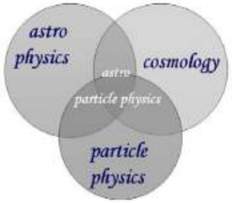
ASTROPARTICLE PHYSICS

Hilary 2021



Oxford Physics

Oxford Master Course in Mathematical and Theoretical Physics

- The universe observed
- Relativistic world models
- Reconstructing the thermal history
- Big bang nucleosynthesis
- Dark matter: astrophysical observations
- Dark matter: relic particles
- Dark matter: direct detection
- Dark matter: indirect detection
- Cosmic rays in the Galaxy
- Antimatter in cosmic rays
- Ultrahigh energy cosmic rays
- High energy cosmic neutrinos
- The early universe: constraints on new physics
- The early universe: baryo/leptogenesis
- The early universe: inflation & the primordial density perturbation
- Cosmic microwave background & large-scale structure

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Observations indicate that the bulk of the matter in the universe is dark (i.e. dissipationless, ~collisionless?, ~cold?)

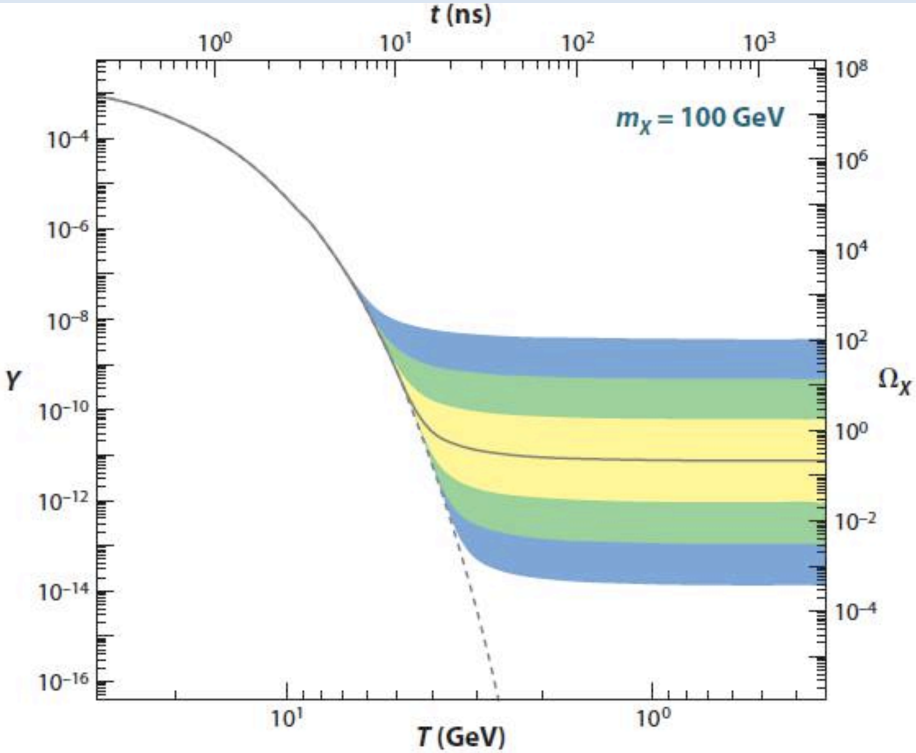
There is a generic expectation that it consists of a new stable particle from physics beyond the Standard Model

… it *cannot* have electric or colour charge (otherwise would bind to ordinary nuclei creating anomalously heavy isotopes → ruled out experimentally at a high level)

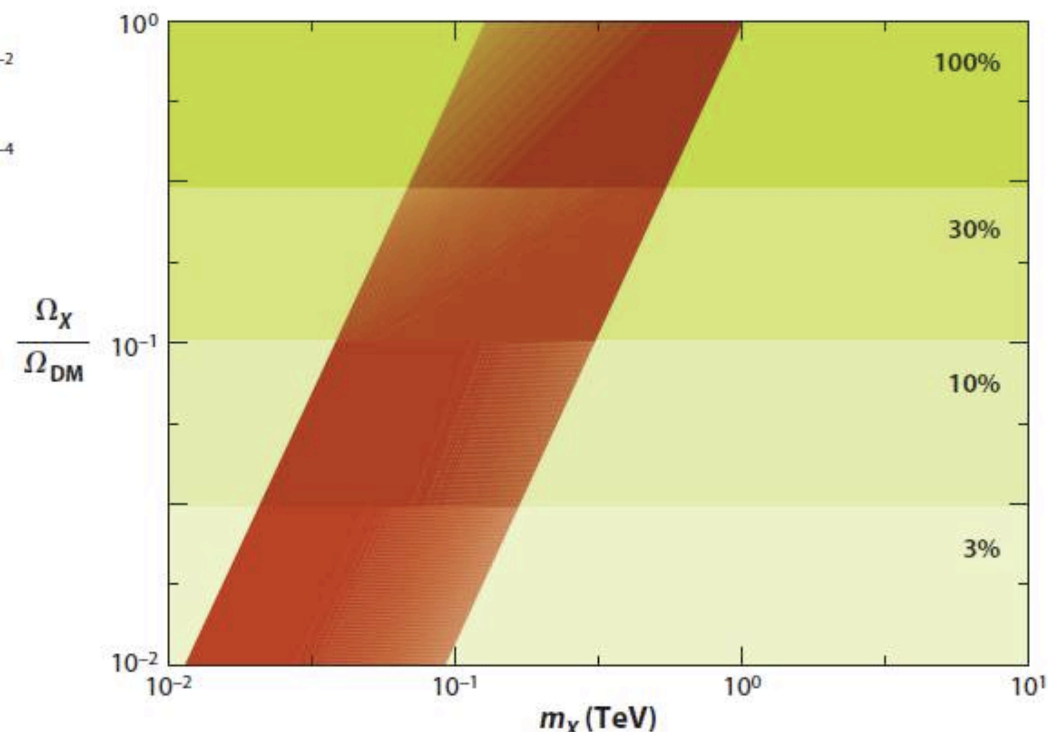
… it *cannot* couple too strongly to the Z^0 (or would have been seen already in accelerator searches)

Underground nuclear recoil detectors are placing restrictive bounds on its elastic scattering cross-section with nucleons … while indirect searches for gamma-rays, neutrinos and other products of dark matter annihilations (positrons, antiprotons) in the Sun, Earth, Milky Way, … have provided exciting hints!

Most dark matter searches have been for the **lightest supersymmetric particle** which is typically neutral and stable (*if* ***R*-parity** is conserved), with a relic (thermal) abundance which is naturally of the required order

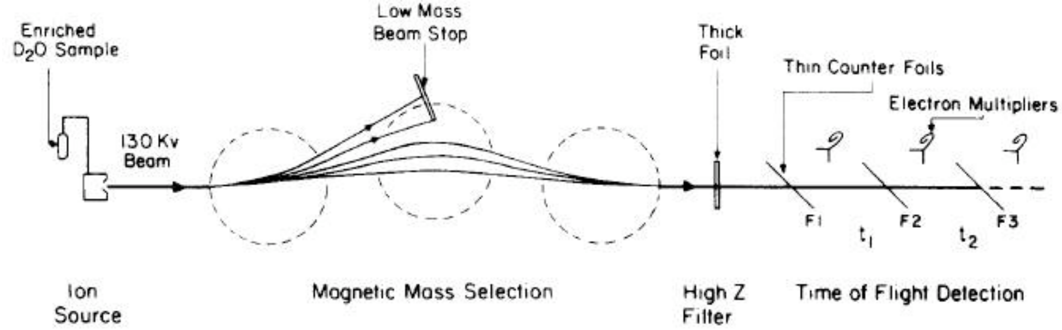


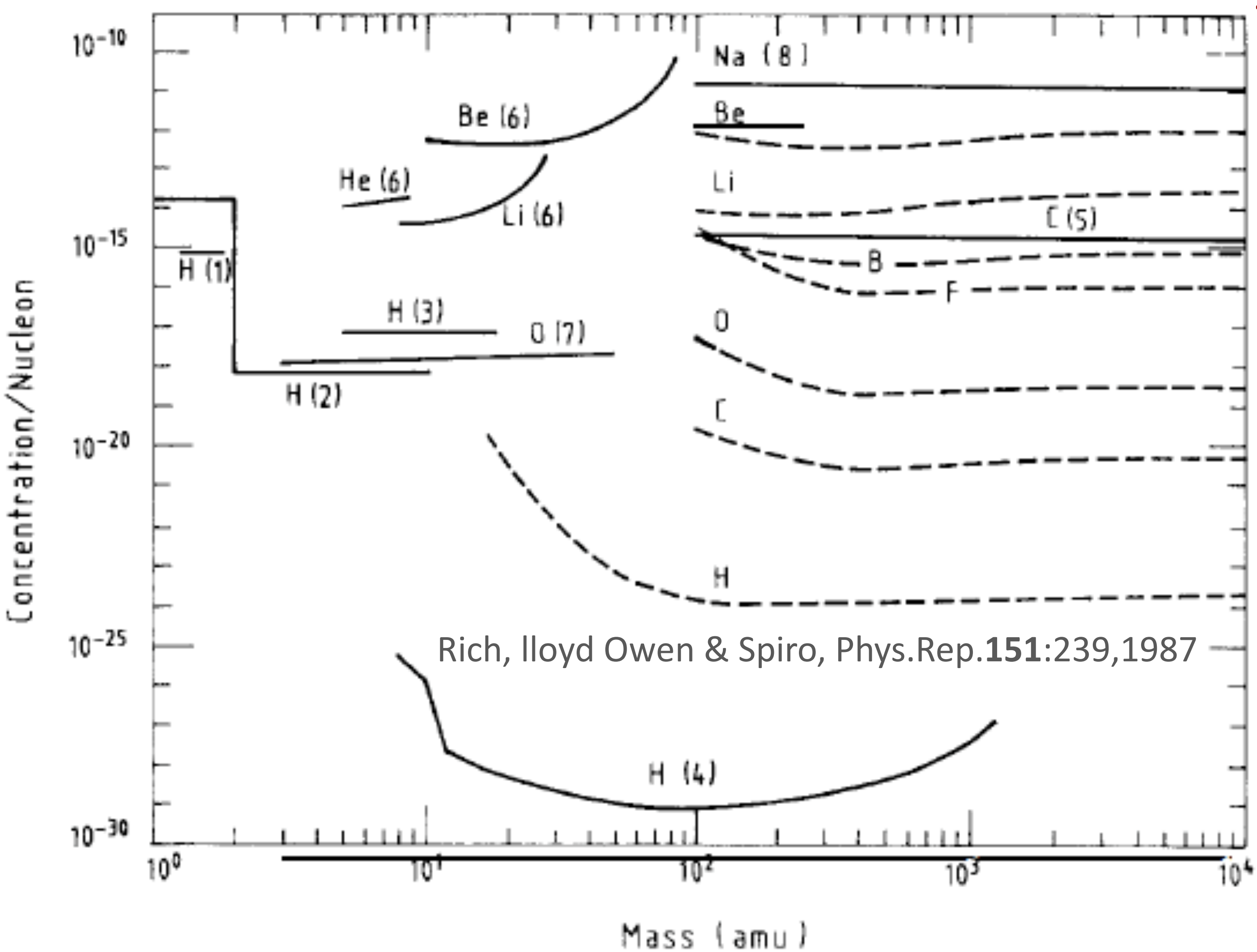
However R-parity need *not* be conserved so the LSP may be unstable so SUSY ≠ dark matter (or other SUSY particles e.g. gravitinos, axinos … may be DM)



Also this does *not* explain why $\Omega_{DM}/\Omega_B \sim 6$ … perhaps $n_{DM} \sim n_B$, so $m_{DM} \sim 6\, m_B$?

Searches for anomalously heavy isotopes of common elements (in oceans *etc*)





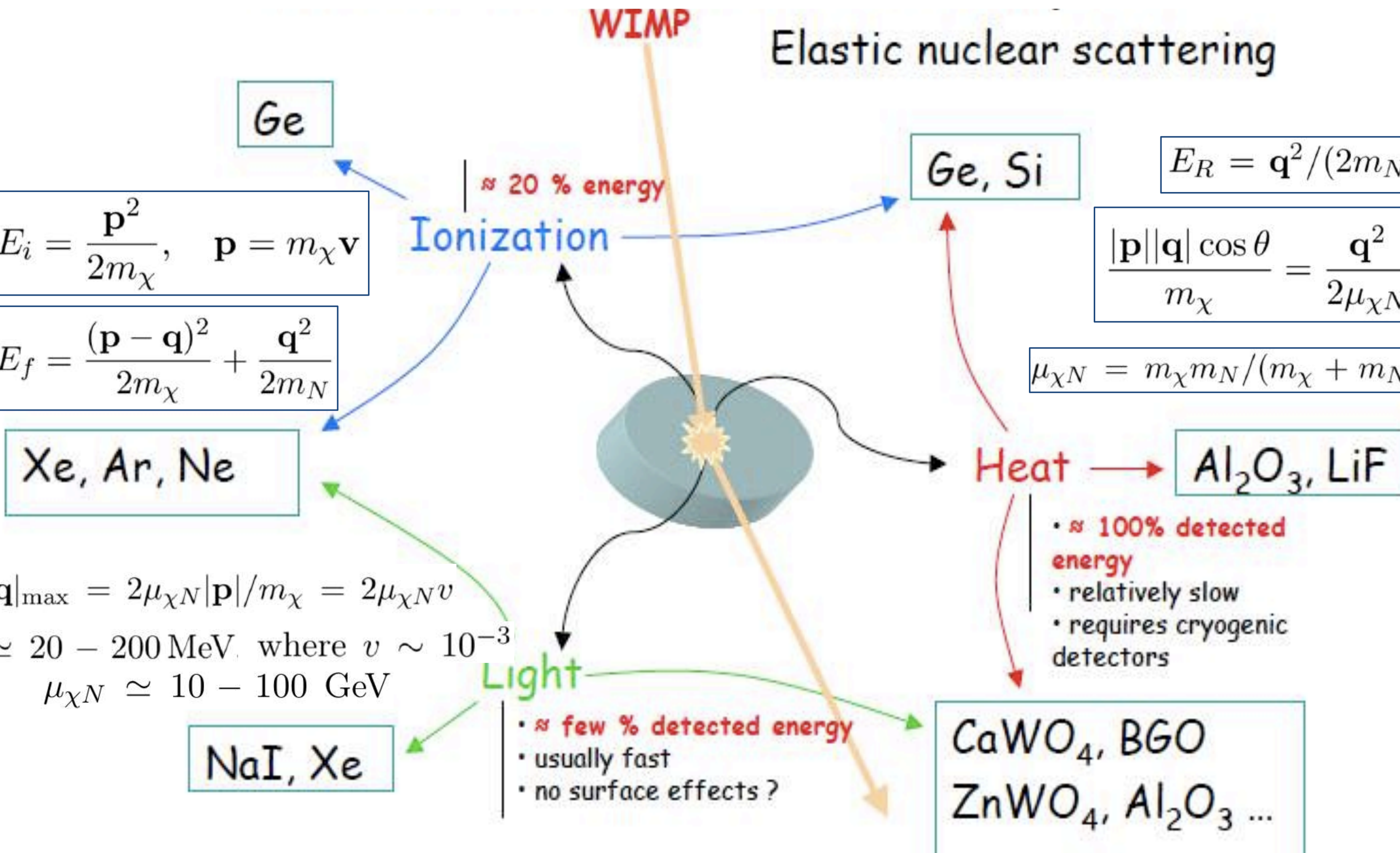
Rich, lloyd Owen & Spiro, Phys.Rep.**151**:239,1987

These very stringent limits require that e.g. the LSP *cannot* be either strongly interacting or electrically charged

NB: Expected relic abundance from thermal equilbrium is $\sim 10^{-19\text{-}17}$/photon (or $\sim 10^{-10\text{-}8}$/baryon)

… failure to find fractional charges motivated idea of quark 'confinement'

Direct detection of dark matter



$$E_i = \frac{\mathbf{p}^2}{2m_\chi}, \quad \mathbf{p} = m_\chi \mathbf{v}$$

$$E_f = \frac{(\mathbf{p}-\mathbf{q})^2}{2m_\chi} + \frac{\mathbf{q}^2}{2m_N}$$

$$E_R = \mathbf{q}^2/(2m_N)$$

$$\frac{|\mathbf{p}||\mathbf{q}|\cos\theta}{m_\chi} = \frac{\mathbf{q}^2}{2\mu_{\chi N}}$$

$$\mu_{\chi N} = m_\chi m_N/(m_\chi + m_N)$$

$$|\mathbf{q}|_{\max} = 2\mu_{\chi N}|\mathbf{p}|/m_\chi = 2\mu_{\chi N} v$$

$$\simeq 20 - 200\,\mathrm{MeV} \quad \text{where } v \sim 10^{-3}$$

$$\mu_{\chi N} \simeq 10 - 100 \ \mathrm{GeV}$$

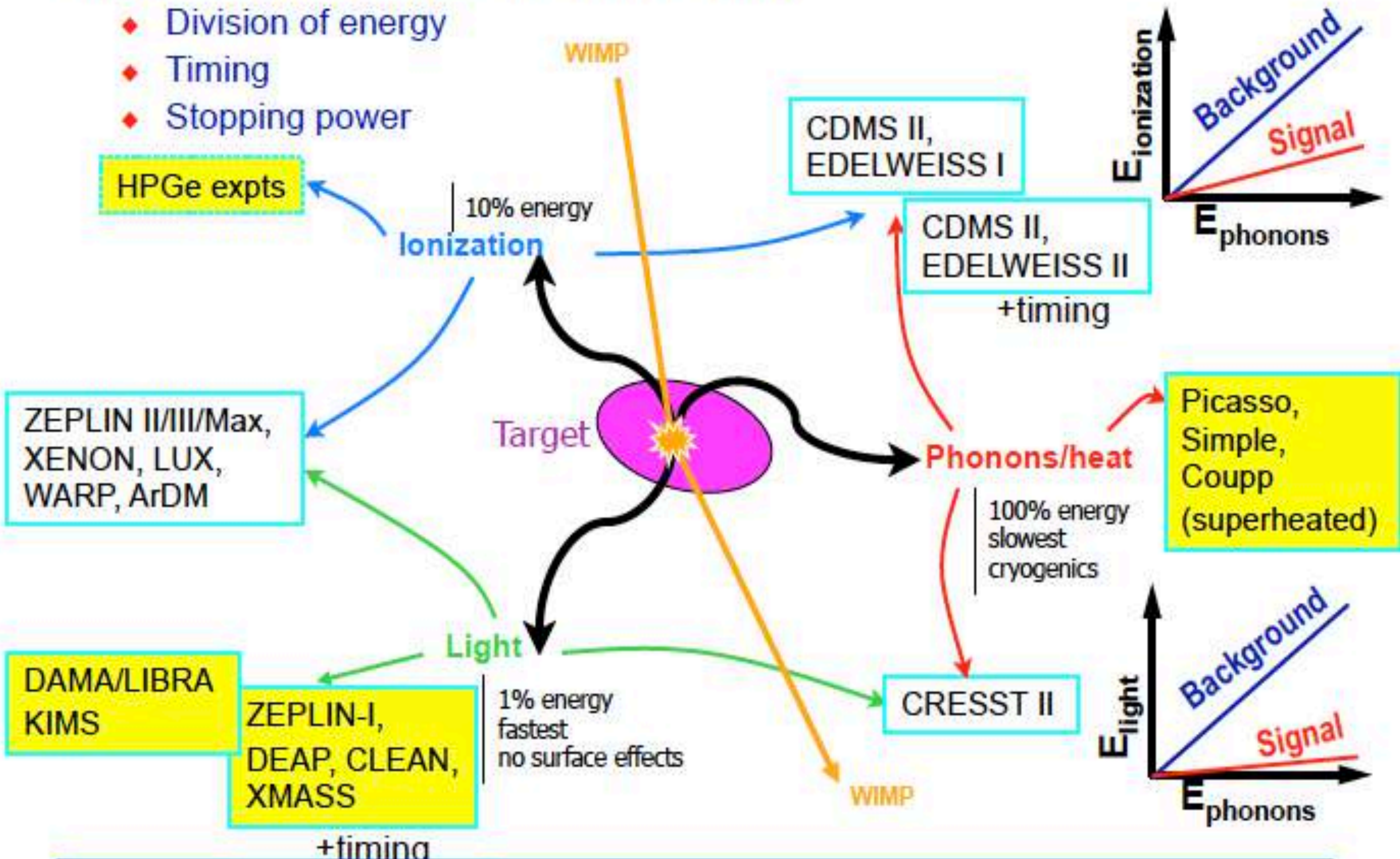
$$E_R^{\max} = \frac{|\mathbf{q}|^2_{\max}}{2m_N} = \frac{2\mu^2_{\chi N} v^2}{m_N} \simeq 20 - 200\,\mathrm{keV}$$

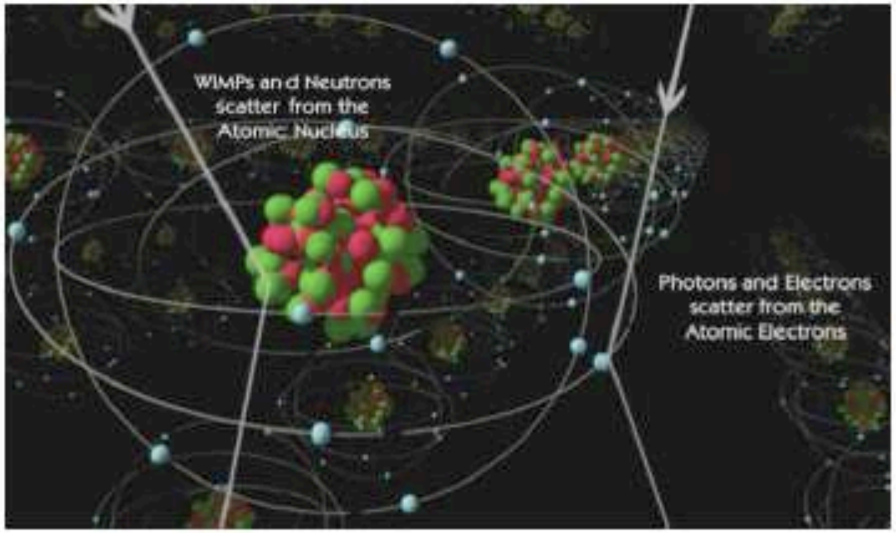
$$v_{\min} = \sqrt{m_N E_R / 2\mu^2_{\chi N}}$$

Drukier & Stodolsky, Phys.Rev.D**30**:2295,1984; Goodman & Witten, PRD**31**:3059,1985

Nuclear recoil discrimination

- Nuclear recoils vs. electron recoils
  - Division of energy
  - Timing
  - Stopping power





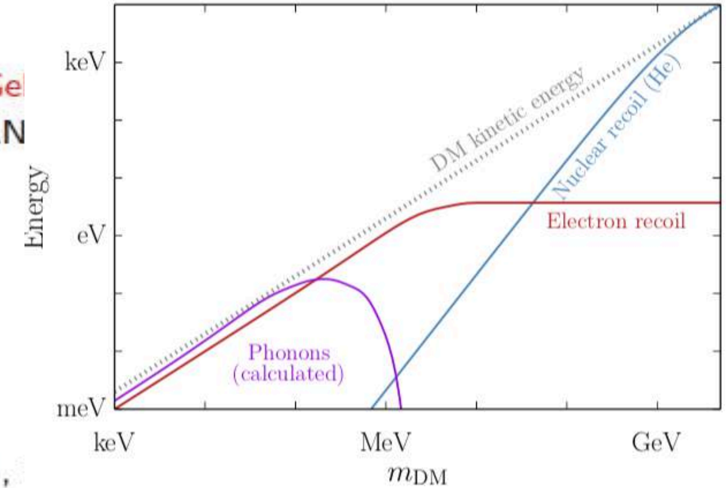
- WIMPs interact with nuclei. In crystals they produce mostly phonons and also ionization/scintillation.
- Photons and electrons interact mostly with electrons and all their energy goes into ionization/scintillation.

In crystals: quenching factor $Q=$ fraction of E_{Recoil} that goes into ionization/scintillation.
$Q_{\rm Ge} \simeq 0.3$, $Q_{\rm Si} \simeq 0.25$, $Q_{\rm Na} \simeq 0.3$, $Q_{\rm I} \simeq 0.09$

In liquid Xe: $L_{\rm eff}$=scintillation efficiency of a WIMP relative to a γ

- **Single Channel Techniques:**
  -Ionization (Ge, Si, CdTe): IGEX, HDMS, GENIUS, TEXONO, CoGeI
  -Scintillation (NaI, Xe, Ar, Ne, CsI): DAMA, NAID, DEAP, CLEAN
  -Phonons (Ge, Si, Al_2O_3, TeO_2): CRESST-I , Cuoricino, CUORE

  -Threshold detectors: PICASSO (bubbles of C_4F_10),
  COUPP (superheated bubble chamber)



- **Hybrid detector techniques for discrimination:**
  -Ionization + Phonons (Ge, Si): CDMS, SuperCDMS, EDELWEISS,
  -Ionization + Scintillation(Xe, Ar, Ne):XENON,LUX,ZEPLIN,WARP,ArDM, DarkSide
  -Scintillation+Phonons ($CaWO_4$, Al_2O_3): CREST-II, EURECA, CRESST I

Dependence on dark matter spin

For WIMP DM in the form of Majorana fermions, there are two terms contributing to the scattering cross section in the non-relativistic limit:

not coherent

Axial-vector
(spin-dependent)

$$\mathcal{L}_A = d_q\ \bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$$

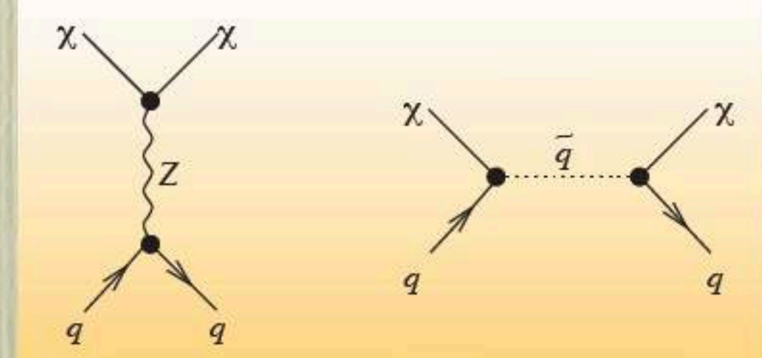
coherent

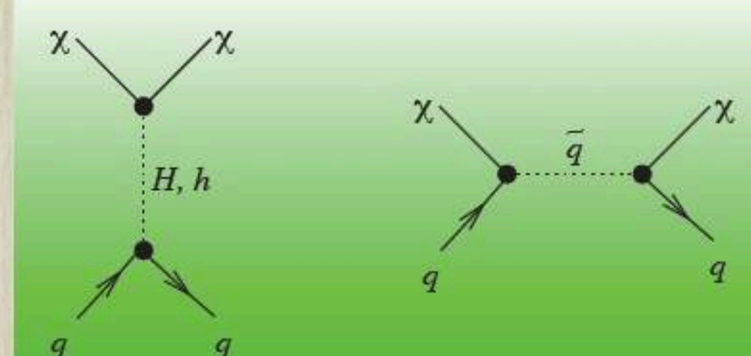
Scalar
(spin-independent)

$$\mathcal{L}_{\text{scalar}} = a_q\bar{\chi}\chi\bar{q}q$$

Signal boosted by a factor $\sim A^2$

In case of neutralinos in the MSSM:





For dirac fermions also:

coherent

Vector: $\mathcal{L}^q_{vec} = b_q\ \bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q$

Signal boosted by a factor $\sim A^2$

For spin-0 or spin-1 WIMPs the discussion is analogous.

What is actually measured?

Recall event rate: events/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nvf(\mathbf{v},t)d^3v$$

$$= \frac{\rho\sigma(q)}{2m\mu^2}\int_{v>v_{\min}} \frac{f(\mathbf{v},t)}{v}d^3v$$

- $\frac{N_T}{M_T}$ = Avogadro's number per mol = Number of atoms per gram; $\mu = mM/(m+M)$
- For elastic scattering: $v_{\min} = \sqrt{ME/2\mu^2}$
- For 1/|q| >> 10 fm, DM interacts coherently with the nucleus … in general there is a form factor suppression

- spin-independent (SI) $\sigma(q) = \sigma_0 F^2(q) = A^2(\mu^2/\mu_{\mathrm{p}}^2)\sigma_{\mathrm{p}}$ for $f_p = f_n$

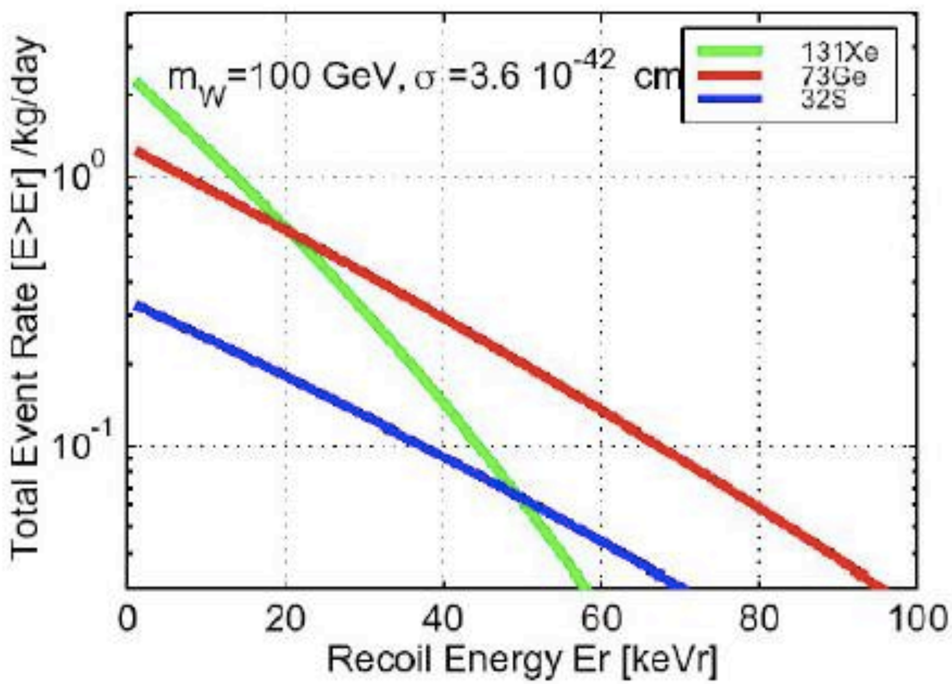
$\sigma_0 = \left[\langle Z f_p + (A-Z) f_n\right]^2 (\mu^2/\mu_{\mathrm{p}}^2)\sigma_{\mathrm{p}}$

- spin-dependent (SD) $\sigma(q) = \frac{32\mu^2 G_F^2 (J_N+1)}{J_N}\left[\langle S_{\mathrm{p}}\rangle a_{\mathrm{p}} + \langle S_{\mathrm{n}}\rangle a_{\mathrm{n}}\right]^2$

Experimental challenges

- Background suppression
  - Deep underground sites
  - Radio-purity of components
  - Active/passive shielding
- Large target mass required
- ~ few keV energy threshold
- Stability and reproducibility

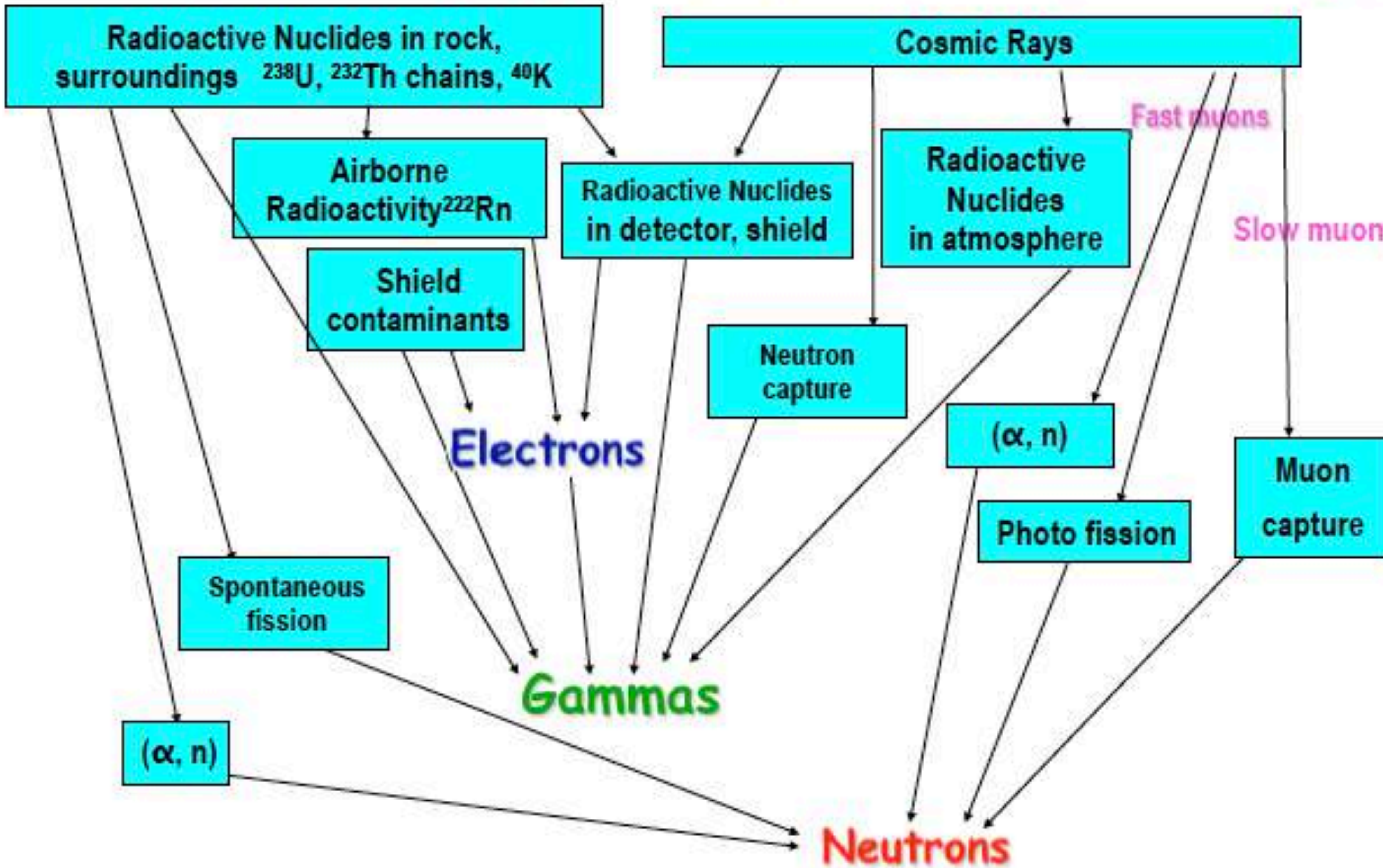
- Discriminate recoil populations
  - **Photons scatter off electrons**
  - **WIMPs/neutrons off nuclei**
  - radon heavy nuclear recoils, alpha tails…



Expected Energy Spectra for a 100 GeV WIMP, illustrating the importance of the choice of detector material

Backgrounds: cosmic rays and natural radioactivity

WIMP scatters (< 1 evts /10 kg/ day) swamped by backgrounds (> $10^{6\text{-}7}$ evts/kg-d)



For a convincing detection will need to demonstrate that events are due to dark matter recoils and *not* backgrounds

Electron recoils (due to βs and γs):

Examine multiple energy deposition channels

Nuclear recoils (due to neutrons from cosmic rays or local radioactivity):

Indistinguishable on an event-by-event basis!

Look for dependence of event rate on:

Time

annual modulation ~few% so need large exposure and *stable* detector operation

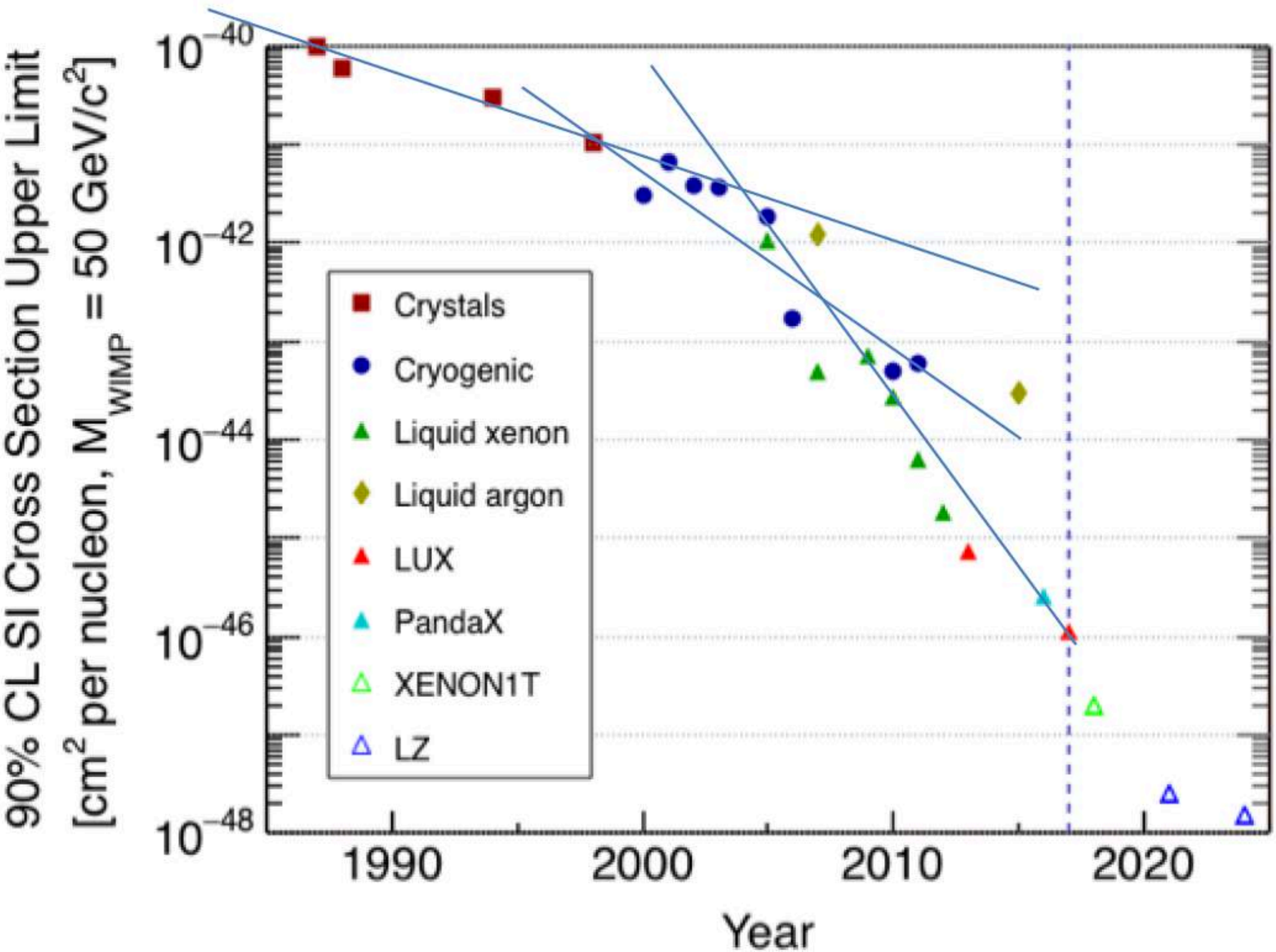
Direction

signal large, but need *directional* detector (usually gaseous so hard to make big)

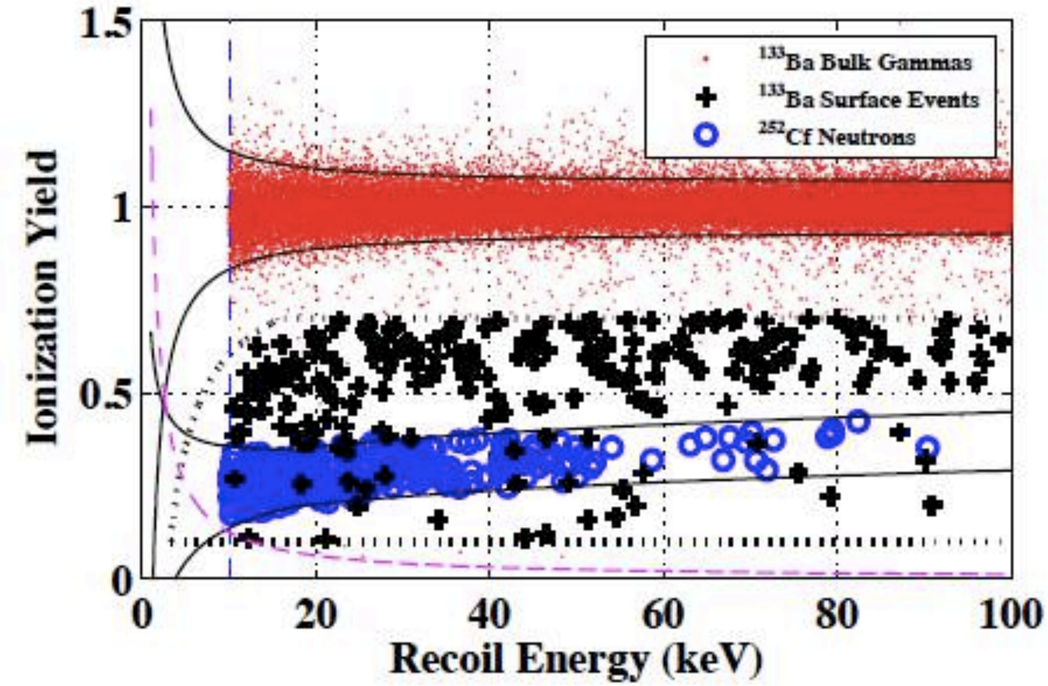
Energy

check that spectra measured with different target nuclei are consistent

EVOLUTION OF EXPERIMENTAL SENSITIVITY



Cryogenic detectors



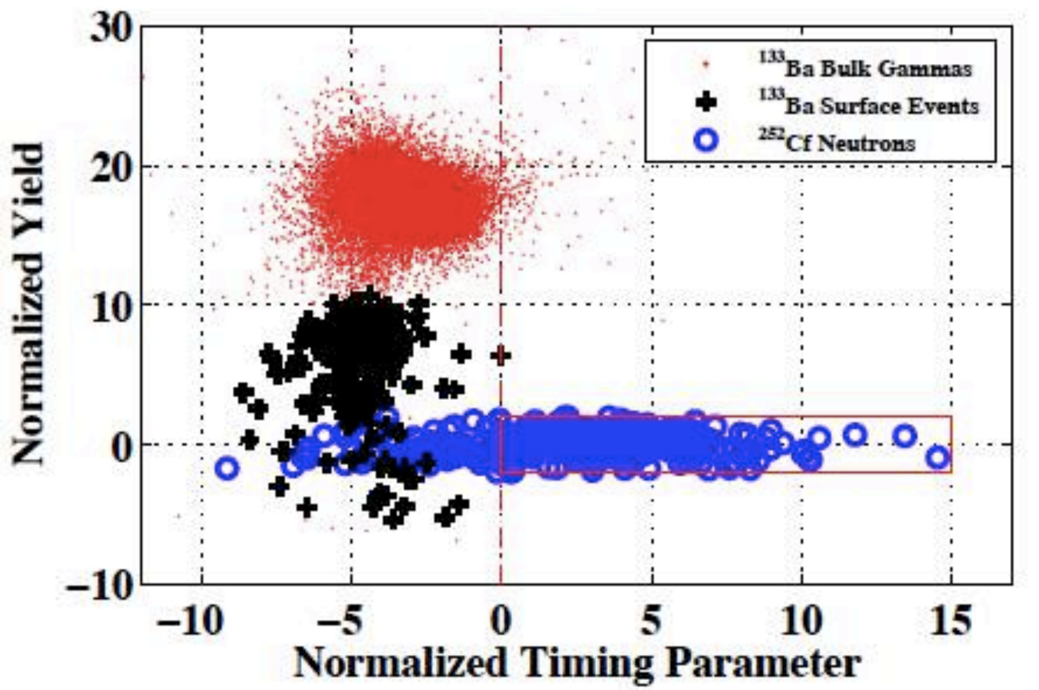
Ionisation yield alone rejects

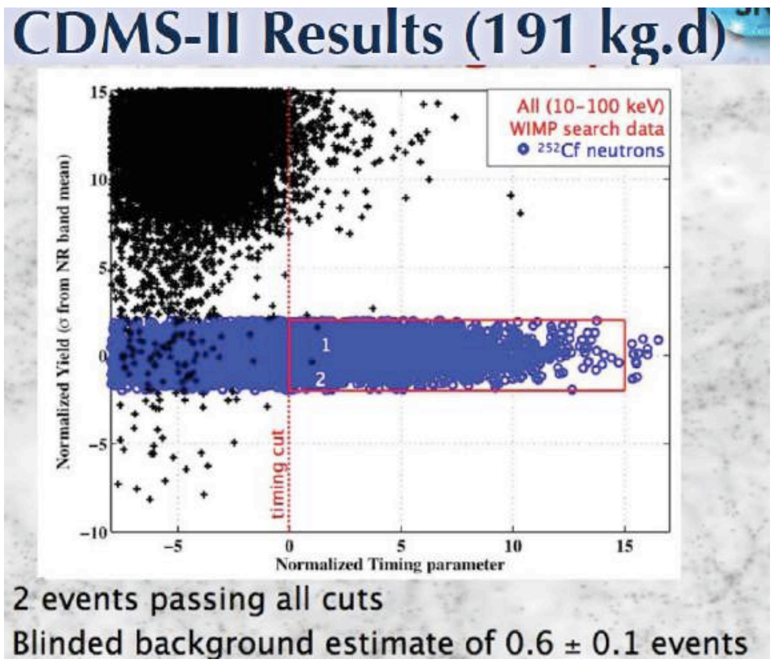
>99.9% γ's, >75% β's

Ionisation + phonon *timing*

rejects >99.9999% γ's, >99% β's

2 events seen … but consistent with expected background



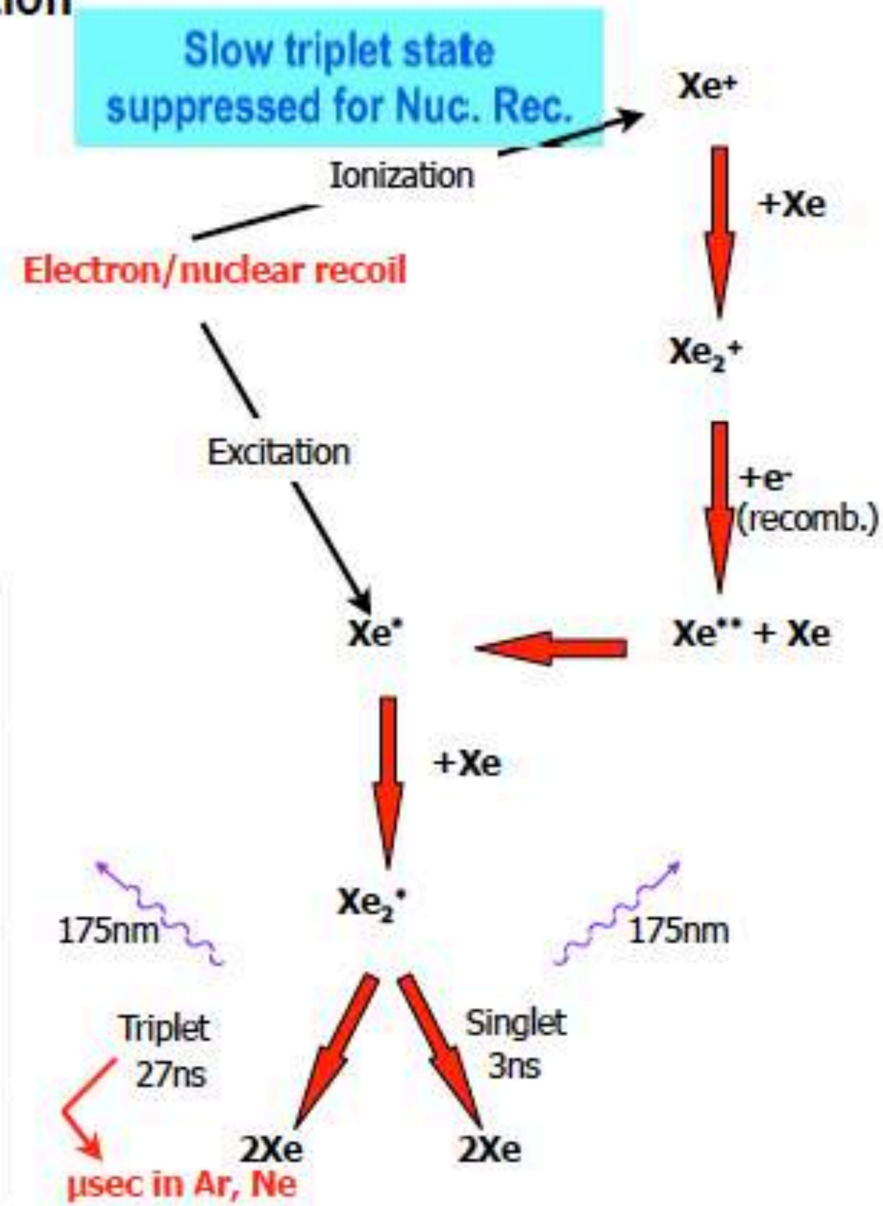


Ahmed *et al*, Science **327**:1619,2010

Liquid Noble Detectors: Xe, Ar, Ne

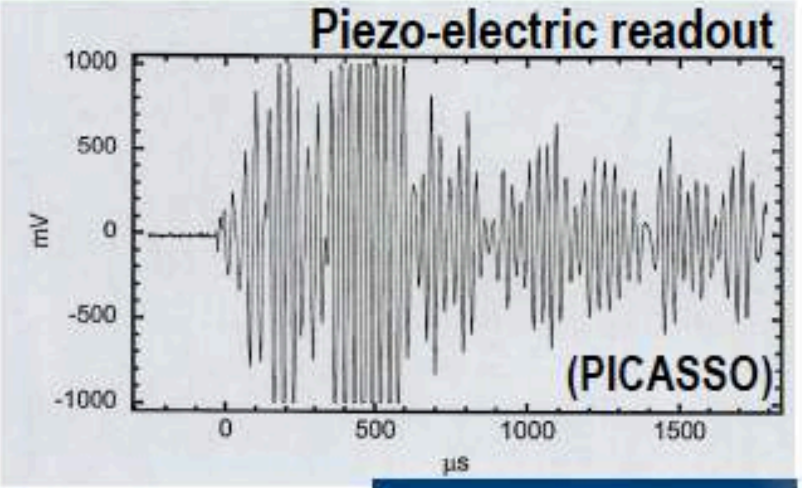
- Atomic excimer states: recoil discrimination
  - Pulse Shape Discrimination
  - Secondary ionization signal
- May readily scale to large mass
- Challenges
  - discrimination at low threshold
  - backgrounds from PMT's and
    - ^{87}Kr in LXe
    - ^{39}Ar in LAr - 1 Bq/kg!

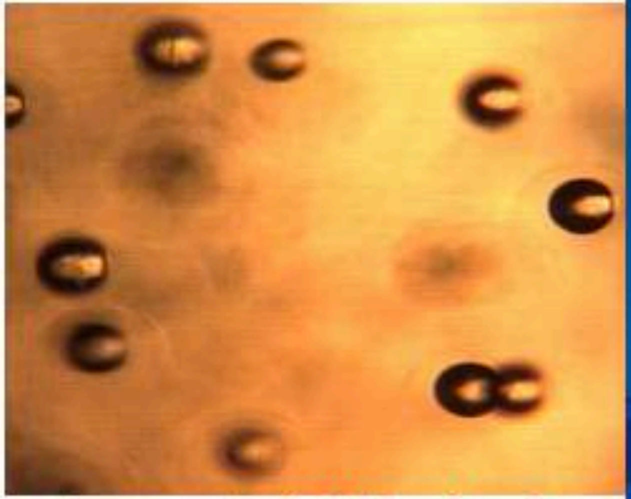
Element	Single phase	Double phase
Xenon	ZEPLIN I, XMASS	ZEPLIN II/III, XENON, LUX
Argon	DEAP, CLEAN	WARP, ArDM
Neon	CLEAN	SIGN



Superheated Droplet Detectors: PICASSO and SIMPLE

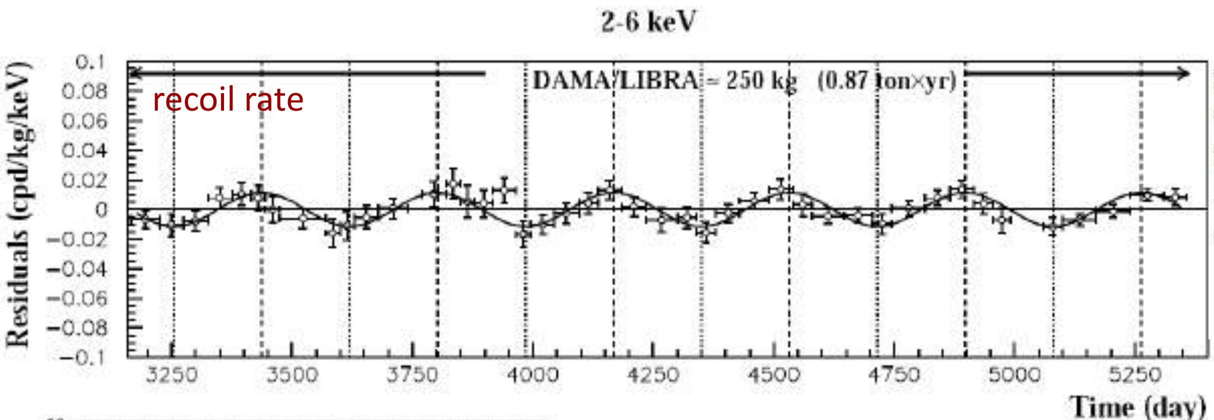
- Superheated droplets, eg, freon, in a passive gel matrix – neutron dosimetry
  - Only high-ionization energy density tracks – nuclear recoils, alphas – sufficient to cause nucleation (droplet explosion)
  - Insensitive to gammas, betas, & minimum ionizing particles
  - Freon: ^{19}F – high *SD* coupling
- Challenges
  - Energy information – vary temperature in threshold detector
  - Develop large-A nucleus for spin-independent coupling
  - Mass scale up
  - Radiopurity of gel matrix (alphas)

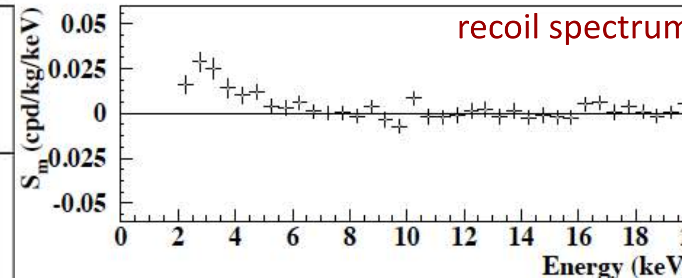




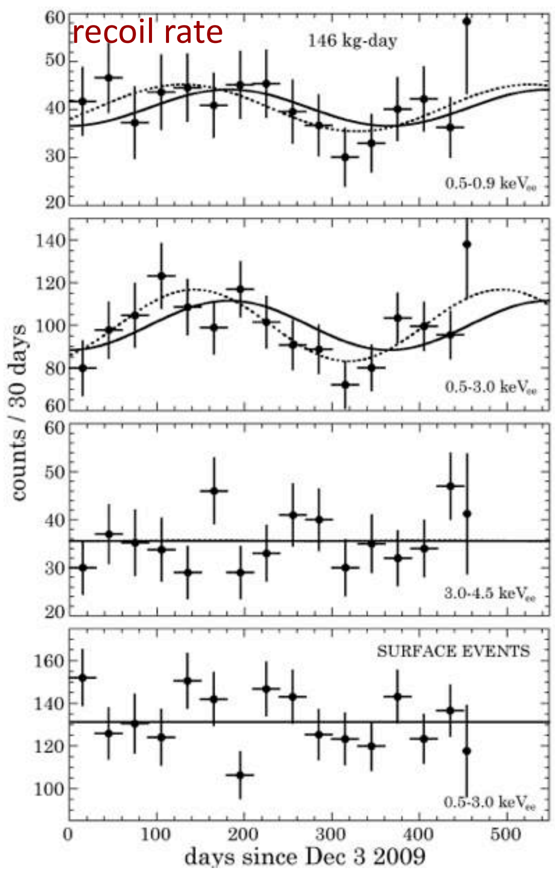
microscopic bubble chambers

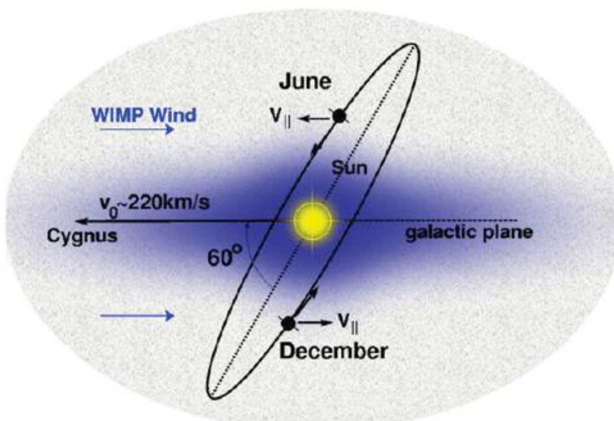
DAMA and CoGeNT have reported modulation signals consistent with ~5-10 GeV dark matter particles with $\sigma_{SI} \sim 10^{-40}$-$10^{-39}$ cm^2



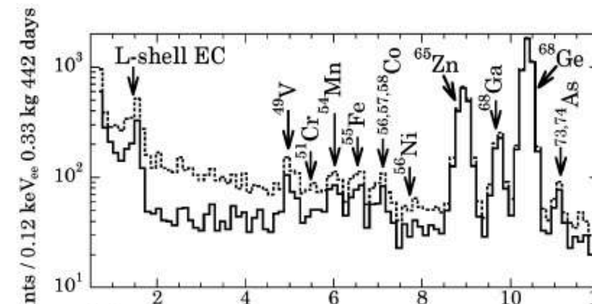


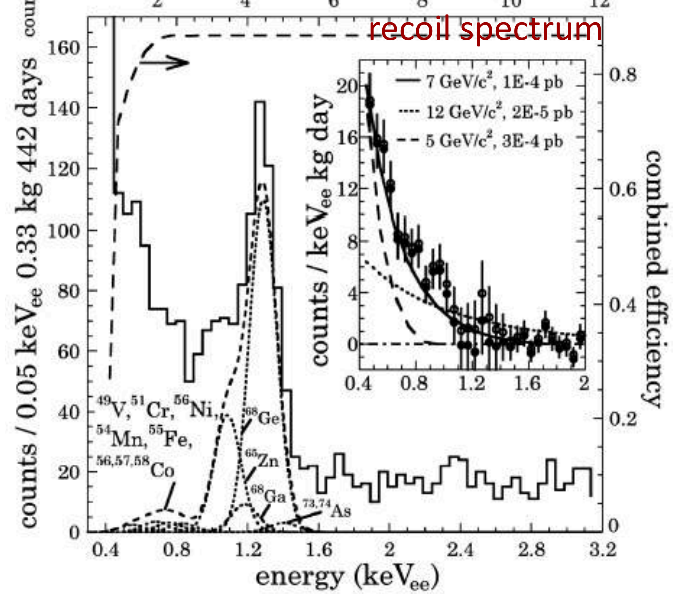
Bernabei *et al*, 1002.1028





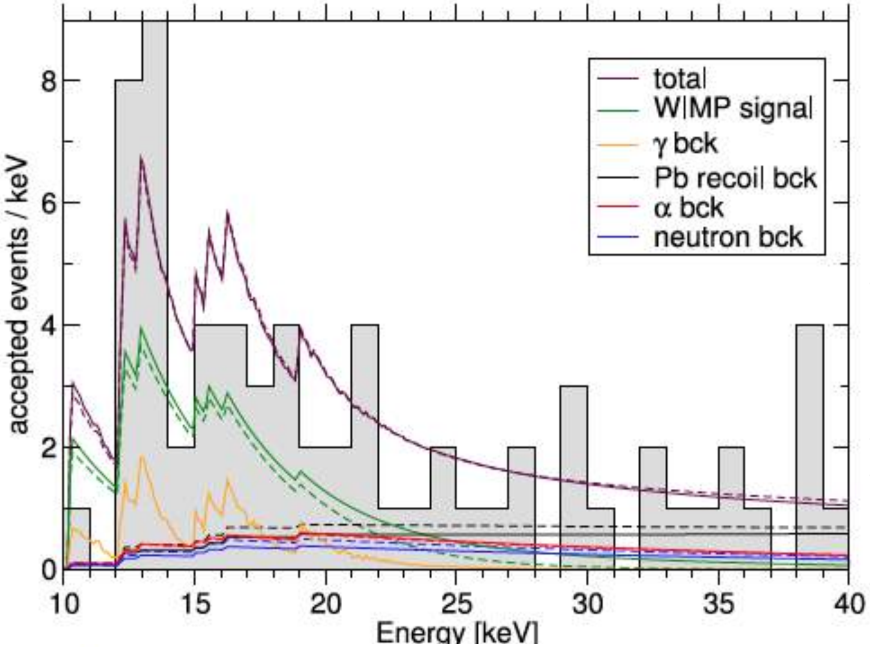
… as is expected due to the motion of the Earth through the DM 'wind'



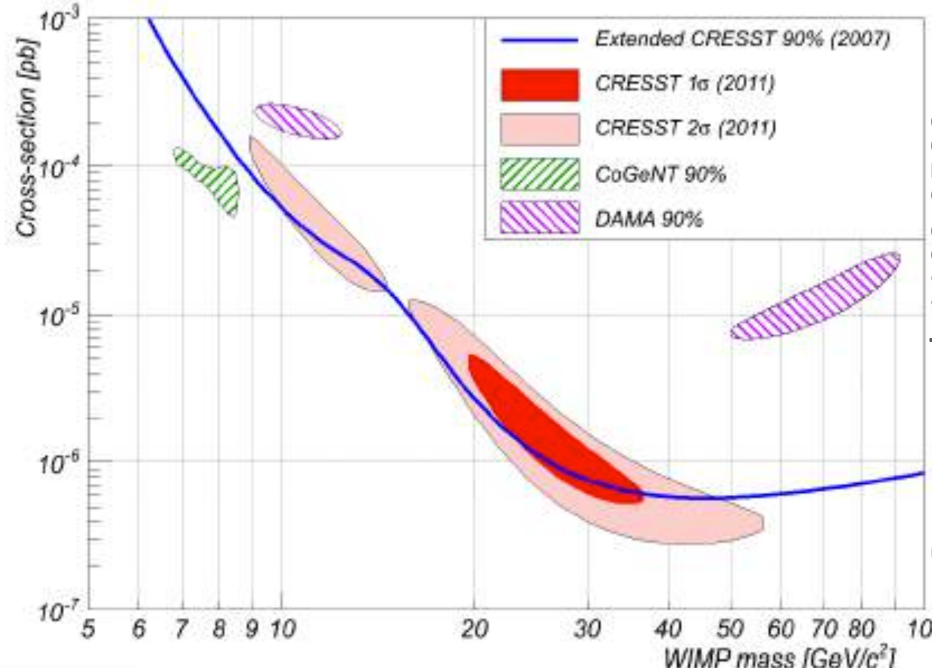


COGeNT: 1106.0650, 1208.5737

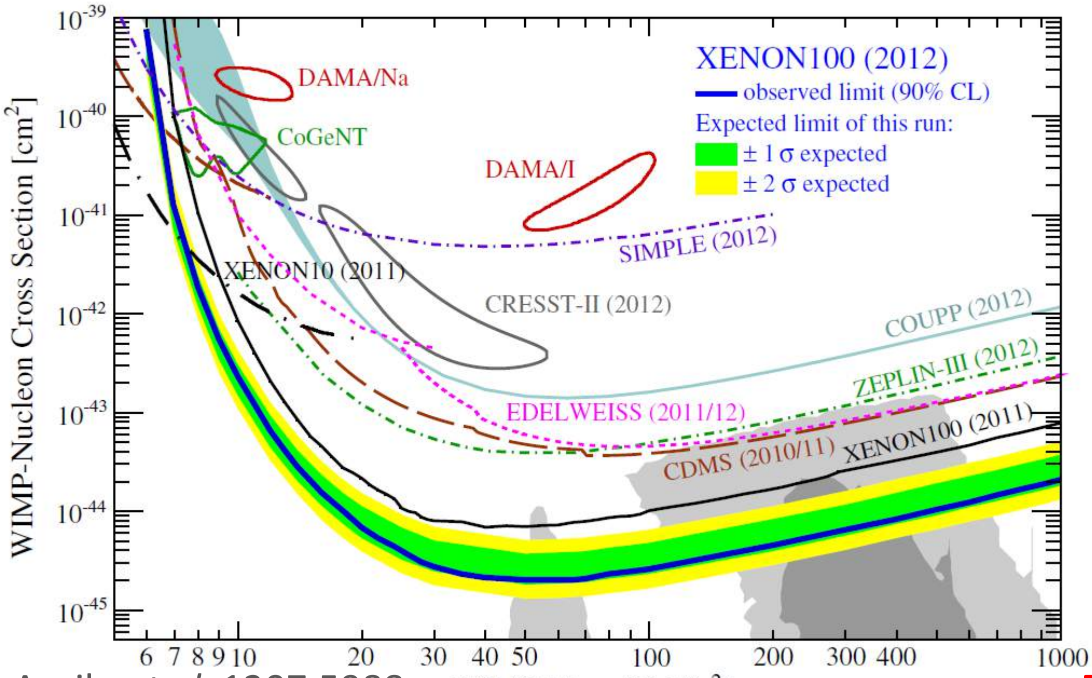
CRESST too reported recoil events consistent with light dark matter



Angloher *et al*, 1109.0702



Brown *et al*, 1109.2589



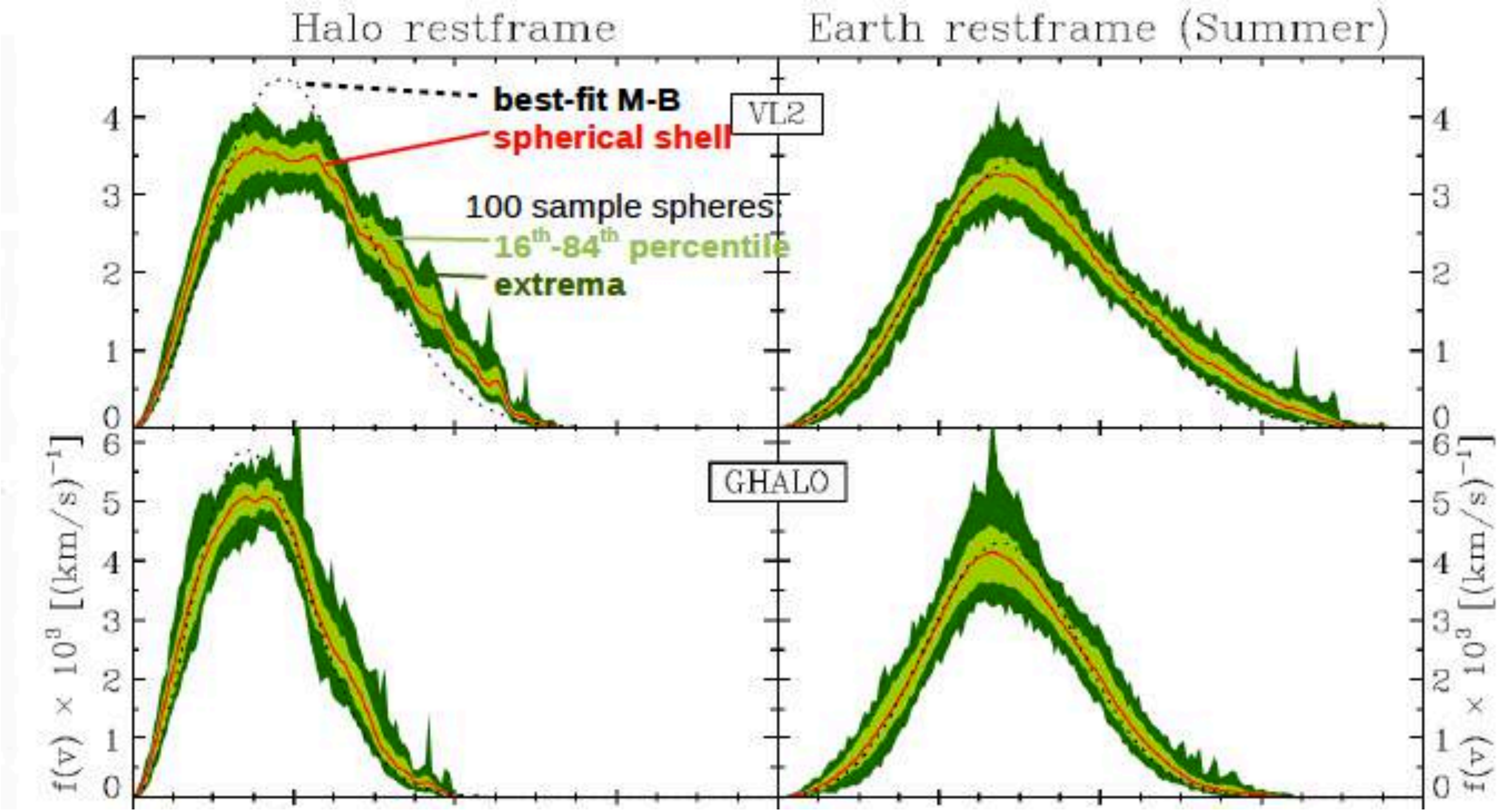
Aprile *et al*, 1207.5988

These signals do not seem to be consistent (assuming the 'Standard Halo Model' with a Maxwellian velocity distribution)

… and are apparently ruled out by data from bigger expts e.g. **CDMS** and **XENON-100**

But are we making a fair comparison?

Numerical simulations (as well as analytic arguments) suggest that the DM velocity distribution may be quite different from Maxwellian



Kuhlen et al, JCAP **02**:030,2010

This can change the expected annual modulation signature!

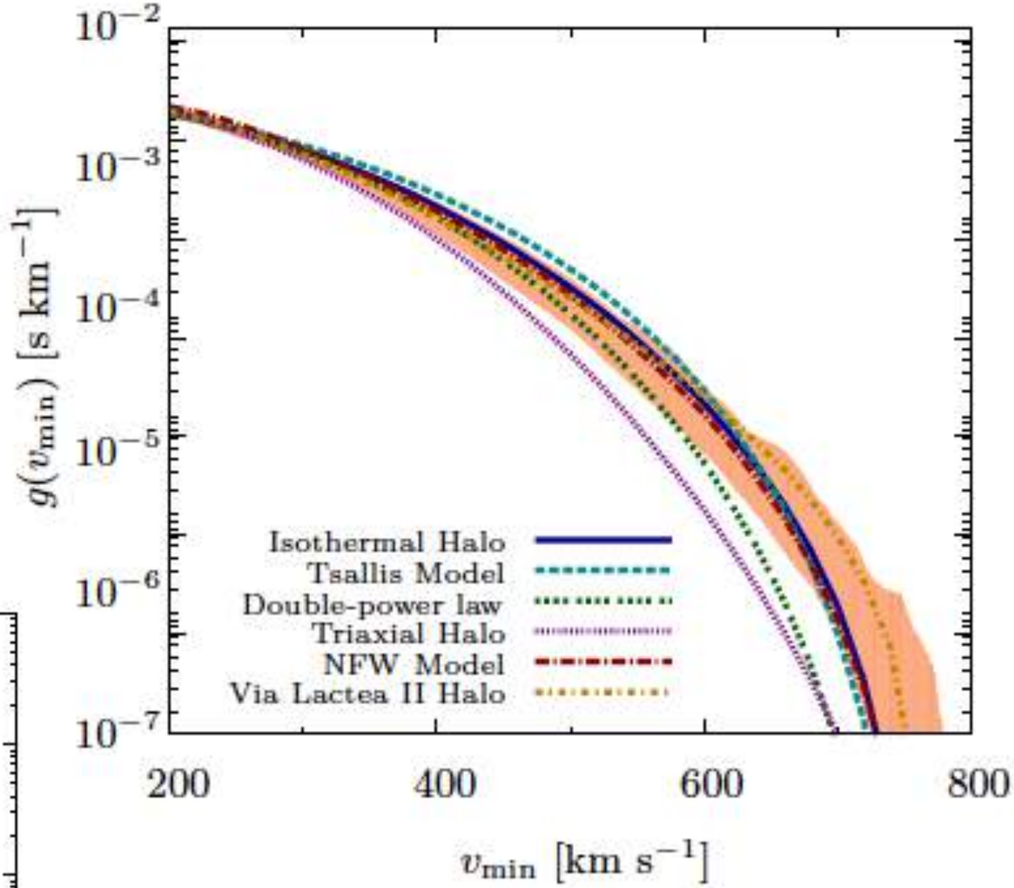
Dark matter density

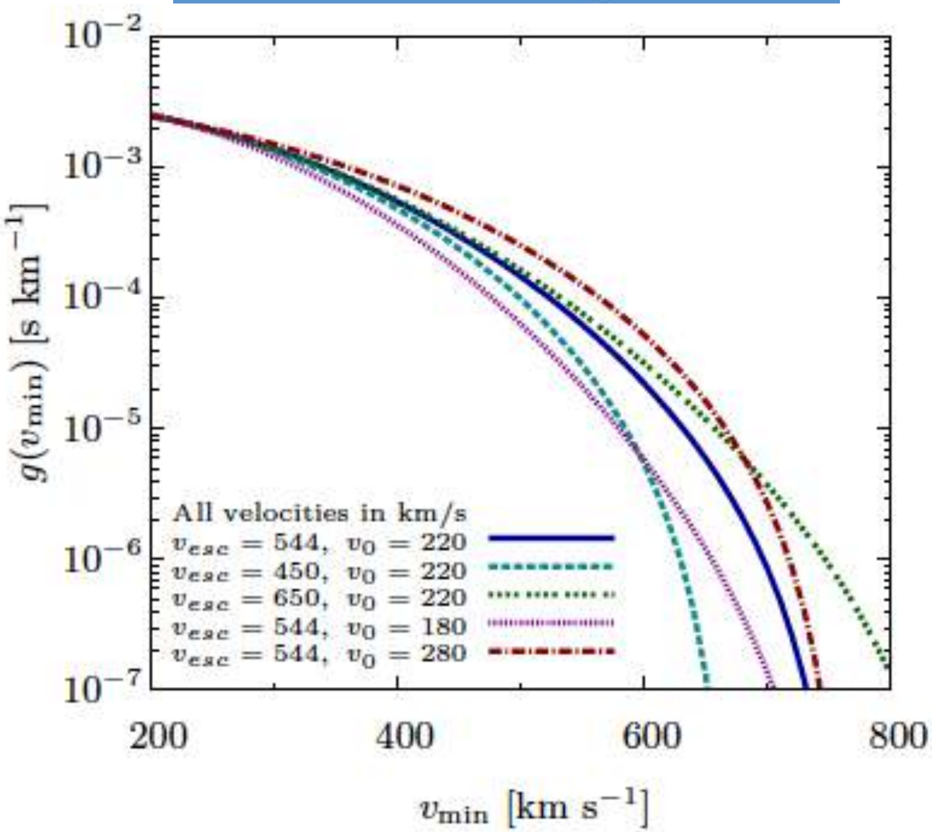
$$\frac{dR}{dE_R} = \frac{\rho\sigma_n}{2m_\chi\mu_{n\chi}^2}A^2F^2(E_R)g(v_{\min})$$

Velocity integral

$$v_{\min}(E_R) = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

$$g(v_{\min}) = \int_{v_{\min}}^{\infty}\frac{f(\vec{v}+\vec{v}_E(t))}{v}d^3v$$



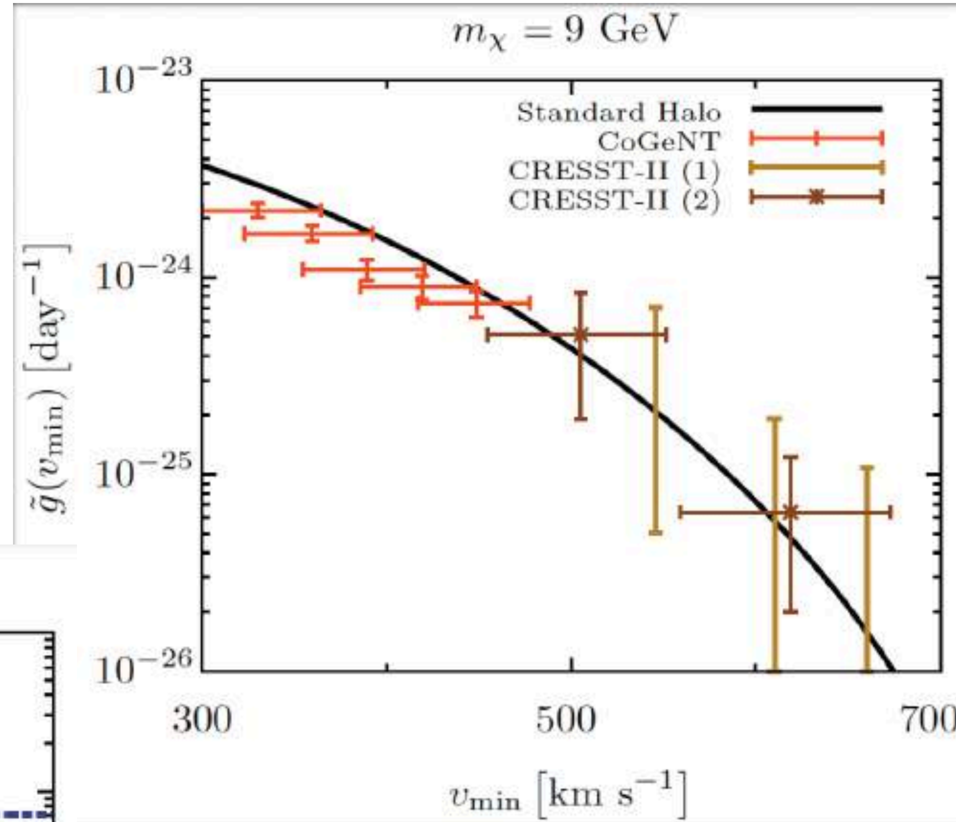


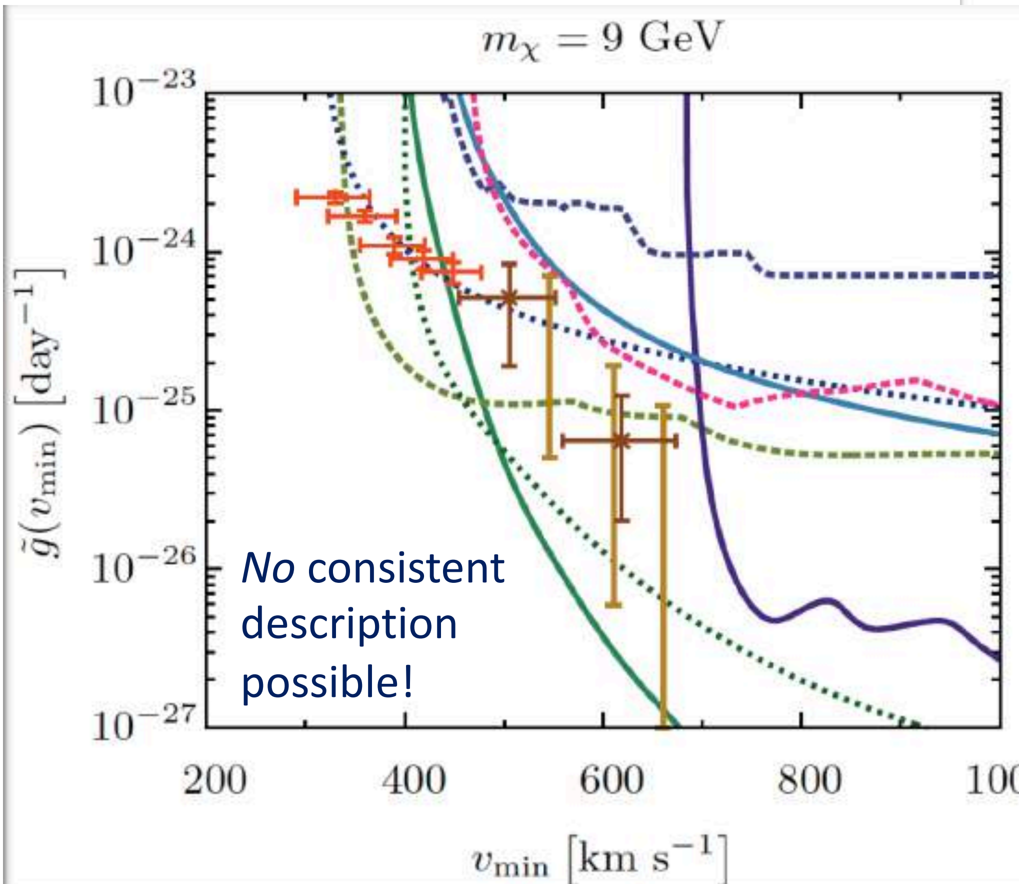
The scattering rate is determined by the **velocity integral** … there is considerable spread amongst the halo models and simulations (or even *within* the SHM)

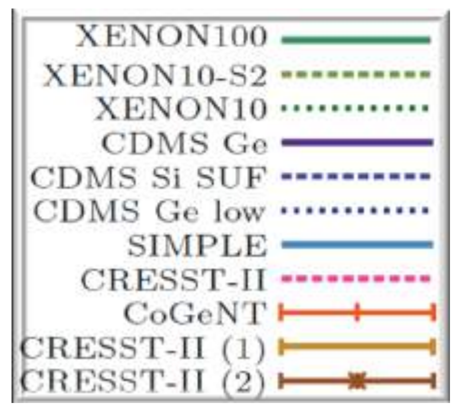
(Frandsen *et al*, JCAP **01**:024,2012)

Since CoGeNT & CRESST-II probe different ranges of $v_{\min}$ space, a consistent description of these *is* in fact possible …

however the upper limit from XENON *cannot* be reconciled







(Frandsen *et al*, JCAP **01**:024,2012)

Cross-checking the claimed modulation fraction

We can expand $g(v_{\min})$ in a harmonic series

$$g(v_{\min},t) = g(v_{\min})\left[1 + A(v_{\min})\cdot\cos\left(2\pi\frac{t-t_0}{1yr}\right)\right]$$

$$\underbrace{\Delta g(v_{\min})}_{\text{Modulation amplitude}} = \frac{1}{2}\left(g(v_{\min},t_0) - g(v_{\min},t_0+0.5yr)\right) = \underbrace{A(v_{\min})}_{\text{Modulation fraction}}g(v_{\min})$$

And thus *infer* the modulation amplitude from data:

$$\Delta\tilde{g}(v_{\min}) = \frac{2\mu_{n\chi}^2}{A^2F^2(E_R)}\Delta\frac{dR}{dE_R}$$

The modulation fraction is related to the derivative of the velocity integral:

$$A(v_{\min}) \leq -\frac{\tilde{g}(v_{\min}+u) - \tilde{g}(v_{\min}-u)}{2\tilde{g}(v_{\min})} \qquad u\text{=}29.8\ \text{km/s}$$

(Frandsen *et al*, JCAP **01**:024,2011)

There are several sources of uncertainty in the measured recoil rate:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R}(E_R, t) = M_{\mathrm{tar}} \frac{\rho_\chi}{2\, m_\chi \mu^2} \frac{(f_p Z + f_n (A - Z))^2}{f_n^2} \sigma_n F^2(E_R) \int_{v_{\mathrm{min}}}^{\infty} \mathrm{d}^3 v \, \frac{f_{\mathrm{local}}(\vec{v}, t)}{v}$$

Nuclear physics

Particle physics

astrophysics

So can reconcile the different results e.g. if dark matter interacts with neutrons and protons *differently* or has interactions that are mainly inelastic or momentum dependent or spin-dependent or electromagnetic … or some combination(s) ⇒ *many* phenomenological studies in recent years

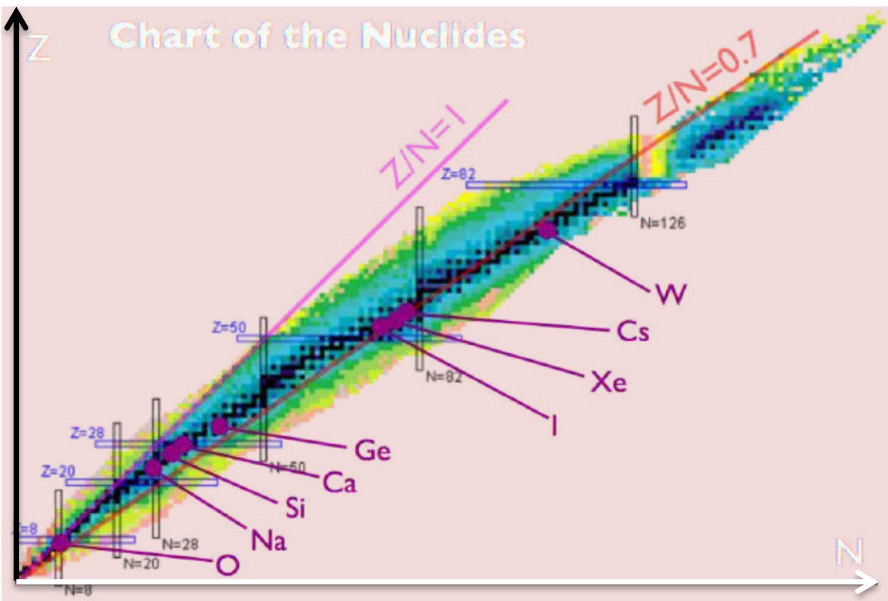
It is clear that *new* experiments are required …especially with *low* recoil energy threshold (to search for relatively light dark matter)

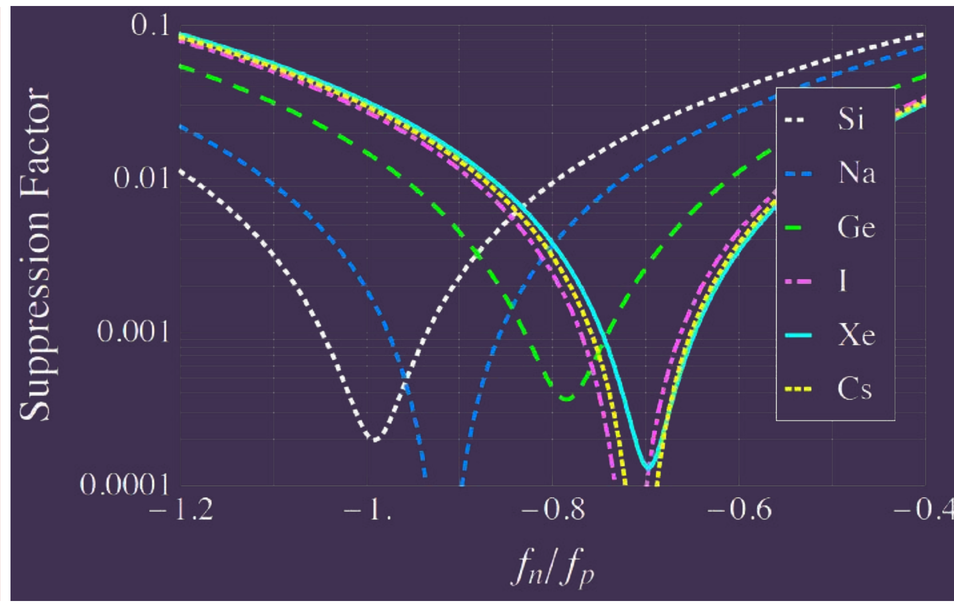
WHY ISOSPIN-*DEPENDENT* COUPLINGS?

- $f_p = f_n$ for a scalar mediator that couples predominantly to heavy quarks e.g. Higgs
- For vector mediators, couplings will in general be *different* for protons and neutrons:

  Photon: $f_p = 1, f_n = 0,$ Z boson: $f_p \approx 0, f_n = 1,$ ρ meson: $f_p = -f_n$

- A new $U(1)$ gauge boson (Z') can have almost *any* value for ratio f_n / f_p

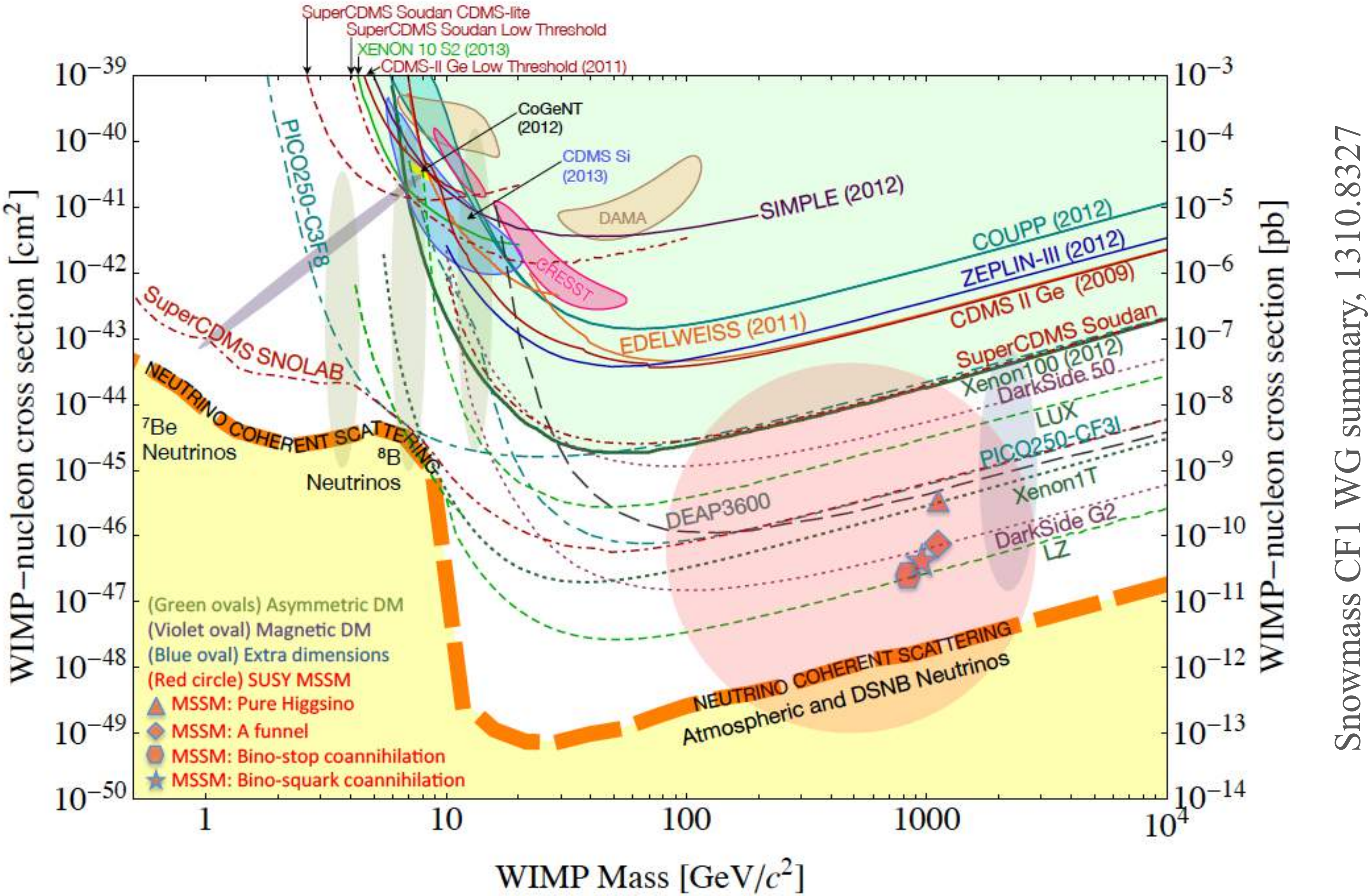




NB: $N f_n + Z f_p = 0$ for $f_n/f_p \approx - Z/N \sim -0.7$

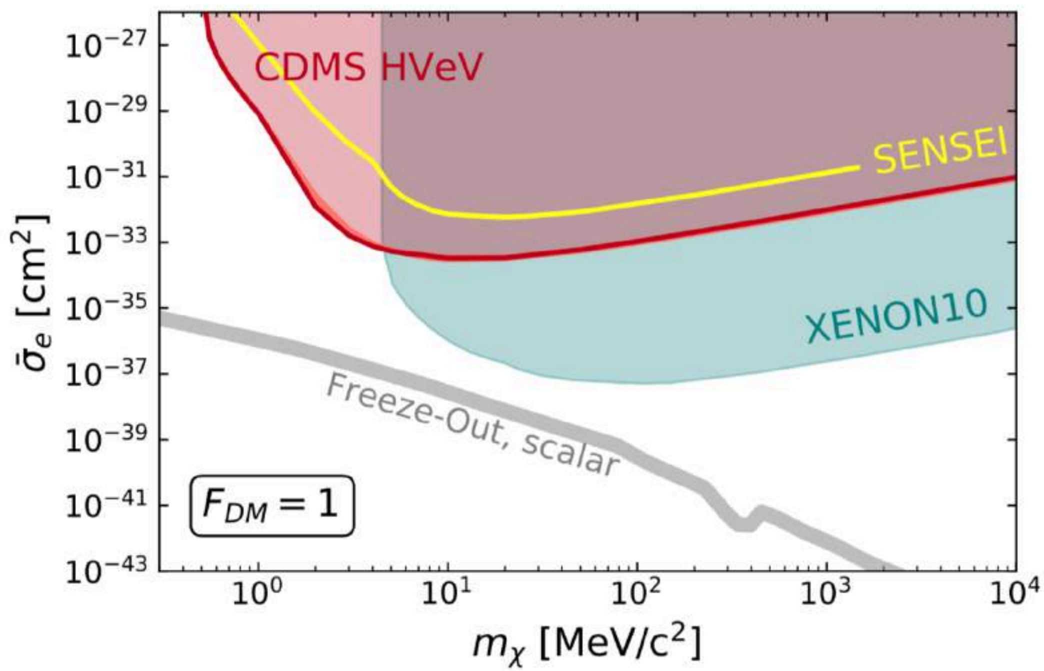
Schwetz, Zupan, JCAP **08**:008,2011; Feng, Kumar, Marfatia, Sanford, Phys.Lett. B**703**:124,2011

Comparison plots like this *ignore* all these caveats!



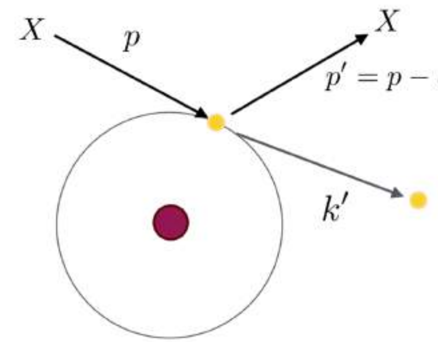
The big experiments are still focussing on the electroweak scale but a number of innovative approaches are targeting much lighter WIMPs

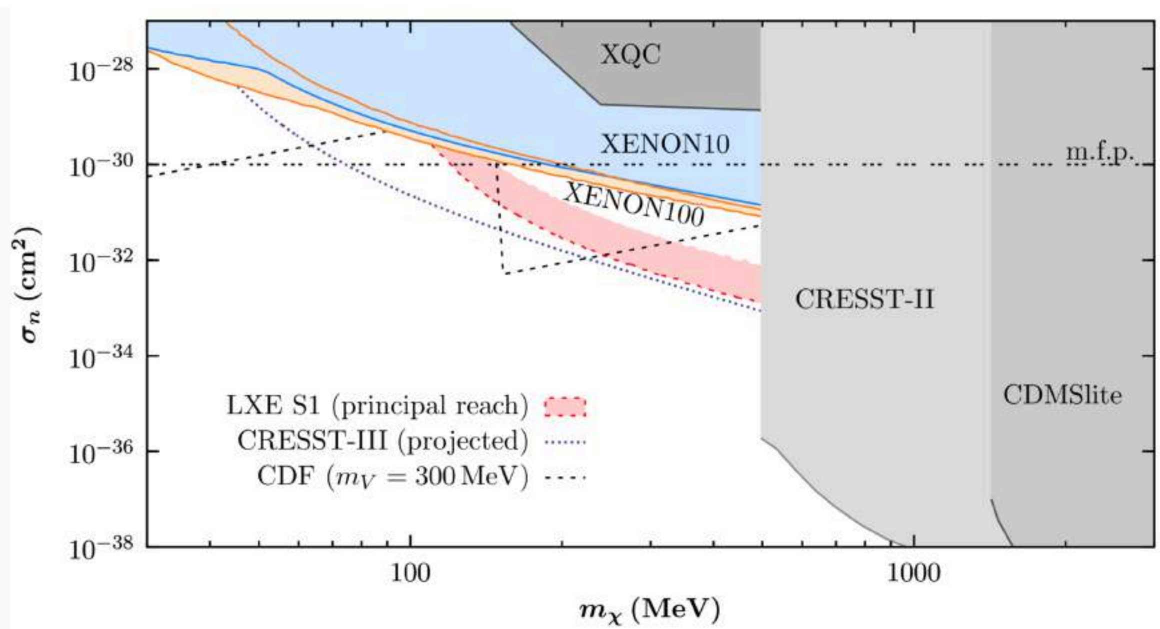
THERE IS GROWING INTEREST IN SUB-GEV MASS DARK MATTER



Agnese *et al*, PRL **121**:051301,2018

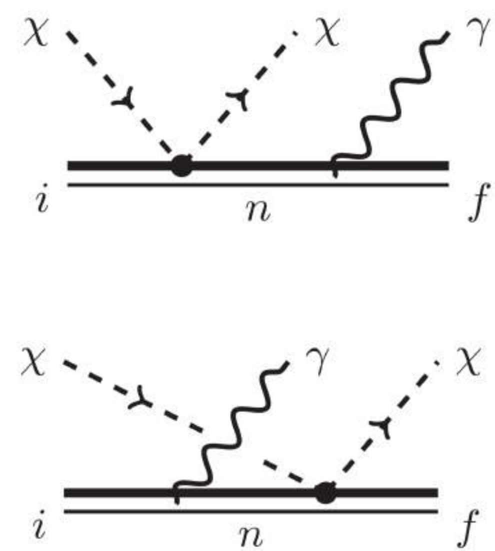
Electron recoil



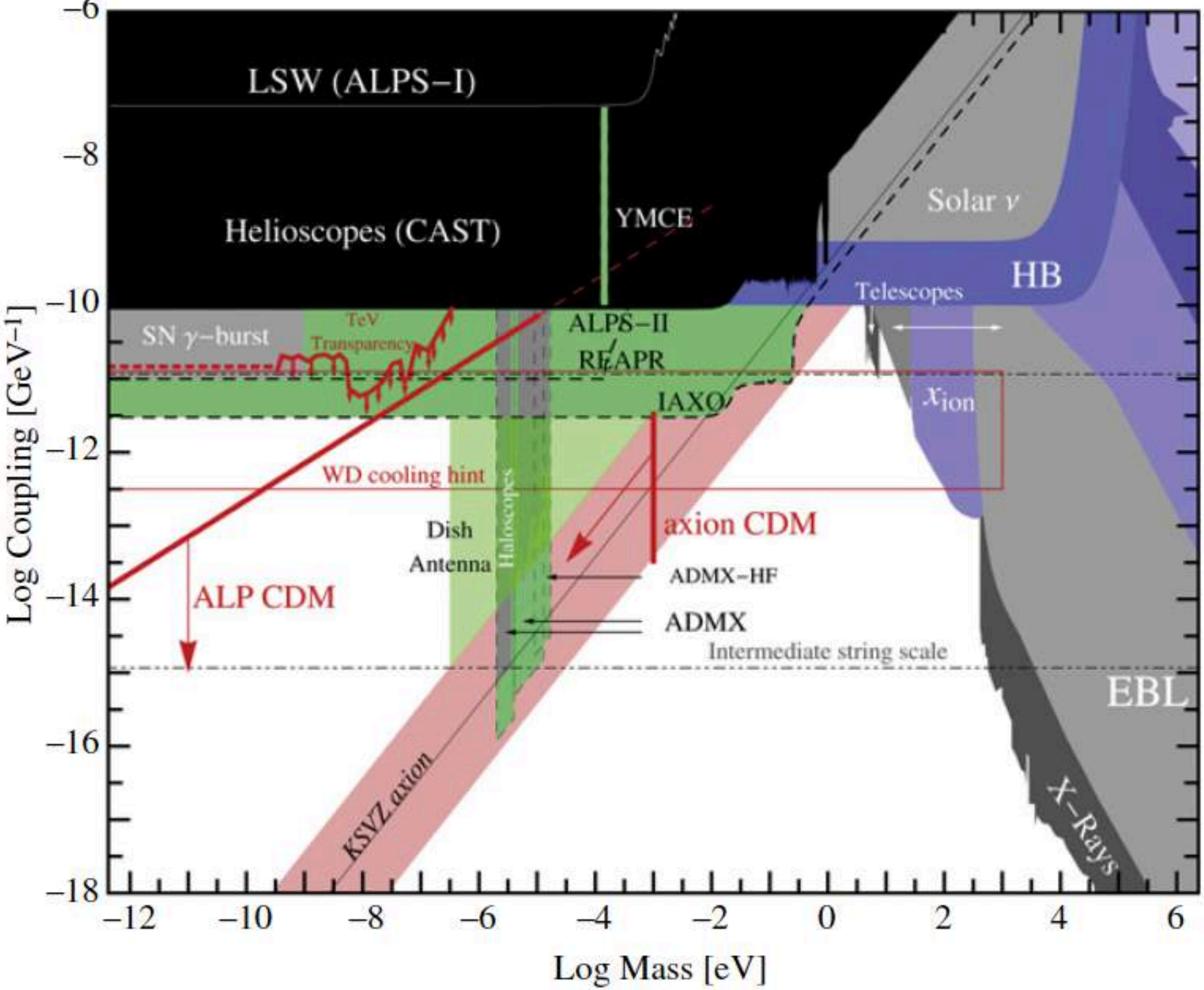


Kouvaris, Pradler, PRL **118**:031803,2017

Bremsstrahlung

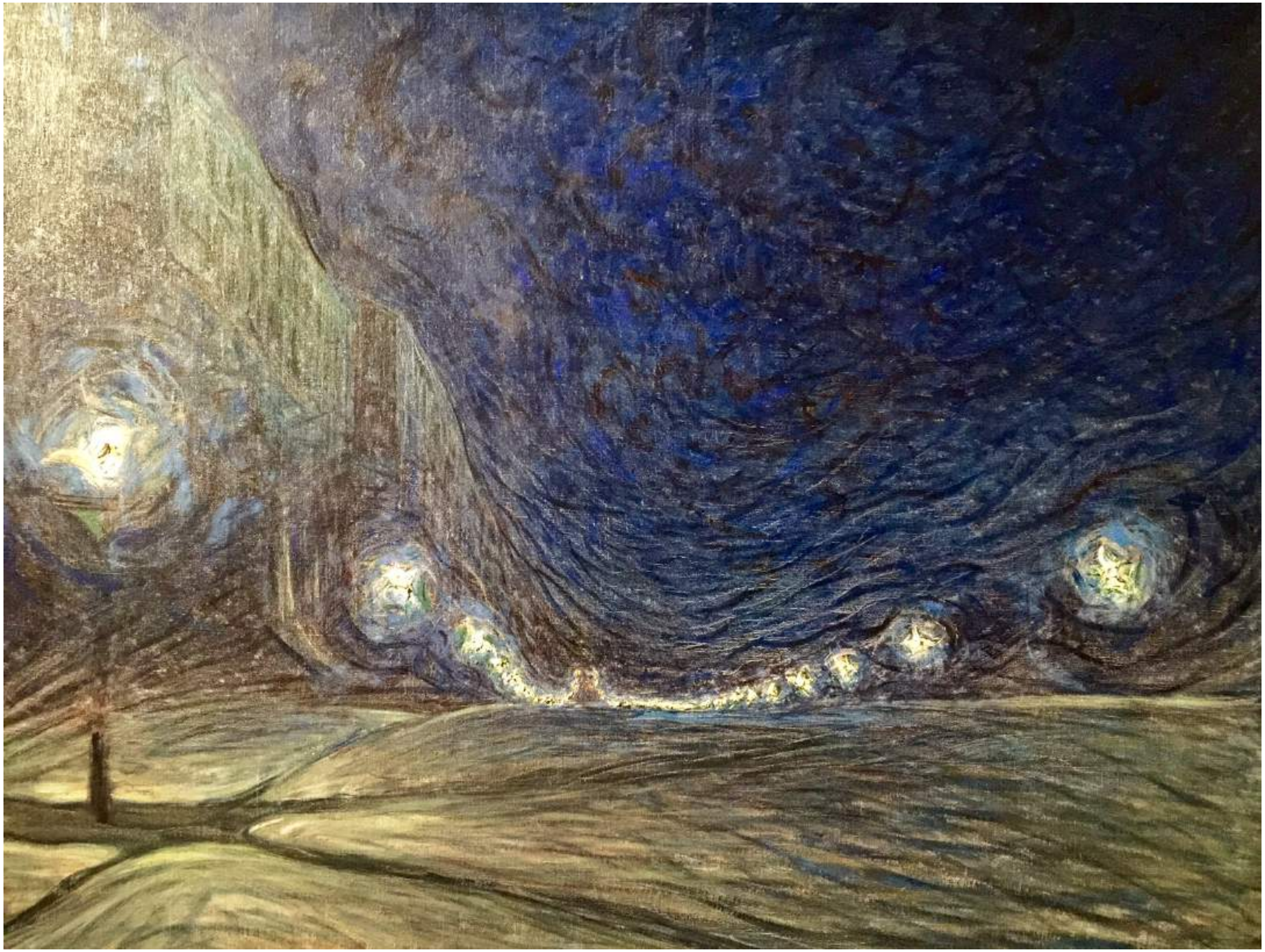


Searches for axions and ALPs are done *very* differently



Snowmass Intensity Frontier WG summary, 1401.6077

Searching for particle dark matter is necessarily guided by (current) theoretical prejudice ...



Of course the probability of success is difficult to estimate, but if we never search then the chance of success is zero! G. Cocconi & P. Morrison (1959)