

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

Bradley J Kavanagh
GRAPPA, University of Amsterdam

17th October 2018
PRISMA Colloquium, Mainz

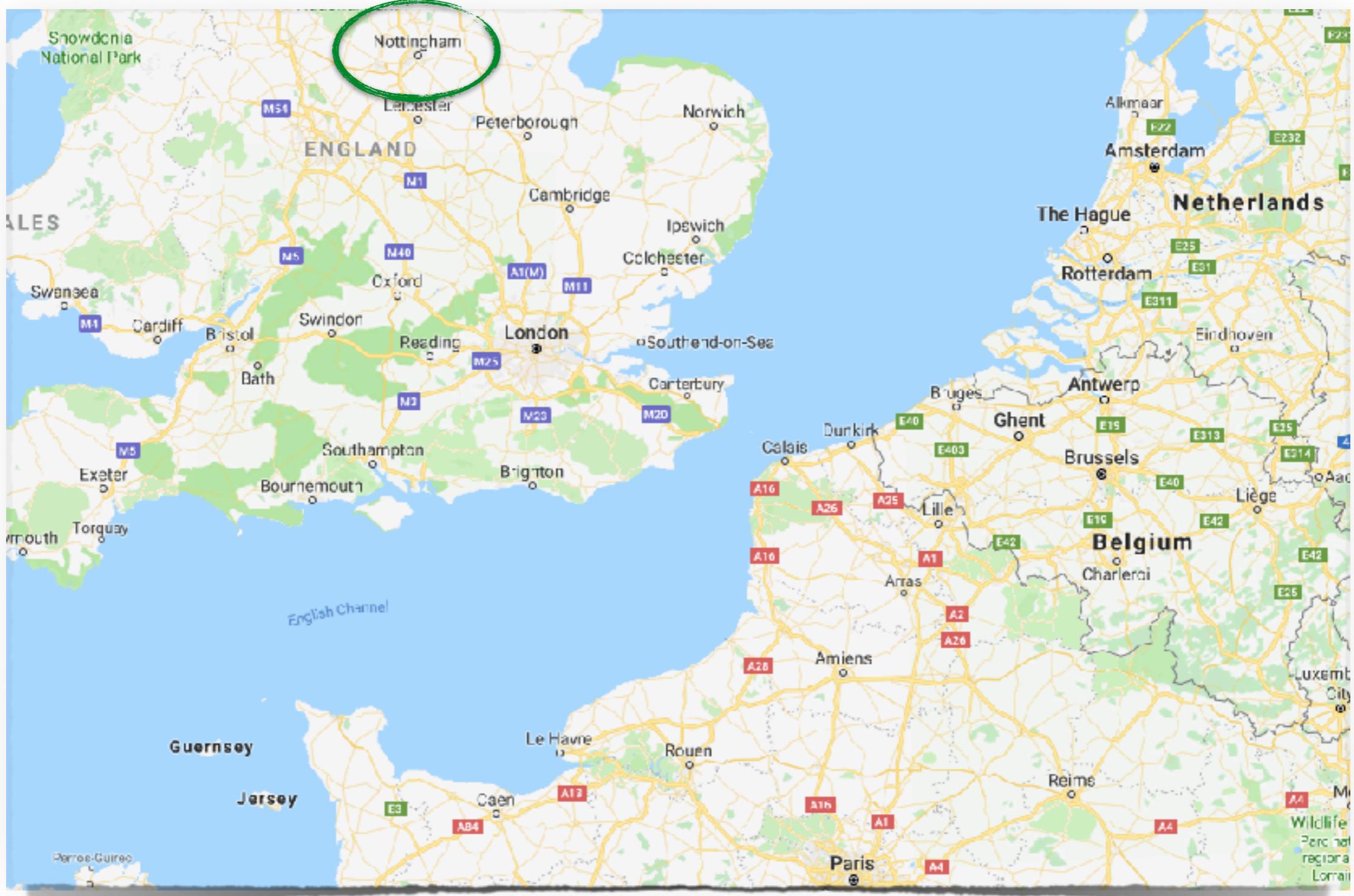


Undergraduate (2007-2011): University of Cambridge, UK



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

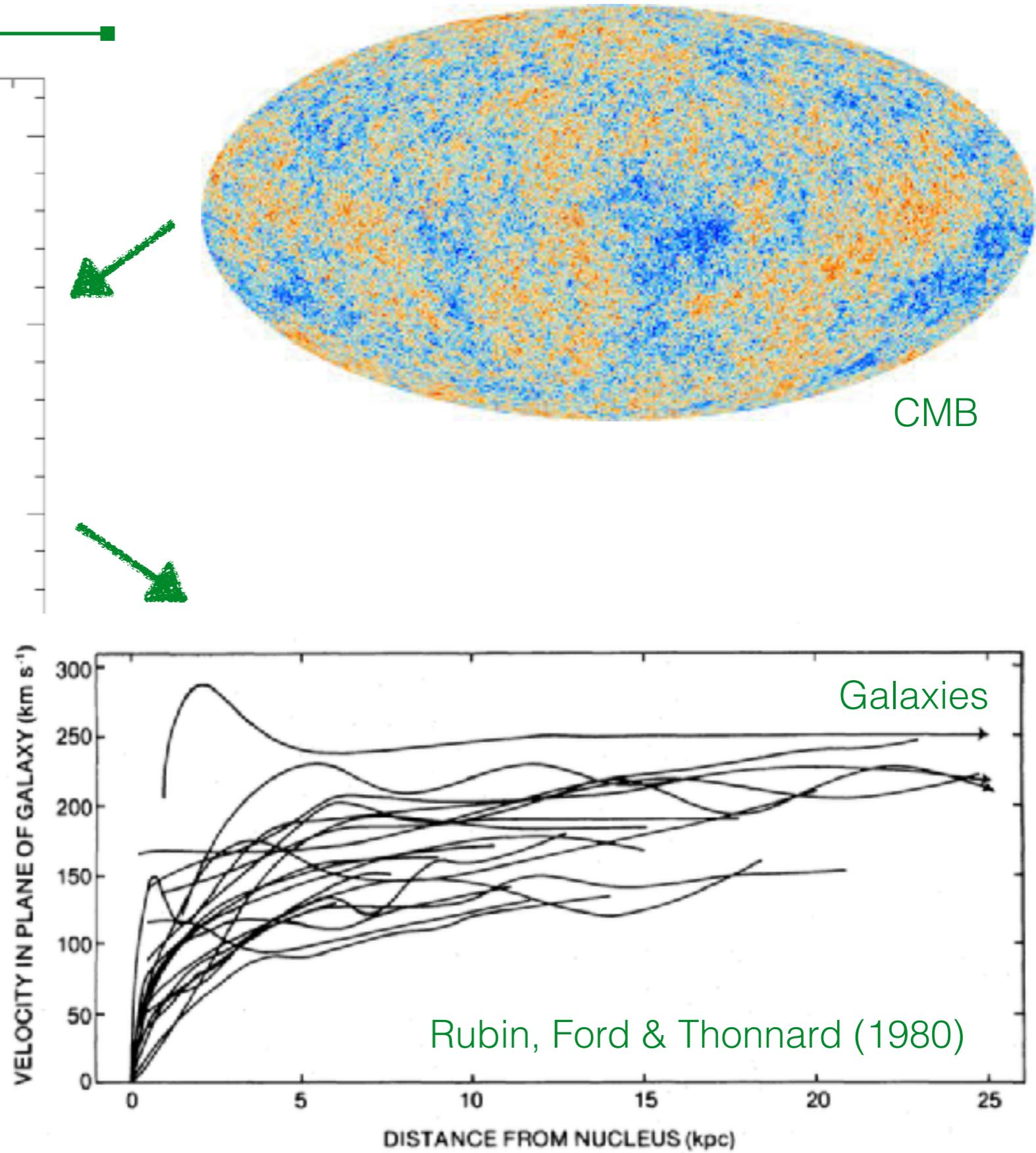
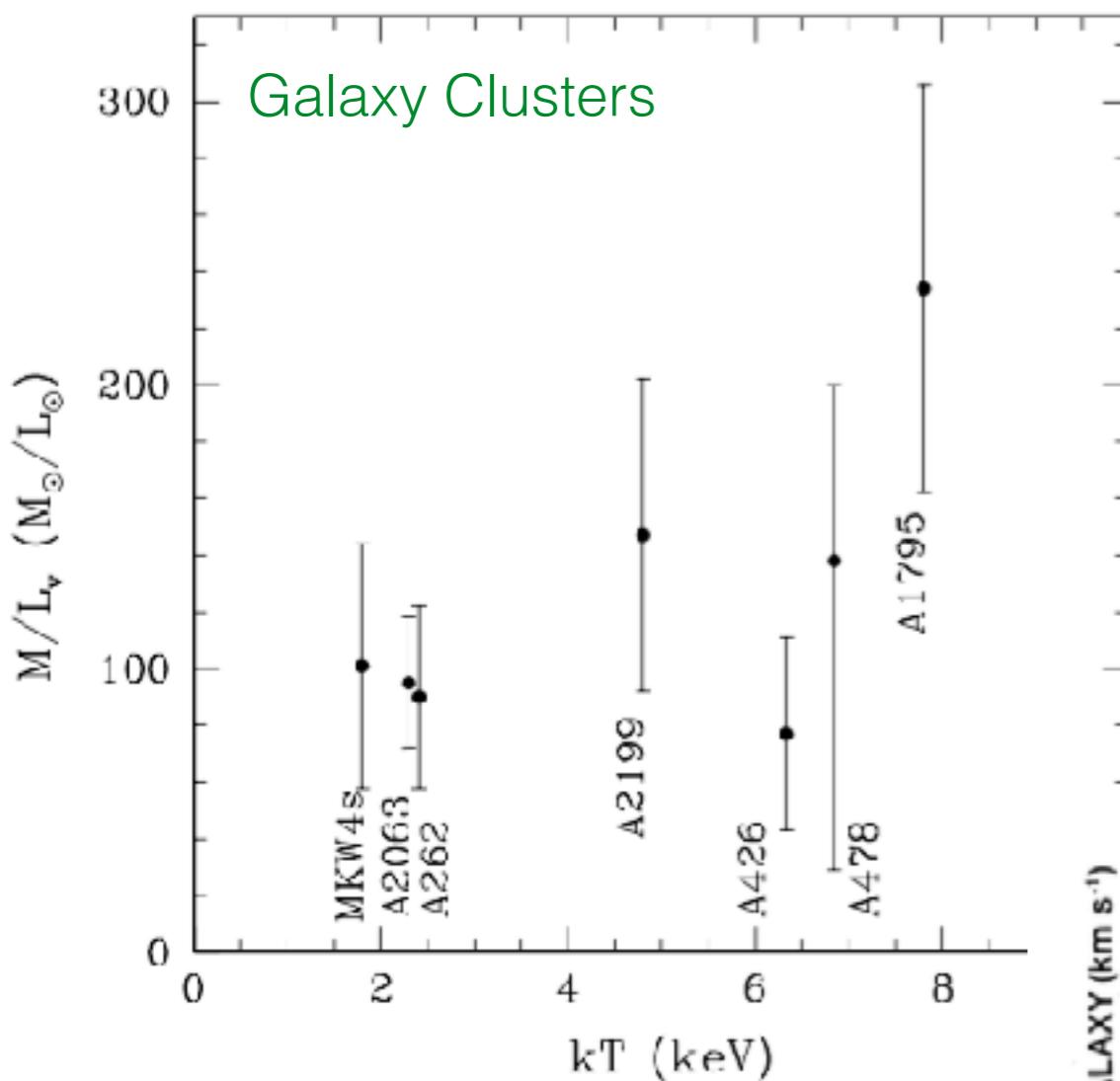


github.com/bradkav



Dark Matter on all scales

Planck [1502.01589]

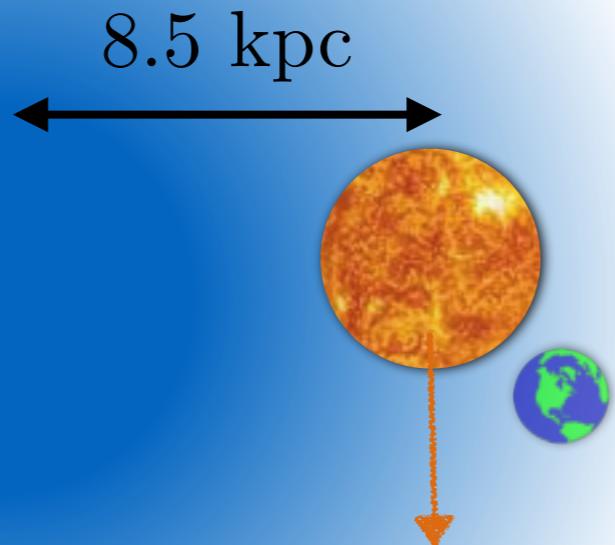


Dark Matter near us

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**.

Overview

Solar system searches for DM: Direct detection and Solar Capture

Astrophysical uncertainties

Halo-independent approaches to setting limits

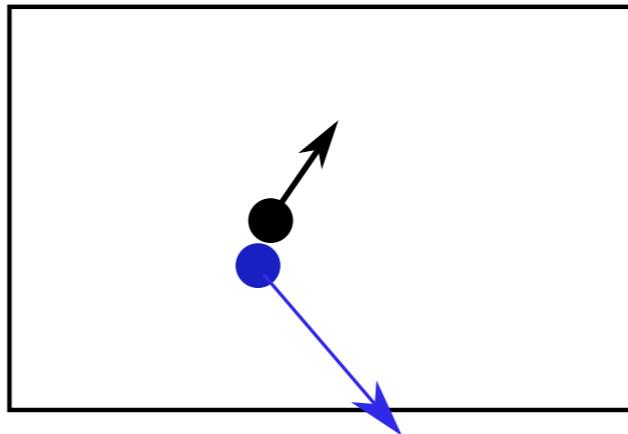
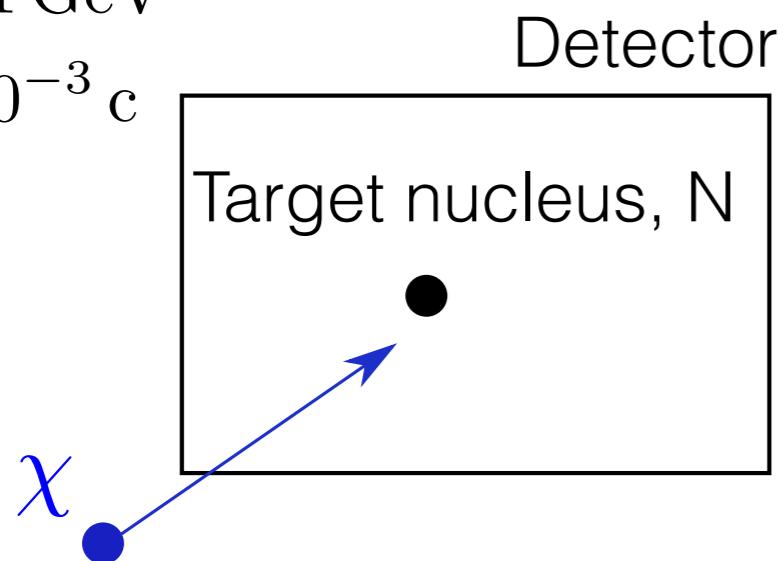
Measuring the DM properties and distribution
with a future detection

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

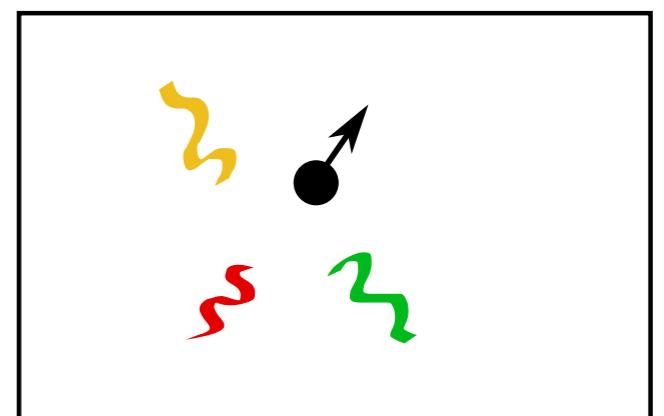
Direct detection

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

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



Light (scintillation)



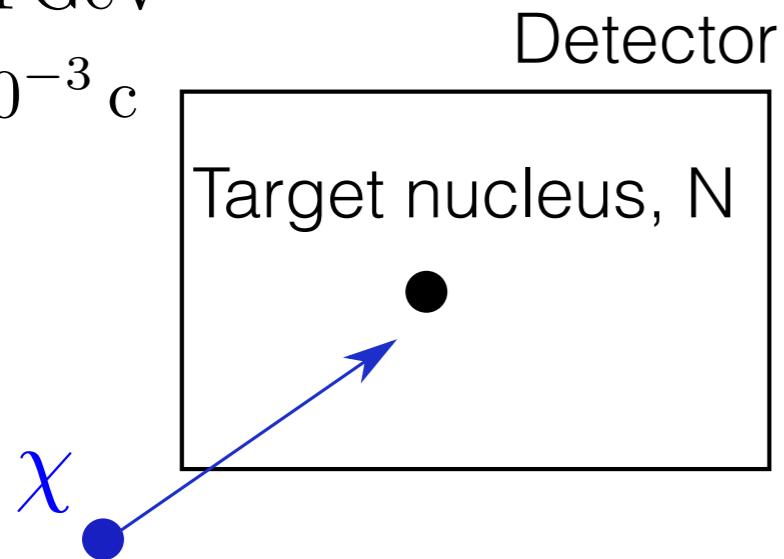
Heat (phonons)

Charge
(ionisation)

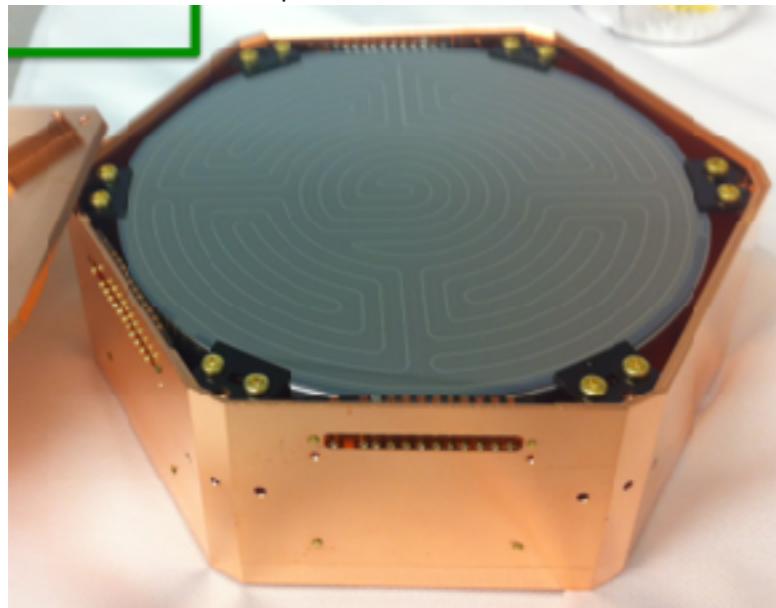
Direct detection

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

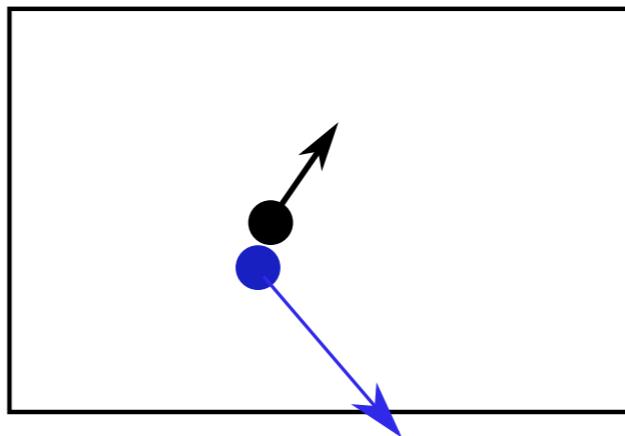
$$v \sim 10^{-3} c$$



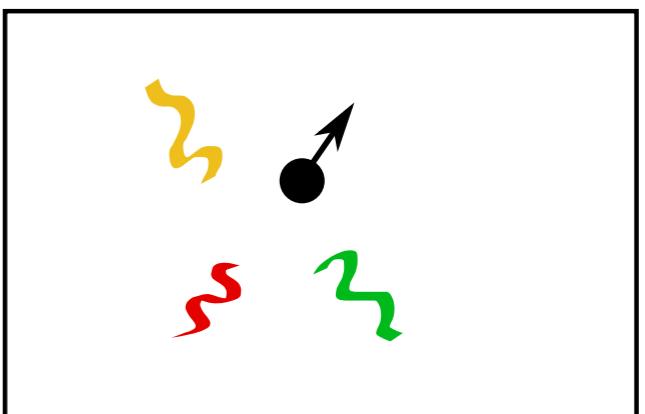
Credit: SuperCDMS Collaboration



SuperCDMS and many others



Light (scintillation)



Heat (phonons)

Charge
(ionisation)

Direct detection signal

$$\frac{dR}{dE_R} \sim \frac{\rho_\chi}{m_\chi} \sigma_p \mathcal{C}_A \eta(v_{\min})$$

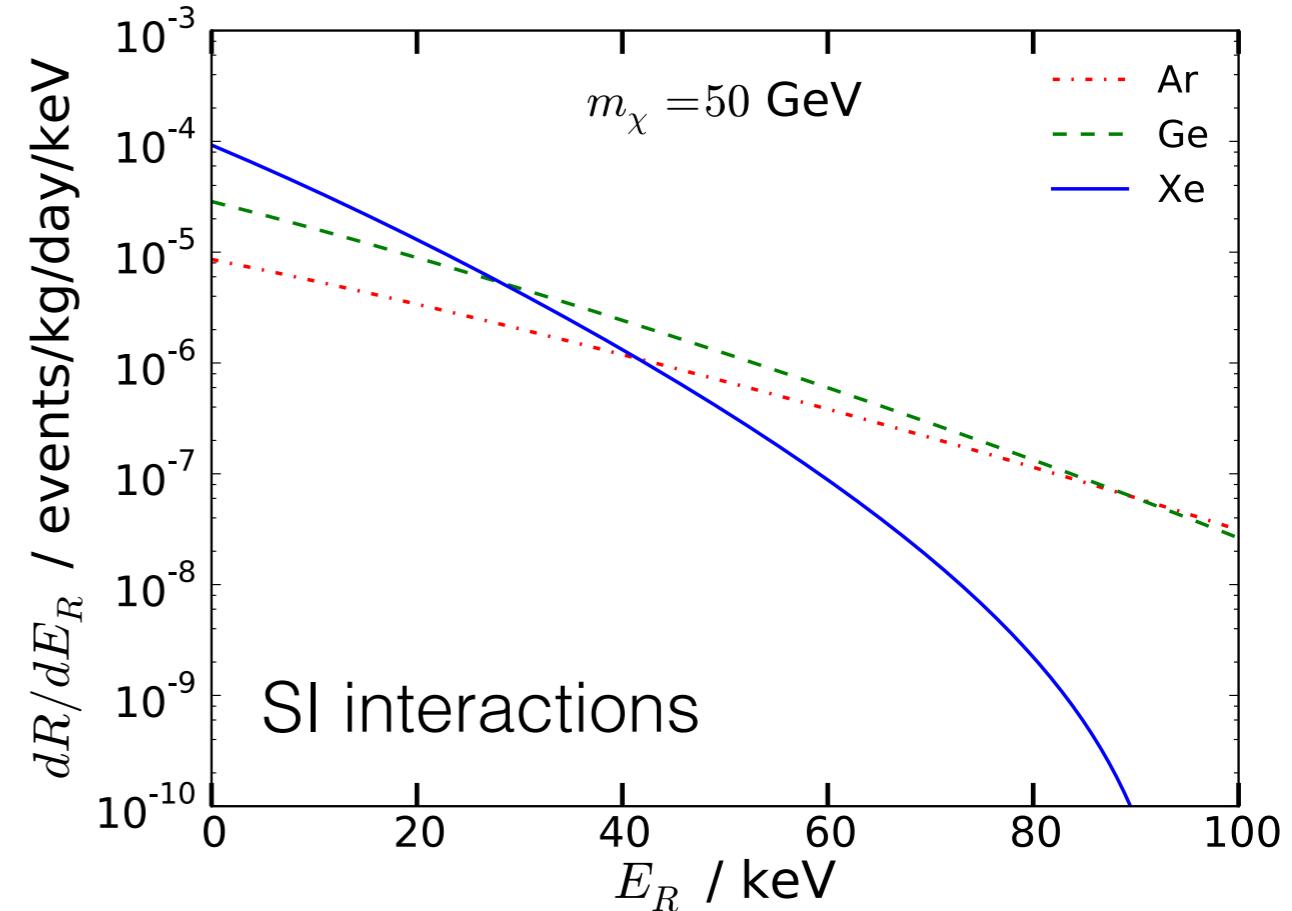
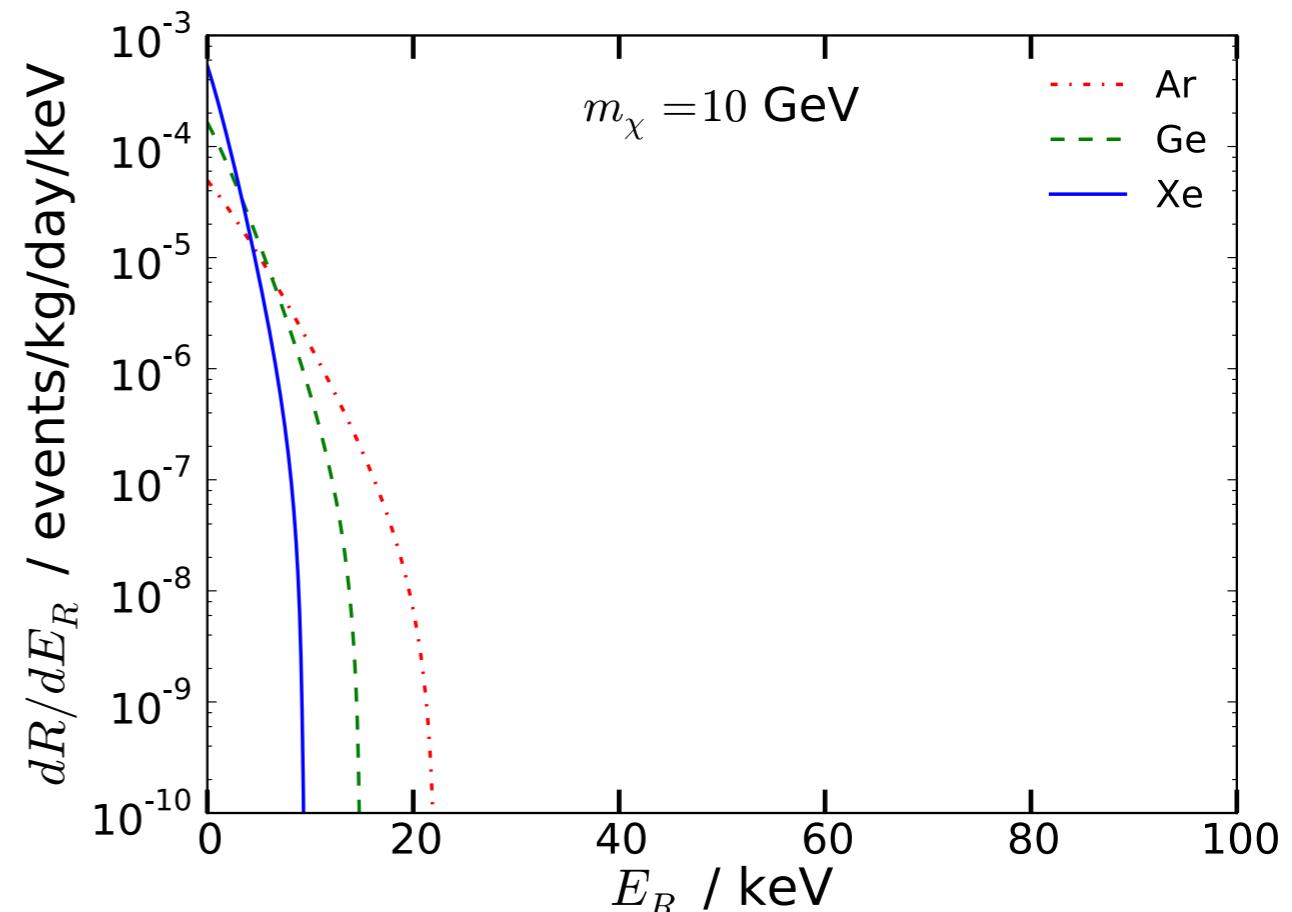
$$\eta(v_{\min}) \equiv \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$

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

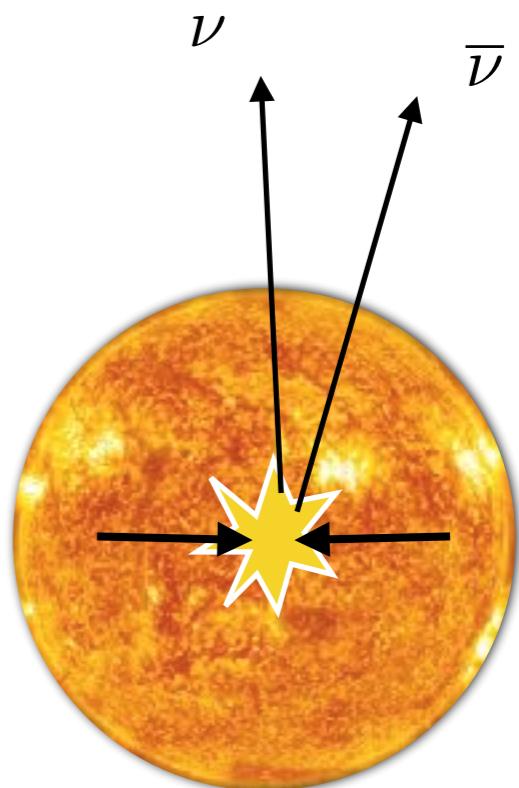
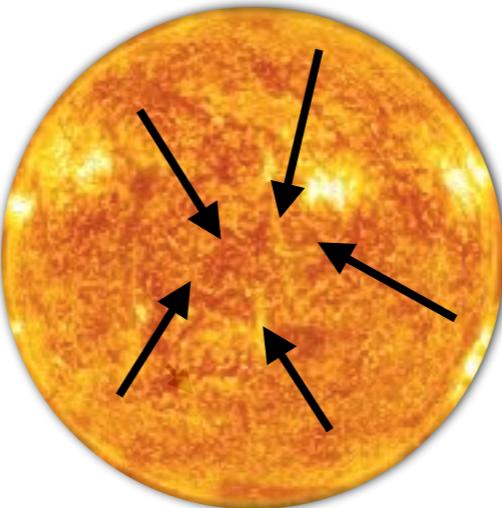
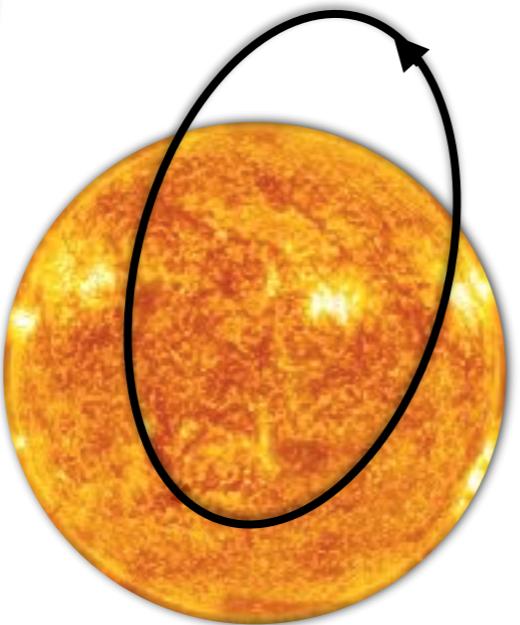
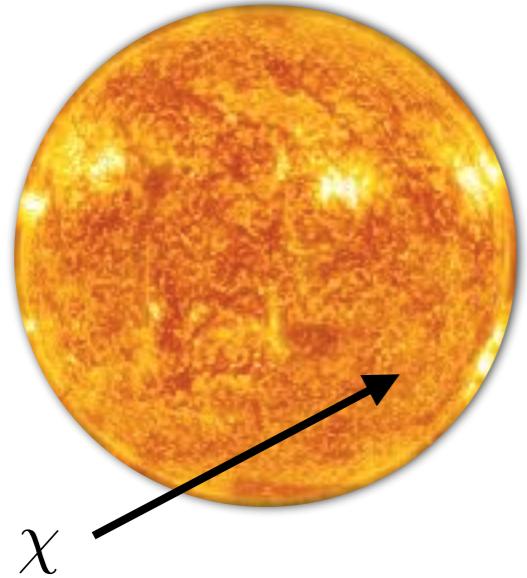
Spin-independent (SI)
interactions: $\mathcal{C}_A^{\text{SI}} \sim A^2$

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

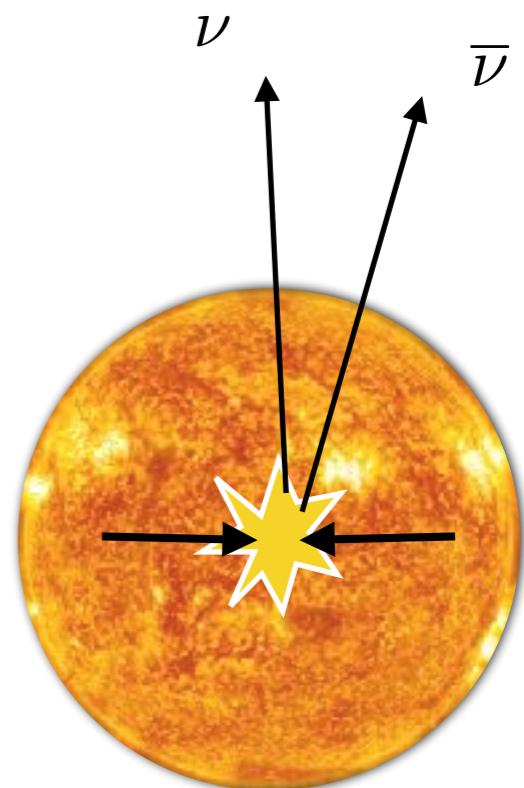
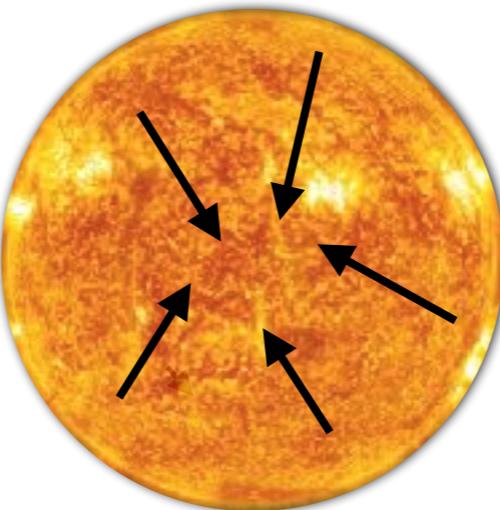
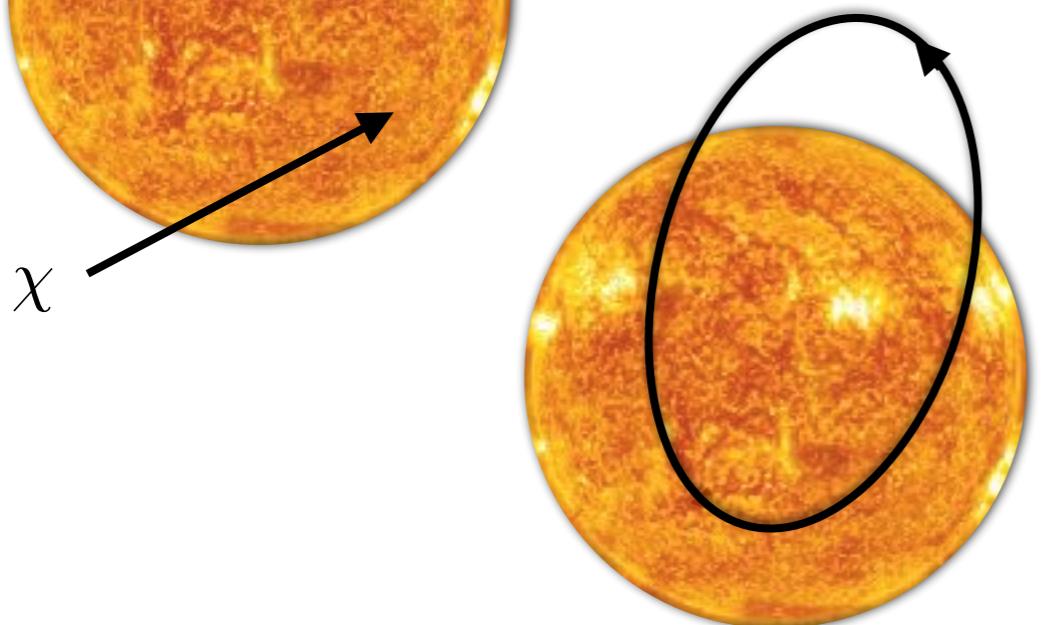
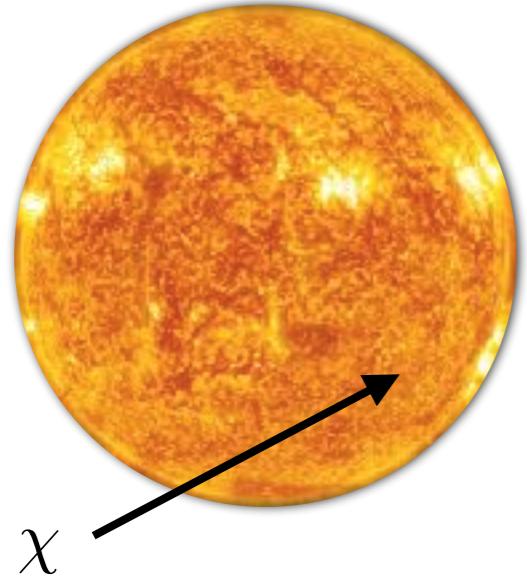
More complicated interactions are possible:
see e.g. Fitzpatrick et al. [1203.3542];
Edwards, **BJK**, Weniger [1805.04117]



Solar Capture



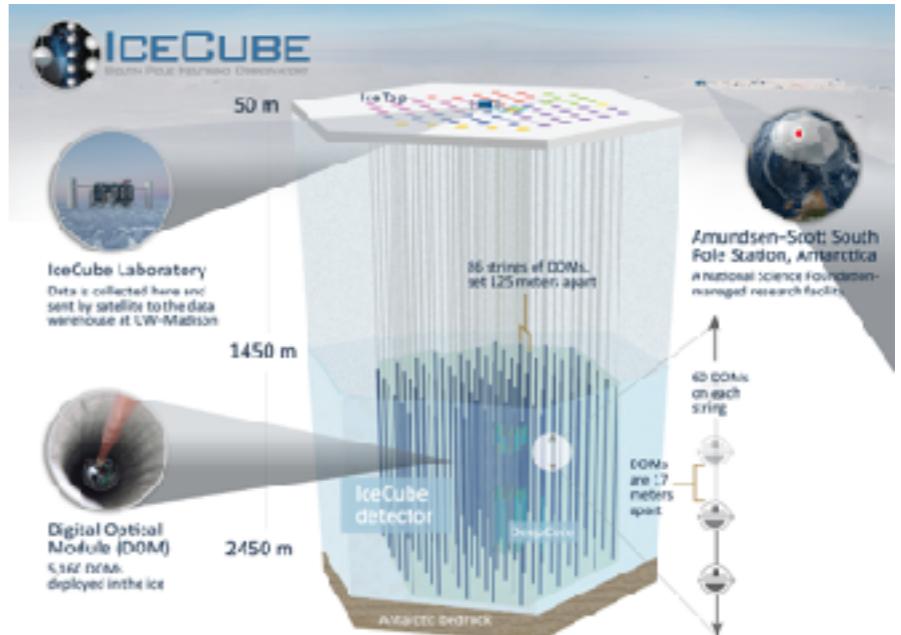
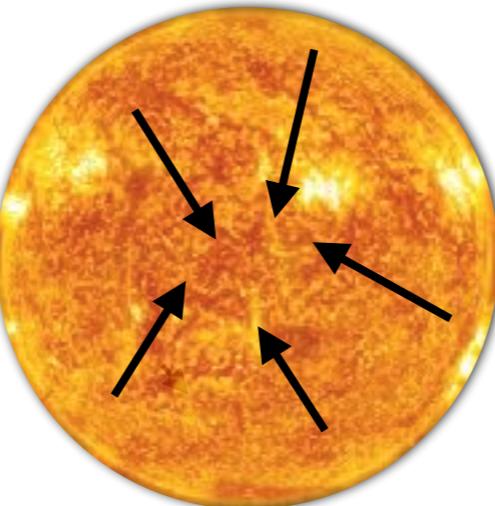
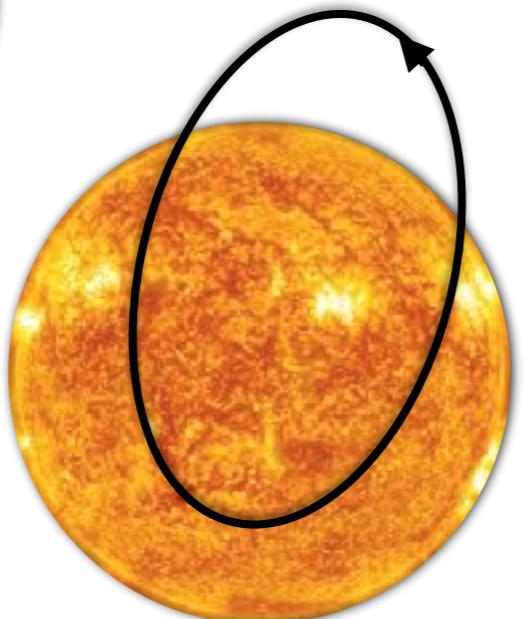
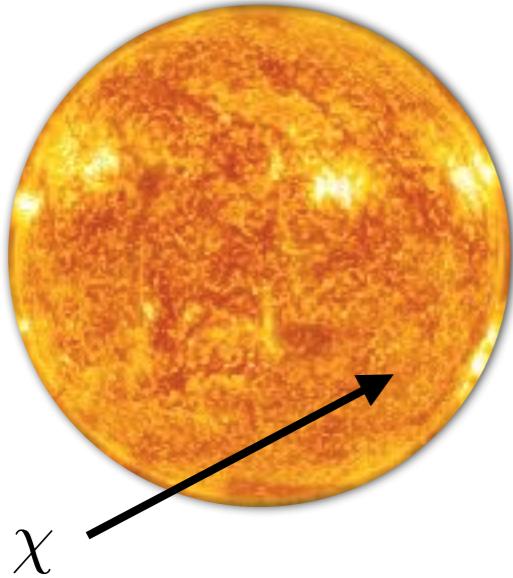
Solar Capture



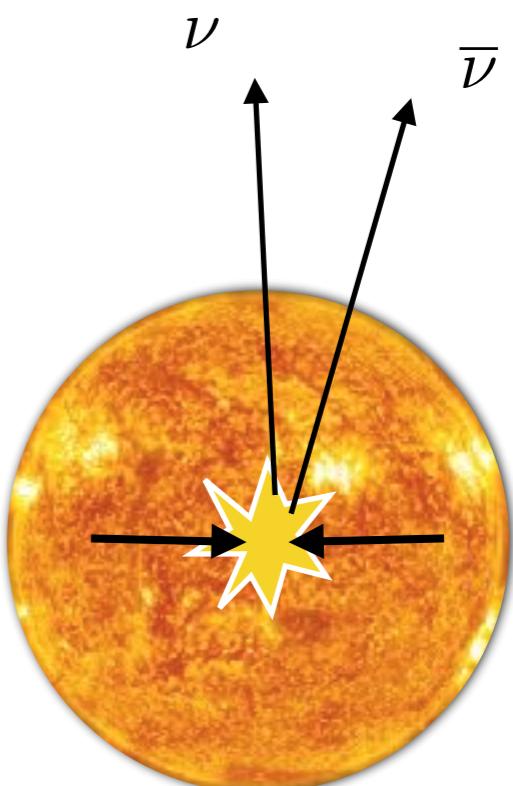
IceCube
and many others

Solar Capture

Credit: icecube.wisc.edu



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 .

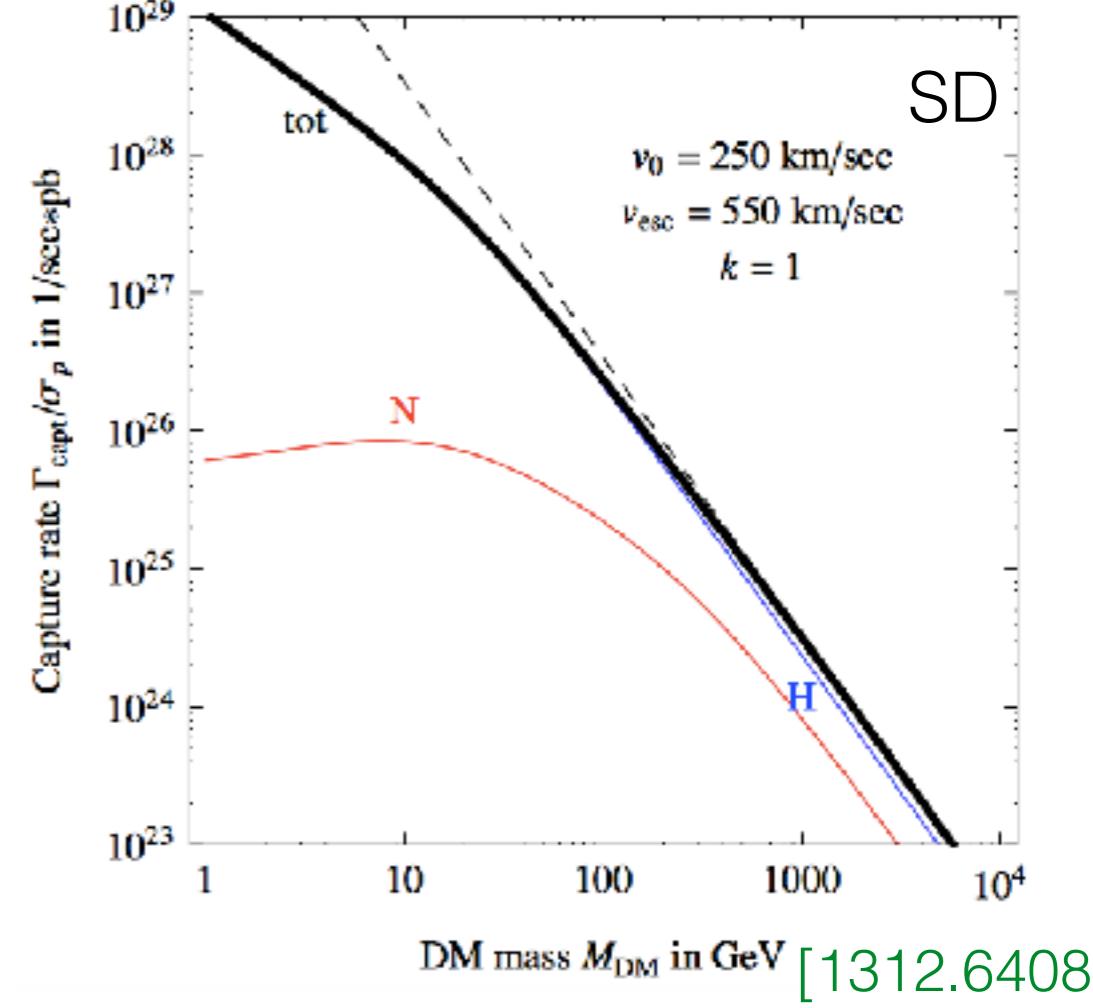
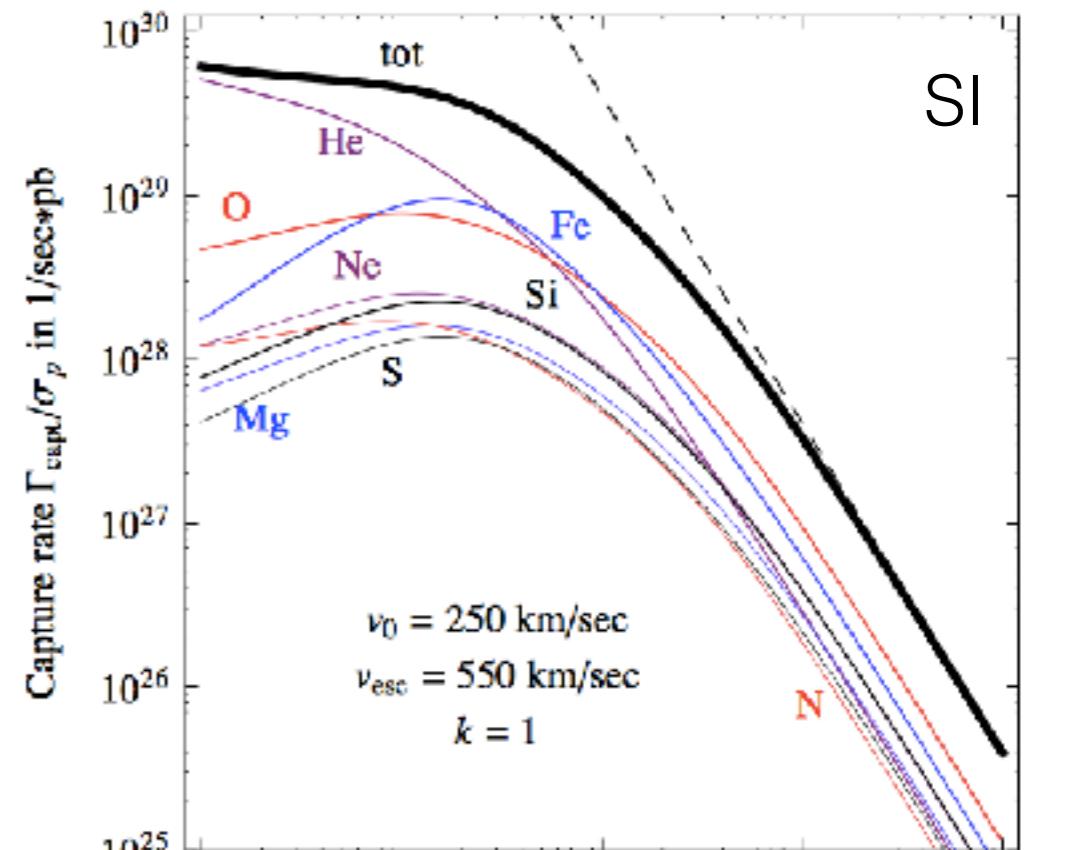
Only include DM particles moving slowly enough to be captured:

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

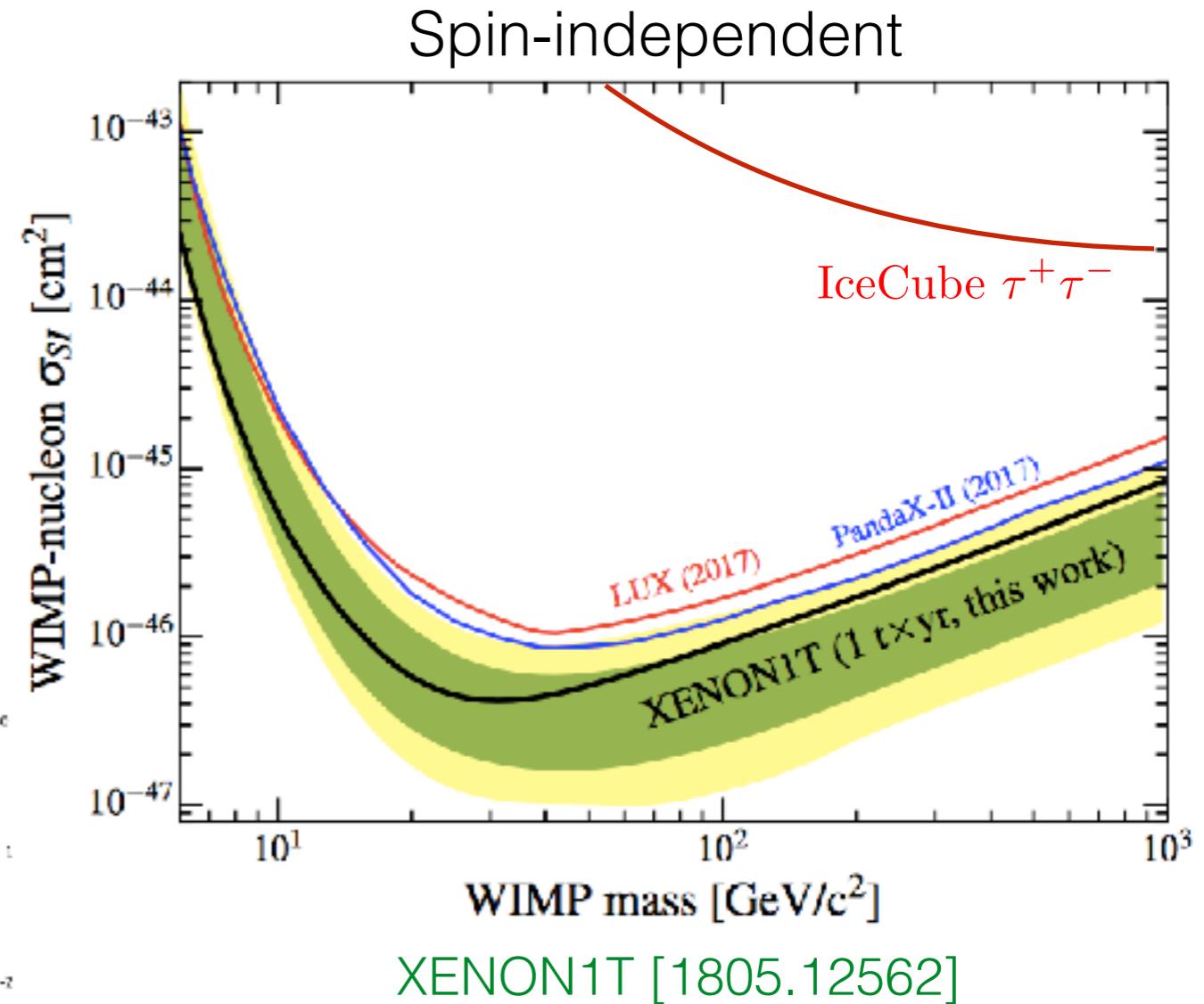
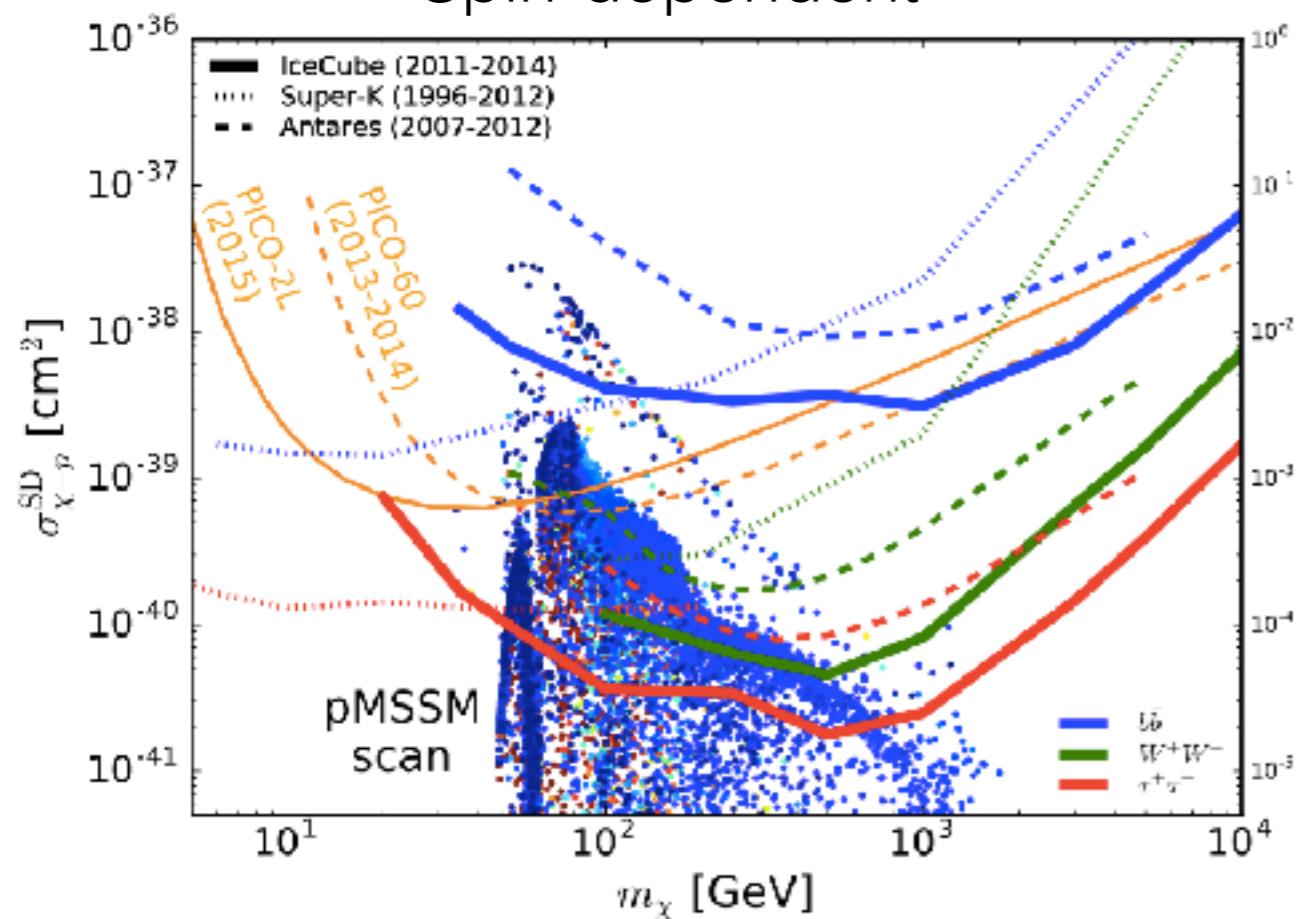
If capture and annihilation are in equilibrium, annihilation rate only depends on DM-nucleon scattering cross section.

Observed neutrino flux depends on DM annihilation channel...

Gould (1991)



Limits on Solar System DM



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?]

Standard Halo Model

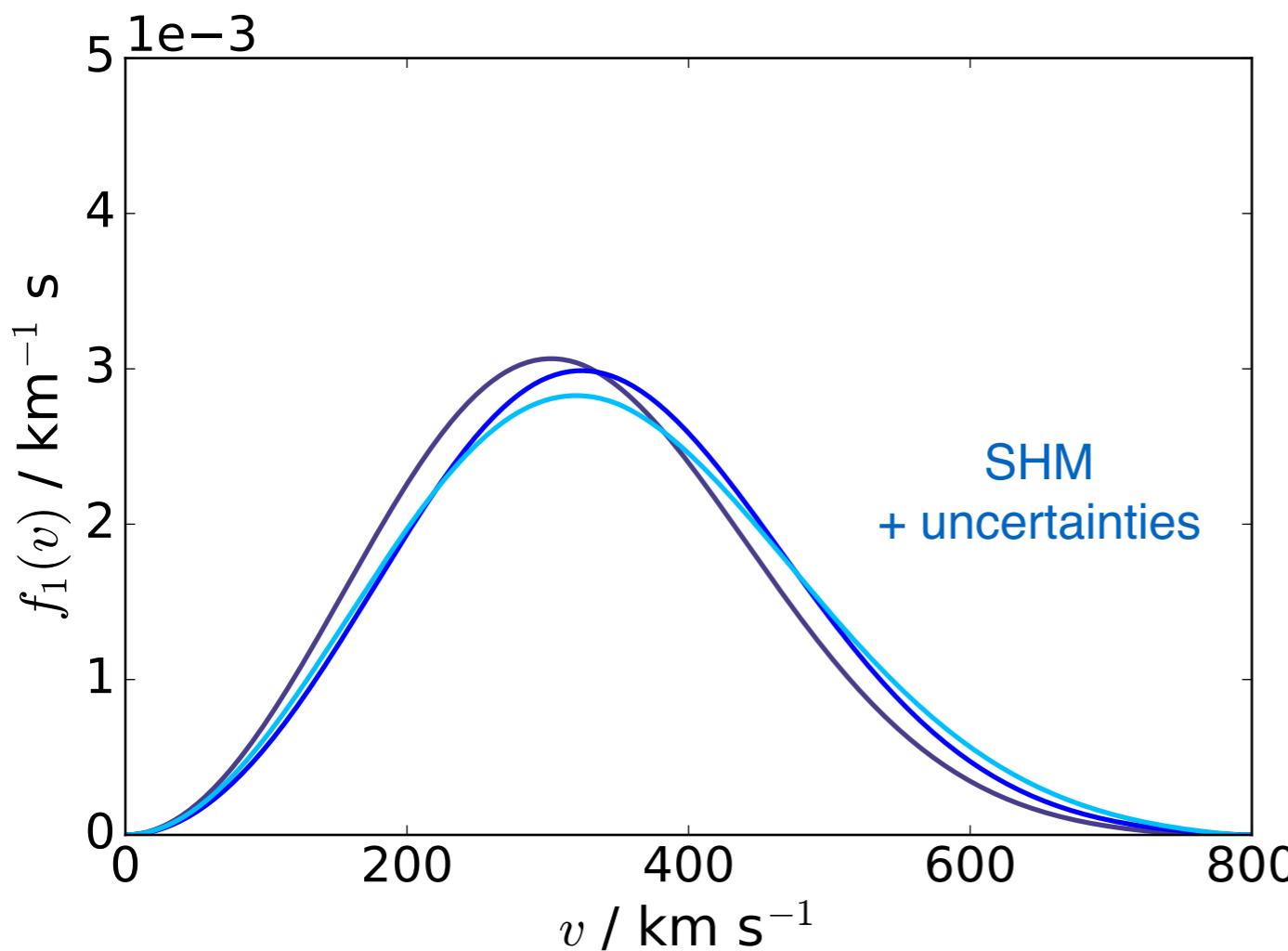
Standard Halo Model (**SHM**) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

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

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

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

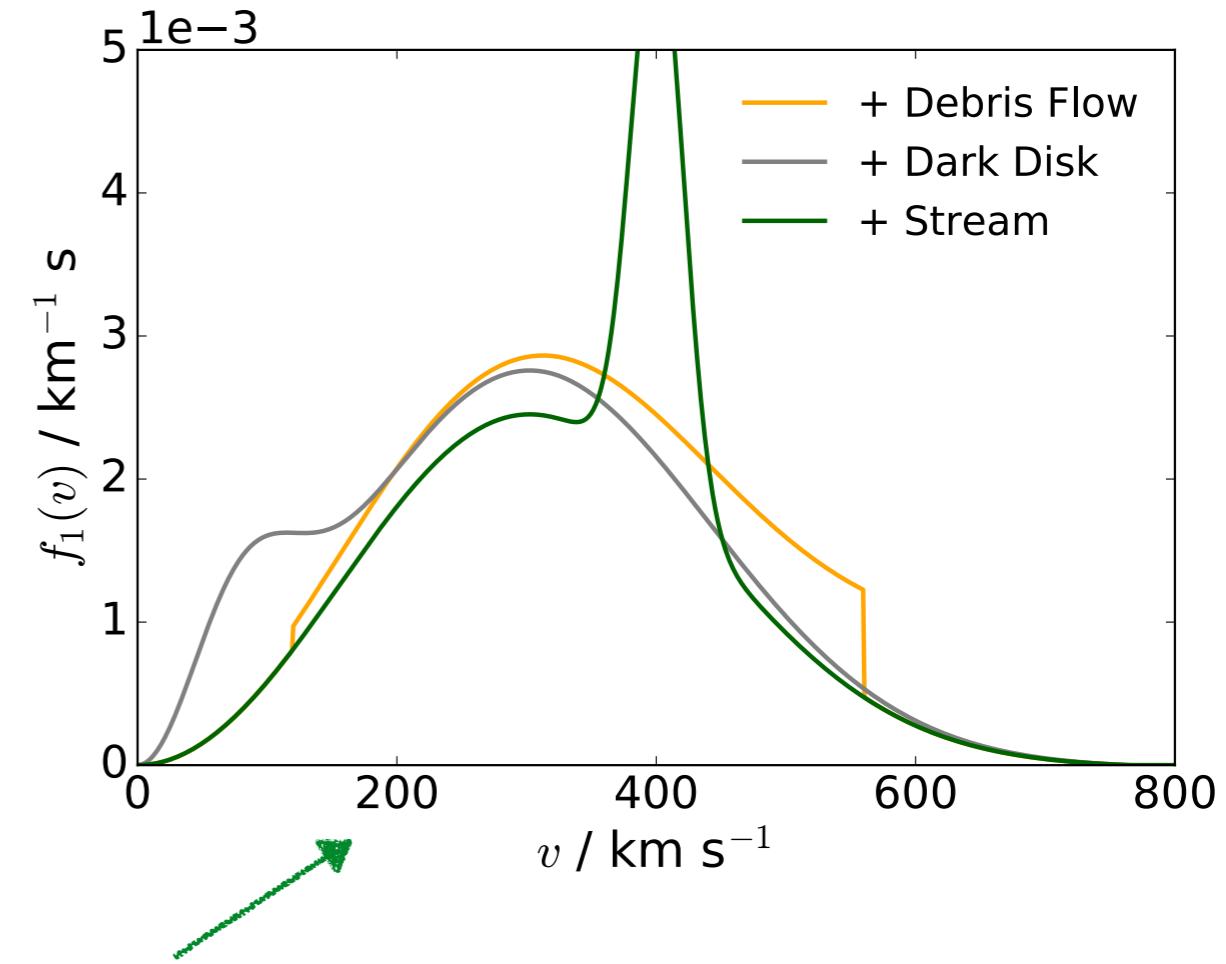
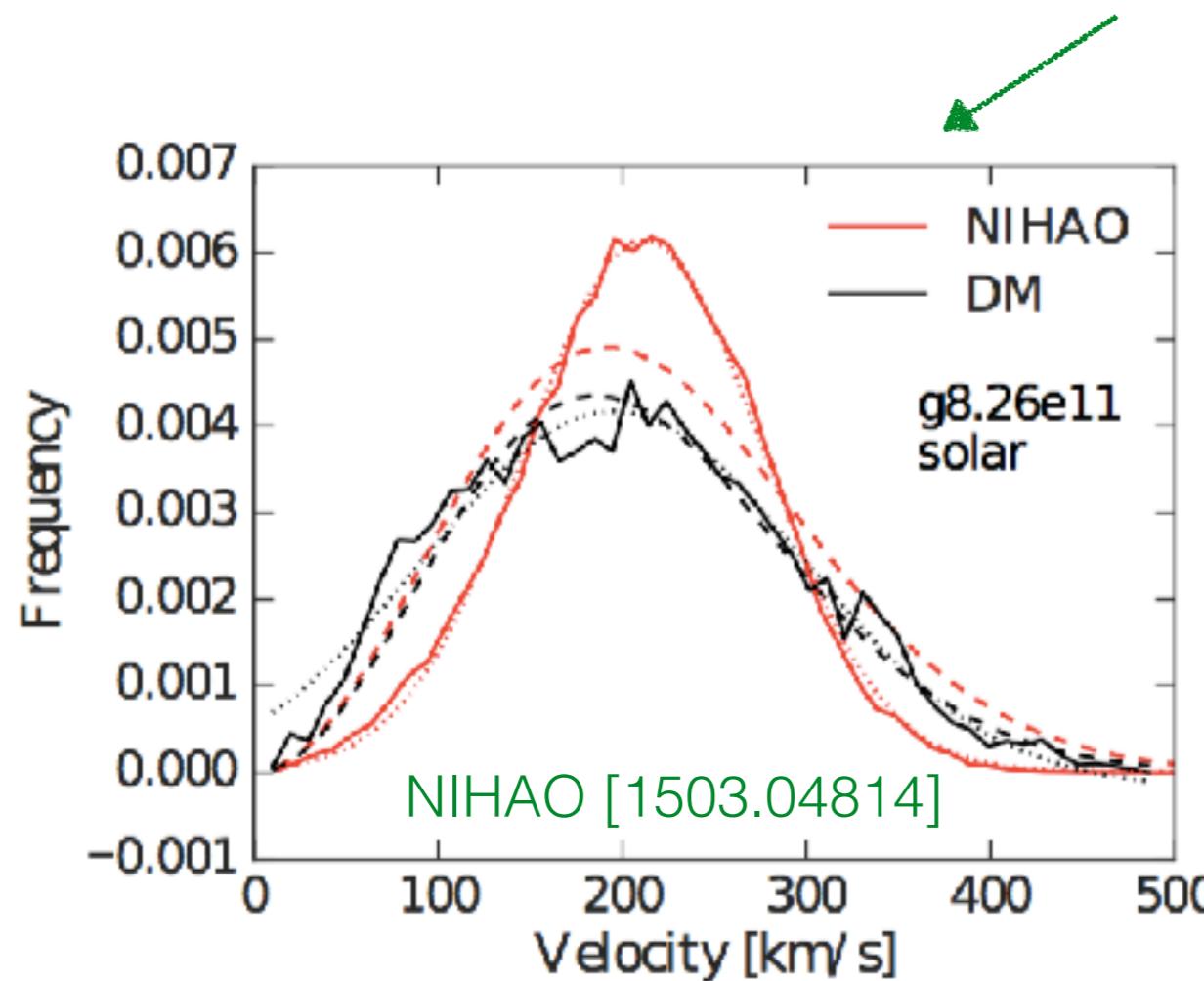
Feast et al. [astro-ph/9706293],
Bovy et al. [1209.0759]

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

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]

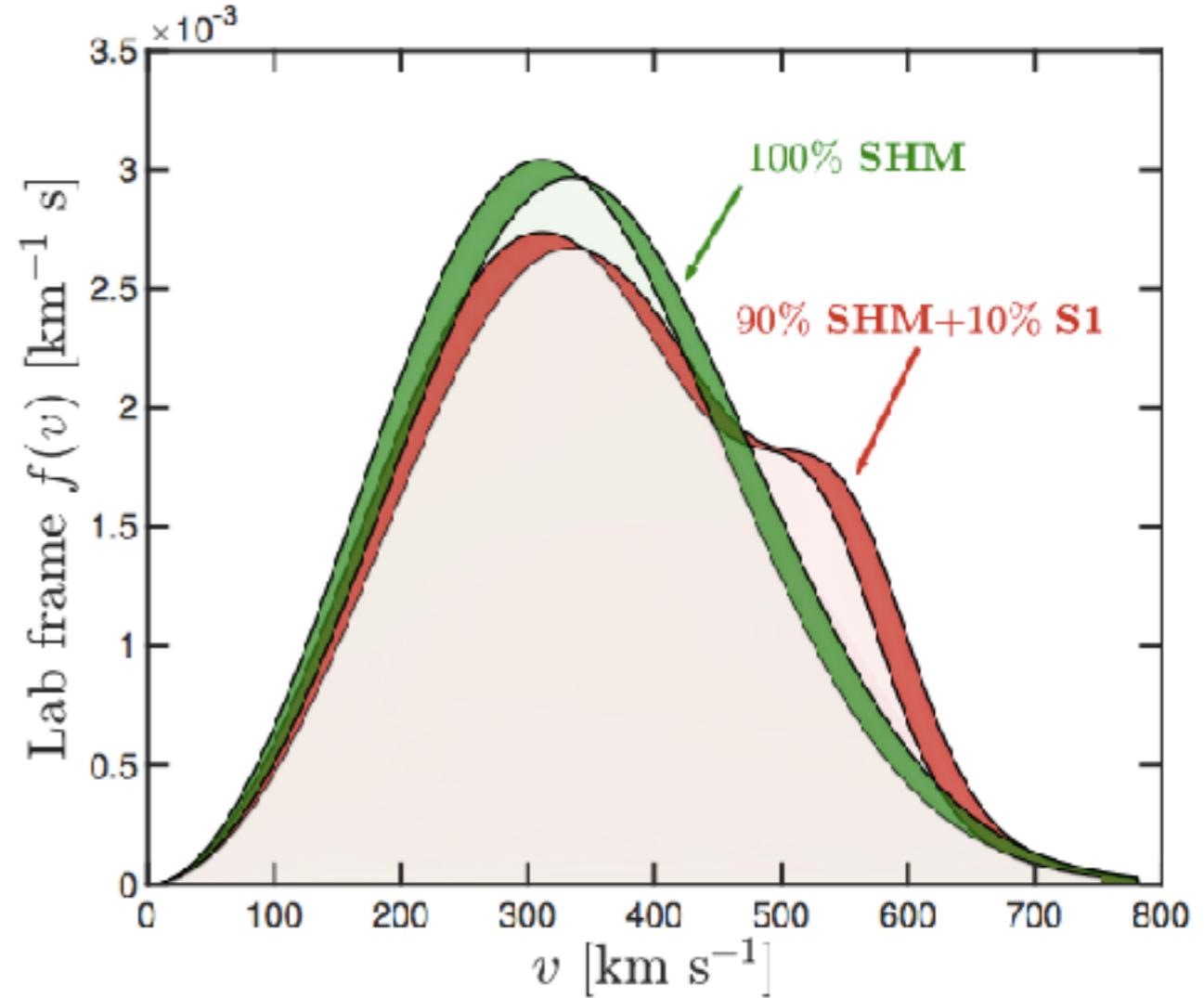
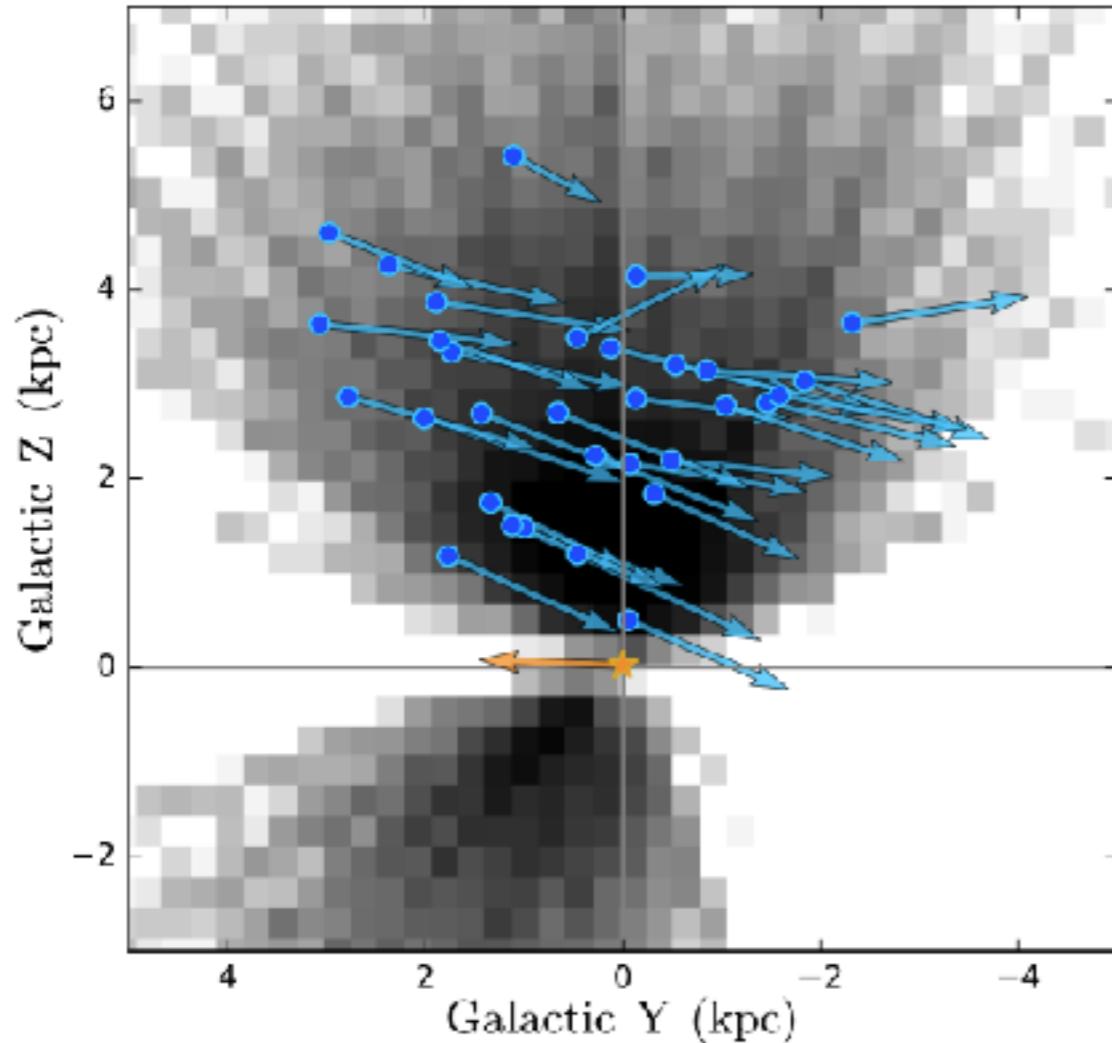
Dark disk Pillepich et al. [1308.1703], Schaller et al. [1605.02770]

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

S1 Stream: DM Hurricane?

Recent GAIA data revealing new stellar streams:

[1712.04071]



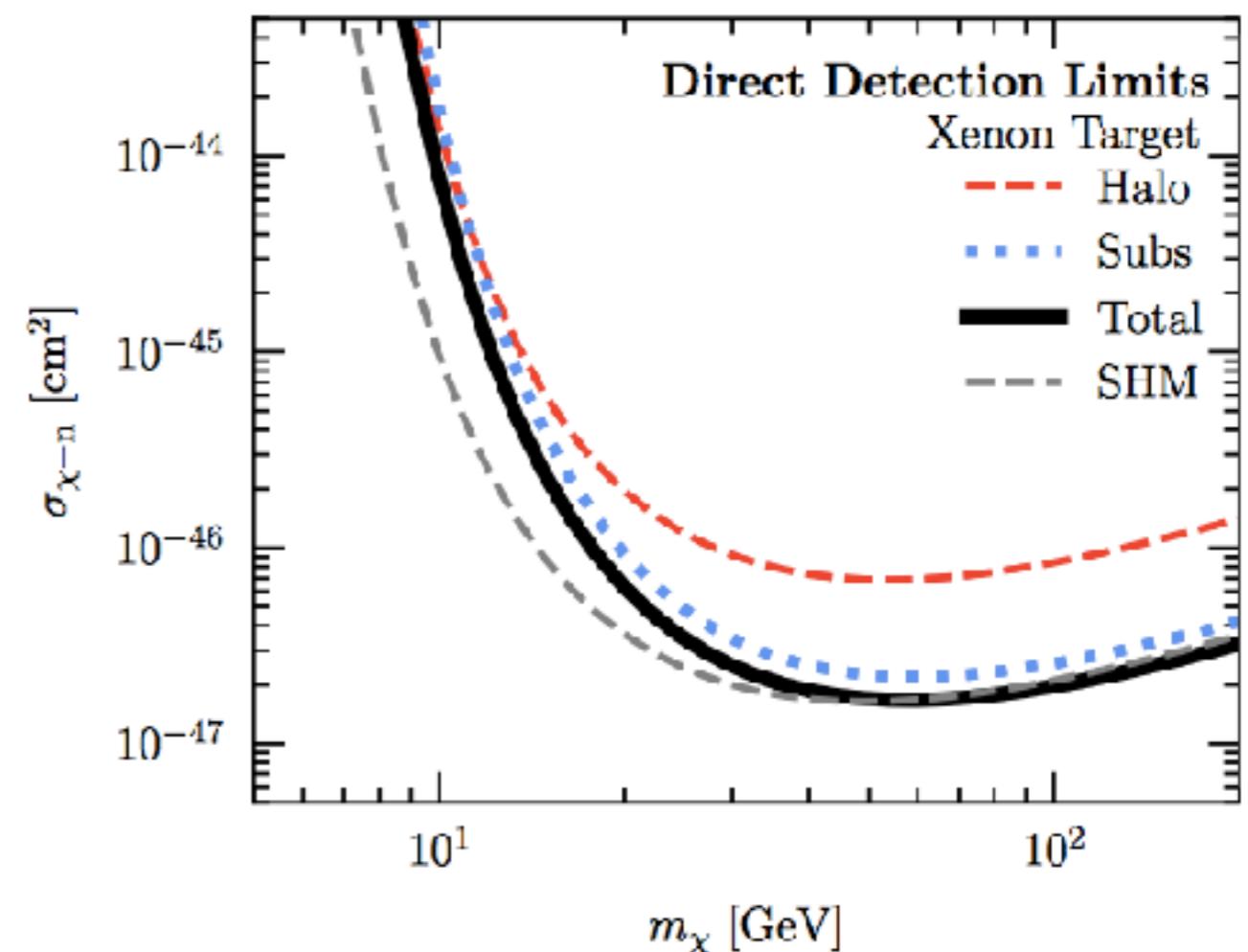
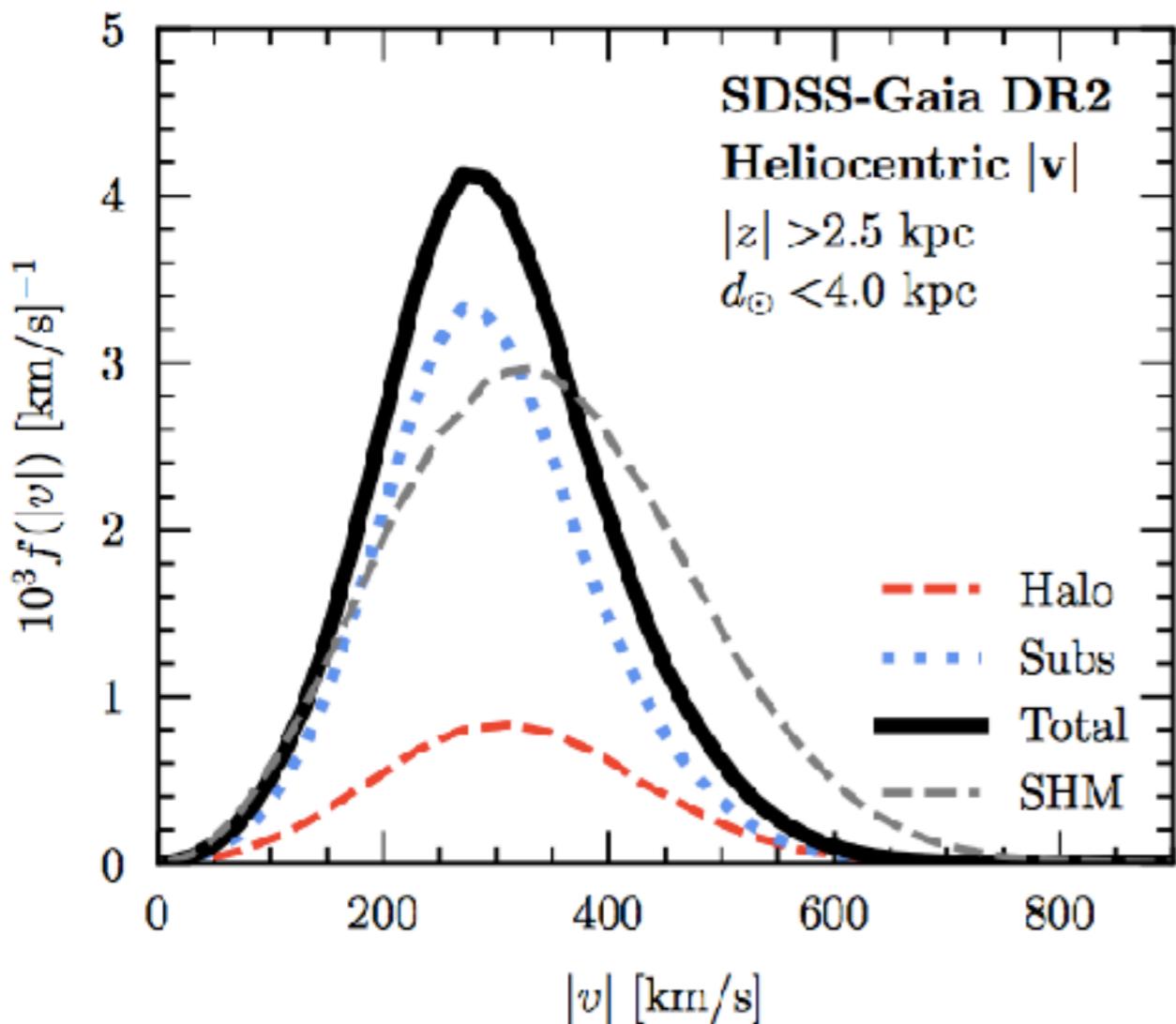
S1 stream counter-rotating at $v_{S1} \approx 300 \text{ km/s}$

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

O'Hare et al. [1807.09004]

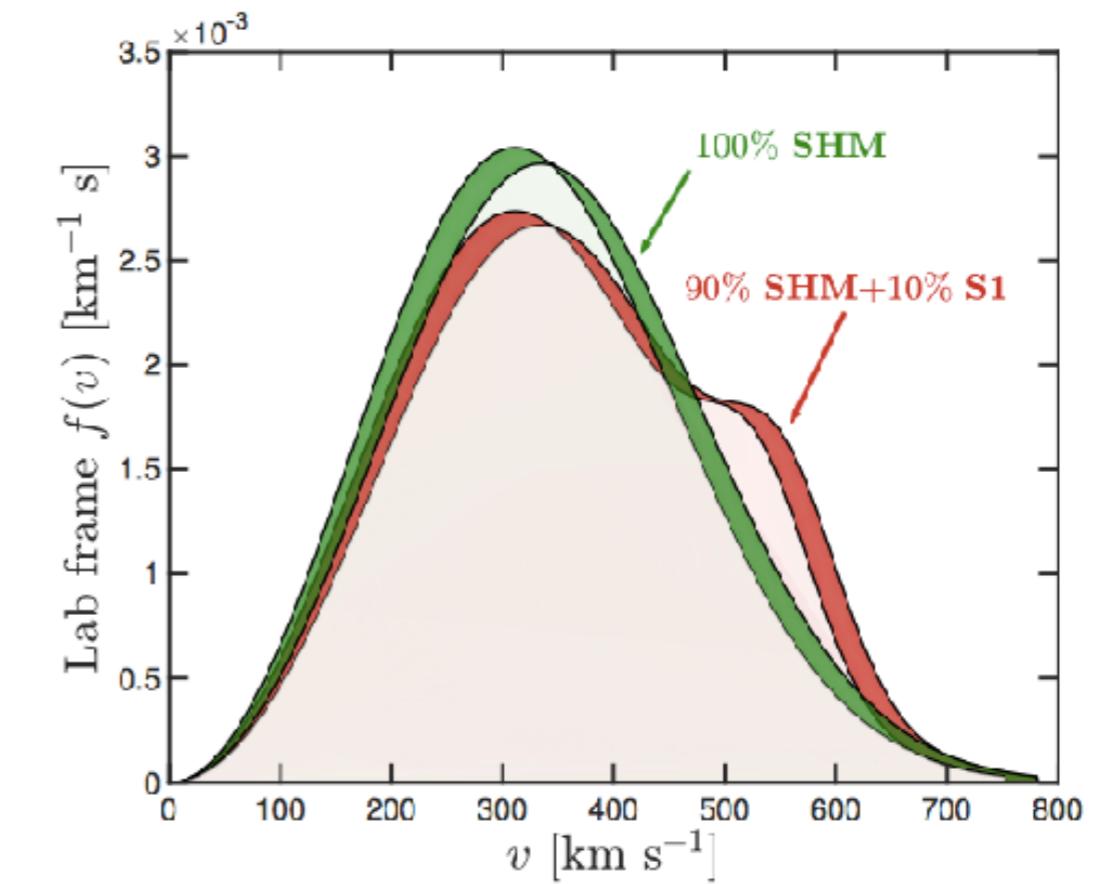
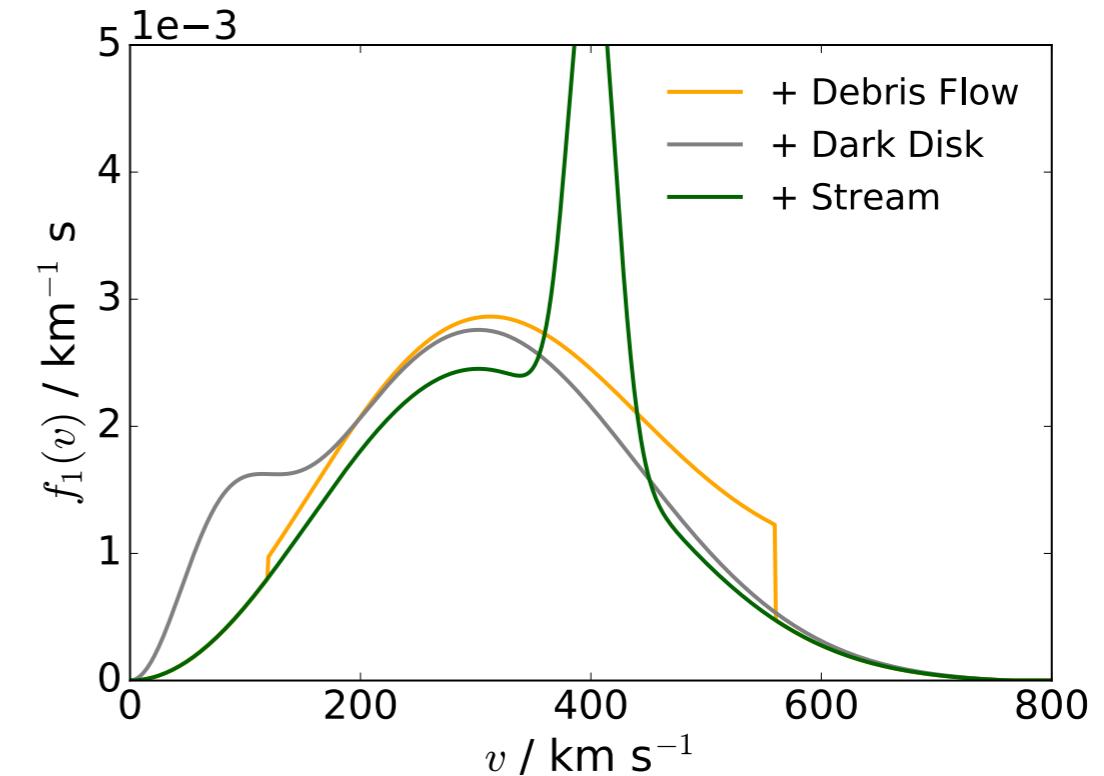
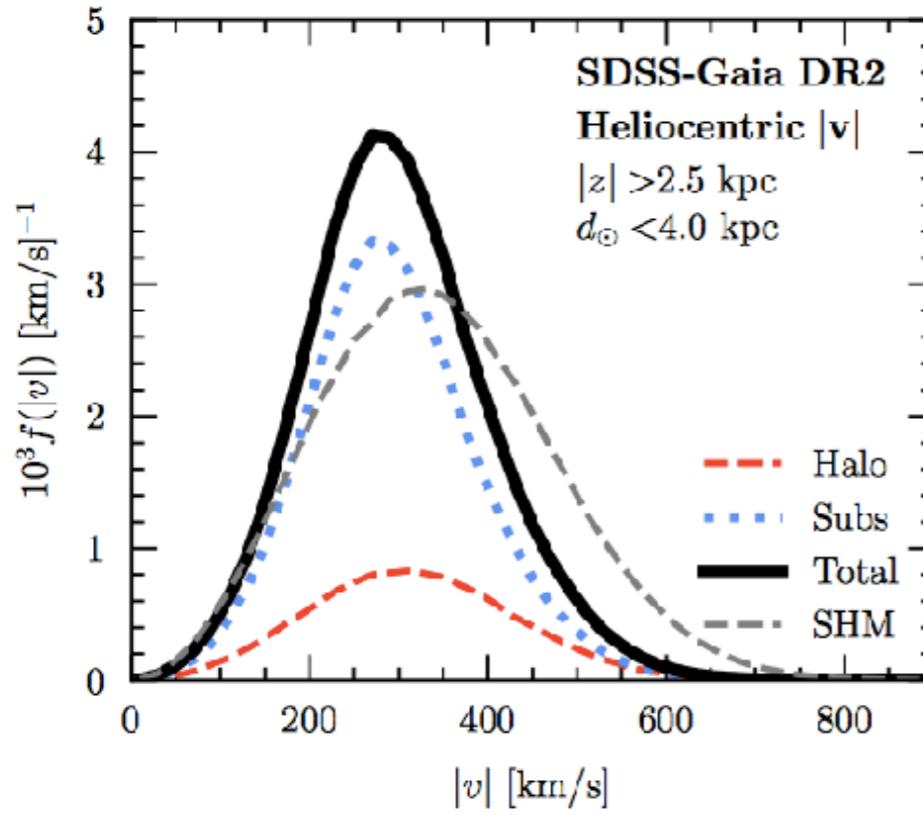
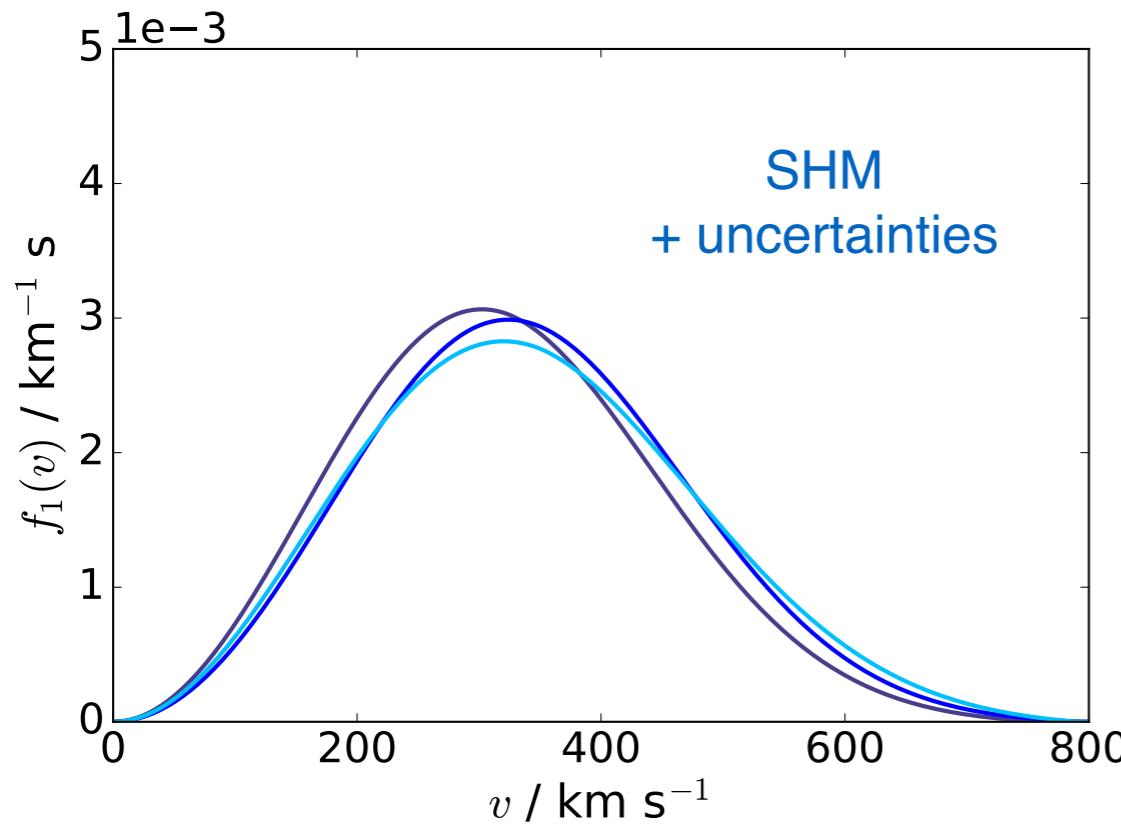
Stars as DM Tracers

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



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

Astro Uncertainties



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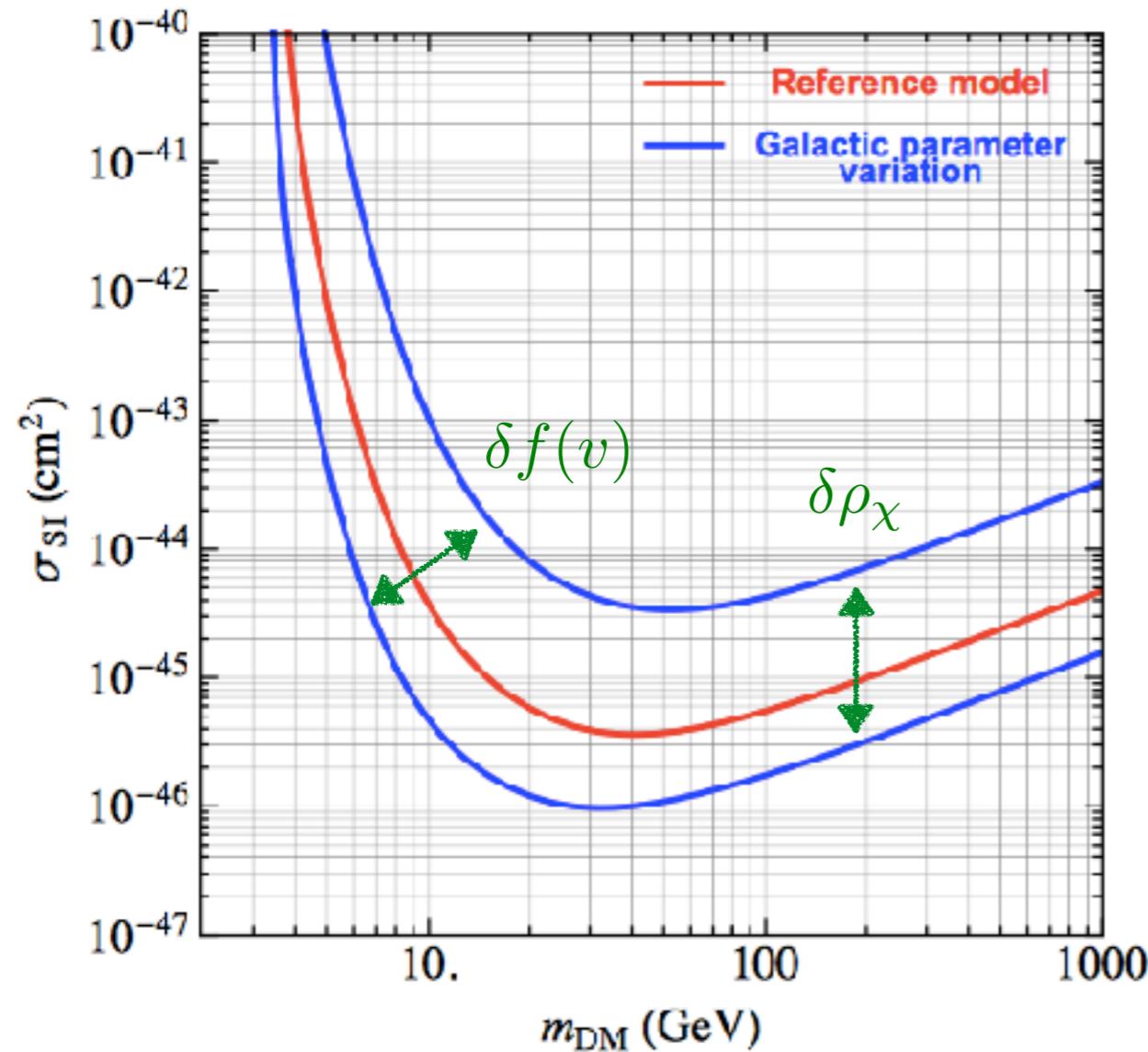
Halo-independent approaches to setting limits

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

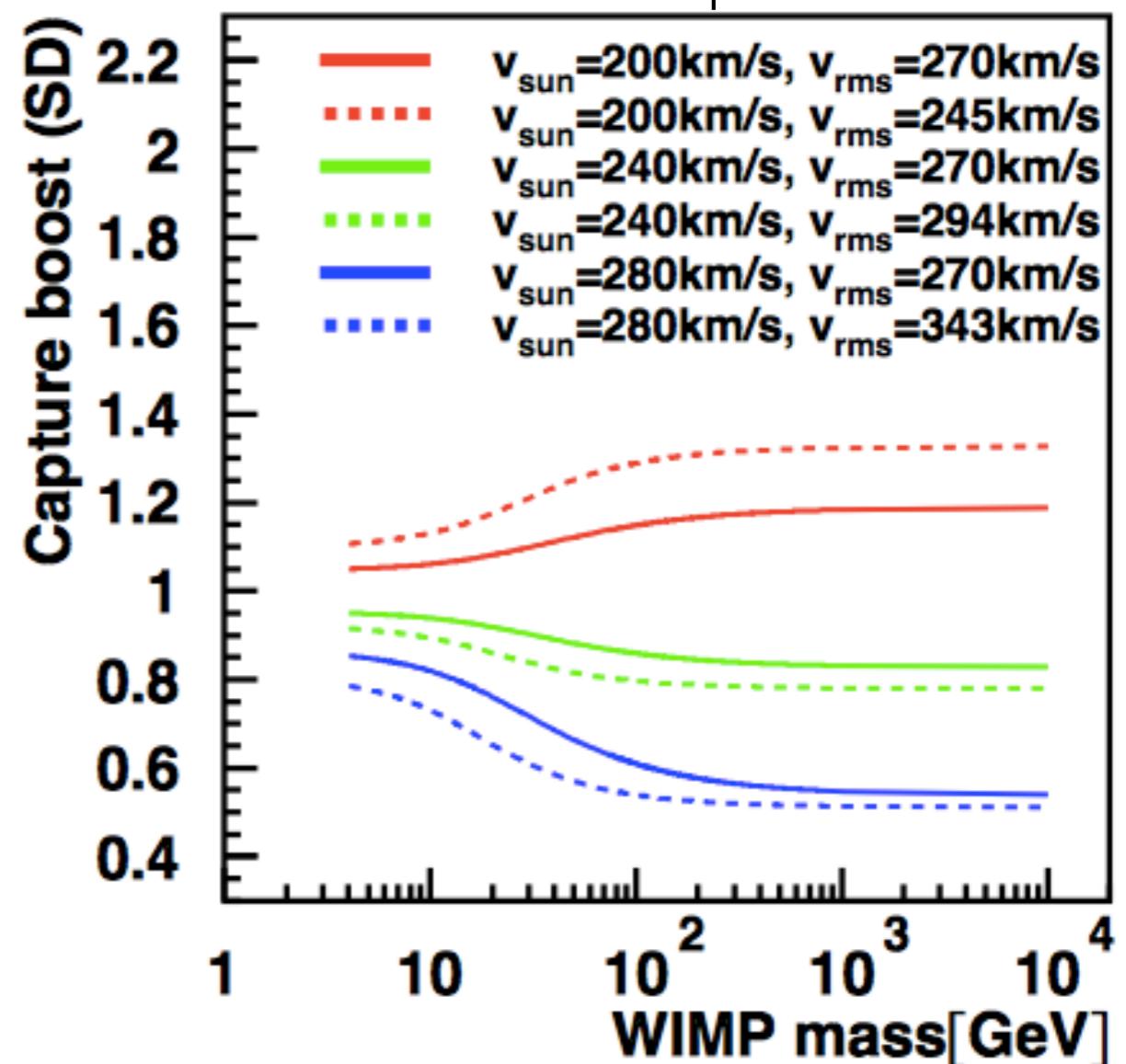
Impact on DM limits

Direct Detection



Benito et al. [1612.02010]

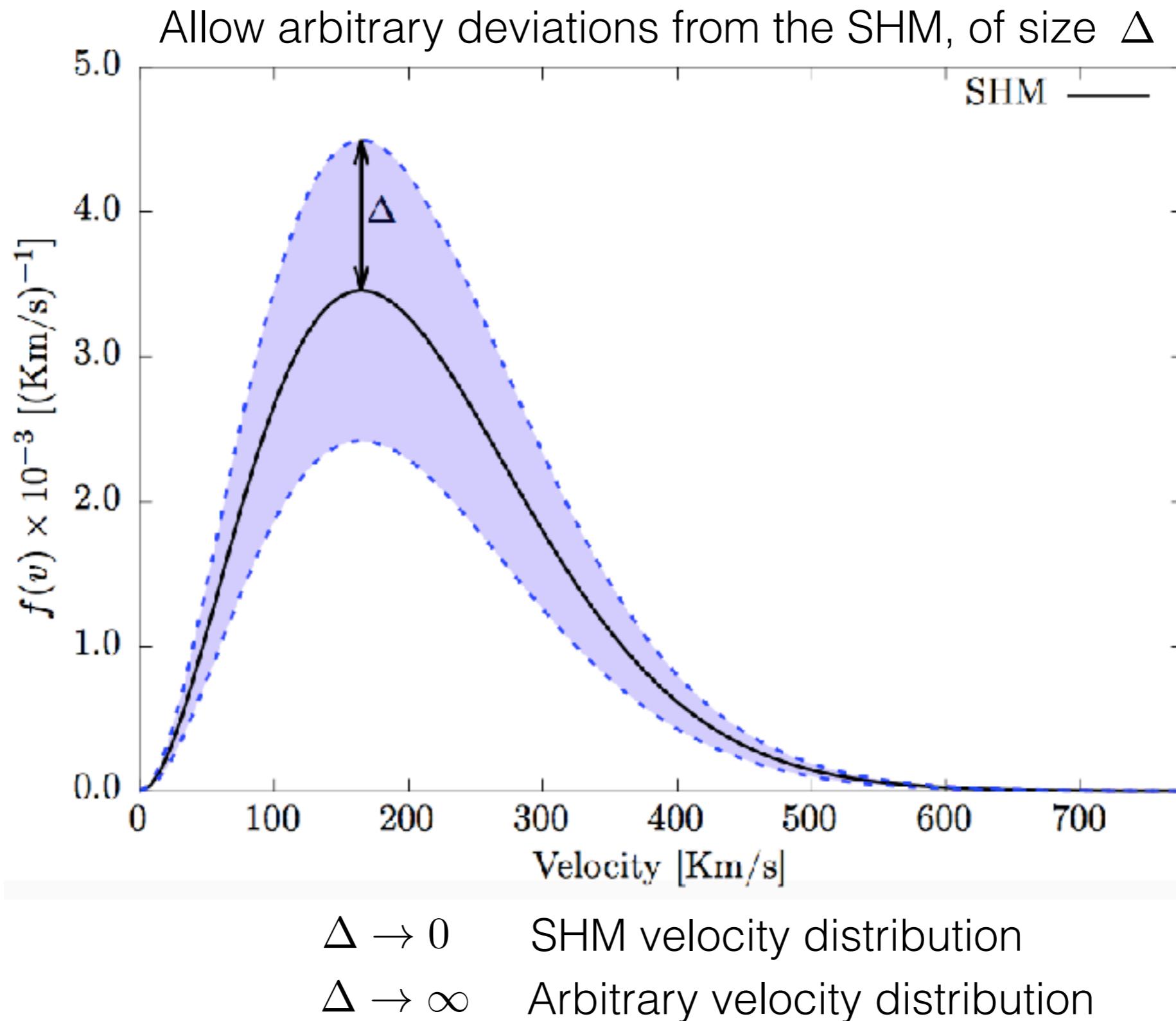
Solar Capture



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:

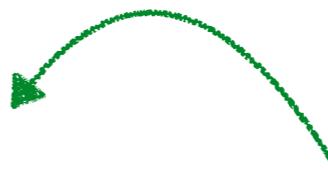
$$\log p(m_\chi, \sigma_p, f(\mathbf{v}))$$

Subject to:

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

and

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

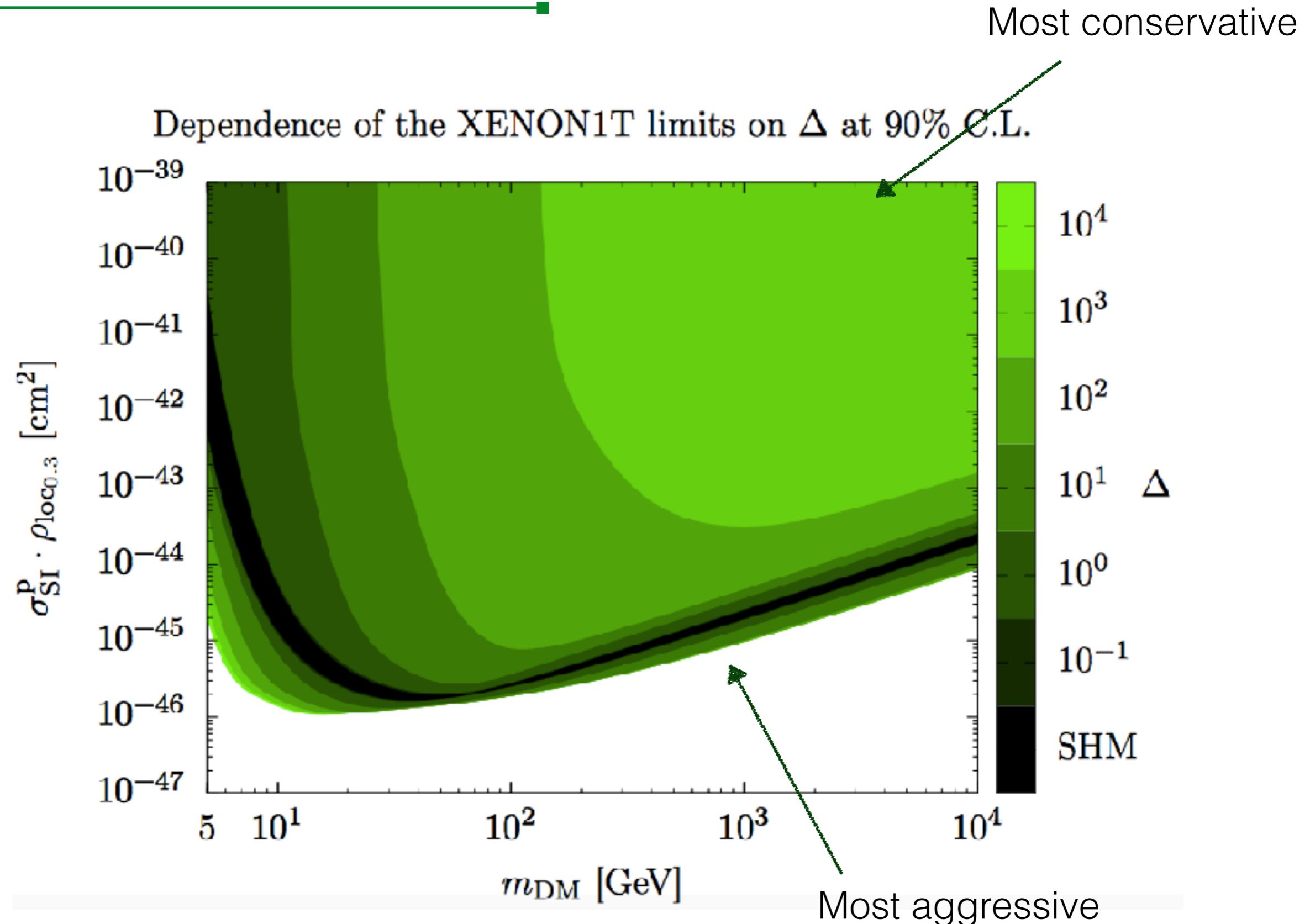


Optimise p-value or
chi-squared or likelihood
or whatever

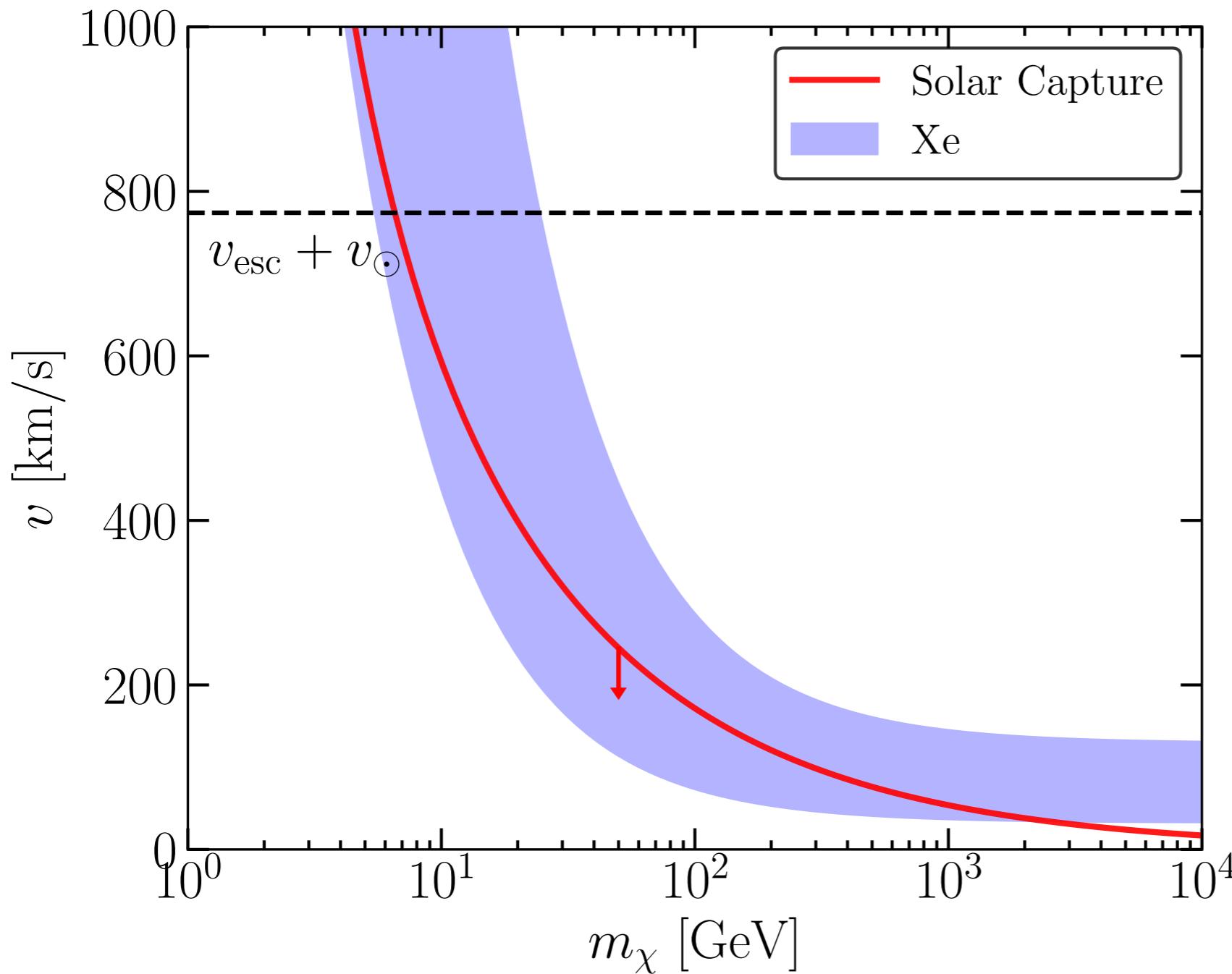
For small event numbers, this can recast this as a
fast optimisation problem for the coefficients c_i .

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

Xenon1T Limits



Velocity Ranges



Direct detection:

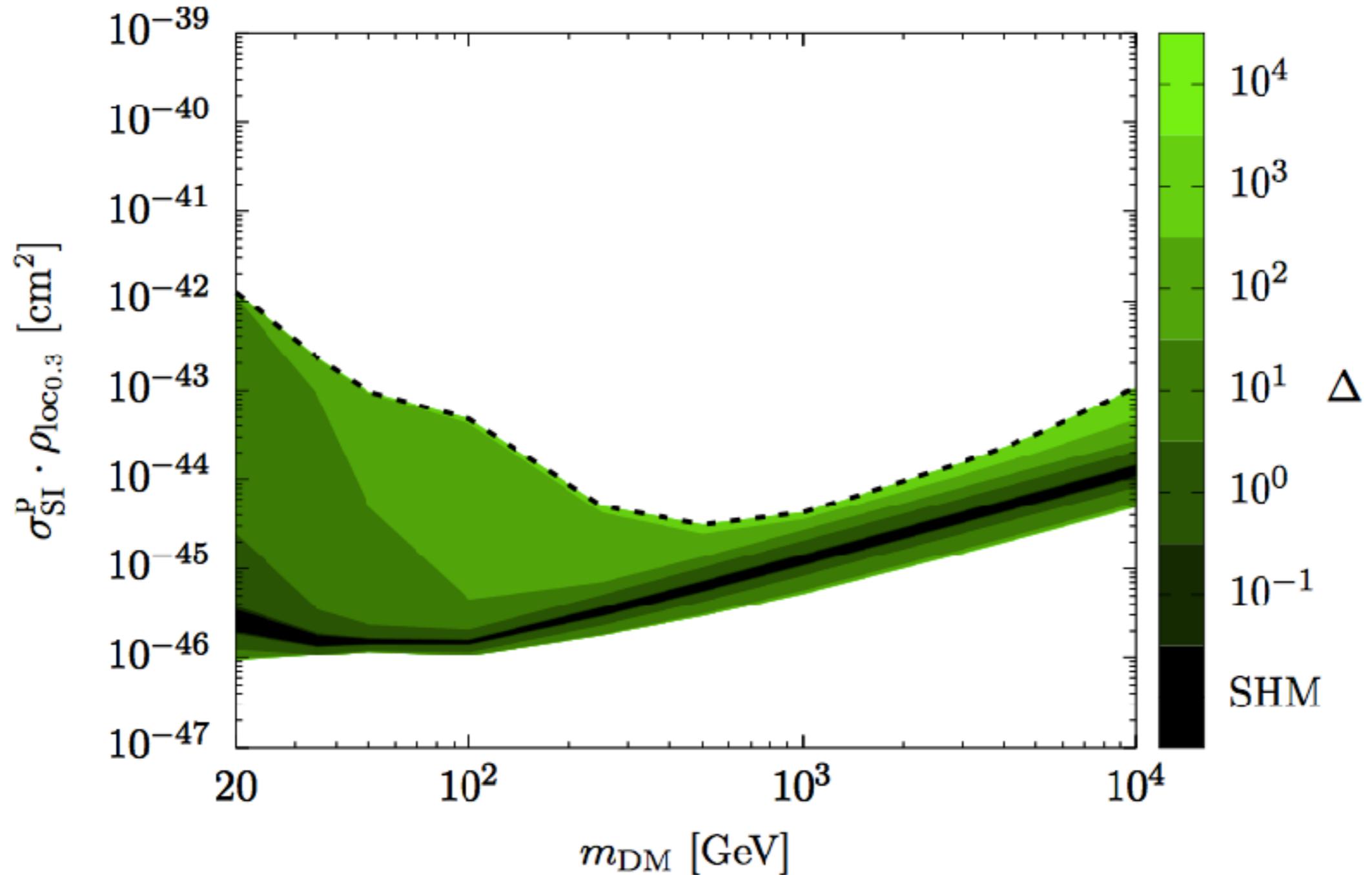
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Solar Capture:

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

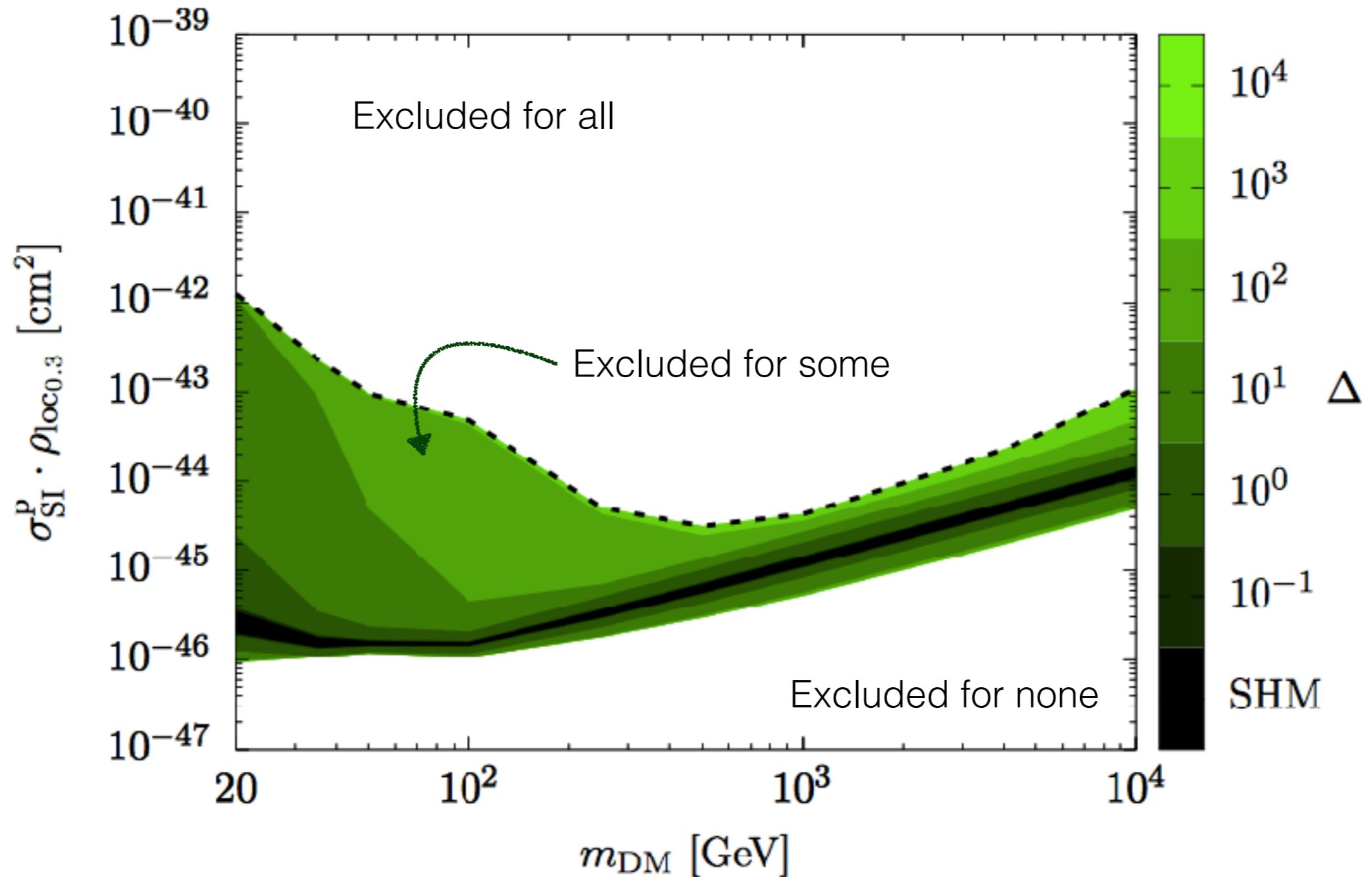
Xenon1T + IceCube

Dependence of the XENON1T+IceCube limits on Δ at 90% C.L.



Xenon1T + IceCube

Dependence of the XENON1T+IceCube limits on Δ at 90% C.L.



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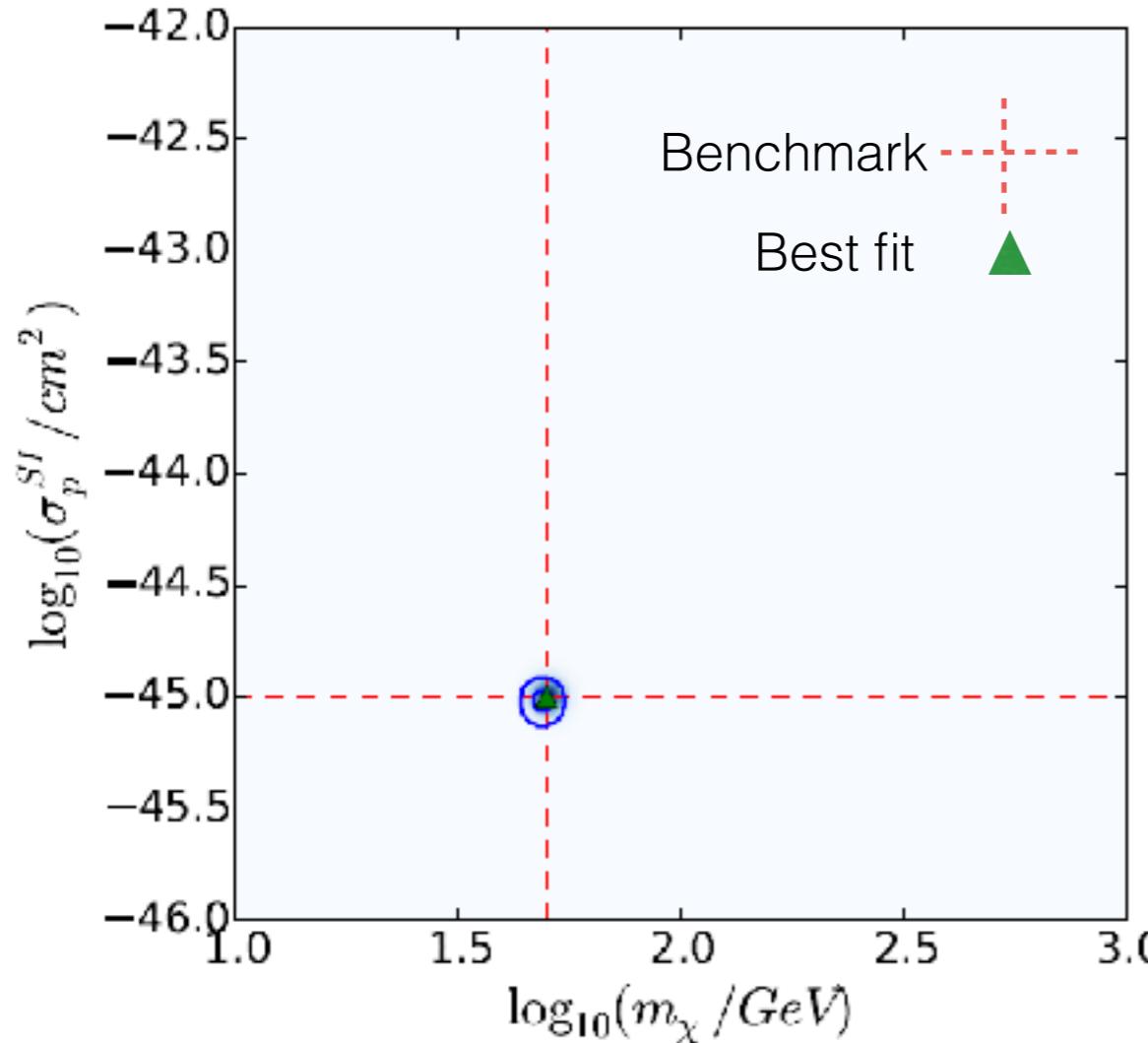
[Bonus: Can we also measure the local DM density?]

Impact on DM Signals

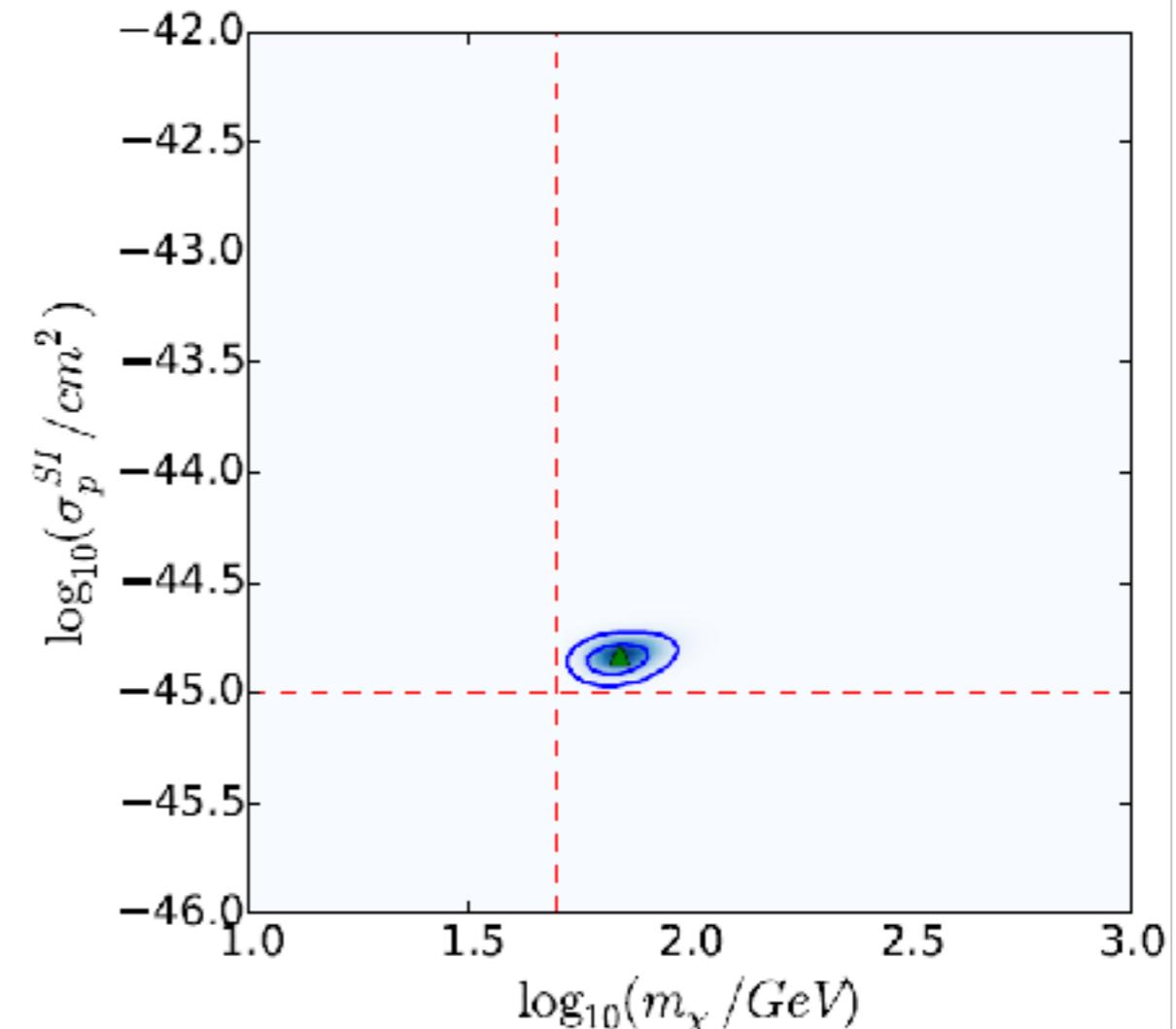
NB: Some of these parameters
are now excluded :(

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



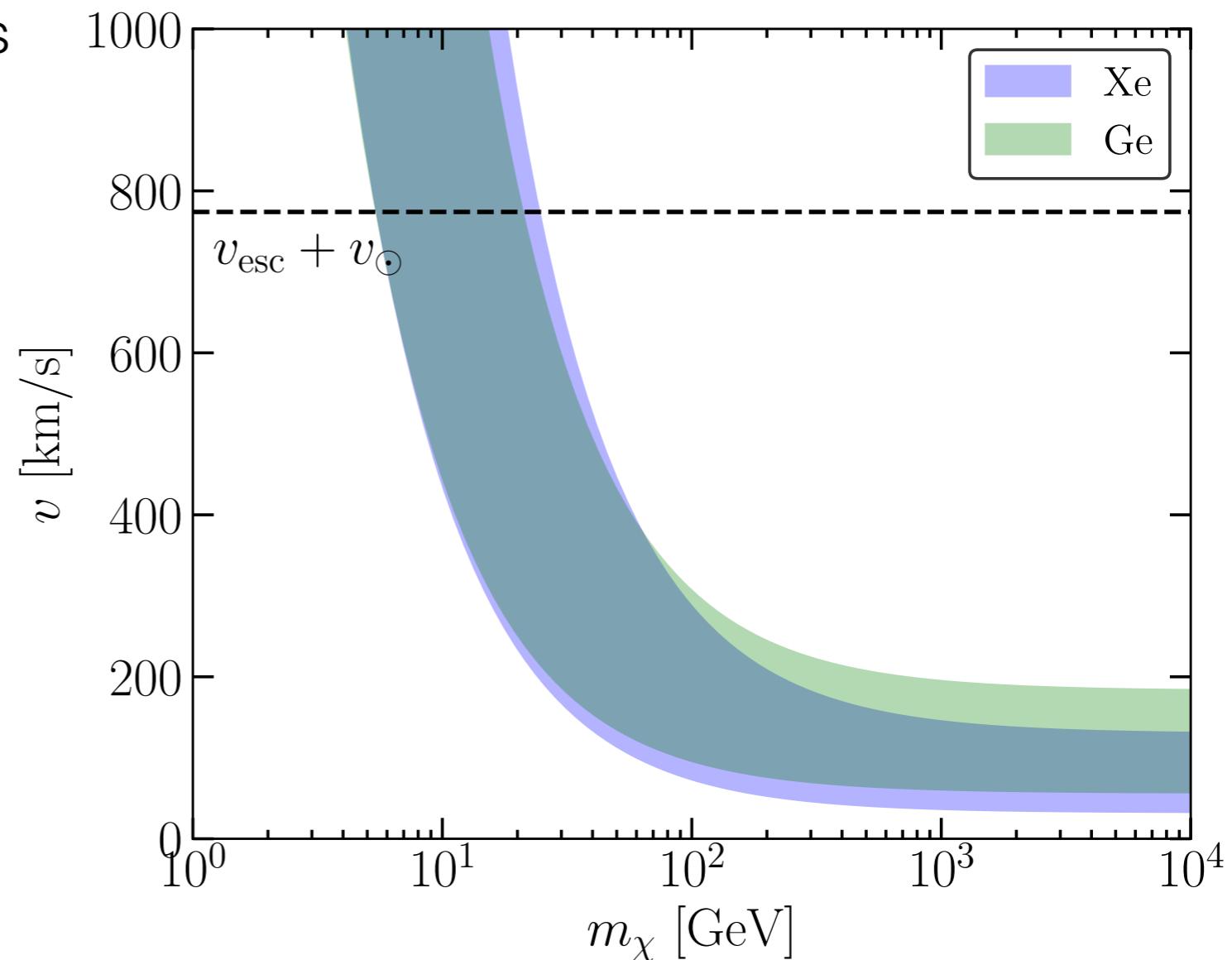
Halo-independent methods

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

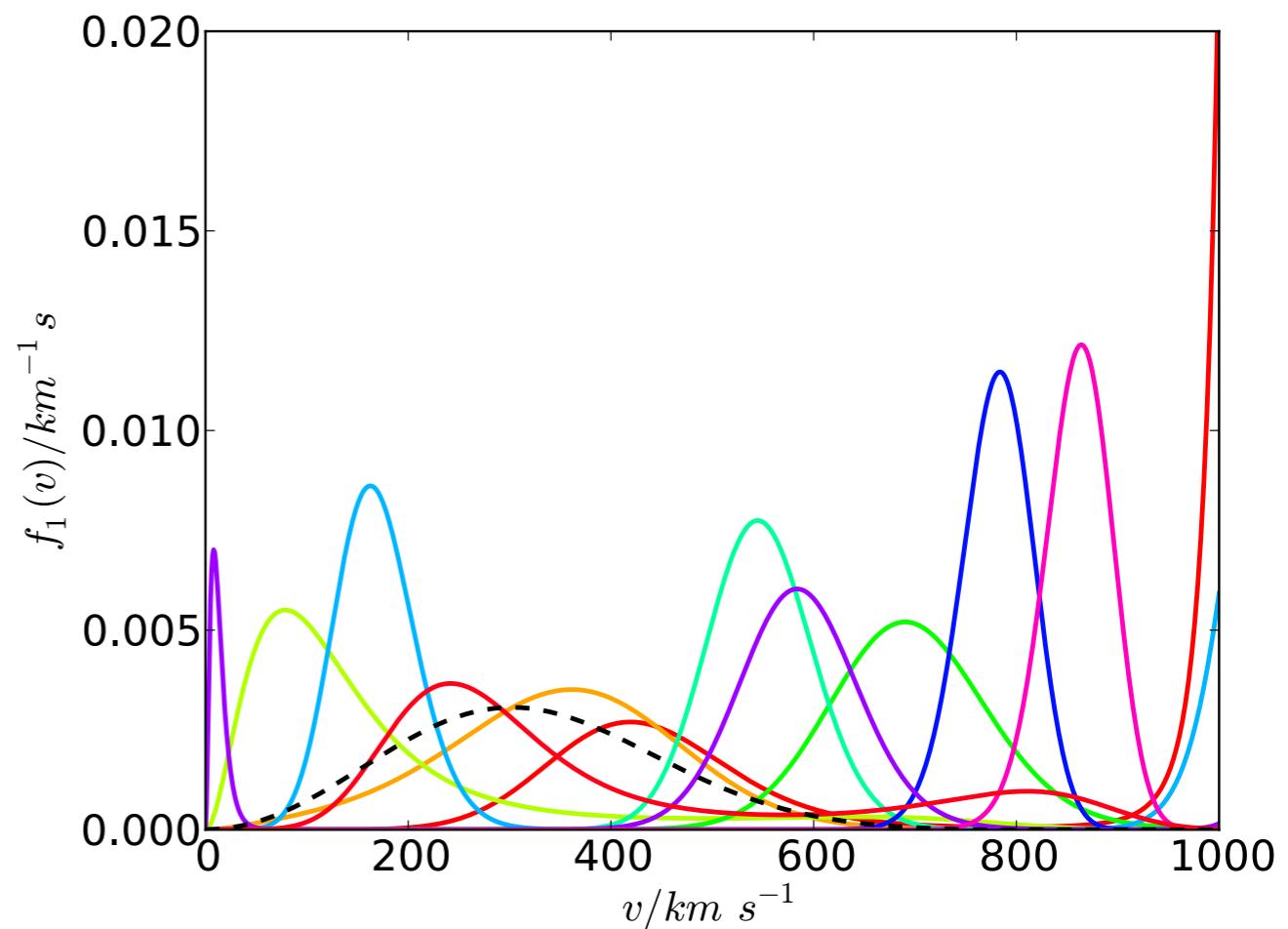
Write a *general parametrisation* for the speed distribution: Peter [1103.5145]

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

BJK & Green [1303.6868]

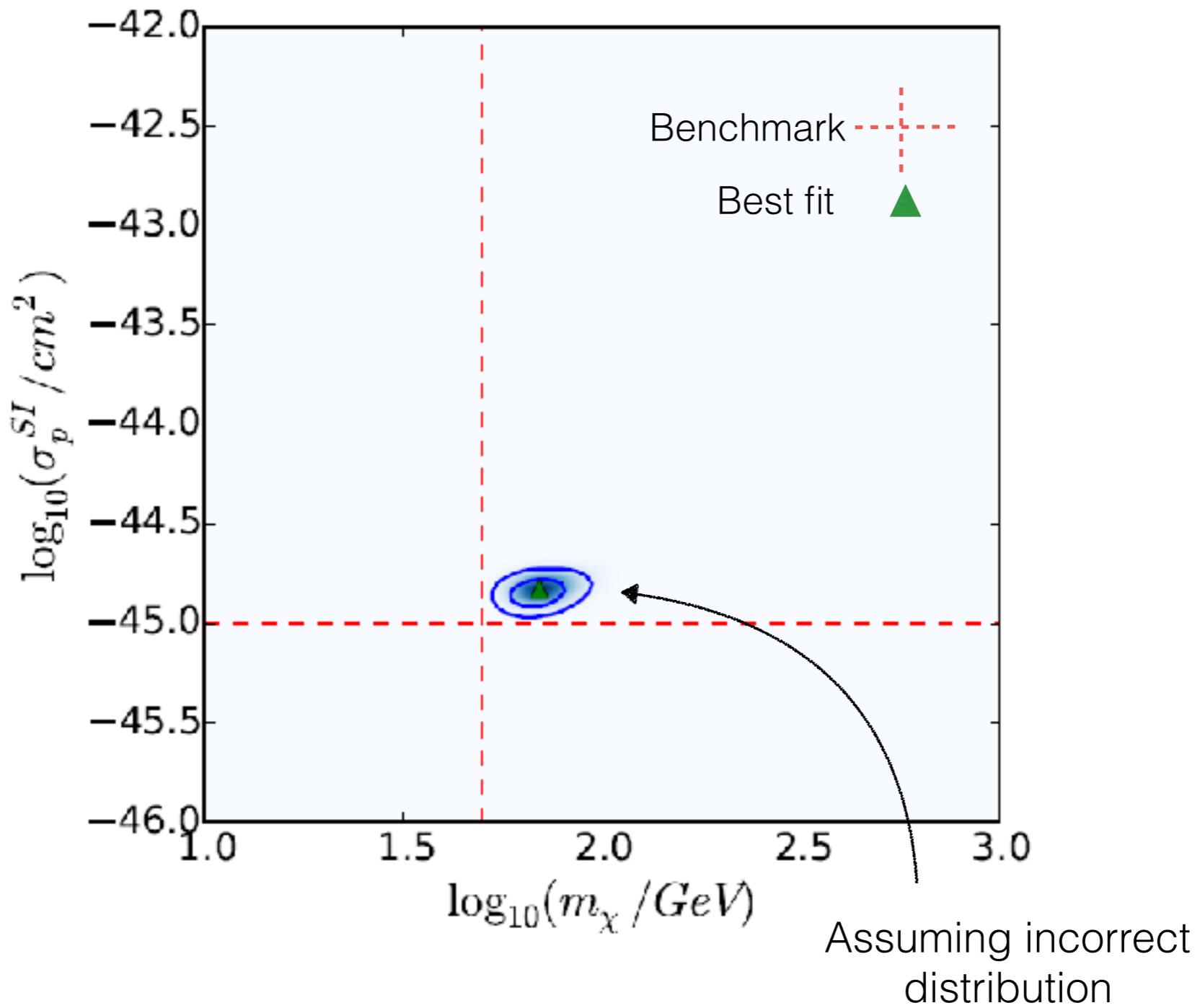
Guarantees a positive distribution function and spans a wide range of functional forms with only a small number N of parameters:

Now fit (m_χ, σ_p) at the same time as $\{a_k\}$...



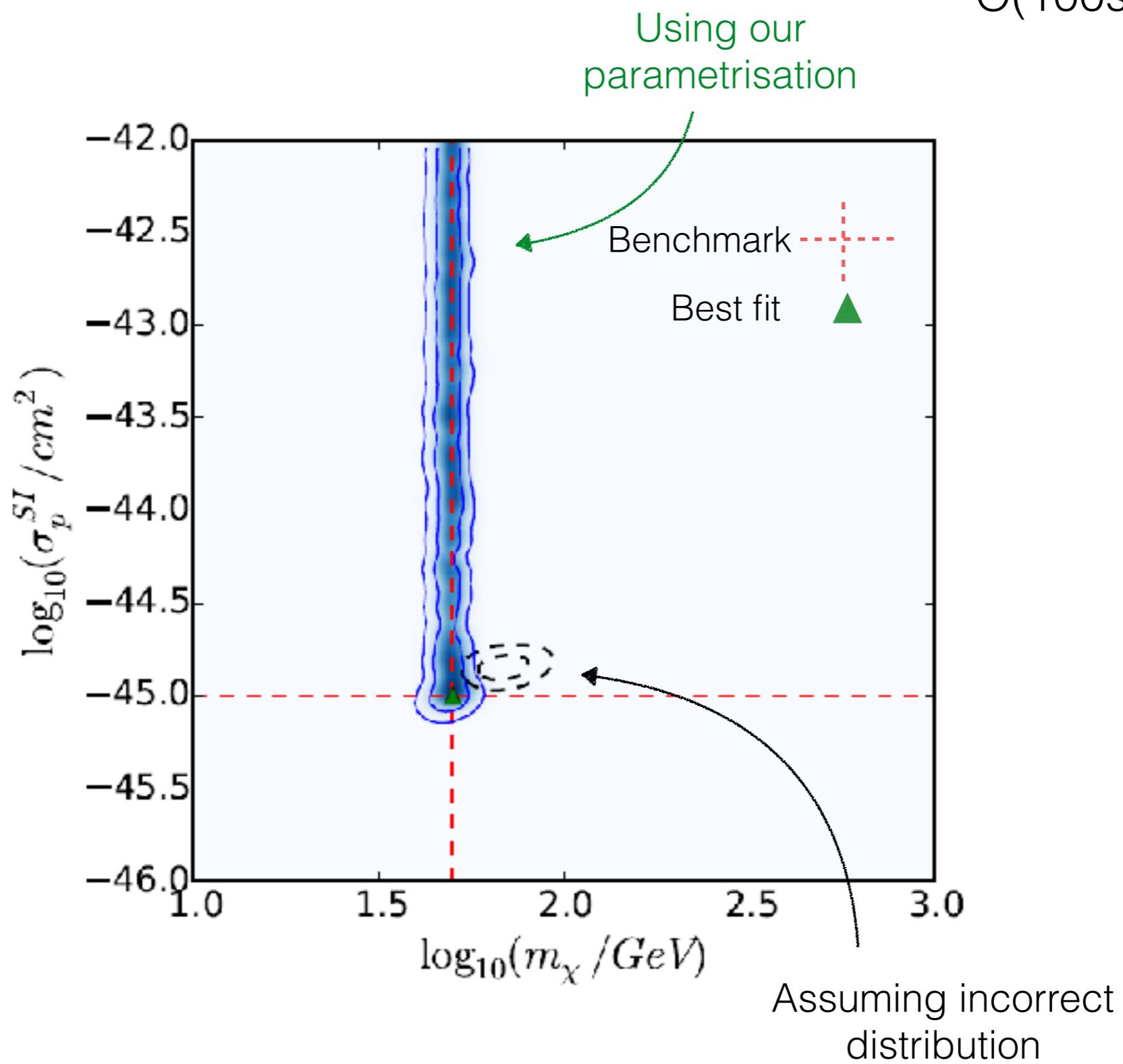
Testing the parametrisation

Direct detection
Xe + Ge + Ar



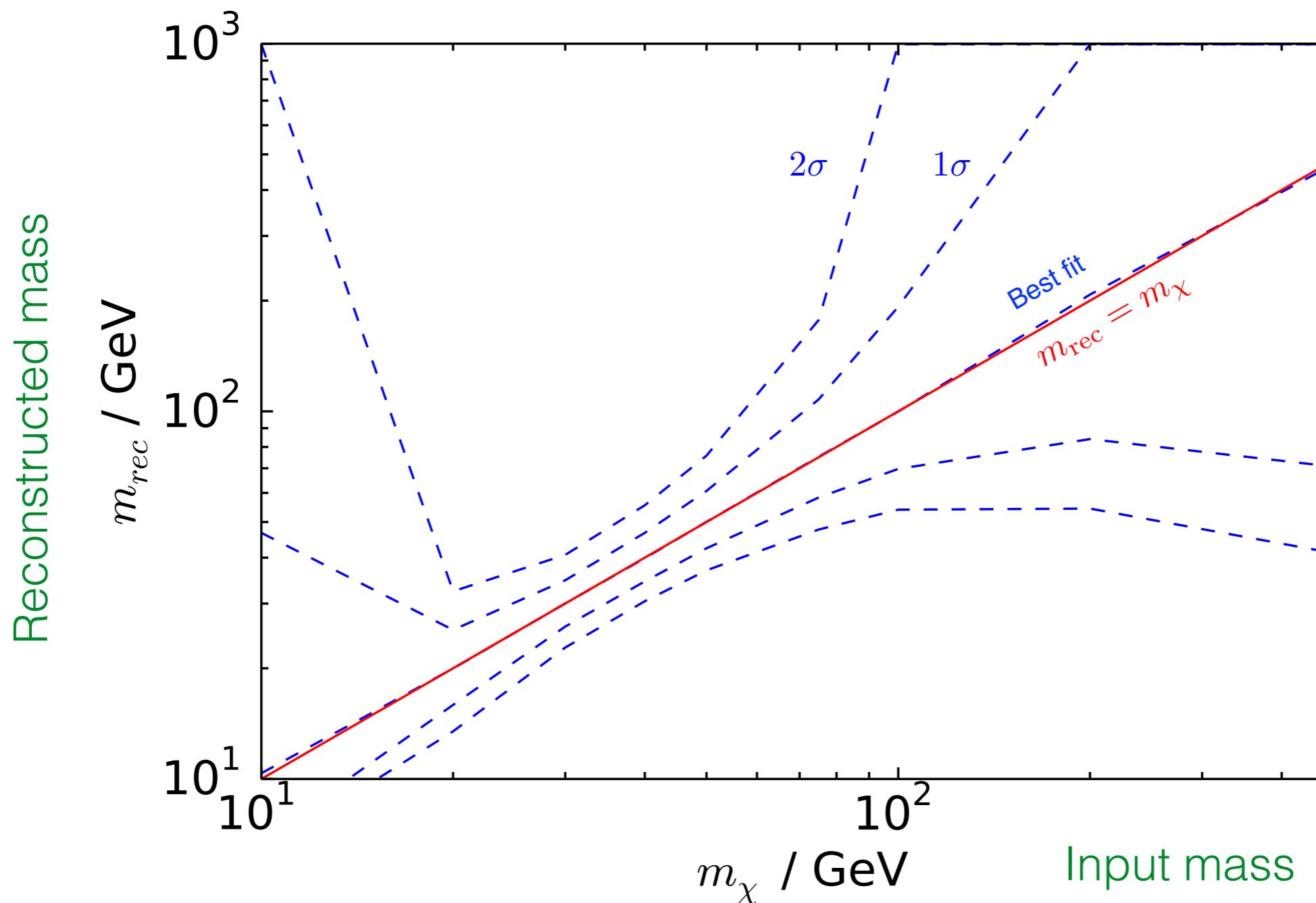
Testing the parametrisation

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



Reconstructing DM mass

BJK [1312.1852]

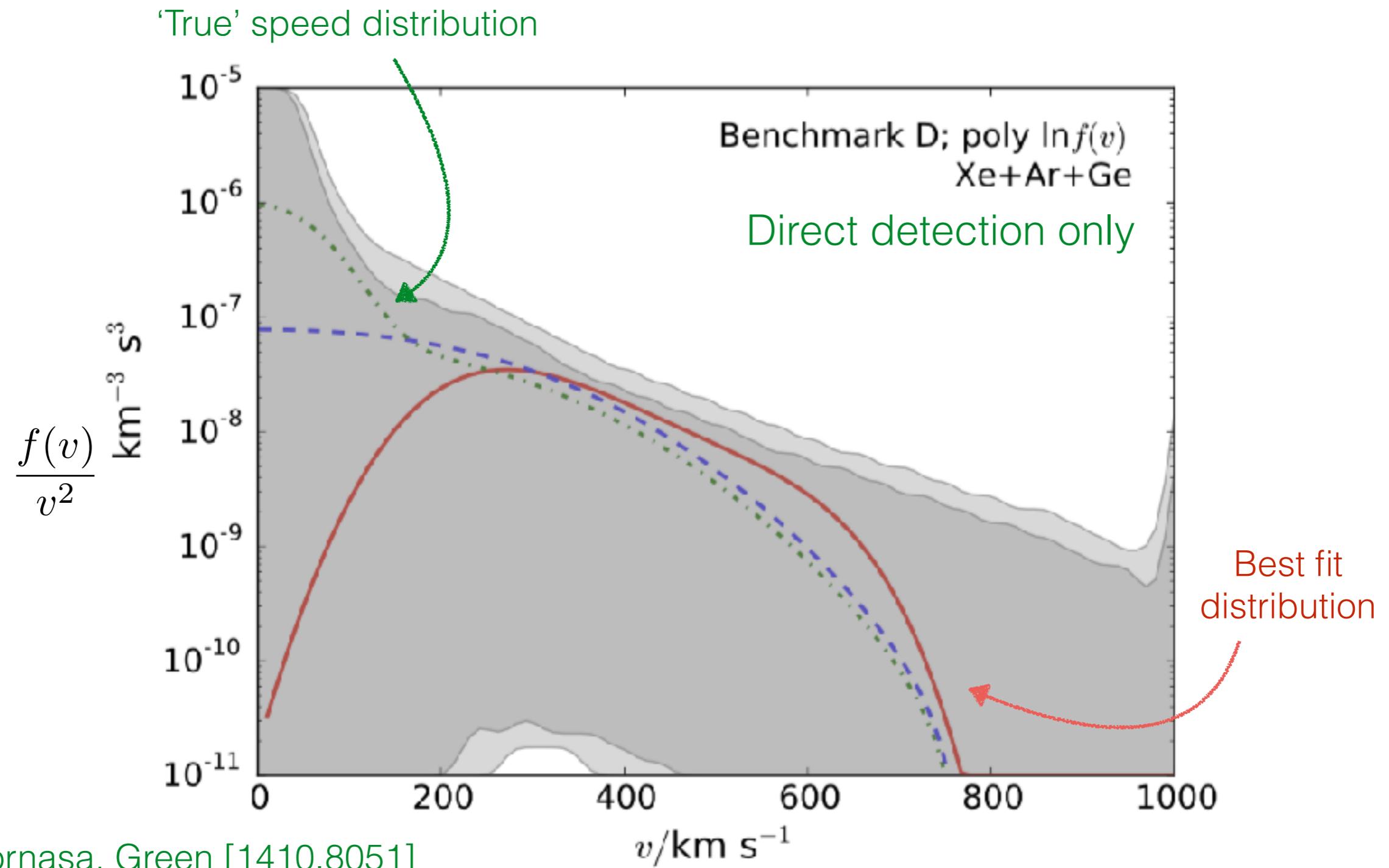


Also works for a range of input velocity distributions.
Recently demonstrated for arbitrary interactions too...

Krauss & Newstead [1801.08523]

Reconstructing $f(v)$

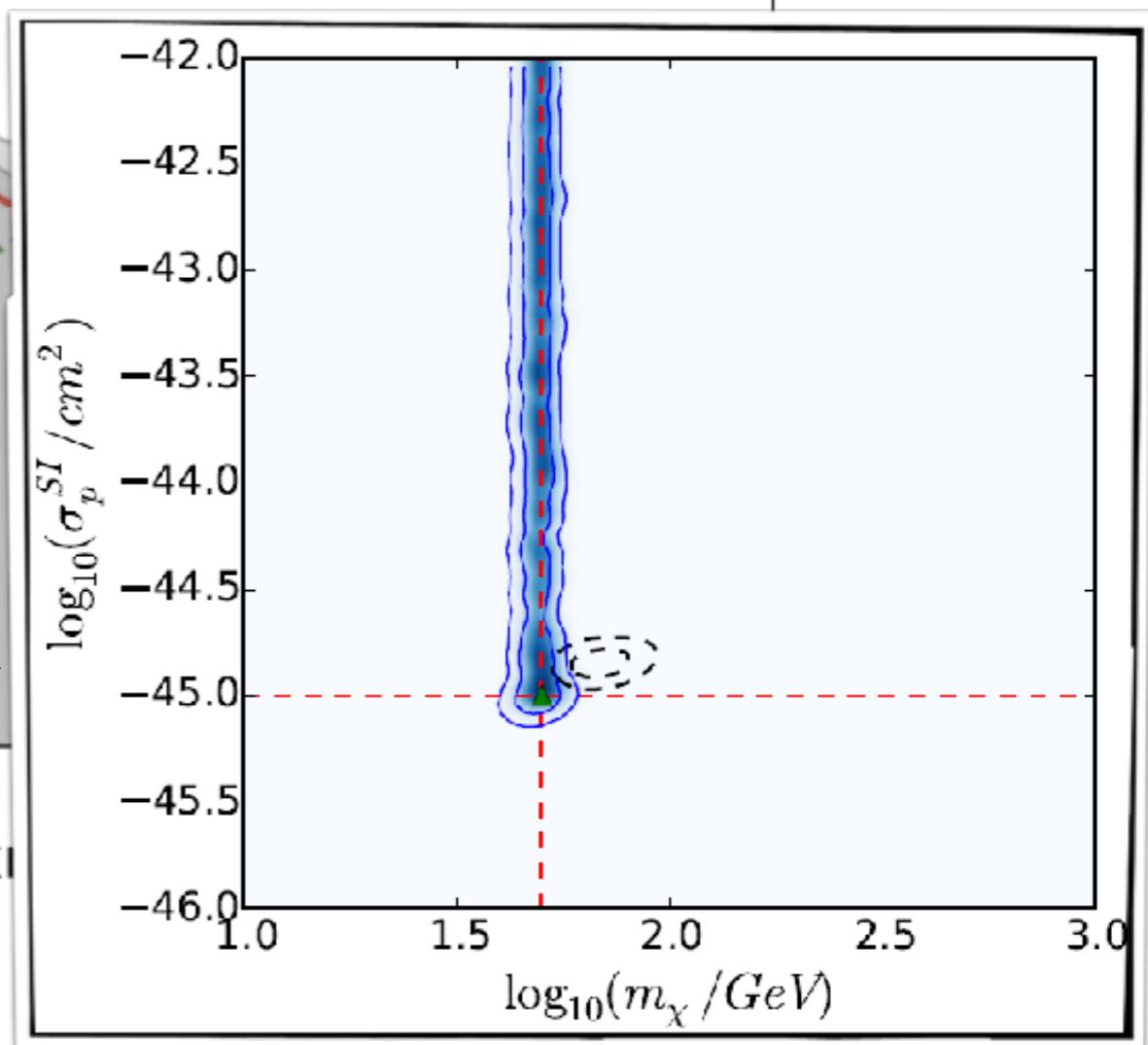
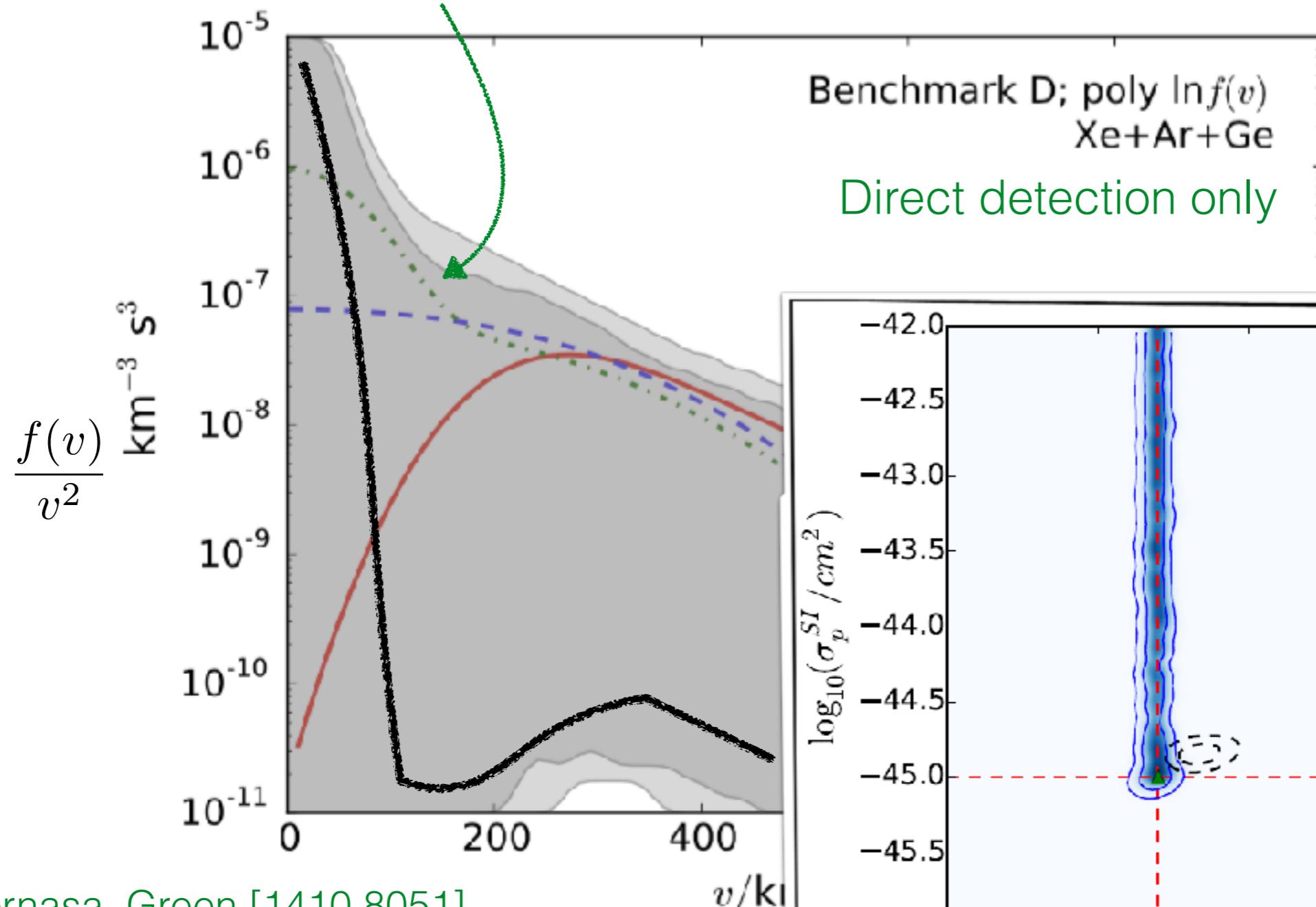
$m_\chi = 30 \text{ GeV}$
SHM+DD distribution



Reconstructing $f(v)$

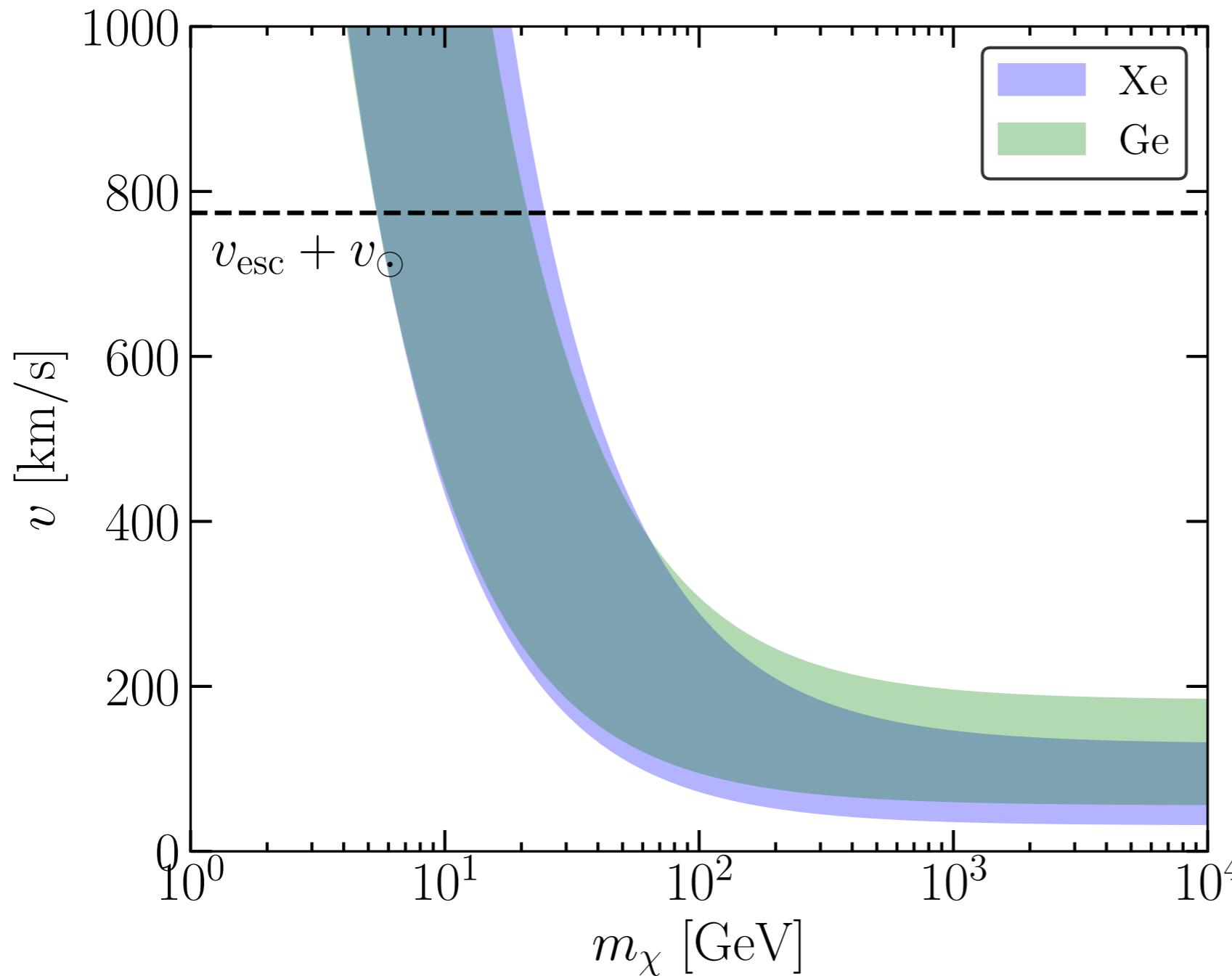
$m_\chi = 30 \text{ GeV}$
SHM+DD distribution

'True' speed distribution



Velocity Ranges

Cannot constrain distribution below threshold...



Direct detection:

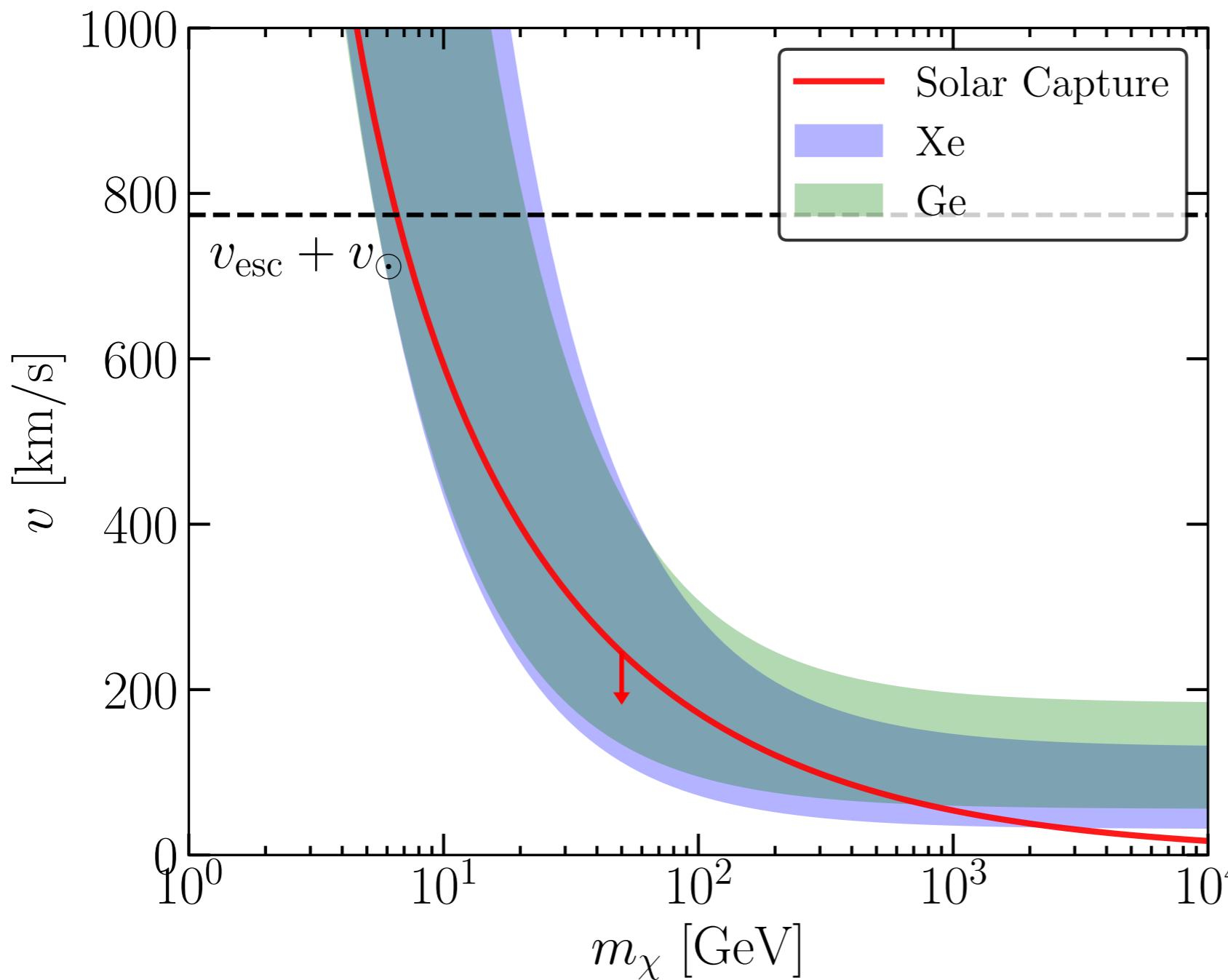
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

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:

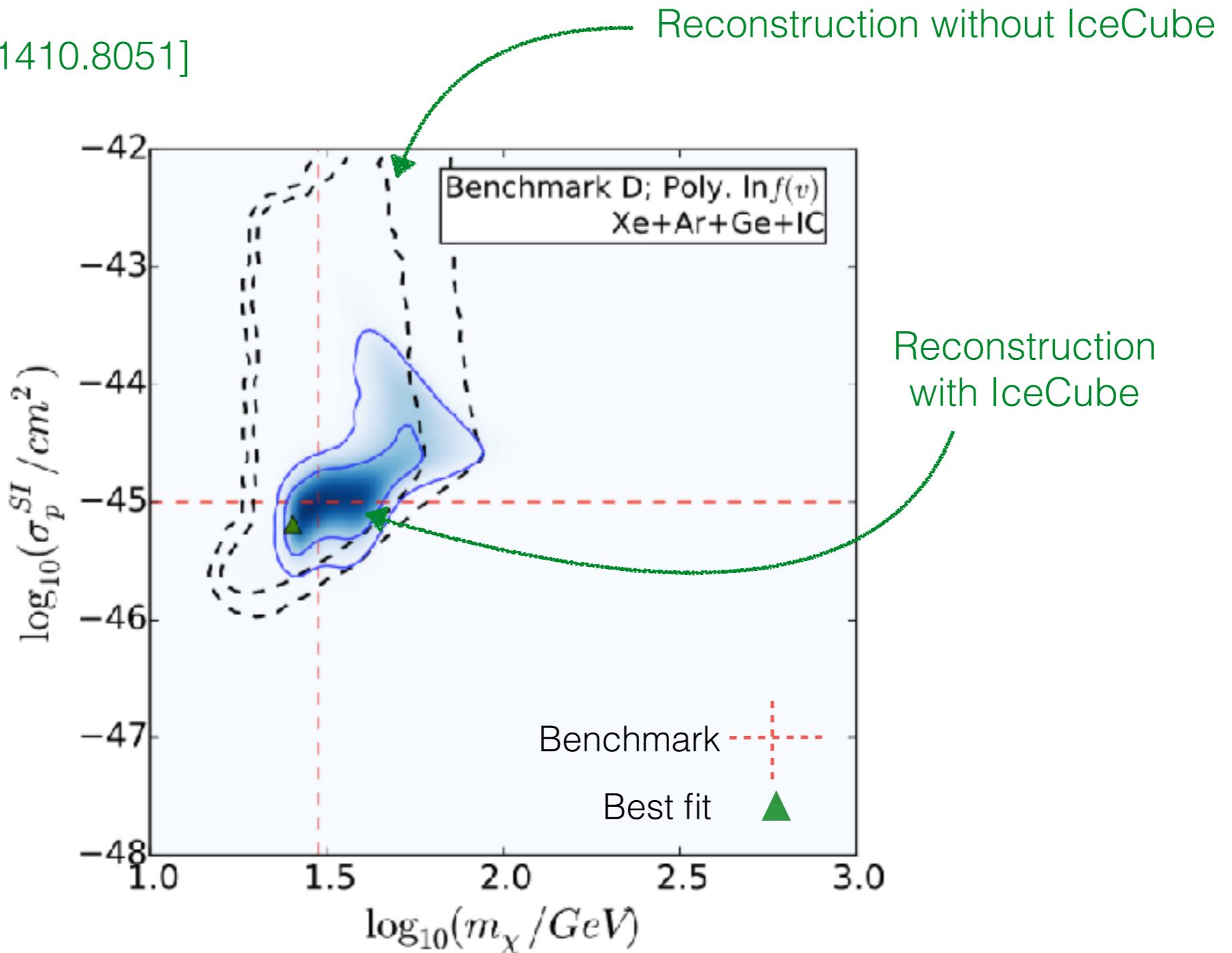
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

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]

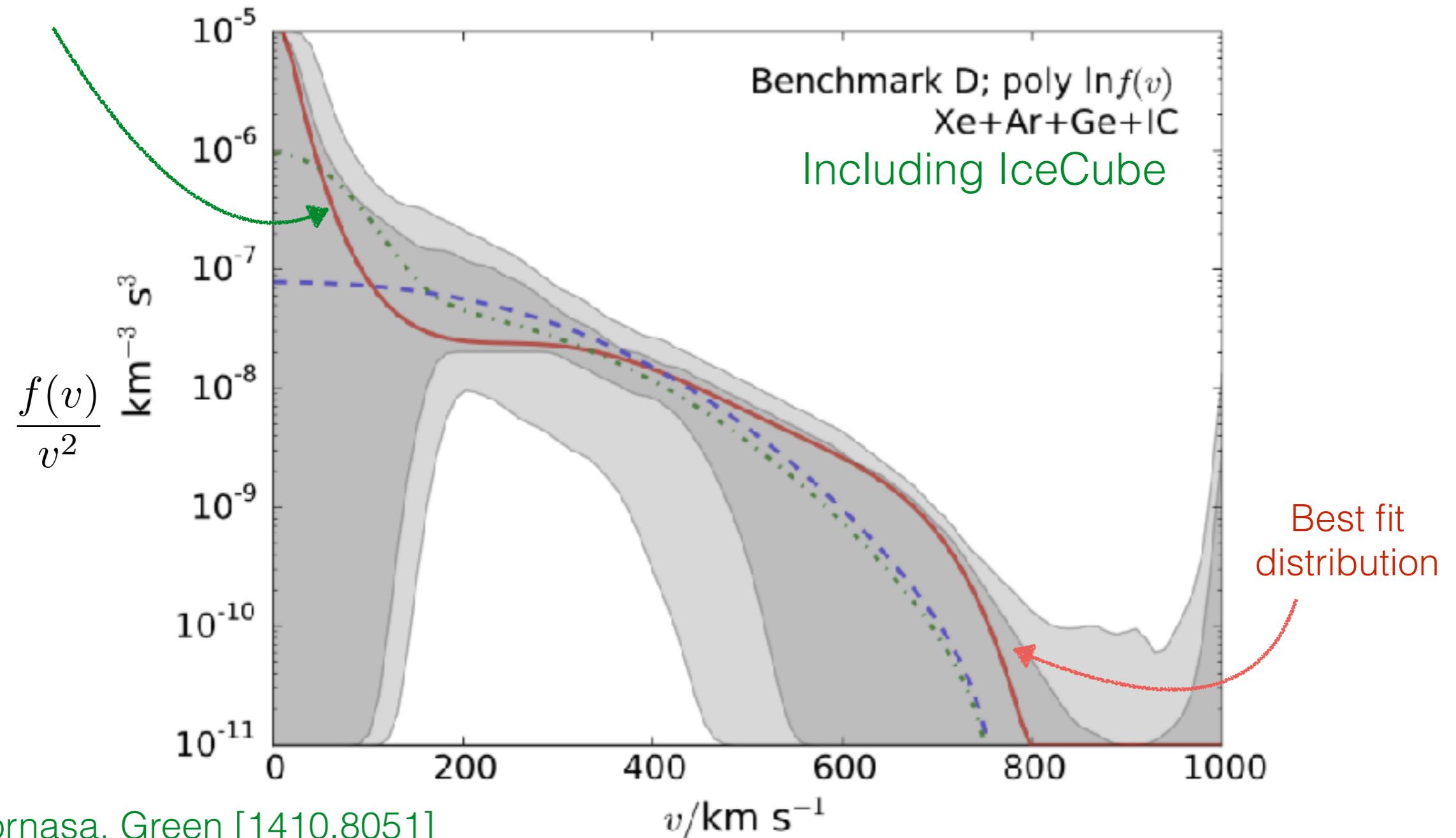


Combining direct detection and solar capture,
we could pin down DM mass and cross section

Reconstructing $f(v)$ with IceCube

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

'True' speed distribution



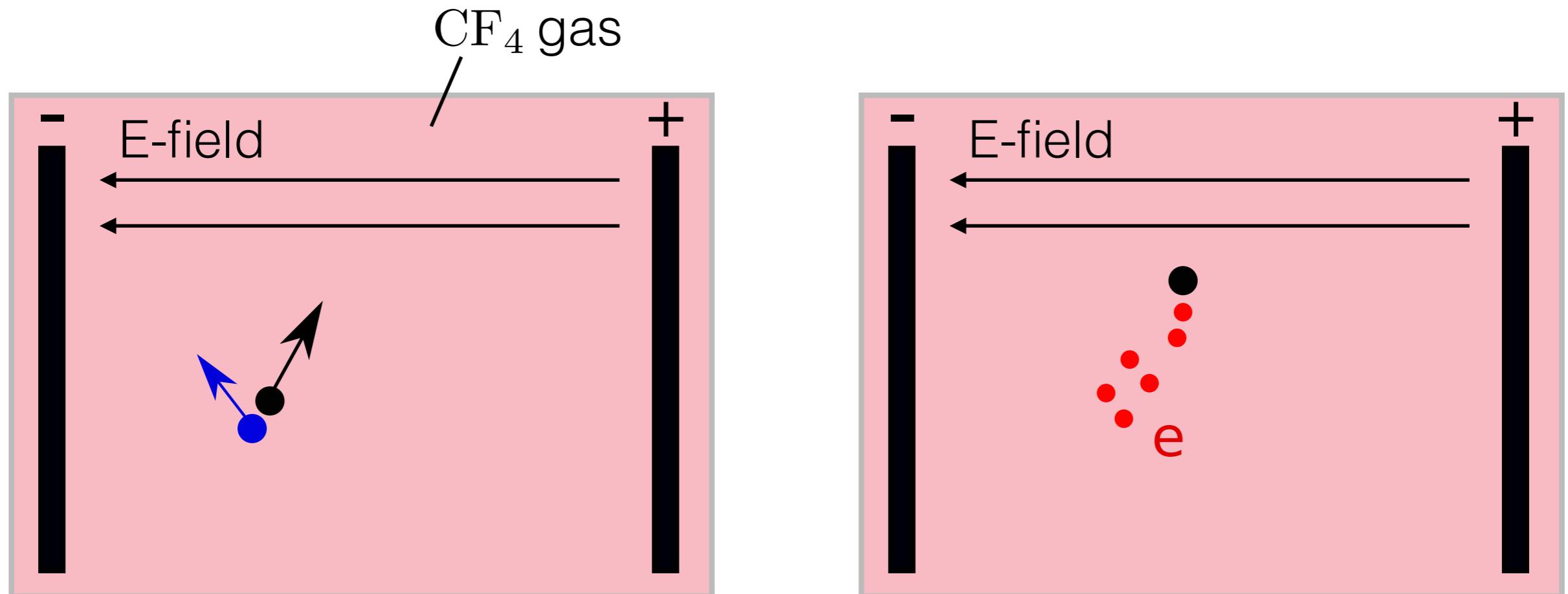
Constraints improved, but still difficult to distinguish underlying distributions (perhaps only at the 1σ level)...

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]



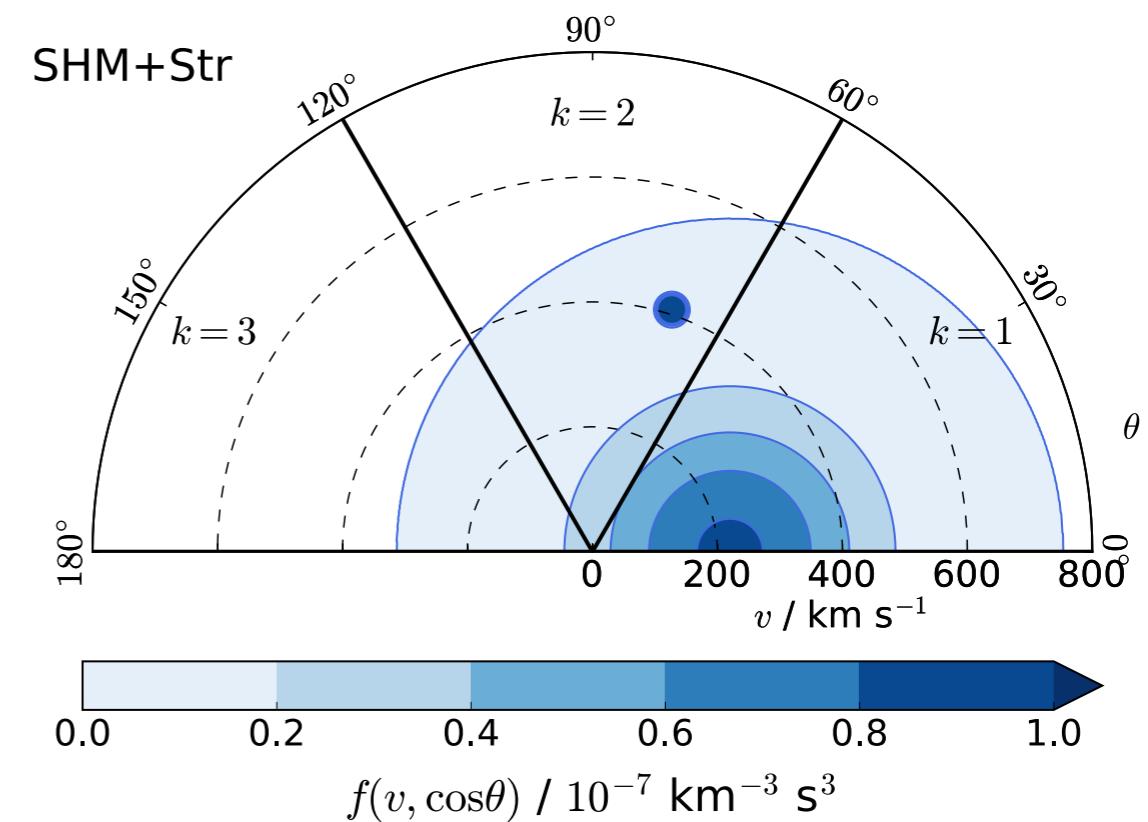
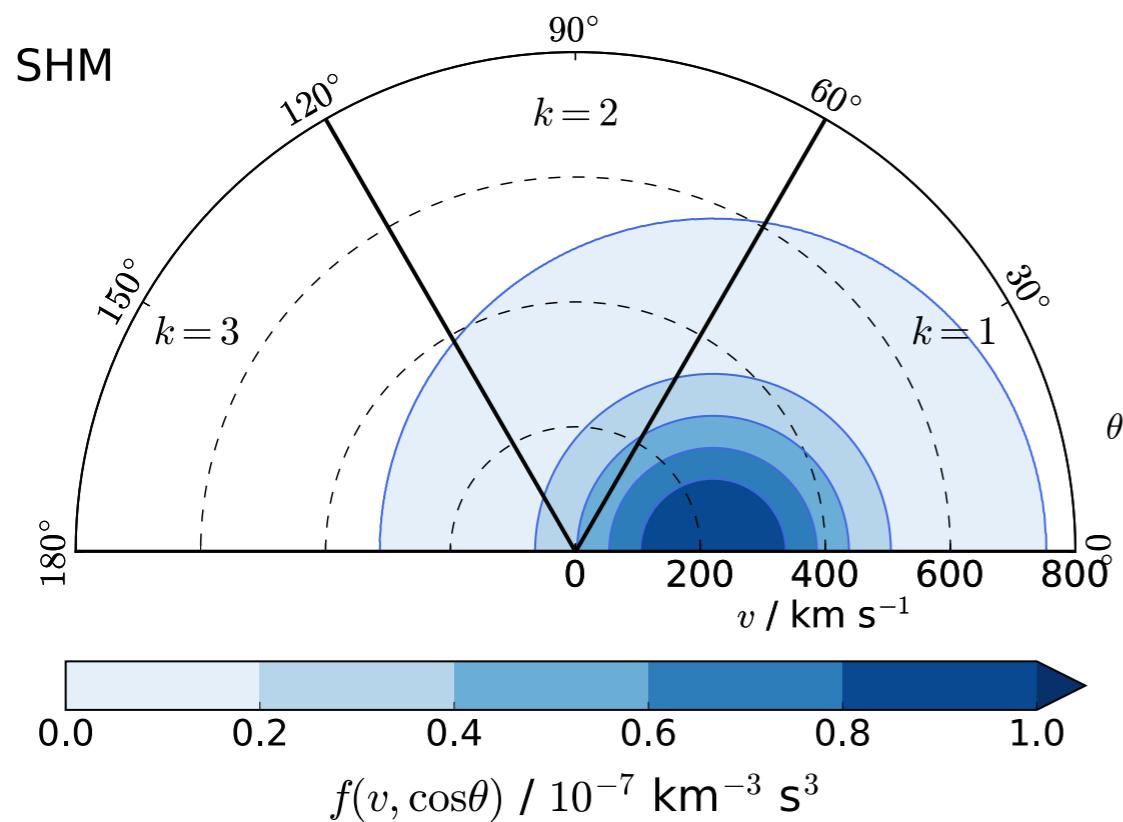
Possible suggestion of (partial) directionality in Xenon detectors

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]



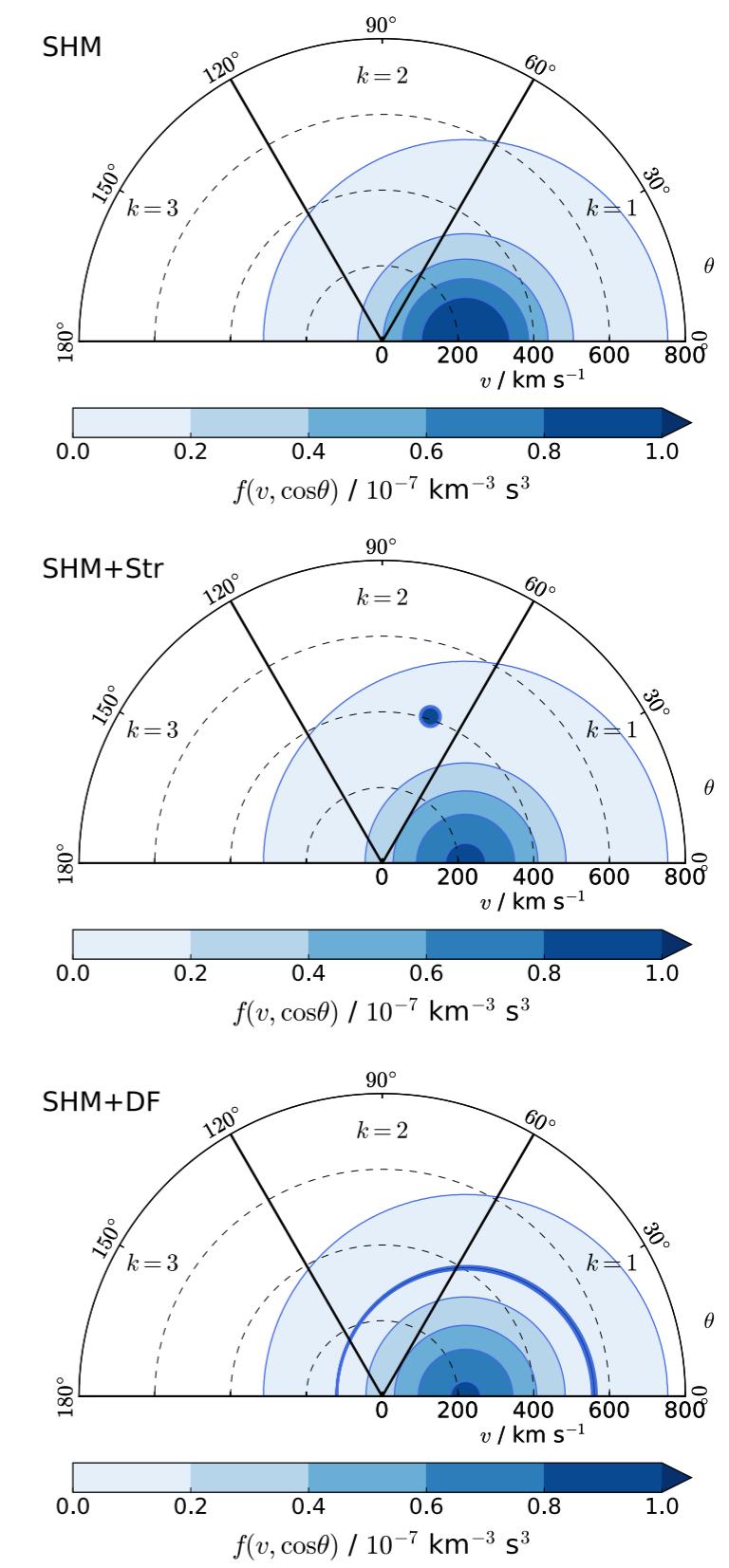
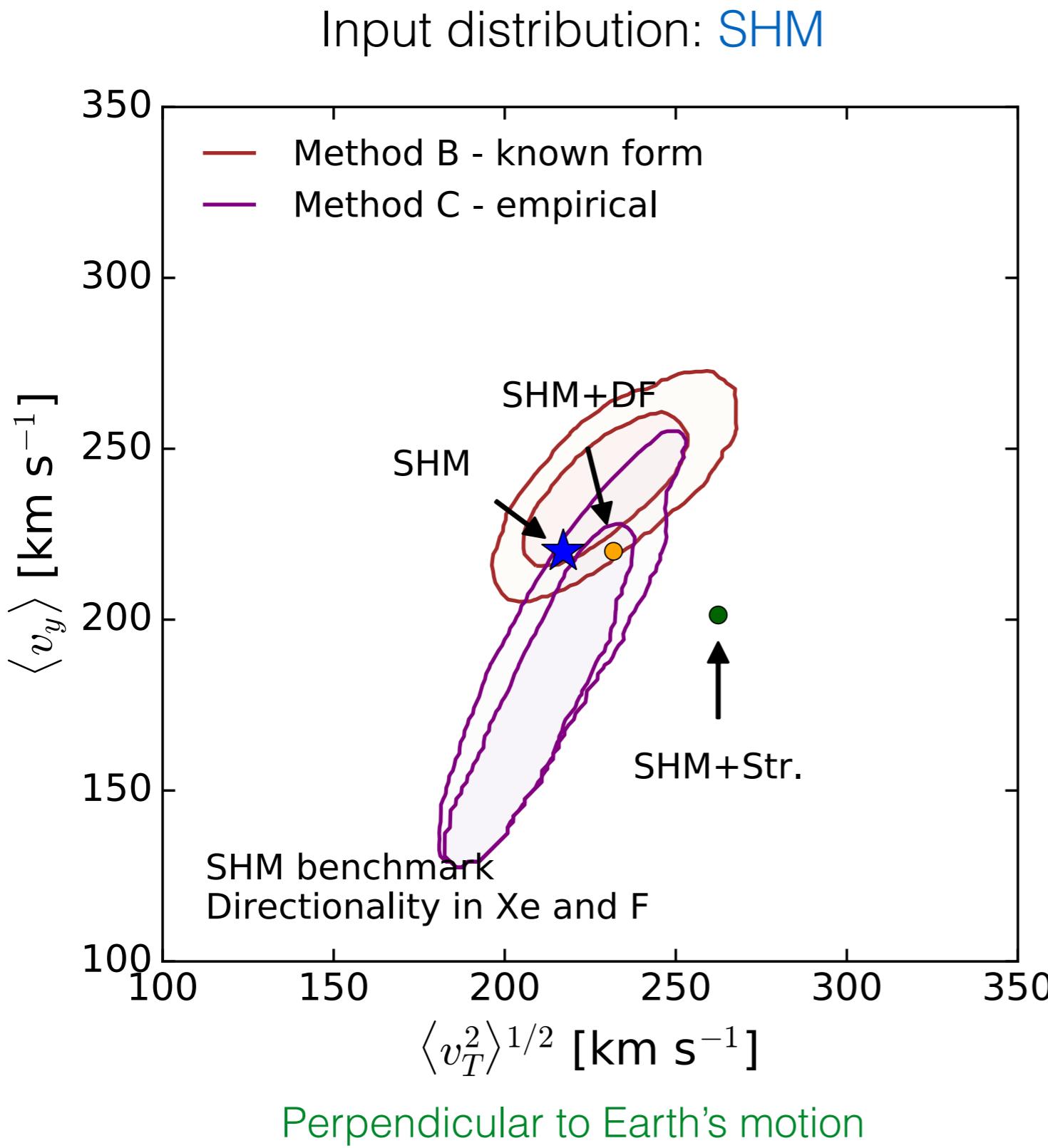
Apply the same parametrisation in 3-D
(note: some technical details, which make things annoying)

BJK [1502.04224]

Directional reconstructions

BJK, CAJ O'Hare [1609.08630]

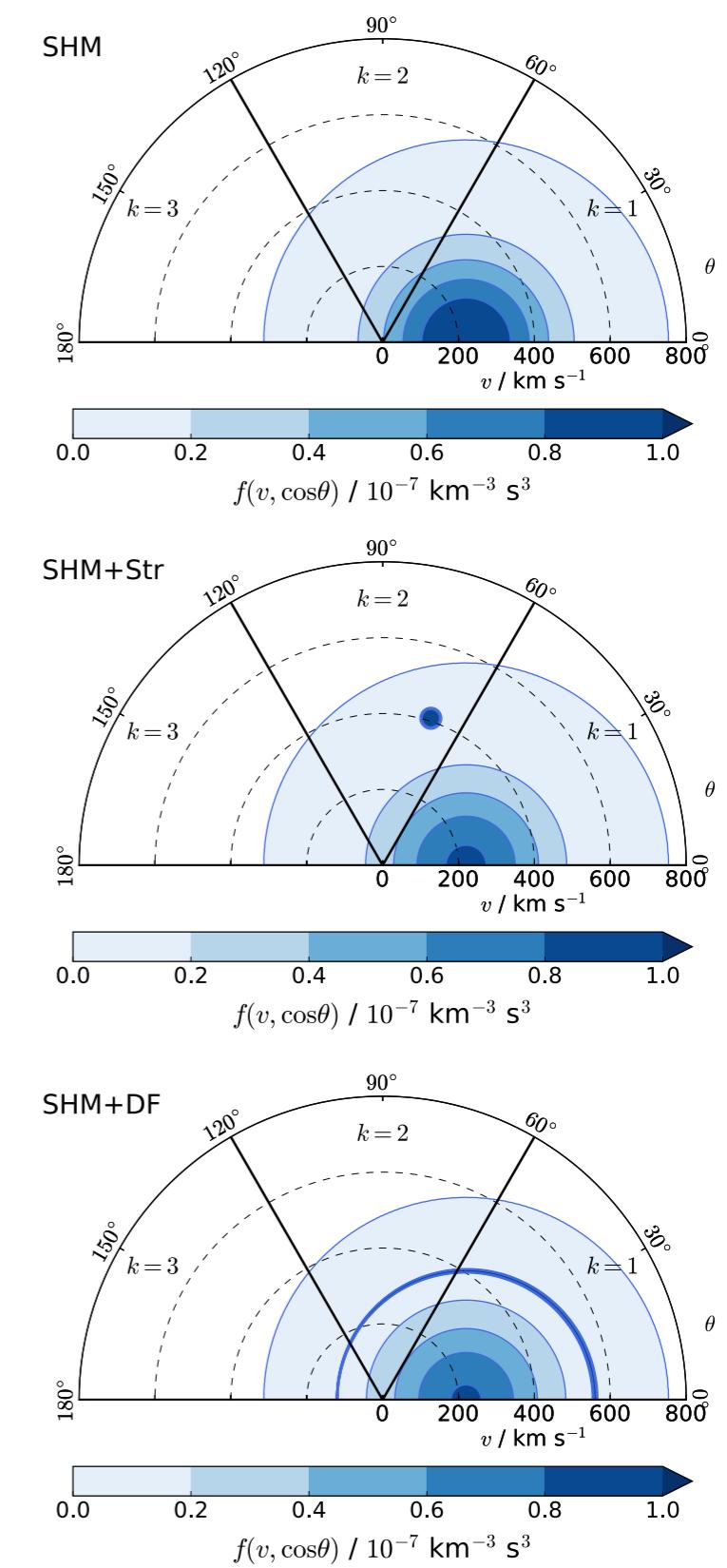
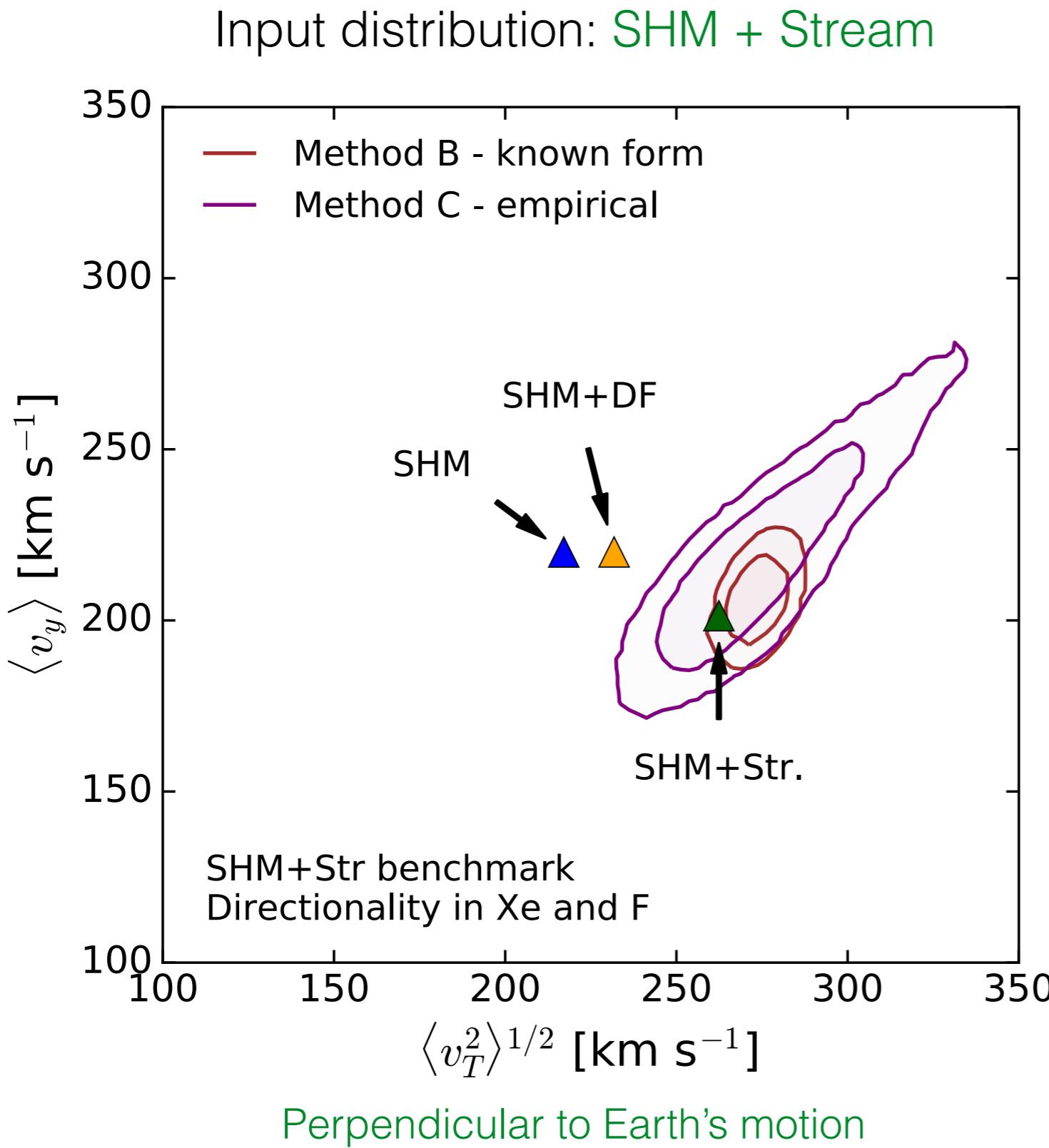
Parallel to Earth's motion



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

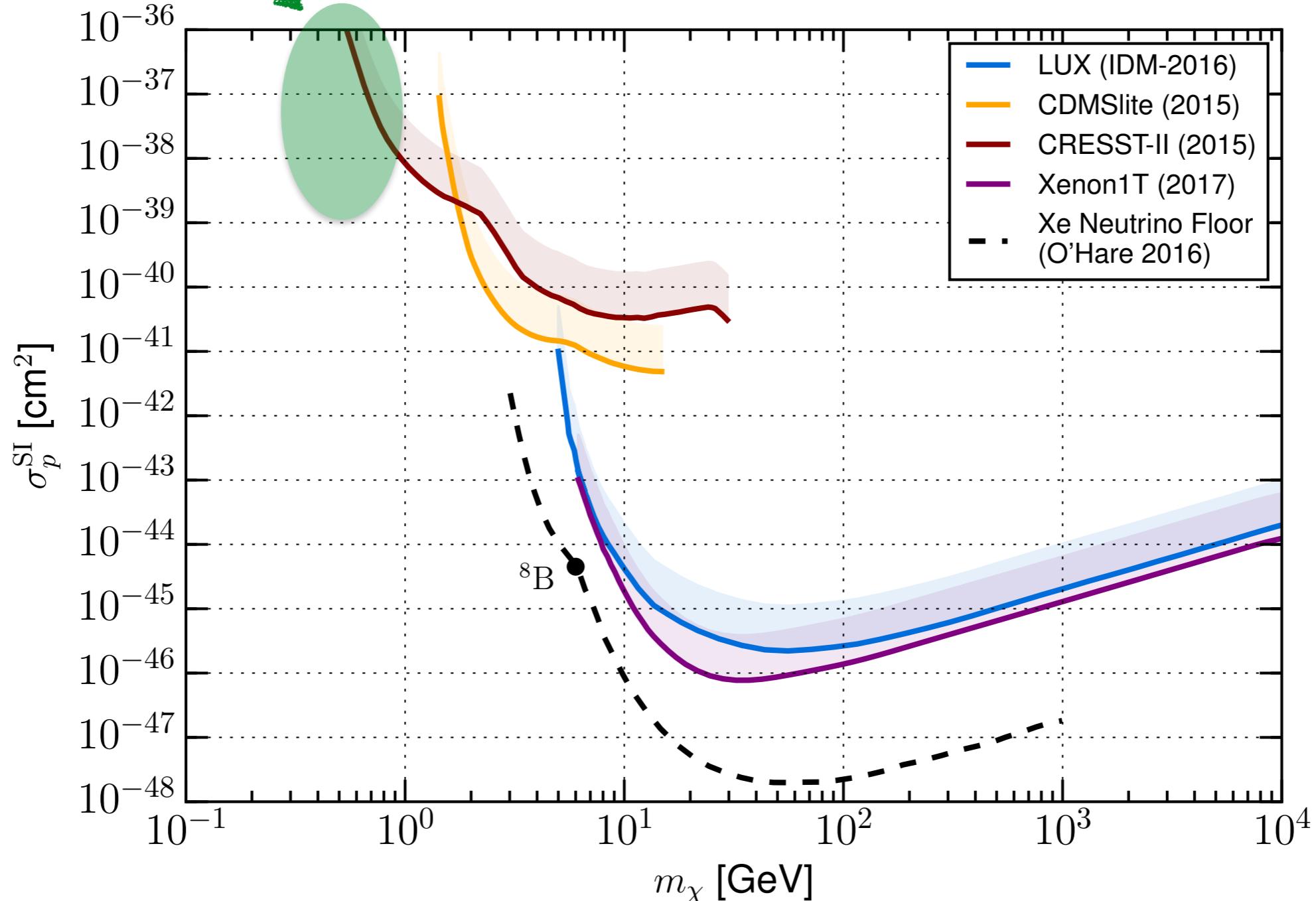
Halo-independent approaches to setting limits

Measuring the DM properties and distribution
with a future detection

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

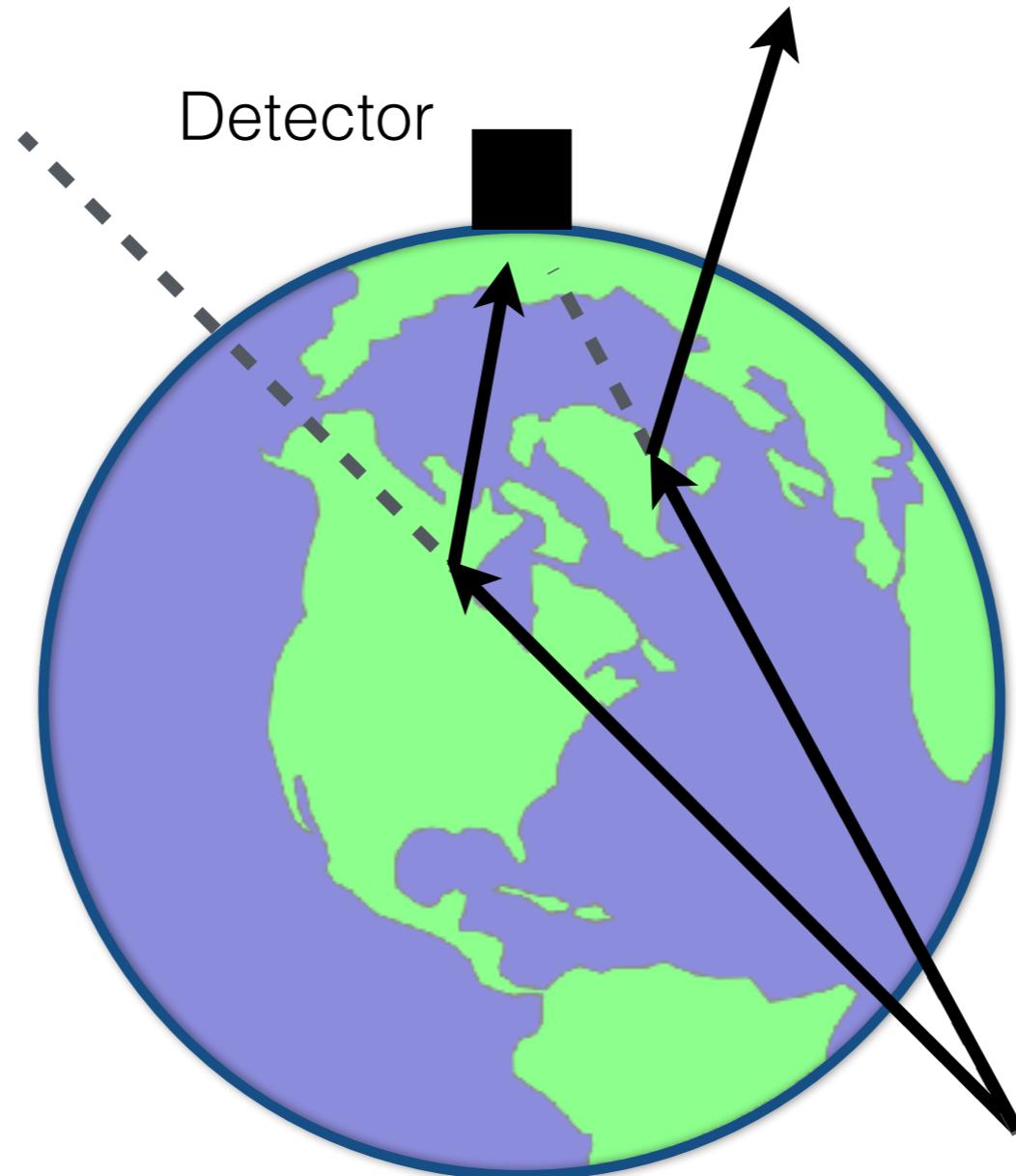
Map of the parameter space

Sub-GeV DM



Earth scattering

Collar & Avignone
[PLB 275, 1992]
and others



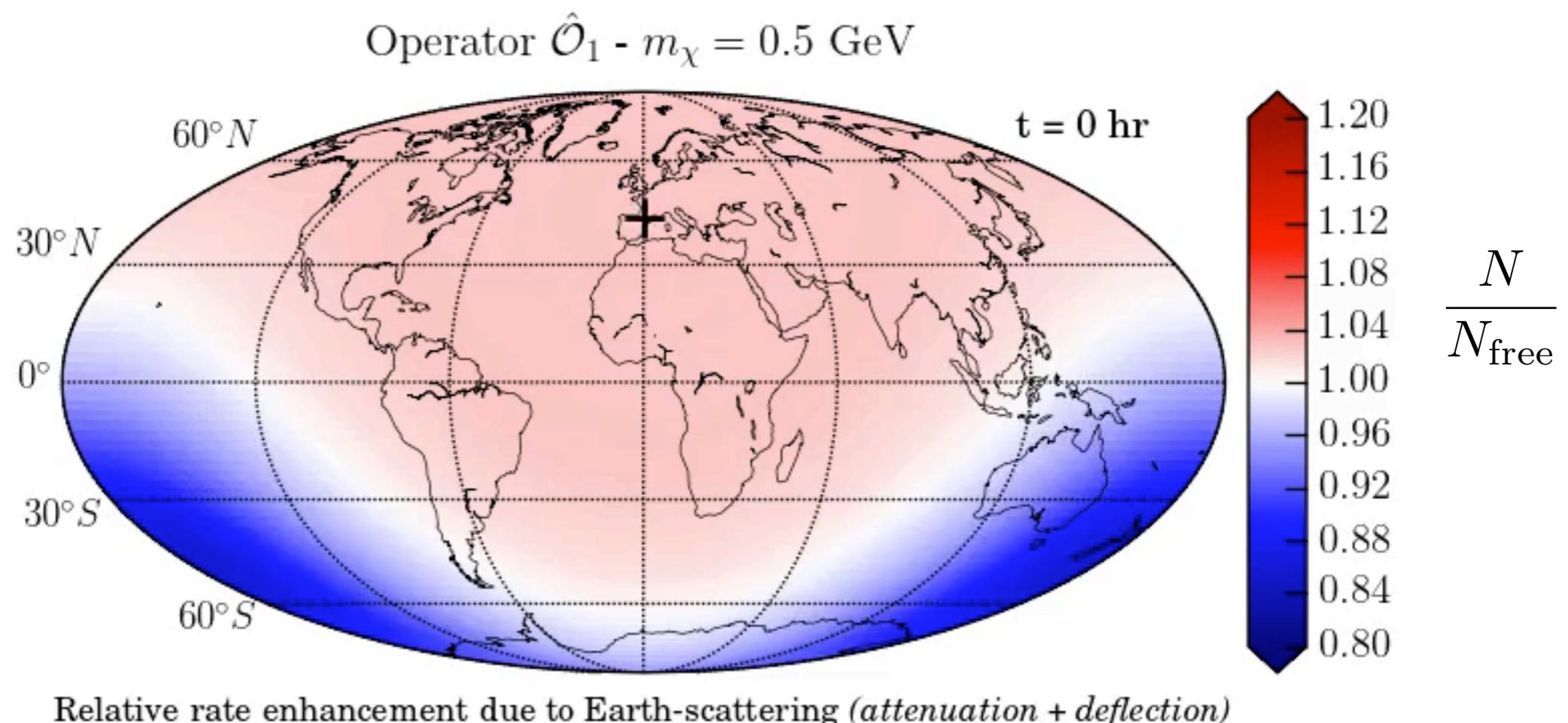
Earth-scattering can distort local density and velocity distribution:

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:

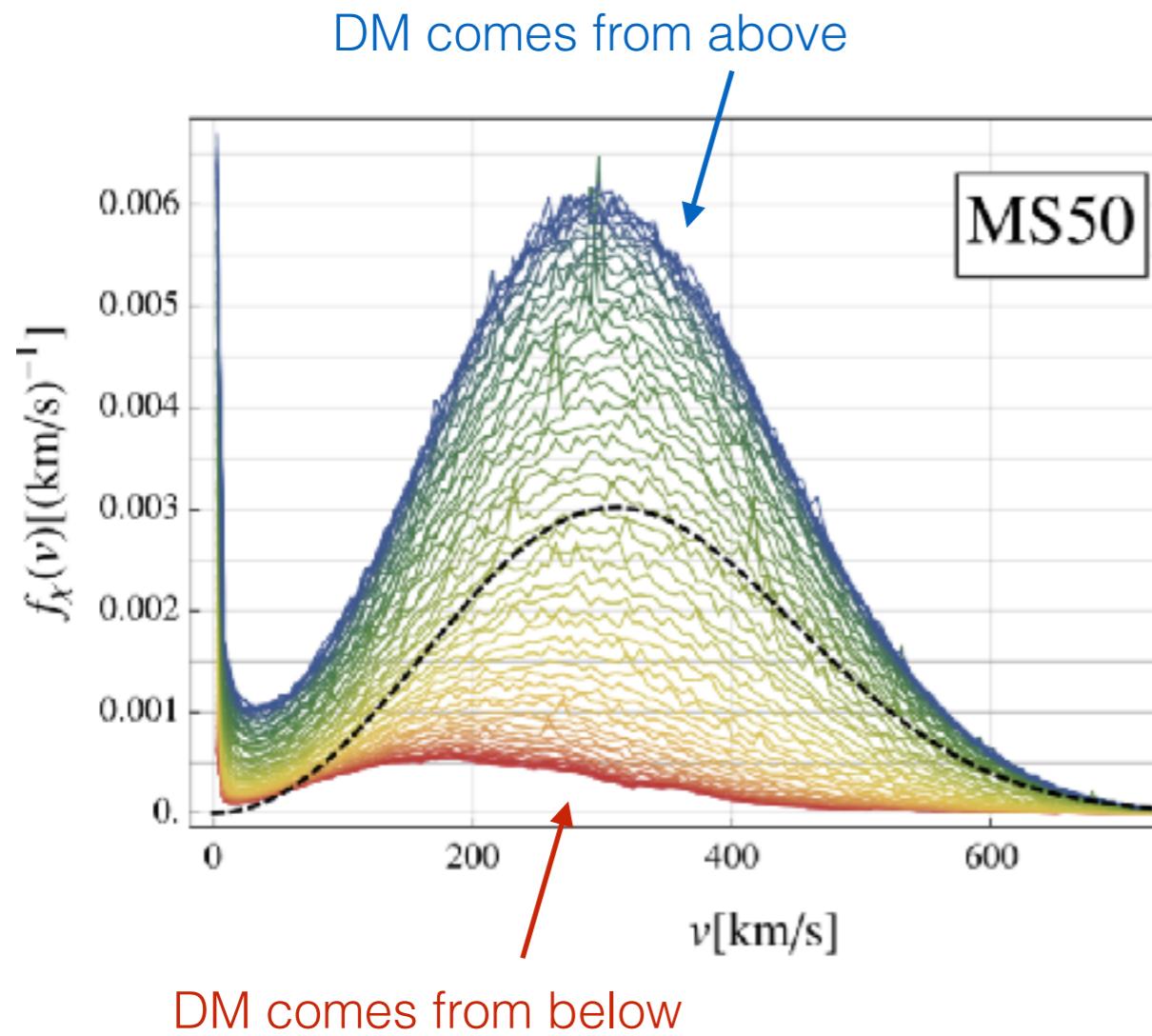


BJK, Catena, Kouvaris [1611.05453];
github.com/bradkav/EarthShadow

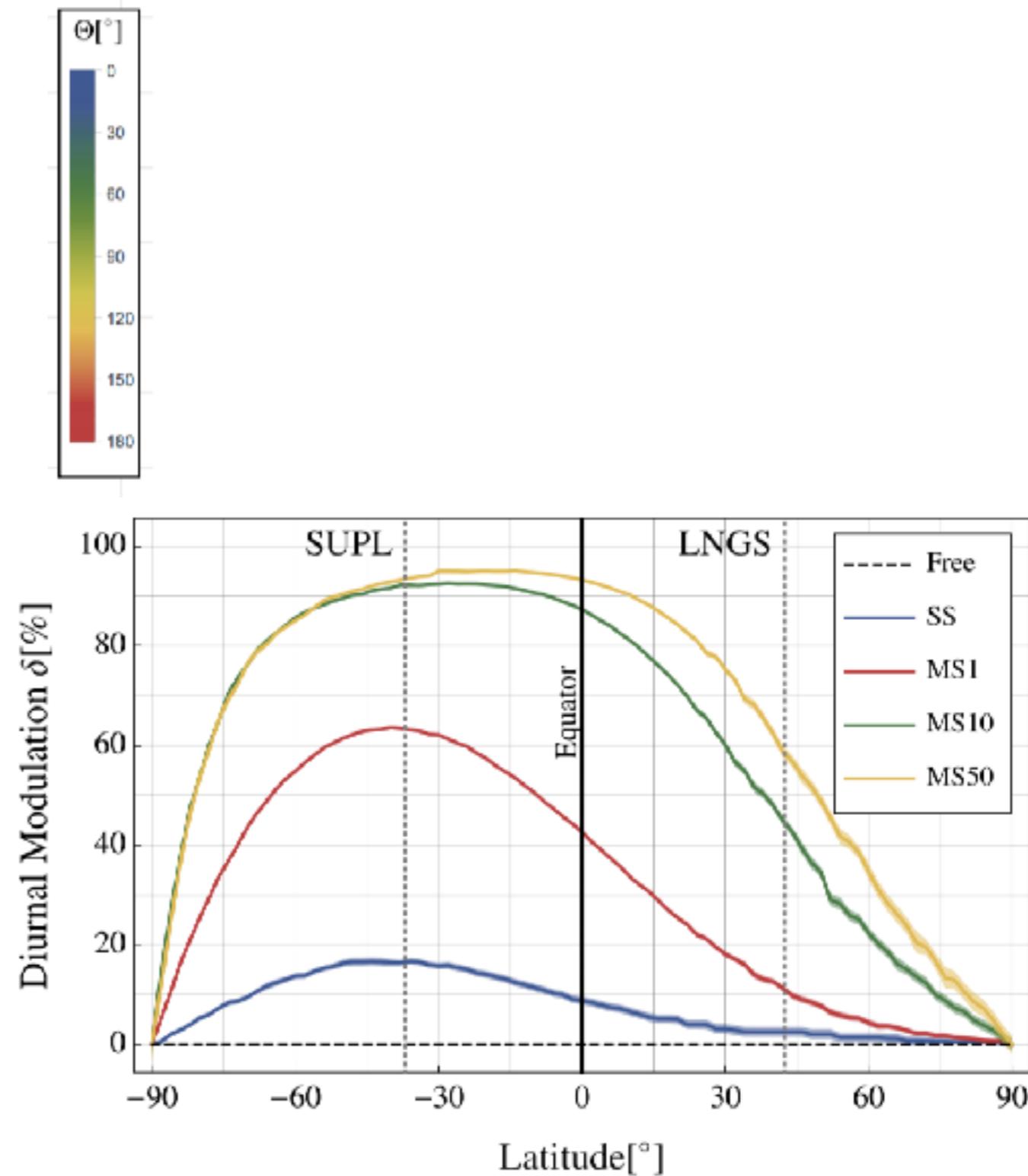
Modulation signals

Extended with Monte Carlo Simulations

github.com/temken/DaMaSCUS



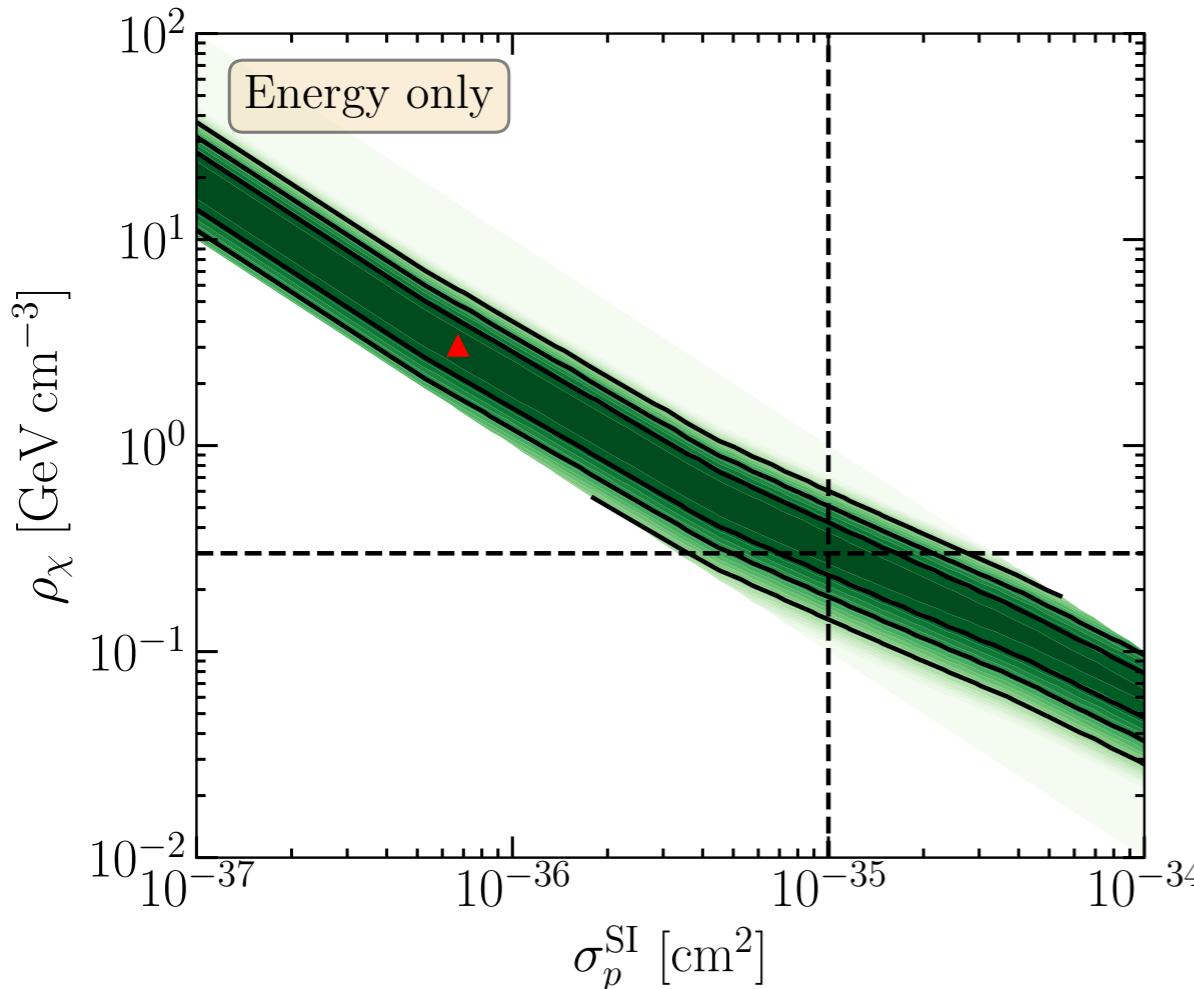
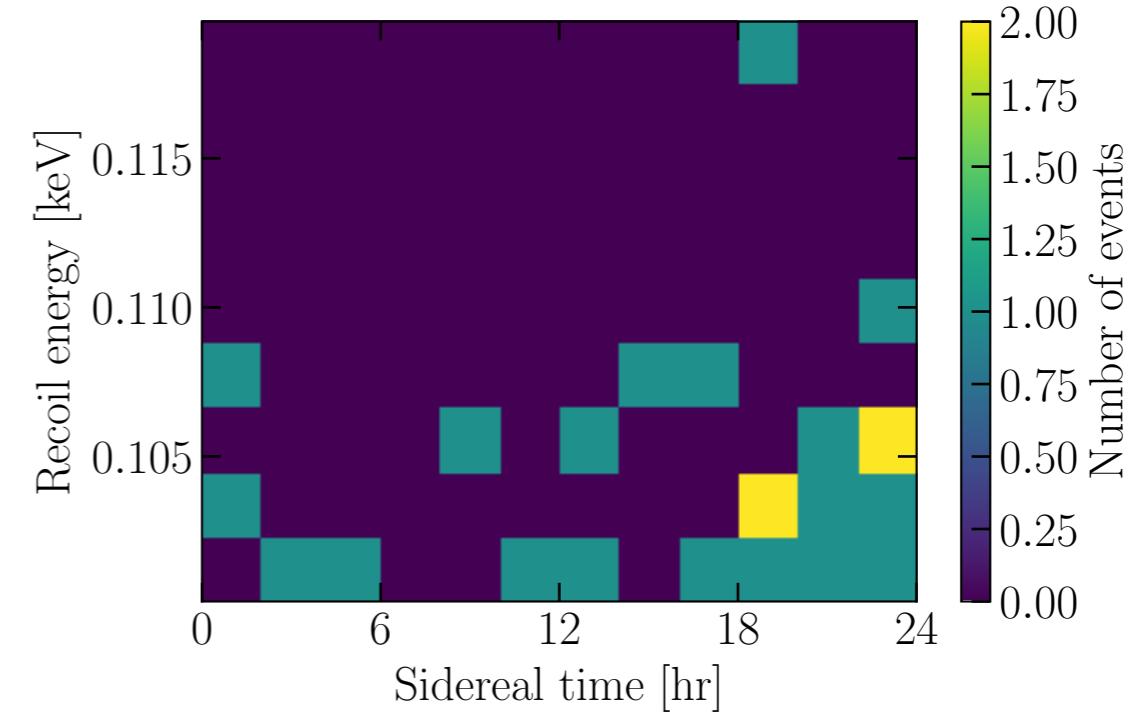
Large O(1) daily modulation if
DM scatters \sim 50 times during
Earth-crossing



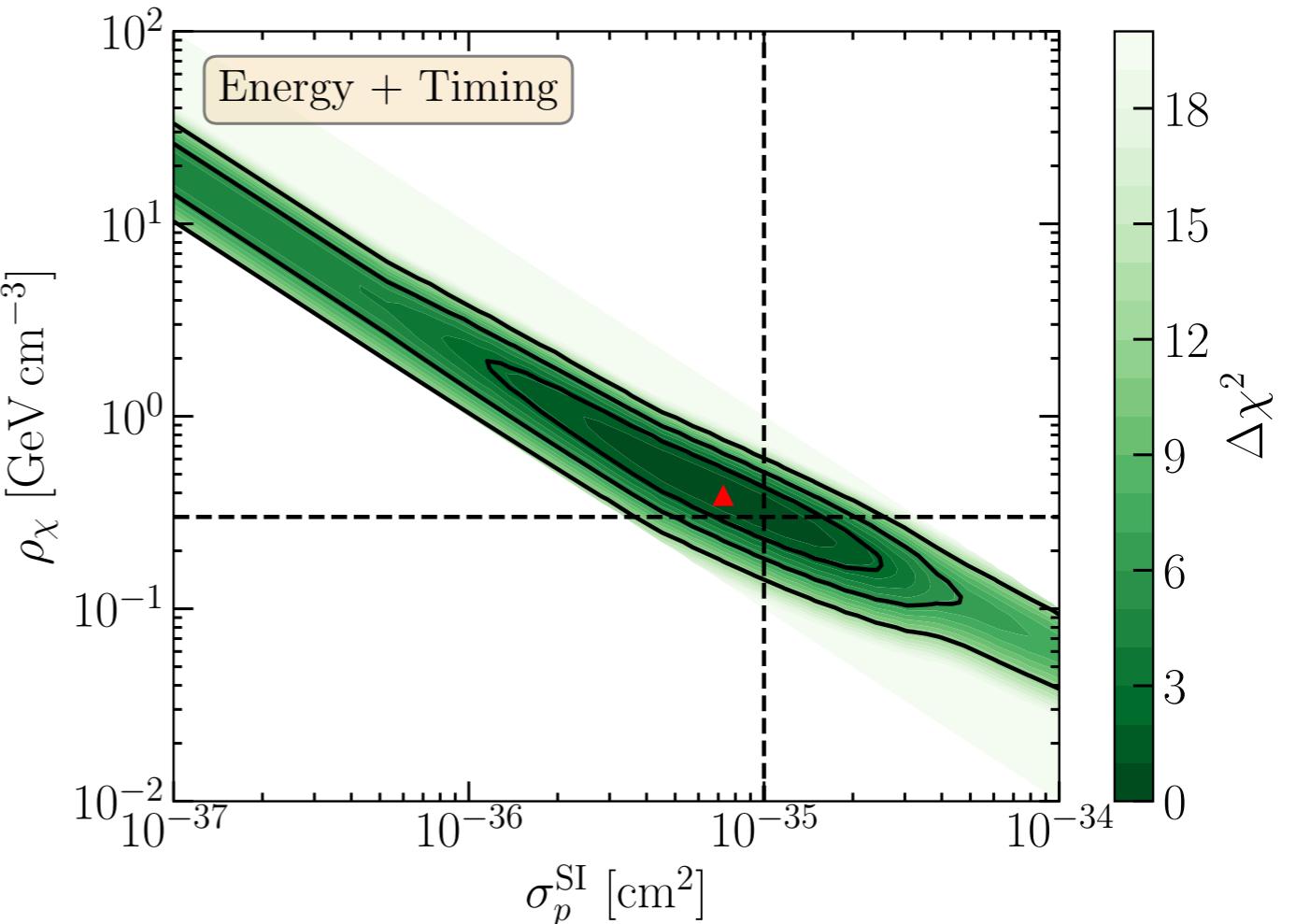
Emken & Kouvaris [1706.02249]

Preliminary results

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

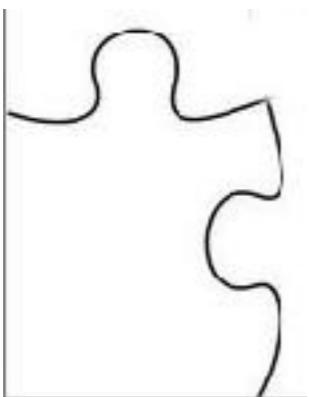


$$m_\chi = 0.5 \text{ GeV}$$

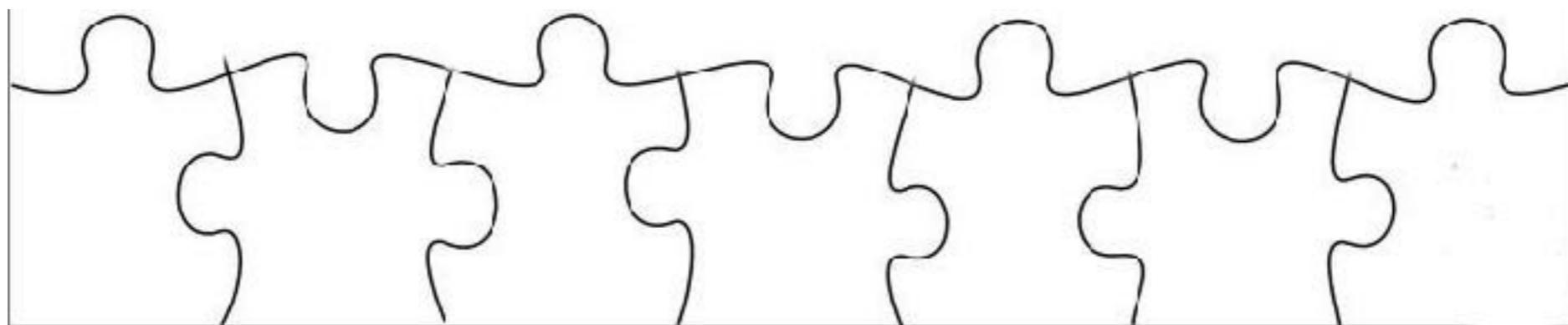


BJK & Catena [XXXX.XXXX]

Summary (I)

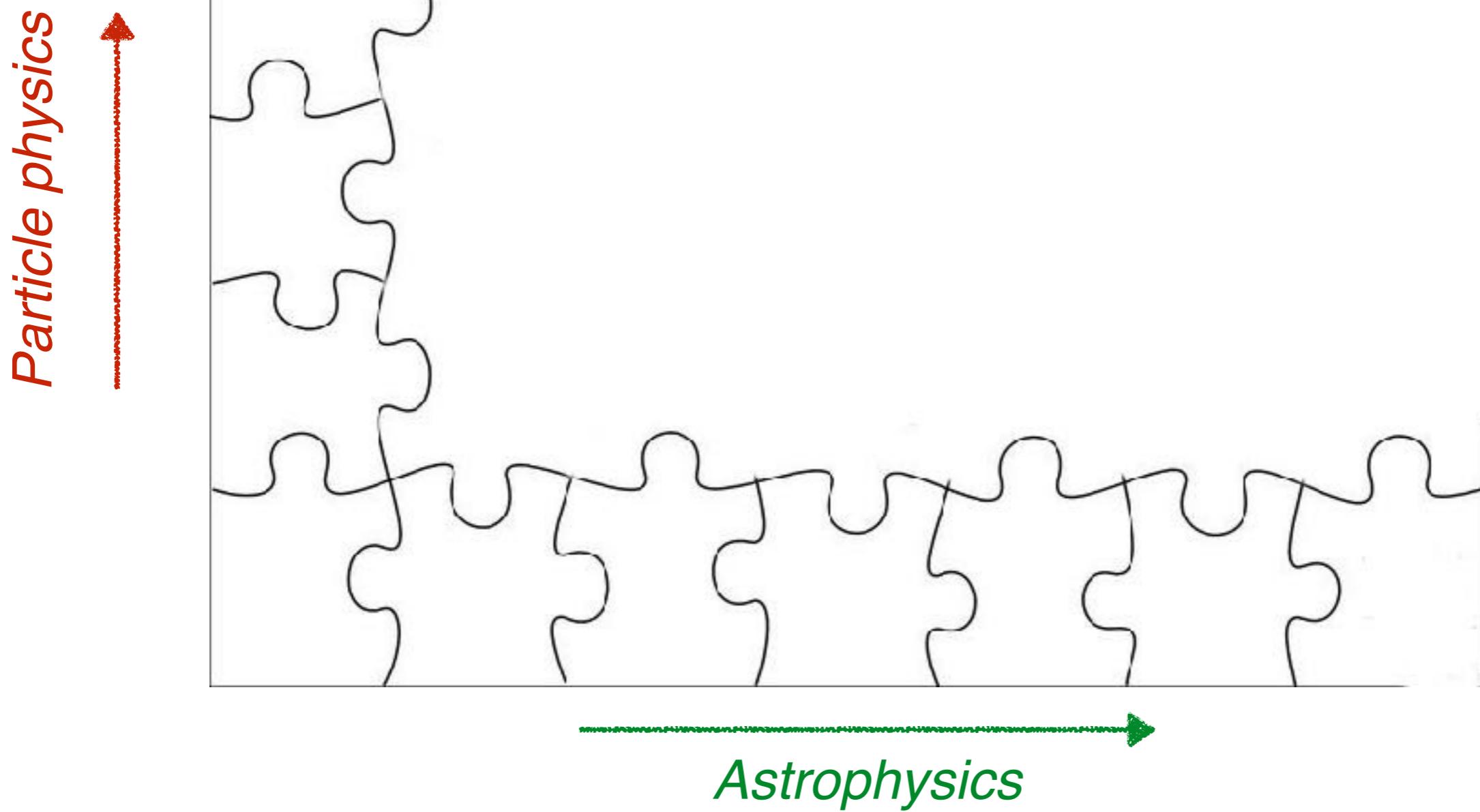


Summary (I)



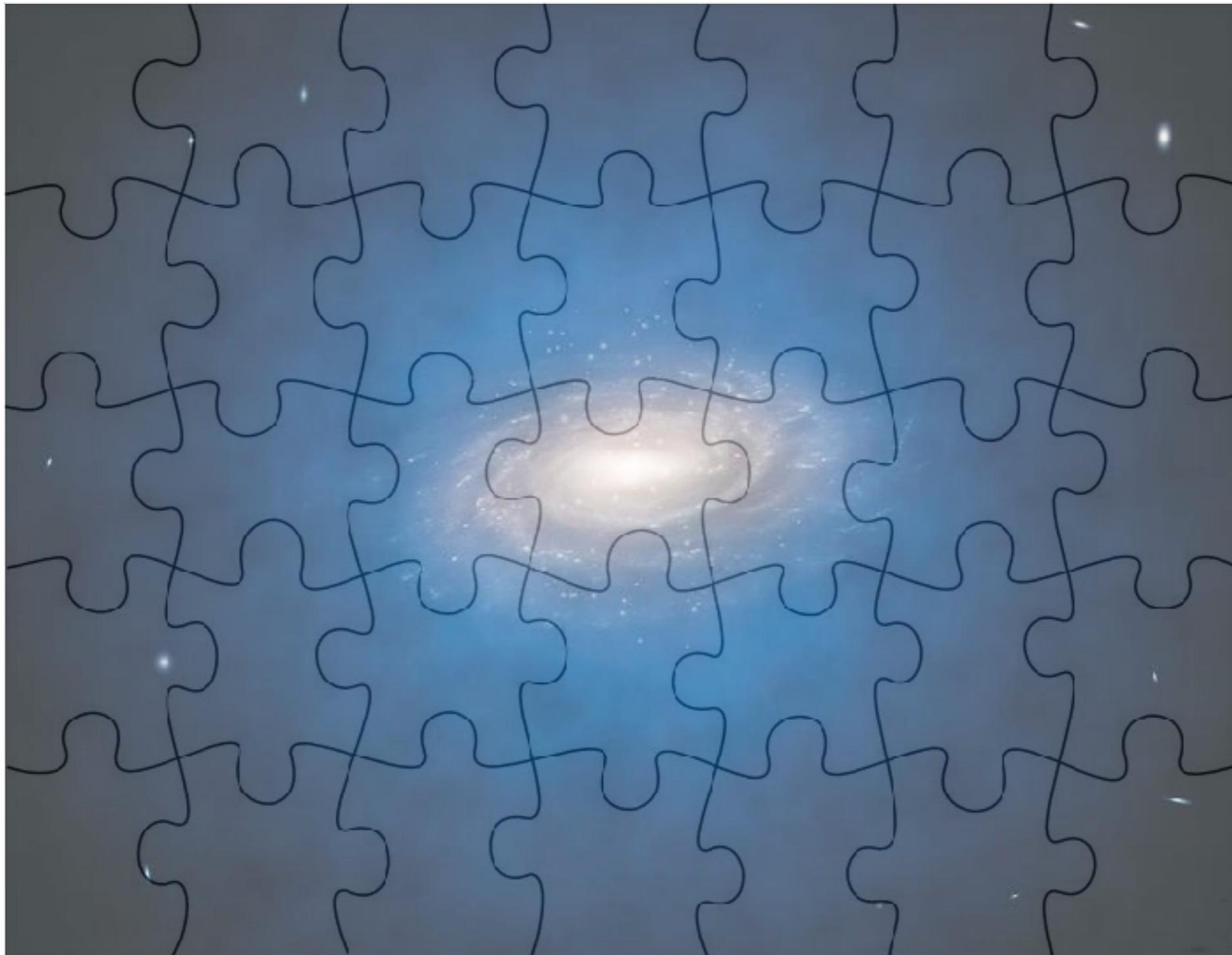
Astrophysics

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:

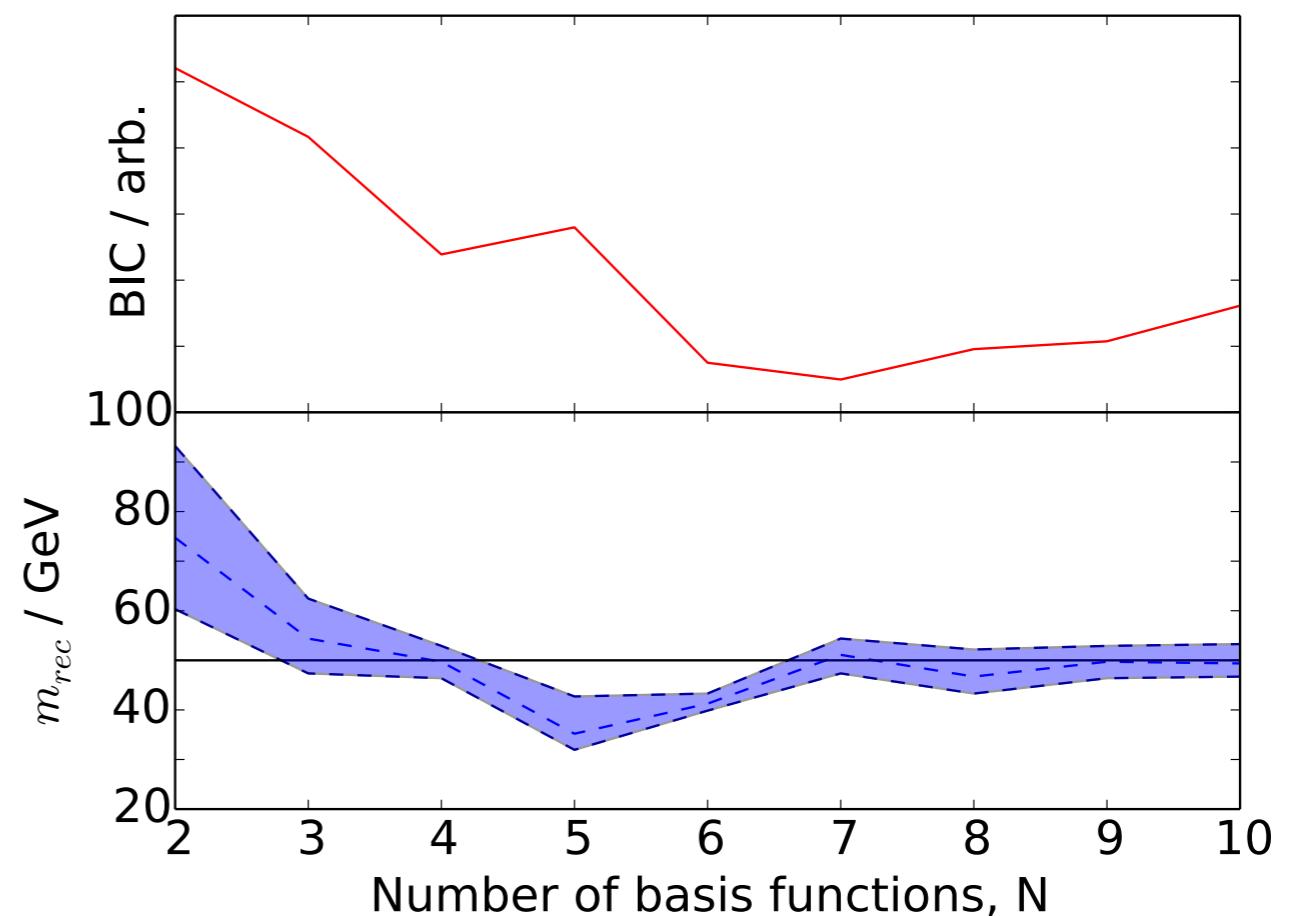
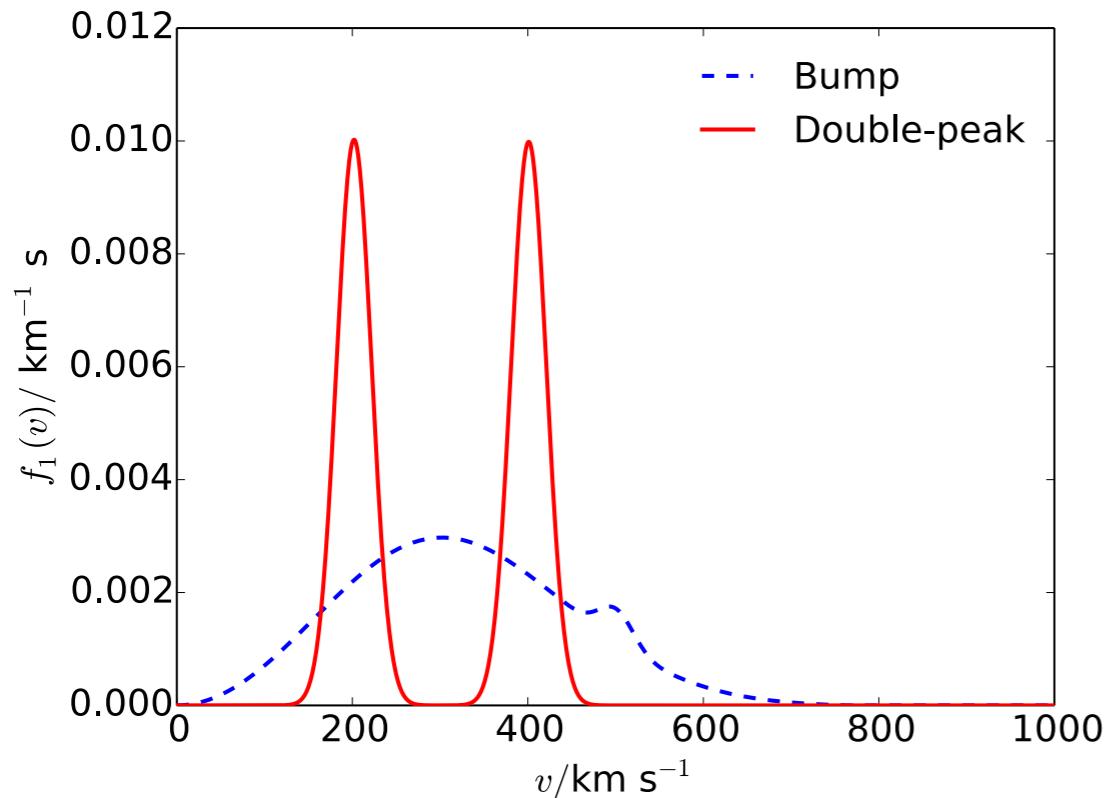
spin-independent (SI) interactions - $\mathcal{C}_A^{\text{SI}} \sim A^2$

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].

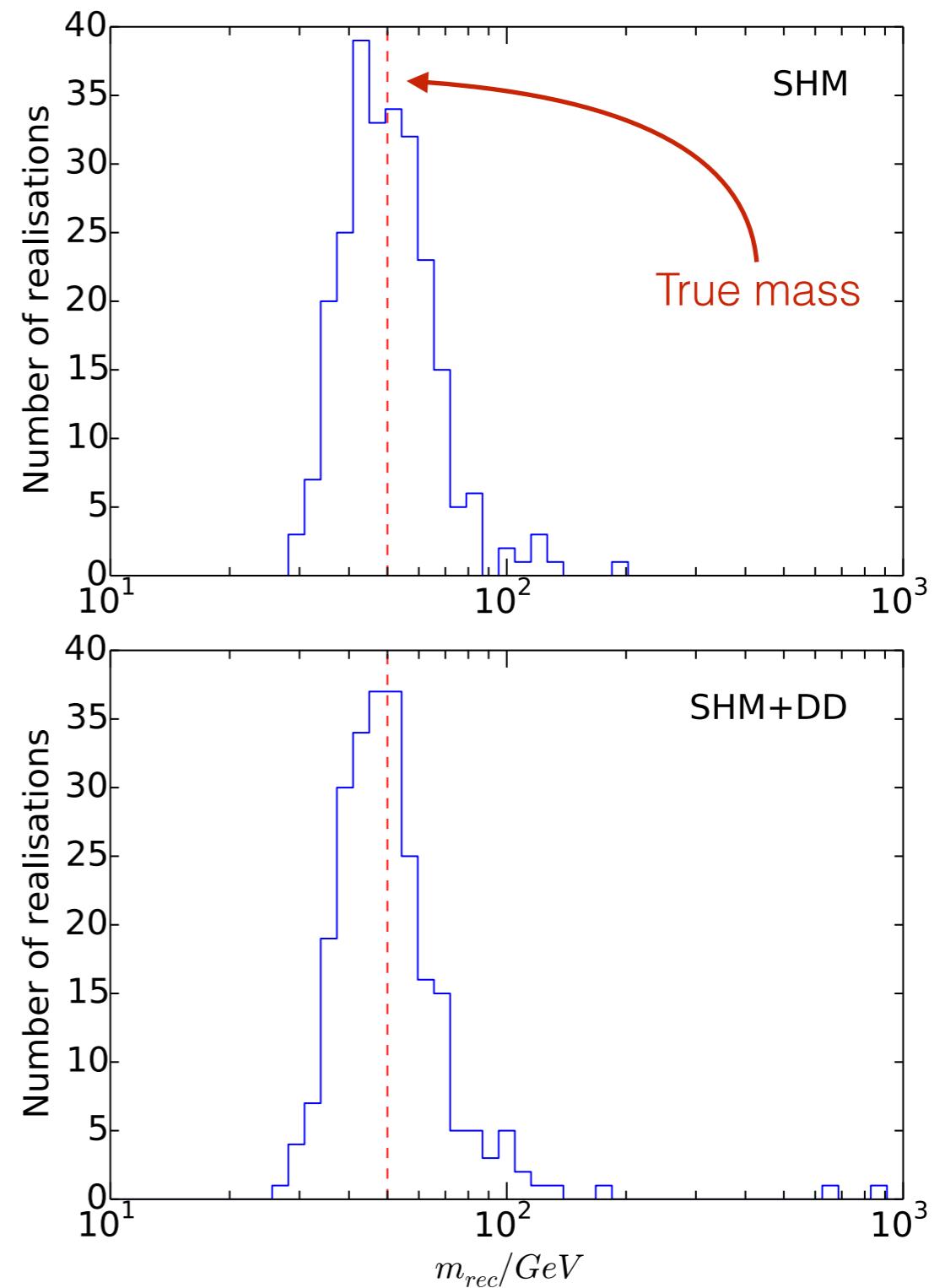
Polynomial Parametrisation

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



Different Speed Distributions

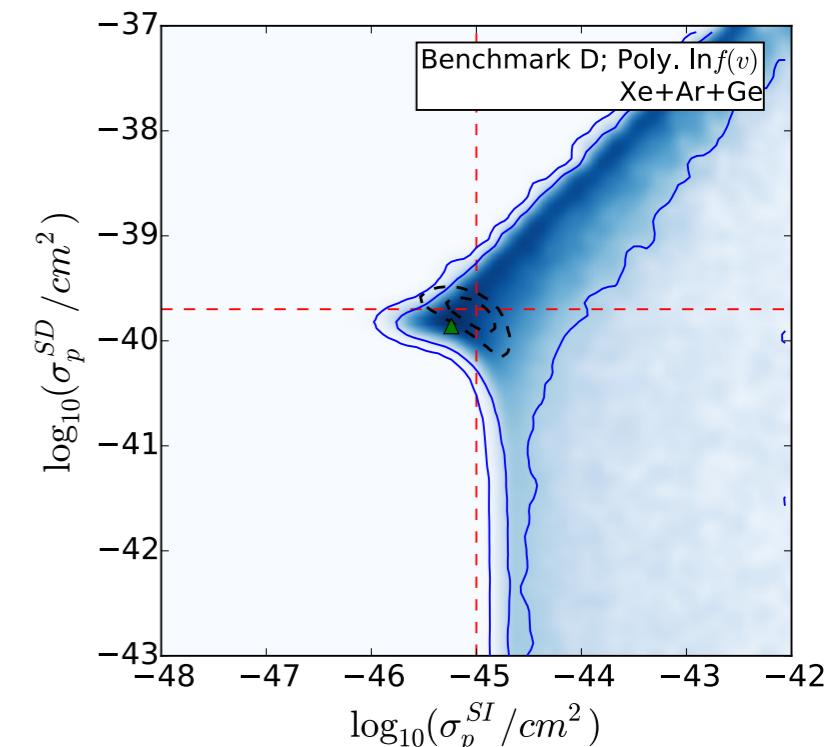
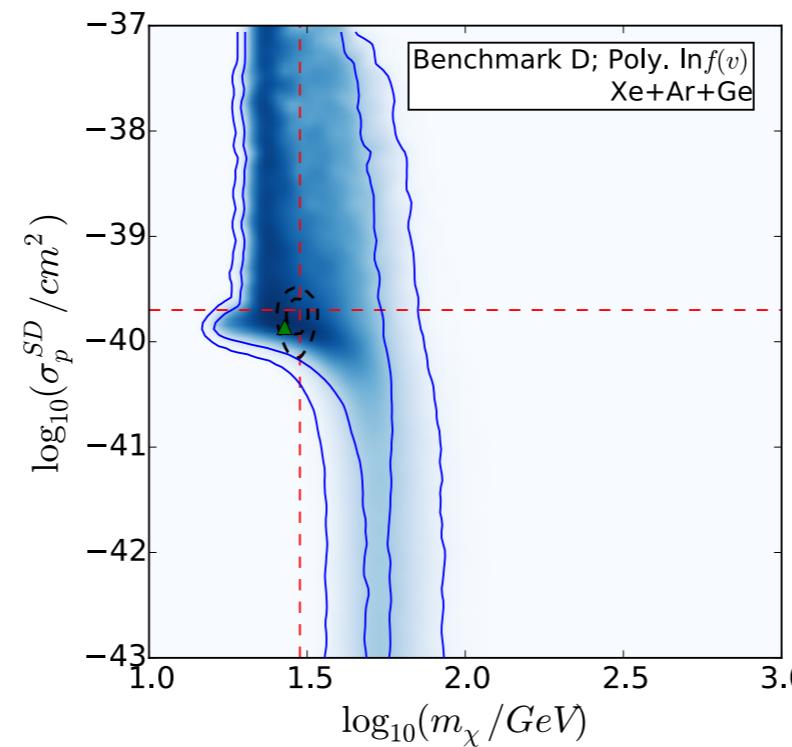
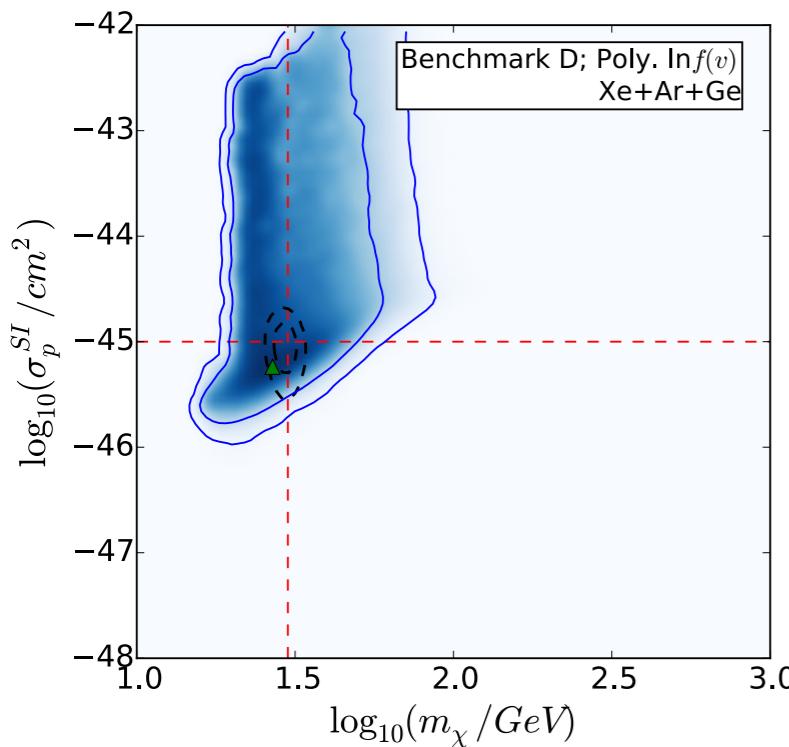
- Generate 250 mock data sets
- Reconstruct mass and obtain confidence intervals for each data set
- True mass reconstructed well (independent of speed distribution)
- Can also check that 68% intervals *are really 68% intervals*



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



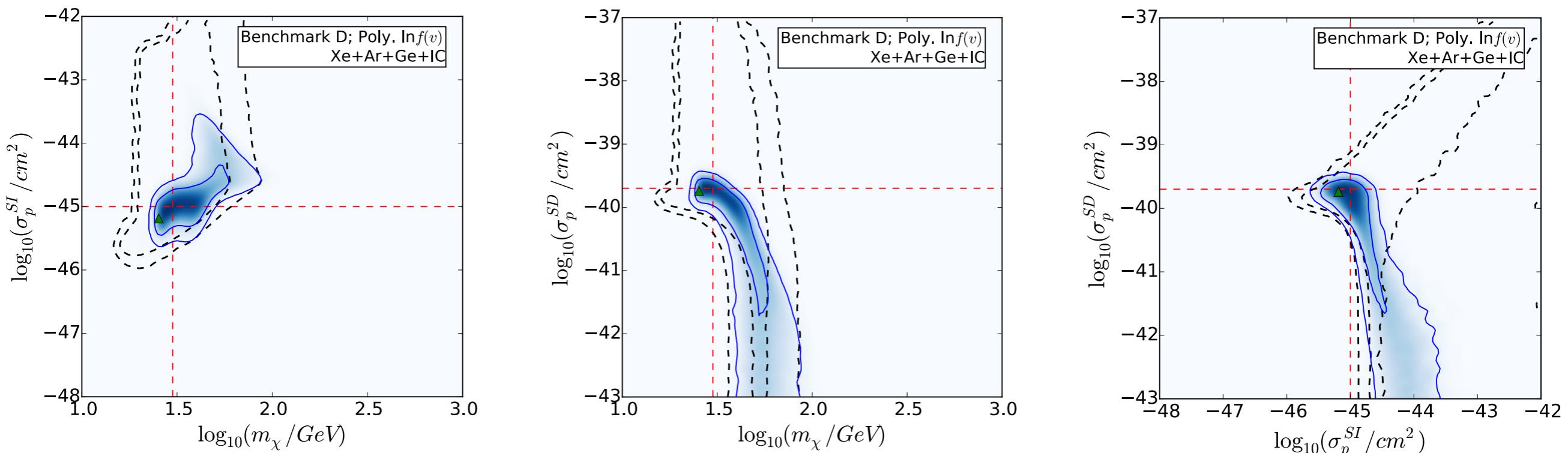
Benchmark
Best fit

Fixed (correct) speed distribution
Our parametrisation

Full reconstructions (with IceCube)

Consider a single benchmark:

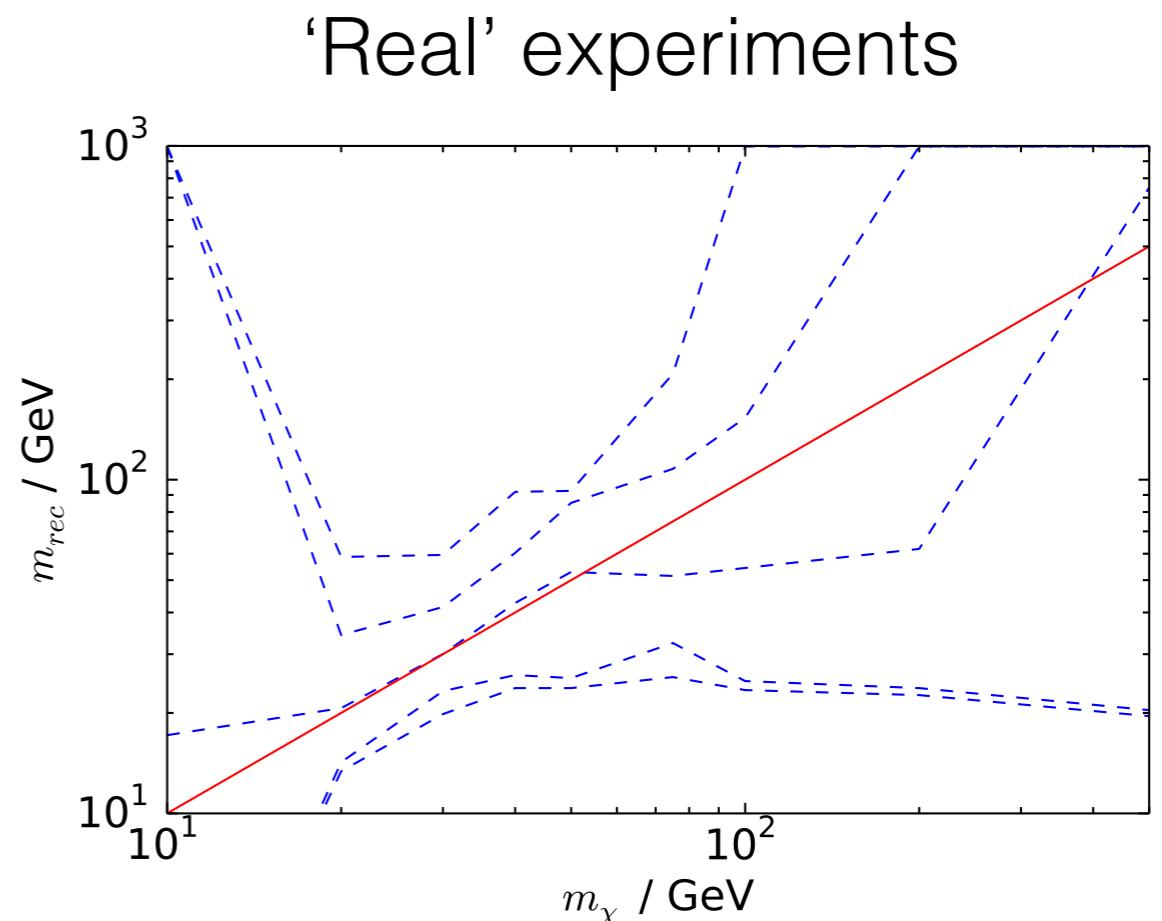
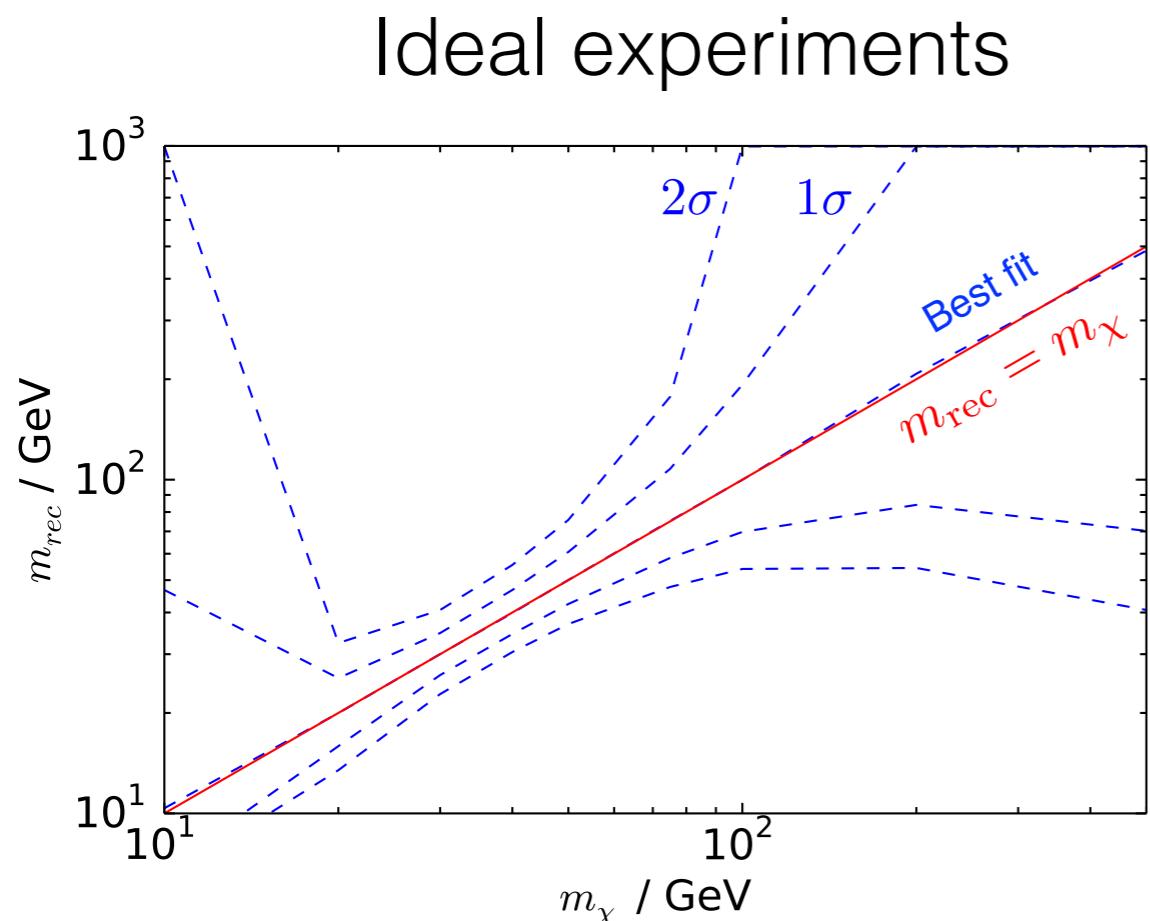
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annihilation to $\nu_\mu \bar{\nu}_\mu$, SHM+DD distribution



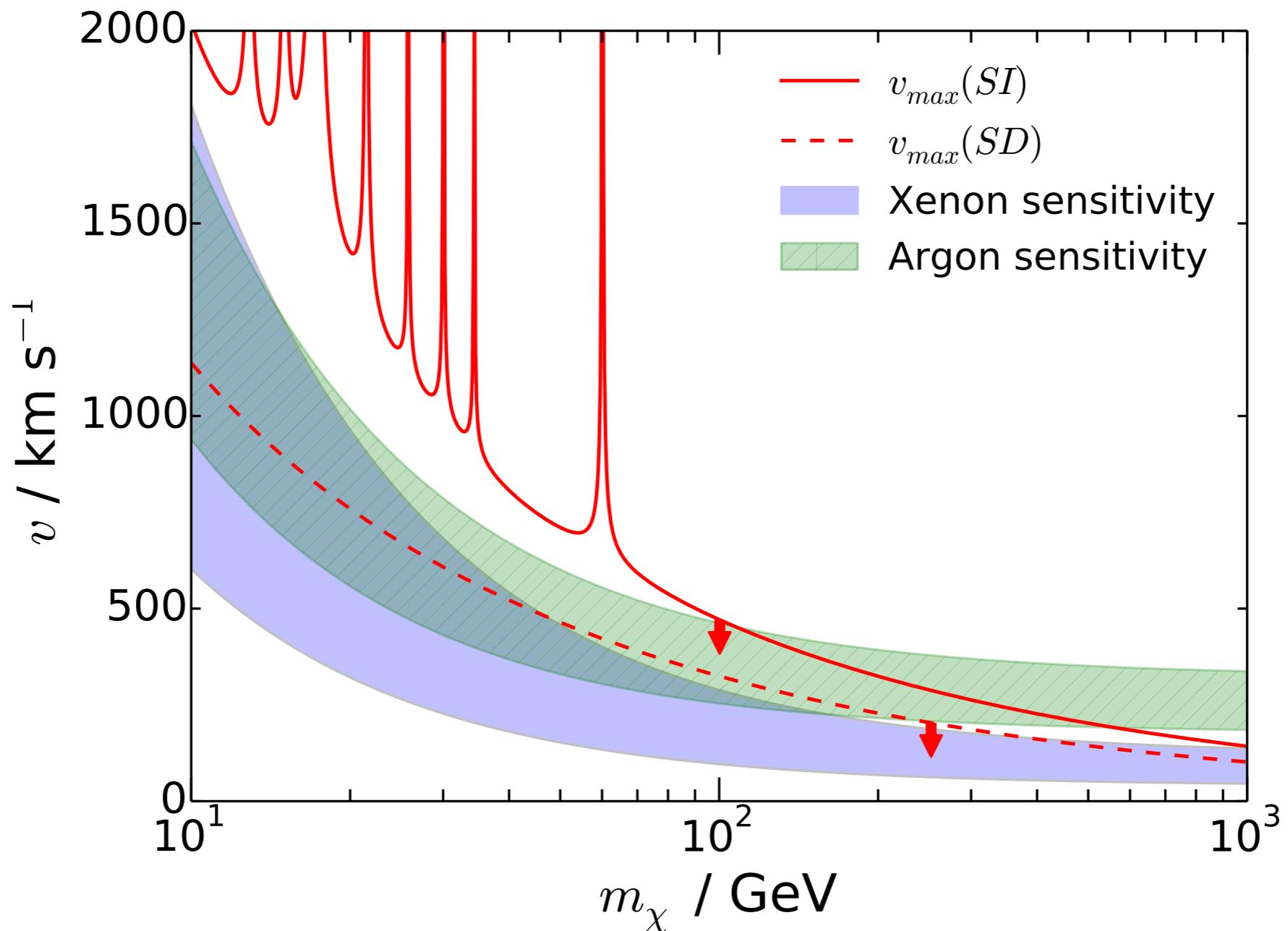
Benchmark
Best fit

Direct detection only (our param.)
Direct detection + IceCube (our param.)

'Real' Experiments



SI vs SD Solar Capture

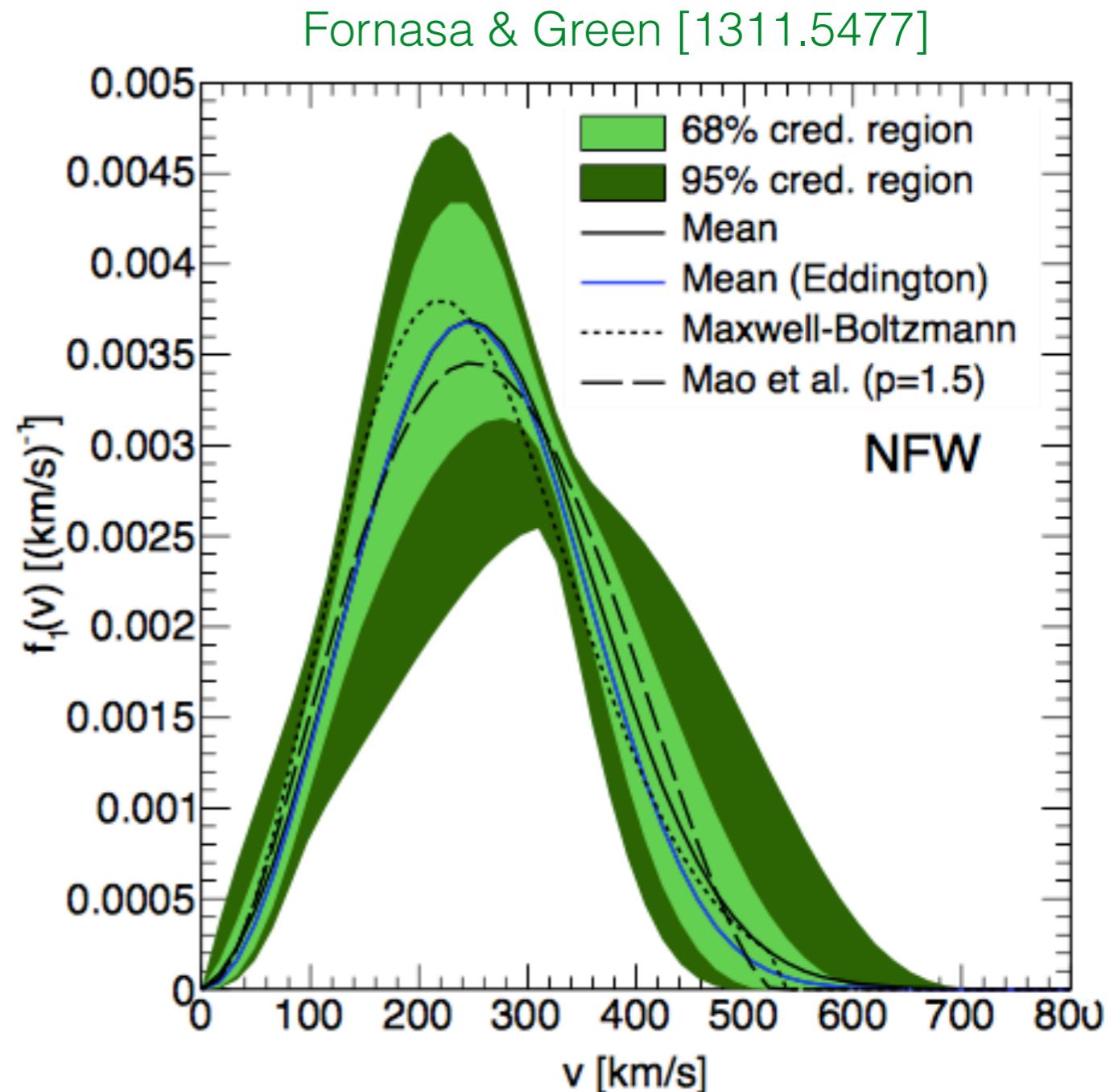


Self-consistent distributions

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

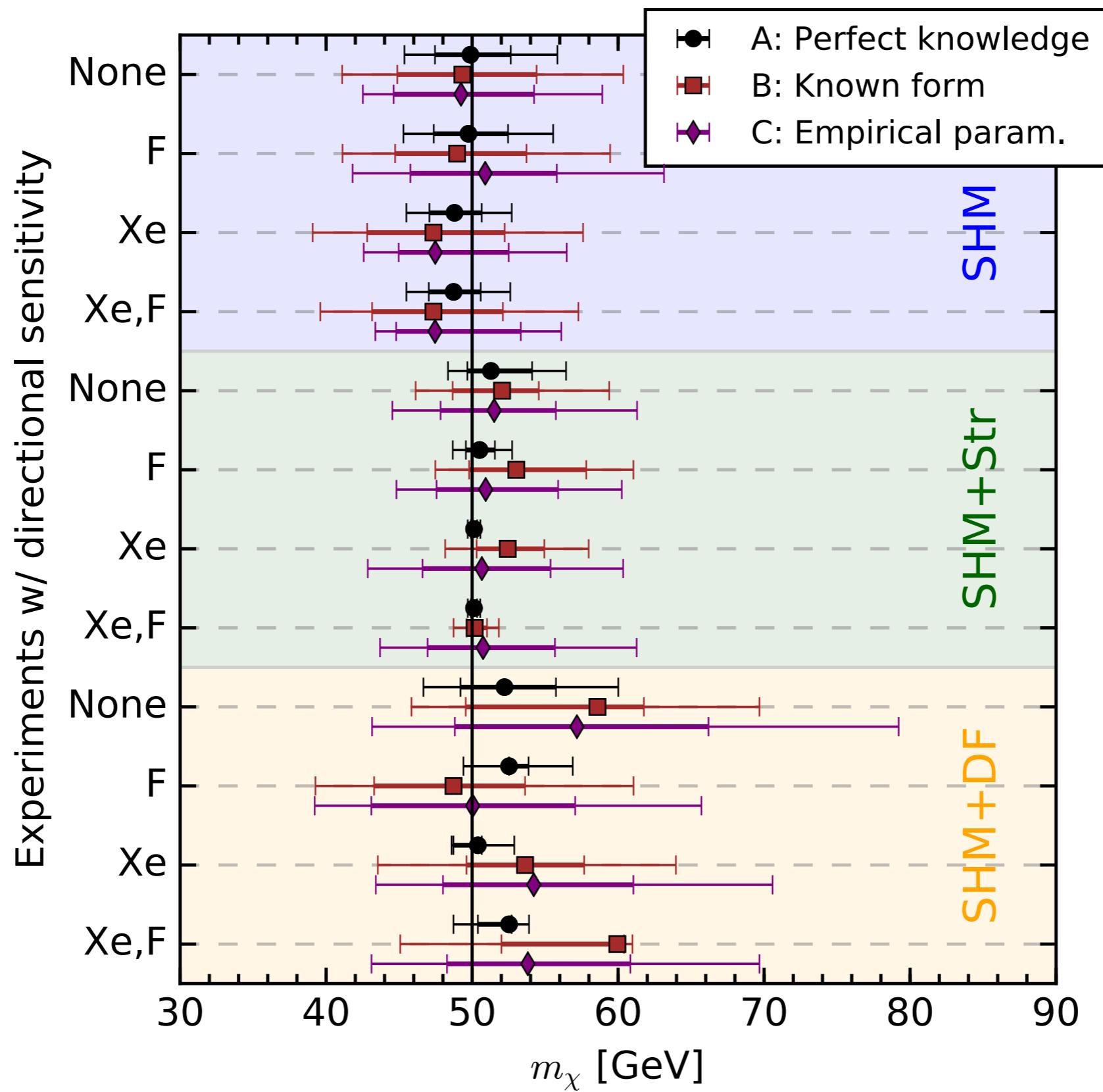
$$\mathcal{F}(\mathcal{E}) = \frac{1}{\sqrt{8\pi^2}} \int_0^{\mathcal{E}} \frac{d\Psi}{\sqrt{\mathcal{E} - \Psi}} \frac{d^2\rho}{d\Psi^2}$$

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



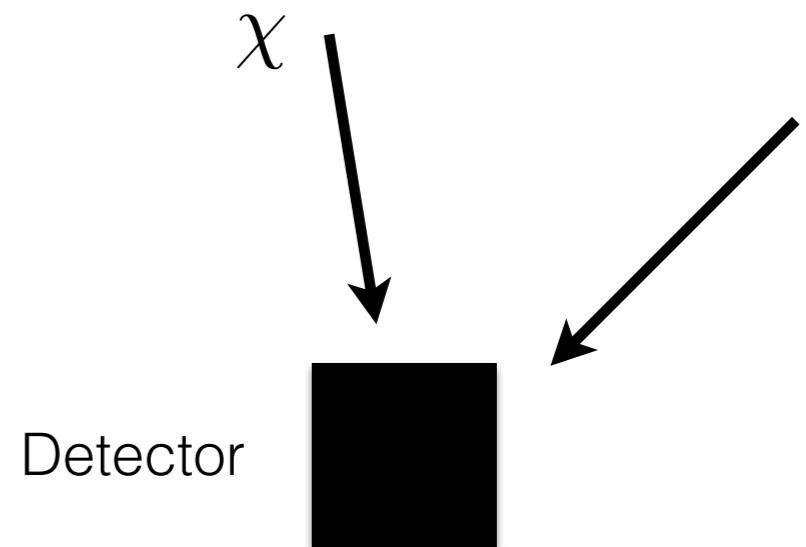
See also Bhattacharjee et al. [1210.2328];
Bozorgnia et al. [1310.0468]; Mandal et al. [1806.06872]

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 (θ, ϕ))!



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 $f(v)$

