Frontiers in Astrophysics

Particle Astrophysics:

Dark Matter 2: Direct Detection

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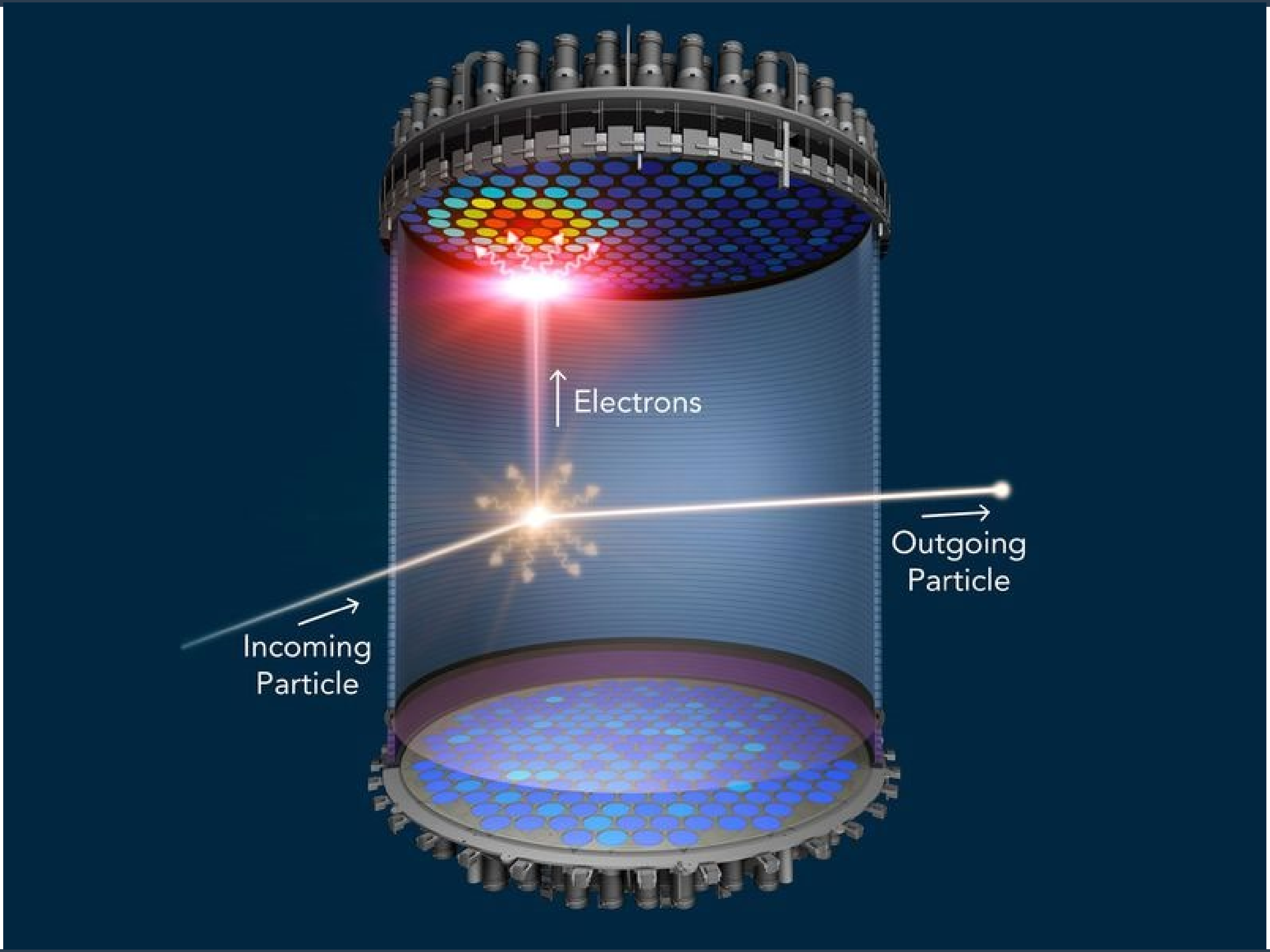
Credit to Pat Scott for many of the slides

Overview

- Background detection theory, scattering rates
- Interaction types
- Even rates, noise, annual modulation
- Intro to calculating rates
- Direct detection experimental techniques
- Look at some direct detections results

Part 1: Theoretical Overview



img: XENON Collab.

Directly detecting dark matter

- Assume DM has some interaction with atoms
- Presumably very small interaction:
  - Need very sensitive detector
  - Low-noise environment (e.g., under mountain)
- Measure event rate
- Link observable back to: mass, cross-section
- See signal: how can you be sure it’s not noise?
  - Annual modulation? (see DAMA)

Directly detecting dark matter

$$R = n\, v\, \sigma \times N_{\text{target}}$$

$$dR = \frac{n_T\, \rho_{\text{DM}}}{m_\chi c^2} \frac{\mathrm{d}\langle \sigma_{njl} v_\chi \rangle}{\mathrm{d}E}\, \mathrm{d}E$$

- WIMP flies in, scatters elastically off an atomic nucleus $\Longrightarrow$ nucleus gets a kick
- Very small kick $\Longrightarrow$ very low threshold detection required

$$\frac{dN}{dE_{\mathrm{r}}} = \frac{\sigma \rho}{2\mu^2 m_\chi} F^2 \int_{v_{\min}(E_{\mathrm{r}})}^{v_{\mathrm{esc}}} \frac{f(v)}{v}\, dv$$

N = number of scatterings
E_{r} = nuclear recoil energy
σ = WIMP-nucleus cross-section
ρ = WIMP density
μ = WIMP-nucleus reduced mass
m_χ = WIMP mass
F = nuclear form factor
$f(v)$ = WIMP velocity distribution
v = WIMP velocity
$v_{\min}(E_{\mathrm{r}})$ = minimum v to produce recoil E_{r}
v_{esc} = halo escape velocity (max v)

Recoil rate is degenerate in unknowns

- WIMP mass
- local WIMP density
- halo velocity distribution
- WIMP-nucleus cross-section

Spin-dependent and -independent cross-sections

Spin-independent

- Scattering off all nucleons
- $\implies$ proportional to A^2 ($A =$ atomic weight)
- Dominates for heavy nuclei due to A^2 enhancement
- Form factor can suppress momentum transfer in very large nuclei though
- Most studied, most accessible

Spin-dependent

- Scattering only off nucleons with *net* nuclear spin (i.e. whose spins remain *unpaired*)
- $\implies$ less increase with A than spin-independent cross-section
- Important for light nuclei (e.g. in stars!)
- Least studied, trickier

DM-nucleon cross-sections

In standard (read: SUSY) WIMP-land, everything is nice and constant. . .

$$\chi\bar{\chi}Q\bar{Q} \quad \rightarrow \sigma_{\rm SI} \qquad \text{spin} - \text{independent} \tag{1}$$
$$\chi\gamma_\mu\gamma_5\bar{\chi}Q\gamma^\mu\gamma_5\bar{Q} \quad \rightarrow \sigma_{\rm SD} \qquad \text{spin} - \text{dependent} \tag{2}$$

No dependence on

- $v_{\rm rel}$ – relative velocity
- q – momentum exchange between DM (χ) and quarks (Q)

. . . but in e.g. pseudoscalar exchange

$$\chi\gamma_5\bar{\chi}Q\gamma_5\bar{Q} \quad \rightarrow \sigma_{\rm SD'} \qquad \text{spin} - \text{dependent}, \ \sigma \propto q^4 \tag{3}$$

In general $\sigma = \sigma(q, v_{\rm rel})$

DM-nucleon cross-sections

In general $\sigma = \sigma(q, v_{\mathrm{rel}})$

Must be taken into account in rate calculation!

$$\frac{dN}{dE_{\mathrm{r}}} = \frac{\sigma\rho}{2\mu^2 m_\chi} F^2 \int_{v_{\mathrm{min}}(E_{\mathrm{r}})}^{v_{\mathrm{esc}}} \frac{f(v_{\mathrm{rel}})}{v_{\mathrm{rel}}} dv_{\mathrm{rel}}$$

$$\downarrow$$

$$\frac{dN}{dE_{\mathrm{r}}} = \frac{\rho}{2\mu^2 m_\chi} \int_{v_{\mathrm{min}}(E_{\mathrm{r}})}^{v_{\mathrm{esc}}} \int_0^{q^2_{\mathrm{max}}(v_{\mathrm{rel}})} \frac{d\sigma(v_{\mathrm{rel}}, q^2)}{dq^2} F(q)^2 \, dq^2 \, \frac{f(v_{\mathrm{rel}})}{v_{\mathrm{rel}}} \, dv_{\mathrm{rel}}$$

DM-nucleon cross-sections
More Details

(Just for reference)

$$\frac{d\sigma_{i\to f}}{d\Omega} = \left|\frac{m_\chi}{2\pi\hbar^2}\langle \mathbf{k}', f|\hat{V}|\mathbf{k}, i\rangle\right|^2 \left(\frac{k'}{k}\right)$$

$$d\sigma_{i\to f} = \frac{1}{4\pi\hbar^2}\frac{1}{v^2}\left|\langle \mathbf{k}', f|\hat{V}|\mathbf{k}, i\rangle\right|^2 d(q^2)$$

$$V(\mathbf{r}, \mathbf{R}) = \hbar c \alpha_\chi \frac{e^{-\mu|\mathbf{r}-\mathbf{R}|}}{|\mathbf{r}-\mathbf{R}|}$$

$$\phi_{\mathbf{k}}(\mathbf{R}) = e^{i\mathbf{k}\cdot\mathbf{R}}$$

$$d\sigma = 4\pi\alpha_\chi^2 \left(\frac{c}{v}\right)^2 \frac{d(q^2)}{(q^2+\mu^2)^2} \left|\langle f|e^{i\mathbf{q}\cdot\mathbf{r}}|i\rangle\right|^2$$

DM-nucleon cross-sections
More Details: Spin-independent

- Scattering amplitude: Born approximation $\vec{q} = \hbar\,(\vec{k}' - \vec{k})$
- Spin-independent scattering is coherent $\lambda = \hbar/q \sim$ few fm $q = \sqrt{2 m_N E_R}$

$$M(\vec{q}) = f_n\, A \underbrace{\int d^3x\, \rho(\vec{x})\, e^{i\,\vec{q}\cdot\vec{x}}}_{F(\vec{q})} \quad \Rightarrow \quad \sigma \propto |M|^2 \propto A^2$$

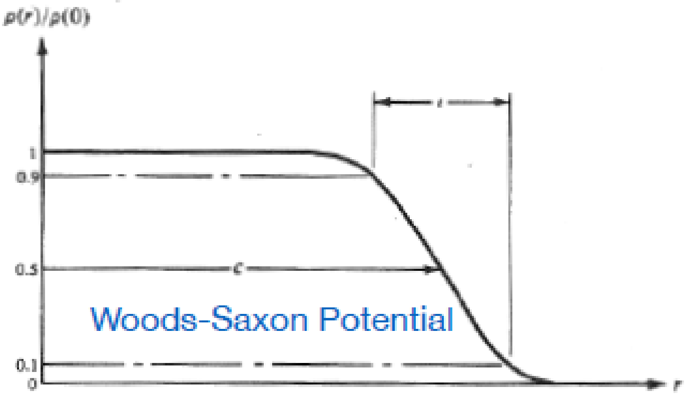
mass number

fundamental couplings to nucleons

Fourier-transform of the density of scattering centers

$$F(qr_n) = \underbrace{\frac{3[\sin(qr_n) - qr_n\cos(qr_n)]}{(qr_n)^3}}_{j_1(qr_n)}\, e^{-(qs)^2/2}$$

"Helm" form factor



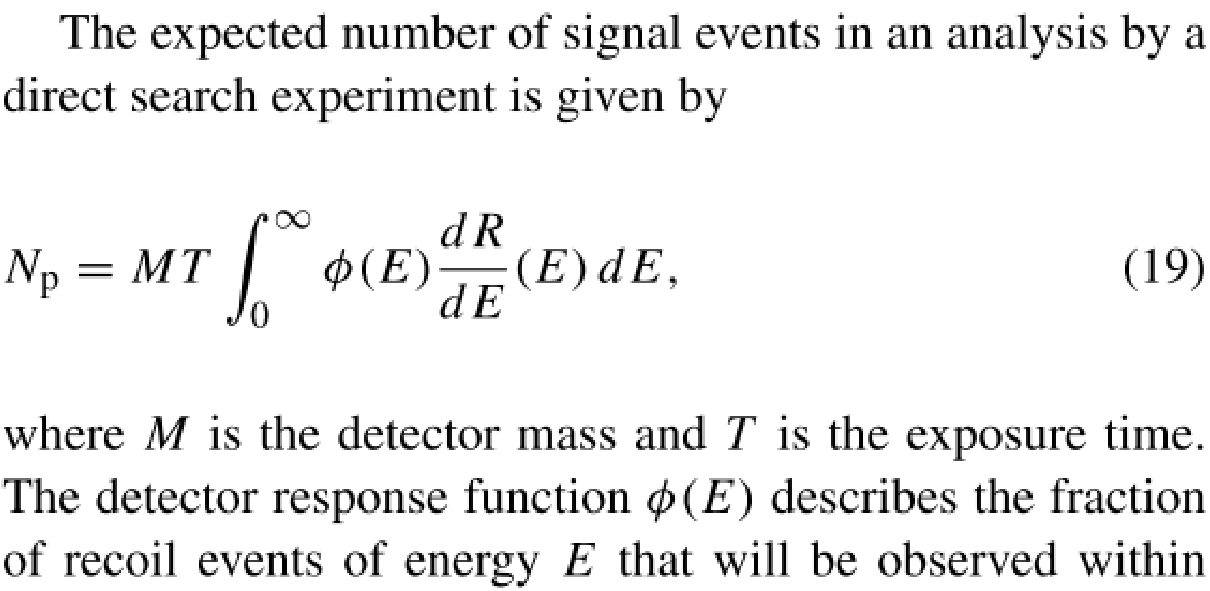
Woods-Saxon Potential

- with r_n = nuclear radius, $r_n \approx 1.2\, A^{1/3}$ fm, s = 1fm (skin thickness)

Example
Simple case

$$dR = \frac{n_T \rho_{\mathrm{DM}}}{m_\chi c^2} \frac{\mathrm{d}\langle \sigma_{njl} v_\chi \rangle}{\mathrm{d}E} \mathrm{d}E$$

$$\frac{dN}{dE_{\mathrm{r}}} = \frac{\sigma\rho}{2\mu^2 m_\chi} F^2 \int_{v_{\mathrm{min}}(E_{\mathrm{r}})}^{v_{\mathrm{esc}}} \frac{f(v_{\mathrm{rel}})}{v_{\mathrm{rel}}} dv_{\mathrm{rel}}$$



The expected number of signal events in an analysis by a direct search experiment is given by

$$N_{\mathrm{p}} = MT \int_0^\infty \phi(E) \frac{dR}{dE}(E)\, dE, \tag{19}$$

where M is the detector mass and T is the exposure time. The detector response function $\phi(E)$ describes the fraction of recoil events of energy E that will be observed within

- **What happens for very low mass? (Kinematics: Vmin)**
- **What happens at very large mass? (DM particle density)**

Eur. Phys. J. C **77**, 831 (2017) [arXiv:1705.07920]

How will we know?

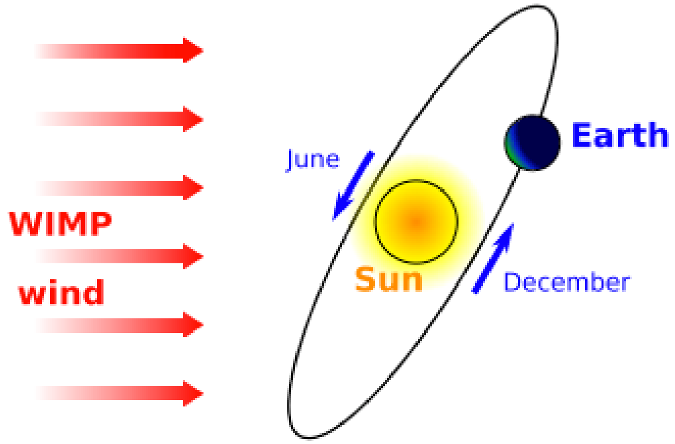
- See signal: have several issues
  1) How do we know it’s not just noise?
  2) Degenerate in (m, ρ, $\sigma, f(v)$)

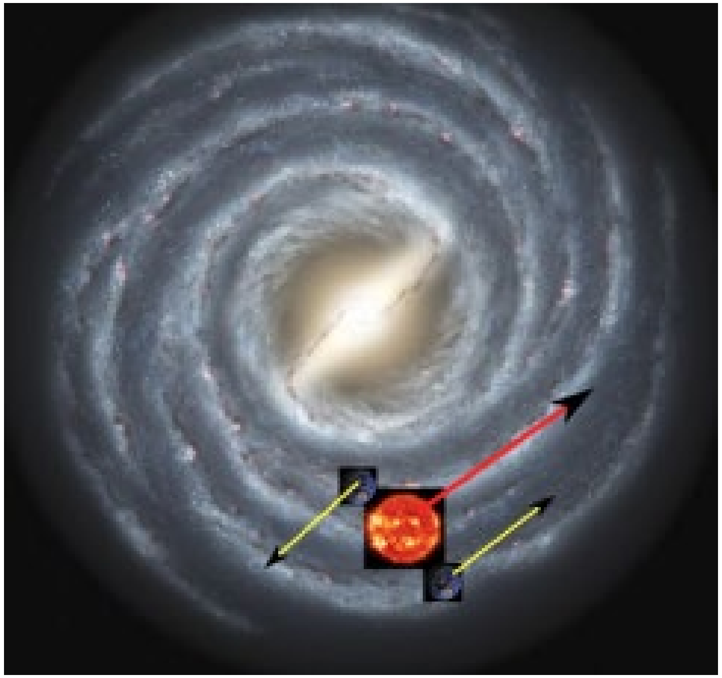
- Ideal: several different detections [solve (2)]

- Ideal: Signatures “unique” to DM, not noise
  - (e.g., annual modulation, directional dependence)

Daily & yearly modulation

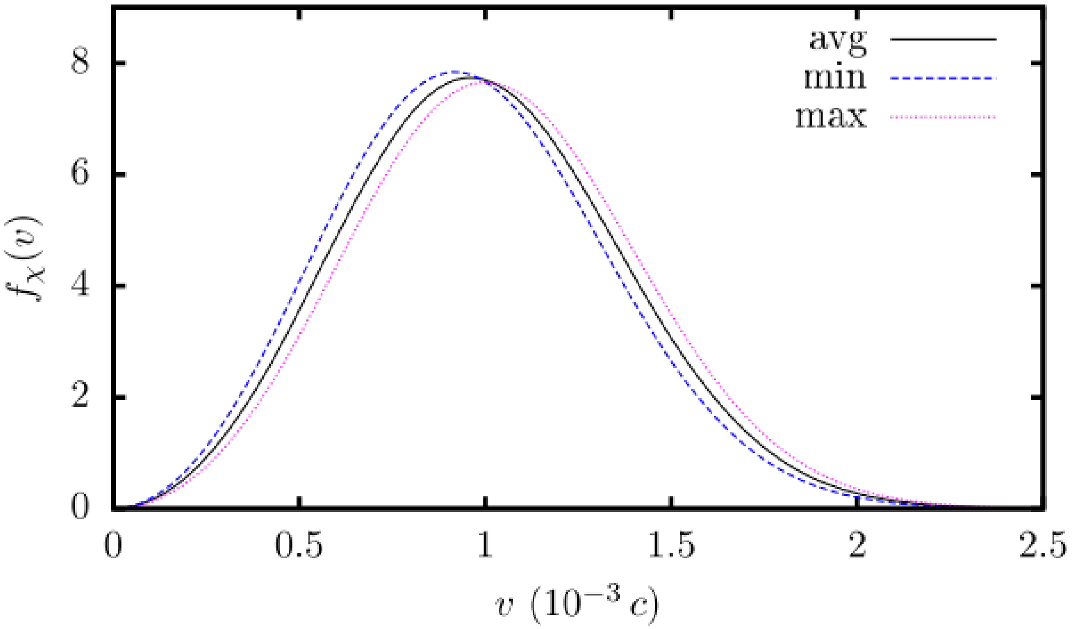
- Earth moves through Galactic frame: WIMP Wind
- Earth + sun velocity changes through year
    - Lab velocity changes throughout day
- Expect: modulation in WIMP flux, and mean WIMP speed/energy
    - Observable signal!

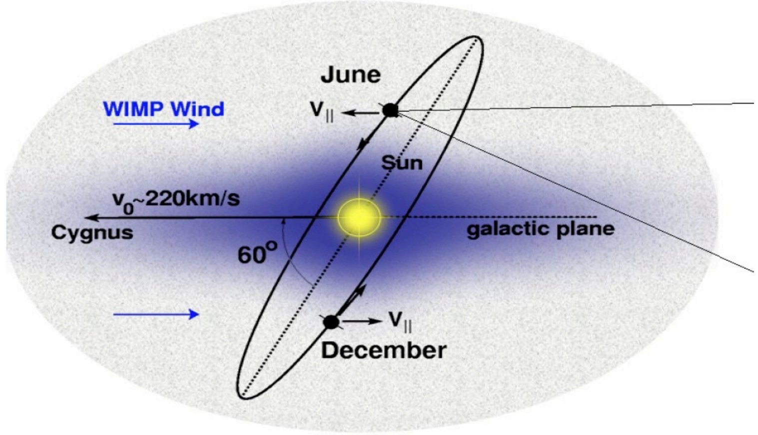




Daily & yearly modulation

- $v_{earth}/v_{galactic}$ ~ 10%
- Plane tilted: => ~5%





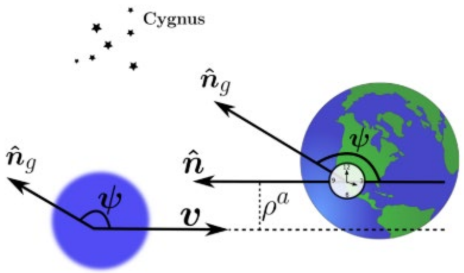
annual modulation

- Expect 5% modulation in event rate
- More if cross-section is velocity dependent
- (Or if experiment sensitive to energy deposited)

- See: DAMA (later in lecture)

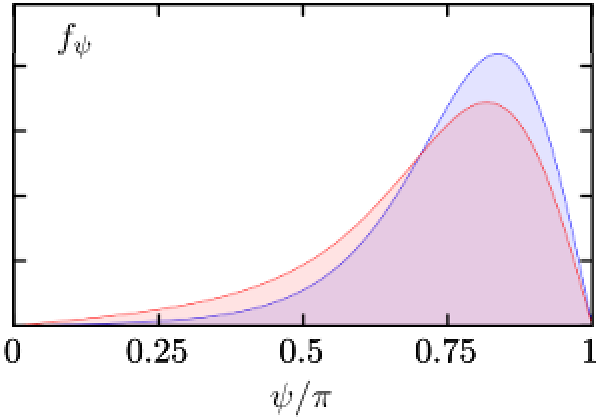
Directional Dependence

- Sun moves in direction of Cygnus constellation
- Gives DM directional preference



- Difficult to have directional sensitivity, but some proposals

Rajendran, Zobrist, Sushkov, Walsworth, Lukin, Phys. Rev. D **96**, 035009 (2017).



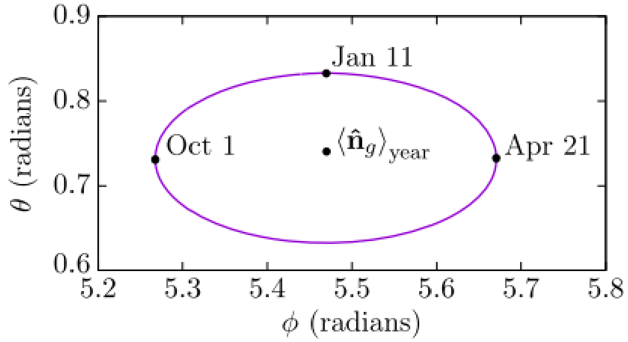


FIG. 4. Annual variation in the direction of the Earth's galactic motion (ECI frame, $\theta \in [0, \pi]$ is the polar angle), which is the most probable incident DM direction. The central point, $\hat{n}_g$, is the average direction, corresponding to the direction of the Sun's velocity through the galaxy.

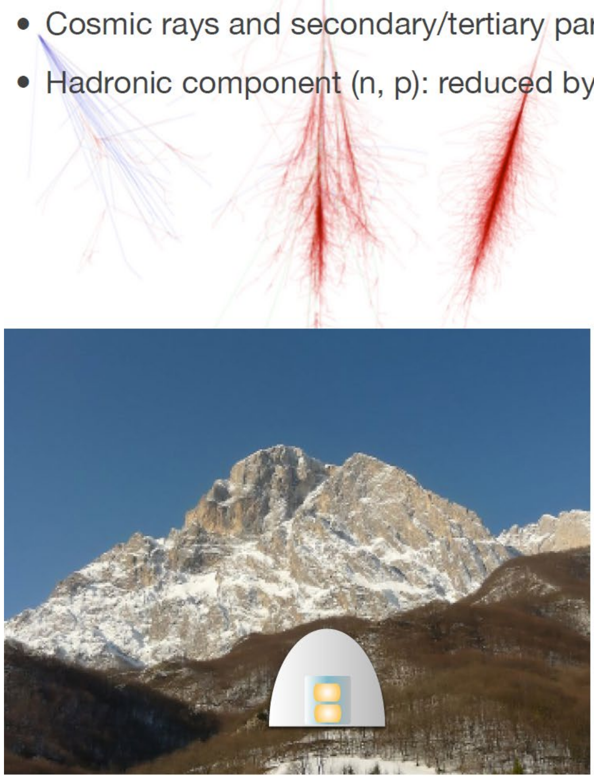
Phys. Rev. D **97**, 083009 (2018).

Backgrounds (noise) in DM Detectors

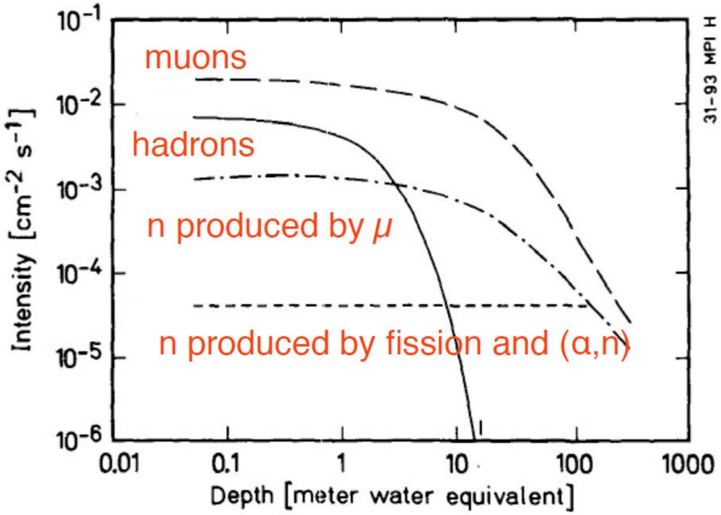
- External, natural radioactivity: ^{238}U, ^{238}Th, ^{40}K decays in rock and concrete walls of the laboratory => mostly gammas and neutrons from (α,n) and fission reactions

- **Internal radioactivity:** ^{238}U, ^{238}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ... decays in the detector materials, target medium and shields

- Cosmic rays and secondary/tertiary particles: go underground!
- Hadronic component (n, p): reduced by few meter water equivalent (mwe)



Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth
Gerd Heusser, 1995



- Go deep underground
- Want signals differ between noise/DM – allow background rejection
- E.g., modulation
- More than 1 detection channel

L. Baudis lectures, Zurich (2012)

Part 2: Experimental Detection Schemes

The XENON1T Time Projection Chamber TPC after assembly in a clean room: XENON Collab.

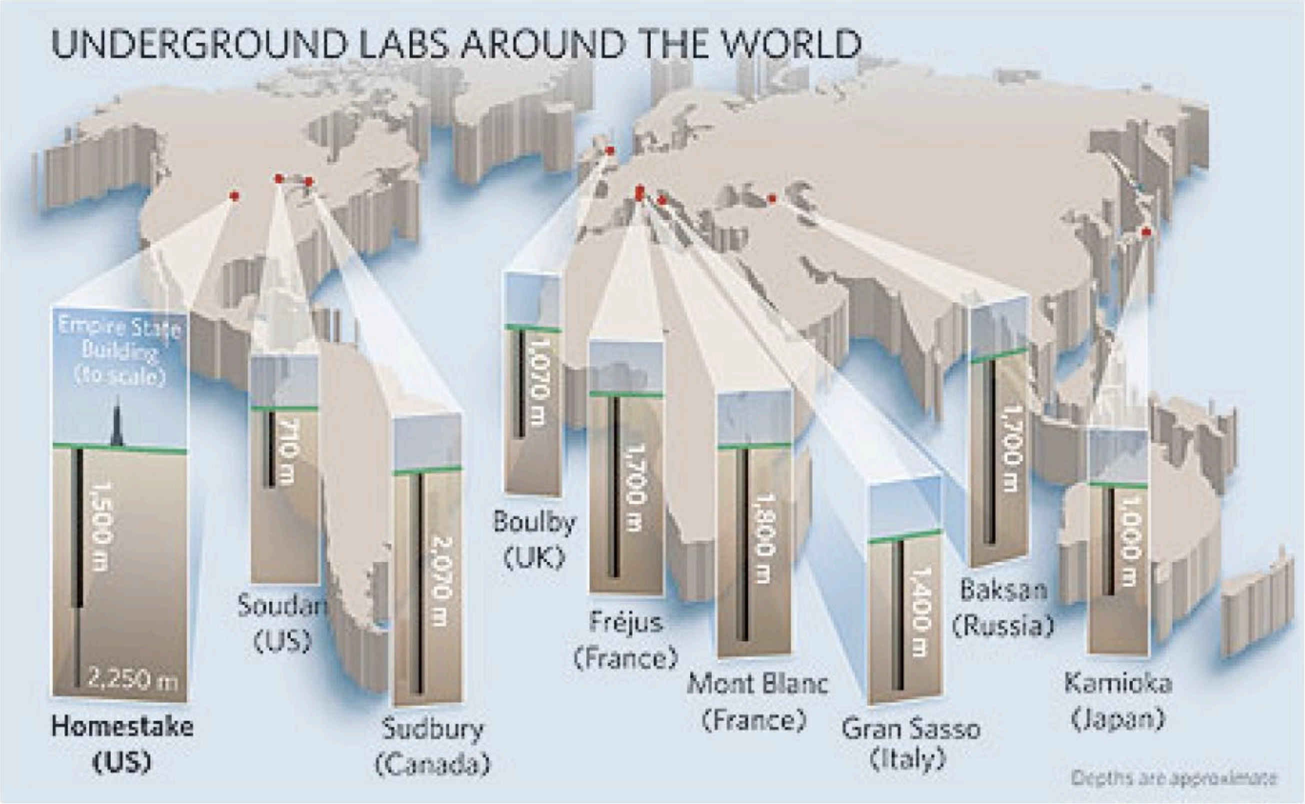
‘Small sample’ of recent and upcoming experiments

Older:

DAMA-LIBRA	Gran Sasso, Italy
XENON-100	Gran Sasso, Italy
ZEPLIN	Boulby, UK
XMASS	Kamioke, Japan
KIMS	Yangyang, South Korea
PICASSO	SNOWLAB, Ontario
COUPP	Fermilab
DRIFT	Boulby, UK
LUX	Sanford, South Dakota

Current/Planned:

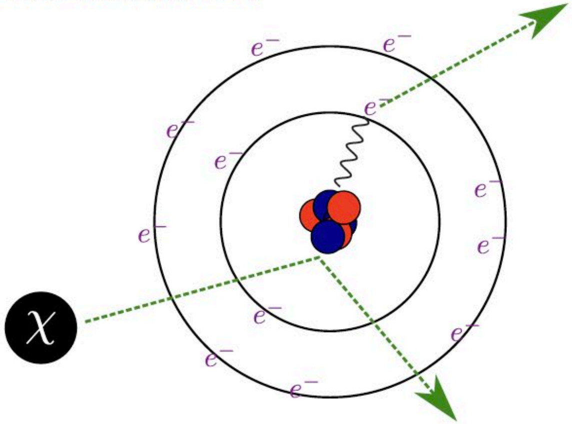
LZ	Sanford, South Dakota
PandaX	Jinping, China
XENON-1T/nT	Gran Sasso
DARKSIDE	Gran Sasso
DEAP/CLEAN	SNOWLAB, Ontario
DARWIN	TBA
CDMS	Soudan, Minnesota
CRESST	Gran Sasso, Italy
PICO	SNOWLAB, Ontario
COSINE-100	Yangyang, Sth Korea
ANAIS	Canfranc, Spain
SABRE	Gran Sasso (+maybe Stawell)


UNDERGROUND LABS AROUND THE WORLD

Depths are approximate

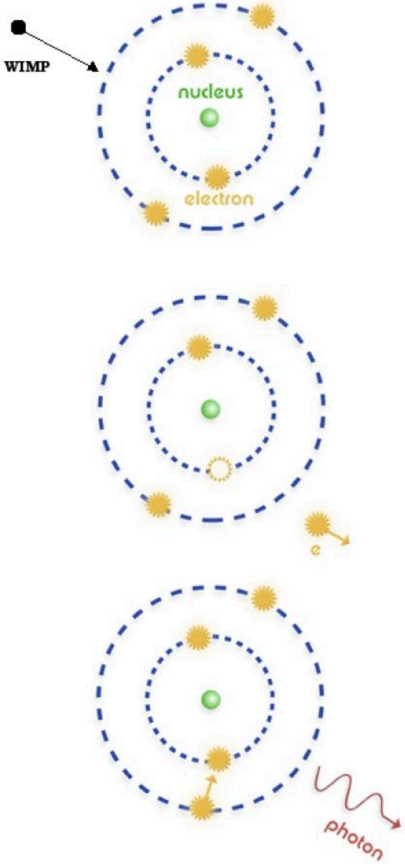
3 (main) ways to detect recoils

Ionisation

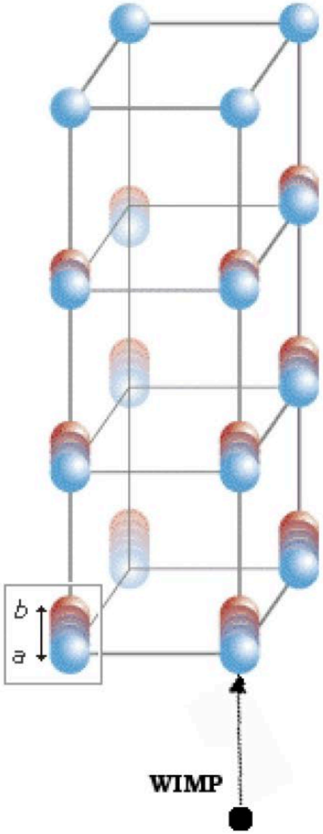


Scintillation

(just fluorescence with a quick recovery and in a transparent medium)

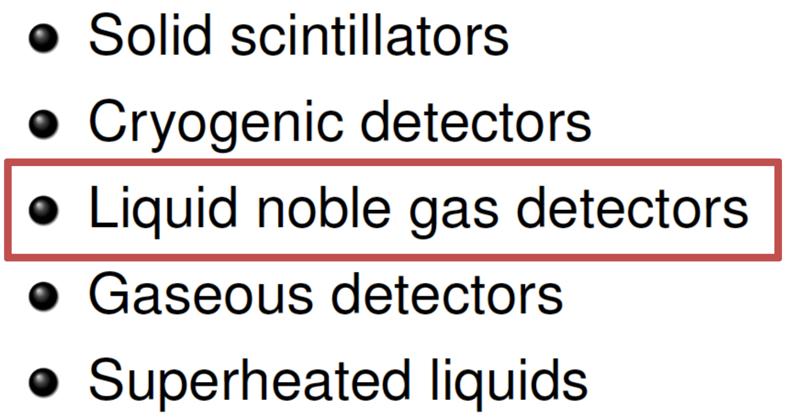


Vibration (phonons)



Detection Technologies

- Several technologies search for different signals
- Each have strengths/weaknesses (different models)



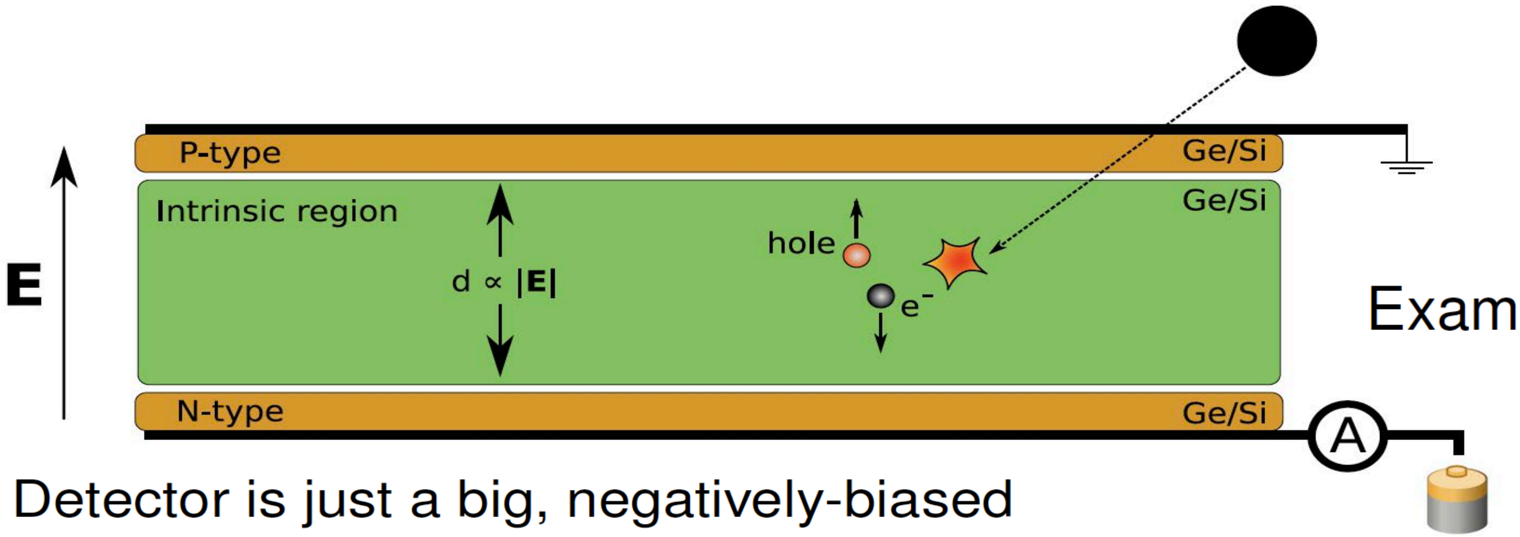
- Solid scintillators
- Cryogenic detectors
- Liquid noble gas detectors
- Gaseous detectors
- Superheated liquids

- Super fast overview incoming:
- Many reviews:
- G. Bertone and D. Hooper, Rev. Mod. Phys. 90, 45002 (2016).
  K. Freese, M. Lisanti, and C. Savage, Rev. Mod. Phys. 85, 1561 (2013).
  J. Liu, X. Chen, and X. Ji, Nat. Phys. 13, 212 (2017).

Ionisation detectors

Ionisation ☑
Scintillation ☒
Phonons ☒

- First detectors; “off the shelf”
- Ge/Si crystal semiconductors @ 77 K
- Simply detect electrons after ionisation in the semiconductor
- Originally designed to look for neutrinoless $\beta\beta$ decay.



Examples: IGEX, HDMS

Detector is just a big, negatively-biased pn-junction semiconductor

Similar to γ-ray detector (e.g., Fermi LAT)

Solid/crystal scintillators

Ionisation ☒
Scintillation ☑
Phonons ☒

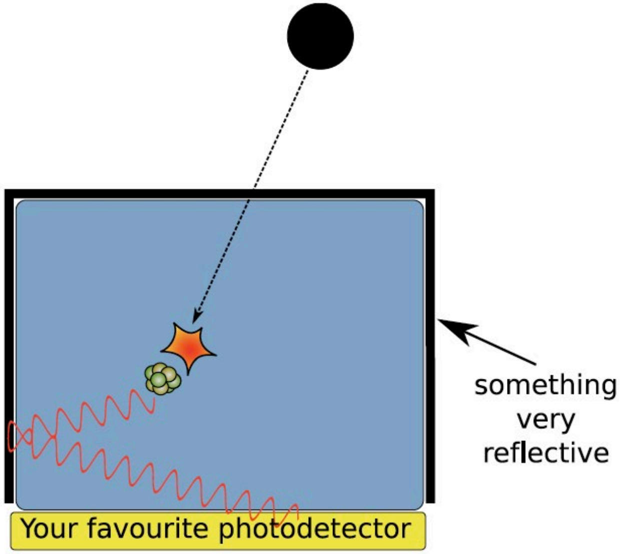
- Scintillating crystals
- NaI, CsI (or sometimes CaF_2)
- @ $\sim$300 K

In theory: WIMP hits atom in crystal, it fluoresces, you observe with photodetector (like e.g. photomultiplier tubes).

Problem: only one mode

In practice: without any other way to reject background, verrrry hard to tell what is DM and what is not (DAMA).

Examples: DAMA, COSINE, ANAIS, SABRE



Cryogenic detectors

One solution: add phonon detection

Ionisation ☒
Scintillation ☑
Phonons ☑

Examples: CRESST, Rosebud
Scintillation measured as per solid scintillators

OR

Ionisation ☑
Scintillation ☒
Phonons ☑

Examples: CDMS, Edelweiss
Ionisation measured as per ionisation detectors

Need to make things very cold ($\sim$10 mK) to see see individual phonons $\Longrightarrow$ ^{3}He-^{4}He *dilution refrigeration*

Make it really cold to reduce background, measure the heat change caused by thermal phonon vibrations (CRESST, most others)

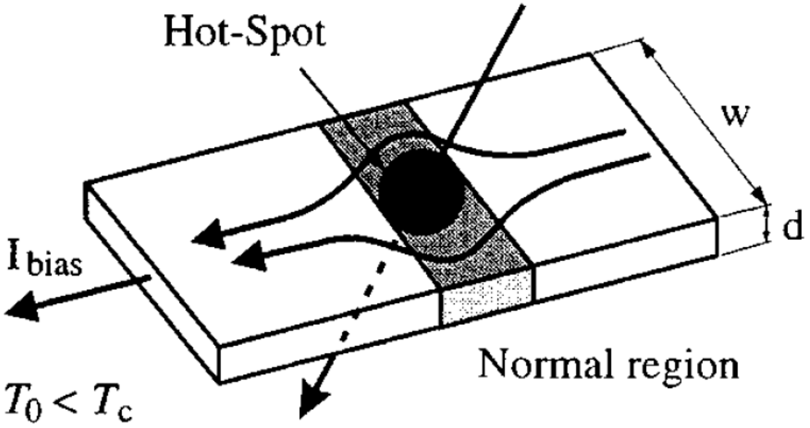
Cryogenic detectors

One solution: add phonon detection

E.g., CRESST:

- Superconductor, held very close to Tc
- WIMP produces phonon: slightly increases T
    - Stops super-conducting

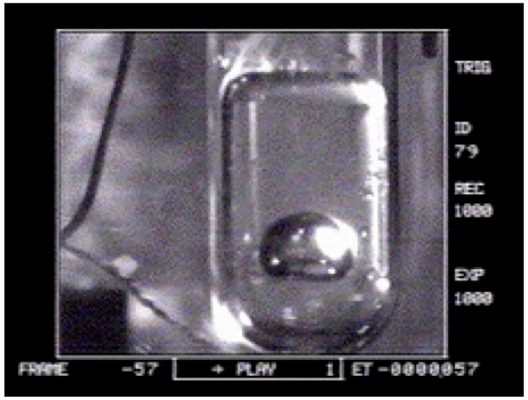
CRESST: superconducting phase-transition tungsten strip thermometer



Alternatively, measure athermal phonon vibrations (CDMS)

Superheated liquids

Ionisation ☒
Scintillation ☒
Phonons ☑



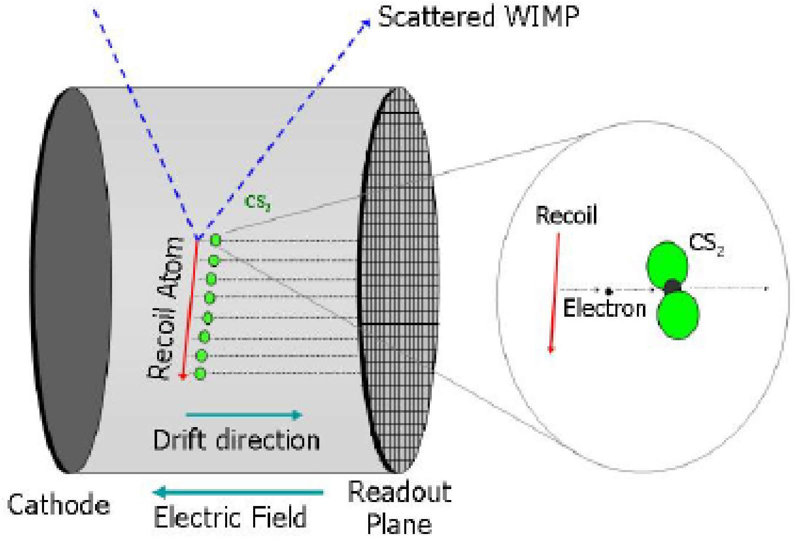
Examples: COUPP, PICASSO, PICO

- CF_3Br / CF_3I
- Superheated pressurised liquid → above boiling point but kept very still. . .
- Single nuclear recoil triggers formation of a gas bubble
- Watch for bubble formation using a camera (find DM with your webcam!)
- Takes time to recompress detector after each event
- light target, low rate $\implies$ best for spin-dependent searches

Gaseous detectors

Ionisation ☑
Scintillation ☒
Phonons ☒

Main examples so far: DRIFT & DMTPC
Detect ionisation tracks caused by recoiling nuclei



- Directional sensitivity

But..

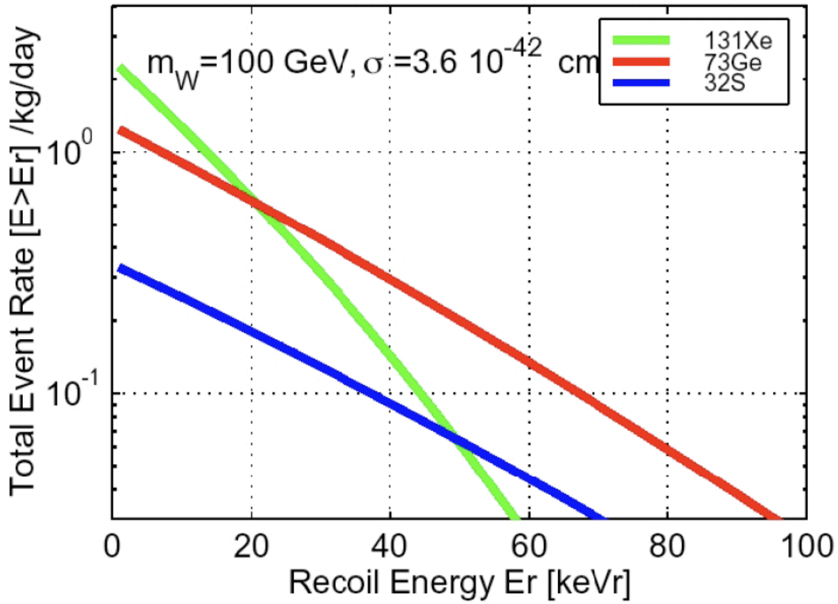
- low-mass density (cf liquid Noble gas) – need to be huge
- Low nuclear mass

Liquid noble gas detectors

Ionisation ☑
Scintillation ☑
Phonons ☒

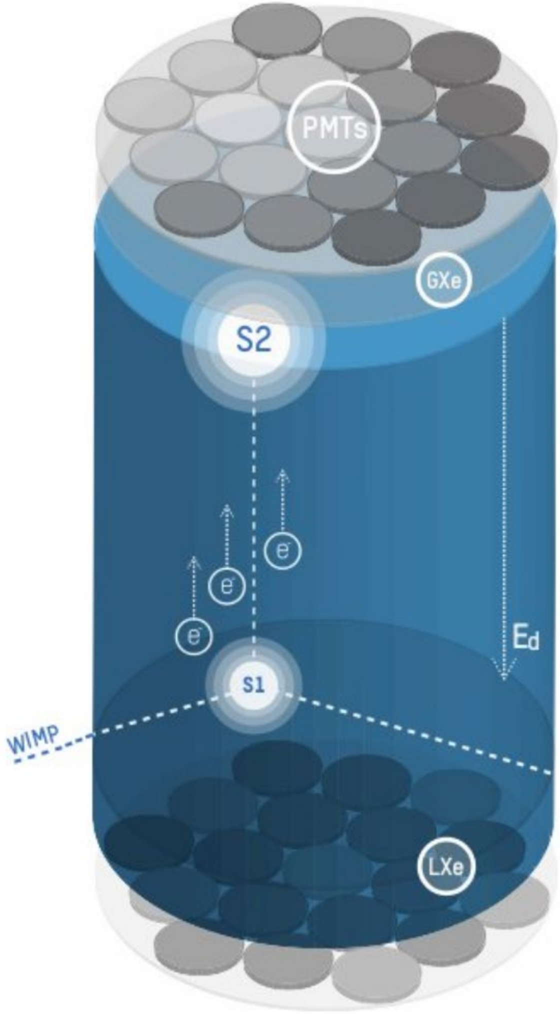
Examples: XENON, LUX, XMASS, DARKSIDE

- Liquid Ne (@ 27 K), Ar (@ 87 K) or Xe (@ 165 K)
- Liquid scintillators, high yield
- Easily scaled up to large mass
- $\Longrightarrow$ current state of the art



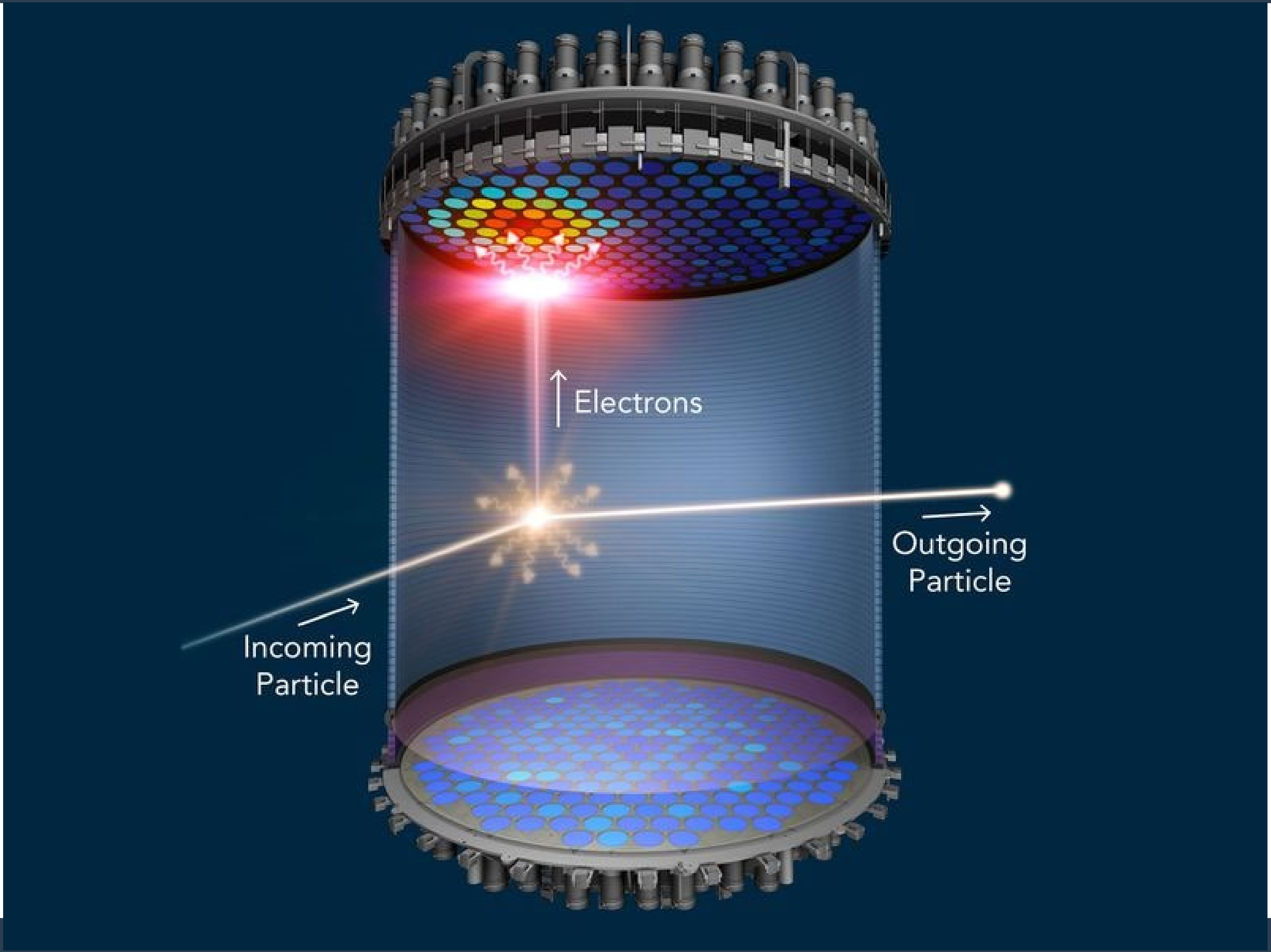
Liquid noble gas detectors: Duel-phase time-projection chamber

- Scintillation detected directly using photomultipliers
- Ionization by
  1. drifting electrons upwards to the surface using an electric field,
  2. across the surface into the gas phase
  3. there they give rise to secondary electroluminescence (give off photons as they accelerate)

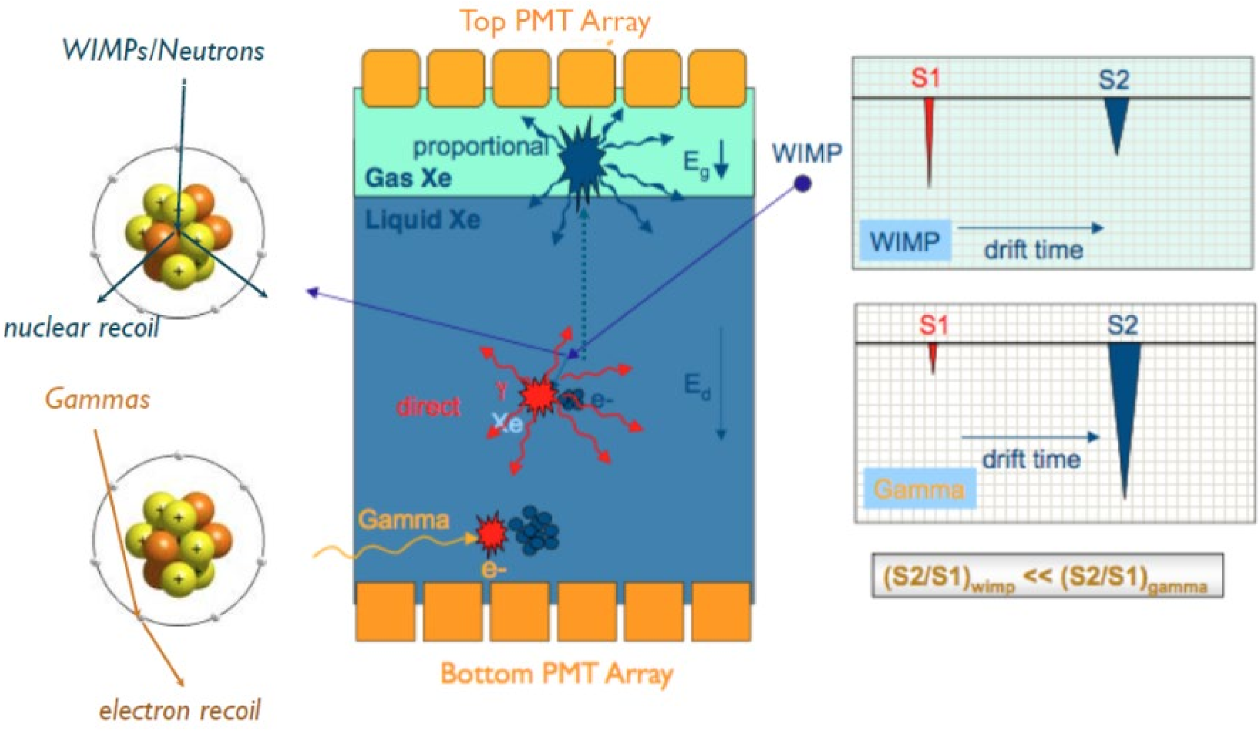


[http://www.xenon1t.org/]

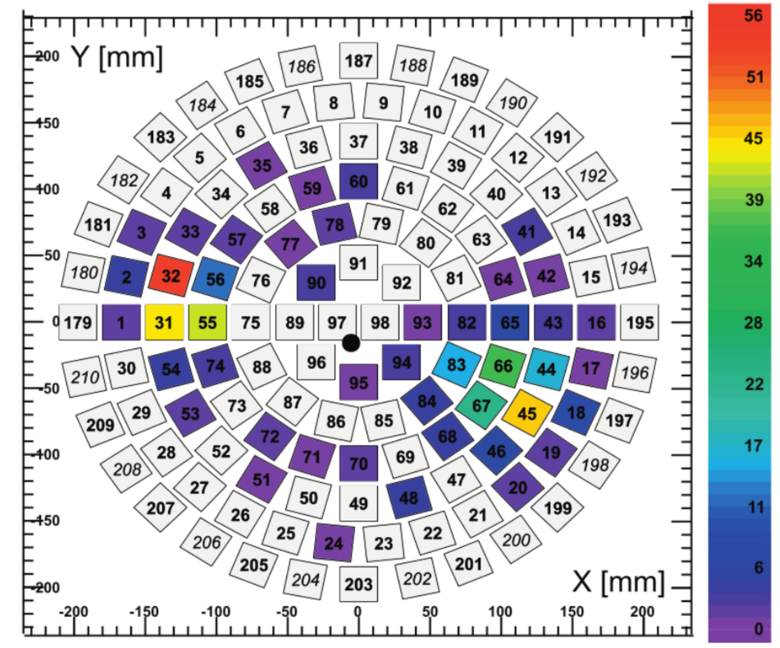
Liquid noble gas detectors:
Duel-phase time-projection chamber



Liquid noble gas detectors:
Duel-phase time-projection chamber



[E. Aprile (SUSY08)]



[XENON100 Collab., Astropart. Phys. 54, 11 (2014)]

- S1 (prompt scintillation), S2 (ionisations)
- 2D photo-detector + s1/s2 time delay: 3D event reconstruction
- Allows background rejection

Background rejection

- Exclude double-scatter events
- Exclude outermost layer of xenon
  - Prob. of EM interactions drops with depth, DM not so
- Compare S1 to S2 + profile calibrations

e.g., Krypton decay:

$$^{85}\mathrm{Kr} \overbrace{\longrightarrow}^{\beta\ (173\,\mathrm{keV})} {}^{85\mathrm{m}}\mathrm{Rb} \overbrace{\longrightarrow}^{\gamma\ (514\,\mathrm{keV})} {}^{85}\mathrm{Rb}$$

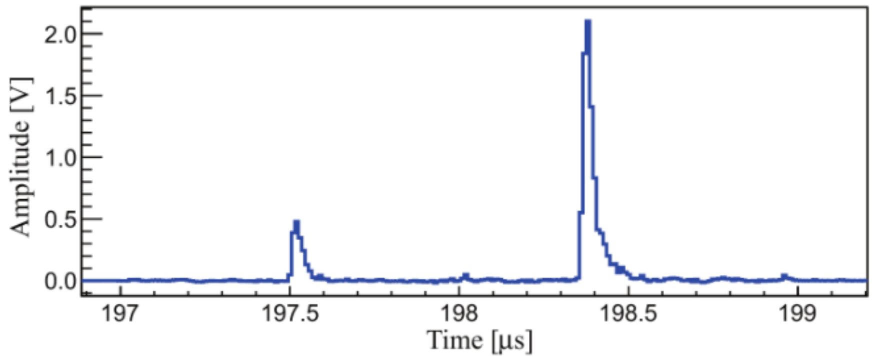


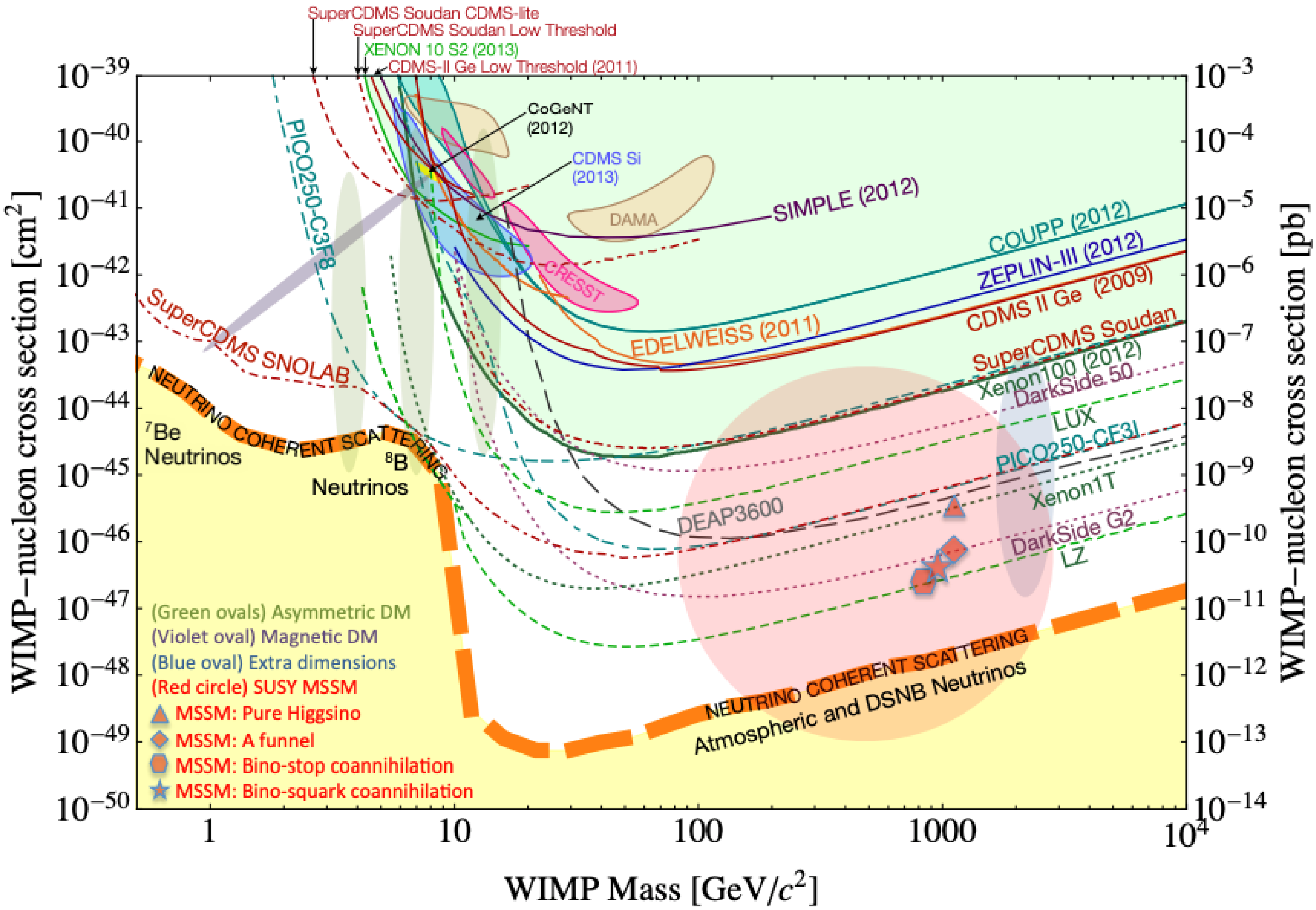
Fig. 14. S1 peaks of a candidate ^{85}Kr event where the second light signal from the γ-ray is delayed by $\sim$ 900 ns.

[XENON100 Collab., Astropart. Phys. 54, 11 (2014)]

Summary

- Background detection theory, scattering rates
  - How to calculate basic rates
- Interaction types
  - Coupling to quarks, nuclei etc.
- Even rates, noise, annual modulation
- Direct detection experimental techniques
  - Detecting DM
  - Distinguishing noise from signal

Part 3: Direct Detection Results



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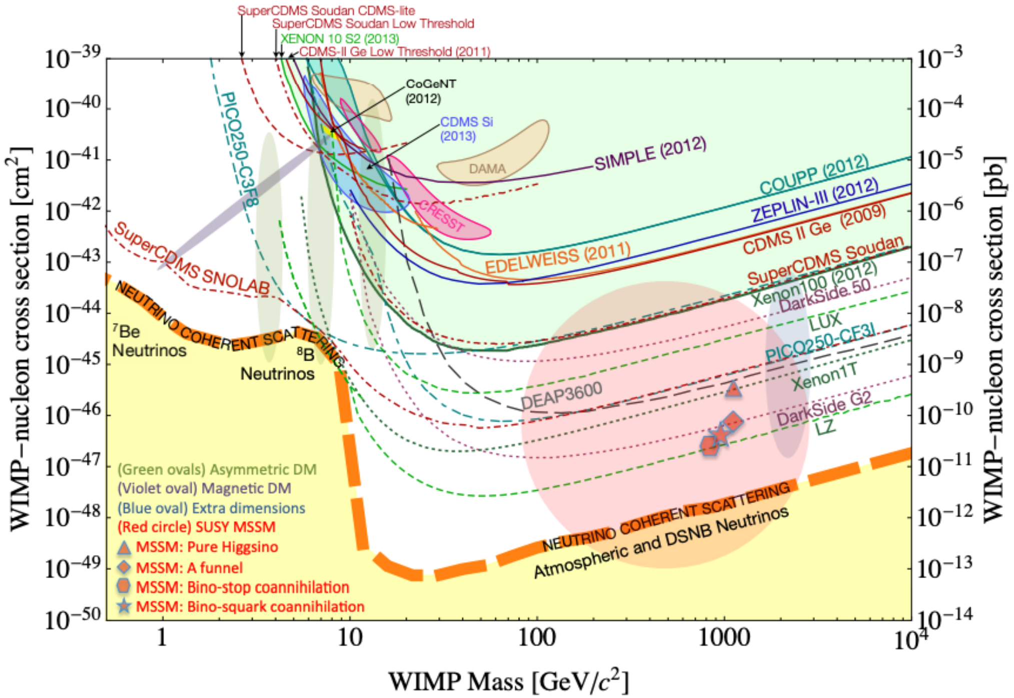
General Remarks



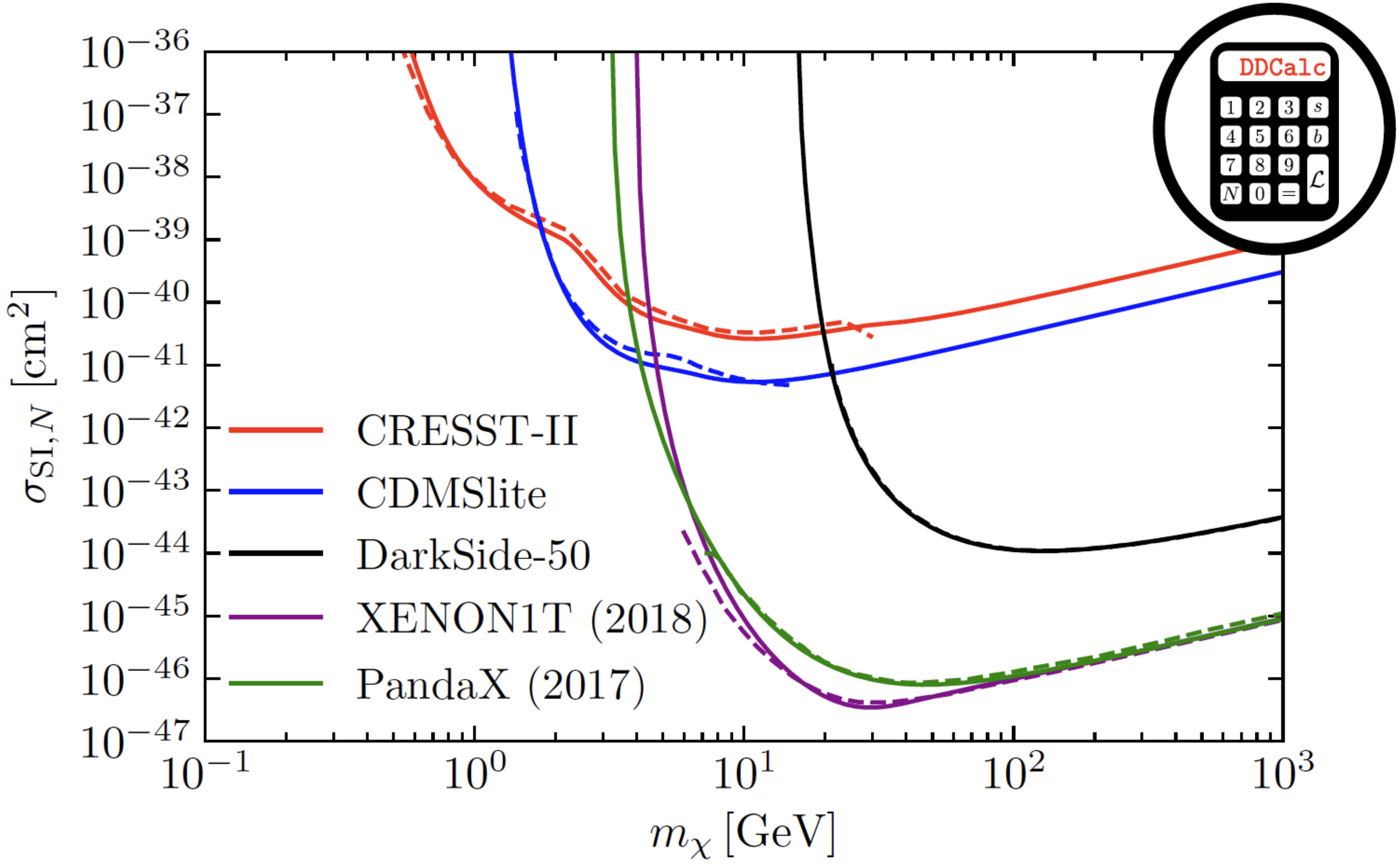
- Plots comparing different experiments
- Not possible to do this for general case
- Detectors are different
- Have to make some assumptions about DM model (couplings, vel. distro etc.)

- Typically interested in <u>nucleon σ,</u> even though we measure <u>nucleus σ</u>
- i.e. Depends on particle theory (σ), astrophysics (v), and nuclear theory (F)

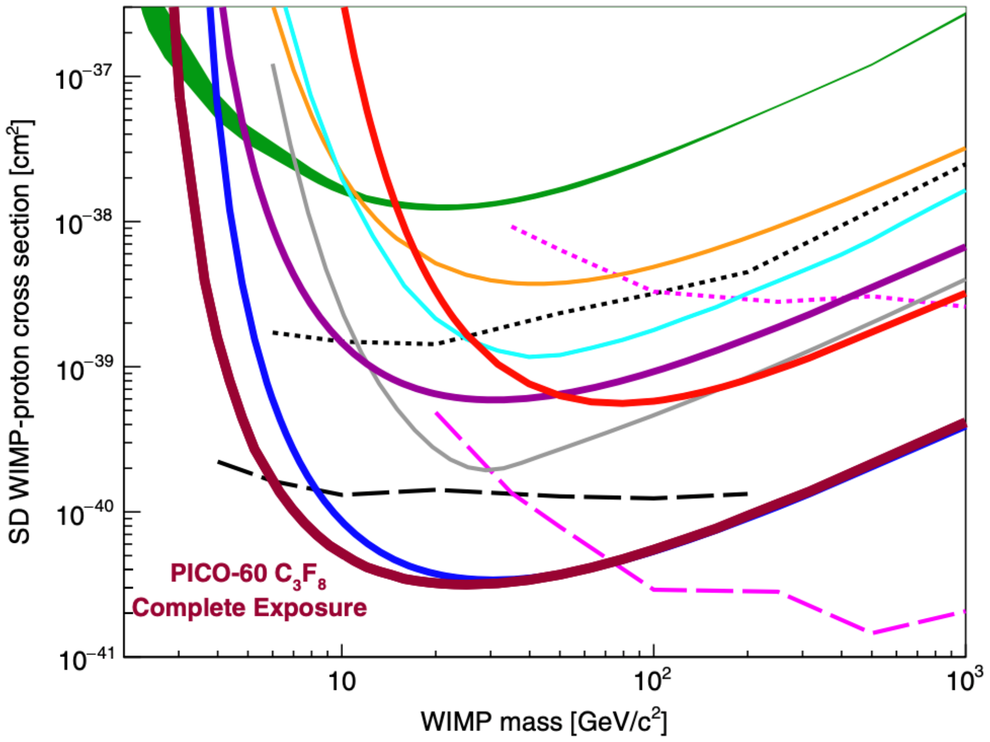
img: arXiv:1310.8327

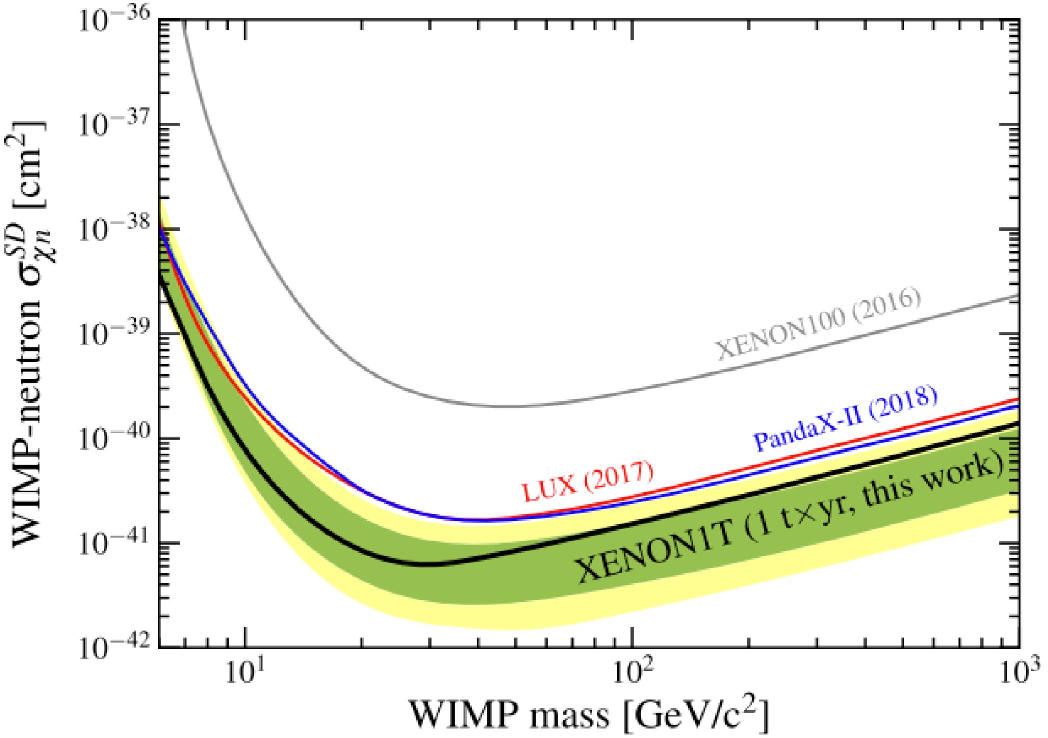
Spin-independent

Leading spin-independent sensitivity is from XENON-1T



Spin-dependent





PICO, Phys. Rev. Lett. **118**, 251301 (2017);
PICO, Phys. Rev. D **100**, 022001 (2019)
+ IceCube (dashed line: later slide)

XENON, Phys. Rev. Lett. **122**, 141301 (2019)