AN INTRODUCTION TO DARK MATTER DIRECT DETECTION METHODS

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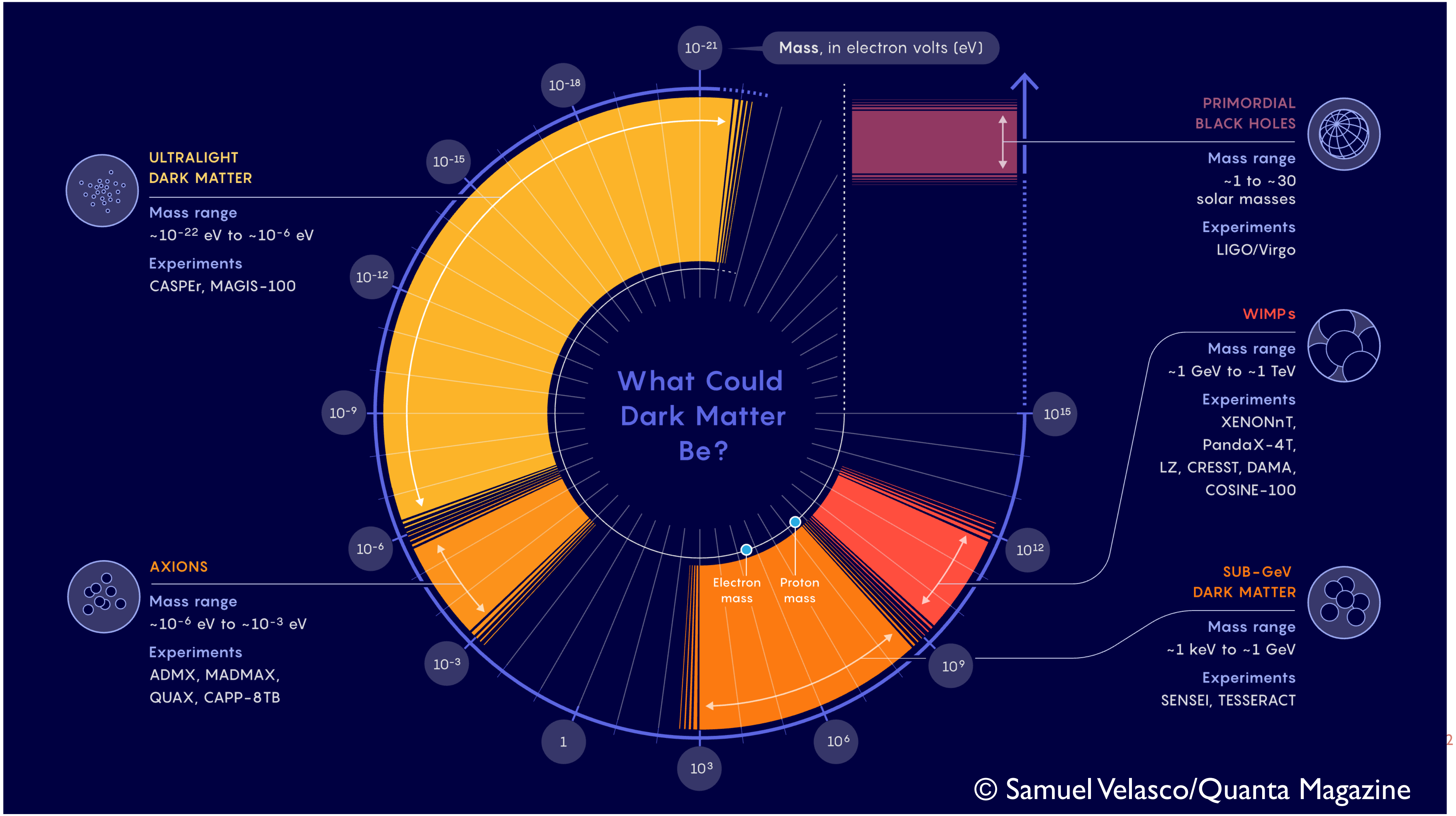
CDM ECR WORKSHOP
21 NOV 2022


Mass, in electron volts (eV)
10^{-21}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
What Could Dark Matter Be?
Electron mass
Proton mass
ULTRALIGHT DARK MATTER
Mass range
~10^{-22} eV to ~10^{-6} eV
Experiments
CASPEr, MAGIS-100
AXIONS
Mass range
~10^{-6} eV to ~10^{-3} eV
Experiments
ADMX, MADMAX, QUAX, CAPP-8TB
PRIMORDIAL BLACK HOLES
Mass range
~1 to ~30 solar masses
Experiments
LIGO/Virgo
WIMPs
Mass range
~1 GeV to ~1 TeV
Experiments
XENONnT, PandaX-4T, LZ, CRESST, DAMA, COSINE-100
SUB-GeV DARK MATTER
Mass range
~1 keV to ~1 GeV
Experiments
SENSEI, TESSERACT
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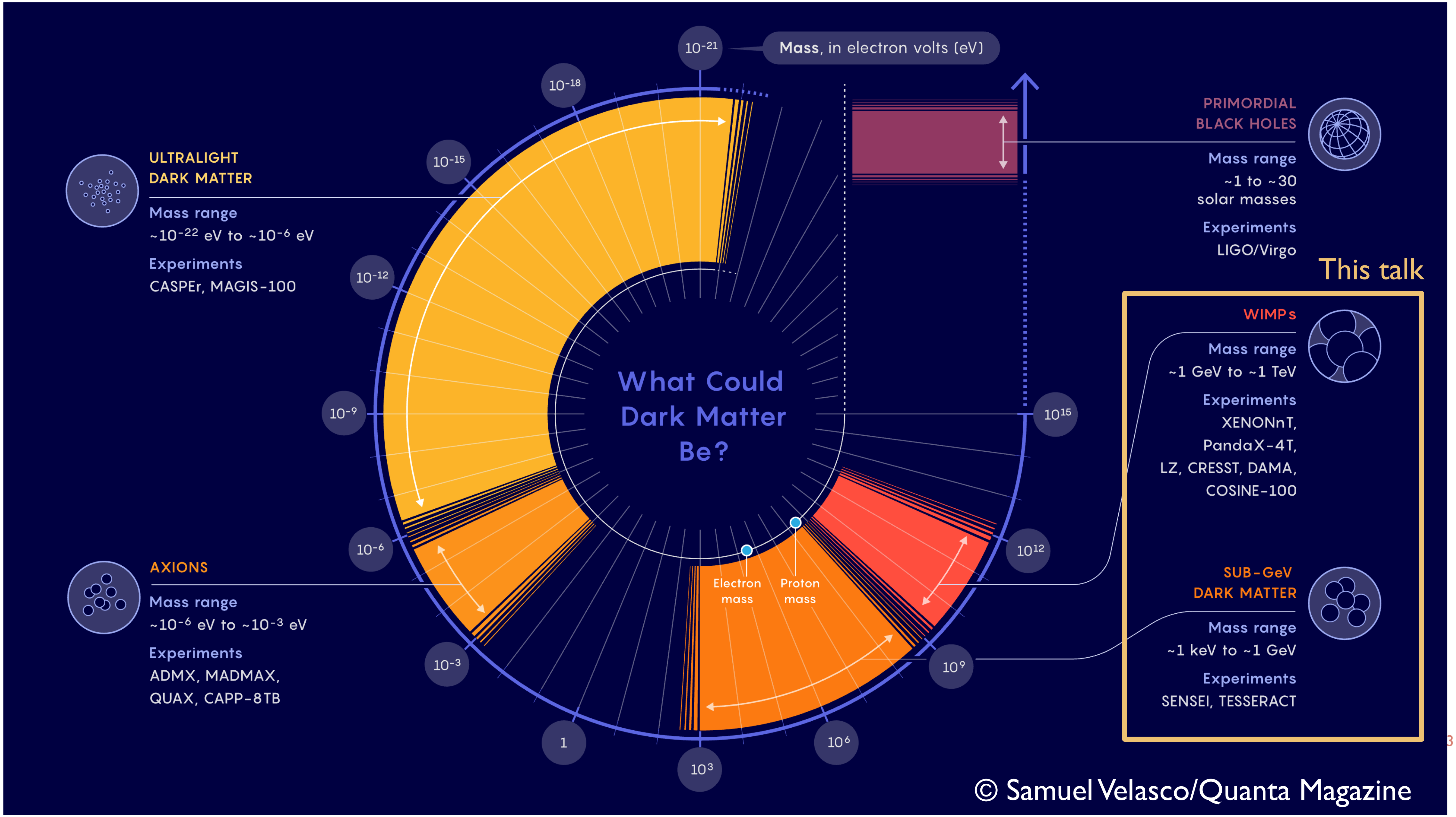
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DIRECT DETECTION BASICS

$$\frac{d\sigma(E_{\rm nr})}{dE_{\rm nr}} = \frac{m_N}{2v^2\mu^2}\left[\sigma_{\rm SI}F^2_{\rm SI}(E_{\rm nr}) + \sigma_{\rm SD}F^2_{\rm SD}(E_{\rm nr})\right]$$

Spin-independent

$$\sigma_{\rm SI} = \sigma_n \frac{\mu^2}{\mu_n^2}\frac{(f_p Z + f_n(A-Z))^2}{f_n^2} = \sigma_n \frac{\mu^2}{\mu_n^2}A^2.$$

Favours heavy targe nuclei (i.e. large A)

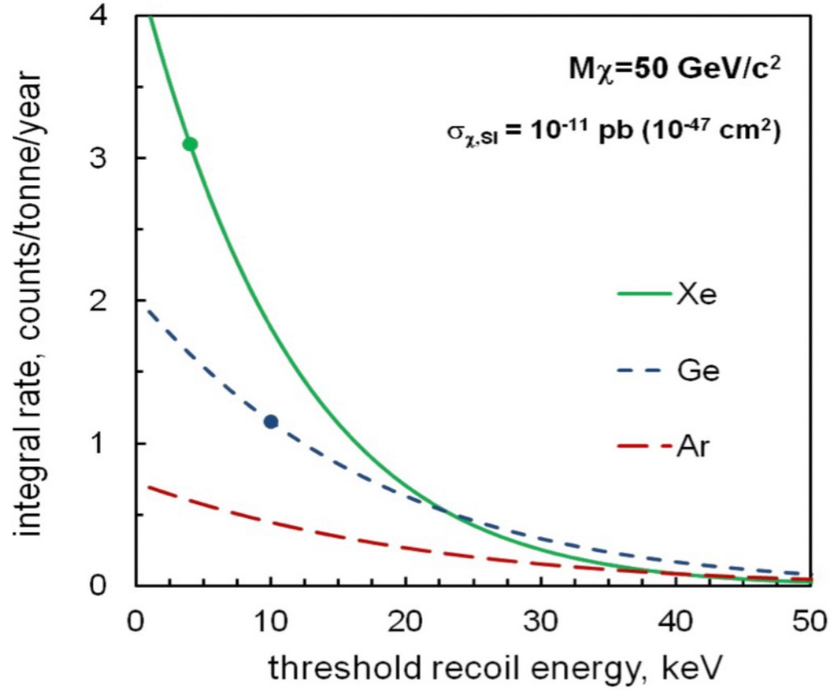
Spin-dependent

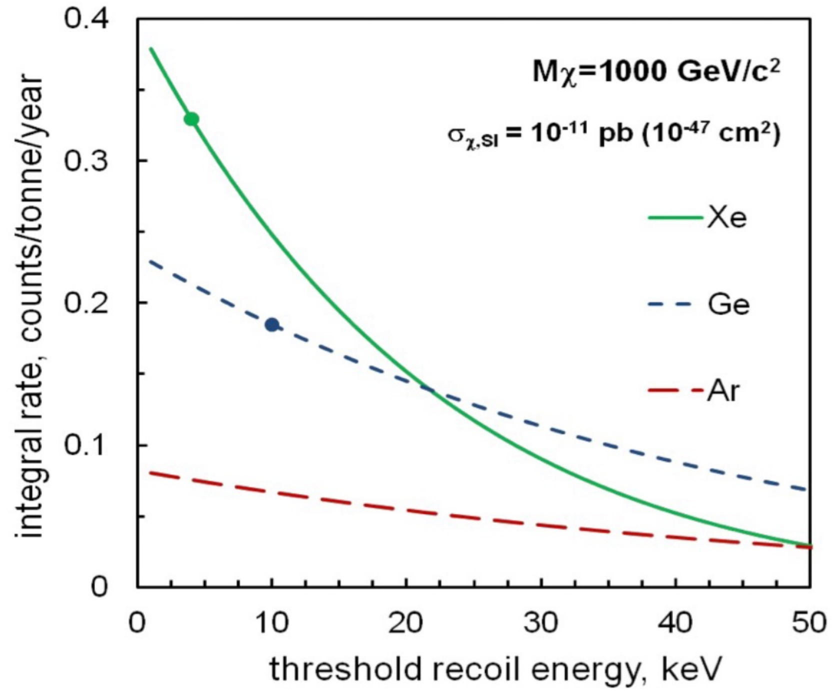
$$\frac{d\sigma_{\rm SD}}{d|\vec{q}|^2} = \frac{8G_F^2}{\pi v^2}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 \frac{J+1}{J}\frac{S(|\vec{q}|)}{S(0)}$$

Nuclei with unpaired neutron or proton

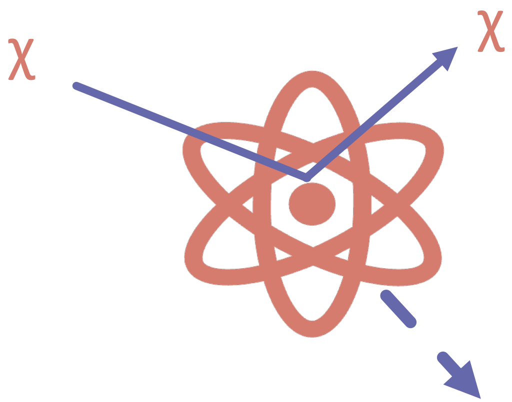
EXPERIMENTAL CHALLENGES

- Nuclear recoils due to dark matter interactions are expected to be:
  - Very rare
  - Low energy
- We need:
  - Target material sensitive to the interaction
  - Technology to detect interaction
  - Understand and reduce backgrounds
  - Calibrate detector response
  - Analysis techniques



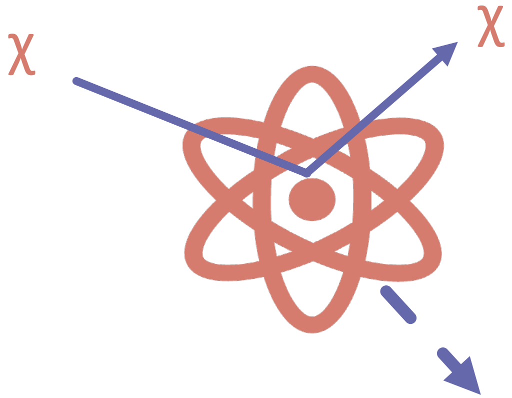


NUCLEAR RECOIL DETECTION



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

NUCLEAR RECOIL DETECTION

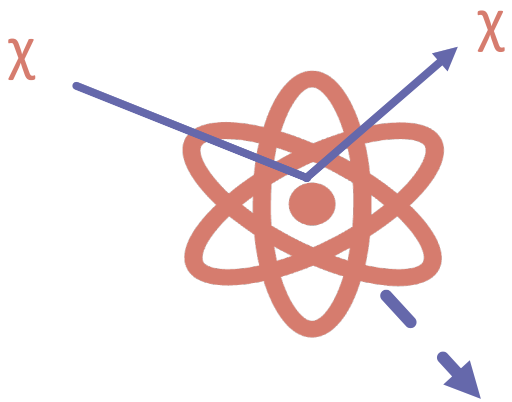


Atomic motion

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

Ionization & excitation

NUCLEAR RECOIL DETECTION



Heat/Phonons

↑

Atomic motion

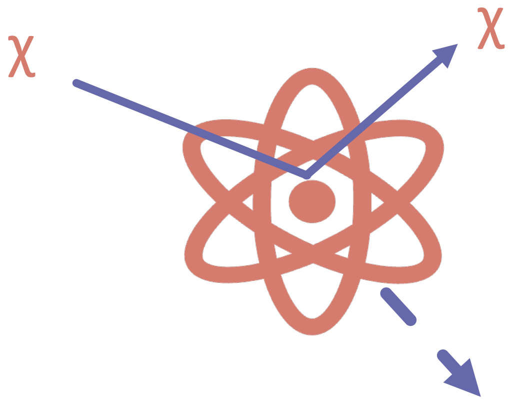
↑

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

↓

Ionization & excitation

NUCLEAR RECOIL DETECTION



Heat/Phonons

↑

Atomic motion

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↓

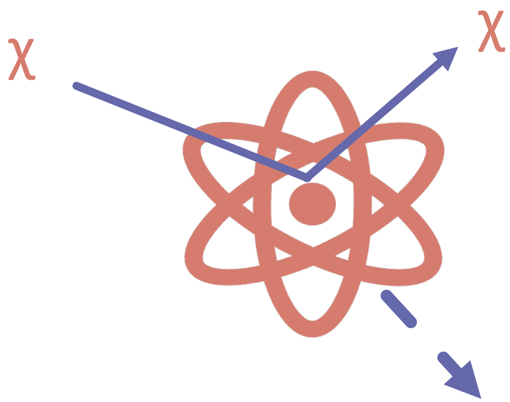
Ionization & excitation

↙ ↘

Charge

Light

NUCLEAR RECOIL DETECTION



Heat/Phonons

Atomic motion

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

Ionization & excitation

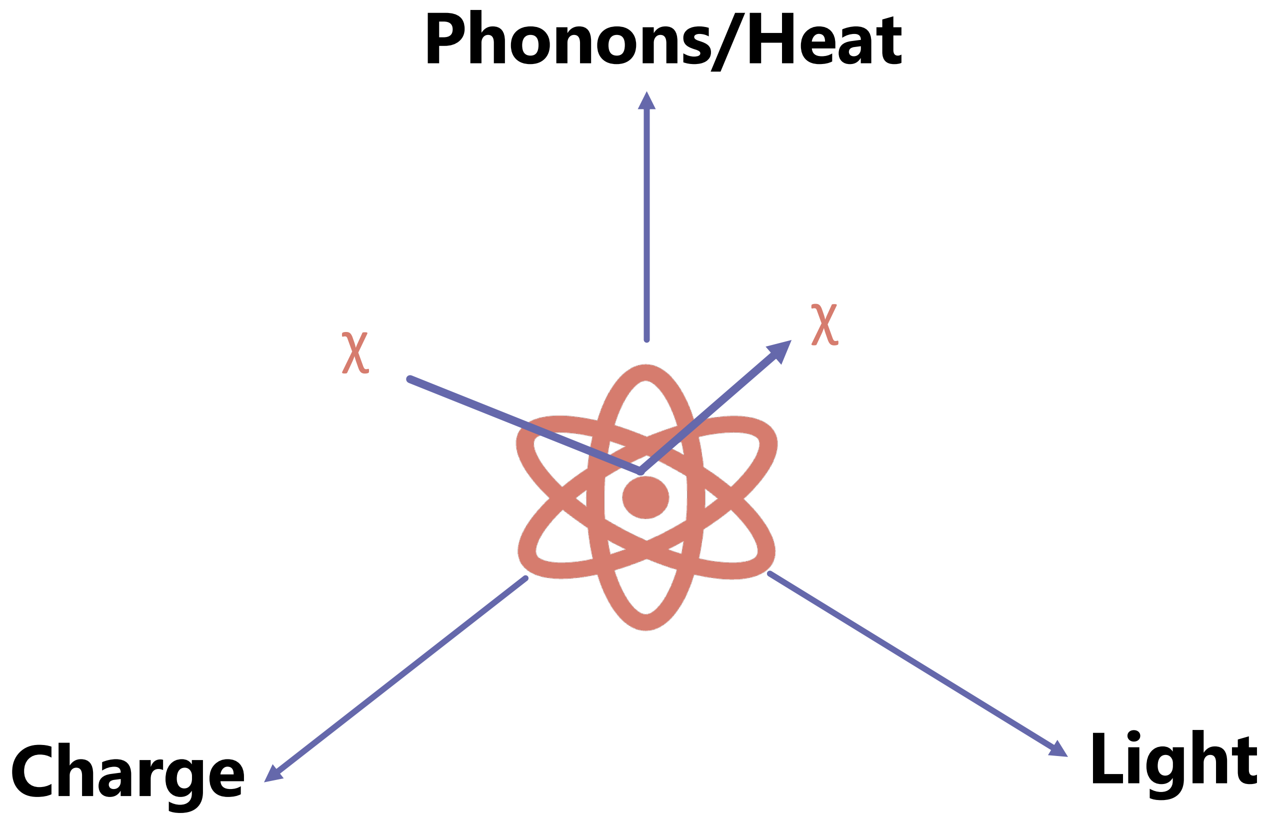
Charge

Light

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

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

NUCLEAR RECOIL DETECTION



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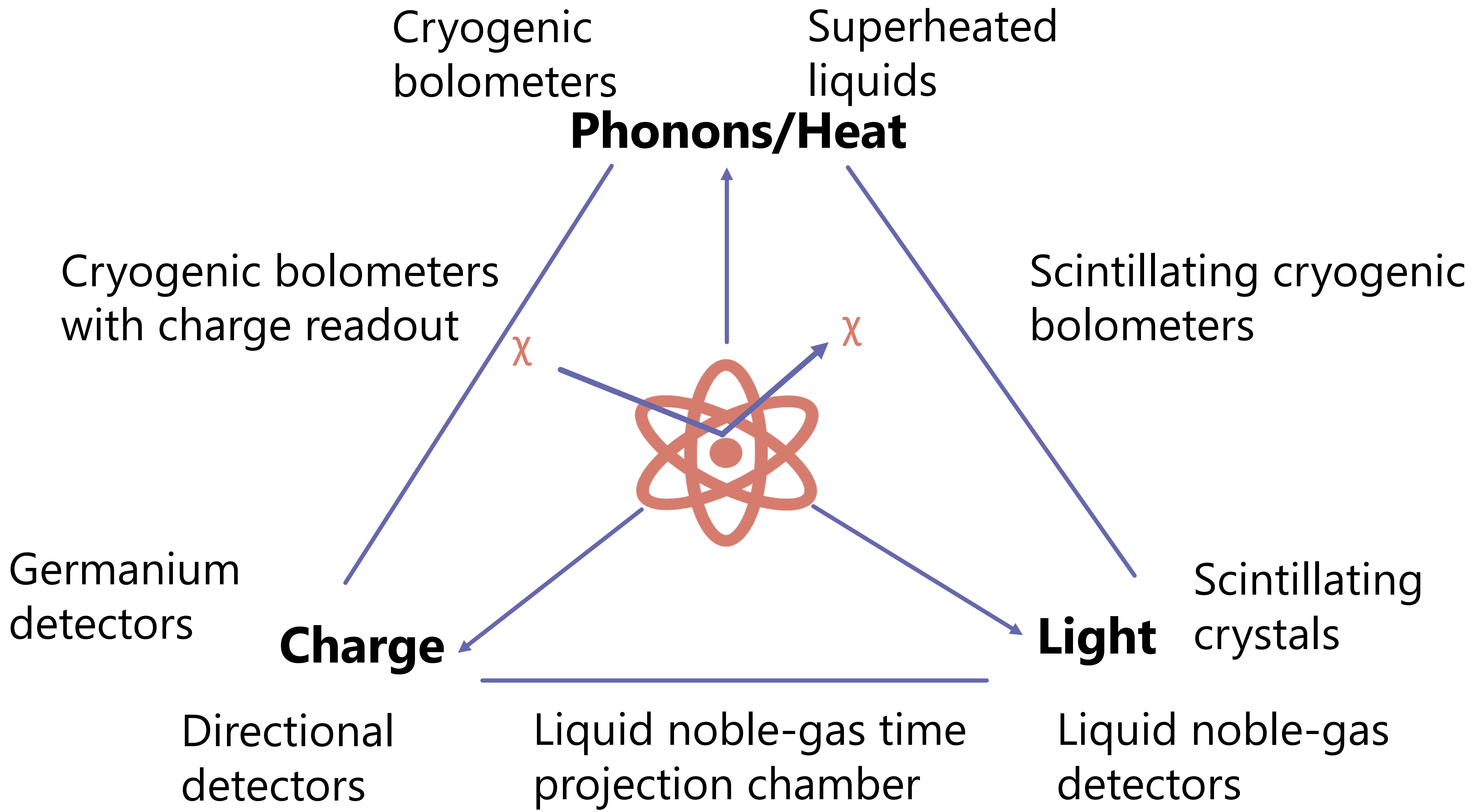

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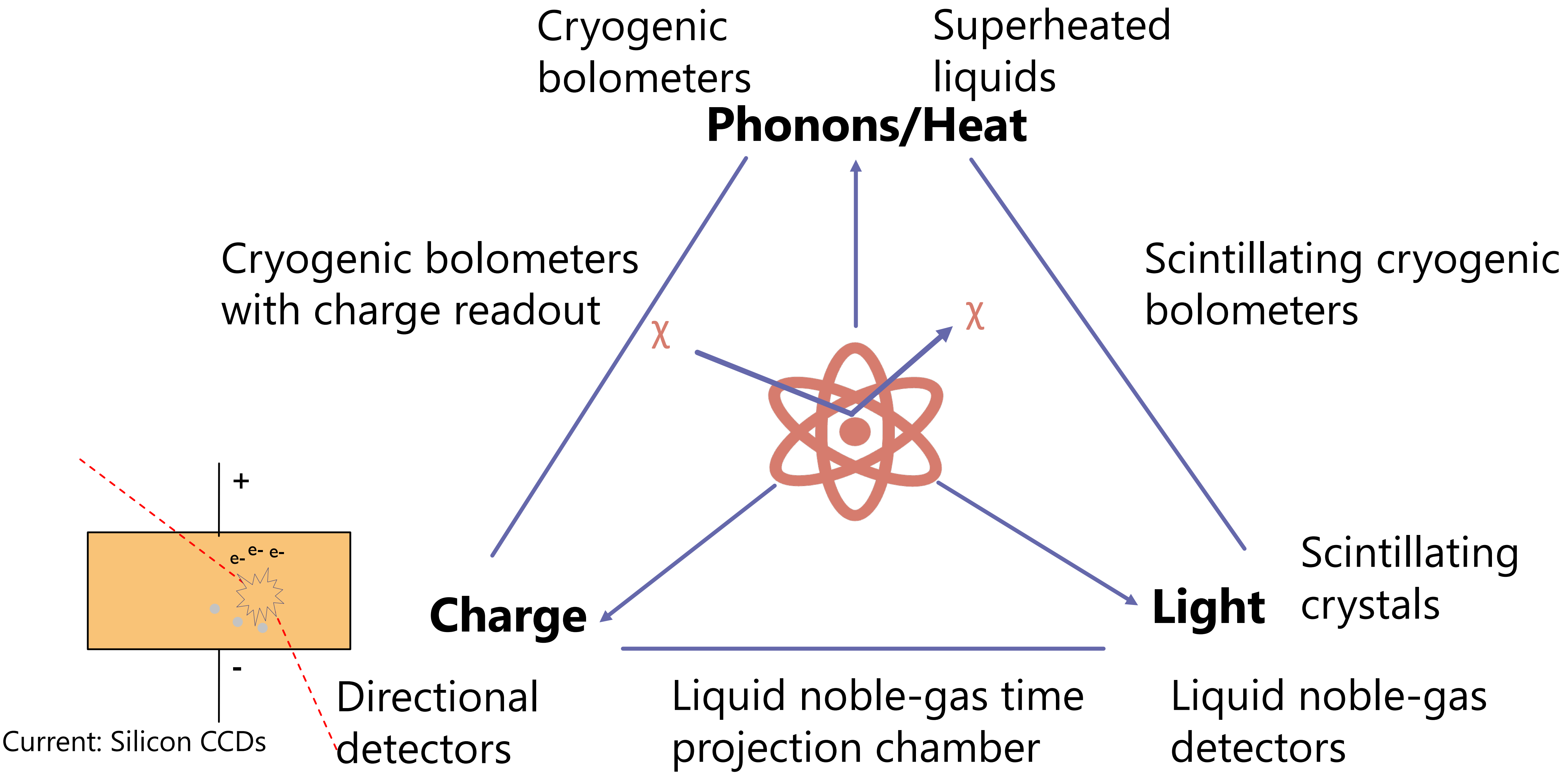

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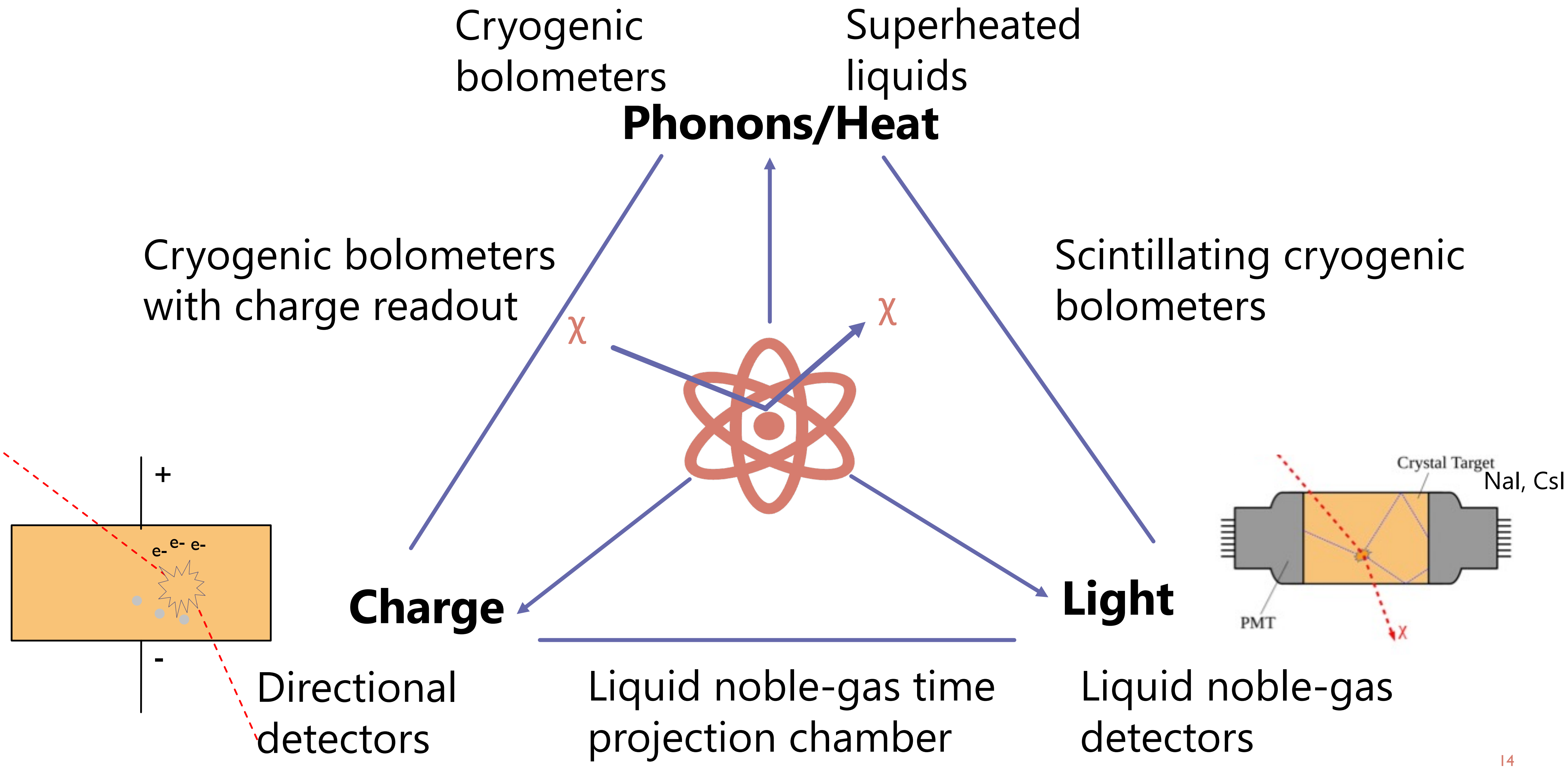

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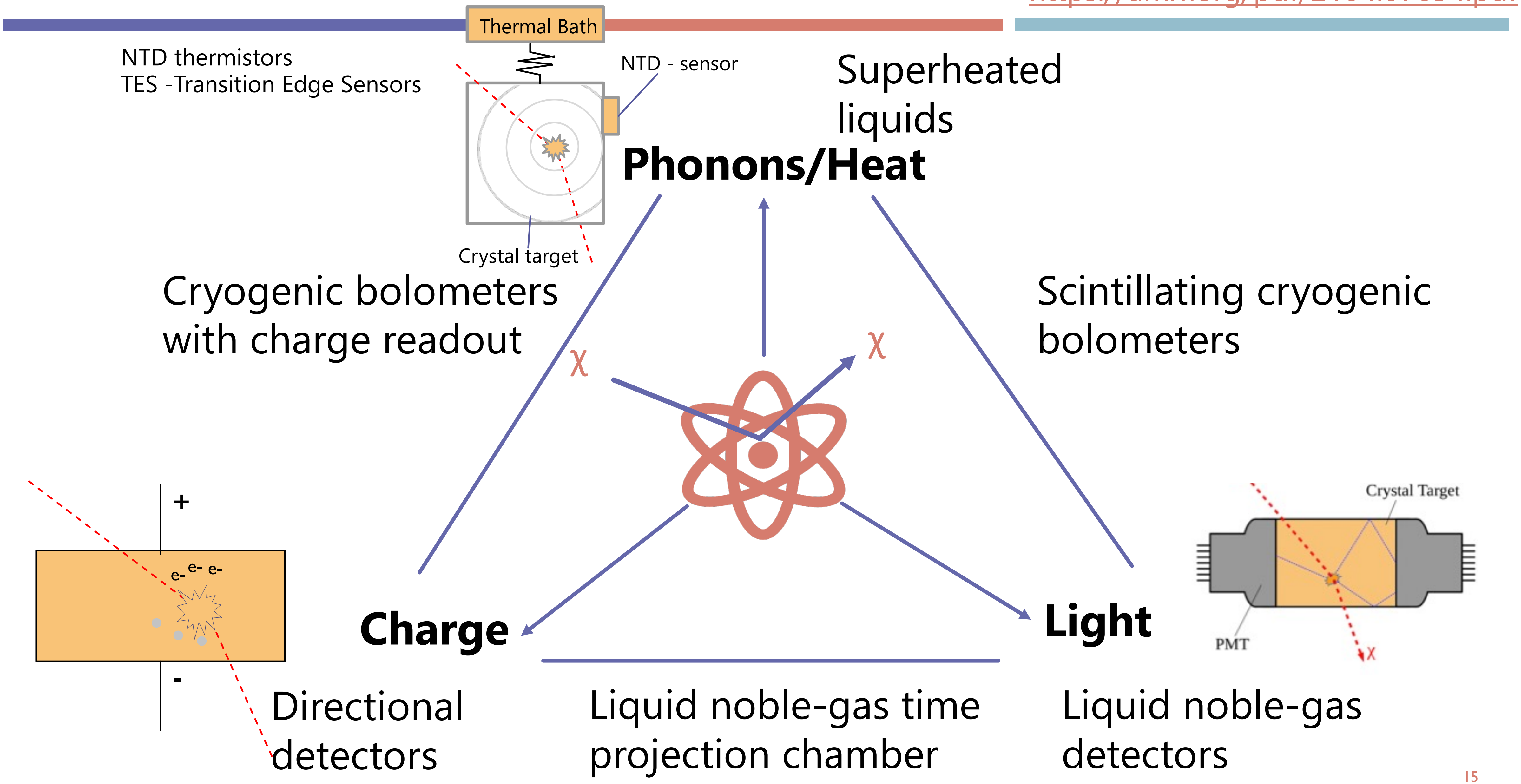

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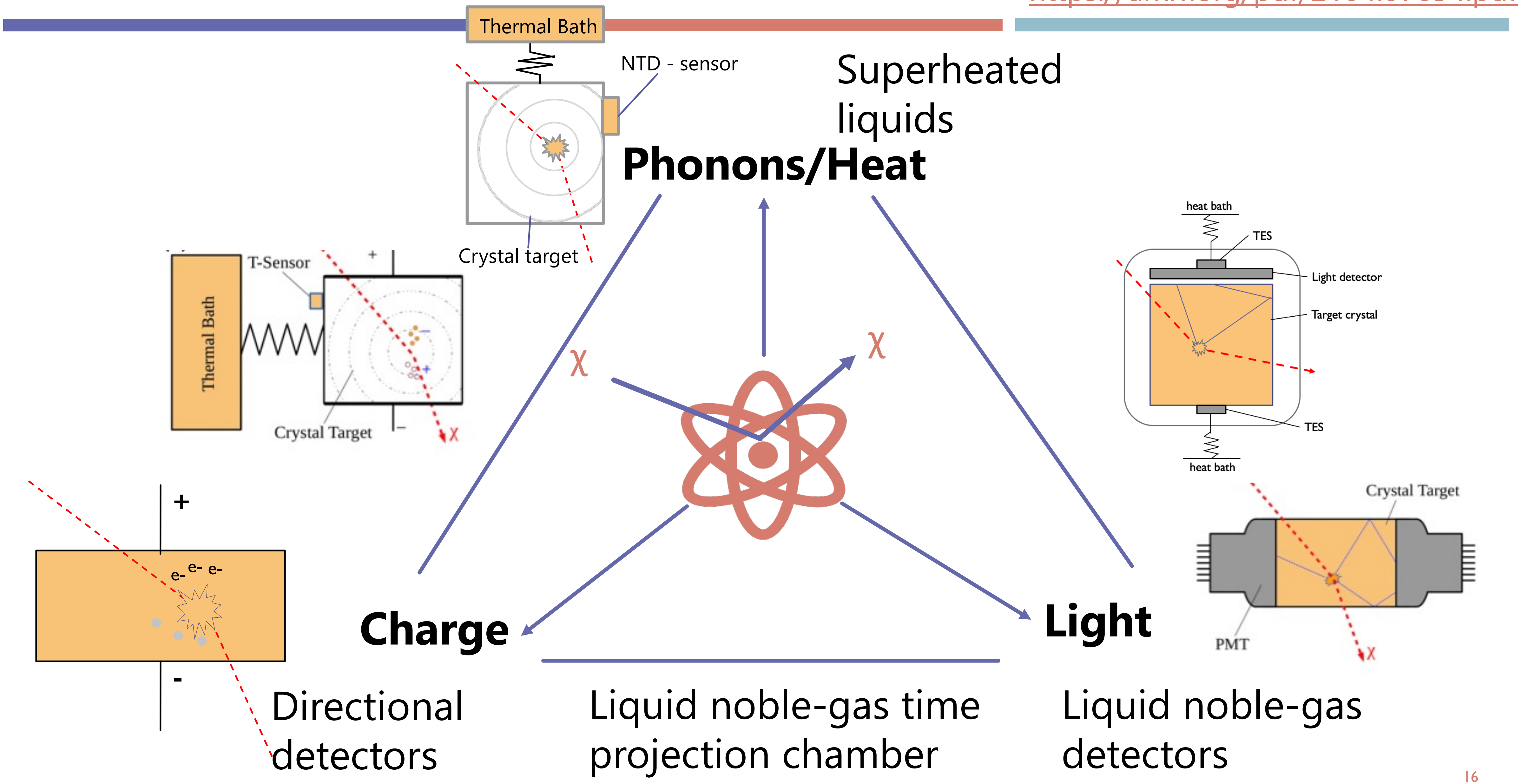

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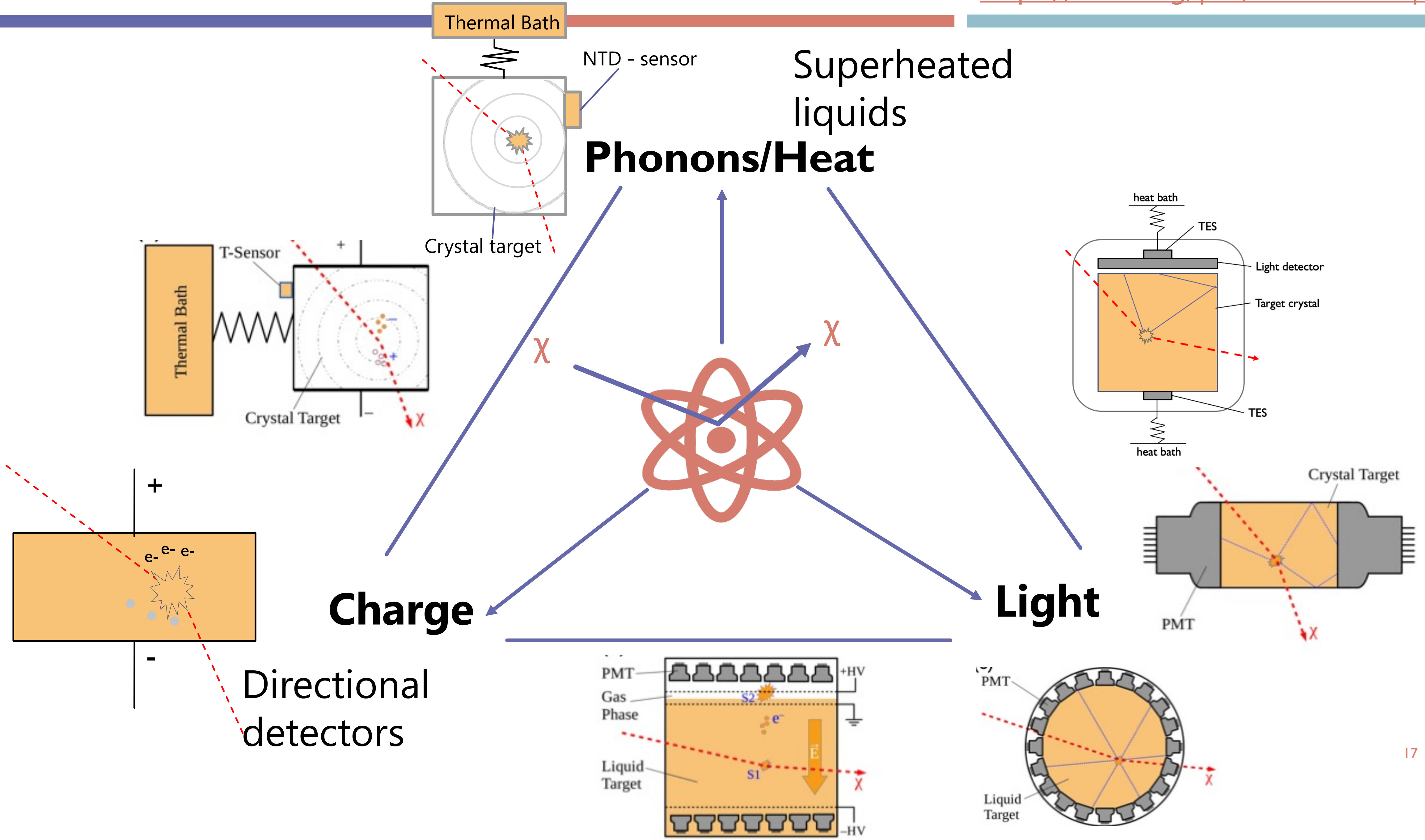

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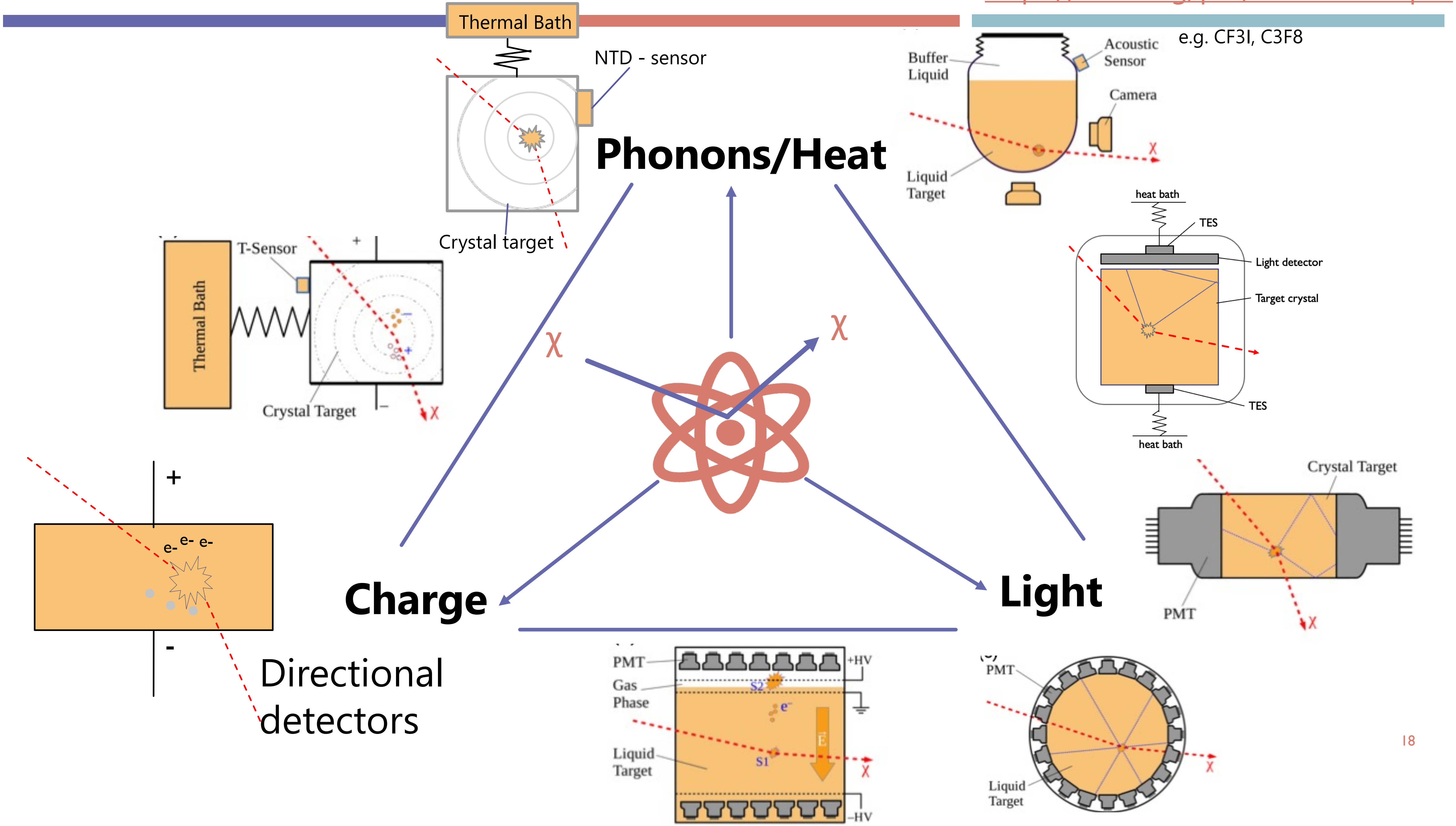

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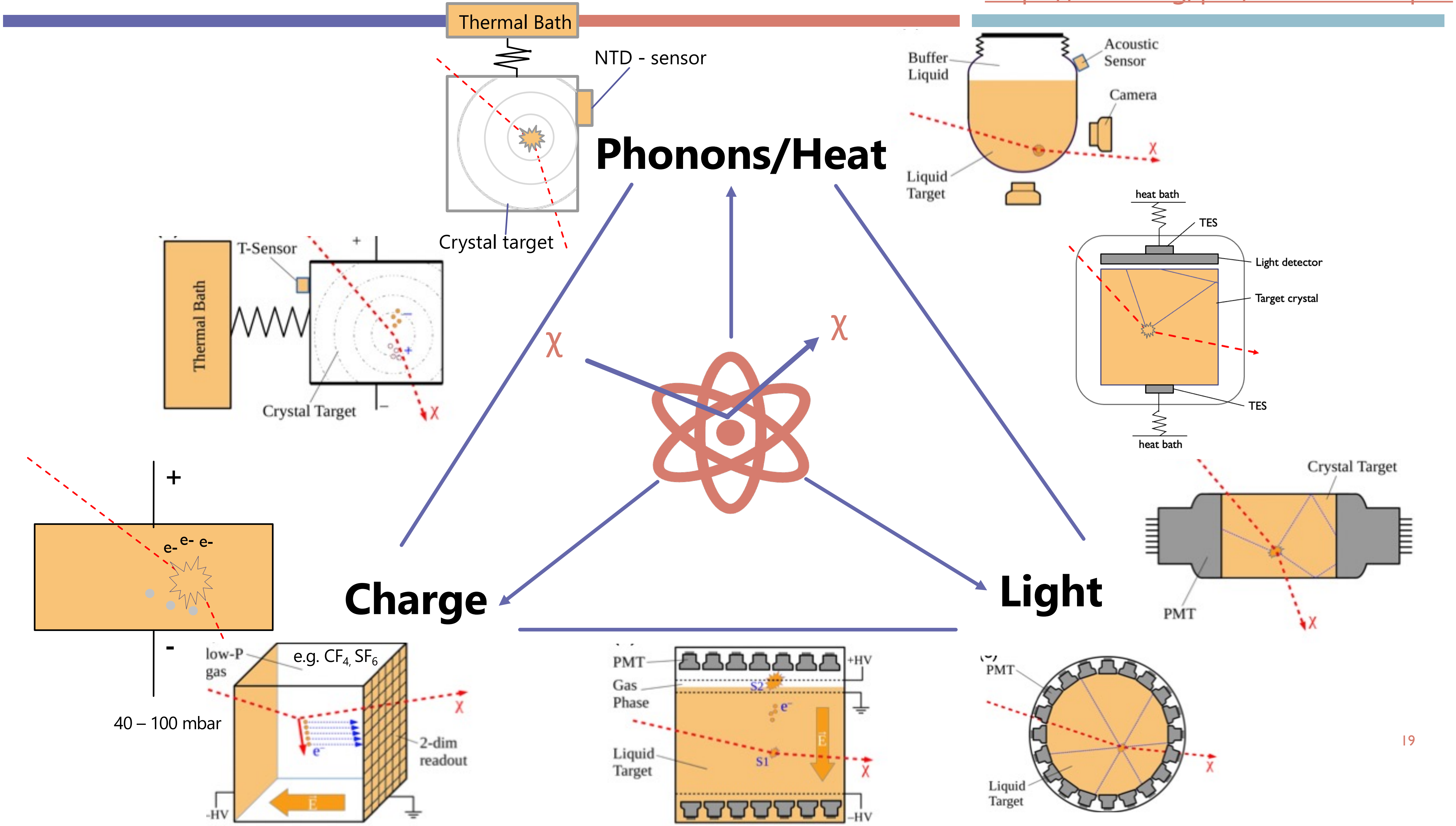


ASIDE: ELECTRON RECOIL SIGNALS

There are some searches making use of electron recoils:

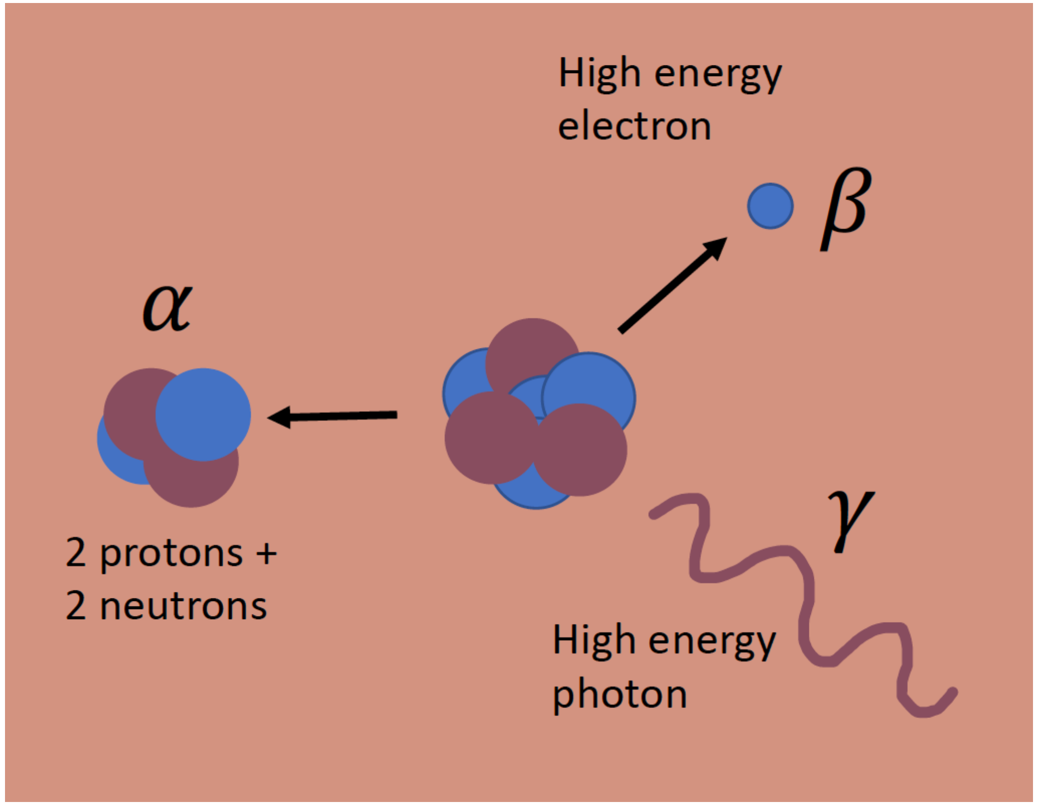
- **Nuclear recoil followed by electron recoil**
  - Inelastic DM scattering: NR is followed by ER from de-excitation of DM particle of target nucleus
  - Migdal effect: Additional excitation & ionization due to electron cloud following recoiling nucleus with delay
  - Bremsstrahlung: Bremsstrahlung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

BACKGROUNDS

Understand background sources.

Reduce backgrounds.

Distinguish signal from background topologies.



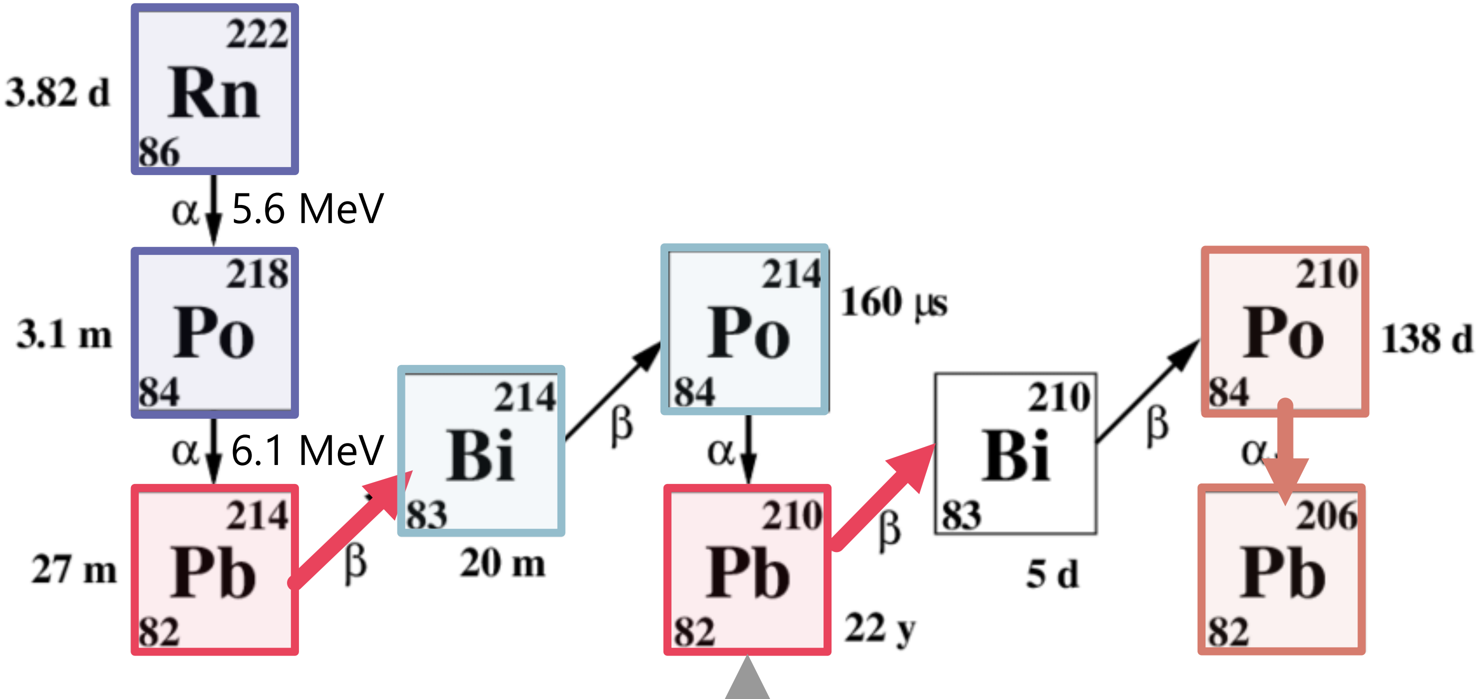
- Radioactive isotopes in the environment and the detector itself:
  - Radioactive decays:
    - Gamma: environment & detector materials
    - Beta: from bulk and surfaces
  - (α, n) and spontaneous fission
- Cosmic rays:
  - muon induced neutrons

ER (Gamma, Beta)

NR ((α, n) and spontaneous fission, muon induced neutrons)

Radioactive isotopes | Radon | Neutrinos

Rn emanates from detector materials dust on surfaces

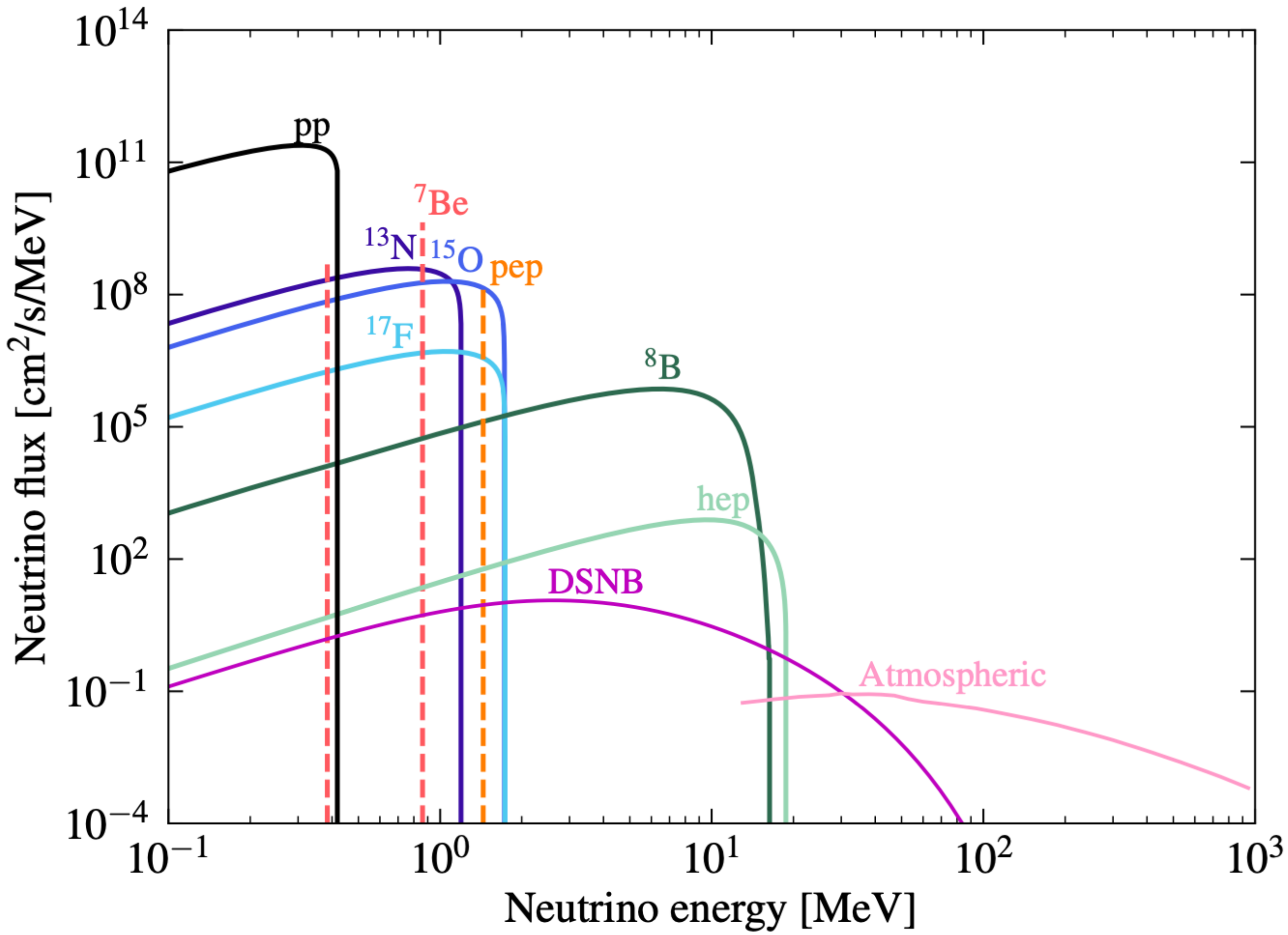


Naked beta-decay (no accompanying gamma) low E ER

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



- **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**

BACKGROUNDS

Understand background sources.

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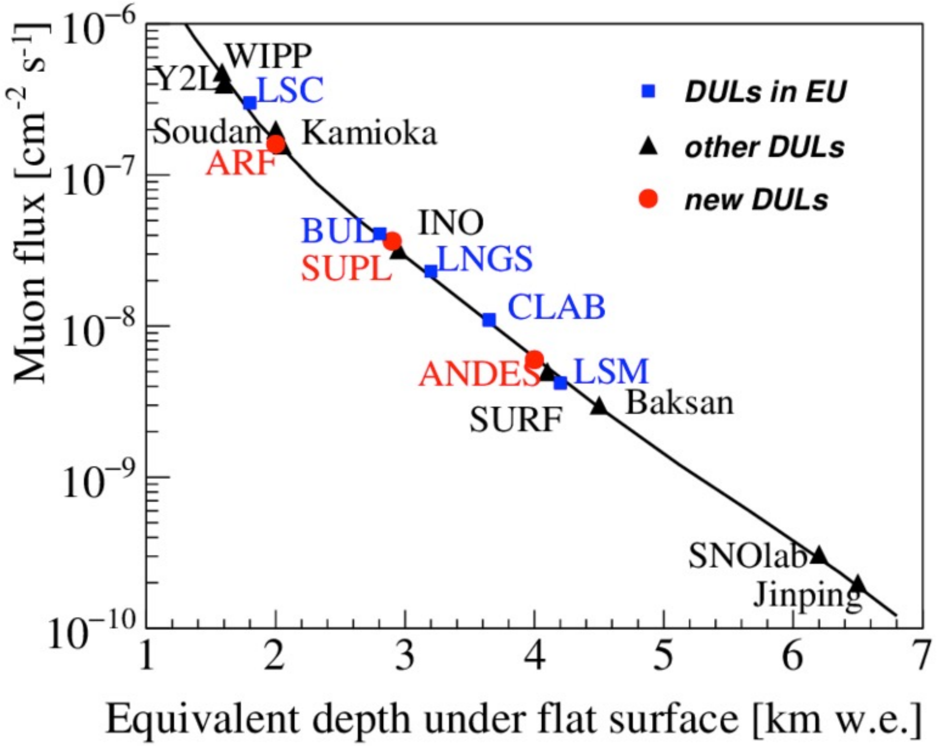
Distinguish signal from background topologies.

Shielding | Material screening & cleanliness | Veto detectors



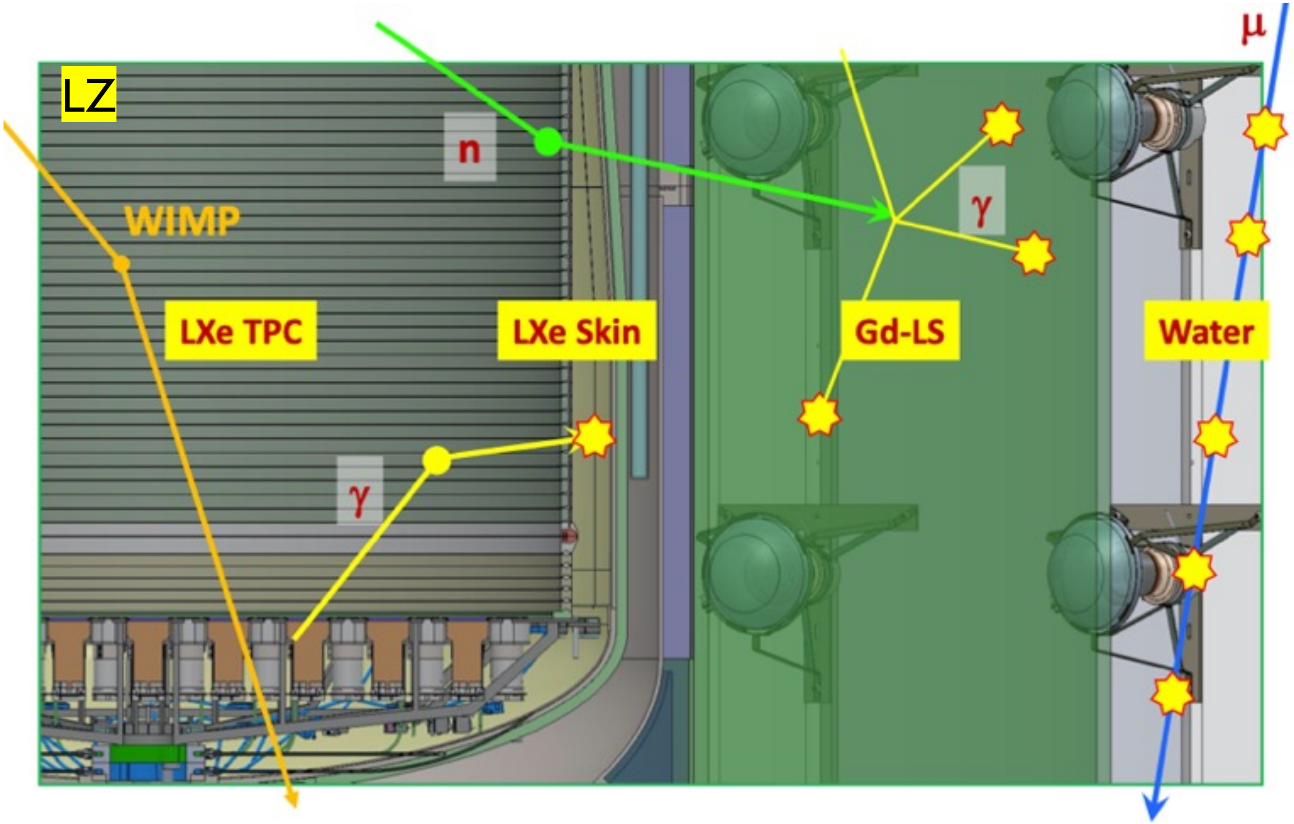
DOI:10.1088/1742-6596/1342/1/012003

- 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

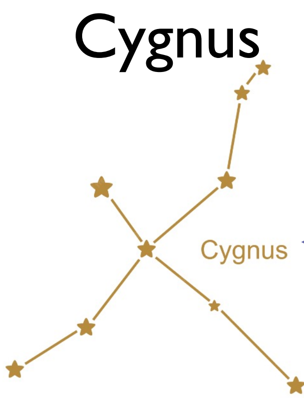
BACKGROUNDS

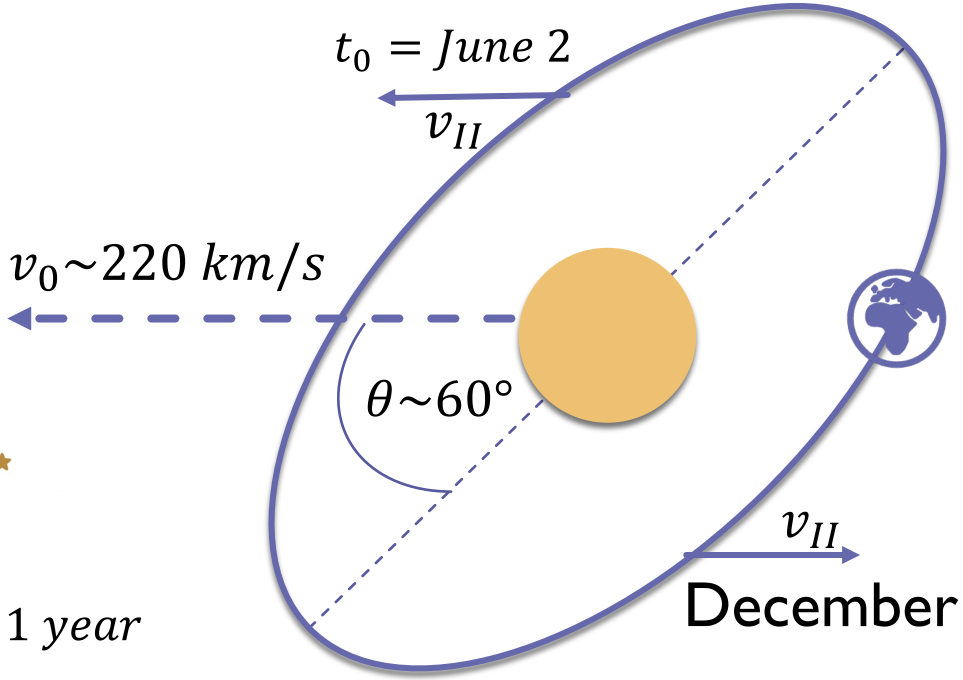
Understand background sources.

Reduce backgrounds.

Distinguish signal from background topologies.

Annual modulation | Directionality | ER-NR discrimination





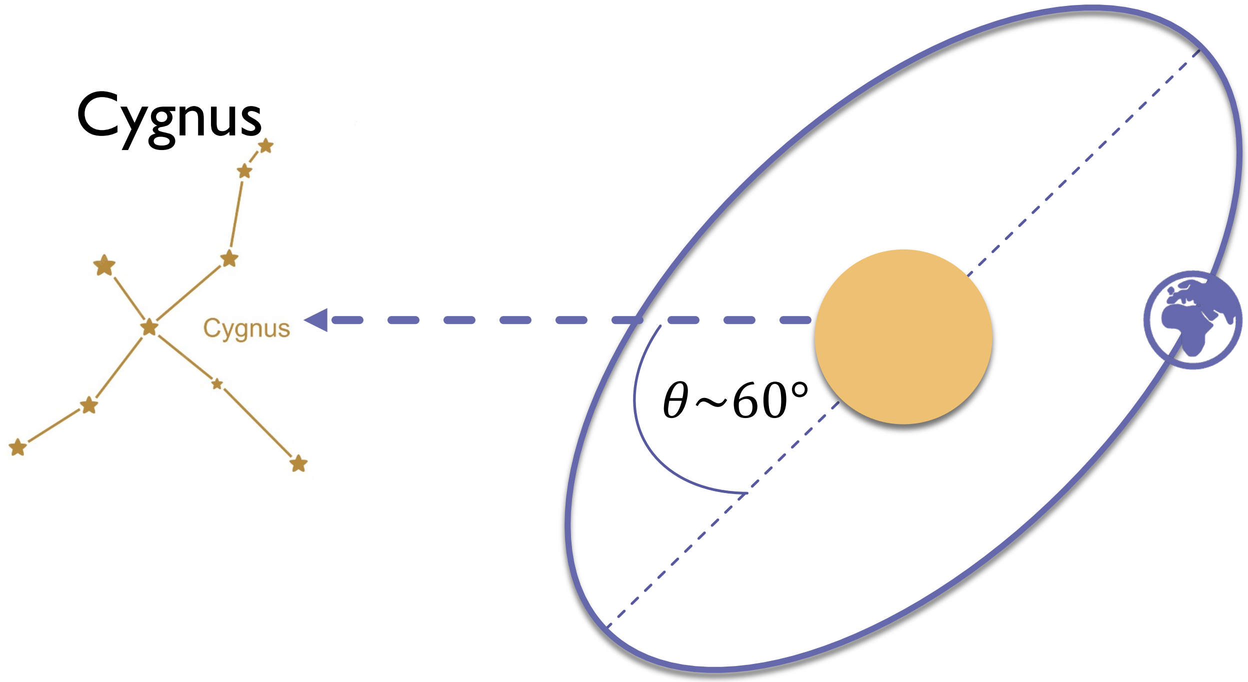
$$\omega = \frac{2\pi}{T}, T = 1\ year$$

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

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

$$\mathcal{O}\left({}^{v_0}/{}_{v_{II}}\right) \sim 5\%$$

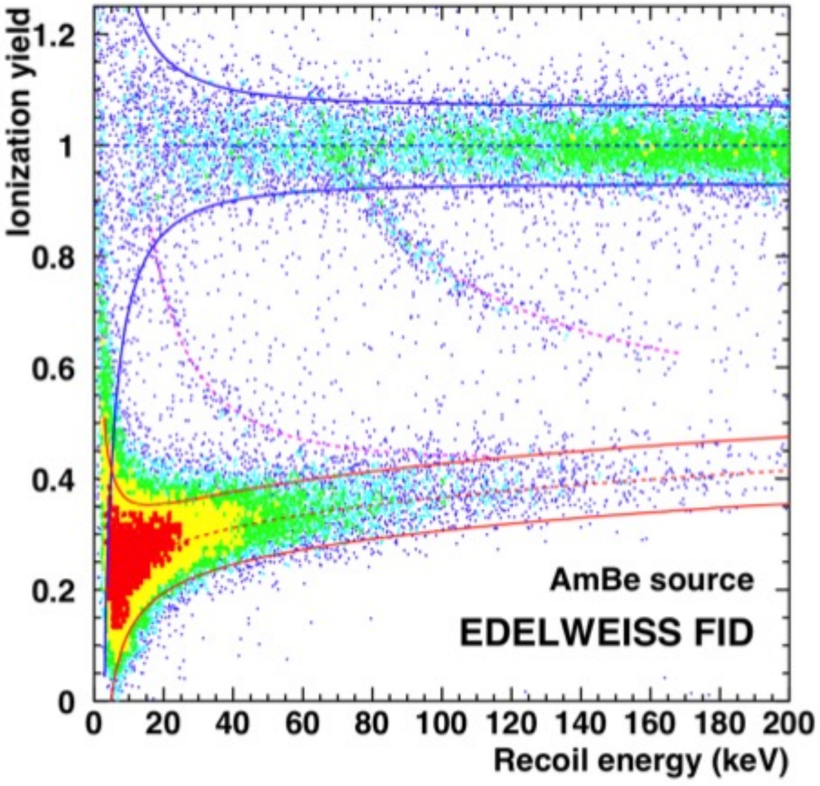
Annual modulation | Directionality | ER-NR discrimination



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

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

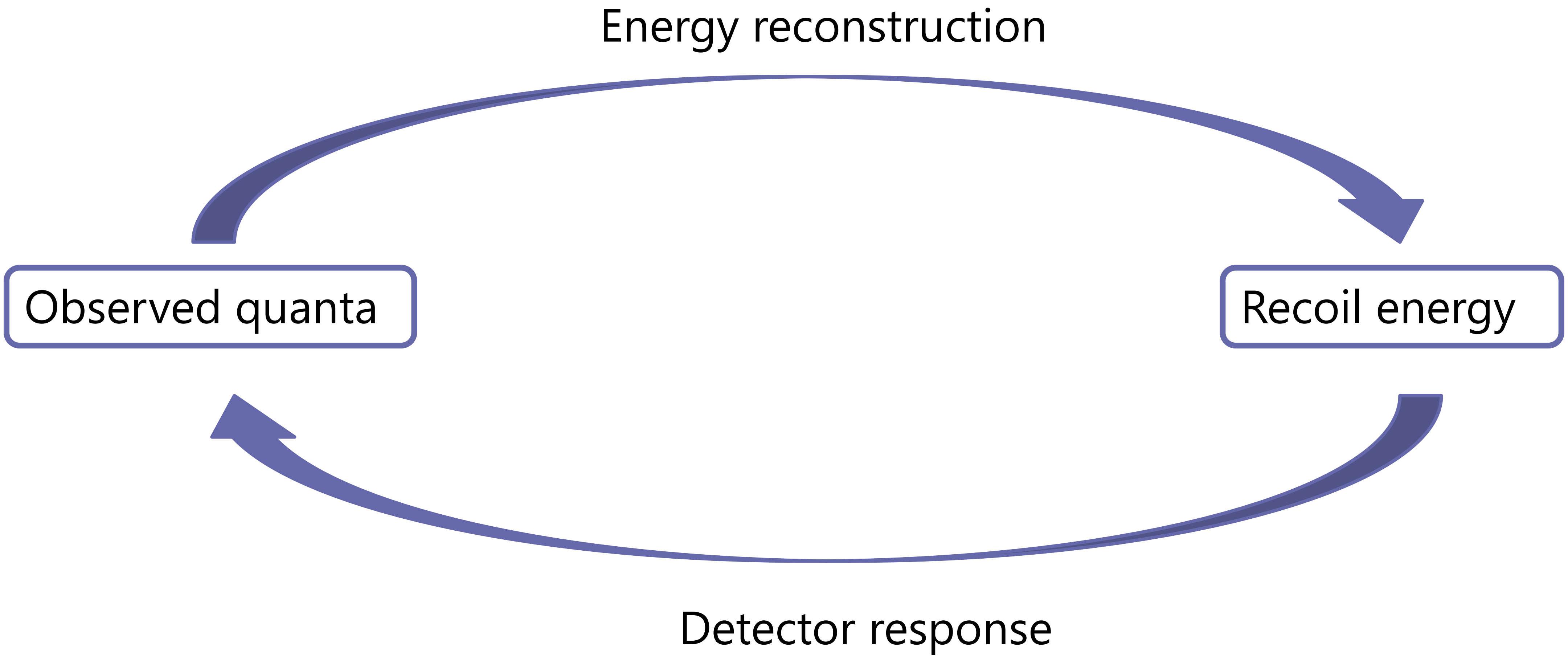
Annual modulation | Directionality | ER-NR discrimination



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

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

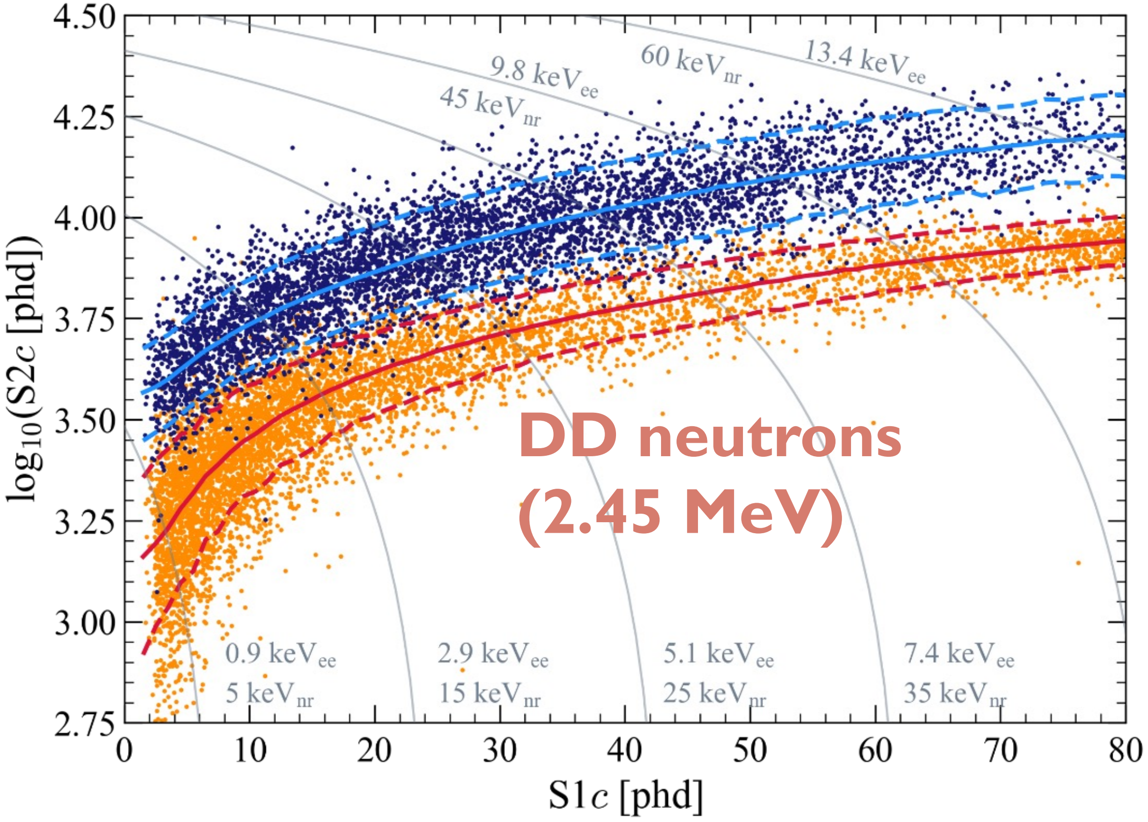
Nuclear recoil

Electron recoil

LUX-ZEPLIN

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 $^{9}Be(\gamma,n)$
- DD and DT neutron generators
  - e.g. $^{2}H + ^{2}H \rightarrow n + ^{3}H$

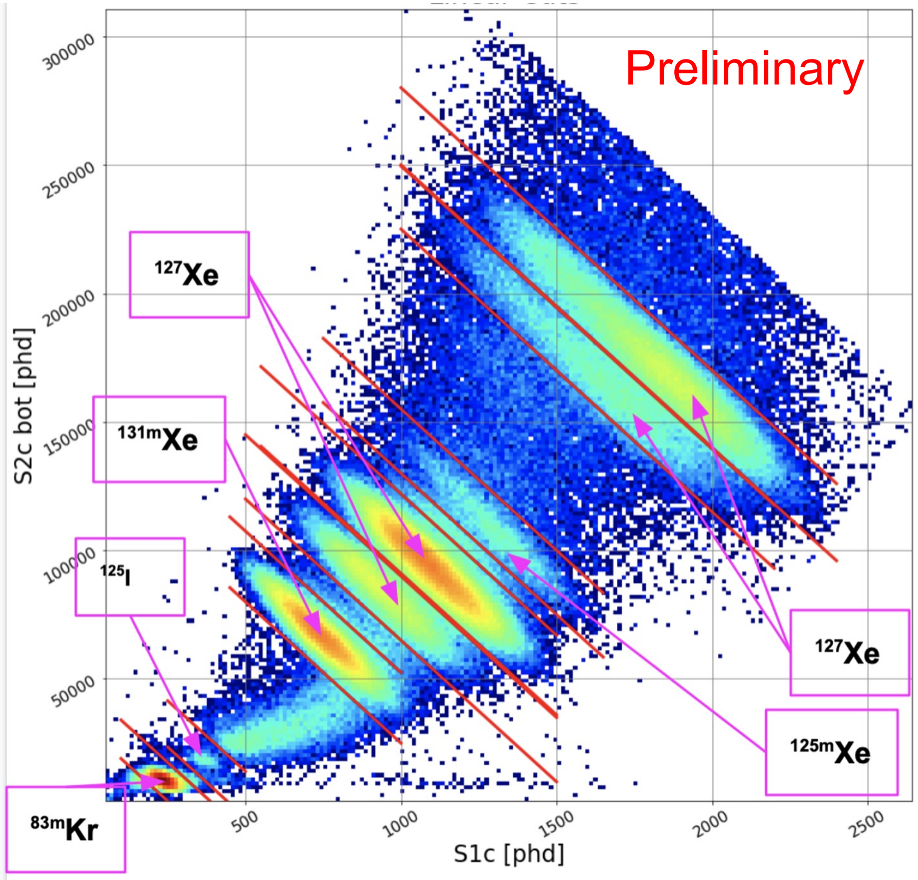


Nuclear recoil

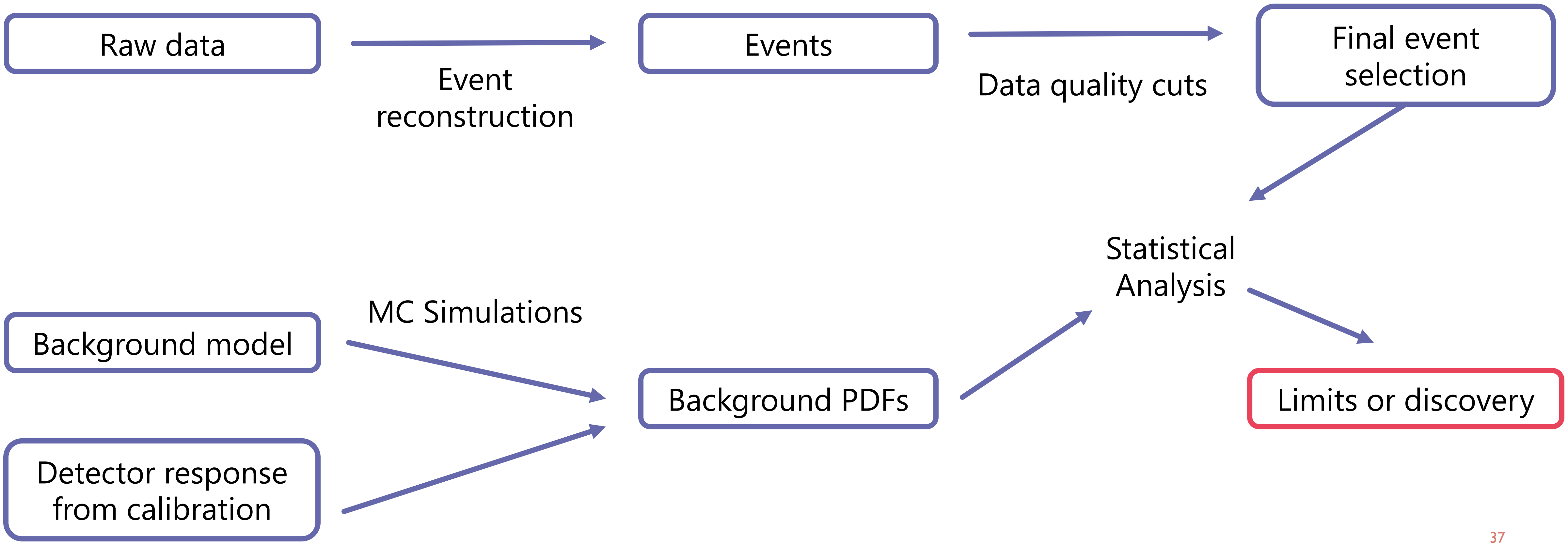
Electron recoil

- 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)

LUX-ZEPLIN



TYPICAL ANALYSIS OVERVIEW



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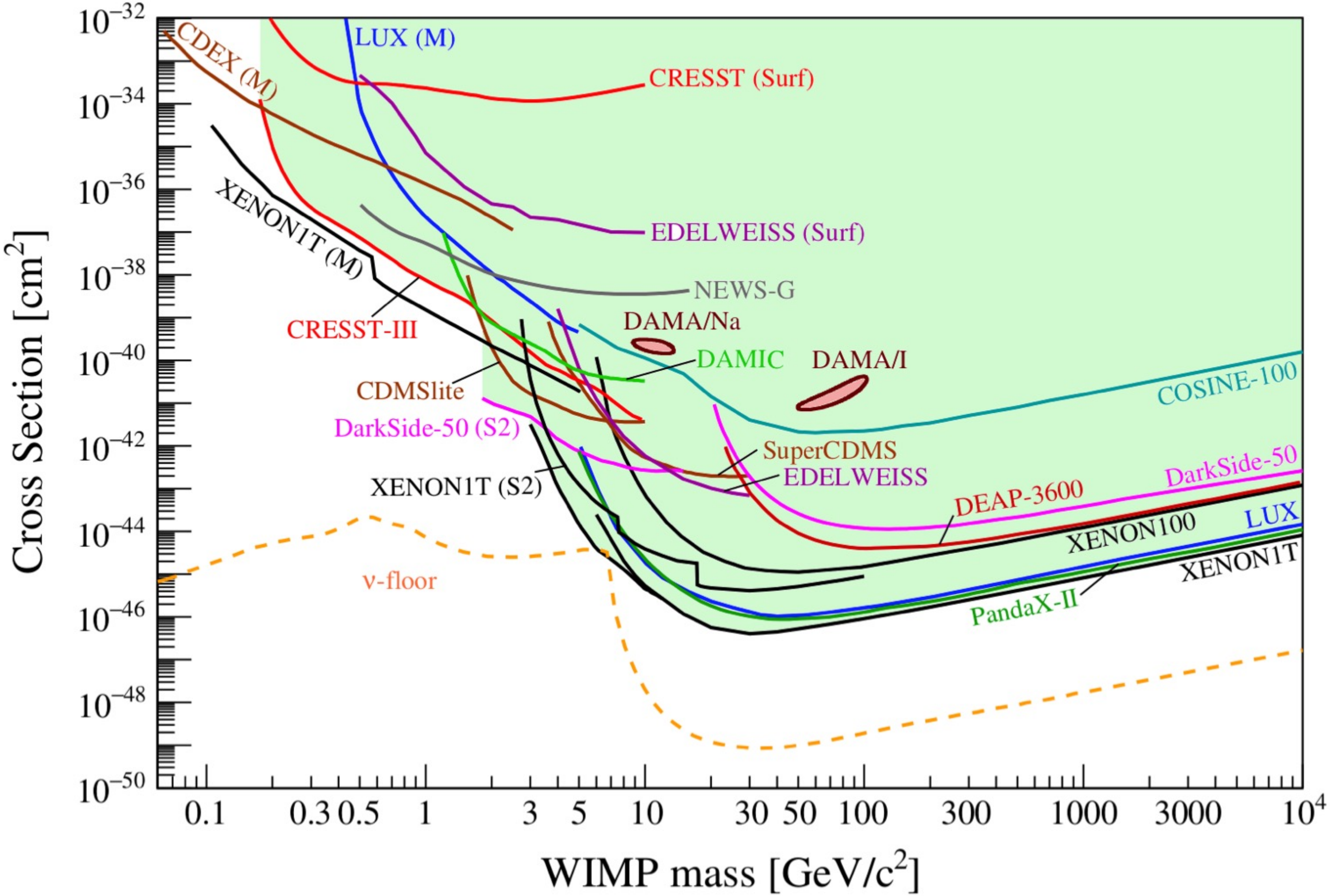
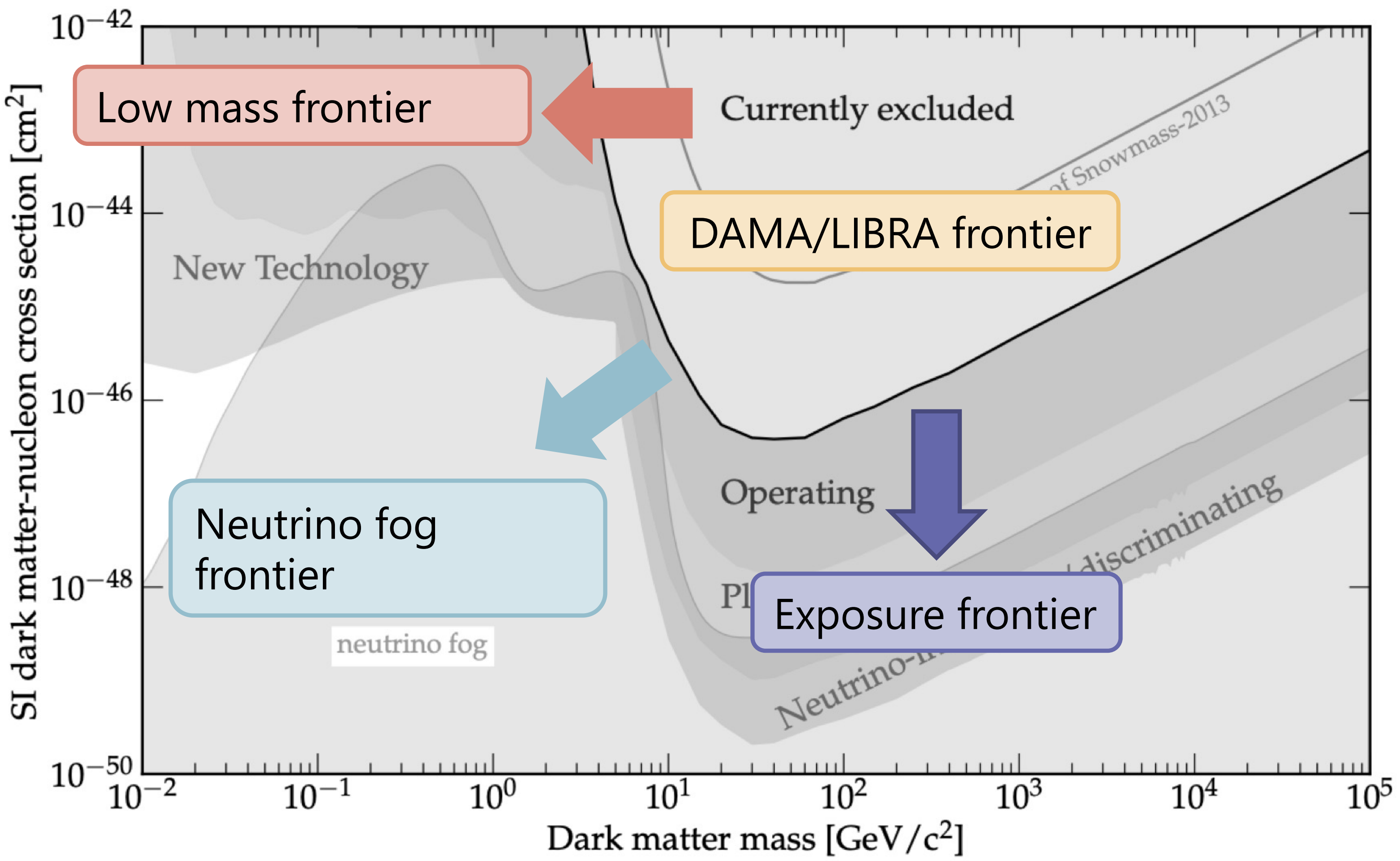


DIRECT DETECTION FRONTIERS



Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

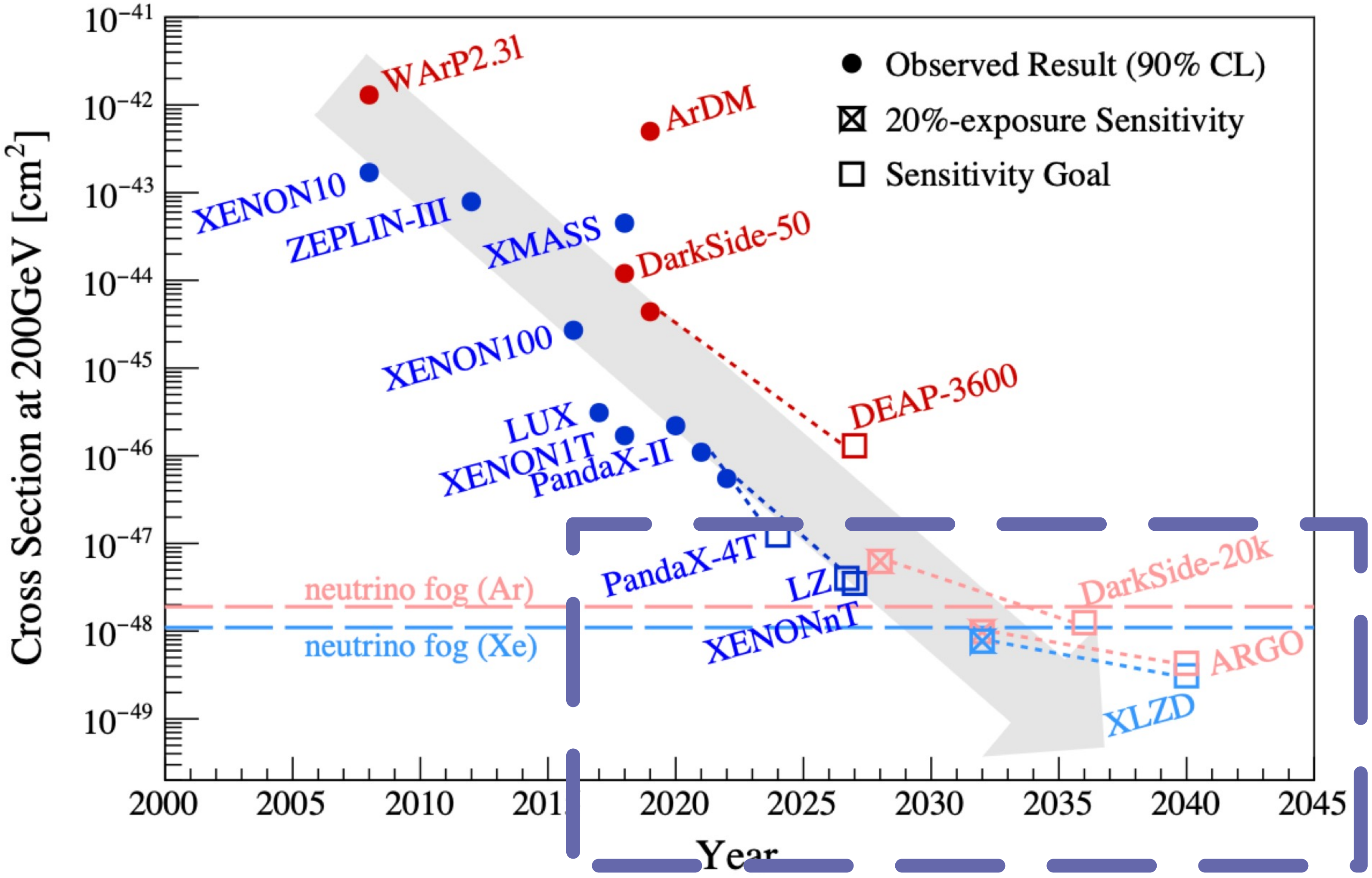
<u>LXe and LAr detectors:</u>

Advantage:

- Established detector design
- Large target mass with self-shielding

Challenges:

- High voltages
- Rn!
- Accidental coincidences



Shengchao Li, SNOWMASS CF1 Convener's Report

Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

LXe 2-phase TPCs

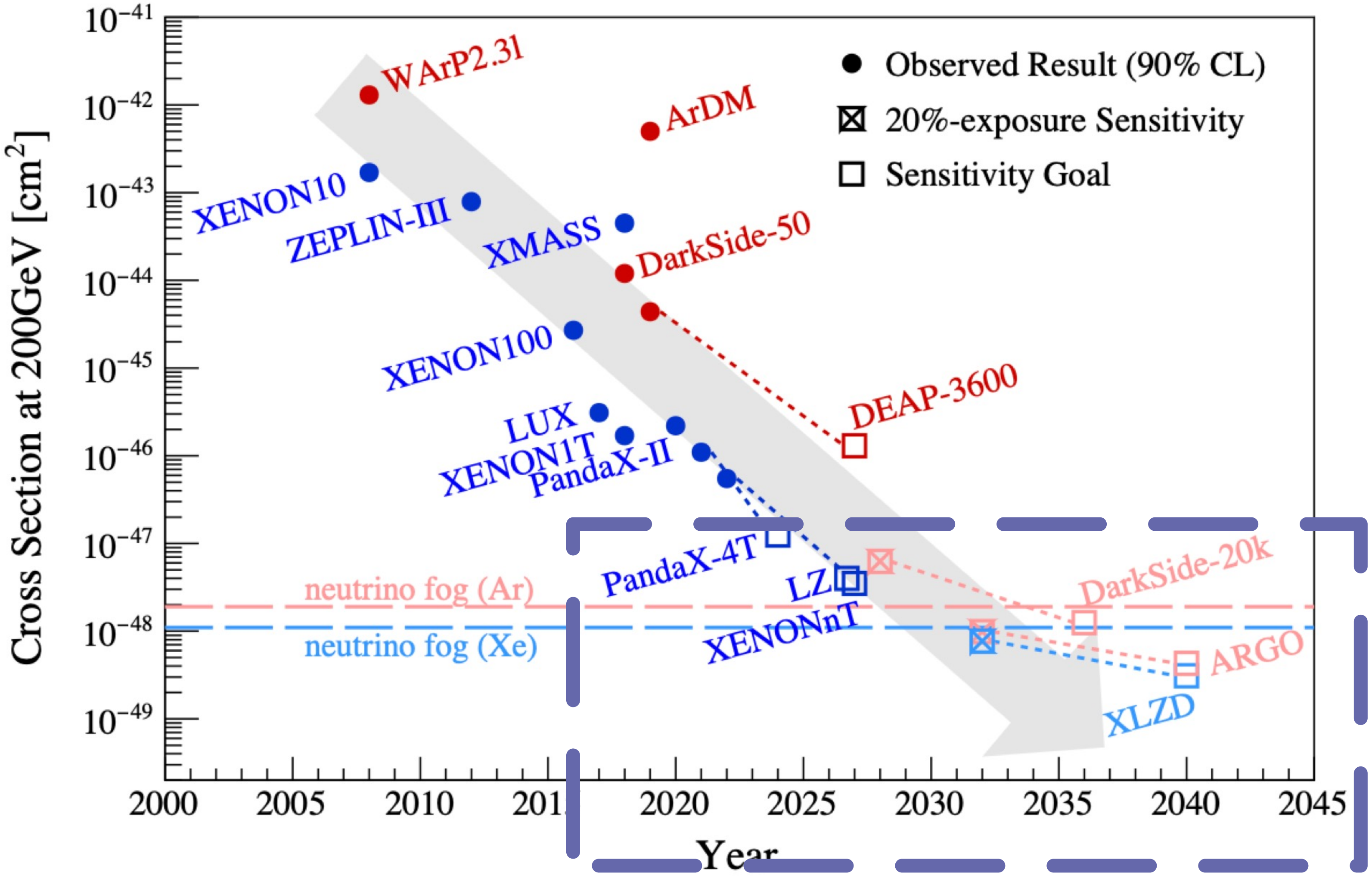
PandaX-4T	4.0 t	running
XENONnT	5.9 t	running
LZ	7.0 t	running
DARWIN	40 t	planning

LAr single-phase

DEAP-3600	3.6 t.	running

LAr 2-phase TPC

DarkSide-50	46.4 kg	running
DarkSide-20k	40 t.	construction
ARGO	400 t.	proposed



Shengchao Li, SNOWMASS CF1 Convener's Report

Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

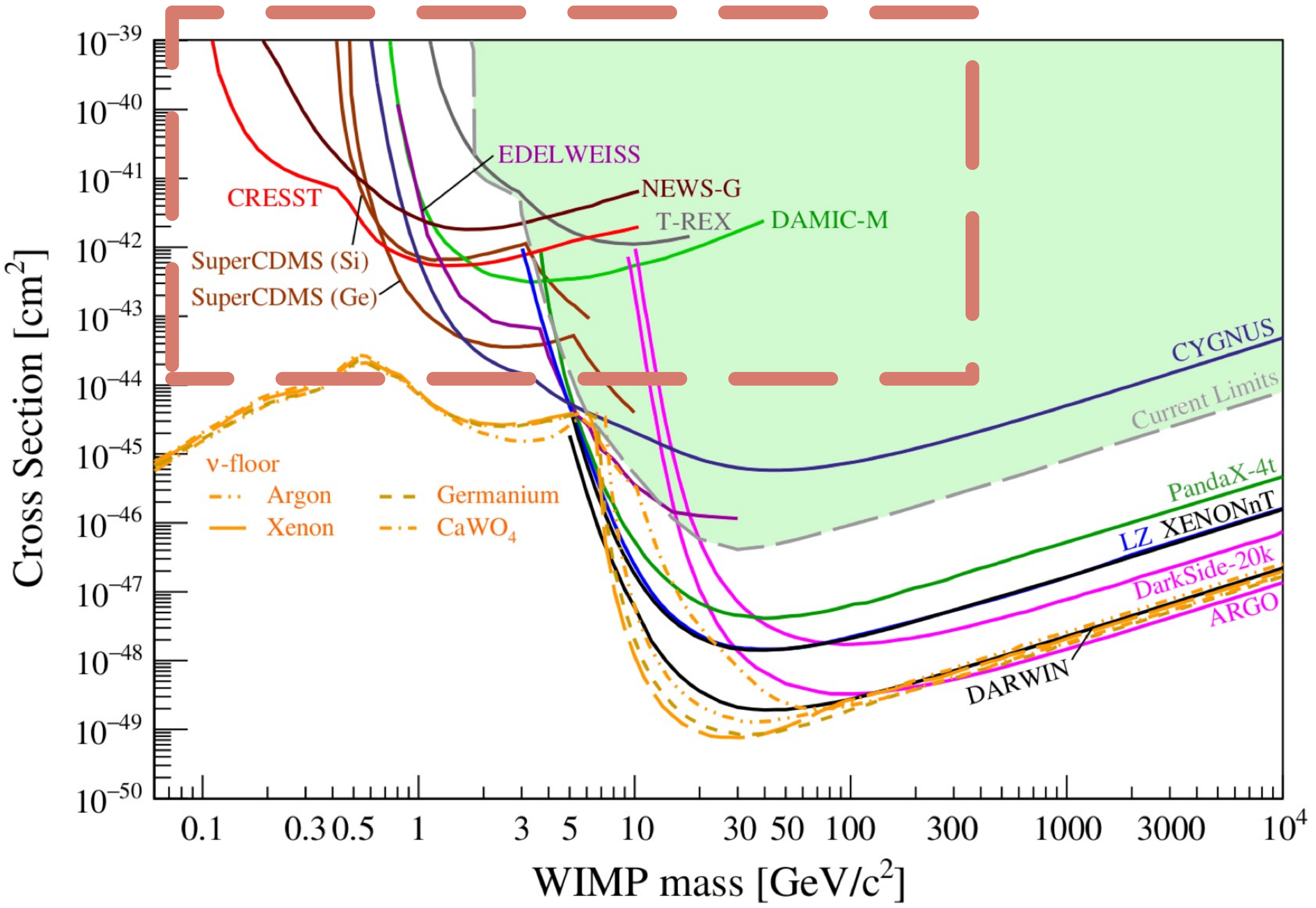
Cryogenic bolometers:

Advantage:

- eV_{nr} and eV_{er} thresholds and energy resolutions
- Two channel readout leads to excellent discrimination

Challenges:

- Small detector volumes – needs many modules
- Low energy excess observed in current experiments



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

Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

Cryogenic bolometers

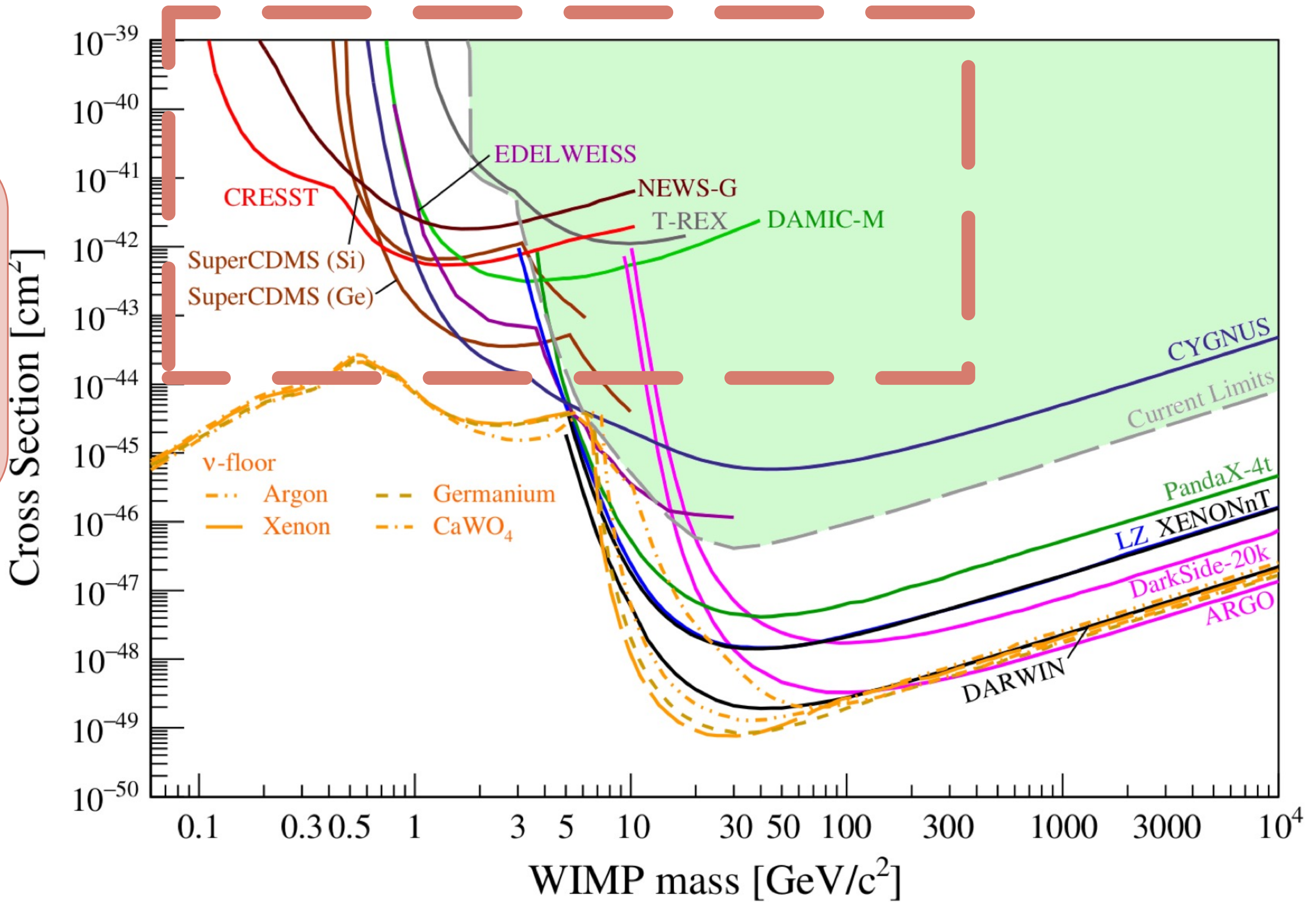
Charge readout

EDELWEISS-subGeV 20 kg in prep

SuperCDMS 24 kg construction

Scintillation readout

CRESST-III 2.5 kg running



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

Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

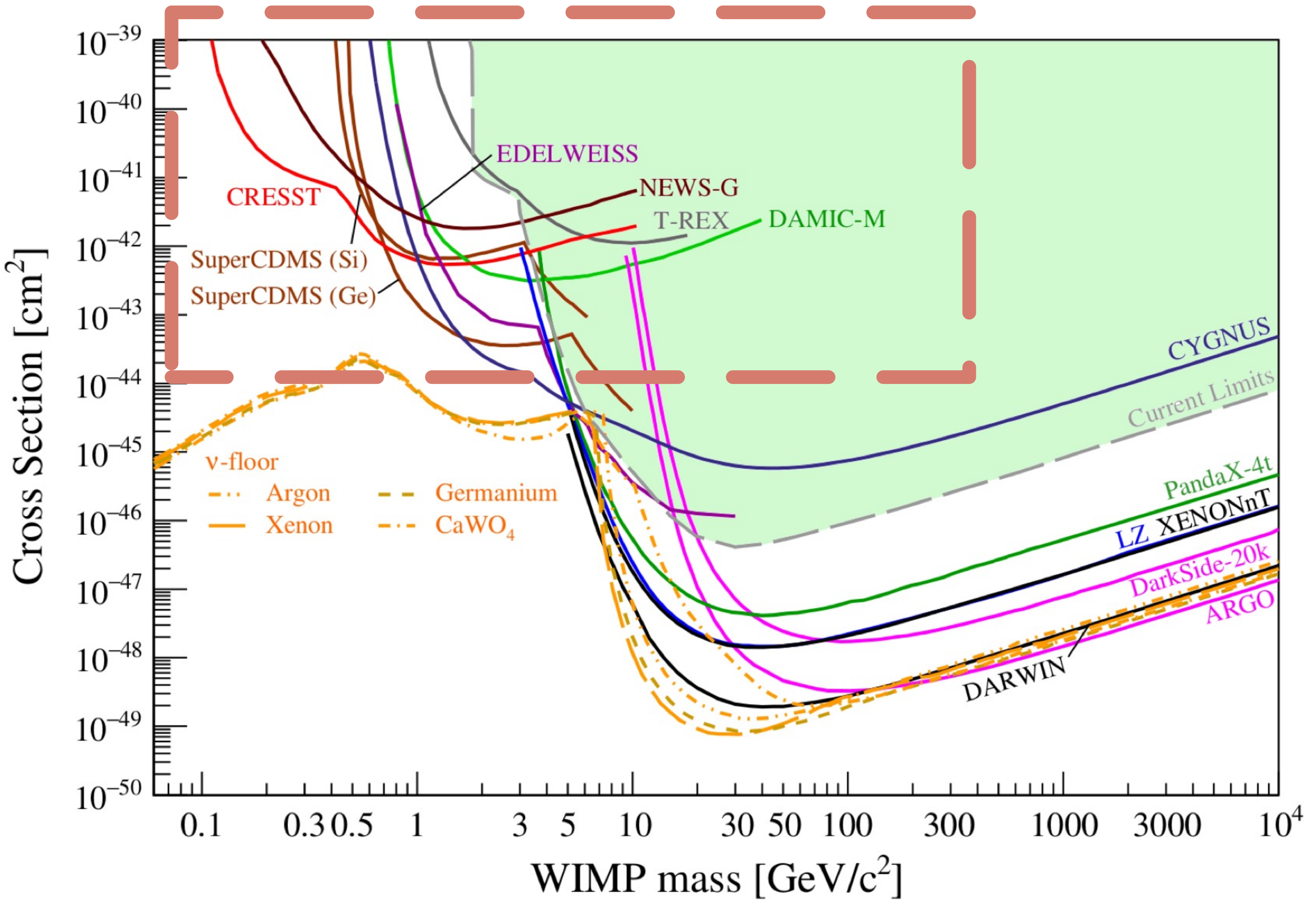
Ionization detectors:

Advantage:

- Very low E threshold (0.1 keV_{ee})
- Si CCDs: 3D position reconstruction and effective particle ID

Challenges:

- Getting to large target volumes/exposures is difficult



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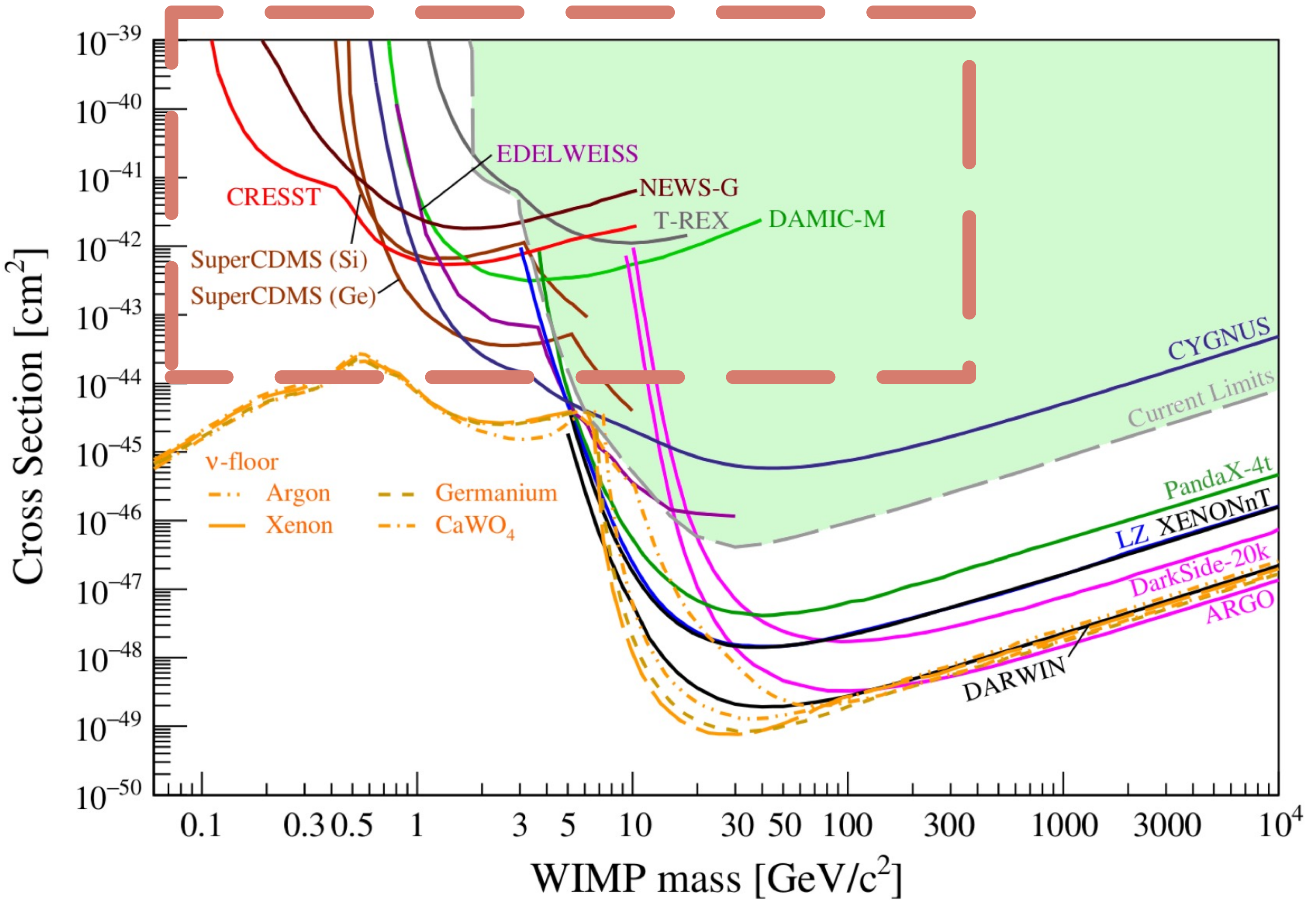
Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

Ionisation detectors

DAMIC	0.04	kg	running
DAMIC-M	0.7	kg	2023
CDEX	10	kg	running
NEWS-G	1	kg	running
TREX-DM	0.16	kg	running



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Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

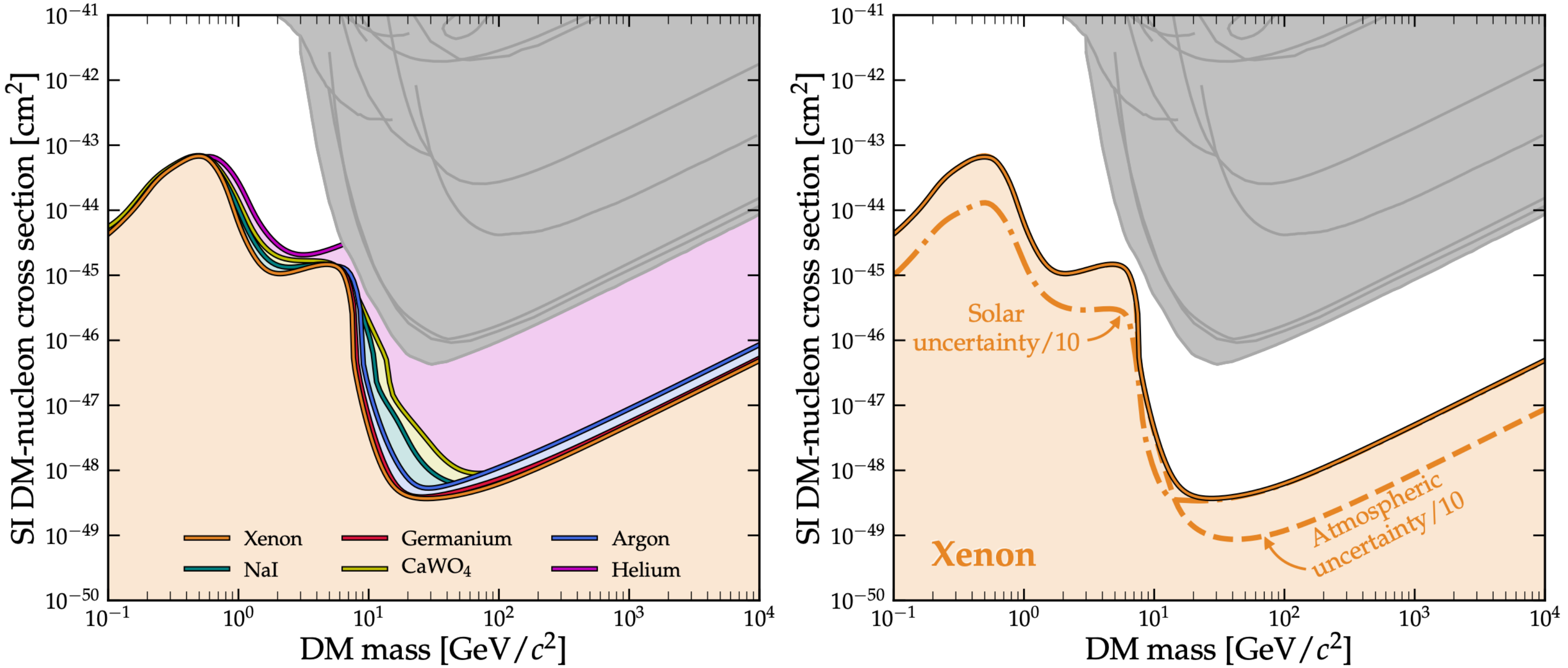
Directional detectors:

Advantage:

- Distinguish between neutrinos and dark matter candidate events
- Different gas mixtures -> sensitivity to spin-dependent etc.

Challenges:

- E threshold in 10s of keV_{ee} typically
- Challenging to reconstruct tracks
- Scaling up is difficult (low density gas, but fine-grained sensors)



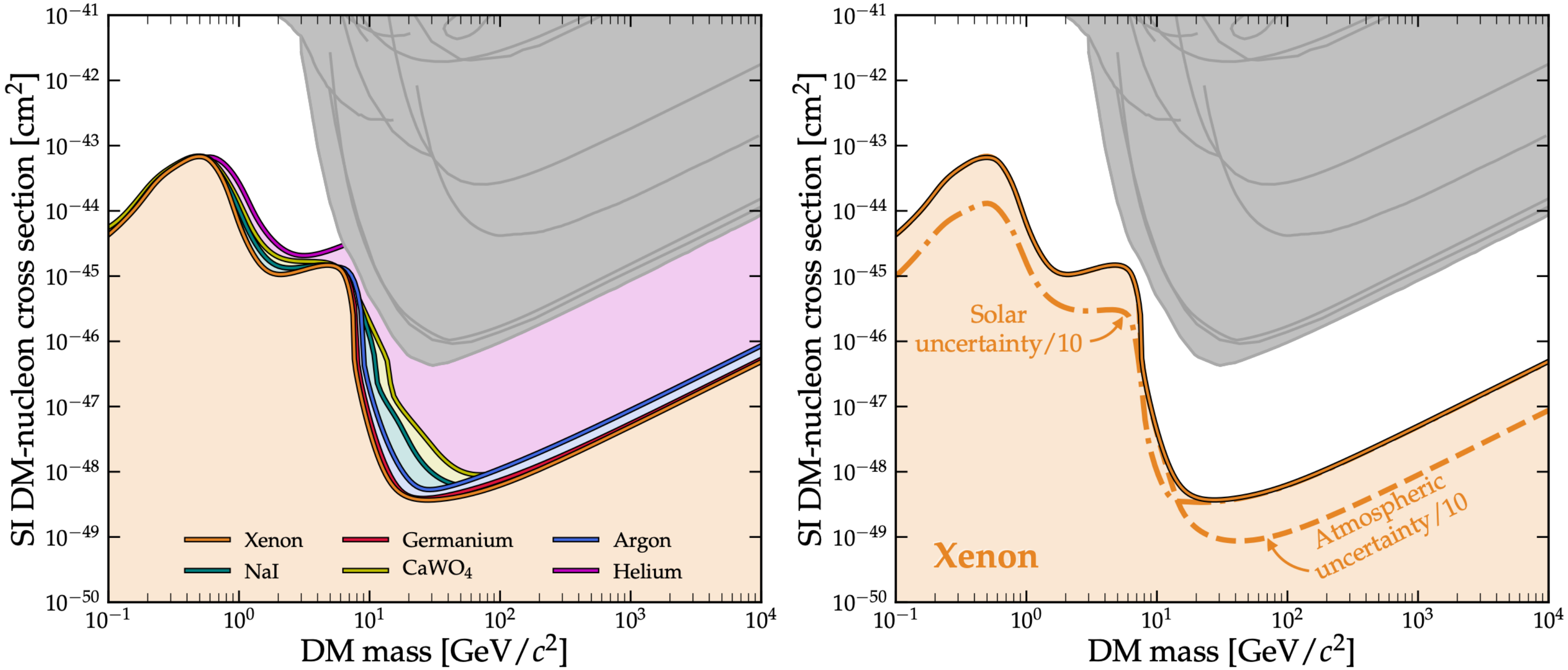
Ciaran O'Hare, Phys. Rev. Lett. 127, 251802 (2021)

Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

Directional detectors

CYGNUS R&D

NEWSdm R&D



Ciaran O'Hare, Phys. Rev. Lett. 127, 251802 (2021)

Exposure frontier | Low mass frontier | Neutrino fog frontier | NaI frontier

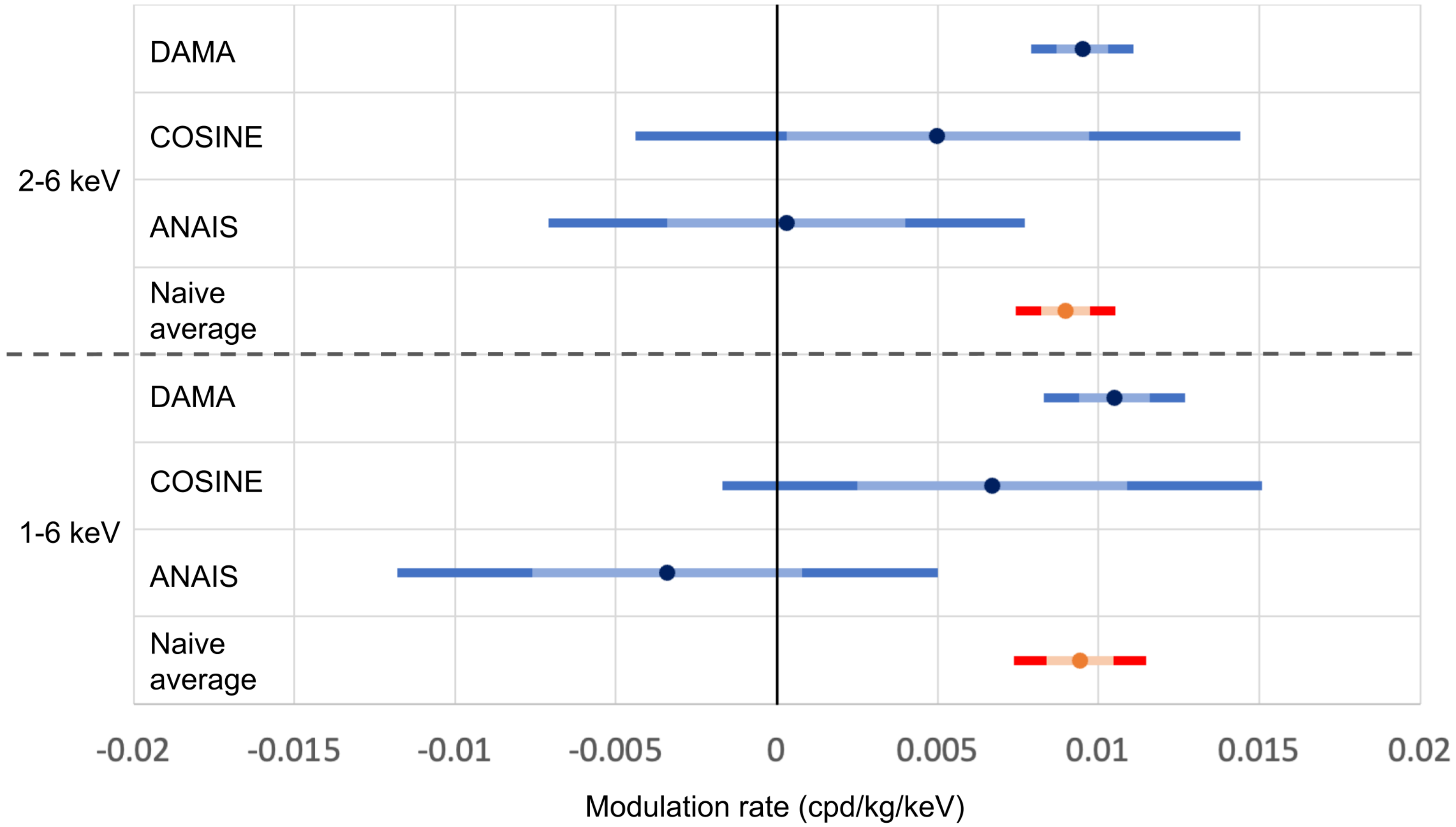
NaI scintillation detectors:

Advantage:

- Can operate stably for a very long time
- Opportunity to test the DAMA /LIBRA claim

Challenges:

- Intrinsic backgrounds in the crystal need to be reduced



https://darkmatteraustralia.atlassian.net/wiki/spaces/SABREPUBLIC/pages/1446117400/Modulation+Rate

[1] Bernabei et al. PPNP114 103810 (2020)

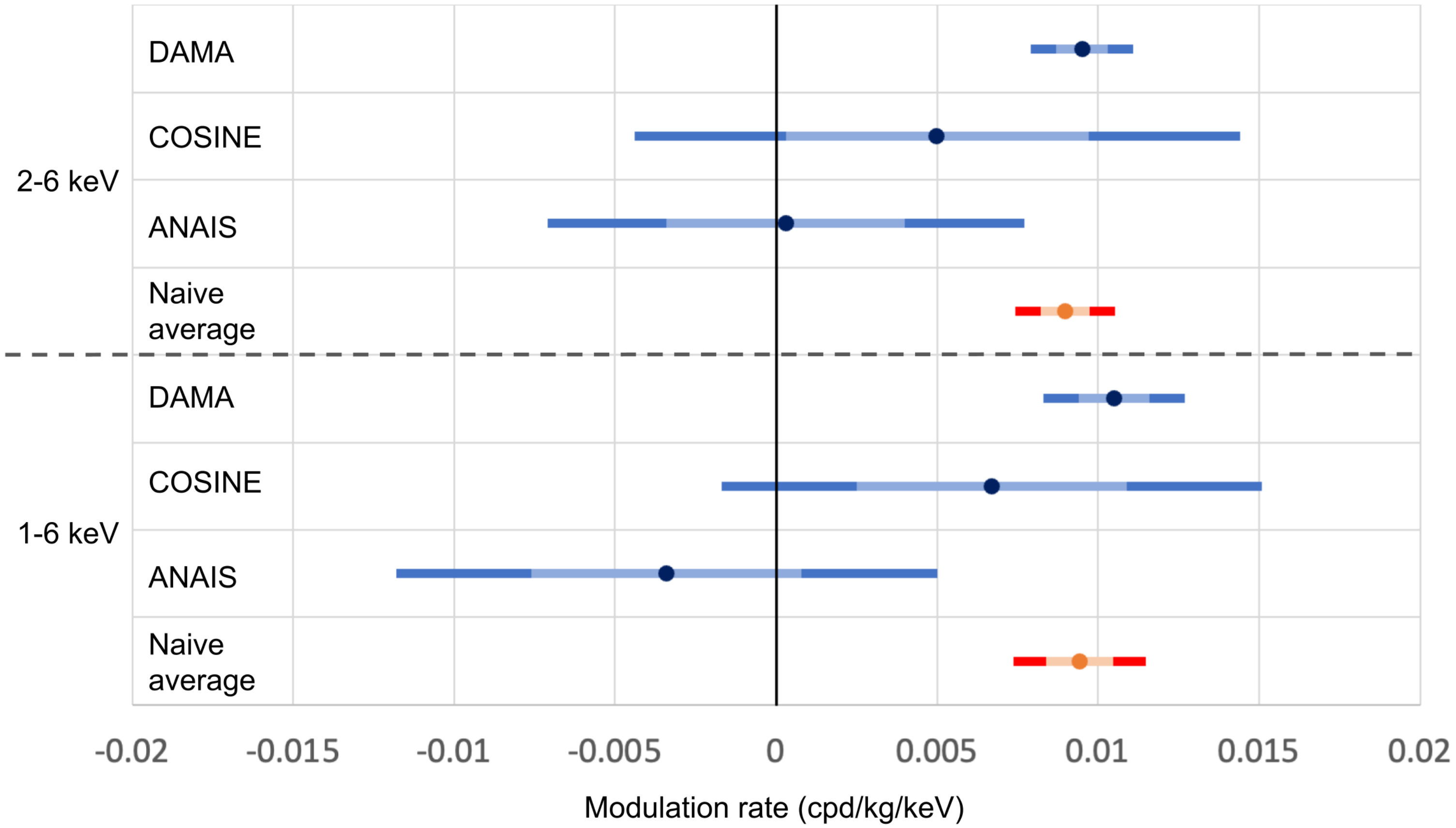
[2] Adhikari et al. arxiv:2111.08863

[3] Amare et al. PRD 103, 102005 (2021)

Exposure frontier | Low mass frontier | Neutrino fog frontier | **NaI frontier**

NaI scintillators
DAMA/LIBRA 250 kg running
COSINE 106 kg running
ANAIS 112 kg running
SABRE 50 kg in prep

NaI bolometer
COSINUS 1 kg in prep



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SUMMARY

- Many different methods for particle dark matter direct detection searches
- Different methods are complimentary and have different strengths
- Exciting new experiments coming online