

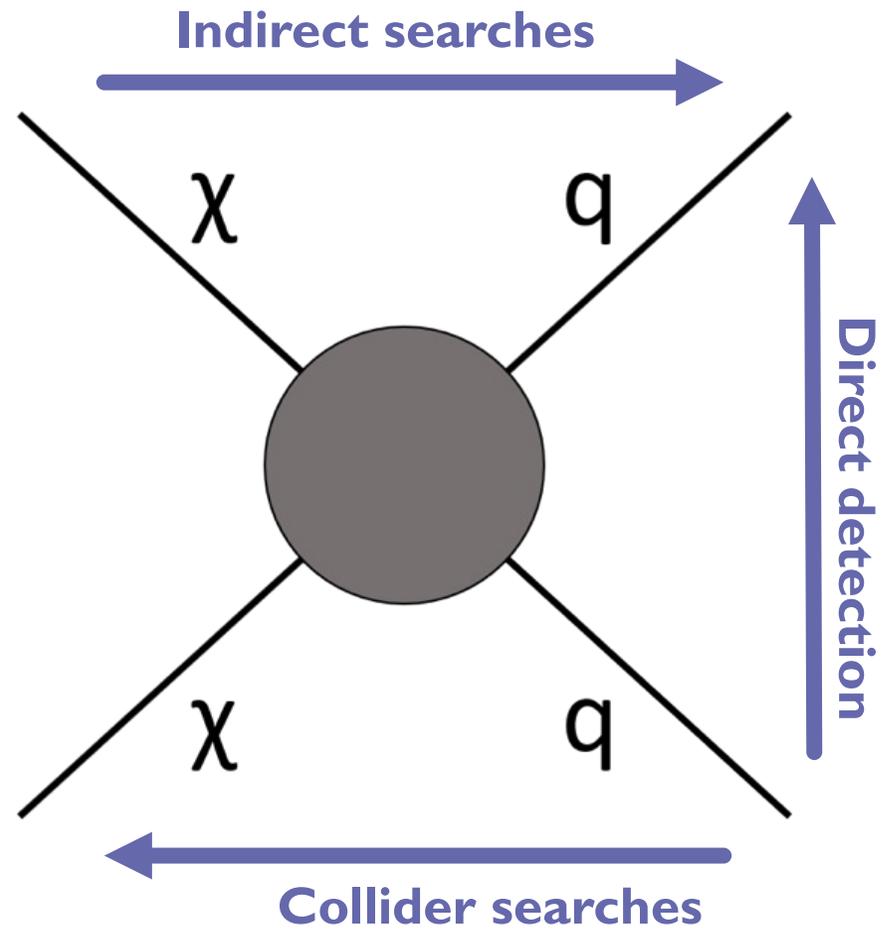


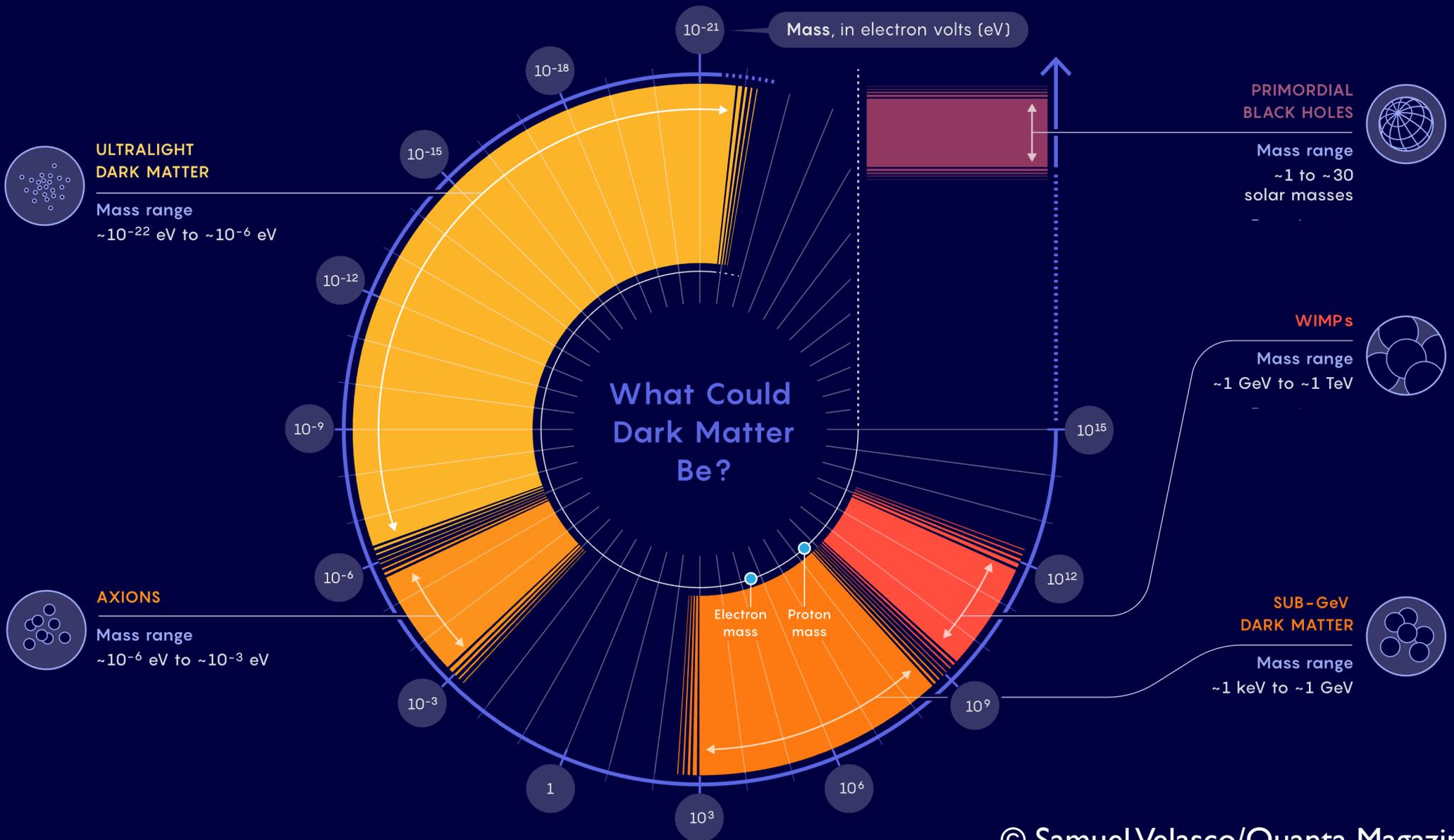
EXPERIMENTAL TECHNIQUES FOR DARK MATTER DIRECT DETECTION

THERESA FRUTH
UNIVERSITY OF SYDNEY

SYDNEY SPRING SCHOOL
30 NOV 2022

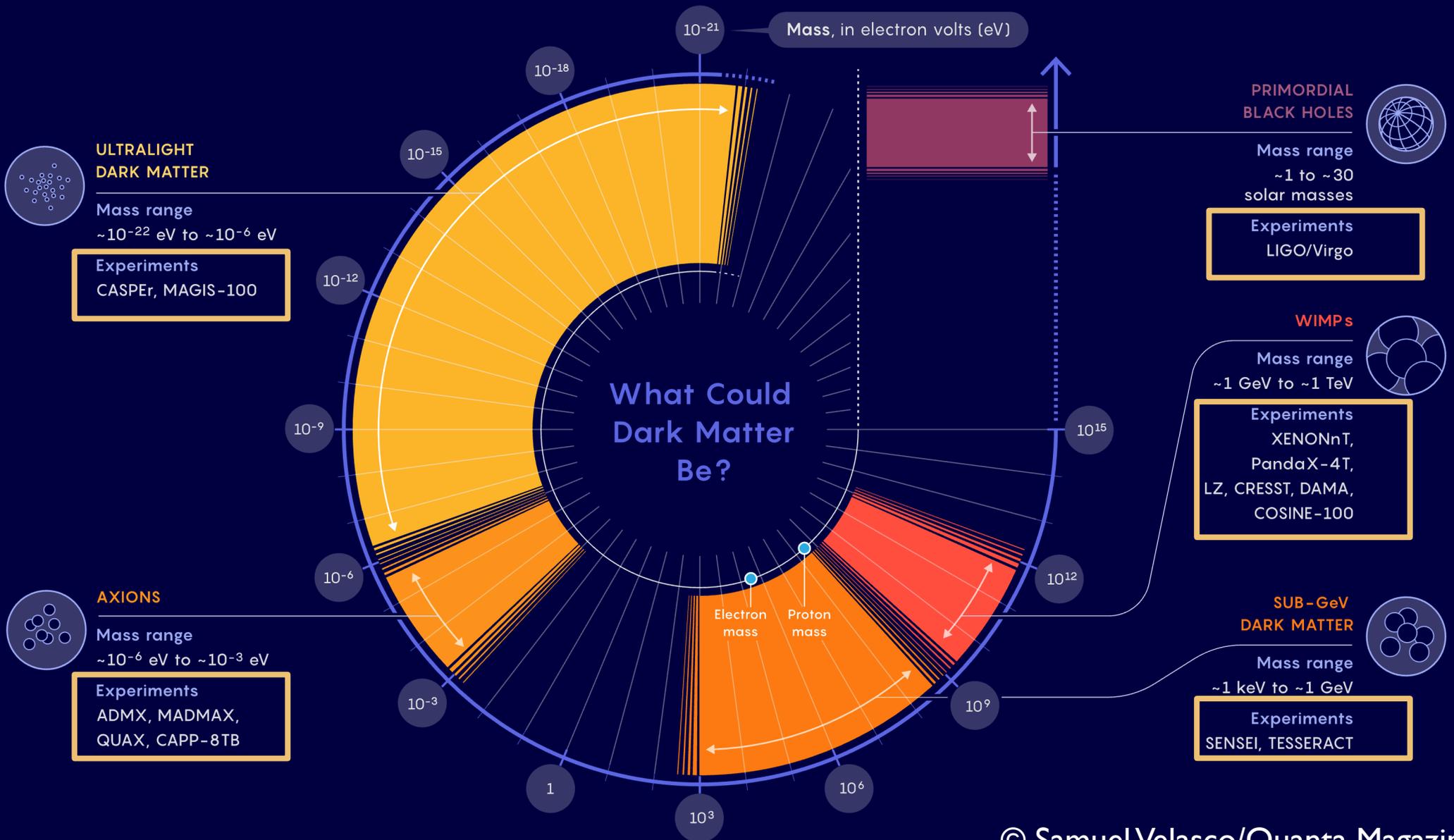
MAKE IT, SHAKE IT, BREAK IT

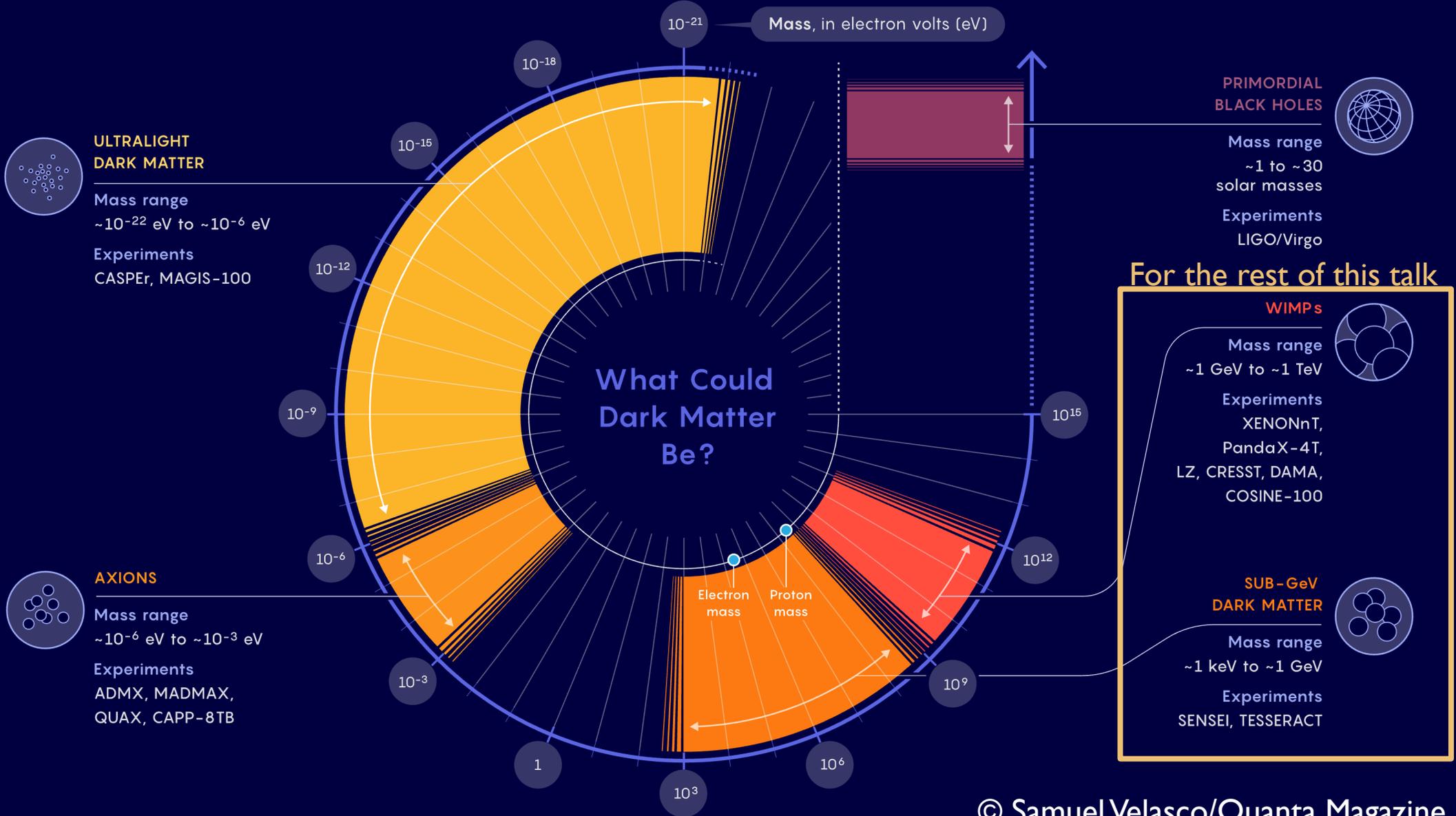






Which direct detection
experiments have you heard of?





For the rest of this talk

WIMPs

Mass range: ~ 1 GeV to ~ 1 TeV

Experiments: XENONnT, PandaX-4T, LZ, CRESST, DAMA, COSINE-100

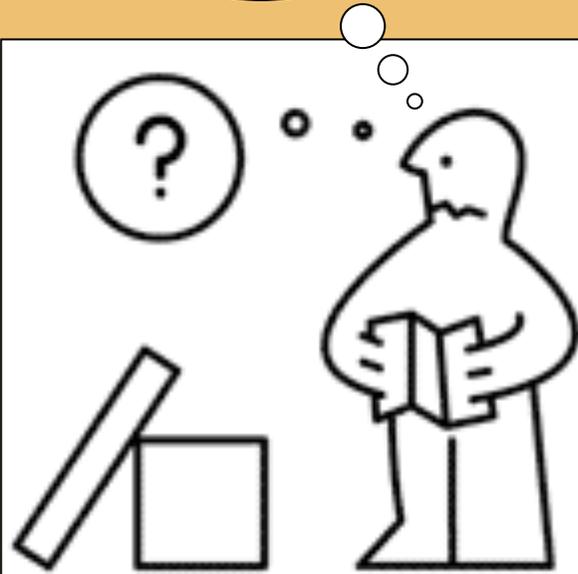
SUB-GeV DARK MATTER

Mass range: ~ 1 keV to ~ 1 GeV

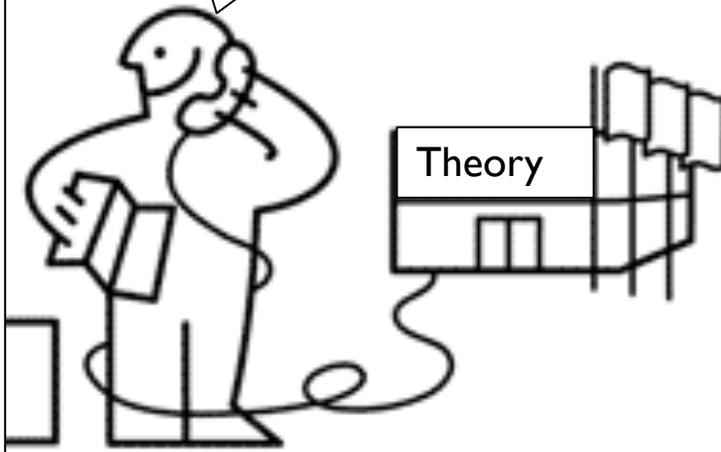
Experiments: SENSEI, TESSERACT

LET'S DESIGN A DETECTOR

I want to find dark matter!



So how would dark matter interact?

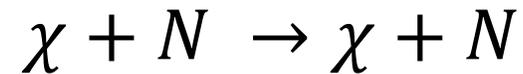


Let's work together!



DIRECT DETECTION BASICS

Scattering of a DM particle of a nucleus:



N	Number of target nuclei
ρ_0	Local dark matter density
m_χ	WIMP mass
$f(v)$	WIMP velocity distribution function

Differential recoil rate:

$$\frac{dR}{dE_{NR}} = N_N \frac{\rho_0}{m_\chi} \int_{v_{min}}^{v_{esc}} \frac{d\sigma}{dE_{NR}} v f(v) dv$$

DIRECT DETECTION BASICS

$$\frac{d\sigma(E_{\text{nr}})}{dE_{\text{nr}}} = \frac{m_N}{2v^2\mu^2} [\sigma_{\text{SI}} F_{\text{SI}}^2(E_{\text{nr}}) + \sigma_{\text{SD}} F_{\text{SD}}^2(E_{\text{nr}})]$$

Spin-independent

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

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

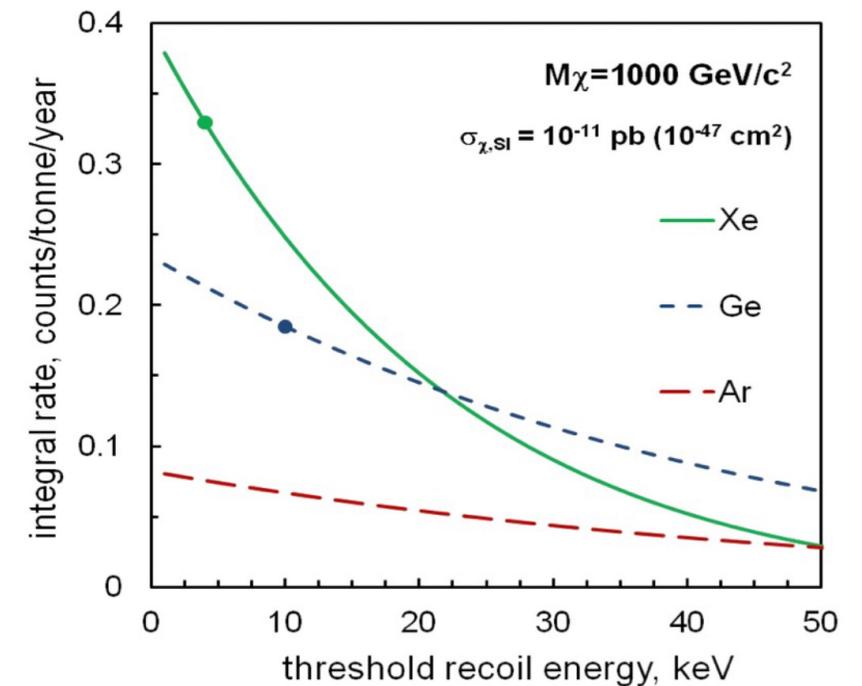
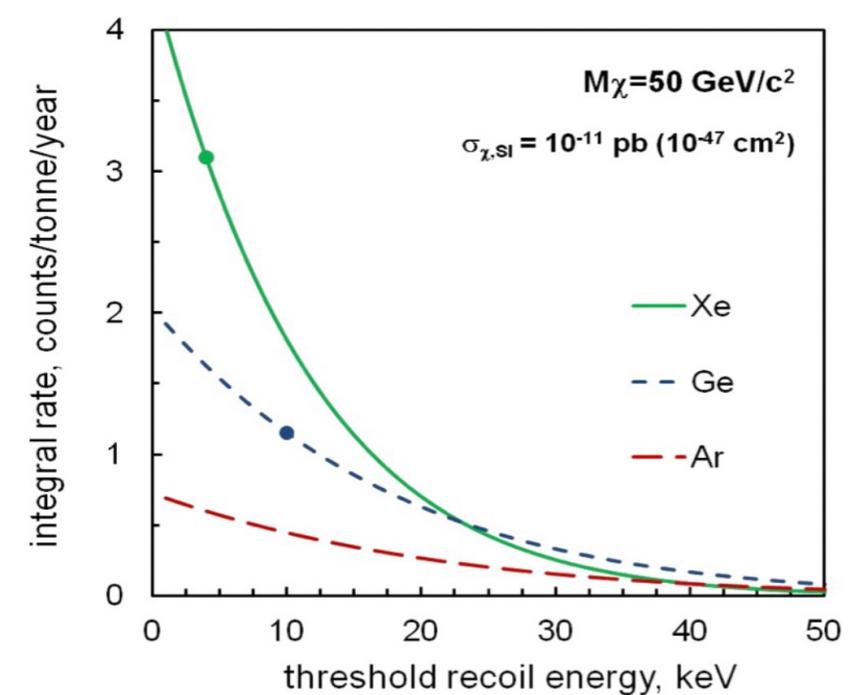
Spin-dependent

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

Nuclei with unpaired neutron or proton

EXPERIMENTAL CHALLENGES

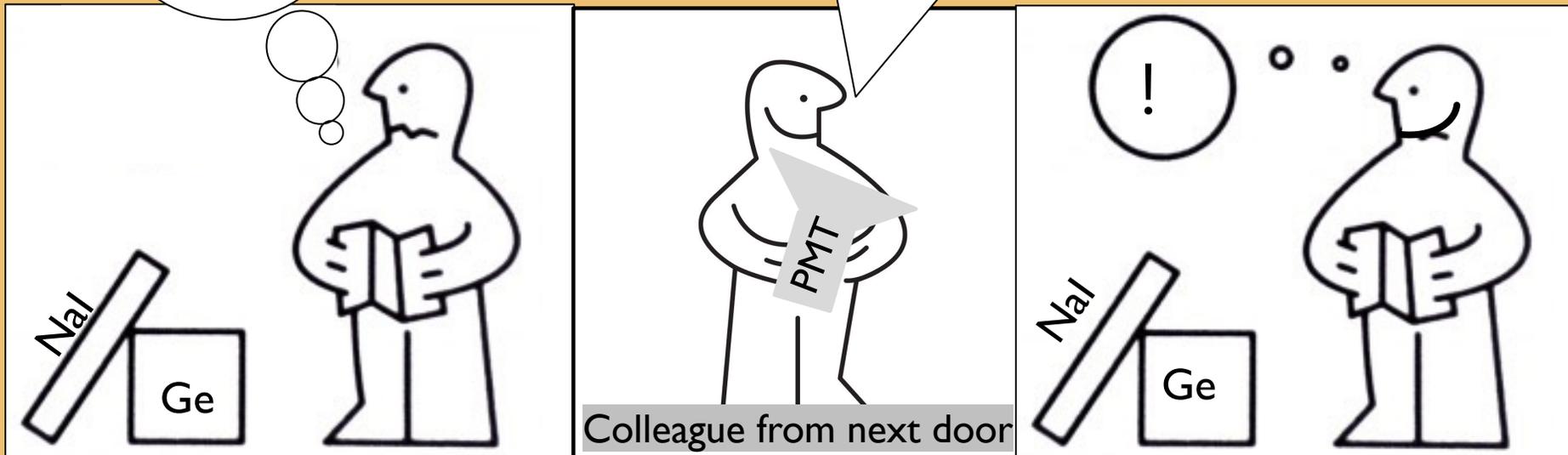
- Nuclear recoils due to dark matter interactions are expected to be:
 - Very rare
 - Low energy
- We need:
 - Target material sensitive to the interaction
 - Technology to detect interaction
 - Understand and reduce backgrounds
 - Calibrate detector response
 - Analysis techniques



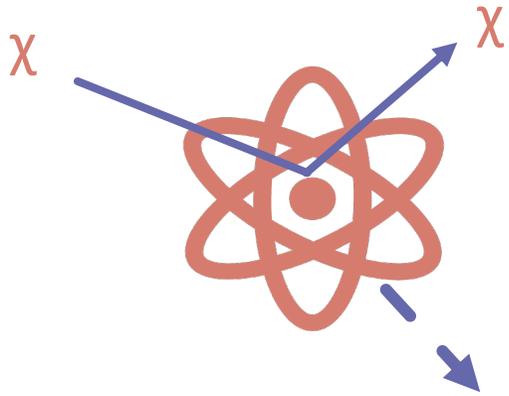
LET'S DESIGN A DETECTOR (2)

How would we detect a nuclear recoil in our target?

Oh, I might have a sensors for this!

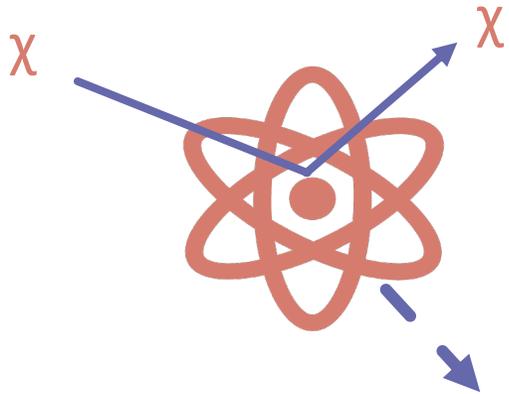


NUCLEAR RECOIL DETECTION



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

NUCLEAR RECOIL DETECTION

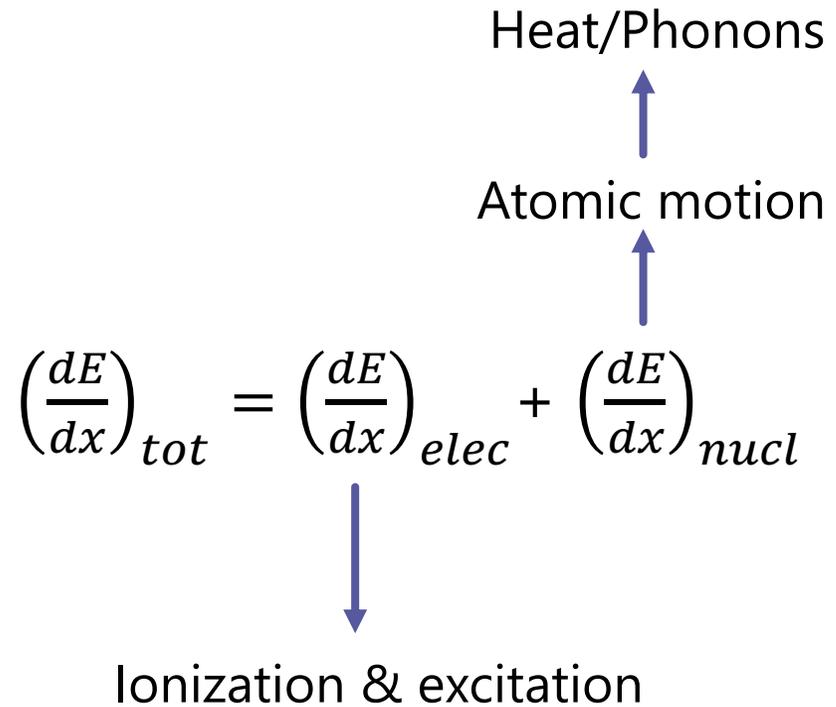
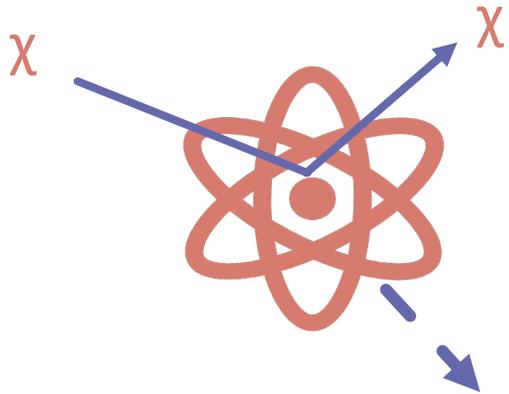


$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{elec} + \left(\frac{dE}{dx}\right)_{nucl}$$

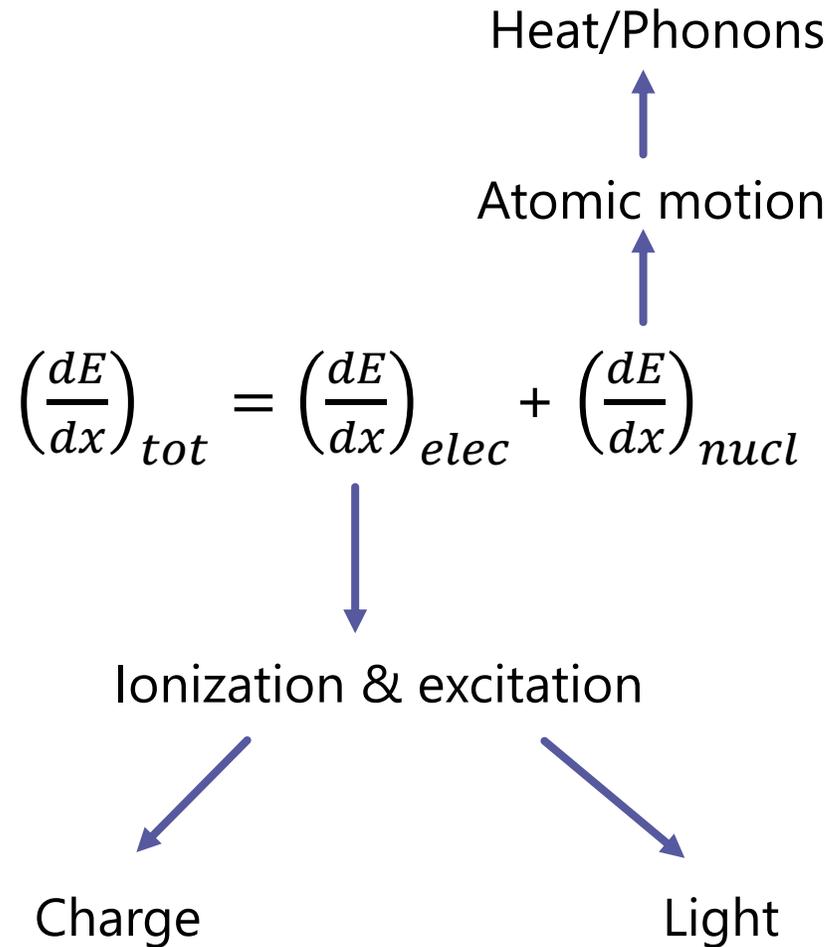
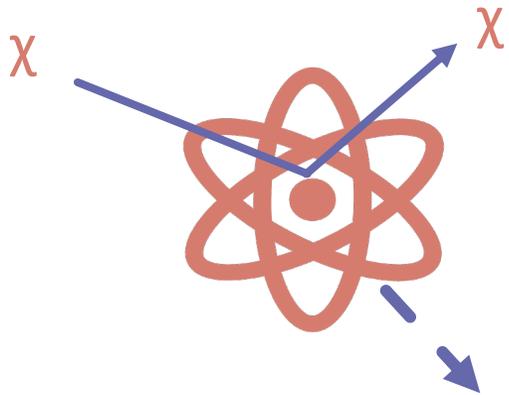
Atomic motion

Ionization & excitation

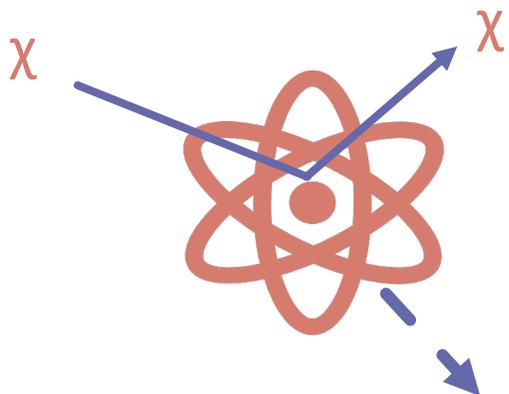
NUCLEAR RECOIL DETECTION



NUCLEAR RECOIL DETECTION



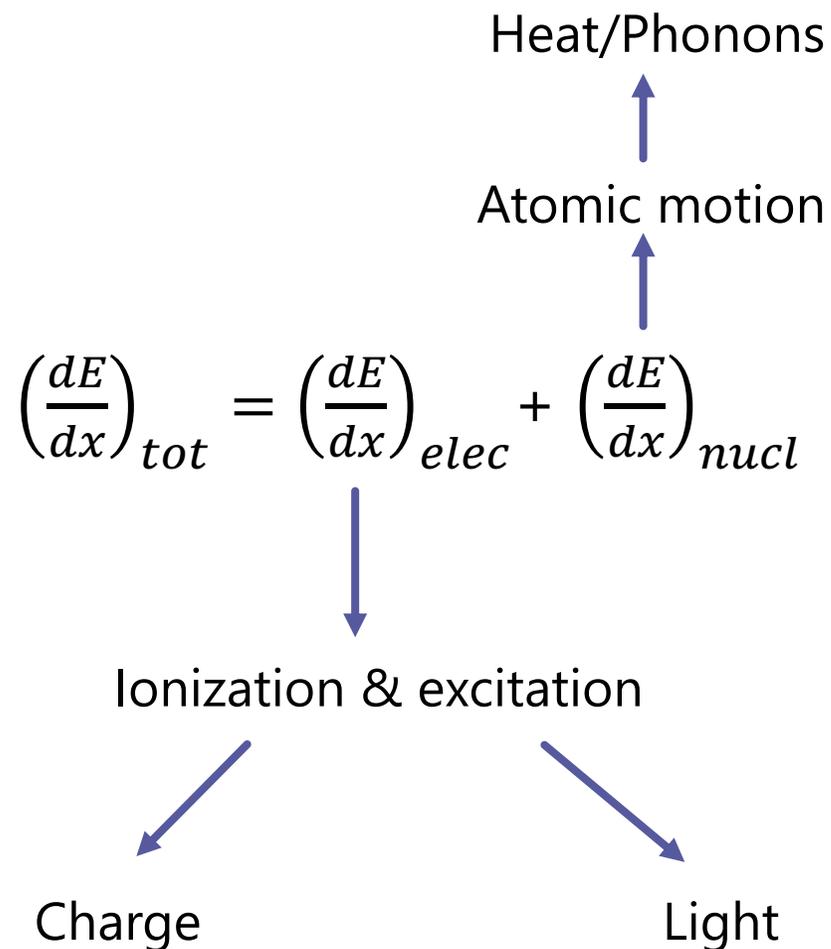
NUCLEAR RECOIL DETECTION



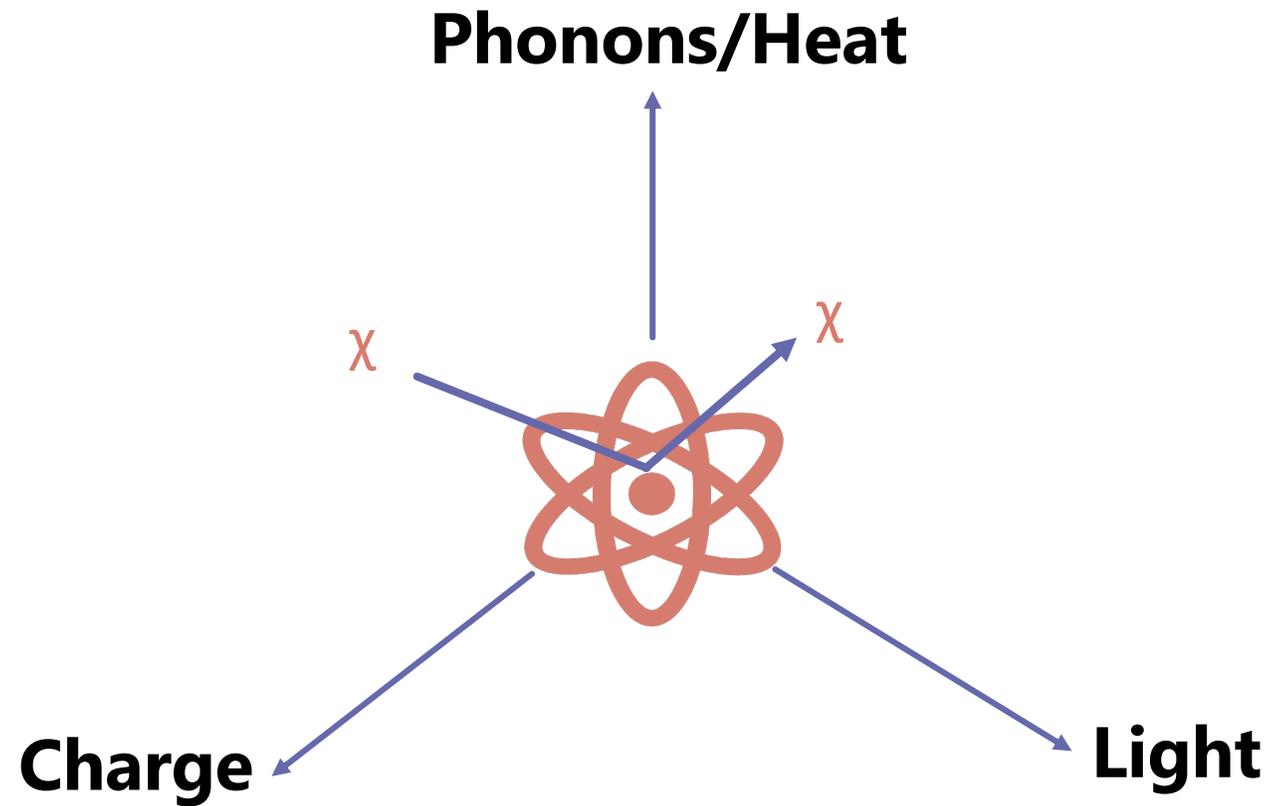
Signal quenching:

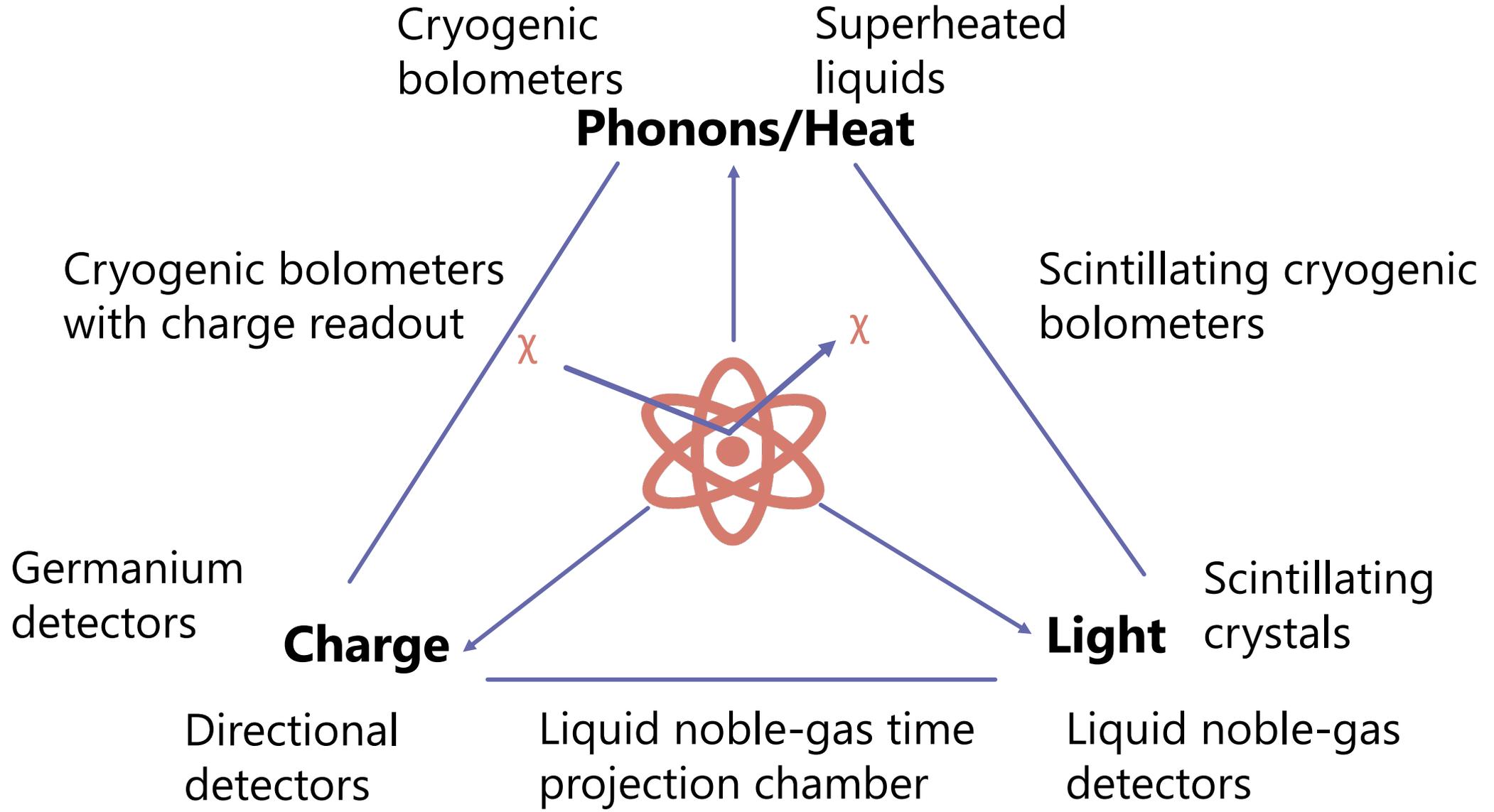
Nuclear recoils "lose" more energy to atomic motion than electron recoils. This is accounted for by the quenching factor Q .

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



NUCLEAR RECOIL DETECTION





Cryogenic bolometers

Superheated liquids

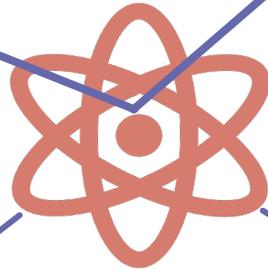
Phonons/Heat

Cryogenic bolometers with charge readout

Scintillating cryogenic bolometers

χ

χ



Charge

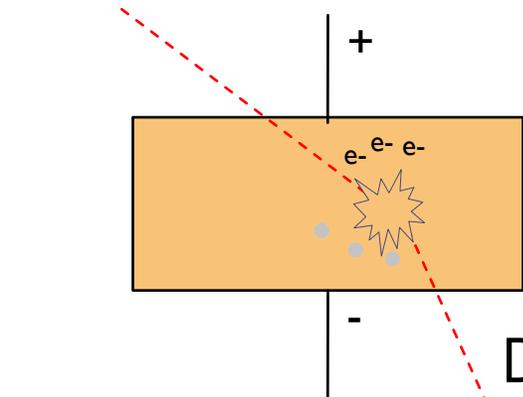
Light

Scintillating crystals

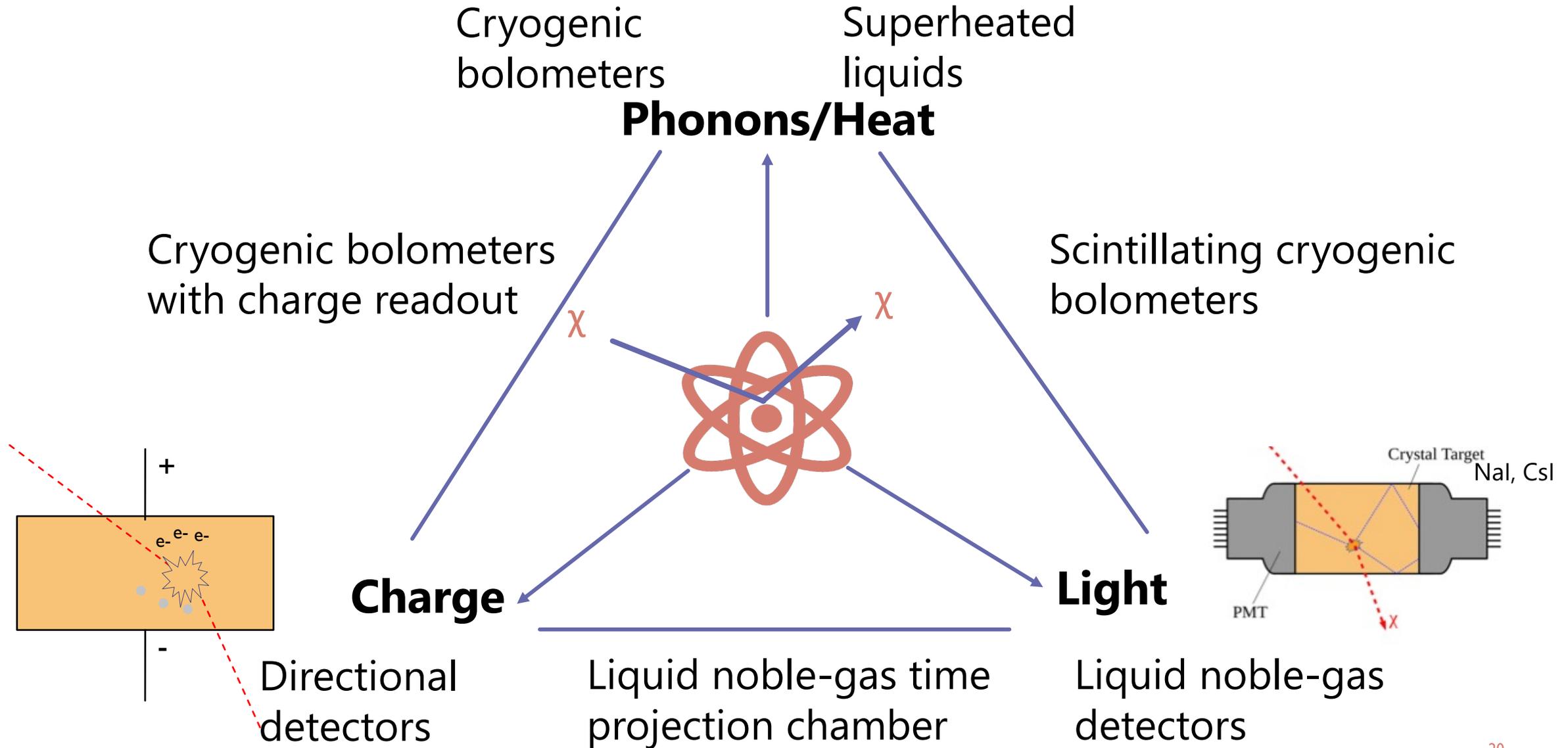
Directional detectors

Liquid noble-gas time projection chamber

Liquid noble-gas detectors

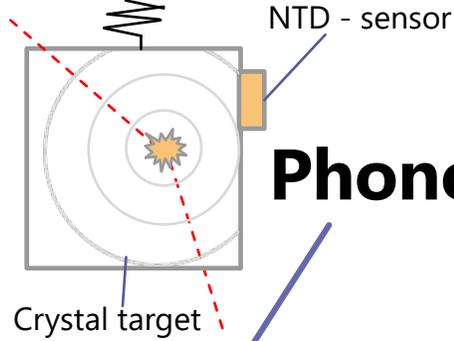


Current: Silicon CCDs



Thermal Bath

NTD thermistors
TES - Transition Edge Sensors



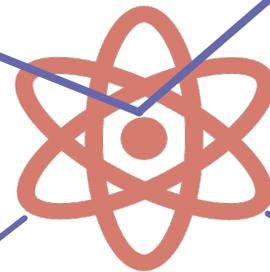
Superheated liquids

Phonons/Heat

Cryogenic bolometers with charge readout

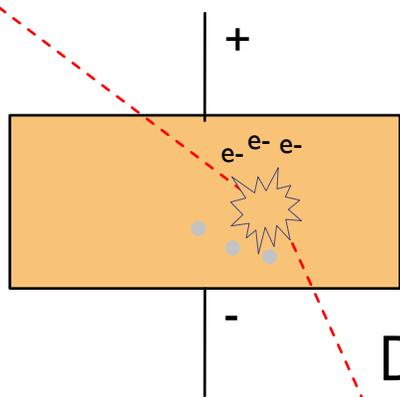
Scintillating cryogenic bolometers

χ



Charge

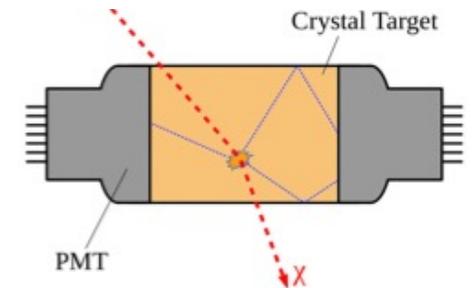
Light

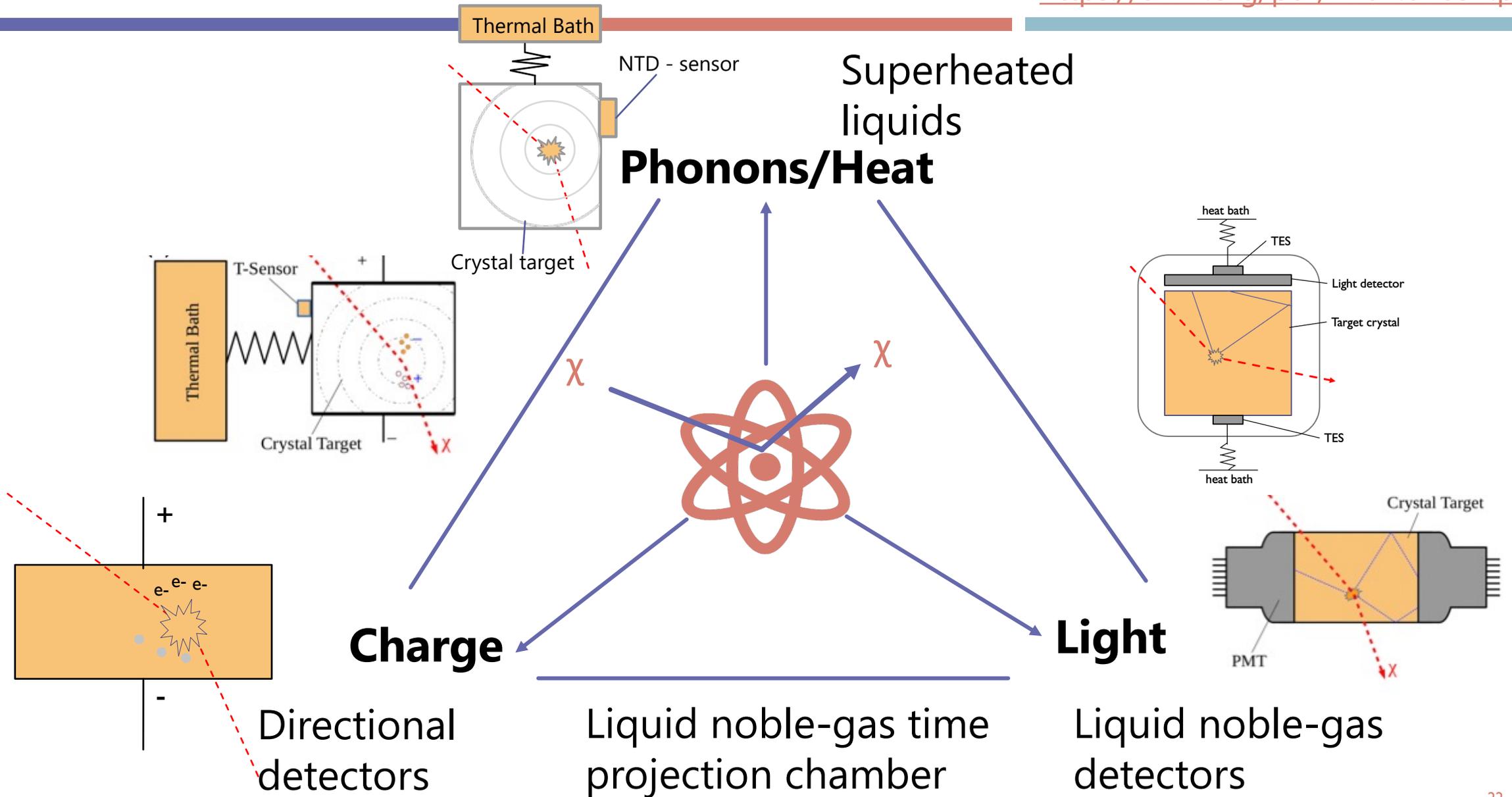


Directional detectors

Liquid noble-gas time projection chamber

Liquid noble-gas detectors





Thermal Bath

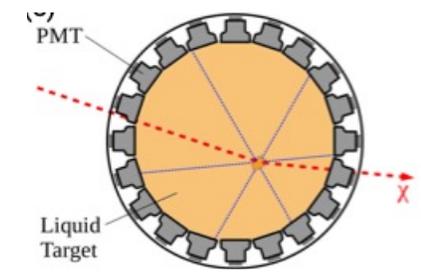
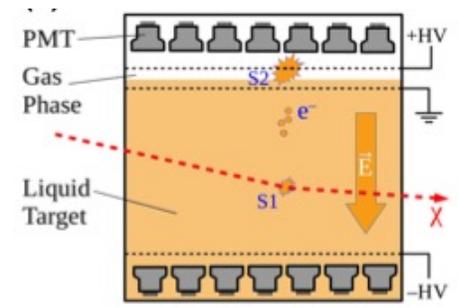
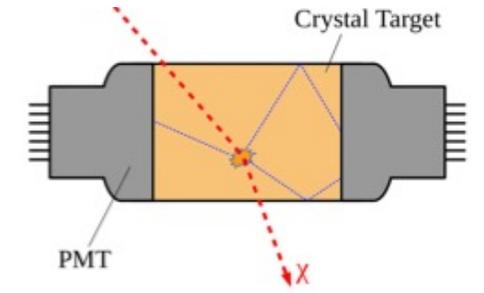
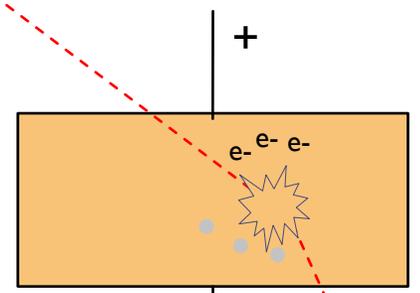
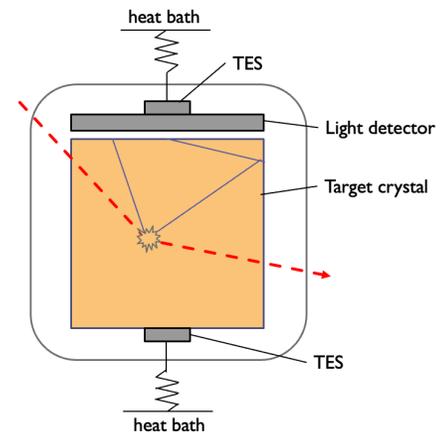
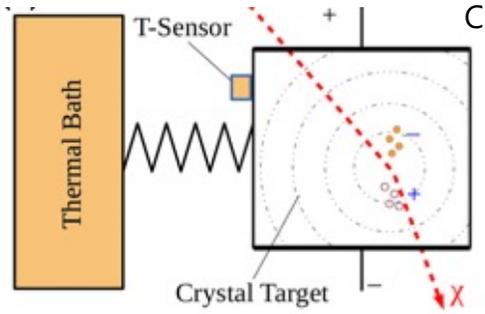
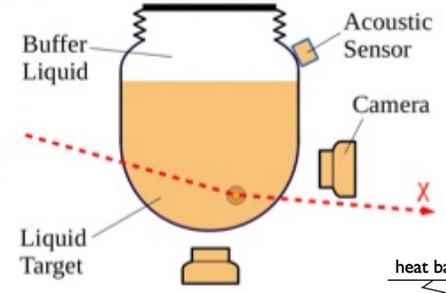
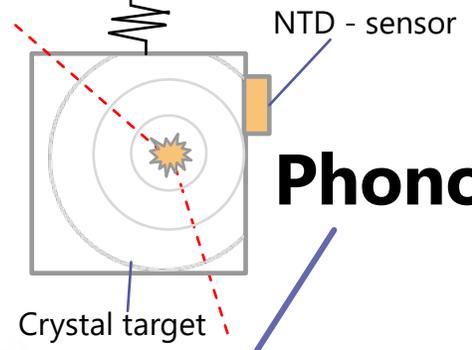
e.g. CF3I, C3F8

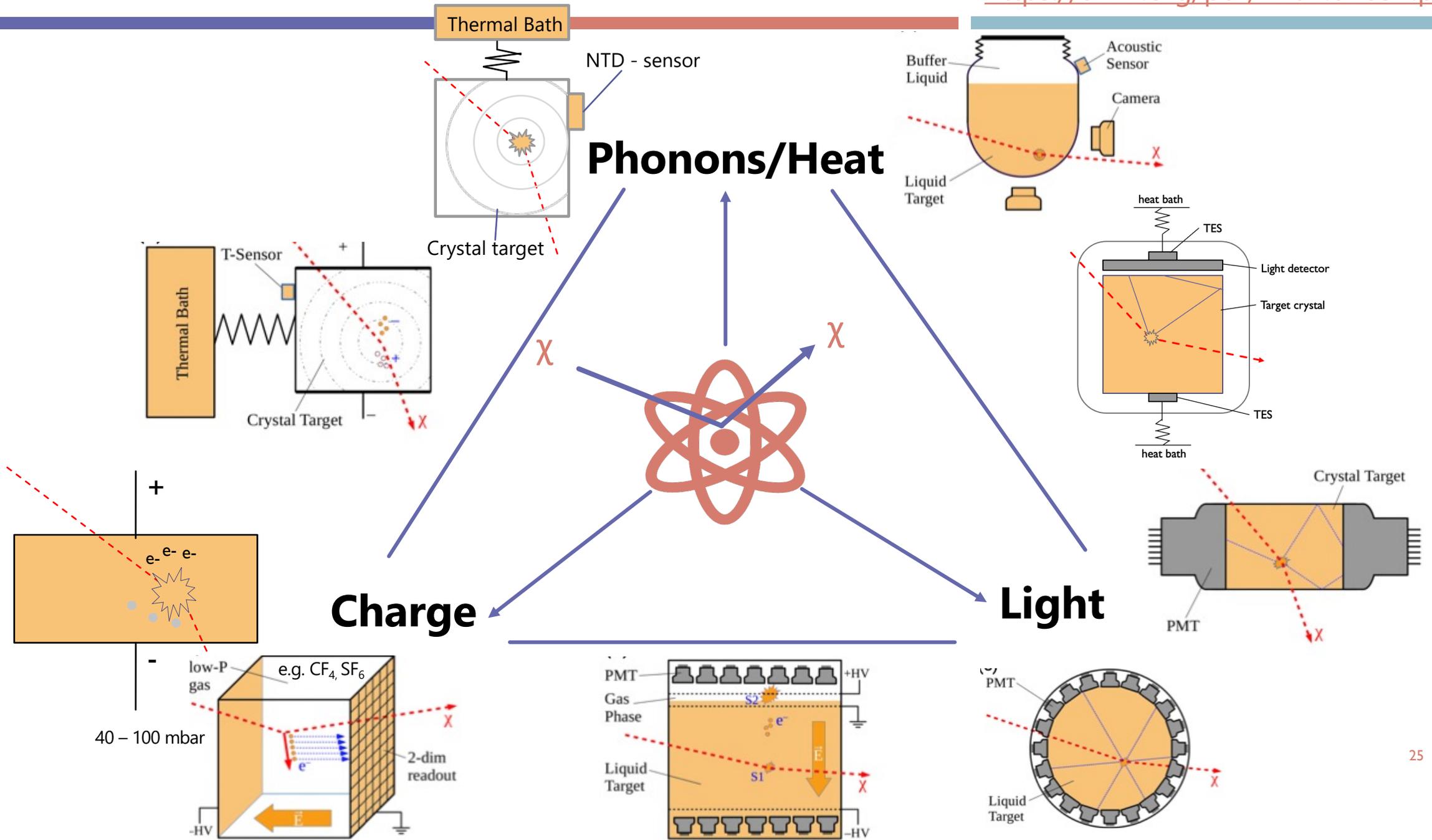
Phonons/Heat

Charge

Light

Directional detectors





ASIDE: ELECTRON RECOIL SIGNALS

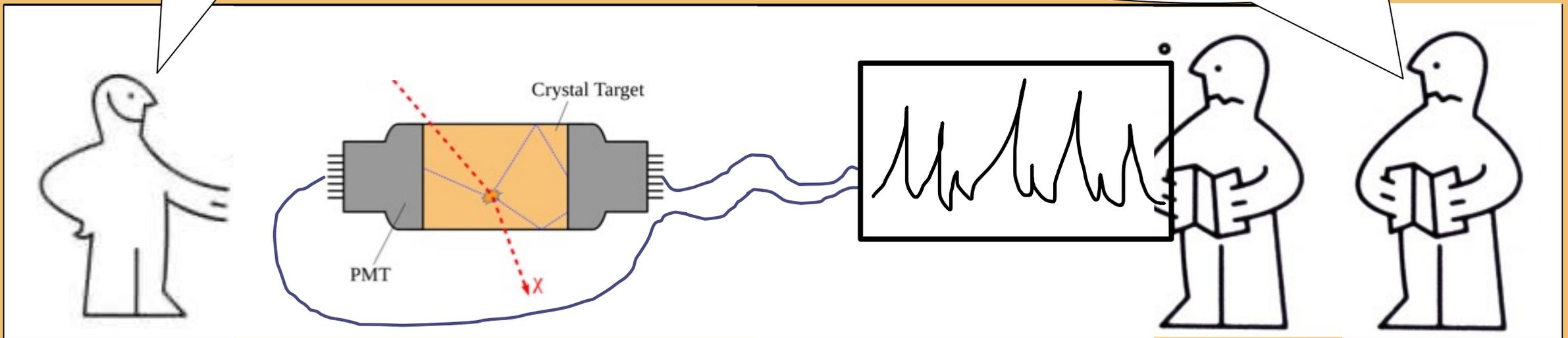
There are some searches making use of electron recoils:

- **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

LET'S DESIGN A DETECTOR (3)

Our detector is running!

I thought dark matter was supposed to be rare?! Why do we see many signals?

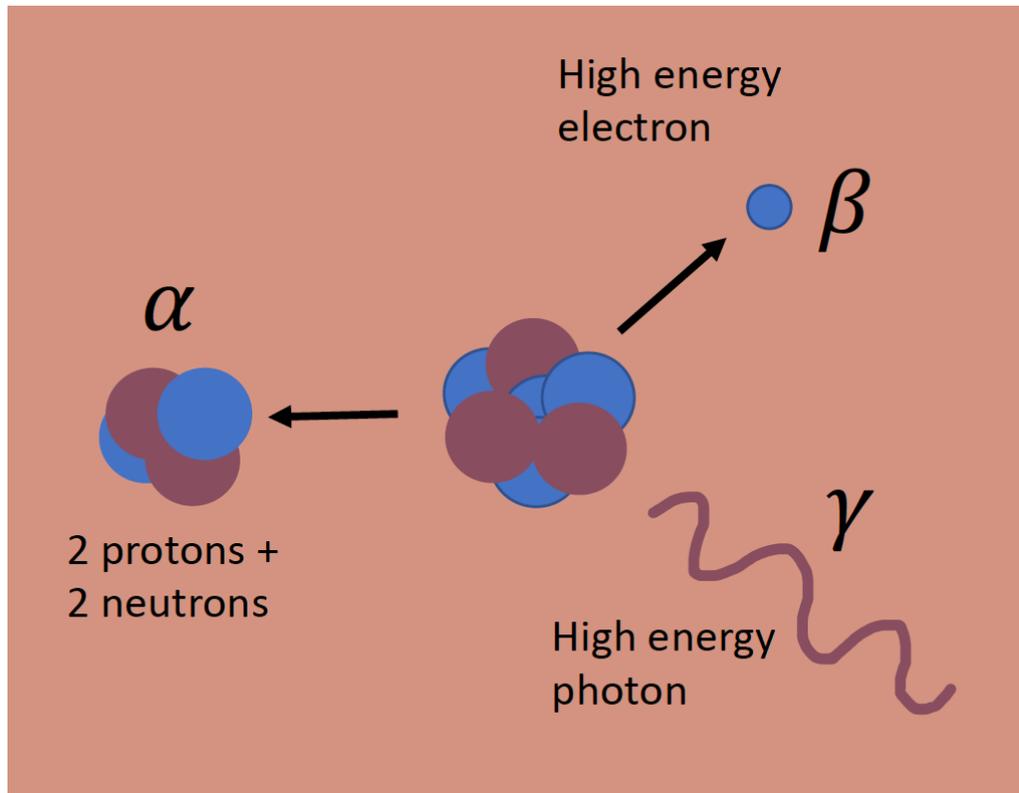


BACKGROUNDS

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

NR

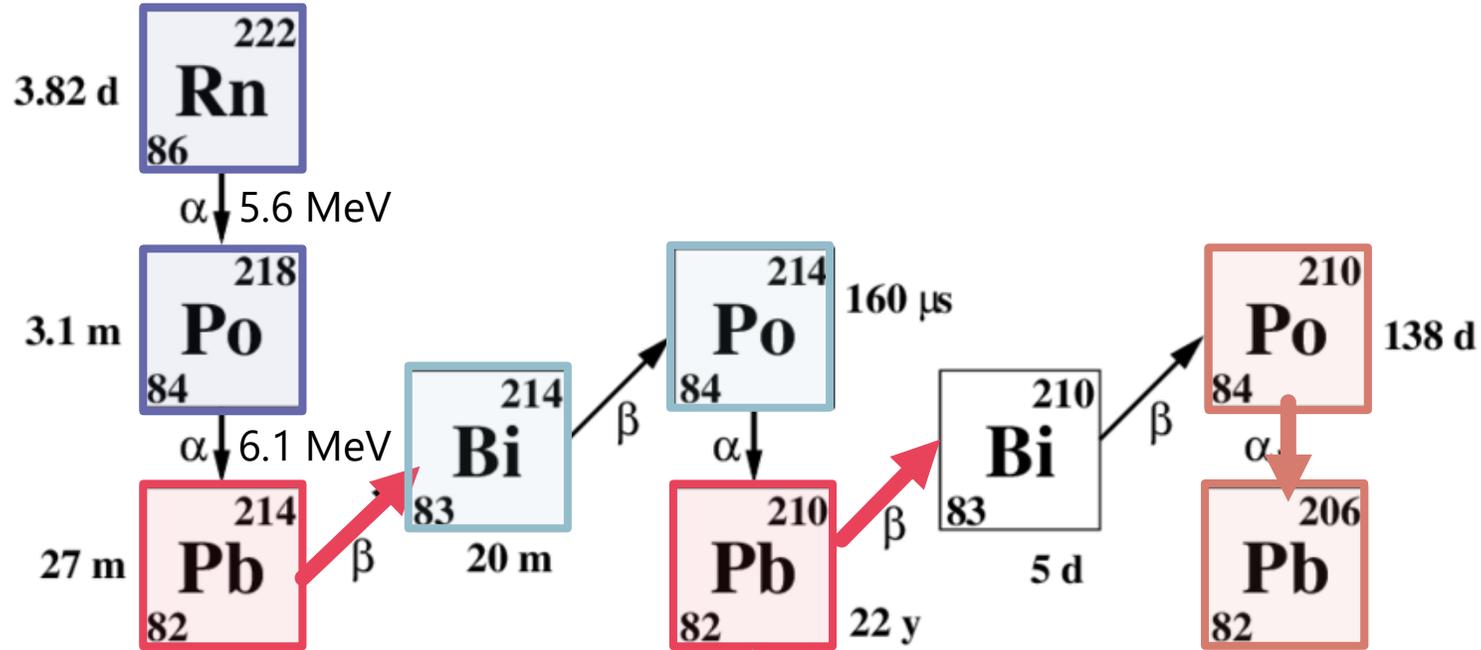
Radioactive isotopes

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)

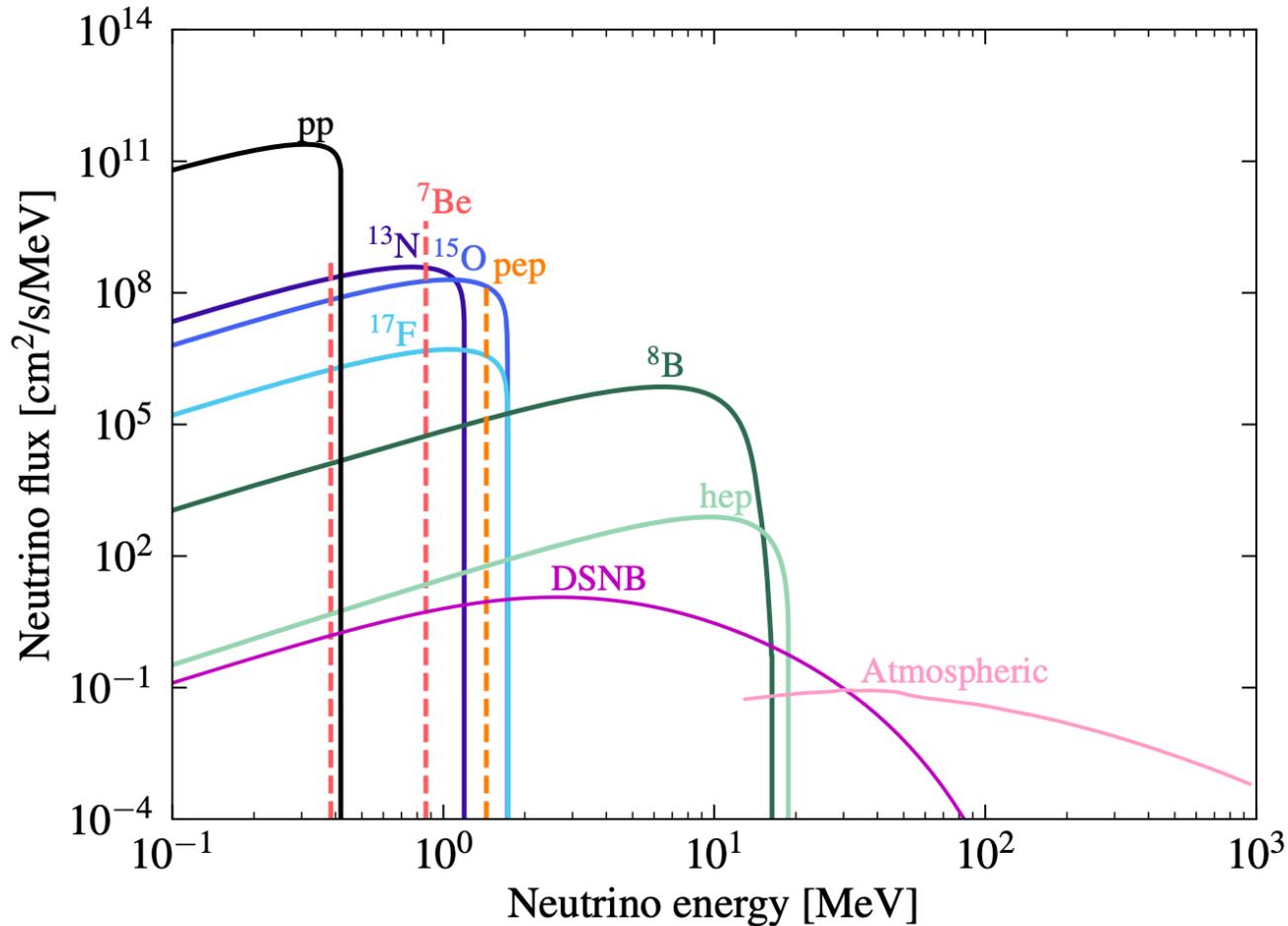
Plate-out onto detector surfaces ($T_{1/2} = 22.3\text{y}$)

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

Radioactive isotopes

Radon

Neutrinos



■ Neutrino fluxes:

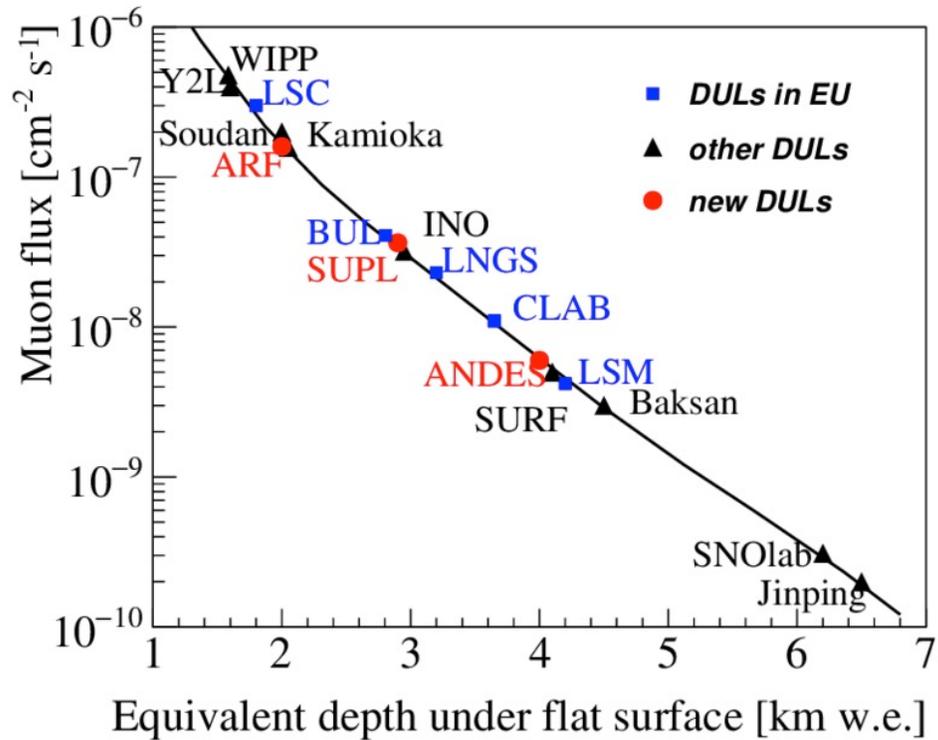
- Solar neutrinos (flux predicted by standard solar model)
- Atmospheric neutrinos: ($< 100 \text{ MeV}$ atmospheric neutrino flux has not been measured, predictions from simulations)
- Diffuse supernovae neutrino background
- **Neutrino-electron scattering => ER band**
- **CEvNS => NR band**

BACKGROUNDS

Understand background sources.

Reduce backgrounds.

Distinguish signal from background topologies.



DOI:[10.1088/1742-6596/1342/1/012003](https://doi.org/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

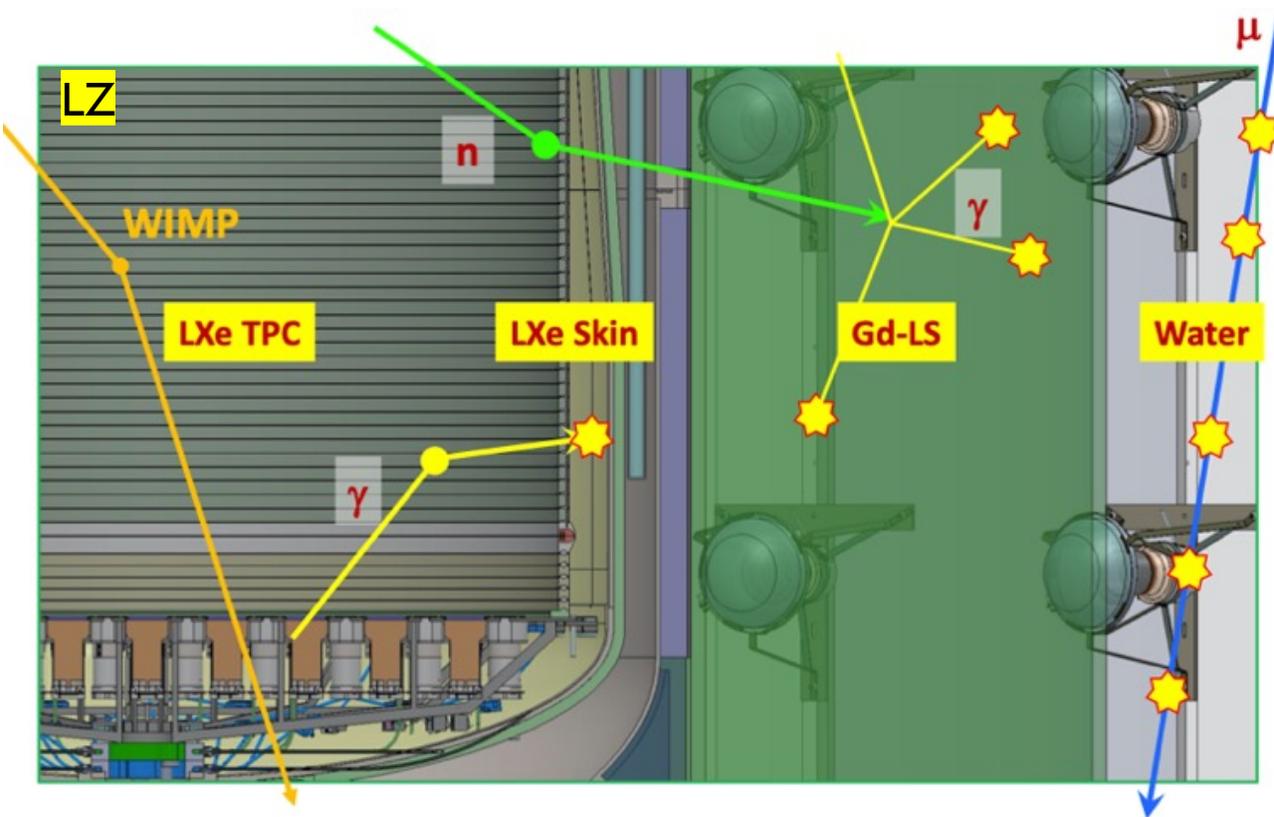
- Purification:
 - Reduce impurities and radioactivity in target material
 - For crystals before and during crystal making
 - For gas and liquid detectors online purification
- Material selection: Dedicated screening campaigns to select radio-pure detector materials
 - Gamma-screening
 - ICPMS
 - Rn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

Veto detectors

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.

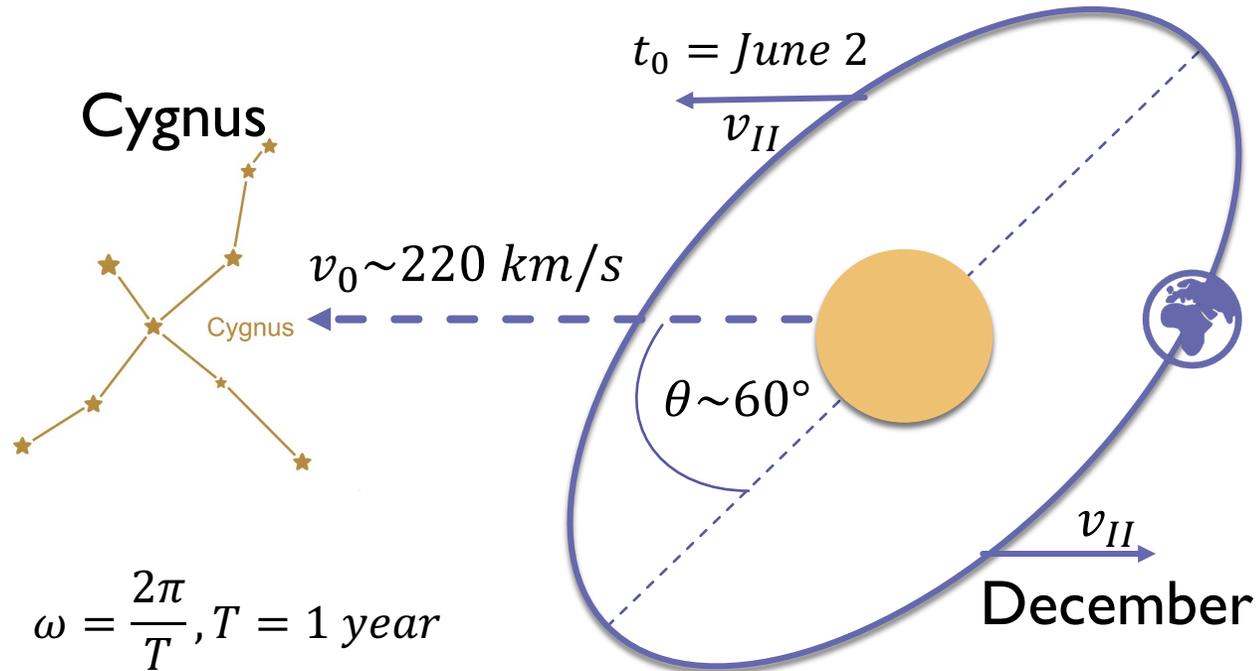
Reduce backgrounds.

Distinguish signal from background topologies.

Annual modulation

Directionality

ER-NR discrimination



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

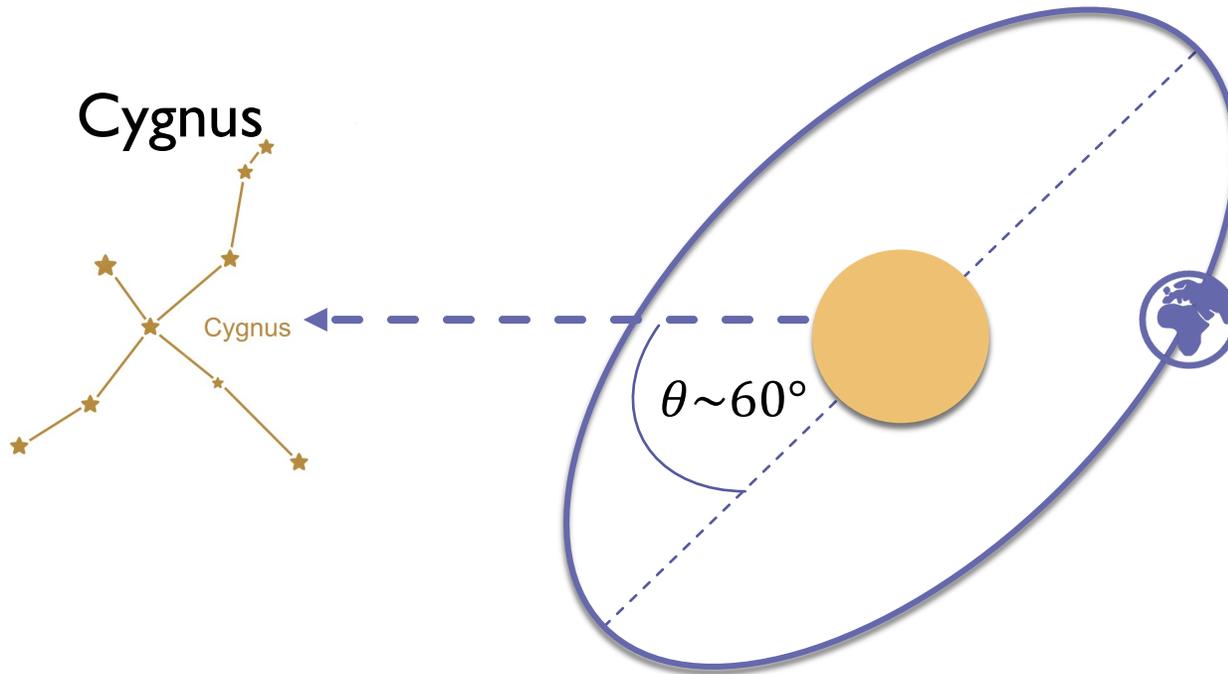
$$S(t) = B(t) + S_0 + \boxed{S_m \cos[\omega(t - t_0)]}$$

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

Annual modulation

Directionality

ER-NR discrimination

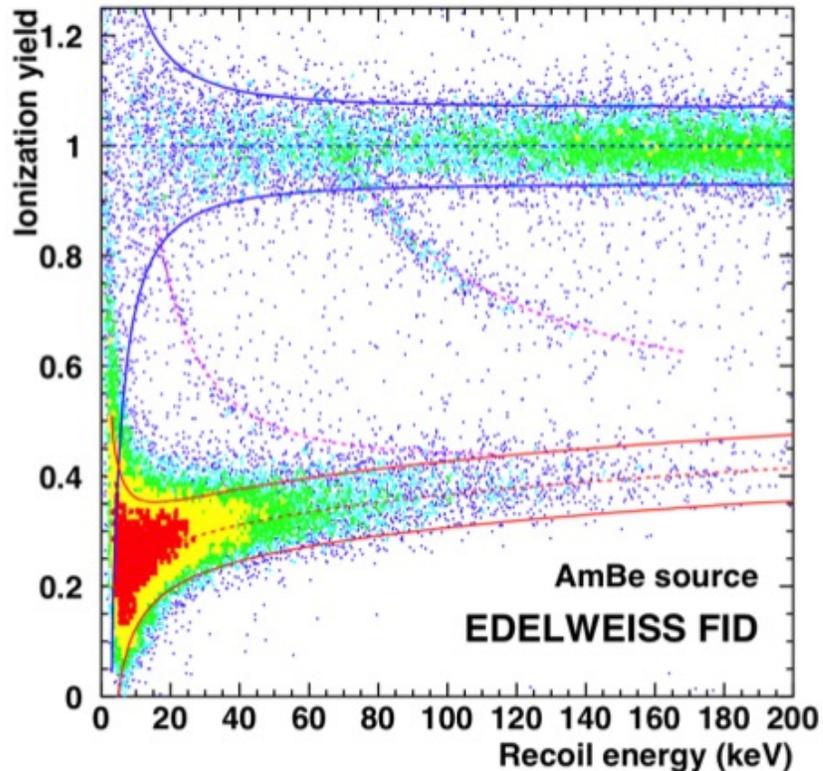


- Dark matter “wind” from the direction of Cygnus
- Measure track direction
- Experimentally challenging:
 - $r < 1\text{mm}$ is very short for keV-scale nuclear recoils

Annual modulation

Directionality

ER-NR discrimination

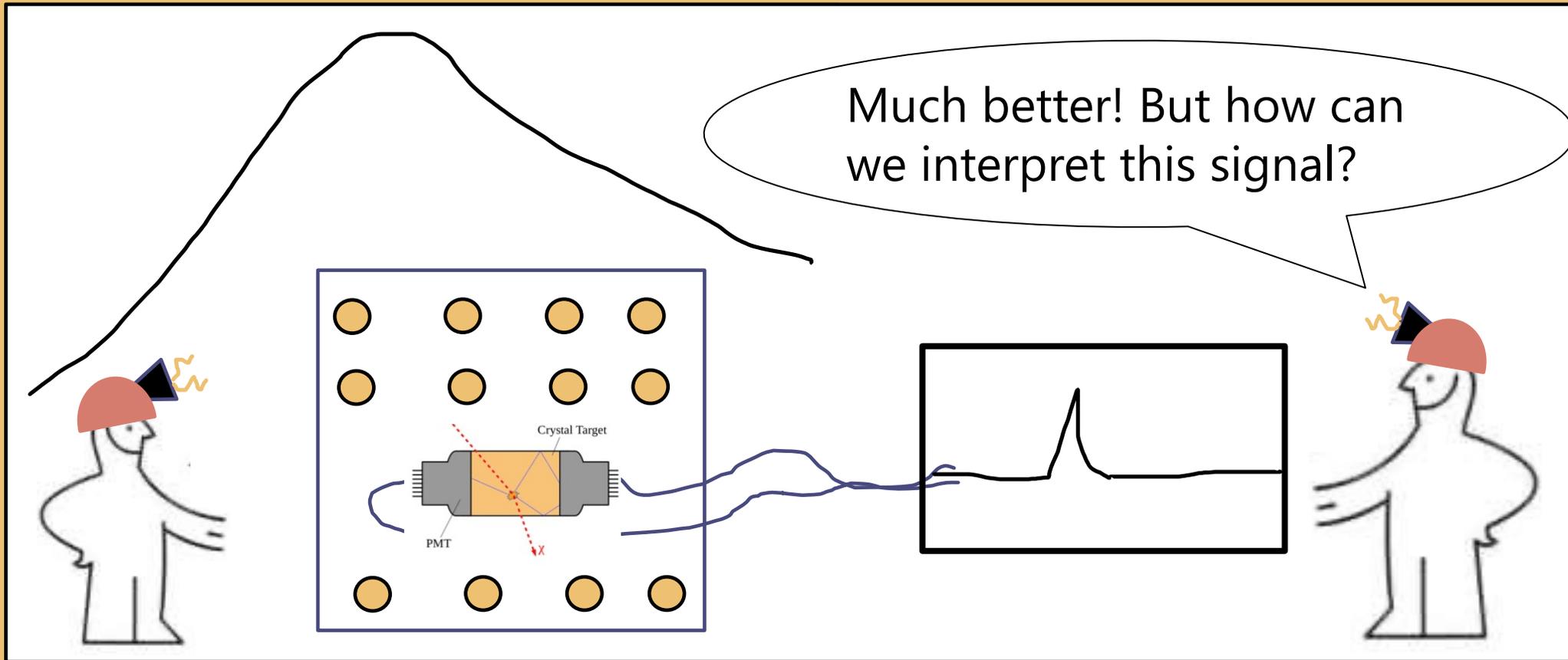


- Difference in interaction between electron recoil and nuclear recoil leads to different ratio in signals
 - Cryogenic bolometers with 2 readout channels are superior here
 - Also possible for LXe/LAr detectors but less efficient
- Pulse-shape discrimination

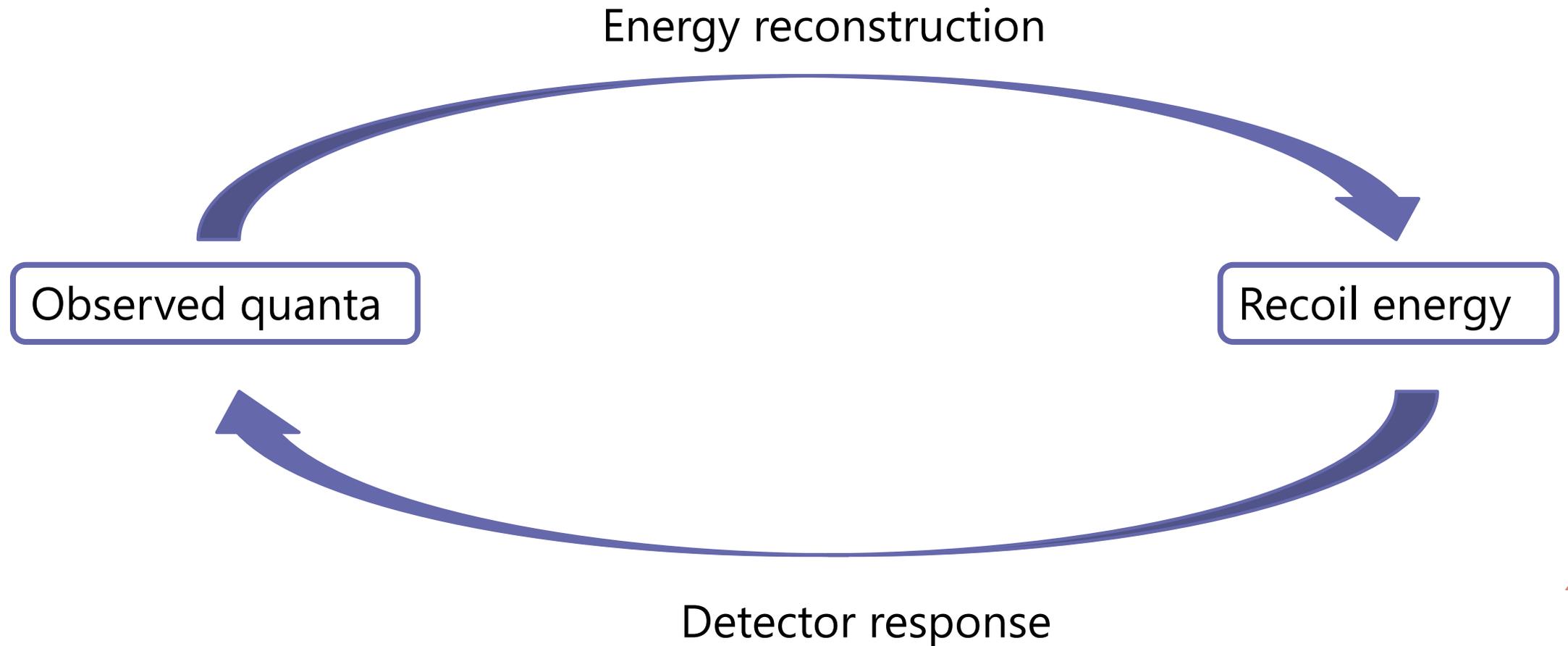
EDELWEISS III

<https://arxiv.org/pdf/1706.01070.pdf>

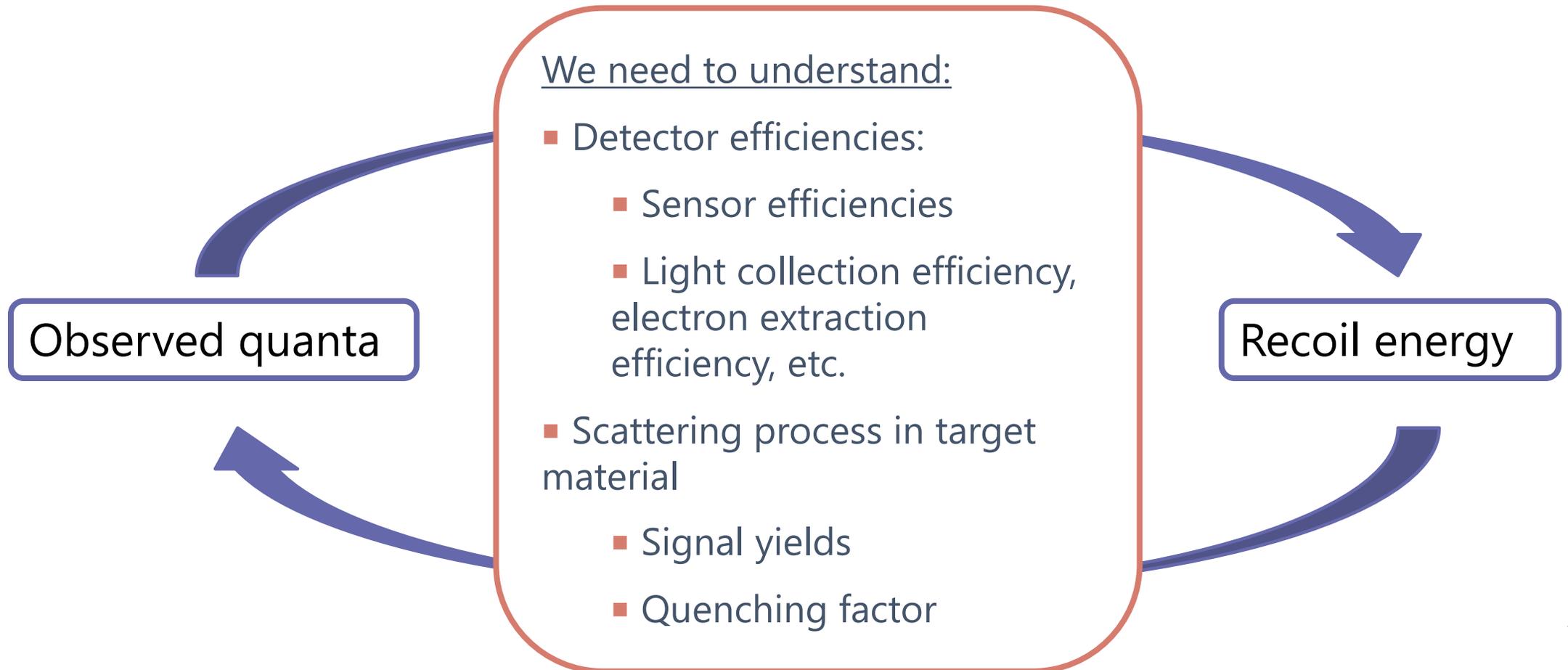
LET'S DESIGN A DETECTOR (4)



ENERGY RECONSTRUCTION



ENERGY RECONSTRUCTION



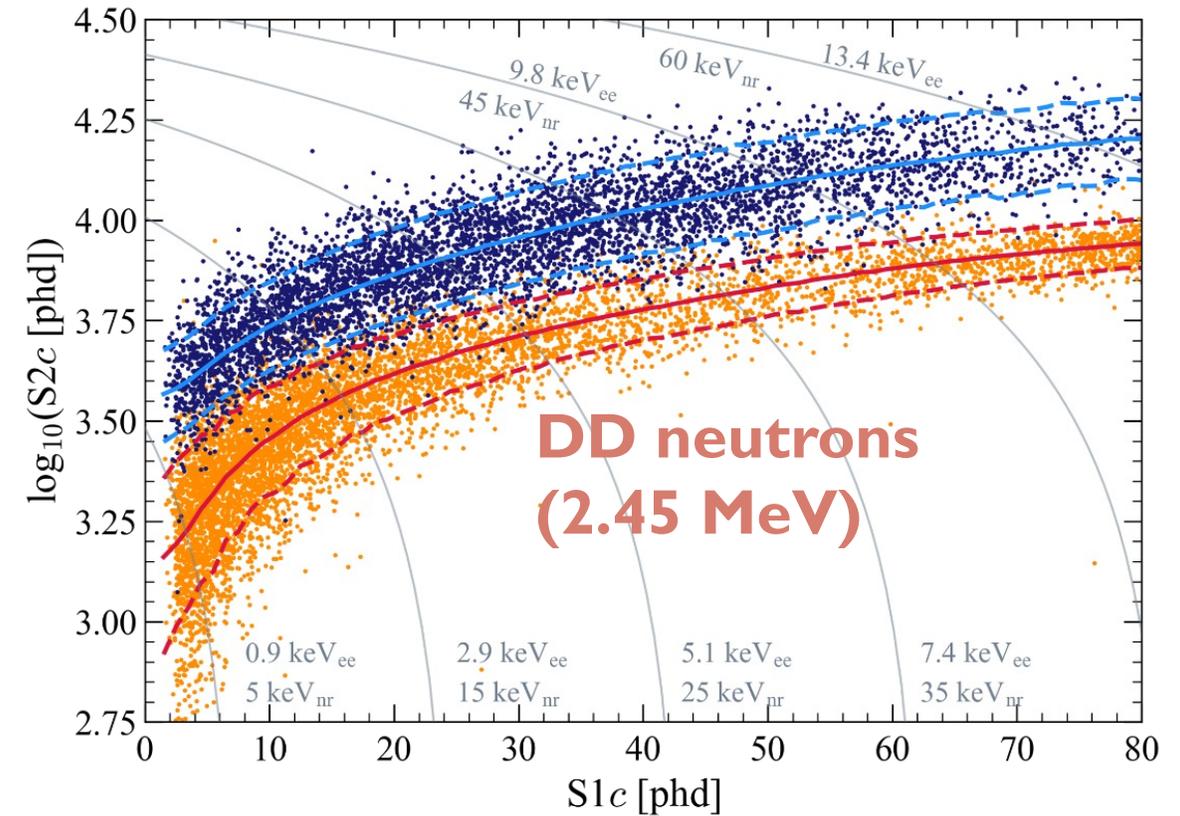
Nuclear recoil

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

LUX-ZEPLIN

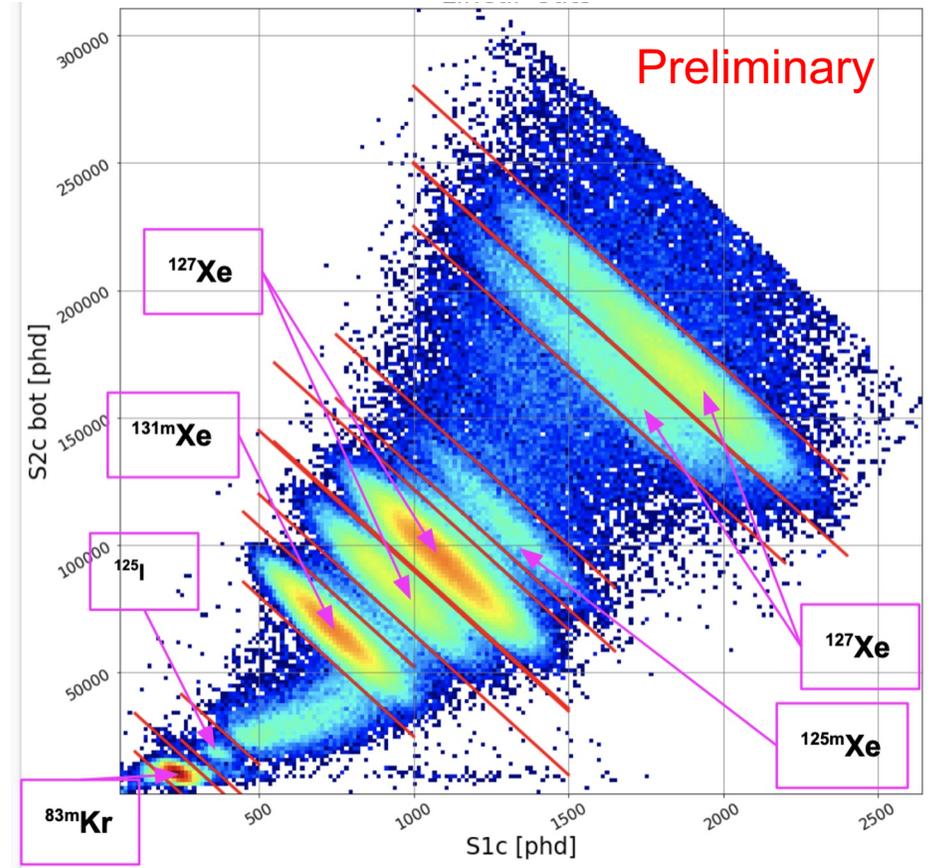


Nuclear recoil

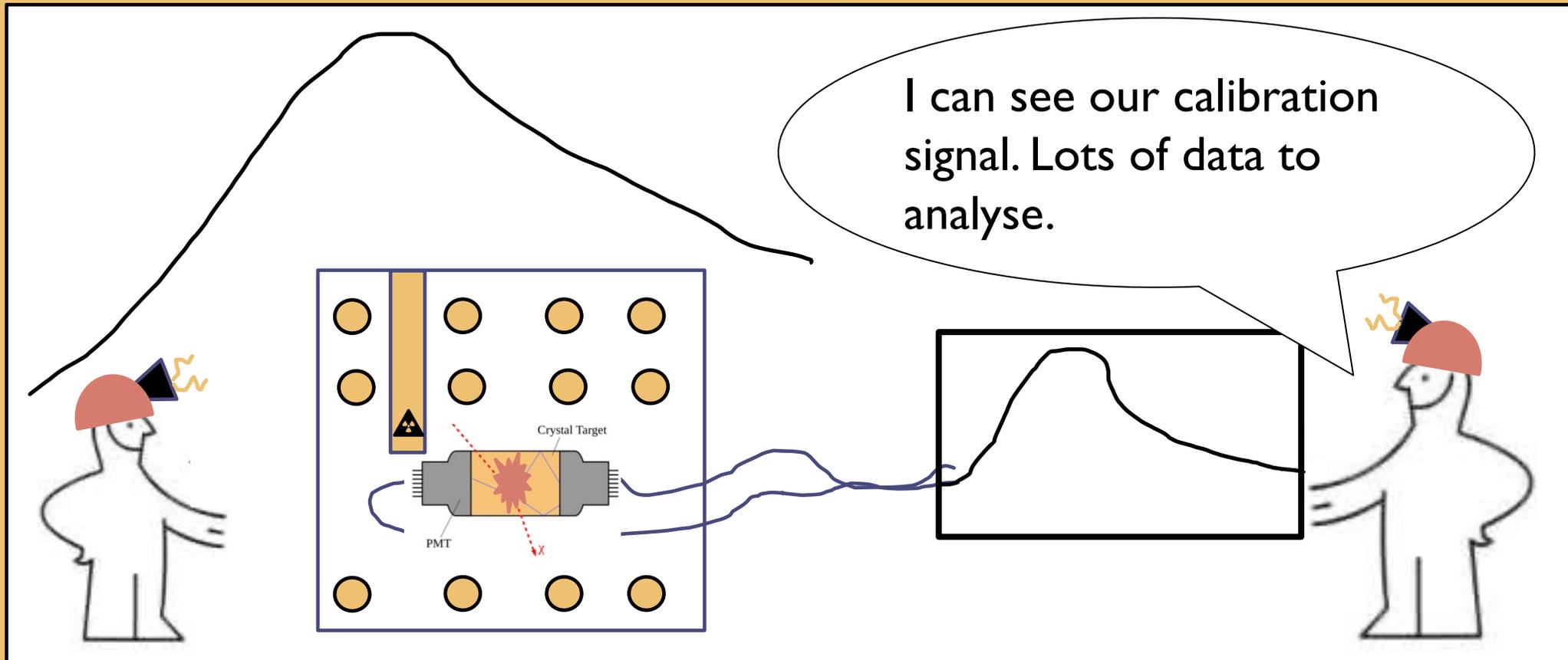
Electron recoil

- 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)

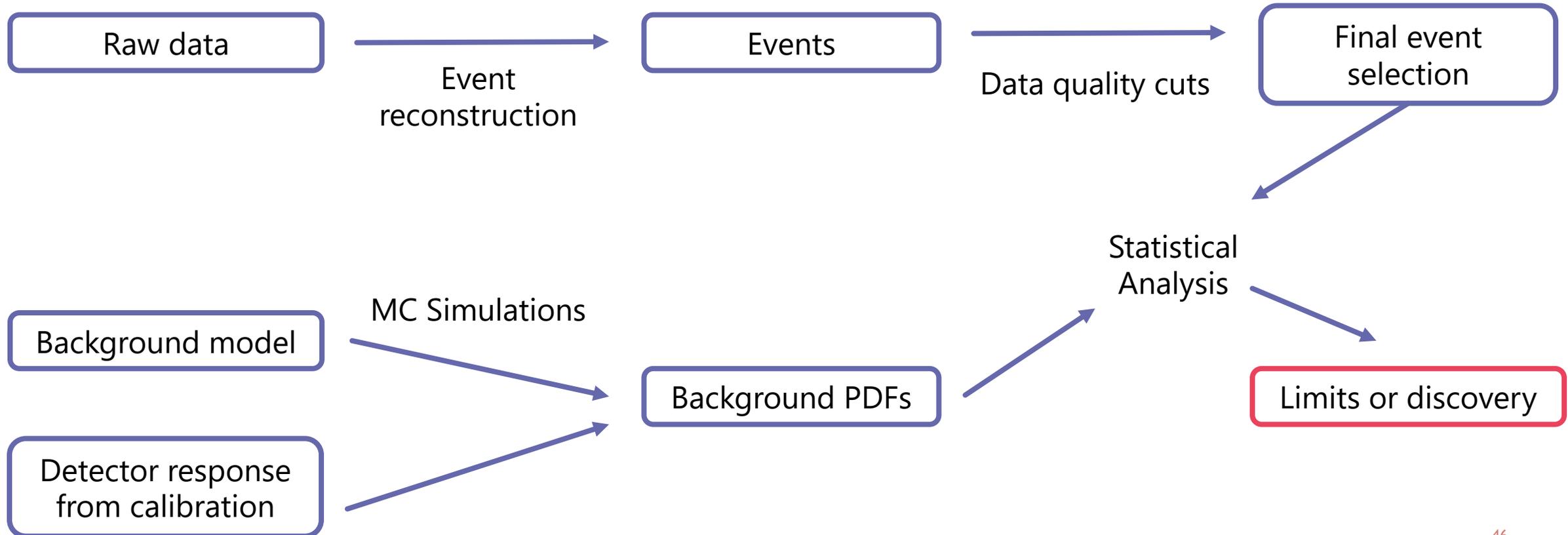
LUX-ZEPLIN



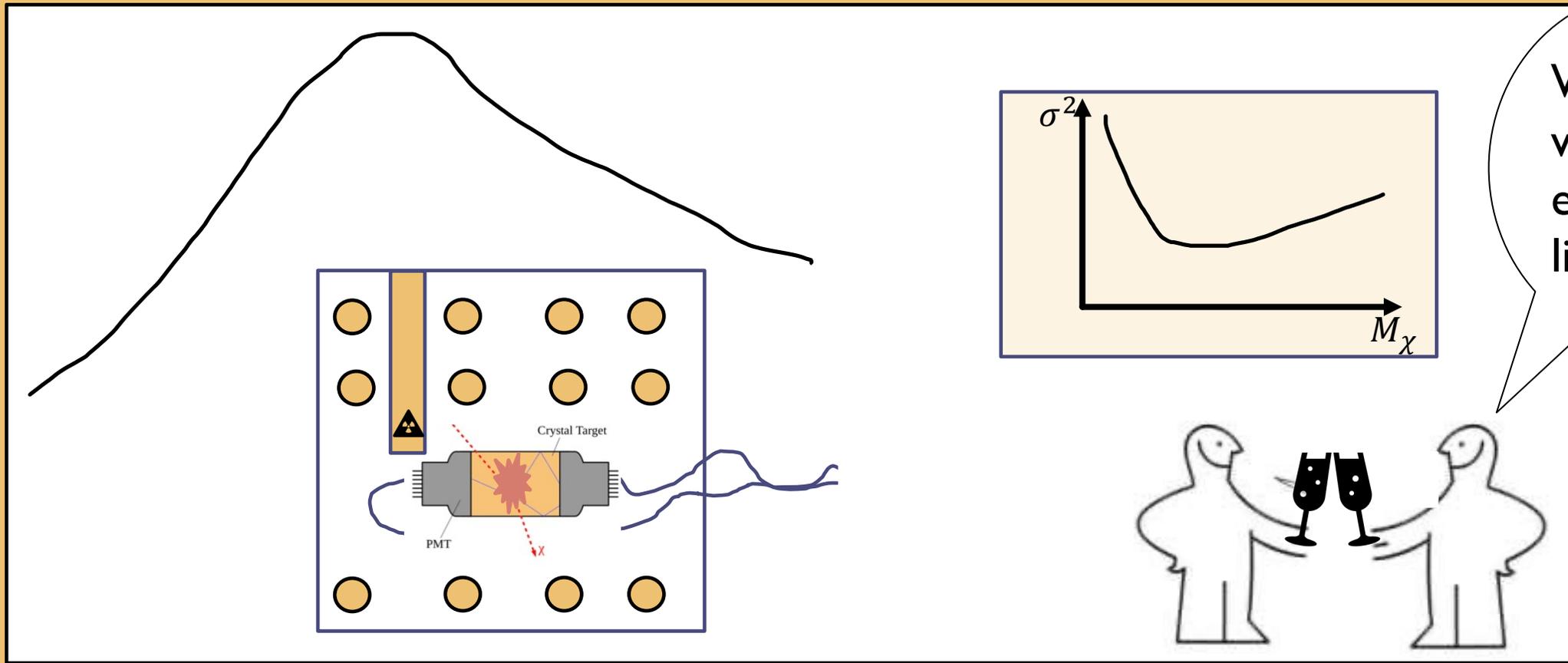
LET'S DESIGN A DETECTOR (5)

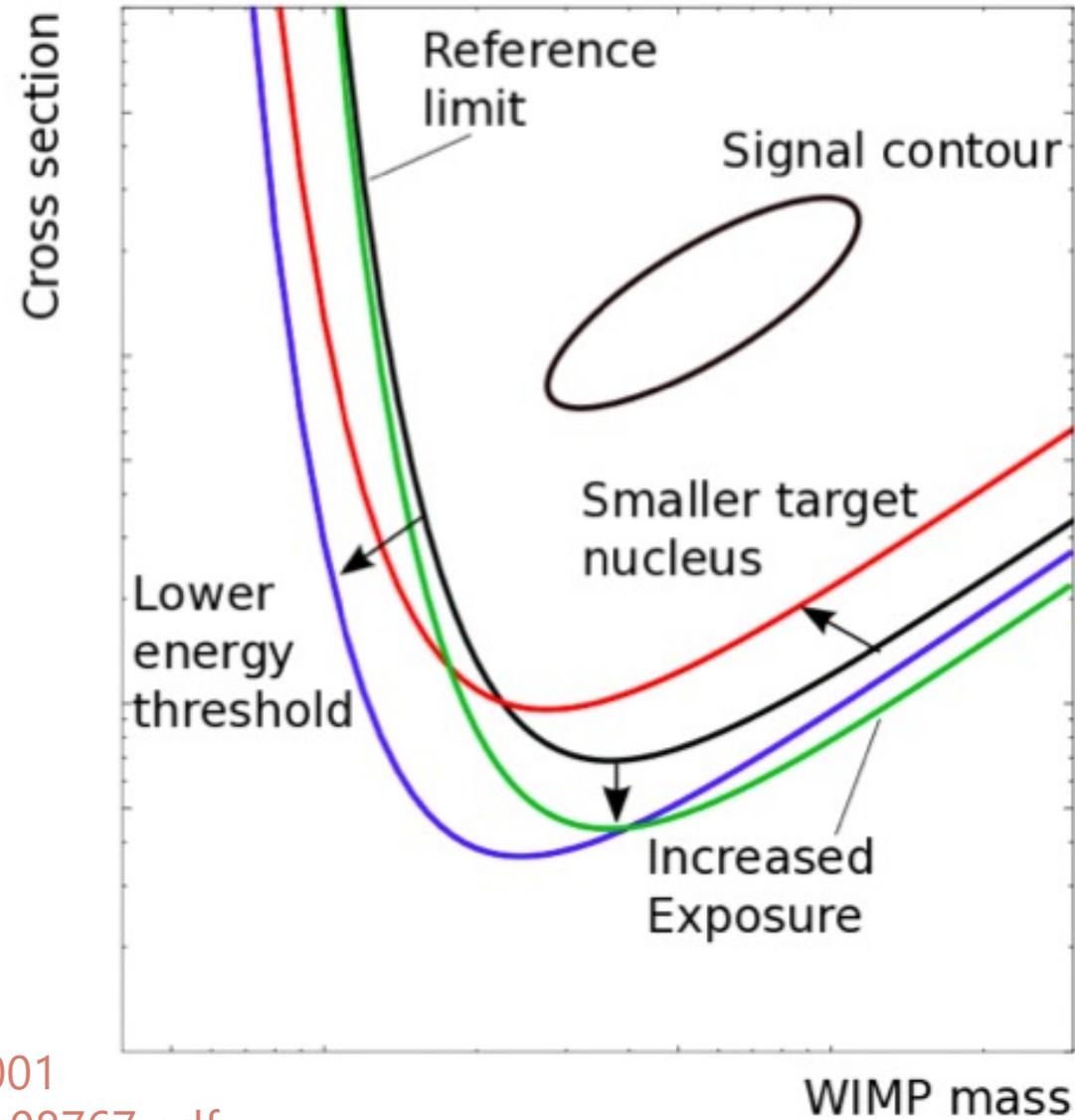


TYPICAL ANALYSIS OVERVIEW

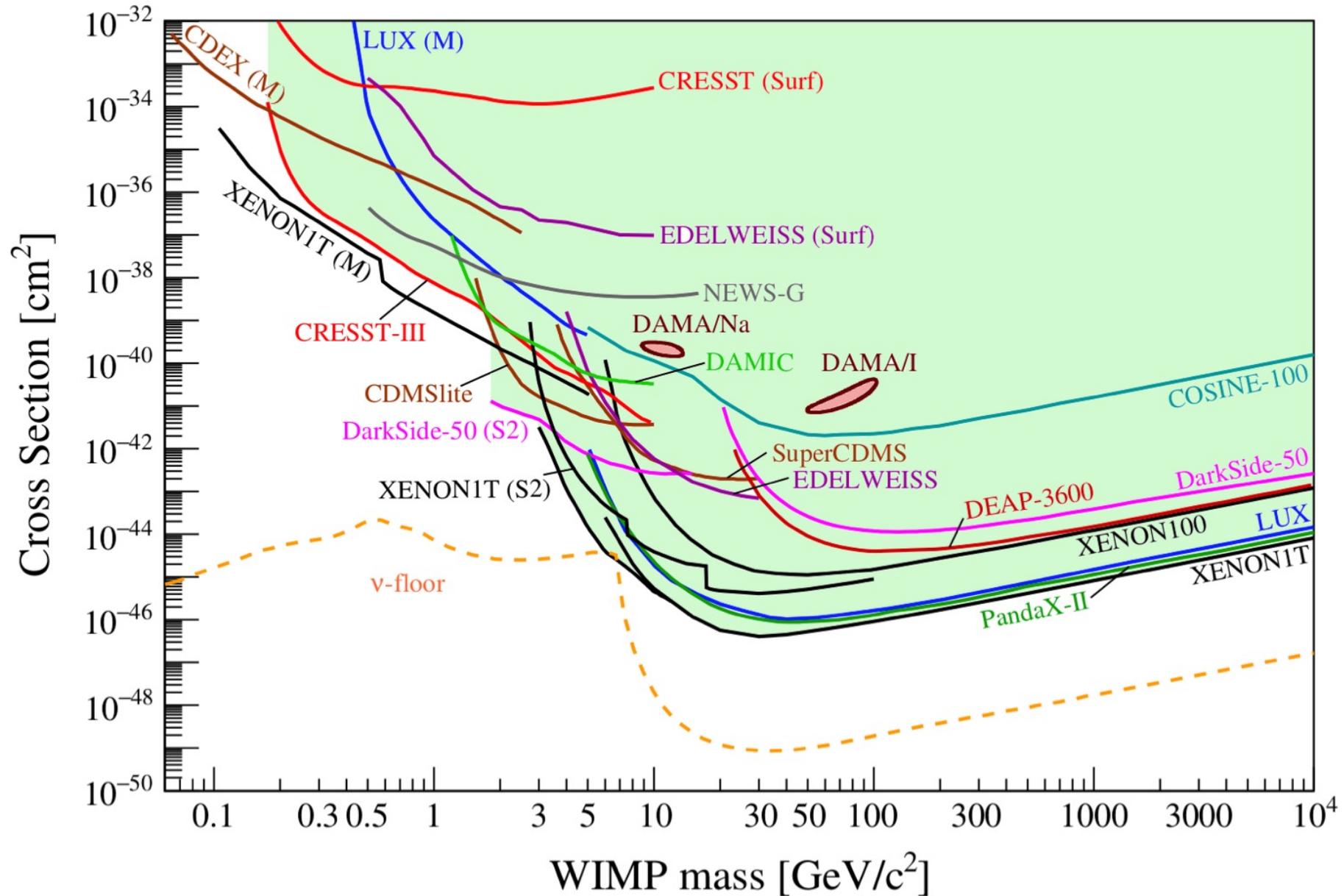


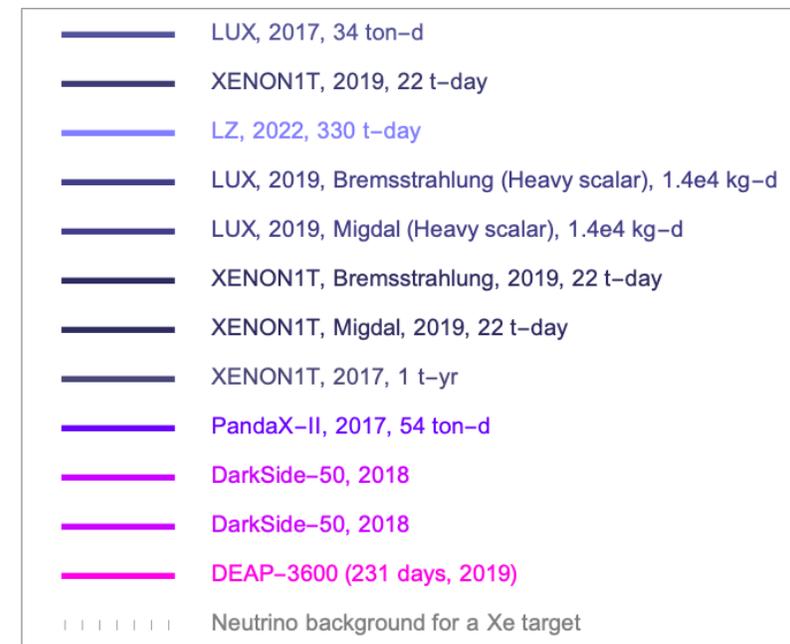
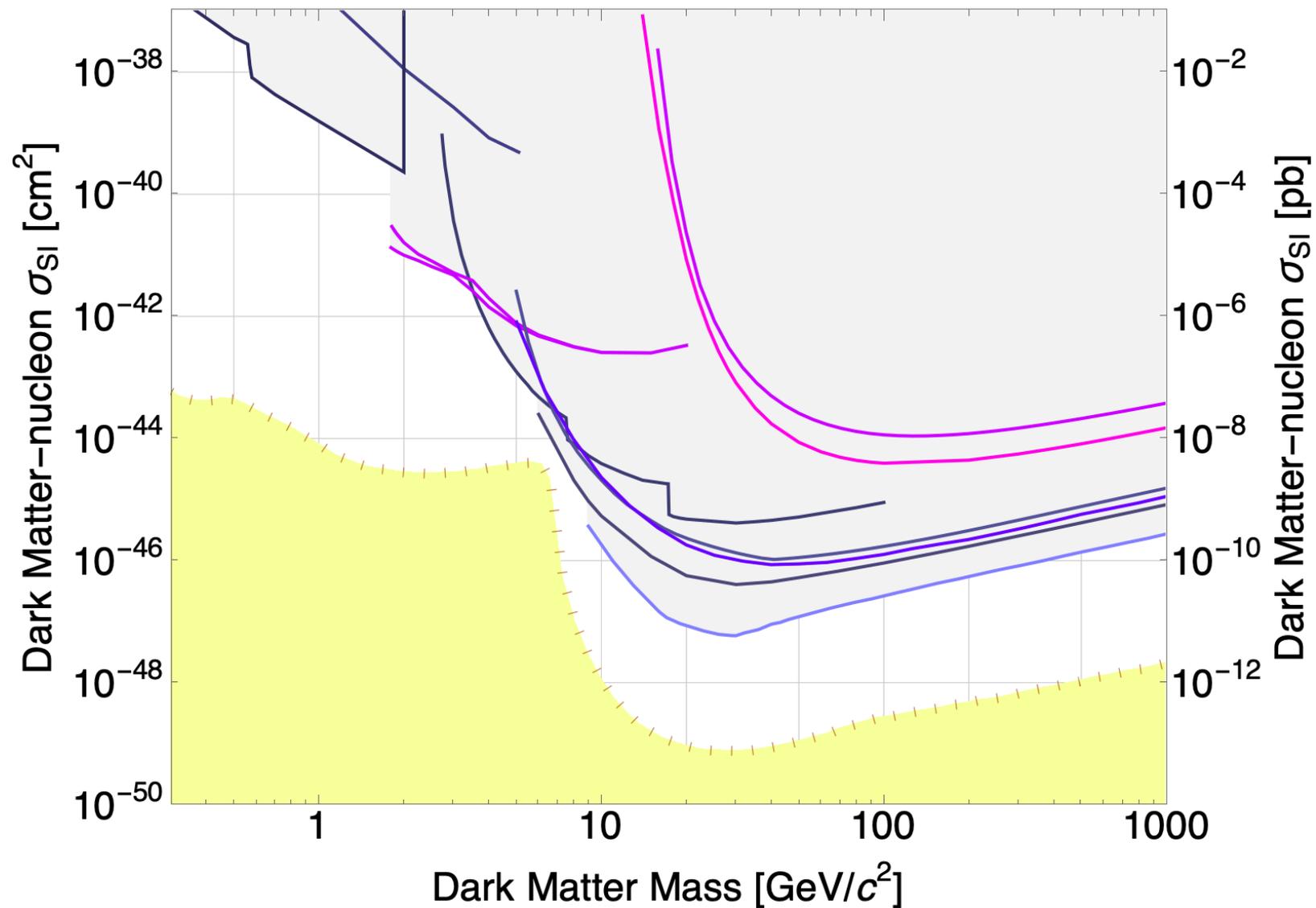
LET'S DESIGN A DETECTOR (6)

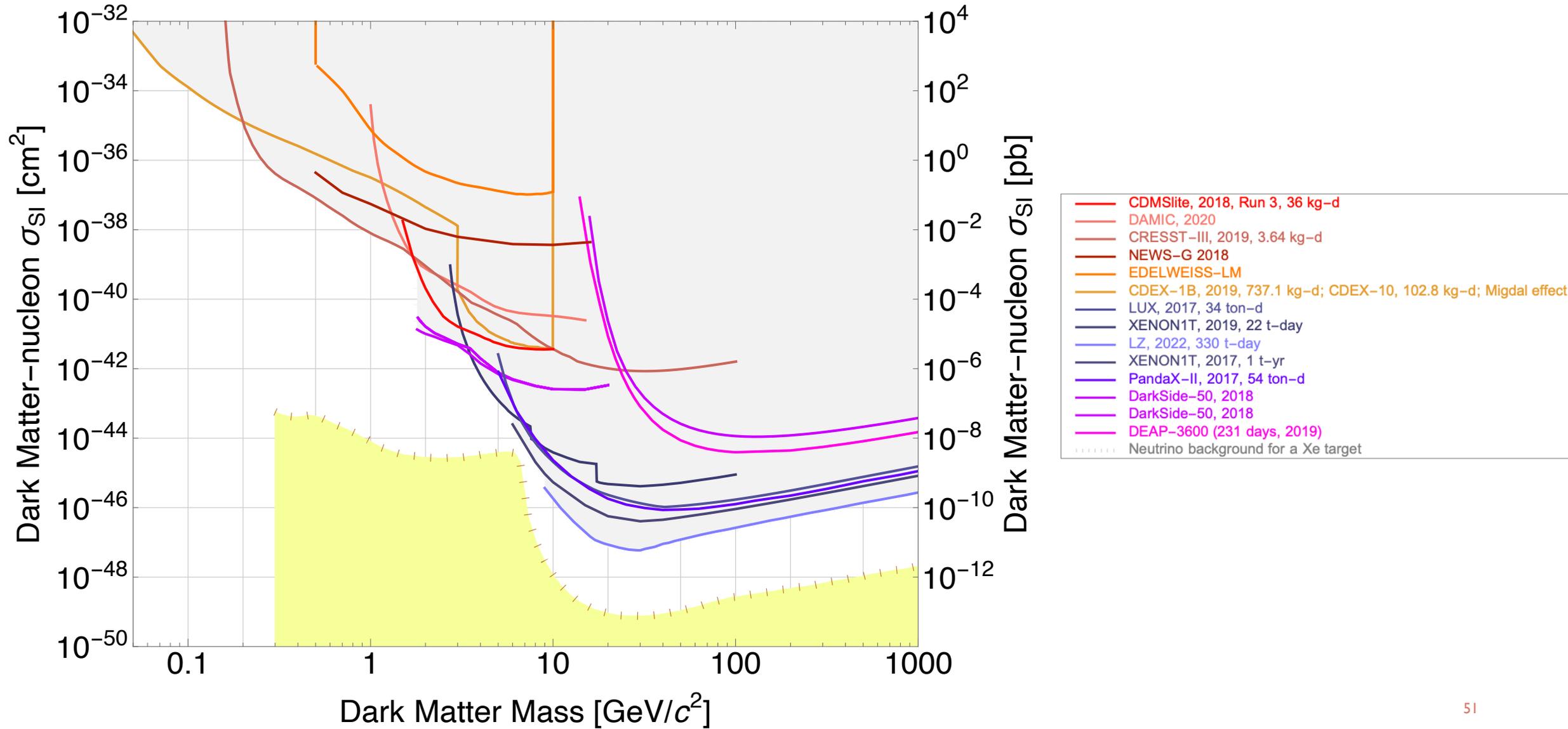


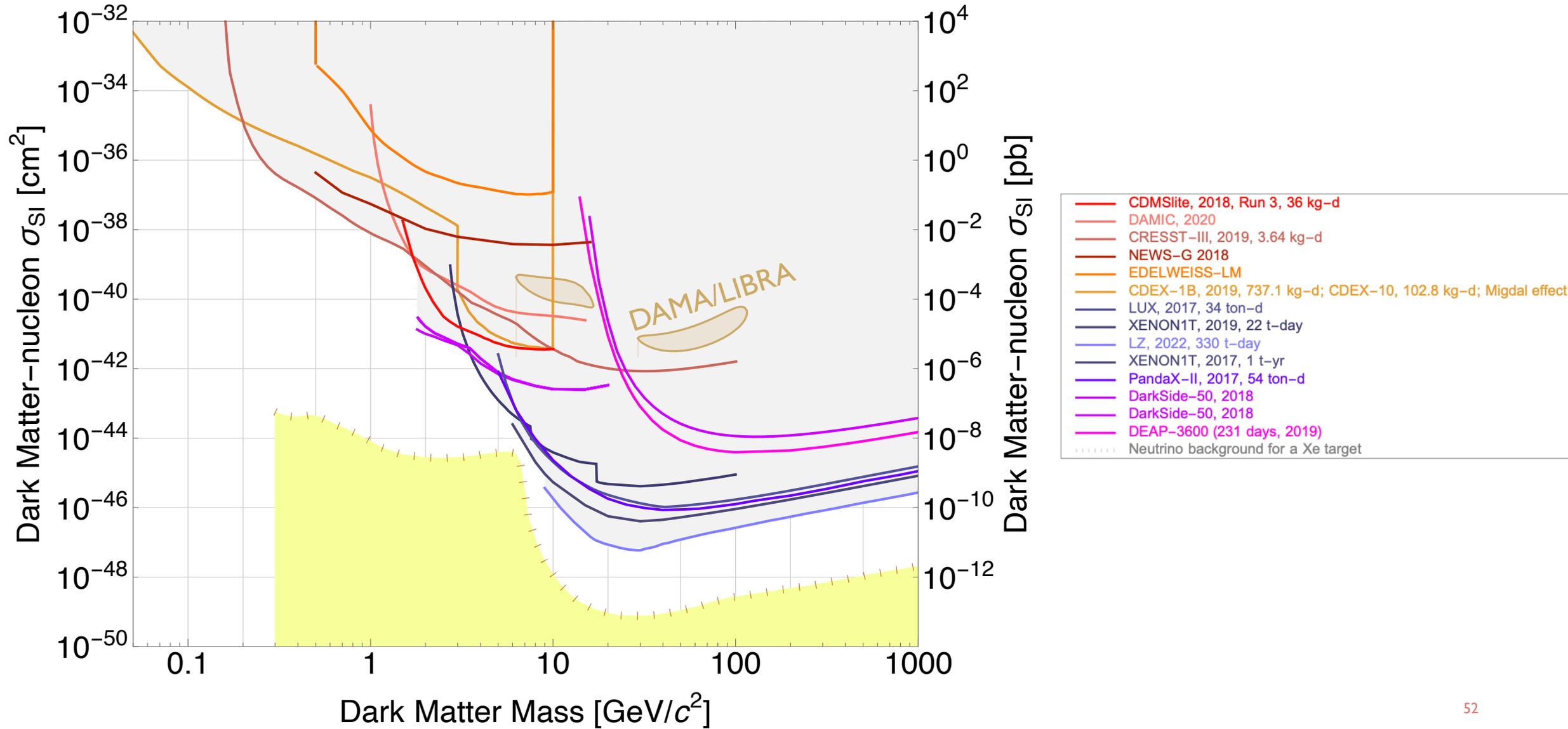


J. Phys. G43 (2016) 1, 013001
<https://arxiv.org/pdf/1509.08767.pdf>

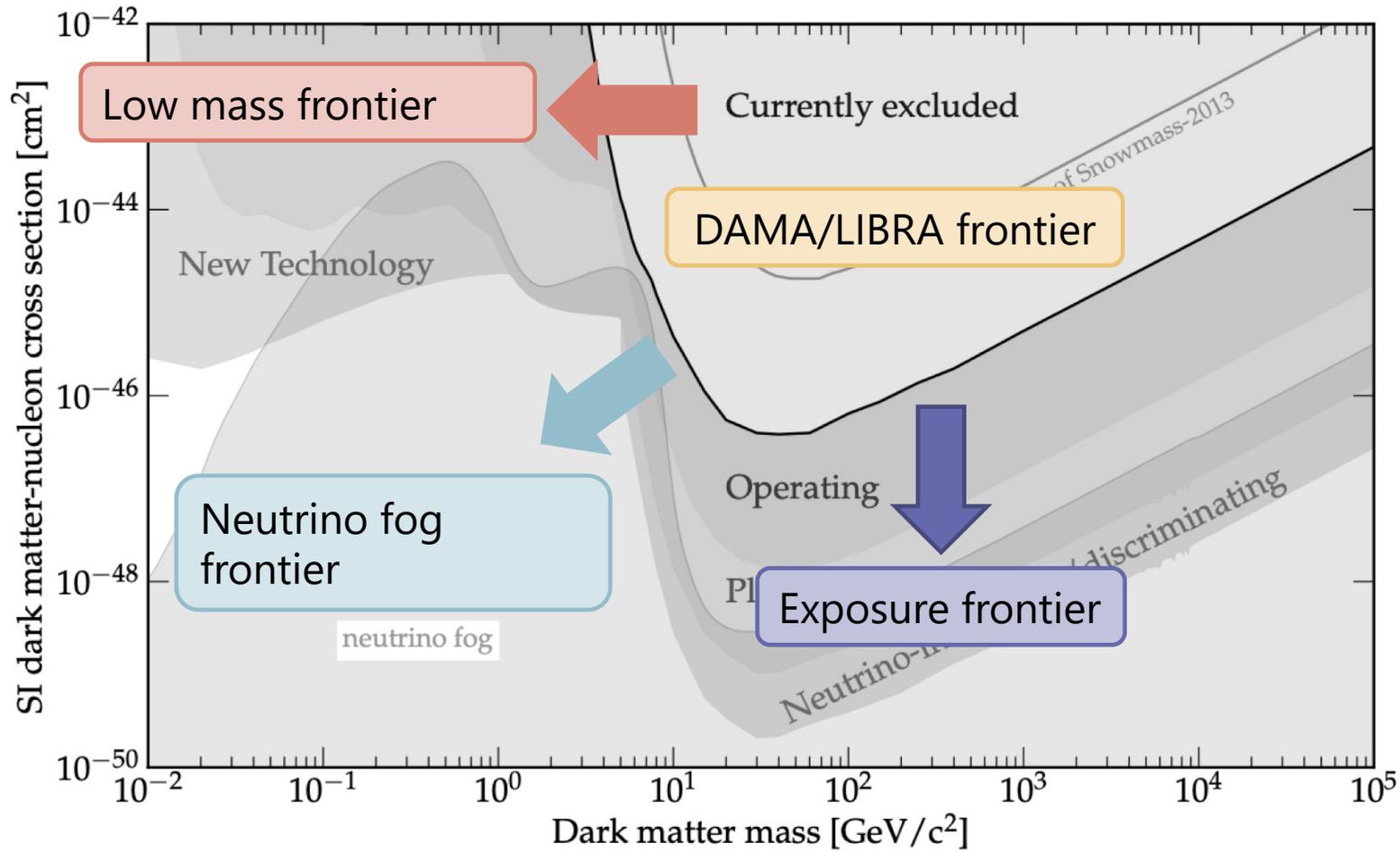








DIRECT DETECTION FRONTIERS



Exposure frontier

Low mass frontier

Neutrino fog frontier

Nal frontier

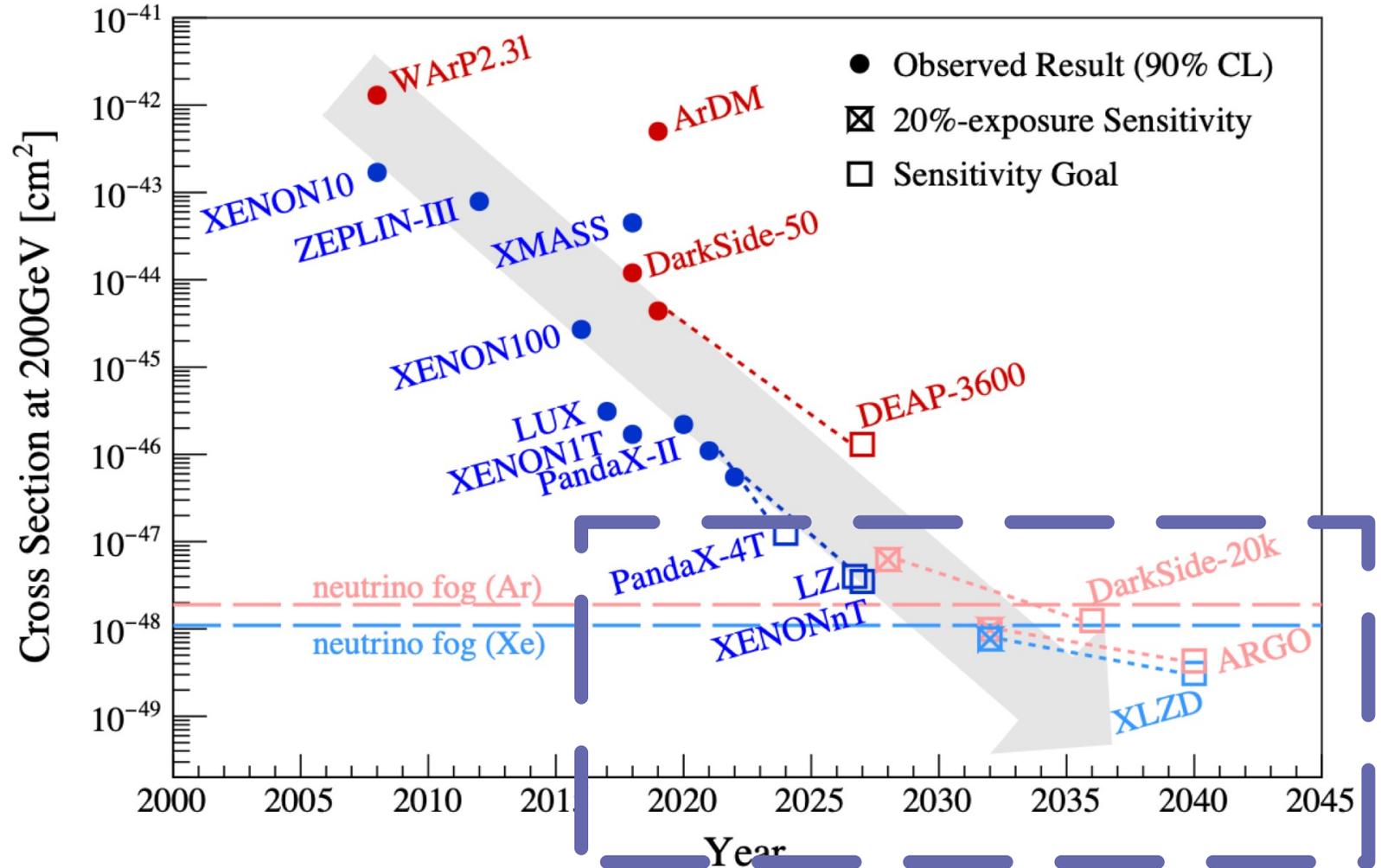
LXe and LAr detectors:

Advantage:

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

Challenges:

- High voltages
- Rn!
- Accidental coincidences



Exposure frontier

Low mass frontier

Neutrino fog frontier

Nal frontier

LXe 2-phase TPCs

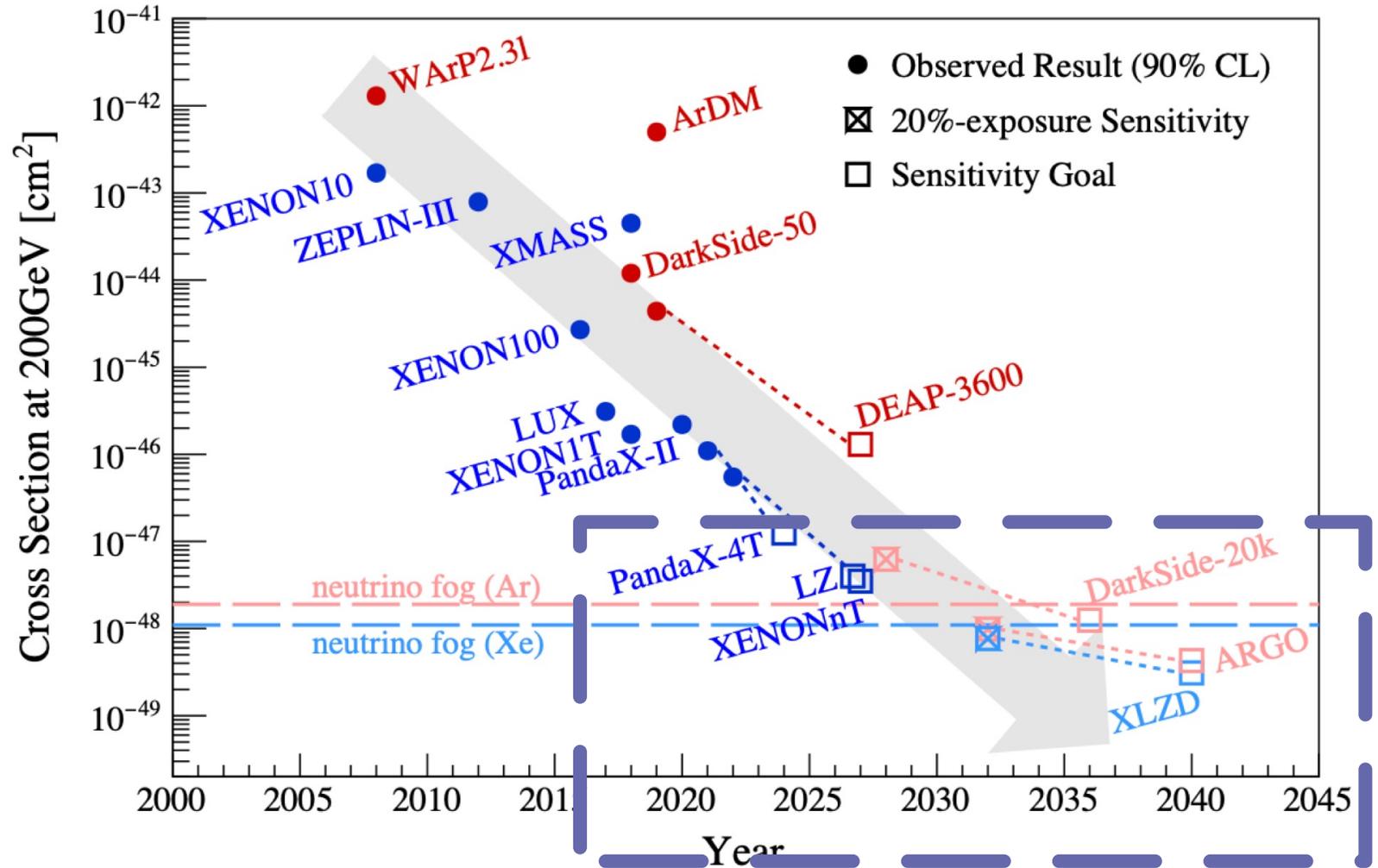
<u>PandaX-4T</u>	4.0 t	running
<u>XENONnT</u>	5.9 t	running
<u>LZ</u>	7.0 t	running
<u>DARWIN</u>	40 t	planning

LAr single-phase

<u>DEAP-3600</u>	3.6 t.	running
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LAr 2-phase TPC

<u>DarkSide-50</u>	46.4 kg	running
<u>DarkSide-20k</u>	40 t.	construction
<u>ARGO</u>	400 t.	proposed



Exposure frontier

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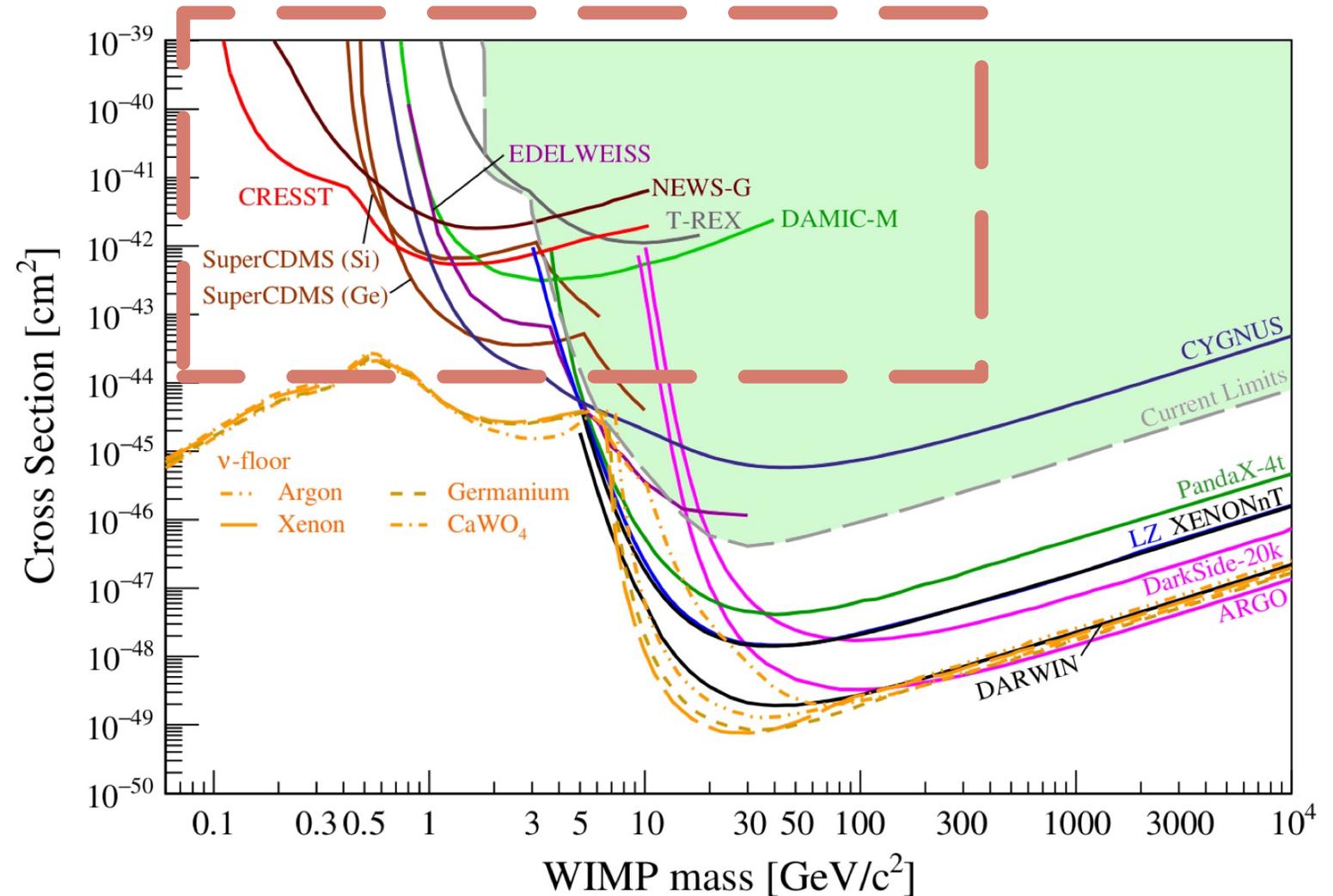
Cryogenic bolometers:

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



Exposure frontier

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Nal frontier

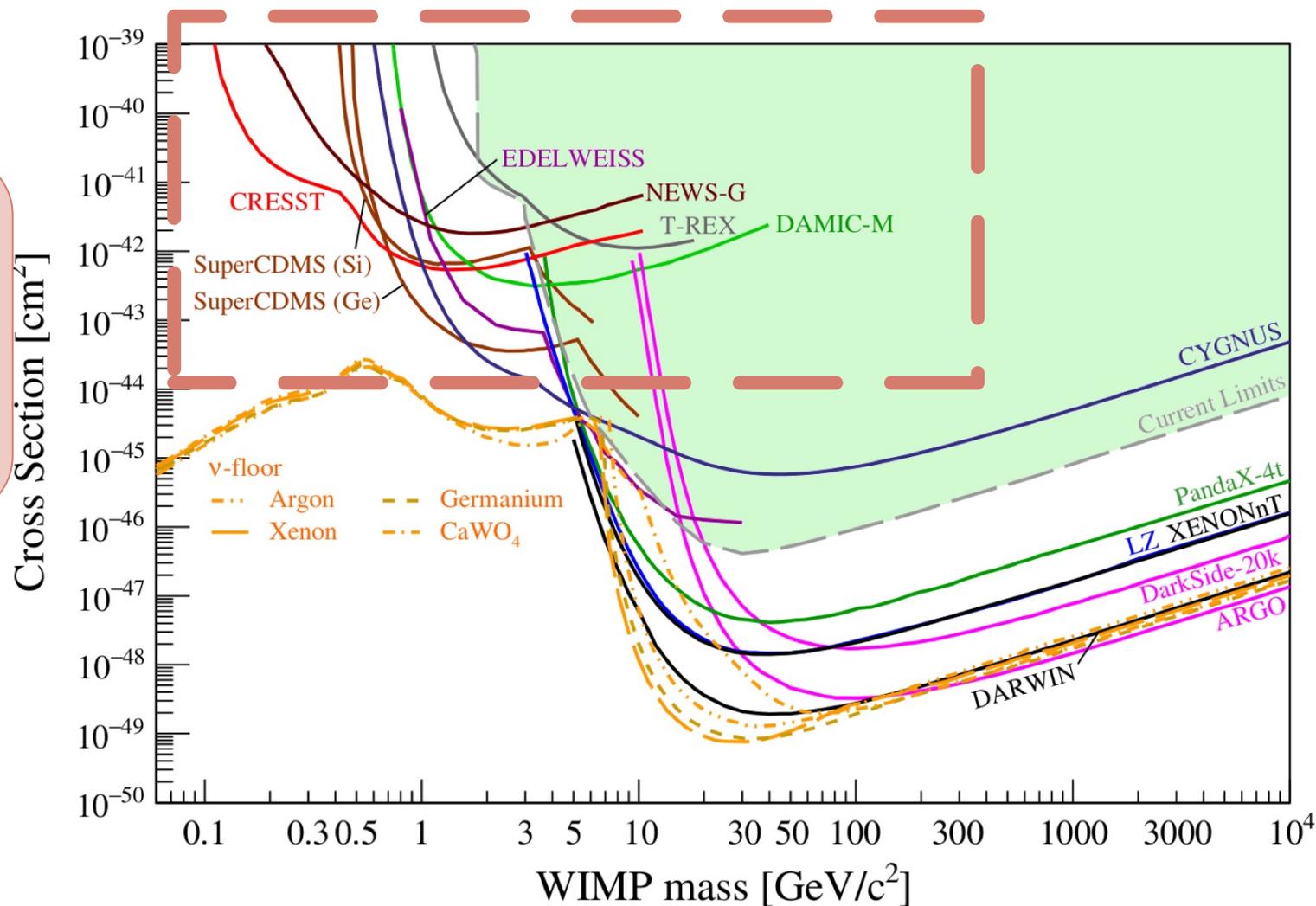
Cryogenic bolometers

Charge readout

EDELWEISS-subGeV 20 kg in prep
SuperCDMS 24 kg construction

Scintillation readout

CRESST-III 2.5 kg running



Exposure frontier

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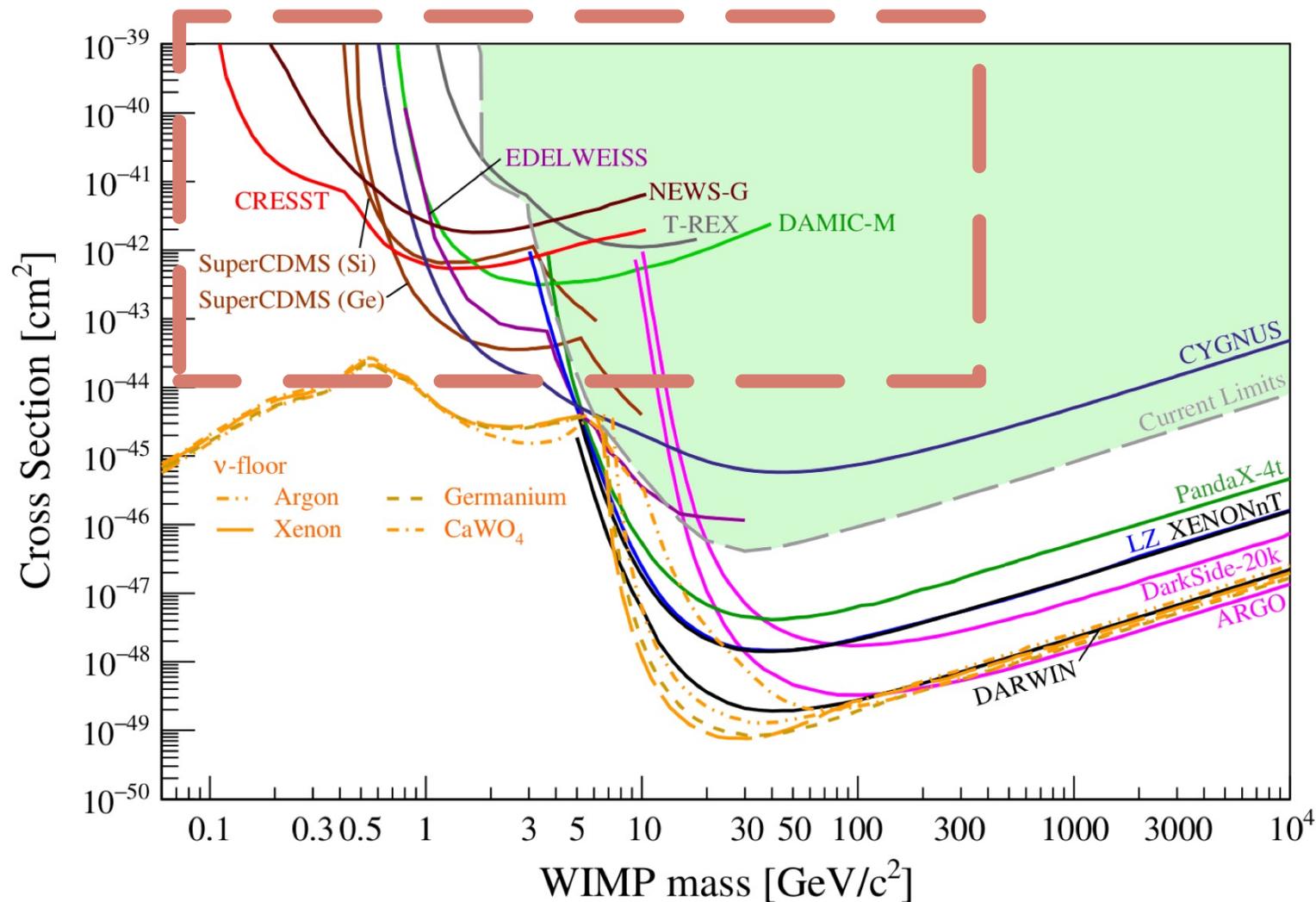
Ionization detectors:

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



Exposure frontier

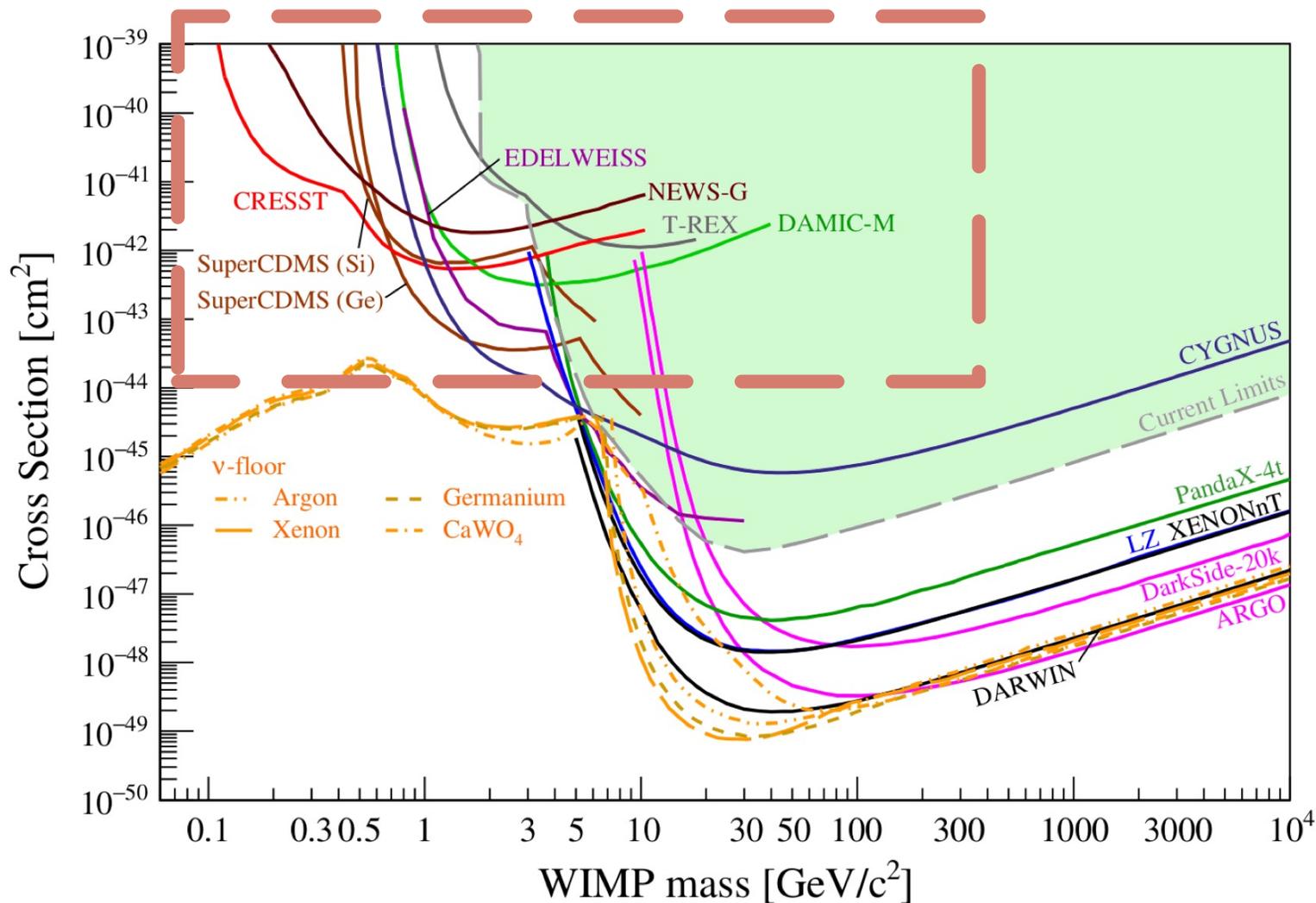
Low mass frontier

Neutrino fog frontier

Nal frontier

Ionisation detectors

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



Exposure frontier

Low mass frontier

Neutrino fog frontier

NaI frontier

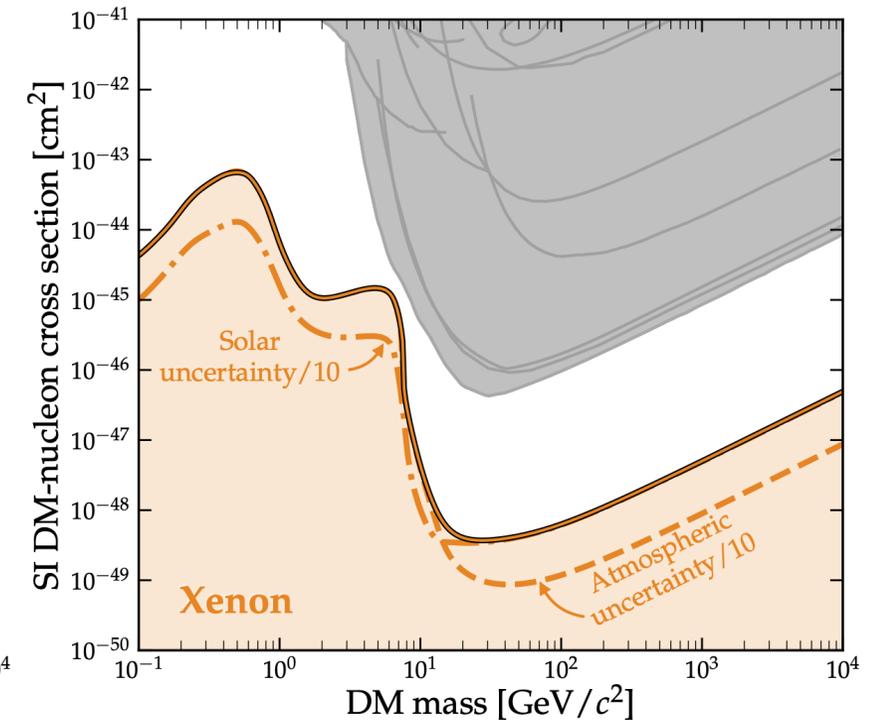
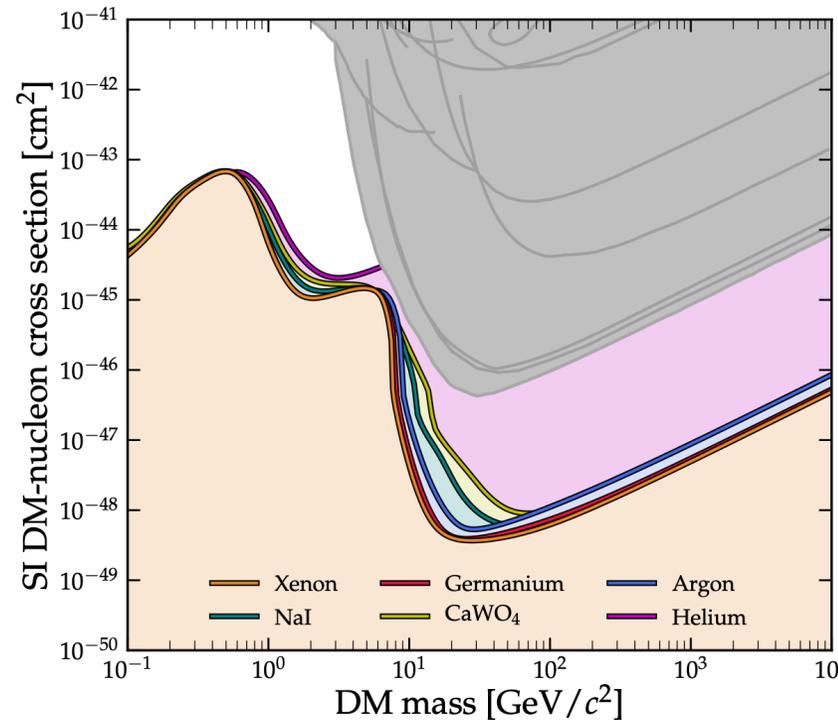
Directional detectors:

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

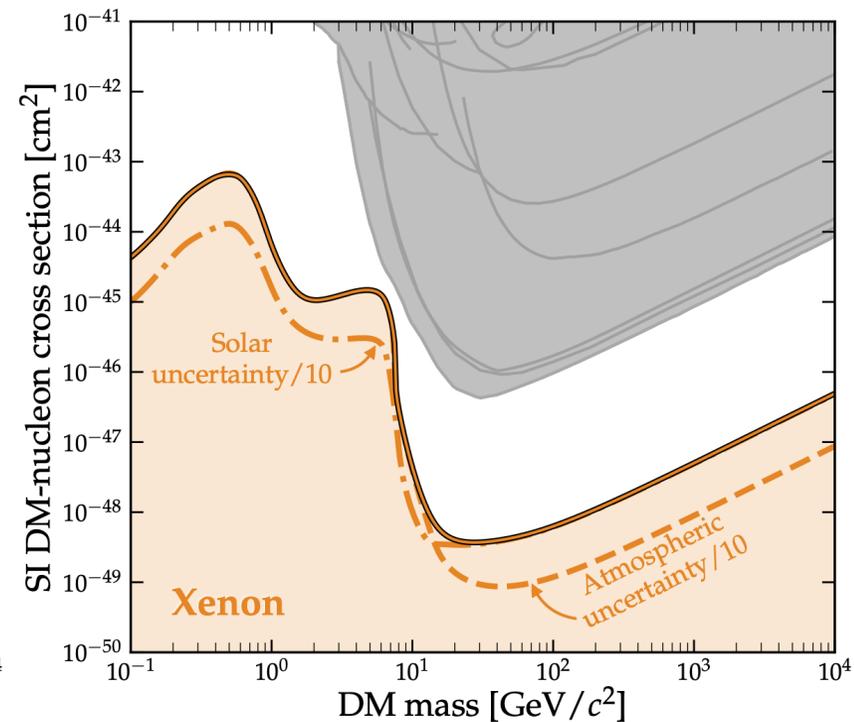
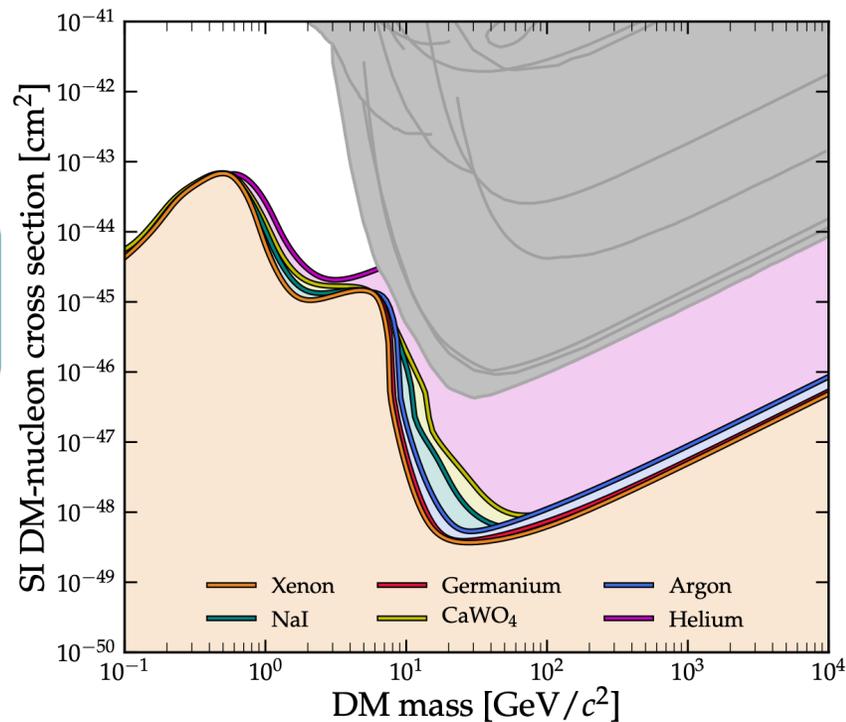
Neutrino fog frontier

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

Nal frontier

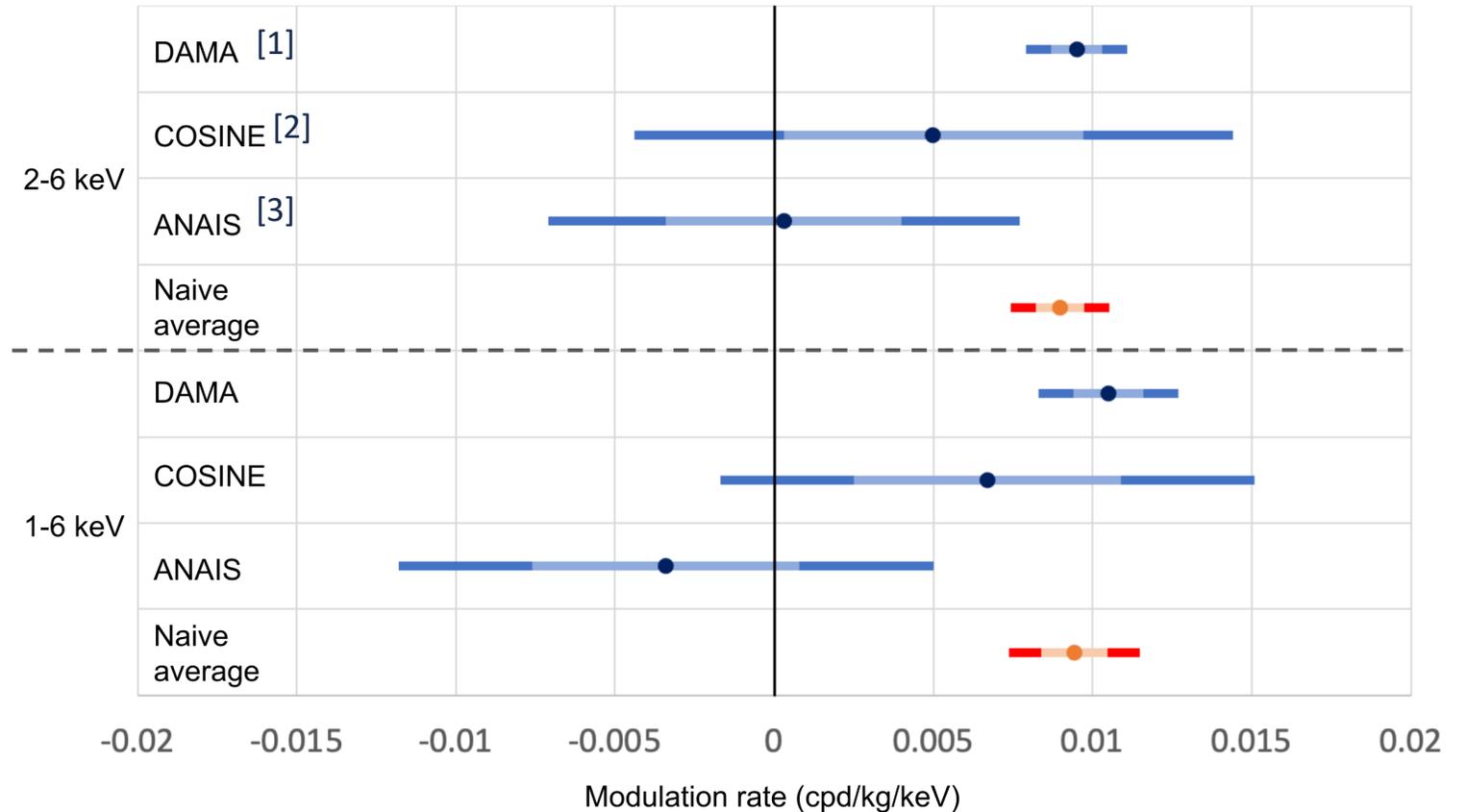
Nal scintillation detectors:

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>

M. J. Zurowski IDM2022

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

[2] Adhikari et al. arxiv:2111.08863

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

Exposure frontier

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Nal frontier

Nal scintillators

DAMA/LIBRA 250 kg running

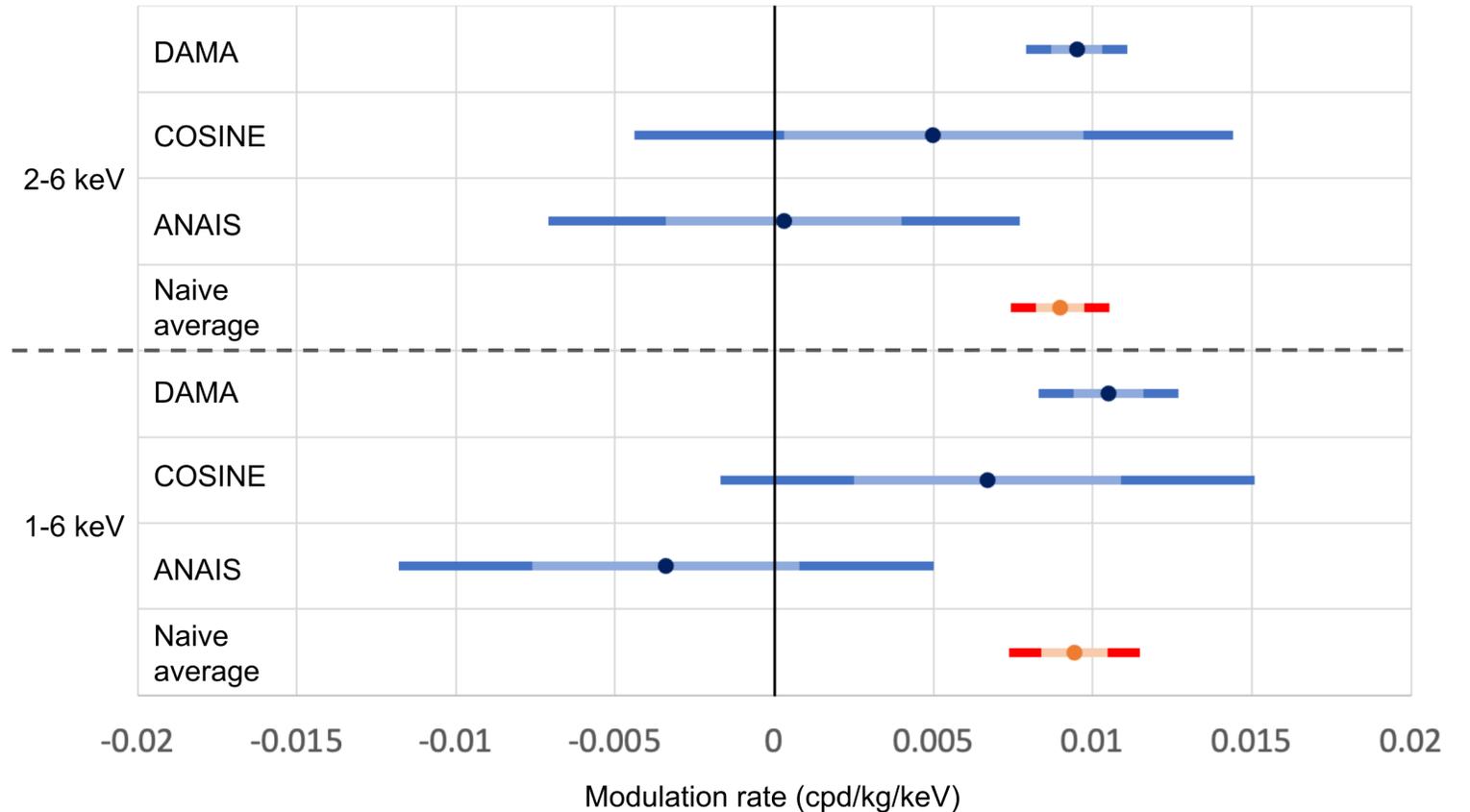
COSINE 106 kg running

ANAIS 112 kg running

SABRE 50 kg in prep

Nal bolometer

COSINUS 1 kg in prep



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

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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

