

# Can we directly measure the local distribution of Dark Matter from Earth?

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Bradley J Kavanagh  
GRAPPA, University of Amsterdam

17th October 2018  
PRISMA Colloquium, Mainz

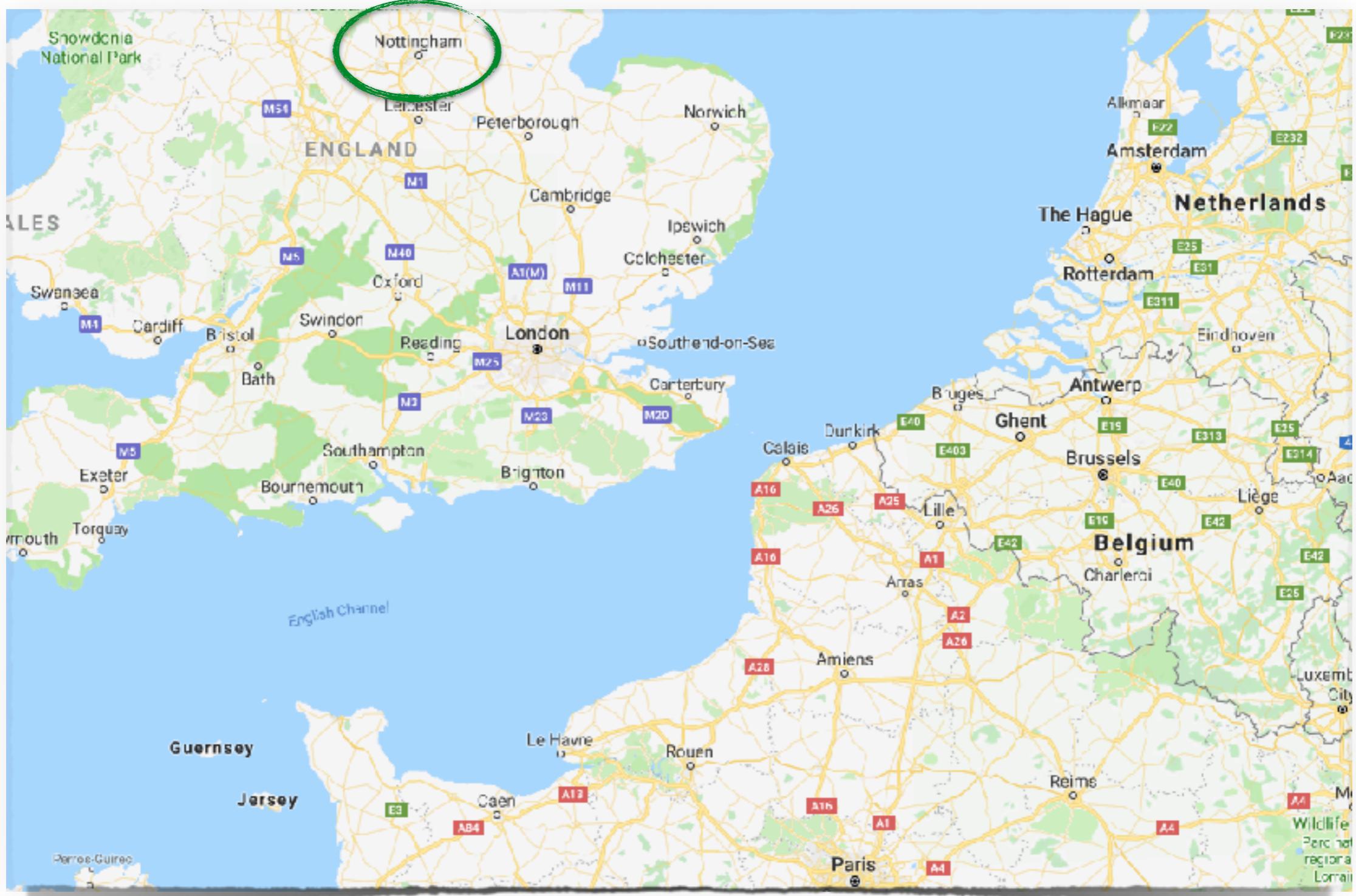


# **Undergraduate (2007-2011): University of Cambridge, UK**



**Studied:** Everything from organic chemistry to crystallography

## PhD (2011-2014): University of Nottingham, UK



### Thesis Title:

“Confronting astrophysical uncertainties in the  
direct detection of dark matter”  
(2014, Supervised by Anne M. Green)

# Postdoc #1 (2014-2017): IPhT & LPTHE, Paris, France



**Spent time worrying about:**

More ‘particle’ aspects of Dark Matter -  
how does it interact with nuclei?  
(Supervised by Marco Cirelli)

## Postdoc #2 (2017-): GRAPPA, University of Amsterdam



**People keep asking me about:**

Dark Matter, primordial black holes, gravitational waves, neutrinos,...

(Supervised by Gianfranco Bertone)

# Open Science

Papers (and talks) are just propaganda...  
...research is notes, calculations, data, **code**.

The more we share, the easier life gets for everyone.  
Plenty of tools to facilitate sharing and collaboration:

Aiming in the last few years to share as much as possible. Not always successful. But every small step is a step in the right direction.



[bradkav.net](http://bradkav.net)

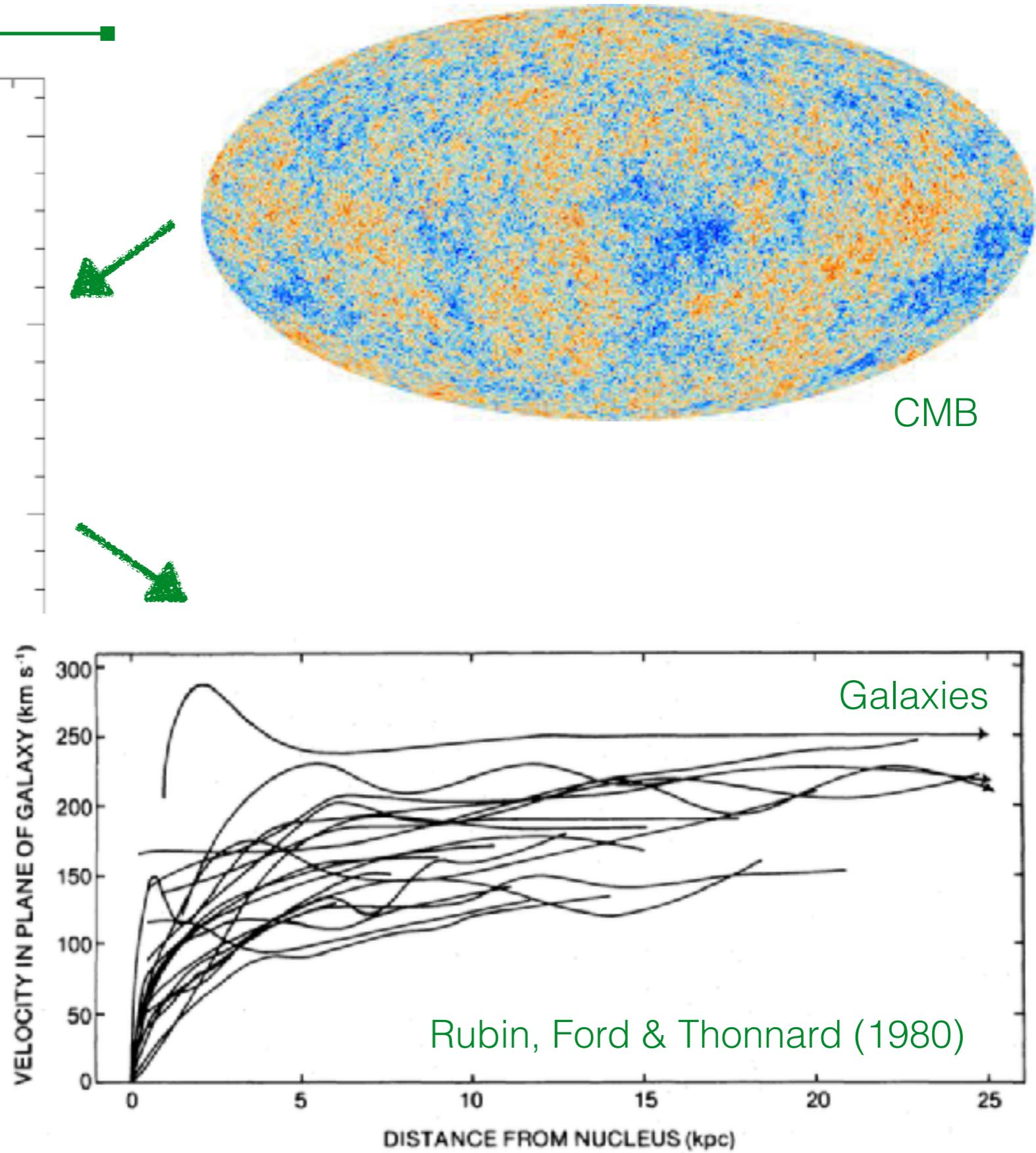
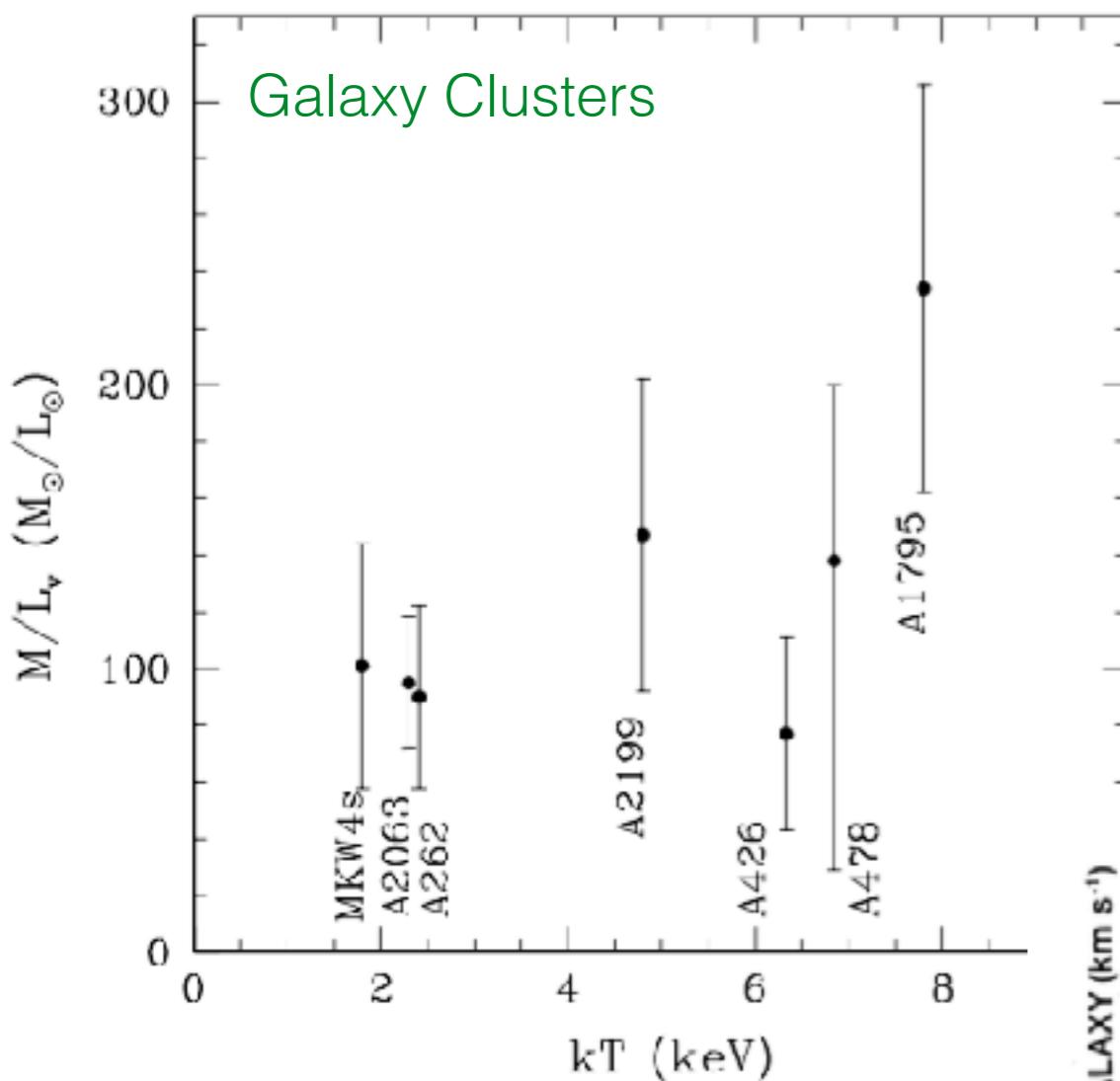


[github.com/bradkav](https://github.com/bradkav)



# Dark Matter on all scales

Planck [1502.01589]

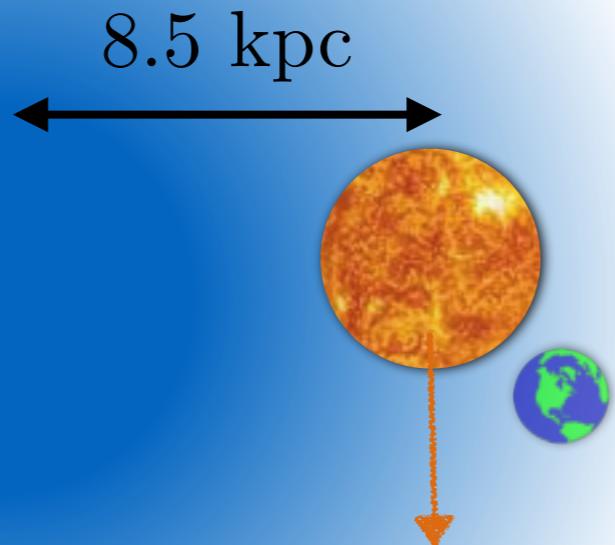


# Dark Matter near us

Global and local estimates  
of DM at Solar radius give:

$$\rho_\chi \sim 0.2 - 0.8 \text{ GeV cm}^{-3}$$

('a few per litre')



$$v_\odot \sim 230 \text{ km/s}$$

See e.g. Iocco et al. [1502.03821];  
Sivertsson et al. [1708.07836];  
and review by Read [1404.1938]

**NOT TO SCALE**

Try to detect the 'wind' of DM particles  
passing through the Solar System,  
using **Direct Detection** and **Solar Capture**.

## Solar system searches for DM: Direct detection and Solar Capture

Astrophysical uncertainties

Halo-independent approaches to setting limits

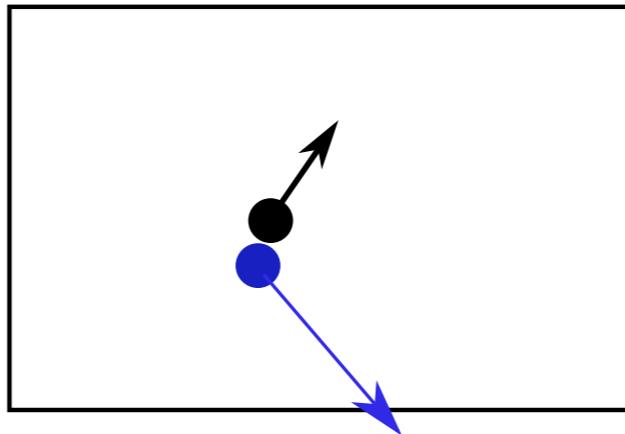
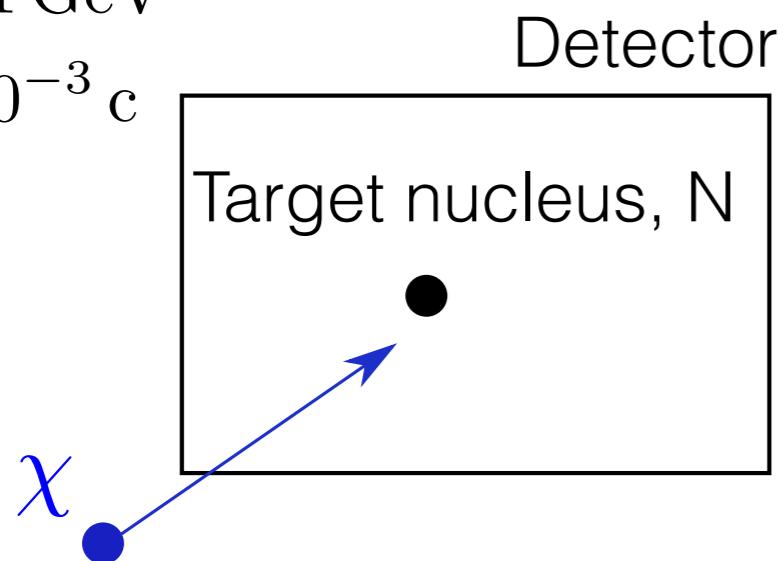
Measuring the DM properties and distribution  
with a future detection

*[Bonus: Can we also measure the local DM density?]*

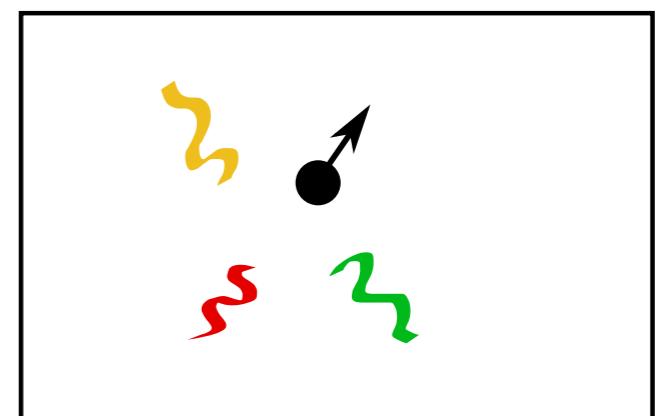
# Direct detection

$m_\chi \gtrsim 1 \text{ GeV}$

$v \sim 10^{-3} c$



Light (scintillation)



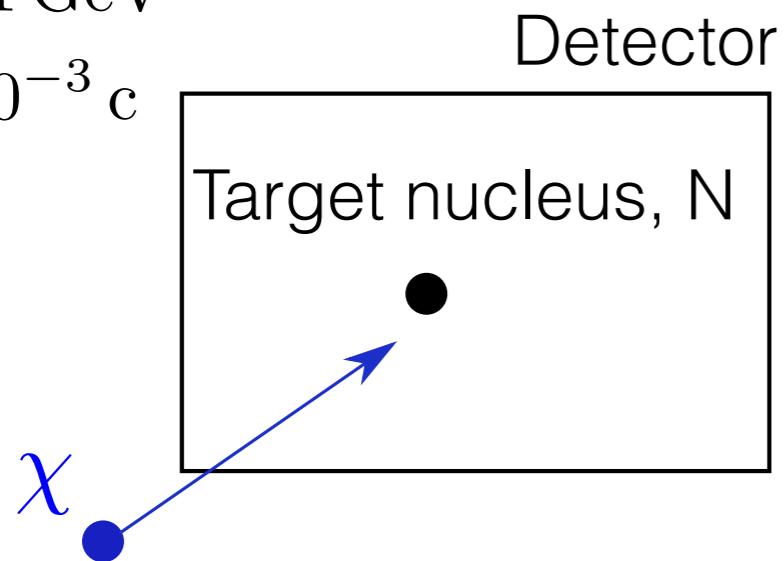
Heat (phonons)

Charge  
(ionisation)

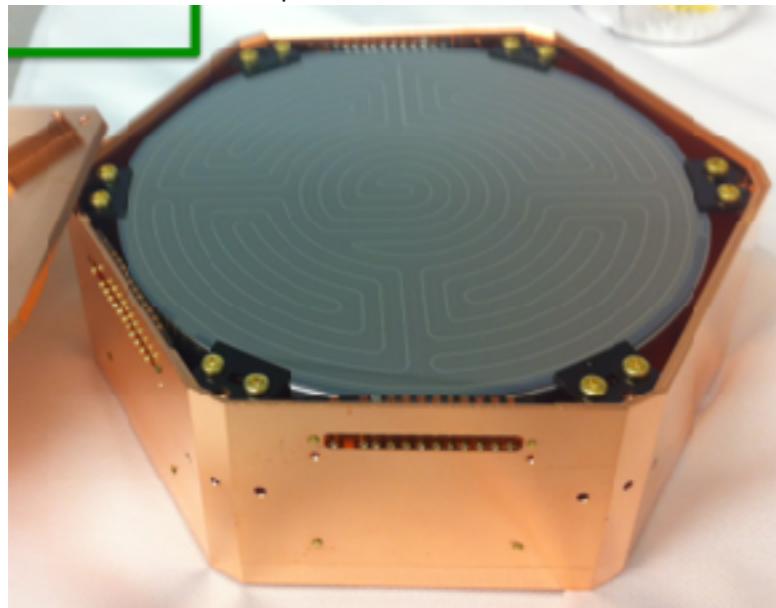
# Direct detection

$$m_\chi \gtrsim 1 \text{ GeV}$$

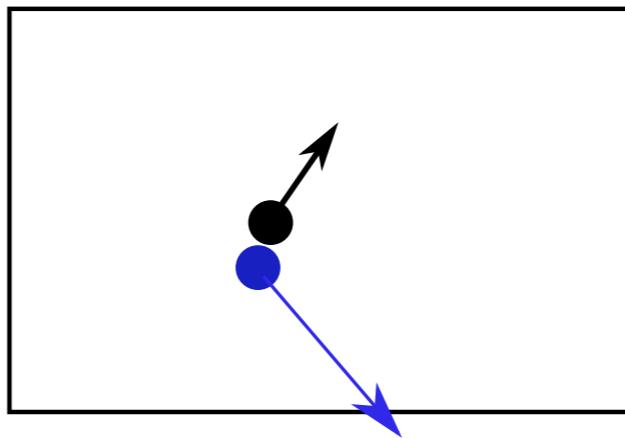
$$v \sim 10^{-3} c$$



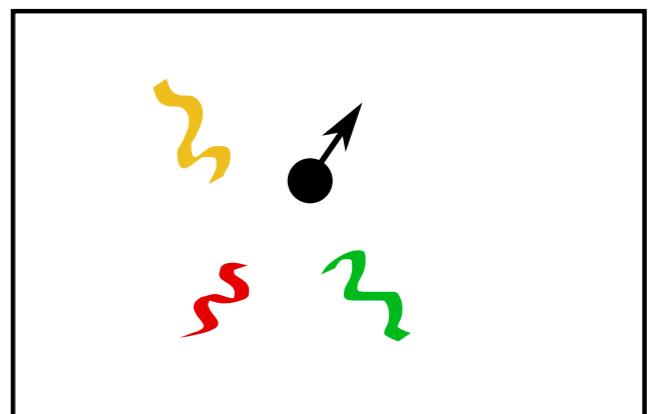
Credit: SuperCDMS Collaboration



SuperCDMS and many others



Light (scintillation)



Heat (phonons)

Charge  
(ionisation)

# Direct detection signal

$$\frac{dR}{dE_R} \sim \frac{\rho_\chi}{m_\chi} \sigma_p \mathcal{C}_A \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$

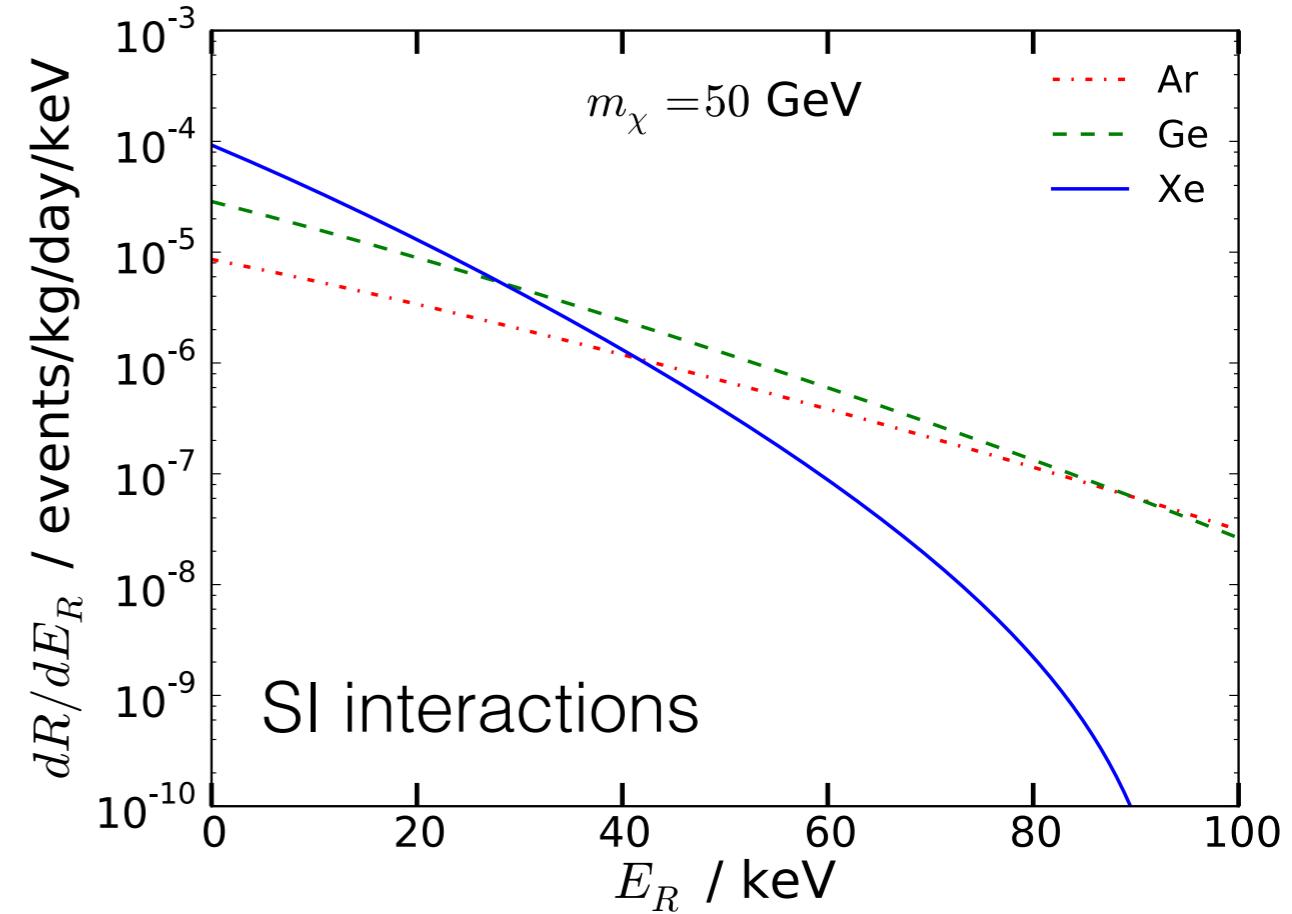
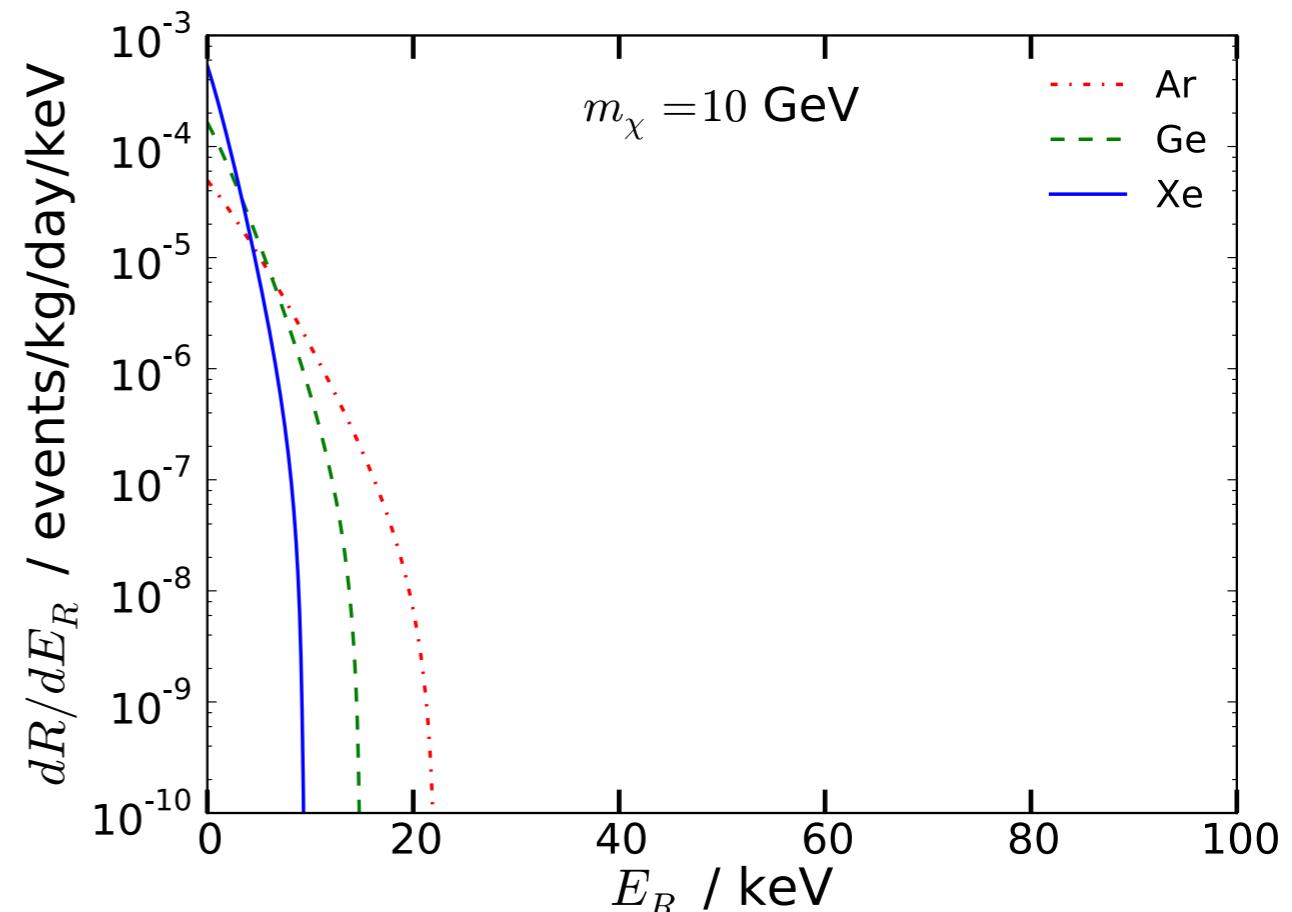
Include only DM particles with enough energy:

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

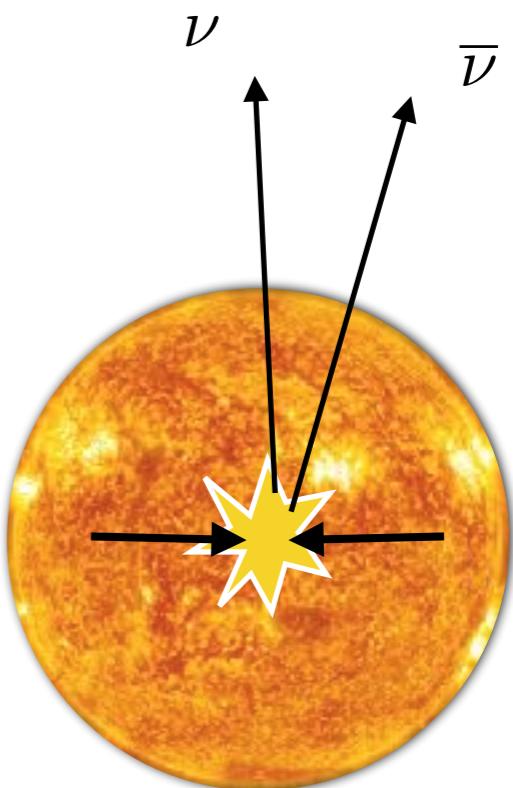
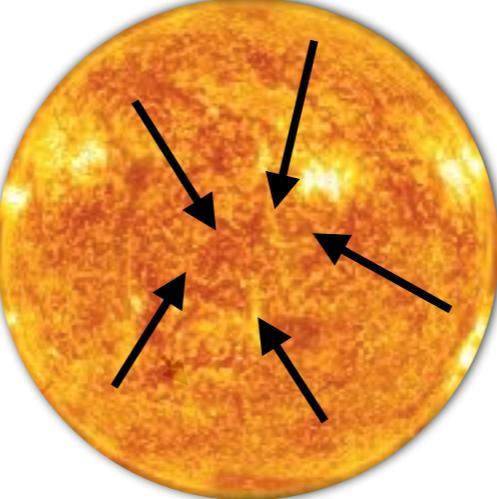
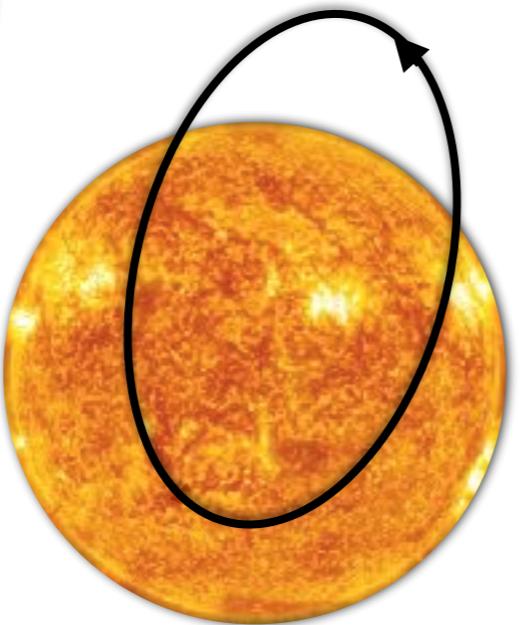
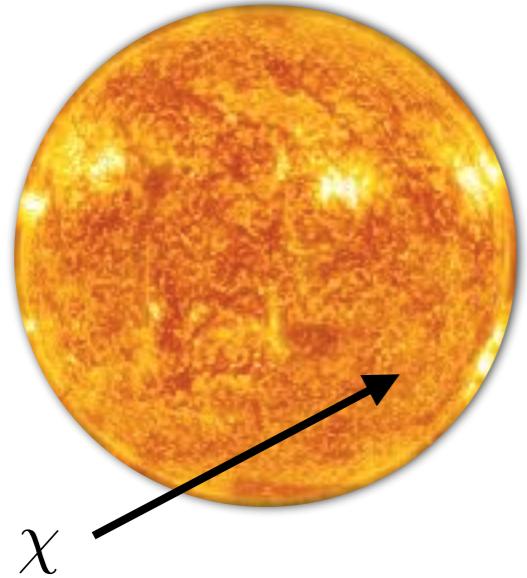
Spin-independent (SI) interactions:  $\mathcal{C}_A^{\text{SI}} \sim A^2$

Spin-dependent (SD) interactions:  $\mathcal{C}_A^{\text{SD}} \sim (J+1)/J$

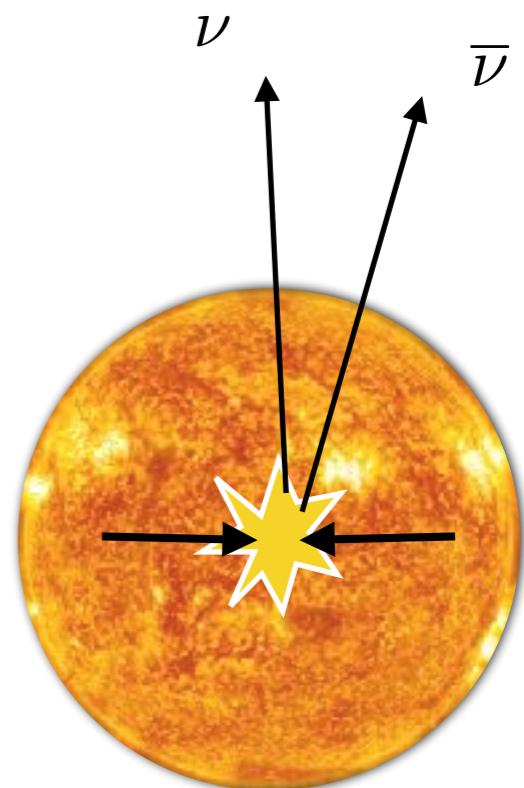
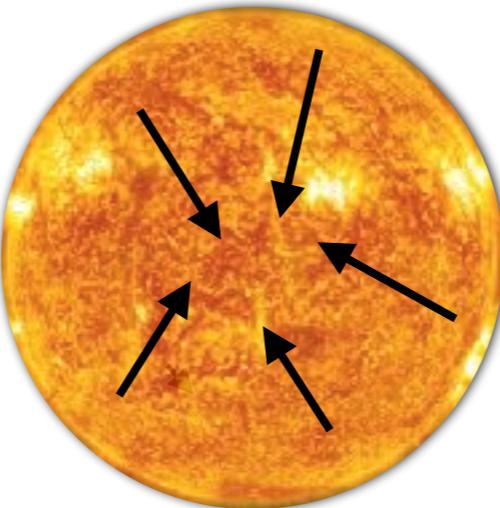
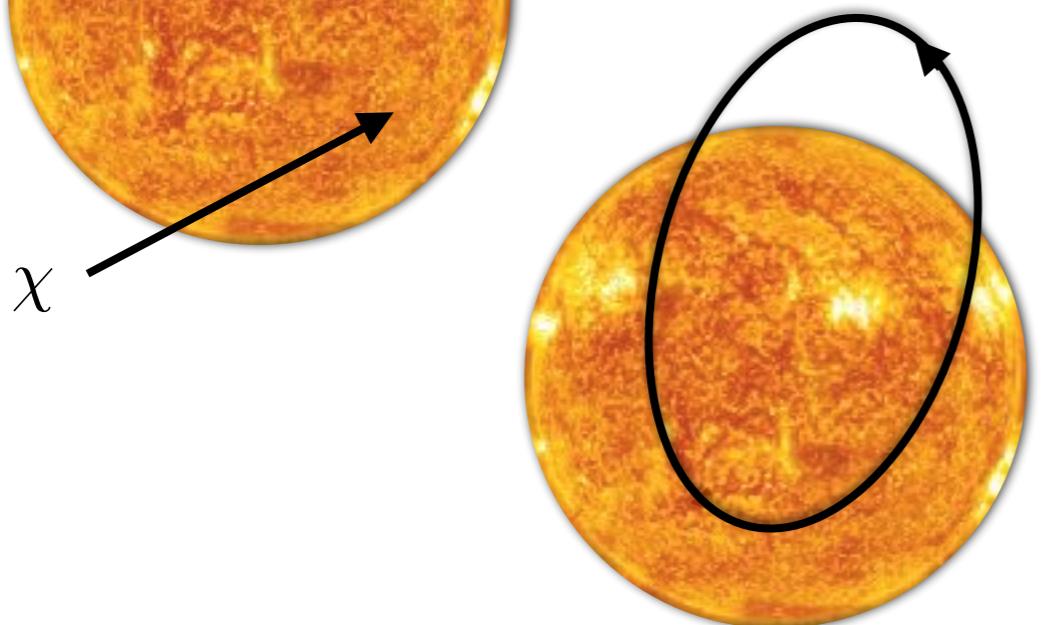
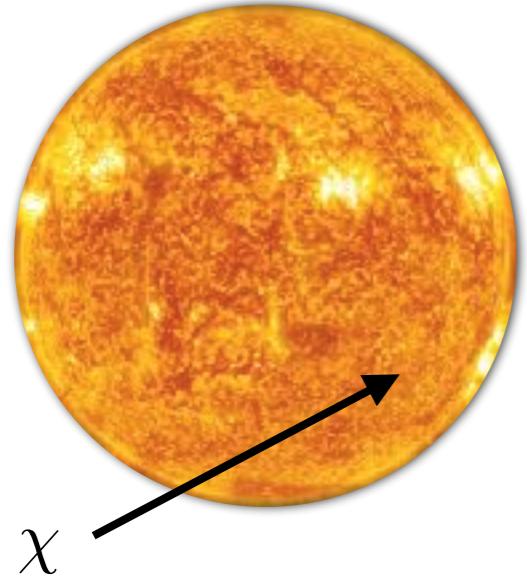
More complicated interactions are possible:  
see e.g. Fitzpatrick et al. [1203.3542];  
Edwards, **BJK**, Weniger [1805.04117]



# Solar Capture



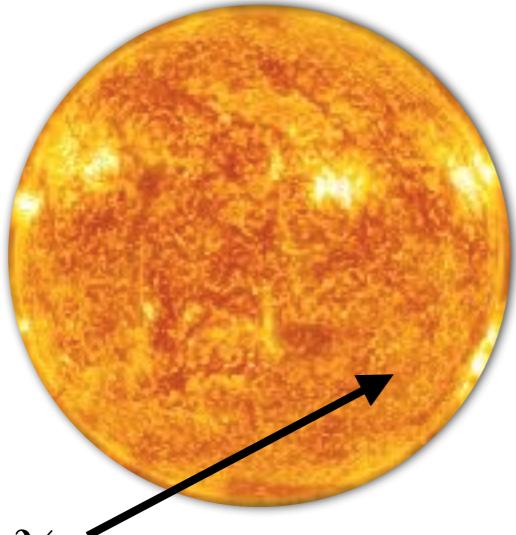
# Solar Capture



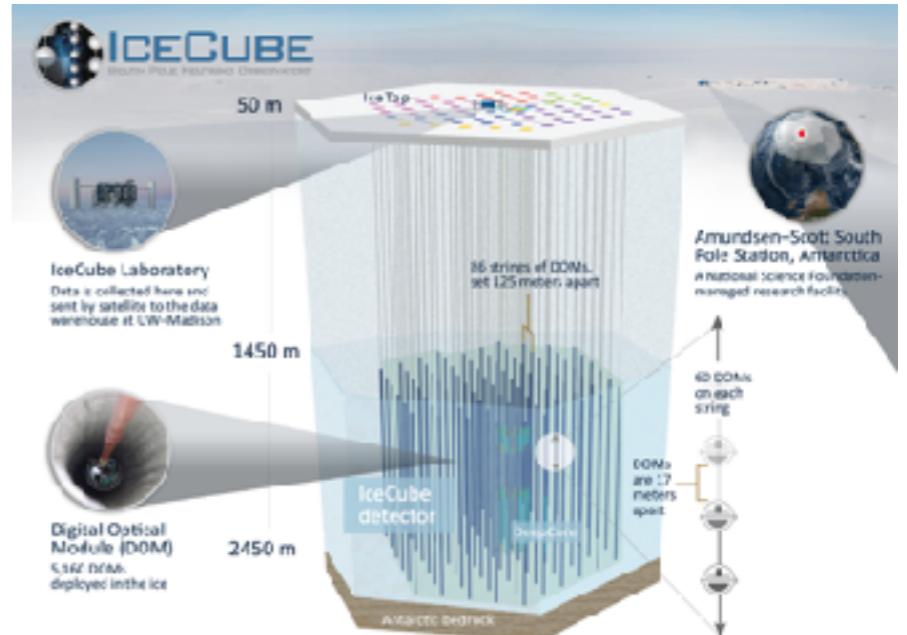
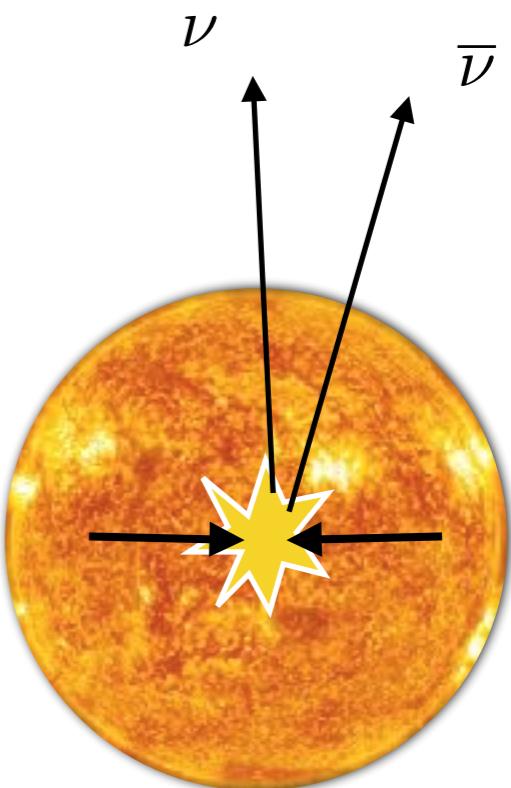
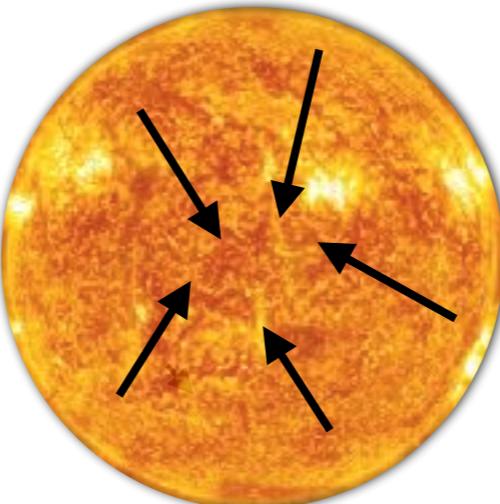
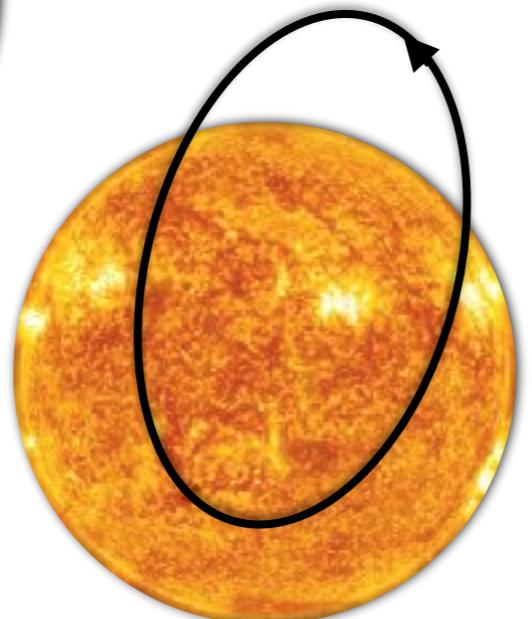
IceCube  
and many others

# Solar Capture

Credit: [icecube.wisc.edu](http://icecube.wisc.edu)



$\chi$



**IceCube**  
and many others

# Solar Capture Rate

$$C_i \sim \frac{\rho_\chi}{m_\chi} \int_0^{v_{\max}} dv \frac{f(v)}{v} \sigma_i n_i P_{\text{cap}}^i(v) dv$$

Sum over species in the Sun,  $i$ .

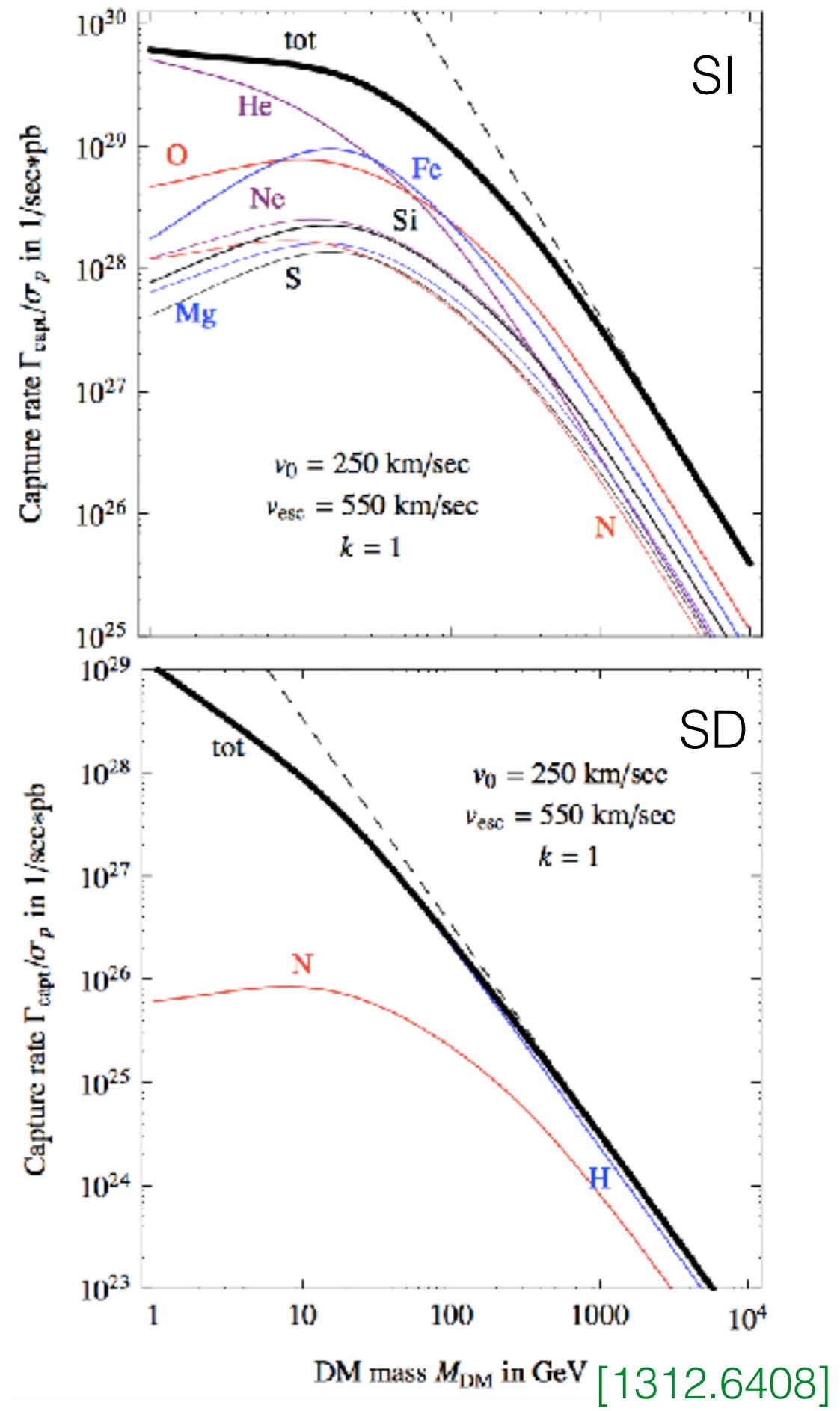
Only include DM particles moving slowly enough to be captured:

$$v_{\max} = \frac{\sqrt{4m_\chi m_{N_i}}}{m_\chi - m_{N_i}} v_{\text{esc}}$$

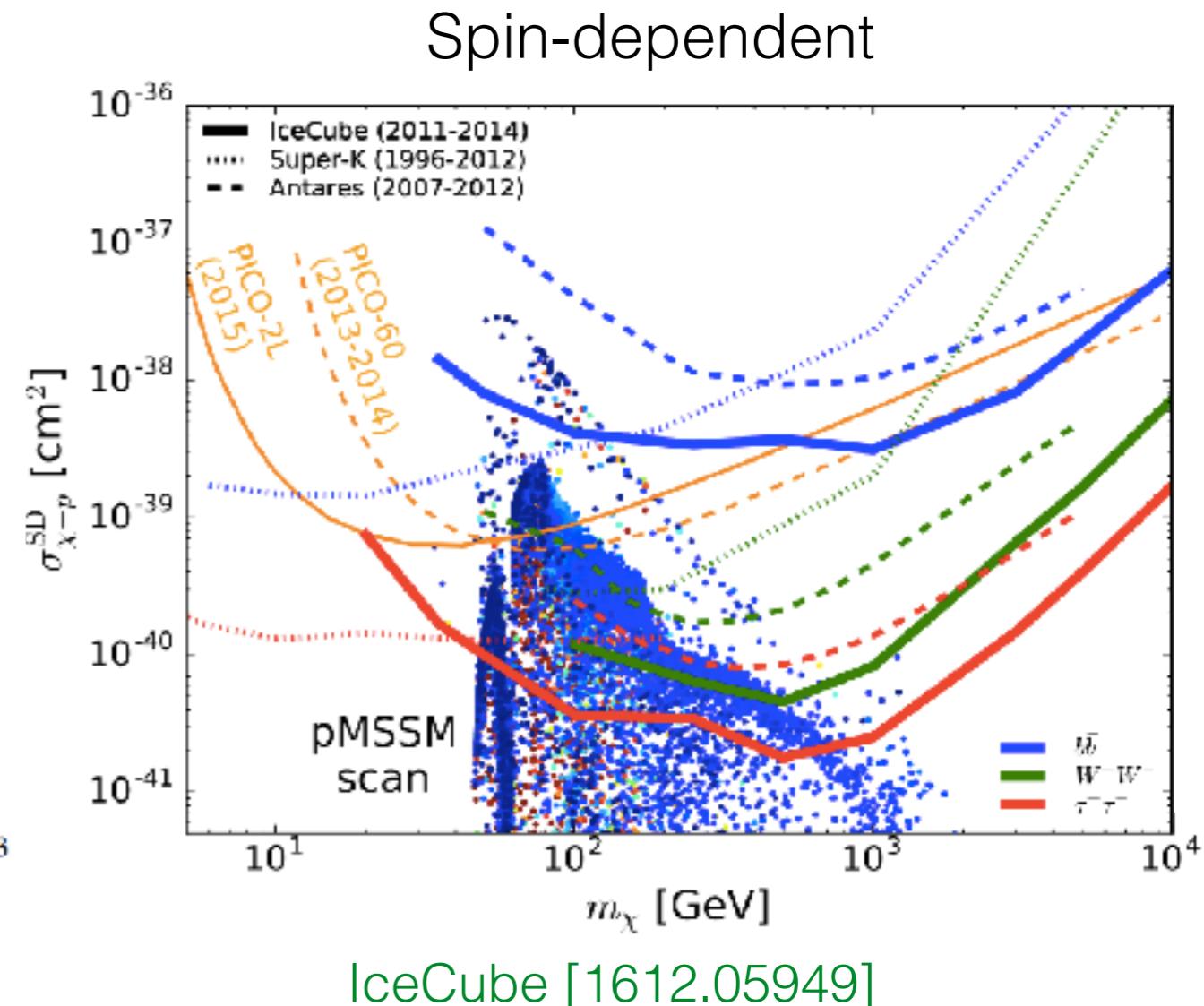
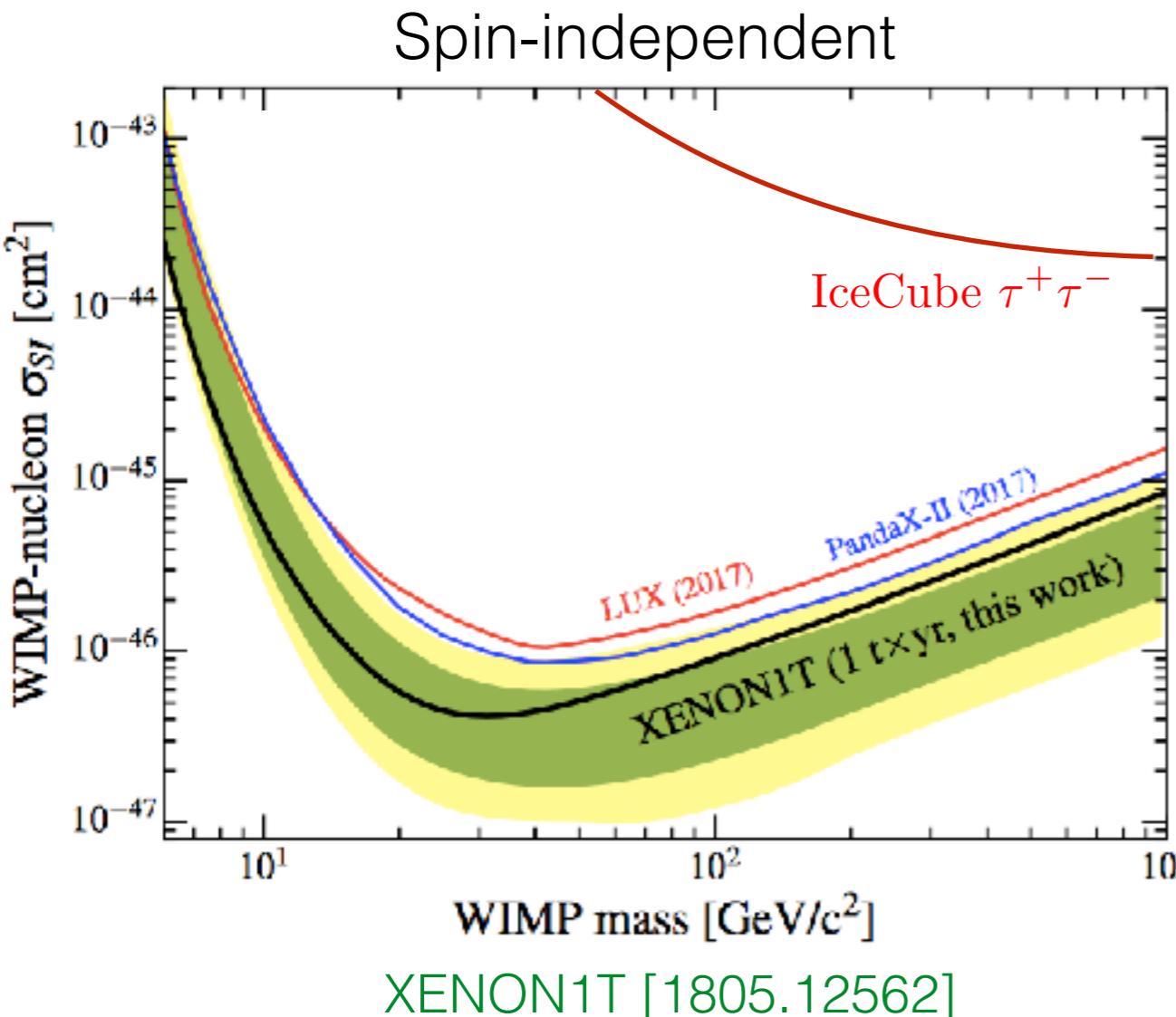
If capture and annihilation are in equilibrium, annihilation rate only depends on DM-nucleon scattering cross section.

Observed neutrino flux depends on DM annihilation channel...

Gould (1991)



# Limits on Solar System DM



*But these rely on a particular assumption on the speed distribution,  $f(v)$  ...*

# Overview

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Solar system searches for DM:  
Direct detection and Solar Capture

## Astrophysical uncertainties

Halo-independent approaches to setting limits

Measuring the DM properties and distribution  
with a future detection

*[Bonus: Can we also measure the local DM density?]*

# Standard Halo Model

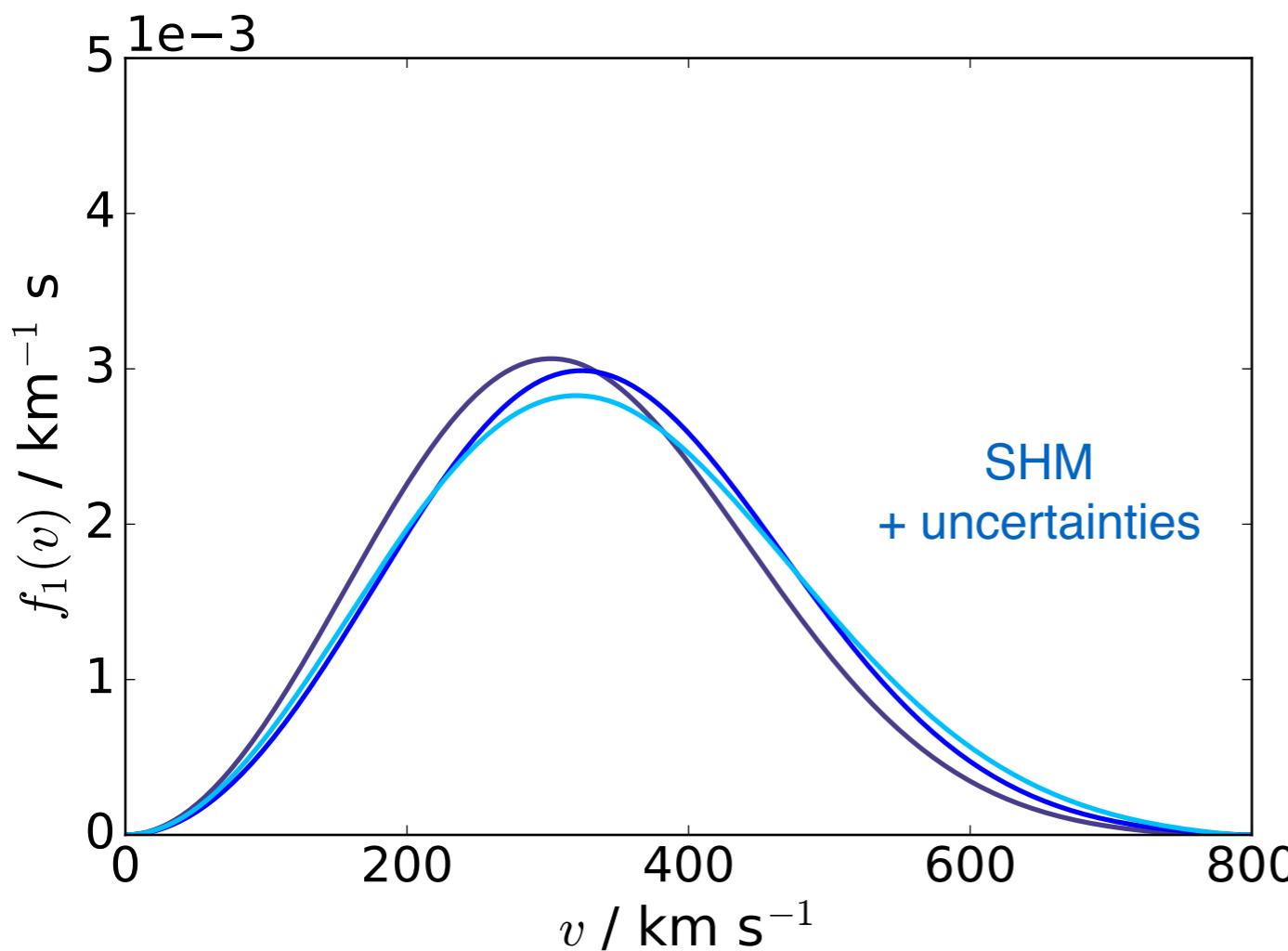
Standard Halo Model (**SHM**) is typically assumed: isotropic, spherically symmetric distribution of particles with  $\rho(r) \propto r^{-2}$ .

Leads to a Maxwell-Boltzmann (MB) distribution,

$$f_{\text{Lab}}(\mathbf{v}) = (2\pi\sigma_v^2)^{-3/2} \exp\left[-\frac{(\mathbf{v} - \mathbf{v}_e)^2}{2\sigma_v^2}\right] \Theta(|\mathbf{v} - \mathbf{v}_e| - v_{\text{esc}})$$

which is well matched in some hydro simulations.

[1601.04707, 1601.04725, 1601.05402]



SHM  
+ uncertainties

$\mathbf{v}_e$  - Earth's Velocity

$v_e \sim 220 - 250 \text{ km s}^{-1}$

$\sigma_v \sim 155 - 175 \text{ km s}^{-1}$

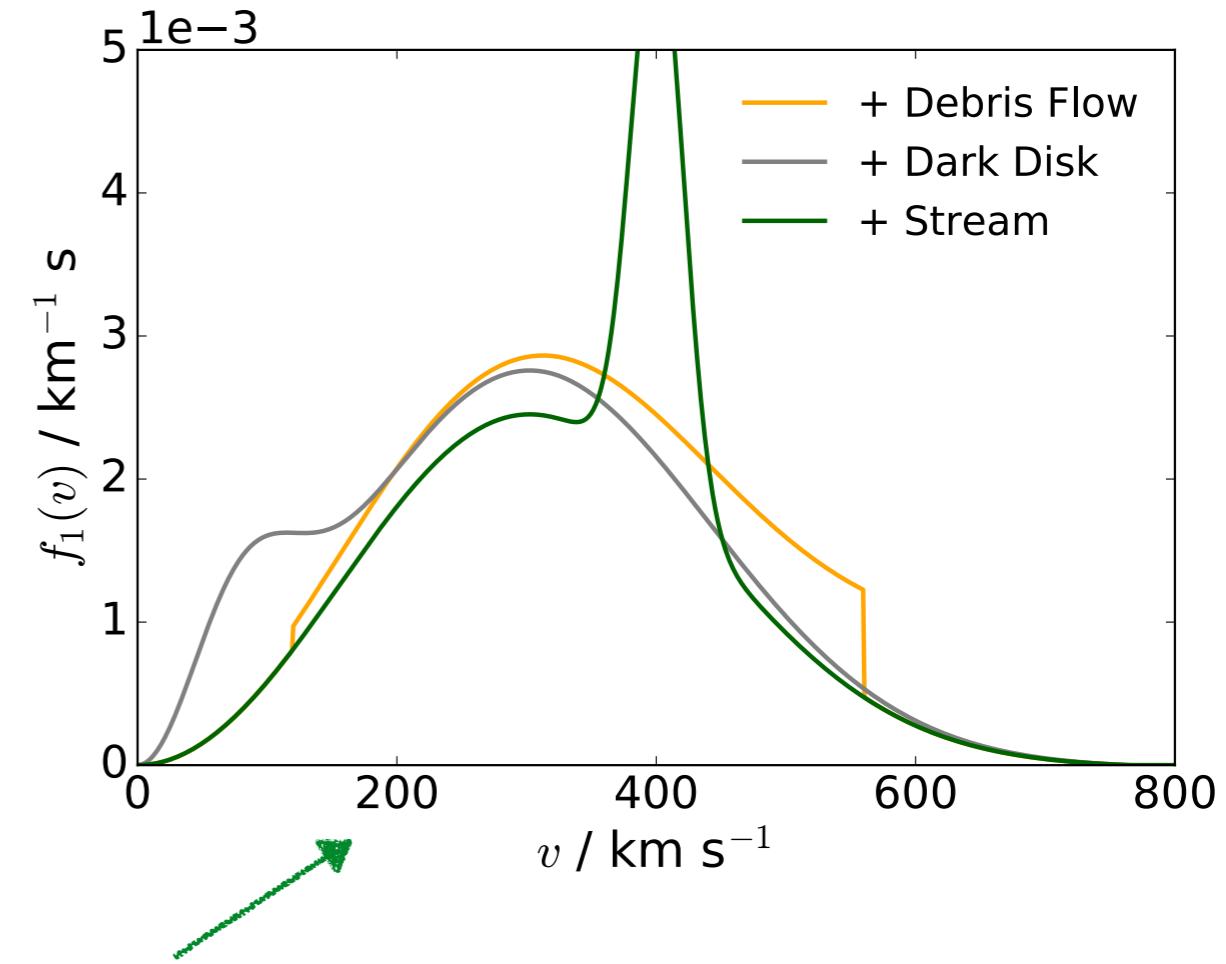
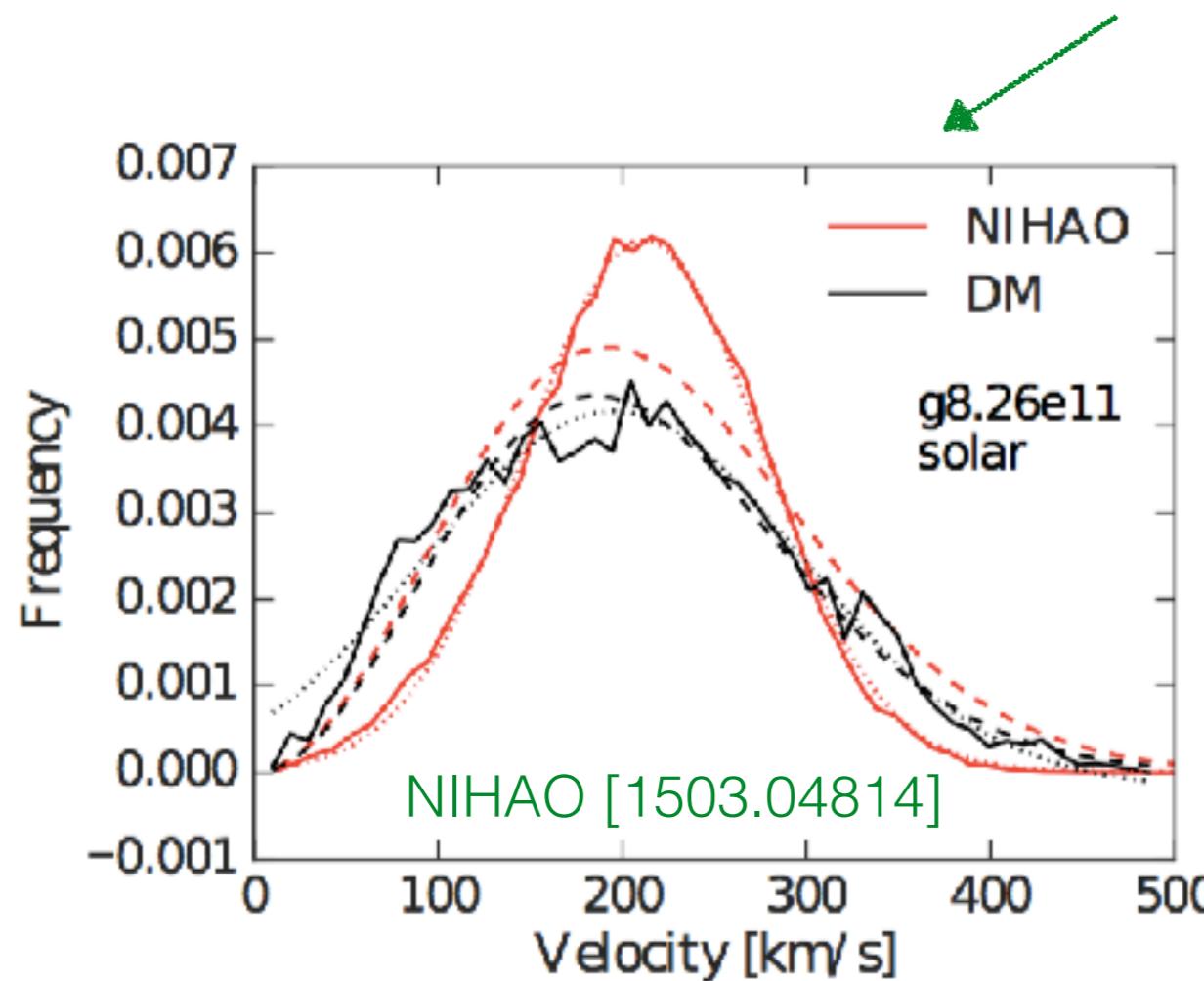
Feast et al. [astro-ph/9706293],  
Bovy et al. [1209.0759]

$v_{\text{esc}} = 533^{+54}_{-41} \text{ km s}^{-1}$

Piffl et al. (RAVE) [1309.4293]

# N-body simulations

The Standard Halo Model (SHM) has some inherent uncertainties.  
But there could also be deviations from MB form:



Simulations suggest there could be also substructure:

Debris flows      Kuhlen et al. [1202.0007]

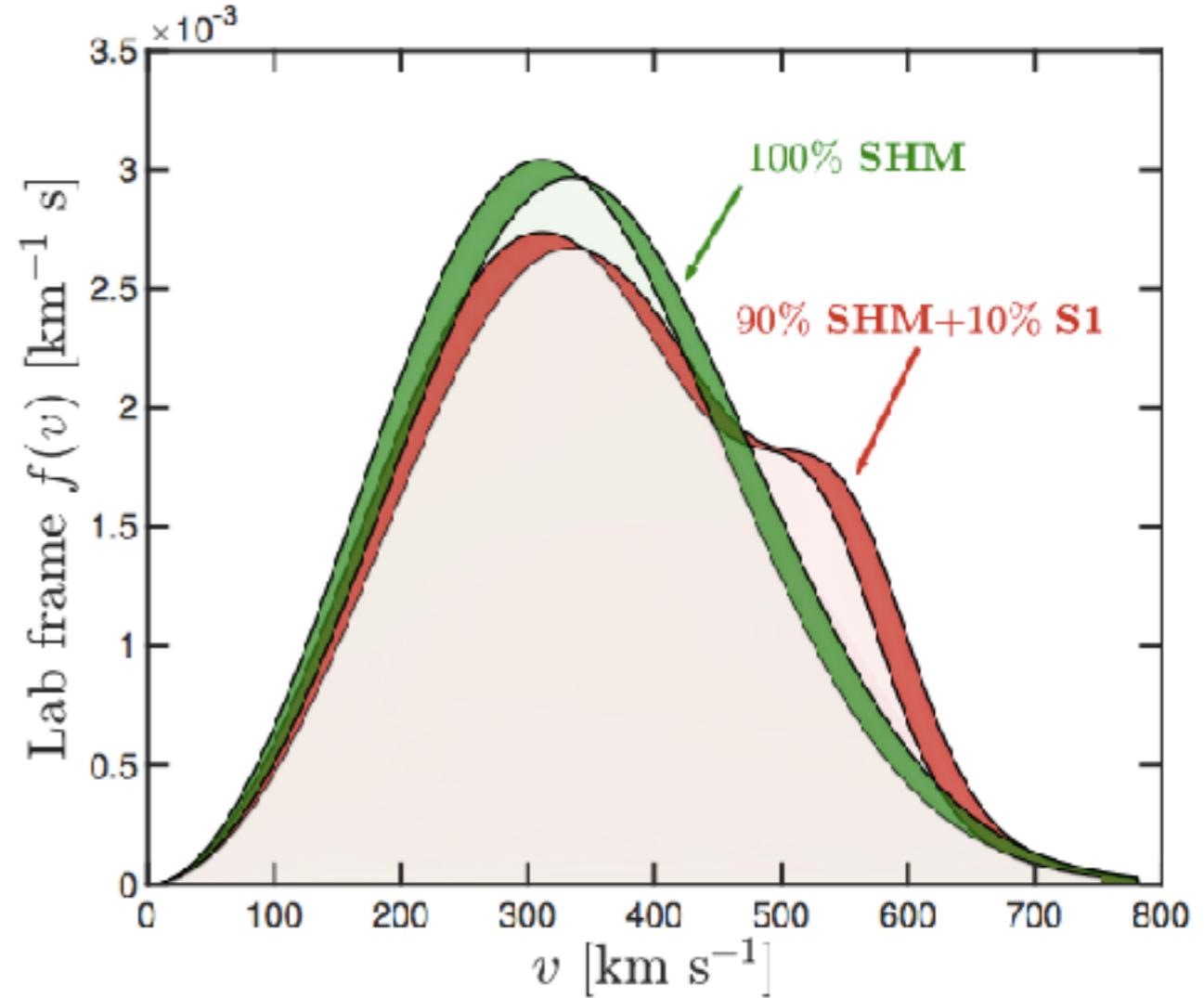
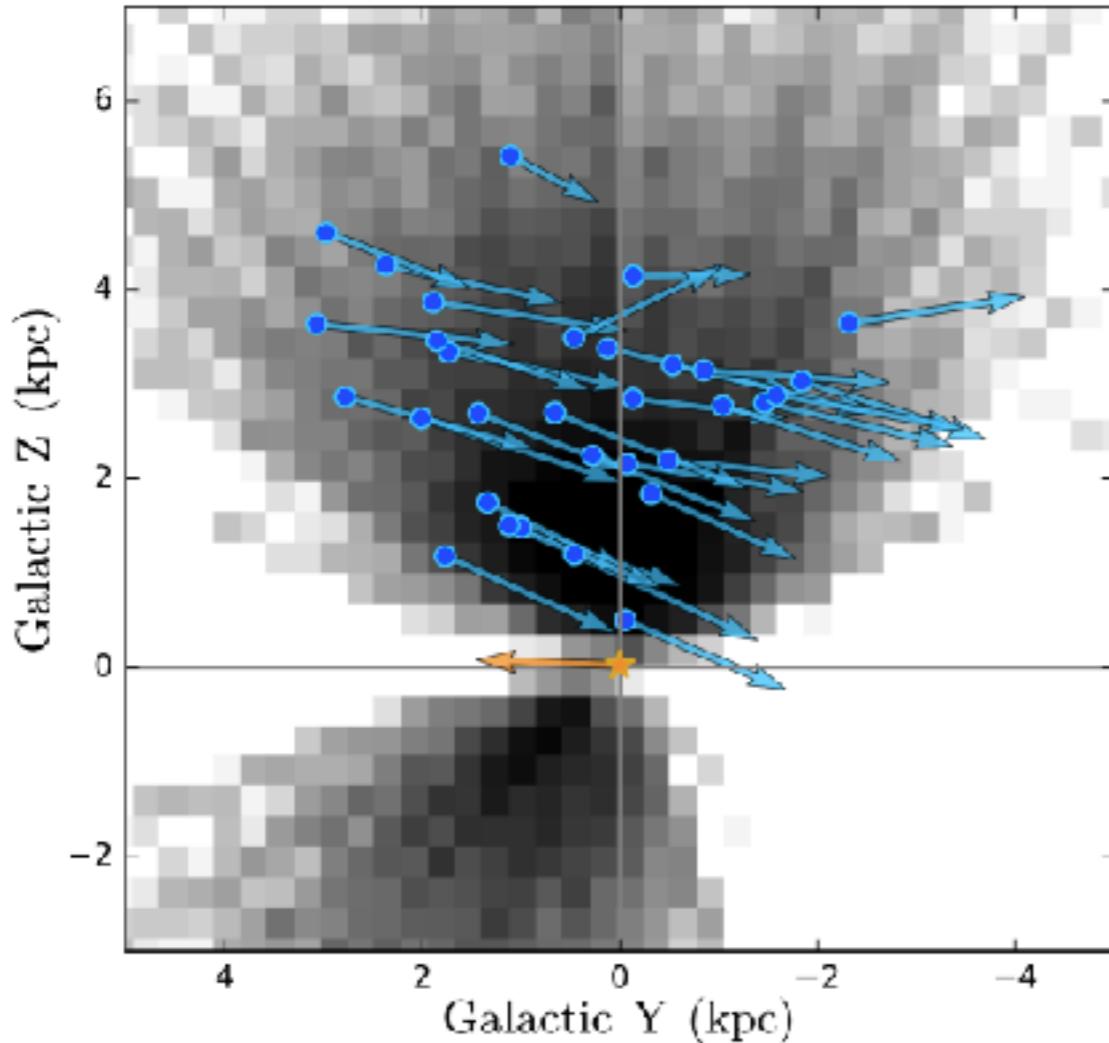
Dark disk      Pillepich et al. [1308.1703], Schaller et al. [1605.02770]

Tidal stream      Freese et al. [astro-ph/0309279, astro-ph/0310334]

# S1 Stream: DM Hurricane?

Recent GAIA data revealing new stellar streams:

[1712.04071]



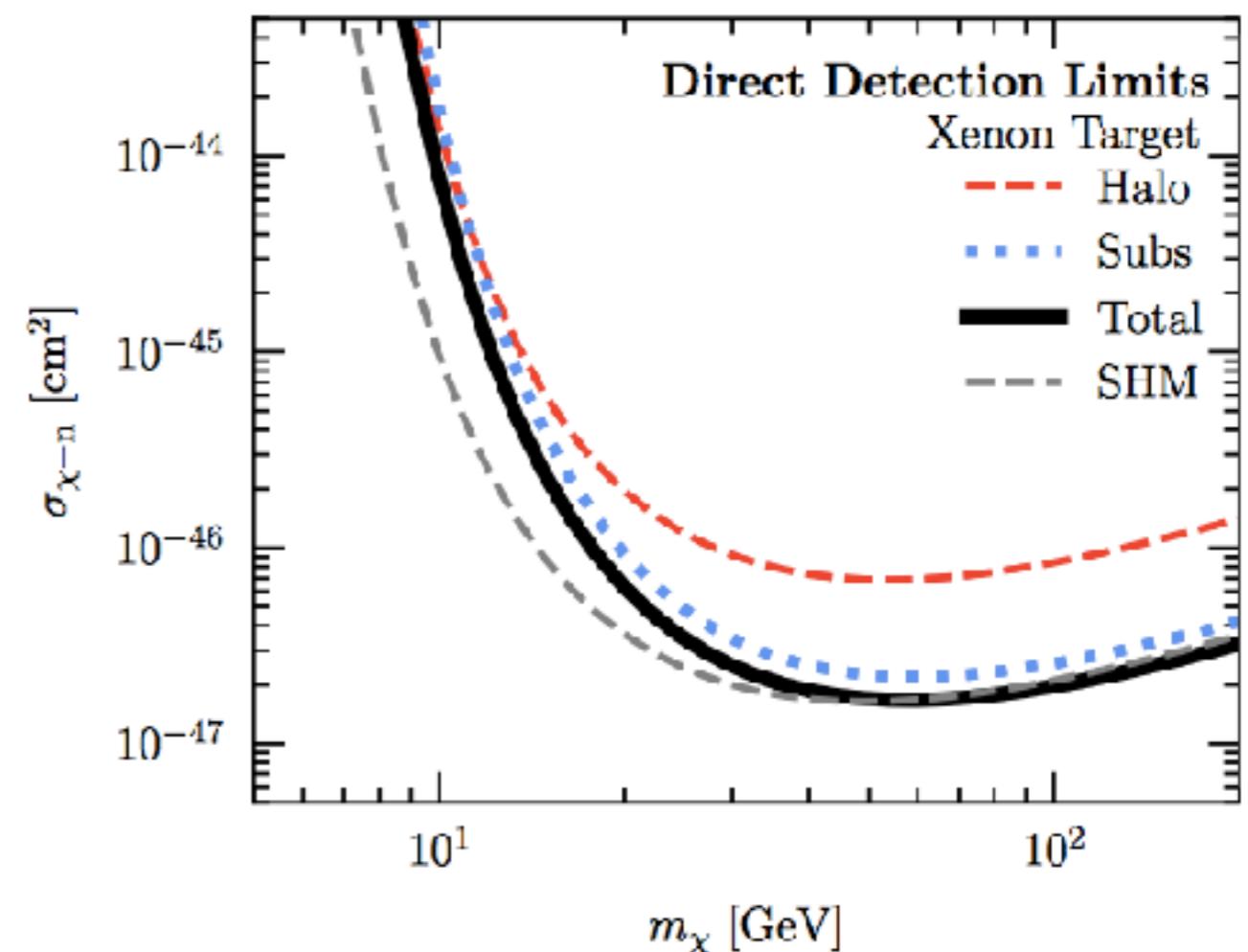
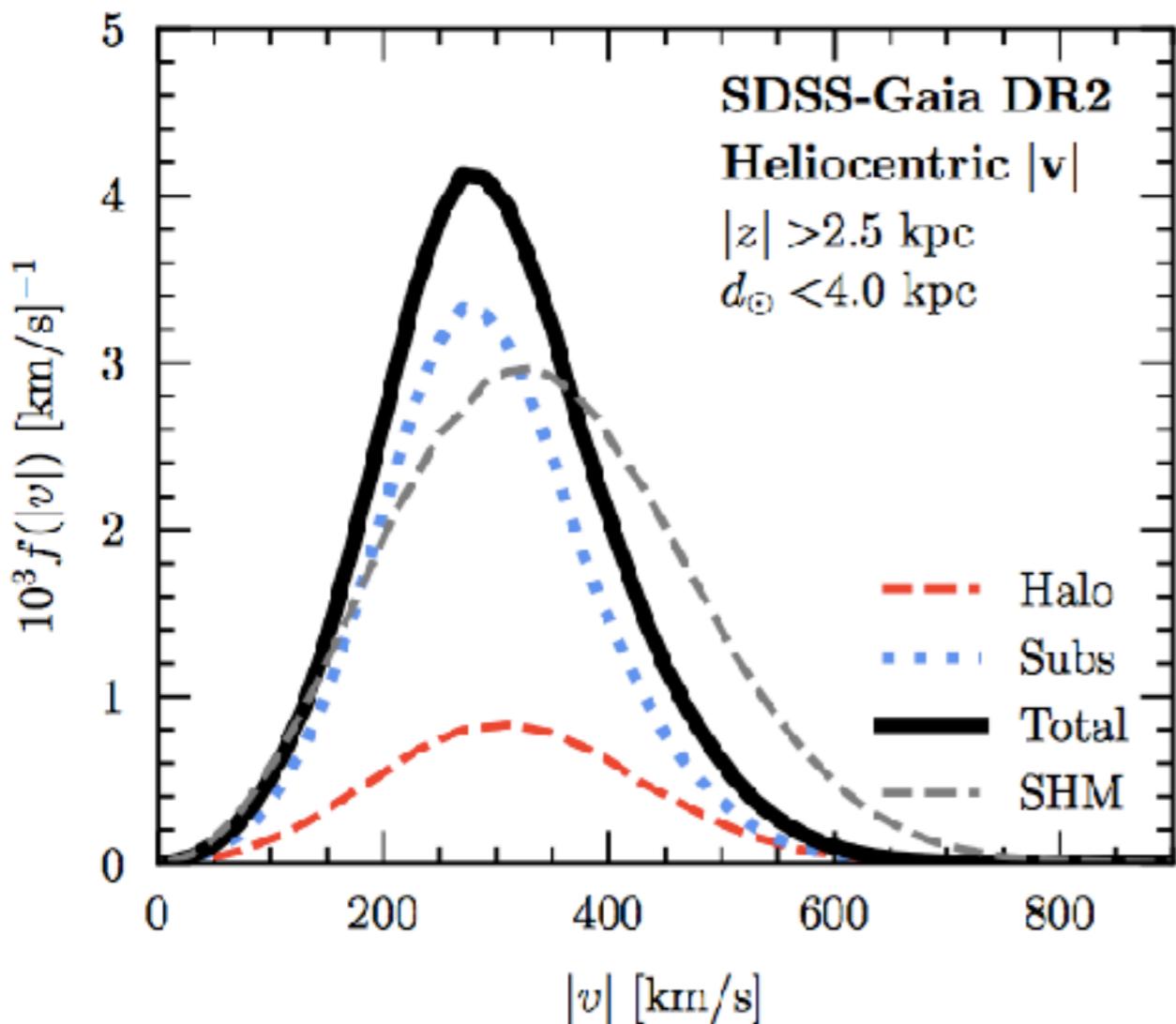
S1 stream counter-rotating at  $v_{S1} \approx 300 \text{ km/s}$

Could be carrying with it a hurricane of Dark Matter...

O'Hare et al. [1807.09004]

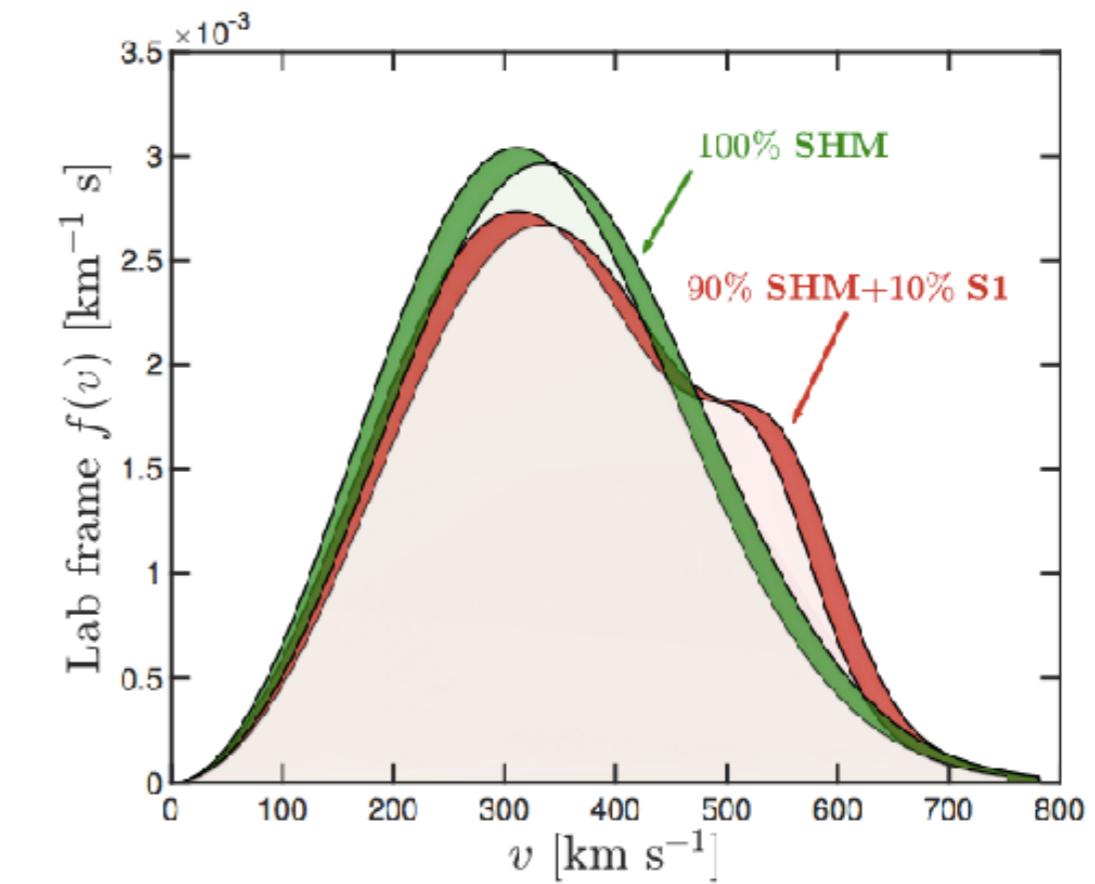
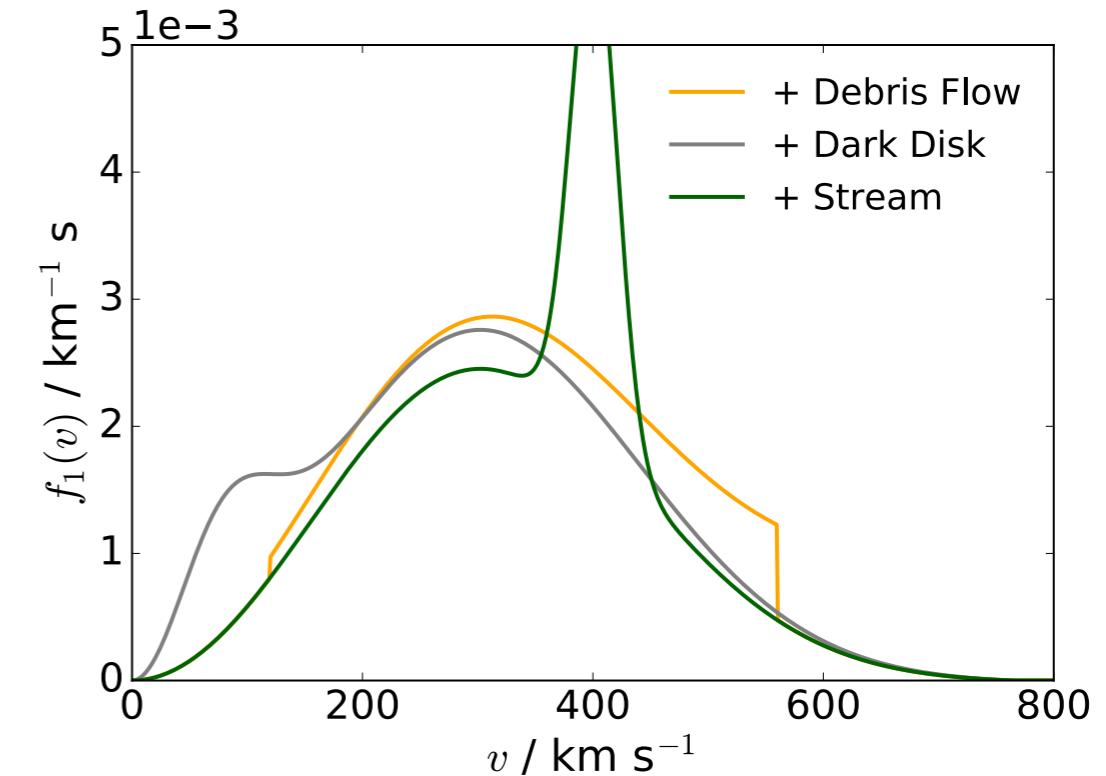
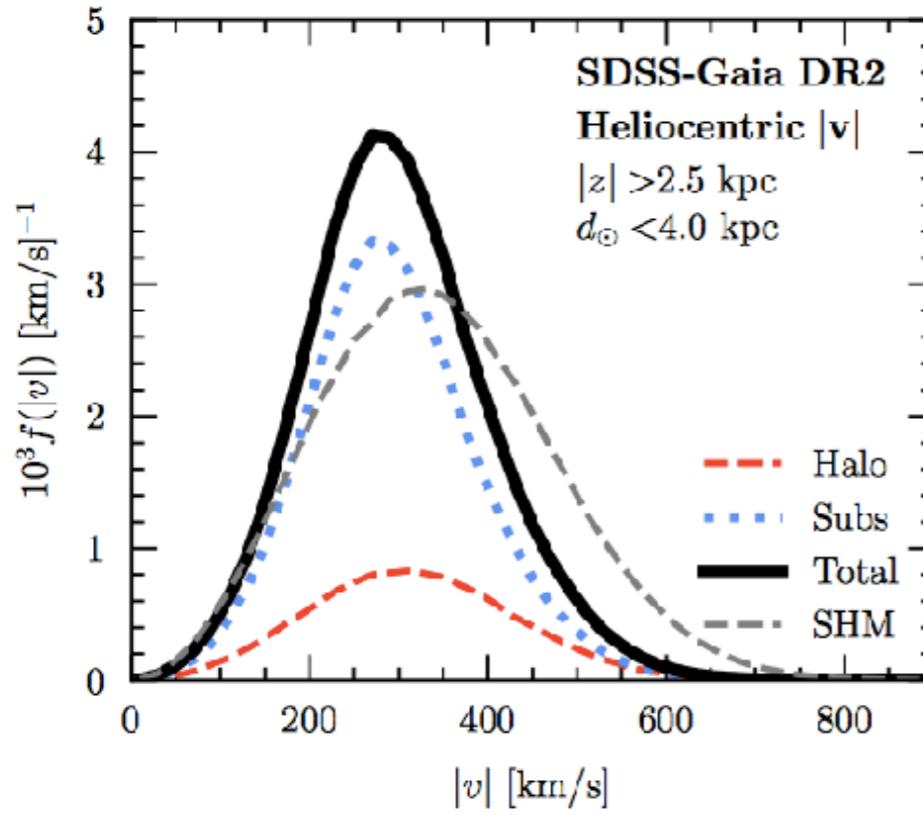
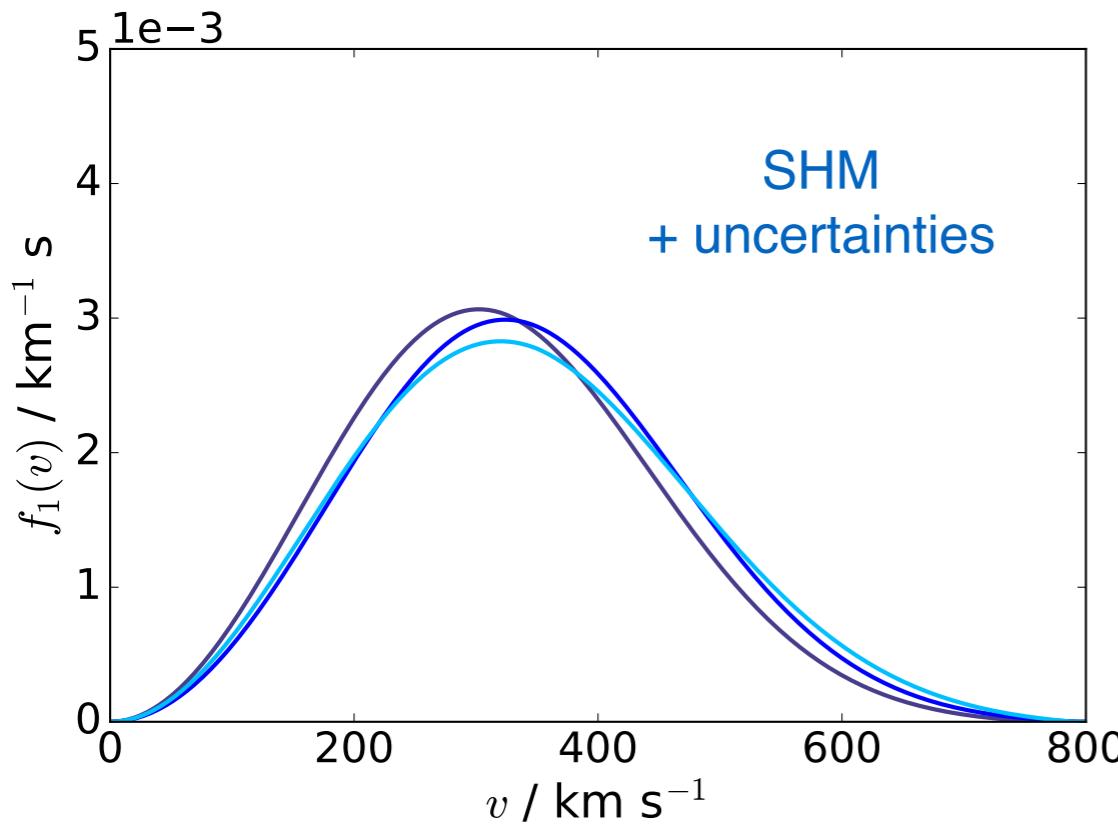
# Stars as DM Tracers

Old, metal-poor stars may trace the DM velocity distribution:



Herzog-Arbeitman et al. [1708.03635]; Necib et. al. [1807.02519]

# Astro Uncertainties



# Overview

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Direct detection and Solar Capture

Astrophysical uncertainties

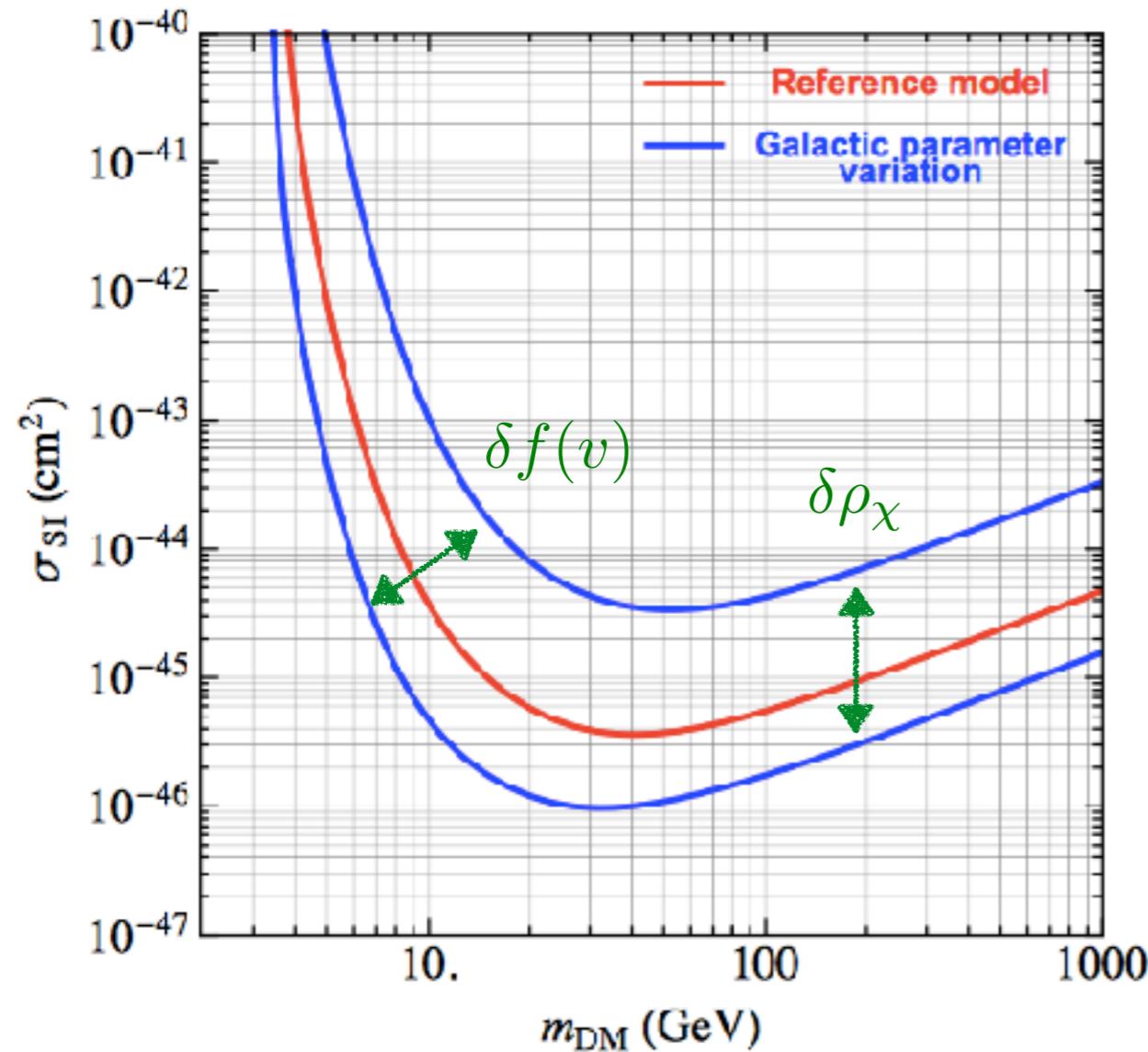
## Halo-independent approaches to setting limits

Measuring the DM properties and distribution  
with a future detection

*[Bonus: Can we also measure the local DM density?]*

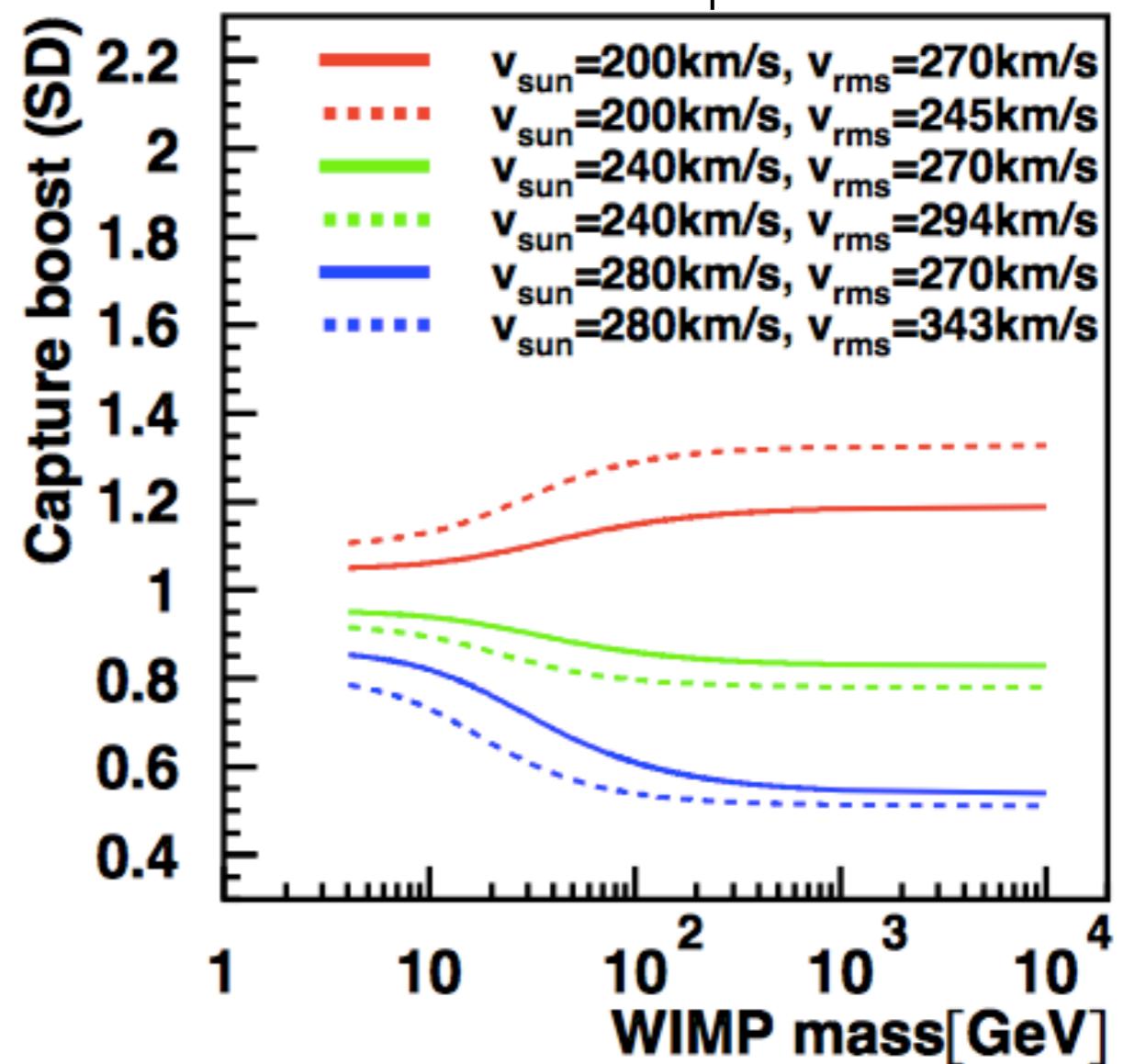
# Impact on DM limits

Direct Detection



Benito et al. [1612.02010]

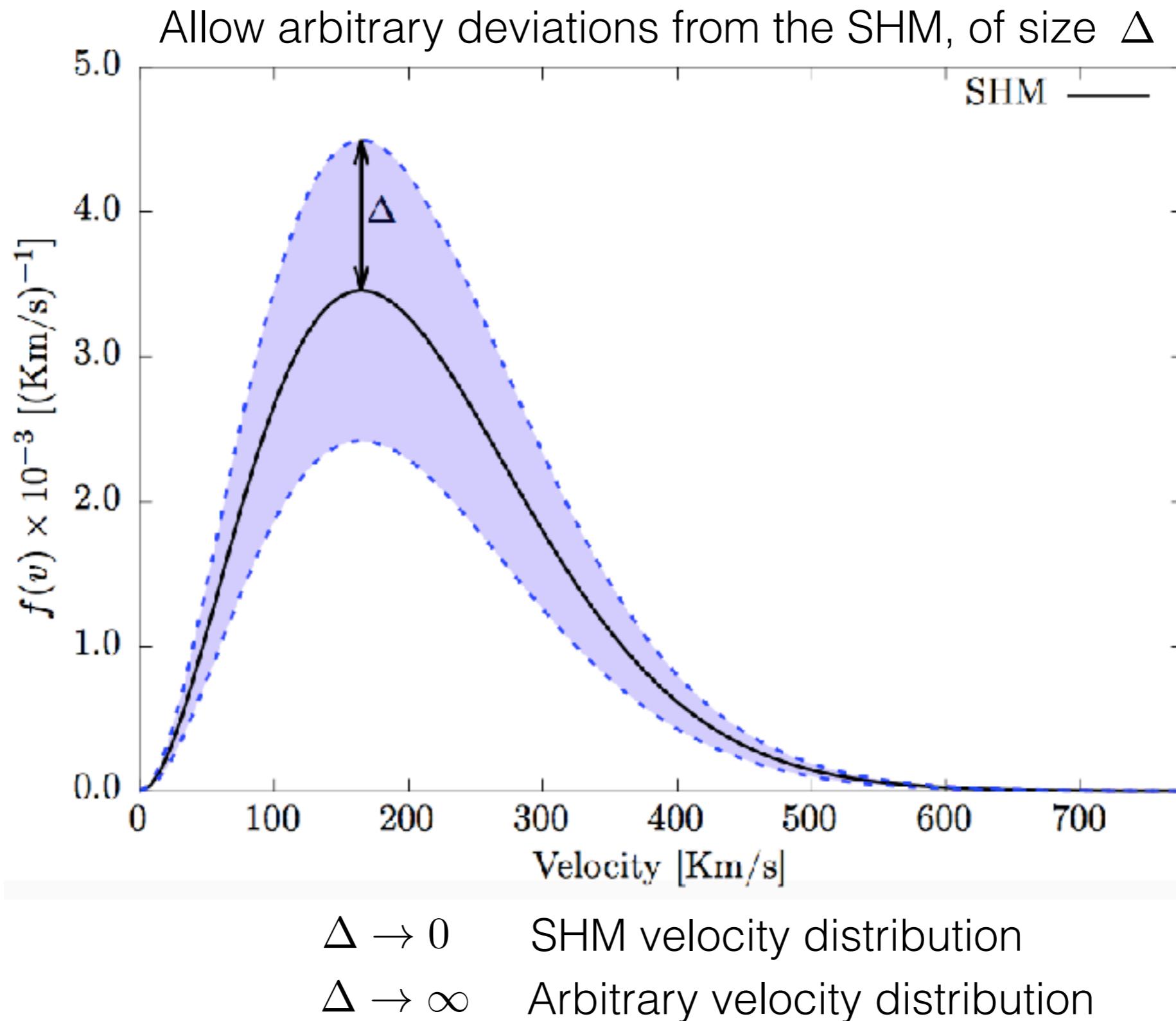
Solar Capture



Choi et al. [1312.0273]

See also e.g. Green [astro-ph/0207366];  
Fairbairn et al. [1206.2693]; Bozorgnia & Bertone [1705.05853]

# Deviation from SHM



See also Fowlie [1809.02323]

# Stream Decomposition

Attempt to be as general as possible:

$$f(\mathbf{v}) = \int f(\mathbf{v}_0) \delta(\mathbf{v} - \mathbf{v}_0) d^3\mathbf{v} \rightarrow a_i \sum_i \delta(\mathbf{v} - \mathbf{v}_i)$$

Optimize:

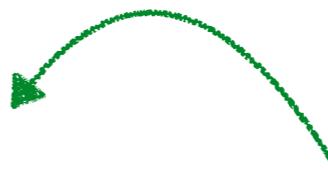
$$\log p(m_\chi, \sigma_p, f(\mathbf{v}))$$

Subject to:

$$\left| \frac{f(\vec{v}) - f_{\text{SHM}}(\vec{v})}{f_{\text{SHM}}(\vec{v})} \right| \leq \Delta$$

and

$$\int d^3v f(\vec{v}) = 1.$$

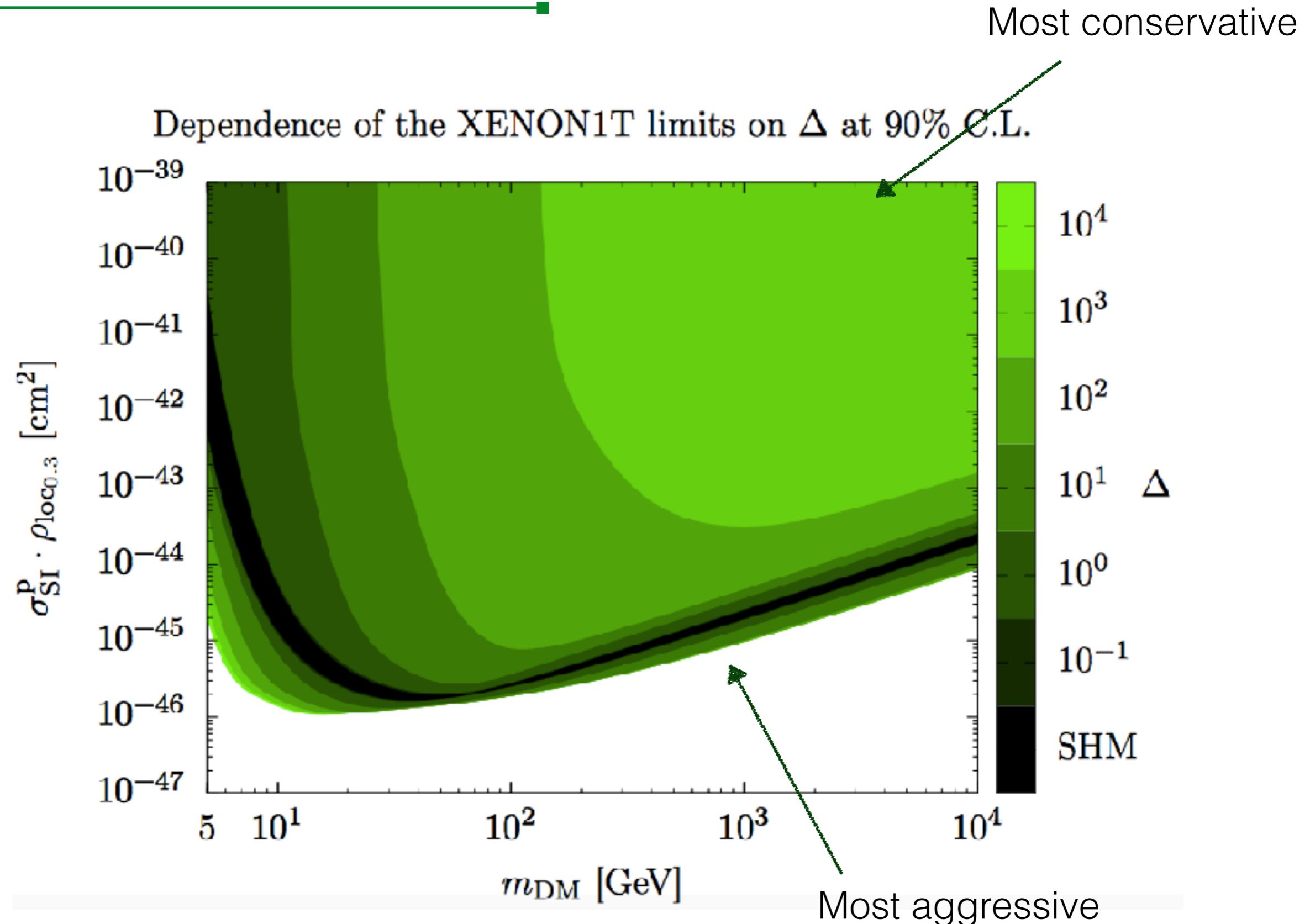


Optimise p-value or  
chi-squared or likelihood  
or whatever

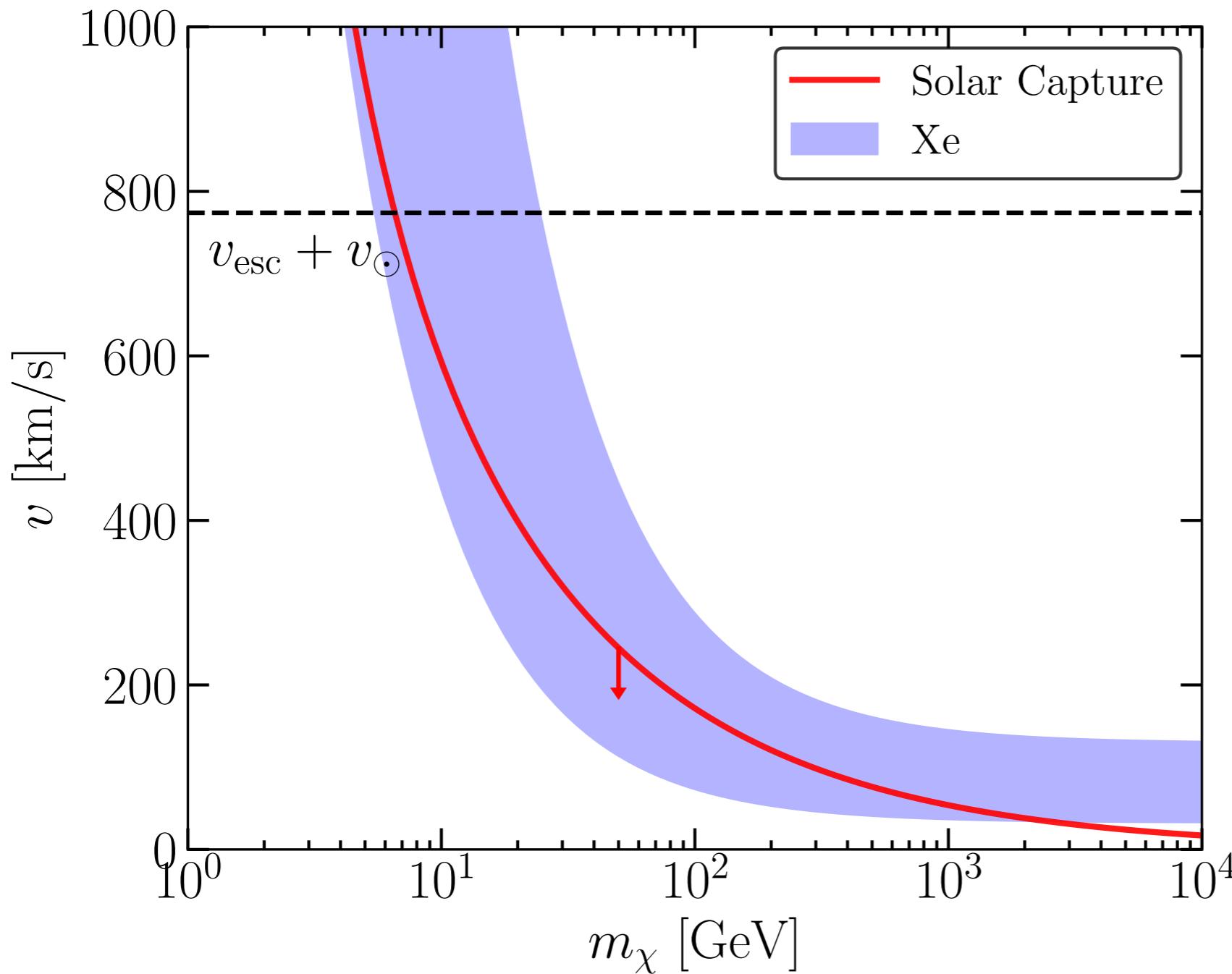
For small event numbers, this can recast this as a  
*fast* optimisation problem for the coefficients  $c_i$ .

Ferrer et al. [1506.03386]; Ibarra & Rappelt [1703.09168]; Ibarra, **BJK**, Rappelt [1806.08714]

# Xenon1T Limits



# Velocity Ranges



Direct detection:

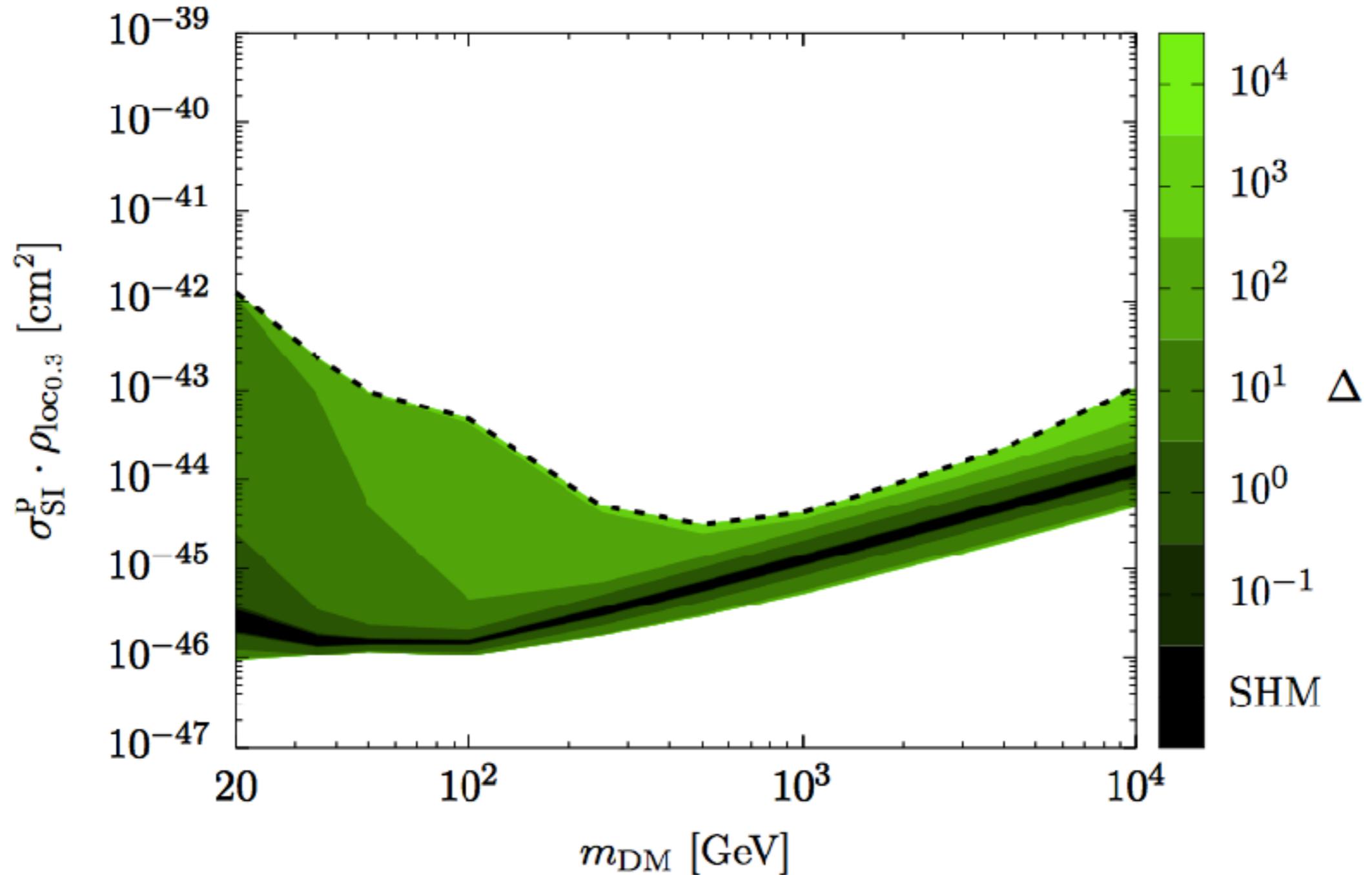
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Solar Capture:

$$v_{\max} = \frac{\sqrt{4m_\chi m_{N_i}}}{m_\chi - m_{N_i}} v_{\text{esc}}$$

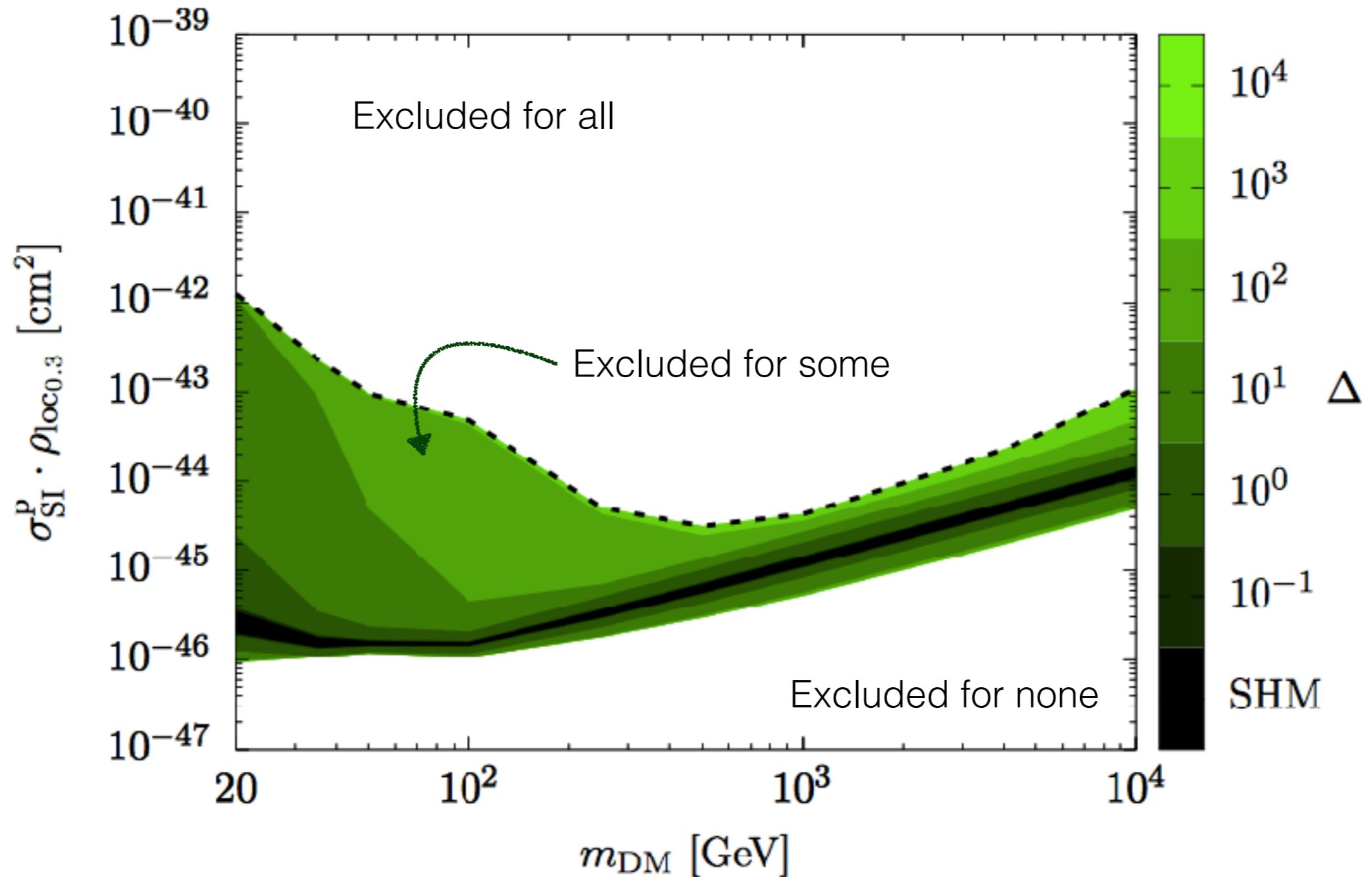
# Xenon1T + IceCube

Dependence of the XENON1T+IceCube limits on  $\Delta$  at 90% C.L.



# Xenon1T + IceCube

Dependence of the XENON1T+IceCube limits on  $\Delta$  at 90% C.L.



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**Measuring the DM properties and distribution  
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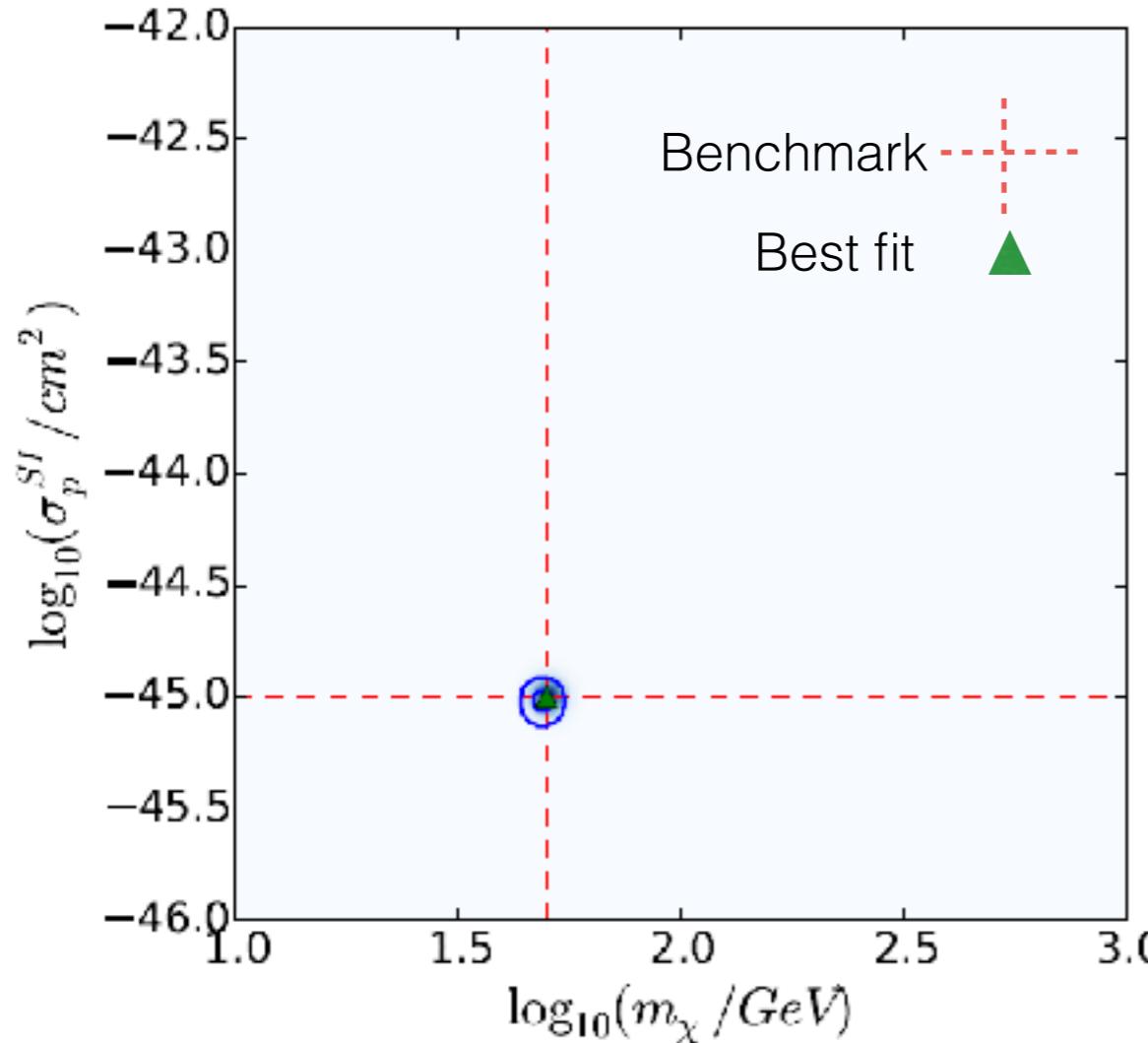
*[Bonus: Can we also measure the local DM density?]*

# Impact on DM Signals

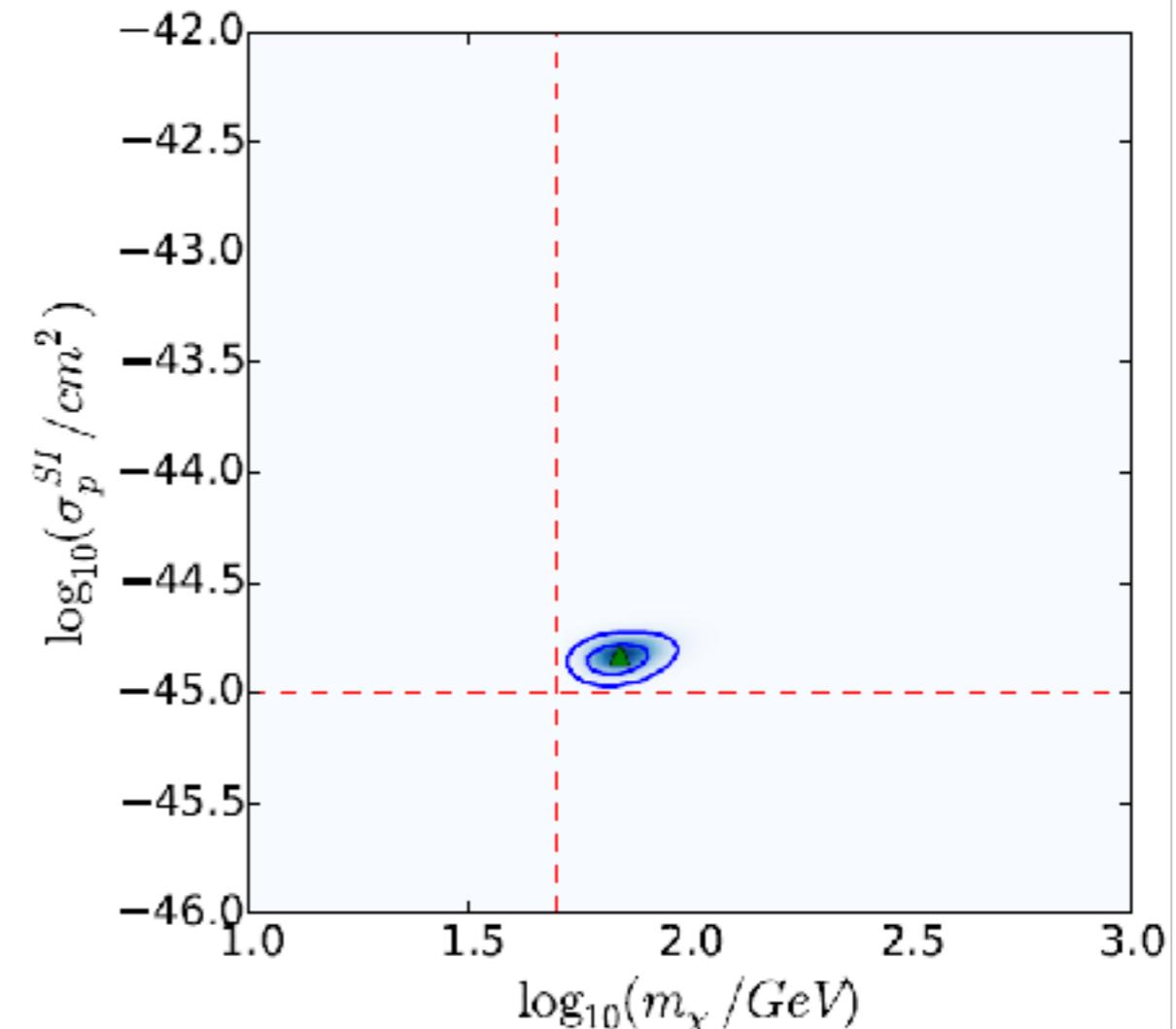
NB: Some of these parameters  
are now excluded :(

Generate mock data for several experiments, assuming a **stream** distribution, then try to reconstruct the mass and cross section assuming:

(correct) **stream** distribution



(incorrect) **SHM** distribution



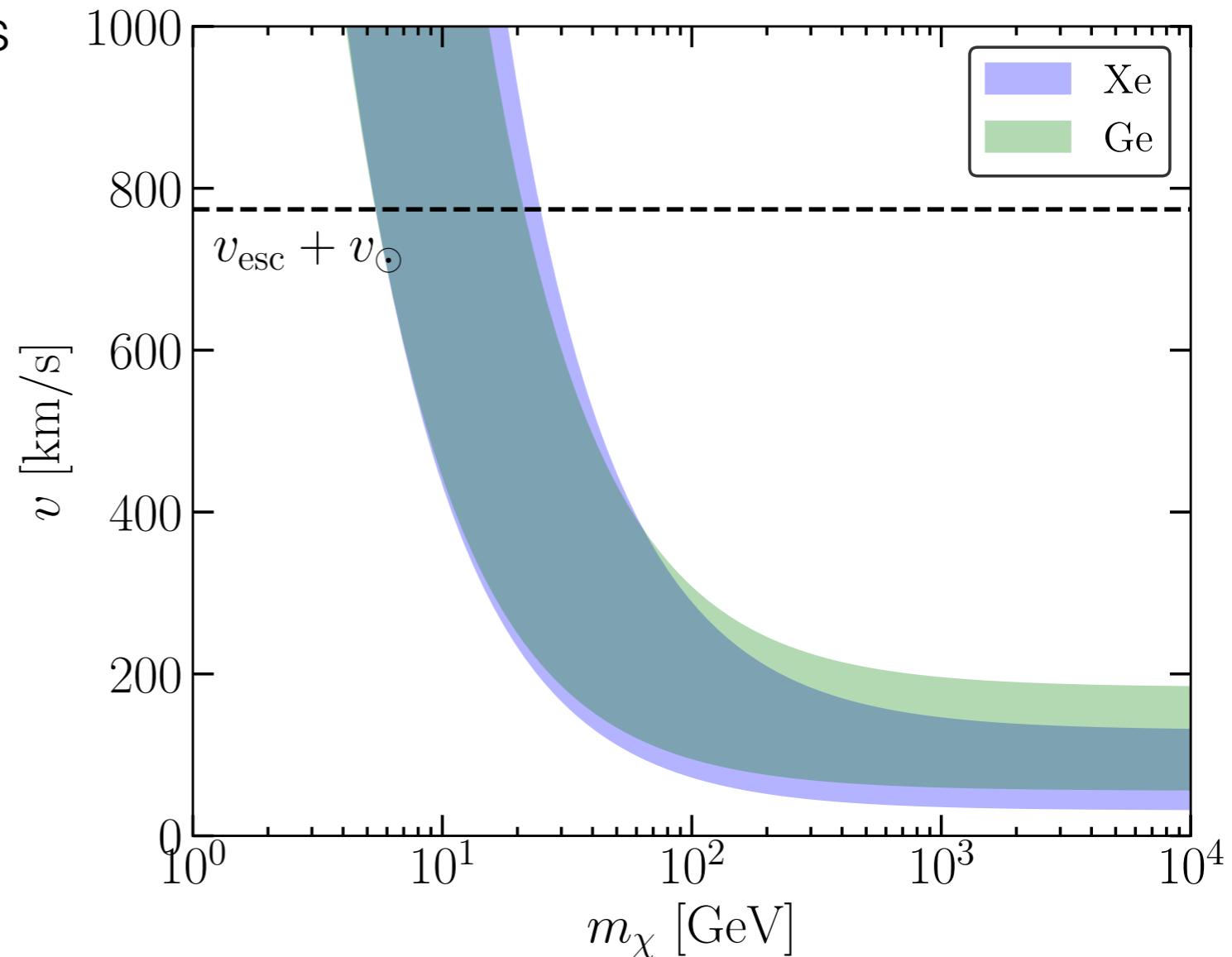
# Halo-independent methods

Could include SHM uncertainties, but are these broad enough?

Strigari & Trotta [0906.5361]

Alternatively, compare experiments only over velocities where they overlap and effectively ‘divide out’ the astrophysical uncertainties:

Need to fix DM mass, and not straightforward to apply to Solar Capture...



Fox et al. [1011.1915, 1011.1910], but see also [1111.0292, 1107.0741, 1202.6359, 1304.6183, 1403.4606, 1403.6830, 1504.03333, 1607.02445, 1607.04418 and more...]

# Fitting the DM distribution

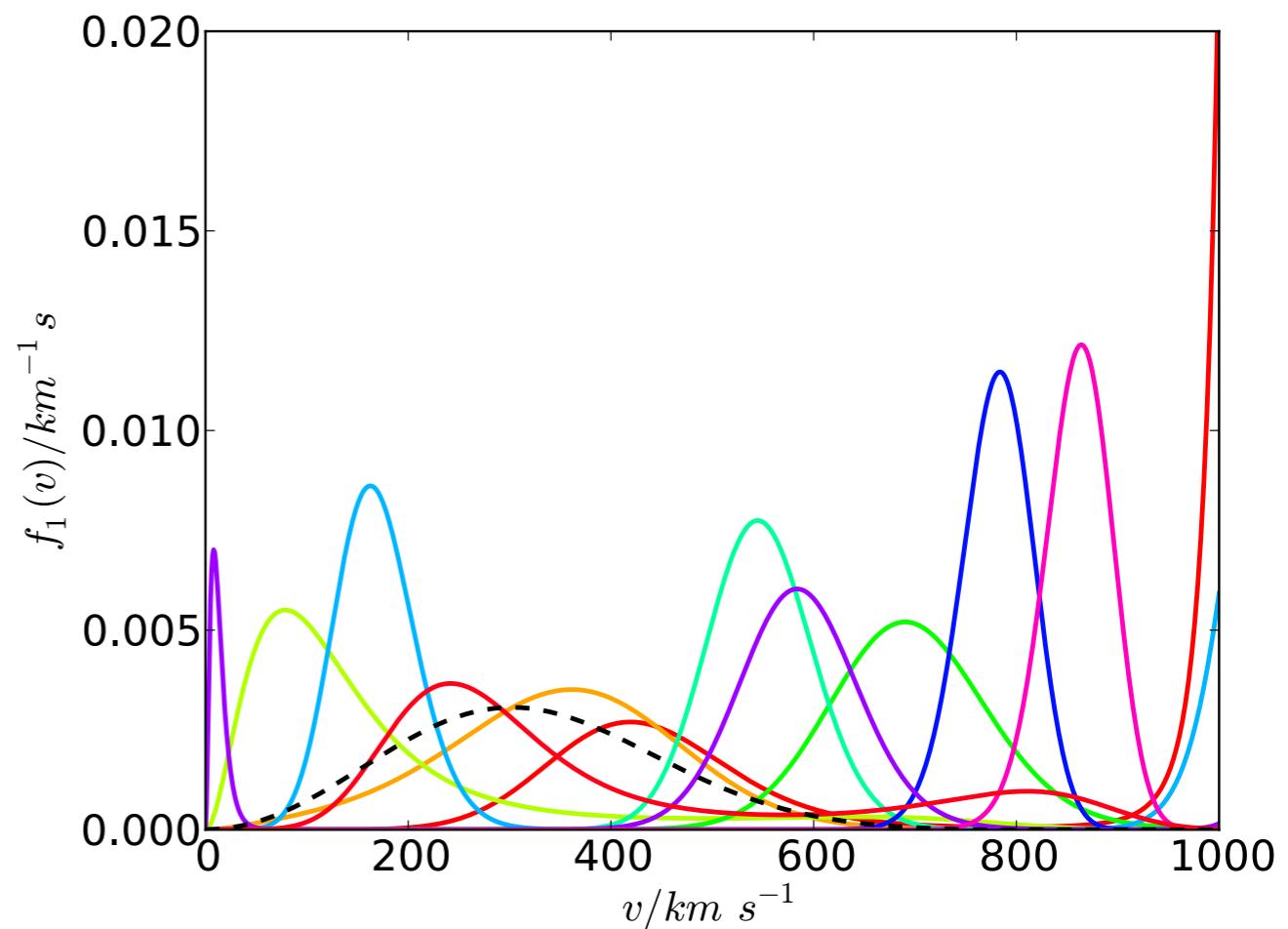
Write a *general parametrisation* for the speed distribution: Peter [1103.5145]

$$f(v) = v^2 \exp \left( - \sum_{k=0}^{N-1} a_k v^k \right)$$

BJK & Green [1303.6868]

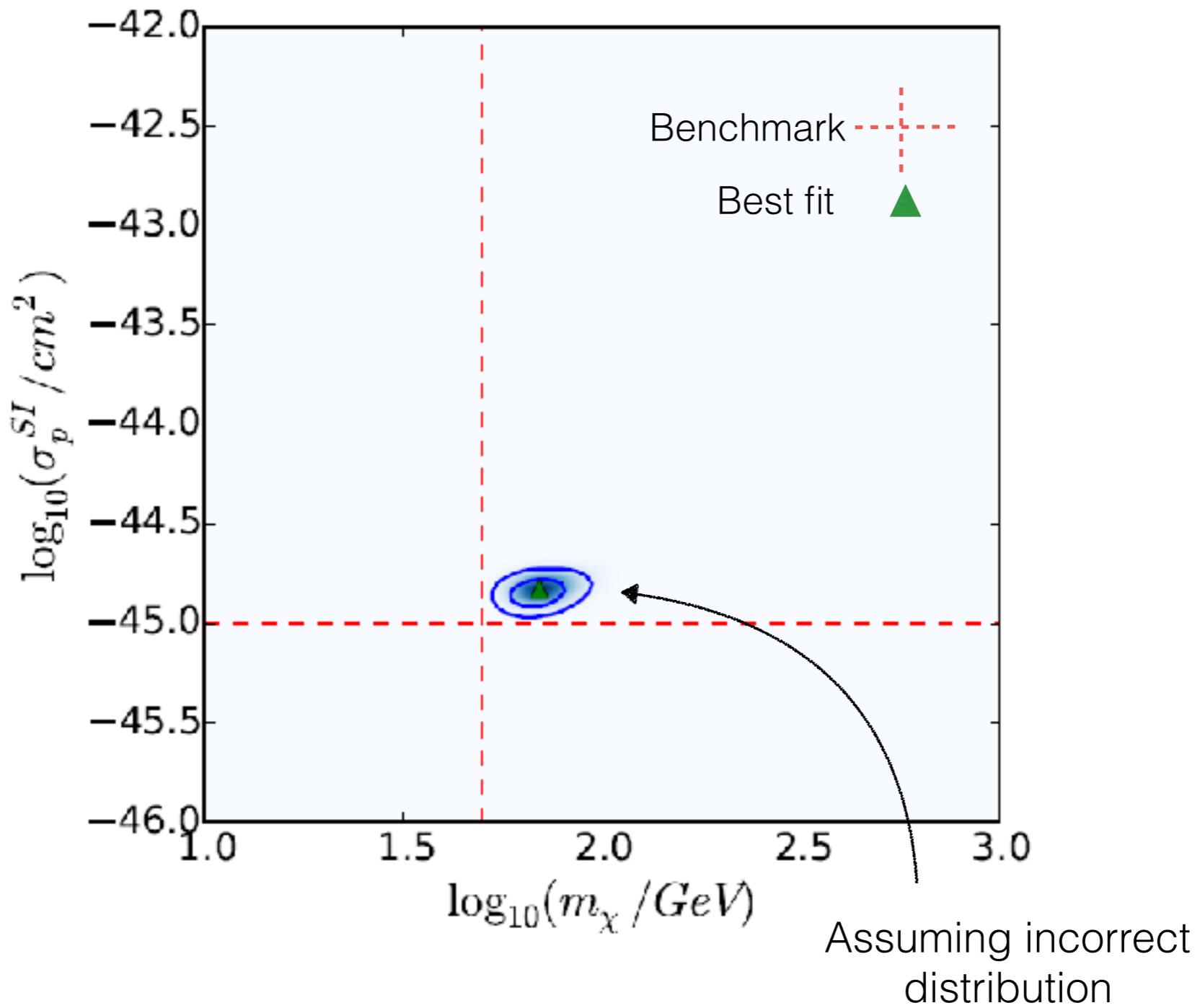
Guarantees a positive distribution function and spans a wide range of functional forms with only a small number  $N$  of parameters:

Now fit  $(m_\chi, \sigma_p)$  at the same time as  $\{a_k\}$  ...



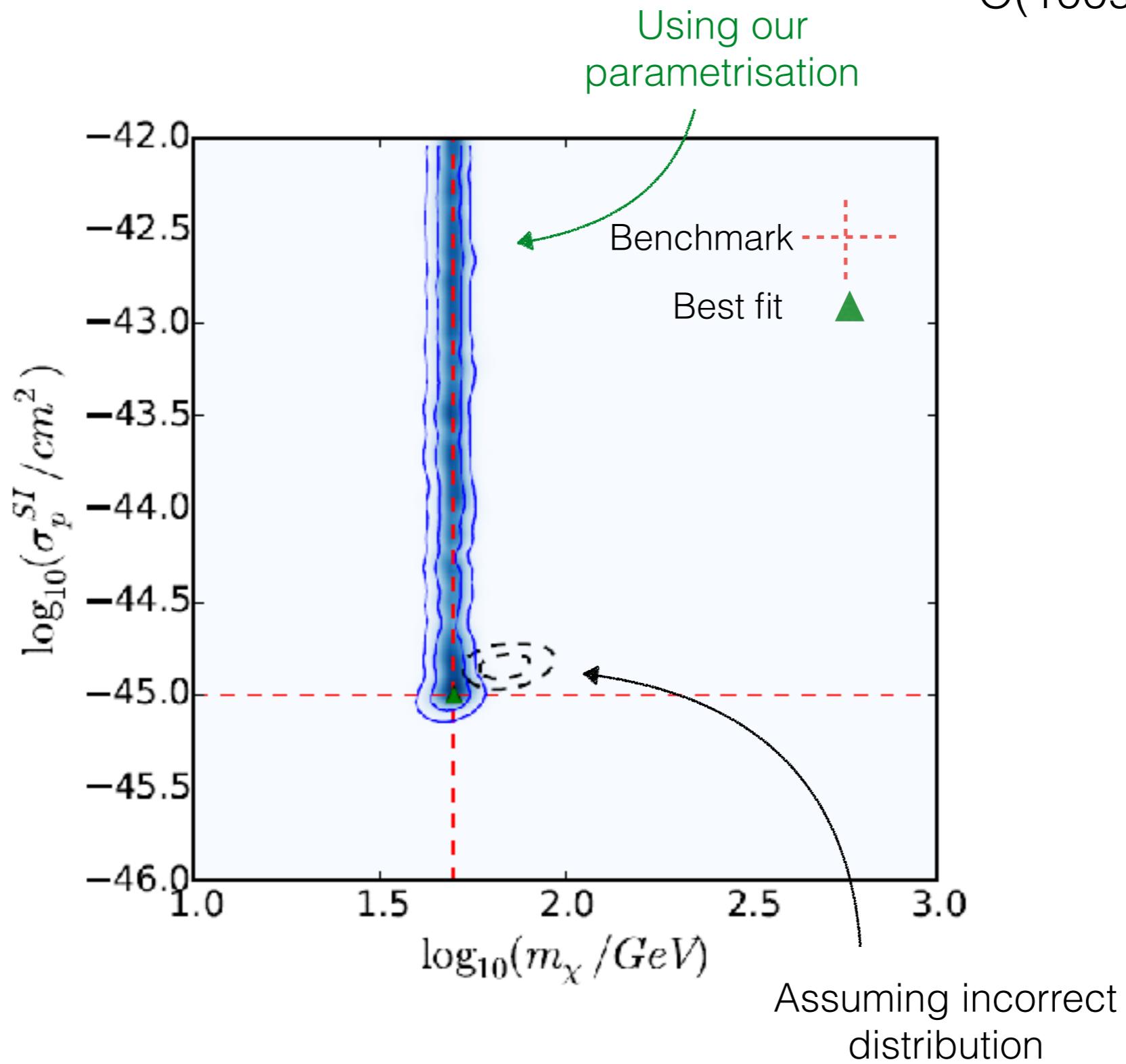
# Testing the parametrisation

Direct detection  
Xe + Ge + Ar



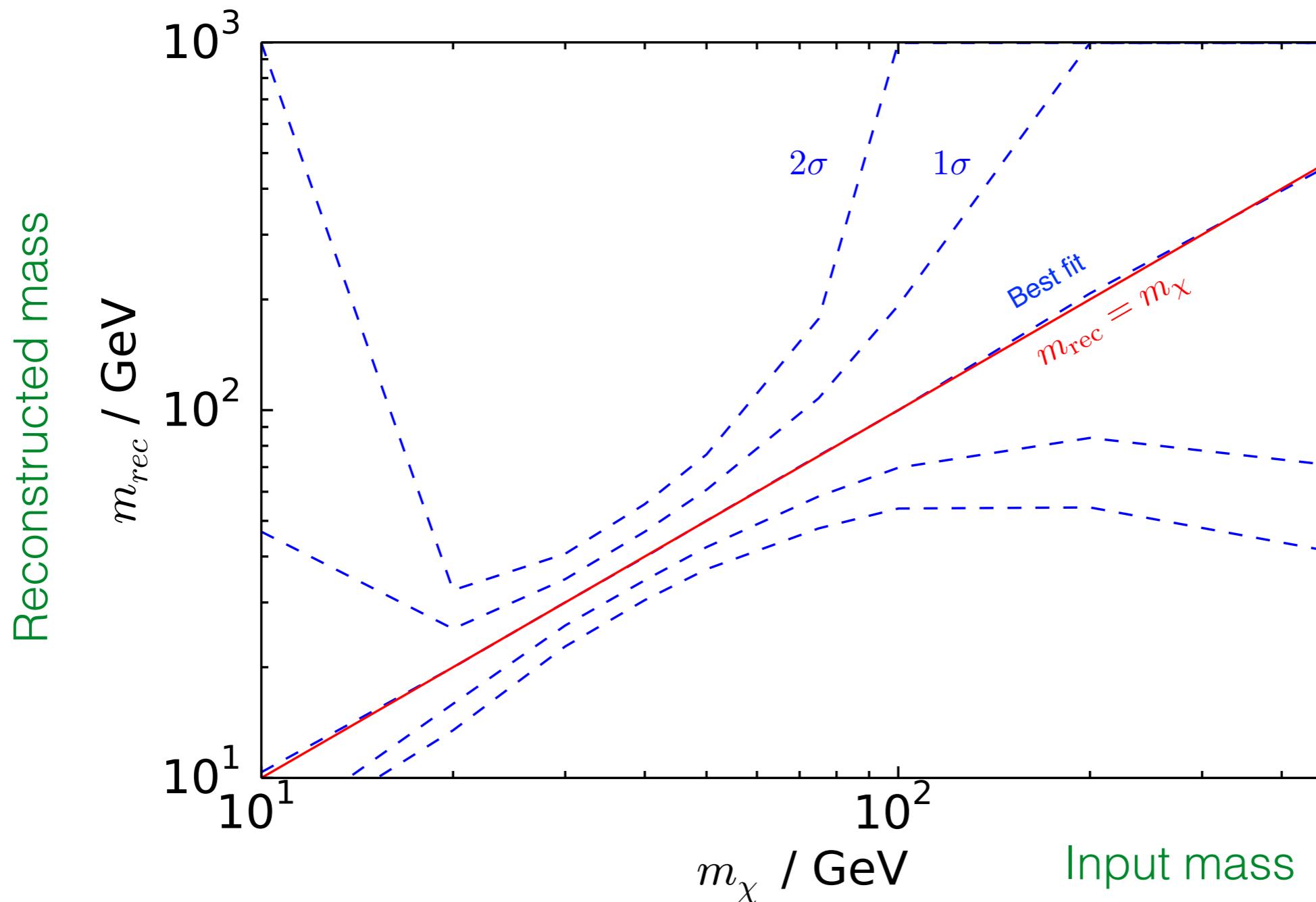
# Testing the parametrisation

Direct detection  
Xe + Ge + Ar targets  
 $O(100s)$  events



# Reconstructing DM mass

BJK [1312.1852]

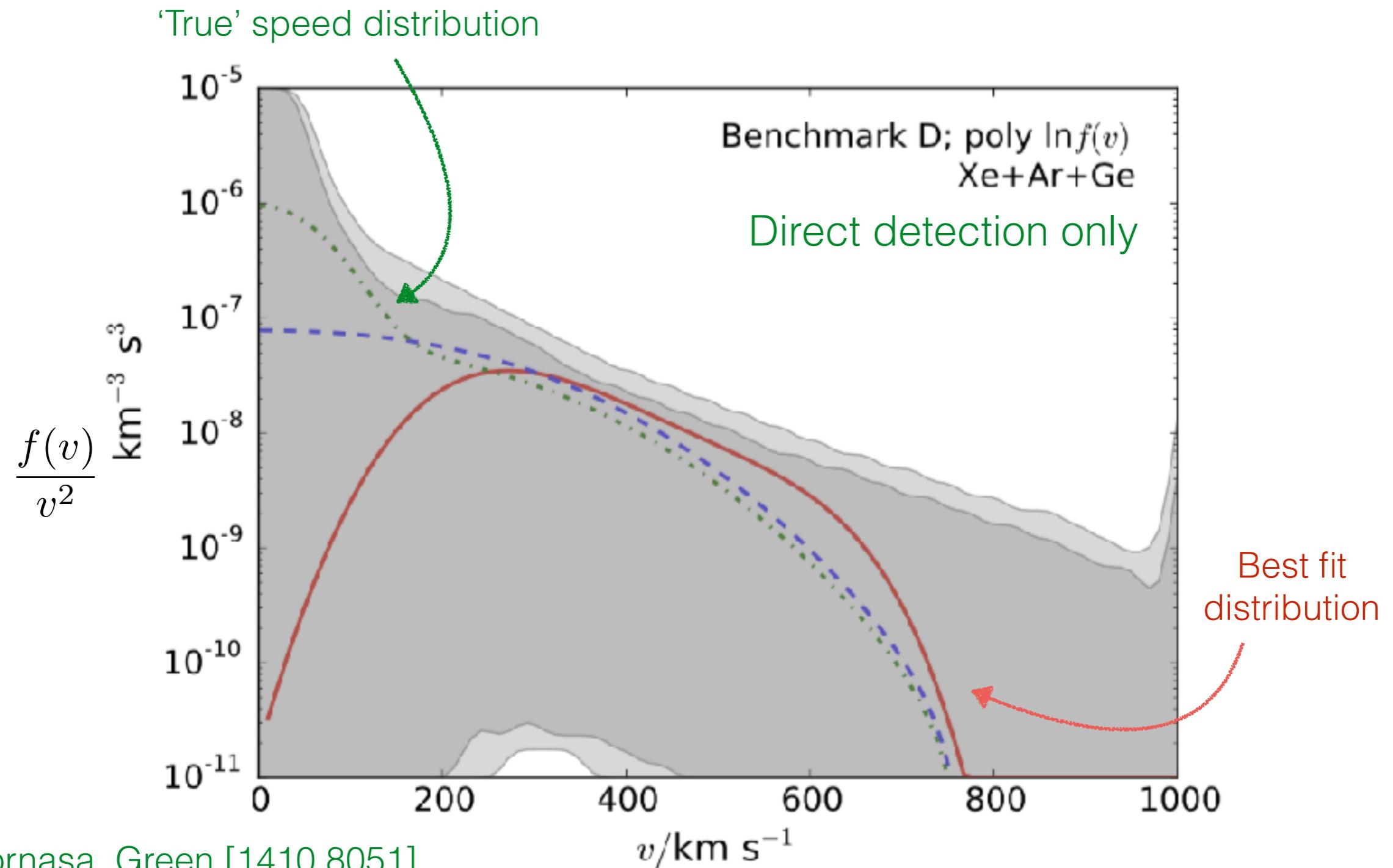


Also works for a range of input velocity distributions.  
Recently demonstrated for arbitrary interactions too...

Krauss & Newstead [1801.08523]

# Reconstructing $f(v)$

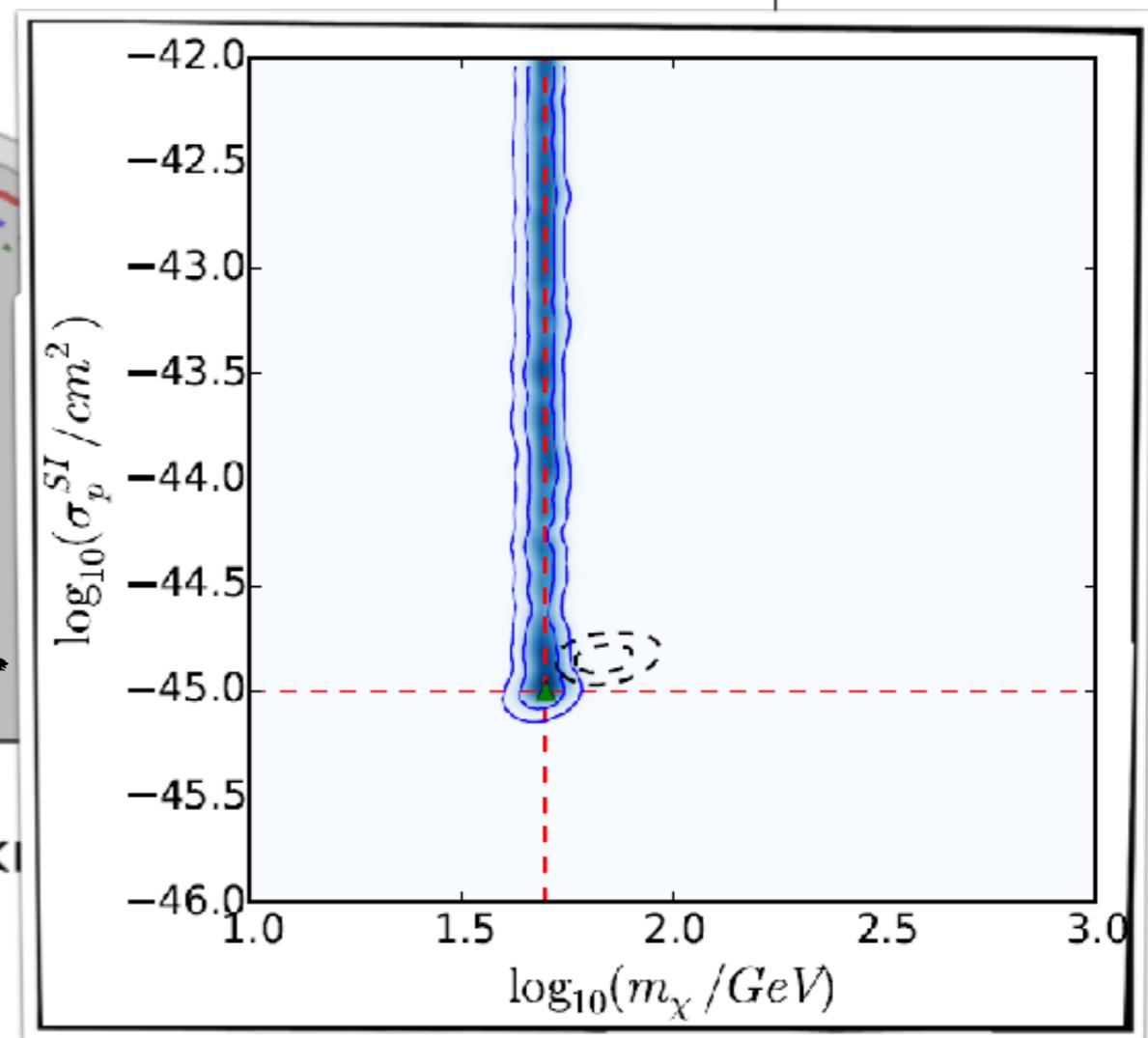
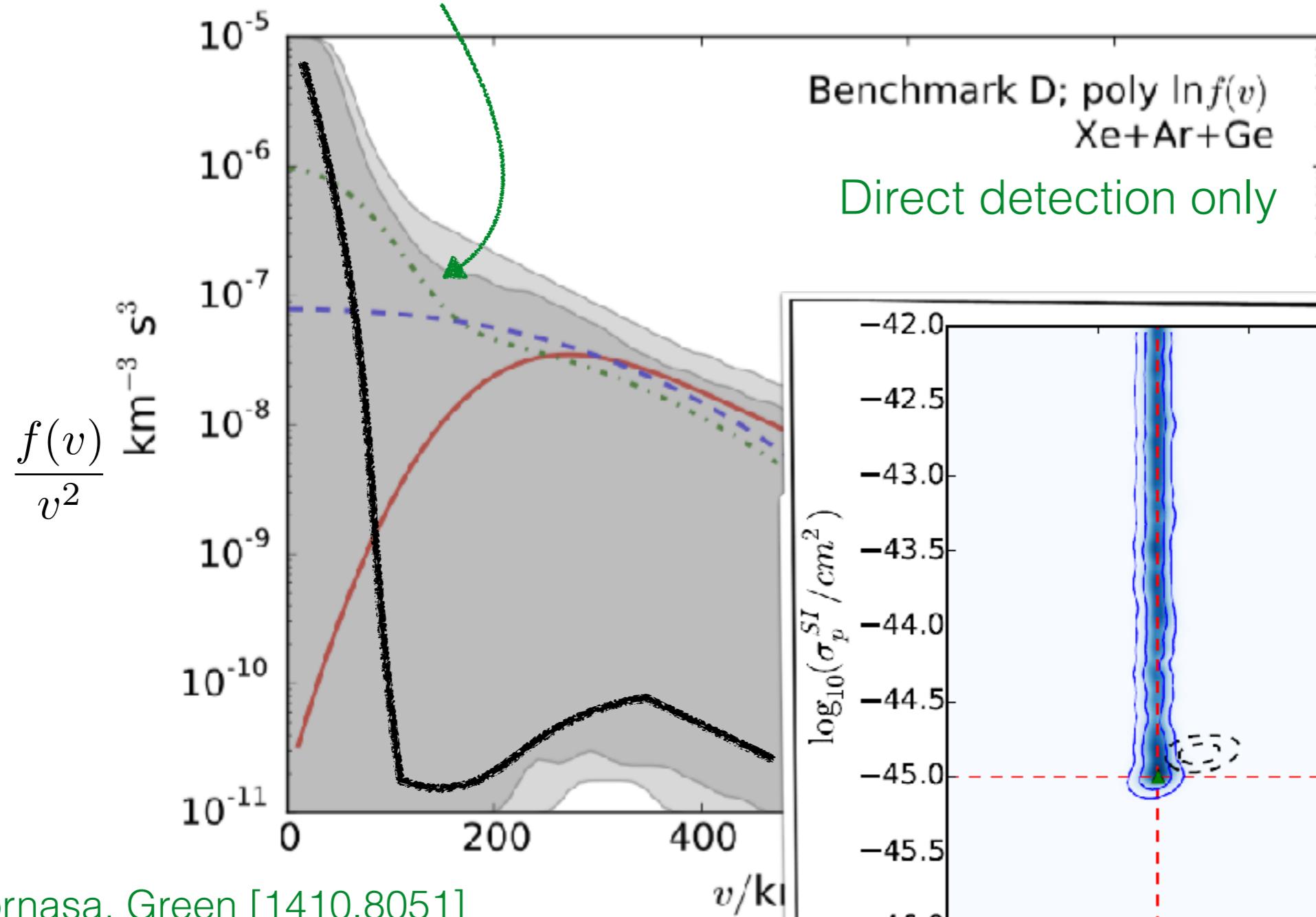
$m_\chi = 30 \text{ GeV}$   
SHM+DD distribution



# Reconstructing $f(v)$

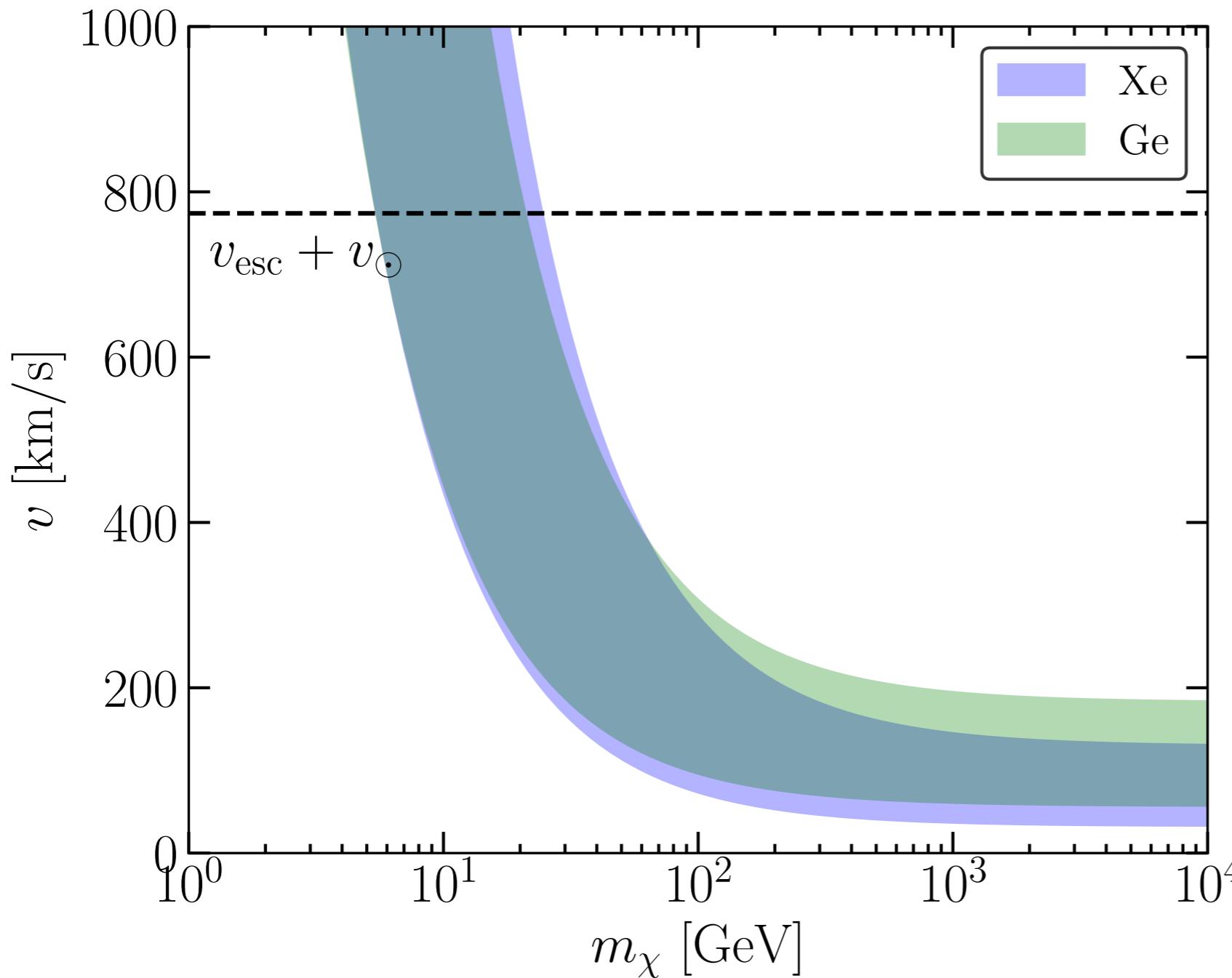
$m_\chi = 30 \text{ GeV}$   
SHM+DD distribution

'True' speed distribution



# Velocity Ranges

Cannot constrain distribution below threshold...



Direct detection:

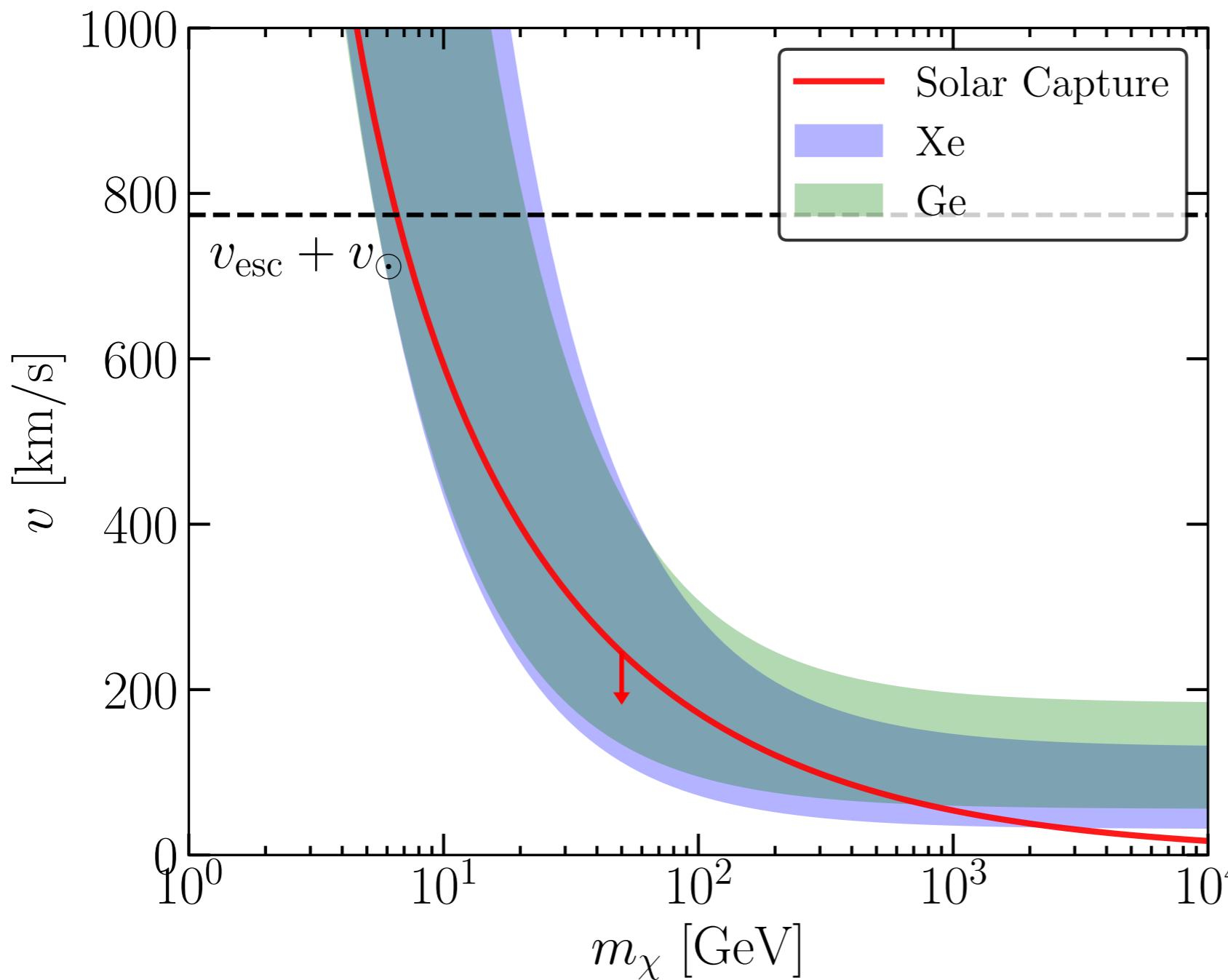
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Solar Capture:

$$v_{\max} = \frac{\sqrt{4m_\chi m_{N_i}}}{m_\chi - m_{N_i}} v_{\text{esc}}$$

...a problem for *any* astrophysics-independent method.

# Velocity Ranges



Direct detection:

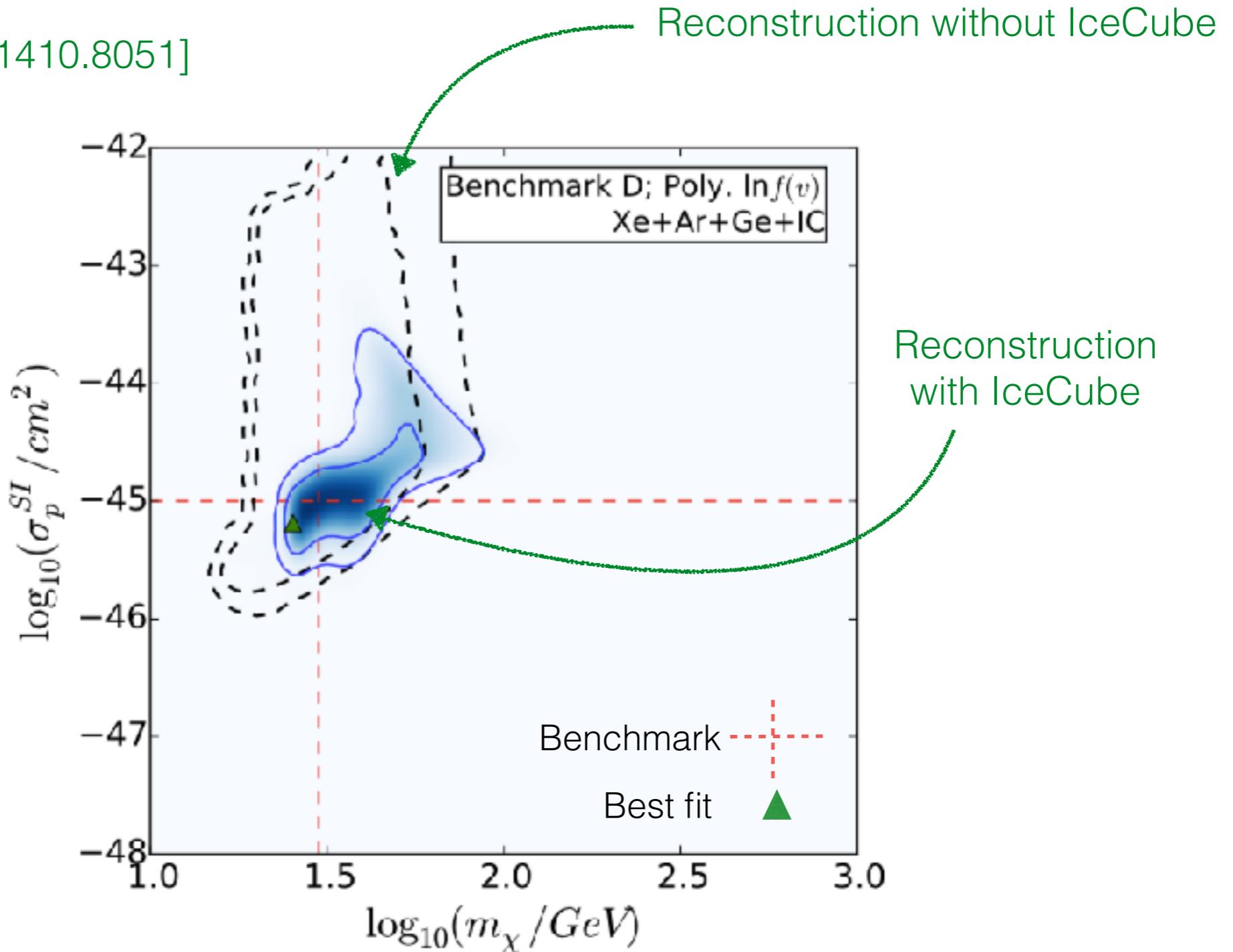
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Solar Capture:

$$v_{\max} = \frac{\sqrt{4m_\chi m_{N_i}}}{m_\chi - m_{N_i}} v_{\text{esc}}$$

# Combining with IceCube

BJK, Fornasa, Green [1410.8051]

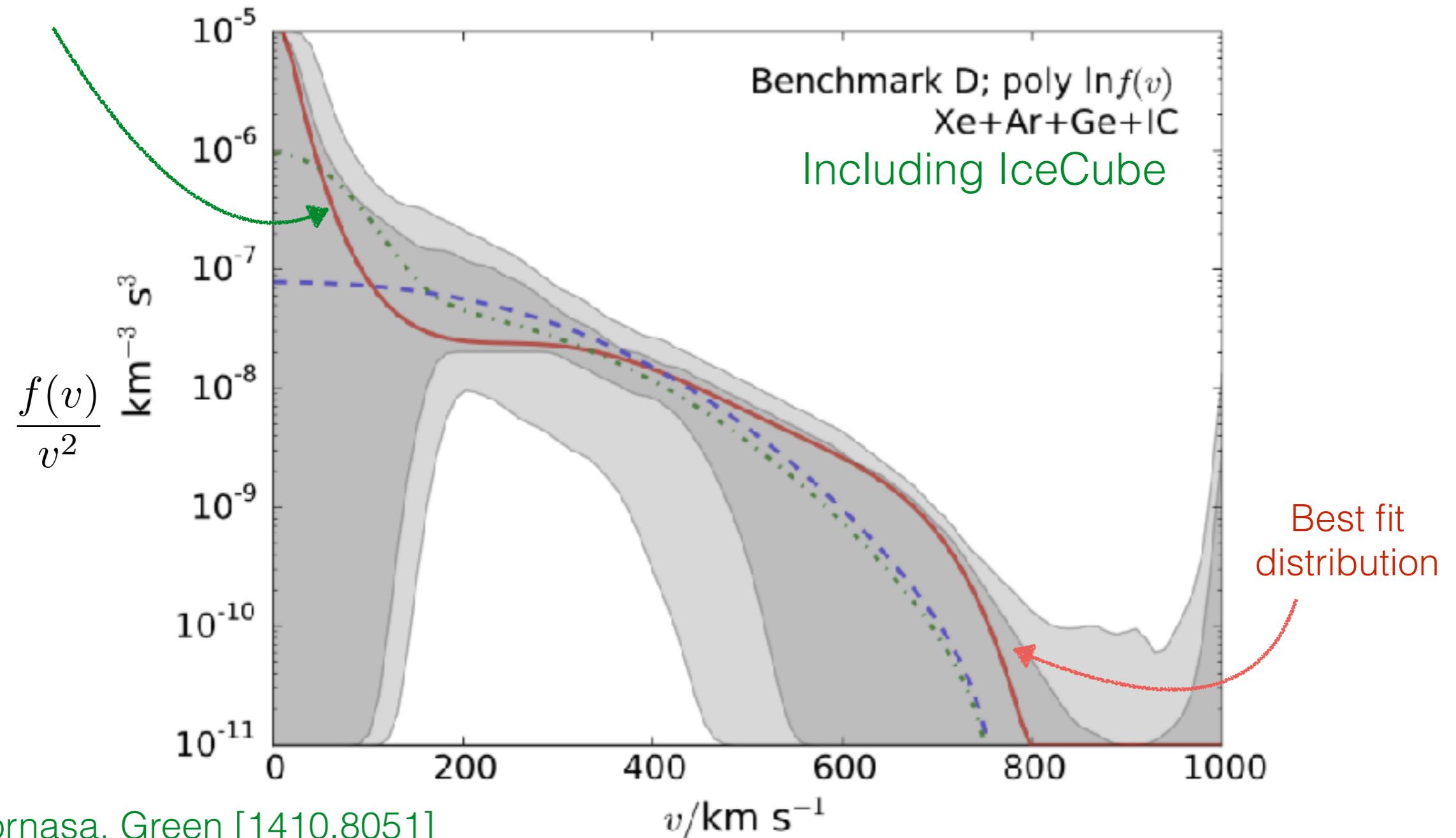


Combining direct detection and solar capture,  
we could pin down DM mass and cross section

# Reconstructing $f(v)$ with IceCube

$m_\chi = 30 \text{ GeV}$   
SHM+DD distribution  
Annihilation to  $\nu_\mu \bar{\nu}_\mu$

'True' speed distribution



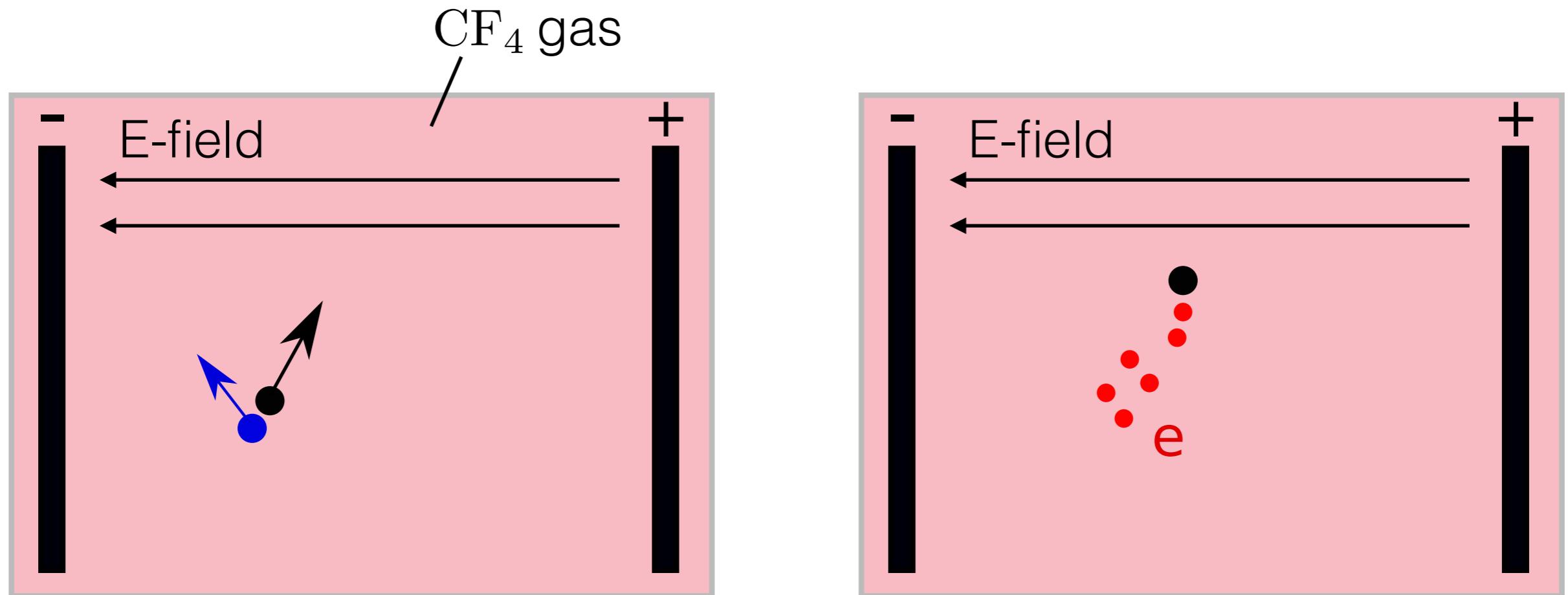
Constraints improved, but still difficult to distinguish underlying distributions (perhaps only at the  $1\sigma$  level)...

# Directional Detection

Try to measure both the energy *and the direction* of the recoil

Mayet et al. [1602.03781]

Most mature technology is the gaseous Time Projection Chamber (TPC)  
[e.g. DRIFT, MIMAC, DMTPC, NEWAGE, D3]



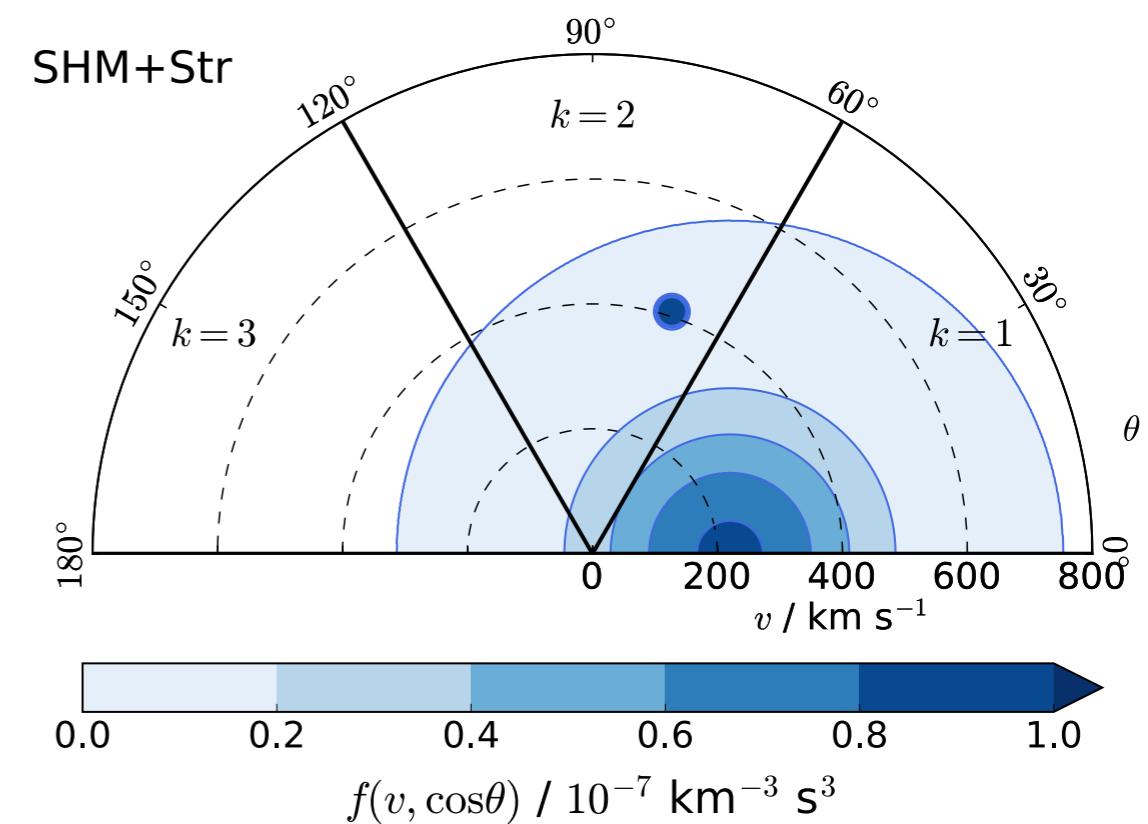
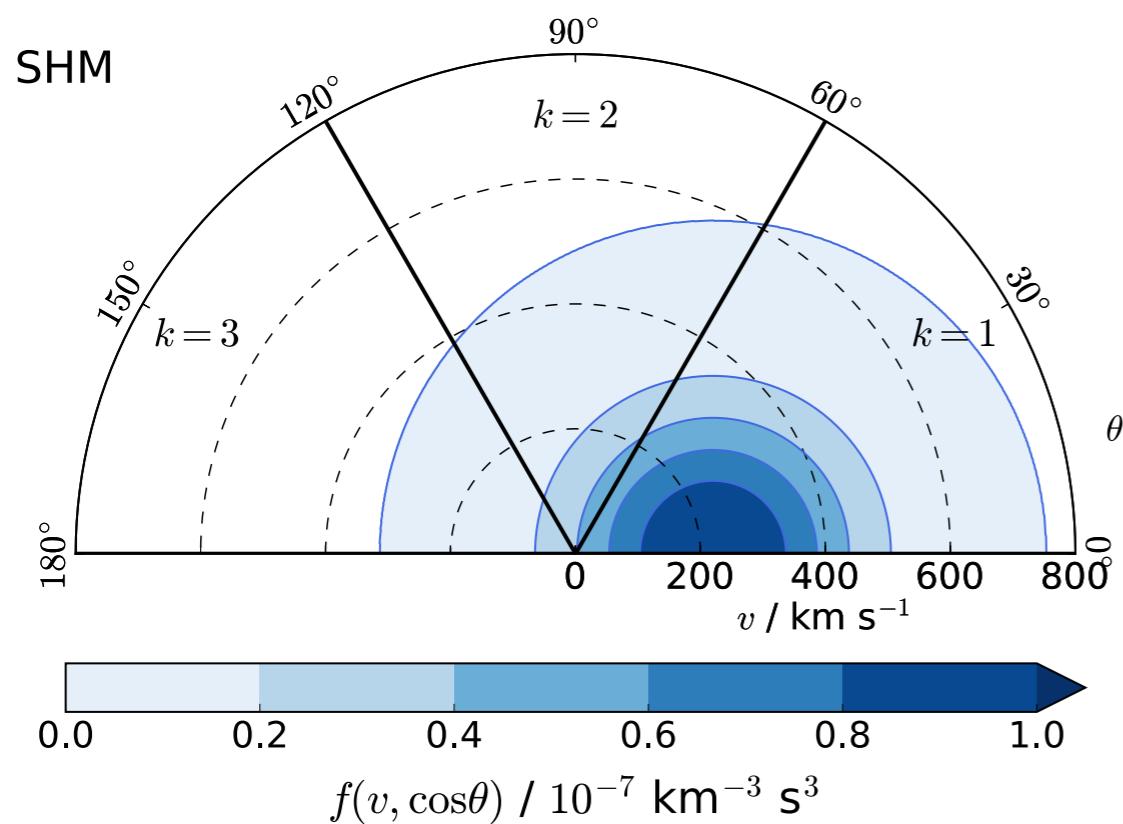
Possible suggestion of (partial) directionality in Xenon detectors

Mohlabeng et al. [1503.03937]; Namakura et al. [1803.00752]

# 3-D Velocity Distribution



Directional detectors are in principle sensitive to full 3-D velocity distribution:  
Gondolo [hep-ph/0209110]



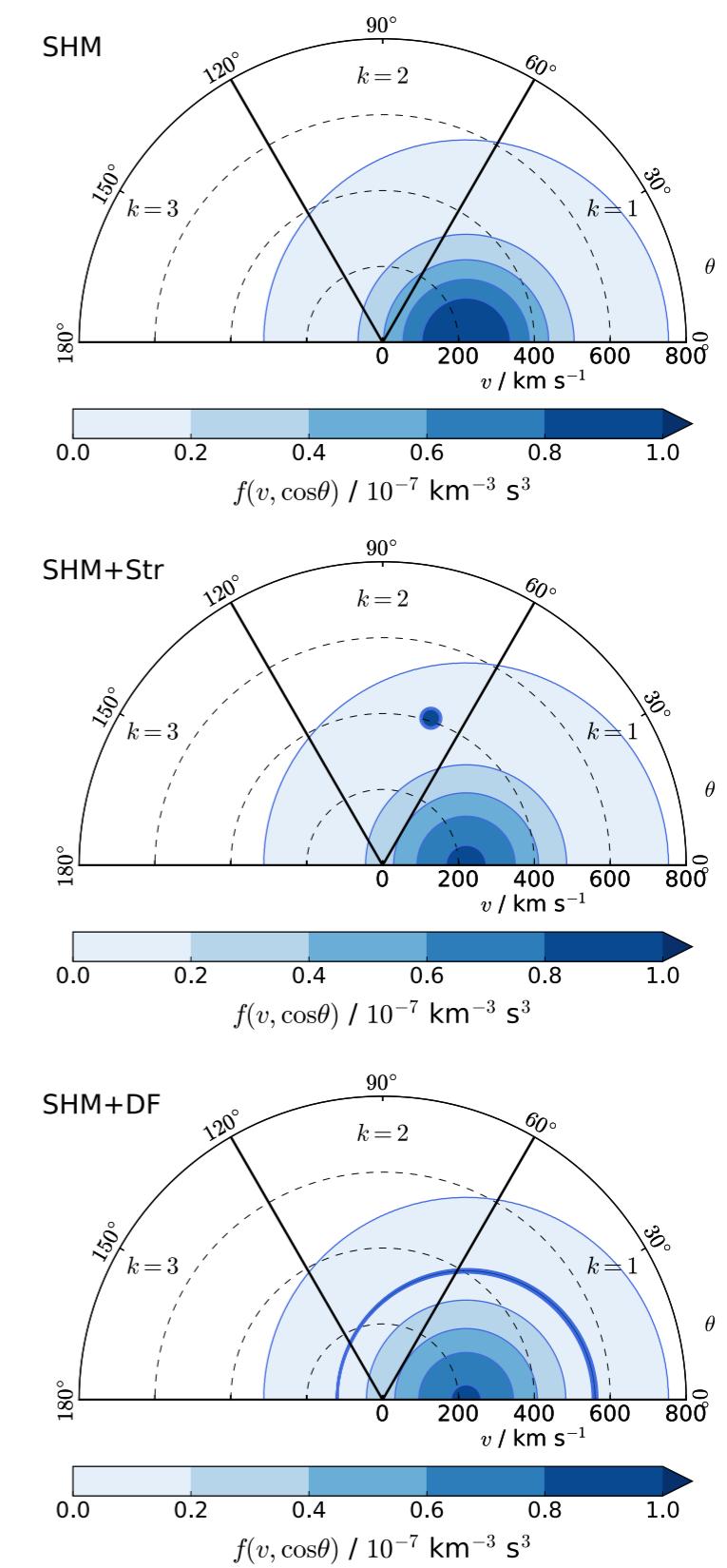
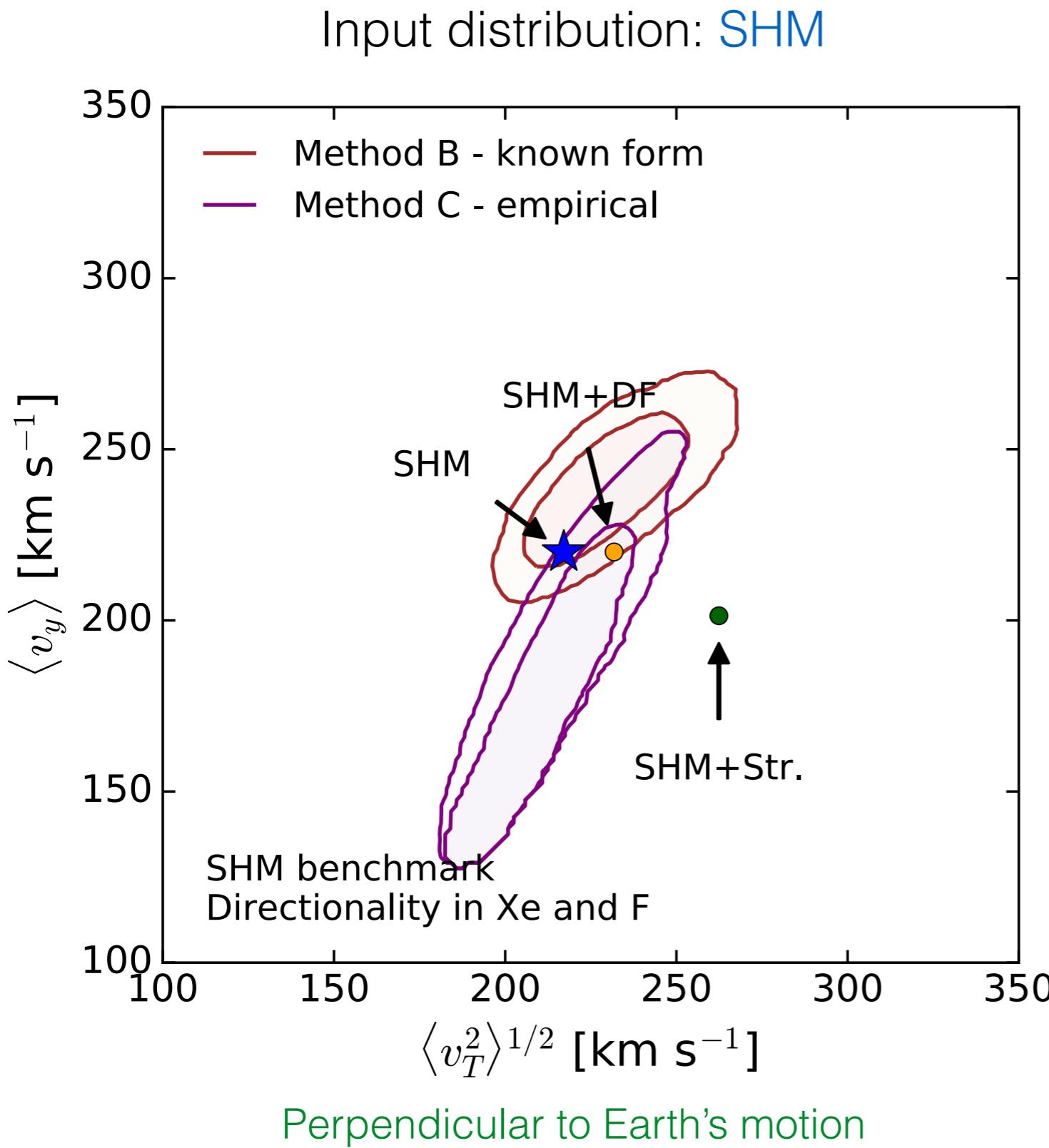
Apply the same parametrisation in 3-D  
(note: some technical details, which make things annoying)

**BJK** [1502.04224]

# Directional reconstructions

BJK, CAJ O'Hare [1609.08630]

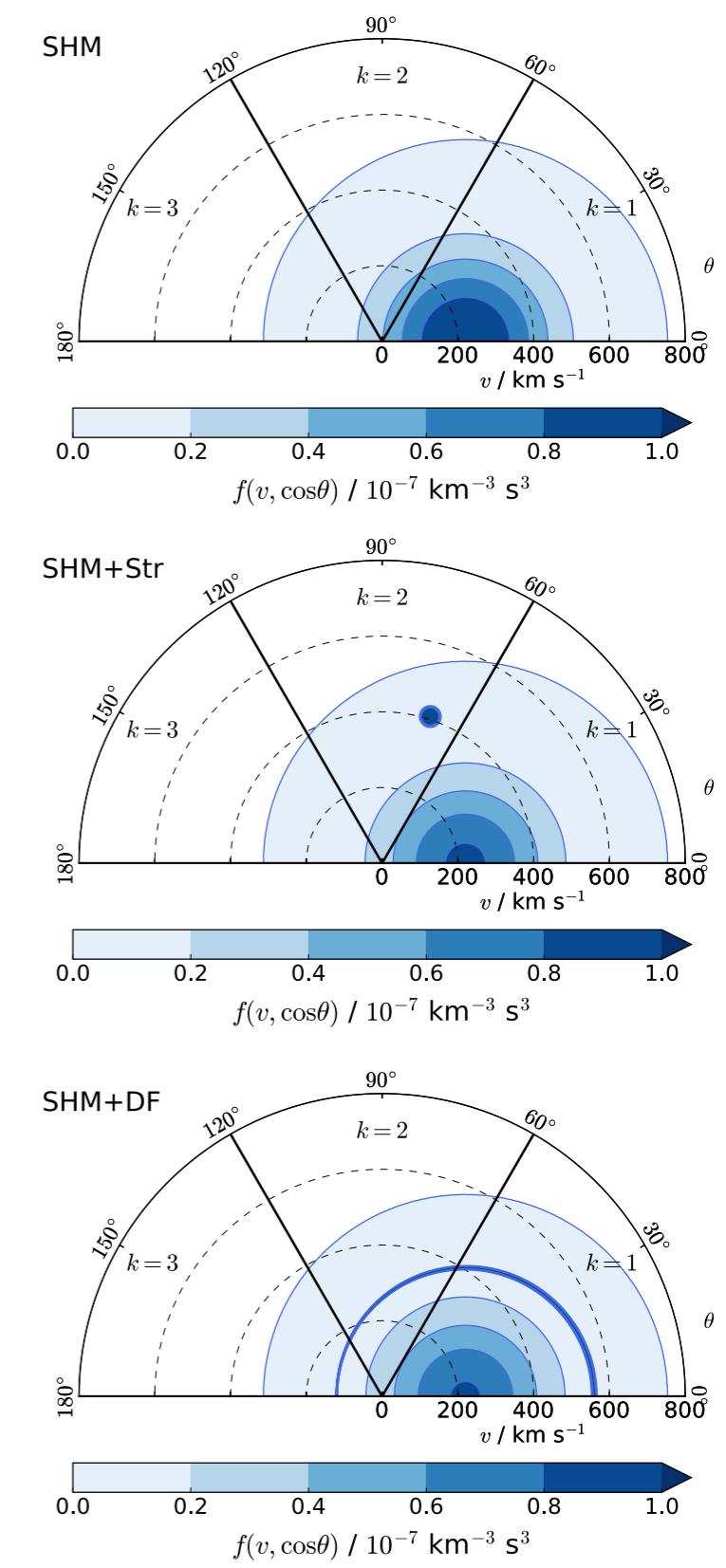
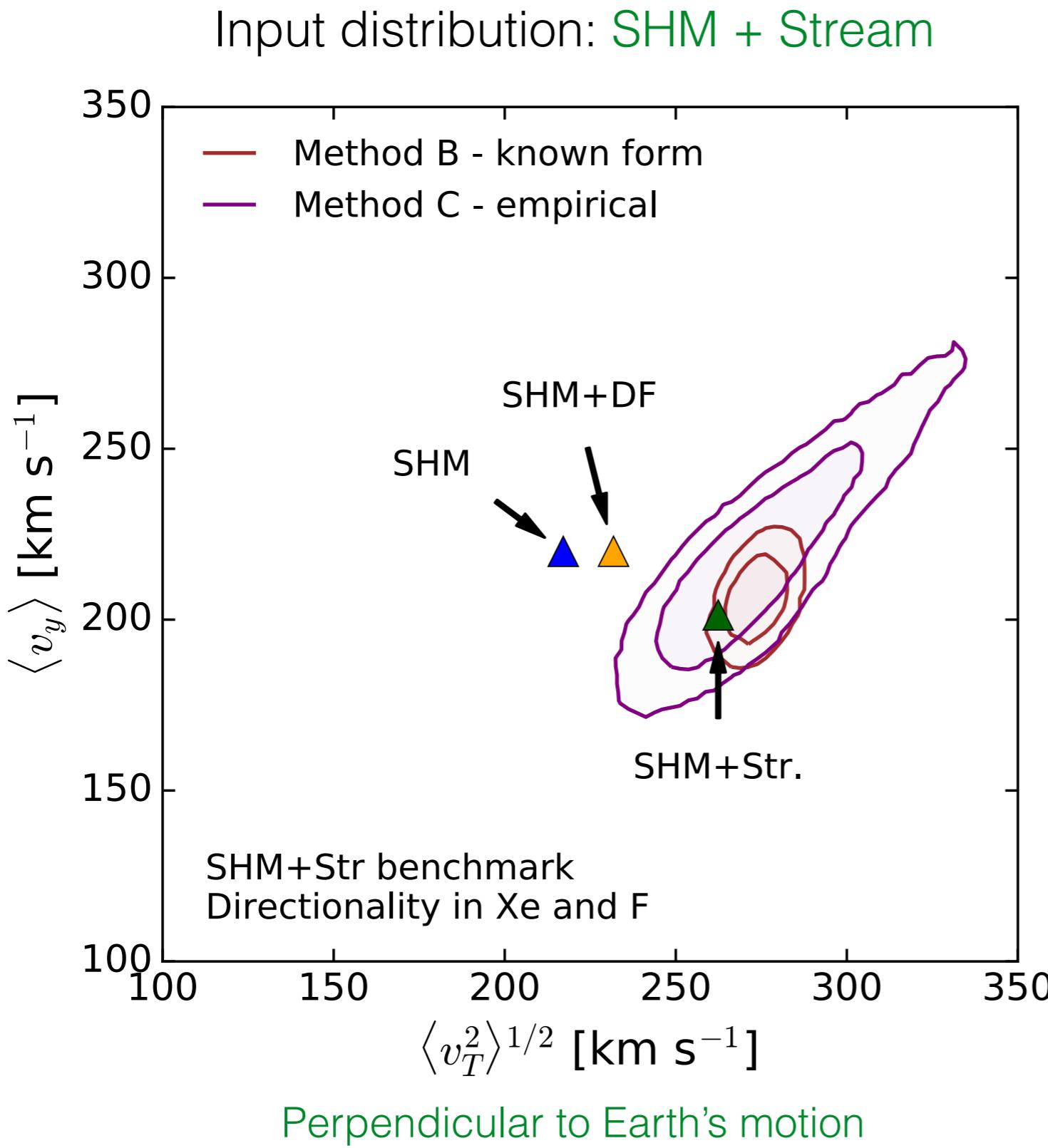
Parallel to Earth's motion



# Directional reconstructions

BJK, CAJ O'Hare [1609.08630]

Parallel to Earth's motion



# Overview

---

Solar system searches for DM:  
Direct detection and Solar Capture

Astrophysical uncertainties

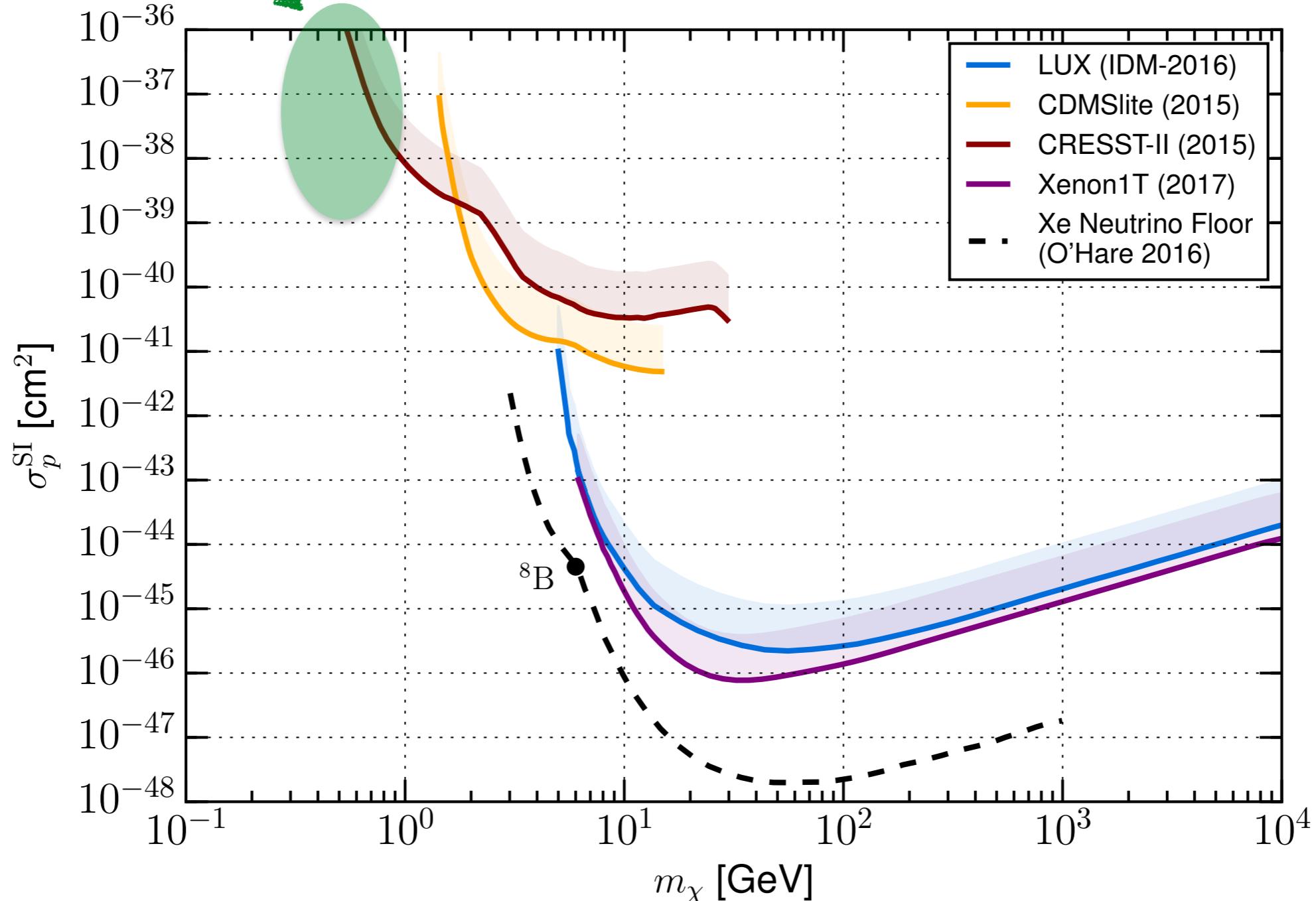
Halo-independent approaches to setting limits

Measuring the DM properties and distribution  
with a future detection

**[Bonus: Can we also measure the local DM density?]**

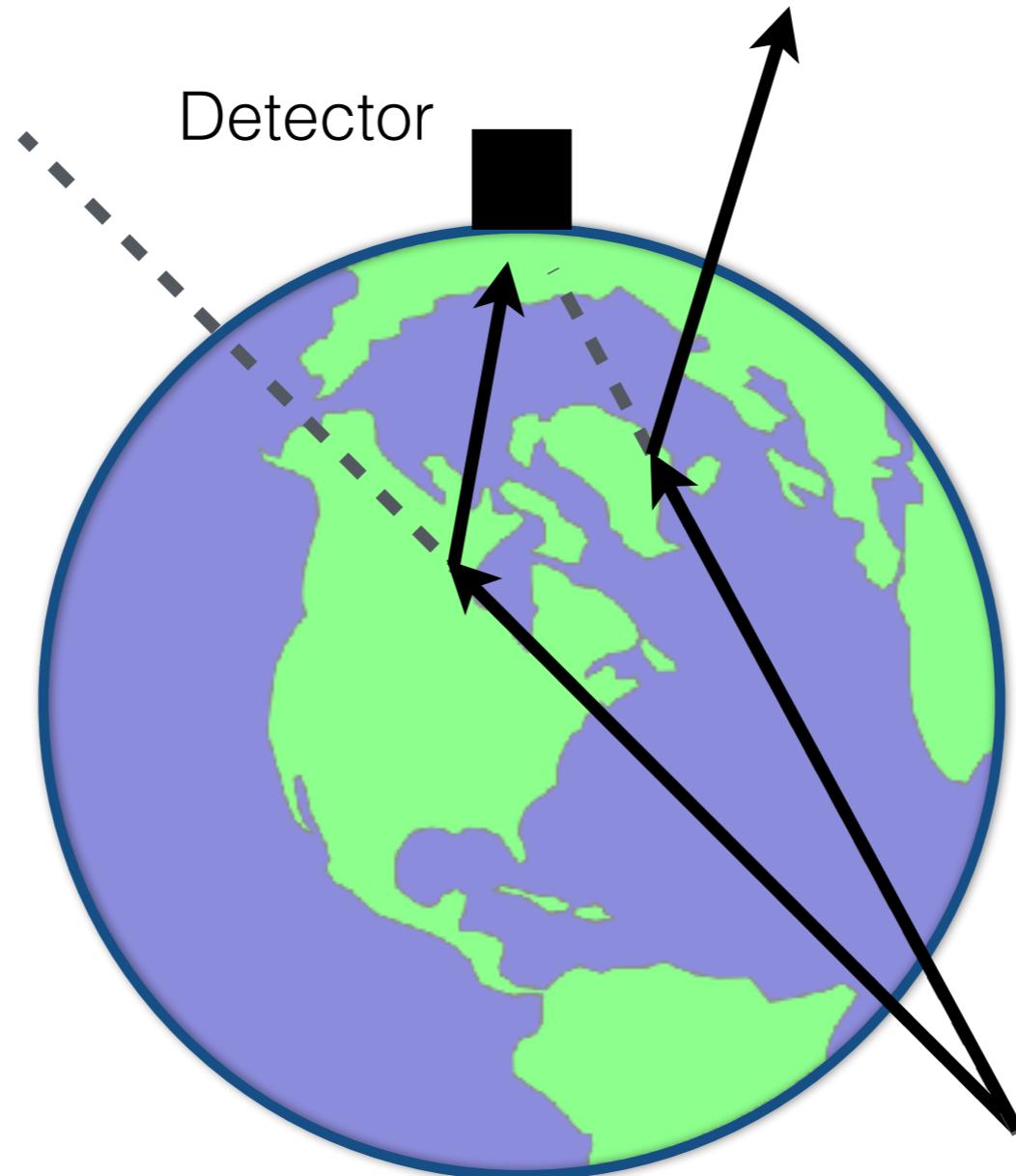
# Map of the parameter space

Sub-GeV DM



# Earth scattering

Collar & Avignone  
[PLB 275, 1992]  
and others



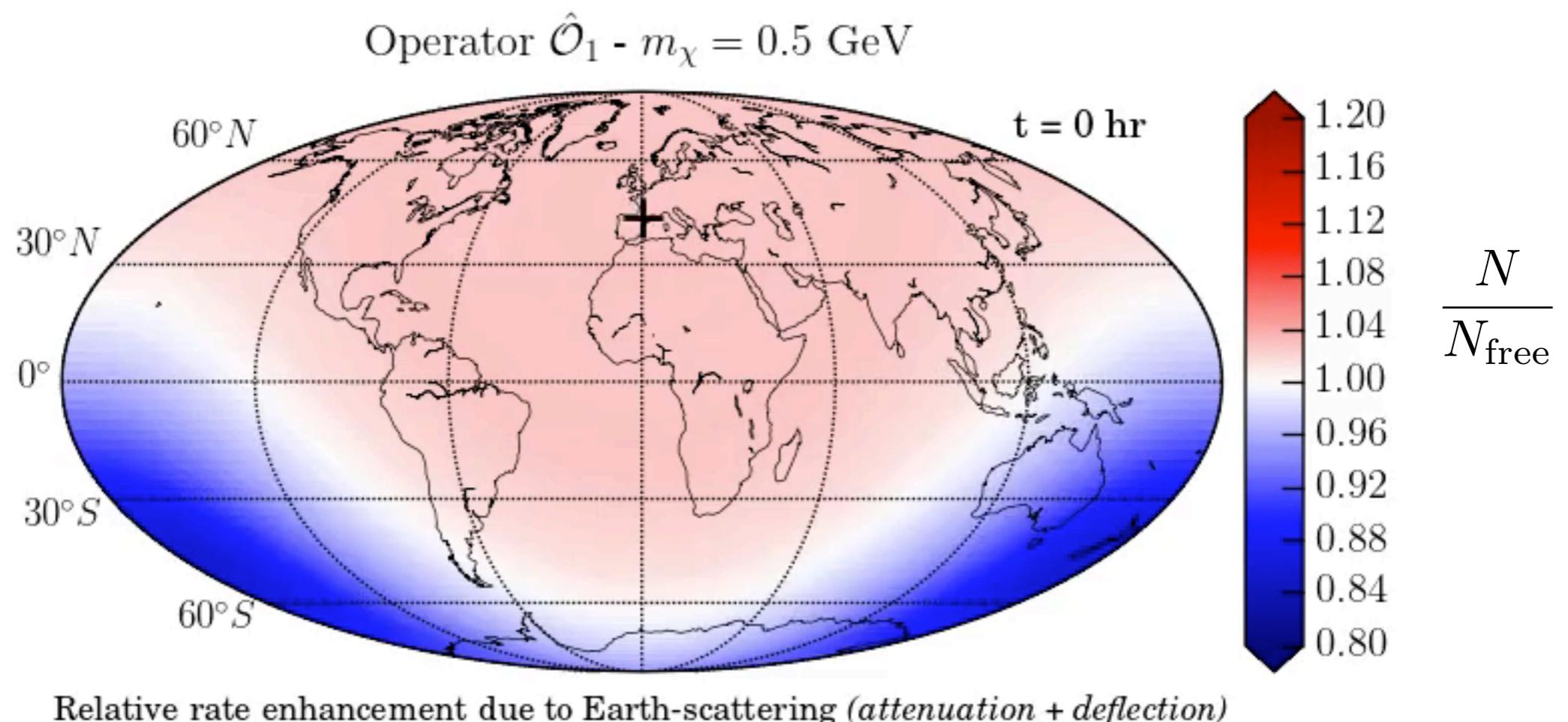
Earth-scattering can distort local density and velocity distribution:

**BJK**, Catena, Kouvaris [1611.05453];  
Emken, Kouvaris, Shoemaker [1702.07750];  
Emken & Kouvaris [1706.02249];  
**BJK** [1712.04901] and others

# Daily Modulation

Assuming DM  
mean free path  
 $\lambda \gtrsim R_E$

In the ‘single-scatter’ regime, can calculate Earth-scattering effects semi-analytically:

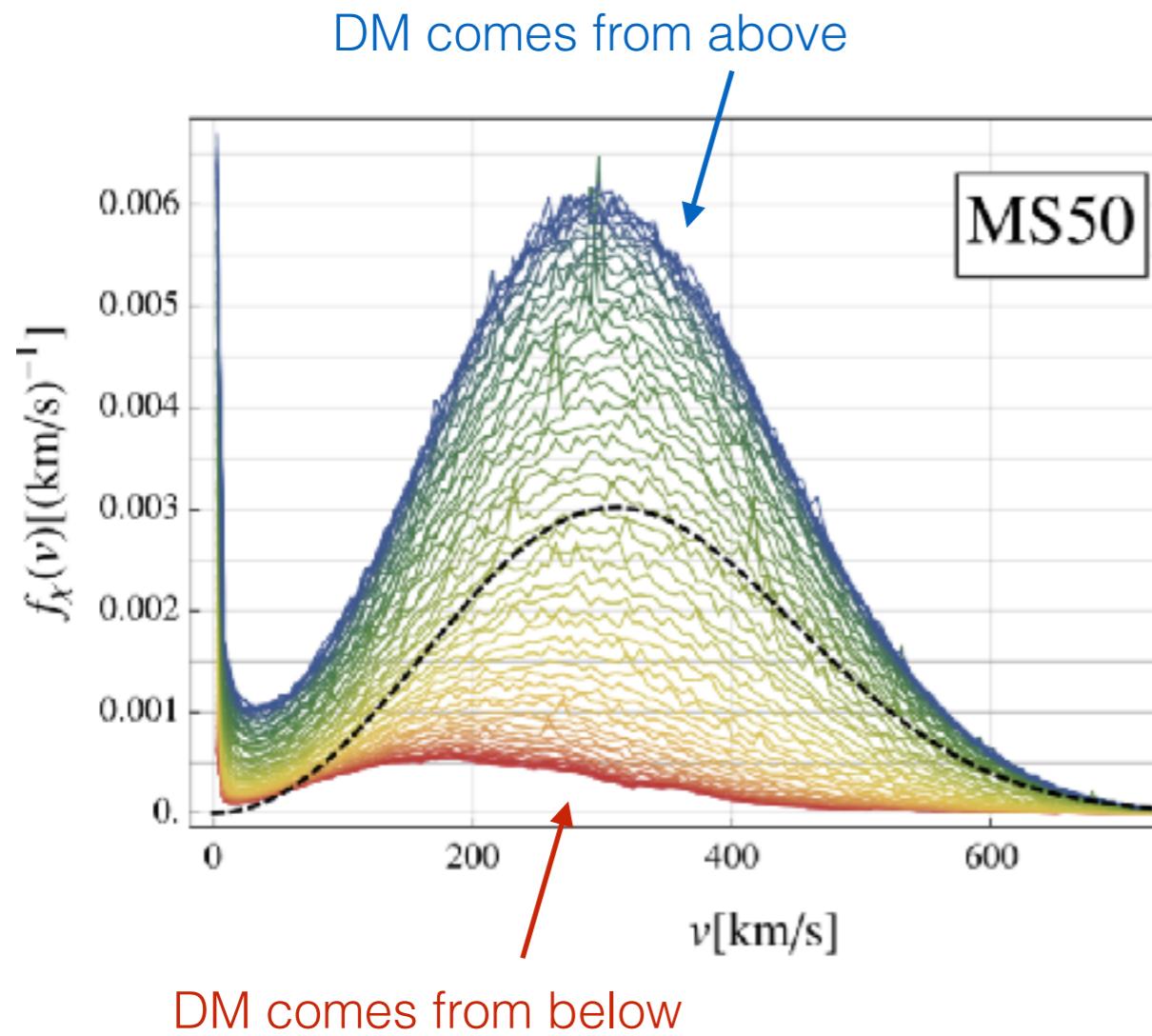


**BJK**, Catena, Kouvaris [1611.05453];  
[github.com/bradkav/EarthShadow](https://github.com/bradkav/EarthShadow)

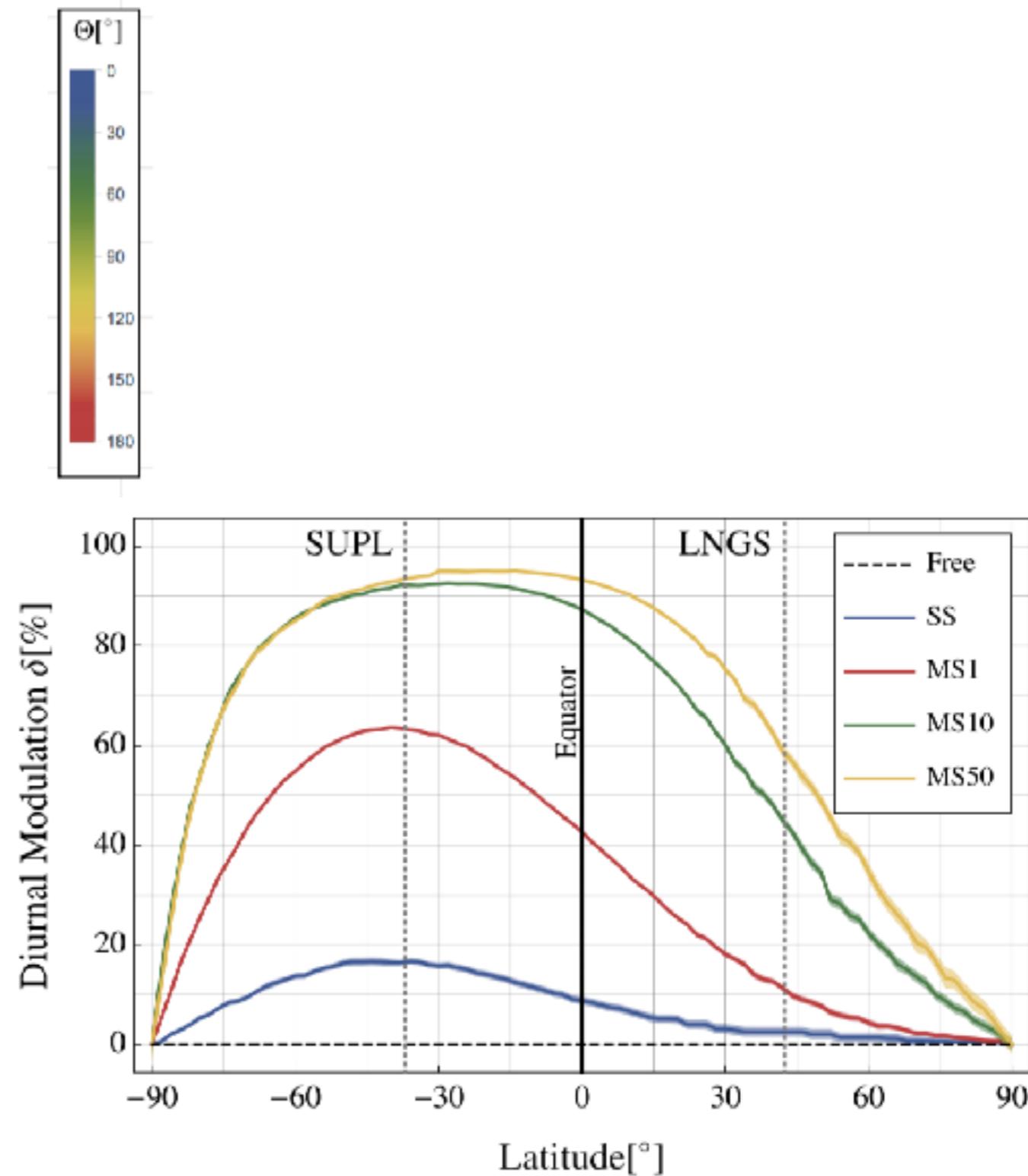
# Modulation signals

Extended with Monte Carlo Simulations

[github.com/temken/DaMaSCUS](https://github.com/temken/DaMaSCUS)



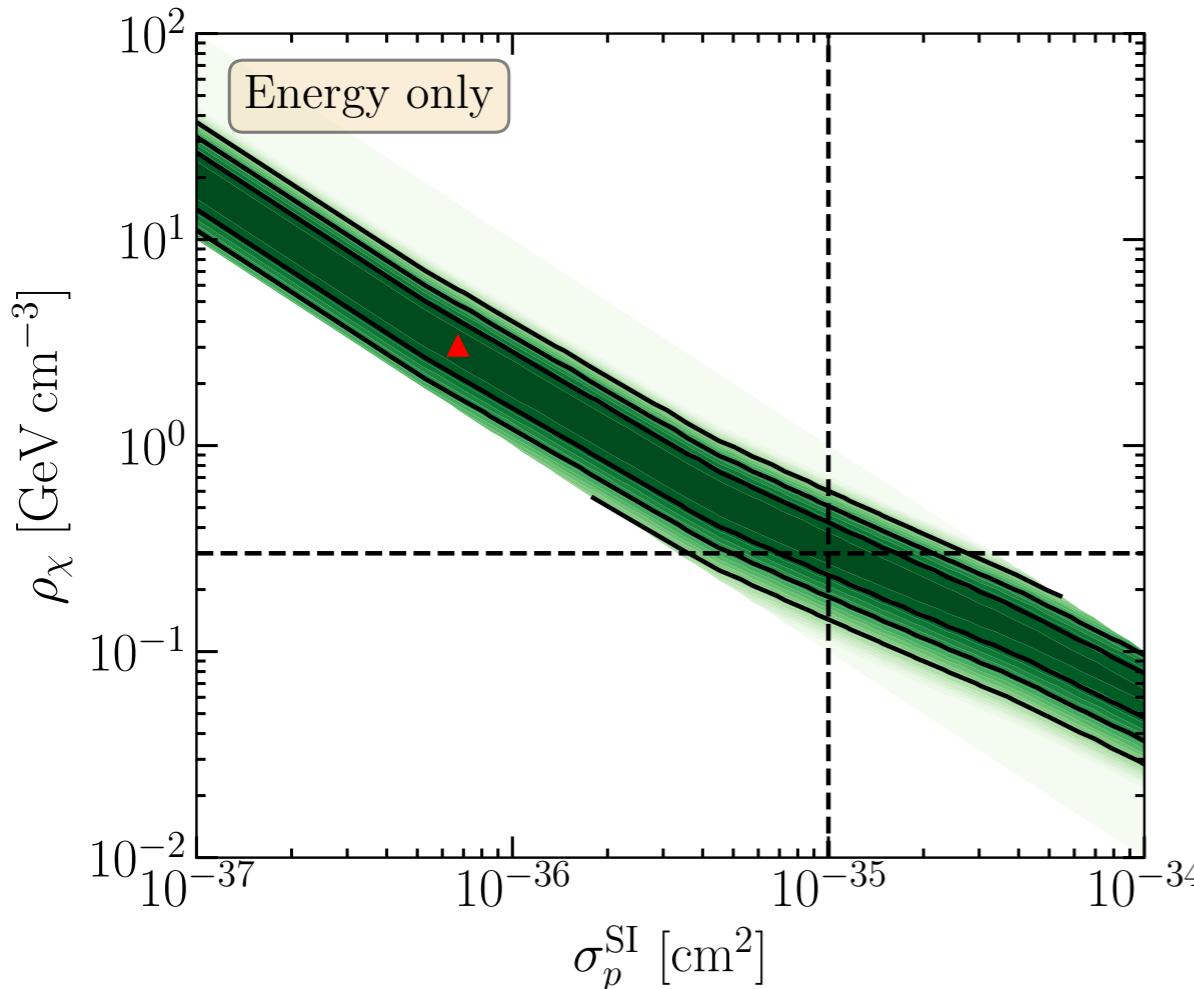
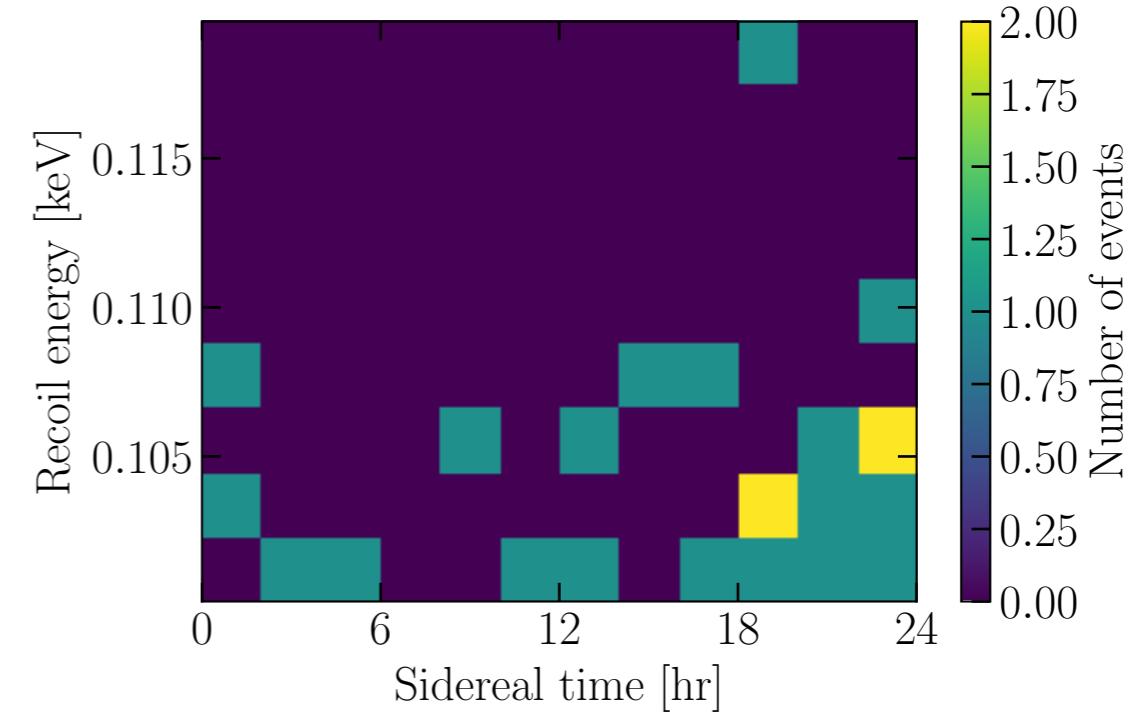
Large O(1) daily modulation if  
DM scatters  $\sim$ 50 times during  
Earth-crossing



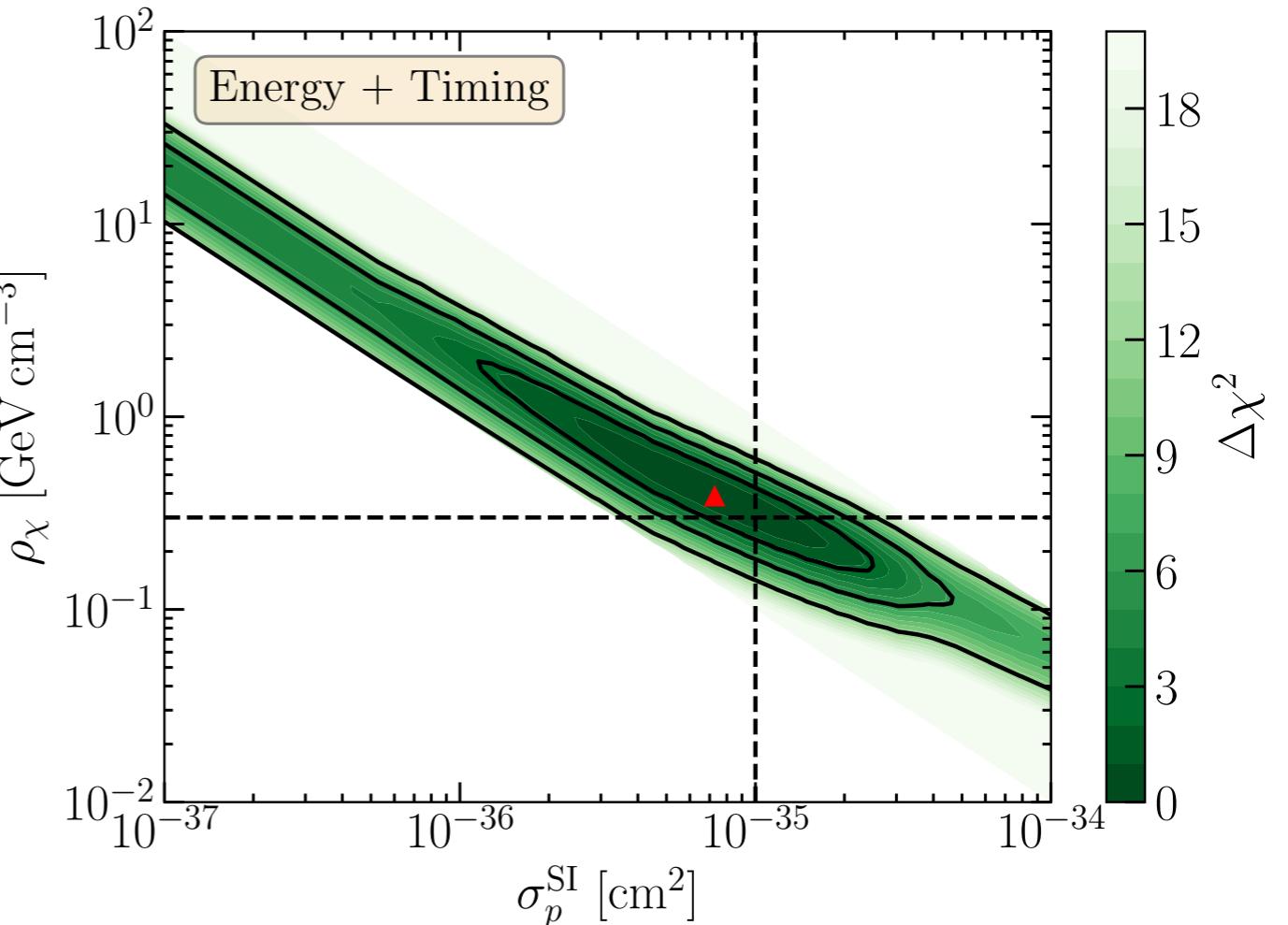
Emken & Kouvaris [1706.02249]

# Preliminary results

100g Ge detector  
30 day exposure  
LNGS, Italy  
 $O(30)$  events



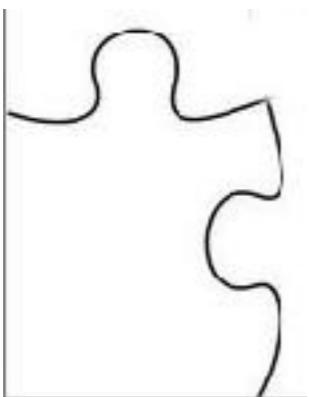
$$m_\chi = 0.5 \text{ GeV}$$



**BJK & Catena [XXXX.XXXX]**

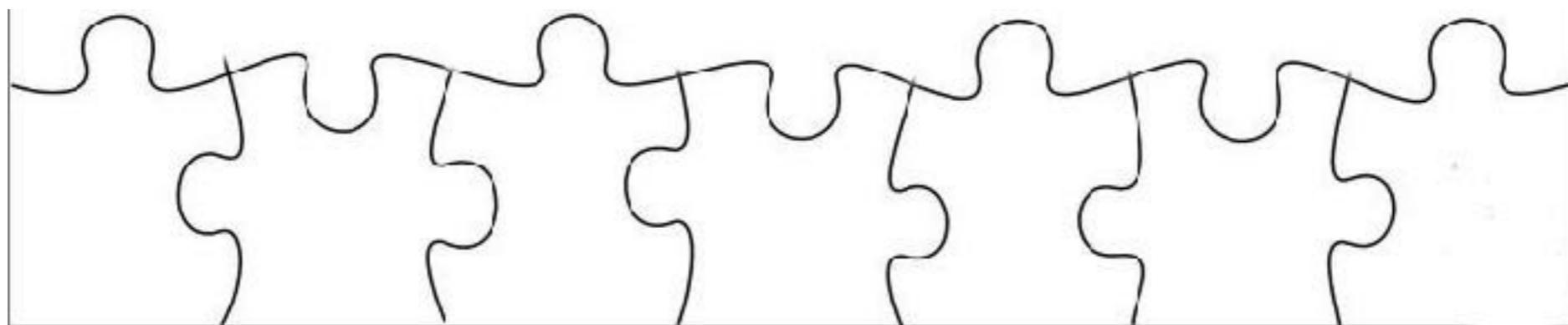
# Summary (I)

---



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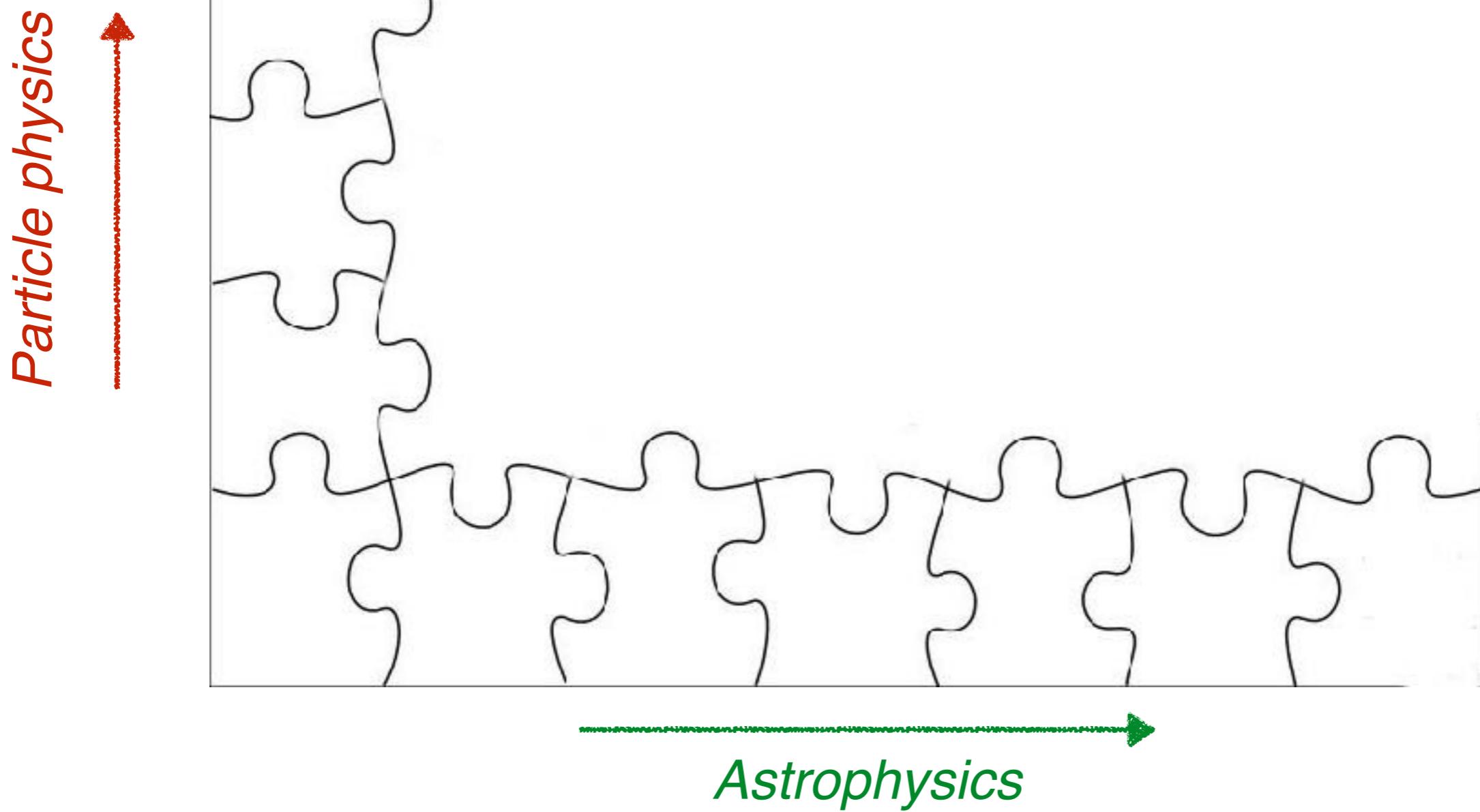
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*Astrophysics*

# Summary (I)

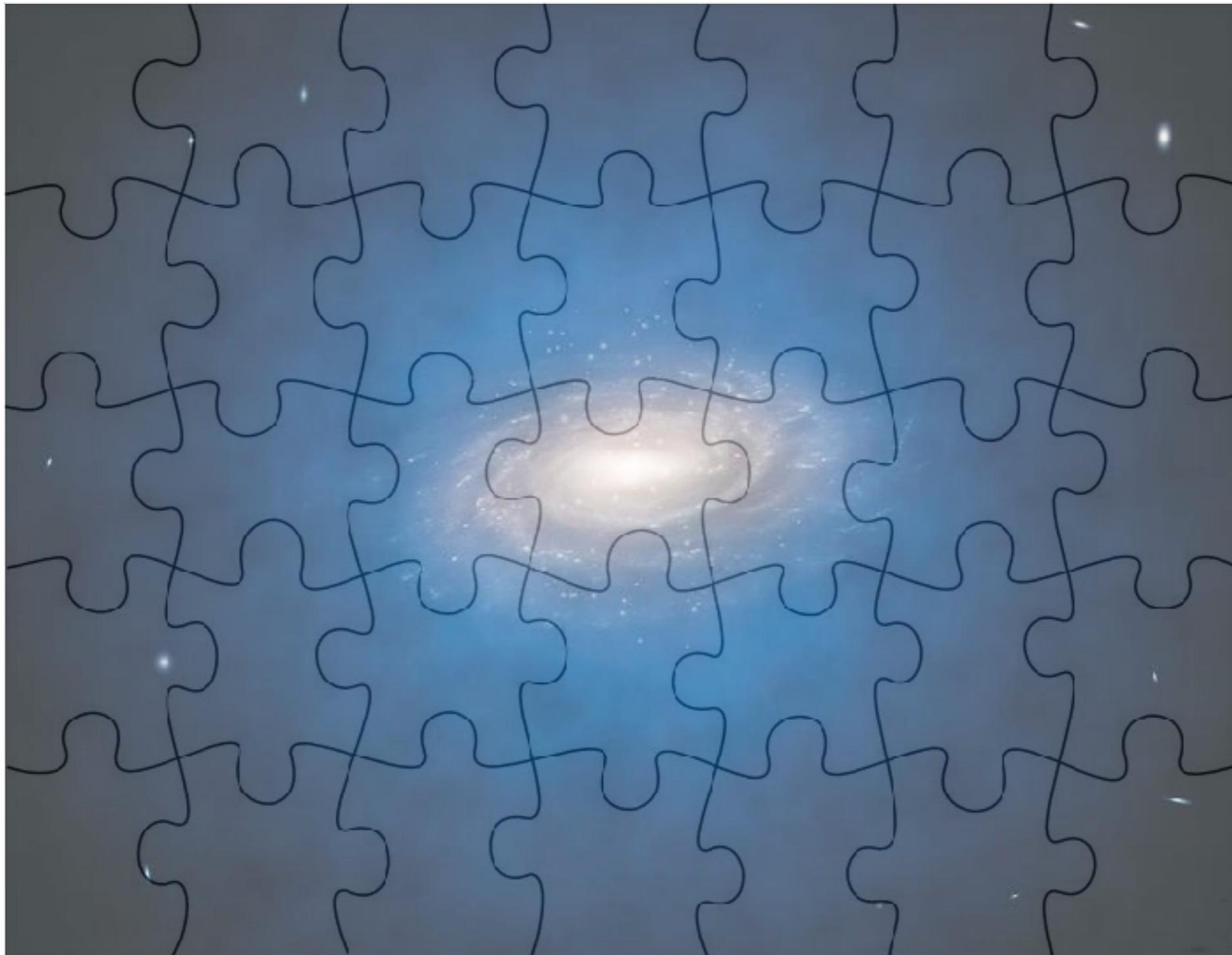
---



# Summary (I)

---

*Particle physics*



*Astrophysics*



# Summary (II)

---

We can set limits from local DM searches in a **fully astrophysics-independent** way

Ibarra, **BJK**, Rappelt [1806.08714]

We can simultaneous extract the mass and shape of the speed distribution of DM with a **future direct detection**

**BJK**, Green [1207.2039, 1303.6868, 1312.1852]

Probing low speed DM with **Solar Capture** allows us to pin down the DM cross section

**BJK**, Fornasa, Green [1410.8051]

It could be possible to measure the full 3-D DM velocity distribution with **directional experiments**

**BJK** [1502.04224];  
**BJK**, O'Hare [1609.08630]

If we're lucky, we may even one day measure the **local DM density**

**BJK** & Catena [XXXX.XXXX]

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If we're lucky, we may even one day measure the **local DM density**

**BJK** & Catena [XXXX.XXXX]

Thank you!

# Back-up Slides

# Particle Physics of DM

---

Typically assume contact interactions (heavy mediators).  
In the non-relativistic limit, leading order cross section scales like:

$$\sigma \sim v^0 \Rightarrow \frac{d\sigma}{dE_R} \sim \frac{1}{v^2}$$

Write in terms of DM-proton cross section:

$$\frac{d\sigma^A}{dE_R} \propto \frac{\sigma^p}{\mu_{\chi p}^2 v^2} \mathcal{C}_A F^2(E_R)$$

Form factor accounts for  
loss of coherence at high  
energy



Enhancement factor different for:

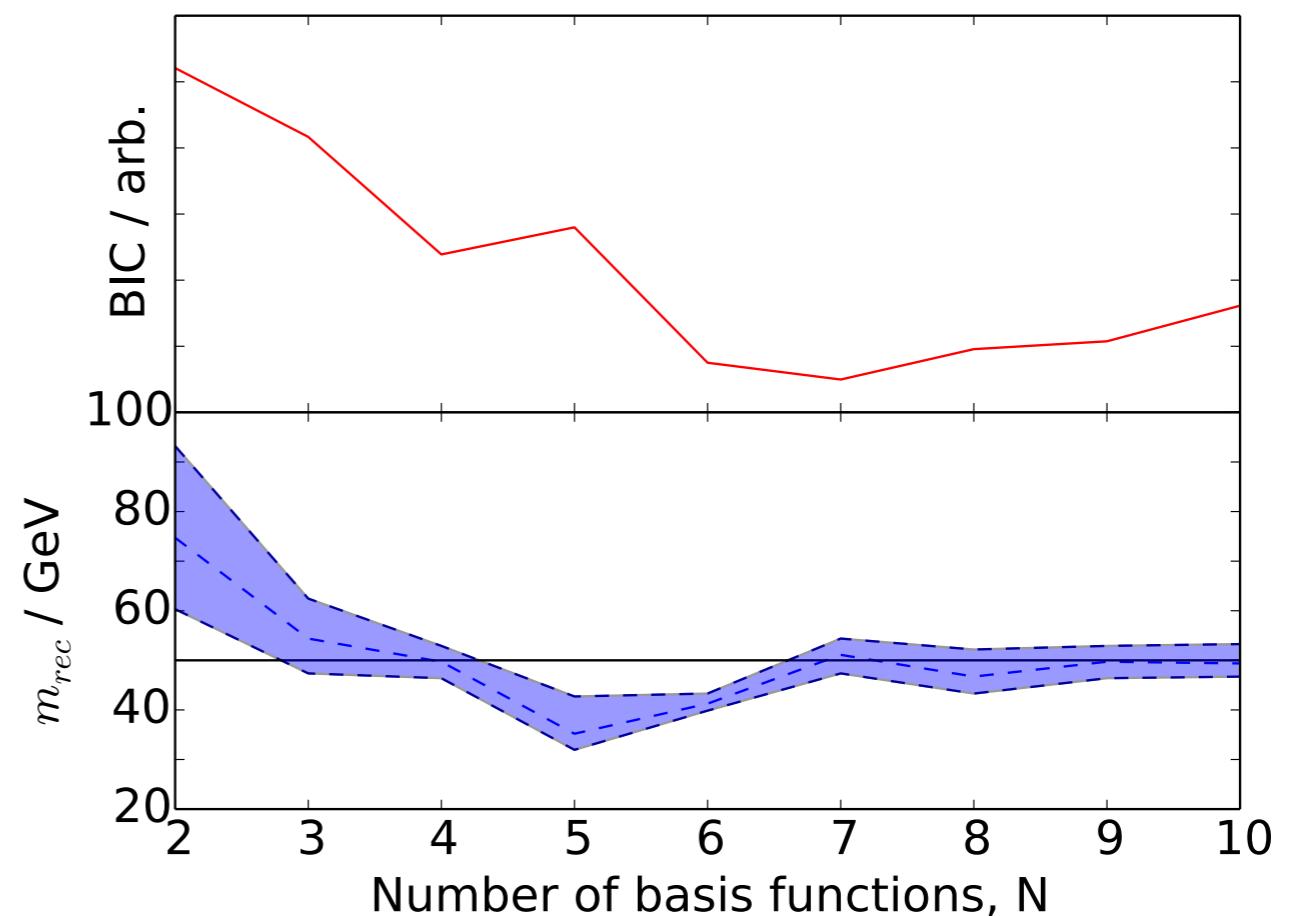
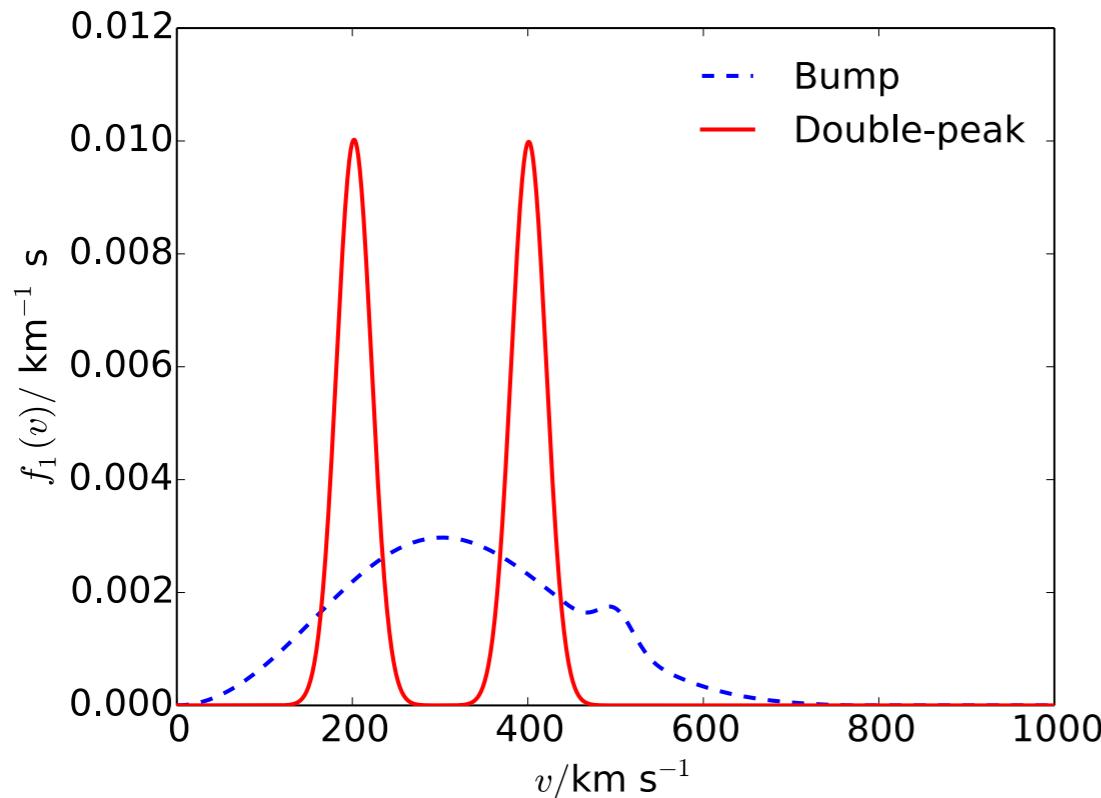
*spin-independent (SI) interactions* -  $\mathcal{C}_A^{\text{SI}} \sim A^2$

*spin-dependent (SD) interactions* -  $\mathcal{C}_A^{\text{SD}} \sim (J+1)/J$

Interactions which are higher order in  $v$  are possible.  
See the non-relativistic EFT of Fitzpatrick et al. [1203.3542].  
See also Edwards, **BJK**, Weniger [1805.04117].

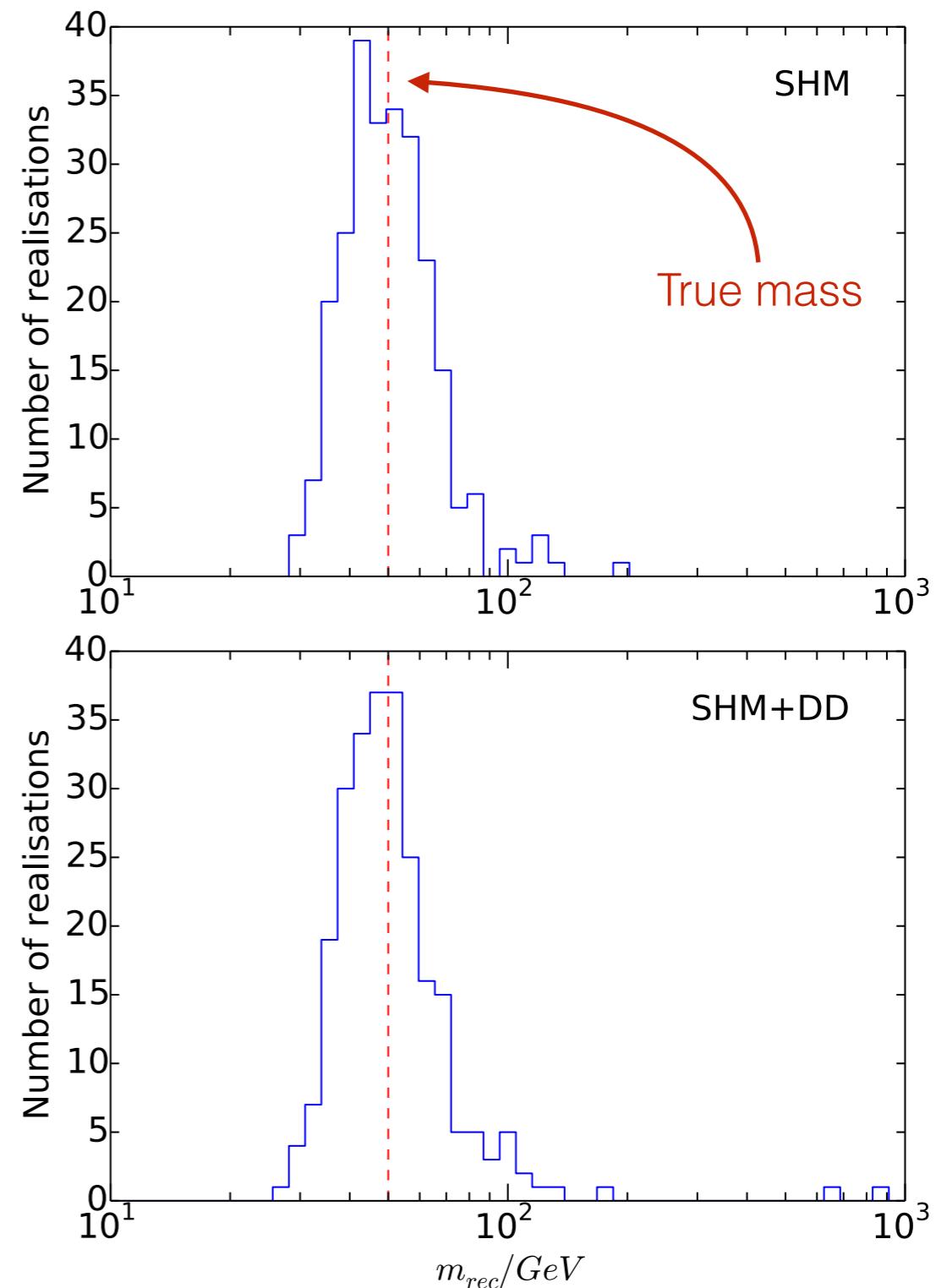
# Polynomial Parametrisation

$$f(v) = v^2 \exp \left( - \sum_{k=0}^{N-1} a_k v^k \right)$$



# Different Speed Distributions

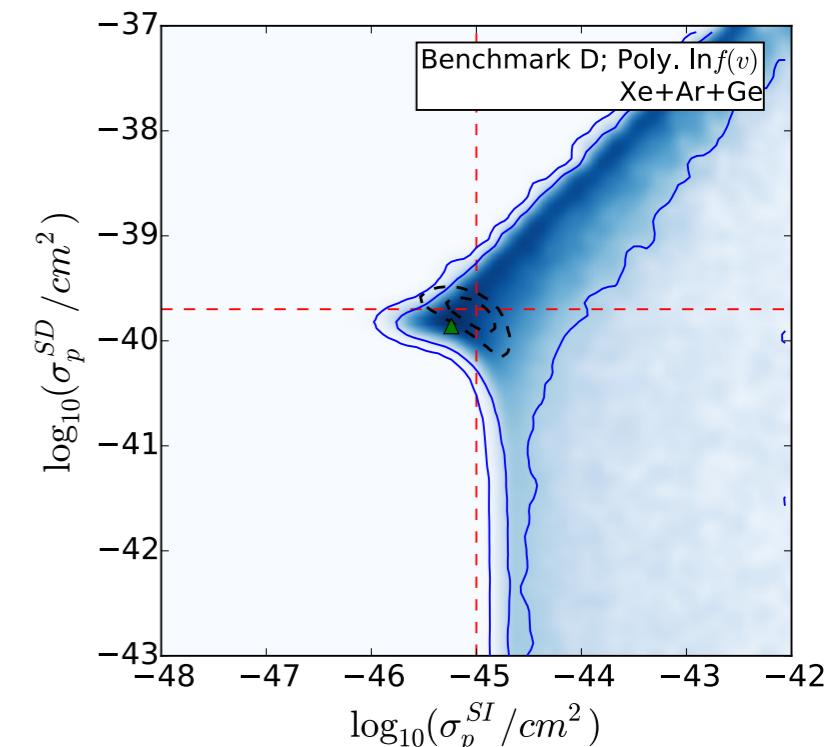
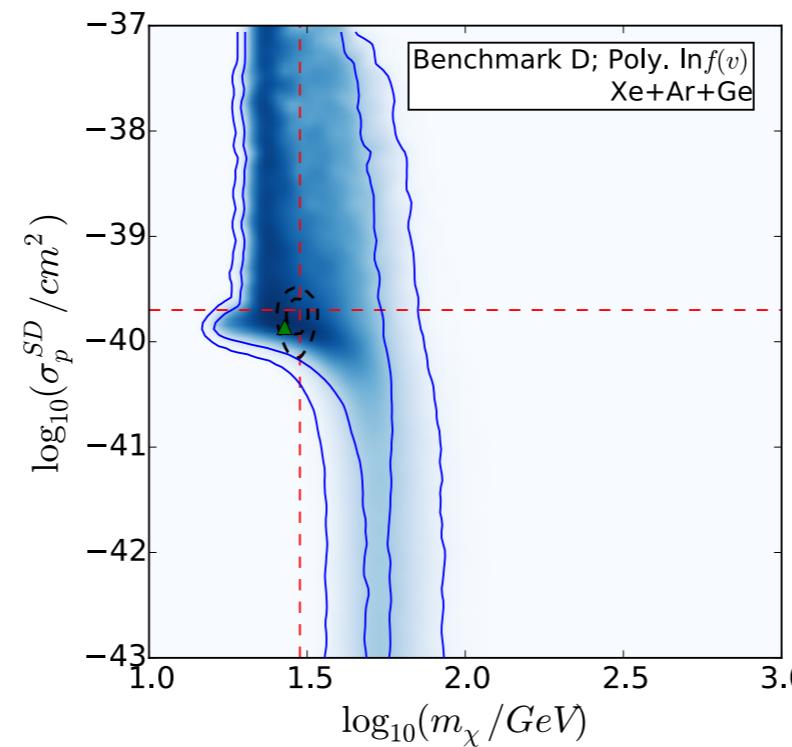
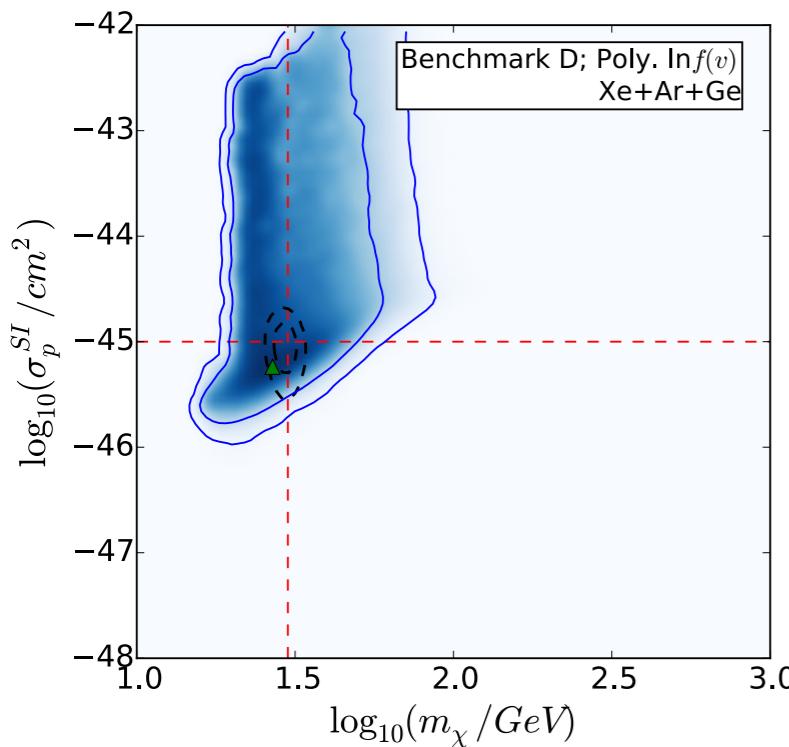
- Generate 250 mock data sets
- Reconstruct mass and obtain confidence intervals for each data set
- True mass reconstructed well (independent of speed distribution)
- Can also check that 68% intervals *are really 68% intervals*



# Full reconstructions (without IceCube)

Consider a single benchmark:

$m_\chi = 30 \text{ GeV}$ ;  $\sigma_{SI}^p = 10^{-45} \text{ cm}^2$ ;  $\sigma_{SD}^p = 2 \times 10^{-40} \text{ cm}^2$   
annihilation to  $\nu_\mu \bar{\nu}_\mu$ , SHM+DD distribution



Benchmark  
Best fit

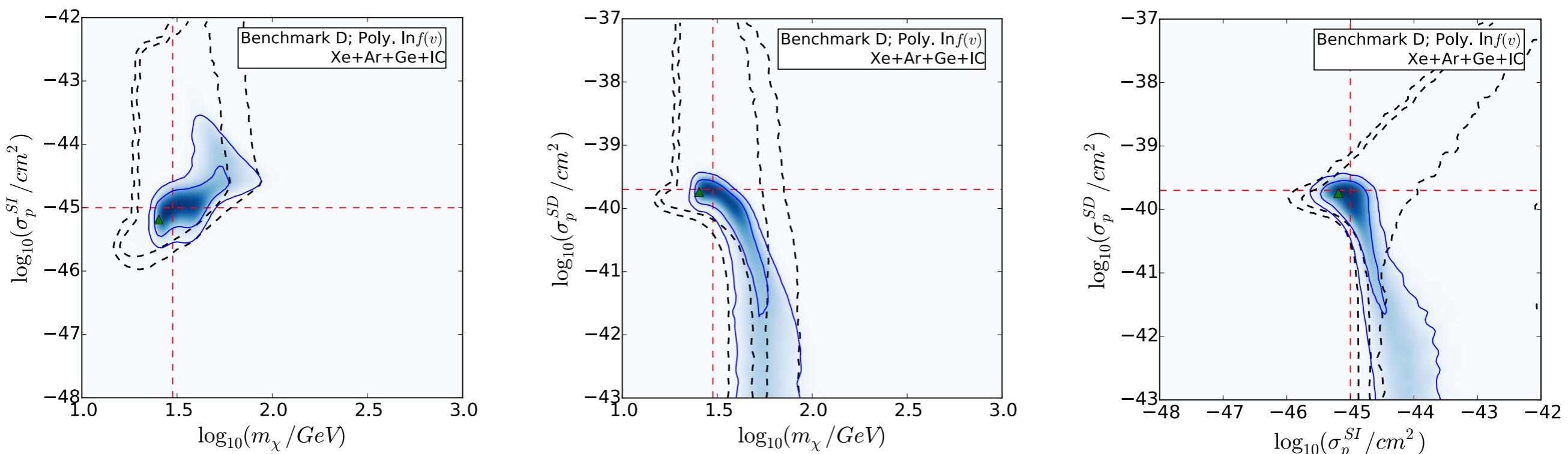
Fixed (correct) speed distribution  
Our parametrisation

-----  
\_\_\_\_\_

# Full reconstructions (with IceCube)

Consider a single benchmark:

$m_\chi = 30 \text{ GeV}$ ;  $\sigma_{SI}^p = 10^{-45} \text{ cm}^2$ ;  $\sigma_{SD}^p = 2 \times 10^{-40} \text{ cm}^2$   
annihilation to  $\nu_\mu \bar{\nu}_\mu$ , SHM+DD distribution



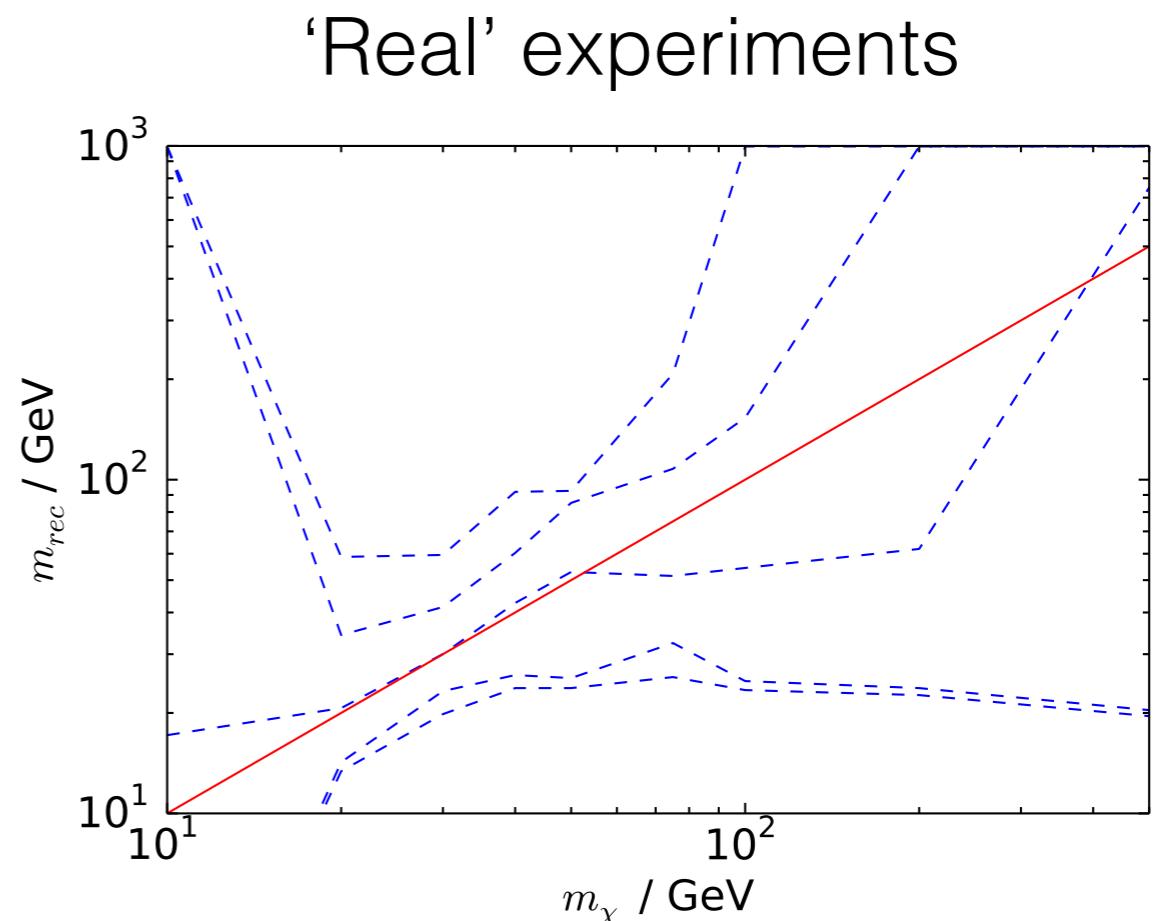
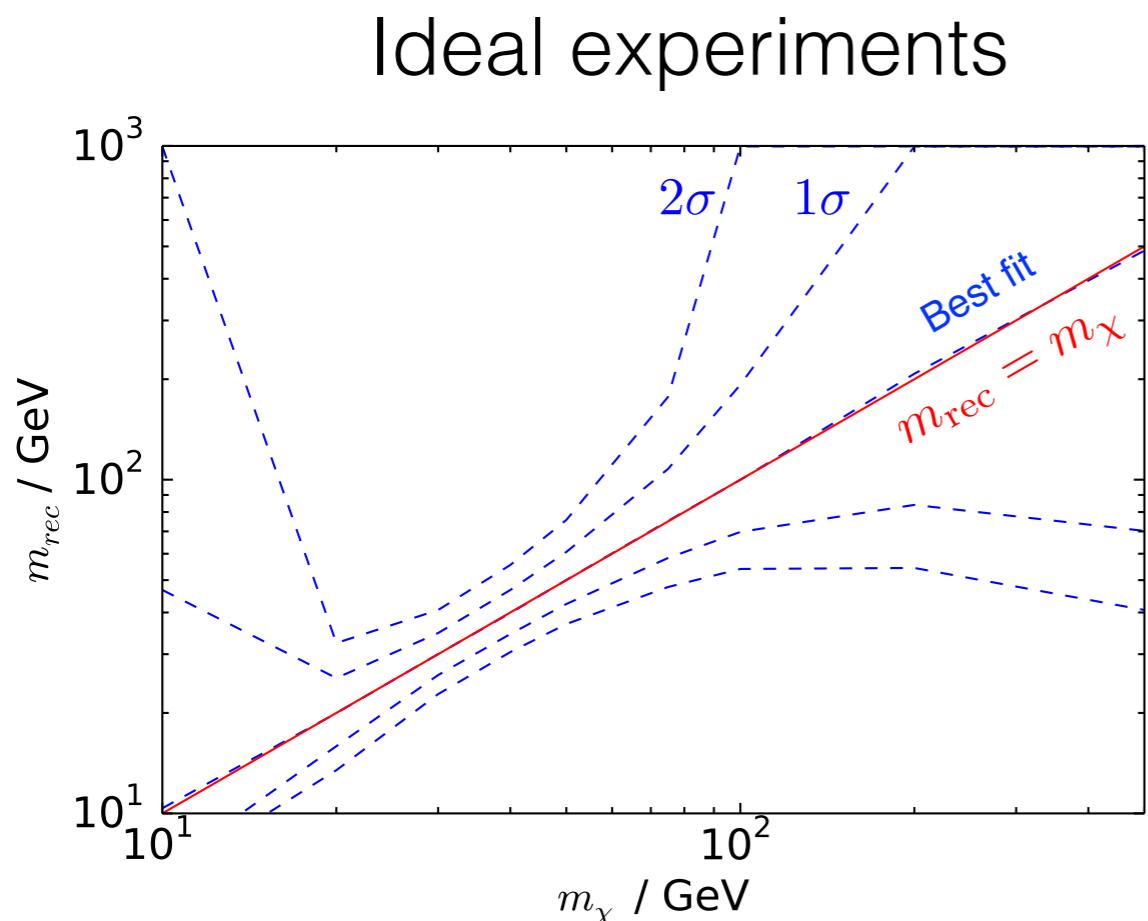
Benchmark

Best fit

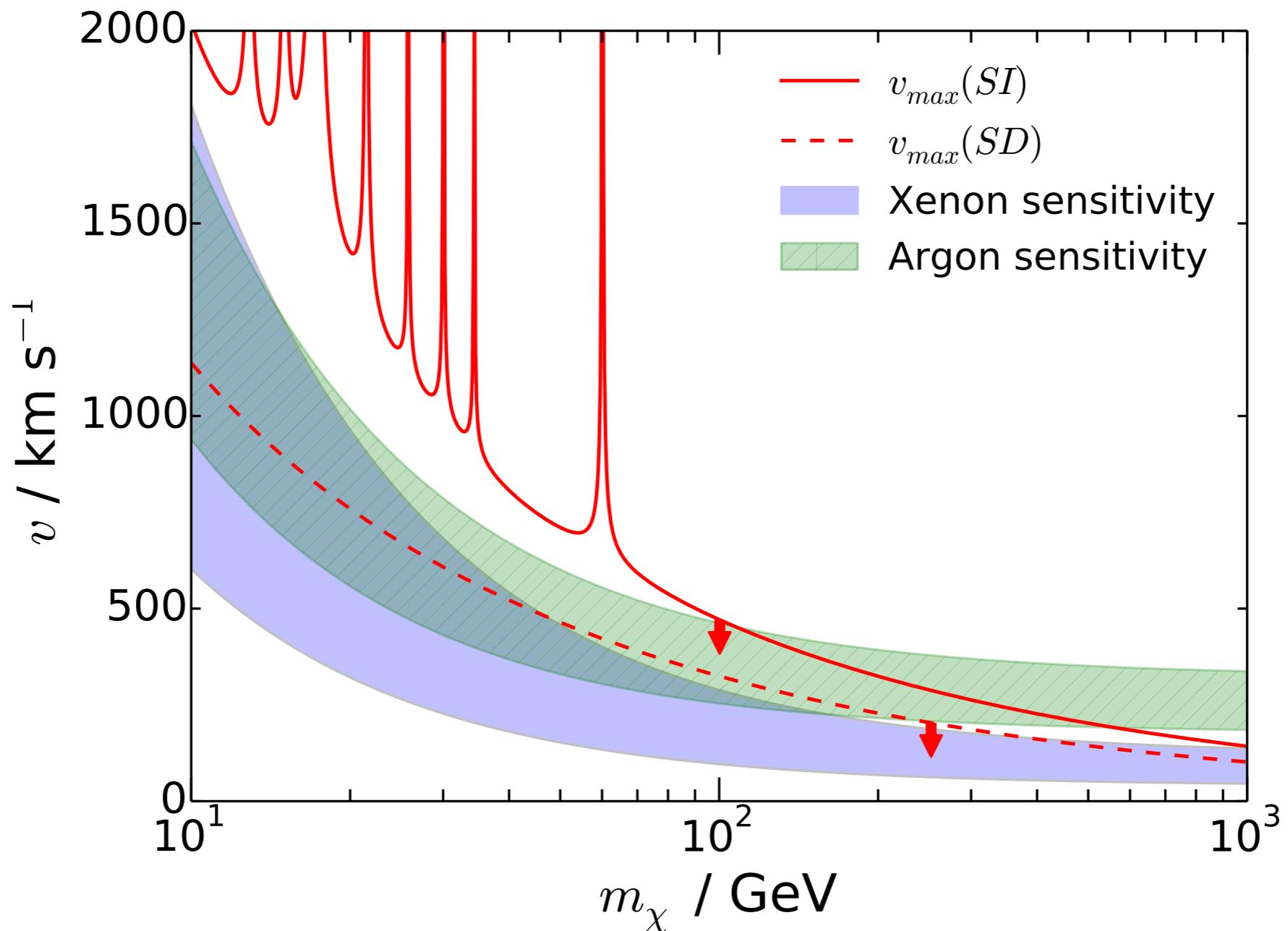
Direct detection only (our param.)

Direct detection + IceCube (our param.)

# 'Real' Experiments



# SI vs SD Solar Capture

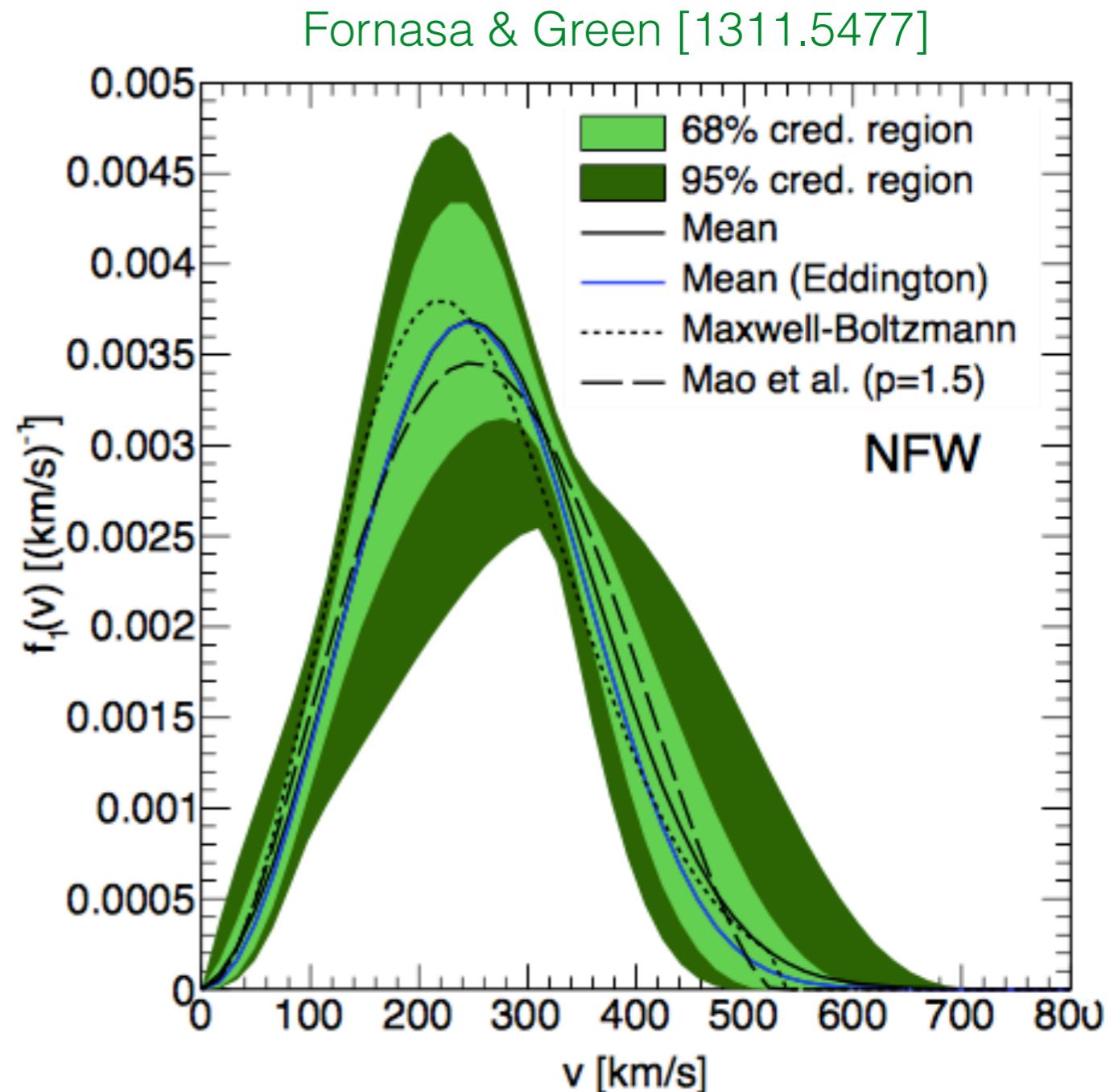


# Self-consistent distributions

Attempt to reconstruct a self-consistent distribution function from the Milky Way mass distribution, by Eddington's formula:

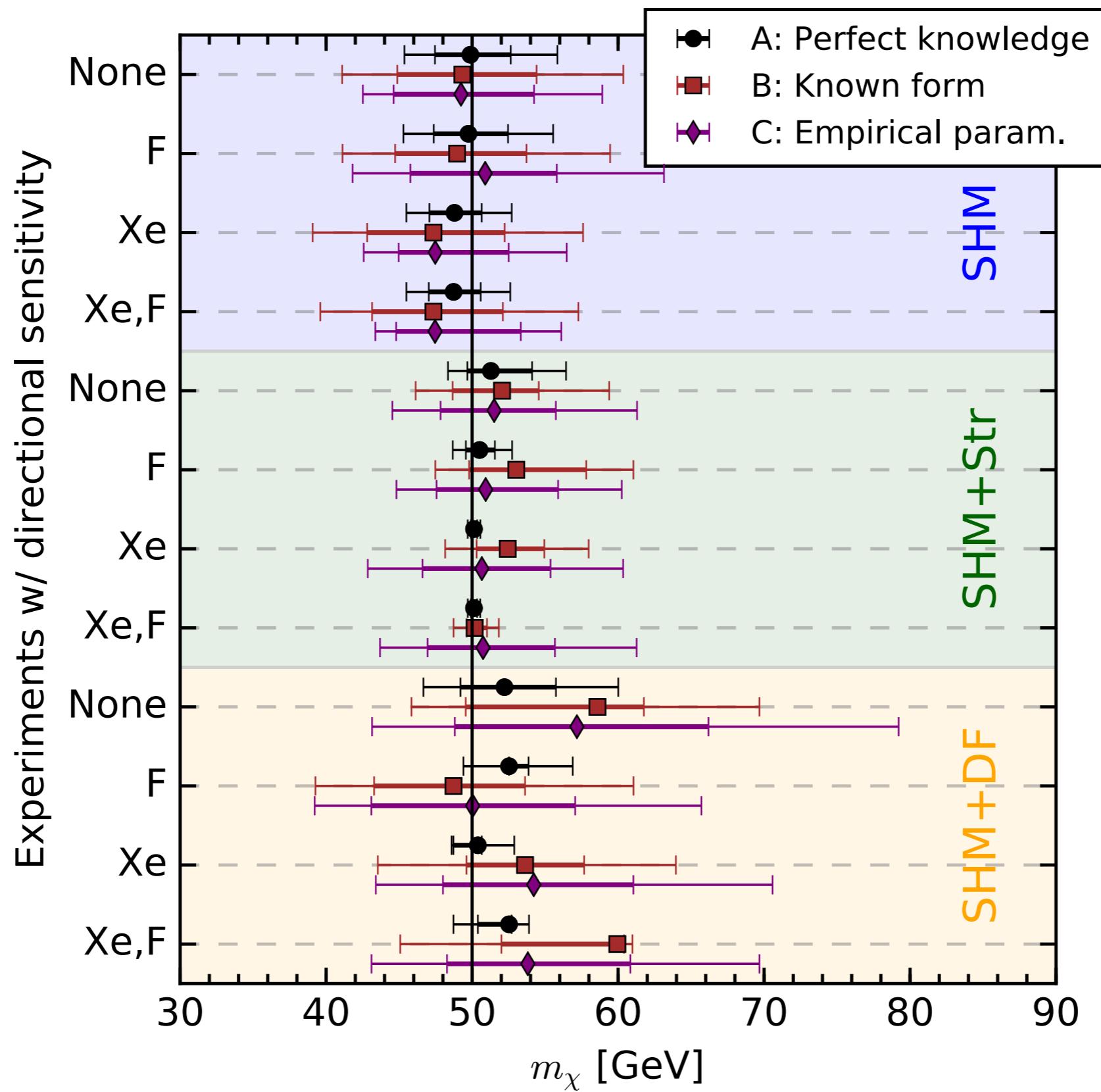
$$\mathcal{F}(\mathcal{E}) = \frac{1}{\sqrt{8\pi^2}} \int_0^{\mathcal{E}} \frac{d\Psi}{\sqrt{\mathcal{E} - \Psi}} \frac{d^2\rho}{d\Psi^2}$$

$$\mathcal{E} = \frac{1}{2}v^2 - \Psi(r)$$



See also Bhattacharjee et al. [1210.2328];  
Bozorgnia et al. [1310.0468]; Mandal et al. [1806.06872]

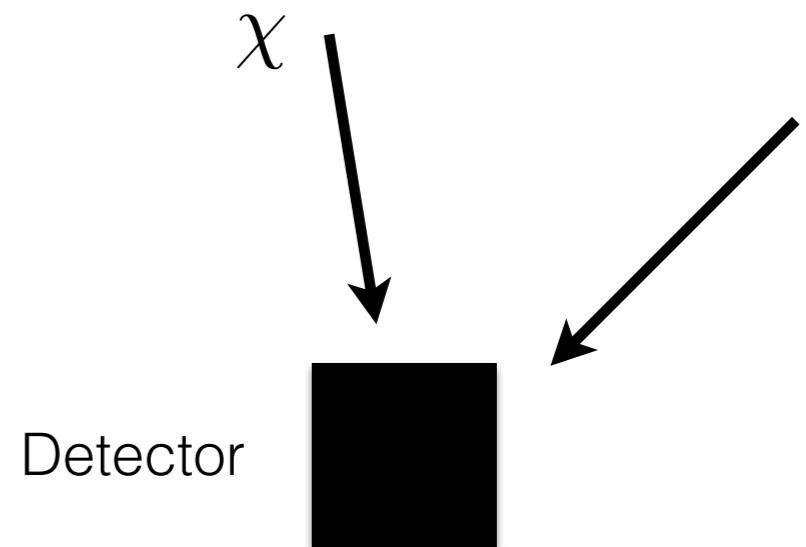
# Mass reconstruction with directionality



# Discretising $f(\mathbf{v})$

---

If we want to fit the *velocity* distribution, we now have an *infinite* number of functions to parametrise (one for each incoming direction  $(\theta, \phi)$ )!



Make the problem more tractable: divide  $f(\mathbf{v})$  into  $N = 3$  angular bins...

$$f(\mathbf{v}) = f(v, \cos \theta, \phi) = \begin{cases} f^1(v) & \text{for } \theta \in [0^\circ, 60^\circ] \\ f^2(v) & \text{for } \theta \in [60^\circ, 120^\circ] \\ f^3(v) & \text{for } \theta \in [120^\circ, 180^\circ] \end{cases}$$

BJK [1502.04224]

...and then parametrise  $f^k(v)$  within each angular bin.

# Discretising $f(v)$

