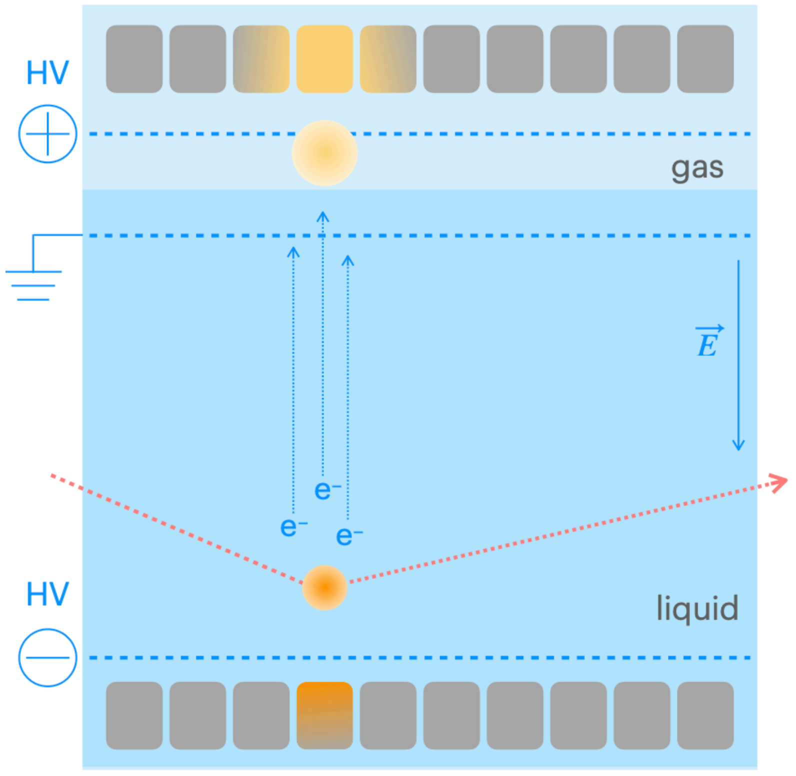
Direct Dark Matter Detection with Liquid Xenon Time Projection Chambers

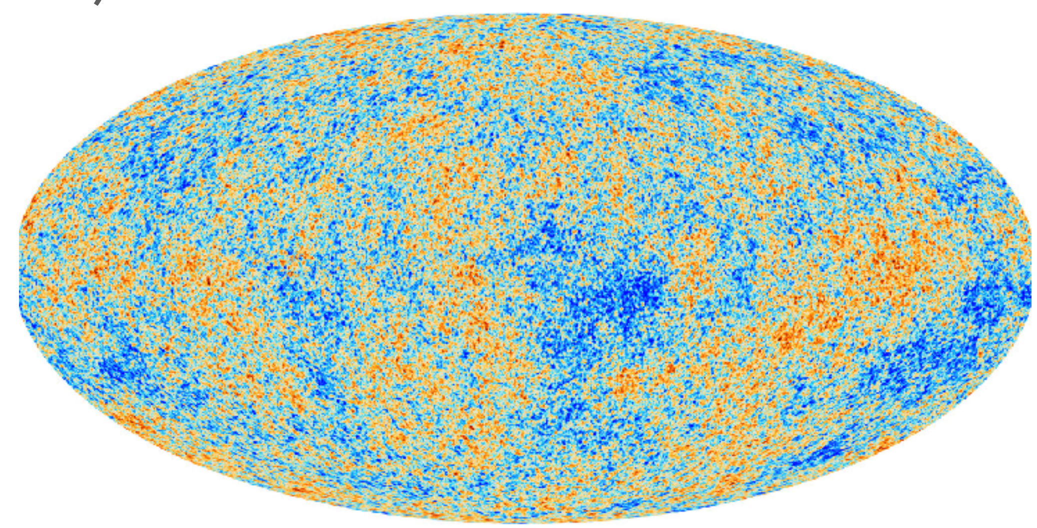
61st International Winter Meeting on Nuclear Physics, Bormio



Laura Baudis
University of Zurich
January 28, 2025

Most of our Universe is invisible

- **Evidence for dark matter across many time and length scales**
  - Early and late cosmology (CMBR, LSS)
  - Clusters of galaxies
  - Galactic rotation curves
  - Big Bang Nucleosynthesis



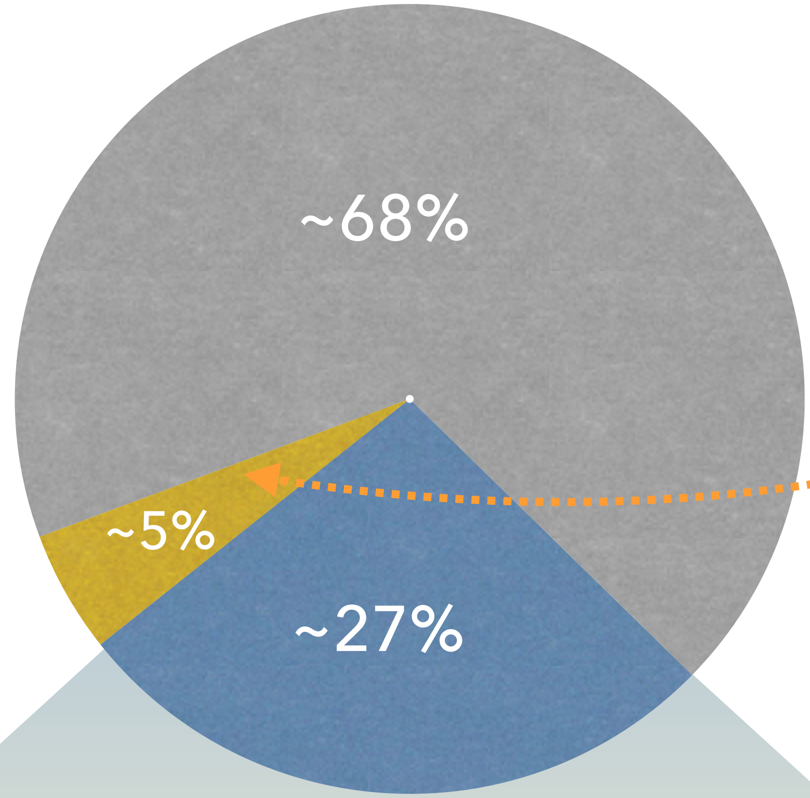
Planck (esa.int): "An almost perfect Universe"

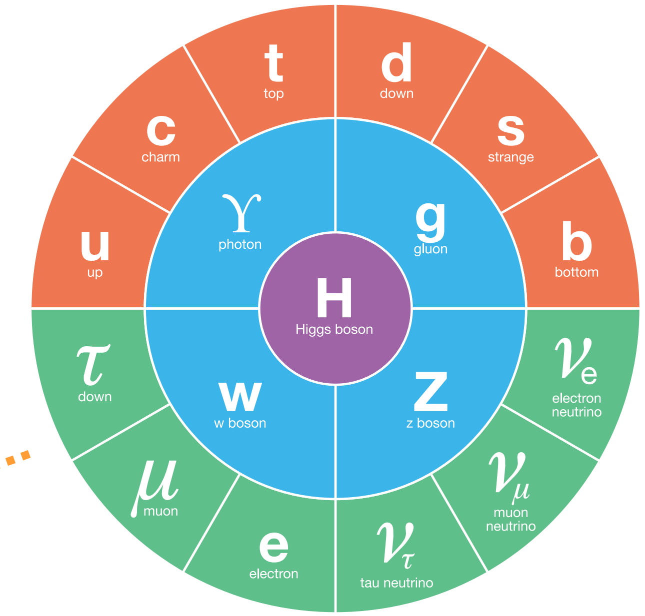
- **ΛCDM:** describes (almost?) all observations well
- **The fundamental nature of dark matter is still a mystery**
  - What is it, how does it interact?

What is the dark matter?

"A component of the universe that is totally invisible is an open invitation to speculation"

B. Ryden

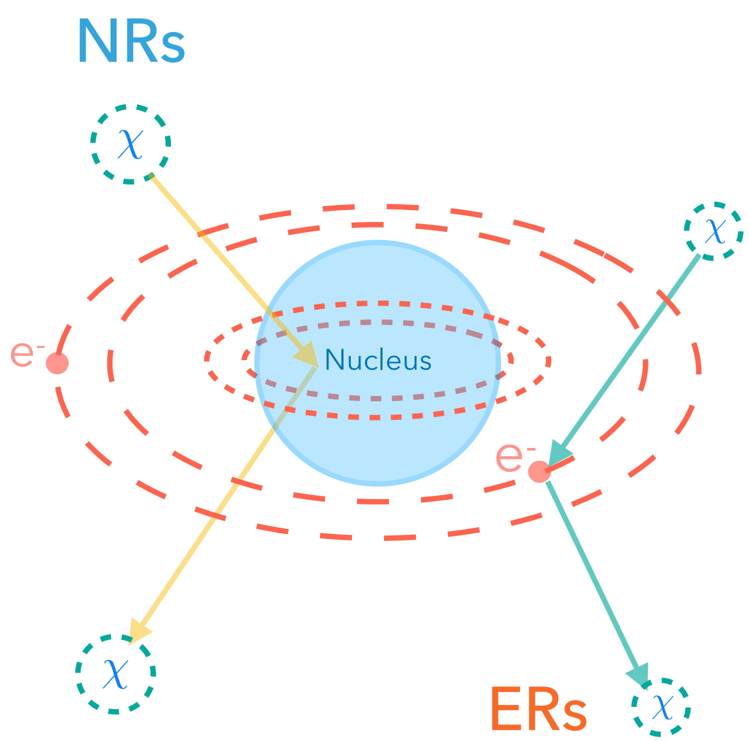


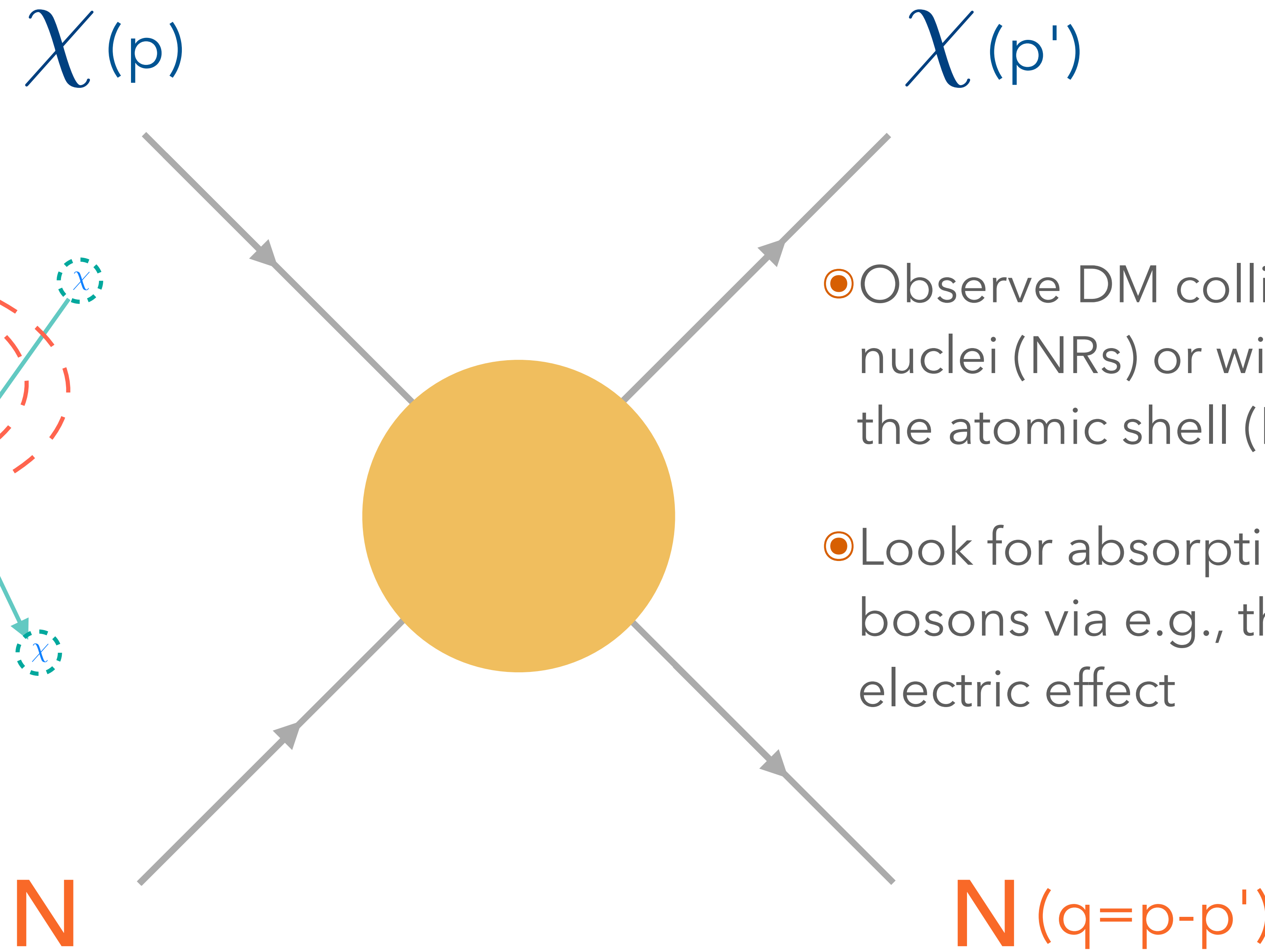


"Known physics"

No particle of the SM is a good candidate

Direct dark matter detection

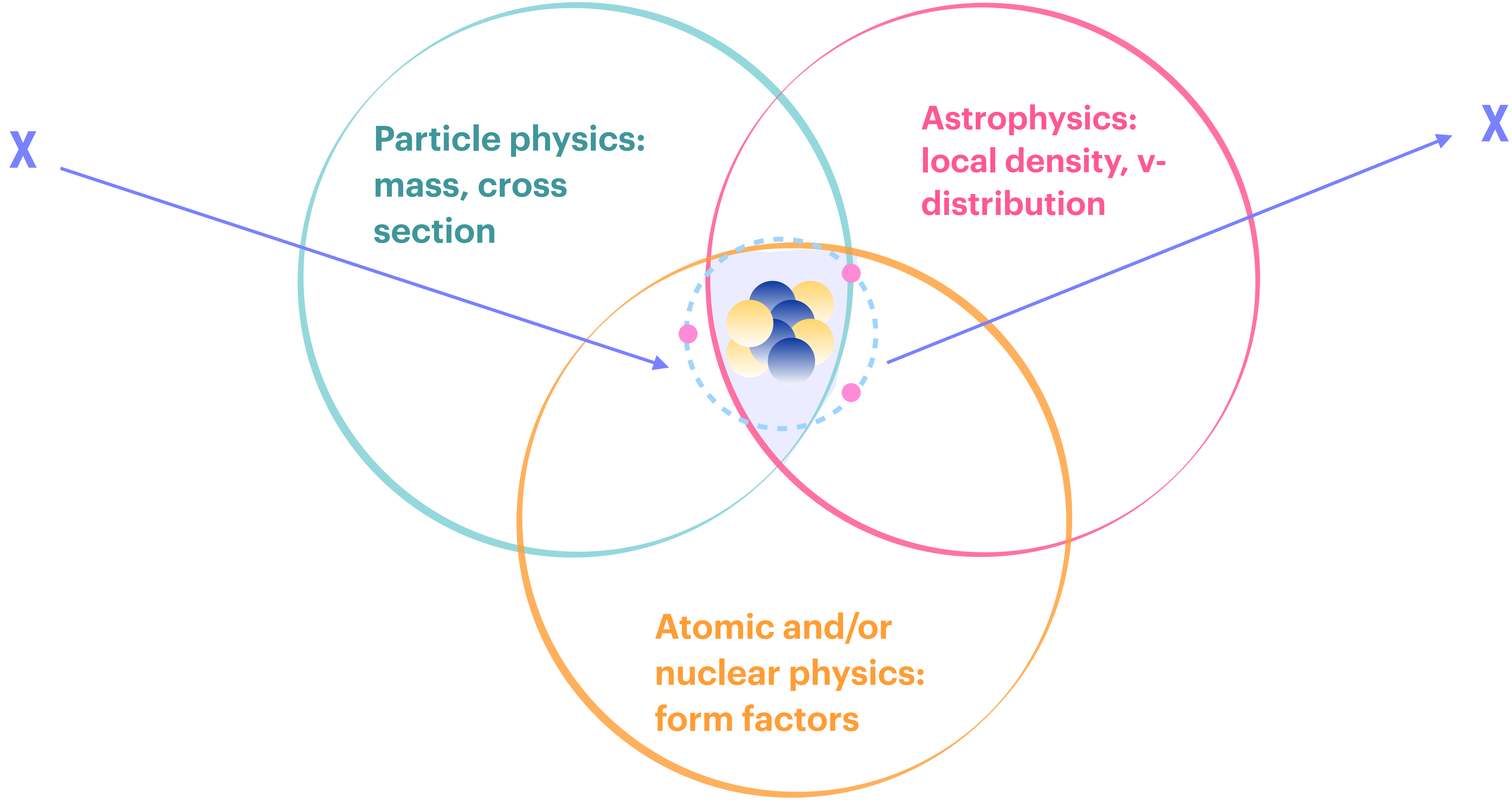




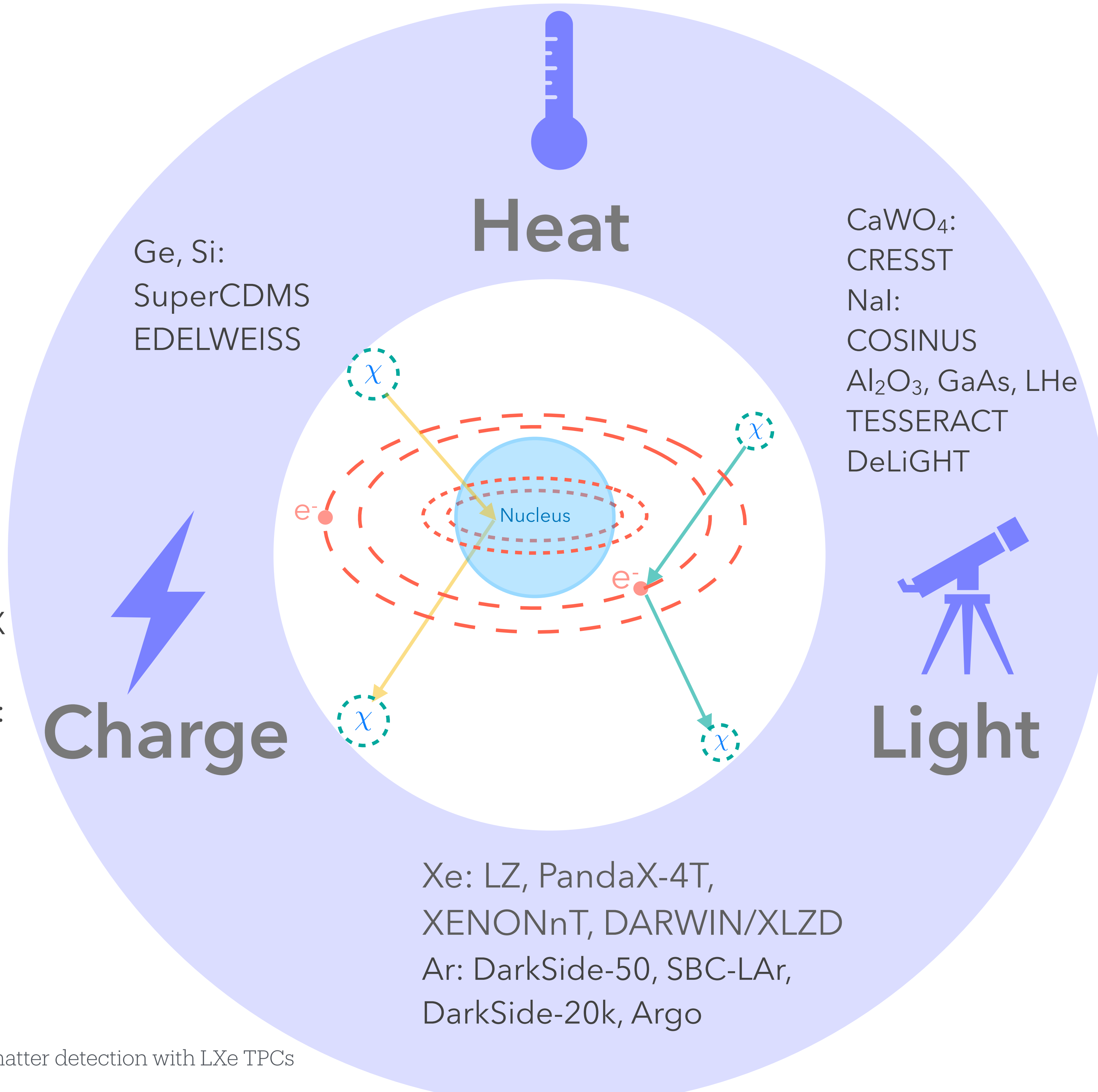
- Observe DM collisions with nuclei (NRs) or with electrons in the atomic shell (ERs)
- Look for absorption of light bosons via e.g., the axio-electric effect

Direct dark matter detection

- Inputs from several fields required to model the expected rates



Techniques and experiments



Ge, Si:
SuperCDMS
EDELWEISS

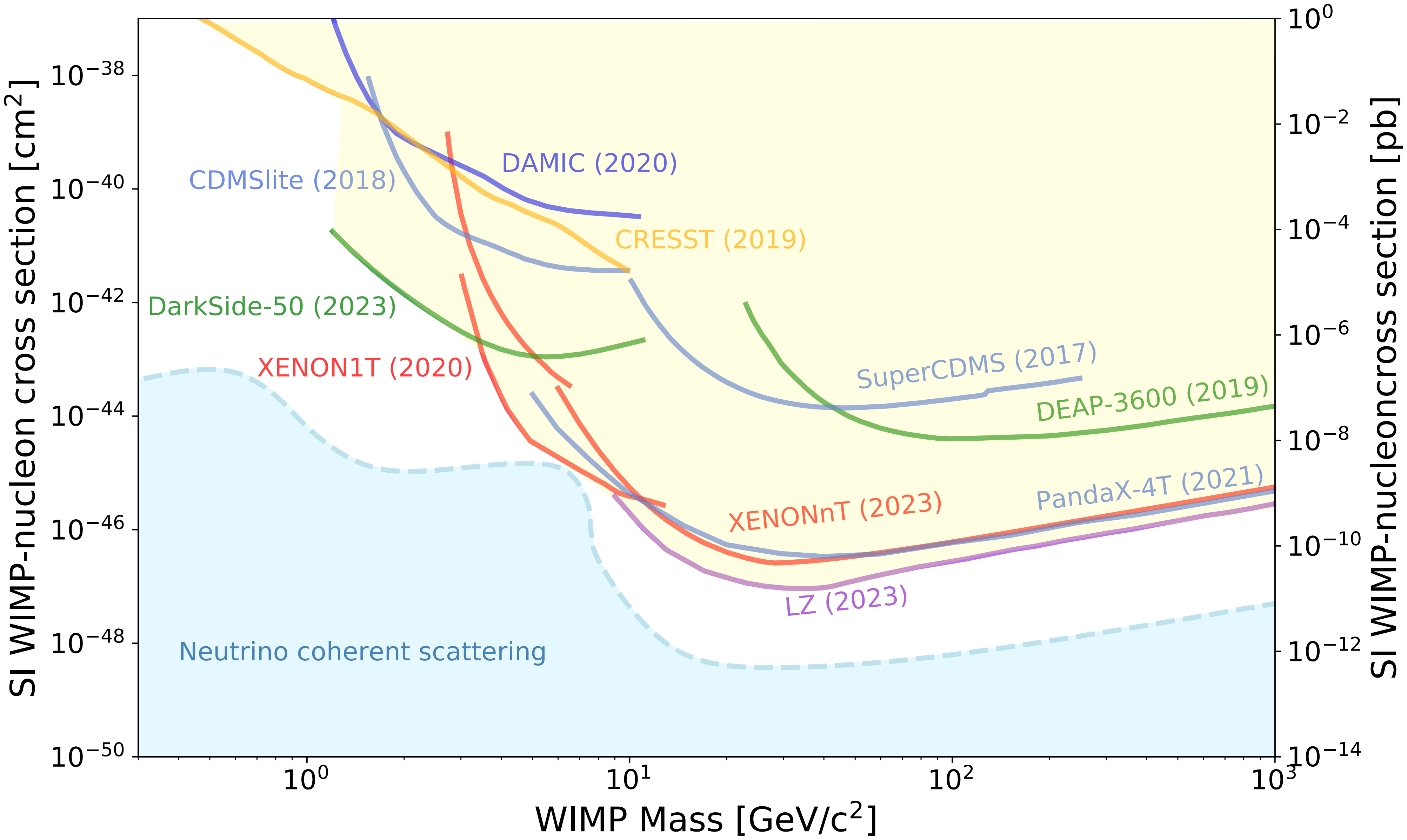
$CaWO_4$:
CRESST
NaI:
COSINUS
Al_2O_3, GaAs, LHe
TESSERACT
DeLiGHT

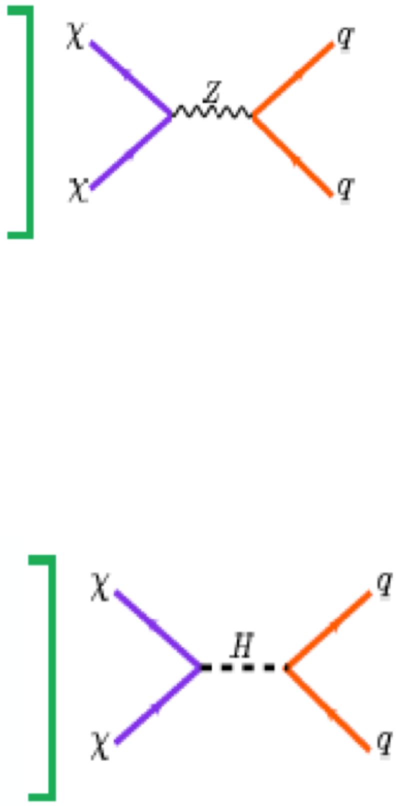
C_3F_8: PICO; Ge: CDEX
Si: DAMIC, SENSEI;
Ne: TREX-DM; He:SF_6:
CYGNUS; SF_6:
NEWAGE; Ag, Br, C:
NEWSdm,; H, He, Ne:
NEWS-G;

Ar: DEAP-3600
Xe: XMASS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE

Xe: LZ, PandaX-4T,
XENONnT, DARWIN/XLZD
Ar: DarkSide-50, SBC-LAr,
DarkSide-20k, Argo

Towards the neutrino fog



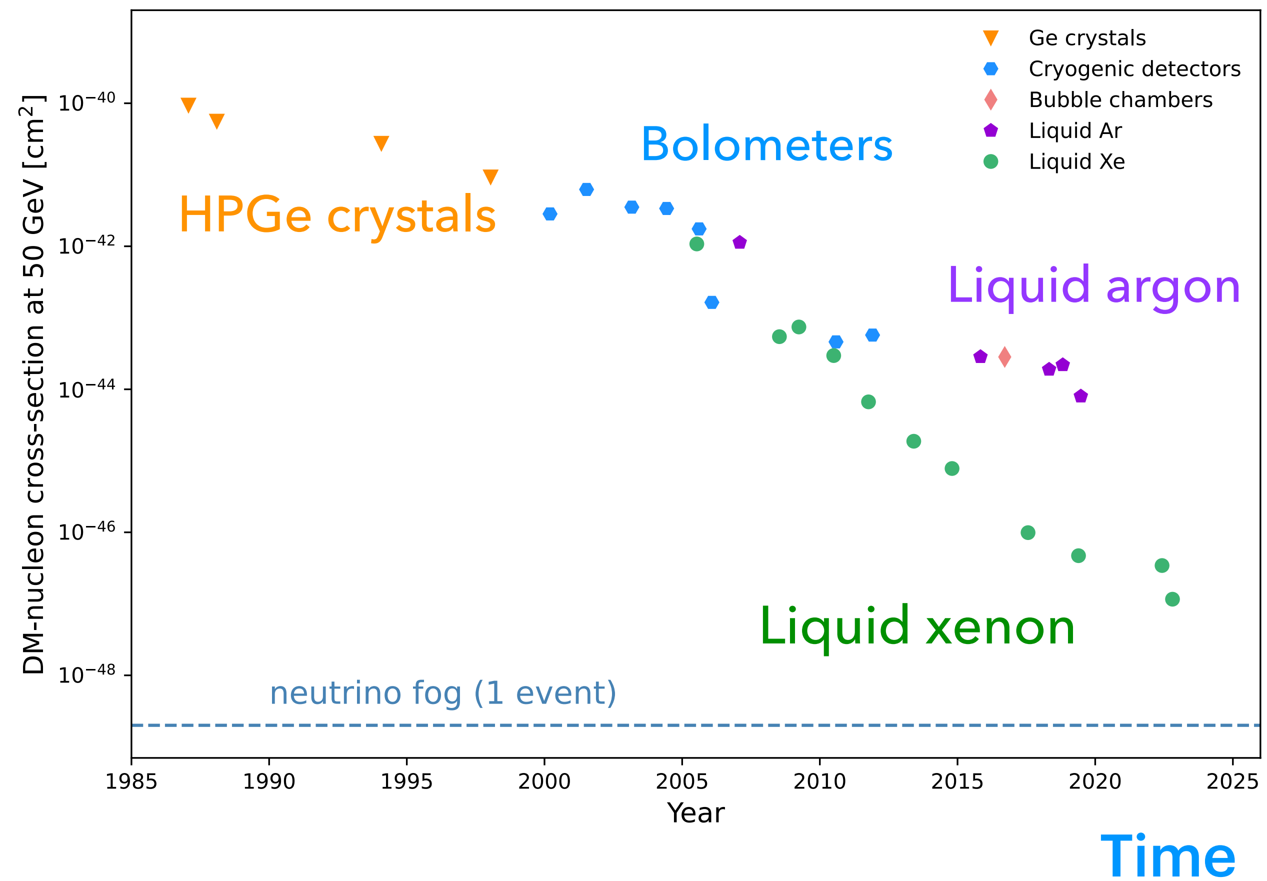


LB and Stefano Profumo, PDG 2024

Why liquid xenon detectors?

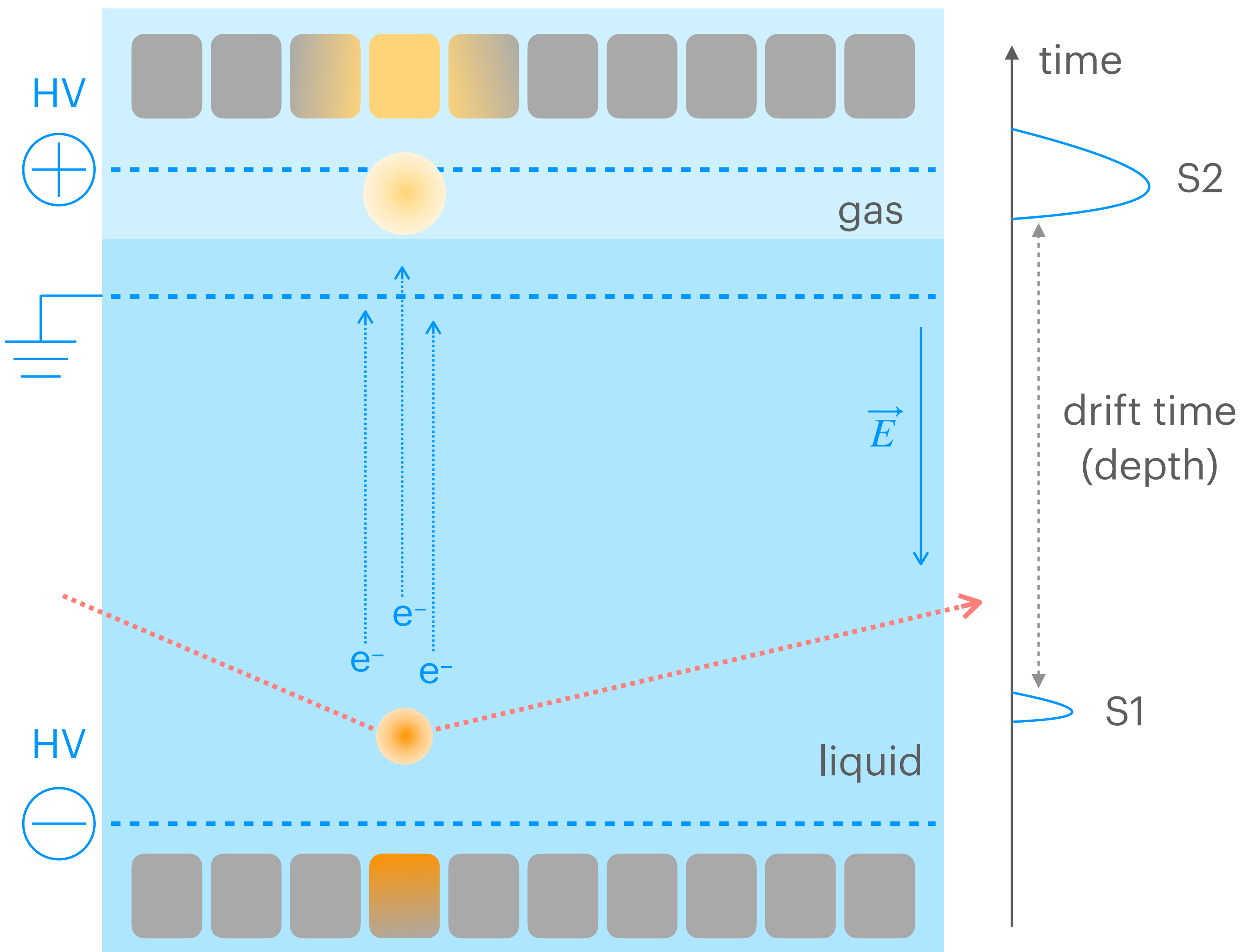
- Leading sensitivity at intermediate/high DM masses since ~2007
- Advantages
  - scalable ⇒ large target masses
  - readily purified ⇒ ultra-low backgrounds
  - high density ⇒ self-shielding
- SI and SD (^{129}Xe, ^{131}Xe) interactions
- Many other science opportunities (second order weak decays of ^{124}Xe, ^{126}Xe, ^{134}Xe, ^{136}Xe; solar and supernova neutrinos)

Upper limits for a 50 GeV WIMP



Two-phase xenon TPCs

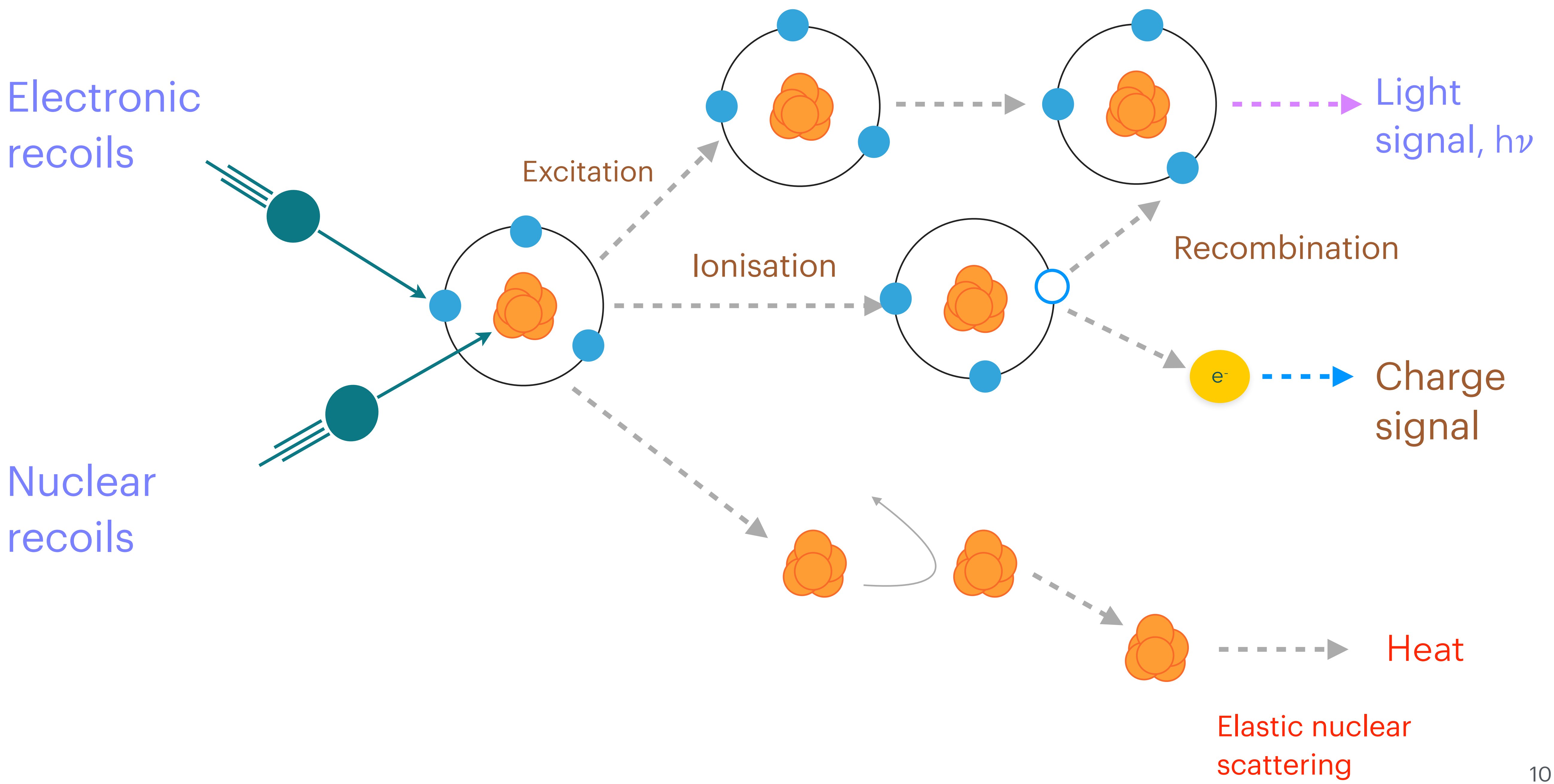
5D detectors: (x,y,z,E,t)



$$\lambda_{LXe} = 175 \text{ nm}$$

- Observe light (S1, primary scintillation) and charge signals (S2, secondary scintillation) when a particle interacts in the dense liquid
- 3D position reconstruction
- Energy reconstruction
- Particle discrimination: ratio of charge/light (ERs vs. NRs)

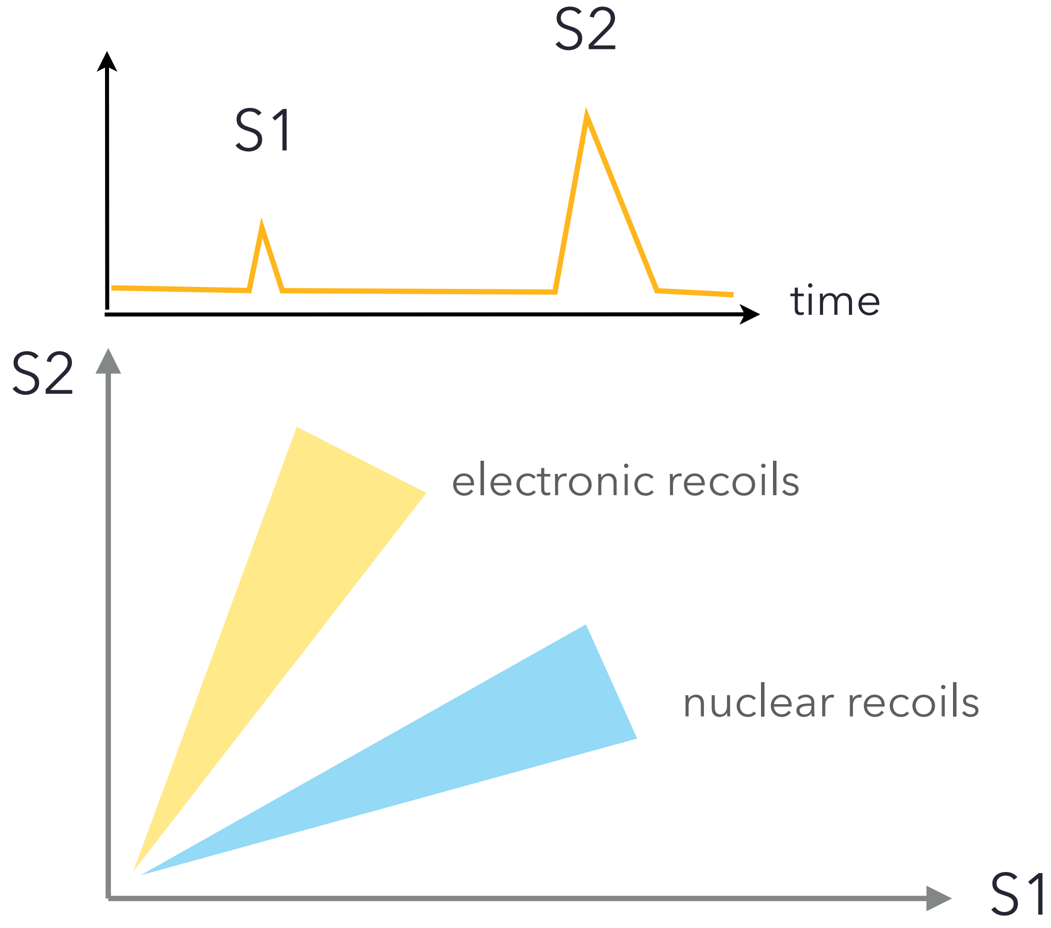
Electronic and nuclear recoils



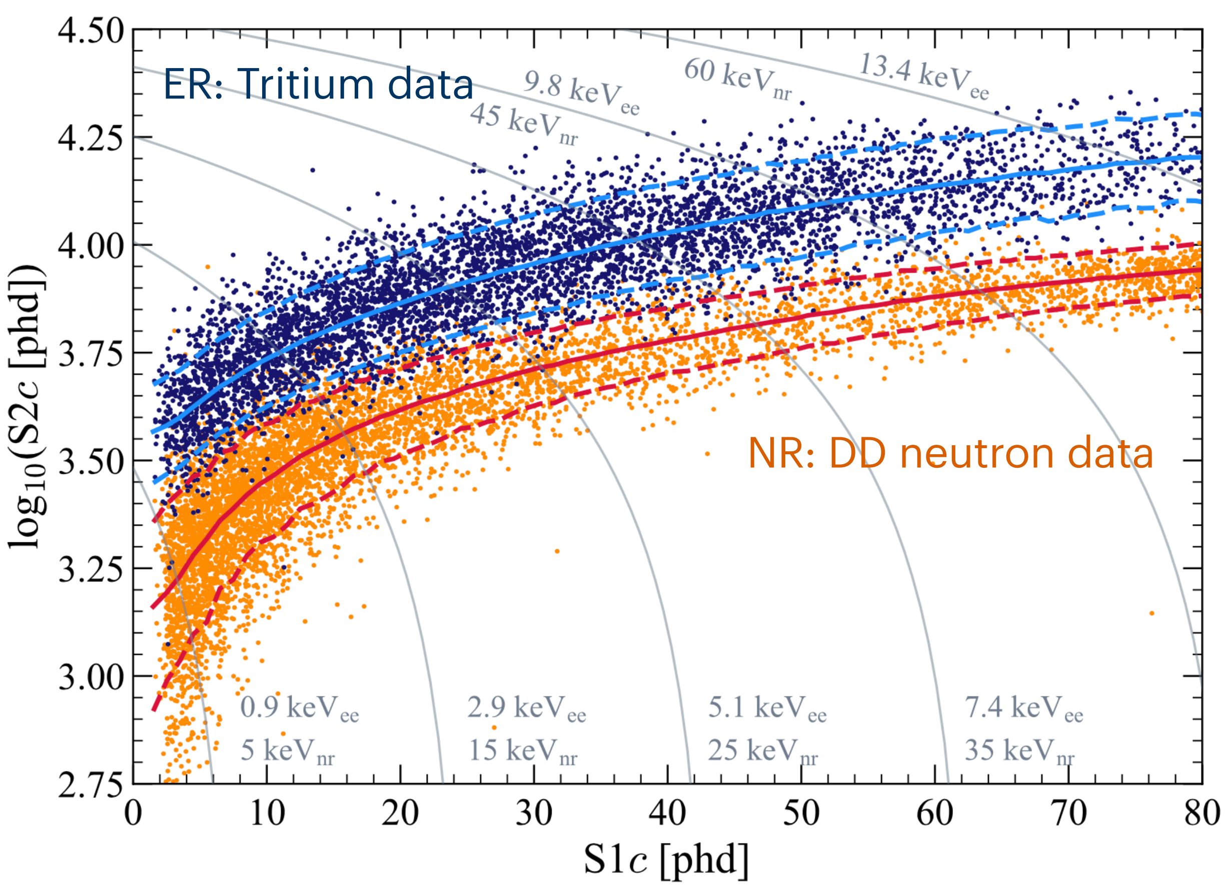
LB, Phil. Trans. R. Soc. A382 (2023), 0083

ER versus NR discrimination

- S2 over S1 depends on the type of particle (dE/dx): in particular, it is different for ERs versus NRs
- **Discrimination power** depends on an interplay between **the drift field** (that changes the mean recombination fraction $\langle r \rangle$ and the recombination fluctuations Δr; and the e⁻-ion recombination factor for ERs is more significantly affected by the field) and **total S1 light collection** (higher field means less S1 light and thus larger statistical fluctuations)
- Typically (99.5 - 99.99)% ER rejection at ~50% NR acceptance

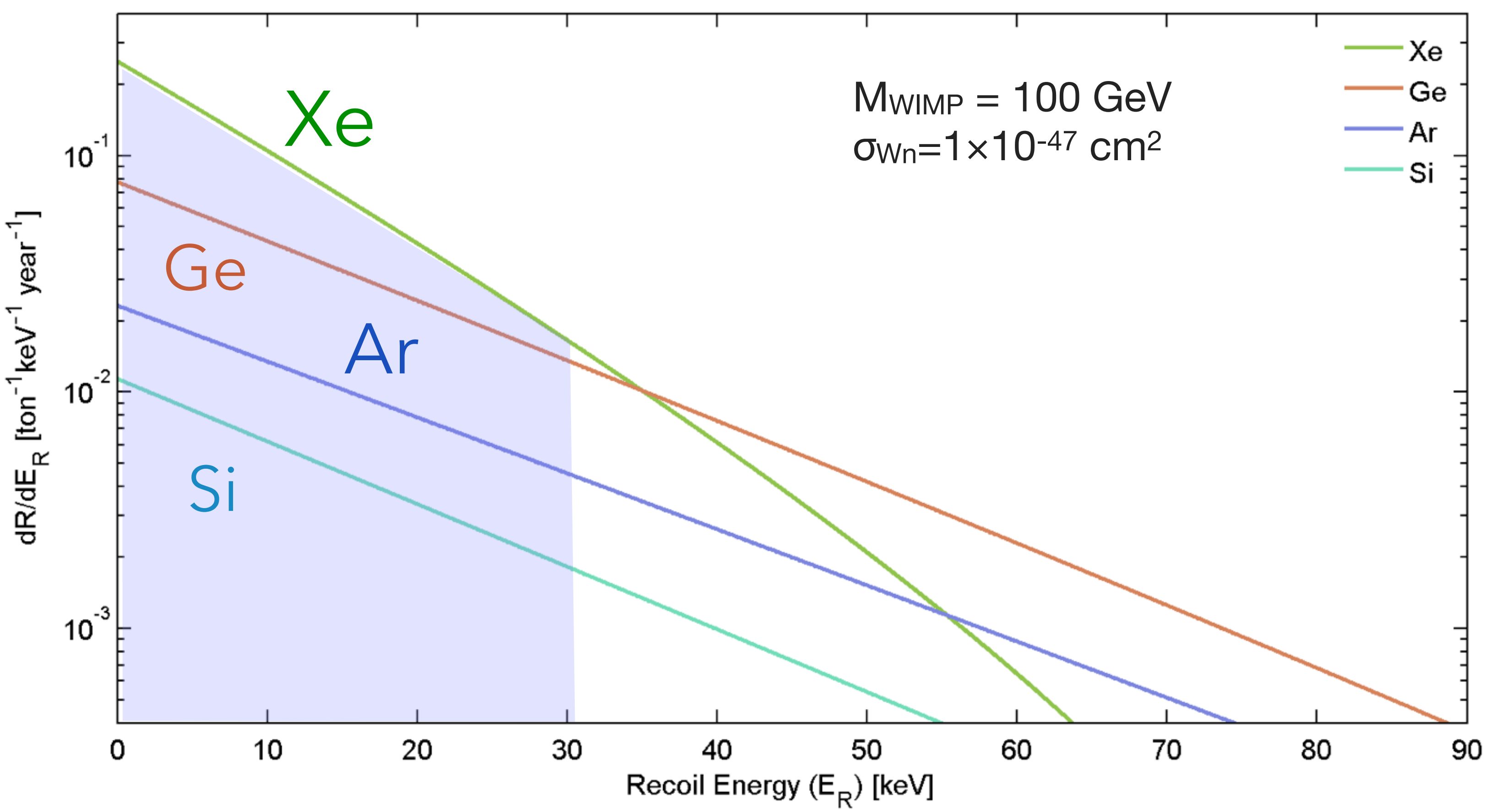


LZ, PRL 131, 2023



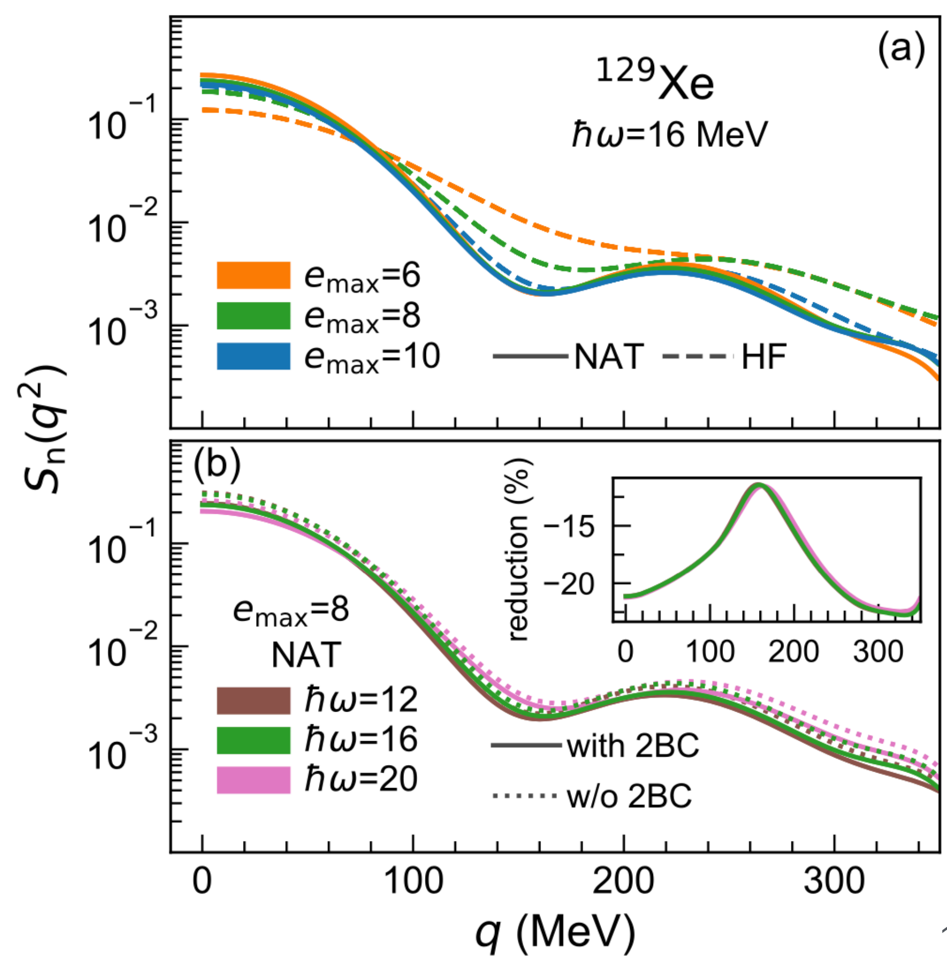
Interaction rates: DM-nucleus

$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



Spin-independent (SI) nuclear recoil spectrum

Spin-dependent

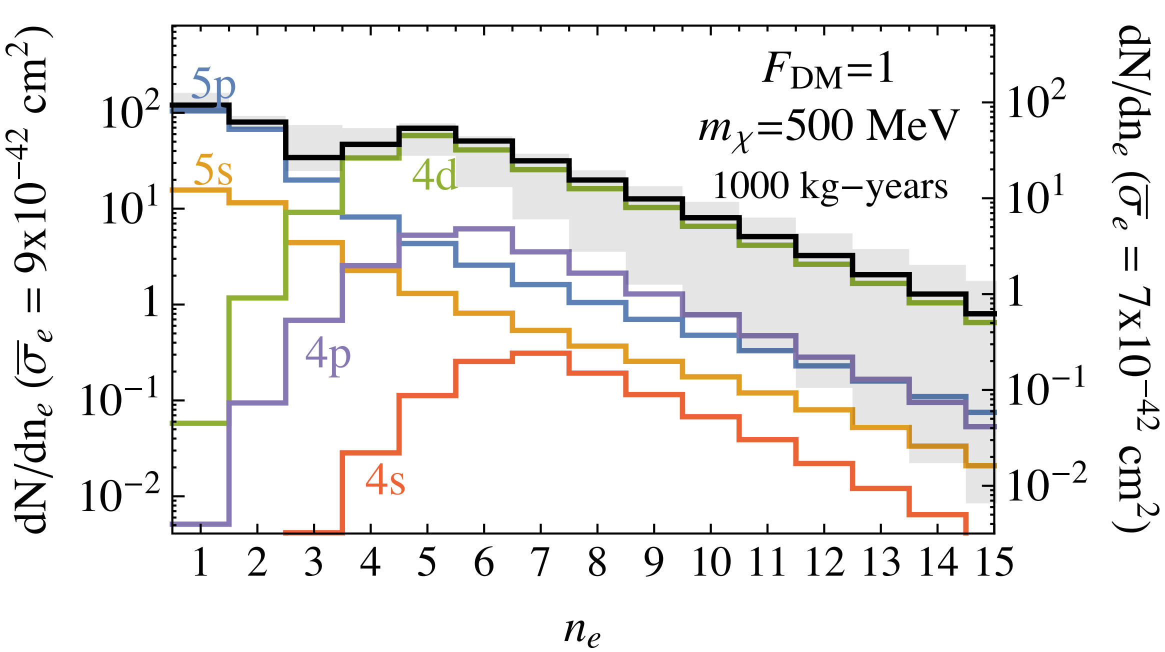


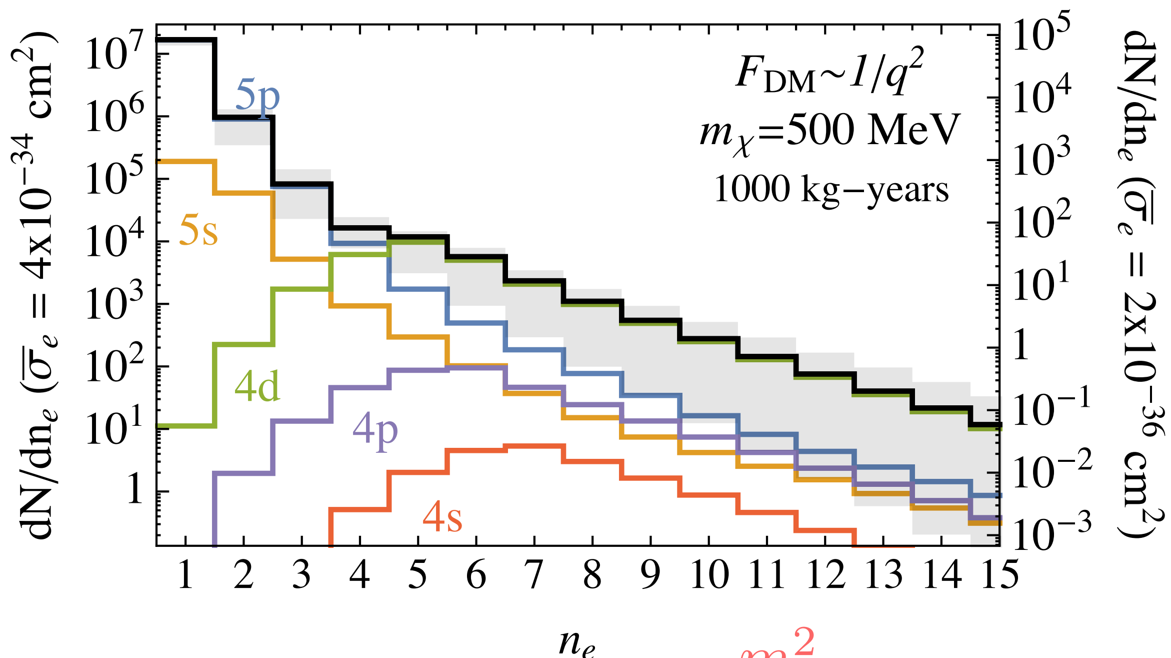
B.S. Hu et al, PRL 128, 2022

Interaction rates: DM-electron

$$\frac{dR_{ion}}{d\ln E_R} = \frac{6.2}{A}\left(\frac{\rho_0}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\sigma_e}{10^{-40}\mathrm{cm}^2}\right)\left(\frac{10\,\mathrm{MeV}}{m_{\mathrm{DM}}}\right)\times\frac{d\langle\sigma_{ion}v\rangle/d\ln E_R}{10^{-3}\sigma_e}\,\frac{\mathrm{events}}{\mathrm{kg\,d}}$$

Number of events for a Xe detector with 1 tonne year exposure (500 MeV DM)





$F_{DM} = 1$

$F_{DM} = \alpha^2 \frac{m_e^2}{q^2}$

Heavy dark photon A′ mediator

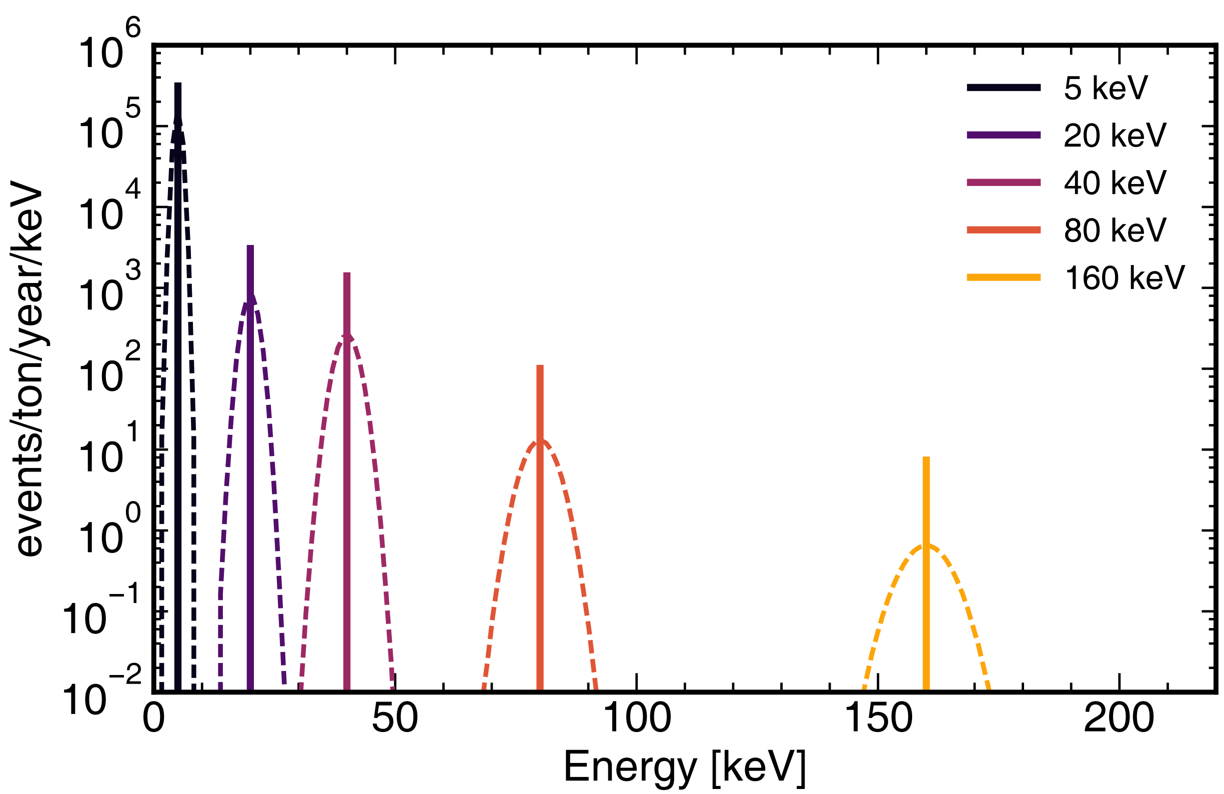
Ultra-light dark photon A′ mediator

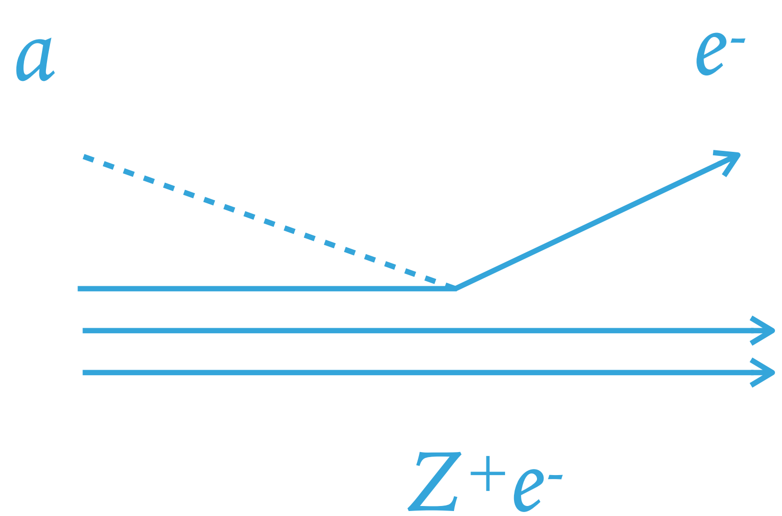
Essig, Volanski, Yu, PRD 96, 2017

Interaction rates: DM absorption

- Absorption of bosonic DM (ALPs, dark photons) ⇒ peak-like signatures
- Rates: ~ φ x σ ~ ρ x v/m x σ (here for ρ = 0.3 GeV/cm³)

$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

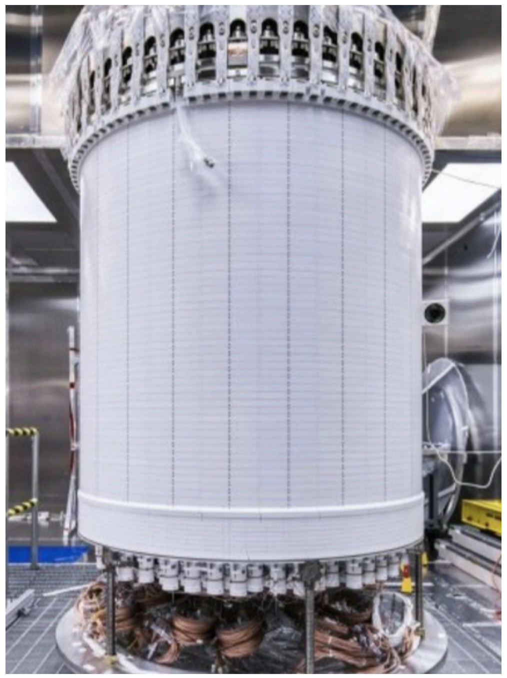




Pospelov, Ritz, Voloshin, PRD 78, 2008; An, Pospelov, Pradler, Ritz, PLB747, 2015

Ongoing LXe experiments

LUX-ZEPLIN

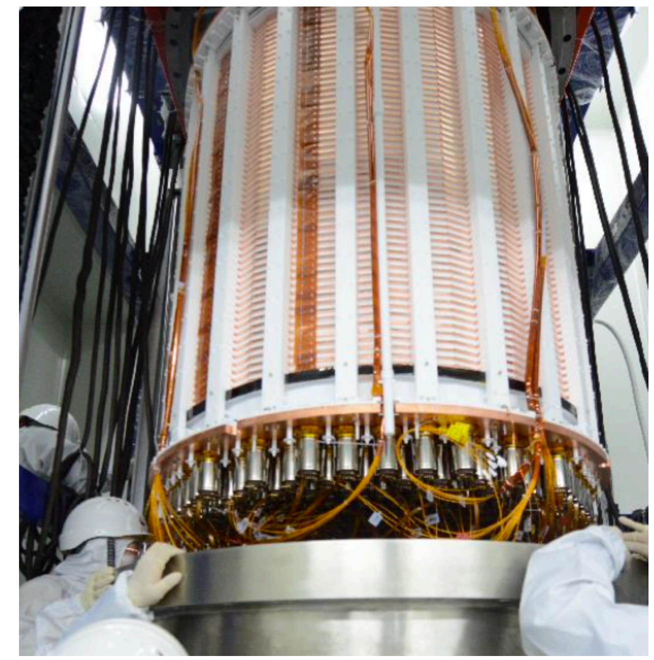


SURF, 7 t

XENONnT

LNGS, 5.9 t

PandaX-4T

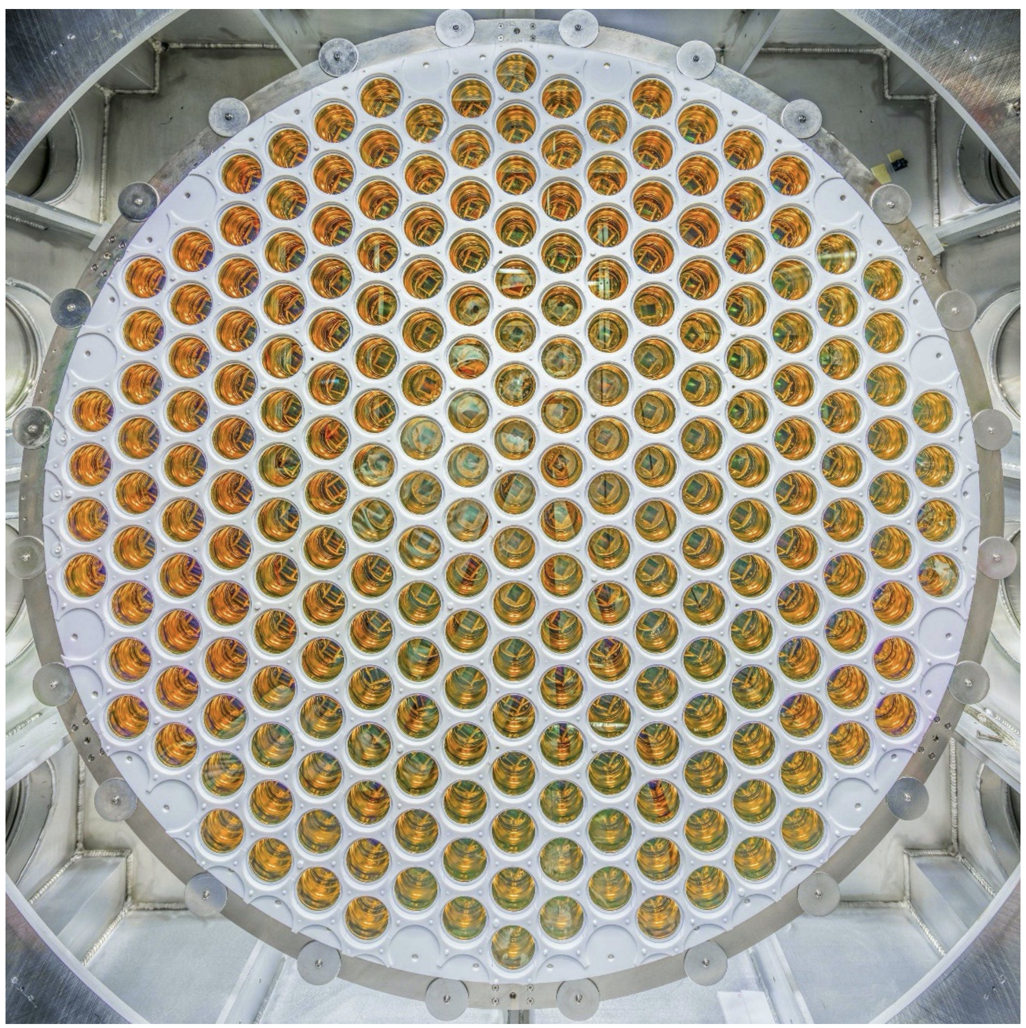


JinPing, 3.7 t

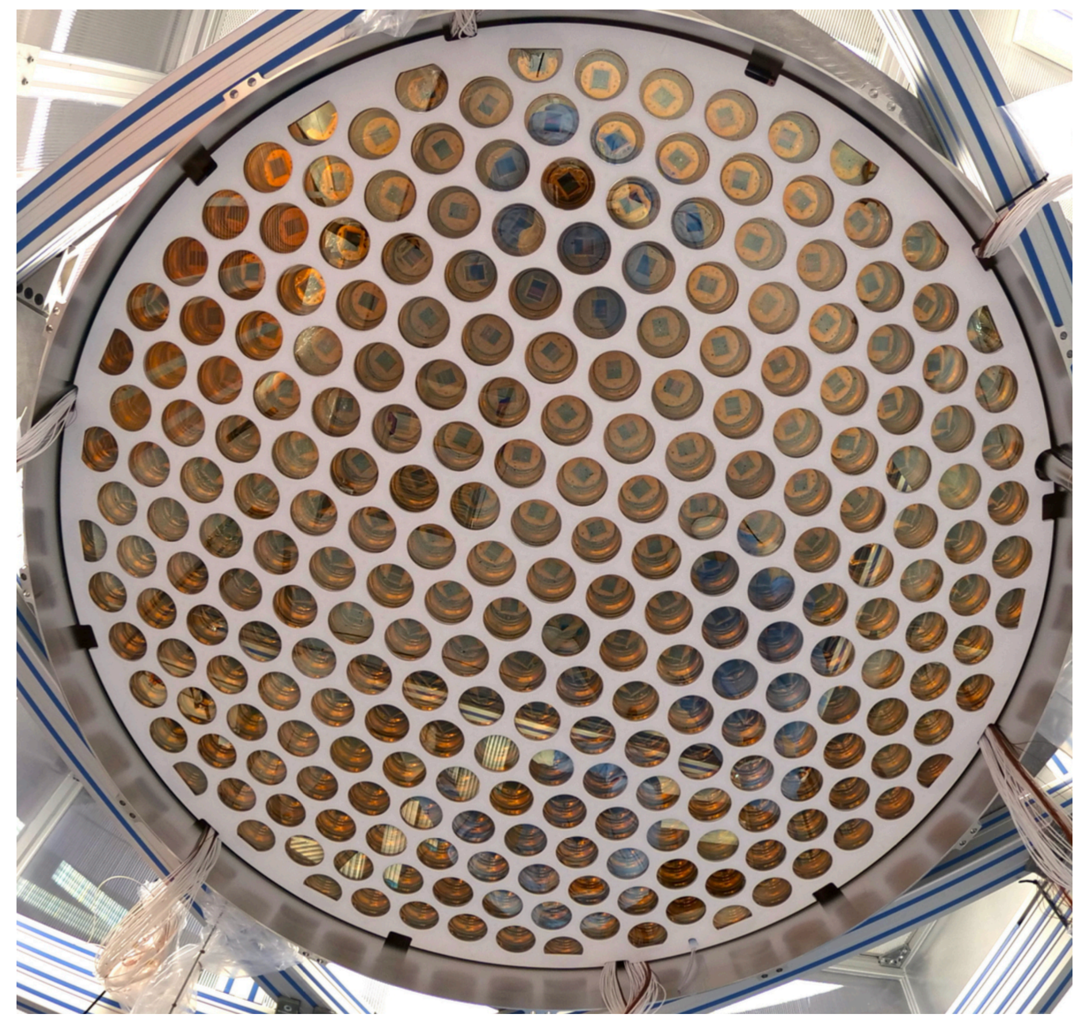
- TPCs with 2 arrays of 3-inch ø PMTs
- Kr & Rn removal techniques (to mitigate ^{85}Kr and ^{222}Rn backgrounds)
- Ultra-pure water shields, neutron & muon vetos

LUX-ZEPLIN and XENONnT

LUX-ZEPLIN top PMT array



XENONnT top PMT array

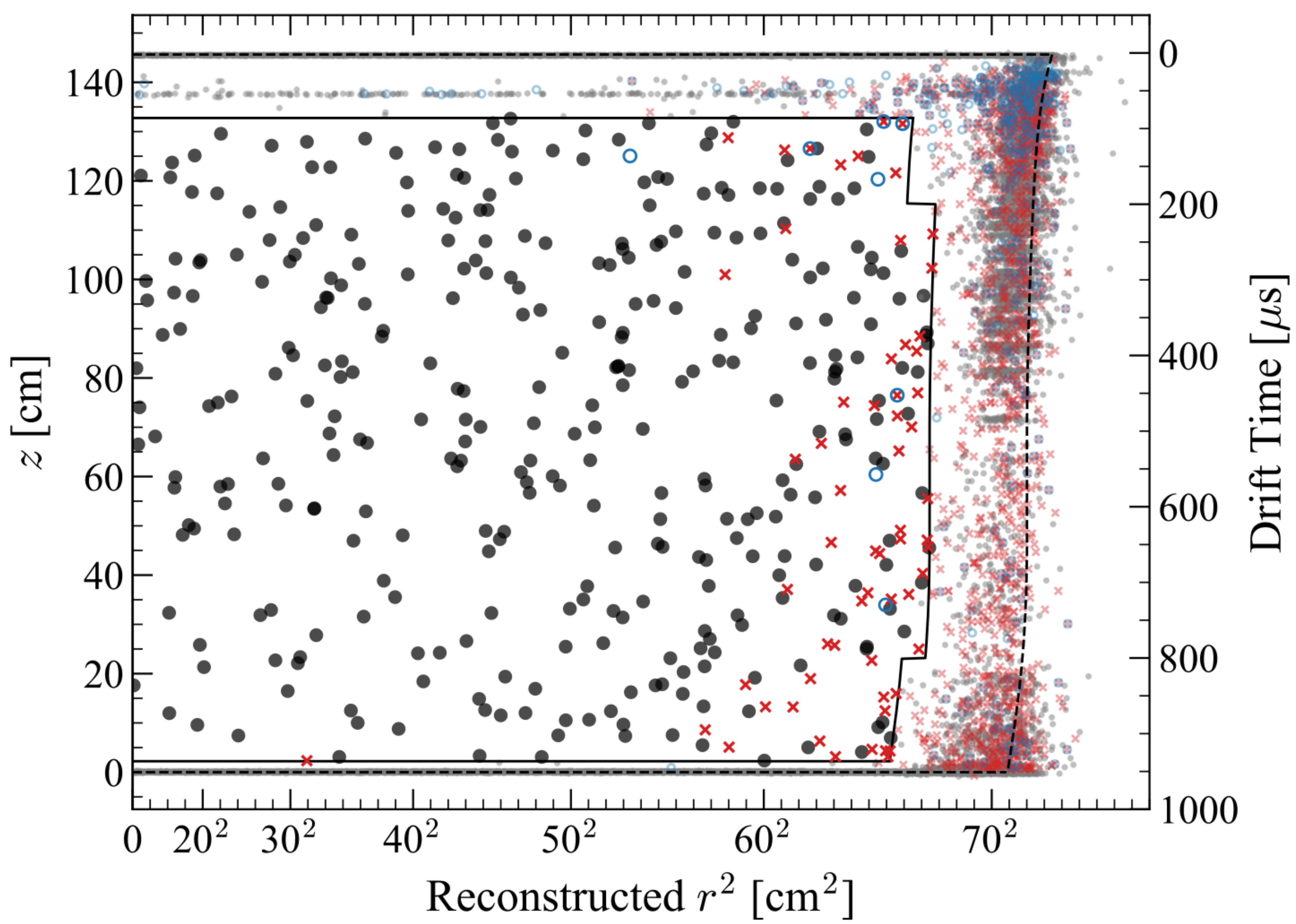


V.C. Antochi et al., JINST 16 (2021) 08, P08033

LUX-ZEPLIN and XENONnT

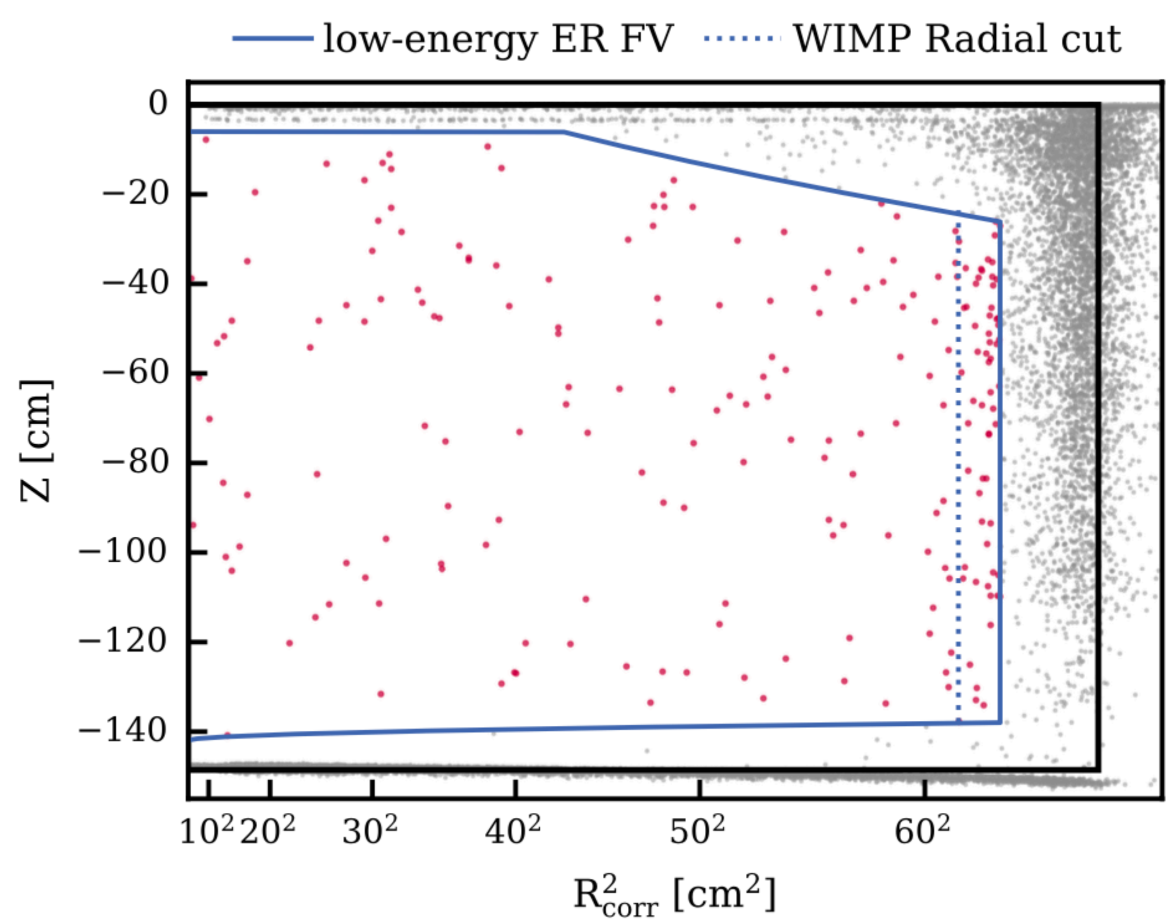
- Spatial distribution of events in the TPCs

LUX-ZEPLIN



LZ, PRL 131, 2023

XENONnT

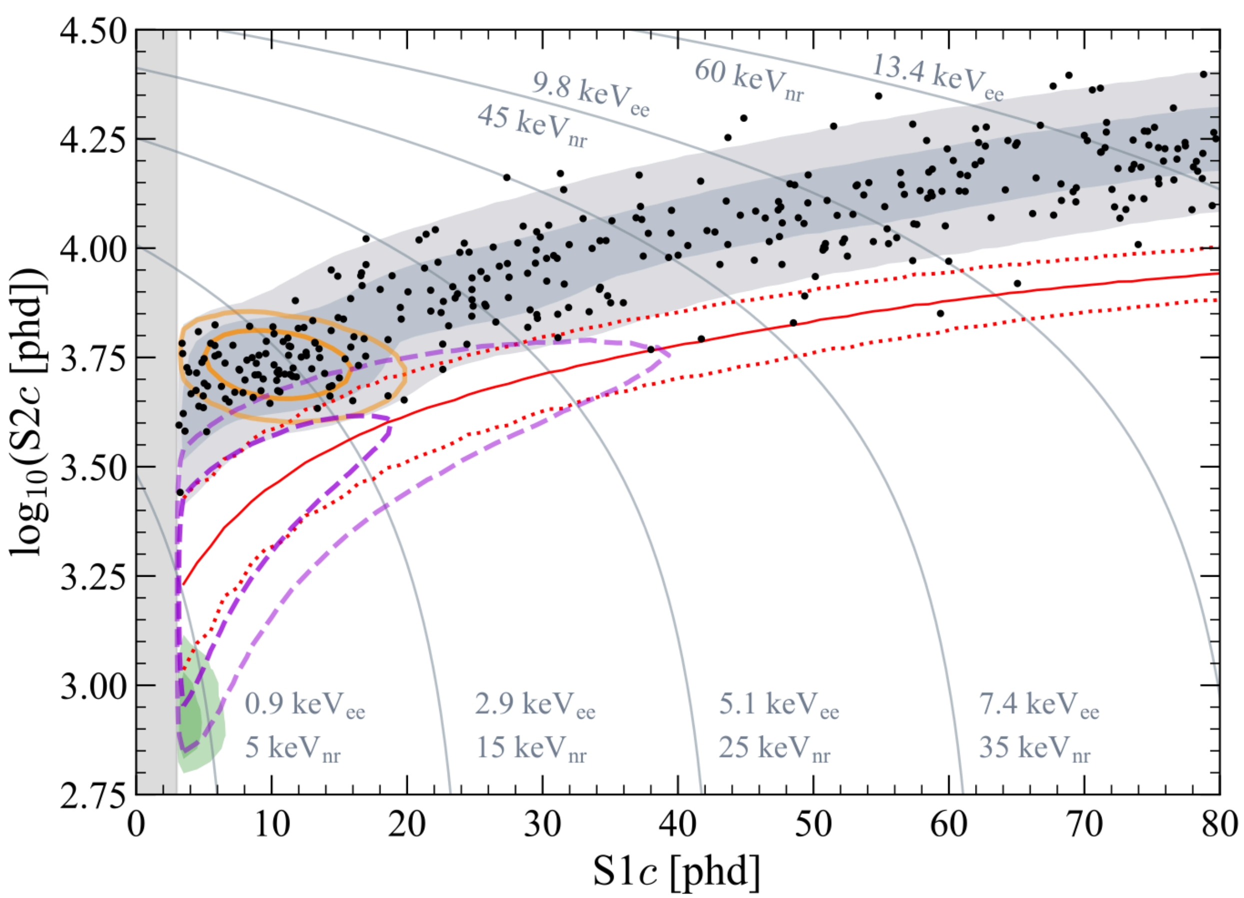


XENONnt, arXiv: 2409.08778 [hep-ex]

LUX-ZEPLIN and XENONnT

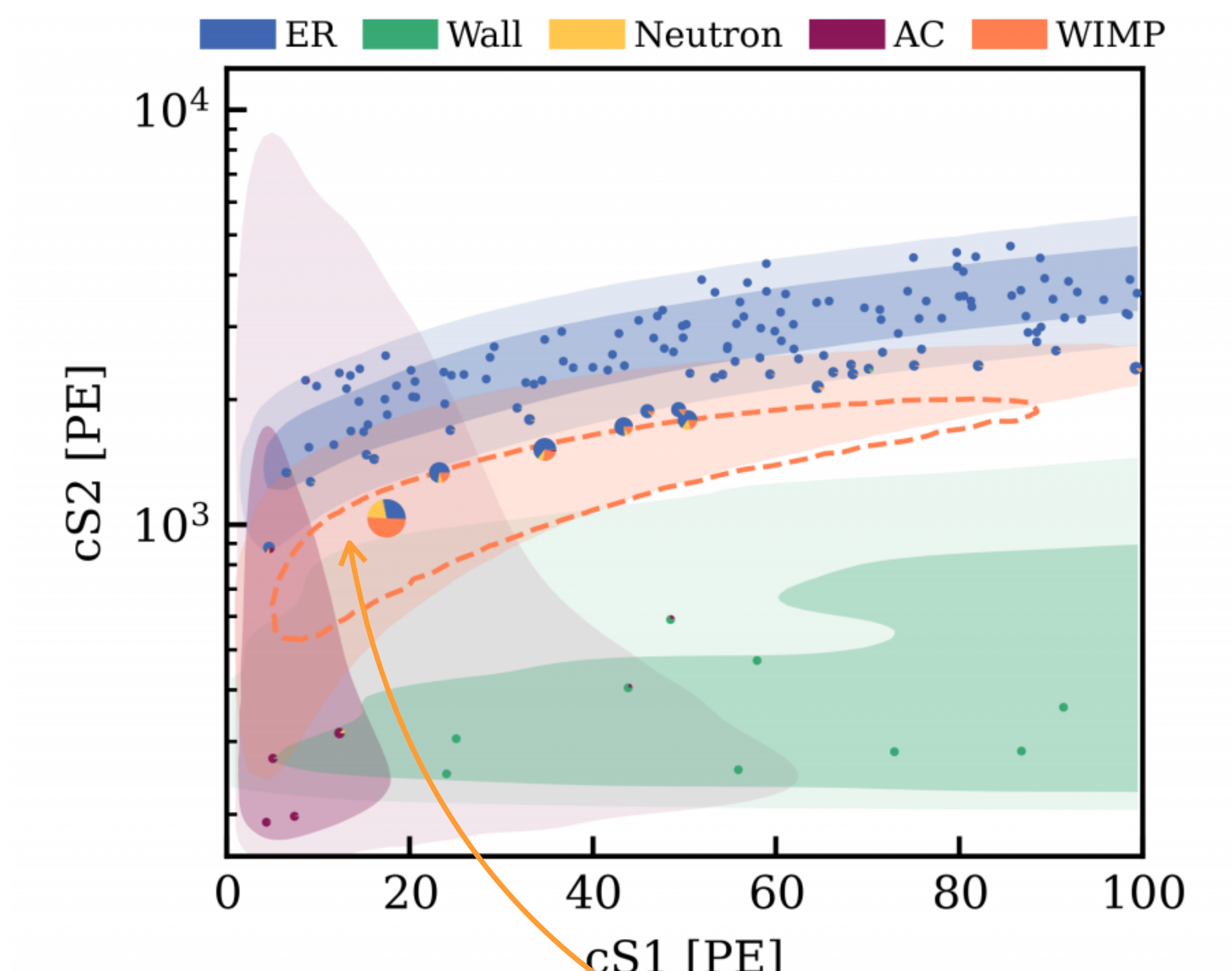
- Distribution of events in S2 versus S1 space in the TPC

LUX-ZEPLIN



LZ, PRL 131, 2023

XENONnT



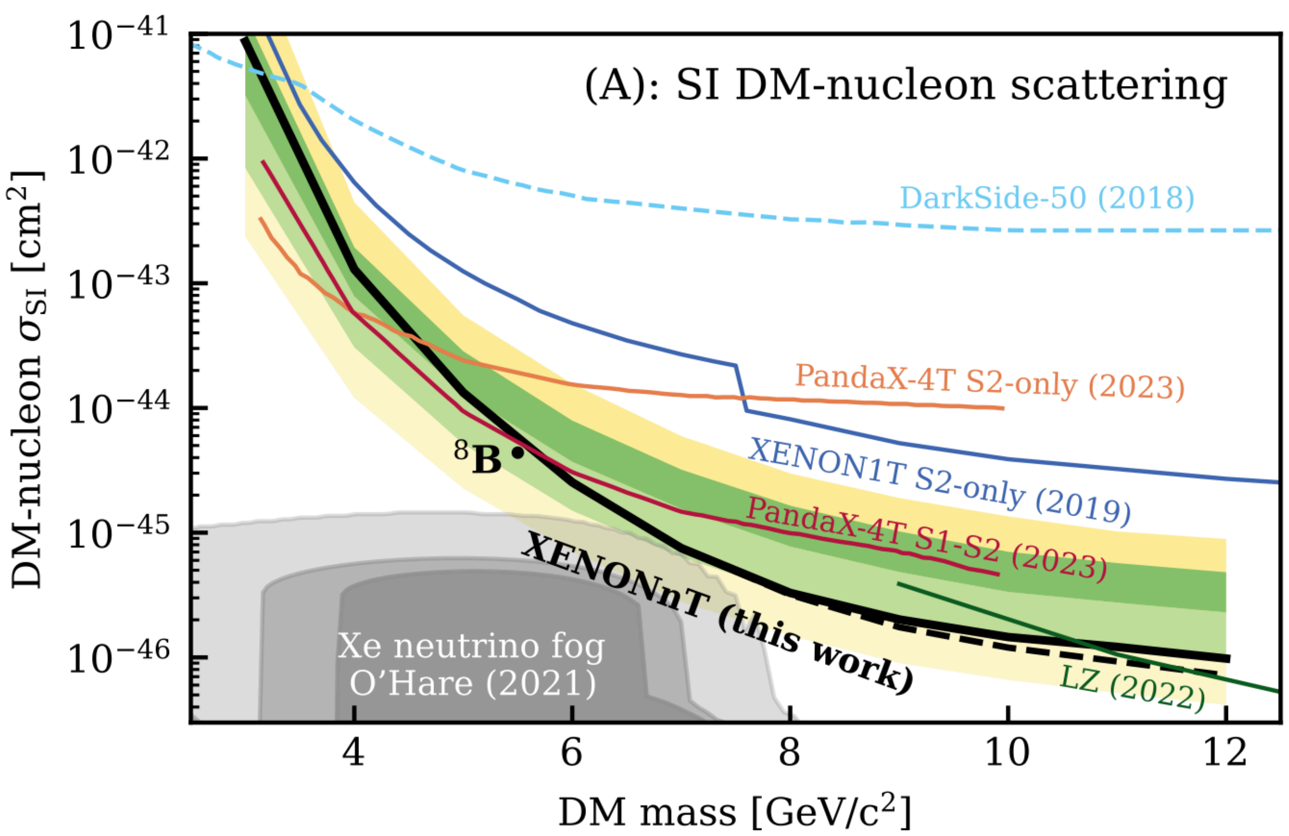
XENON PRL 131, 2023

2σ contour of 200 GeV/c² WIMP

Recent results: DM-nucleus

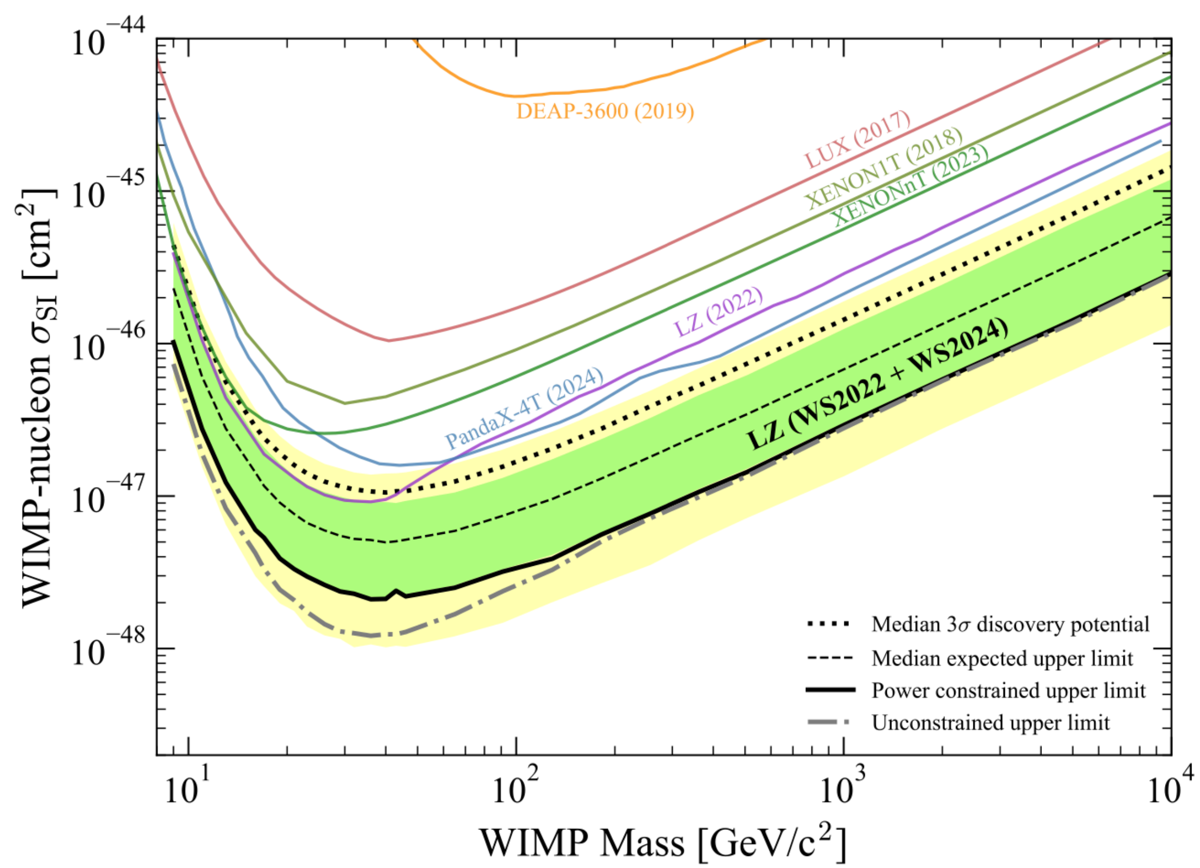
- DM mass range: ~ 3 GeV - 10 TeV

XENONnT



XENONnT 2024 arXiv:2409.17868
accepted in PRL, Jan 21, 2025

LUX-ZEPLIN



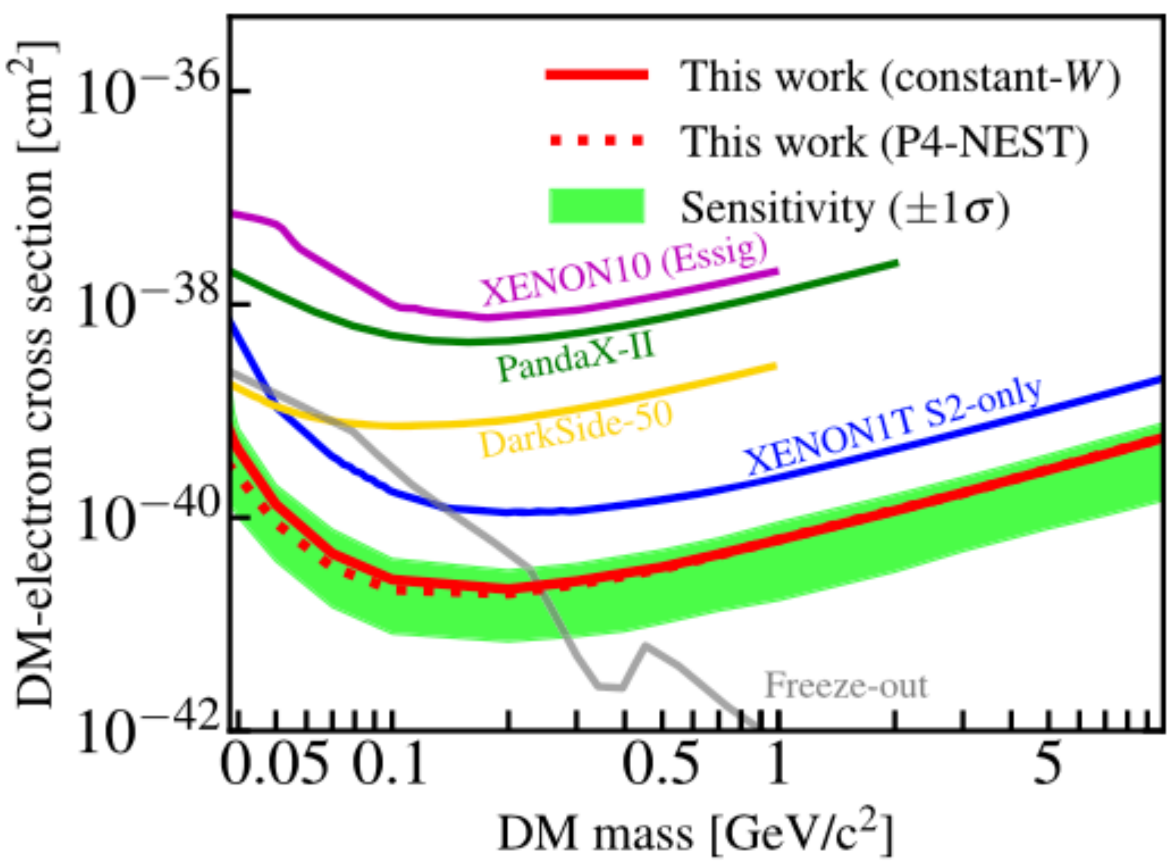
LUX-ZEPLIN 2024, arXiv:2410.17036

Recent results: DM-electron

- DM mass range: ~ 50 MeV - 10 GeV

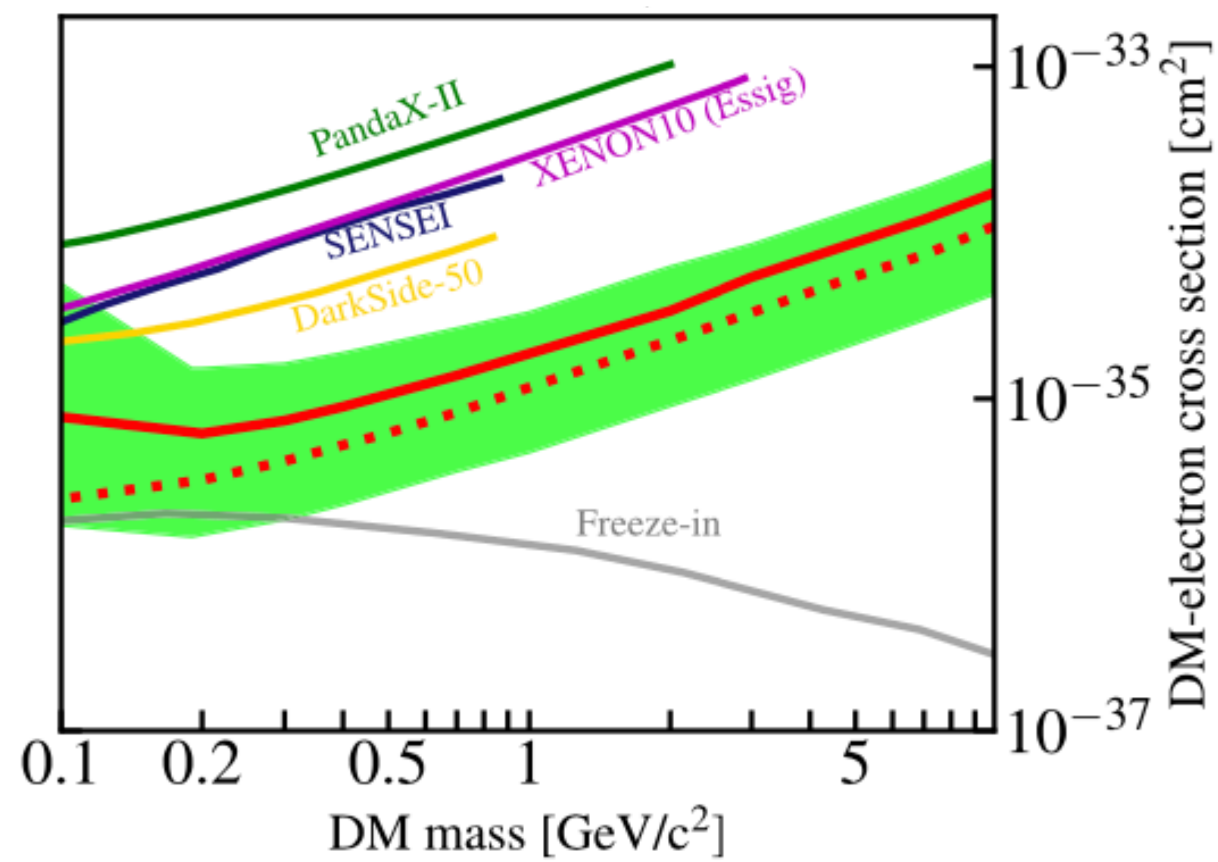
PandaX-4T

$F_{DM} = 1$



Heavy dark photon A′ mediator

$F_{DM} = 1/q^2$



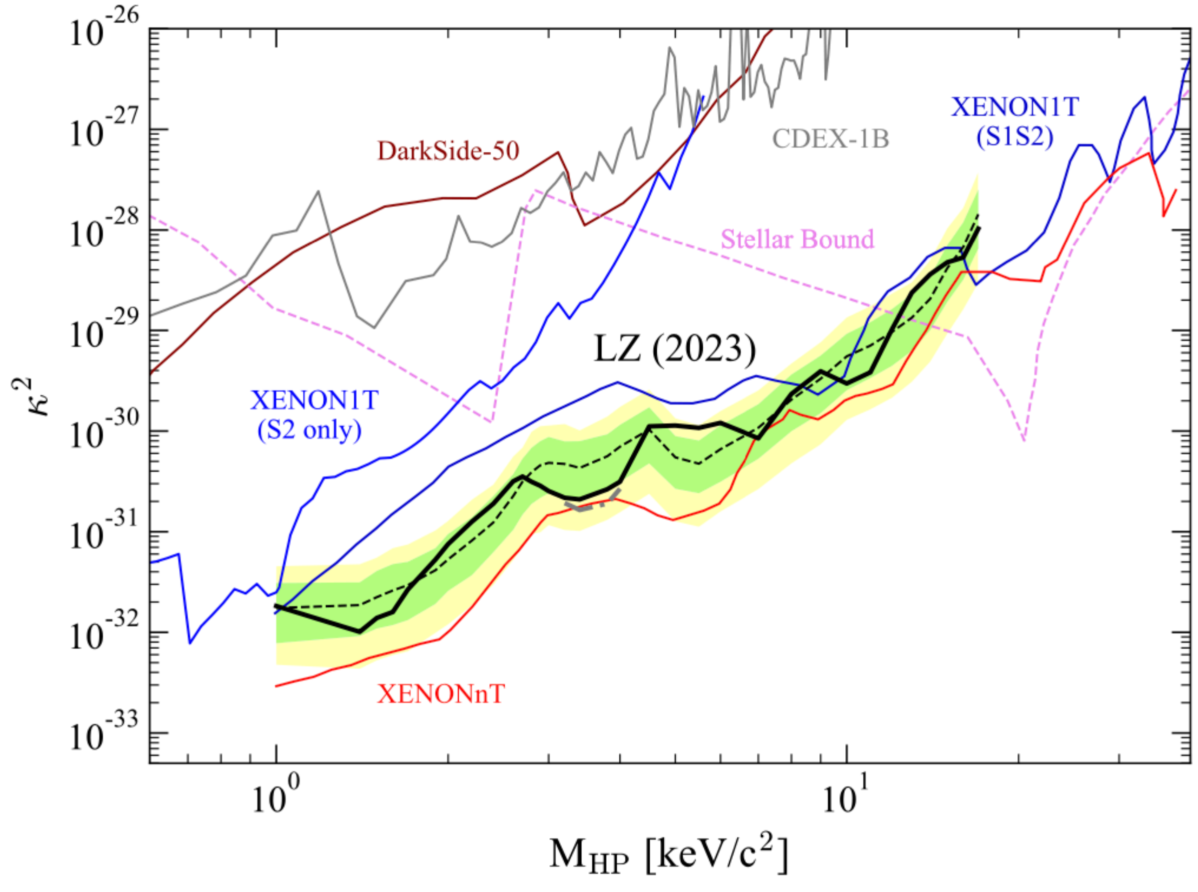
Ultra-light dark photon A′ mediator

PandaX-4T, PRL 130, 2023

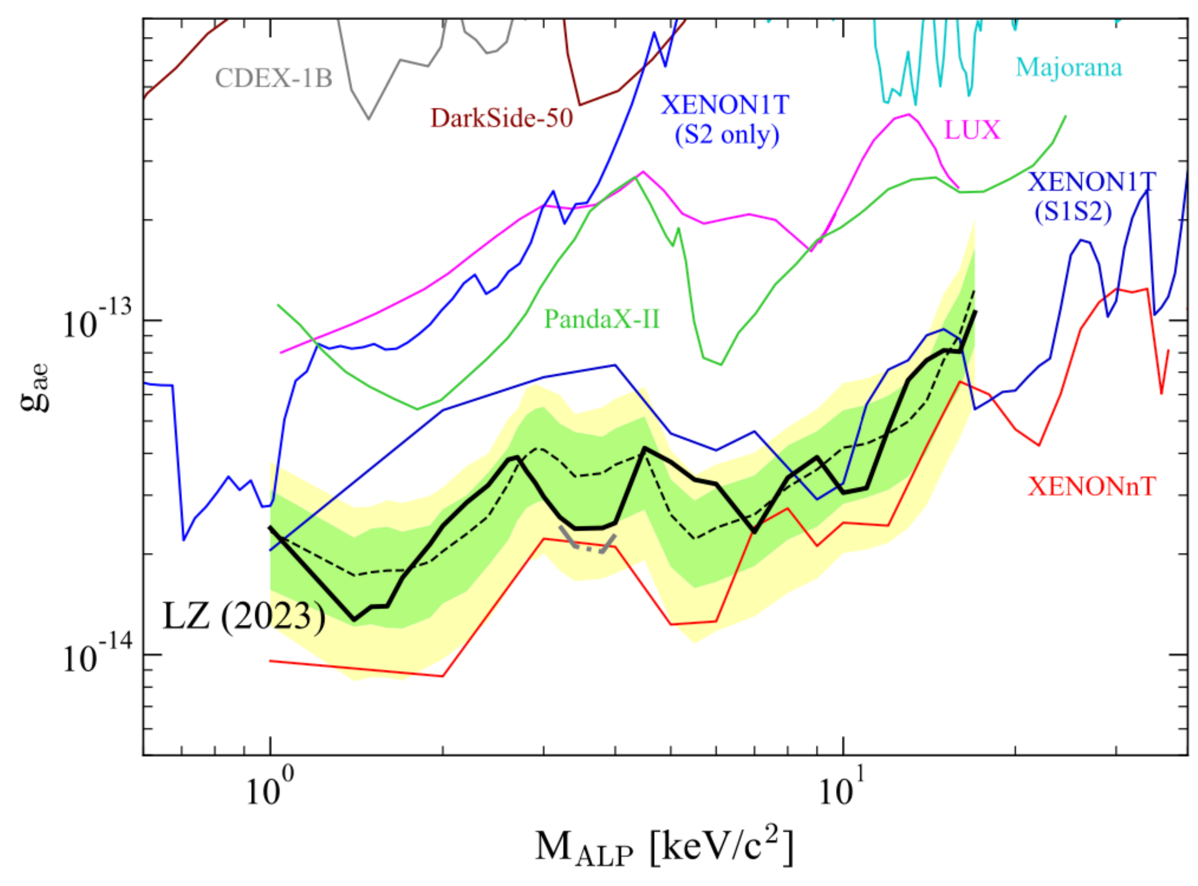
Recent results: DM absorption

- DM mass range: ~ 0.5 keV - 100 keV

Dark photons



Axion like particles

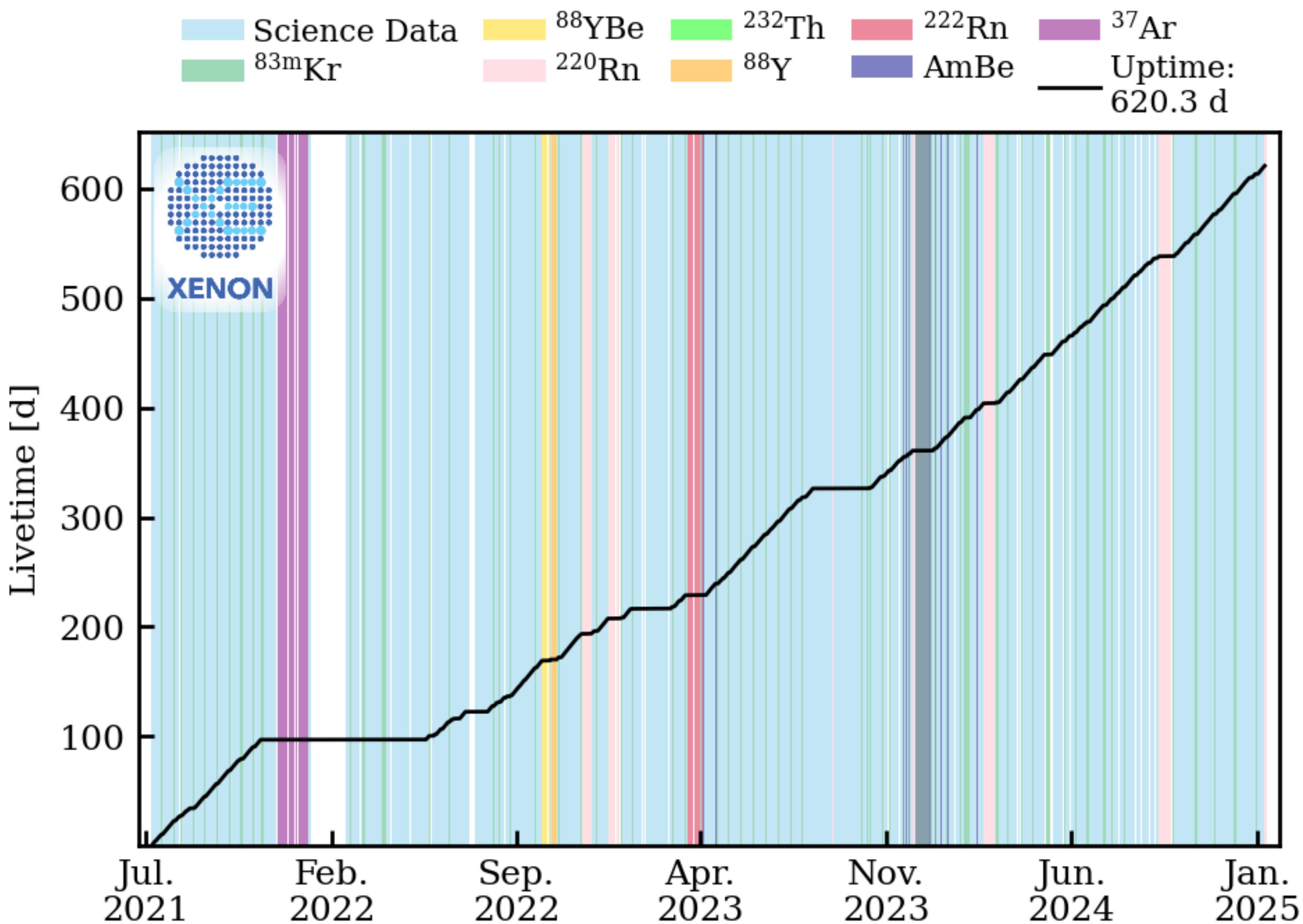


XENONnT, PRL 129, 2022; LZ, PRD 108, 2023

XENONnT at LNGS

XENONnT at LNGS

- Several science runs (SR0, SR1, SR2), analyses ongoing



XENONnT at LNGS

- Several science runs (SR0, SR1, SR2), analyses ongoing: examples

✳ pp and ^{7}Be solar neutrinos
✳ bosonic DM
✳ solar axions

✳ double beta decay ^{136}Xe ($Q_{\beta\beta}$ = 2.46 MeV)
✳ double electron capture ^{124}Xe (Q_{DEC} = 2.86 MeV)

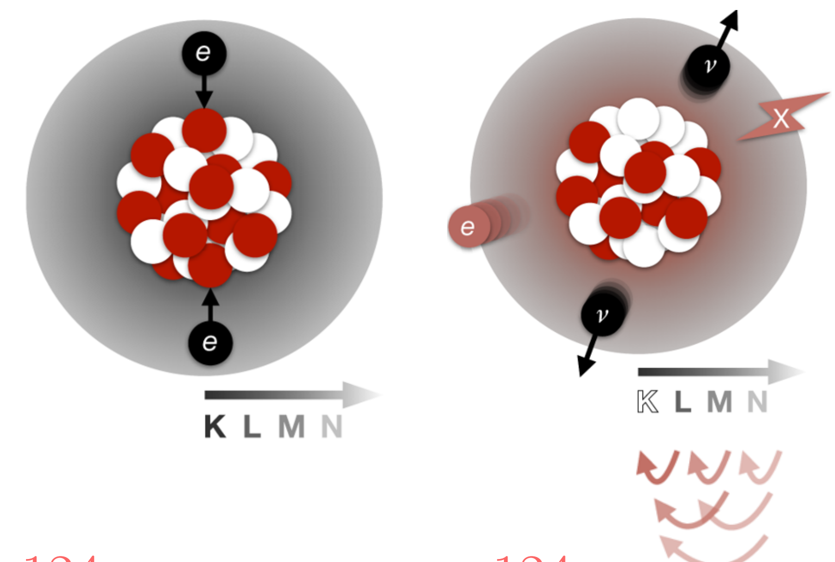
✳ ^{8}B solar neutrinos
✳ WIMP DM (SI, SD)

✳ inelastic DM
✳ EFT DM models

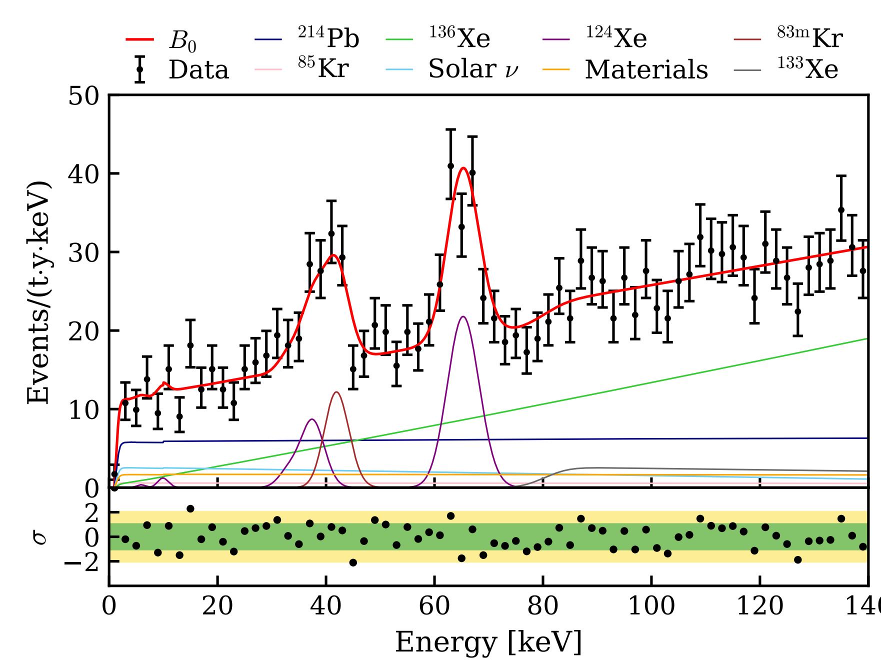
Second order weak decays

$$T_{1/2} = (1.8 \pm 0.5_{\rm stat} \pm 0.1_{\rm sys}) \times 10^{22}\ {\rm y}$$

Double electron capture



$$^{124}{\rm Xe} + 2{\rm e}^- \rightarrow\ ^{124}{\rm Te} + 2\nu_e$$



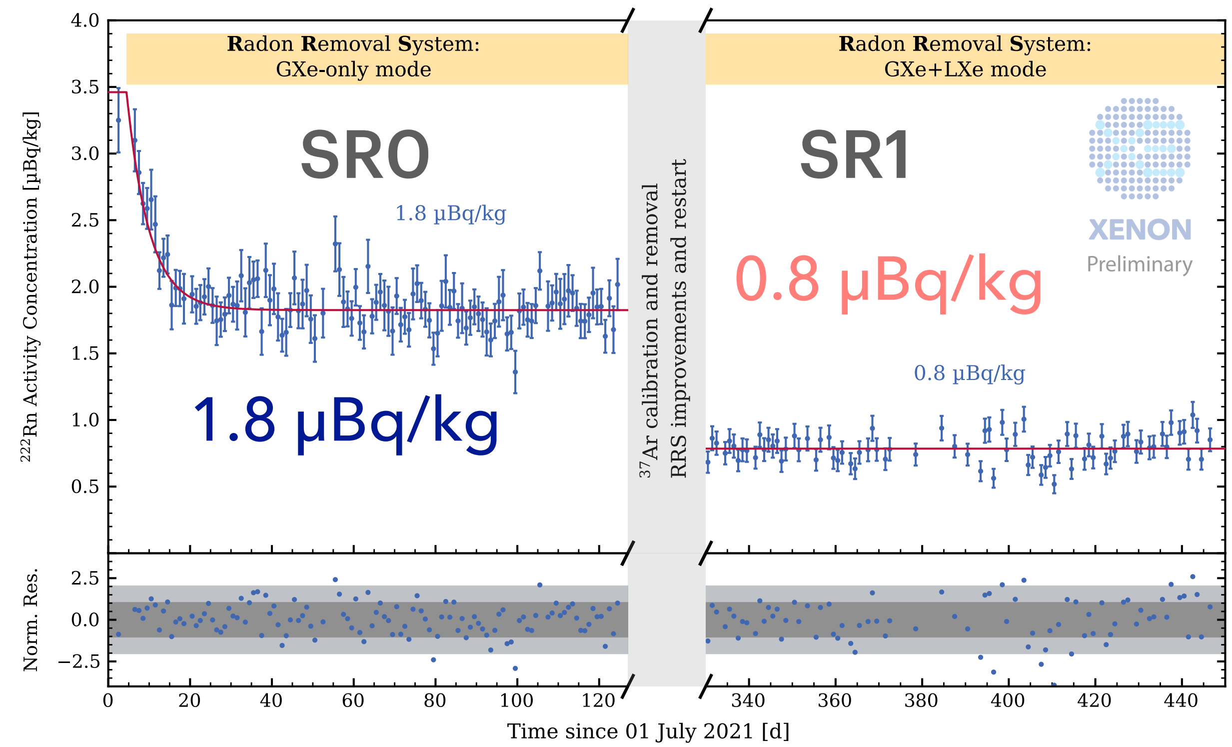
XENON, Nature 568, 2019

Solar neutrinos: ν-e scattering

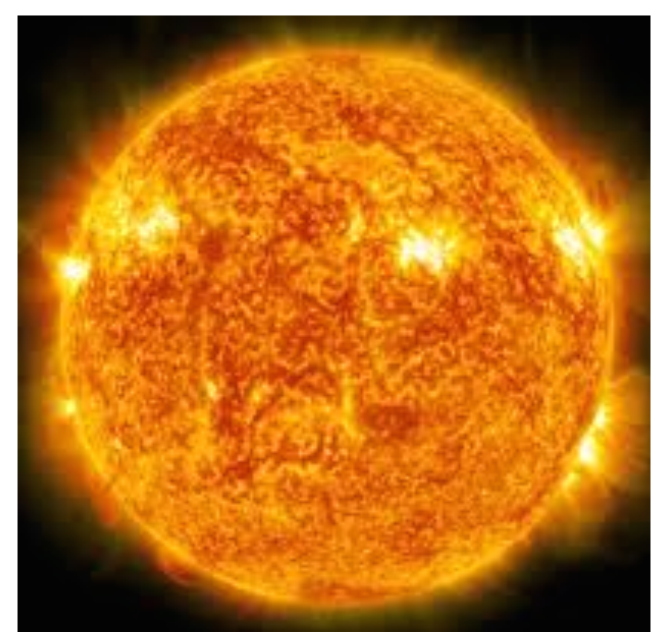
ER events in SR0

Component	(1,10) keV
^{214}Pb (^{222}Rn)	**56±7**
^{85}Kr	6±4
Materials	16±3
Solar ν	**25±2**
^{124}Xe	2.6±0.3
^{136}Xe	8.7±0.3
AC	0.7±0.03

Rn concentration reduced for SR1



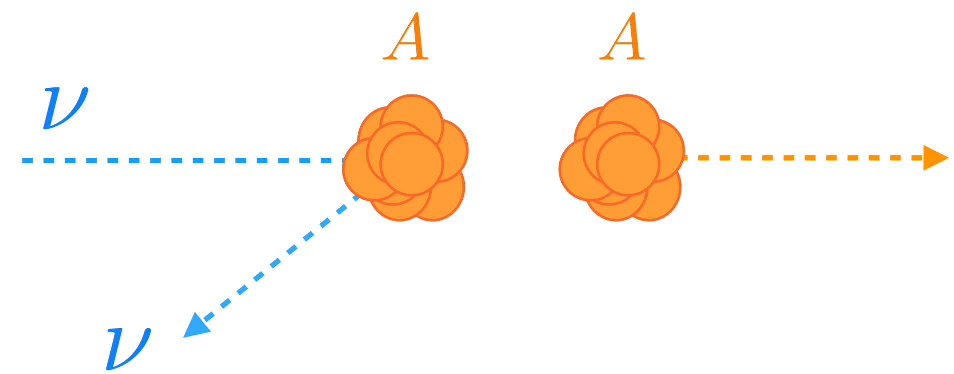
Solar neutrino flux at low energies (pp and ^{7}Be)



ν-e scattering

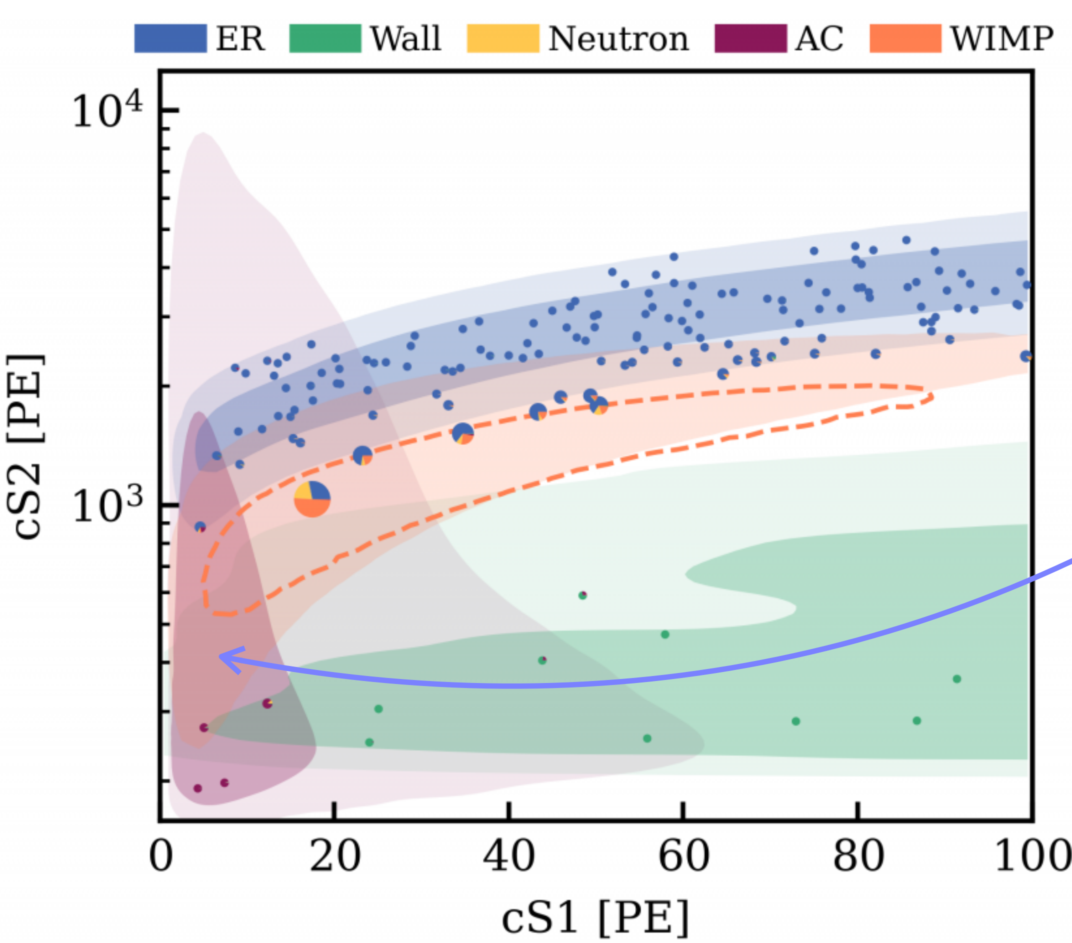
Solar neutrinos: ν-nucleus scattering

- Observed ^{8}B neutrinos via CEvNS
- In LXe: ~99% of events < 4 keV NR energy
- Expect: ~ 10^4 events/(200 t y)



$$\nu_x + A \rightarrow \nu_x + A$$

XENON, PRL 131, 2023

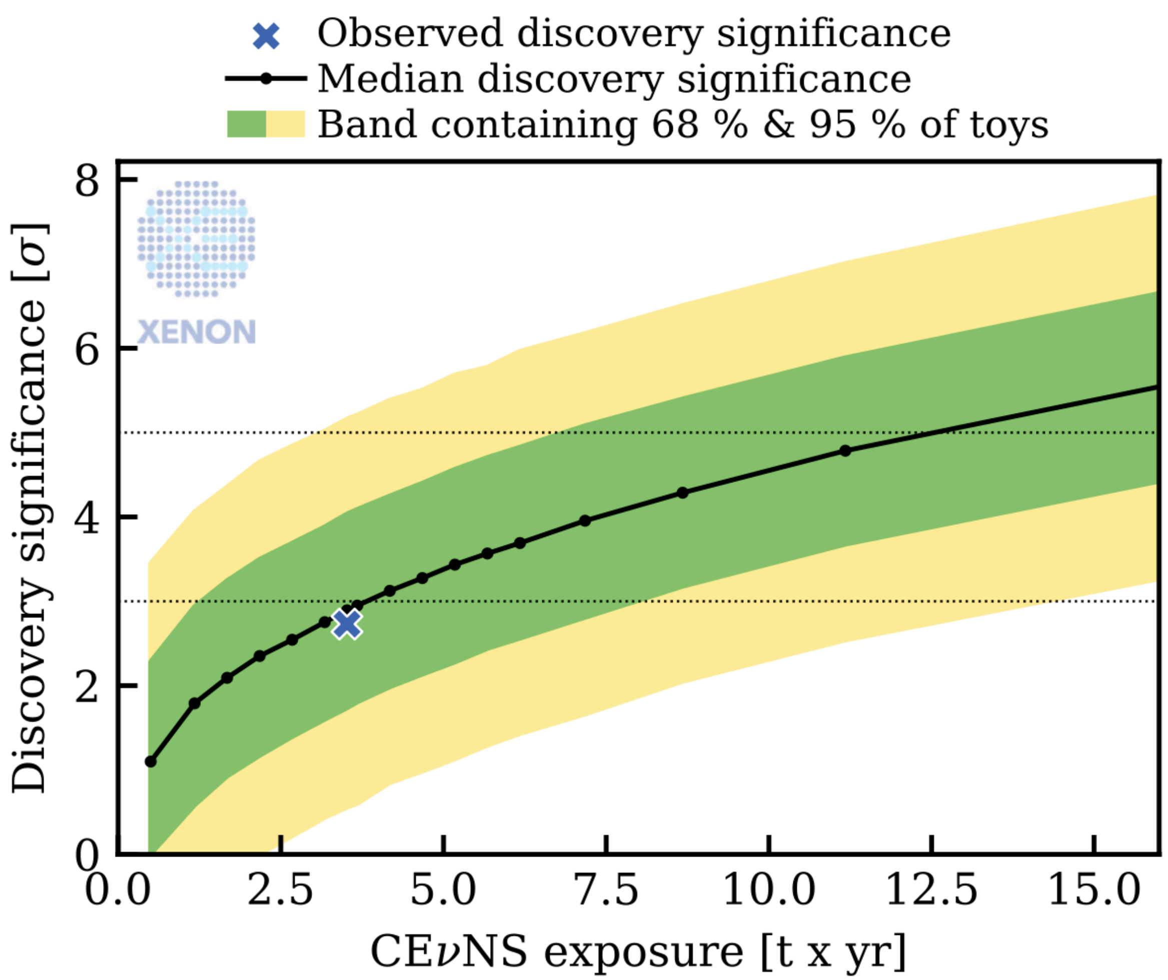


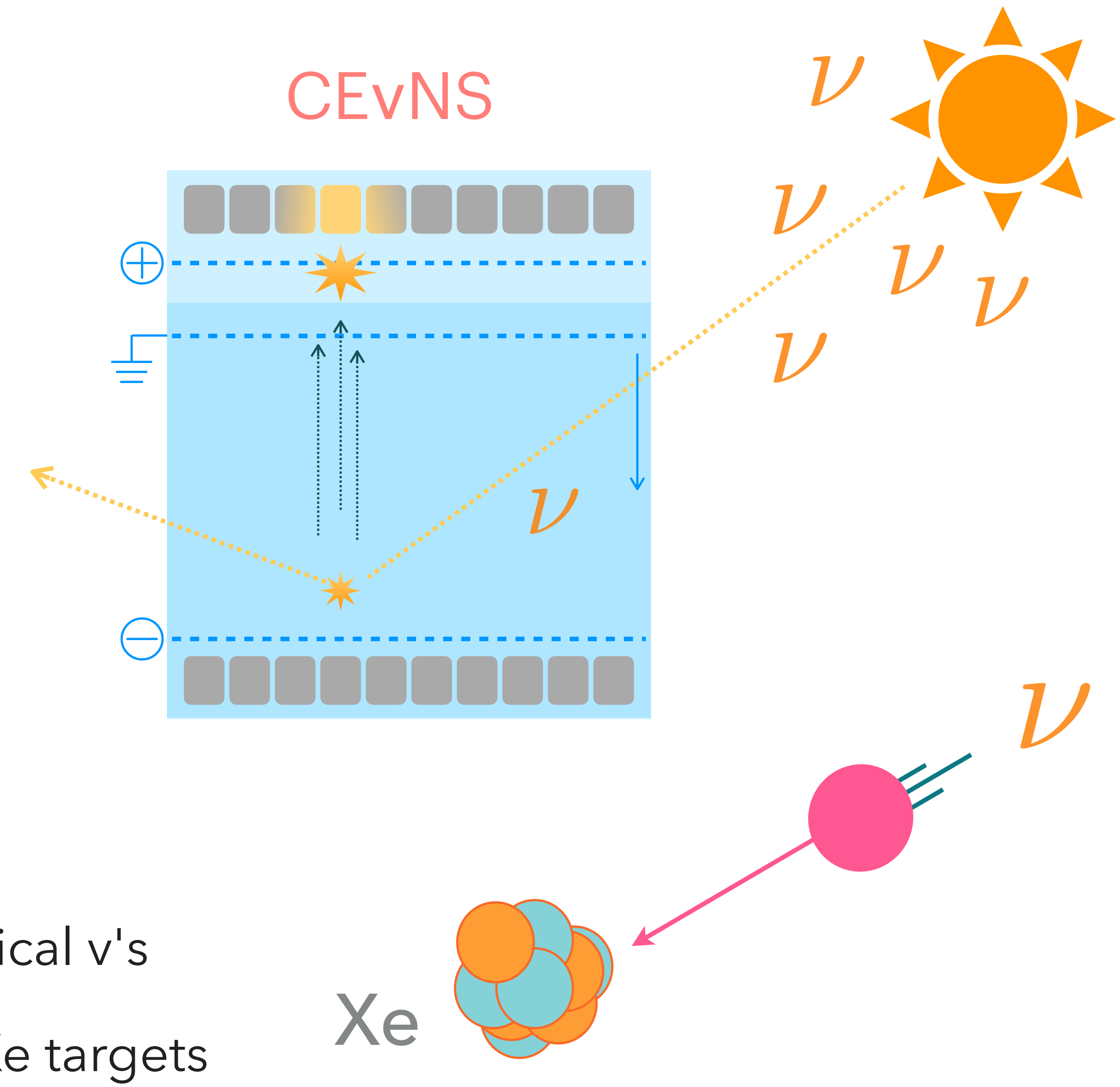
expect 8B CEvNS events here!

✳ Complementary measurements to experiments using CC reactions

✳ "Flavour democratic" (C. Lunardi, Neutrino-2024)

Solar neutrinos: ν-nucleus scattering





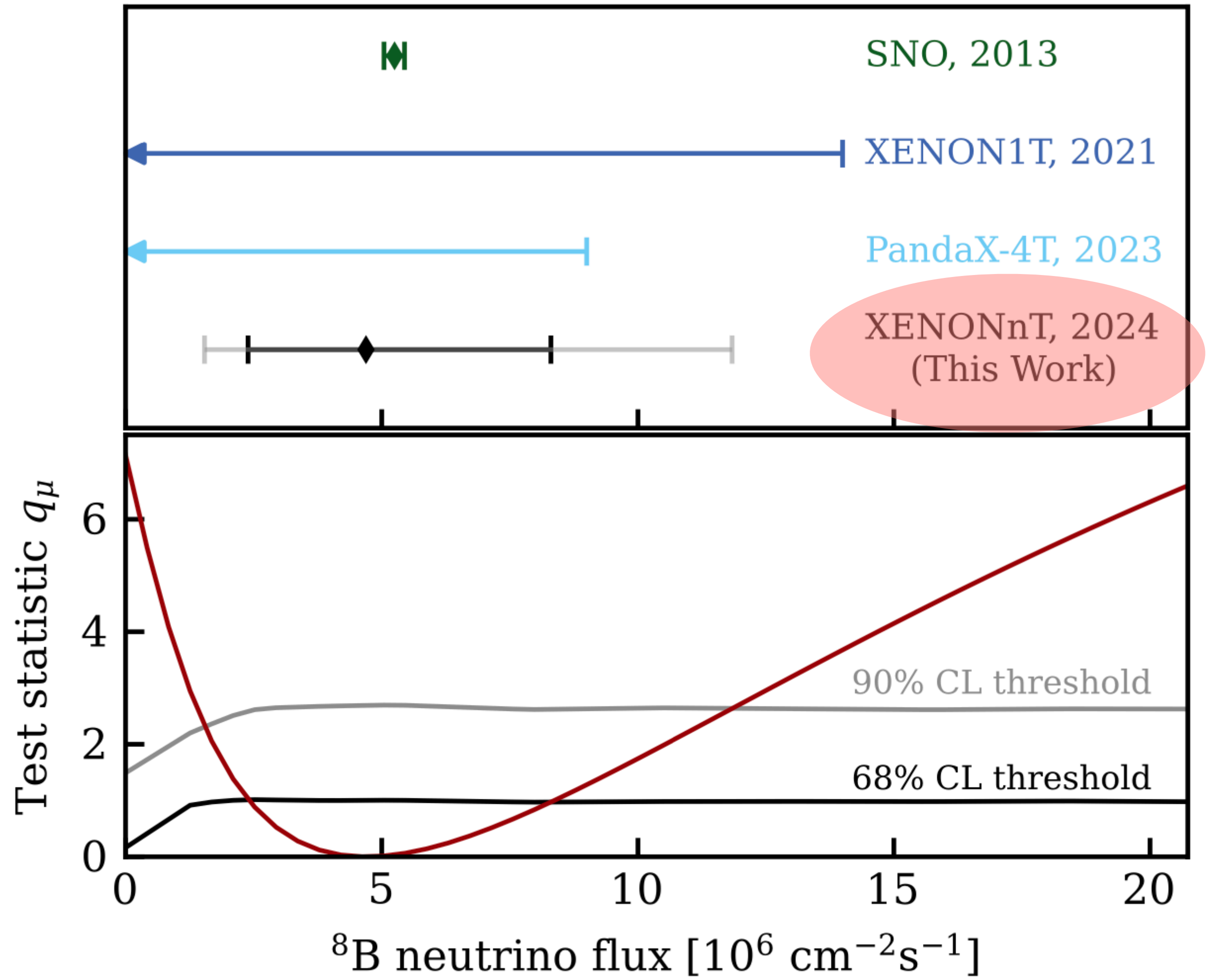
- **First** detection of elastic NRs from astrophysical ν's
- **First** measurement of CEvNS process with Xe targets
- **First** step into the "neutrino fog" by a DM experiment

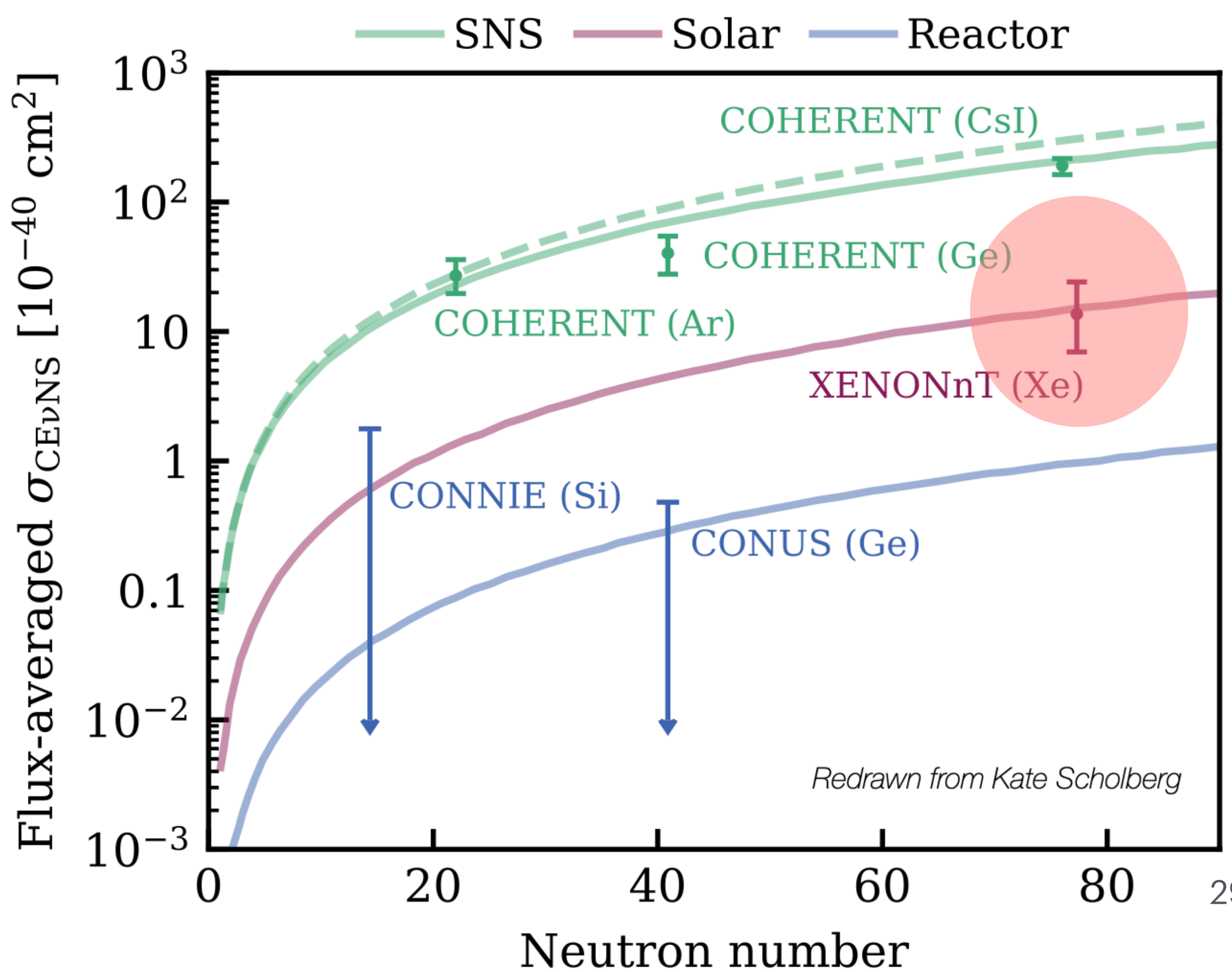
XENONnT: PRL 123, 2024

Solar neutrinos: ν-nucleus scattering

- Measured ^{8}B flux: (4.7 +3.6 - 2.6) x 10^{6} $cm^{-2}s^{-1}$
- 5-σ discovery and precision measurement in reach with XENONnT data

XENONnT: PRL 123, 2024





Solar neutrinos: ν-nucleus scattering

Highlights of the Year

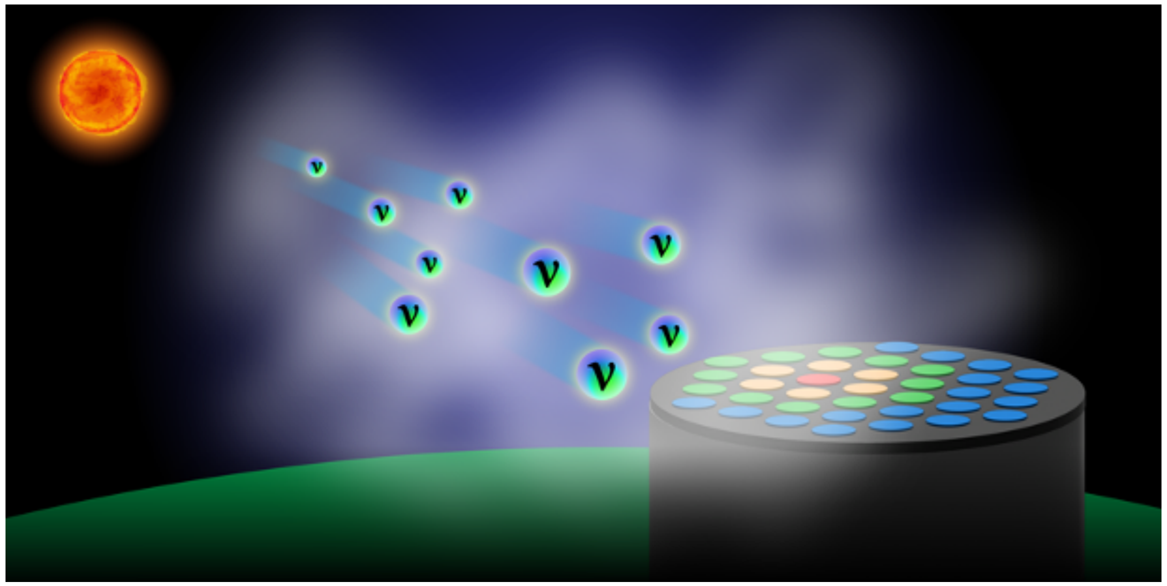
December 16, 2024 • *Physics* 17, 181

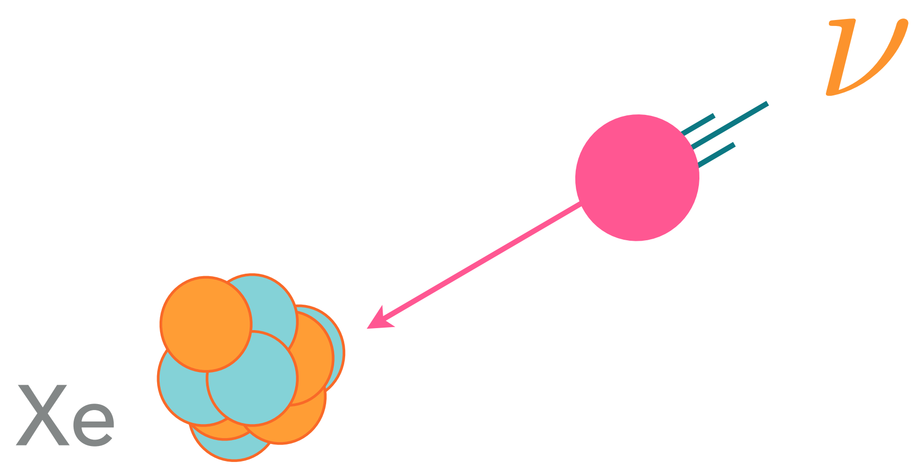
Physics Magazine **Editors pick their favorite stories from 2024.**

APS/Alan Stonebraker

Neutrino Fog Rolling into Sight

After years of null results, dark matter searches might finally have a real signal to contend with. Alas, the signal doesn't come from dark matter particles but from a stream of neutrinos produced by nuclear reactions in the Sun (see **Research News: First Glimpses of the Neutrino Fog**). In 2024, the PandaX and XENON collaborations independently reported that their detectors have likely started to see this "neutrino fog." Whereas in the long run the neutrino fog could pose a threat to dark matter searches, researchers agree that its impact won't be felt until next-generation experiments kick off in a decade or so. What's more, dark matter experiments could be turned into multipurpose detectors for probing various aspects of neutrino physics.





XENONnT: PRL 123, 2024

Some history…

- CEvNS-based detectors were proposed as "neutrino observatories" in the mid eighties (1984, Drukier & Stodolsky)
- These detectors were then proposed to detect "some possible candidates for dark matter" (1985, Goodman and Witten)
- **Forty year later**: dark matter detectors observed solar neutrinos via CEvNS for the first time* (2024, XENONnT and PandaX-4T)

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Phys. Rev. D **30**, 2295 – Published 1 December 1984

ABSTRACT

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10-10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Received 21 November 1984

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PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.

*not with superconducting grains, but with large liquid Xe detectors

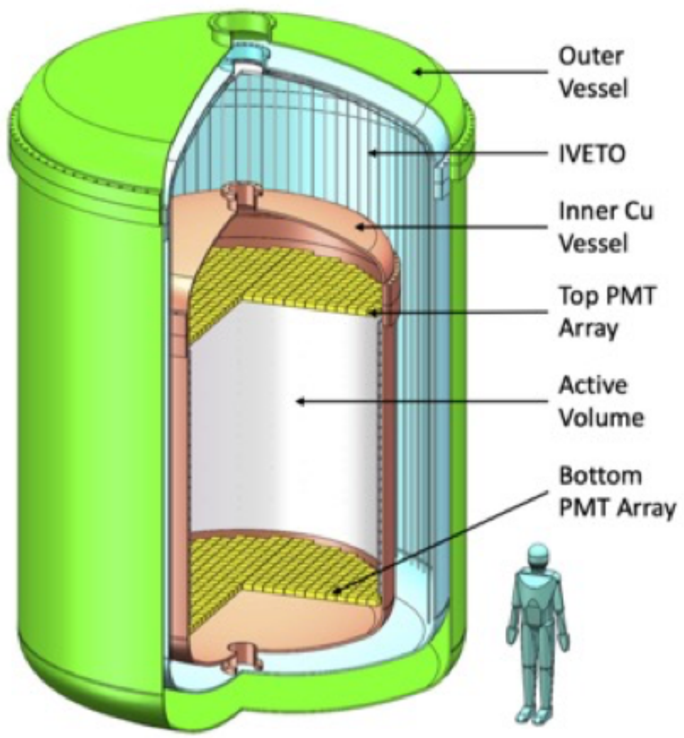
Future liquid xenon TPCs

XLZD (XENON-LZ-DARWIN)

78 t LXe (60 t active target)

2 arrays of 3-inch PMTs

PandaX-xT

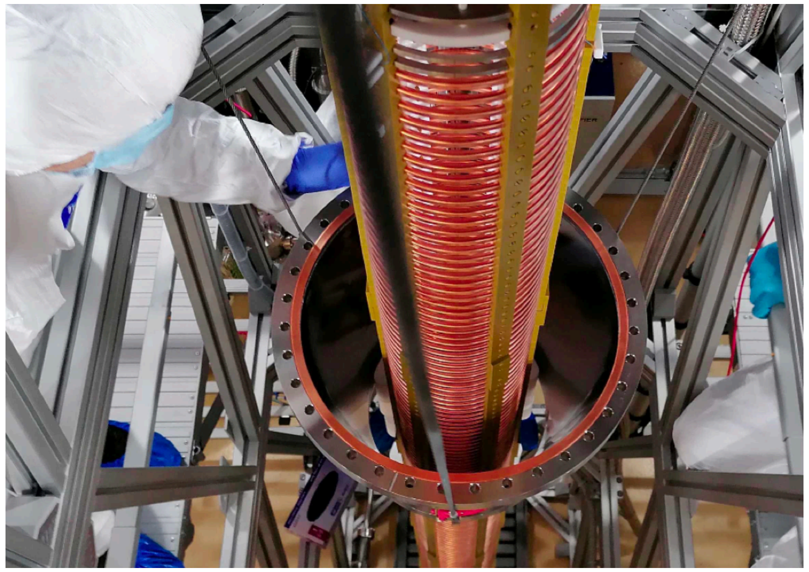


47 t LXe (43 t active target)

2 arrays of 2-inch PMTs

DARWIN R&D

- R&D for next-generation liquid xenon detector since ~2010
- Several large-scale demonstrators: Xenoscope, Pancake, LowRad (3 ERCs)
- Photosensors, TPC design, large-scale purification, etc

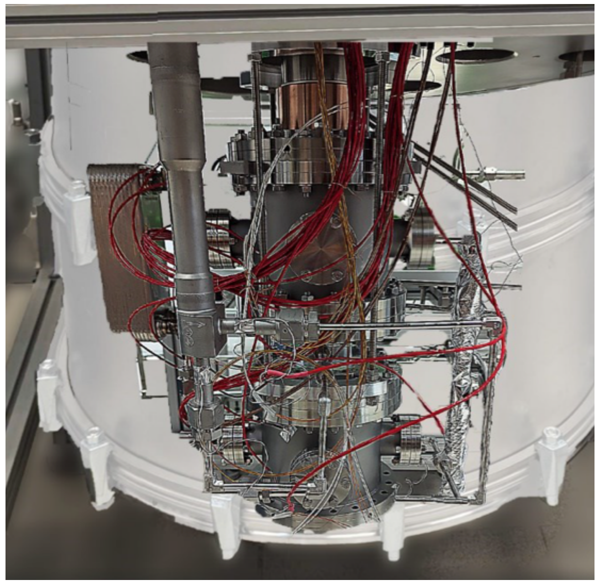


Xenoscope at UZH

LB et al., JINST 16, 2021, EPJ-C 83, 2023

Pancake in Freiburg

A. Brown at al., JINST 19, 2024



LowRad in Münster

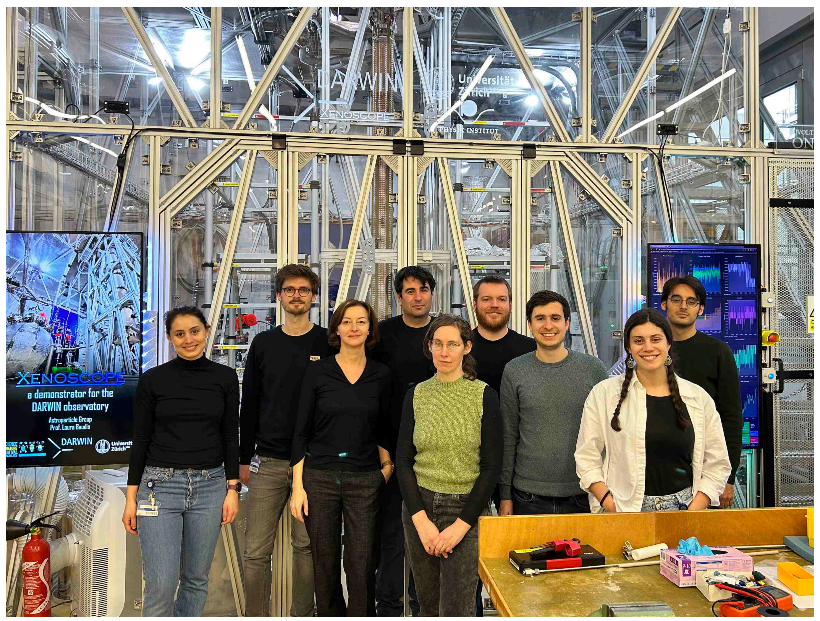
C. Weinheimer et al.

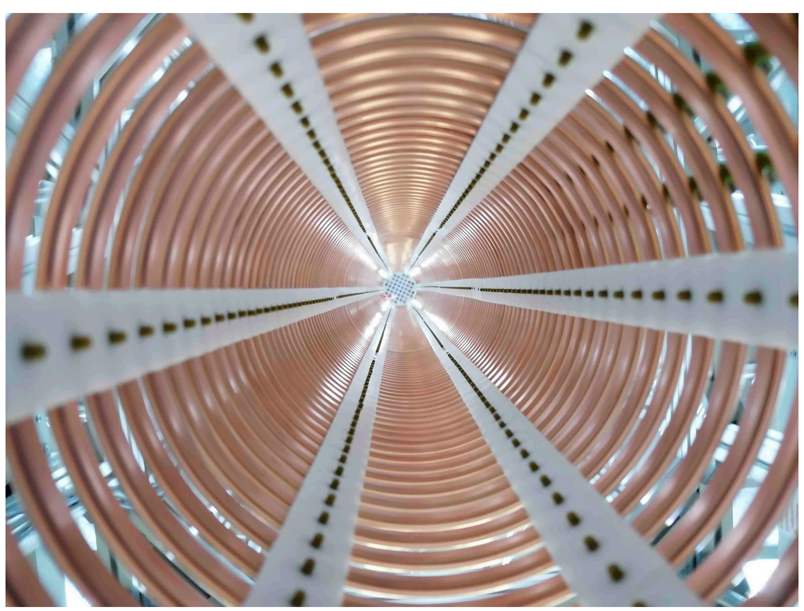
"1 Rn atom in 100 moles of Xe"

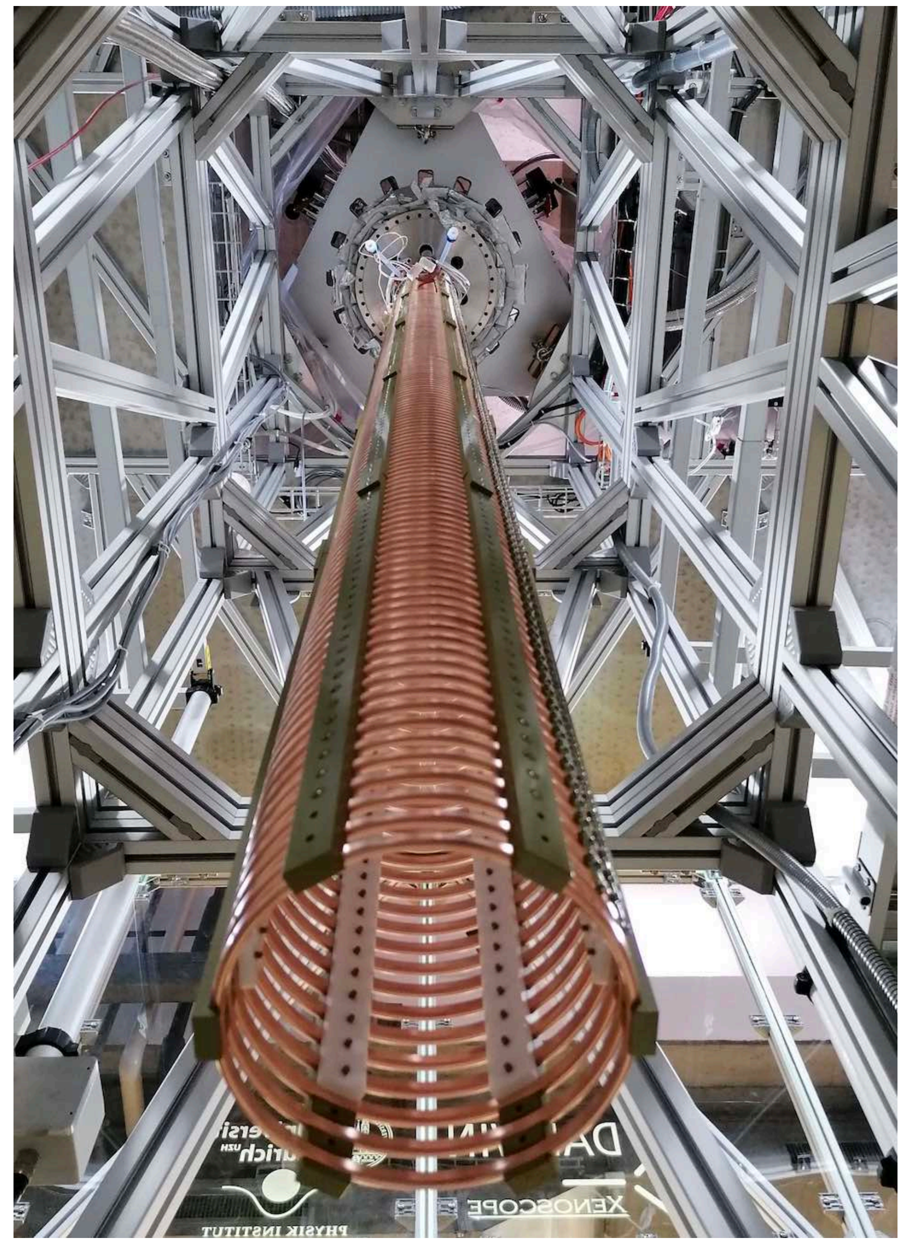
Xenoscope

DARWIN

European Research Council
Established by the European Commission





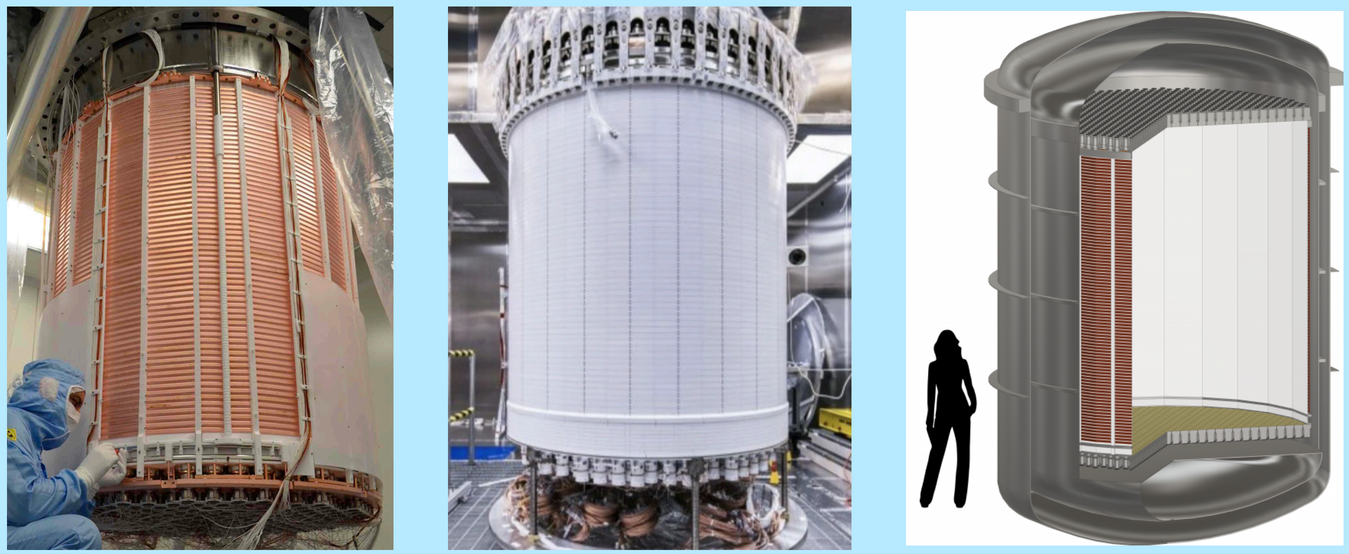


New run planned for 2025, starting in April

Liquid xenon commissioning run with full TPC in 2024: 2411.08022

XLZD

XENON-LUX-ZEPLIN-DARWIN



DARWIN collaboration
JCAP 1611 (2016) 017

- New collaboration to build & operate next-generation detector
- Demonstrated experience in large-scale LXe TPCs
- July 2021: MoU signed by 104 research group leaders from 16 countries
- Several meetings (KIT, UCLA, RAL); since fall 2024 full collaboration
- Executive committee and WGs in place; design book submitted

XLZD

XENON-LUX-ZEPLIN-DARWIN

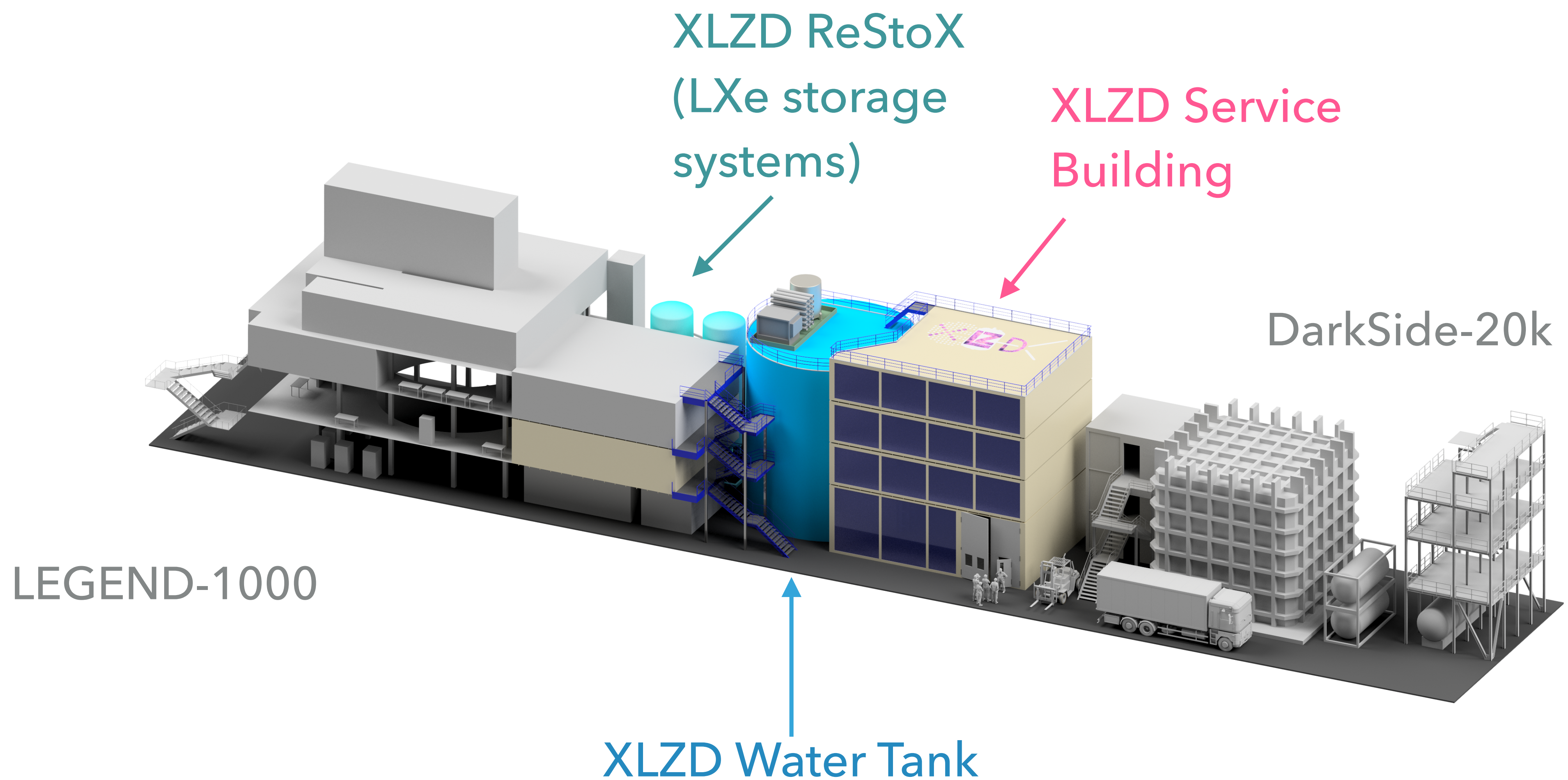
KIT, summer 2022

UCLA, spring 2023

RAL, spring 2024

XLZD underground sites

- Three experimental sites are being considered within XLZD: LNGS, a new lab at Boulby (UK) and SURF (USA)
- Example: the LNGS option in Hall-C of the underground lab (between LEGEND-1000 and DarkSide-50k)



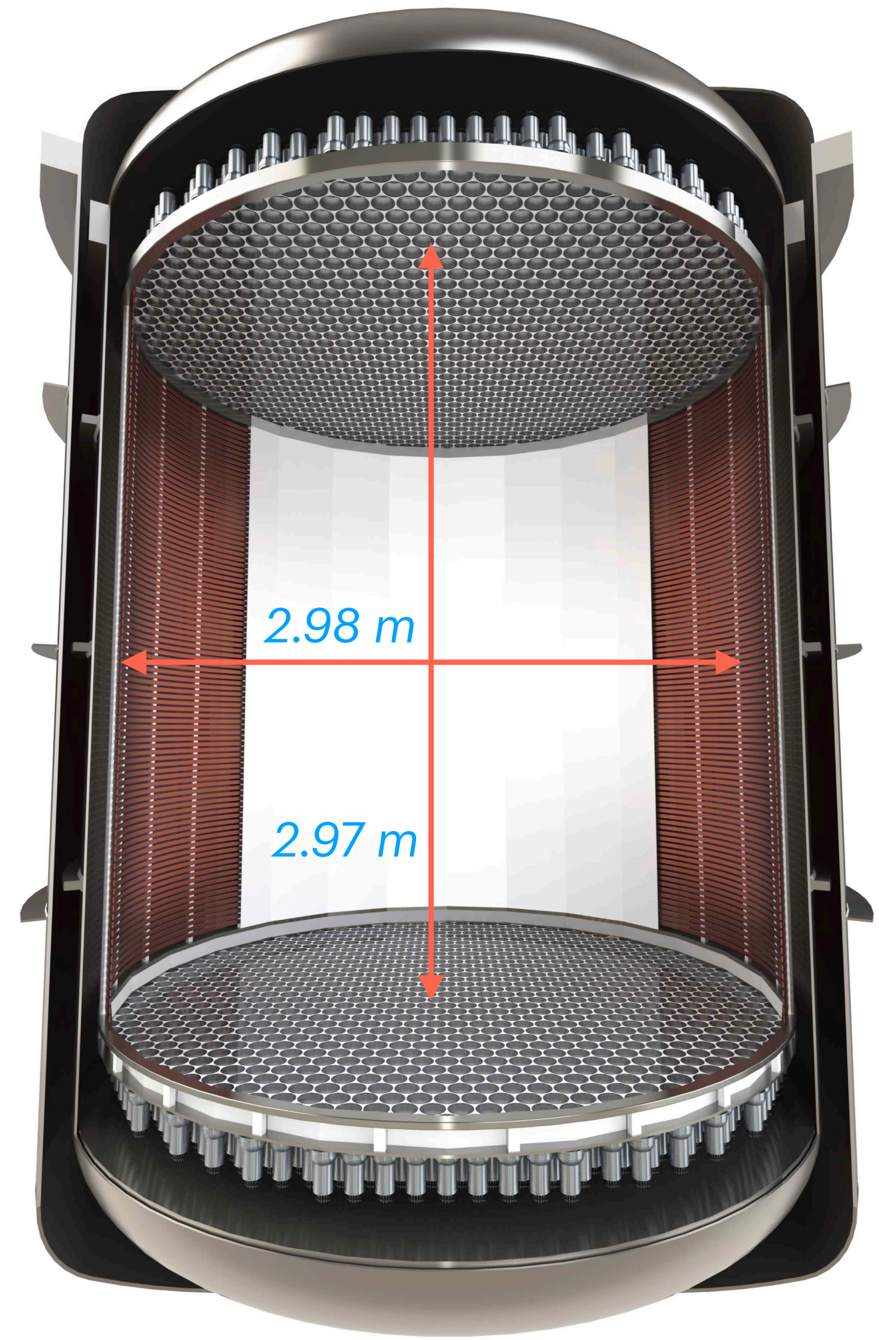
XLZD underground sites

LNGS, summer 2024

XLZD nominal design

- Nominal plan: 60 t LXe in TPC (78 t total), early science with 45 t LXe*
- Two arrays of 3-inch PMTs, 1182/array
- 2.97 m e^- drift, 2.98 m diameter
- Drift field: 240-290 V/cm
- Extraction field: 6-8 kV/cm
- Double-walled Ti cryostat, 7 cm LXe "skin" detector around the TPC

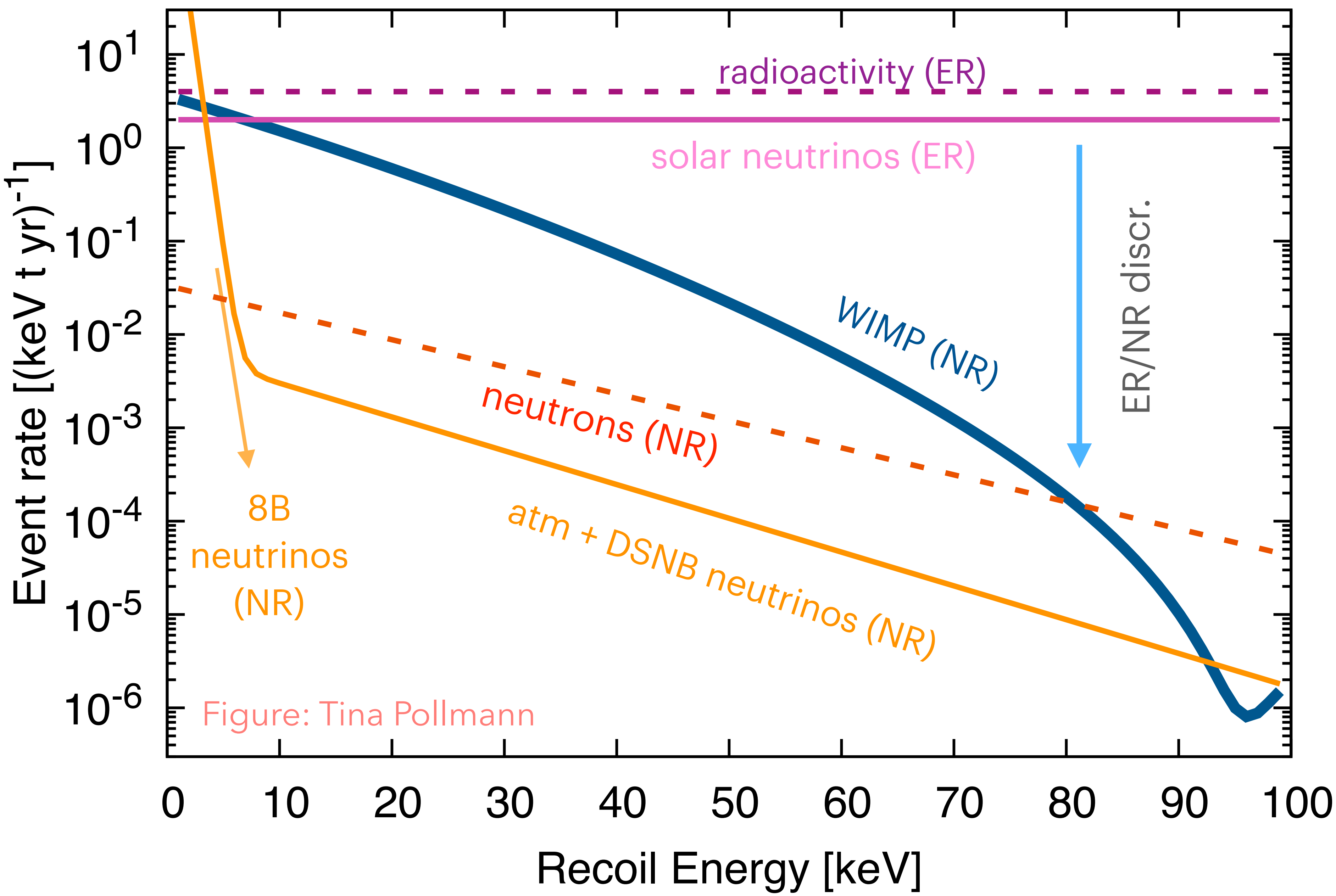
XLZD TPC



*80 t LXe in TPC final size if market is favourable

Background goals

- ER and NR regions: dominated by cosmic neutrinos



materials, intrinsic etc

ν-e scattering: solar ν's

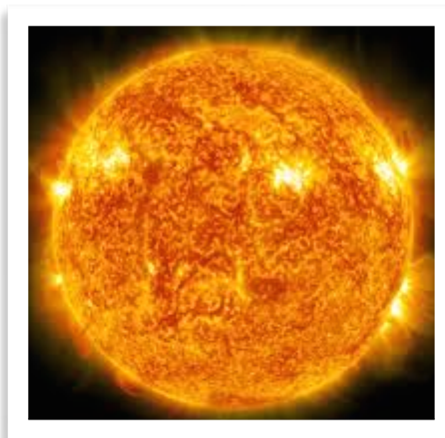
WIMP: 50 GeV, $\sigma_{\chi n}$= 10^{-10} pb

radiogenic, cosmogenic

CEνNS: solar ν's, atm ν's + DSNB

Science goals

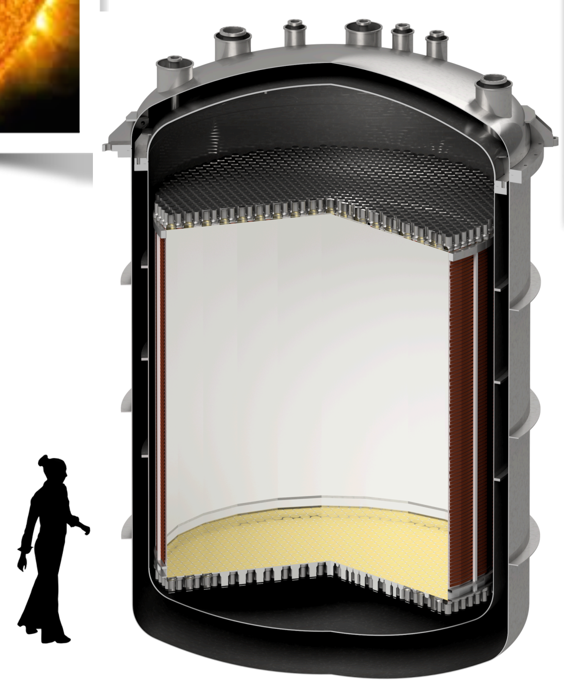
Solar neutrinos (pp + ^{8}B)



Eur. Phys. J. C 80, 12 (2020)
Phys.Rev.D 106 (2022)

Dark matter

JCAP 10, 016 (2015)



Supernova neutrinos

PRD 94, 103009 (2016)
Phys.Rev.D 105 (2022)

Neutrino nature

Eur. Phys. J. C 80, 9 (2020)

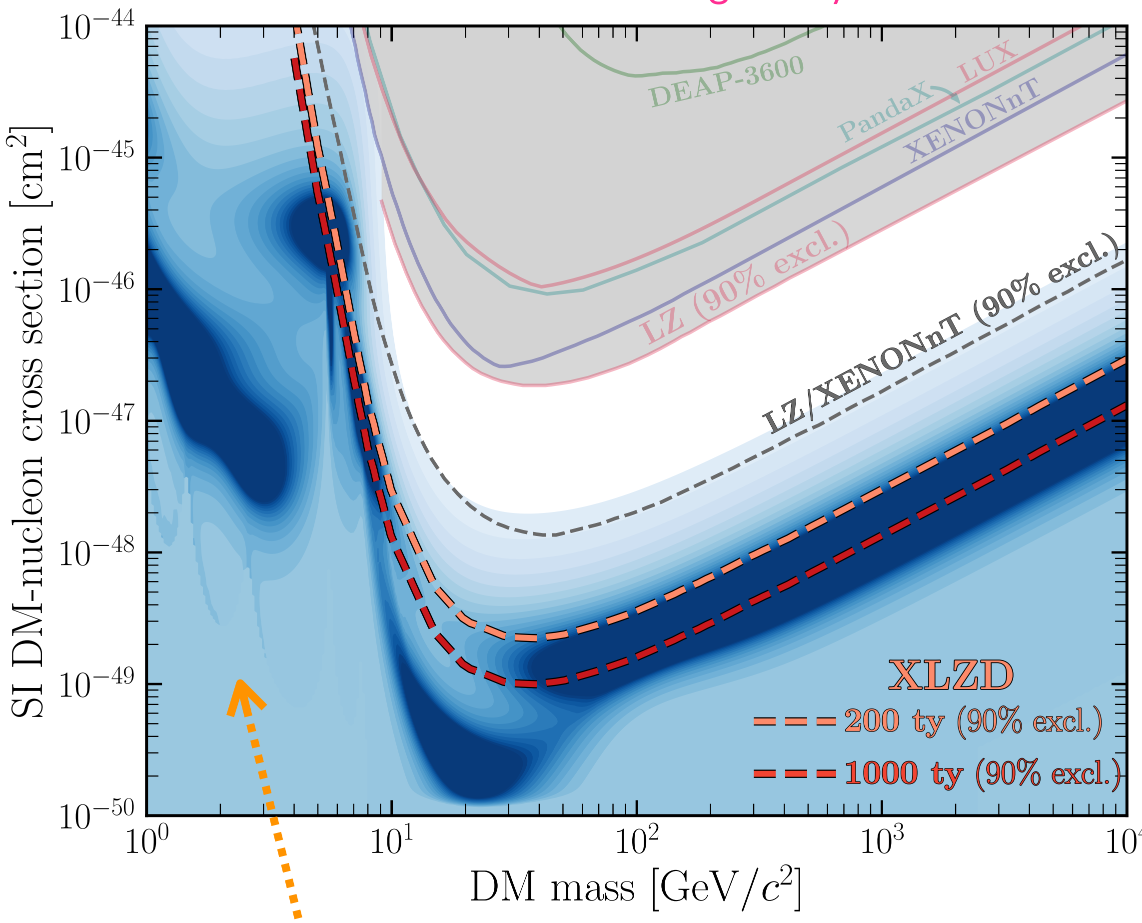
Physics case for a large liquid xenon detector: JoPG and arXiv:2203.02309 (600 authors)

WIMPs

- Definite search for medium to high WIMP masses
  - reach the systematic limit of the neutrino fog (~ 1000 tonnes × years exposure)
  - 3-σ discovery at SI cross section of 3×10^{-49} cm^2 at 40 GeV mass

Projected SI upper limits for 200 t y and 1000 t y exposures

Figure by Ciaran O'Hare



Systematic limit imposed by CEvNS from atmospheric neutrinos

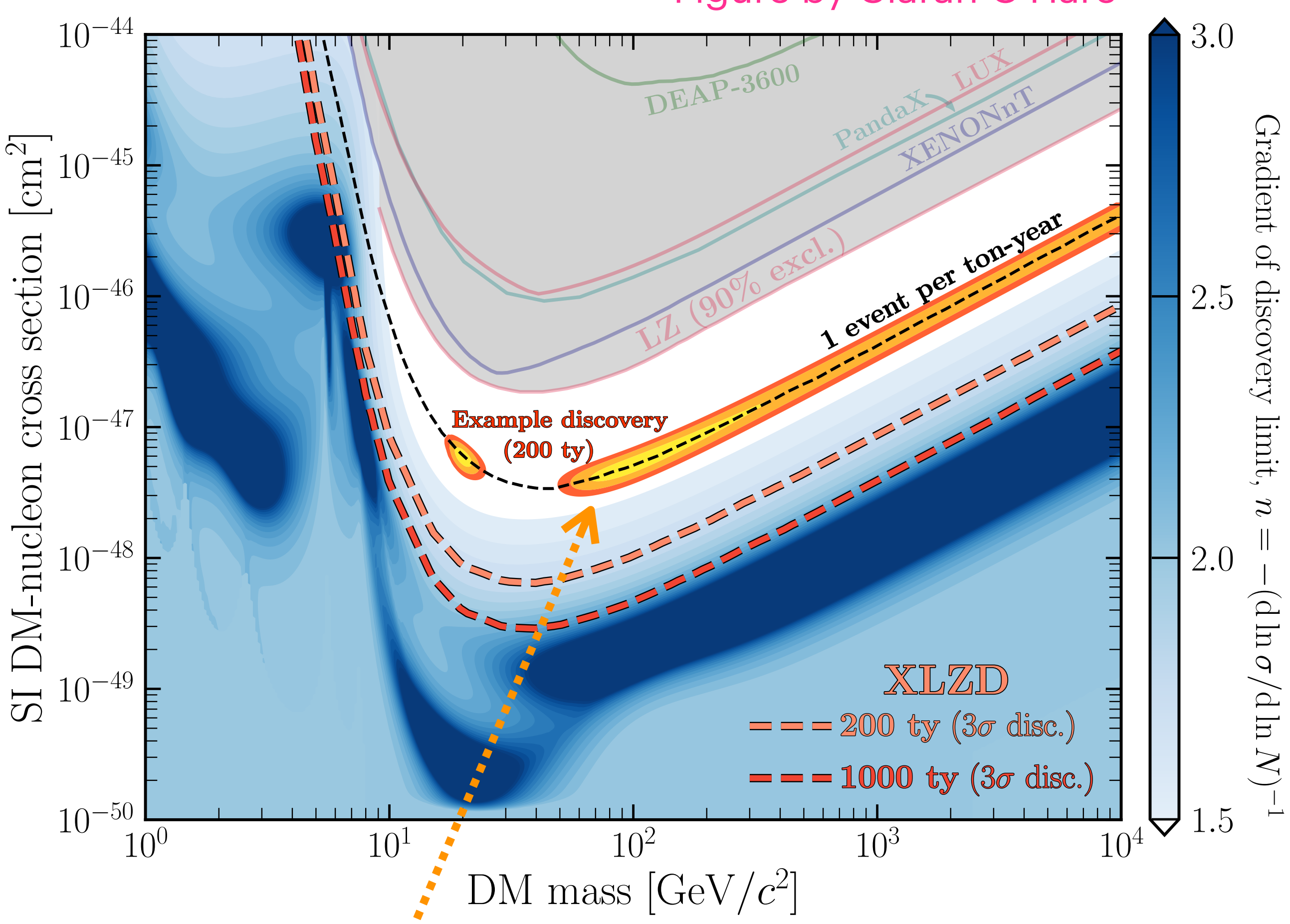
At contour n: obtaining a 10 times lower cross section sensitivity requires an **increase in exposure of at least 10^n**

WIMPs

Median discovery potential 200 t y and 1000 t y exposures

Figure by Ciaran O'Hare

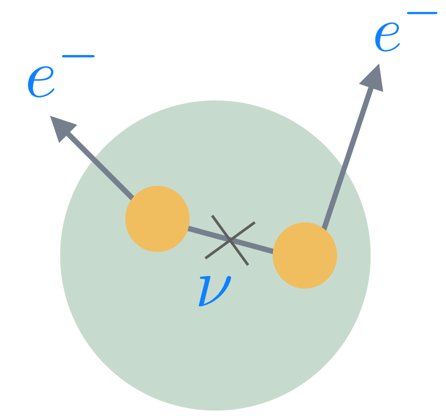
- Definite search for medium to high WIMP masses
  - reach the systematic limit of the neutrino fog
    (~ 1000 tonnes × years exposure)
  - 3-σ discovery at SI cross section of 3 × 10^{-49} cm^2 at 40 GeV mass



Confidence intervals for 200 t x y (1-, 2-, 3-σ: yellow, orange, red)

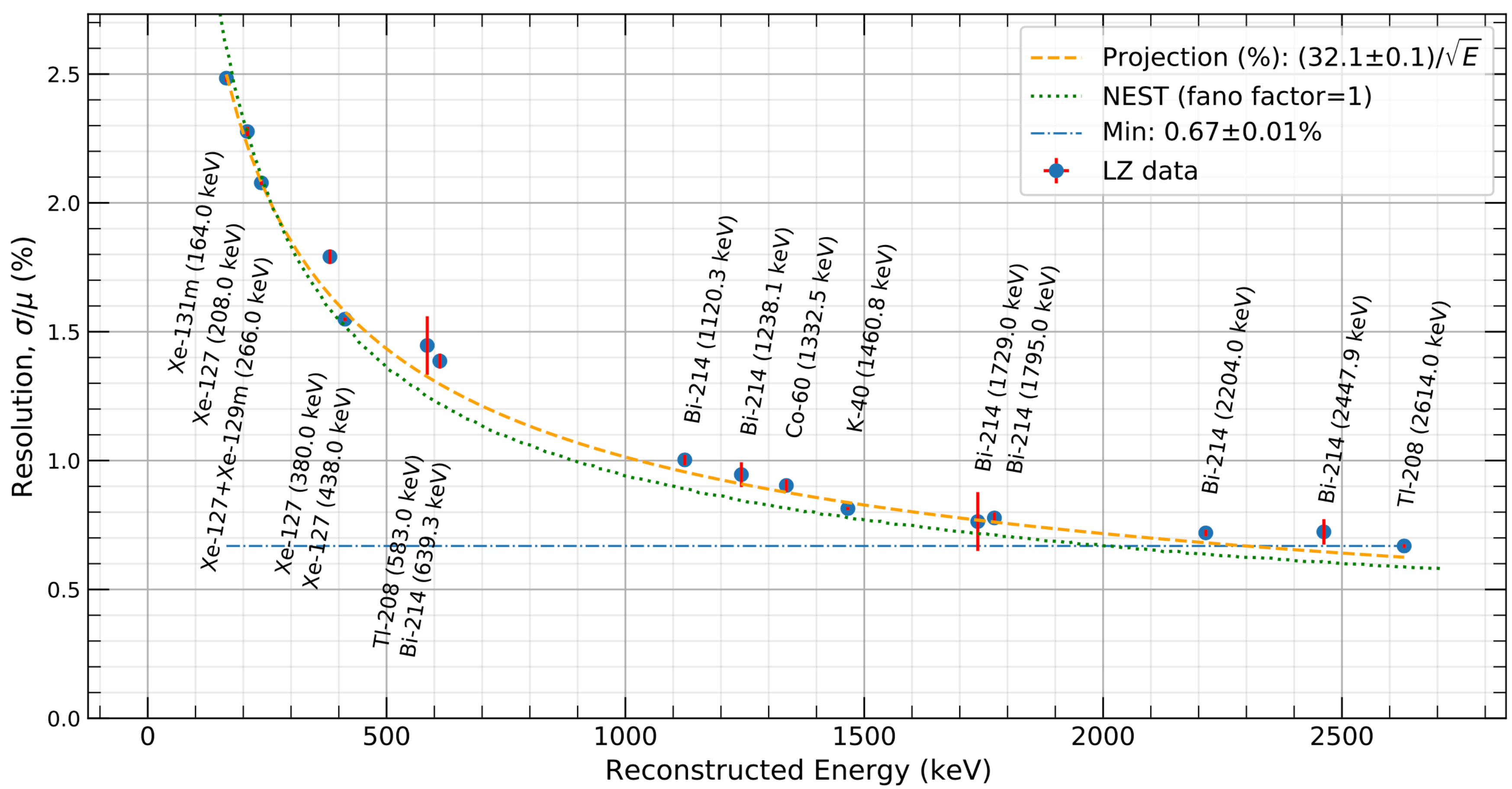
Dashed line: ≡ 1 event per t-y

0νββ decay of ^{136}Xe

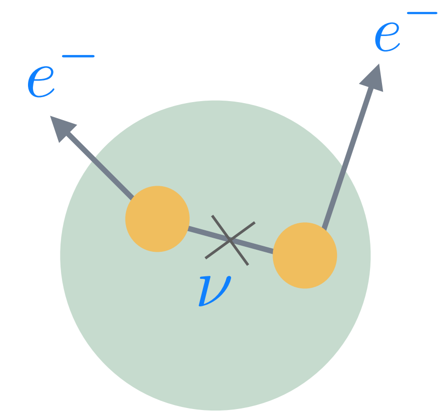


- ^{136}Xe: present at 8.9% abundance in ^{nat}Xe
- Energy resolution of large two-phase Xe TPCs at $Q_{\beta\beta}$: < 1% (σ/E)

LUX-ZEPLIN, JINST 18, 2023

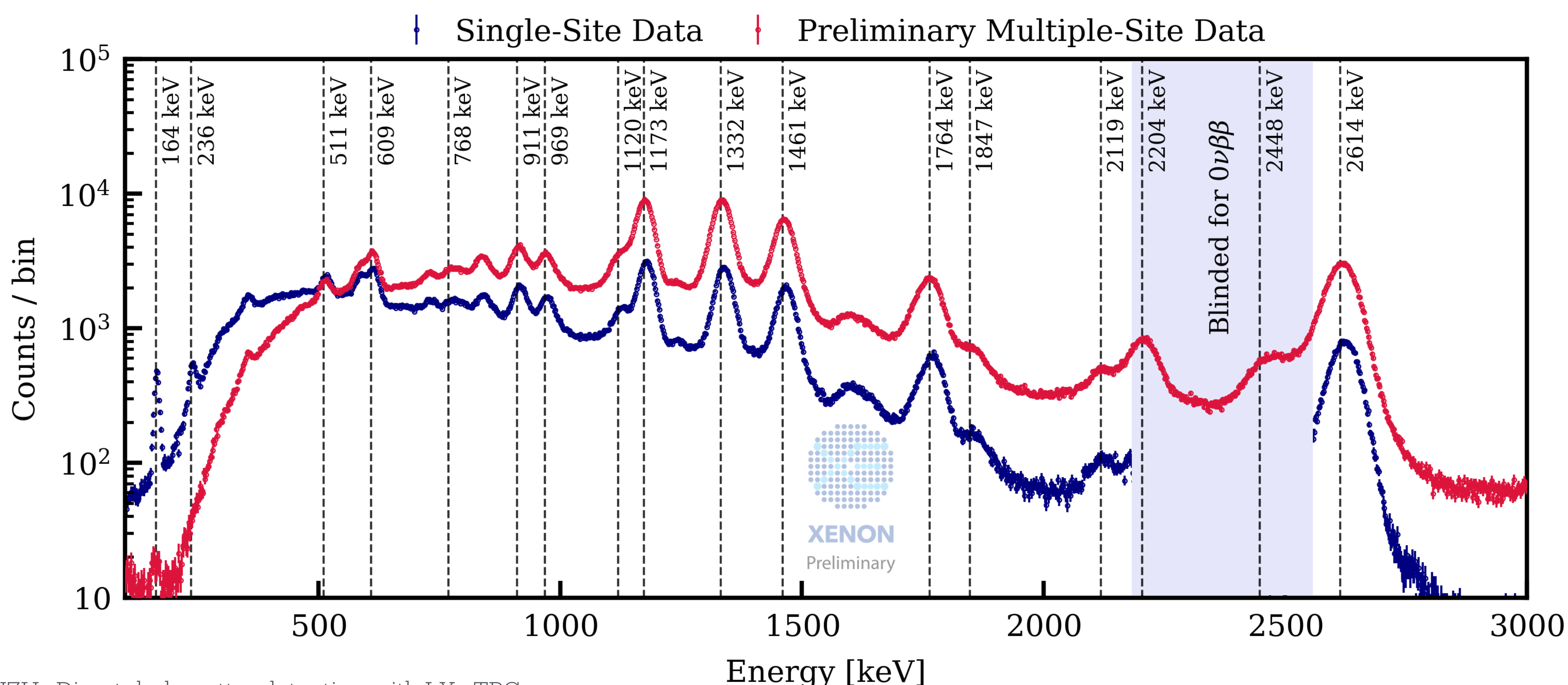


0νββ decay of ^{136}Xe

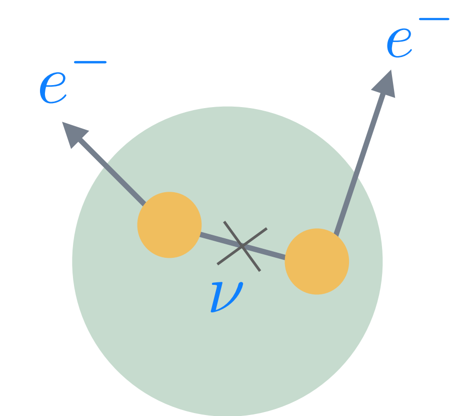


- Ongoing searches in **LZ and XENONnT**
- LZ sensitivity: $T_{1/2}$ ~ 1.1 x 10^{26} y, Phys.Rev.C 102 (2020) 1

XENONnT, preliminary; ^{136}Xe 0νββ region blinded



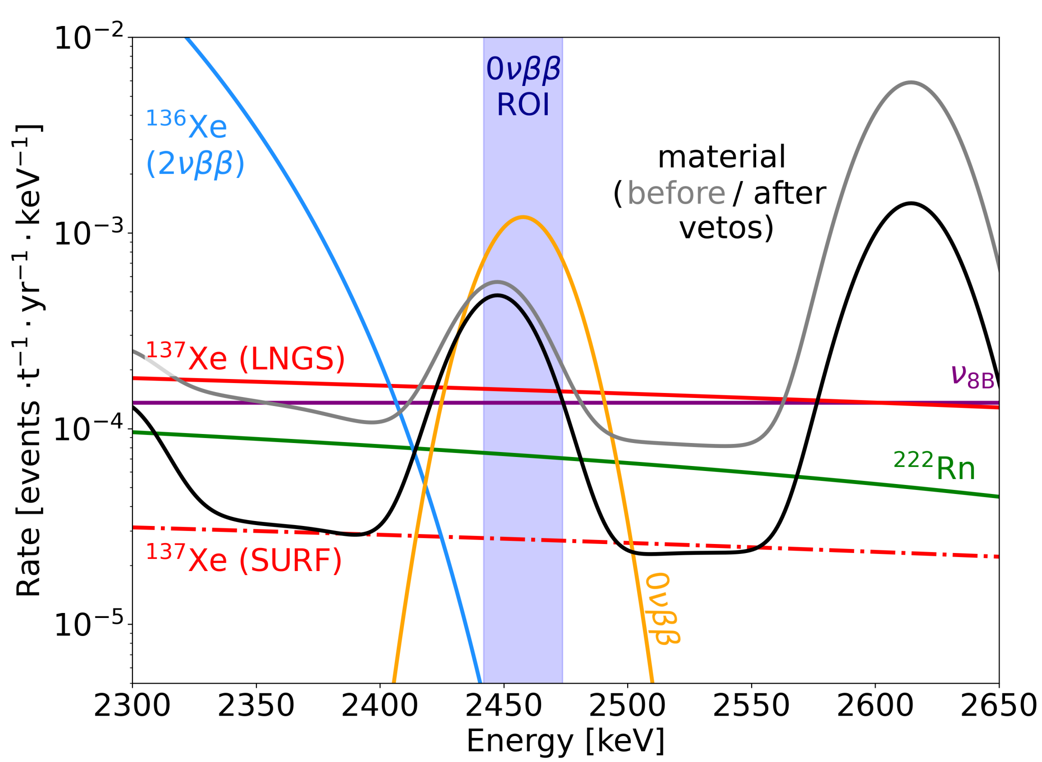
0νββ decay of ^{136}Xe



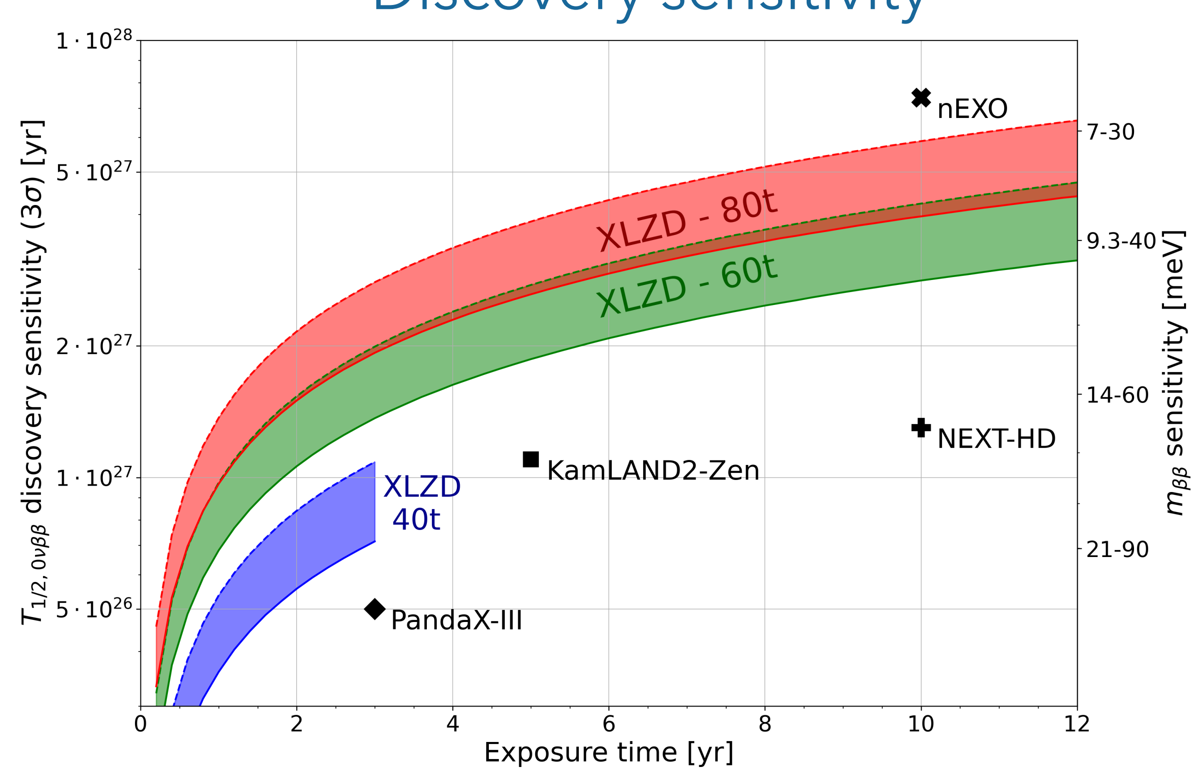
- **XLZD:** competitive sensitivity to dedicated experiments
- Assumptions: 0.1 μBq/kg ^{222}Rn, materials radiopurity already identified

XLZD preliminary

Signal: $T_{1/2}^{0\nu\beta\beta} = 5 \times 10^{27}$ y



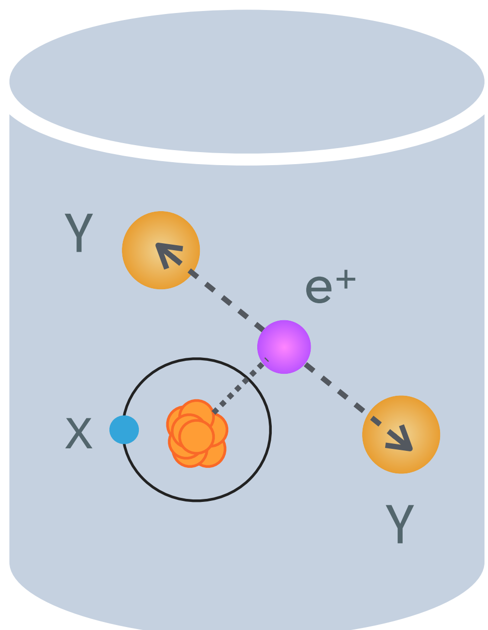
Discovery sensitivity



DARWIN study: EPJ-C 80, 2020

Other 2nd order weak decays

- ^{124}Xe, ^{126}Xe, ^{134}Xe
- Some with **interesting topologies** 0ν/2νECβ⁺, 0ν/2νβ⁺β⁺
- Can also probe SM/nuclear physics

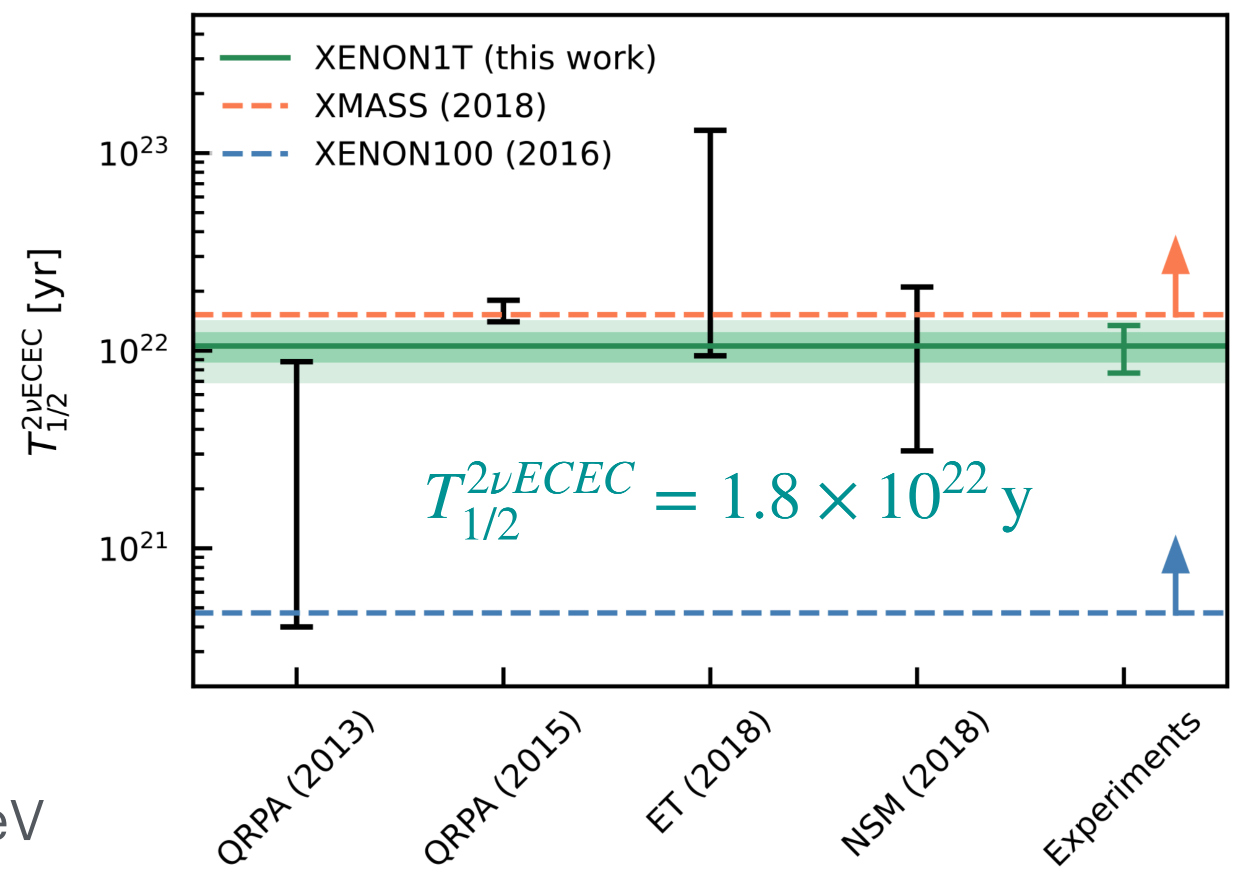


$$^{124}\mathrm{Xe} + e^- \rightarrow ^{124}\mathrm{Te} + e^+ + X_K$$

1.8 MeV 31.8 keV

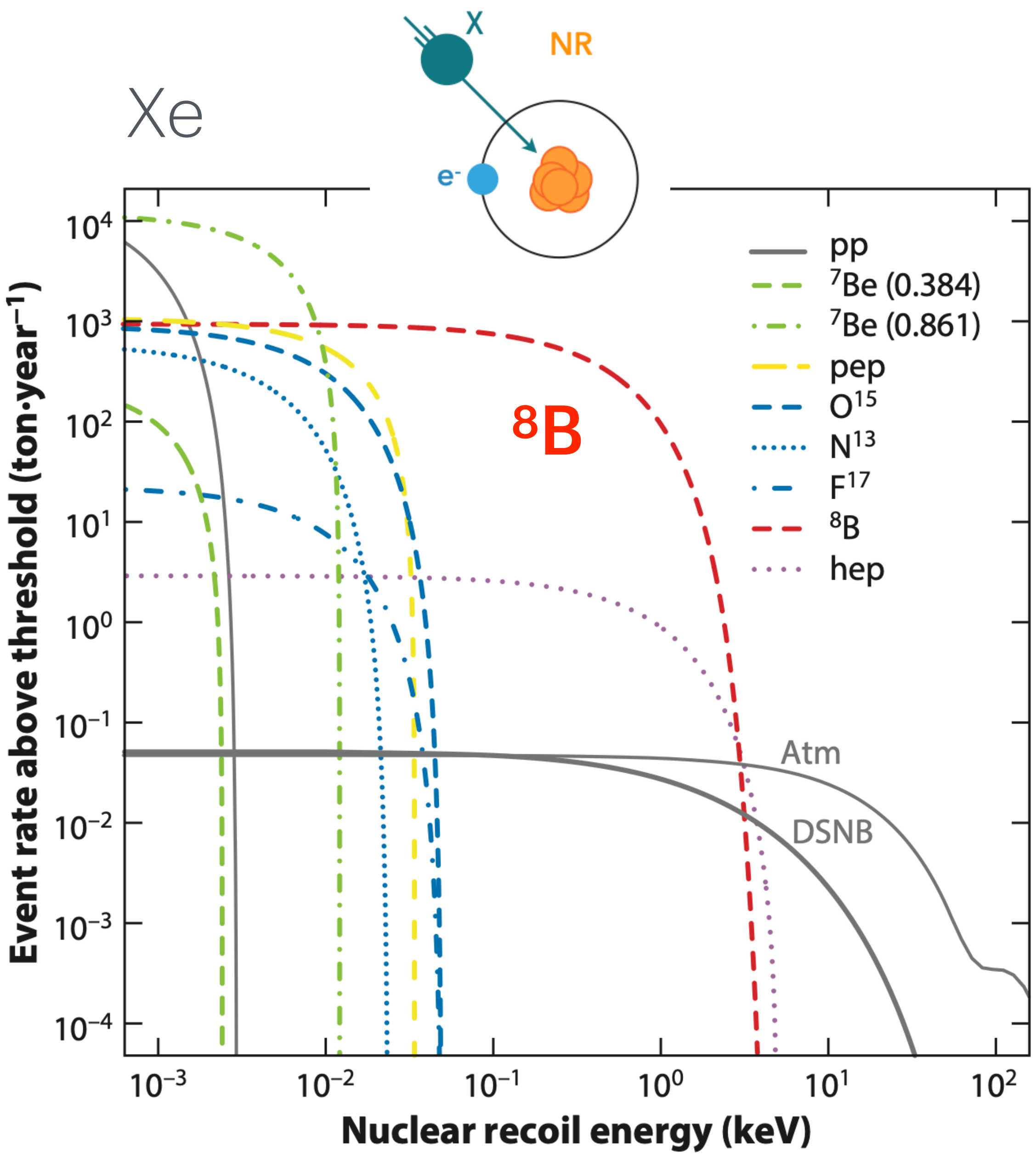
Q (^{124}Xe) = (2856.73 ± 0.12) keV

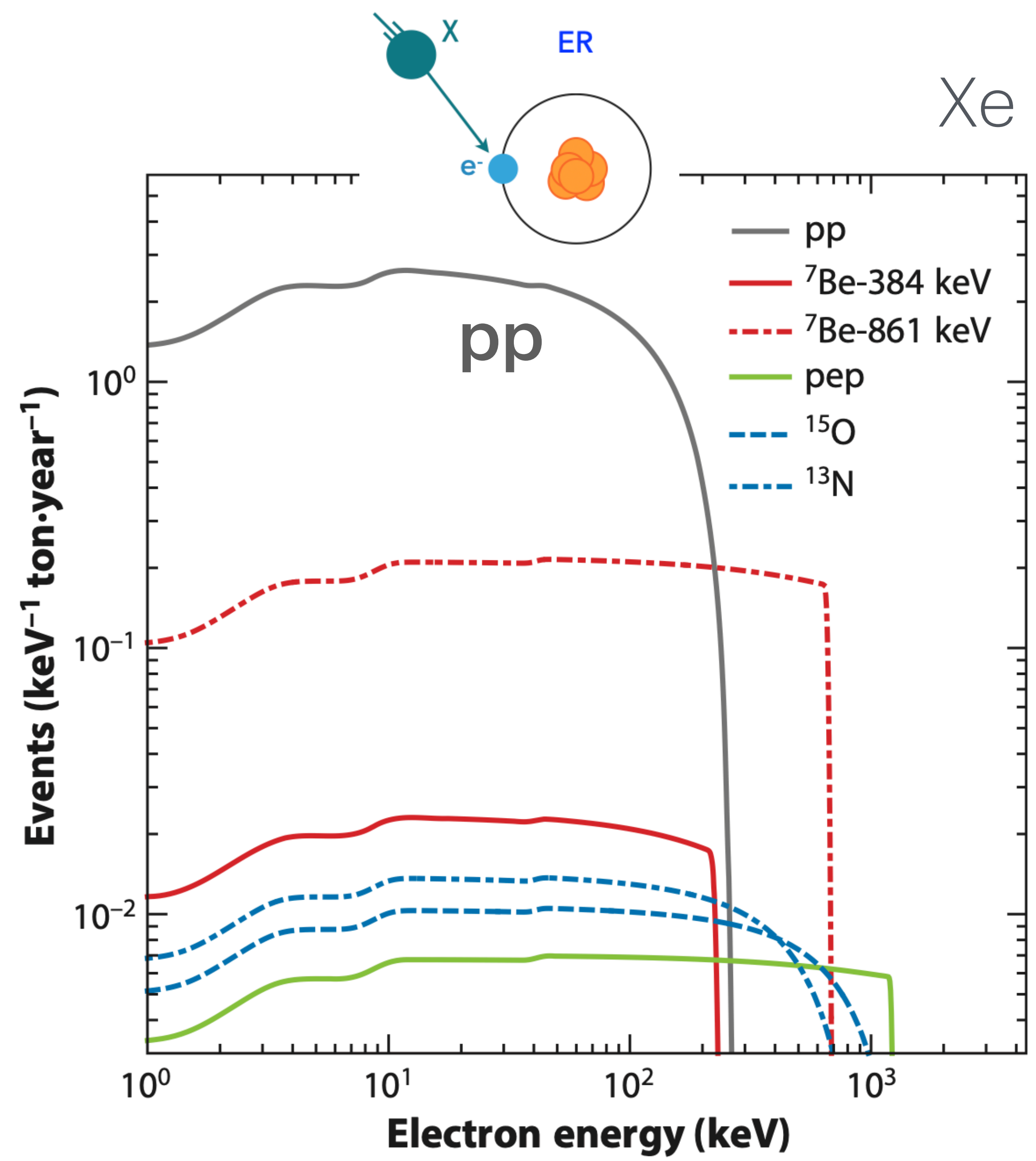
XENON, Nature 568, 2019 , PRC 106, 2022



Solar neutrino signals

- Neutrino signals: NRs (CEvNS), ERs (all other reactions)



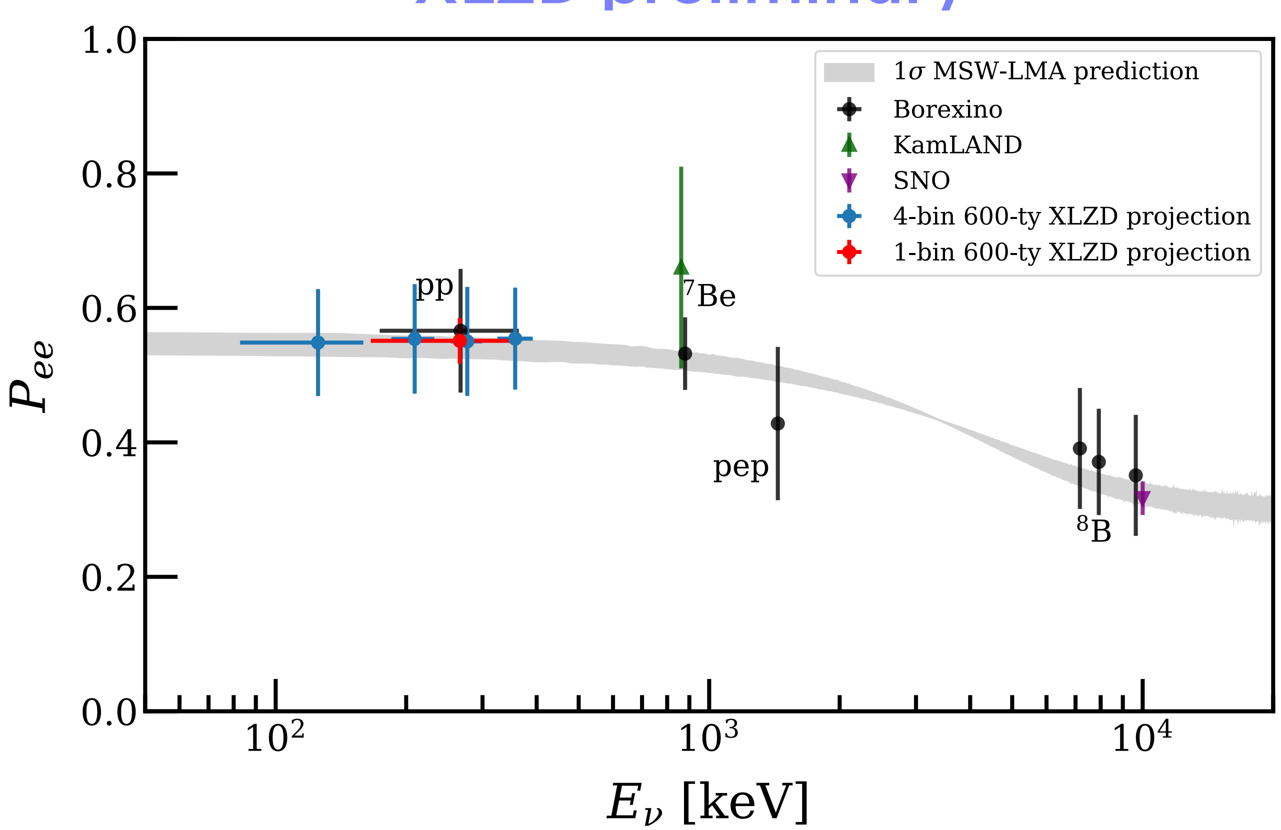


B. Dutta, E. Strigari, Annu. Rev. Nucl. Part. Sci. 2019

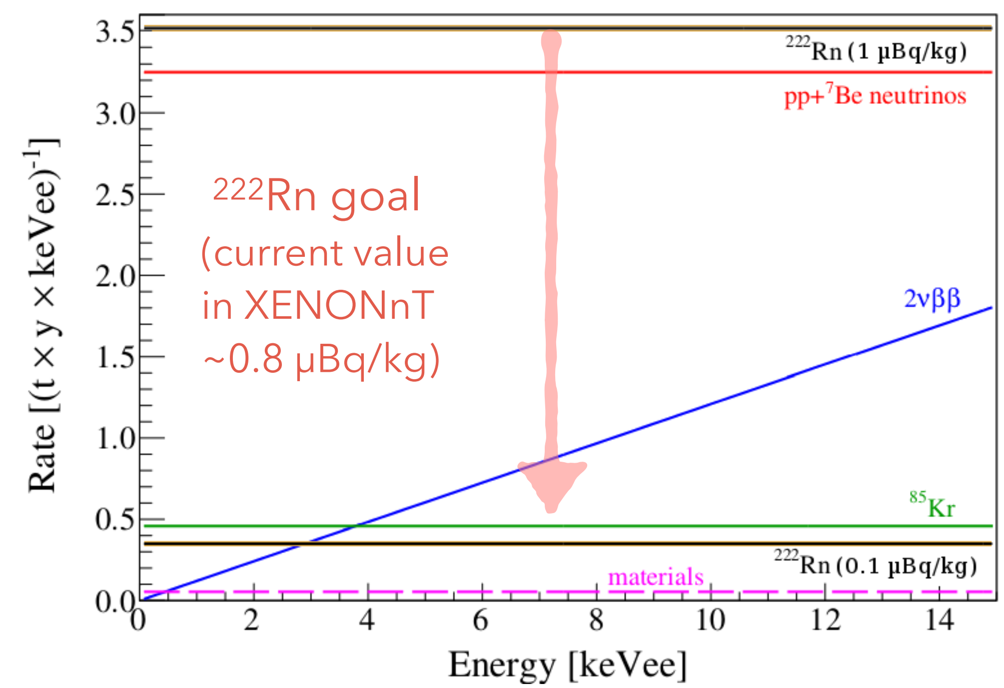
Solar ν-electron scattering

- Main challenge: reduce ^{222}Rn (^{214}Pb β-decay) background to x 10 below the pp rate (0.1 μBq/kg)

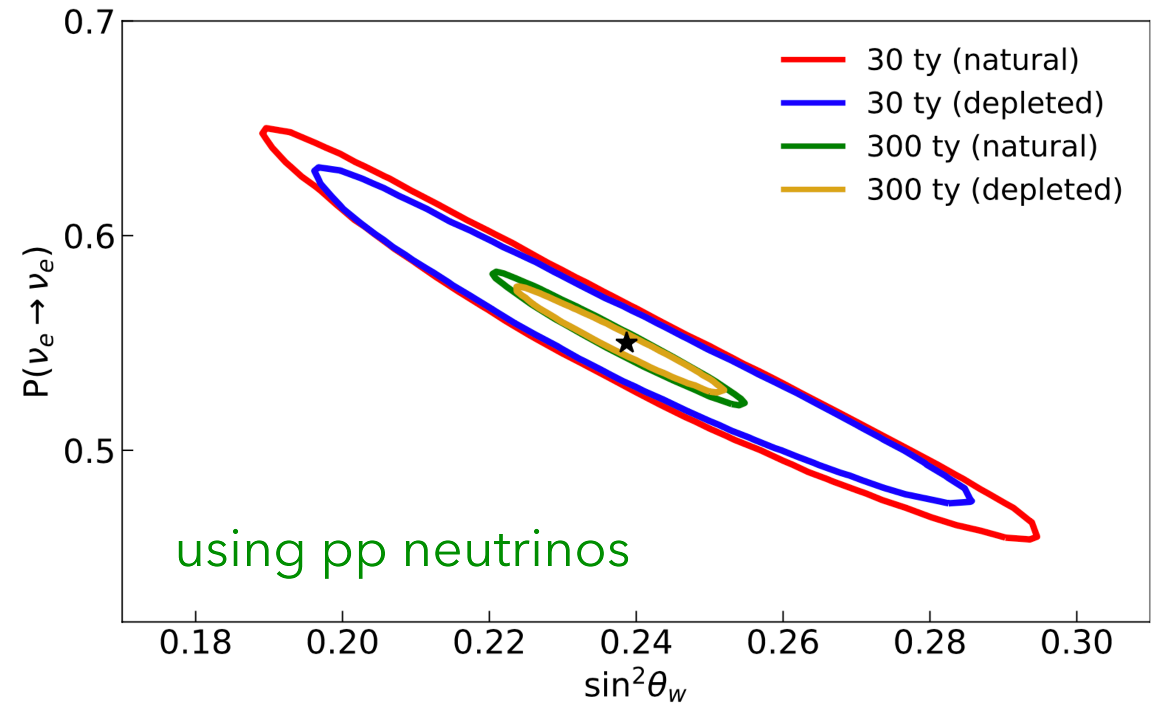
XLZD preliminary



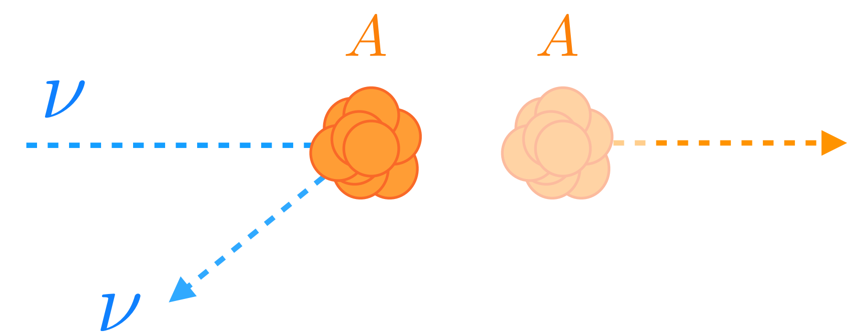
600 t y exposure, 1 and 4 energy bins



DARWIN collaboration, EPJ-C 80 12 (2020)

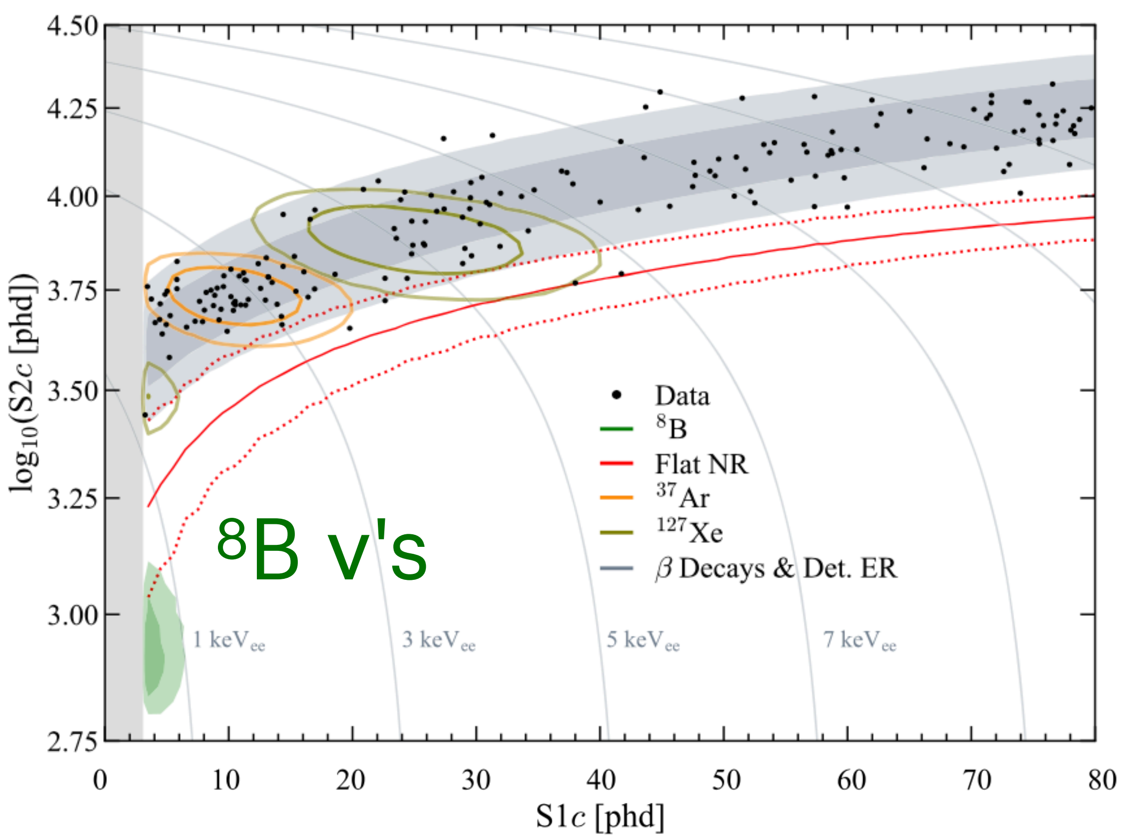


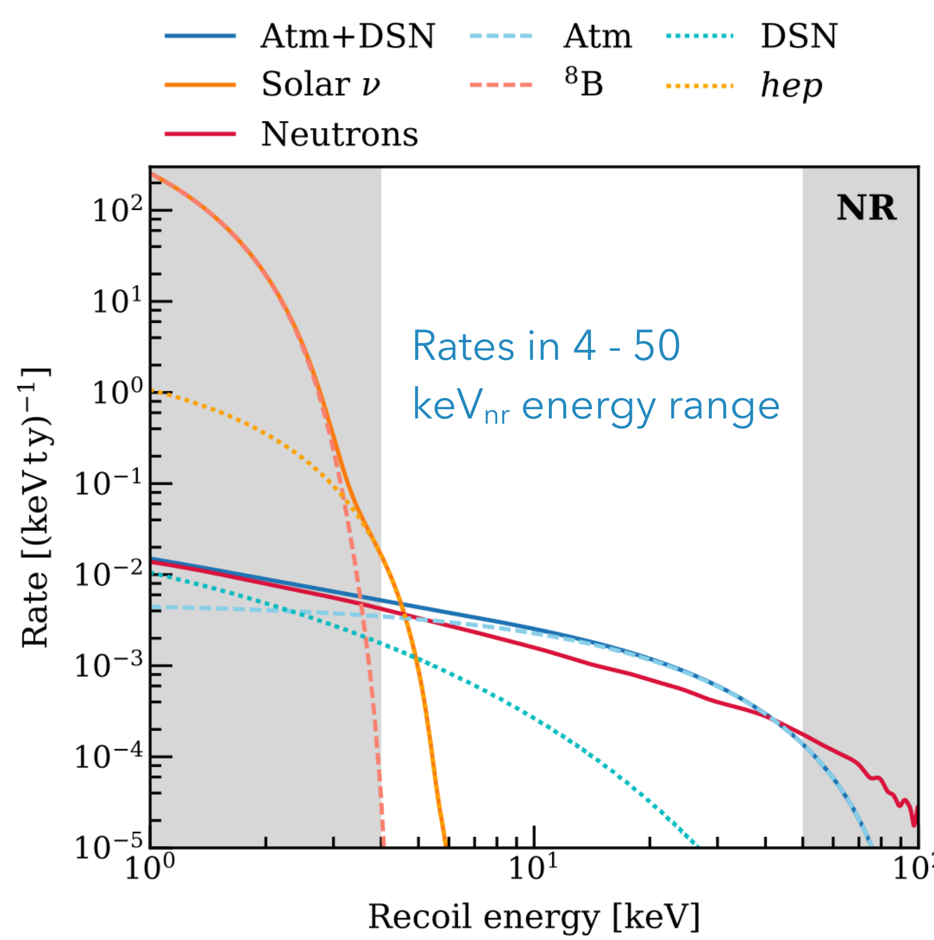
Solar ν-nucleus scattering



- Main goal: observe ^{8}B neutrinos via CEvNS
- In LXe: ~99% of events expected < 4 keV NR energy
- Expect: 10^4 events/(200 t y) for 2-fold S1 and 5 n_e S2*

LZ, PRD 108, 2023

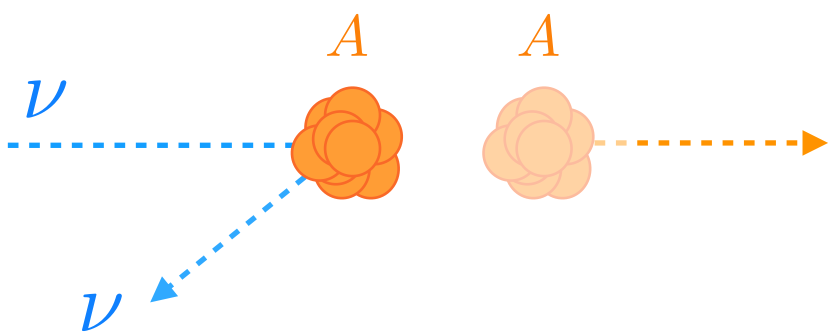




XENON, JCAP11. 2020

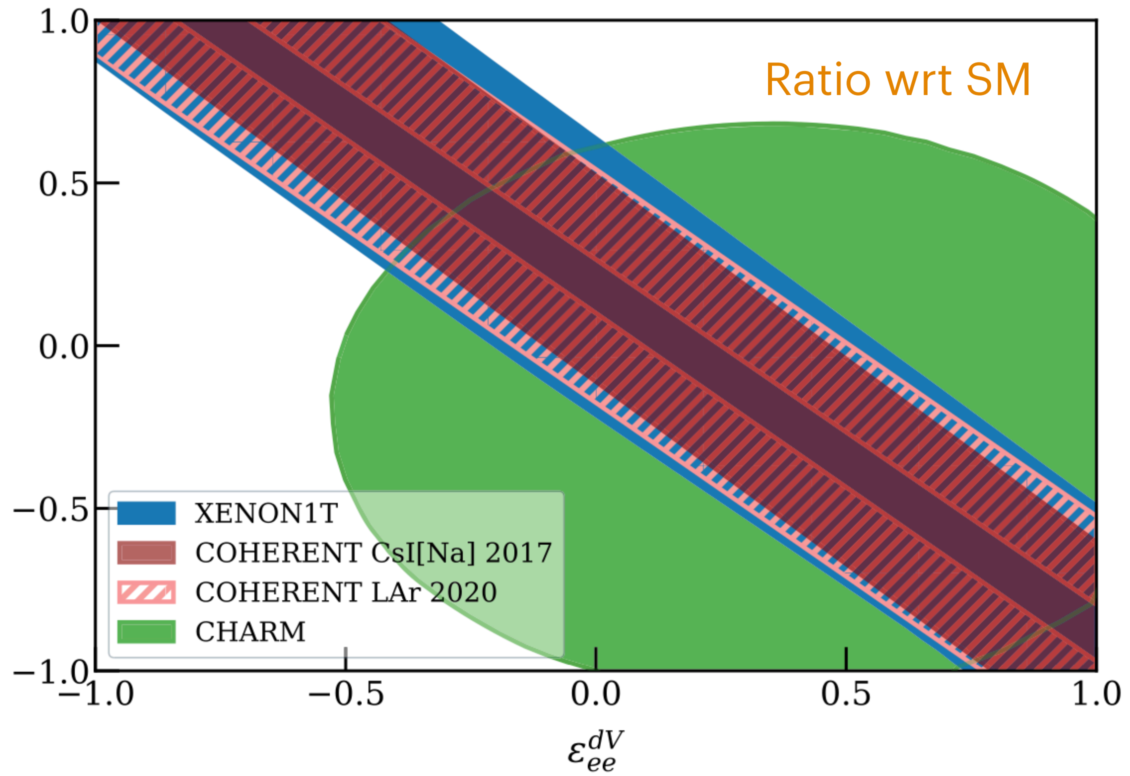
*e.g., X. Xiang et al., PRD 108, 2023

Solar ν-nucleus scattering



- Main goal: observe ^{8}B neutrinos via CEvNS
- Look for non-standard interactions

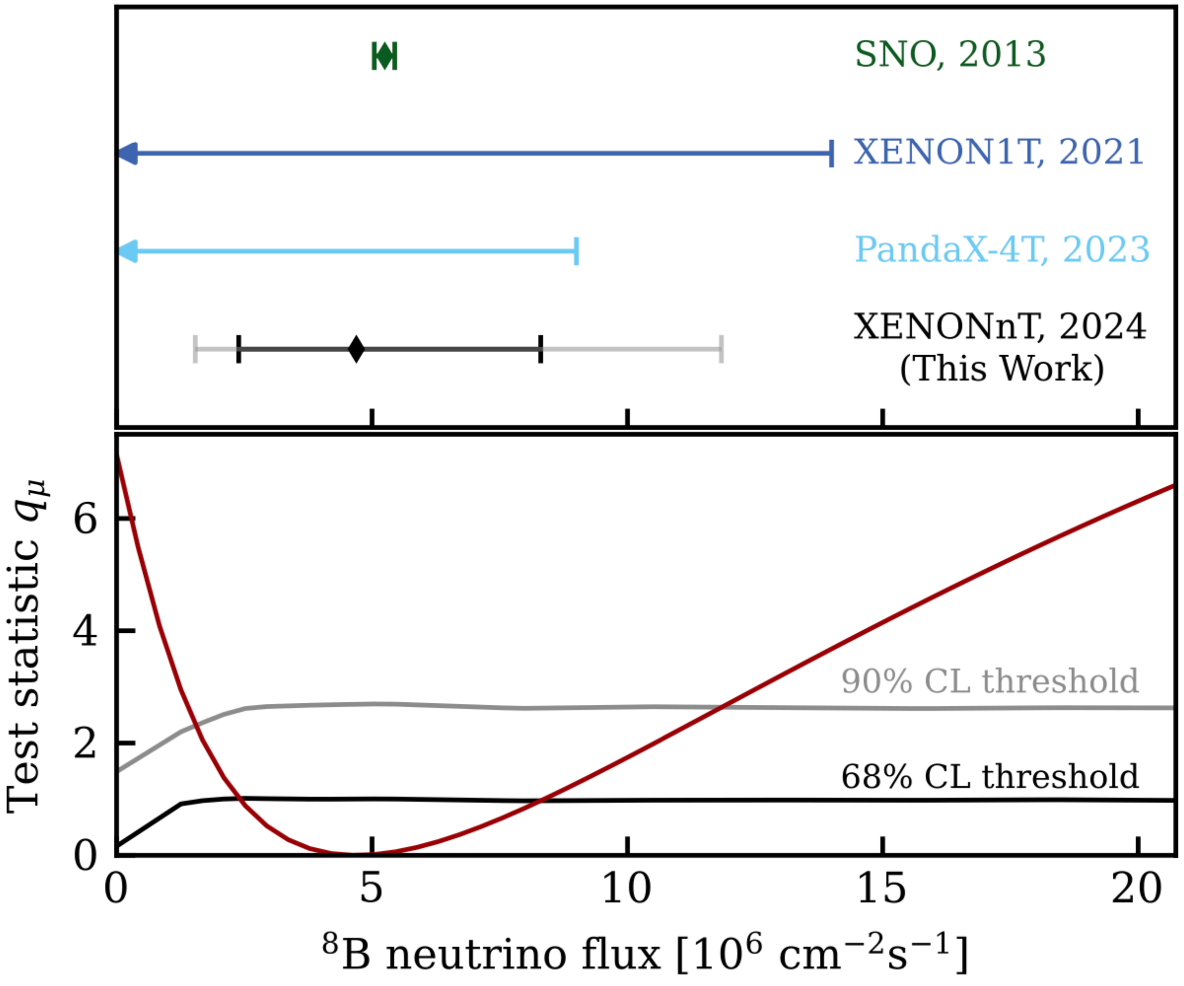
XENON1T, PRL 126, 2021



New νe-u quark interaction

New νe-d quark interaction

XENONnT: PRL 123, 2024



Conclusions & Outlook

- Liquid xenon detectors: at the forefront of direct DM searches
- LZ, PandaX, XENONnT: many results by early 2025, continue to take data towards design exposures and sensitivities
- DARWIN: leading the R&D efforts towards next-generation detectors
- XLZD (XENON-LZ-DARWIN): new international collaboration to build and operate a ≥ 60 tonne scale LXe TPC; PandaX-xT: upgrade to 20 t, then will construct 50 tonne scale detector
- Main goal: test WIMP paradigm into the neutrino fog (& other DM candidates)
- Neutrino physics: search for $0\nu\beta\beta$-decay in ^{136}Xe, address inverted ordering scenario, observe solar and SN neutrino, other second order weak decays

Bormio 2033 (?) A new particle ;-)

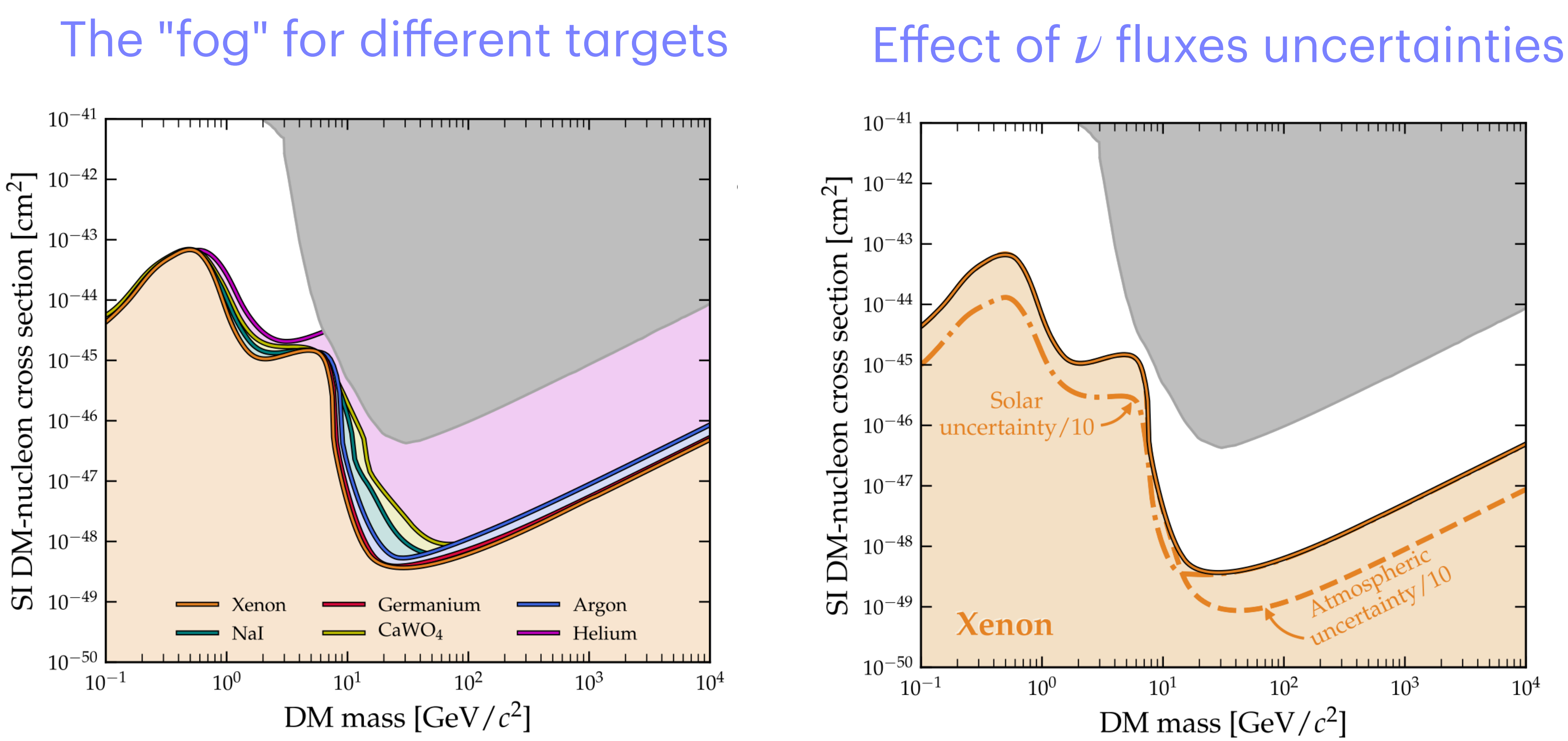
- Mass =?
- J = ?
- $\tau > ?$
- $\sigma(\chi + \bar{\chi} \rightarrow SM + SM) = ?$
- $\sigma(\chi + SM \rightarrow \chi + SM) = ?$
- ...

Thank you

Additional material

Approaching the neutrino fog

- Here shown for nuclear recoils (ν floor as boundary to "ν fog")
- Region where experiments leave the Poissonian regime*

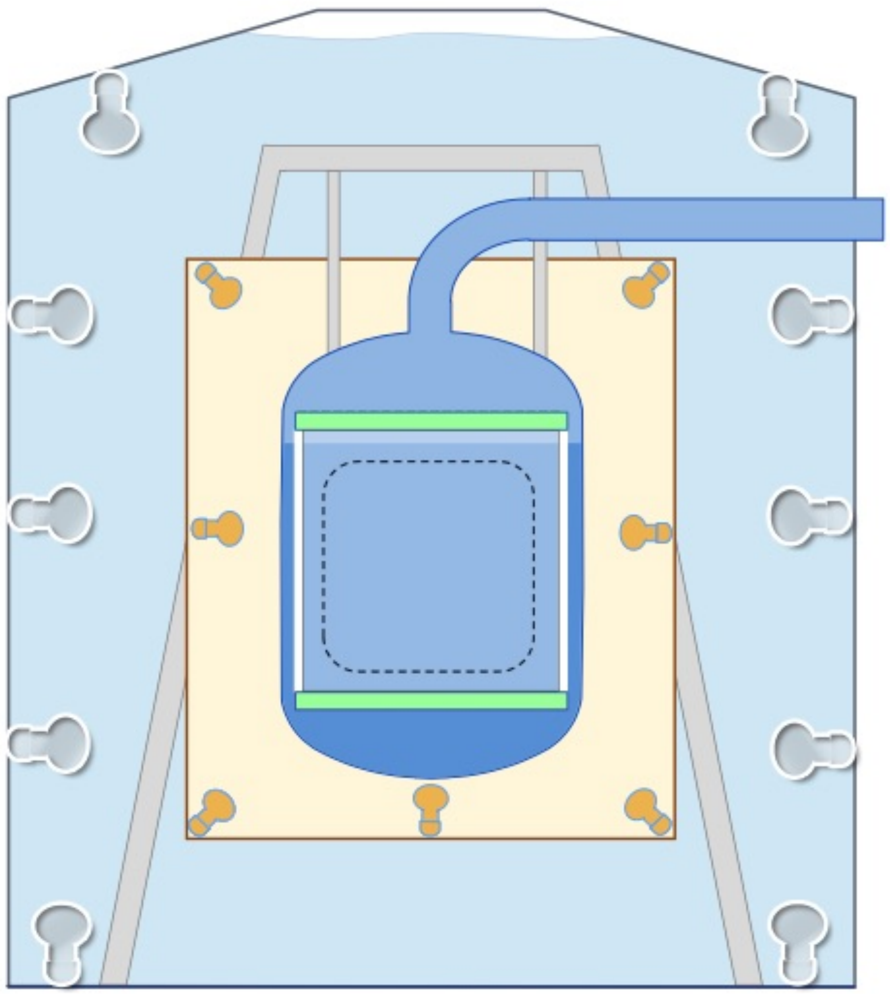


C. O'Hare, PRL 127, 2021

* σ where the DM discovery limit scales as $\sim (Mt)^{-1/n}$

XLZD nominal design

- Neutron and muon vetoes
- Underground site: several options are being considered (LNGS, Boulby extension, SURF, SNOLAB)
- Large-scale underground demonstrator planned



XLZD n and μ shields, schematic view

XLZD: endorsement

XENON-LUX-ZEPLIN-DARWIN

- APPEC Mid-Term Roadmap
- Helmholtz Roadmap
- P5 report
- UKRI infrastructure funds allocated for design study
- Several national roadmaps in Europe

APPEC report

RECOMMENDATIONS:

APPEC strongly supports the European leadership role in Dark Matter direct detection, underpinned by the pioneering LNGS programme, to realise at least one next-generation xenon (order 50 tons) and one argon (order 300 tons) detector, respectively, of which at least one should be situated in Europe. APPEC strongly encourages detector R&D to reach down to the neutrino floor on the shortest possible time scale for WIMP searches for the widest possible mass range.

View of the external structure of XENON nT, experiment devoted to direct search of dark matter, which constitutes 85% of the matter in the Universe. Beside the tank, containing the sensitive part of the detector, it is visible the three levels building which hosts the apparatus necessary for the functioning of the detector.
© Fabrizio Ursini / LNGS-INFN

P5 report

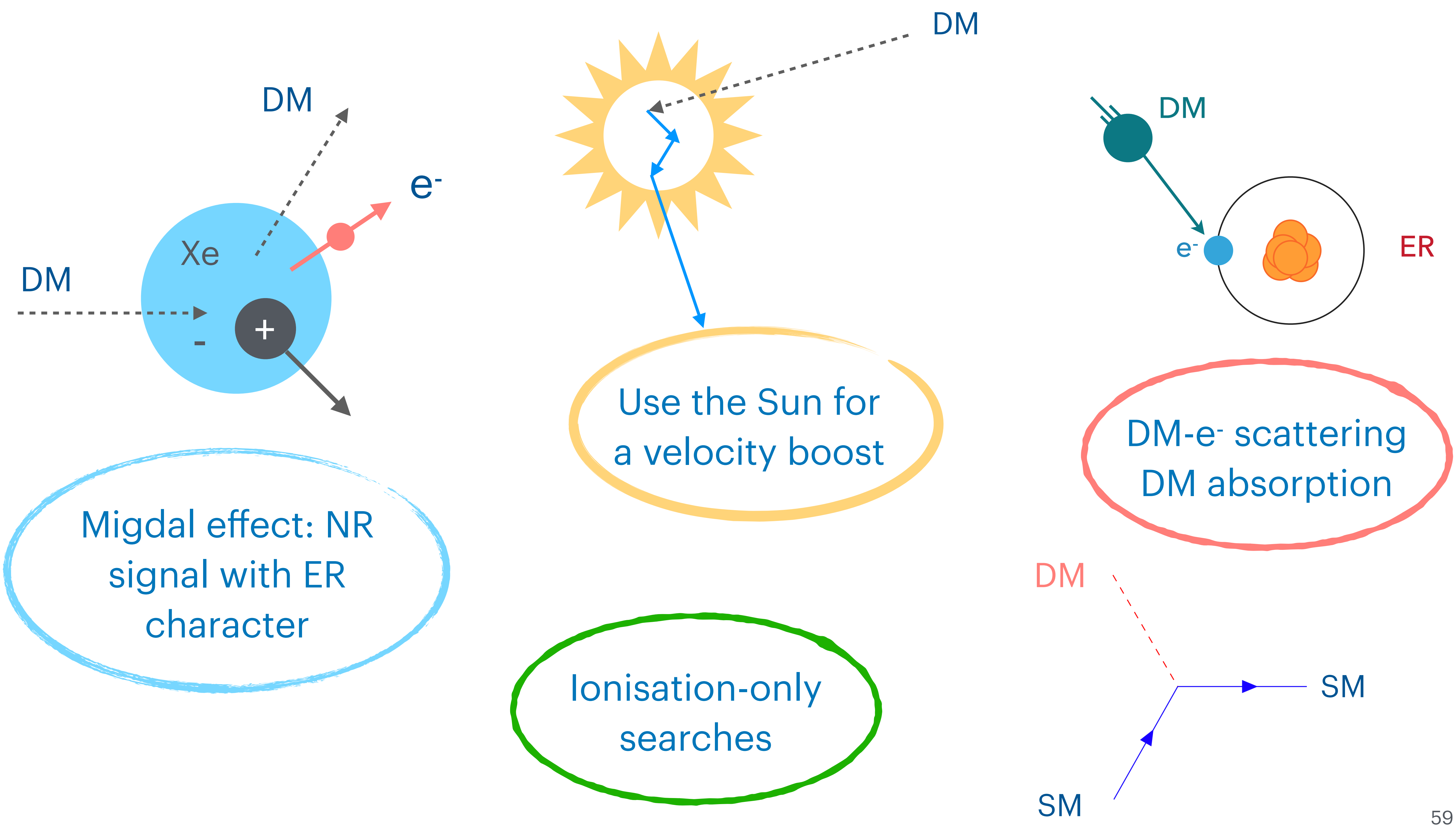
4.1.4 – Major Initiative: G3, the Ultimate WIMP Dark Matter Search

The next phase of the search for WIMP dark matter requires experiments capable of reaching roughly order-of-magnitude weaker interaction strengths than current experiments. A large Generation-3 (G3) WIMP dark matter search would build on the most successful designs of the current G2 experiments, providing sensitivity to dark matter-Standard Model interactions that are small enough that neutrinos become an irreducible background (the "neutrino fog").

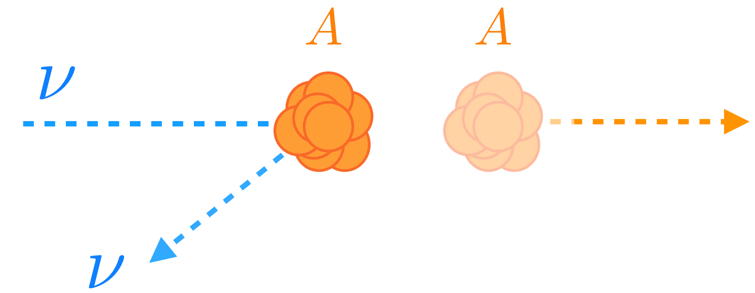
This improvement in reach would provide coverage of important benchmark WIMP models, such as most remaining potential dark matter parameter space under the constrained minimal supersymmetric extension to the Standard Model. Such a G3 experiment would also perform important measurements of solar and possibly supernova neutrinos. A G3 direct detection experiment would be the ultimate WIMP search within the current approach; moving past the reach of the G3 experiment and deeper into the neutrino fog would require significant changes in method and technology.

Although supporting more than one G3 experiment would be beneficial, expected costs are high enough, especially compared to the costs of the portfolio of smaller dark matter projects, that funding two does not appear feasible. Our recommendation supports one G3 experiment, preferably sited on US soil to help maintain US leadership (Recommendation 2d). Investment in the expansion of SURF, taking advantage of the DUNE excavation infrastructure and potential private funding, would enable such siting. Continued support by both DOE and NSF is needed to maximize the science and US leadership. A second, complementary G3 experiment would maximize the discovery potential and would teach us more about dark matter if one of the G2 experiments has promising results.

Light dark matter searches

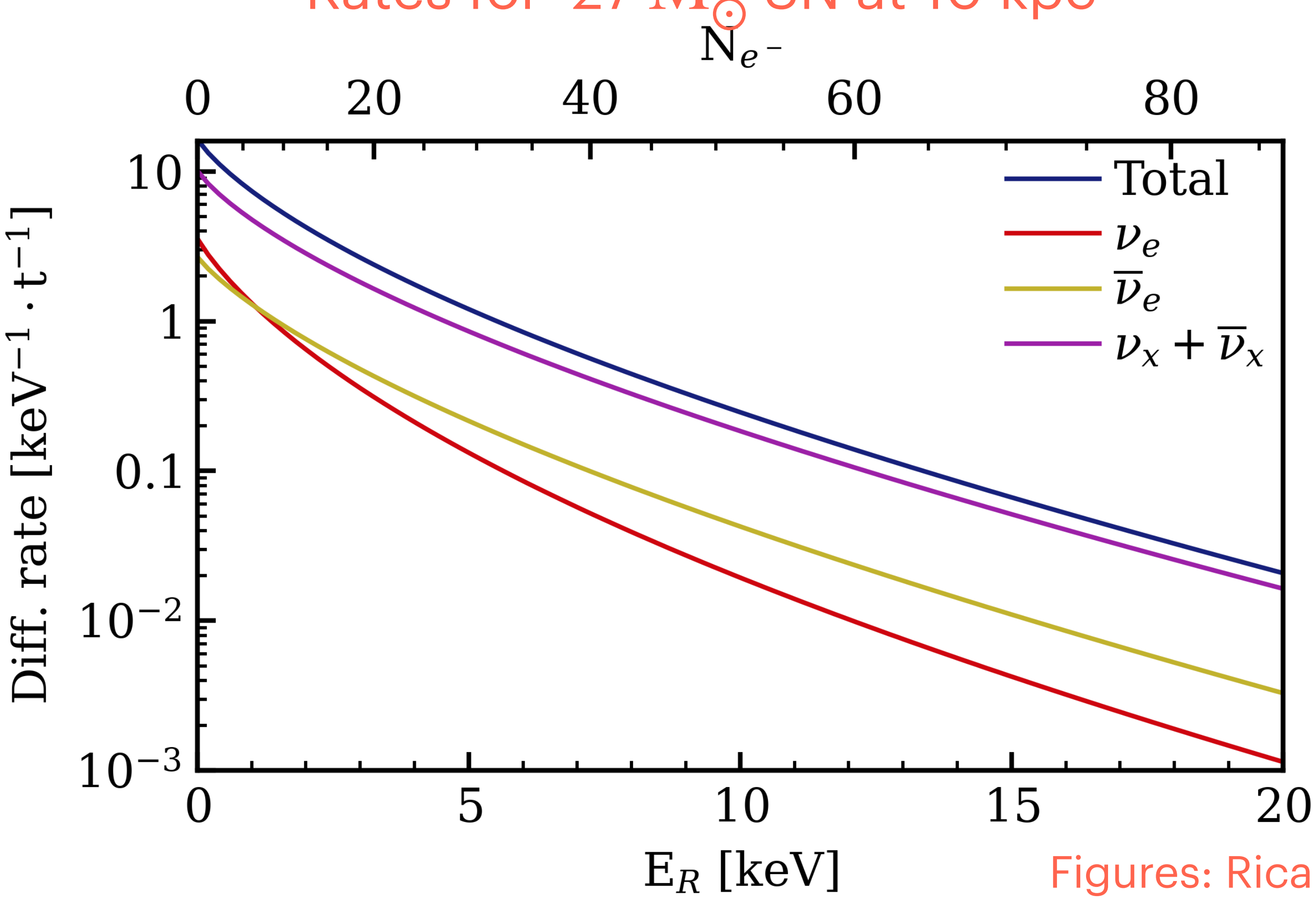


SN ν-nucleus scattering

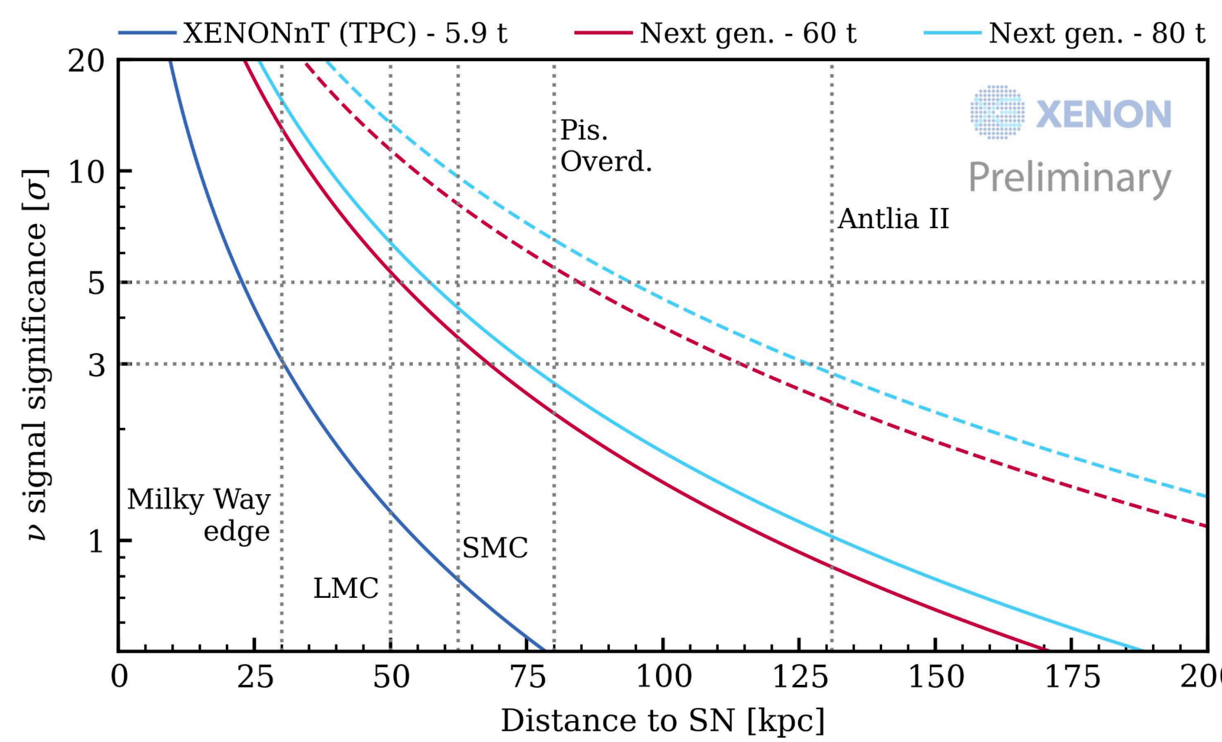


- Sensitivity to all ν flavours: few events/ton expected from SN at ~10 kpc
- Main challenge: low energies, understand few-e- backgrounds
- **XLZD:** sensitivity beyond SMC; part of SNEWS2.0

Rates for 27 $M_\odot$ SN at 10 kpc



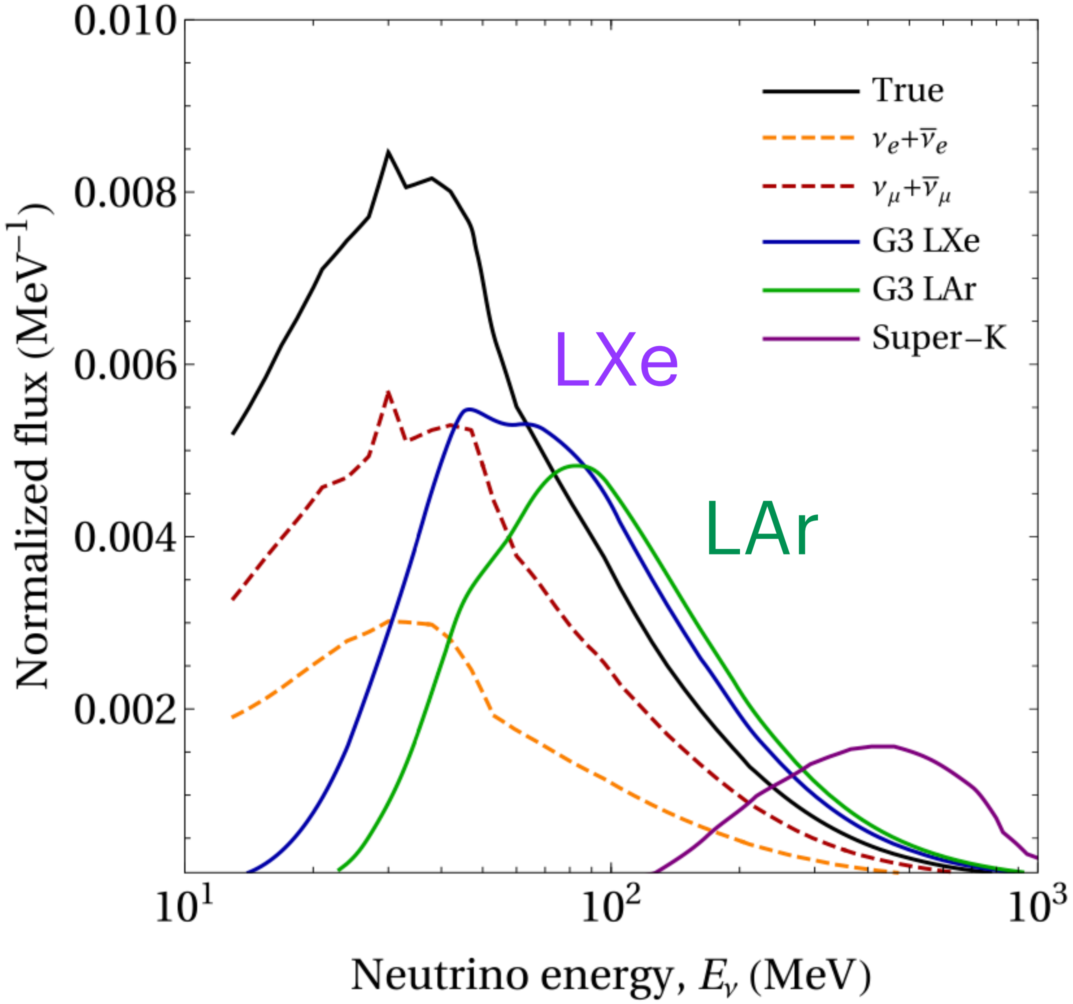
XENONnT/LZ and XLZD

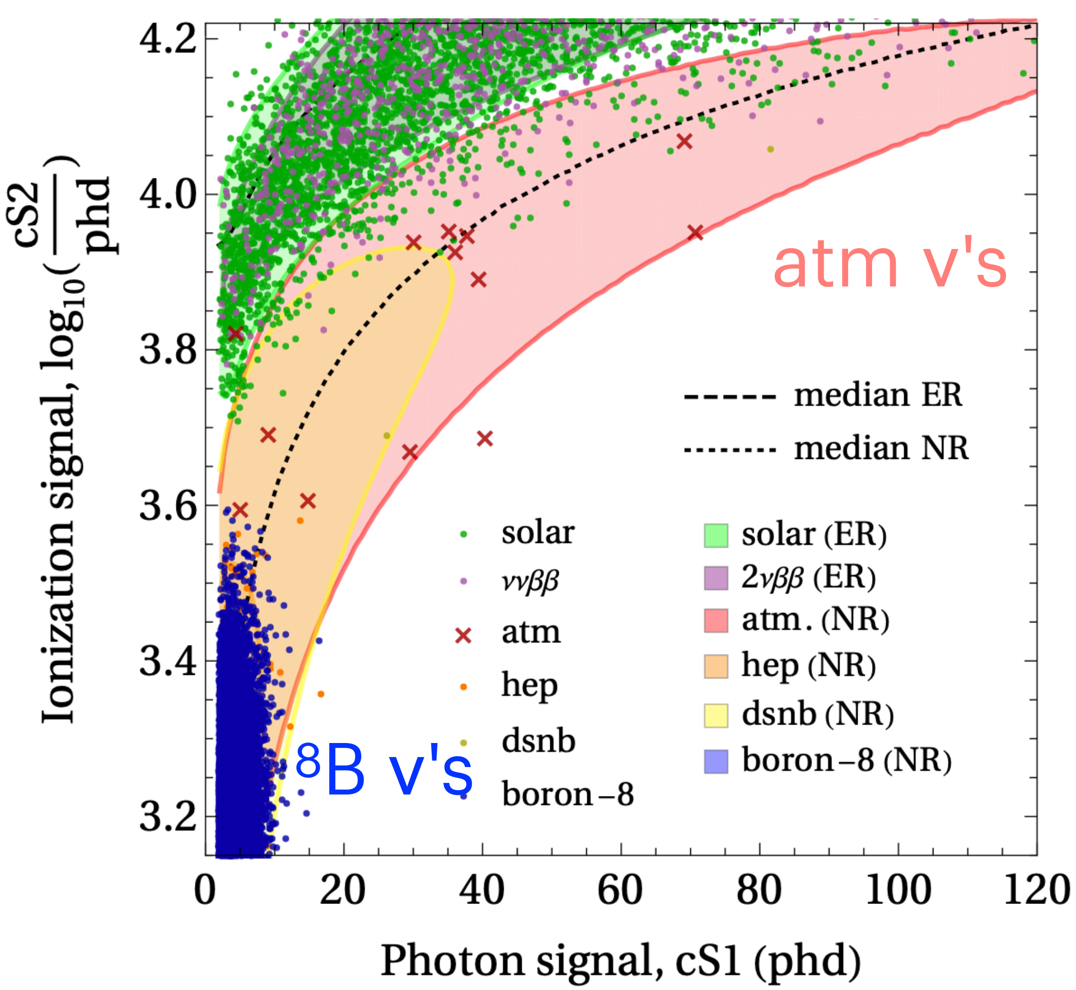


Figures: Ricardo Peres, UZH

Atmospheric neutrinos

- In general, exposures > few 100 t y are needed for 5-σ detection



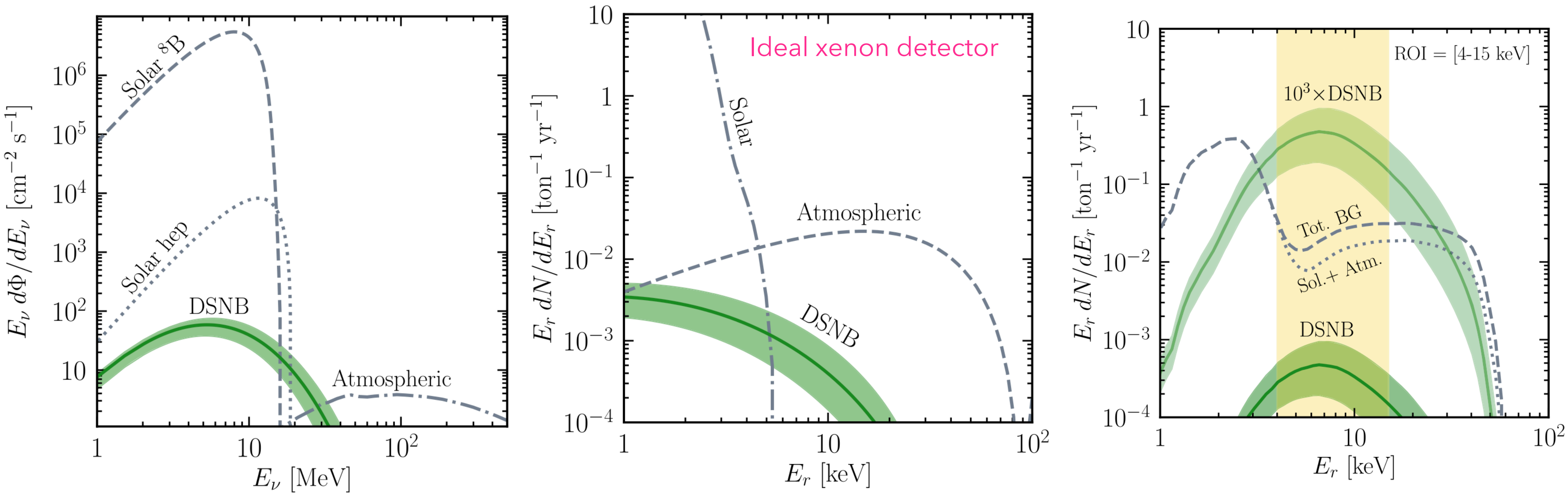


Newstead, Lang, Strigari, PRD 104, 2021

DSNB with CEvNS

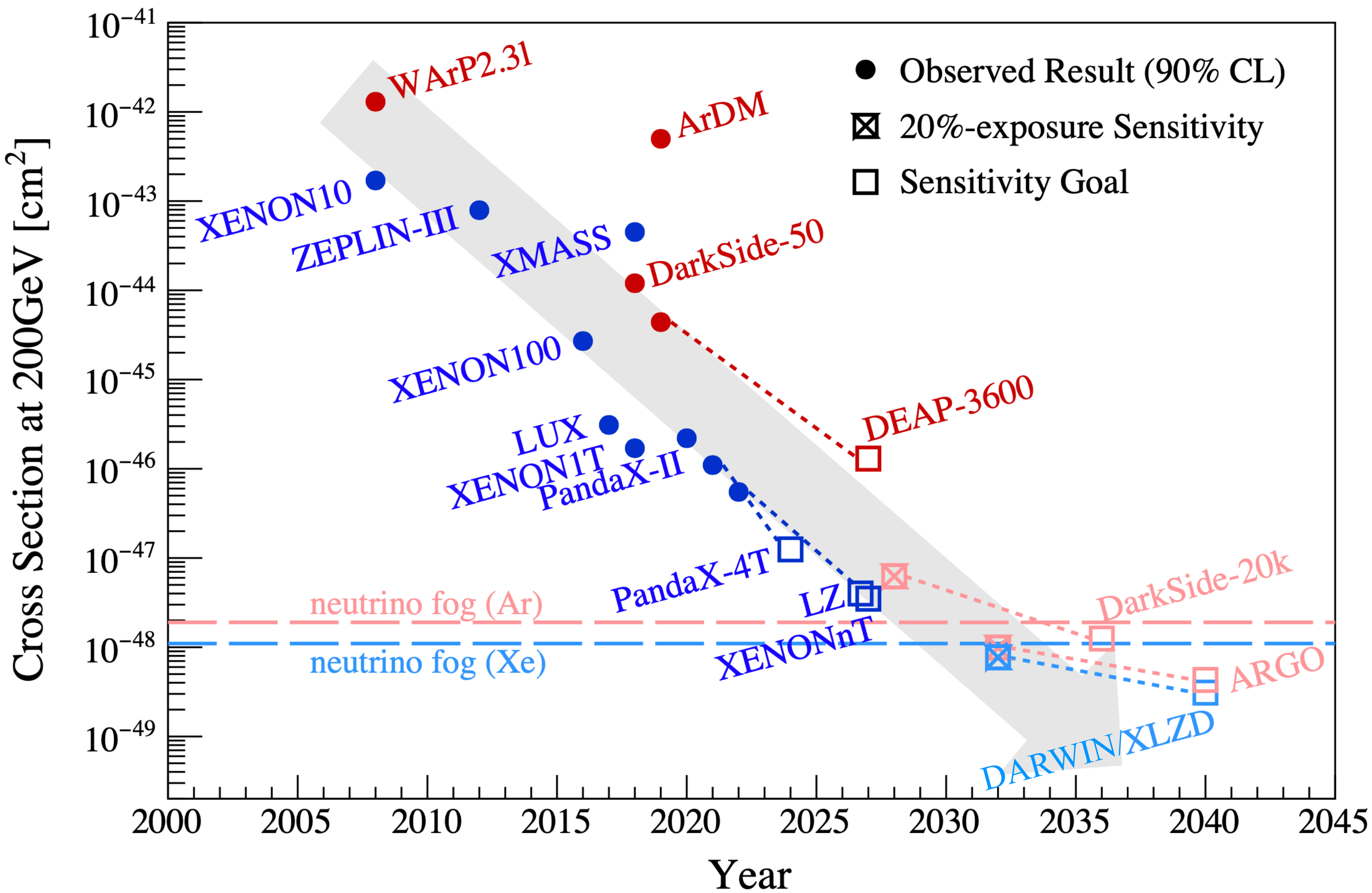
- Understanding of core-collapse SN depends on probing DSNB with all flavours
- So far, only upper limits in ν_e and $\bar{\nu}_e$ flux by SNO and SuperK (19 cm^{-2}s^{-1}, 2.7 cm^{-2}s^{-1}), limits on in $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ fluxes much weaker (per flavour, ~10^3 cm^{-2}s^{-1}), XLZD could probe these down to ~ 10 cm^{-2}s^{-1} or better, depending on fiducial mass

Suliga, Beacom, Tambora, PRD 105, 2022

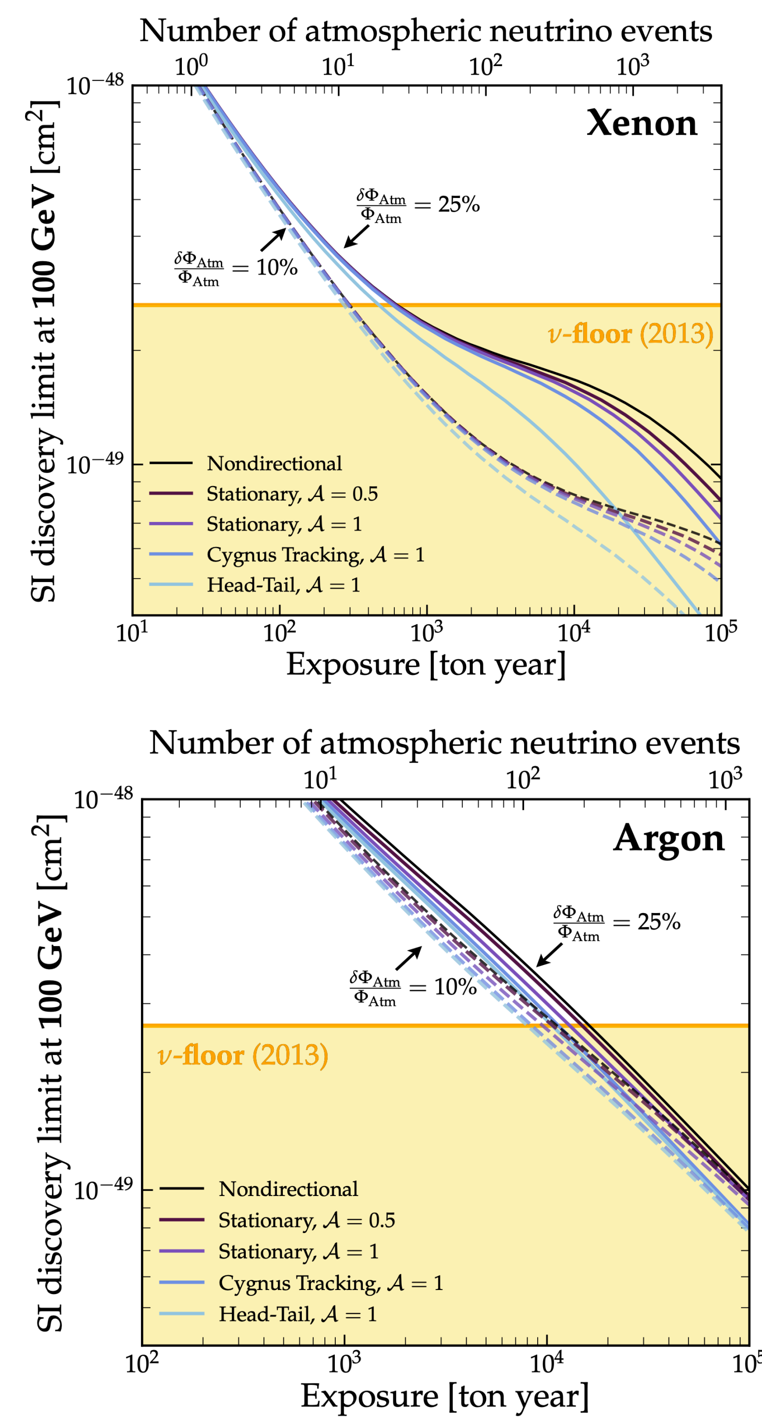


Approaching the neutrino fog

- Current & future noble liquid experiments



100 GeV WIMP discovery limits



Snowmass, Topical Group on Particle Dark Matter Report, 2209.07426:
"A critical feature of the neutrino fog is that it will move to lower cross section if uncertainties in the neutrino fluxes are reduced, opening up new space for continuing searches."

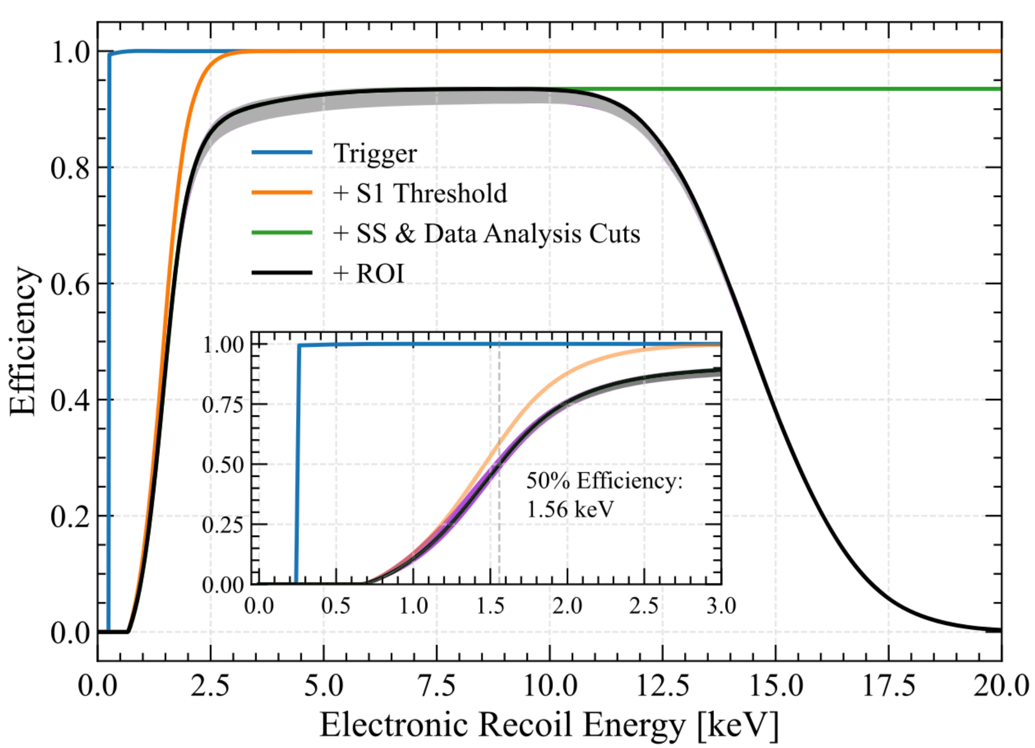
C. O'Hare, PRD 102, 2020

Energy thresholds in Xe TPCs

- S1 + S2: ~ 1 keV with 3-fold coincidence (ER) (hits in ≥ 3 PMTs within ~50-100 ns); lower threshold (< 1 keV) with 2-fold coincidence (with lower signal efficiency)

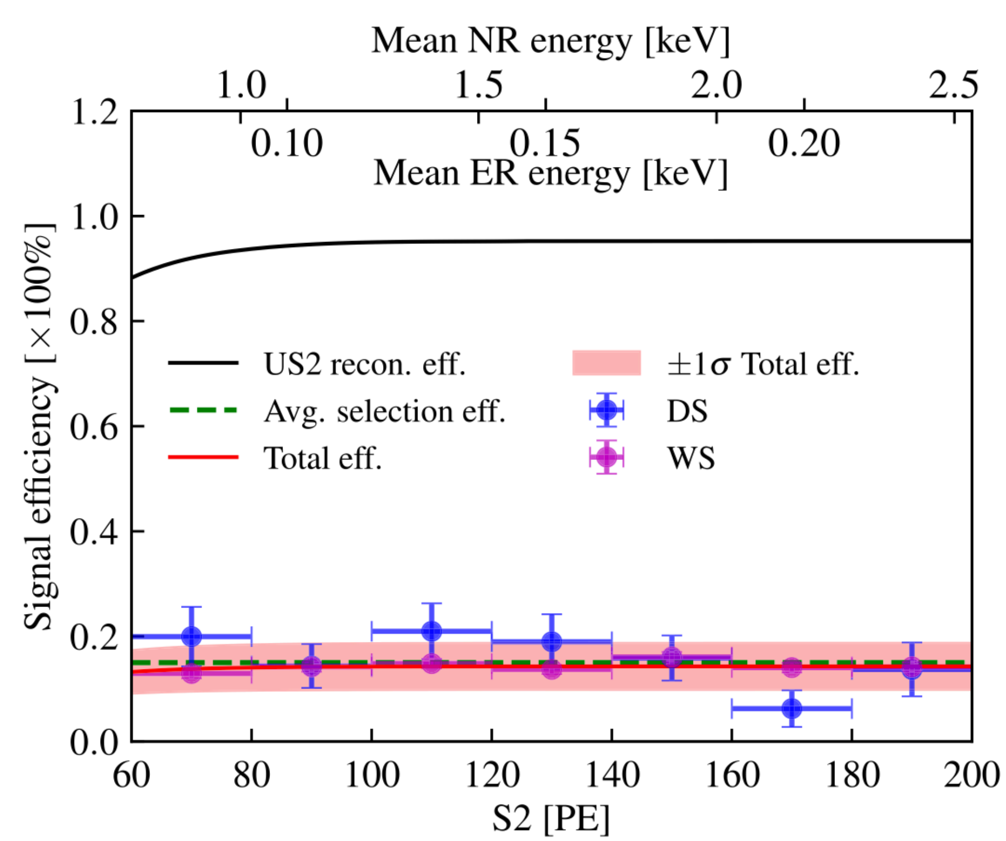
- S2-only: ~ 0.2 keV, with 5 e⁻ - 100 e⁻ detected (probe ER and NR interactions), down to W-value, with 1 e⁻ - 5 e⁻ signal (mostly probe ER interactions due to large uncertainty in quenching factor for NRs at lowest energies)

LZ, PRD 108, 2023



At least 3 PMTs see a signal, summed signal > 3 phd

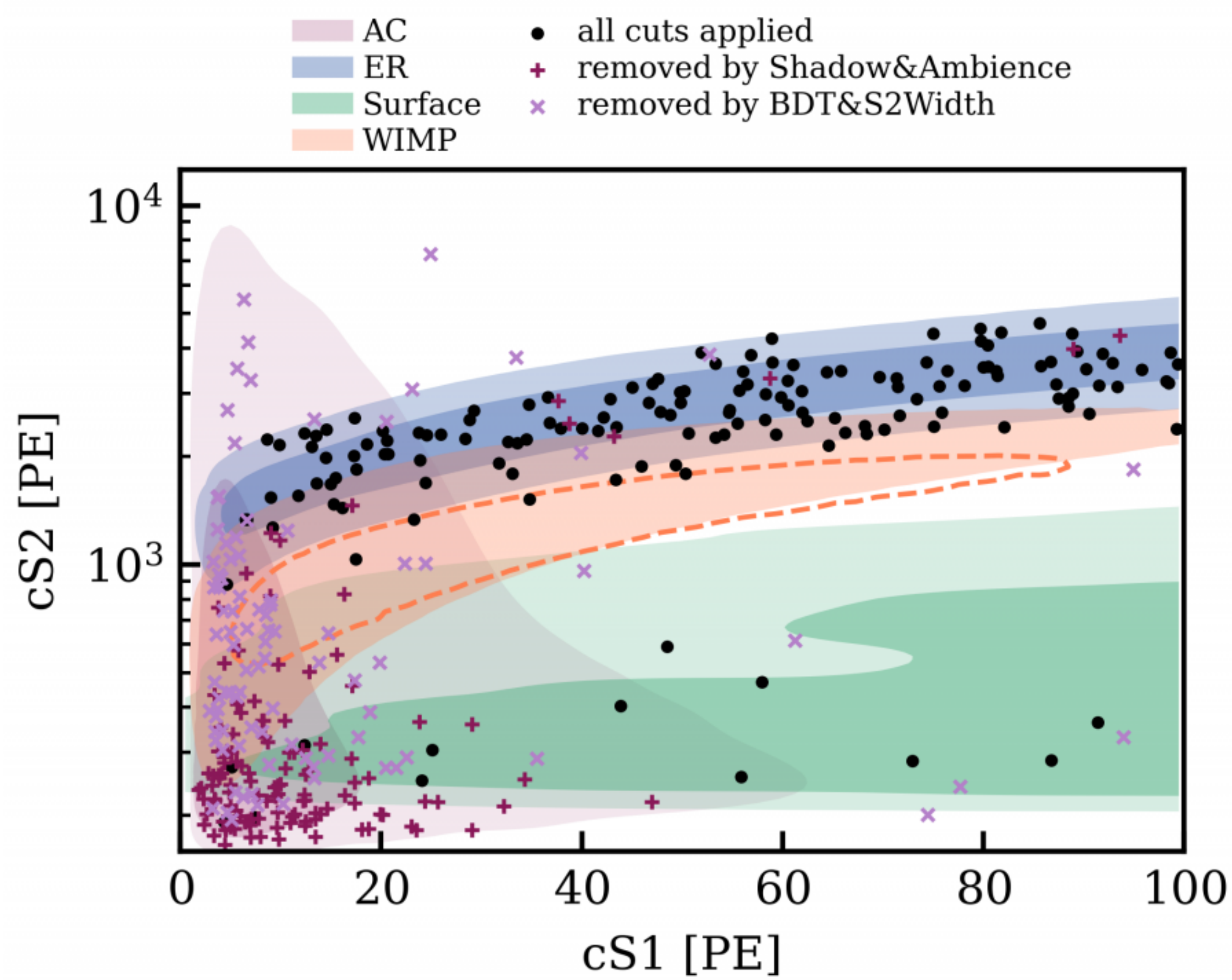
PandaX-4T, PRL 130, 2023



AC backgrounds in TPCs

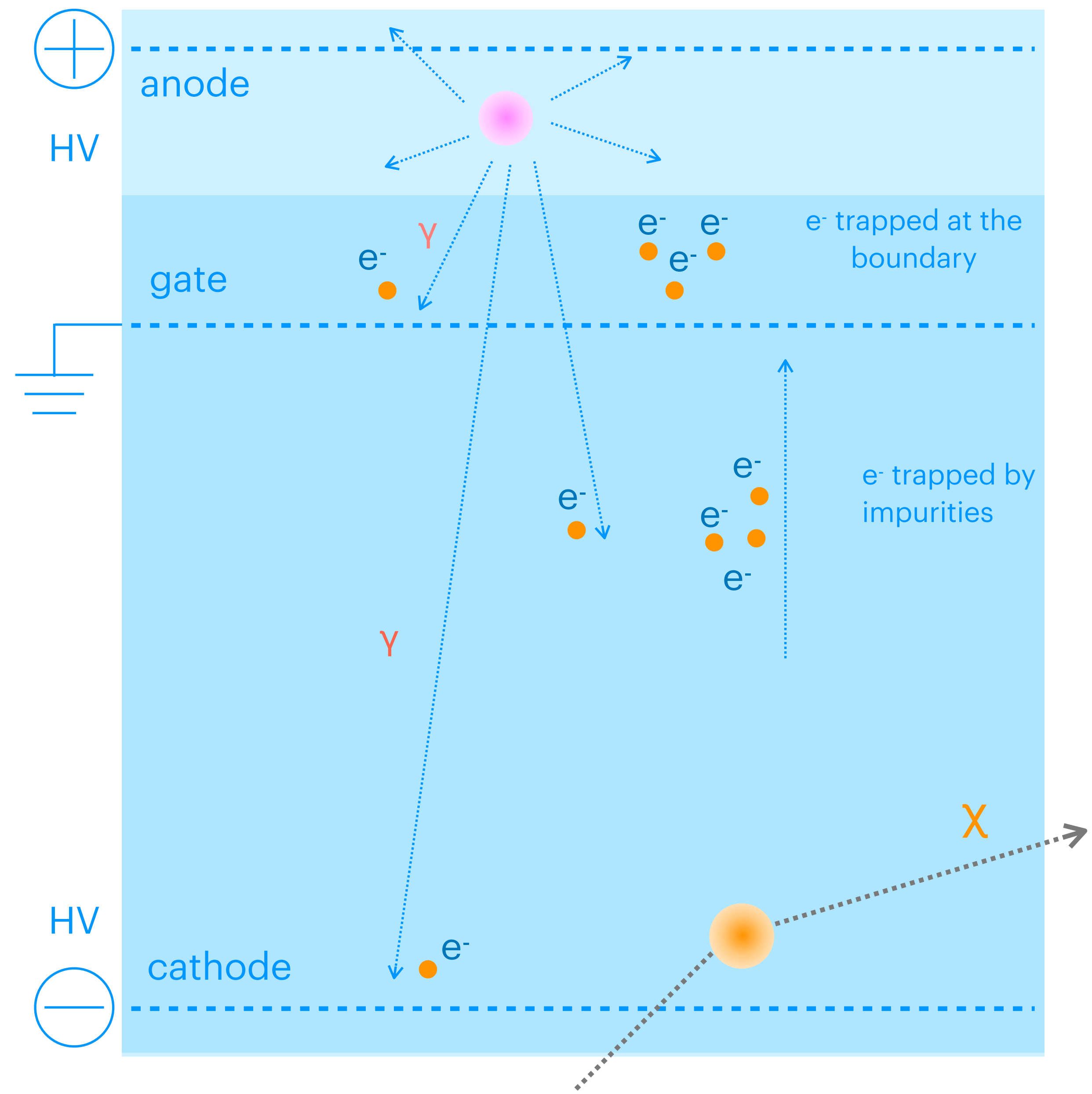
- Combinatorial background at low energies can be significant
- Main sources for isolated S1 and isolated S2 signals
  - Primary scintillation (S1s)
    - Dark counts (pile-up) ∝ nr. channels
    - Charge-insensitive regions
    - Delayed photons
  - Electroluminiscence (S2s)
    - Bulk xenon S2-only events
    - Delayed electrons
    - Electrode events

Example from XENONnT



Ionisation only backgrounds

- Radioactivity
- Solar neutrinos
- Instrumental
  - Spurious emission of single and few electrons from the cathode
  - Delayed e^- after large S2 signals: trapped e^- at the liquid/gas interface; e^- emitted from impurities, etc
- Important to understand & mitigate origin, develop background models



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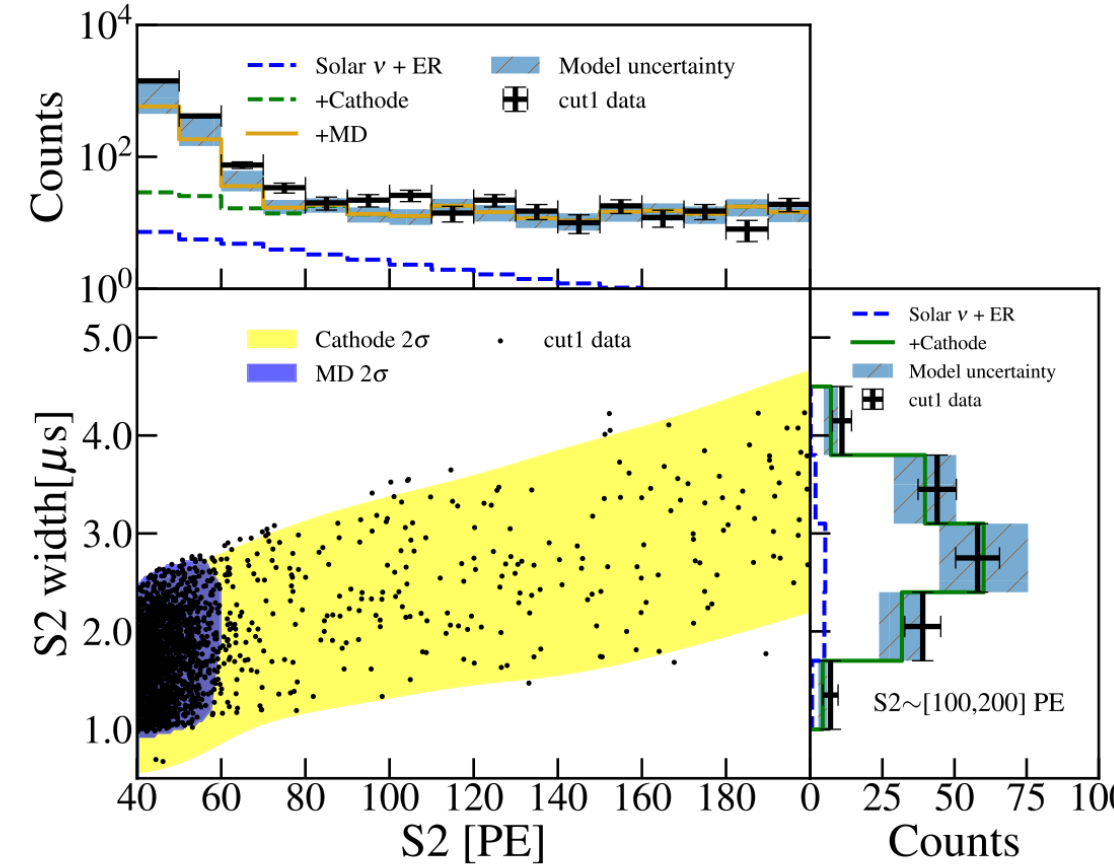
PandaX-4T, PRL 130, 2023



XENON1T, PRL 123, 2019