Worried by astrophysical uncertainties? New methods to compare experiments

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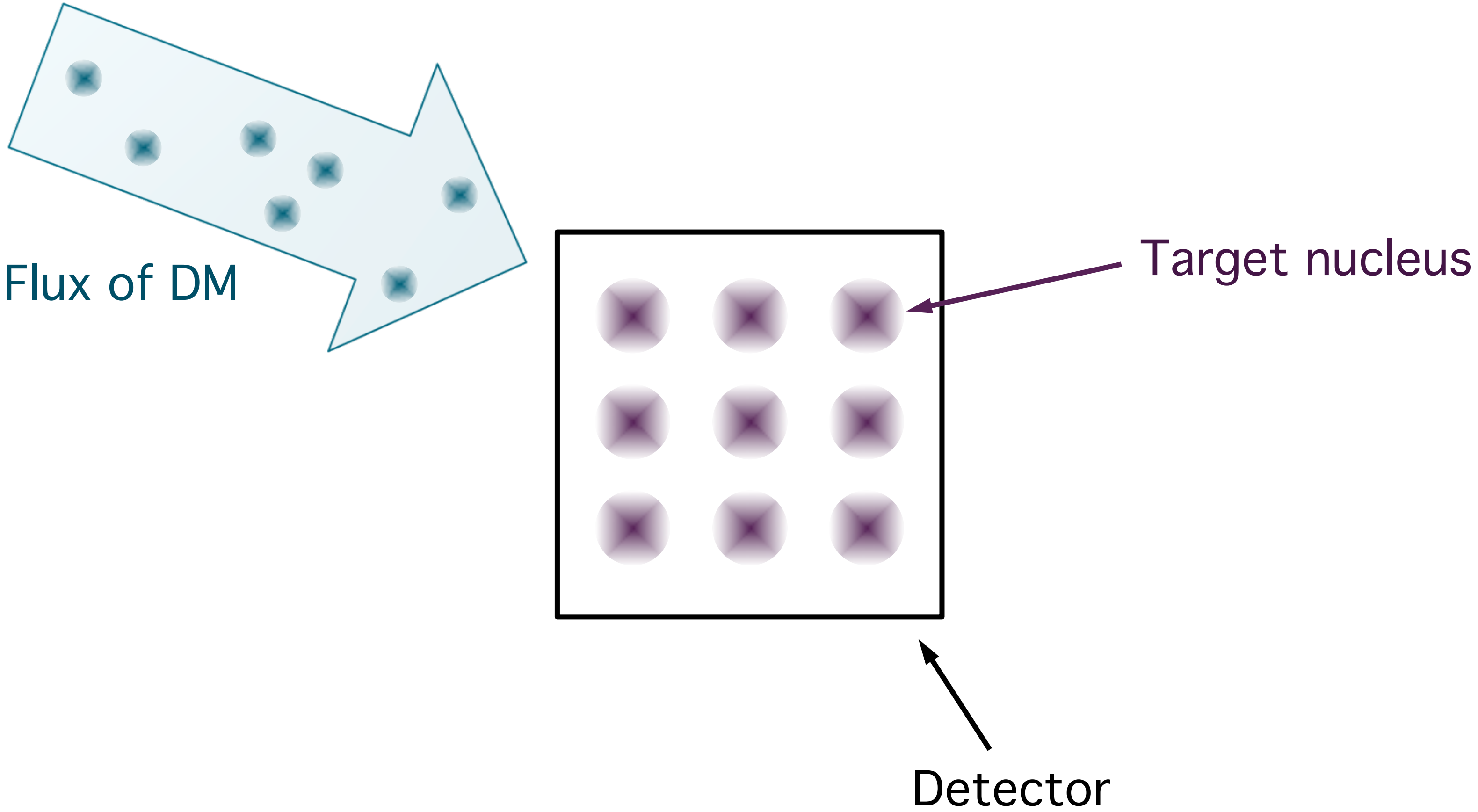
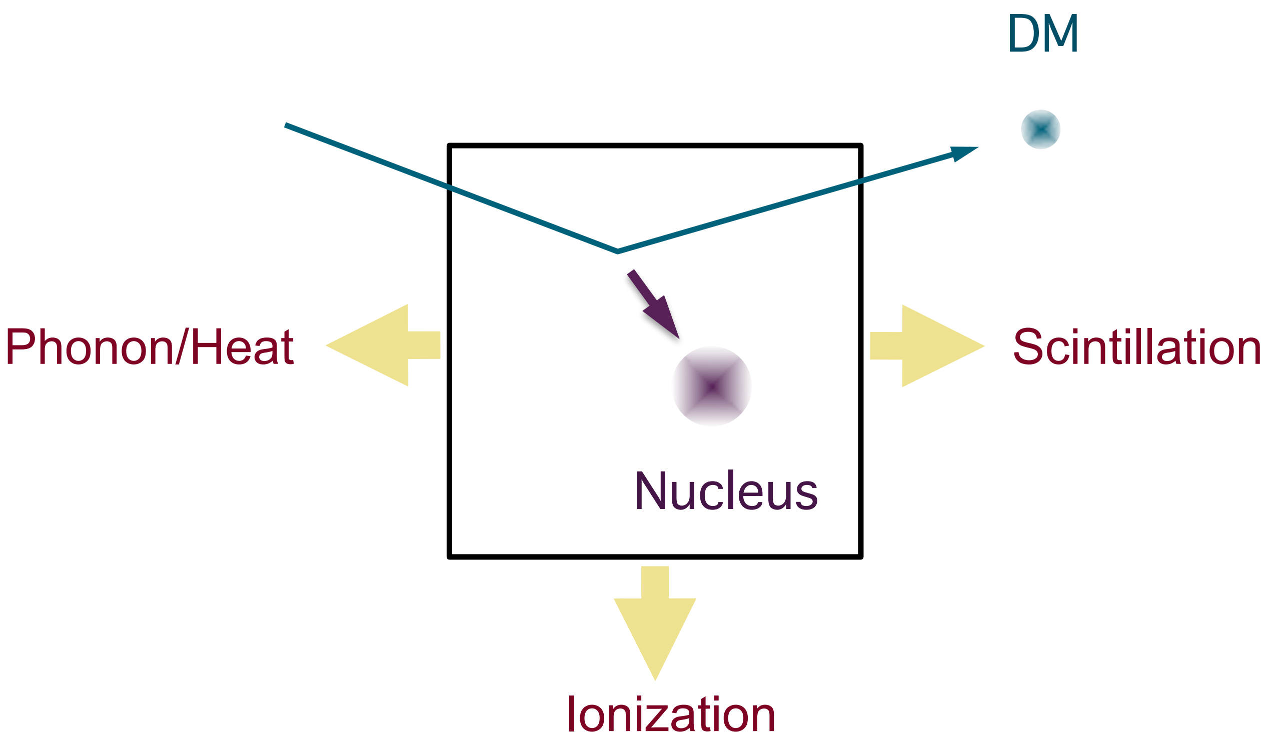
Outline

1. Direct detection
2. Motivation: Usual approach and its limitations
3. New methods: Working in v_{min} space
4. Conclusion

Direct detection: the basics



Direct detection: the basics



Aim: Detect the nuclear recoil energy

The differential event rate

- The rate for spin-independent scattering:

$$\frac{dR}{dE_{\mathrm{R}}} = \frac{1}{2}\frac{\sigma_n}{m_\chi \mu_{n\chi}} \cdot A_{\mathrm{eff}}^2 \, F^2(E_{\mathrm{R}}) \cdot \rho_\chi g(v_{\mathrm{min}}, t)$$

- This depends on many parameters!

The differential event rate

$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\sigma_n}{m_\chi \mu_{n\chi}} \cdot A_{\rm eff}^2\, F^2(E_R) \cdot \rho_\chi g(v_{\rm min}, t)$$

Properties of dark matter:
Things we would like to know!

m_χ DM mass

σ_n DM-neutron cross section

$\mu_{n\chi}$ DM-neutron reduced mass

From nuclear and particle physics:
Usually completely specified

$F^2(E_R)$ Nuclear form factor

$A_{\rm eff} \equiv f_p/f_n\, Z + (A - Z)$

A, Z Nucleon and proton number

f_p, f_n Ratio of DM coupling to protons to neutrons.

Usually take: $f_p/f_n = 1$

The differential event rate

$$\frac{dR}{dE_{\rm R}} = \frac{1}{2}\frac{\sigma_n}{m_\chi \mu_{n\chi}} \cdot A_{\rm eff}^2\, F^2(E_{\rm R}) \cdot \rho_\chi g(v_{\rm min}, t)$$

From astrophysics:
Determined after choosing your favourite halo model

Local DM density:

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

Local DM velocity distribution:

$$f(v)$$

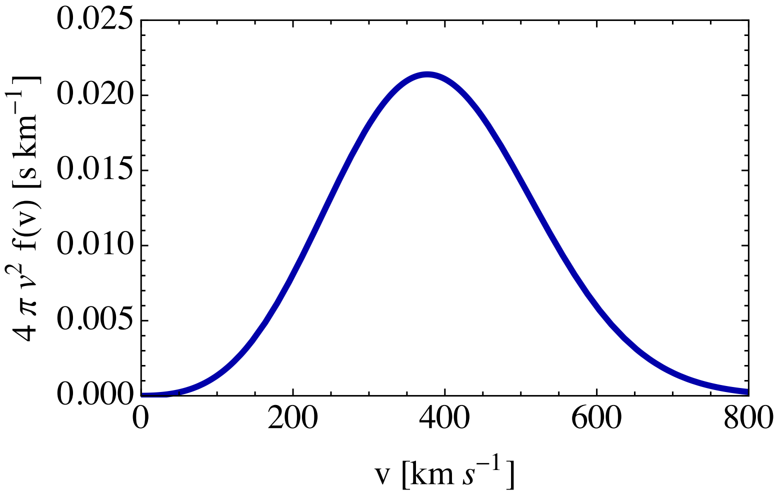
Velocity integral:

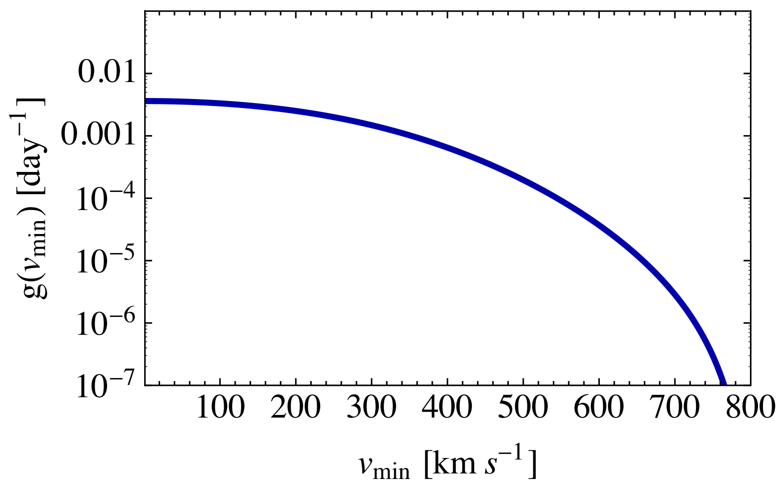
$$g(v_{\rm min}, t) \equiv \int_{v_{\rm min}}^{\infty} d^3 v\, \frac{f(v)}{v}$$

Minimum DM speed for nucleus to recoil with energy $E_{\rm R}$

$$v_{\rm min} = \sqrt{\frac{m_N E_{\rm R}}{2\mu_N}}$$

Usual choice: SHM





- (Truncated) Maxwell-Boltzmann velocity distribution

$$f(v) = \begin{cases} N_0 \exp\left(-\frac{v^2}{v_0^2}\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

- Canonical values are $v_0 = 220\ {\rm kms}^{-1}$ and $v_{\rm esc} = 544\ {\rm kms}^{-1}$
- Typical ranges are:

$$200\ {\rm kms}^{-1} \lesssim v_0 \lesssim 250\ {\rm kms}^{-1}$$ McMillan, Binney: 0907.4685

$$498\ {\rm kms}^{-1} \lesssim v_{\rm esc} \lesssim 608\ {\rm kms}^{-1}$$ RAVE survey: 0611671

Usual approach

- Specify everything except m_χ and σ_n
- For each value of m_χ, find the limit/best fit value for σ_n and produce a plot. eg:

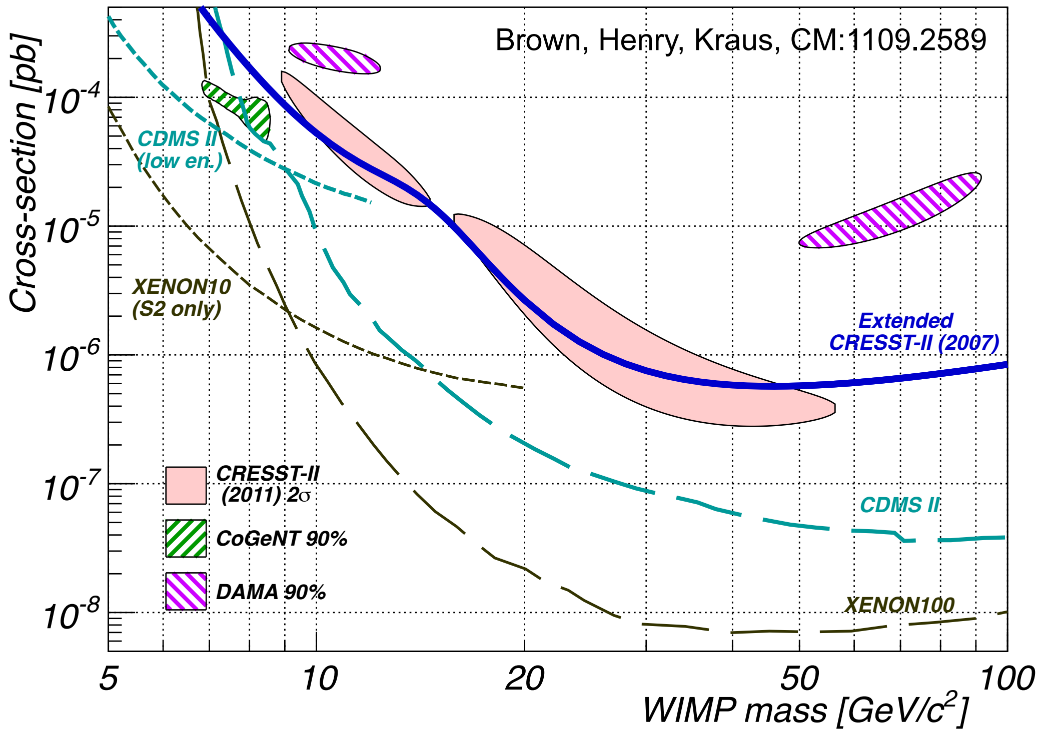
Standard choices:

SHM with

$$v_0 = 220\ \mathrm{km/s}$$

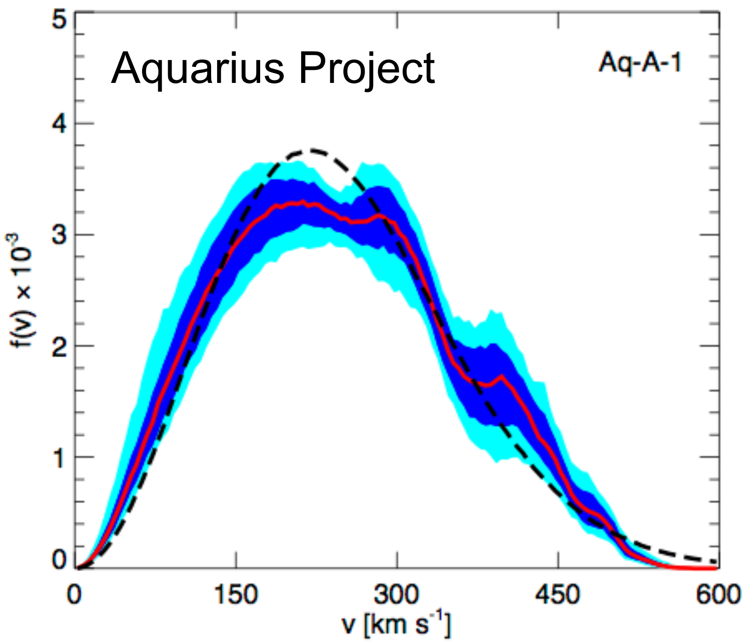
$$v_{\mathrm{esc}} = 544\ \mathrm{km/s}$$

$$\rho_\chi = 0.3\ \mathrm{GeV\ cm^{-3}}$$

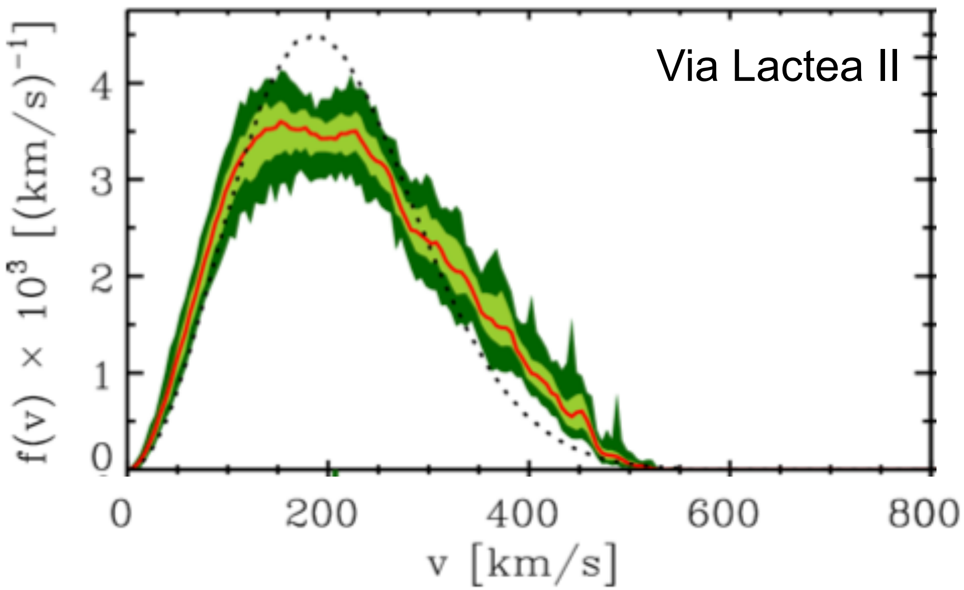


But...did we make the right choice?

- (Dark matter only) N-body simulations show deviations from a Maxwell-Boltzmann distribution:



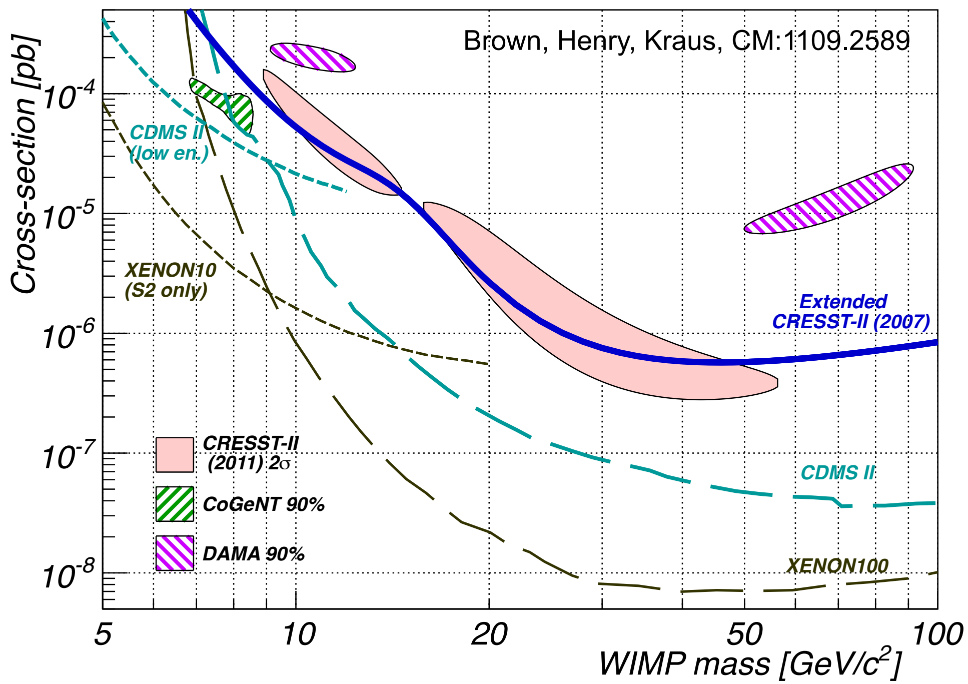
Vogelsberger et al: 0812.0362



Kuhlen et al: 0912.2358

Usual approach: limitations

- Can all experiments be brought into line with a different choice of astrophysical parameters?



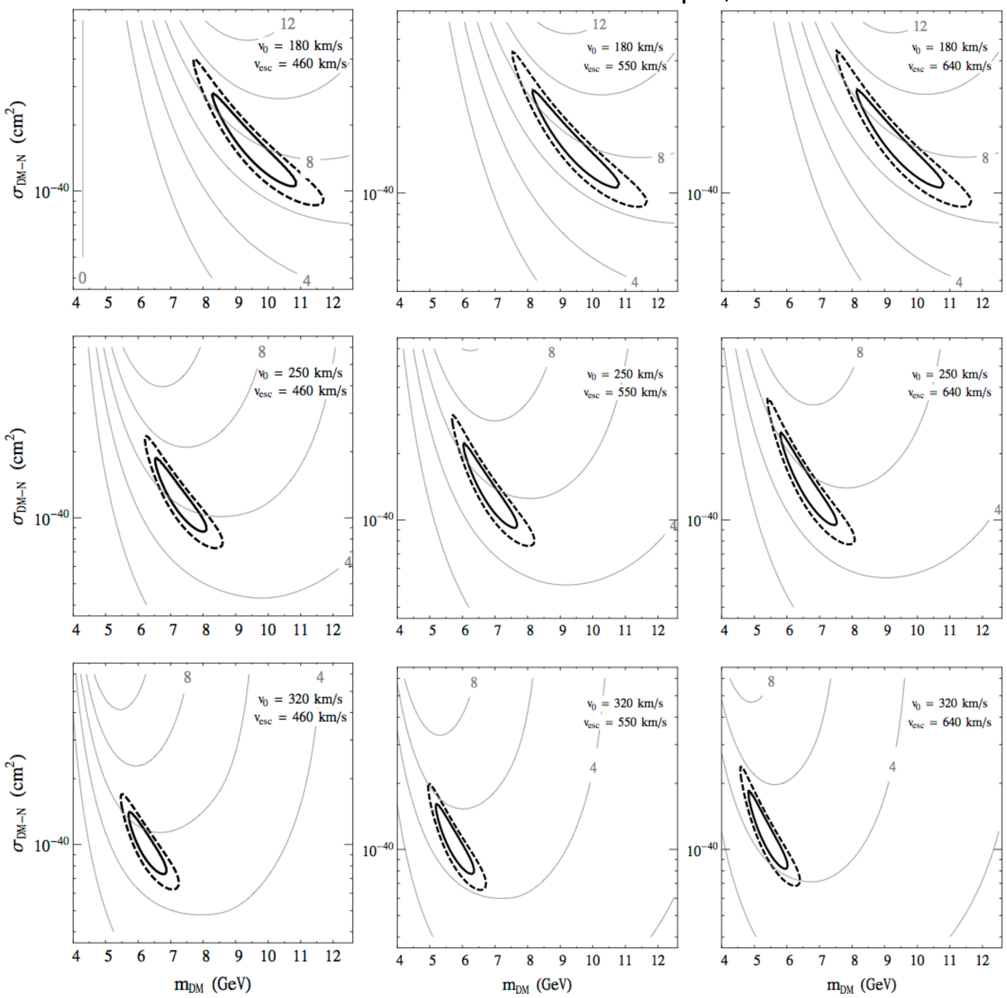
Usual approach: limitations

- Can all experiments be brought into line with a different choice of astrophysical parameters?

- A naïve option is to repeat ad infinitum with different parameters

- Is there an alternative?

Hooper, Kelso:1106.1066



A different approach

Fox, Liu & Weiner
arXiv:1011.1915

- Basic idea: there is a 1-1 map between energy and minimum speed...

$$v_{\min} = \sqrt{\frac{m_N E_{\rm R}}{2\mu_N}}$$

- ...rewrite the rate equation in terms of $v_{\min}$

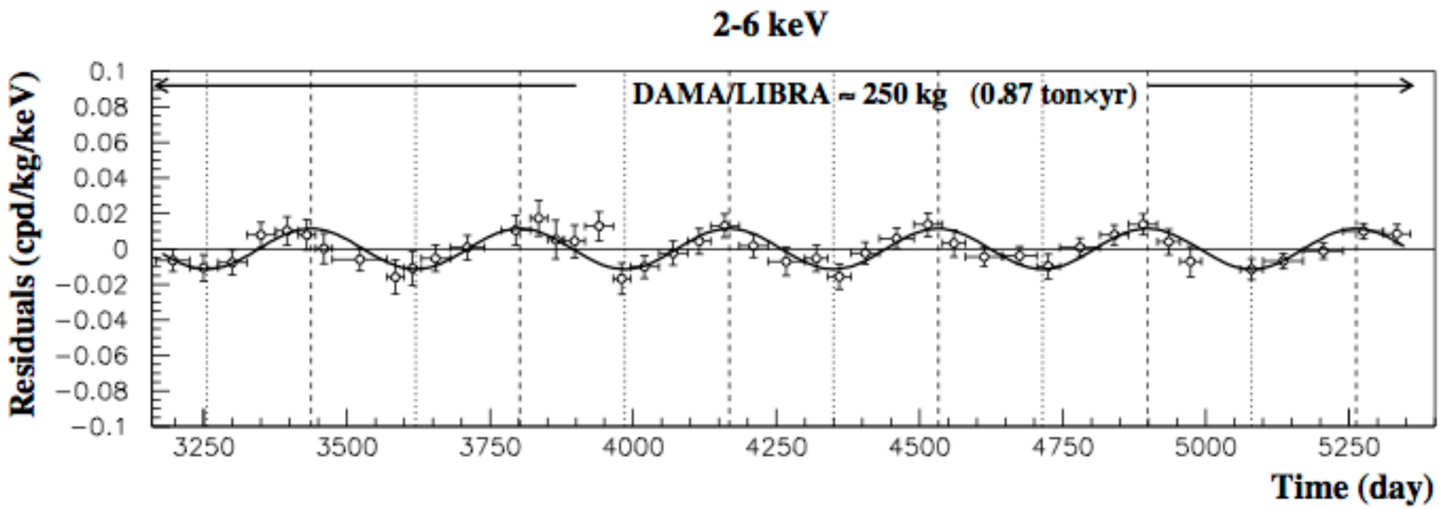
$$\frac{dR}{dv_{\min}} = \tilde{C}_\chi \, \rho_\chi \, v_{\min} \, g(v_{\min}, t) \qquad \left(\tilde{C}_\chi = \frac{2\sigma_n A_{\rm eff}^2 \mu_N^2 \bar{F}^2(E_{\rm R})}{m_\chi \mu_{n\chi}^2} \right)$$

- In this form we can:
  1. Map the experimental signal from one experiment to another while factoring out astrophysical parameters
  2. Infer the form of $g(v_{\min})$ from measured data – learn about halo properties from the data
  3. Set halo-independent exclusion bounds on positive signals

Mapping CoGeNT onto DAMA

'DAMA and CoGeNT without astrophysical uncertainties'
CM:1107.0741

- DAMA measure a modulation in an energy range which we map to $v_{\rm min}$ space: $[E^D_{\rm low}, E^D_{\rm high}] \rightarrow [v^{\rm low}_{\rm min}, v^{\rm high}_{\rm min}]$



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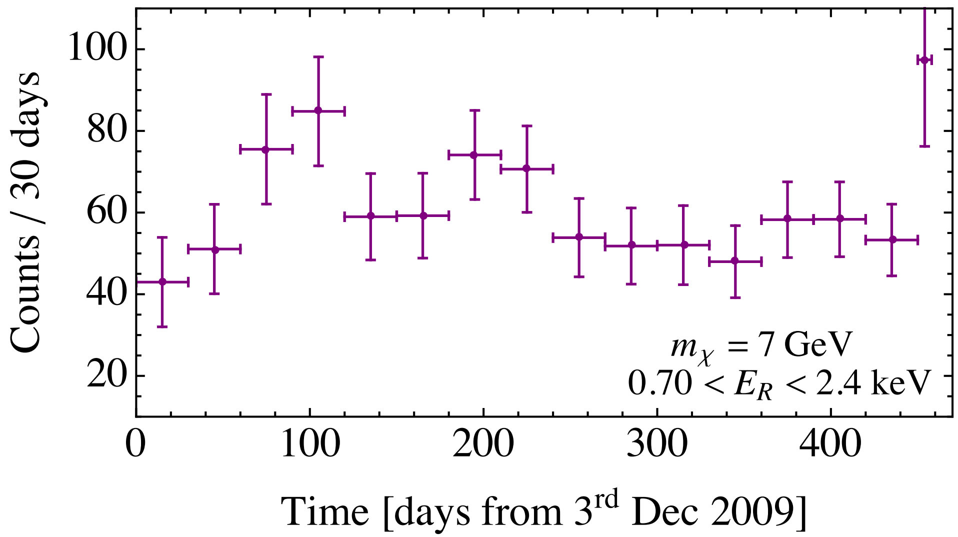
- CoGeNT probe the same $v_{\rm min}$ space in the energy range:

$$[E^C_{\rm low}, E^C_{\rm high}] = \frac{\mu_C^2 m_N^D}{\mu_D^2 m_N^C}[E^D_{\rm low}, E^D_{\rm high}]$$



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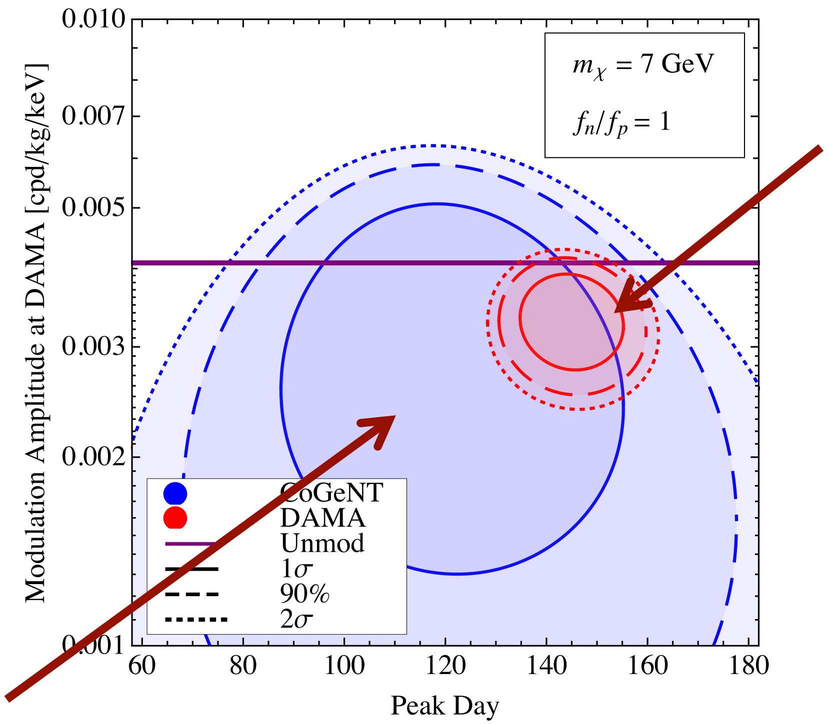
- The rate at a given experiment is $R = \tilde{C}_\chi \, \rho_\chi \int_{v^{\rm low}_{\rm min}}^{v^{\rm high}_{\rm min}} dv_{\rm min} \, v_{\rm min} \, g(v_{\rm min}, t)$
- By construction, all astrophysical parameters will cancel in the ratio:

$$\frac{R^{\rm DAMA}}{R^{\rm CoGeNT}} = \frac{\tilde{C}_\chi^{\rm DAMA}}{\tilde{C}_\chi^{\rm CoGeNT}} \qquad \rightarrow \qquad R^{\rm DAMA}_{\rm expected} = \frac{\tilde{C}_\chi^{\rm DAMA}}{\tilde{C}_\chi^{\rm CoGeNT}} R^{\rm CoGeNT}_{\rm obs}$$

- From the observed rate at CoGeNT, we can calculate the expected rate at DAMA and compare with the rate DAMA actually observe - they should be the same!

Mapping CoGeNT onto DAMA



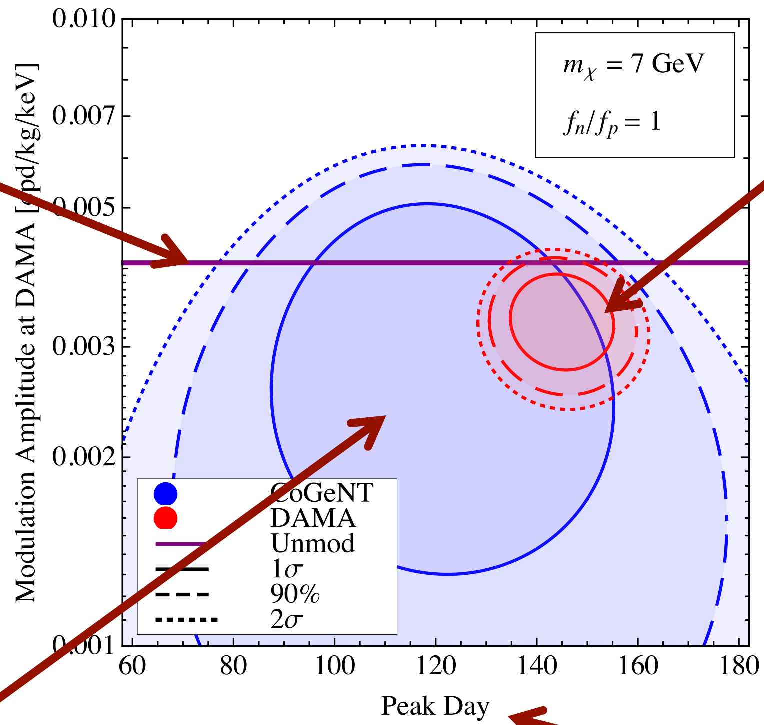
Modulation amplitude and peak day from 2-6 keV DAMA data

Expected modulation amplitude and peak day at DAMA, determined from a fit to the CoGeNT data in the energy range: $[E^C_{\rm low}, E^C_{\rm high}] = \frac{\mu_C^2 m_N^D}{\mu_D^2 m_N^C}[E^D_{\rm low}, E^D_{\rm high}]$

Mapping CoGeNT onto DAMA

The CoGeNT un-modulated rate mapped onto DAMA. Amplitudes near this line require a large modulation fraction

SHM predicts ~10% modulation fraction



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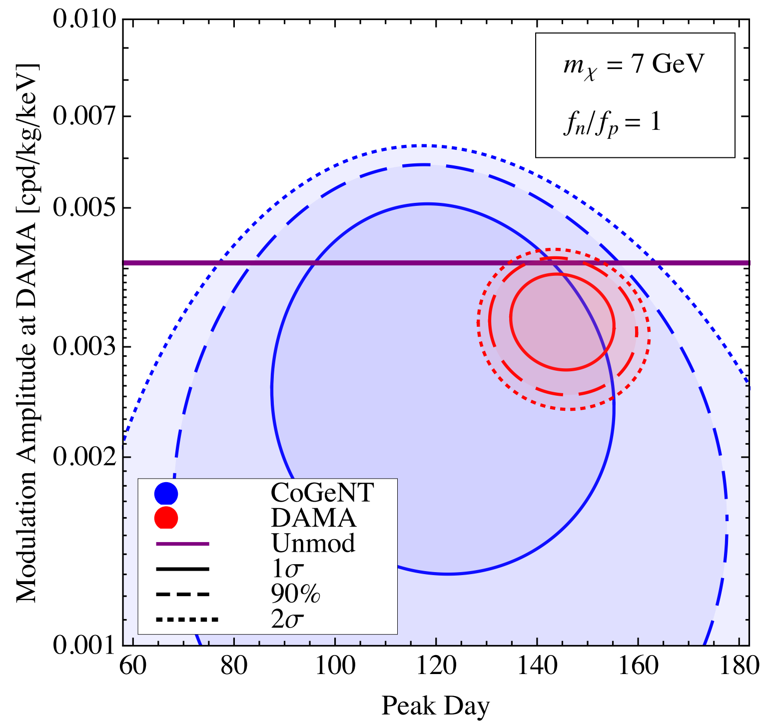
$$[E^C_{\rm low}, E^C_{\rm high}] = \frac{\mu_C^2 m_N^D}{\mu_D^2 m_N^C}[E^D_{\rm low}, E^D_{\rm high}]$$

SHM predicts Peak Day = 152

Mapping CoGeNT onto DAMA



What did we learn?

- Both experiments are in reasonable agreement (although CoGeNT region is very large)
- The SHM will not give a good fit to both experiments – need to dramatically boost the modulation fraction

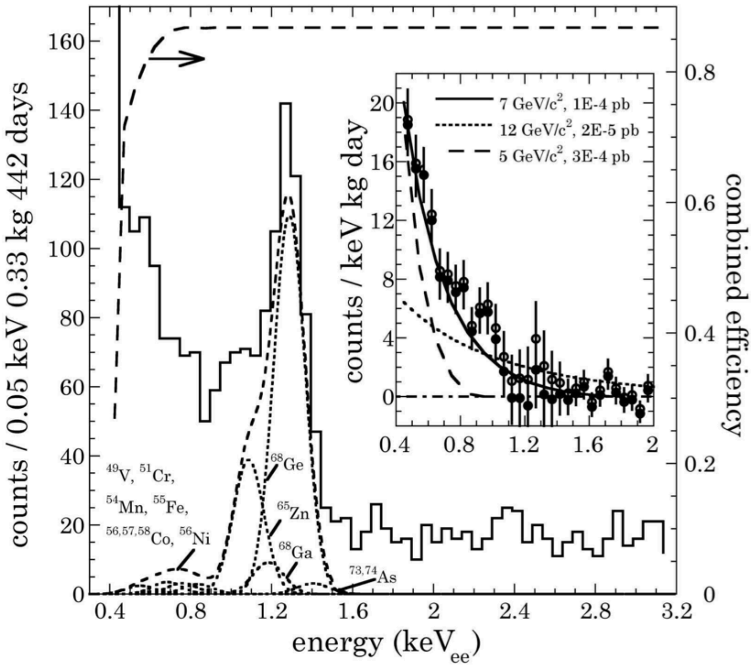
Inferring $\tilde{g}(v_{\rm min})$

'Resolving astrophysical uncertainties in dark matter direct detection'
Frandsen, Kahlhoefer, CM, Sarkar, Schmidt-Hoberg:1111.0292

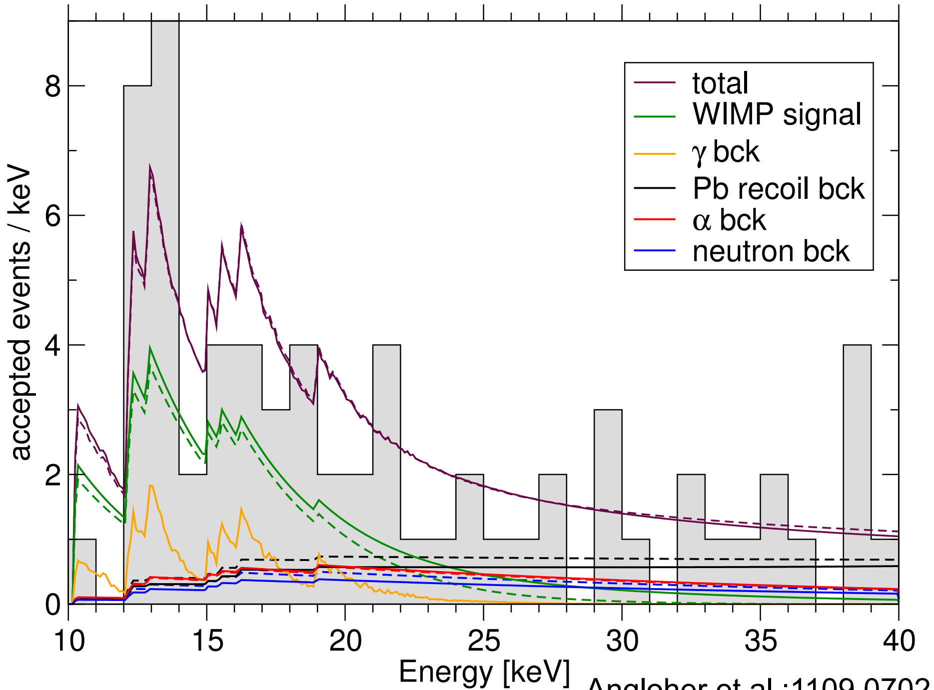
- If we measure $dR/dE_{\rm R}$, we can infer $\tilde{g}(v_{\rm min}) \equiv \frac{\rho_\chi \sigma_n}{m_\chi} \cdot g(v_{\rm min})$

$$\tilde{g}(v_{\rm min}) = \frac{2\mu_{n\chi}^2}{A_{\rm eff}^2\, F^2(E_{\rm R})} \left. \frac{dR}{dE_{\rm R}} \right|_{\rm measured}$$

- Example: use spectra measured by CoGeNT and CRESST-II



Aalseth et al:1106.0650



Angloher et al :1109.0702

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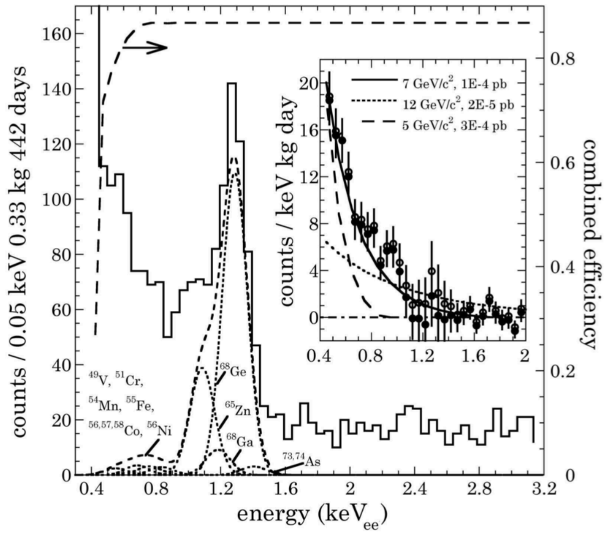
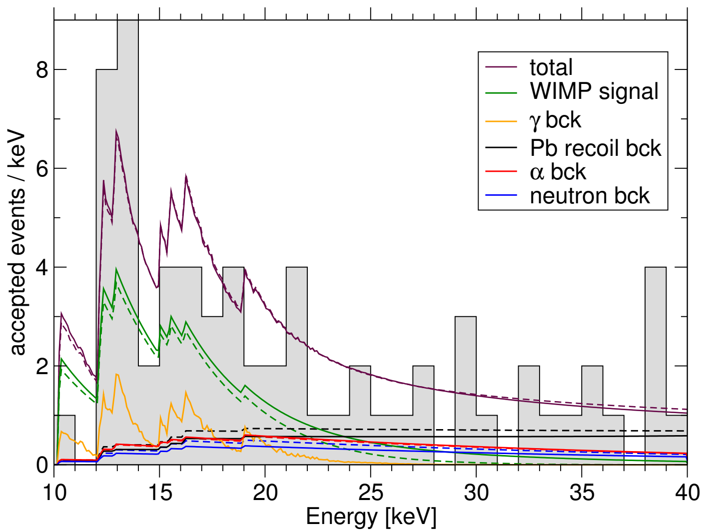
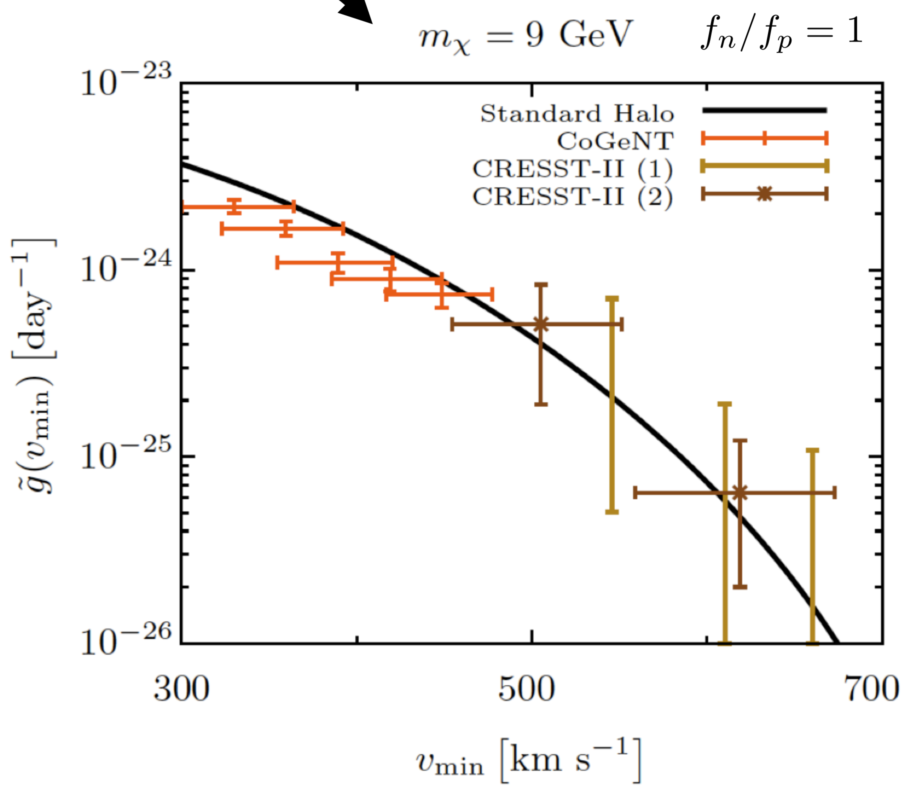




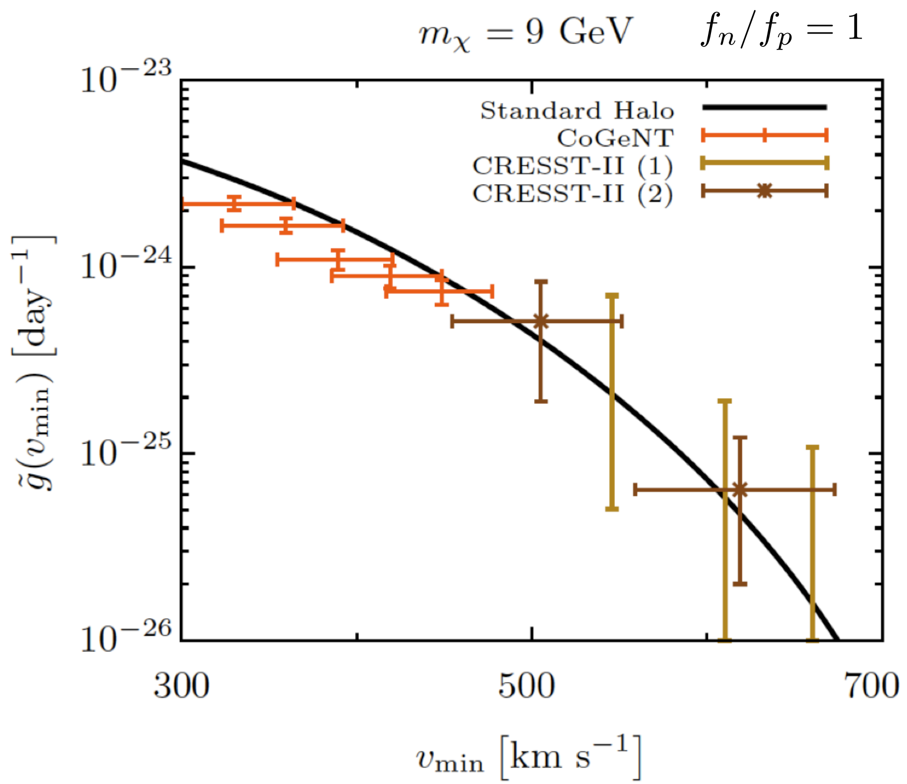
$$\tilde{g}(v_{\min}) = \frac{2\mu_{n\chi}^2}{A_{\rm eff}^2\, F^2(E_R)} \left.\frac{dR}{dE_R}\right|_{\rm measured}$$



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

- CoGeNT and CRESST-II probe different regions of $v_{\min}$ space (when $m_\chi = 9$ GeV)

- The SHM provides a reasonable fit to the data



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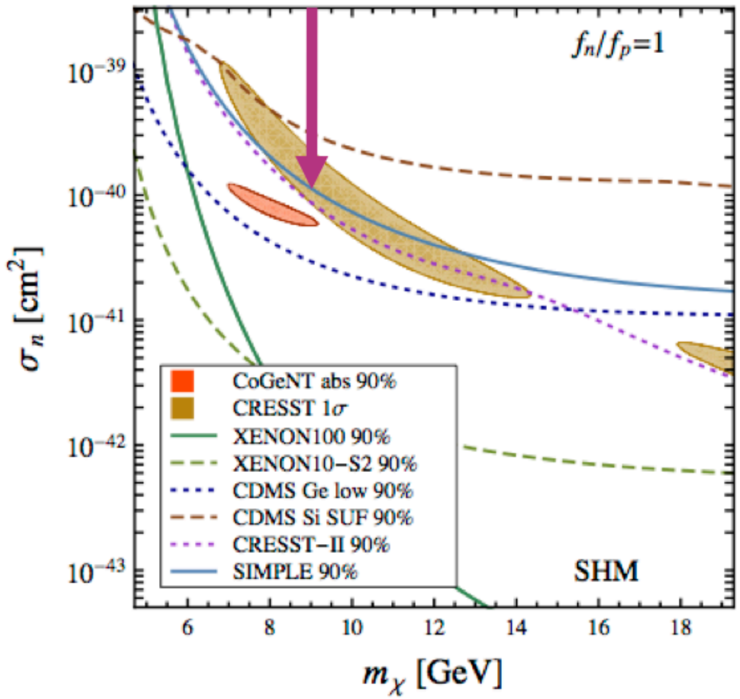

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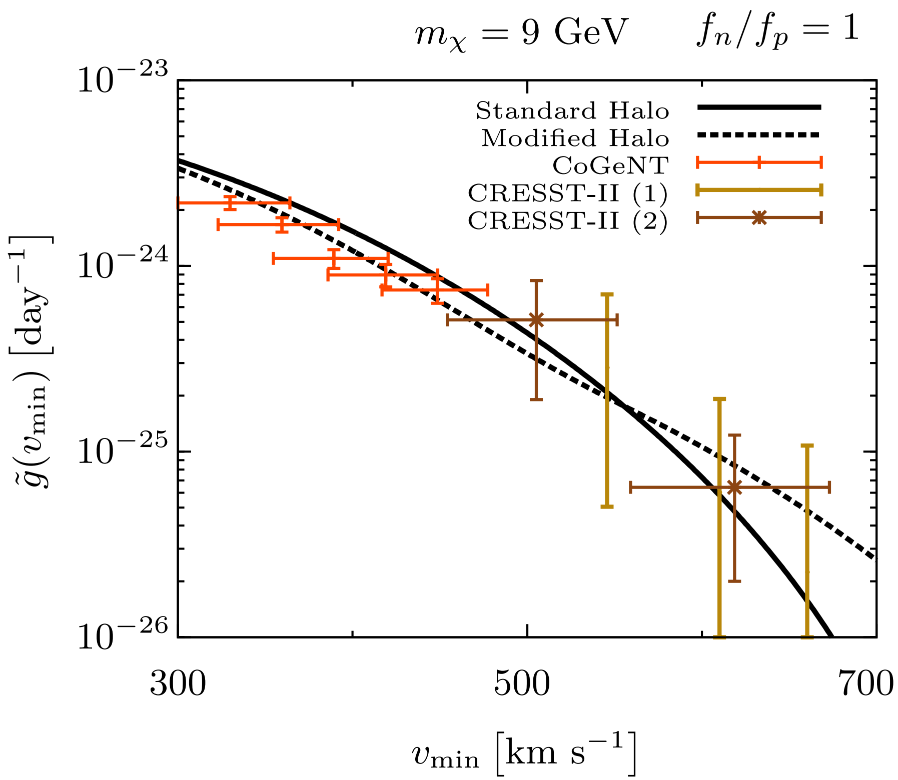
- We can see what changes are required to get better agreement: introduce a modified halo model
  - Warning: this is purely ad-hoc at this stage



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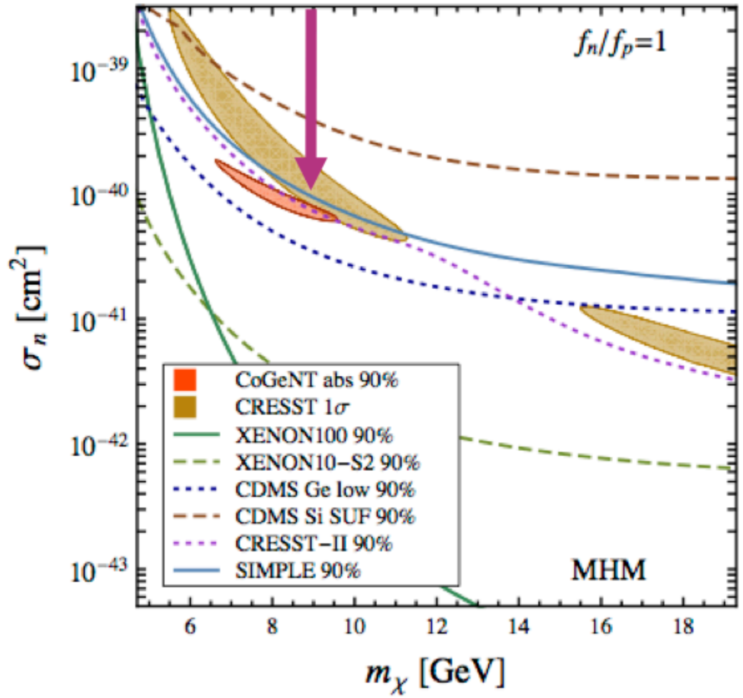
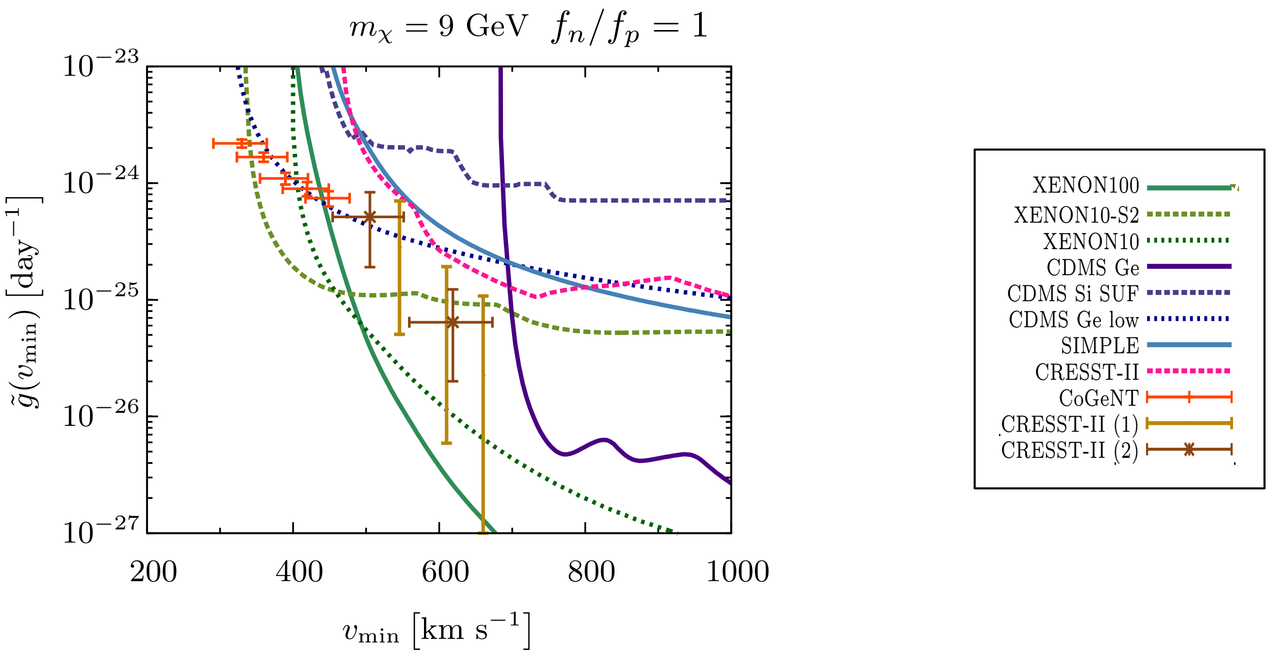


Constraining $\tilde{g}(v_{\min})$

- Set constraints from experimental null results
  - Constraints set by choosing $\tilde{g}(v_{\min}) = \tilde{g}(v_0)\Theta(v_0 - v_{\min})$

Fox et al:
1011.1910
1011.1915



- No halo model can sufficiently reduce the XENON and CDMS constraints!

Conclusions

- The usual method of analyzing direct detection experiments has limitations when comparing positive signals
- Introduced complementary approaches for analyzing experimental data that
  - factorize out astrophysical parameters when comparing experimental results
  - highlight the modifications required to bring results into agreement
  - allow a conservative exclusion bound to be set that any realistic halo model must satisfy
- Using all methods together allow us to build a deeper understanding of experimental results