Beyond Standard Model Searches with Liquid Xenon Detectors

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Beyond the Standard Model Workshop
Chung-Ang University
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Beyond Standard Model Searches

Probing the nature of dark matter, neutrinos, and fundamental symmetries.

- Galactic sources: dark matter (WIMPs, dark photons, axion-like particles)
- Solar sources: axions, neutrinos
- Detector as source: neutrinoless double beta decay

Liquid xenon time projection chambers *(underground!)*

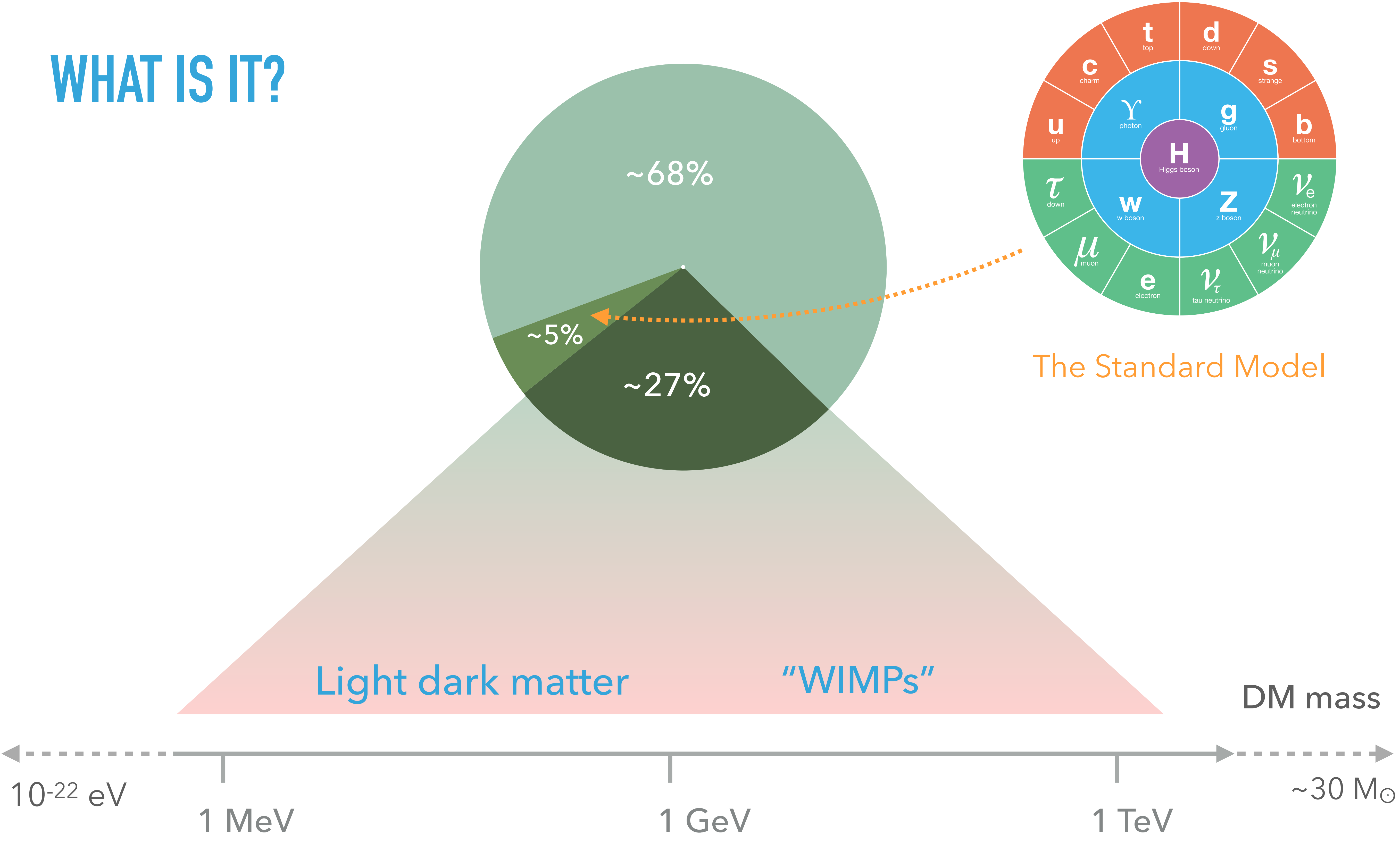
- Accelerator beam sources: muon decay ($\mu \to e\gamma$), neutrinos

Today's talk

- Dark Matter - Weakly Interacting Massive Particle (WIMP) searches have motivated the detector development
- Liquid xenon (LXe) time projections chamber (TPCs) detection principle
- Probing dark matter beyond the standard WIMP
- Experimental status and future

Dark Matter

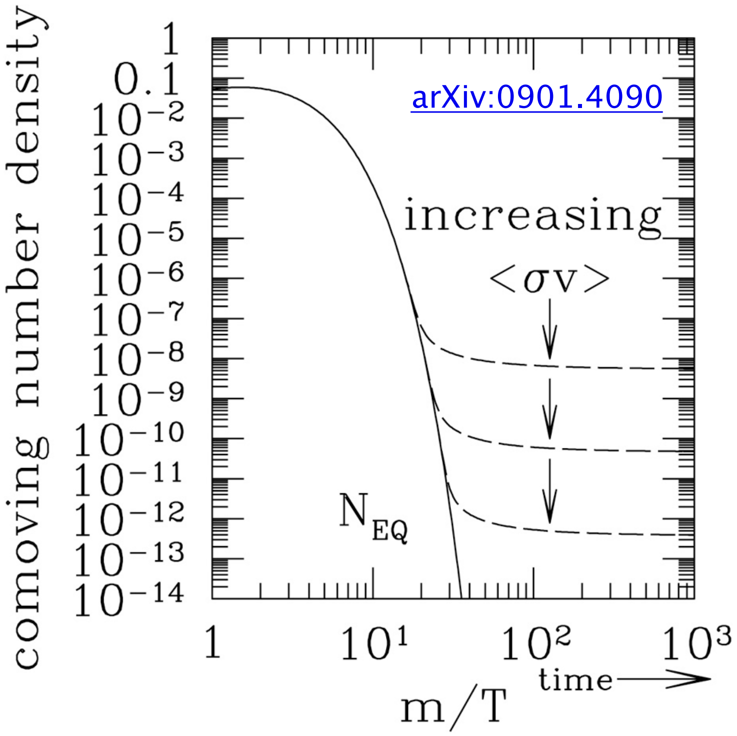
WHAT IS IT?


~68%
~5%
~27%
t top
d down
c charm
s strange
u up
b bottom
γ photon
g gluon
H Higgs boson
τ down
w w boson
z z boson
ν_e electron neutrino
μ muon
ν_μ muon neutrino
e electron
ν_τ tau neutrino
The Standard Model
Light dark matter
"WIMPs"
DM mass
10^{-22} eV
1 MeV
1 GeV
1 TeV
~30 $M_\odot$

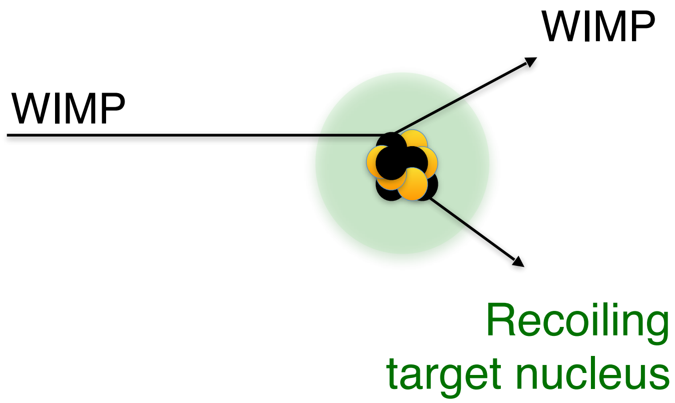
~ 80 orders of magnitude in mass!

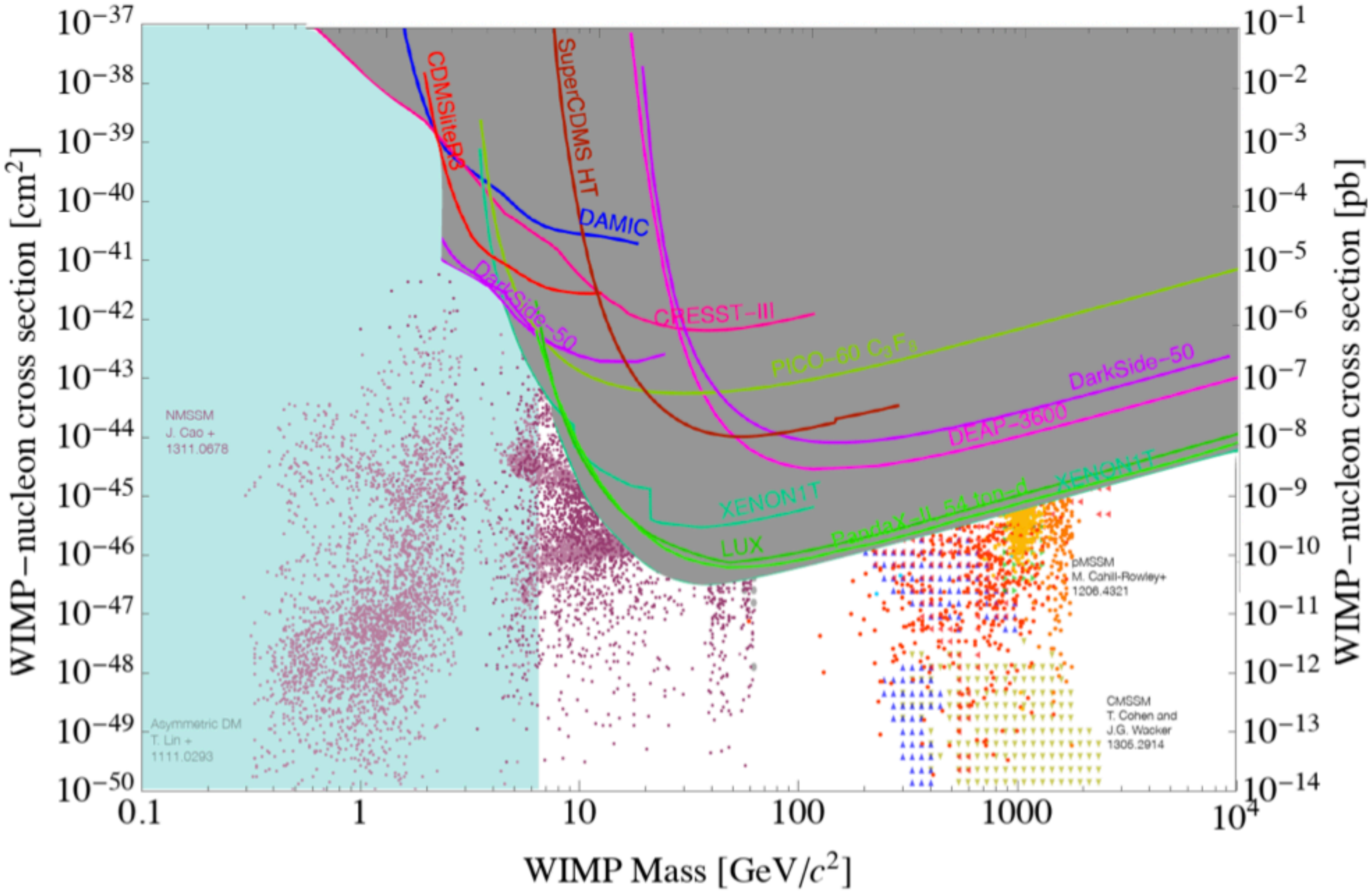
Figure: L. Baudis

The call of the WIMP



relic density at freeze-out





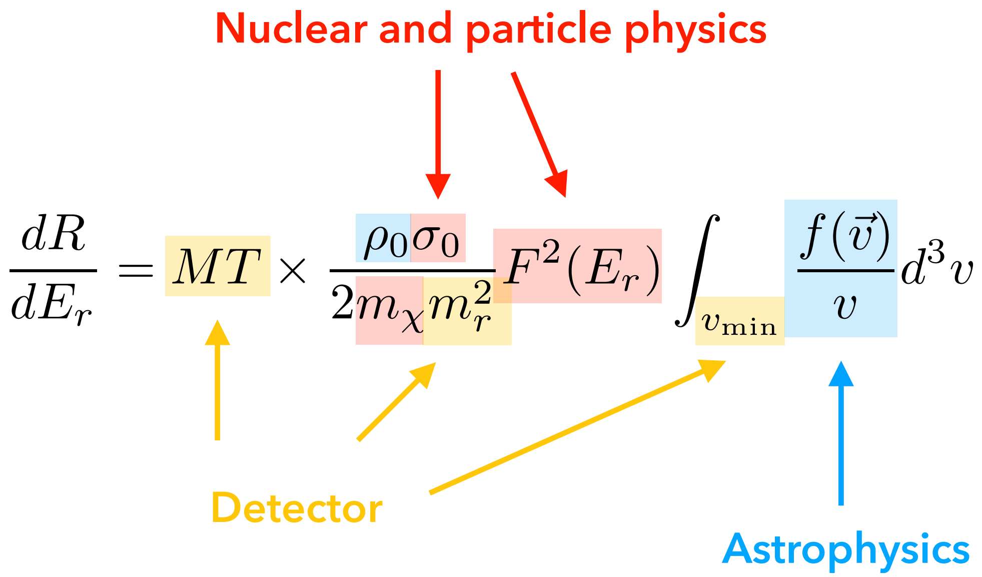
theory-driven search space for WIMP-nucleon interactions

J. Cooley, arXiv:2104.07634 (2021)

- favoured by supersymmetry (Beyond Standard Model): new physics expected at these masses and with **weak-scale cross section** (thermal relic - "**WIMP miracle**")
- can look for elastic scattering of WIMPs off of target nuclei (quark level, mediated by Higgs or Z boson)

WIMP rates and parameter space

Expected differential event rate



Nuclear and particle physics

$$\frac{dR}{dE_r} = MT \times \frac{\rho_0 \sigma_0}{2 m_\chi m_r^2} F^2(E_r) \int_{v_{\min}} \frac{f(\vec{v})}{v} d^3v$$

Detector

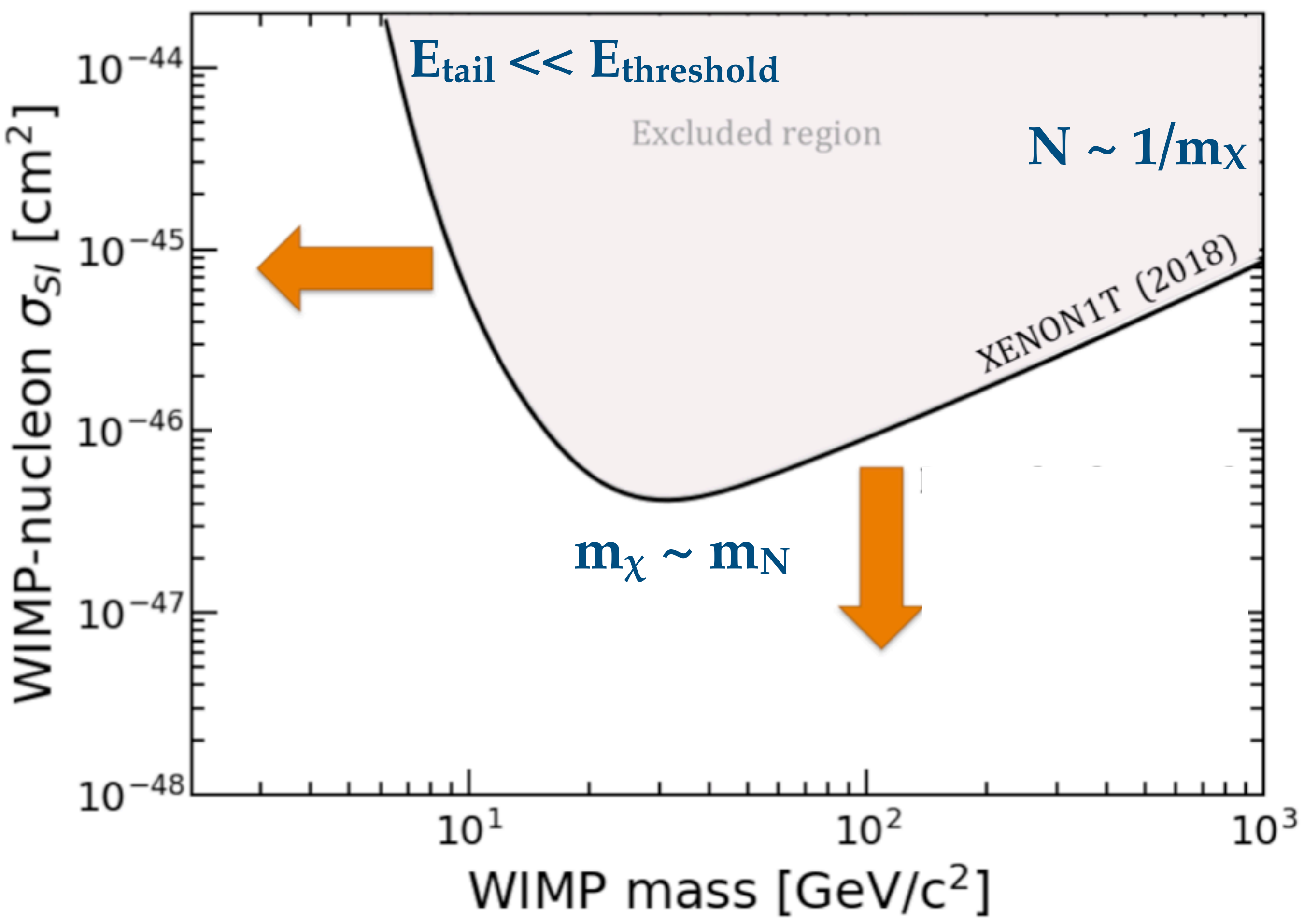
Astrophysics

WIMP masses in the range of 10 - 1000 GeV c^{-2} typically yield recoil energies of 1 - 100 keV.

Dependencies:

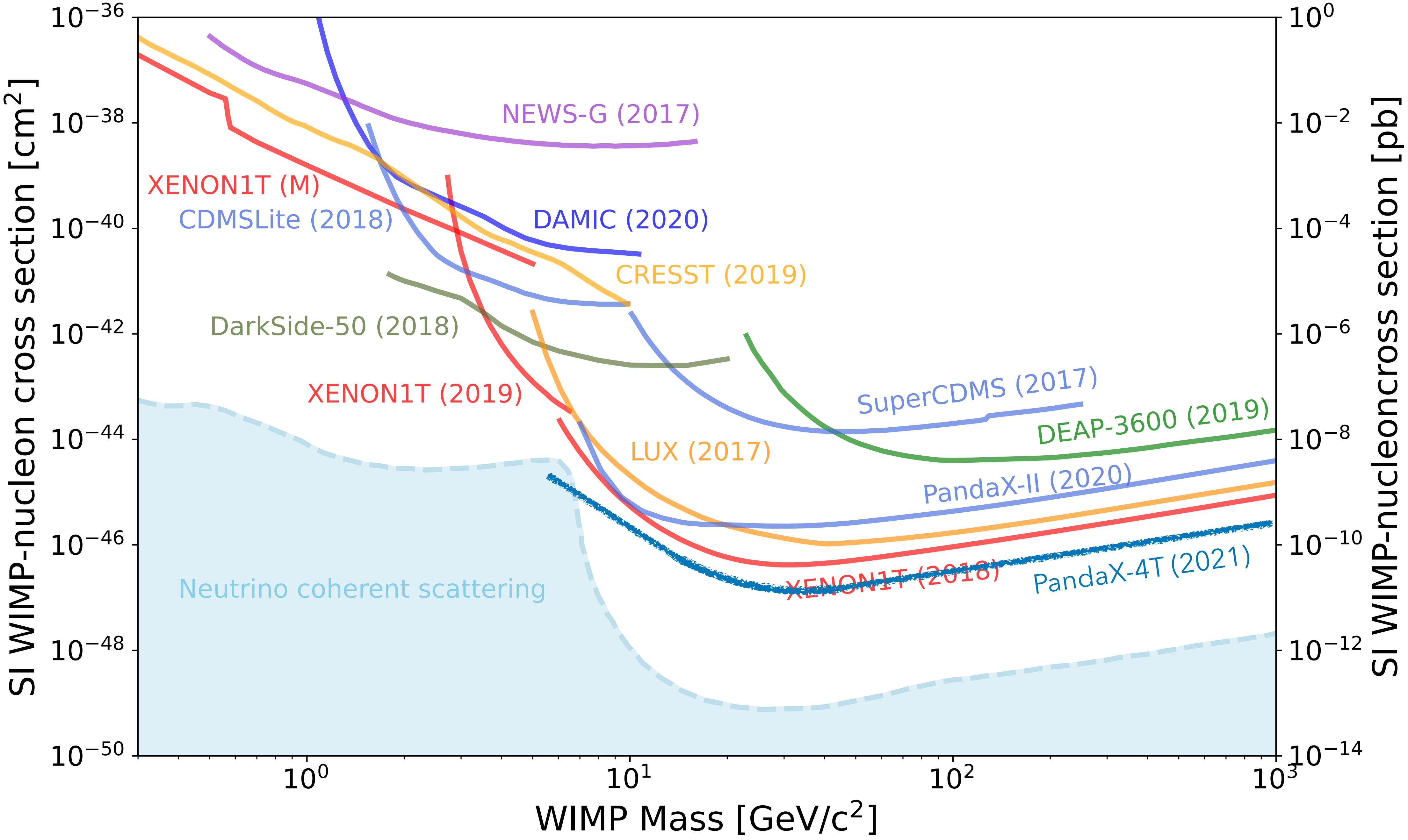
target atom (detectability of recoil energy)
detector effects (threshold, efficiency, resolution)

NR-WIMP cross section vs mass



increase exposure
lower background
discrimination power (PID)

Current limits: spin-independent WIMP



P.A. Zyla et al. (Particle Data Group) (2020)

PhysRevLett.127.261802 (2021)

Past, present, future

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

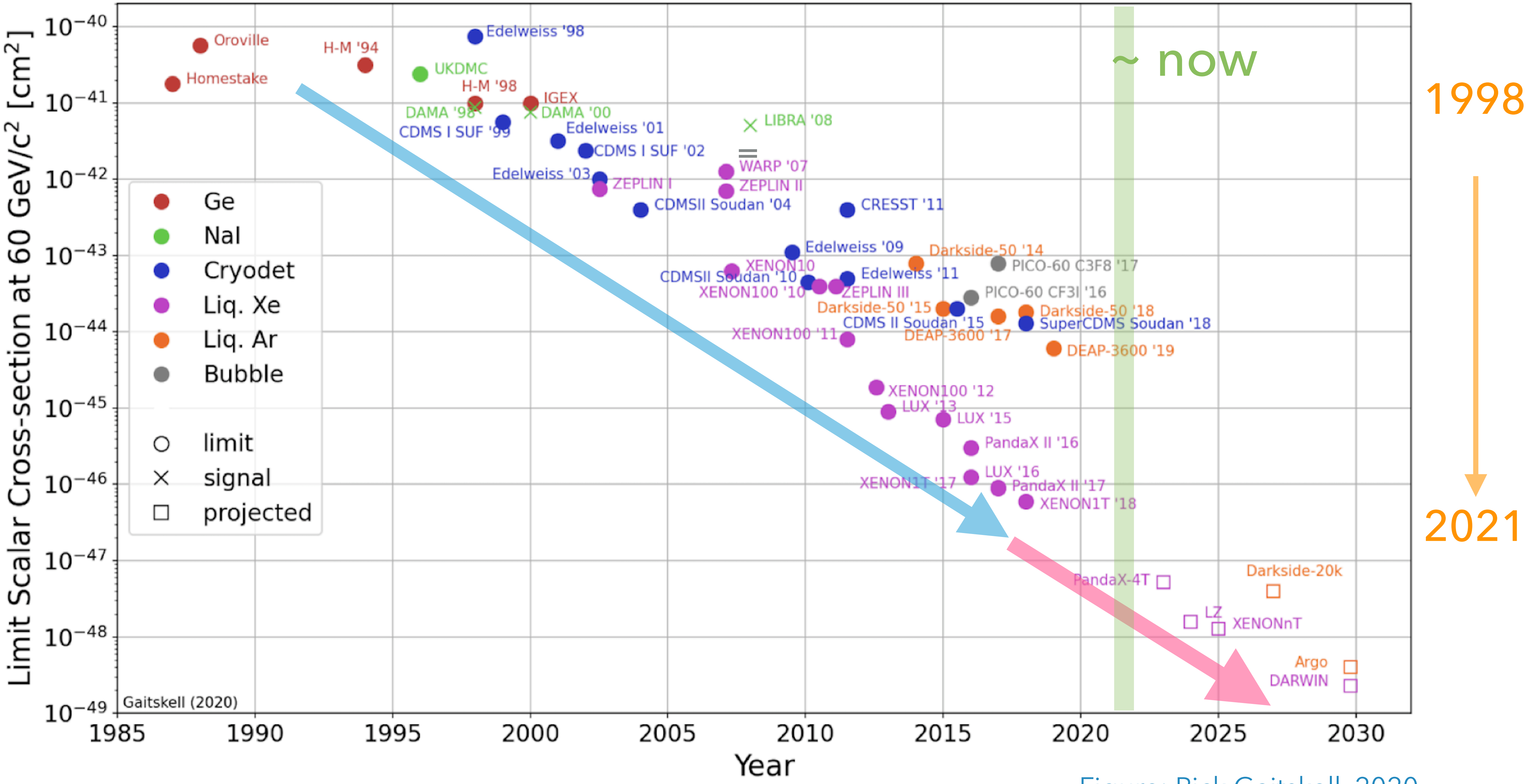


Figure: Rick Gaitskell, 2020

● **Xenon-based TPCs** □

The XENON dark matter project

15 kg XENON10

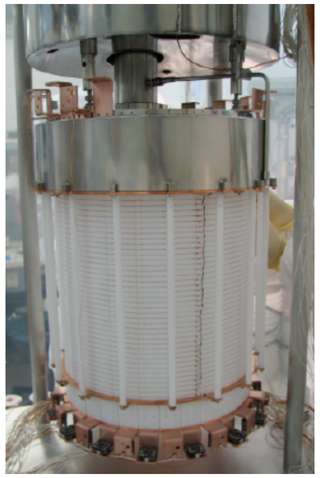
161 kg XENON100

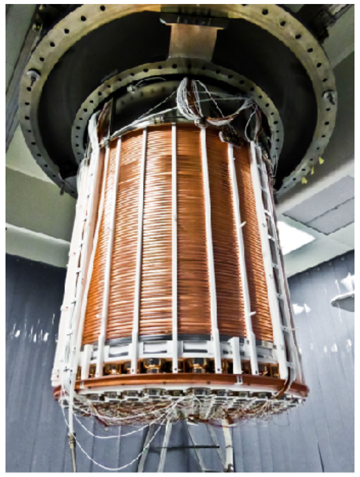
3.2 t XENON1T

8.6 t XENONnT

50 t DARWIN

2005 2007 2009 2016 2018 Now



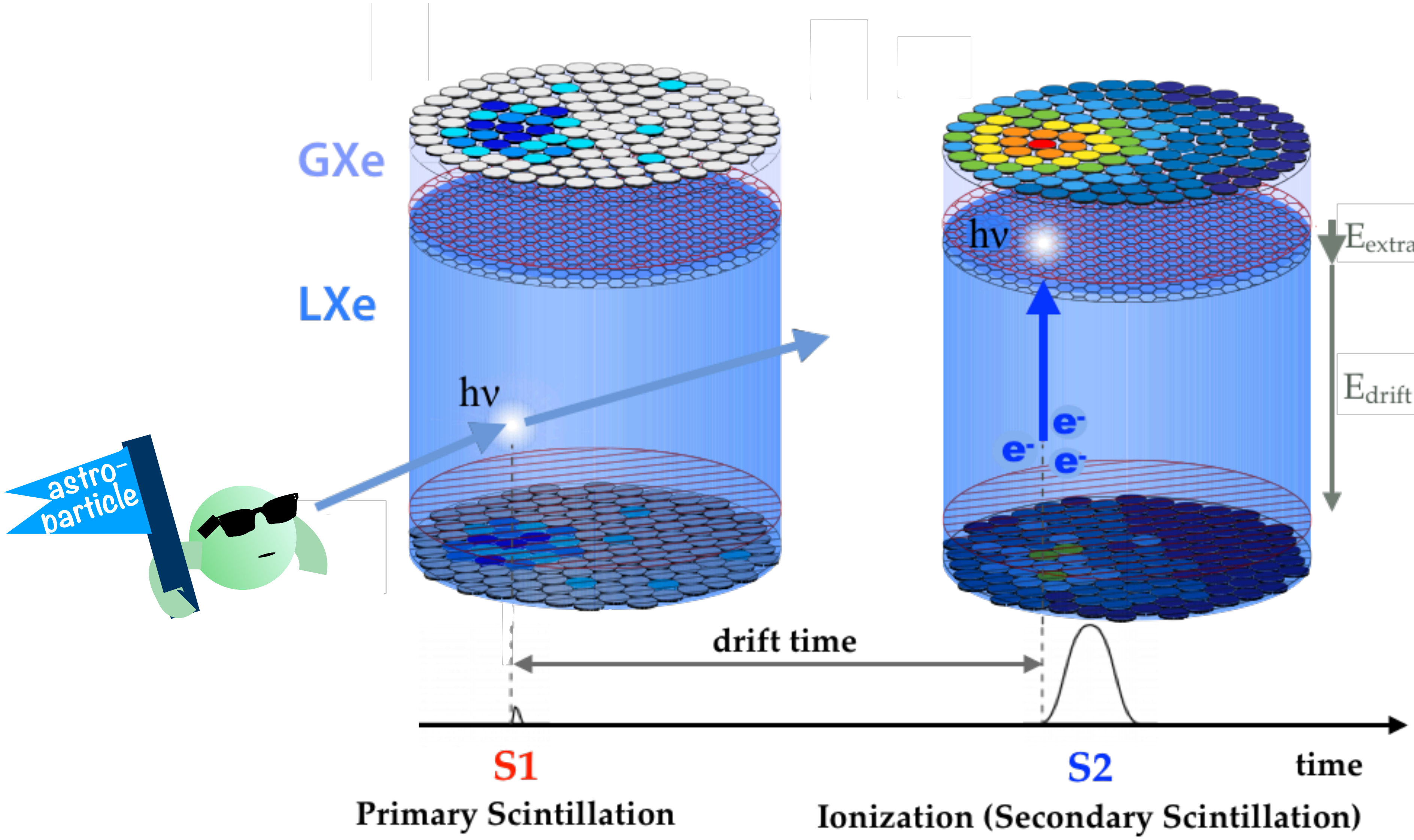


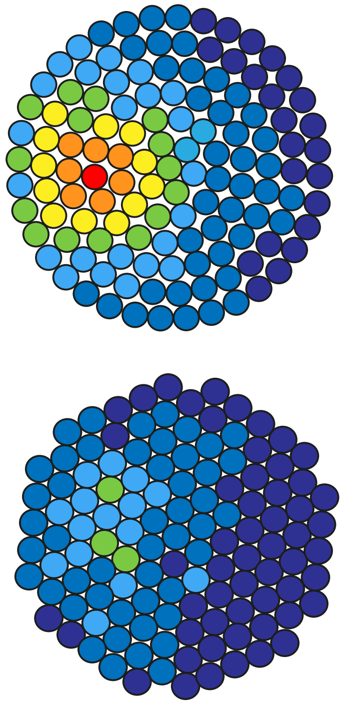
2 pixels

Exposure	0.87 kg • yr	48 kg • yr	1 t • yr	20 t • yr	**200 t • yr**
BG index	~ 1	~ 5 • 10^{-3}	~ 2 • 10^{-4}	~ 3 • 10^{-5}	

cnts/(keV • kg • yr)

TPC detection principle


GXe
LXe
hν
astro-particle
hν
e-
e-
e-
Eextraction
Edrift
drift time
time
S1
Primary Scintillation
S2
Ionization (Secondary Scintillation)



Position reconstruction (fiducialization)

- Cryogenic (-100 C) gas/liquid xenon (GXe/LXe)
- z-position from drift time
- x-y position from S2 hit pattern
- particle discrimination from S2:S1 ratio

Figure: XENON collaboration

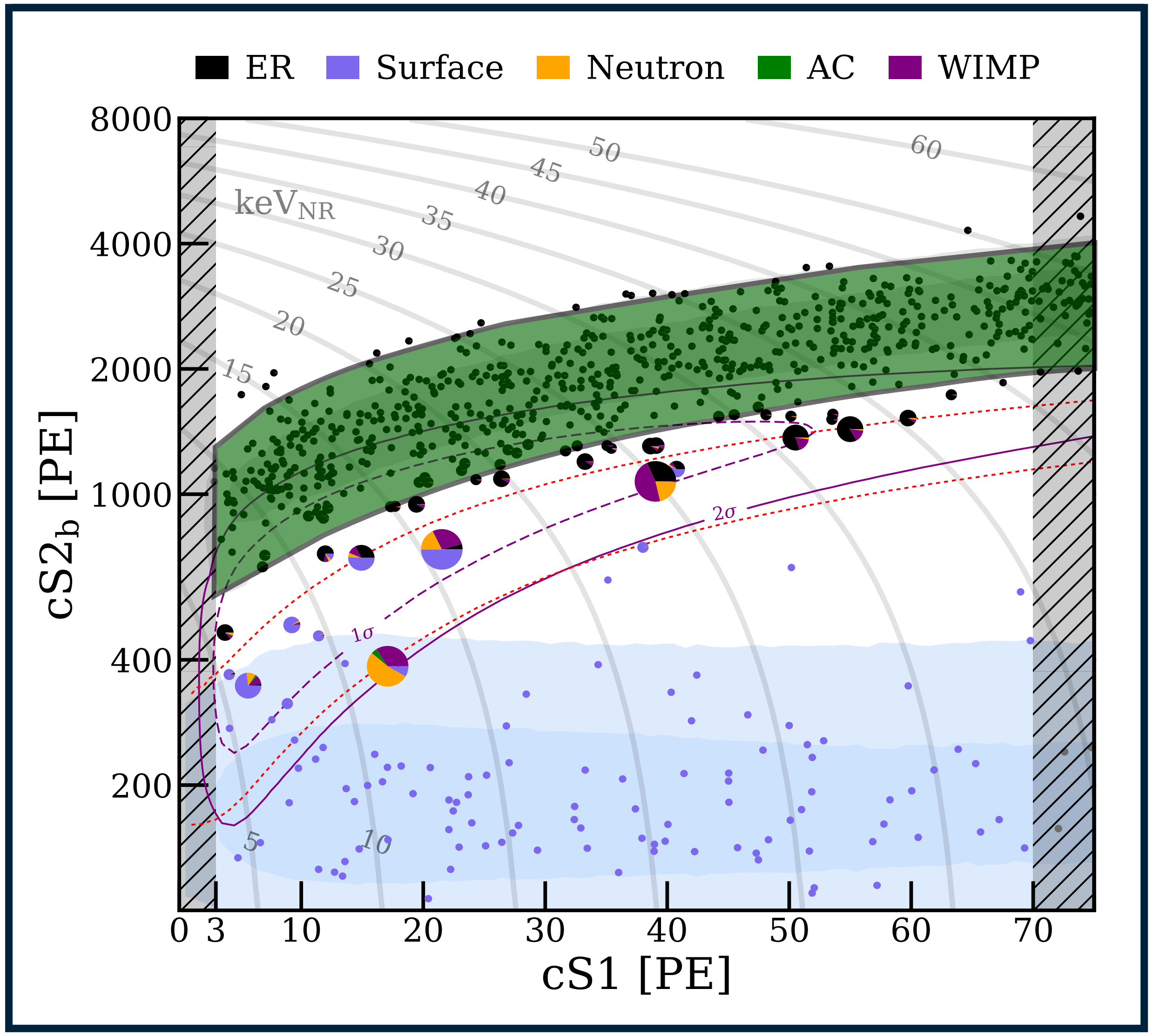
Particle discrimination

Electronic Recoils (ER)
gamma, beta backgrounds;

neutrino physics, solar axions, bosonic dark matter

Nuclear Recoils (NR)
neutron background;

WIMPs, coherent neutrino scattering



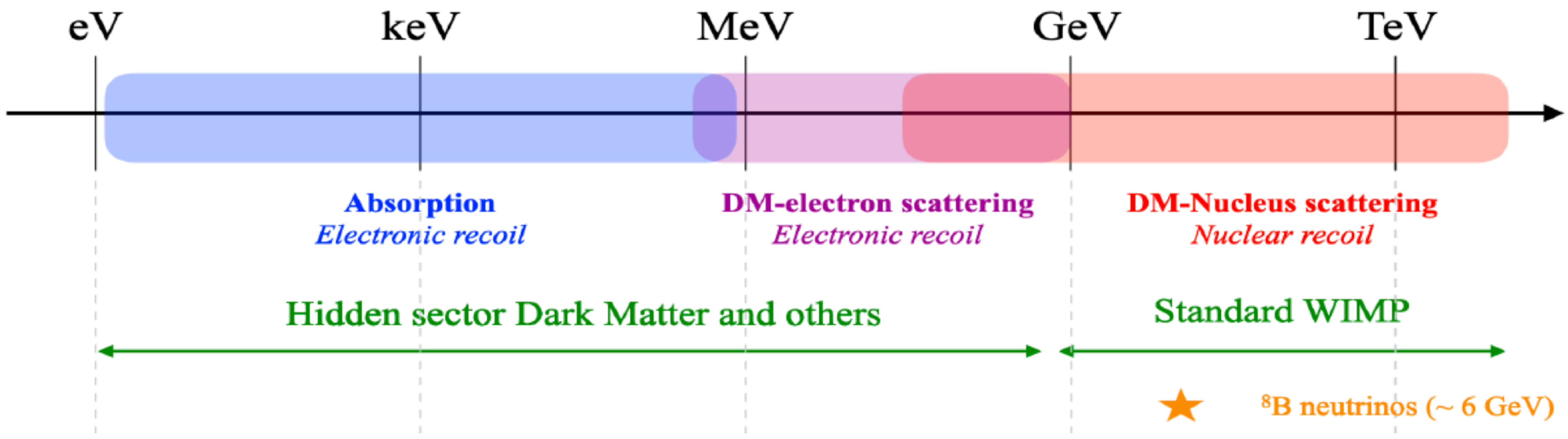
XENON1T achieved < 100 events/(t/yr/keV$_{ee}$)

Discriminate NR from ER events; candidates above small neutron and instrumental backgrounds.

Search for excess above known, well-modelled ER backgrounds.

XENON Collab., PRL 121, 111302 + PRL 123, 251801

Extending the search range


eV
keV
MeV
GeV
TeV
Absorption
Electronic recoil
DM-electron scattering
Electronic recoil
DM-Nucleus scattering
Nuclear recoil
Hidden sector Dark Matter and others
Standard WIMP
★ ^{8}B neutrinos (~ 6 GeV)

J. Cooley, arXiv:2104.07634 (2021)

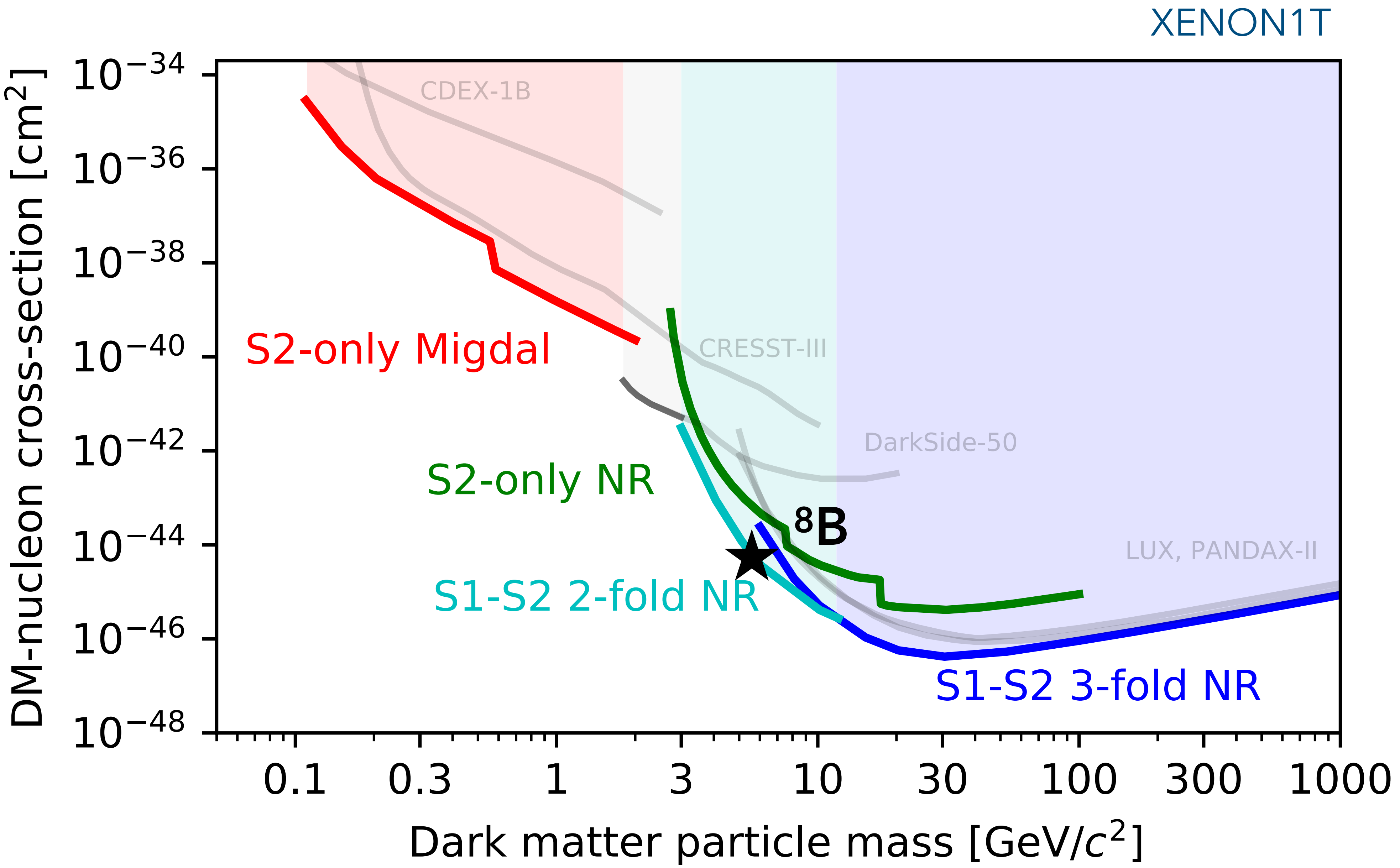
Nuclear recoil: the threshold is statistically limited by the prompt scintillation signal (S1):

- Lower the 3-fold PMT coincidence requirement to 2-fold
- Drop the S1 and use the ionisation (S2) only channel for limit setting

Electronic recoil:

- Set S2 limits assuming electronic recoils (no discrimination)
- Use S1, S2 anti-correlation and combine them (better event statistics)
- Reduce and model the ER backgrounds

DM-nucleon: lower thresholds

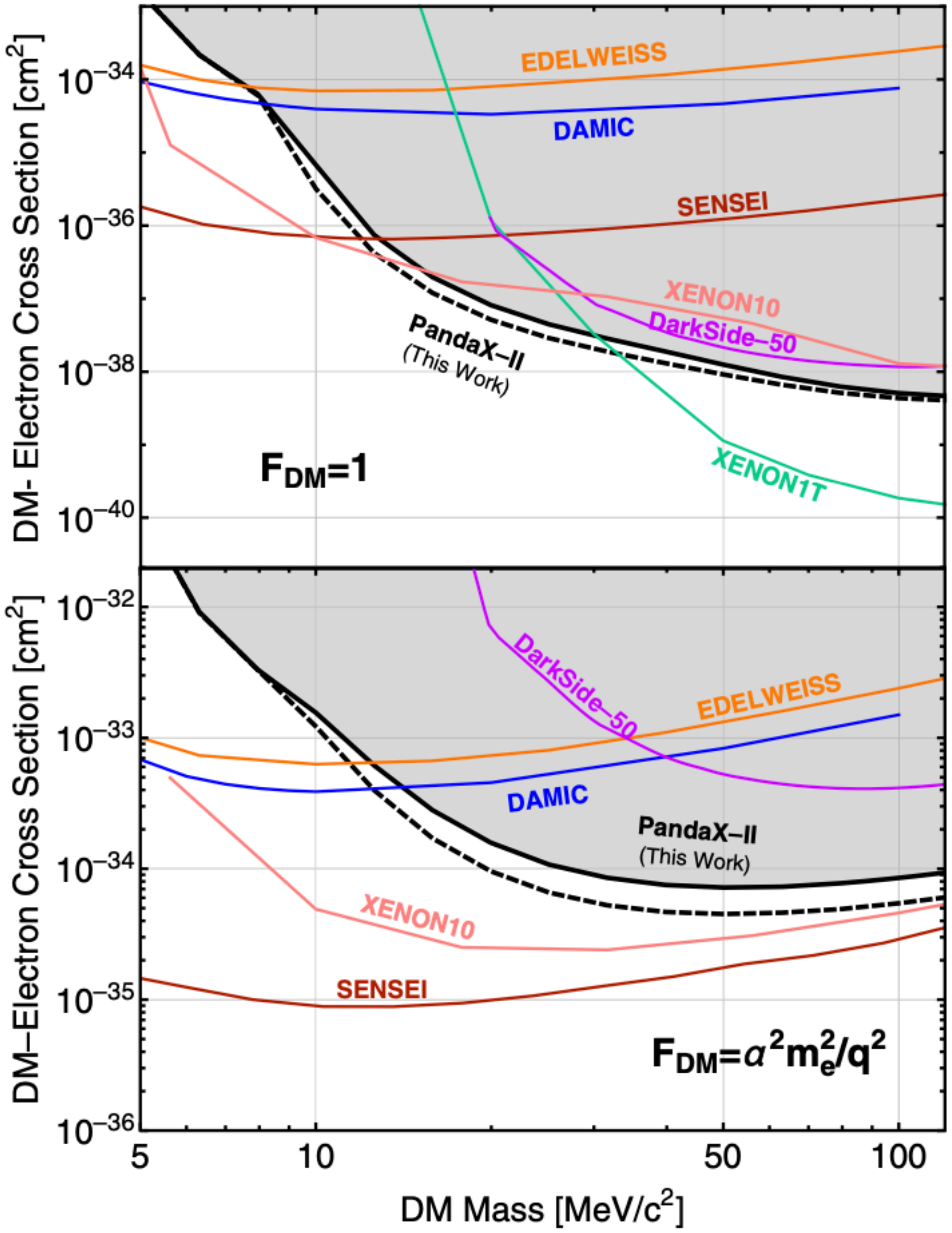


Can also look for secondary emission (Migdal effect) in S2-only data.

Phys. Rev. Lett. 126 (2021) 091301

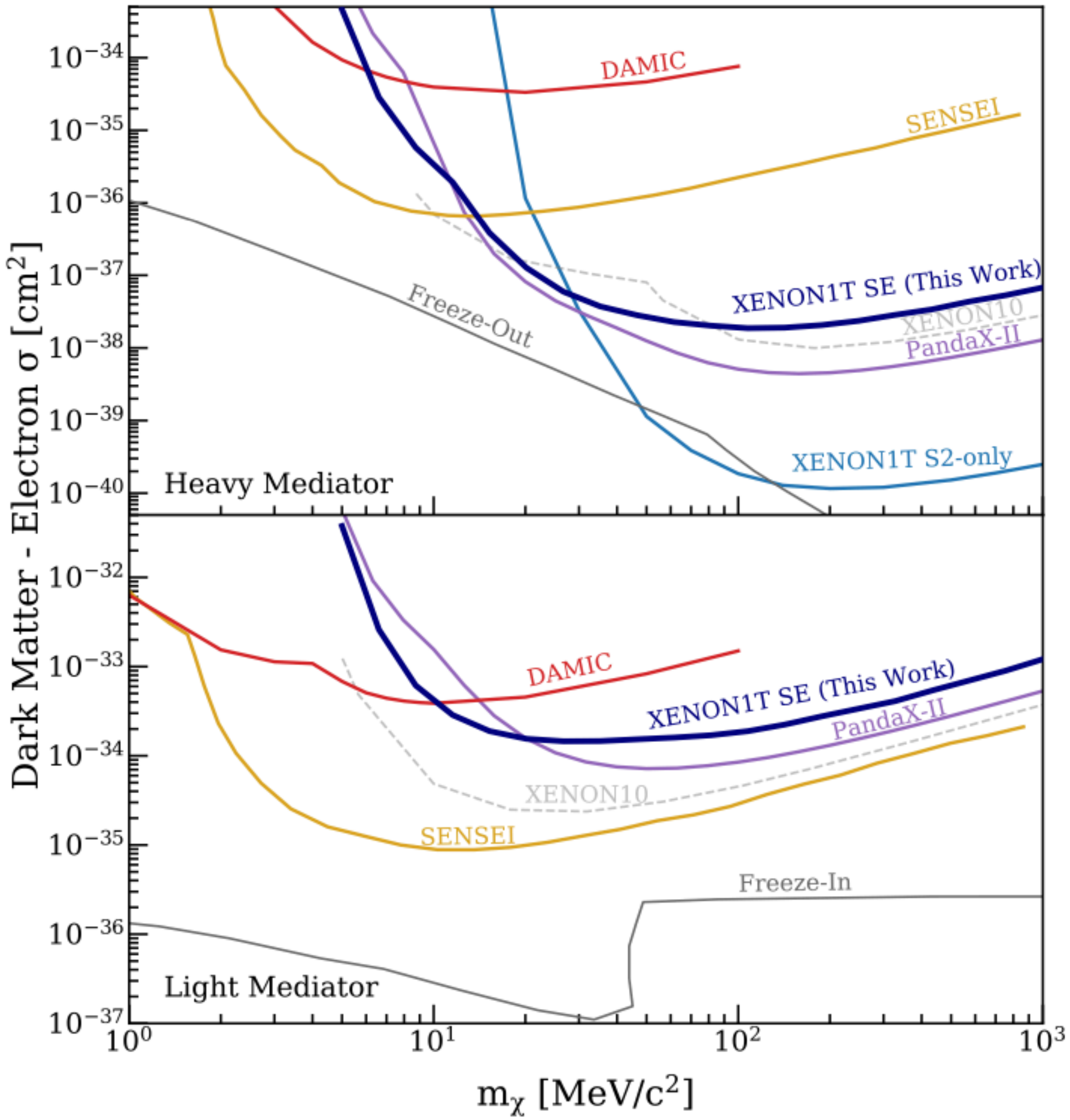
DM-electron: S2-only

PandaX-II



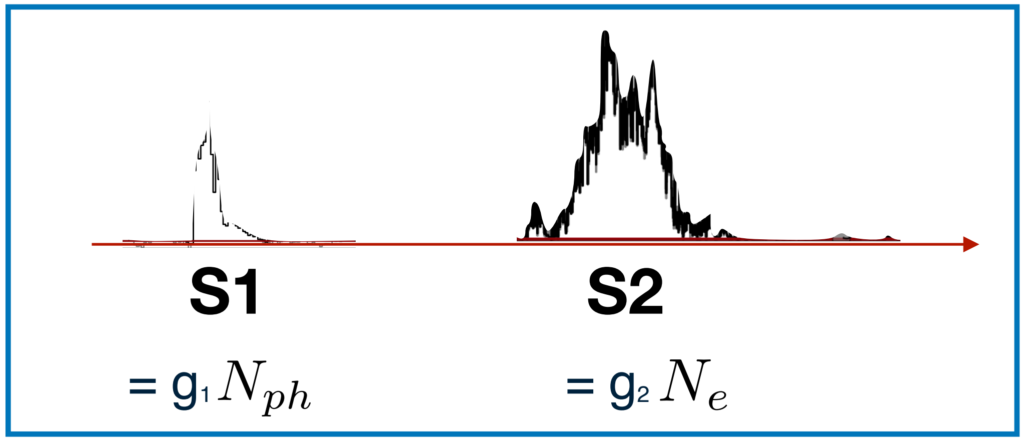
Phys. Rev. Lett. 126 (2021) 211803

XENON1T



arXiv:2112.12116v1

Electronic recoil: energy scale



S1 $= g_1 N_{ph}$ S2 $= g_2 N_e$

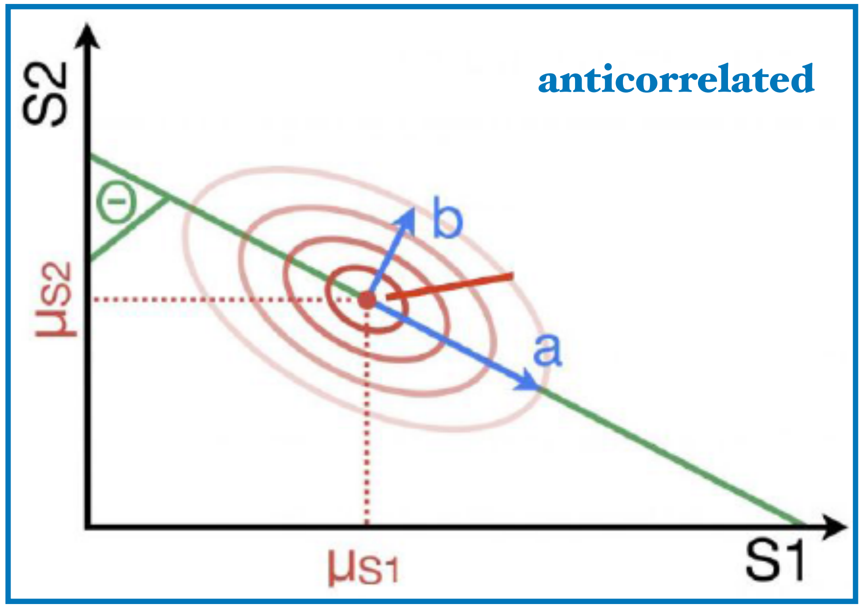
$$E = (N_{ph} + N_e) \cdot W$$

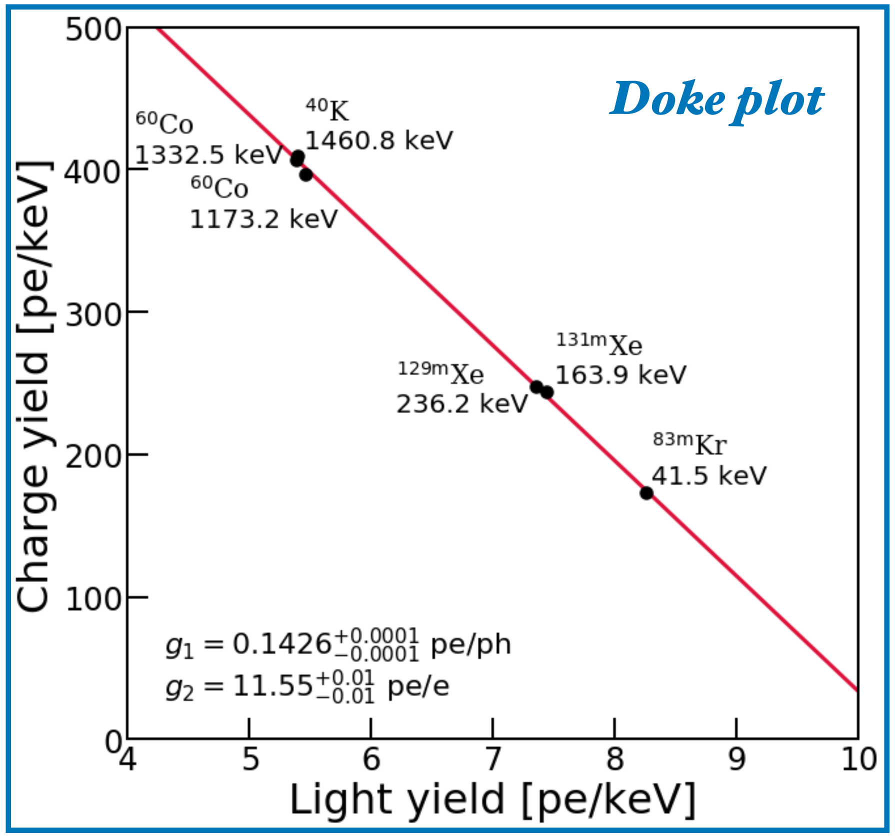
with *W* = 13.7 eV/quanta for xenon

g_1 and **g_2**:

detector-specific gain constants;

extract g_1/g_2 from calibration data


anticorrelated
S2
S1
Θ
b
a
μS2
μS1

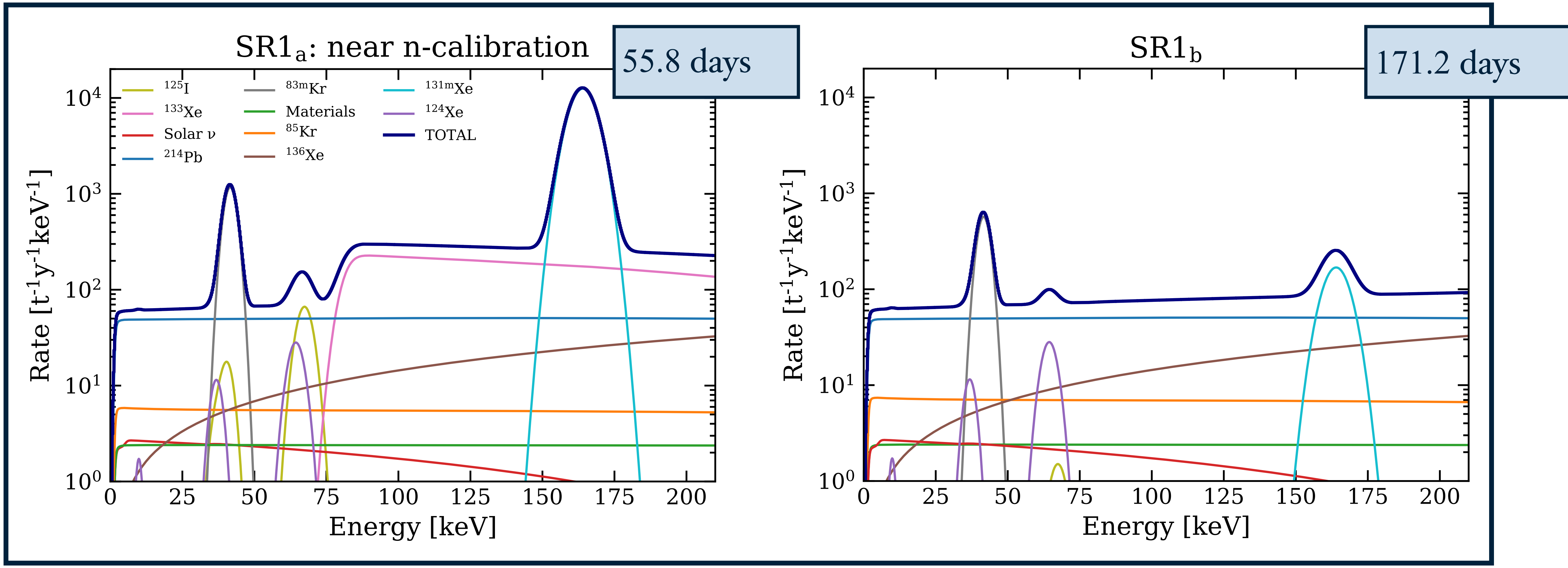


$$\boxed{\frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}}$$

g_1 and g_2 are used to reconstruct energy of each event

$$E = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$

Electronic recoil: backgrounds


SR1$_a$: near n-calibration

55.8 days

SR1$_b$

171.2 days

Background model B_0

Partitioned into two datasets and fit simultaneously

SR1$_a$: activated backgrounds, peaks

SR1$_b$: allows to constrain the dominant ^{214}Pb background at low energies

- Unbinned profile likelihood
- Likelihood of 2 partitions combined

Test statistic q for inference

$$\boxed{q(\mu_s) = -2\ln\frac{\mathcal{L}(\mu_s,\hat{\hat{\boldsymbol{\mu}}}_b,\hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\mu}_s,\hat{\boldsymbol{\mu}}_b,\hat{\boldsymbol{\theta}})}}$$

max. L with specified signal parameter μ_s

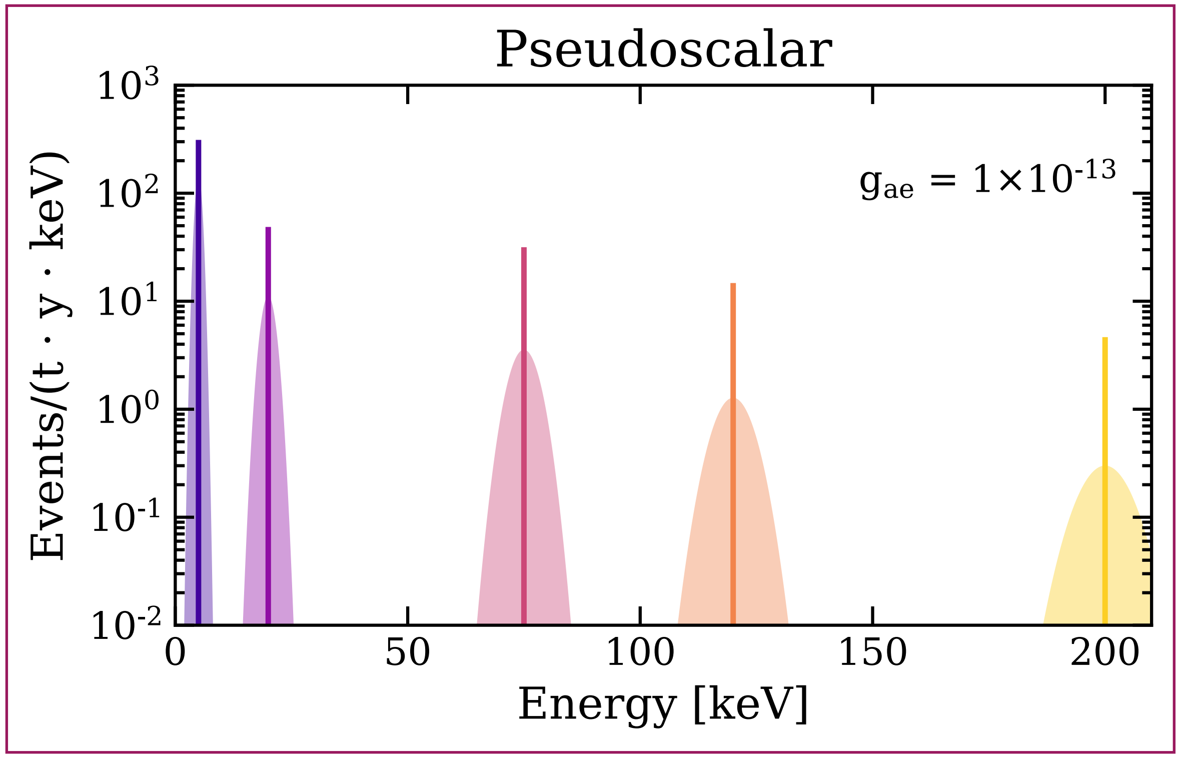
nuisance parameters that maximise L

XENON Collab., Phys. Rev. D 102, 2020

Bosonic dark matter

Thermal DM, non-relativistic: deposited energy is rest mass of particle.

axion-like particles

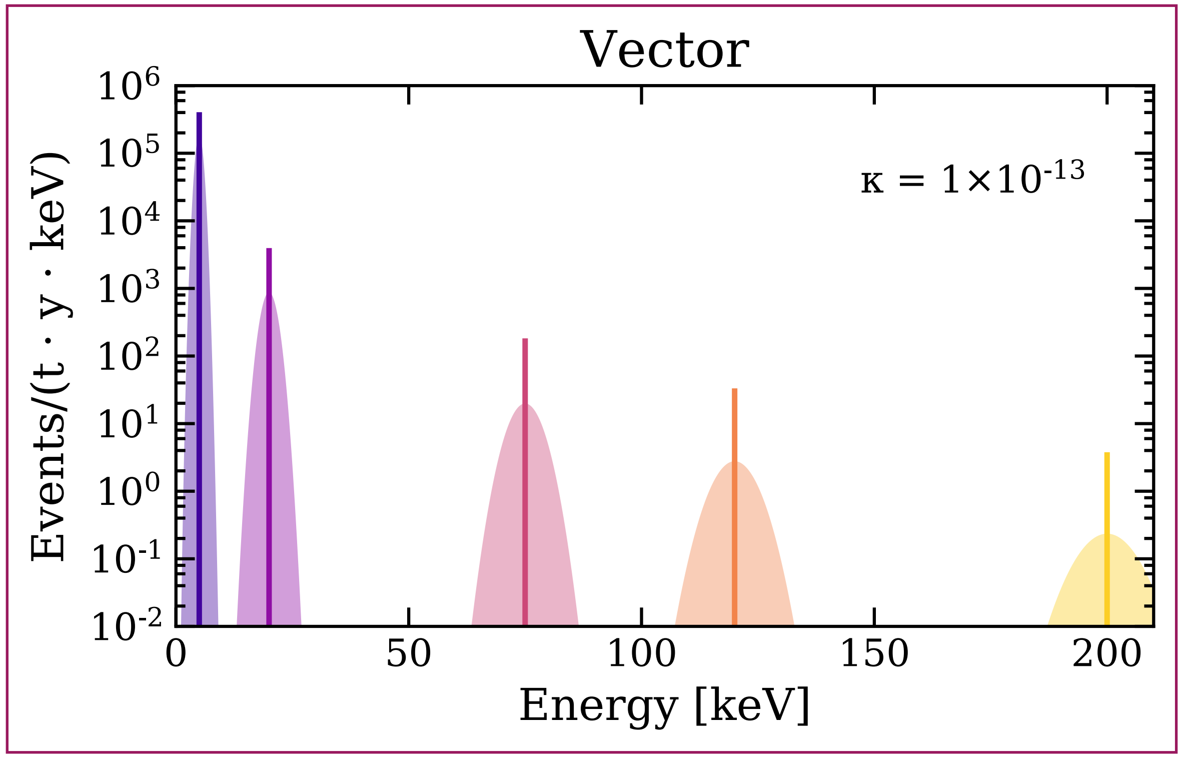


$$R \simeq \frac{1.5\times10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}/c^2}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

Detection via axioelectric effect

$$\sigma_{ae} = \sigma_{pe}\frac{g_{ae}^2}{\beta}\frac{3E_a^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{2/3}}{3}\right)$$

dark photons

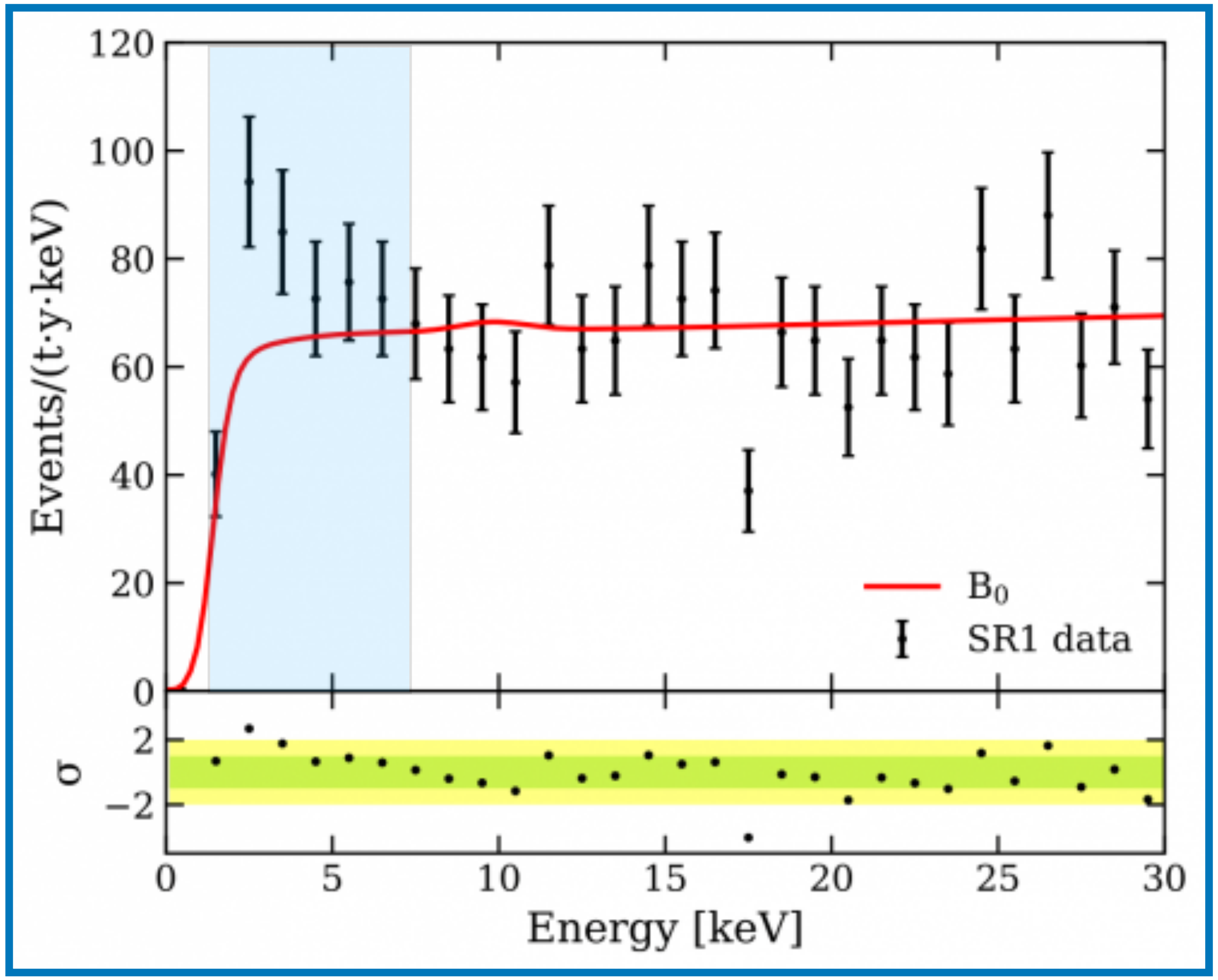


$$R \simeq \frac{4.7\times10^{23}}{A}\kappa^2\left(\frac{\mathrm{keV}/c^2}{m_V}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$

Kinetic mixing with SM photons

$$\sigma_V \simeq \frac{\sigma_{pe}}{\beta}\kappa^2$$

The XENON1T excess

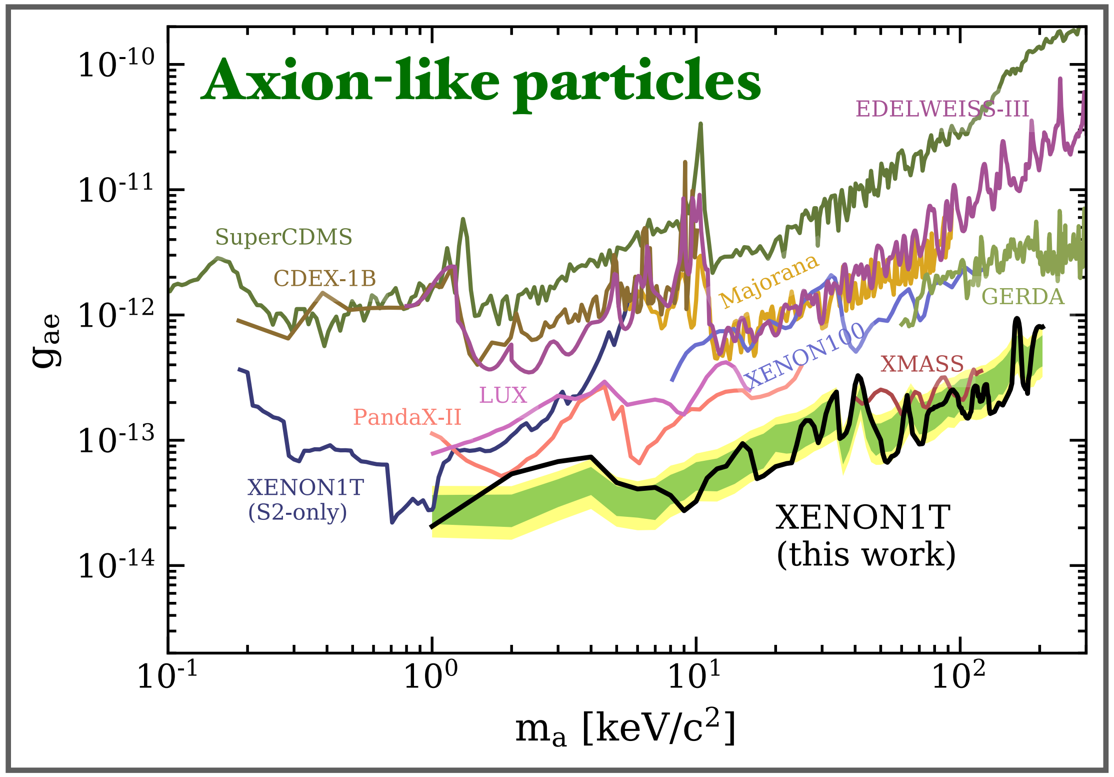


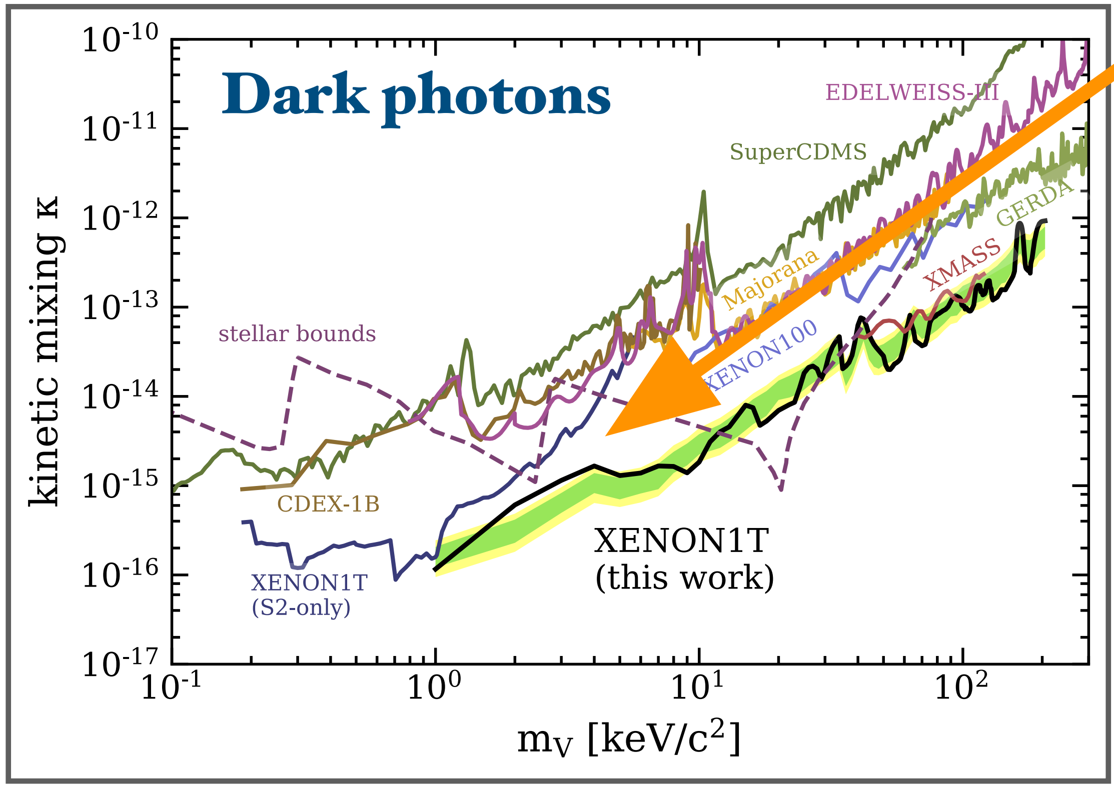
reference region 1-7 keV

XENON Collab., Phys. Rev. D 102, 2020

- Excess between (1,7) keV; number of observed events: 285, expected from background: (232±15) events
- Solar axion favoured over background-only at 3.4 σ (however discrepancy with stellar cooling constraints, see e.g. 2006.12487)
- Unknown origin: tritium, solar axions, ALPs, dark photons, something else?

Bosonic dark matter

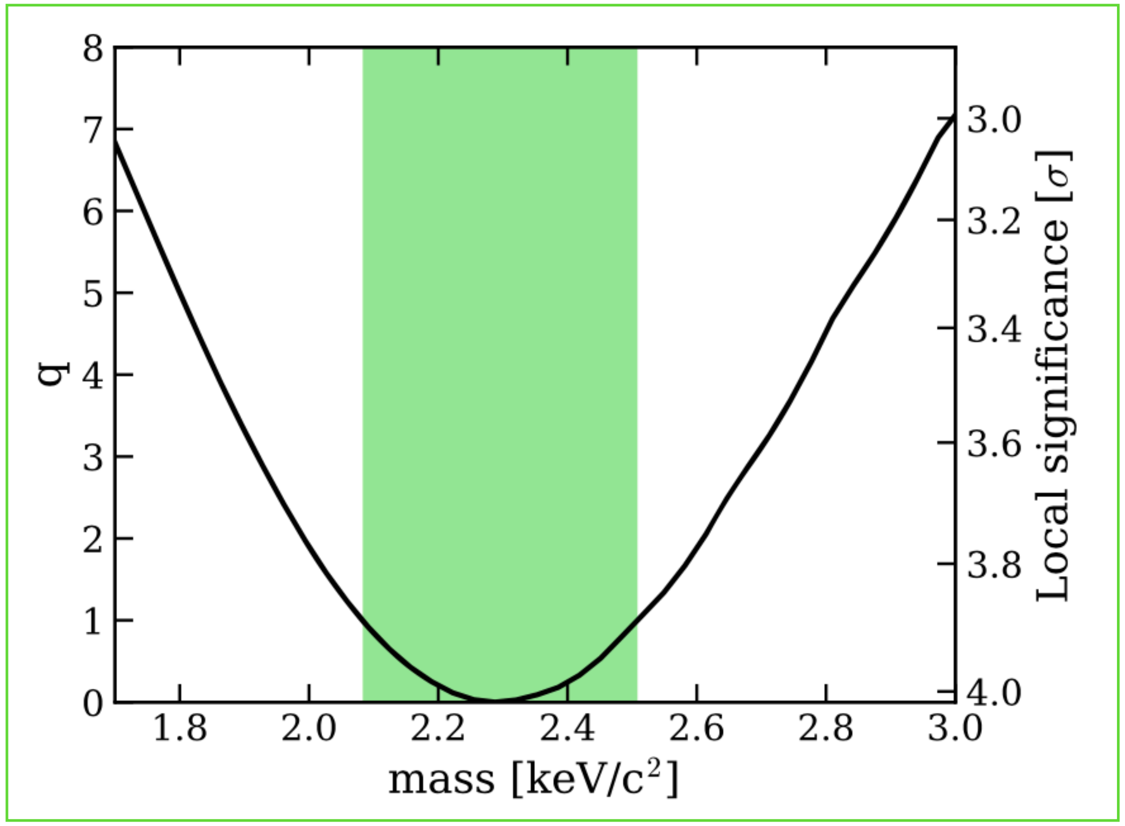




90% CL upper limits and sensitivities

Fitting a mono-energetic peak to the excess:

2.3 +/- 0.2 keV



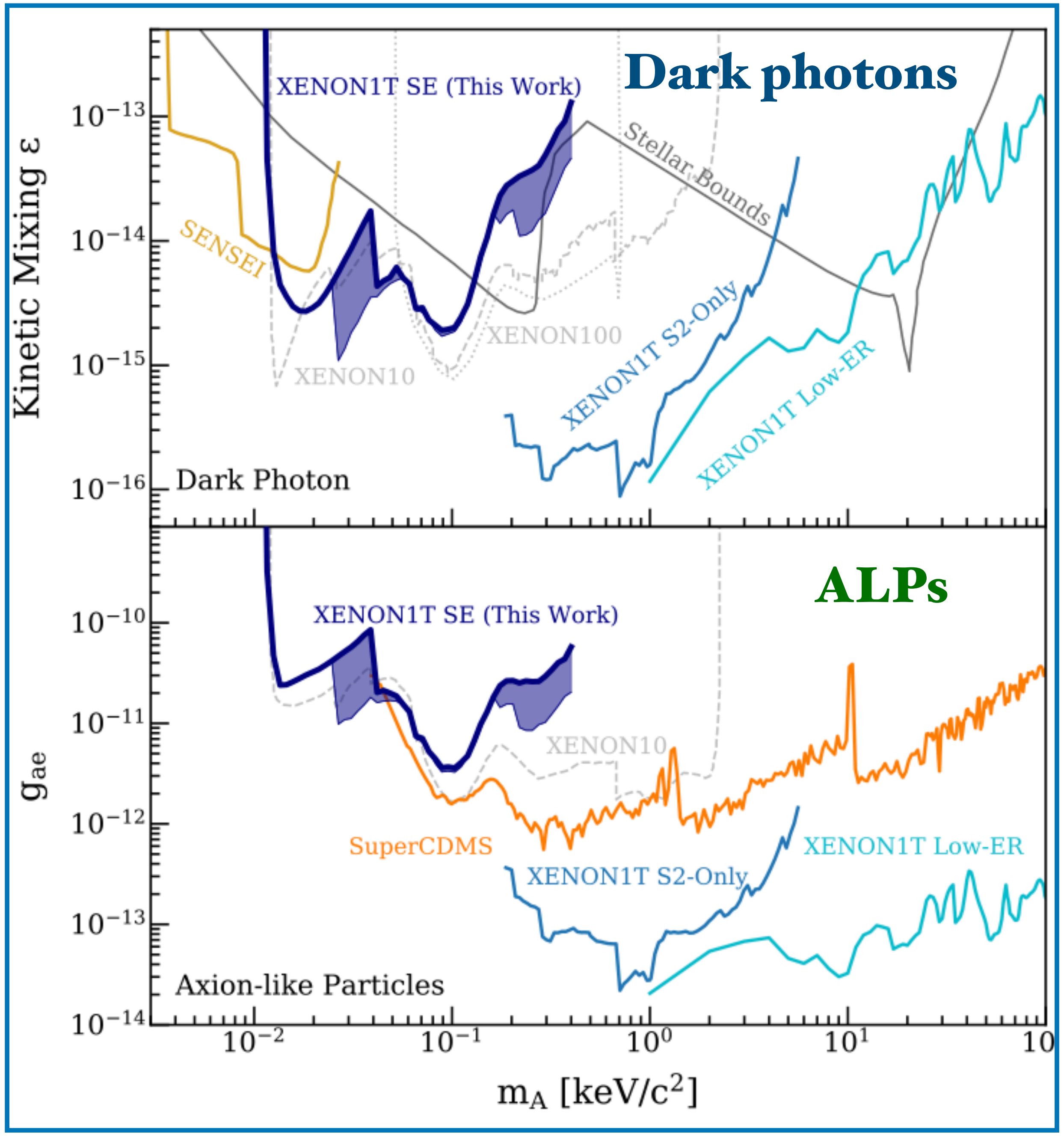
Best fit: ~60 events/tonne/year

4.0 σ local significance

XENON Collab., Phys. Rev. D 102, 2020

3.0 σ (global)

Bosonic dark matter

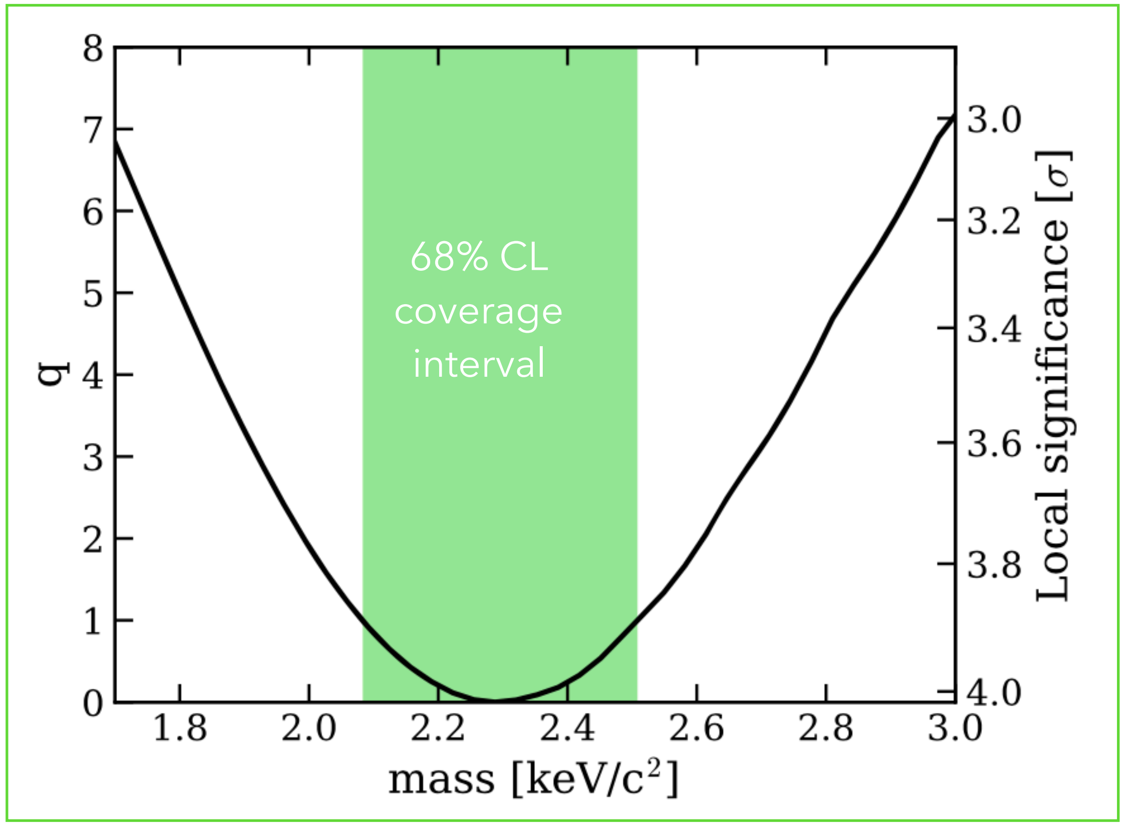


S2-only down to single electrons

XENON Collab., arXiv:2112.12116v1

Fitting a mono-energetic peak to the excess:

2.3 +/- 0.2 keV



Best fit: ~60 events/tonne/year

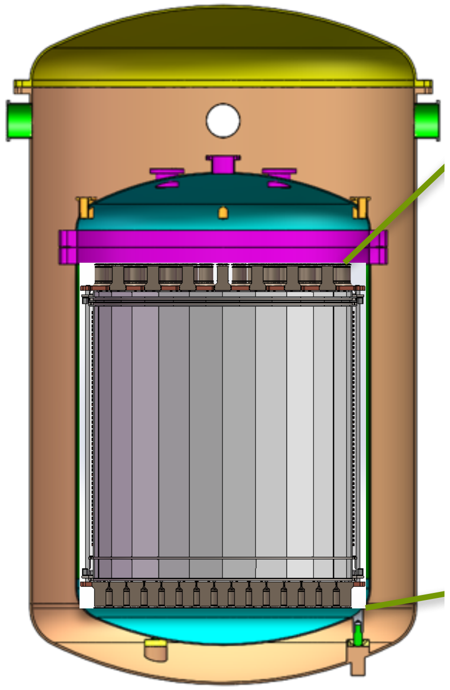
4.0 σ local significance

3.0 σ (global)

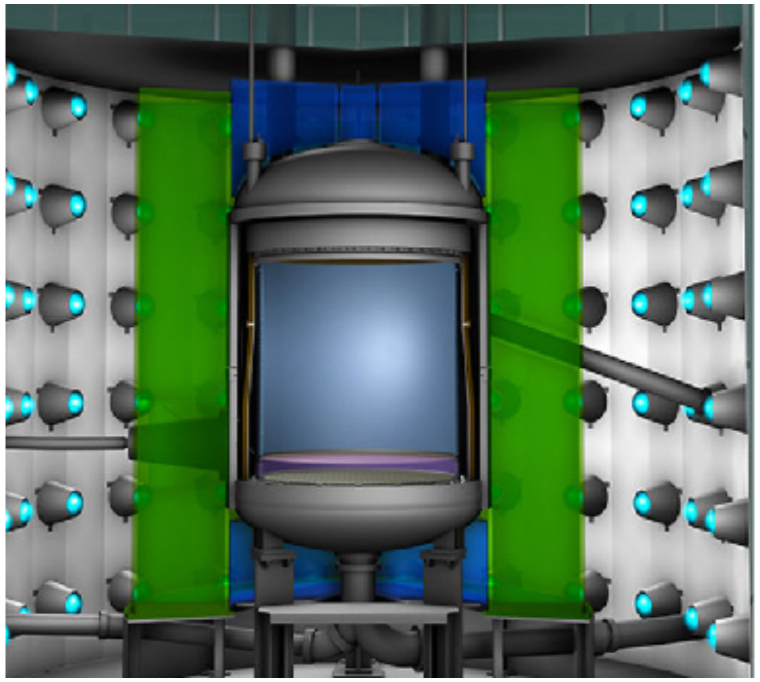
XENON Collab., Phys. Rev. D 102, 2020

The current generation

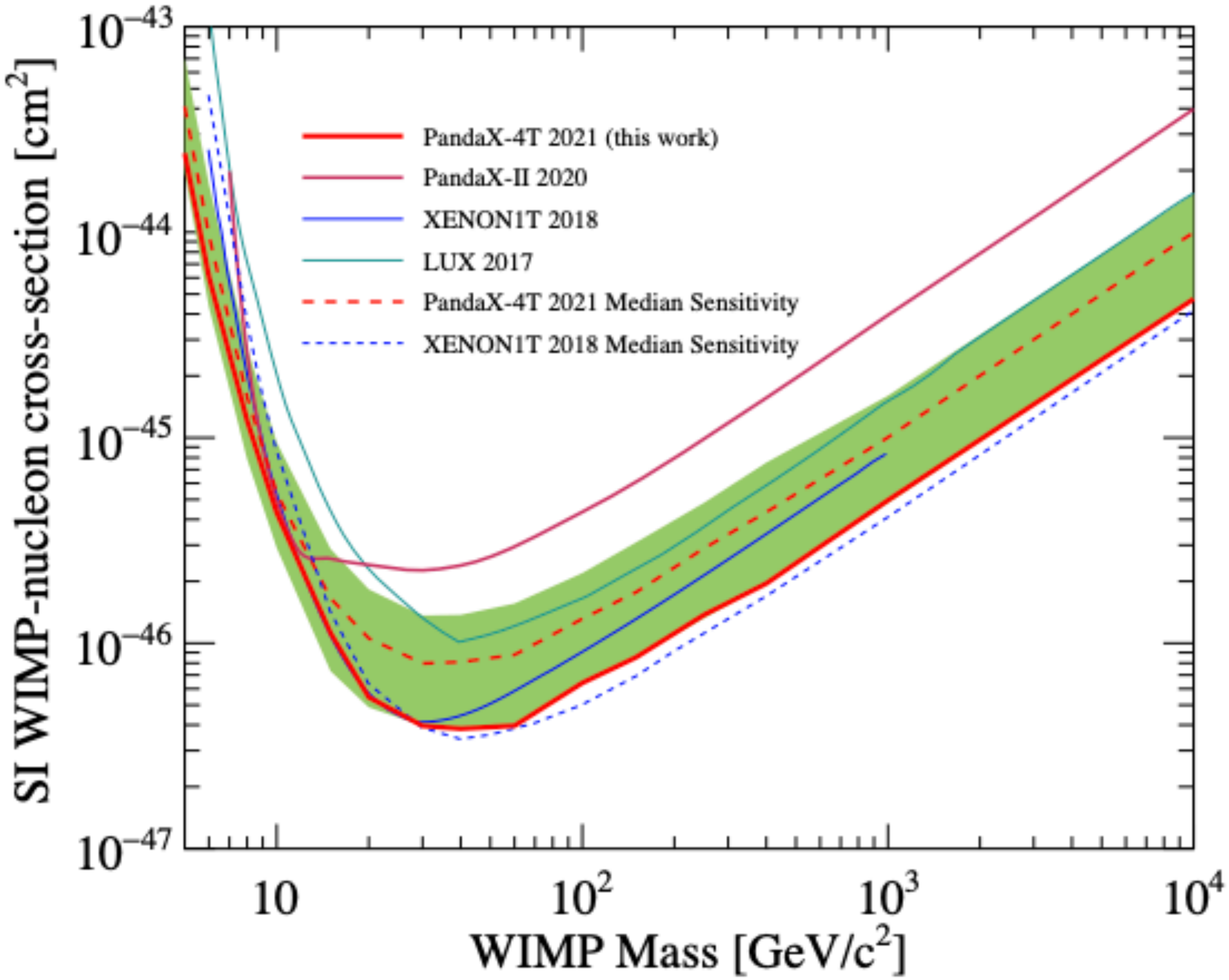
XENONnT: 8.6 t LXe
Data taking 2021



PandaX-4t LXe
First result 2021



LUX-ZEPLIN: 10 t LXe
Data taking 2021

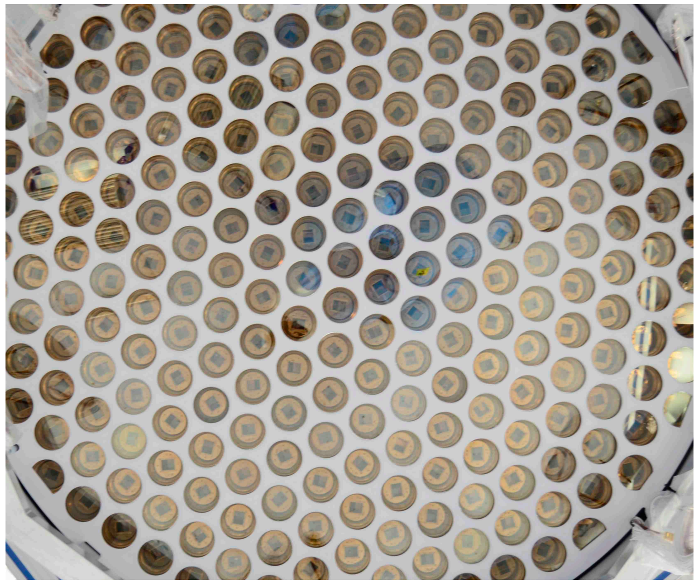


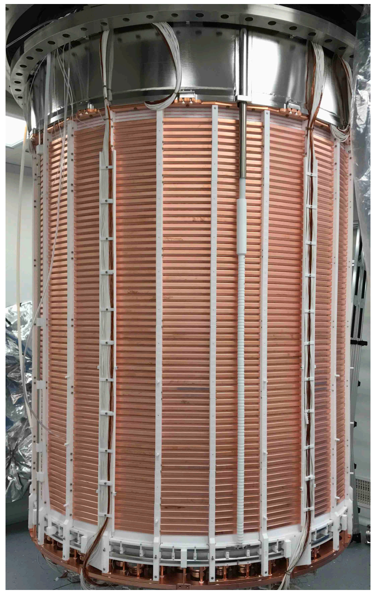
PandaX-4T
0.63 tonne yr (3.7 t)
(90% C.L.)

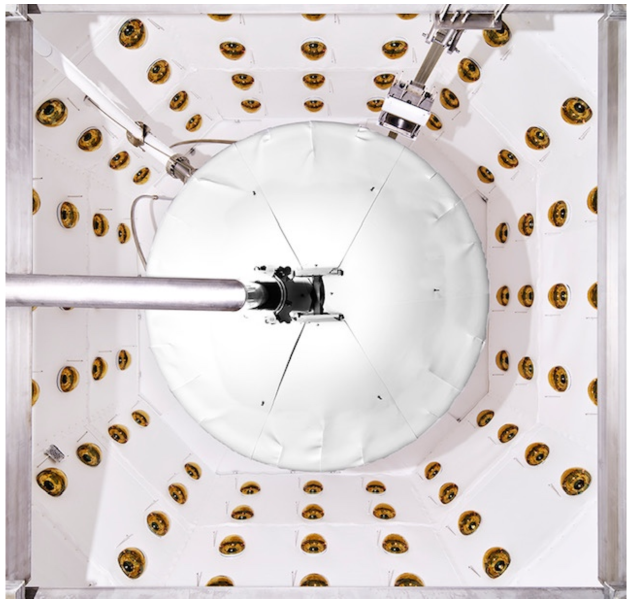
PhysRevLett.127.261802 (2021)

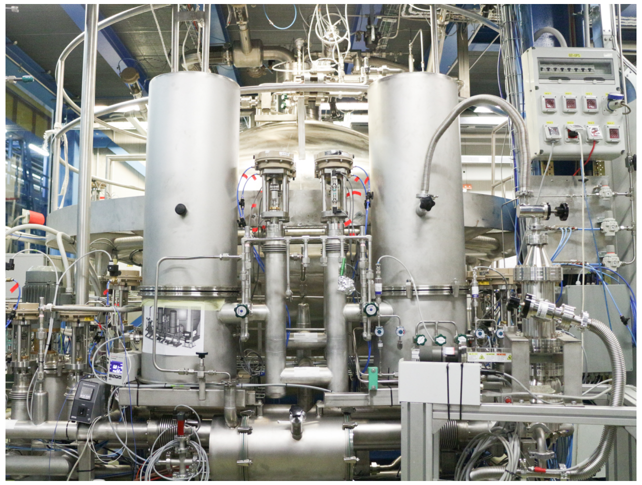
XENONnT

Laboratori Nazionali del Gran Sasso


PMT array (494 PMTs in total, in 2 arrays)


TPC (5.9 t LXe, 4 t fiducial)


Neutron veto (120 PMTs, Gd-doped water)

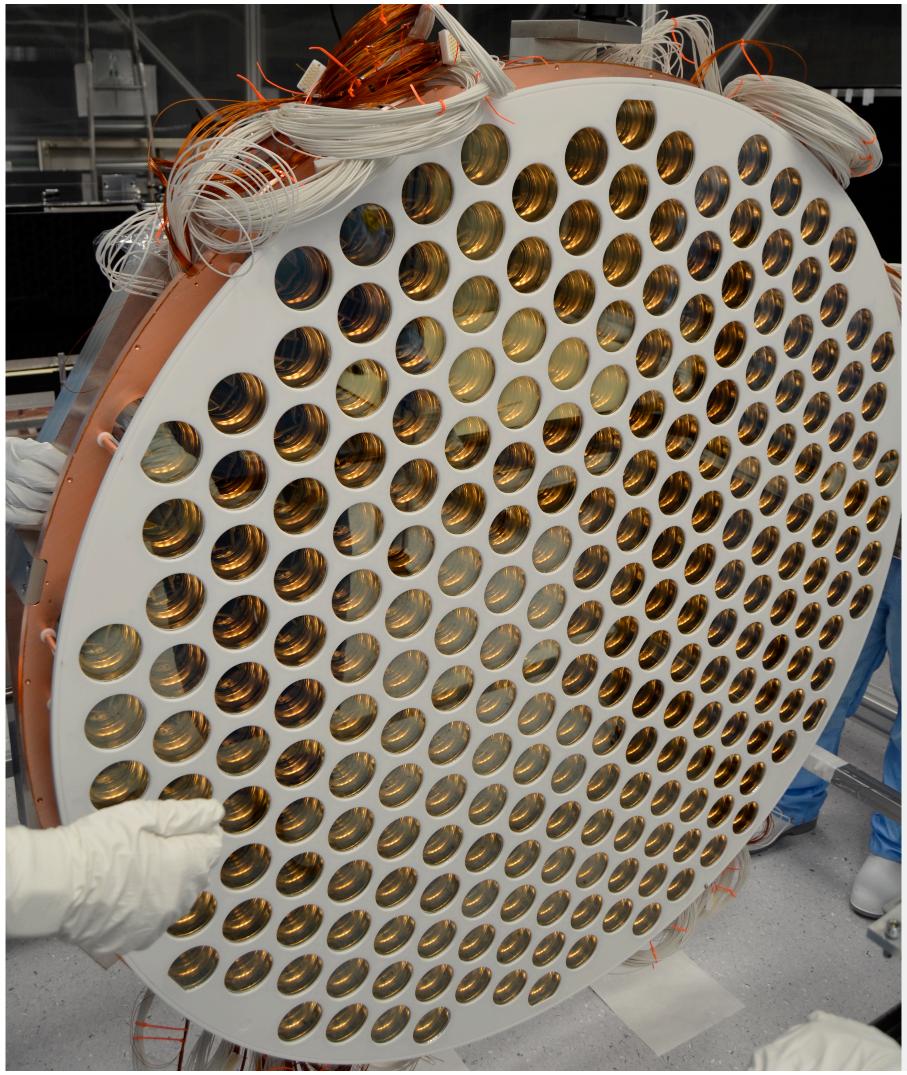

LXe purification system

Rn distillation column

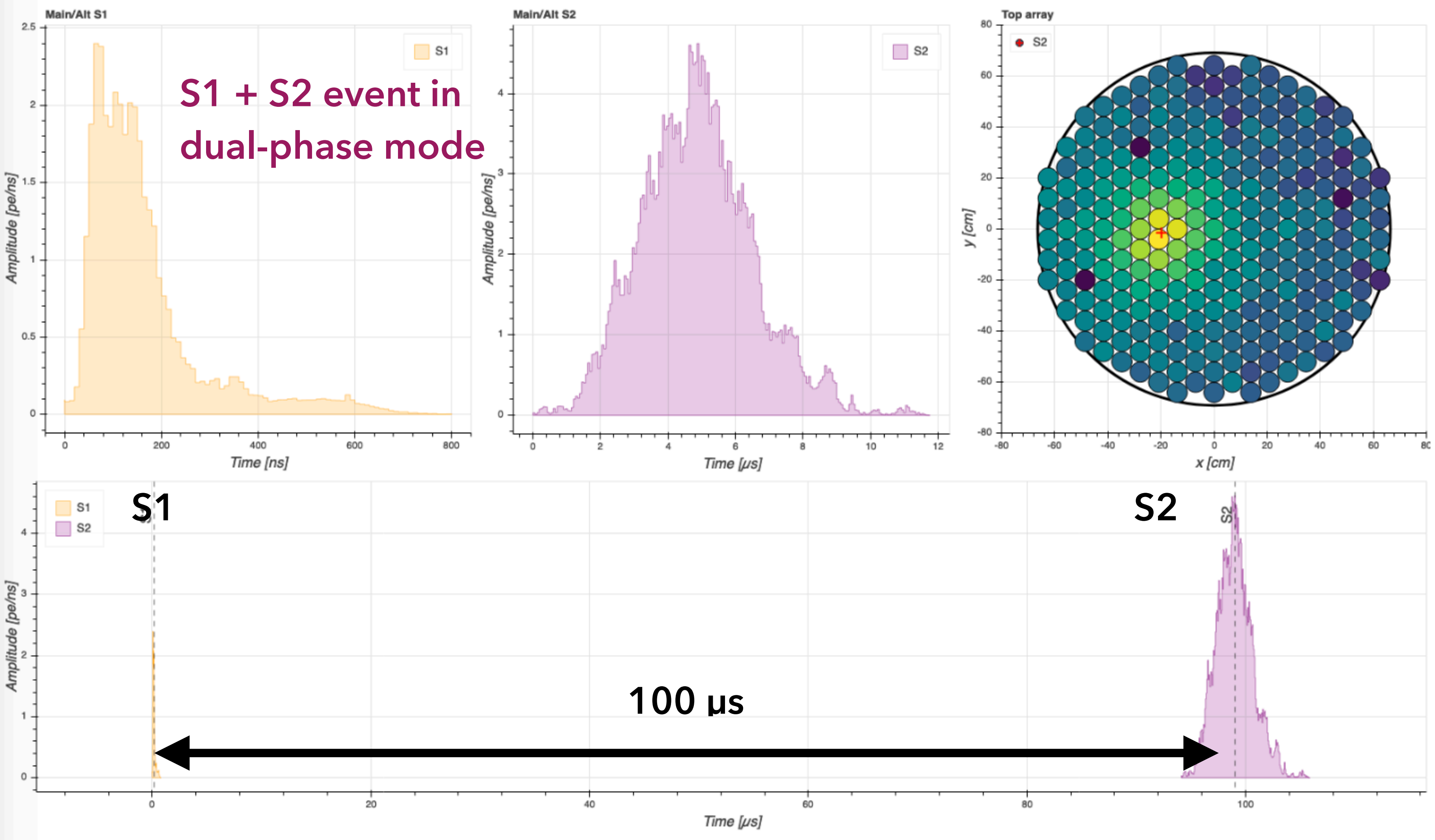
reduce ^{222}Rn (^{214}Pb)

Currently acquiring science data!

XENONnT



PMT array during assembly



S1 + S2 event in dual-phase mode

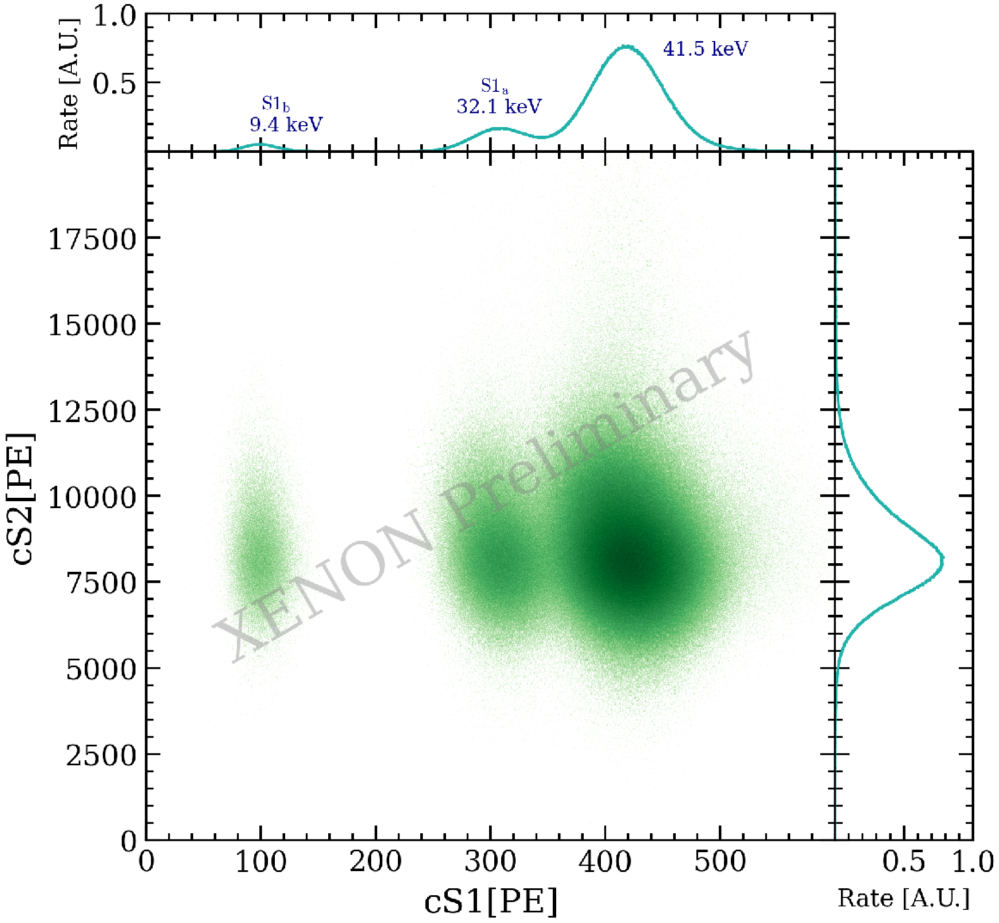
S1

S2

100 µs

Waveform during current operation

XENONnT

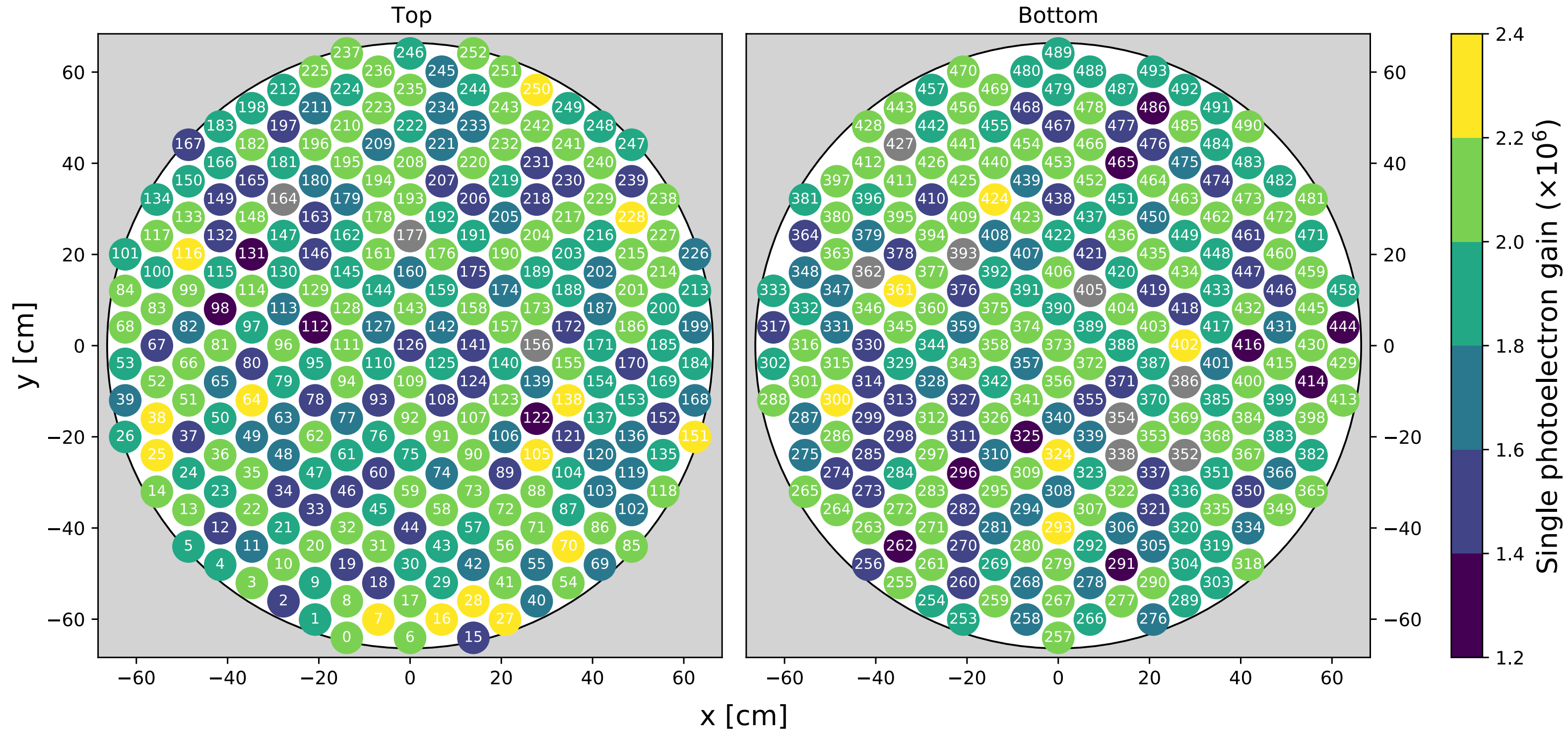


^{83m}Kr calibration

- Resolved peaks in S1-S2 space resolved
- Photon detection efficiency ~ 0.17 PE/photon (XENON1T 0.14 PE/photon)
- Energy resolution at 41.5 keV ~ 7.6 % (XENON1T 8 %)
- S2 resolution of 15.1 % (XENON1T 13.7 %)

PMTs

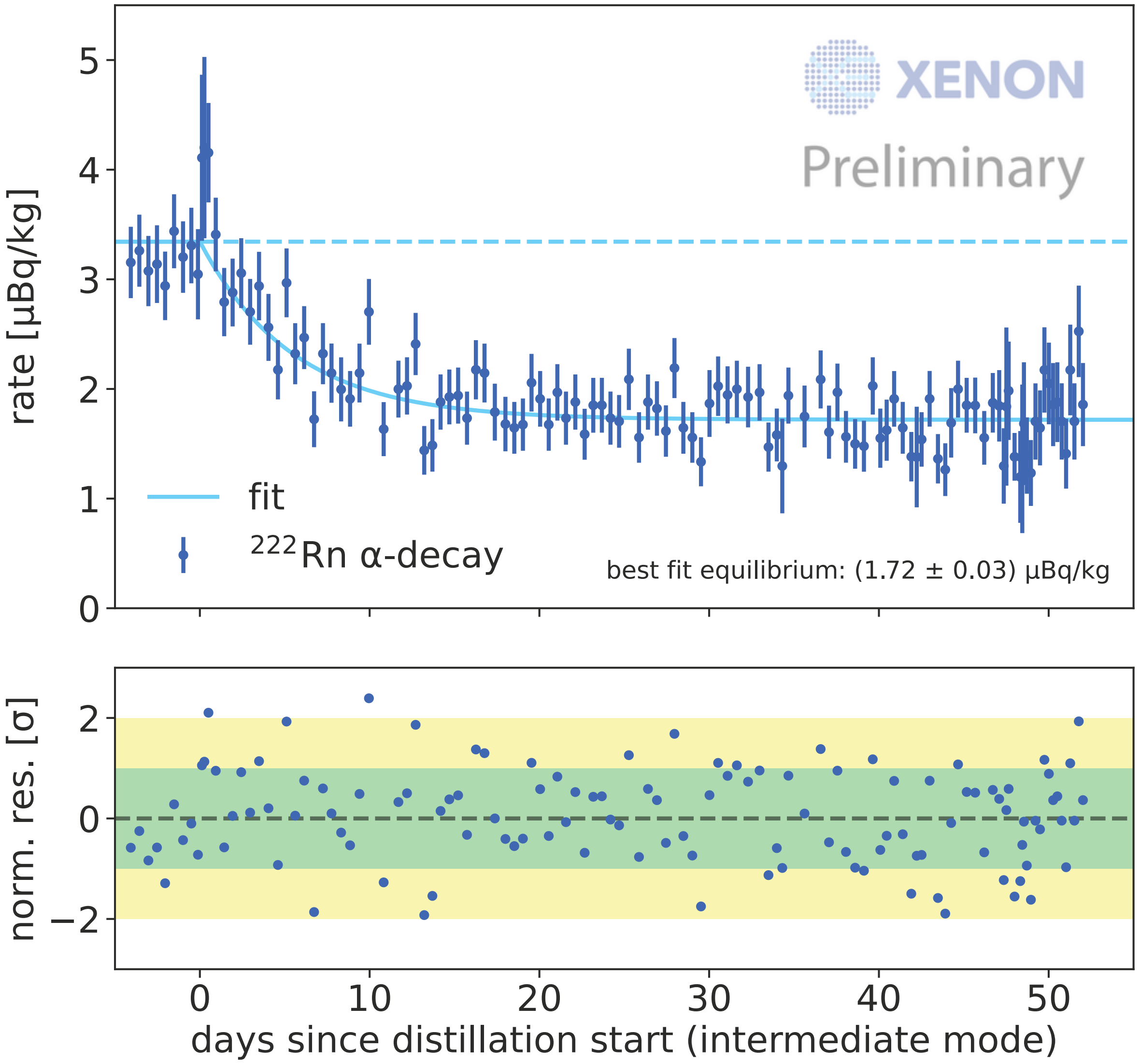
- 485 PMTs used in data analysis
- Average quantum efficiency 34 %



XENONnT

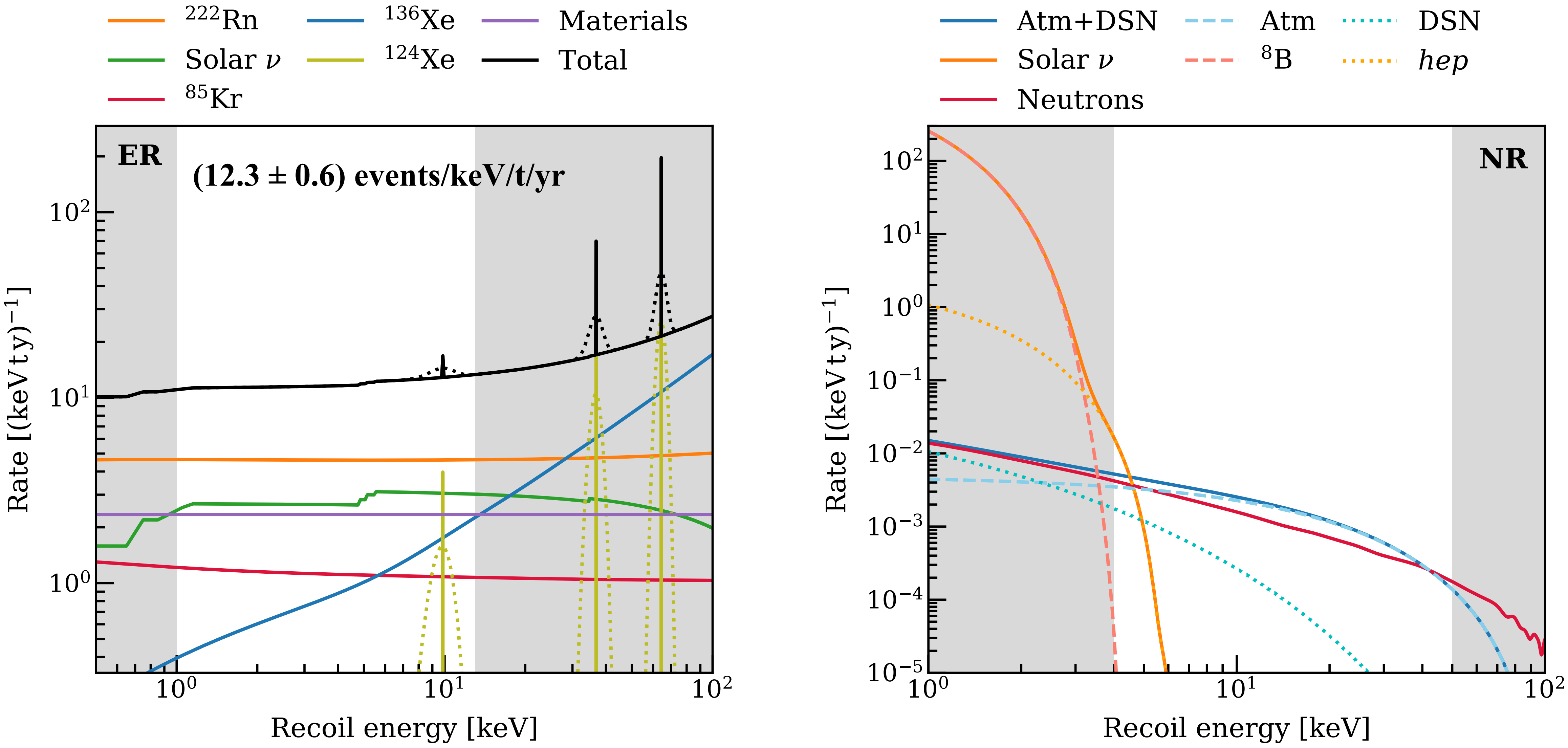
Xenon
Radon

Constant removal of emanating radon from xenon using difference in vapor pressure



- Reached equilibrium concentration of 1.72 μBq/kg by gas extraction only
- Background goal 1 μBq/kg
- Additional factor 2 in Rn removal possible via liquid extraction

XENONnT

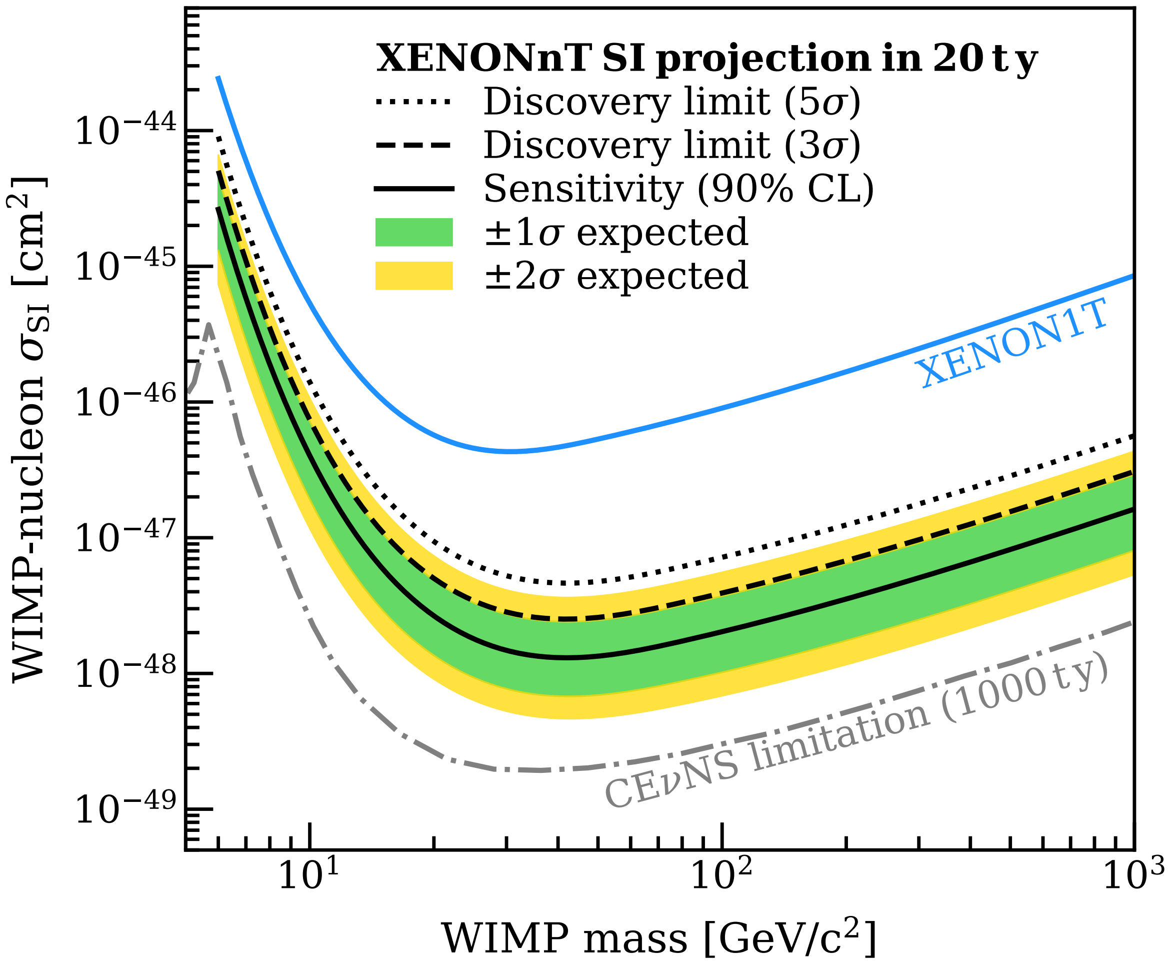


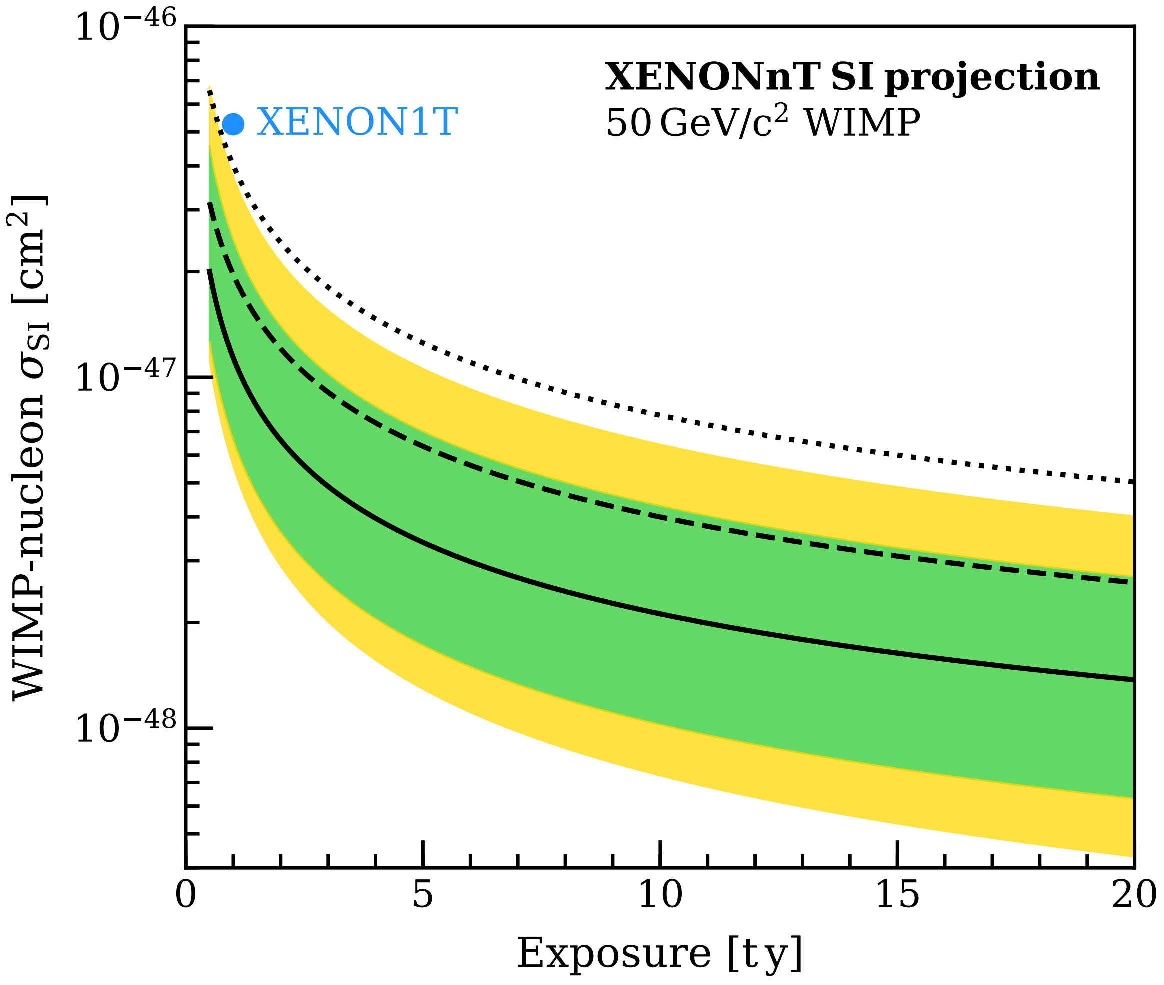
- Total ER rate reduced by factor six
- ER background for WIMP and axion search dominated by **^{222}Rn** (2νββ of ^{136}Xe above 30 keV)
- **Neutrino-dominated NR**: target < 1 neutron NR event per 20 t-yr target exposure

XENON Collab., JCAP 11 (2020) 031

XENONnT: WIMPs

JCAP 11 (2020) 031

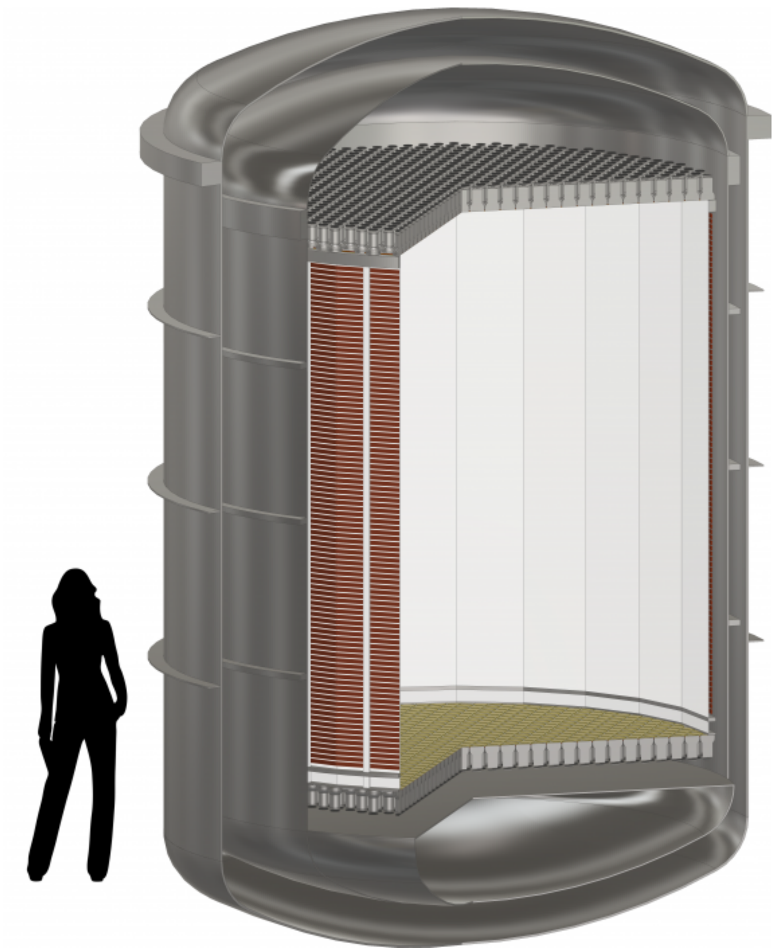




- Improve existing WIMP limits by more than one order of magnitude with 20 tonne-year exposure
- Discovery potential beyond 10^{-47} cm^2 for 50 GeV/c^2 WIMP in ~ one year live time

XENON Collab., JCAP 11 (2020) 031

The future



DARWIN: 50 t LXe

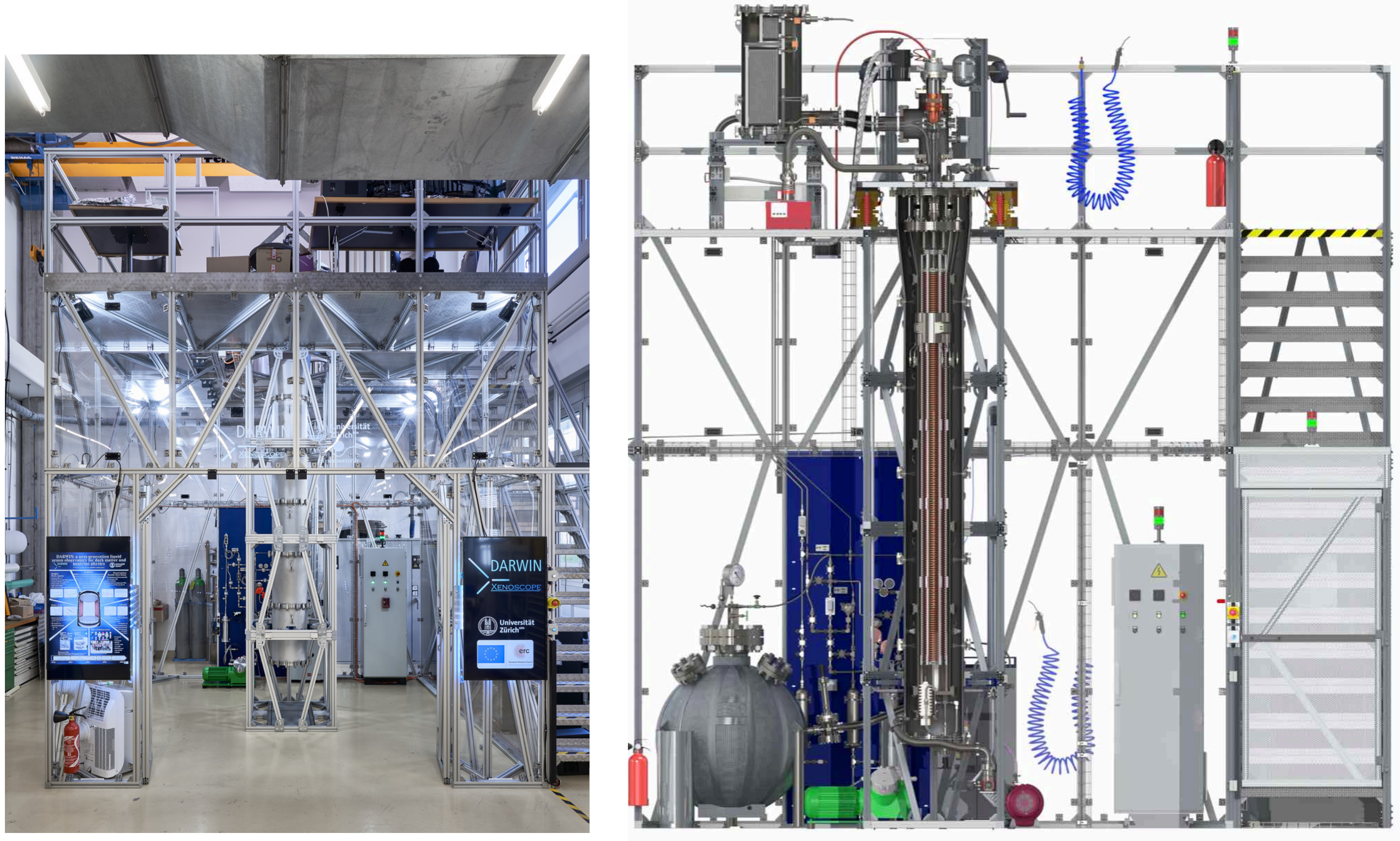
DARWIN

LZ

- Future merger of DARWIN and LZ collaborations to build/operate next-generation liquid xenon experiment
  - new, stronger international collaboration
  - comes after LZ and XENONnT are done ~ 2026
- Paving the way now
  - first joint and very successful DARWIN LZ meeting April 26-27: https://indico.cern.ch/event/1028794/
  - MoU signed July 6, 2021: 104 research group leaders from 16 countries
  - Will combine expertise and technologies

DARWIN R&D

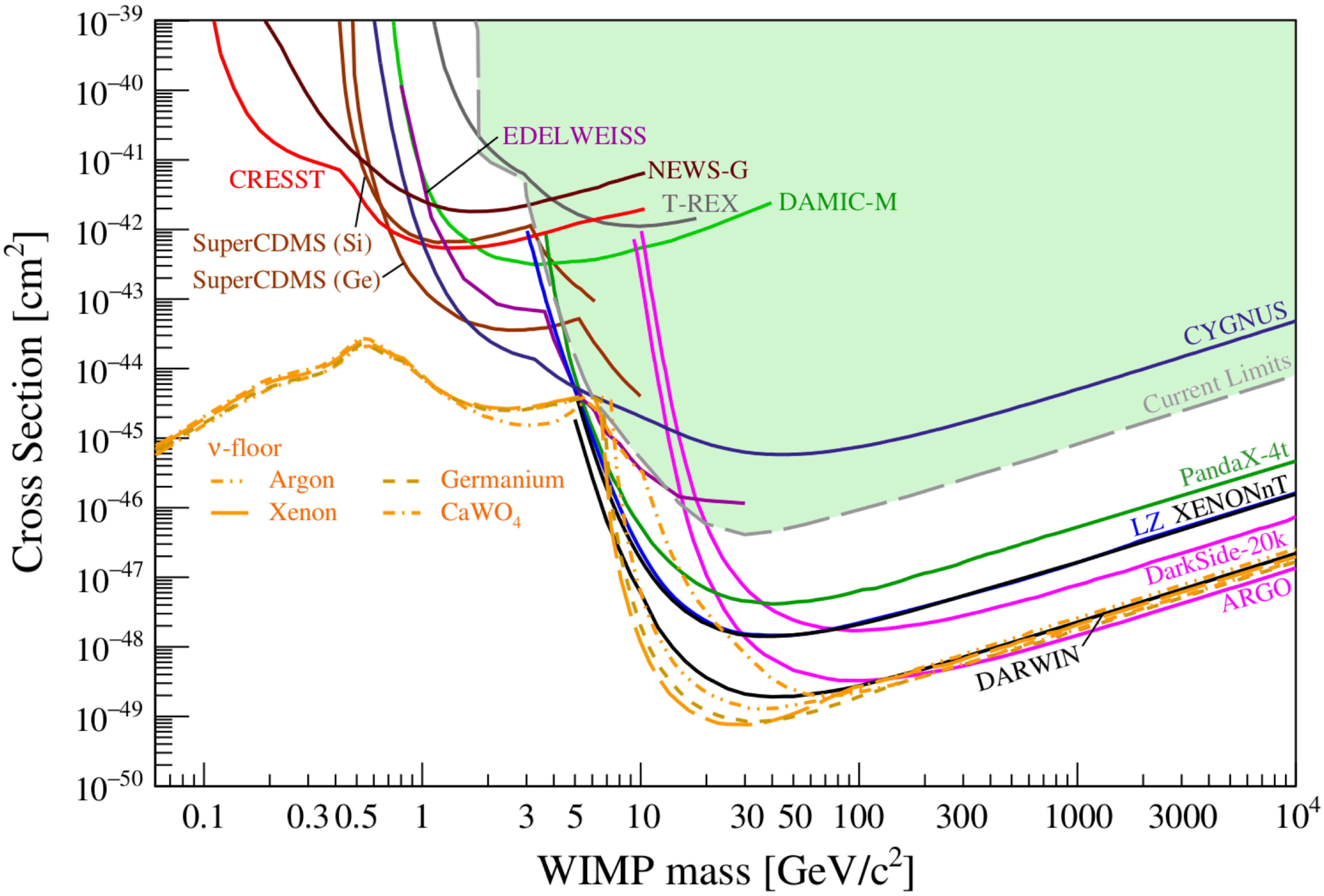
- Detector, Xe target, background mitigation, photosensors, etc
- Two large-scale demonstrators (in z & in x-y) supported by ERC grants: demonstrate electron drift over 2.6 m, operate 2.6 m ø electrodes
- Demonstrators (Xenoscope, 2.6 m tall & Pancake, 2.6 m diam TPCs) in commissioning stage



Test e^- drift over 2.6 m (purification, high-voltage): U. Zurich

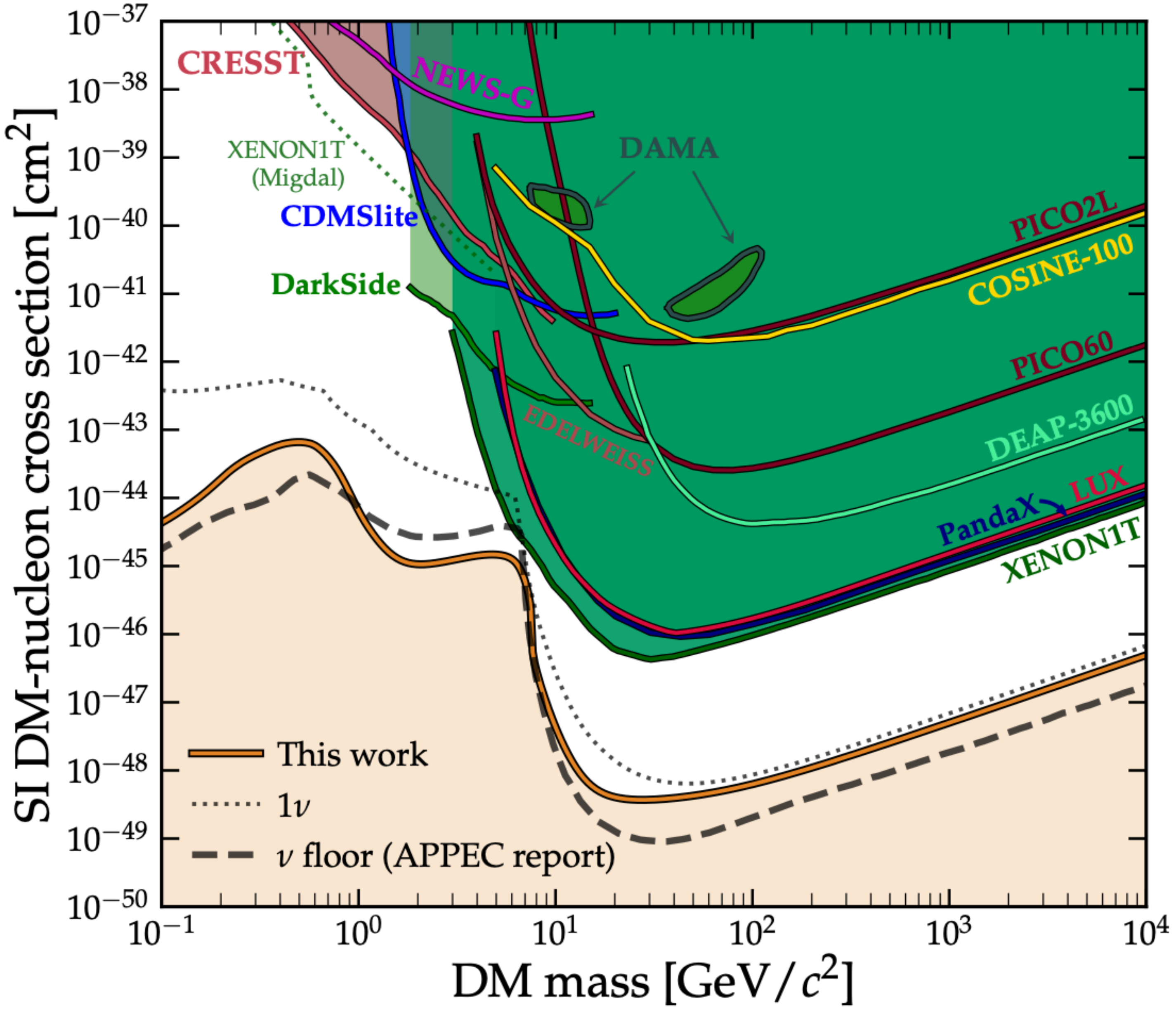
Test electrodes with 2.6 m diameter: U. Freiburg

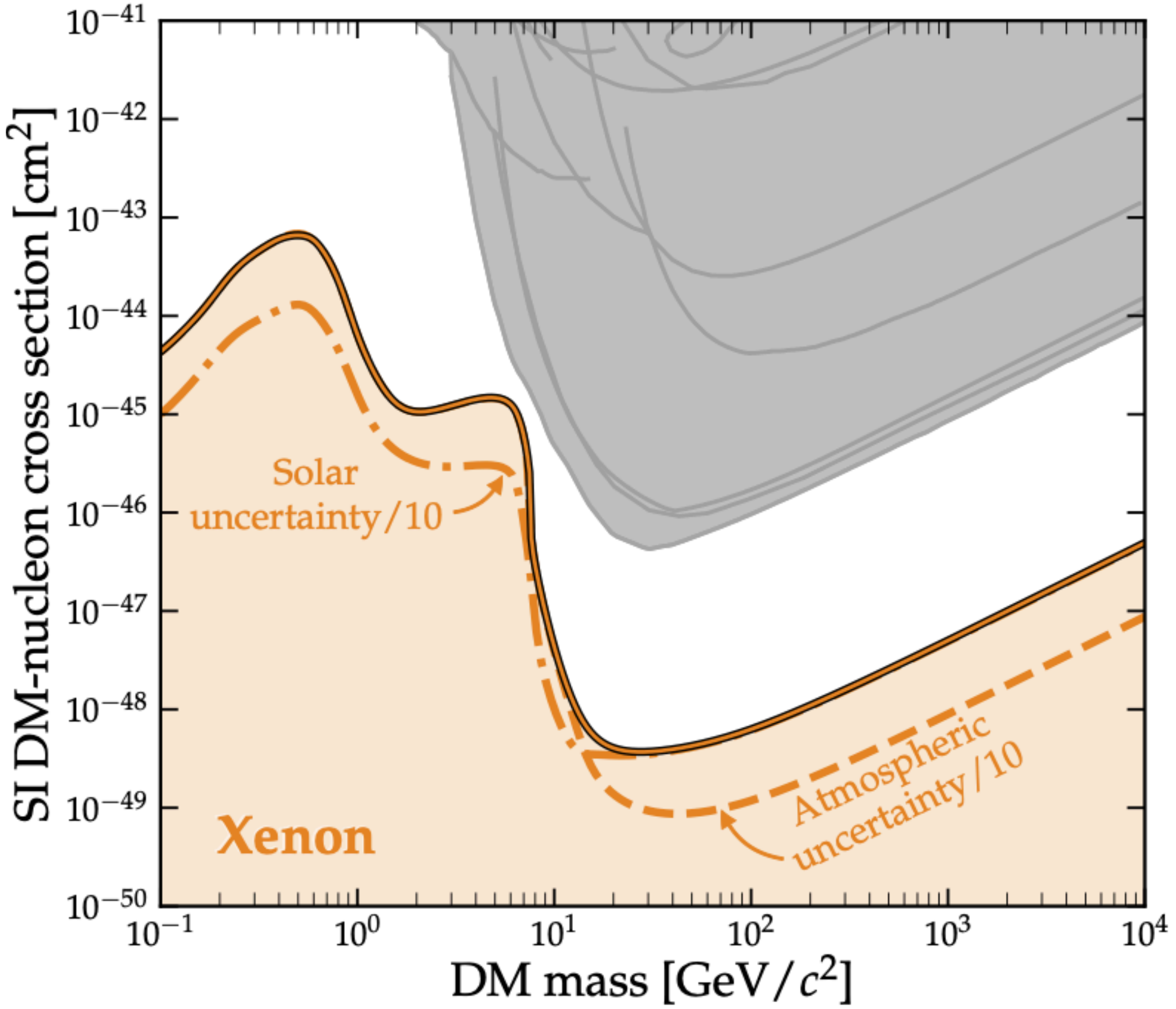
Sensitivity projections



APPEC DM Report, Billard et al, arXiv:2104.07634 (2021)

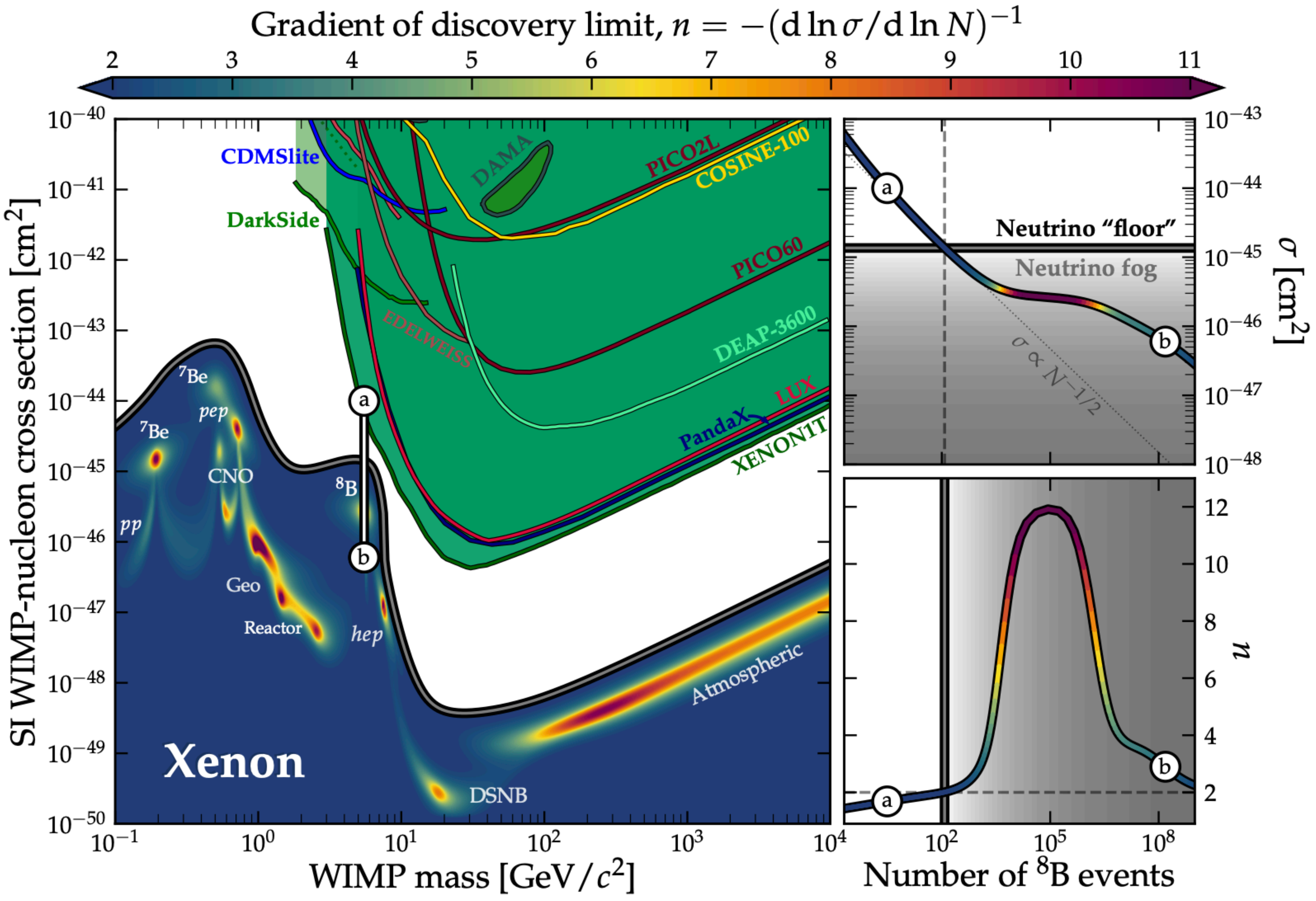
Fog on the horizon





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

Mapping the fog



discovery limit scales as N events increases

through the fog, spectral differences should be come apparent.

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

Summary

- Over two decades of WIMP searches have covered more than 6 orders of magnitude in cross-section vs mass parameter space.
- LXe TPCs, driven by standard WIMP searches, have reached exceedingly low backgrounds, thus opening new detection channels.
- A new generation of multi-ton scale detectors are now taking science data, already with first results.
- Competition gives way to collaboration in the future, and R&D for the ultimate LXe detector is underway.
- An inevitable neutrino fog is on the horizon, but patience may bring clarity.

Thank you for listening!