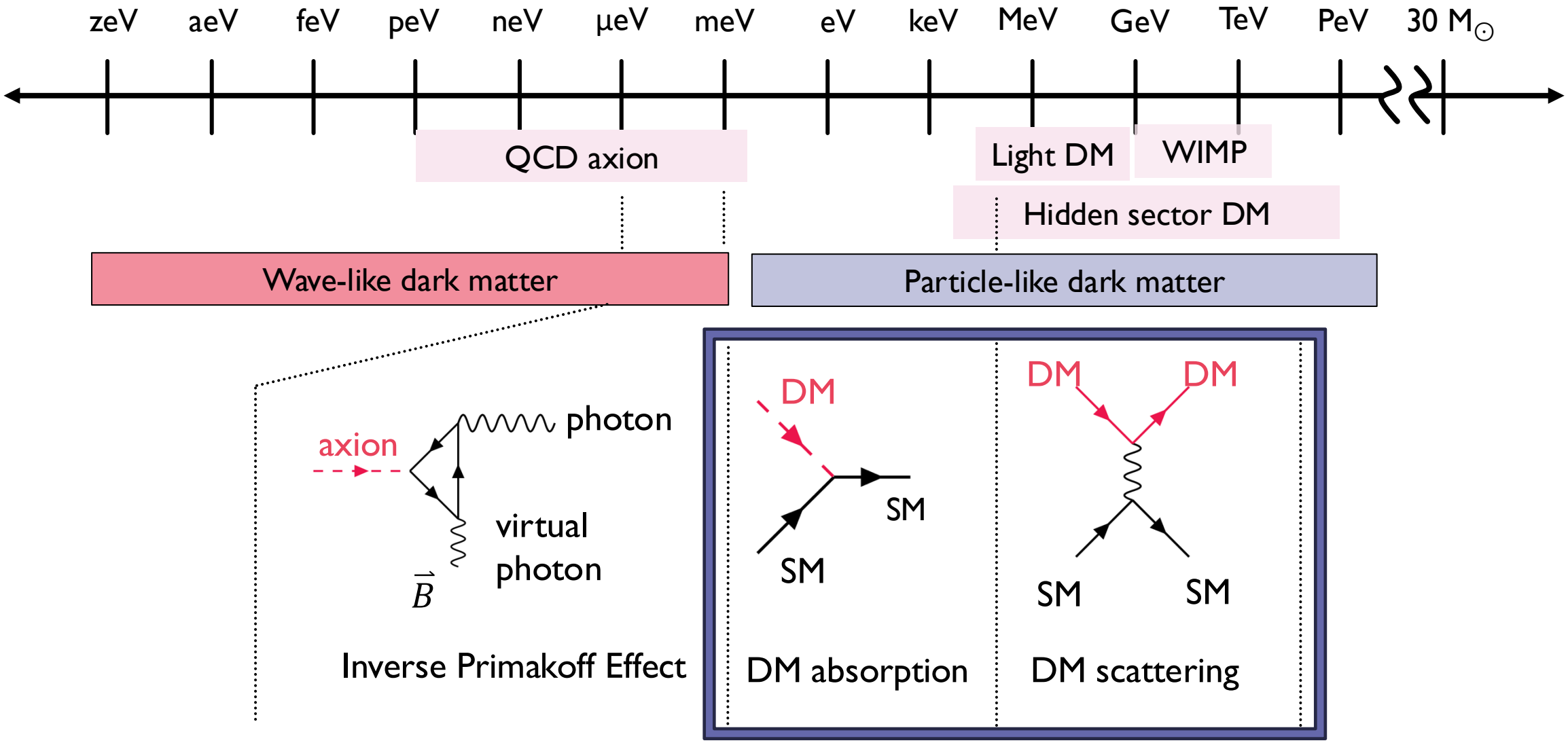
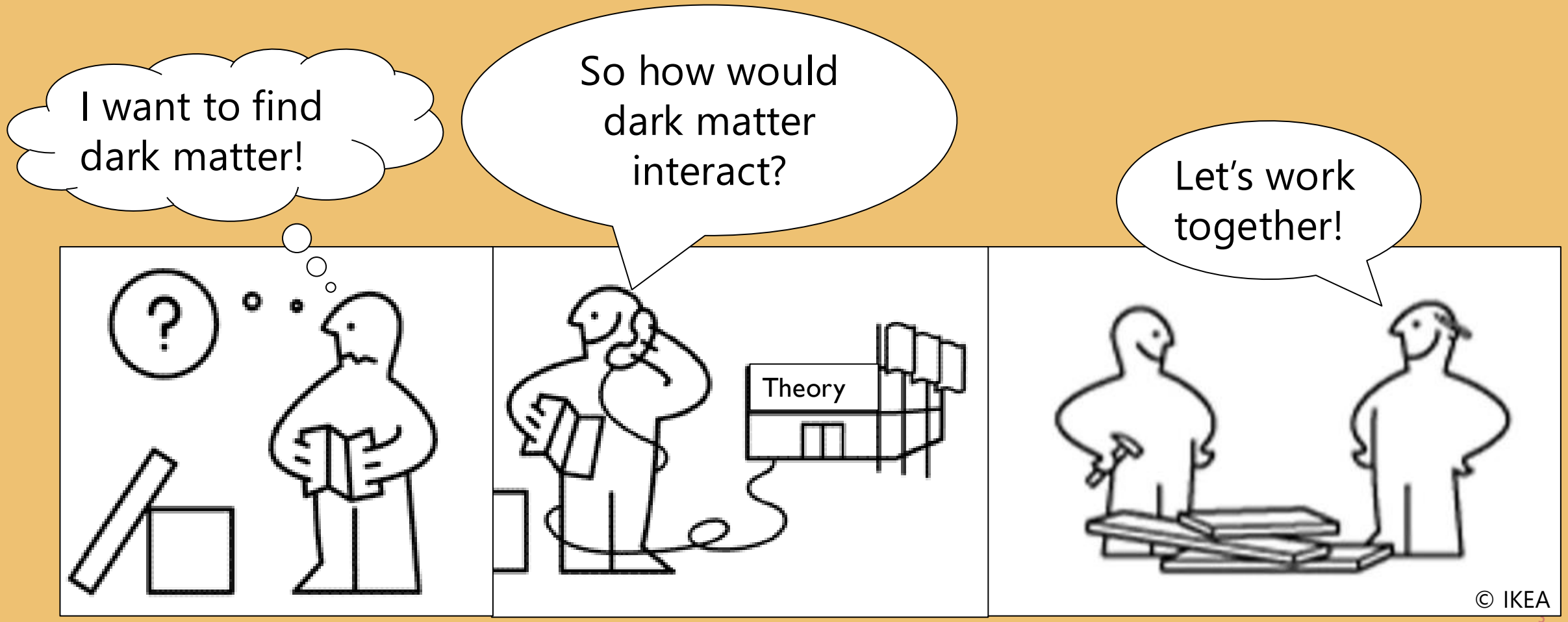
EXPERIMENTAL TECHNIQUES FOR DARK MATTER DIRECT DETECTION

THERESA FRUTH
UNIVERSITY OF SYDNEY

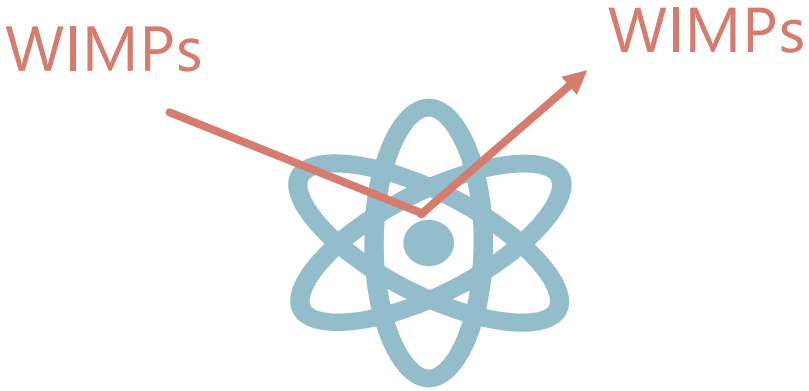
NUPP SUMMER SCHOOL
23 JAN 2026


zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
30 M⊙
QCD axion
Light DM
WIMP
Hidden sector DM
Wave-like dark matter
Particle-like dark matter
axion
photon
virtual
photon
$\vec{B}$
Inverse Primakoff Effect
DM
SM
SM
DM absorption
DM
DM
SM
SM
DM scattering

LET'S DESIGN A DETECTOR



DARK MATTER – NUCLEUS SCATTERING



DM particle (mass: GeV-TeV) scatters elastically of nucleus causing a nuclear recoil

- Rare events (< 0.0001 evt/kg/day)
- Low energy (~ keV scattering)

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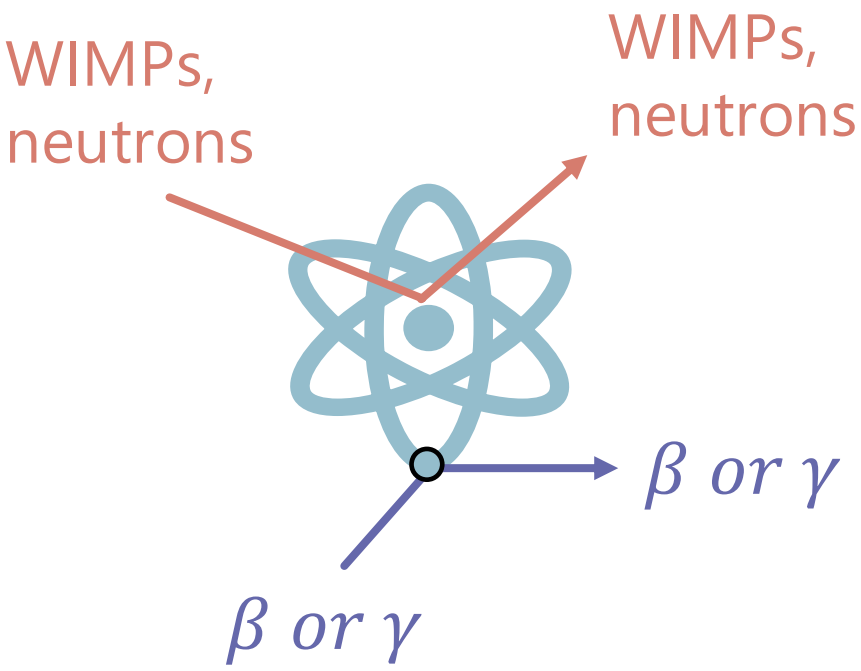

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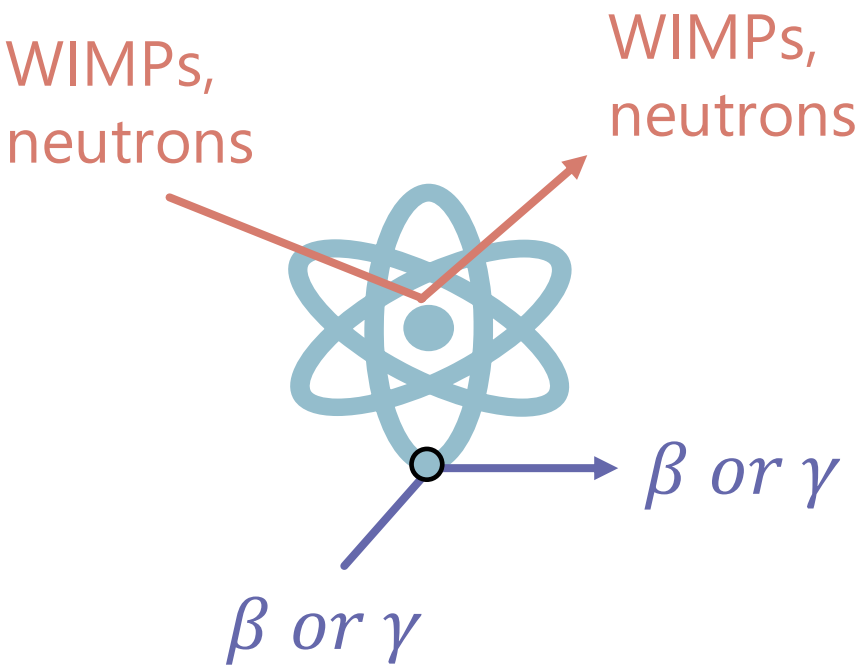

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We need to:

- Reduce backgrounds
- Achieve low energy thresholds
- Maximise exposure

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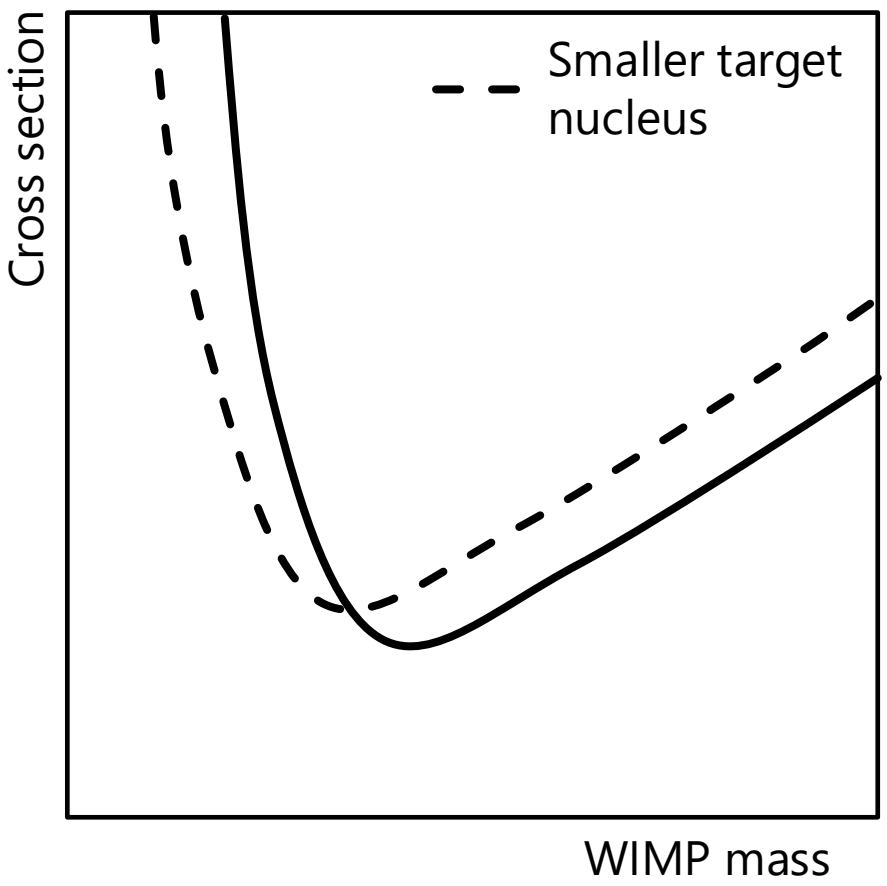

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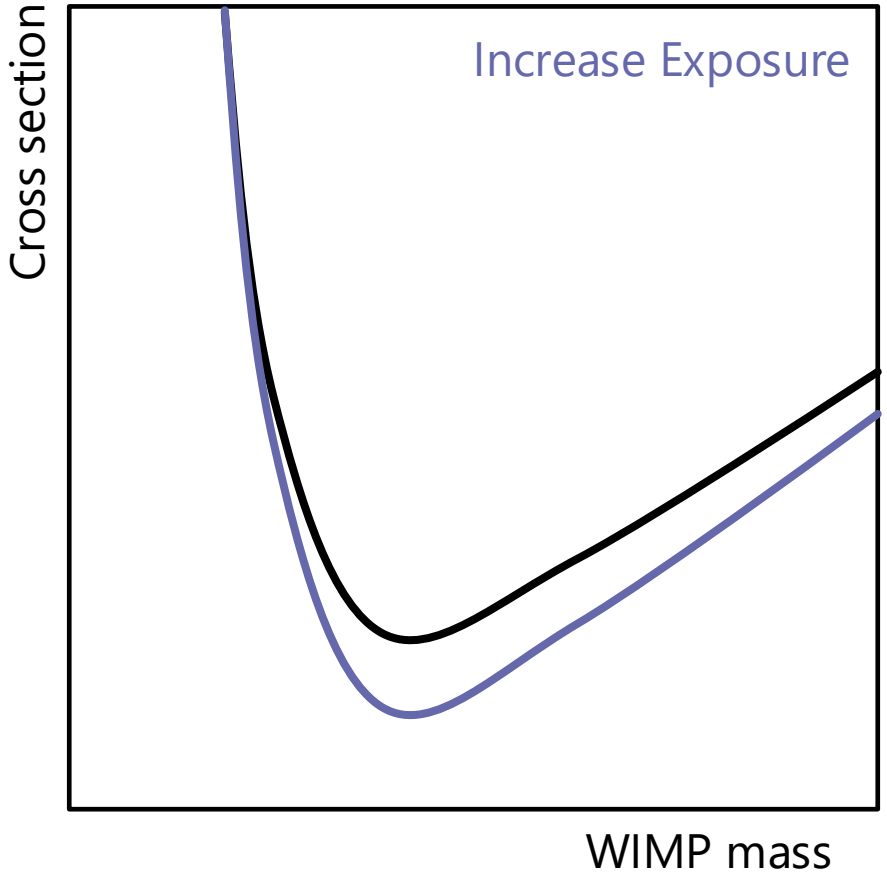

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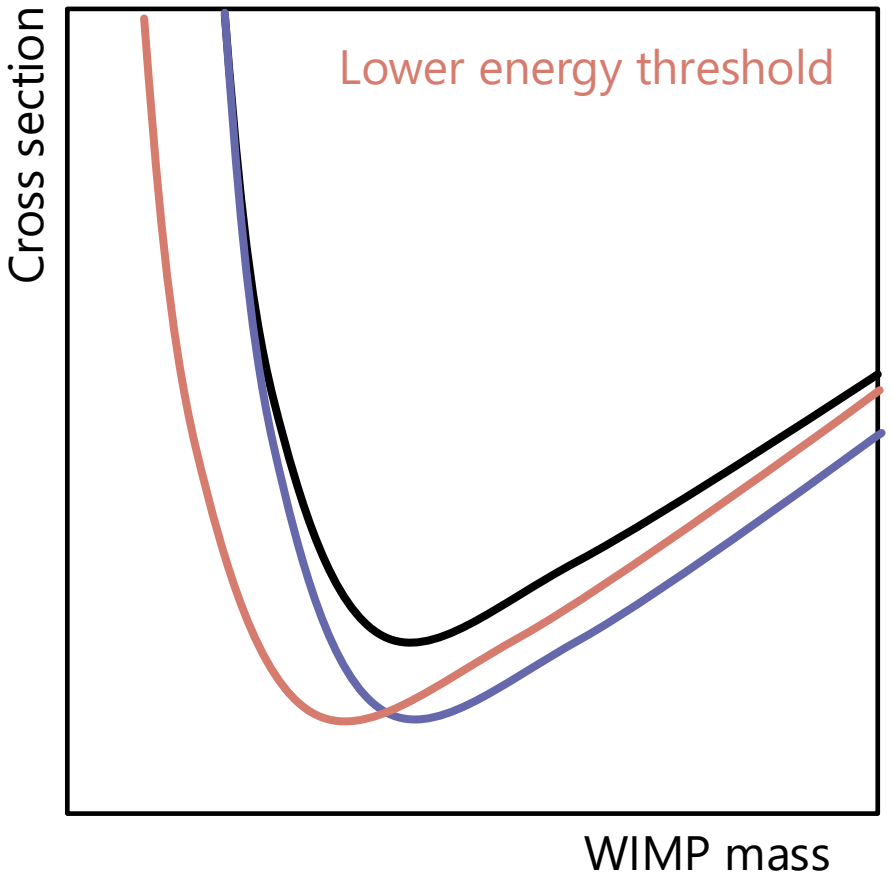

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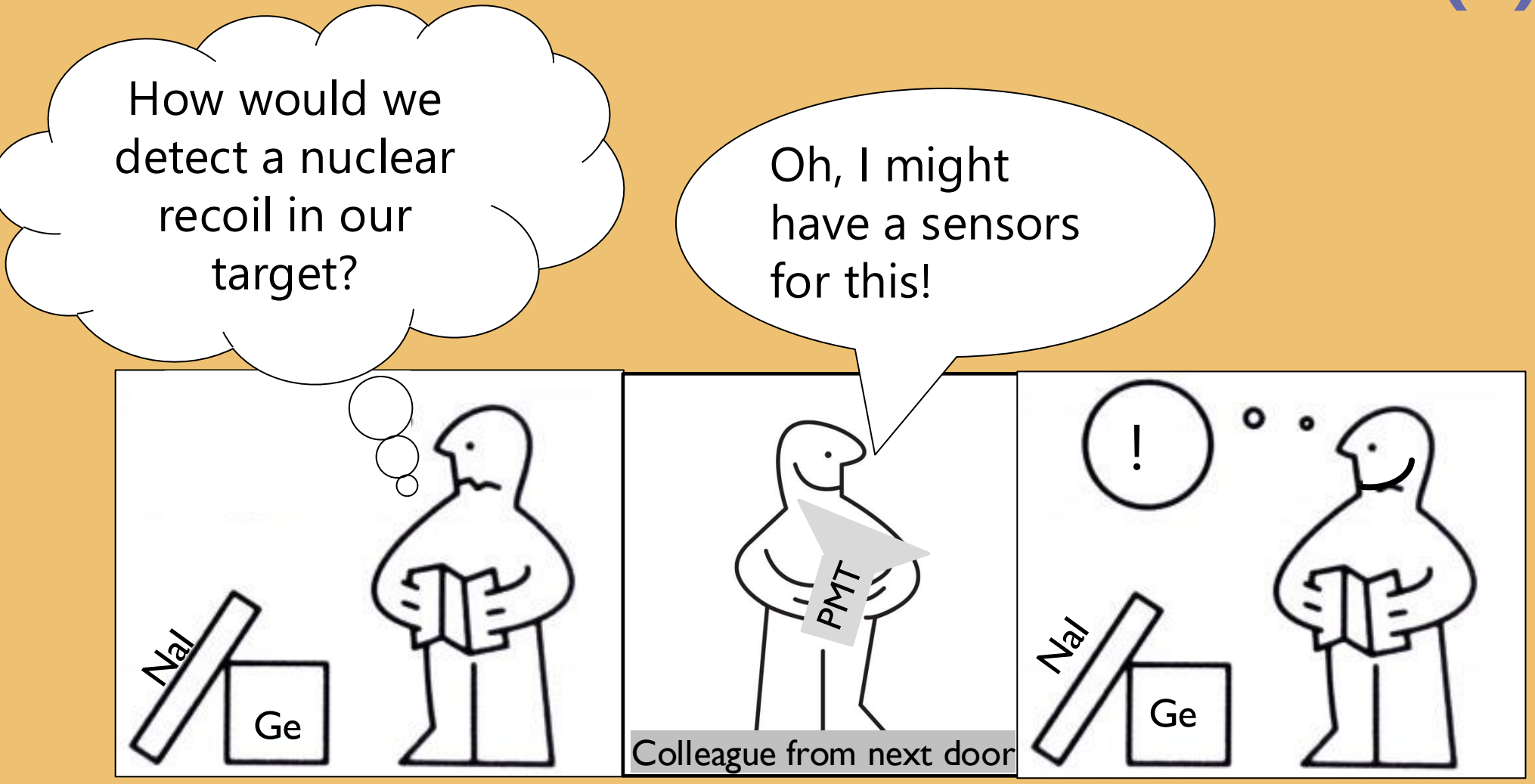
EXPERIMENTAL CHALLENGES

- Target material sensitive to the interaction
- Technology to detect interaction
- Understand and reduce backgrounds
- Calibrate detector response
- Analysis techniques

LET'S DESIGN A DETECTOR (2)



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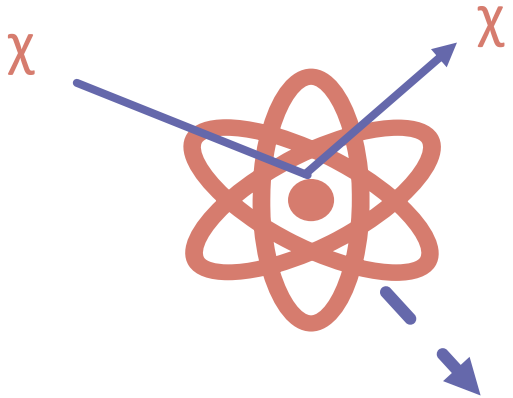
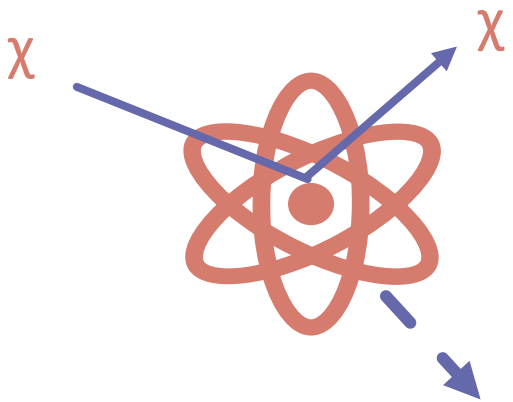
NUCLEAR RECOIL DETECTION



$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{elec} + \left(\frac{dE}{dx}\right)_{nucl}$$

NUCLEAR RECOIL DETECTION

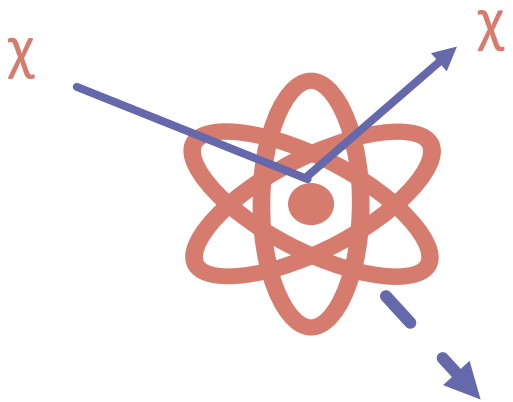


Atomic motion

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{elec} + \left(\frac{dE}{dx}\right)_{nucl}$$

Ionization & excitation

NUCLEAR RECOIL DETECTION



Heat/Phonons

↑

Atomic motion

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Ionization & excitation

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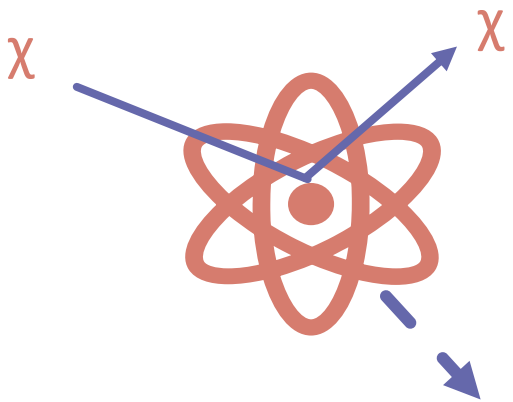

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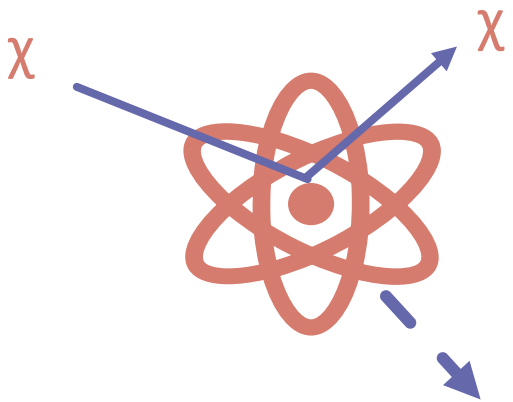
Ionization & excitation

↙ ↘

Charge Light

NUCLEAR RECOIL DETECTION



Signal quenching:
Nuclear recoils "lose" more energy to atomic motion than electron recoils. This is accounted for by the quenching factor Q.

$$E_{ee}[keV_{ee}] = Q(E_{nr}) \times E_{nr}[keV_{nr}]$$

Heat/Phonons

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Atomic motion

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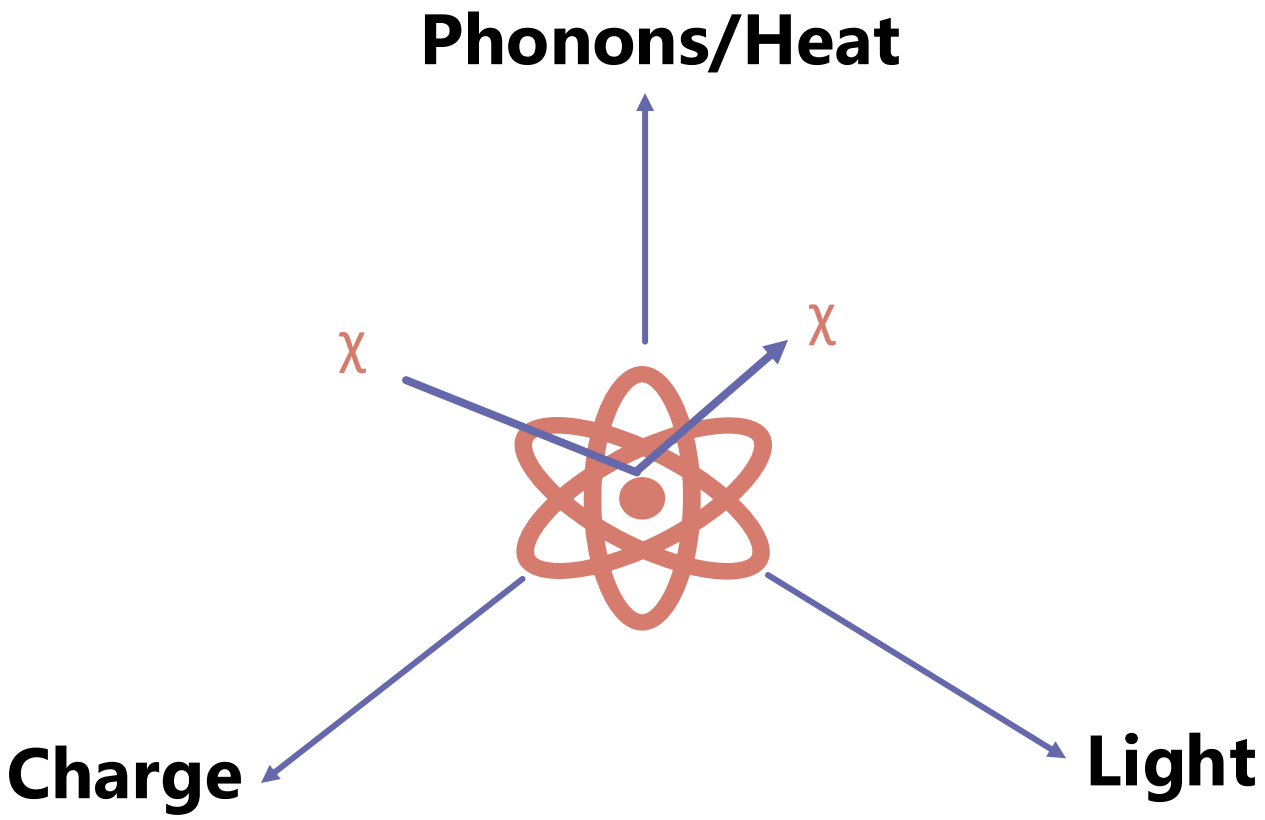
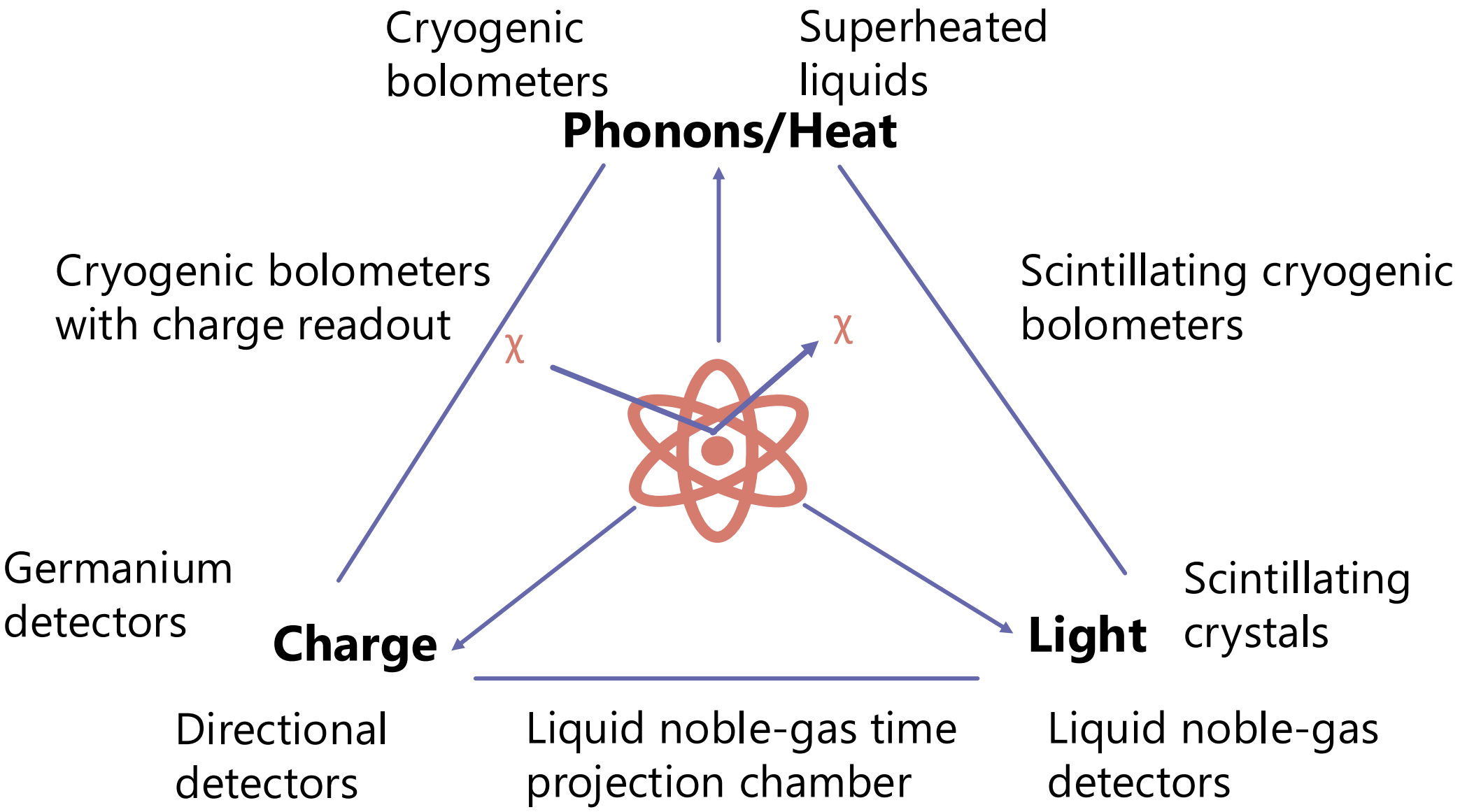


https://arxiv.org/pdf/2104.07634.pdf



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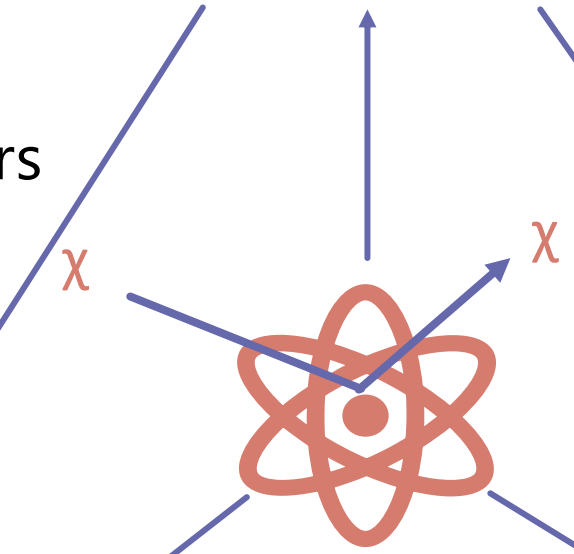
Cryogenic bolometers

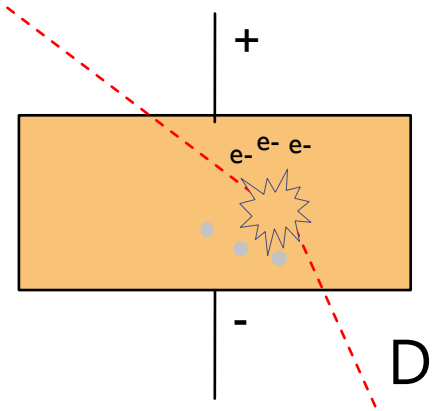
Superheated liquids

Phonons/Heat

Cryogenic bolometers with charge readout

Scintillating cryogenic bolometers





Current: Silicon CCDs

Charge

Light

Scintillating crystals

Directional detectors

Liquid noble-gas time projection chamber

Liquid noble-gas detectors

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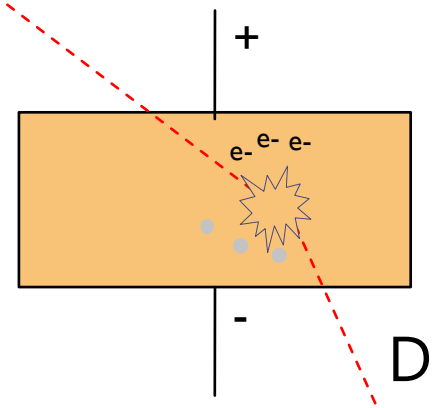

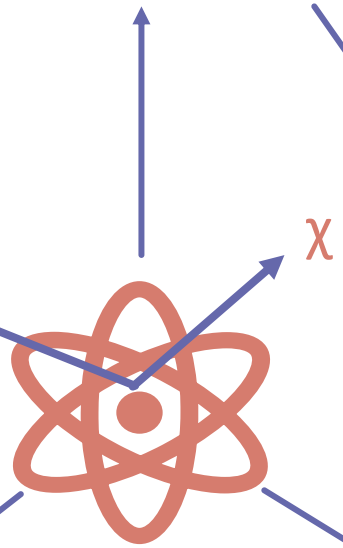

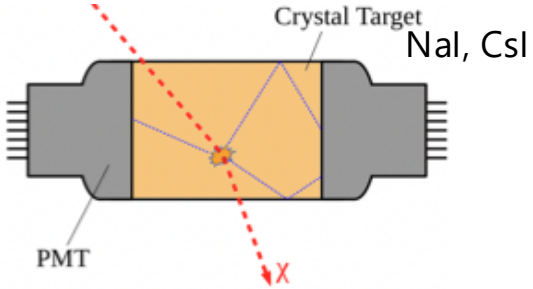

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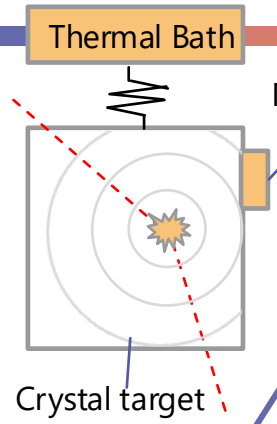
NTD thermistors
TES -Transition Edge Sensors



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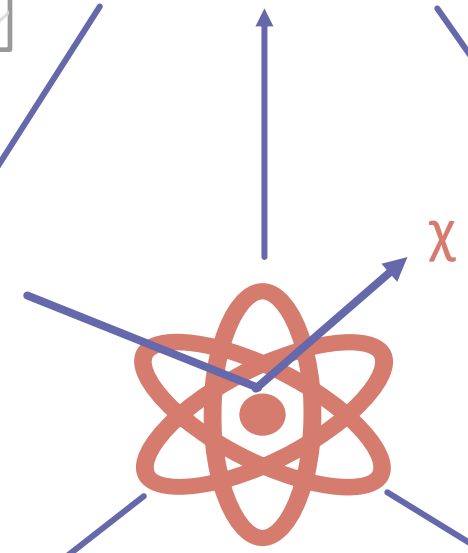

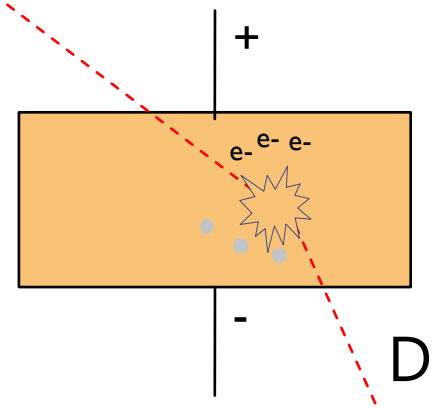

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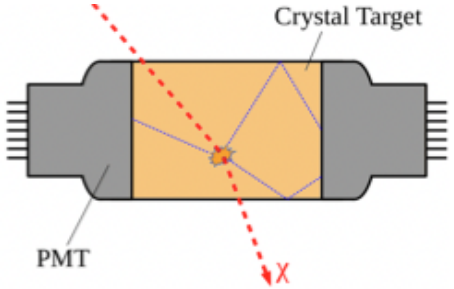

Directional detectors

Liquid noble-gas time projection chamber

Liquid noble-gas detectors

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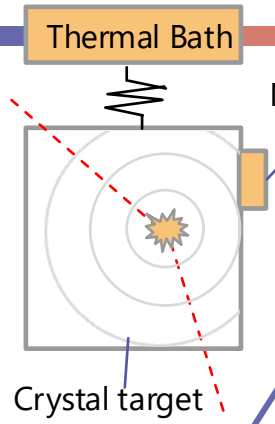

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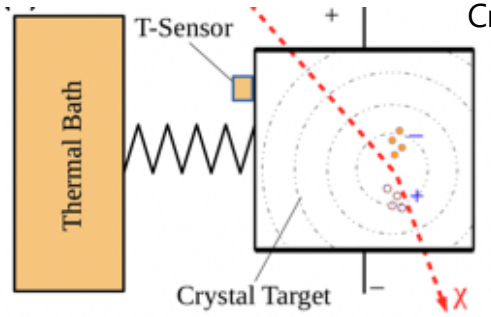

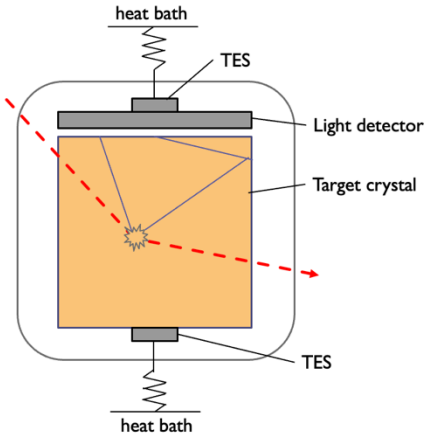

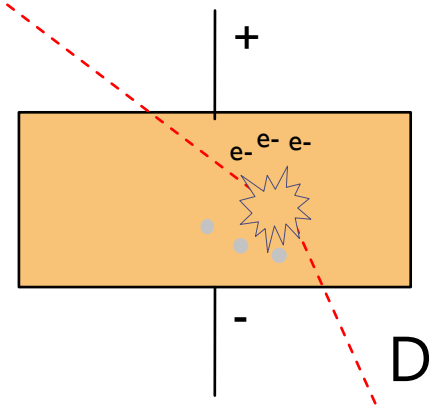

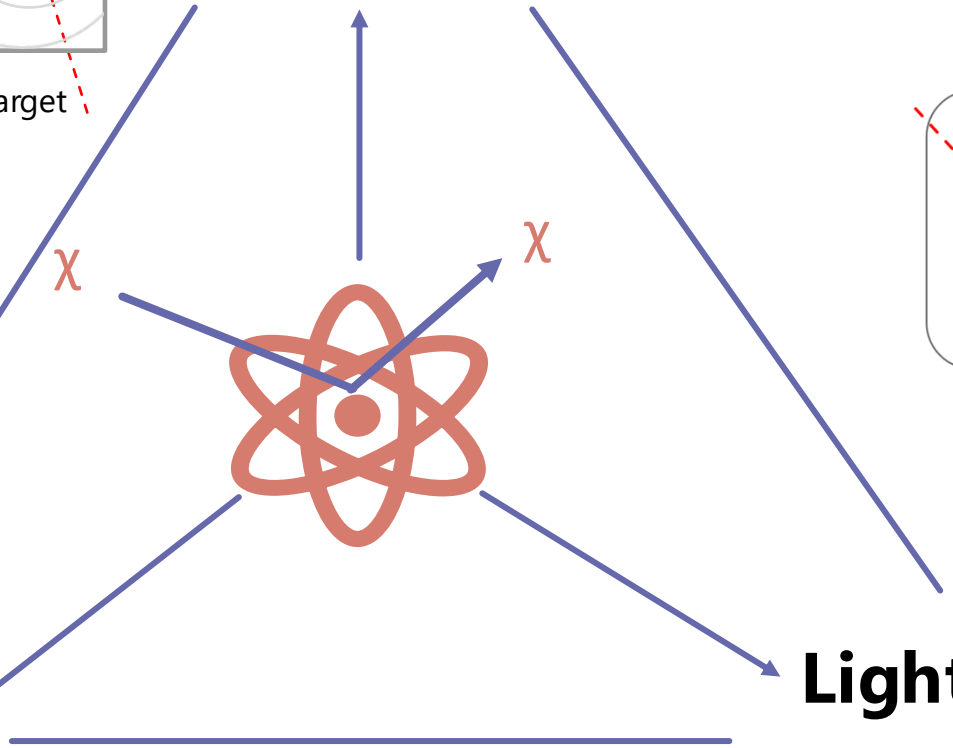

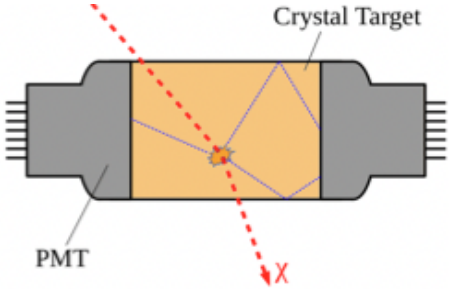

Charge

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Directional detectors

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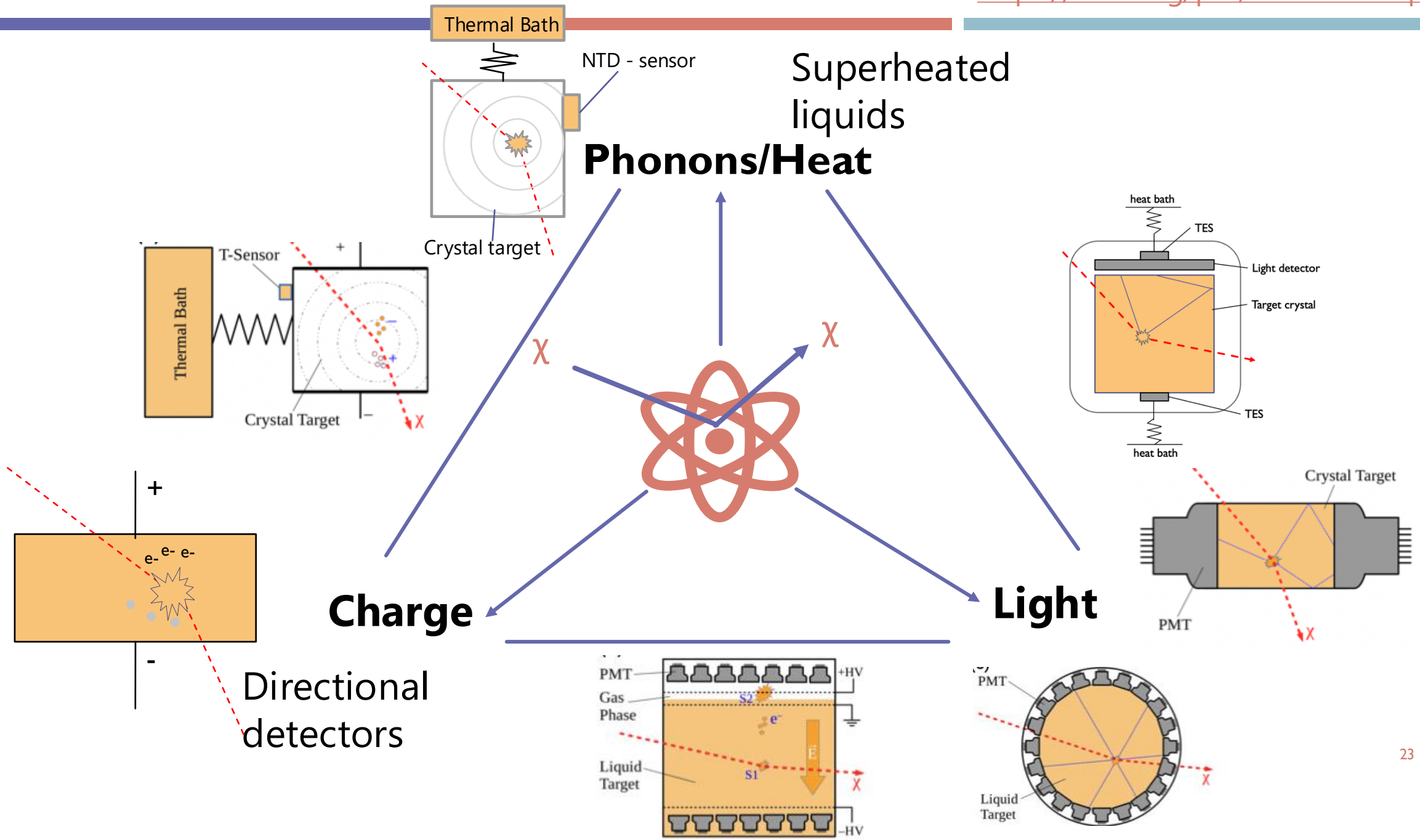

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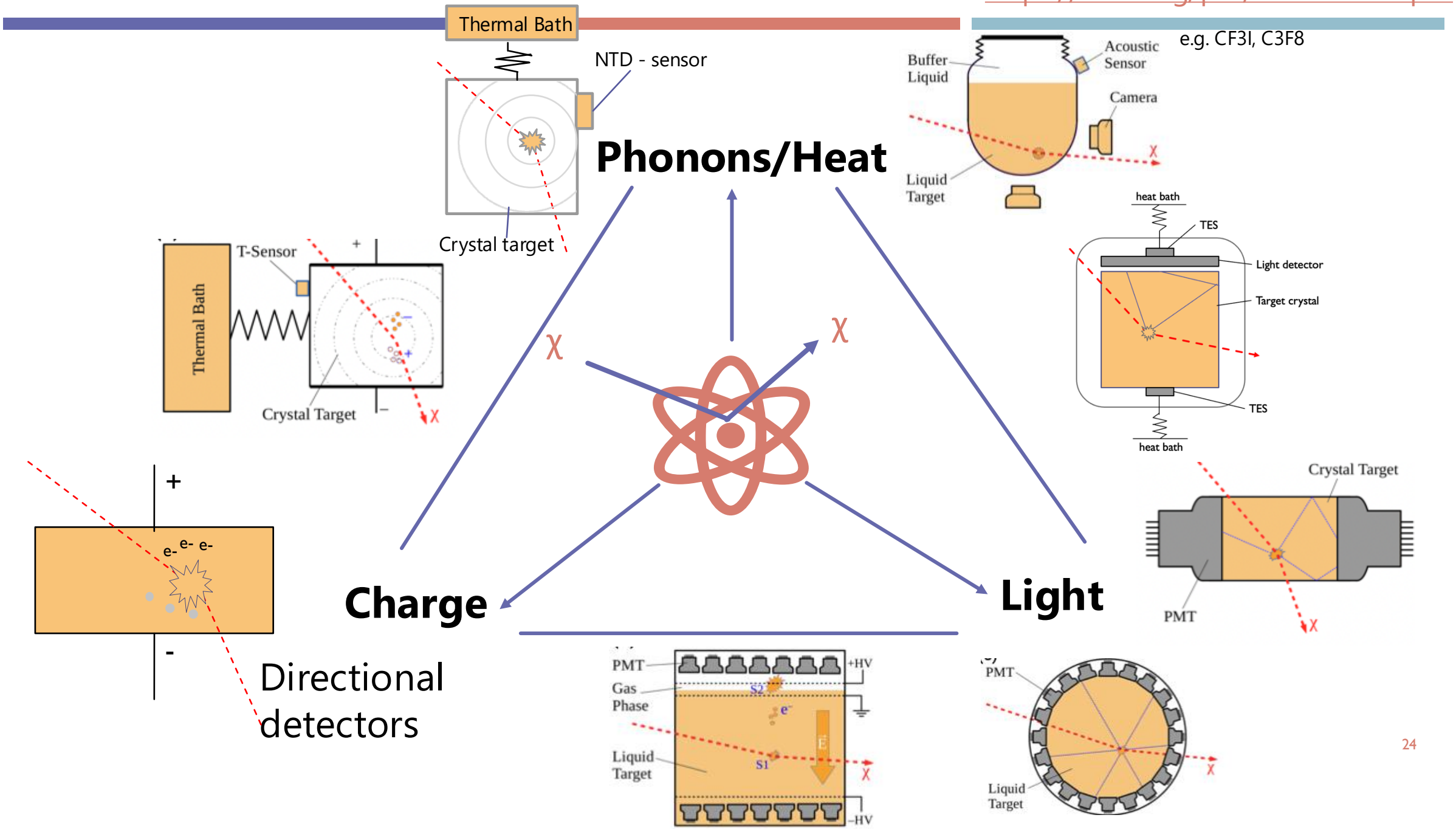

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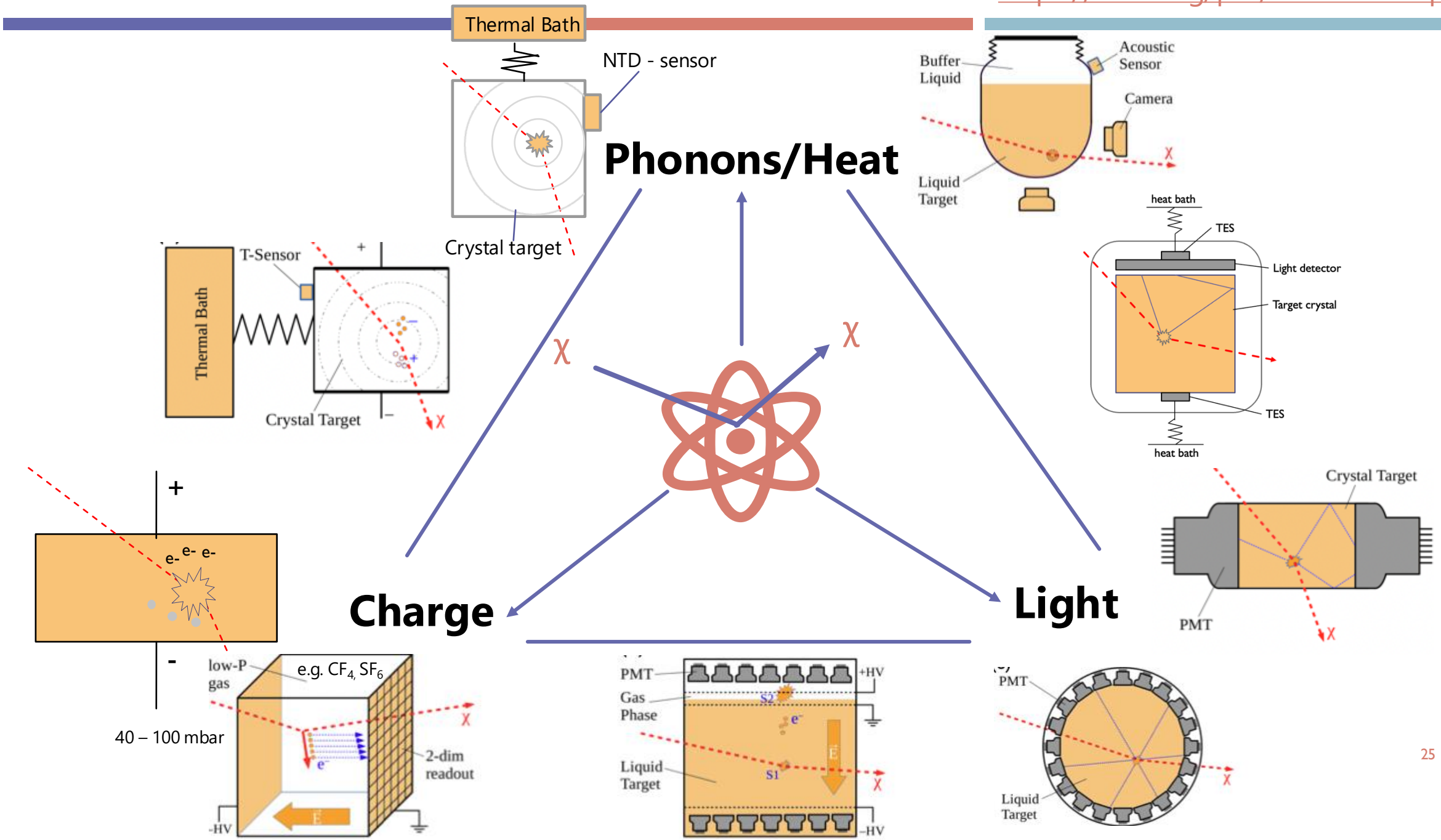


ASIDE: ELECTRON RECOIL SIGNALS

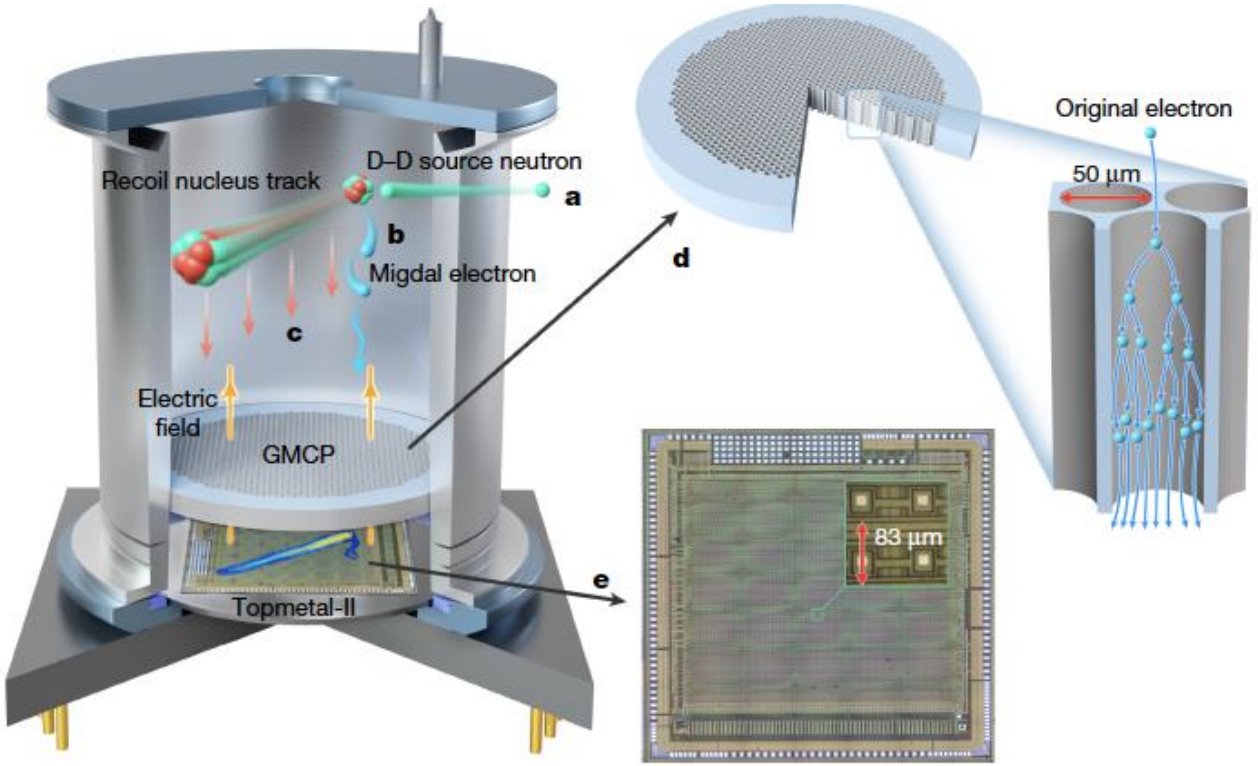
There are some searches making use of electron recoils:

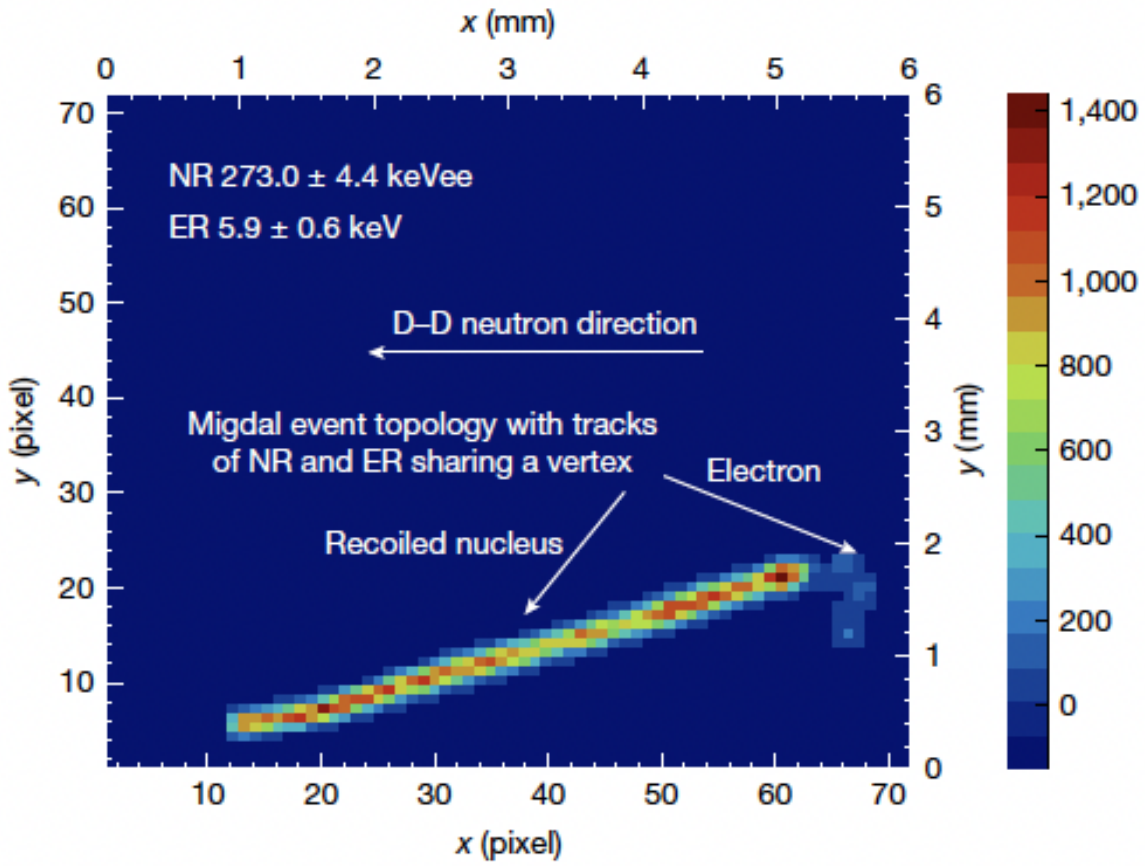
- **Nuclear recoil followed by electron recoil**
  - Inelastic DM scattering: NR is followed by ER from de-excitation of DM particle of target nucleus
  - Migdal effect: Additional excitation & ionization due to electron cloud following recoiling nucleus with delay
  - Bremsstrahlung: Bremsstrahlung follows an undetected nuclear recoil
- **DM-electron scattering:**
  - Light (MeV) dark matter particles don't have enough momentum to create NR signals

Nature **volume 649**, pages 580–583 (2026)

MIGDAL EFFECT

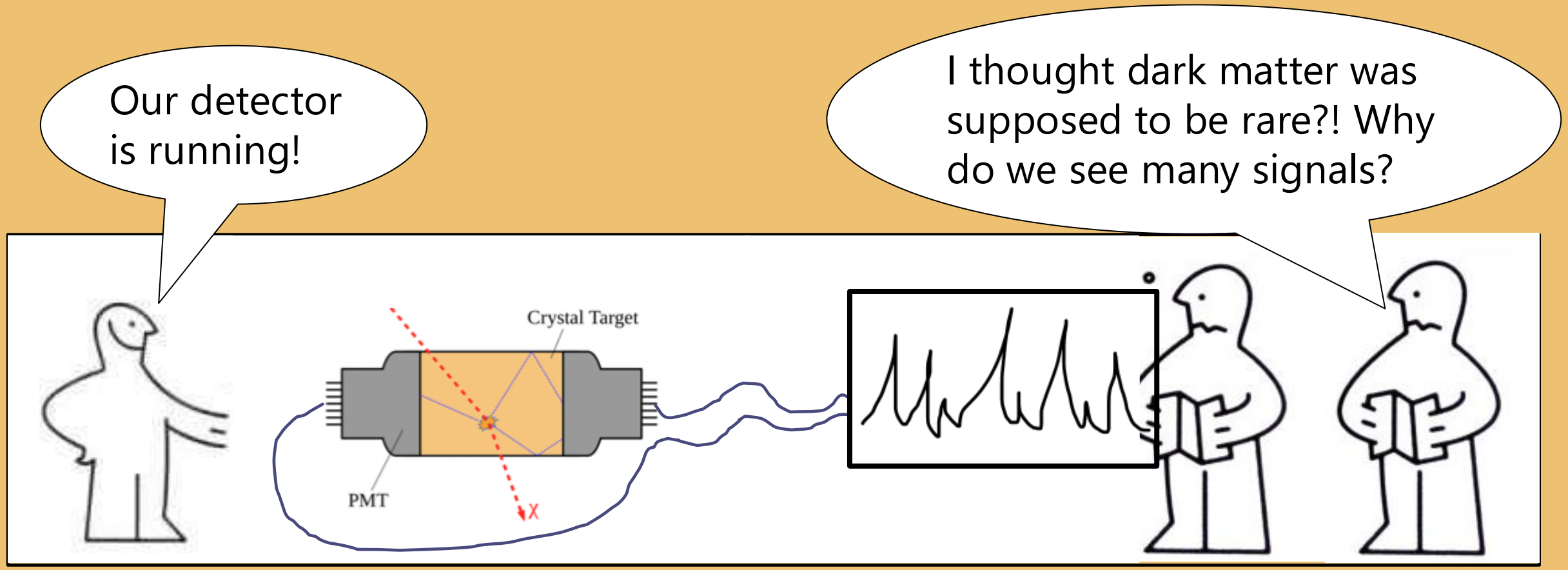
Nature paper from this month!





40% helium, 50% dimethyl ether

LET'S DESIGN A DETECTOR (3)



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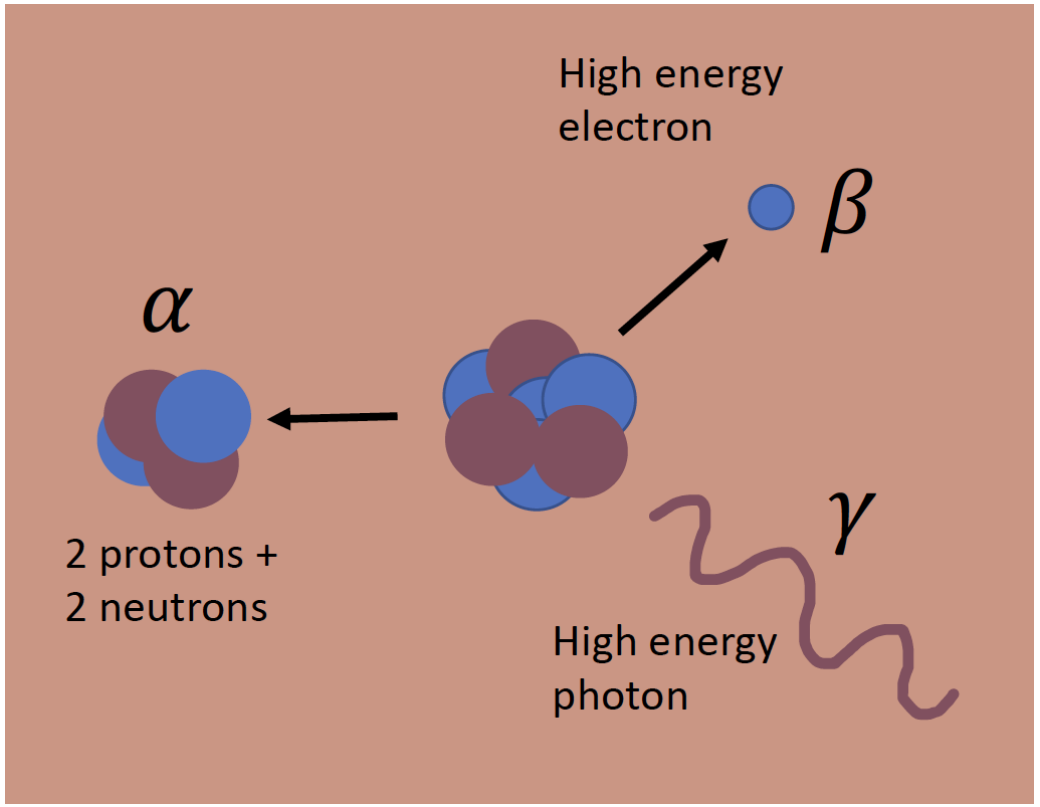
BACKGROUNDS

Understand background sources.

Reduce backgrounds.

Distinguish signal from background topologies.



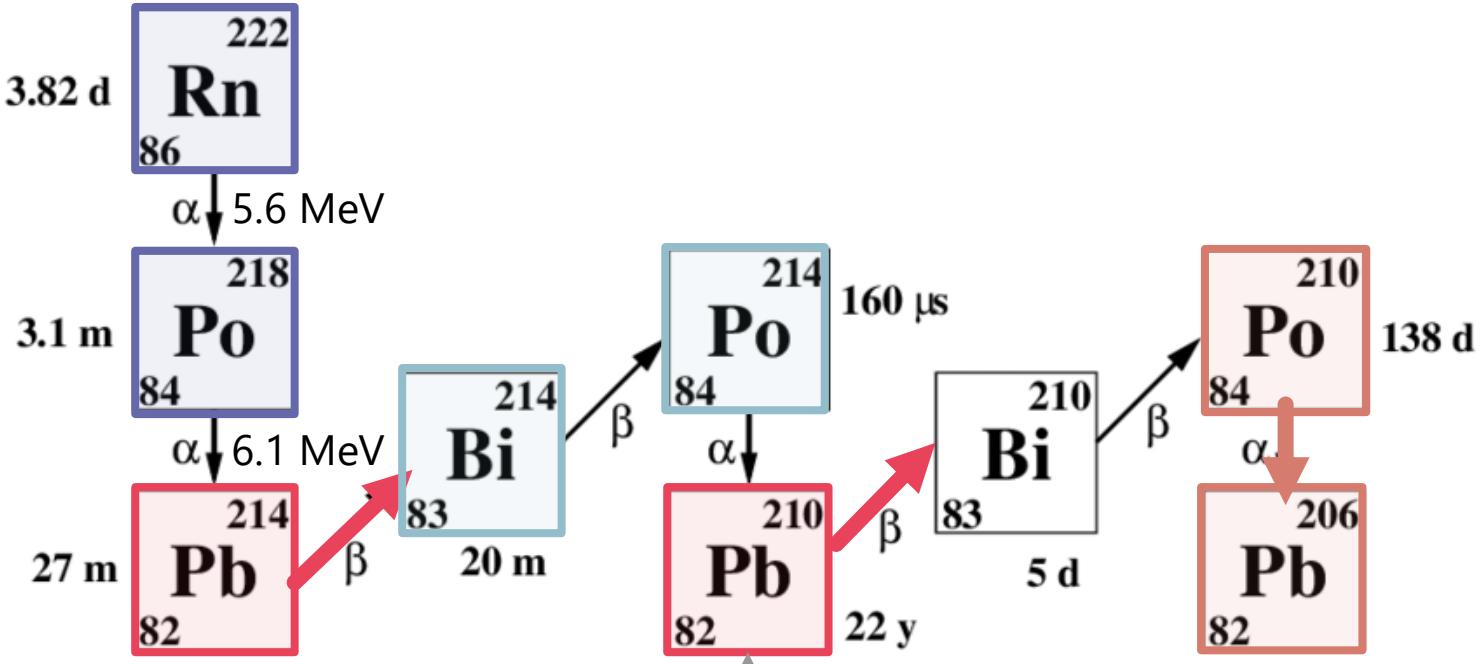
- Radioactive isotopes in the environment and the detector itself:
  - Radioactive decays:
    - Gamma: environment & detector materials
    - Beta: from bulk and surfaces
  - (α, n) and spontaneous fission
- Cosmic rays:
  - muon induced neutrons

ER

NR

Radioactive isotopes | Radon | Neutrinos

Rn emanates from detector materials dust on surfaces



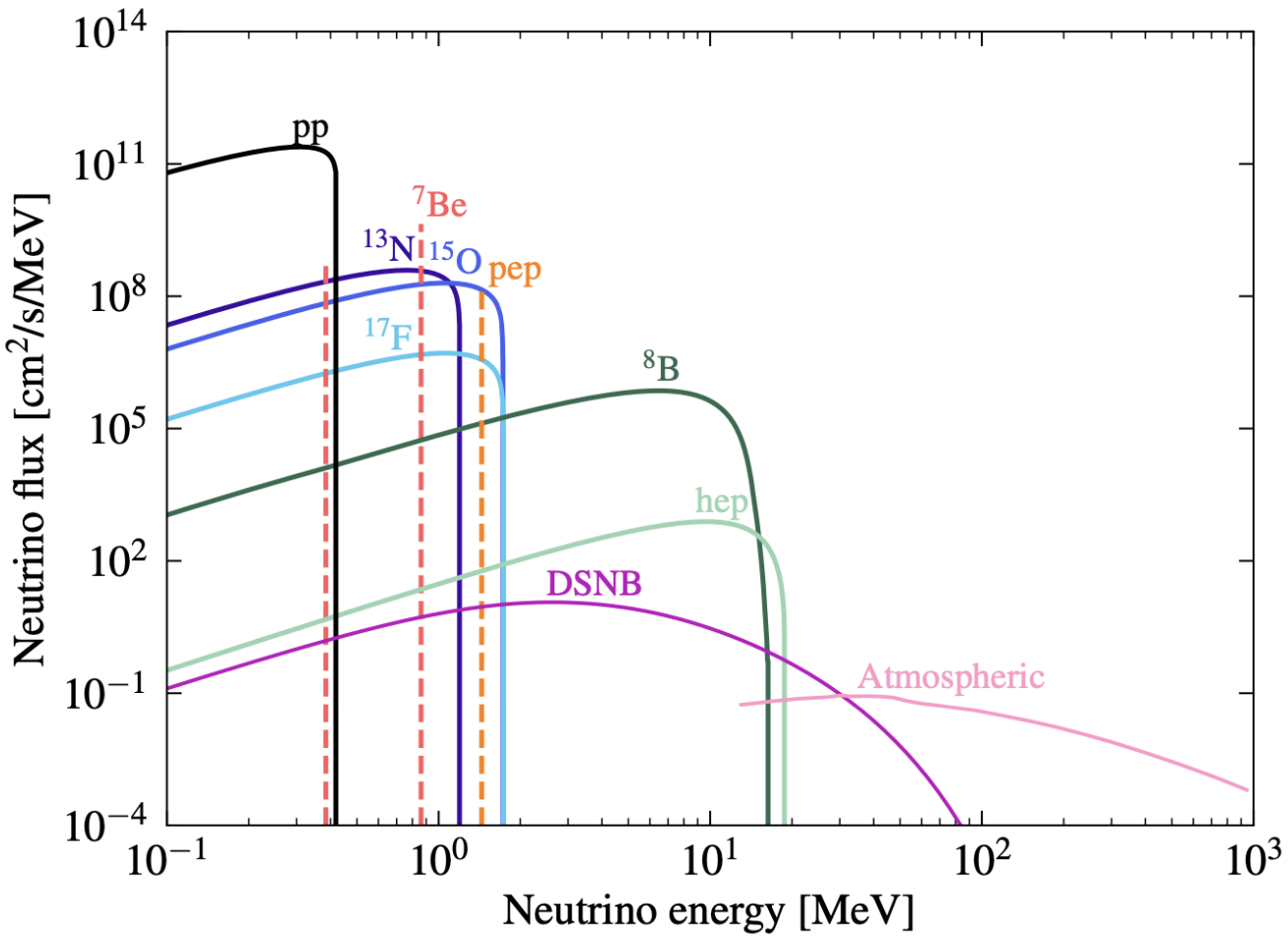
Naked beta-decay (no accompanying gamma) low E ER

5.3 MeV alpha (alpha, n) -> neutron backgrounds (especially on PTFE, due to fluorine)

Plate-out onto detector surfaces ($T_{1/2}$ = 22.3y)

^{206}Pb can be recoil into detector volume and cause complicated wall background

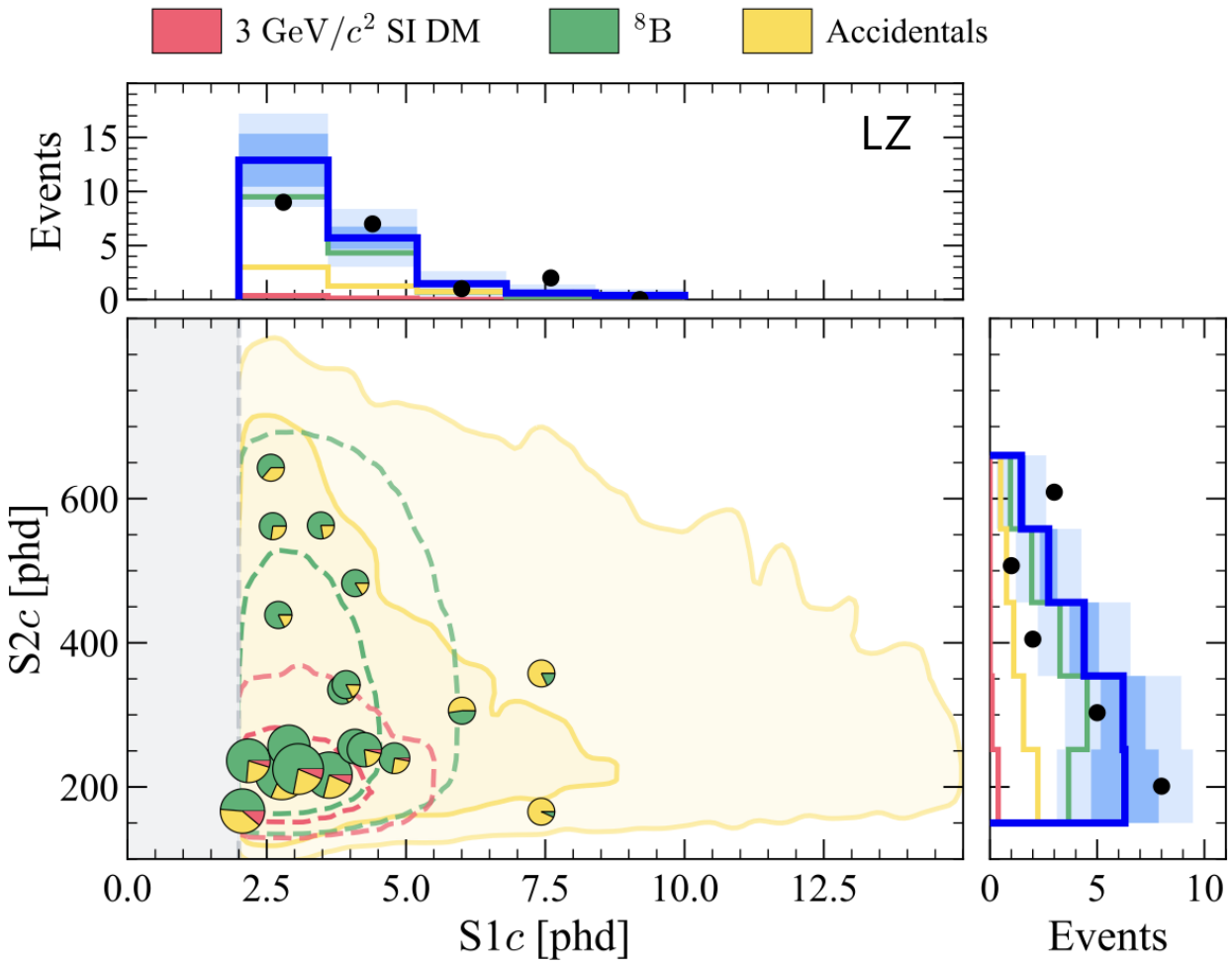
Radioactive isotopes | Radon | Neutrinos



- **Neutrino fluxes:**
  - Solar neutrinos (flux predicted by standard solar model)
  - Atmospheric neutrinos: (< 100 MeV atmospheric neutrino flux has not been measured, predictions from simulations)
  - Diffuse supernovae neutrino background
- **Neutrino-electron scattering => ER band**
- **CEvNS => NR band**

https://arxiv.org/pdf/2512.08065v1

Radioactive isotopes | Radon | Neutrinos



- XENONnT, PandaX and LZ have now all seen Boron-8 solar neutrinos
- Only impacts low-energy DM searches

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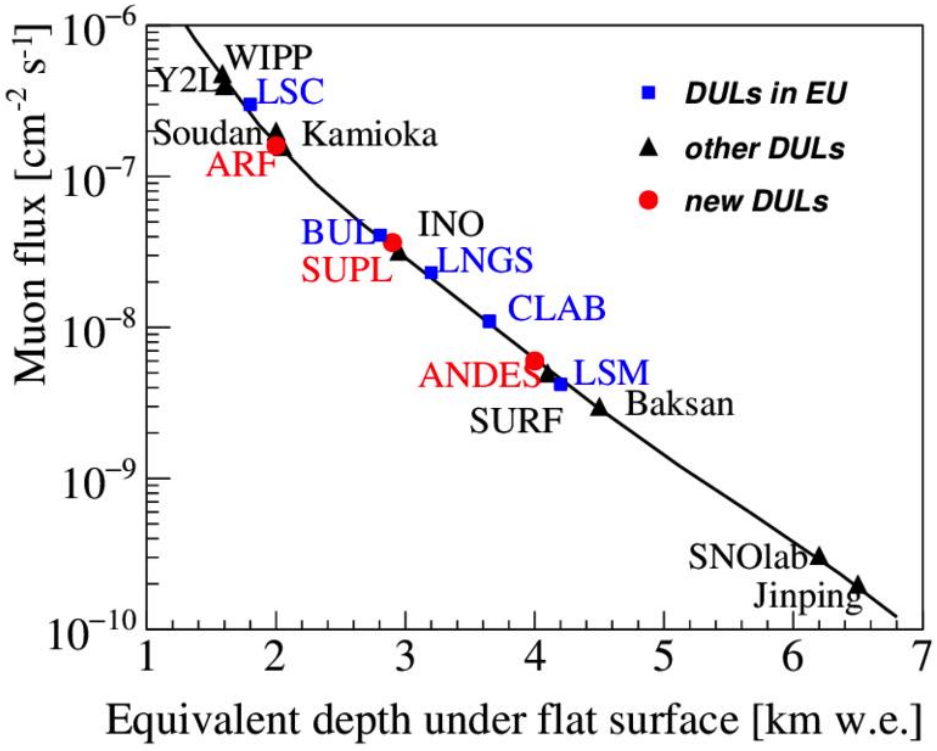
Distinguish signal from background topologies.

Shielding | Material screening & cleanliness | Veto detectors



DOI:10.1088/1742-6596/1342/1/012003

- Deep underground laboratories
  - Reduces muon flux (and muon-induced neutrons)
- Water tank & additional shielding
  - Lead-shielding
  - Gamma shielding
  - Neutron absorption & moderation
- Self-shielding/fiducialisation
  - Backgrounds from surfaces and detector materials likely to interact towards the outside of the detector

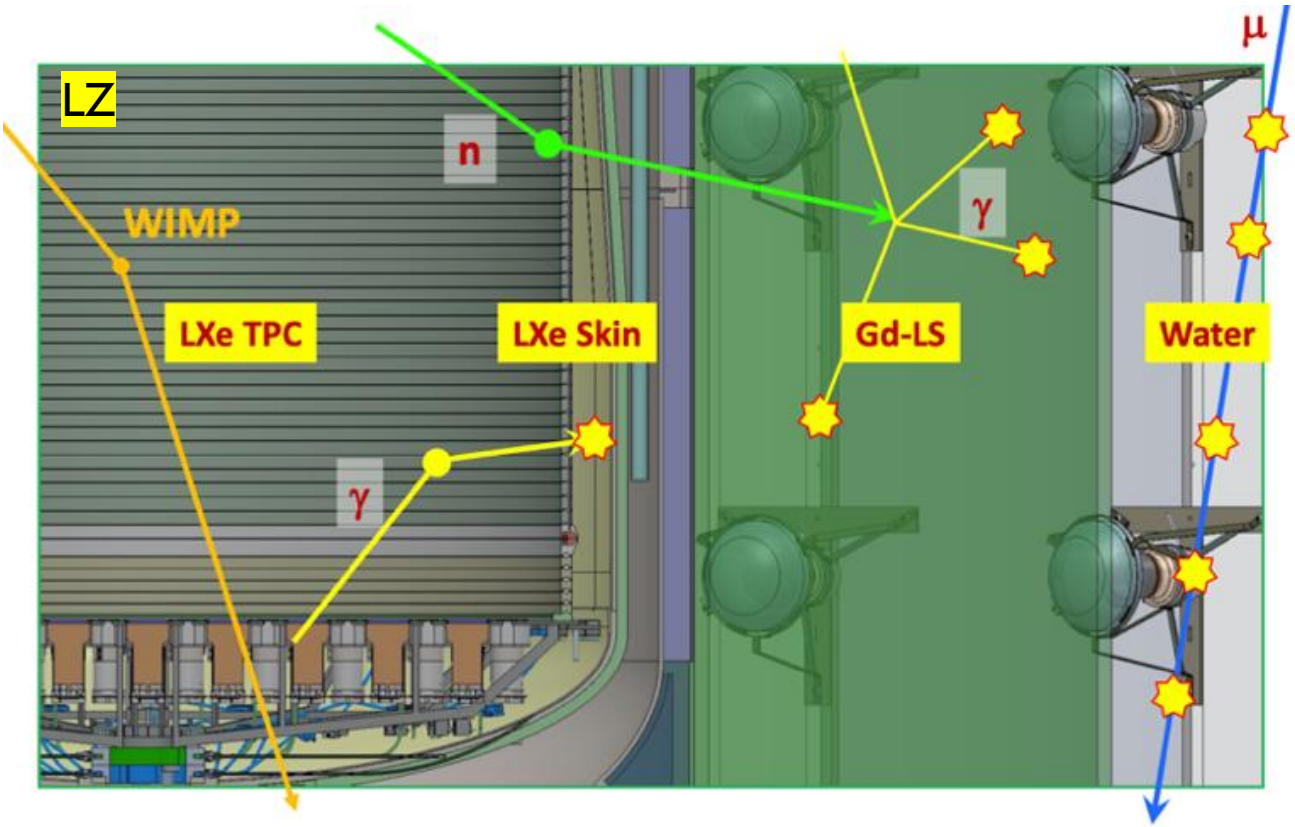
Shielding

Material screening & cleanliness

Veto detectors

- Purification:
  - Reduce impurities and radioactivity in target material
  - For crystals before and during crystal making
  - For gas and liquid detectors online purification
- Material selection: Dedicated screening campaigns to select radio-pure detector materials
    - Gamma-screening
    - ICPMS
    - Rn emanation
- Cleanliness:
  - Ensure minimal depositions on detector surfaces during construction

Shielding | Material screening & cleanliness | Veto detectors



- Veto interactions which interact multiple times within the detector
- Dedicated veto detectors for
  - Gammas
  - Neutrons
  - Muons

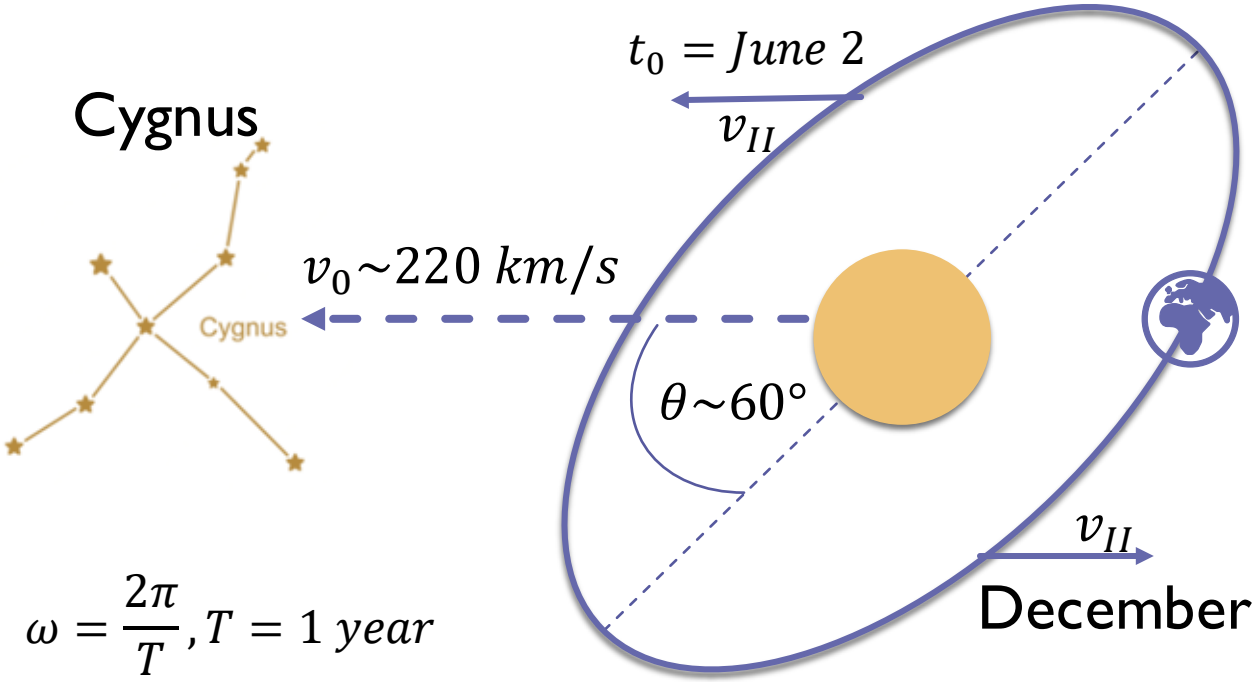
BACKGROUNDS

Understand background sources.

Reduce backgrounds.

Distinguish signal from background topologies.

Annual modulation | Directionality | ER-NR discrimination



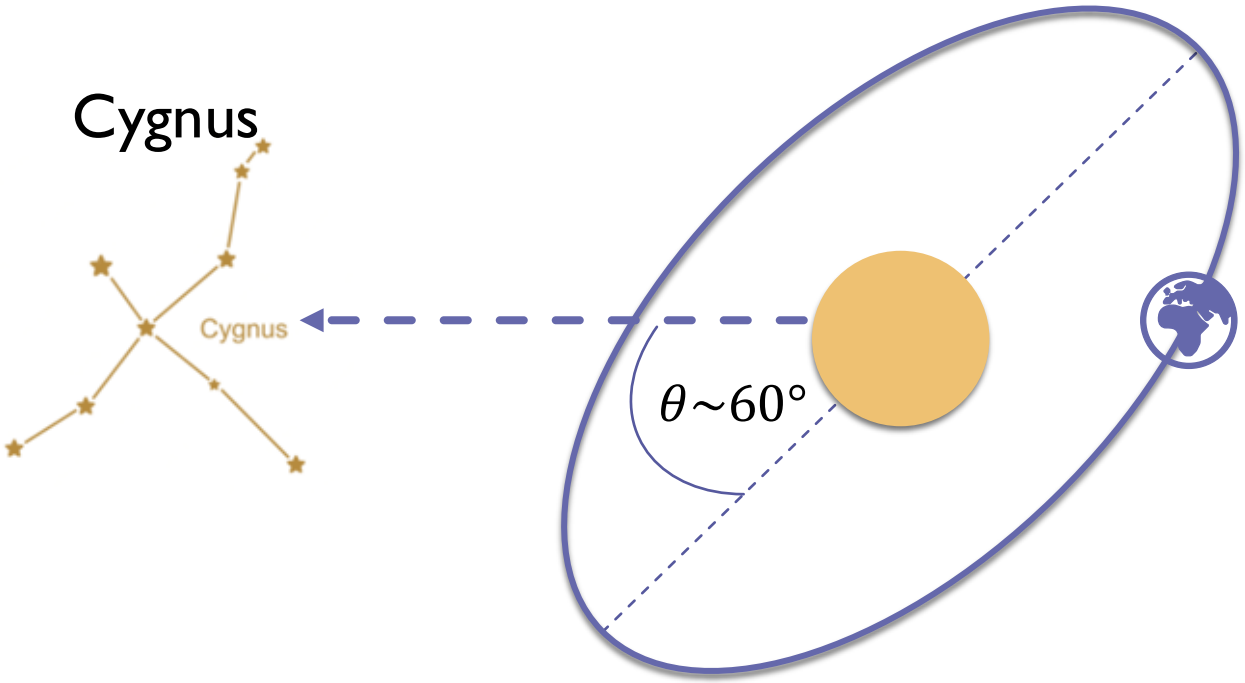
$$\omega = \frac{2\pi}{T}, T = 1\ year$$

$$v_{earth} = v_0 + v_{II} \cos\theta \cos[\omega(t - t_0)]$$

$$S(t) = B(t) + S_0 + \boxed{S_m \cos[\omega(t - t_0)]}$$

$$\mathcal{O}(v_0/v_{II}) \sim 5\%$$

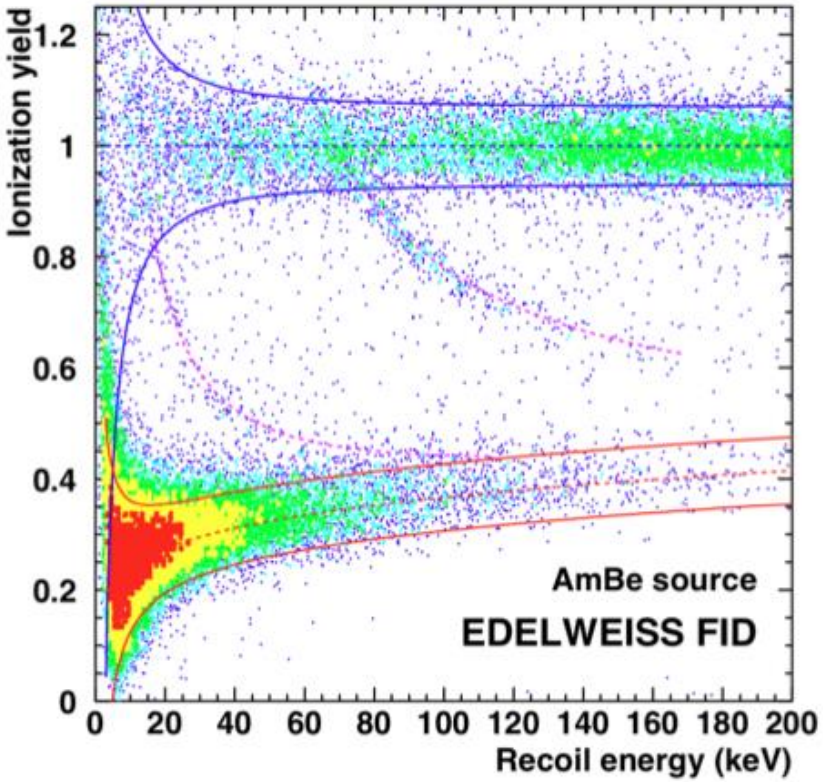
Annual modulation | Directionality | ER-NR discrimination



- Dark matter "wind" from the direction of Cygnus
- Measure track direction
- Experimentally challenging:

  r < 1mm is very short for keV-scale nuclear recoils

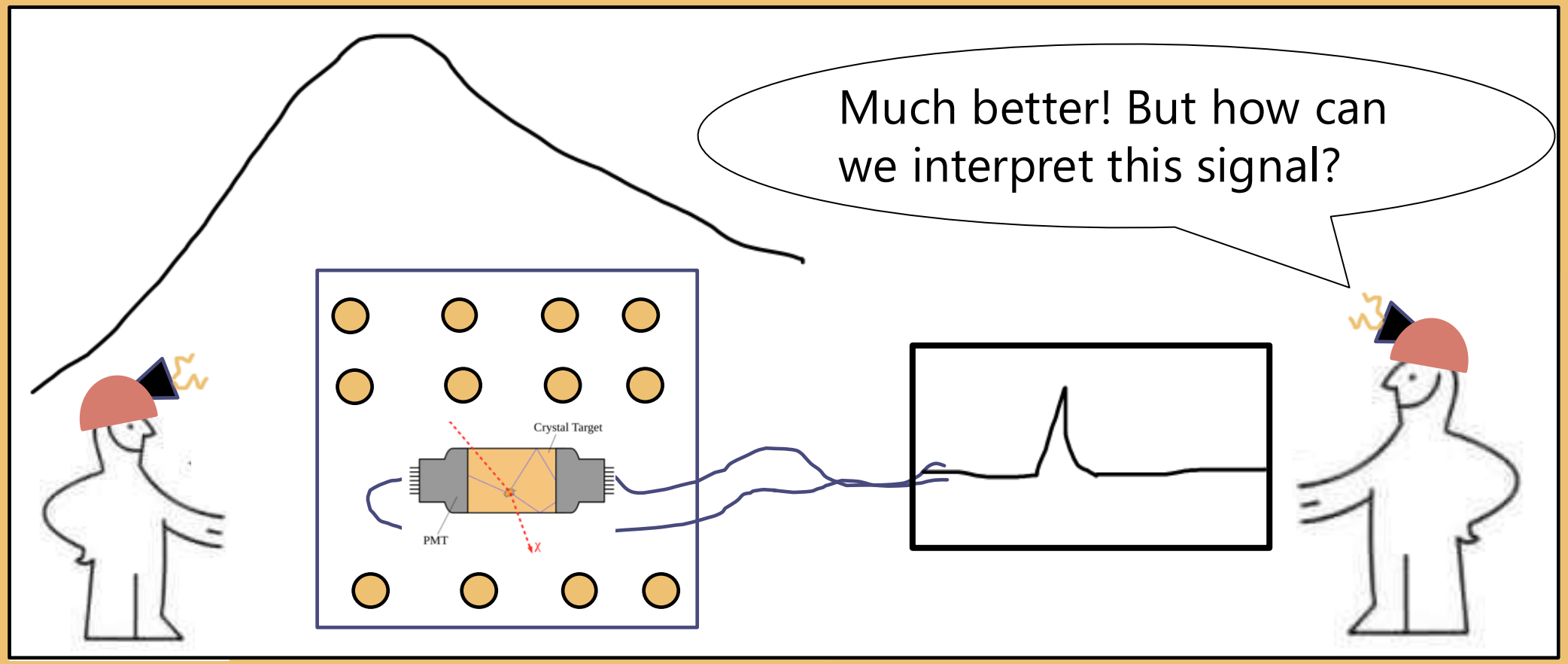
Annual modulation | Directionality | ER-NR discrimination



EDELWEISS III
https://arxiv.org/pdf/1706.01070.pdf

- Difference in interaction between electron recoil and nuclear recoil leads to different ratio in signals
  - Cryogenic bolometers with 2 readout channels are superior here
  - Also possible for LXe/LAr detectors but less efficient
- Pulse-shape discrimination

LET'S DESIGN A DETECTOR (4)



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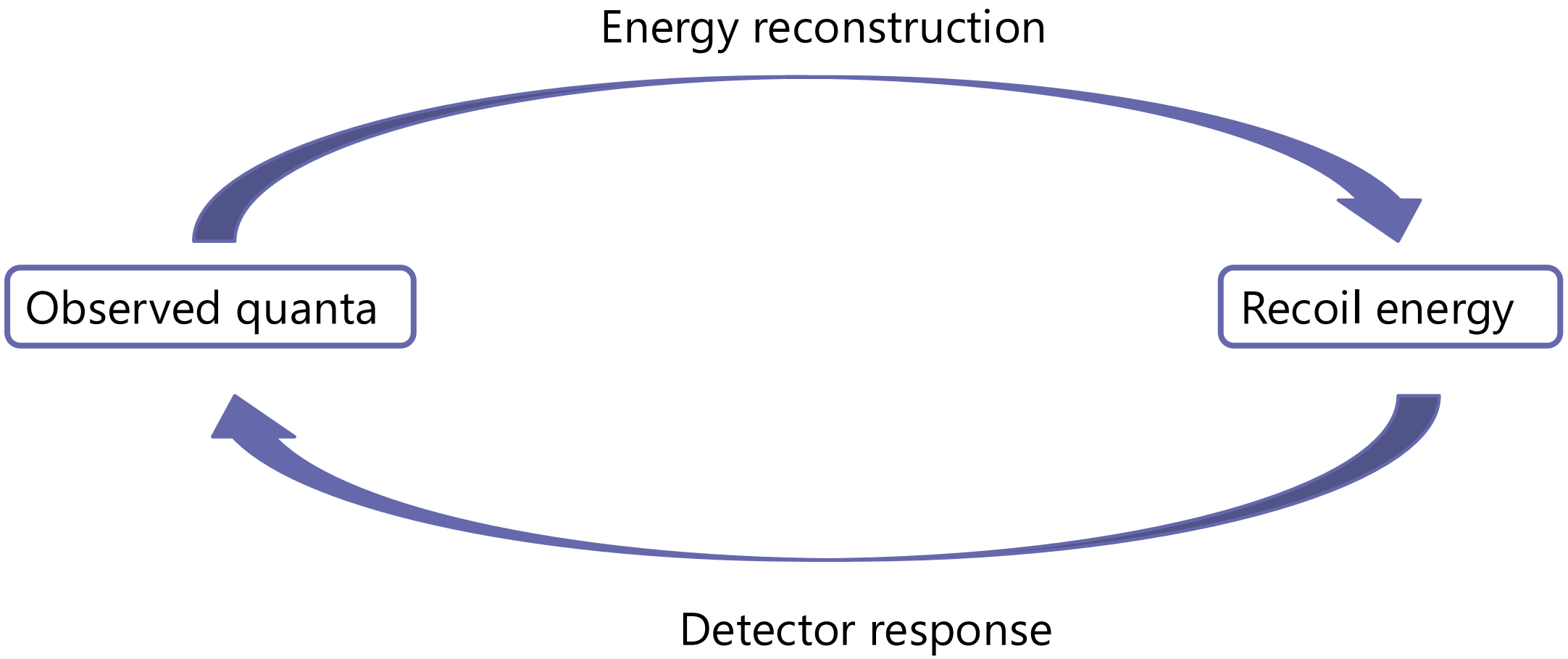
ENERGY RECONSTRUCTION



ENERGY RECONSTRUCTION

Observed quanta

We need to understand:

- Detector efficiencies:
  - Sensor efficiencies
  - Light collection efficiency, electron extraction efficiency, etc.
- Scattering process in target material
  - Signal yields
  - Quenching factor

Recoil energy

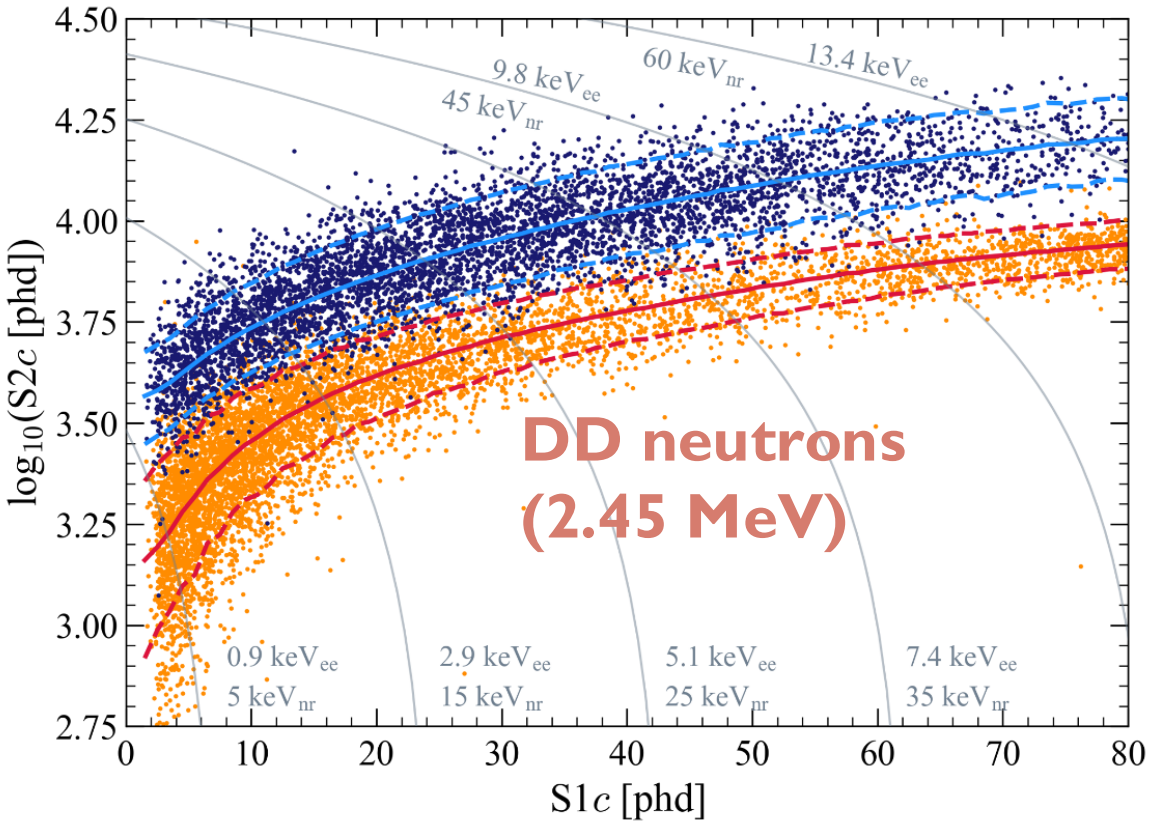
Nuclear recoil

Electron recoil

External neutron sources:

- Spontaneous fission (e.g. ^{252}Cf)
- Alpha decay + light isotope via (α, n) (e.g. AmLi)
- Photoneutron sources: Be target + γ source to produce nearly mono-energetic neutrons via the two-body reaction ^{9}Be(γ,n)
- DD and DT neutron generators
  - e.g. $^{2}H + ^{2}H \rightarrow n + ^{3}H$

LUX-ZEPLIN

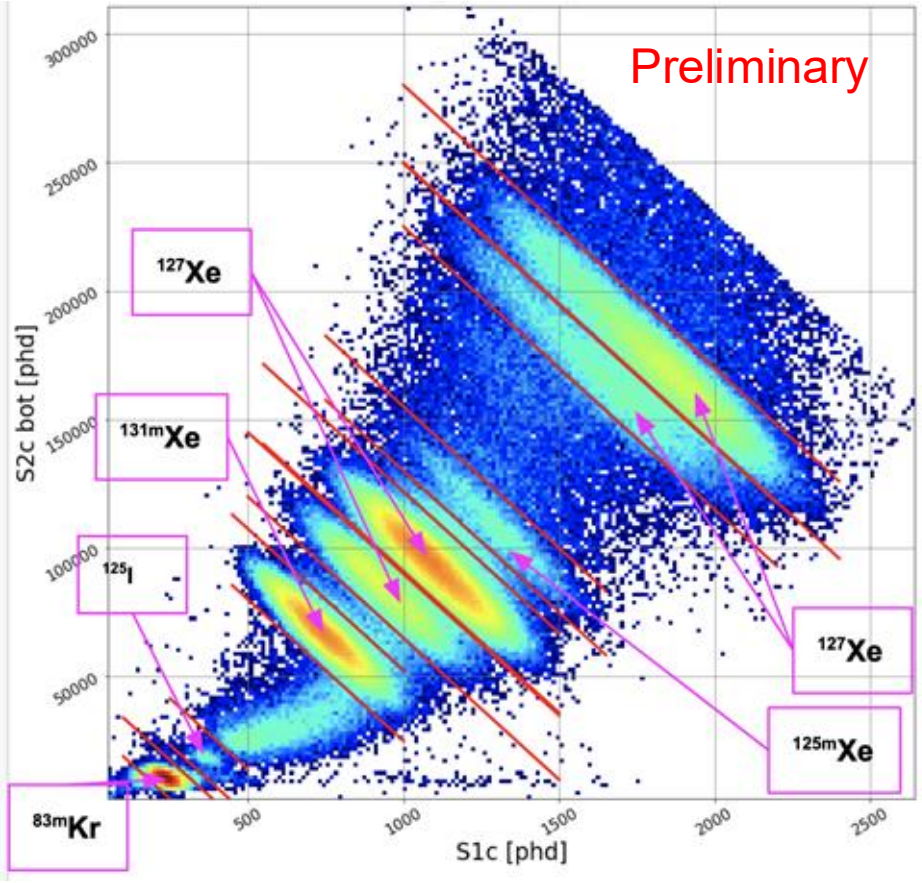


Nuclear recoil

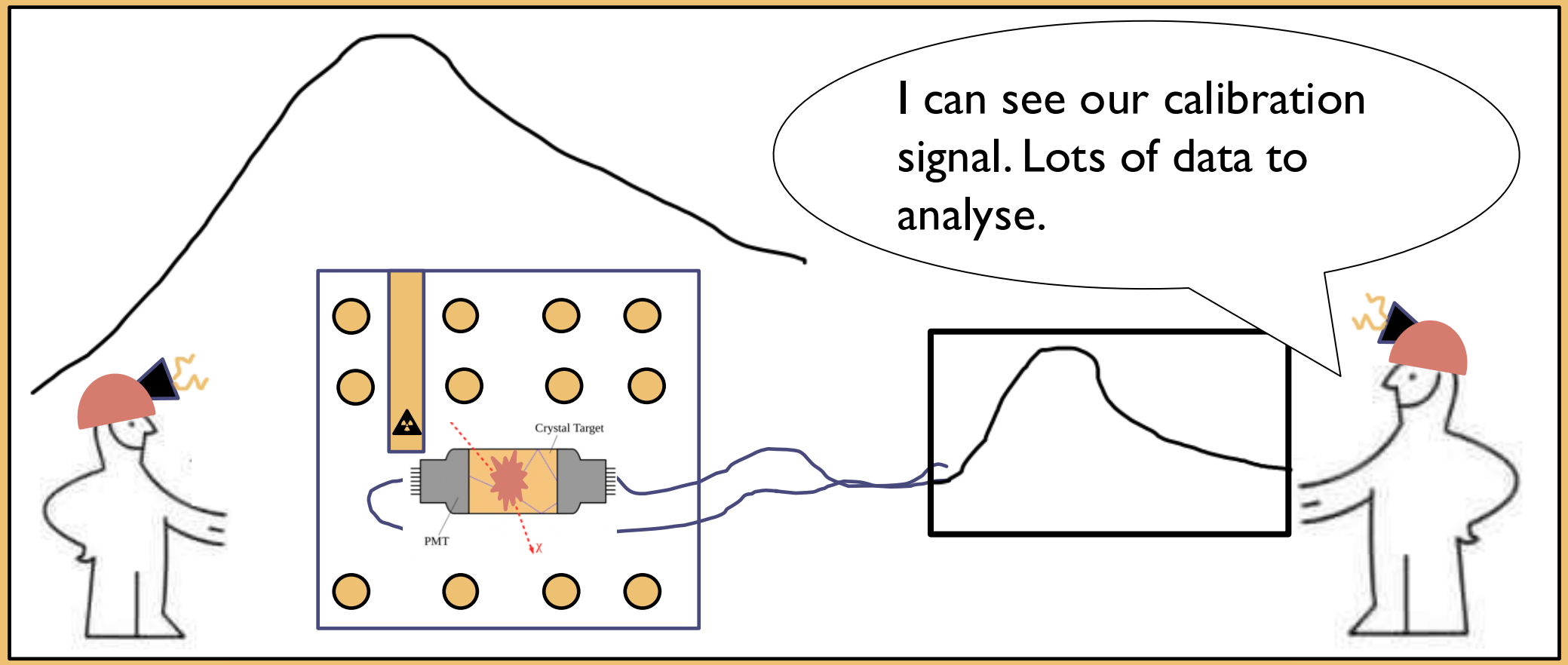
Electron recoil

LUX-ZEPLIN

- Intrinsically present radioactive isotopes or activation products from neutron calibrations
- Internal sources (liquid and gas detectors)
  - inject short lived radio-isotopes (need to be long-lived enough to distribute in the detector volume)
  - inject long-lived radio-isotopes which can be removed by purification
- External sources (gamma sources)



LET'S DESIGN A DETECTOR (5)



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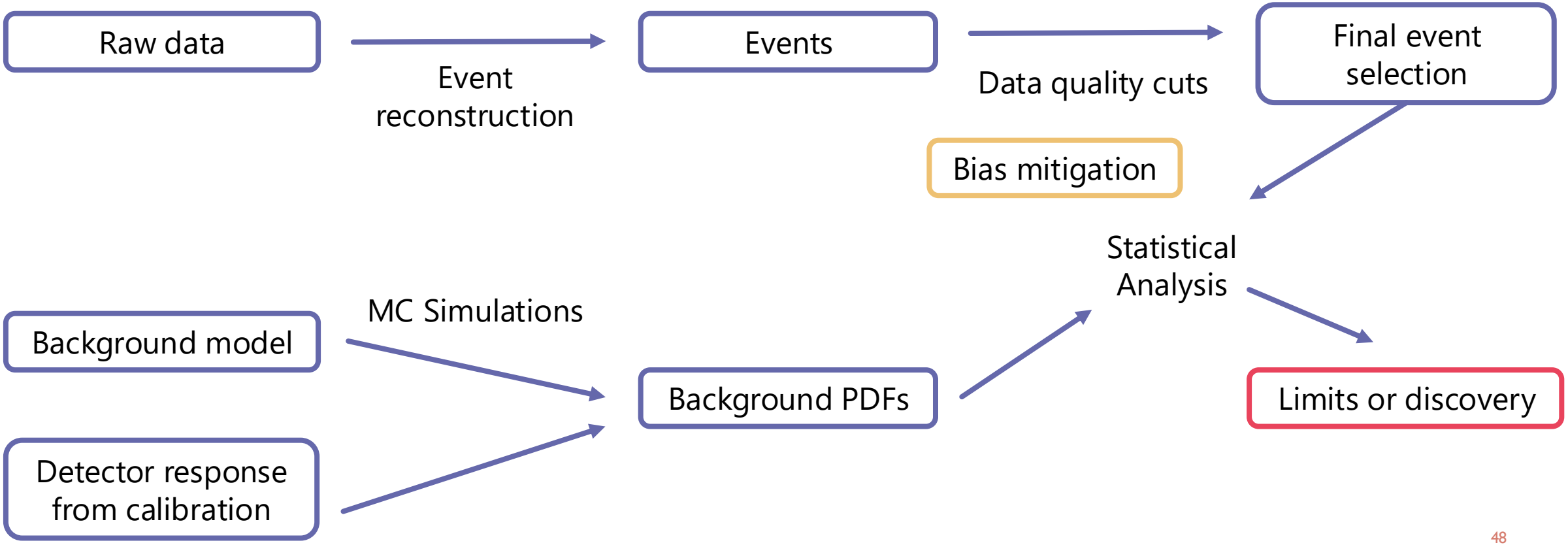
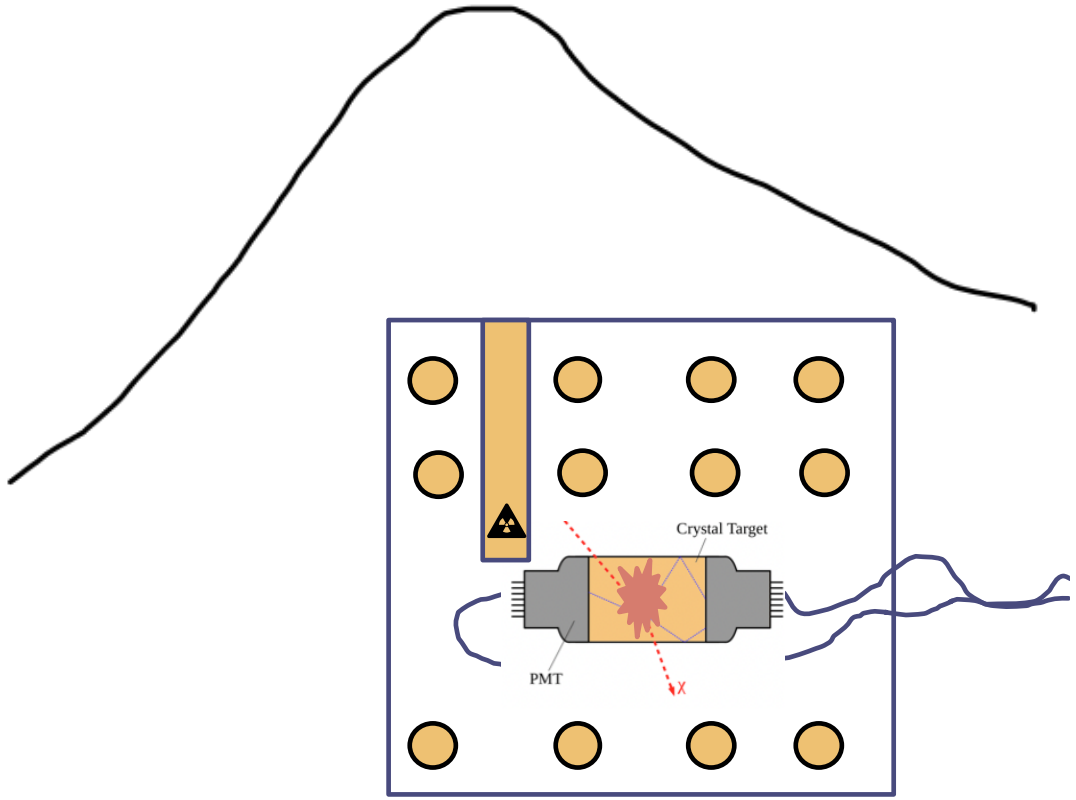
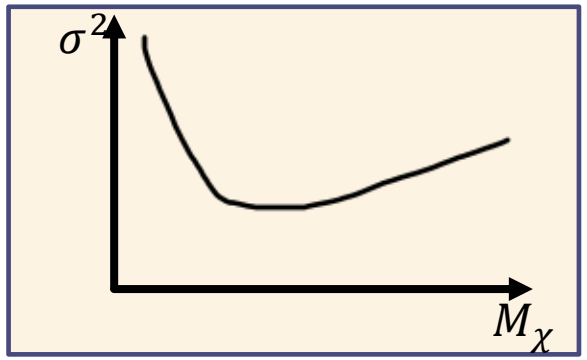
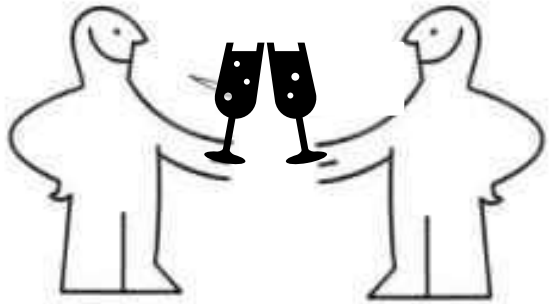
TYPICAL ANALYSIS OVERVIEW



LET'S DESIGN A DETECTOR (6)







Wow – we've set exclusion limits!

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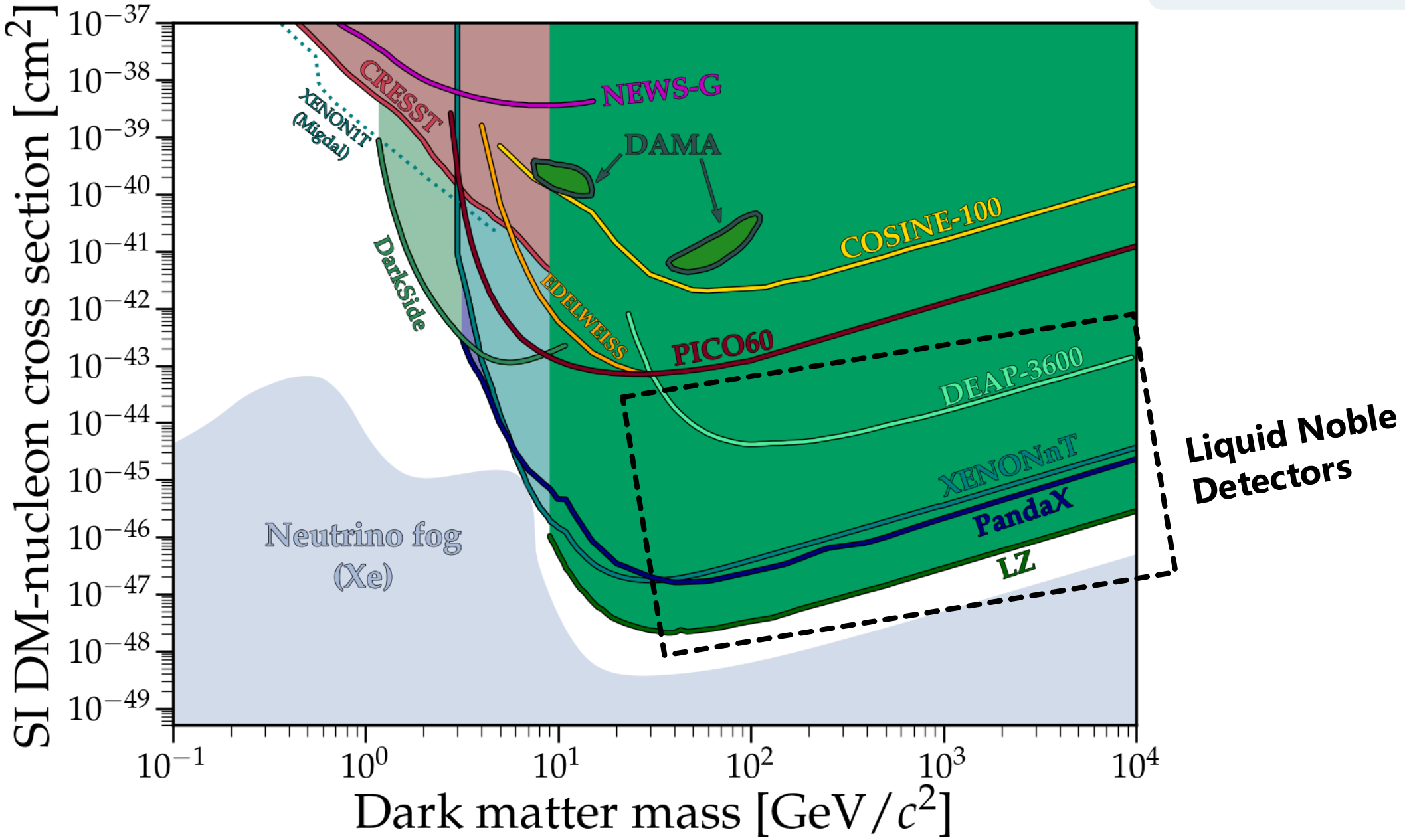
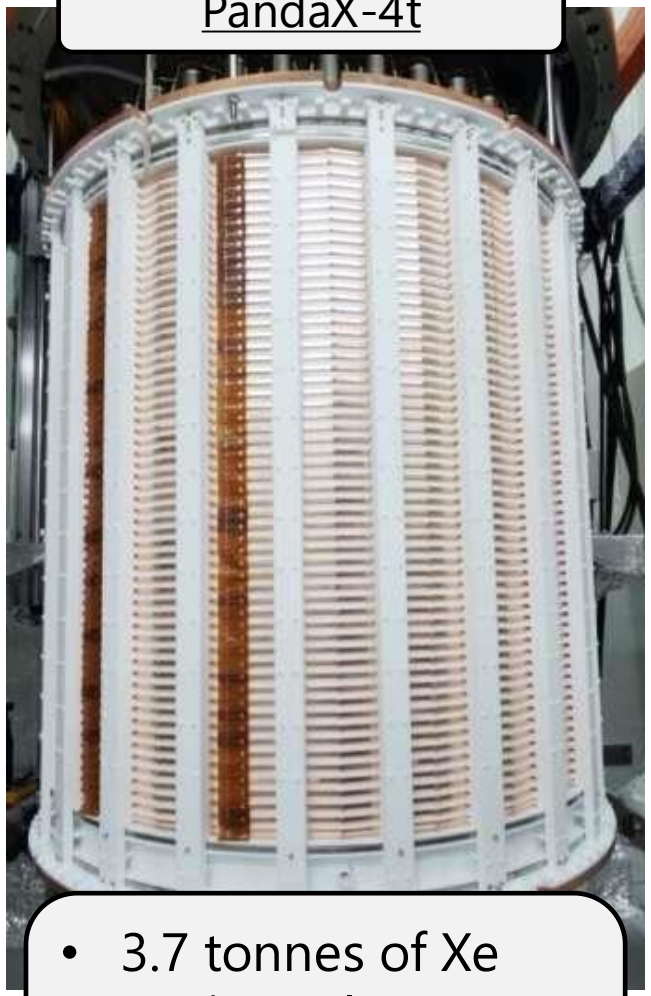
Plots by Ciaran O'Hare
(https://github.com/cajohare)



Xenon detectors

PandaX-4t



- 3.7 tonnes of Xe (active volume)
- 368 PMTs
- Status: running

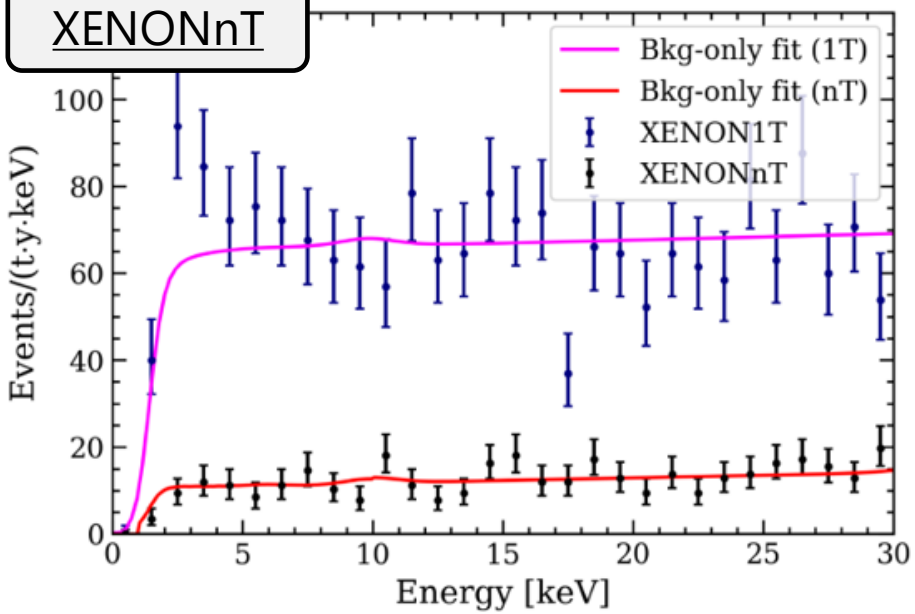
XENONnT

- 5.9 tonnes of Xe (active volume)
- 494 PMTs
- Status: upgrade

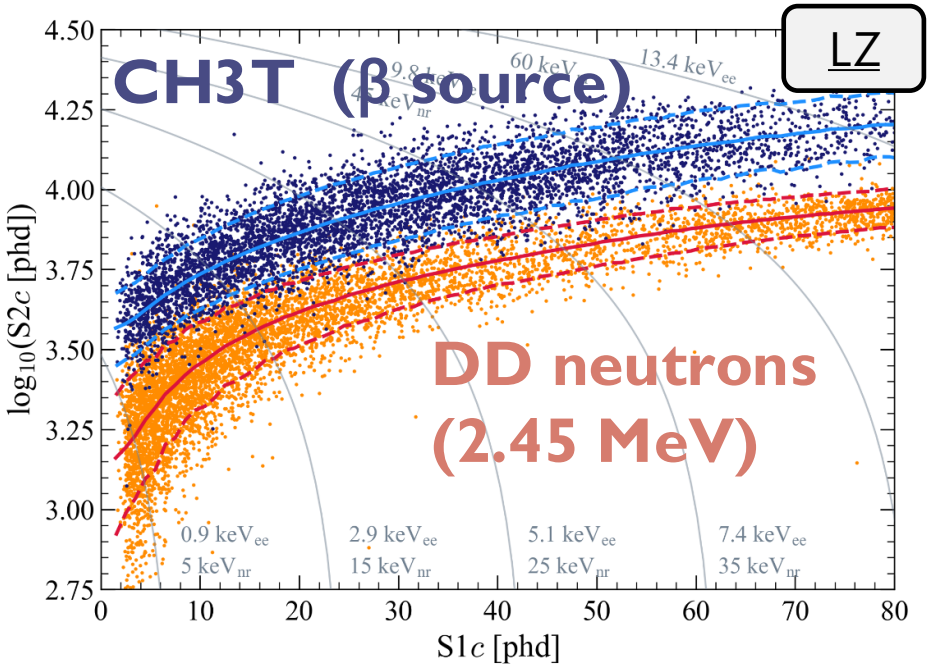
LZ

- 7 tonnes of Xe (active volume)
- 494 PMTs
- Status: running

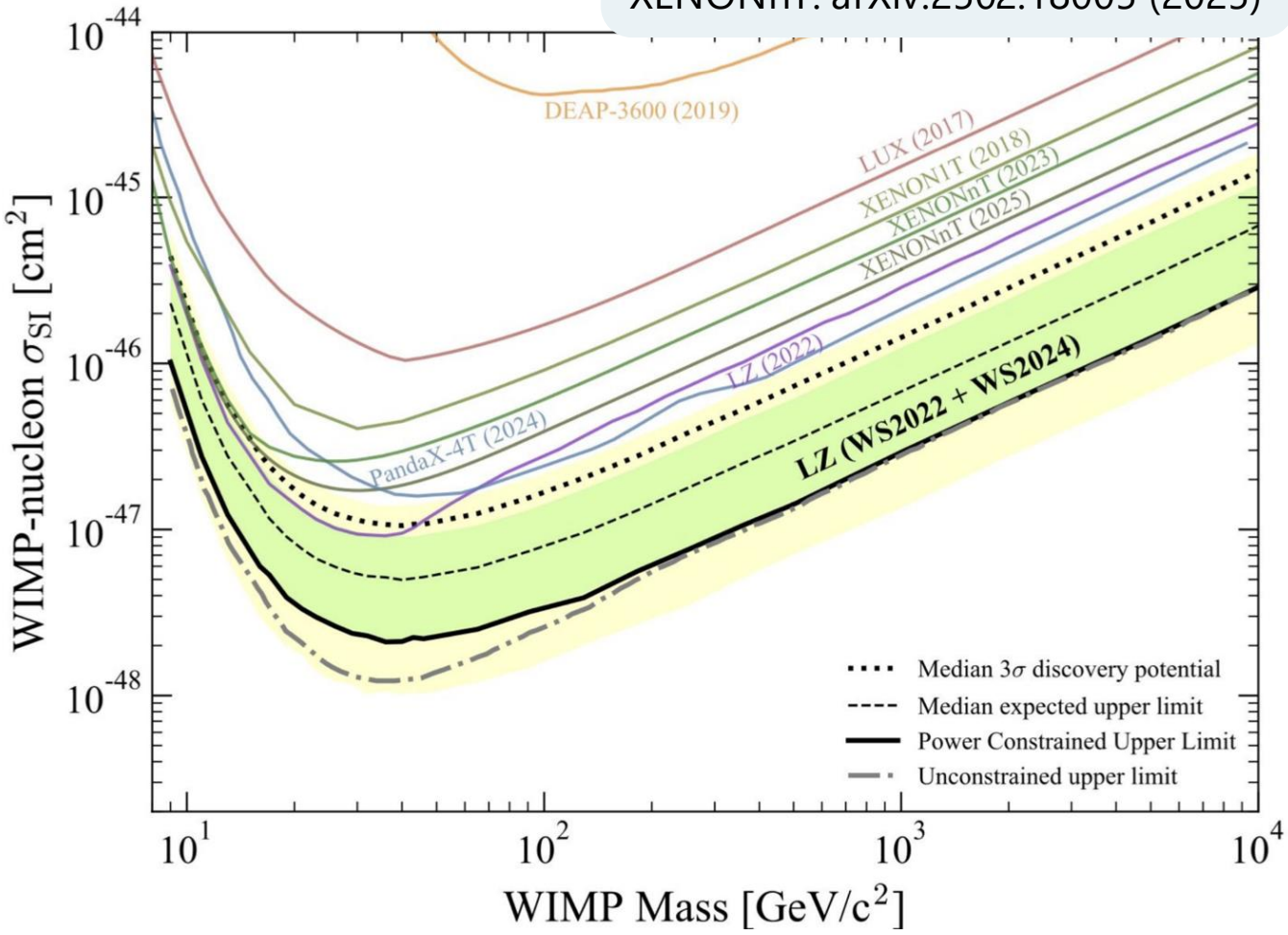
XENONnT



LZ

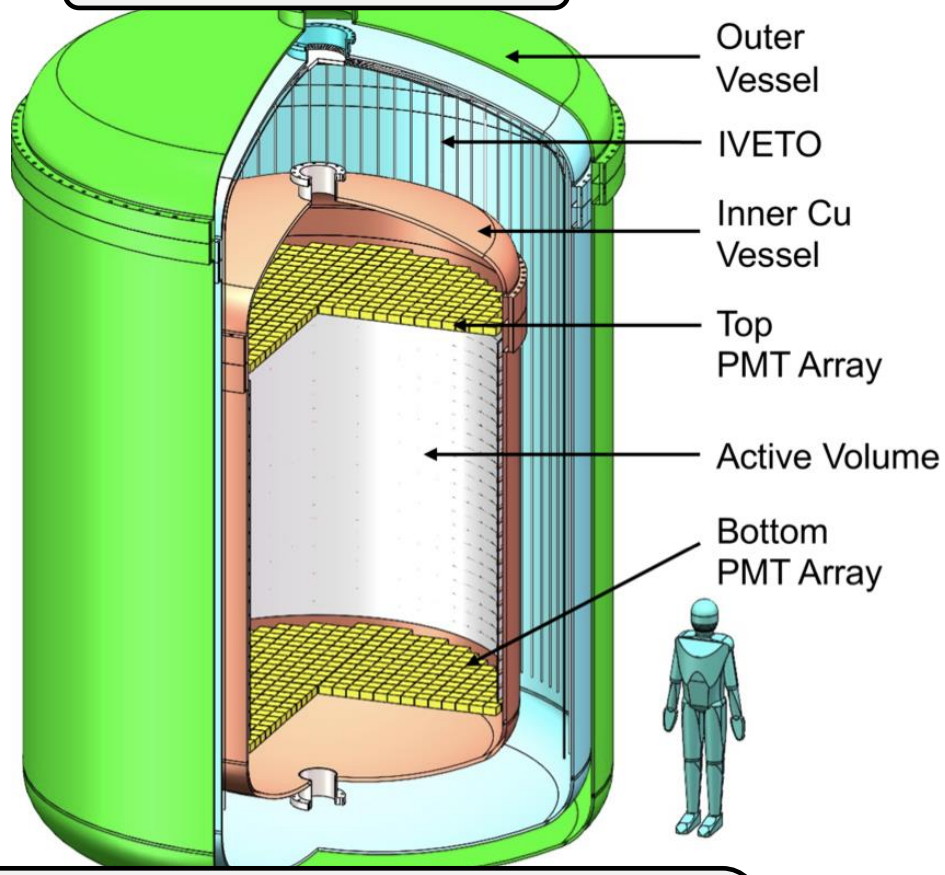


PandaX-4T: PRL134 (2025) 011805
LZ: PRL 135 (2025) 011802
XENONnT: arXiv:2502.18005 (2025)



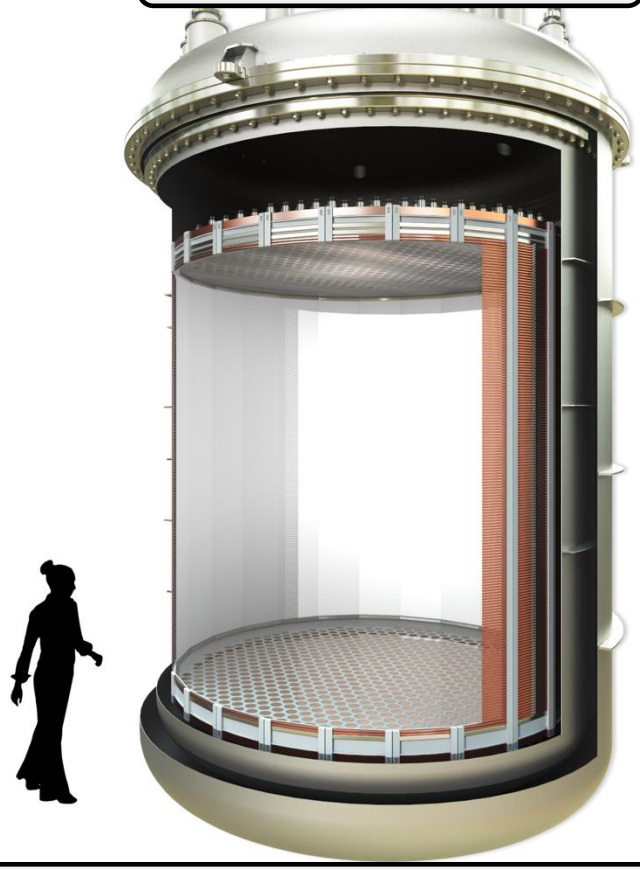
NEXT GENERATION

PandaX-xt



- 43 tonnes of Xe (active volume)
- Panda collaboration
- Design paper: arXiv:2402.03596

XLZD

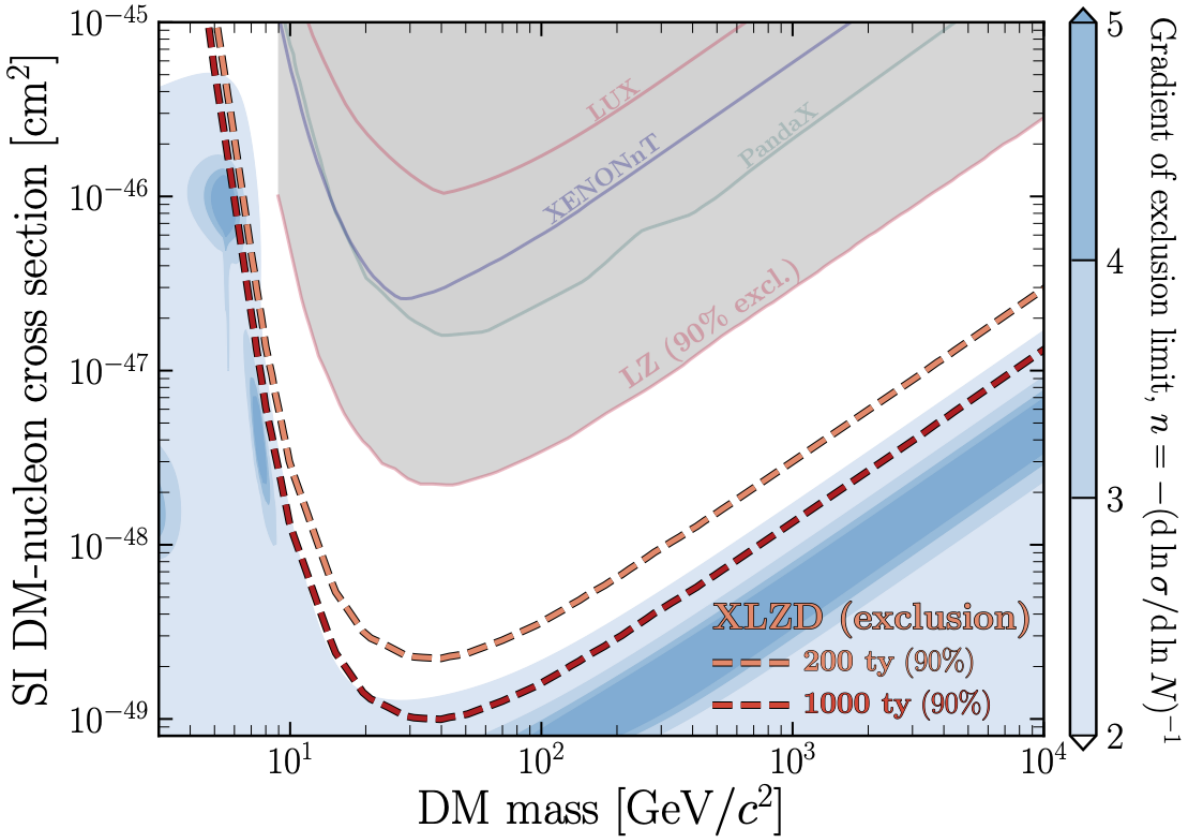


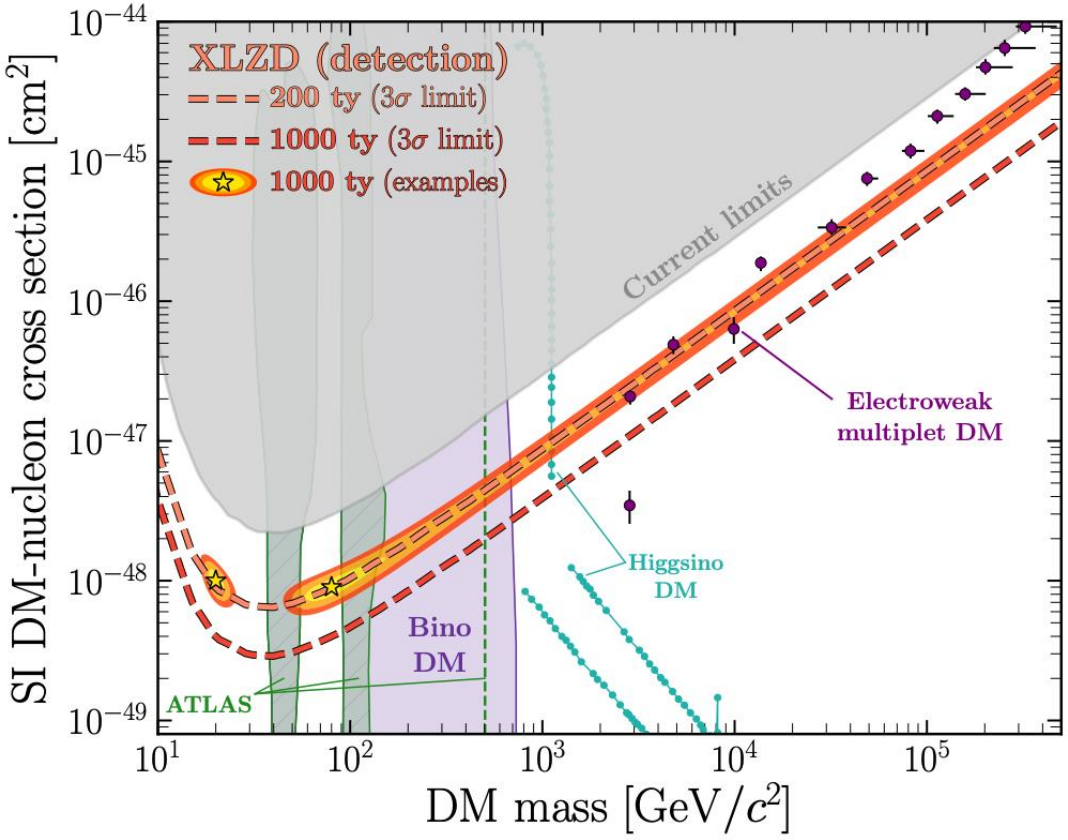
- 60-80 tonnes of Xe (active volume)
- Xenon, LZ and DARWIN merged into formal collaboration in 2024
- Design Book: arXiv:2410.17137

NEXT GENERATION

XLZD

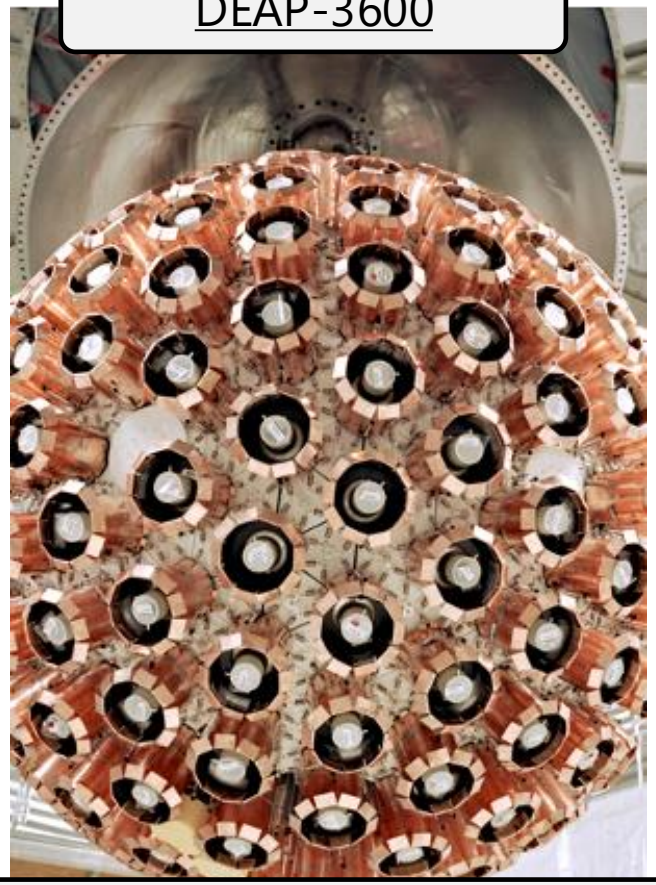
XLZD Design Book
arXiv:2410.17137





Argon detectors

DEAP-3600



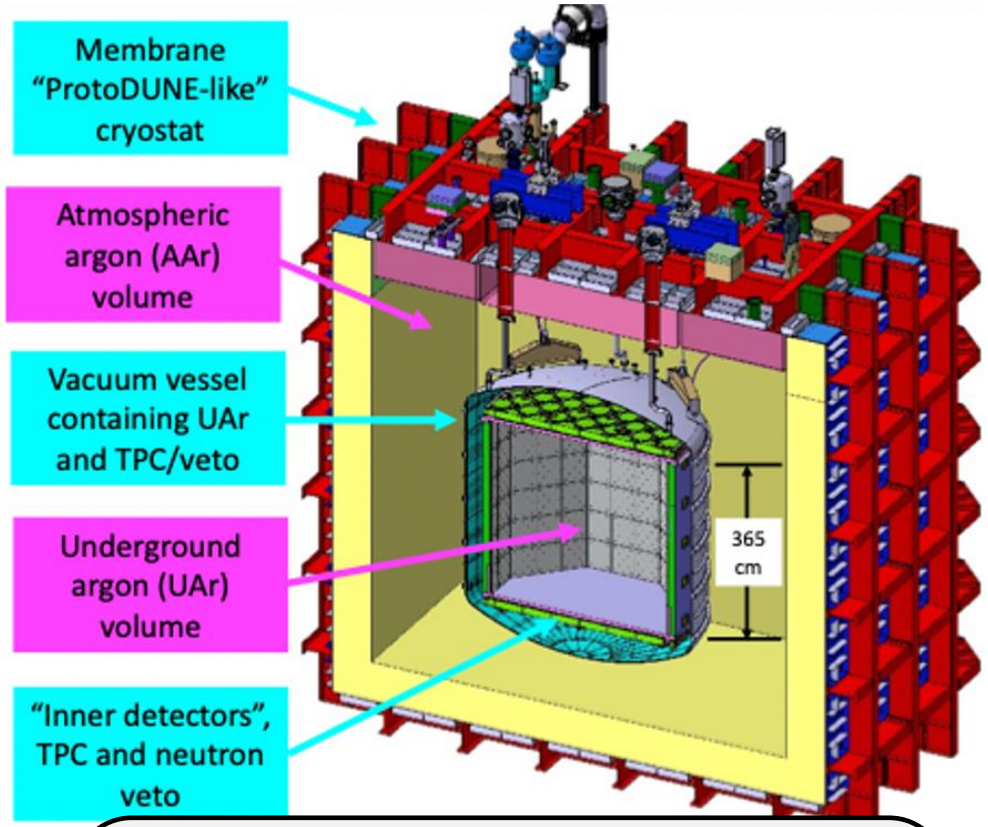
- 3.3 t of Argon
- 255 PMTs & light guides
- Status: commissioning after hardware updates to reach design sensitivity

DarkSide-50

- 46 kg of UAr
- 38 PMTs
- Status: ended

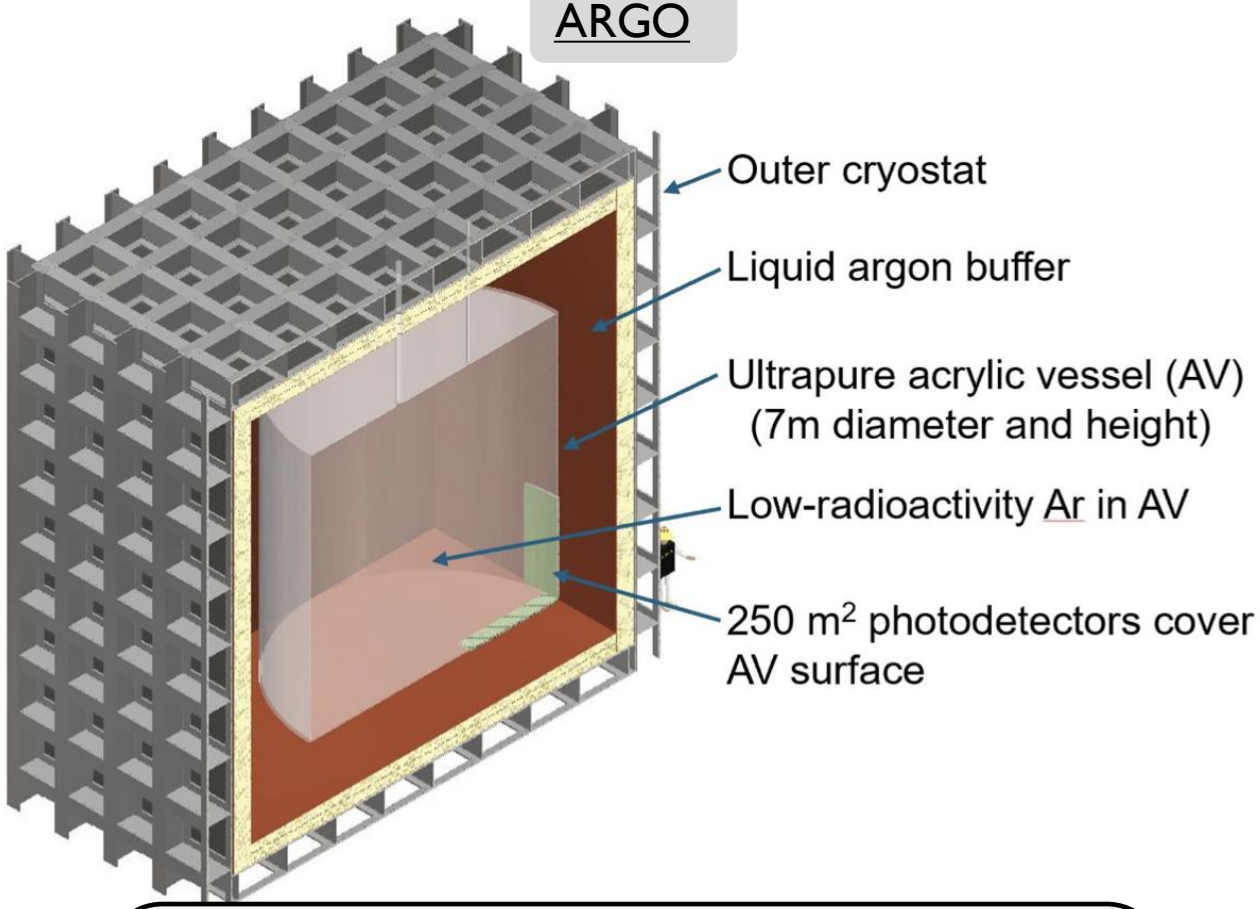
GLOBAL ARGON DARK MATTER COMMUNITY

DarkSide – 20k



- 50 tonnes active target
- 2-phase detector, switch to SiPMs
- Aim for 460 t-y exposure
- Status: under construction, data taking expected in 2028

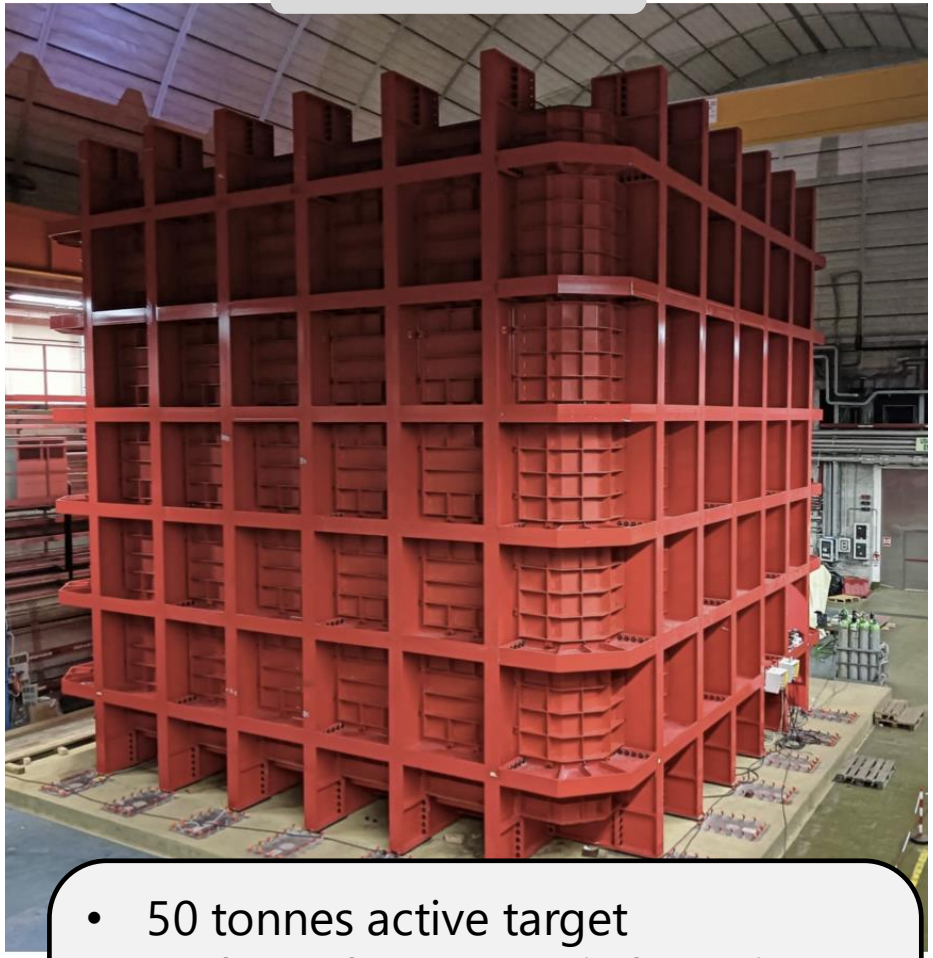
ARGO



- 400 tonnes total mass (300 t fiducial mass)
- Pixelated digital photodetector readout
- Both single-phase and TPC design being considered
- Status: Conceptual design

GLOBAL ARGON DARK MATTER COMMUNITY

DarkSide – 20k



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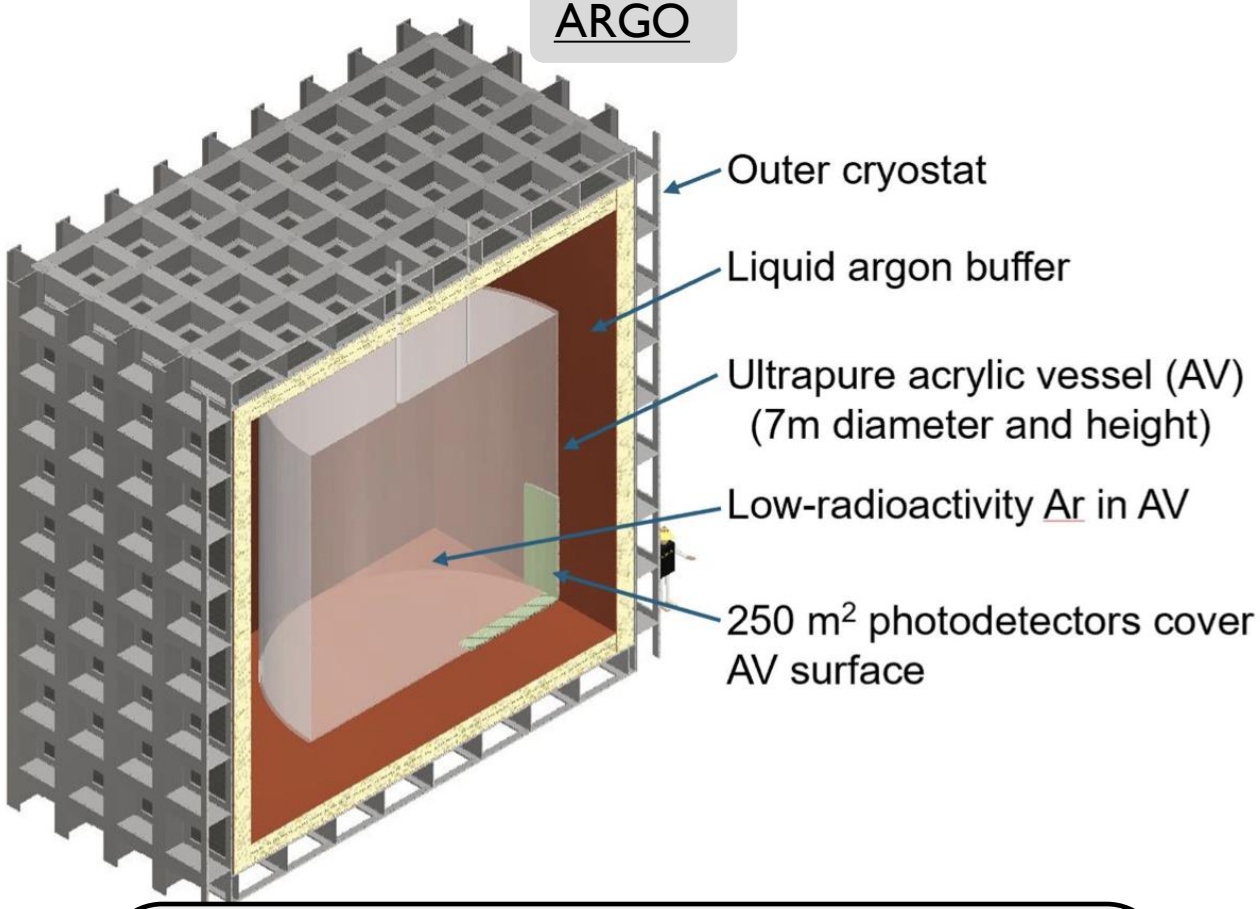
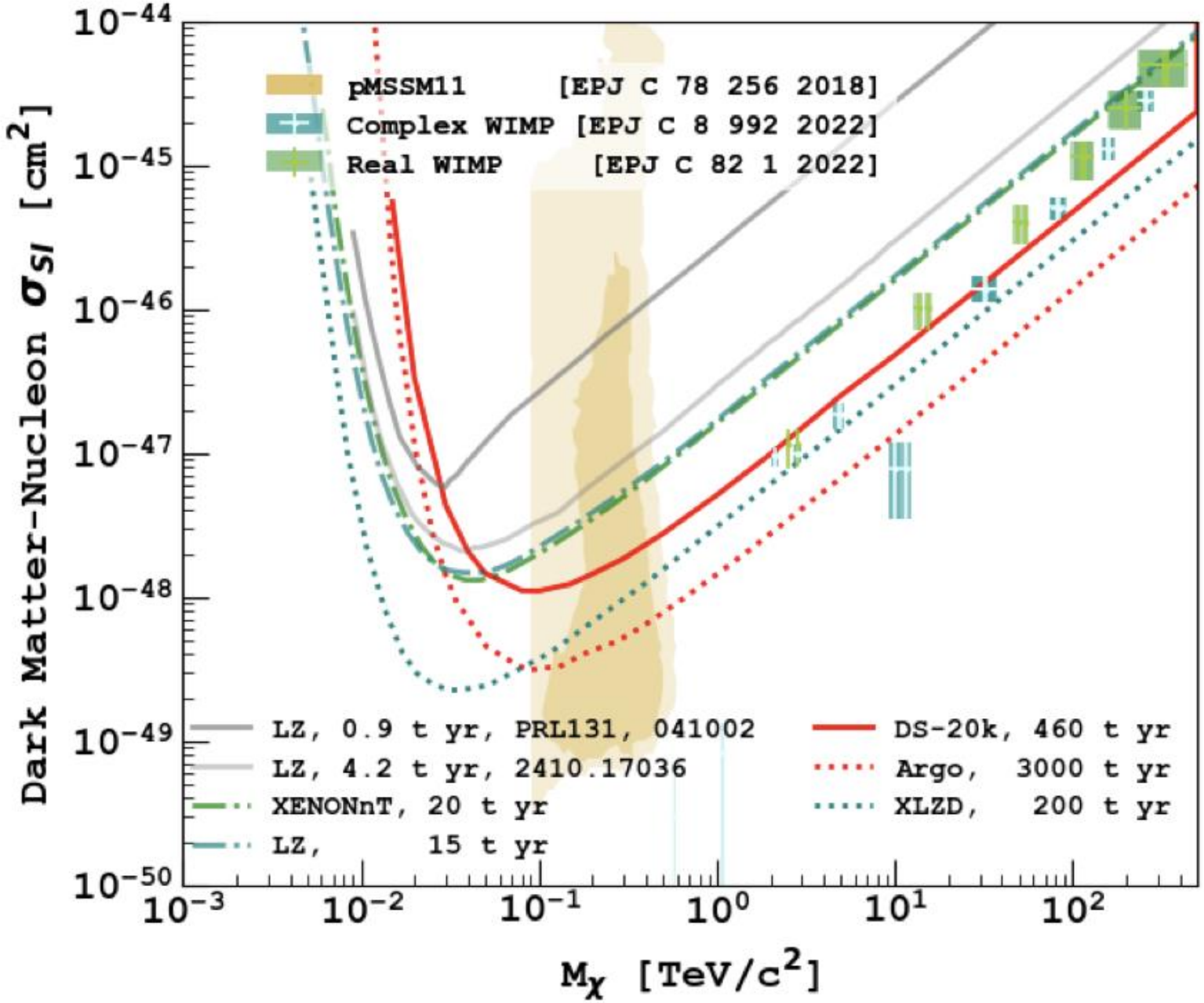
ARGO



- 400 tonnes total mass (300 t fiducial mass)
- Pixelated digital photodetector readout
- Both single-phase and TPC design being considered
- Status: Conceptual design

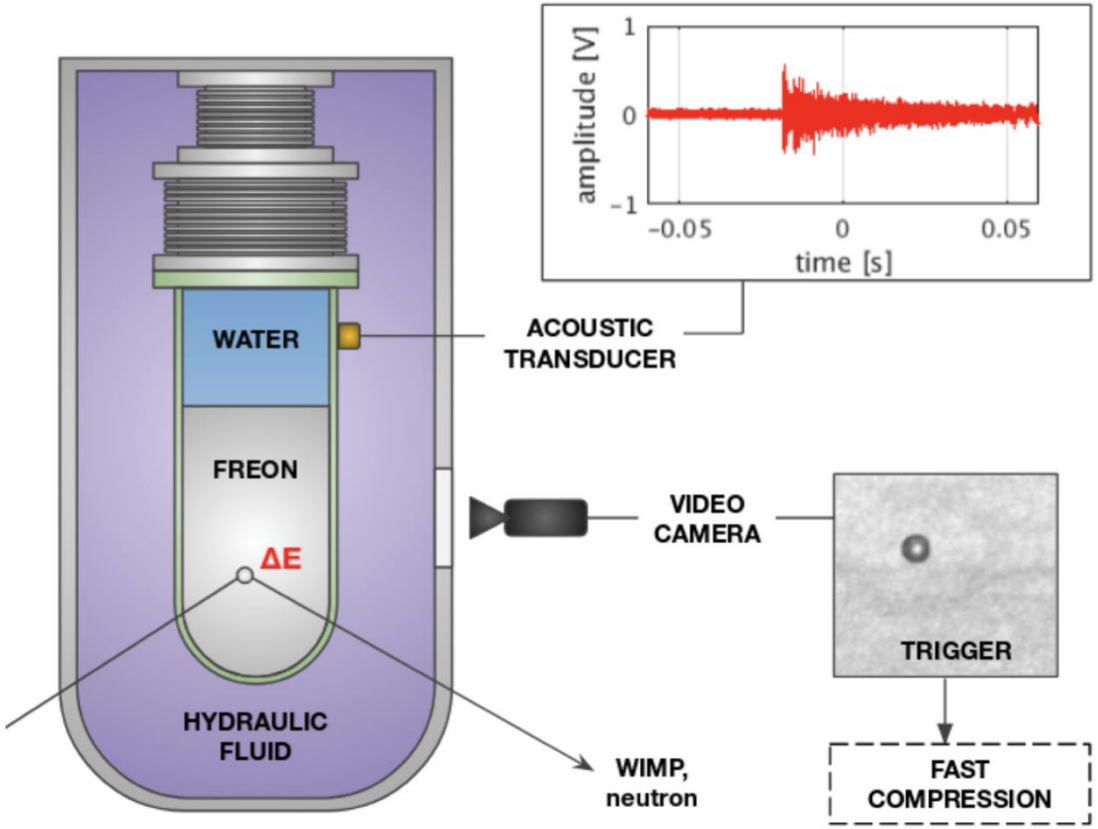
NEXT GENERATION

GADMC input to ESPP2025



BUBBLE CHAMBERS

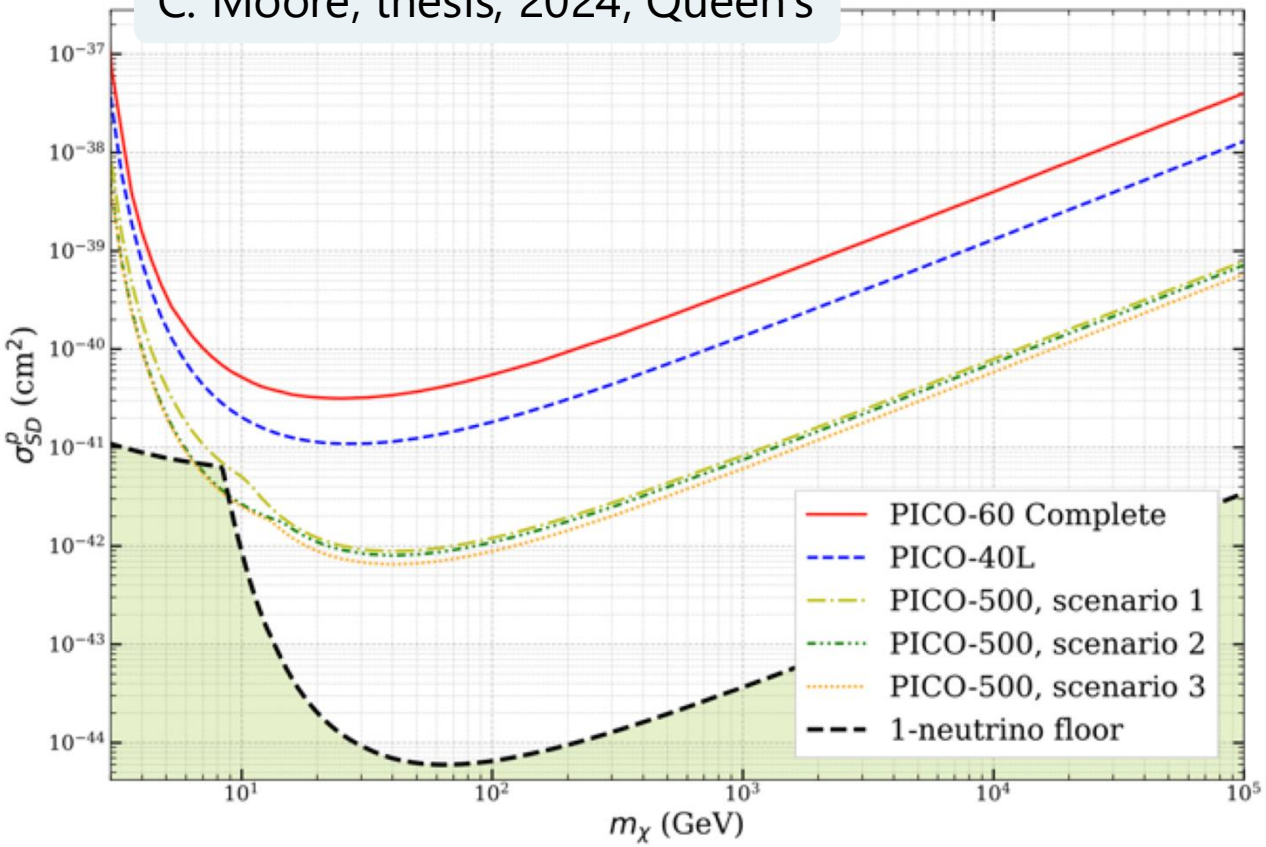
Guillaume Giroux 2021 J. Phys.: Conf. Ser. 2156 012068



- Bubble chambers using superheated liquids (Freon-based).
- Threshold detector, ER background suppression by energy tuning
- 3D event reconstruction

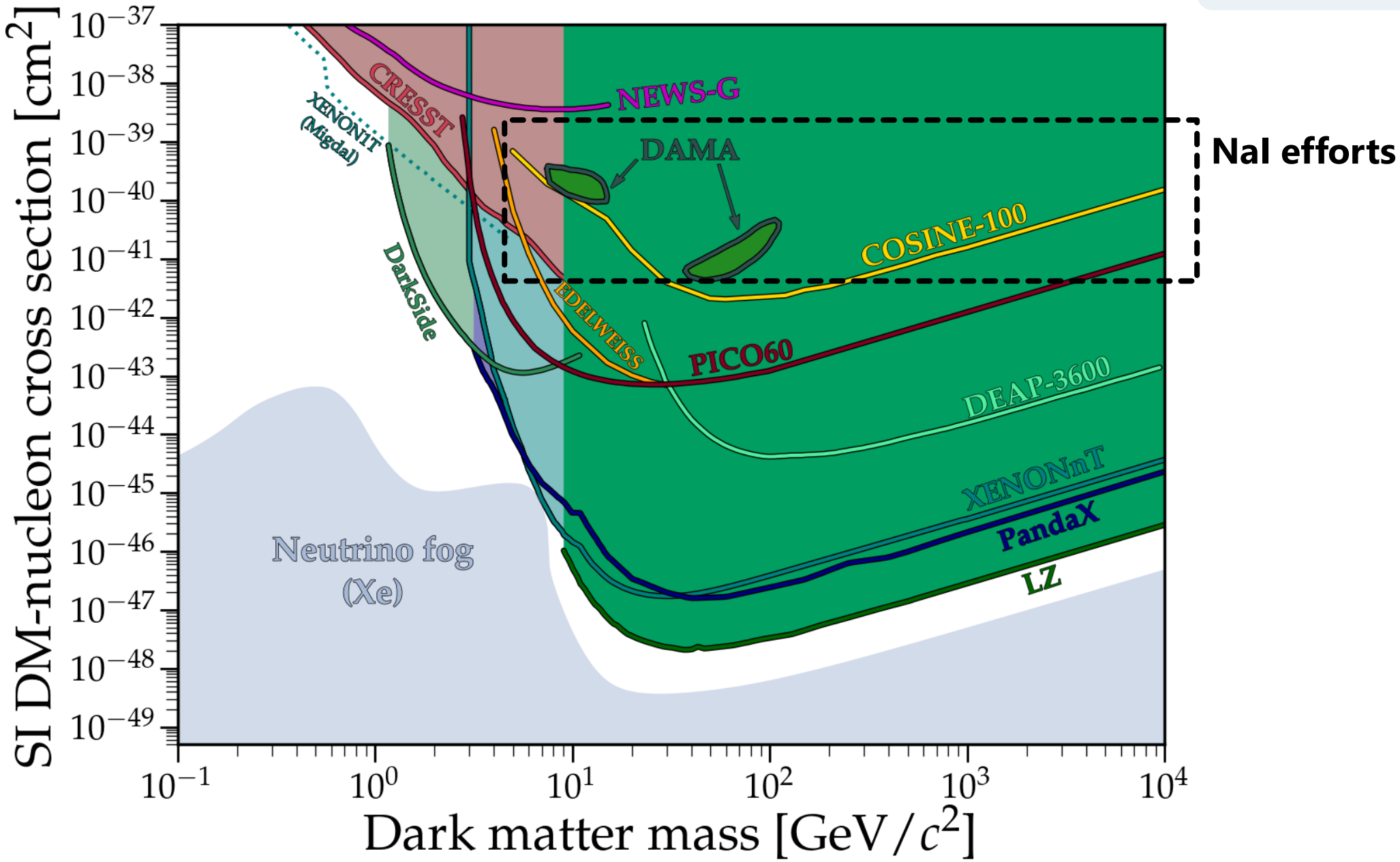
BUBBLE CHAMBERS

C. Moore, thesis, 2024, Queen's



- Leading WIMP-proton spin-dependent limits with PICO-60
- PICO- 40L running (right-side-up design)
- Next generation: PICO-500 (commissioning expected 2026)

Plots by Ciaran O'Hare
(https://github.com/cajohare)

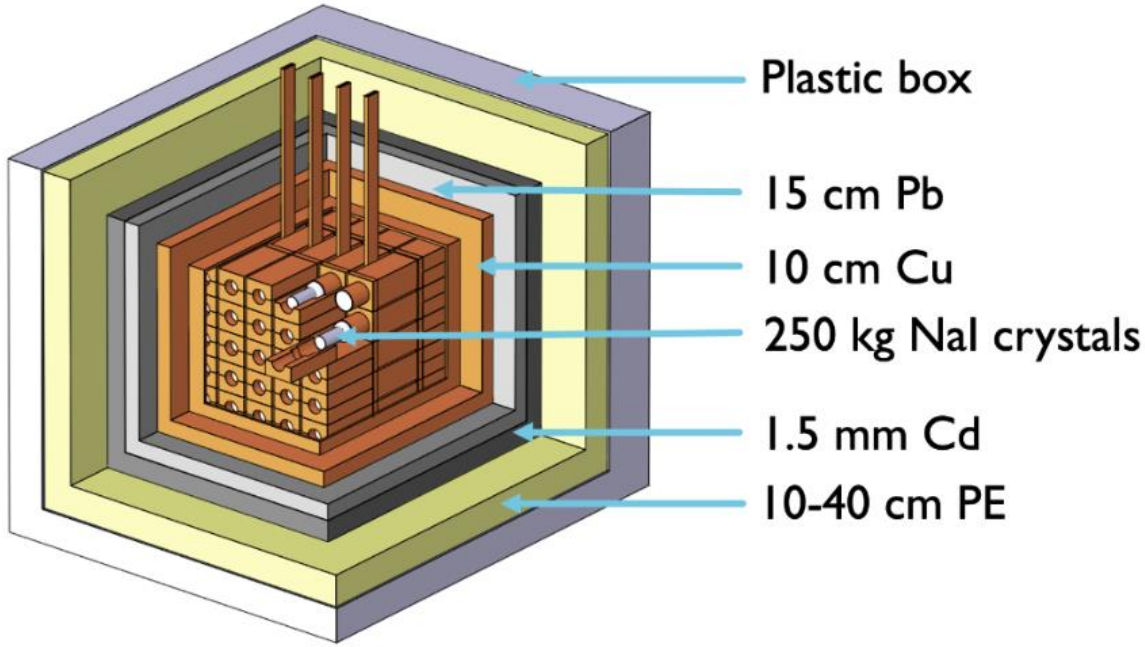


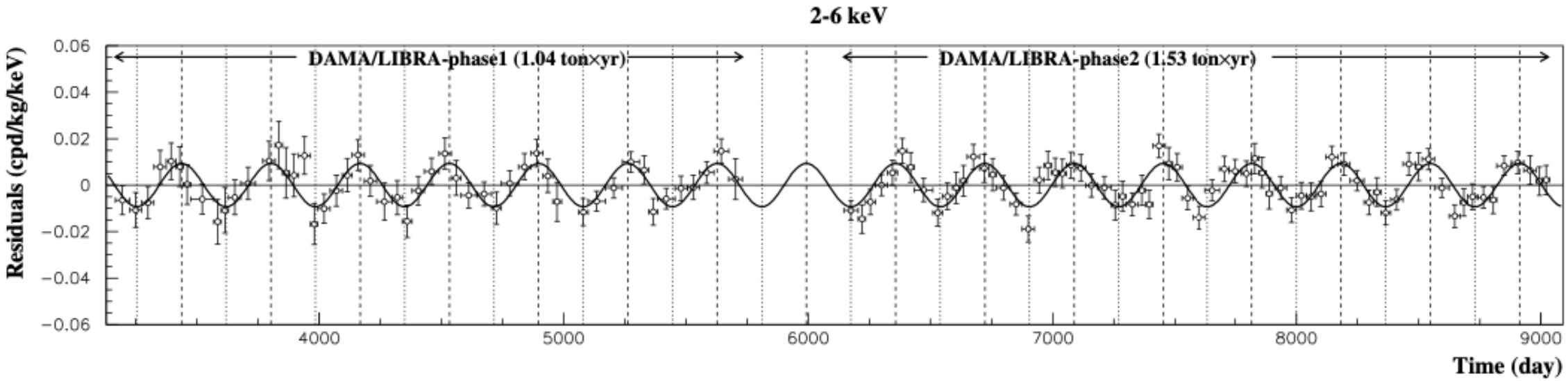
NaI efforts

DAMA/LIBRA

https://scipost.org/SciPostPhysProc.12.025

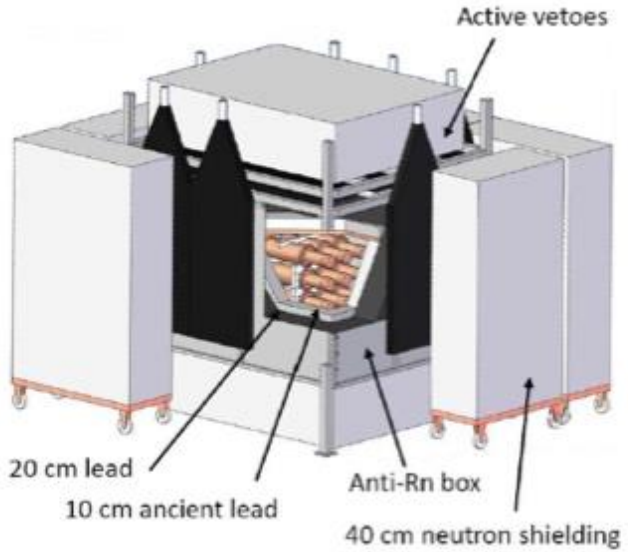
- Phase 2 setup (2011-2025):
  - 250 kg high-purity NaI(Tl) crystals
- Total exposure: 2.86 ton x yr over 22 annual cyc
- Claiming 13.7 sigma
- Now decommissioning





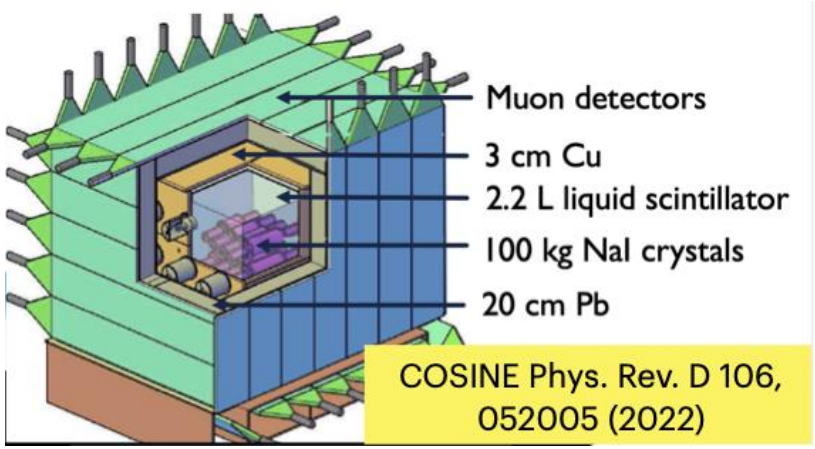
NaI experiments

ANAIS



- 112.5 kg total
- Active muon veto
- Status: data taking since 2017 at Canfranc

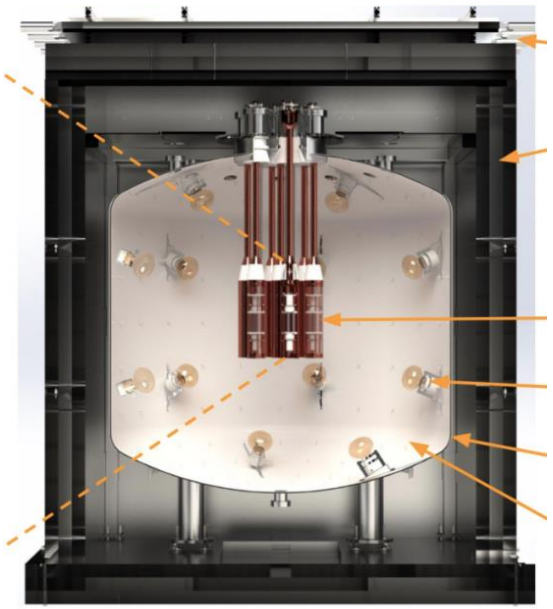
COSINE



COSINE Phys. Rev. D 106, 052005 (2022)

- 106 kg total
- Liquid scintillator & muon veto
- Status: Concluded operations in 2023
- COSINE-100U, enhance sensitivity to low E (enhanced light collection efficiency)

SABRE

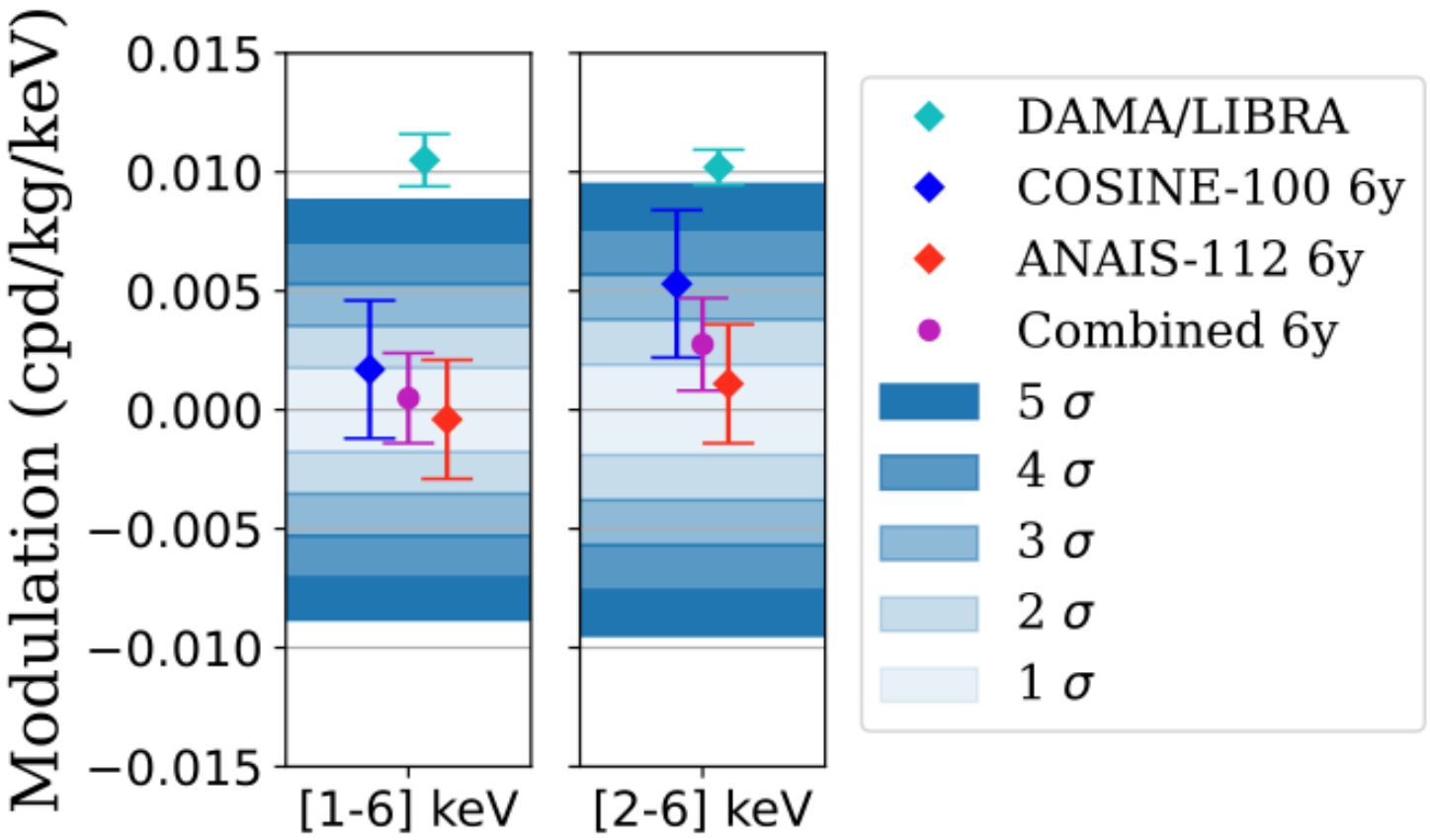


- North & South detectors with 35-50kg each
- Focus on ultra radio-pure crystals
- Status: Preparation

NaI experiments

ANAIS

COSINE



Combined 6 year analysis:

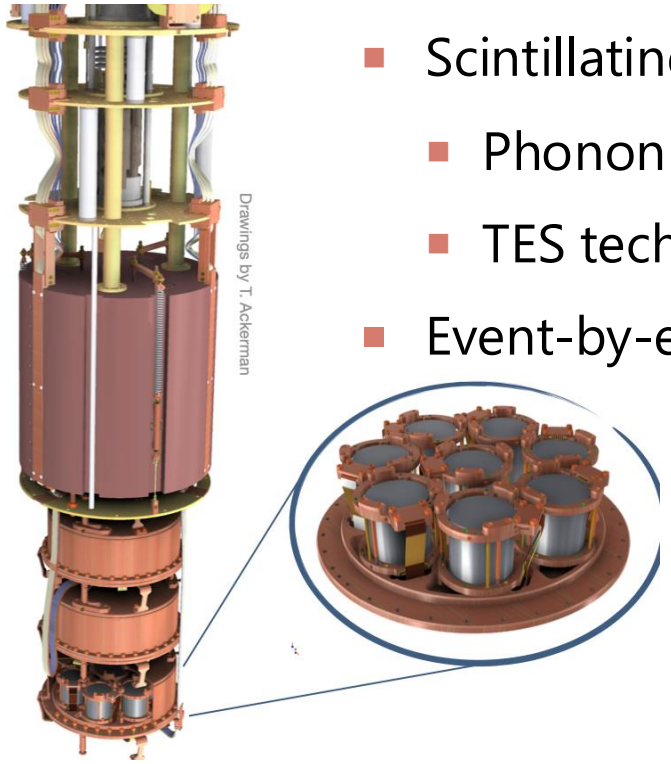
- Incompatible at 4 σ (1-6 keV) and 3.5 σ (2-6 keV) with DAMA/LIBRA
- ANAIS and COSINE results compatible at 1 σ

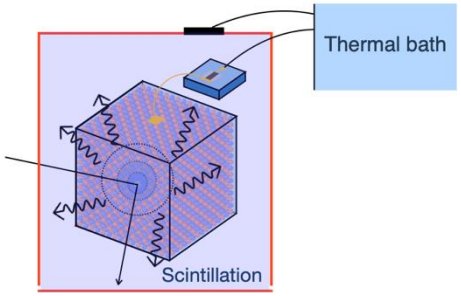
N. Carlin et al. 2025 arXiv:/2503.19559

NaI experiments

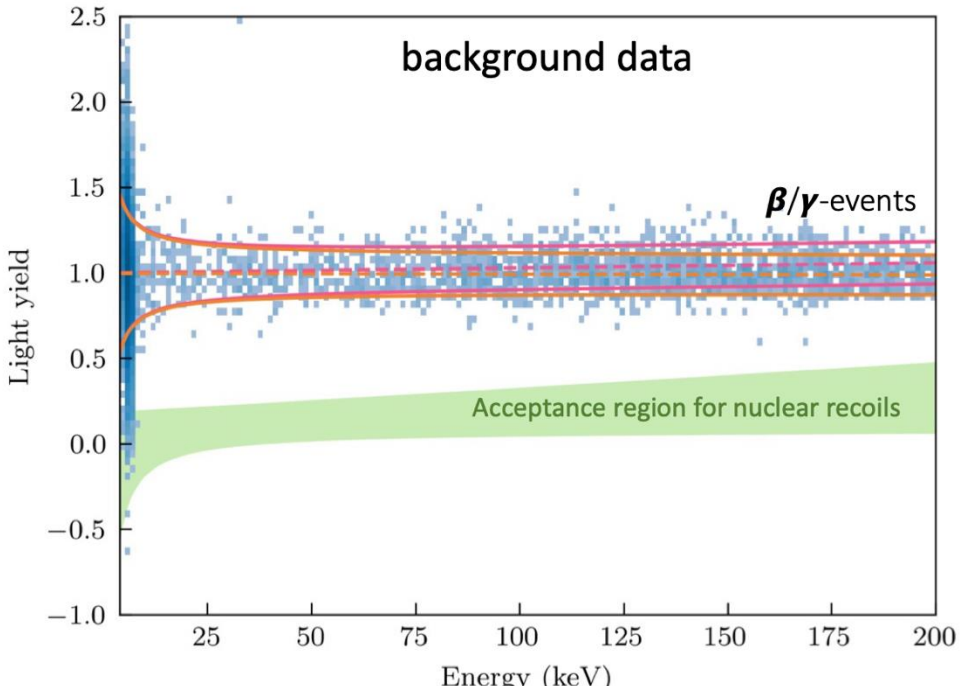
COSINUS

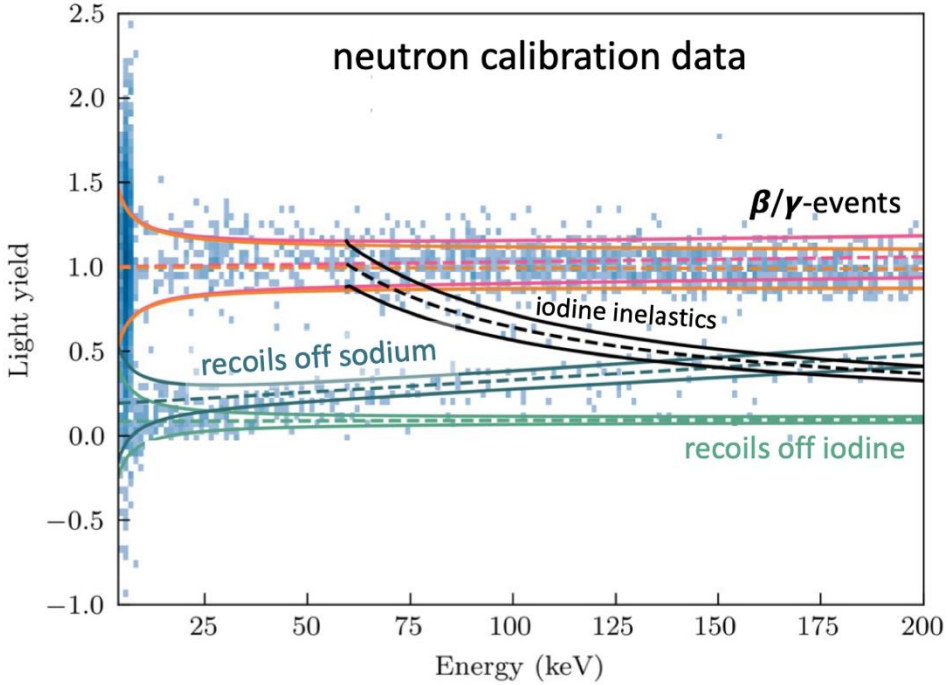
- Detector:
  - Scintillating cryogenic calorimeter:
    - Phonon and scintillation signal
    - TES technology from CRESST
  - Event-by-event background discrimination





- Plan:
  - Data taking to start in 2025
  - 100 kg days 2025-2026

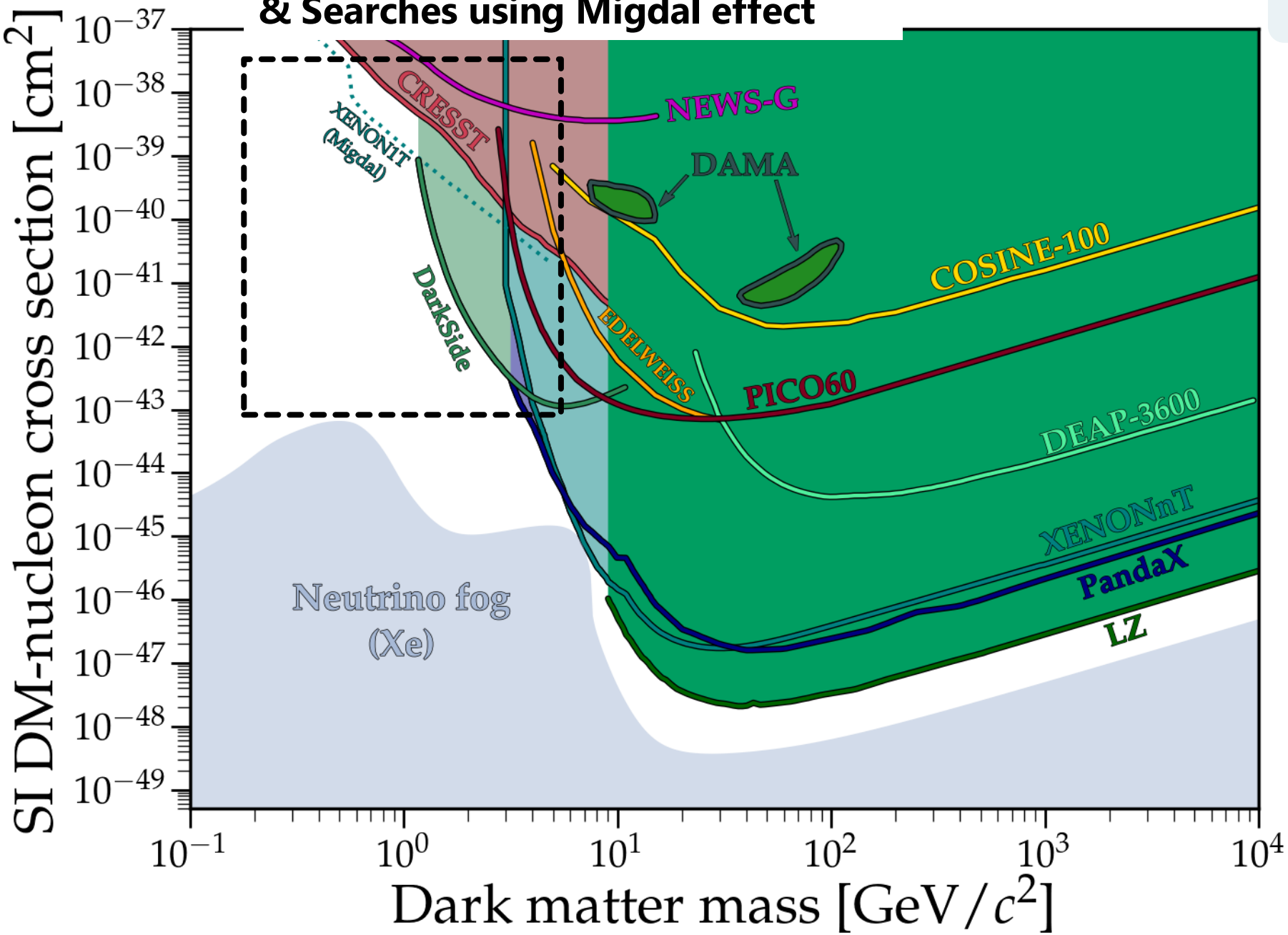




K. Schaeffner at UCLA 2025
PRD 110, 043010, 2024

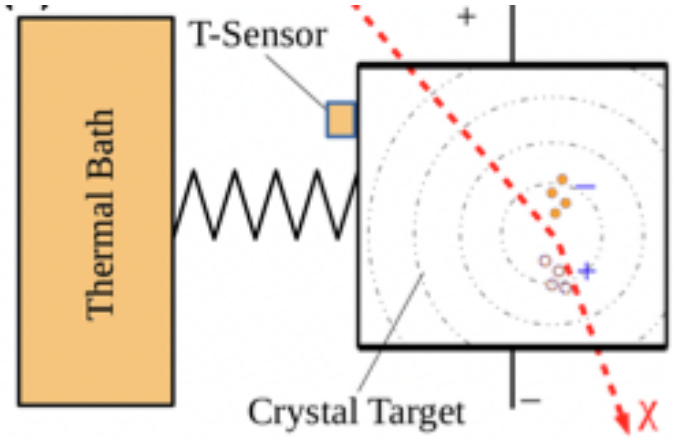
Solid-state detectors
& Searches using Migdal effect

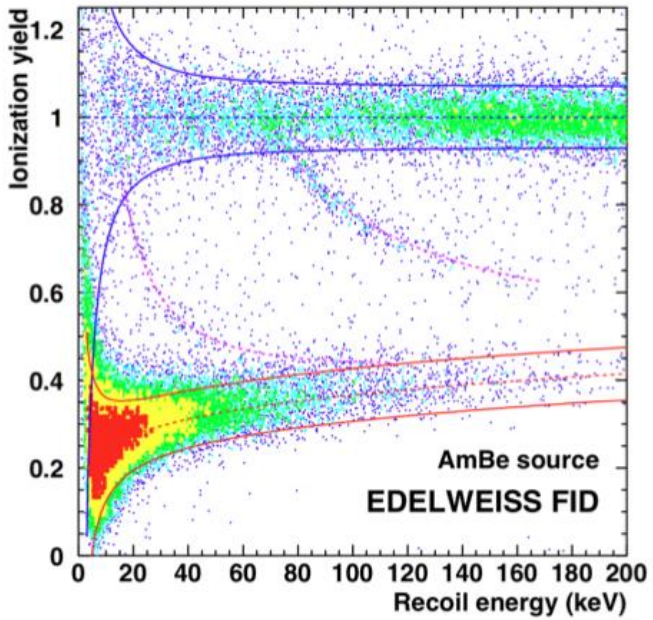
Plots by Ciaran O'Hare
(https://github.com/cajohare)



CRYOGENIC BOLOMETERS

APPEC Committee Report 2021, arXiv:2104.07634
E. Armengaud *et al* 2017 *JINST* **12** P08010

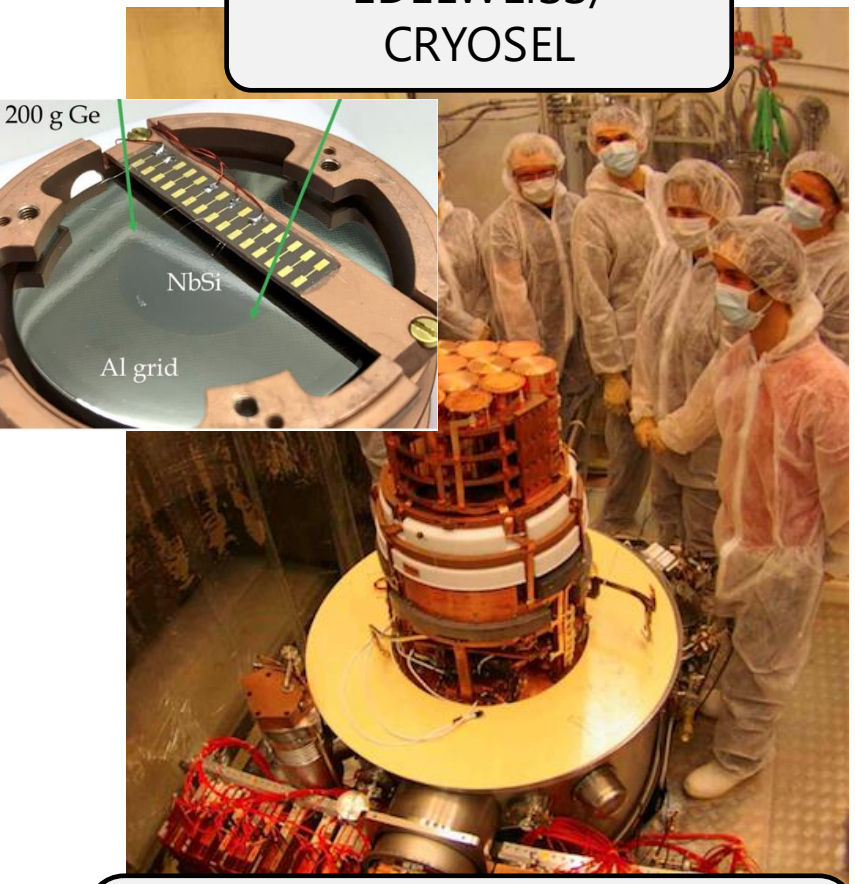




- Crystal targets (Ge, $CaWO_4$) operated < 50mK
- Phonon readout via NTD or transition edge sensors
- Simultaneous readout of ionization or scintillation signal allows background discrimination
- Excellent energy resolution

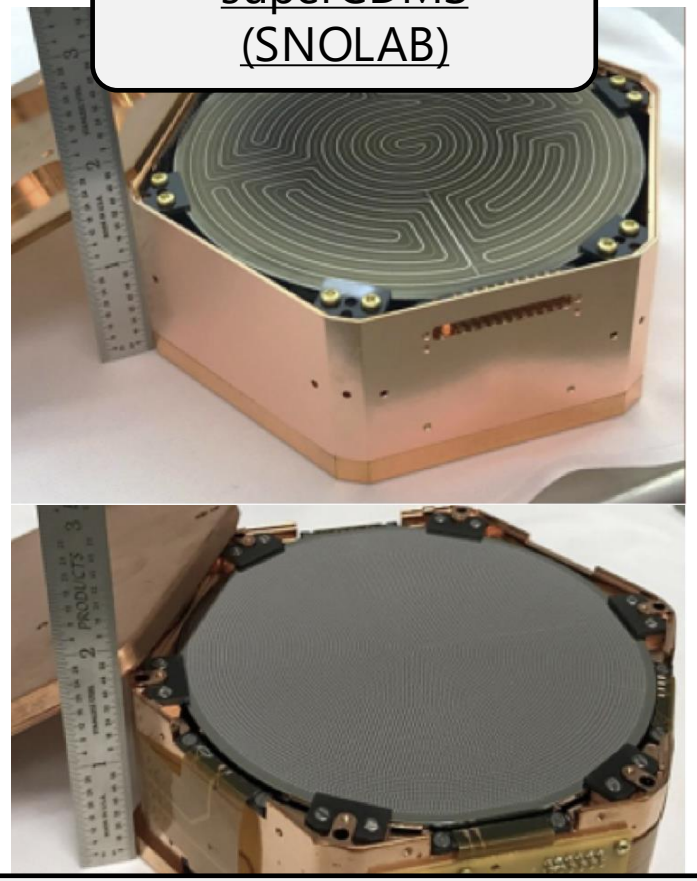
CRYOGENIC BOLOMETERS

EDELWEISS/ CRYOSEL



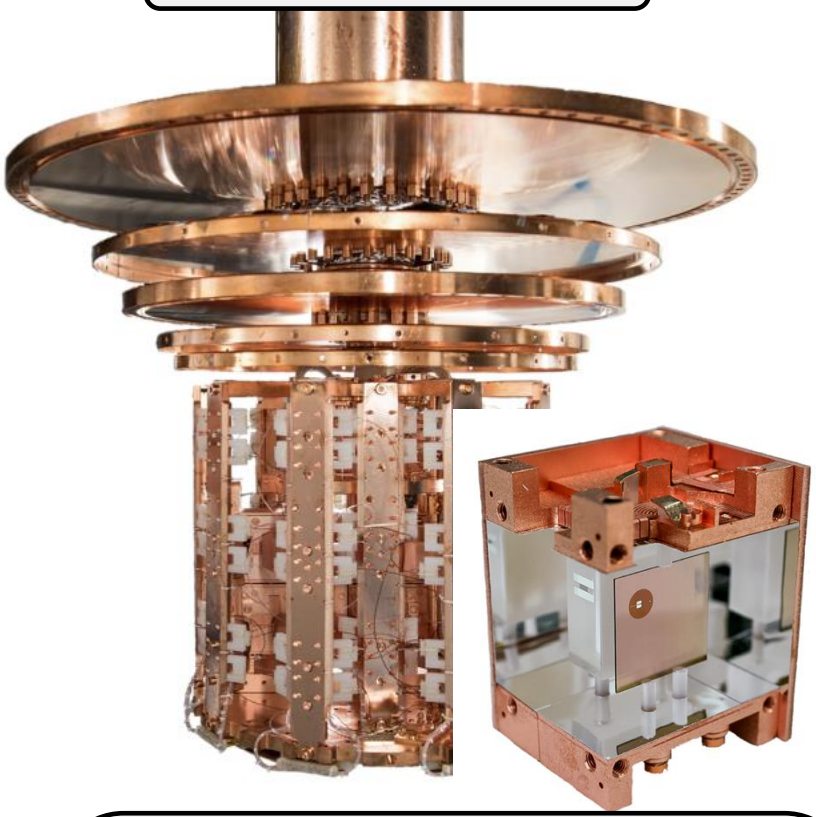
- Germanium crystals
- Moving towards SSED sensors
- Status: R&D for CRYOSEL

superCDMS (SNOLAB)



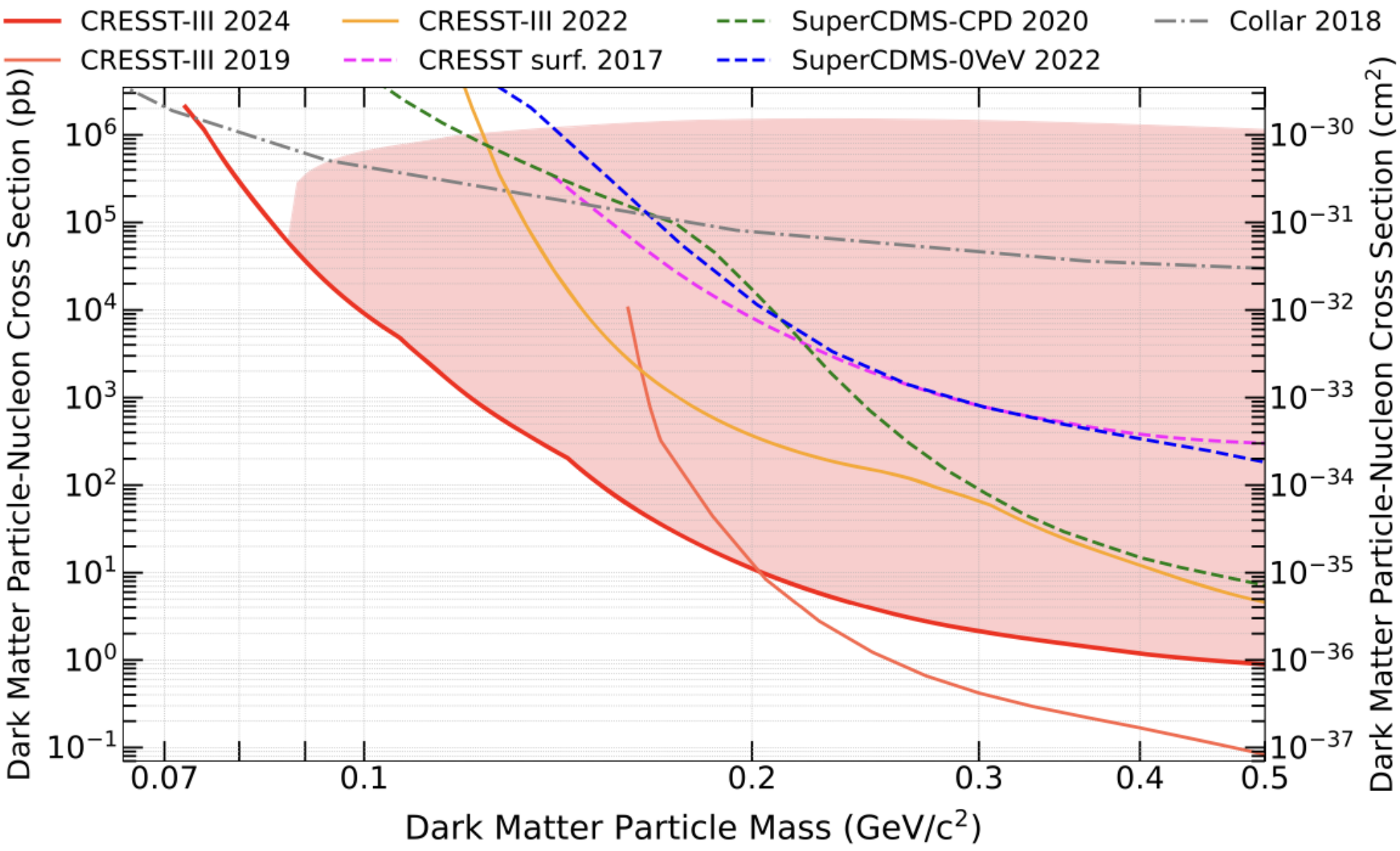
- Si and Ge crystals, total 30kg
- Phonons: QETES, Charge: interleaved electrodes
- Status: Construction ongoing, commissioning later this year

CRESST-III (LNGS)



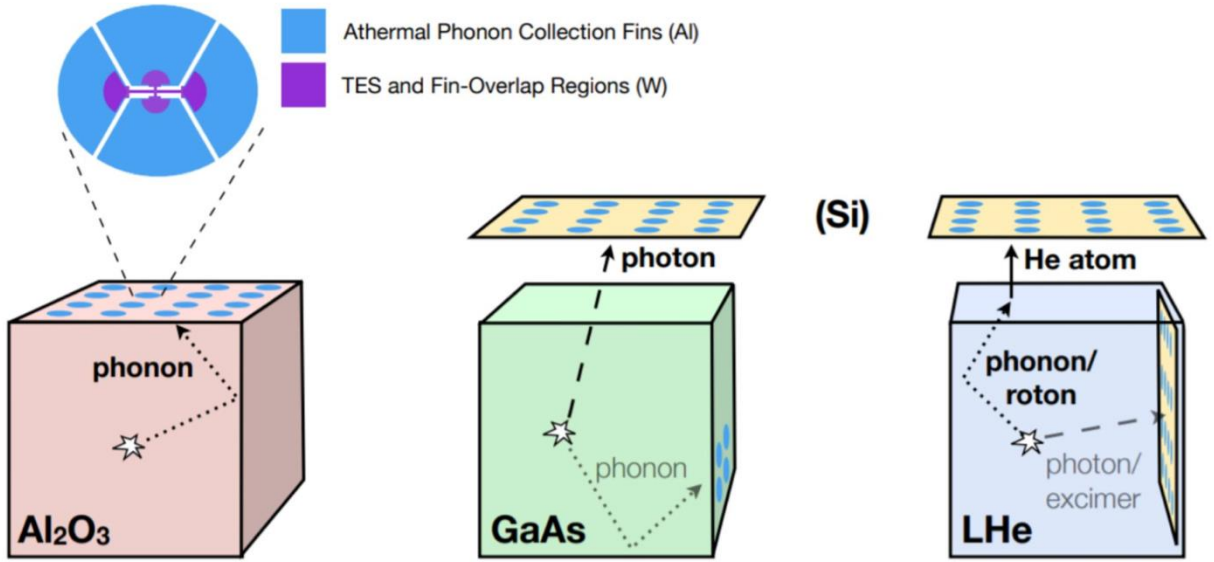
- $CaWO_4$, Al_2O_3 LiAlO2, Si
- Phonons: W-TES
- Light: Silicon-on-Sapphire wafer
- Status: Running, electronics upgrade for more modules/channels

Phys. Rev. D **110**, 083038



CRYOGENIC BOLOMETERS

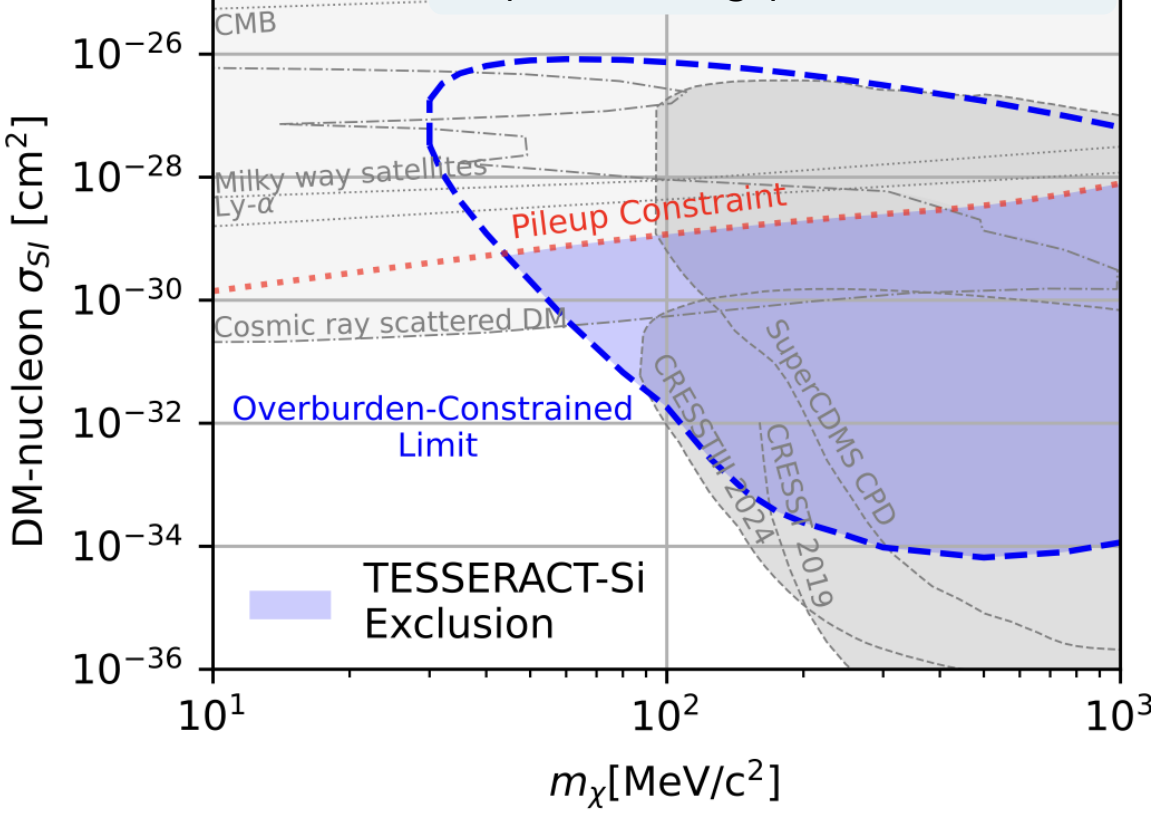
TESSERACT



- Apply diverse TES-based methods to the low-mass regime
- Push phonon sensors to sub-eV thresholds
- Diverse target materials
- Understand and mitigate Low Energy Excess (LEED)
- Status: Aiming for UG operations at LSM in 2028

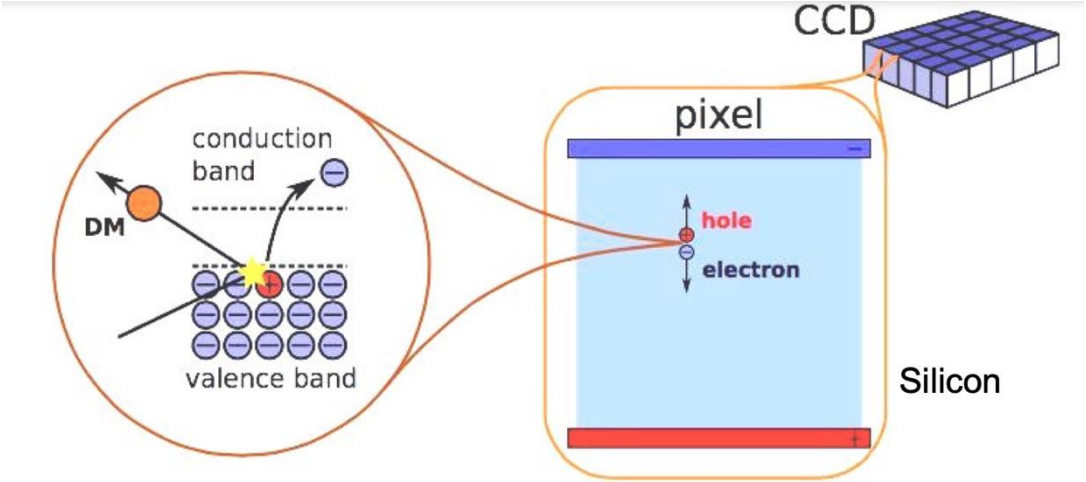
24h DM search at LBNL

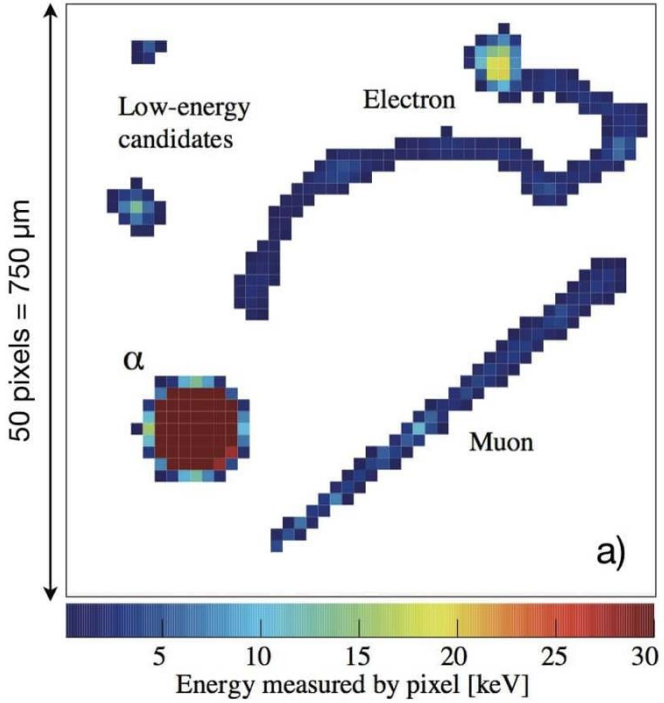
https://arxiv.org/pdf/2503.03683



SILICON CCDs

https://damic.uchicago.edu/detector.php

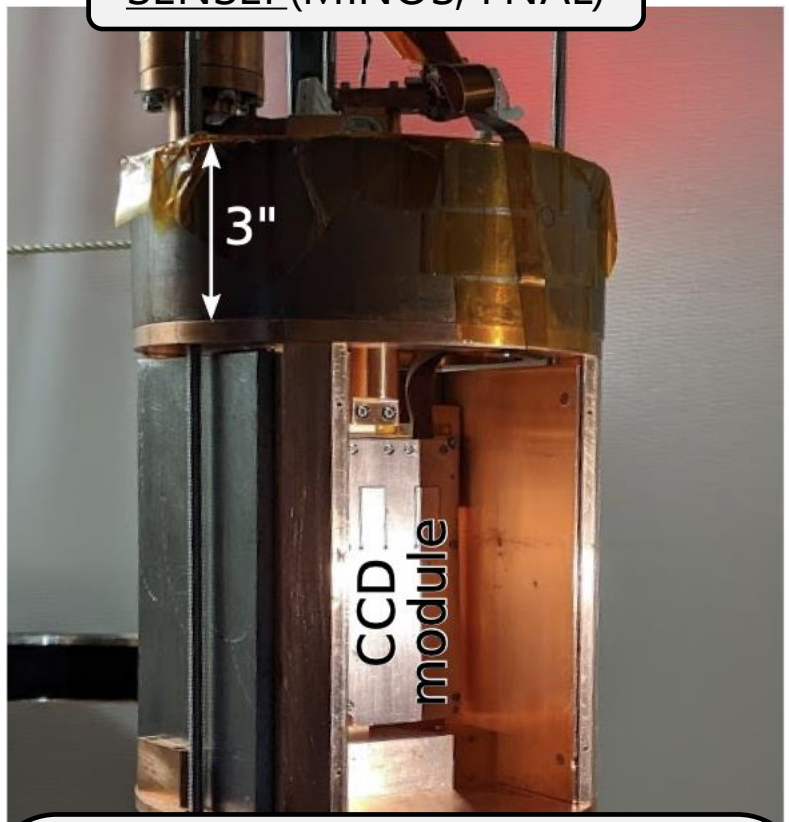




- DM-electron scattering in silicon CCDs (Charge coupled devices)
- Charge is drifted to pixel gates (readout)
- Position reconstruction form diffusion
- Spatial resolution allows particle ID

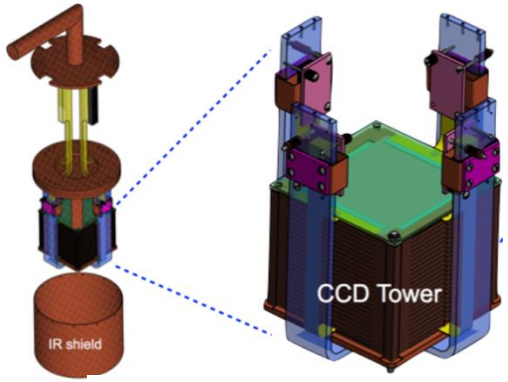
SILICON CCDs

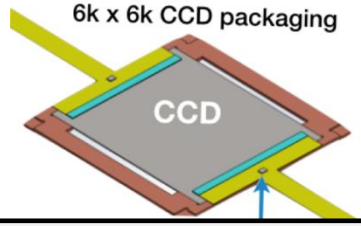
SENSEI (MINOS, FNAL)



- 2-gram -> 100 gram
- high-resistivity Skipper-CCD (charge readout)
- Status: third science run of 40-gram version at SNOLAB, lowest dark current record

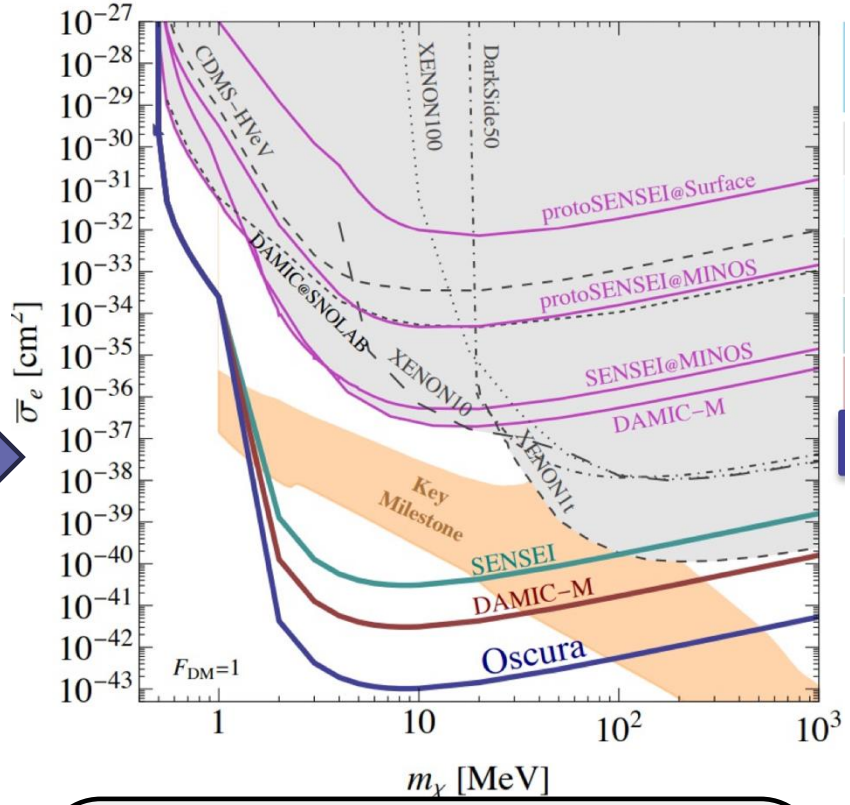
DAMIC-M (Modane)





- 1kg Si
- High resistivity CCD-Skipper (charge readout)
- Status: First run at Modane

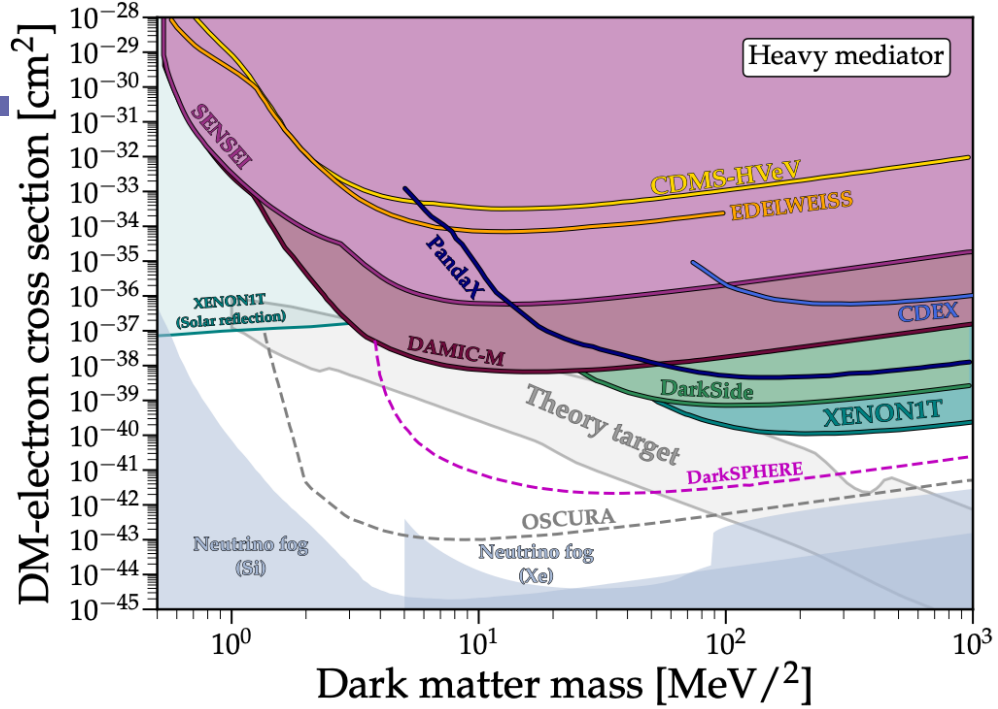
Oscura

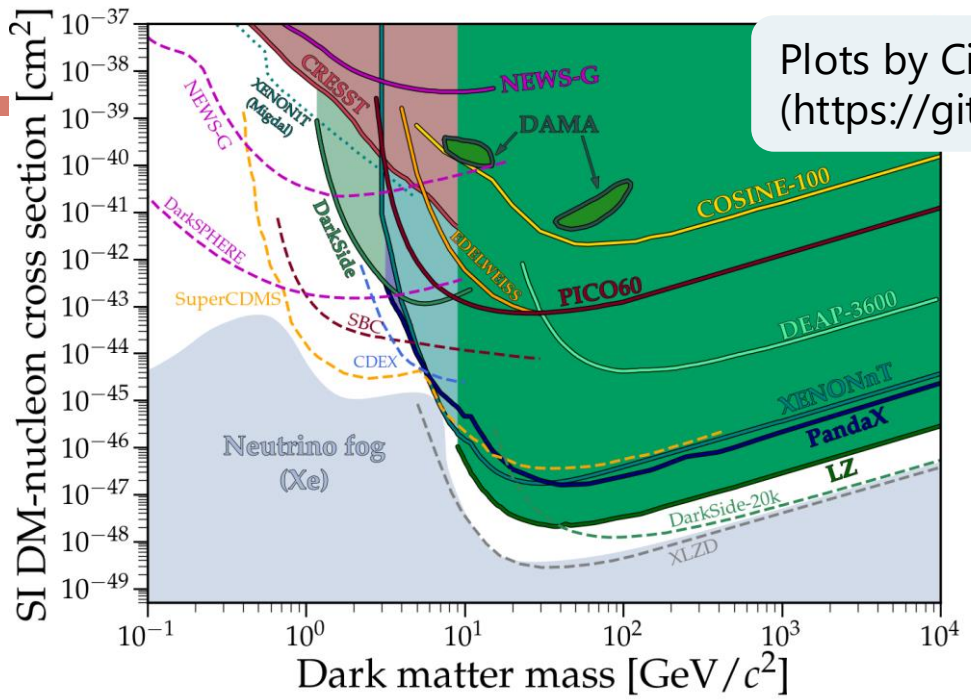


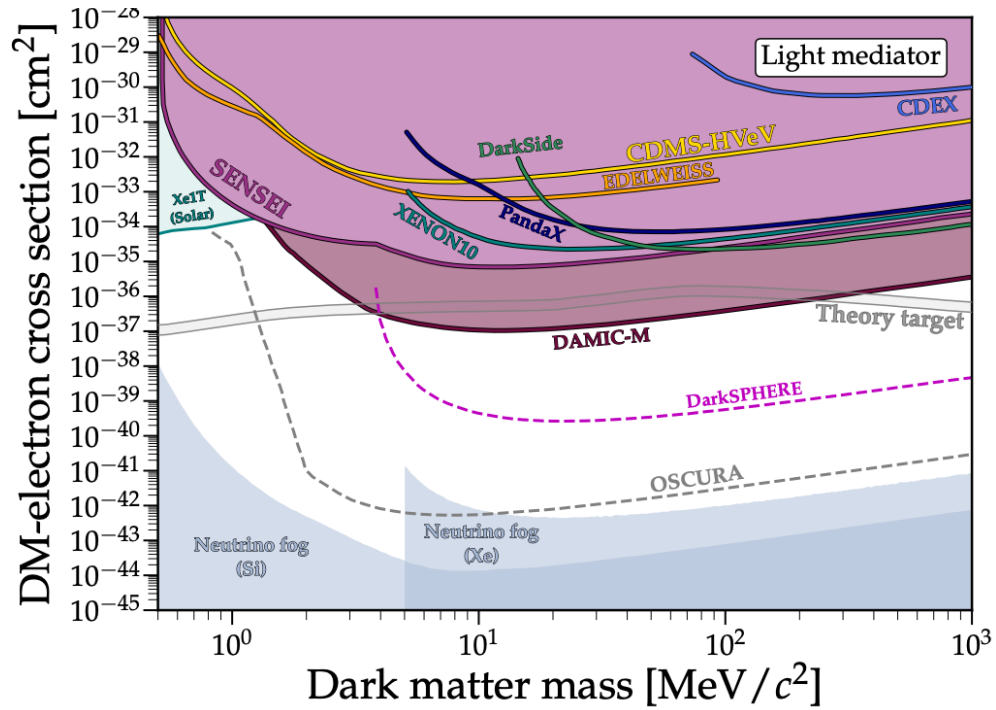
- 10 kg
- R&D needed to increase mass and reduce backgrounds (2 orders of magnitude)
- Status: 1kg prototype funded

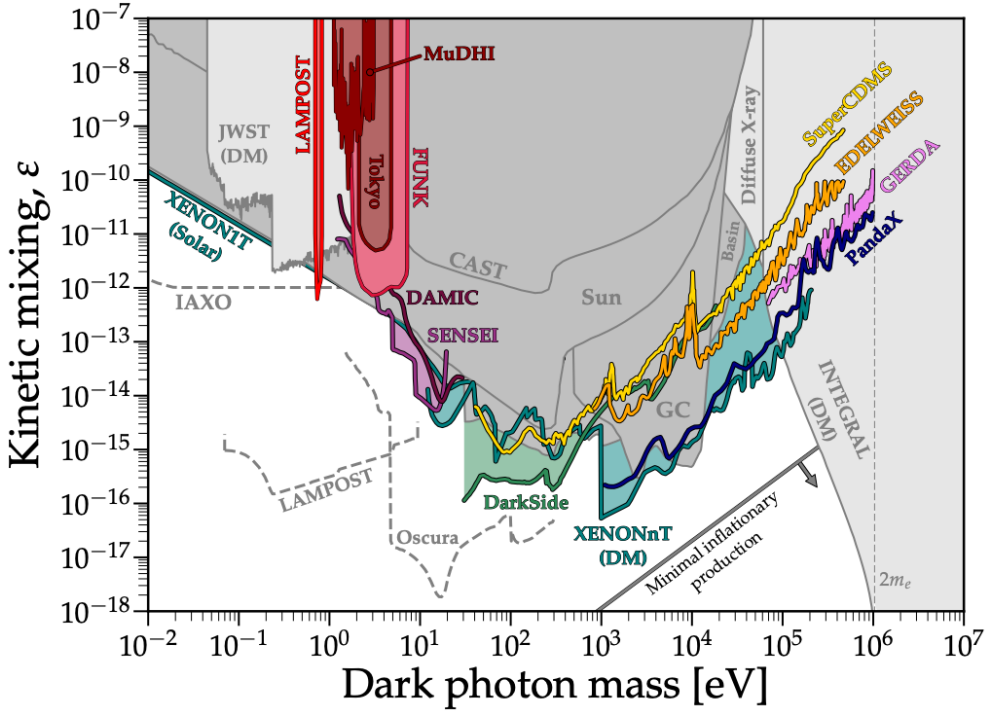
PROSPECTS

Plots by Ciaran O'Hare (https://github.com/cajohare)









SUMMARY

- Many different methods for particle dark matter direct detection searches
- Different methods are complimentary and have different strengths
- Exciting searches with current and near-future experiments