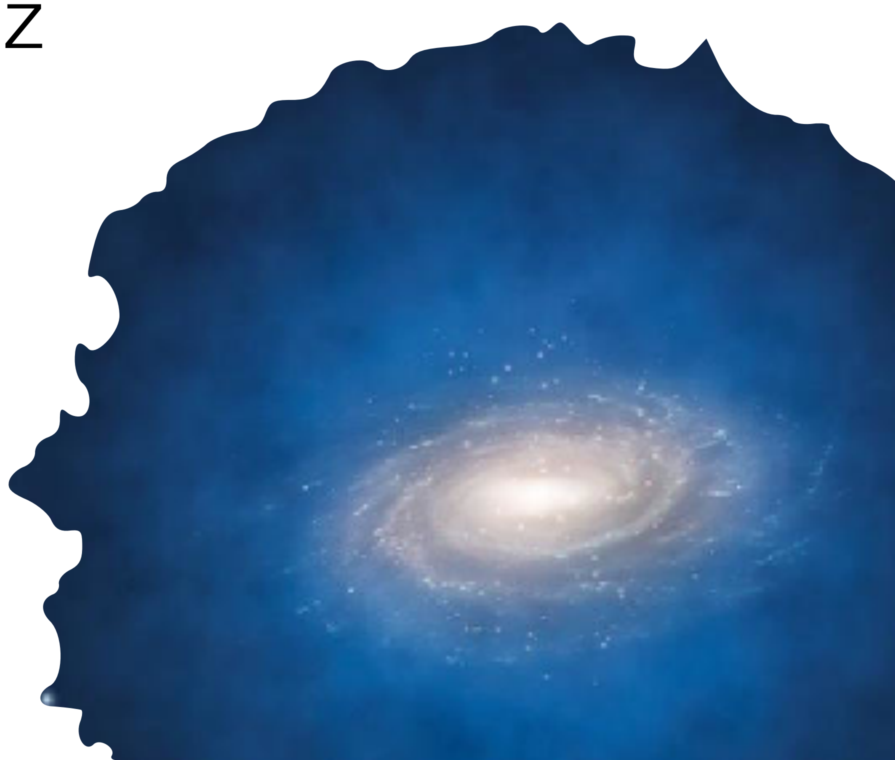
Can we directly measure the local distribution of Dark Matter from Earth?

Bradley J Kavanagh
GRAPPA, University of Amsterdam

17th October 2018
PRISMA Colloquium, Mainz



GRAPPA
GRavitation AstroParticle Physics Amsterdam

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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:

GitHub

GitLab

zenodo

figshare

ASCL.net
Astrophysics Source Code Library

docker

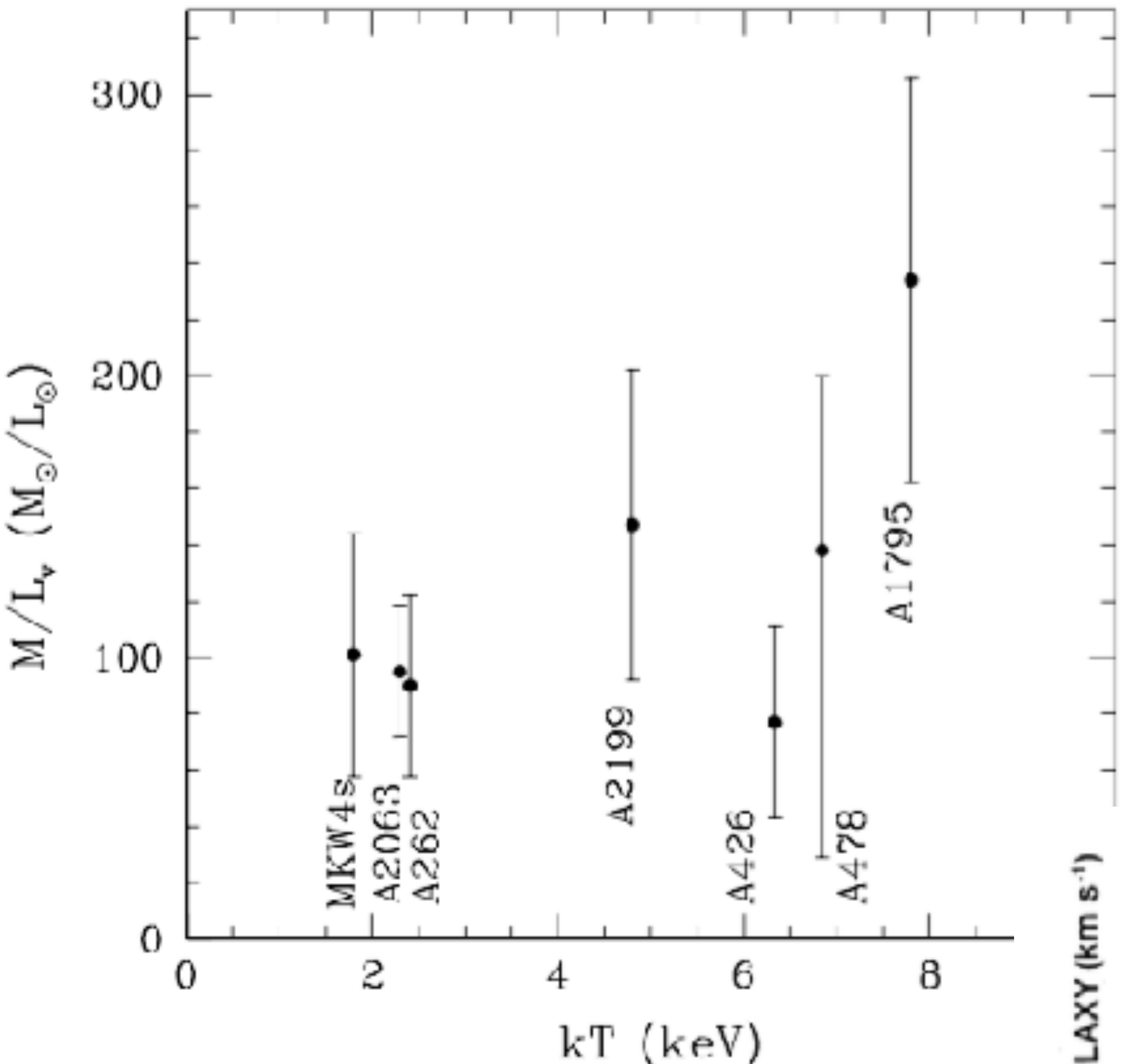
binder
(beta)

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.

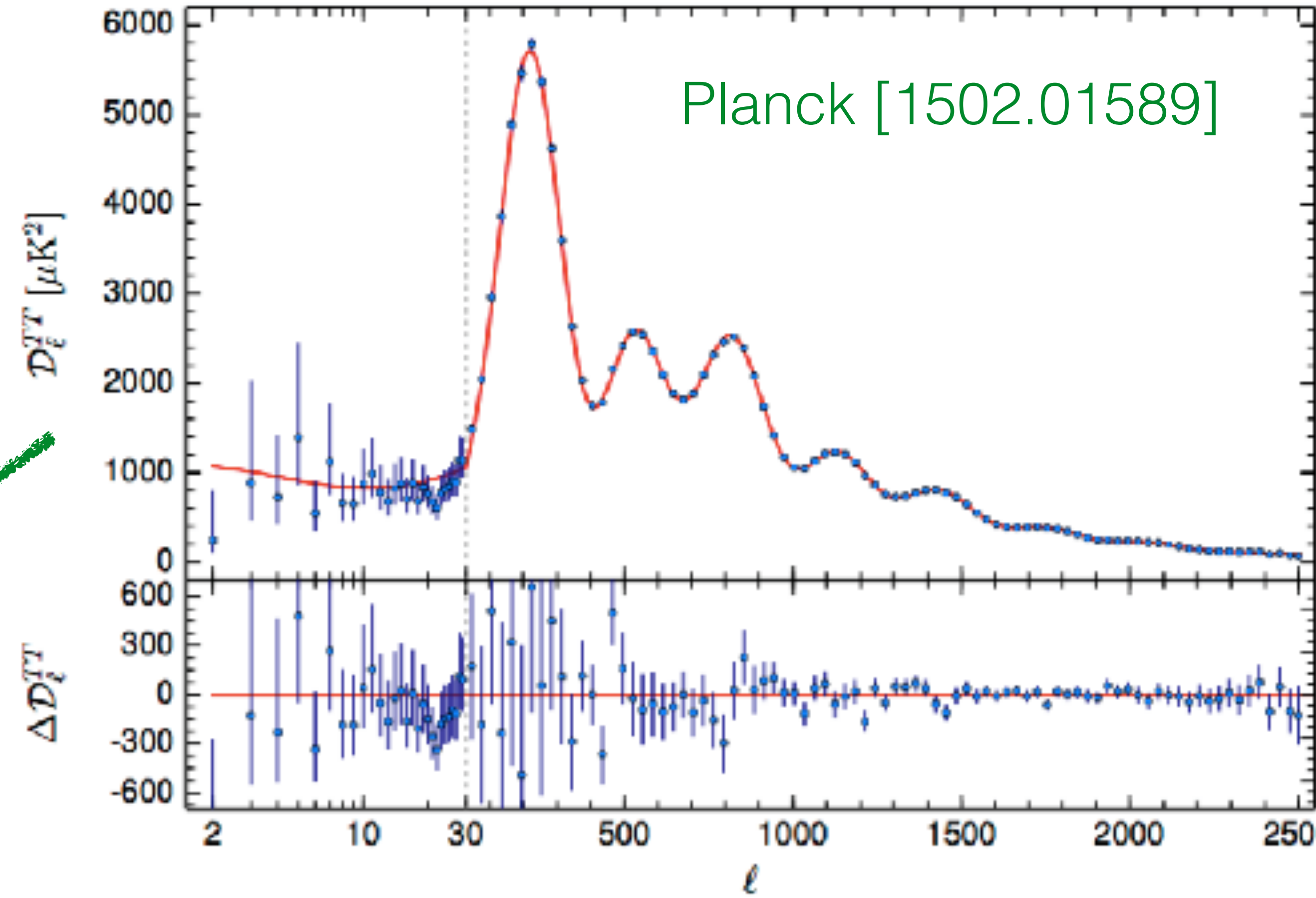
bradkav.net

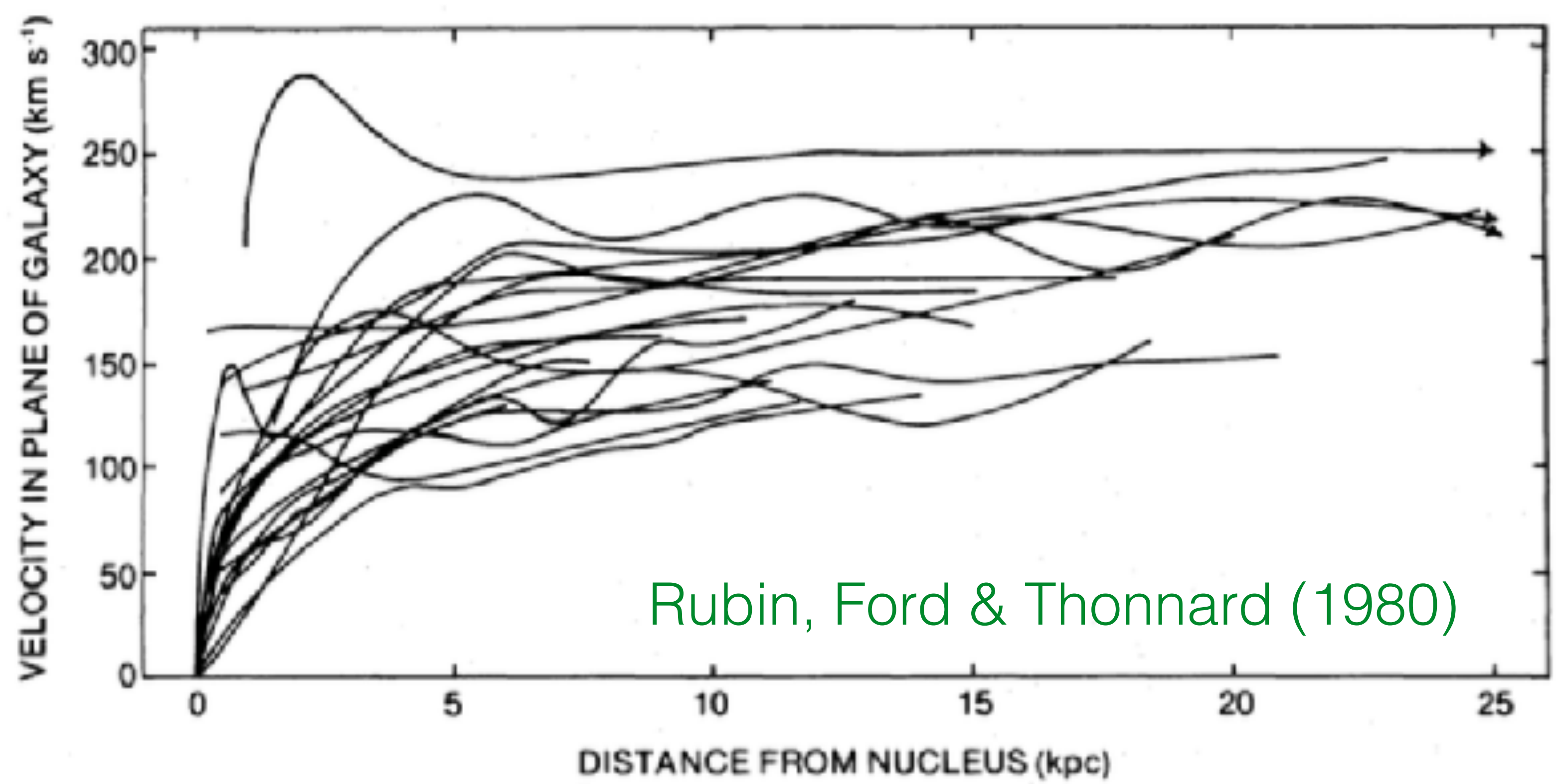
github.com/bradkav

Dark Matter on all scales

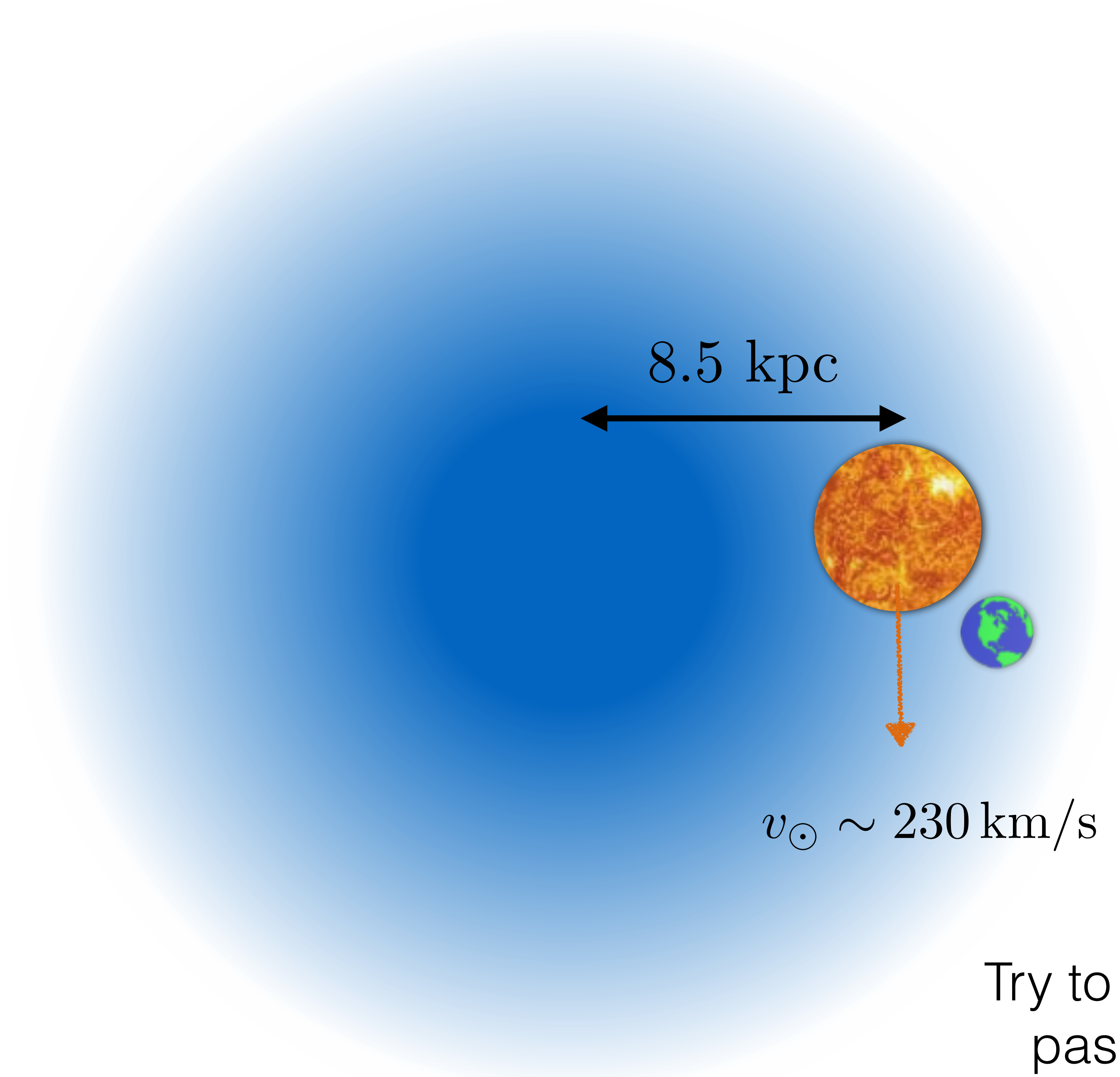


Hradecky et al. [astro-ph/0006397]





Dark Matter near us



Global and local estimates of DM at Solar radius give:

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

(`a few per litre')

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

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

NOT TO SCALE

Overview

Solar system searches for DM:
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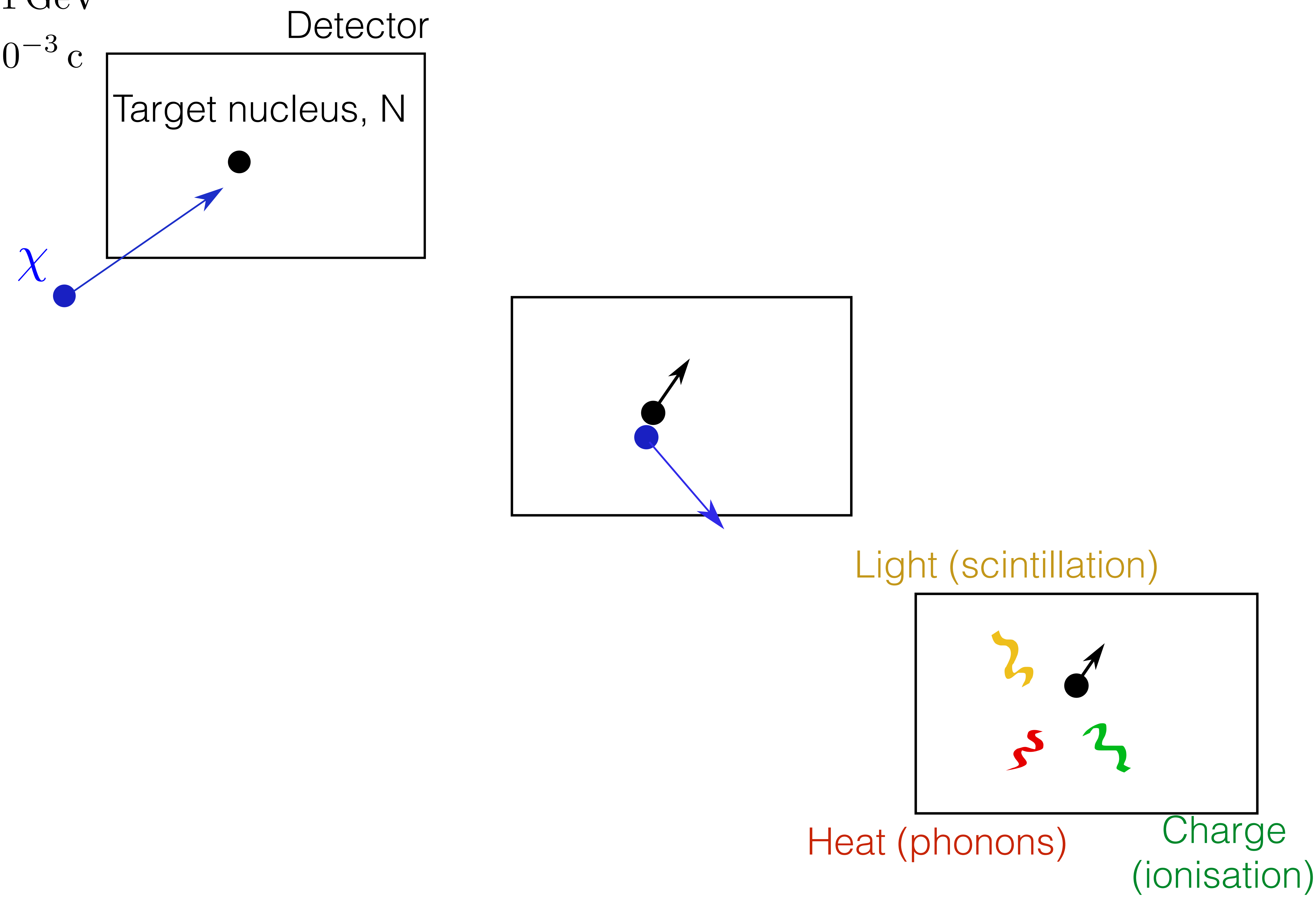
Measuring the DM properties and distribution
with a future detection

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

Direct detection

$m_\chi \gtrsim 1\,\mathrm{GeV}$

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



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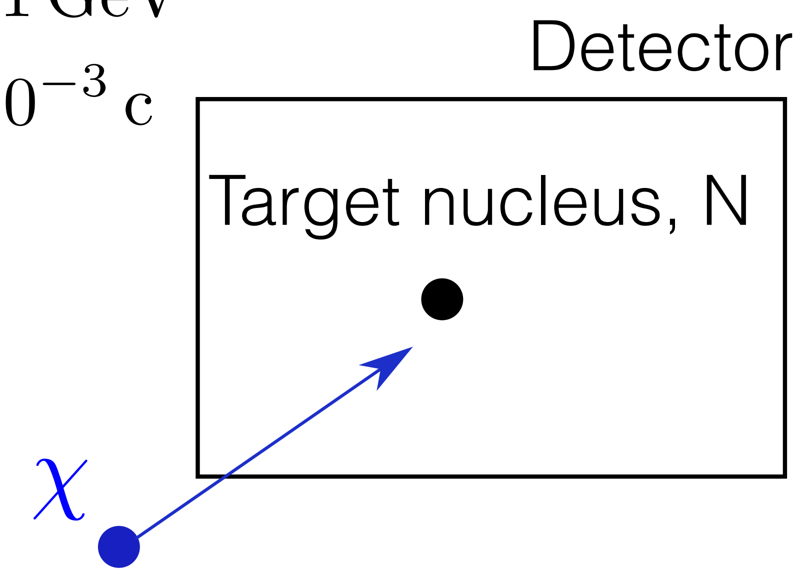
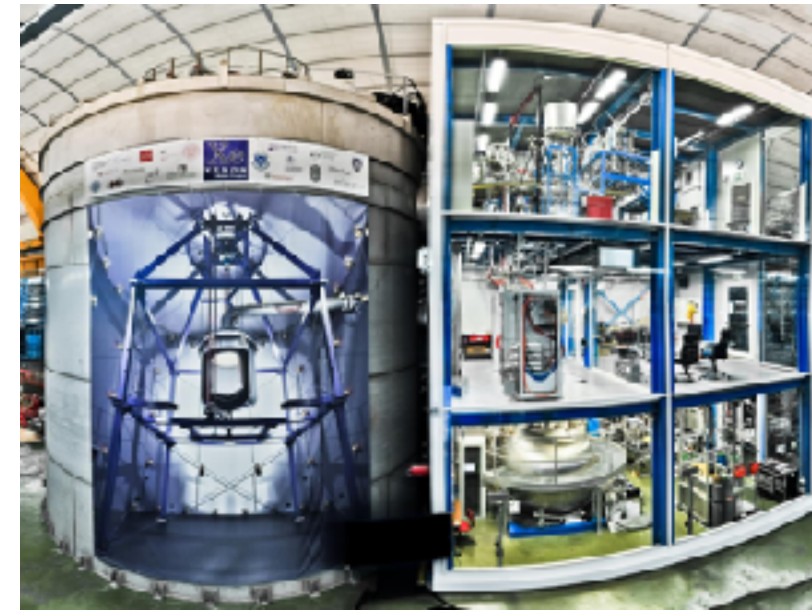
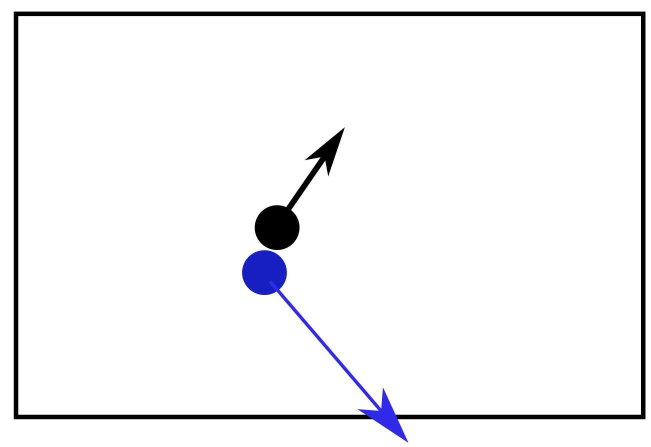


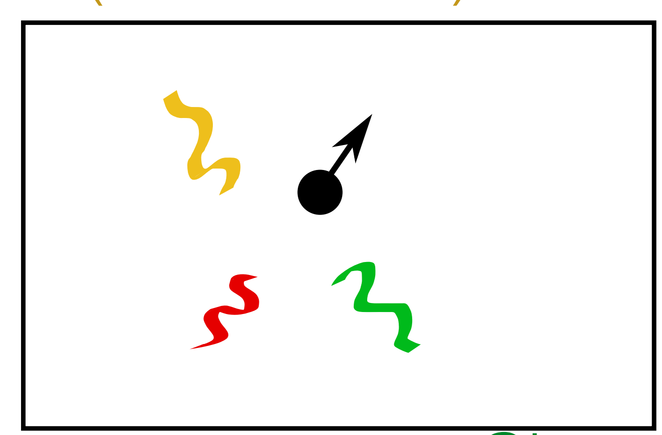
Credit: Roberto Corrieri and Patrick De Perio



Xenon1T



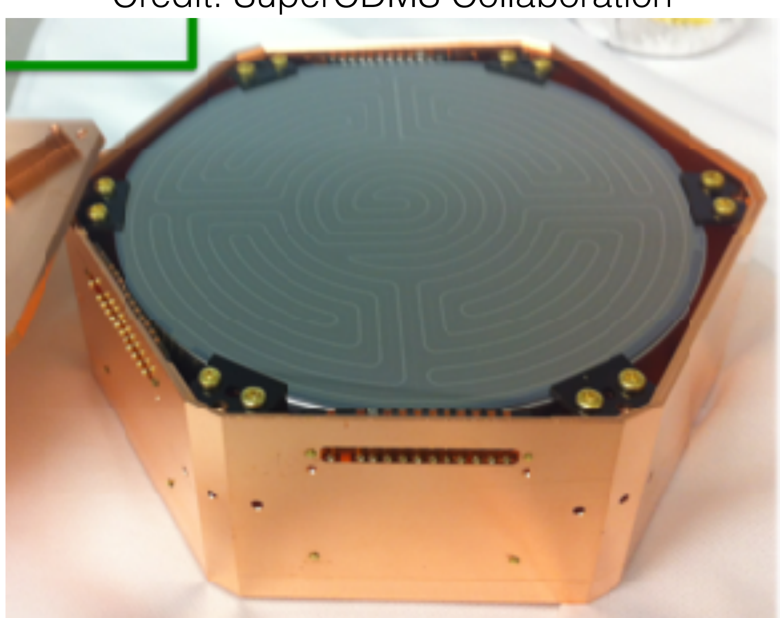
Light (scintillation)



Heat (phonons)

Charge (ionisation)

Credit: SuperCDMS Collaboration



SuperCDMS and many others

Direct detection signal

$$\boxed{\frac{\mathrm{d}R}{\mathrm{d}E_R} \sim \frac{\rho_\chi}{m_\chi}\sigma_p \mathcal{C}_A \eta\left(v_{\min}\right)}$$

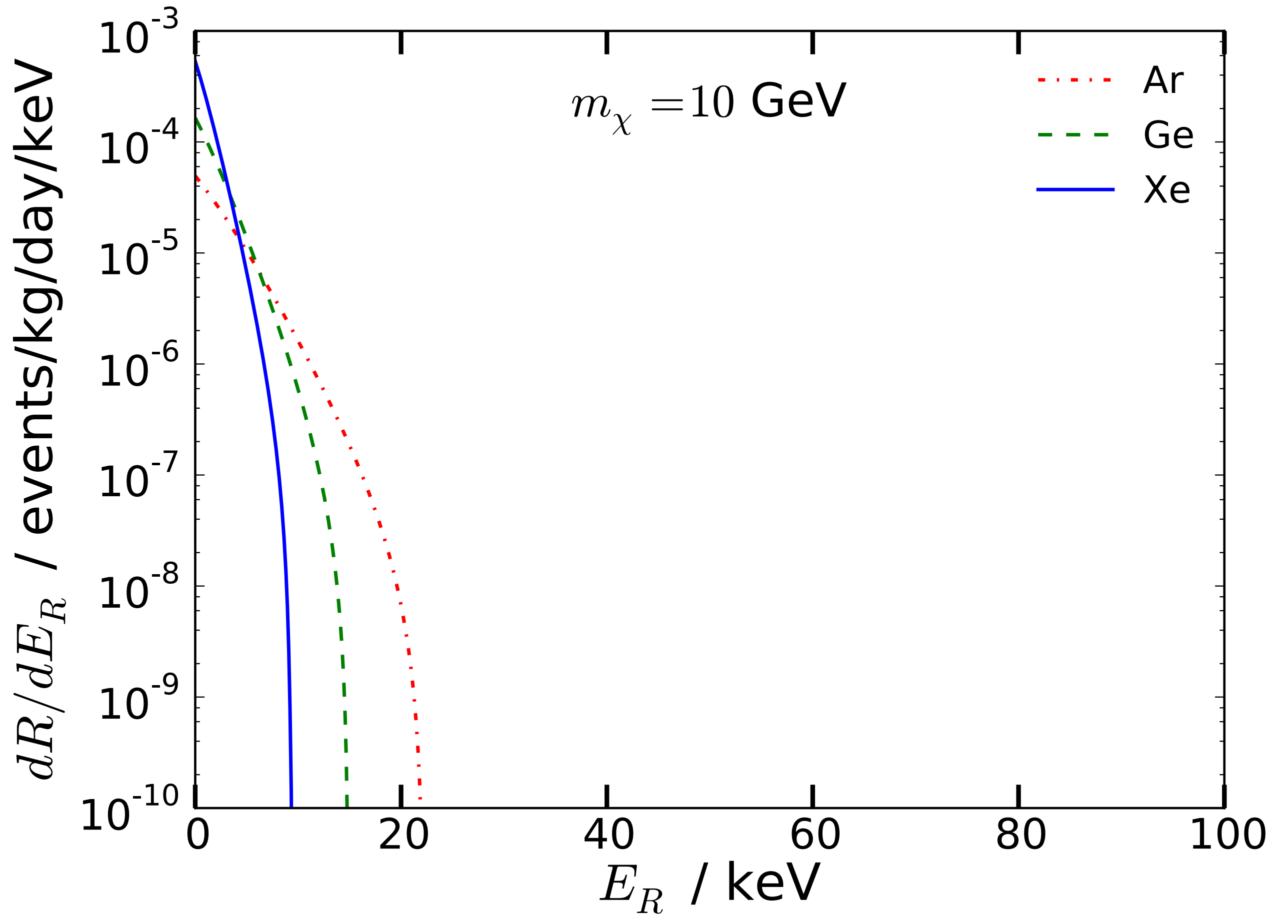
$$\eta(v_{\min}) \equiv \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\,\mathrm{d}v$$

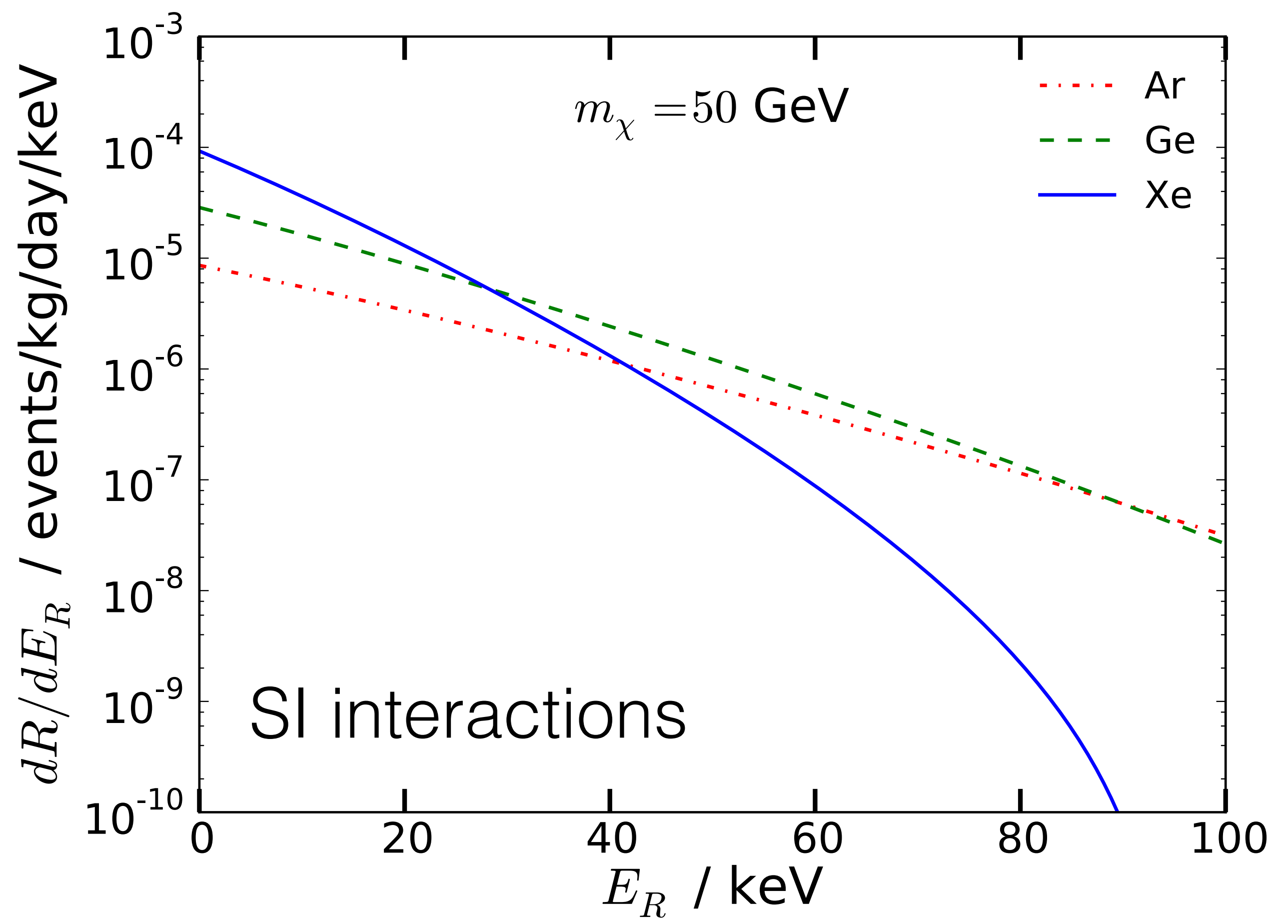
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

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

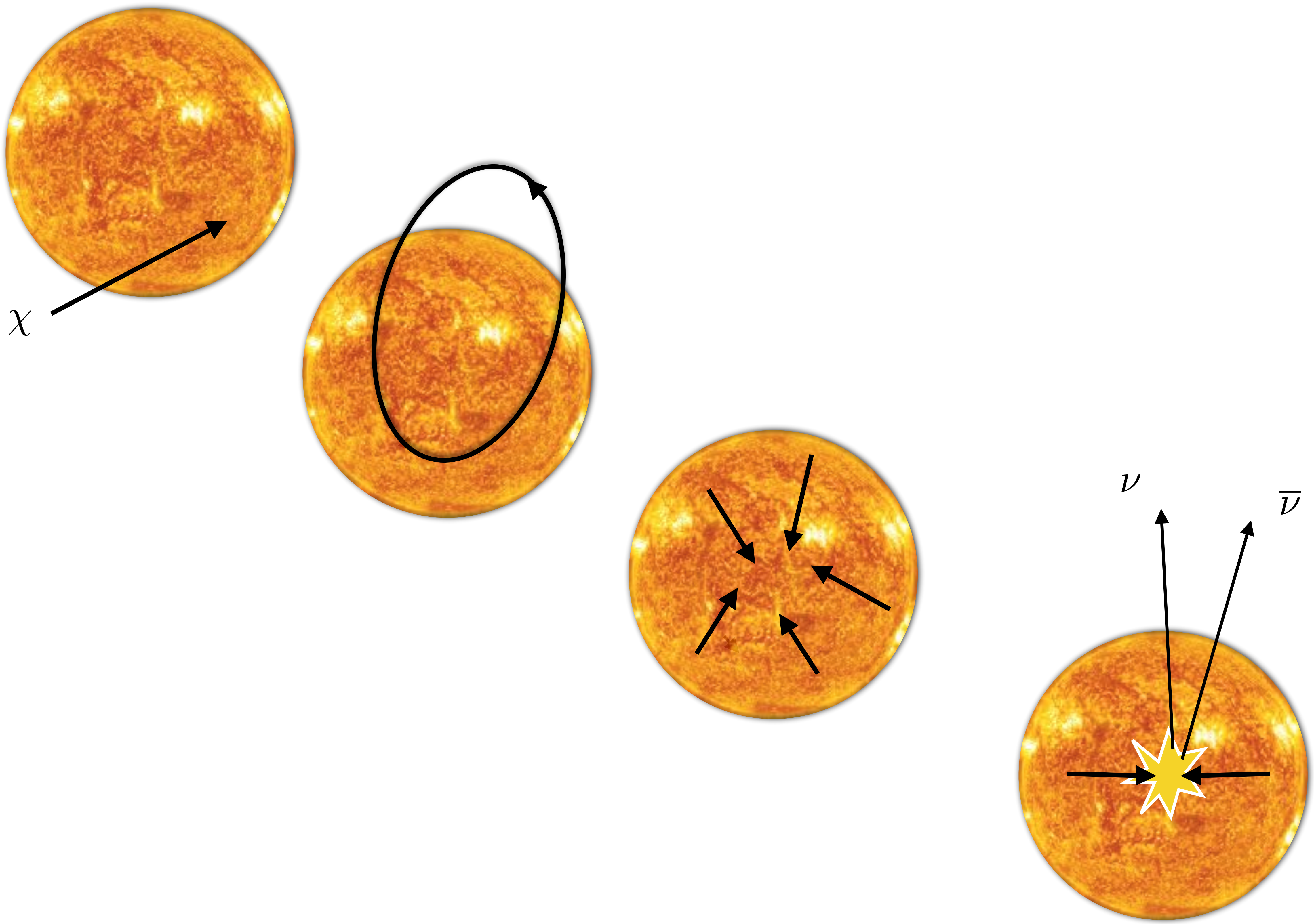
Spin-dependent (SD) interactions: $\mathcal{C}_A^{\mathrm{SD}} \sim (J+1)/J$

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

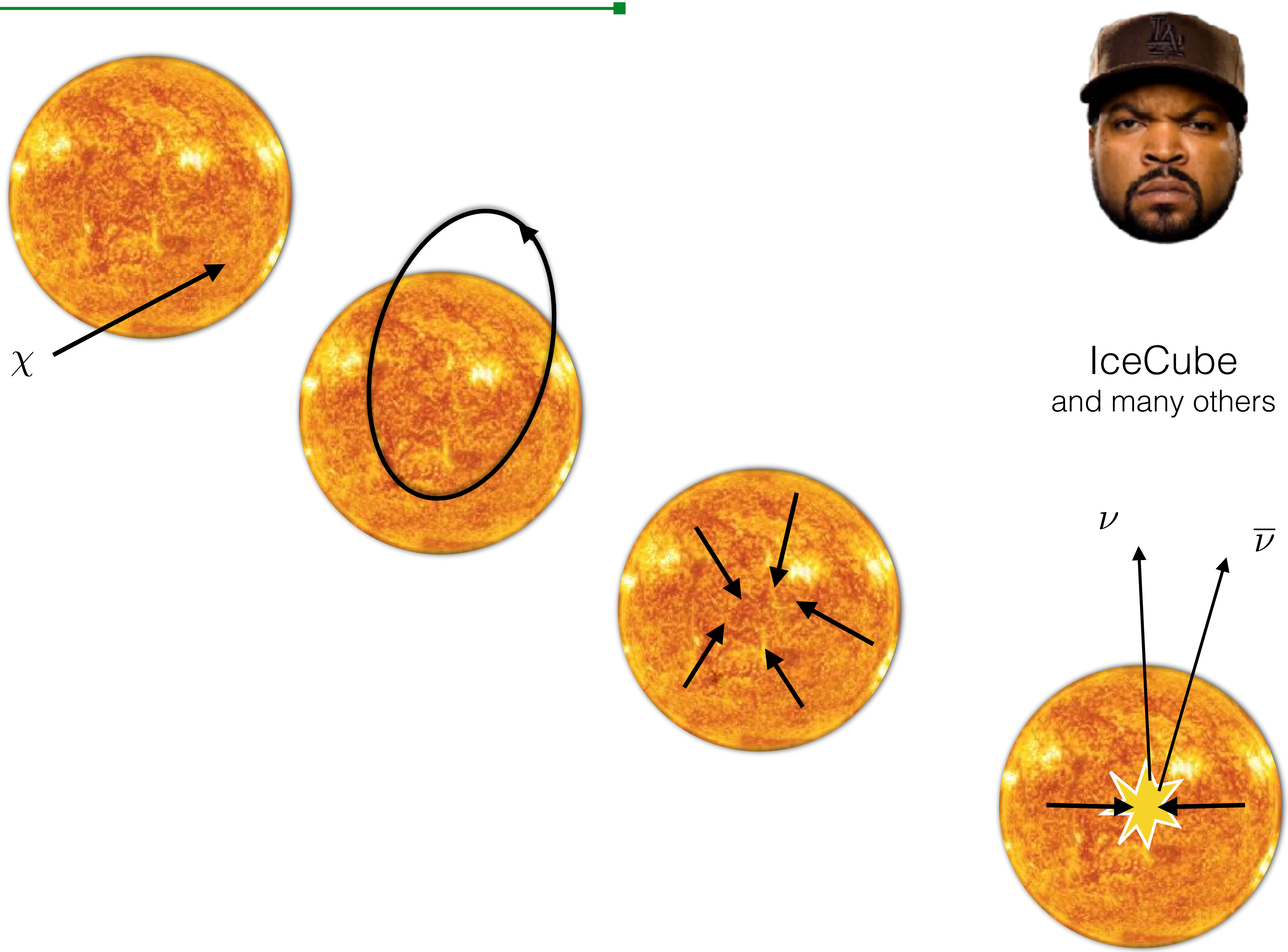




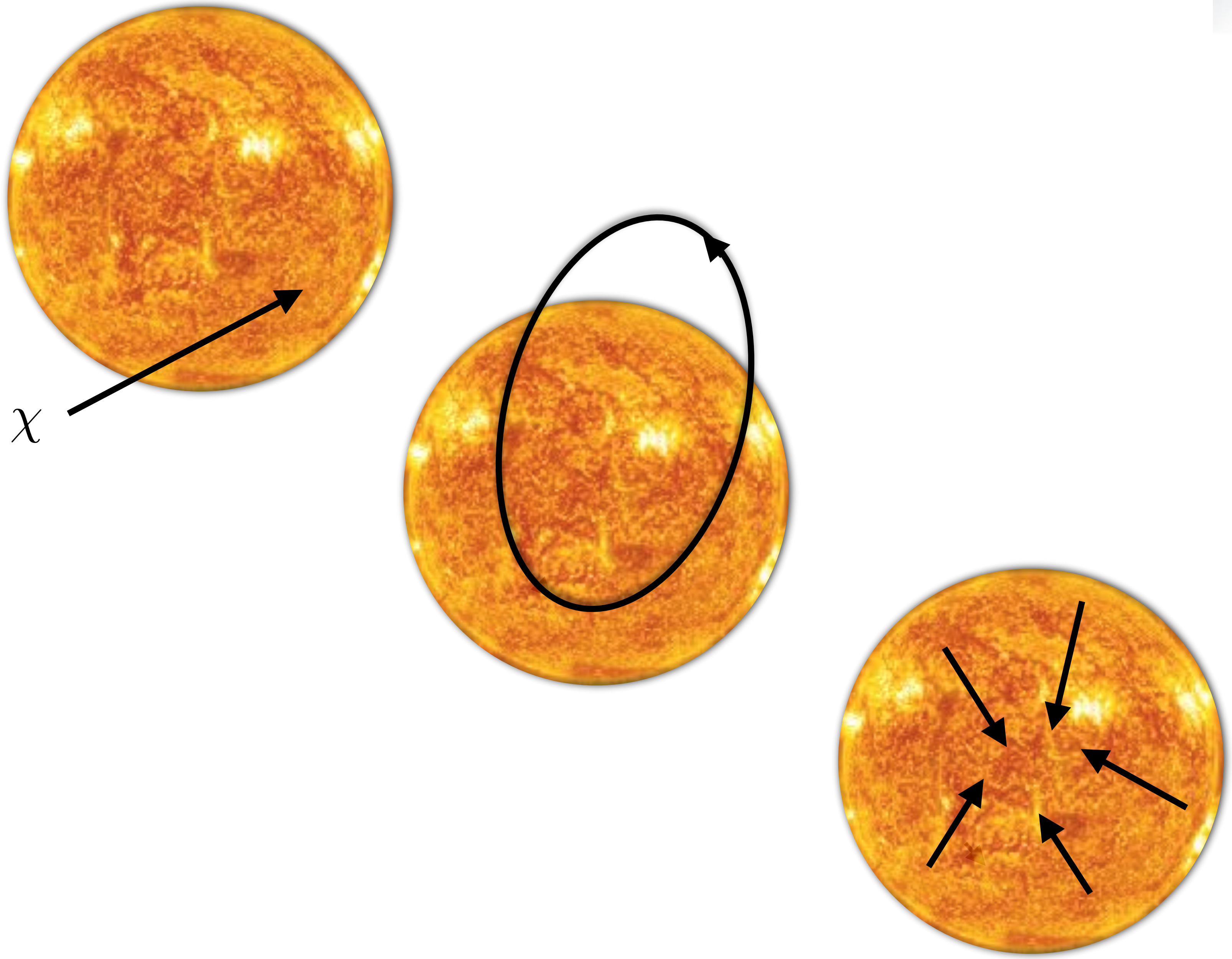
Solar Capture

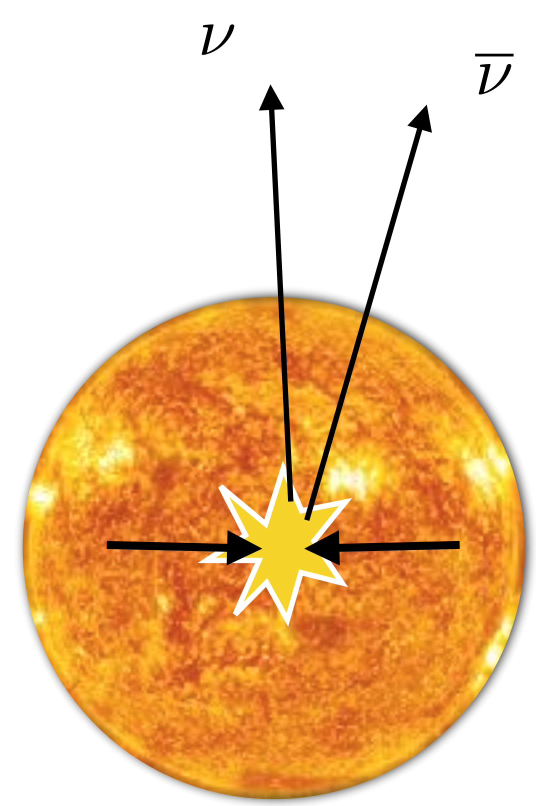


Solar Capture

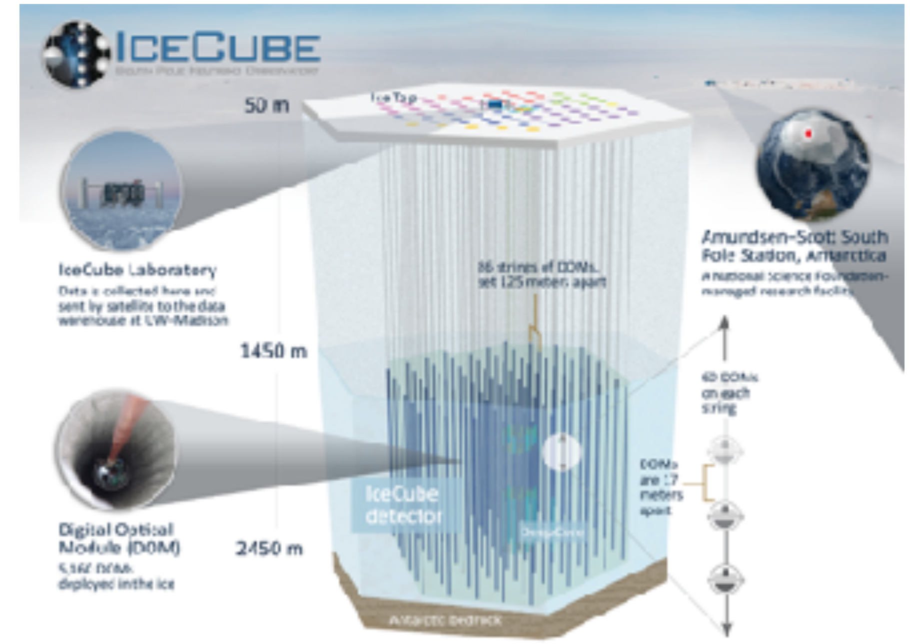


Solar Capture





Credit: icecube.wisc.edu



IceCube
and many others

Solar Capture Rate

$$\boxed{C_i \sim \frac{\rho_\chi}{m_\chi}\int_0^{v_{\max}} \mathrm{d}v \frac{f(v)}{v}\sigma_i n_i P^i_{\mathrm{cap}}(v)\,\mathrm{d}v}$$

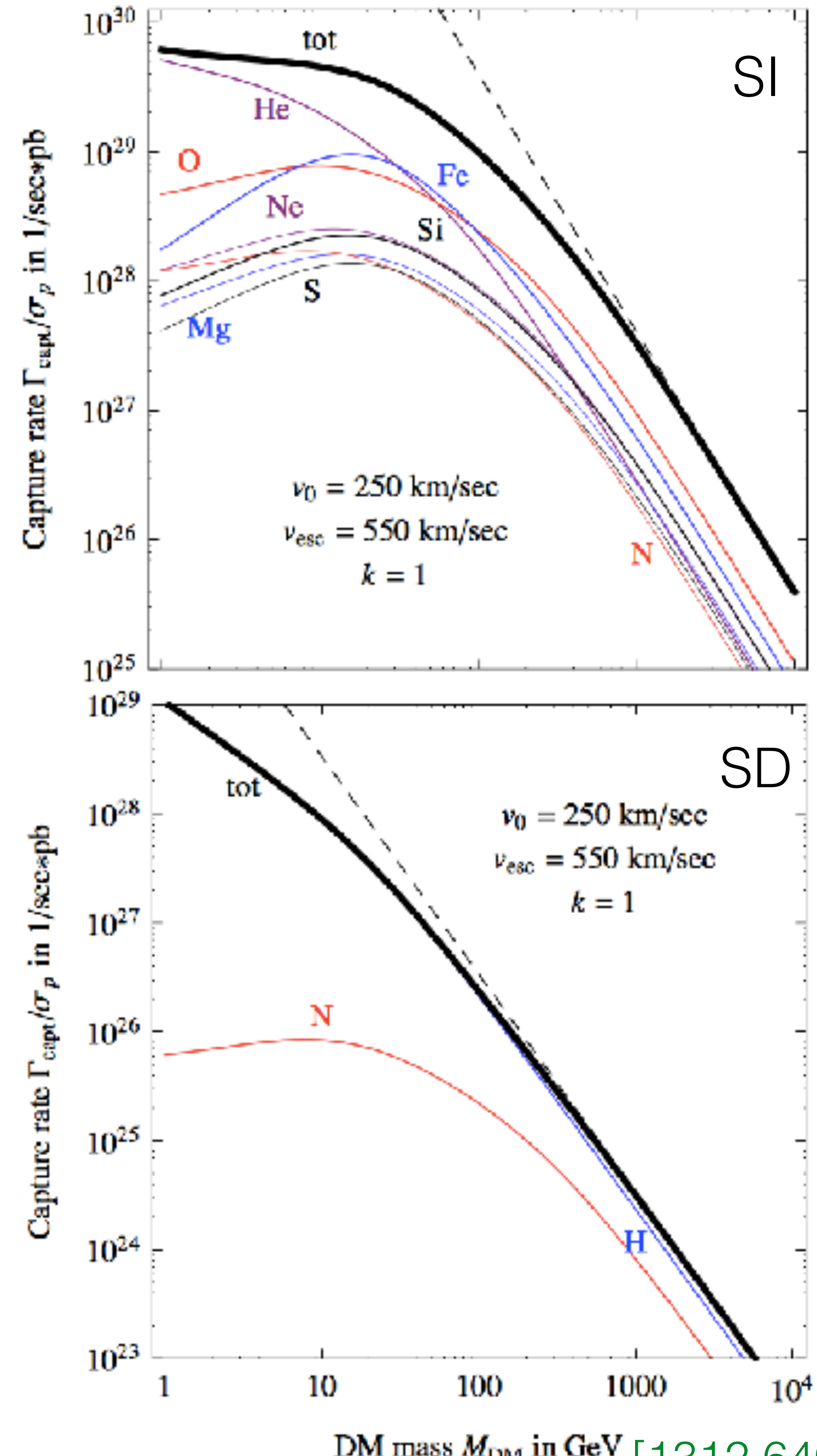
Sum over species in the Sun, *i*.

Only include DM particles moving slowly enough to be captured:

$$v_{\max} = \frac{\sqrt{4m_\chi m_{\mathrm{N}_i}}}{m_\chi - m_{\mathrm{N}_i}} v_{\mathrm{esc}}$$

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…

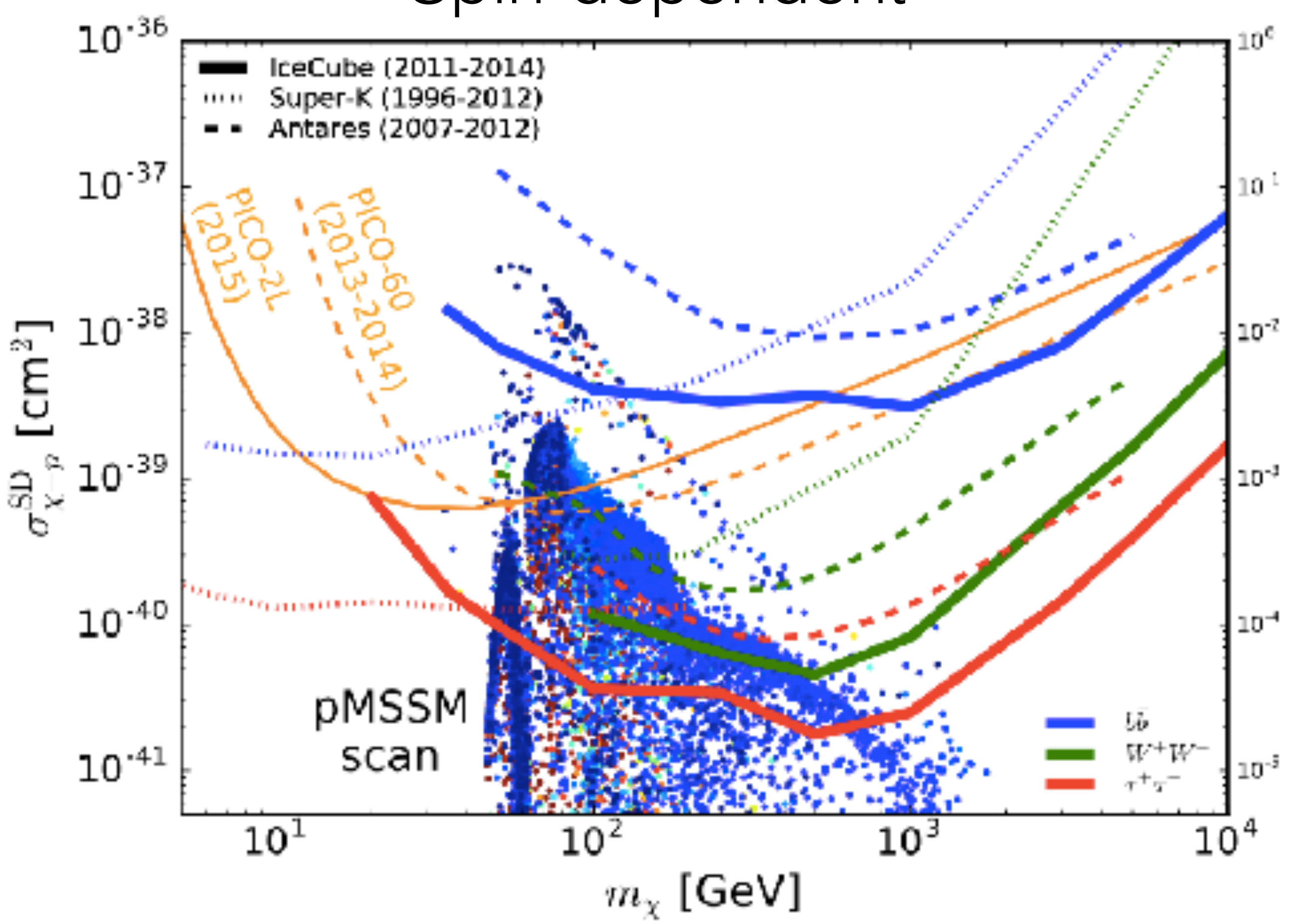


Gould (1991)

[1312.6408]

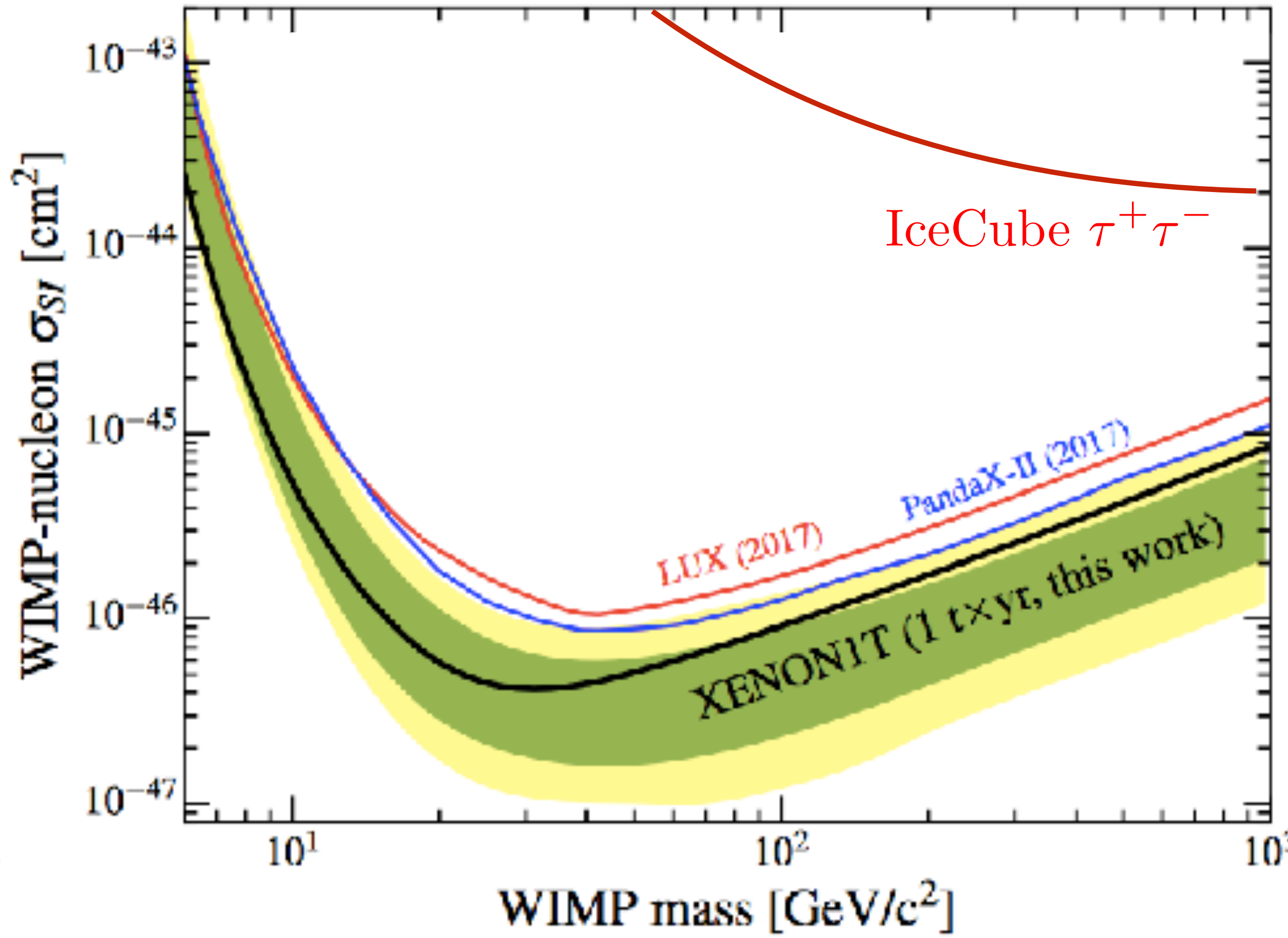
Limits on Solar System DM

Spin-dependent



IceCube [1612.05949]

Spin-independent



XENON1T [1805.12562]

Overview

Solar system searches for DM:
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Standard Halo Model

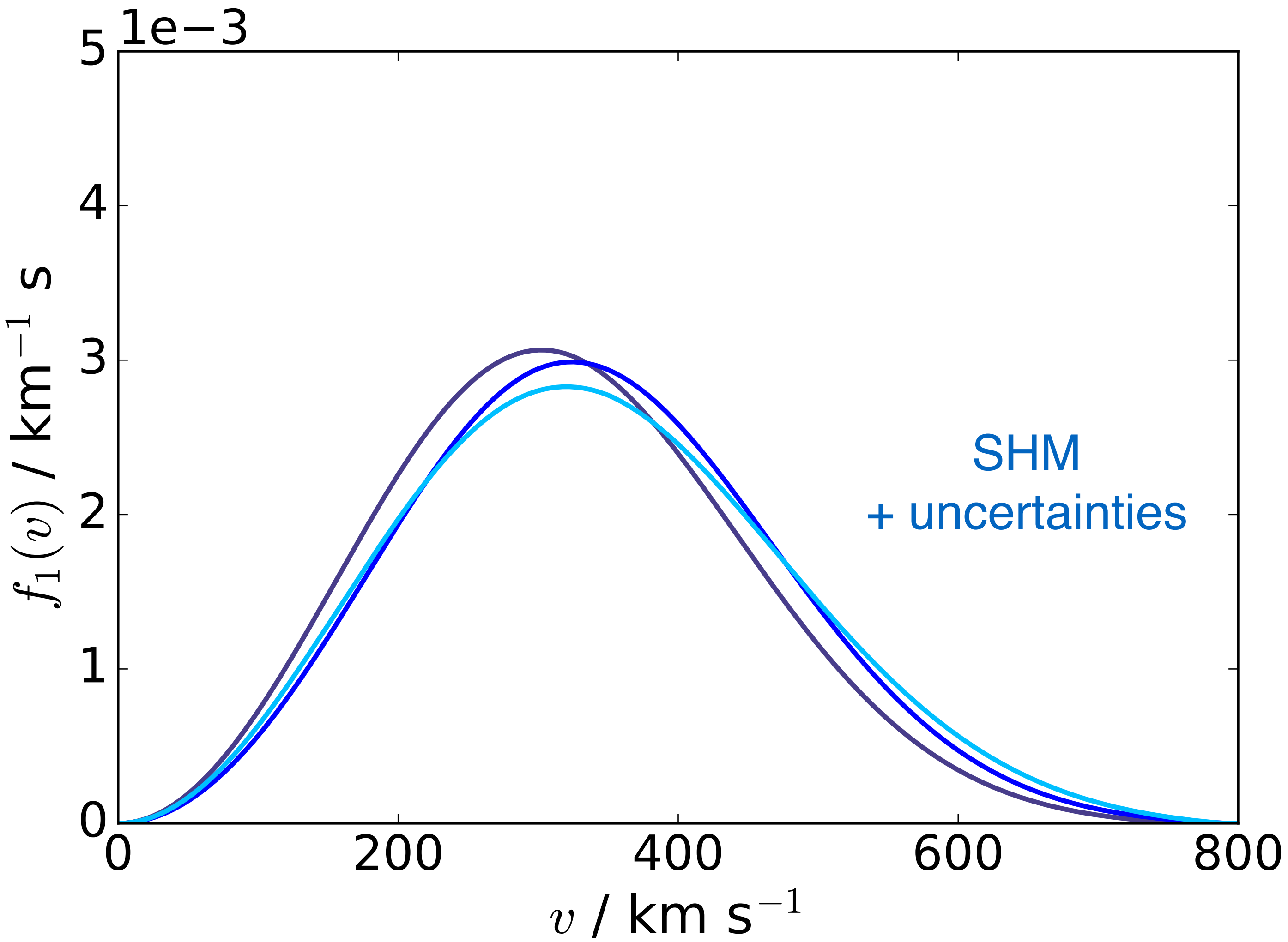
Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

Leads to a Maxwell-Boltzmann (MB) distribution,

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

which is well matched in some hydro simulations.

[1601.04707, 1601.04725, 1601.05402]



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

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

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

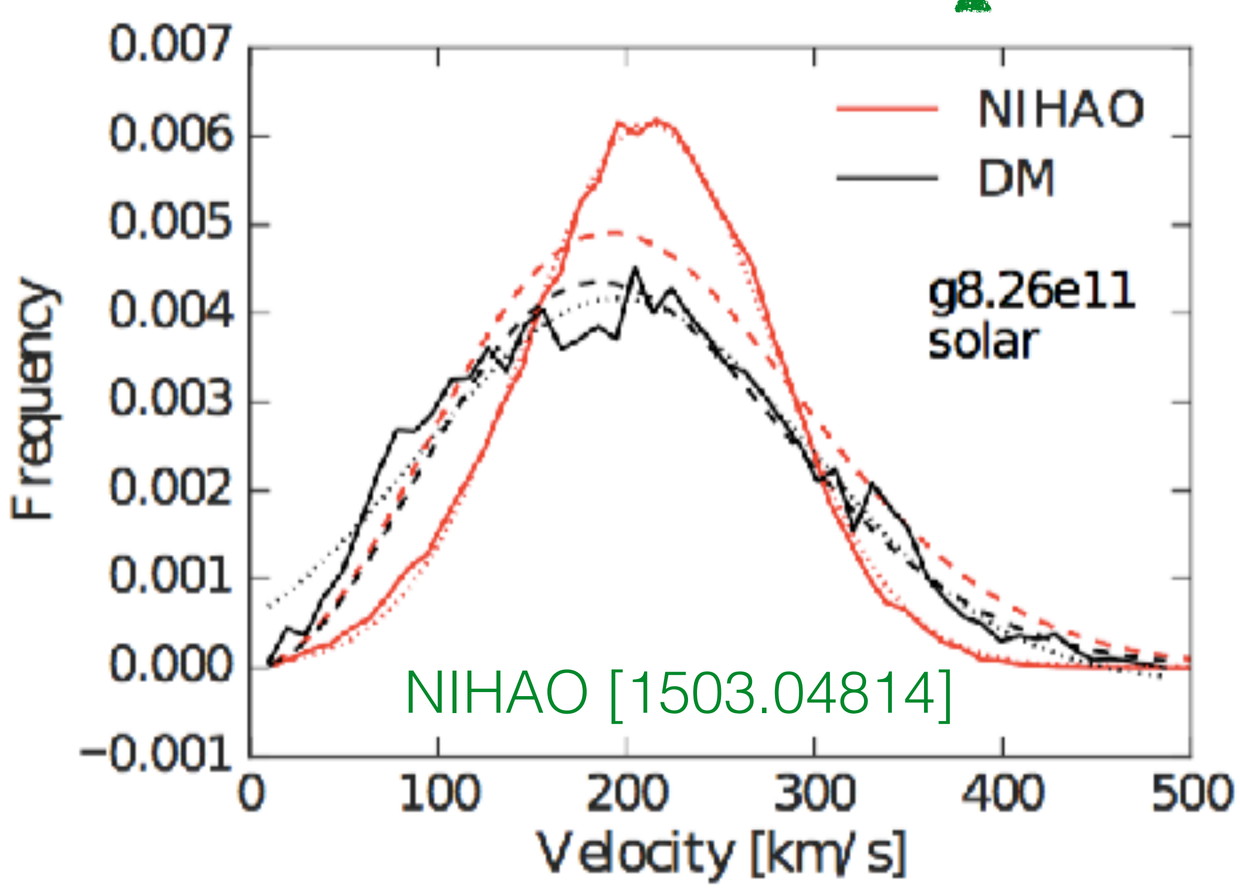
Feast et al. [astro-ph/9706293], Bovy et al. [1209.0759]

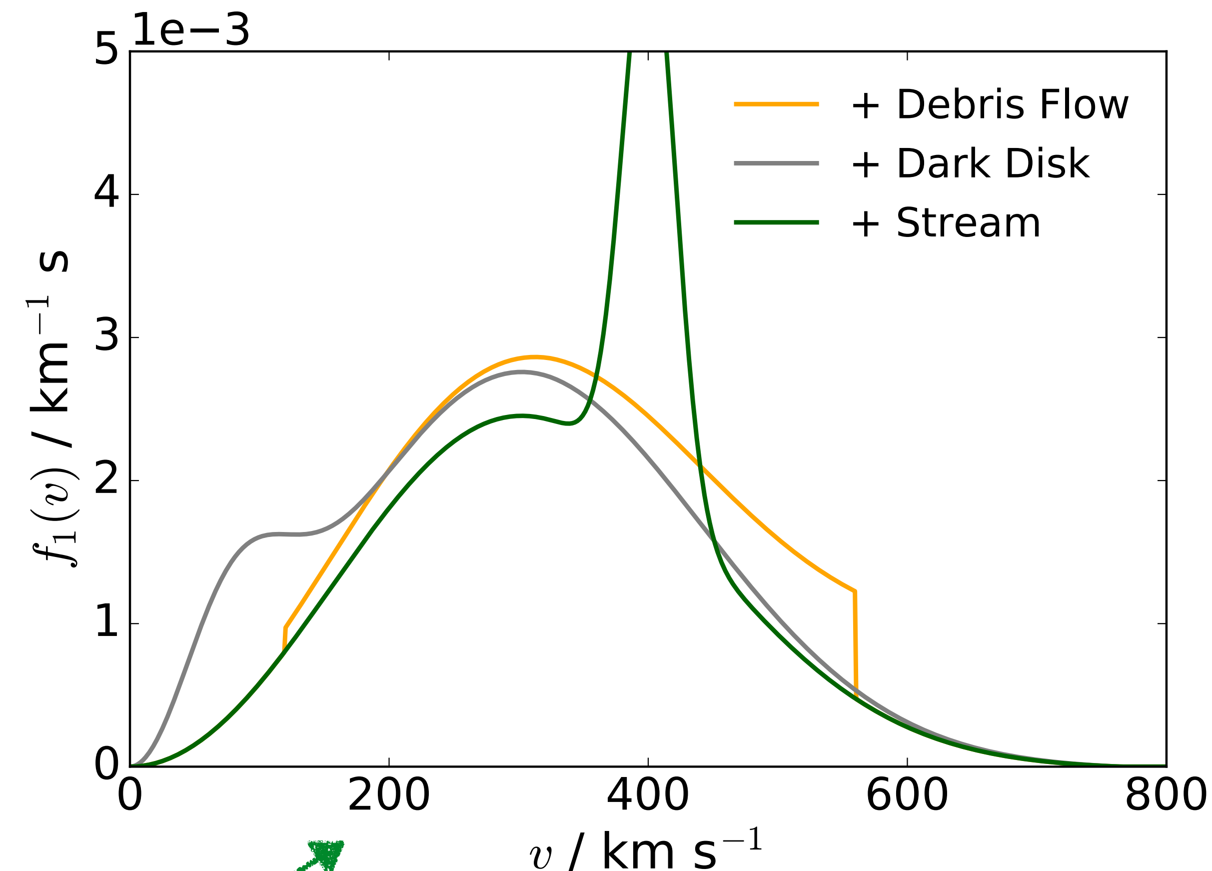
$$v_{\mathrm{esc}} = 533^{+54}_{-41}\,\mathrm{km\,s^{-1}}$$

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]

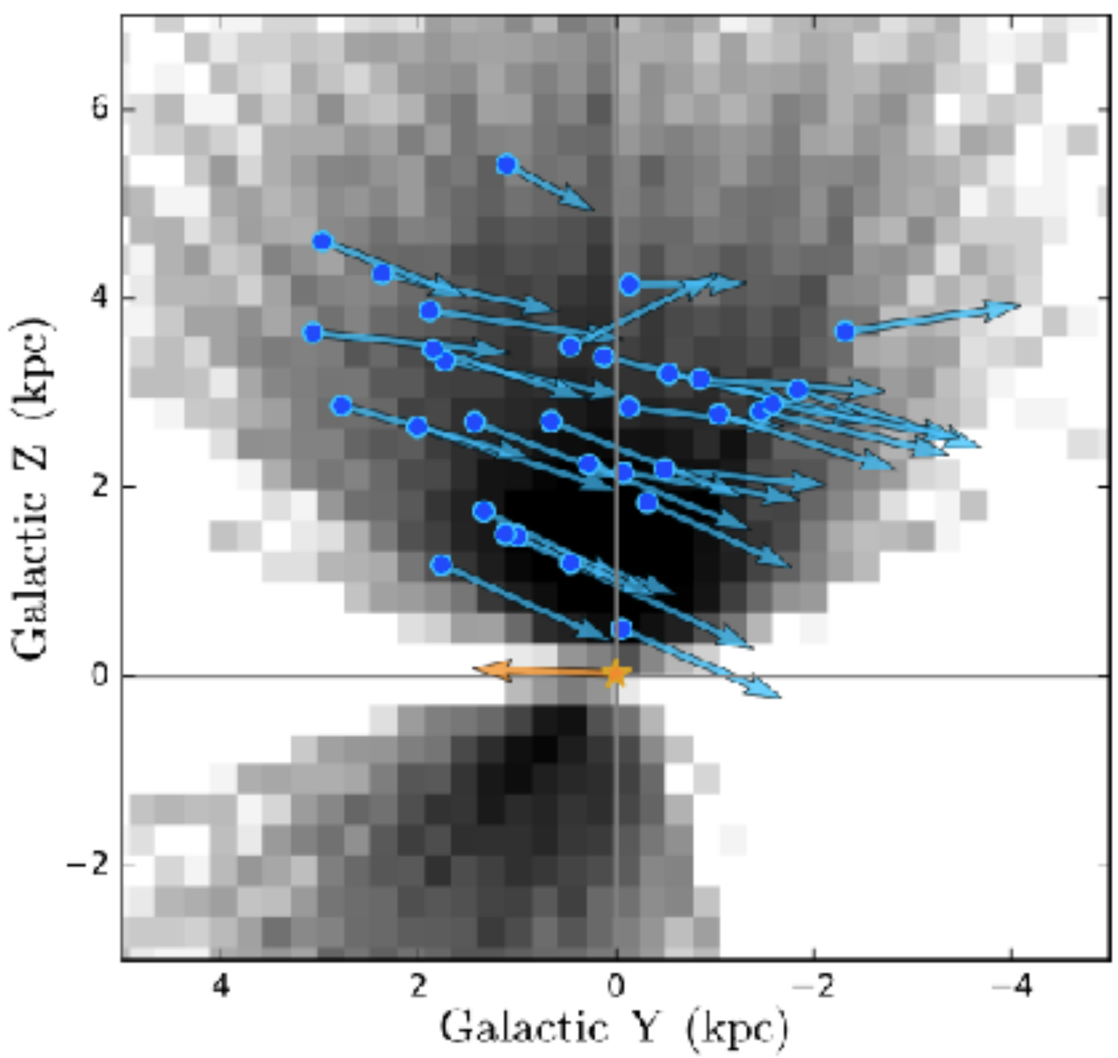
Dark disk — Pillepich et al. [1308.1703], Schaller et al. [1605.02770]

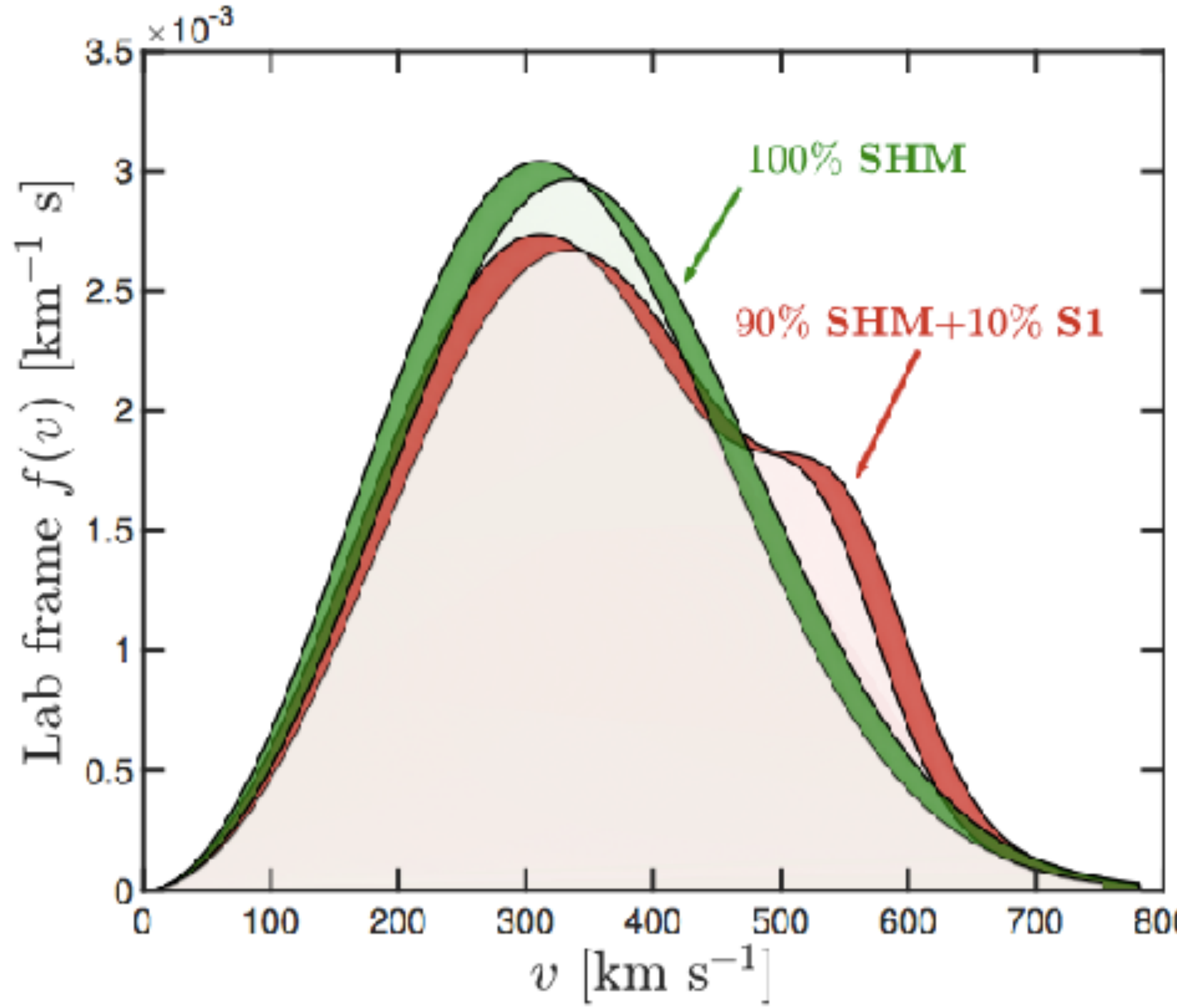
Tidal stream — Freese et al. [astro-ph/0309279, astro-ph/0310334]

S1 Stream: DM Hurricane?

Recent GAIA data revealing new stellar streams:

[1712.04071]





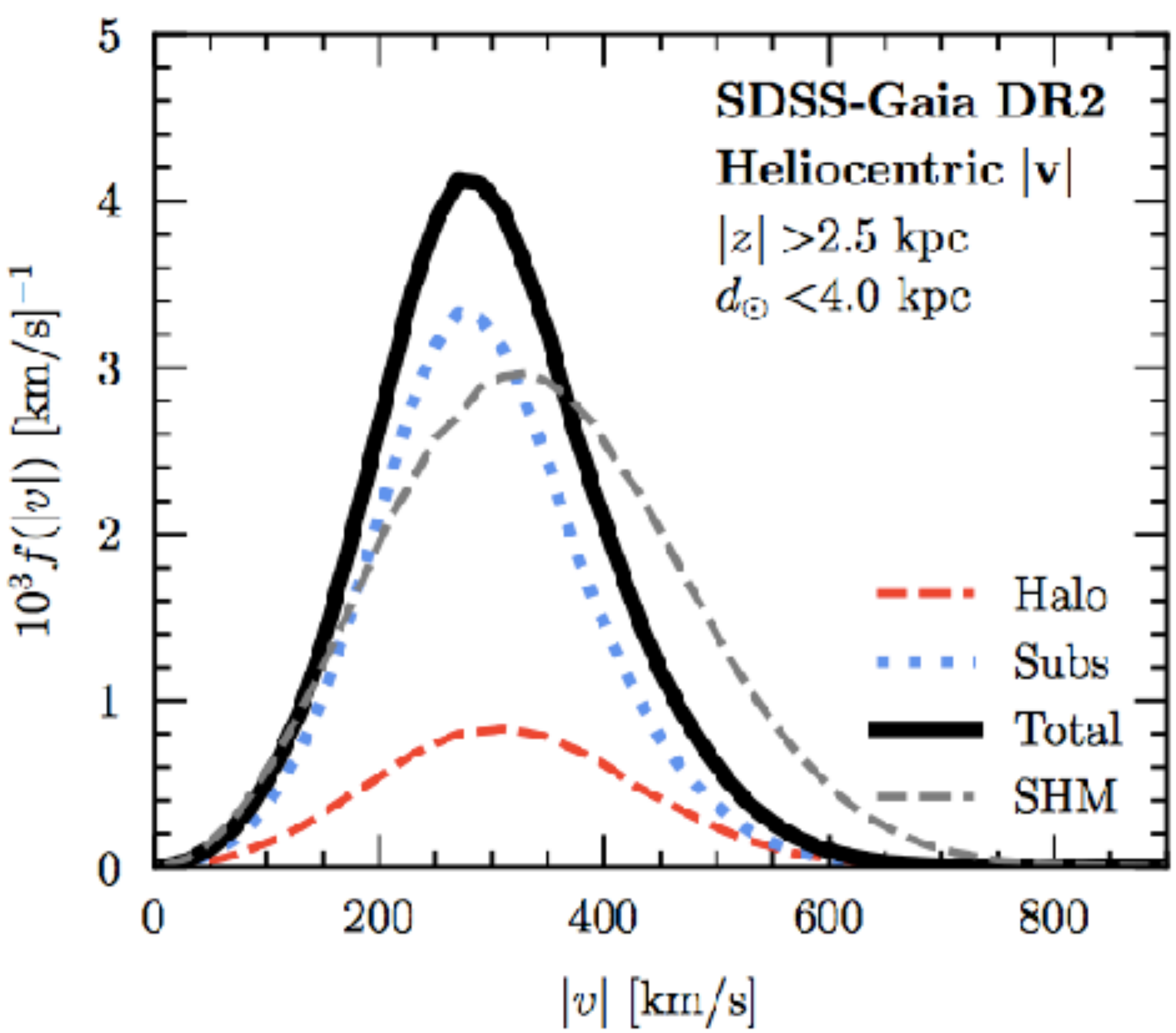
S1 stream counter-rotating at $v_{\rm S1} \approx 300\,\mathrm{km/s}$

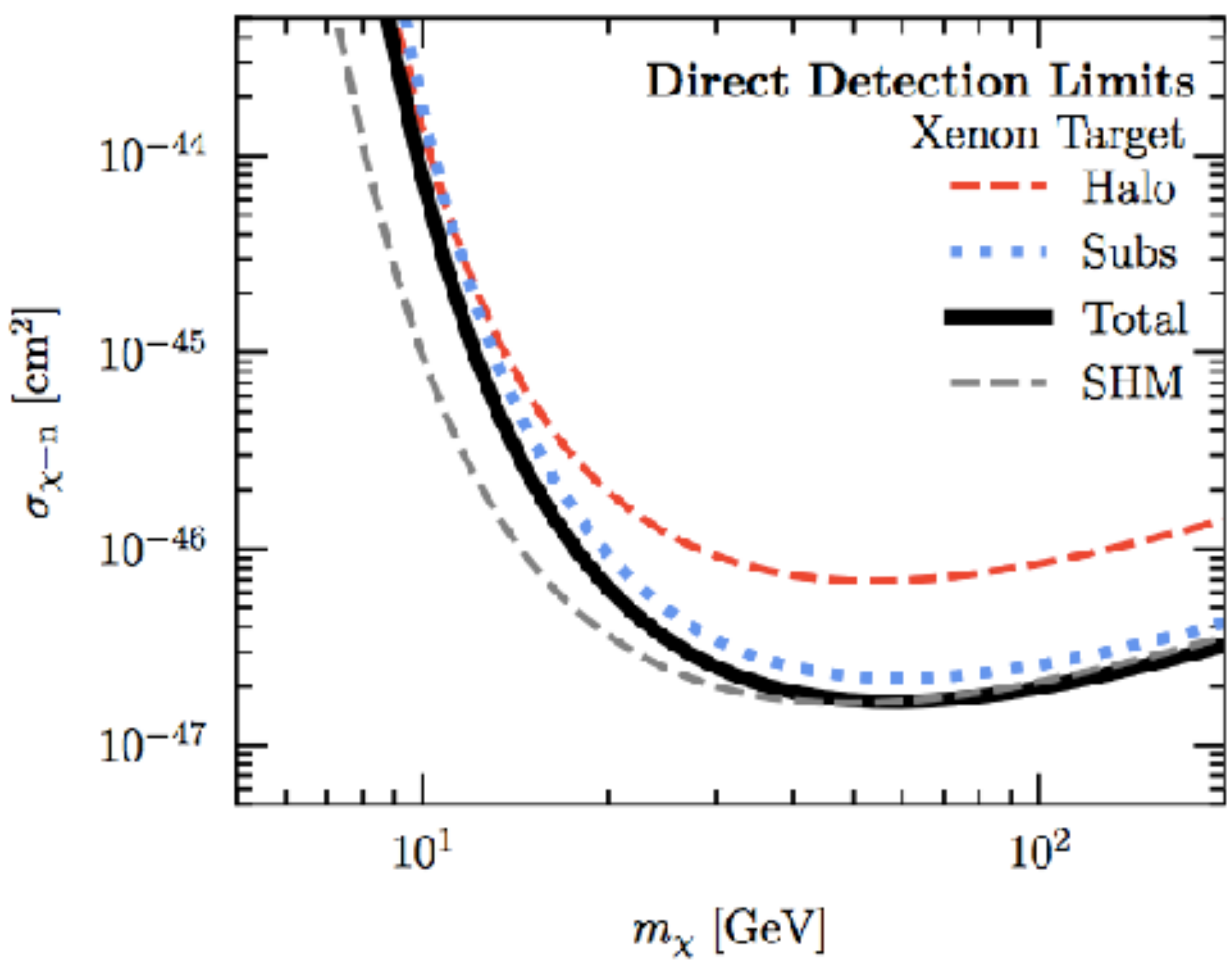
Could be carrying with it a hurricane of Dark Matter…

O'Hare et al. [1807.09004]

Stars as DM Tracers

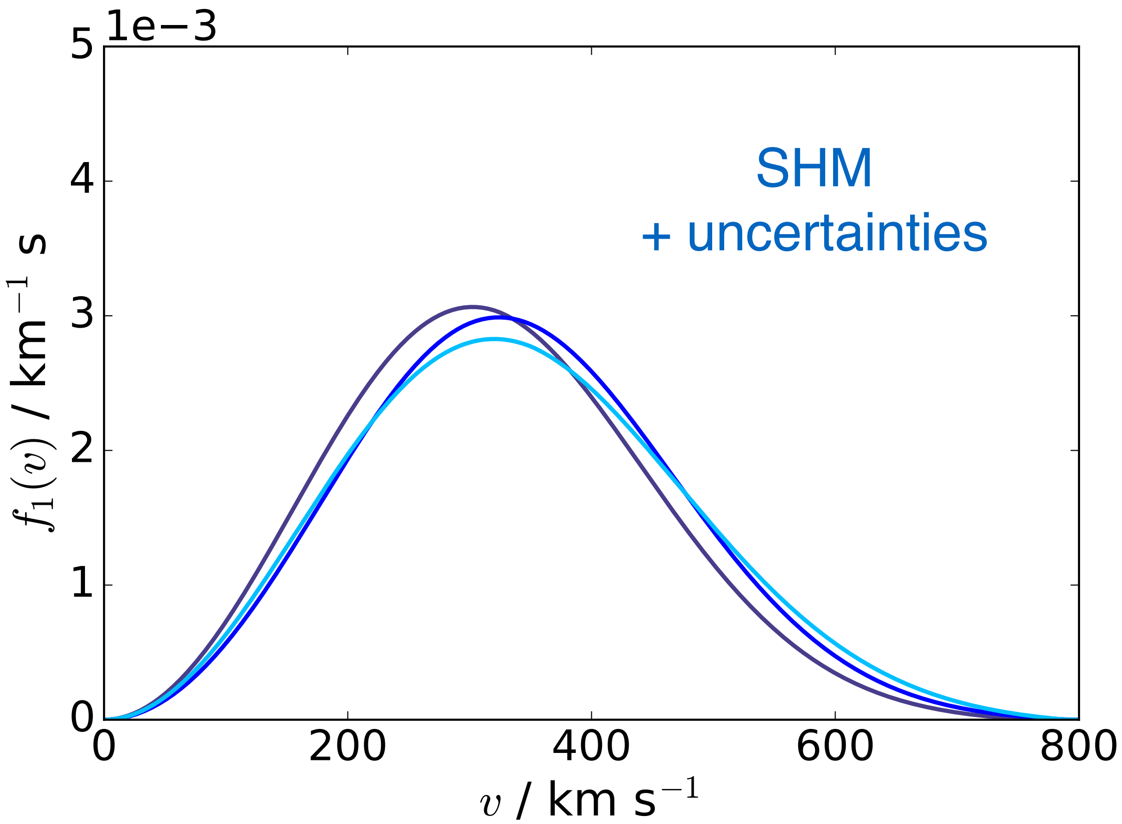
Old, metal-poor stars may trace the DM velocity distribution:

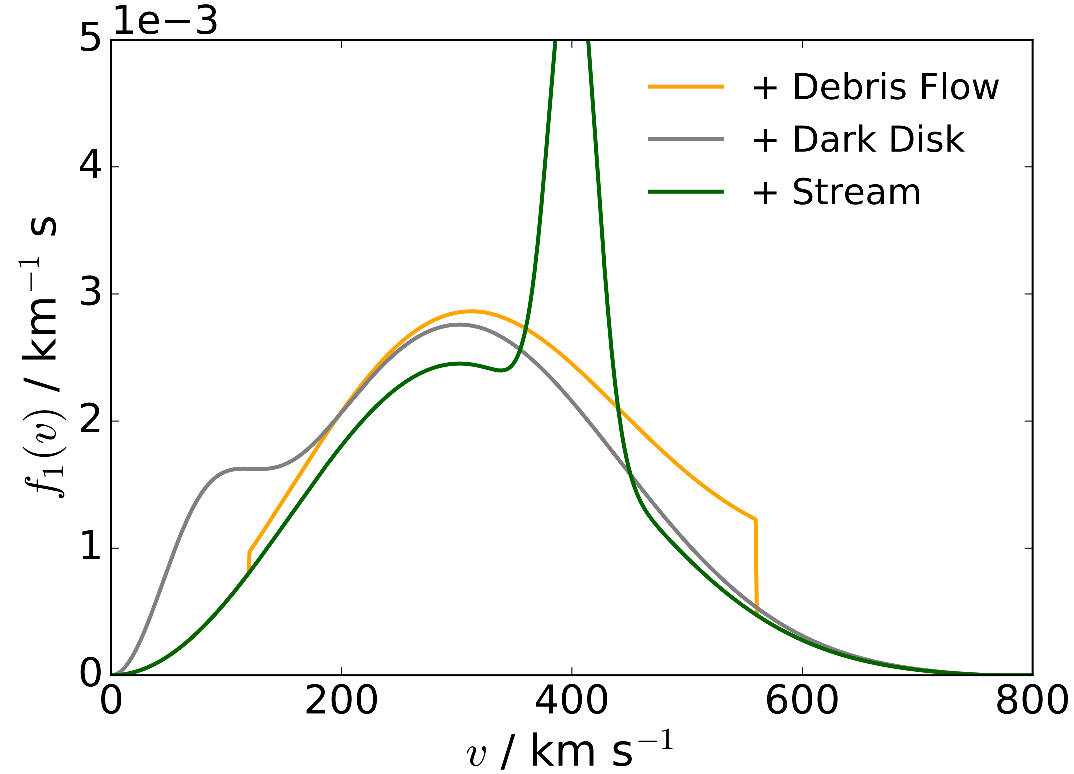


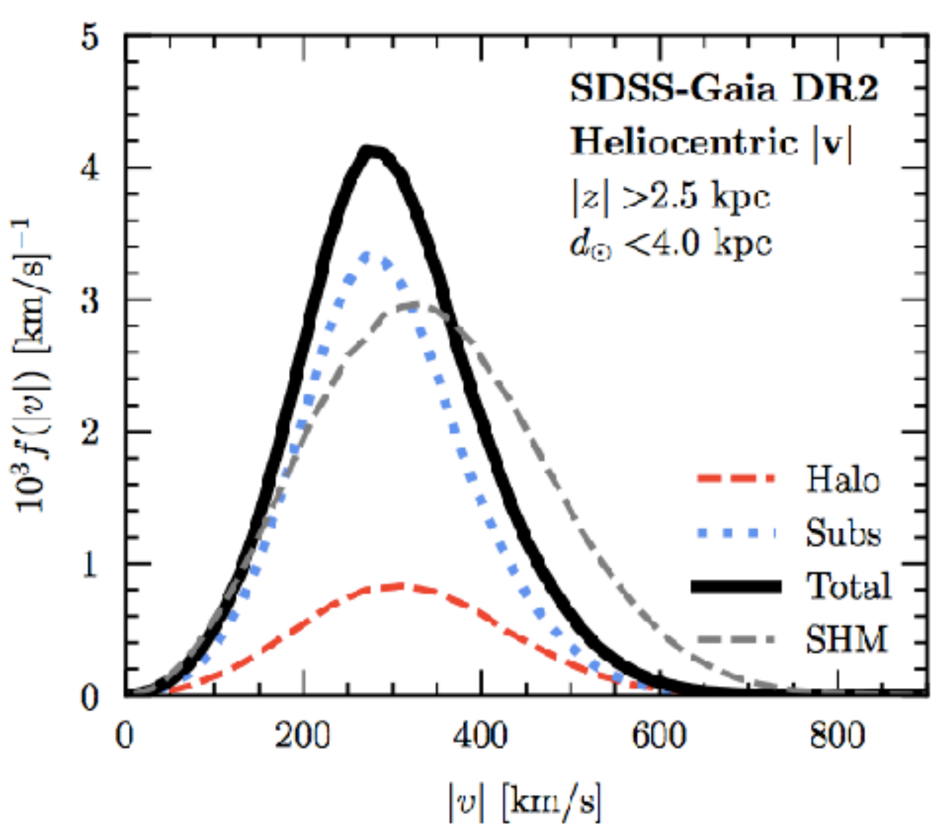


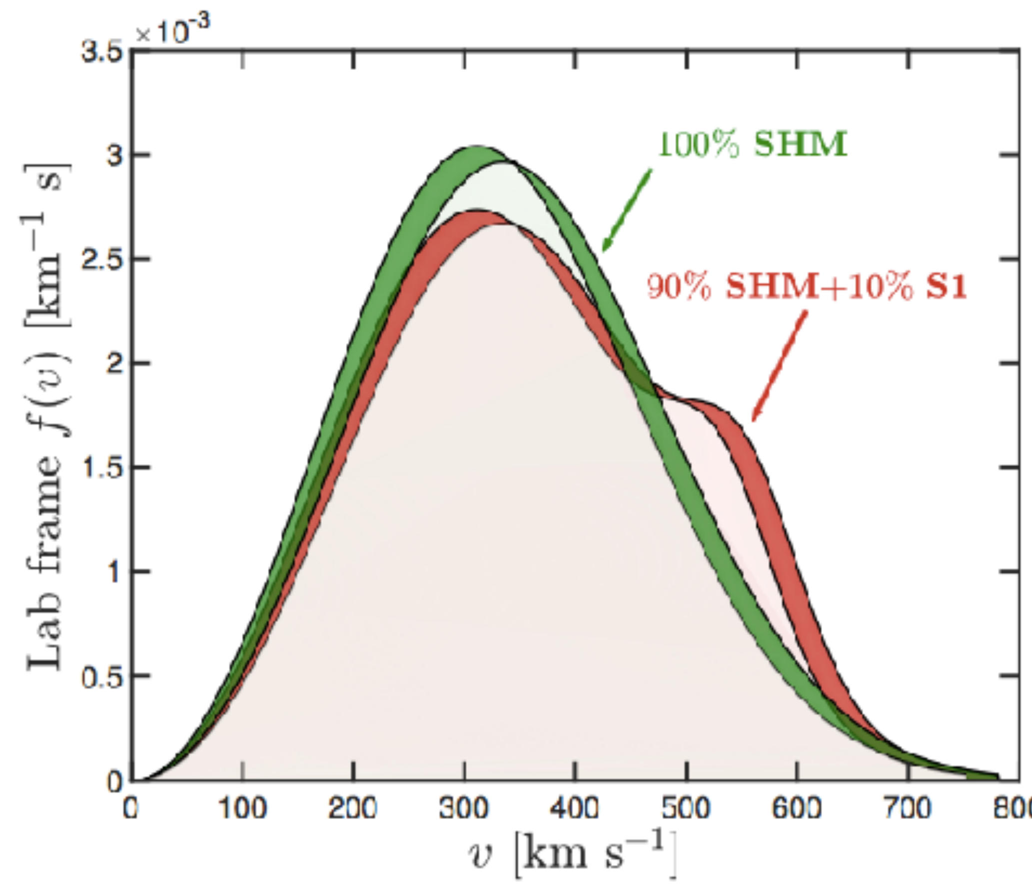
Herzog-Arbeitman et al. [1708.03635]; Necib et. al. [1807.02519]

Astro Uncertainties









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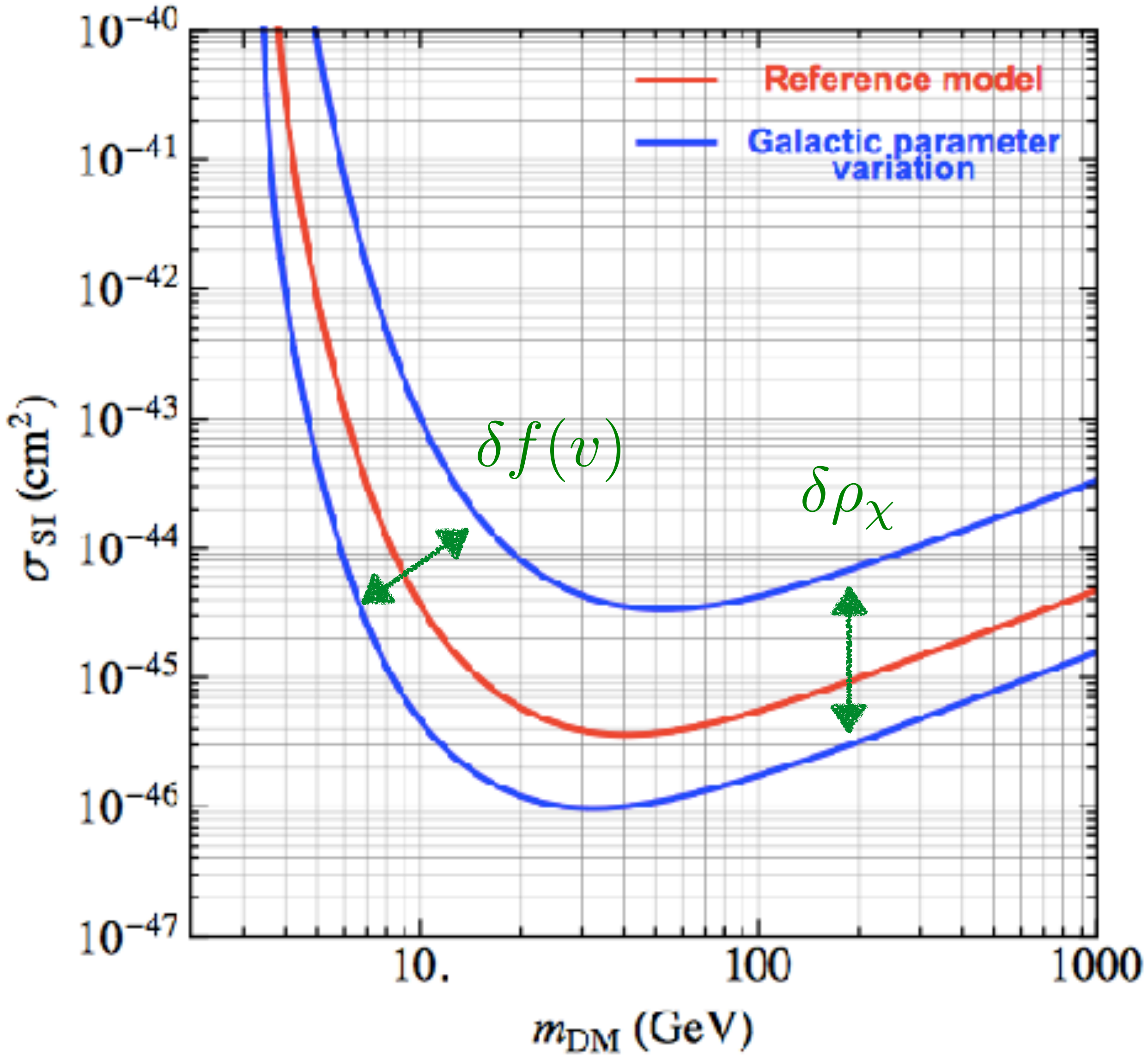
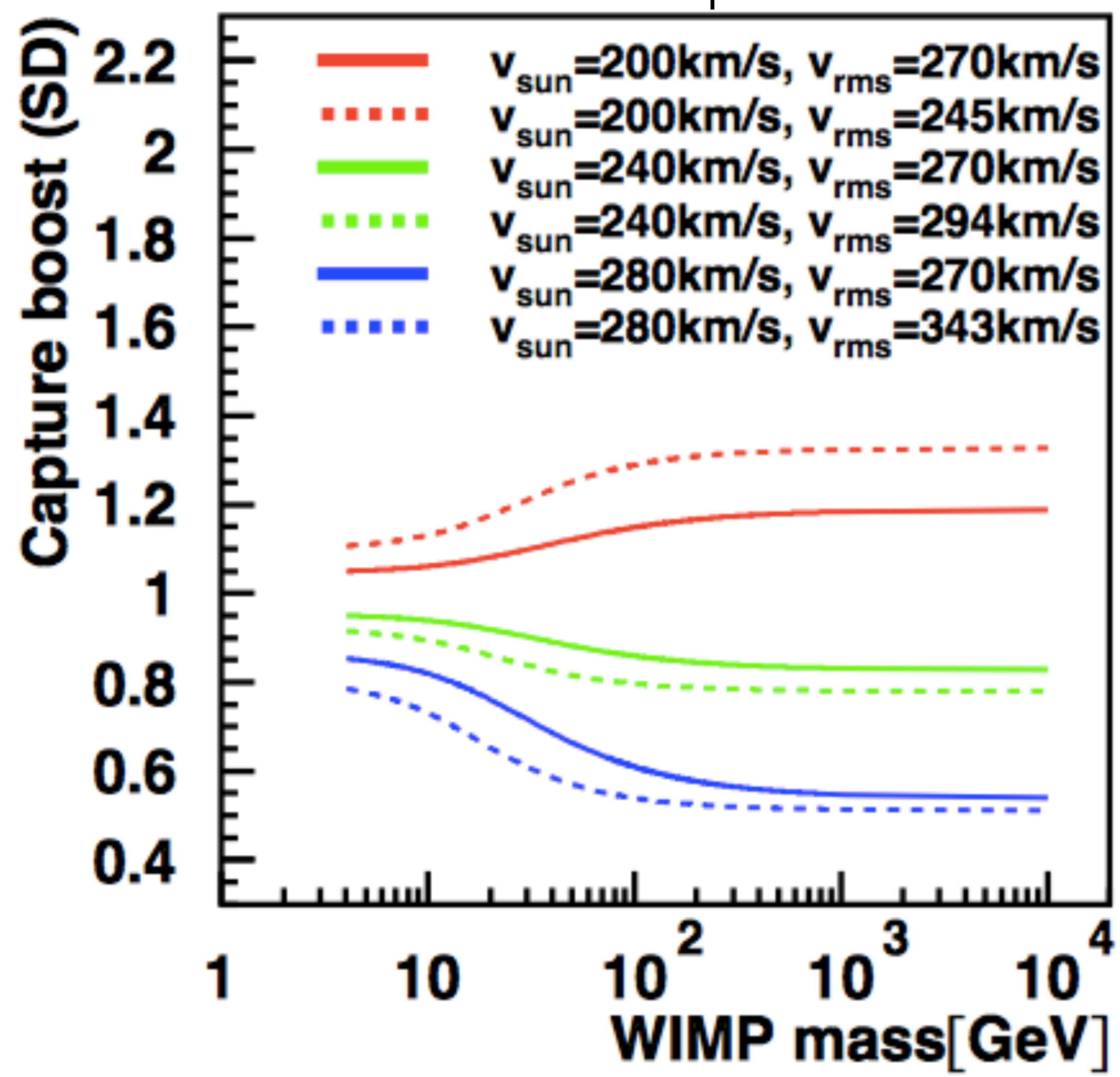
Impact on DM limits

Direct Detection



Benito et al. [1612.02010]

Solar Capture

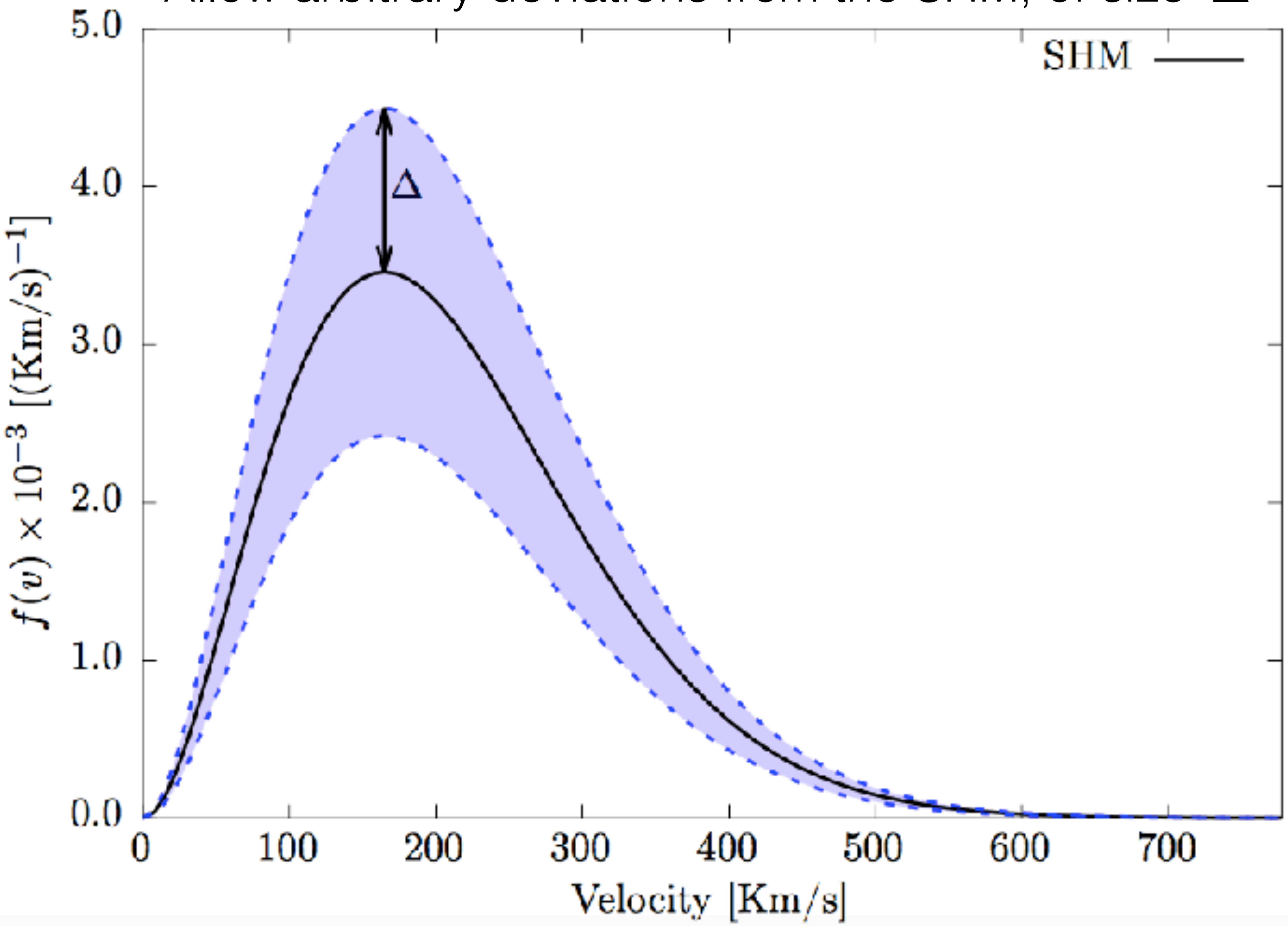


Choi et al. [1312.0273]

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

Deviation from SHM

Allow arbitrary deviations from the SHM, of size Δ



$\Delta \to 0$ SHM velocity distribution

$\Delta \to \infty$ Arbitrary velocity distribution

See also Fowlie [1809.02323]

Stream Decomposition

Attempt to be as general as possible:

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

$$\begin{aligned}
\text{Optimize:} \quad & \log p\left(m_\chi, \sigma_p, f(\mathbf{v})\right) \\
\text{Subject to:} \quad & \left| \frac{f(\vec{v}) - f_{\mathrm{SHM}}(\vec{v})}{f_{\mathrm{SHM}}(\vec{v})} \right| \leq \Delta \\
\text{and} \quad & \int \mathrm{d}^3 v\, f(\vec{v}) = 1\,.
\end{aligned}$$

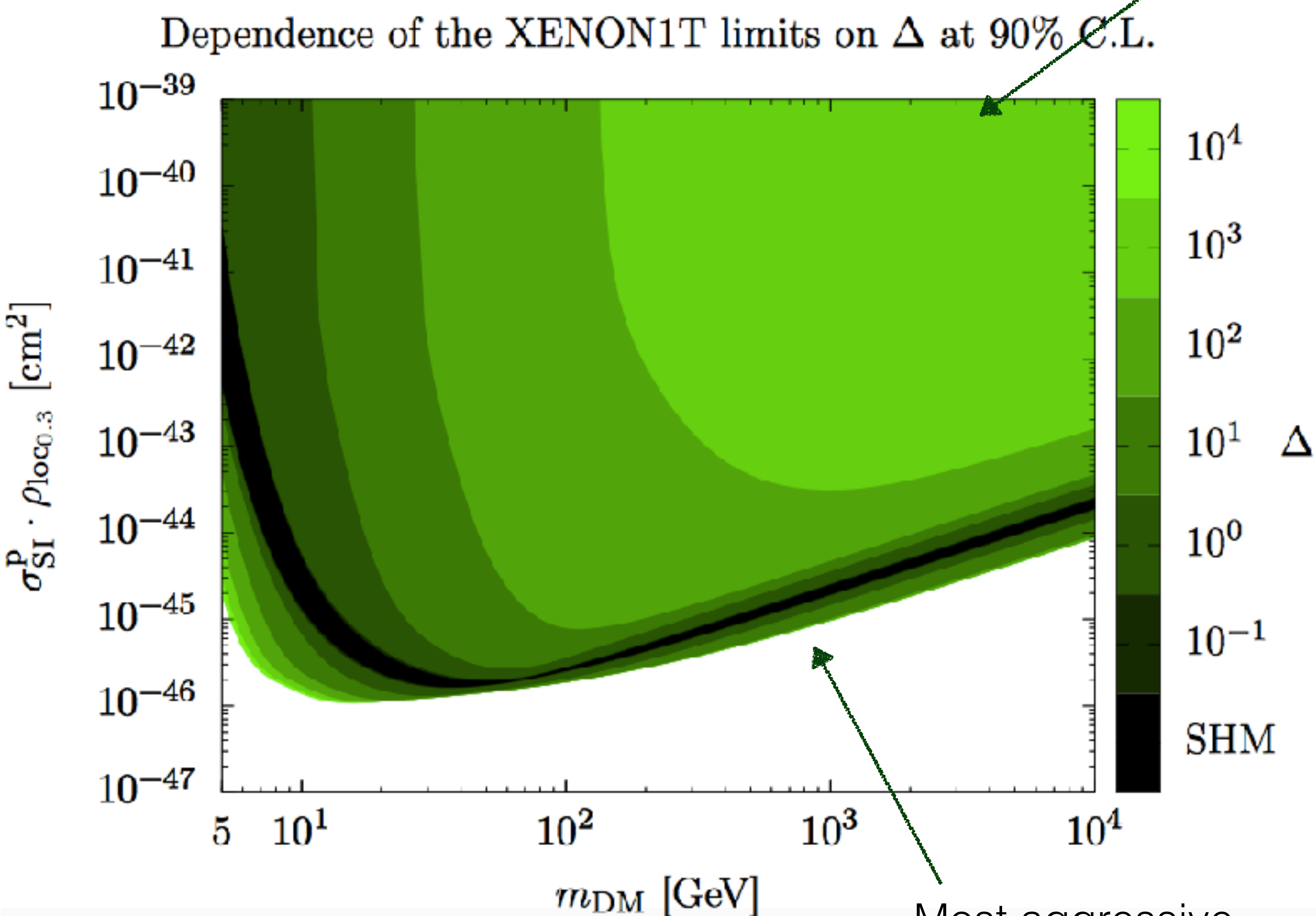
Optimise p-value or chi-squared or likelihood or whatever

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]

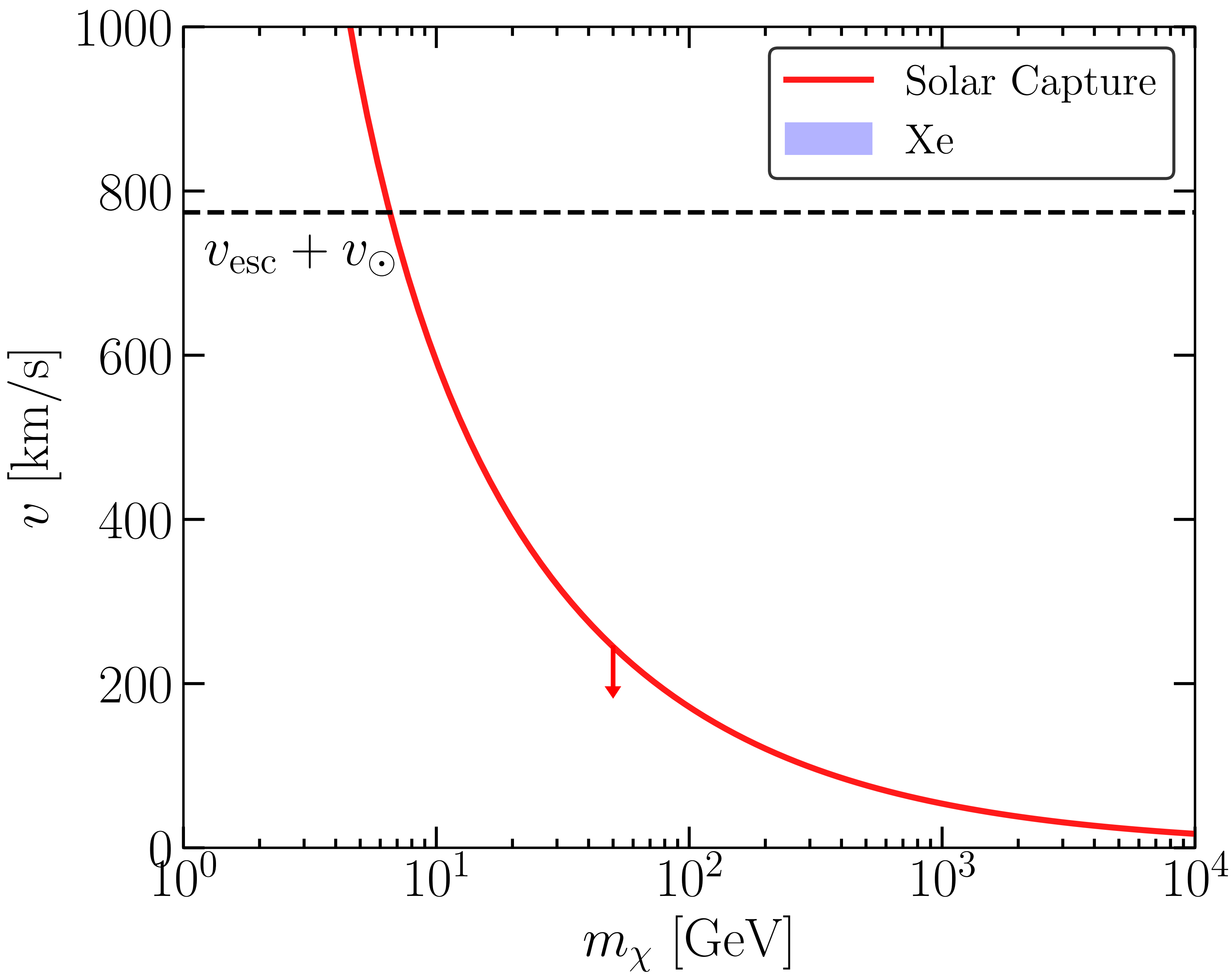
Xenon1T Limits

Most conservative



Most aggressive

Velocity Ranges



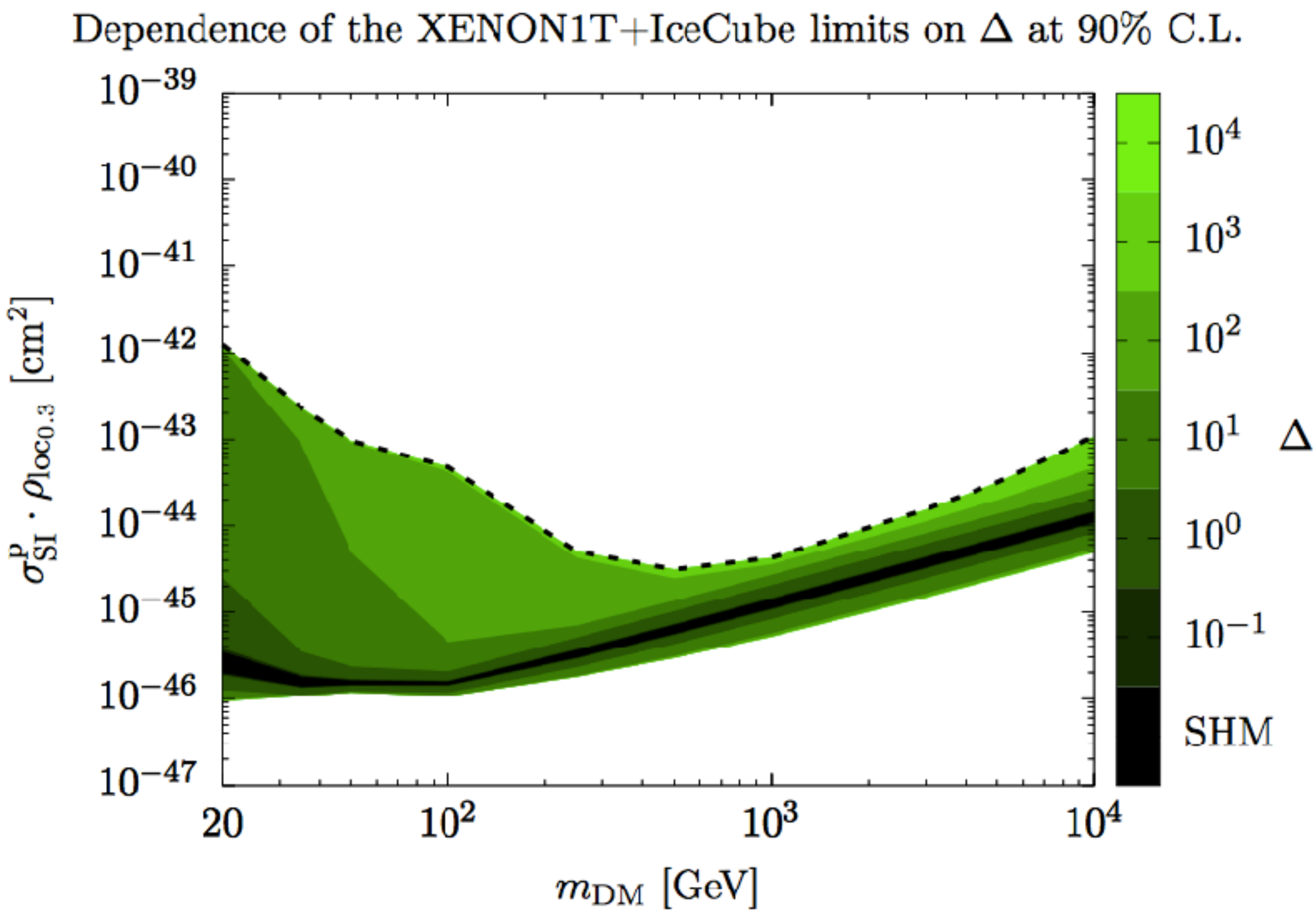
Direct detection:

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

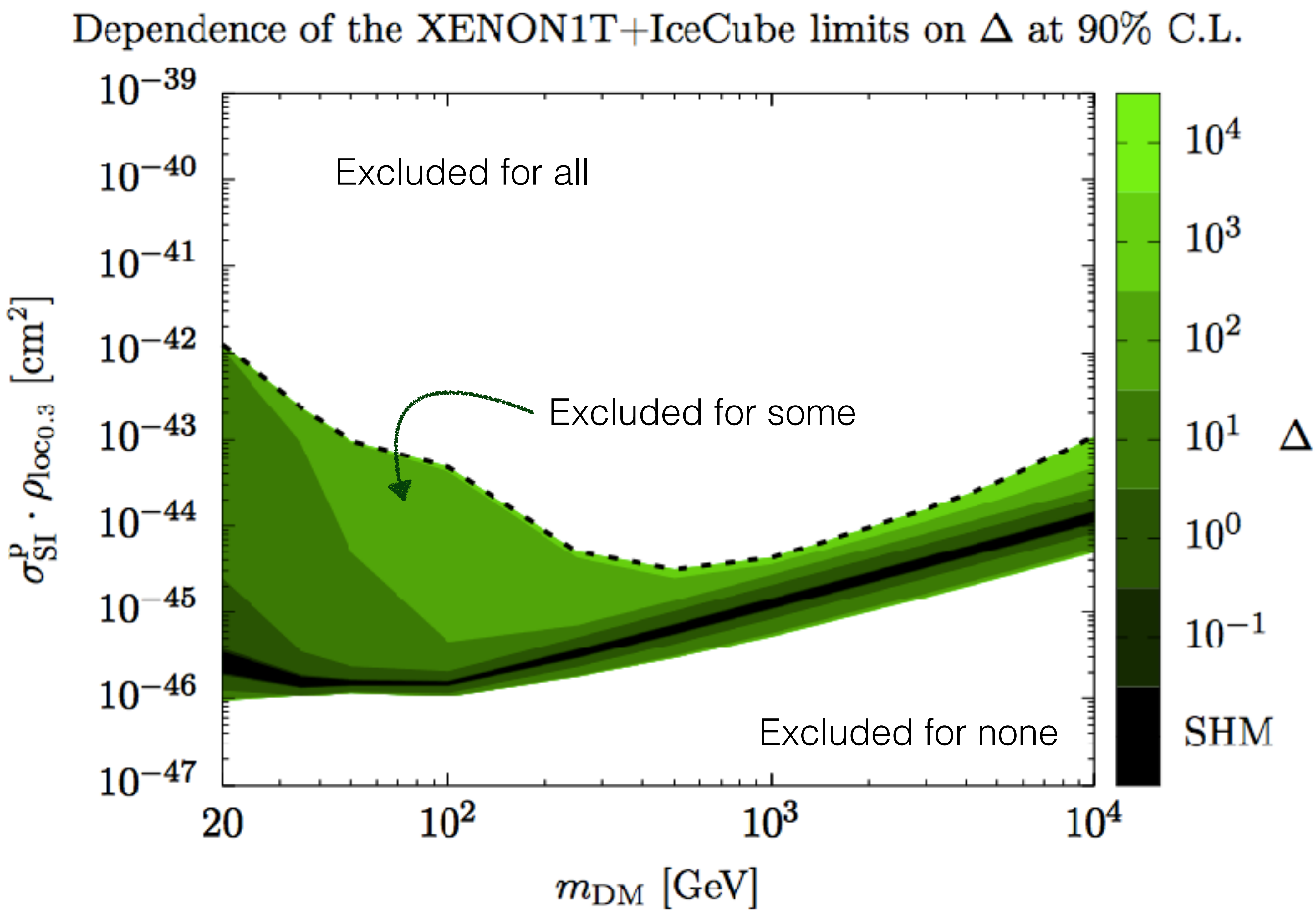
Solar Capture:

$$v_\mathrm{max} = \frac{\sqrt{4 m_\chi m_{\mathrm{N}_i}}}{m_\chi - m_{\mathrm{N}_i}} v_\mathrm{esc}$$

Xenon1T + IceCube



Xenon1T + IceCube



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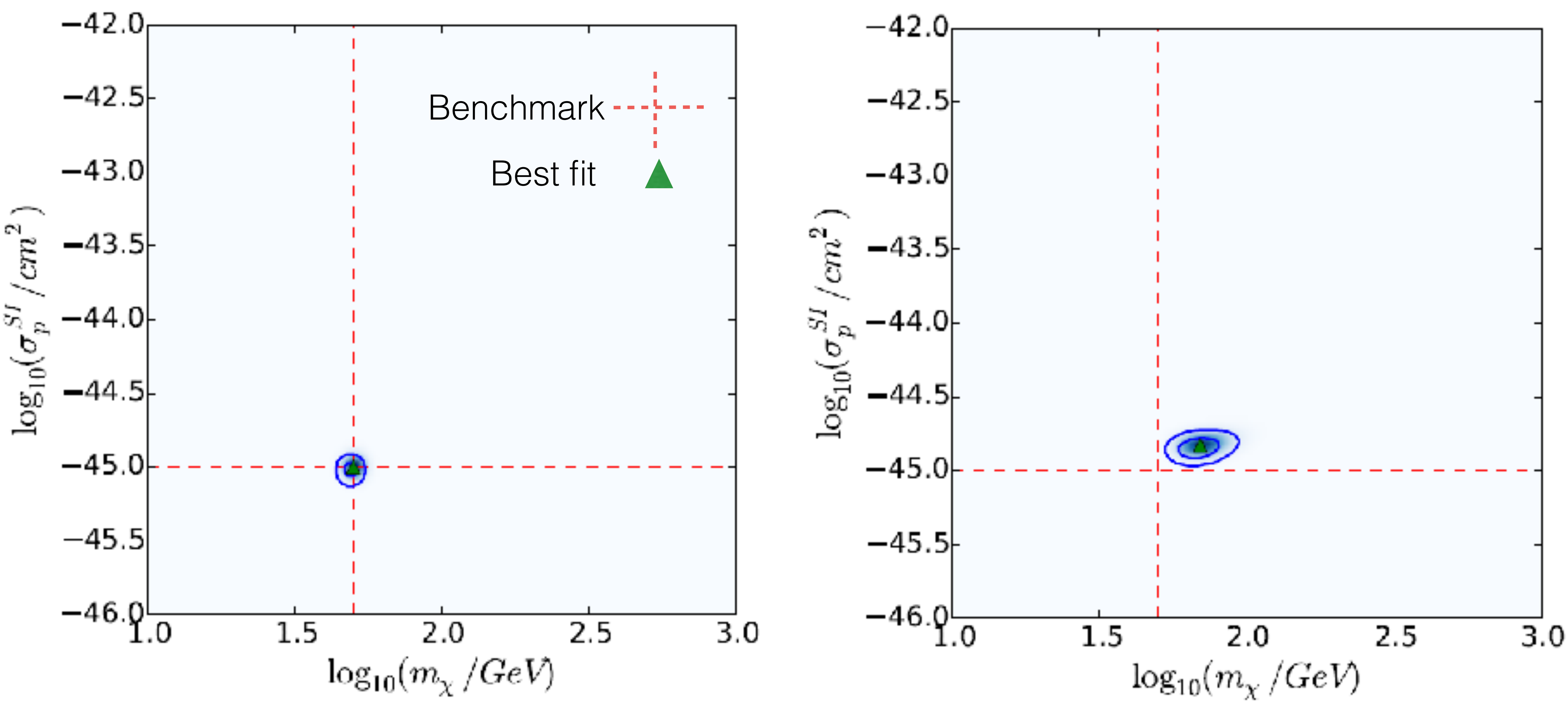
Impact on DM Signals

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

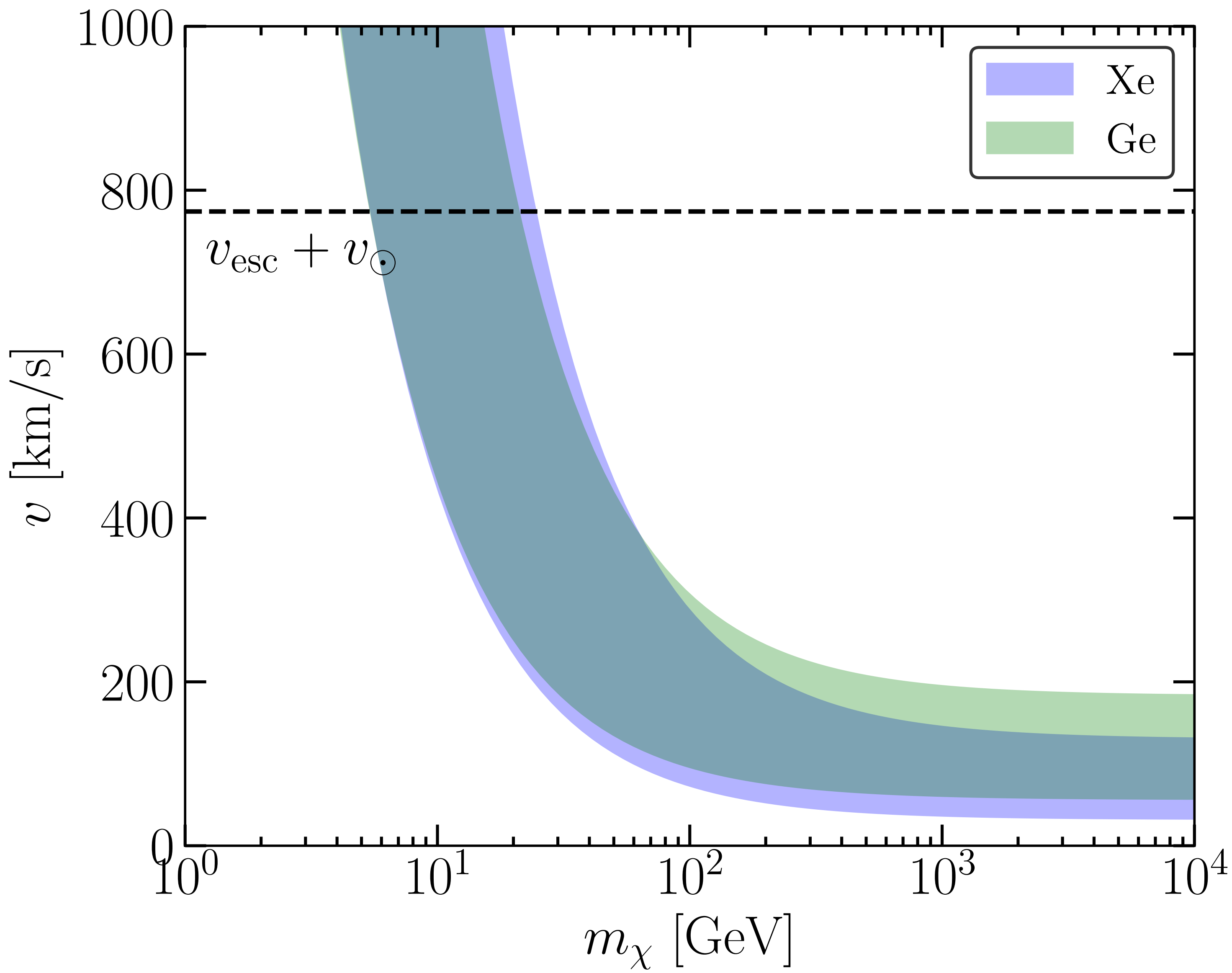


Halo-independent methods

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…]

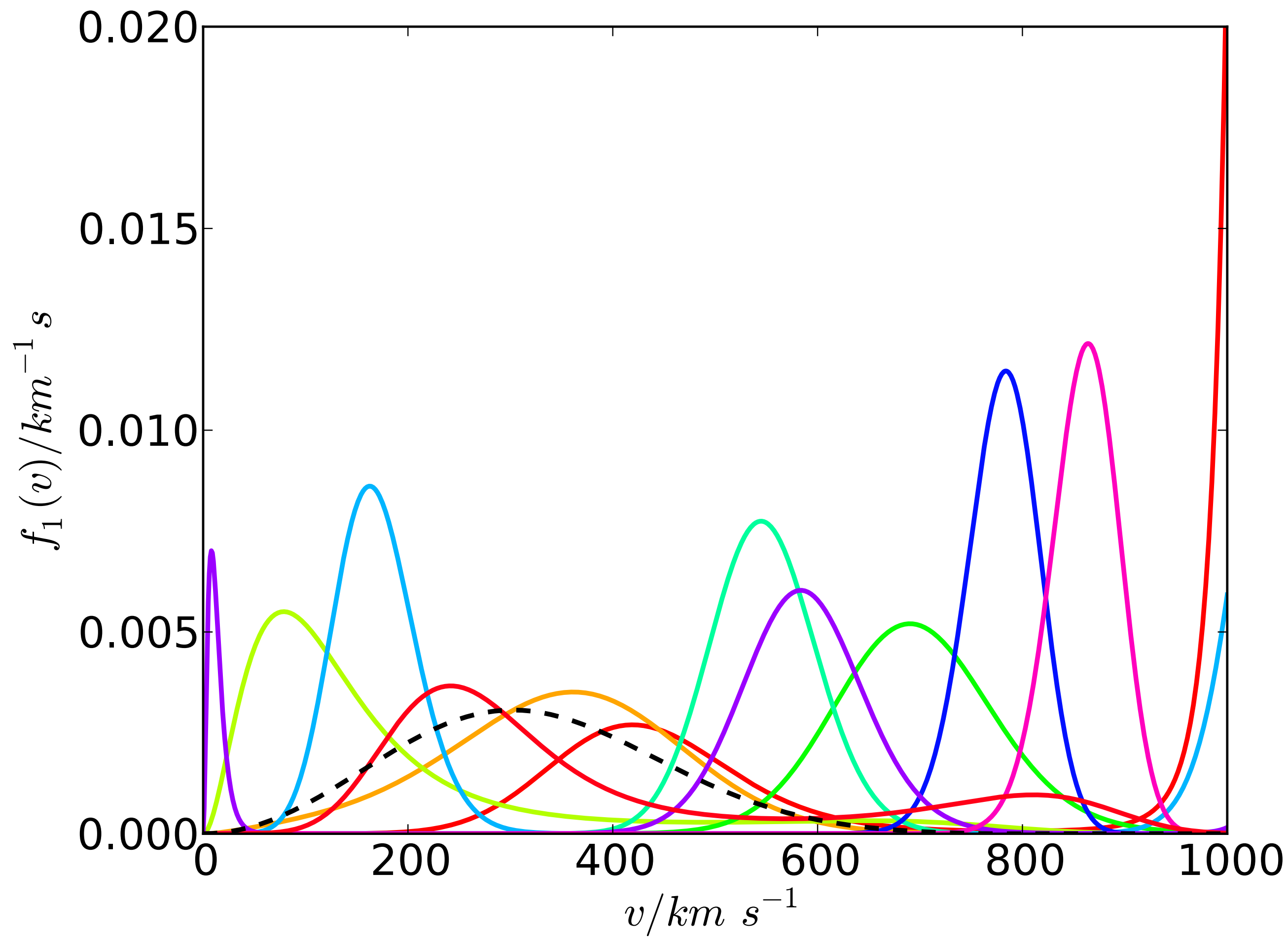
Fitting the DM distribution

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

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

BJK & Green [1303.6868]

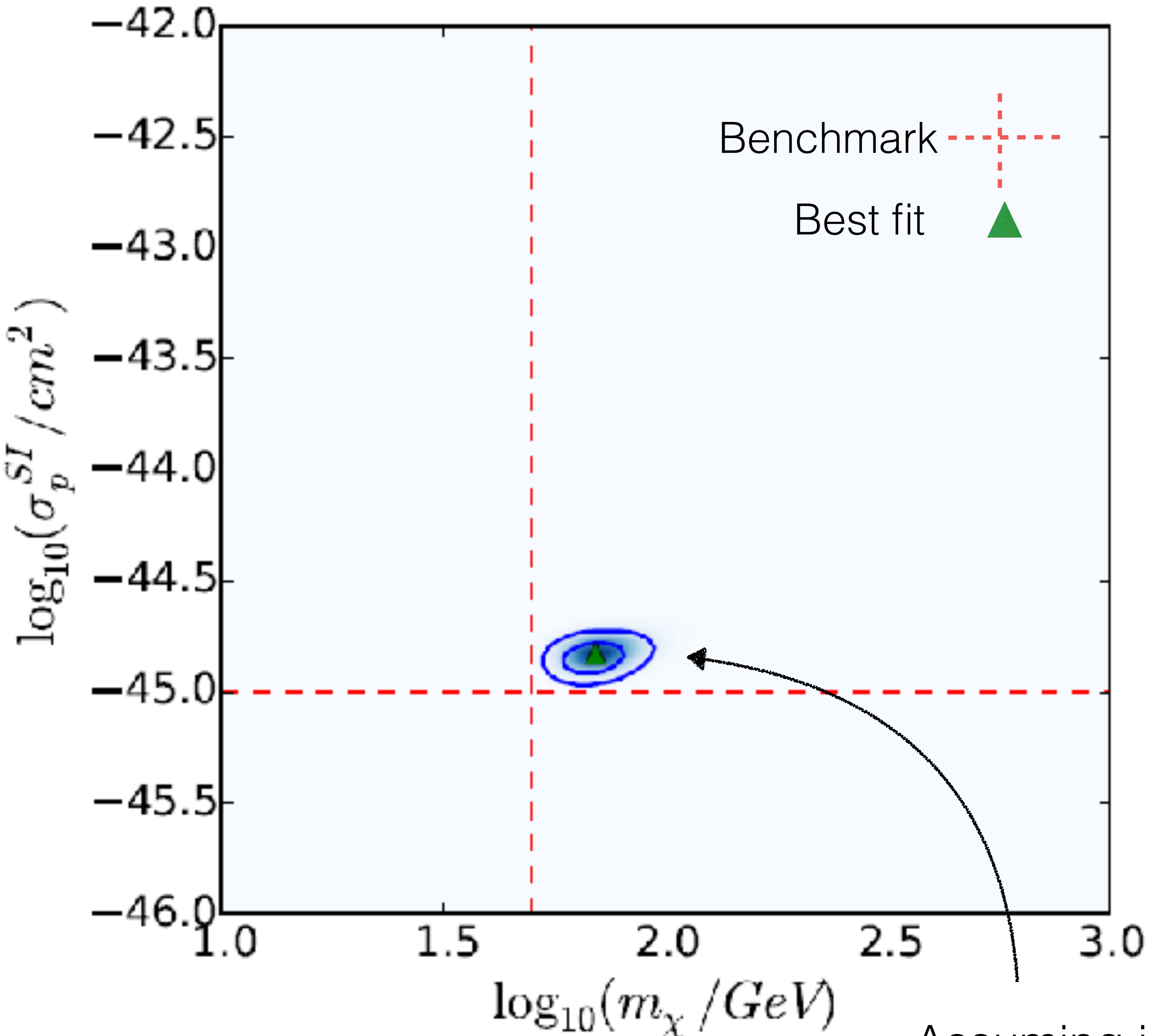
Guarantees a positive distribution function and spans a wide range of functional forms with only a small number *N* of parameters:



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

Testing the parametrisation

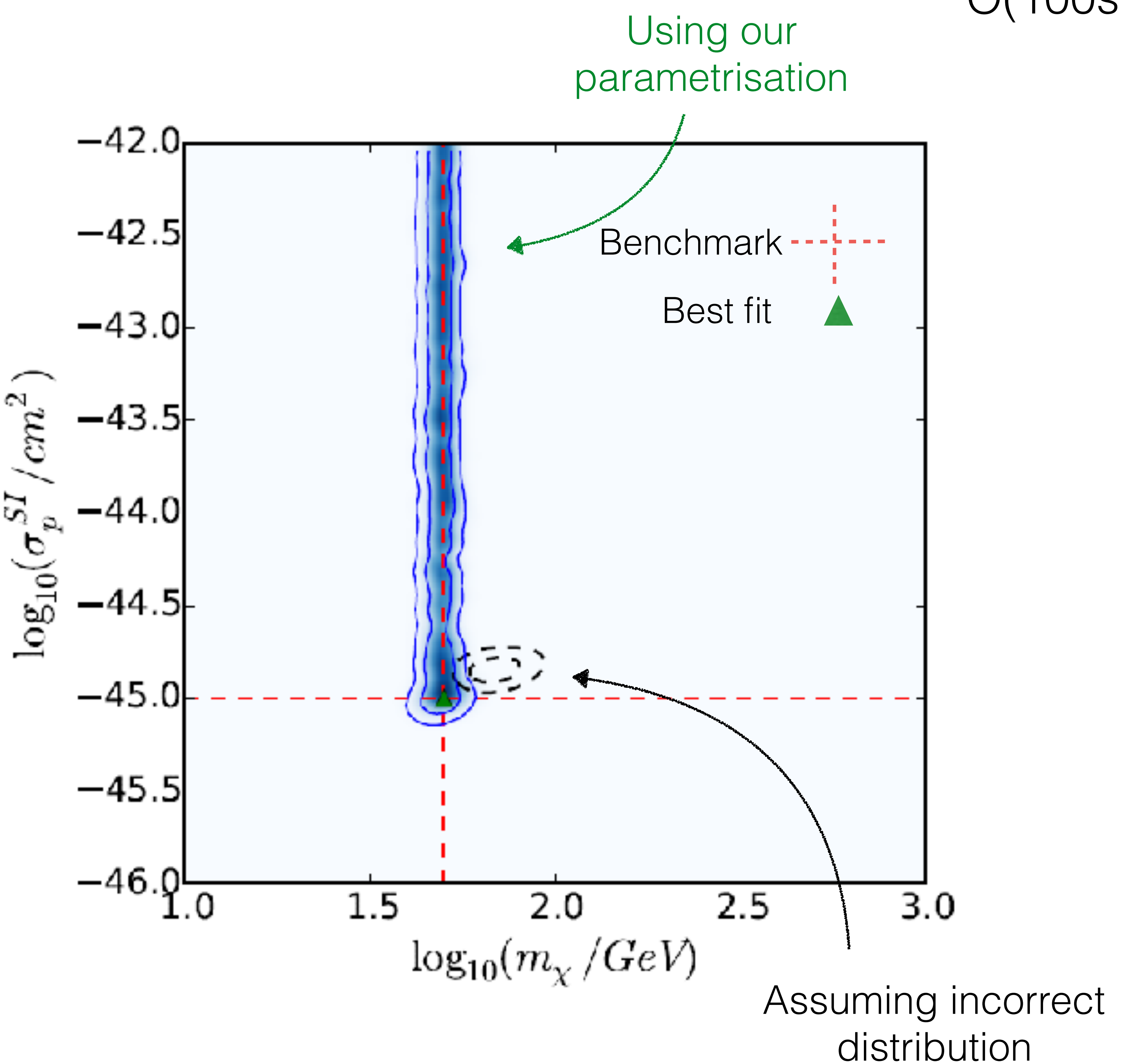
Direct detection
Xe + Ge + Ar



Assuming incorrect distribution

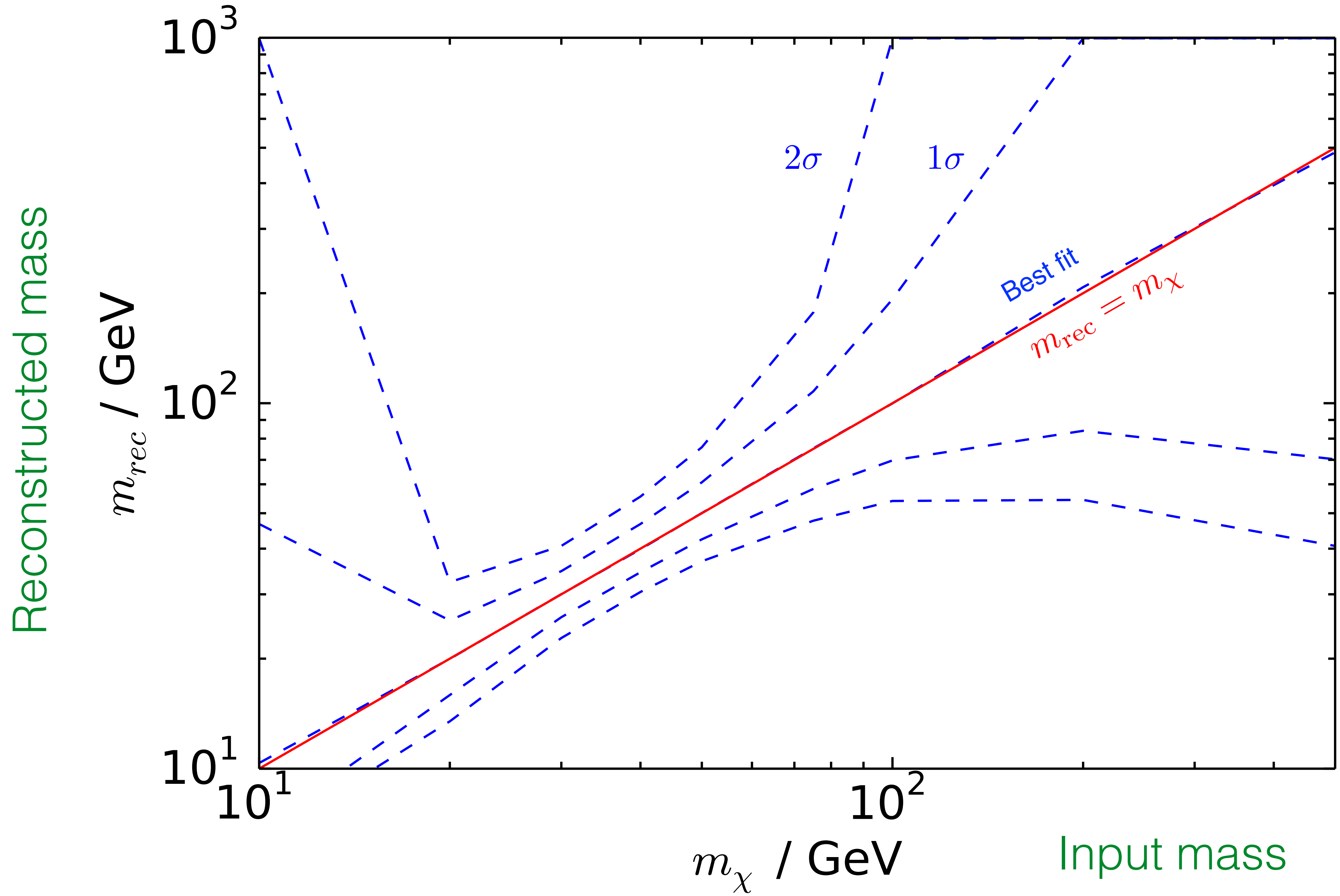
Testing the parametrisation

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



Reconstructing DM mass

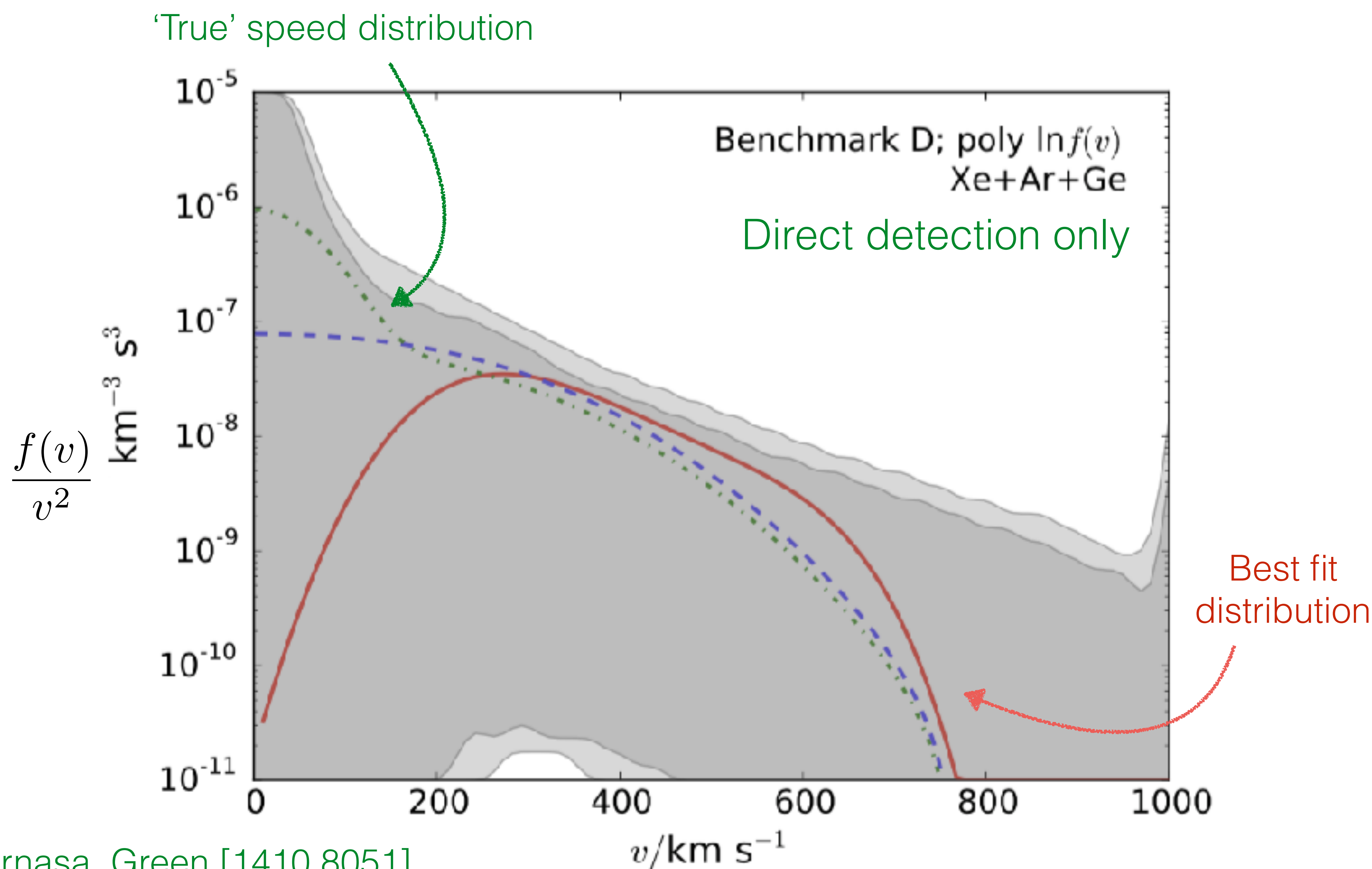
BJK [1312.1852]



Also works for a range of input velocity distributions.
Recently demonstrated for arbitrary interactions too…
Krauss & Newstead [1801.08523]

Reconstructing f(v)

$m_\chi = 30$ GeV
SHM+DD distribution



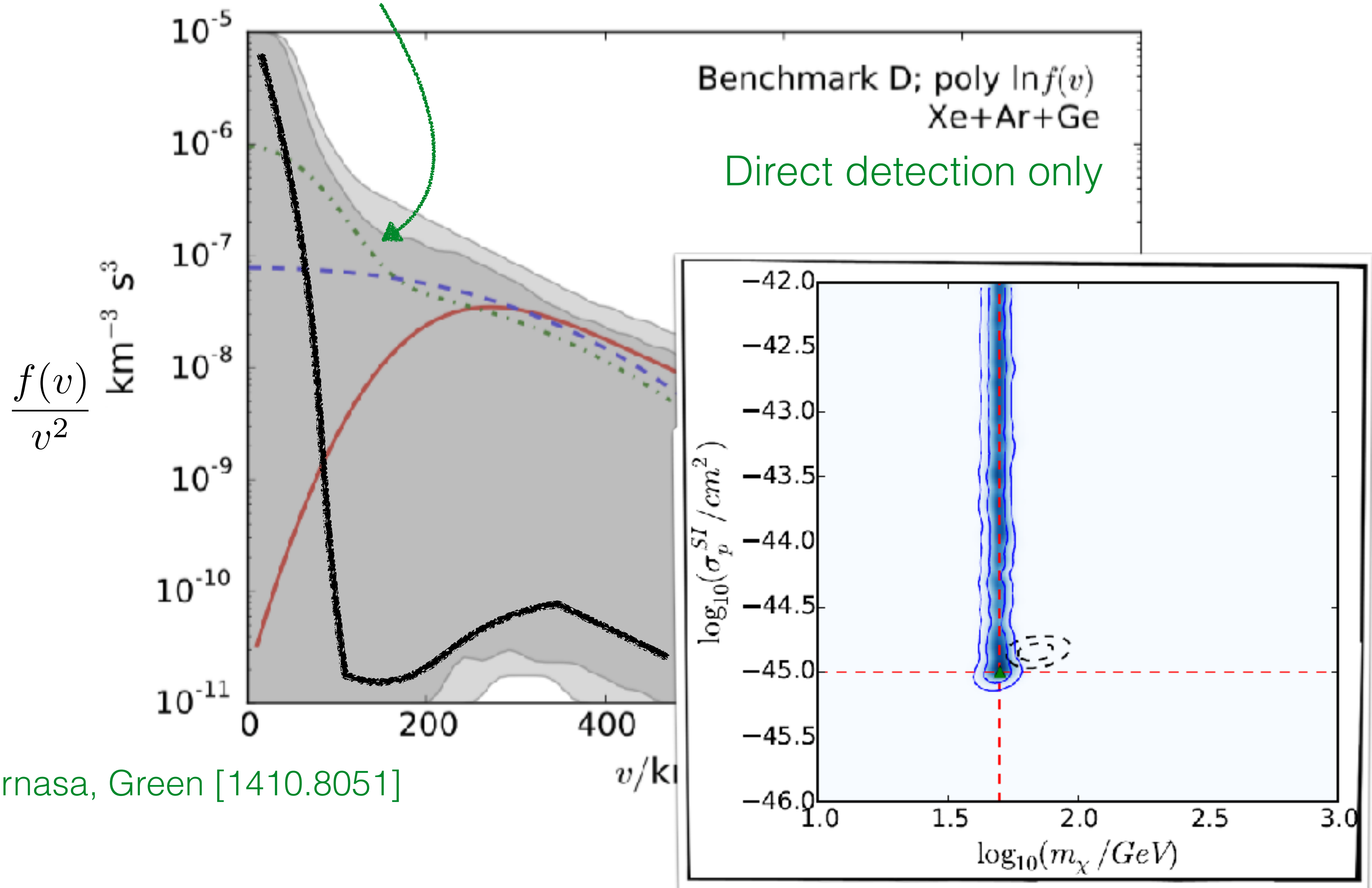
BJK, Fornasa, Green [1410.8051]

Reconstructing f(v)

$m_\chi = 30$ GeV

SHM+DD distribution

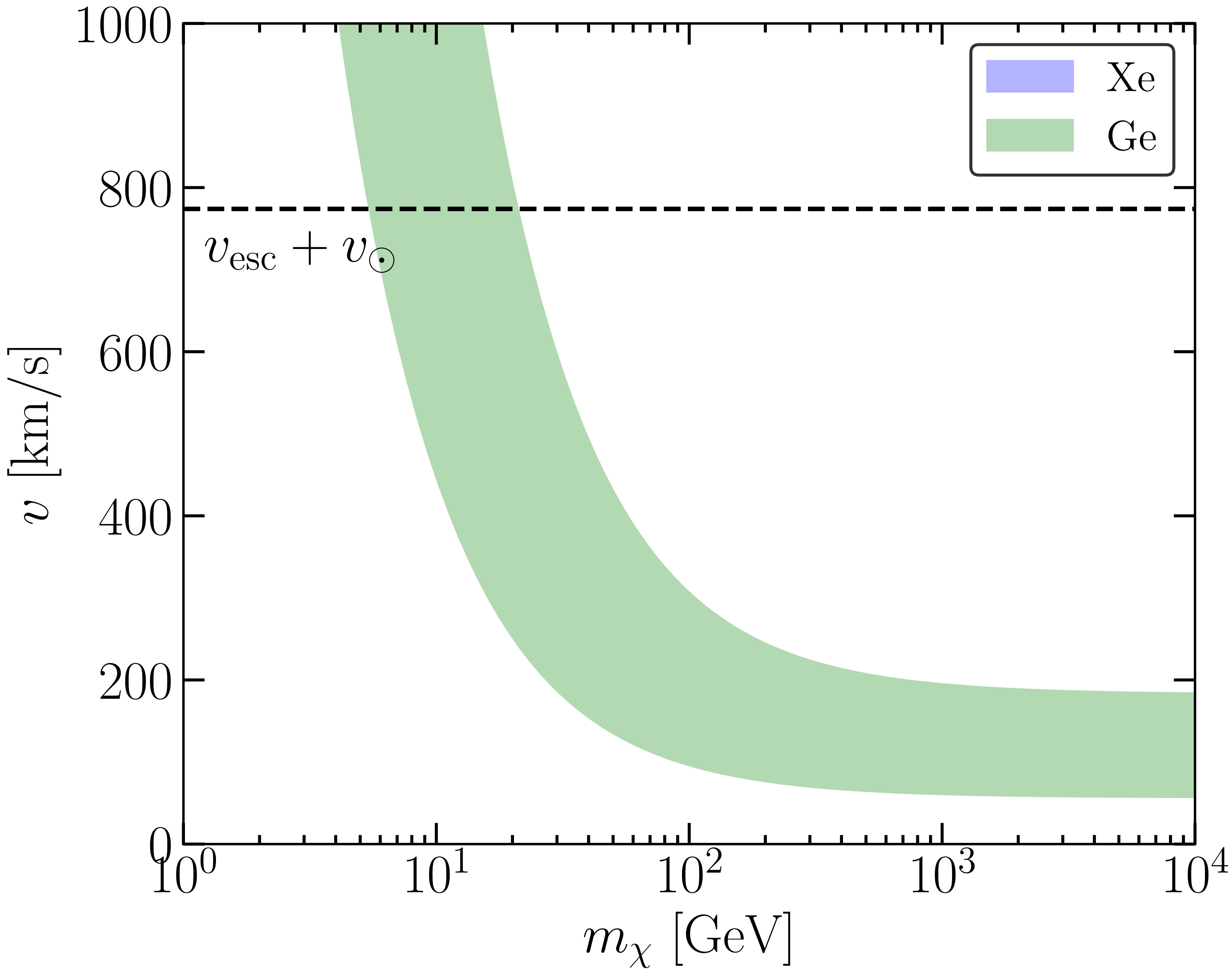
‘True’ speed distribution



BJK, Fornasa, Green [1410.8051]

Velocity Ranges

Cannot constrain distribution below threshold…



Direct detection:

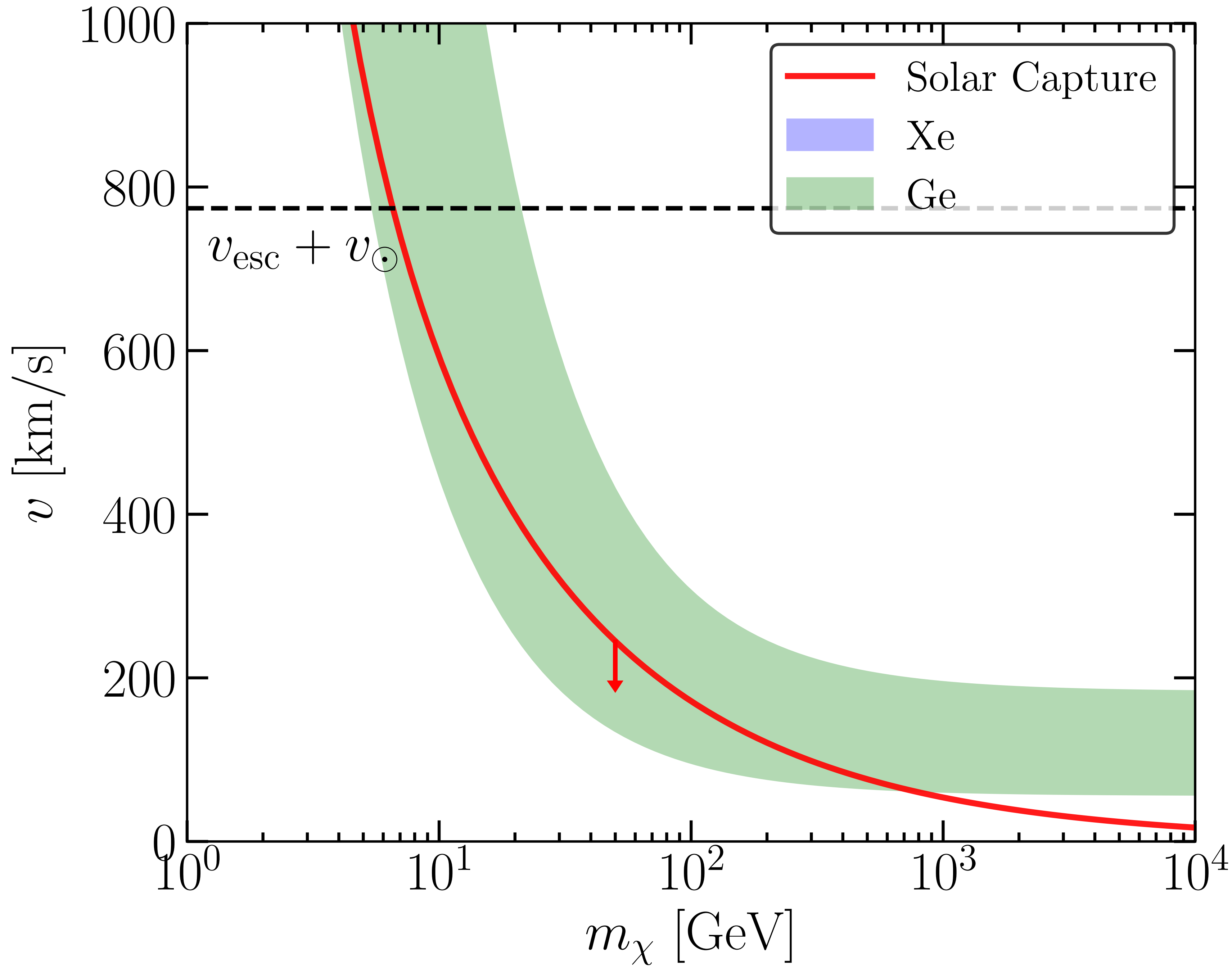
$$v_{\rm min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Solar Capture:

$$v_{\rm max} = \frac{\sqrt{4 m_\chi m_{\mathrm{N}_i}}}{m_\chi - m_{\mathrm{N}_i}} v_{\rm esc}$$

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

Velocity Ranges



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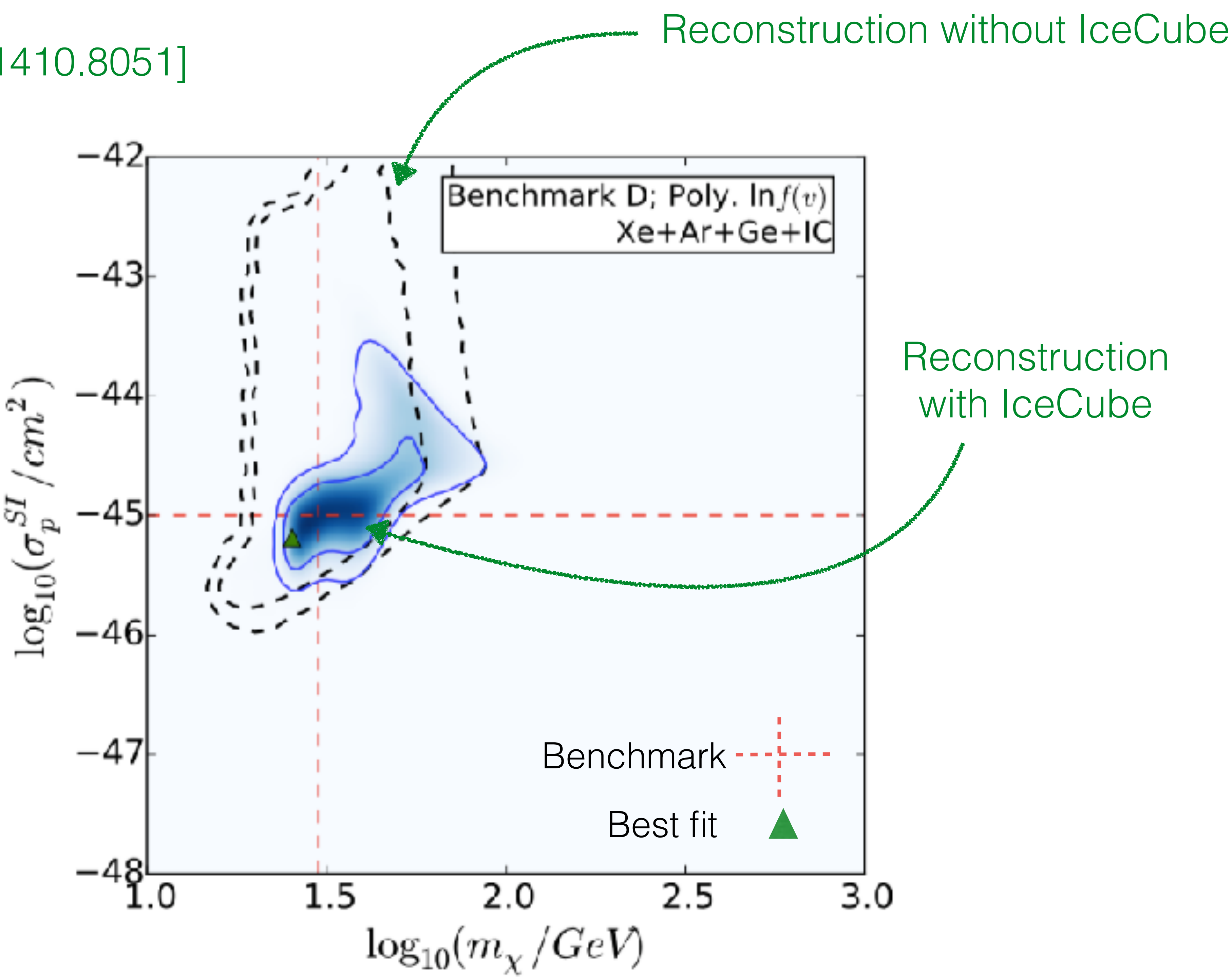
Combining with IceCube

BJK, Fornasa, Green [1410.8051]

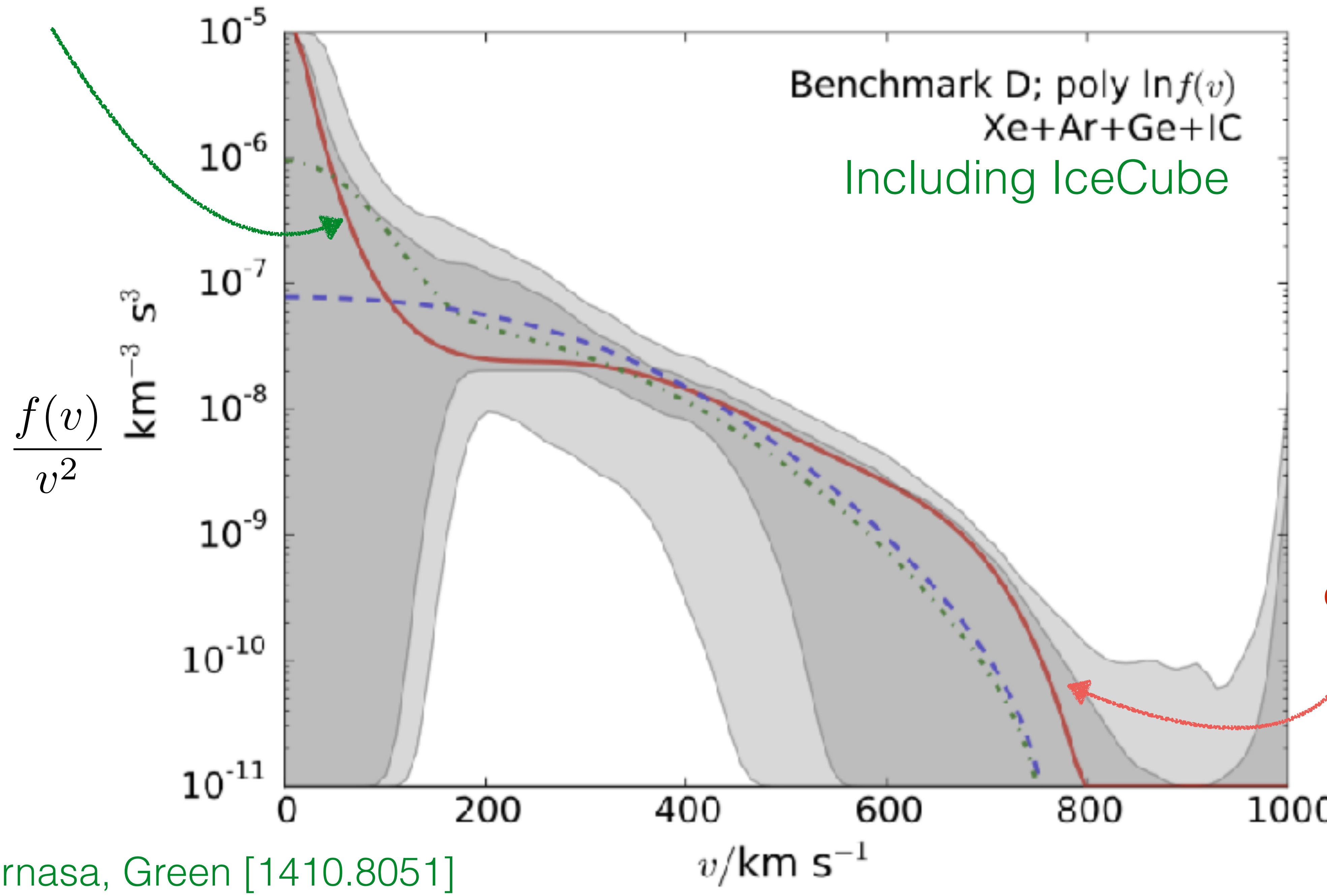


Combining direct detection and solar capture,
we could pin down DM mass *and* cross section

Reconstructing f(v) with IceCube

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

'True' speed distribution



Best fit distribution

BJK, Fornasa, Green [1410.8051]

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

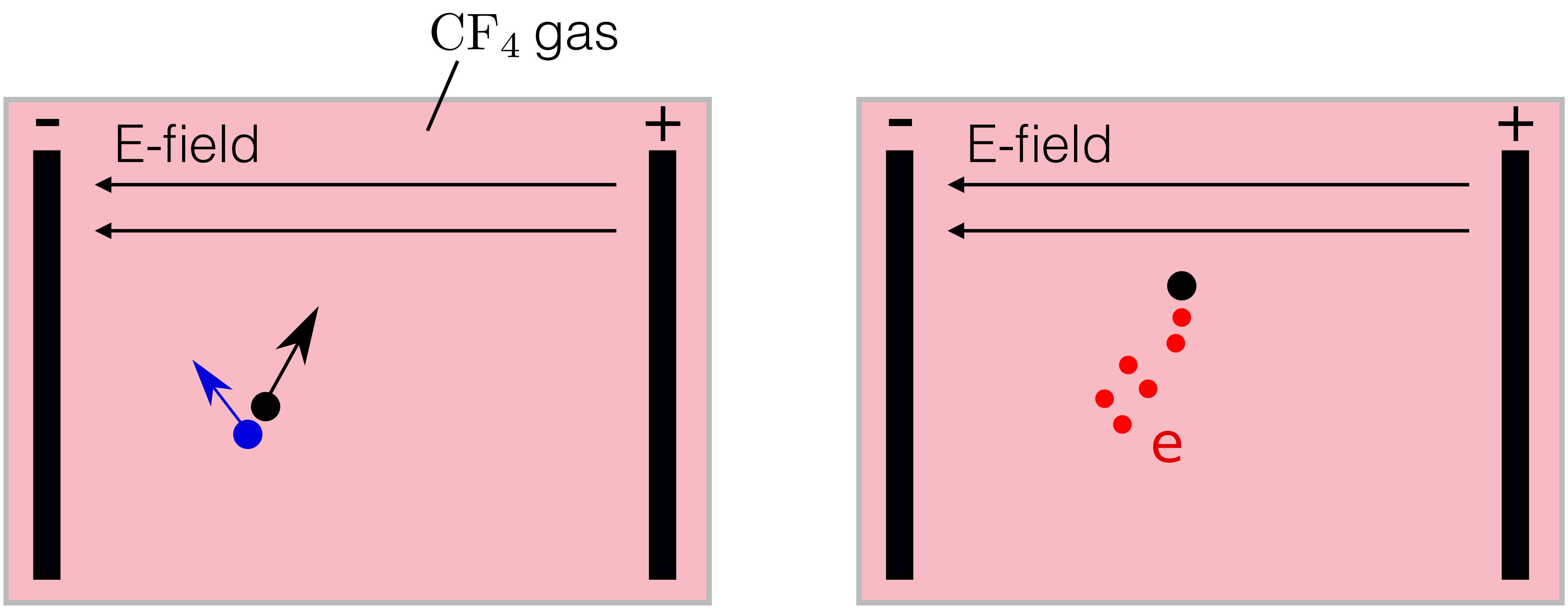
Directional Detection

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

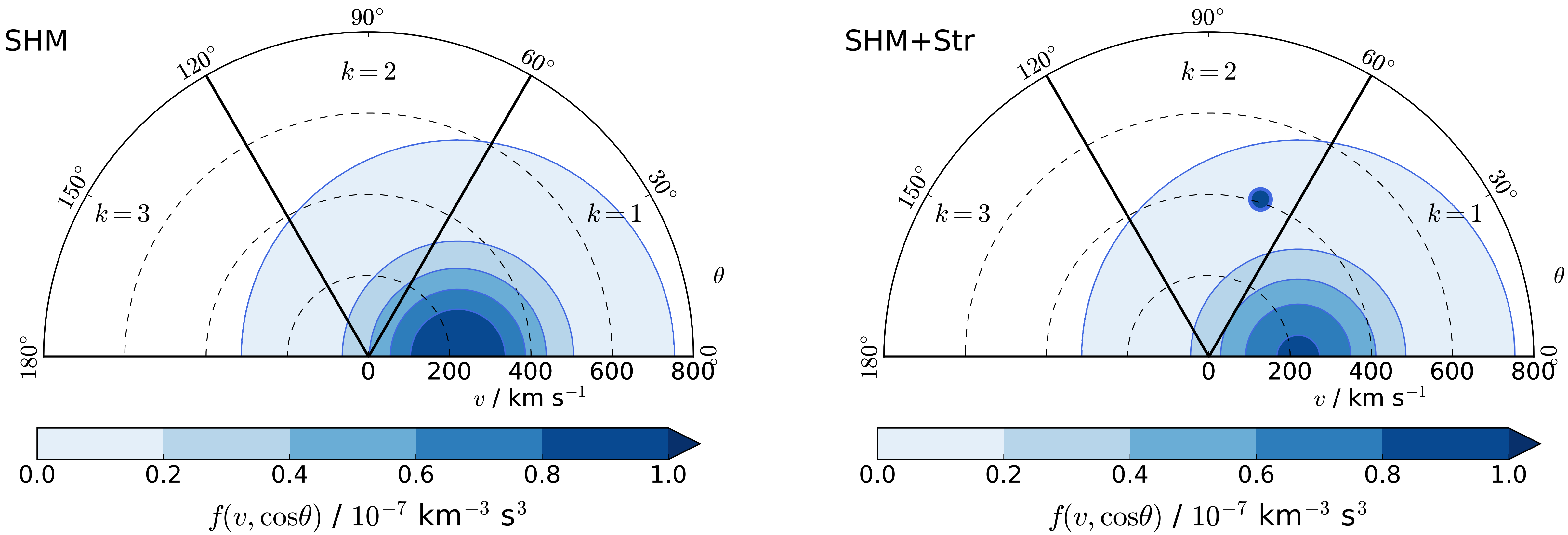
Mohlabeng et al. [1503.03937]; Namakura et al. [1803.00752]

3-D Velocity Distribution

DM wind

Directional detectors are in principle sensitive to full 3-D velocity distribution:

Gondolo [hep-ph/0209110]

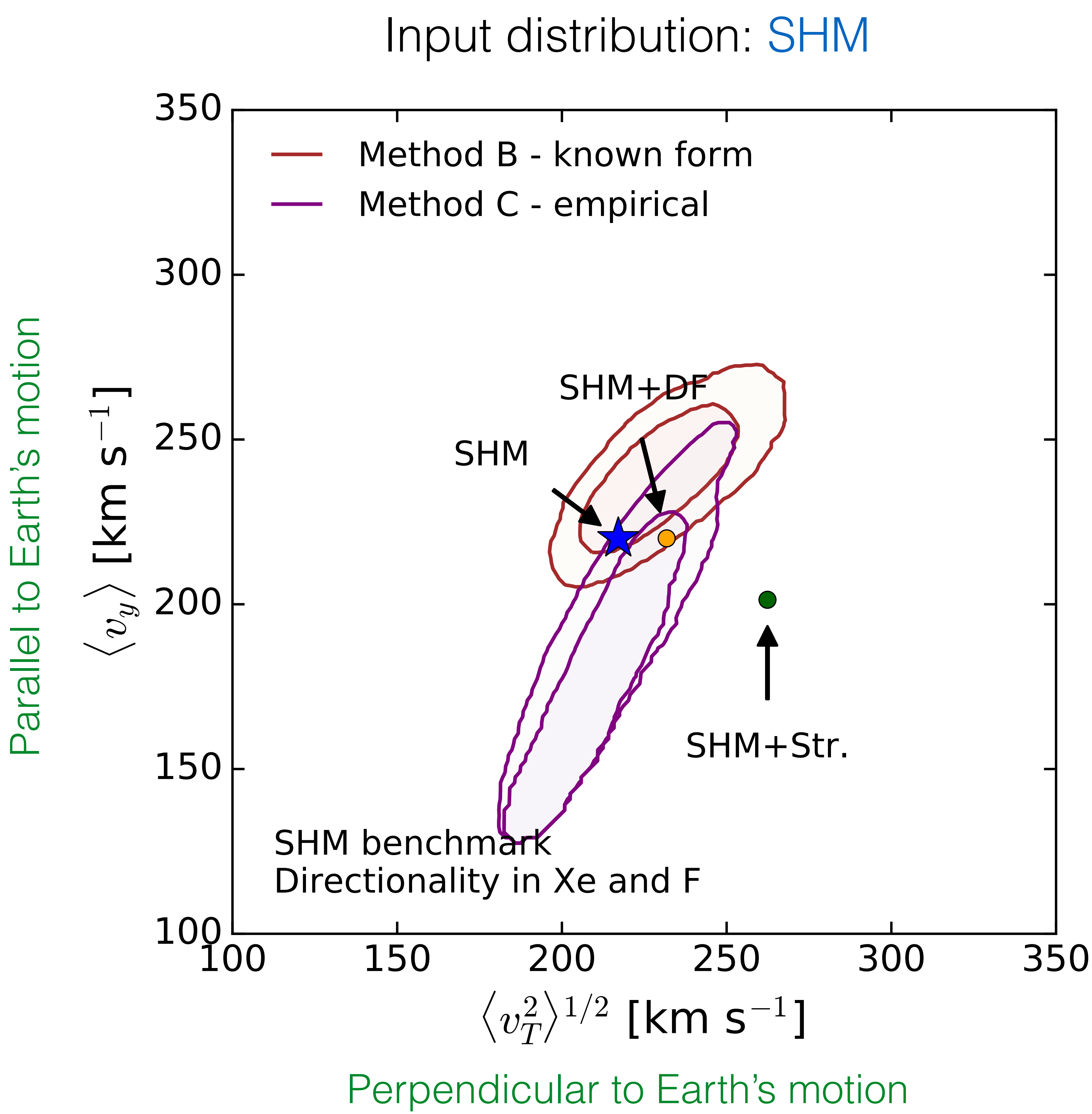


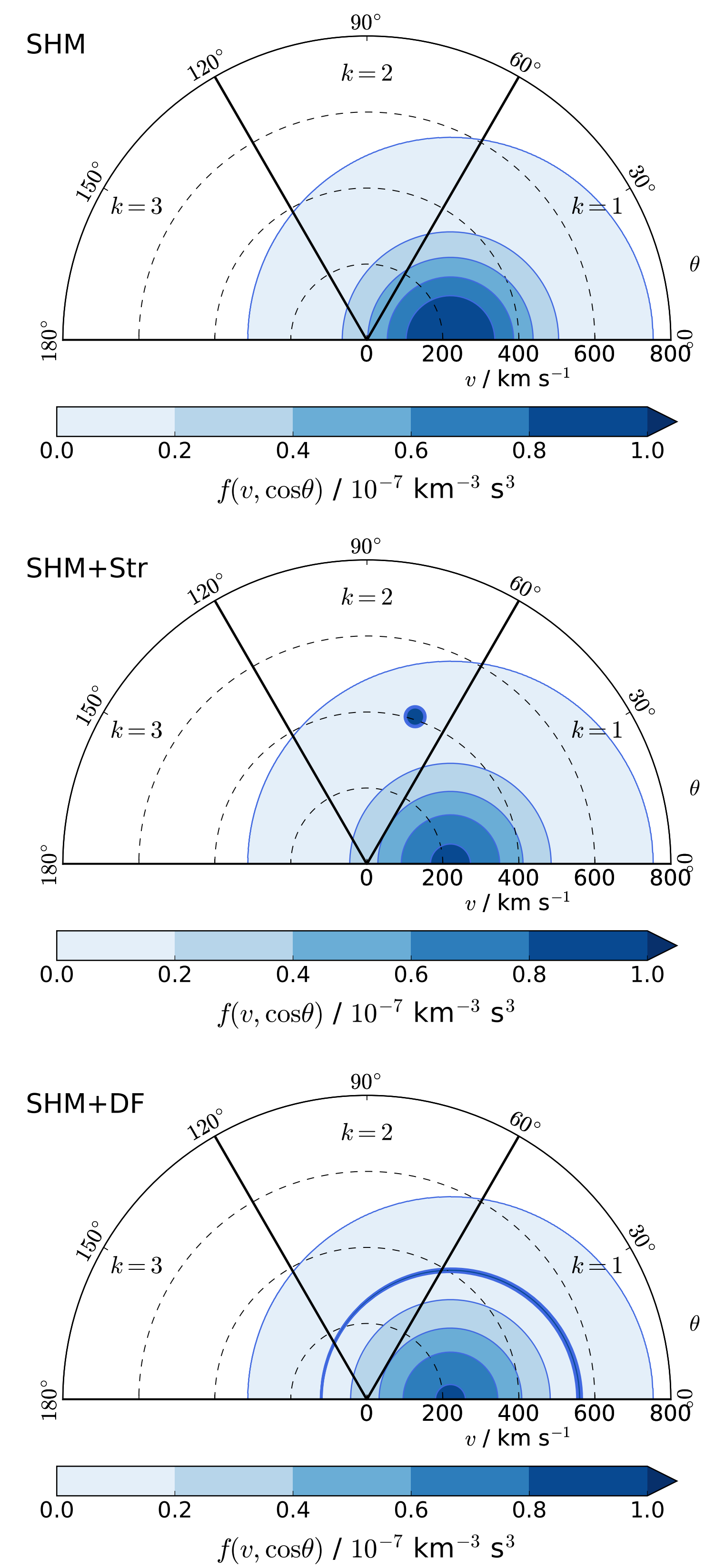
Apply the same parametrisation in 3-D
(note: some technical details, which make things annoying)

BJK [1502.04224]

Directional reconstructions

BJK, CAJ O'Hare [1609.08630]

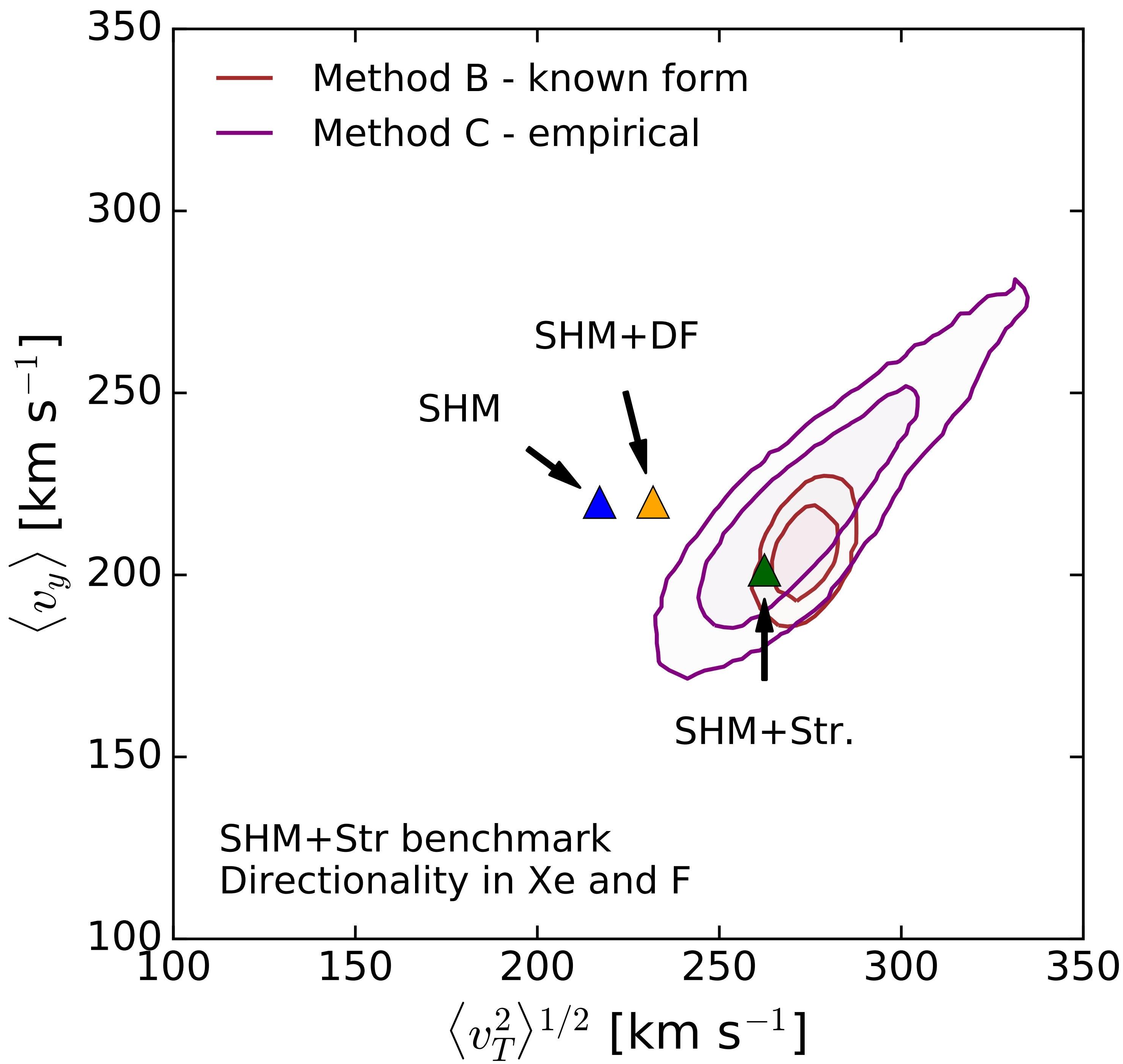




Directional reconstructions

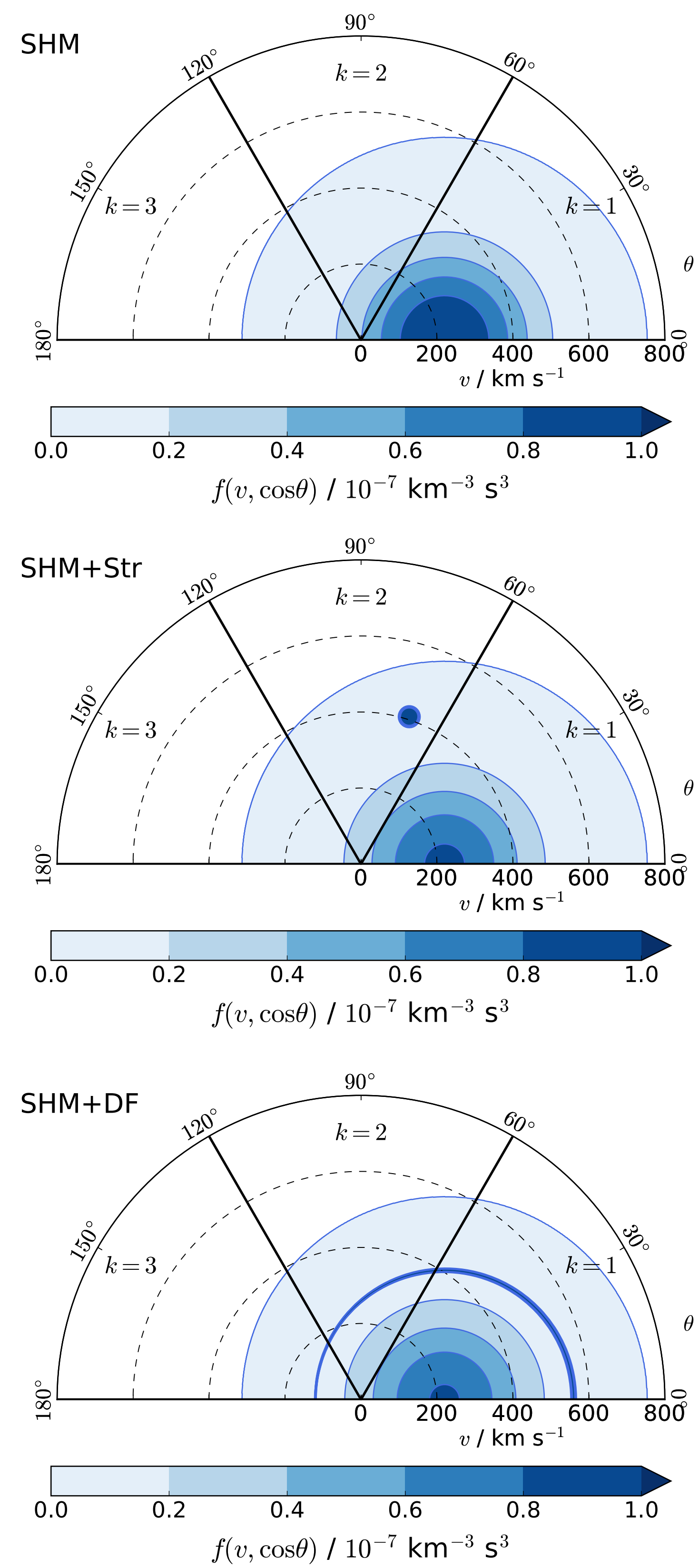
BJK, CAJ O'Hare [1609.08630]

Input distribution: SHM + Stream



Parallel to Earth's motion

Perpendicular to Earth's motion



Overview

Solar system searches for DM:
Direct detection and Solar Capture

Astrophysical uncertainties

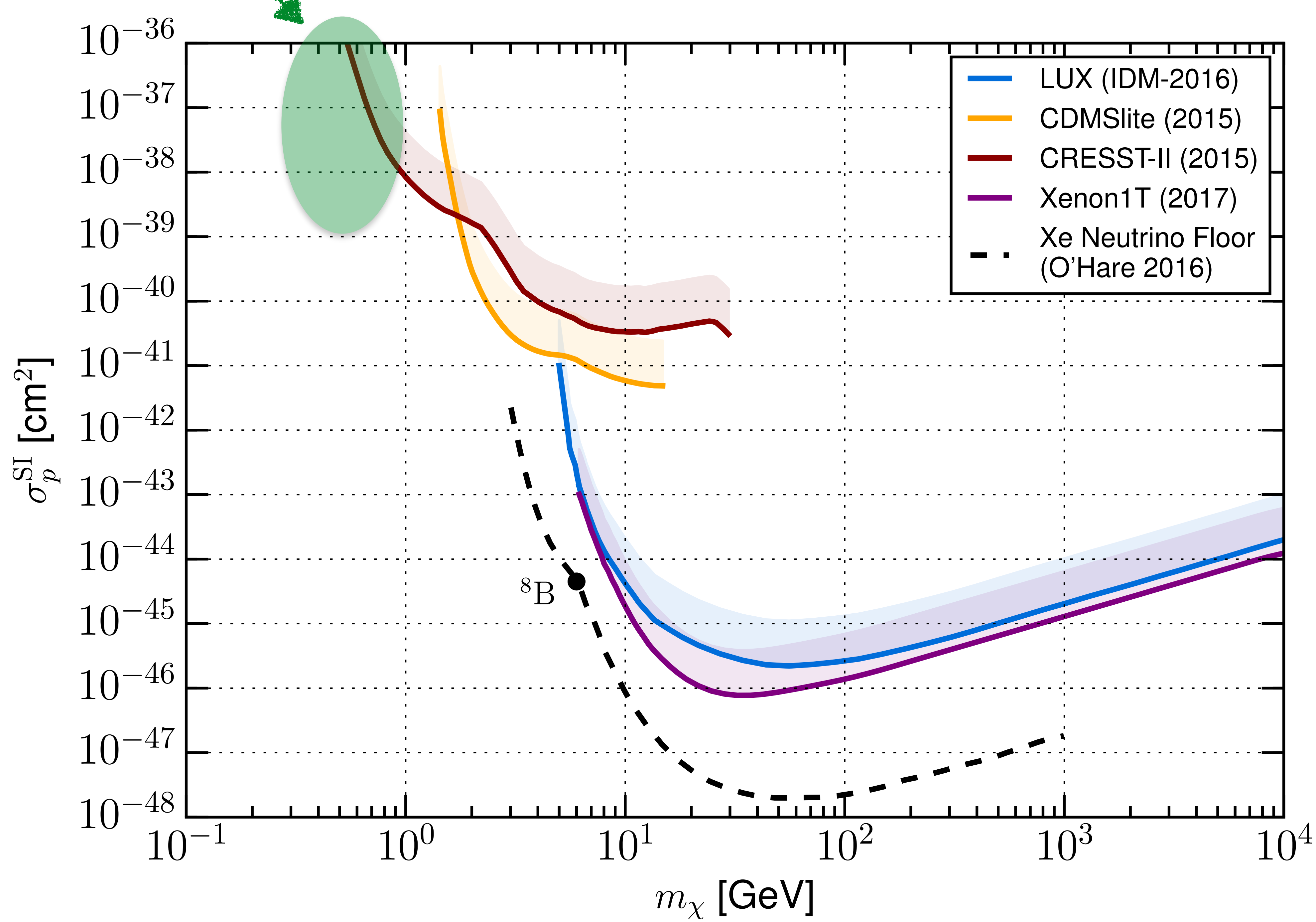
Halo-independent approaches to setting limits

Measuring the DM properties and distribution
with a future detection

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

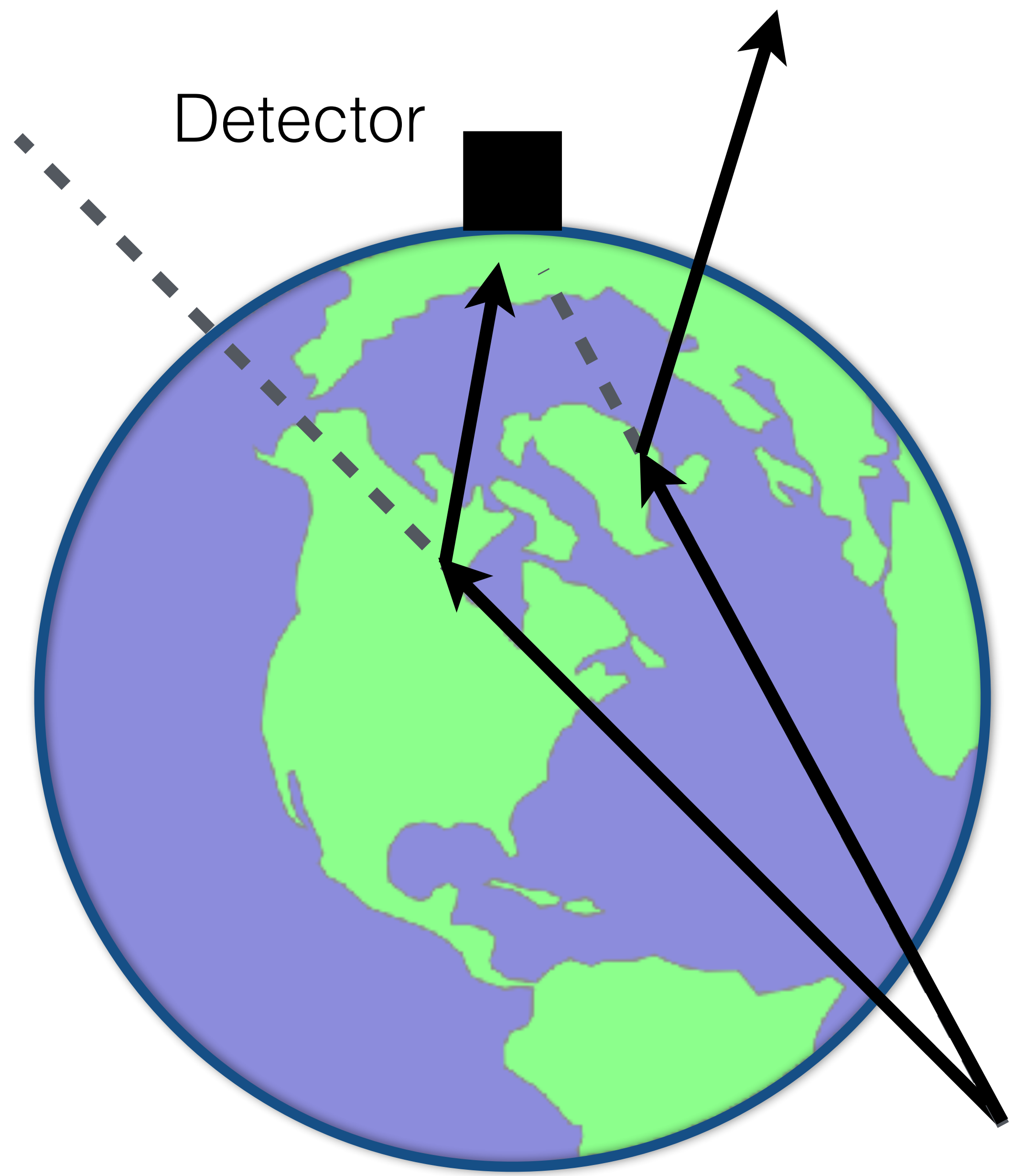
Map of the parameter space

Sub-GeV DM



Earth scattering

Collar & Avignone
[PLB 275, 1992]
and others



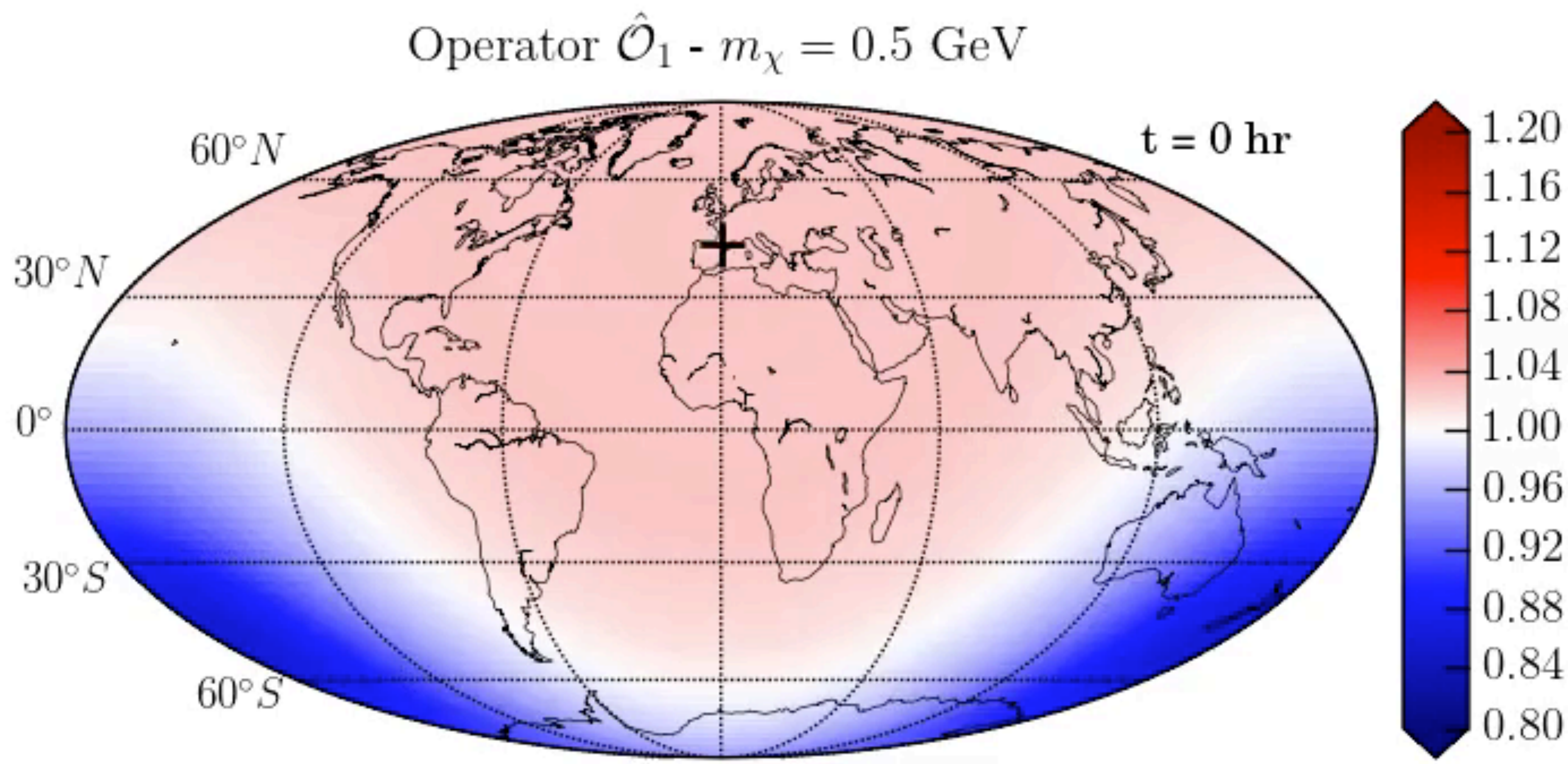
Earth-scattering can distort local density and velocity distribution:

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:



Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

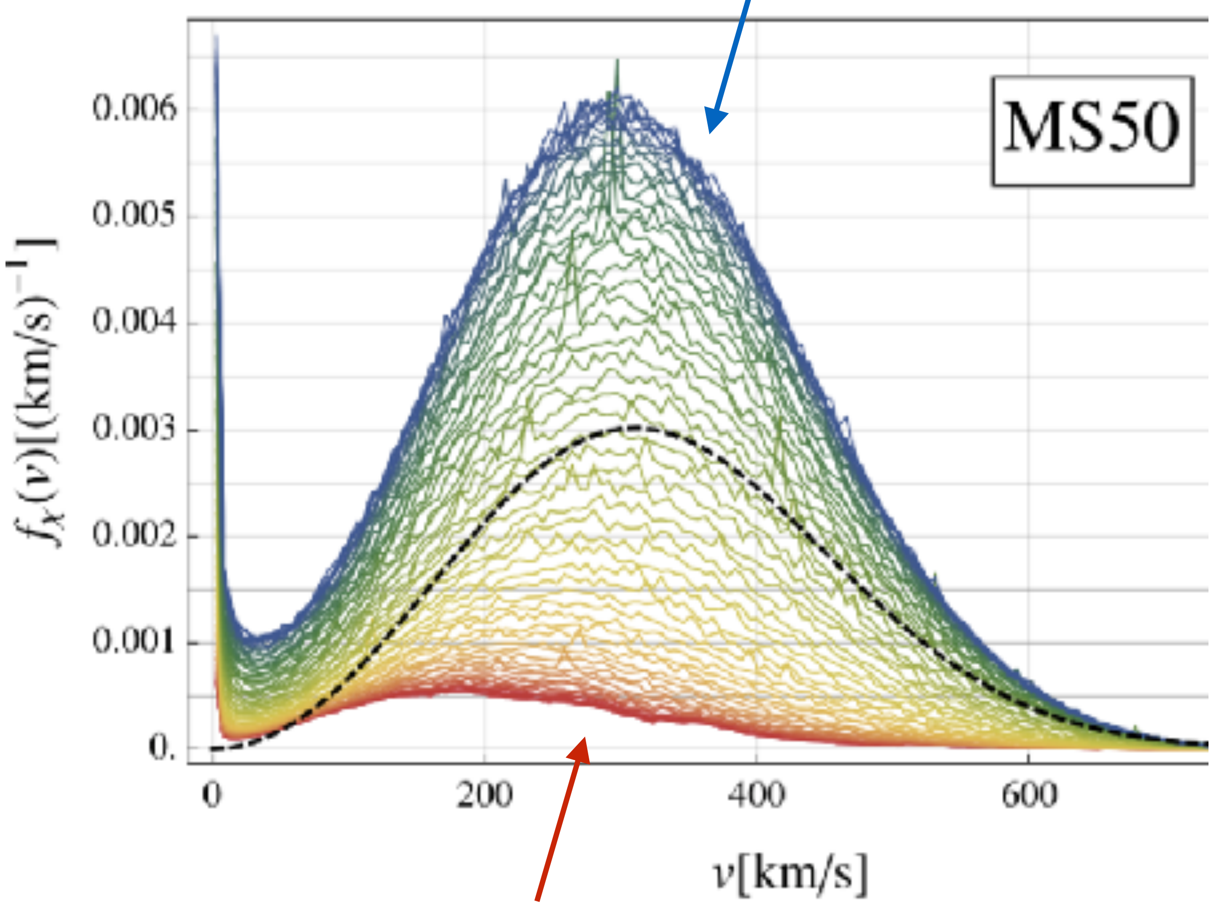
BJK, Catena, Kouvaris [1611.05453]; github.com/bradkav/EarthShadow

Modulation signals

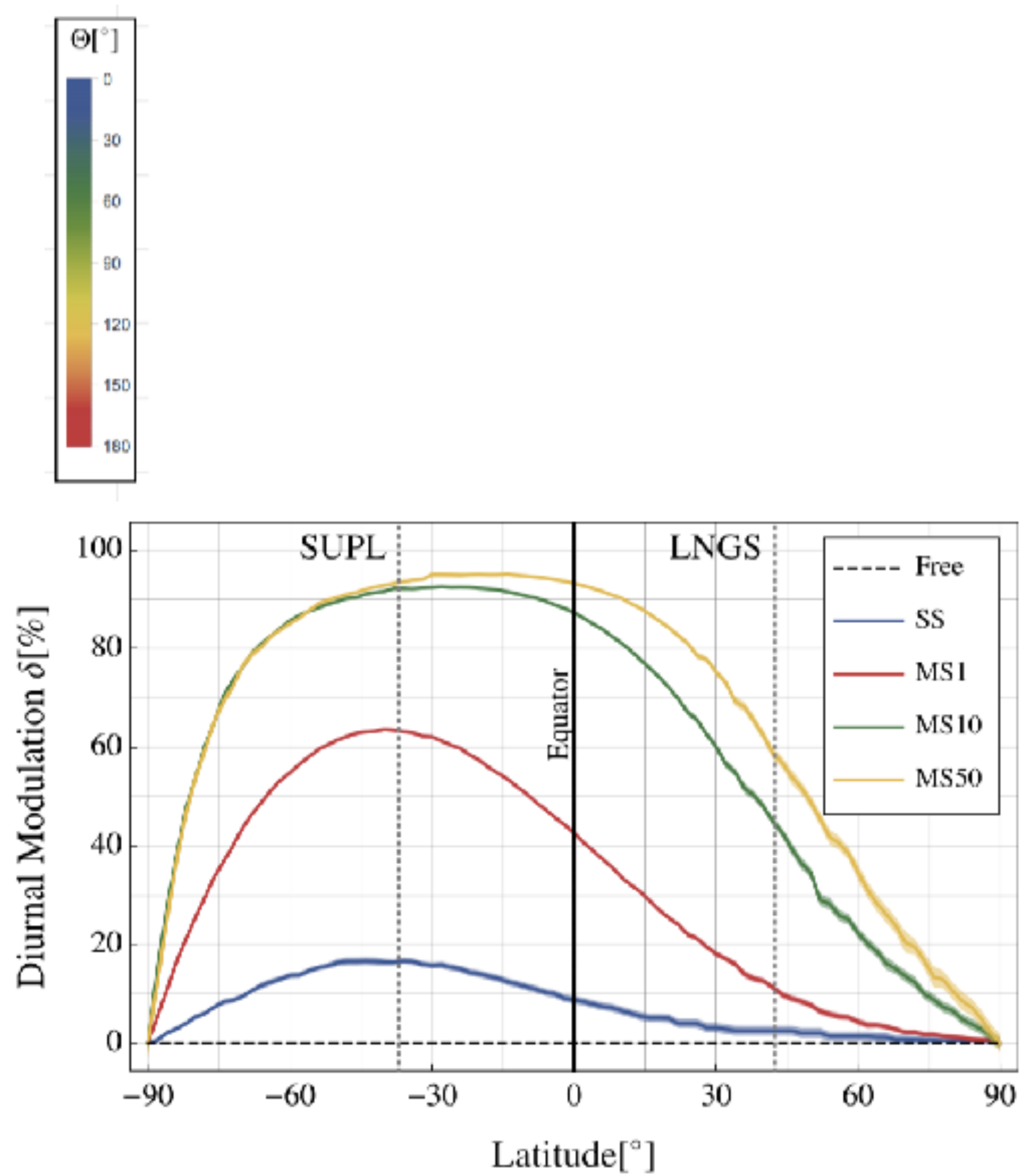
Extended with Monte Carlo Simulations

github.com/temken/DaMaSCUS

DM comes from above



DM comes from below

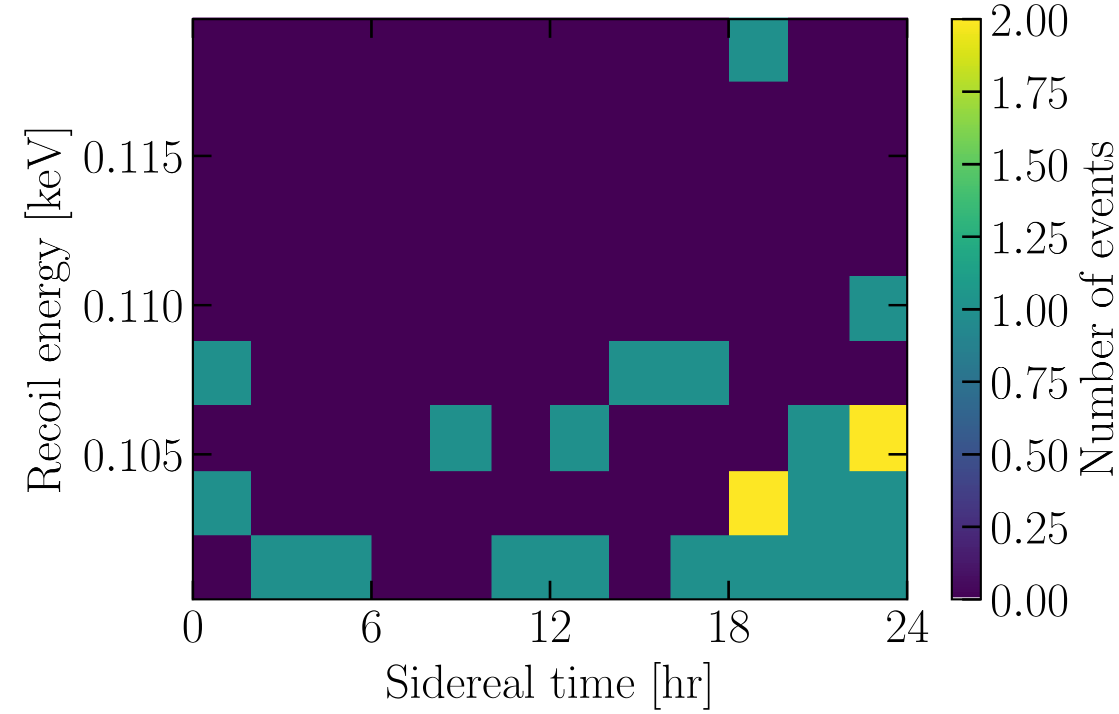


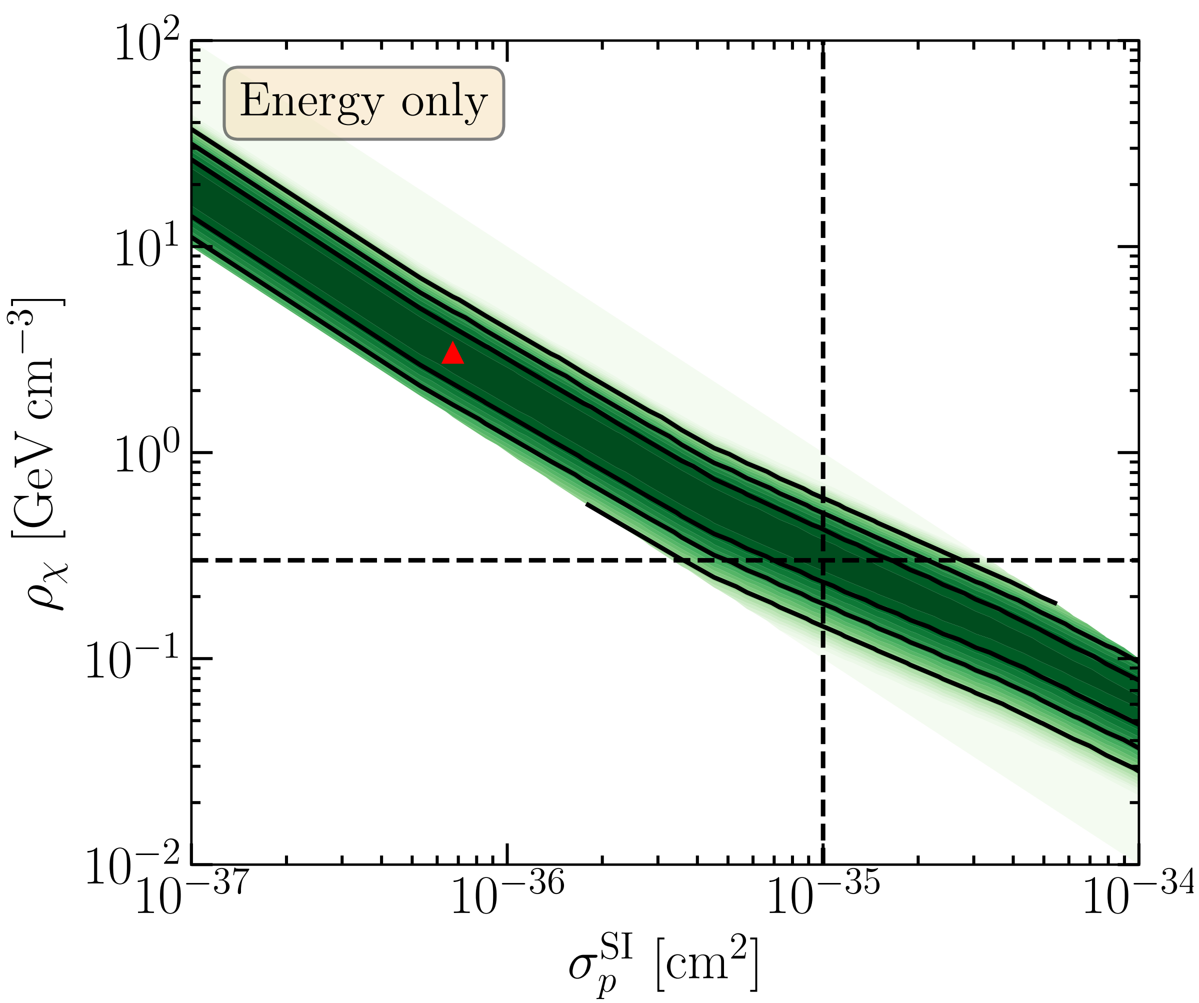
Large O(1) daily modulation if DM scatters ~50 times during Earth-crossing

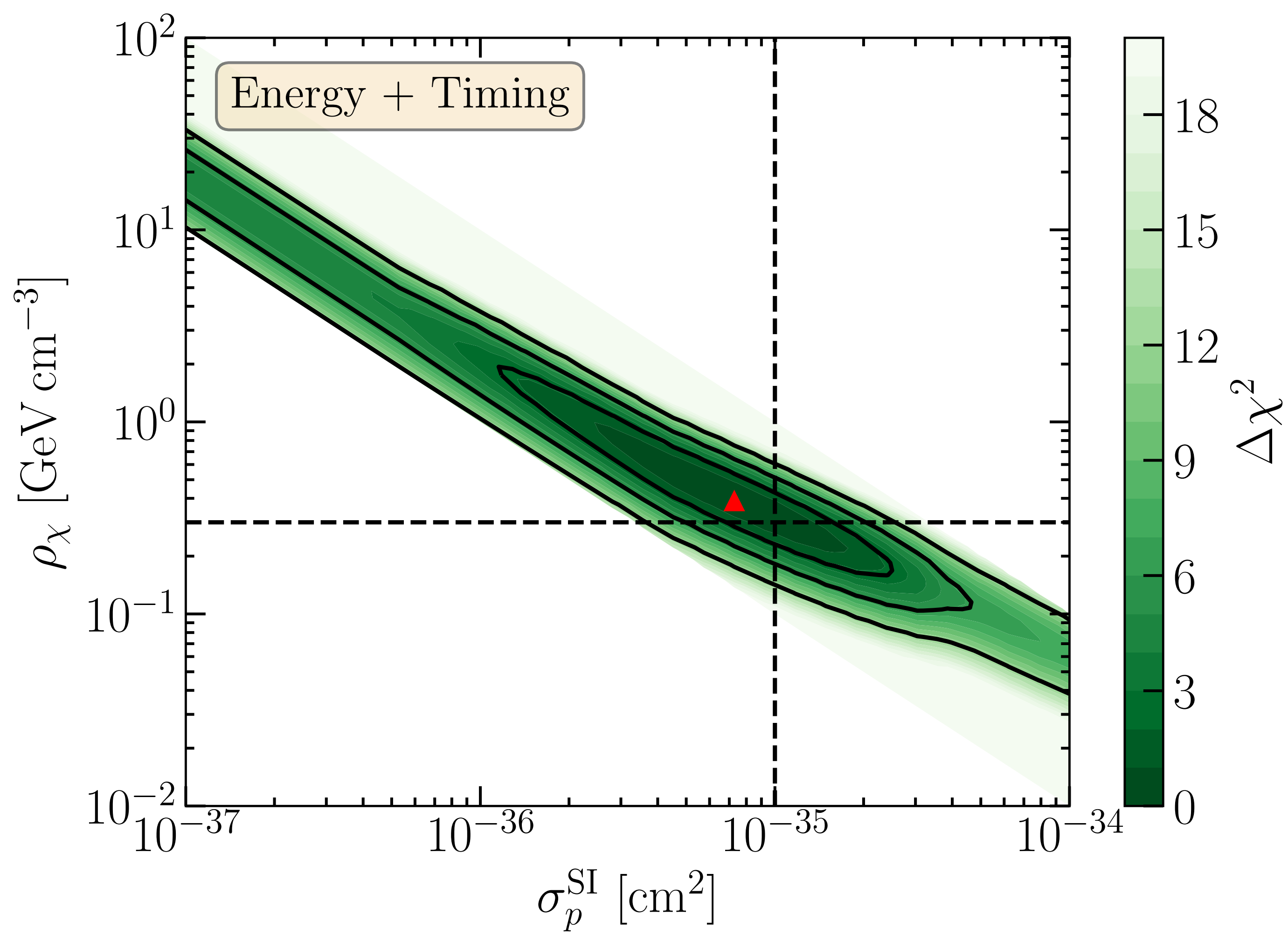
Emken & Kouvaris [1706.02249]

Preliminary results

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



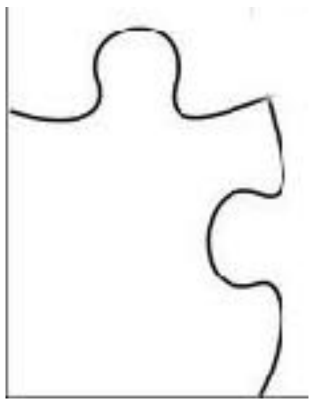




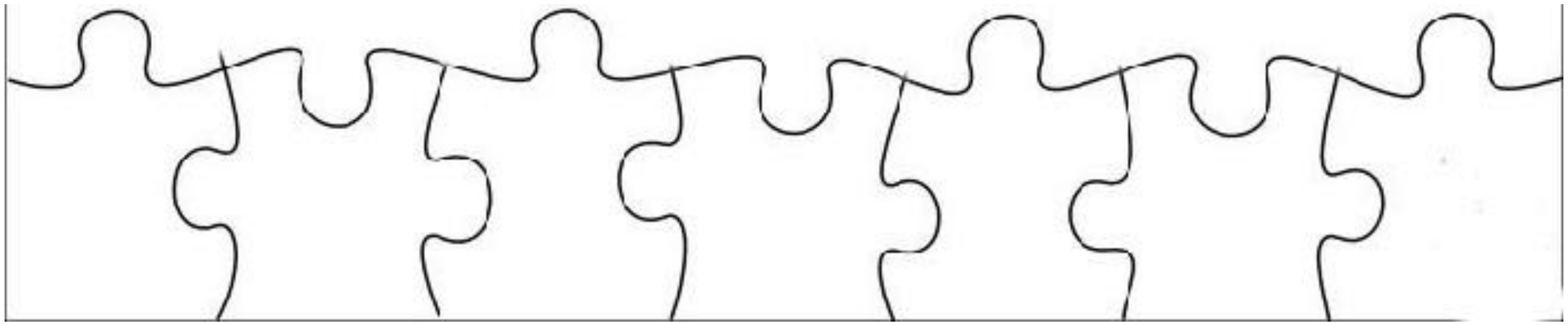
$m_\chi = 0.5\,\mathrm{GeV}$

BJK & Catena [XXXX.XXXX]

Summary (I)

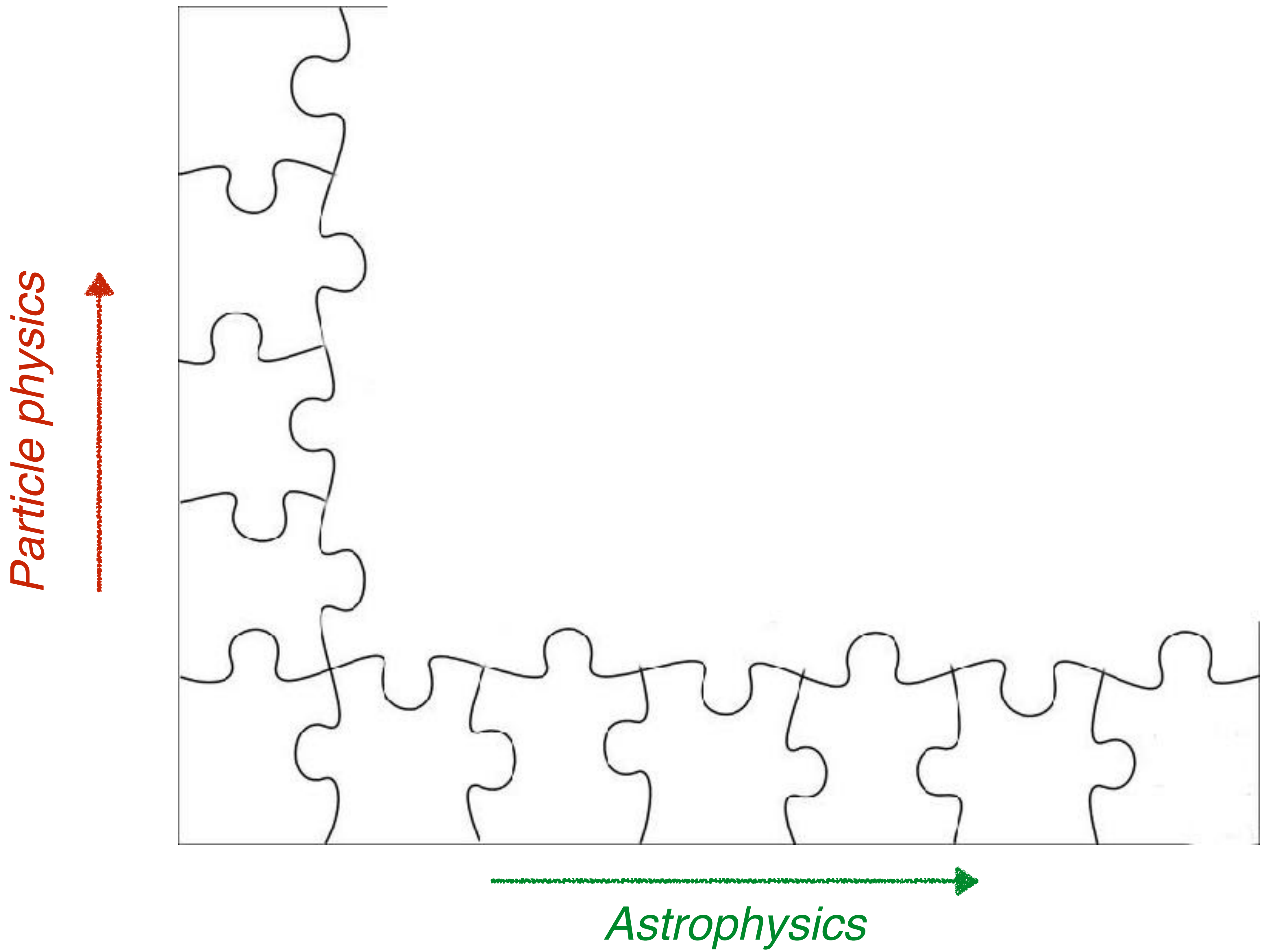


Summary (I)



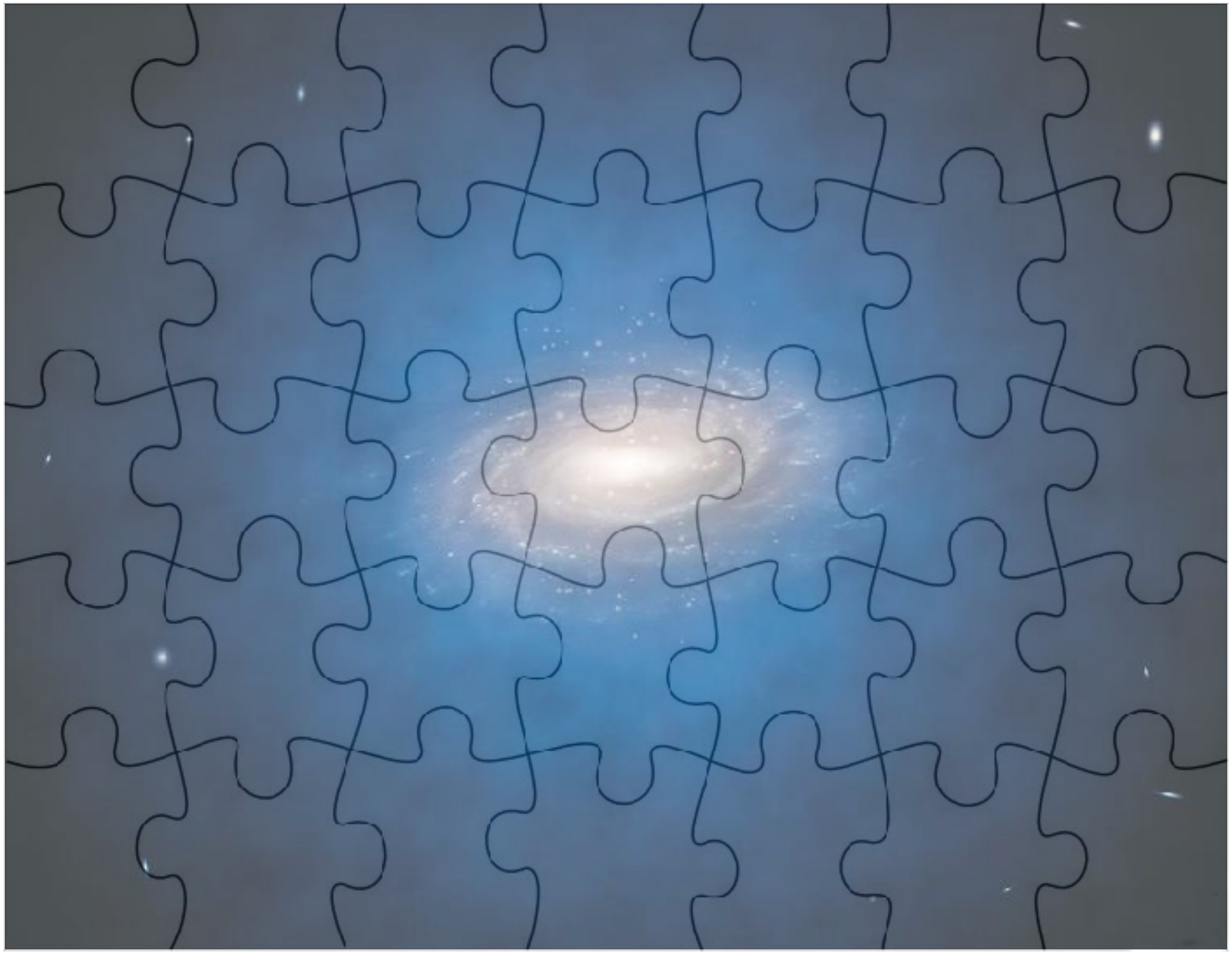
Astrophysics

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

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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:

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

Write in terms of DM-proton cross section:

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

Form factor accounts for loss of coherence at high energy

Enhancement factor different for:

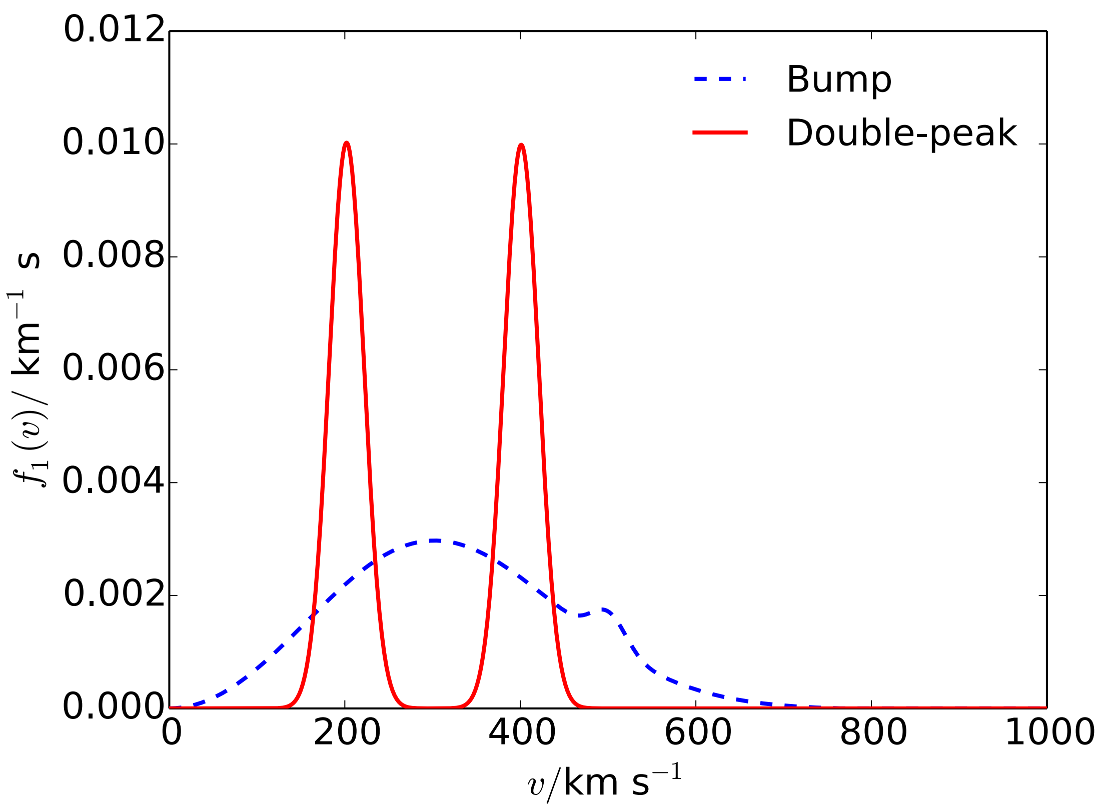
spin-independent (SI) interactions - $\mathcal{C}_A^{\mathrm{SI}} \sim A^2$

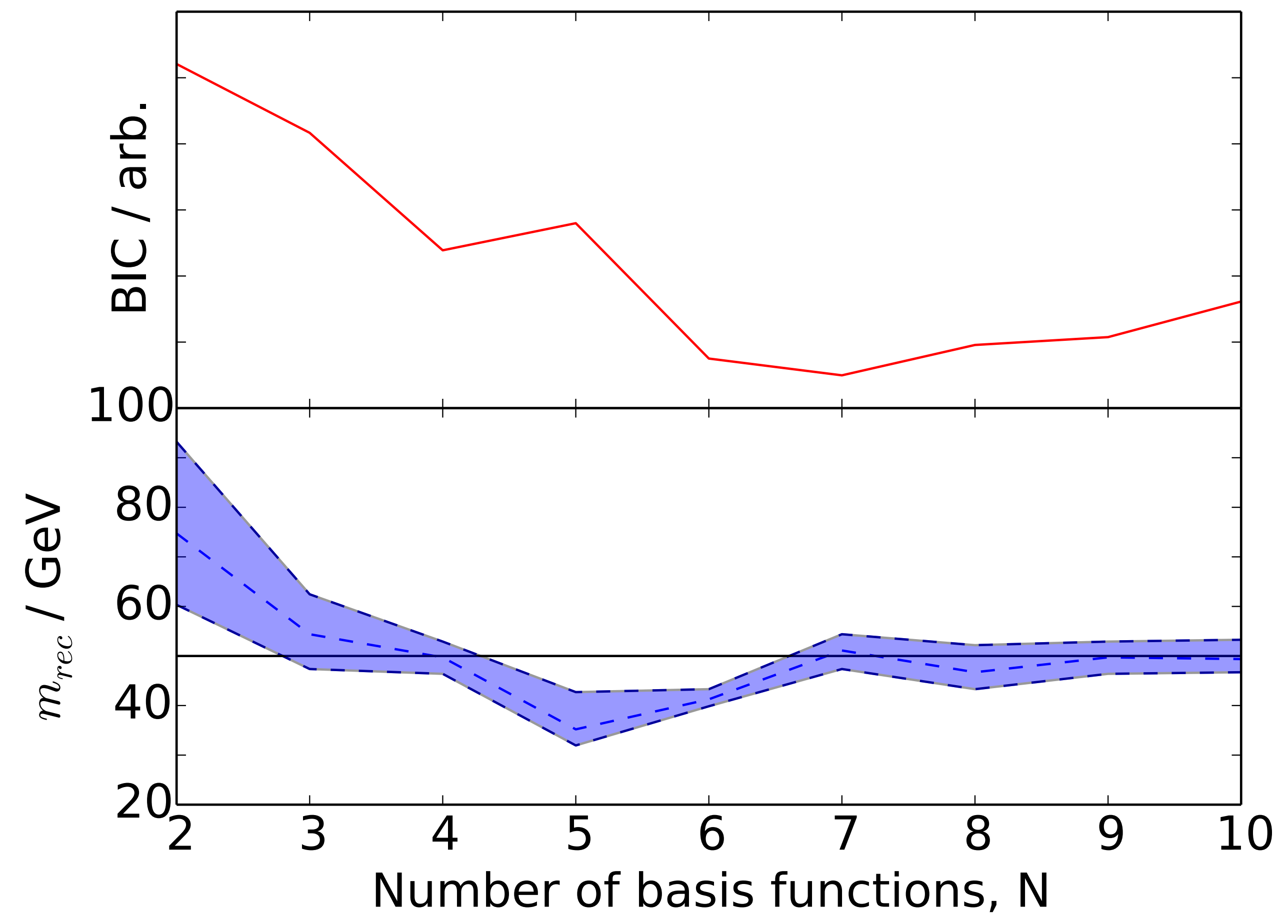
spin-dependent (SD) interactions - $\mathcal{C}_A^{\mathrm{SD}} \sim (J+1)/J$

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

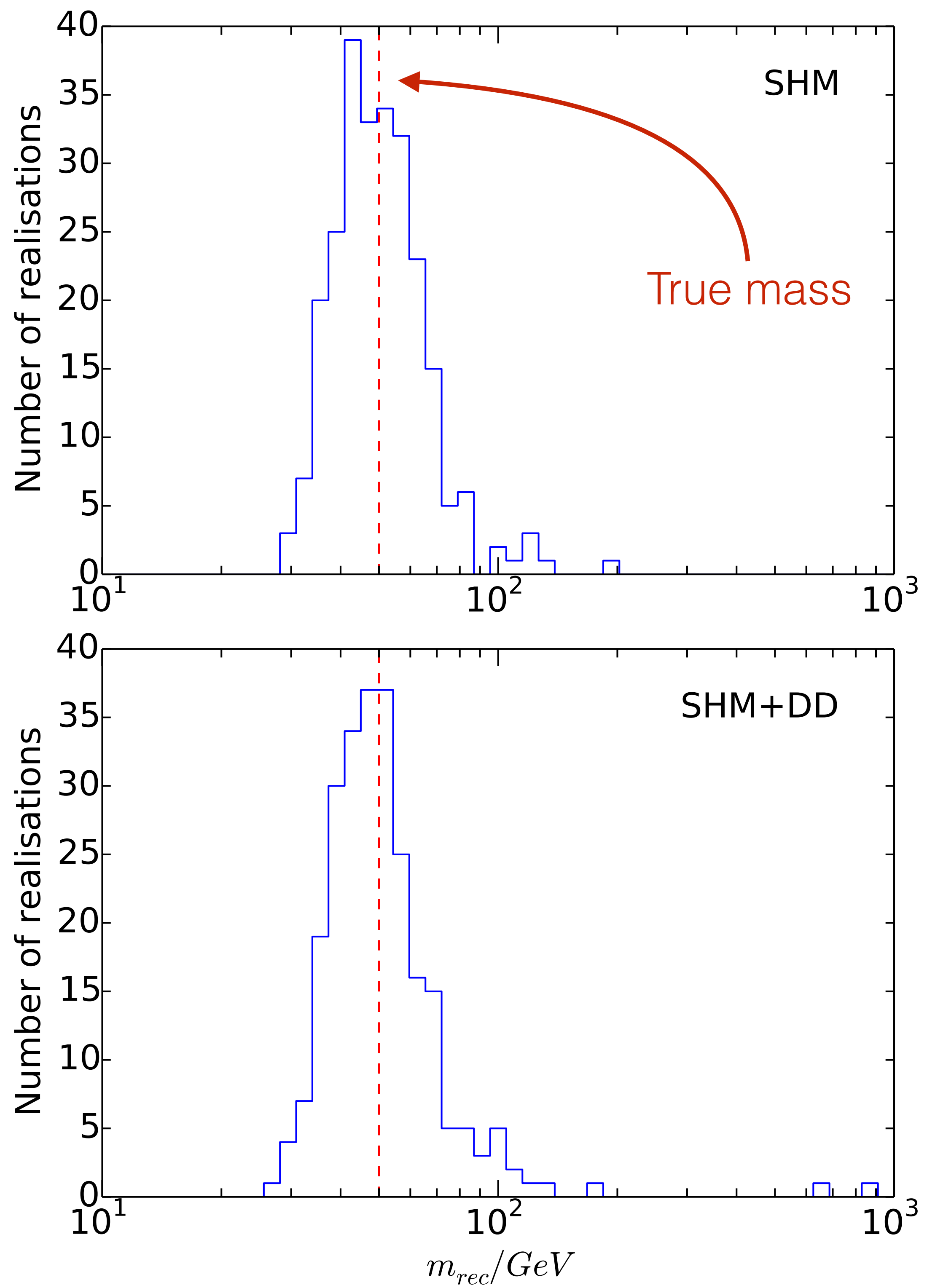
$$f(v) = v^2 \exp\left(-\sum_{k=0}^{N-1} a_k v^k\right)$$





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*

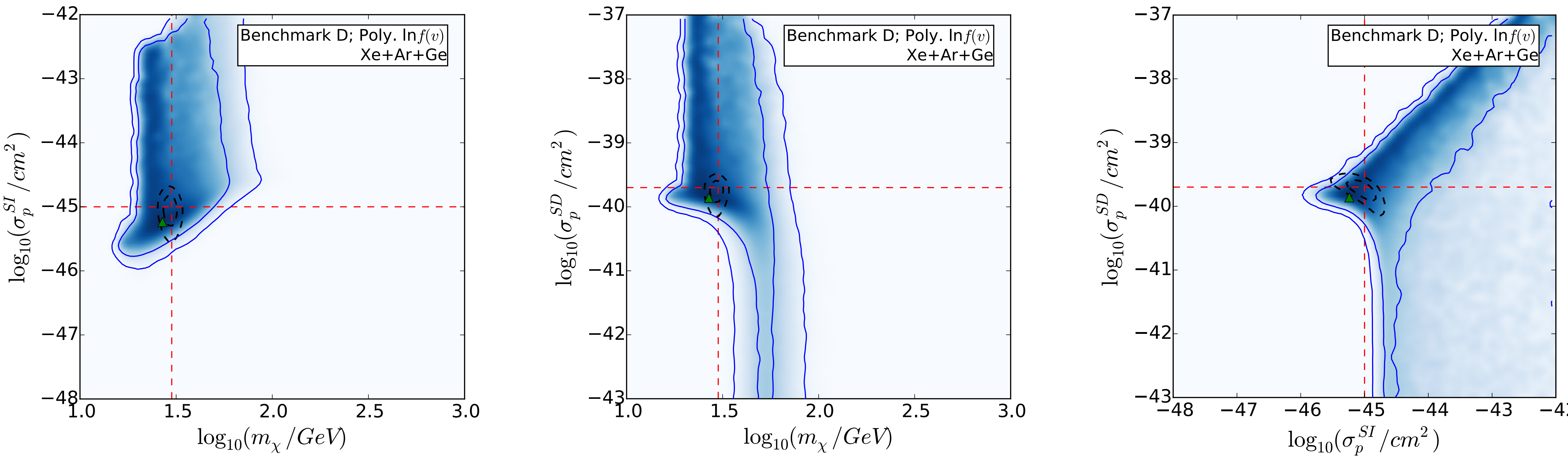


Full reconstructions (without IceCube)

Consider a single benchmark:

$$m_\chi = 30\,\mathrm{GeV};\;\; \sigma_{SI}^p = 10^{-45}\,\mathrm{cm}^2;\;\; \sigma_{SD}^p = 2\times10^{-40}\,\mathrm{cm}^2$$

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:

$$m_\chi = 30\,\mathrm{GeV};\;\; \sigma_{SI}^p = 10^{-45}\,\mathrm{cm}^2;\;\; \sigma_{SD}^p = 2\times 10^{-40}\,\mathrm{cm}^2$$

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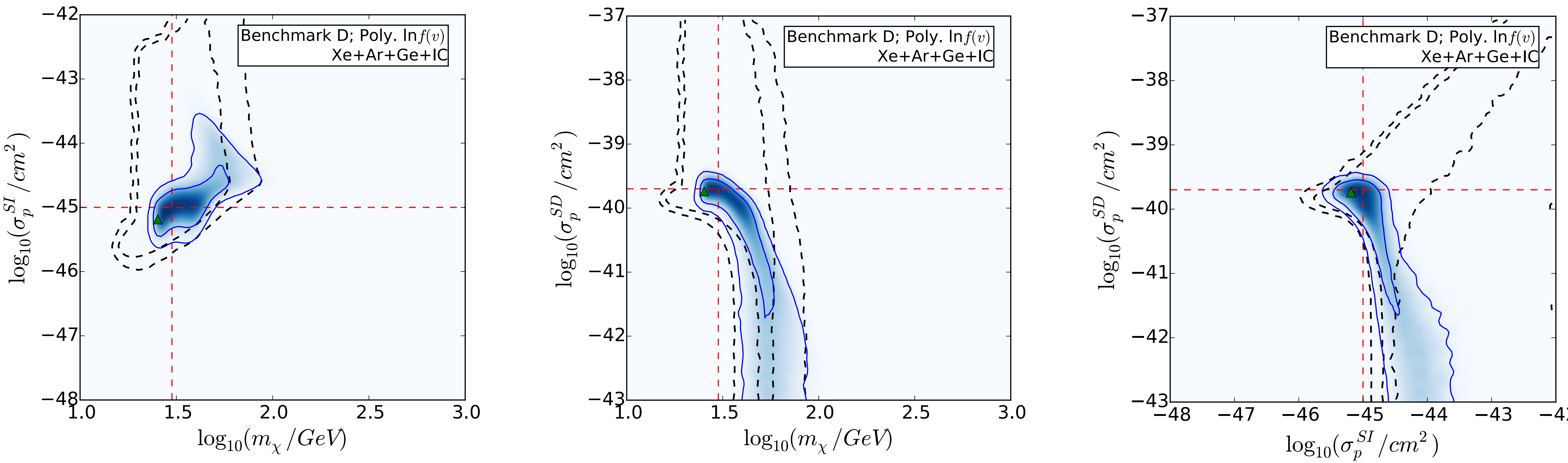


Benchmark

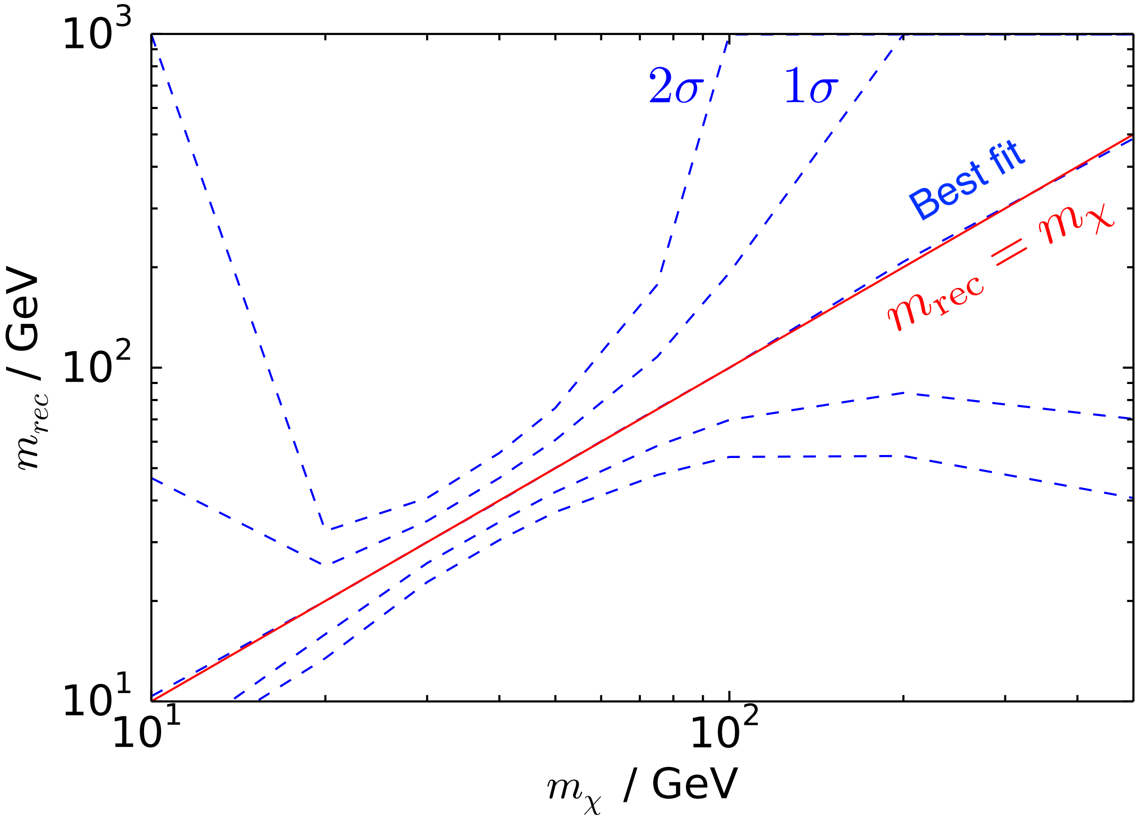
Best fit

Direct detection only (our param.)

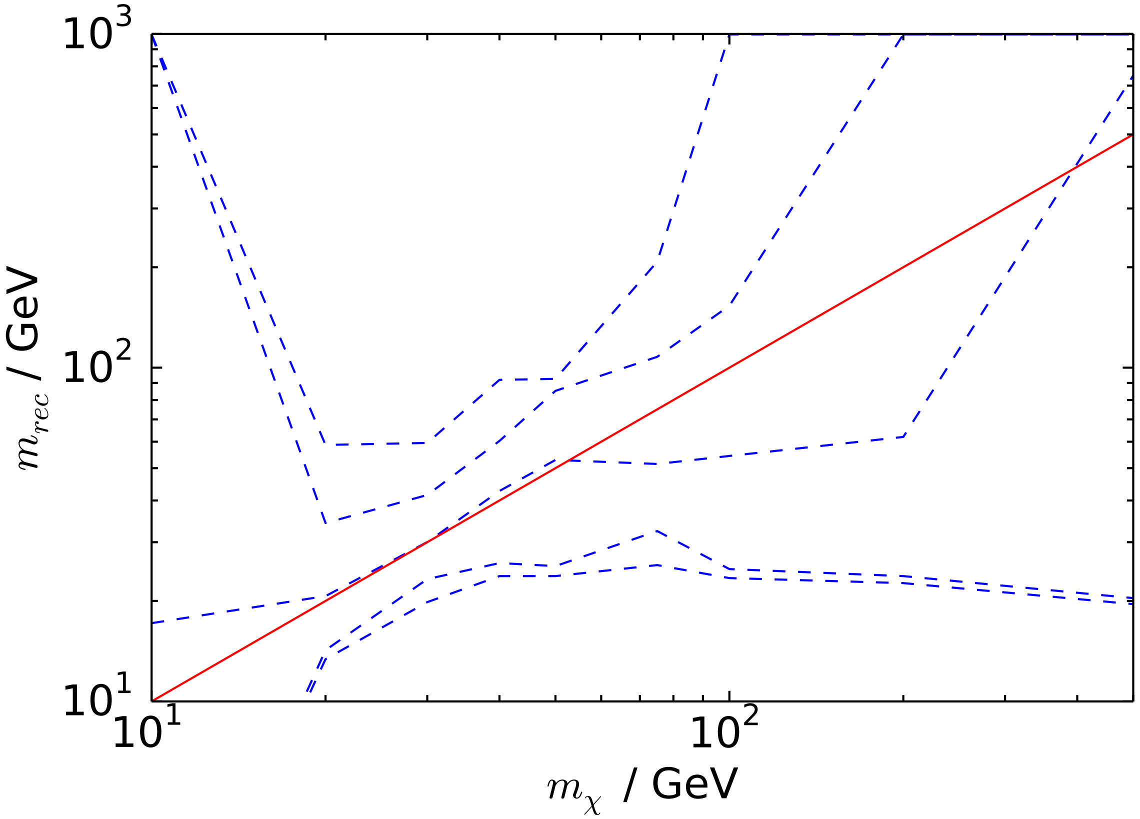
Direct detection + IceCube (our param.)

‘Real’ Experiments

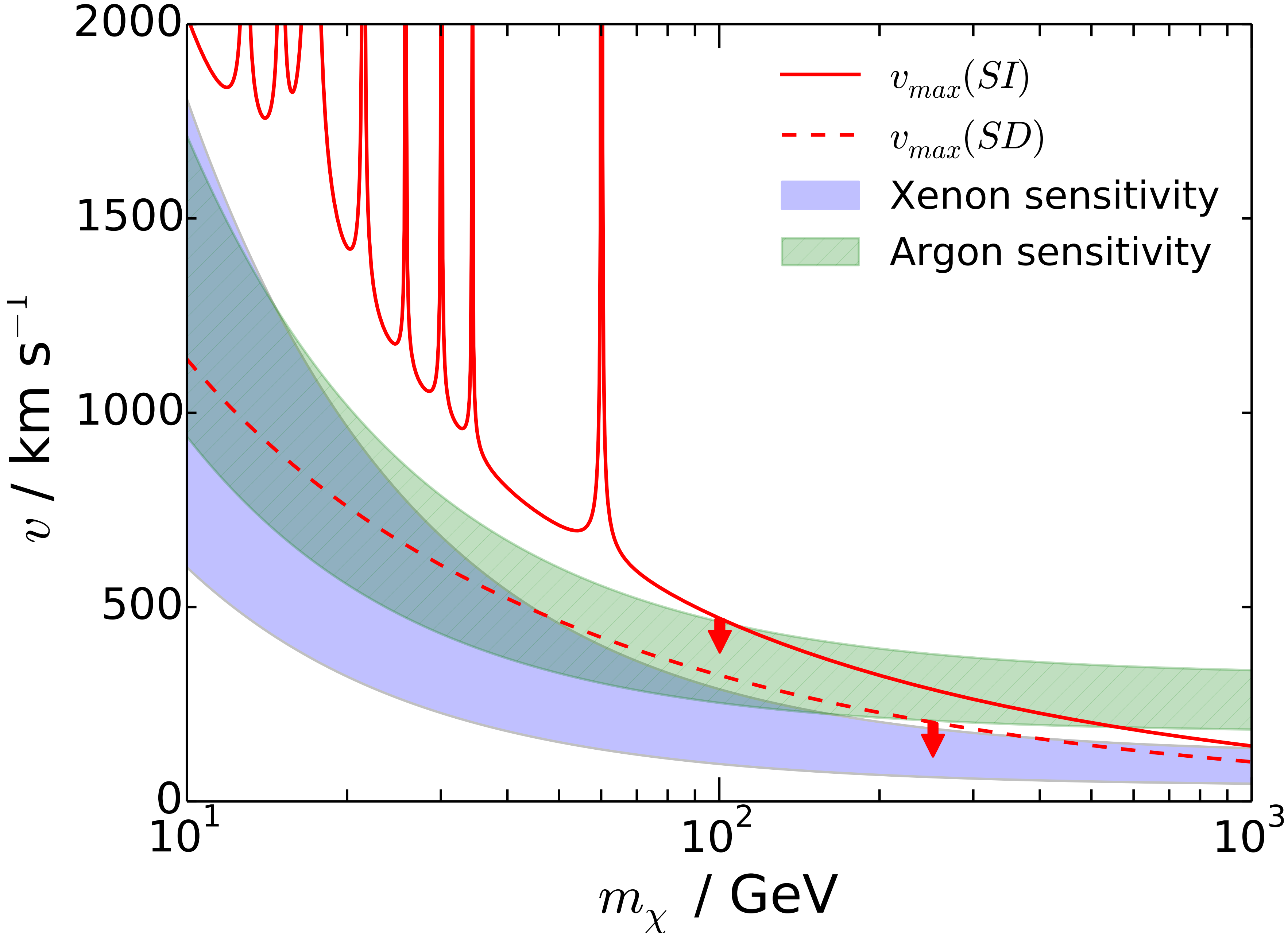
Ideal experiments



‘Real’ experiments



SI vs SD Solar Capture



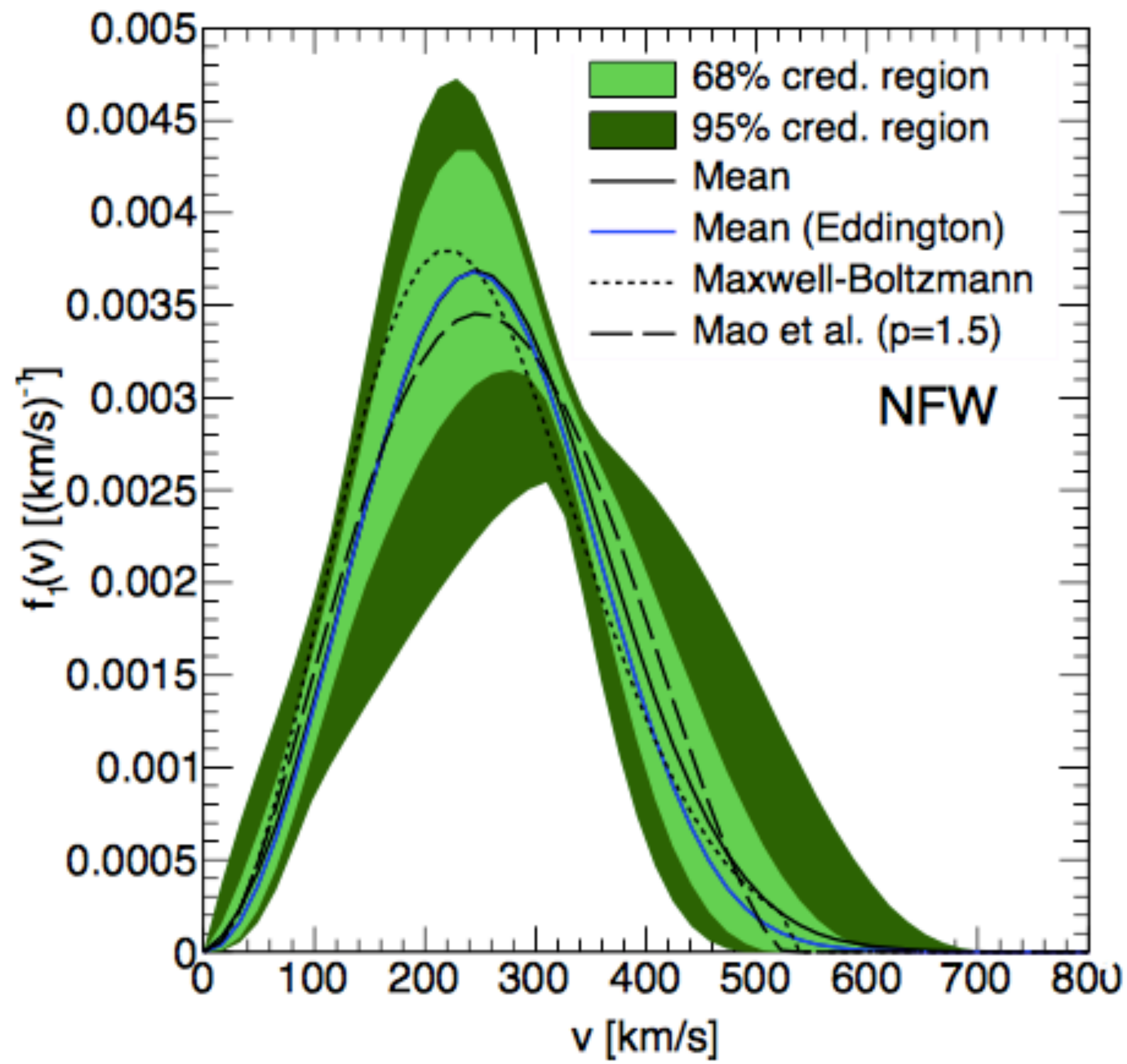
Self-consistent distributions

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

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

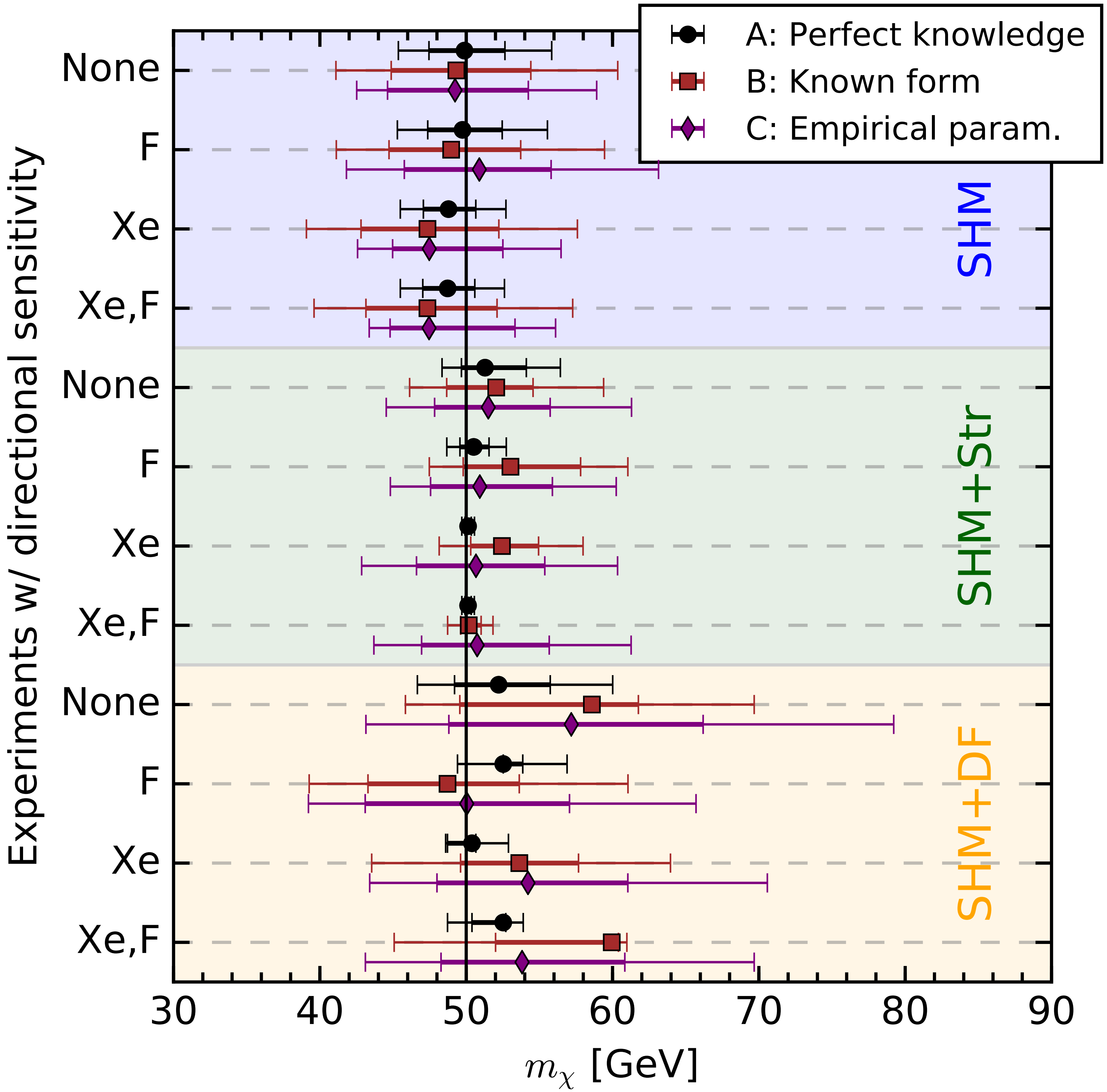
$$\mathcal{E} = \frac{1}{2}v^2 - \Psi(r)$$

Fornasa & Green [1311.5477]

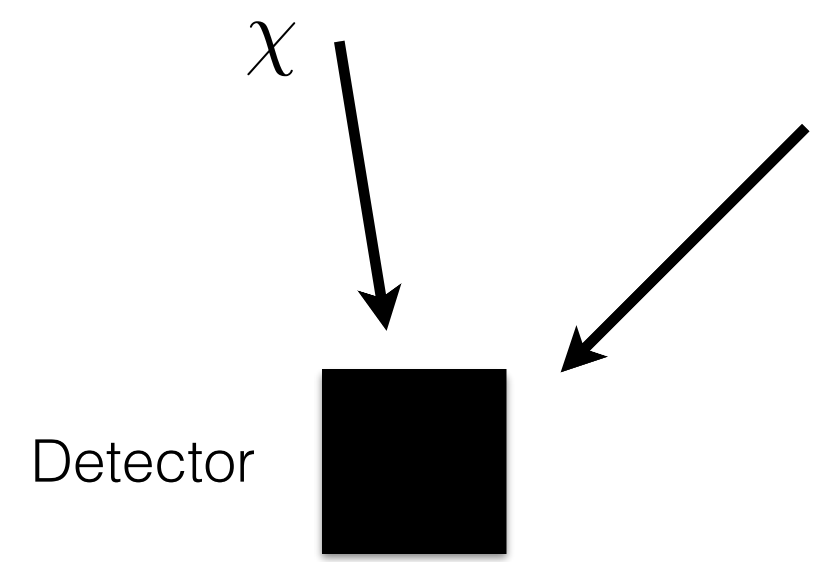


See also Bhattacharjee et al. [1210.2328];
Bozorgnia et al. [1310.0468]; Mandal et al. [1806.06872]

Mass reconstruction with directionality



Discretising f(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…

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

BJK [1502.04224]

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

Discretising f(v)