Imperial College London

MINING FOR WIMPS

DIRECT SEARCHES FOR DARK MATTER UNDERGROUND

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Outline

1. **The dark matter problem**
   – A dark universe
   – Galactic dark matter
   – Weakly Interacting Massive Particles

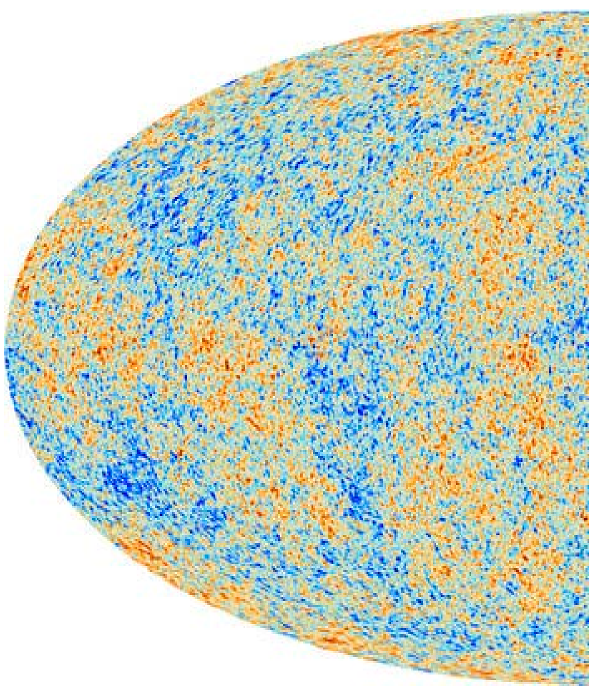
2. **How to catch a WIMP**
   – The experimental challenge
   – Direct detection technologies
   – World Status

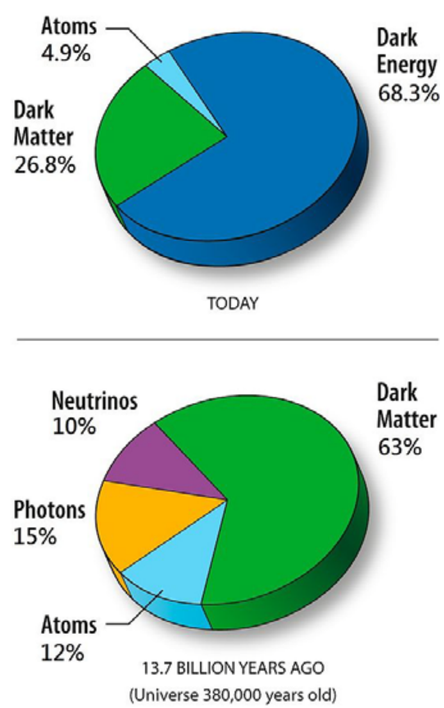
3. **Signal estimation**
   – "Counts in boxes"
   – Maximum Likelihood analysis

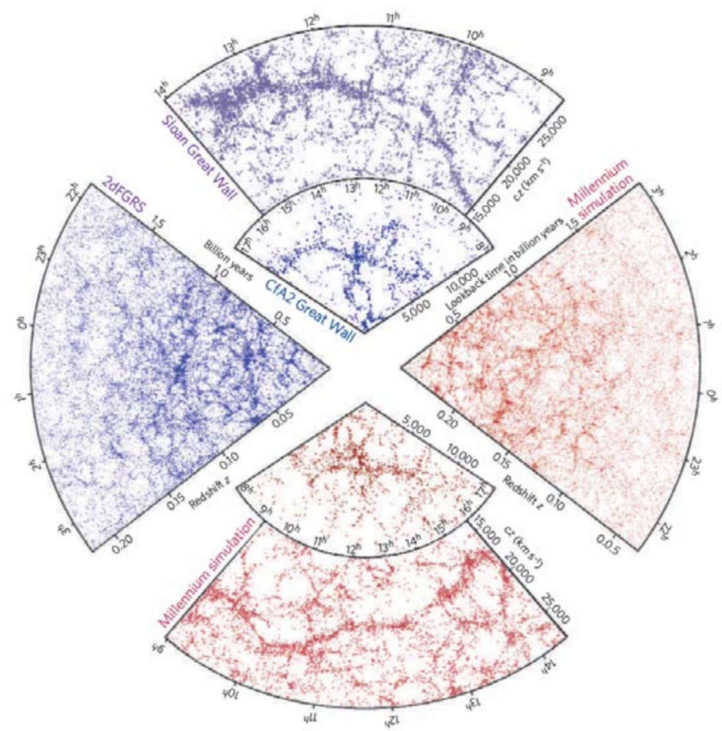
Motivation →

1、 A DARK UNIVERSE

- Λ-CDM cosmology is a remarkably successful model
- Initial conditions photographed at last scatters (CMB)
- Left to evolve for 13.7 Gyr under two dark ‘fluids’ – DE and DM
- To what we see today

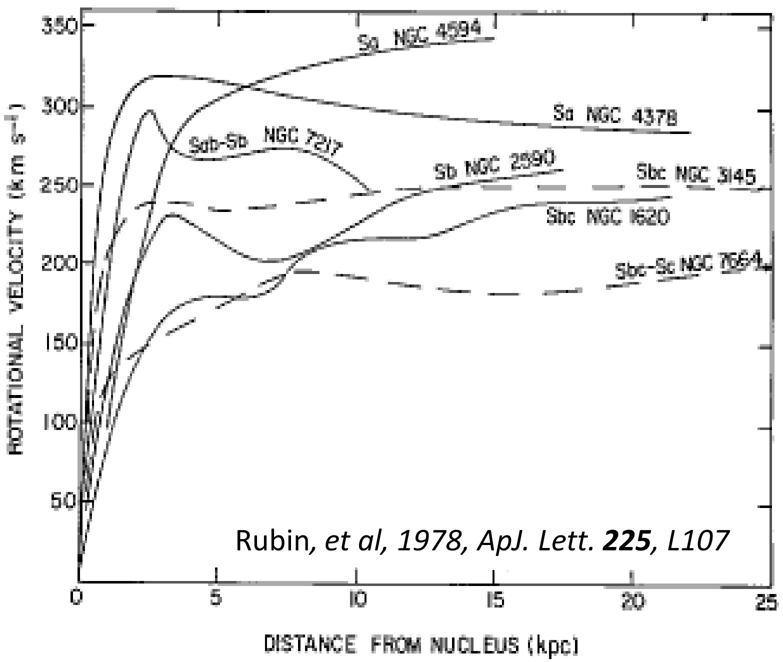




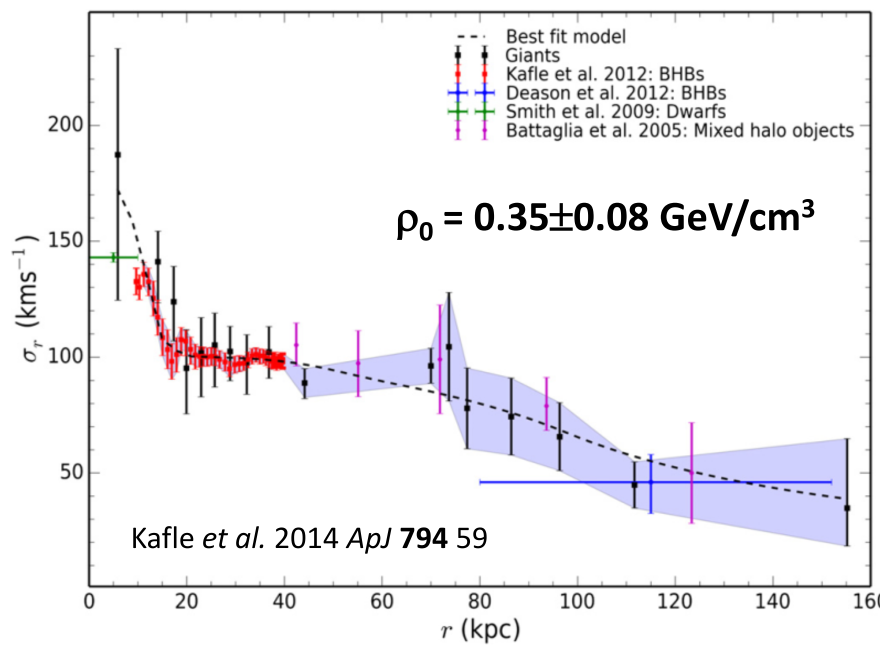


OUR DARK MILKY WAY

- Spiral galaxies 'spin' too quickly for observed 'luminous' mass
- Our Milky Way is no exception: we are immersed in DM halo
- Direct search experiments probe our galactic dark matter
- Density near Sun ~0.3 GeV/cm^3



Rubin, *et al, 1978, ApJ. Lett.* ***225****, L107*



Kafle *et al.* 2014 *ApJ* **794** 59

DARK MATTER CANDIDATES

- **WIMPs**

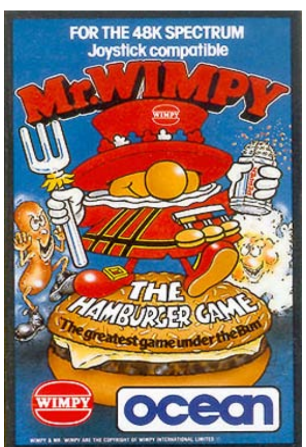
  Solve DM problem

  Electroweak stabilisation

- **Axions**

  Solve DM problem

  Strong CP problem

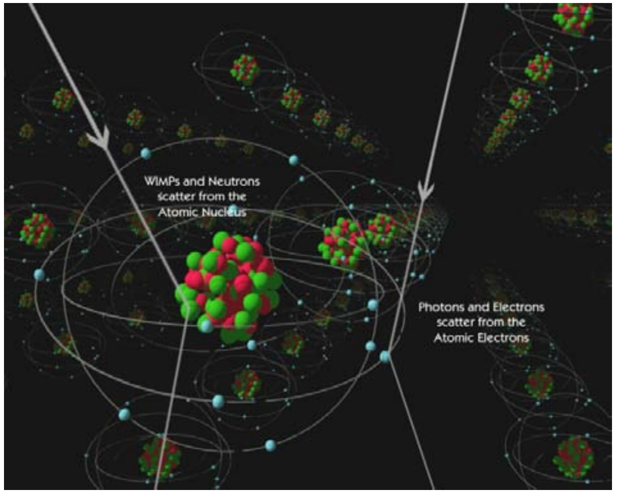


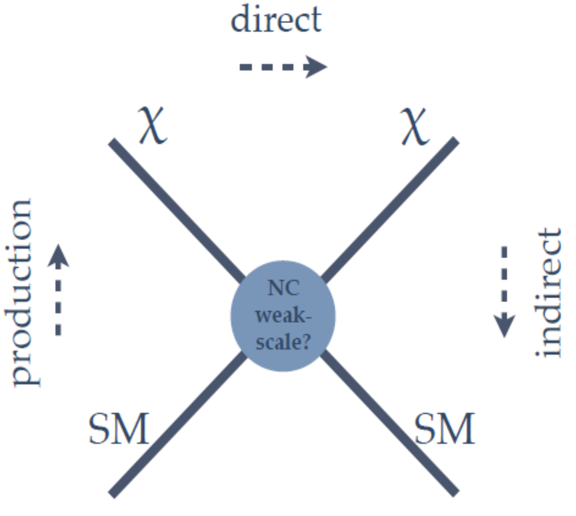
- Focus on WIMPs: stable, neutral, cold, heavy particles, interacting via gravity – and (by definition) the weak force
- Can solve the DM problem in all its glory: astrophysical, cosmological and particle physics
- Λ-CDM was made for WIMPs; but there are puzzles too: e.g. why is their present density similar to that of baryons?

2. HOW TO CATCH A WIMP

1. Direct detection (scattering XS)

- **Nuclear (atomic) recoils from elastic scattering**
- A- & J-dependence, annual modulation, directionality
- Galactic DM at the Sun's position – our DM!
- Mass measurement (if not too heavy)





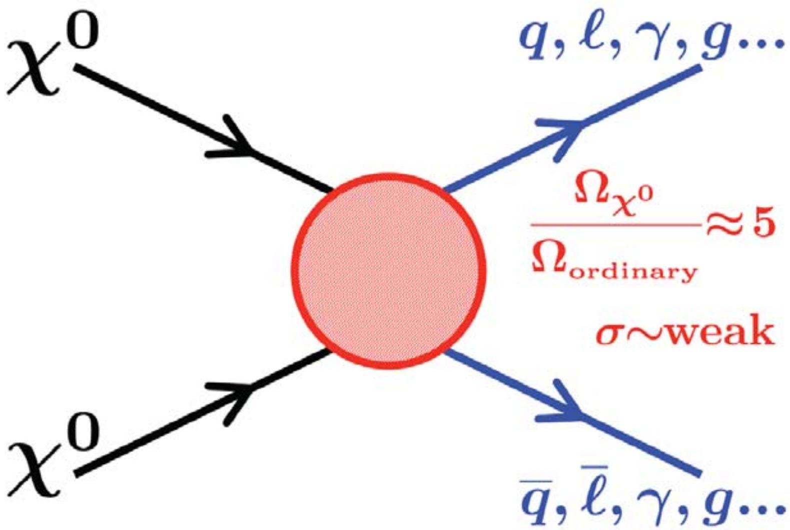
2. Indirect detection (decay, annihilation XS)

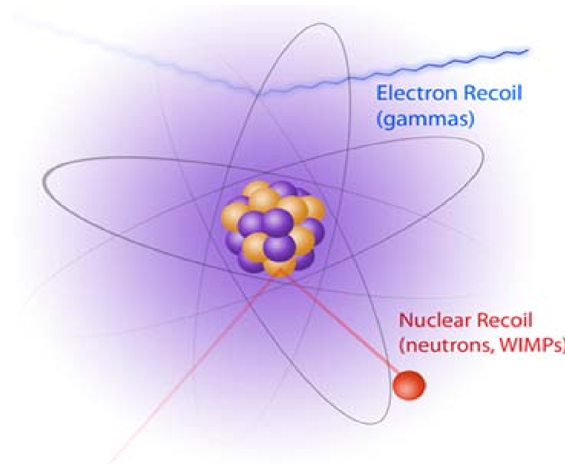
- High-energy cosmic-rays, γ-rays, neutrinos, etc.
- Over-dense regions, annihilation signal $\propto n^2$
- Very challenging backgrounds

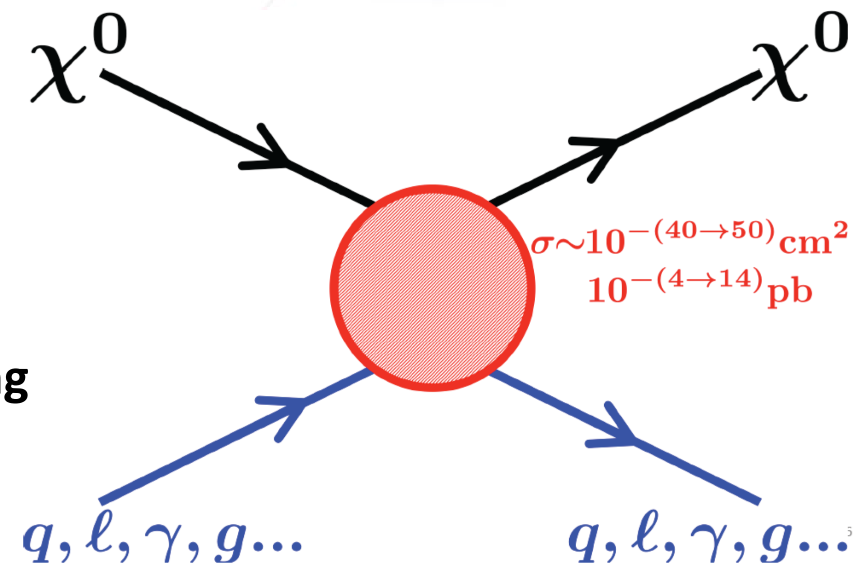
3. Accelerator searches (production XS)

- MET, mono-X, dark photons, etc.
- Mass measurement may be poor at least initially
- May not establish that new particle is the DM

WEAKLY INTERACTING MASSIVE PARTICLES







Main observable:
Very low-energy nuclear recoils (NR)
From elastic WIMP-nucleus scattering
Spin-independent XS ~ A^2
Spin-dependent XS ~ J

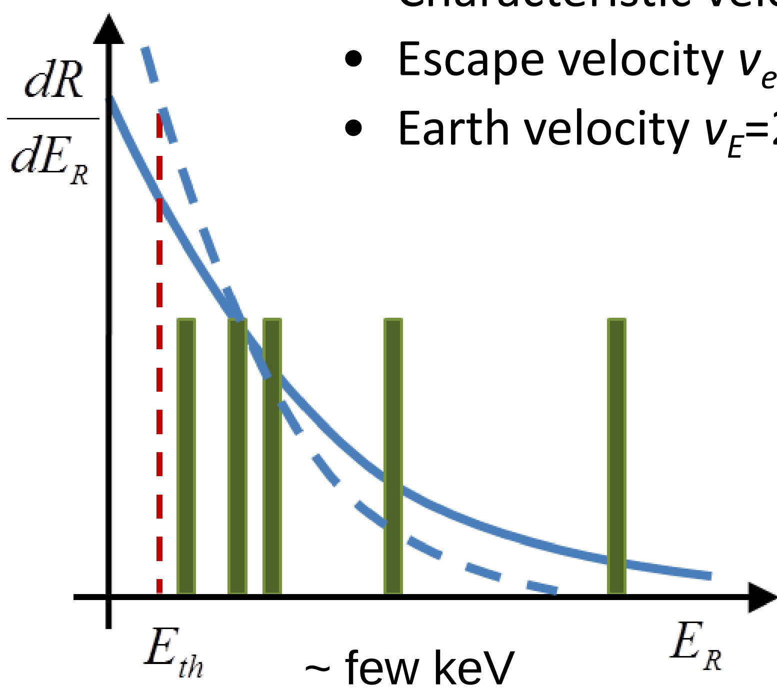
WIMP-NUCLE<u>US</u> ELASTIC SCATTERING RATES

The ‘spherical cow’ galactic model

- DM halo is 3-dimensional, stationary, with no lumps
- Isothermal sphere with density profile $\rho \propto r^{-2}$
- Local density $\rho_0 \sim 0.3$ GeV/cm^3 (~1/pint for 100 GeV WIMPs)

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]

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

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

WIMP-NUCLEON ELASTIC SCATTERING XS

- **Coupling to p and n more useful than coupling to nucleus**
  - Compare different targets materials, accelerator & 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 factor (coherence) – c/pMSSM within reach

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

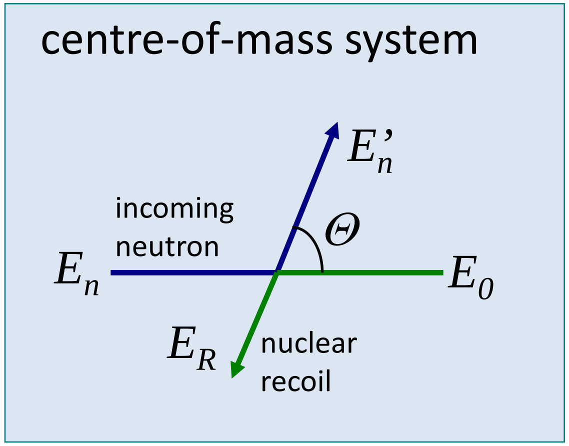
$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$

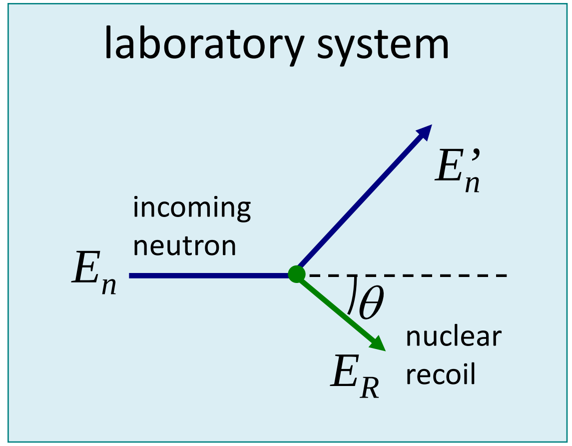
  – Note J (nuclear spin) replaces A^2 enhancement – less sensitive than SI

  – Some targets more sensitive to proton, others to neutron scattering

– **Non-Relativistic Effective Theory: WIMP-nucleon XS has 6 components**
(cf. Fitzpatrick, Haxton, Anand, et al: 1203.3542, 1405.6690)

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)

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

In general, for a projectile with mass m_W and kinetic energy E_W

$$E_R = \frac{2Am_W}{(A+m_W)^2}\left(1-\cos\Theta\right)E_W; \text{ defining } r = \frac{4Am_W}{(A+m_W)^2} \rightarrow E_{R,\max} = rE_W$$

Nuclear Recoils in WIMP Detectors

- Kinematic factor peaks (*r=1*) for equal masses
  - In this case, the projectile transfers all its energy for head-on collisions
  - Heavier nuclei for heavier WIMPs, lighter nuclei for lighter WIMPs
  - And hydrogenated materials are best to moderate neutrons
- Calibration of WIMP targets
  - For 100 GeV WIMPs, a Xe target is well calibrated by MeV neutrons
  - Sources: AmBe and YBe (α,n), Cf-252 fission, D-D generators
  - Signal and calibration <u>maximum</u> energies:

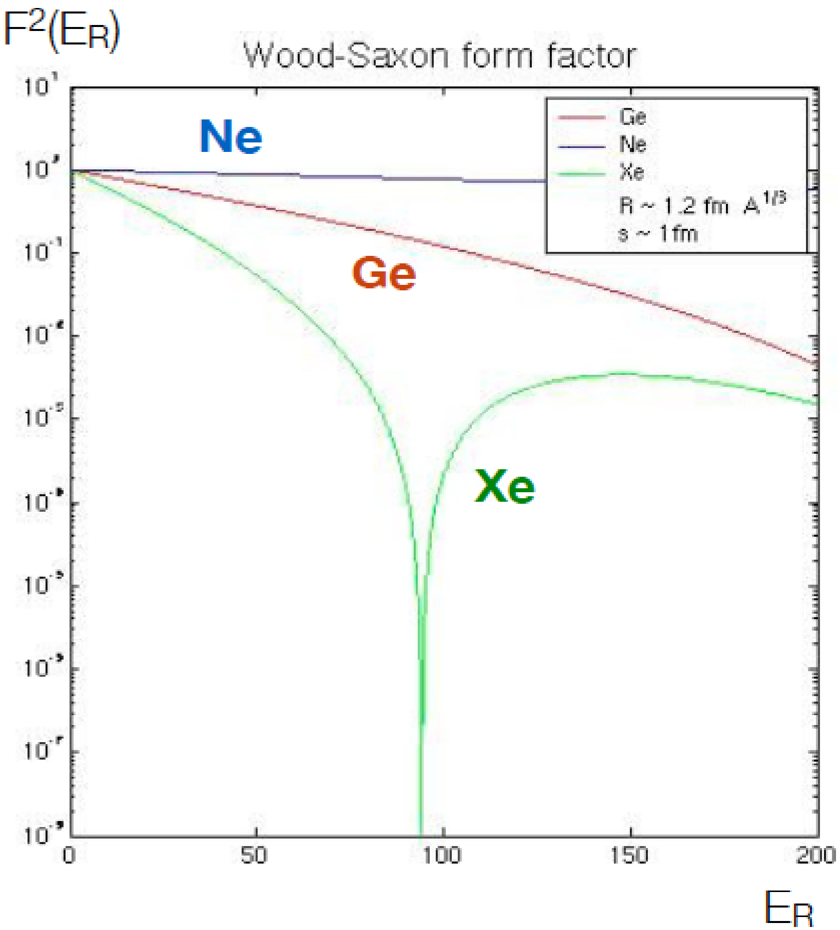
$$E_{R,\max} = r\,E_W = \sim E_W \quad (\mathrm{m}_W = 100\,\mathrm{GeV})$$

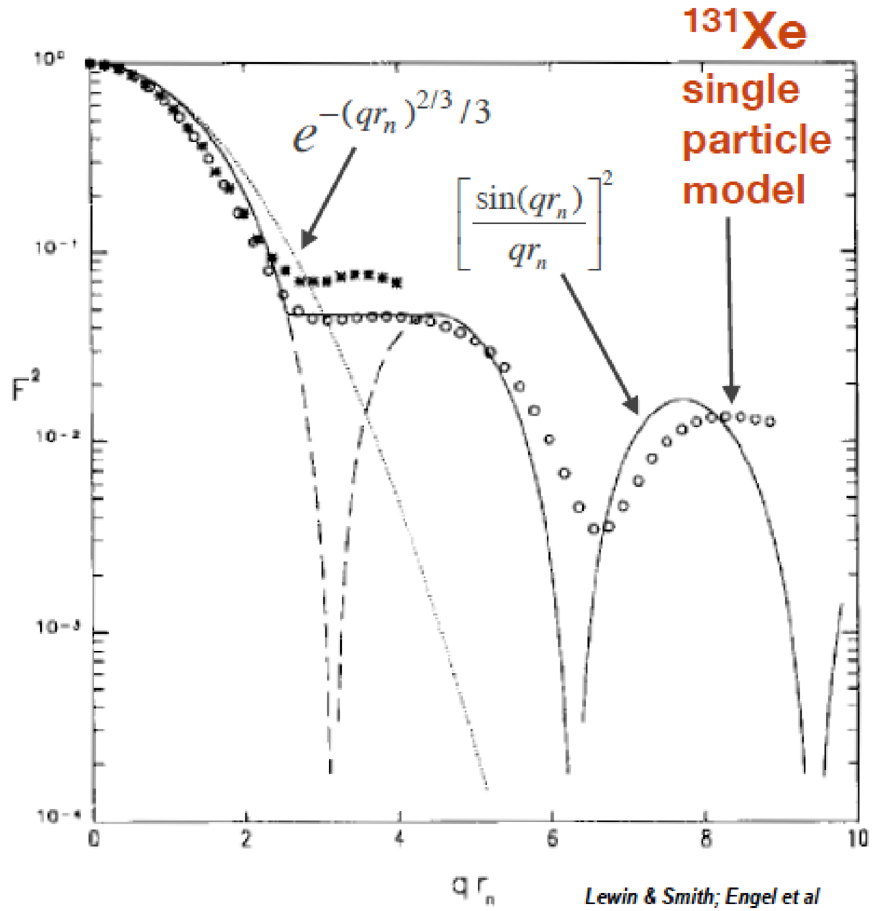
220 km/s WIMP → $E_{R,max}$ = 30 keV

$$E_{R,\max} = \frac{4A}{(A+1)^2}\,E_n = 0.03\,E_n \quad (\mathrm{n} \to \mathrm{Xe})$$

1 MeV neutron → $E_{R,max}$ = 30 keV

Nuclear Form Factor, $F^2(q)$

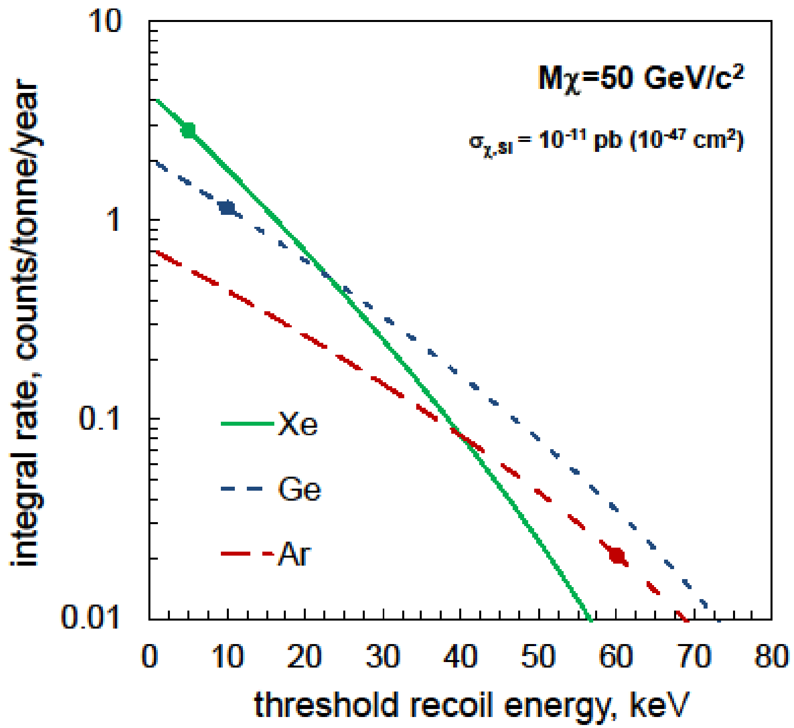


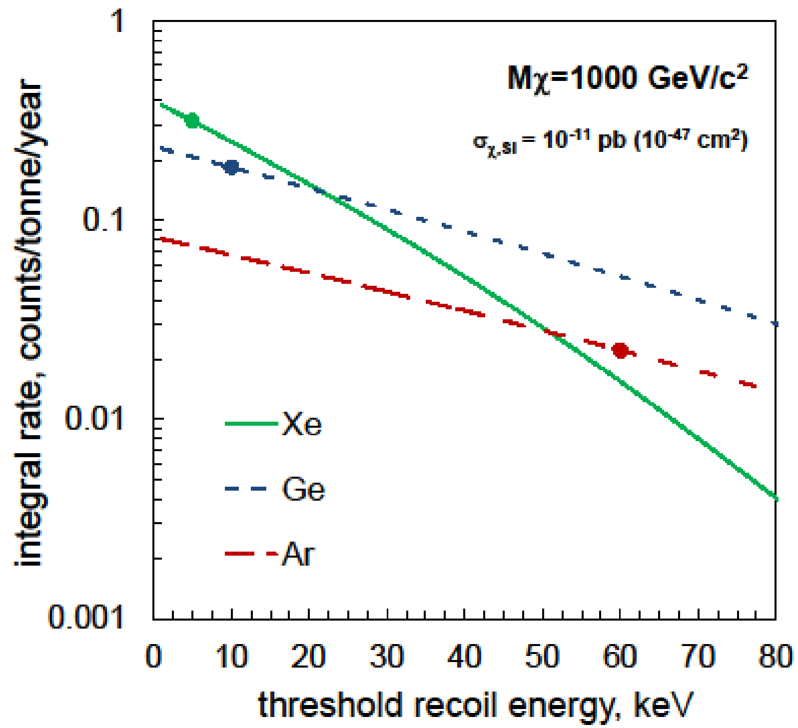


Lewin & Smith; Engel et al

$$E_R = \frac{q^2}{2m_\chi}$$

SI scattering rates



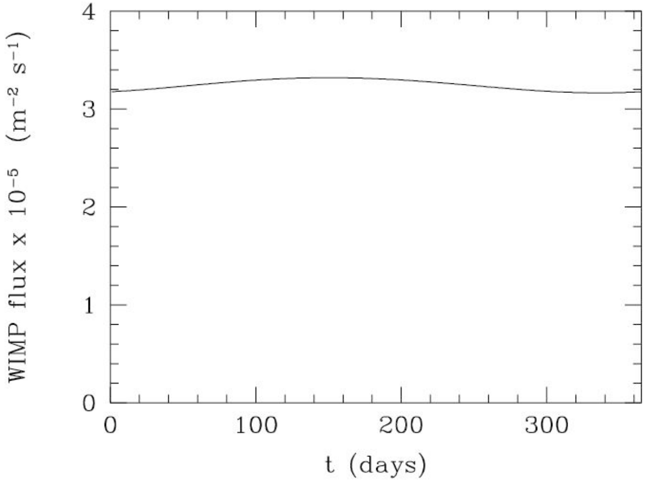


Annual Modulation

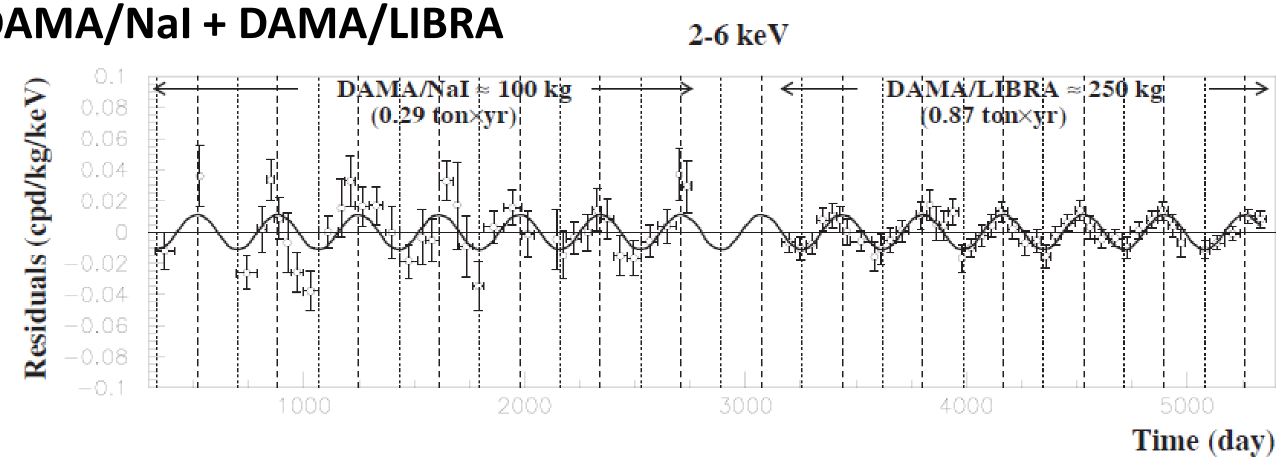
Galactic rotation through stationary halo:

"The Earth bathes in a WIMP wind"

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{4 v_e m_\chi m_r^2} F^2(Q) \left[\mathrm{erf}\left(\frac{v_{min} + v_e}{v_0} \right) - \mathrm{erf}\left(\frac{v_{min} - v_e}{v_0} \right) \right].$$



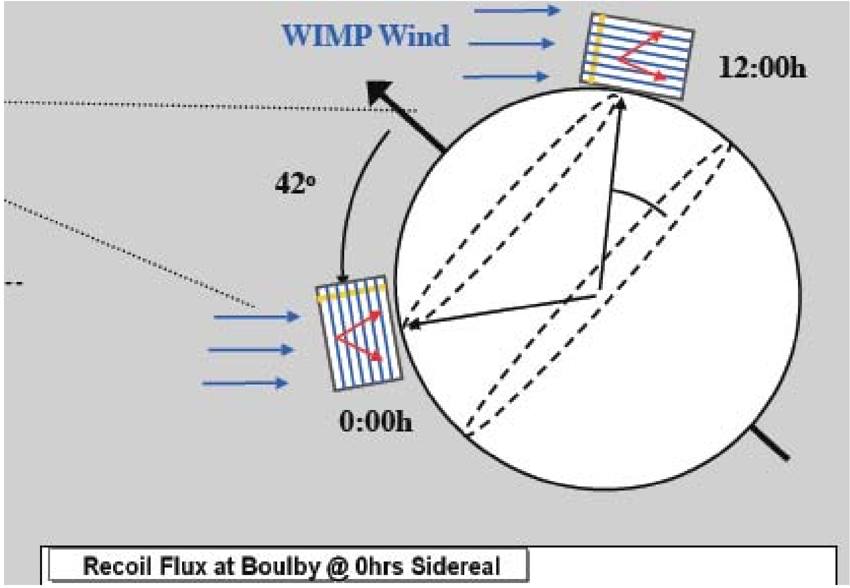
DAMA/NaI + DAMA/LIBRA



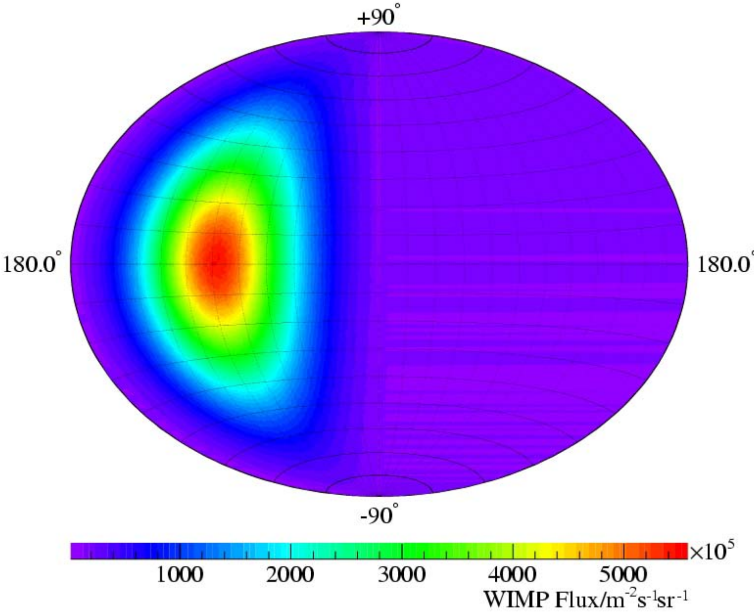
9σ effect

- Any seasonal effects will have opposite polarity in Southern hemisphere
- Difficulty: many things modulate seasonally....

Directional Detection



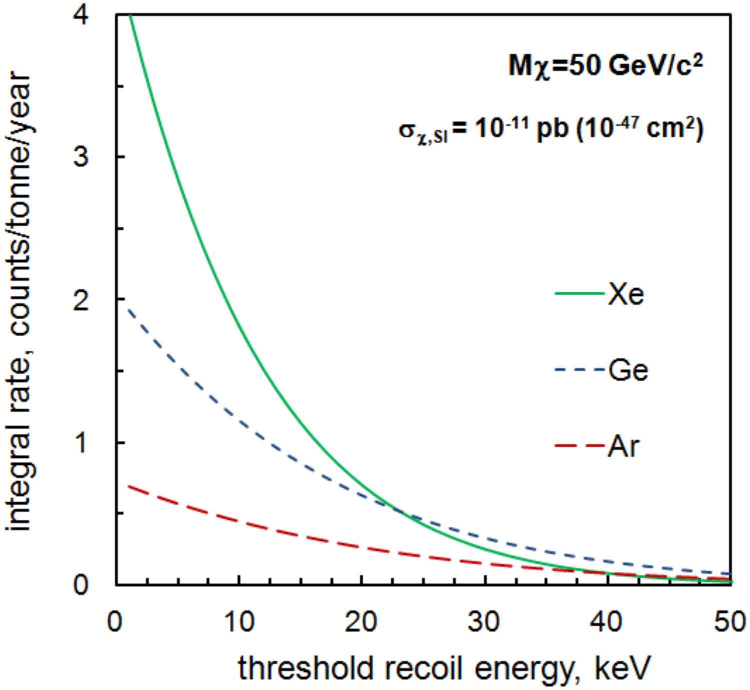
DRIFT Experiment



$$\frac{dR}{dE_R\, d\cos\gamma} \propto \exp\left[\frac{-(v_\odot \cos\gamma - v_{\rm min})^2}{v_{\rm halo}^2}\right]$$

- Signal has fixed distribution in sky (Sygnus): effective background discrimination
- Difficulty: to implement large targets with a gas (required to detect directionality)

THE EXPERIMENTAL CHALLENGE



Key requirements

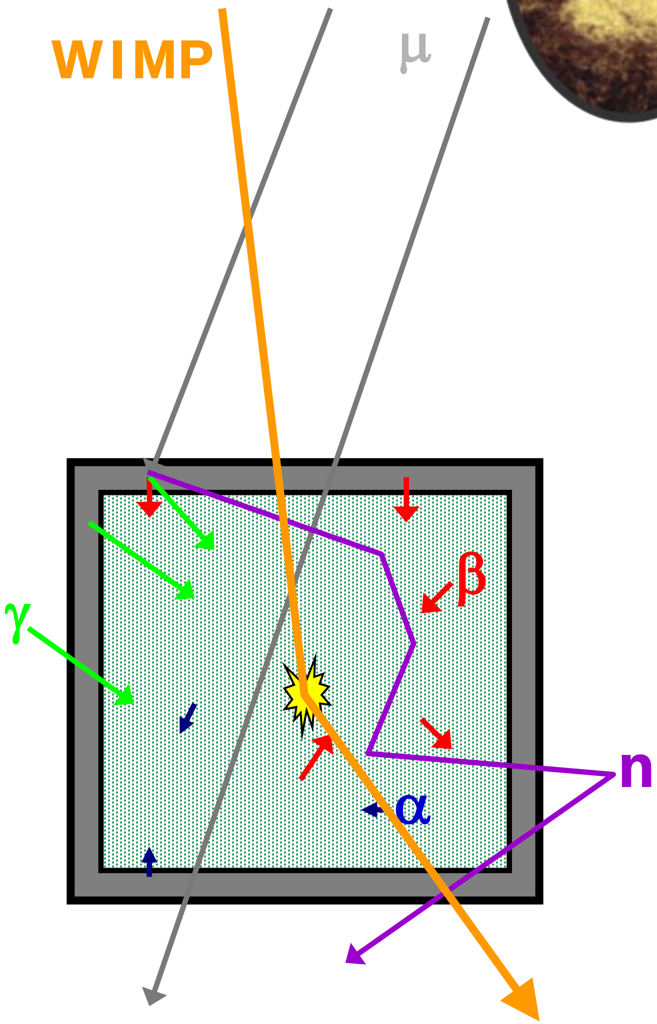
- Large mass x time
  - Low E_R threshold
    - Low background
      - ER/NR discrimination

- Low-energy detection is easy ;)
  - o Several technologies allow sub-keV NR detection
- Rare event searches are also easy ;)
  - o Not a problem at >100 MeV, think neutrinos
- But doing both is hard!
  - Large is better for shielding against external backgrounds
  - But harder to collect quantum-level signal ‘carriers’ from deep inside detector volume

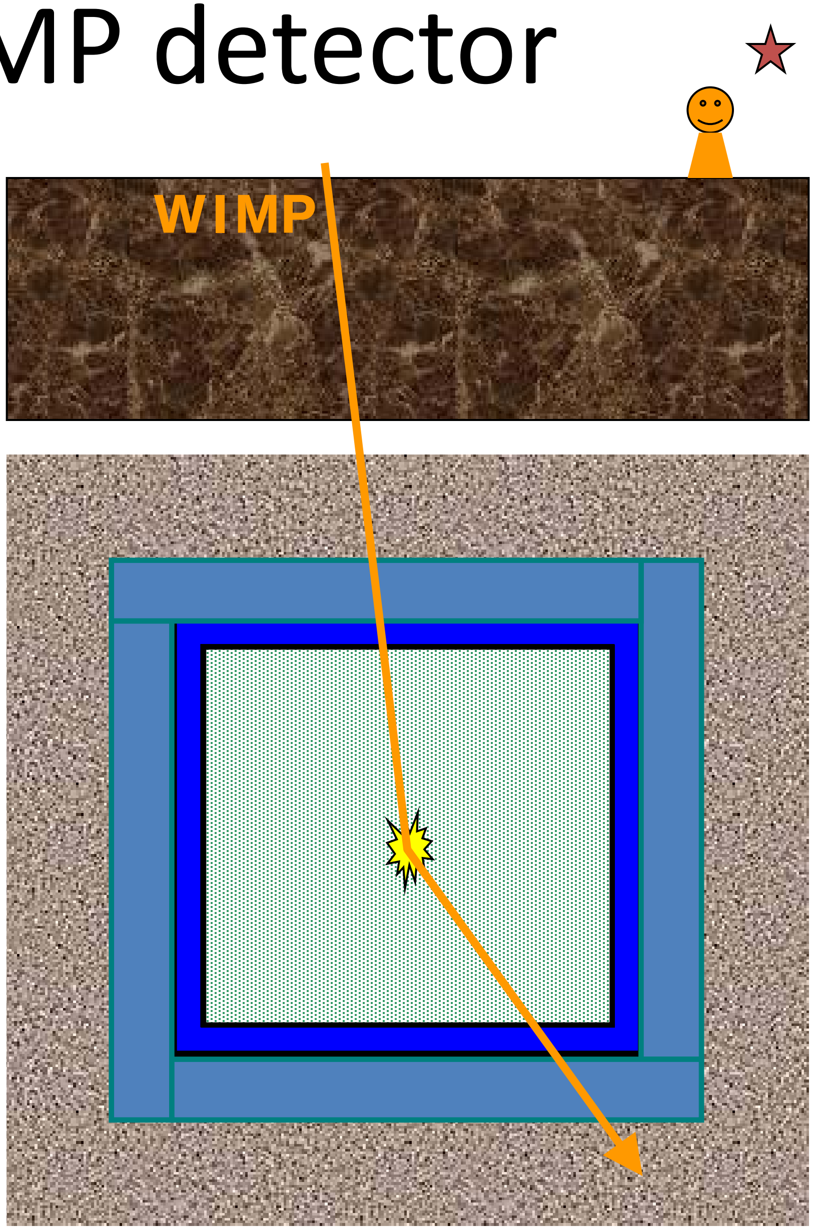
- Also: there is no trigger…

Building a WIMP detector

- Consider 1 kg target
  Sensitive to E_{dep}>1 keV
- Expected WIMP rates
  - 0.01−0.000001 evt/day
- However…
- Cosmic rays, α, β, γ-rays
  - >1,000,000 evt/day
- Neutrons are dangerous!
  - Several evt/day
- Neutrinos will be ultimate background



Building a WIMP detector

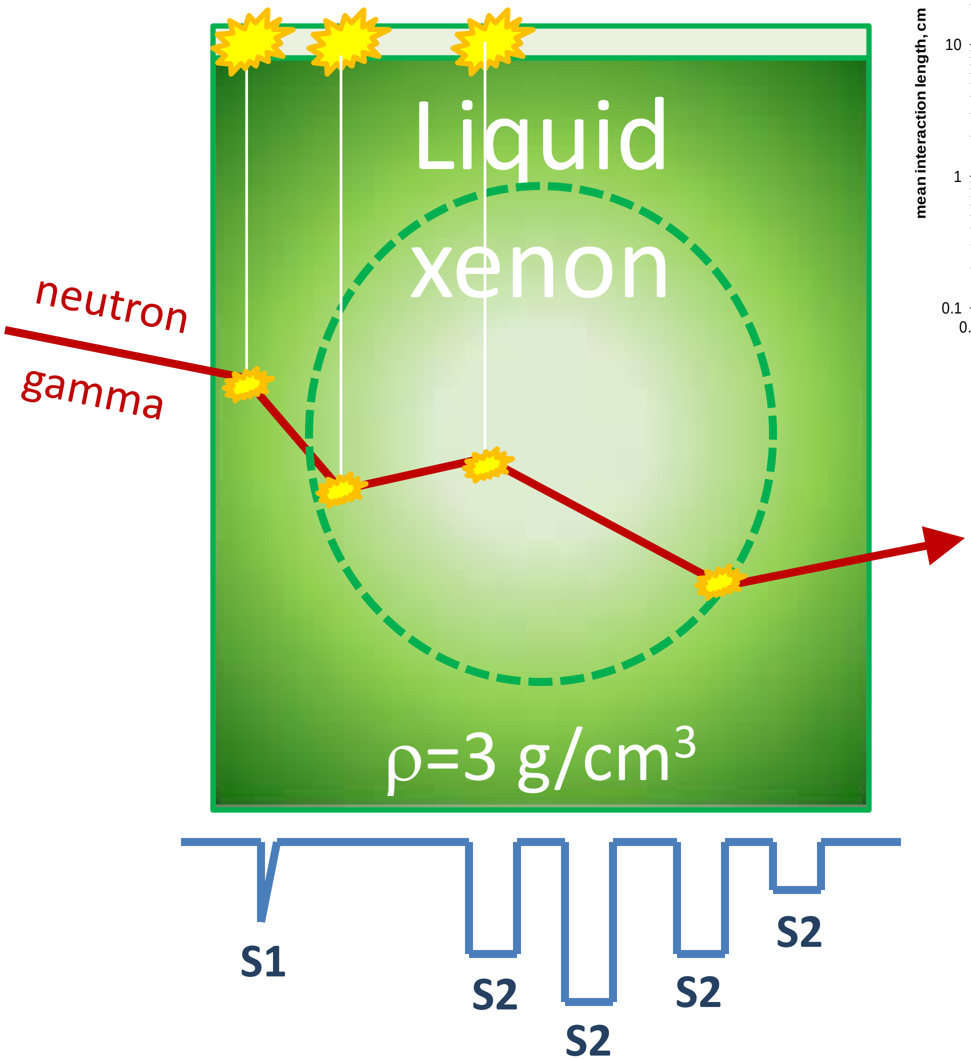


- Move underground
- Use radio-pure materials
- Shield external γ-rays
- Shield external neutrons
- Actively veto neutrons
- Discriminate ***e-recoils*** (γ, β, ν) from ***n-recoils*** (WIMPs, n, ν)
- Coherent ν-A scattering: (probably) irreducible background

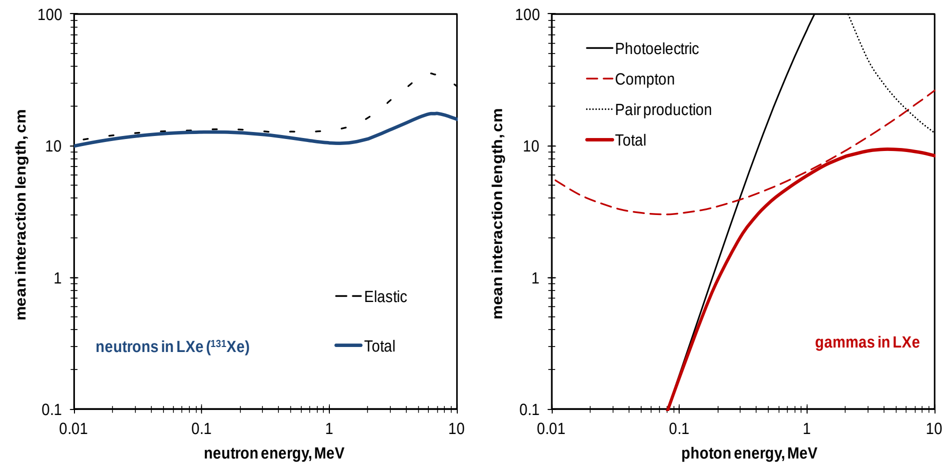
Backgrounds

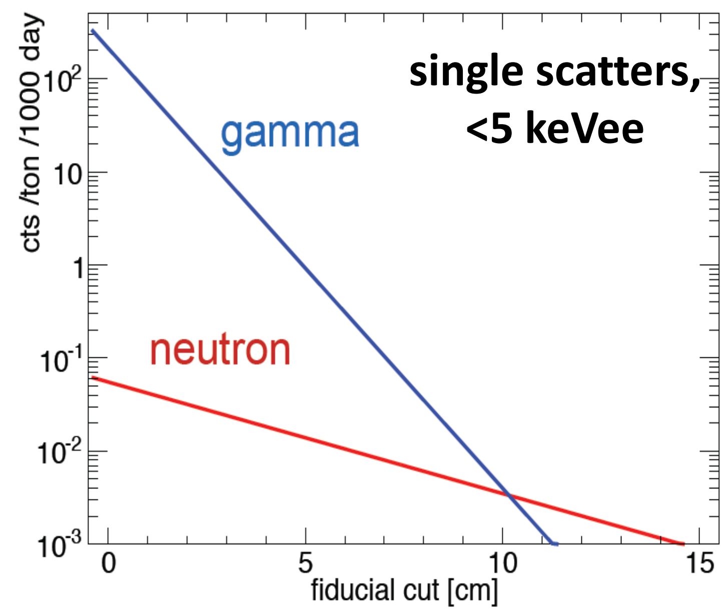
- **Nuclear recoils – same signature, possibly irreducible**
  - **Neutrons from (α,n) and SFission from U/Th trace contamination**
    - Local environment, shields, vessels, components, target material itself
  - **Nuclear recoils from alpha decay (e.g. radon daughter plate-out)**
    - Contaminating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

Self-shielding
in noble liquids

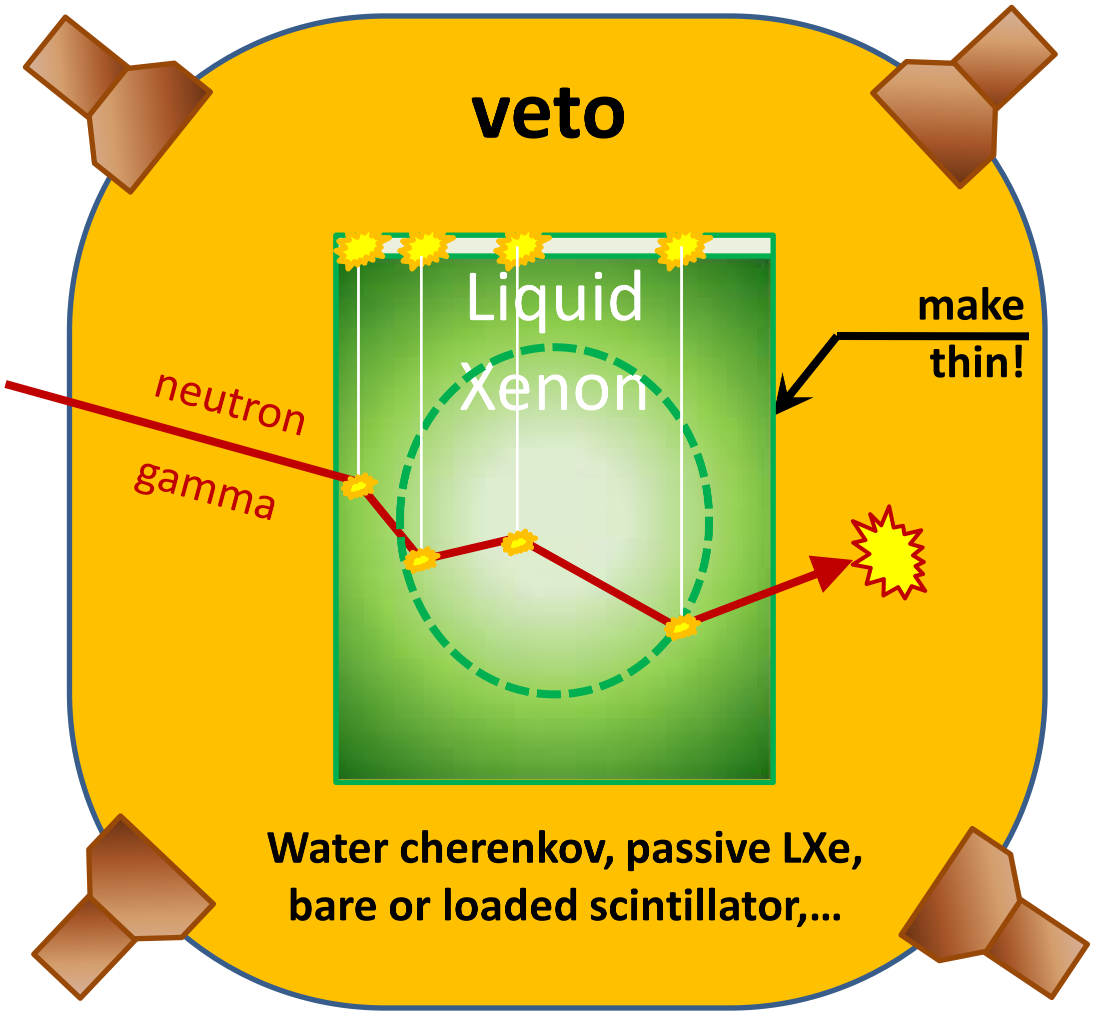


neutron and gamma
mean Interaction lengths in liquid xenon





Anticoincidence detector around WIMP target



WIMP SEARCH TECHNOLOGY ZOO

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, CDEX, **DAMIC**, DRIFT, DM-TPC, GENIUS, IGEX, NEWAGE

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, **LUX**, WARP, DarkSide

Panda-X, **XENON**, ZEPLIN, **LZ**

cold (LN_2)

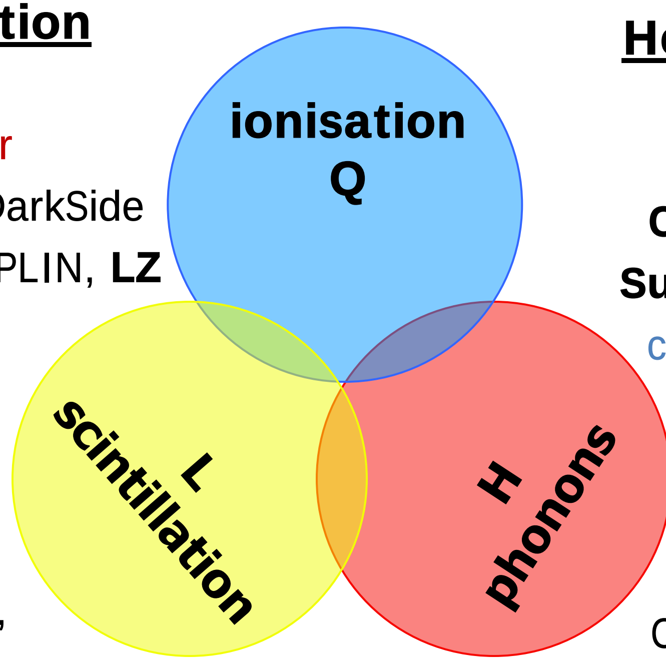
Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, EDELWEISS

SuperCDMS, EURECA

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, CLEAN, DAMA, **DEAP3600**, KIMS, LIBRA, NAIAD, XMASS, ZEPLIN-I

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

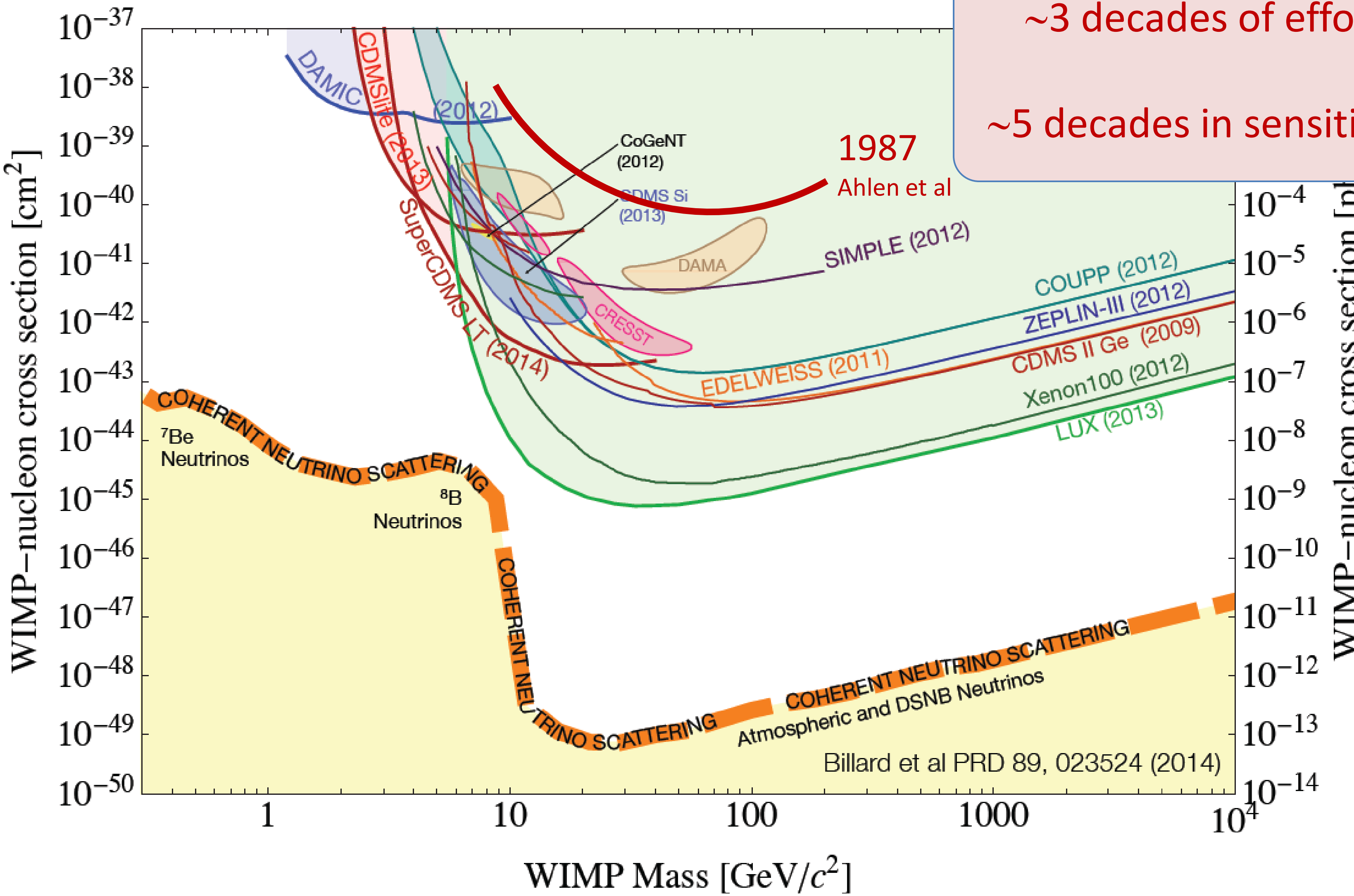
cryogenic (<50 mK)

Bubbles & Droplets

CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, PICO, SIMPLE

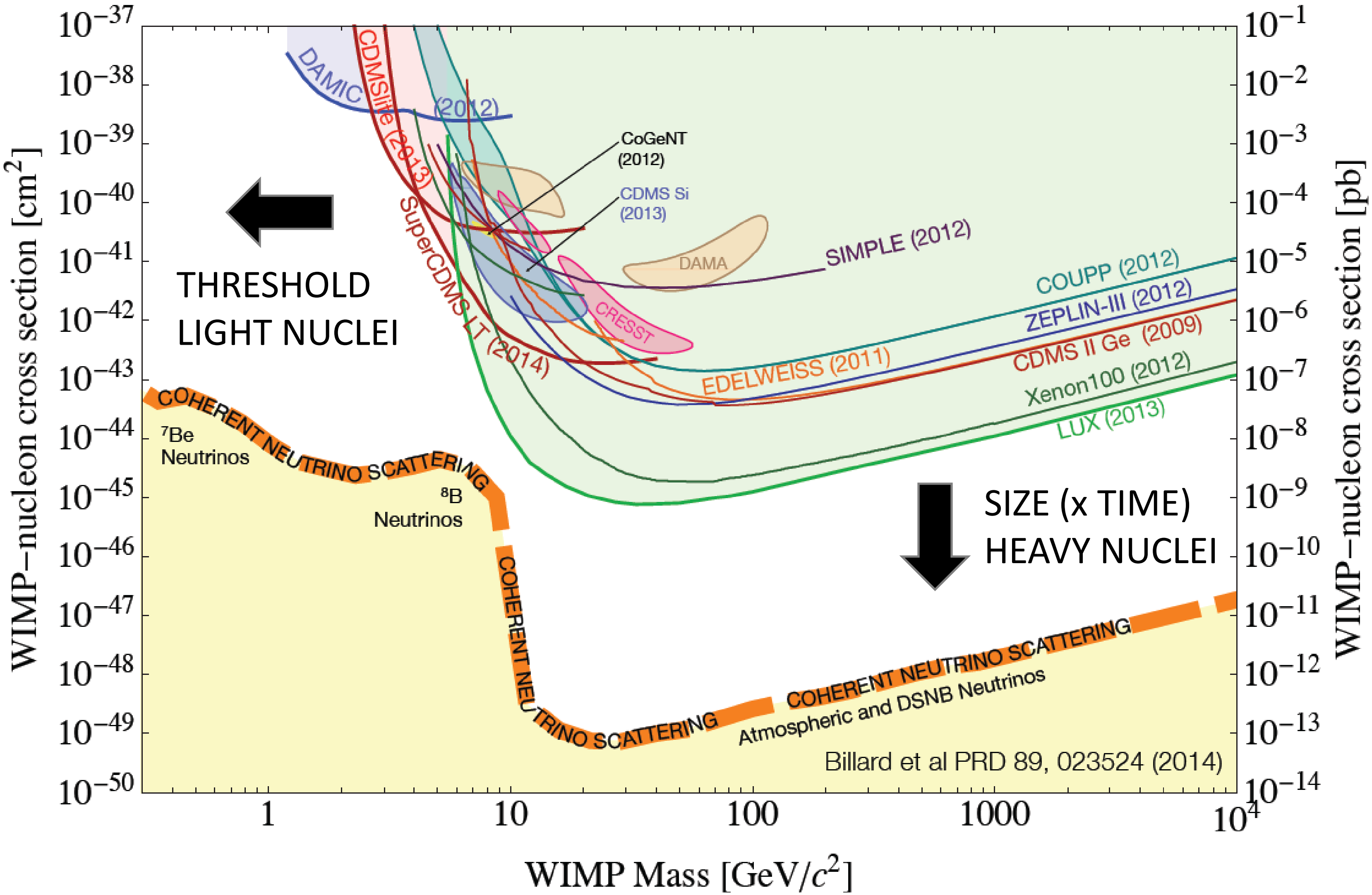
PRESENT STATUS



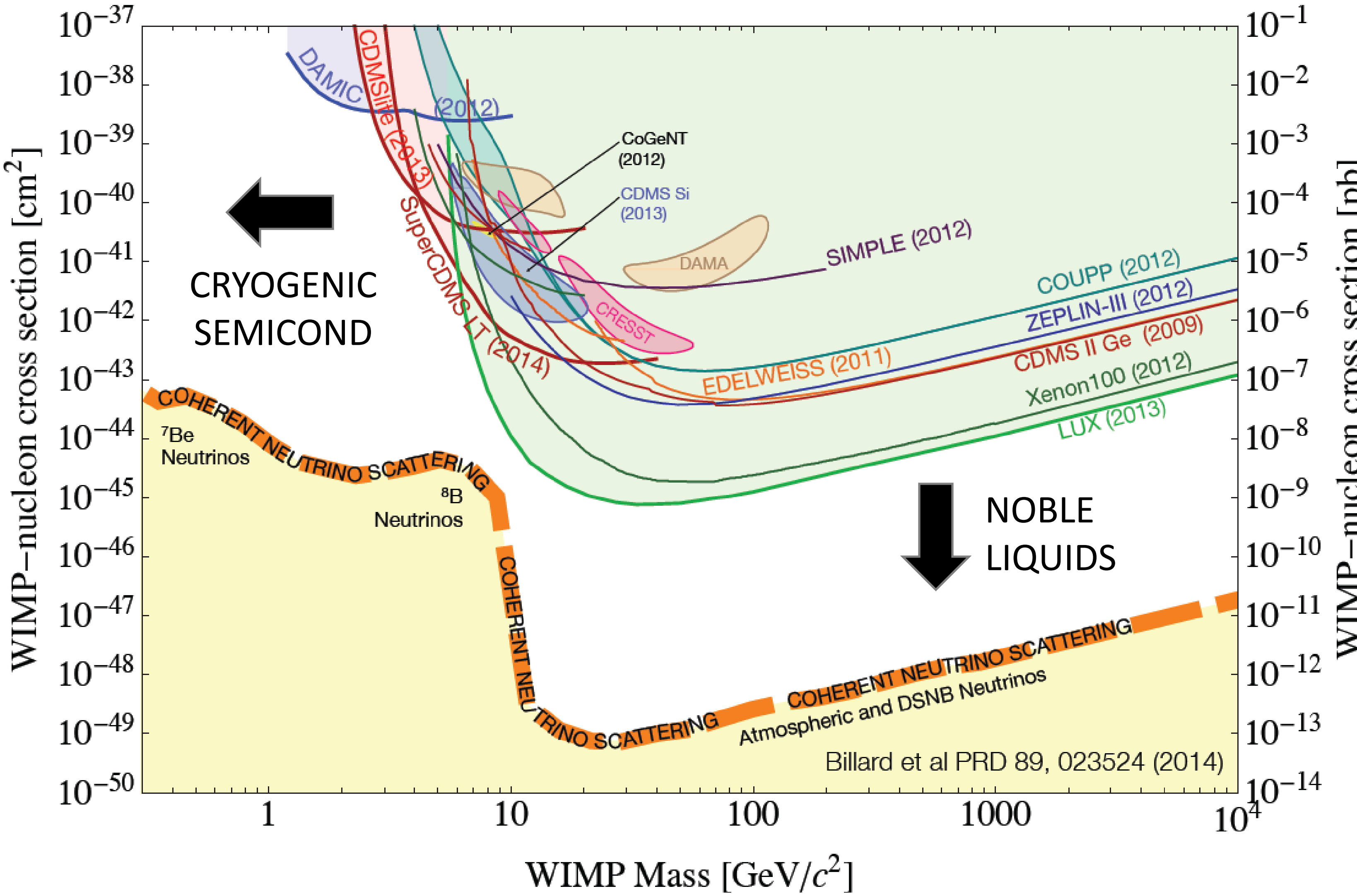
~3 decades of effort

~5 decades in sensitivity

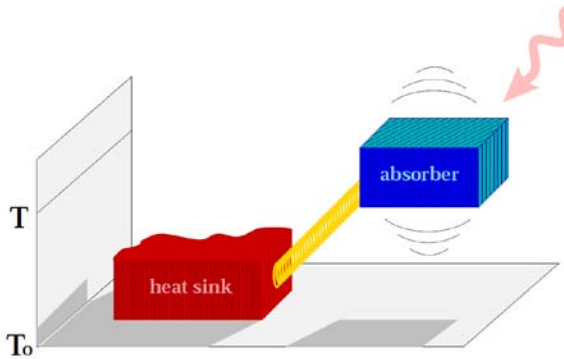
PRESENT STATUS



PRESENT STATUS



CRYOGENIC DETECTORS



T_0~10-50 mK

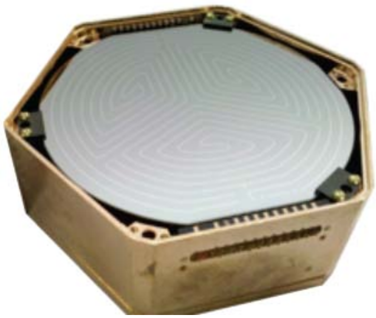
$$\Delta T_{\max} = \frac{E}{C}$$

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

EDELWEISS DETECTORS

CRESST DETECTORS

S-CDMS DETECTORS

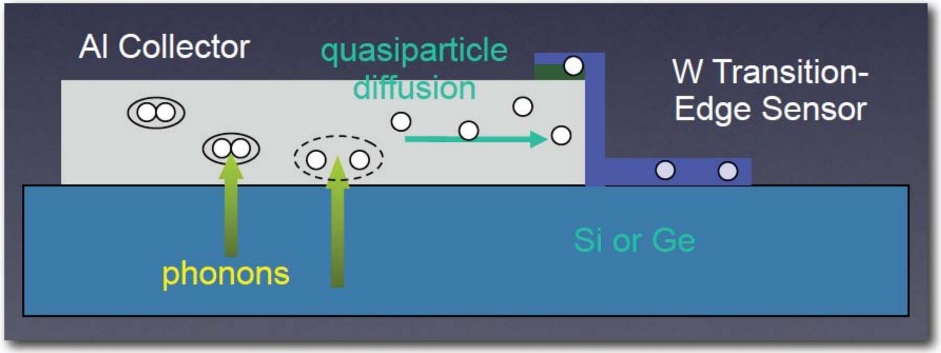


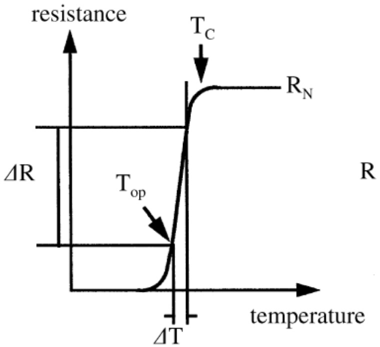
Phonon channel: ~keV threshold, no quenching

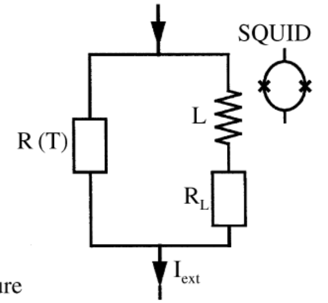
Can collect a second signature for discrimination:

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

Superconducting Transition-Edge Sensor (CDMS)





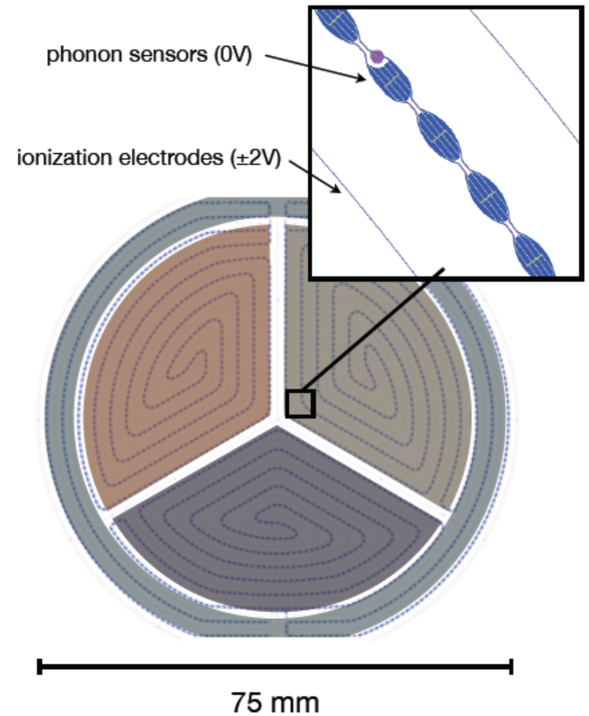


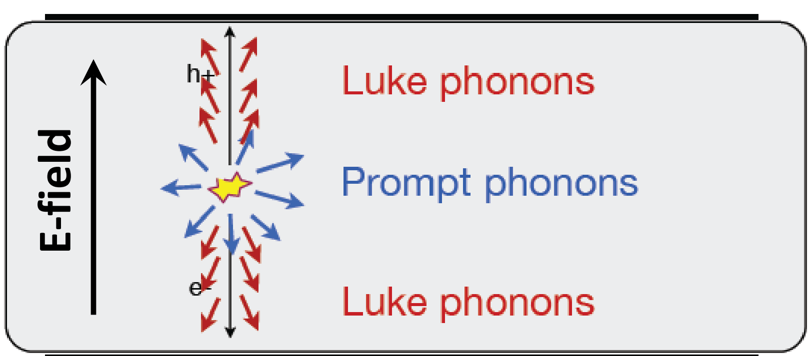
CDMSLite/SuperCDMS SOUDAN

1309.3259
1402.7137

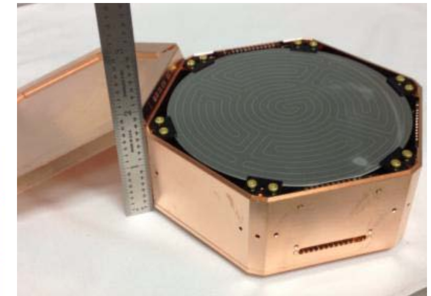
iZIPs, interleaved ionisation & phonon readout

- Improved fiducialisation wrt CDMS-II
- Same location & infrastructure
- **CDMSLite:** low ionisation threshold
  via Luke-Neganov phonon amplification
  1 iZIP, 6 kg*days Ge
- **SuperCDMS**: LE analysis on selected detectors
  7 iZIPs (15 installed), 577 kg*days Ge
- **Key parameters**
  - CDMSLite: 0.8 keVr (no discrimination)
  - S-CDMS LE: 1.6-10 keVr (some discriminatior
- **Sensitivity**
  - 3.4×10^{-41} cm^2 at 8 GeV (Lite)
  - 1.2×10^{-42} cm2 at 8 GeV
- Onwards: SuperCDMS at SNOLab (~100 kg)

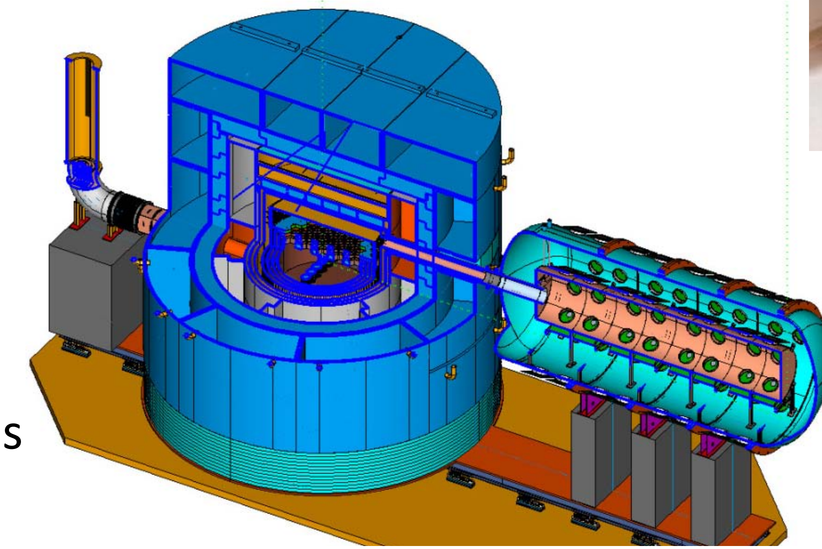


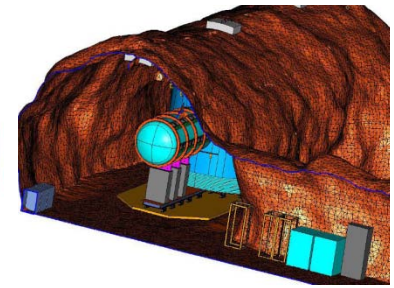


SuperCDMS AT SNOLab



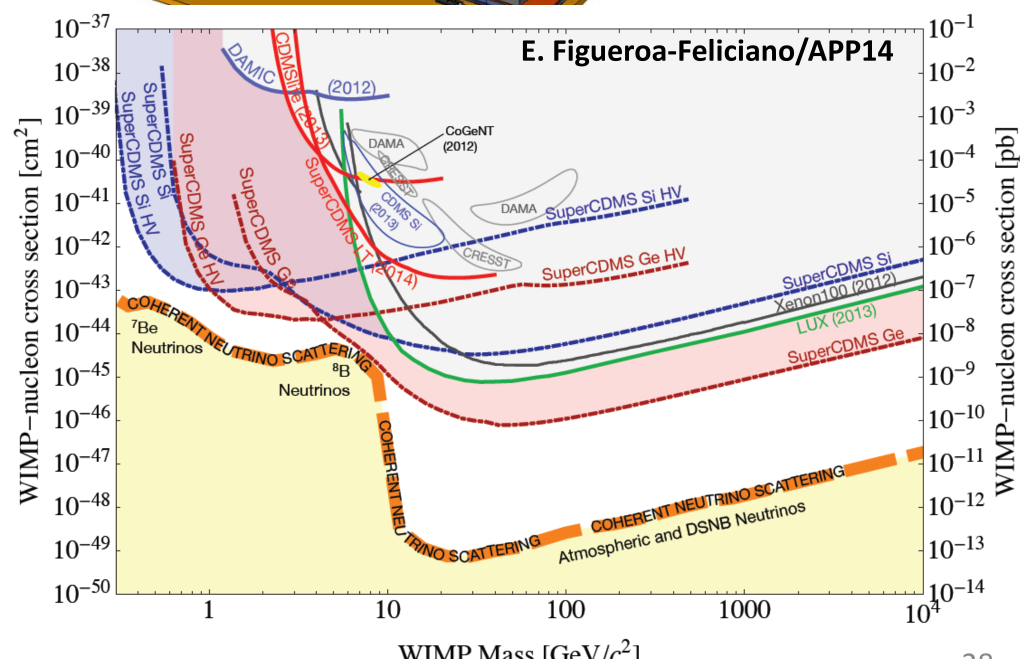
B. Loer, DM2014



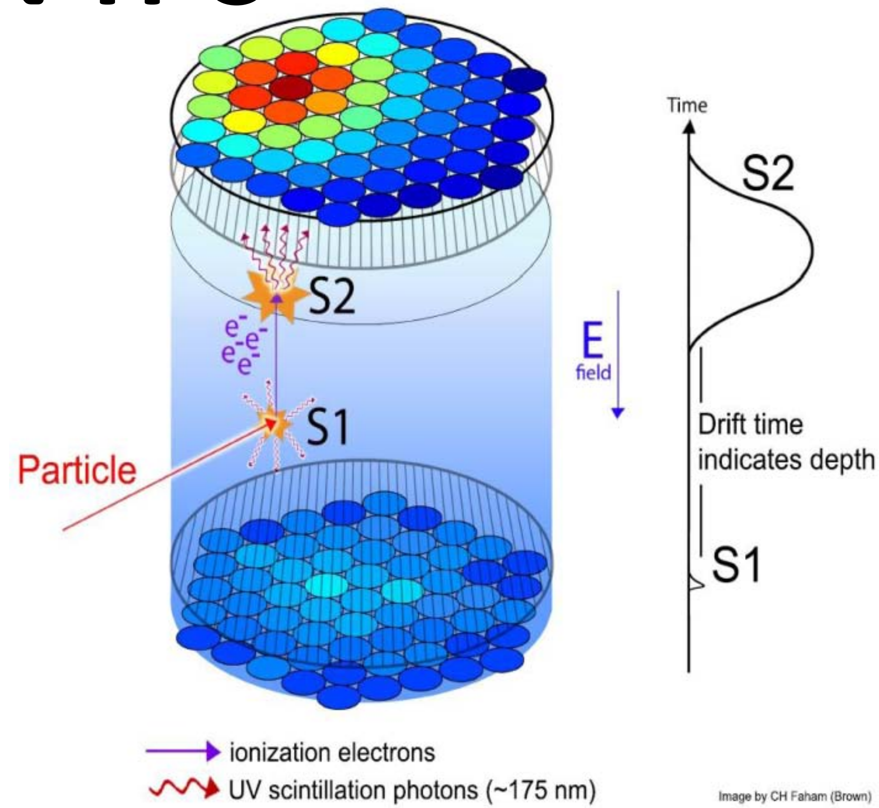


iZIP detectors

- 98 kg Ge (70 x 1.4 kg)
- 12 kg Si (20 x 0.6 kg)
- 10 cm diam, 3.3 cm thick
- 12 phonon, 4 charge chans
- Adding LAB active veto
- Det fabrication from late 2014
- Commissioning 2016
- *Common phase w/ EURECA?*
- **Key parameters**
  - NR threshold: 0.8 keV, 8 keV
  - Background: <0.2 evts (5 yrs)
- **Sensitivity**
  - ~1x10^{-46} cm^2 at 40 GeV by 2021



TWO-PHASE XENON TPC



S1: prompt scintillation signal

- Light yield: ~60 ph/keV (ER, 0 field)
- Scintillation light: 178 nm (VUV)
- **Nuclear recoil threshold ~5 keV**

S2: delayed ionisation signal

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

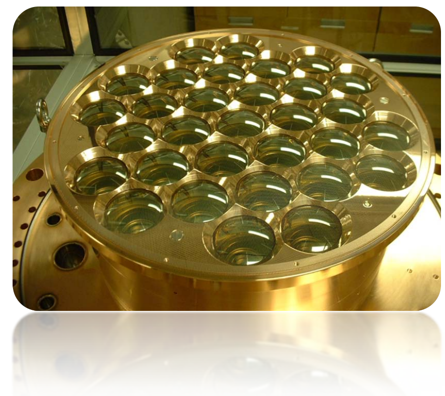
S1+S2 event by event

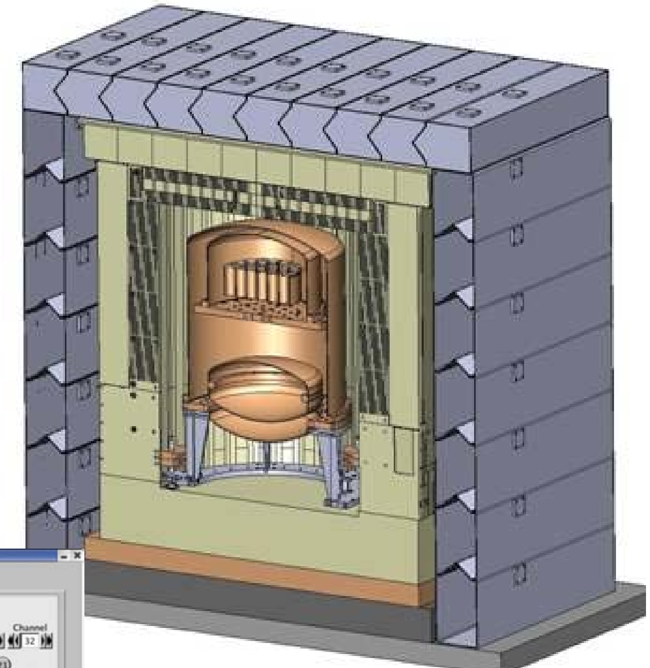
- ER/NR discrimination (>99.5% rejection)
- mm vertex resolution + high density: *self-shielding* of radioactivity backgrounds

LXe is the leading WIMP target:

- Scalar WIMP-nucleon scattering rate dR/dE~A^2, broad mass coverage >5 GeV
- Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable SD sensitivity; target exchange
- No damaging intrinsic nasties (^{127}Xe short-lived, ^{85}Kr removable, ^{136}Xe $2\nu\beta\beta$ ok)

ZEPLIN-III: TWO-PHASE XENON
UK-LED PROGRAMME AT BOULBY

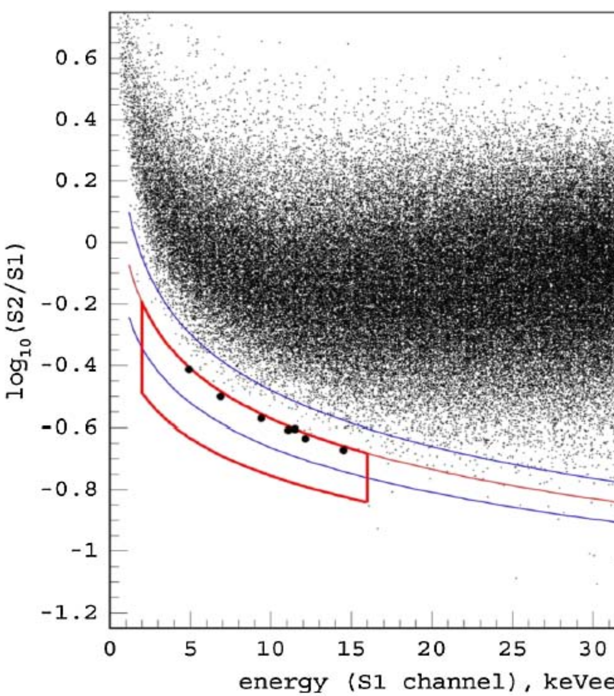


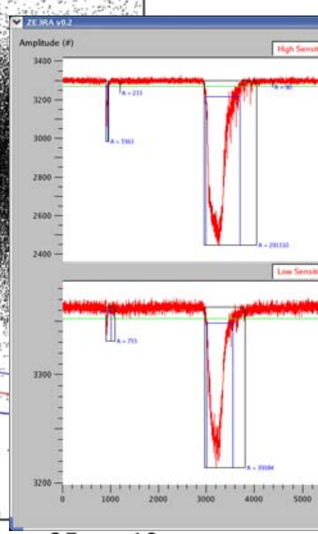


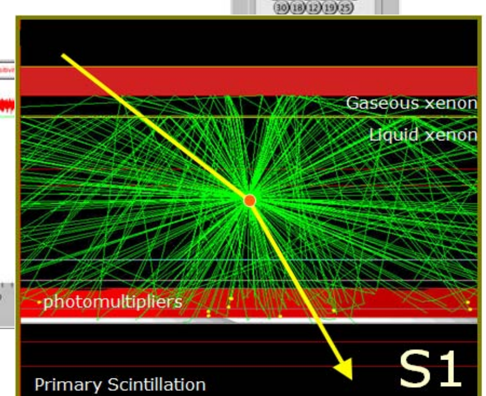
- ZEPLIN developed 2-phase Xe detectors
- Boulby programme completed in 2012
- Z3 achieved best discrimination in LXe

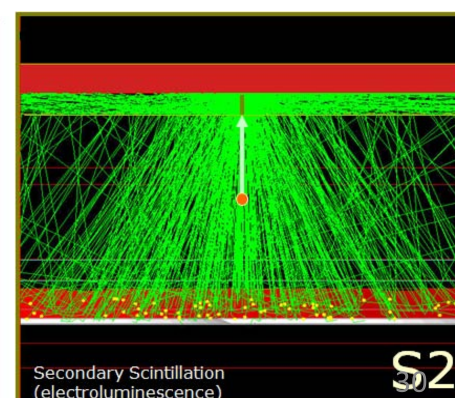
  Lebedenko *et al*, PRD 80 (2009) 052010

  Akimov et al, PLB 709 (2012) 14





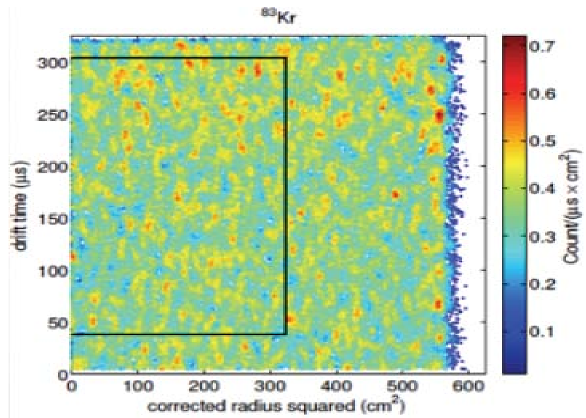


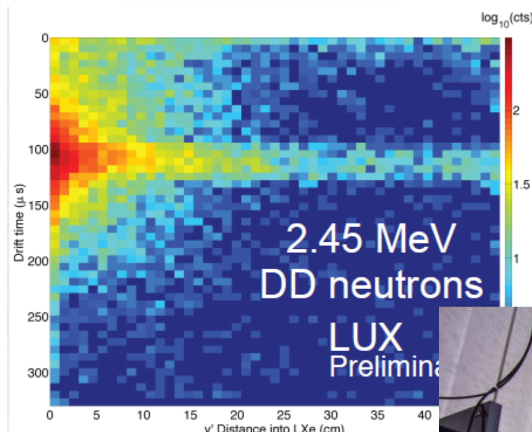


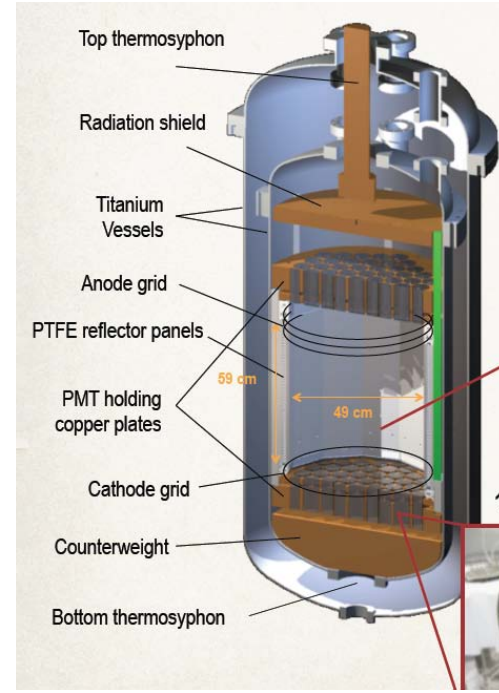
LUX: TWO-PHASE XENON

Liquid xenon TPC

- 250 kg LXe (118 kg fiducial)
- PTFE field cage, 122 PMTs
- 3D imaging (<1 cm)
- Calibration: *in situ* D-D gen, Dispersed ^{83m}Kr and CH_3T
- **Key parameters**
  - Light yield: >8 phe/keVee
  - Drift field: 0.2 kV/cm
  - NR threshold: 4.3 keV
  - ER discrimination: 99.6%
  - Background: 2 ER/day (ROI total!)
- **Sensitivity**
  - 7.6×10^{-46} cm^2 at 33 GeV (Run 3)
- Onwards: LUX-ZEPLIN (7-tonne TPC)



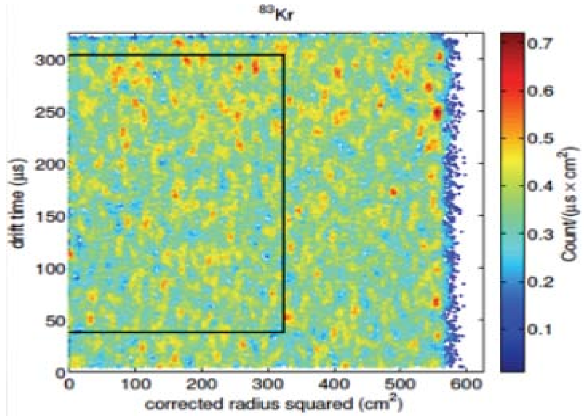


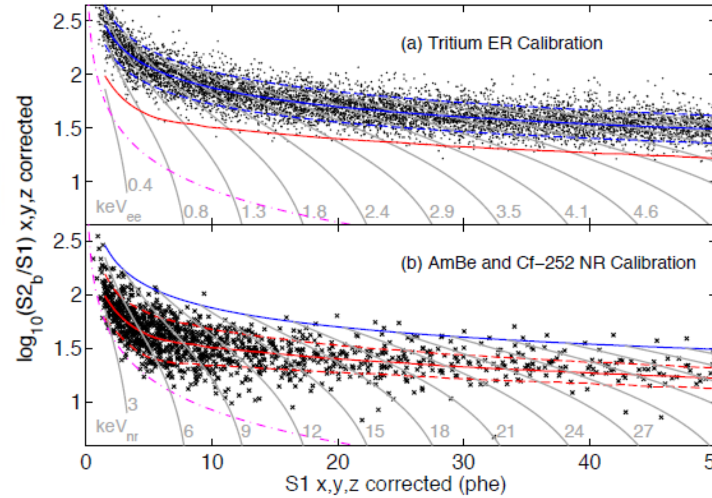


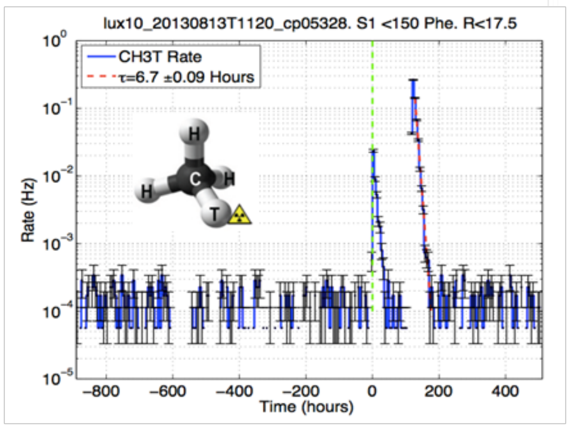
LUX: CALIBRATION

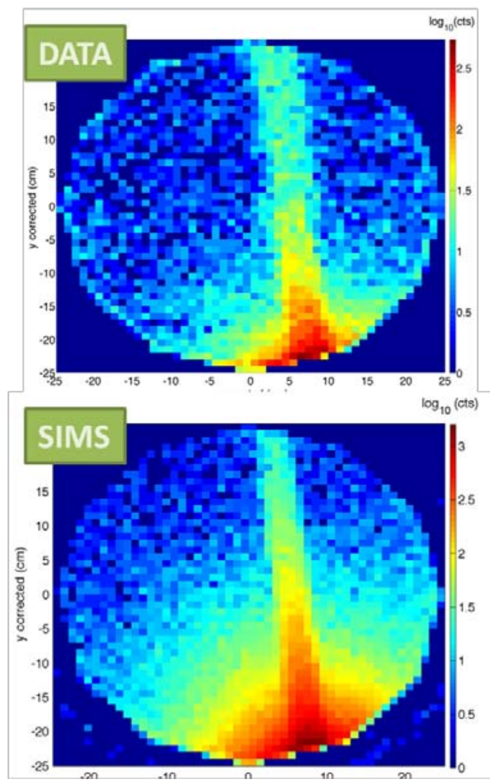
Electron Recoils

- Dispersed β sources:
- ^{83m}Kr: S1 & S2 cal
- CH_3T: ER band







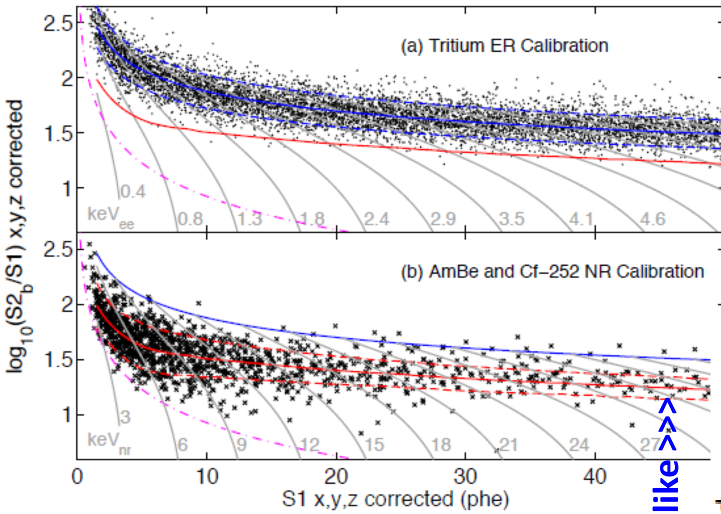


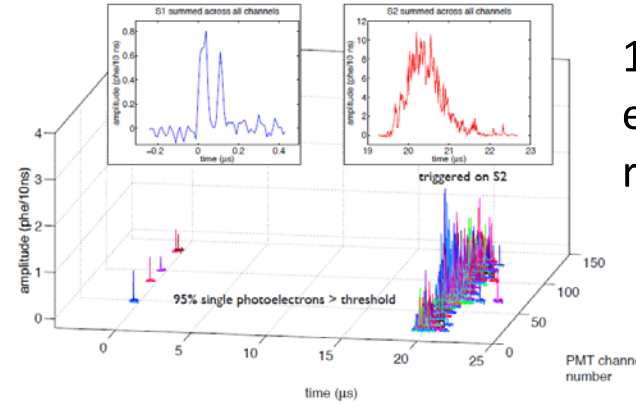
Neutron pipe

Nuclear Recoils

- D-D neutron generator
- S1 & S2 yields for recoils in LXe to O(keV)

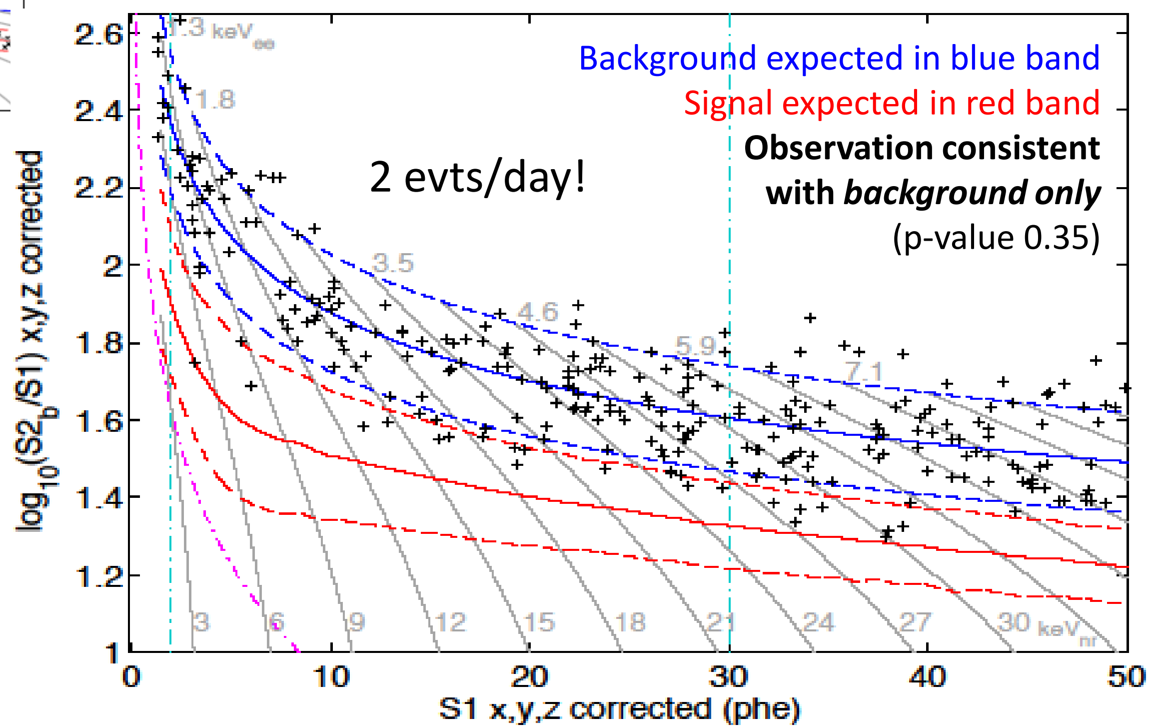
LUX: RESULTS





1.5 keV electron recoil

Events recorded in 85.3 live days of exposure



<<< signal-like background-like >>>

recoil energy (loosely) >>>

The Economist

"Absence of evidence, or evidence of absence?"

New York Times

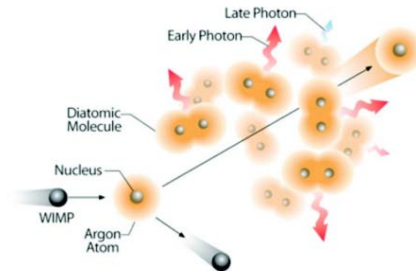
"Dark Matter Experiment Has Detected Nothing, Researchers Say Proudly"

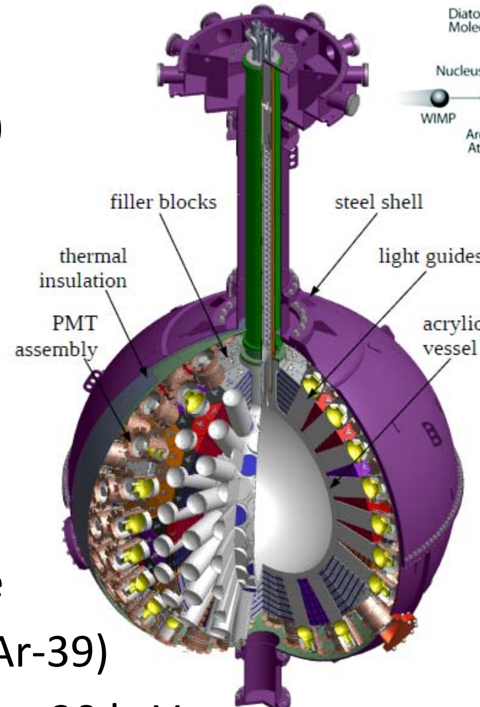
0904.2930

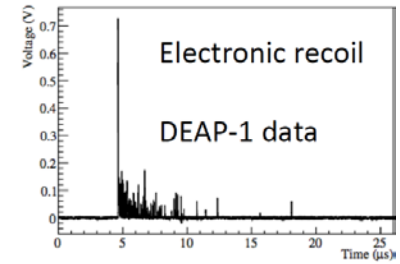
DEAP-3600: SINGLE PHASE LAr

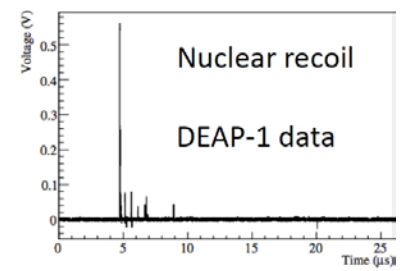
PSD in single phase LAr

- 3.6 t LAr (1 t kg fiducial)
- 255 PMTs (75% coverage) light-guide coupled
- Inside 8 m water shield
- Vessel resurfaced *in situ* prior to WLS evaporation



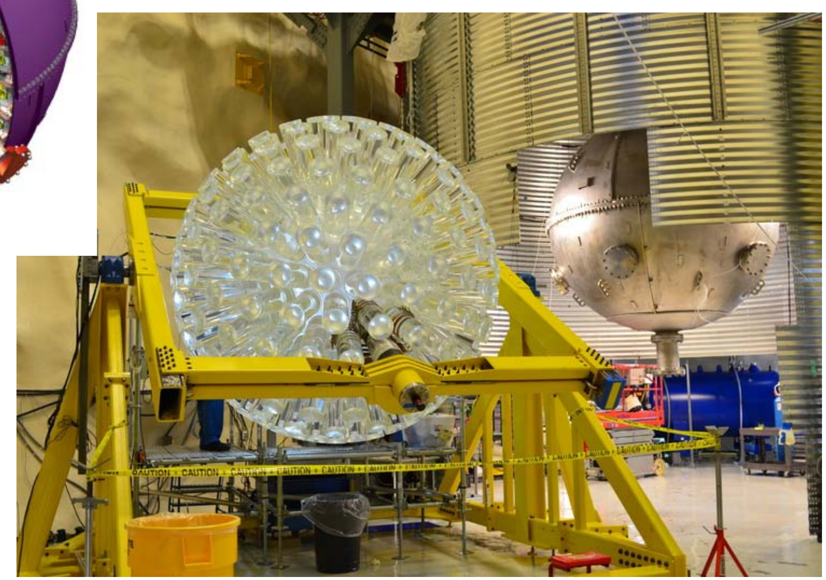






S. Peeters/APP14

- **Key parameters**
  - Light yield: 8 phe/keVee
  - NR threshold: 60 keVr (Ar-39)
  - ER discrimination: 10^{-10} at 20 keVee
  - Background: <0.3 events (3 t·yr)
- **Sensitivity goal**
  - $1\text{x}10^{-46}$ cm^2 at 100 GeV by 2017
- Onwards: DEAP-50 tonnes



XENON-1T: TWO-PHASE XENON

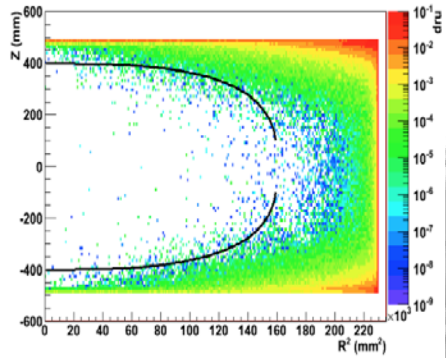
Liquid xenon TPC

- 3.3 t LXe (1 t fiducial)
- 1 m long TPC, 248 PMTs
- 10 m water Cherenkov
- Construction now
- Operation from 2015
- (Oversized OV for nT phase)

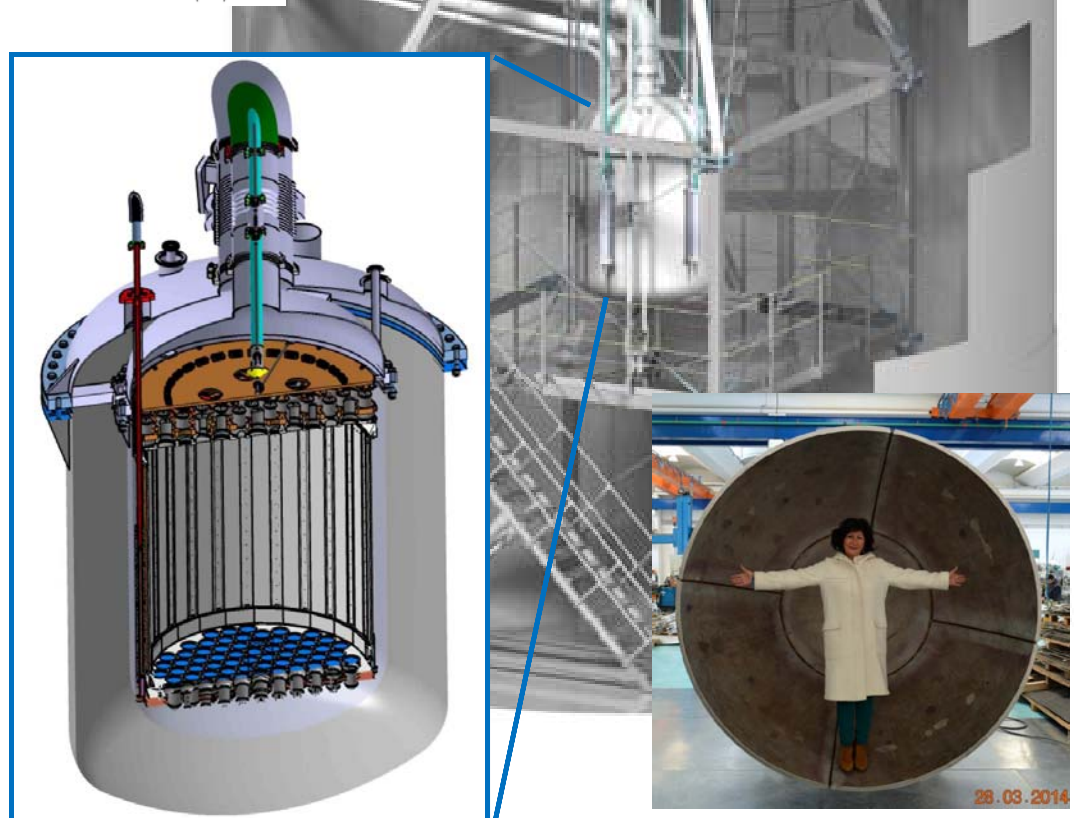
- **Key parameters**
  - Drift field: 1 kV/cm
  - Background: ~1.5 evt (2.7 t·yr)

- **Sensitivity**
  - $2\text{x}10^{-47}$ cm^2 by 2017

- Onwards: XENON-nT, DARWIN



Oberlack
APP14



LZ: TWO-PHASE XENON

Liquid xenon TPC

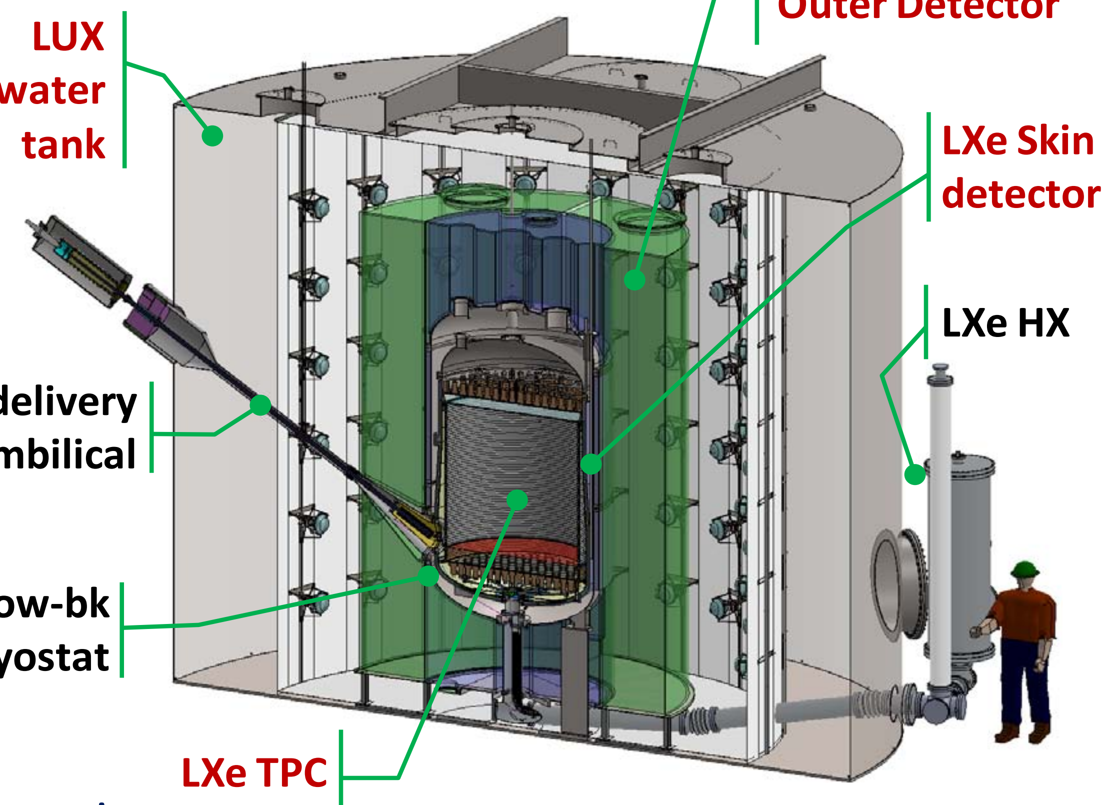
- 7.0 t LXe active (5.6 t fiducial)
- LXe Skin detector (~2 t)
- Gd-loaded Scintillator Veto
- 8-m water tank (post-LUX)
- Construction from 2015

- **Key parameters**
  - Light yield: >6 phe/keVee
  - NR threshold: ~6 keV
  - ER discrimination: >99.5%
  - Background: ~1.9 evt (8 t·yr)

- **Sensitivity**
  - $2.5\text{x}10^{-48}$ cm^2 circa 2020

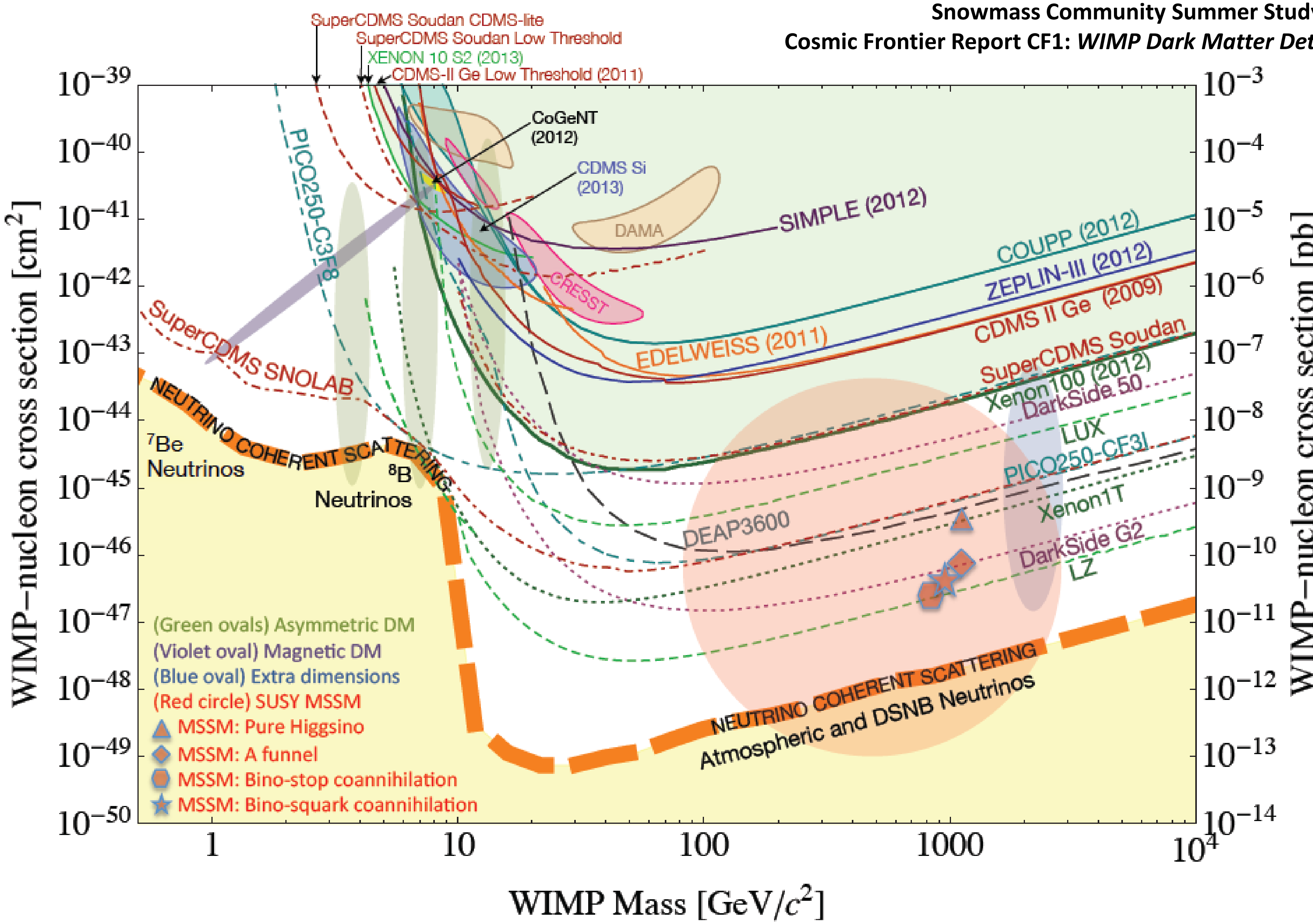
- UK-supported next-generation experiment

LZ DETECTOR(S)



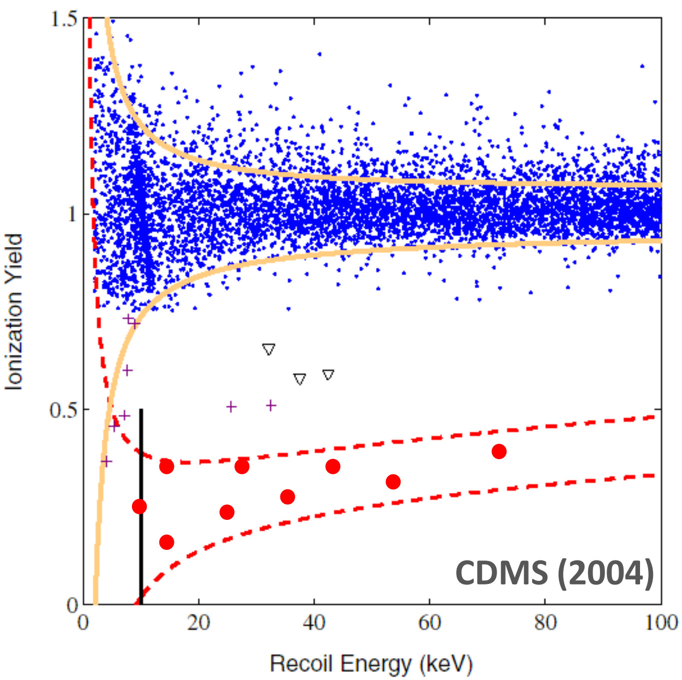
PROSPECTS

Snowmass Community Summer Study 2013
Cosmic Frontier Report CF1: *WIMP Dark Matter Detection*



3, DISCOVERY – “COUNTS IN BOXES”, IDEAL WORLD

1. **Define nuclear-recoil acceptance band/box using calibration data only**
2. **Calculate the background expected within that region (hopefully <<1)**
3. **Blind data analysis (at least a fraction, in & around search region)**
4. **Apply statistical analysis defined *a priori***
   – Feldman-Cousins, Profile Likelihood Ratio, etc.



“Unblind” your search data with great aplomb:

- 0 events
  – Corresponds to 2.44 events at 90% CL – publish XS limit
- Some (very few) events
  – lower bound consistent with 0 – publish XS limit
  – lower bound just about excludes 0 – be reasonable
- Quite a few events
  – Calculate significance (how many “sigma” effect?)
  – Spend a long time re-examining your systematics
  – If you’d bet your house, then book Stockholm!
  (but would you?)

DISCOVERY – “COUNTS IN BOXES”, REAL WORLD

1. **Define nuclear-recoil acceptance band/box using calibration data only**
   - Difficult to calibrate nuclear recoil band *in-situ* with low systematic error (self shielding…)
   - Conversion between nuclear recoil energy and gamma-ray energy is not straightforward
   - The detector blew up before enough calibration could be collected…
2. **Calculate the background expected within that region (hopefully ~0)**
   - How large is ~0?
   - Did you really find *all* background contributions, or just the *nice* ones that you could simulate?
   - What is uncertainty in background and how to treat this in the statistical analysis?
3. **Analyse your data blindly (at least a fraction, in & around search box)**
   - Sorry, not enough data to optimise cuts – need to open more (or all?)
   - Maybe a new type of background was revealed only after you looked at the search data?
   - Bug in the analysis software, not apparent in 10% dataset…
4. **Apply statistical analysis defined *a priori***
   - Single-sided statistical analysis (upper limit only) – background treated as signal, no discovery
   - Maximal gap method, some Poisson analyses, etc

- **Most experiments suffer from some of these when they first run…**
  - **Publish (probably over-conservative) upper limit**
  - **Work even harder to understand your systematics next time…**

LUX PROFILE LIKELIHOOD RATIO SIGNAL ESTIMATION

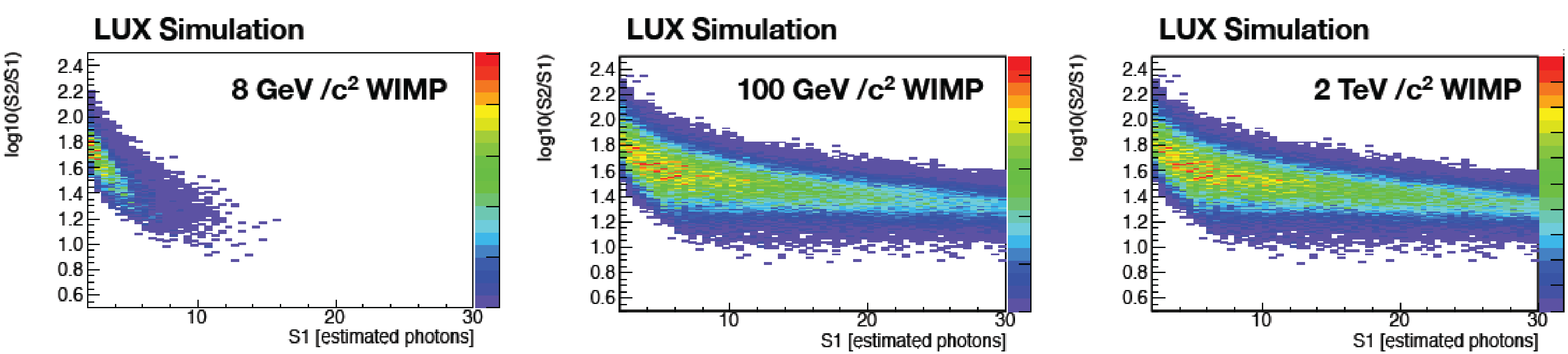
$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{i=1}^{\mathcal{N}} N_s P_s(\boldsymbol{x}; \boldsymbol{\sigma}, \boldsymbol{\theta_s}) + N_{Compt} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Compt}})$$
$$+ N_{Xe-127} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Xe-127}}) + N_{Rn} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Rn}})$$

Observables: $\mathbf{x}$ = (S1, $\log_{10}$(S2/S1), r, z)

Parameter of interest: N_s

Nuisance parameters: N_{Compt}, N_{Xe-127}, $N_{Rn,Kr-85}$

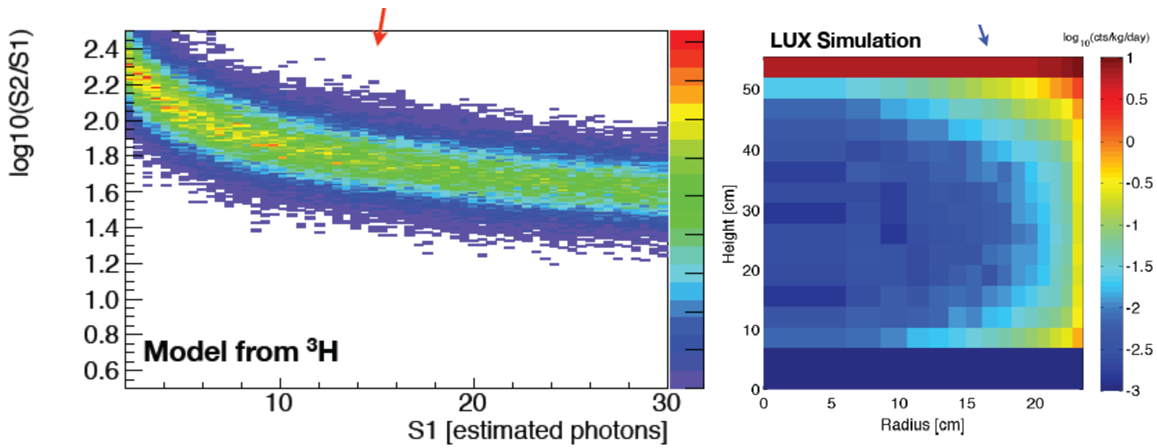
SIGNAL MODEL: simulated 2D PDFs including resolution/efficiencies; uniform in (r^2,z)



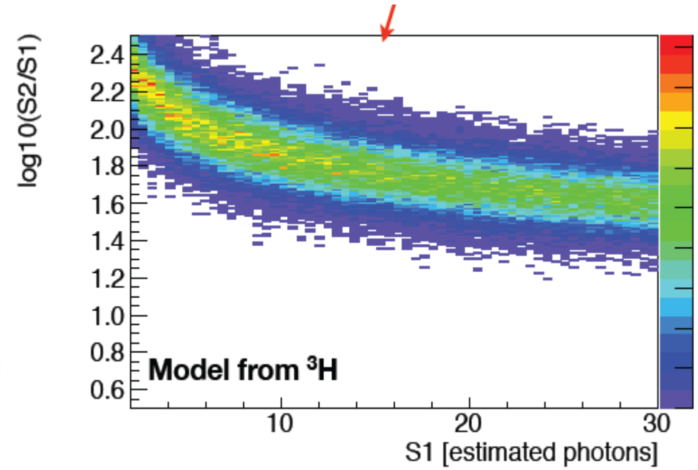
LUX PROFILE LIKELIHOOD RATIO SIGNAL ESTIMATION

BACKGROUND MODEL: simulated 2D PDFs including resolution/efficiencies

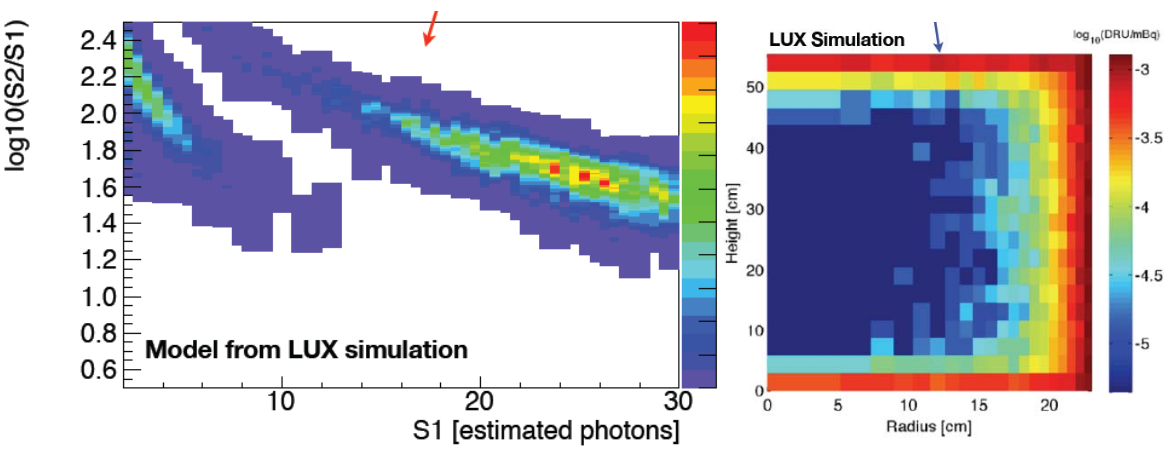
External radioactivity (Compton-scattered gammas)



Pb-214/Kr-85
Uniform in Eee and space



Xe-127 atomic cascade with HE gamma escape



Dark Matter: big problem,
must keep looking!