Dark matter

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1. Evidence, properties and distribution

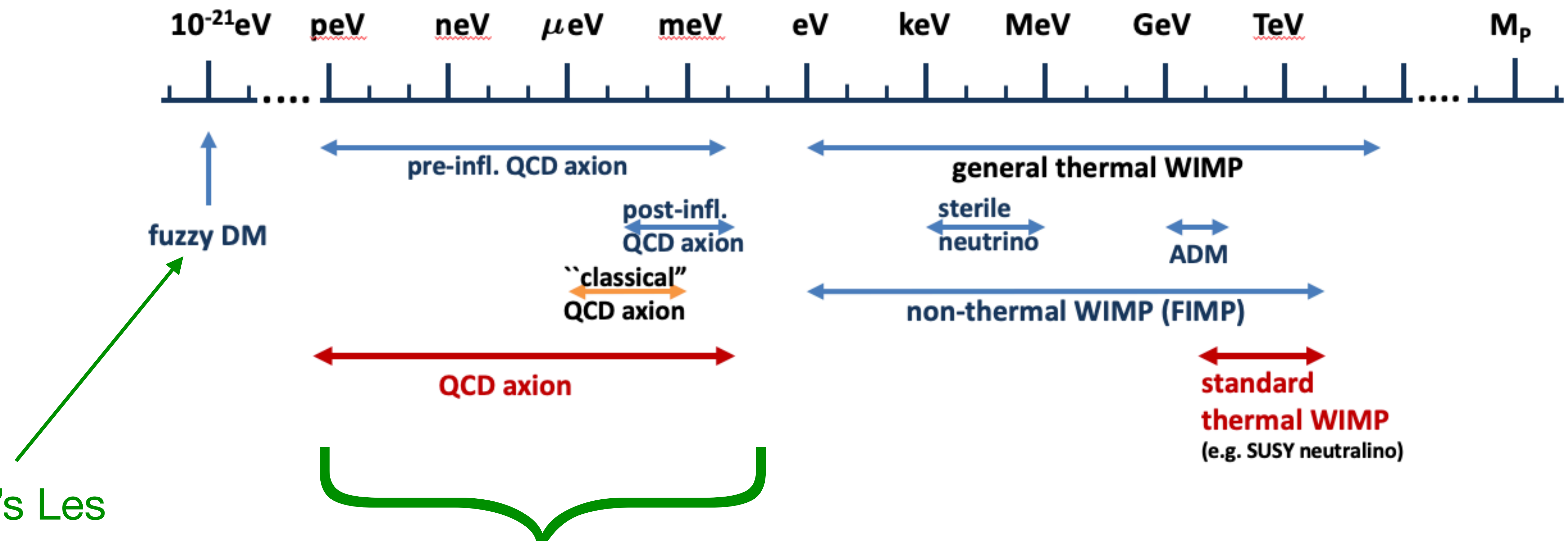
2. **WIMPs: production & direct detection**

3. Primordial Black Holes

Recap: 1. Evidence, properties & distribution

(Assuming Newton's laws of gravity and general relativity are correct) astronomical and cosmological observations indicate that 85% of the matter in the Universe is **cold**, **non-baryonic**, **dark matter**, which is **stable** on cosmological timescales.

Particle DM candidates



Hui's Les Houches lectures

Redondo's lectures

Direct detection of dark matter-APPEC committee report

2. recommended further reading/viewing

- ‘Supersymmetric dark matter’ (in particular chapter 8) Jungman, Kamionkowski & Griest, Phys. Rep. 1996.
- Chapters 2, 3 & 4 of ‘An introduction to particle dark matter’, Profumo, World Scientific.
- ‘Yet another introduction to dark matter, the particle physics approach’, Bauer & Plehn, Lect. Notes. Phys. 959 (2019)
- Particle Data Group review of Particle Physics
  - Dark matter, Baudis & Profumo
- Les Houches Dark Matter Summer School 2021: videos and lecture notes
  - ‘Standard WIMPs’, Feng
  - ‘Direct detection of classical WIMPs’, Cooley

2. WIMPs

Production

Direct detection

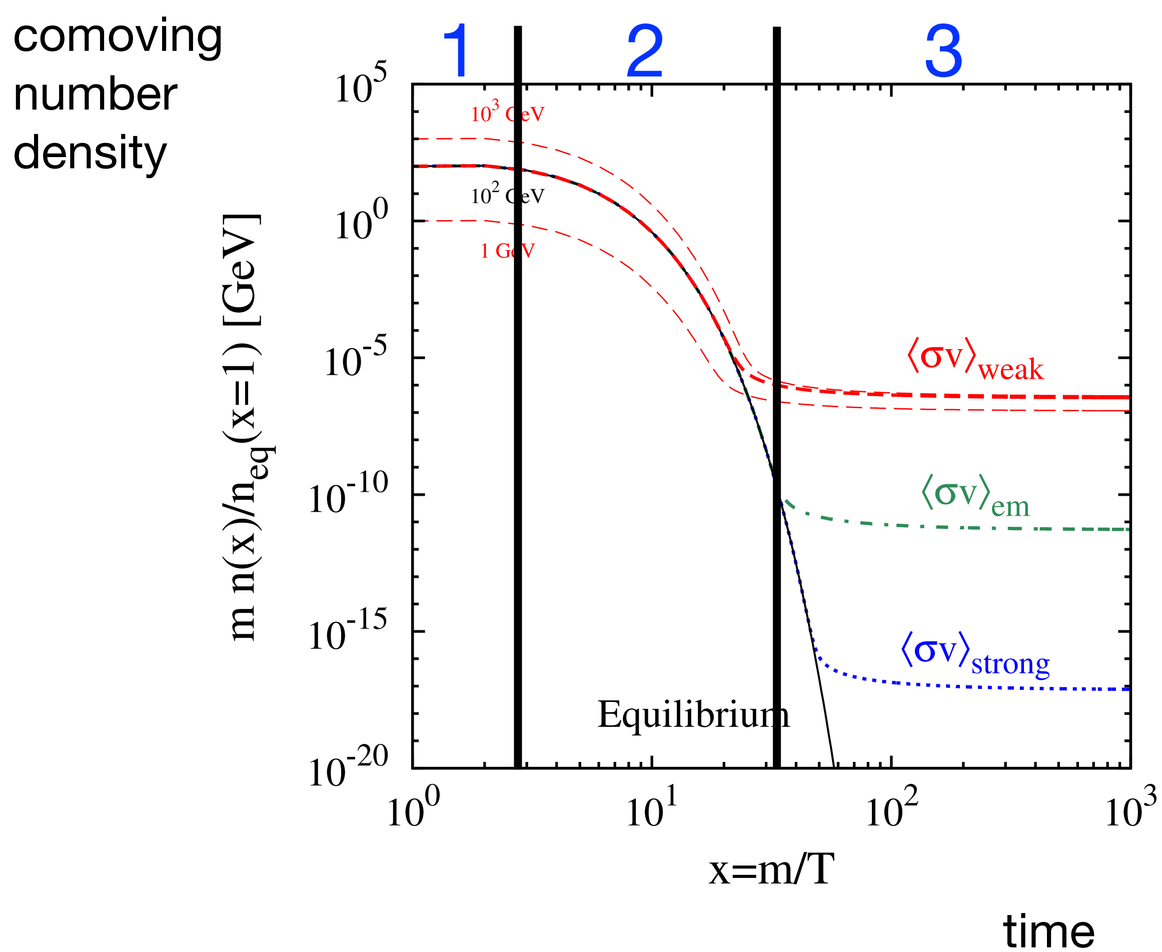
Production

Freeze-out

n.b. this is a qualitative overview, for more detailed and rigorous calculations see e.g. Profumo book; Bauer and Plehn lecture notes; Steigman, Dasgupta & Beacom.

A stable weakly interacting massive particle (WIMP) which is in thermal equilibrium at early times, will generically have roughly the right abundance to be the dark matter ('WIMP miracle').

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



Steigman, Dasgupta & Beacom

region 1:
created and destroyed at same rate
comoving number density, n, constant

region 2:
production drops once $T \ll m$
n drops rapidly

region 3:
destruction stops once annihilate rate much less than expansion rate
n constant ('freeze out')

Boltzmann equation:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -3Hn - \langle \sigma_{\mathrm{A}} v \rangle \left[n^2 - n_{\mathrm{eq}}^2 \right]$$

dilution from expansion $\qquad \chi\chi \to X\bar{X} \qquad X\bar{X} \to \chi\chi$

$n_{\mathrm{eq}} \propto T^3$ for $T \gg m$ i.e. relativistic

$n_{\mathrm{eq}} \propto (m_\chi T)^{3/2} \exp(-m_\chi/T)$ for $T \ll m$ i.e. non-relativistic

$n \approx n_{\mathrm{eq}}$ until interaction rate drops below expansion rate and interactions 'freeze-out':

$$\Gamma = n_{\mathrm{eq}} \langle \sigma_{\mathrm{A}} v \rangle \sim H$$

$(m_\chi T)^{3/2} \exp(-m_\chi/T) \qquad \dfrac{\alpha^2}{m_\chi^2} \qquad \dfrac{\rho^{1/2}}{M_{\mathrm{Pl}}} \sim \dfrac{T^2}{M_{\mathrm{Pl}}}$ from Friedmann equation

$$\frac{m_\chi}{T_{\mathrm{fo}}} \sim \ln\left(\frac{\alpha^2 M_{\mathrm{Pl}}}{\sqrt{m_\chi T_{\mathrm{fo}}}} \right) \xrightarrow{\text{for } m_\chi \sim m_{\mathrm{ew}} \sim 100\,\mathrm{GeV}} \frac{m_\chi}{T_{\mathrm{fo}}} \sim 25$$

WIMP abundance today:

$$\Omega_{\chi,0} = \frac{m_\chi n_0}{\rho_{c,0}}$$

Using:

WIMP number density at freeze-out:

$$n_{fo} \sim \frac{H_{fo}}{\langle \sigma_A v \rangle} \sim \frac{T_{fo}^2}{M_{Pl} \langle \sigma_A v \rangle}$$

Dilution of WIMP due to expansion:

$$n_0 \sim n_{fo} \left(\frac{T_0}{T_{fo}} \right)^3$$

critical density today:

$$\rho_{c,0} \sim M_{Pl}^2 H_0^2$$

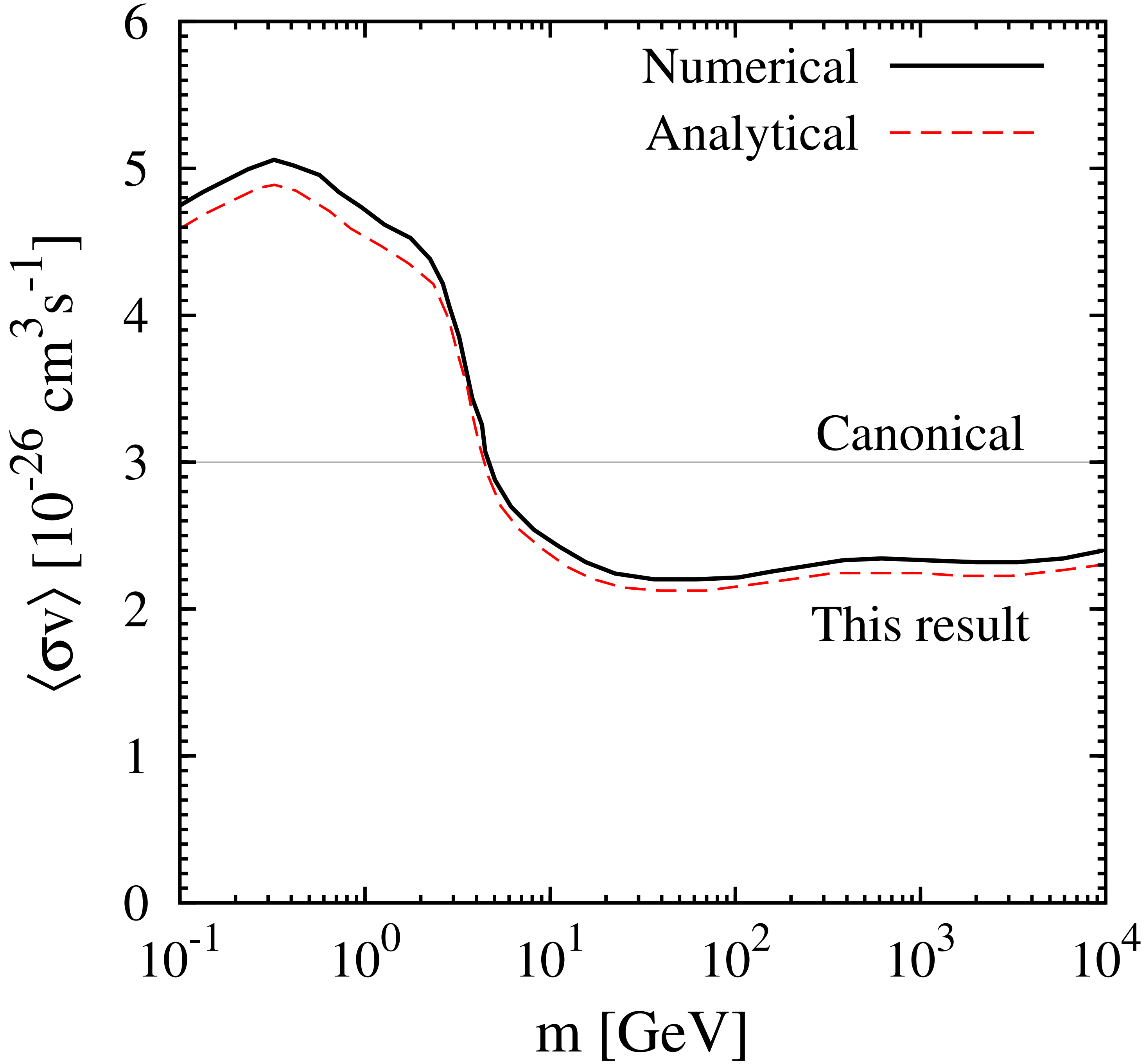
$$\boxed{\Omega_{\chi,0} h^2 \sim 0.1 \left(\frac{10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma_A v \rangle} \right)}$$

For weak scale interactions:

$$\sigma \sim G_F^2 T_{fo}^2 \sim \left(10^{-5}\,\mathrm{GeV}^{-2}\right)^2 (10\,\mathrm{GeV})^2 \sim 10^{-8}\,\mathrm{GeV}^{-2} \sim 10^{-36}\,\mathrm{cm}^2$$

$$\sigma v \sim 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

cross-section for which $\Omega_\chi h^2 = 0.11$



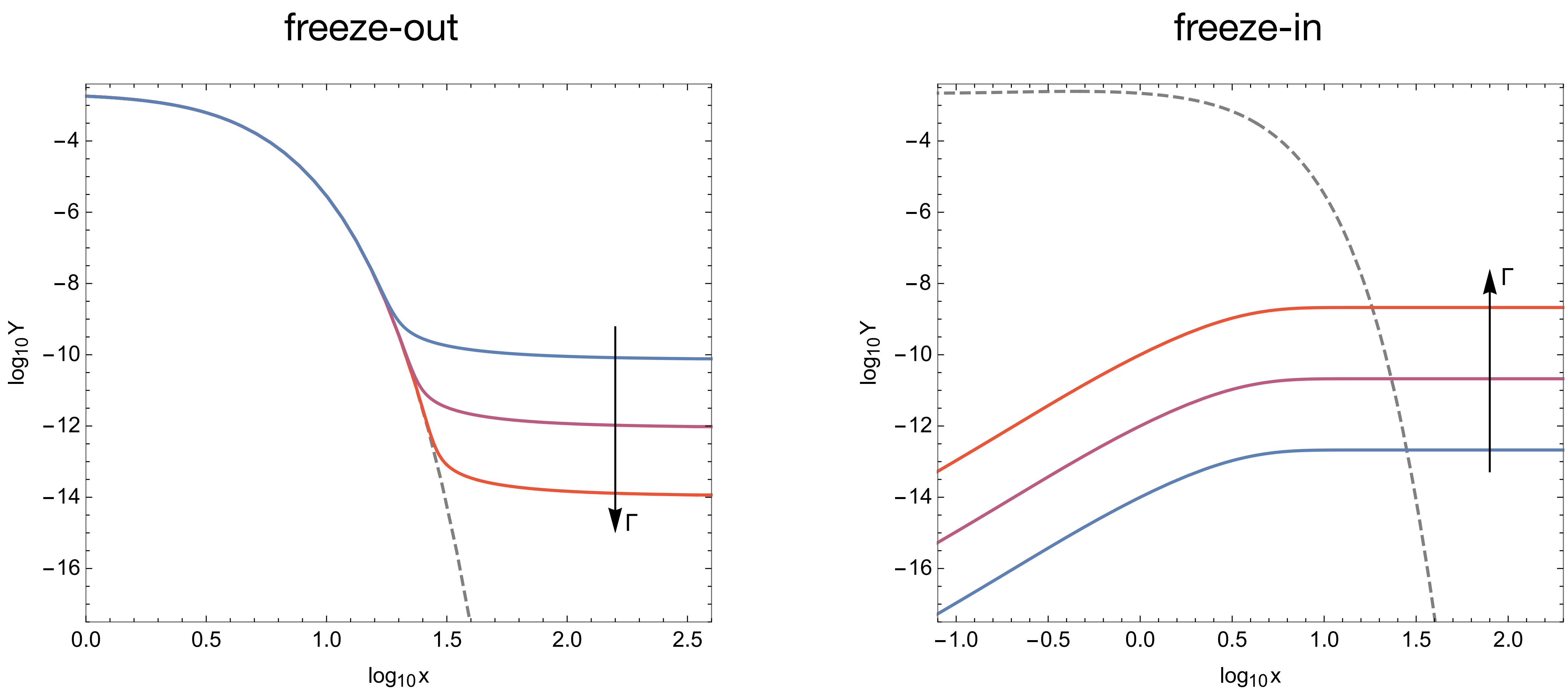
$3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$

Steigman, Dasgupta & Beacom

See Sanz lectures for BSM models which contain WIMP candidates, in particular the lightest neutralino in SUSY.

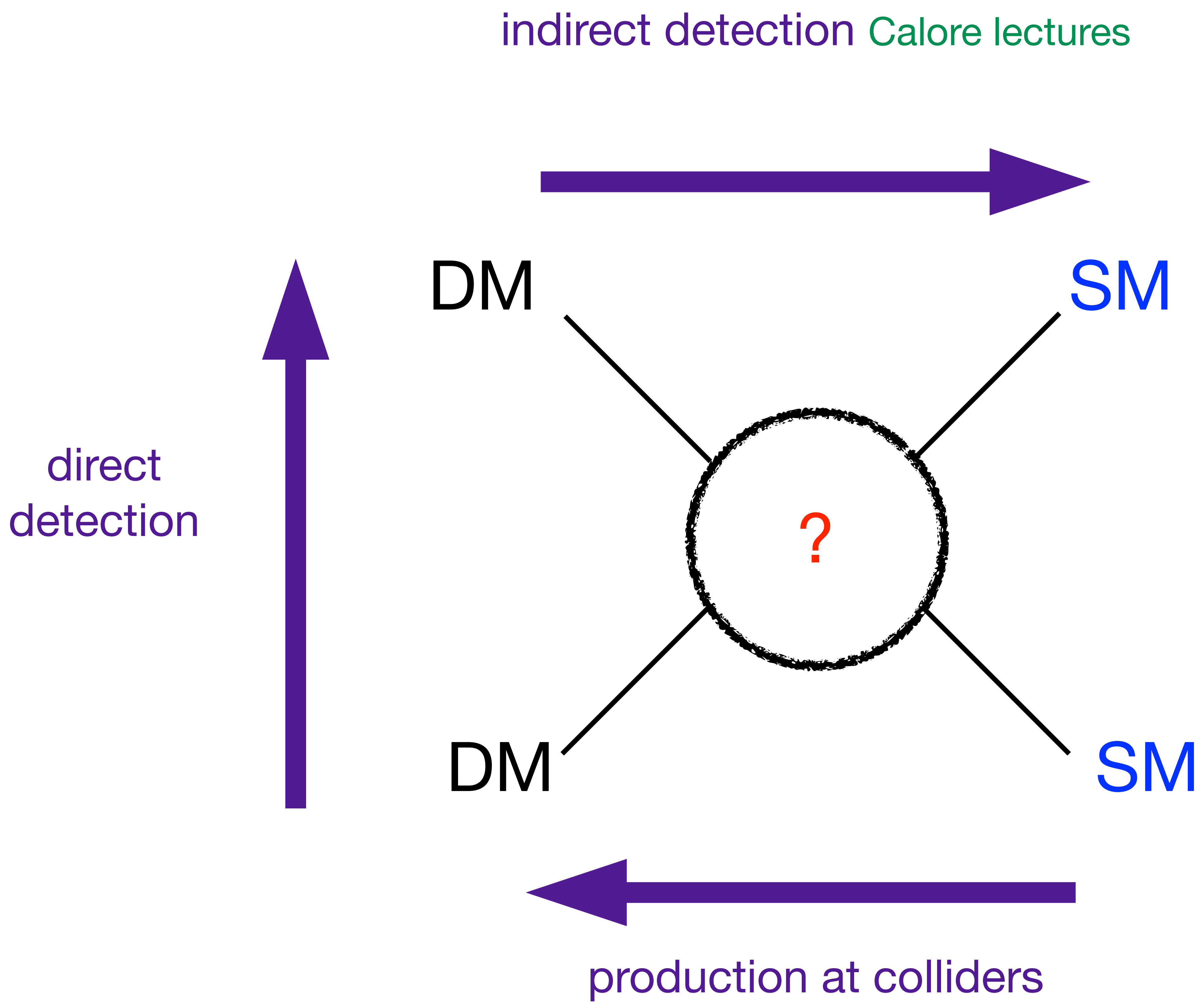
Freeze-in

Feebly interacting massive particles (FIMPs) are too weakly interacting to be in thermal equilibrium, but an ‘interesting’ abundance can be produced by the decay or annihilation of SM particles.



Bernal et al.

WIMP detection

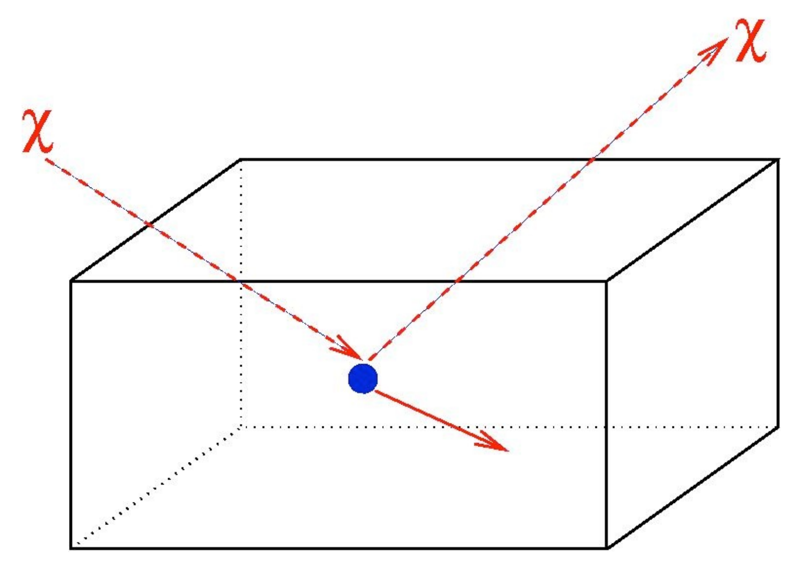


SM = standard model

Direct detection

Via (default elastic) scattering on detector nuclei in the lab:

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



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

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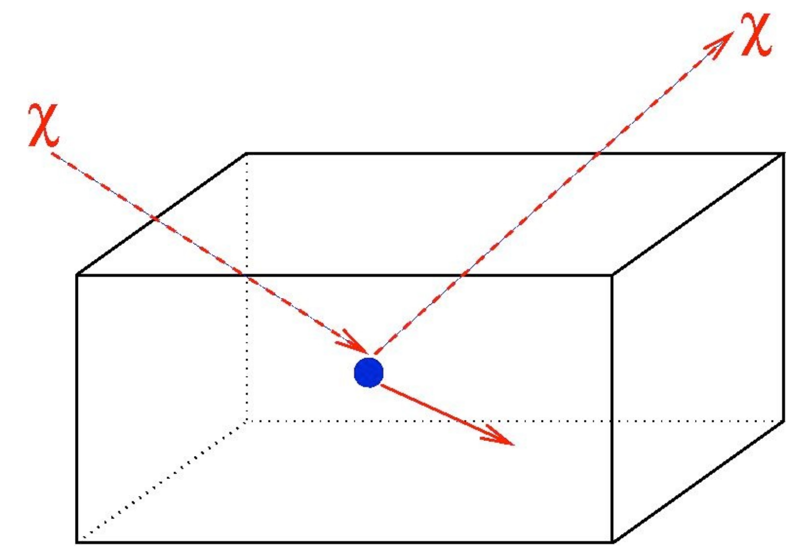


For a convincing detection will need to demonstrate that events are due to WIMPs and not backgrounds:

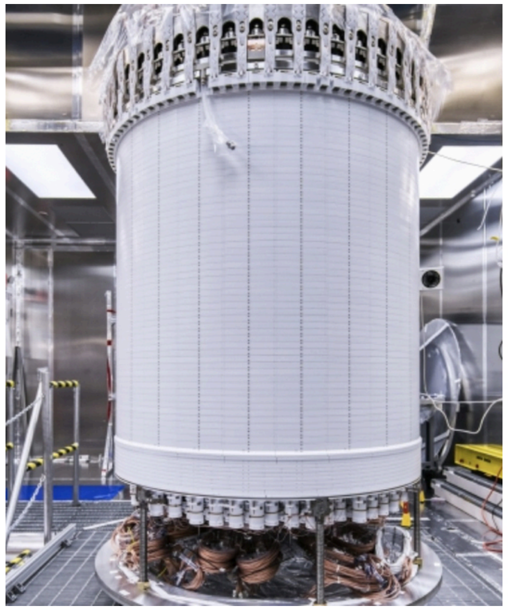
electron recoils due to βs and γs

look at multiple energy deposition channels (scintillation, ionisation, phonons)

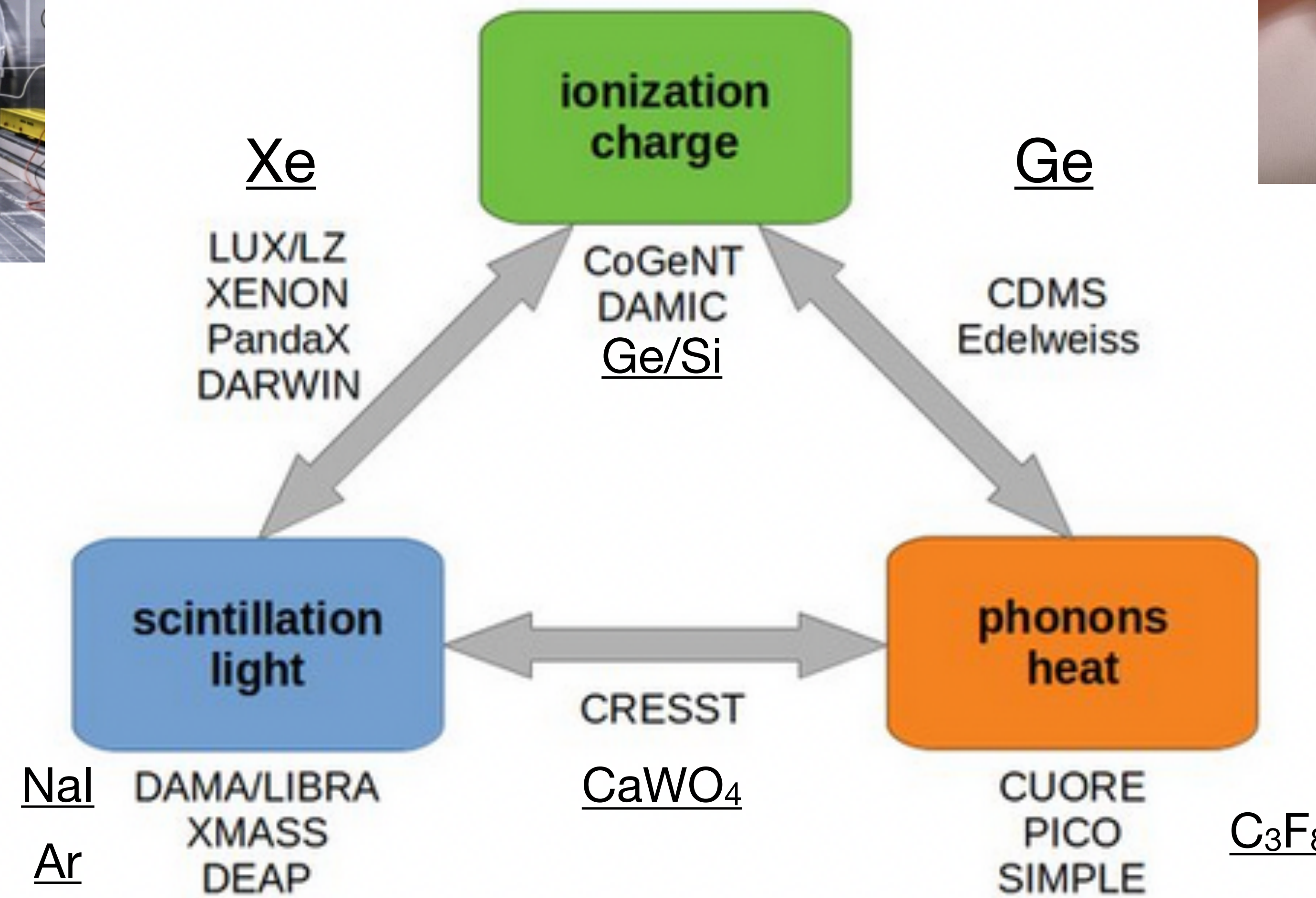
nuclear recoils due to neutrons from cosmic rays or local radioactivity

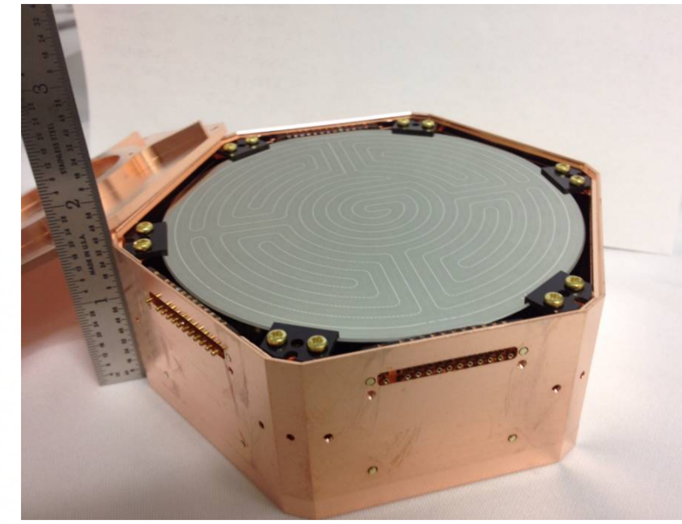
indistinguishable on an event by event basis

operate detector deep underground, use shielding and radiopure components



LZ





SuperCDMS

Bismark

n.b. not all DD experiments are shown

Rate at which particles with number density, n, speed, v, and cross section, σ_{N}, interact with target containing N_{T} nuclei:

$$R = nvN_{\mathrm{T}}\sigma_{\mathrm{N}}$$

<u>Differential event rate for nuclear recoils</u>

(events per kg detector mass, per unit time, per unit energy):

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\rho_0}{m_\chi m_{\mathrm{N}}} \int_{v_{\mathrm{min}}} v f(v) \frac{\mathrm{d}\sigma_{\mathrm{N}}}{\mathrm{d}E} \, \mathrm{d}v$$

v_{min} minimum WIMP speed that can cause a recoil of energy E:

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

Predicted energy spectrum in an experiment: multiply by exposure (detector mass x data taking time) and detection efficiency (probability that a nuclear recoil with energy E passes data cuts).

Threshold energy: energy below which experiment can't detect nuclear recoils (& distinguish them from electron recoils).

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

$$\frac{\mathrm{d}\sigma_{\mathrm{N}}}{\mathrm{d}E} = \frac{m_{\mathrm{N}}}{2\mu_{\mathrm{N}\chi}^2 v^2}\left[\sigma_{\mathrm{N}}^{\mathrm{SI}} F_{\mathrm{SI}}^2(E) + \sigma_{\mathrm{N}}^{\mathrm{SD}} F_{\mathrm{SD}}^2(E)\right]$$

$\mu_{\mathrm{N}\chi}$ WIMP-nucleus reduced mass

σ_{N} WIMP-nucleus cross-section

$F(E)$ form factors (takes into account nuclei isn't point particle)

* Effective field theory: for most general Lagrangian get additional 13 operators that can contribute to elastic scattering cross-section. Fan et al.; Fitzpatrick et al.

Spin-independent

From couplings to gluons or quarks (mediated via Higgs or squark exchange):

$$\sigma_{\mathrm{N}}^{\mathrm{SI}} = \frac{4}{\pi}\mu_{\mathrm{N}\chi}^{2}\left[Zf_{\mathrm{p}} + (A-Z)f_{\mathrm{n}}\right]^{2}$$

$f_{\mathrm{p/n}}$ coupling between WIMPs and protons/neutrons

Common assumption $f_{\mathrm{p}} = f_{\mathrm{n}}$ leads to:

$$\sigma_{N}^{\mathrm{SI}} = \left(\frac{\mu_{\mathrm{N}\chi}}{\mu_{\mathrm{p}\chi}}\right)^{2} A^{2}\sigma_{\mathrm{p}}^{\mathrm{SI}}$$

WIMP-proton spin-independent cross-section: $\sigma_{\mathrm{p}}^{\mathrm{SI}} = \frac{4}{\pi}\mu_{\mathrm{p}\chi}^{2} f_{\mathrm{p}}^{2}$

Spin-dependent

From WIMP-quark axial coupling:

$$\sigma_{\mathrm{N}}^{\mathrm{SD}} = \frac{32}{\pi}\mu_{\mathrm{N}\chi}^2 G_{\mathrm{F}}^2 \frac{J+1}{J}\left[a_{\mathrm{p}}\langle S_{\mathrm{p}}^{\mathrm{N}}\rangle + a_{\mathrm{n}}\langle S_{\mathrm{n}}^{\mathrm{N}}\rangle\right]^2$$

G_{F}	Fermi coupling constant
J	nuclear angular momentum
$\langle S_{\mathrm{p/n}}^{\mathrm{N}}\rangle$	expectation values of spin content of nucleons
$a_{\mathrm{p/n}}$	nuclear matrix elements

Can be rewritten as:

$$\sigma_{\mathrm{N}}^{\mathrm{SD}} = \frac{4}{3}\left(\frac{\mu_{\mathrm{N}\chi}}{\mu_{\mathrm{p}\chi}}\right)^2 \frac{J+1}{J}\sigma_{\mathrm{p}}^{\mathrm{SD}}\left[\langle S_{\mathrm{p}}^{\mathrm{N}}\rangle + \frac{a_{\mathrm{n}}}{a_{\mathrm{p}}}\langle S_{\mathrm{n}}^{\mathrm{N}}\rangle\right]^2$$

WIMP-proton spin-dependent cross-section: $\sigma_{\mathrm{p}}^{\mathrm{SD}} = \frac{32}{\pi}\mu_{\mathrm{p}\chi}^2 G_{\mathrm{F}}^2 \frac{3}{4} a_{\mathrm{p}}^2$

Focusing on spin-independent interactions:

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

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

Particle physics parameters: WIMP mass and cross-section m_χ σ_{p}

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

Normalization: σ and ρ_0 are degenerate.

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

Standard halo model

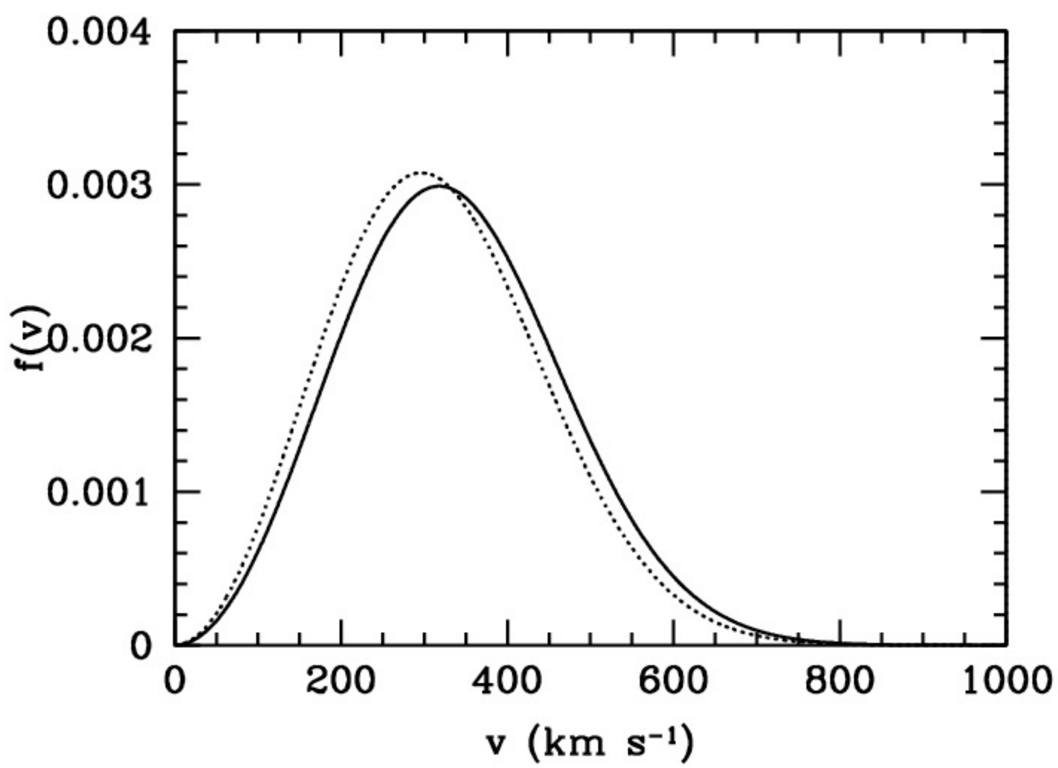
Usually used when calculating experimental constraints on σ and m_χ.

isotropic, isothermal sphere, with Maxwell-Boltzmann speed distribution

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

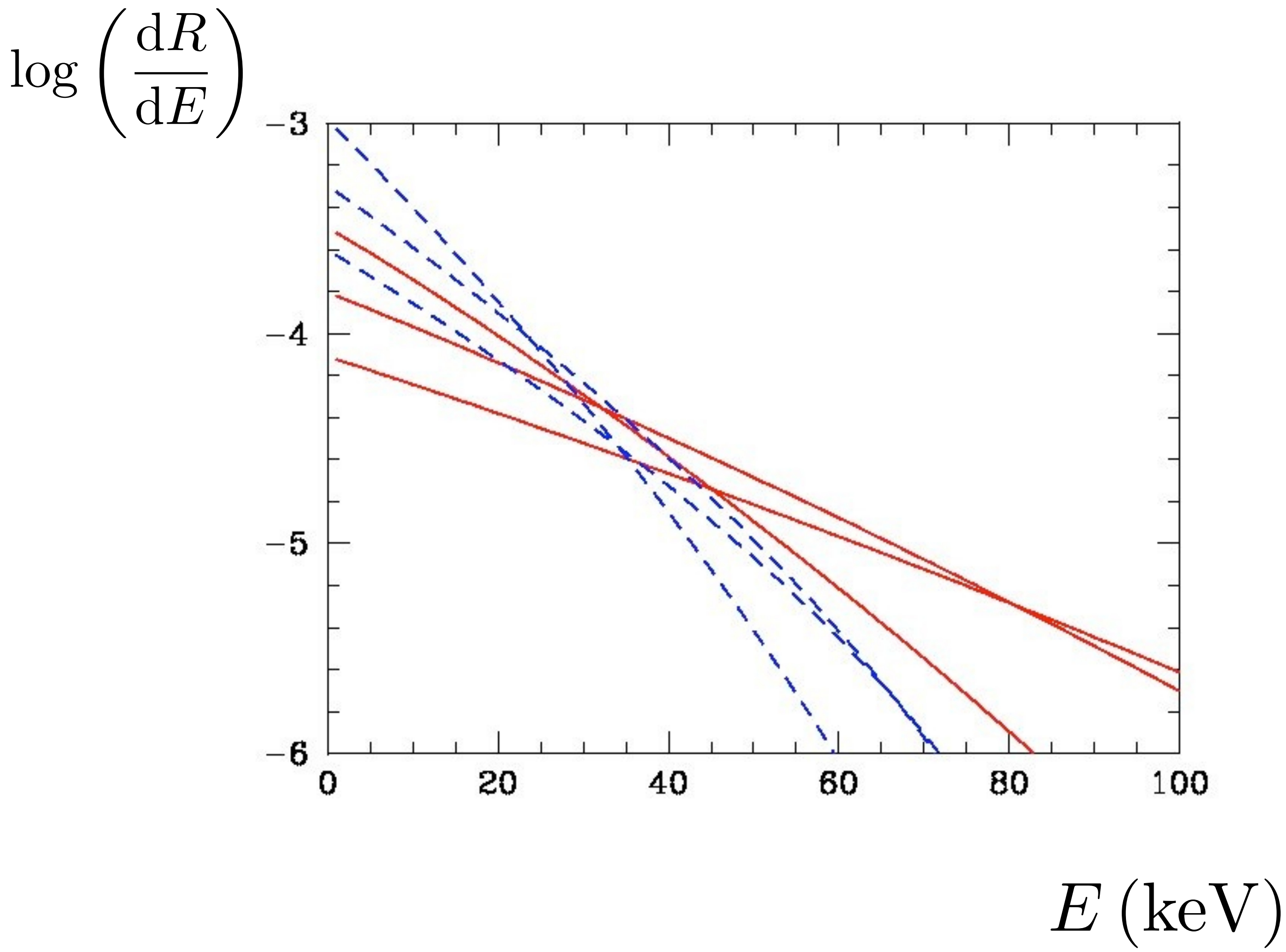
with circular speed $v_{\rm c} = 220\,{\rm km\,s^{-1}}$ and local density $\rho_0 = 0.3\,{\rm GeV\,cm^{-3}}$

probably an OK-ish approximation (c.f. lecture 1).



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

Energy spectrum



Ge and Xe

m_χ: 50 GeV,
100 GeV,
200 GeV

Energy spectrum is quasi-exponential with characteristic energy scale:
Lewin & Smith

$$E_\mathrm{R} = \frac{2\mu_{A\chi}^2 v_\mathrm{c}^2}{m_A}$$

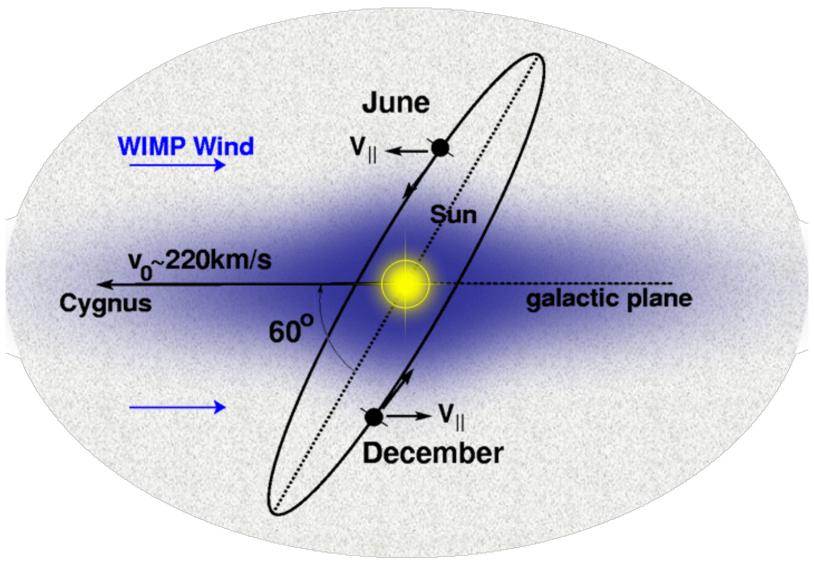
$\propto m_\chi^2$ if $m_\chi \ll m_A$

~ const if $m_\chi \gg m_A$

- sub GeV WIMPs: rate above energy threshold small.
- heavy ($\gg 100\,\mathrm{GeV}$) WIMPS: shape of energy spectrum independent of WIMP mass (but total rate $\propto m_\chi^{-1}$).

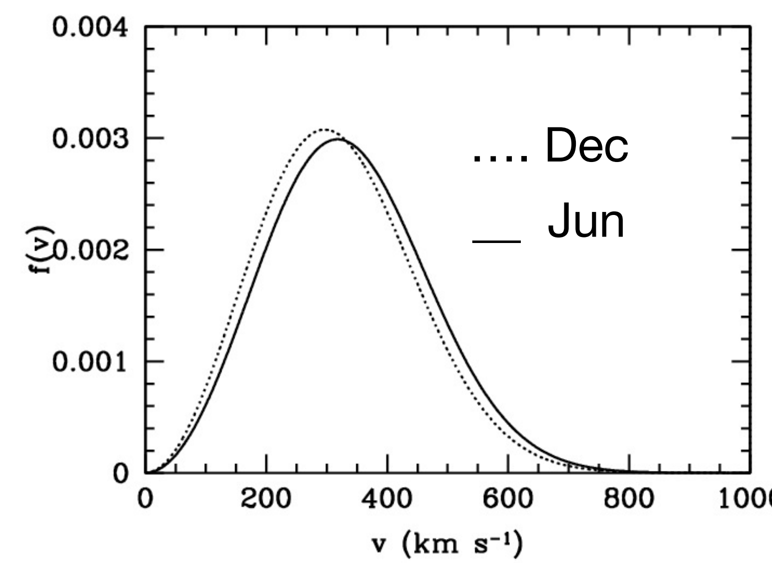
Annual modulation Drukier, Freese & Spergel

Due to Earth's orbit around Sun, WIMP flux + speed distribution in laboratory frame and hence recoil rate and spectrum vary annually.

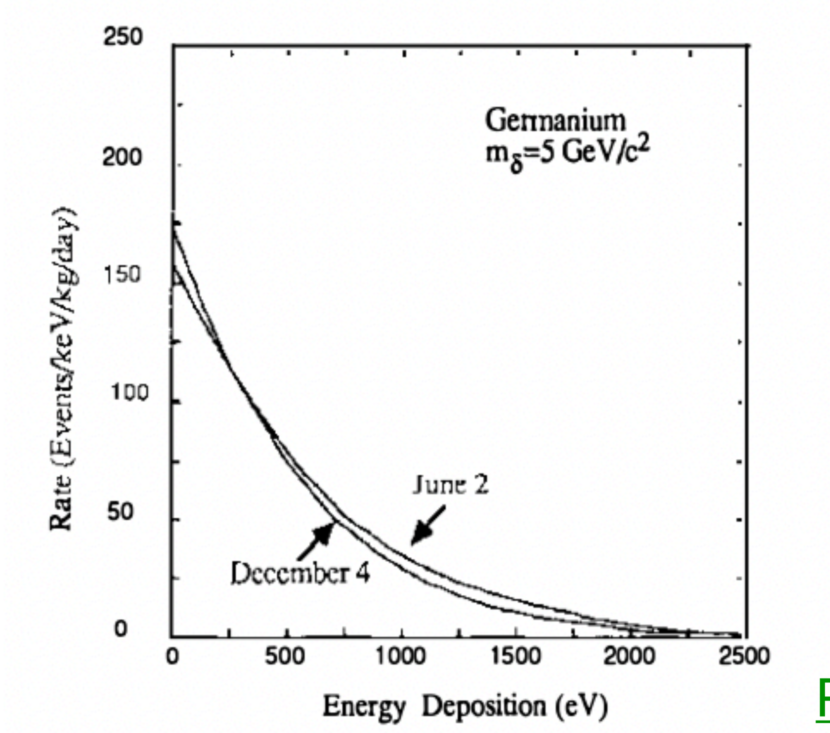


Sheffield DM group

speed dist. lab. frame

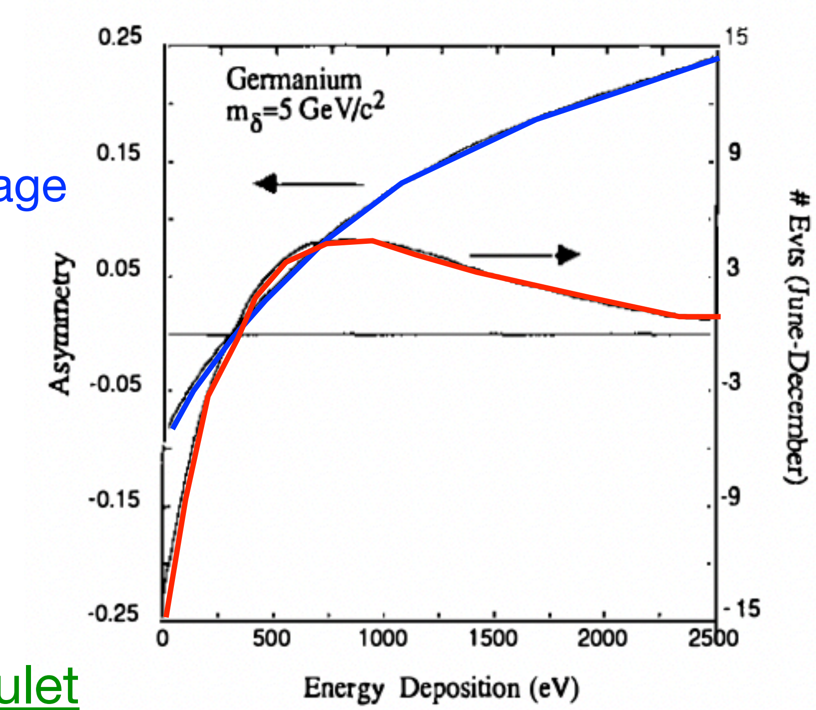


differential event rate



modulation amplitude

(June-Dec)/average

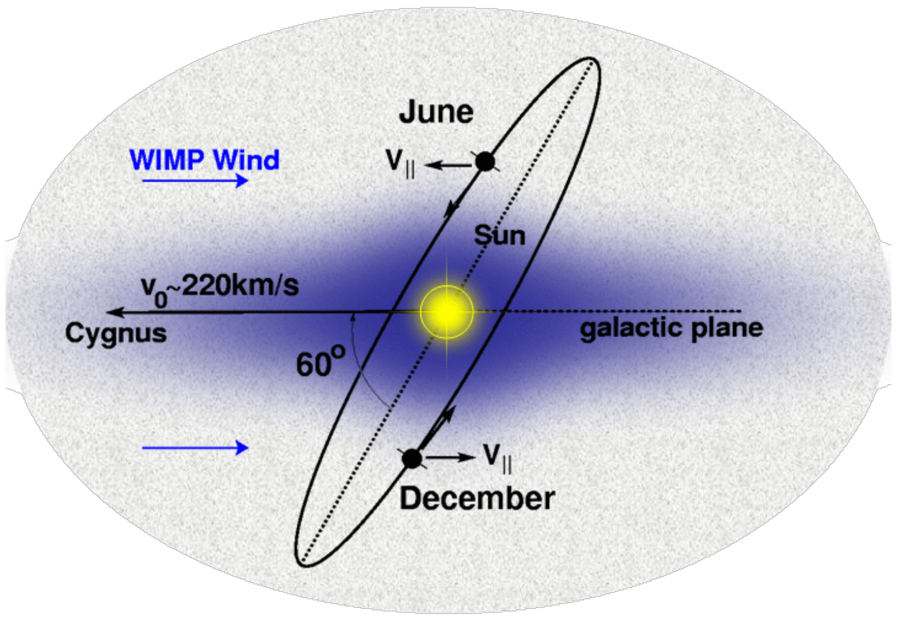


June-Dec

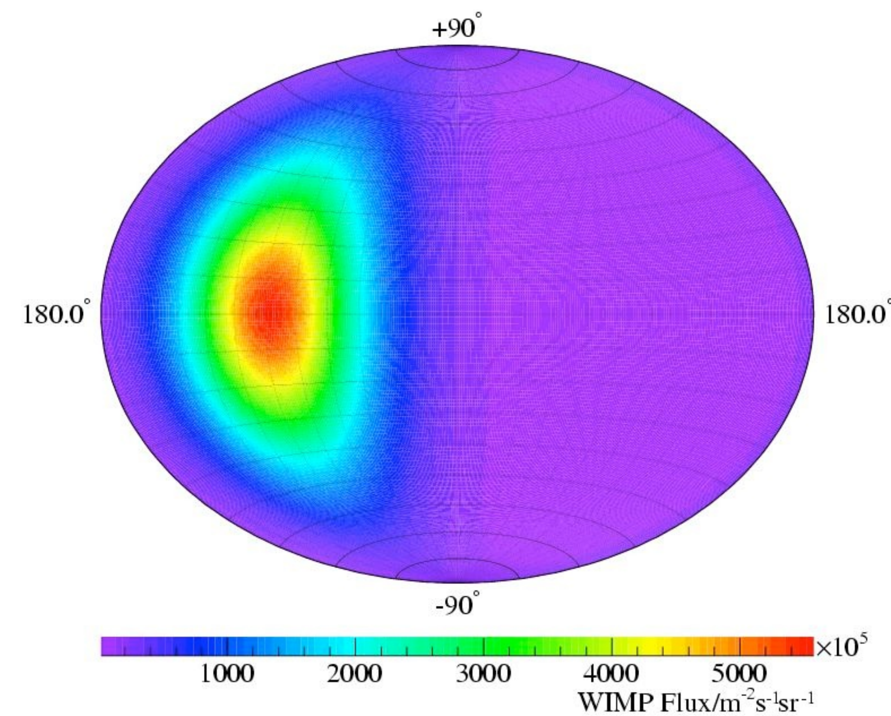
Primack, Seckel, Sadoulet

Directionality Spergel

Motion of detector with respect to Galactic rest frame also leads to direction dependence of recoil rate:



Sheffield DM group



Morgan, Green & Spooner

Potentially large signal.

with an ideal detector:

~10 events required to reject isotropy of recoil directions Copi, Heo & Krauss; Morgan, Green & Spooner

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

But need a detector which can 'measure' recoil directions, recent review: O'Hare, Loomba et al. Snowmass 2021 white paper

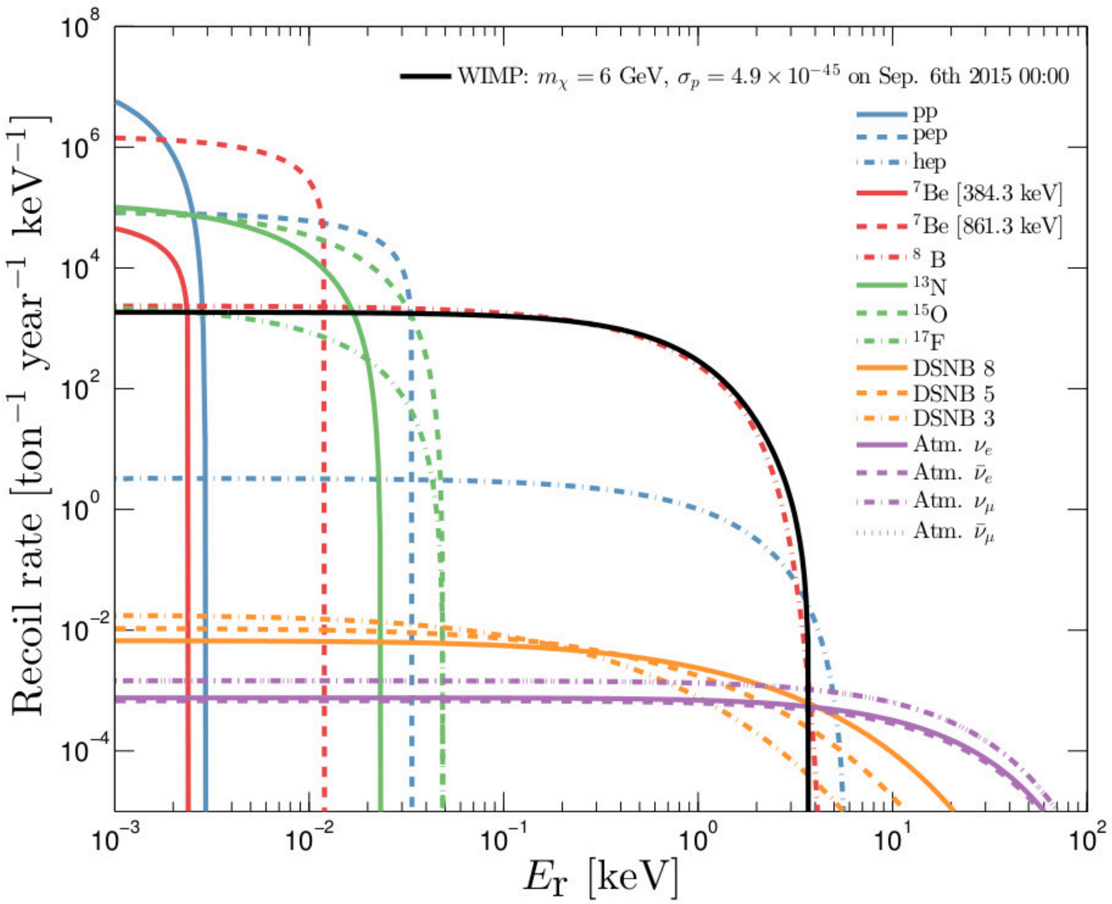
Neutrino floor/fog

Neutrinos will soon become a background for WIMP direct detection experiments!

Coherent neutrino-nucleus scattering produces recoil energy spectra that are similar to WIMP elastic scattering.

Billard, Strigari & Figueroa-Feliciano

Recoil energy spectra in a Xe detector



6 GeV WIMP

pp, ^{7}Be, ^{8}B, ^{13}N, ^{15}O, ^{17}F Solar neutrinos

Diffuse supernovae background (DSNB)

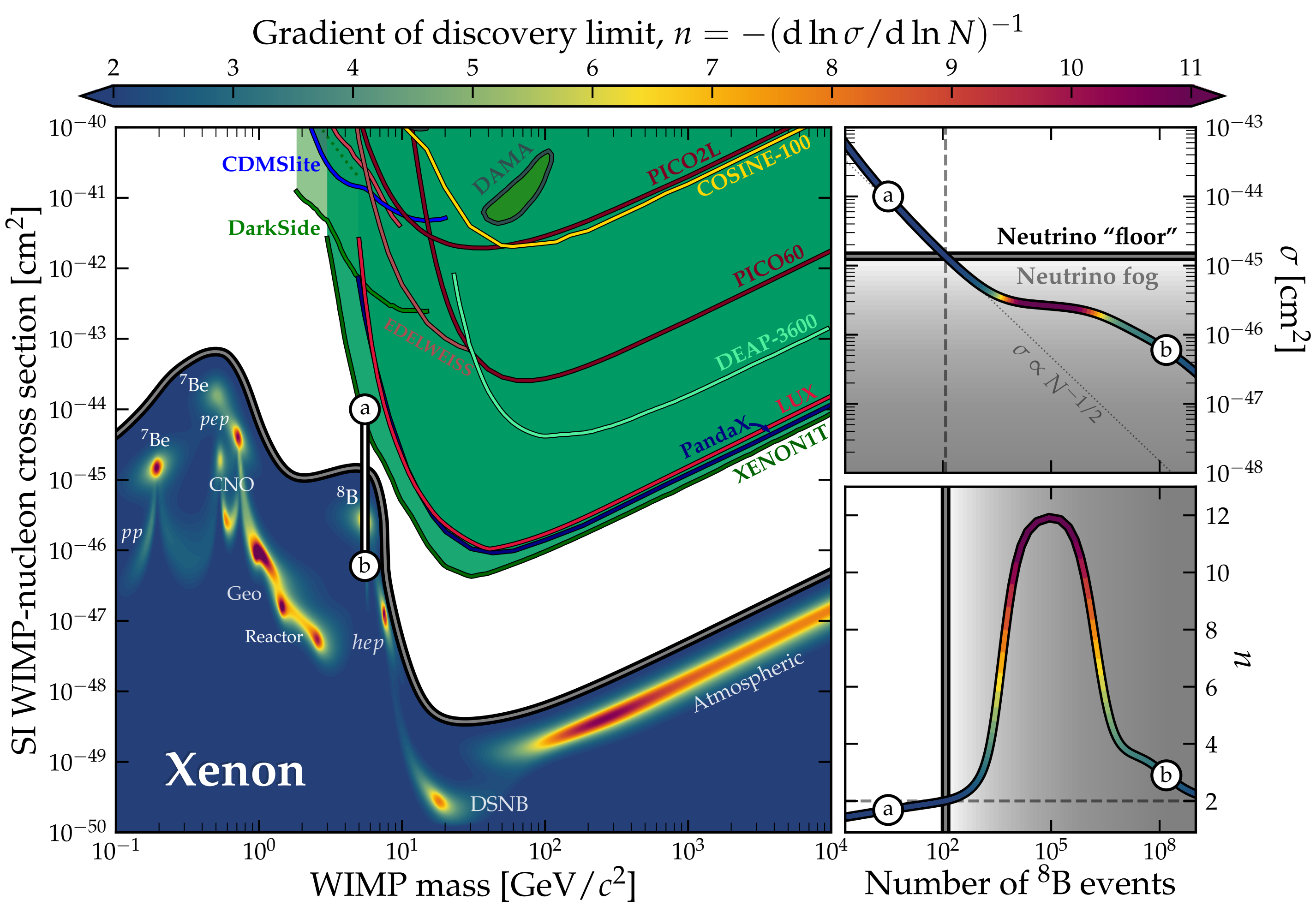
Atmospheric

O'Hare et al.

DSNB and atmospheric neutrinos produce similar recoil spectra to ~20 GeV and > 100 GeV WIMPs respectively.

However the neutrino floor isn't a hard floor: can probe cross sections below it, but rate at which cross-section sensitivity improves with increasing exposure slows down.

Neutrino floor as boundary of neutrino fog: O'Hare



O'Hare

$$\sigma \propto N^{-1/n}$$

N = number of background events

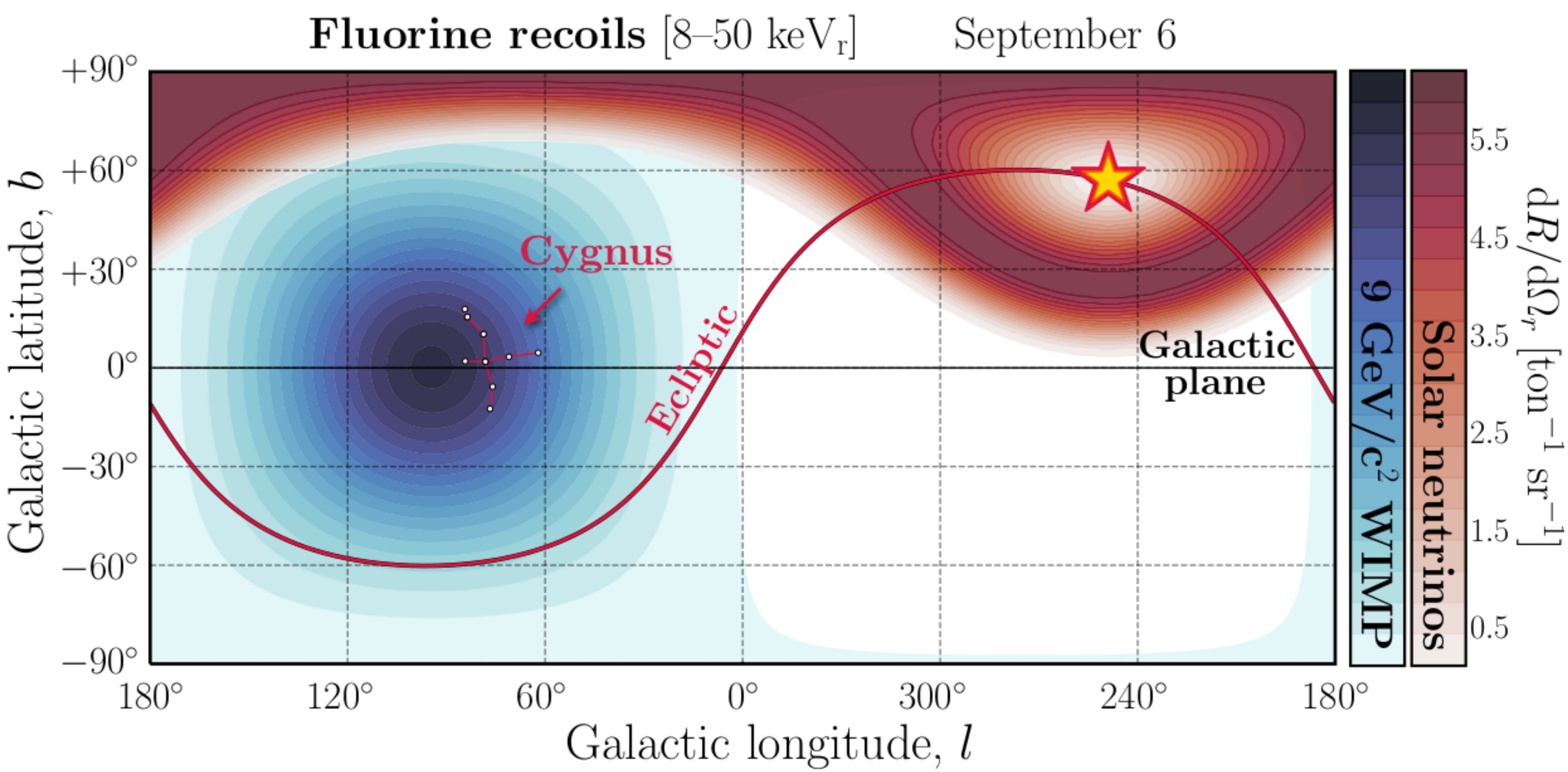
Poisson regime: signal rate similar to background, n = 2

Saturation regime: signal rate similar to *uncertainty* in background, n > 2

Directional detectors can ‘see through the neutrino fog’ as neutrinos have different angular dependence than WIMPs:

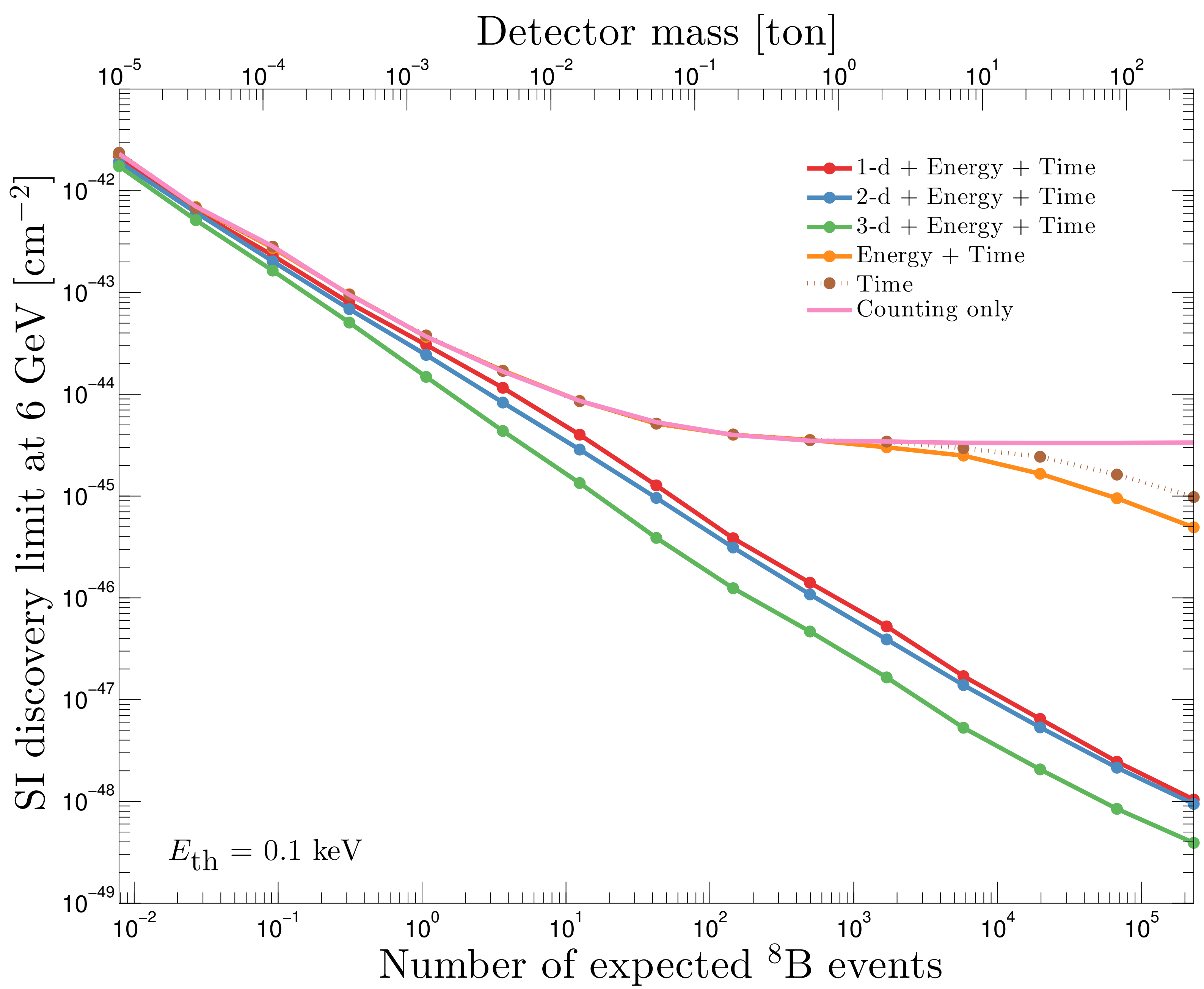
Billard, Strigari & Figueroa-Feliciano; Grothaus, Fairburn & Monroe.

Directional event rate for Fluorine: 9 GeV WIMP and Solar neutrinos



Vahsen, O’Hare & Loomba

Improvement in cross-section sensitivity of a Xe experiment to a 6 GeV WIMP as exposure/number of events due to ^{8}B Solar neutrinos increases:



annual modulation

+ energy spectrum

+ 1d directionality

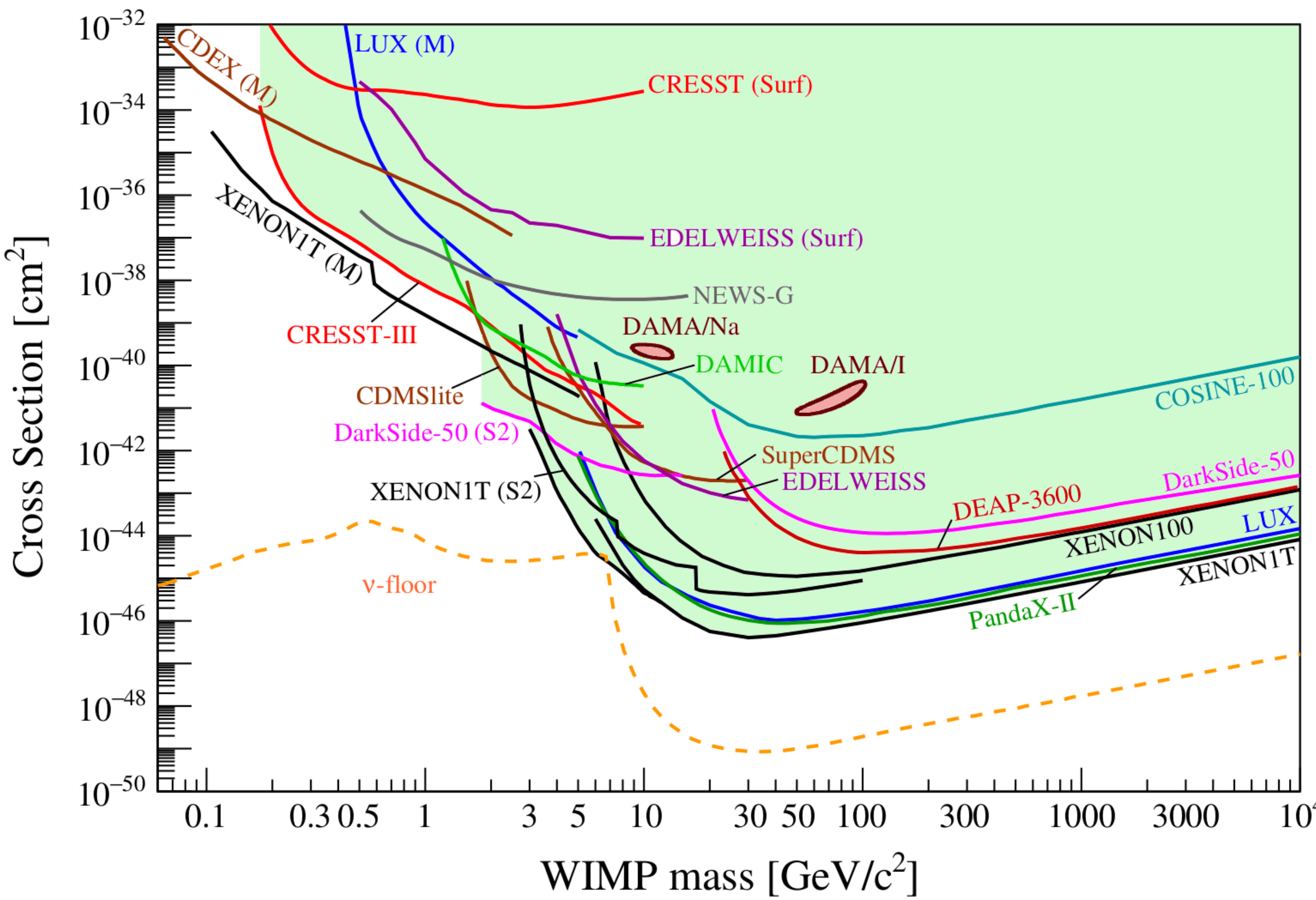
+ 2d

+ 3d

O'Hare et al.

Spring 2022 status

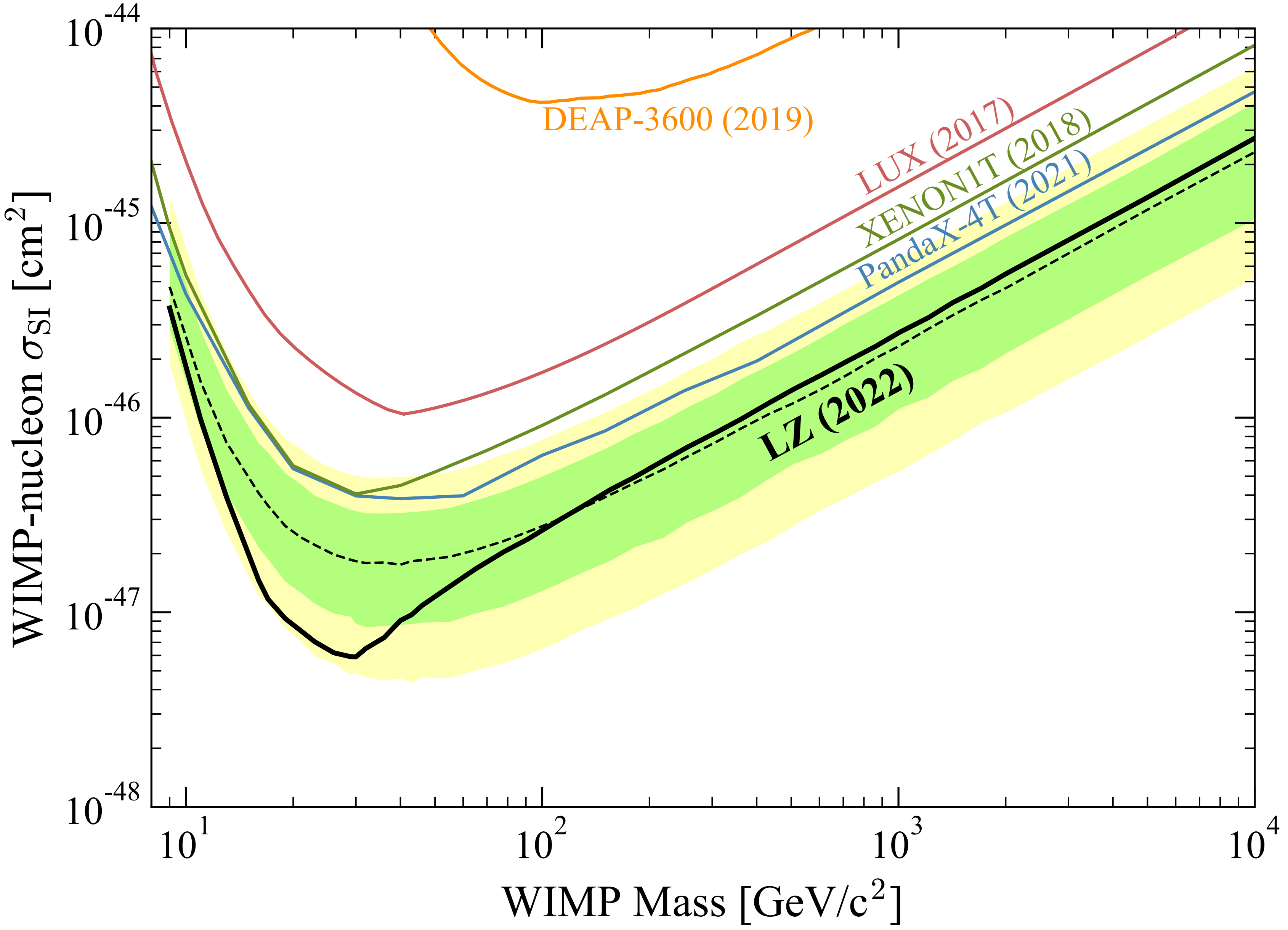
spin-independent cross section



[Direct detection of dark matter-APPEC committee report]()

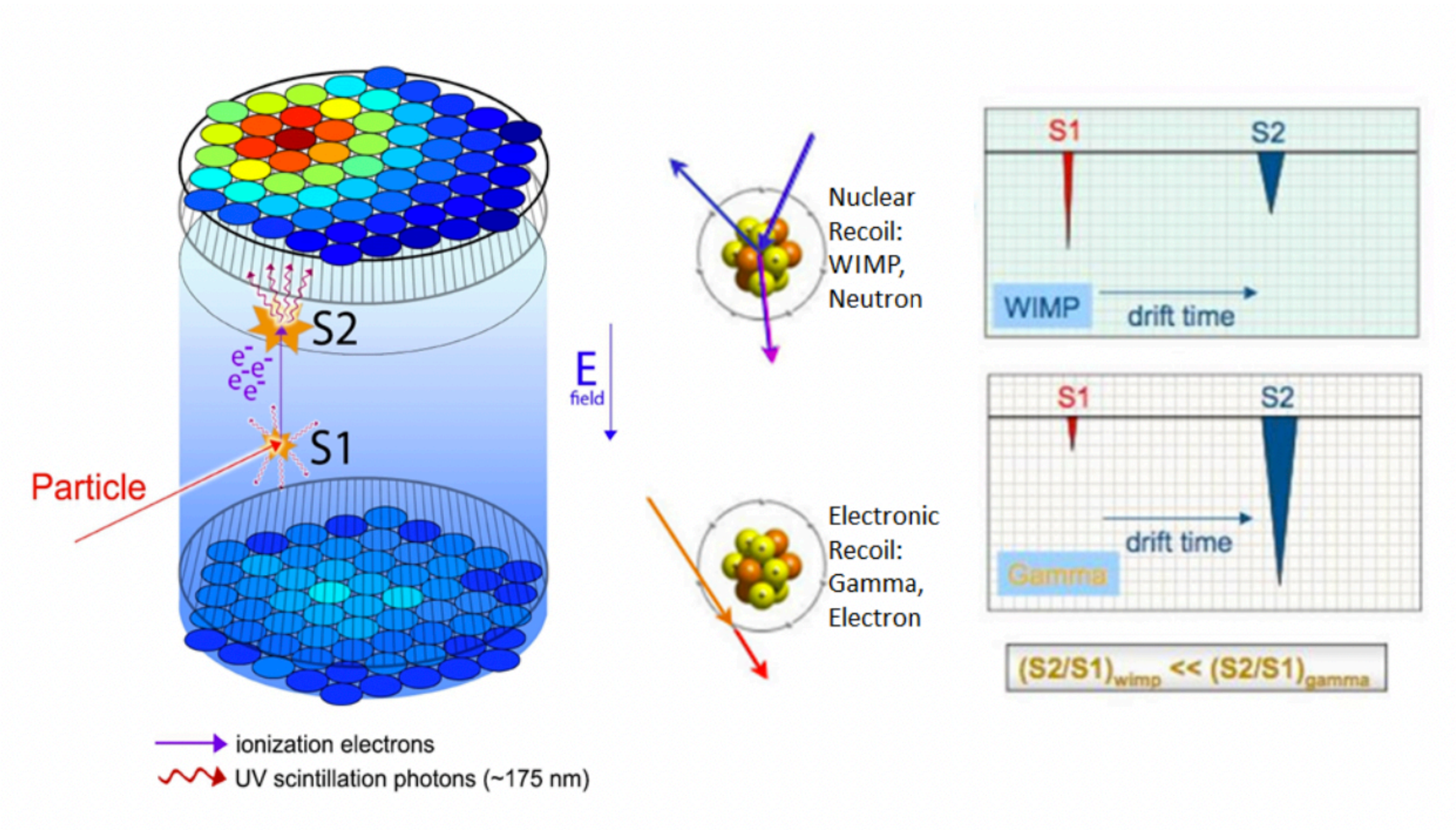
Summer 2022 status

New results from Lux-Zeplin (LZ):



Lux-Zeplin (LZ)

Essentials of dual-phase xenon experiments (LZ, Xenon-nT, Panda-X)



S2: induced scintillation (from ionisation)

S1: direct/prompt scintillation

Xenon-nT

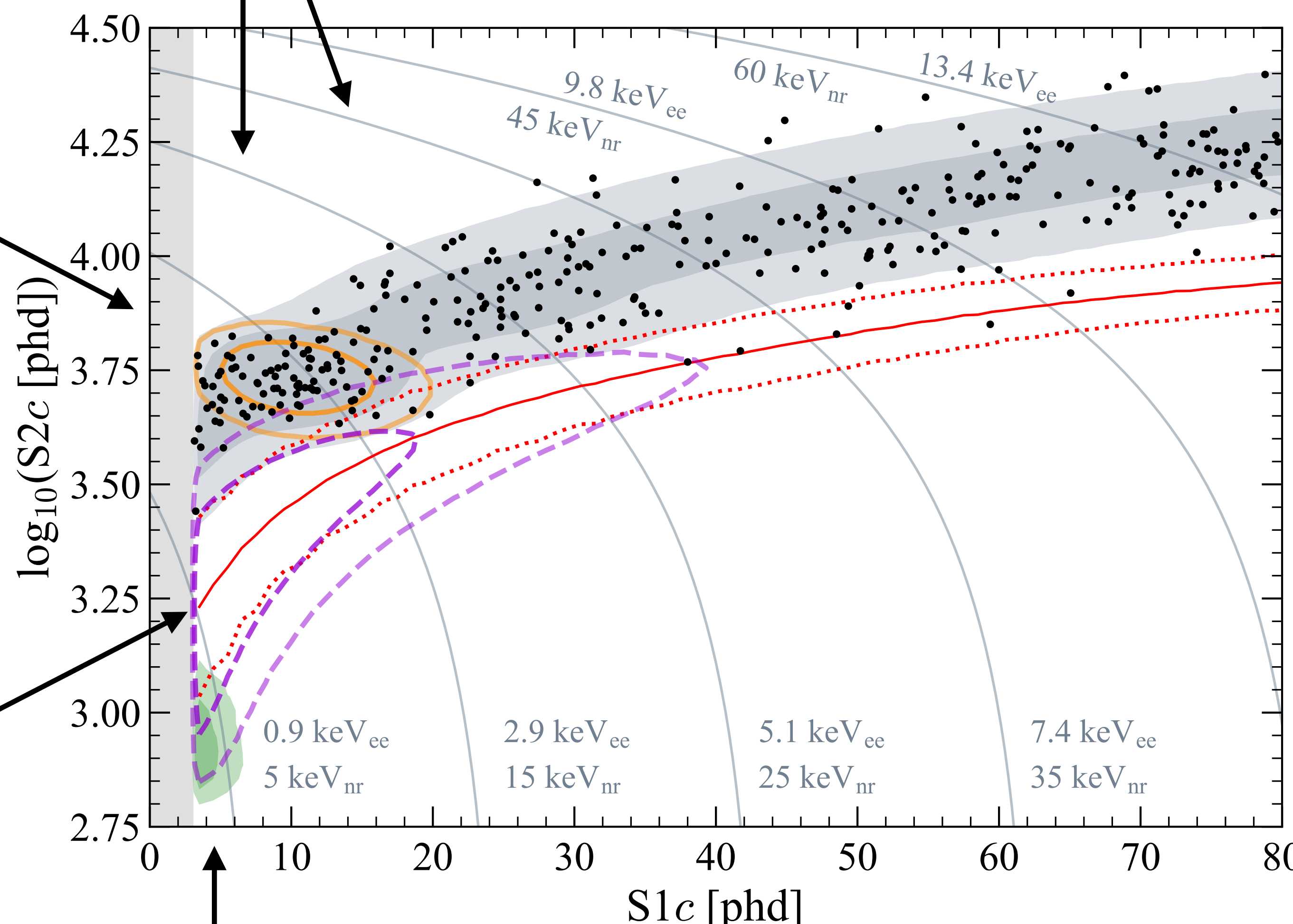
LZ data (S2 v. S1)

contours of constant recoil energy

S2

^{37}Ar background (from exposure to cosmic rays above ground)

30 GeV WIMP



- data after cuts

1 & 2σ range best fit background model

nuclear recoil 'band'

median

10 & 90% range

S1

^{8}B Solar neutrinos

number of photons detected

Lux-Zeplin (LZ)

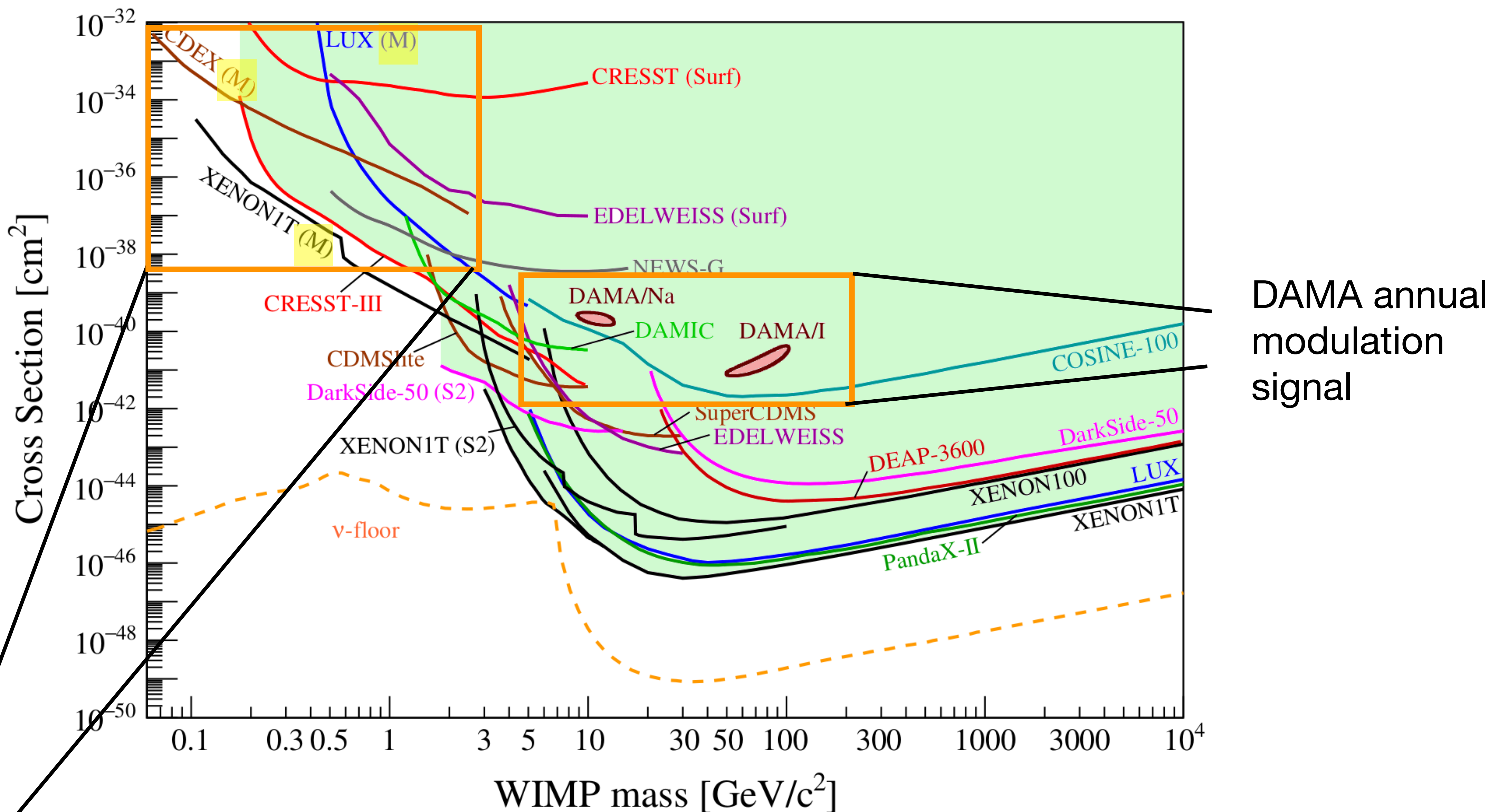
Number of events (expected and best fit)

Source	Expected Events	Fit Result
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Lux-Zeplin (LZ)

Spring 2022 status

spin-independent cross section



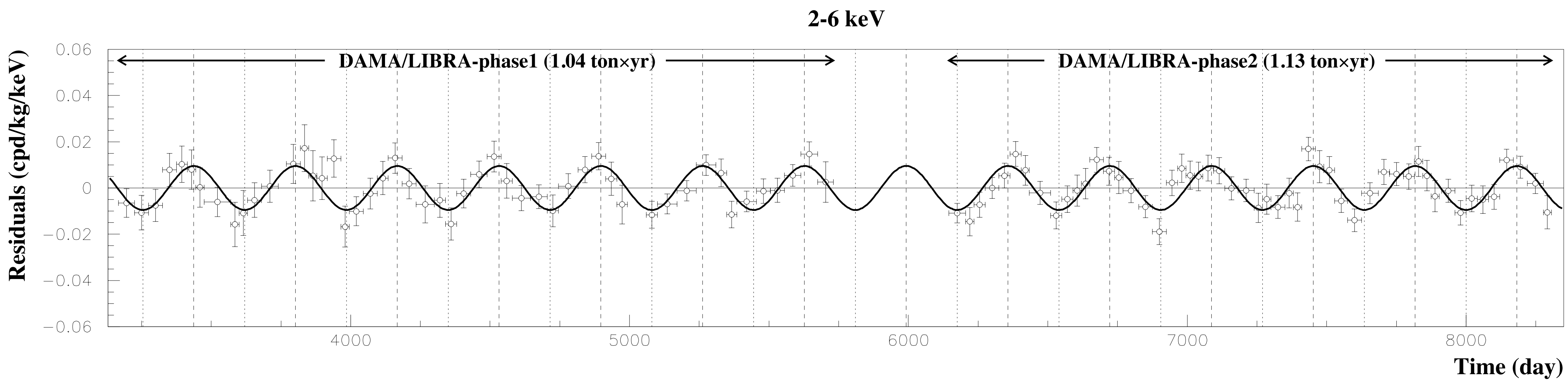
Direct detection of dark matter-APPEC committee report

M = assumes Migdal effect occurs

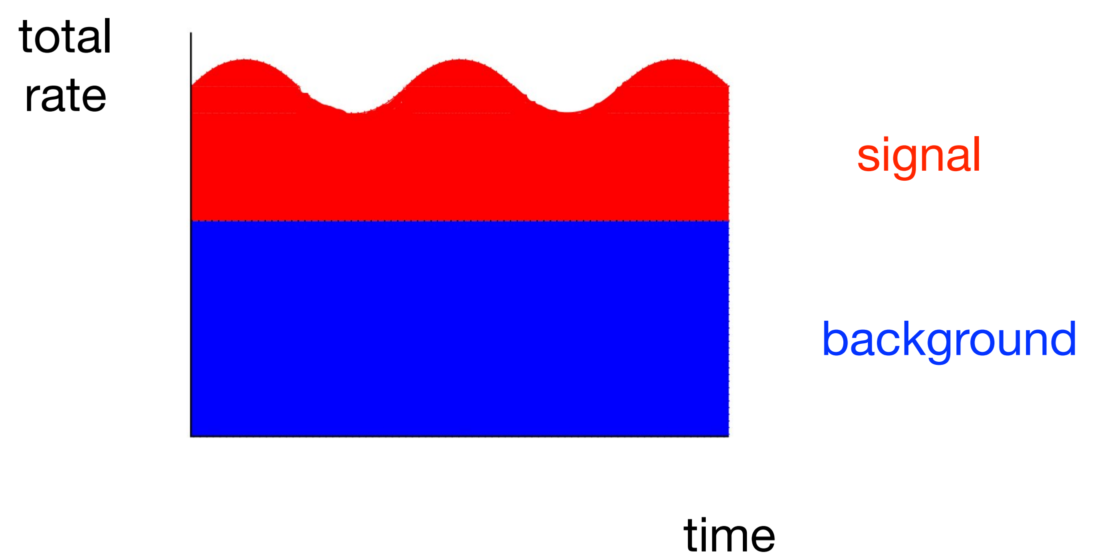
(electron cloud doesn't immediately follow nucleus → excitation & ionisation)

DAMA-Libra annual modulation signal

DAMA-Libra (Sodium Iodide, scintillation only) has a long standing (> 2 decades) annual modulation in their event rate.



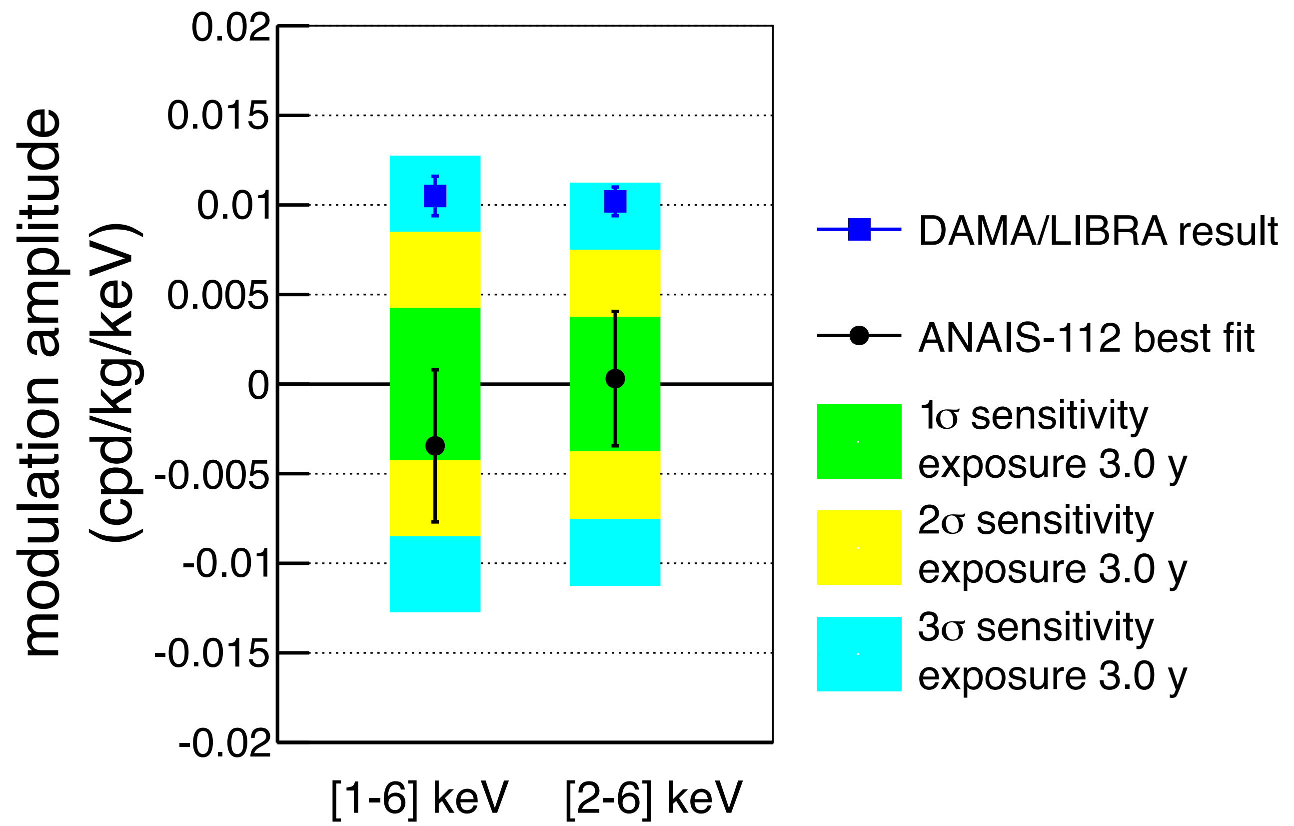
DAMA-Libra



Hard to reconcile high rate with exclusion limits from other experiments (Xeno-phobic DM…).

Several experiments ongoing with NaI crystals to directly check DAMA-Libra annual modulation (ANAIS-112, COSINE-100, SABRE).

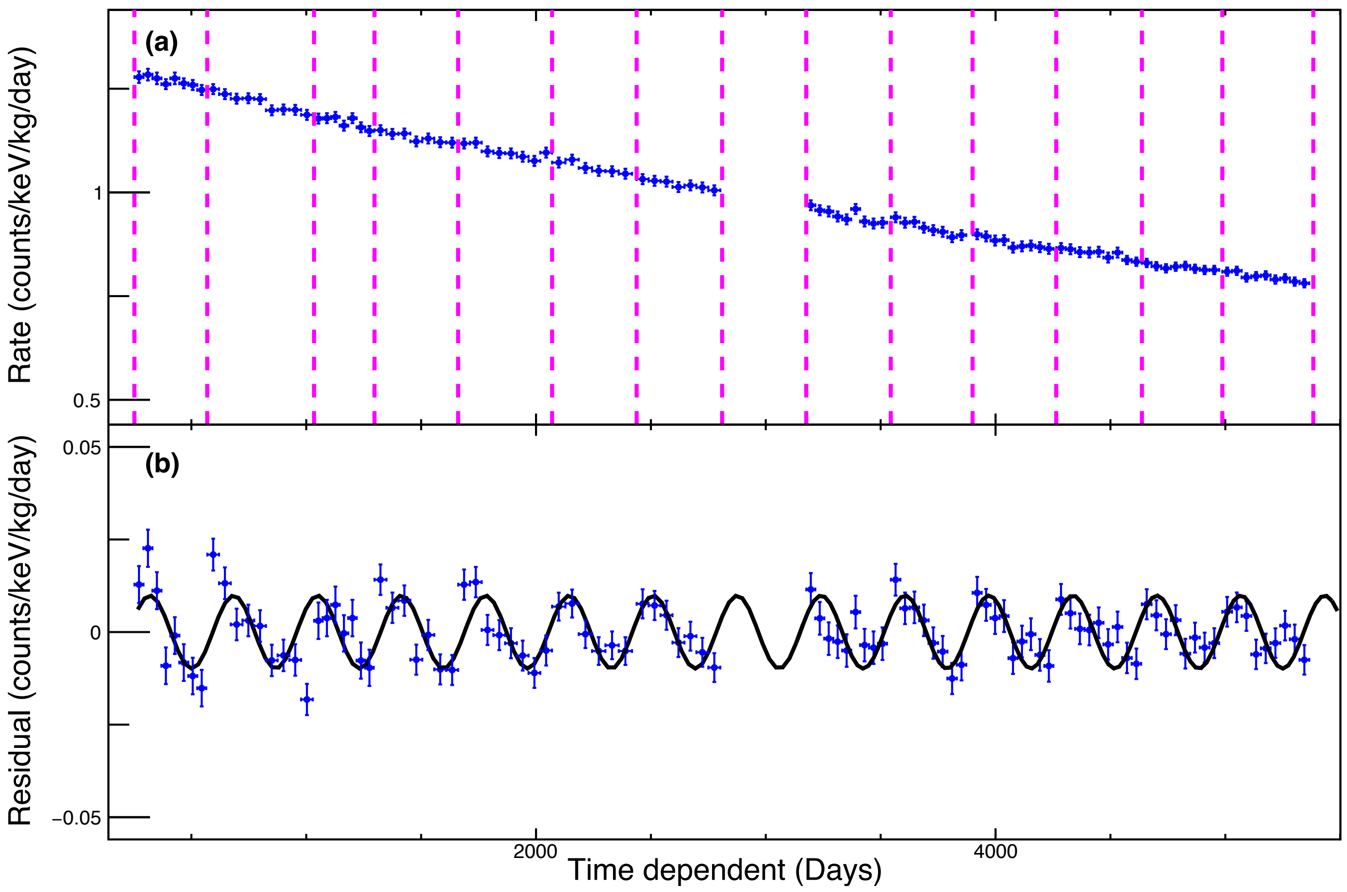
So far no annual modulation observed, but sensitivity not quite yet high enough to exclude DAMA-Libra annual modulation at 3σ significance:



ANAIS-112

DAMA analyse data by removing average rate, calculated on an annual basis.

If the background varies on long timescales, this process could induce a spurious annual modulation signal. Buttazzo et al.

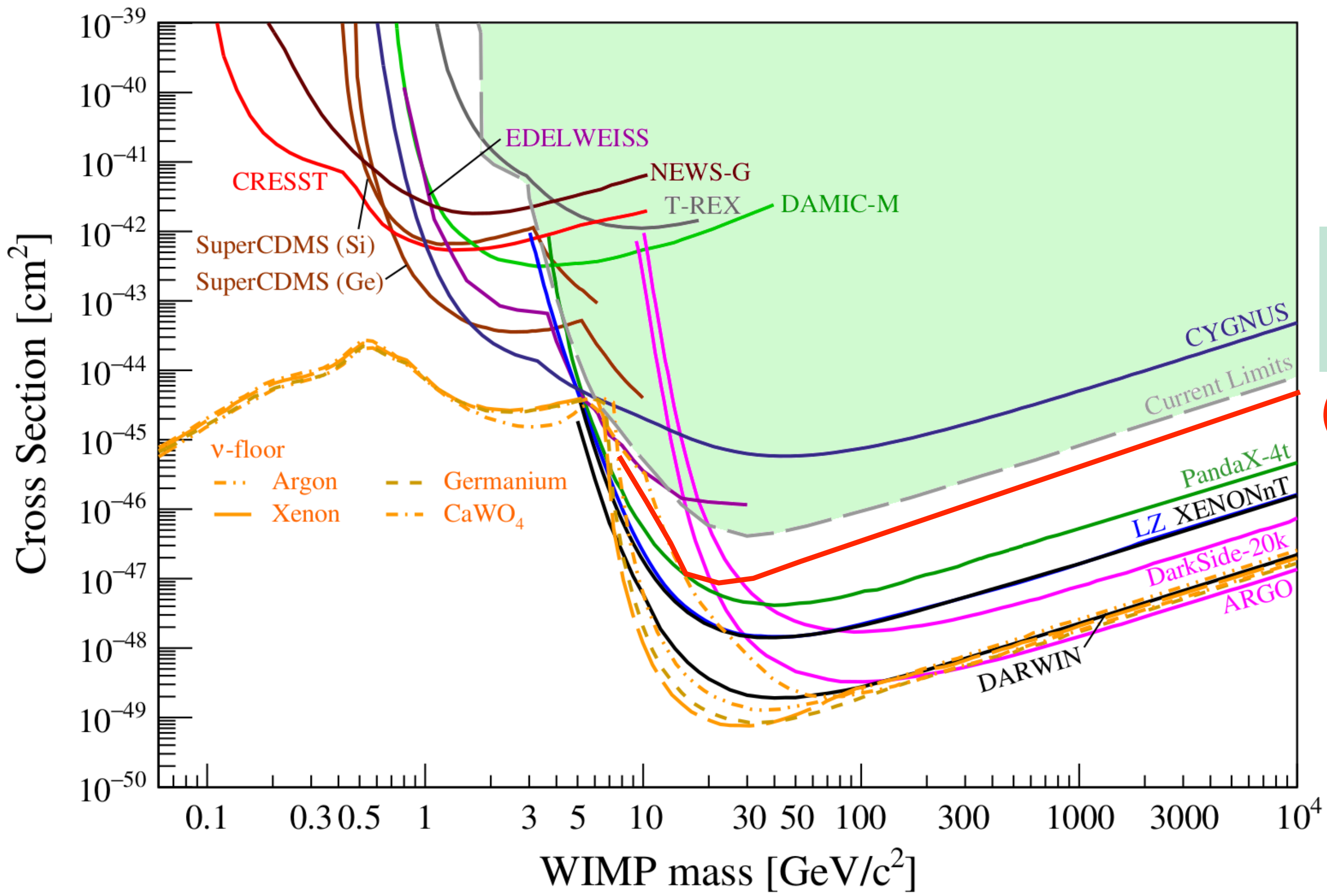


COSINE-100

COSINE-100 have analysed their data using this technique, and found an induced ‘wrong sign’ (i.e. peak in Dec) annual modulation. COSINE-100

Future projections

spin-independent cross section



excluded pre-Summer 2022

(approx) LZ Summer 2022

Direct detection of dark matter-APPEC committee report

Merger of xenon-based based experiments:

LZ + XENON + DARWIN = XLZD (40-100 tonnes, data taking 2027-28)

Many new experiments/ideas to detect MeV & superheavy DM, see e.g.:

'New directions in the search for DM', Rajendran, Les Houches DM Summer school
'Landscape of low-threshold DM direct detection in the next decade', Essig et al. Snowmass white paper
'Ultraheavy DM', Carney et al. Snowmass white paper

Summary

Freeze-out of a stable Weakly Interacting Massive Particle leads to a relic density which is consistent with the observed dark matter density.
(And freeze-in for Feebly Interacting Massive Particles.)

WIMPs can be detected directly (via scattering off nuclei in laboratory experiments), indirectly (via the products of their annihilation) or produced at colliders.

Direct detection experiments have reached multi-tonne scale and will 'soon' encounter neutrino floor/fog (background from coherent scattering of Solar/atmospheric/diffuse supernovae neutrinos).

Earth's motion with respect of Galactic rest frame leads to annual modulation and directional dependence of even rate (need detector that can measure directions of recoils).

BACK-UP SLIDES

DAMA-Libra annual modulation signal

$$R(t) = R_0 + S_\mathrm{m} \cos \omega (t - t_0)$$

R_0 average rate

S_m amplitude of modulation

t_0 phase of modulation

R_0 and S_m both E dependent

<u>LZ nuclear recoil detection efficiency</u>