

# Direct Detection Techniques

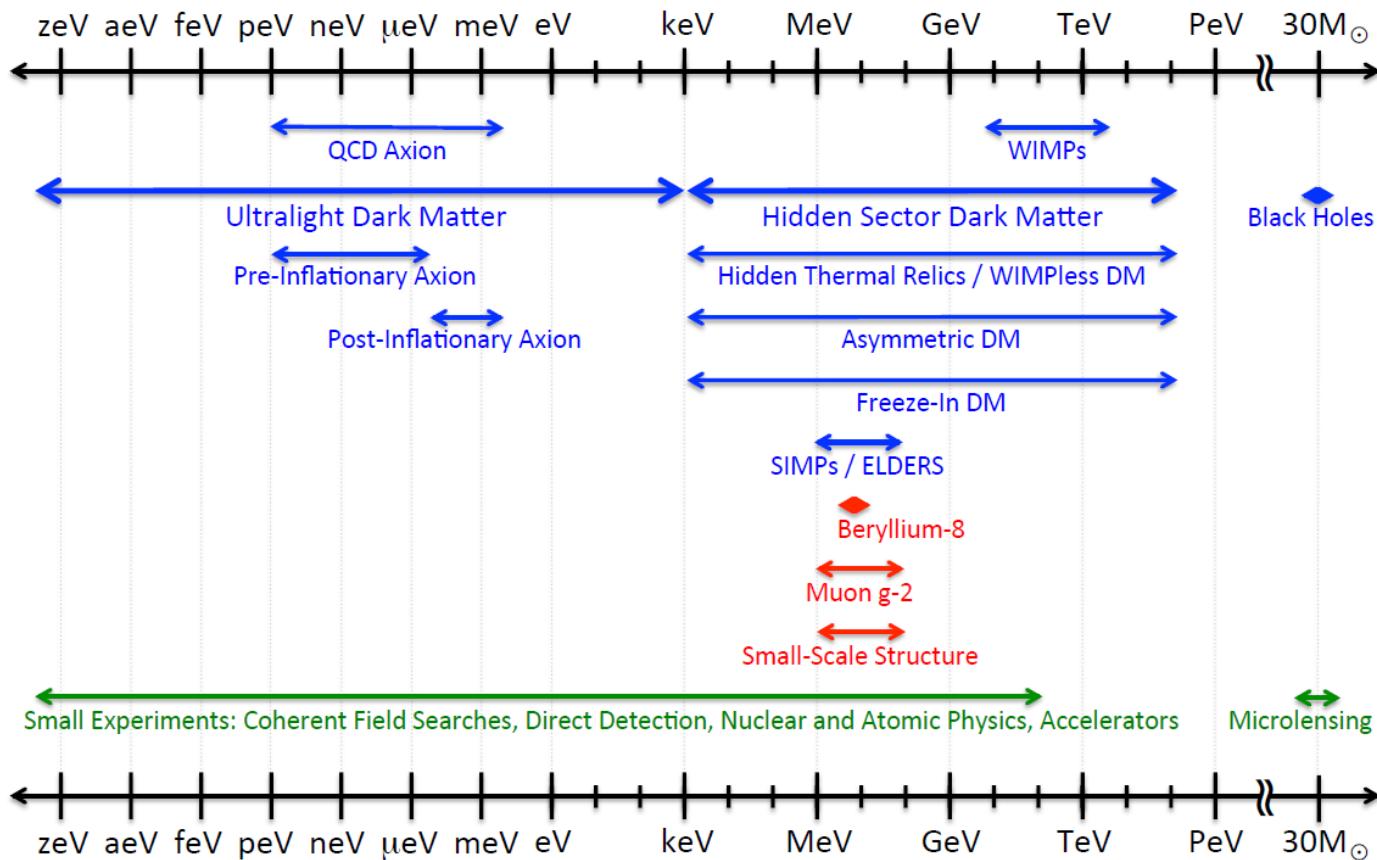
Hans Kraus

- Introduction to Direct Search Techniques
- Noble Liquid Detectors
- Cryogenic Detectors

# A Vast Parameter Space

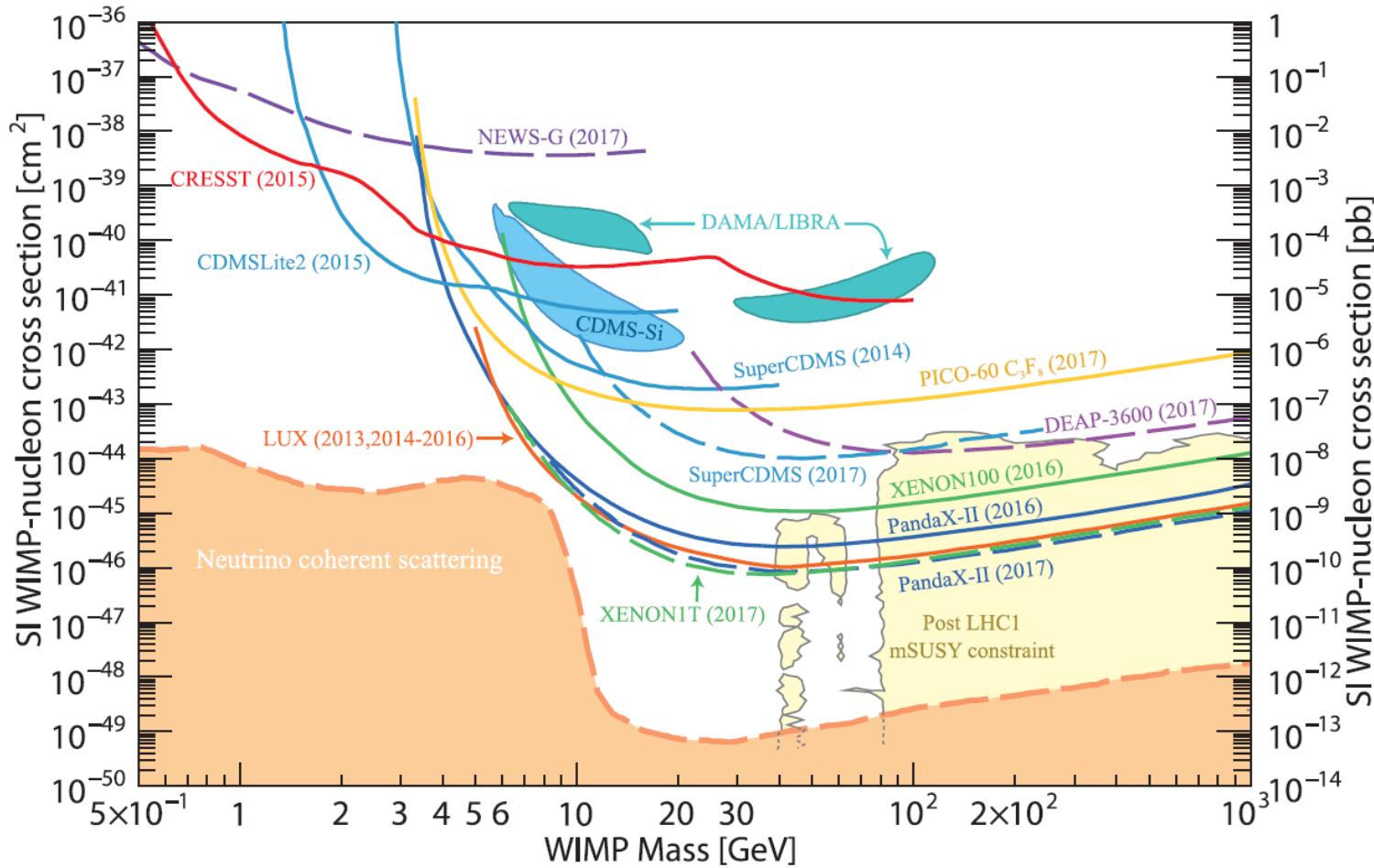
Direct detection experiments targeting  
the sub-GeV to TeV mass range.

Dark Sector Candidates, Anomalies, and Search Techniques



From: US Cosmic Visions 2017

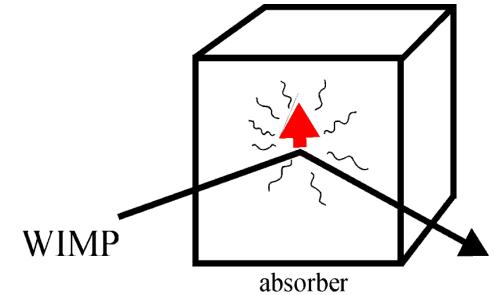
# Physics Results Landscape (2017)



# WIMP-Nucleus Elastic Scattering

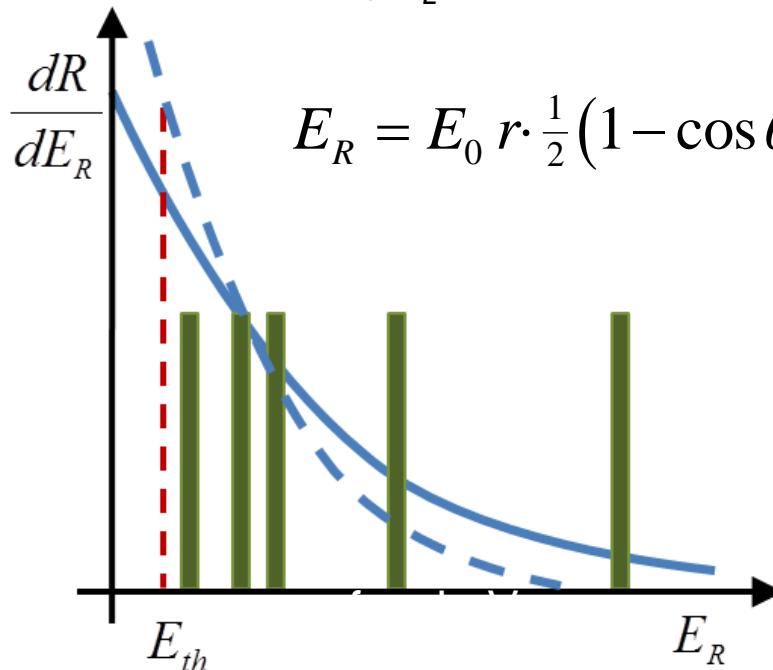
The simplified spherical galactic model

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



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

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



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

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

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

# WIMP-Nucleon Elastic Scattering Cross Sections

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

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

- Note  $A^2$  enhancement factor (coherence)
- Spin-dependent (axial-vector) interaction

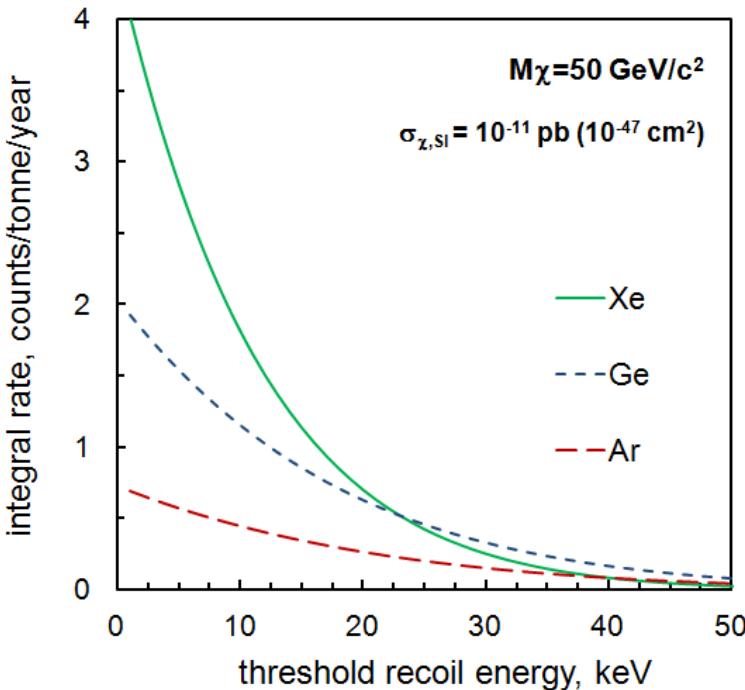
$$\sigma_A^{SD}(q \rightarrow 0) = \frac{\mu_A^2}{\mu_p^2} \sigma_{p,n}^{SD} \left[ \frac{4}{3} \frac{J+1}{J} (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2 \right]$$

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

# The Backgrounds

- Nuclear recoils – same signature, possibly irreducible
  - Neutrons from ( $\alpha$ ,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!)<sup>6</sup>*

# Experimental Challenge



## Key requirements

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

- 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 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...

# Detectors for Direct Searches

## Ionisation Detectors

Targets: Ge, Si,  $\text{CS}_2$ , CdTe

CoGeNT, CDEX, DAMIC, DRIFT,  
DM-TPC, SENSEI, DANAЕ

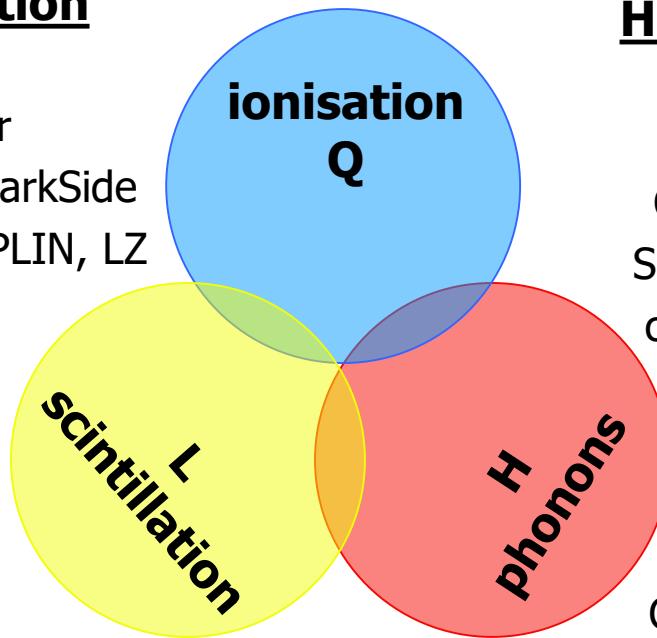
## Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, LUX, WARP, DarkSide  
Panda-X, XENON, ZEPLIN, LZ  
cold ( $\text{LN}_2$ )

## Scintillators

Targets: NaI, Xe, Ar  
ANALIS, CLEAN, DAMA,  
DEAP3600, KIMS, LIBRA,  
NAIAD, XMASS, ZEPLIN-I



## Light & Heat Calorimeters

Targets:  $\text{CaWO}_4$ , BGO,  $\text{Al}_2\text{O}_3$   
CRESST, ROSEBUD  
cryogenic (<50 mK)

## Heat & Ionisation Calorimeters

Targets: Ge, Si  
CDMS, EDELWEISS  
SuperCDMS, EURECA  
cryogenic (<50 mK)

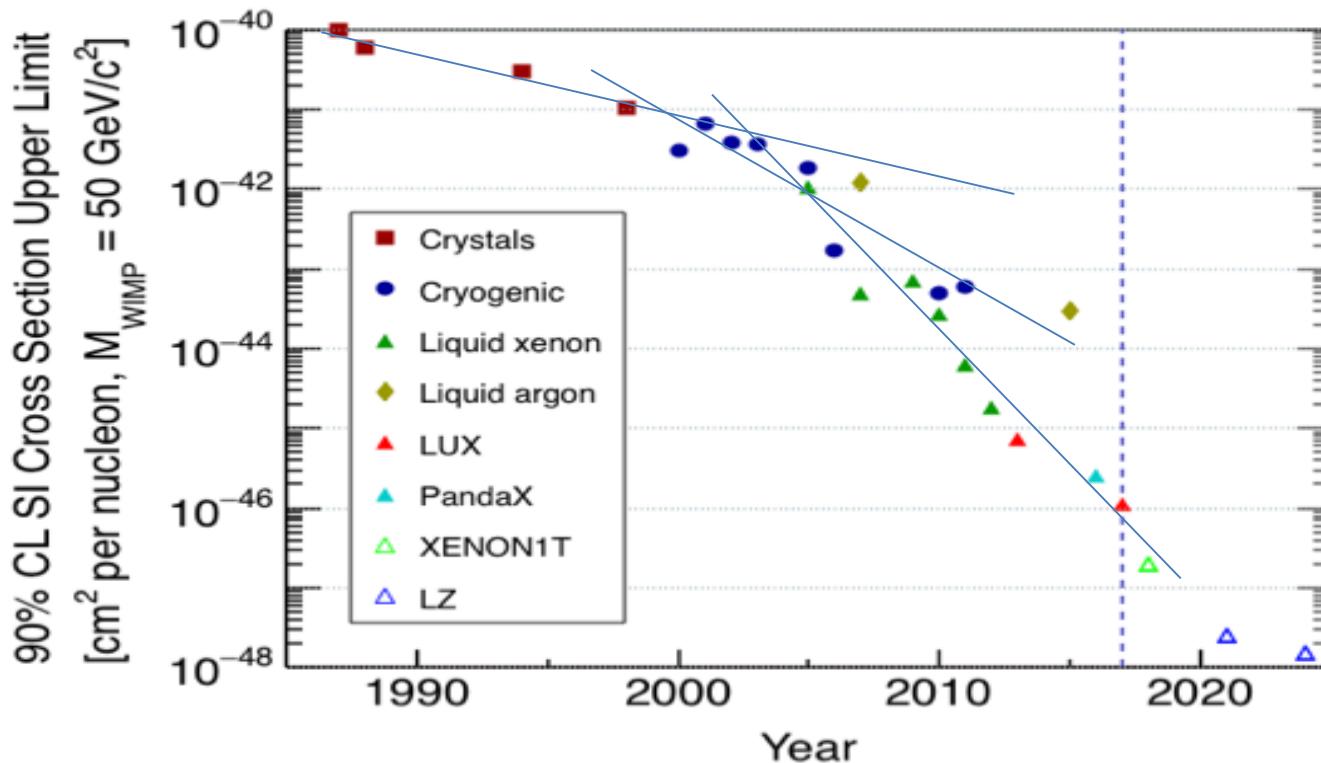
## Calorimeters

Targets: Ge, Si,  $\text{Al}_2\text{O}_3$ ,  $\text{TeO}_2$   
CRESST-I, CUORE, CUORICINO

## Bubbles & Droplets

$\text{CF}_3\text{Br}$ ,  $\text{CF}_3\text{I}$ ,  $\text{C}_3\text{F}_8$ ,  $\text{C}_4\text{F}_{10}$   
COUPP, PICASSO, PICO, SIMPLE

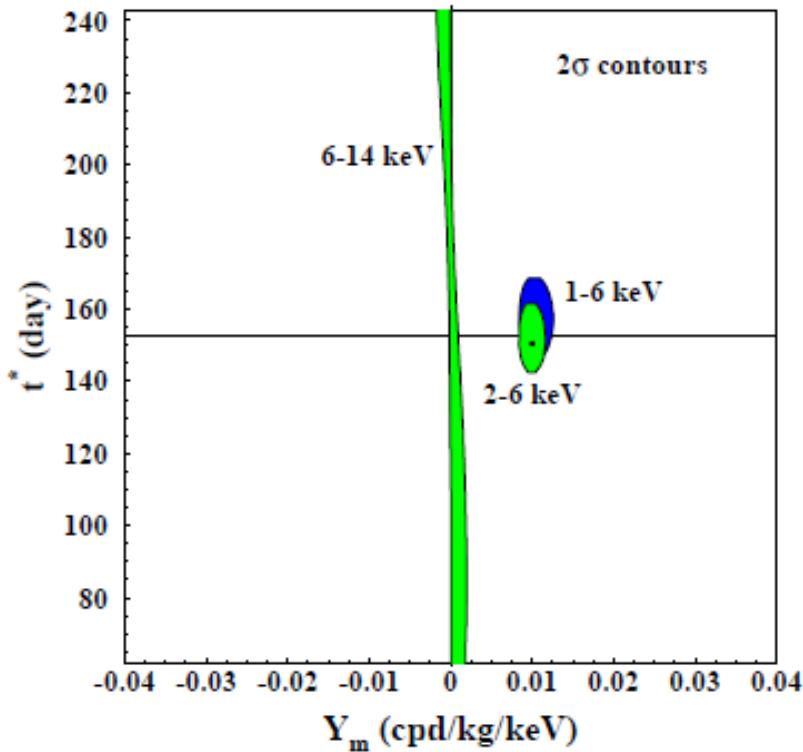
# Direct Detection Techniques



Great progress (every 3 years factor 10) over past 15 years...

Maintaining progress may from time to time require change of technology.

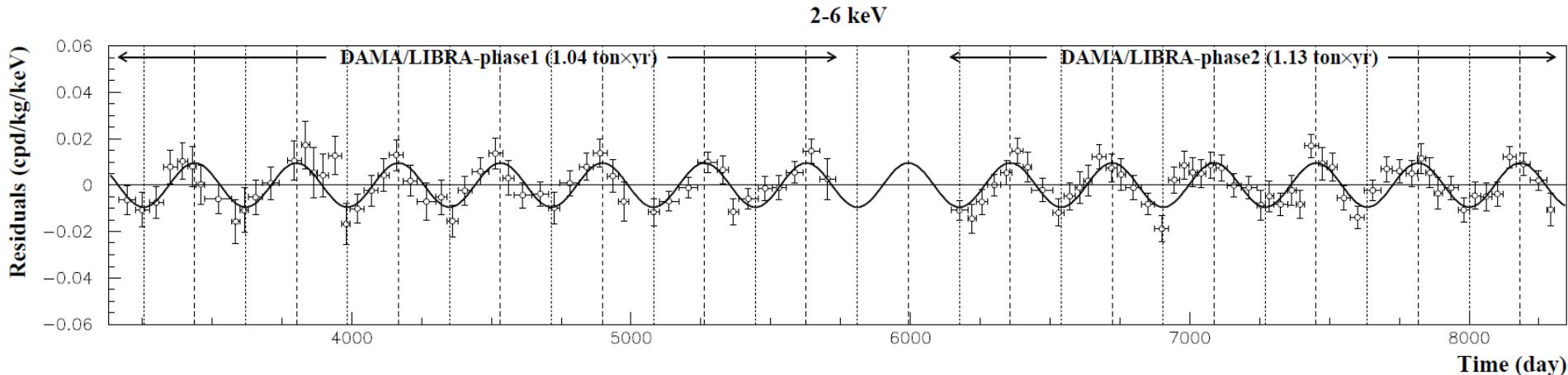
# Annual Modulation – DAMA/LIBRA



- Reduced threshold to 1 keV
- R. Bernabei, arXiv:1805.10486
- $12.9\sigma$  effect

## Cross-checking:

- ANAIS
- DM-ICE
- KIMS/COSINE
- SABRE



# Two-phase Xenon TPC Principle

## 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

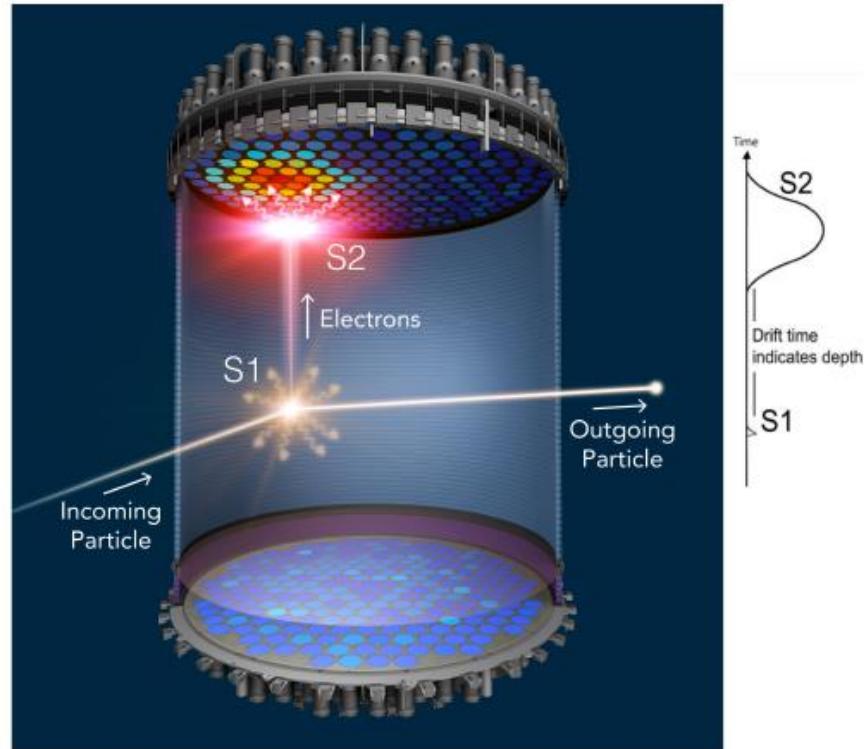
- Electroluminescence in vapour phase
- Sensitive to single ionisation electrons
- Nuclear recoil threshold ~1 keV

## S1+S2 event by event

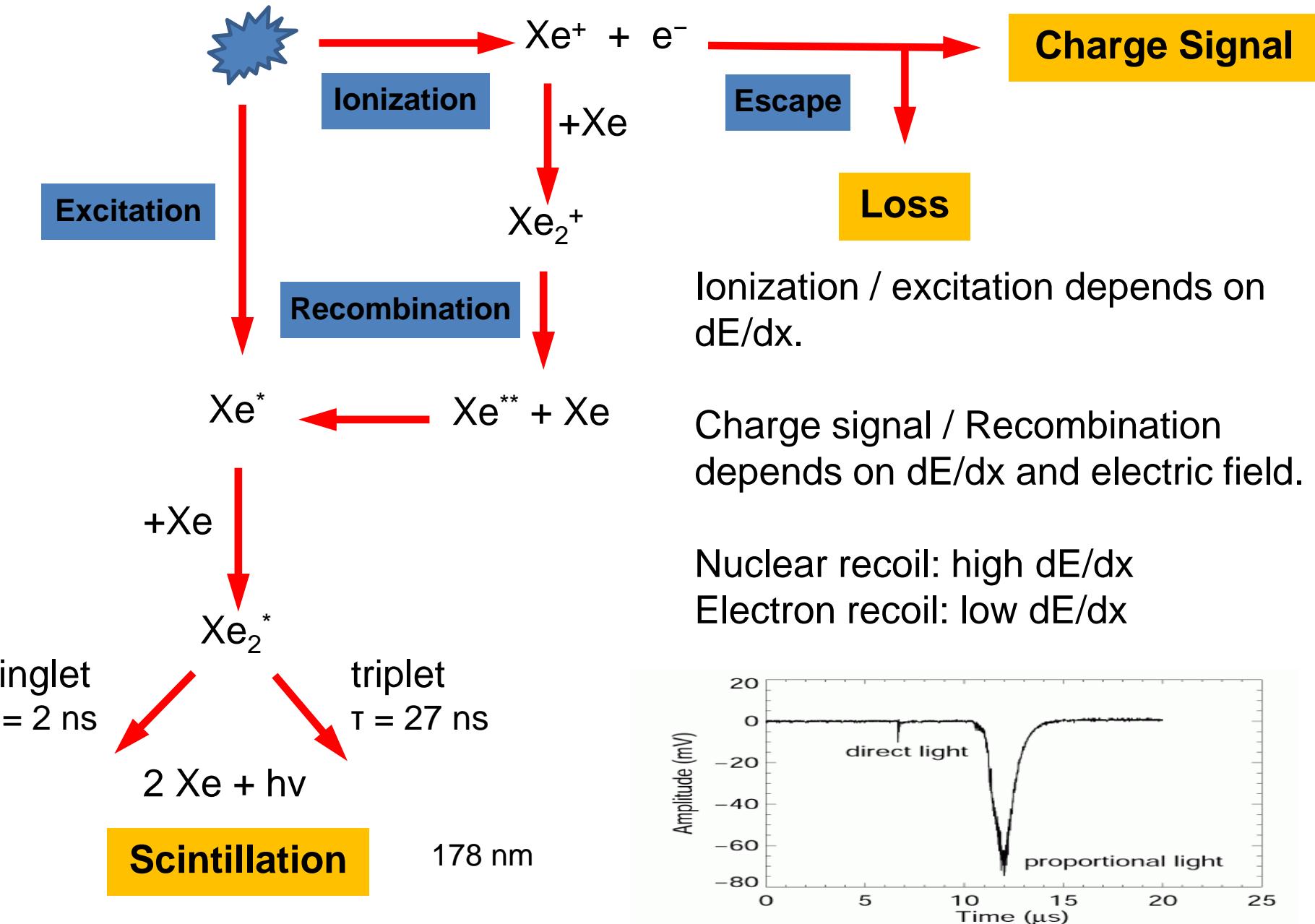
- ER/NR discrimination (>99.5% rejection)
- mm vertex resolution + high density: self-shielding of radioactive backgrounds

## LXe is the leading WIMP target:

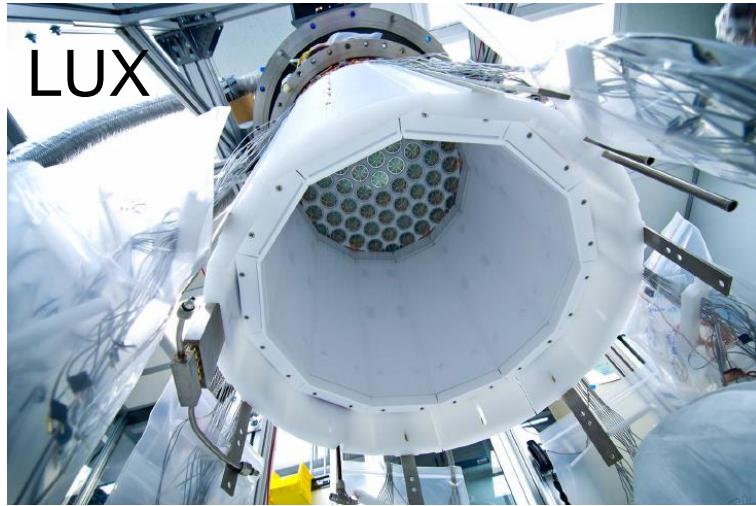
- Scalar WIMP-nucleon scattering rate  $dR/dE \sim A^2$ , broad mass coverage (> 5 GeV)
- Odd-neutron isotopes ( $^{129}\text{Xe}$ ,  $^{131}\text{Xe}$ ) enable SD sensitivity; target exchange possible
- No damaging intrinsic nasties ( $^{127}\text{Xe}$  short-lived,  $^{85}\text{Kr}$  removable,  $^{136}\text{Xe}$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



# Ionization and Scintillation

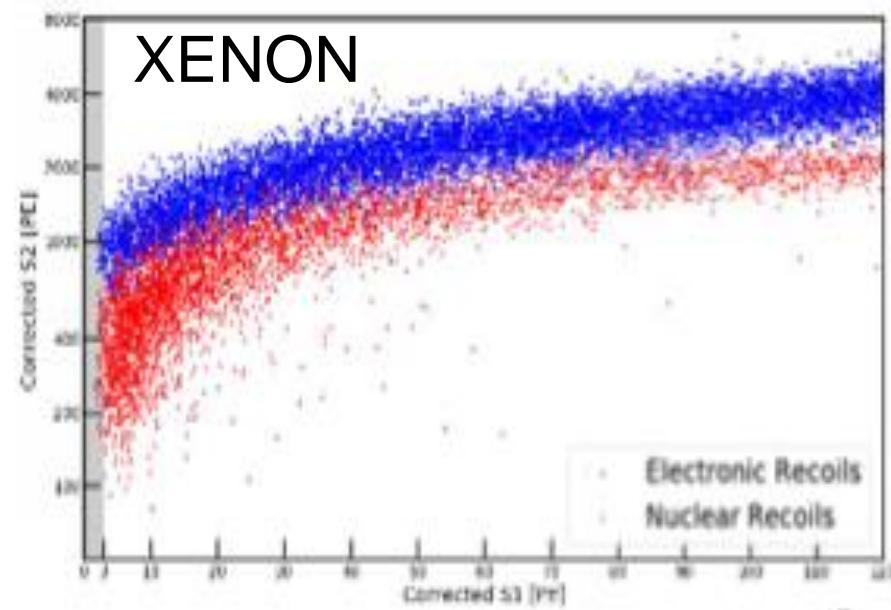
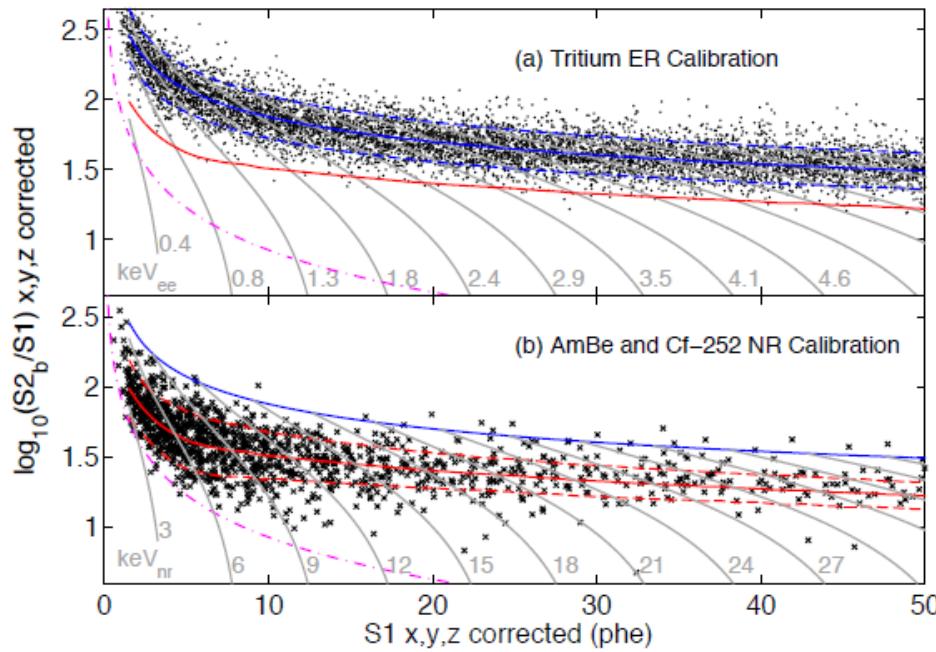


# NR / ER Discrimination



2-phase Xenon Detectors:  
XENON 10, 100, 1T, nT  
Panda-X  
ZEPLIN-III, LUX, LZ

Typically >99.5% discrimination



# XENON1T at LNGS

XENON collaboration, EPJ-C 77 (2017) 12

Water tank and  
Cherenkov muon  
veto

Cryostat / support  
structure for TPC

Time projection  
chamber

Cryogenics pipe  
(cables, xenon)

Cryogenics and  
purification

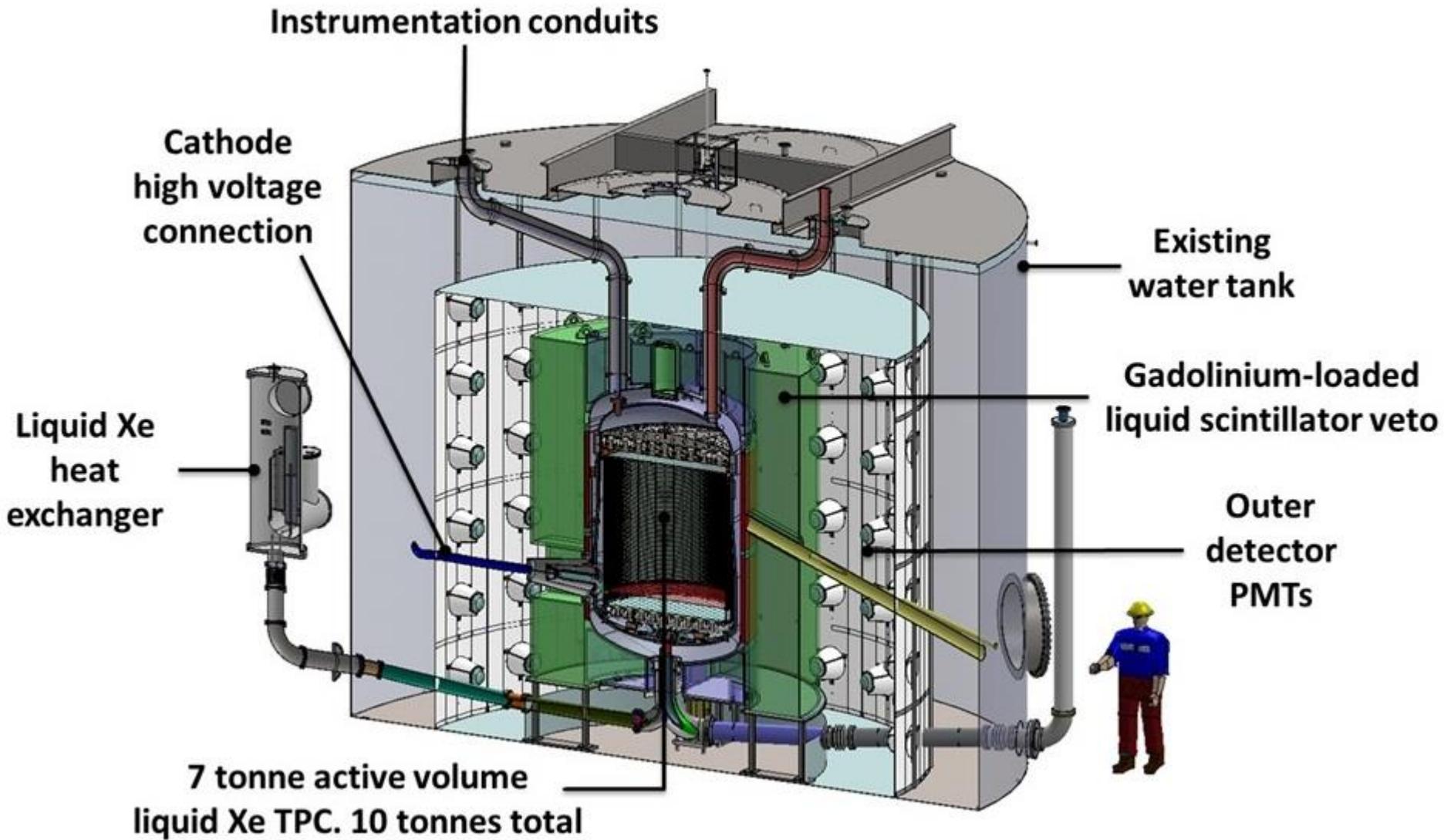
Data acquisition  
and  
slow control

Xenon storage,  
handling and  
Kr removal via  
cryogenic  
distillation



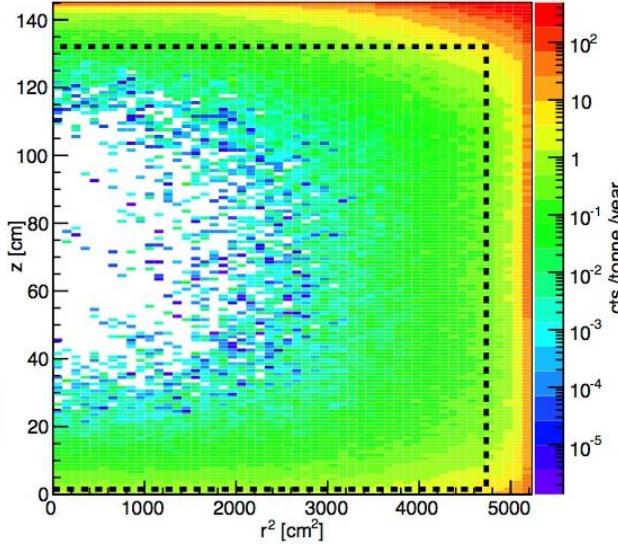
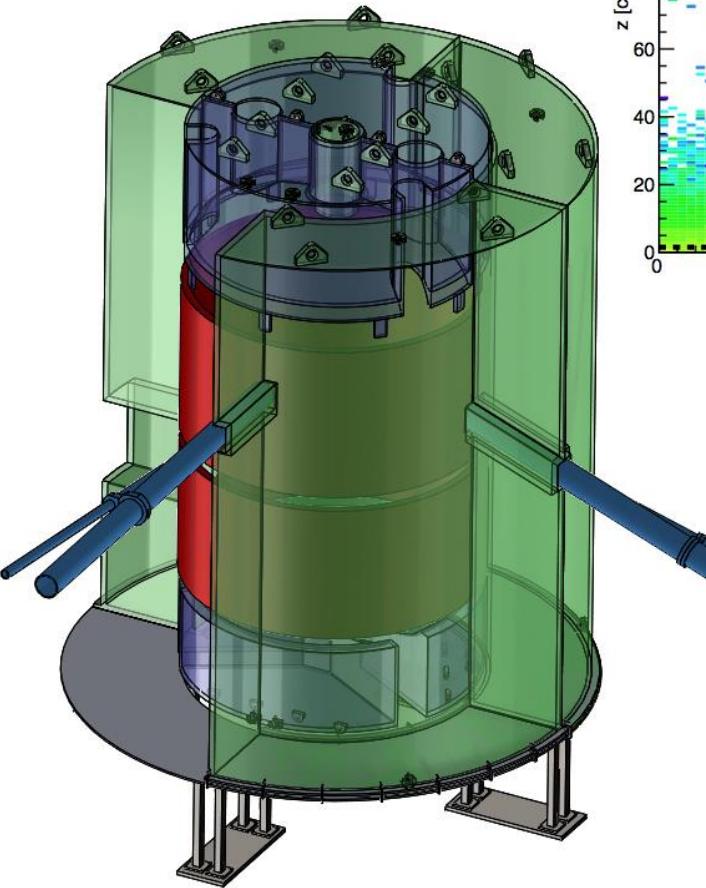
# LZ at SURF

LZ Technical Design Report, arXiv:1703.09144

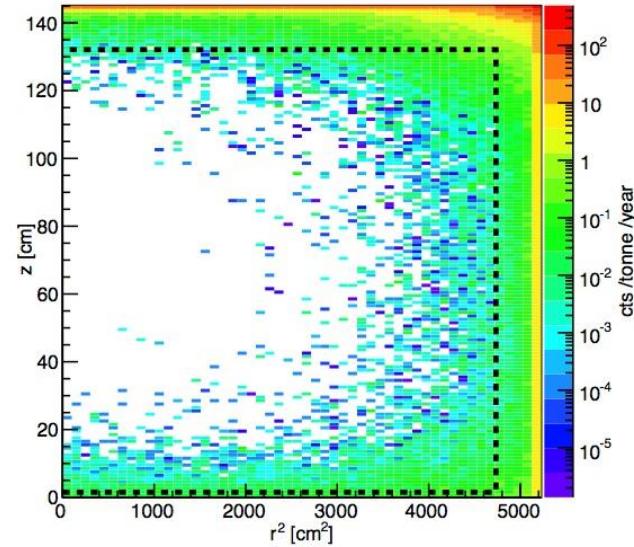


# LZ Outer Detector Design and Impact

LXe TPC only: 3.8t fid

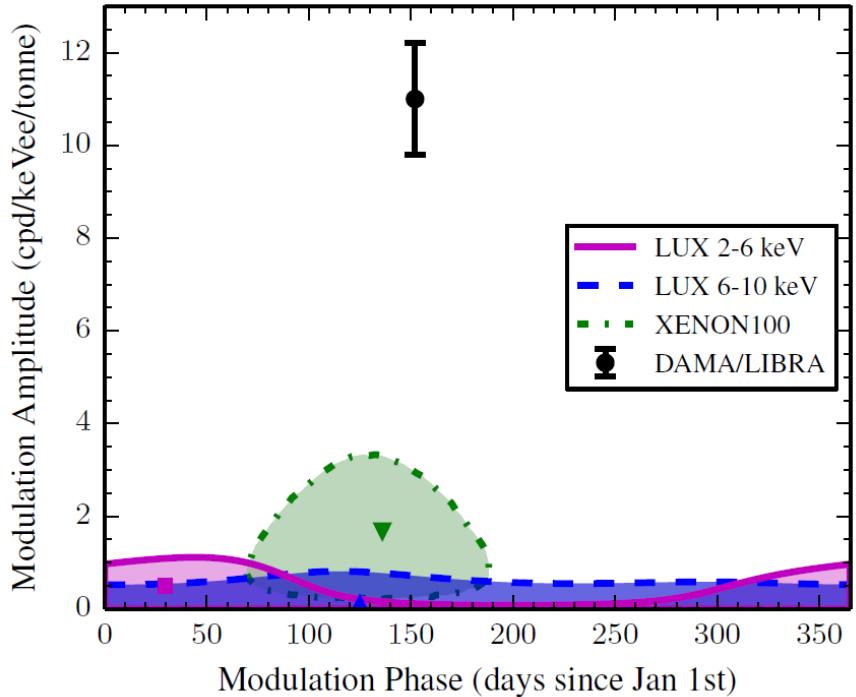


TPC+Skin+OD 5.6t fid

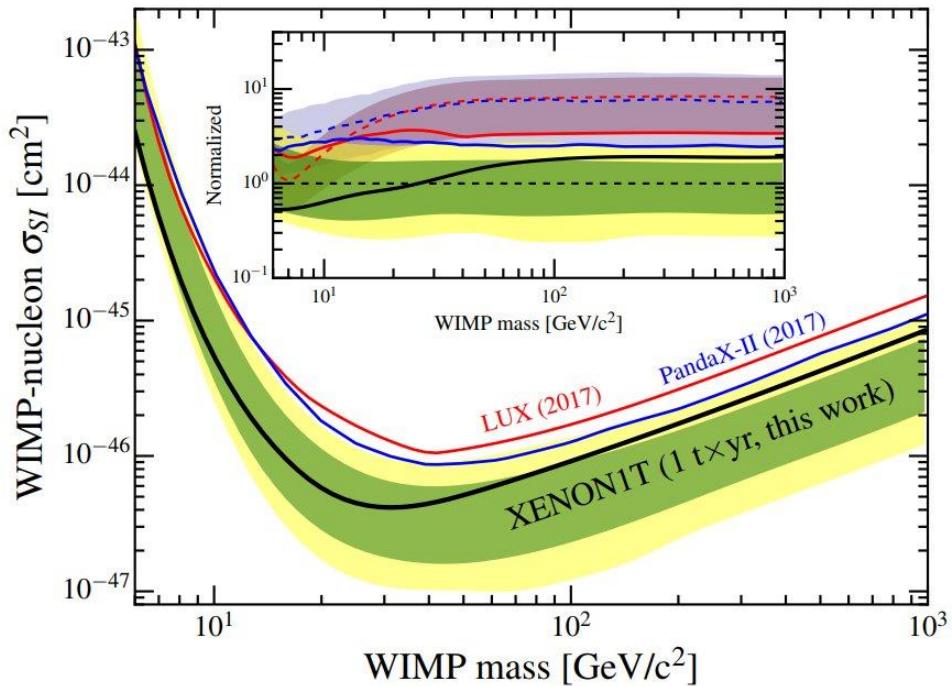


- External tagging allows greater fiducial volume for analysis
- 60 cm thick, 17.2 t of gadolinium-loaded liquid scintillator, 120 8" PMTs
- 97% efficiency for neutrons

# Xe TPC Results



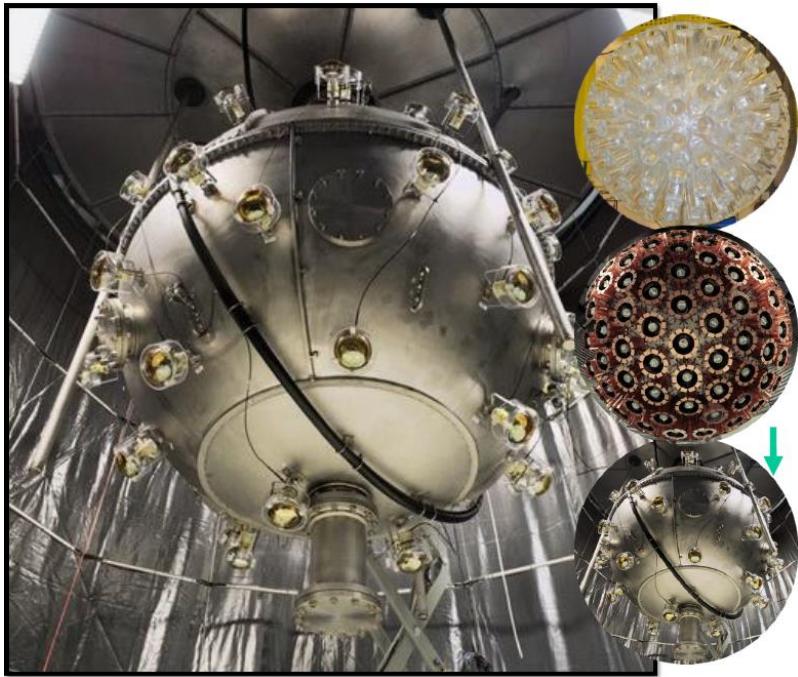
No evidence for annual modulation signal in LUX



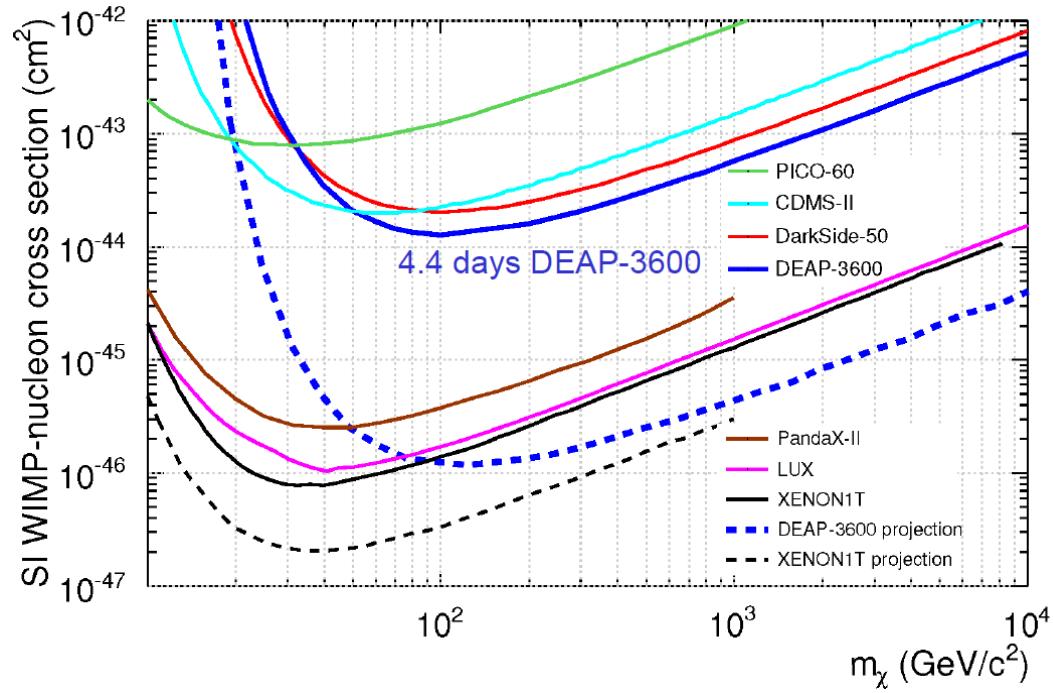
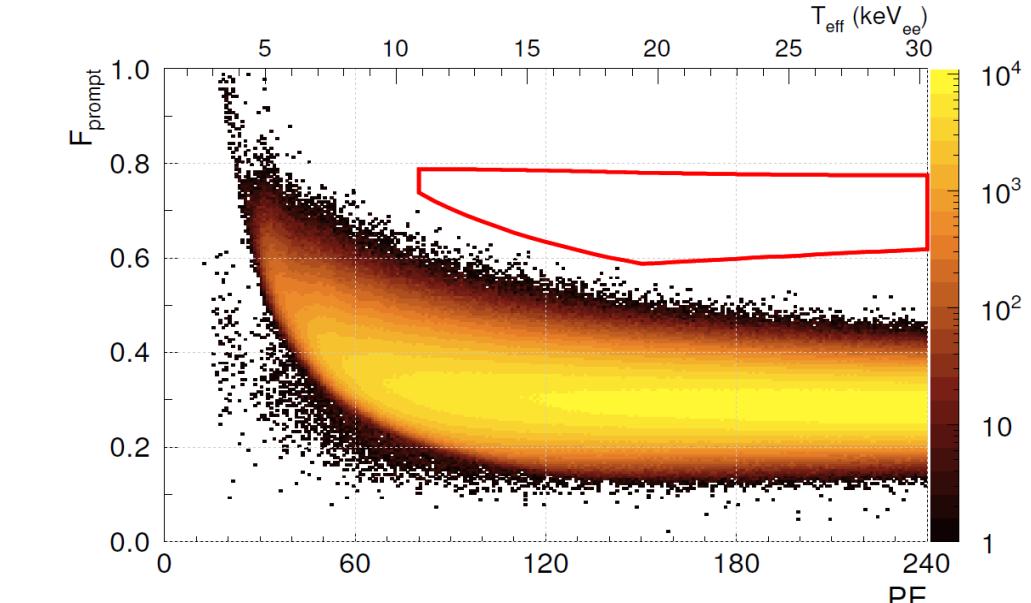
1- $\sigma$  fluctuation at higher WIMP masses could be due to background or signal

$$\sigma_{SI} < 4.1 \times 10^{-47} \text{ cm}^2 \text{ at } 30 \text{ GeV/c}^2$$

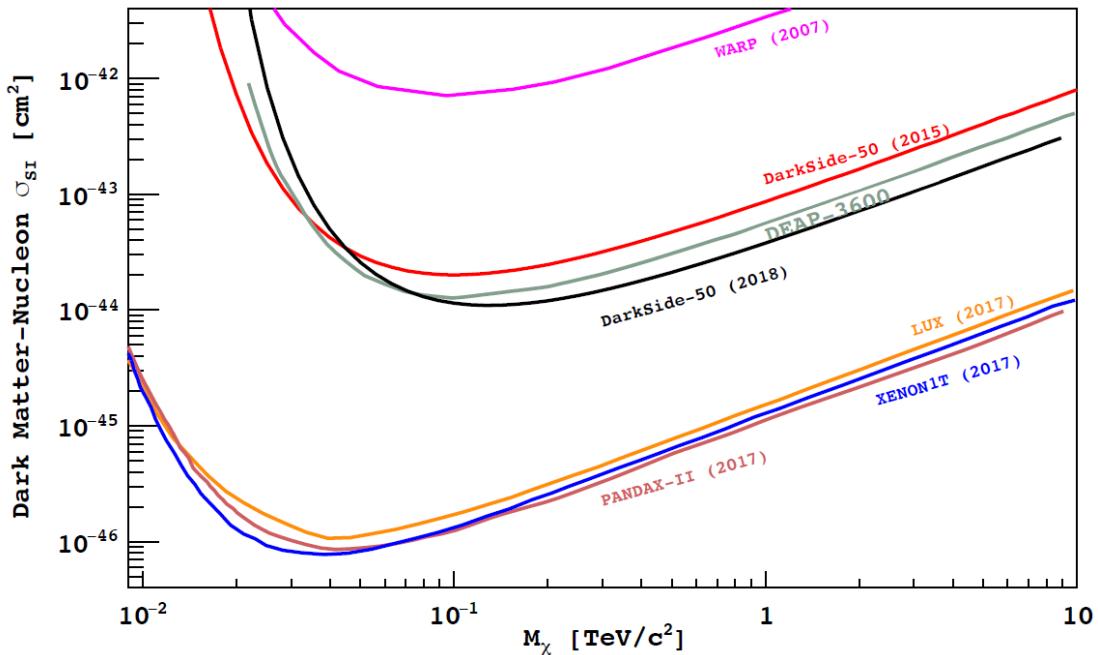
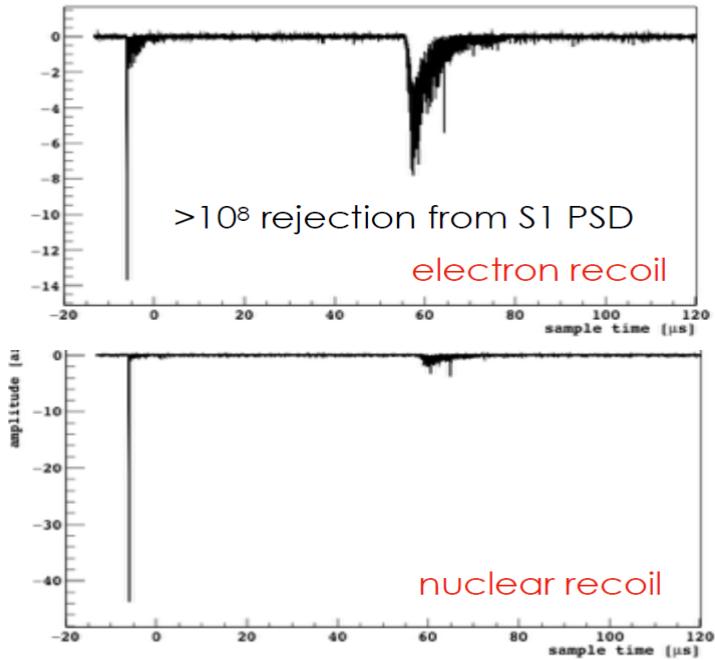
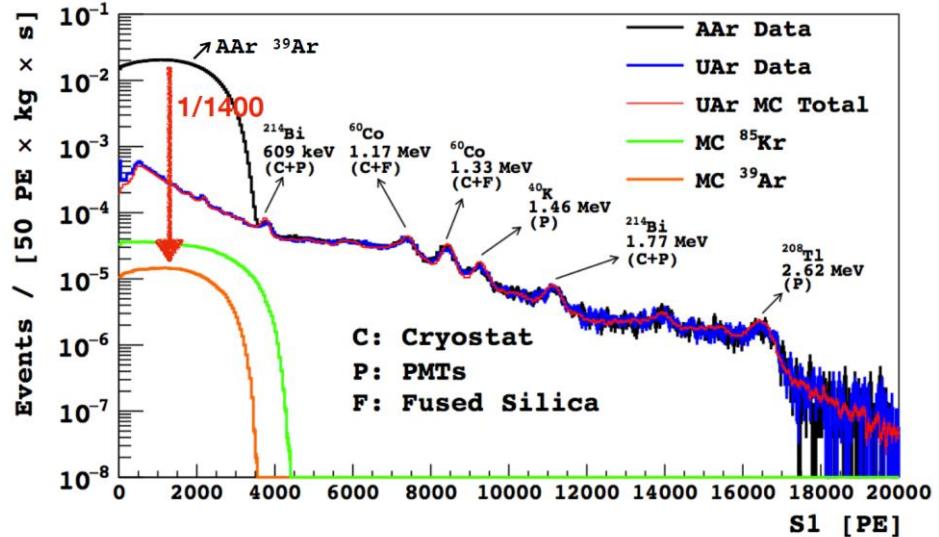
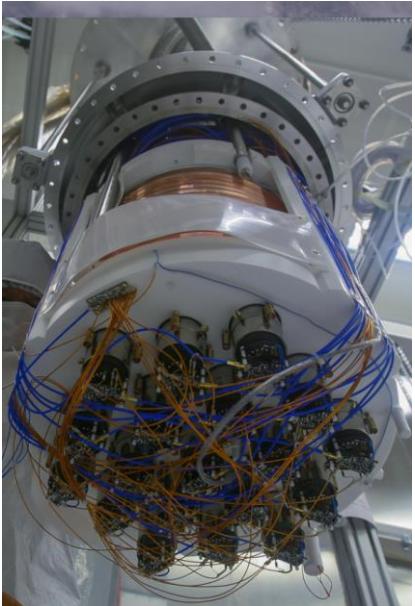
# DEAP-3600



- Will run to 2020.
- Beyond DEAP-3600: significant global collaboration of argon DM searches.
- DS-20K at LNGS and future multi-hundred tonne detector.

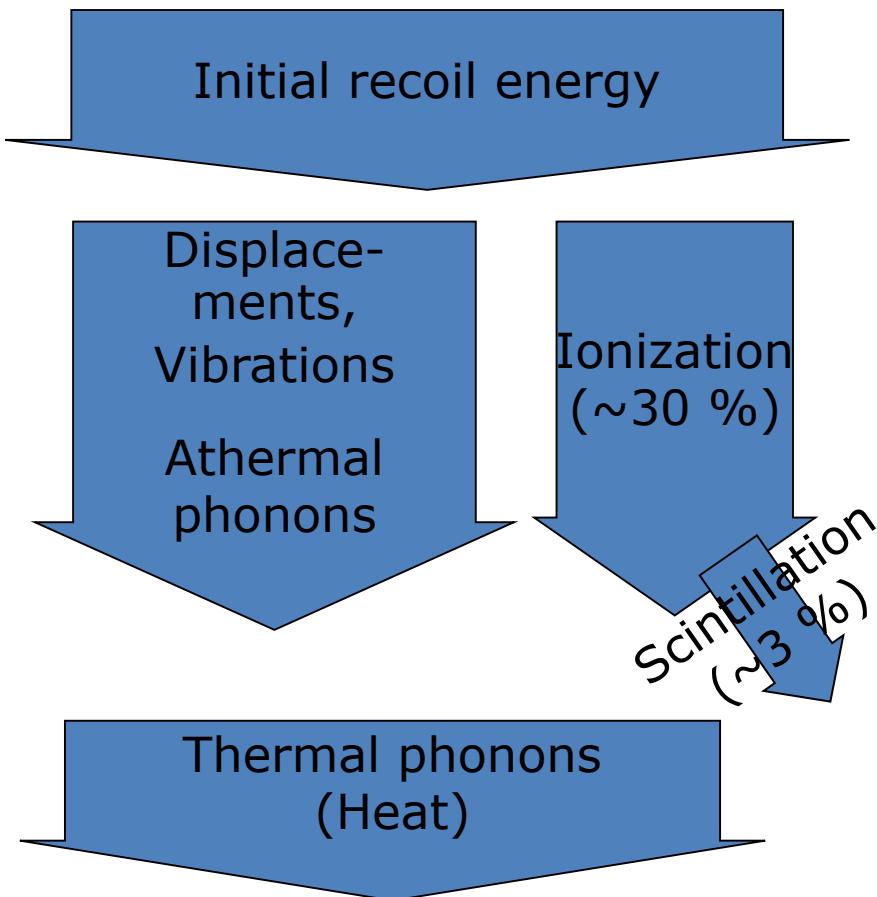


# DarkSide



# Cryogenic Detectors

## Phonon-ionization / phonon-scintillation

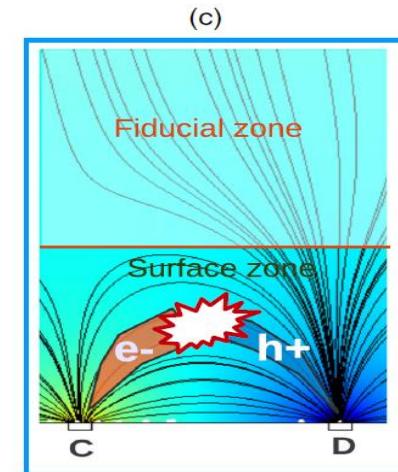
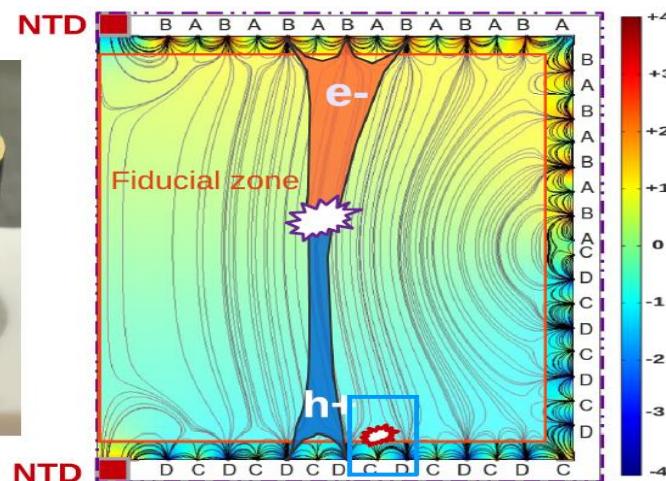
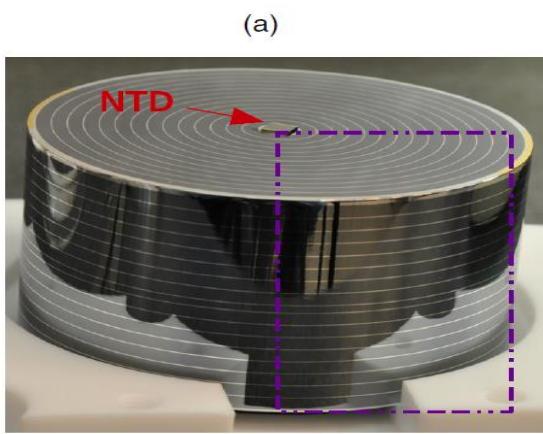


**Phonon:** most precise total energy measurement

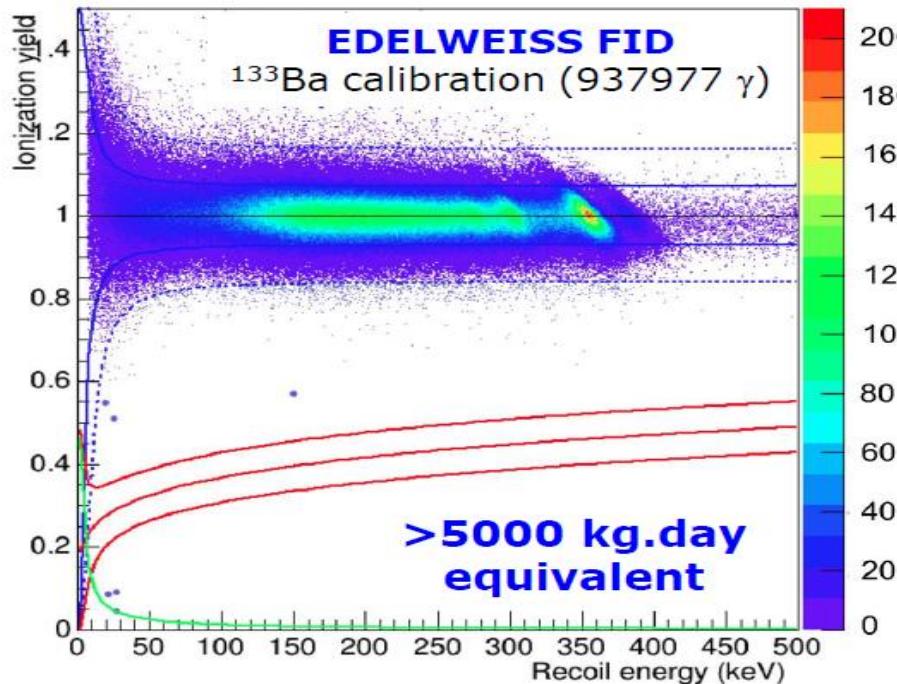
**Ionization / Scintillation:** yield depends on recoiling particle

Nuclear / electron recoil discrimination.

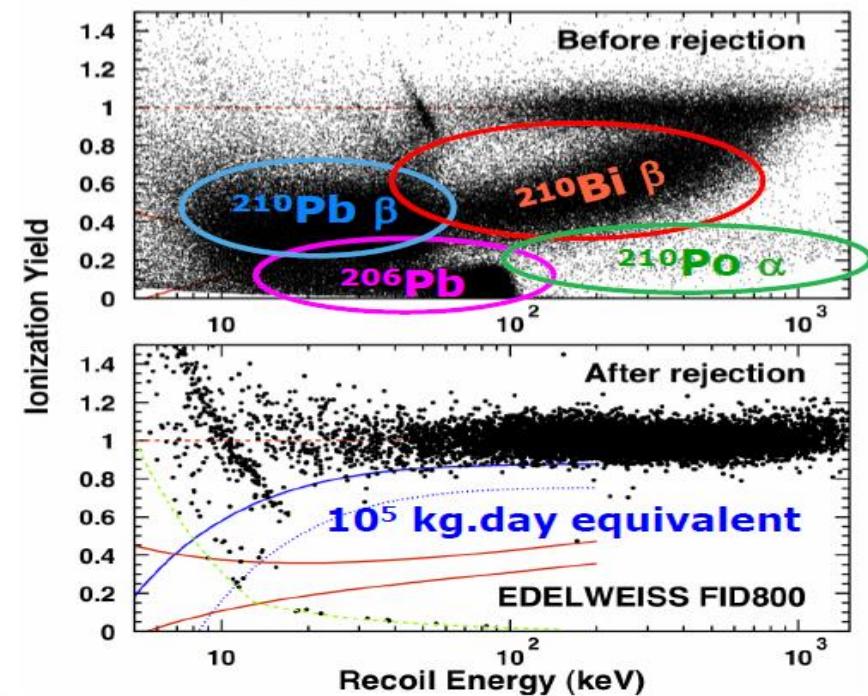
# EDELWEISS Detectors



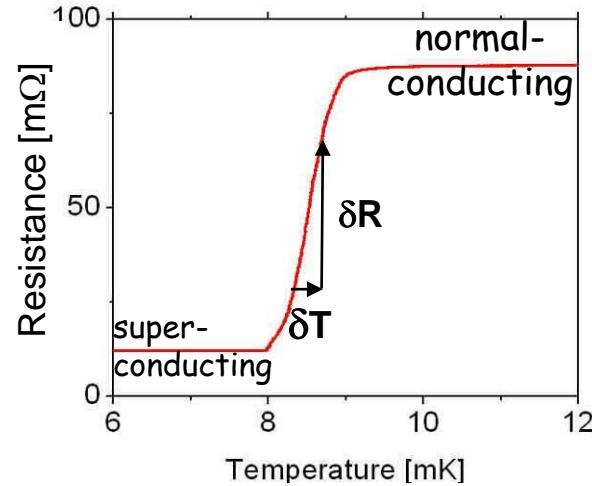
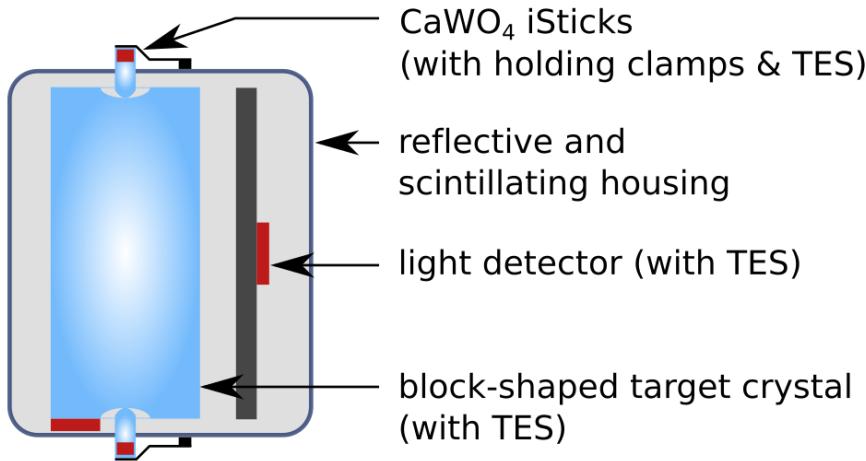
Gamma rejection  $< 2.5 \times 10^{-6}$



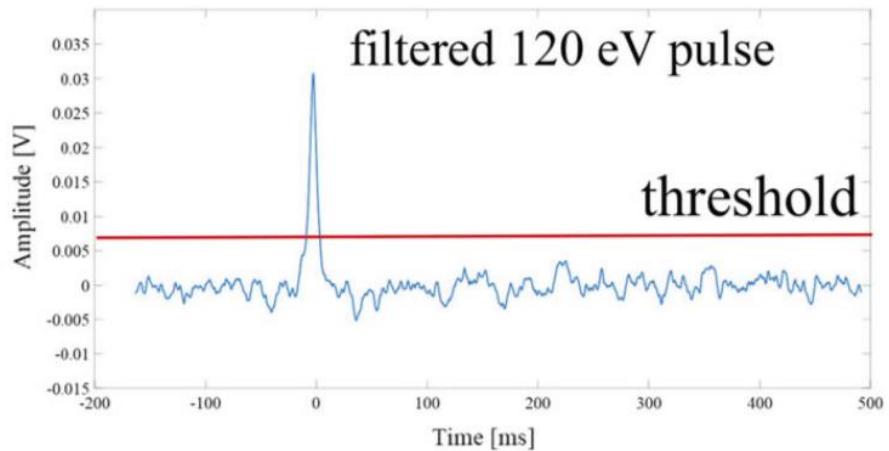
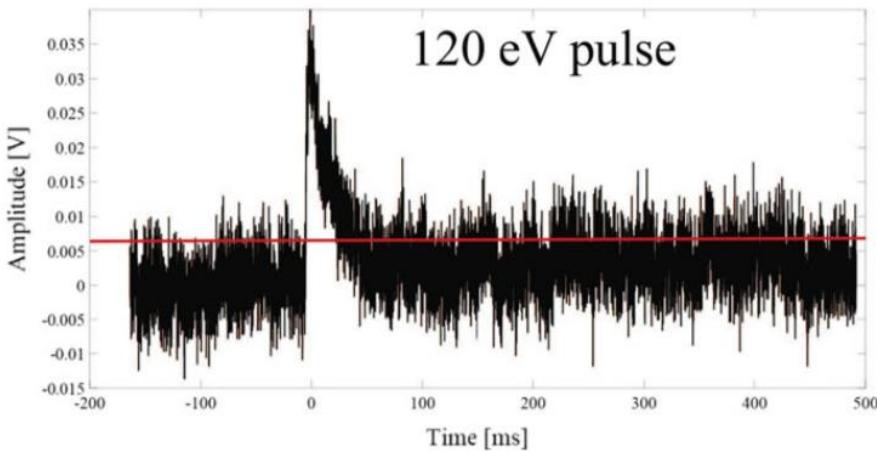
Surface event rejection  $< 4 \times 10^{-4}$



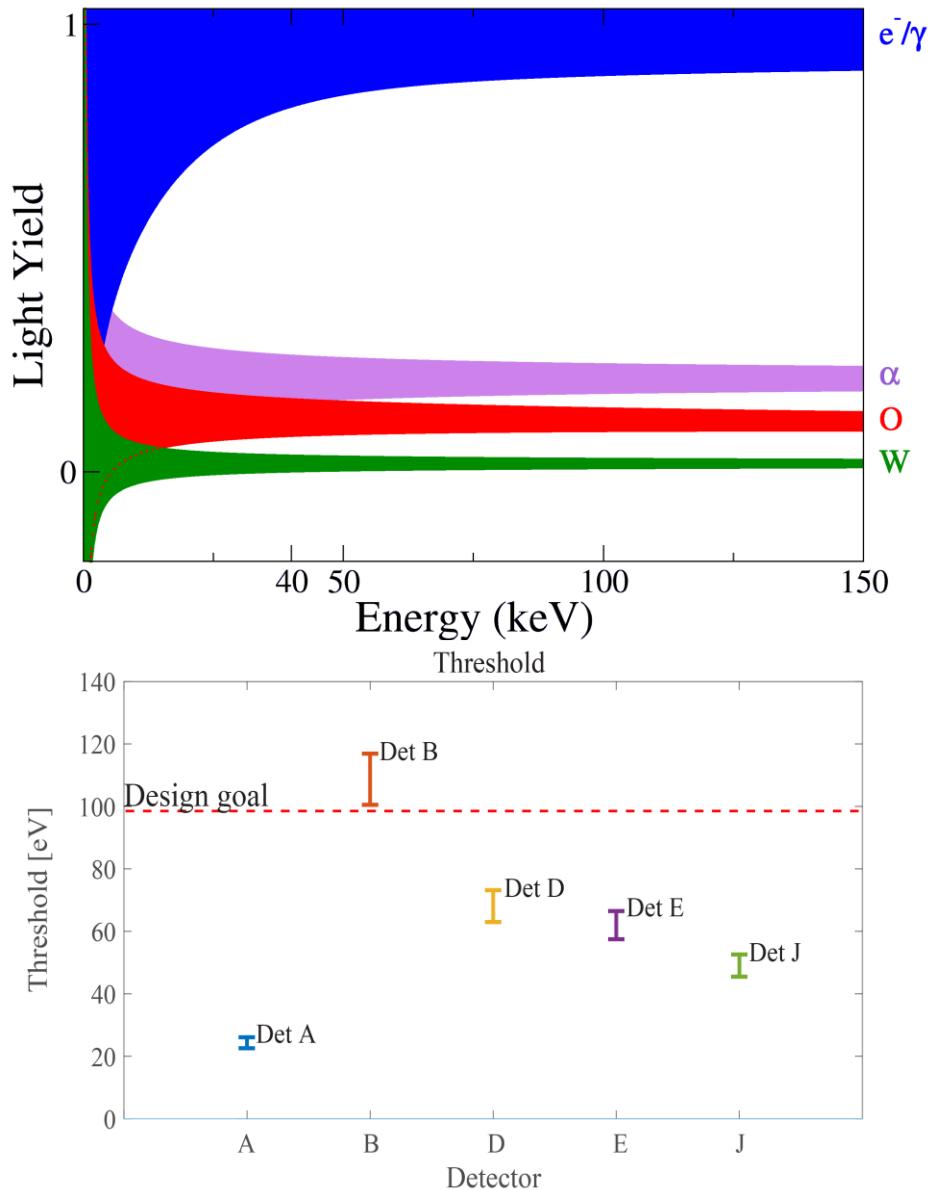
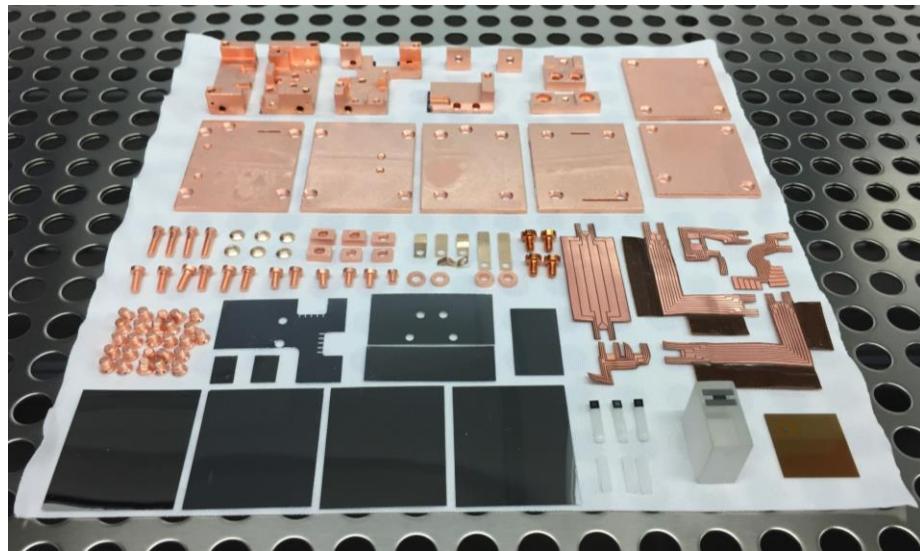
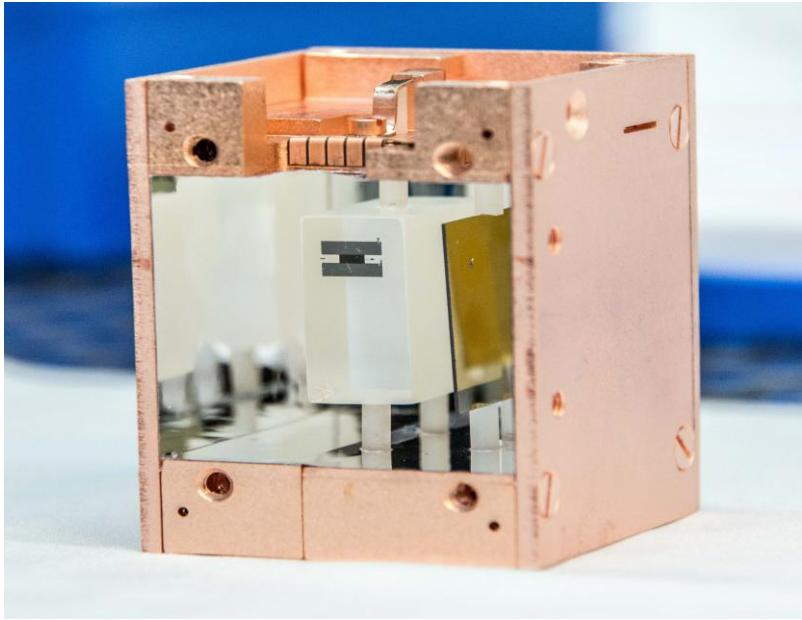
# CRESST Detectors



Width of transition: ~1mK  
Signals: few  $\mu$  K  
Stability: ~  $\mu$  K

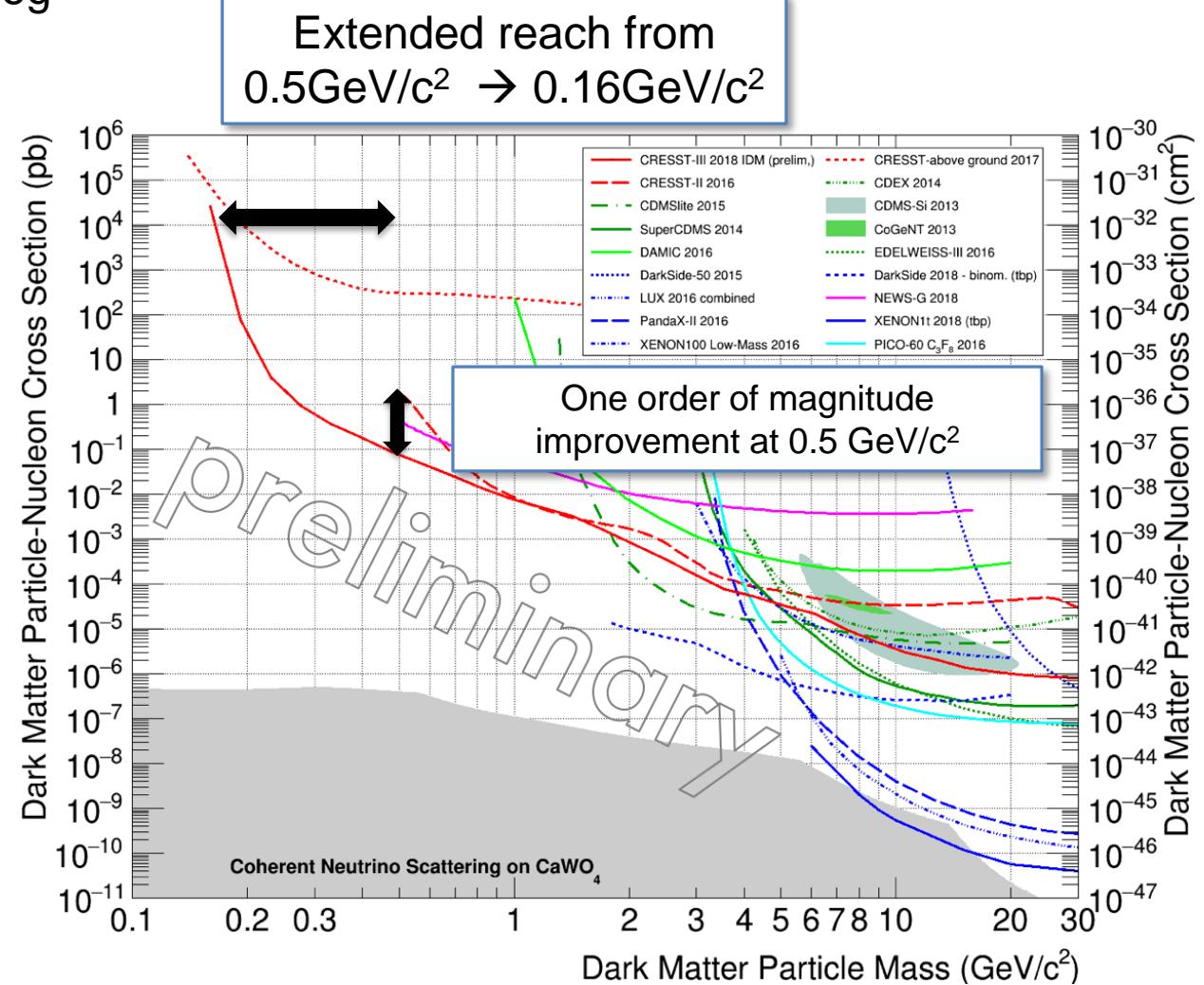


# Phonon Scintillation (CRESST-III)



# CRESST Status (2018 results)

- Exposure 2.21 kg days
- Absorber volume 23.6g
- Threshold 30.1 eV



# Summary

- Many more experiments / techniques, not covered here
- Xenon TPC racing towards  $10^{-48} \text{ cm}^2$
- Argon community working towards global collaboration
- Cryogenic calorimeter focussing at lowering energy threshold
- Annual modulation in NaI to be tested by multiple detectors
- Creative new approaches emerging – and necessary now