WIMP astronomy with directional detectors

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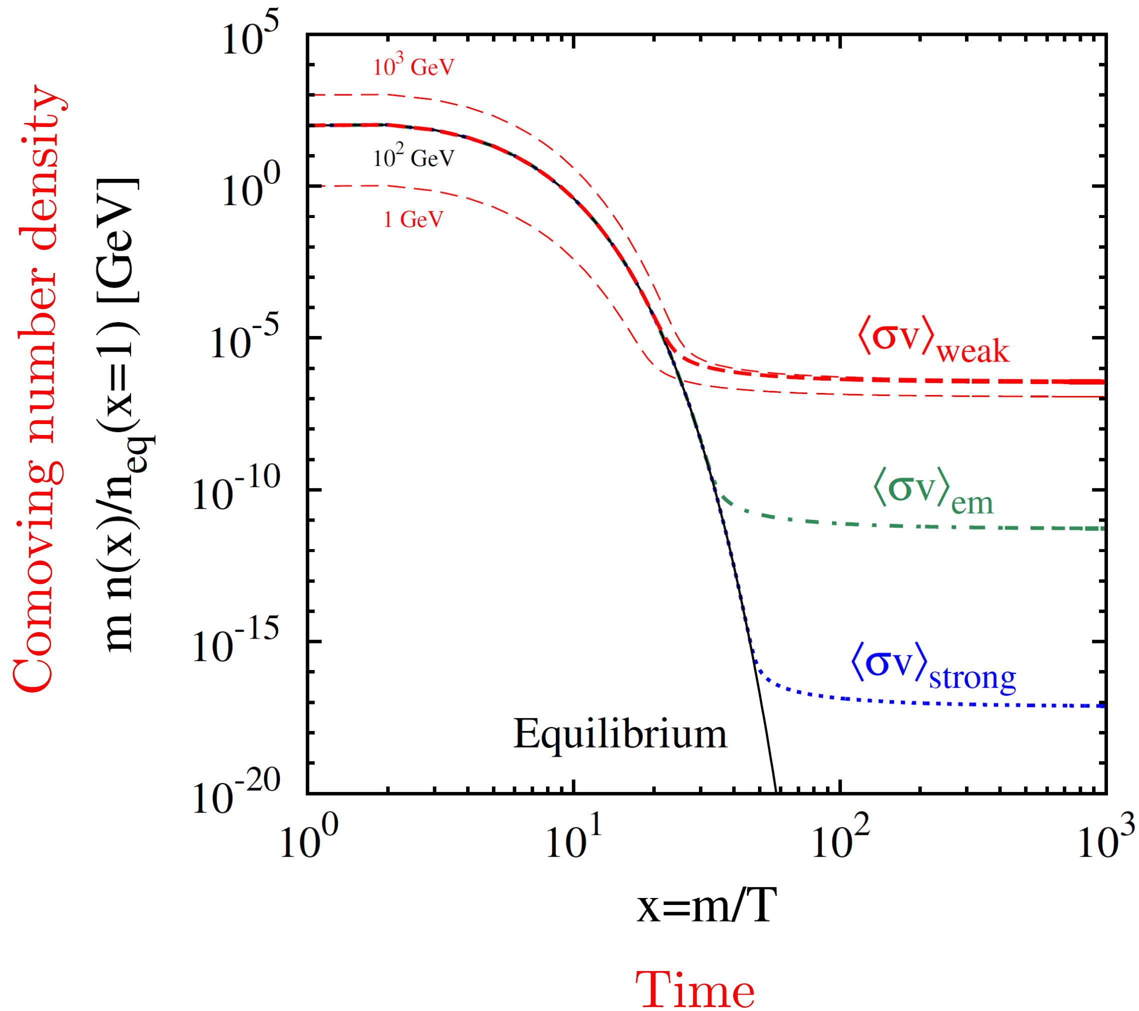
Based on arXiv:1410.2749 + current work

Overview

- Introduction
  - Dark matter detection
  - Directional detection
- Probing galactic dark matter velocity distribution
  - Expected signals from N-body simulations
  - Tidal streams and substructure
- Neutrino floor

Weakly interacting massive particles (WIMPs)

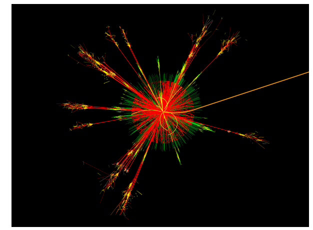
- Self-annihilating particles with weak scale interactions



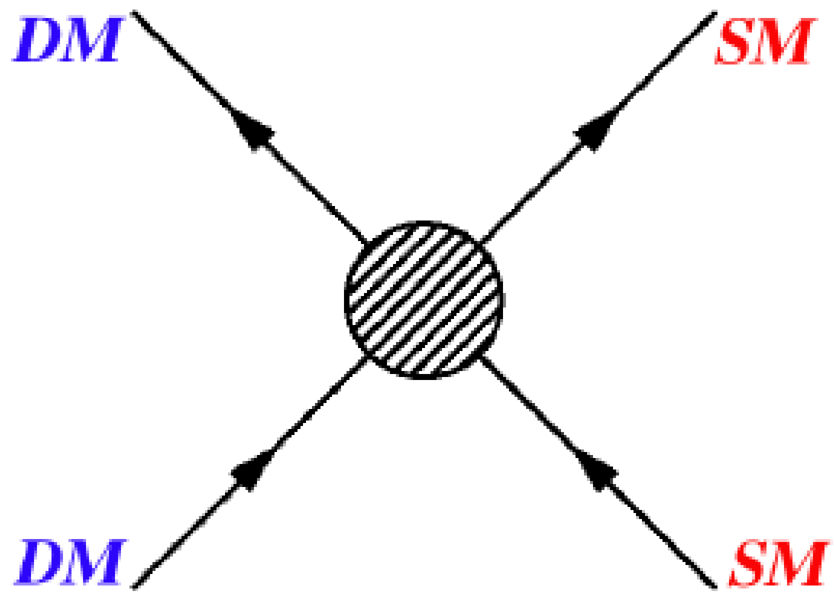
$$\chi + \chi \longleftrightarrow X + \bar{X}$$

$$\Omega_{\mathrm{dm}} h^2 \sim \langle \sigma v \rangle^{-1}$$

Detecting WIMPs



Production
(Particle colliders)



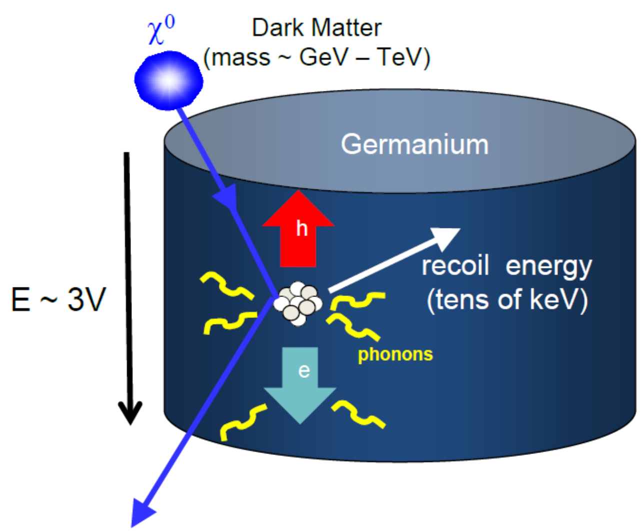
Direct detection
(Lab based experiments)

Indirect detection
(Astronomical observation)

Direct detection

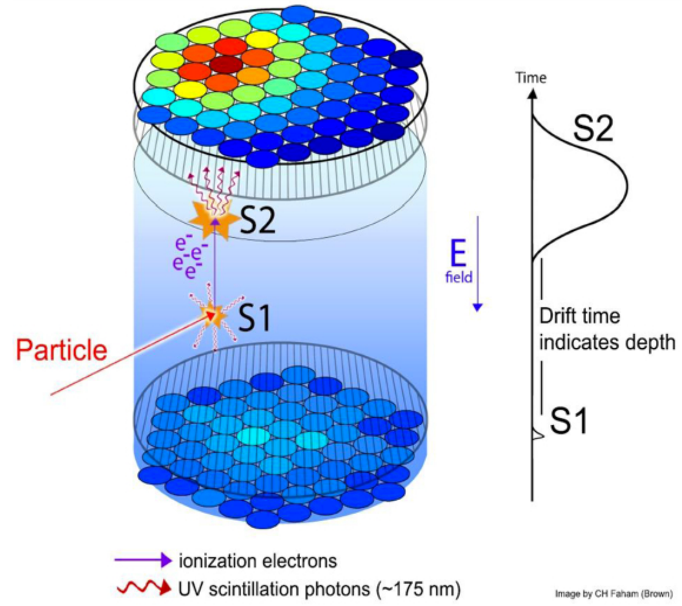
- Look for recoiling nuclei struck by WIMPs in Milky Way halo
- Very hard – lots of backgrounds

Cryogenic (heat)

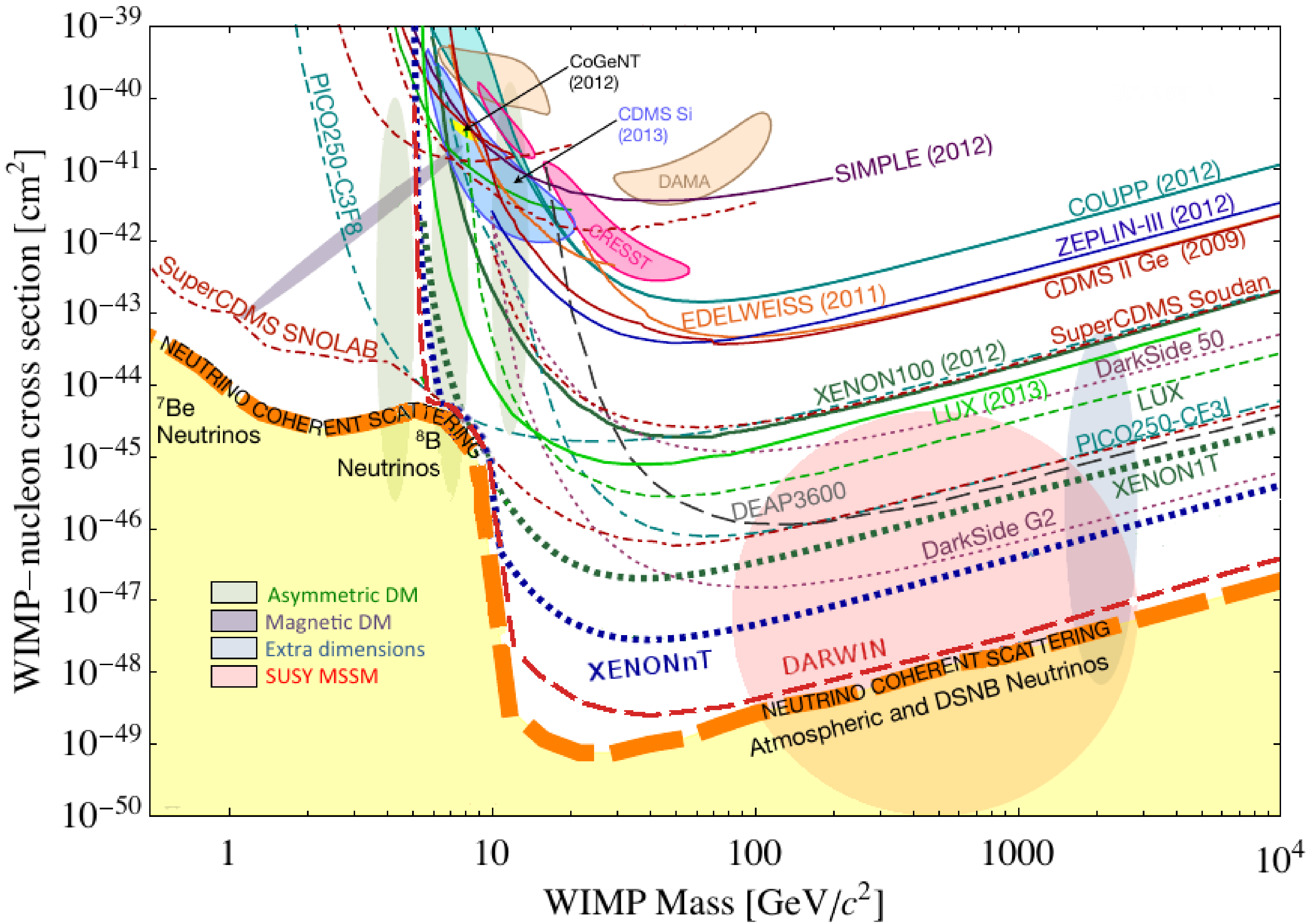


e.g. CDMS, CRESST, EDELWEISS

Liquid Noble (scintillation)



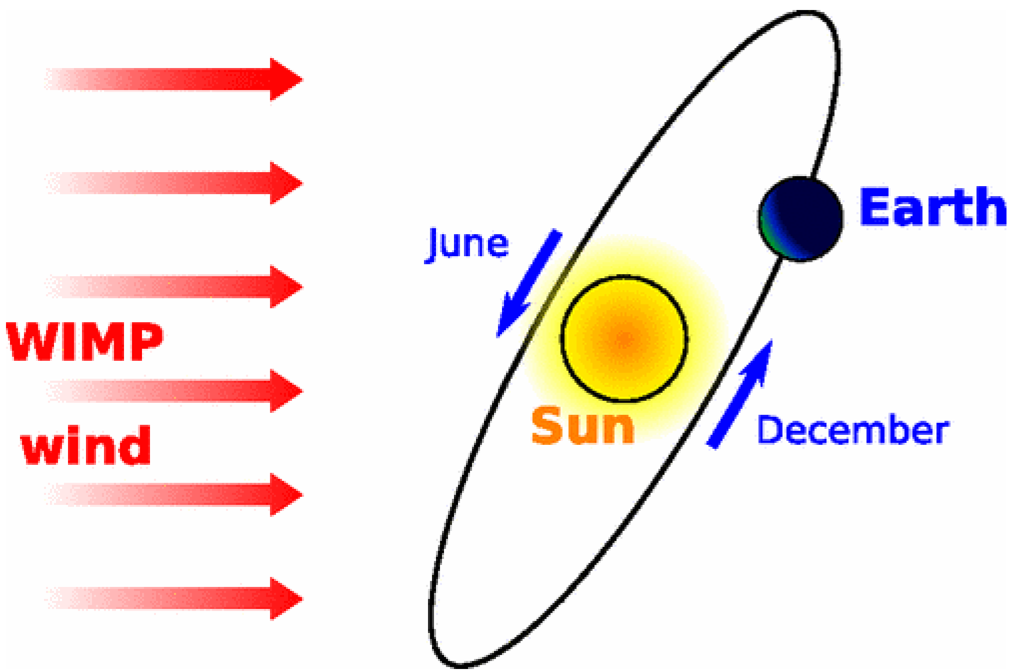
e.g. LUX, XENON, ZEPLIN



WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10
100
1000
10^4
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
XENON100 (2012)
DarkSide 50
LUX (2013)
LUX
PICO250-CF3I
XENON1T
DEAP3600
DarkSide G2
XENONnT
DARWIN
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
Asymmetric DM
Magnetic DM
Extra dimensions
SUSY MSSM

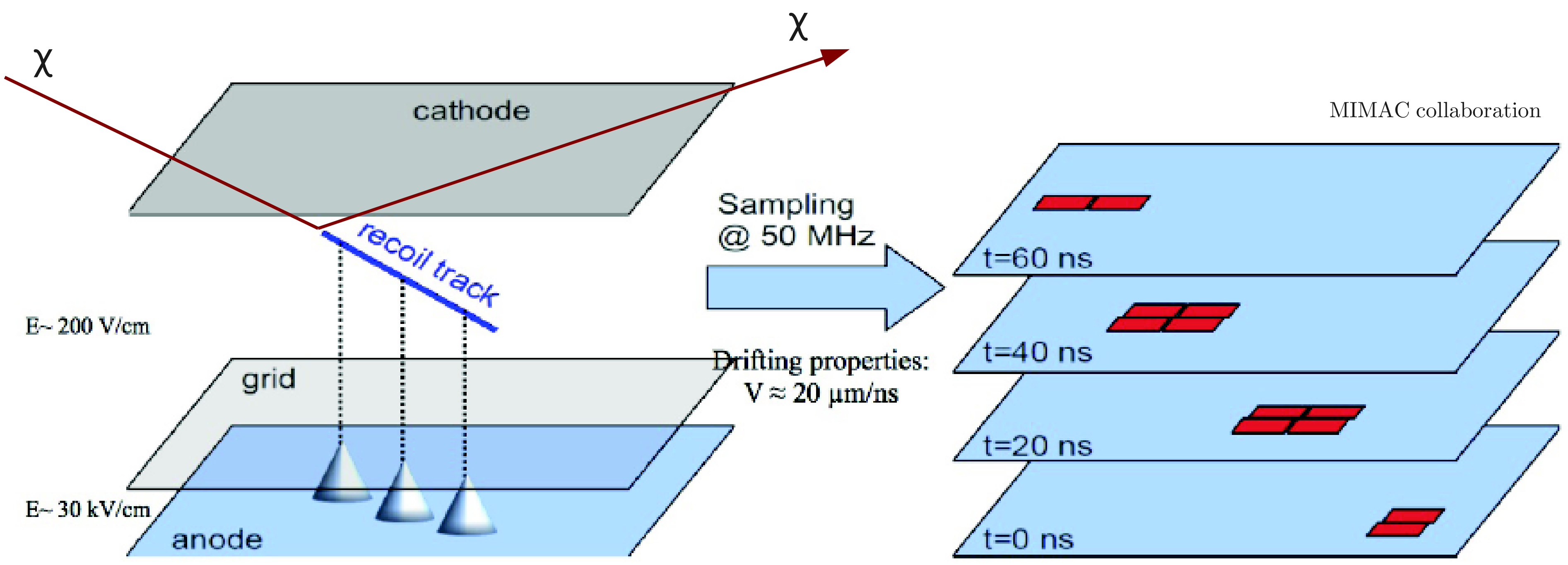
“Smoking gun” signals

- Annual Modulation (*Drukier, Freese & Spergel 1986*)
- Direction dependence (*Spergel 1988*)



Directional Detection

- Measure **energy and direction** of nuclear recoils
- Time Projection Chamber (TPC), usually with CF_4



- Others?
  - Emulsions, DNA strands, nano-explosives, carbon nanotubes ...

Directional Detection

- Advantages:
  - No mimicking backgrounds (c.f. DAMA/LIBRA ...)
  - Measure *velocity* distribution
  - Probe below neutrino floor

- Disadvantages:
  - Experimental challenge

But given time/compensation...?

Directional detection

- Double differential event rate:

$$\frac{\mathrm{d}^2 R}{\mathrm{d}E\mathrm{d}\Omega_q} = \frac{\rho_0 \sigma_N}{4\pi m_\chi \mu^2} F^2(E) \hat{f}(v_{\mathrm{min}}(E), \hat{\mathbf{q}})$$

WIMP:	m_χ	WIMP mass
	σ_N	WIMP-nucleus cross section
Galactic Halo:	ρ_0	Local WIMP density
	$\hat{f}(v_{\mathrm{min}}, \hat{\mathbf{q}})$	Radon transform of velocity dist.
Nuclear physics:	$F(E)$	Nuclear form factor
	m_N	Nucleus mass
	μ	$m_\chi m_N/(m_\chi + m_N)$

Directional detection

- Radon transform of WIMP velocity distribution,

$$\hat{f}(v_{\rm min}, \hat{\mathbf{q}}) = \int \delta(\mathbf{v} \cdot \hat{\mathbf{q}} - v_{\rm min}) f(\mathbf{v}) {\rm d}^3 v$$

- at the smallest speed that can cause a recoil of energy, E

$$v_{\rm min} = \frac{1}{\mu} \sqrt{\frac{m_N E}{2}}$$

- Lab frame distribution $=$ boost of Galactic frame distribution

$$f(\mathbf{v}) = f_{\rm gal}(\mathbf{v} + \mathbf{v}_{\rm lab})$$

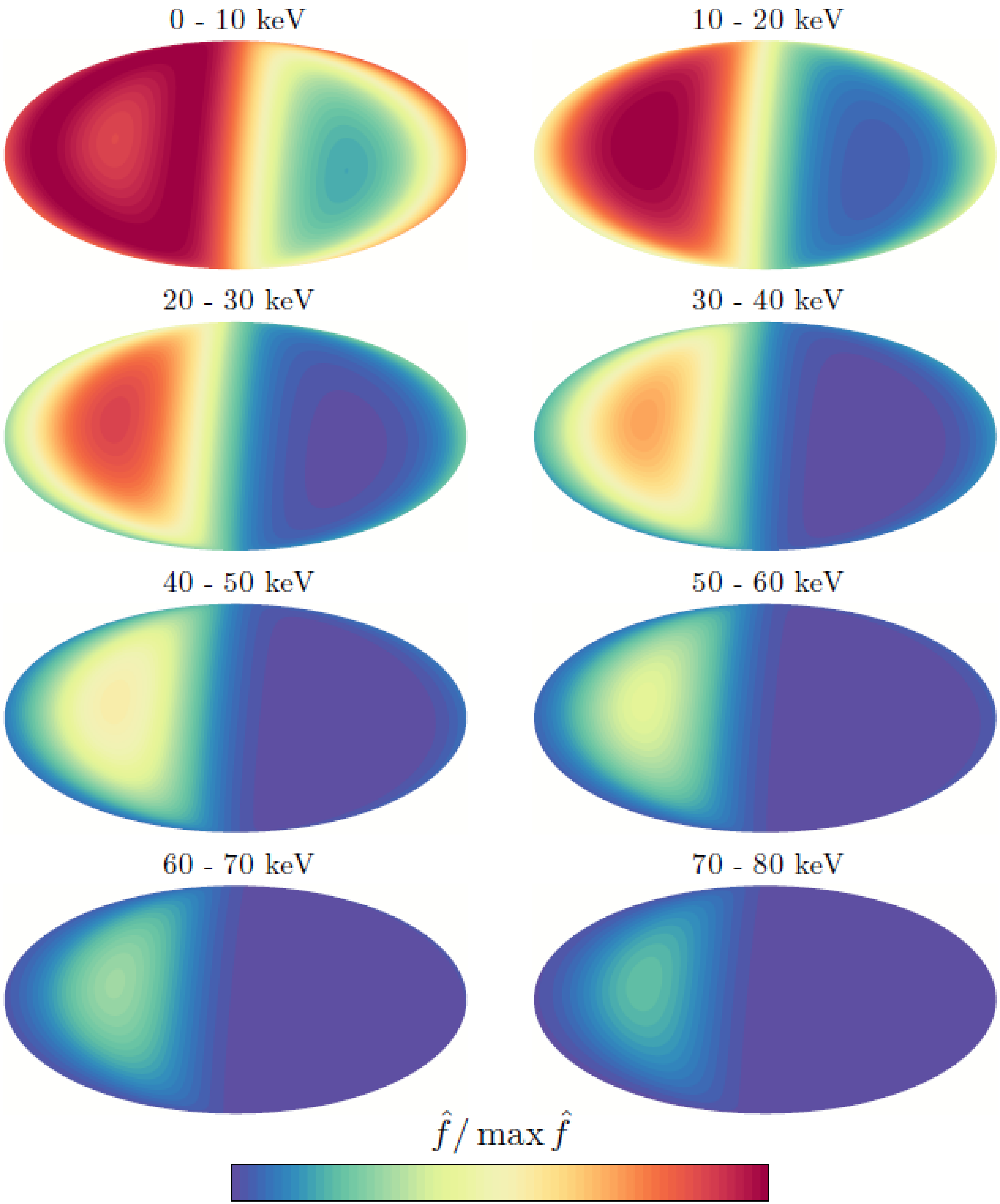
Velocity distribution

- "Standard Halo Model" used ubiquitously in current data analysis

$$f_{\rm gal}(\mathbf{v}) = \frac{1}{N_{\rm esc}(2\pi\sigma_v^2)^{3/2}} \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma_v}\right)\theta(v_{\rm esc} - |\mathbf{v}|)$$

- Radon transform of lab frame distribution

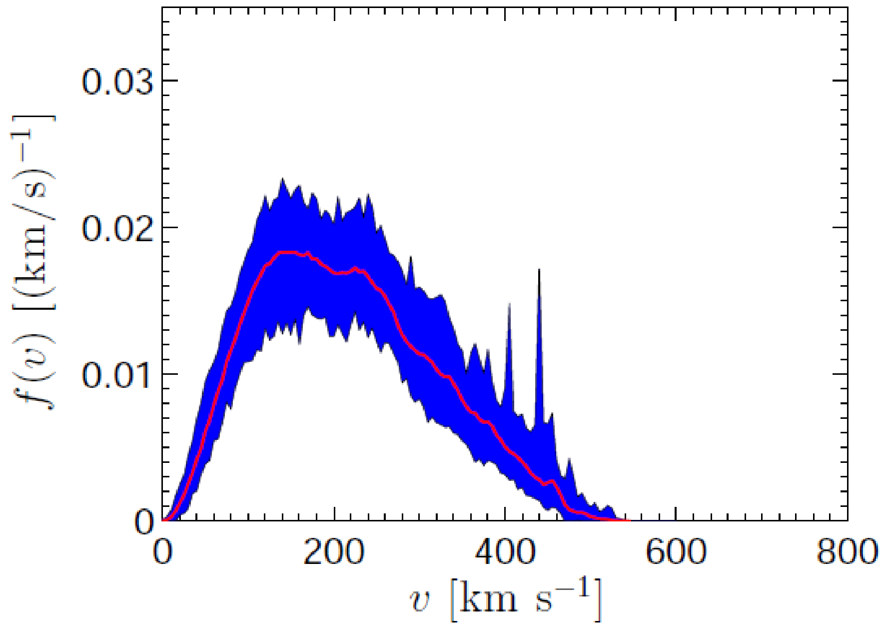
$$\hat{f}_{\rm lab}(v_{\rm min}(E), \hat{\mathbf{q}}) = \frac{1}{N_{\rm esc}(2\pi\sigma_v^2)^{1/2}}\left[\exp\left(-\frac{|v_{\rm min}(E) + \mathbf{v}_{\rm lab}\cdot\hat{\mathbf{q}}|^2}{2\sigma_v^2}\right) - \exp\left(-\frac{v_{\rm esc}^2}{2\sigma_v^2}\right)\right]$$


0 - 10 keV
10 - 20 keV
20 - 30 keV
30 - 40 keV
40 - 50 keV
50 - 60 keV
60 - 70 keV
70 - 80 keV
$\hat{f}\,/\,\max\hat{f}$

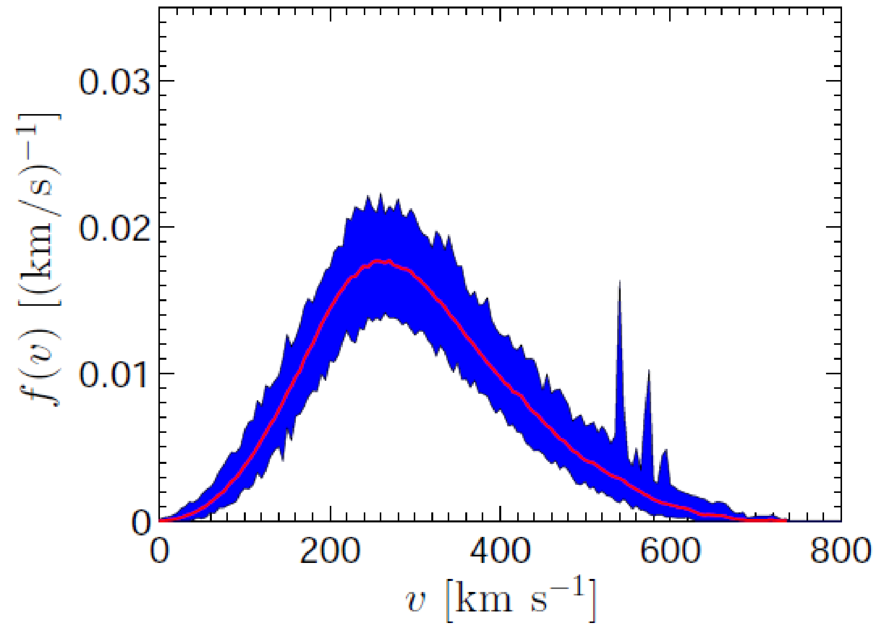
More realistic distributions

- Evidence from simulations that distribution is *not* smooth or isotropic
- E.g. Via-Lactea2 analogue Earth distributions:

Galactic Frame



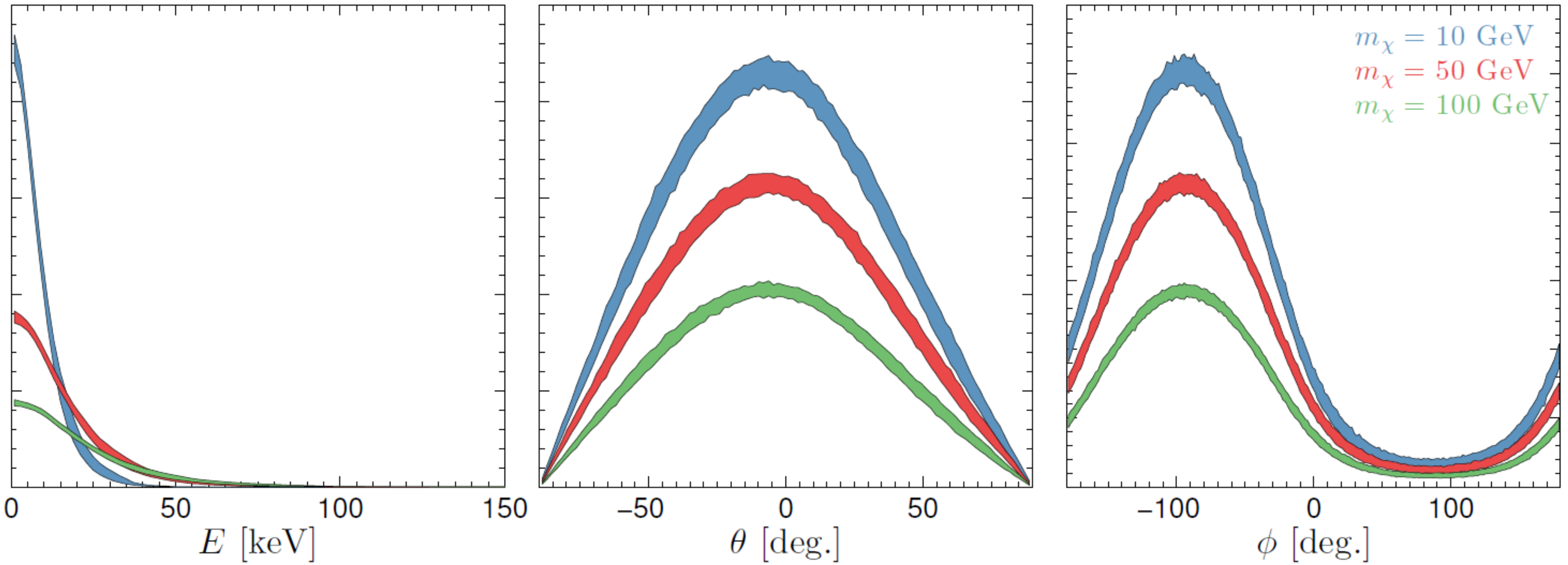
Lab Frame



More realistic distributions

- Avg. recoil signals from VL2 distributions over 10 kg yr exposure
- Distributions in energy, angle:

Re-scaled distributions



- To detect broad changes in the model need > several thousand events

Tidal streams

- Tidal stream from accretion of dark matter from satellite galaxy
- Full distribution = Background halo + Stream

Background halo dispersion ~ 200 km/s

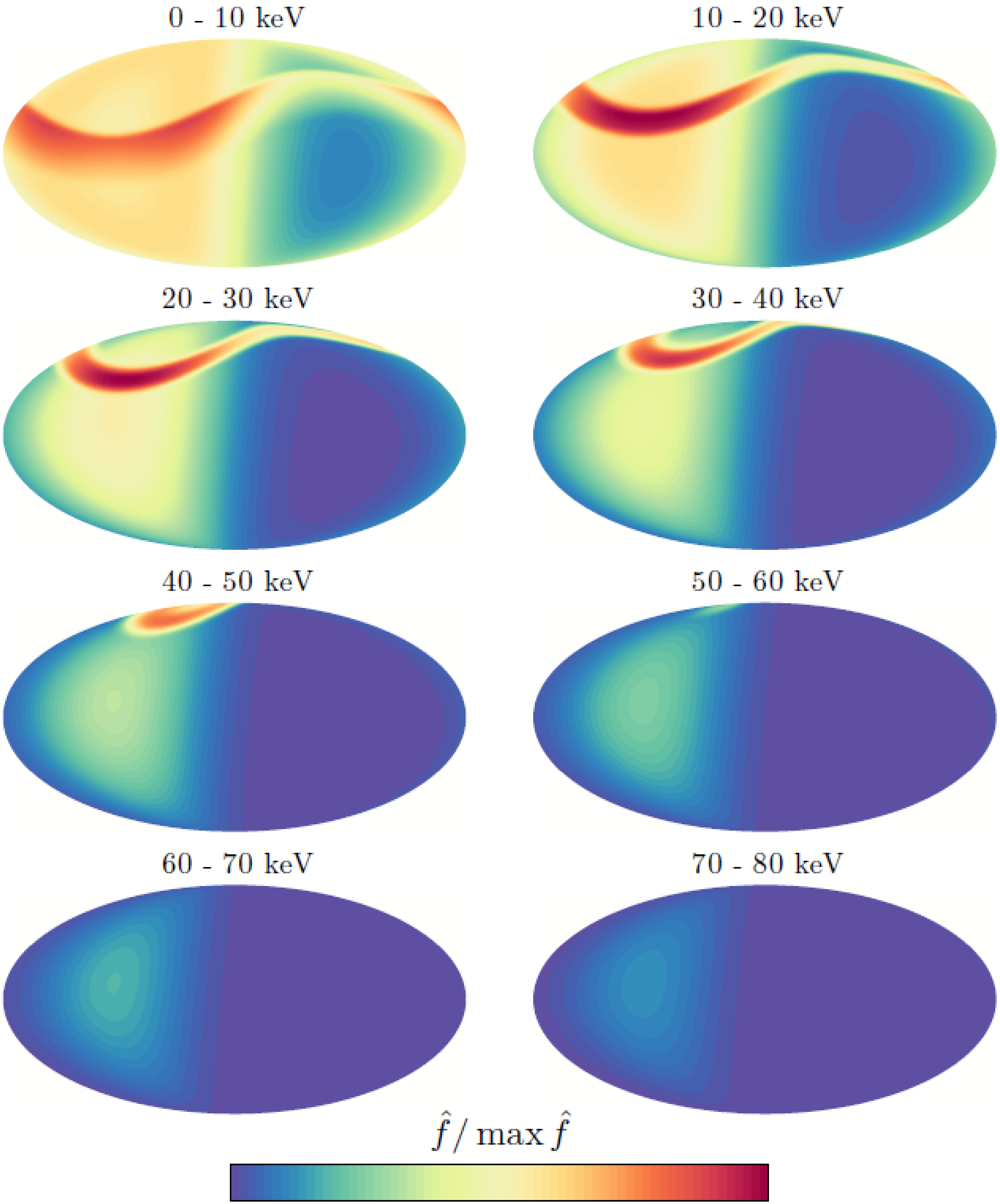
$$\hat{f}_{\rm lab}(v_{\rm min}, \hat{\mathbf{q}}) = (1-\xi)\hat{f}_{\rm gal}(v_{\rm min} + \mathbf{v}_{\rm lab} \cdot \hat{\mathbf{q}}, \hat{\mathbf{q}}; \sigma_v, v_{\rm esc})$$

$$+ \xi \hat{f}_{\rm gal}(v_{\rm min} + (\mathbf{v}_{\rm lab} - \mathbf{v}_{\rm str}) \cdot \hat{\mathbf{q}}, \hat{\mathbf{q}}; \sigma_{\rm str}, v_{\rm esc})$$

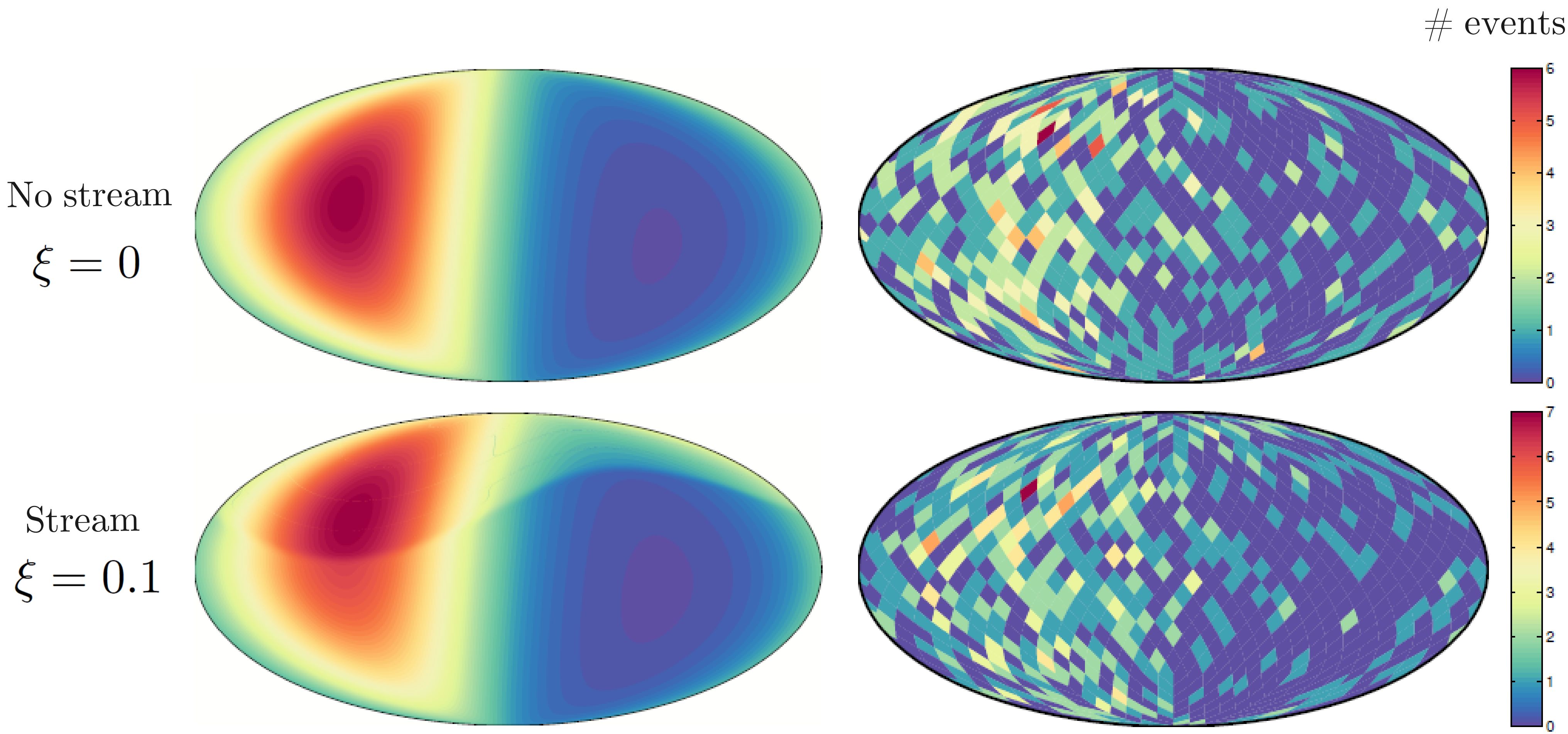
Stream fraction ~ 10%

Stream dispersion ~10 km/s

Galactic frame stream velocity


0 - 10 keV
10 - 20 keV
20 - 30 keV
30 - 40 keV
40 - 50 keV
50 - 60 keV
60 - 70 keV
70 - 80 keV
$\hat{f} / \max \hat{f}$

Detecting streams



1. Discriminate between smooth halo and halo with substructure

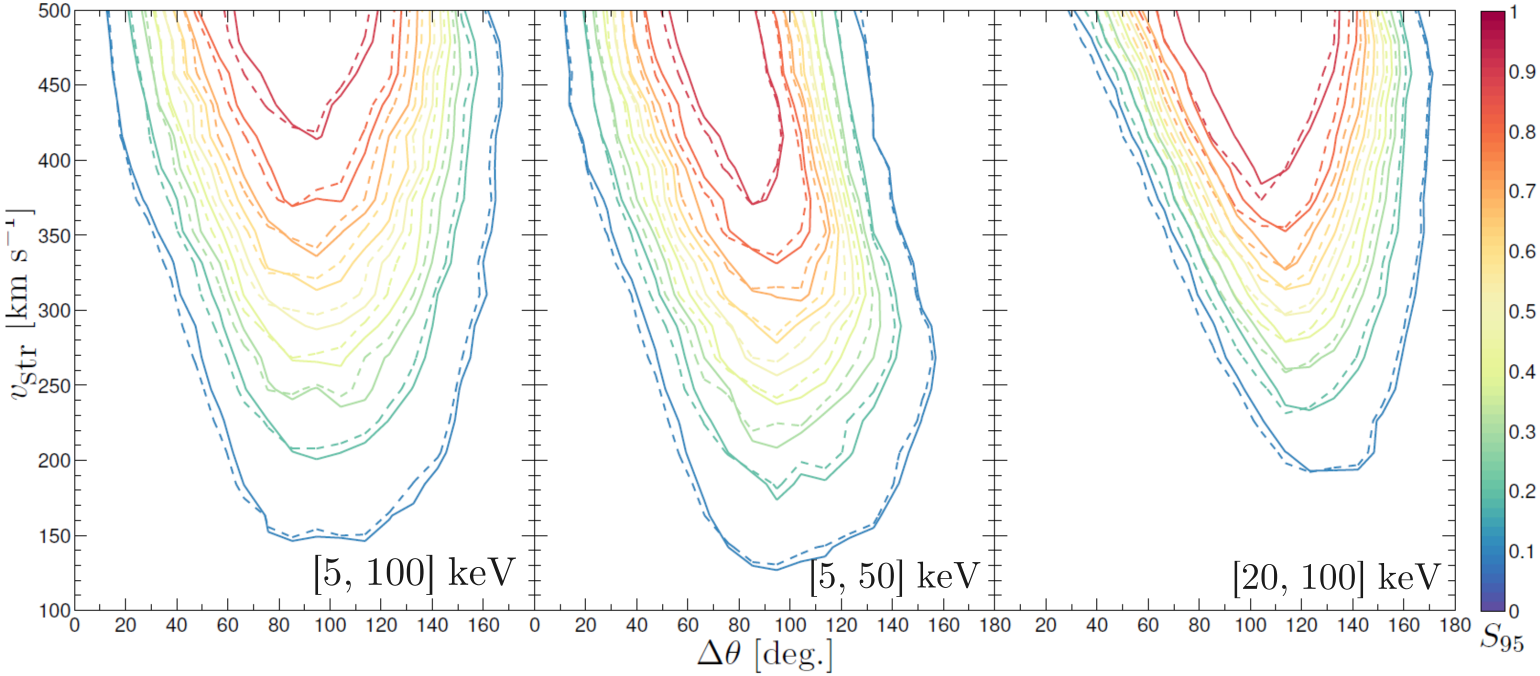
2. Measure properties of stream (density, velocity, dispersion)

Detecting streams: results

1. Discriminate between isotropic halo and halo with substructure

- Non-parametric tests (median direction, rotational symmetry)
- Need > 30 kg yr exposure to detect at 95% confidence
- Favours fast streams and streams aligned at 90 degrees to solar motion

Stream speed



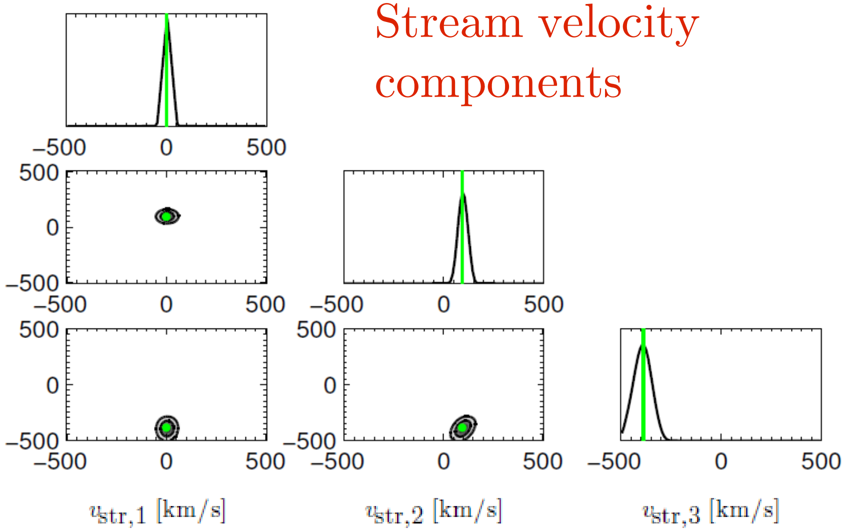
Detection significance

Angle between stream and solar velocities

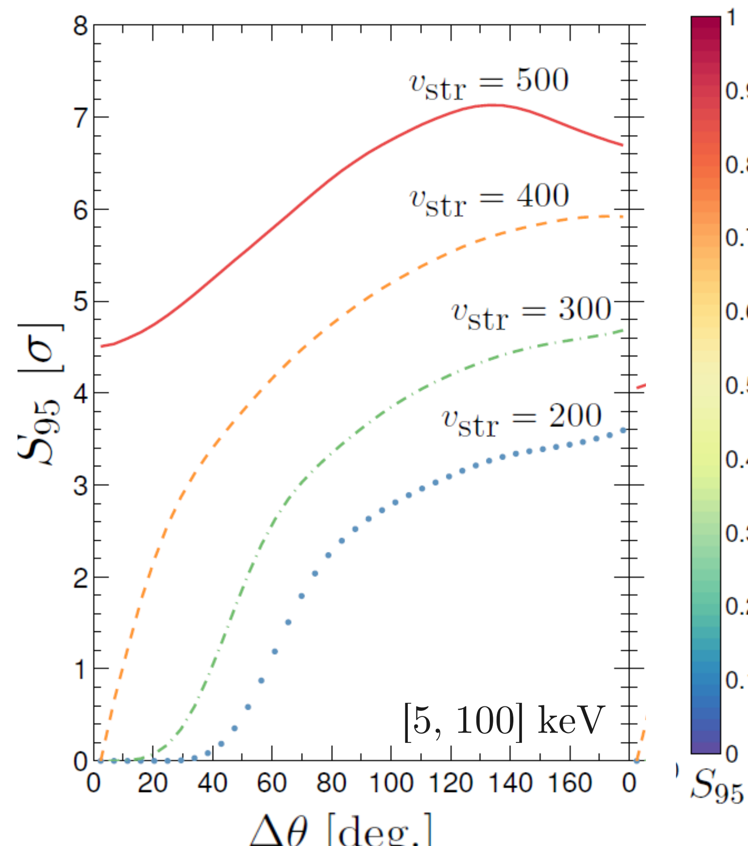
Detecting streams: results

2. Measure properties of stream (density, velocity, dispersion)

- Bayesian parameter reconstruction, profile likelihood ratio test
- Discriminate between isotropic halo and stream at 95% level with 5 kg yr, and achieve correct parameter reconstruction



Stream velocity components

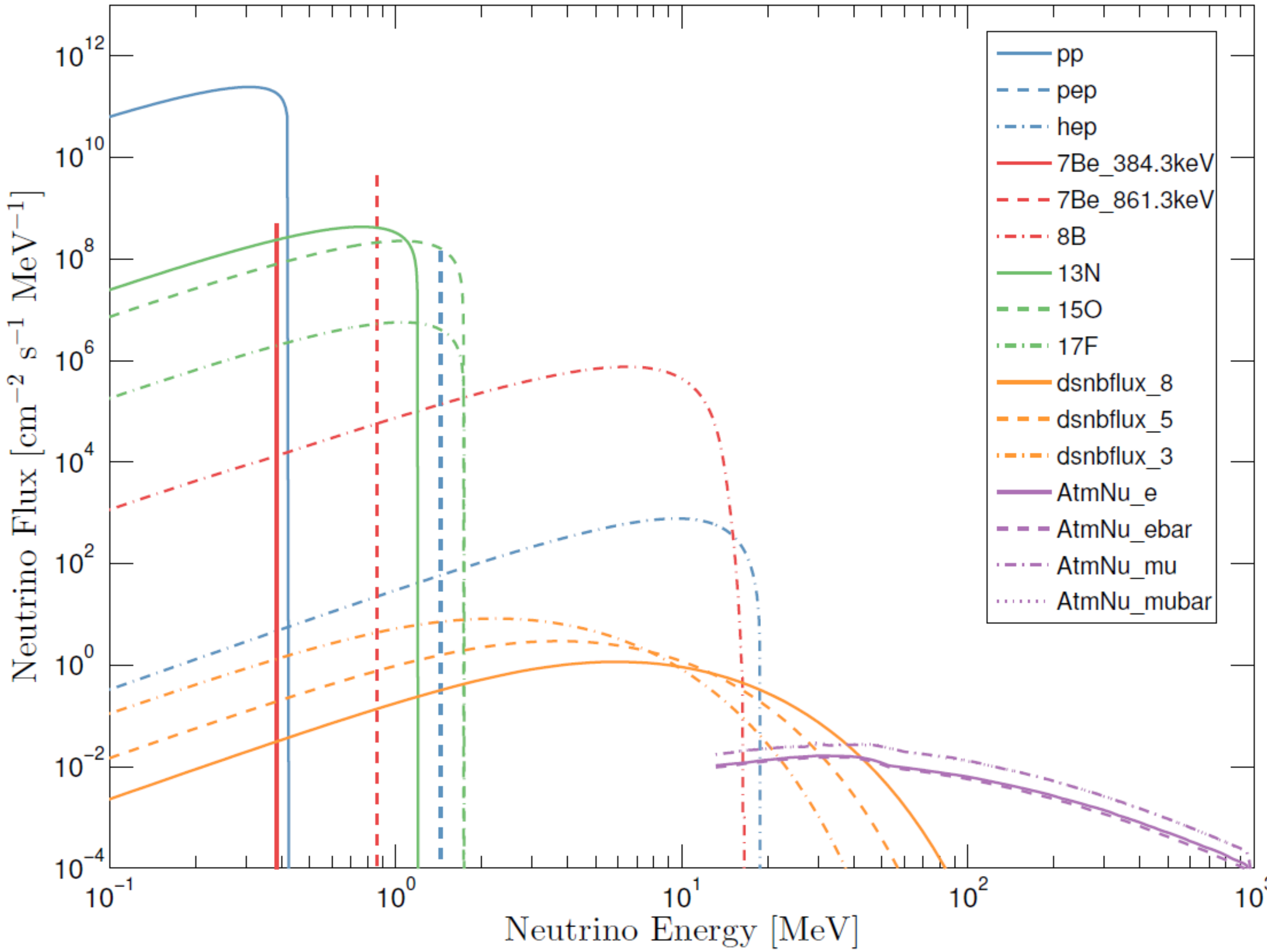


Other forms of substructure

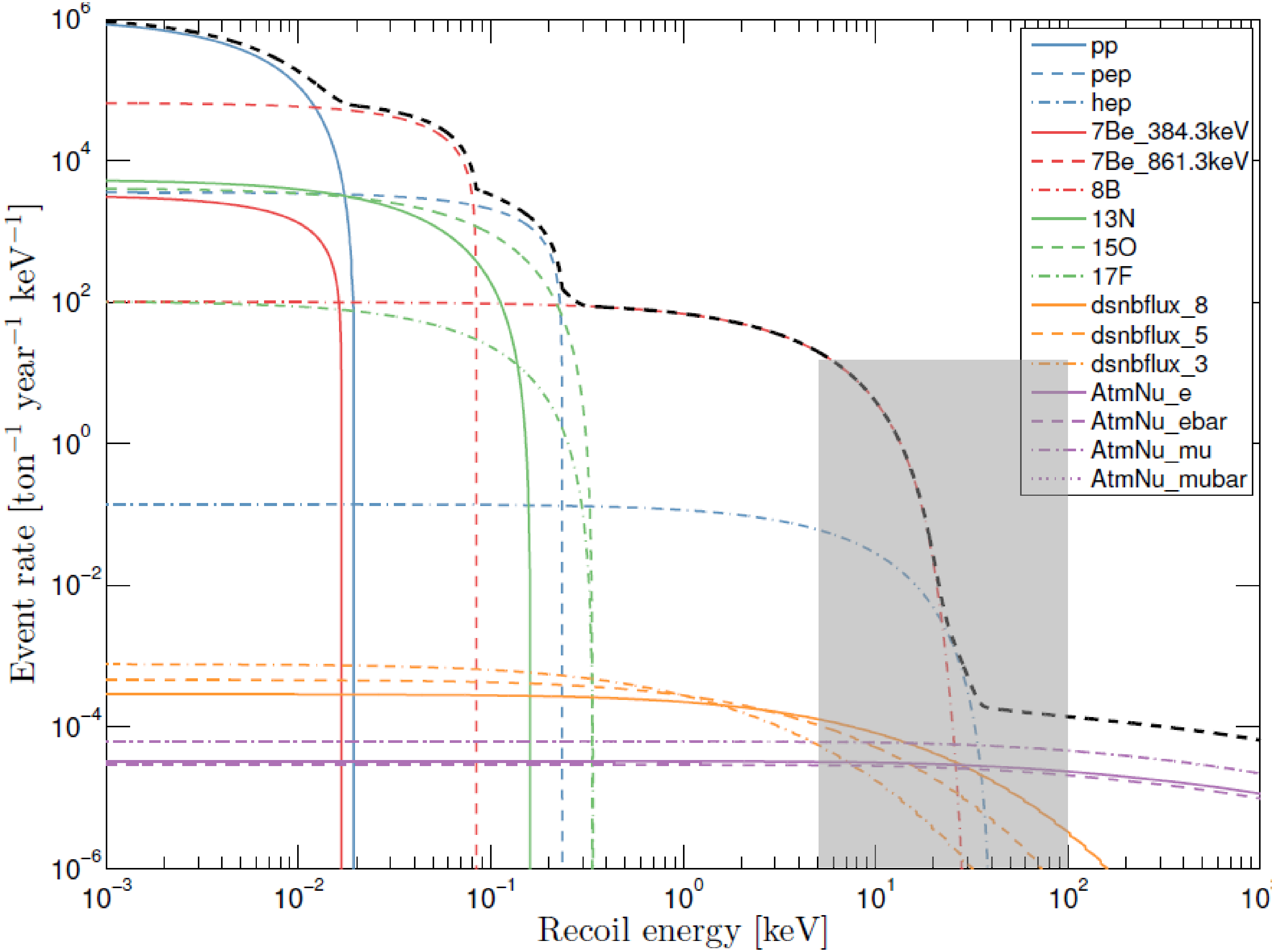
- Streams highly spatially and kinematically localised hence (relatively) easy to detect
- Other forms of substructure, e.g. dark disc, debris flow, harder to detect

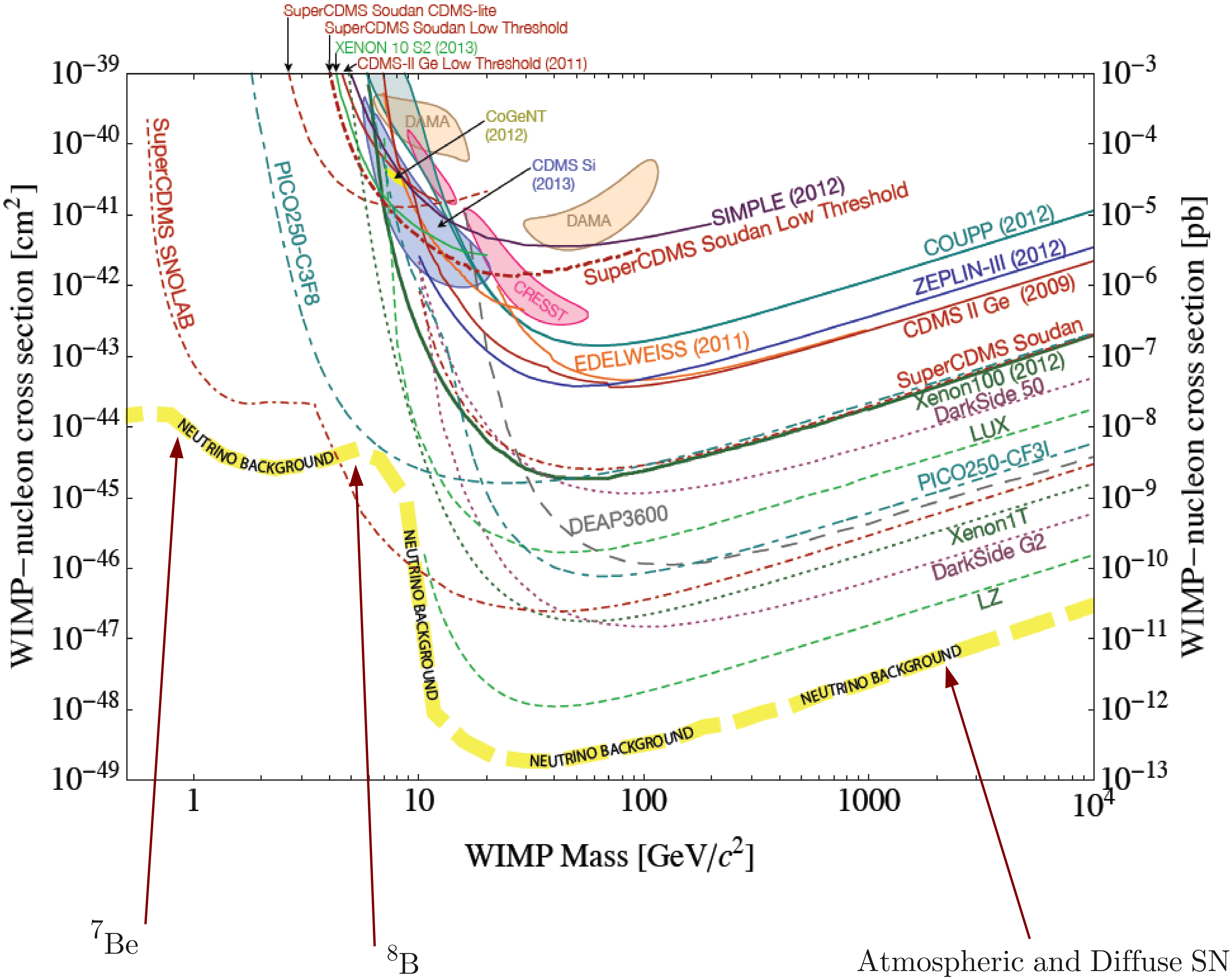
Neutrino backgrounds

- Neutrino-nucleus scattering an irreducible background
- Solar, atmospheric, supernovae, reactor …



Neutrino backgrounds





SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
DAMA
CRESST
SIMPLE (2012)
SuperCDMS Soudan Low Threshold
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
PICO250-C3F8
NEUTRINO BACKGROUND
NEUTRINO BACKGROUND
NEUTRINO BACKGROUND
NEUTRINO BACKGROUND
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
^{7}Be
^{8}B
Atmospheric and Diffuse SN

Summary

- Directional detection provides unambiguous evidence for signal of galactic origin
- Can probe local velocity distribution
- Streams may be observed with long exposures or scaled up detectors
- However, detectability dependent on orientation of substructure with respect to Earth's motion
- Directional detection capable of probing below the neutrino floor