Dark matter direct detection: status, results and future plans

Shingo Kazama (Nagoya, KMI)

May 12th 2022, @Physics in LHC and Beyond

Dark Matter Candidates

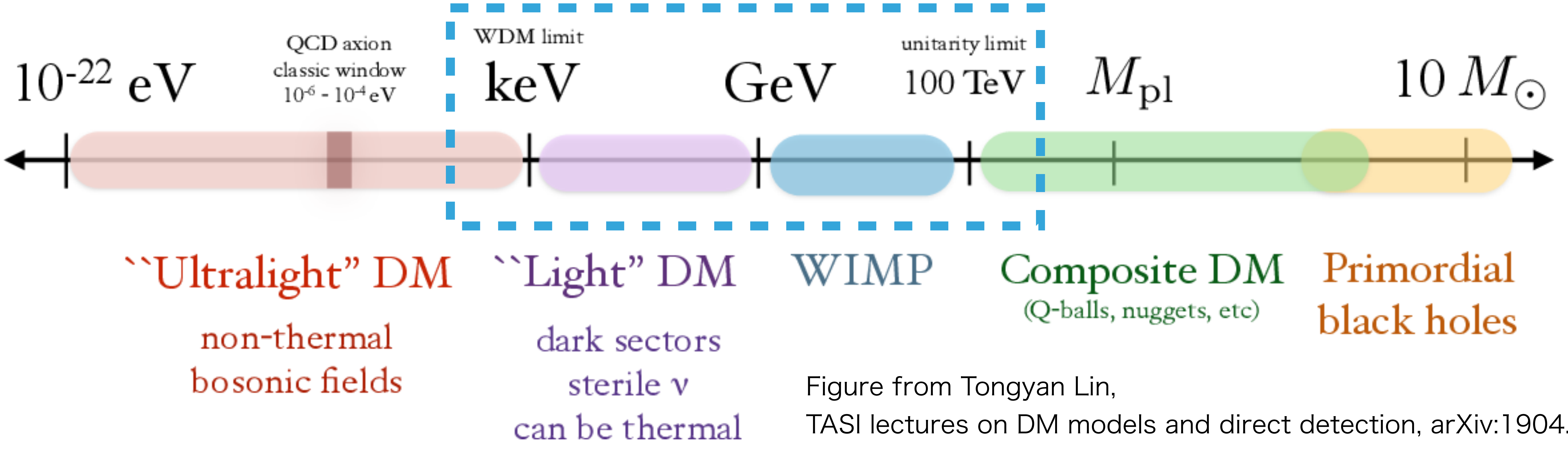
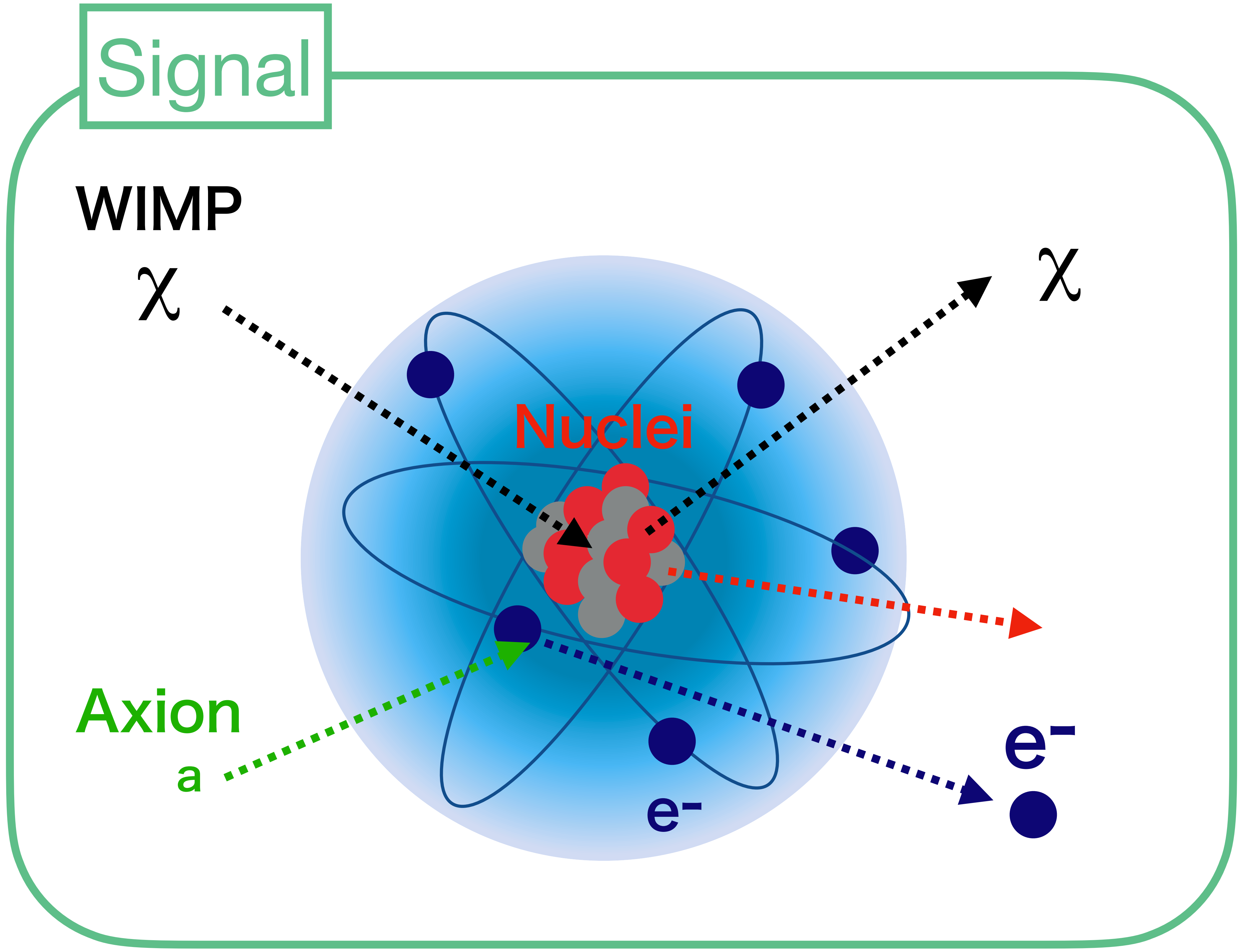


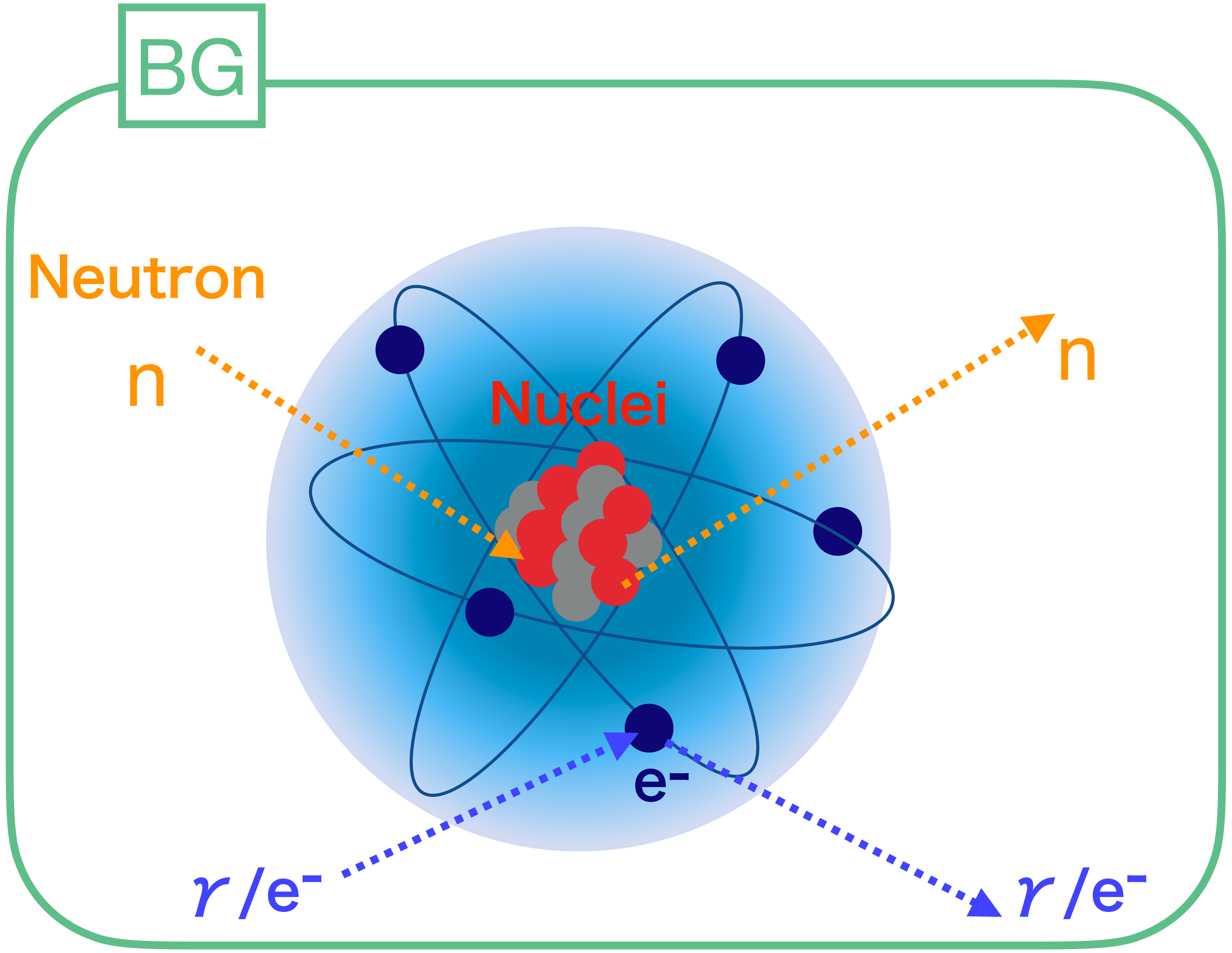
Figure from Tongyan Lin,
TASI lectures on DM models and direct detection, arXiv:1904.07915

- 10^{-55} g and 10^{40} g: 100 orders of magnitude in mass…
- Promising candidate is thermal dark matter with weak charge (weak-charged WIMP)
- Direct detection experiments usually cover in a mass range between GeV and ~TeV

Direct Dark Matter Detection

- Observe DM collision with nuclei (NR) or with electrons in the atomic shells (ER)
  - Momentum transfer: O(10) MeV
  - Recoil energy:O(1-10) keV
- Look for absorption of light bosons via e.g. the axio-electric effect





Direct Dark Matter Detection: Event Rate

- Observable: a differential recoil spectrum

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Detector physics

N_N, E_{th}

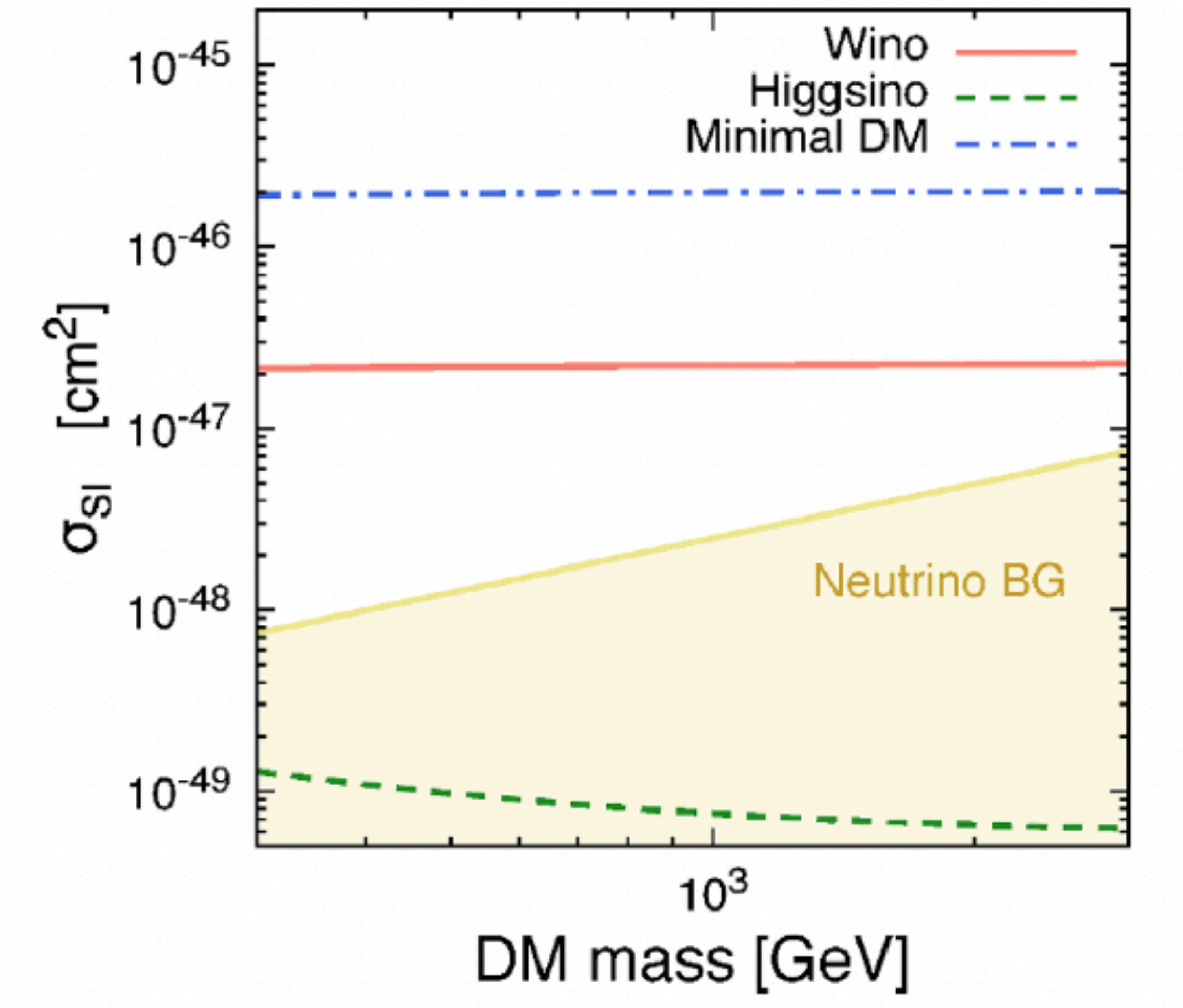
Particle/nuclear physics

$m_W, d\sigma/dE_R$

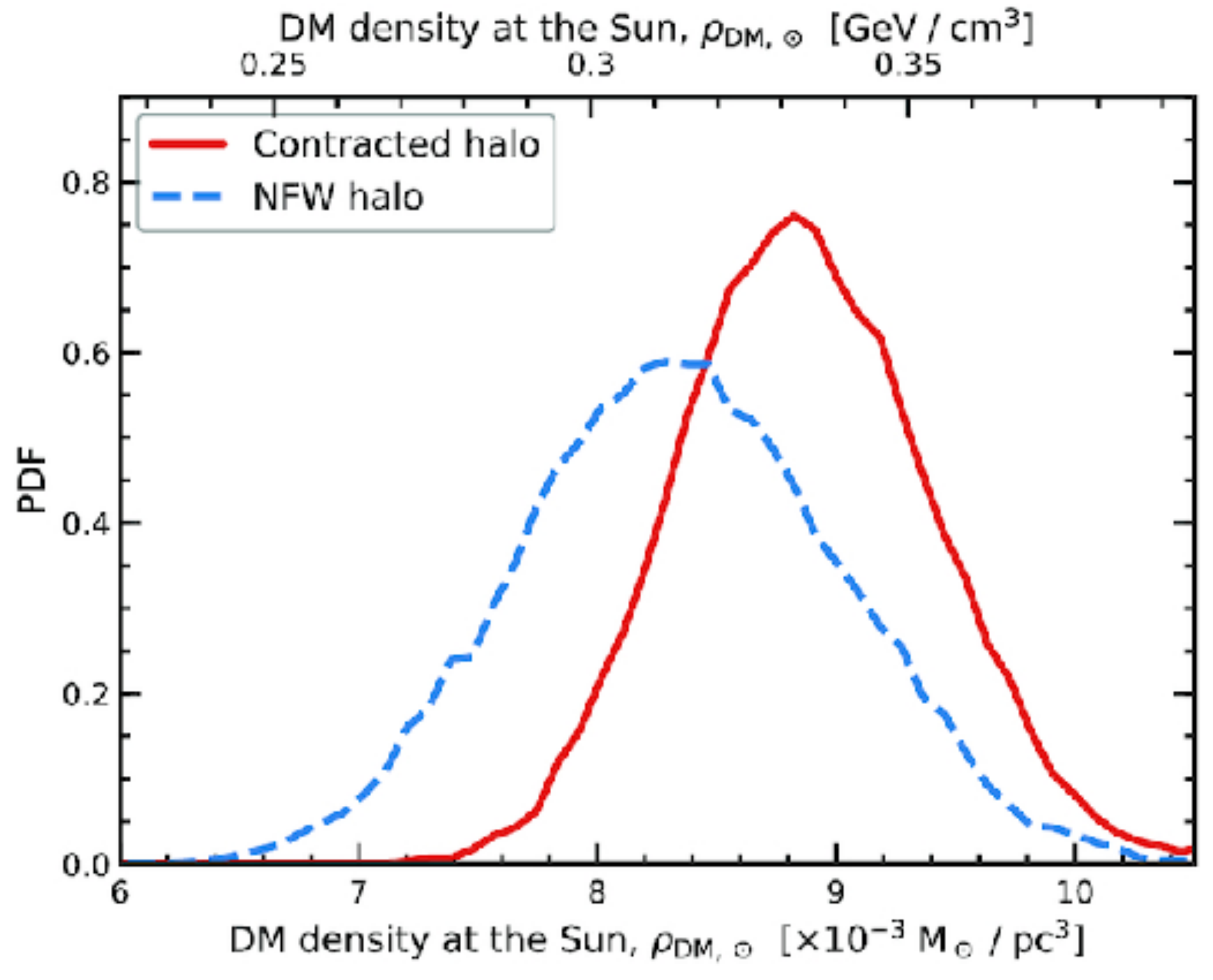
Astrophysics

$\rho_0, f(v)$

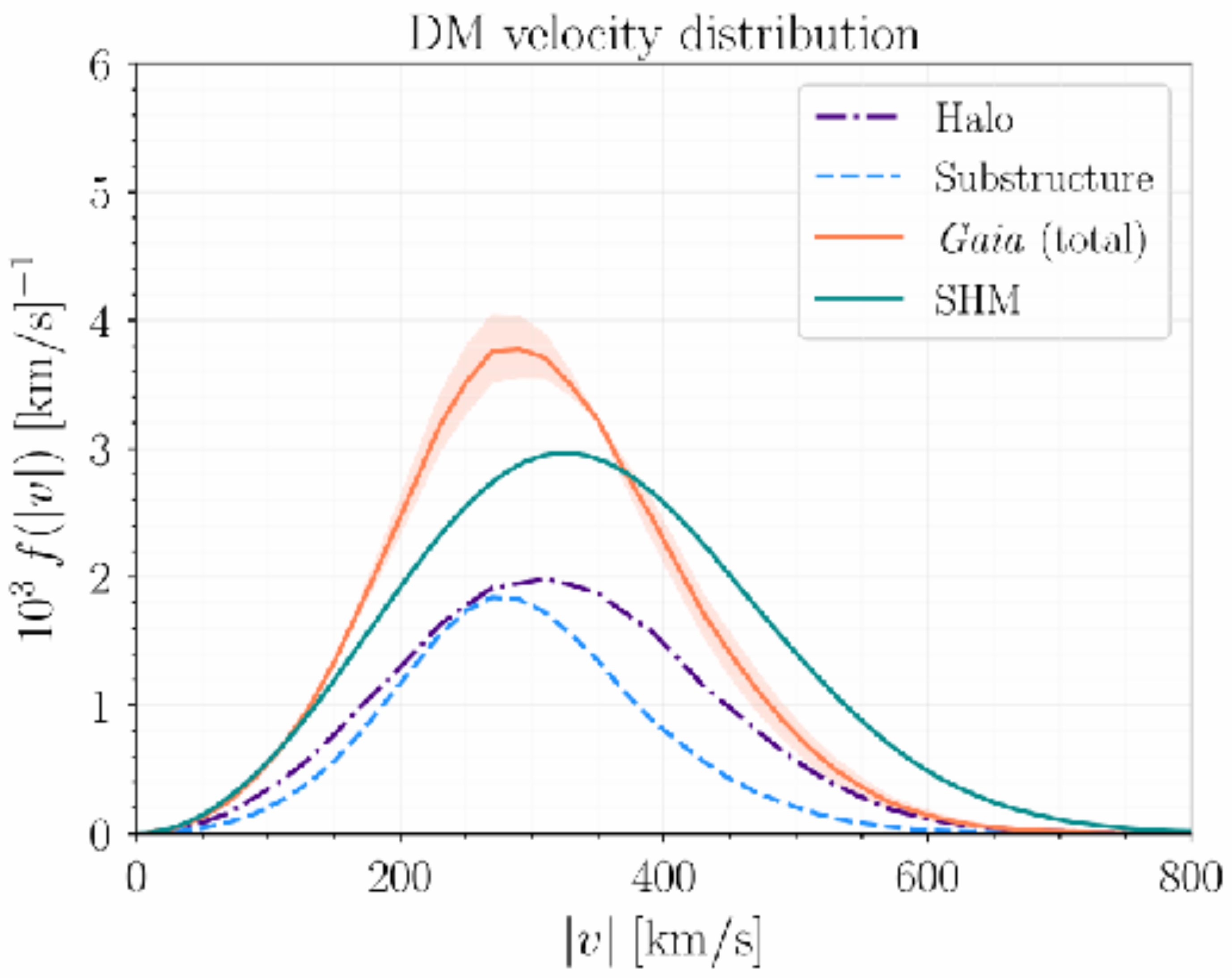
Hisano et al., JHEP 06 (2015)



See more details for the talk by Alejandro



M. Cautun et al, MNRAS 2020



Buch et al, PRD101, 2020

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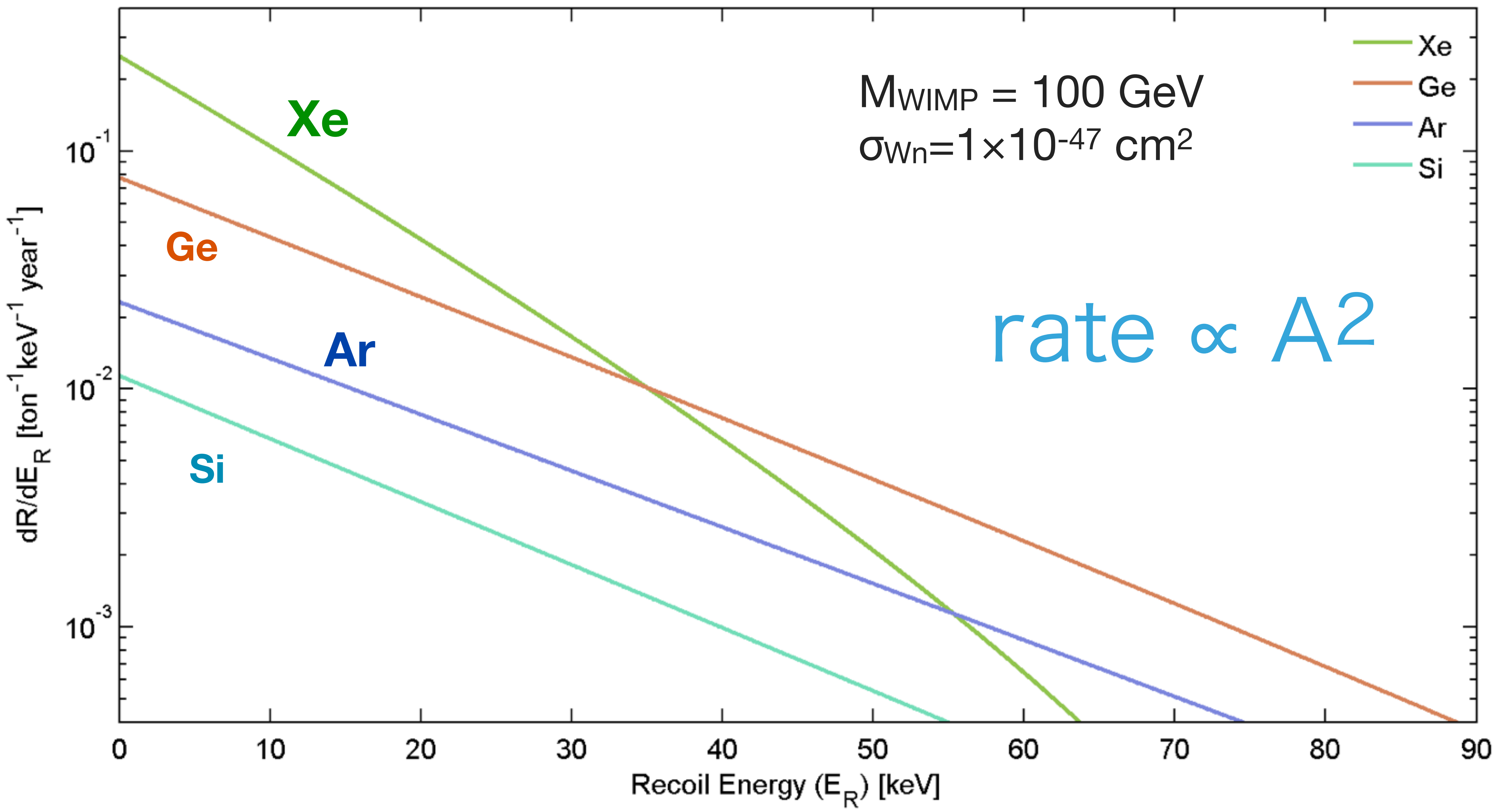
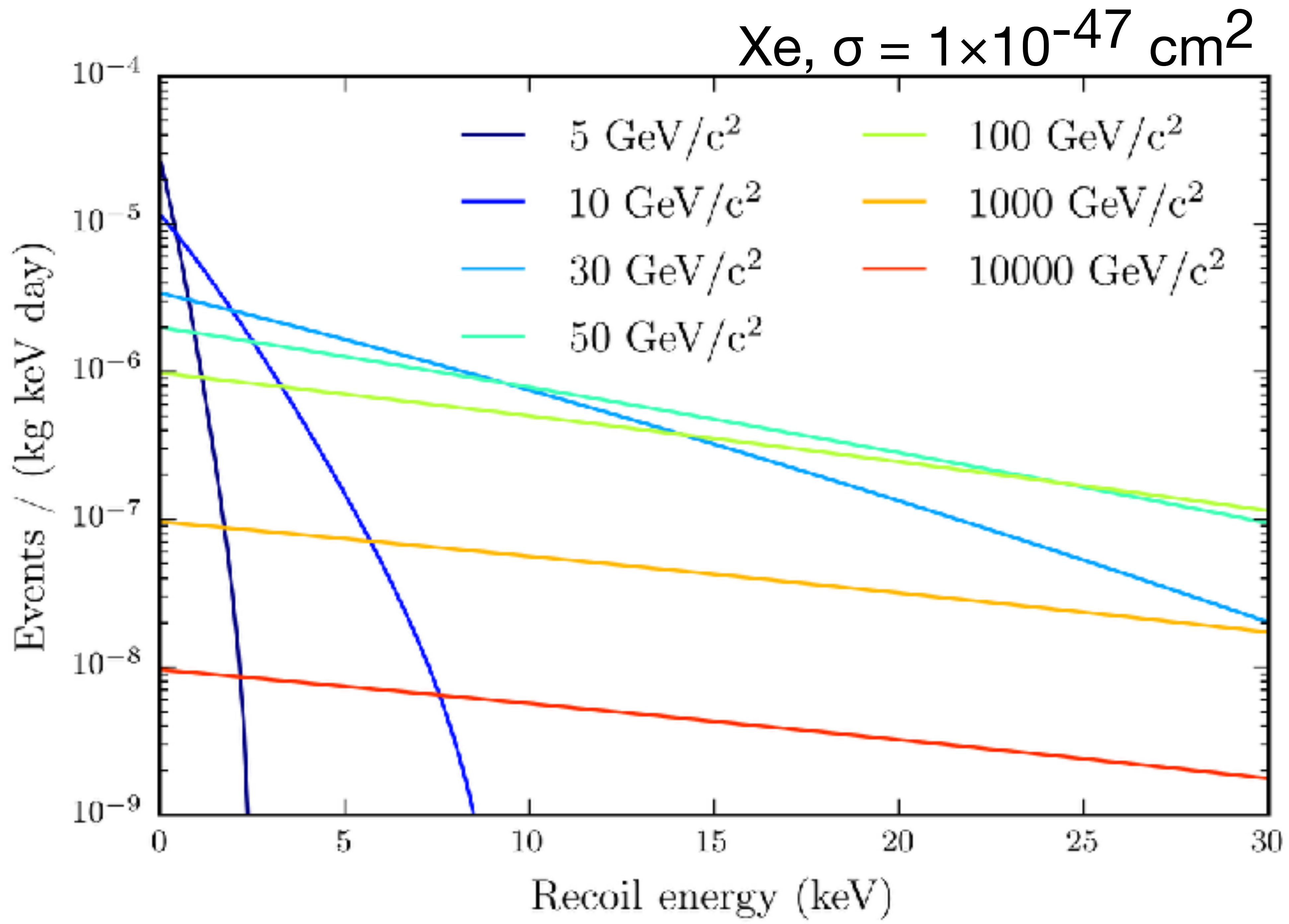
Detector physics: N_N, E_{th}

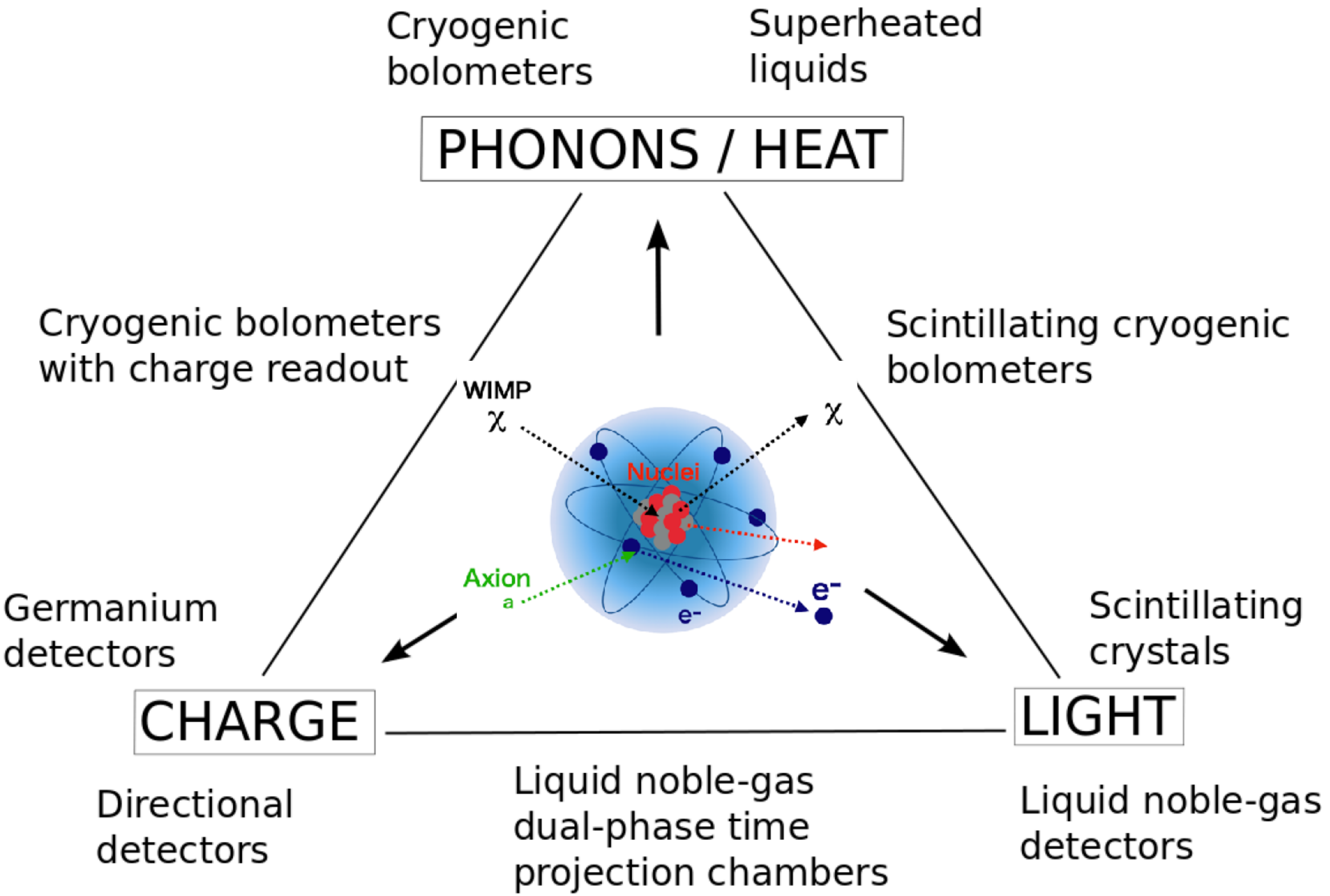
Particle/nuclear physics: $m_W, d\sigma/dE_R$

Astrophysics: $\rho_0, f(v)$





Direct Dark Matter Detection: Signals



J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

Direct Dark Matter Detection: Current Status

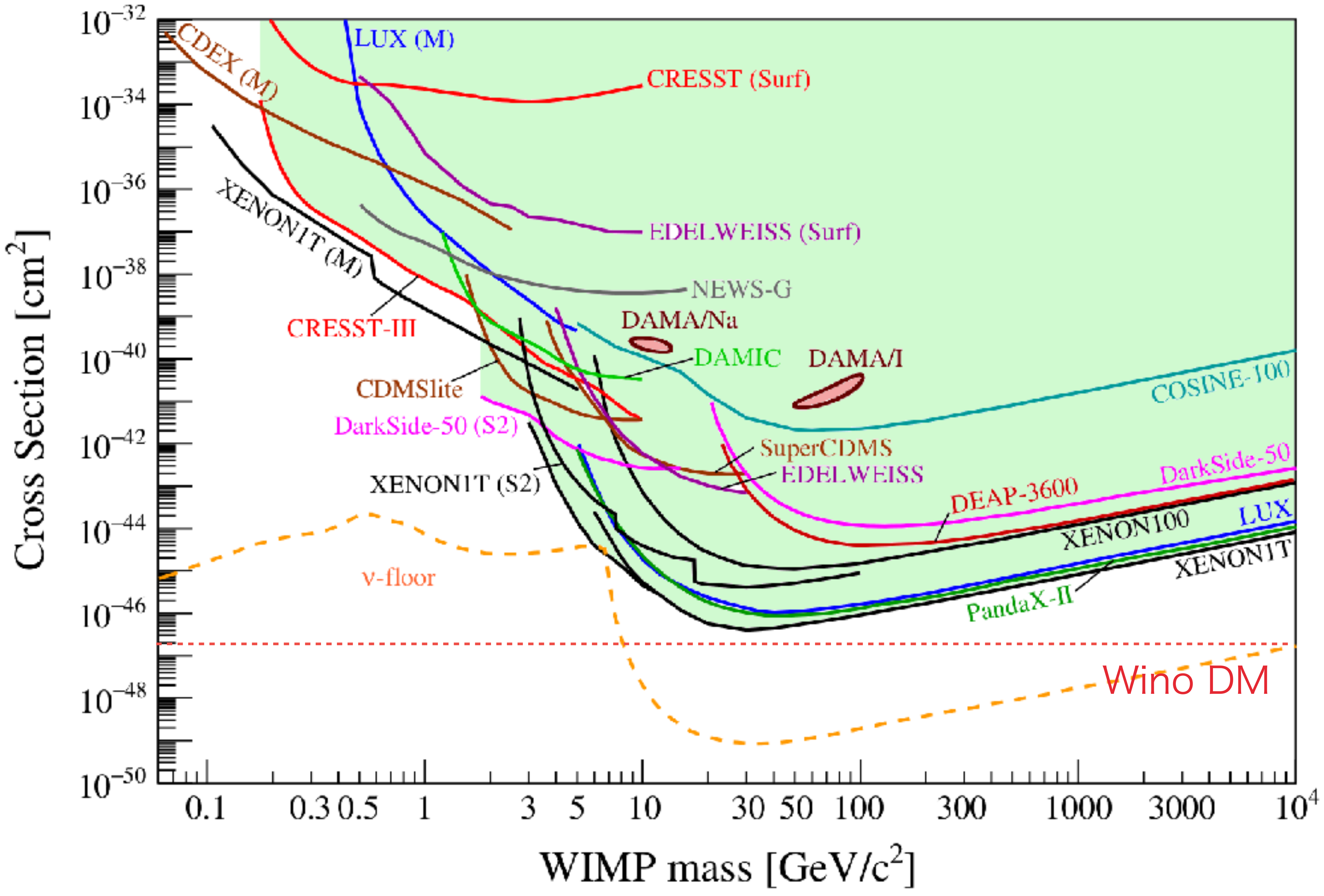


Figure: APPEC DM Report: https://indico.cern.ch/event/982757/overview

Liquid Noble Targets

- Largest and most sensitive over the wide WIMP range
- 5 GeV - 10 TeV WIMP masses probed
- XENON1T, XENONnT, LUX, LZ, Panda-X, XMASS, Darkside, DEAP3600

Cryogenic crystal targets

- Oldest technologies with new innovations
- 0.1-10 GeV WIMP masses probed
- CRESST, EDELWEISS, SuperCDMS

Alternate targets with unique properties

- NaI crystals, bubble chambers
- ANAIS, COSINE, DAMA/LIBRA, SABRE, PICO
- Directional DM detection (gas/emulsion, etc)

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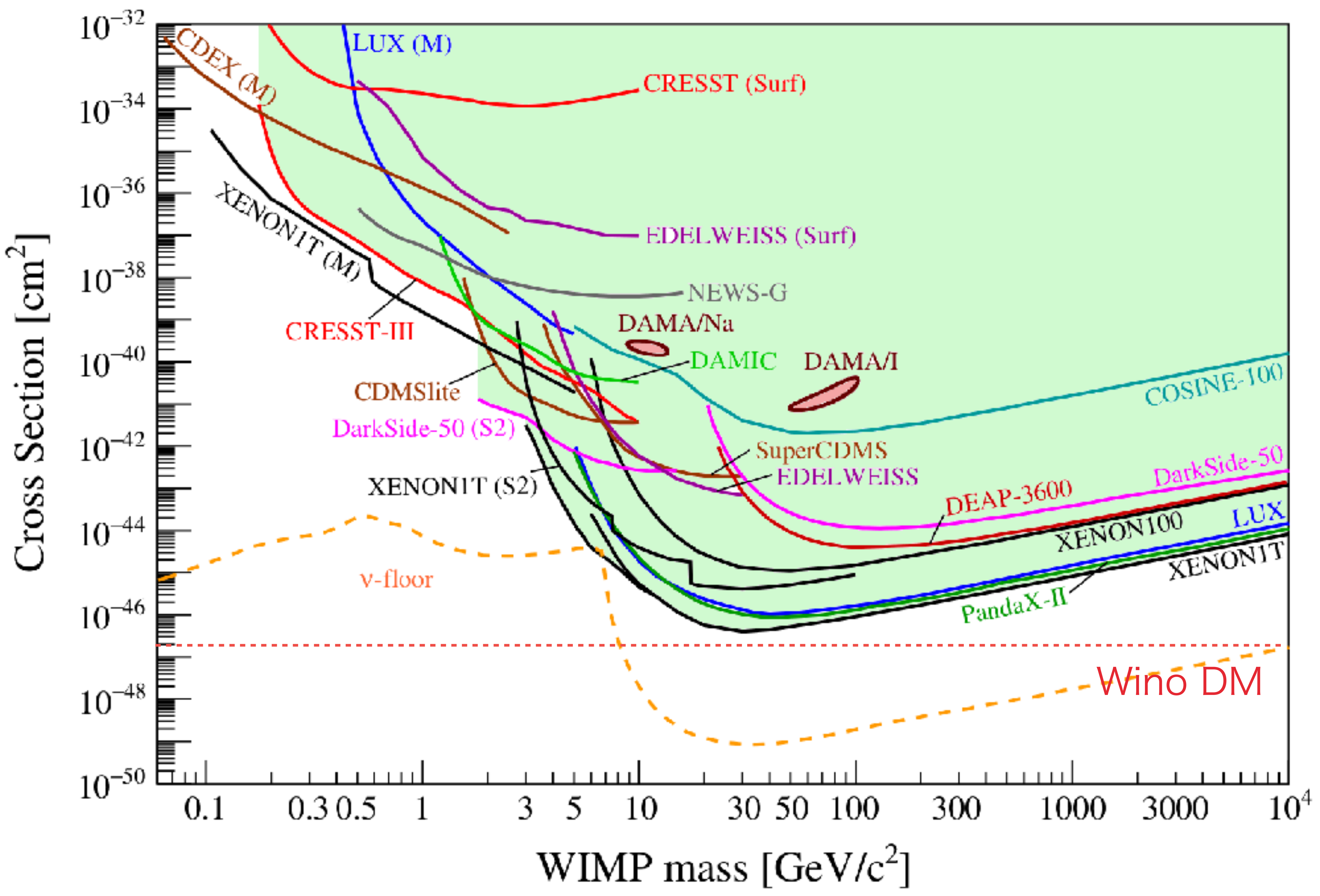

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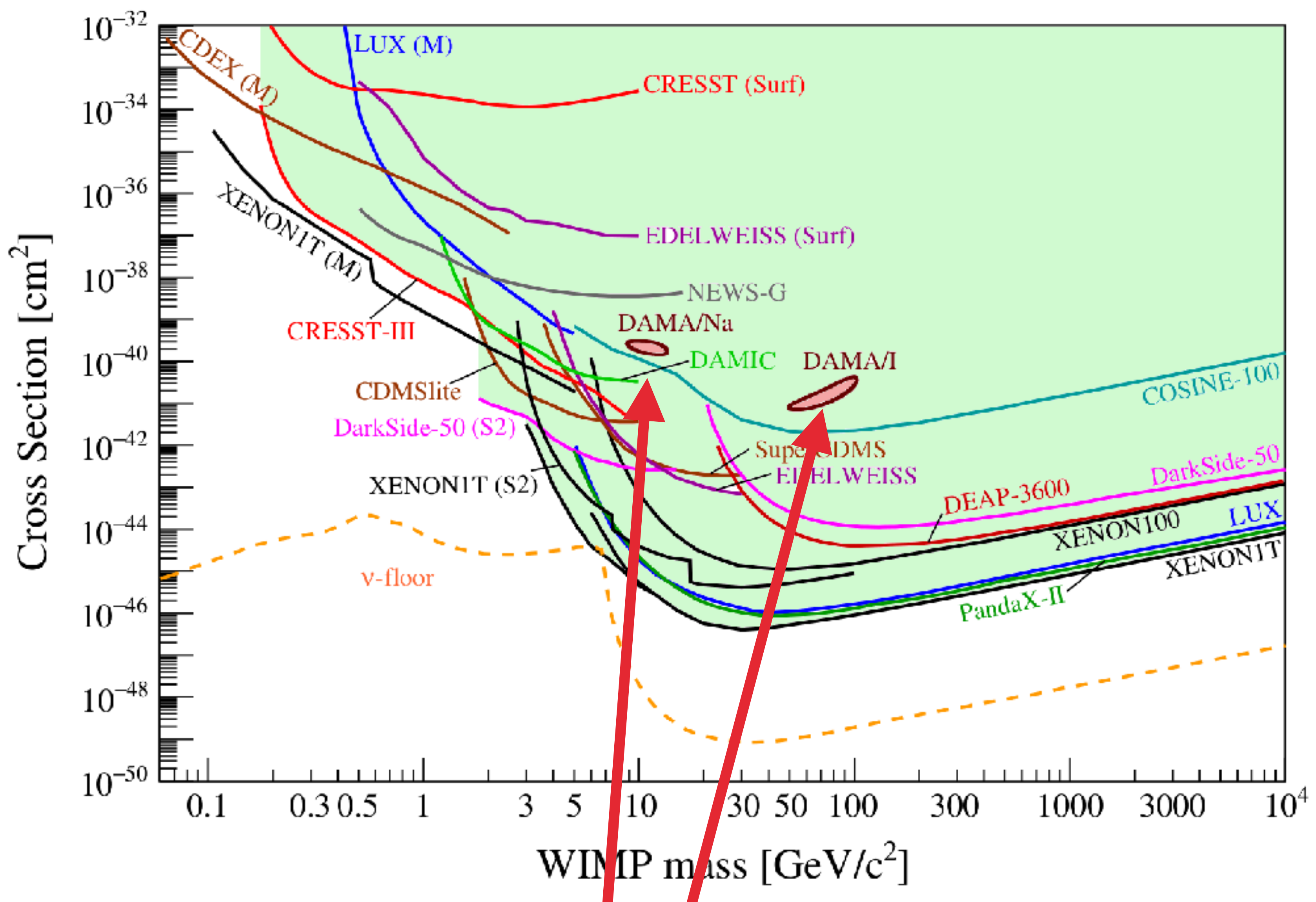
DAMA/LIBRA

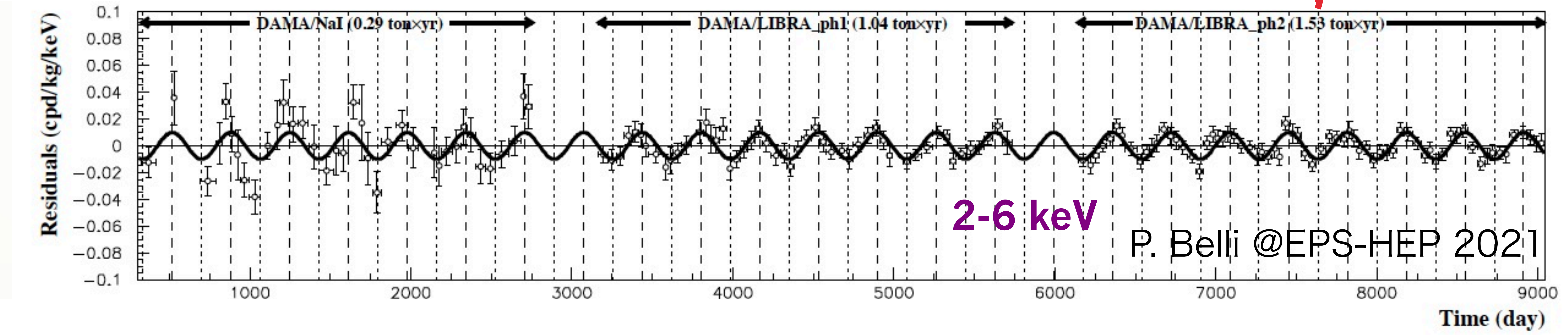
- ~250 kg NaI(Tl) scintillators
- DAMA/LIBRA-phase2: high QE PMTs and new electronics enable to lower energy-threshold down to 0.75 keV
- Annual modulation since 1998 (~9000 days)
- 2.86 ton-year exposure: 13.7 σ in 2-6 keV

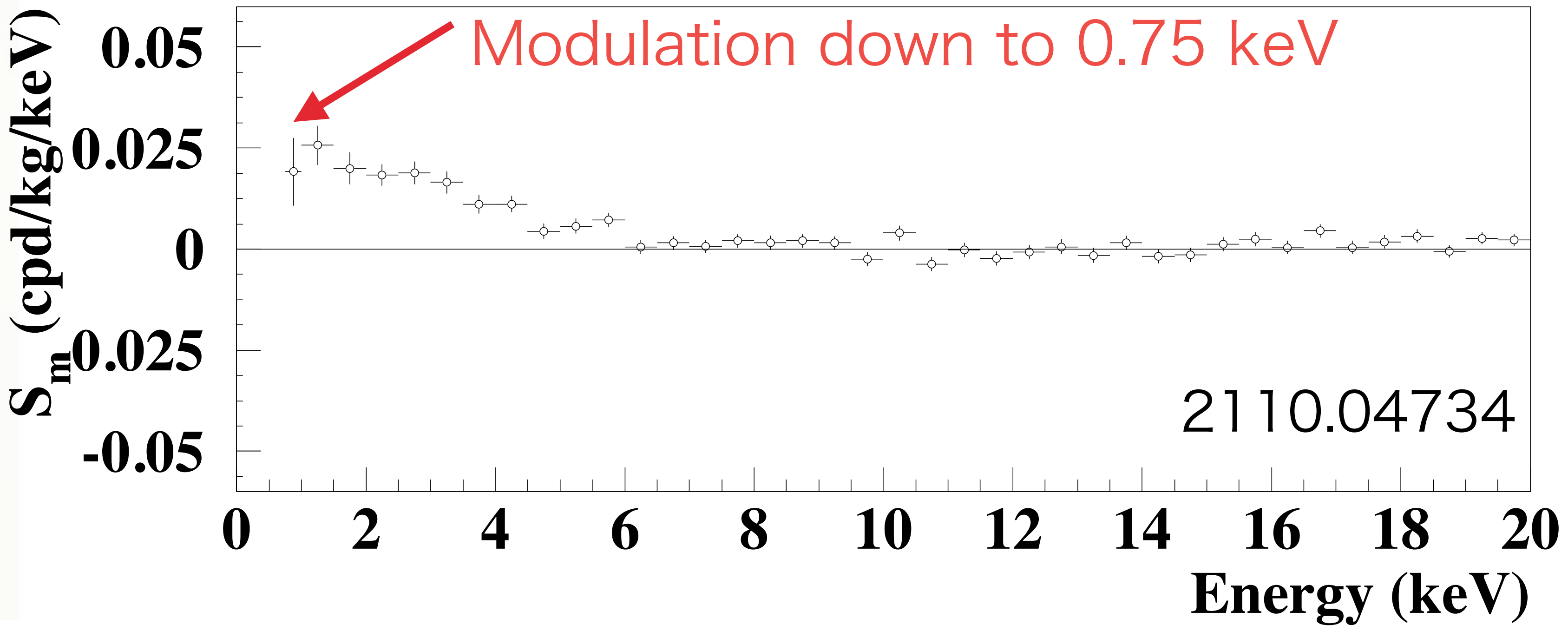
, but challenged by

- SI/SD-induced NRs ruled out by many experiments with lower BGs
- Modulation from DM-e scattering excluded by LXe TPCs

—> need independent measurements with NaI(Tl)







DAMA vs COSINE/ANAIS

2111.08863 PRD 103, 102005 (2021)

COSINE100(106kg) @Yangyang in South-Korea

- Already excluded DAMA interpreted as SI interaction with standard halo model (2104.03537)
- 3 year data: 0.173 t x y exposure
- data consistent with null and also DAMA yet

ANAIS (112kg) @Canfranc in Spain

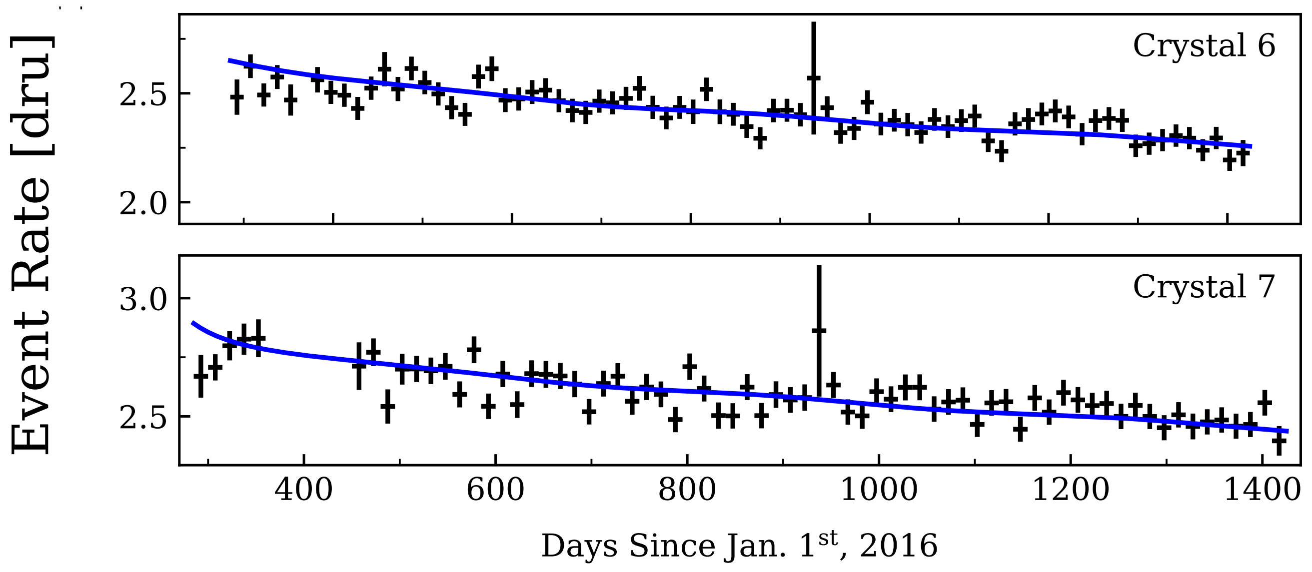
- 3 year data: 0.31 t x y exposure
- same threshold but ~3x higher background
- data consistent with no modulation; incompatible with DAMA at 3.3 σ [1-6 keV]

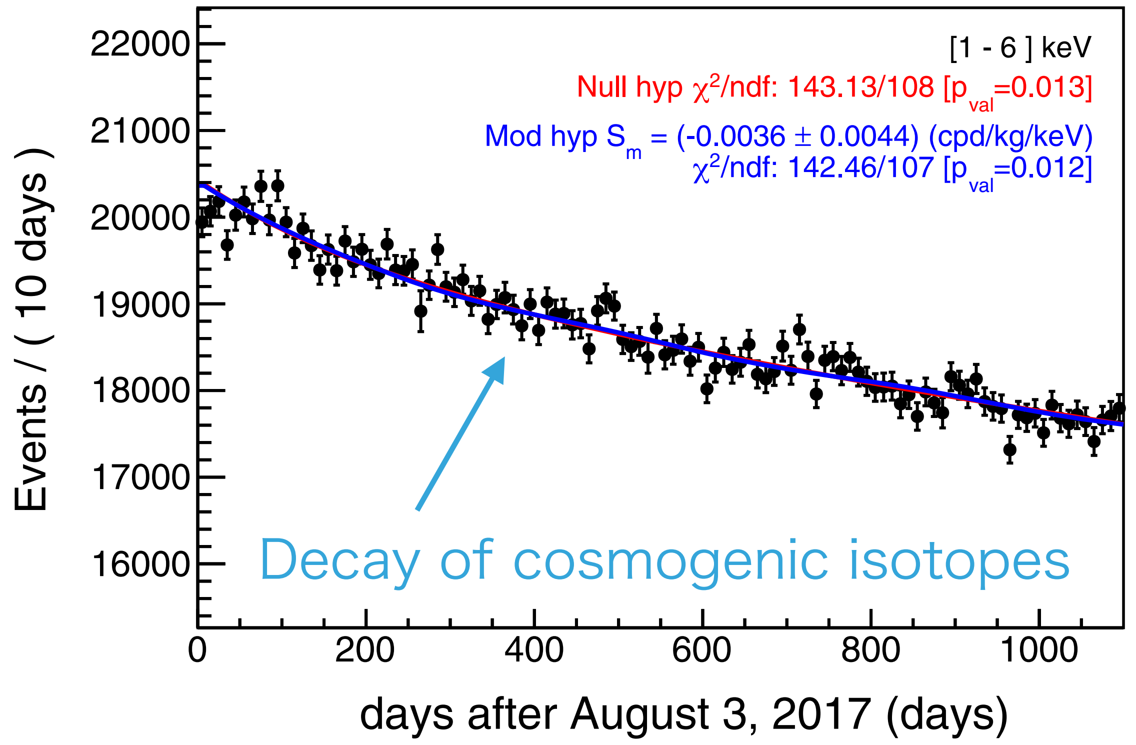
More NaI detectors in progress:

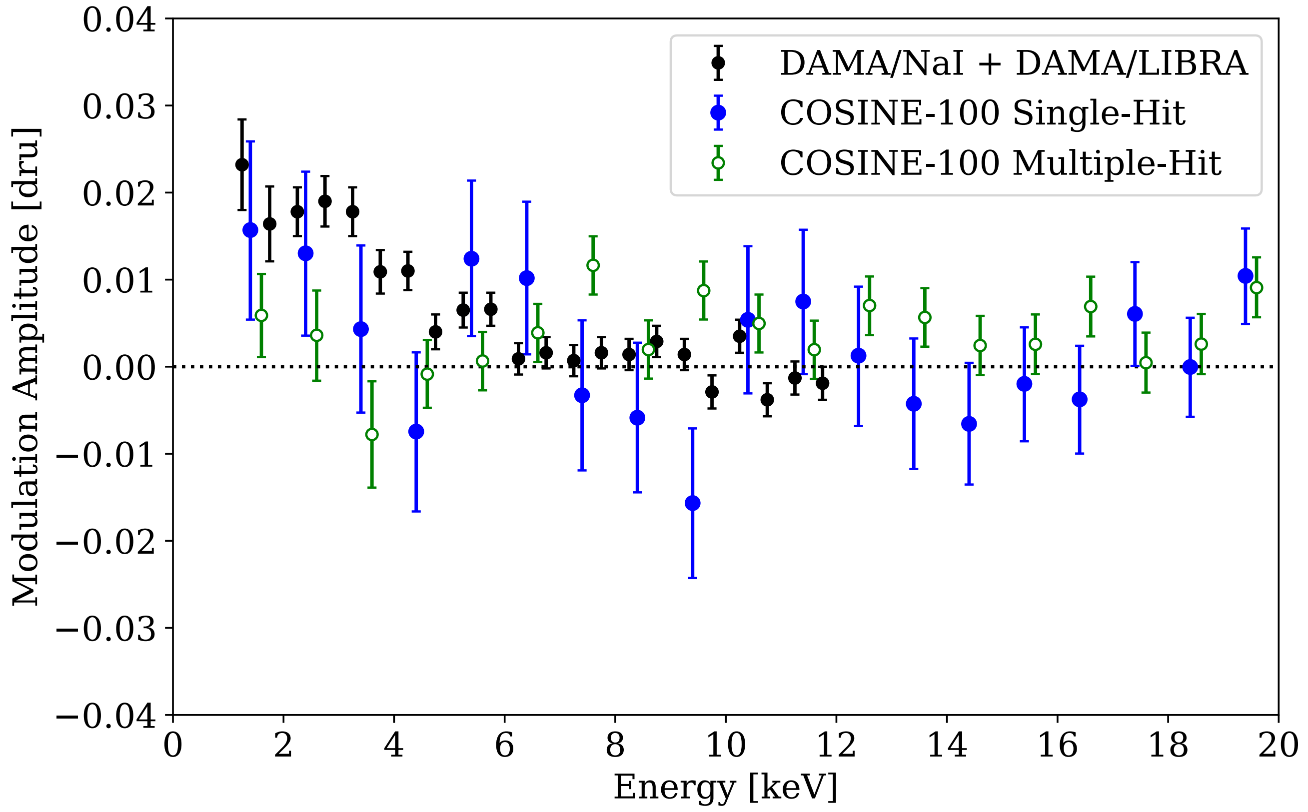
- COSINUS: detects also phonons in undoped NaI construction at LNGS in 2022
- SABRE, PICOLON, etc

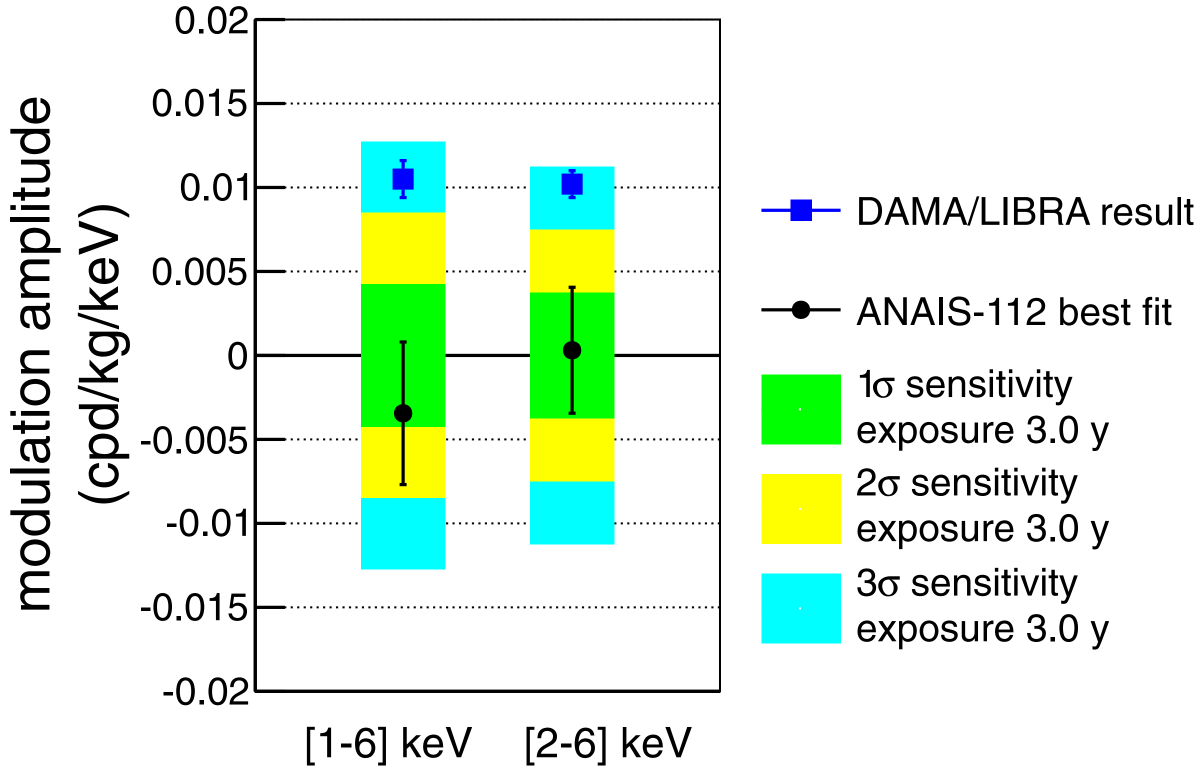
COSINE-100 NaI detectors

ANAIS 112.5 kg NaI(Tl) @Canfranc





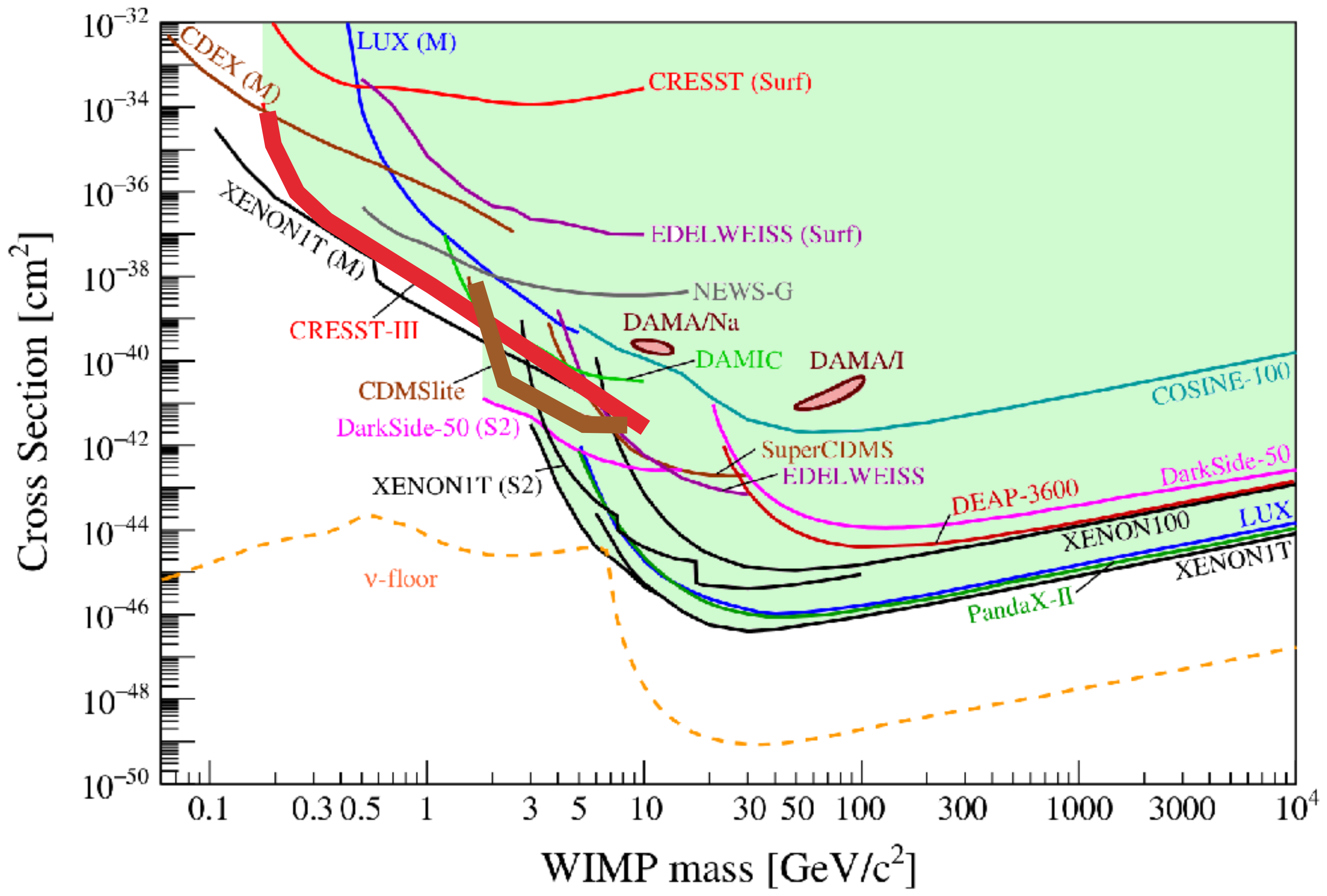


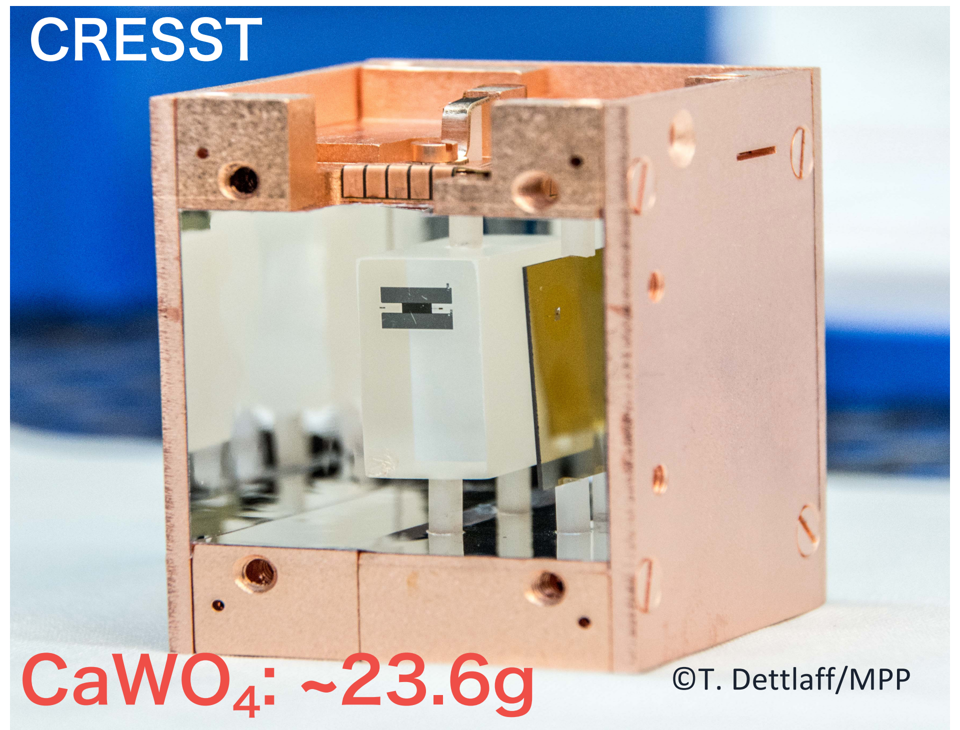


Cryogenic Bolometers

CRESST

- 24 g of $CaWO_4$ crystals (~15mK) for phonon/scintillation
- Energy threshold of ~30eV

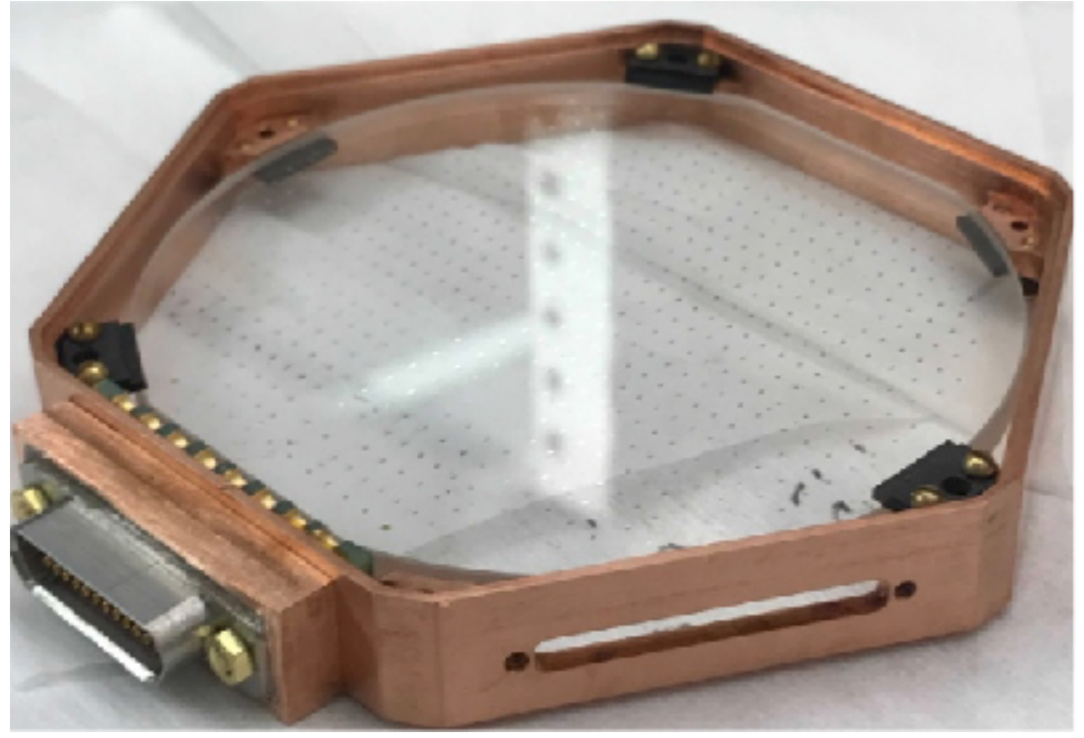


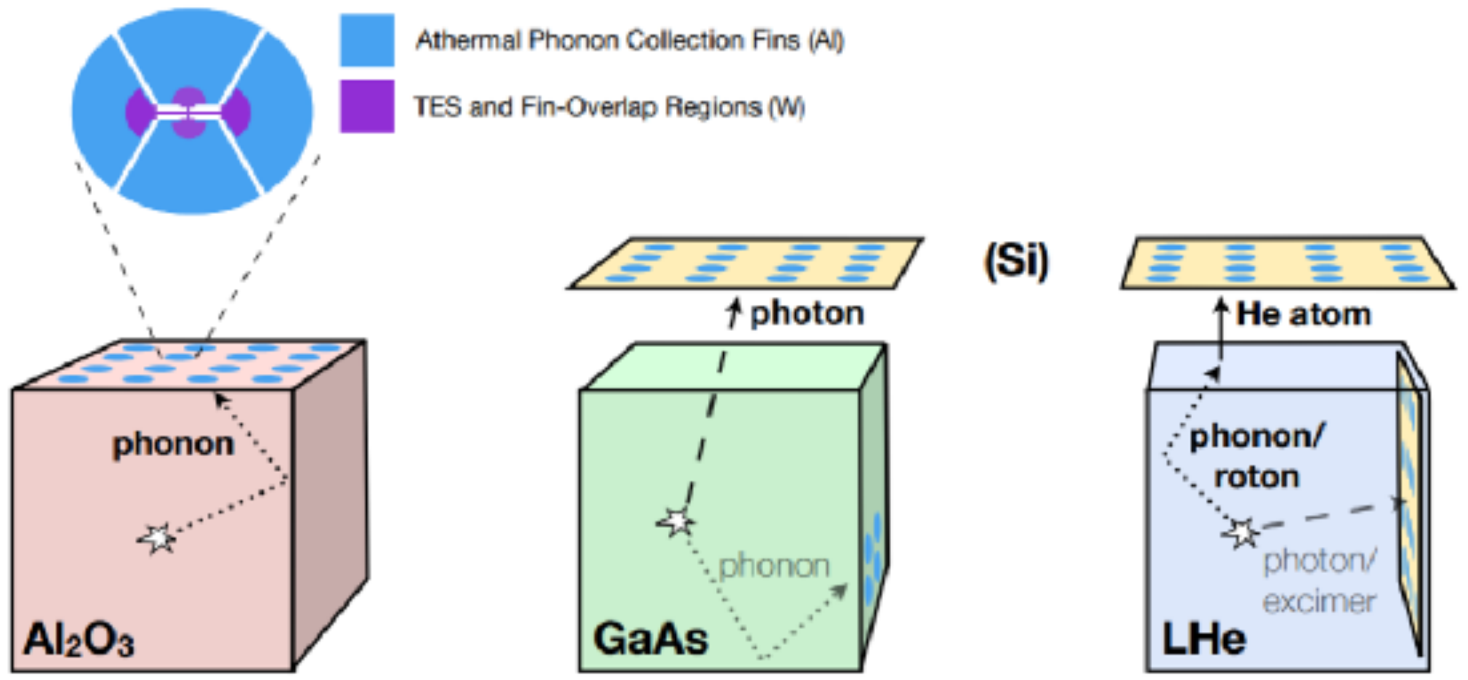


(Super)CDMS / EDELWEISS2

- Ge bolometers
- CDMS-lite: amplified Luke phonos, low threshold but not ER/NR discrimination (no ionization signals)
- 600g Ge, energy threshold of ~70 eV

Golden reference TES





SPICE-HeRALD experiment: planed at Kamioka

- Quantum sensing consortium is established for a new underground cryogenic facility at Kamioka (Tohoku/LBNL/QUP)
- improving TES athermal phonon detectors and using same sensors on multiple targets
- ~1eV energy threshold in a large area (3” dia.)

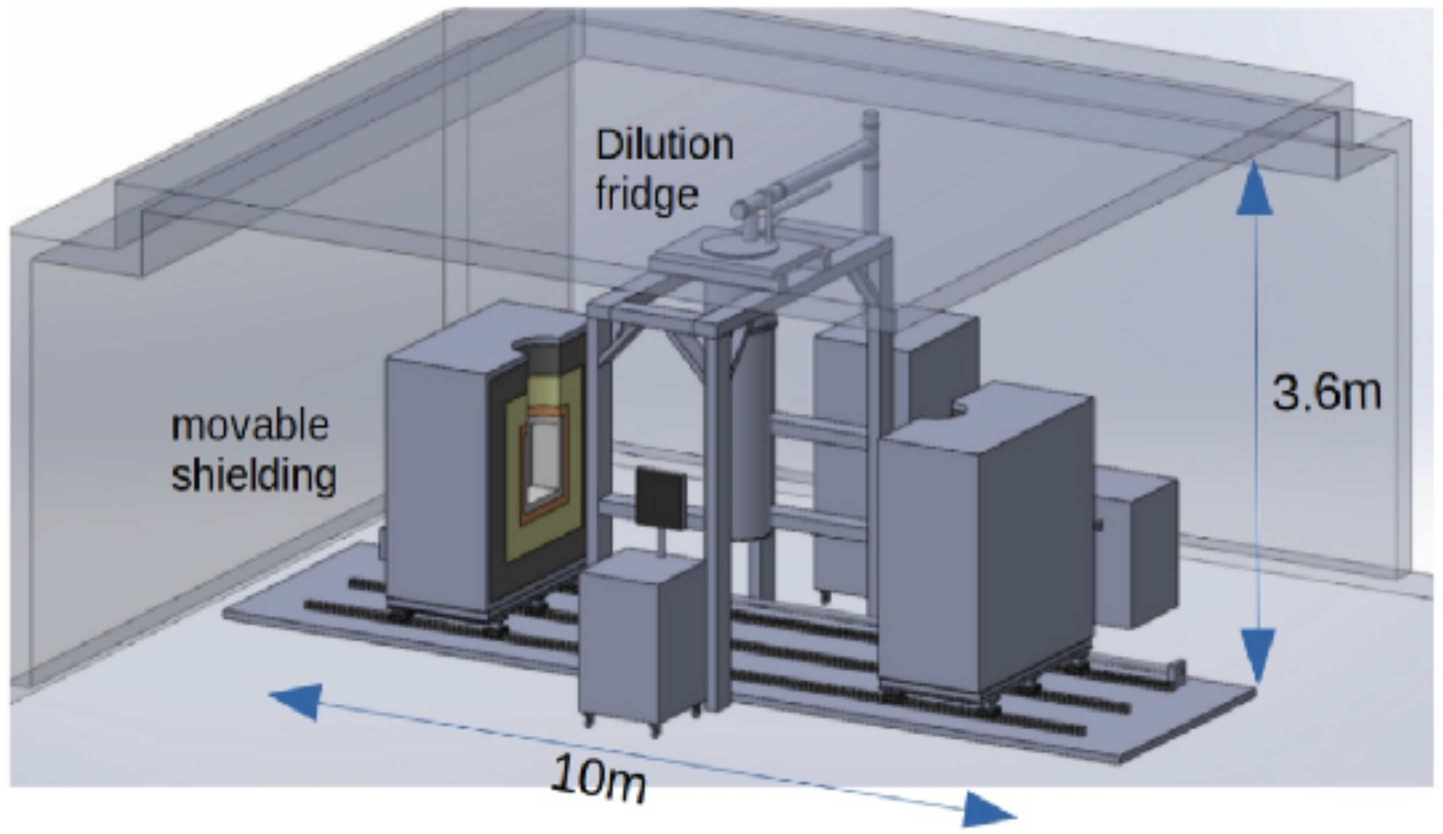
M. Garcia-Sciveres @ KEK-IPNS-IMSS-QUP Workshop

https://www-conf.kek.jp/joint-colloquium/slides/Garcia-Sciveres.pdf

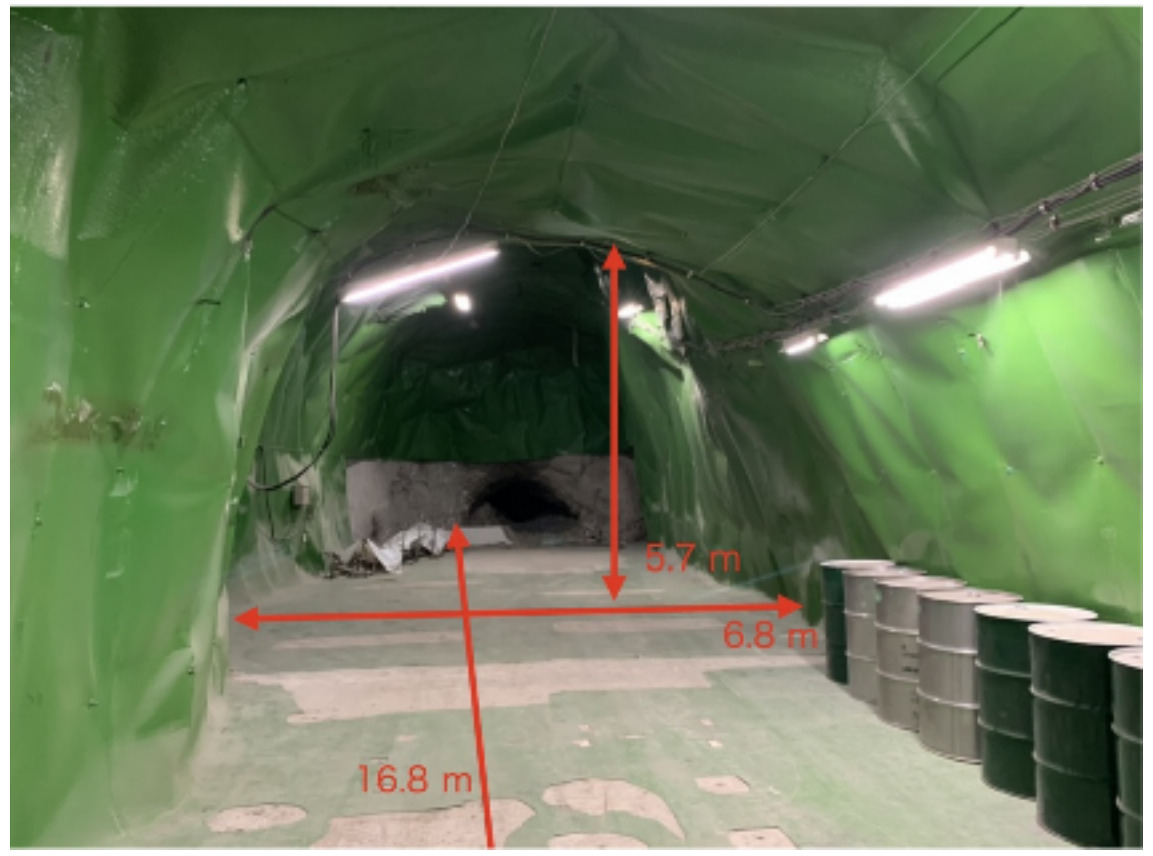
Cryogenic Bolometers

SPICE-HeRALD experiment: planed at Kamioka

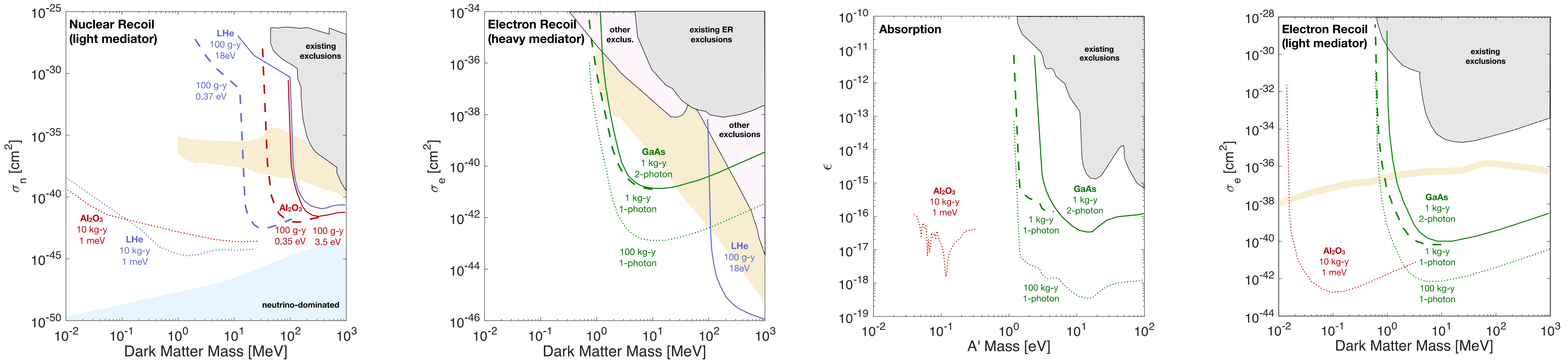
- Quantum sensing consortium is established for a new underground cryogenic facility at Kamioka (Tohoku/LBNL/QUP)
- Data-taking is planed to start in 2024



Detector design by LBNL



Cavern preparation by Tohoku RCNS



Figures from https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf

Liquid Noble Gases

Single and two-phase Ar & Xe detectors

Time Projection Chambers:

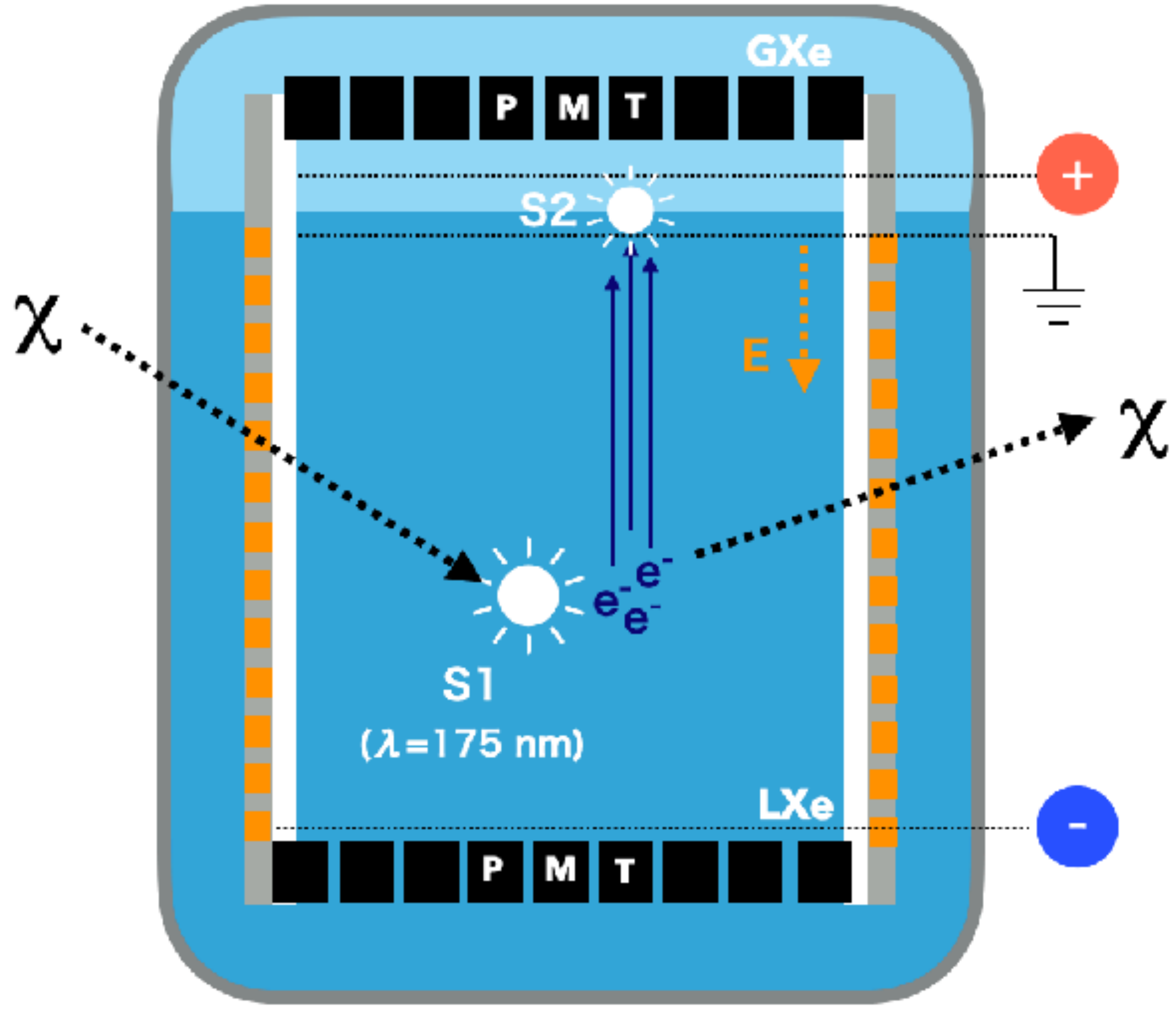
- leading the searches for high-mass WIMPs:

- energy determination, 3D position resolution via light (S1) & charge (S2): fiducialization

- S2/S1⇒ ER/NR discrimination

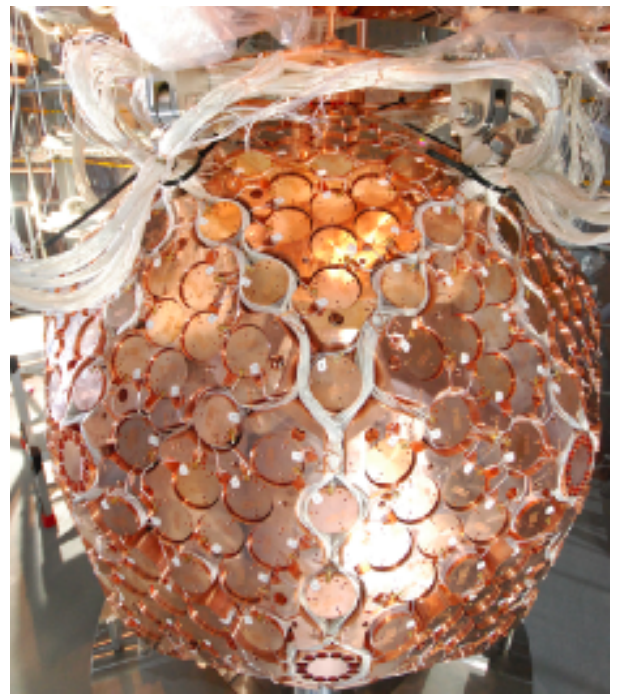
- Single vs multiple interactions

- XENON1T currently leads the search for both low/high-mass WIMPS

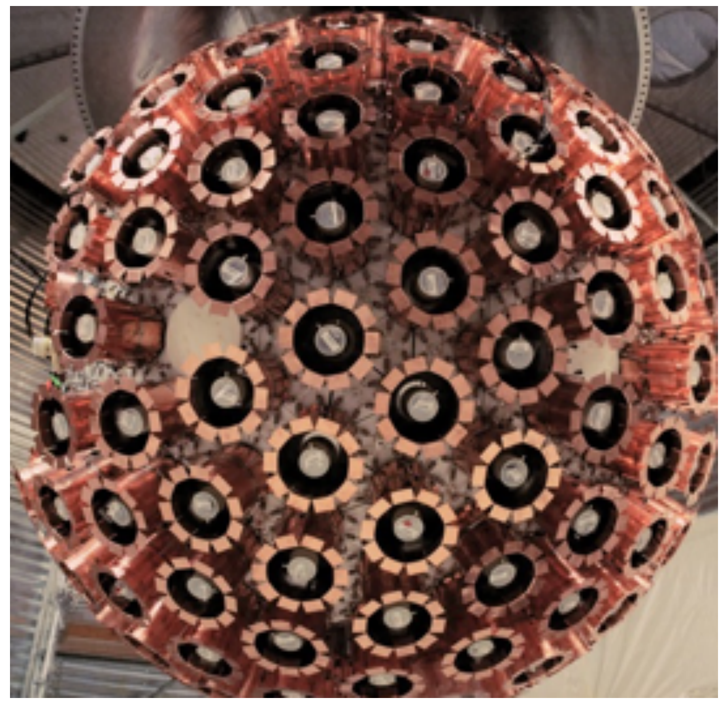


Element	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e^-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.4	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165	3.06	64	46

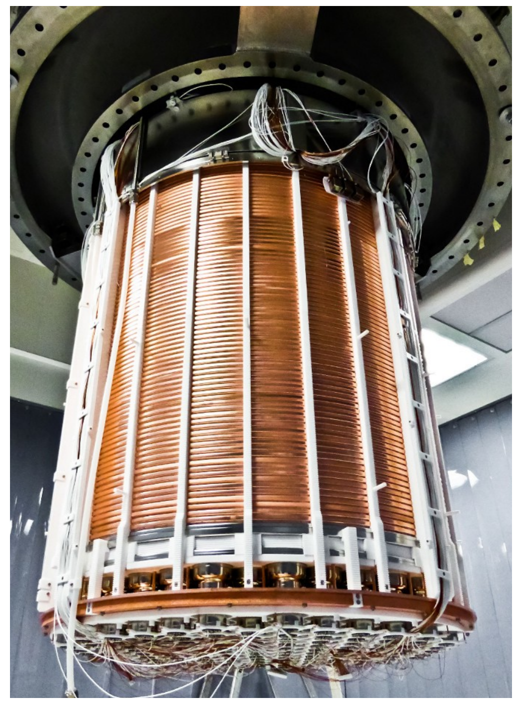
XMASS



DEAP-3600



XENON1T



LUX

DarkSide-50

PandaX-II

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Single and two-phase Ar & Xe detectors

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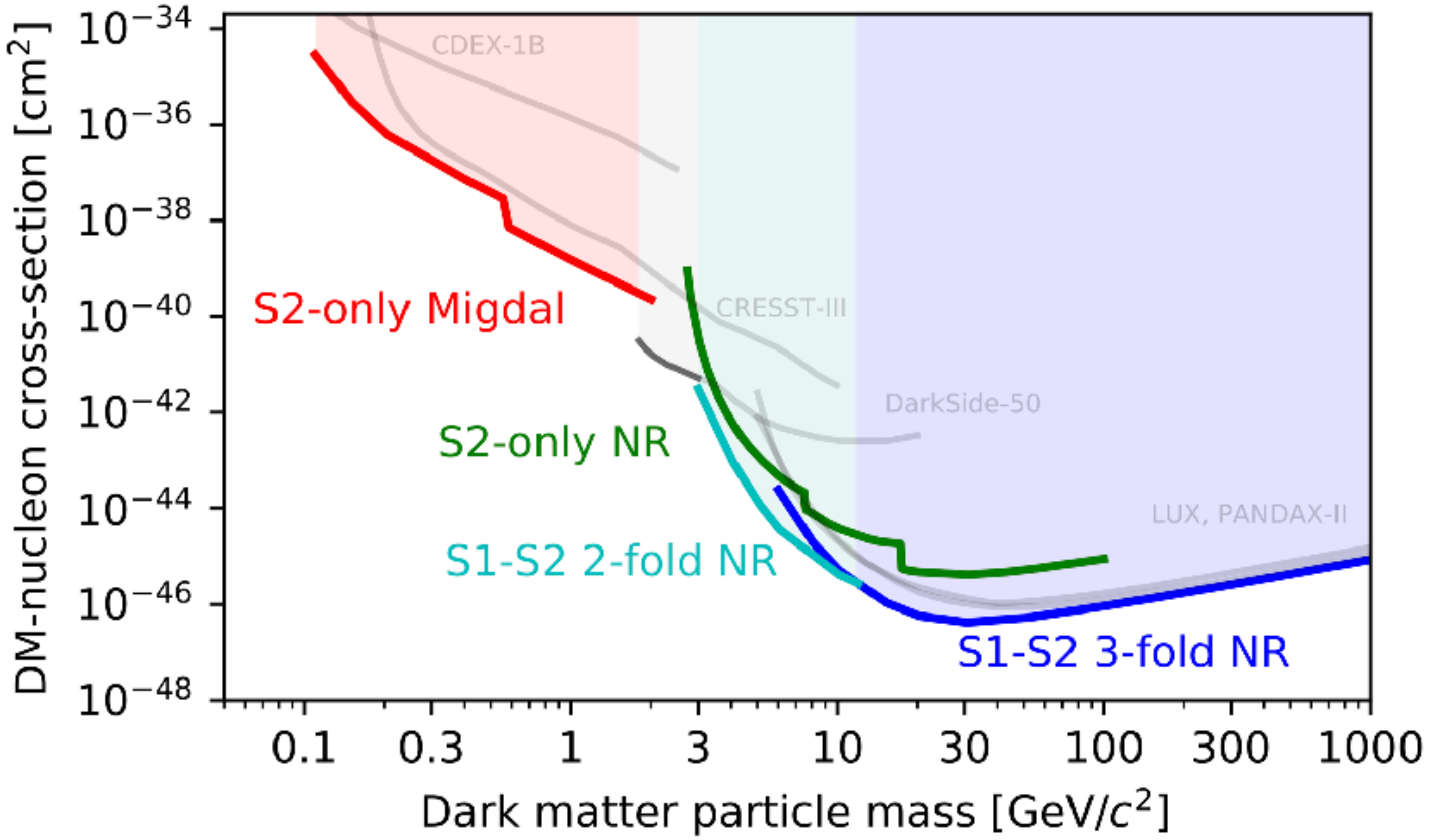

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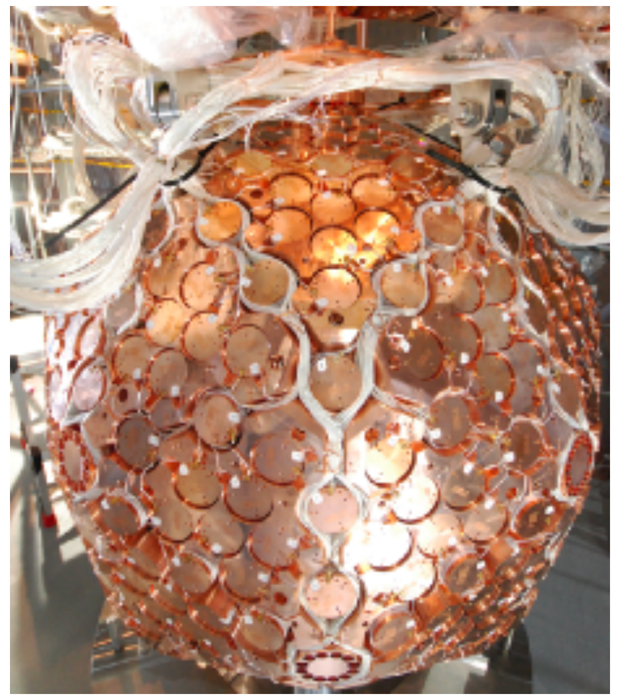
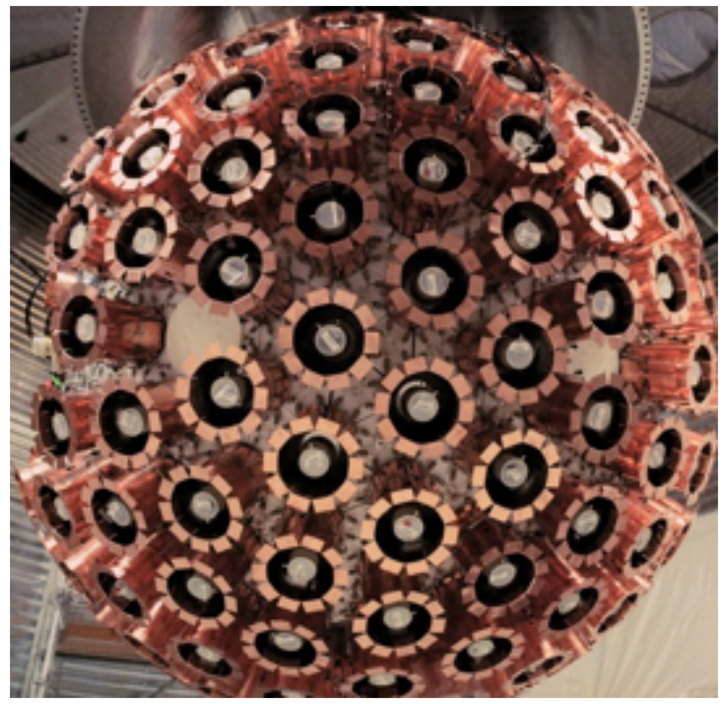
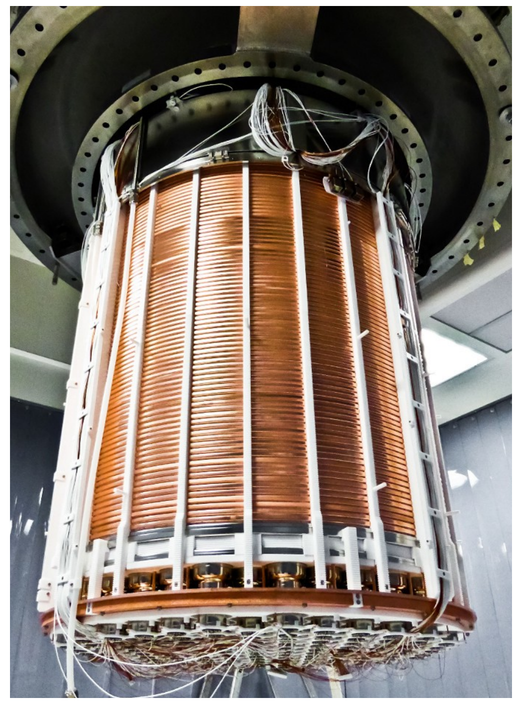


DEAP-3600



XENON1T



LUX

DarkSide-50

PandaX-II

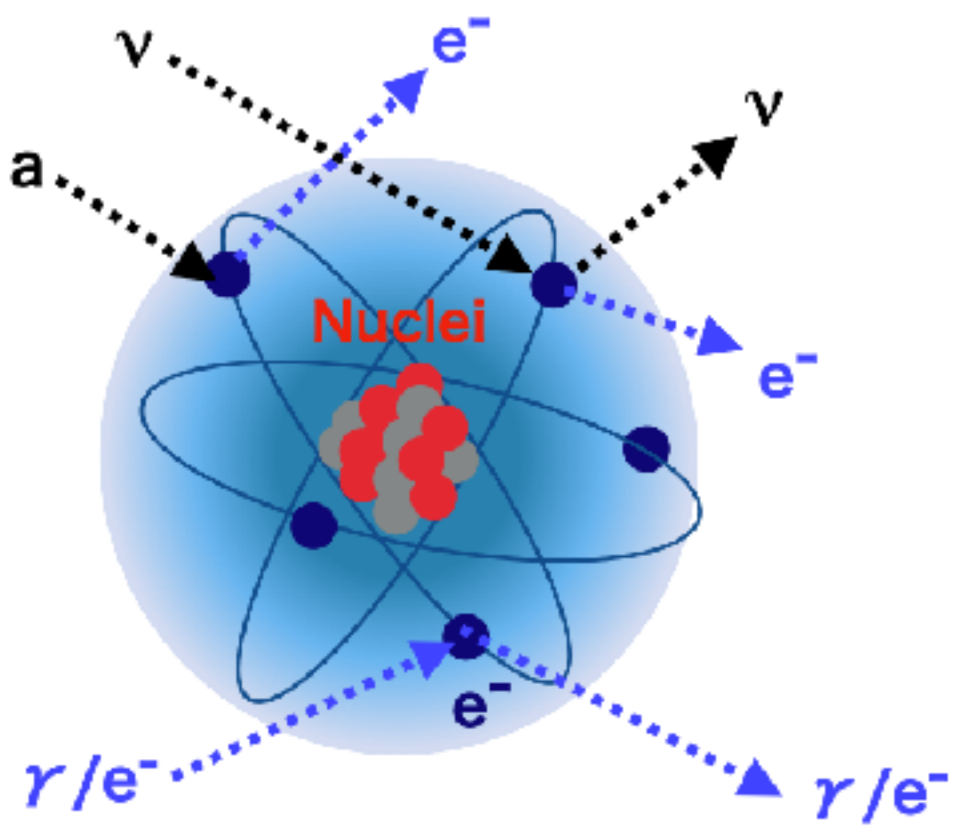
XENON1T: Electronic Recoil Excess

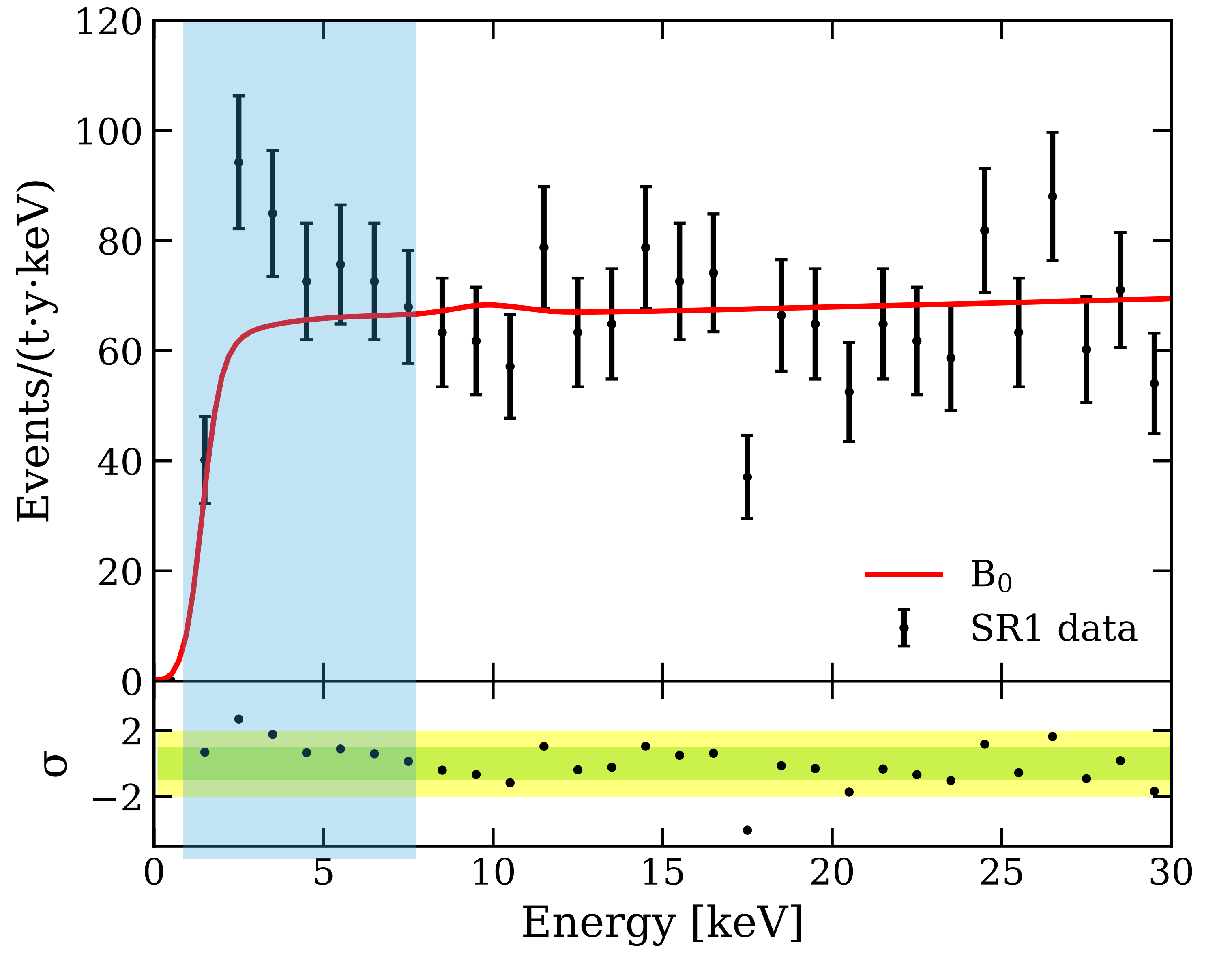
Excess in (1,7) keV;
- 285 events expected
- (232±15) events expected

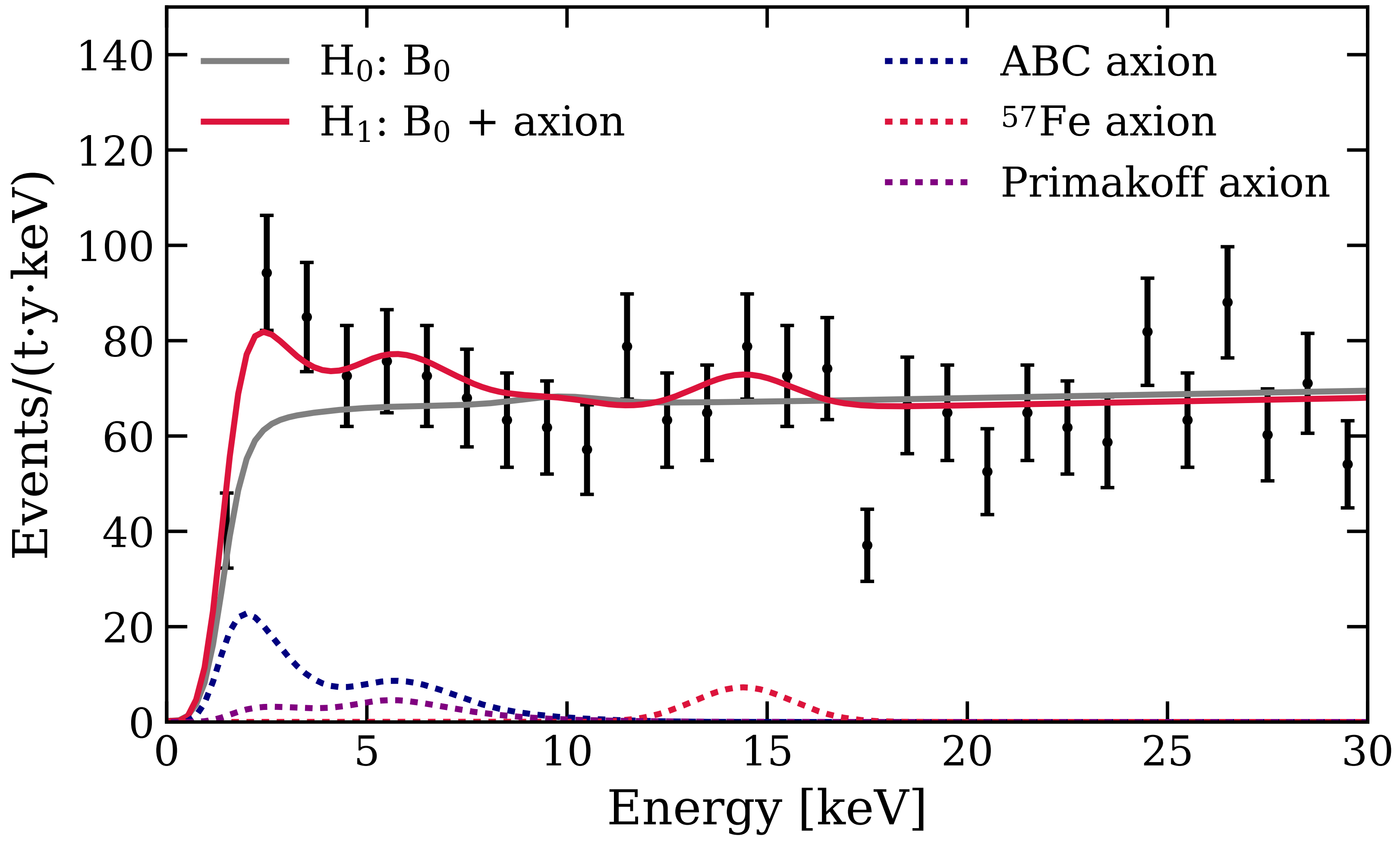
⇒ 3.3 σ fluctuation

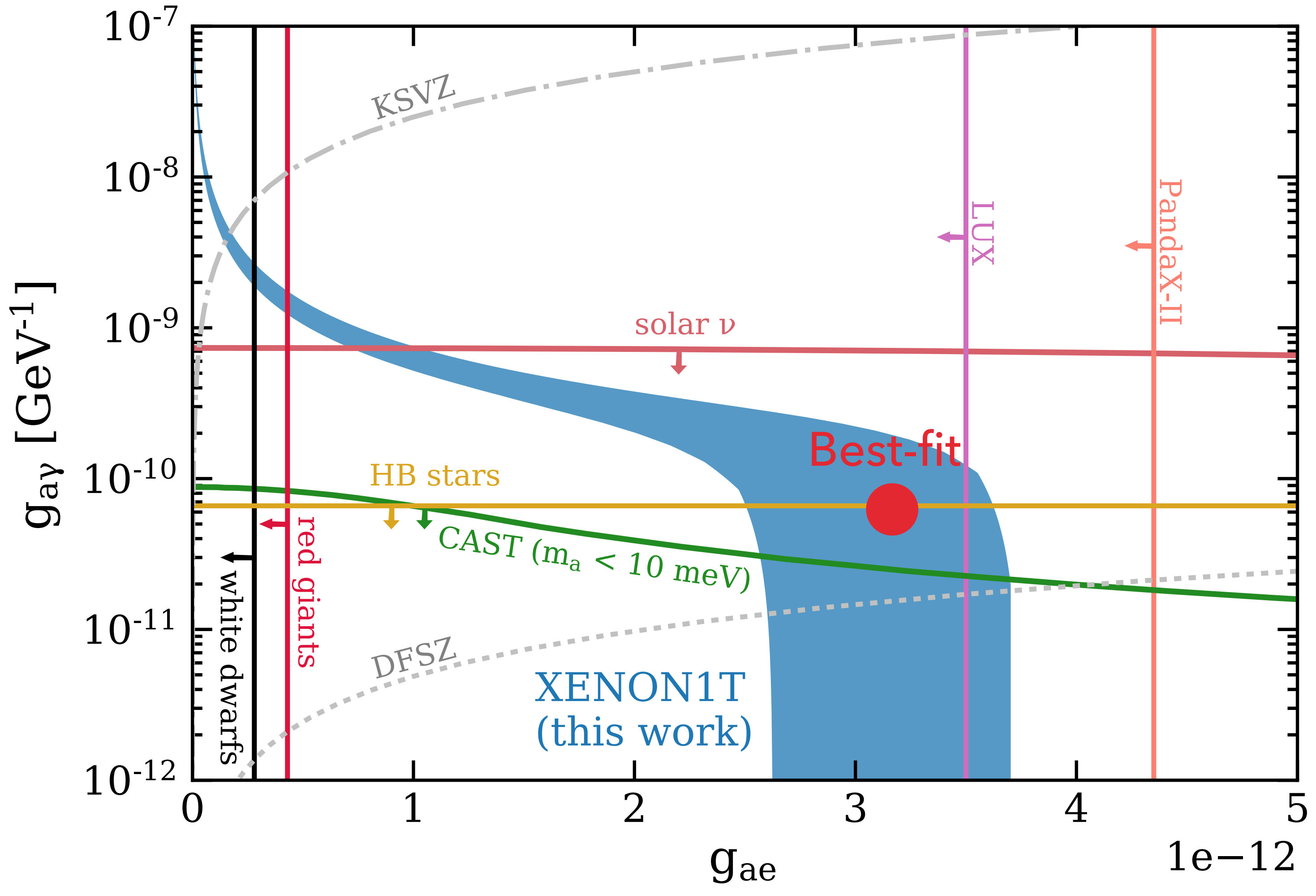
Unknown origin: tritium, solar axions, ALPs, dark photons, something else?

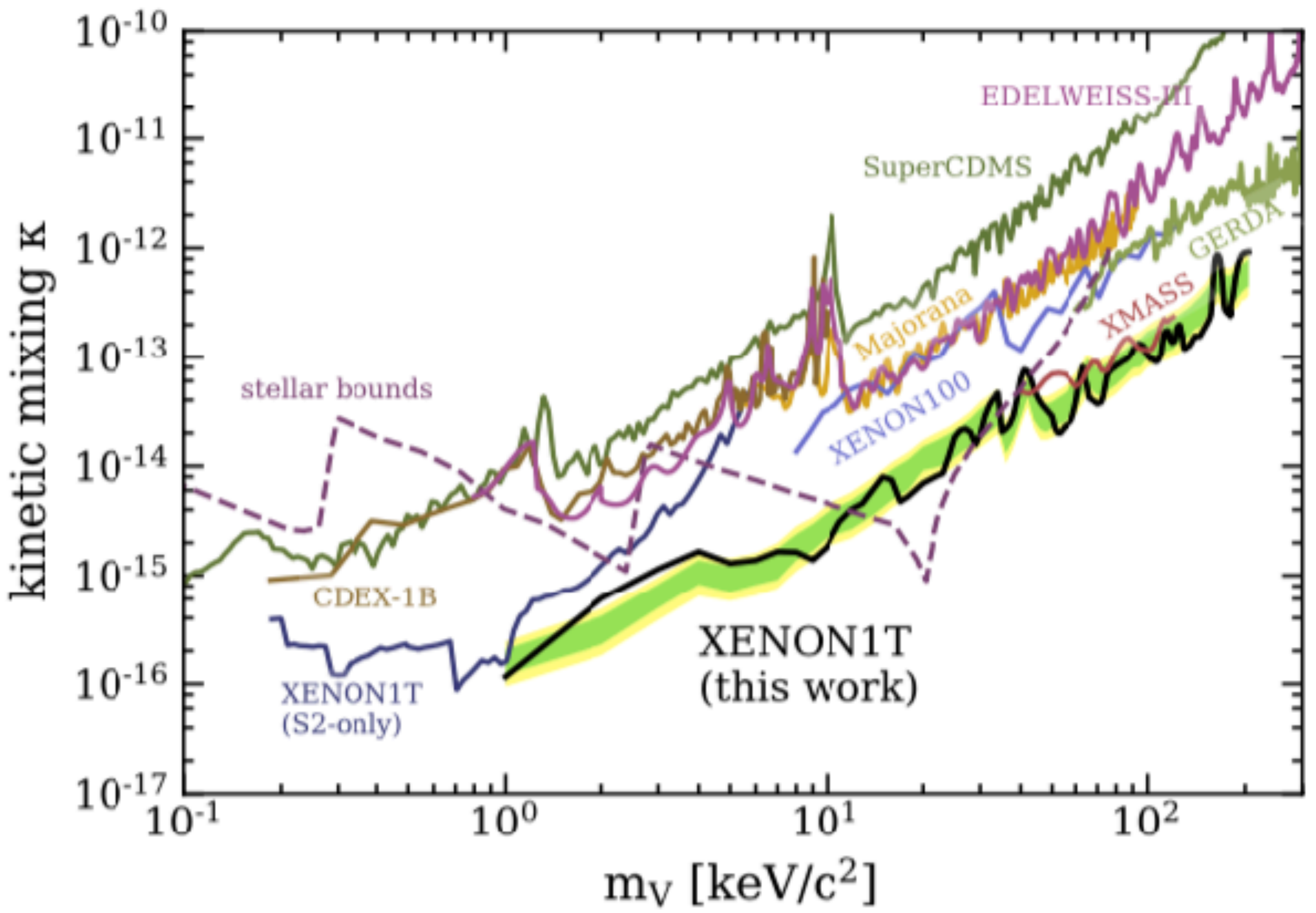
⇒ XENONnT can probe the excess with better LXe purity and lower BG level (~10%)











Current / Future: Liquid Noble Gases

In construction, commissioning or first data-taking:

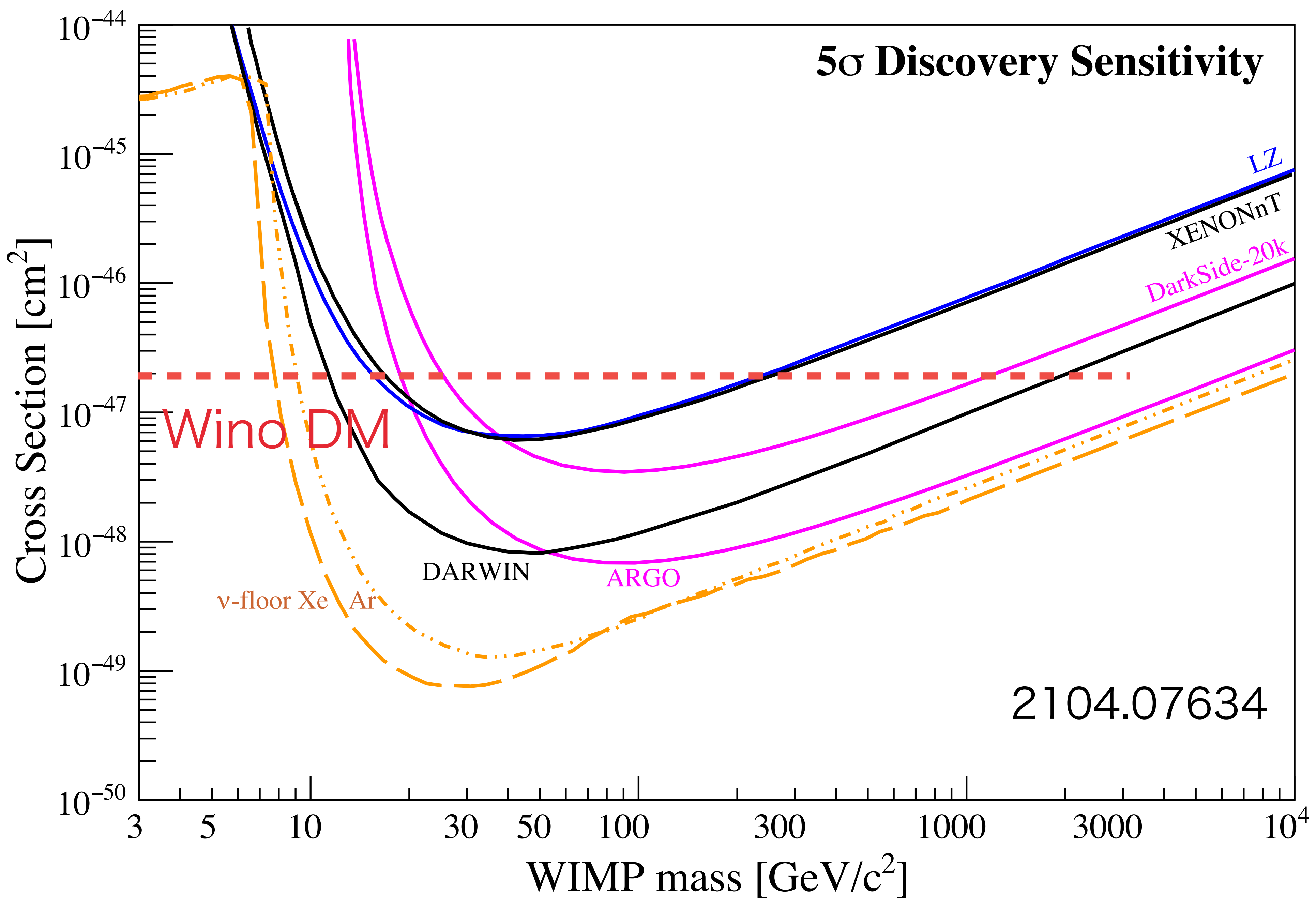
- LUX-ZEPLIN(LXe), XENONnT(LXe), PandaX-4t(LXe), DarkSide-20k(LAr)

Planned (in a design and R&D phase):

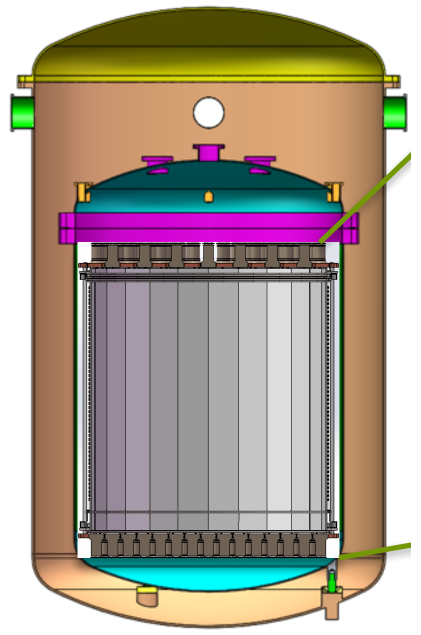
- DARWIN (50 t LXe), ARGO (300t LAr)
- Future merger of DARWIN and LZ to build/operate G3 experiment (MoU)

Physics reach

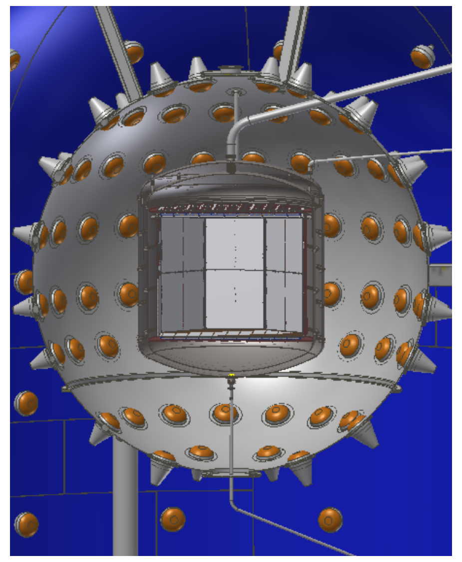
- 5σ discover sensitivity will reach 3TeV Wino DM scenario (thermal DM)



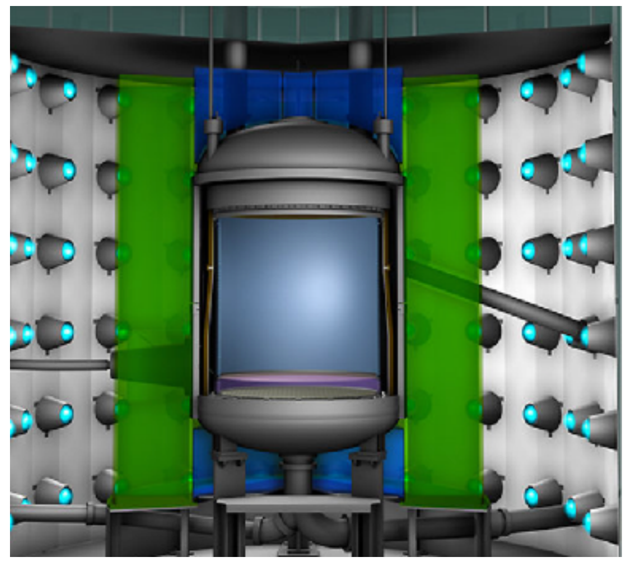
XENONnT: 8.6 t LXe
Data taking 2021



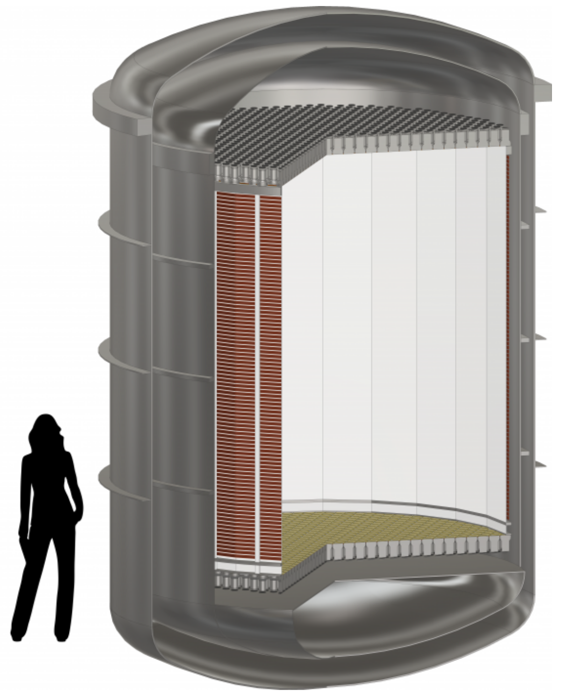
PandaX-4t LXe
Data taking 2021



DarkSide: 20 t LAr
Data taking 2023



LUX-ZEPLIN: 10 t LXe
Data taking 2021



DARWIN: 50 t LXe
Data taking ~2027/28

XENONnT/LZ

XENONnT @ LNGS

- 5.9 t LXe target

- Rn activity achieved: 1.7 μBq/kg (~13% of 1T)
  (still can reduce by a factor of 2)

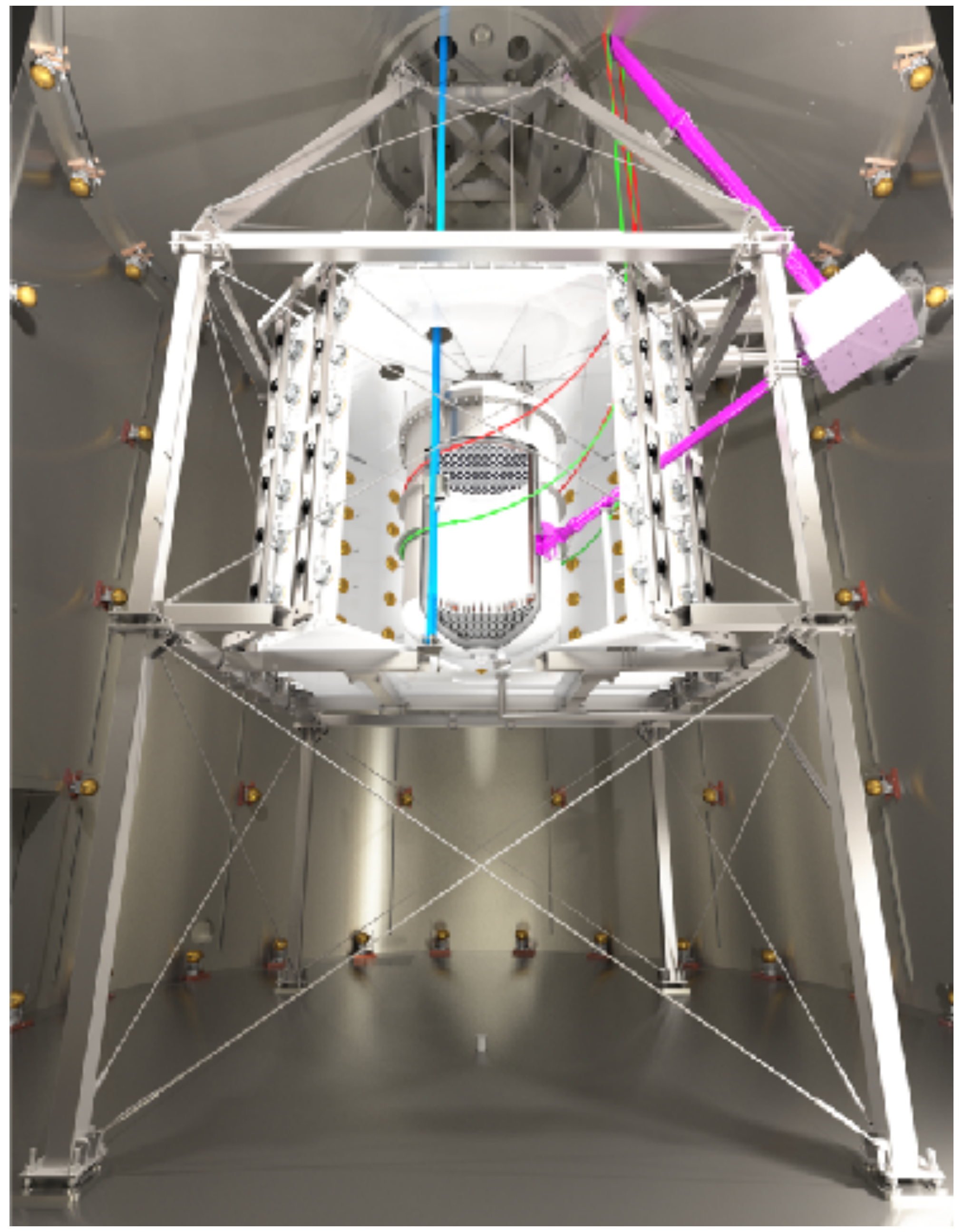
LZ @ SURF

7.0 t LXe target

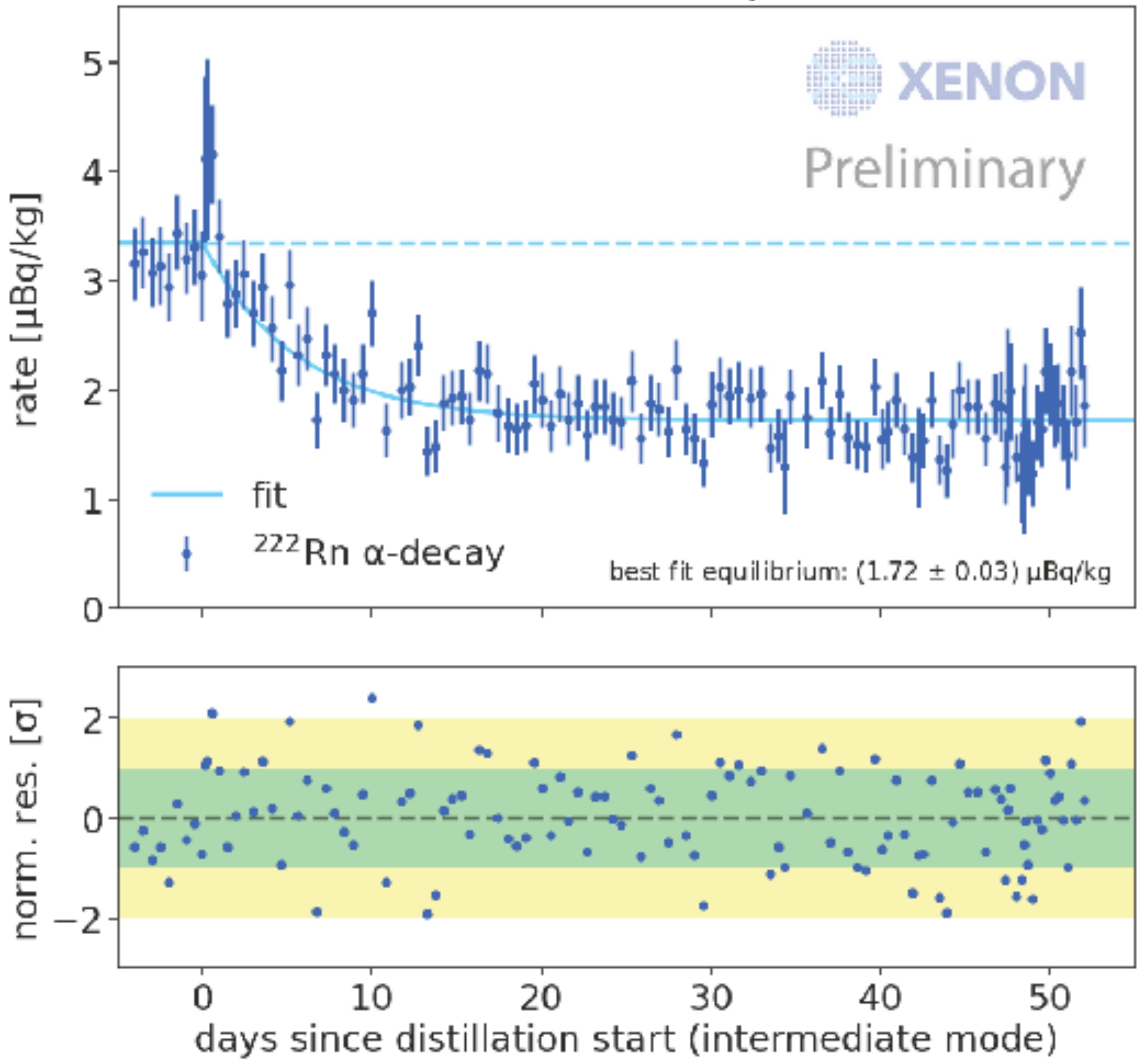
Rn activity (goal): 2 μBq/kg

Both experiments have started taking science data, and extensive analyses are underway

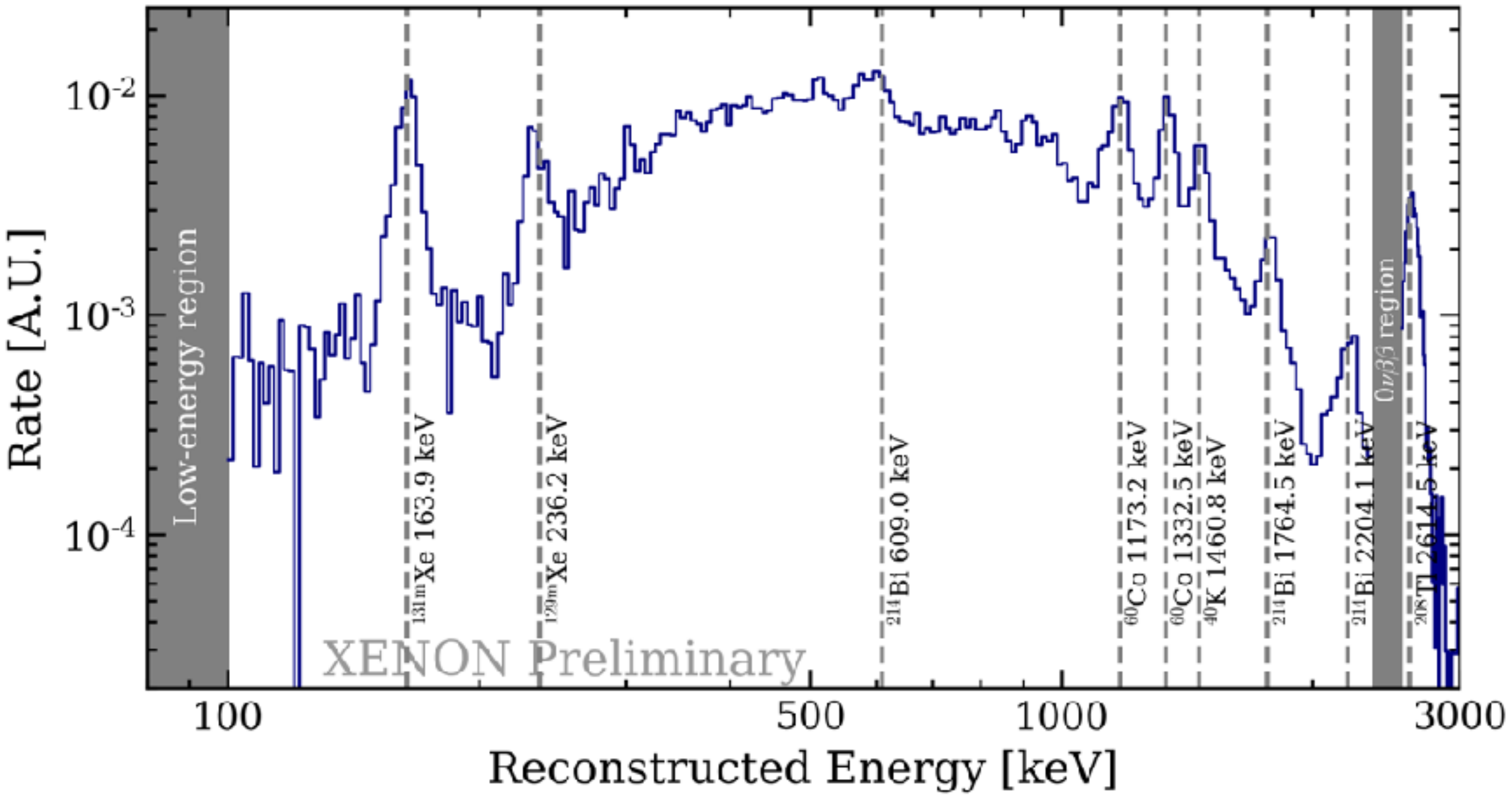
XENONnT



Rn activity@XENONnT



BG event rate@XENONnT



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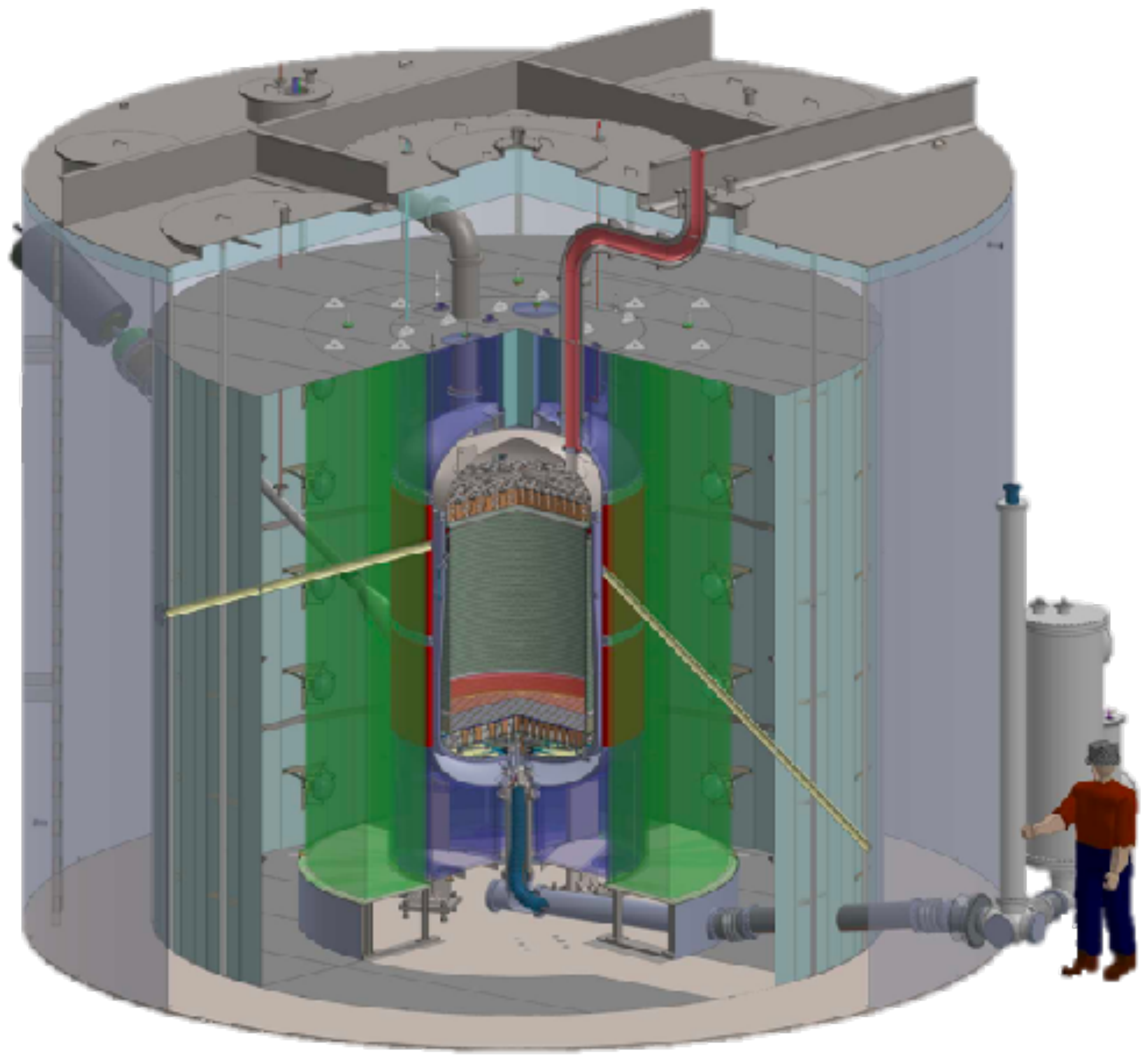
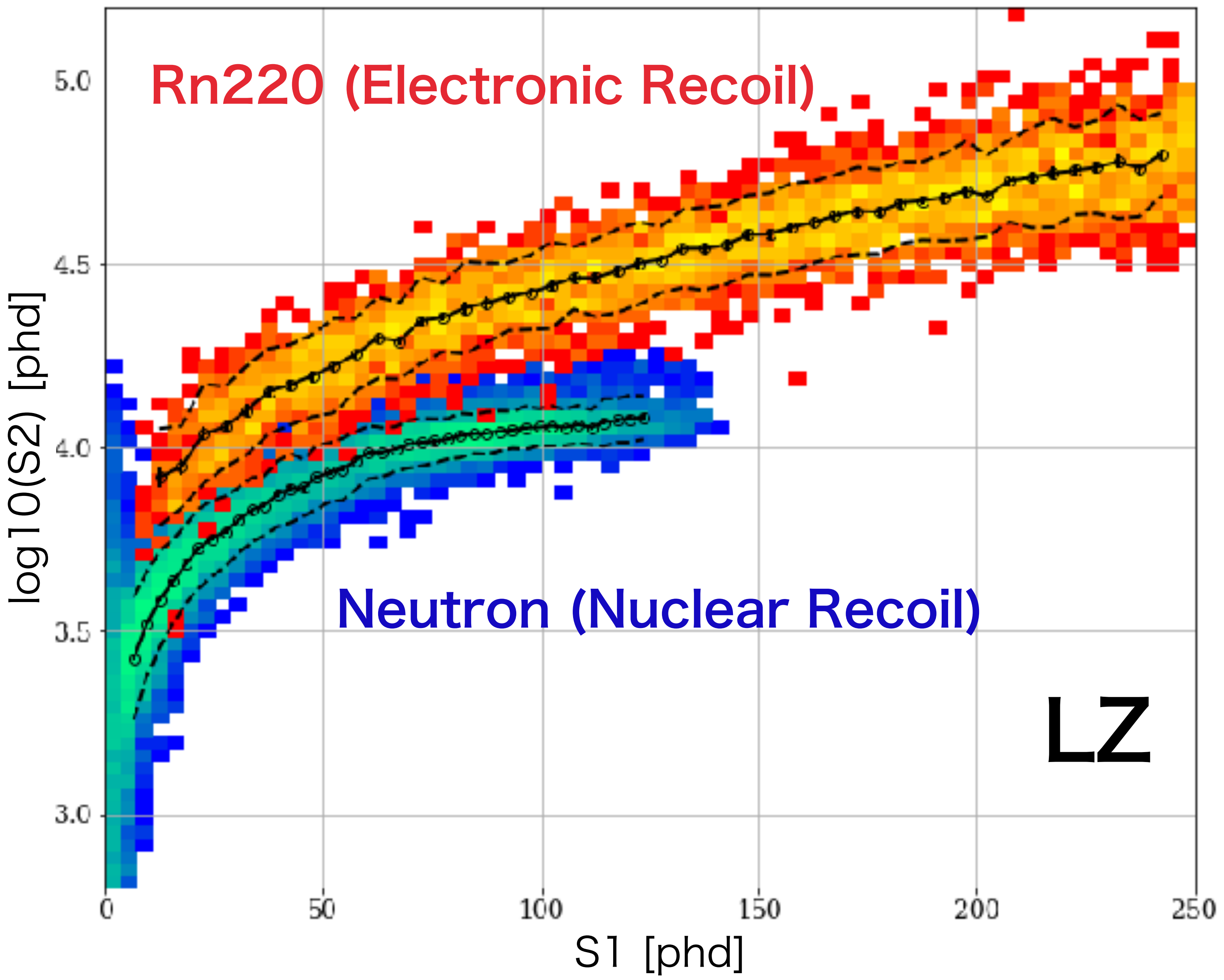


Plot from Amy Cottle@IOP HEPP 2022



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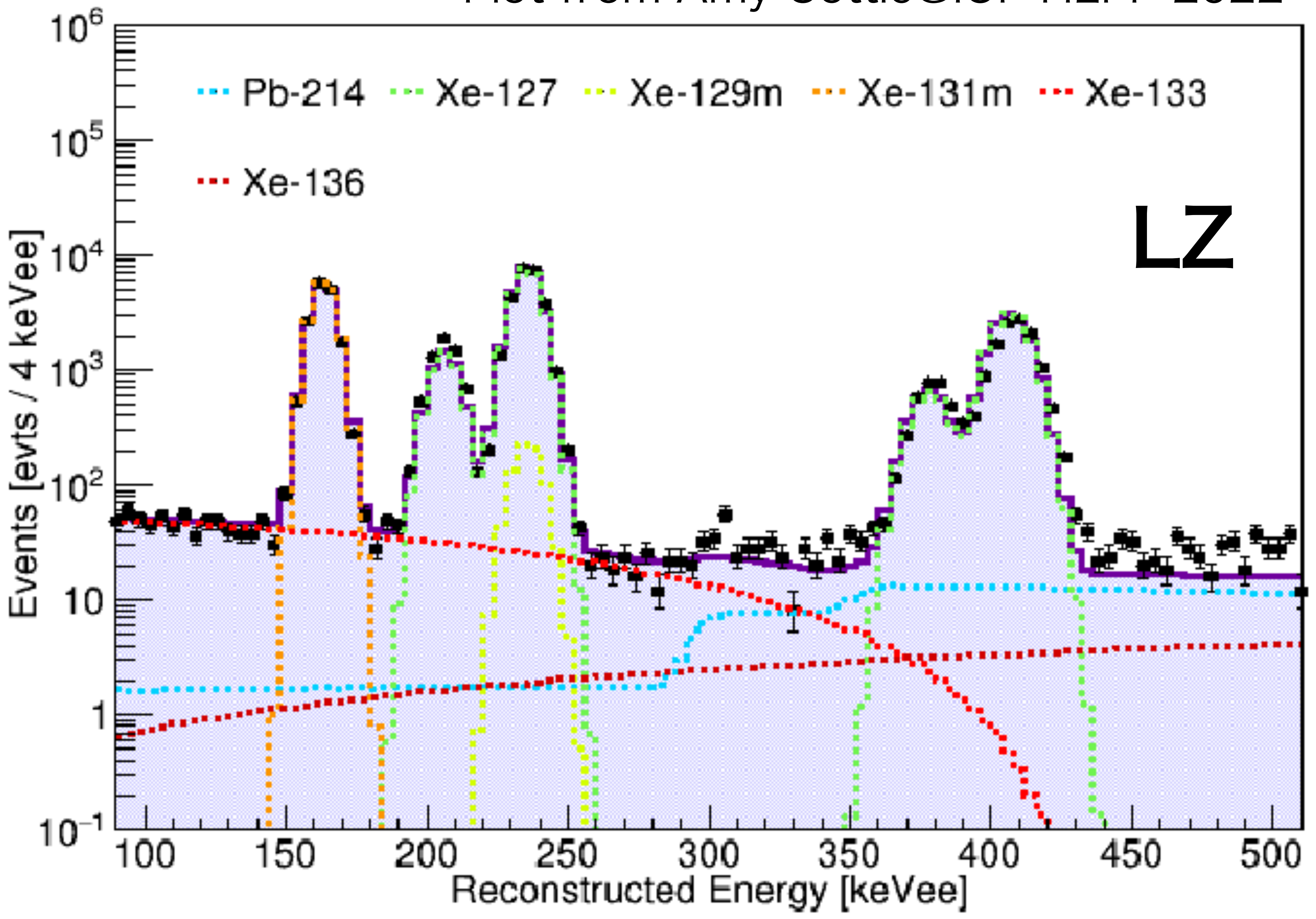

DARWIN: R&Ds

	XENON nT	DARWIN
Time	2020~2025	2027~
Diameter × Height	1.3 m × 1.5 m	2.6 m × 2.6 m
Total LXe	8.6 ton	50 ton
Fiducial volume	4 ton	40 ton
^{222}Rn BG level	1 μBq/kg	0.1 μBq/kg

BG level: 10% of XENONnT

Two demonstrators in commissioning stage:

- Xenoscope, 2.6 m tall (Zurich)
- Pancake, 2.6 m diam TPCs (Freiburg)

New low BG techniques being developed in Japan:

- new VUV SiPM with lower DC rate
- hybrid photosensor (PMT/SiPM)
- hermetic TPC for further Rn reduction

← Cooperation with Hamamatsu

L. Baudis et al, JINST 16, P08052, 2021

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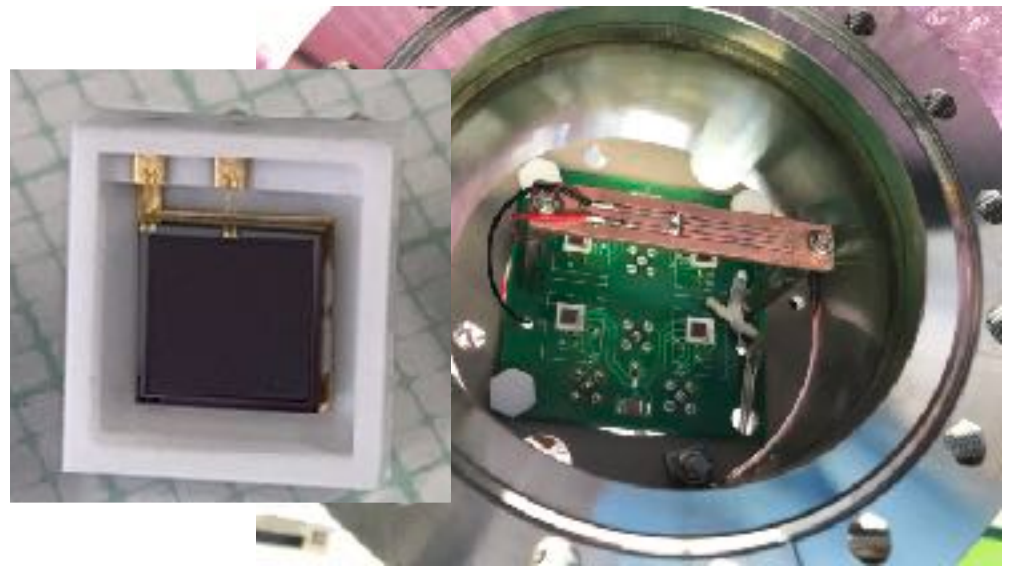
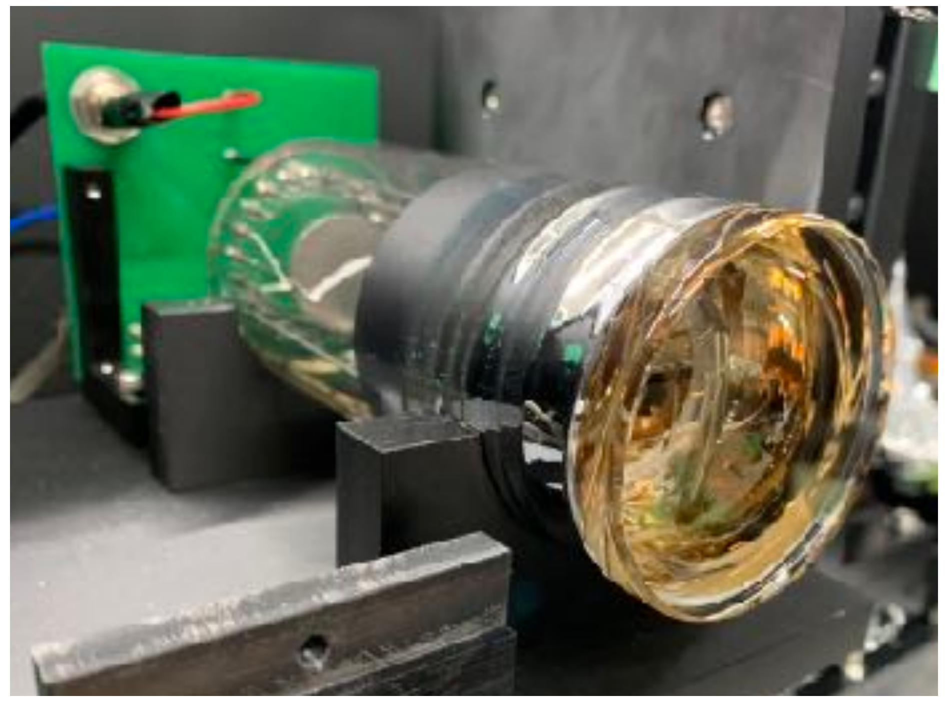
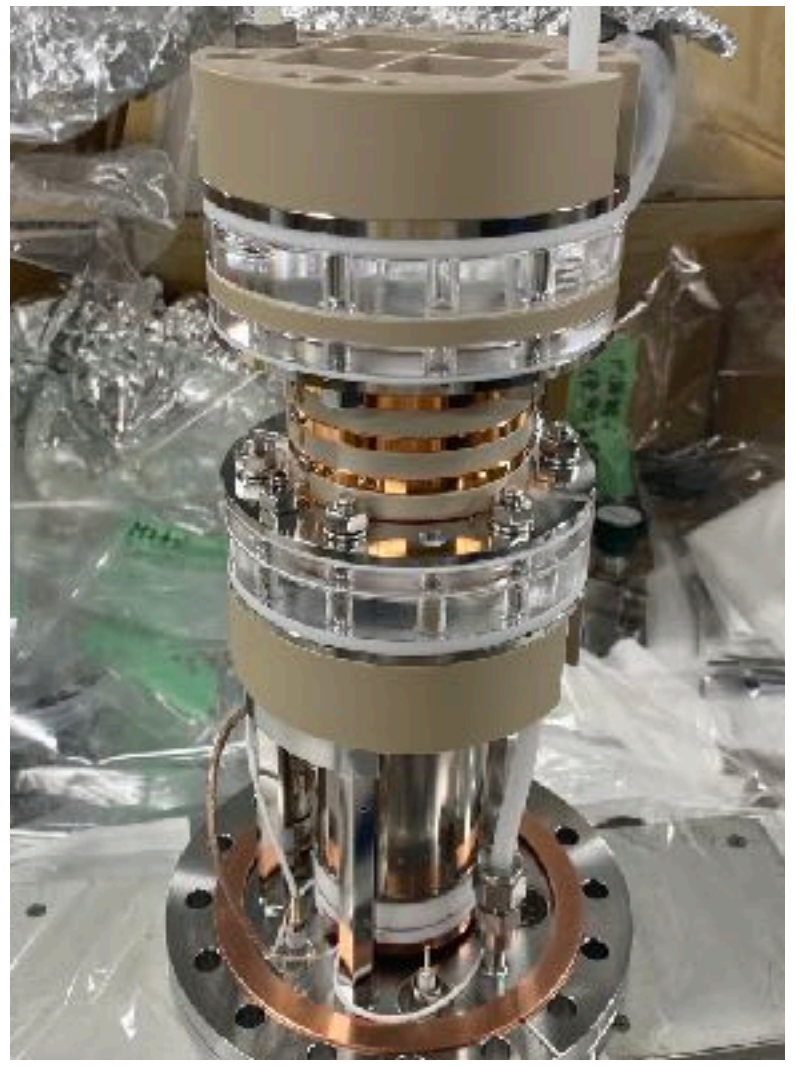
Test e- drift over 2.6 m (purification, high-voltage)

Test electrodes with 2.6 m diameter







Neutrino Fog

Sensitivity of the experiments: eventually limited by the neutrino backgrounds

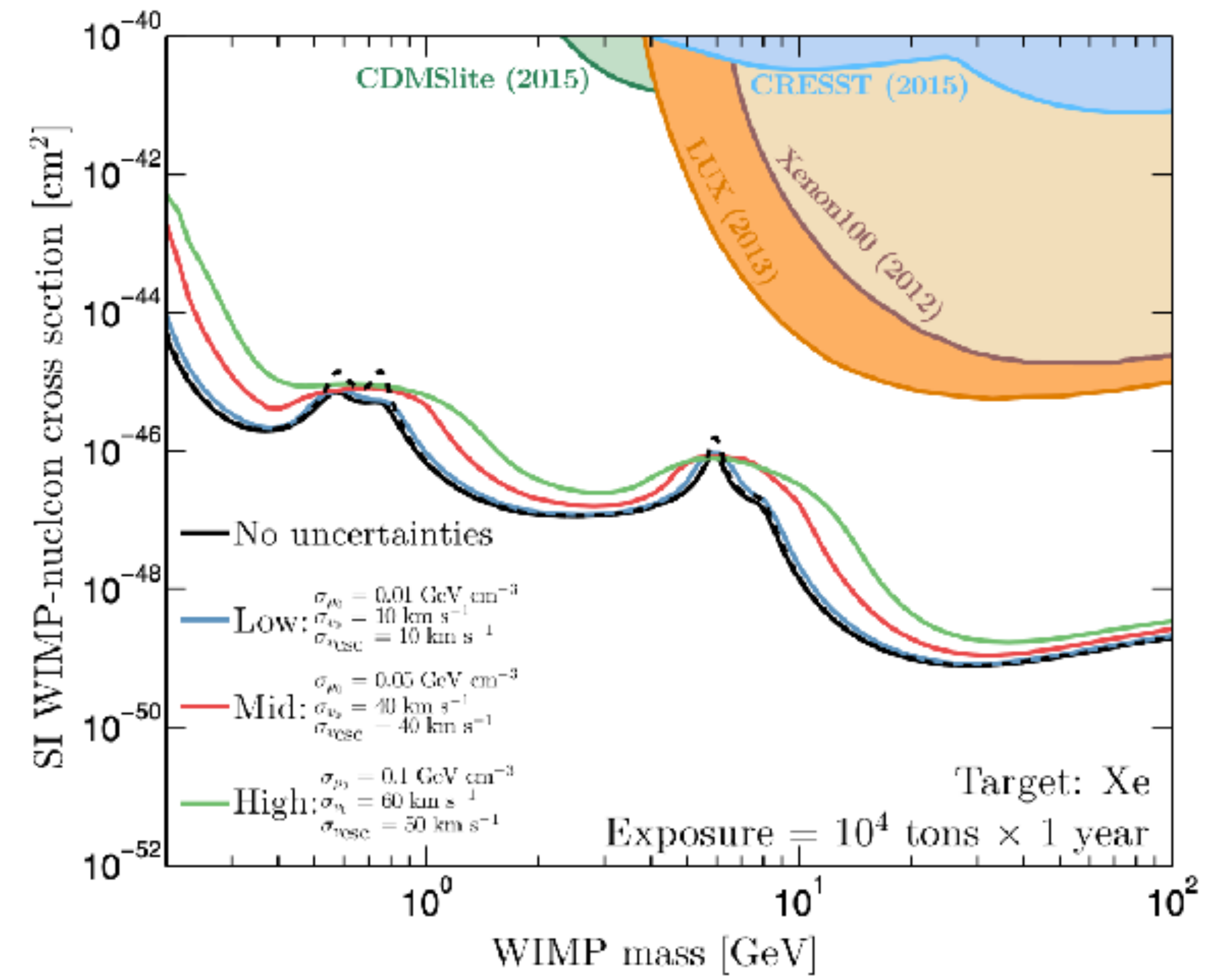
Discovery of a signal: only possible if excess in events > stat. fluctuations in the background

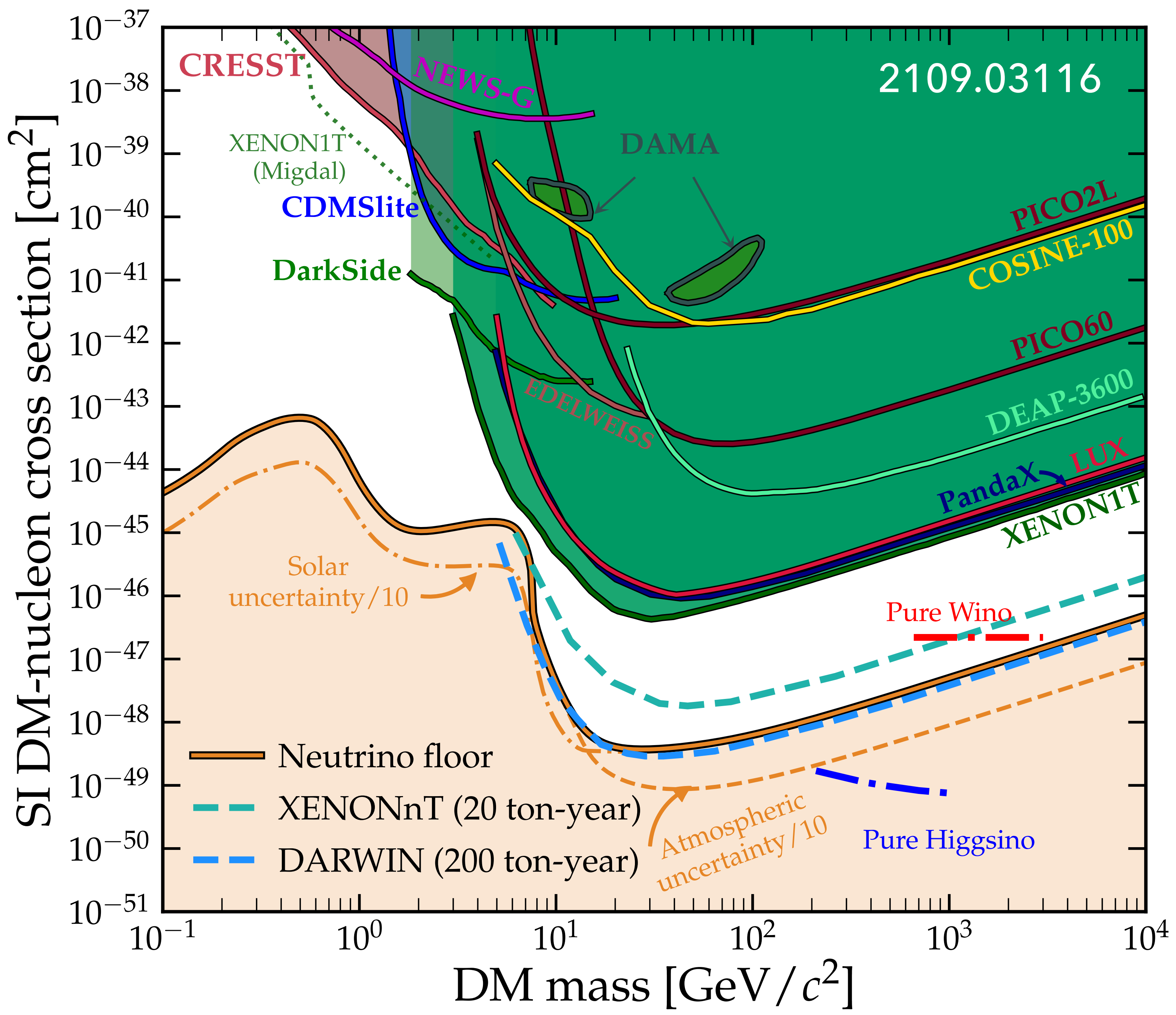
The "neutrino fog/floor“ depends on

- systematic uncertainty in neutrino fluxes (~2% in 8B,~20% for atmospheric neutrinos)

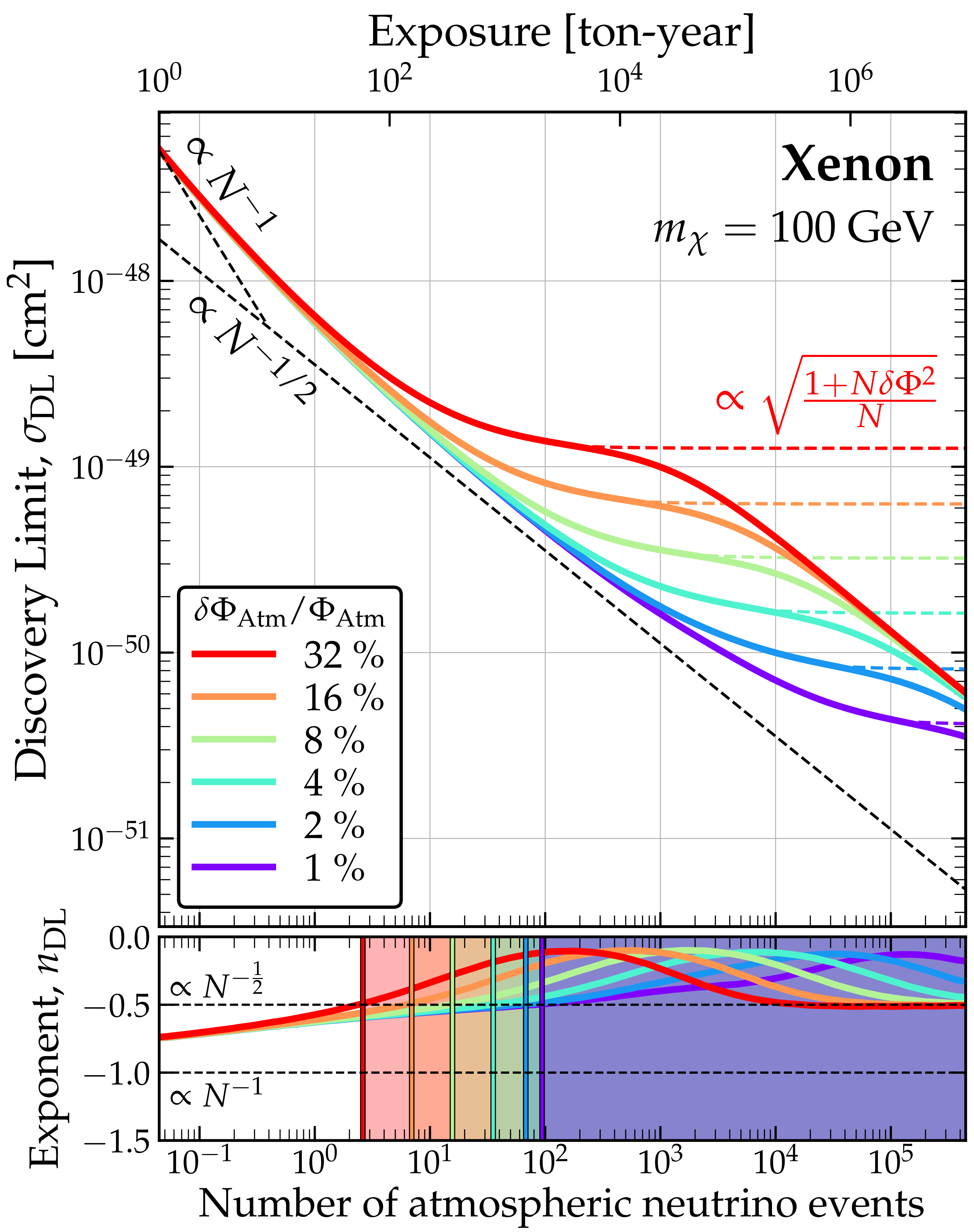
- astrophysics inputs for the DM signal: halo model

C. A. J. O'Hare PRD 94, 2016





C. A. J. O'Hare PRD 102, 2020



Direct Dark Matter Detection: Past/Present/Future

Spin-independent cross section upper limits at 60 GeV WIMP mass

10^{-41} cm^2 in ~1998 to few x 10^{-47} cm^2 in ~2018

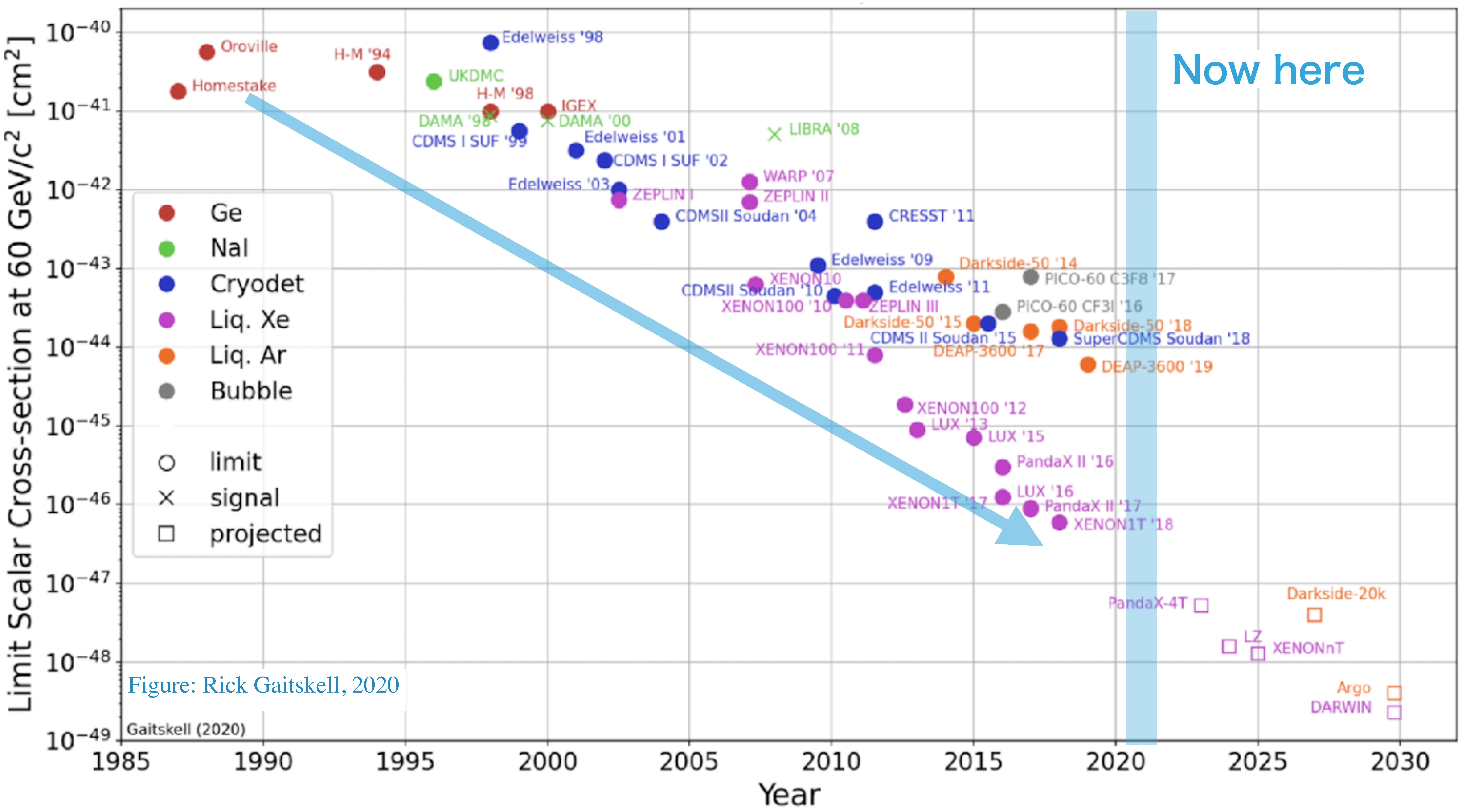


Figure: Rick Gaitskell, 2020

Exciting Future for Direct Detection

very diverse experimental landscape – many different projects

aim at closing most interesting parameter space in the next decade(s)