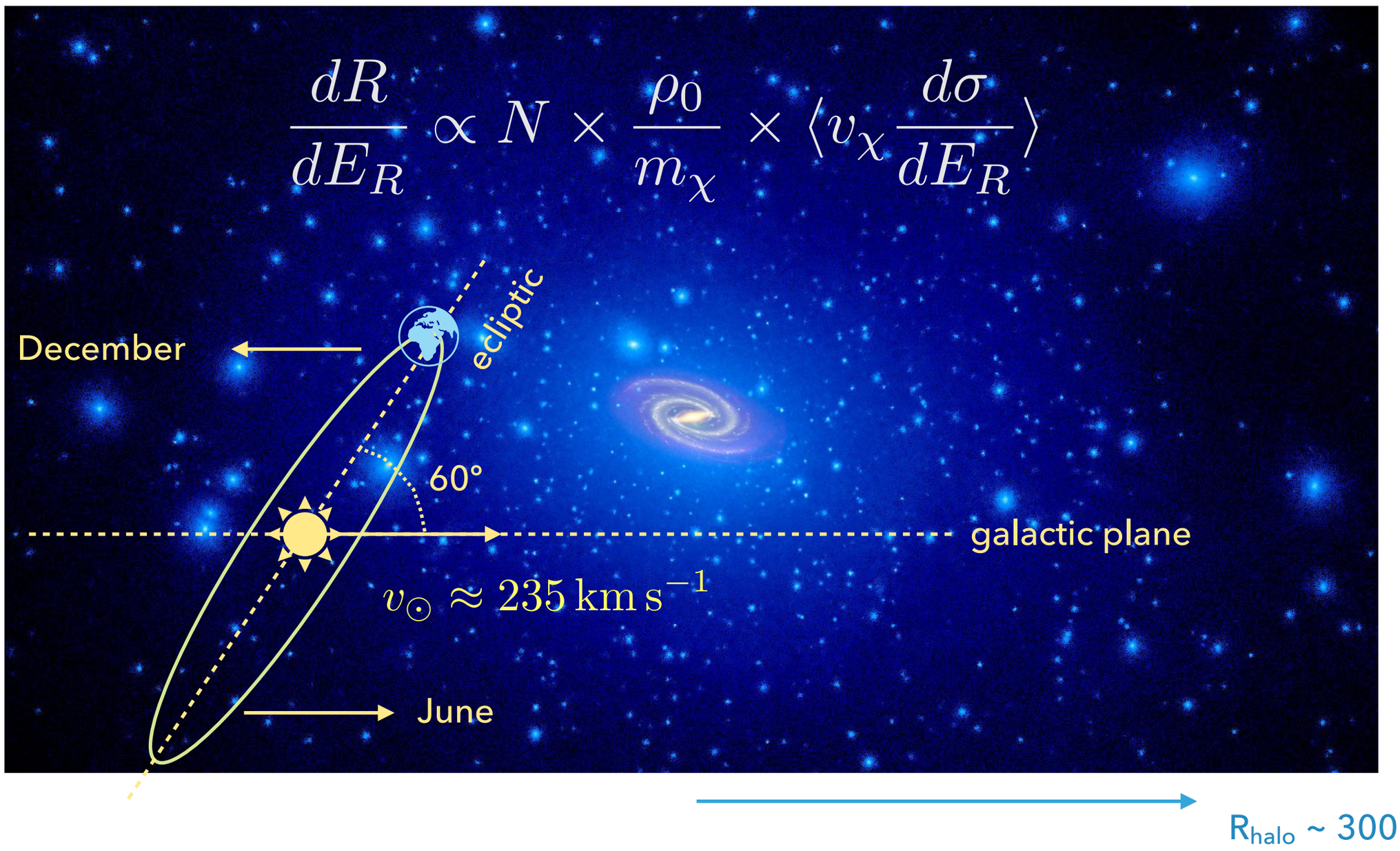
Looking into the heart of darkness: dark matter searches with future noble liquid experiments

XeSAT2023 - International Workshop on Applications of Noble Gas Xenon to Science and Technology

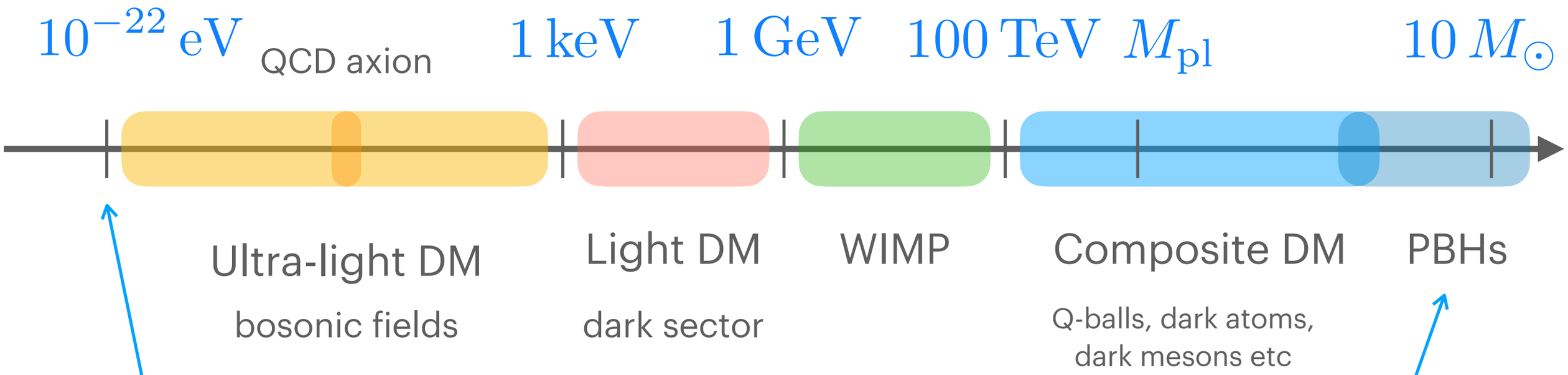
Laura Baudis, University of Zurich, June 7, 2023

Dark matter is all around us

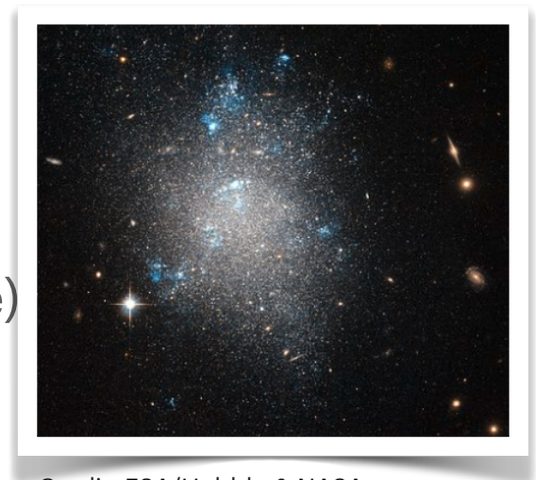
- We look for (very rare) scatters of DM particle in detectors operated deep underground



Allowed mass parameter space



Structures on the scale of dwarf galaxies (kpc-scale) can form

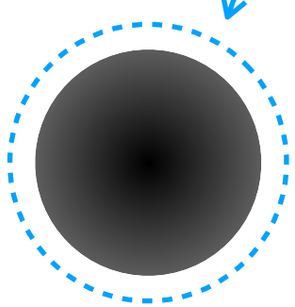


Credit: ESA/Hubble & NASA

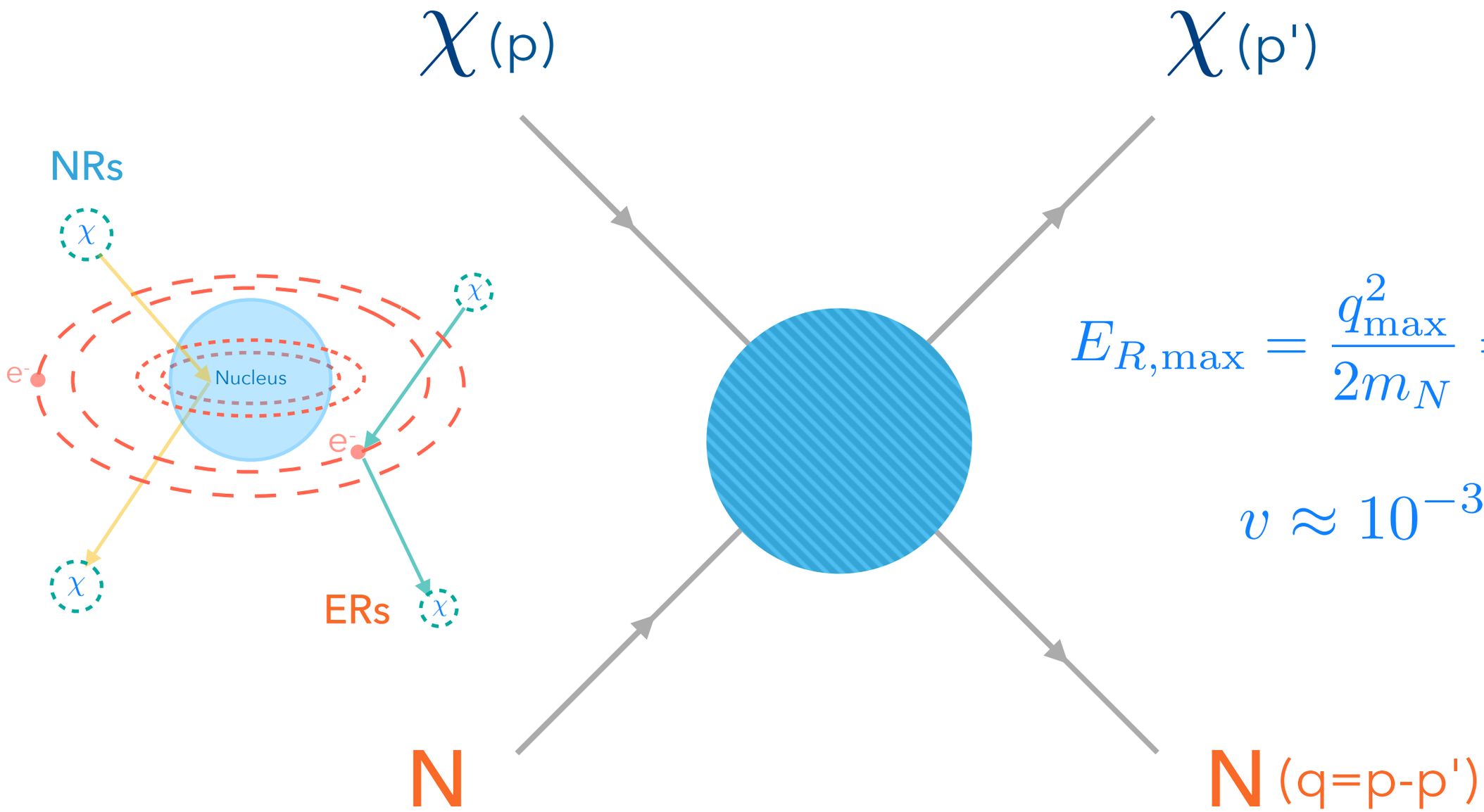
$$\Delta p \Delta x \sim 1$$

$$\Delta p \sim m_\chi v$$

$$\Delta x \sim 2 r_{\rm halo}$$



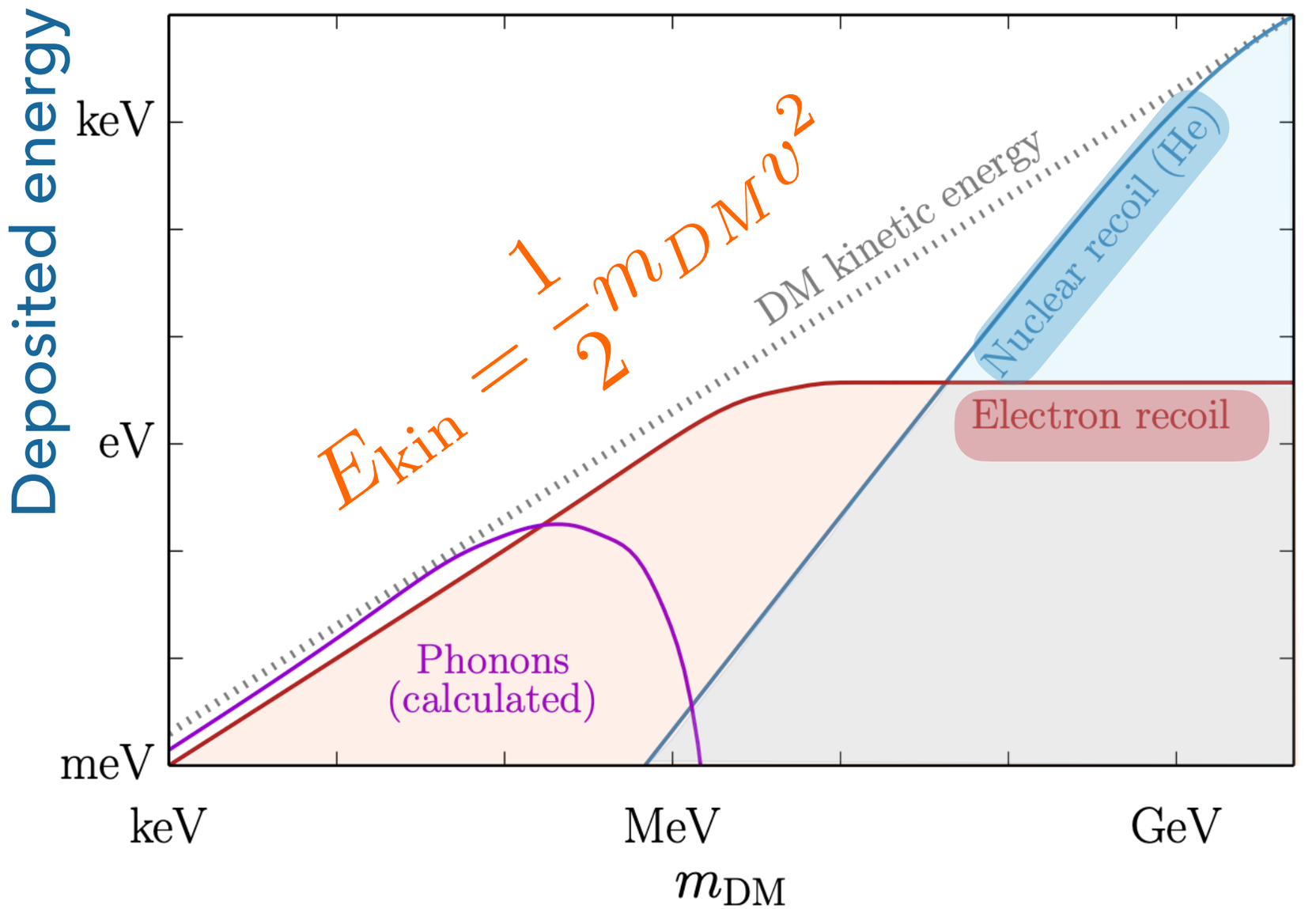
Kinematics

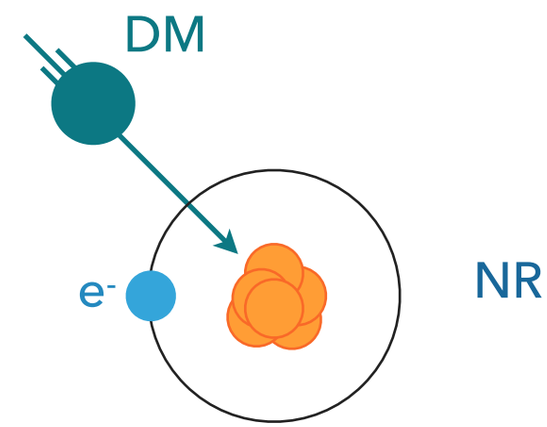


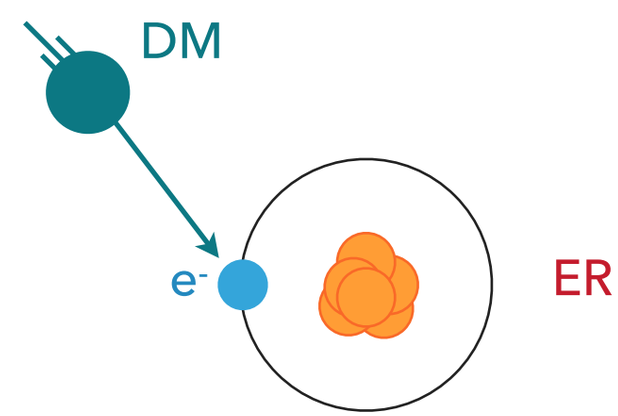
$$E_{R,\max} = \frac{q^2_{\max}}{2m_N} = \frac{2\mu^2_{\chi N} v^2}{m_N}$$

$$v \approx 10^{-3} c$$

Kinematics



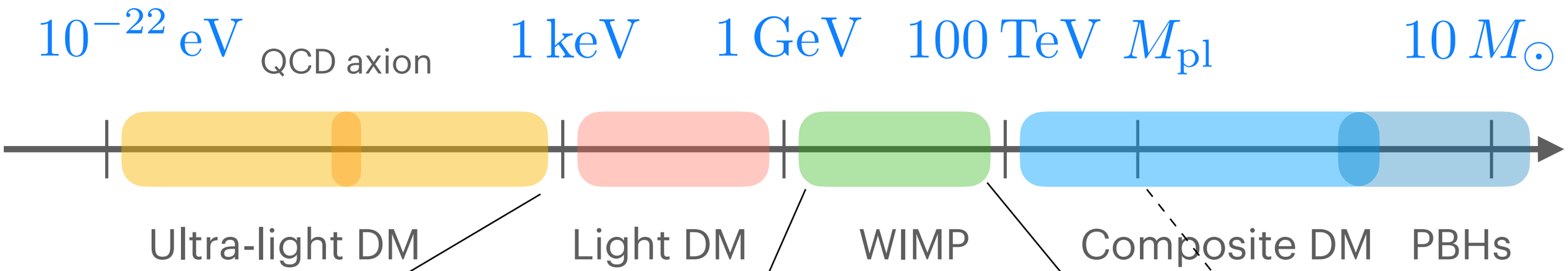




Dark matter particle mass

Tongyan Lin, arXiv:1904.07915

Allowed mass parameter space

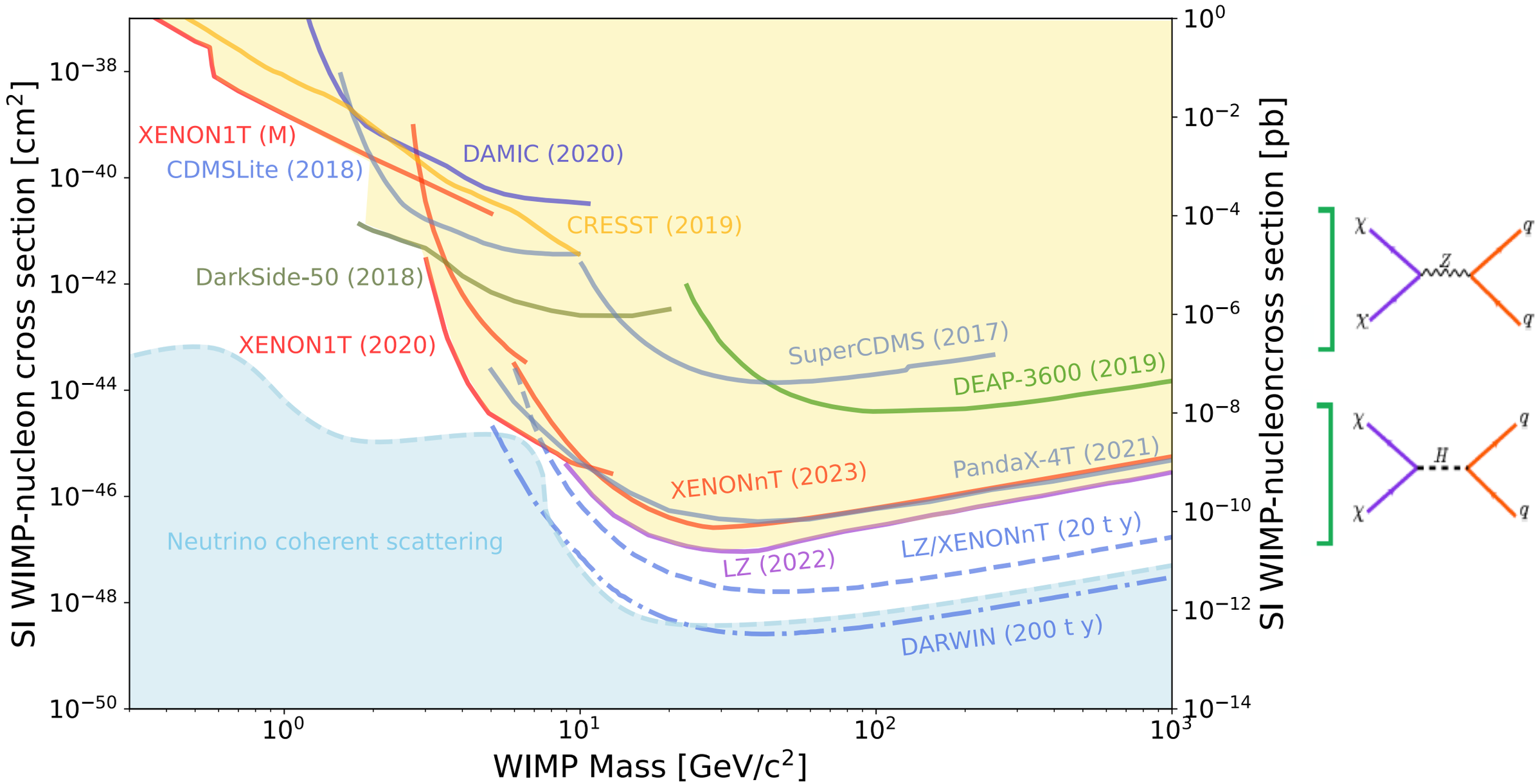


Noble liquids:
- Migdal effect
- Scatters with e^- *(interaction with SM though new mediator)*
- Absorption *(bosonic DM with direct coupling to SM particles)*

Noble liquids:
- Scatters with nuclei *(interactions with SM through, e.g., Higgs or new mediator)*
- Coherent enhancement across the nucleus for elastic scattering

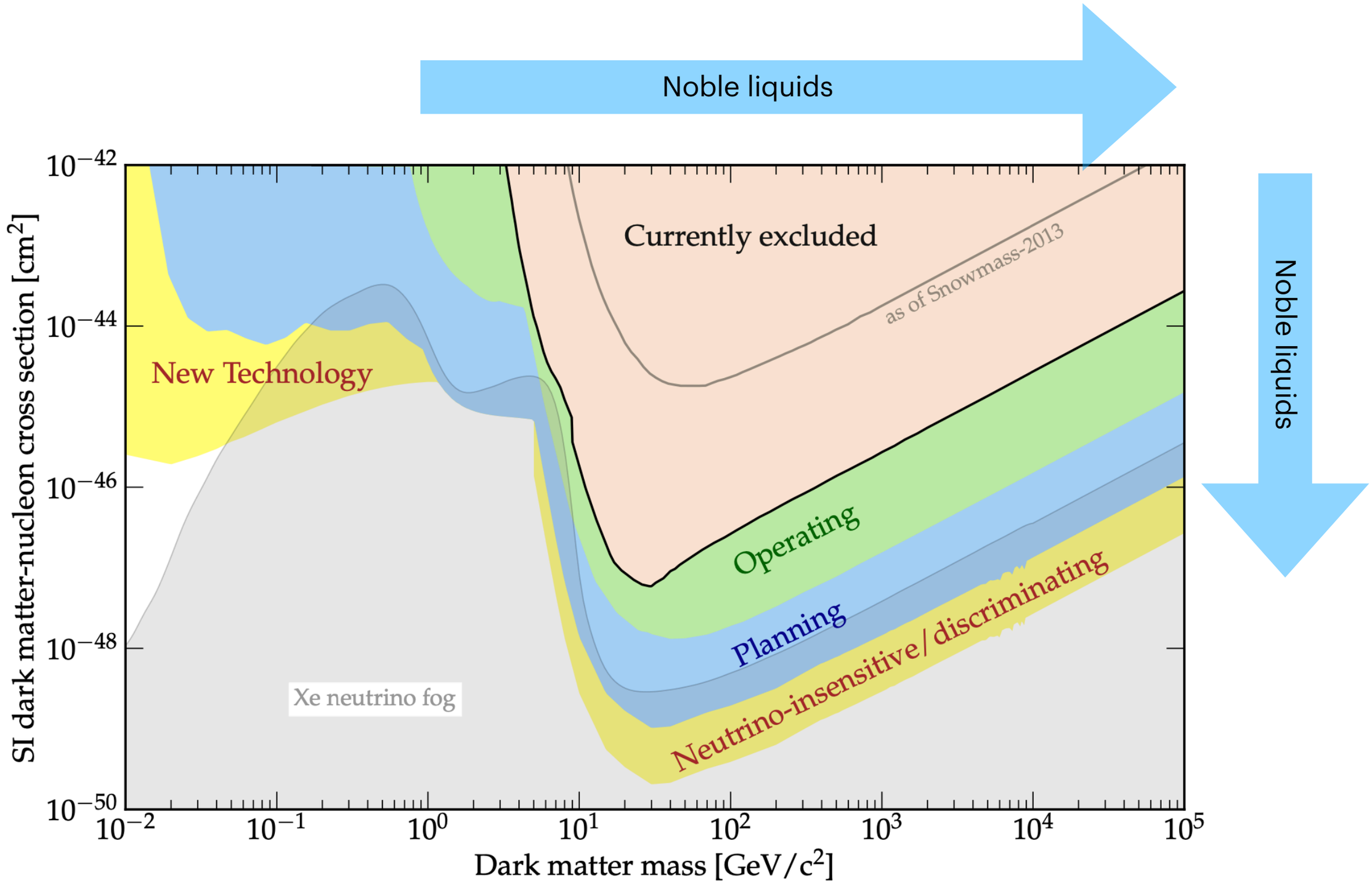
Noble liquids:
- Multiple scatters with nuclei

Direct detection landscape in 2023



Update after LB and Stefano Profumo, PDG 2022

Direct detection landscape in 2023



Snowmass, Cosmic Frontier Report, arXiv: 2211.09978

Liquid Noble Technology

- Leading sensitivity at intermediate/high DM masses since ~2007
- Liquid detectors
  - 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 (double weak decays, solar and SN neutrinos, etc)

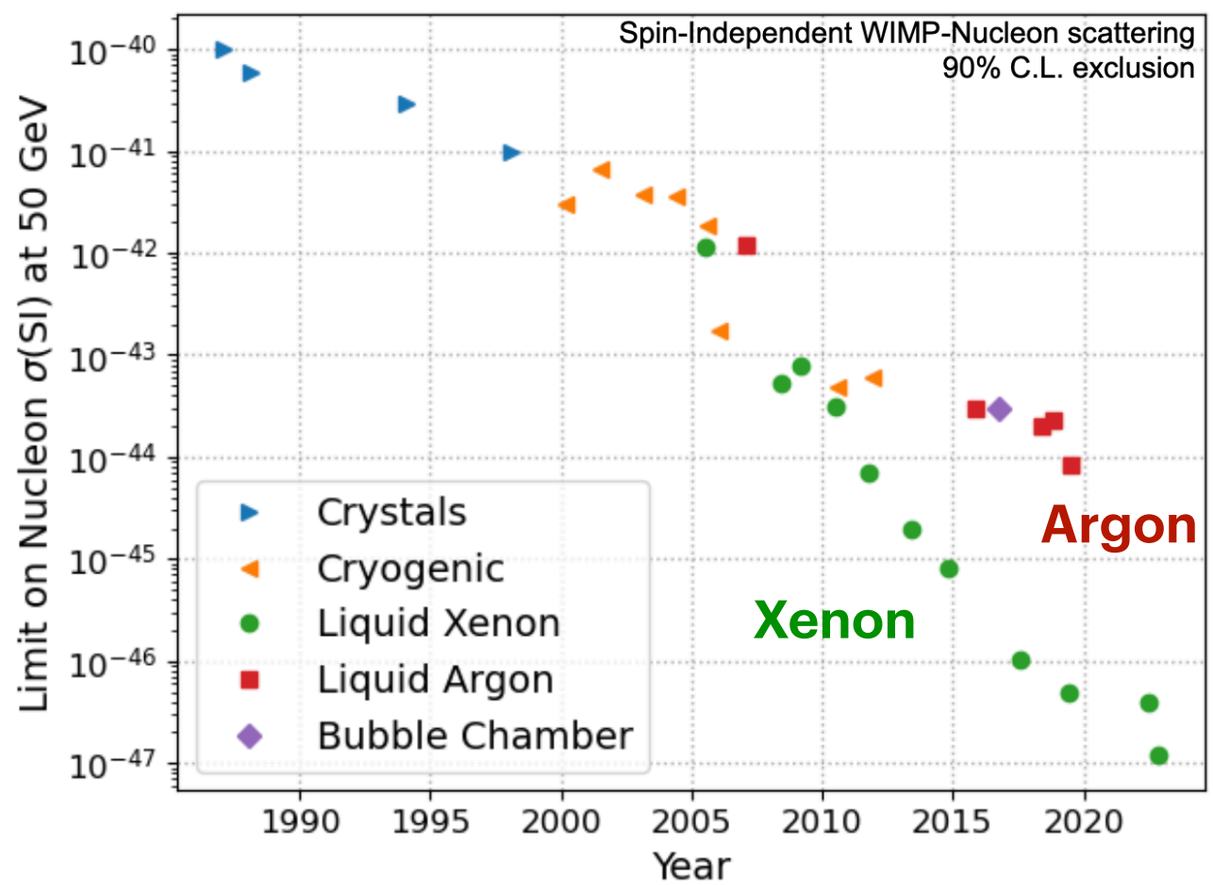
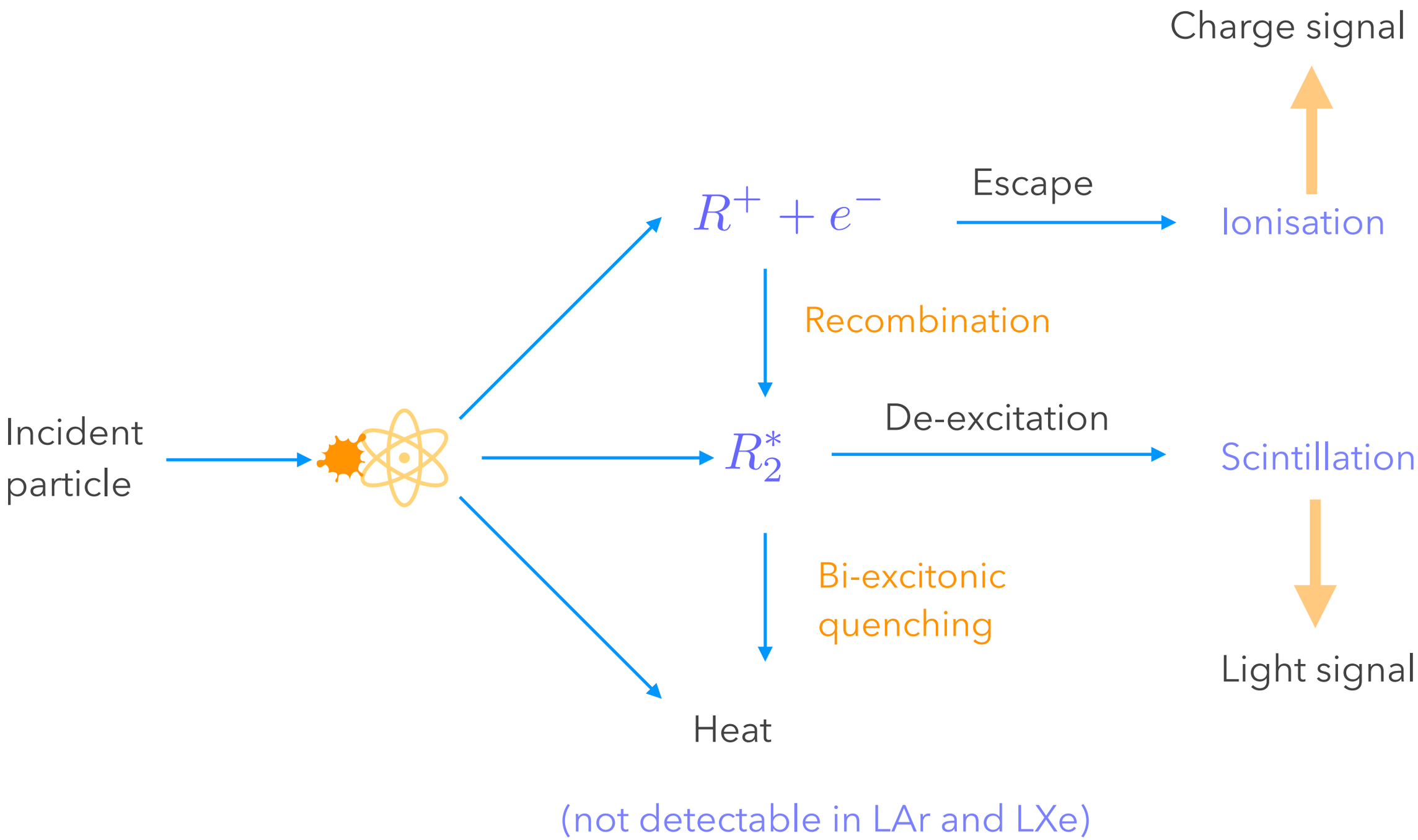
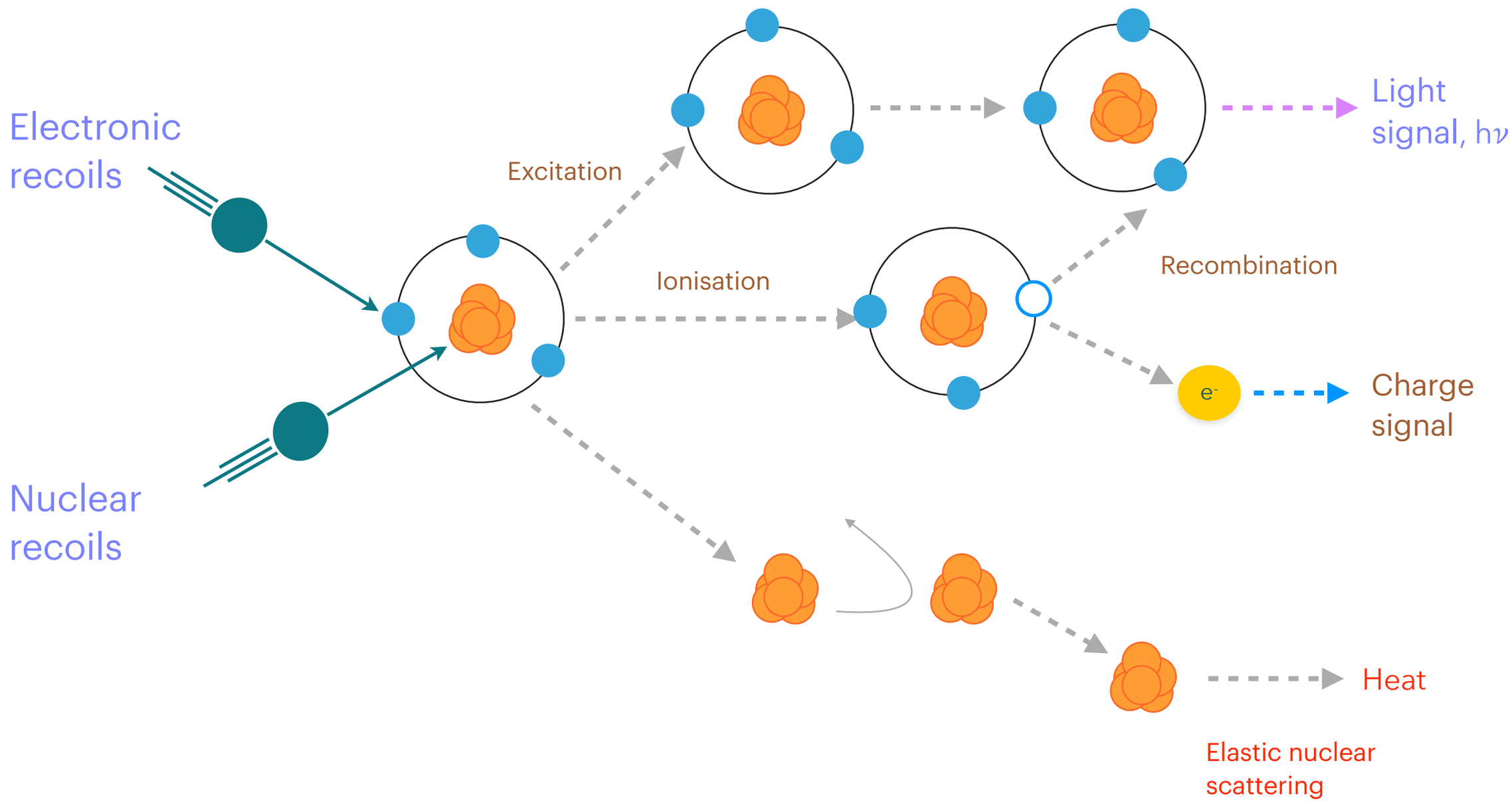


Figure by Tom Shutt, SLAC

Energy Deposits in Noble Liquids

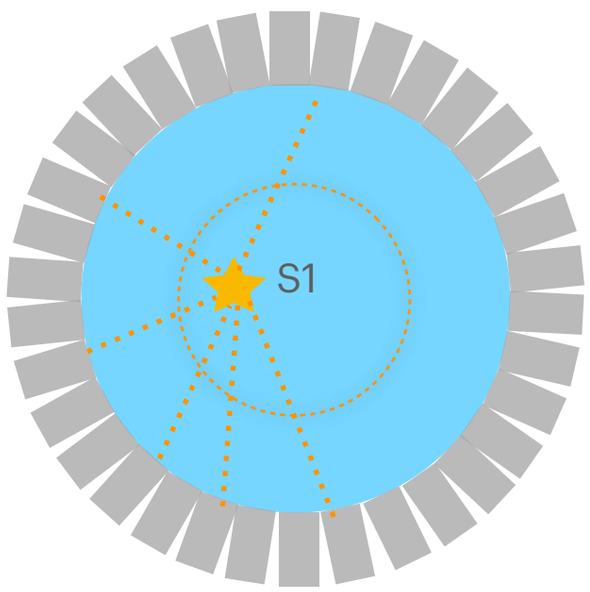


Electronic and nuclear recoils



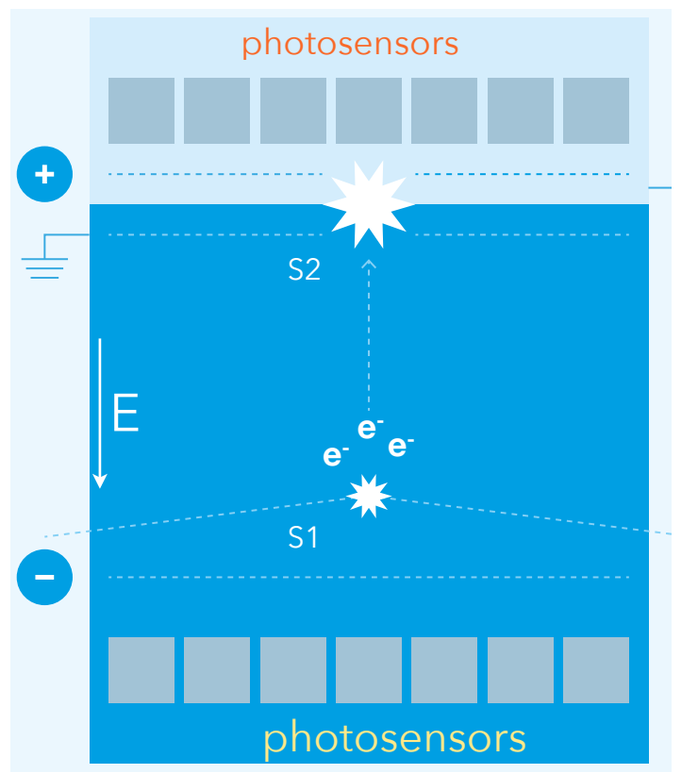
Detector Types

Single phase,
light readout



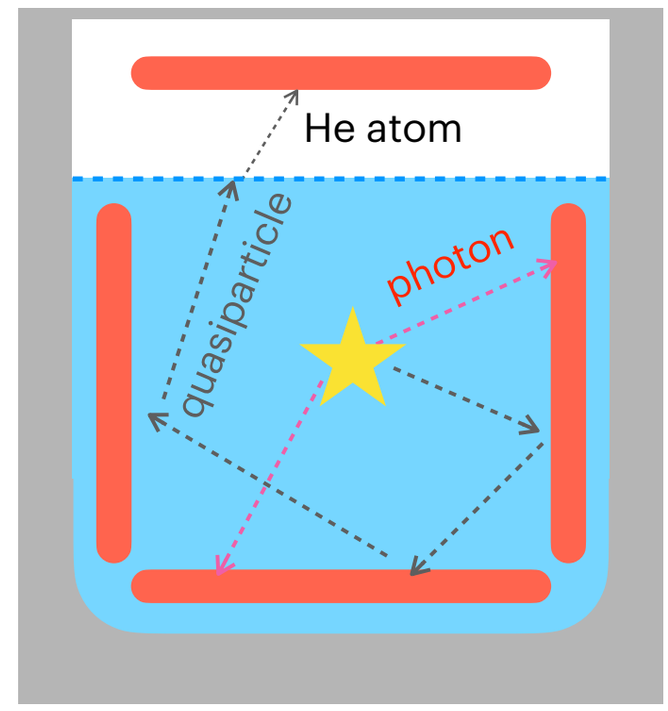
- High light yields, simple geometry, no E-fields
- Scintillation with PMTs
- LAr: DEAP-3600
- LXe: XMASS (until 2019)

Two-phase TPC
with light readout



- Light and charge with PMTs
- 3D position resolution, improved energy resolution, discrimination based on S2/S1
- LAr: DarkSide-50 (until 2019)
- LXe: LZ, PandaX-4T, XENONnT

Superfluid ^{4}He,
phonon readout

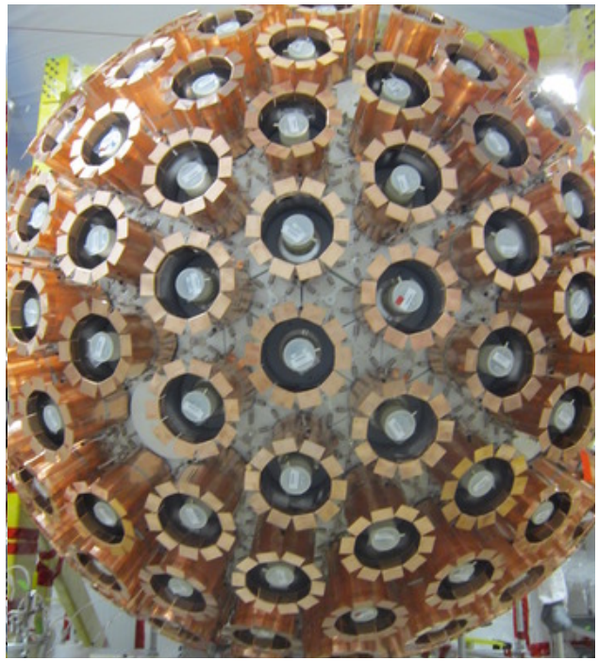


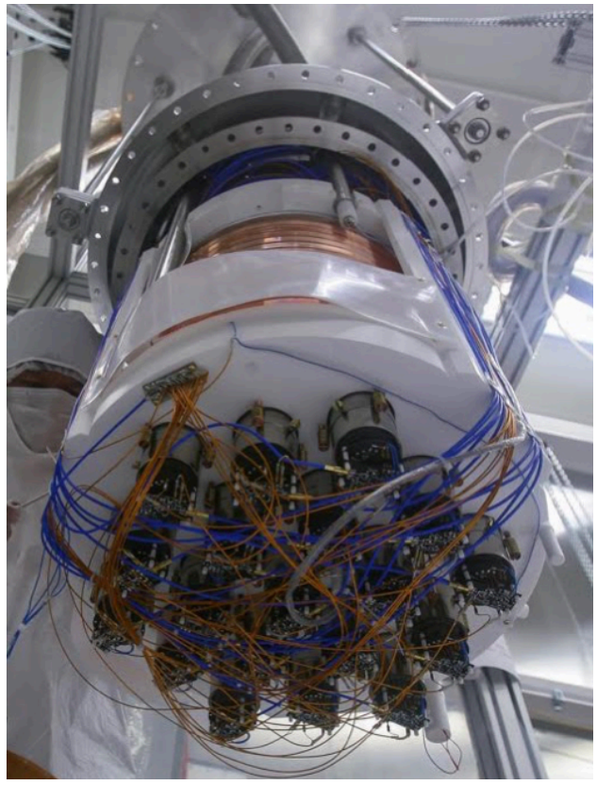
- R&D phase for light DM
- Signals: phonons and rotons; detect excitations down to ~ 1 meV (via ejection of ^{4}He atom), TES/MMC readout
- HeRALD, DELight, etc

Liquid Argon Detectors

- DEAP-3600 at SNOLAB: 3300kg LAr (1 t fiducial), 255 PMTs
  - Data taking since 2016
  - Detector upgrades in progress
- DarkSide-50 at LNGS: 50 kg LAr, depleted in ^{39}Ar (33 kg fiducial), 38 PMTs

  See talk by T. Hessel
  - Data taking: 2013-2019
  - New constraints on light DM: S2-only analysis (0.6 keV$_{nr}$ threshold $\equiv$ 4 e$^-$)





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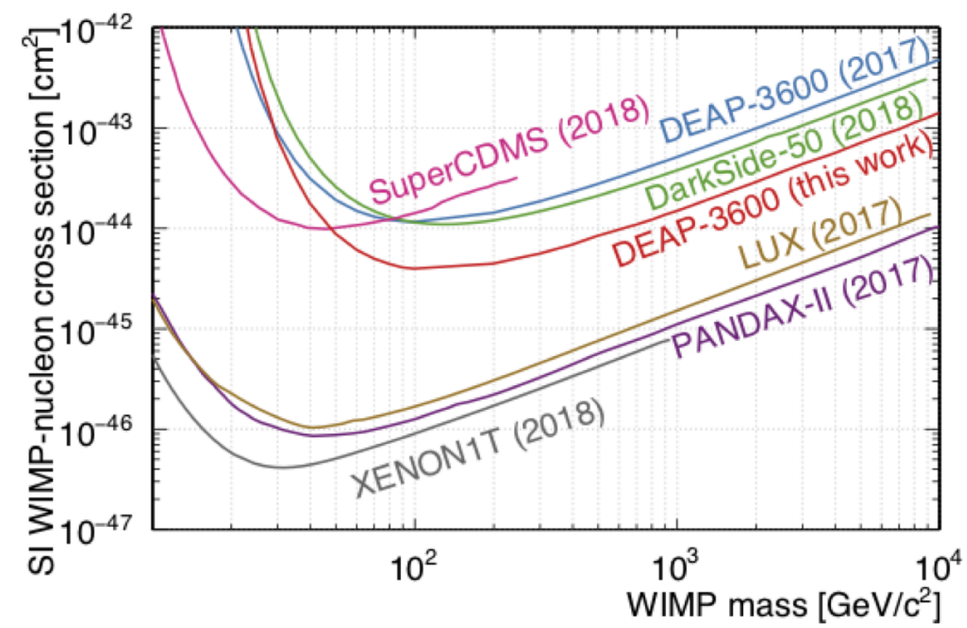
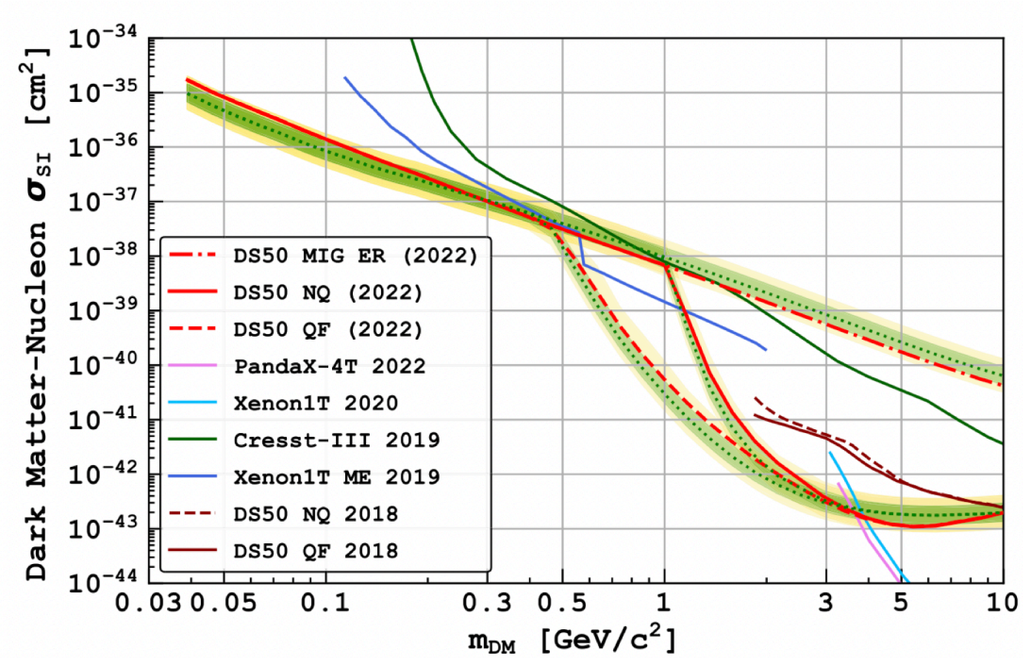
DEAP-3600, PRD 100



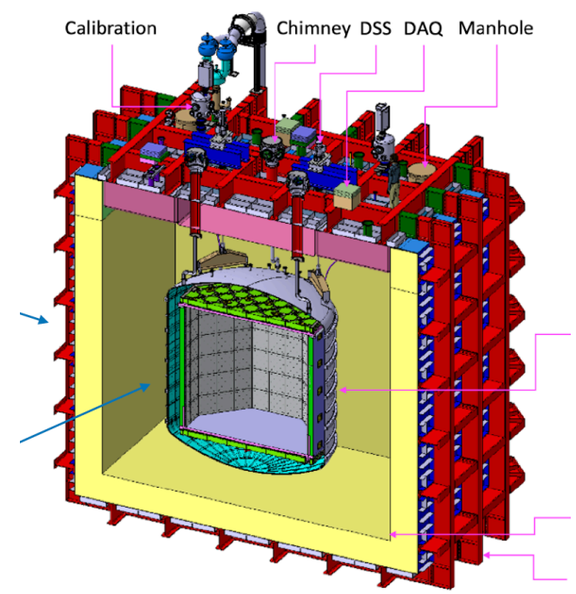


DarkSide-50, PRL 130 (2023) 10

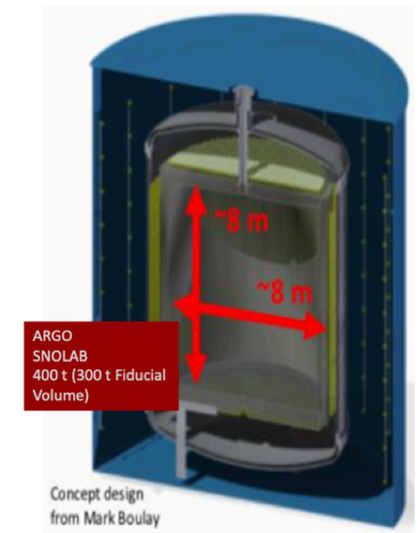
Future Liquid Argon Detectors

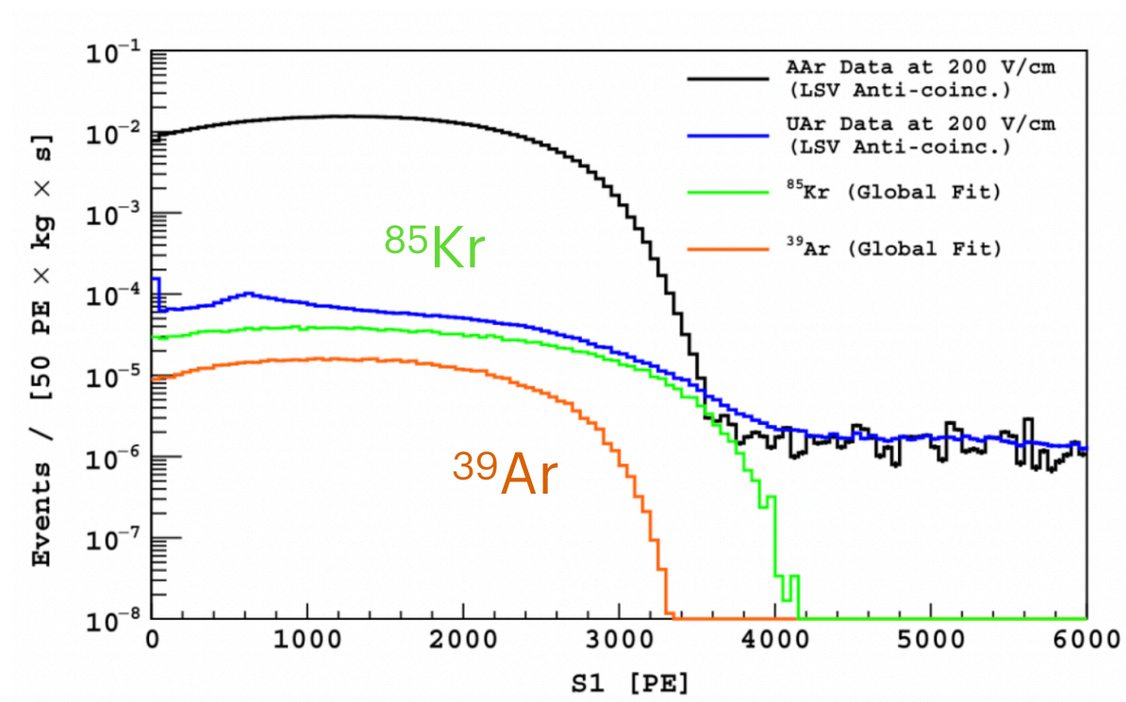
- Global Argon Dark Matter Collaboration See talk by T. Hessel
  - DarkSide-20k: 51.1 t underground LAr (20 t fiducial volume) in octagonal TPC with SiPM arrays
  - Cryostat currently under construction in Hall C at LNGS
  - First data expected in 2025
  - ARGO: 400 t LAr (300 t fiducial), likely at SNOLAB

DarkSide-20k



ARGO





Underground argon, DarkSide-50, PRD 93, 2016

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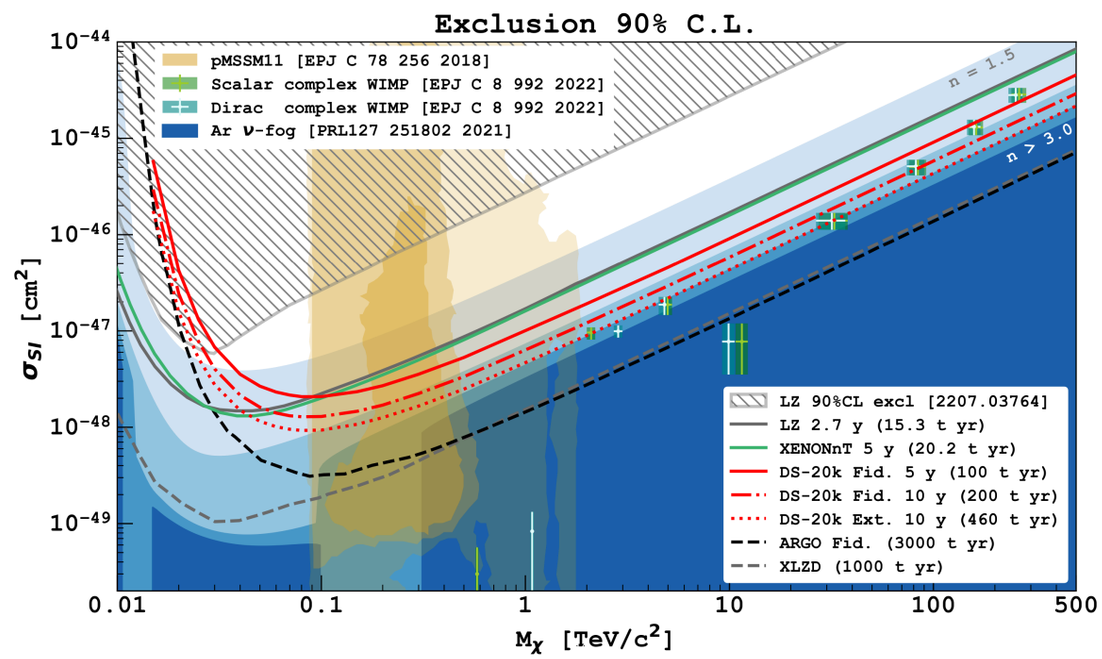
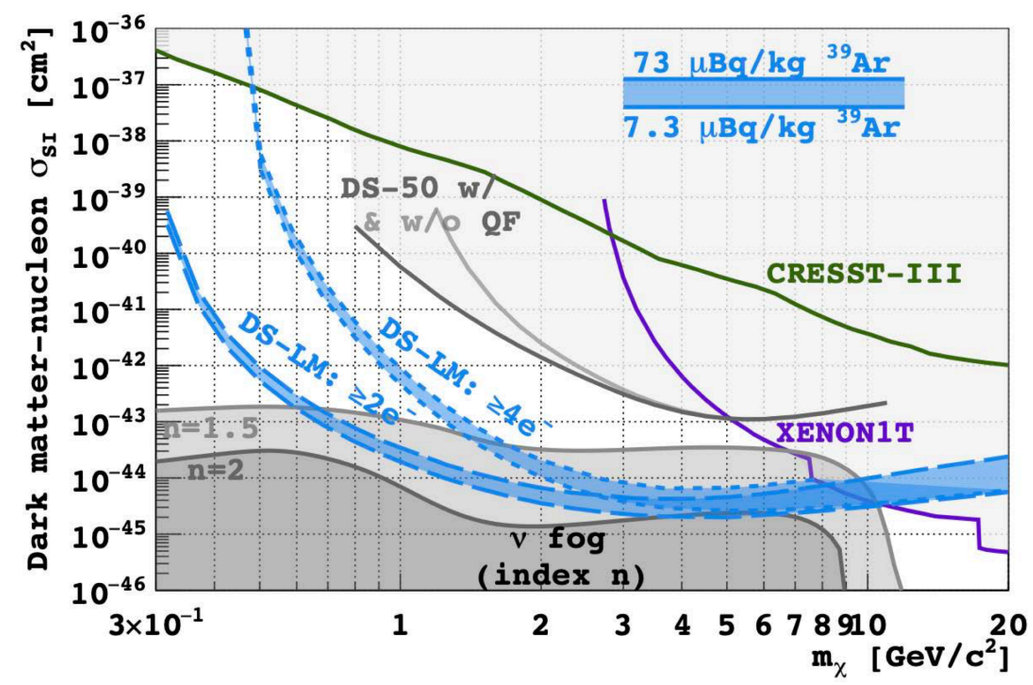




C. Galbiati, UCLA DM 2023

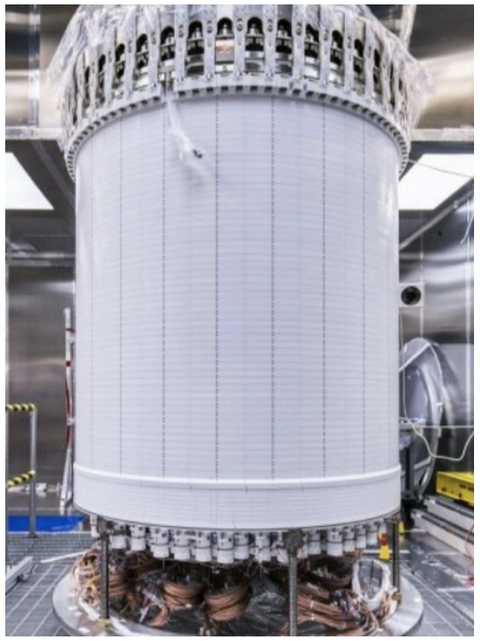
Liquid xenon detectors

See talk by P. Brás

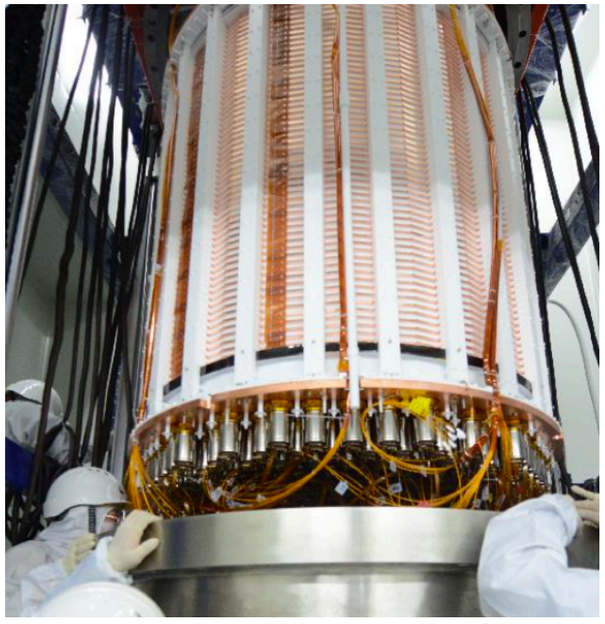
See talk by A. Elykov

- LZ at SURF, PandaX-4T at JinPing, XENONnT at LNGS
- Detector scales: 10 t (LZ), 6 t (PandaX-4T) and 8.6 t LXe (XENONnT) in total xenon mass
  - TPCs with 2 arrays of 3-inch PMTs
  - Kr and Rn removal techniques
  - Ultra-pure water shields, n & μ vetos
  - External and internal calibration sources
- Status: PandaX-4T first result in 2021 from commissioning run, LZ first results from run in 2022, XENONnT first results from SR0 in 2021/22

LUX-ZEPLIN



XENONnT



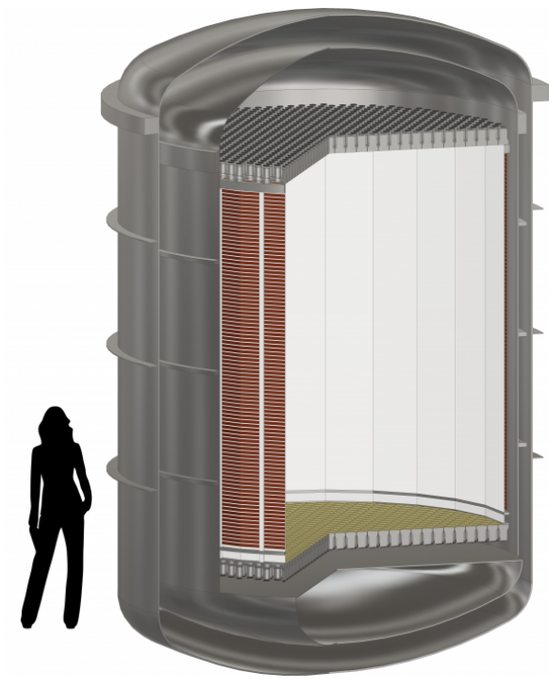
See talk by Y. Tao

PandaX-4T

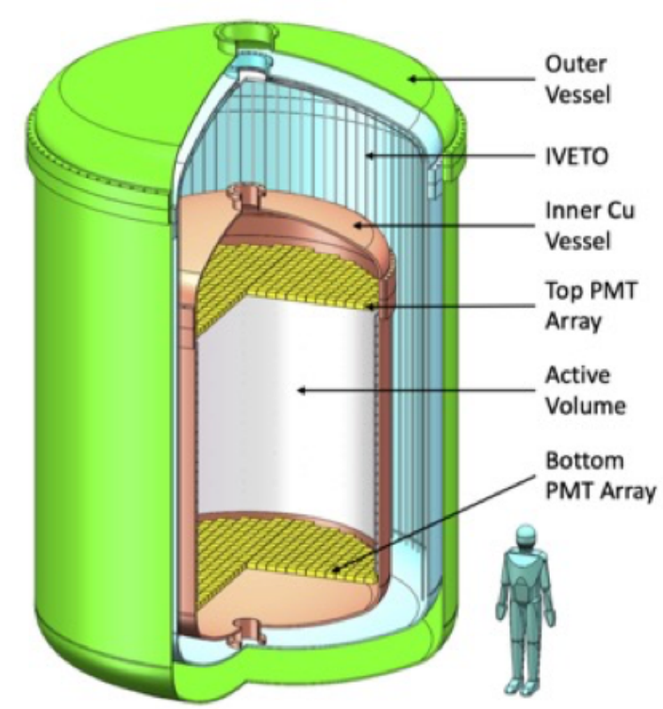
Future Liquid Xenon Detectors

- DARWIN/XLZD See talk by R. Budnik
  - DARWIN: 50 t LXe (40 t active target) at LNGS; ~1900 3-inch PMTs (baseline design); Gd-doped water n and μ vetoes
  - R&D and prototyping in progress
  - XLZD: 75 t LXe (60 t active target), several labs are considered See talk by A. Lindote
- PandaX-xT: > 30 t active volume at JinPing; 2 arrays of 2-inch PMTs

See talk by Y. Tao



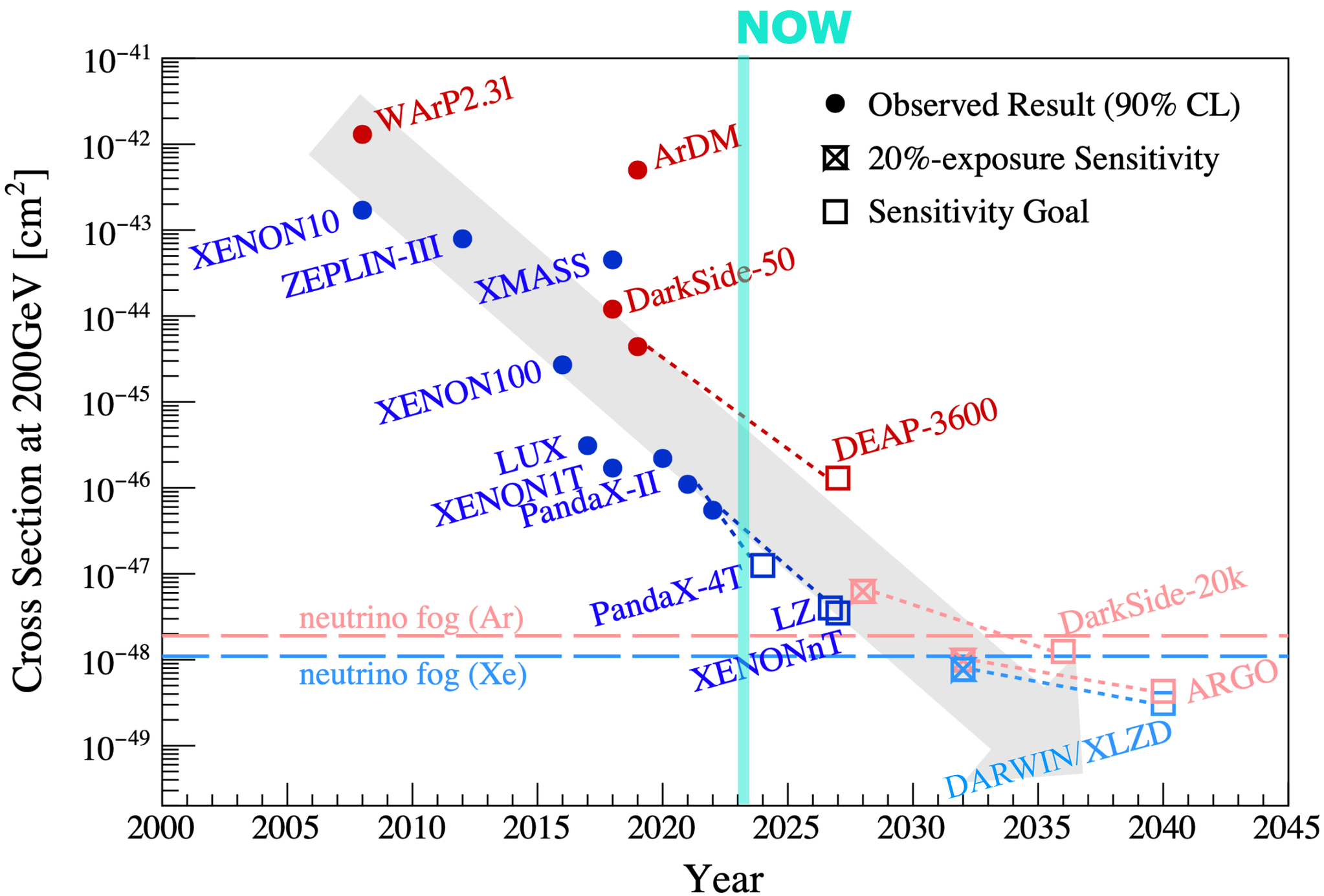
DARWIN collaboration
JCAP 1611 (2016) 017



The XLZD Consortium

- Merger of DARWIN/XENON and LUX-ZEPLIN collaborations to build and operate next-generation liquid xenon detector
  - new, stronger international collaboration with demonstrated experience in xenon time projection chambers
- Paving the way now
  - First joint, successful DARWIN/XENON & LZ workshop, April 26-27 2021 https://indico.cern.ch/event/1028794/
  - MoU signed July 6, 2021 by 104 research group leaders from 16 countries
  - Summer meeting at KIT June 2022; spring meeting at UCLA April 2023; several working groups in place to study science, detector, Xe procurement, R&D etc
  - XLZD consortium (xlzd.org) to design and build a common multi-ton xenon experiment

DM cross section versus time

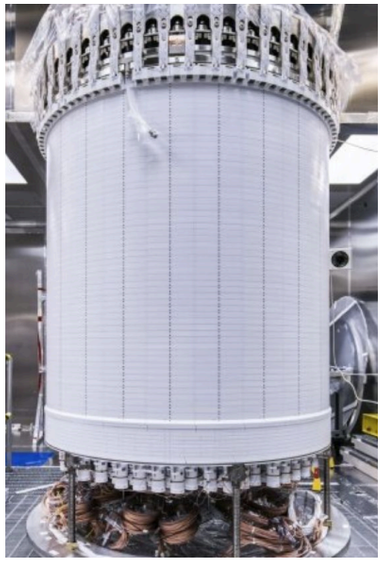


Snowmass, Topical Group on Particle Dark Matter Report, arXiv: 2209.07426

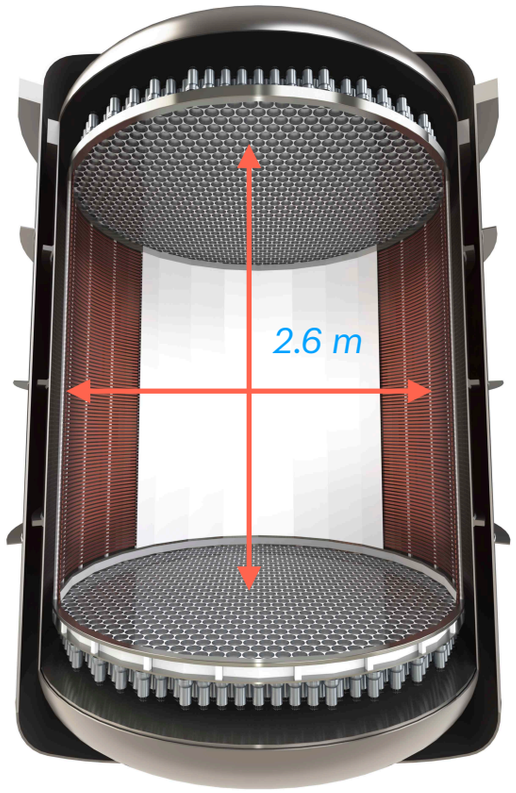
Size matters

- LUX-ZEPLIN and XENONnT: 1.5 m e^- drift and ~ 1.5 m diameter electrodes
- **DARWIN/XLZD: 2.6 - 3.0 m ⇒ new challenges**
  - Design of electrodes: robustness (minimal sagging/ deflection), maximal transparency, reduced e^- emission
  - Electric field: ensure spatial and temporal homogeneity, avoid charge-up of PTFE reflectors
  - High-voltage supply to cathode design, avoid high-field regions
  - Liquid level control
  - Cryogenic purification (^{222}Rn and ^{85}Kr below solar pp neutrino level) See talk by C. Weinheimer
- Electron survival in LXe: > 10 ms lifetime
- Diffusion of the e^--cloud: size of S2-signals

LUX-ZEPLIN



XENONnT



Large-scale demonstrators

European Research Council
Established by the European Commission

- Full scale demonstrators in *z* and in *x-y*, supported by ERC grants
  - *Xenoscope*, 2.6 m tall TPC and *Pancake*, 2.6 m ø TPC in double-walled cryostats
  - Both facilities available to the collaboration/consortium for R&D purposes
  - LowRad to demonstrate large-scale cryogenic distillation at Münster

Vertical demonstrator: *Xenoscope*

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

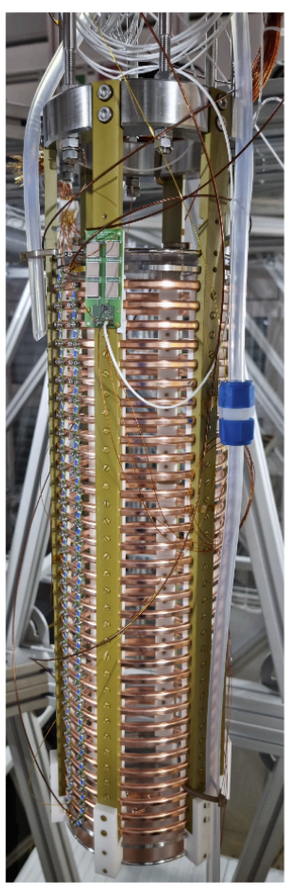
Horizontal demonstrator: *Pancake*

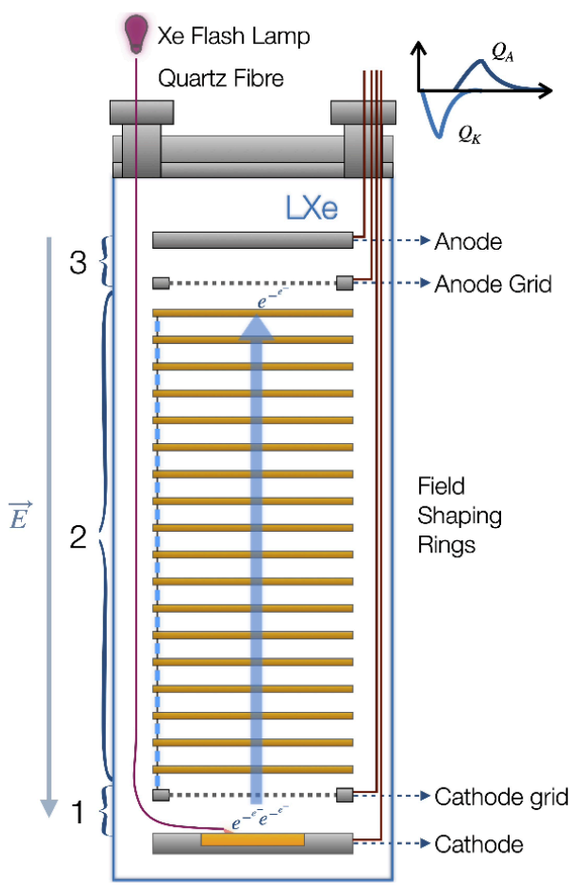
See talk by J. Müller

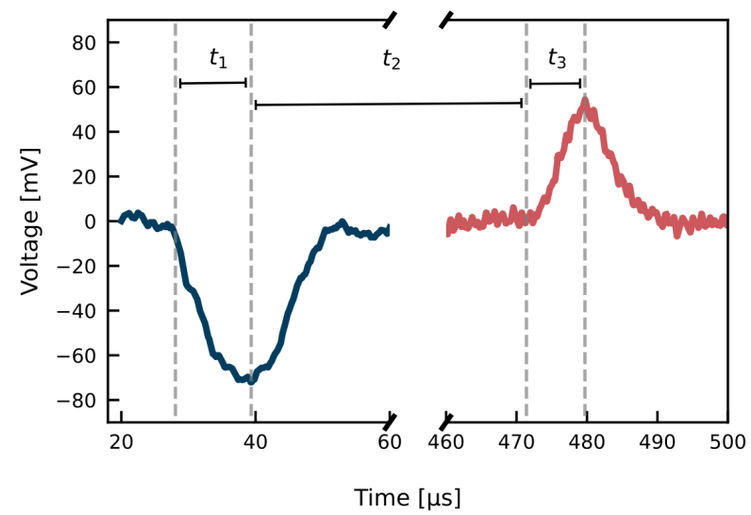
Test electrodes with 2.6 m Ø

Xenoscope first results & status

- Xe purity monitor (53 cm tall) with charge readout
- Run: 88 d with 343 kg LXe, three different Xe flow regimes

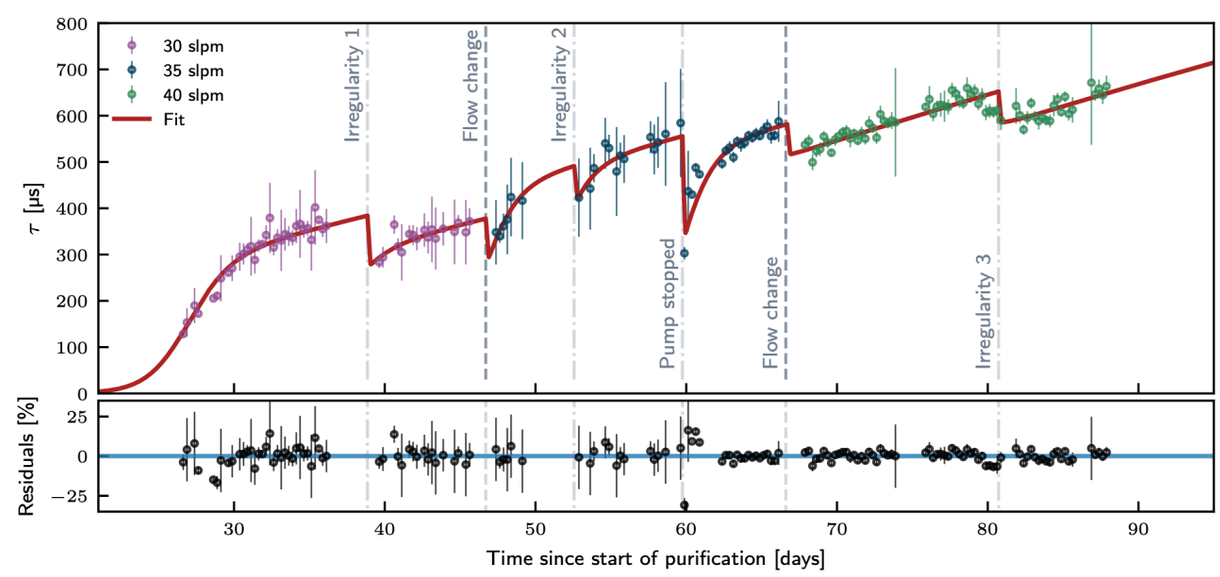






$$\frac{Q_A}{Q_C} = e^{-t_d/\tau_e}$$

$$\frac{Q_A}{Q_C} = \frac{t_1}{t_3} e^{-(t_1+t_2+t_3)/\tau} \frac{(e^{t_3/\tau}-1)}{(e^{-t_1/\tau}-1)}$$

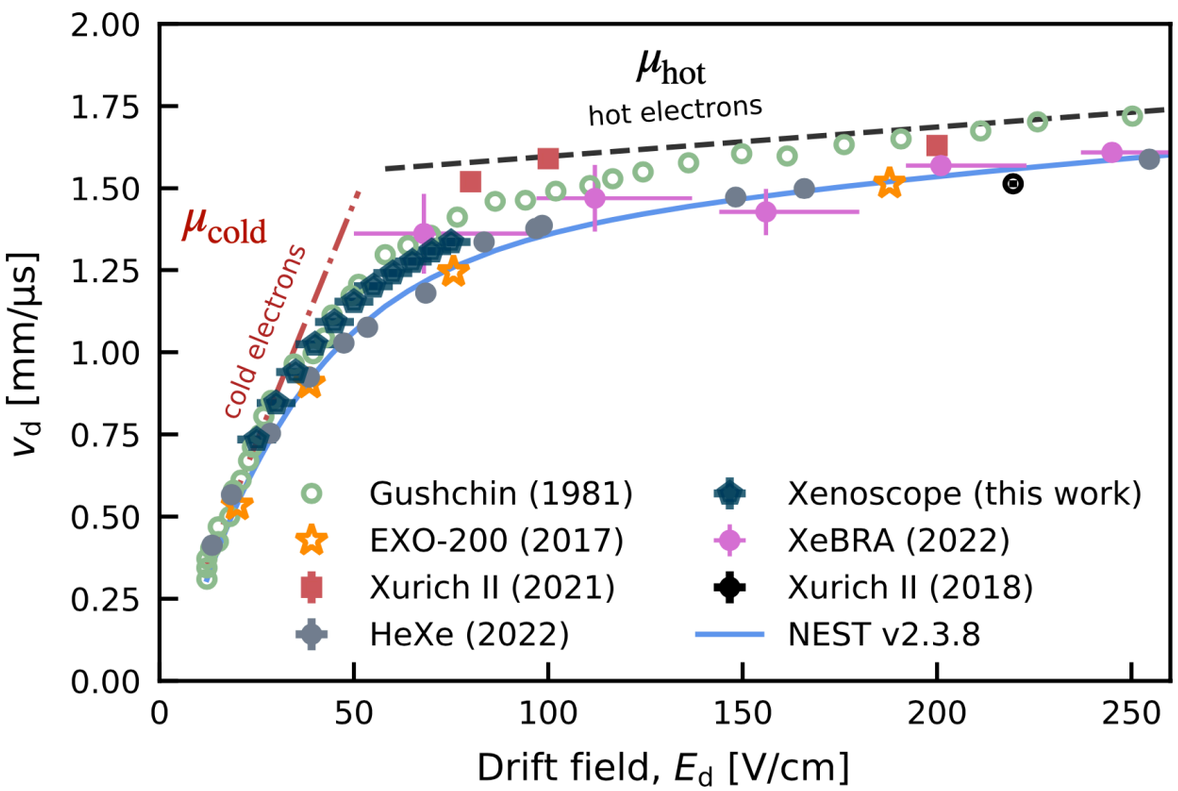


L. Baudis et al., arXiv:2303.13963

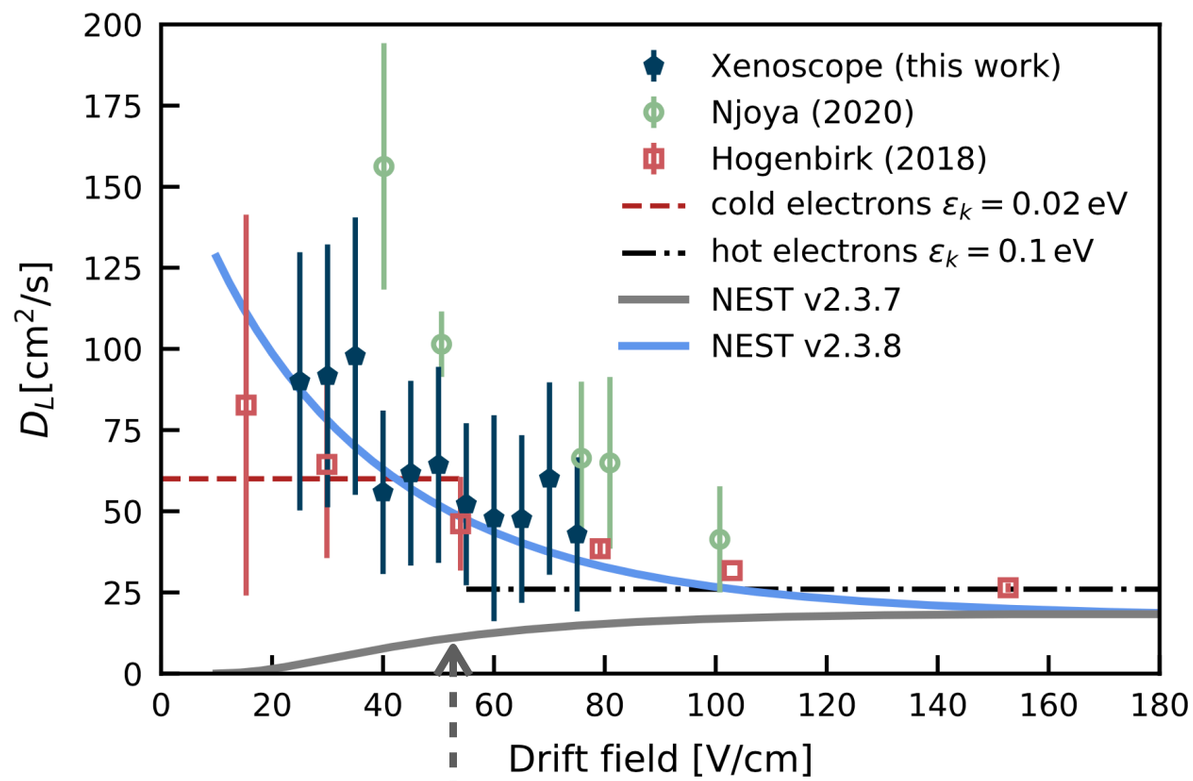
Xenoscope first results & status

- Measured drift velocity and longitudinal diffusion at drift fields from 25 - 75 V/cm

Electron drift velocity at τ_e ~ 650 μs



Longitudinal diffusion of e- cloud

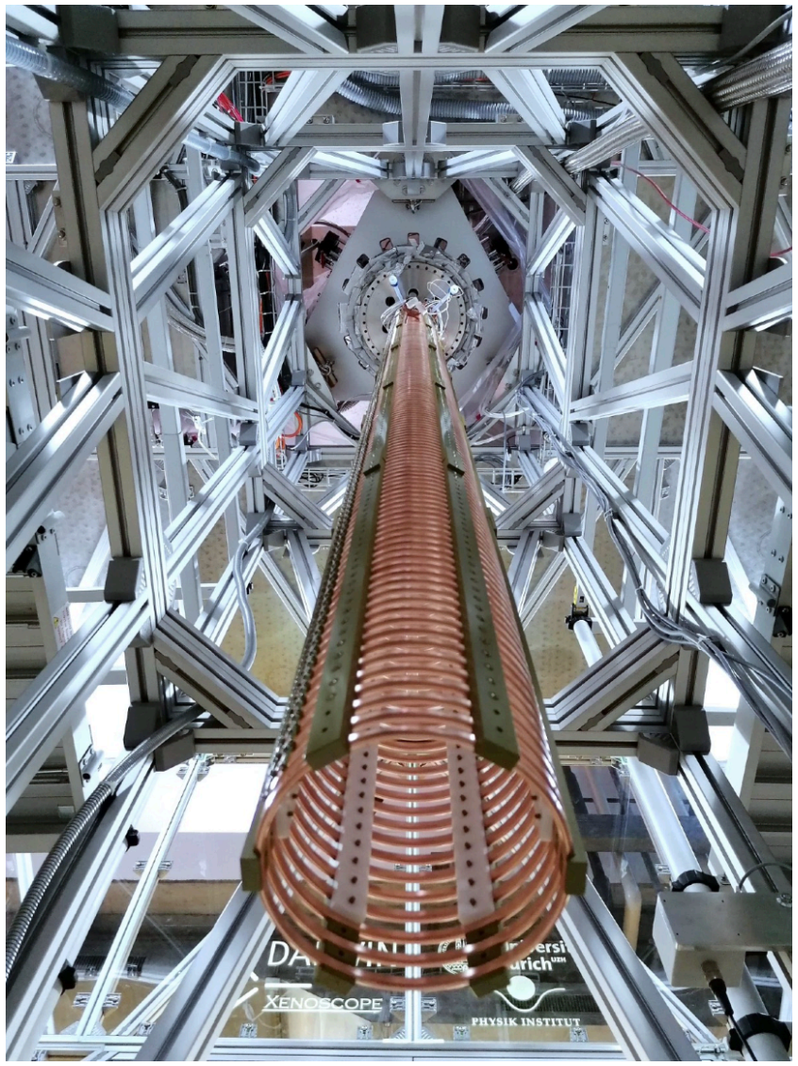


L. Baudis et al., arXiv:2303.13963

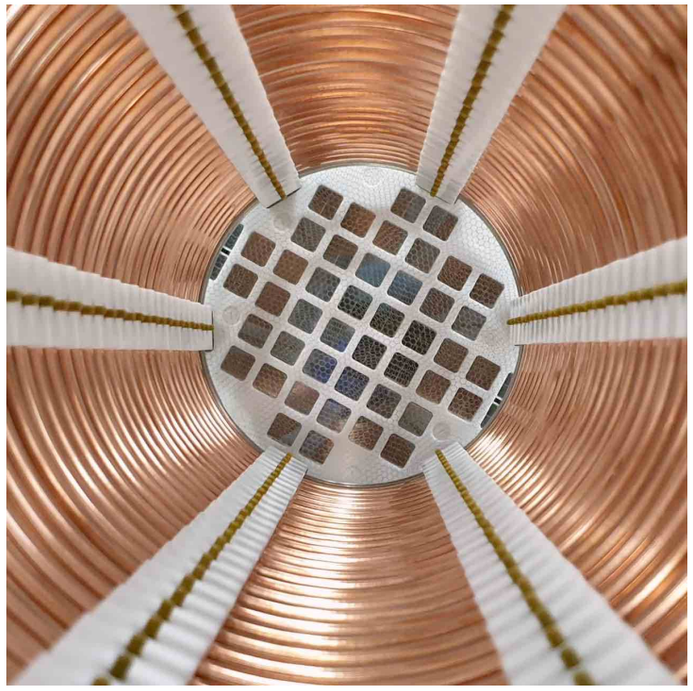
NEST prediction before our data

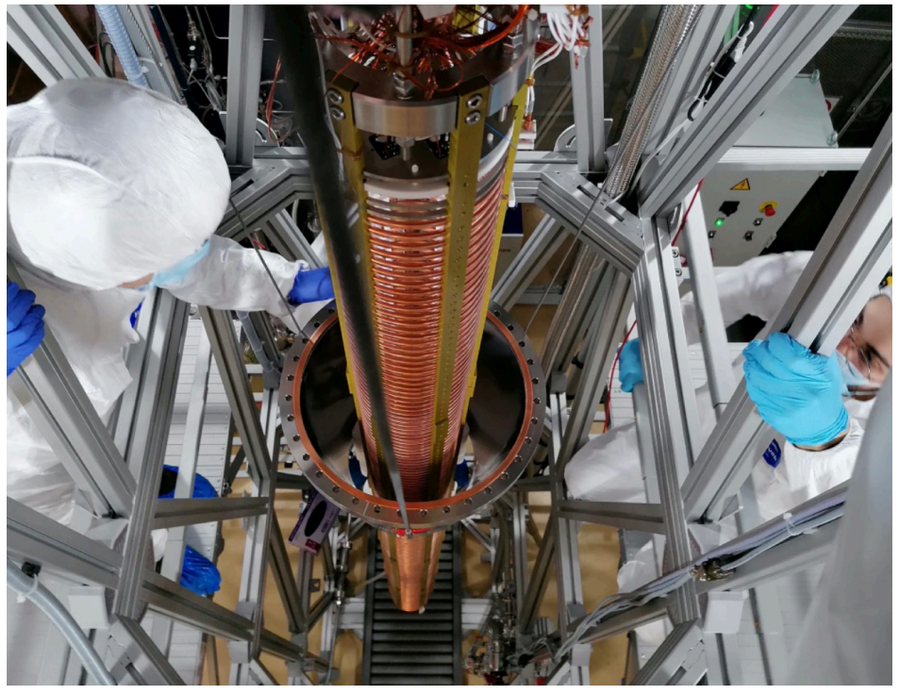
Xenoscope first results & status

- Full-scale (2.6 m tall) TPC assembled and installed
- Top SiPM array with 48 VUV4 Hamamatsu MPPCs (arranged in 12 tiles) with LED + fibres calibration system; tested in vacuum (and previously at low-T)
- Added also: long & short level meters, weir, HV system
- Ready to start first xenon run in June 2023



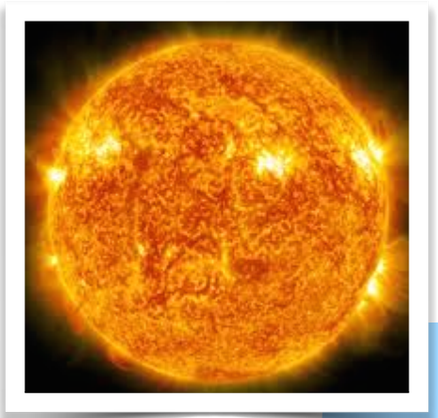
2.6 m tall TPC during installation: Cu rings, torlon pillars



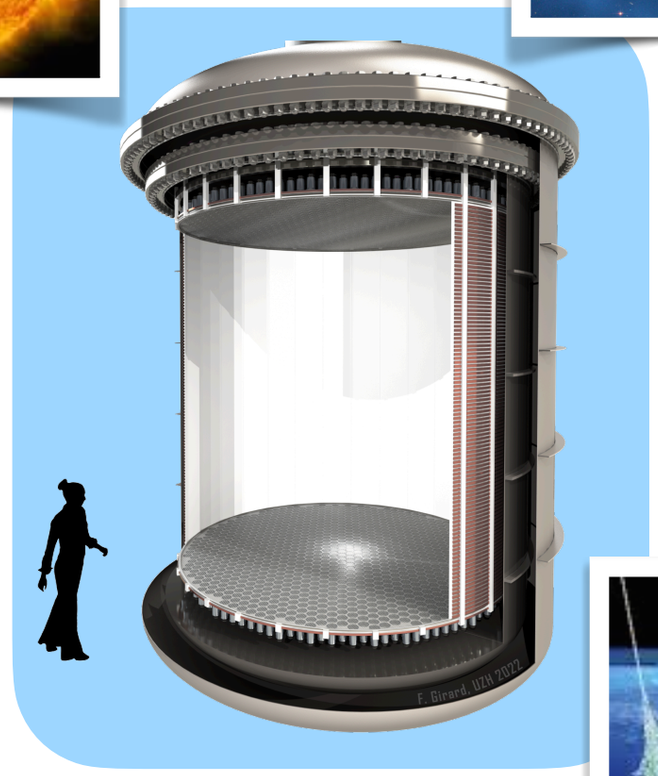


Future detectors: multipurpose observatories for rare events

Solar neutrinos (pp + ^{8}B)



Dark matter



Neutrino nature

Supernova neutrinos

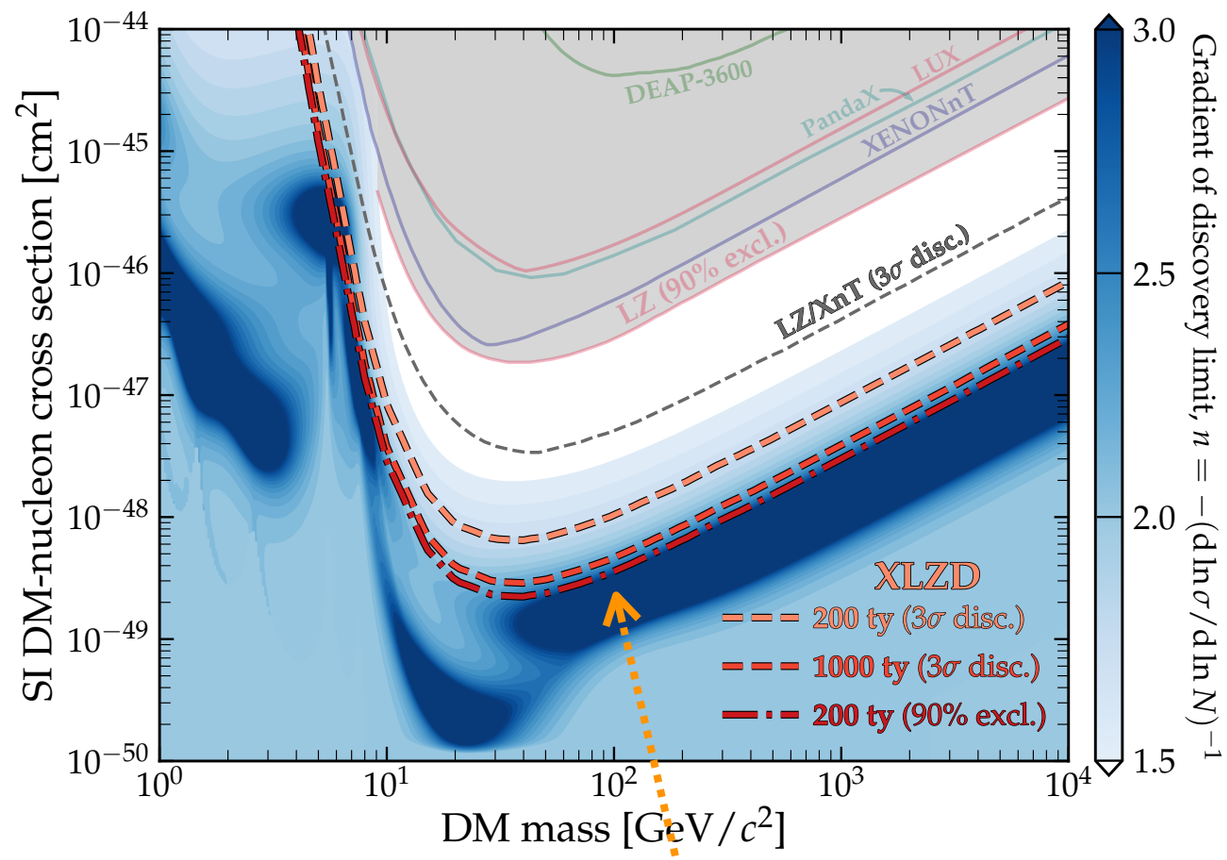
Atmospheric neutrinos

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

Definitive search for medium to high-mass WIMPs

- Larger LXe mass with XLZD
  - reaches sooner the systematic limit of the neutrino fog (~ 1000 tonnes × years exposure)
  - allows for 3-σ discovery at SI cross section of 3 × 10^{-49} cm^2 at 40 GeV mass
- Detector design: combine best of LZ and XENONnT

Figure by Ciaran O'Hare



Systematic limit imposed by CEvES from atmospheric neutrinos

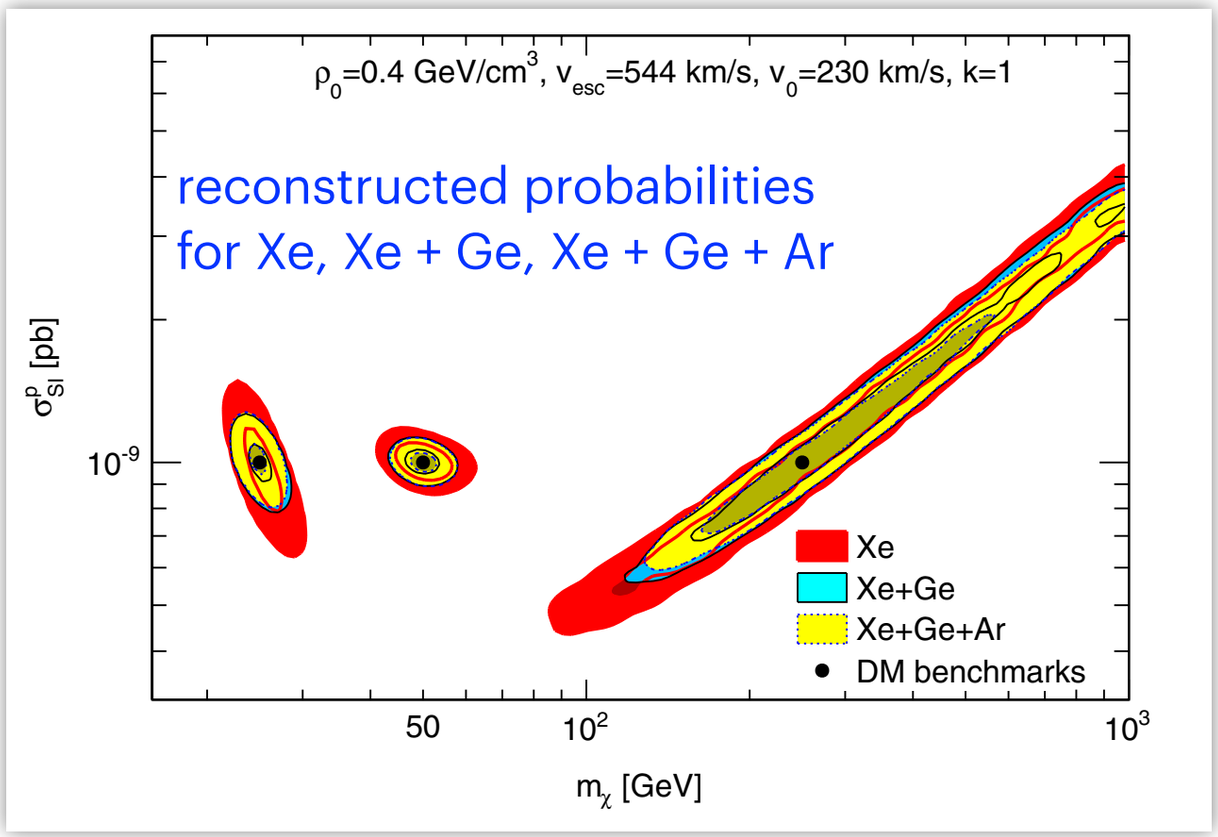
At contour n: obtaining a 10 times lower cross section sensitivity requires an increase in exposure of at least 10^n

Ar and Xe DM complementarity

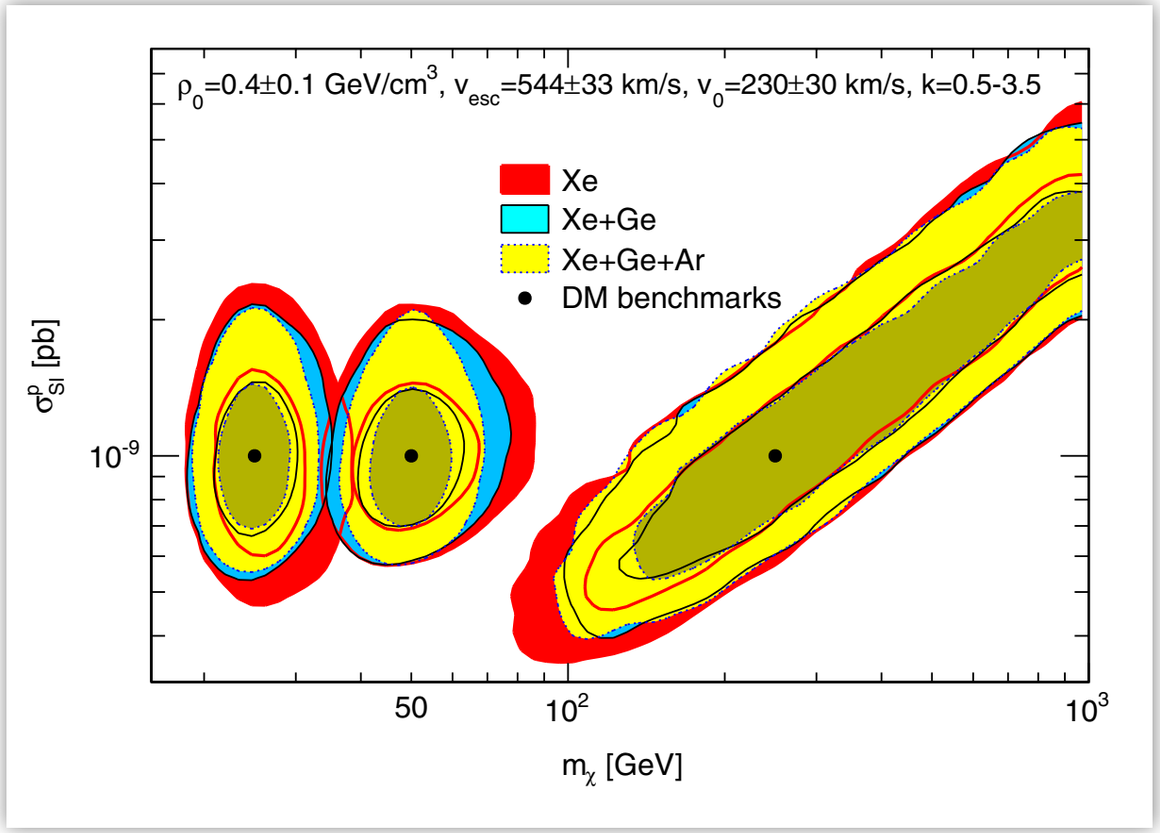
- Different DM targets are sensitive to different directions in the m_χ- σ_{SI} plane

Xe: 2.0 t x yr, E_{th} =10 keV_{nr}
Ge: 2.2 t x yr, E_{th} =10 keV_{nr}
Ar: 6.4 t x yr, E_{th} = 30 keV_{nr}

fixed galactic model



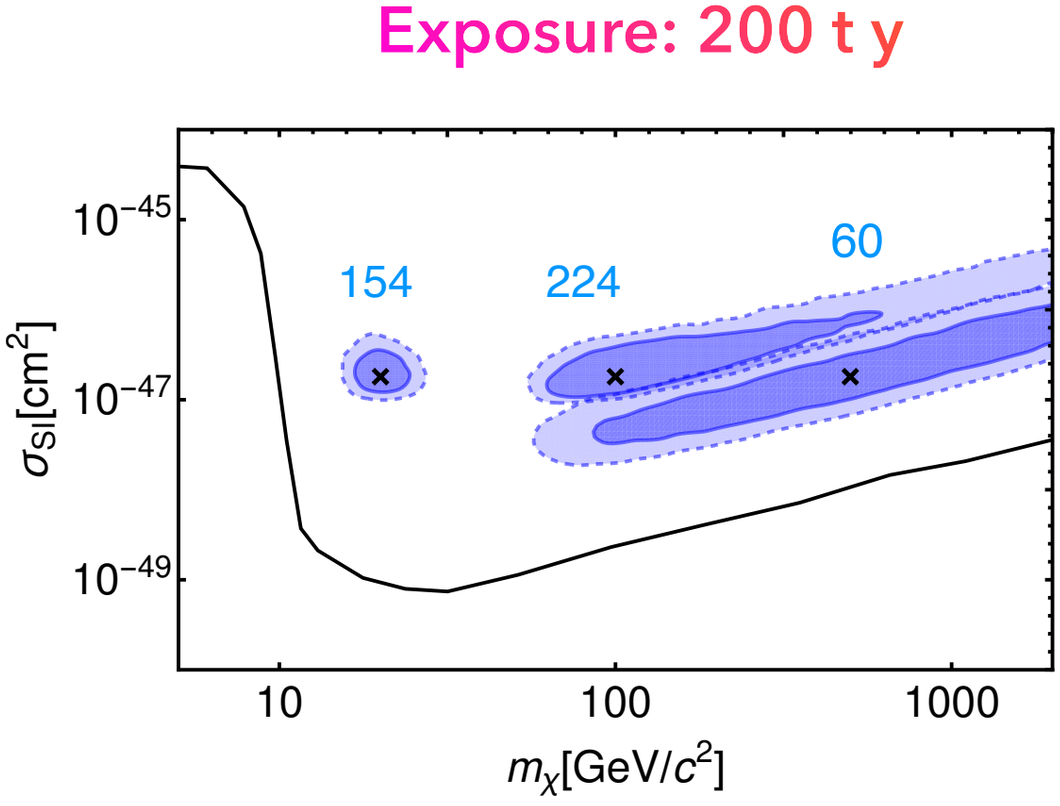
including galactic uncertainties

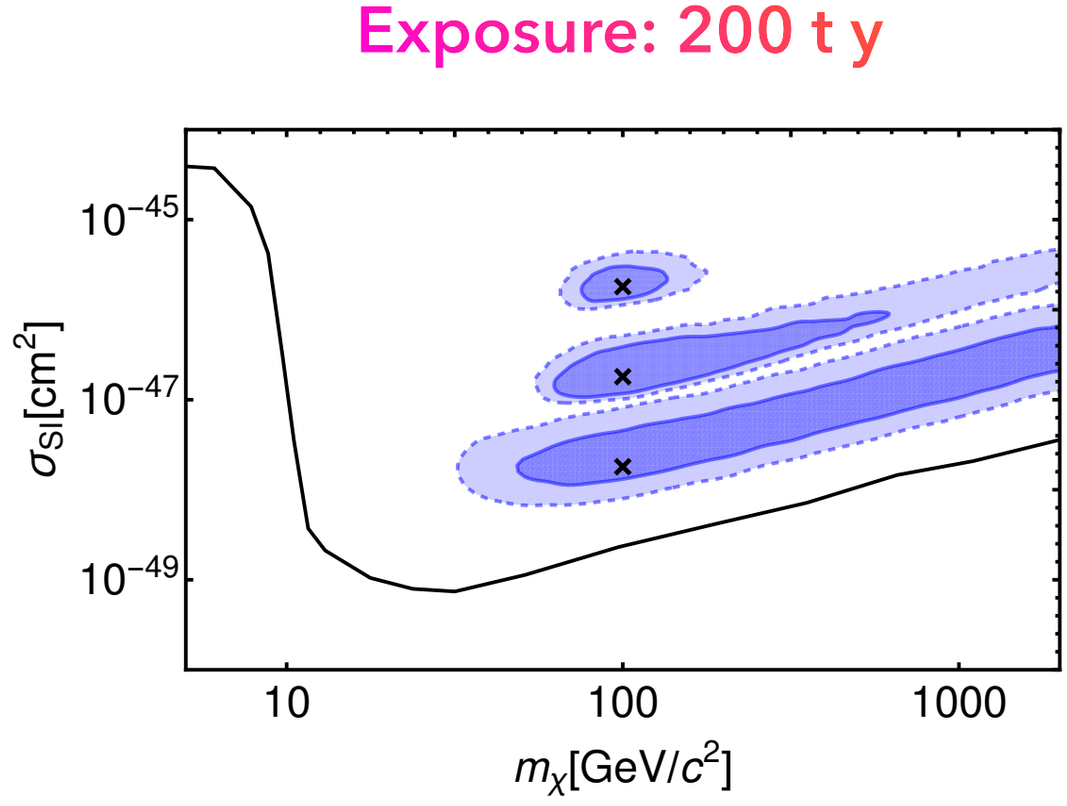


Pato, Baudis, Bertone, Ruiz de Austri, Strigari, Trotta: Phys. Rev. D 83, **2011**

WIMP spectroscopy

- Capability (in LXe) to reconstruct the WIMP mass and cross section for various masses - here 20, 100, 500 GeV/c^2 - and cross sections





Newstead et al., PRD D 88, 076011 (2013)

1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

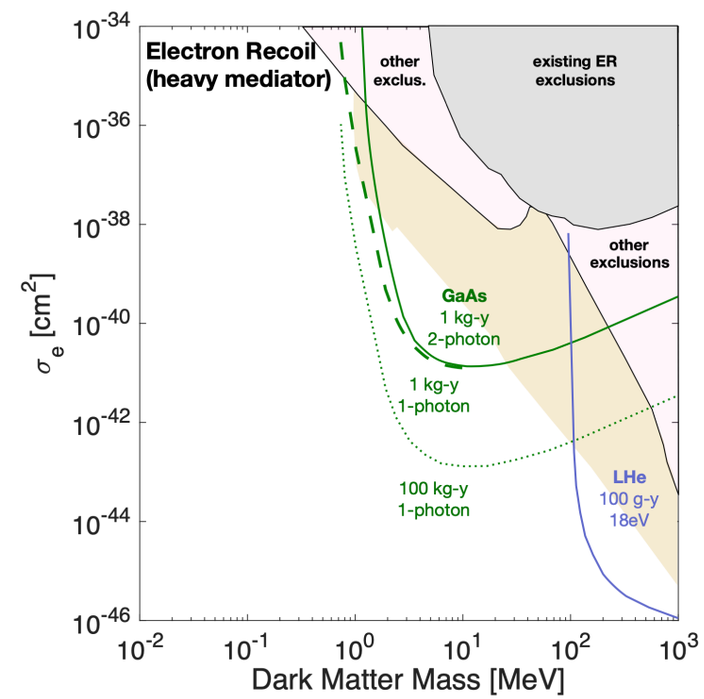
$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

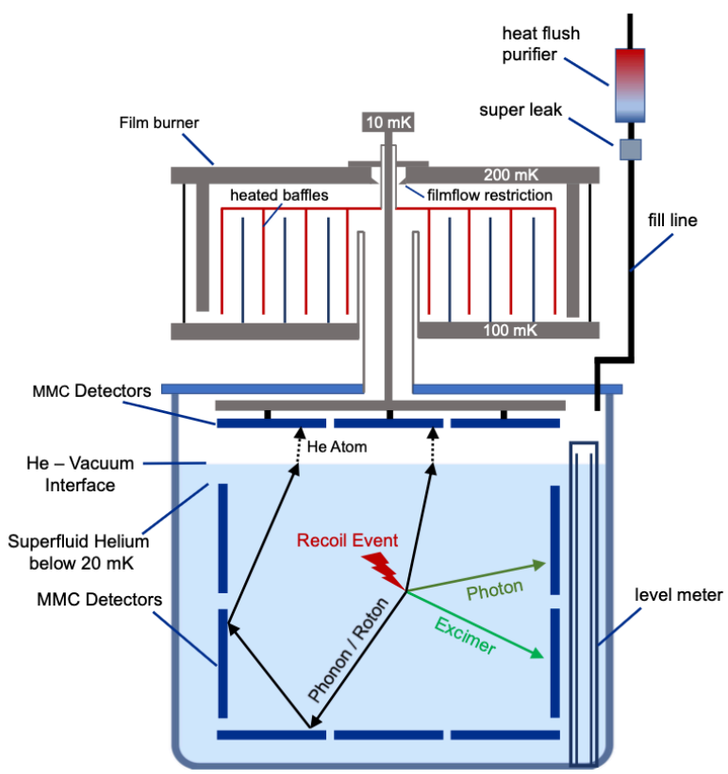
$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

Superfluid He detectors

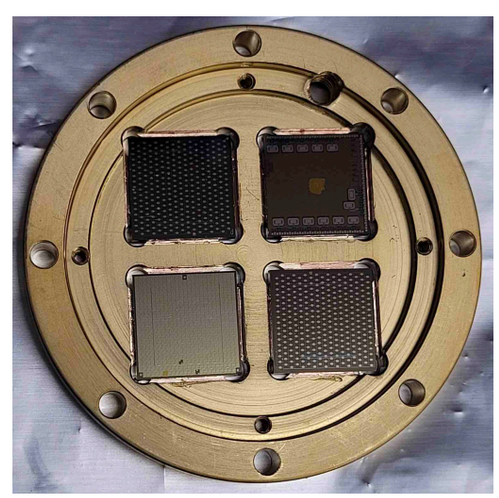
- Calorimeters with TES or MMC readout, operated at ~ 20-50 mK
- TES/MMC in liquid: UV photons, triplet molecules and IR photons
- TES/MMC in vacuum: detect in addition ^{4}He atoms evaporated by quasiparticles



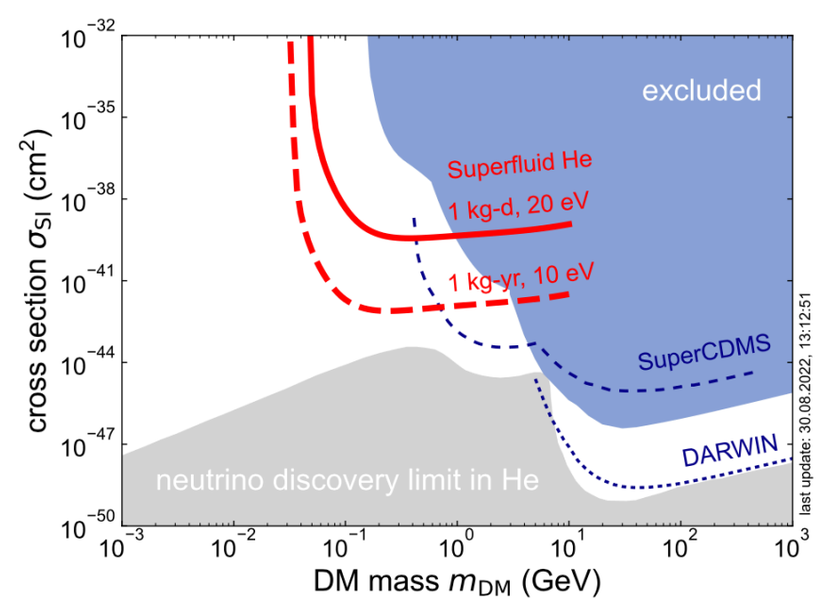


DELight: arXiv:2209.10950

HeRALD: Si pixel arrays at LBL
Under assembly, 11 g active ^{4}He



HeRALD: PRD 100, 2019



Summary and Outlook

- The nature of dark matter in our universe remains an enigma
- In the worldwide race to directly detect dark matter particles, liquid noble detectors remain at the forefront
- LAr, LXe: highest sensitivity for medium-heavy WIMPs; superfluid He: light DM (< 100 MeV) sensitivity
- In general, to probe the experimentally accessible parameter space until the neutrino fog, larger detector masses with lower backgrounds are needed
- Current generation of detectors presented first results, and they continue to take data
- Next-generation LAr detector (DarkSide-20k) under construction; R&D and design of next-generation LXe detector (DARWIN/XLZD) is ongoing; superfluid ^{4}He detectors in developments
- Eventually, direct detection experiments will limited by neutrino interactions *(but also new physics opportunities & be prepared for surprises!)*

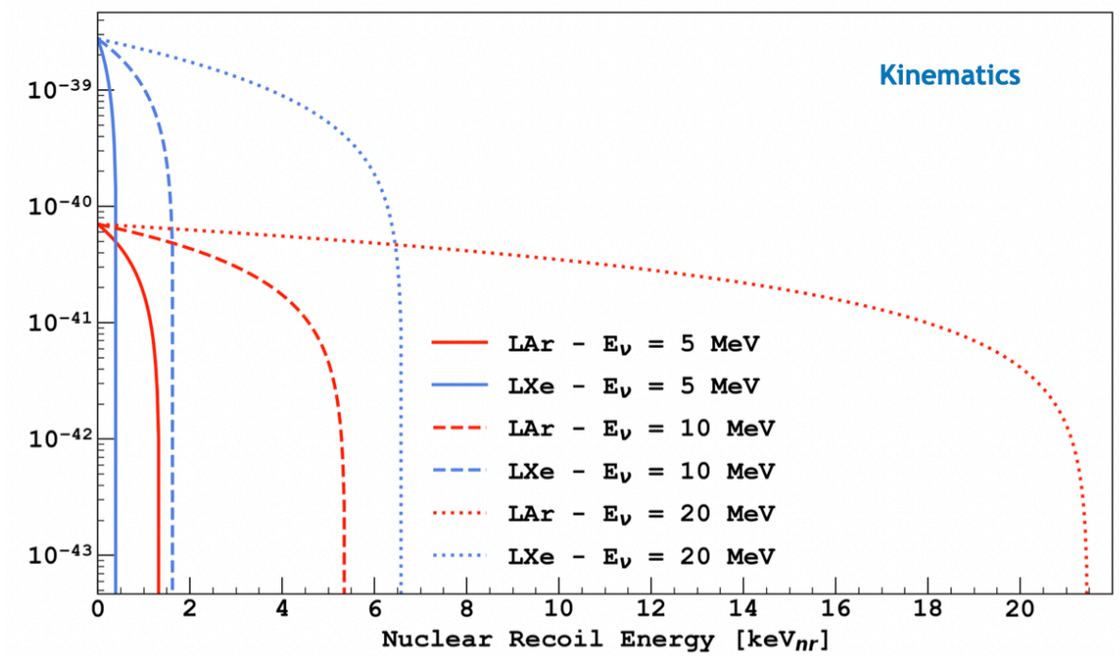
The end

Backup slides

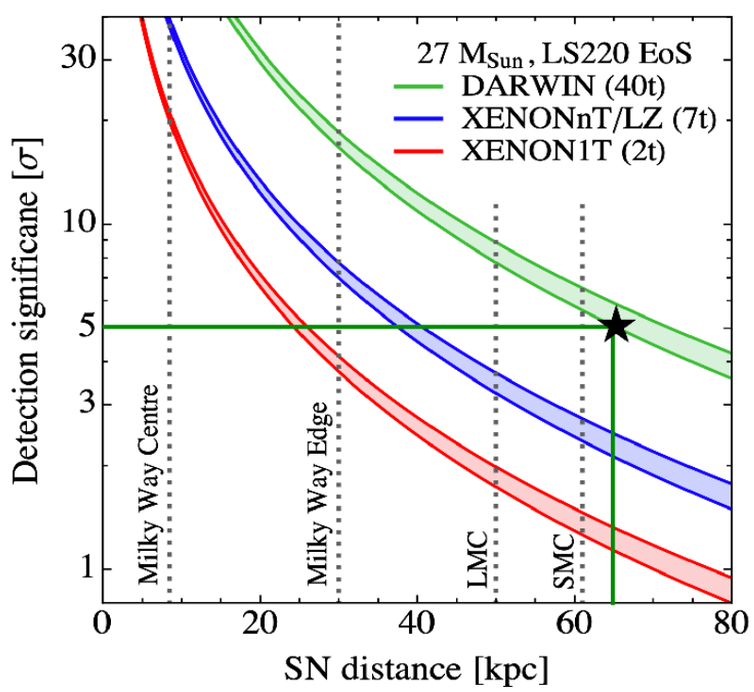
Example: Core-collapse SN via CEvNS

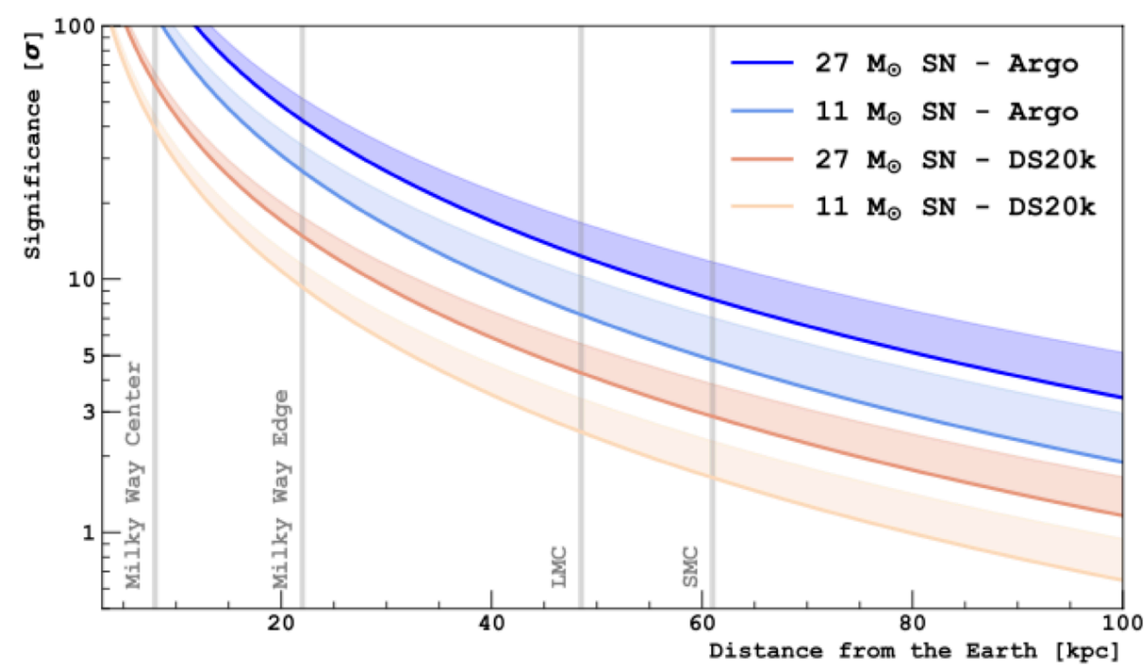
JCAP 03 (2021) 043)

- SN with $27\,M_\odot$ at 10 kpc
  - 27 events/t in LXe
  - 7 events/t in LAr

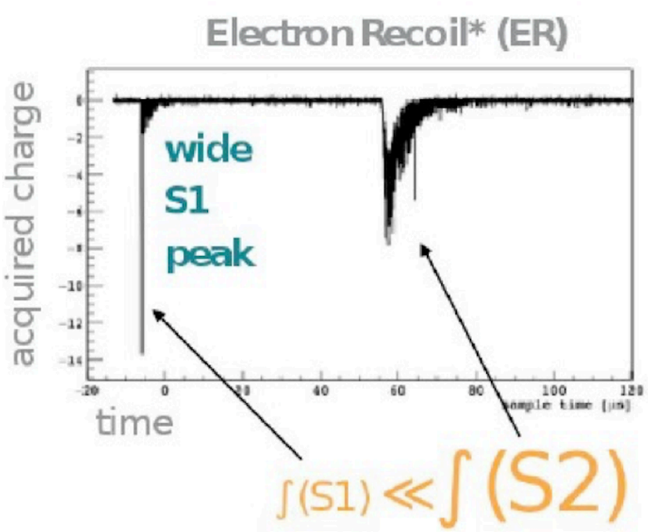


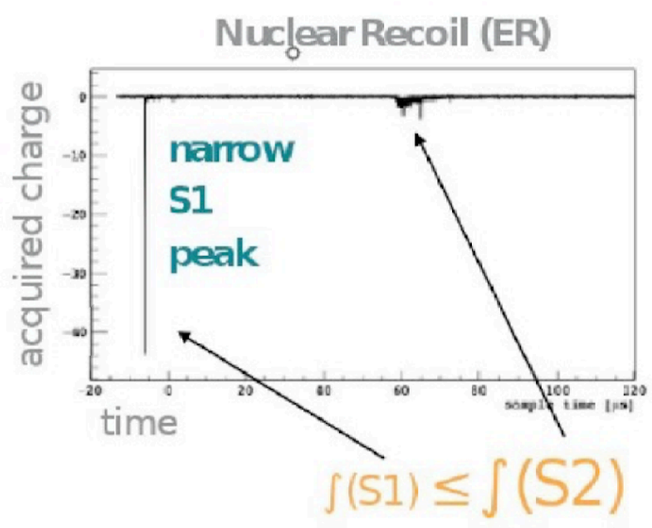
R. Lang et al., PRD 94, 103009



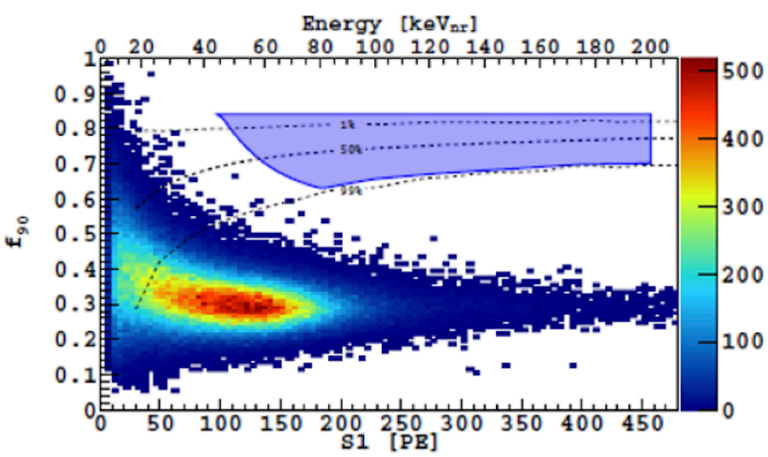


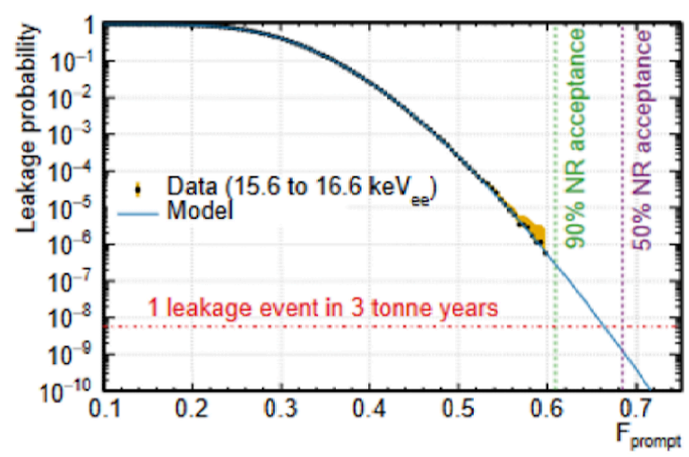
Discrimination in LAr TPCs





- NRs: predominantly excite the singlet state of LAr, with larger relative amplitudes compared to ERs
- ERs: the low density of e-ion pairs results in less recombination, thus more free electrons, compared with NRs of the same S1
- f_{90}: defined as the integral over the S1 pulse in the first 90 ns over the pulse in 7 μs
- typically f_{90} is 0.7 for NRs and 0.3 for ERs





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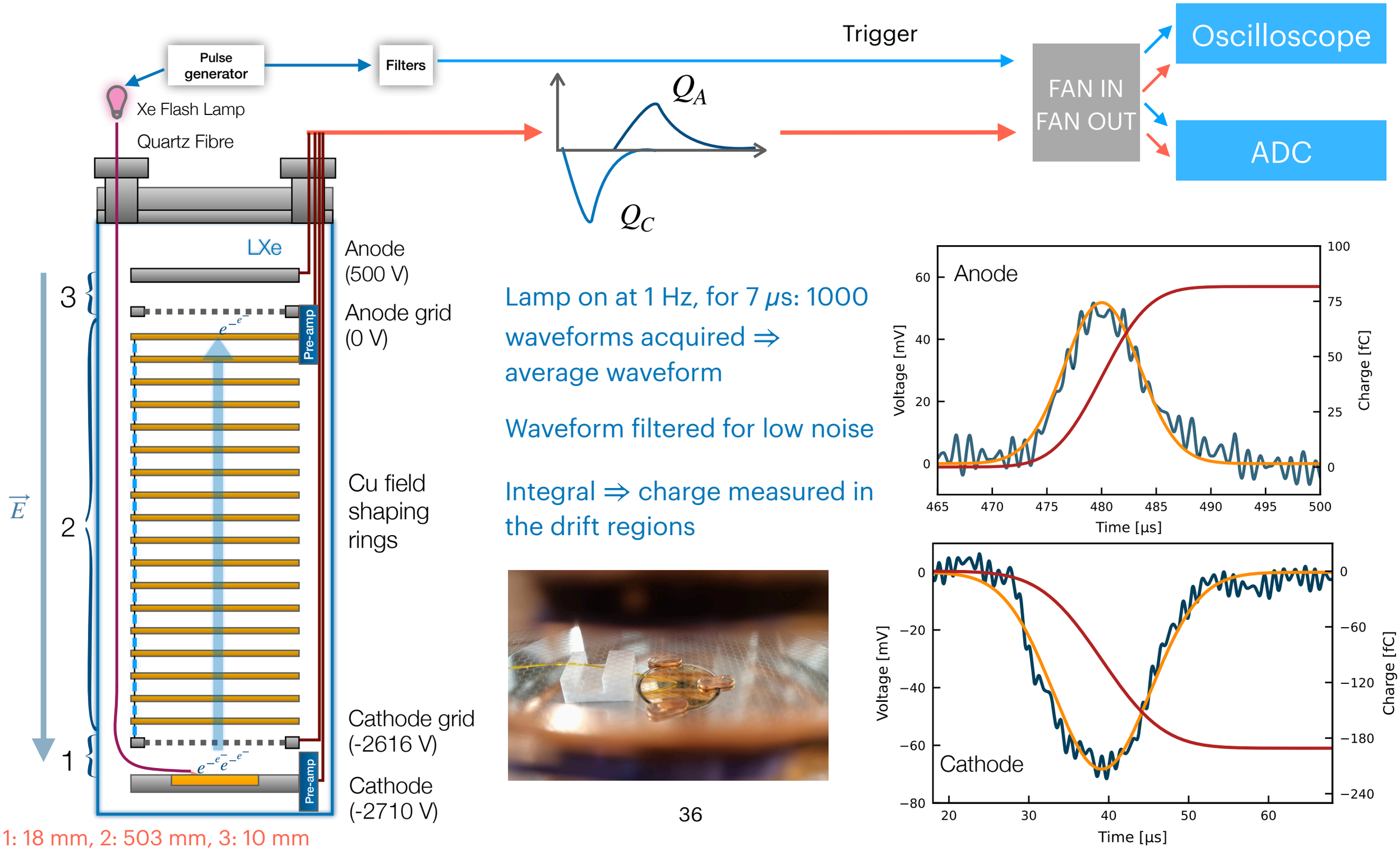
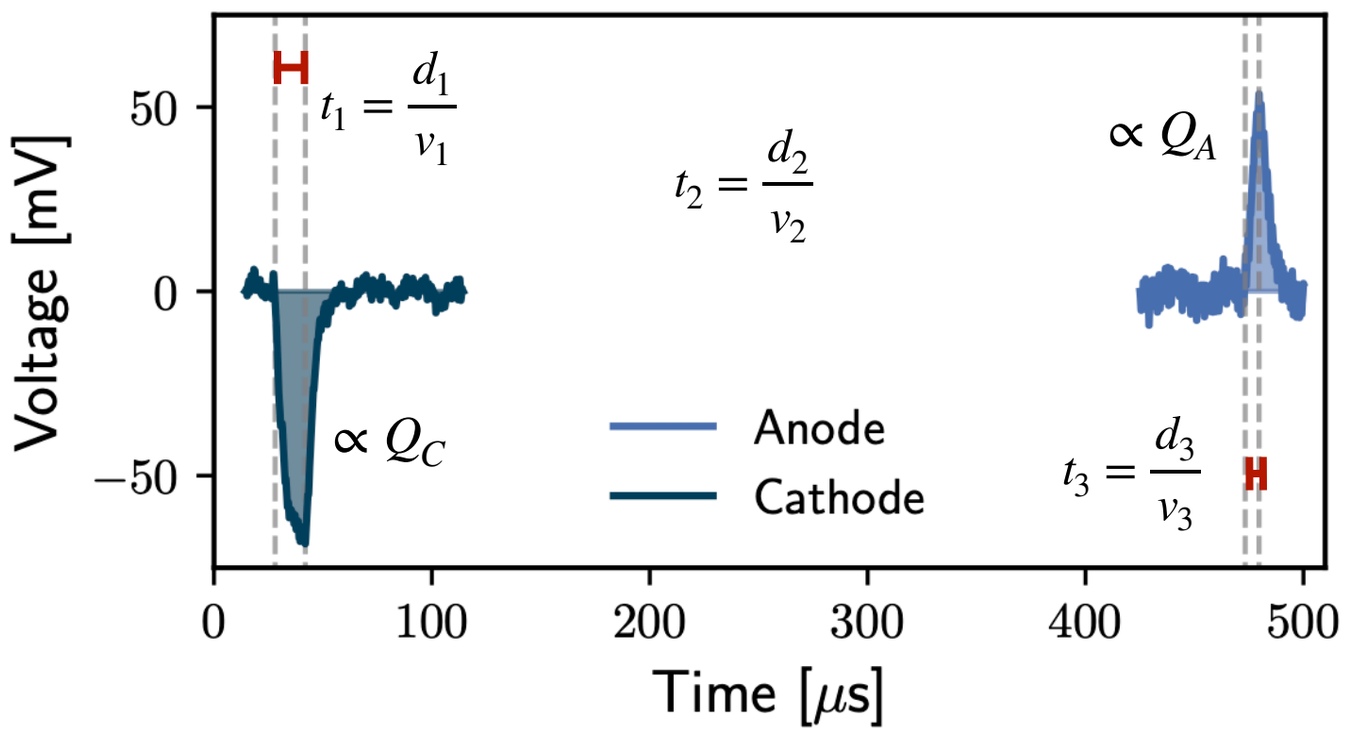
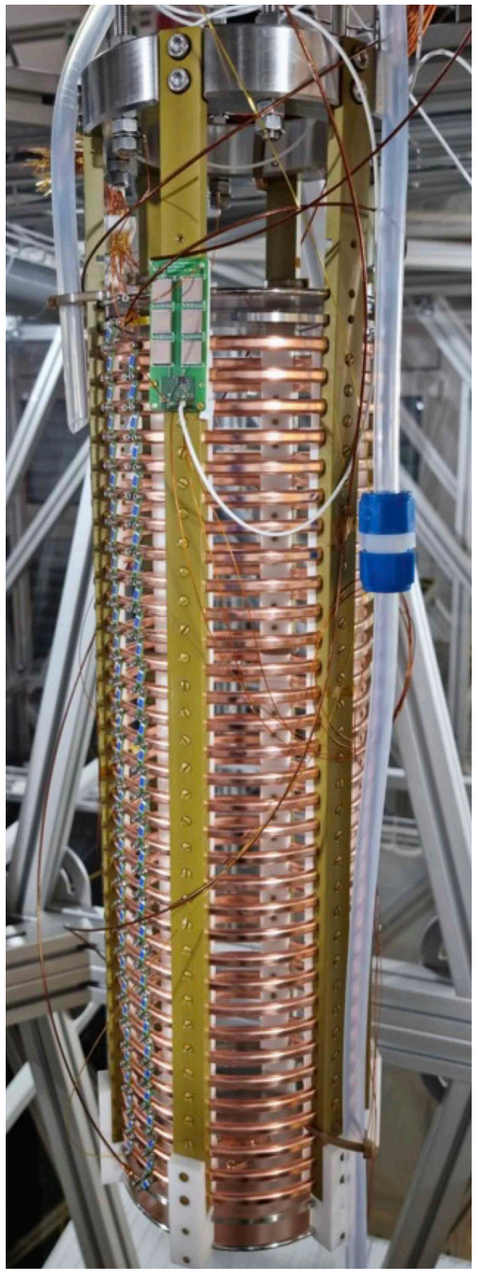
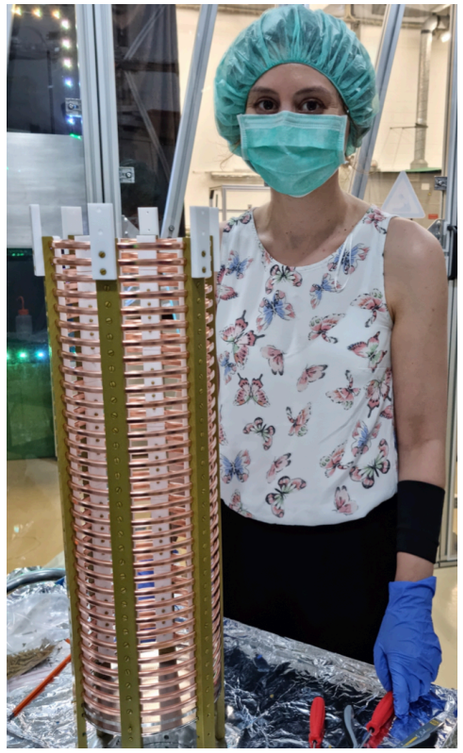
The purity monitor: signal readout



Xenoscope purity monitor: e^--lifetime determination







- Waveforms: acquired by oscilloscope and ADC
- Charges: integrals of the current pulses
- The e-lifetime (with $\Delta t = t_2$, rise times t_1, t_3)*

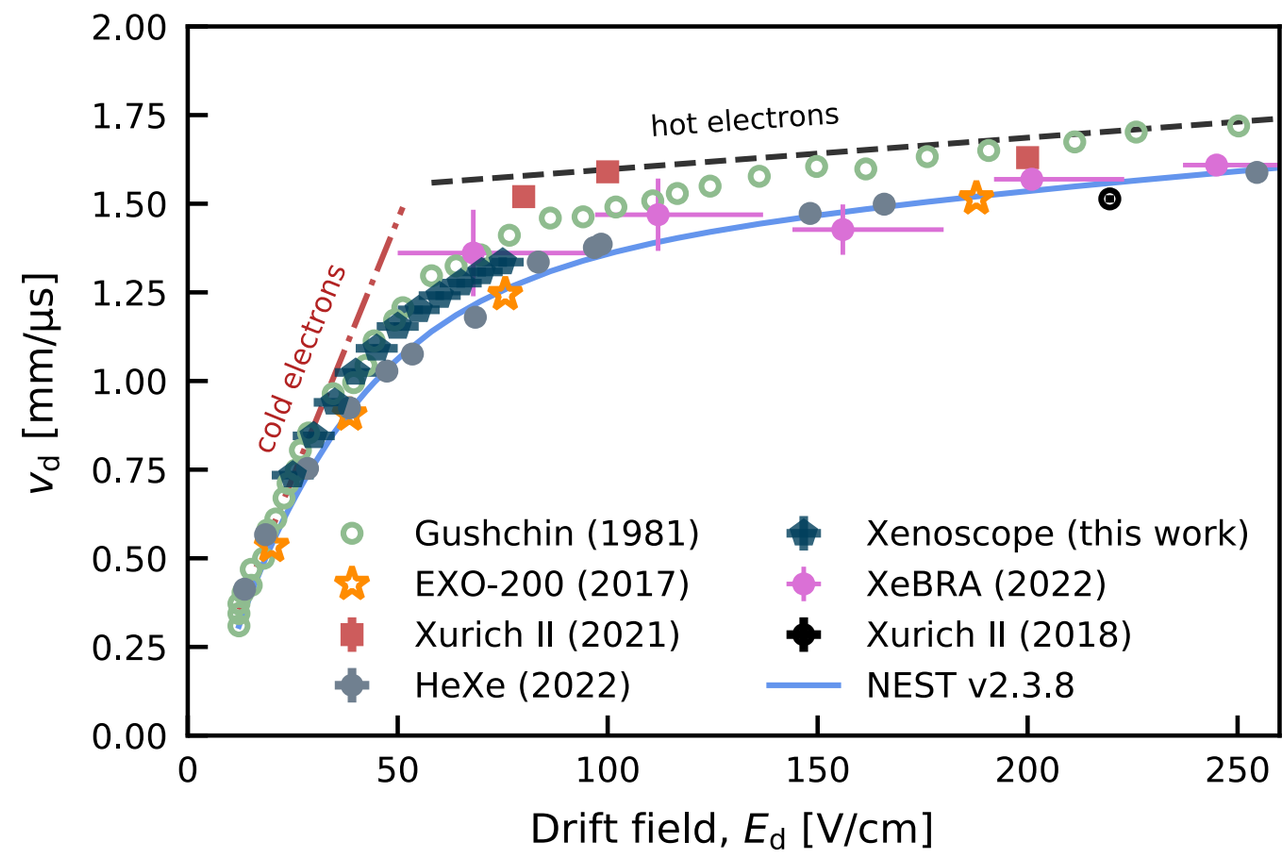
$$\tau_e \approx \frac{1}{\ln(Q_A/Q_C)}\left(t_2 + \frac{t_1 + t_3}{2}\right)$$

*L. Manenti et al., JINST 15, 2020

Drift velocity

- Measured for drift fields between 25 - 75 V/cm
- Compared to NEST predictions and literature values

$$v_d = \frac{d_2 + d_3}{t_2 + t_3}$$



- The drift velocity is related to the mobility μ:

$$v_d = \mu E_d$$

- which can be approximated for two regimes:

Cold electrons $$\mu = \frac{2}{3}\frac{e\lambda}{v}\left(\frac{2}{\pi m_e k_B T}\right)^{\frac{1}{2}}$$

Hot electrons $$\mu = \frac{4}{3}\frac{e\lambda}{v}\frac{1}{\sqrt{\pi} m_e^*}$$

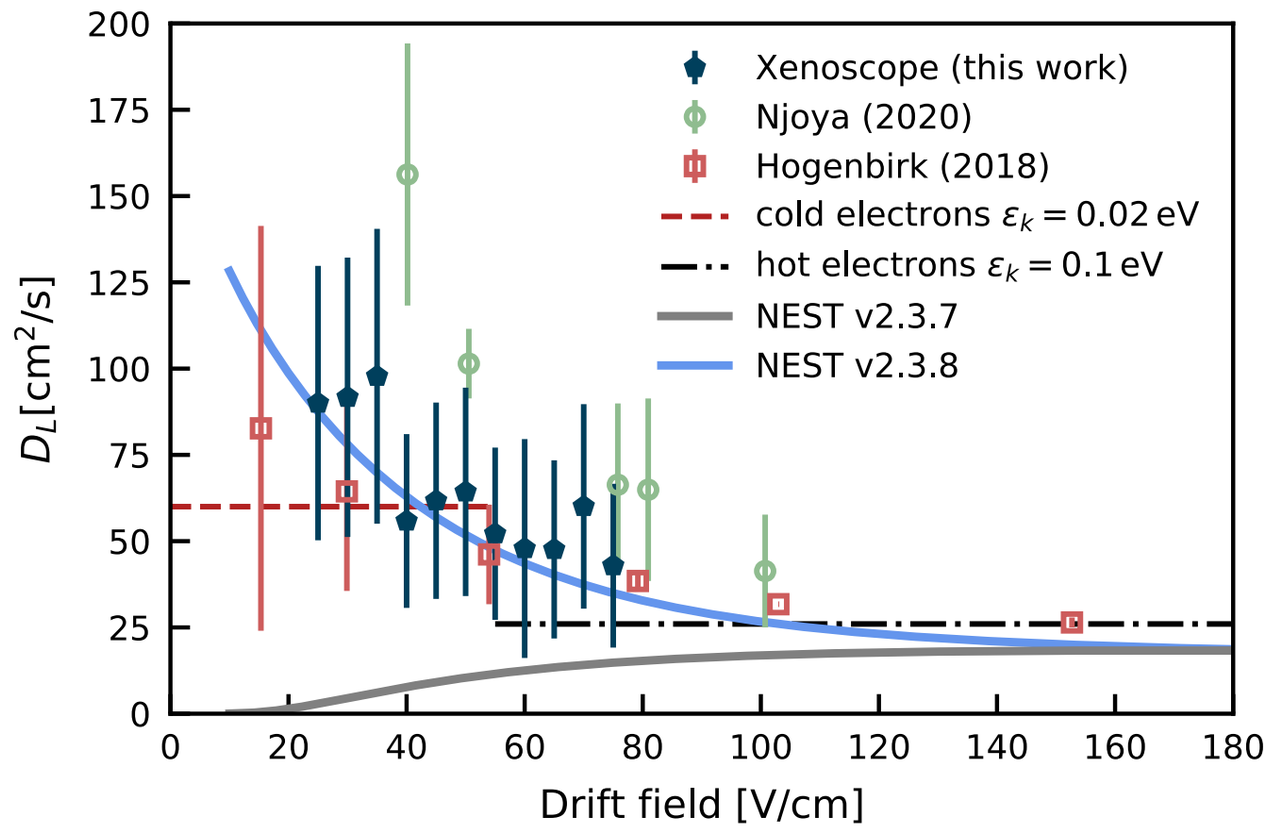
Longitudinal diffusion

- Study the width of the anode signal (assume Gaussian distributions for both cathode and anode)

$$\sigma^2 = \frac{2D_L t^3}{d^2} + \sigma_0^2$$

width of anode signal

width of cathode signal



- The diffusion coefficient is related to the electron mobility

$$\epsilon_k = \frac{eD_L}{\mu}$$

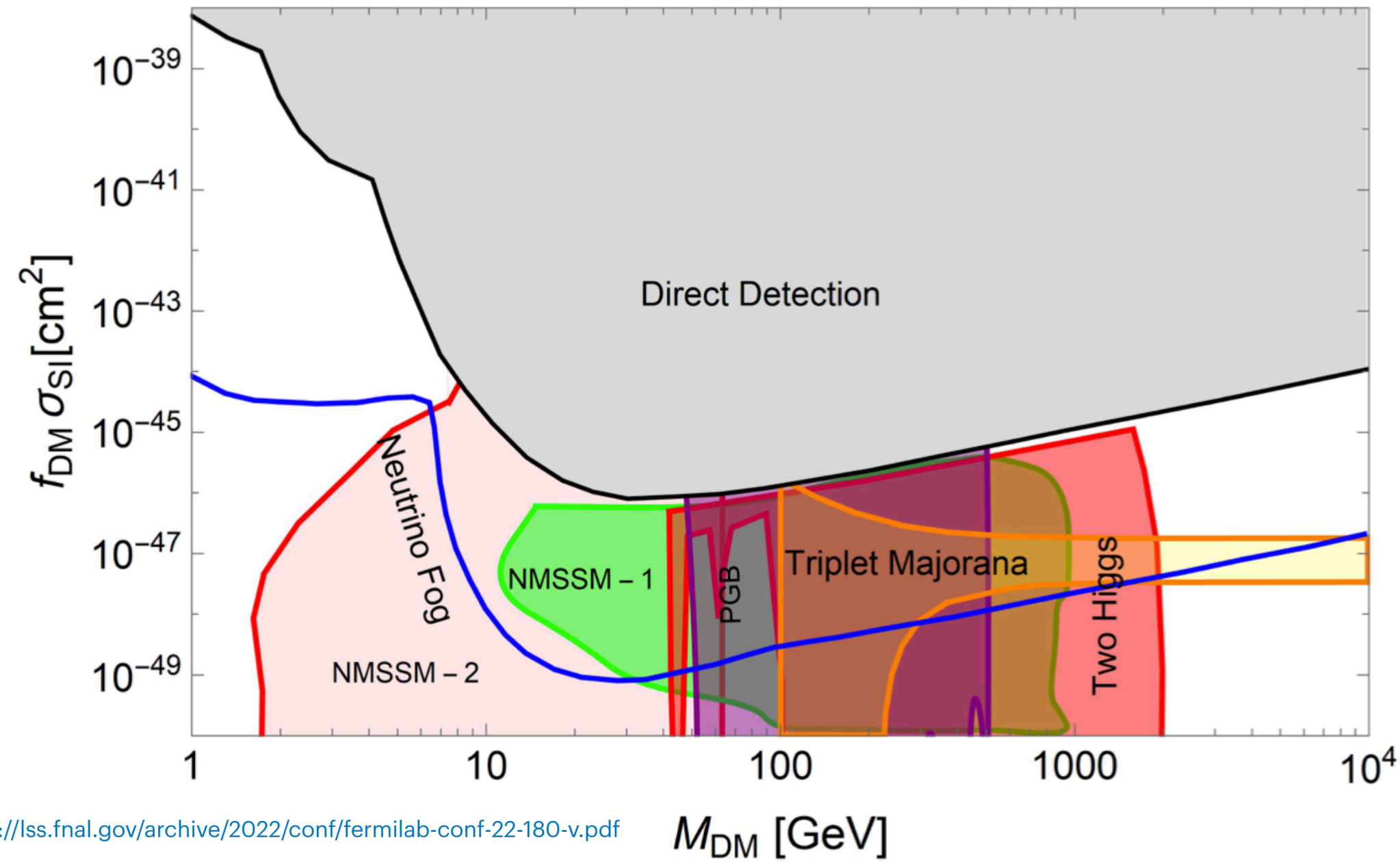
- via a characteristic energy ϵ_k

Cold electrons: $\epsilon_k \approx 0.02\,\mathrm{eV}$, $\mu \approx 0.29\,\mathrm{mm}^2/(\mu\mathrm{s}\cdot\mathrm{V})$

Hot electrons $\epsilon_k \approx 0.1\,\mathrm{eV}$, $\mu \approx 0.01\,\mathrm{mm}^2/(\mu\mathrm{s}\cdot\mathrm{V})$ (???)

Theory predictions

- SI scattering cross sections for various "visible sector" models

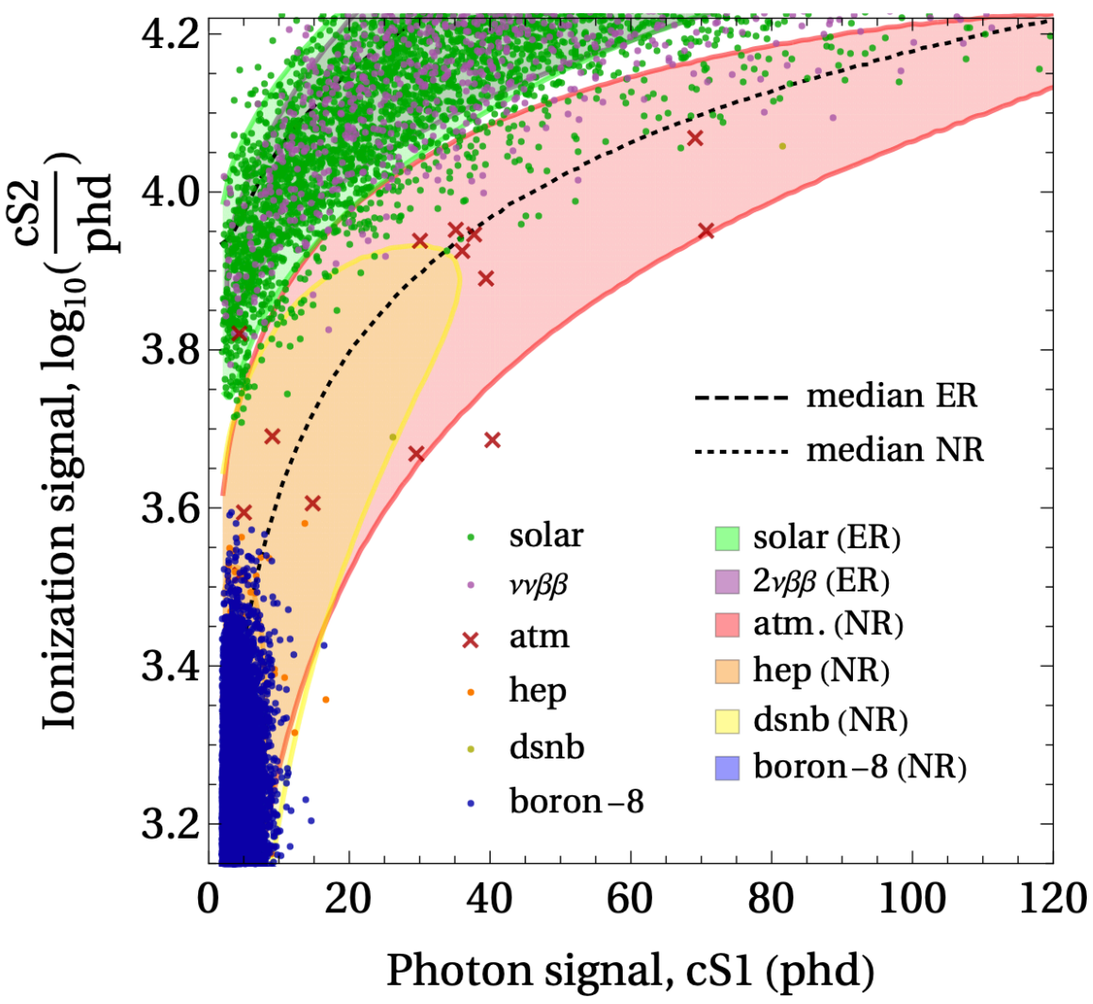


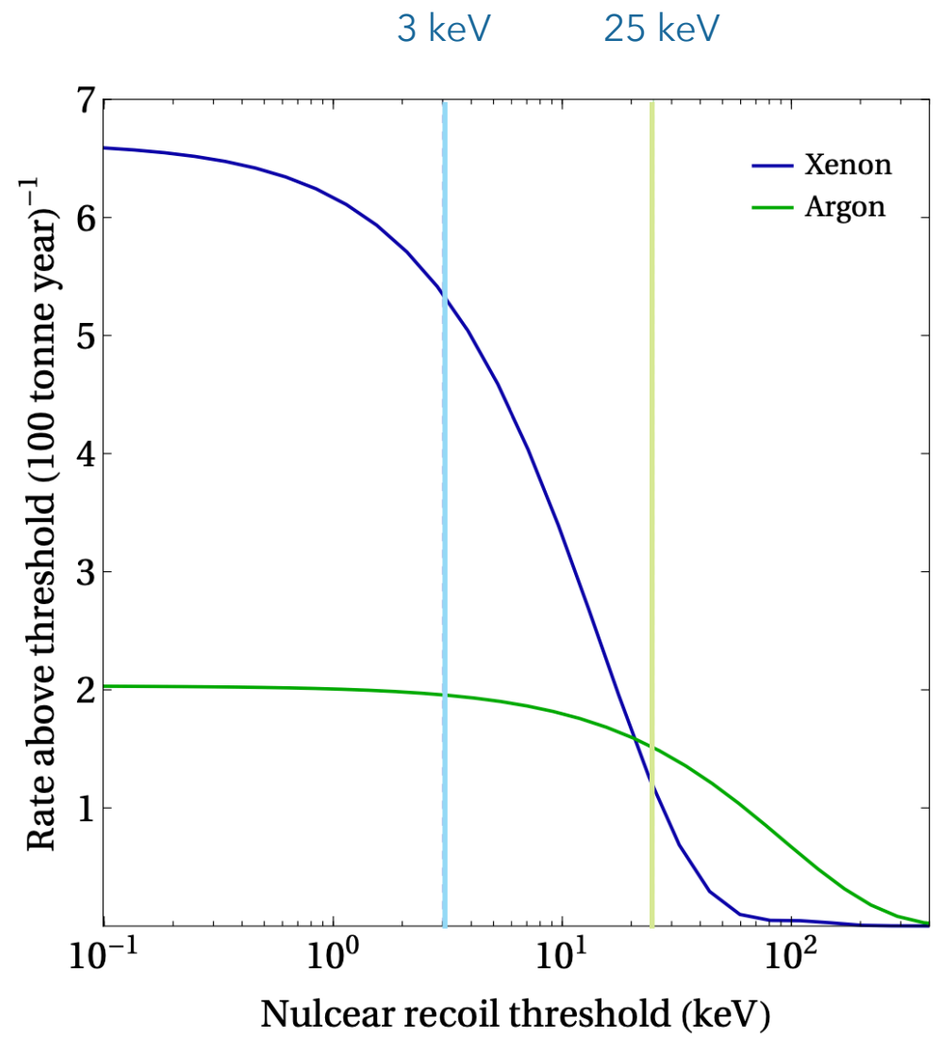
https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-180-v.pdf

Neutrinos in a DARWIN-like detector

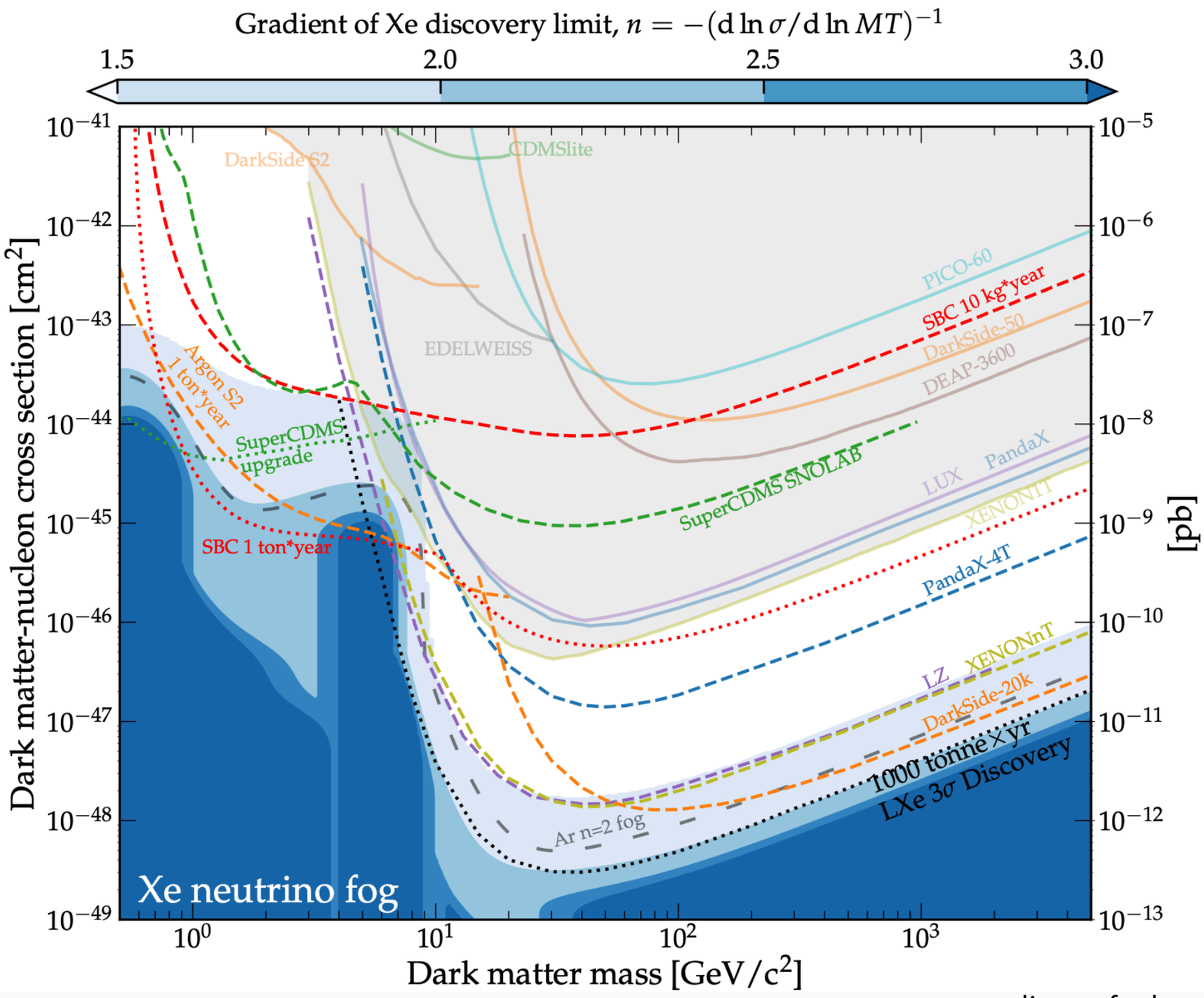
- Study of sensitivity to atmospheric neutrinos (using NEST to model the signals)
- Below: exposure of 200 t y; need 700 t y to obtain a 5-σ detection of atmospheric neutrinos

Newstead, Lang, Strigari, arXiv: 2002.08566





Neutrino backgrounds



Effect of the astrophysical neutrino backgrounds: gradual, hence the "neutrino fog"

Here the neutrino fog for a xenon target: blue contour map

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

n = gradient of a hypothetical experiment's median cross section for 3σ discovery with respect to the exposure

https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-180-v.pdf