The Dark Side of the Forces

DIRECT DARK MATTER DETECTION (II)

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DIRECT DM DETECTION – OUTLINE

1a. The dark matter landscape

- The big picture
- Dark matter candidates

1b. Weakly Interacting Massive Particles

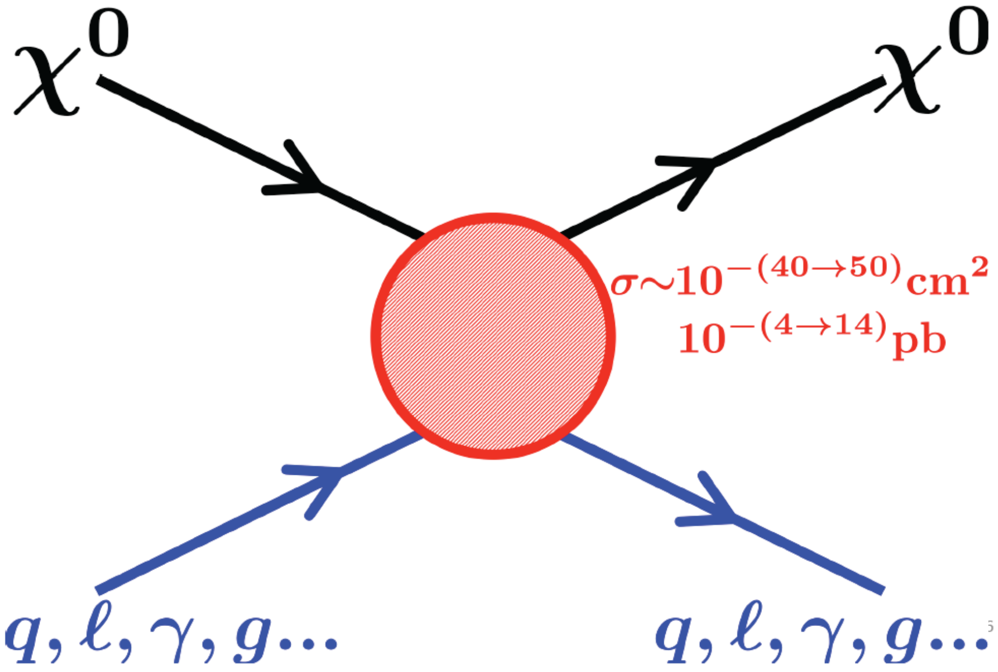
- Thermal relics: the WIMP paradigm
- Our own (galactic) WIMPs

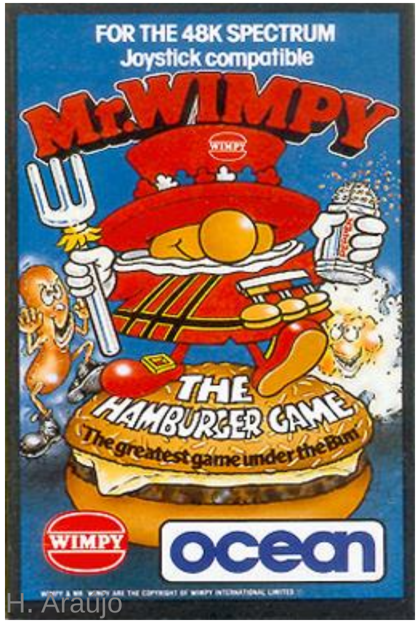
2. How to catch a WIMP

- Direct detection strategies
- The experimental challenge
- Detector technologies

4. Exercises – This afternoon

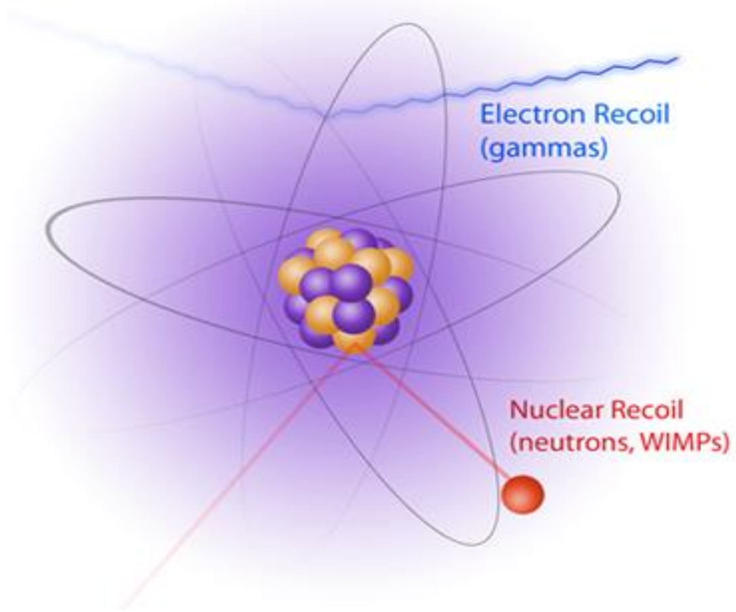
HOW TO CATCH A WIMP





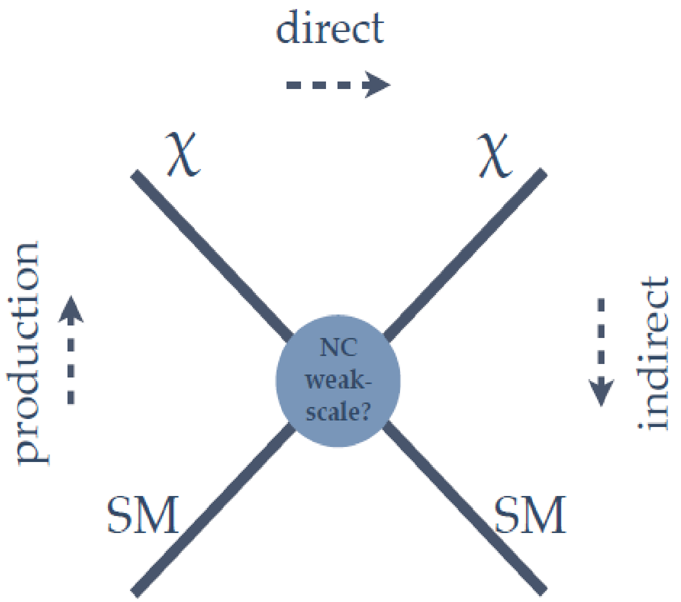
- Focus on WIMPs: stable, neutral, cold, massive particles, interacting via gravity – and hopefully via the weak force
- WIMPs can solve the DM problem in all its glory: astrophysical, cosmological and particle physics

HOW TO CATCH A WIMP



1. Direct detection (scattering XS)

- **Nuclear recoils from elastic scattering**
- Rate, A- & J-dependence, annual modulation, directionality
- Particle mass (if not too heavy)
- Maybe some astrophysical parameters (v_{esc})?



2. Indirect detection (decay, annihilation XS)

- High-energy cosmic-rays, γ-rays, neutrinos, etc.
- Over-dense regions, annihilation signal $\propto$ n^2
- Very challenging backgrounds

3. Accelerator searches (production XS)

- MET, mono-X, dark photons, etc.
- Mass measurement may be poor at least initially
- Can it establish that new particle is the DM?

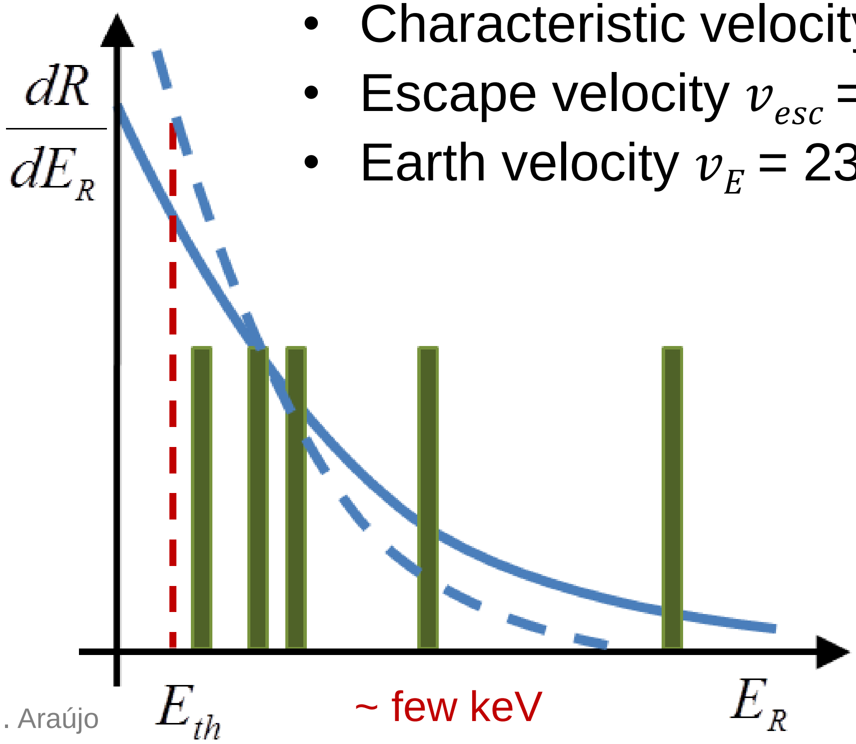
WIMP-NUCLEUS ELASTIC SCATTERING RATES

The ‘spherical cow’ galactic model

- DM halo is 3-dimensional, stationary, has no lumps
- Isothermal sphere with density profile $\rho \propto r^{-2}$
- Local density $\rho_0 \sim 0.3$ GeV/cm^3

Maxwellian (truncated) velocity distribution, $f(v)$

- Characteristic velocity v_0 = 220 km/s
- Escape velocity v_{esc} = 544 km/s
- Earth velocity v_E = 230 km/s



Nuclear recoil energy spectrum [events/kg/day/keV]

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_\chi \mu_A^2} F^2(q) \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3 v$$

$$\frac{dR}{dE_R} \approx \frac{R_0}{E_0 r} e^{-E_R / E_0 r}, \quad r = \frac{4 m_W m_T}{(m_W + m_T)^2} \leq 1$$

NUCLEAR FORM FACTOR, $F^2(q)$

The FF accounts for the finite nuclear size: for higher momentum transfer, when $\lambda = h/q$ becomes smaller than the nuclear radius, the scattering XS decreases

- F(q) is the Fourier transform of a spherically symmetric ground-state mass distribution normalised so that F(0) = 1
- Mass distribution approximated by charge distribution
- Since $E_R = q^2/2m_T$, we can express it as $F^2(E_R)$ instead

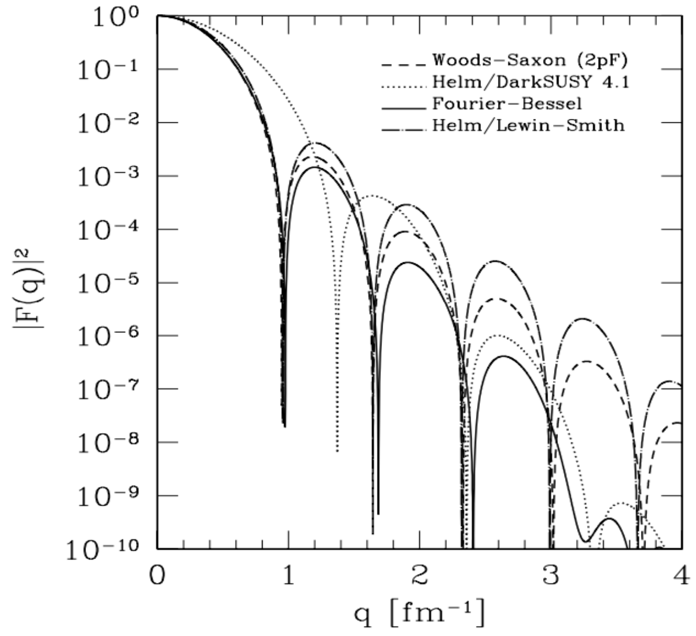
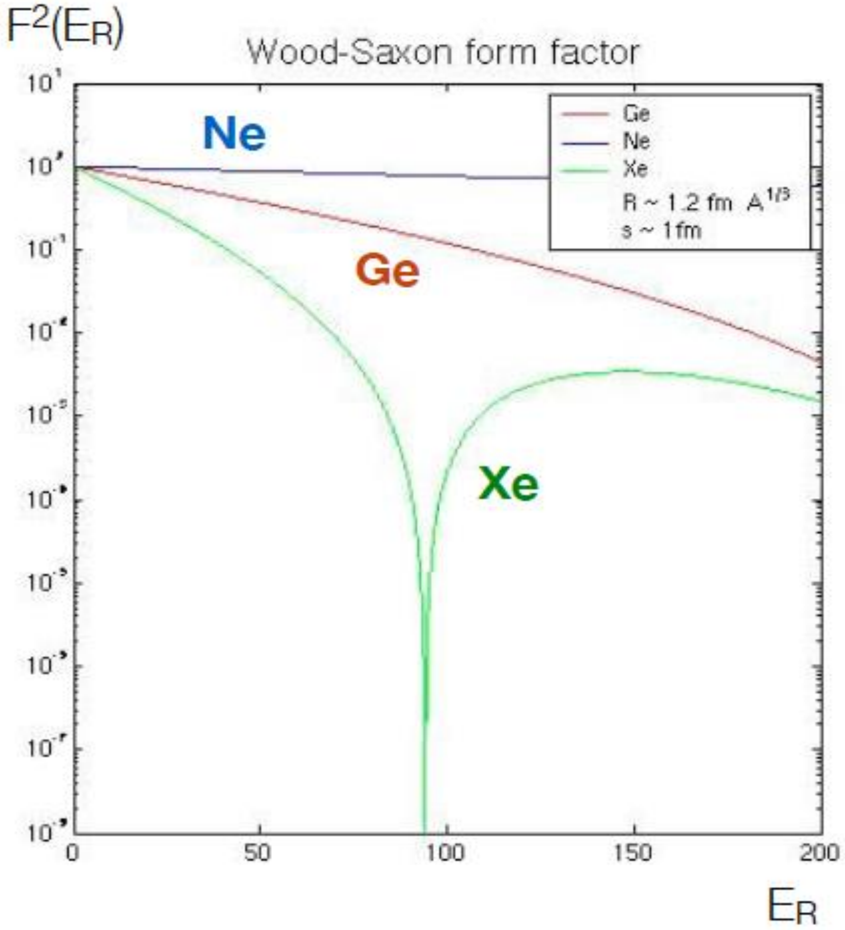
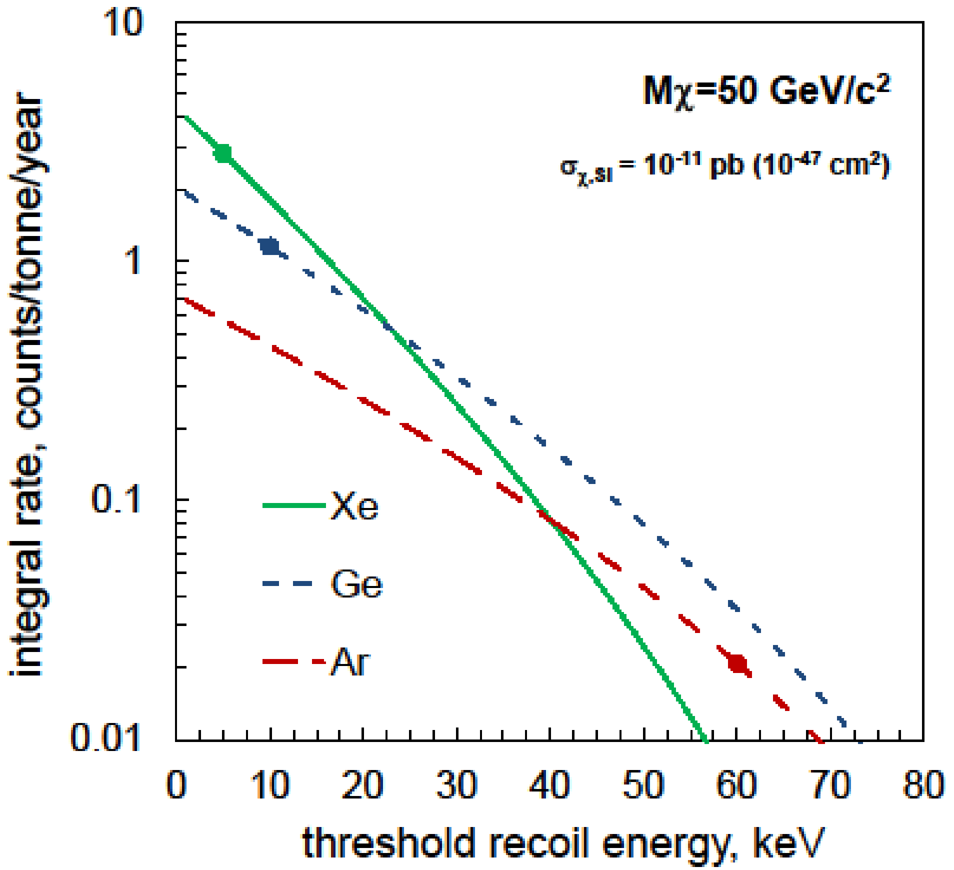
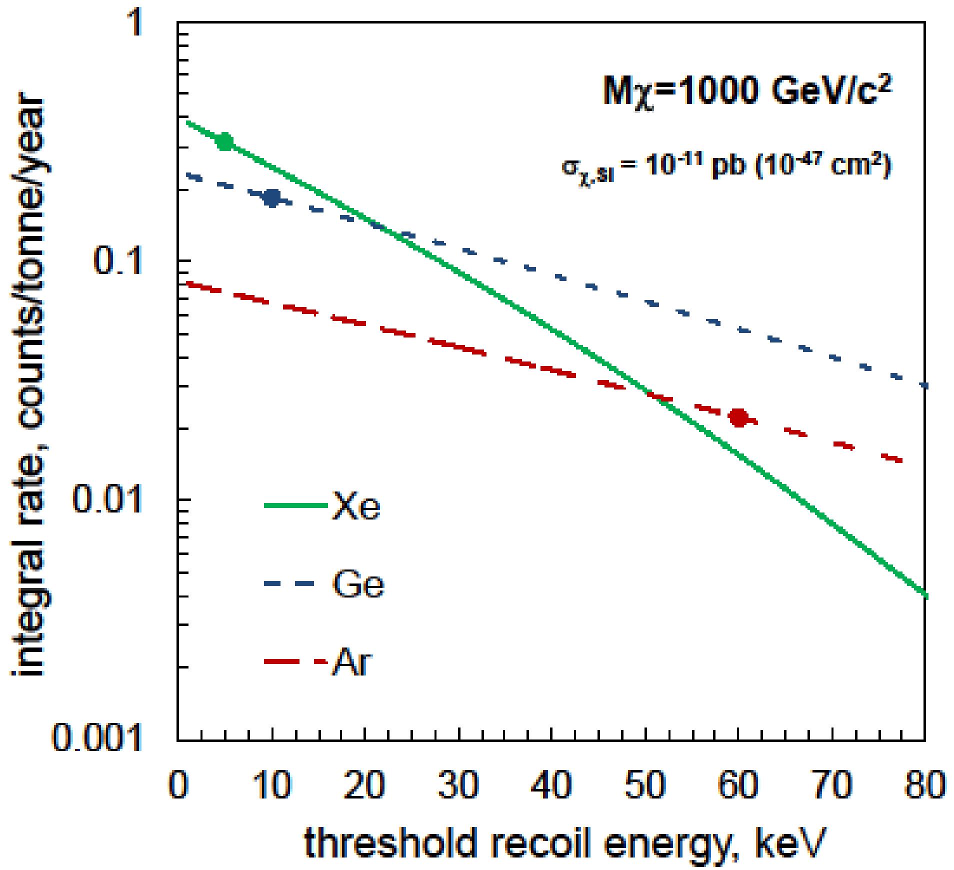


FIG. 4: Helm and FB form factors for ^{70}Ge.

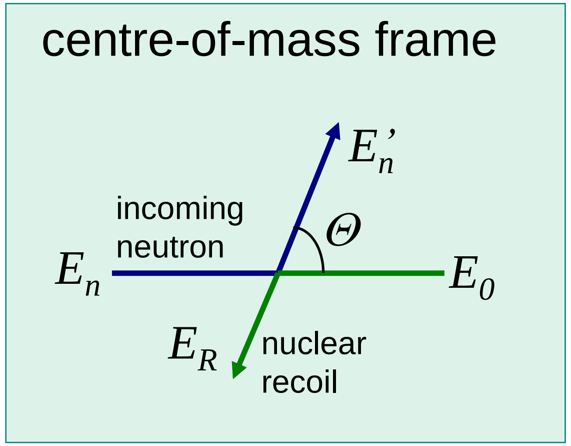


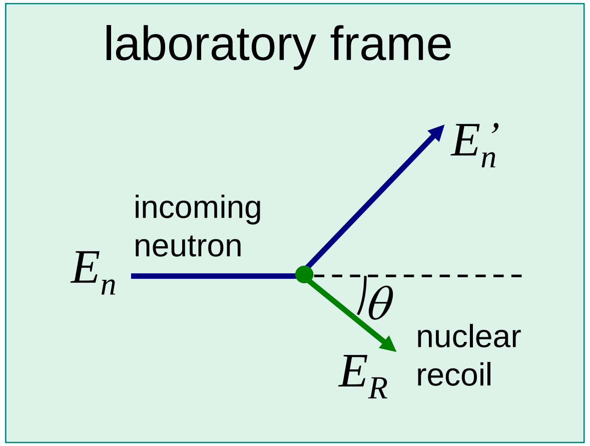
(SPIN-INDEPENDENT) SCATTERING RATES





ANALOGY: NEUTRON ELASTIC SCATTERING





E_n = neutron energy (lab)
E_R = recoil energy (lab)
A = mass of target
Θ = scattering angle (CM)
θ = recoil angle (lab)

$$E_R = E_n \frac{2A}{(A+1)^2}(1-\cos\Theta) \qquad E_R = E_n \frac{4A}{(A+1)^2}\cos^2\alpha \qquad E_{R,max} = E_n \frac{4A}{(A+1)^2}$$

Generally, for a (non-relativistic) projectile with mass *m* and kinetic energy E_i hitting a target with mass M, the recoil energy is given by

$$E_R = E_i \frac{4mM}{(m+M)^2}\cos^2\alpha \qquad \text{defining } r = \frac{4mM}{(m+M)^2} \qquad \rightarrow \qquad E_{R,max} = r\,E_i$$

ANALOGY: NEUTRON ELASTIC SCATTERING

- Kinematic factor peaks at $r = 1$ when projectile and target have the same mass
  - In this case, the projectile transfers all its energy for head-on collisions
  - *Heavier nuclei for heavier WIMPs, lighter nuclei for lighter WIMPs*
  - *Also why hydrogenated materials are best at moderating neutrons*
- Calibration of WIMP targets
  - For 100 GeV WIMPs, a Xe target is well calibrated by MeV neutrons
  - Sources of MeV neutrons: Am-Be (α,n), Cf-252 fission, D-D generators
  - *Signal and calibration <u>maximum</u> energies:*

Neutrons:
Good NR calibration
but that means also
good NR background…

100 GeV WIMP on xenon (A~131)

$$E_{R,max} = r\,E_\chi \sim E_\chi$$

220 km/s WIMP → $E_{R,max}$ = 30 keV

MeV neutron on xenon

$$E_{R,max} = r\,E_n \sim 0.03\,E_n$$

1 MeV neutron → $E_{R,max}$ = 30 keV

WIMP-NUCLEON ELASTIC SCATTERING XS

- **Coupling to p and n more useful than coupling to nucleus**
  - Compare different targets materials, collider searches, indirect searches,…
- **Spin-independent (scalar) interaction**

$$\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$$

  – Note A^2 enhancement (coherence) – more sensitive search

σ_A- WIMP-nucleus XS (we measure this)

σ_p- WIMP-proton XS

σ_n- WIMP-neutron XS

- **Spin-dependent (axial-vector) interaction**

$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$

  – Note J (nuclear spin) replaces A^2 enhancement – less sensitive
  – Some targets more sensitive to proton, others to neutron scattering

More complete approach: non-relativistic EFT

11 operators for exchange of spin-0 or spin-1 mediators

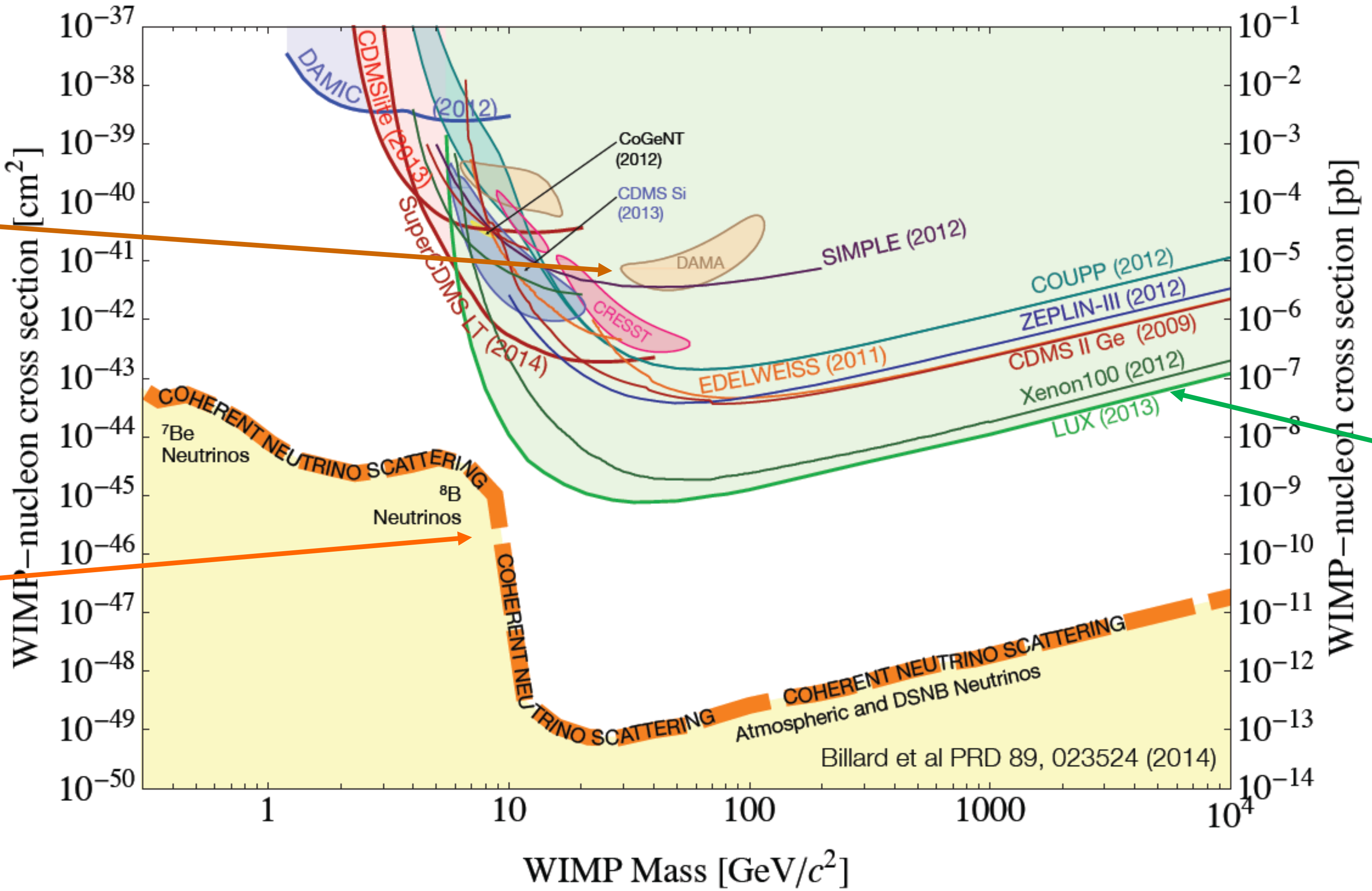
6 independent responses contribute to amplitude

(Fitzpatrick, Haxton, Anand, et al: 1203.3542, 1405.6690)

WIMP-NUCLEON ELASTIC SCATTERING XS

3σ “evidence” region (claim)

Neutrino “floor”



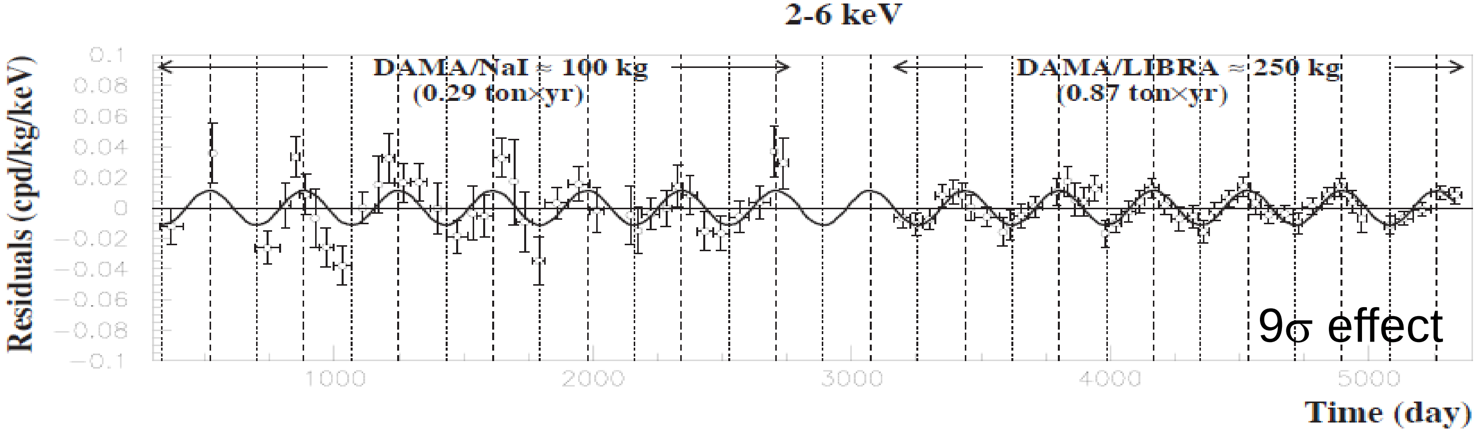
90% CL upper limit

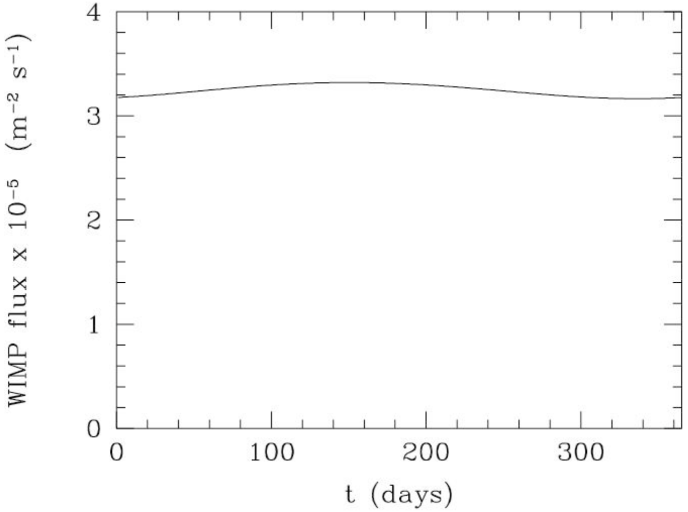
ANNUAL MODULATION

- Galactic rotation through stationary halo: “The Earth bathes in a WIMP wind”

$$v_E = 230\,\mathrm{km/s} + 15\,\mathrm{km/s}\ \times\ \cos\left[\frac{2\pi(t - t_p)}{1\,\mathrm{yr}}\right]$$

DAMA/NaI + DAMA/LIBRA

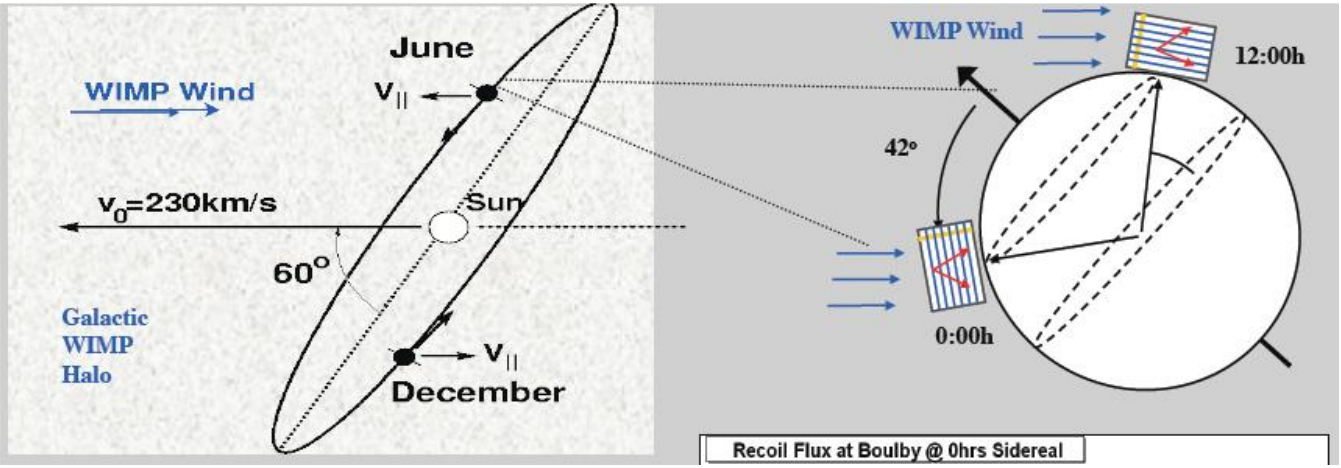


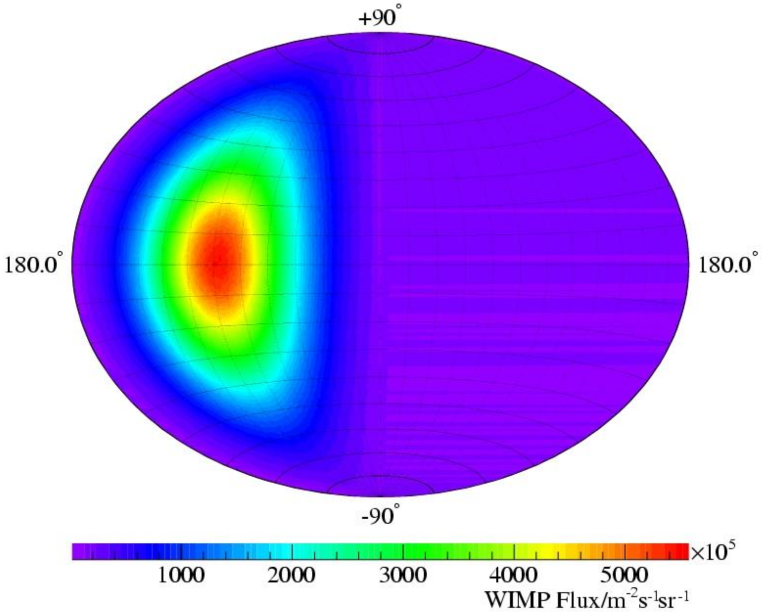


- Modulation phase can differ for different targets
- Any seasonal effects will have opposite polarity in the Southern hemisphere
- DAMA modulation has finally been ruled out with the same target material

DIRECTIONAL DETECTION

- Effective background discrimination: signal from fixed point in the sky (Cygnus)

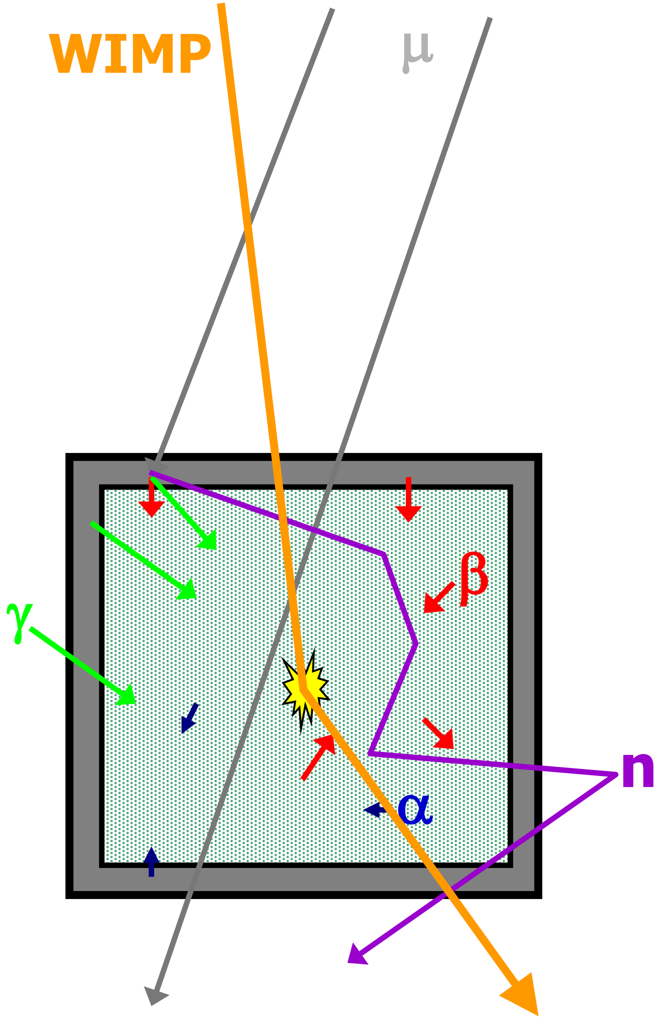




- Difficult to achieve large target masses with a gas (needed for directionality)
- Would require very large detectors – but R&D and concrete plans exist

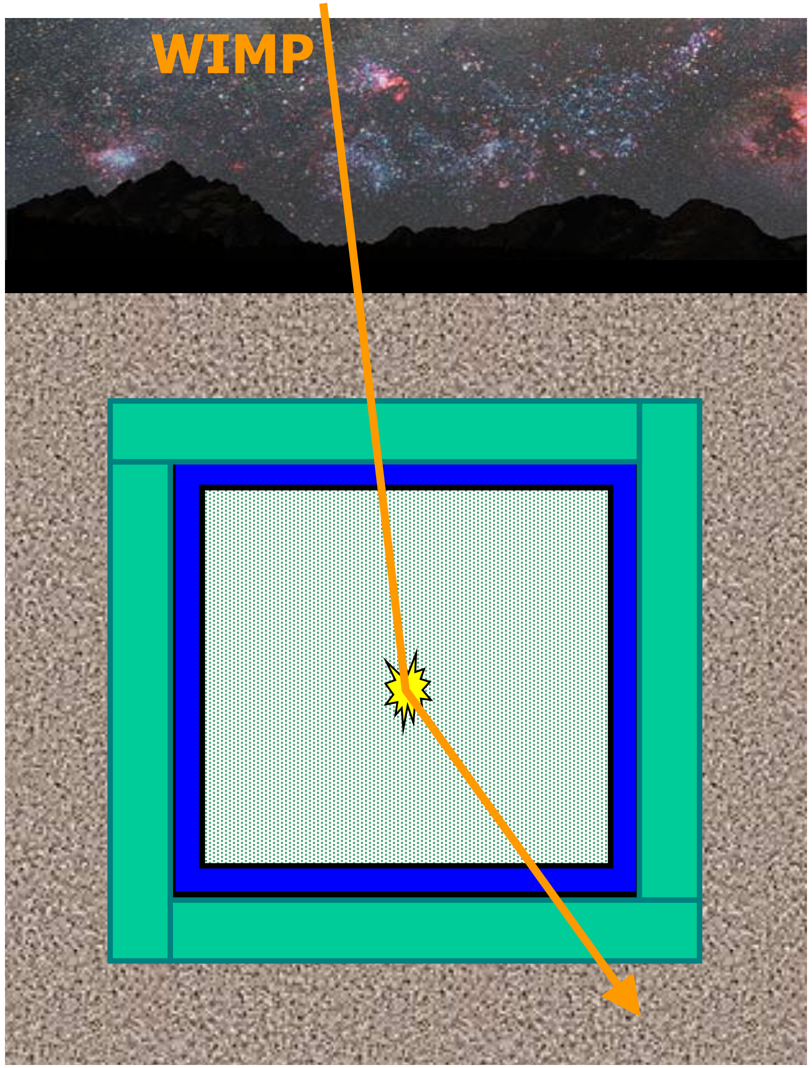
BUILDING A WIMP DETECTOR

- Consider 1 kg detector target, sensitive to very low energies
- Expected WIMP interaction rates
  - 0.001–0.000,000,001 events/day
- However…
- Radioactivity and cosmic rays
  - >1,000,000 events/day
- Neutrons are a fatal background!
  - Several events/day



BUILDING A WIMP DETECTOR

- Move deep underground
- Select radio-pure materials
- Shield against external γ-rays
- Shield against external neutrons
- ‘Veto’ internal neutrons
- Discriminate between
  ‘nuclear recoils’ and ‘electron recoils’



THE EXPERIMENTAL CHALLENGE

- Low-energy detection is easy ;)
  - Several technologies allow sub-keV NR detection
- Rare event searches are also easy ;)
  - Not a problem at >100 MeV, think neutrinos
- But doing *both* is hard!
  - Large mass gives exposure & self-shielding
  - Hard to collect signal ‘carriers’ (threshold)
- And – there is no trigger…

Key detector requirements

- Large mass x time (~tonne·yr)
- Low E_R threshold (~keV)
- Low NR background (~0 in ROI)
- ER/NR discrimination

BACKGROUNDS

- **Nuclear recoils – same signature, possibly irreducible**
  - **Neutrons from (α,n) reactions and spontaneous fission from U/Th trace contamination**
    - Local environment, shields, vessels, components, target material itself
  - **Nuclear recoils from alpha decay (e.g. radon daughter plate-out)**
    - Contaminating detector surfaces
  - **High energy neutrons from atmospheric muon spallation**
    - Difficult to shield completely even underground
  - ***Eventually, coherent neutrino-nucleus scattering***

- **Electron recoils – discrimination power is finite**
  - **Gamma-ray background external to target**
    - U/Th, K-40, Cs-137, from environment, shields, vessels, components
  - **Contamination in target bulk and detector surfaces**
    - U/Th betas and gammas (Pb-214, Bi-214, Pb-210,…)
    - Cosmogenic (Ar-39, Ge-68, Ge-71,…), anthropogenic (Kr-85, Cs-137,…)
  - ***Eventually, elastic scattering of solar pp neutrinos off electrons***

NEUTRINOS AND MORE NEUTRINOS…

- Two neutrino processes trying to spoil the party for next-generation experiments
- But these are also interesting physics signals in their own right

- **Neutrino-electron elastic scattering** $\boldsymbol{\nu + e^- \longrightarrow \nu + e^-}$
  - Solar pp neutrinos will dominate ER background in the best experiments
  - Flat-(ish) ER spectrum at low energy, can discriminate from NR
  - Interesting physics? Maybe, if we could measure this at % level or better

- **Coherent neutrino-nucleus scattering** $\boldsymbol{\nu + A \longrightarrow \nu + A}$
  - Several neutrino fluxes produce very low energy NR events which eventually will limit us
  - Single scatters, uniformly distributed, recoil spectrum looks like WIMPs
  - Interesting physics? Yes.

CEνNS OBSERVED IN 2017!

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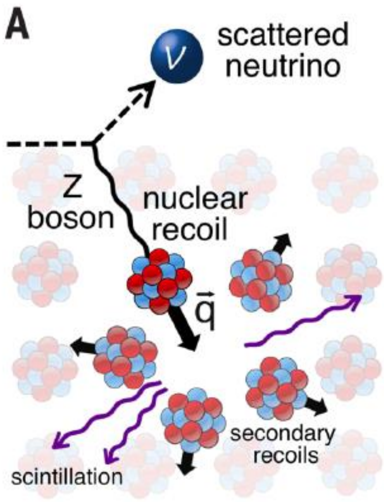
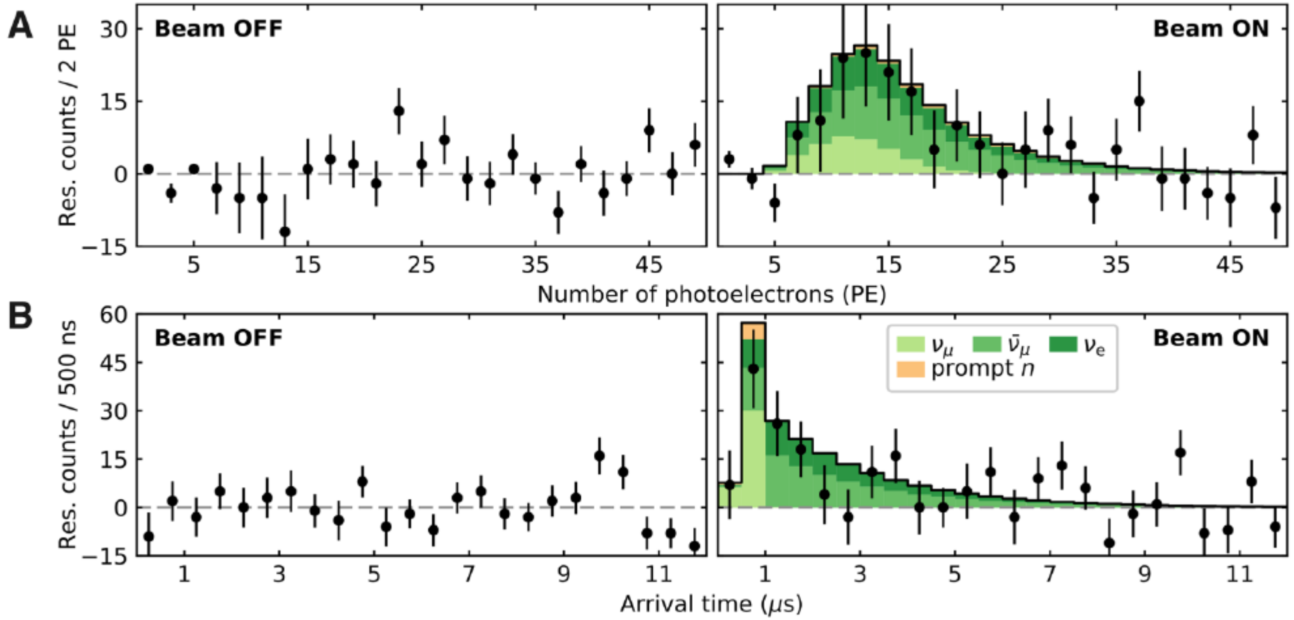
10.1126/science.aao0990 (2017).



Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9*] R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13†] D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9‡] W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9§] M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3||] S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13¶] S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#



Coherence condition $qR \lesssim 1$

Translates to $E_\nu \lesssim 50\ \mathrm{MeV}$

$$T_{\max} = \frac{2E_\nu^2}{M + 2E_\nu}$$ ~ keV

WIMP SEARCH TECHNOLOGY ZOO

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, CDEX, D3, DAMIC, DRIFT, DM-TPC, GENIUS, IGEX, MIMAC, NEWAGE, NEWS, TREX

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, Argo, LUX, WARP, DarkSide, DARWIN, Panda-X, XENON, ZEPLIN, LZ

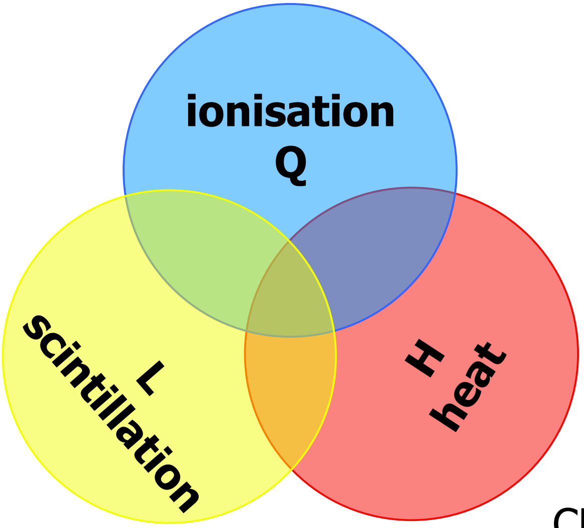
cold (LN_2)

Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, EDELWEISS, SuperCDMS

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, MiniCLEAN, DAMA, ZEPLIN-I, DEAP-3600, DM-ICE, KIMS, LIBRA, PICOLON, NAIAD, SABRE, XMASS

Bolometers

Targets: Ge, Si, Al_2O_3, TeO_2

CRESST-I, CUORE, CUORICINO

Light & Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3

CRESST, ROSEBUD

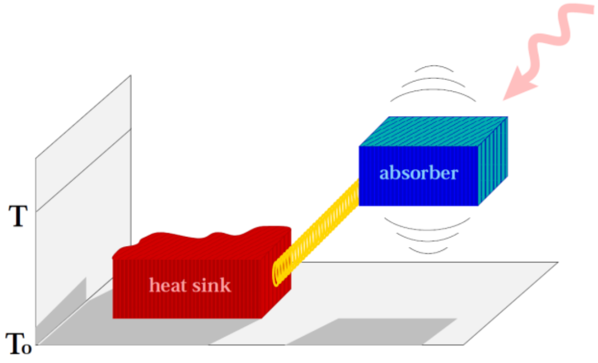
cryogenic (<50 mK)

Bubbles & Droplets

CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, PICO, SIMPLE

CRYOGENIC DETECTORS



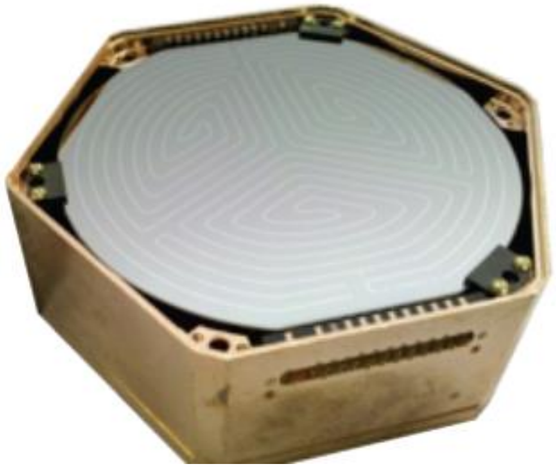
T_0~10-50 mK

$$\Delta T_{max} = \frac{E}{C}$$

Thermal signal lost with increasing mass:
ideally, collect phonons *before* they thermalise

EDELWEISS DETECTORS

S-CDMS DETECTORS



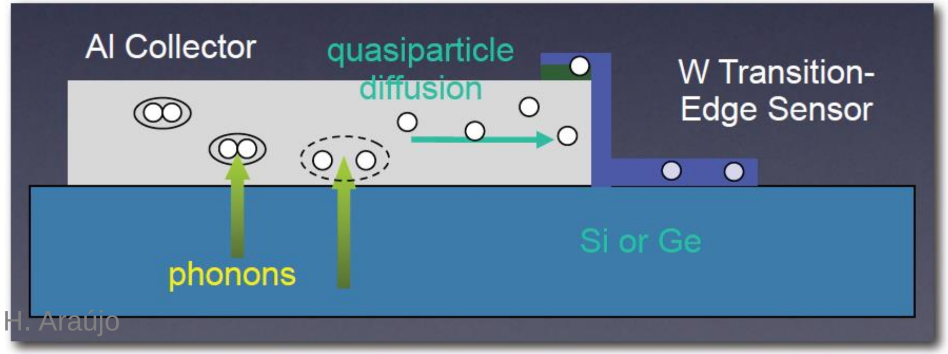
Phonon channel: ~keV threshold, no quenching

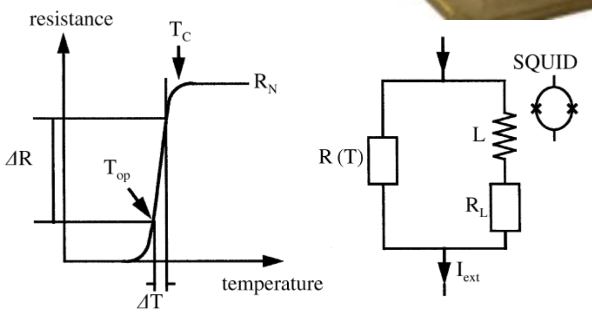
Can collect a second signature for discrimination:

- Phonons + ionisation (e.g. CDMS, EDELWEISS)
- Phonons + scintillation (e.g. CRESST)

CRESST DETECTORS

Superconducting Transition-Edge Sensor (CDMS)





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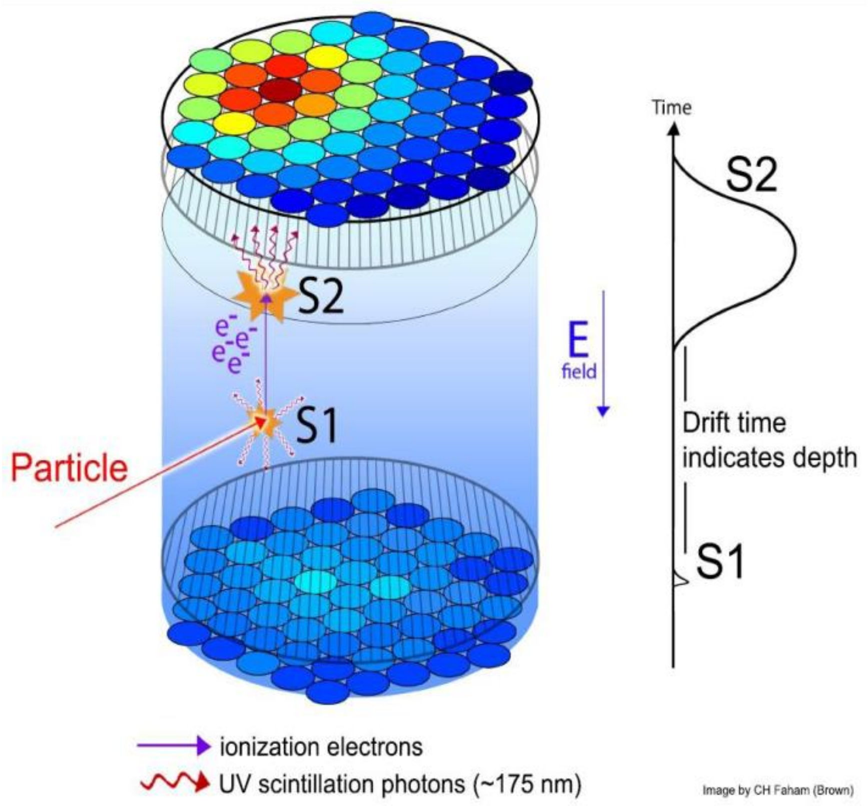
TWO-PHASE XENON DETECTORS



S1: prompt scintillation signal

- High scintillation yield: ~60 ph/keV (ER, 0 field)
- Scintillation light: 175 nm (VUV)
- **Nuclear recoil threshold ~few keV**

S2: delayed ionisation signal

- Electroluminescence in vapour phase
- Sensitive to single ionisation electrons
- **Nuclear recoil threshold <1 keV**

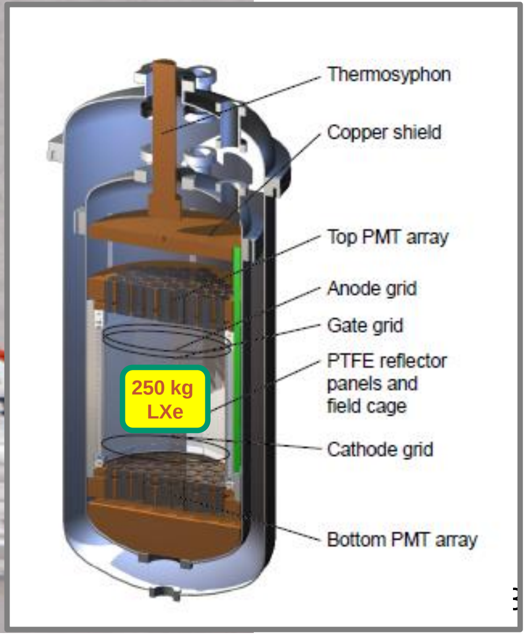
S1+S2 event by event

- ER/NR discrimination (~99.9% rejection)
- mm resolution + high density: *self-shielding* of external backgrounds

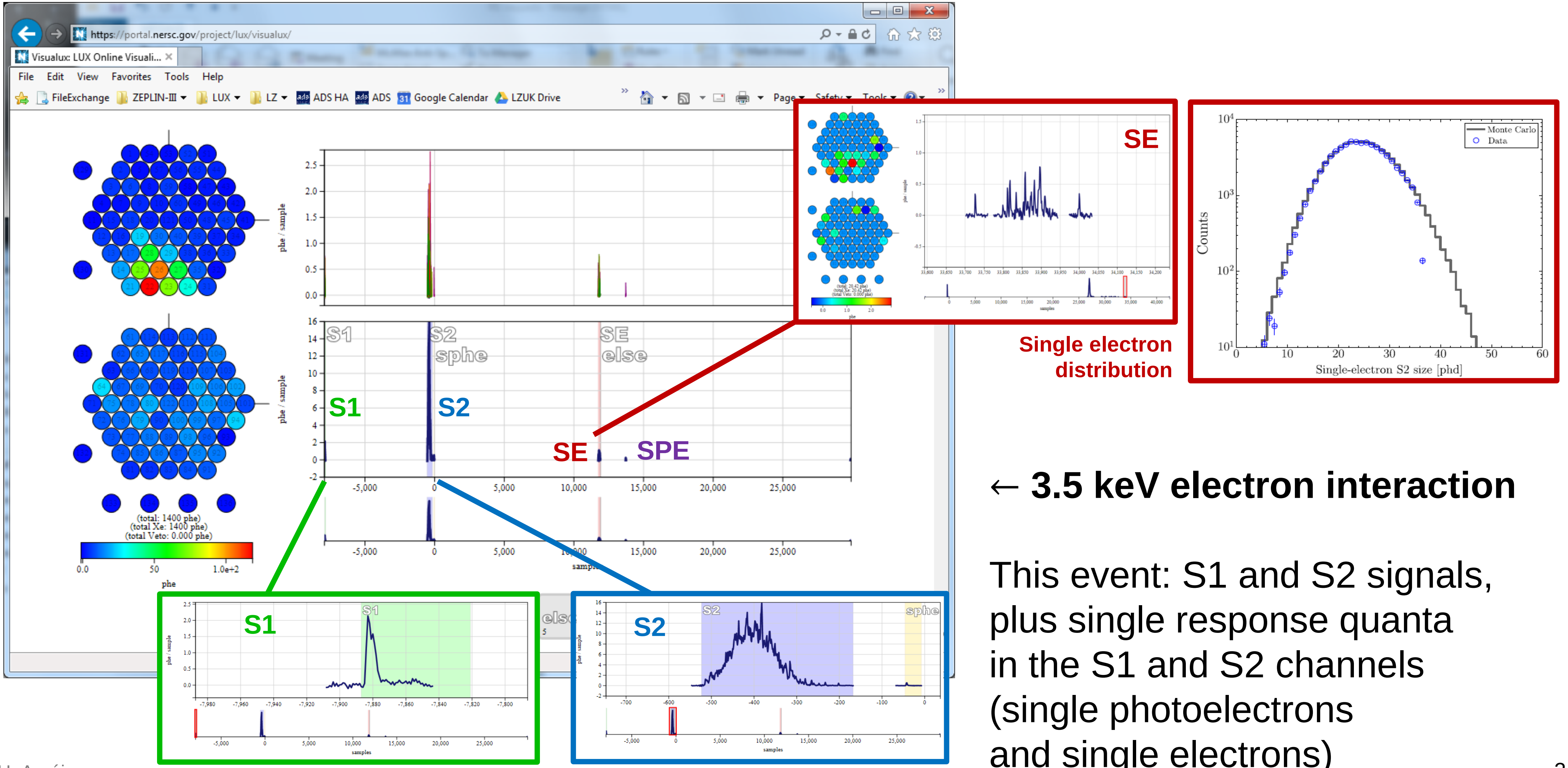
Liquid xenon nucleus as a WIMP target

- SI sensitivity benefits from large A^2 enhancement; broad mass coverage $\gtrsim$5 GeV
- Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable SD sensitivity (~1/2 of natural abundance)

LARGE UNDERGROUND XENON EXPERIMENT



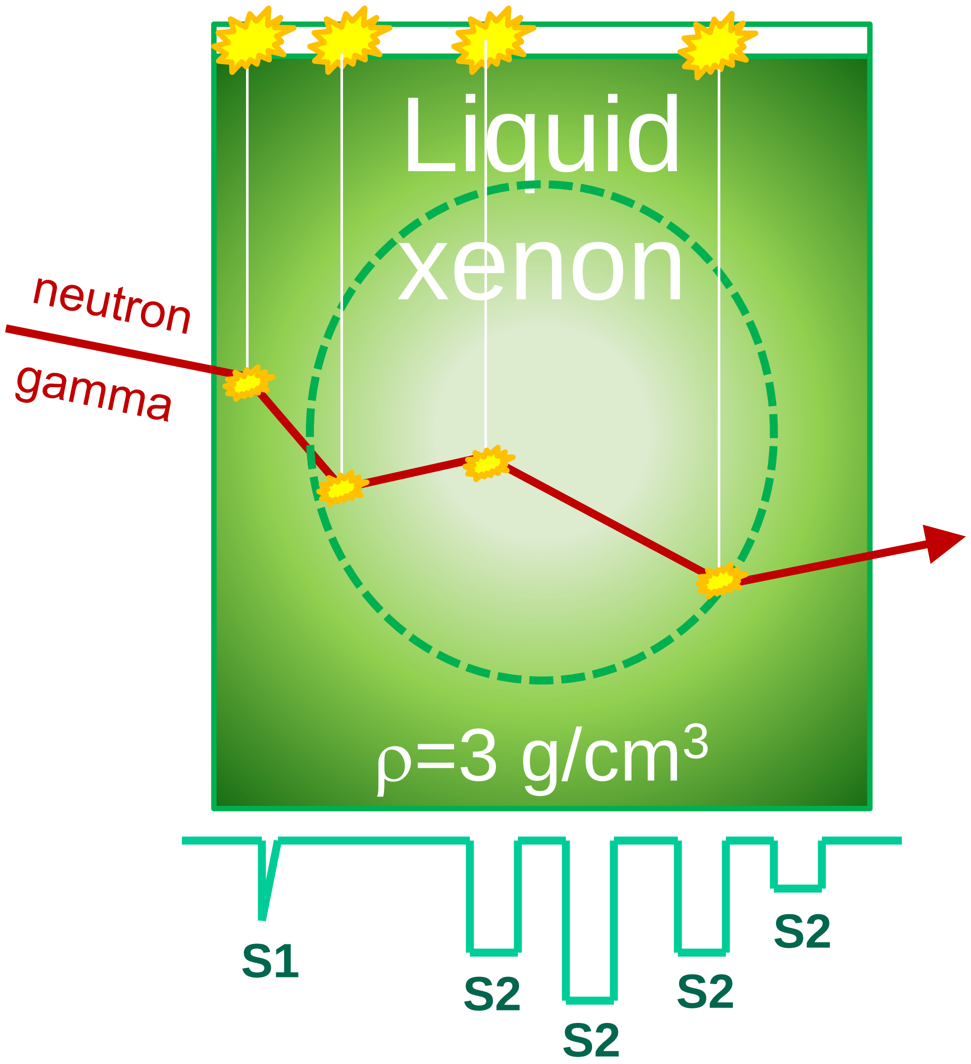
LOW-ENERGY SIGNALS

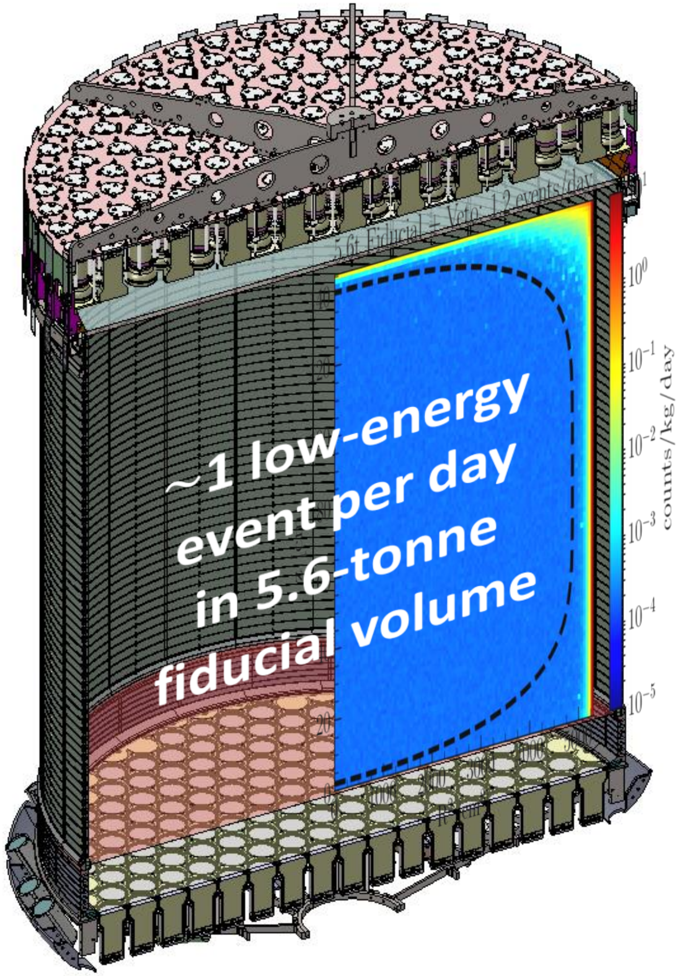


← 3.5 keV electron interaction

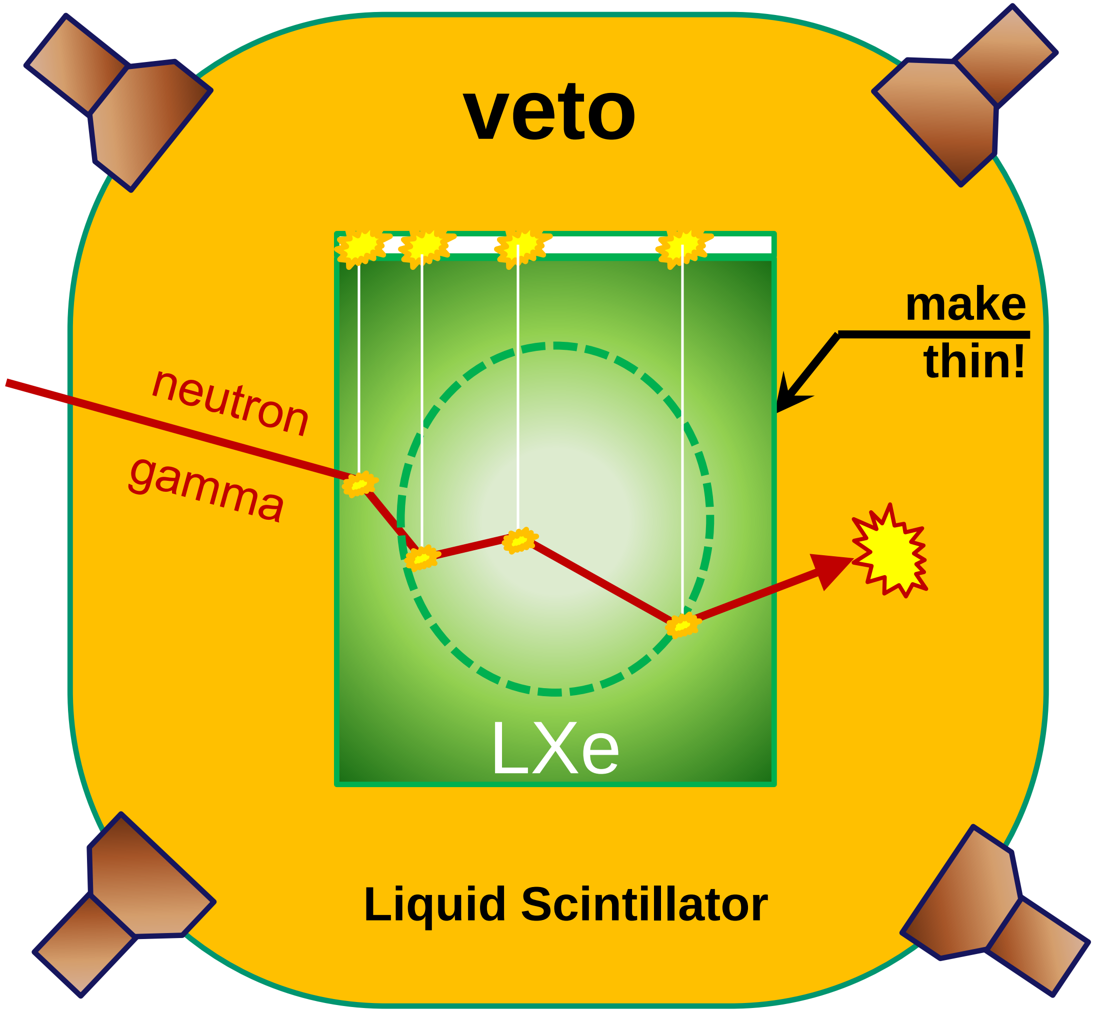
This event: S1 and S2 signals, plus single response quanta in the S1 and S2 channels (single photoelectrons and single electrons)

SELF-SHIELDING IN NOBLE LIQUIDS





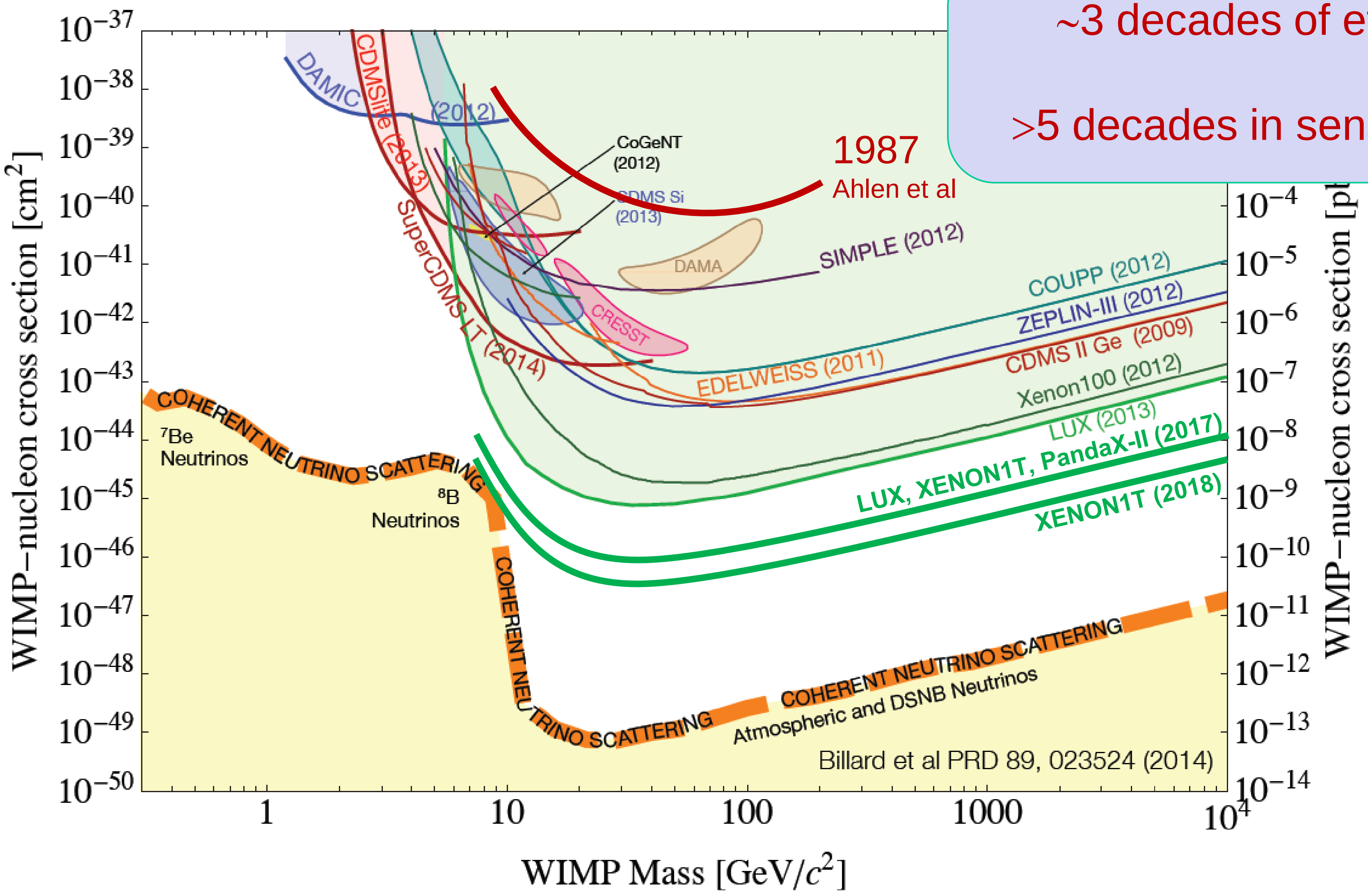
ANTICOINCIDENCE DETECTOR AROUND TARGET



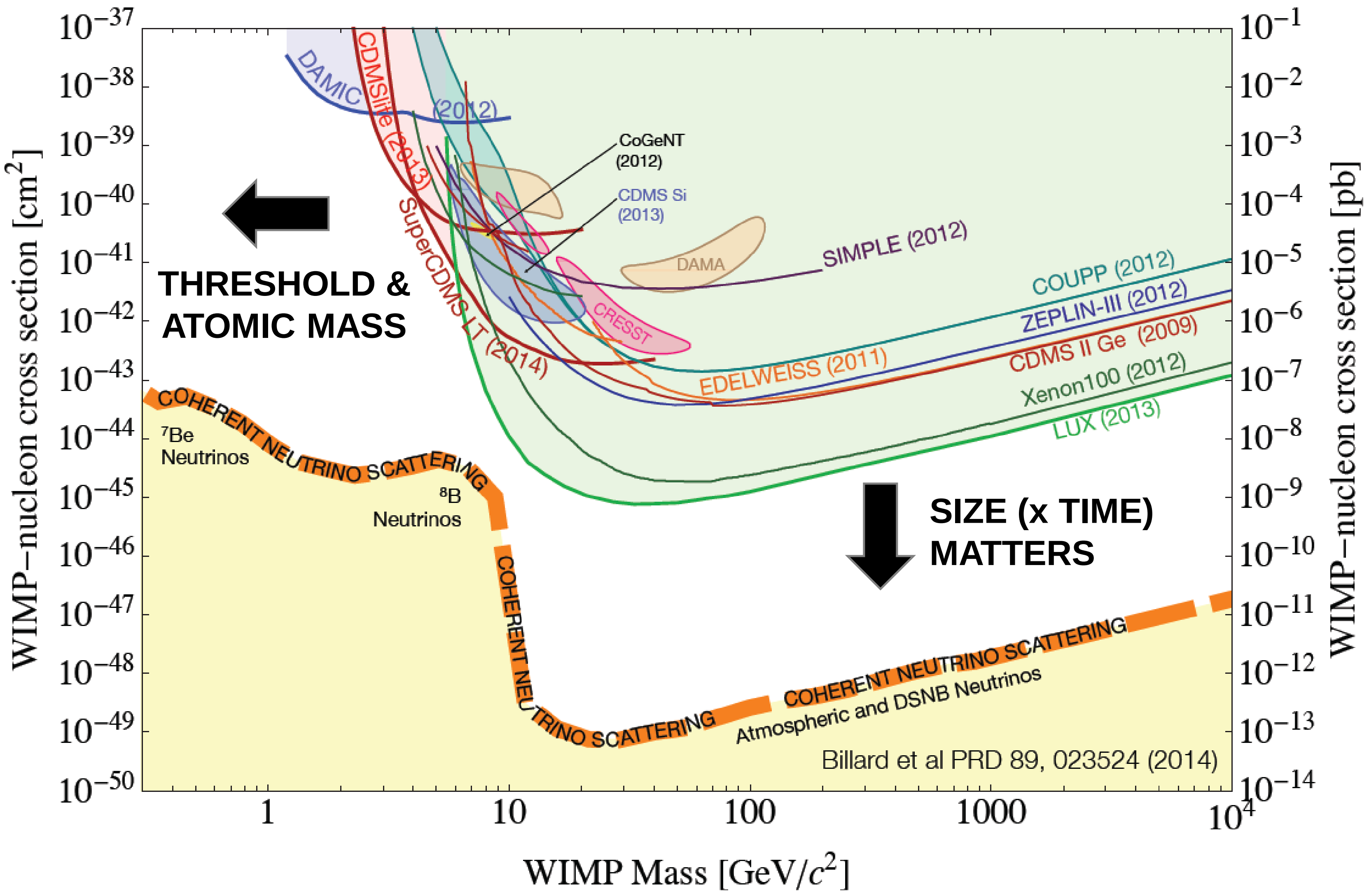
PRESENT STATUS

~3 decades of effort

>5 decades in sensitivity

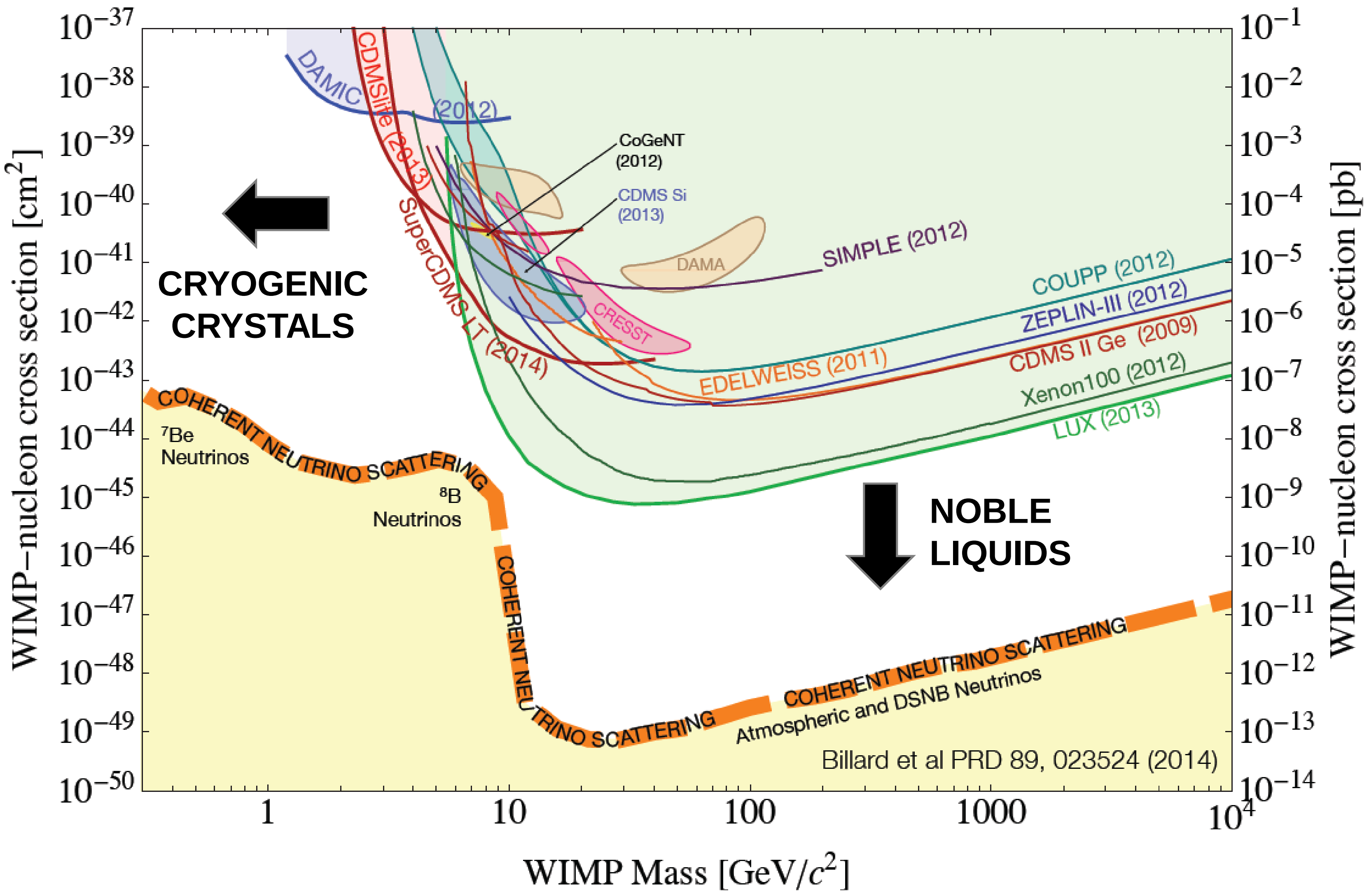


TRENDS



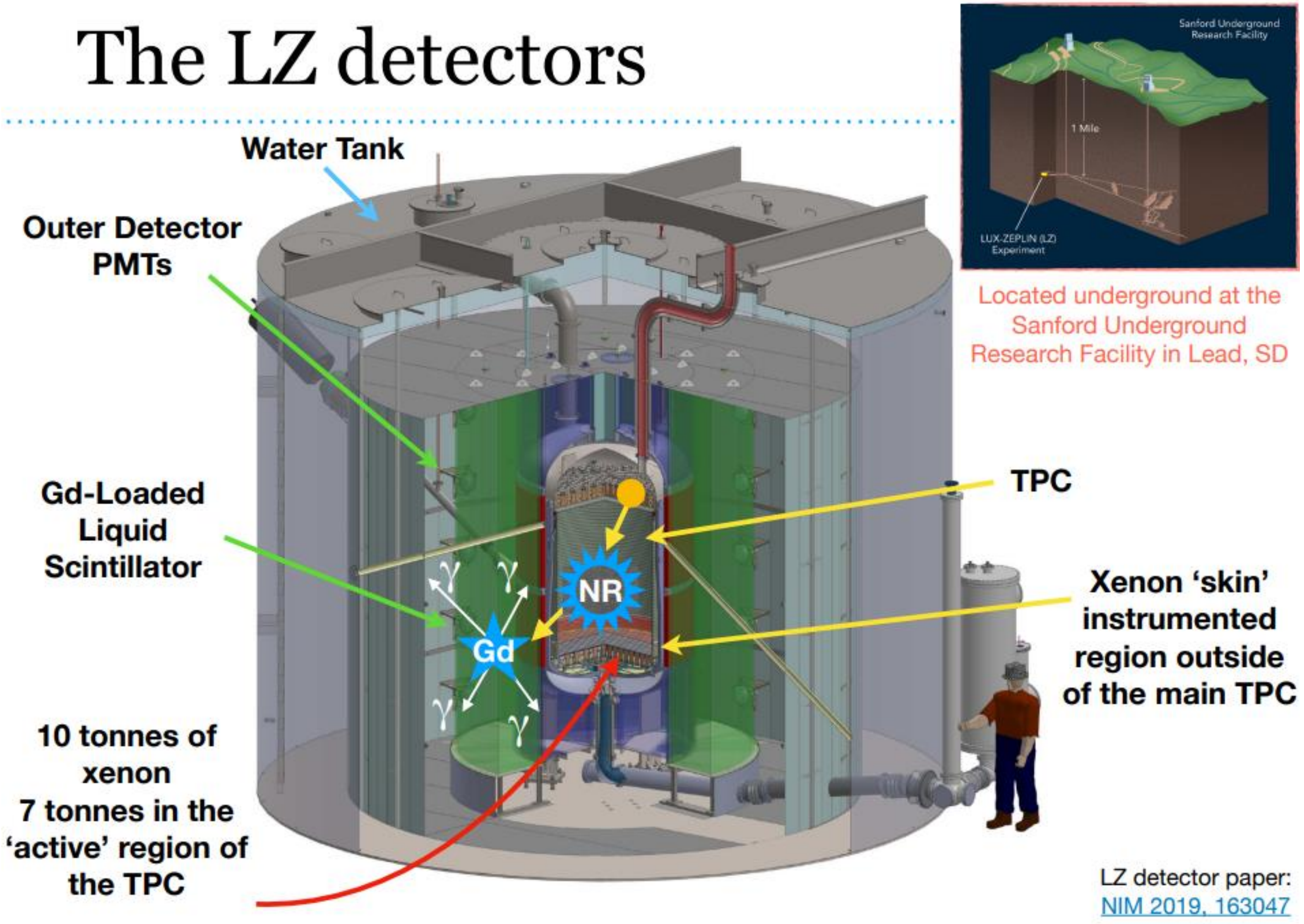
THRESHOLD & ATOMIC MASS
SIZE (x TIME) MATTERS
WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
DAMIC (2012)
CDMSlite (2013)
SuperCDMS LT (2014)
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
COHERENT NEUTRINO SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
Atmospheric and DSNB Neutrinos
Billard et al PRD 89, 023524 (2014)

TRENDS

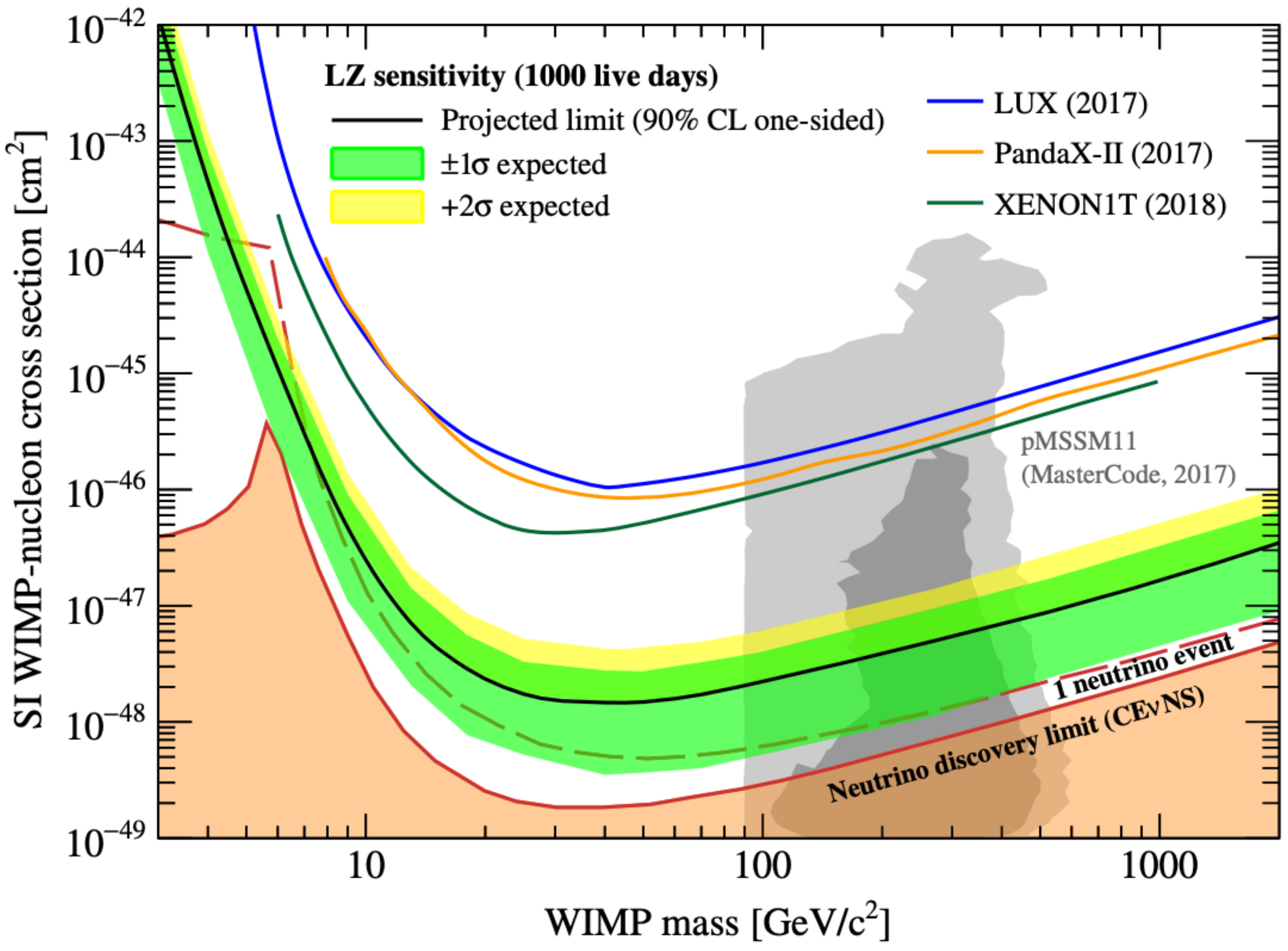


WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
CRYOGENIC CRYSTALS
NOBLE LIQUIDS
DAMIC
CDMSlite (2013)
SuperCDMS LT (2014)
(2012)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
Billard et al PRD 89, 023524 (2014)

LUX-ZEPLIN (LZ) – COMING SOON TO A MINE NEAR YOU



LUX-ZEPLIN (LZ) – COMING SOON TO A MINE NEAR YOU



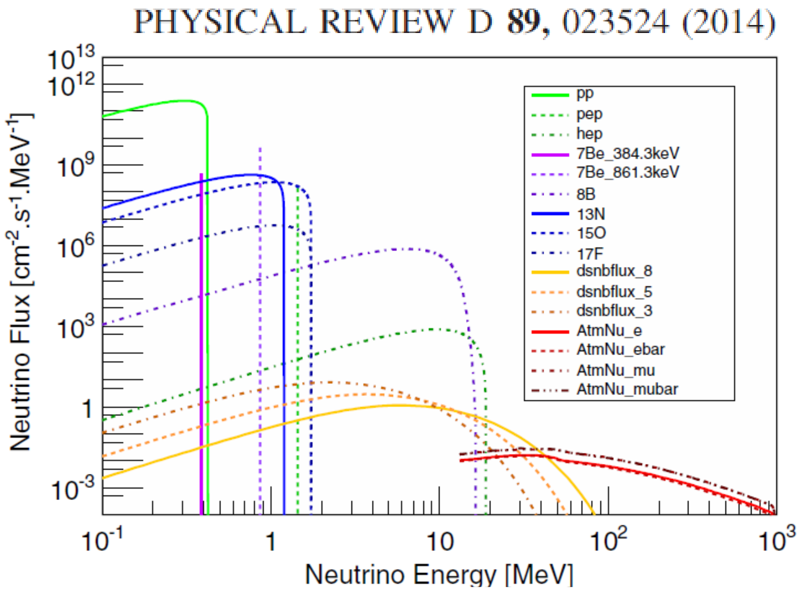
TODAY'S CONCLUSIONS

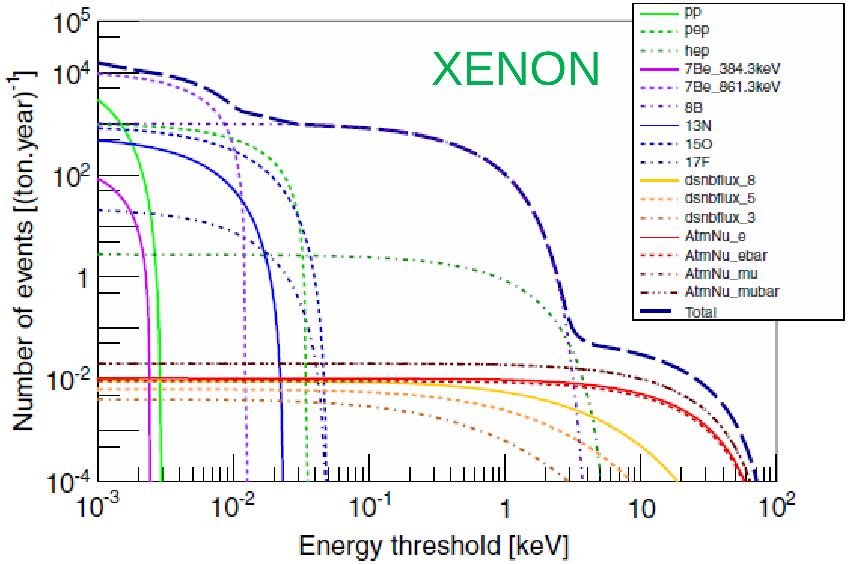
- Direct dark matter searches mostly involve ultra-low background experiments with very low energy thresholds operating deep underground
- The experimental challenge: searching for rare signals at low energies is hard
- Many instrumental and environmental backgrounds need to be controlled, leaving ultimately "physics backgrounds" from neutrino interactions
- Many experiments and technologies are searching for DM all around the world. Multi-tonne noble liquid detectors approaching neutrino floor in the next decade

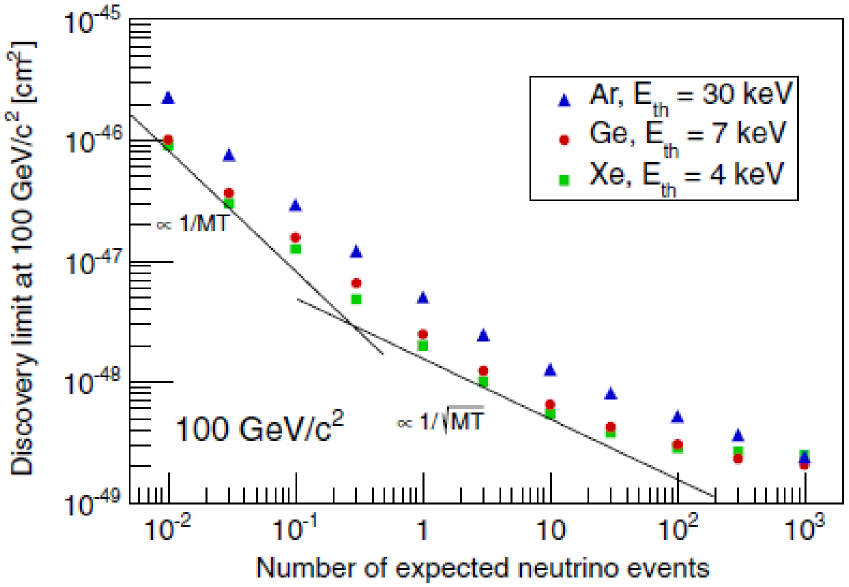
- *Exercise class this afternoon: how to work from a scattering rate observed in a detector target through to a WIMP-nucleon cross section result*
- *Read ahead from Lewin & Smith if not possible*

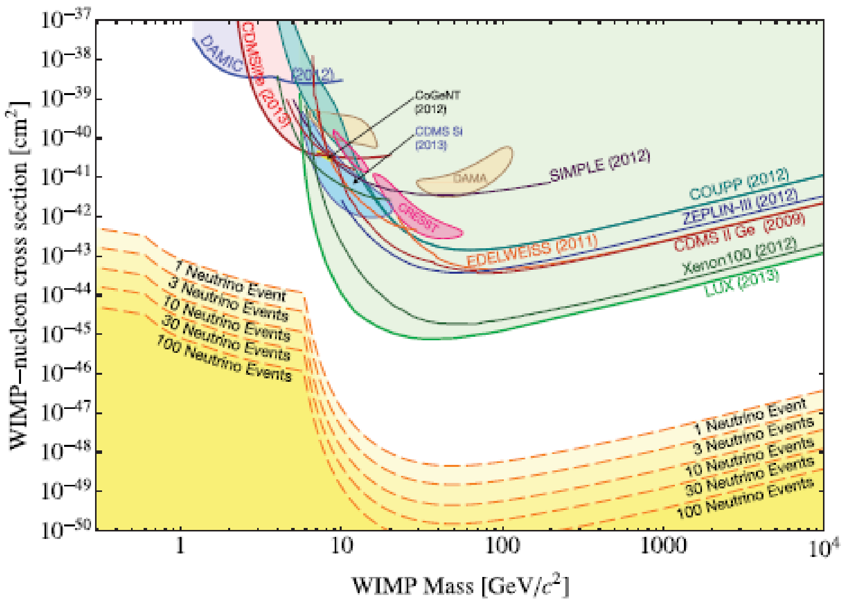
BACKUP SLIDES

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING









COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING