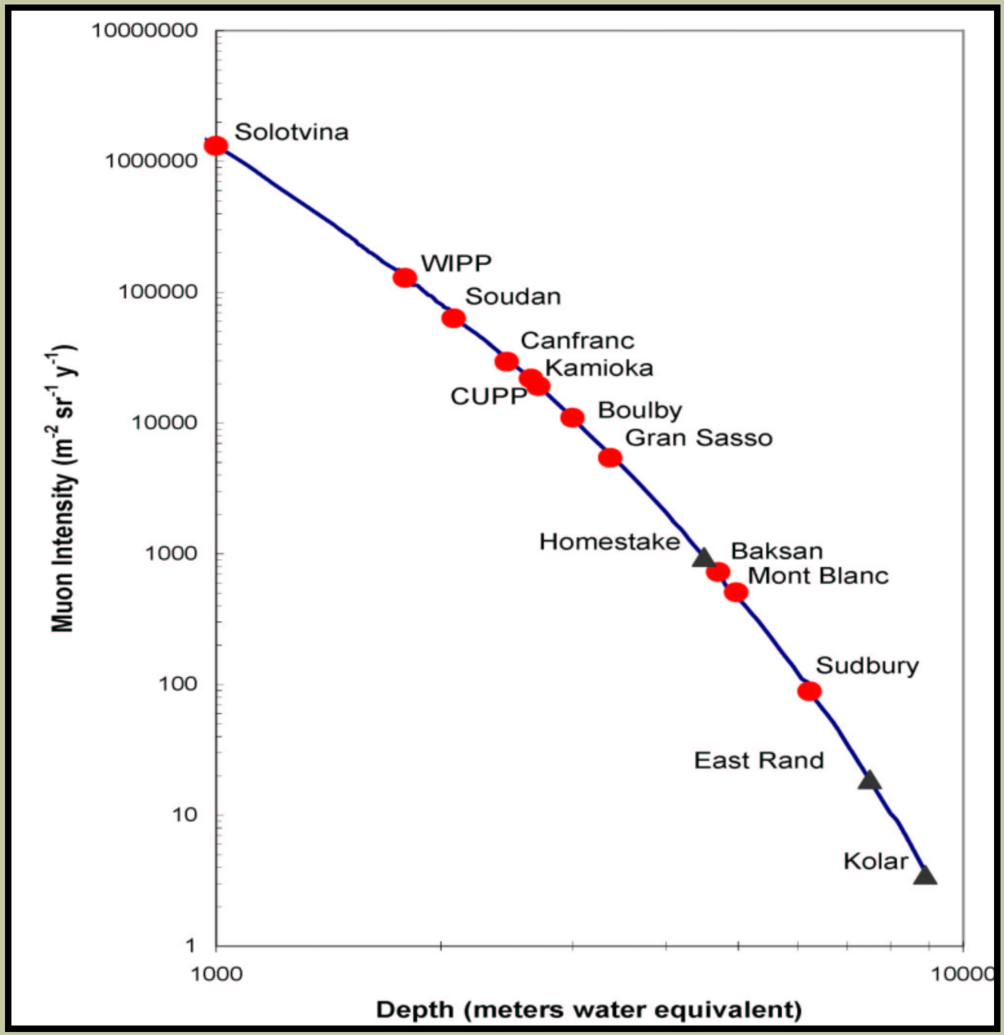
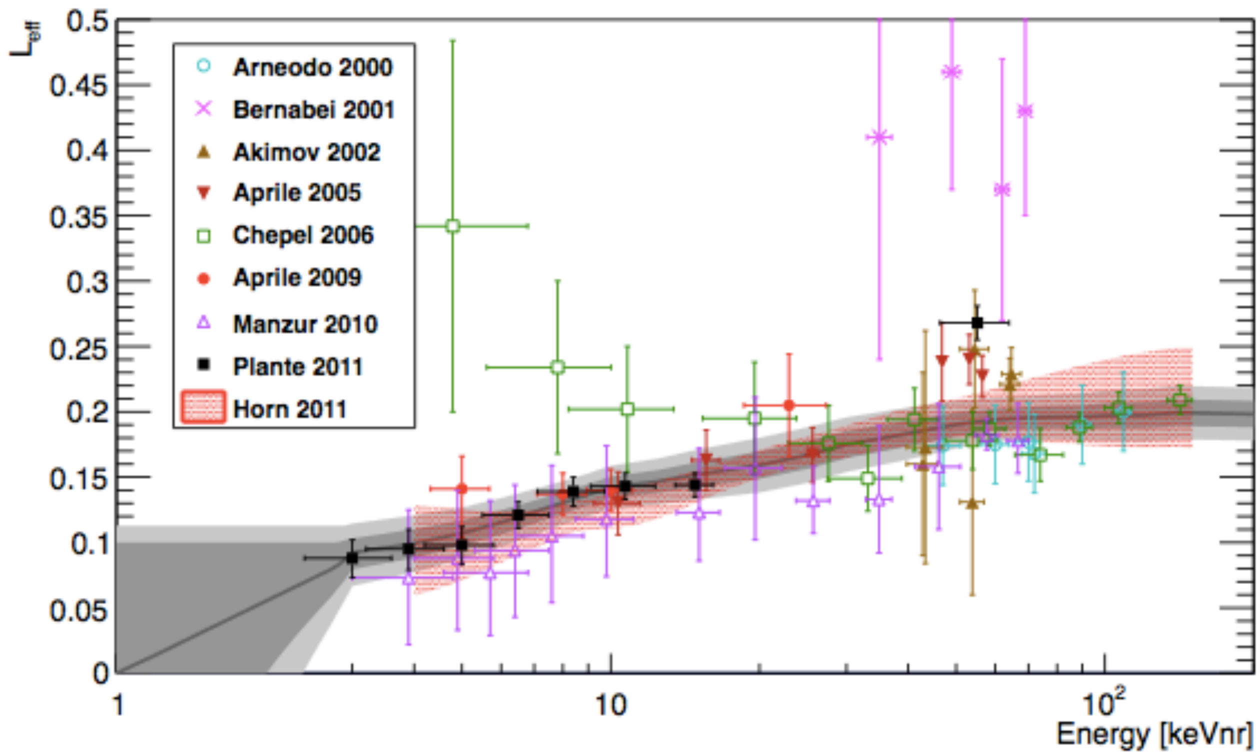


FIG. 5: Fractional change in the scattering rate for $k = 2.5$ compared to $k = 1$ for an elastically scattering dark matter with $v_0 = 220$ and $v_{esc} = 550$ km/s. The plot on the left illustrates the dependence of the scattering rate on the dark matter mass for DAMA-Na (dot-dashed) [42], CoGeNT (solid gray) [43], XENON (dashed) [44, 45], CDMS (solid black) [46], and CRESST-W (dotted) [47] for threshold energies of 7.5, 1.7, 5, 10, and 10 keV, respectively. The plot on the right illustrates the dependence of the scattering rate on the threshold energy for an 8 GeV dark matter scattering elastically off a Xe (dashed), Ge (solid), and Na (dot-dashed) target. In both plots, the Earth's velocity was taken at ∼ June 2.

Direct Detection Muon Background



L_{eff} - Scintillation Efficiency



$$E_{\mathrm{nr}} = \frac{S1}{L_{y,\mathrm{er}}} \frac{1}{\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}})} \frac{S_{\mathrm{er}}}{S_{\mathrm{nr}}}$$

- $L_{y,er}$ - light yield for electron recoils of 122keVee
- S_{nr}, S_{er} - quenching factors due to drift field

Measuring WIMP Properties at LHC

Point	m_0	$m_{\frac{1}{2}}$	$\tan\beta$	A_0	sign mu	m_t	reference	$\Omega_\chi h^2$
LCC1	100	250	10	-100	+	175	[86]	0.192
LCC2	3280	300	10	0	+	175	[87]	0.109
LCC3	213	360	40	0	+	175	[88]	0.101
LCC4	380	420	53	0	+	178	[90]	0.114
SPS1a′	70	250	10	-300	+	175	[91]	0.115

Table 1: mSUGRA parameter sets for four illustrative models of neutralino dark matter. Masses are given in GeV. The table also lists the value of $\Omega_\chi h^2$. The references given are the primary references for simulation studies of the accuracy of spectrum measurements at colliders. The point SPS1a′ has a phenomenology similar to that of LCC1 but gives a more correct value of the relic density.