The Principles of Dark Matter Direct Detection

Patrick Fox

Fermilab

Fermilab Academic Lectures 2013

Outline

- Evidence for DM, and its gross properties
- Relic abundance and thermal DM
- WIMP DM
- Direct Detection
- “Non-standard” DM
- Recent Developments
- ....

Related lectures

Thursday, December 5, 2013

11:00 - 12:30 Principles of Direct Dark Matter Detection *1h30'* (One West)
Speaker: Dr. Patrick Fox (Fermilab)

(theory, DM models)

Tuesday, December 10, 2013

11:00 - 12:30 Evidence for Dark Matter from the Cosmos *1h30'* (One West)
Speaker: Dr. Scott Dodelson (Fermilab)

(CMB, large scale structure, ...)

Tuesday, December 17, 2013

11:00 - 12:30 Direct Dark Matter Detection Experiments 1 *1h30'* (One West)
Speaker: Prof. Jodi Cooley (Southern Methodist University)

Thursday, December 19, 2013

11:00 - 12:30 Direct Dark Matter Detection Experiments 2 *1h30'* (One West)
Speaker: Prof. Jodi Cooley (Southern Methodist University)

(experimental techniques and technologies,...)

The Standard Model (as of July 4th, 2012)

We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !

ATLAS today's main result (preliminary):

5.0 σ excess at m_H~126.5

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Do we now have a complete microscopic description of nature?

The Standard Model (as of July 4th, 2012)

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125.3

4.9 σ si

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at m_H~126.5

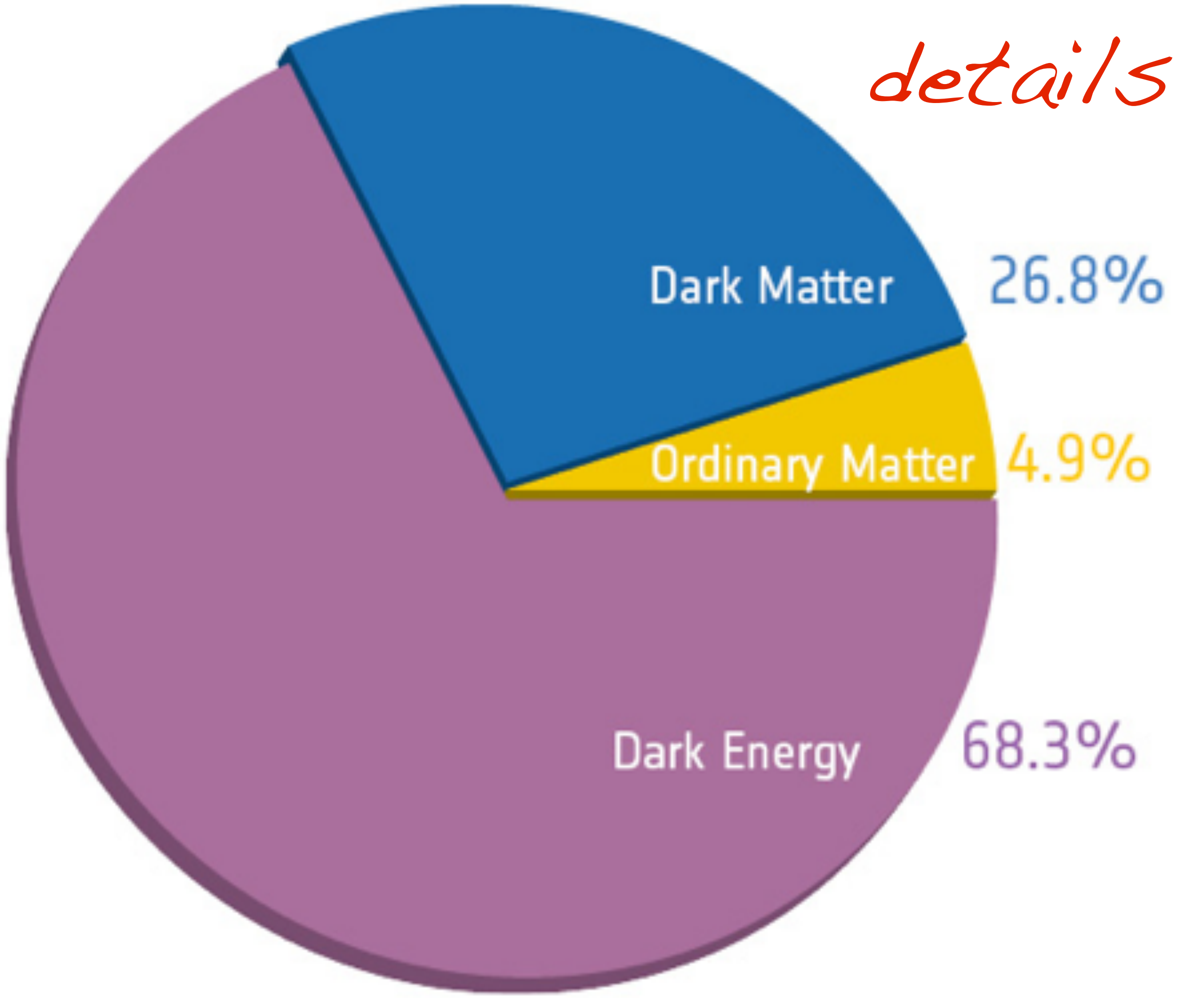
Do we

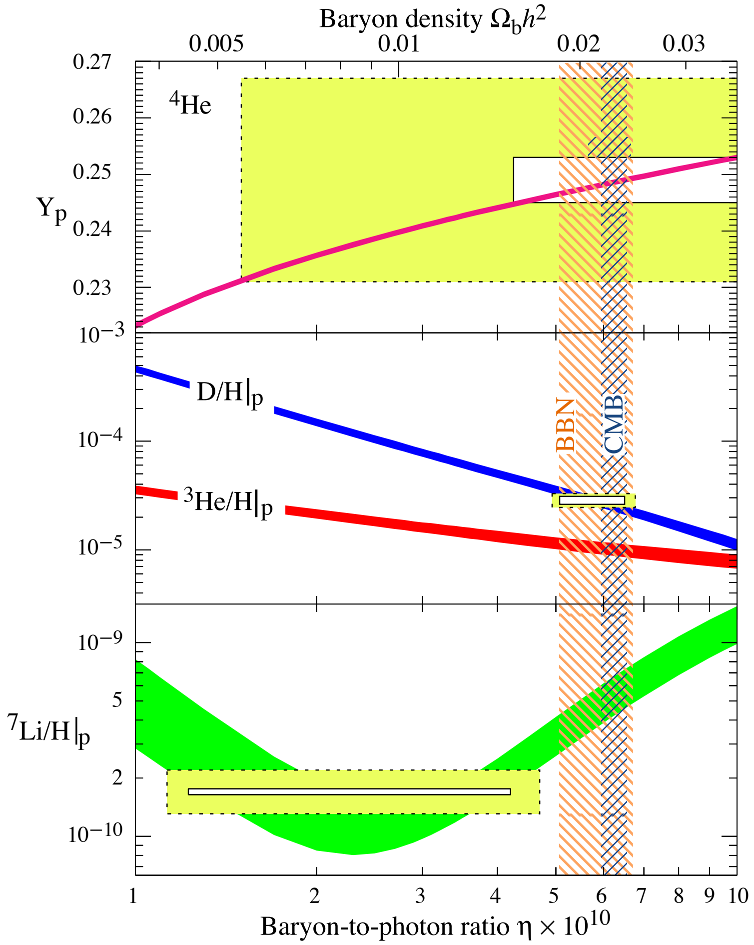
croscopic

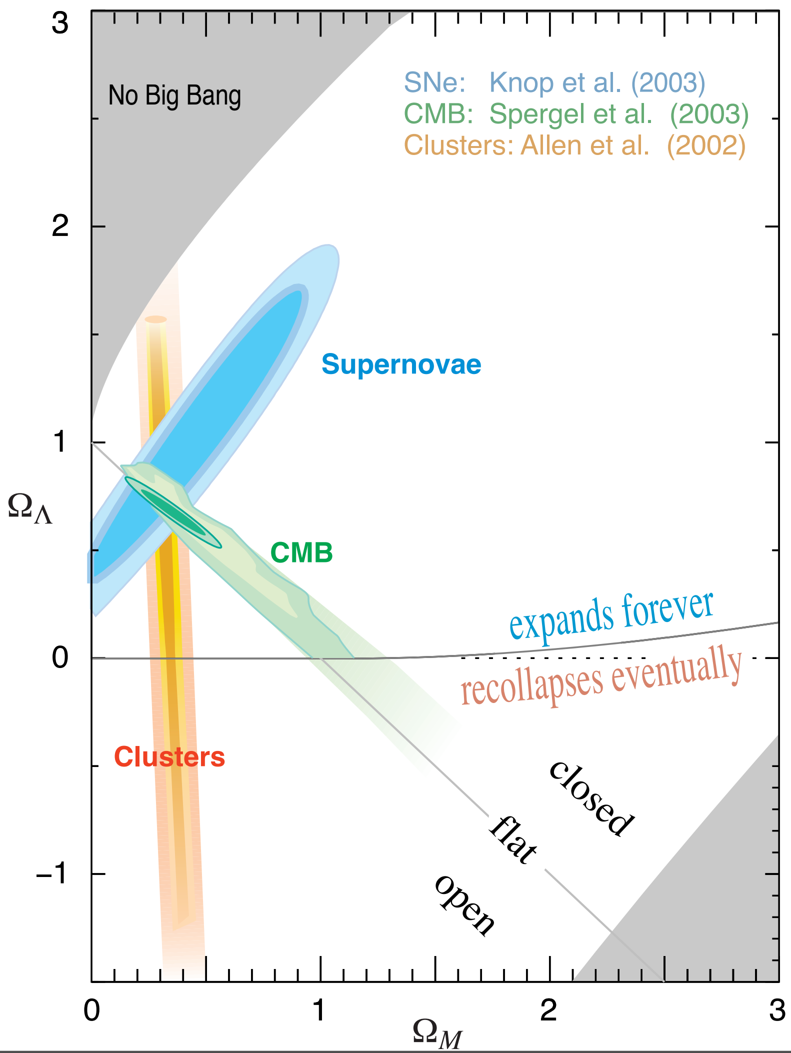
?

Extra stuff

(Scott will give more details)







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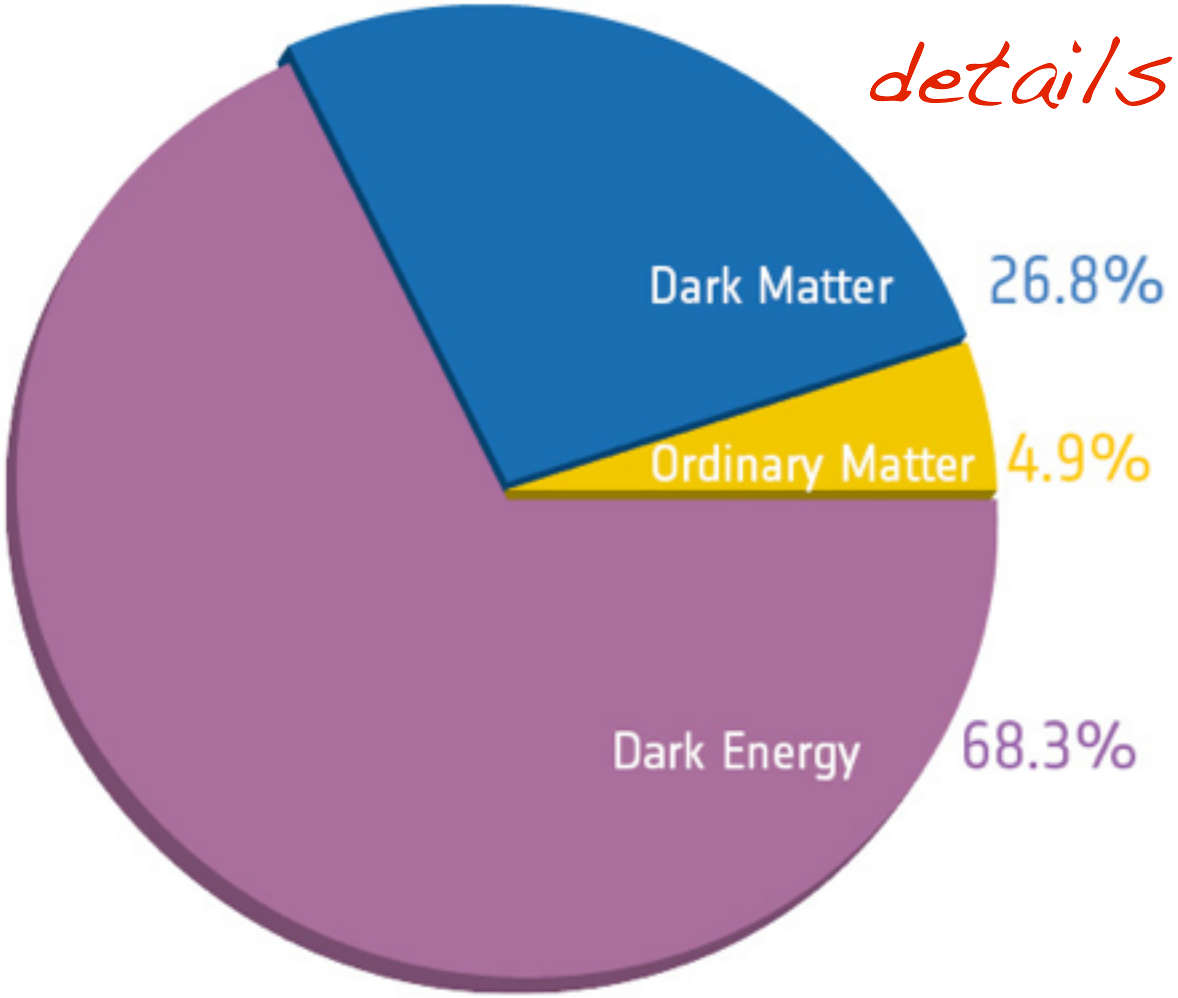
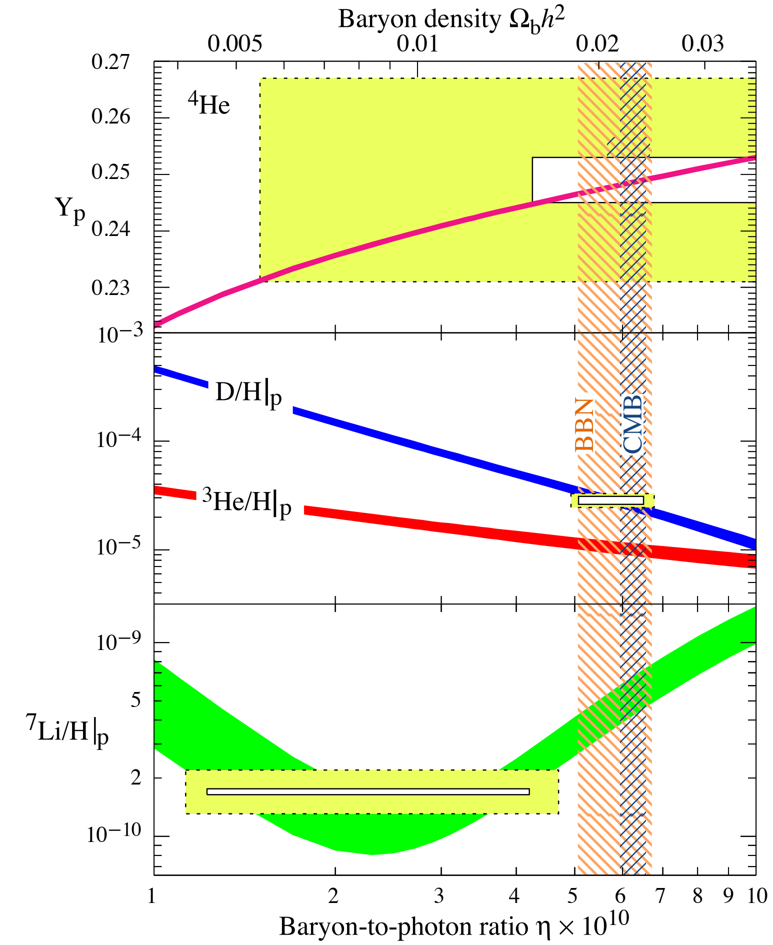
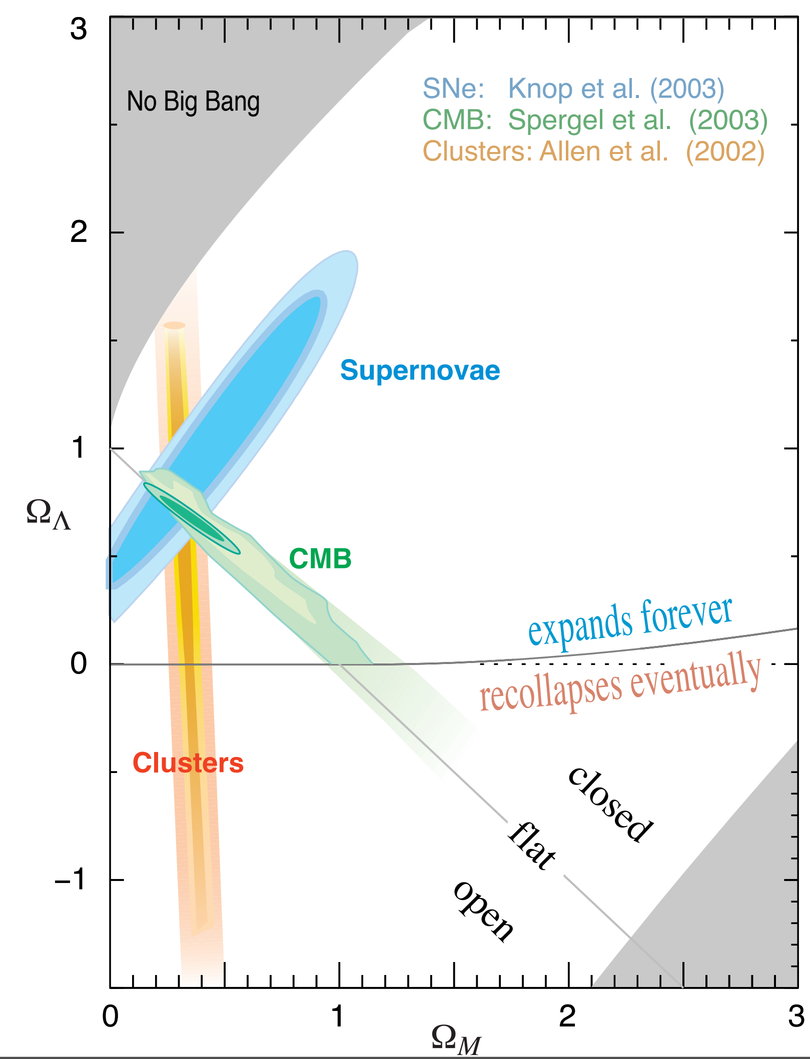
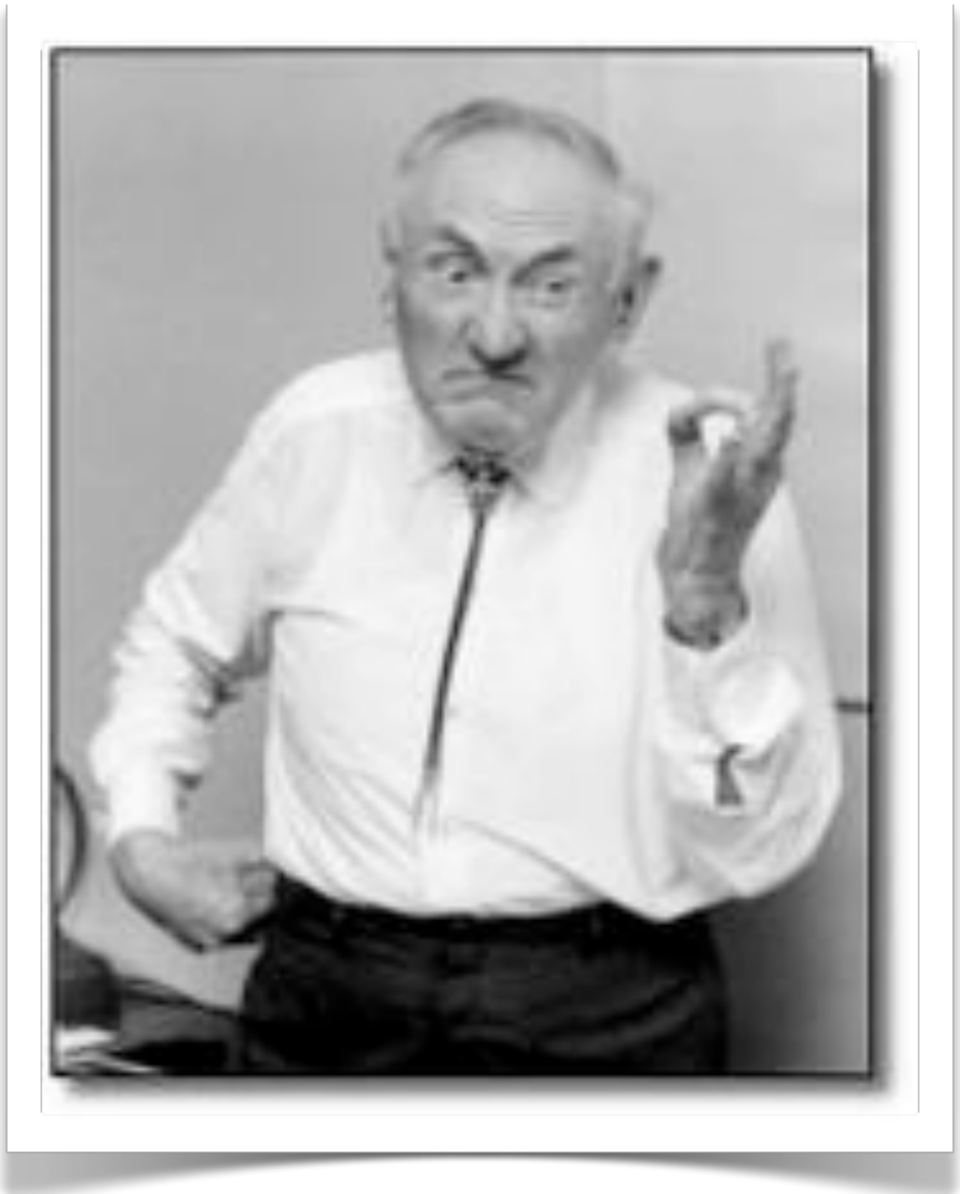


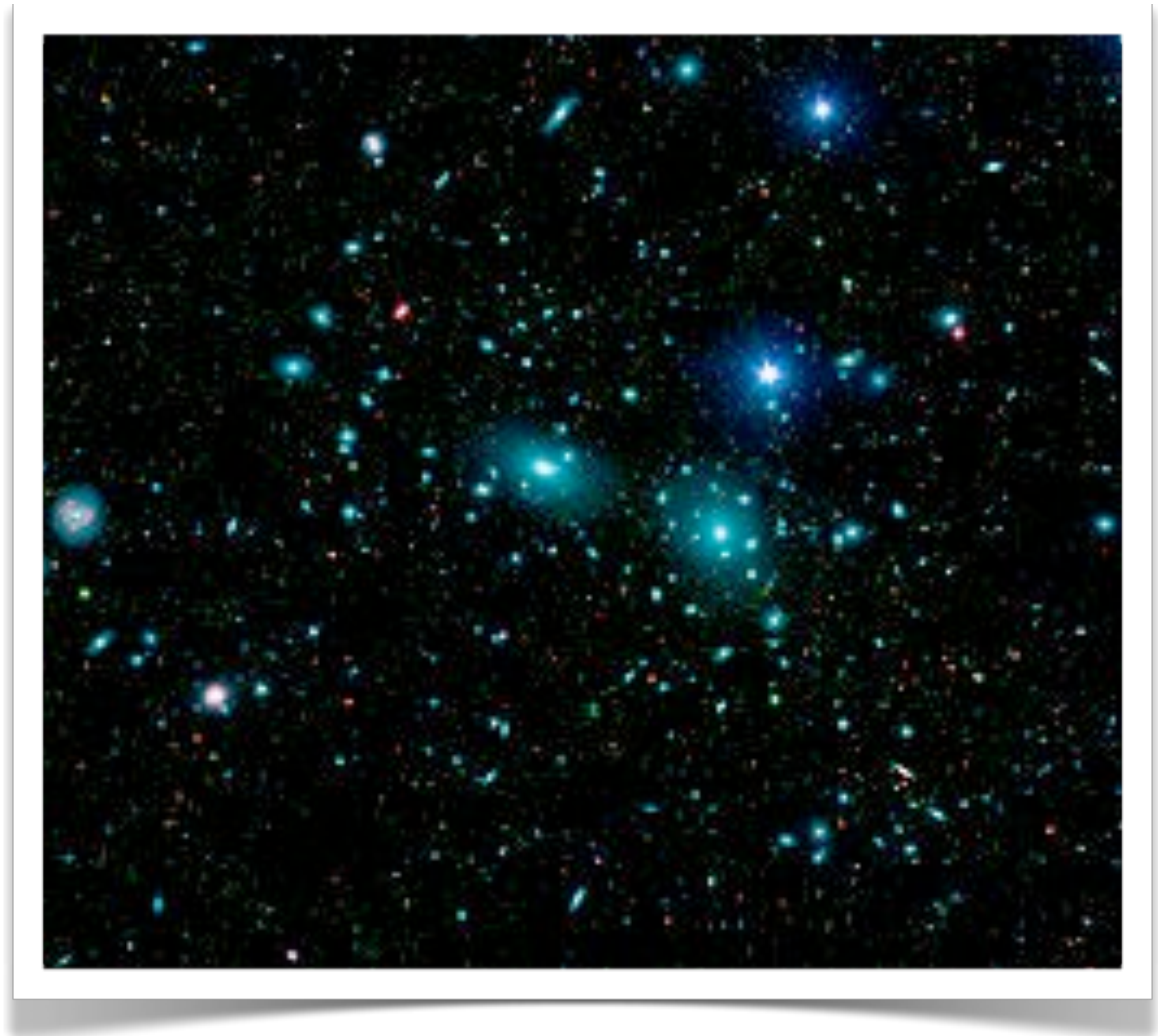
- 27% of universe energy/matter is a new type of (non-baryonic) matter
- 68% is a new type of energy (cosmological constant)
- SM is 5%





Evidence for Dark Matter





Coma Cluster

90% of the matter in the cluster doesn't shine

Evidence for Dark Matter (there)

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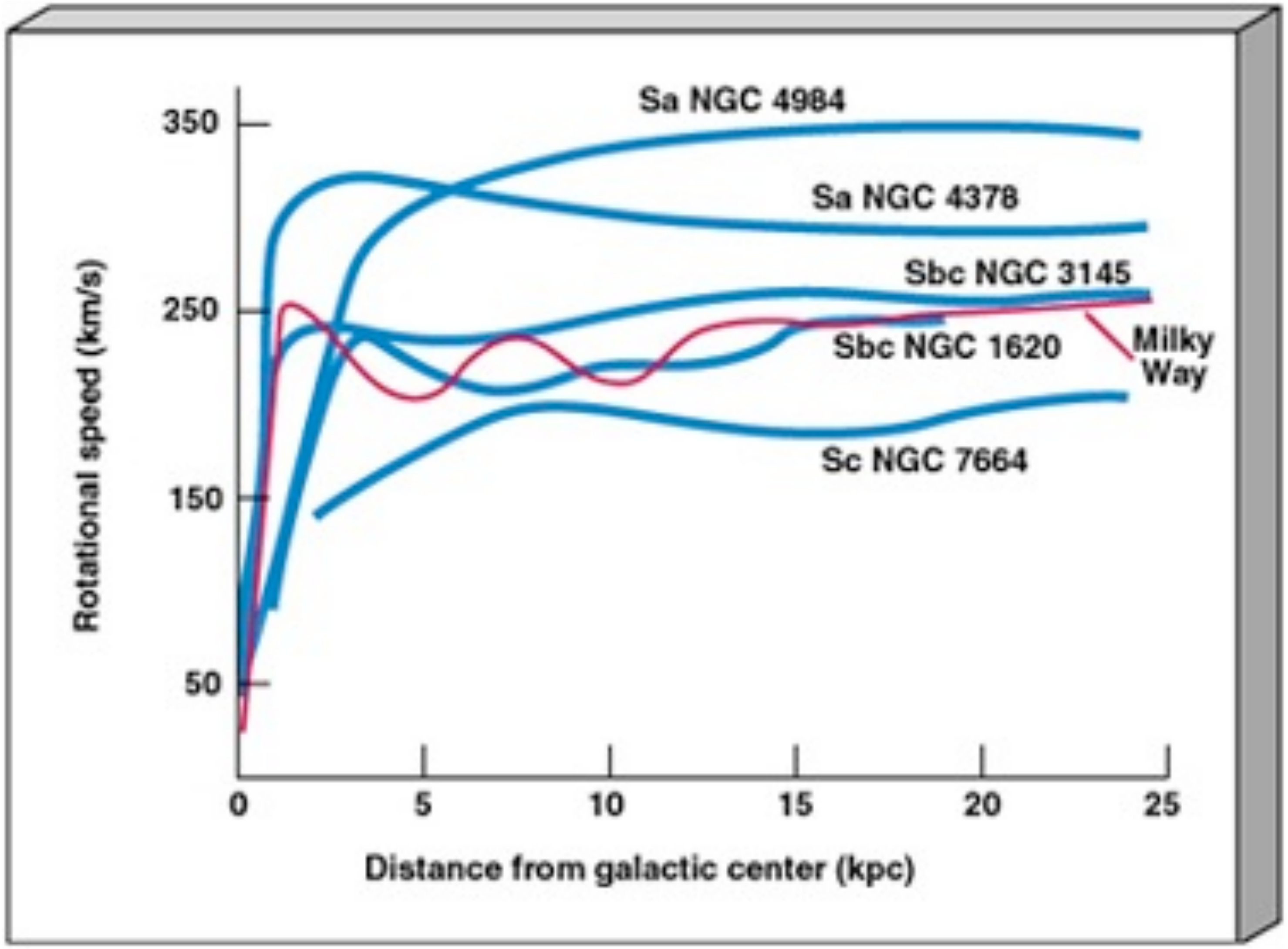
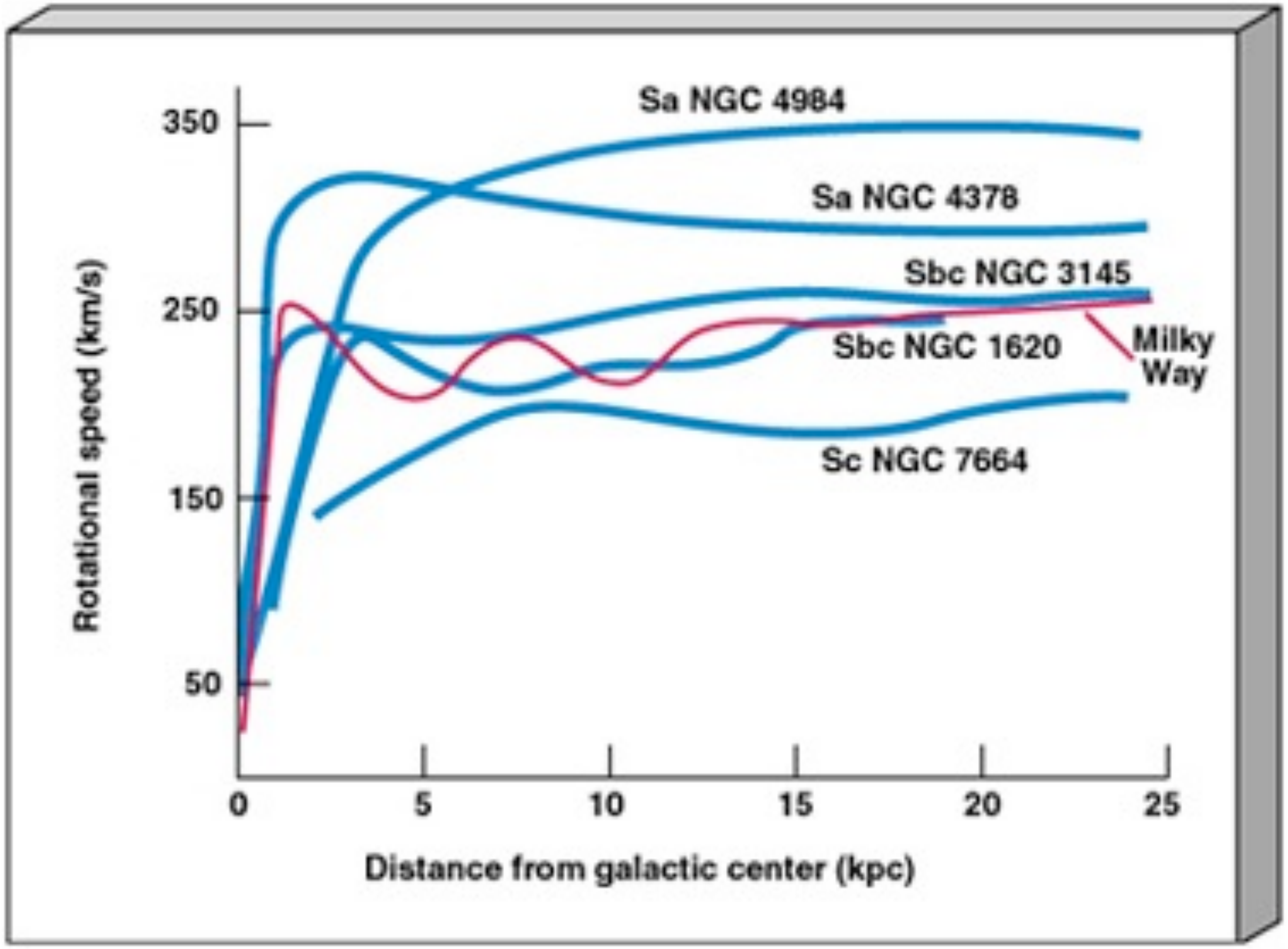
Evidence for Dark Matter



For large radii: $$\frac{v^2}{r} = \frac{G_N M}{r^2}$$

Something invisible is holding stars in orbit

Evidence for Dark Matter (here and there)



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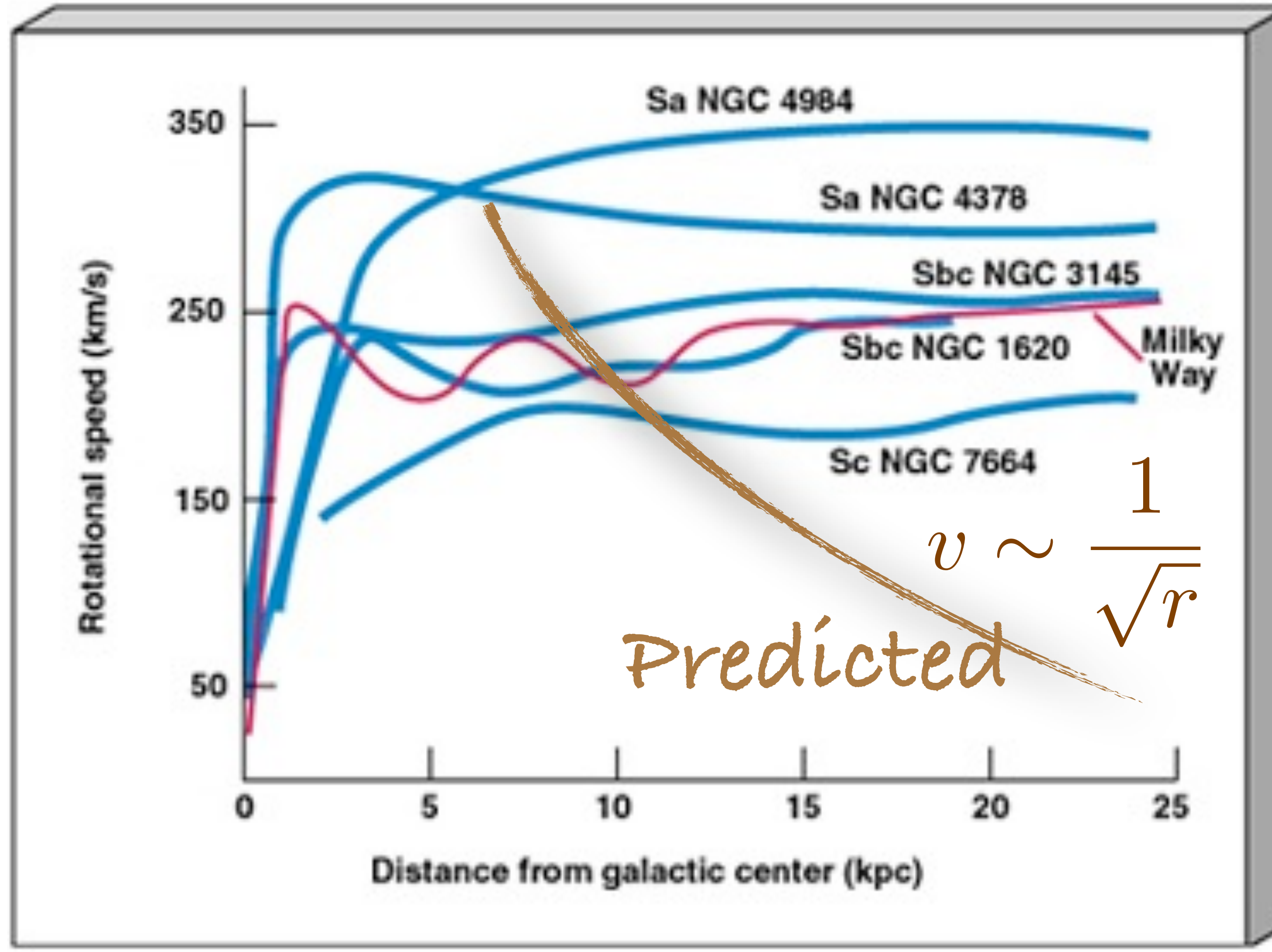

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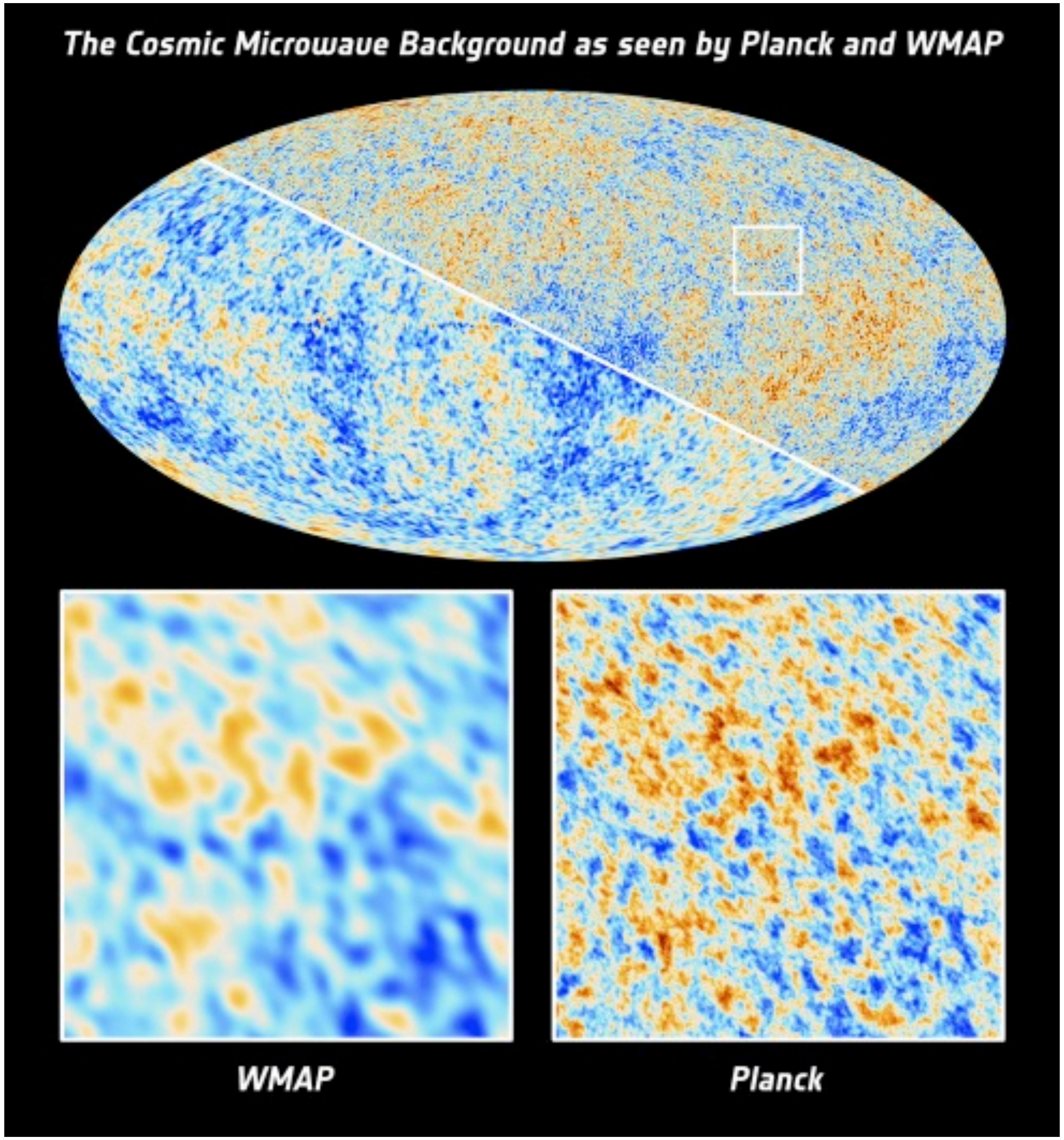
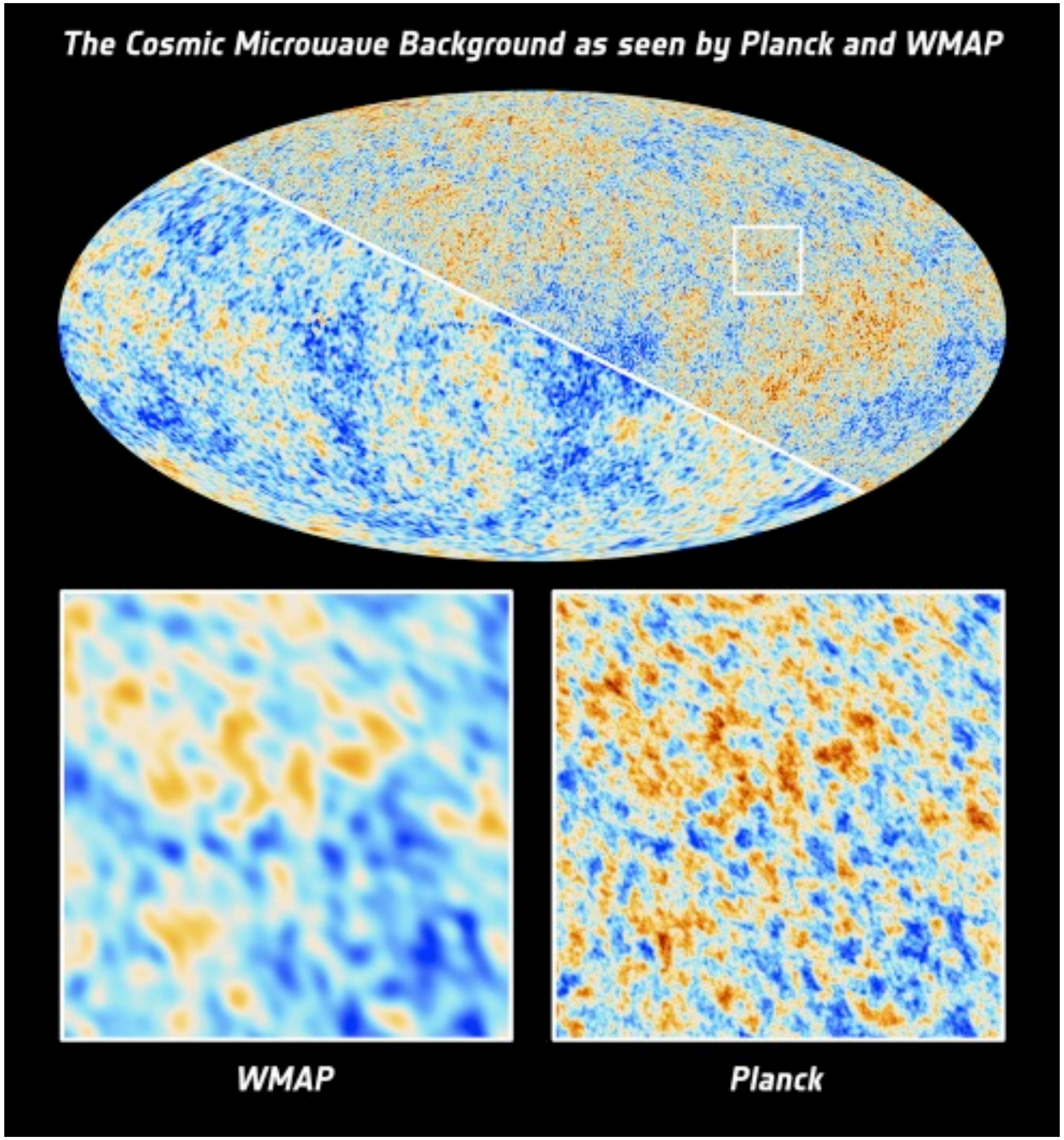


Hot plasma of hydrogen atoms and photons

Evidence for Dark Matter (everywhere)



Hot plasma of hydrogen atoms and photons

Recap on DM's (gross) properties

- DM makes up 27% of the universe
- Gravitates like ordinary matter, but is non-baryonic
- Is dark i.e. neutral under SM (not coloured, or charged)
- Does not interact much with itself $\frac{\sigma_{\chi\chi}}{m_\chi} \lesssim 3\,\mathrm{GeV}^{-3}$
- Does not couple to massless particle
- Was not relativistic at time of CMB
- Is long lived

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<u>No such particle exists in the SM</u>

Axions

Primordial Black Holes

?

MACHOs

?

Sterile neutrinos

WIMPs

Axions

Primordial Black Holes

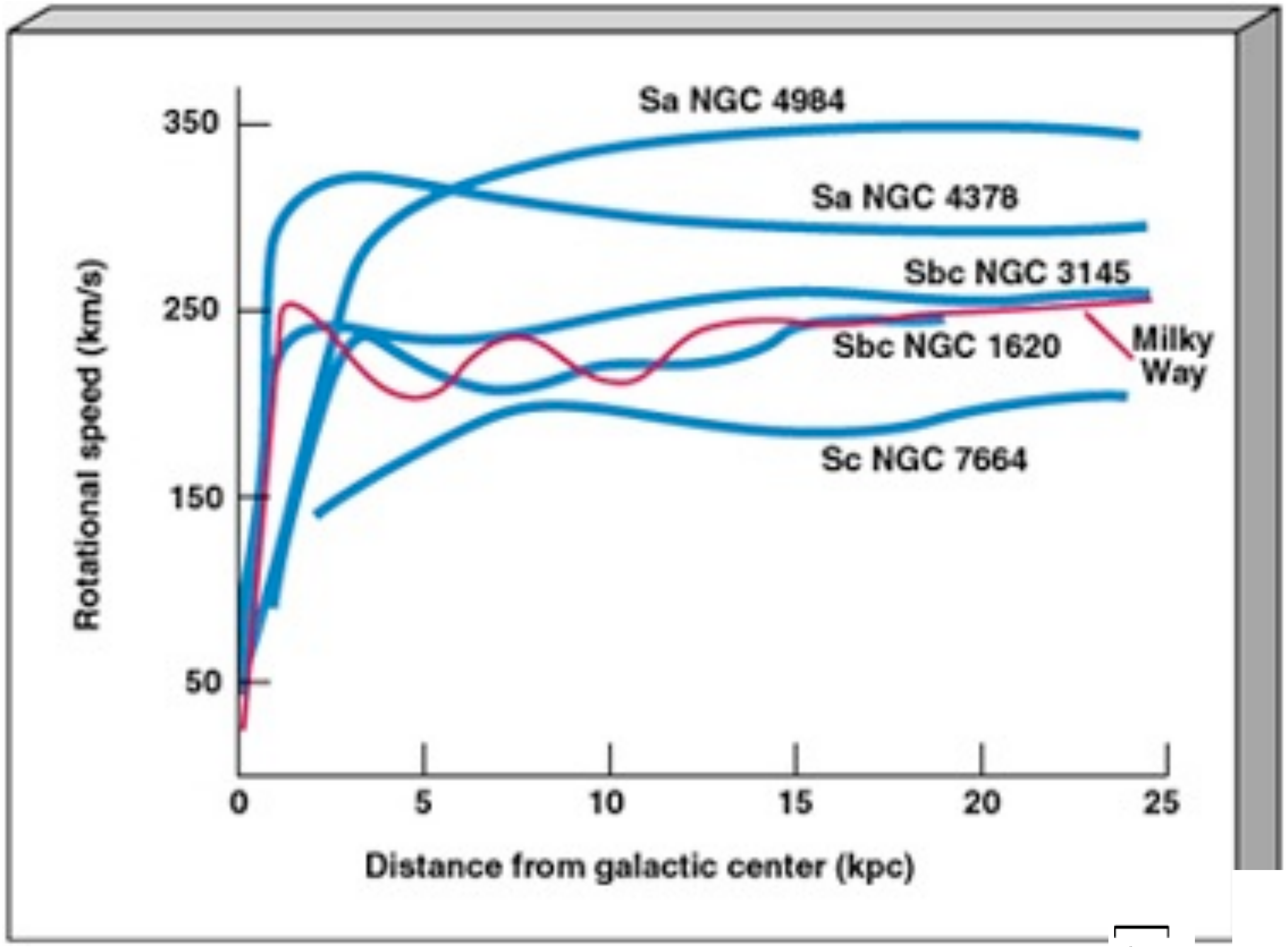
?

?

Sterile neutrinos

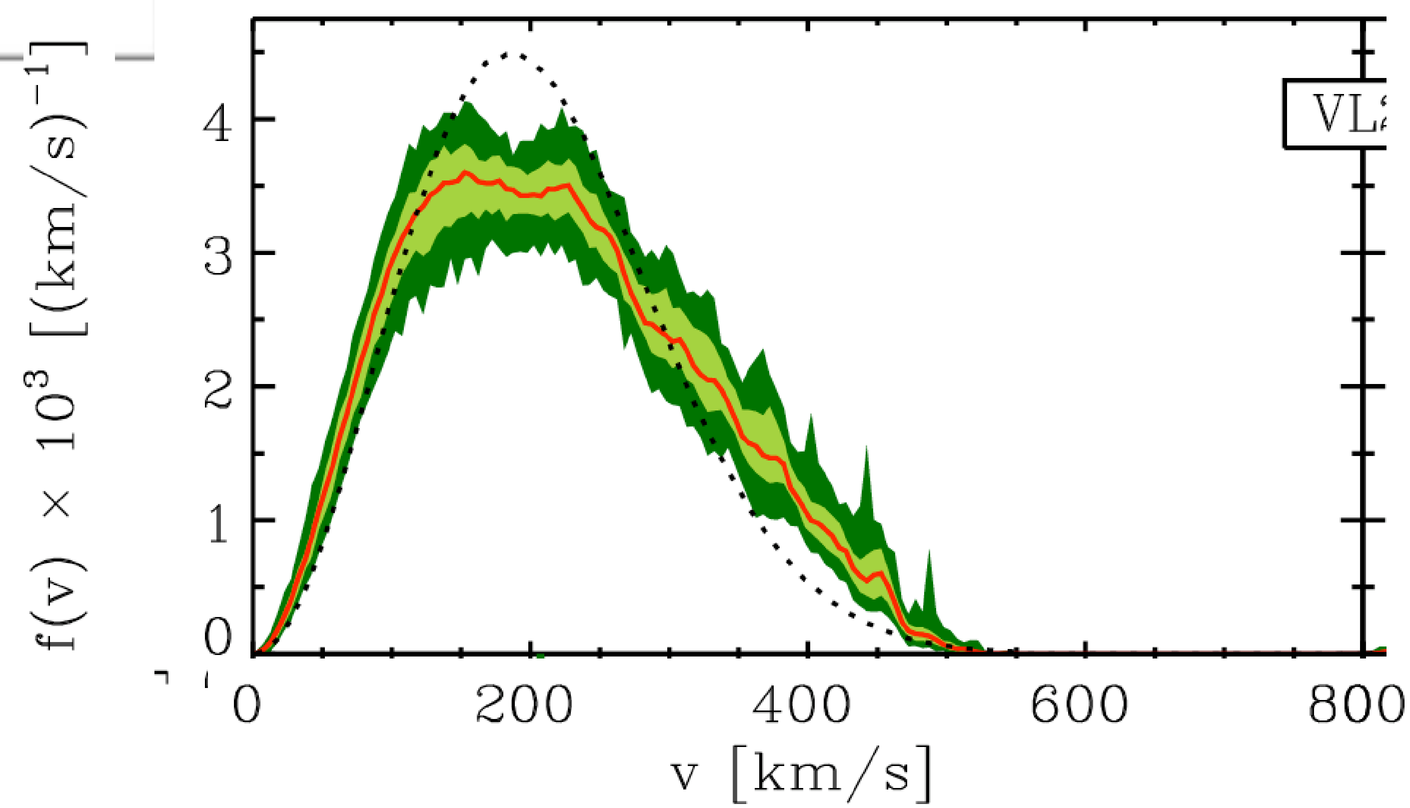
WIMPs

Evidence for DM locally?



[Bovy and Tremaine 1205.4033]

Via Lactea II



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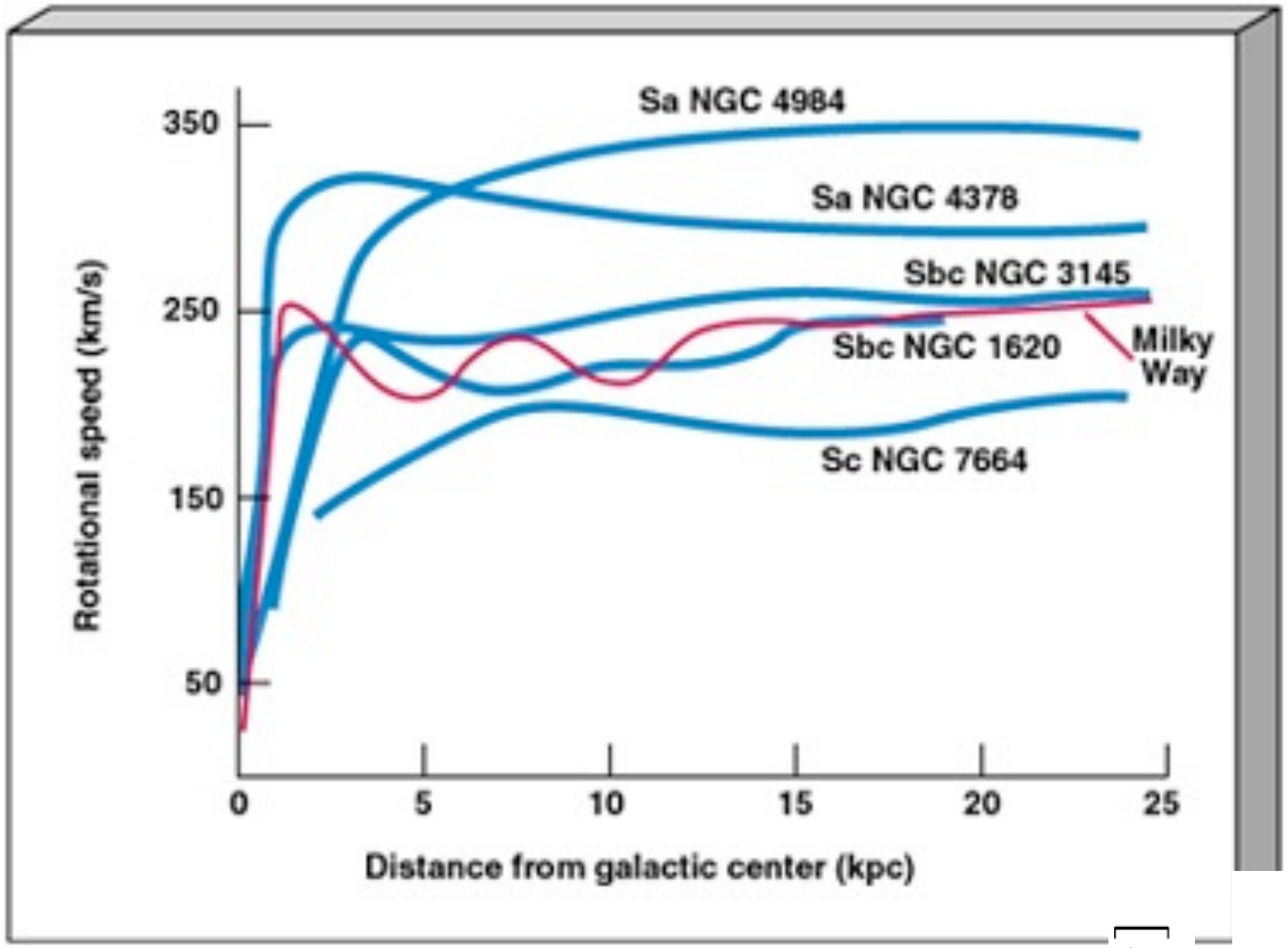

$$*\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$$

[Bovy and Tremaine 1205.4033]

$$f(v) \propto d^3v\, e^{-(v/v_0)^2}$$

$$v_0 = 220 \text{ km s}^{-1}$$

$$498 \text{ km/s} \leq v_{esc} \leq 608$$

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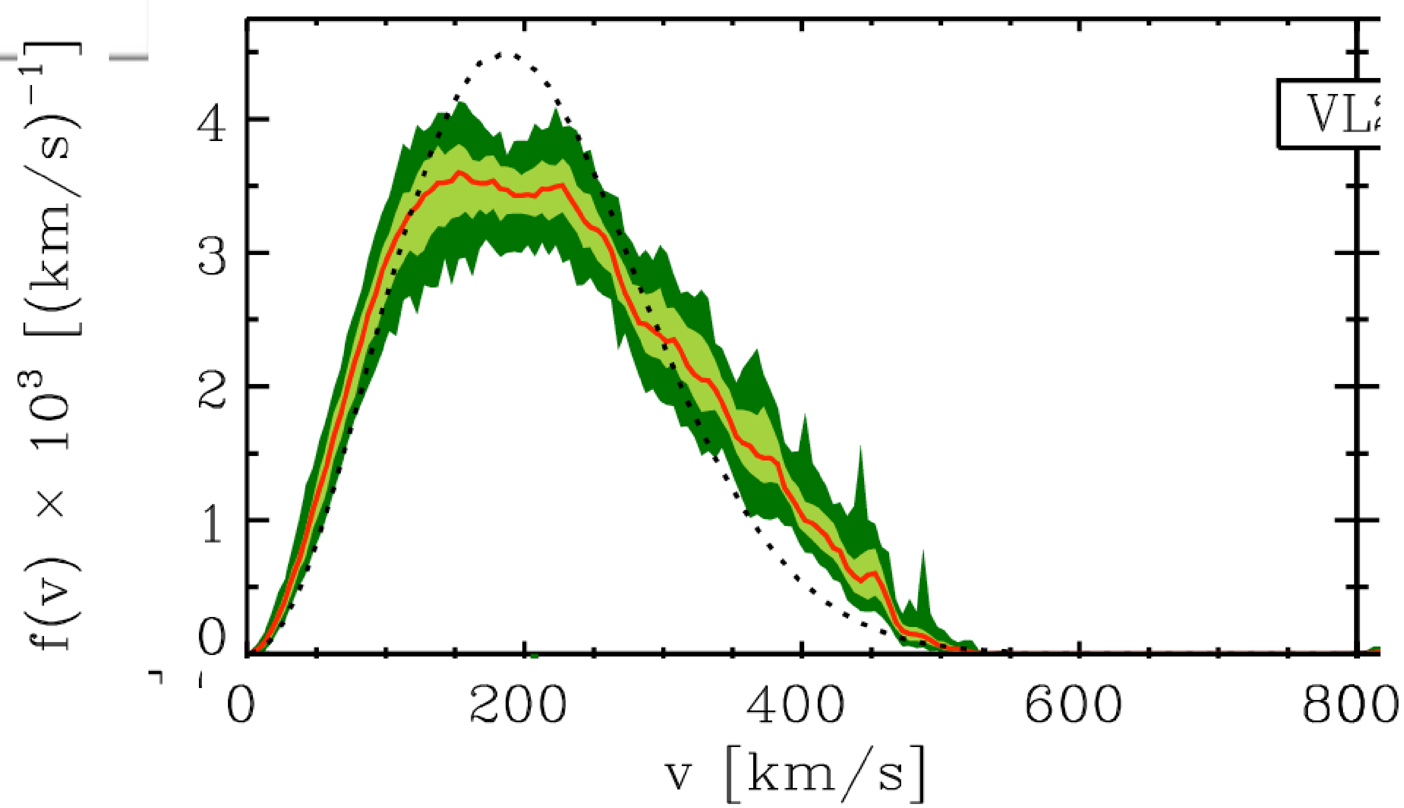

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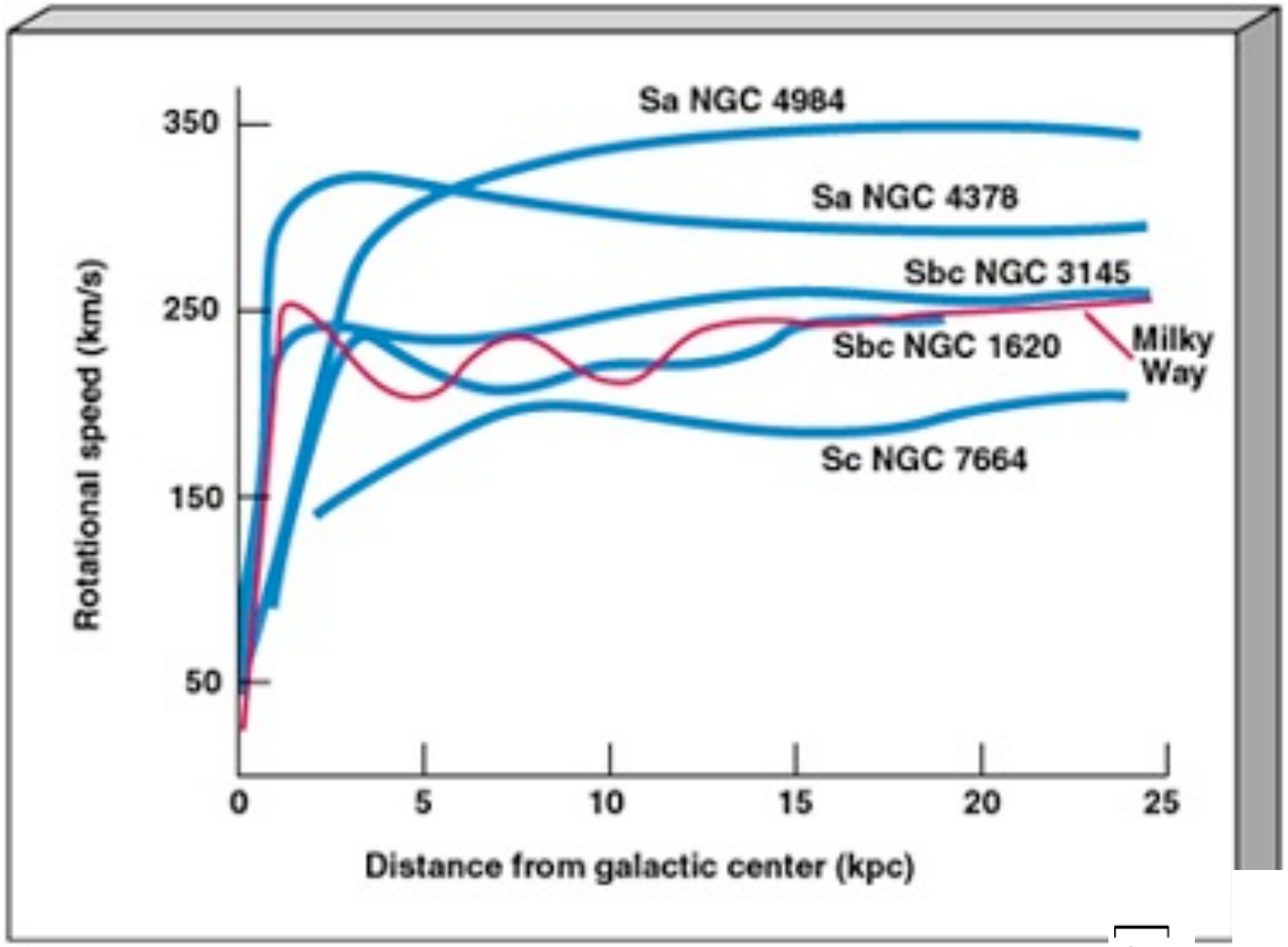

* $\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$

* $\pm$ a factor of two

[Bovy and Tremaine 1205.4033]

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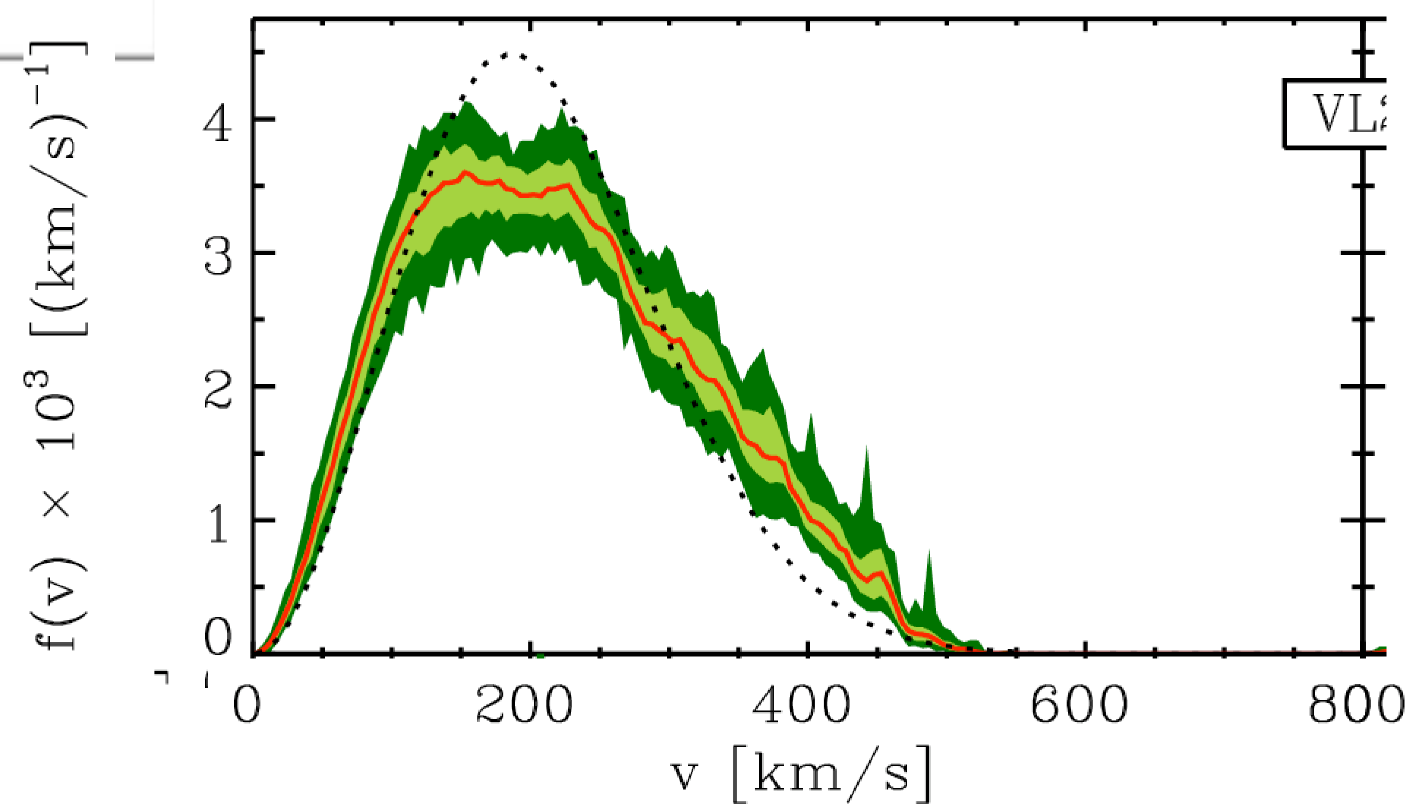

So far all probes have been gravitational in nature

What about other interactions?

DM as a thermal relic

"The weak shall inherit the Universe"

If there are DM-SM couplings leading to annihilation/ production, DM will be produced in the hot early universe

$$T \gg m_\chi : \; n_\chi^{eq} \sim T^3 \qquad\qquad \chi\chi \leftrightarrow \bar{f} f$$

$$T \lesssim m_\chi : \; n_\chi^{eq} = g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi / T} \qquad\qquad \chi\chi \to f \bar{f}$$

Universe is expanding while this is happening

Need to solve Boltzmann equation

$$\frac{dn_\chi}{dt} + 3 H n_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{eq}^2 \right)$$

$$H = \frac{\dot{a}}{a} \sim \frac{T^2}{M_{pl}}$$

DM as a tl

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production, D ... ot early universe

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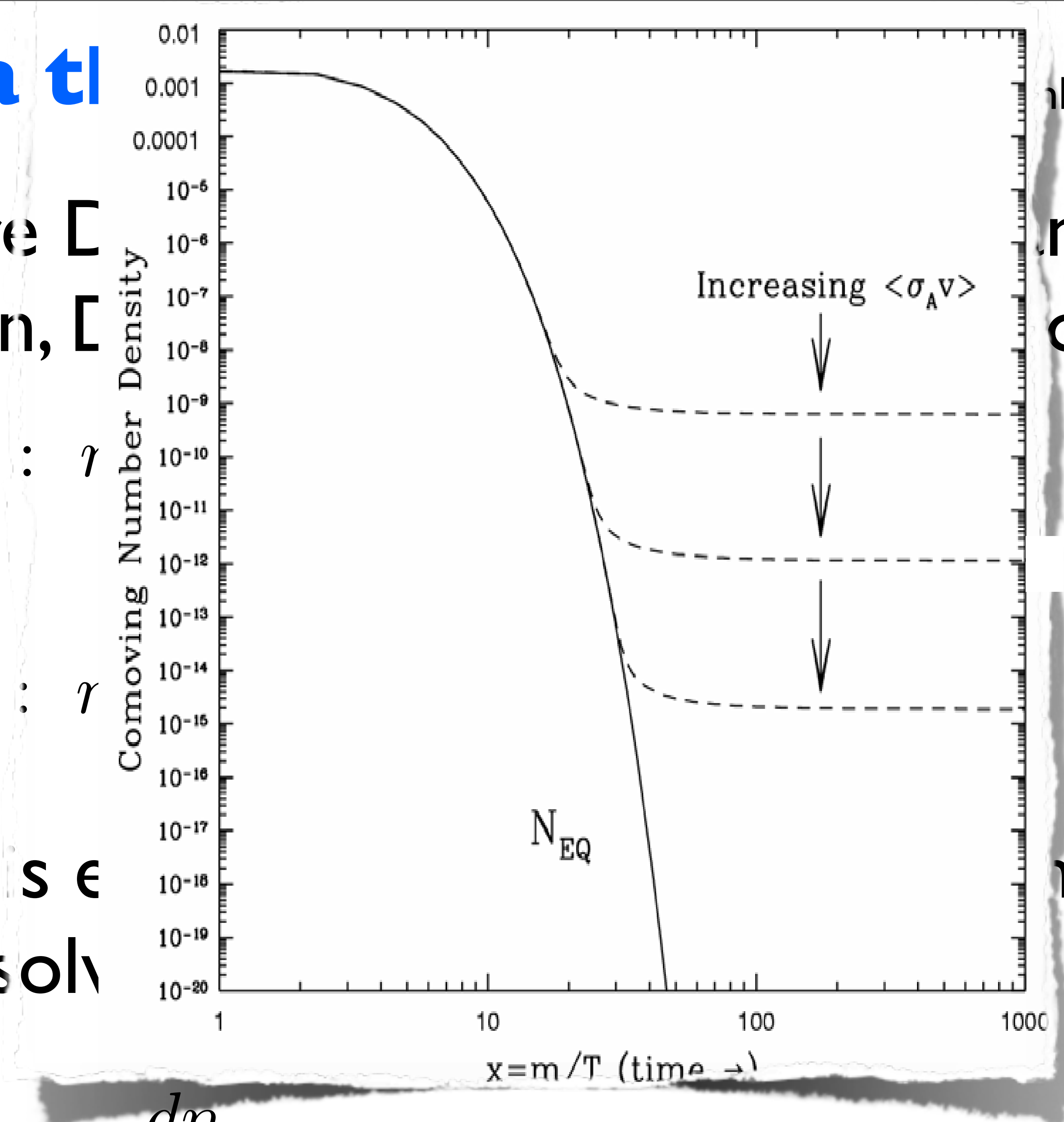

Universe s e ... ing
Need to solv

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Some examples

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

$$\langle \sigma v \rangle = const$$

Freeze out occurs when

$$\left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi / T} \sim \frac{T_f^2}{M_{pl} \langle \sigma v \rangle}$$

Numerical solution show x=20..30

$$\rho_c = \frac{3H^2}{8\pi G_N} = 8 \times 10^{-47} h^2 \mathrm{GeV}^{-4}$$

$$\Omega_\chi = \frac{m_\chi n_0}{\rho_c} \sim \frac{T_0^3}{\rho_c} \frac{x}{M_{pl} \langle \sigma v \rangle}$$

Some examples

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$$\rho_c = \frac{3H^2}{8\pi G_N} = 8 \times 10^{-47} h^2 \mathrm{GeV}^{-4}$$

$$\boxed{\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right)\left(\frac{g_*}{80}\right)^{-1}\left(\frac{3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)}$$

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IF DM is a thermal relic:

- A weak scale annihilation x-sec gives correct abundance
- Mass range is $10 \text{ MeV} \lesssim m_\chi \lesssim 70 \text{ TeV}$

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WIMPs

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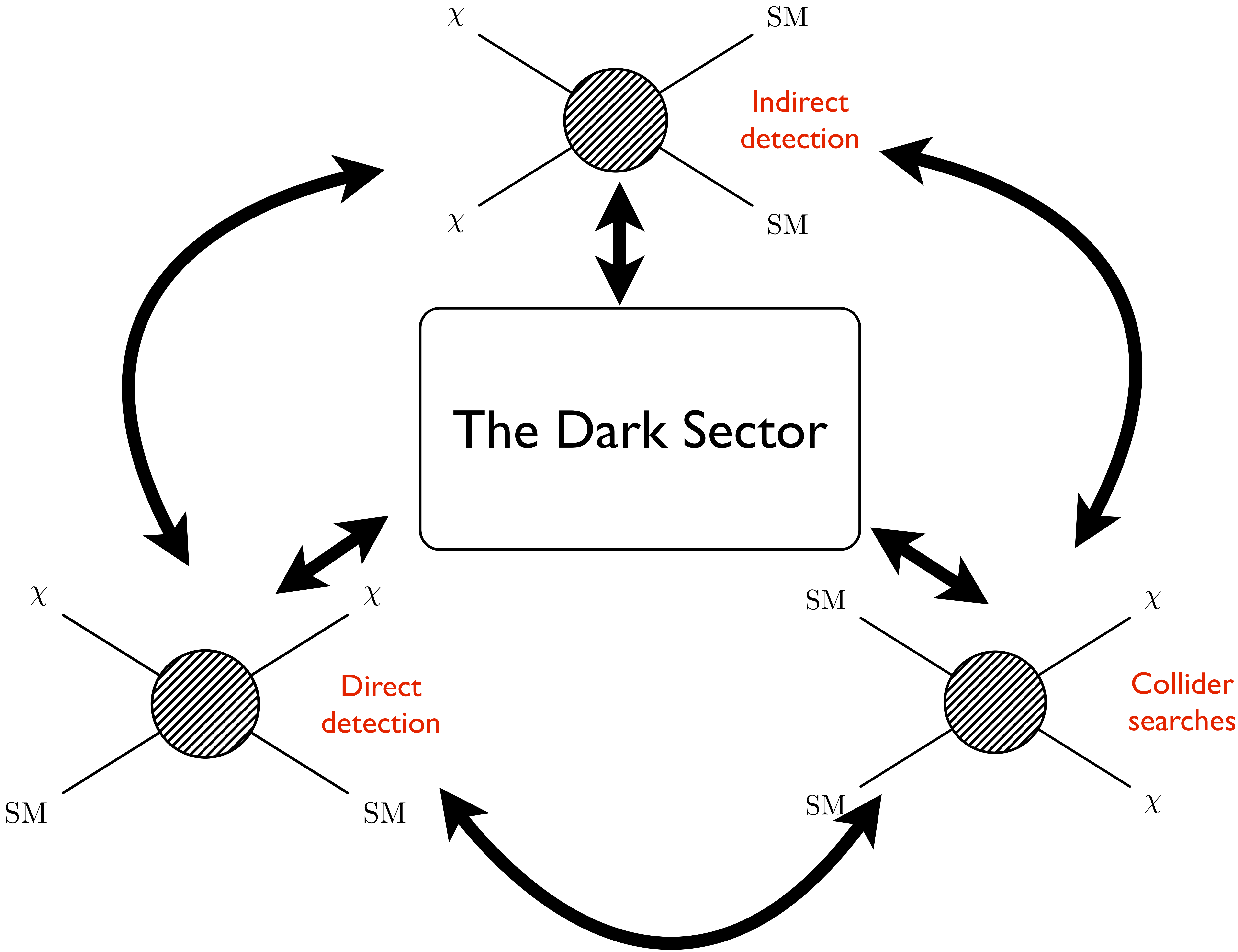
WIMPs and BSM physics

- Higgs hierarchy problem "predicts" new states at weak scale with/without SM charge
- Flavour constraints require high scale (1000 TeV) suppression of FCNC operators
- "New physics parity"
- LPOP often has possibility to be a DM WIMP

- WIMPs e.g. SUSY neutralino, KK-mode of UED, techni-baryons, lightest T-odd little Higgs particle, LPOPs....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SM
Indirect detection
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SM
The Dark Sector
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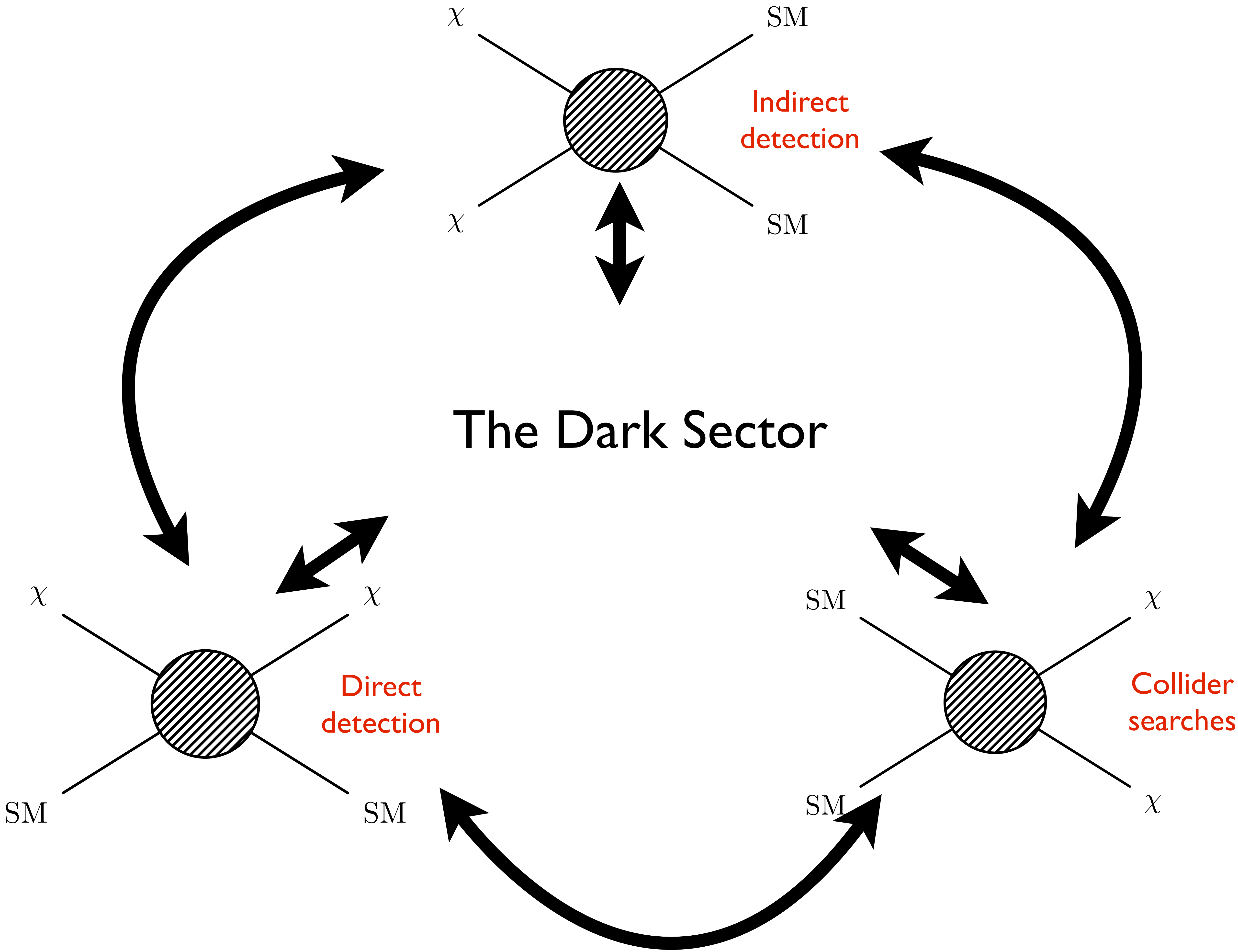
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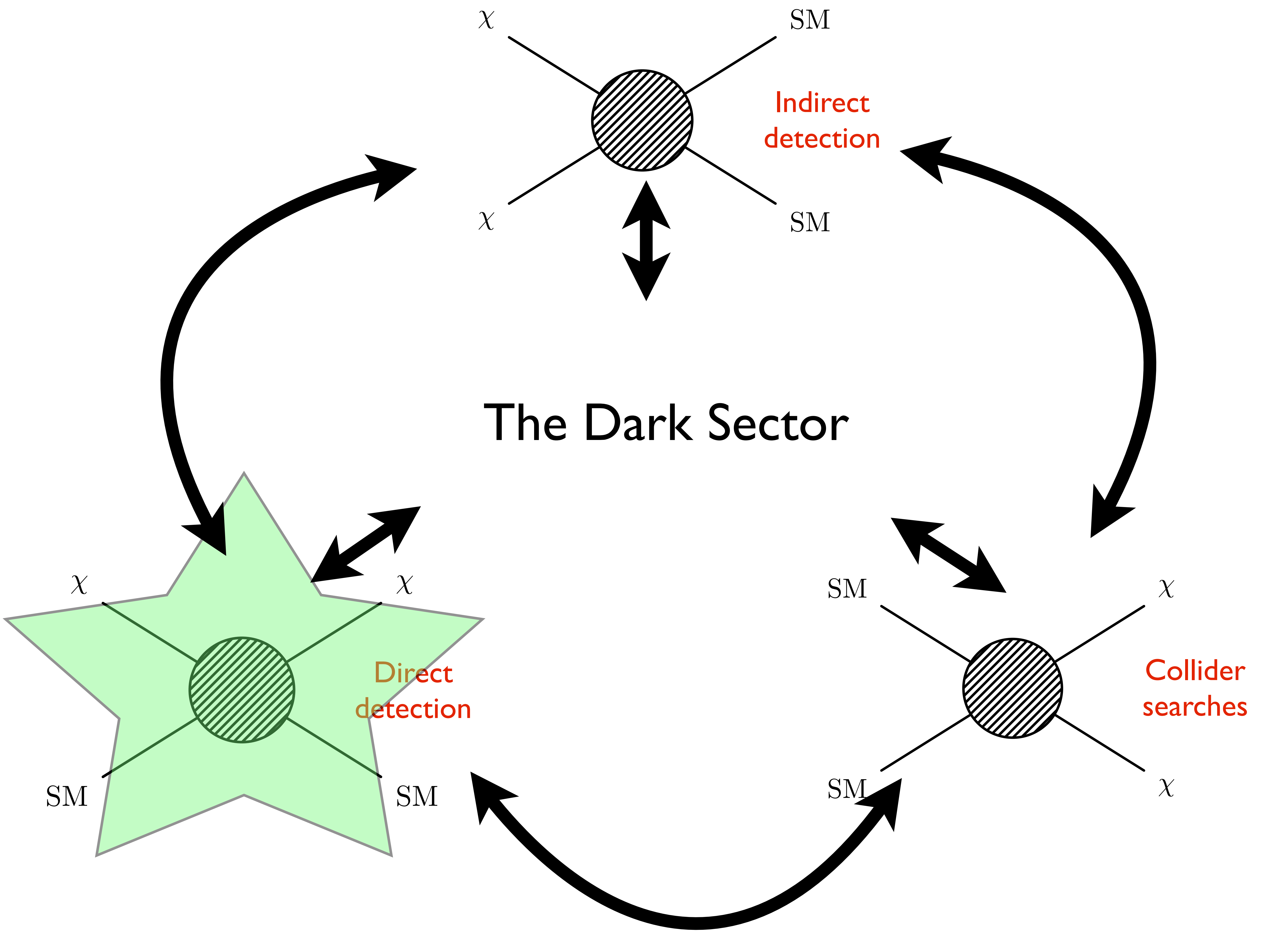

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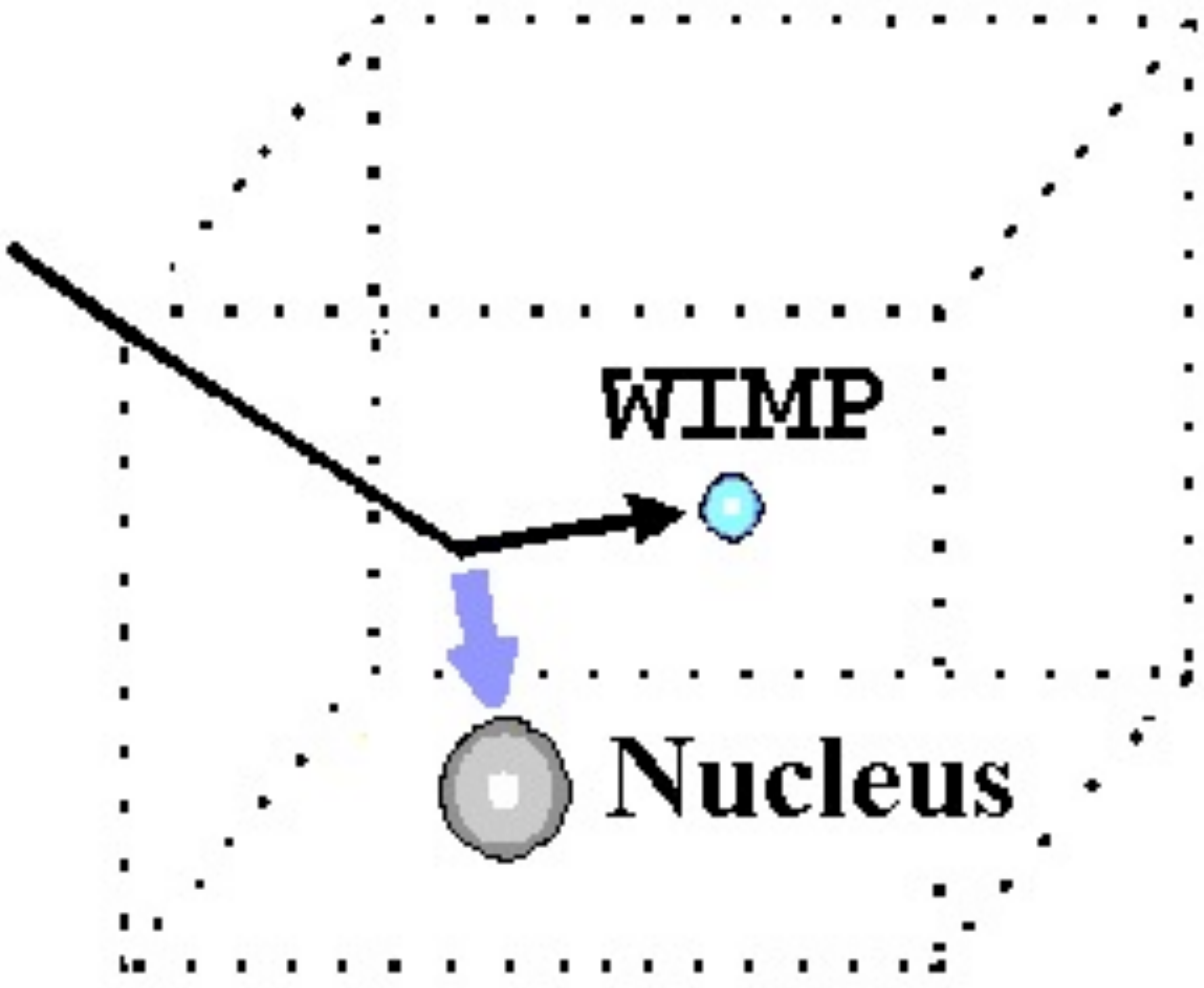
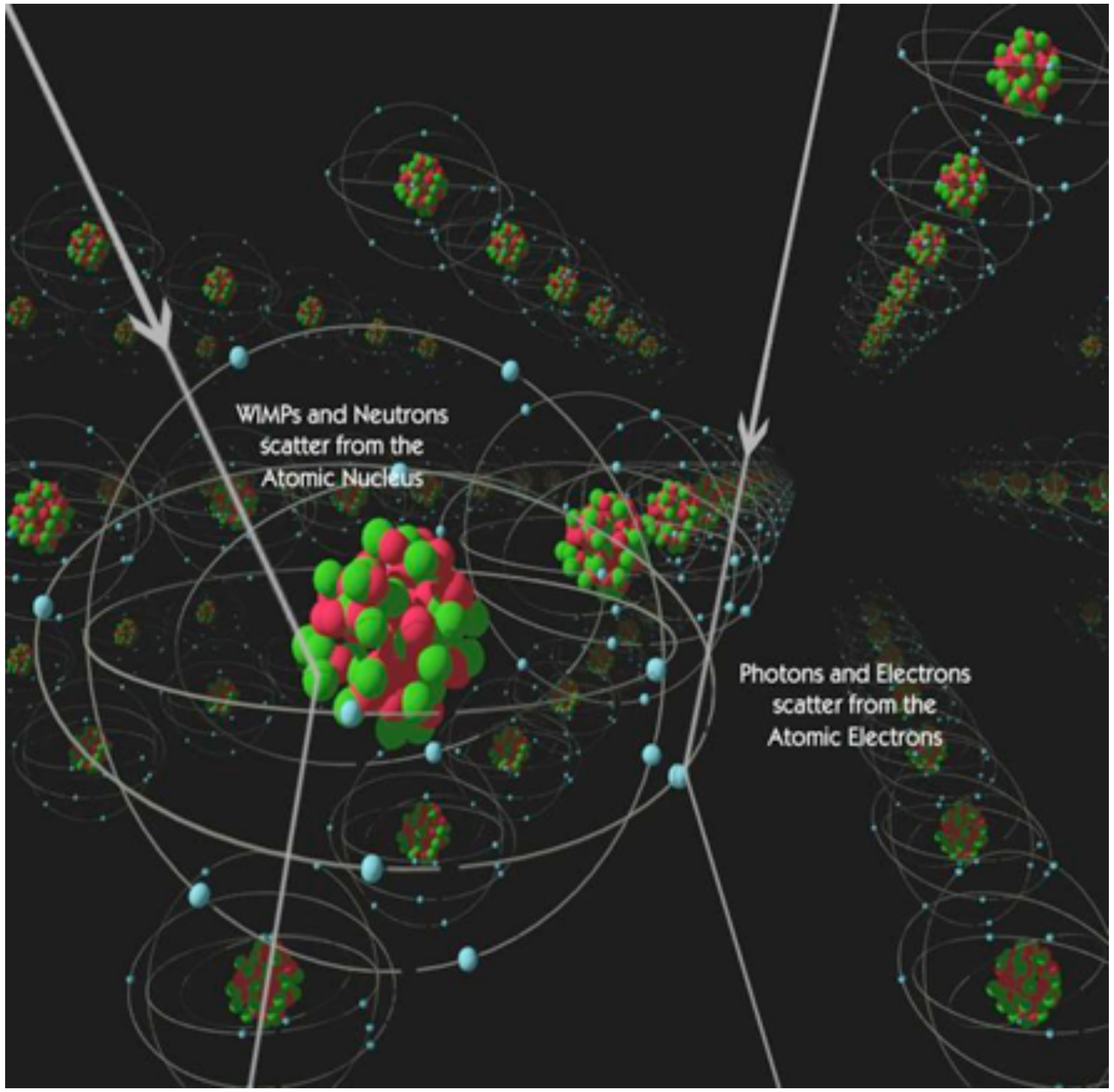
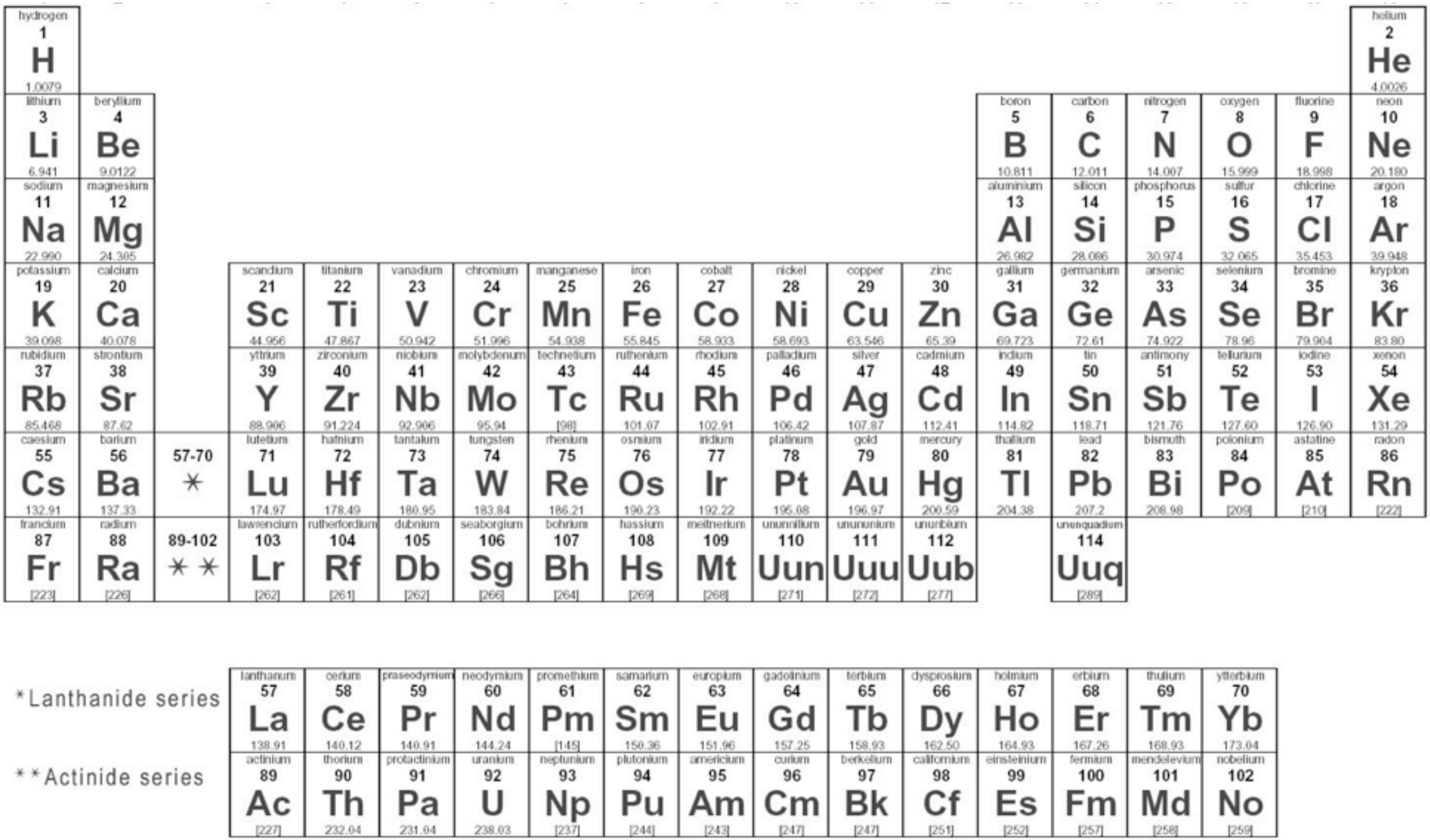
Dark Matter Direct Detection

(the theorist's perspective)





An exciting time, many experiments



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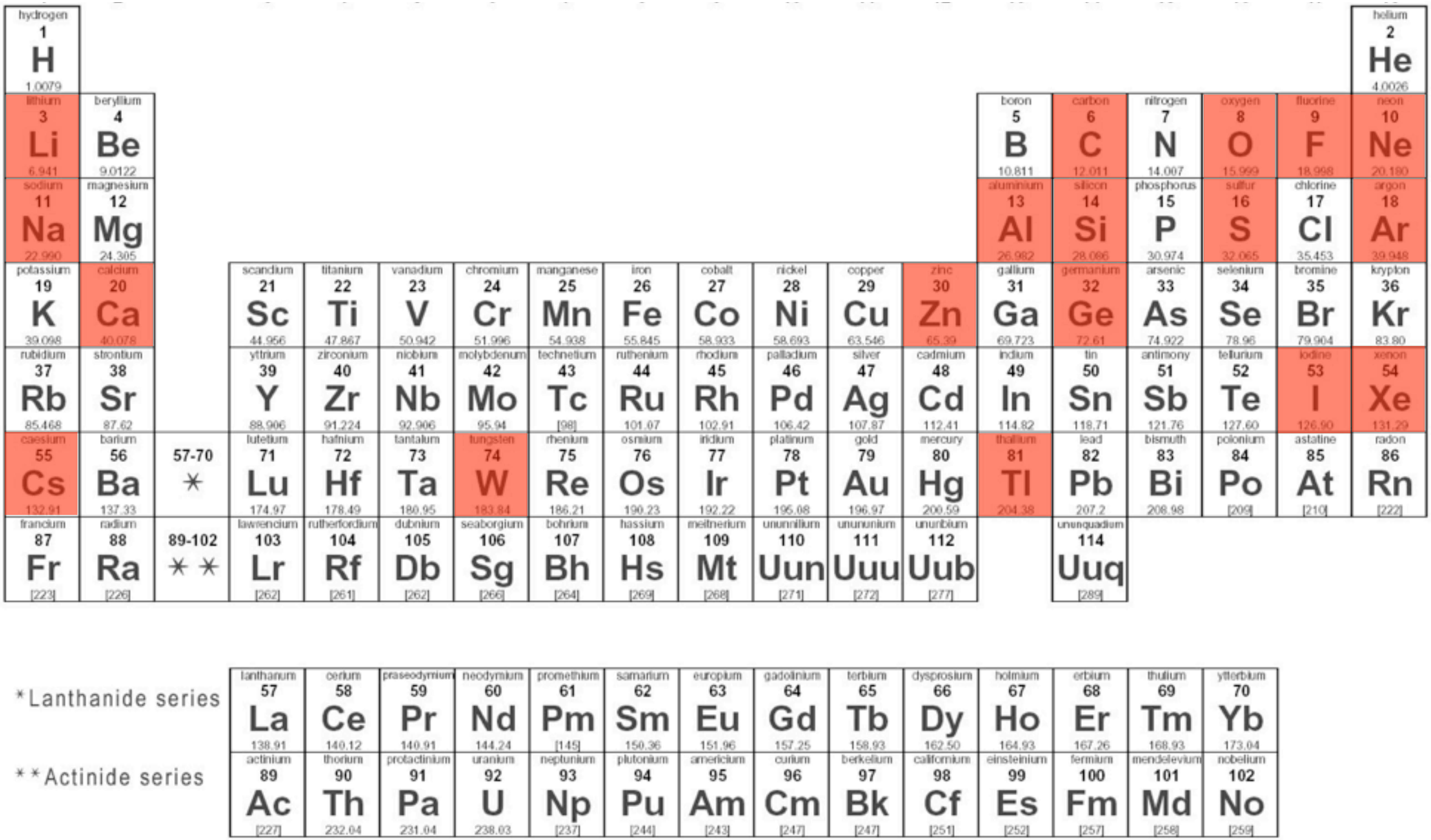
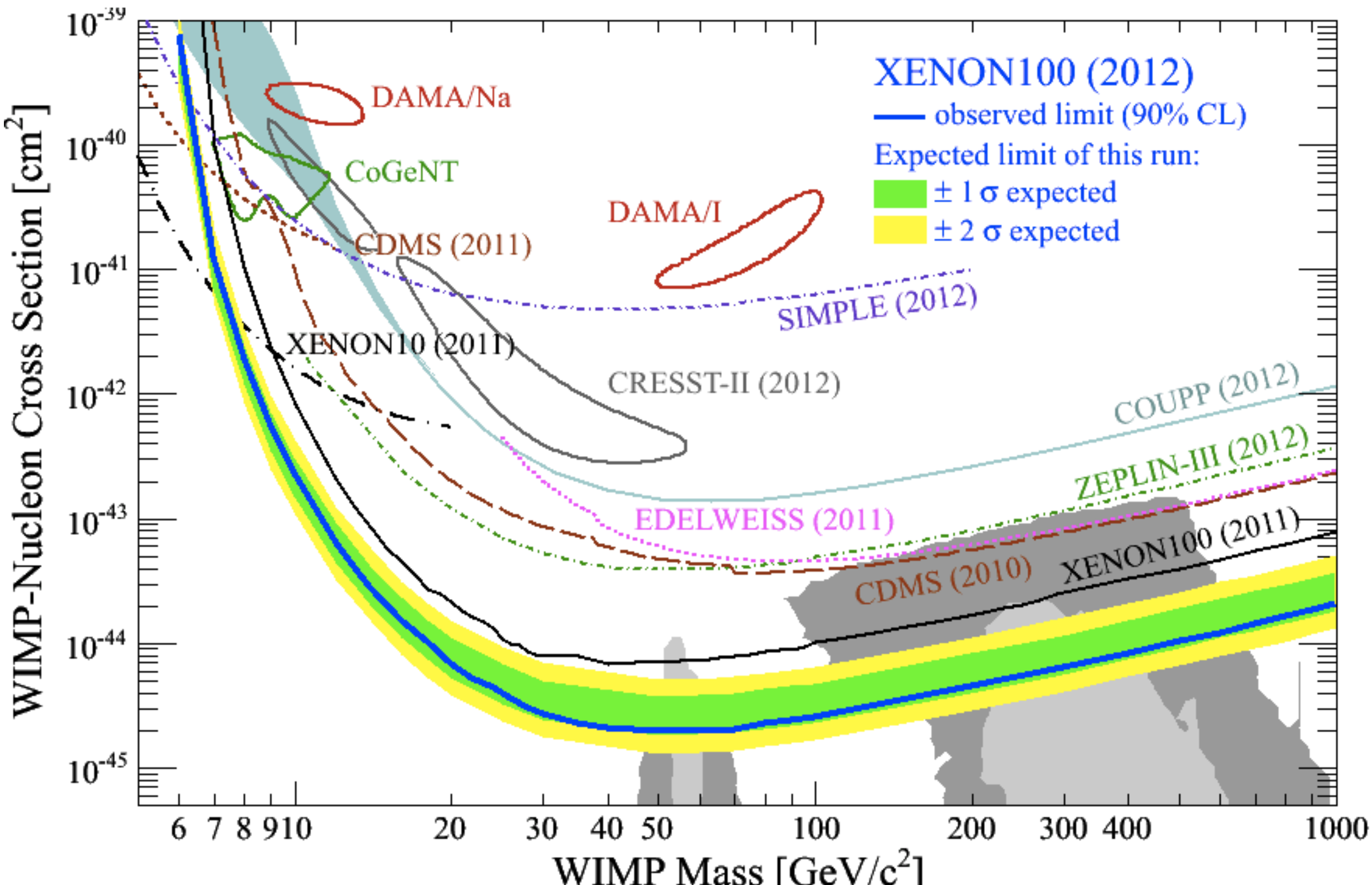


Aim: to understand everything that goes into this plot



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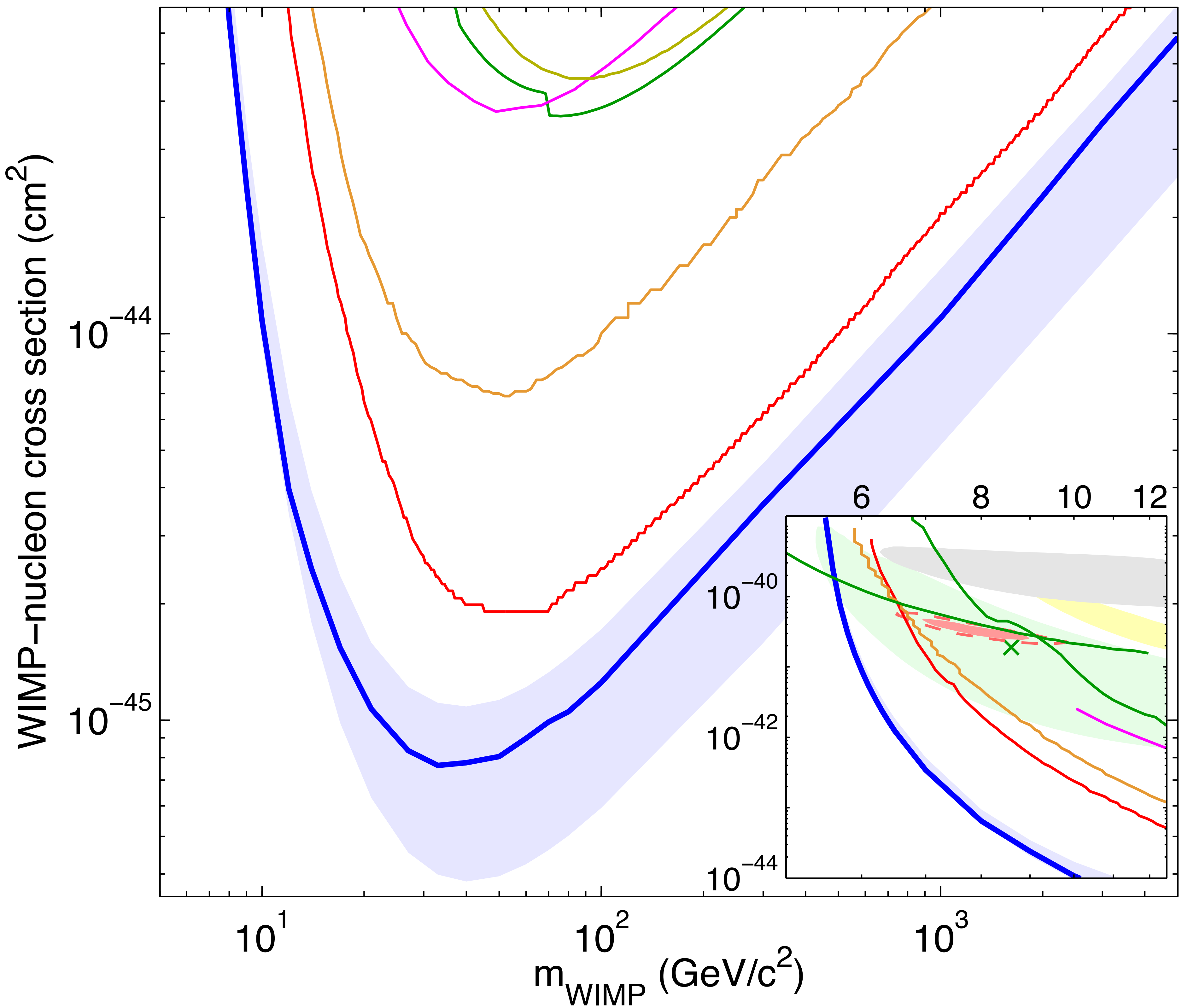
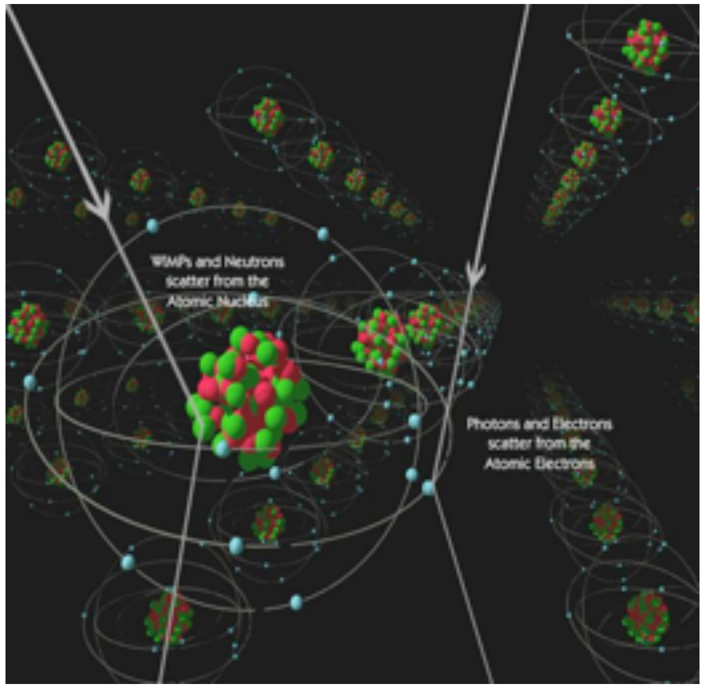


“The Master formula”



$$\frac{dR}{dE_R} = \frac{N_T \rho}{m_\chi} \int_{v_{\min}}^{v_{\max}} d^3v \, f(v(t)) \frac{d\sigma |v|}{dE_R}$$

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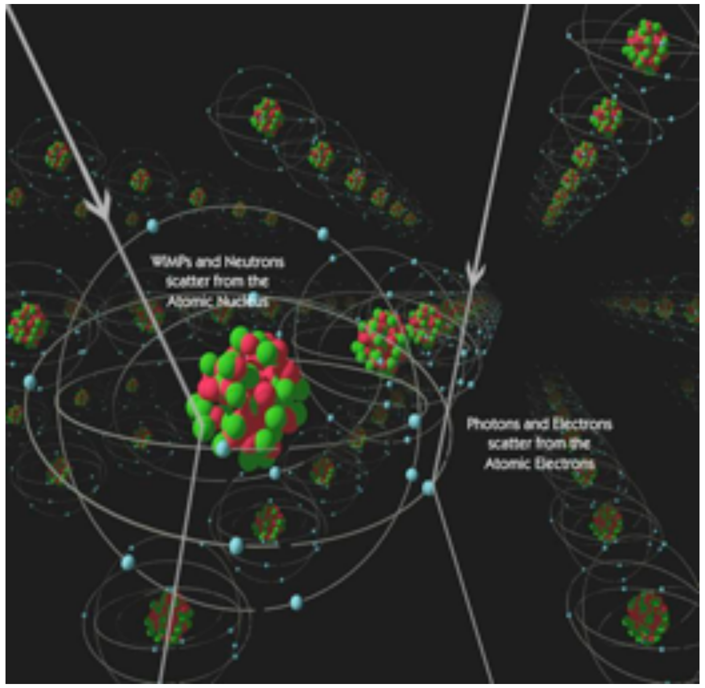

Recoil rate as a function of recoil energy

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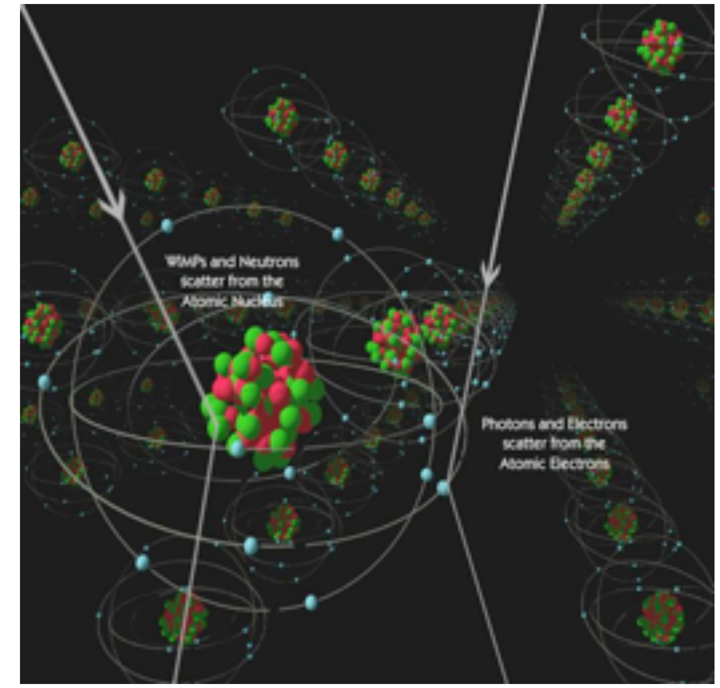

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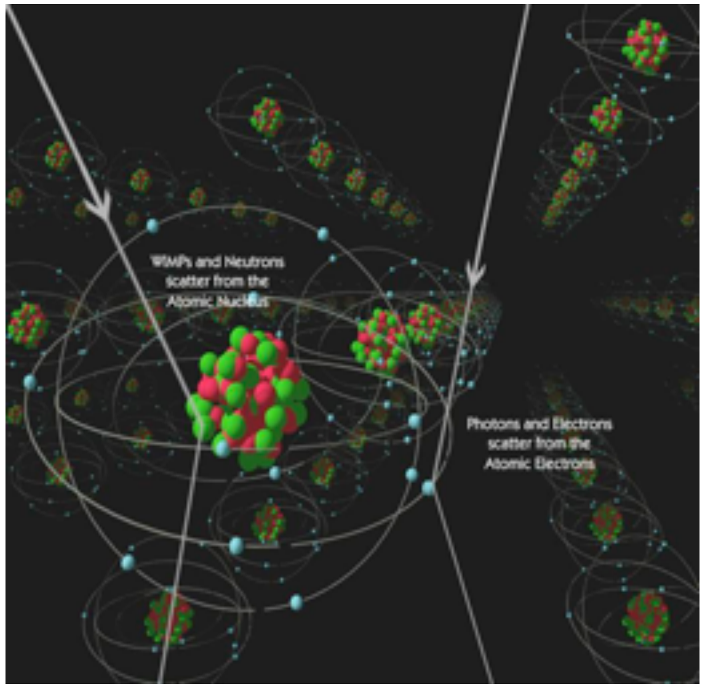
Number of targets in experiment

“The Master formula”



Depends on how much DM is around...

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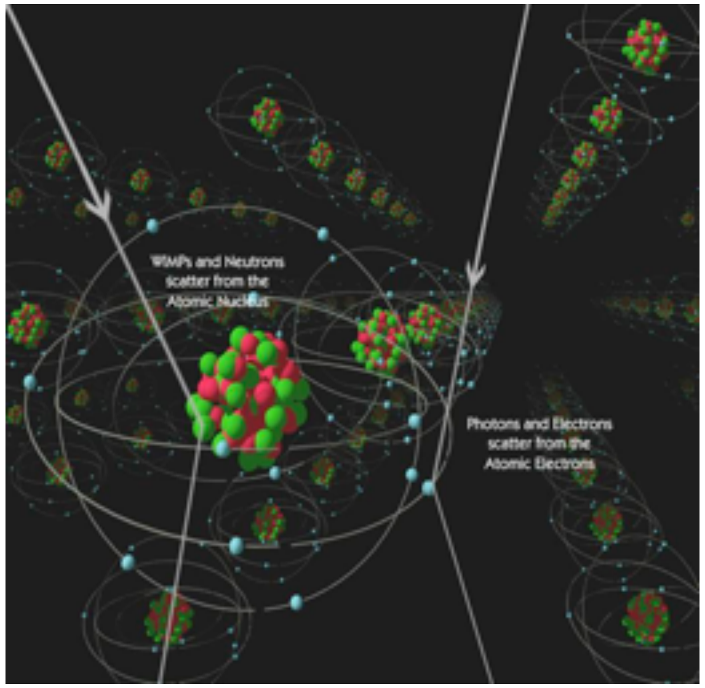

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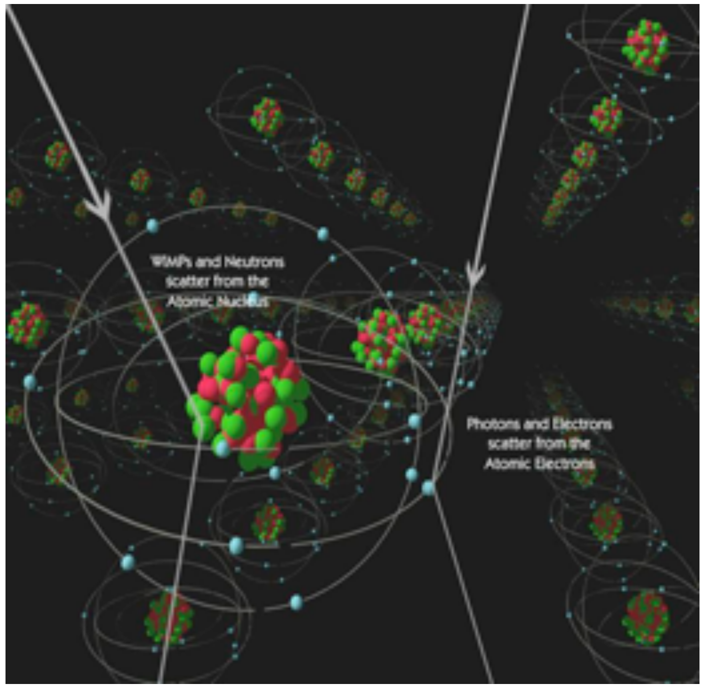
...and how it’s moving...

“The Master formula”



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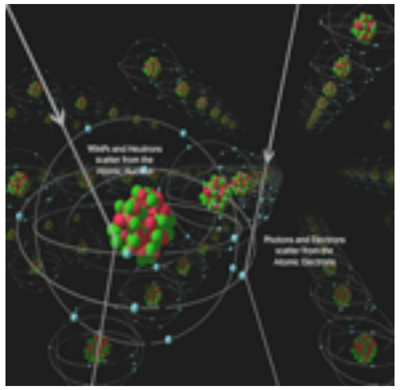
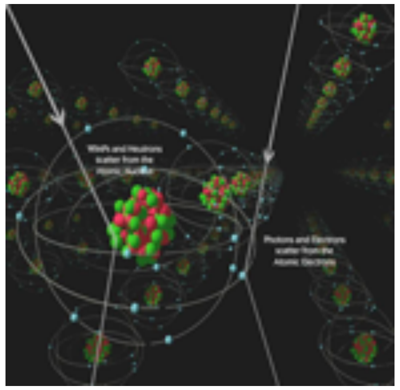
...and how it interacts with nuclei.

“The Master formula”



$$\frac{d\sigma}{dE_R} = F_N^2(E_R) F_\chi^2(E_R) \frac{m_N}{\mu v^2} \sigma_N$$

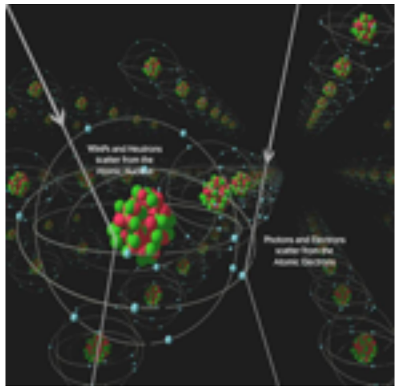
“The Master formula”



Differential
cross section

$$\frac{d\sigma}{dE_R} = F_N^2(E_R)F_\chi^2(E_R)\frac{m_N}{\mu v^2}\sigma_N$$

“The Master formula”



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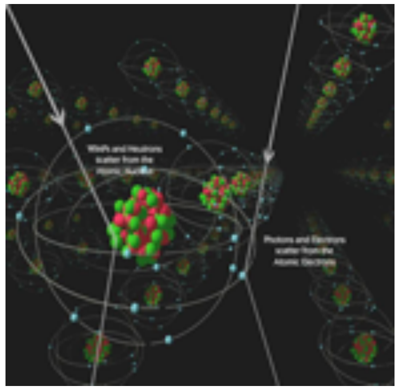
Form factor
(nuclear)

“The Master formula”



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(DM)

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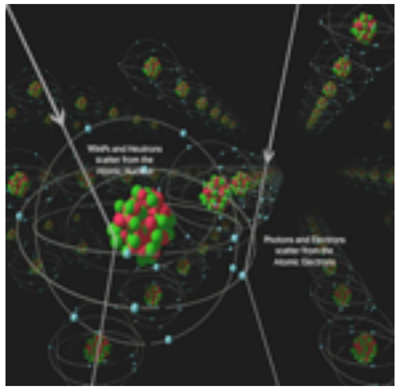

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Cross section

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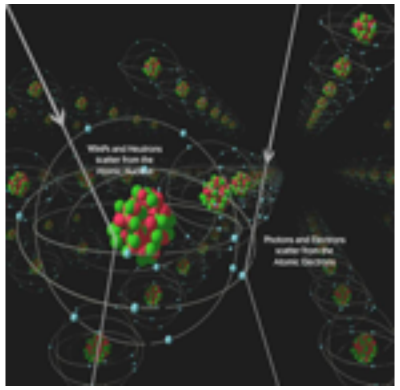
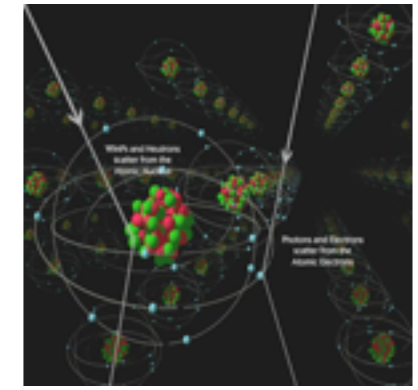


$$\frac{d\sigma}{dE_R} = F_N^2(E_R)F_\chi^2(E_R)\frac{m_N}{\mu v^2}\sigma_N$$

$$\sigma^{\text{SI}} = \frac{[Zf_p + (A-Z)f_n]^2}{f_p^2}\frac{\mu_{\chi N}^2}{\mu_{\chi p}^2}\sigma_p^{\text{SI}}$$

“The Master formula”



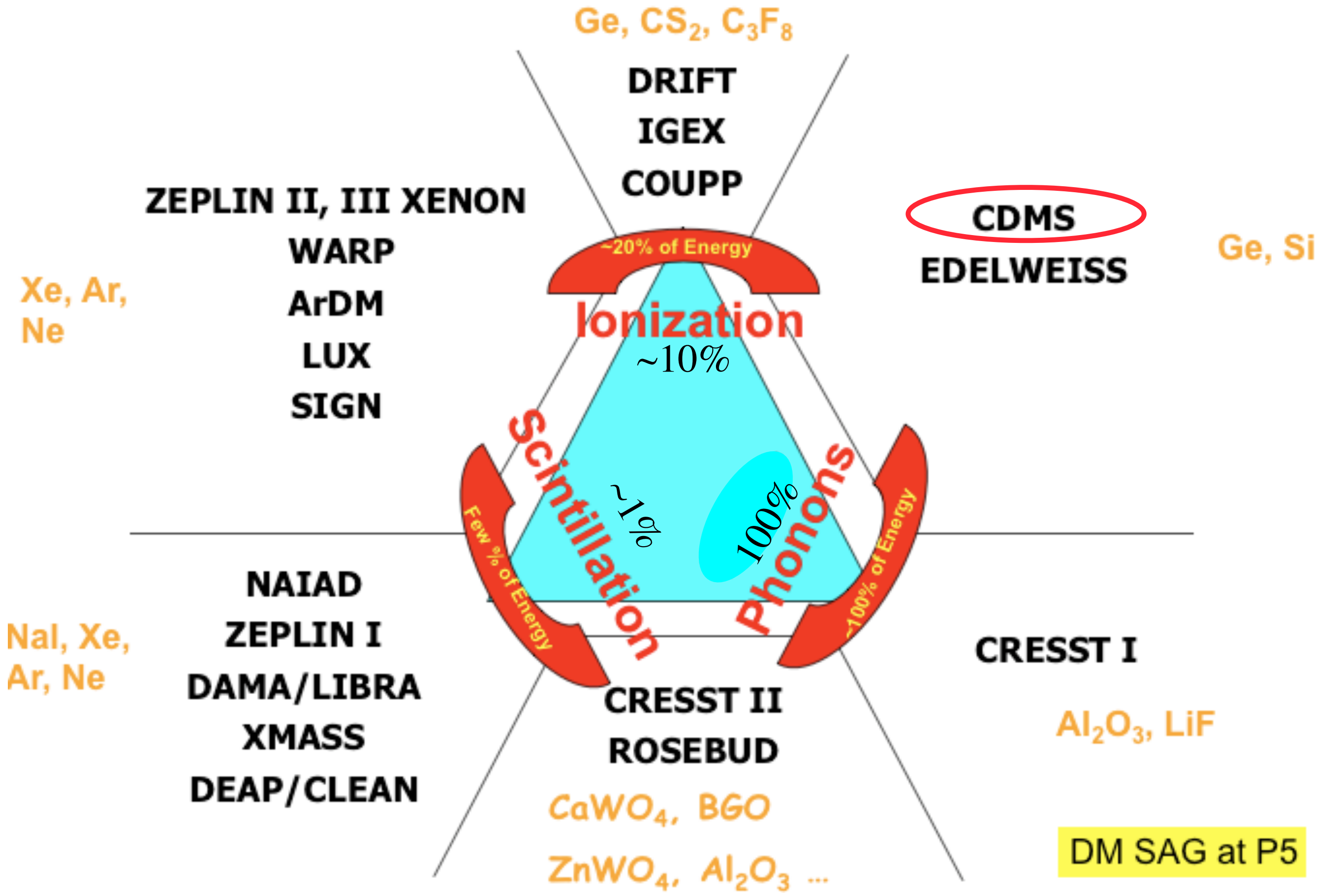
$$\frac{d\sigma}{dE_R} = F_N^2(E_R) F_\chi^2(E_R) \frac{m_N}{\mu v^2} \sigma_N$$

$$\sigma^{\rm SI} = \frac{[Z f_p + (A - Z) f_n]^2}{f_p^2} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \sigma_p^{\rm SI}$$

$$\sigma^{\rm SD} S(E_d) = \frac{4\mu_{\chi N}^2 \pi}{3\mu_{\chi p}^2 a_p^2 (2J+1)} [a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q)] \sigma_p^{\rm SD}$$

Of course, don't actually measure DM recoils directly

In reality also have to include backgrounds and combine with detector effects
e.g. energy resolution, quench factors, target composition, deadtime etc etc



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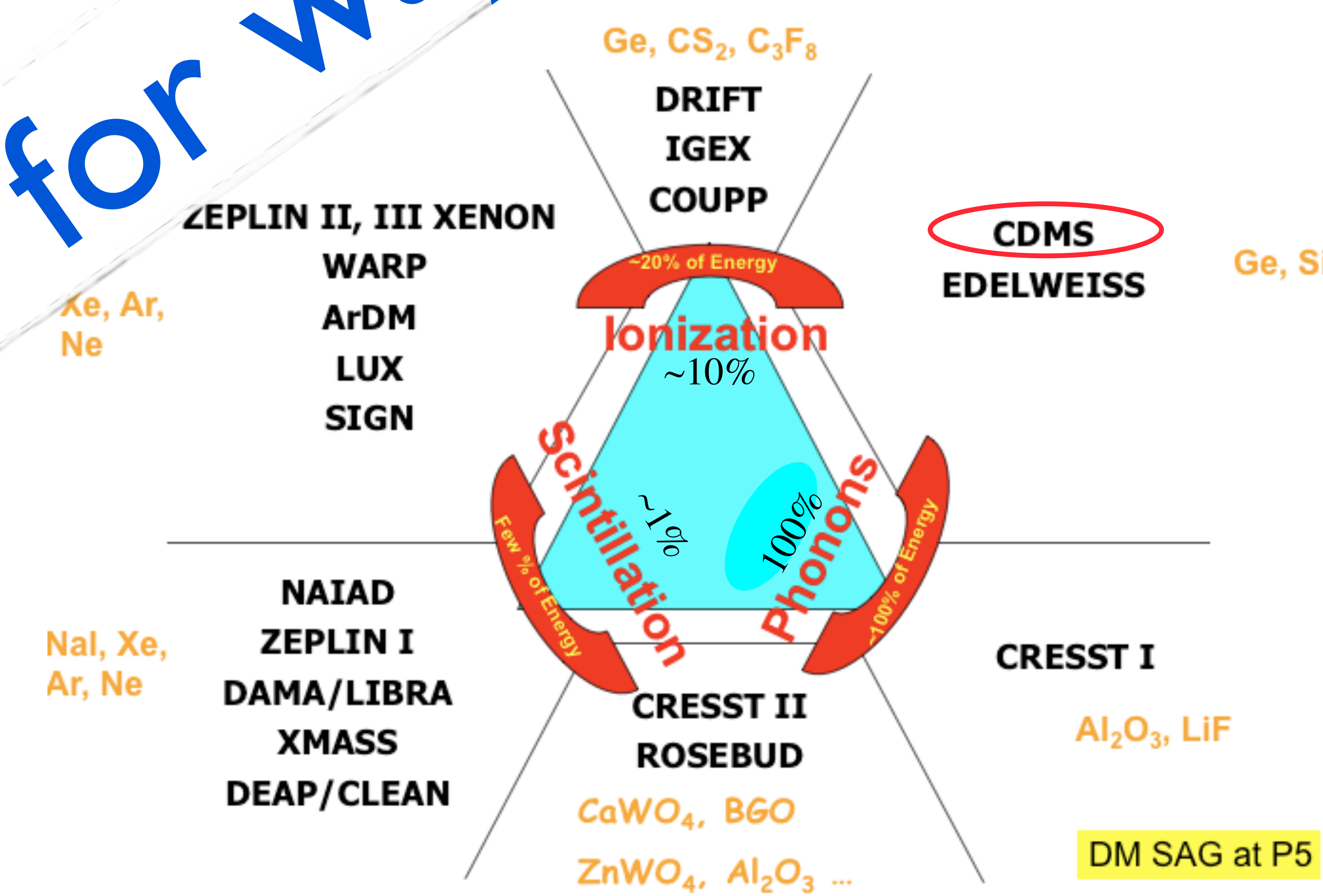
e.g. energy resoluti…

quench factors, ta…

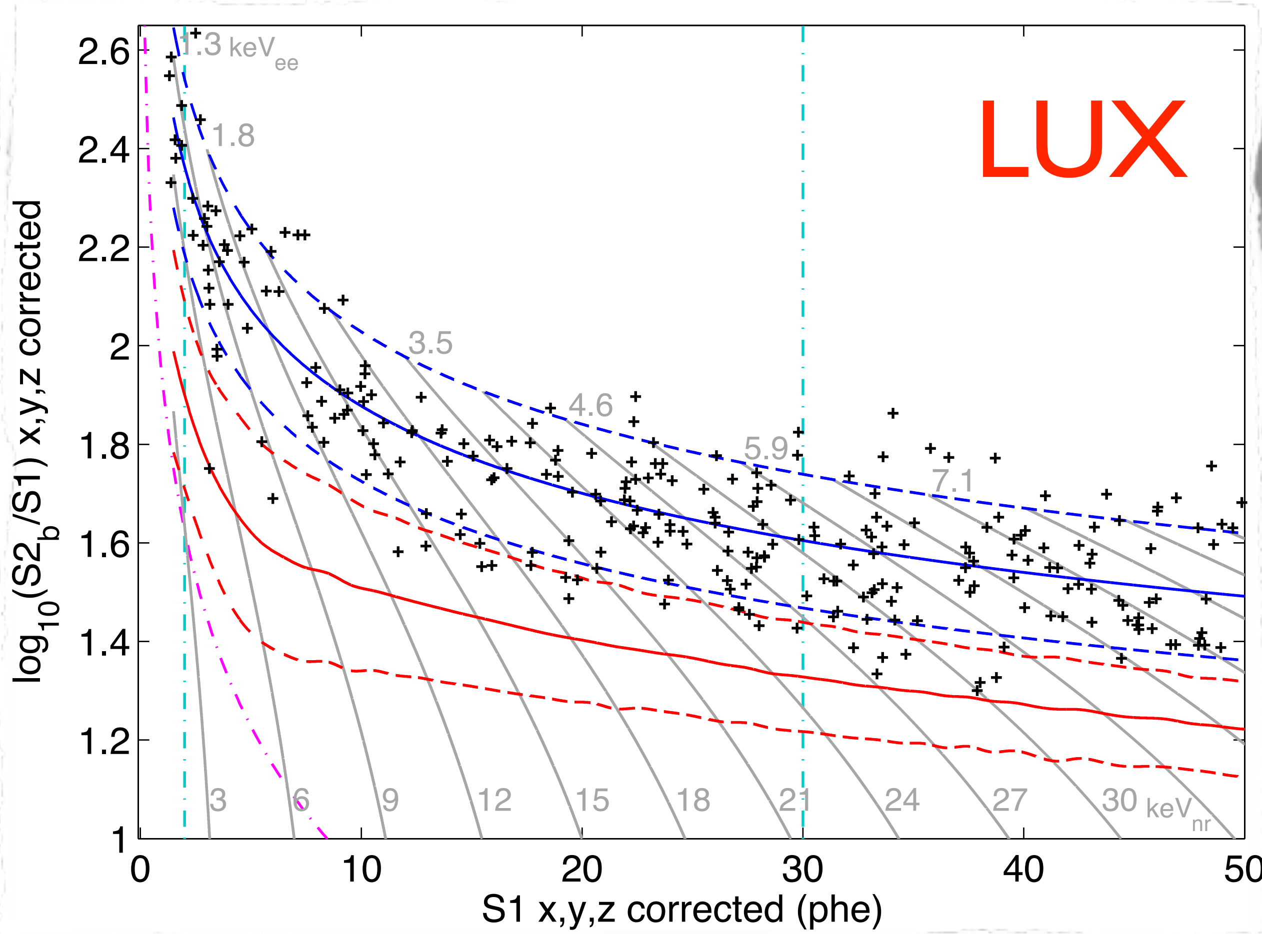
compositio…, d… …me

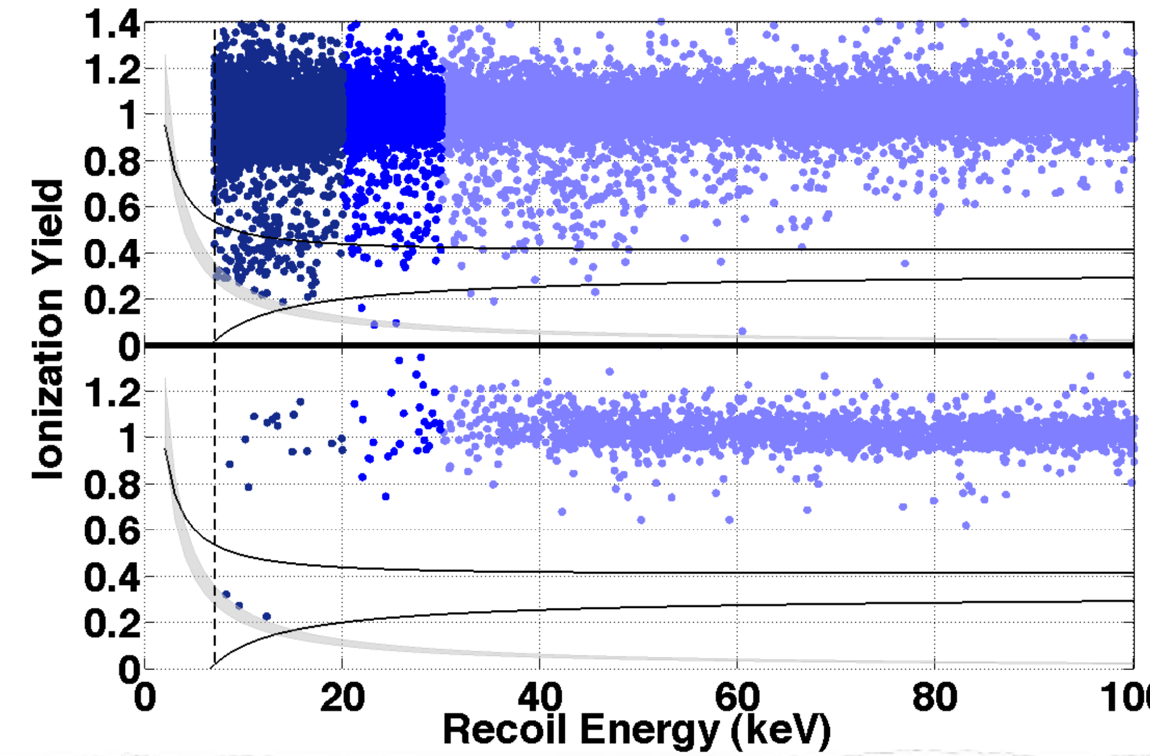
etc etc

See Jodi's talk(s) for way more detail

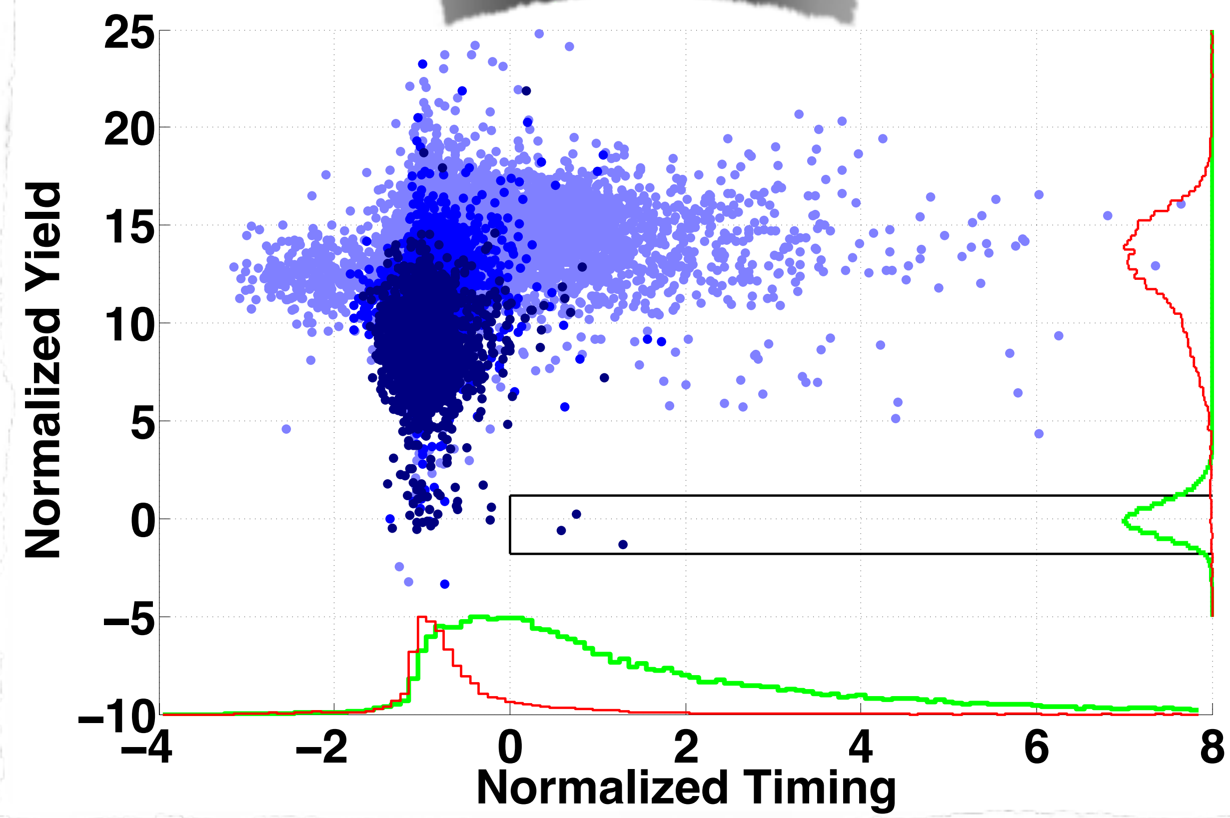


LUX

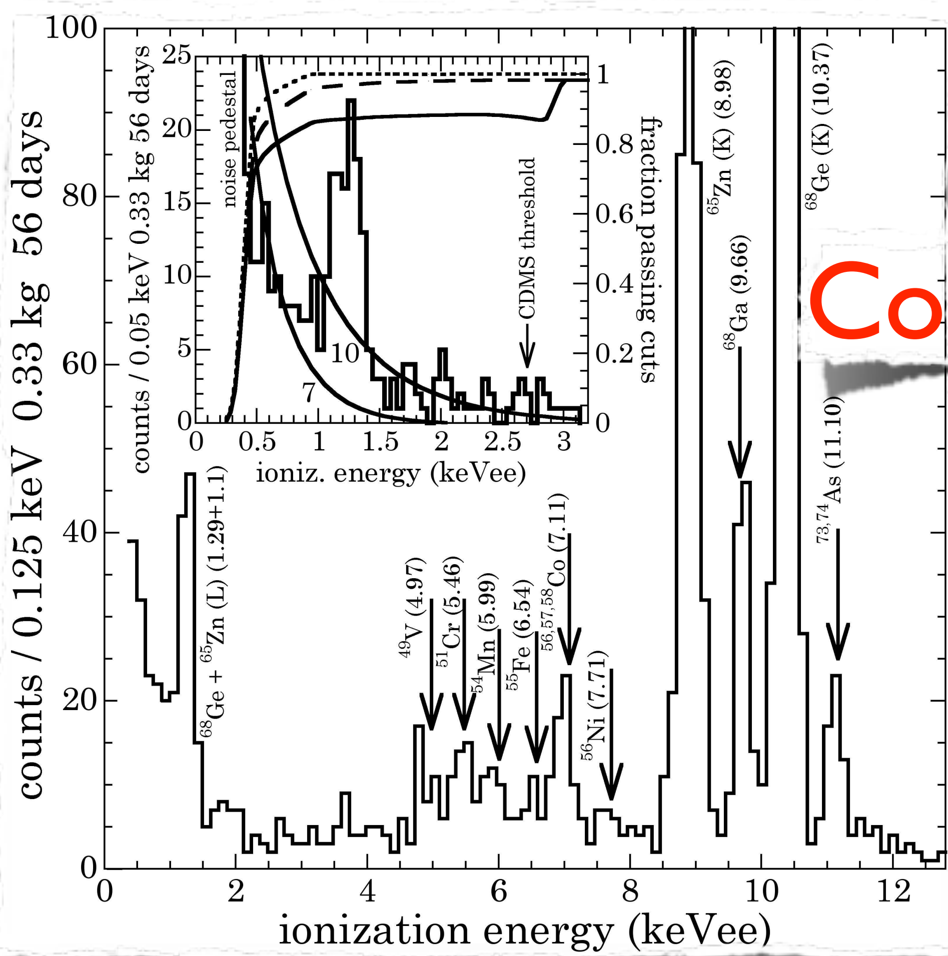




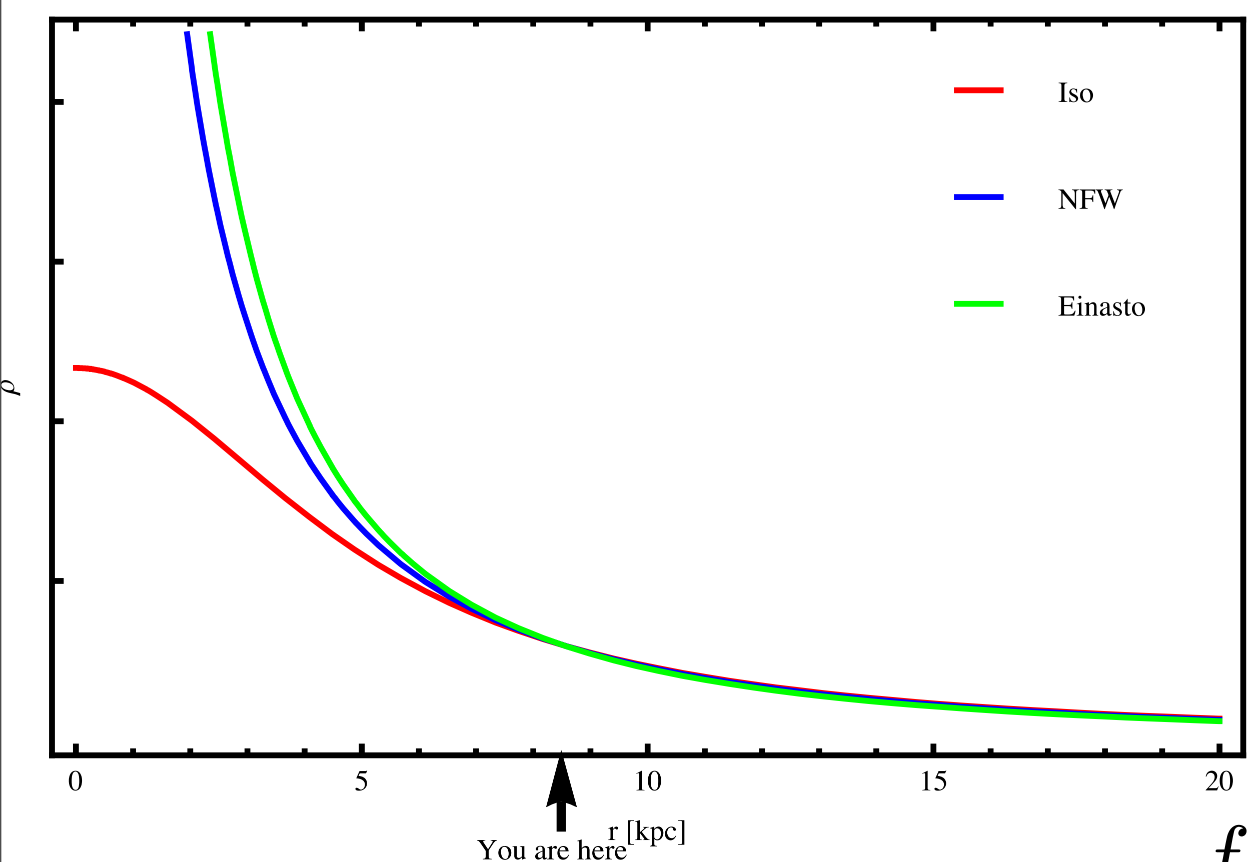
CDMS-Si



CoGeNT



DM’s local properties (?)

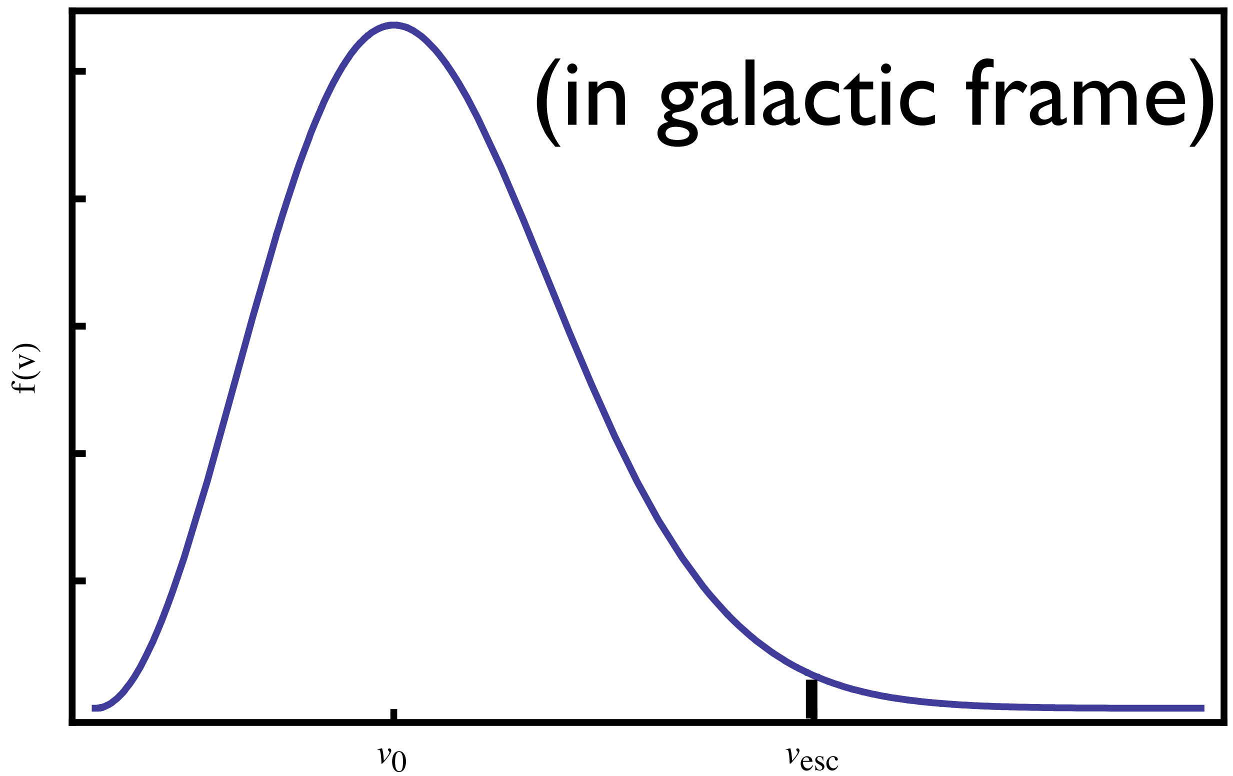


Overall scaling by local density

$^*\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$

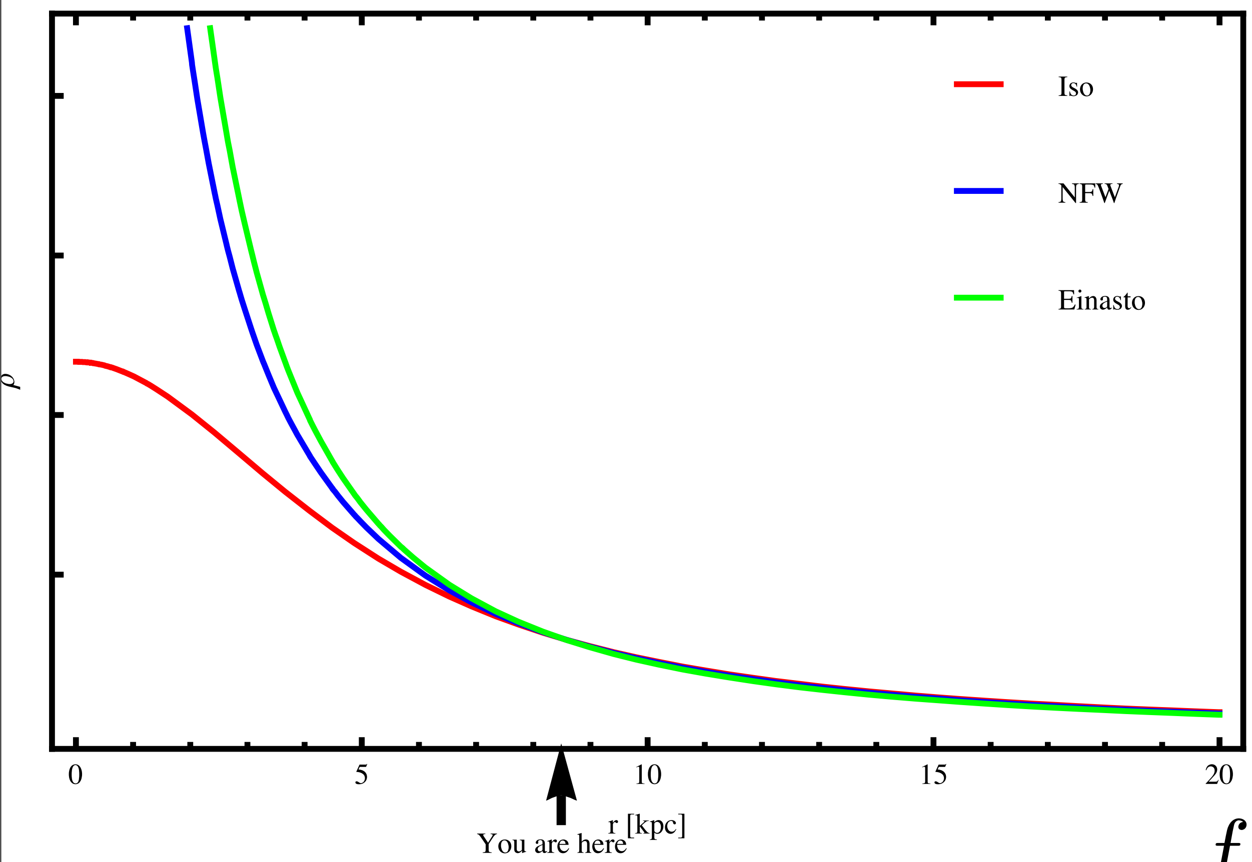
$^* \pm$ a factor of two

$$f(v) \propto \left(e^{-v^2/v_0^2} - e^{-v_{esc}^2/v_0^2}\right)\Theta(v_{esc} - v)$$



Maxwell Boltzmann distribution
or
Standard Halo Model

DM's local properties (?)



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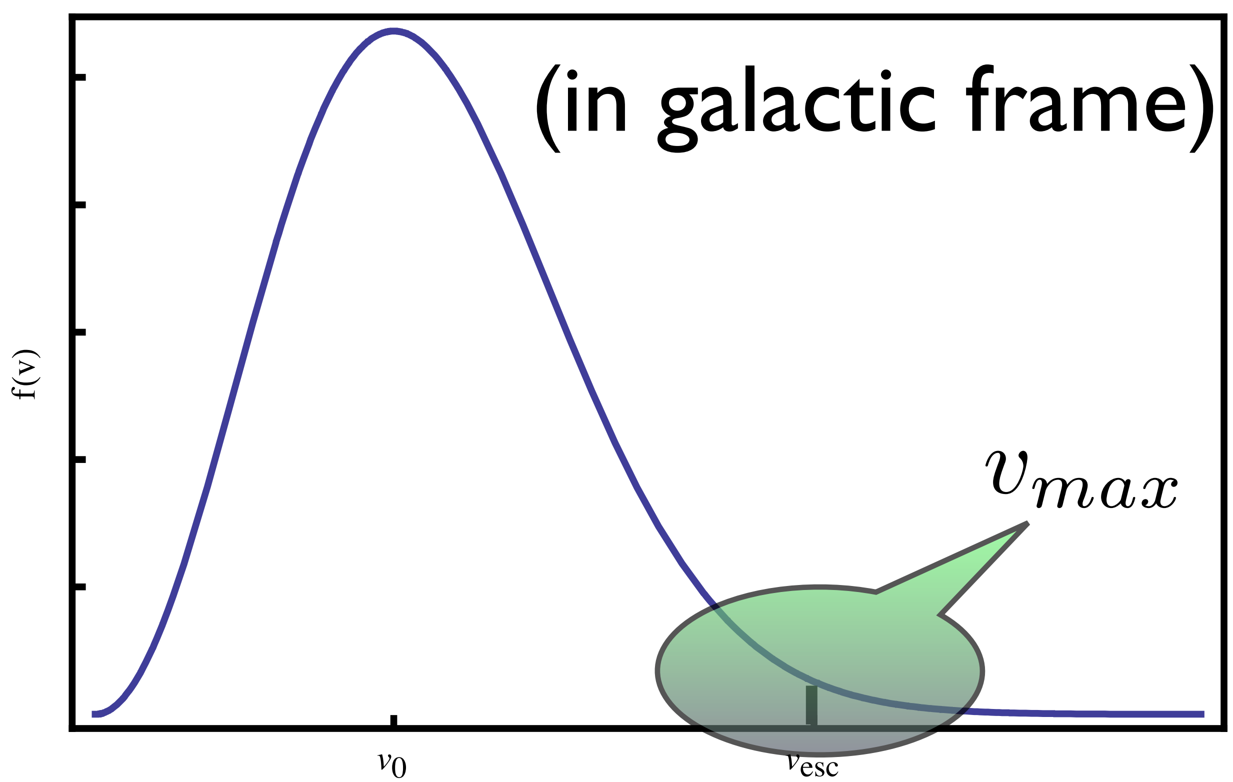

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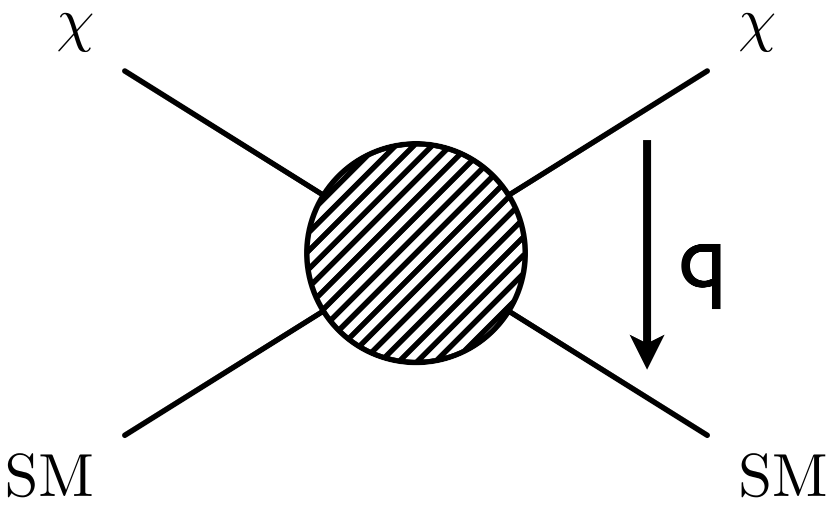
Kinematics



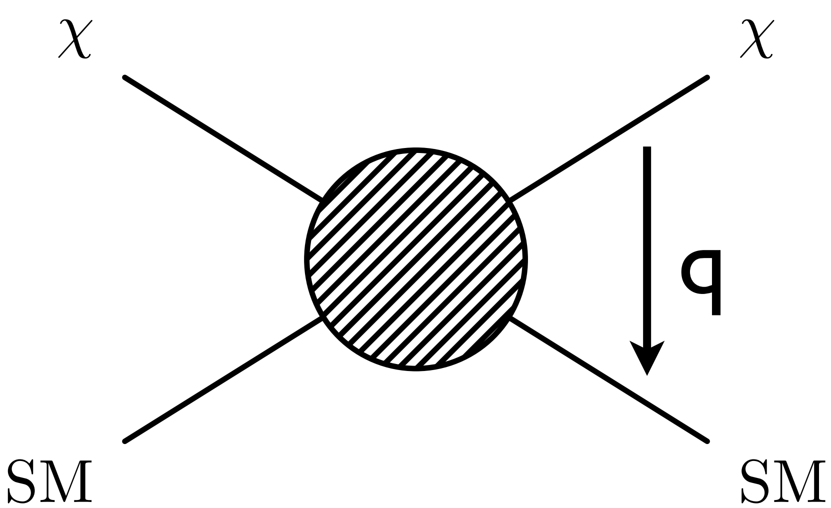
$$q^2 = 2\mu_{N\chi}^2 v^2 (1 - \cos\theta)$$

$$E_R = \frac{q^2}{2m_N}$$

Minimum speed DM must have to give recoil energy Er

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

Kinematics



$$q^2 = 2\mu_{N\chi}^2 v^2 (1 - \cos\theta) \sim (100\,\mathrm{MeV})^2$$

$$E_R = \frac{q^2}{2m_N} \sim 10\,\mathrm{keV}$$

$\Downarrow$

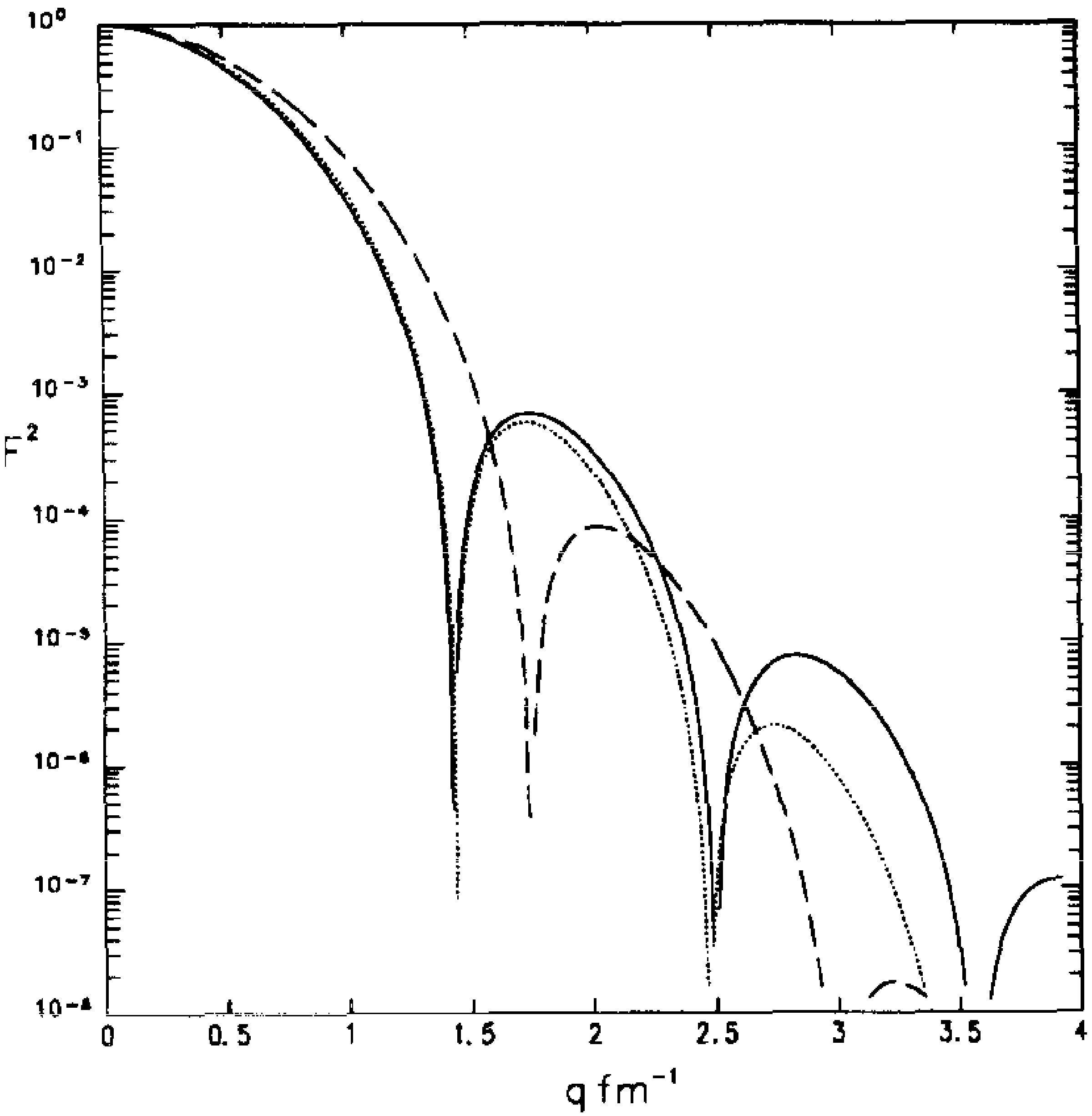
Minimum speed DM must have to give recoil energy Er

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

Nuclear Physics

Nuclear radius $r_N \sim A^{1/3} fm$

[Lewin and Smith]



SI:Helm, or Fermi distribution

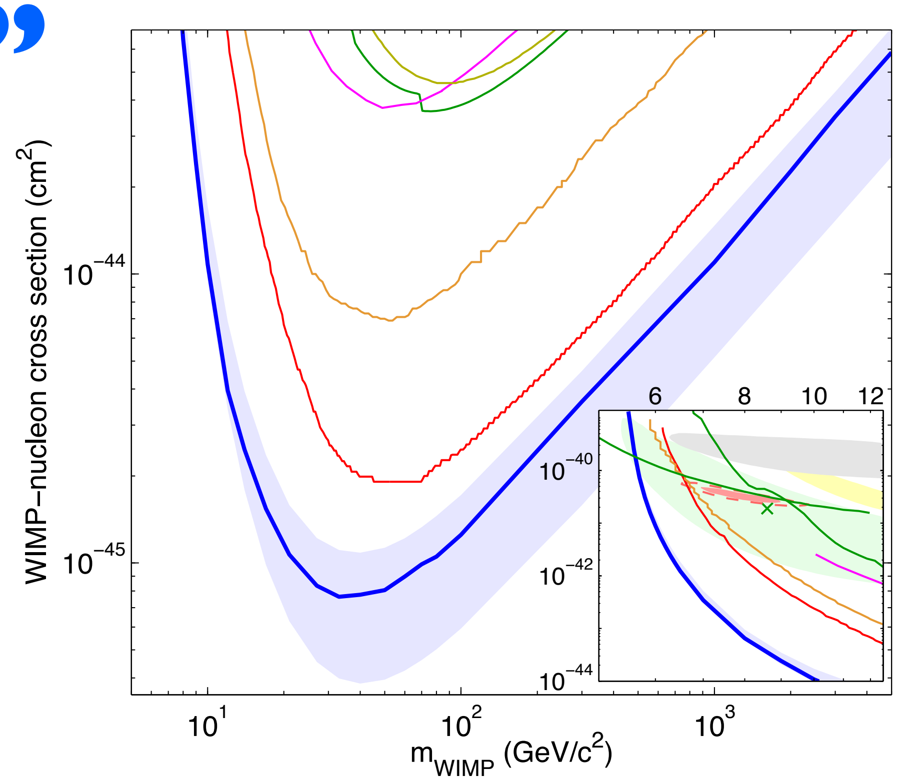
SD:

$$S(q) = a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q)$$

Converting nuclear to nucleon x-sec

$$\sigma^{\mathrm{SI}} = \frac{[Zf_p + (A-Z)f_n]^2}{f_p^2} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \sigma_p^{\mathrm{SI}}$$

Some "standard candles"

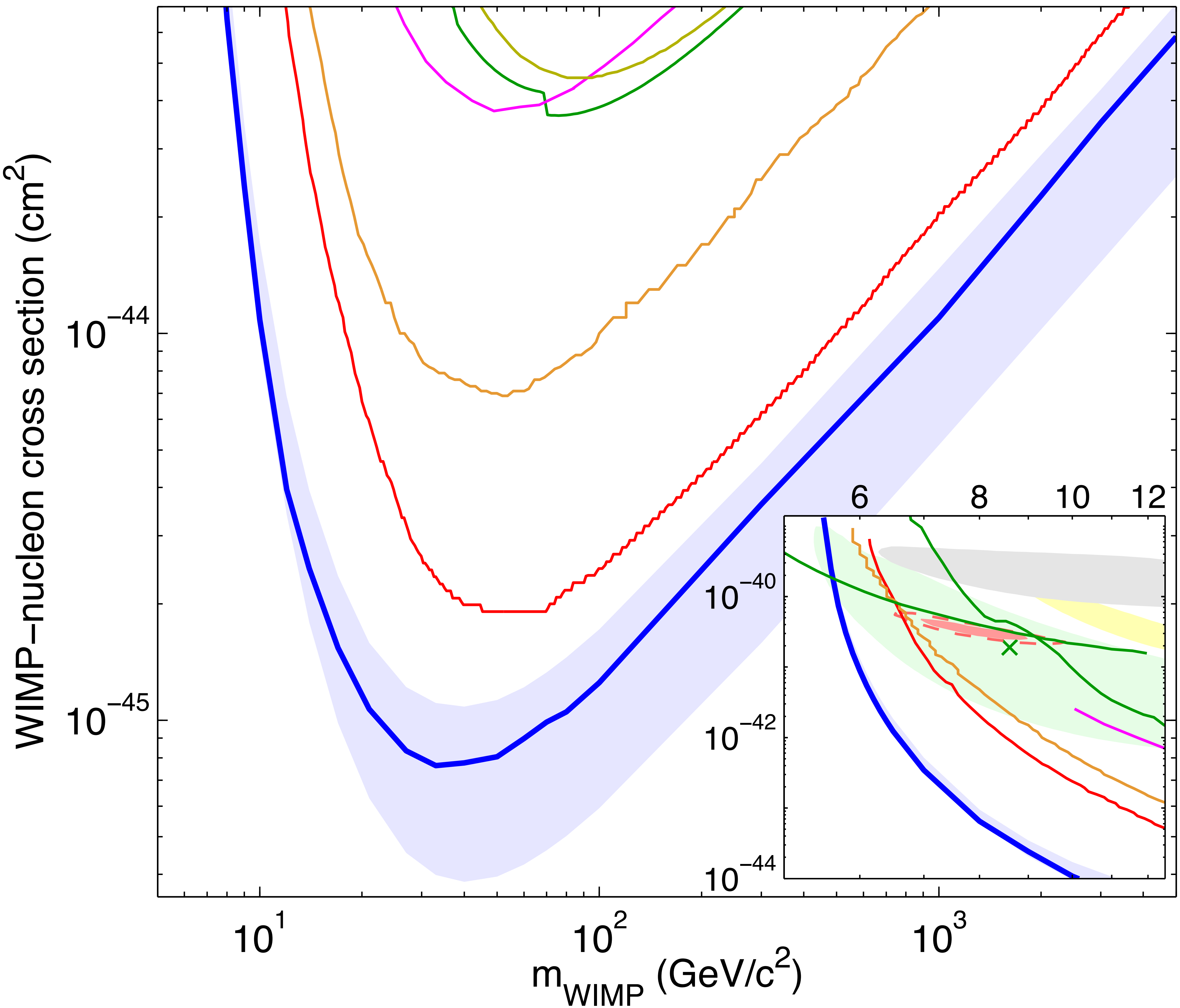


Z-exchange

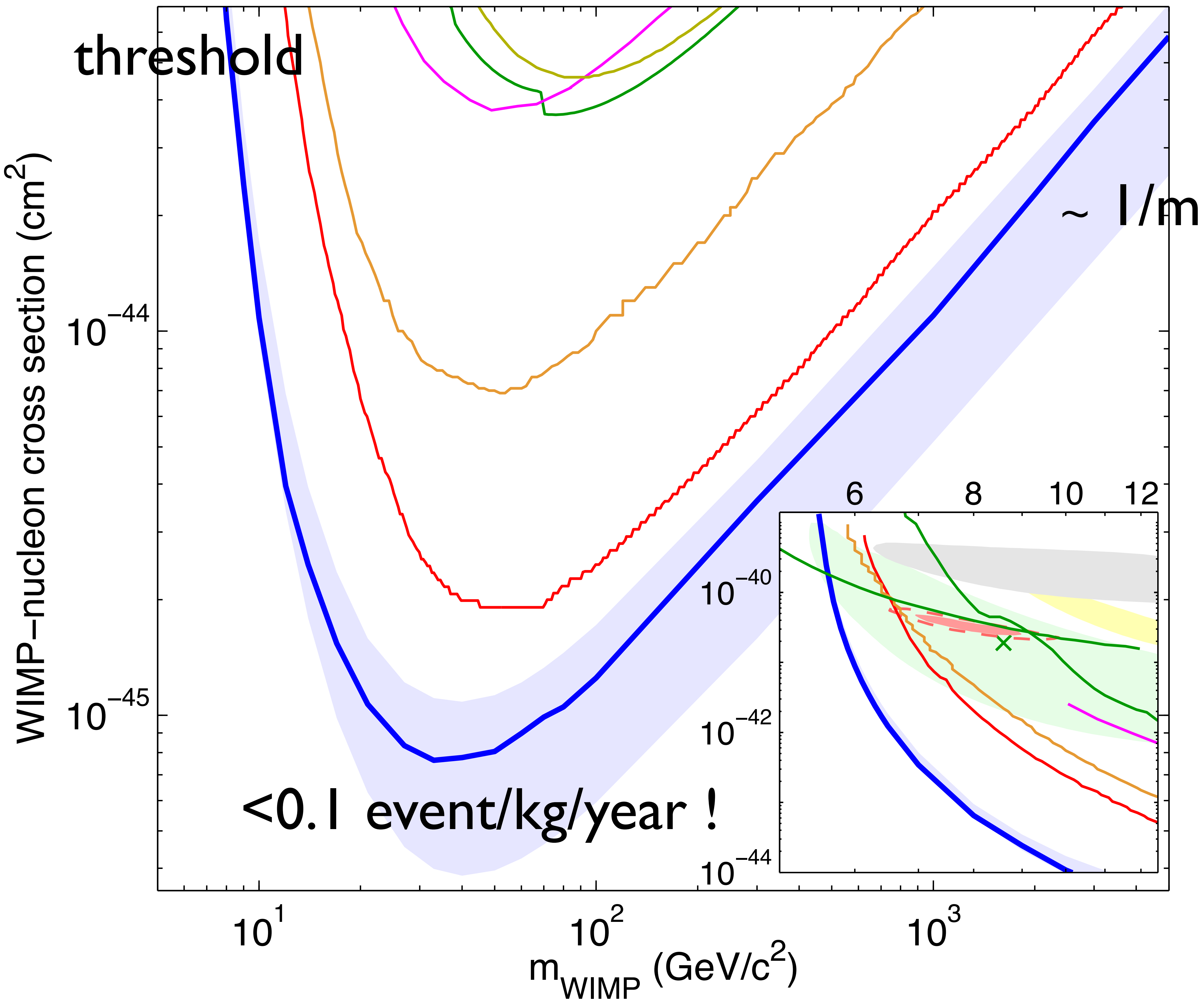
$$\sigma_p \sim \frac{G_F^2 \mu^2}{2\pi} \frac{\left[(1-4s_W^2)Z + (A-Z)\right]}{A^2} \approx 10^{-39}\,\mathrm{cm}^2$$

H-exchange $\quad \lambda S^2 |h|^2$

$$\sigma_p \sim \frac{\lambda^2 v^2}{16\pi m_h^4} \left|\langle p| \sum y_q \bar{q} q |r\rangle\right|^2 \frac{m_p^2}{(m_\chi + m_p)^2} \approx \lambda^2 \left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2 \times 10^{-43}\,\mathrm{cm}^2$$



WIMP–nucleon cross section (cm^2)
10^{-44}
10^{-45}
10^1
10^2
10^3
m_{WIMP} (GeV/c^2)
6
8
10
12
10^{-40}
10^{-42}
10^{-44}



threshold
~ 1/m
<0.1 event/kg/year !
WIMP–nucleon cross section (cm^2)
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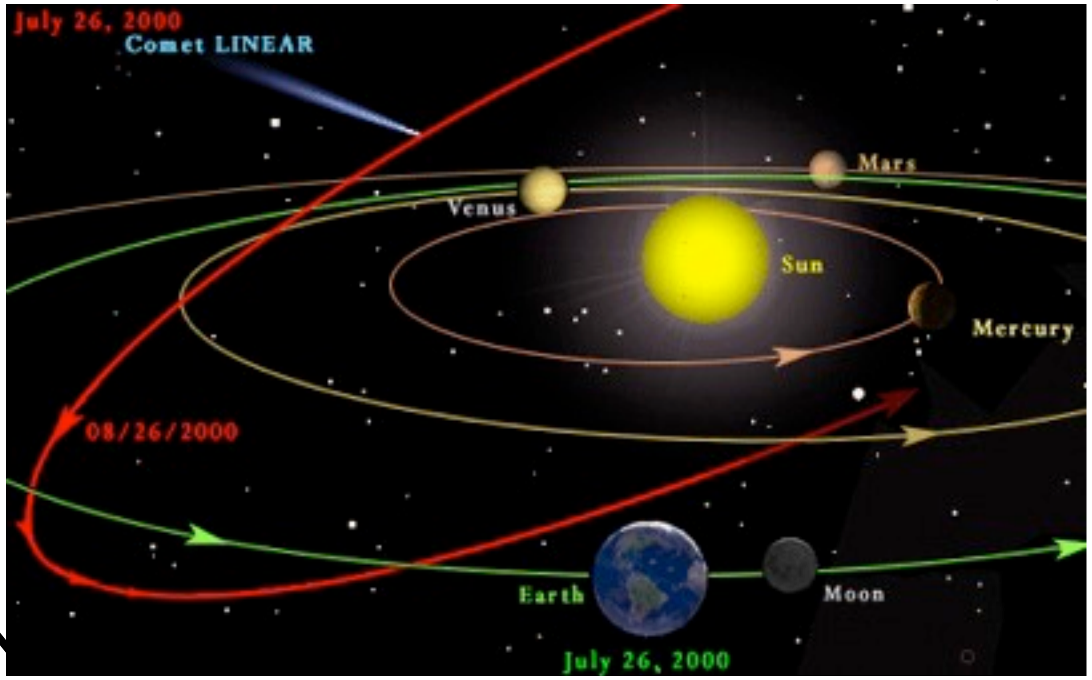
Annual Modulation

Another Way:

DAMA uses this to eliminate background, other expts. can look at modulation once they acquire enough data



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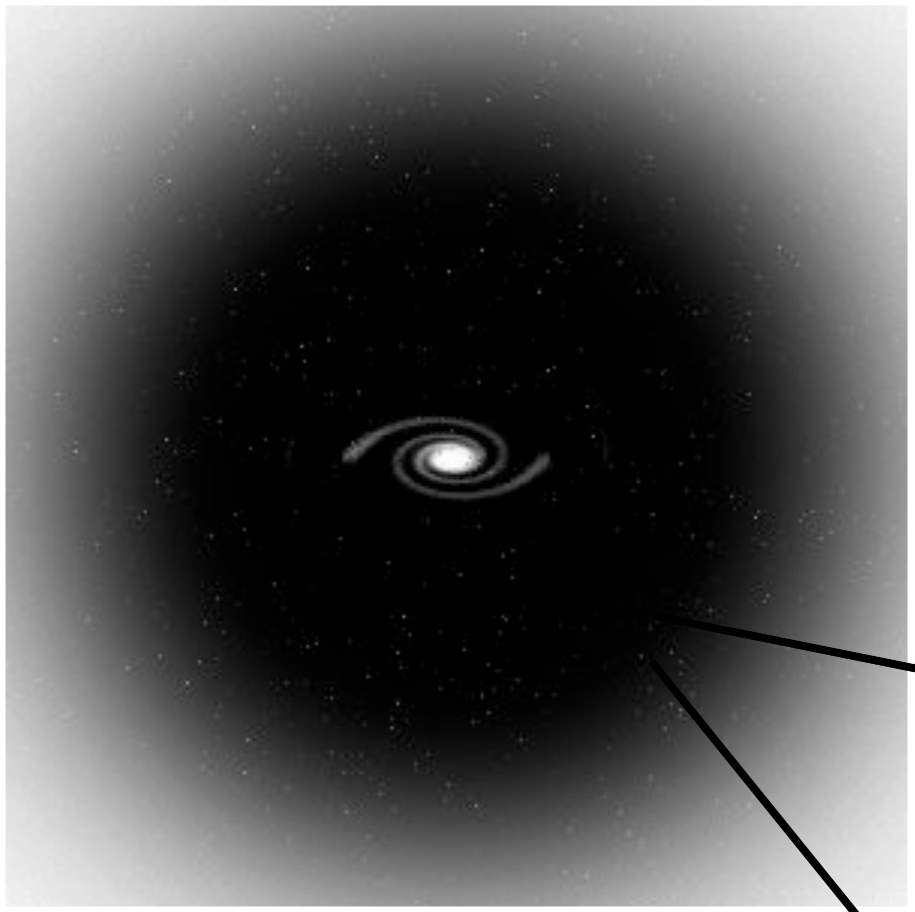

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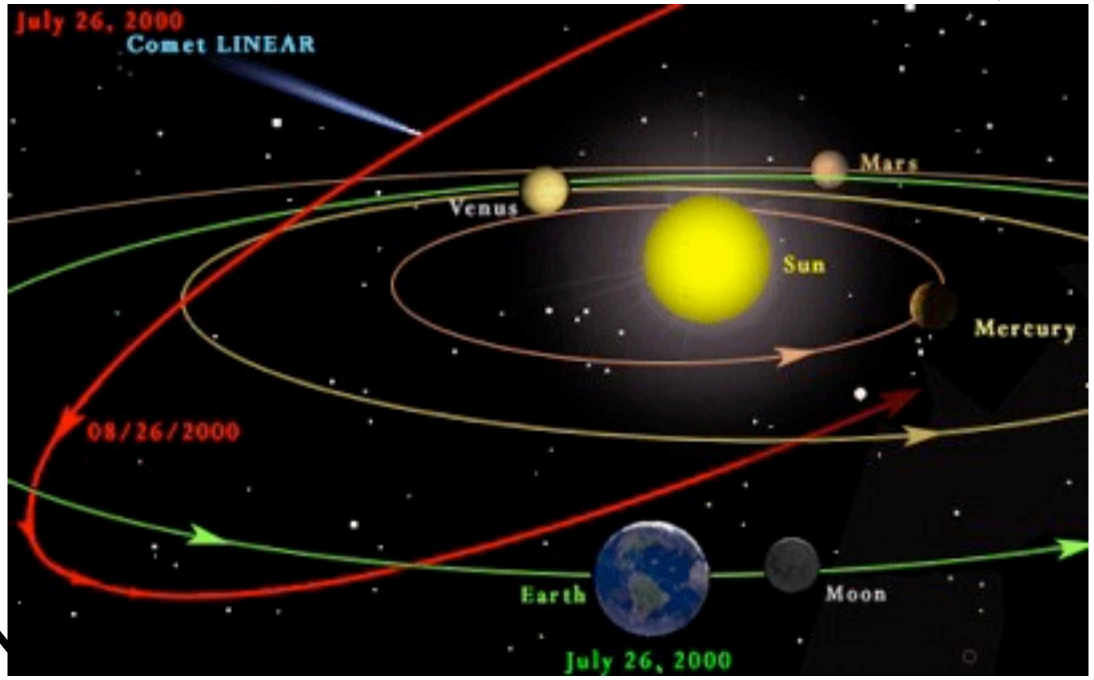


Annual Modulation

In galactic frame:

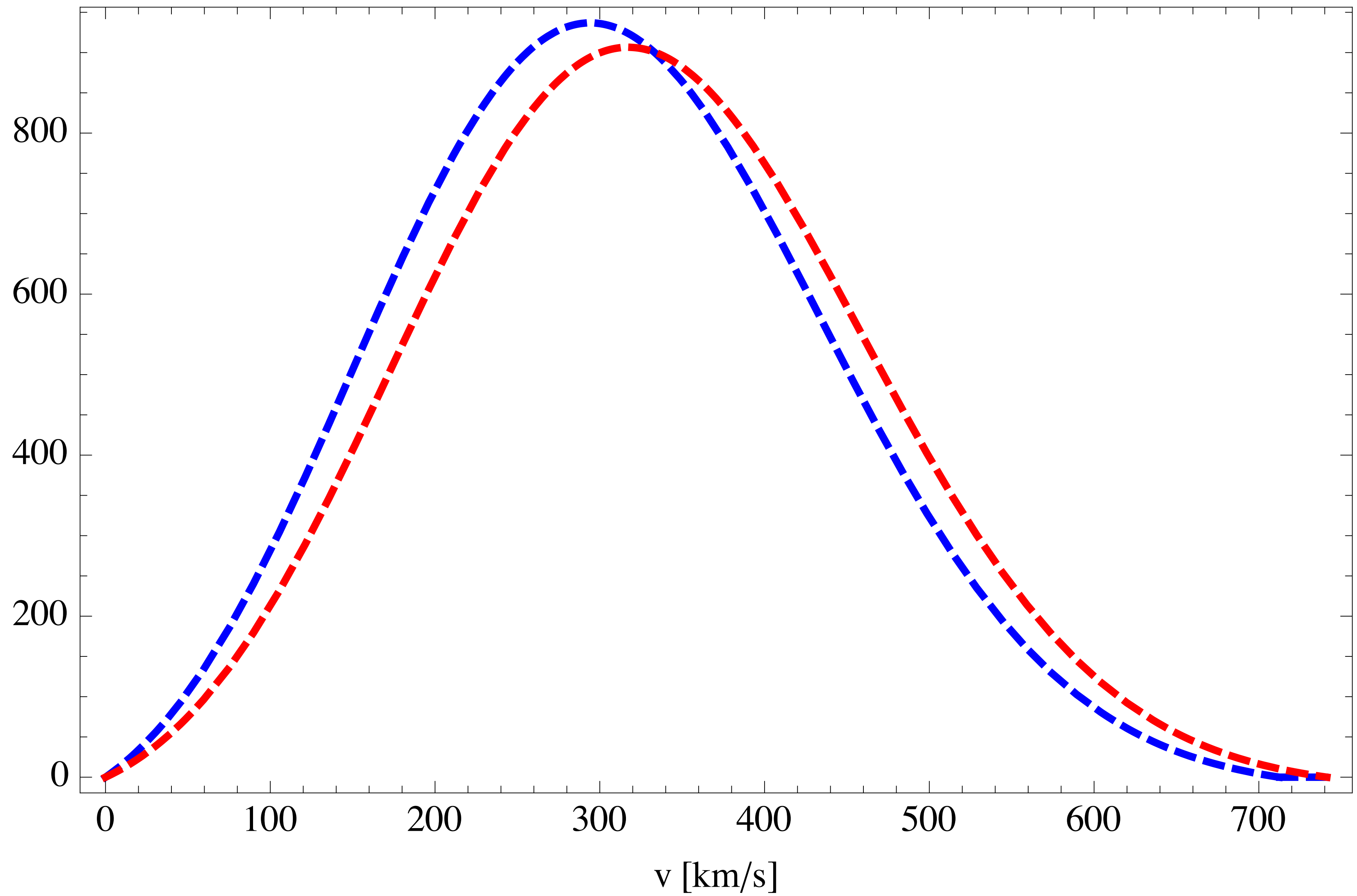
$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$$

$$498 \ \mathrm{km/s} \leq v_{esc} \leq 608$$

In Earth's frame:

$$f(\vec{v}, \vec{v}_E) = \frac{1}{(\pi \, v_0^2)^{3/2}} \, e^{-(\vec{v}+\vec{v}_E)^2/v_0^2}$$

$$v_E \approx 227 + 14.4 \cos\left[2\pi\left(\frac{t-t_0}{T}\right)\right] \quad t_0 = \mathrm{June}\ 2^{\mathrm{nd}}$$



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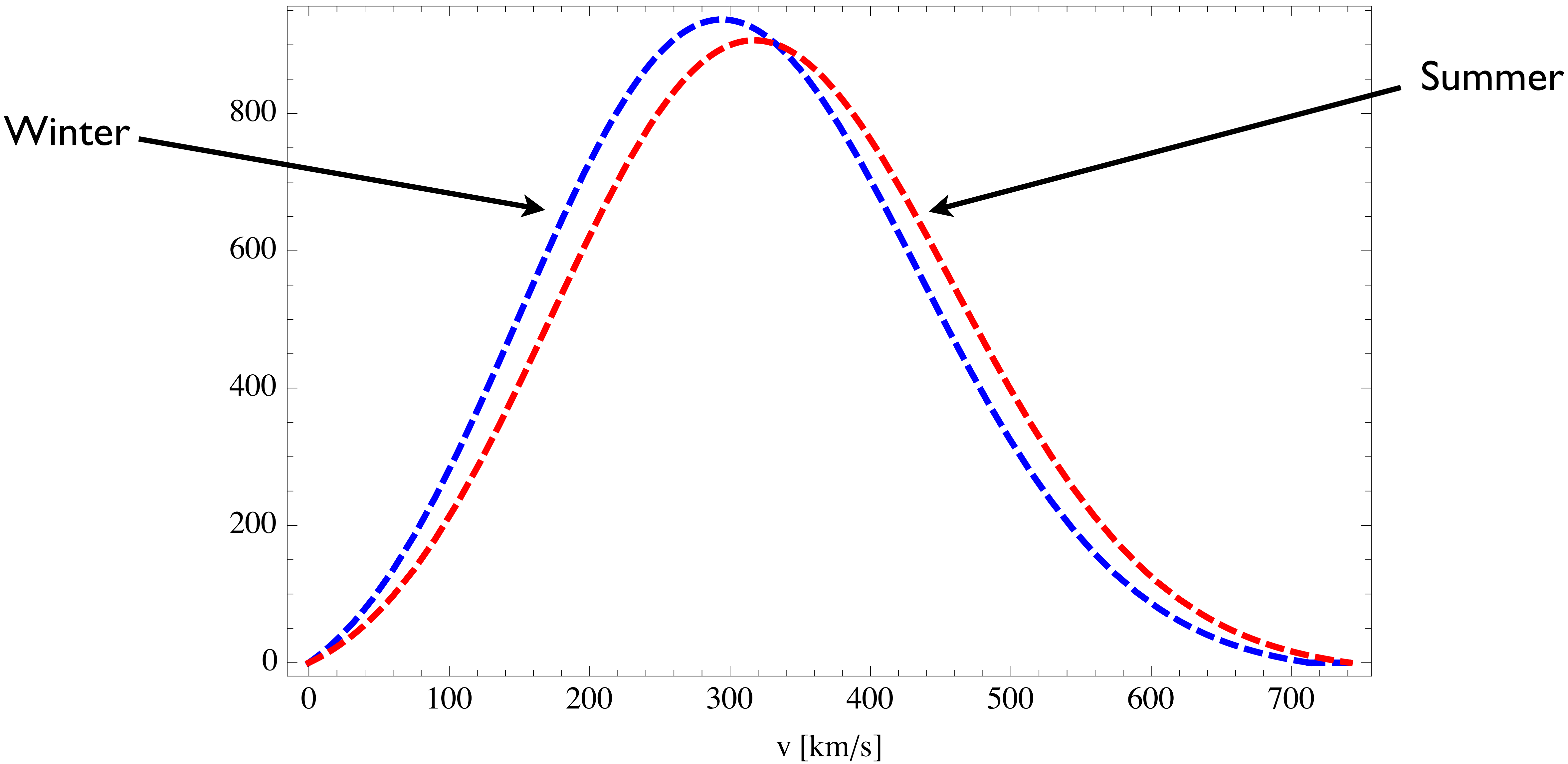

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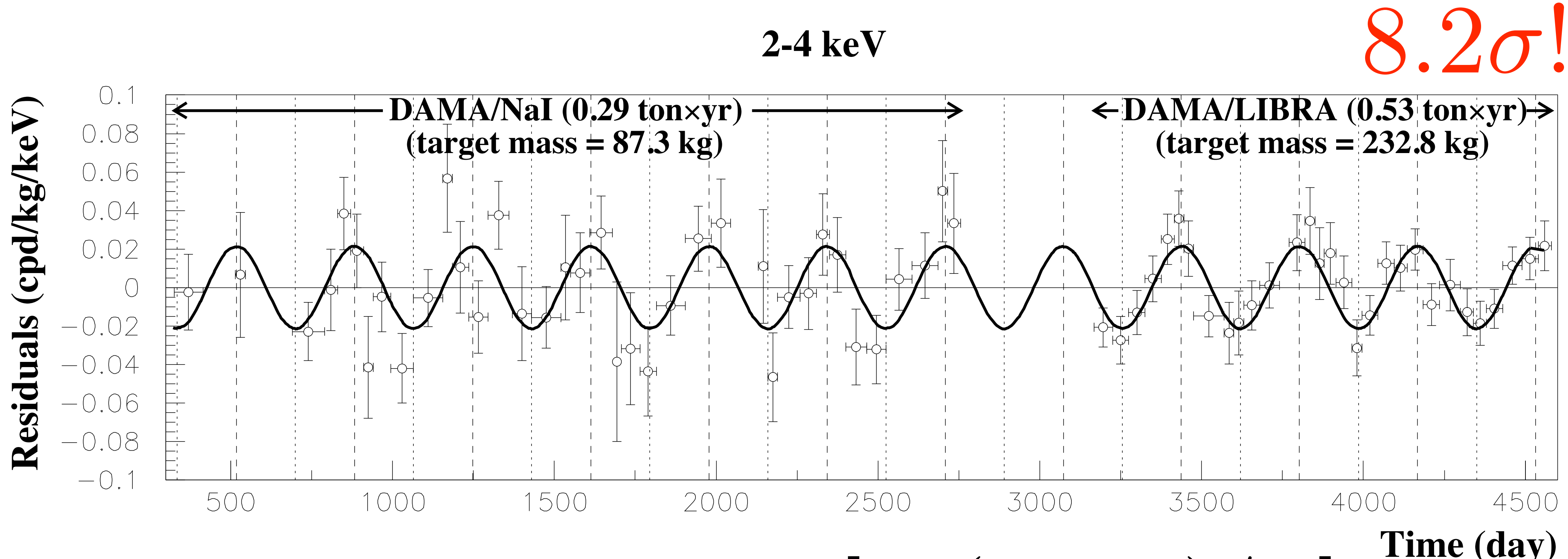
$8.2\sigma!$



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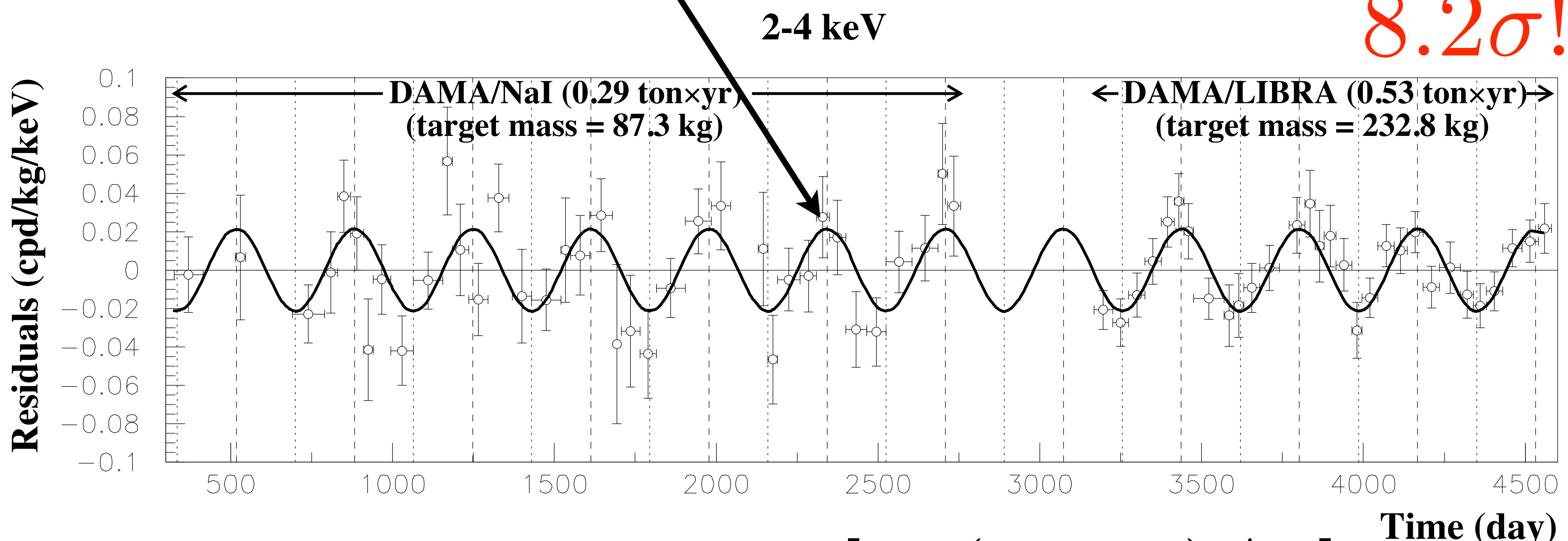

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Does annual modulation = discovery of DM?

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Many things modulate on a year timescale:

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- temperature

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- temperature
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- ice-cream sales....

Does annual modulation = discovery of DM?

Many things modulate on a year timescale:

- temperature
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- ice-cream sales....

But, very few line up year-on-year with June 2nd

DM models pre-DAMA

DM models pre-DAMA

DM models pre-DAMA


DM models pre-DAMA
direct detection
experimentalist?

Possible explanations

- Low mass dark matter with channelling, M~10 GeV
- Leptophilic DM
- Inelastic Dark Matter (iDM)
- Form Factor Dark Matter (FFDM or MDDM)
- Exothermic DM (exoDM)
- Resonant Dark Matter (rDM)

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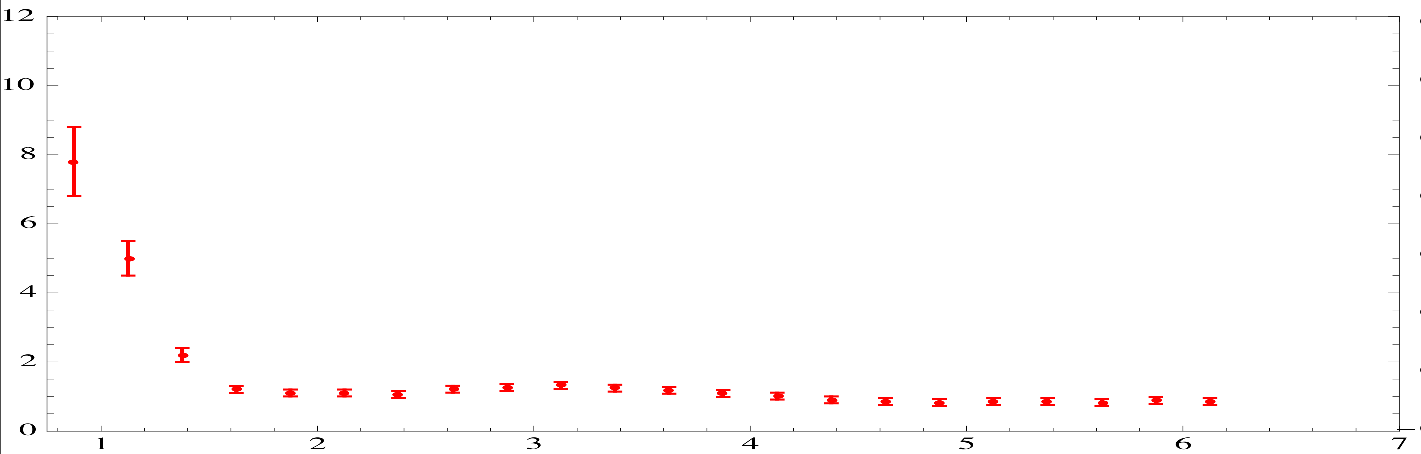

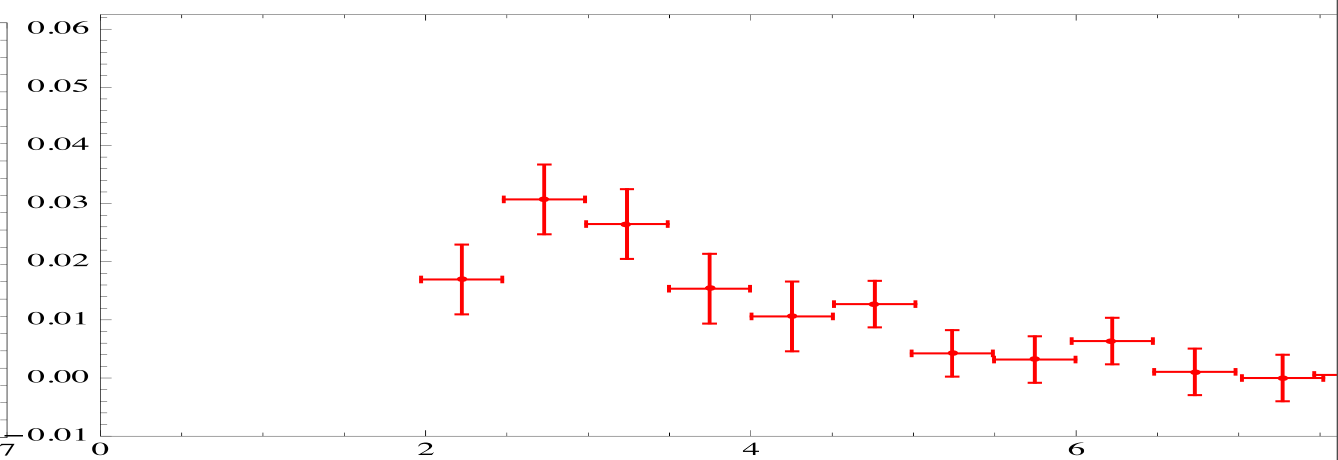

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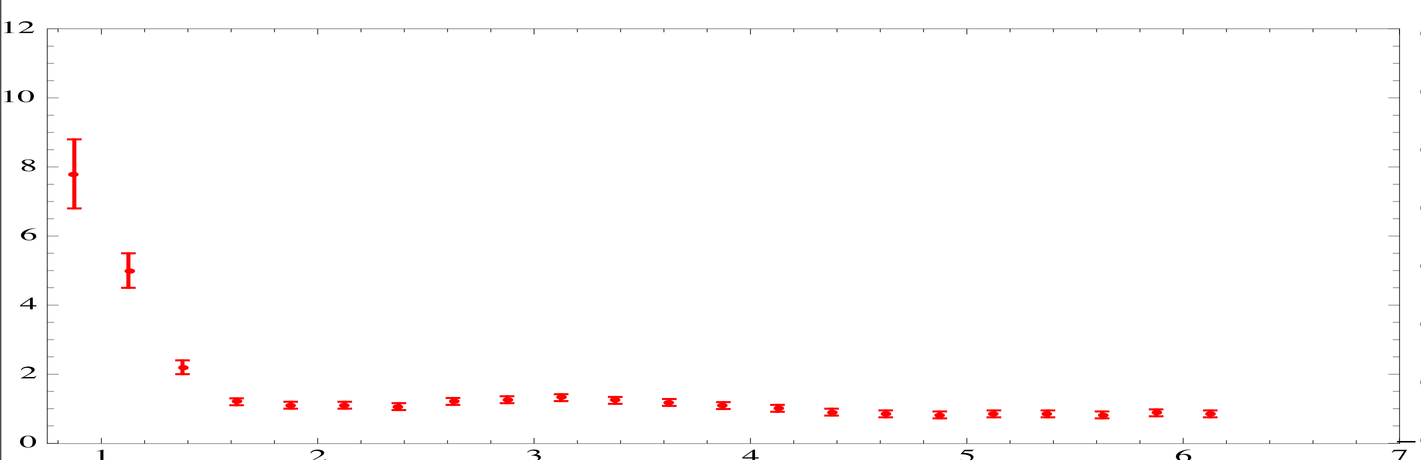

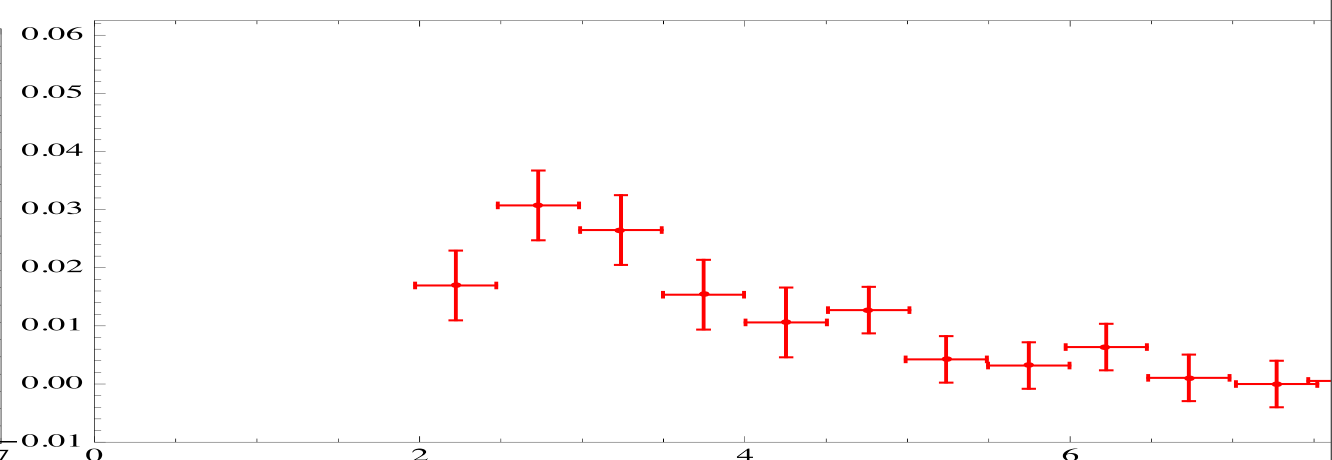

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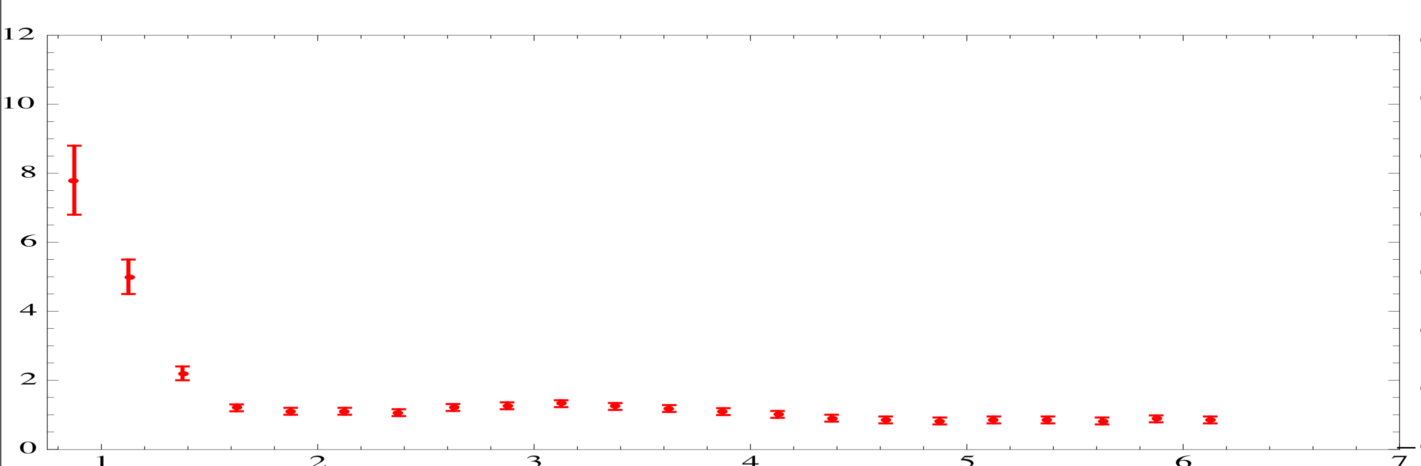

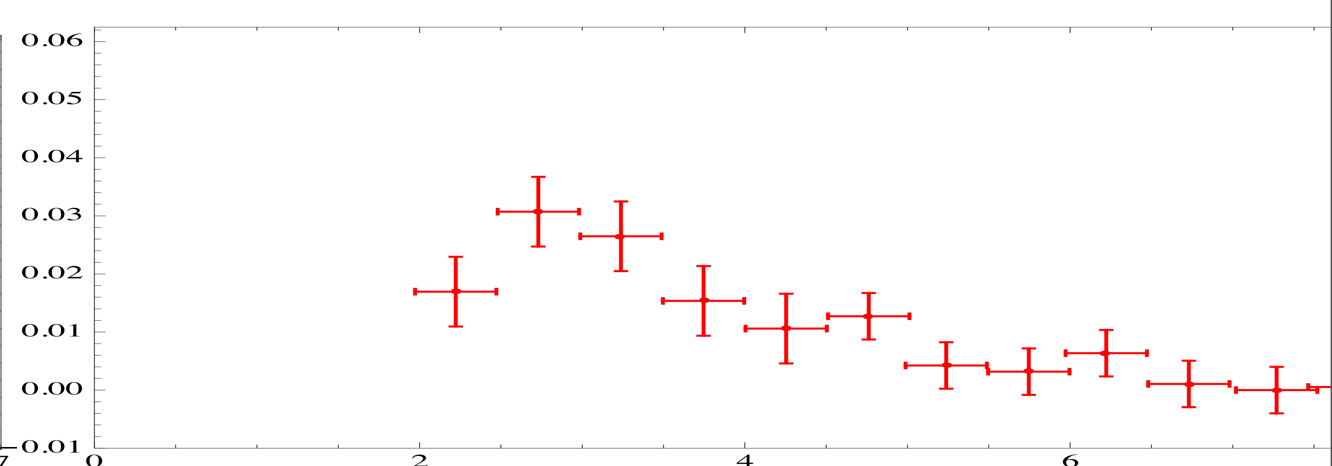

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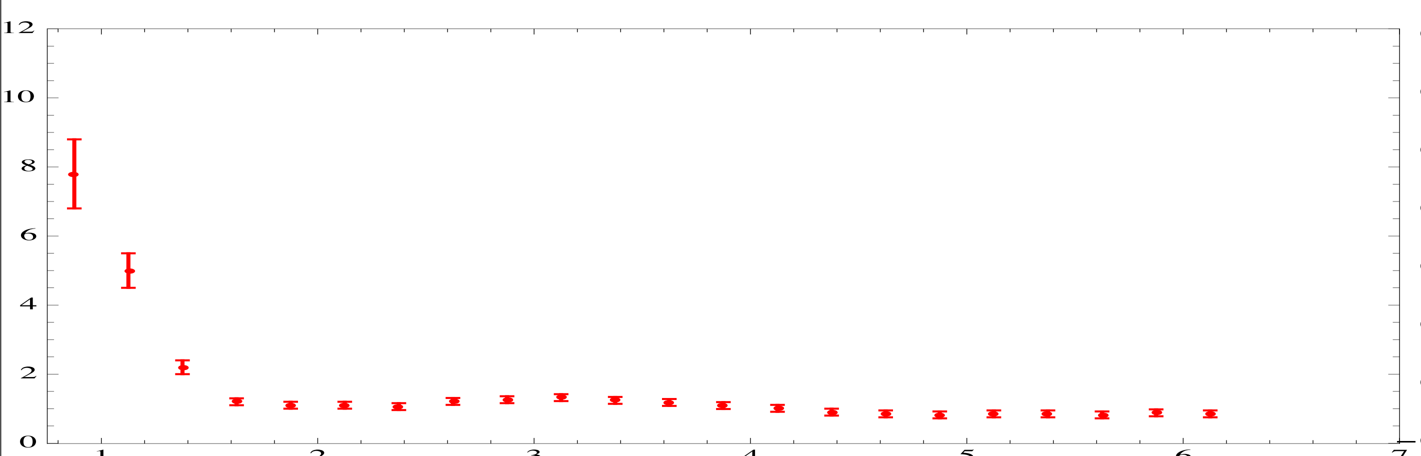

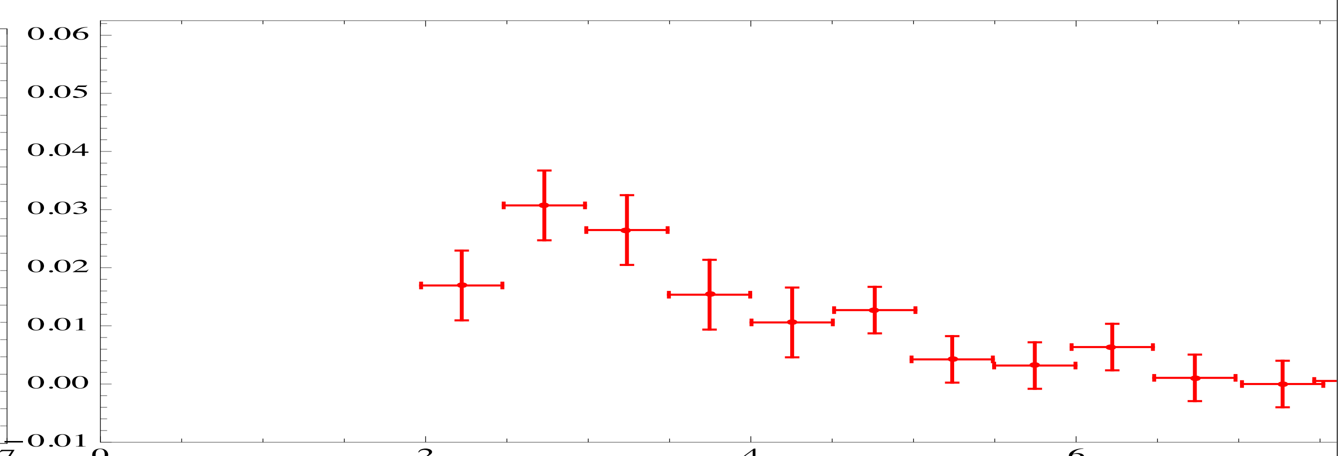

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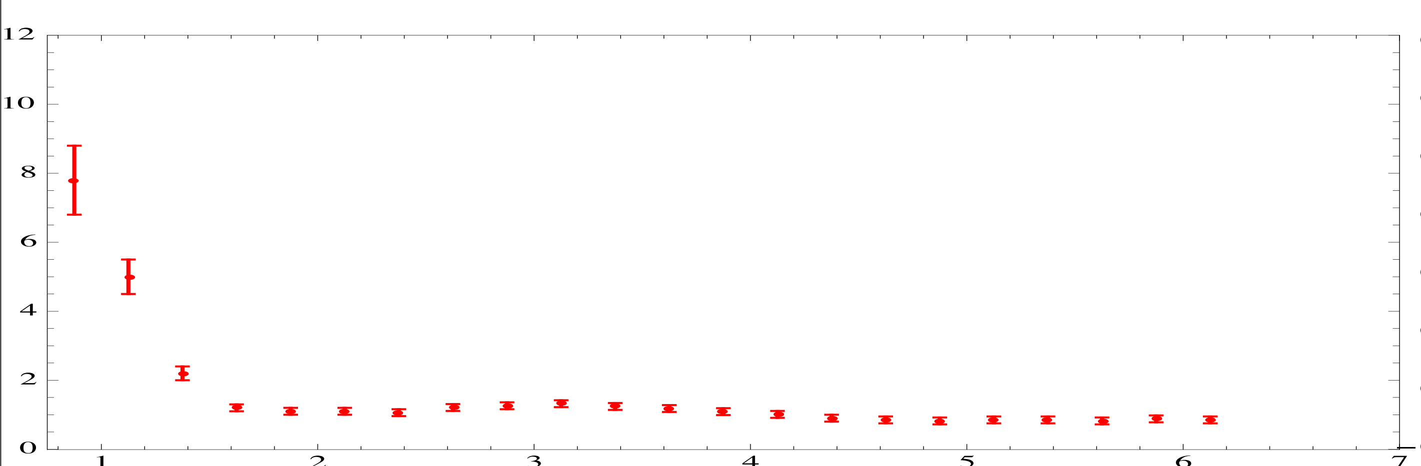

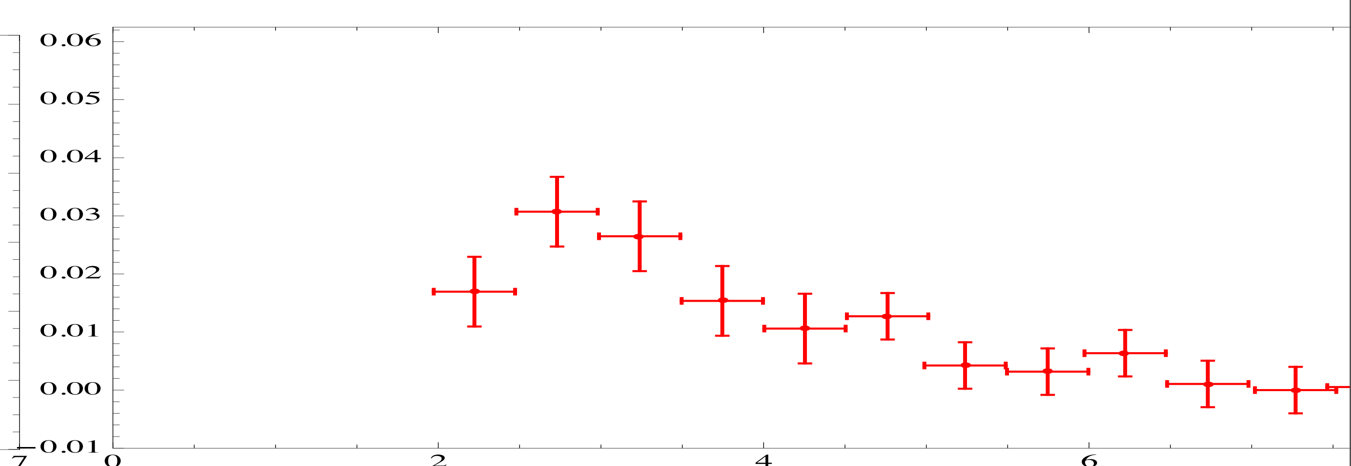

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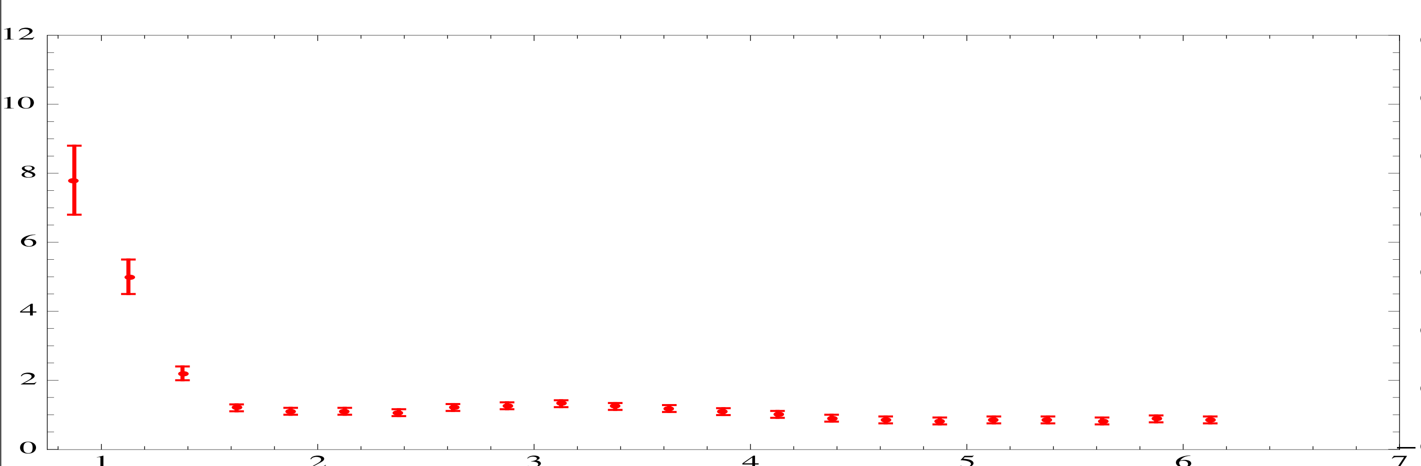
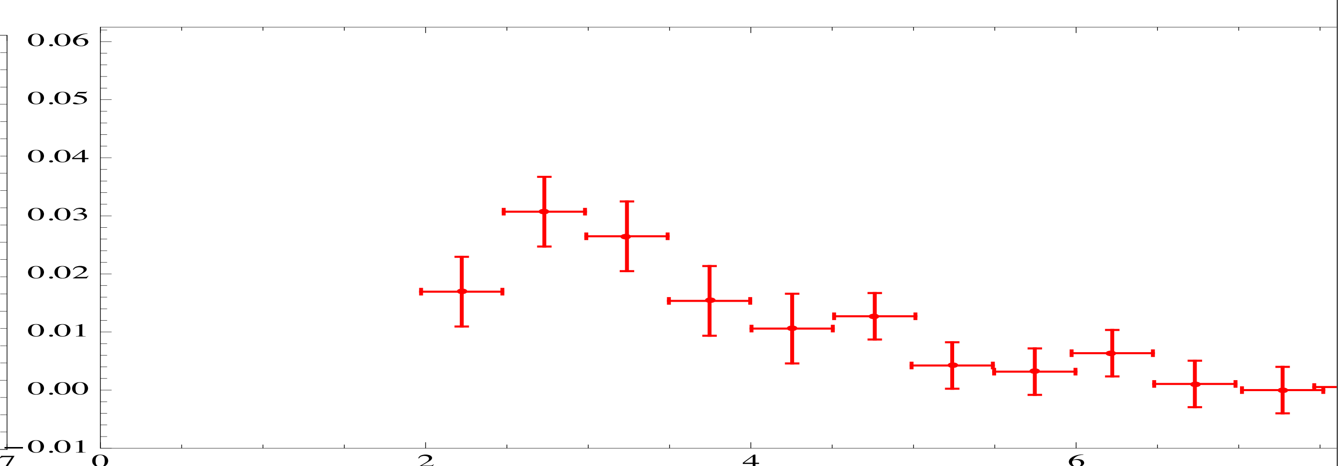




DM: a phenomenologist's playground

Explore the landscape of possible ways DM can interact with the SM

Experiments originally designed for a ~100 GeV SUSY WIMP, but there are many more possibilities

Thankfully many experiments and clever experimentalists

Light Dark Matter

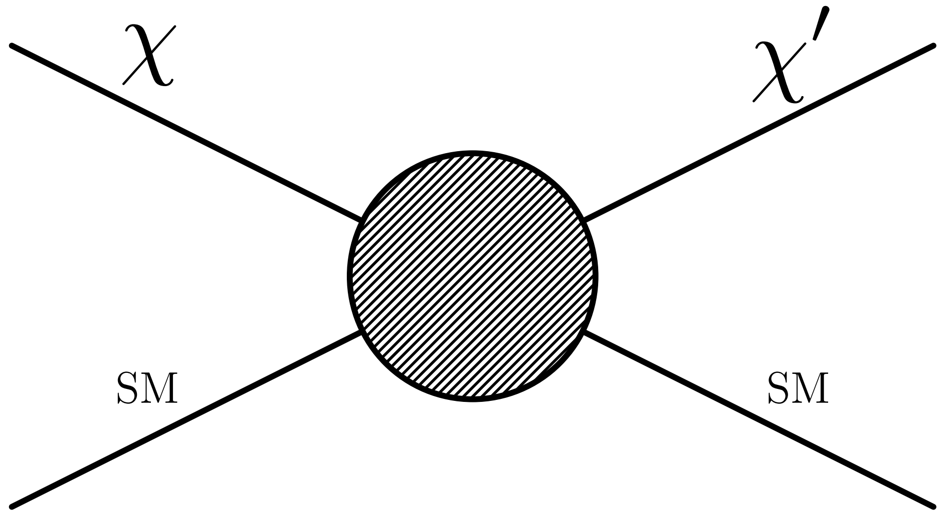
Motivated by fact that $\Omega_{DM} \sim 5\ \Omega_b$

If baryon and DM abundance related then expect DM to be (5-10) x proton mass

Also, hard for direct detection because of thresholds, backgrounds, etc (ask Jodi ☺)

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



$$\frac{dR}{dE_R} = \frac{N_T\, m_N\, \rho_\chi}{2\, \mu_{N\chi}^2\, m_\chi} \int_{v_{min}}^{v_{max}} d^3\vec{v}\, \frac{f(\vec{v}, \vec{v}_E)}{v}\, \sigma_N\, F^2(E_R)$$

$$v_{min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu_{N\chi}} + \delta \right)$$

$$m_\chi - m_{\chi'} = \delta \sim 100\,\mathrm{keV}$$

- Requires "large" momentum exchange to upscatter
- Favours high velocity tail of MB distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
- Recoil spectrum has a peak

All of the above helped to make DAMA consistent with CDMS, predicts events at other heavy element detectors

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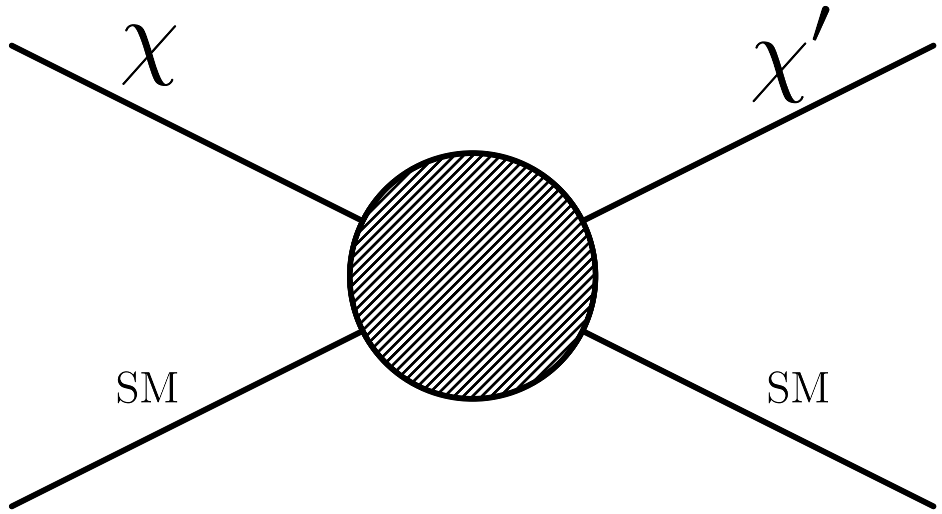
[Weiner and Tucker-Smith]



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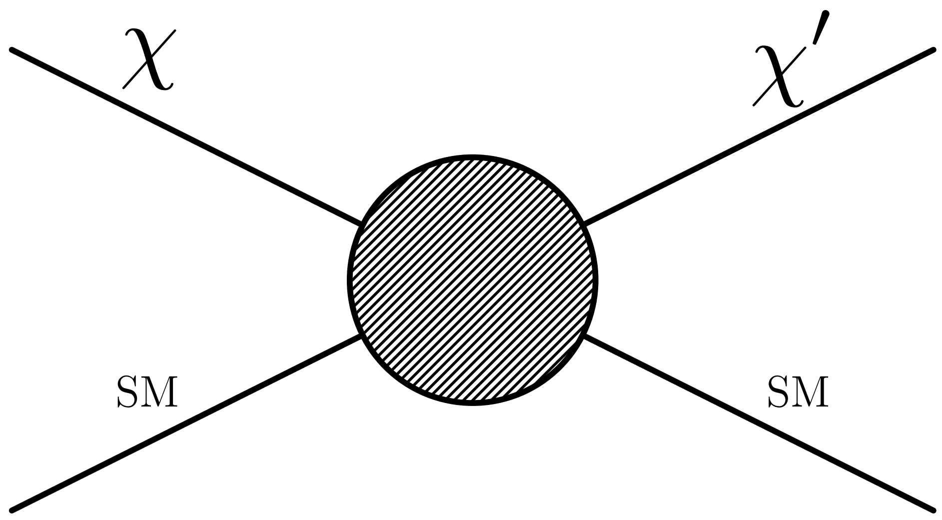
Exothermic DM (exoDM)
[Graham, Harnik, Rajendran, Saraswat]

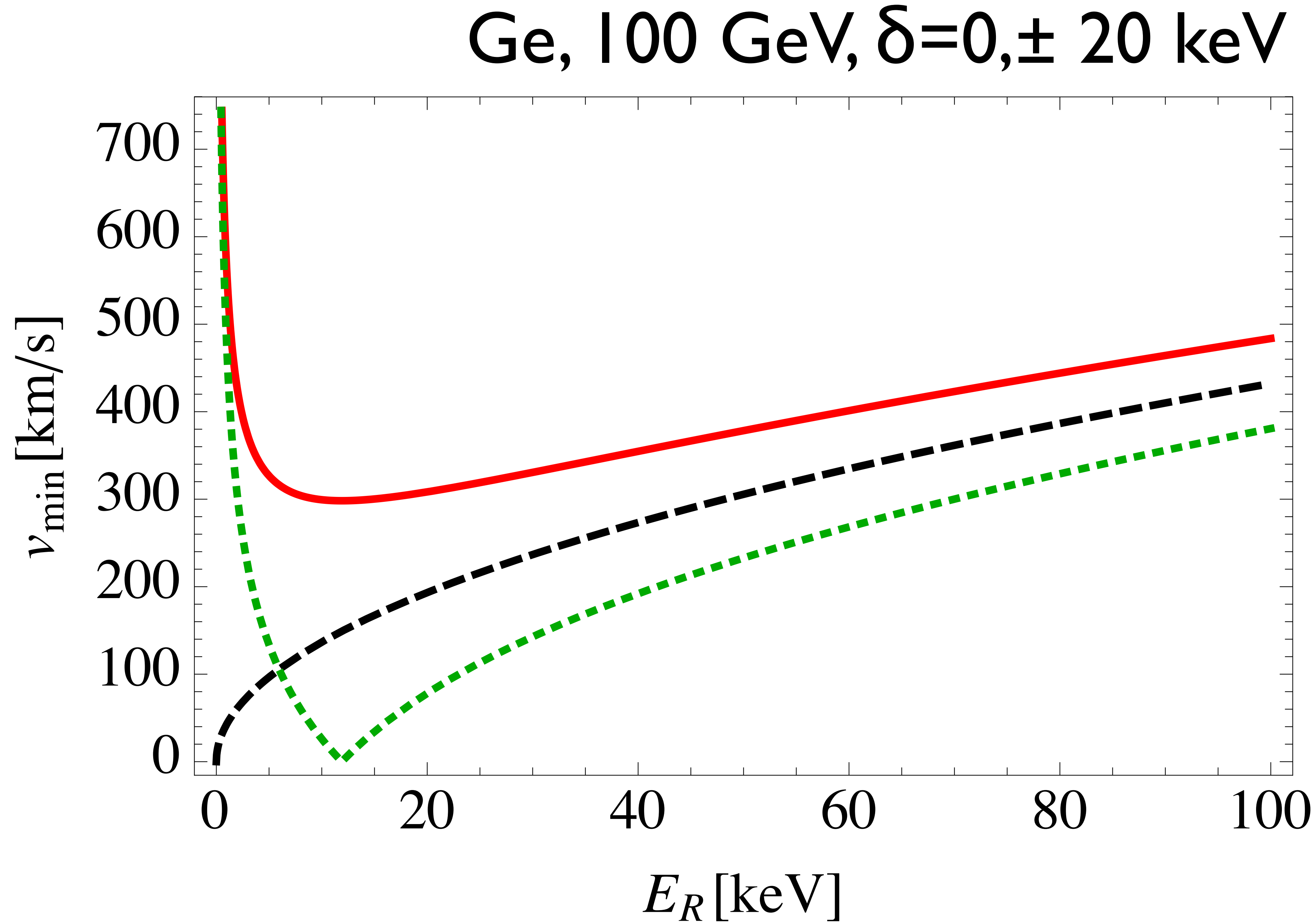


$$m_\chi - m_{\chi'} = \delta \sim -10\,\mathrm{keV}$$

$$v_{\min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu_{N\chi}} + \delta \right|$$

- Can deposit energy even at zero speed
- Decreased (but still some) modulation
- Prefers light targets
- Recoil spectrum has a peak

e/i/exo-DM



Ge, 100 GeV, δ=0,± 20 keV
700
600
500
400
300
200
100
0
0
20
40
60
80
100
v_{min} [km/s]
E_R [keV]

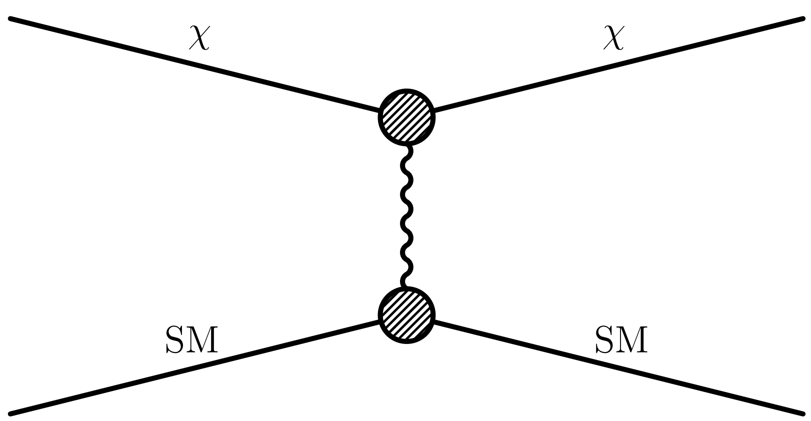
Form Factor DM

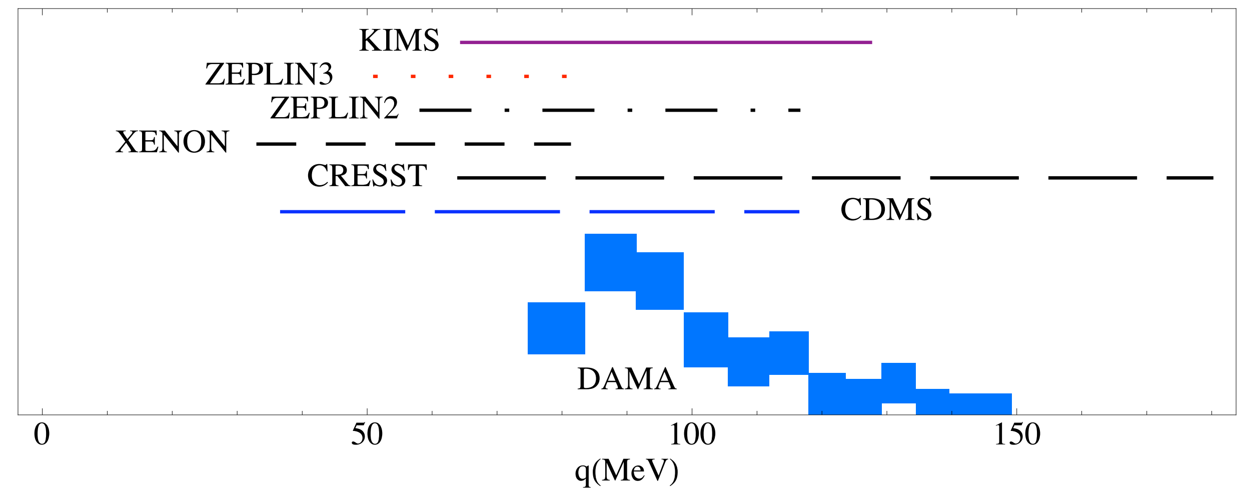
[Chang, Weiner, Pierce and Feldstein, Fitzpatrick, Katz]

$$\frac{dR}{dE_R} = \frac{N_T\, m_N\, \rho_\chi}{2\, \mu_{N\chi}^2\, m_\chi} \int_{v_{min}}^{v_{max}} d^3\vec{v}\, \frac{f(\vec{v}, \vec{v}_E)}{v}\, \sigma_N\, F^2(E_R)$$

DM has a form factor, dipole coupling to light gauge boson

$$\frac{1}{\Lambda^2} D_\mu \phi^\dagger D_\nu \phi F^{\mu\nu}$$





[arXiv:0908.2991]

- Form factors suppress certain ranges of recoil energy
- Works best with SD couplings, or non-standard velocity distributions e.g. via Lactea
- Although suppresses events at other detectors still expect some signal
- Peak in spectrum at non-zero recoil energy

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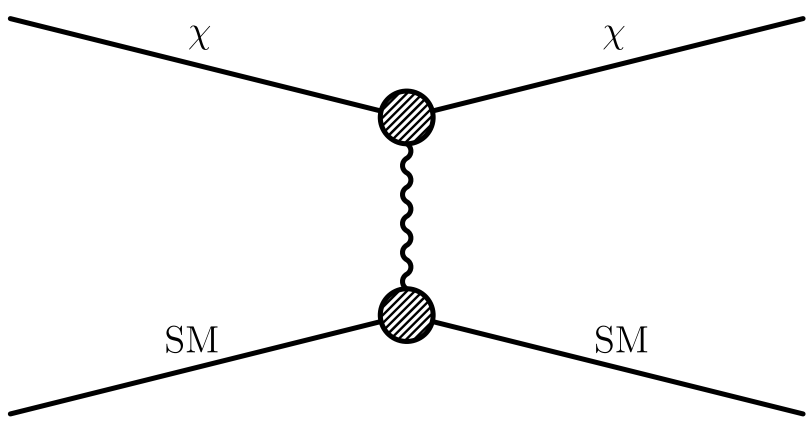

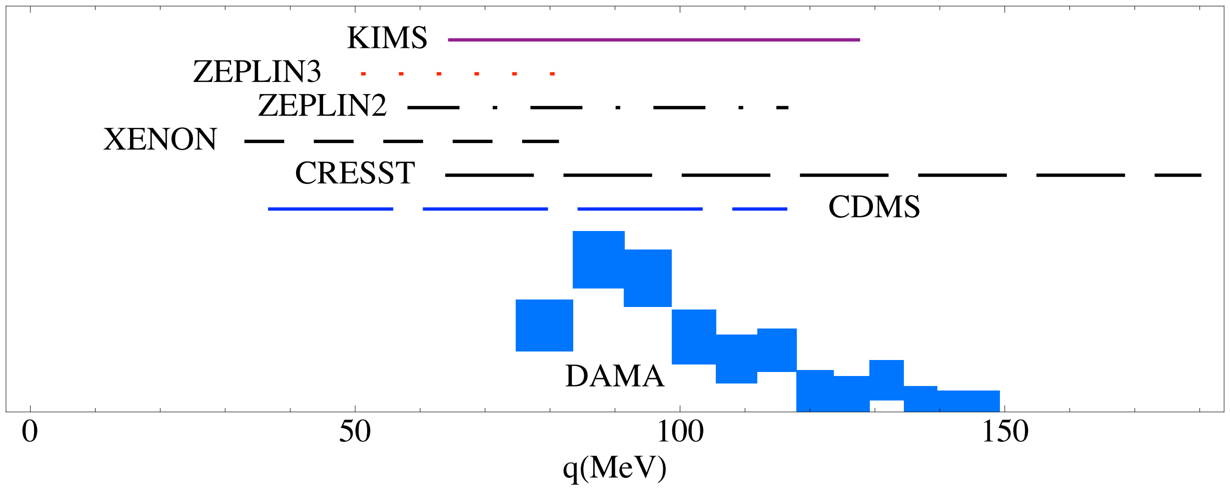

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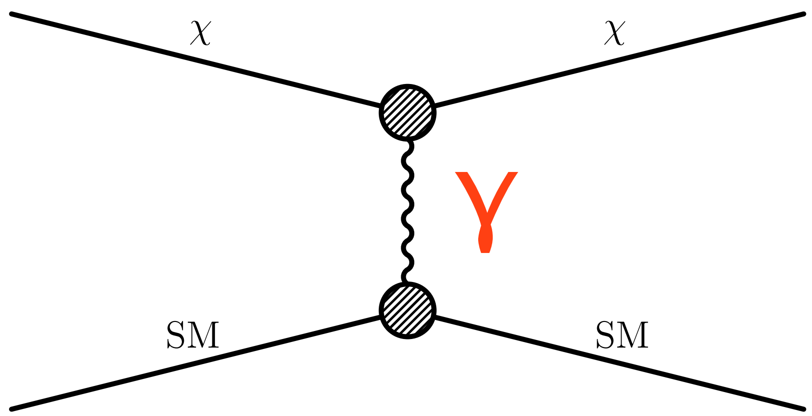
A moment with the photon

[Pospelov and ter Veldhuis]



Although DM is electrically neutral it can have higher electromagnetic moments e.g. EDM, MDM, quadropoles, anapole, charge radius,...

DM couples to nucleus through photon exchange

Leads to interesting momentum dependence e.g.

$$\frac{d\sigma_{EDM}}{dE_R} = \frac{1}{4\pi} \mathrm{d}_\chi^2 Z^2 e^2 \frac{(S+1)}{3S} \frac{1}{v_r^2} \frac{1}{E_R} |G_E(\boldsymbol{q}^2)|^2$$

Isospin dependent DM [Kurylov and Kamionkowski; Feng and Kumar]

Typically assume fn~fp
But different elements have different ratios of p/n
Can remove some of the strongest constraints if

$$\frac{f_n}{f_p} \approx -0.7$$

Isospin dependent DM [Kurylov and Kamionkowski; Feng and Kumar]

$$\sigma^{\mathrm{SI}} = \frac{[Zf_p + (A-Z)f_n]^2}{f_p^2}\frac{\mu_{\chi N}^2}{\mu_{\chi p}^2}\sigma_p^{\mathrm{SI}}$$

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Resonant Dark Matter (rDM)

[Bai and PJF]

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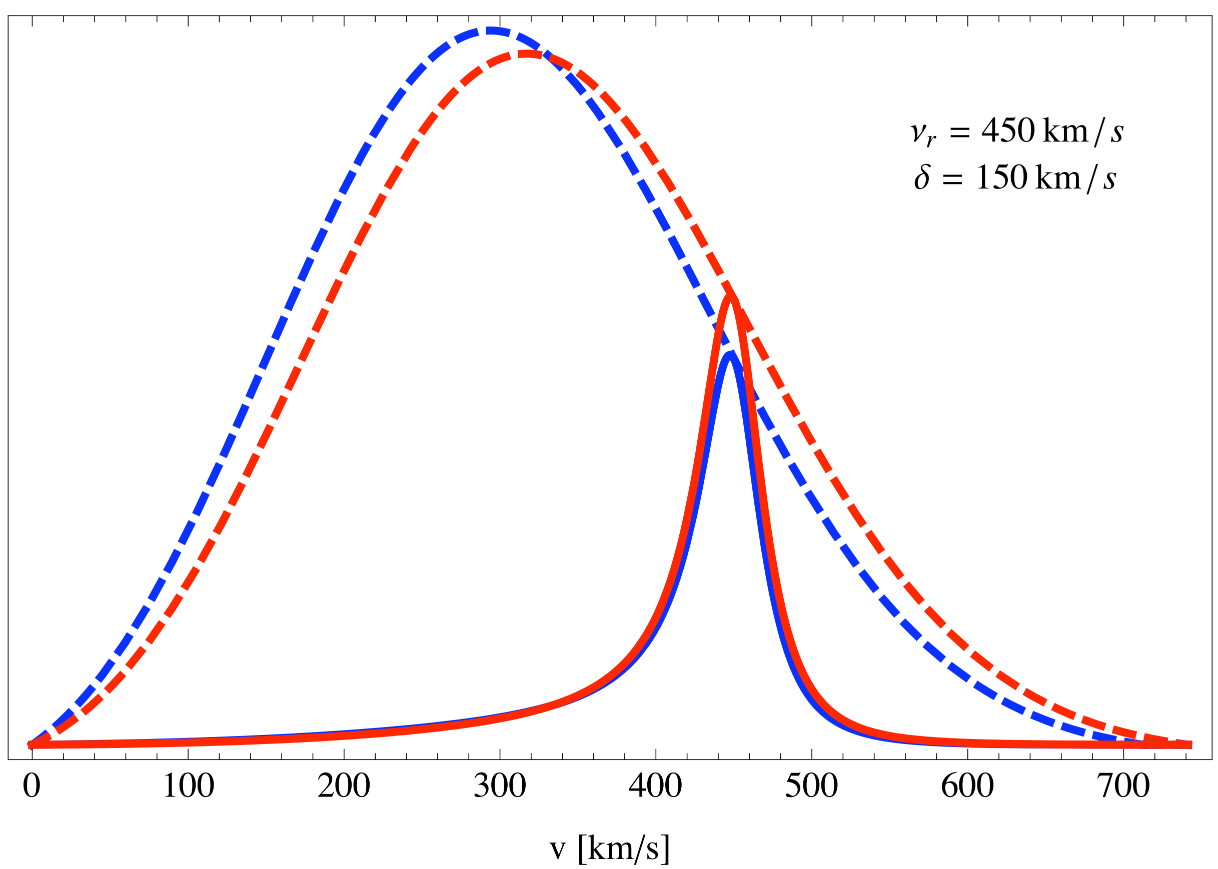
- Cross section is velocity dependent
- In particular the velocity dependence is “resonant”
- Picks out small range of velocities
- Increases modulation
- In our particular model realisation scattering is highly element dependent



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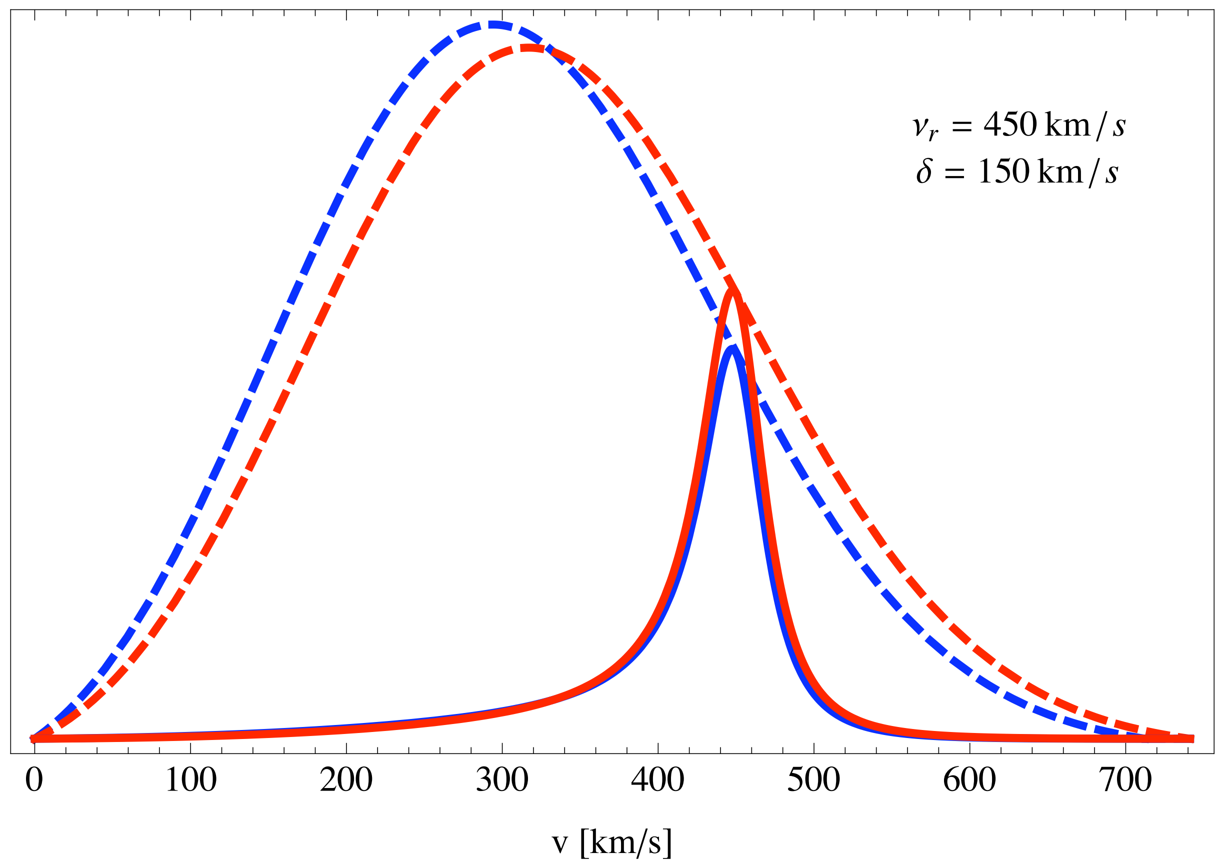

The list goes on

- Luminous dark matter [Feldstein et al.]
- Magnetic iDM [Weiner and Yavin]
- Rayleigh Dark Matter [Weiner and Yavin]
- ……

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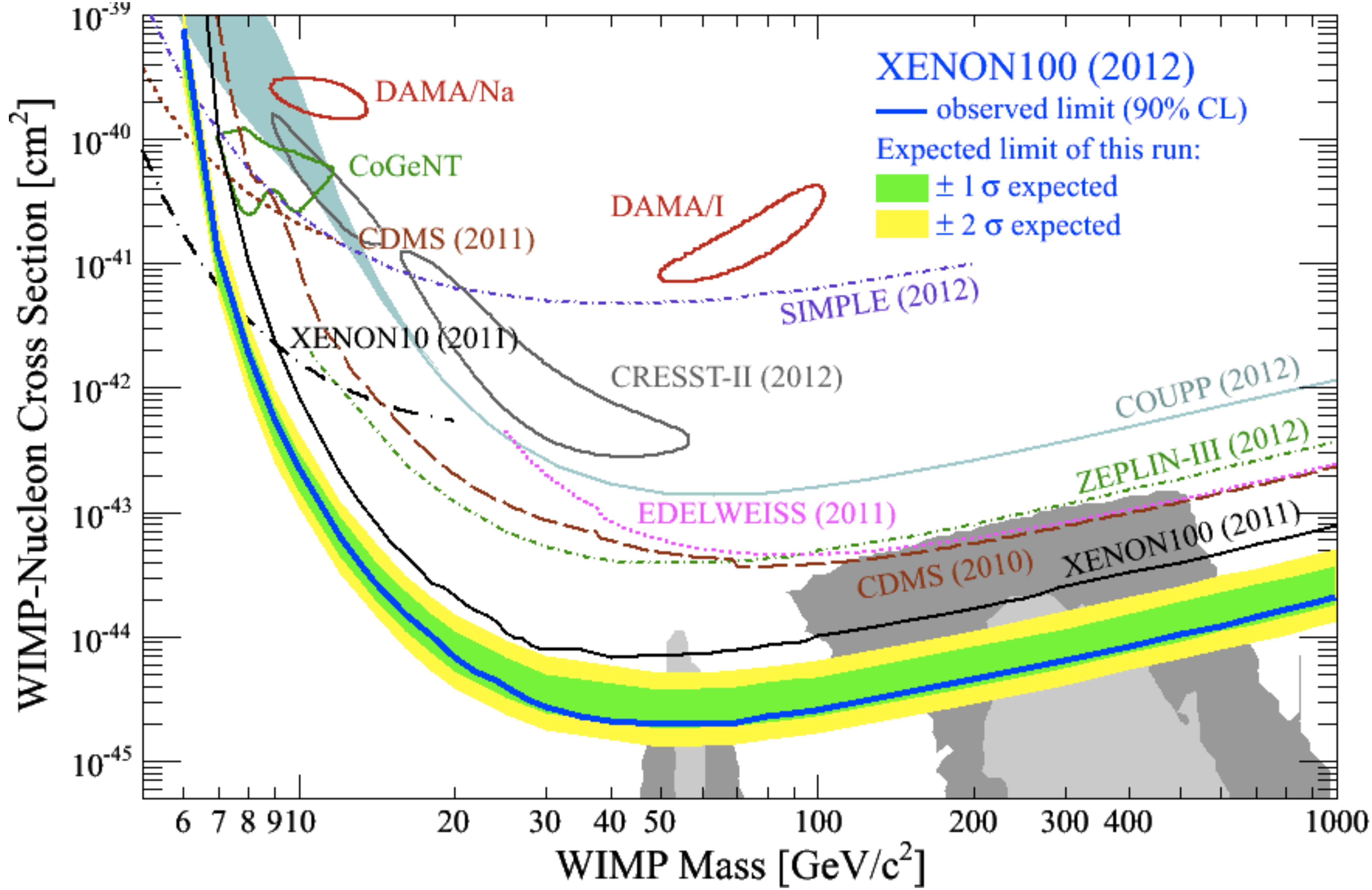
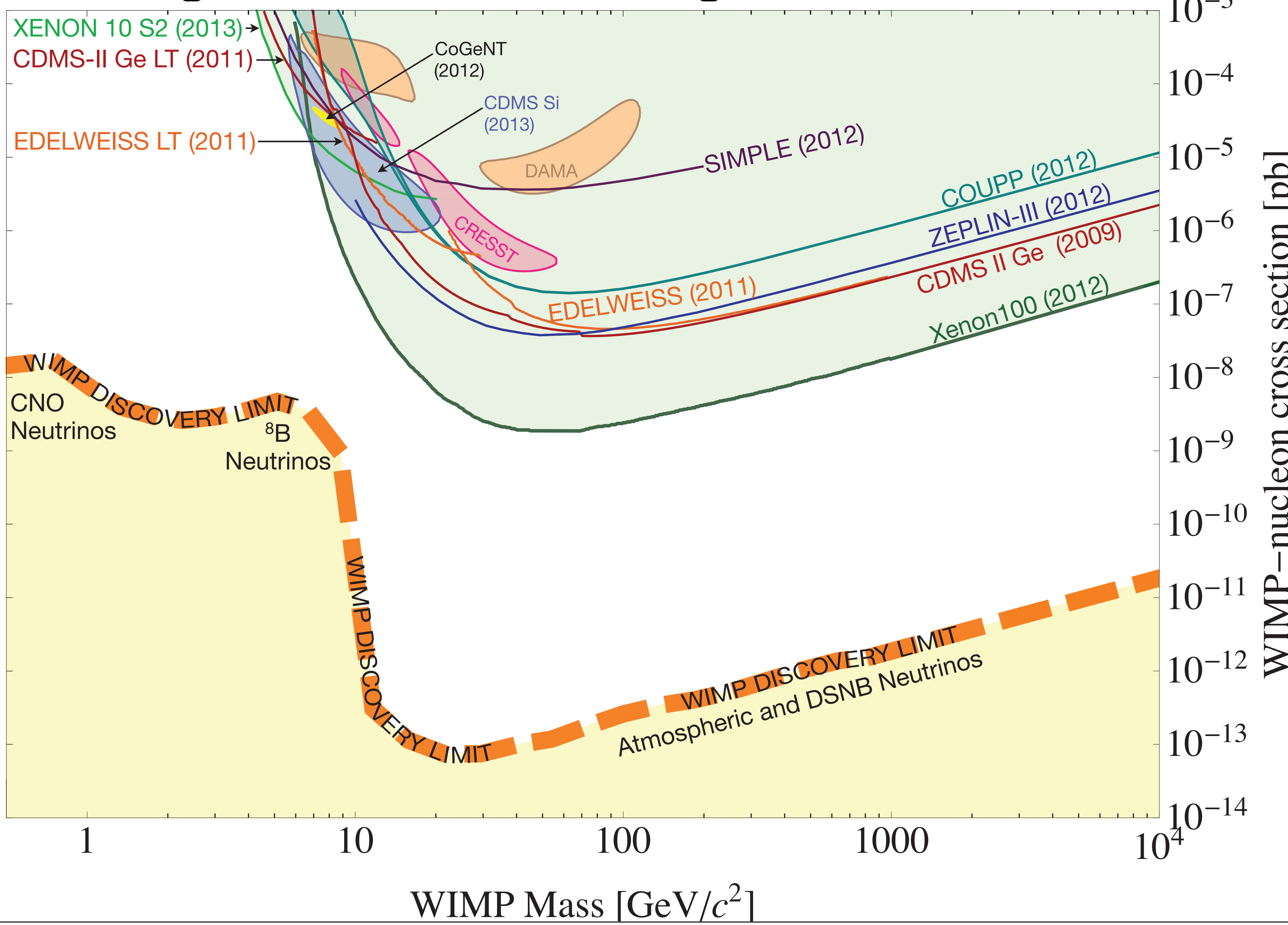
How to compare experiments?



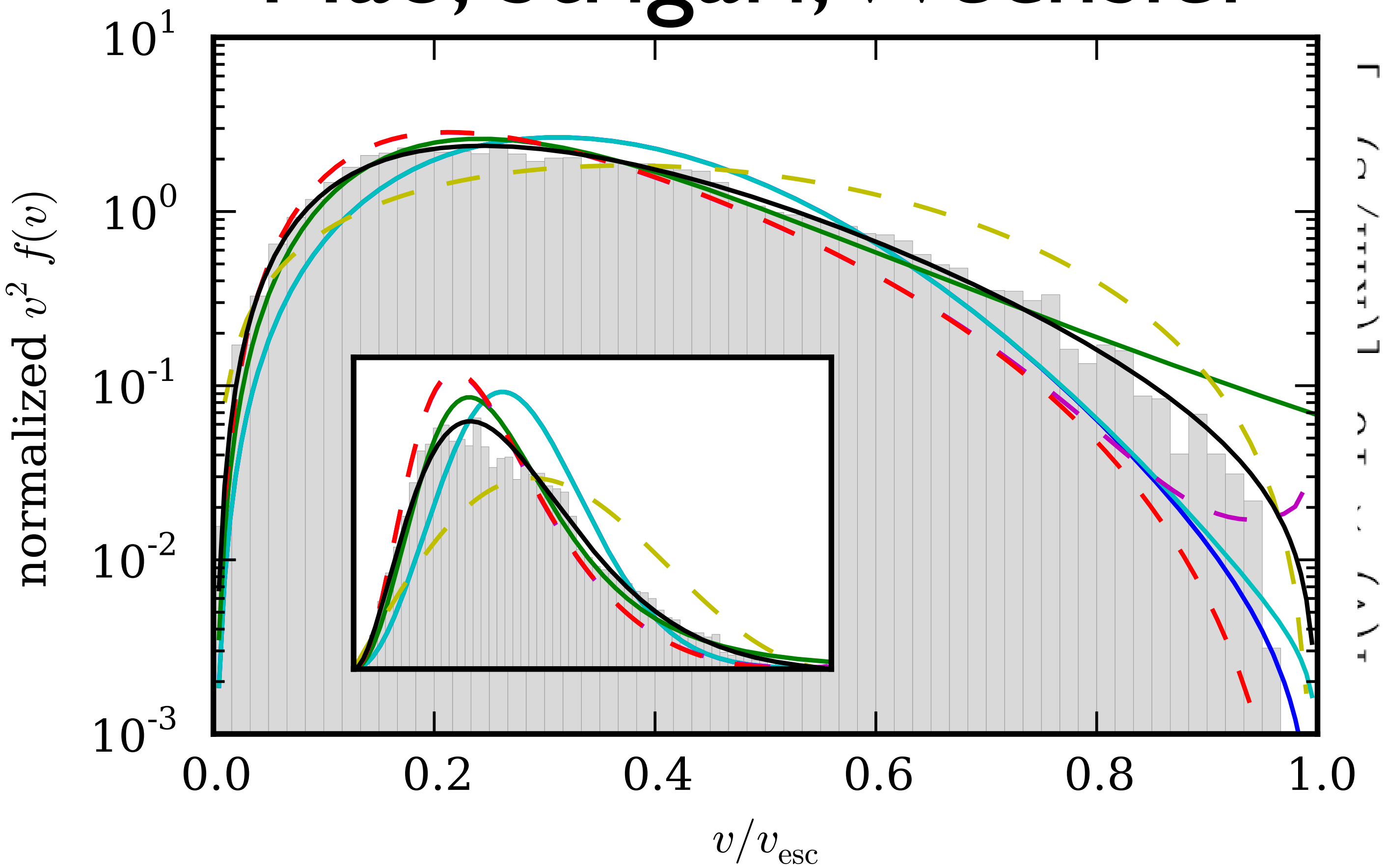
How low can we go?

Billard, Figueroa-Feliciano, Strigari

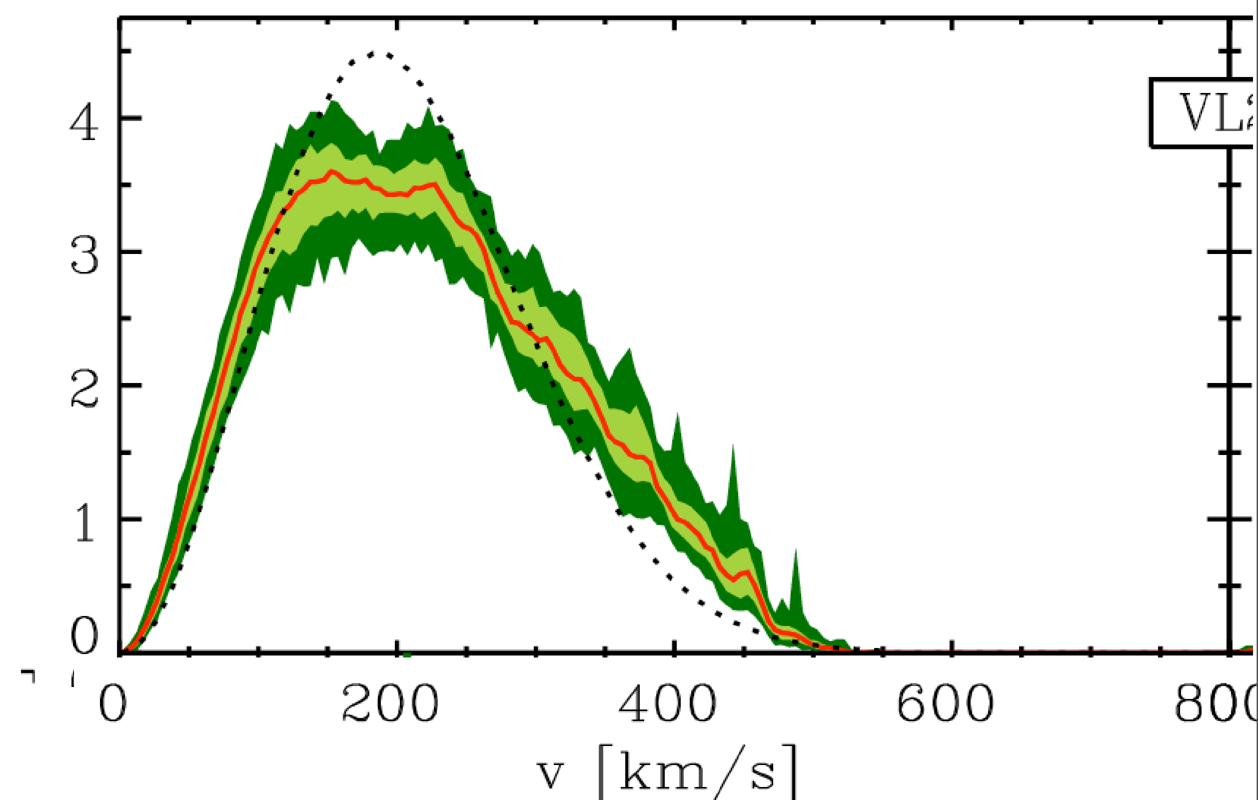


Winds, streams and flows

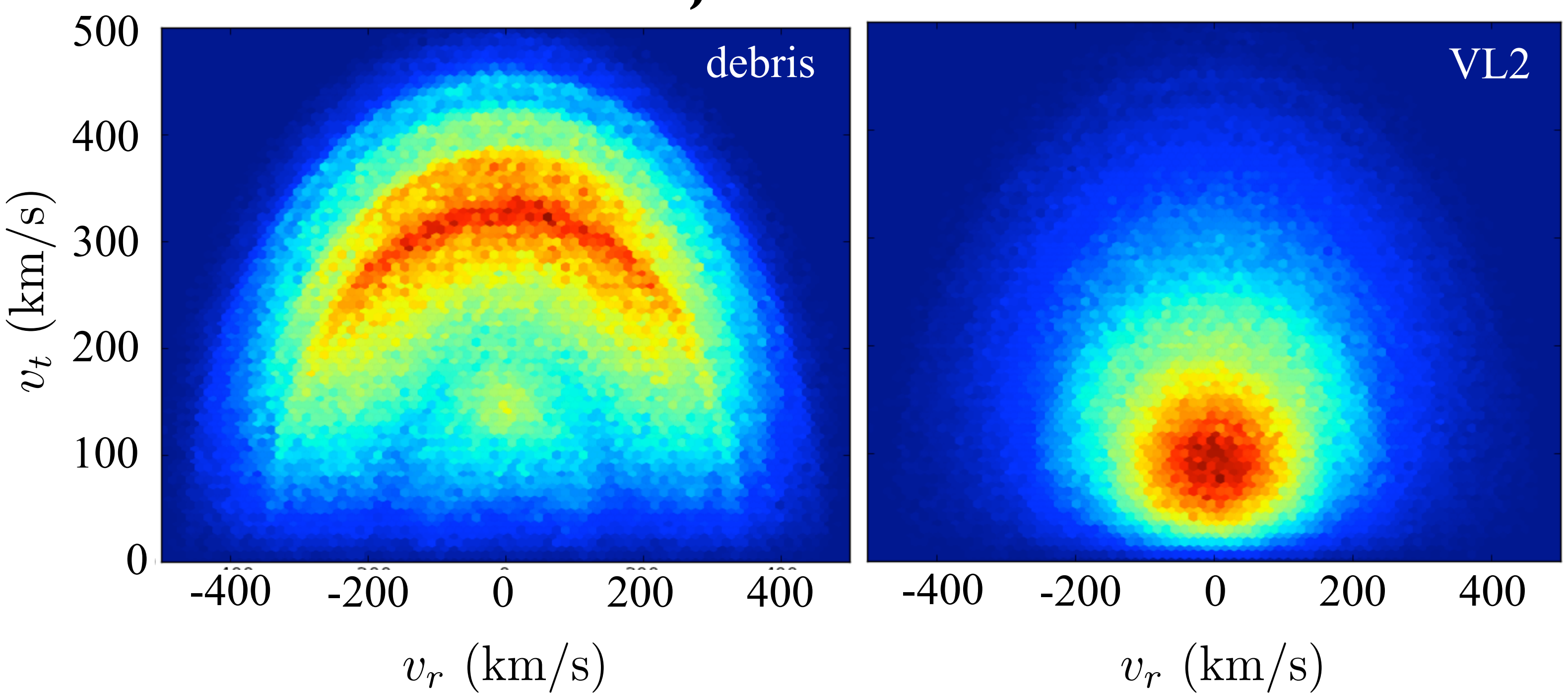
Mao, Strigari, Wechsler



Via Lactea II



Debris flow, Lisanti et al.



Local abundance and velocity distribution are inputs into the interpretation of direct detection experiments

Only way to measure these things is through direct detection experiments

[PJF, Kribs, Tait]

$$f_1(v_{\rm min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2}\frac{1}{\mathcal{N}\sigma_0(v_{\rm min}(E_R))F_\chi^2(E_R)}\left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)}\frac{dF_\chi^2(E_R)}{dE_R}\right)$$

f-condition: $f(v) \geq 0$

(Deconvoluted) rate is a monotonically decreasing function, or there is non-standard particle physics e.g. inelastic or a increasing DM form factor

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"Deconvoluted" rate

$$f_1(v) = \int d\Omega f(\vec{v})$$

$$\mathcal{R} \equiv \frac{1}{F_N^2(E_R)}\frac{dR}{dE_R}$$

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Two experiments allow us to test particle physics independent of astrophysics

1) Make hypothesis about DM e.g. elastically scattering DM with mass 100 GeV and x-sec 10^{-40} cm^2
2) Use experiment A to extract astrophysics i.e. rho x f(v)
3) Use these extracted astrophysics properties to predict result at experiment B
4) Compare to B's measurement/bound
5) Rule in our out each particle physics hypothesis

Doesn't allow extraction of "unique" x-sec, mass
Need relatively large statistics ~10's events
Experiments must run over same part of year
Other uncertainties (nuclear, atomic etc not addressed)

Halo model independence

[PJF, Liu, Weiner]

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \underbrace{\int_{v_{min}}^{v_{max}} d^3\vec{v} \frac{f(\vec{v}, \vec{v_E})}{v}}_{g(v)} \sigma(E_R)$$

$$\frac{dR}{dE_R} = \frac{N_T M_T}{2\mu^2} \frac{\rho\sigma}{m_\chi} g(v)$$

$$v_{min} = \sqrt{\frac{M_T E_R}{2\mu^2}}$$

Recoil energy uniquely determines **minimum** DM velocity

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Target independent

$$\tilde{g}(v_{\mathrm{min}})$$

$$v_{min} = \sqrt{\frac{M_T E_R}{2\mu^2}}$$

Recoil energy uniquely determines **minimum** DM velocity

Using vmin space

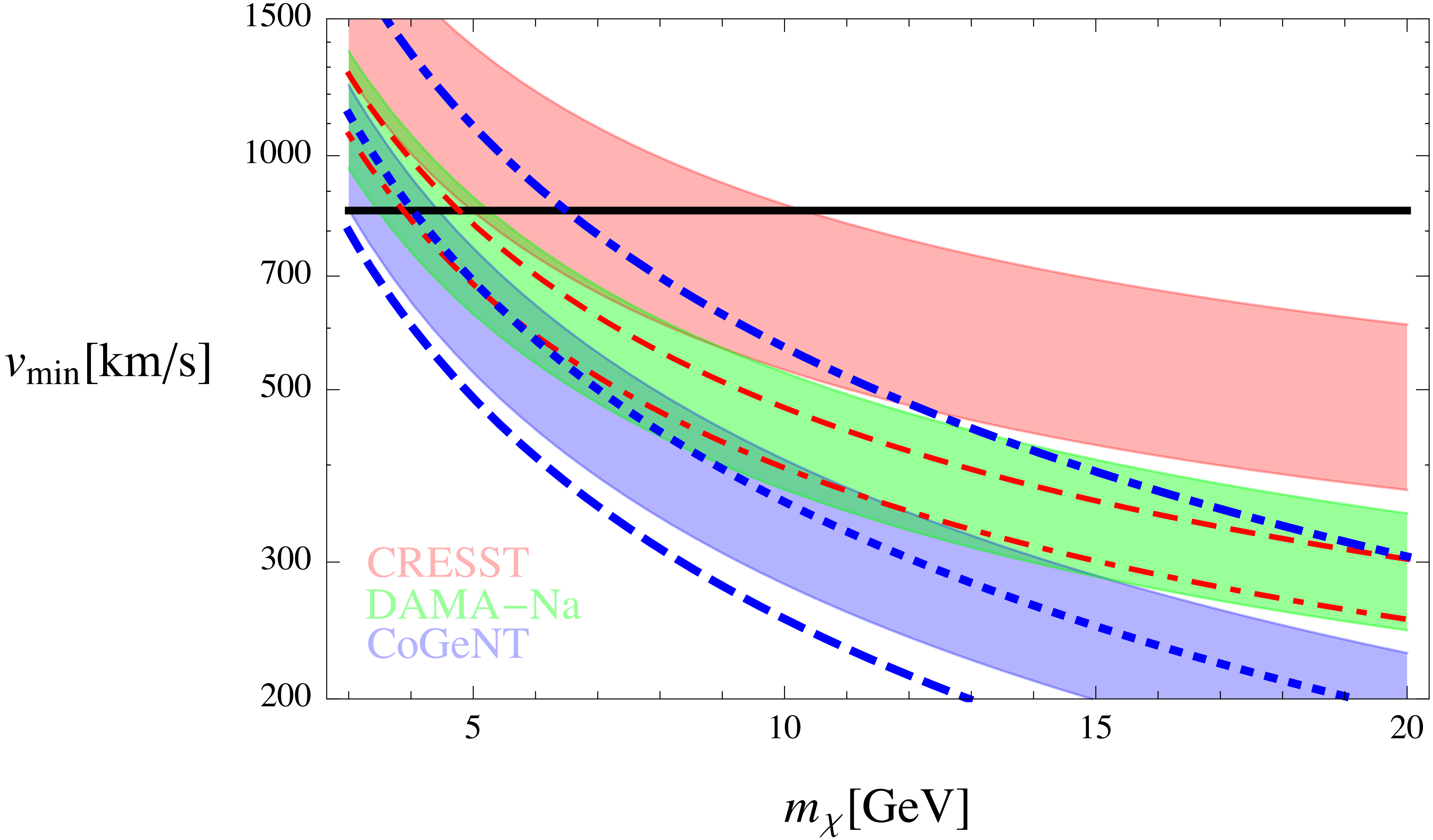
Experiment 1 $\longleftrightarrow$ Experiment 2

$$[E^{(1)}_{low}, E^{(1)}_{low}] \Longleftrightarrow [v^{low}_{min}, v^{high}_{min}] \Longleftrightarrow [E^{(2)}_{low}, E^{(2)}_{high}],$$

$$[\mathrm{E}^{(2)}_{\mathrm{low}}, \mathrm{E}^{(2)}_{\mathrm{high}}] = \frac{\mu_2^2 M_T^{(1)}}{\mu_1^2 M_T^{(2)}} [\mathrm{E}^{(1)}_{\mathrm{low}}, \mathrm{E}^{(1)}_{\mathrm{high}}]$$

Bin	CoGeNT	Ge	Na (Q=0.3)	Si	O	Xe
1	[0.5,0.9] 0.90 ± 0.72	[2.3,3.8] 0.23 ± 0.18	[1.5,2.5] 0.078 ± 0.062	[4.5,7.6] 0.035 ± 0.028	[5.8,9.9] 0.011 ± 0.009	[1.4,2.3] 0.72 ± 0.58
2	[0.9,1.5] 0.37 ± 0.55	[3.8,6.1] 0.1 ± 0.149	[2.5,4.0] 0.035 ± 0.052	[7.6,11.9] 0.015 ± 0.023	[9.9,15.6] 0.005 ± 0.008	[2.3,3.7] 0.31 ± 0.46
3	[1.5,2.3] 0.48 ± 0.22	[6.1,8.9] 0.136 ± 0.063	[4.0,5.8] 0.049 ± 0.022	[11.9,17.5] 0.021 ± 0.01	[15.6,22.8] 0.007 ± 0.003	[3.7,5.4] 0.41 ± 0.19
4	[2.3,3.1] 0.27 ± 0.23	[8.9,11.6] 0.08 ± 0.068	[5.8,7.6] 0.029 ± 0.025	[17.5,22.8] 0.013 ± 0.011	[22.8,29.8] 0.004 ± 0.004	[5.4,7] 0.23 ± 0.2

Using vmin space



Halo model independence

$$N_T = \kappa N_A m_p / M_T$$

Solve for g(v)

$$g(v_{min}) = \frac{2 m_\chi \mu^2}{N_A \kappa\, m_p\, \rho\, \sigma(E_R)} \frac{dR_1}{dE_1}$$

$$\frac{dR_1}{dE_1} \Longleftrightarrow g(v_{min}) \Longleftrightarrow \frac{dR_2}{dE_2}$$

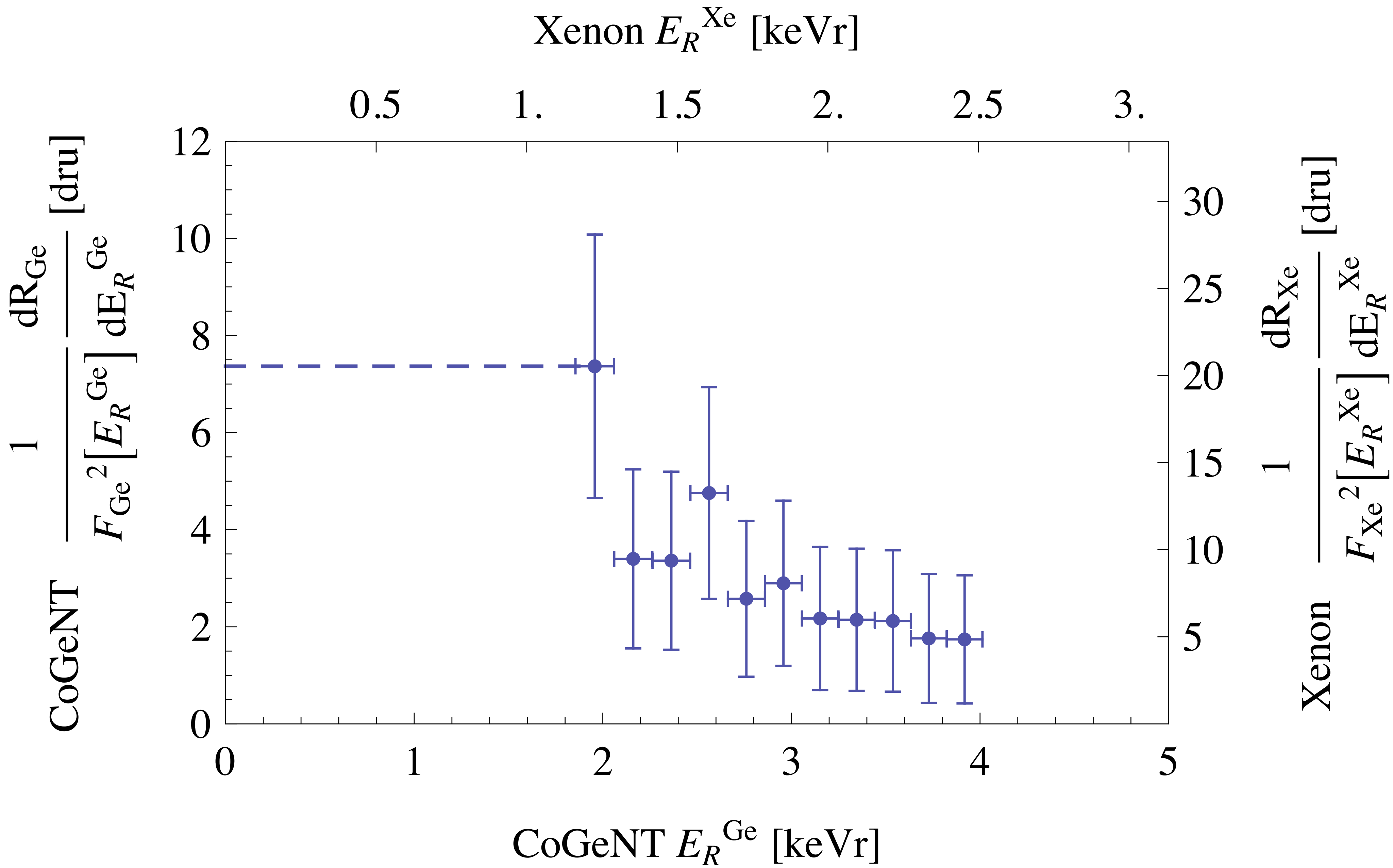
The master formula (SI):

$$C_T^{(i)} = \kappa^{(i)} \left(f_p\, Z^{(i)} + f_n \left(A^{(i)} - Z^{(i)} \right) \right)^2$$

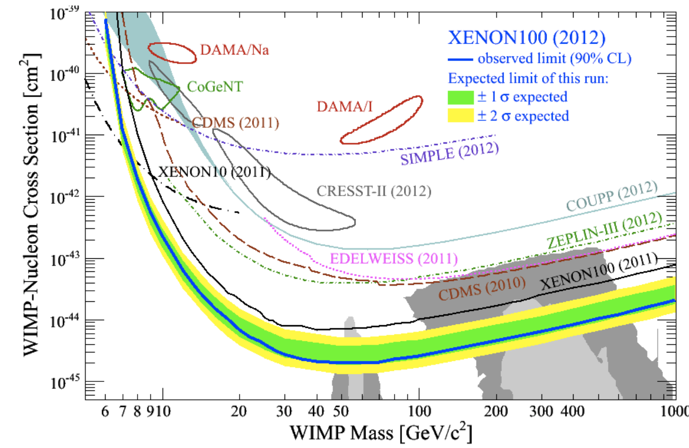
$$\frac{dR_2}{dE_R}(E_2) = \frac{C_T^{(2)}}{C_T^{(1)}} \frac{F_2^2(E_2)}{F_1^2\left(\frac{\mu_1^2\, M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2 \right)} \frac{dR_1}{dE_R} \left(\frac{\mu_1^2\, M_T^{(2)}}{\mu_2^2\, M_T^{(1)}} E_2 \right)$$

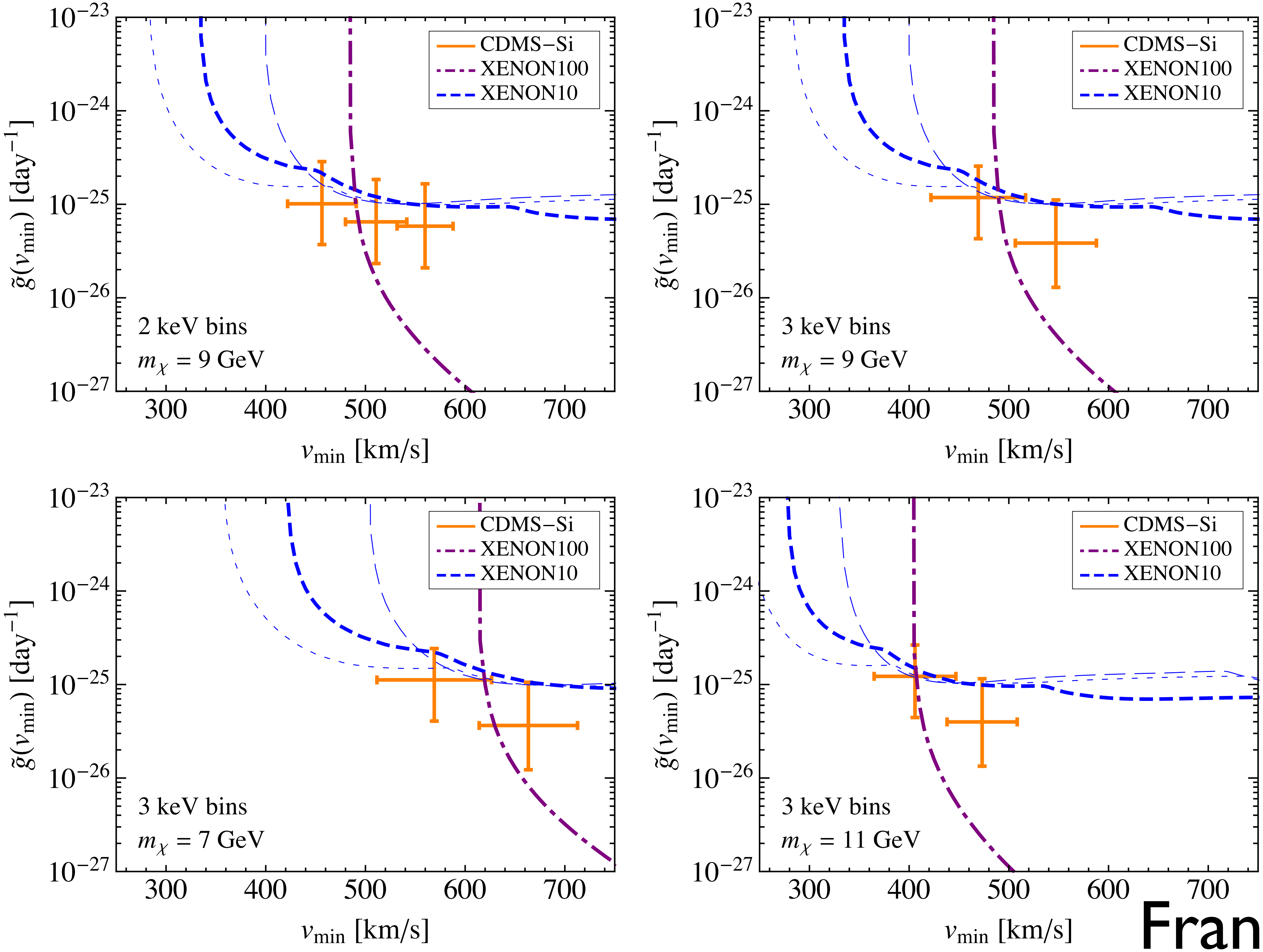
CoGeNT and XENON10

$$m_\chi = 10\,\mathrm{GeV}$$



A new plot





Frandsen et al.

In <u>addition</u> to standard $\sigma - m$ plots because..

A more direct comparison of data than x-sec--m plots

Easy to derive from data

Ultimately allows measurement of g(v)

Consistency of g(v) determines allowed DM params

Conclusions

- DM is definitely out there
- Many possibilities for what it is
- Searching on many fronts
- VERY exciting times
- Did not have time to talk about MANY things
- ......

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"Stupidity is coming to a conclusion"