Probing the astrophysics and particle physics of WIMPs with direct detection experiments

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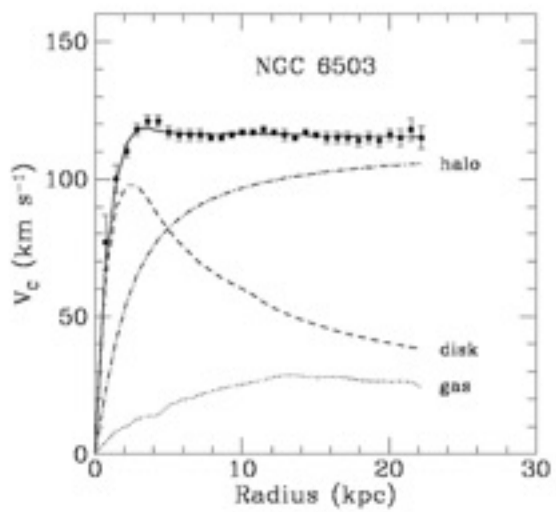
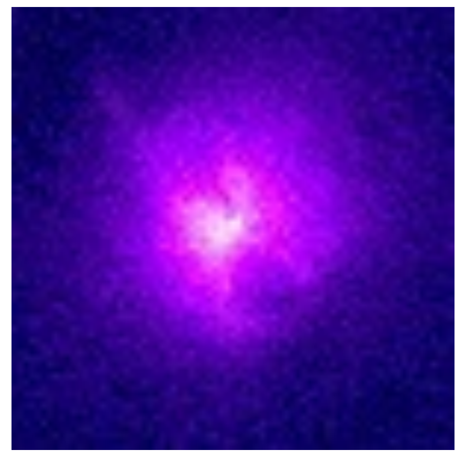
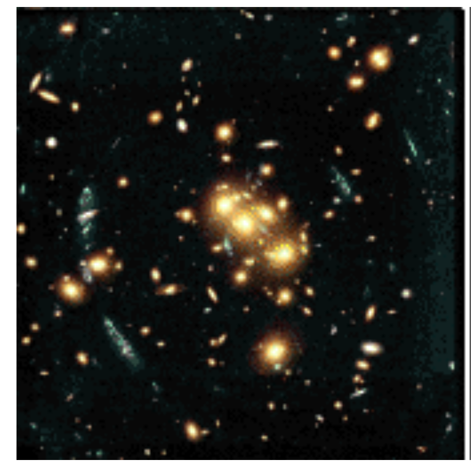
- Observational evidence for dark matter
- WIMPs: theory
- WIMPs: detection
- Measuring the WIMP mass and cross-section

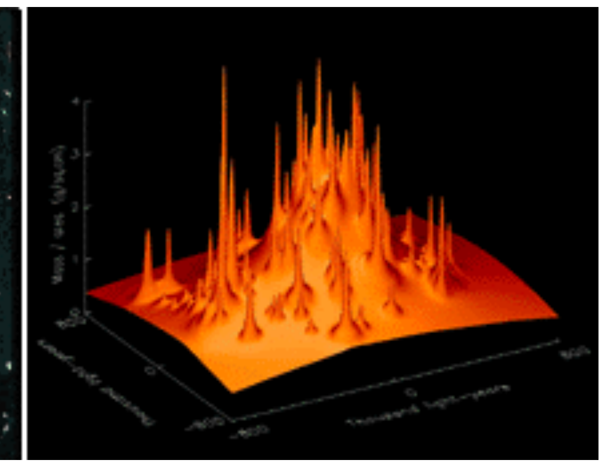
Featuring work in collaboration with Ciaran O'Hare, Bradley Kavanagh & Mattia Fornasa.

Observational evidence for dark matter





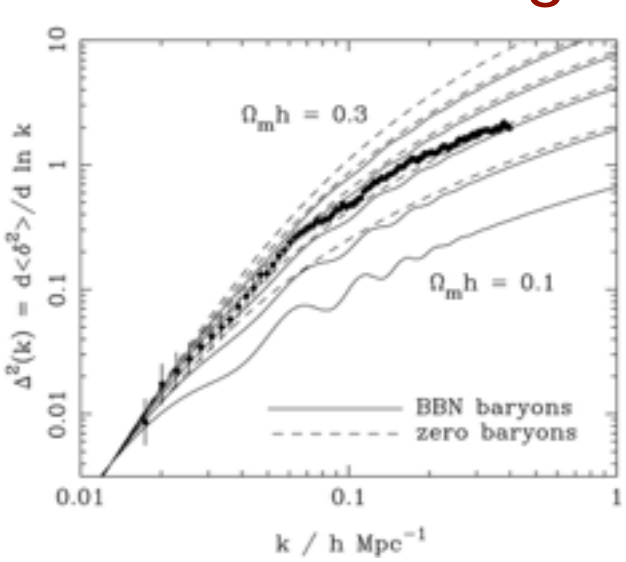


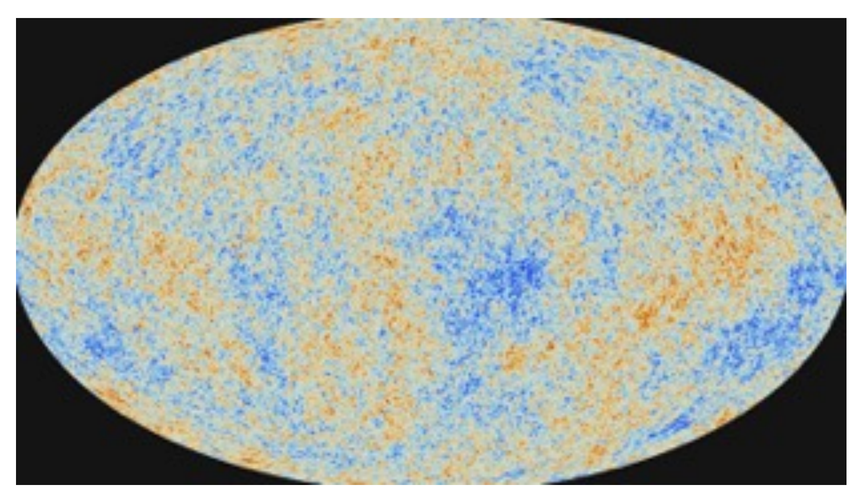


Lots of evidence for (non-baryonic cold) dark matter from diverse astronomical and cosmological observations

[galaxy rotation curves, galaxy clusters (galaxy velocities, X-ray gas, lensing), galaxy red-shift surveys, Cosmic Microwave Background]

assuming Newtonian gravity/GR is correct.





Detecting dark matter would:

★ answer a major fundamental question (‘what is the Universe made of?’).

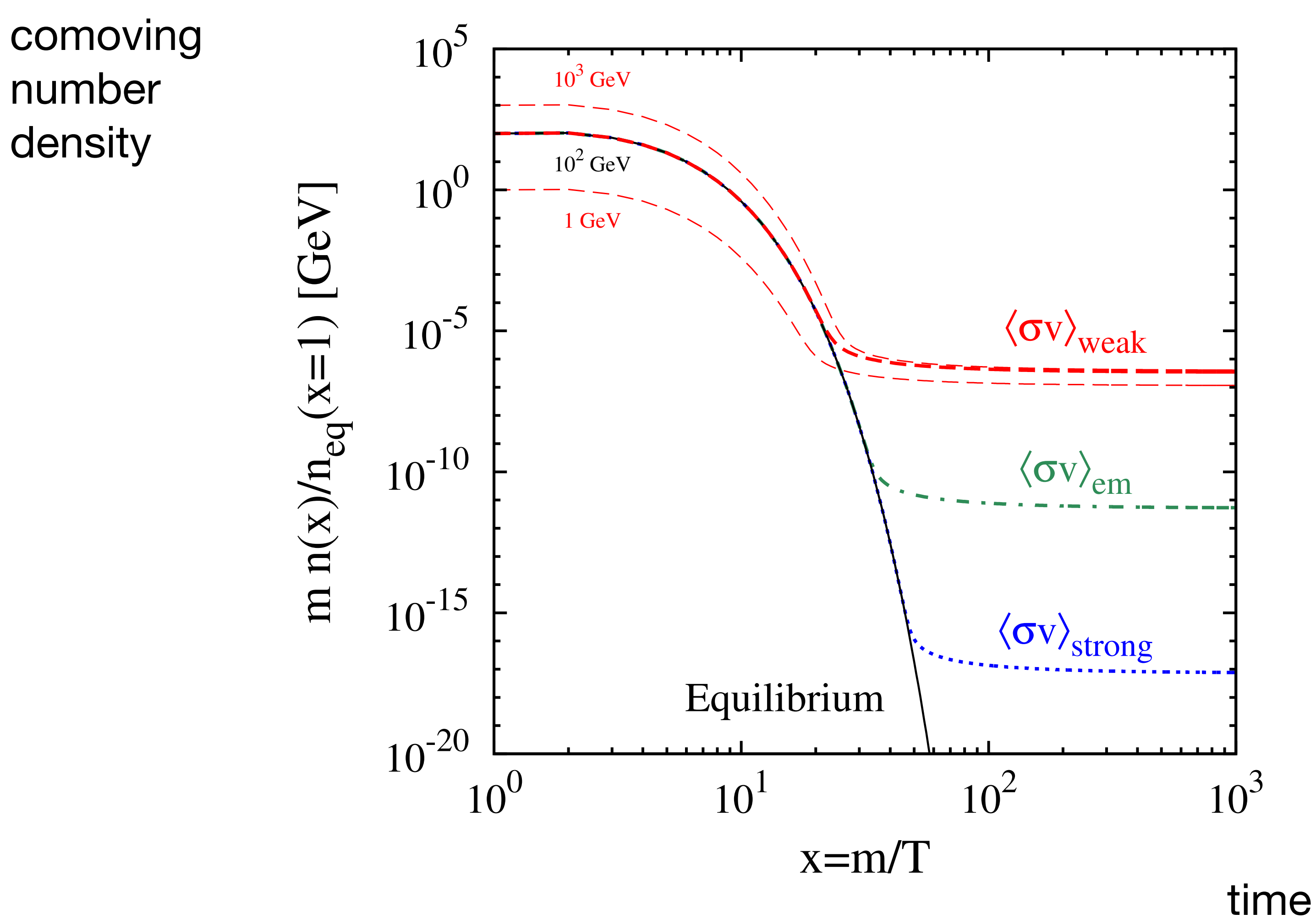
★ provide confirmation of the standard cosmological model (and effectively rule out modified gravity e.g. MOND, TeVeS).

★ probe physics beyond the standard model.

WIMPs

Any Weakly Interacting Massive Particle in thermal equilibrium in the early Universe will have an interesting density today.

$$\chi + \chi \longleftrightarrow X + \bar{X}$$



$$\Omega_\chi h^2 \approx 0.3 \left(\frac{10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle} \right)$$

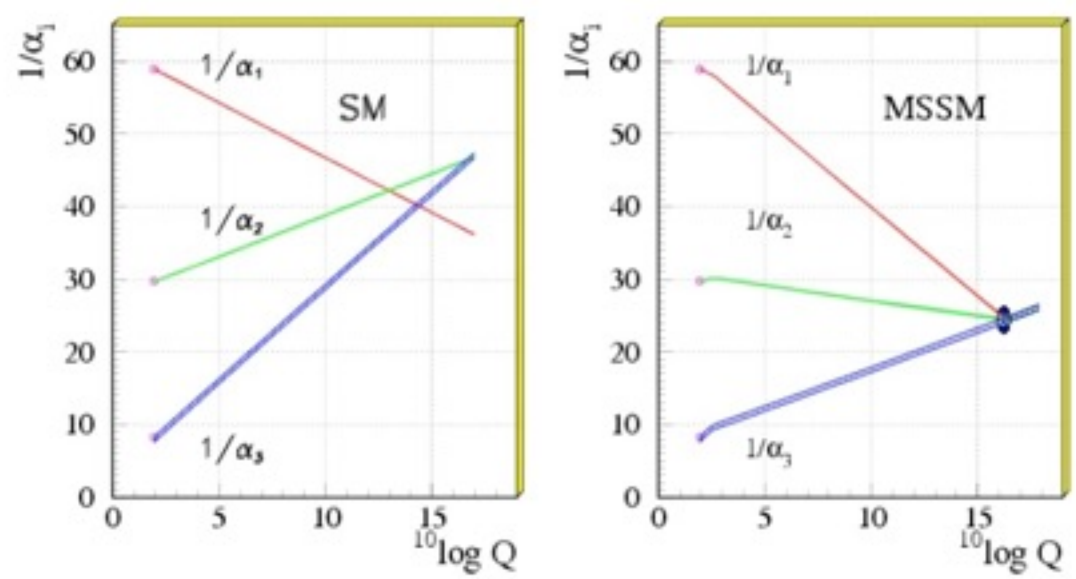
[Steigman, Dasgupta & Beacom]

Supersymmetry

Every standard model particle has a supersymmetric partner. (Bosons have a fermion spartner and vice versa)

Motivations:

- ✦ Gauge hierarchy problem
  (M_W ~100 GeV << M_{Pl} ~ 10^{19} GeV)
- ✦ Unification of coupling constants
- ✦ String theory



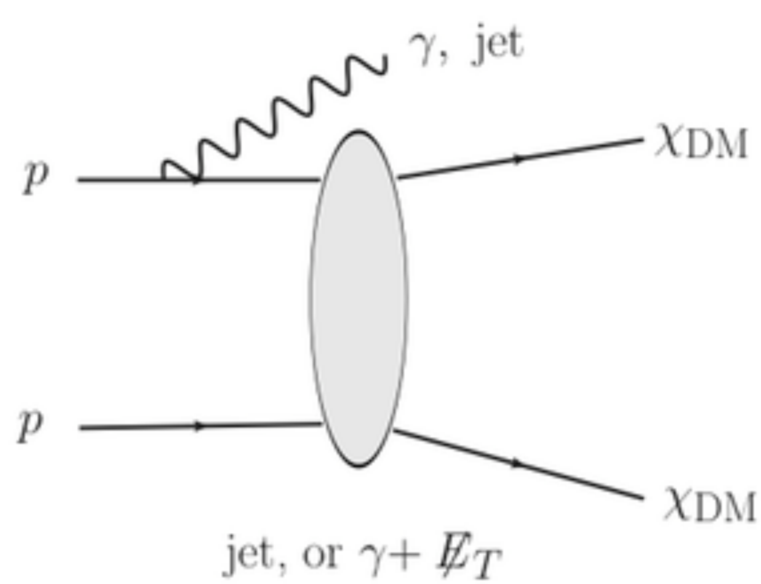
[Kazakov]

In most models the Lightest Supersymmetric Particle (which is usually the lightest neutralino, a mixture of the susy partners of the photon, the Z and the Higgs) is stable (R parity is conserved) and is a good CDM candidate.

How to detect WIMPs?

Particle Colliders (LHC)

Various missing transverse momentum + mono-X (X= photon, jet, Z, W, top, Higgs, …) searches.



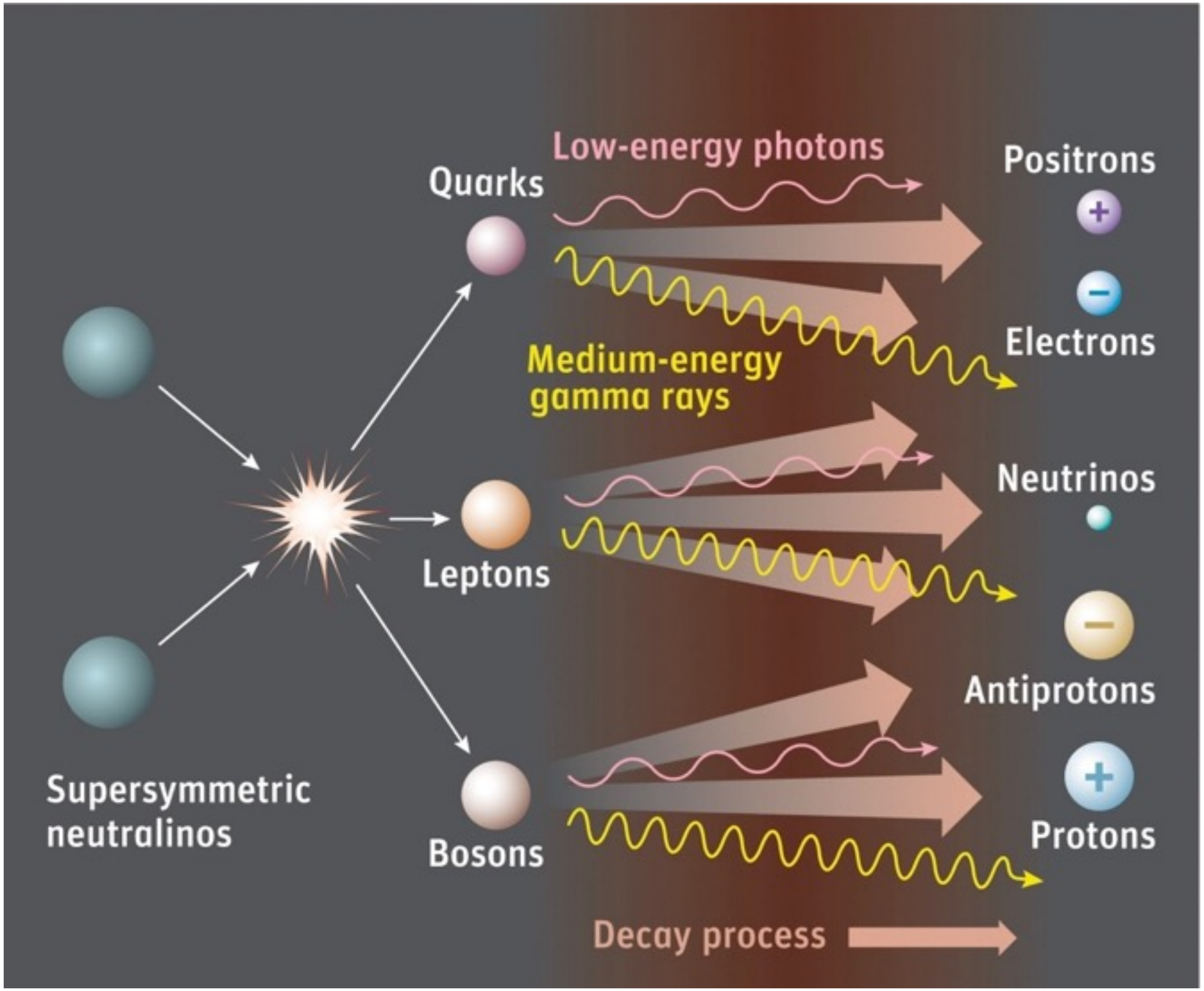
[Wang]

Collider production and detection of a WIMP-like particle would be very exciting, but wouldn't demonstrate that the particles produced have lifetime greater than the age of the Universe and are the dark matter.

Current status: waiting… (and hoping for some sign of BSM physics!)

Indirect detection

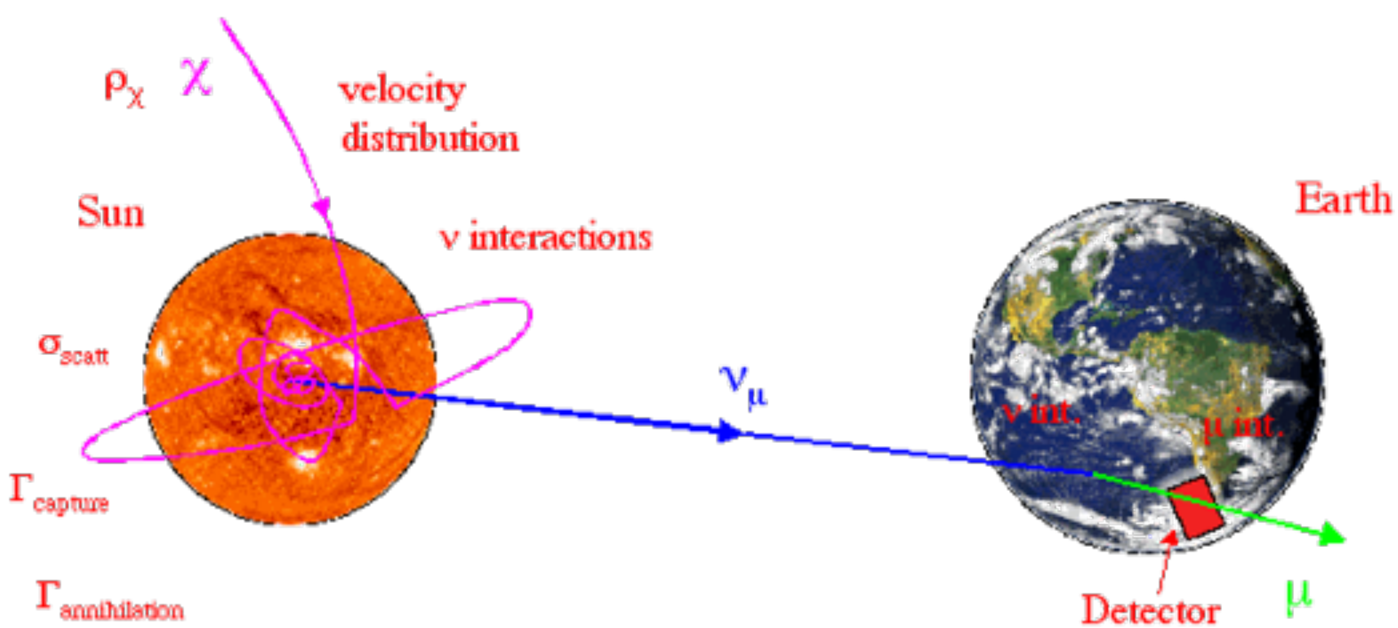
Via products of annihilations, gamma-rays, positrons and anti-protons

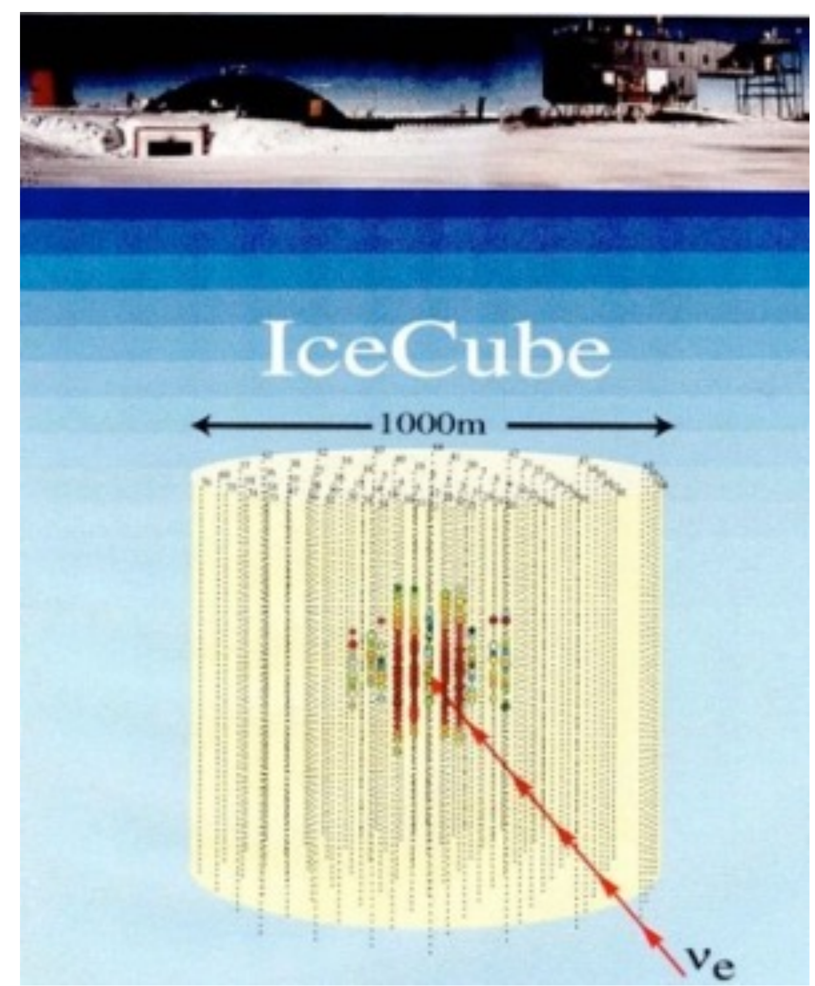


Indirect detection via neutrinos:

Low speed WIMPs lose energy due to scattering are gravitationally captured in Sun then annihilate producing energetic neutrinos which escape.

Muon neutrinos produce muons which can then be detected (via Cherenkov radiation) using neutrino telescopes.



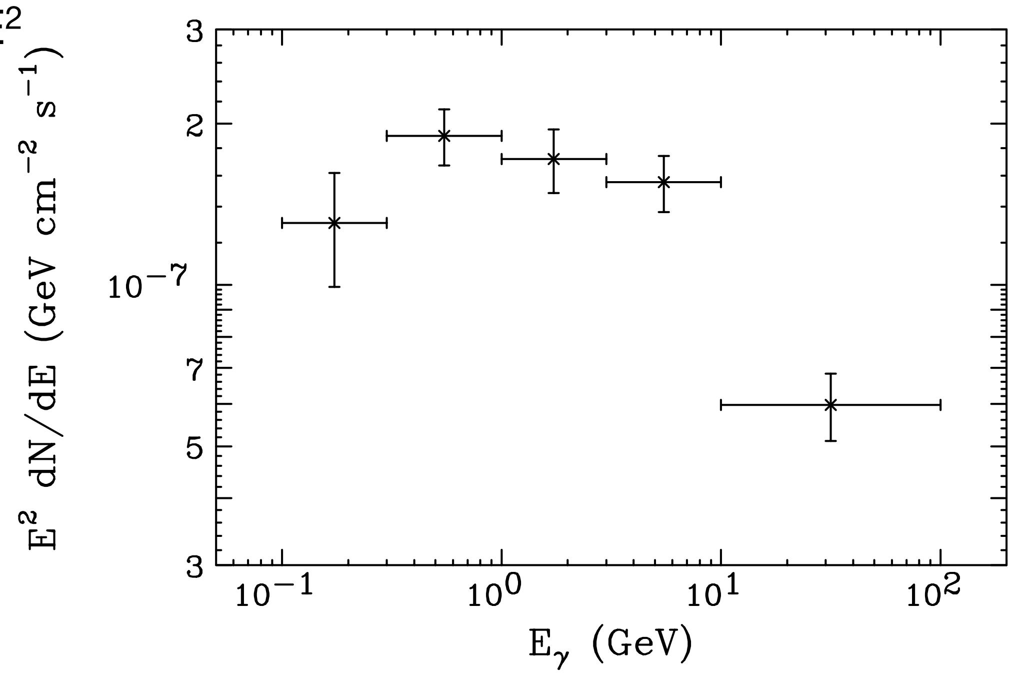


Gamma-rays i) Galactic centre/inner galaxy:

Expect high DM density close to the Galactic centre, but also lots of astrophysical sources of gamma-rays (e.g. point sources + products of cosmic ray interactions).

After modelling the astrophysical sources there appears to be an excess at latitudes b < ~10° which peaks around E~1 GeV:

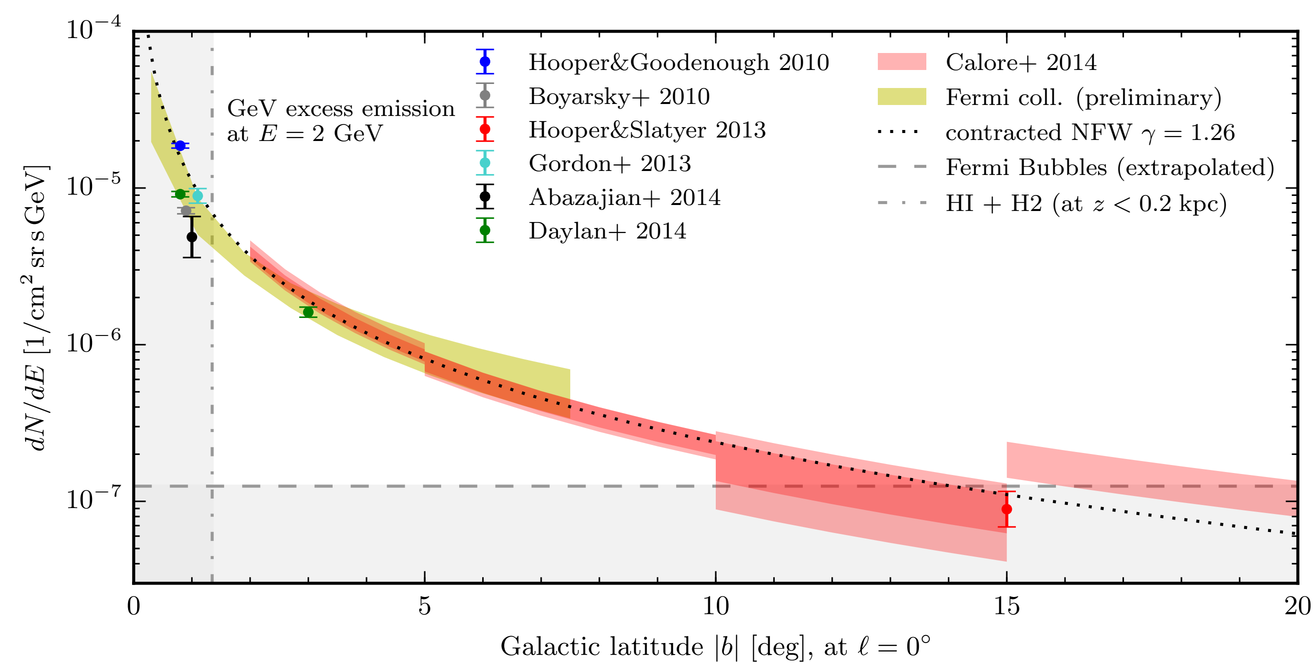
gamma-ray spectrum x E^2



[Linden & Hooper]

energy (GeV)

gamma-ray spectrum



[Calore et al.]

Galactic latitude (b)

Could be due to WIMP annihilation.

Or: unresolved millisecond pulsars [Abazajian et al.; Bartels et al.; Lee et al.]

cosmic-ray outburst in the past [Carlson & Profumo; Petrovic et al.]

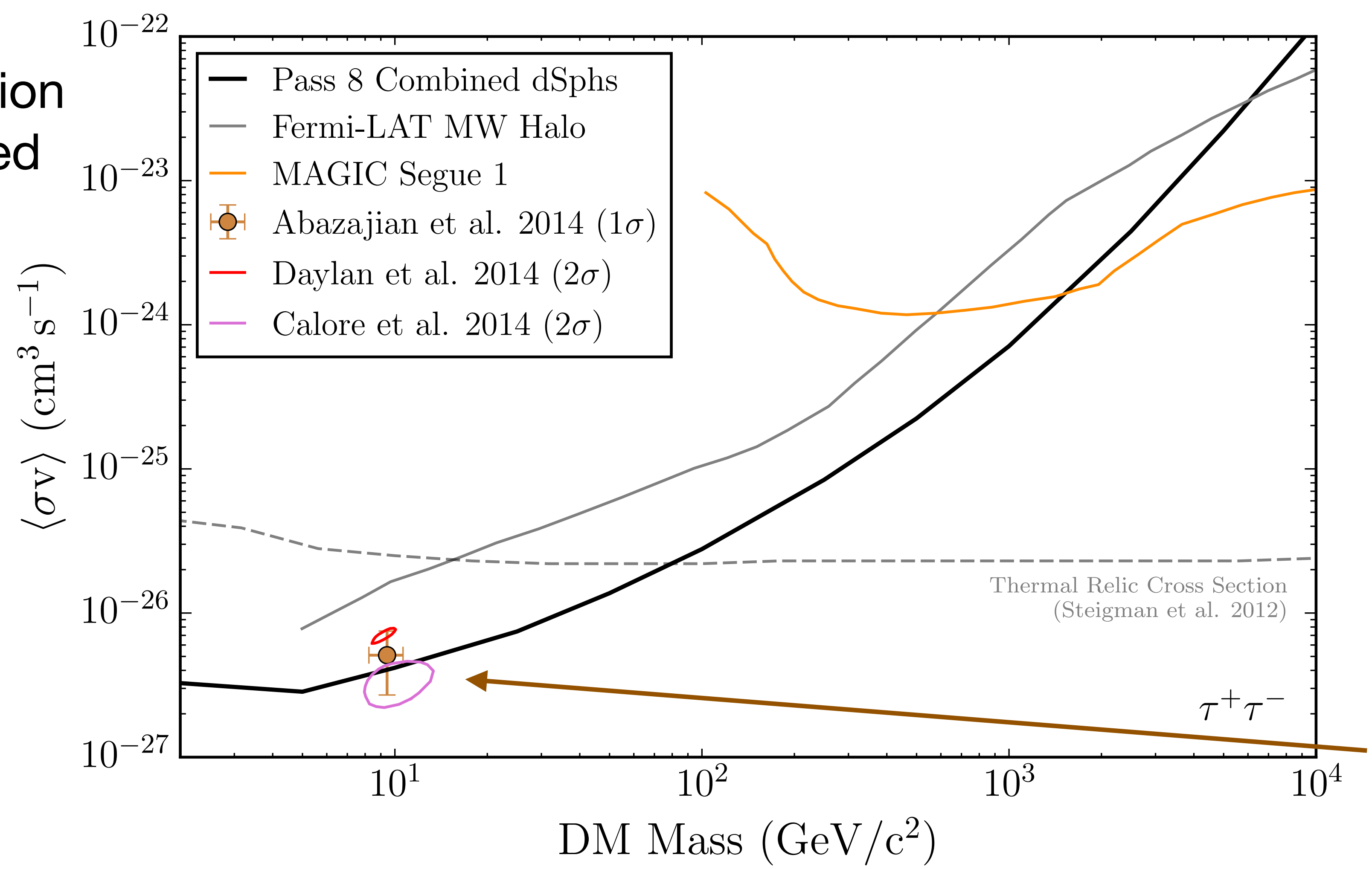
Gamma-rays ii) dwarf galaxies:

Astrophysical backgrounds small.

Fermi just reaching sensitivity required to detect gamma-rays from WIMP annihilation.

Latest Fermi results (for annihilation via $\tau^+\tau^-$, get slightly different results for other channels):

WIMP
cross section
times speed



Fermi dwarf constraints

Fermi MW halo constraints

thermal relic cross section

Closed regions & point correspond to different analyses of the Galactic centre excess.

WIMP mass (GeV)

Particle theorists can produce models to fit almost any astrophysical data…. (e.g. HEAT/PAMELA/Fermi/AMS positron excess)

So is it possible to convincingly detect WIMPs indirectly?

Possibly...

e.g. gamma-ray line

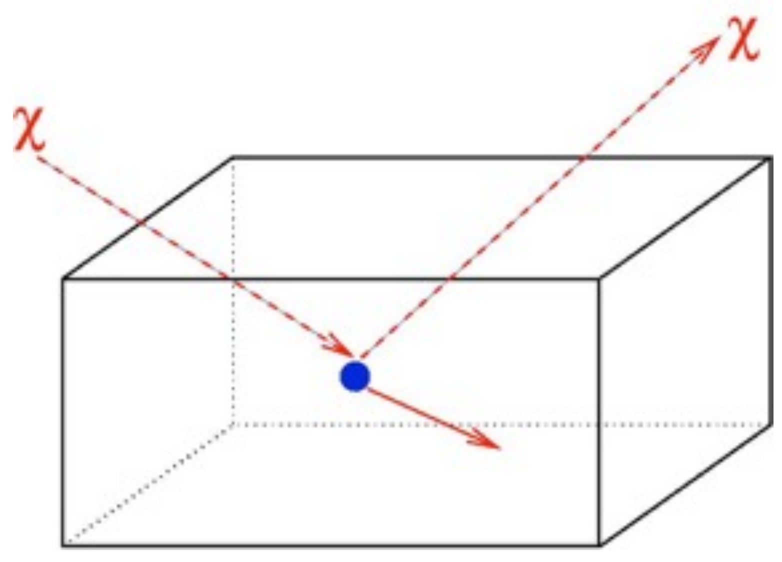
different sources with same energy spectrum

multi-wavelength signals

Direct detection

Via elastic scattering on detector nuclei in the lab.

$$\chi + N \rightarrow \chi + N$$



Interaction between WIMP and nucleus can be spin-independent (scalar) or spin-dependent (axial-vector). Most experiments most sensitive to spin-independent.

Differential event rate: (per kg/day/keV)

$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_p \rho_\chi A^2 F^2(E) \int_{v_{\min}}^{\infty} \frac{f(v)}{v} \mathrm{d}v$$

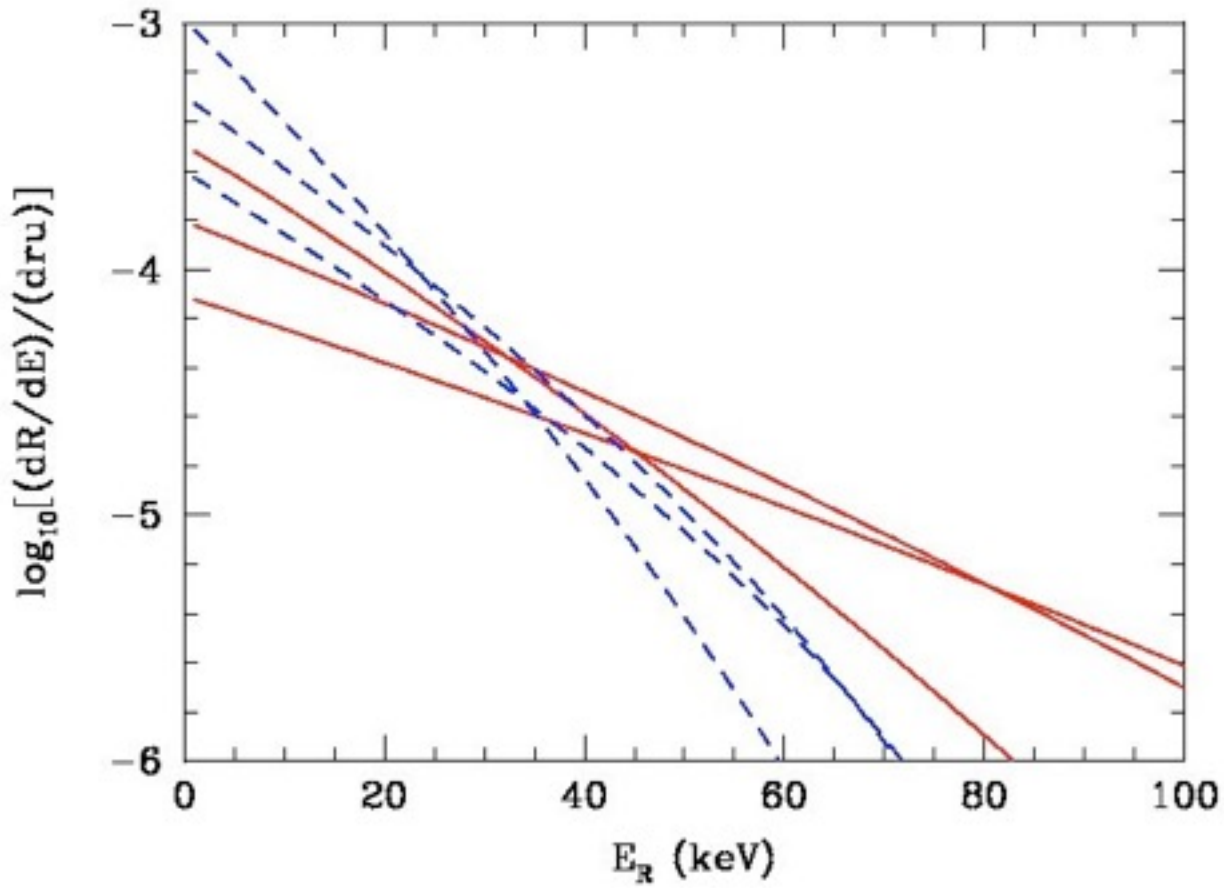
$$v_{\min} = \left(\frac{E(m_A + m_\chi)^2}{2 m_A m_\chi^2} \right)^{1/2}$$

Multiply by exposure (detector mass x running time) to get energy spectrum.

signals:

i) dependence of event rate on mass of target nuclei [Lewin & Smith]

Ge and Xe m_χ = 50, 100, 200 GeV



Measure consistent energy spectra using detectors made of different target nuclei.

Can also (in principle) measure the WIMP mass from the energy spectrum:

Assuming the standard halo model (isothermal sphere) with a Maxwellian velocity distribution:

$$f(v) \propto \exp\left(-\frac{v^2}{2\sigma^2}\right) \qquad \sigma = \frac{v_c}{\sqrt{2}}$$

v_c is local circular speed

Energy spectrum is exponential with characteristic energy scale:
[Lewin & Smith]

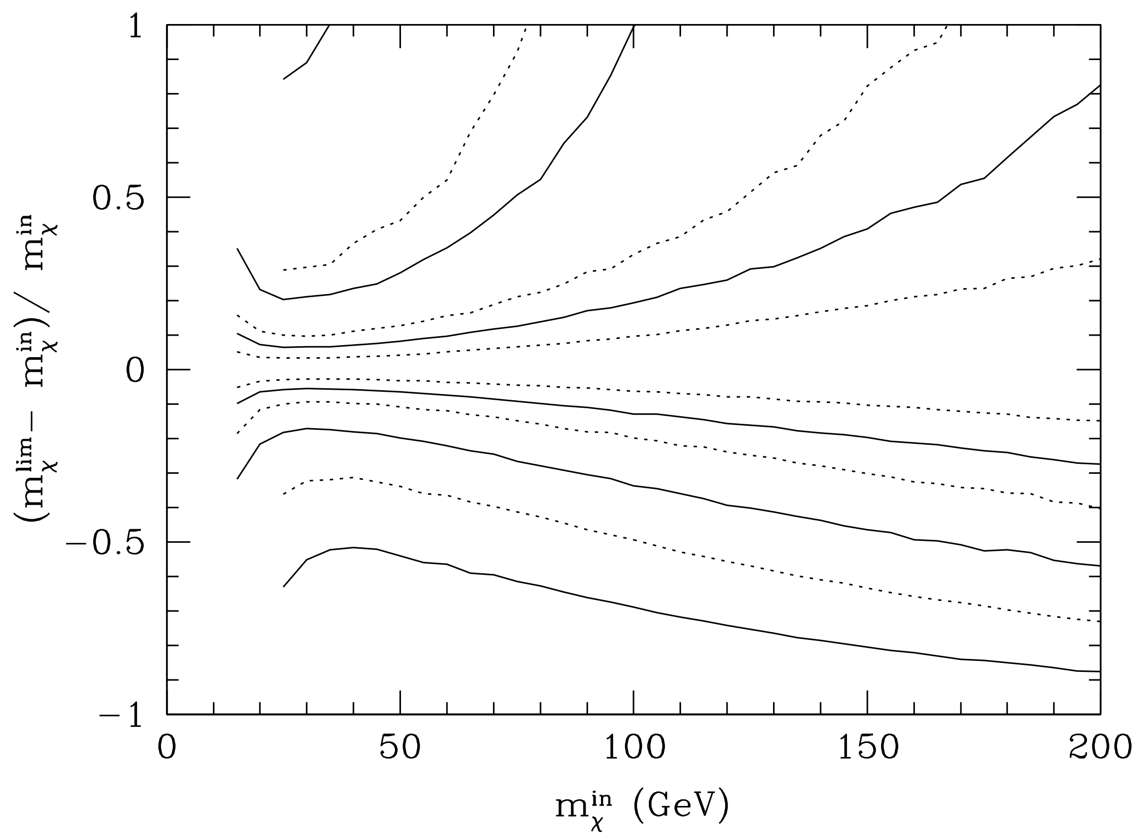
$$E_R = \frac{2\mu_{A\chi}^2 v_c^2}{m_A}$$

$\propto m_\chi^2$ if $m_\chi \ll m_A$

~ const if $m_\chi \gg m_A$

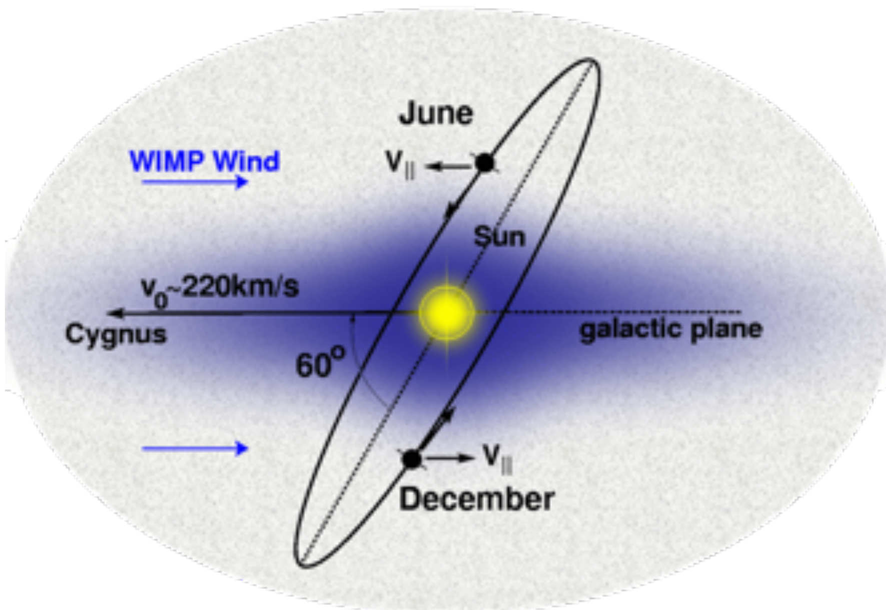
Projected fractional mass limits as a function of input mass

light WIMPs: no limits, most events are below threshold.

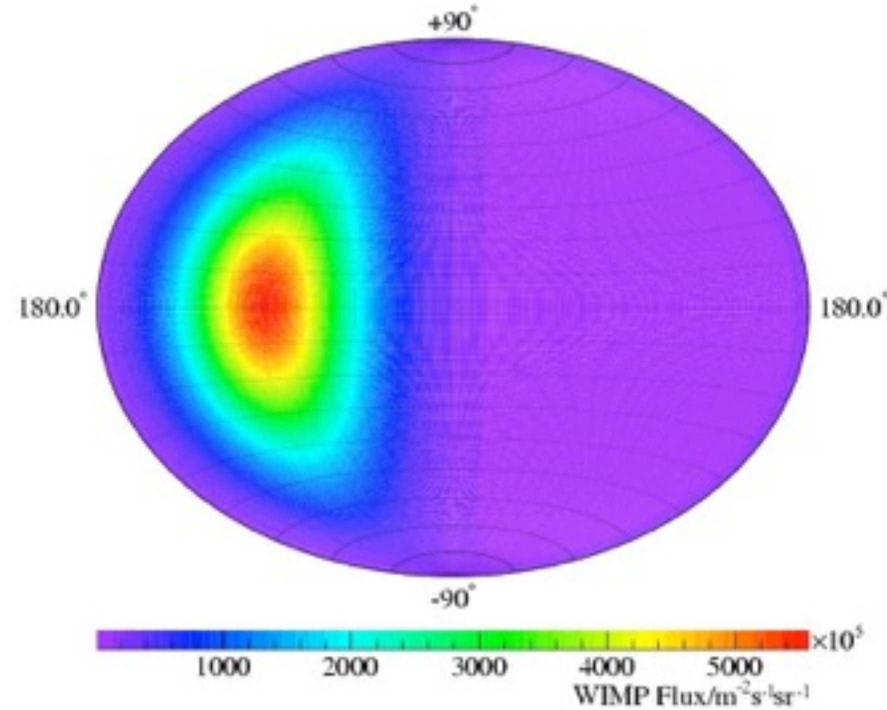


heavy WIMPs: no upper limit, shape of spectrum independent of mass

ii) direction dependence of event rate [Spergel]



[Sheffield DM group]



Large signal.

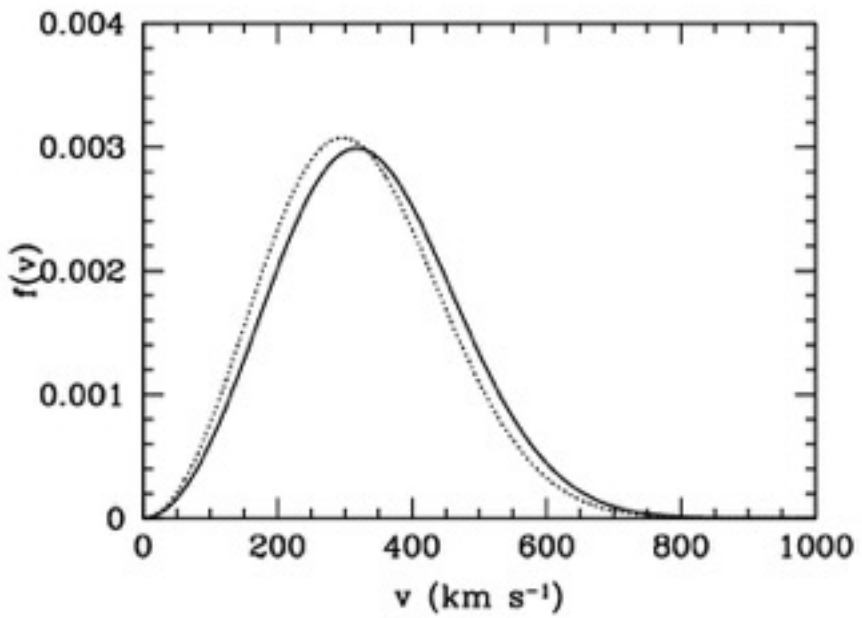
With an ideal detector:

~10 events required to reject isotropy of recoil directions [Morgan, Green & Spooner]

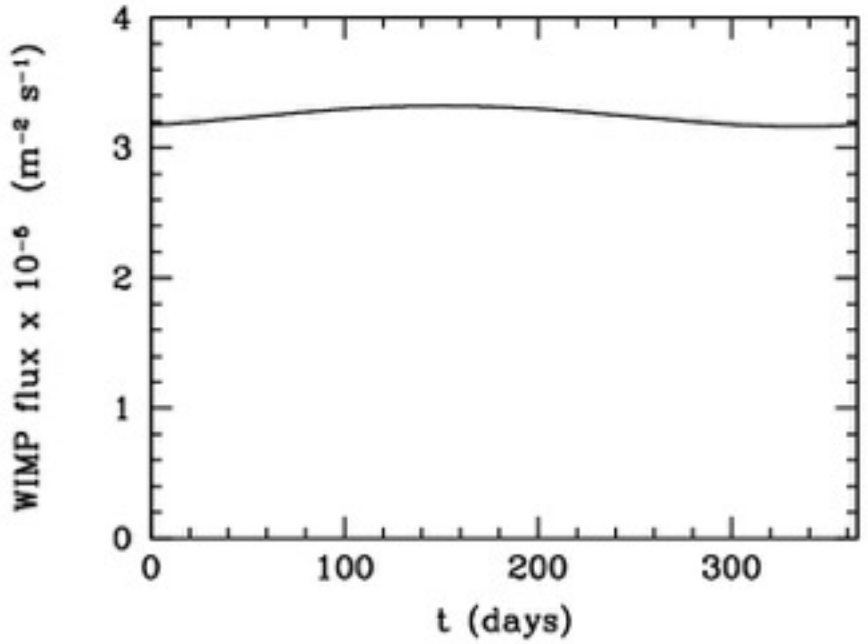
~30 events required to confirm peak direction coincides with direction of solar motion [Billard et al.; Green & Morgan]

Need a detector which can measure recoil directions e.g. DMTPC, DRIFT, MIMAC, NEWAGE.

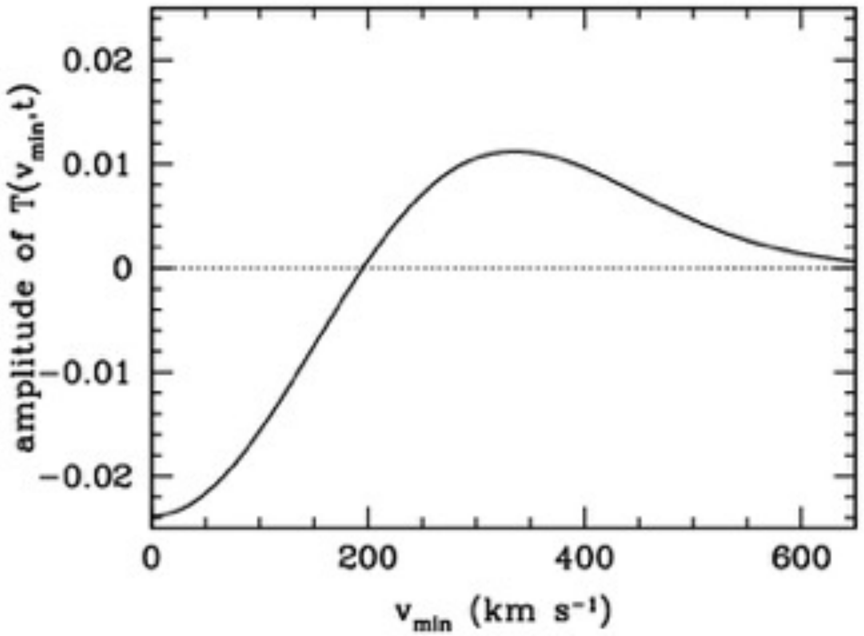
iii) annual modulation of event rate [Drukier, Freese & Spergel]



WIMP 'standard' (Maxwellian) speed dist.
detector rest frame (summer and winter)



total WIMP flux



modulation amplitude

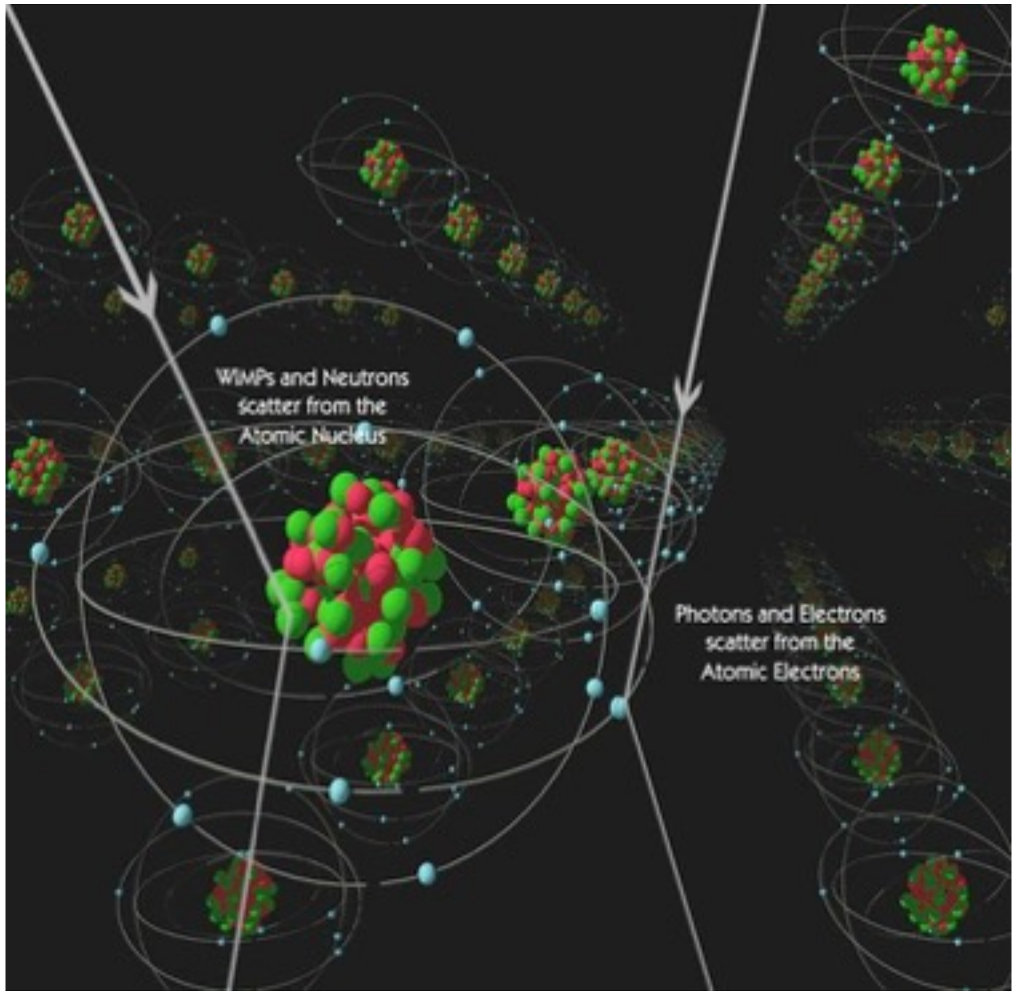
Signal fairly small, therefore need large detector running stably for a long time.

Depends on shape of f(v).

For a convincing detection will need to demonstrate that events are due to WIMPs and not backgrounds:

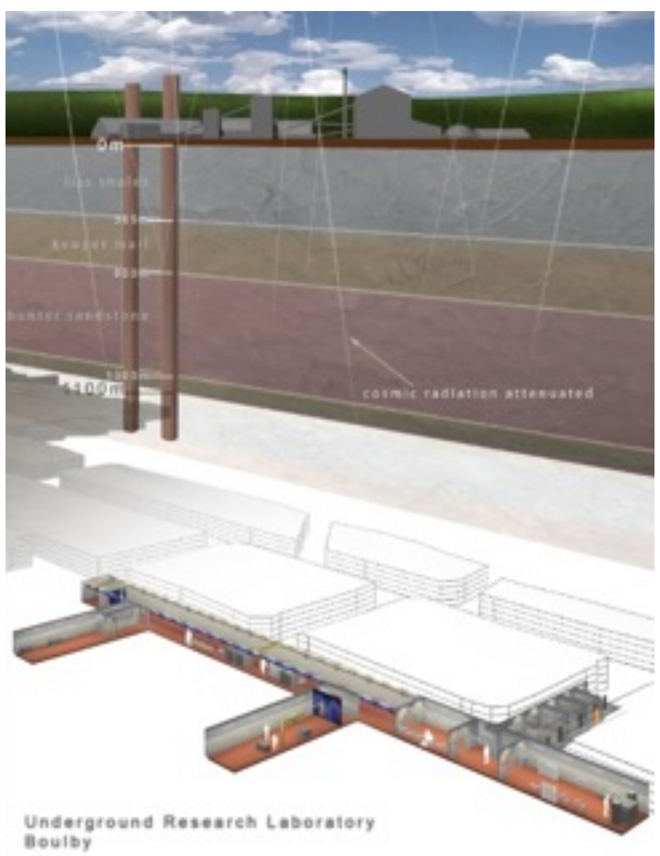
electron recoils due to βs and γs

nuclear recoils due to neutrons from cosmic rays or local radioactivity



For a convincing detection will need to demonstrate that events are due to WIMPs and not backgrounds:

- electron recoils due to βs and γs
  - look at multiple energy deposition channels (scintillation, ionisation, phonons)
- nuclear recoils due to neutrons from cosmic rays or local radioactivity
  - indistinguishable on an event by event basis
  - operate detector deep underground, use shielding and radiopure components

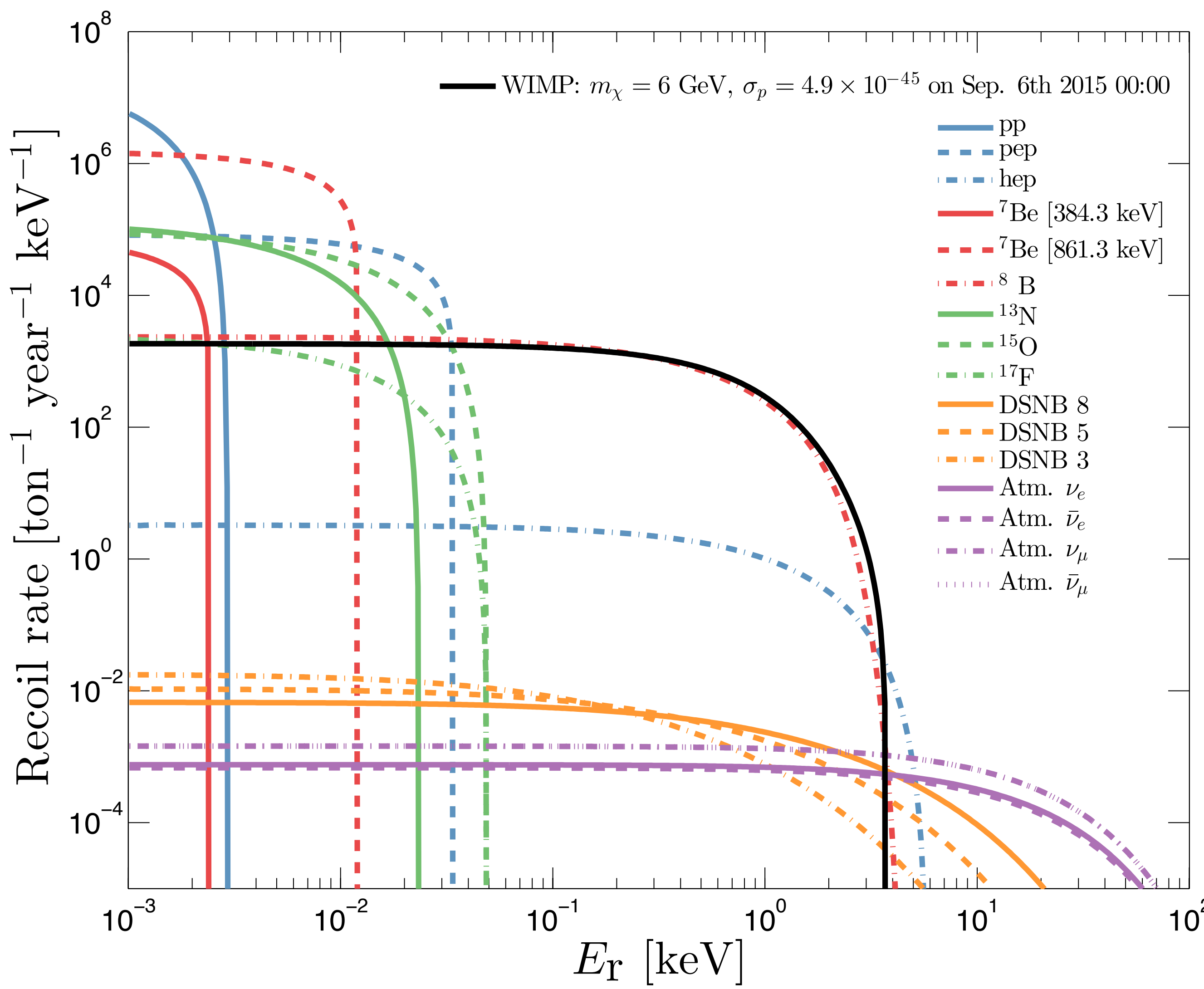


[Boulby mine]

[Zeplin III]

In the future coherent neutrino-nucleus scattering will be a background for direct detection experiments. [Drukier, Freese & Spergel; Monroe & Fisher; Strigari]

Energy spectra for Xe target



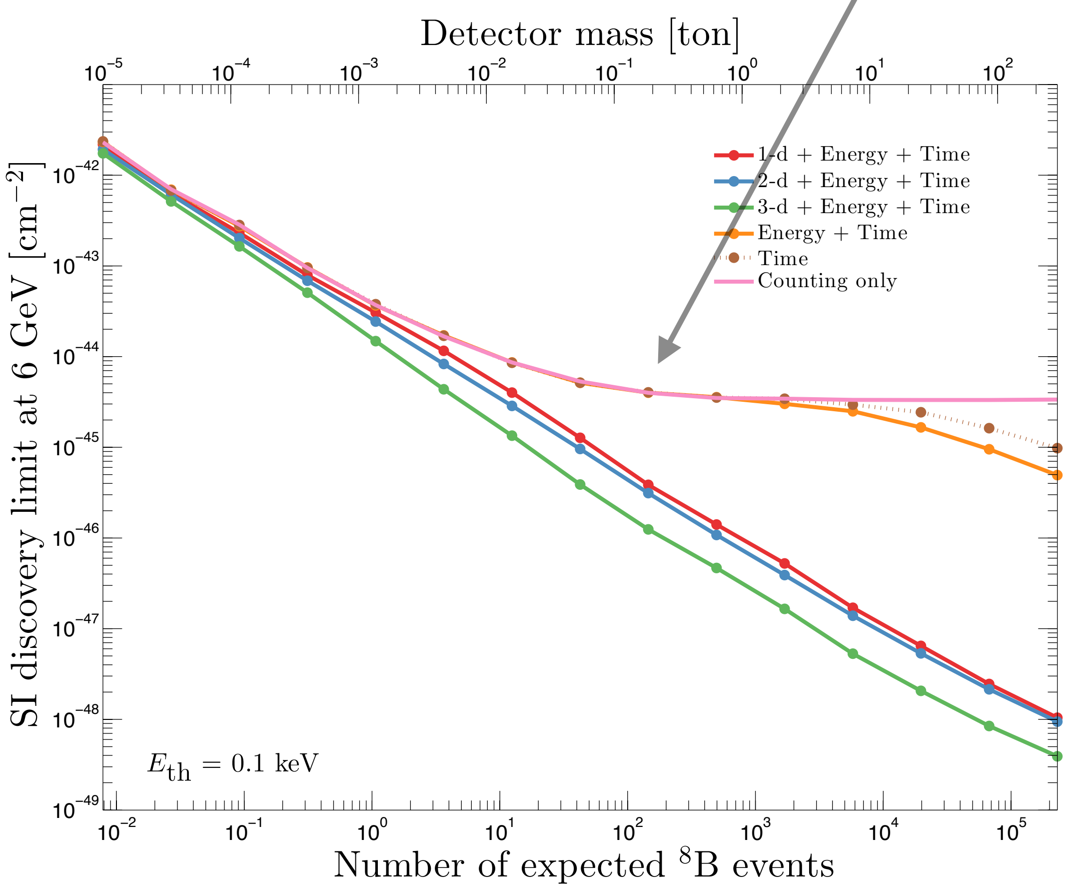
6 GeV WIMP

coloured lines: different neutrino species
(solar, diffuse SNe background & atmospheric)

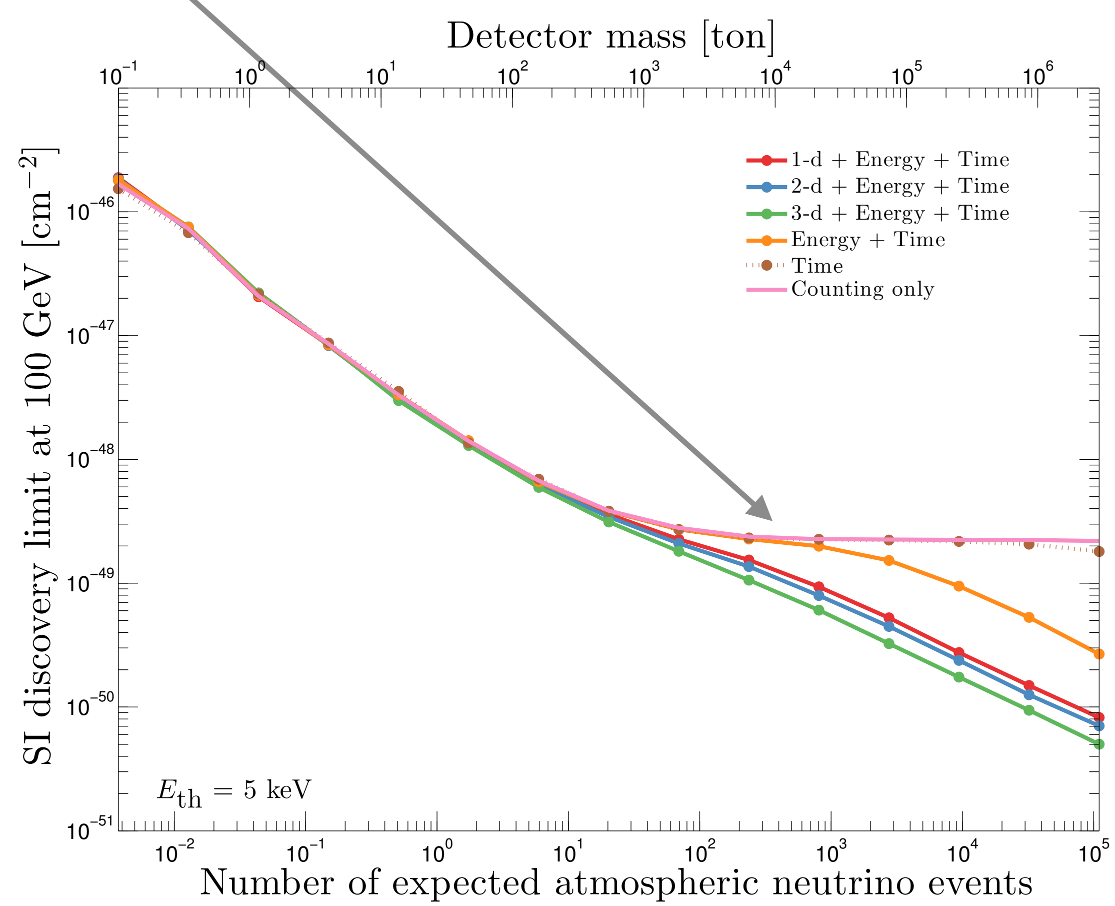
Directional detection can also discriminate WIMPs from neutrino backgrounds and probe cross-sections below the 'neutrino floor': [Billard et al.; Grothaus et al.; **O'Hare**,Green, Billard, Figueroa-Feliciano, Strigari]

Cross section sensitivity for as a function of exposure

6 GeV WIMP, 0.1 keV threshold



100 GeV WIMP, 5 keV threshold



counting only
time
energy + time

1d directionality + energy + time
2d + energy + time
3d + energy + time

Summary of current status:

Various ‘hints’:

excesses above expected backgrounds (CoGeNT, CDMS-Si)

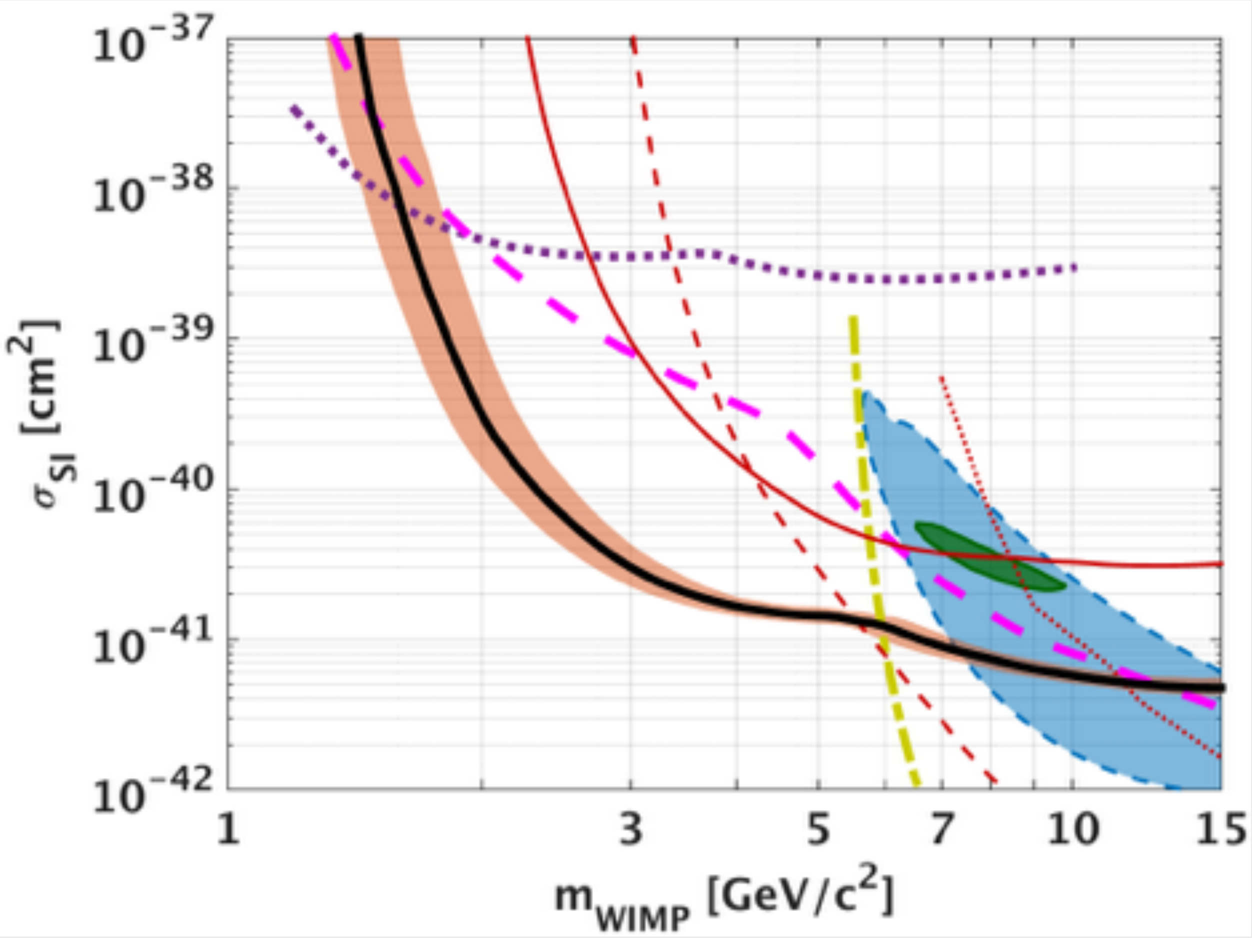
annual modulations (DAMA-LIBRA, CoGeNT)

which can individually be interpreted in terms of light (~10 GeV) WIMPs.

BUT

Hints are incompatible with each other and also null results from CDMSlite, CRESST (- -), LUX (- - -), SuperCDMS (- - - -).

WIMP-proton cross-section (cm^2)



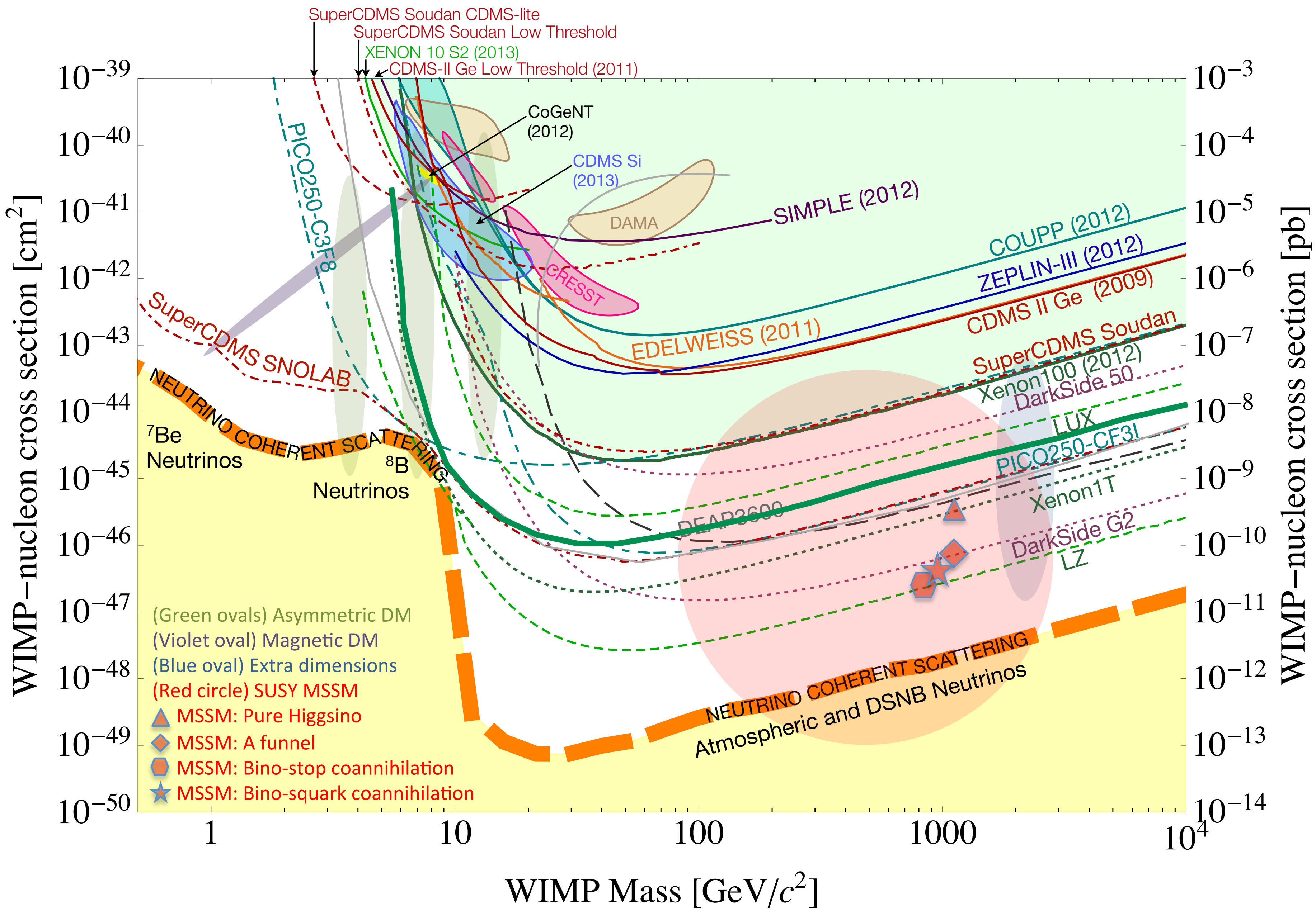
WIMP mass (GeV)

[CDMSlite]

Future prospects:

Upgrades of current experiments to the multi-tonne scale, improving sensitivity by up to 3 orders of magnitude.
(e.g. DARWIN, EURECA, LUX-Zeplin, SuperCDMS)

[Snowmass CF1 WG c. 2013]



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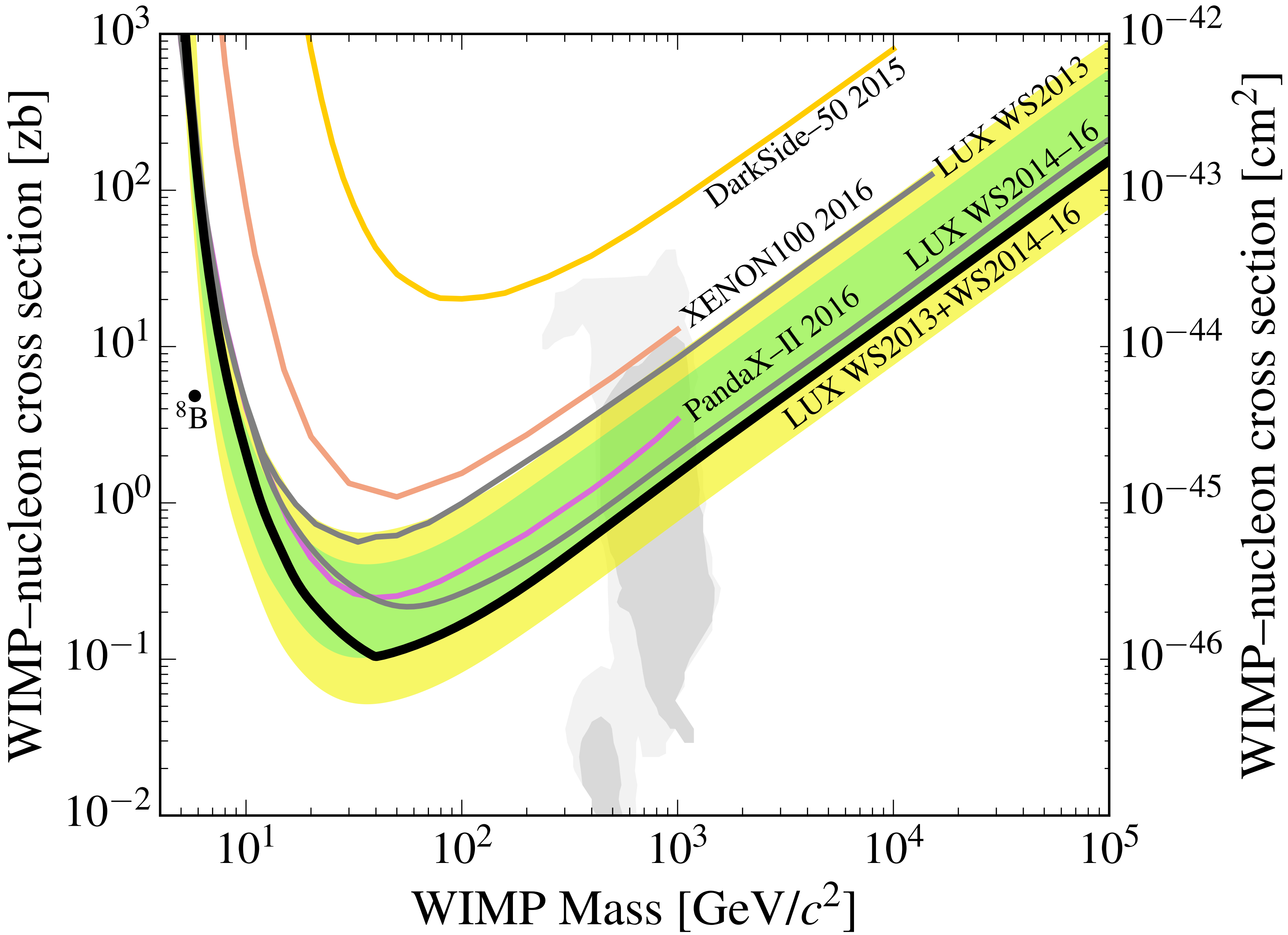
Significant recent improvements in sensitivity from LUX and PANDA-X:



So how can we (convincingly....) detect WIMPs?

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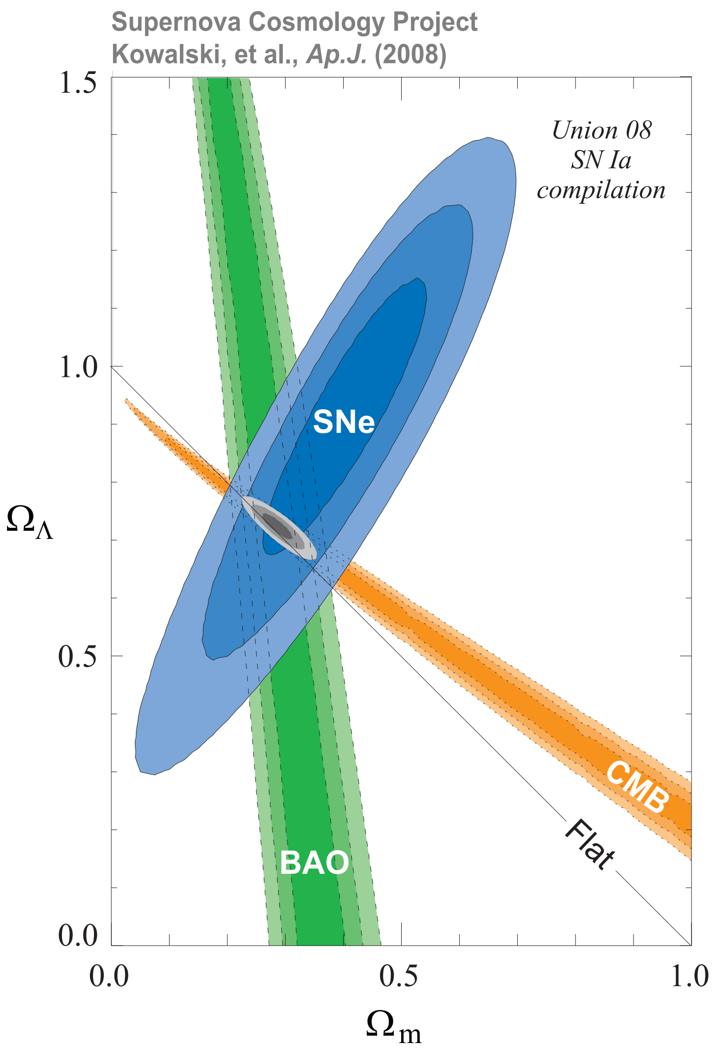
Consistent measurements of WIMP properties (e.g. mass) from different direct, indirect and collider experiments.

c.f. cosmic concordance



Measuring the WIMP mass & cross section

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\sigma_{\rm p}\rho_0}{\mu_{\rm p,\chi}^2 m_\chi} A^2 F^2(E) \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v}\,\mathrm{d}v$$

$$v_{\rm min} = \left(\frac{E(m_A + m_\chi)^2}{2 m_A {m_\chi}^2} \right)^{1/2}$$

minimum speed that can cause a recoil with energy E

Particle physics parameters: WIMP mass and cross-section m_χ $\sigma_{\rm p}$

Astrophysical input: local DM density and speed distribution ρ_0 $f(v)$

Normalization: σ and ρ are degenerate.

Shape of energy spectrum: depends on m_χ and f(v).

Experimental constraints on σ-m_χ plane usually calculated using 'standard halo model':

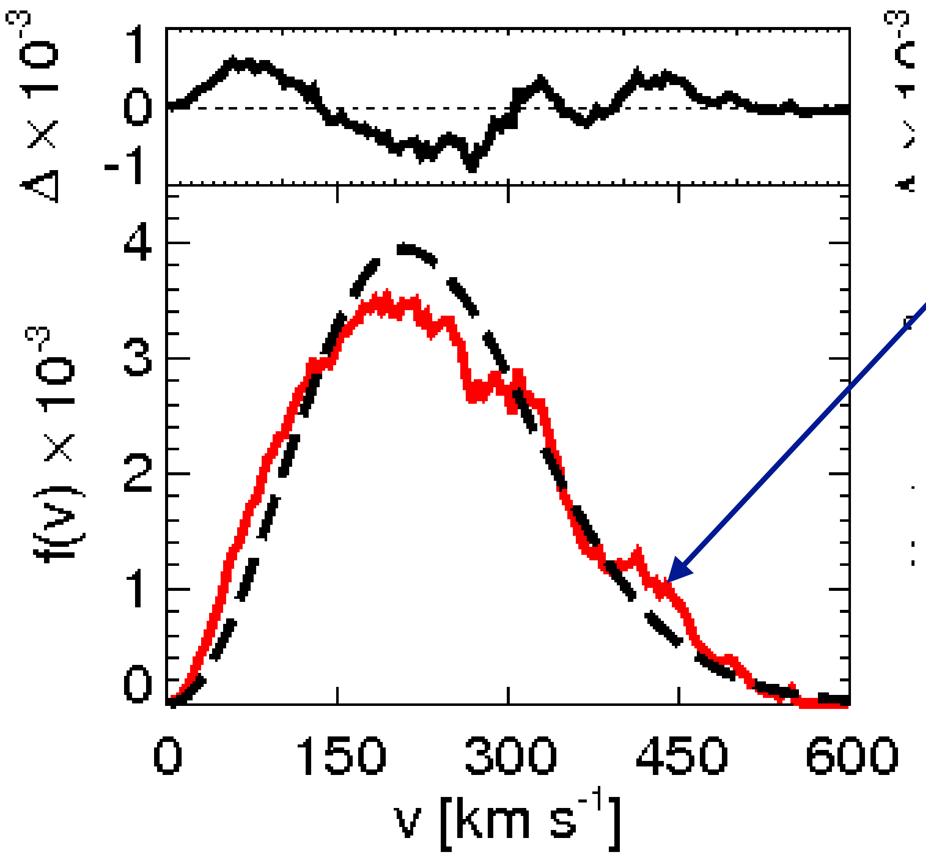
isotropic, isothermal sphere, with Maxwell-Boltzmann speed distribution

$$f(\mathbf{v}) \propto \exp\left(-\frac{3|\mathbf{v}|^2}{2\sigma^2} \right) \qquad \sigma = \sqrt{\frac{3}{2}} v_{\rm c}$$

with v_c=220 km s^{-1} and local density ρ_0=0.3 GeV cm^{-3}

But halos in DM only simulations have f(v) which deviate systematically from multi-variate gaussian: more low speed particles, peak of distribution lower/flatter. [Fairbairn & Schwetz; Vogelsberger et al., Kuhlen et al.]

Features in tail of distribution: potential tidal streams + 'debris flows' (incompletely phased mixed material) [Lisanti & Spergel; Kuhlen, Lisanti & Spergel].



[Vogelsberger et al.]

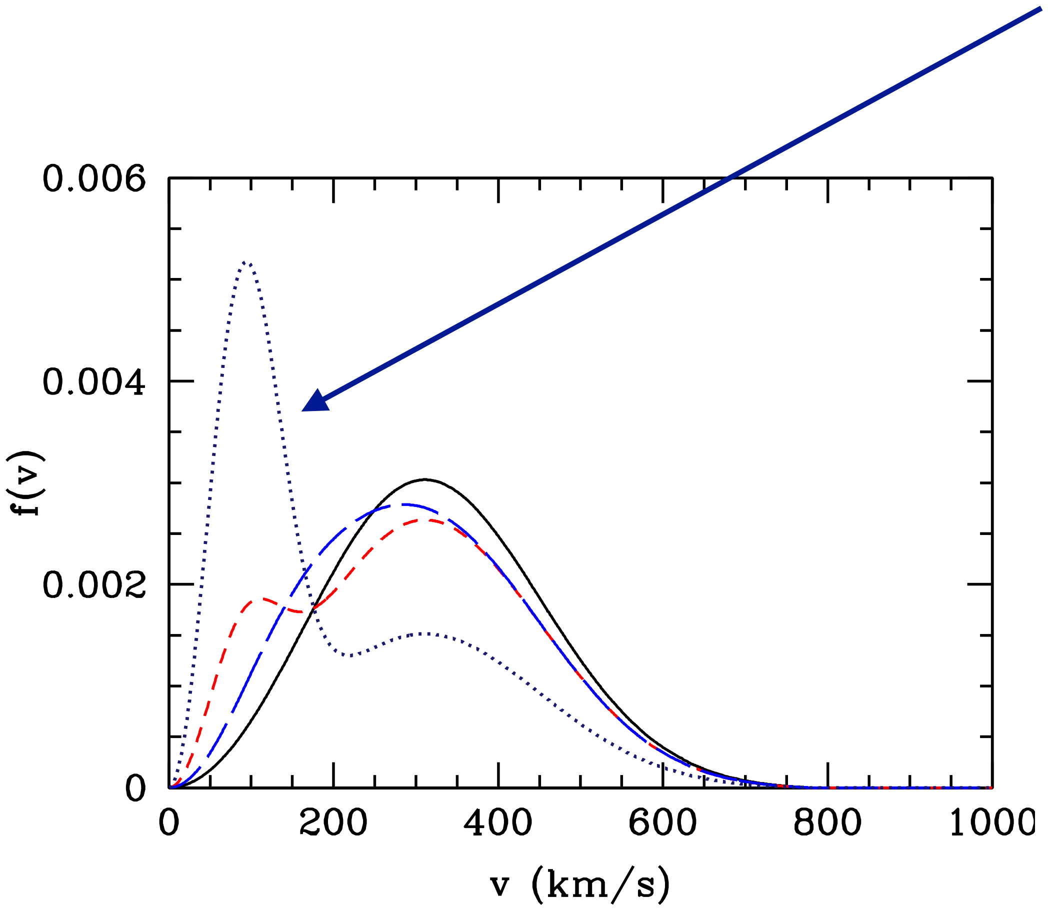
red lines: simulation data,
black lines: best fit multi-variate Gaussian

Recent progress in hydrodynamical simulations (including baryons) [Sloane et al.; EAGLE/APOSTLE: Borzognia et al.; MaGICC Kelso et al,]: Maxwellian distribution is a better fit, but no consensus as to whether it's a *good* fit.

dark-disc:

Sub-halos merging at z<1 preferentially dragged towards disc, where they're destroyed leading to the formation of a co-rotating dark disc. [Read et al., Bruch et al., Ling et al.]

Could have a significant effect on f(v) if density is high and velocity dispersion low.



However:

Recent hydrodynamical simulations of MW-like galaxies (e.g. [Guedes et al.; Borzognia et al.; Kelso et al.; Sloane et al.]): find low density or no dark disc.

[Ruchti et al.]: no sign of stellar component in GAIA data.

Deviations from the standard halo model are almost certainly not as large as (I) once feared.

However, the standard halo model may well not be a great approximation to the real Milky Way halo.

How should we handle our ignorance of the local WIMP speed distribution?
n.b. with a single experiment can't extract any information about the WIMP properties without making assumptions about f(v).

Marginalise Strigari & Trotta (also Catena & Ullio):

Assume isotropic Maxwellian f(v) characterised by v_0 and v_{esc}, use astronomical data (kinematics of MW halo stars and measurements of local escape speed), marginalise over parameters of model for MW density distribution and anisotropy.

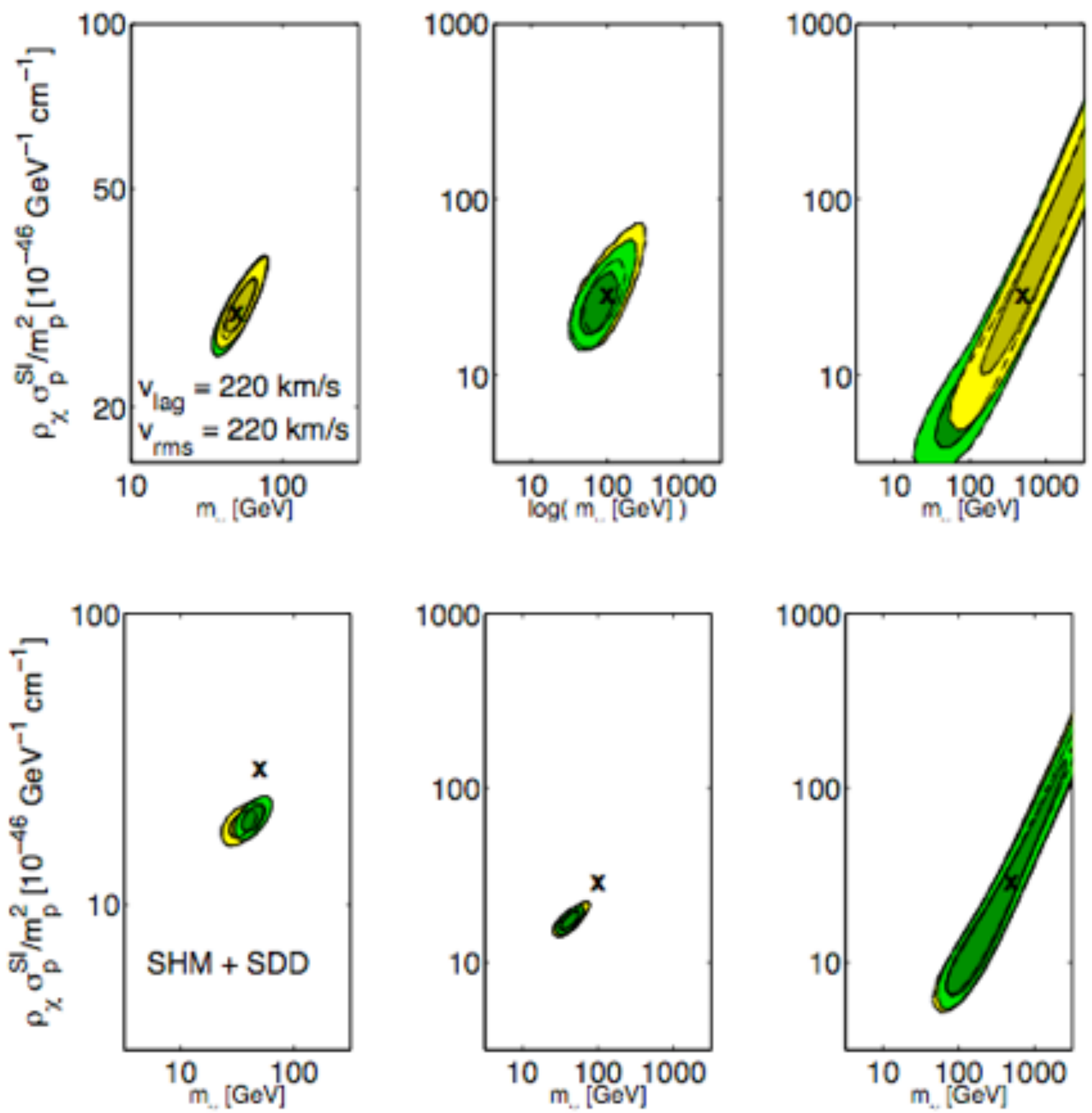
Parameterise Peter:

Combine data sets from different direct detection experiments, parameterise WIMP speed distribution, jointly constrain WIMP mass, cross-section and speed distribution parameters.

If actual shape of f(v) is similar to assumed shape marginalisation approach works well, but if not can get significant biases:

$$D = \frac{\rho_0 \sigma_{\rm p}}{m_\chi^2}$$

$m_\chi = 50\,\mathrm{GeV}$ $\quad 100\,\mathrm{GeV}$ $\quad 500\,\mathrm{GeV}$



m_χ

Peter simulated data from future tonne scale Xe, Ar & Ge expts, analysed assuming standard halo model (allowing v_{lag} & v_{rms} to vary).

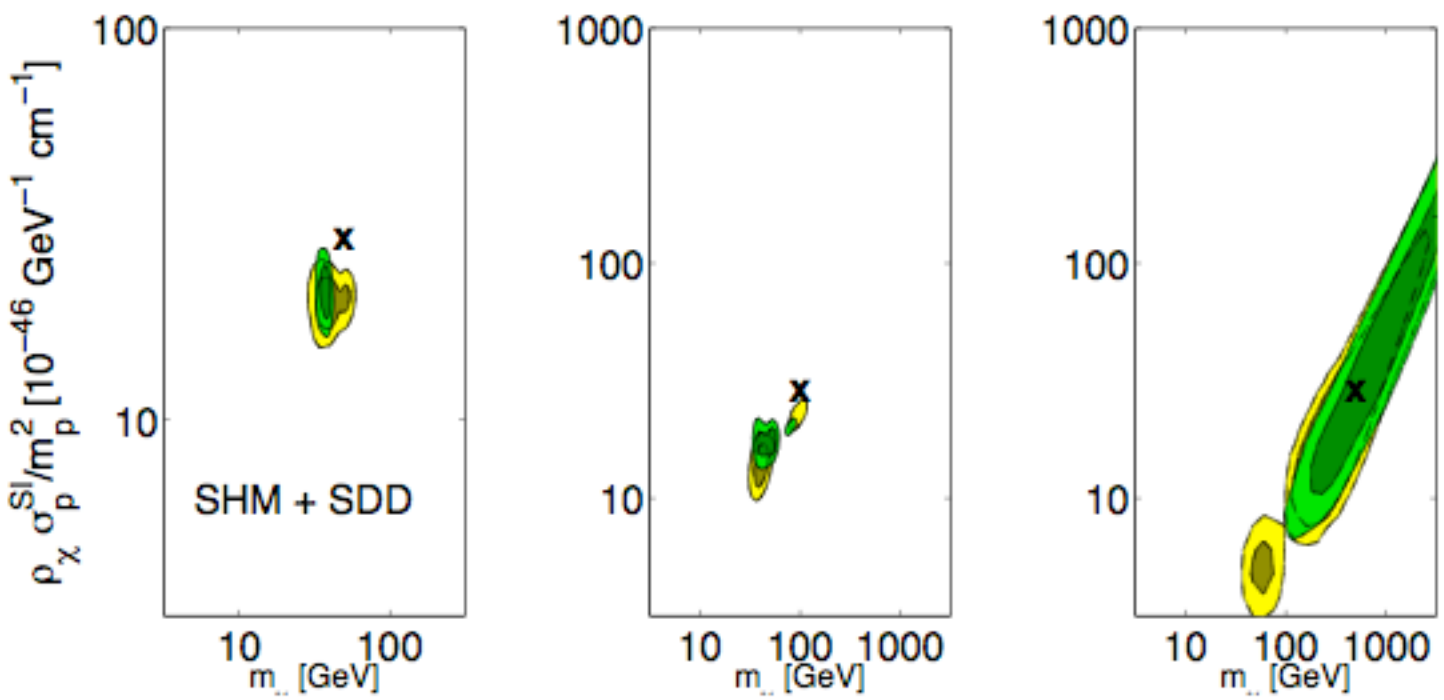
standard halo model in

standard halo model + dark disc in

How to parameterise f(v)?

Peter Use empirical parameterization of f(v), and constrain its parameters along with mass & cross-section.

First approach: piece-wise constant in bins



standard halo model + dark disc in

Better than assuming wrong f(v), but mass & cross-section both biased.

Cross section: a significant (but a priori unknown) fraction of the WIMPs are below threshold. Inevitable problem when doing model independent analysis of direct detection data (but see later…)

Mass: reducing m reduces width of bins in E, and enables better fit. Kavanagh & Green

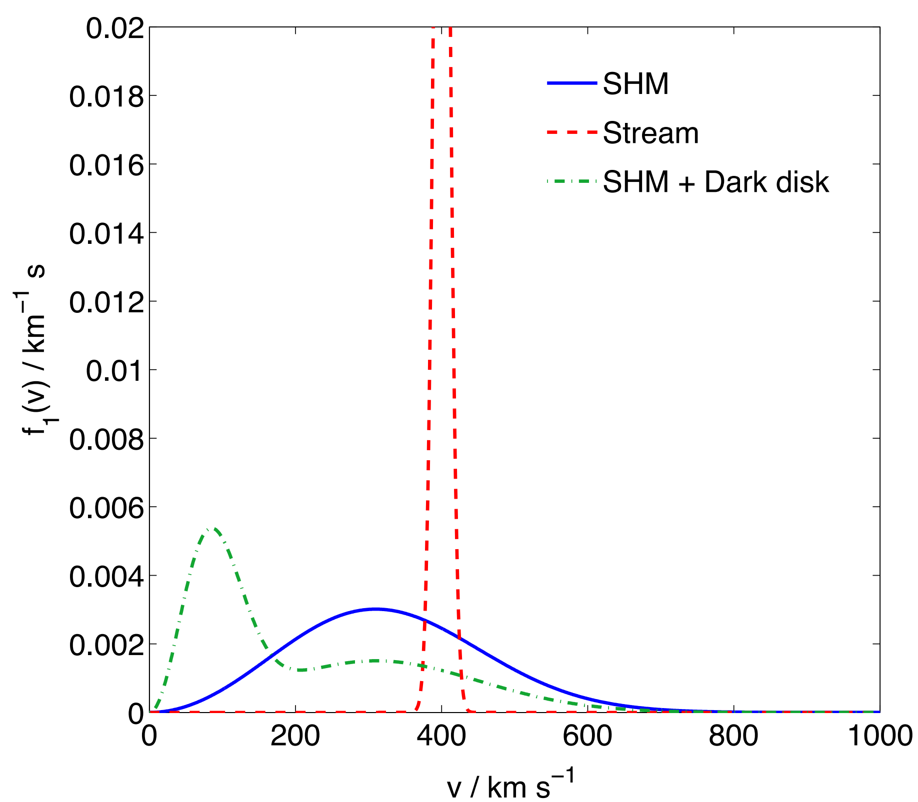
Kavanagh & Green; Kavanagh

Parameterise log of f(v) in shifted Legendre polynomials:

$$f(v) \propto \exp\left\{ -\sum_{k=0}^{N} a_k \bar{P}_k(v/v_{\rm max}) \right\}$$

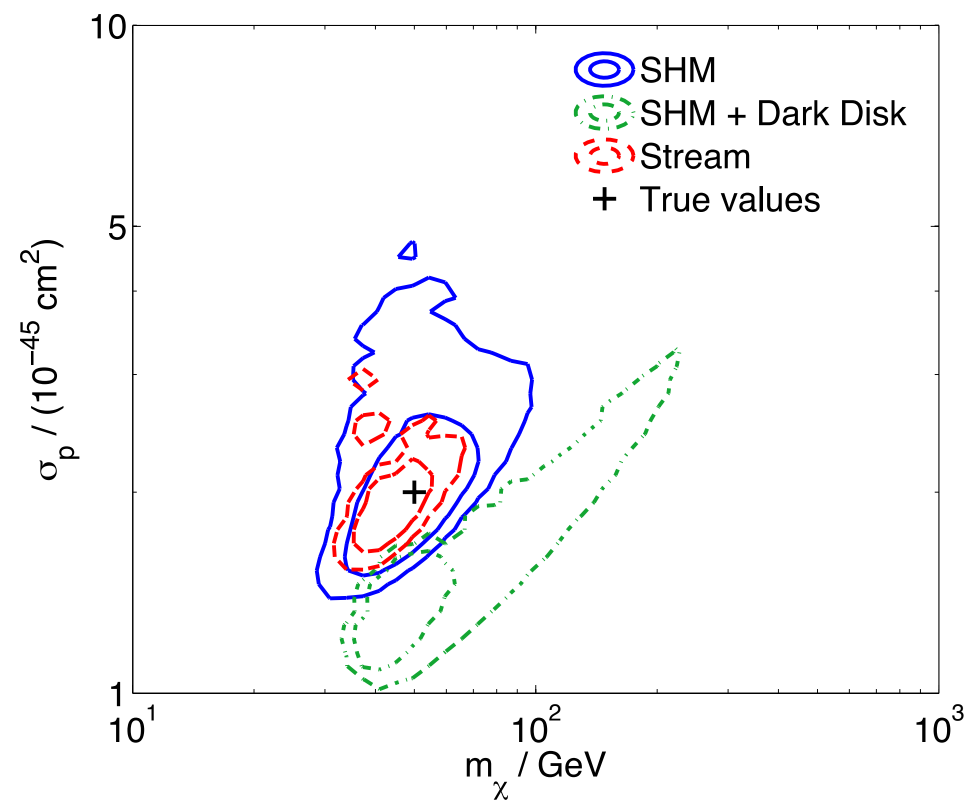
Gives good reconstruction of WIMP mass even for extreme input f(v) (stream or dark disc), and allows f(v) to be reconstructed (using simulated data from future tonne scale experiments):

input speed distributions



SHM
Stream
SHM + dark disc

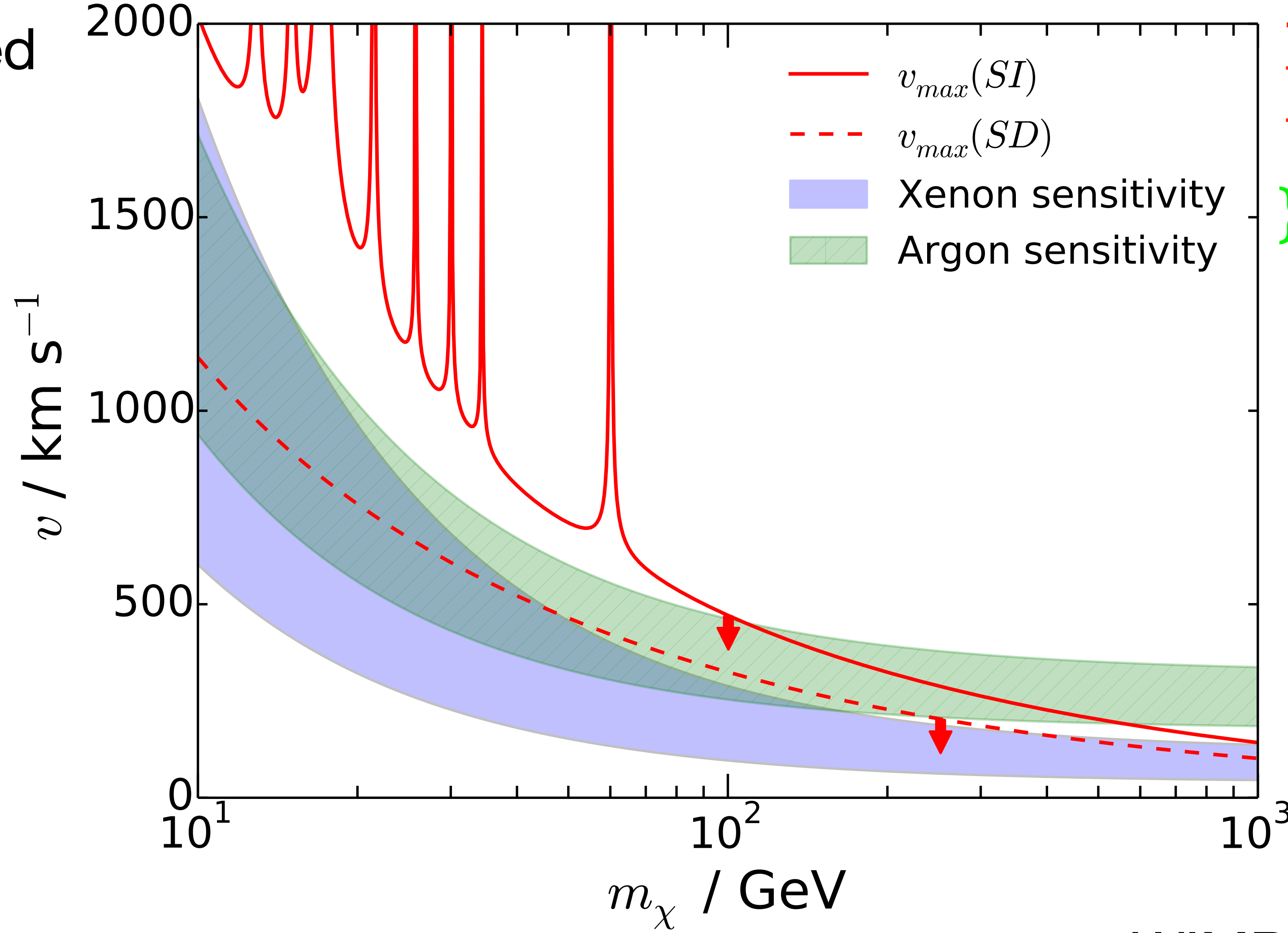
reconstructed mχ and σ



Kavanagh, Fornasa & Green

To get an unbiased estimate of the cross section, need to probe entire speed distribution:

combine IceCube and direct detection data



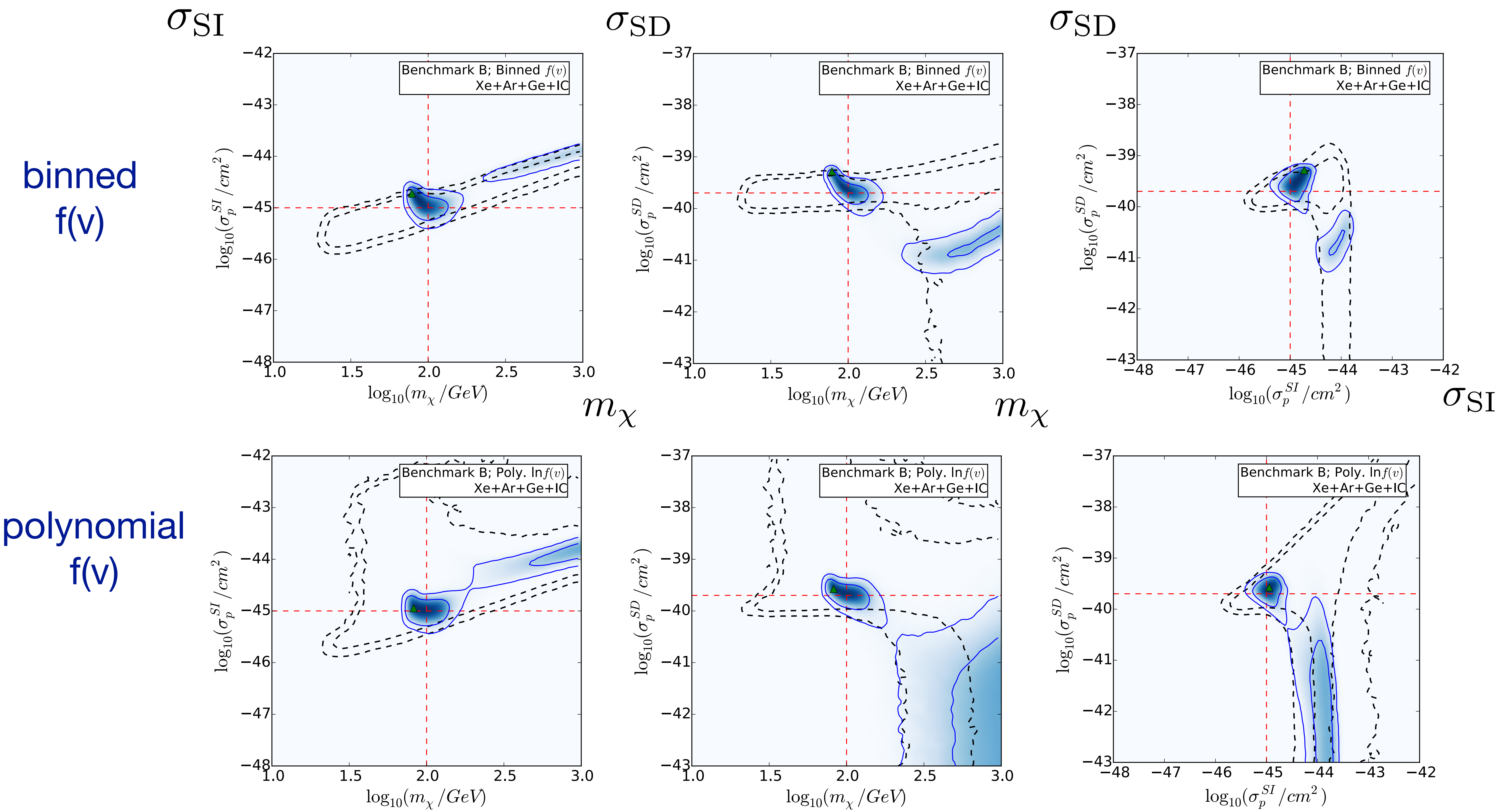
maximum speed captured in Sun for
_____ spin-independent
- - - - spin-dependent
} interactions

} range of sensitivity of typical direct detection experiments

WIMP mass

Kavanagh, Fornasa & Green

Reconstructed mass and cross-sections for a 100 GeV WIMP annihilating into W^+W^- with f(v) = SHM + DD using simulated data from Xe, Ar & Ge direct detection experiments + IceCube. - - - - - using DD data only - - - - - input values



Get unbiased determinations of the WIMP mass and cross-sections, for both f(v) parameterisations

A self-consistent anisotropic f(v) (Mattia Fornasa)

Model the luminous & dark components of MW (consider cuspy & cored halo density profiles).

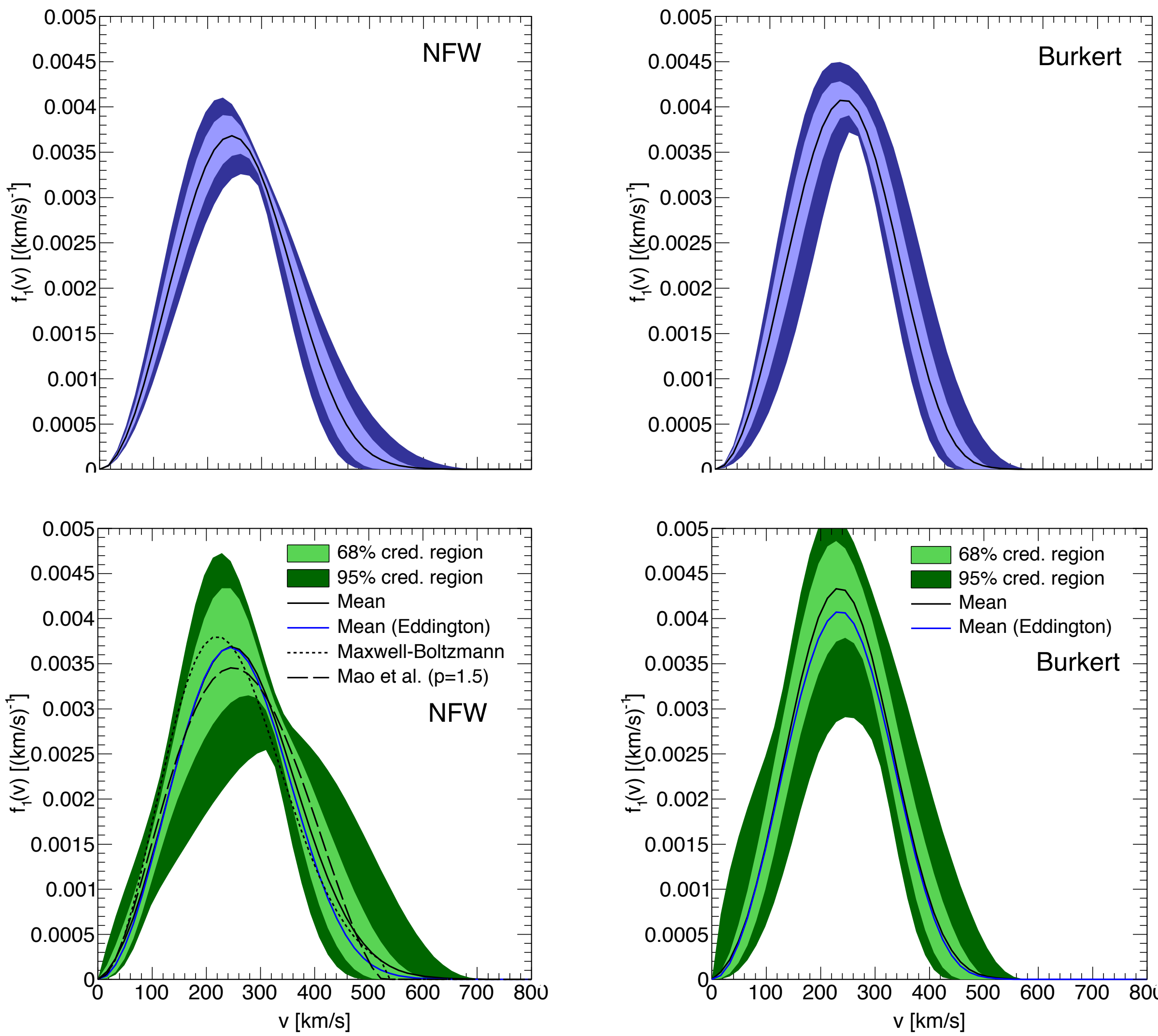
Constrain parameters using ensemble of observations.

Derive self-consistent f(v) using Eddington formalism, allowing for anisotropy in f(v).

NFW Burkert

Isotropic:

Anisotropic:



Find similar results using Einasto profile for DM halo.

Can use this approach to derive direct detection constraints that are compatible with the Galactic centre excess being due to WIMP annihilation (either by using a DM halo profile with inner slope consistent with excess, or including excess in data sets used to constrain model). [Cerdeno, Fornasa, Green & Piero]

Summary

❊ Galaxy halos (and the Universe as a whole….) contain significant amounts of non-baryonic dark matter (assuming Newtonian gravity/GR is correct).

❊ WIMPs generically have the right sort of present day density and supersymmetry provides us with a concrete candidate, the lightest neutralino.

❊ WIMPs can be detected indirectly (via their annihilation products) and and directly (via their elastic scattering from nuclei).

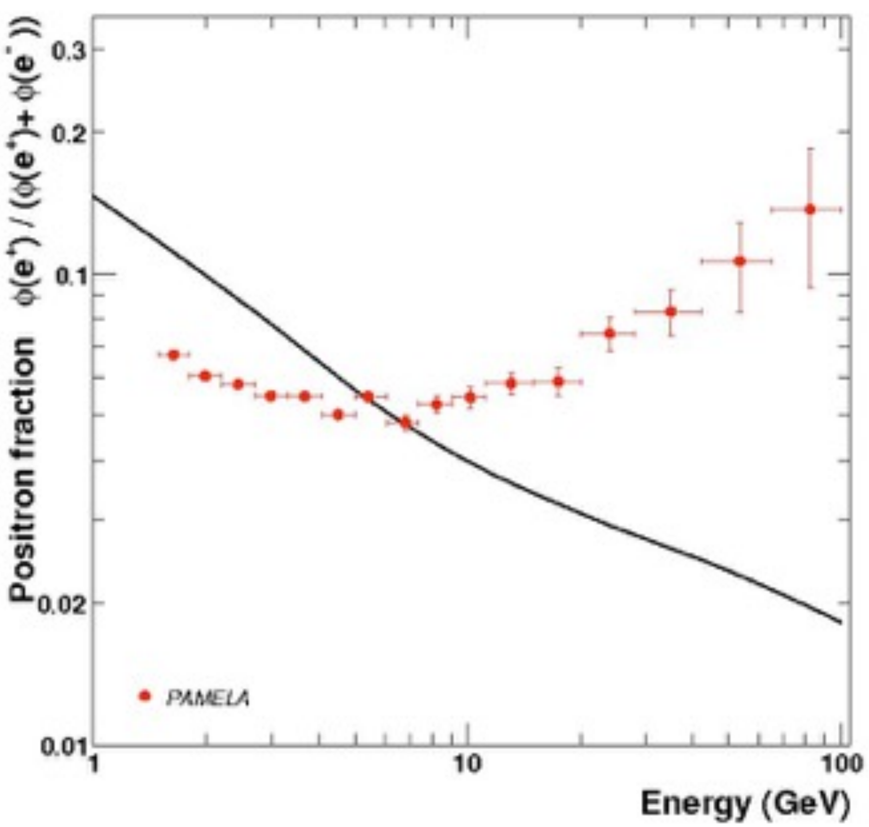
❊ Can handle astrophysical uncertainties in direct detection experiments with a suitable parameterisation of the WIMP speed distribution.

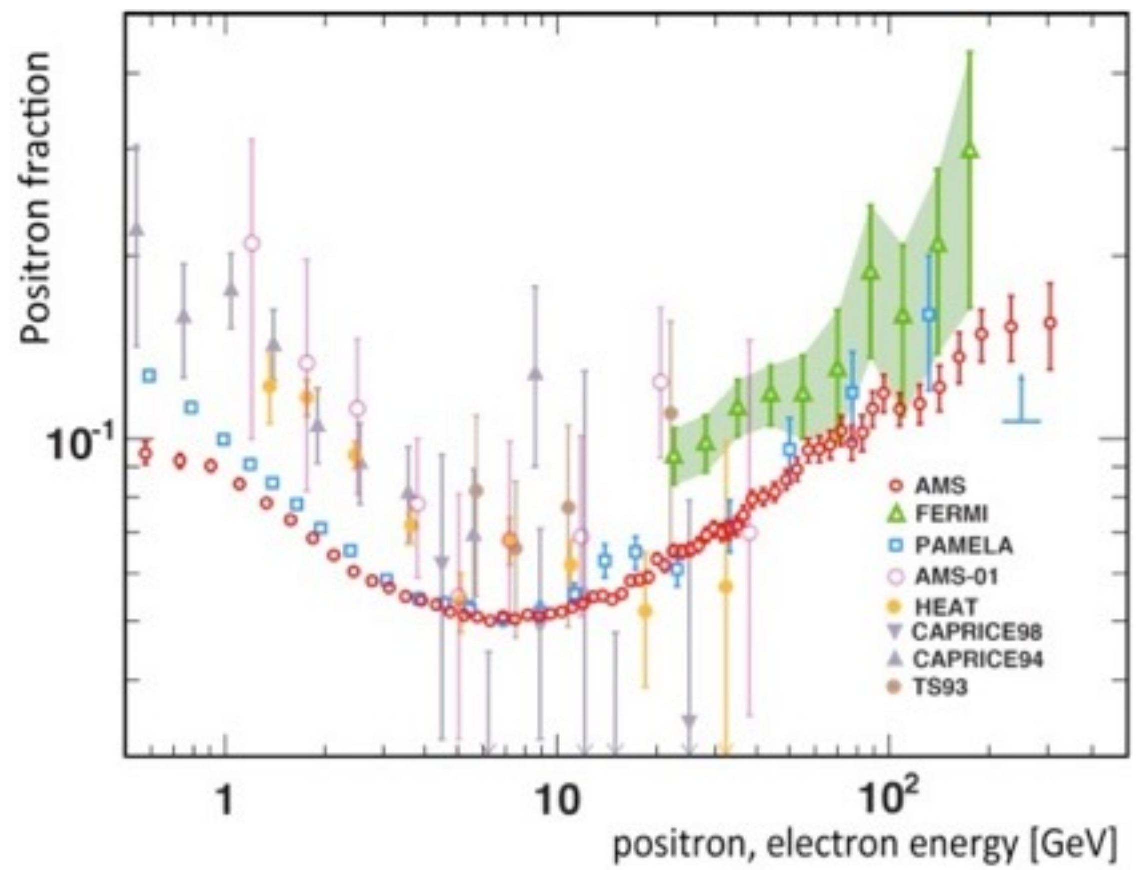
❊ Combining (future) direct detection & IceCube data allows unbiased measurement of cross-section and reconstruction of f(v).

Back up slides

Various other excesses which can be potentially explained by WIMP annihilation

e.g. HEAT/PAMELA/Fermi/AMS positron excess:





Can explain it using DM annihilation but need:

i) large enhancement in annihilation rate (clumpy DM within ~kpc, or enhancement of annihilation cross-section, or non-thermal WIMP production)

ii) to not overproduce anti-protons (or gamma-rays or affect the CMB…)

And there are various plausible astrophysical sources e.g. pulsars, SNe remnants

Particles produced in WIMP annihilations

Particle physics

+

WIMP spatial (density) distribution

Astrophysics (with some particle input)

+

(for charged particles) propagation of annihilation products

⇩

predicted signals

Particles produced in WIMP annihilations

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predicted signals

Event rates depend on WIMP distribution $\propto \rho^2$. Largest gamma-ray signals expected from high density regions (e.g. Galactic centre, dwarf galaxies,...)

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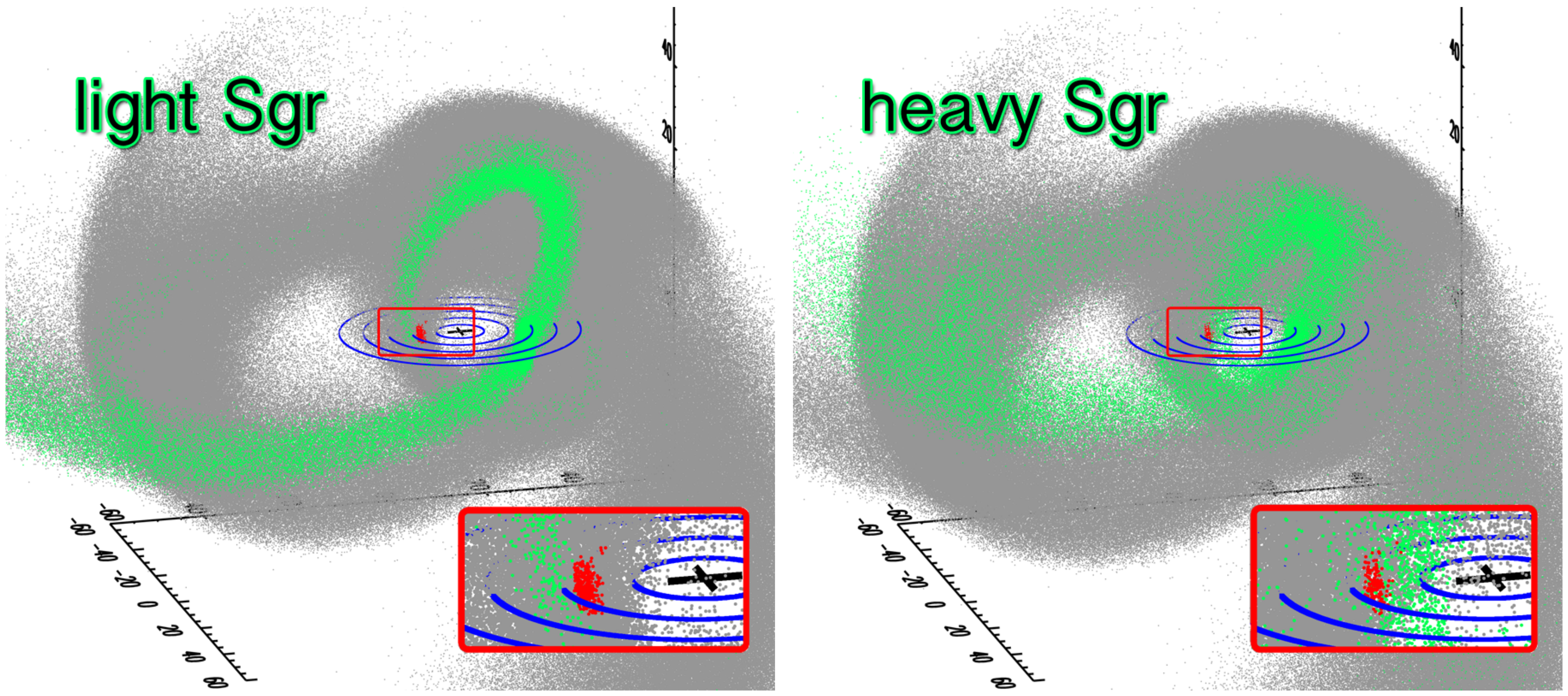
Enhancement of rate w.r.t that produced by smooth halo, parameterised by boost factor.

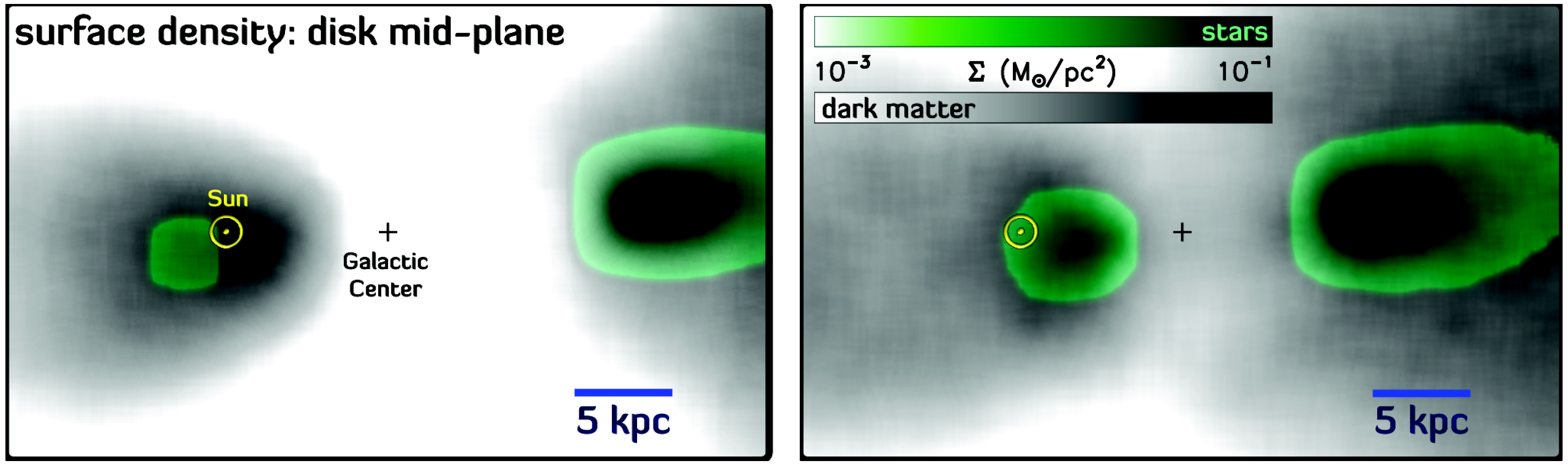
Different species probe different scales/regions (and often on scales far smaller than those directly resolved by numerical simulations). Boost factor species dependent and not accurately known.

Often need to distinguish WIMP annihilation from astrophysical backgrounds.

tidal streams:

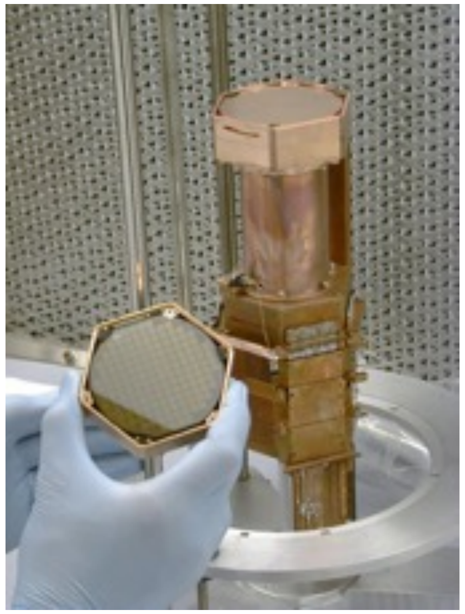
DM component of Sagittarius leading **stream** may pass through the solar neighbourhood [Purcell, Zentner & Wang] (as originally suggested by [Freese, Gondolo & Newberg]).





Current status: i) null results

CDMS-II



cryogenic germanium (phonons and ionization)

612 kg days raw exposure, energy threshold 10 keV

2 events in signal region

0.8 background events expected
(surface events-electron recoils close to surface of detector)

Xenon100

two phase liquid/gas Xe (scintillation and ionisation)

48 kg fiducial volume, 101 days, energy threshold ~8.4 keV

3 events in signal region

1.8 ± 0.6 background events expected (mainly electron recoils)

Zeplin III

two phase liquid/gas Xe, (scintillation and ionisation)

raw exposure 1334 kg days (127.8 kg days after cuts), energy threshold ~7 keV

8 events in signal region, consistent with background estimates

ii) ‘excesses’

CoGeNT

germanium (ionization)

330 g fiducial mass, 56 days, energy threshold ~2 keV

“excess” of low energy events after fitting for exponential + constant background consistent with ~10 GeV WIMPs

CRESST

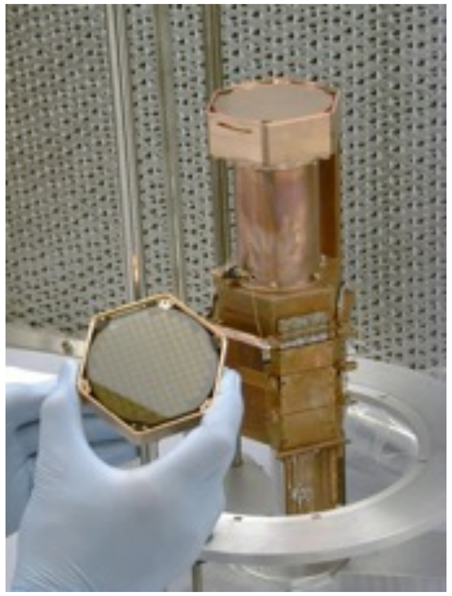
$CaWO_4$ (phonons and ionization)

net exposure 730 kg days, energy threshold 10-20 keV

67 events in signal region

maximum likelihood analysis:
(including parameterizations of 4 backgrounds)
~20 events due to light (10-25 GeV) WIMPs

An example of background rejection: electron recoil discrimination in CDMS-Ge (similar principles apply to other detectors/experiments)

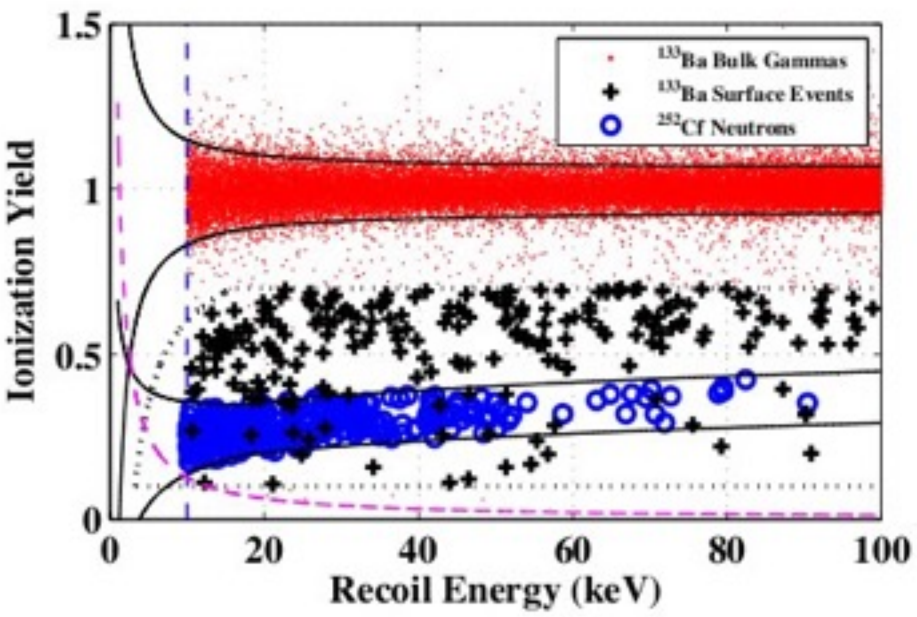


cryogenic Ge detectors can detect ionisation & phonons

electron recoils deposit larger fraction of energy in ionisation than nuclear recoils

Use radioactive sources to study electron & (neutron-induced) nuclear recoils.

Formulate data cuts which reject electron recoils (trade off between background rejection efficiency and signal acceptance).



electron recoils induced by gammas in bulk of detector
nuclear recoils induced by neutrons
electron recoils induced by gammas close to surface of detector

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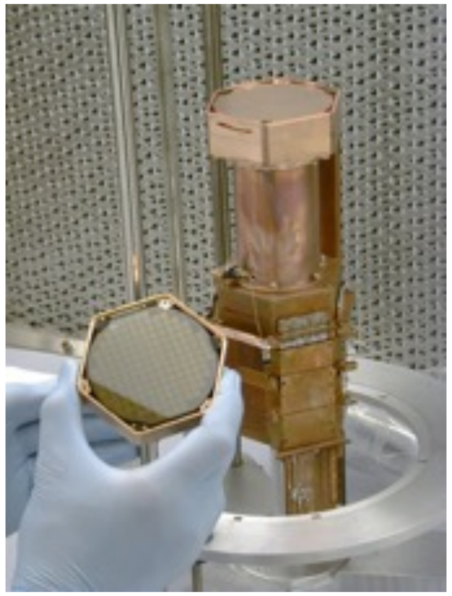

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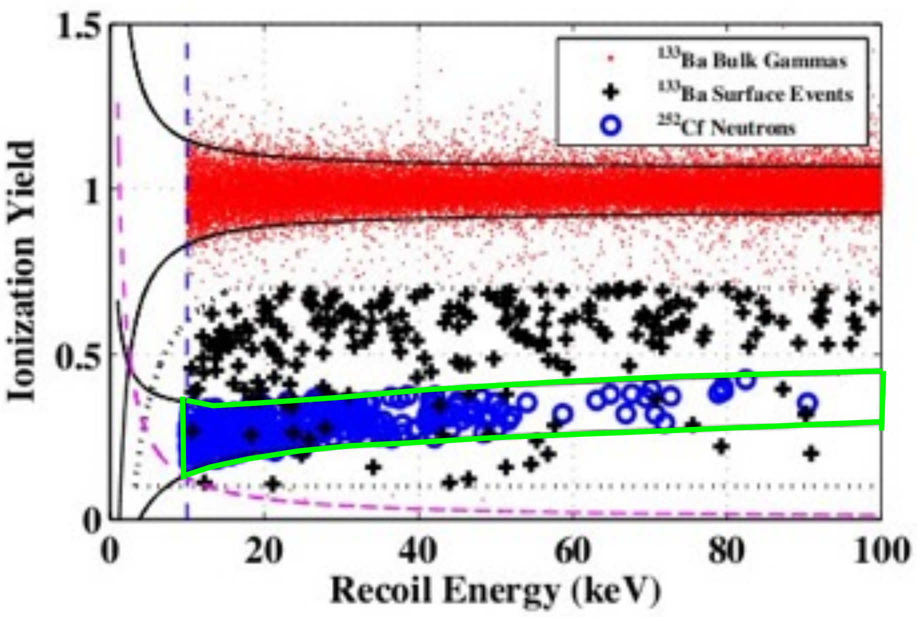

signal region

Ionization from electron recoils close to surface isn't collected completely, and they 'leak' into the nuclear recoil signal region.

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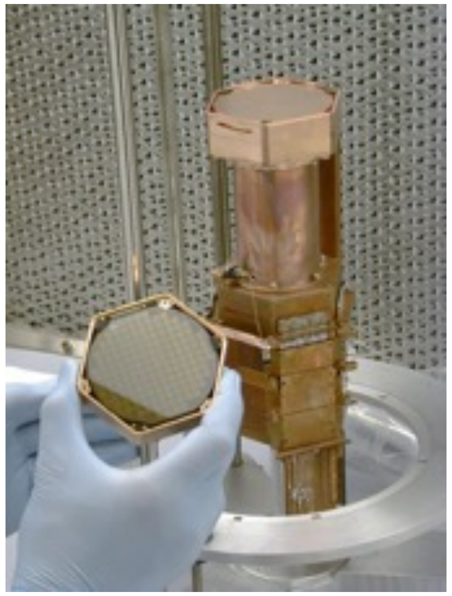

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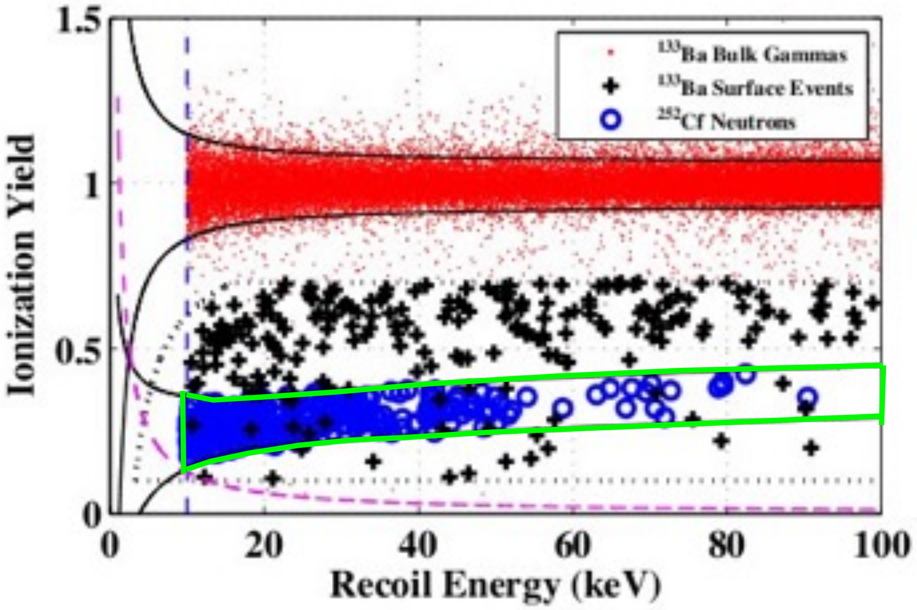
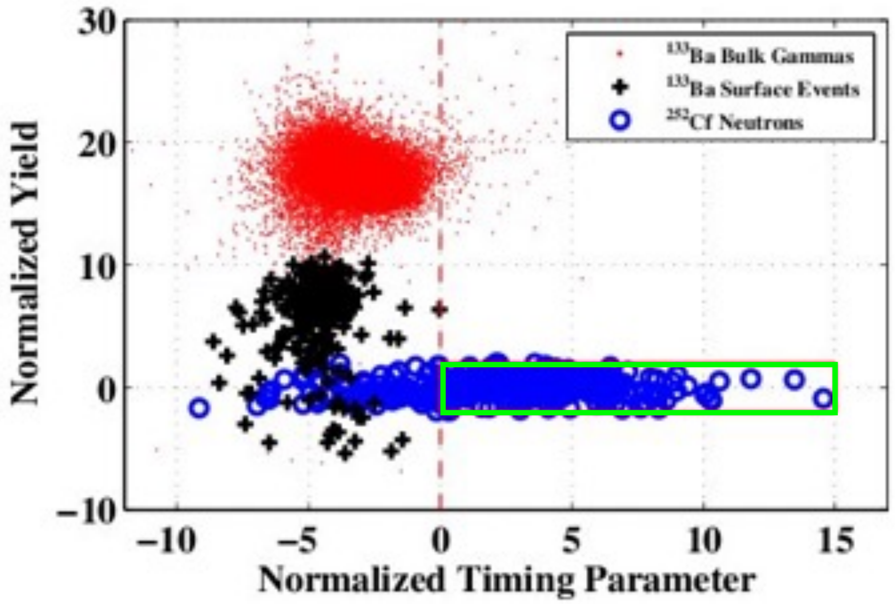


signal region



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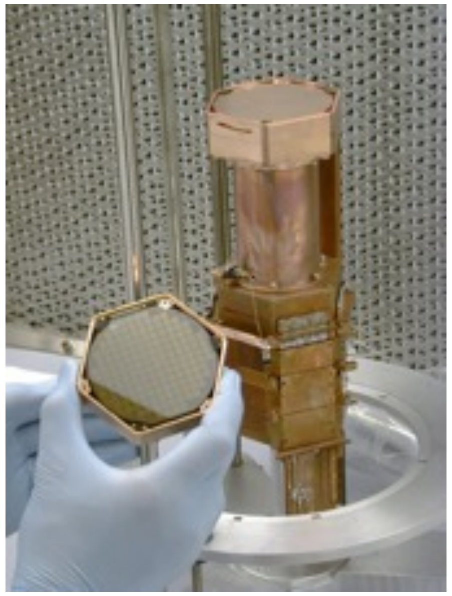

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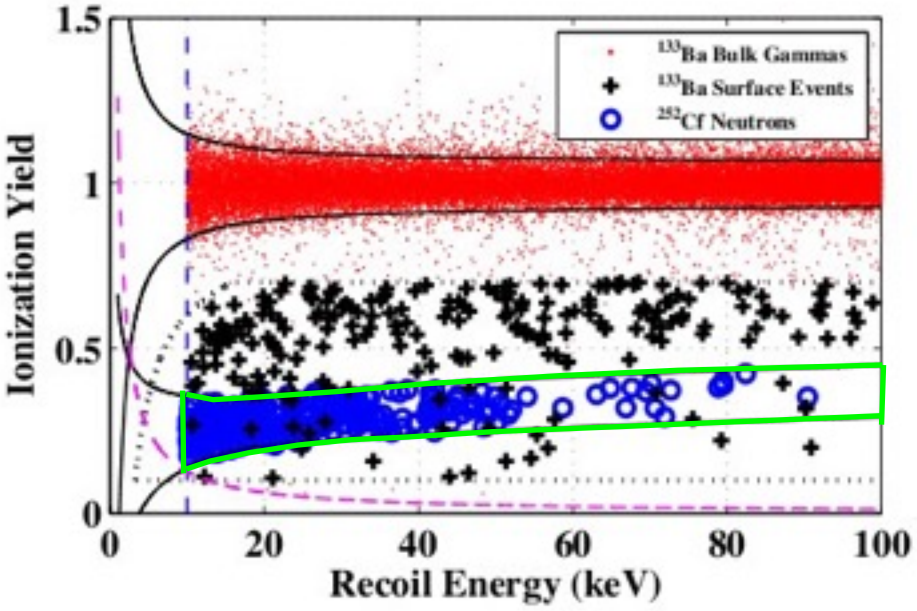

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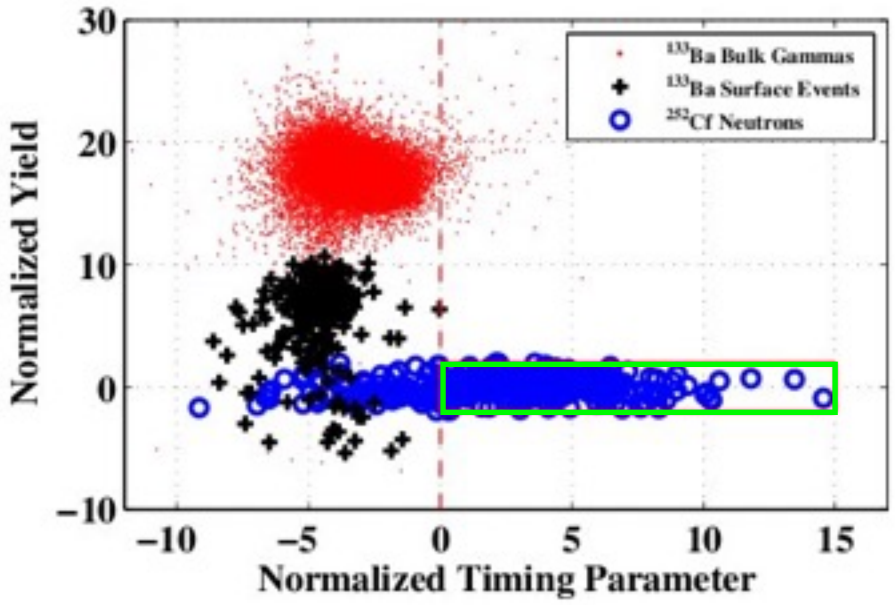


Next generation Super-CDMS experiment uses redesigned detectors to reduce this issue.

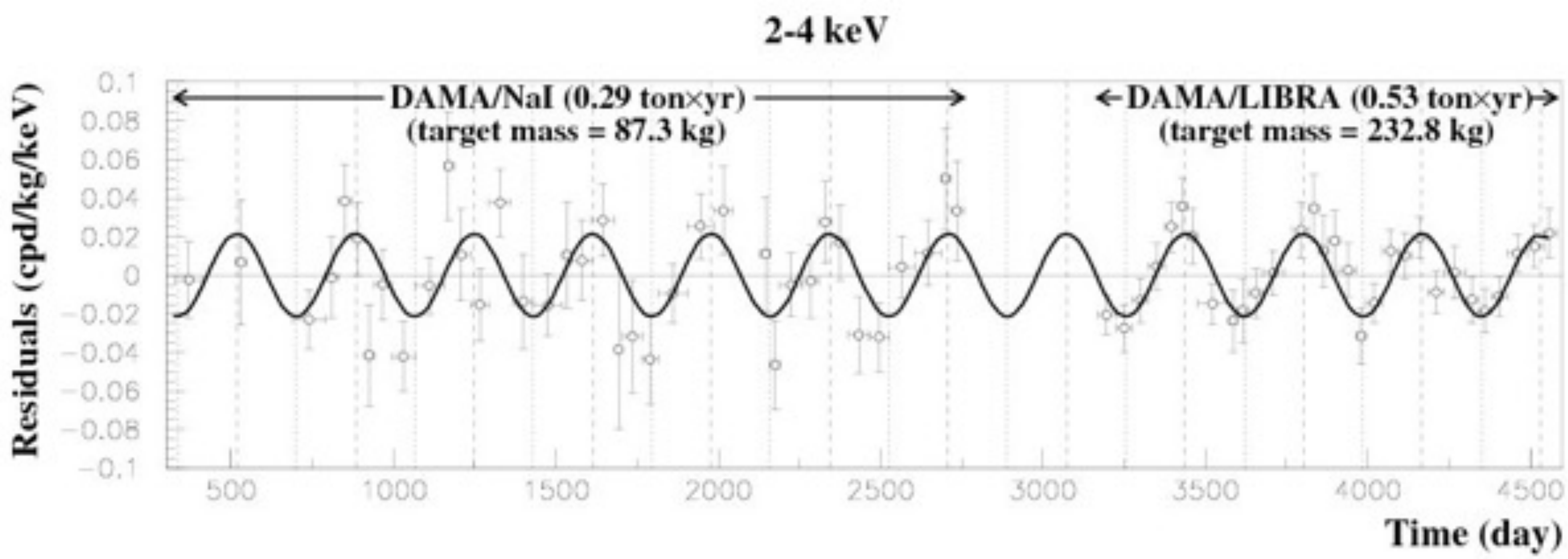
iii) annual modulations

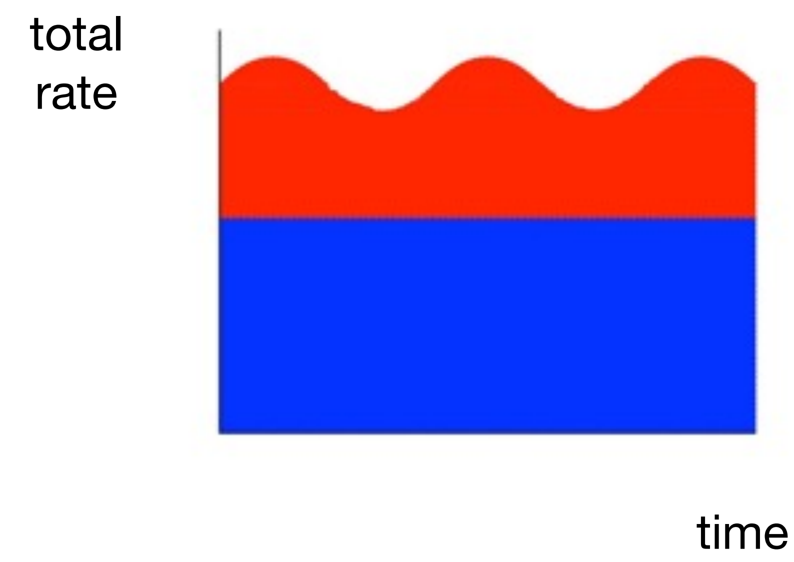
DAMA/LIBRA

NaI (scintillation)

exposure 1.2 ton years, energy threshold ~6 keV

8.4 σ annual modulation signal (over 12 years), phase compatible with WIMP expectations





CoGeNT

germanium (ionization)

145 kg days, energy threshold ~2 keV

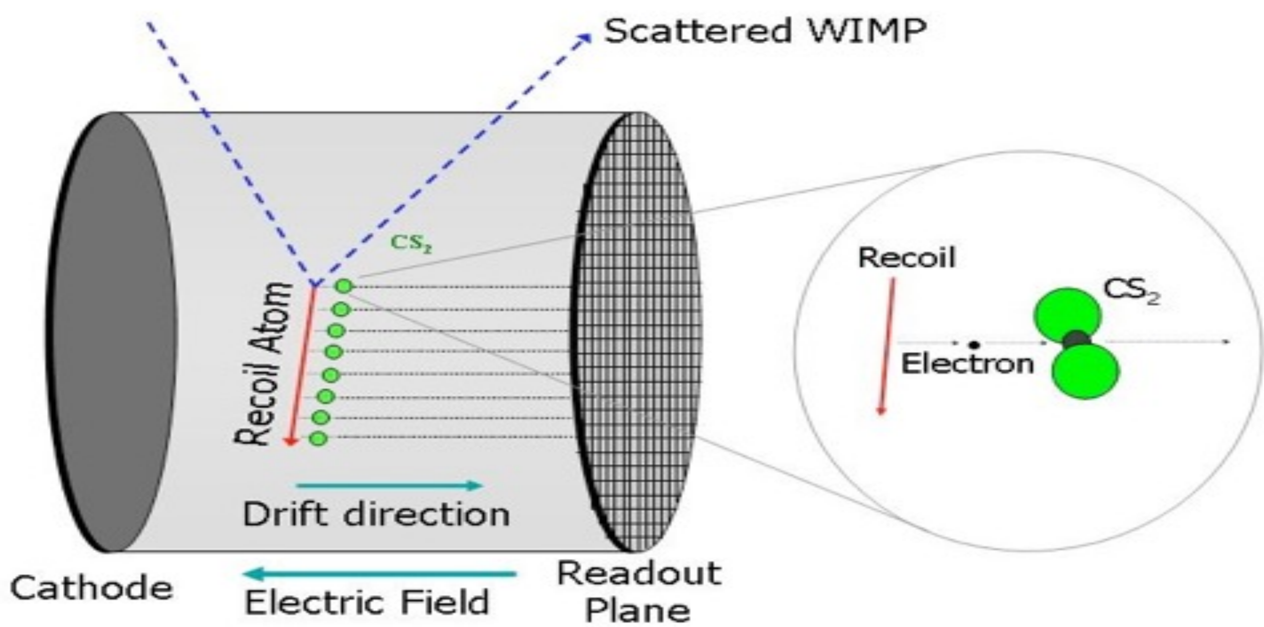
2.8 σ annual modulation signal (roughly compatible with DAMA).

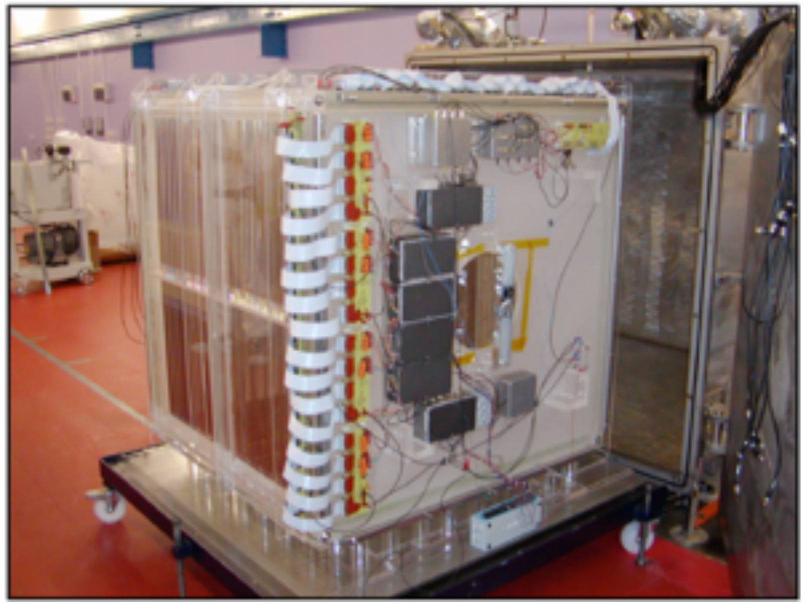
An example of a direction sensitive experiment:

Directional **R**ecoil **I**denitifcation **F**rom **T**racks

Low pressure gas Time Projection Chamber (recoil tracks in solid or liquid are very short)

Filled with electro-negative CS_2 (drift ions rather than electrons to minimise diffusion)





Other directional experiments:

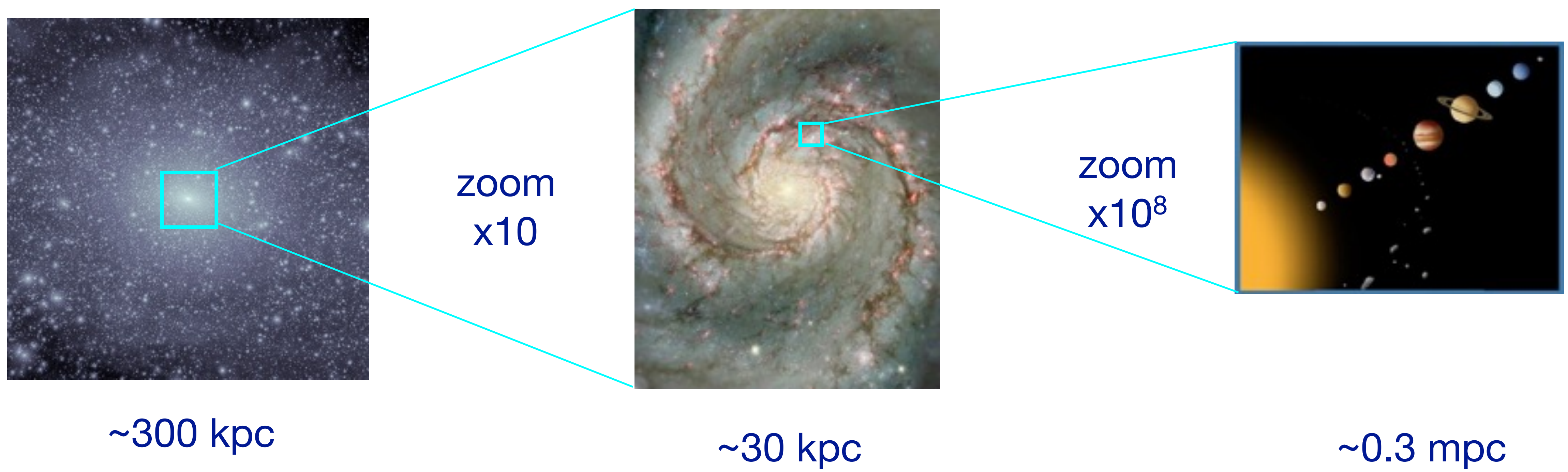
DMTPC, CF_4 filled TPC, scintillation detected with CCD camera

MIMAC, microTPC filled with H_3 or CF_4

NEWAGE, microTPC filled with CF_4

simulation caveats:

i) scales resolved by simulations are many orders of magnitude larger than those probed by direct detection experiments.



Ultra-local DM distribution may contain fine structure. [e.g. Fantin, Green & Merrifield]

ii) effect of baryons on DM speed distribution?

Sub-halos merging at $z<1$ preferentially dragged towards disc, where they're destroyed leading to the formation of a co-rotating dark disc. [Read et al, Bruch et al., Ling et al.]

Consequences of astrophysical uncertainties:

uncertainty in local DM density → uncertainty in normalisation of event rate and hence cross-section

uncertainty in WIMP velocity dispersion → uncertainty in characteristic scale of energy spectrum and hence WIMP mass

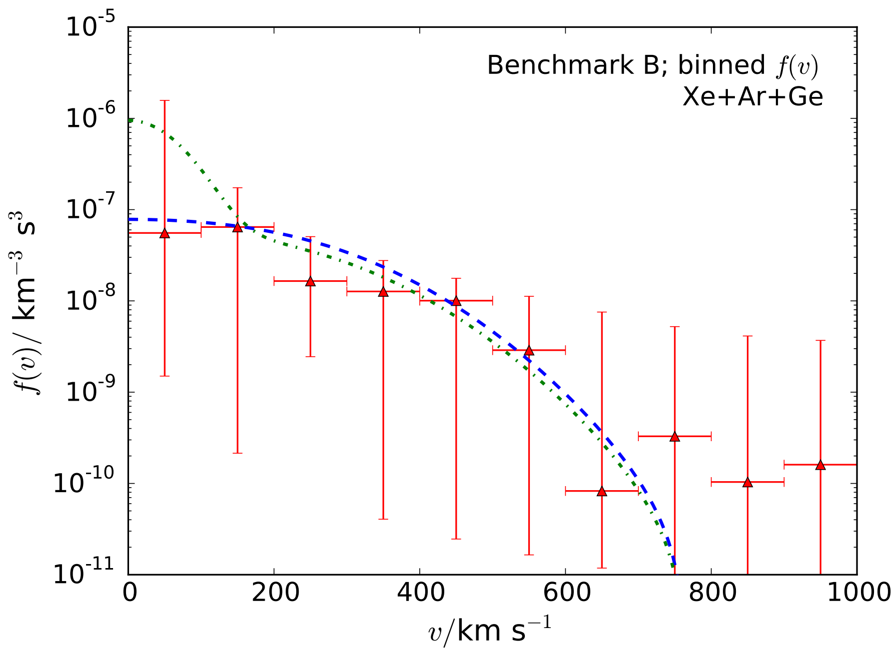
uncertainty in shape of WIMP velocity distribution → uncertainty in amplitude and phase of annual modulation signal and hence WIMP parameters

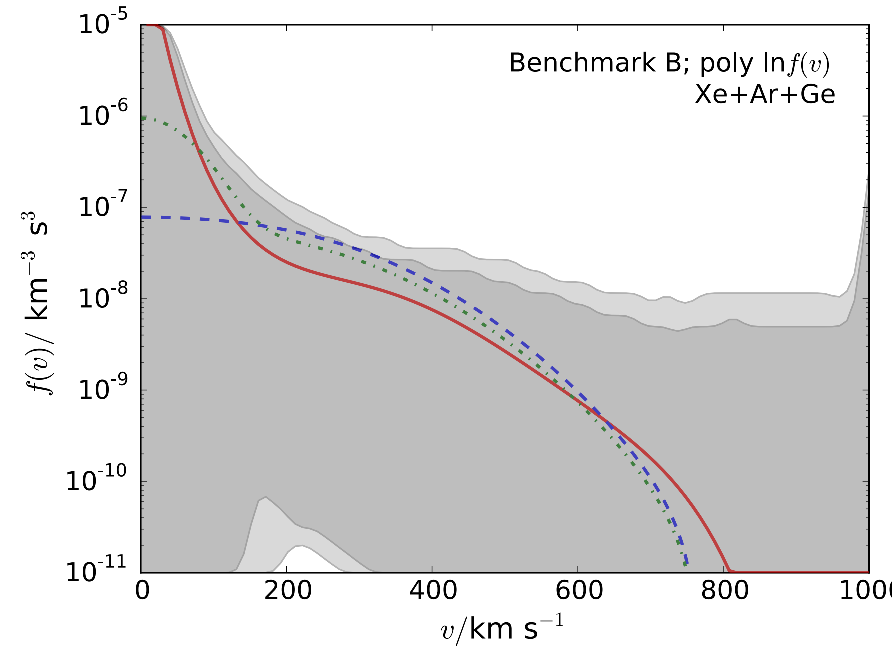
And can also reconstruct the speed distribution:

binned f(v)

polynomial f(v)

direct detection only





direct detection + IceCube