Astrophysical uncertainties: New methods to compare experiments

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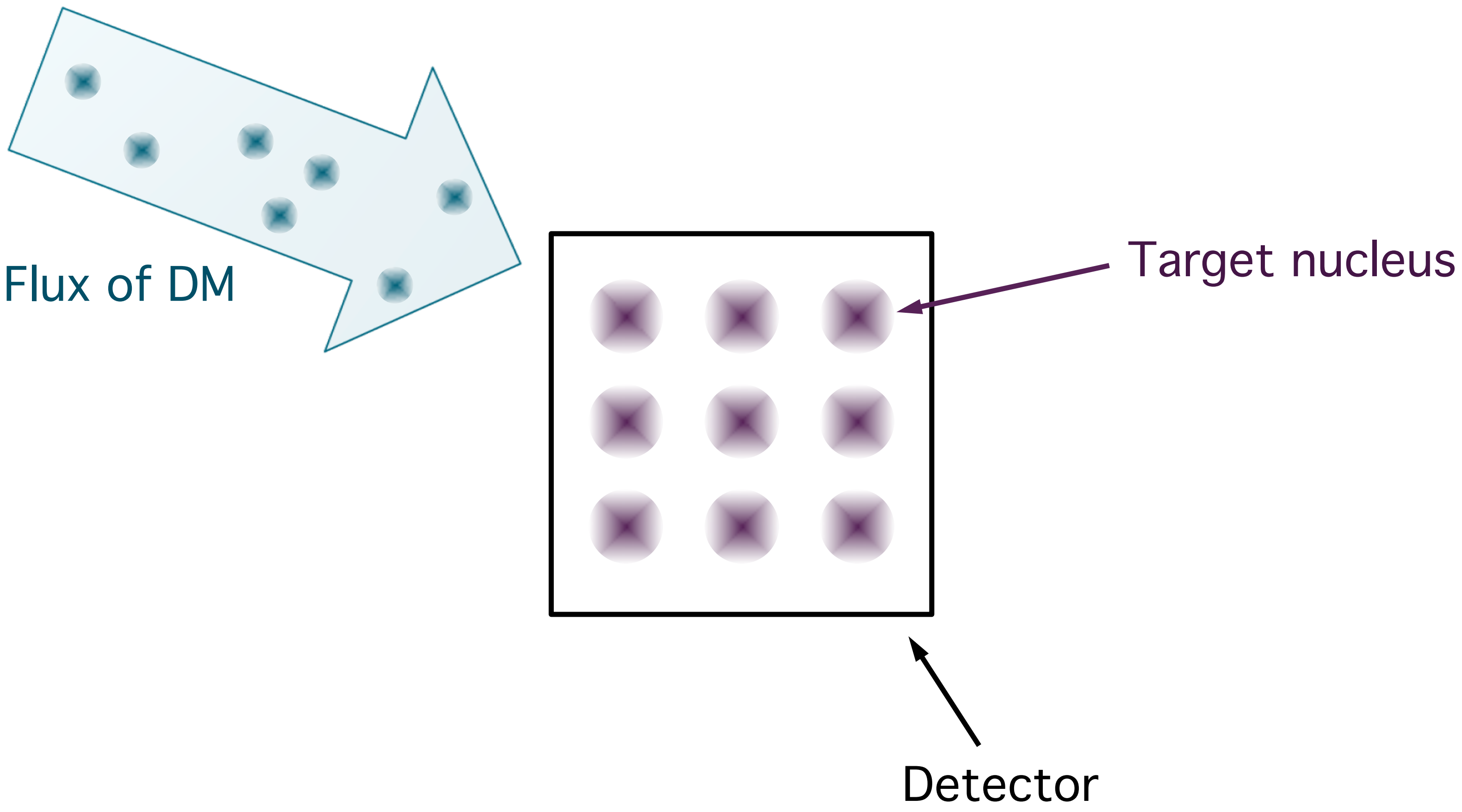
New paths to particle dark matter – Oxford - 30th March 2012

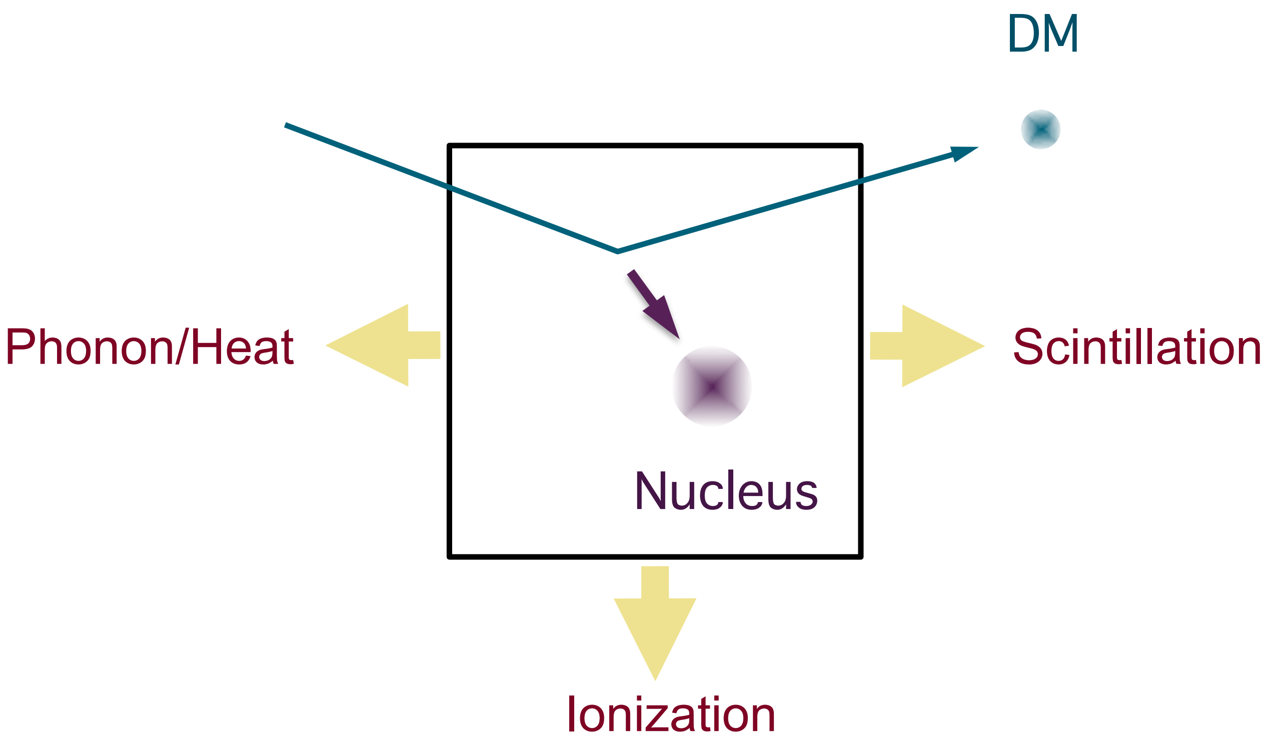
Outline

1. Direct detection
2. The 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:

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

- It depends on many parameters!

The differential event rate

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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:
These are usually completely specified

$F^2(E_\mathrm{R})$	Nuclear form factor

$$C_T(A,Z) \equiv (f_p/f_n Z + (A-Z))^2$$

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

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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:

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

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

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

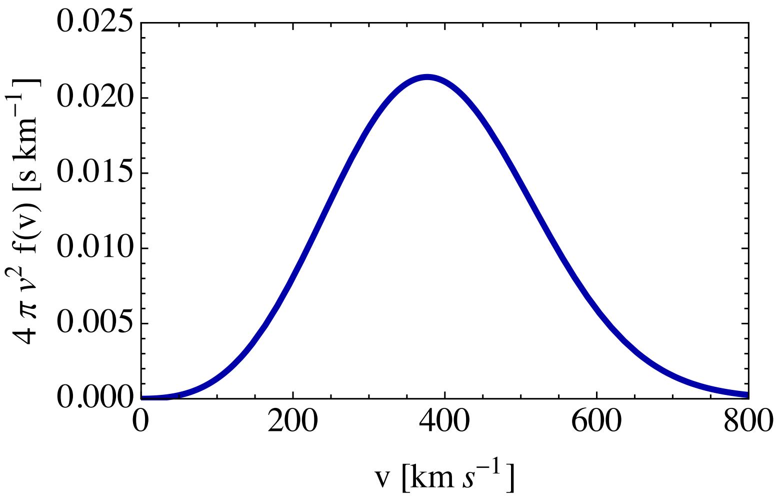
Canonical choice: SHM

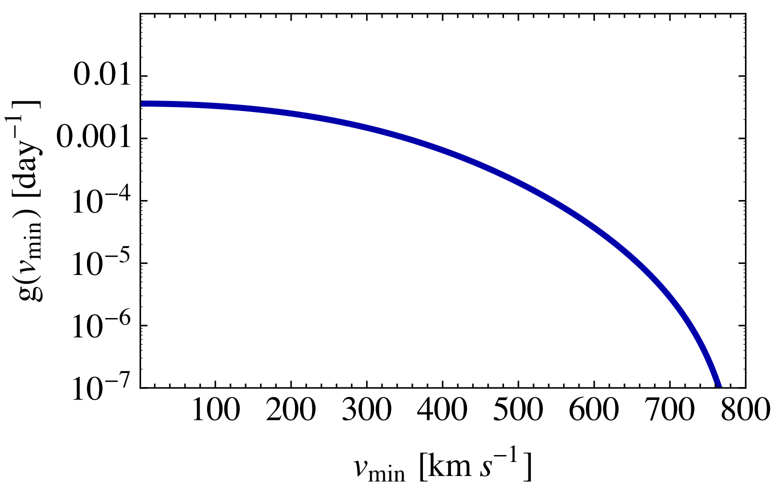
- A simple choice capturing much of the physics
- (Truncated) Maxwell-Boltzmann velocity distribution

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

v_0 Local circular speed: Range 200-260 $\mathrm{kms^{-1}}$: Canonical value 220 $\mathrm{kms^{-1}}$

$v_{\rm esc}$ Local galactic escape speed: Range 450-650 $\mathrm{kms^{-1}}$: Canonical value 544 $\mathrm{kms^{-1}}$





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:

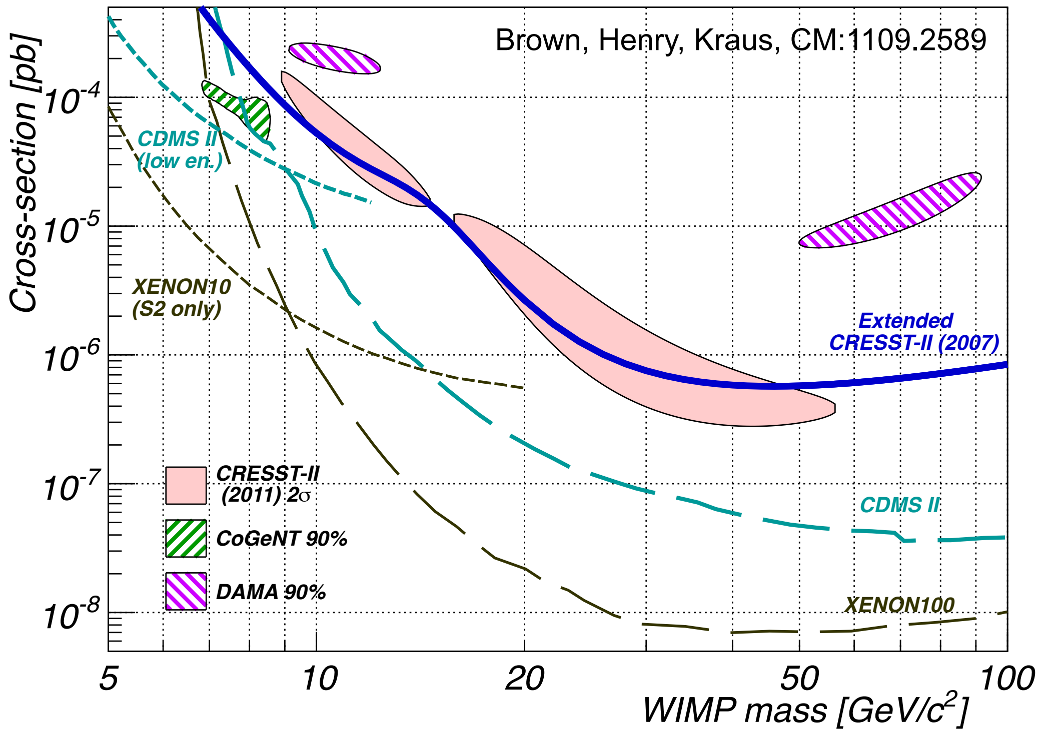
$$f_n/f_p = 1$$

SHM with

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

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

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

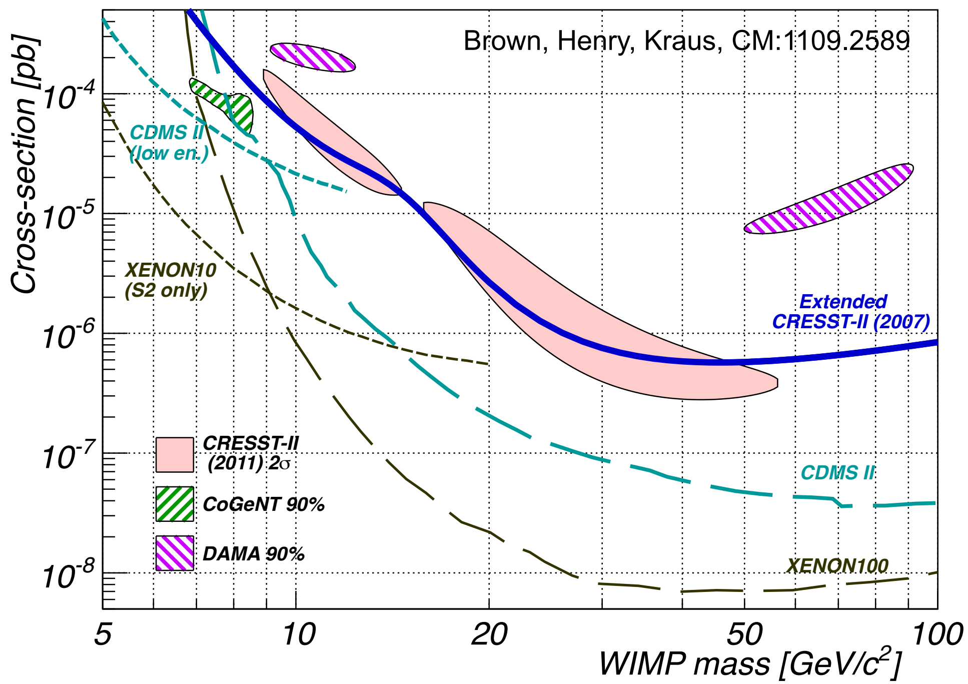


Usual approach: limitations

- Best fit regions almost match up and exclusion limits just exclude the best fit regions

- Can I be confident that things won't change with different choices of astrophysical parameters?

- We could repeat with different parameters:
  – But not all signal regions and limits change by the same amount.



- Is there an alternative?

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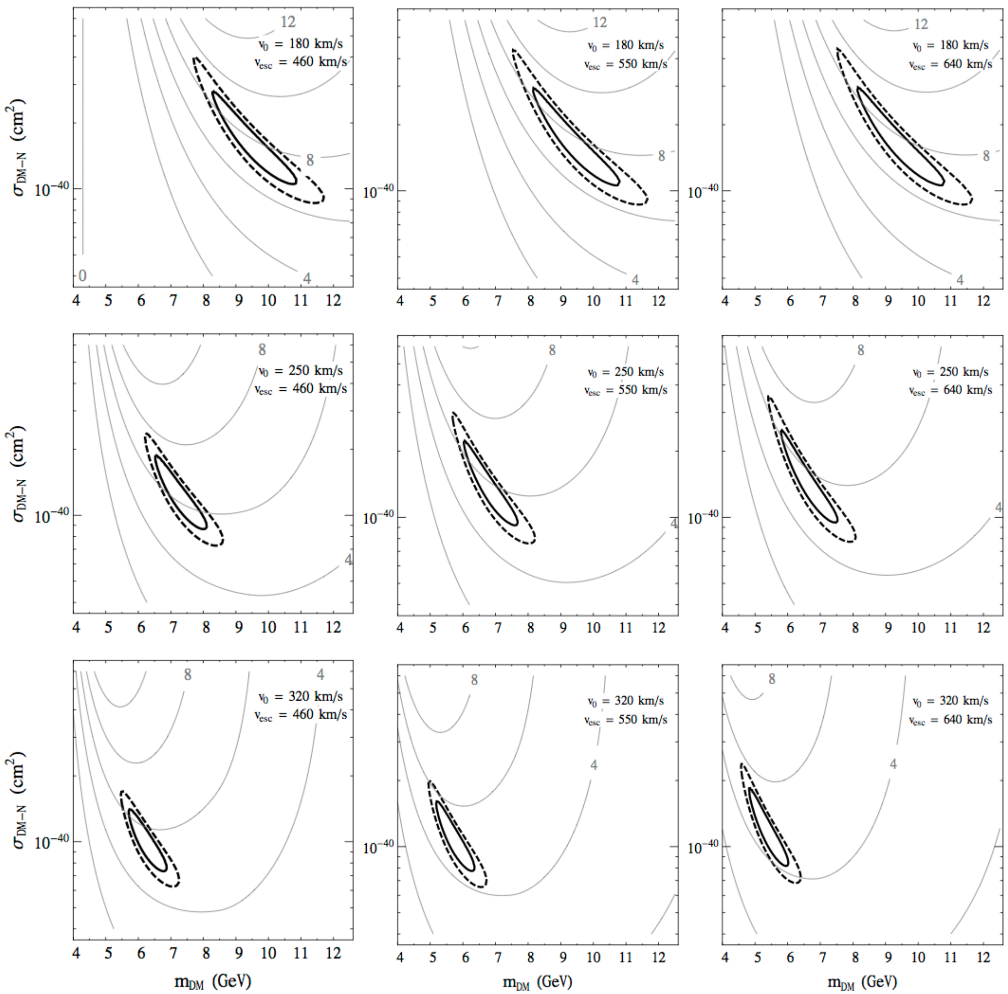
- Is there an alternative?

Hooper, Kelso:1106.1066



A different approach

Fox, Liu, Weiner: arXiv:1011.1915

- New methods: Rewrite the rate equation in terms of $v_{\rm min}$

$$R = \int_{v_{\rm min}^{\rm low}}^{v_{\rm min}^{\rm high}} dv_{\rm min} \, \frac{\sigma_n}{m_\chi \mu_{n\chi}^2} \cdot \frac{2 C_{\rm T} \mu_N^2}{m_N} \, F^2(v_{\rm min}) \cdot \rho_\chi \, v_{\rm min} \, g(v_{\rm min}, t)$$

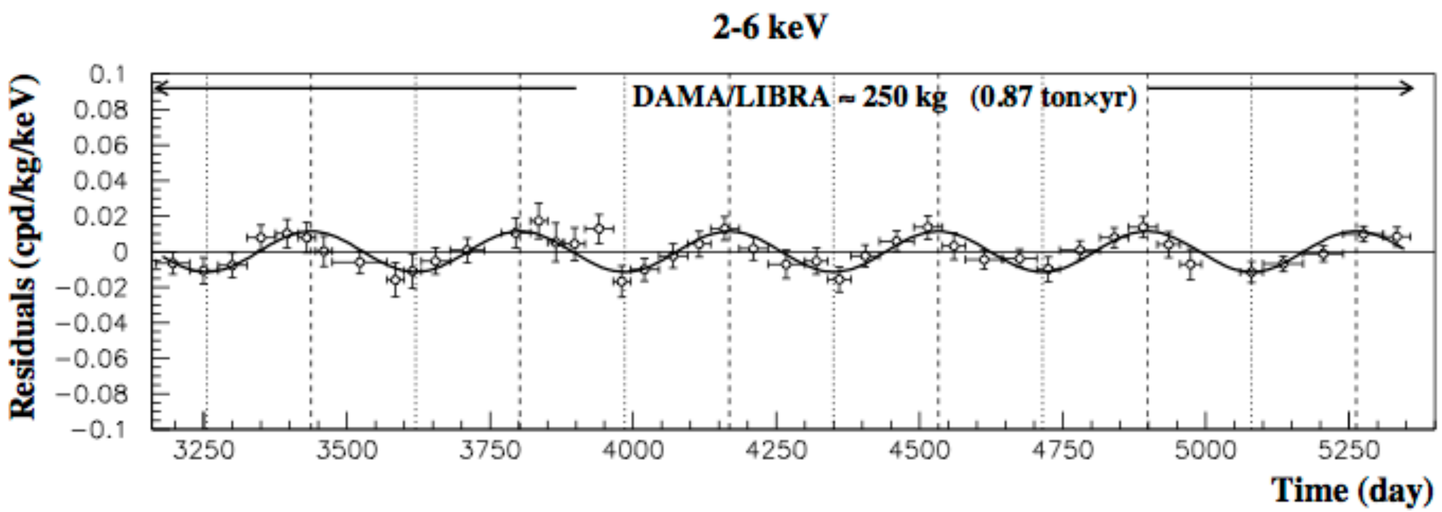
$$\equiv \tilde{C}_\chi \int_{v^{\rm low}}^{v^{\rm high}} dv \, \rho_\chi \, v \, g(v,t) \qquad \text{(Recall } v_{\rm min} = \sqrt{\frac{m_N E_{\rm R}}{2\mu_N}} \text{)}$$

- This allows us to
  1. Map the experimental signal from one experiment to another without making any assumptions on astrophysical parameters
  2. Infer the form of $g(v_{\rm min})$ from the data – learn about halo properties
  3. Set halo-independent exclusion bounds on positive signals

Mapping CoGeNT onto DAMA

'DAMA and CoGeNT without astrophysical uncertainties' CM:1107.0741

- Rate: $R = \tilde{C}_\chi \int_{v_{\rm low}}^{v_{\rm high}} dv\, \rho_\chi\, v\, g(v,t)$
- DAMA measure a modulation in an energy range which we can map to $v_{\rm min}$ space: $[E^D_{\rm low}, E^D_{\rm high}] \to [v_{\rm low}, v_{\rm high}]$



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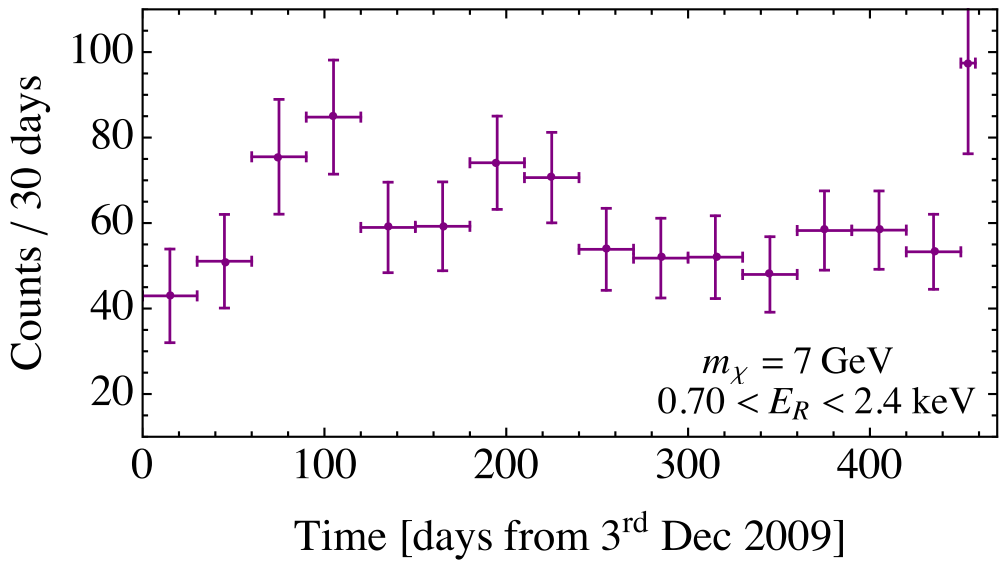
- CoGeNT probe the same $v_{\rm min}$ space in the energy range:

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



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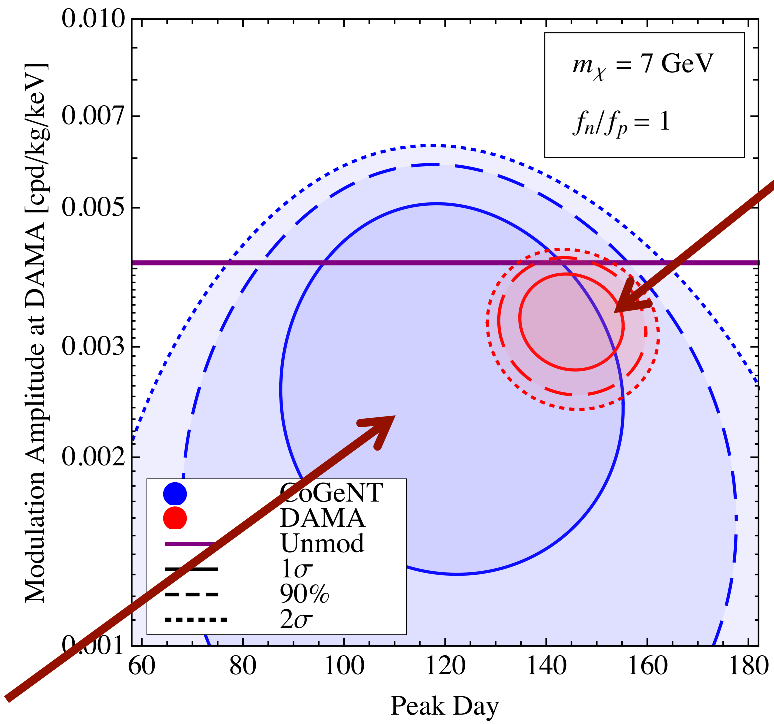
- By construction, all astrophysical parameters will cancel from the ratio:

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

- 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



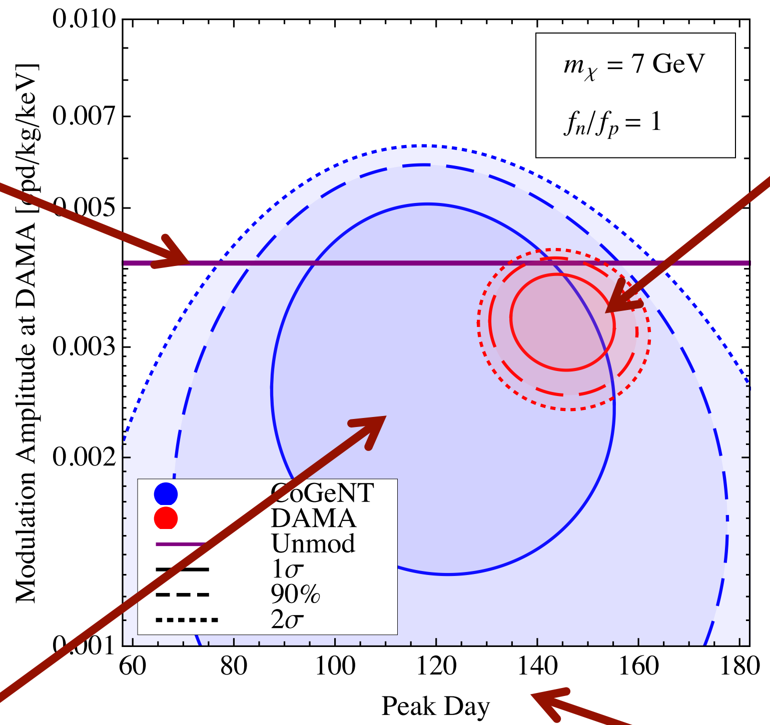
Fit to modulation amplitude and peak day in 2-6 keV DAMA data

Expected modulation amplitude and peak day at DAMA, determined from a fit to the CoGeNT data in the energy range: $[E^C_{\text{low}}, E^C_{\text{high}}] = \frac{\mu^2_C m^D_N}{\mu^2_D m^C_N}[E^D_{\text{low}}, E^D_{\text{high}}]$

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



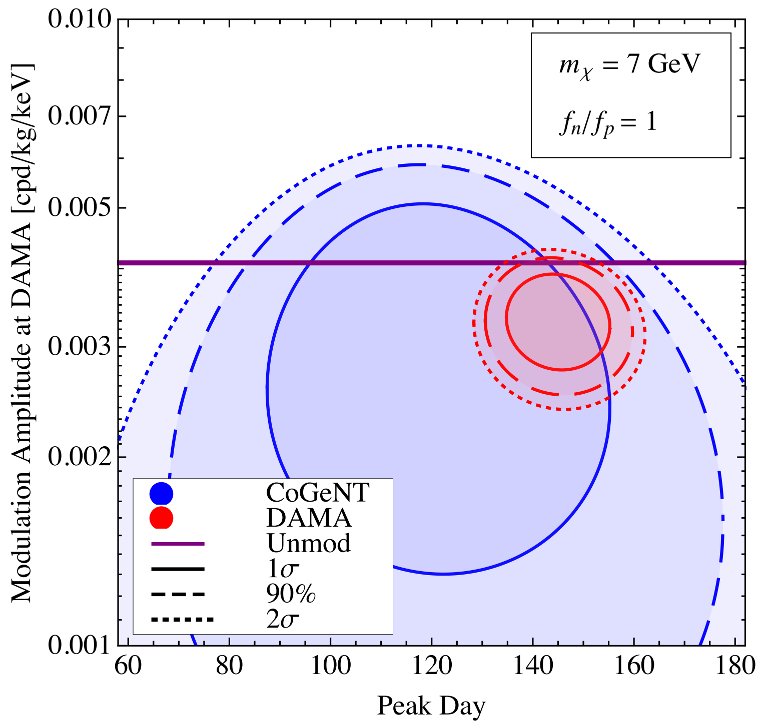
Fit to modulation amplitude and peak day in 2-6 keV DAMA data

CoGeNT peak day ~35 days earlier than DAMA but consistent at 90%

SHM predicts modulation peaks on day 152

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



What did we learn?

- Reasonable agreement between the signals from both experiments
- The SHM will not give a good fit to both experiments – need to boost the modulation fraction and possibly move the peak day

It is clear that the CoGeNT region will shrink dramatically with more data

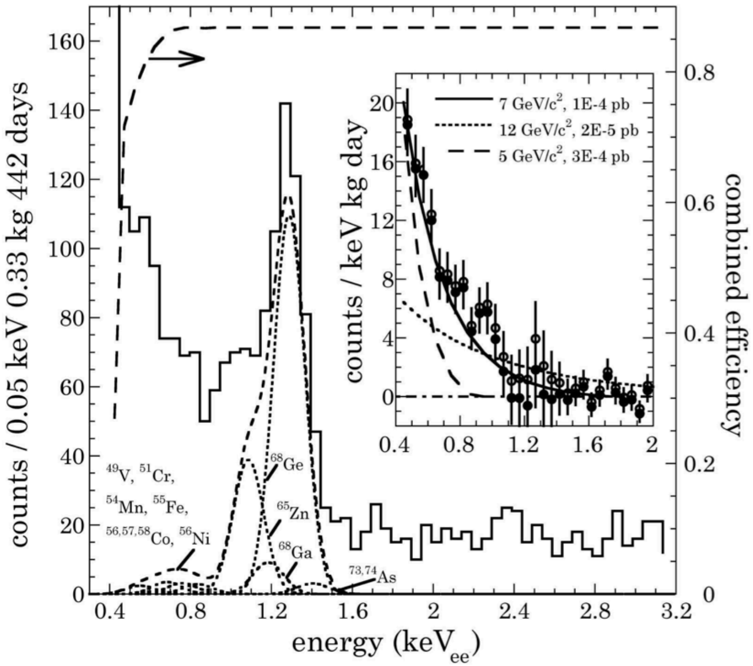
Inferring $\tilde{g}(v_{\min})$

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

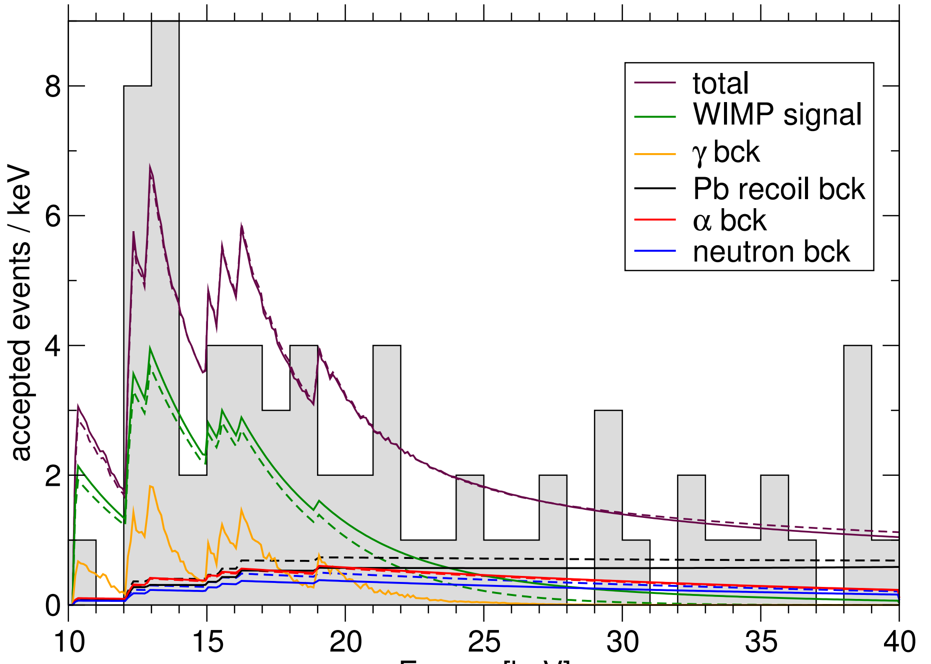
- If we measure $dR/dE_{\rm R}$, we can infer $\tilde{g}(v_{\min}) \equiv \dfrac{\rho_\chi \sigma_n}{m_\chi} \cdot g(v_{\min})$

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

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



Aalseth et al:1106.0650



Angloher et al :1109.0702

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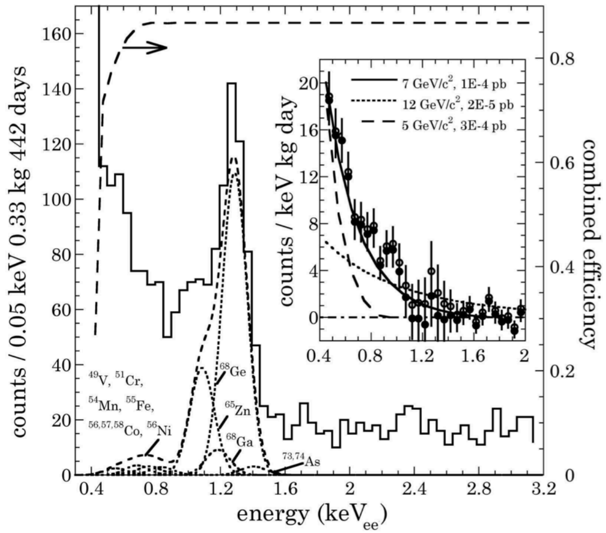
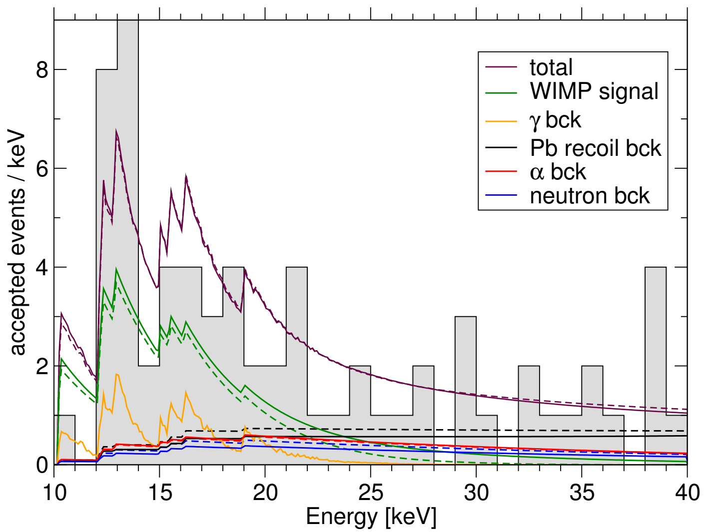
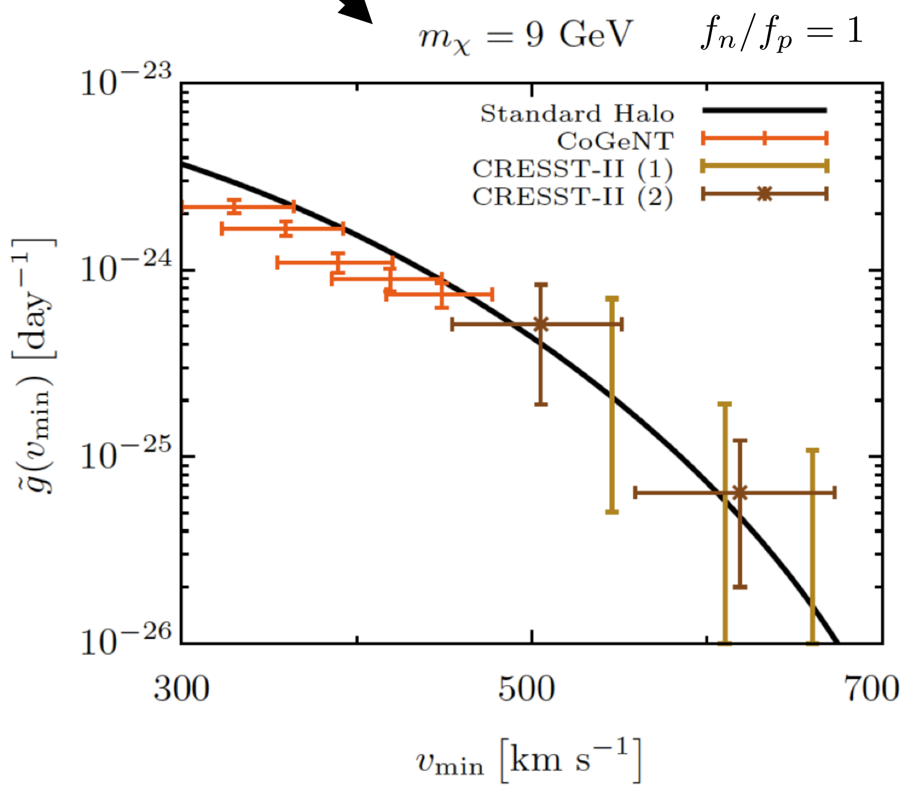




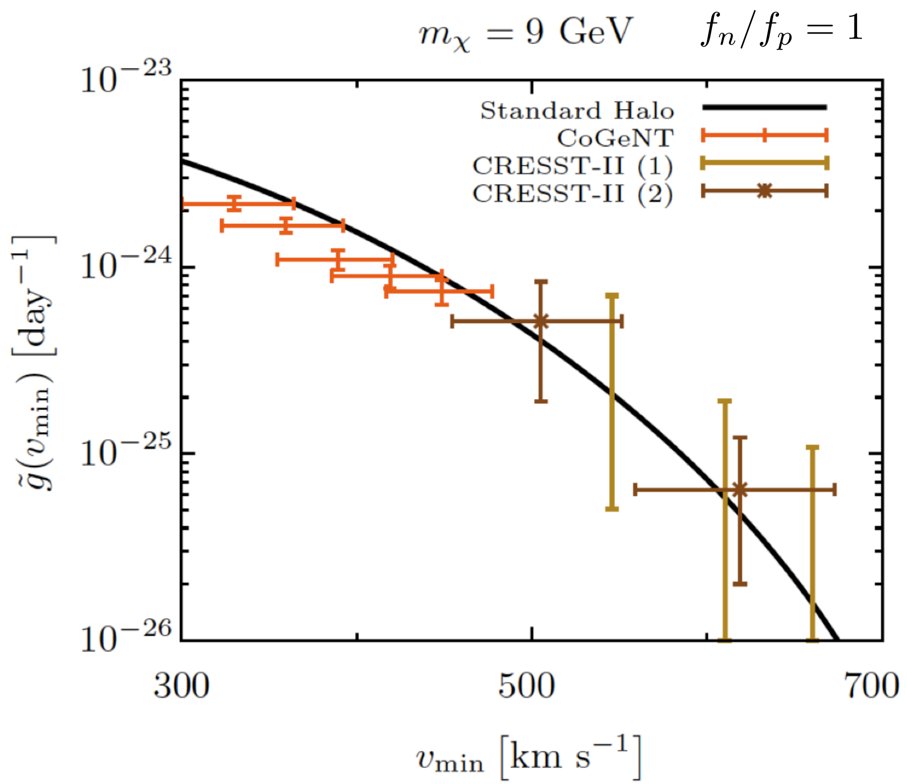
$$\tilde{g}(v_{\min}) = \frac{2\mu_{n\chi}^2}{C_T(A,Z)F^2(E_R)} \left.\frac{dR}{dE_R}\right|_{\text{measured}}$$



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

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

- The SHM provides a reasonable fit to the data



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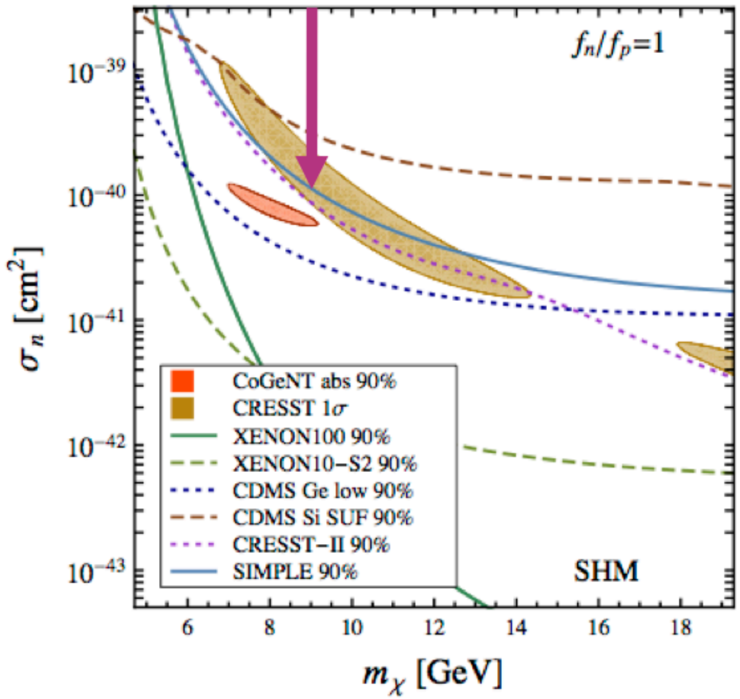

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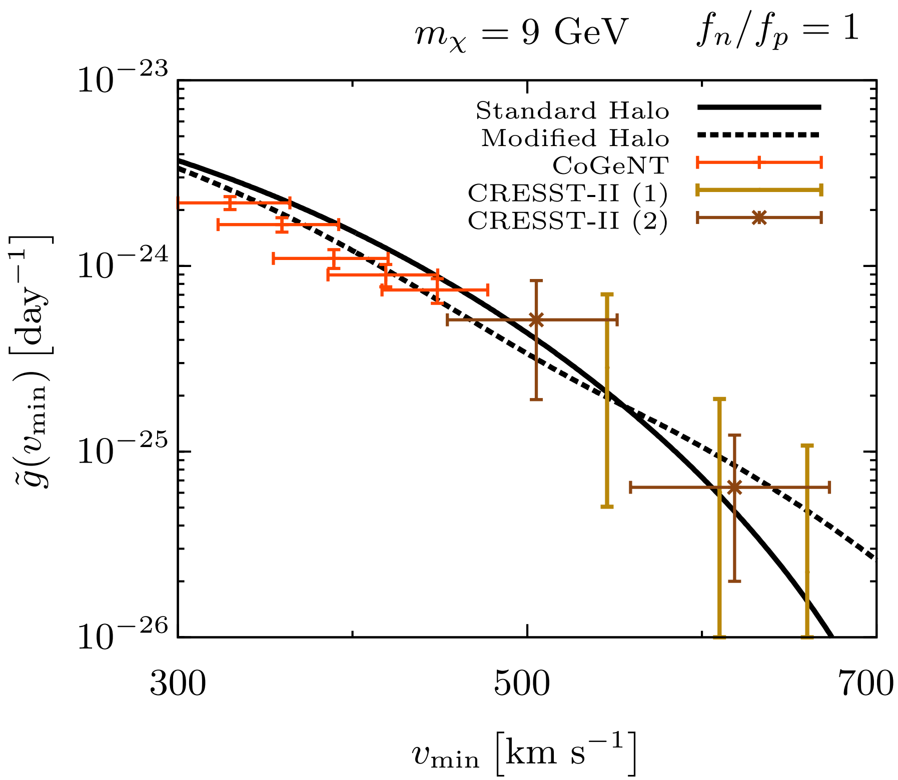
- We can see what changes are required to get better agreement: introduce a modified halo model
  - Warning: this is purely ad-hoc at this stage



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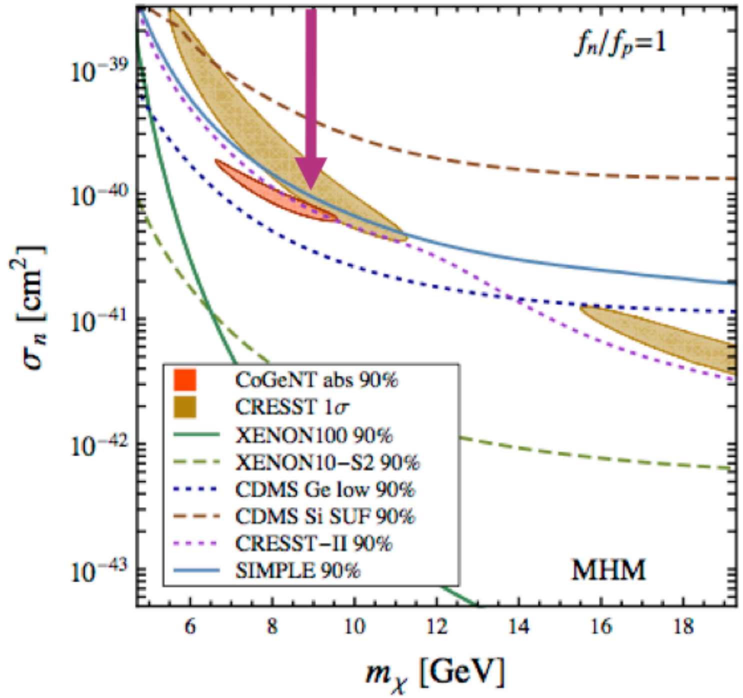
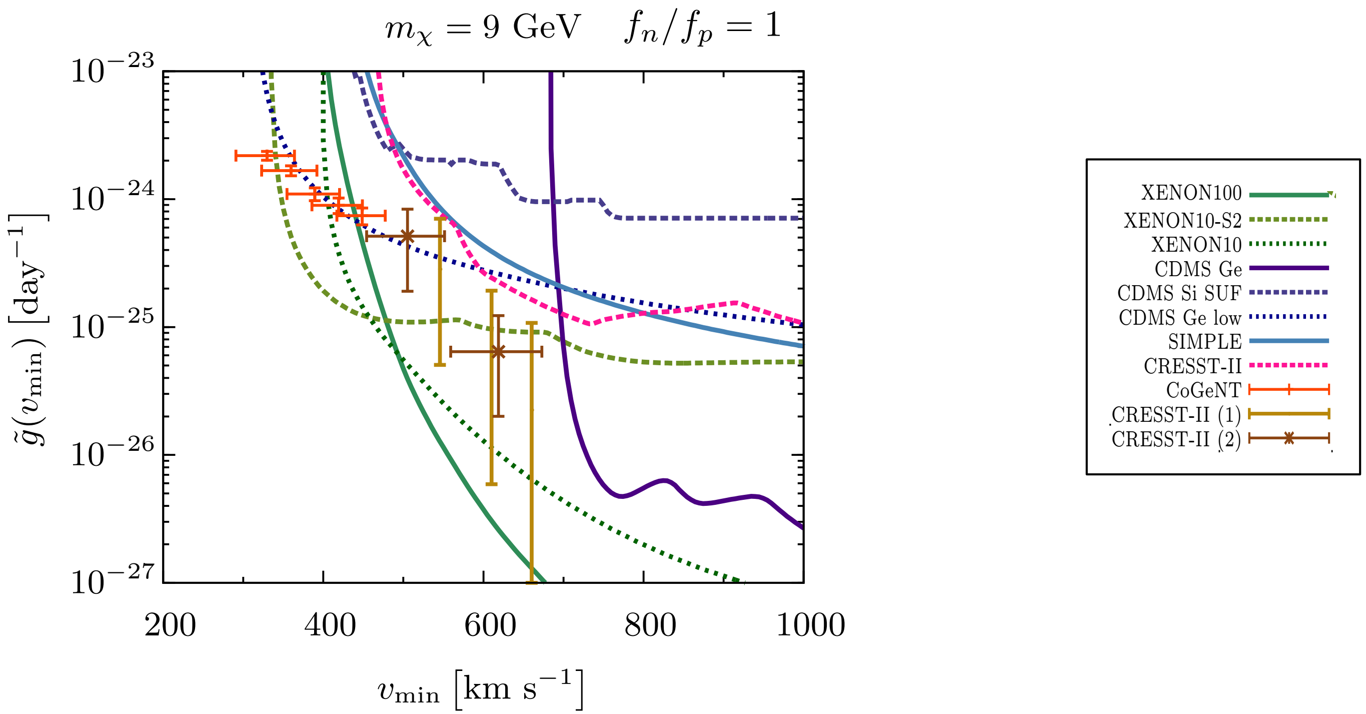


Constraining $\tilde{g}(v_{\min})$

- Set constraints from experimental null results
  - Lines indicate the largest value of $\tilde{g}(v_{\min})$ compatible with the absence of a signal



- No halo model can sufficiently reduce the constraints!

Conclusions

- Discussed the usual method of analyzing direct detection experiments and its limitations

- Introduced complementary approaches for analyzing experimental data that
  - factorize out astrophysical parameters
  - 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 allows us to build a deeper understanding of experimental results and what they tell us about the properties of dark matter