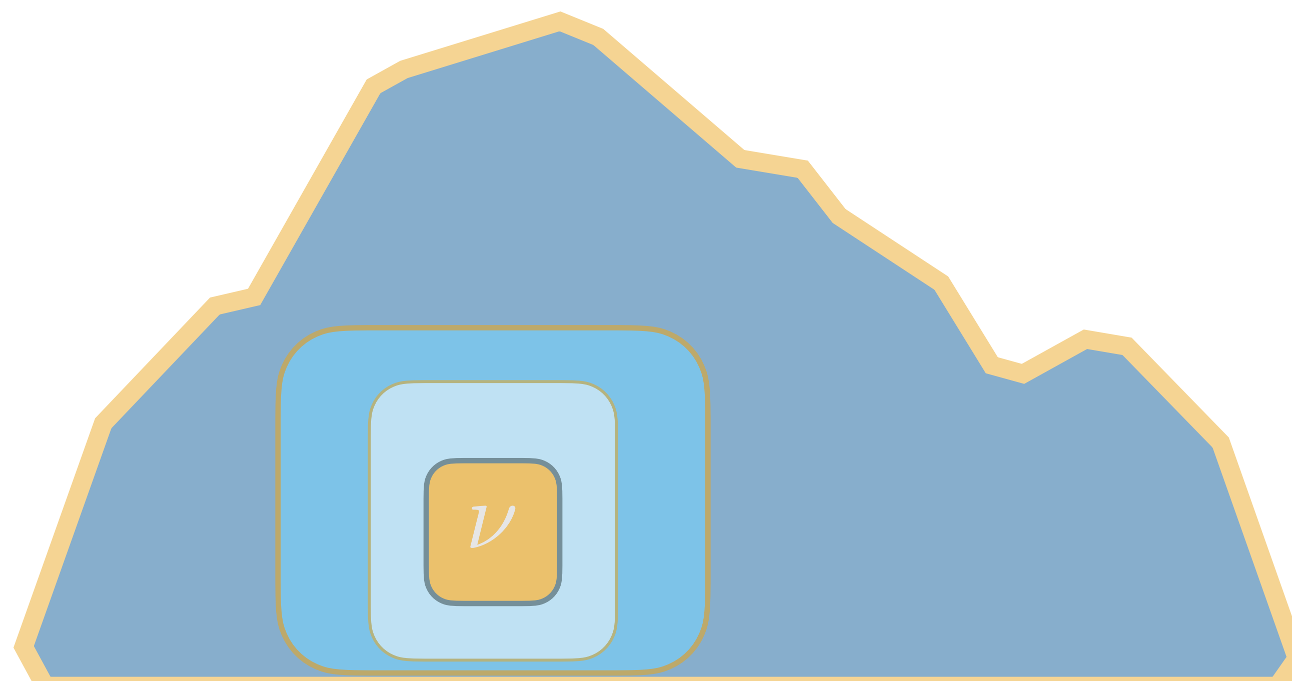
Neutrinos with dark matter detectors

Neutrino 2024
Milano

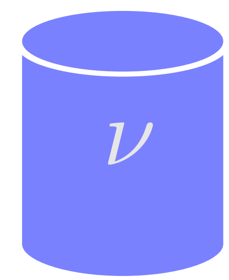
Laura Baudis
University of Zurich
June 21, 2024



Why dark matter detectors?

Neutrino detectors

Dark matter detectors

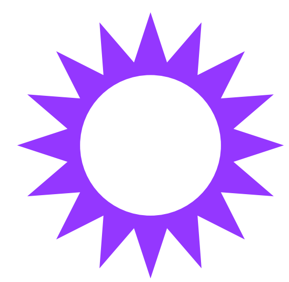


- ✓Low energy thresholds
- ✓Low backgrounds
- ✓Good energy resolutions
- ✓Particle ID

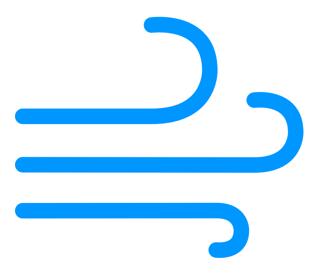
What kind of neutrinos?

- From the Sun

- From supernovae



- From the atmosphere



- No neutrinos

What kind of neutrinos?

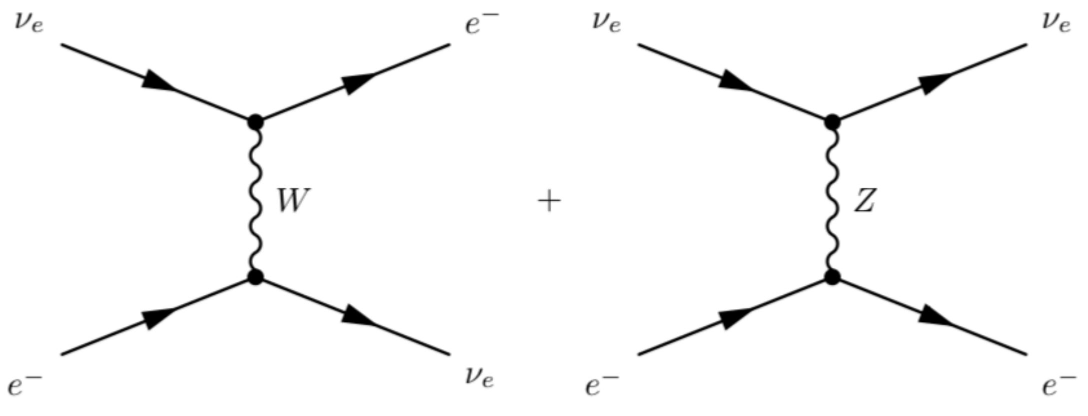
- From the Sun

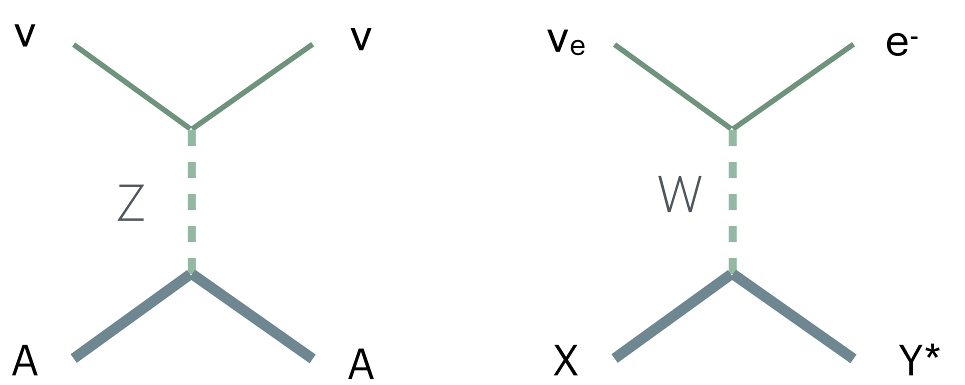
- pp, ^{7}Be, pep, ^{8}B, (possibly) CNO: via ES, CEvNS and IBD

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

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

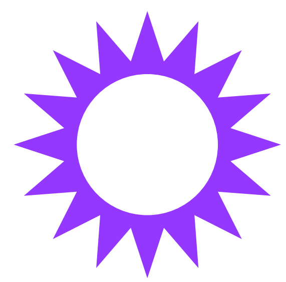
$$\nu_e + {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y}^* + e^-$$





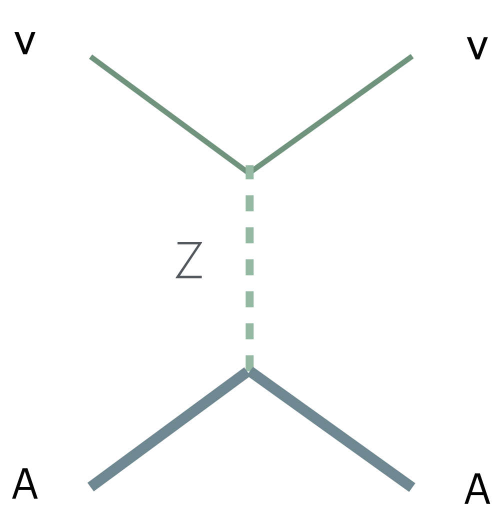
What kind of neutrinos?

- From supernovae



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

Sensitivity to all neutrino flavours from a core-collapse SN



Complementary measurements to experiments using CC reactions

"Flavour democratic" (C. Lunardi)

What kind of neutrinos?

- From the atmosphere

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

"Ultimate" background for dark matter detectors at high DM masses

Sub-GeV atmospheric neutrino flux not yet measured, uncertainty on the predicted flux ~ 20%

Large exposures needed

What kind of neutrinos?

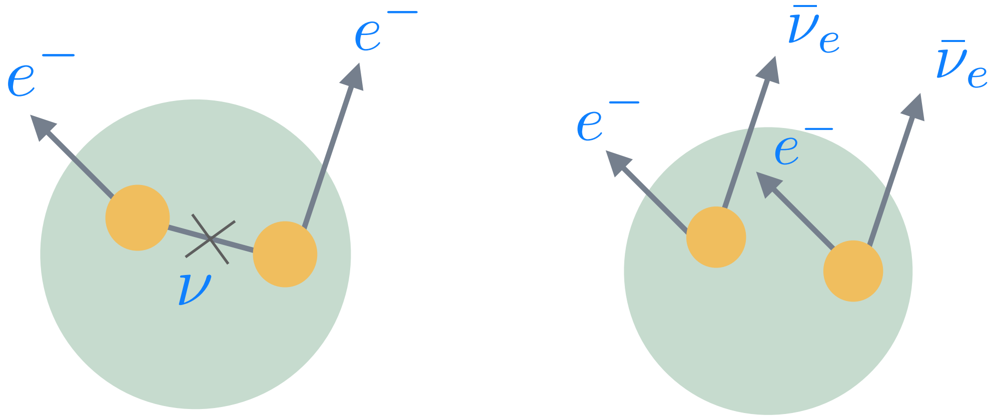
- No neutrinos

Second order weak decays:

$0\nu\beta\beta$ ($2\nu\beta\beta$), $0\nu ECEC$ ($2\nu ECEC$), $0\nu\beta^{+}EC$ ($2\nu\beta^{+}EC$), etc

^{136}Xe

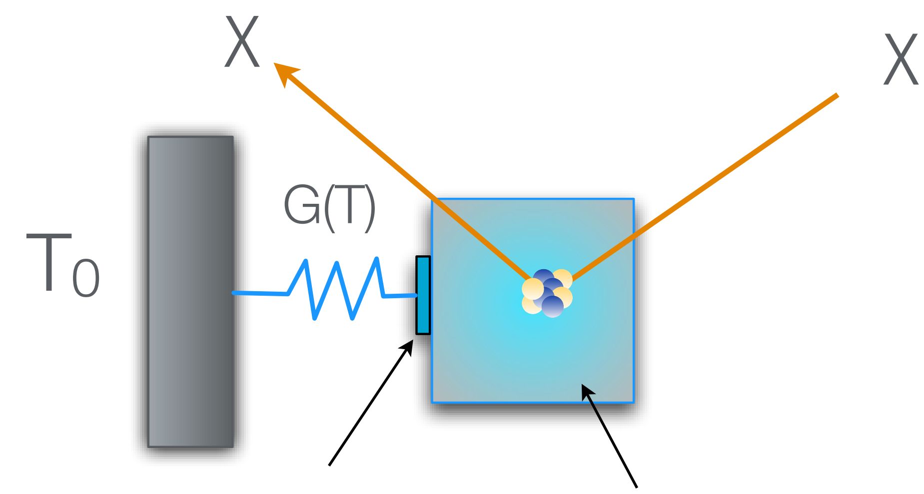
^{36}Ar, ^{124}Xe, ^{126}Xe, ^{134}Xe



Which dark matter detectors?

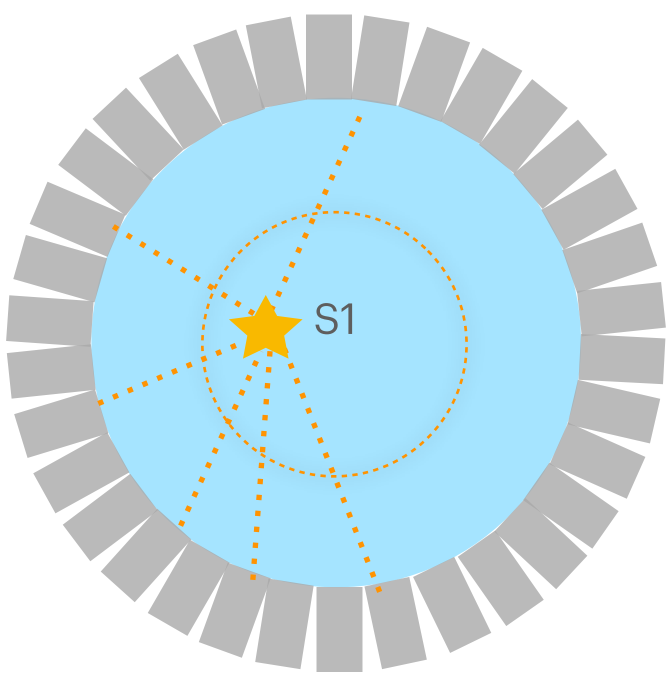
- Large mass, noble liquid detectors using Ar, Xe
- Cryogenic crystal calorimeters
- Directional, gaseous TPCs

Bolometers



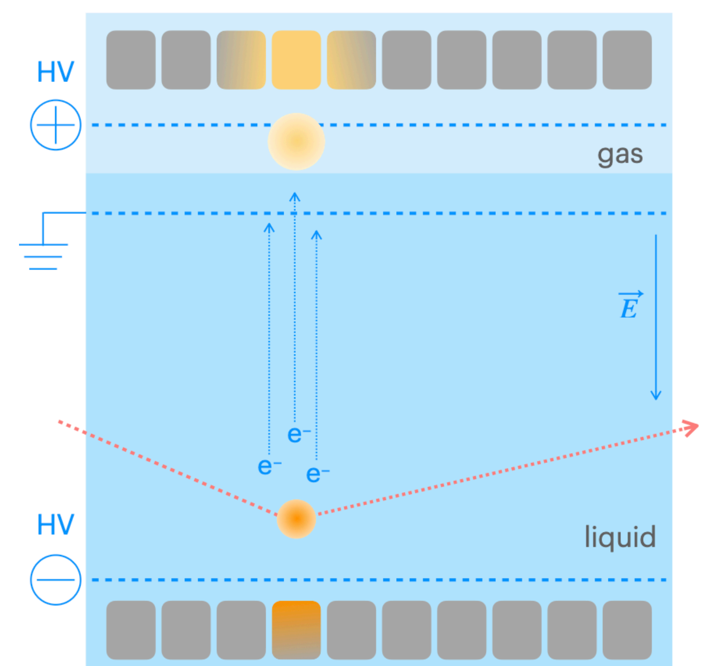
CRESST, SuperCDMS, COSINUS

Single phase



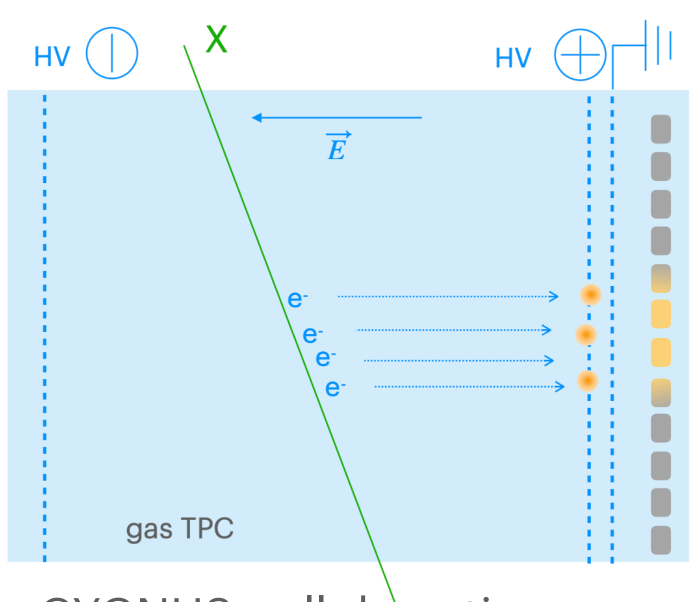
Ar: DEAP-3600 (operating)

Two phase TPCs



Ar: DarkSide-20k (in construction), Argo (future)
Xe: LZ, PandaX-4T, XENONnT (operating)
DARWIN/XLZD, PandaX-xT (future)

Directional TPCs

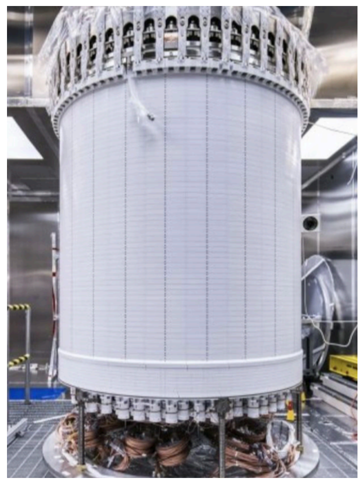


CYGNUS collaboration (future)

Which dark matter detectors?

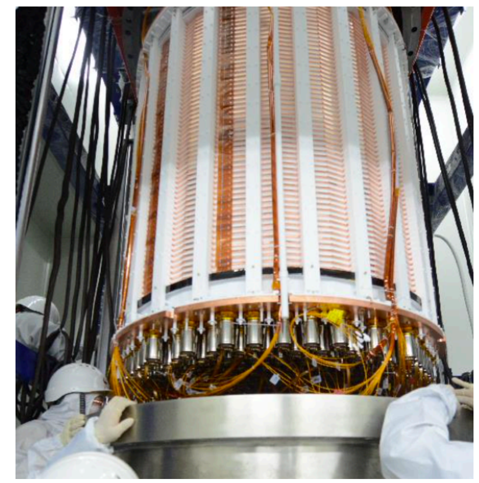
DEAP-3600

LUX-ZEPLIN

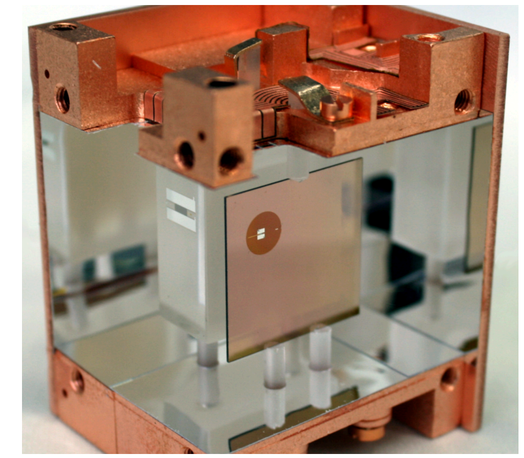


XENONnT

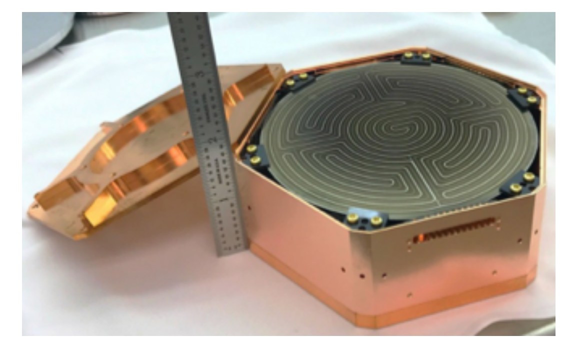
PandaX-4T



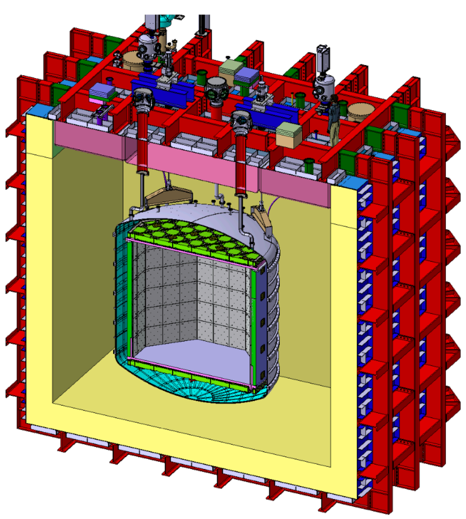
CRESST



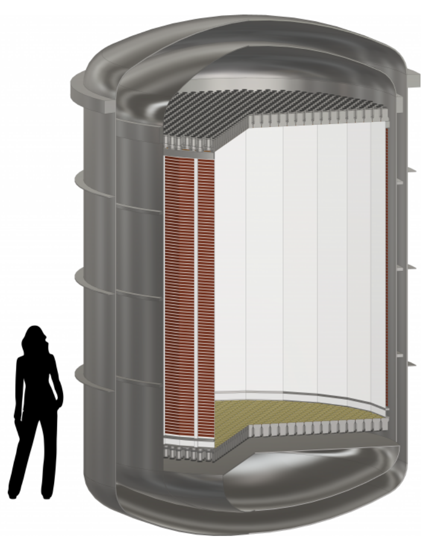
SuperCDMS



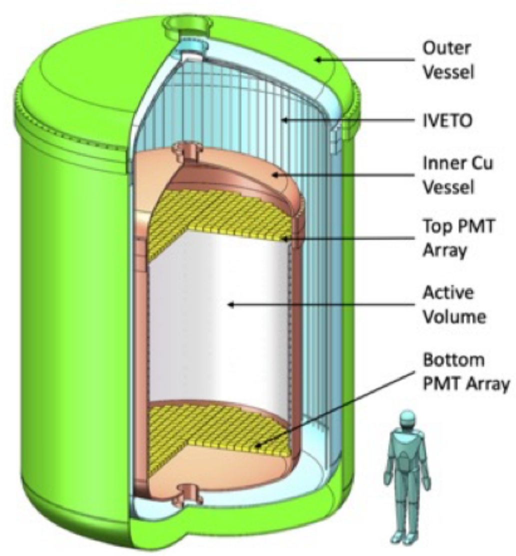
COSINUS



DarkSide-20k (+ future Argo)

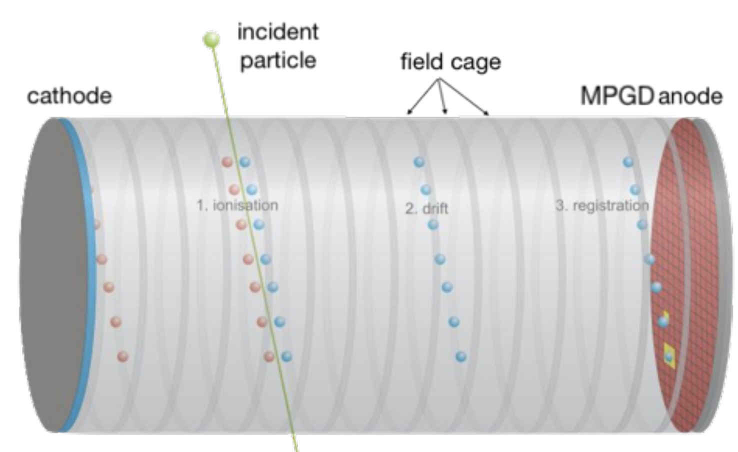


DARWIN/XLZD



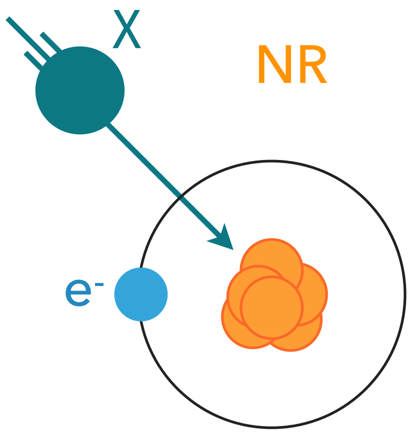
PandaX-xT

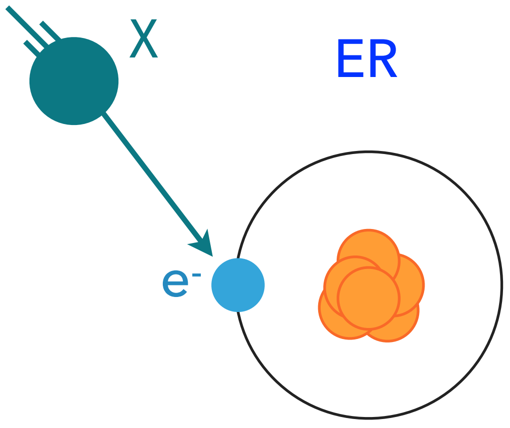
CYGNUS



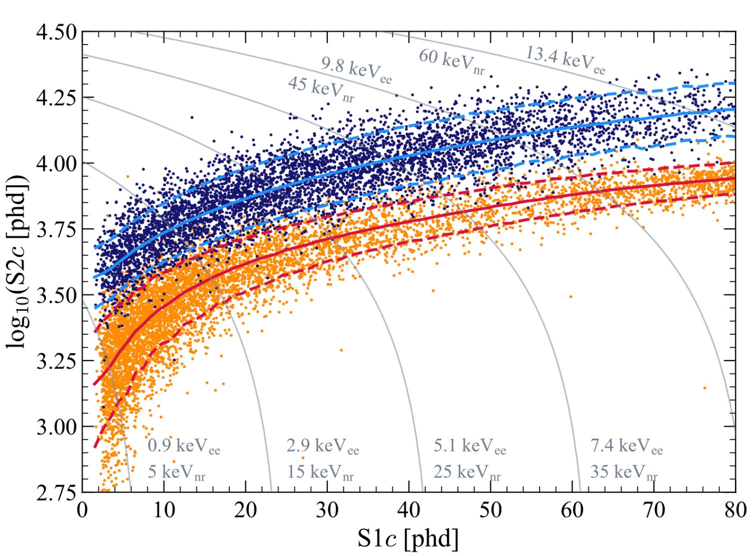
Signals and backgrounds

- Interactions with atomic nuclei and electrons: NRs and ERs
- Discrimination: charge/phonon/light ratio & pulse shape (LAr)



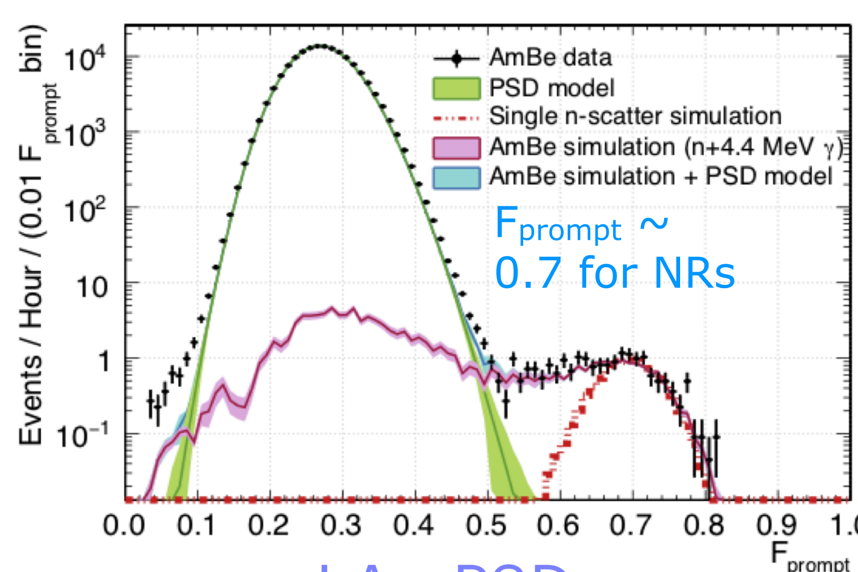


LUX-ZEPLIN



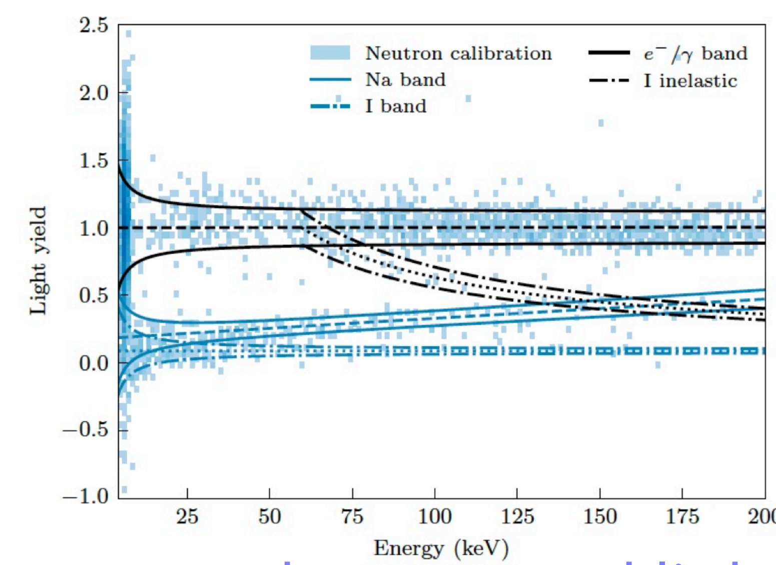
LXe: light and charge

DEAP-3600



LAr: PSD

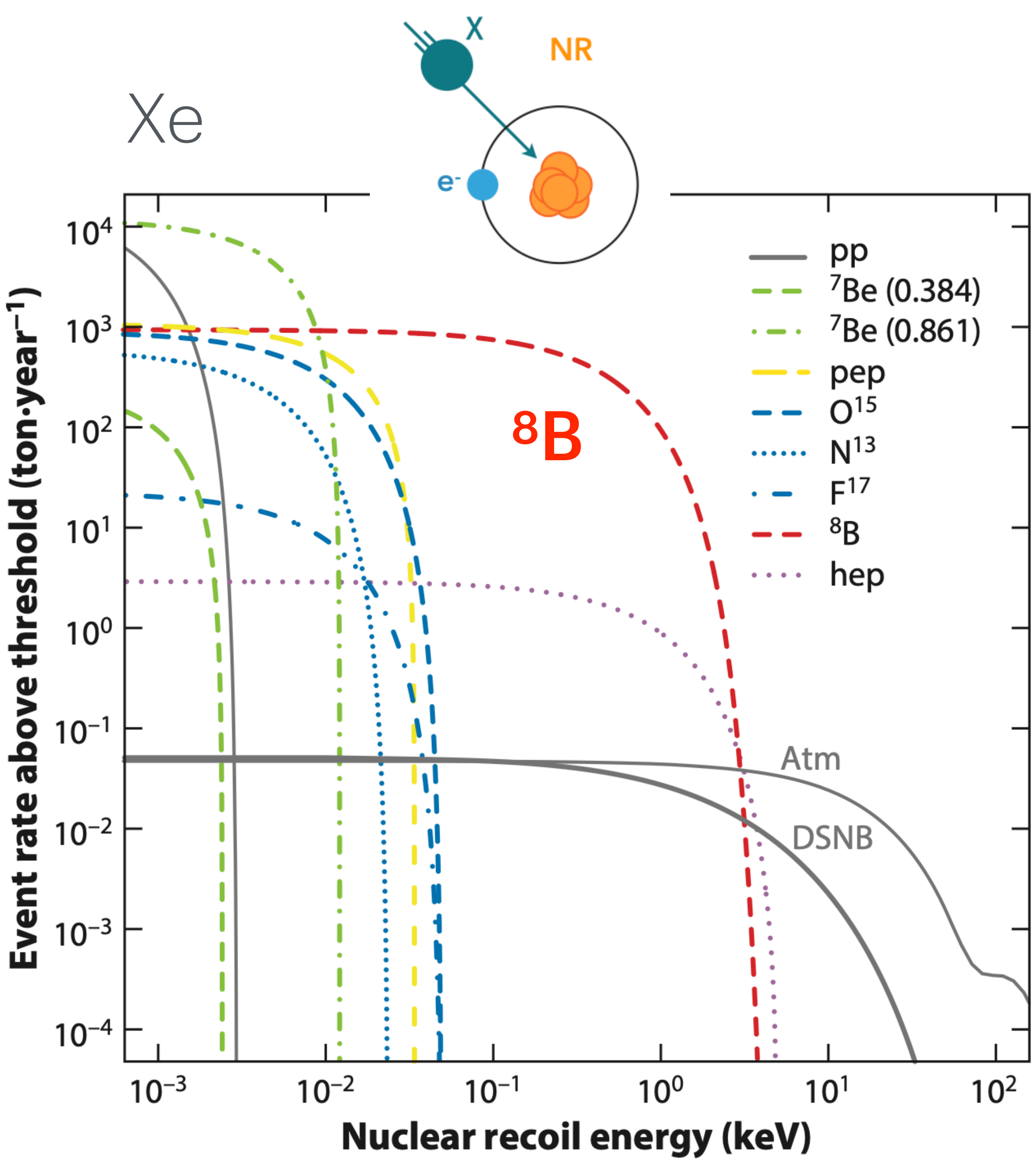
COSINUS

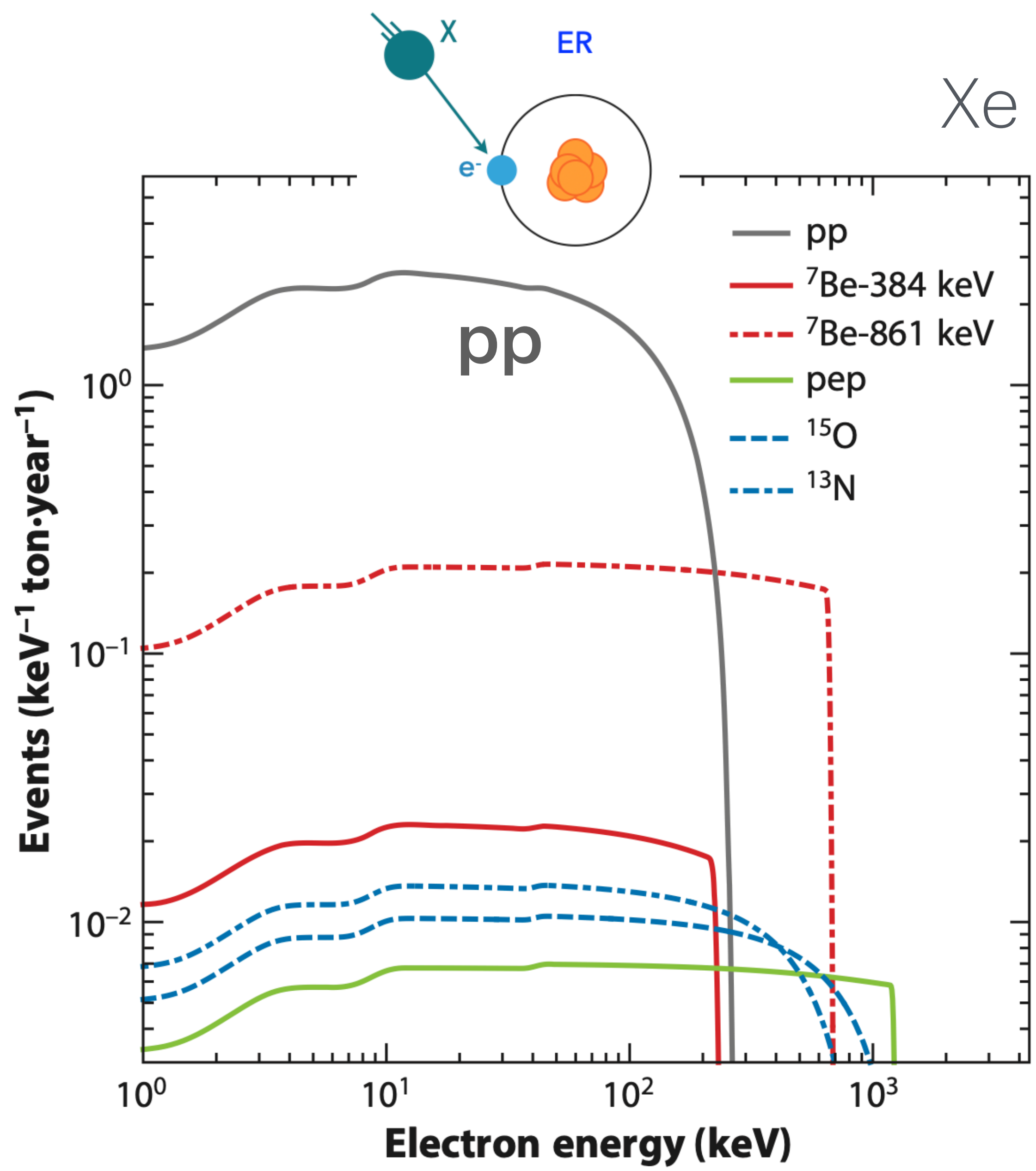


NaI: phonons and light

Neutrino signals

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

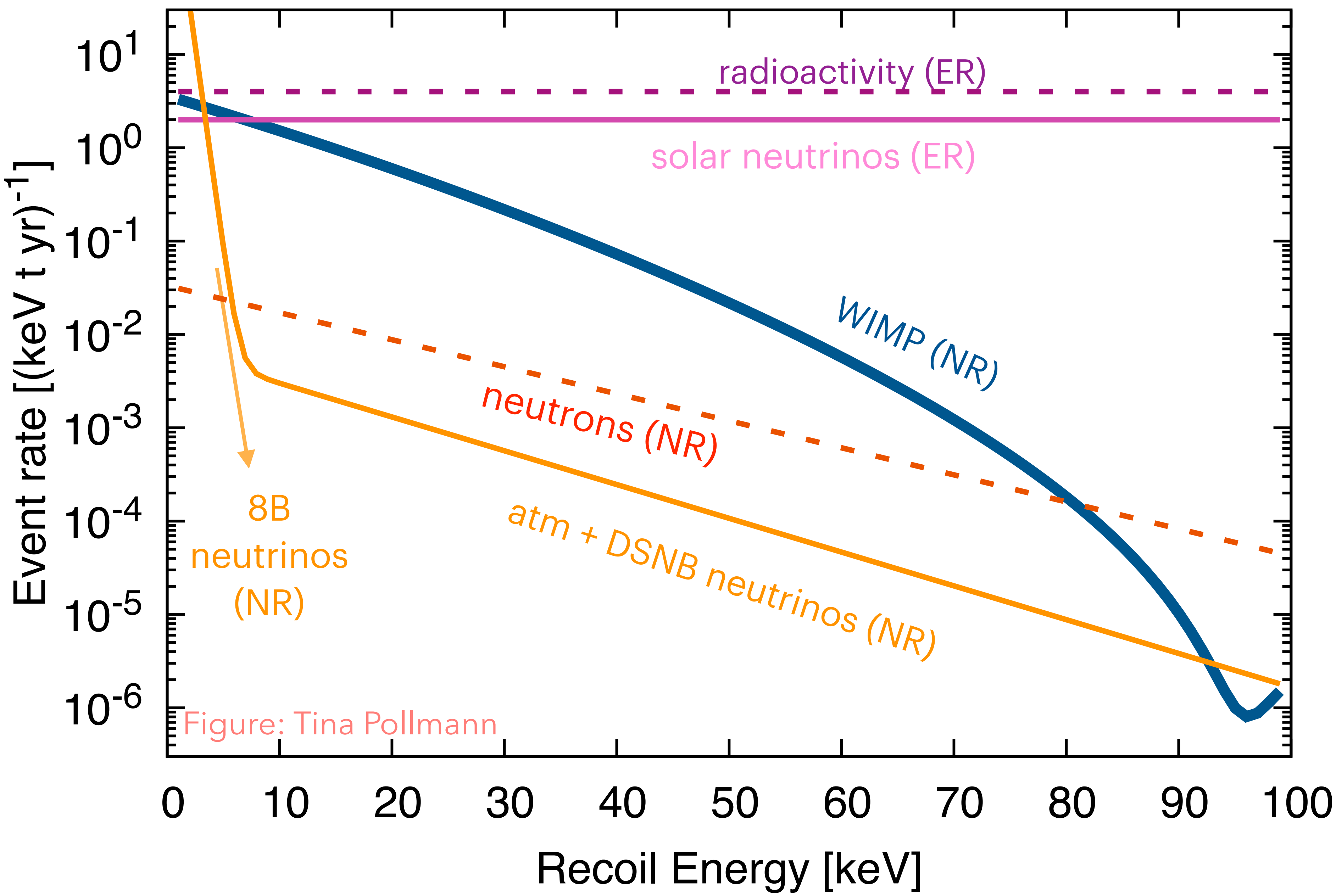




B. Dutta, E. Strigari, Annu. Rev. Nucl. Part. Sci. 2019

Signals and backgrounds

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



materials, intrinsic etc

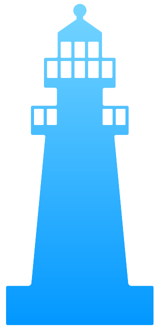
ν-e scattering: solar ν's

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

radiogenic, cosmogenic

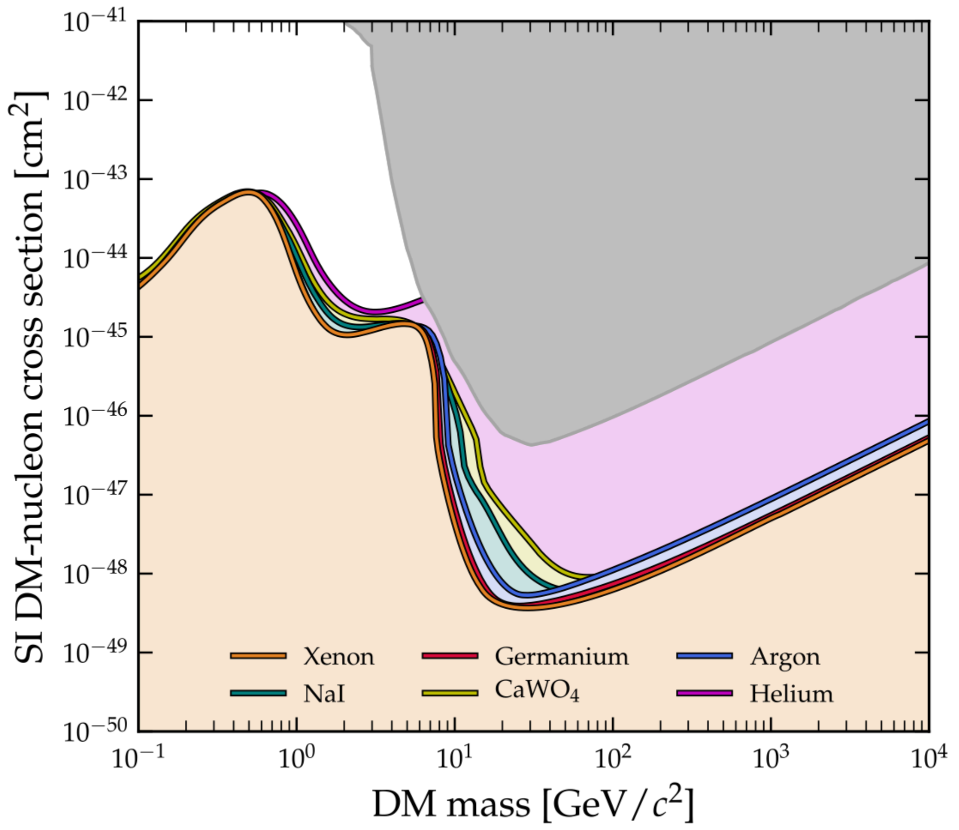
CEvNS: solar ν's, atm ν's + DSNB

Approaching the neutrino fog

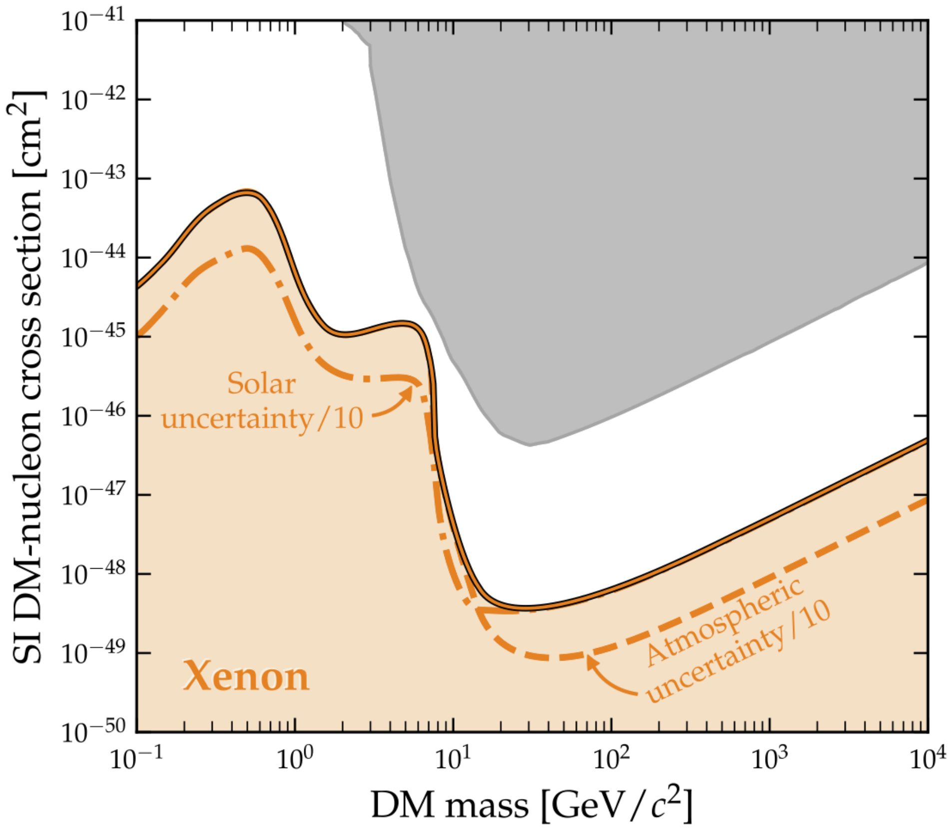


- Here shown for nuclear recoils (ν floor as boundary to "ν fog")
- Region where experiments leave the Poissonian regime*

The "fog" for different targets



Effect of ν fluxes uncertainties

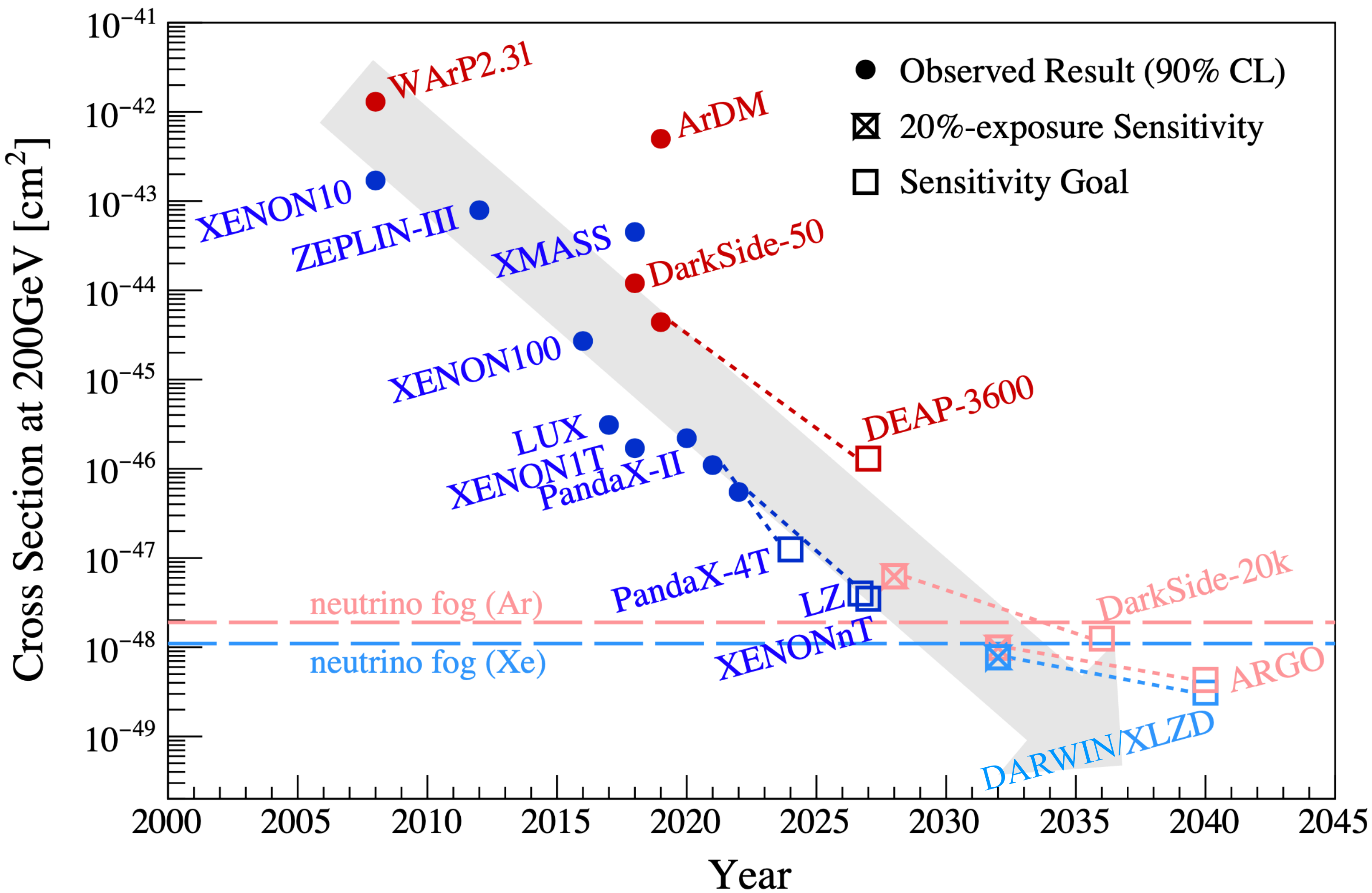


C. O'Hare, PRL 127, 2021

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

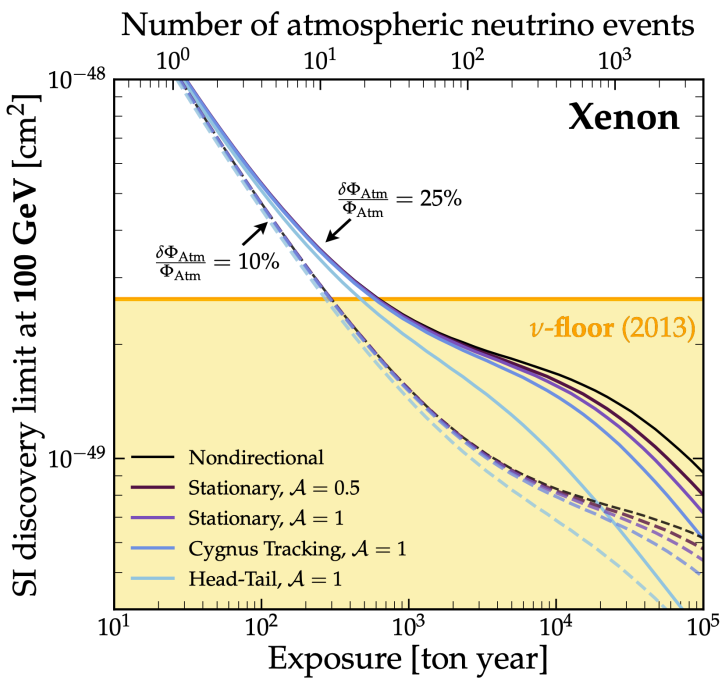
Approaching the neutrino fog

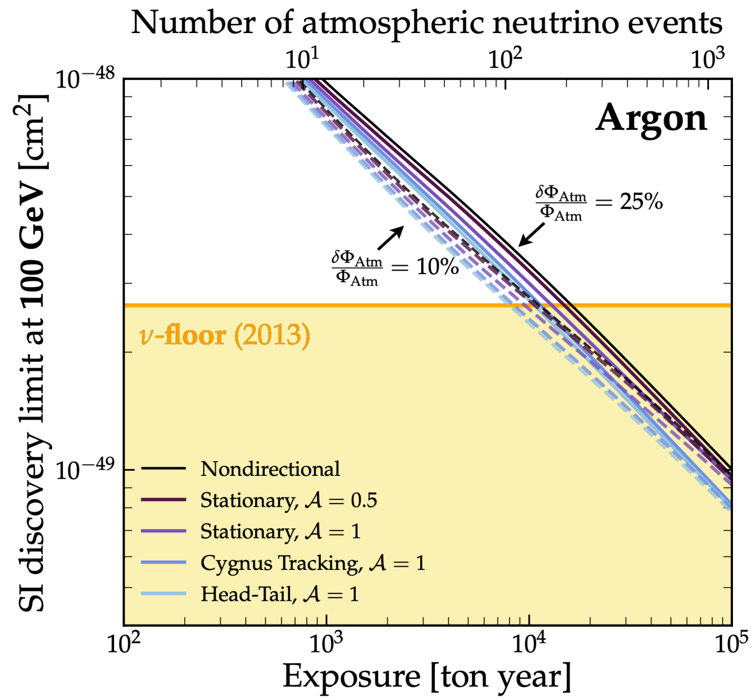
- Current & future noble liquid experiments



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."

100 GeV WIMP discovery limits



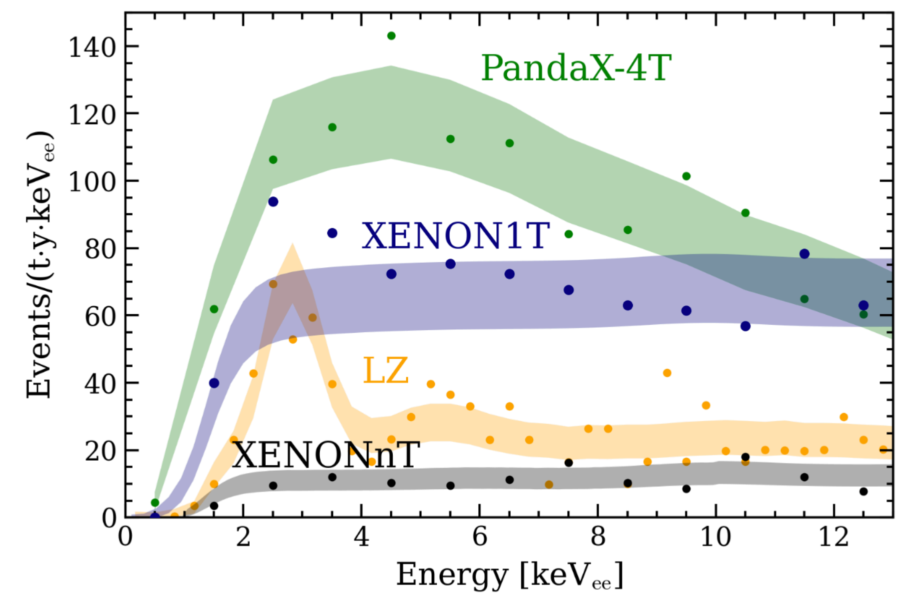


C. O'Hare, PRD 102, 2020

Solar ν-electron scattering

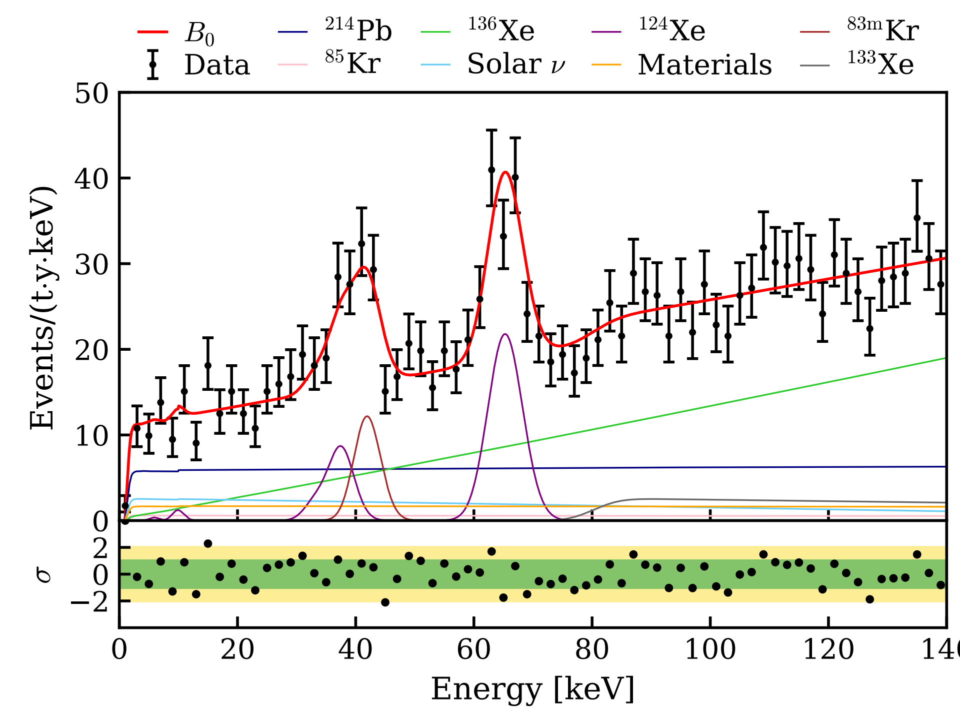
Posters: Cecilia Ferrari, Carlo Fuselli

- Main goal: real-time measurement of solar neutrino flux at low energies
- In LXe: ~ 365 events/(t y) from pp ν and 140 events/(t y) from ^{7}Be ν
- Infer P_{ee} and the weak mixing angle < 300 keV



Example: XENONnT backgrounds, SR0

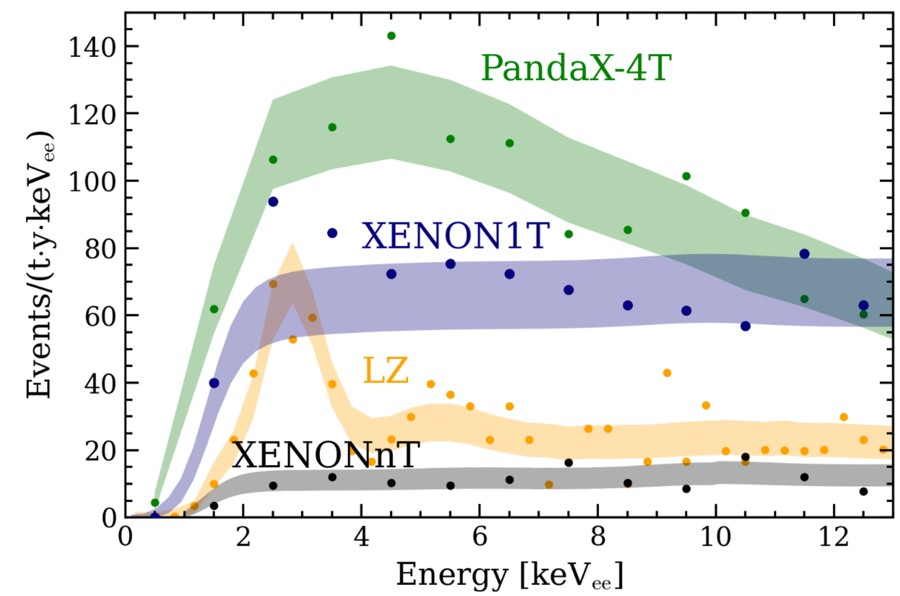
Component	(1,10) keV
^{214}Pb	**56±7**
^{85}Kr	6±4
Materials	16±3
Solar ν	**25±2**
^{124}Xe	2.6±0.3
^{136}Xe	8.7±0.3
Accidentals	0.7±0.03



XENON collaboration, PRL 129, 2022

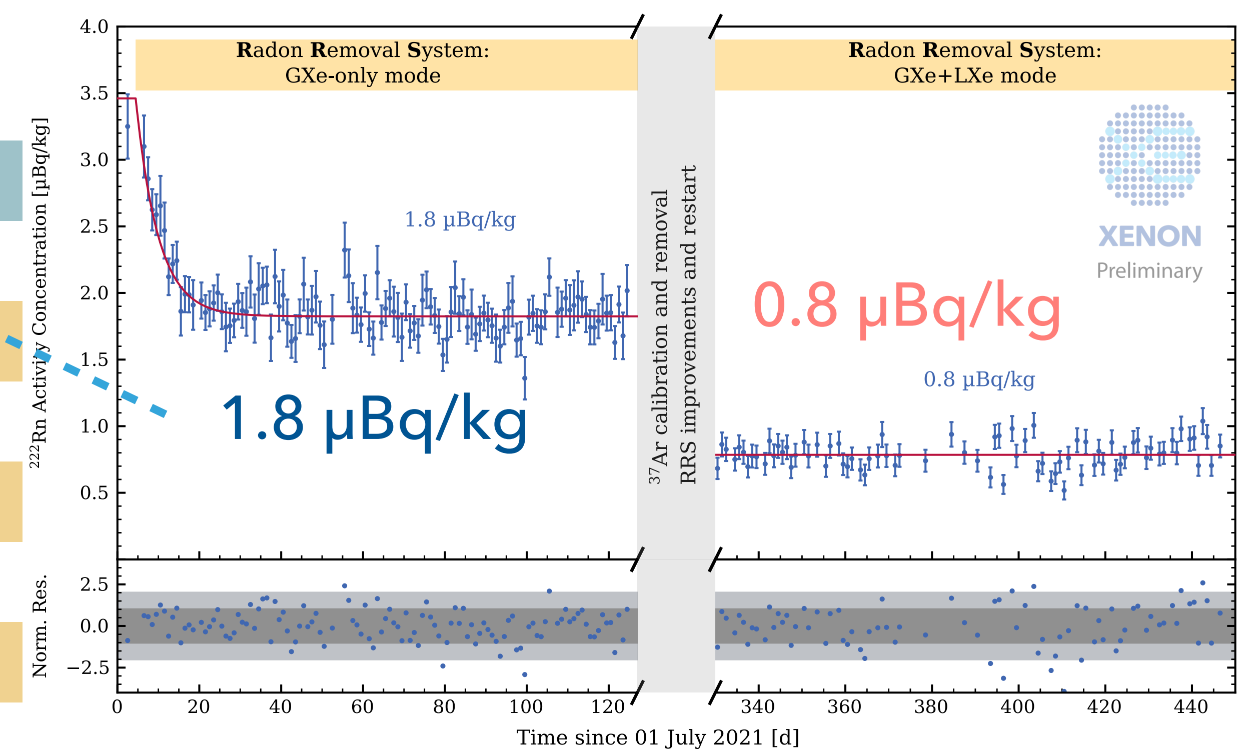
Solar ν-electron scattering

- Main goal: real-time measurement of solar neutrino flux at low energies
- In LXe: ~ 365 events/(t y) from pp ν and 140 events/(t y) from ^{7}Be ν
- Infer P_{ee} and the weak mixing angle < 300 keV



Example: XENONnT backgrounds, SR0

Component	(1,10) keV
^{214}Pb	**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
Accidentals	0.7±0.03

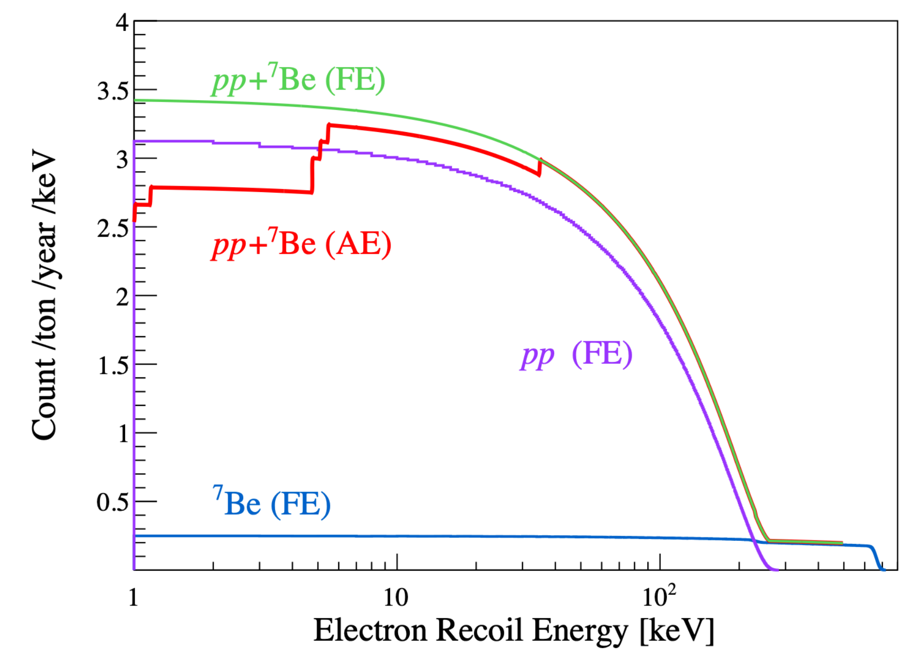


XENONnT: Rn concentration reduced for SR1

Solar ν-electron scattering

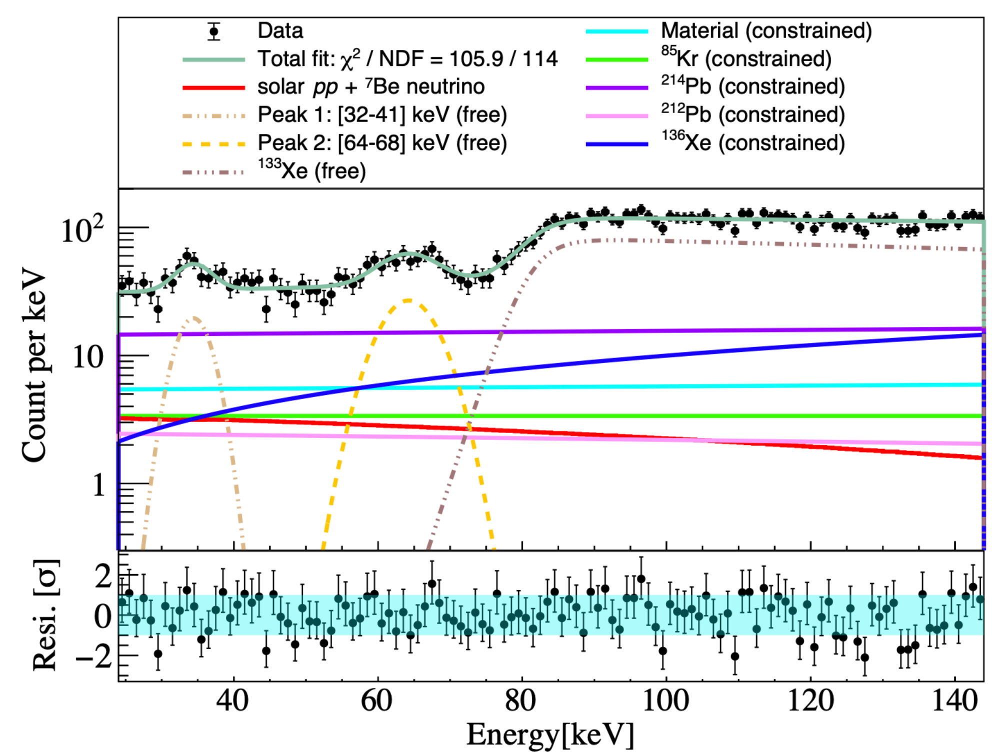
Poster: Xinning Zeng

- Main goal: real-time measurement of solar neutrino flux at low energies
- In LXe: ~ 365 events/(t y) from pp ν and 140 events/(t y) from ^{7}Be ν
- Infer P_{ee} and the weak mixing angle < 300 keV



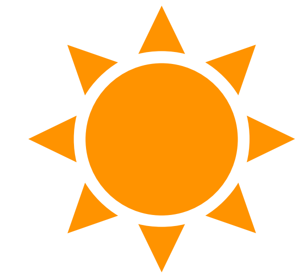
Example: PandaX-4T backgrounds

Components	Expected counts	Fitted counts
^{214}Pb	1865 ± 110	1845 ± 113
^{212}Pb	276 ± 71	270 ± 80
^{85}Kr	489 ± 254	405 ± 249
Material	683 ± 27	681 ± 27
^{136}Xe	1009 ± 46	999 ± 47
^{133}Xe	free	4751 ± 136
Peak 1: [32-41] keV	free	119 ± 27
Peak 2: [64-68] keV	free	268 ± 37
pp+^{7}Be neutrino	**-**	**297 ± 260**



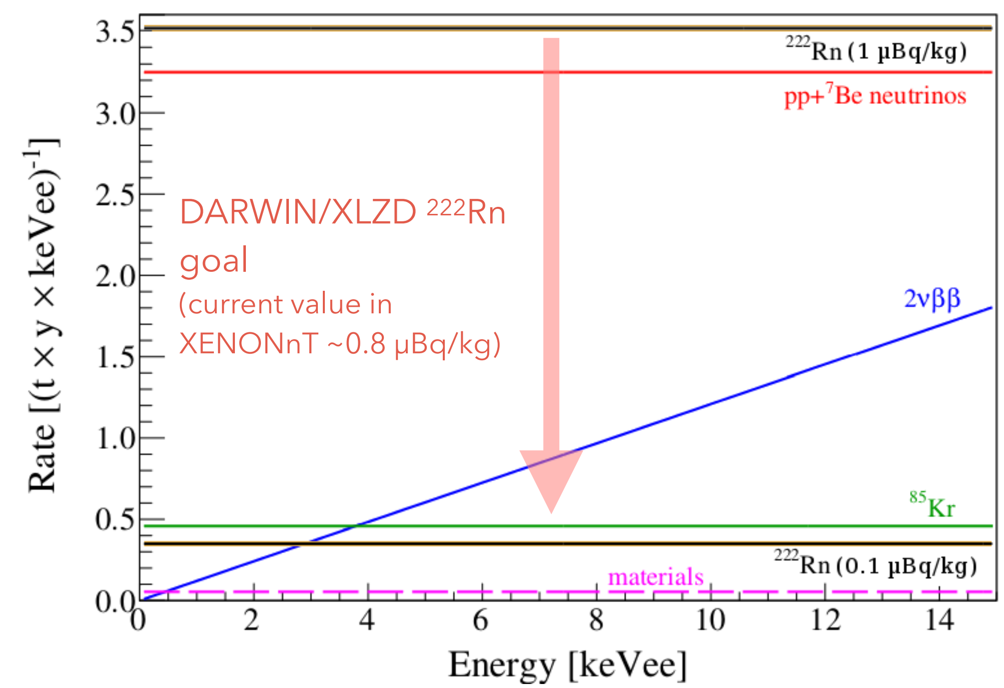
PandaX collaboration, arXiv:2401.07045, Chinese Physics C, in press

Solar ν-electron scattering

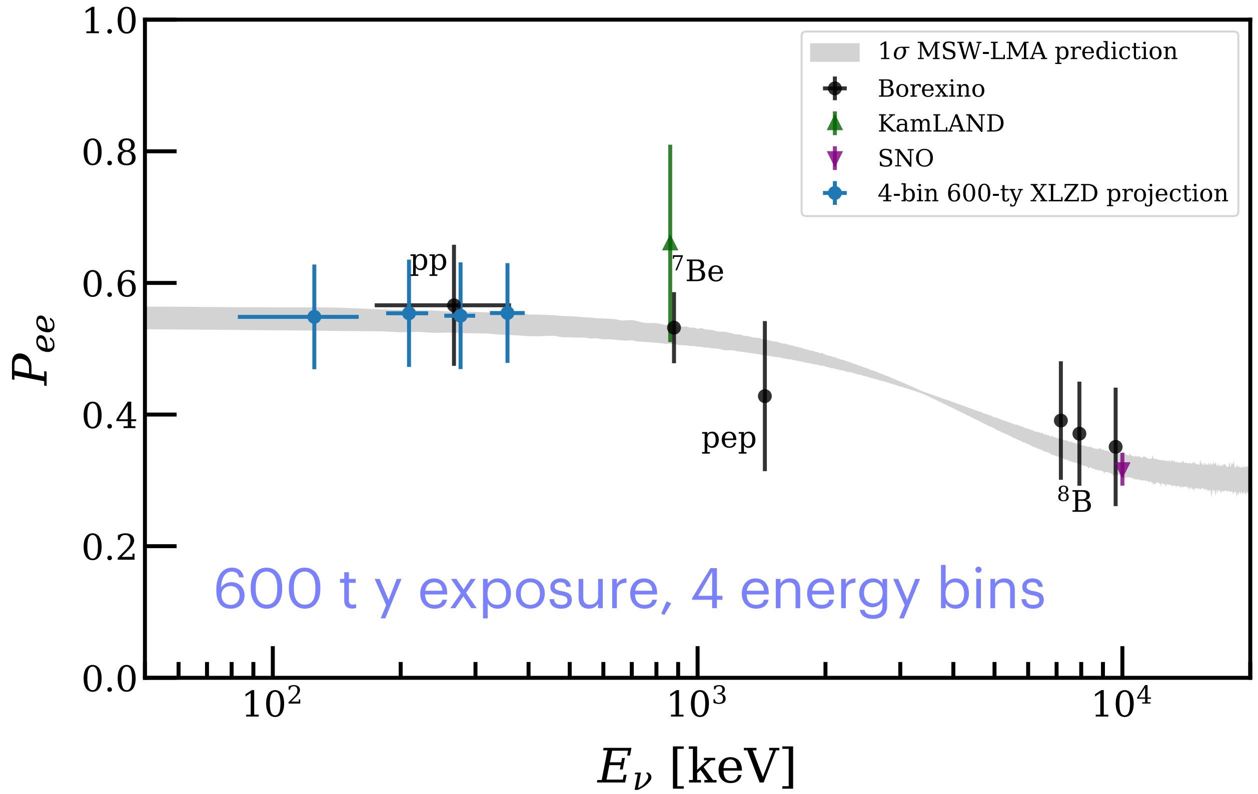


- **Main challenge**: reduce ^{222}Rn (^{214}Pb β-decay) background to x 10 below the pp rate (0.1 μBq/kg)

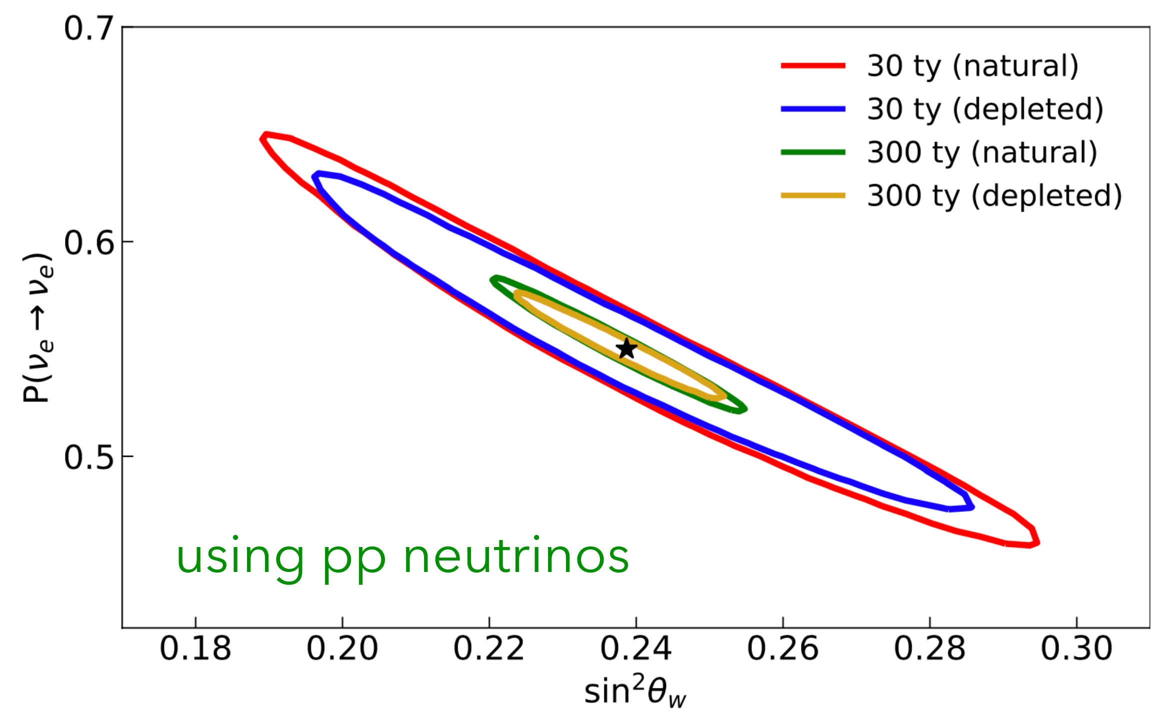
Poster: Diego Ramirez



DARWIN/XLZD predictions



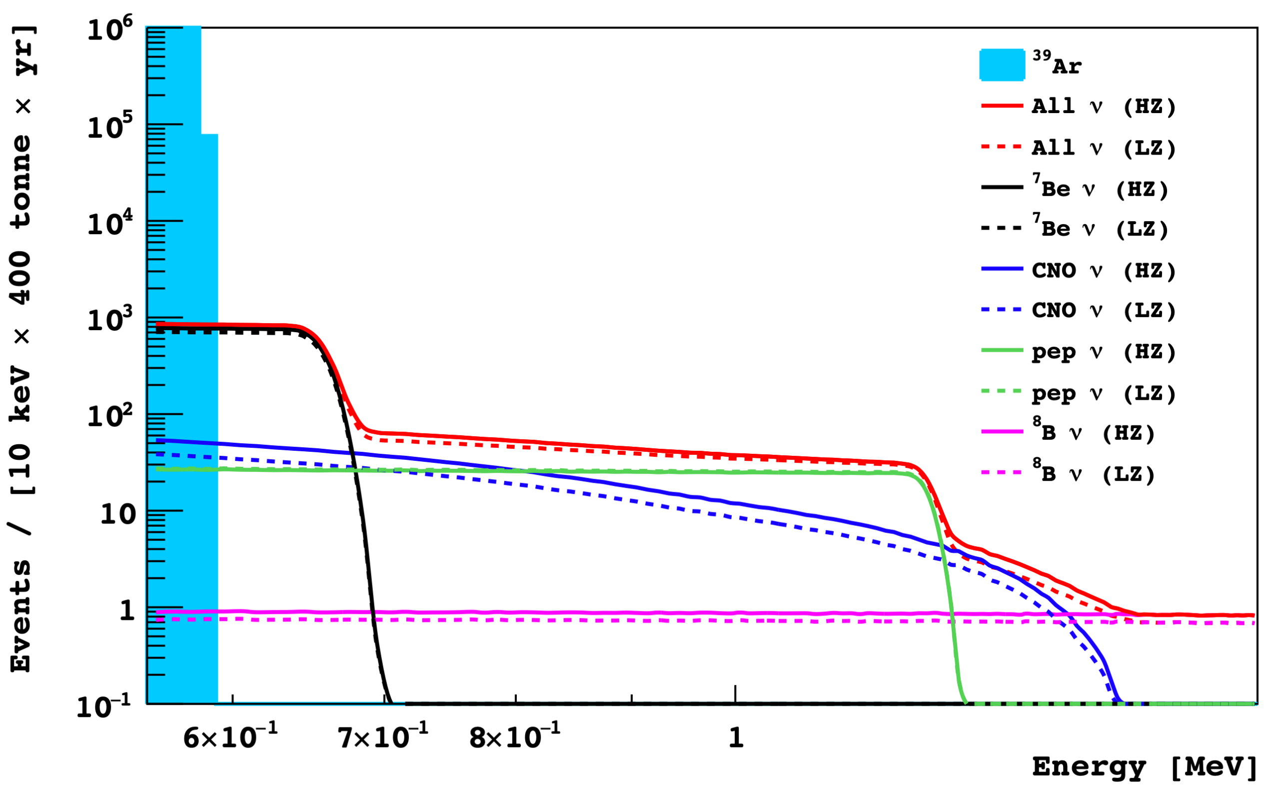
DARWIN collaboration, EPJ-C 80 12 (2020)



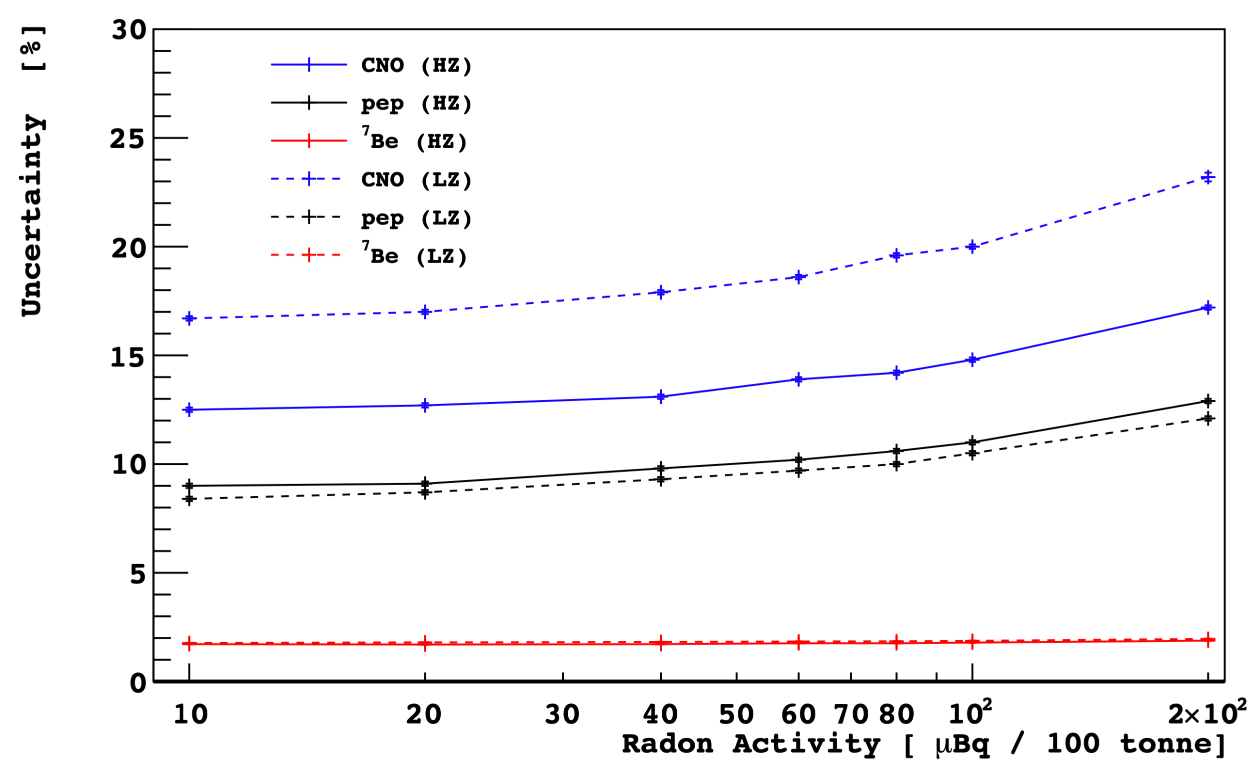
Solar ν-electron scattering

- In LAr: ~ 5 events/(100 t d) from pep, ^{7}Be, CNO and ^{8}B ν
- With 400 t x years exposure: ~2%, ~10%, ~15% for the Be, pep and CNO ν's
- CNO measurement could discriminate between the LZ and the HZ SSM

Neutrino-induced events in LAr



Uncertainty versus ^{222}Rn level



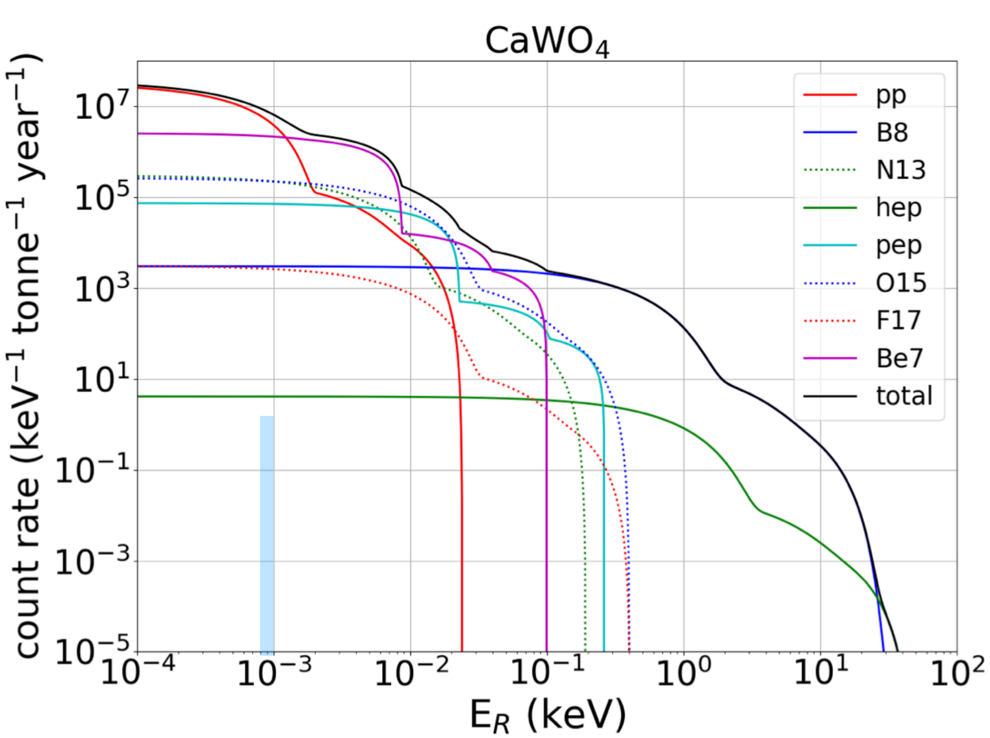
D. Franco et al., JCAP 08, 2016

Solar ν-electron scattering

Poster: Dominik Fuchs

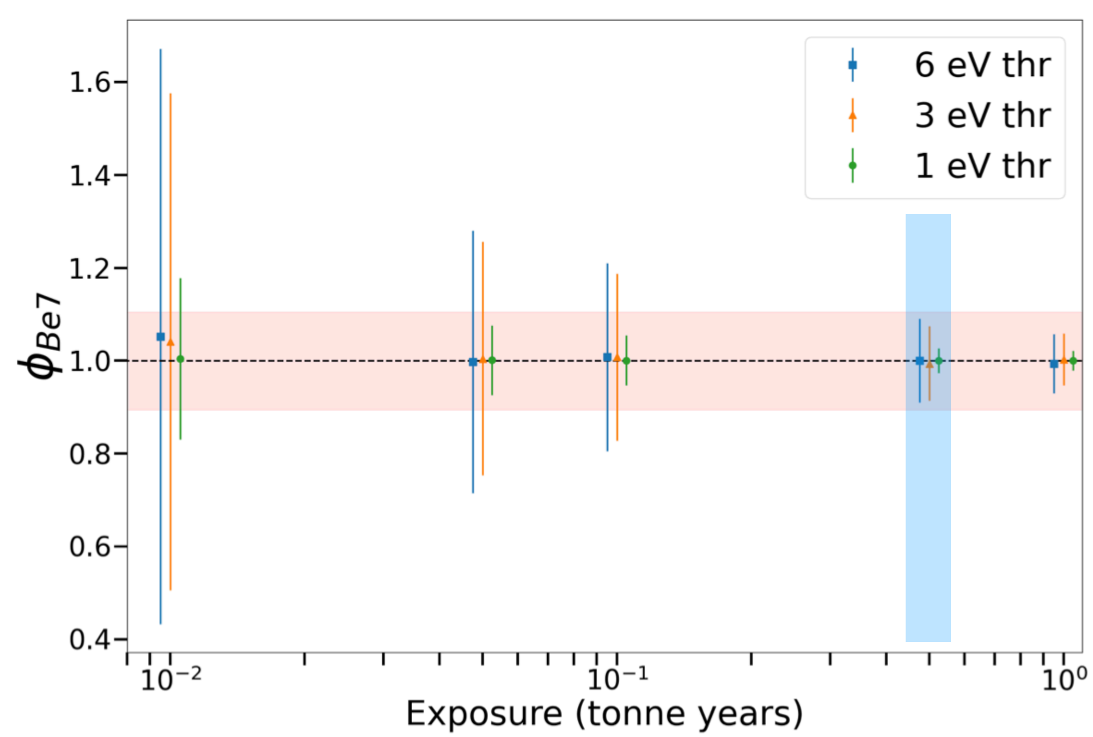
- In low-threshold, cryogenic calorimeters: high rates due eV-scale energy thresholds
- With 500 kg y: ^{7}Be flux uncertainty < theoretical one
- CNO: discriminate between the LZ and the HZ SSM with 1 tonne year exposure

Neutrino-induced events in $CaWO_4$



1 eV

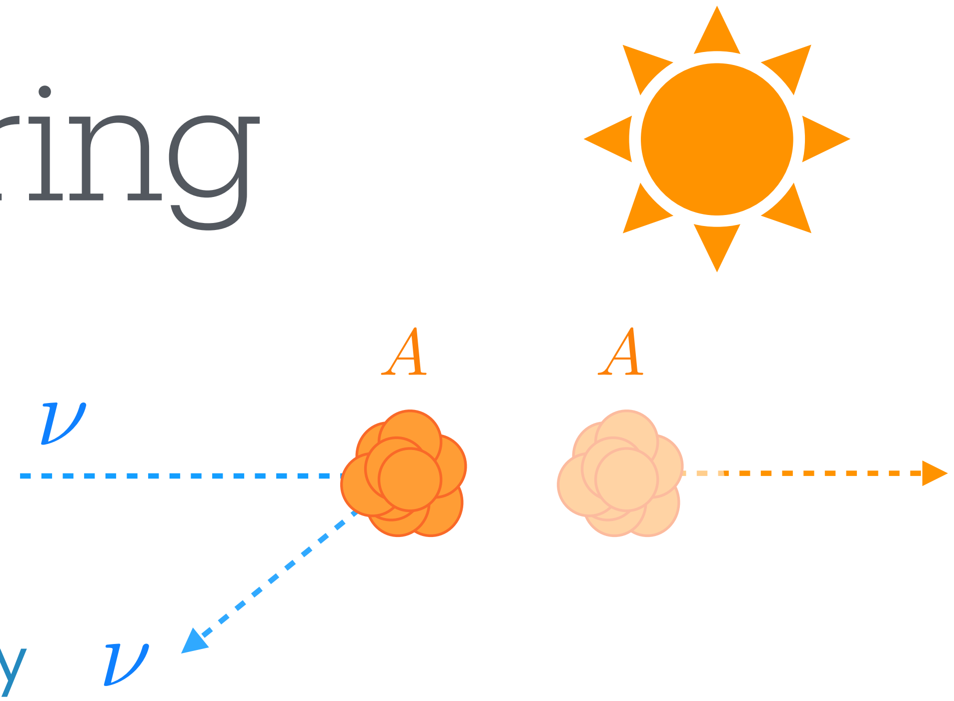
^{7}Be flux vs exposure



500 kg y

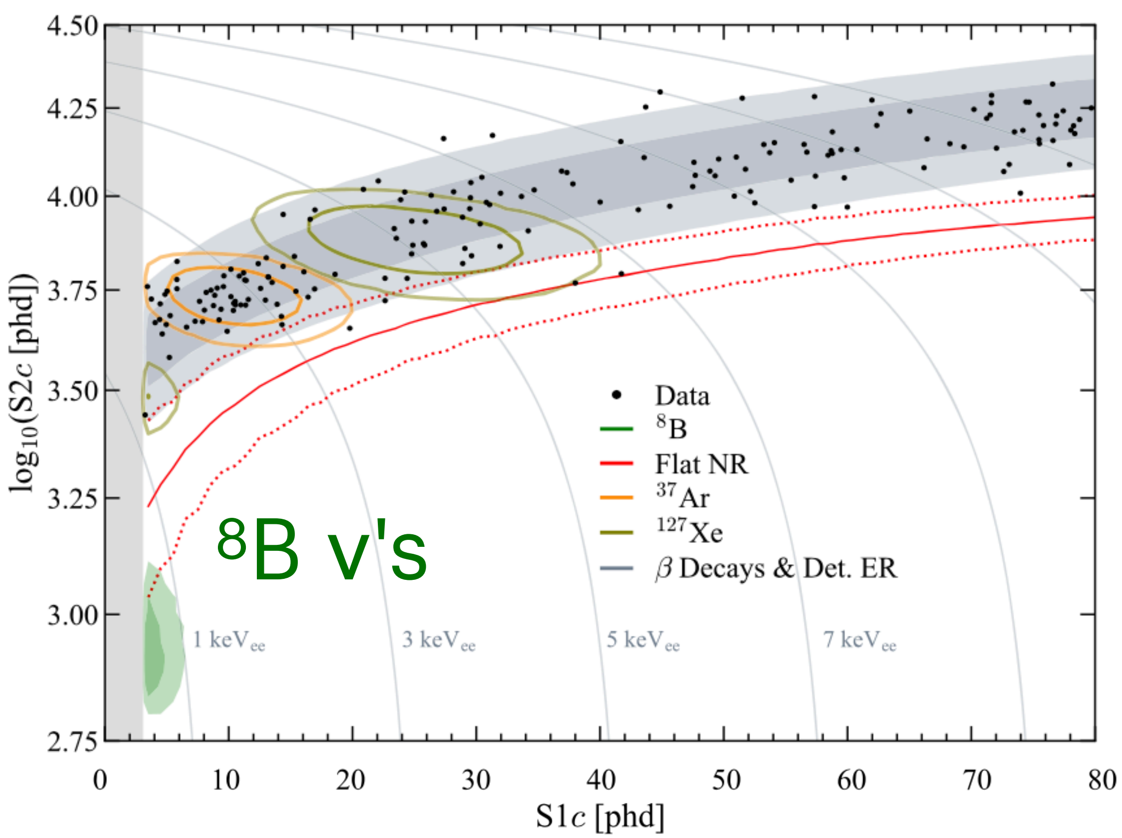
A. Bento et al., arXiv: 2405.02482

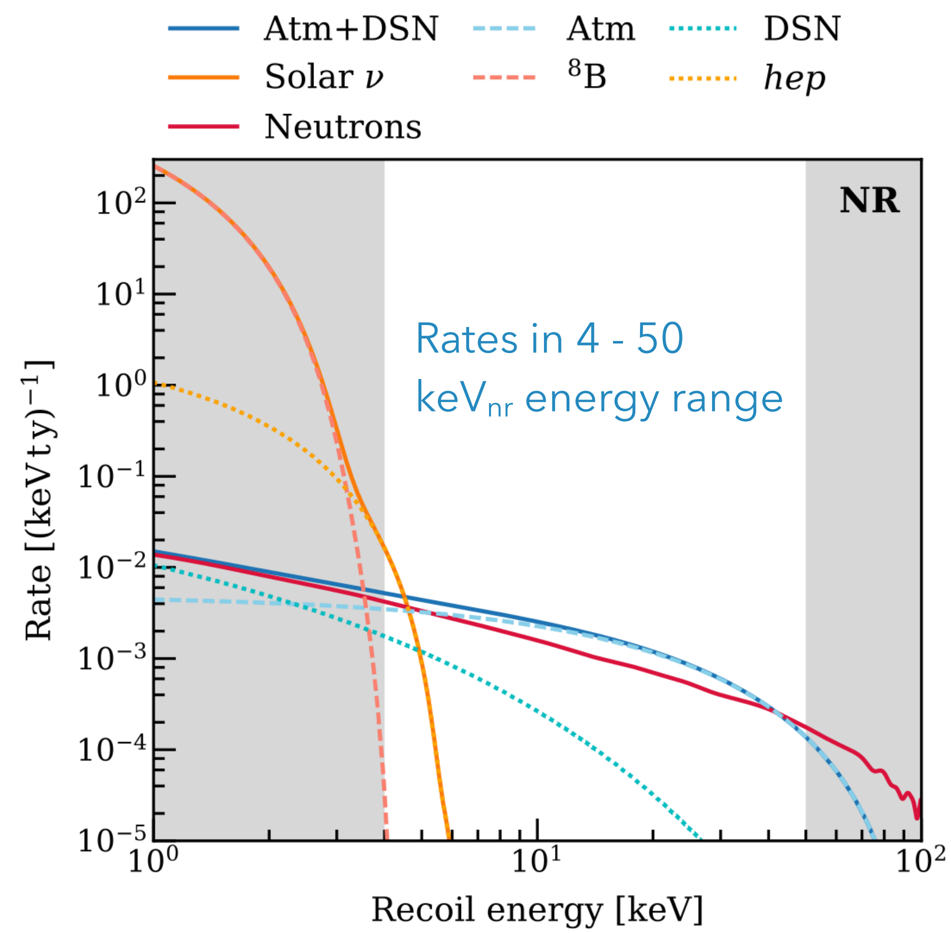
Solar ν-nucleus scattering



- 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 collaboration, JCAP11(2020)031

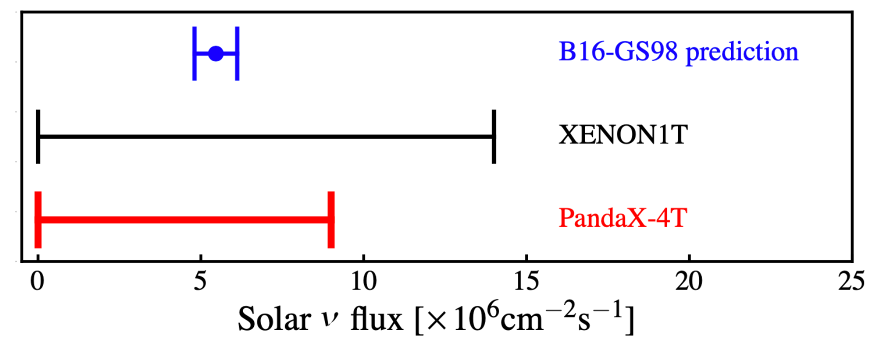
*e.g., X. Xiang et al., PRD 108, 2023

Solar ν-nucleus scattering

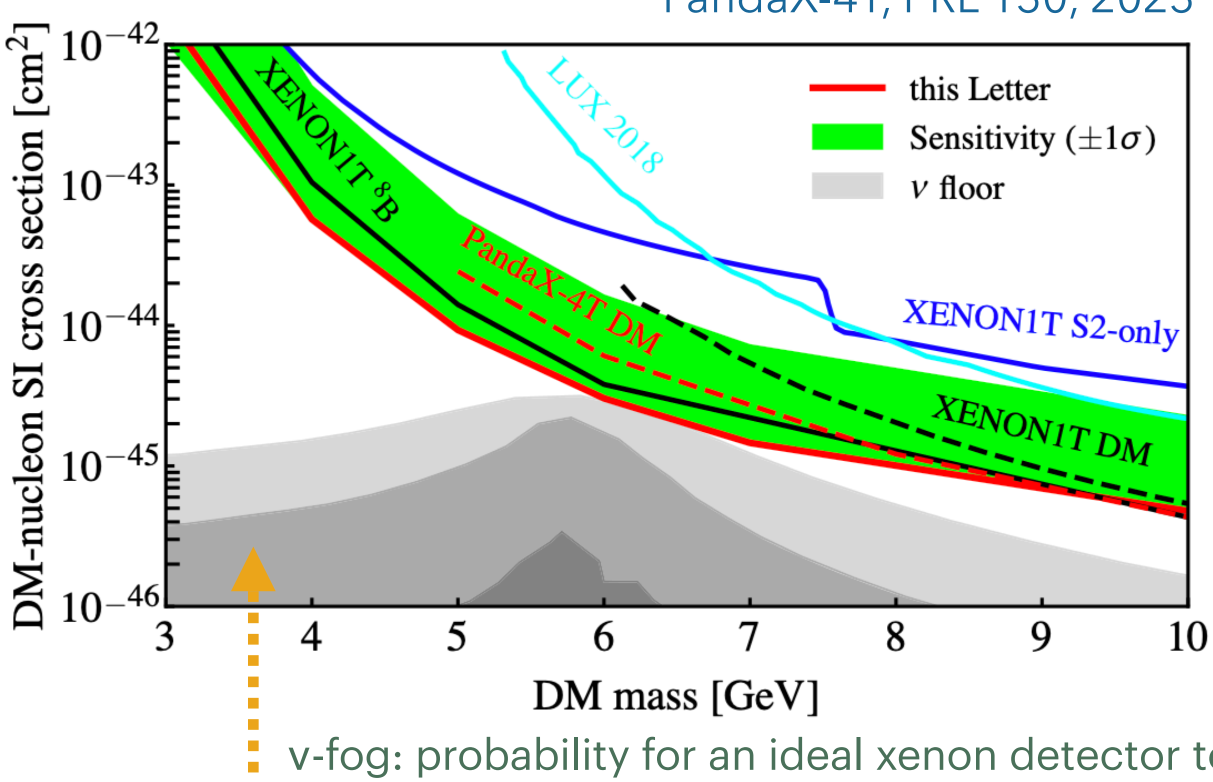
Poster: Yue Meng

- Main goal: observe ^{8}B neutrinos via CEvNS
- Constraints from XENON1T and PandaX-4T
- Ongoing analyses in LZ, XENONnT, PandaX-4T

^{8}B flux prediction & constraints from XENON1T and PandaX-4T

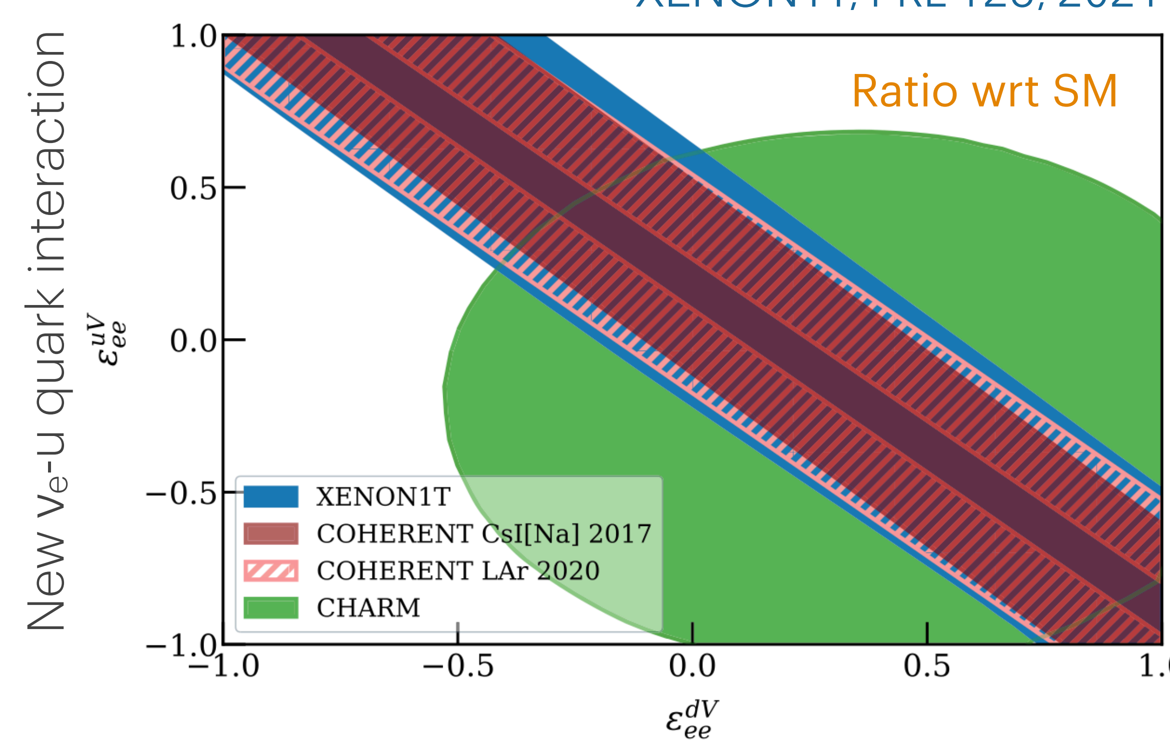


PandaX-4T, PRL 130, 2023



ν-fog: probability for an ideal xenon detector to see < 3-σ DM signal

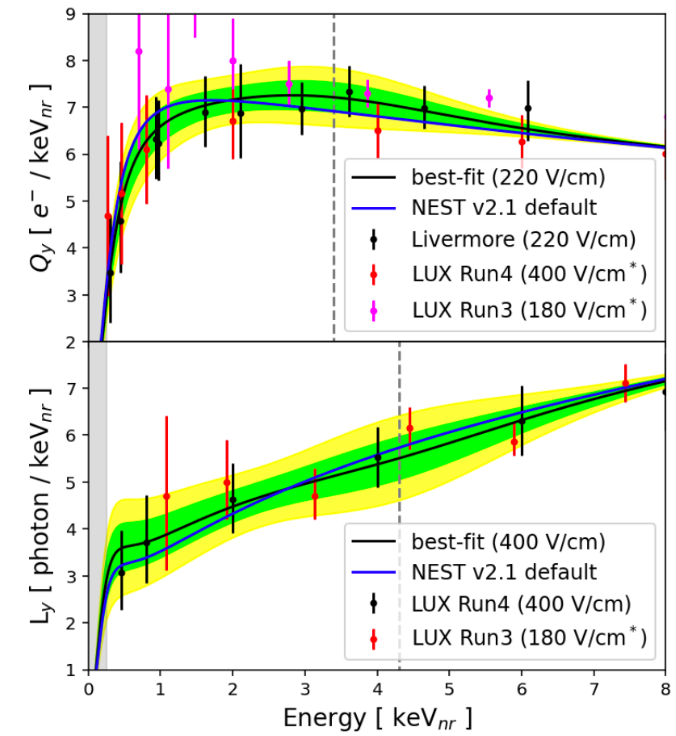
XENON1T, PRL 126, 2021



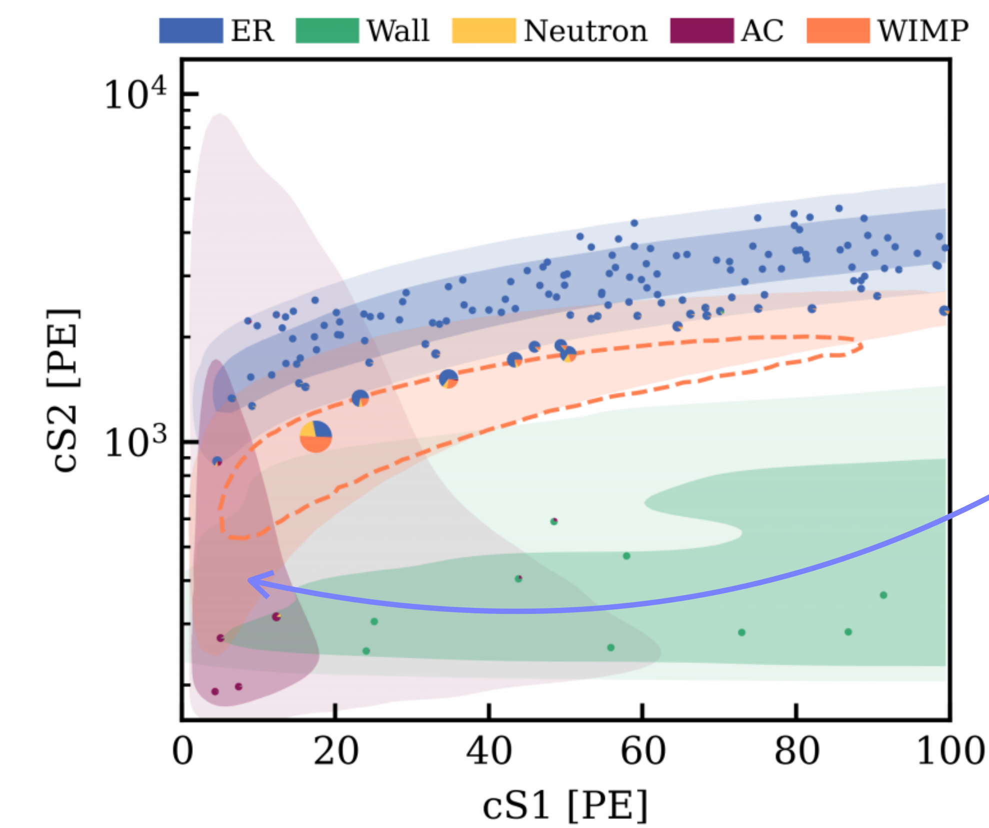
New ν_e-d quark interaction

Solar ν-nucleus scattering

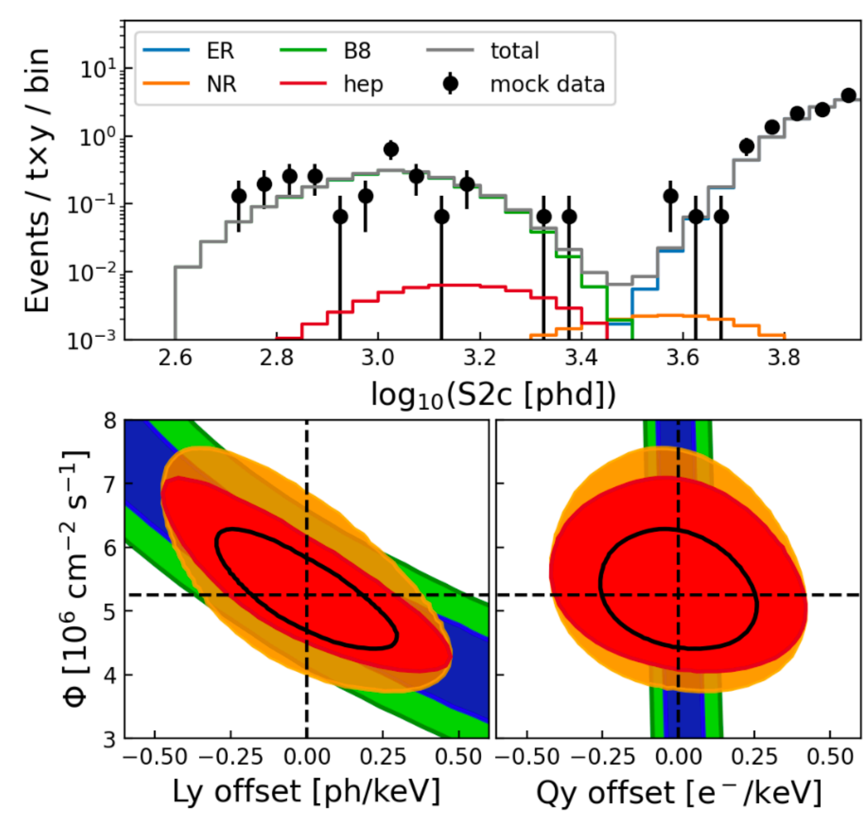
- Main goal: observe ^{8}B neutrinos via CEvNS
- Main background: accidentals
- Main uncertainty: light and charge yields at LEs



XENON, PRL 131, 2023



expect CEvNS events here!

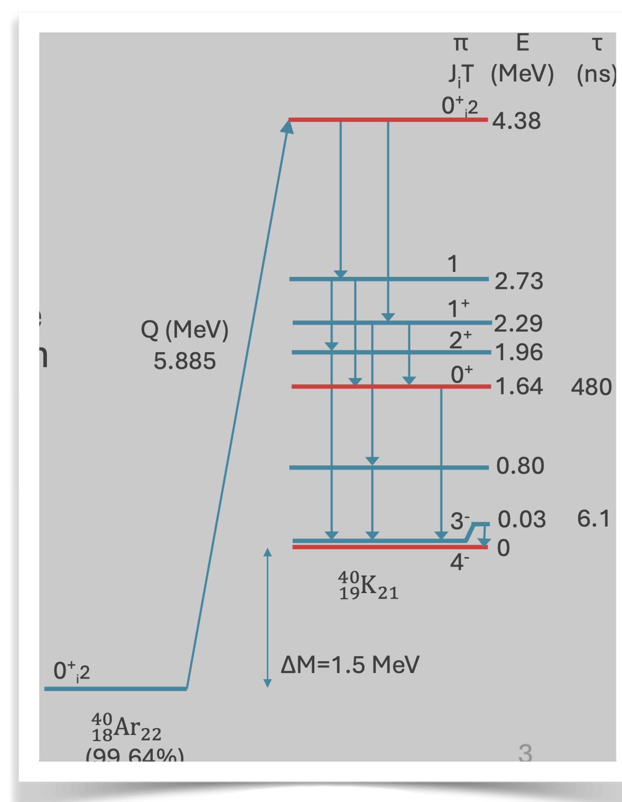


X. Xiang et al., PRD 108, 2023

Solar neutrinos: IBD

- LAr: ν absorption on ^{40}Ar to an excited state of ^{40}K (E_{thr} = 3.9 MeV)*
- Expected rate: ~ 2.2 events/(tonne x year)
- Ongoing search in DEAP-3600** for a first observation
- DarkSide-20k and Argo will provide higher stats measurements

$$\nu_e + ^{40}_{18}\mathrm{Ar} \rightarrow ^{40}_{19}\mathrm{K}^* + e^-$$



*Raghavan 86, Bhattacharia 98

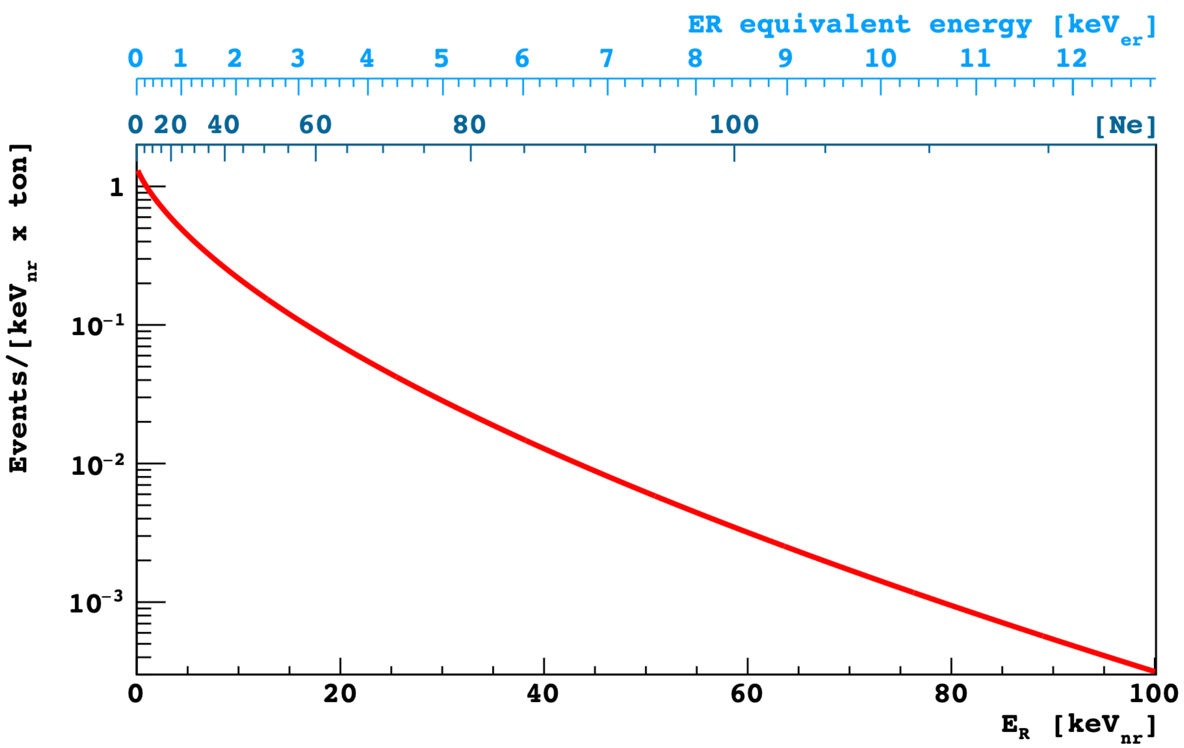
**E. Ellingwood, talks at CAP 2024

SN ν-nucleus scattering

Poster Ricardo Peres

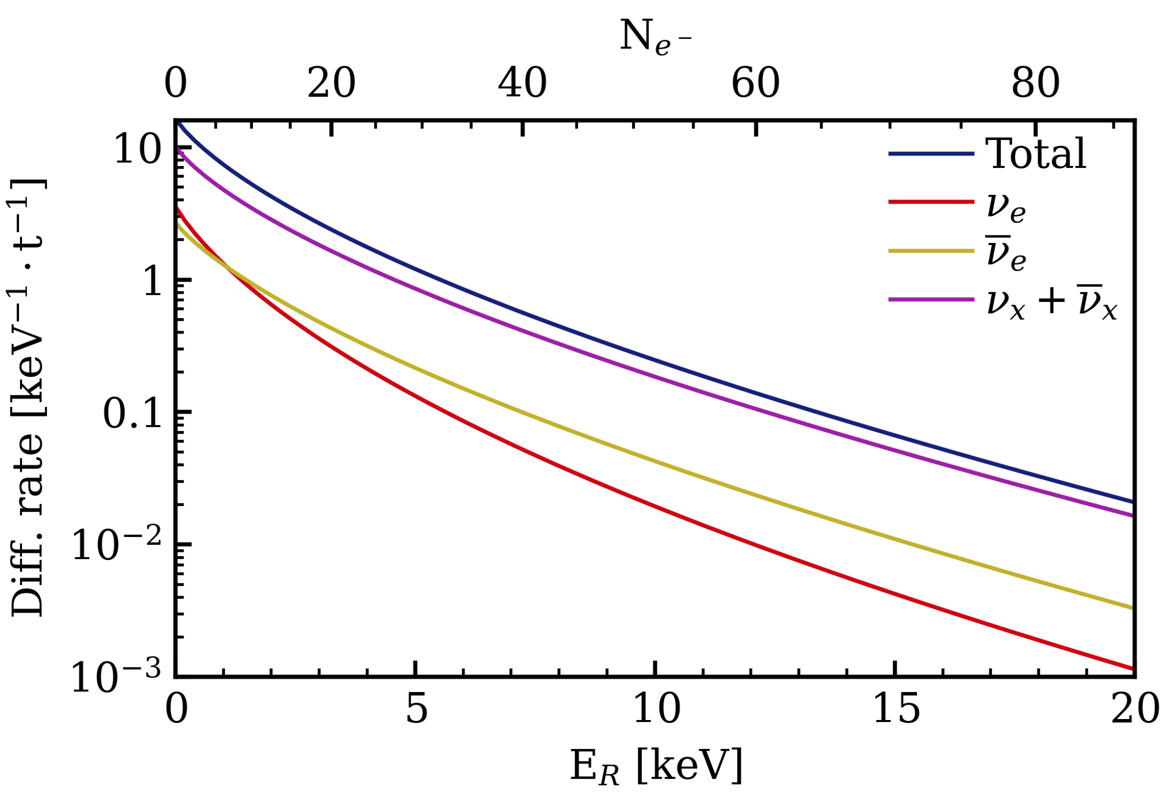
- Sensitivity to all ν flavours: few events/ton expected from SN at ~10 kpc
- LAr: 70% (50%) of events < 10 keV (5 keV) NR; LXe: 90% of events < 5 keV NR
- Main challenge: low energies, understand few-e$^-$ backgrounds

Rate in LAr, 27 $M_\odot$ SN at 10 kpc



Agnes et al., JPCAP 043, 2021

Rates in LXe, 27 $M_\odot$ SN at 10 kpc

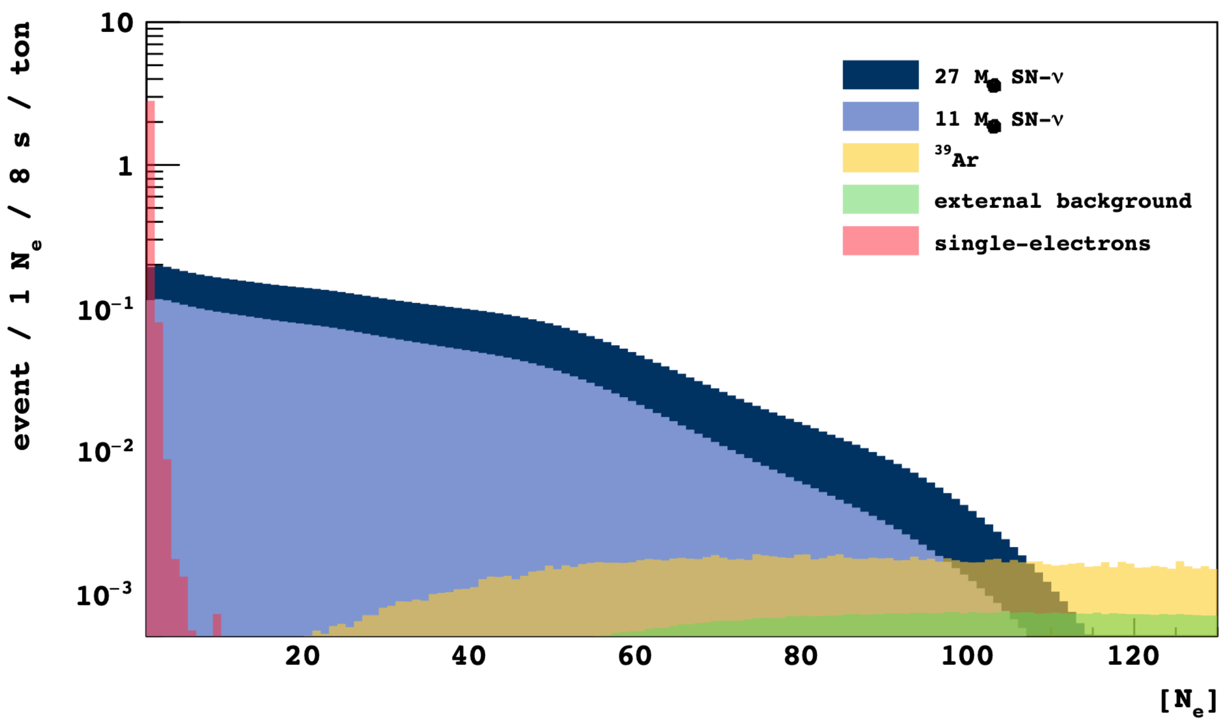


R. Peres, XENON

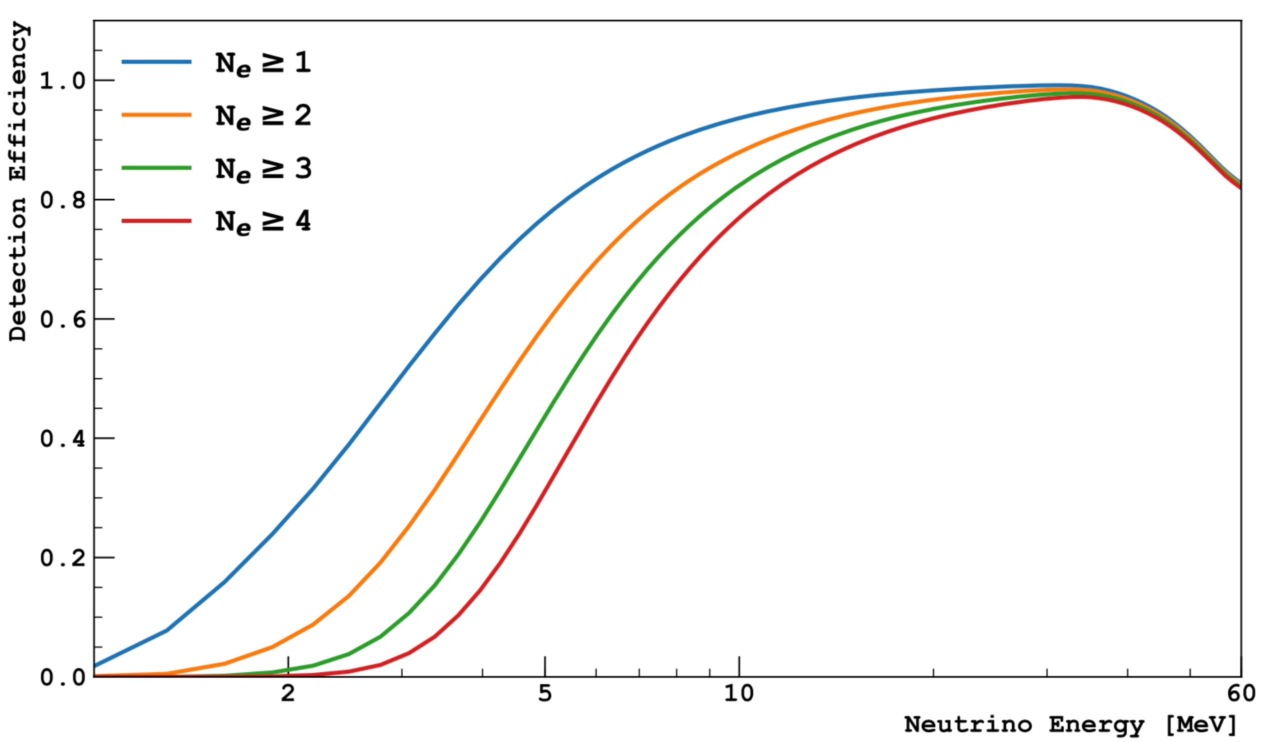
SN ν-nucleus scattering

- Sensitivity to all ν flavours, few events/ton expected from SN at ~10 kpc
- LAr: 70% (50%) of events < 10 keV (5 keV) NR; LXe: 90% of events < 5 keV NR
- Main challenge: low energies, understanding of few-e⁻ backgrounds

DarkSide-20K: rate in LAr, 11 and 27 $M_\odot$ SN at 10 kpc



Detection efficiency for different thresholds, LAr

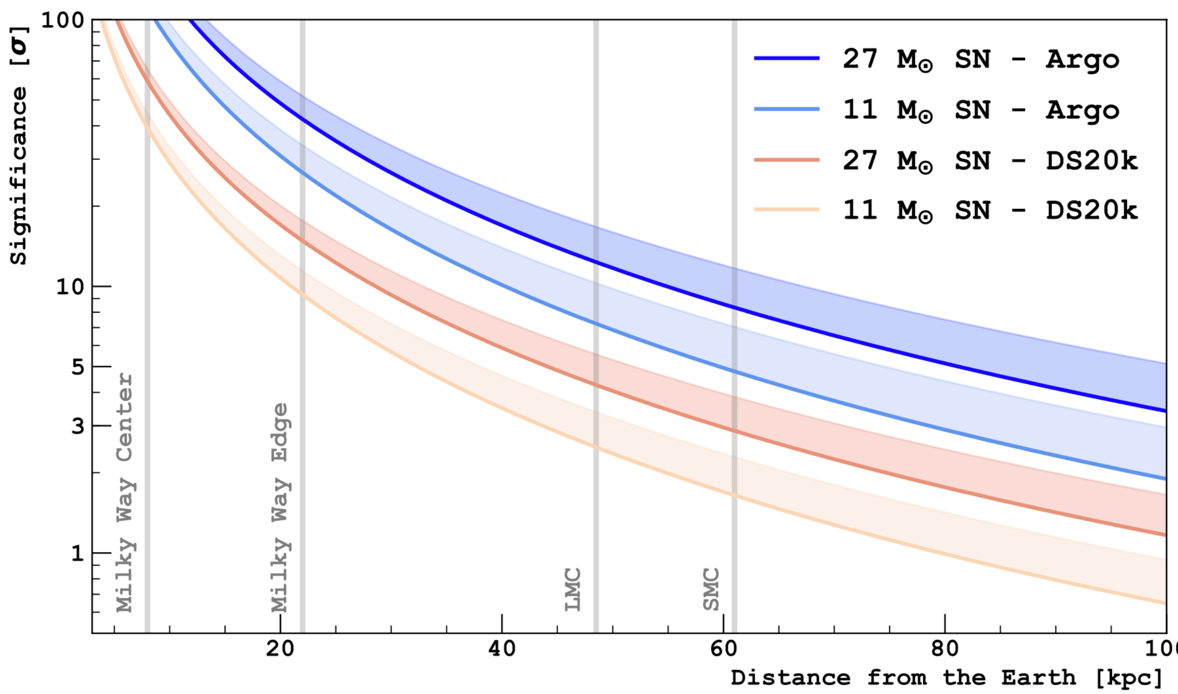


Agnes et al., JPCAP 043, 2021

SN ν-nucleus scattering

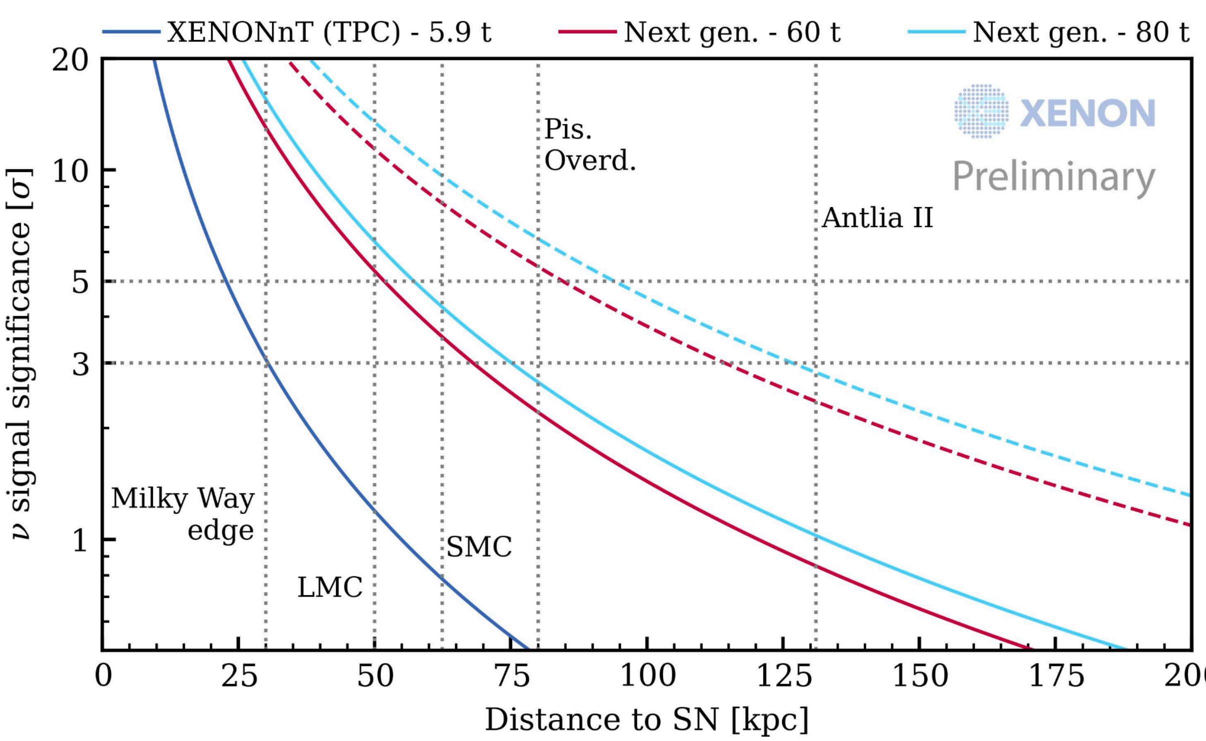
- Next-generation detectors: sensitivity beyond SMC
- XENONnT and DarkSide-20k at LNGS: part of SNEWS2.0
- Good time resolution due to CC interactions in outer vetoes

LAr: DarkSide20k and Argo



Agnes et al., JPCAP 043, 2021

LXe: XENONnT/LZ and DARWIN/XLZD



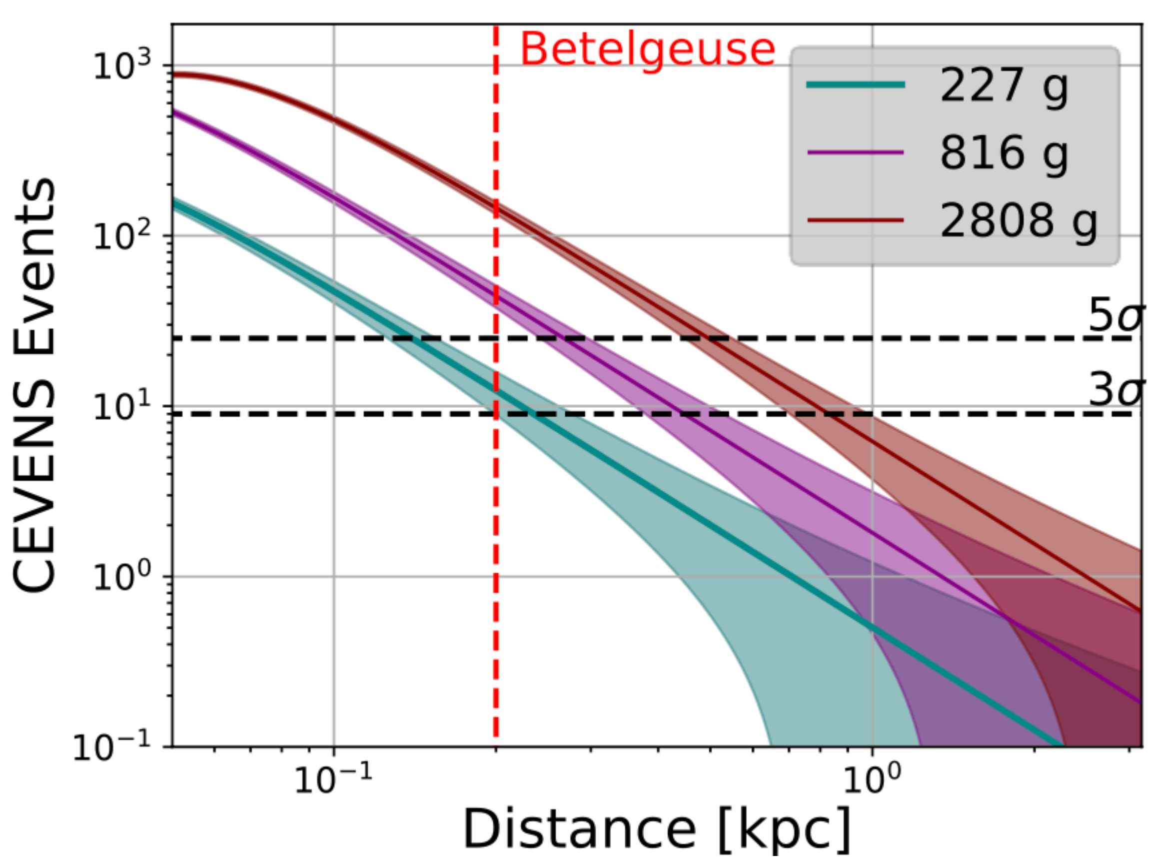
XENON collaboration

SN ν-nucleus scattering

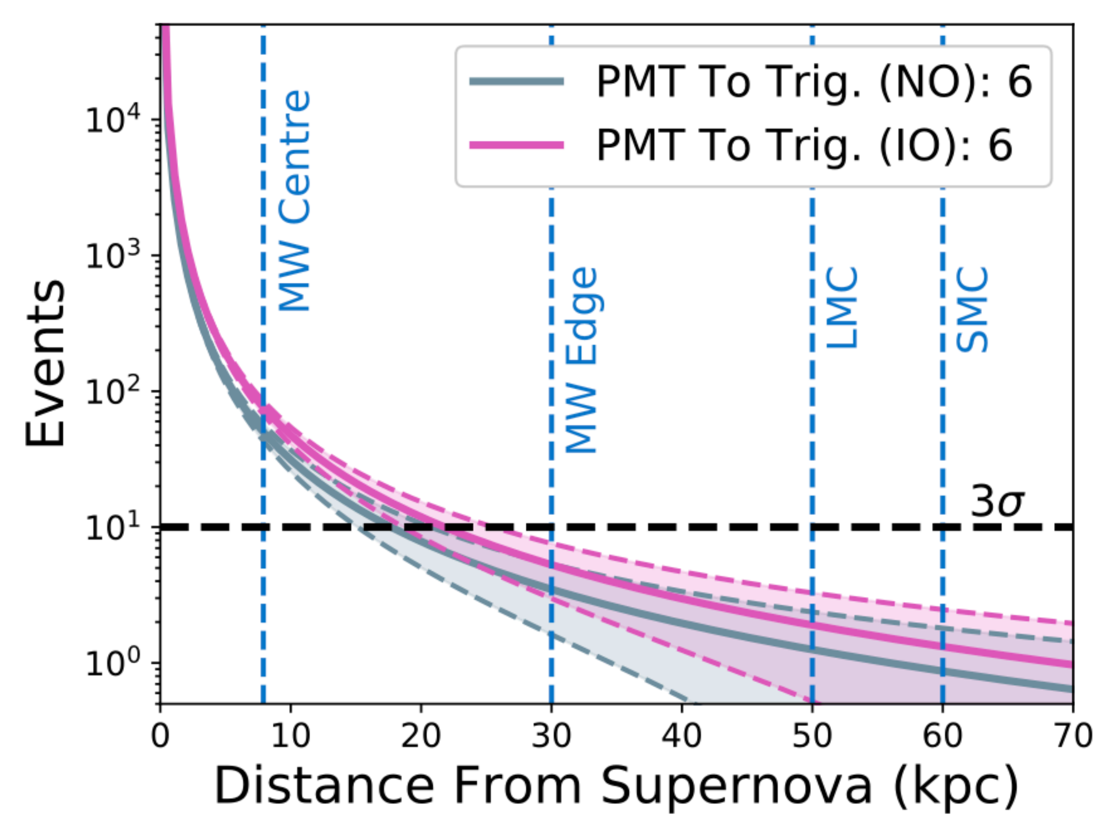
Poster Max Hughes

- Cryogenic bolometers can probe the local region in the MW
- NaI bolometer: sensitive up to 1 kpc
- Muon veto (water Cherenkov): sensitive up to 16 kpc

COSINUS: NaI bolometers



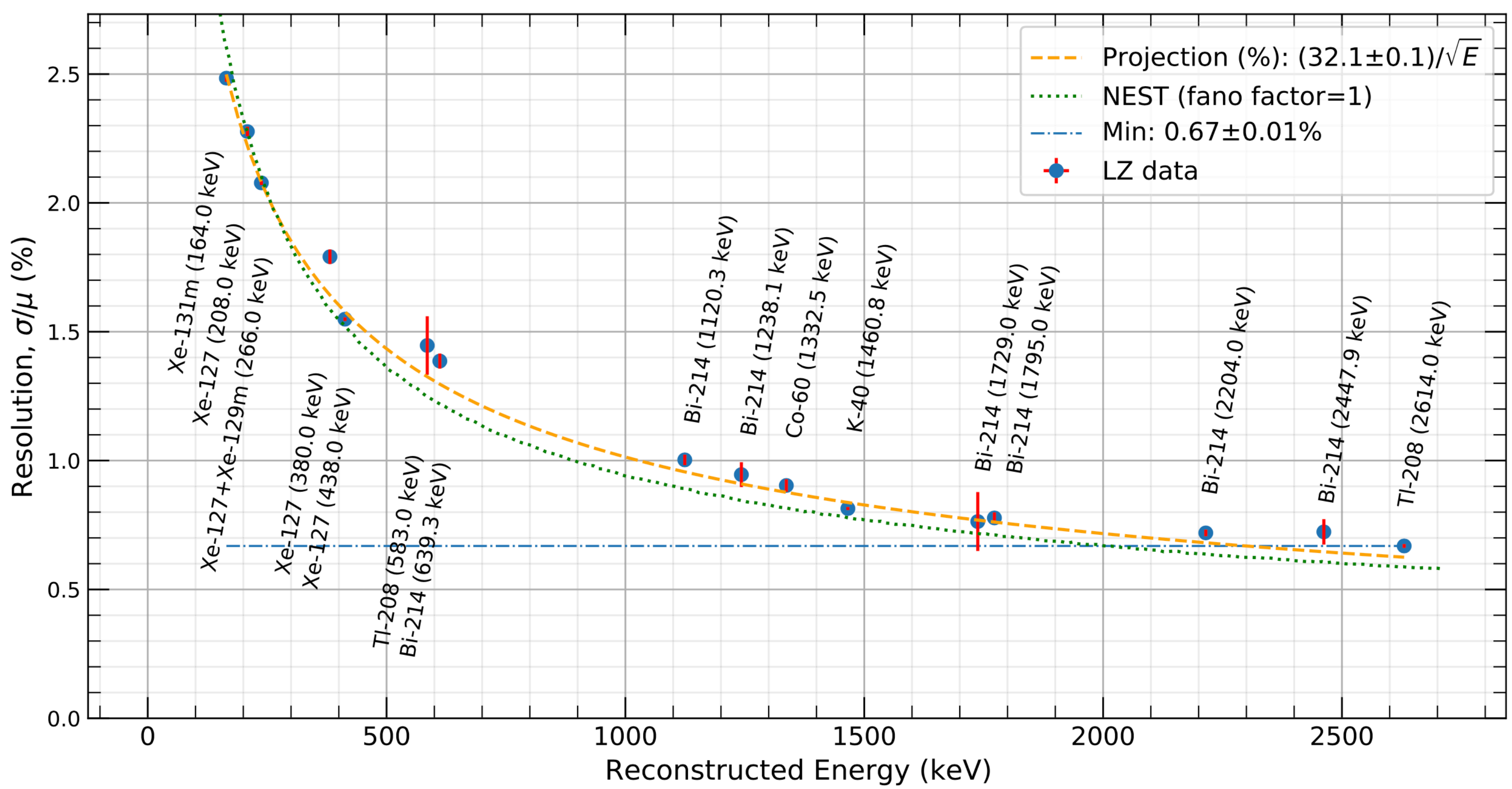
COSINUS: muon veto



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

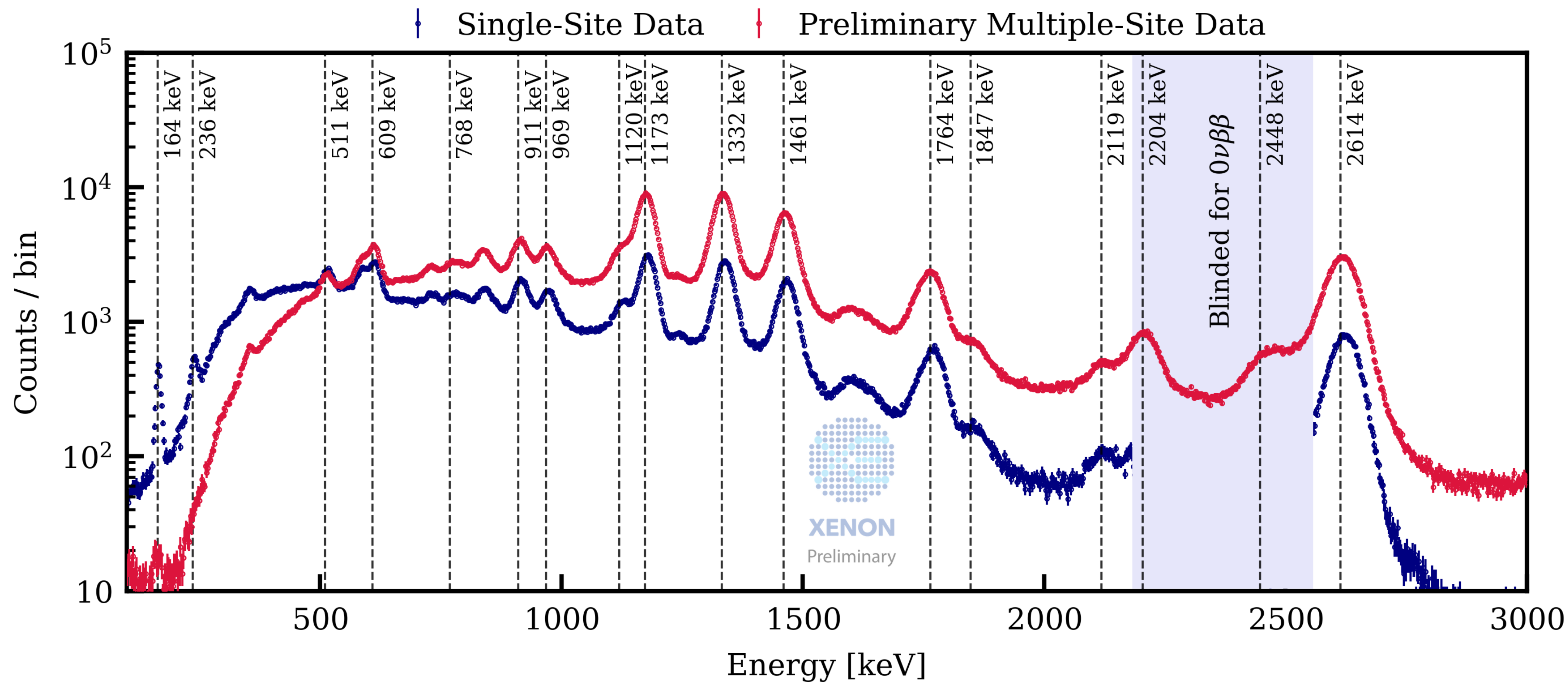


$0\nu\beta\beta$ decay of ^{136}Xe

Poster Maxime Pierre

- Ongoing searches in LZ, PandaX-4T, XENONnT
- LZ sensitivity: $T_{1/2} \sim 1.2 \times 10^{26}$ y

XENONnT, preliminary; ^{136}Xe $0\nu\beta\beta$ region blinded



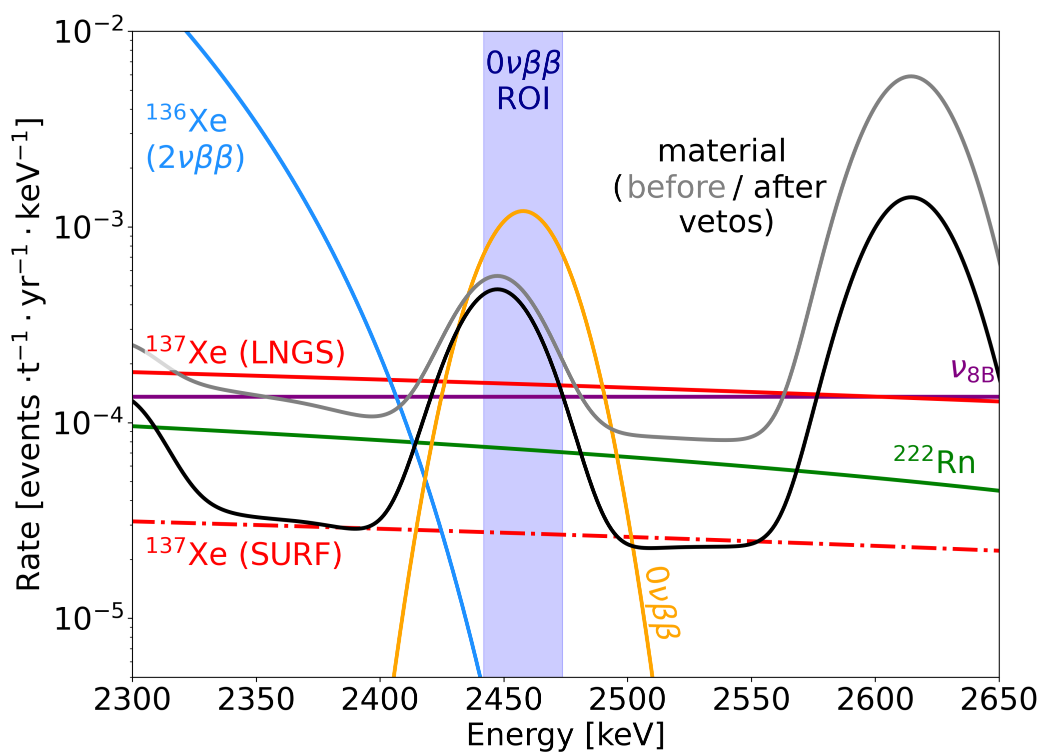
$0\nu\beta\beta$ decay of ^{136}Xe

Posters: Jose Cuenca, Diego Ramirez

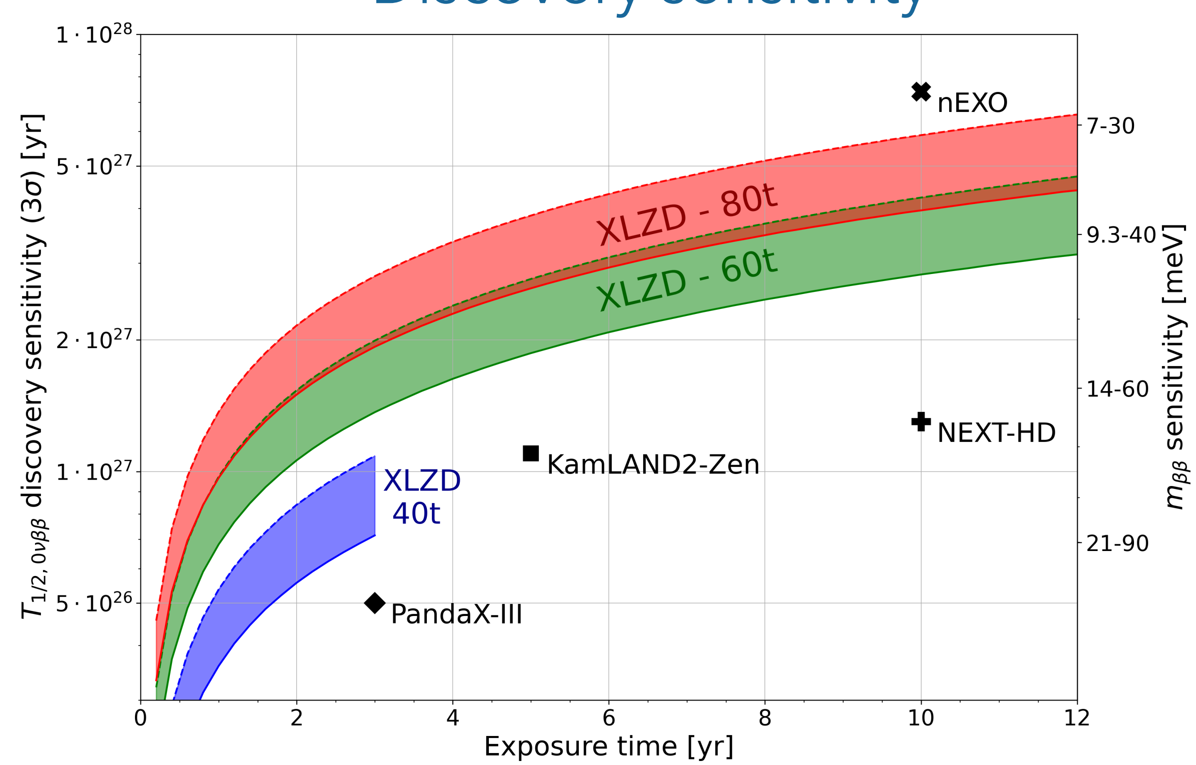
- Proof-of-concept for next-generation detectors, XLZD and PandaX-xT
- Assumptions: 0.1 μBq/kg ^{222}Rn, materials radiopurity already identified

XENON-LUX-ZEPLIN-DARWIN (XLZD) preliminary

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



Discovery sensitivity

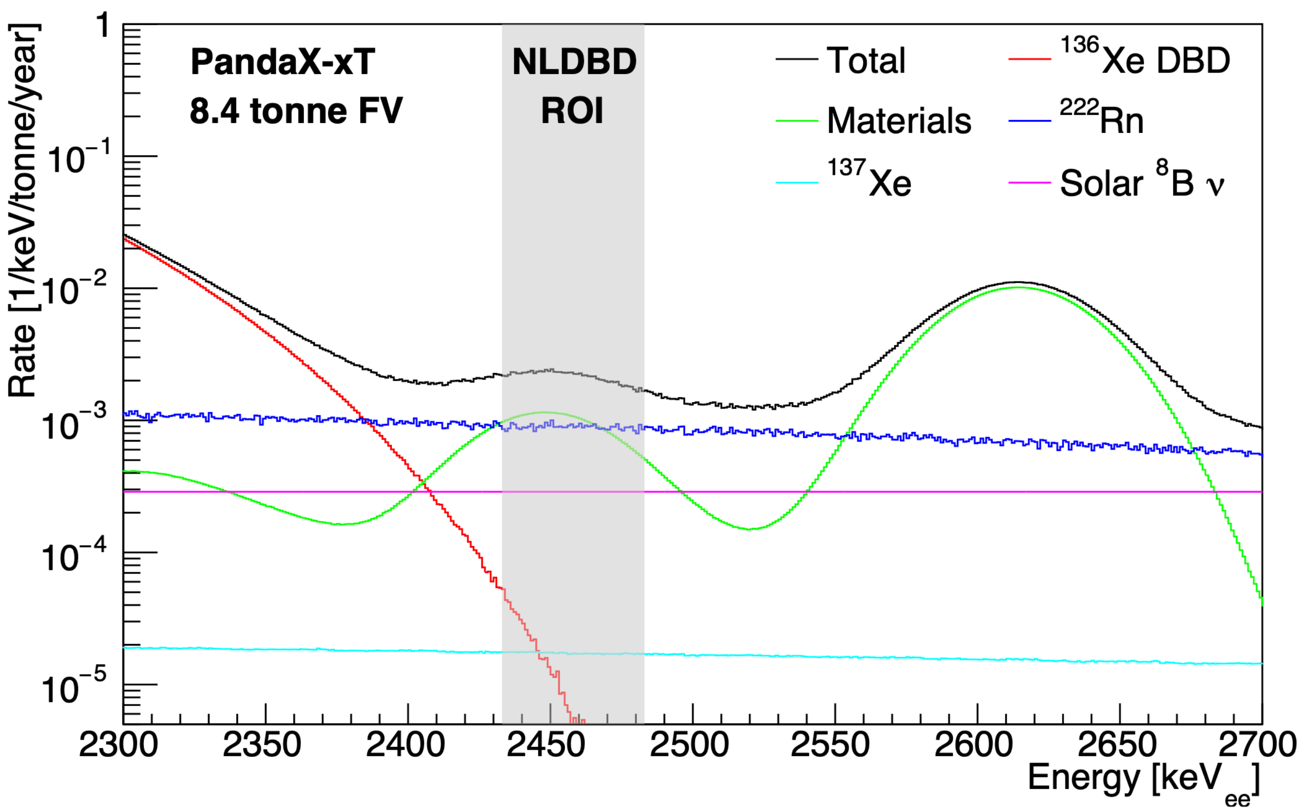


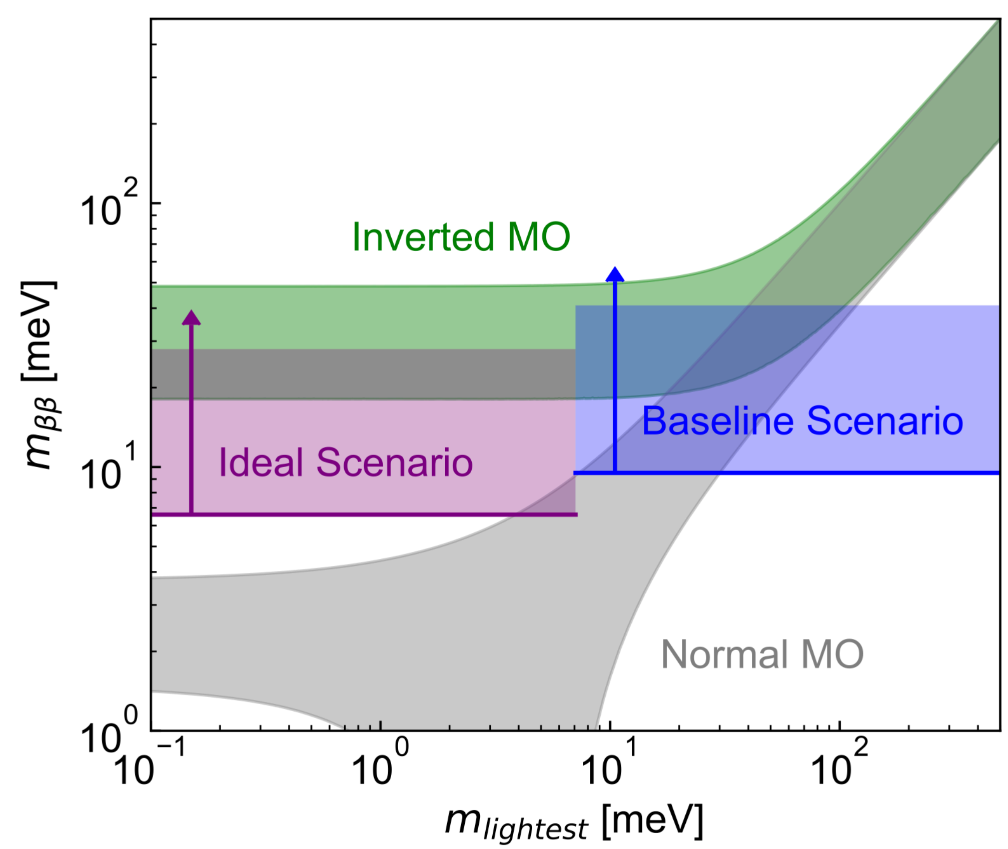
DARWIN study: EPJ-C 80, 2020

0νββ decay of ^{136}Xe

- Proof-of-concept for next-generation detectors, XLZD and PandaX-xT
- Assumptions: 0.1 μBq/kg ^{222}Rn, materials radiopurity already identified

Projections for PandaX-xT (4 t of ^{136}Xe)

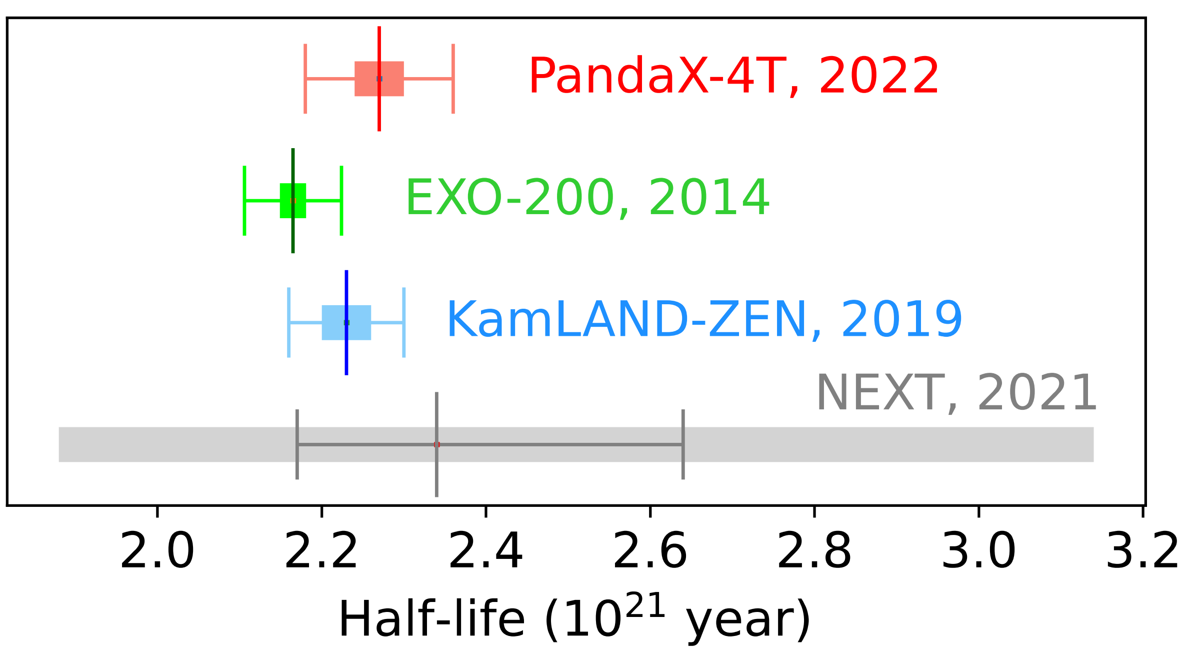


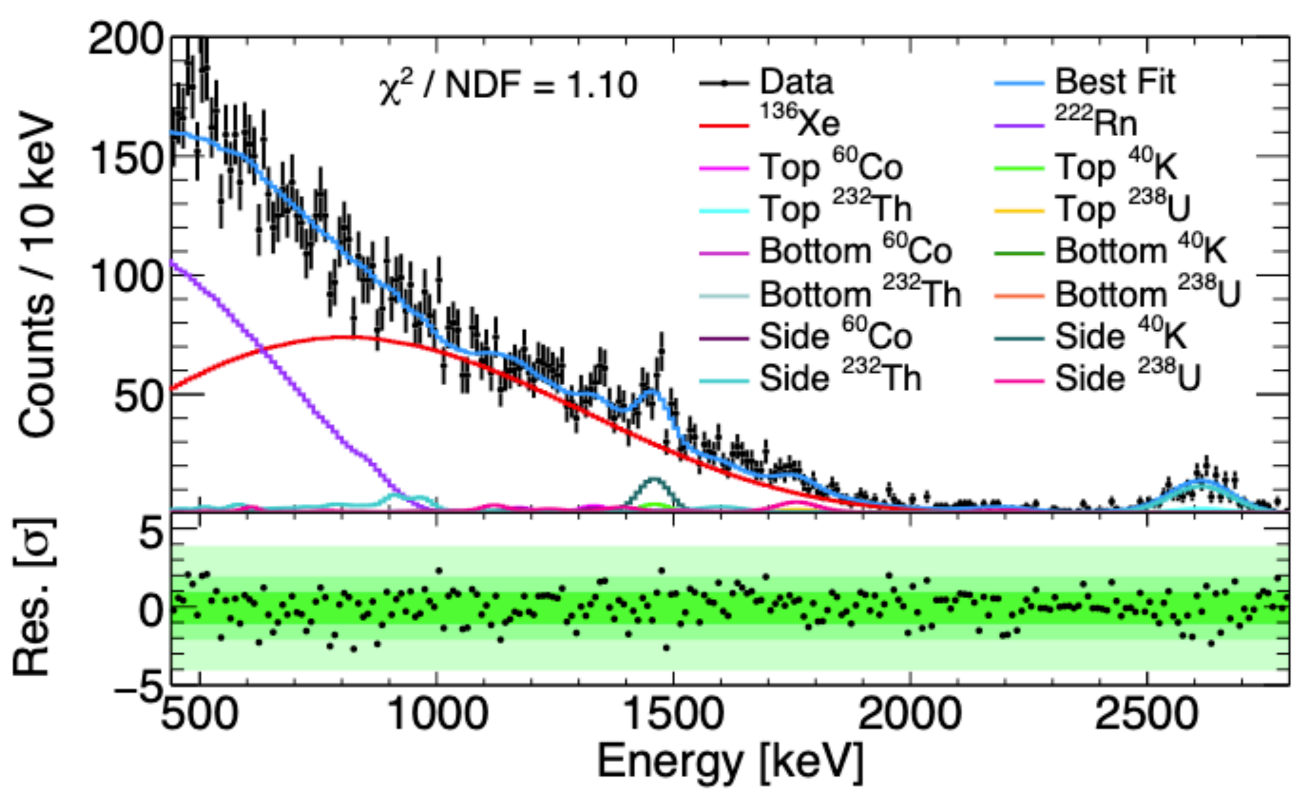


HAN, Ke (Shanghai Jiao Tong University)

2νββ decay of ^{136}Xe

- $T_{1/2}$ measured by PandaX-4T: 2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} y
- First measurement in ^{nat}Xe, in large (440 - 2800 keV) ROI





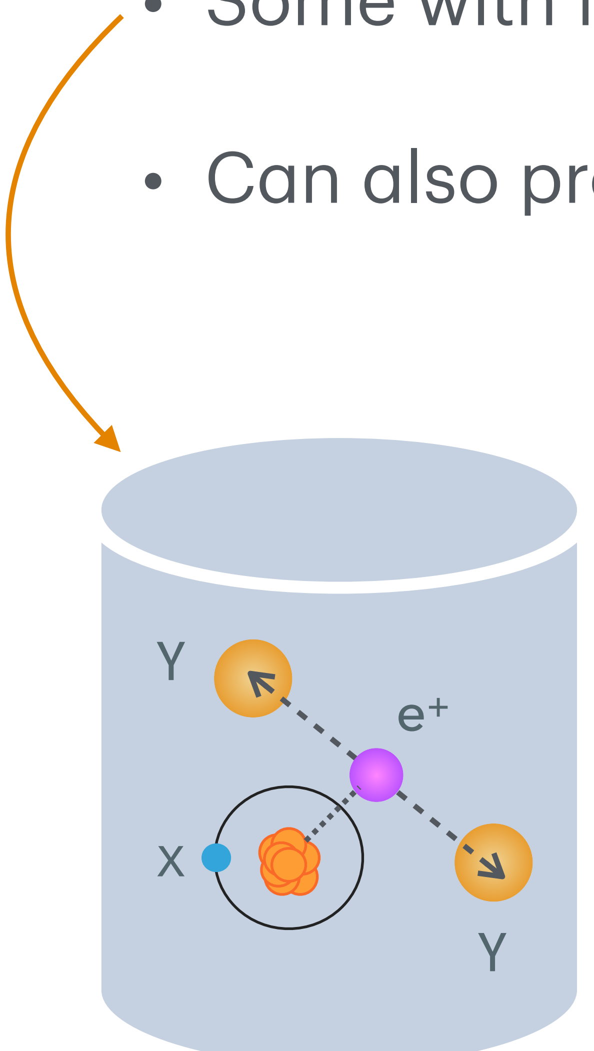
PandaX, Research, 9798721 (2022)

HAN, Ke (Shanghai Jiao Tong University)

Other 2nd order weak decays

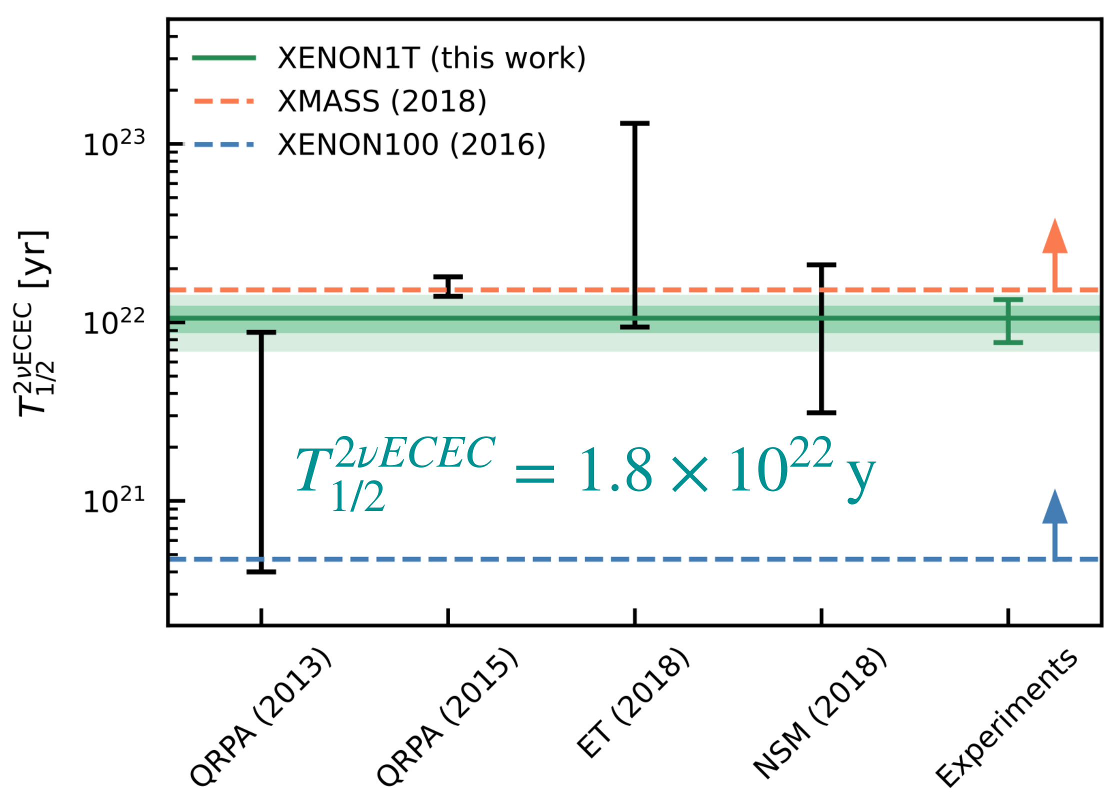
Posters: Zihao Bo, Paloma Cimental

- ^{36}Ar, ^{124}Xe, ^{126}Xe, ^{134}Xe
- Some with interesting topologies 0ν/2νECβ⁺, 0ν/2νβ⁺β⁺
- Can also probe SM/nuclear physics



Q (^{124}Xe) = (2856.73 ± 0.12) keV

XENON, PRC 106, 2022

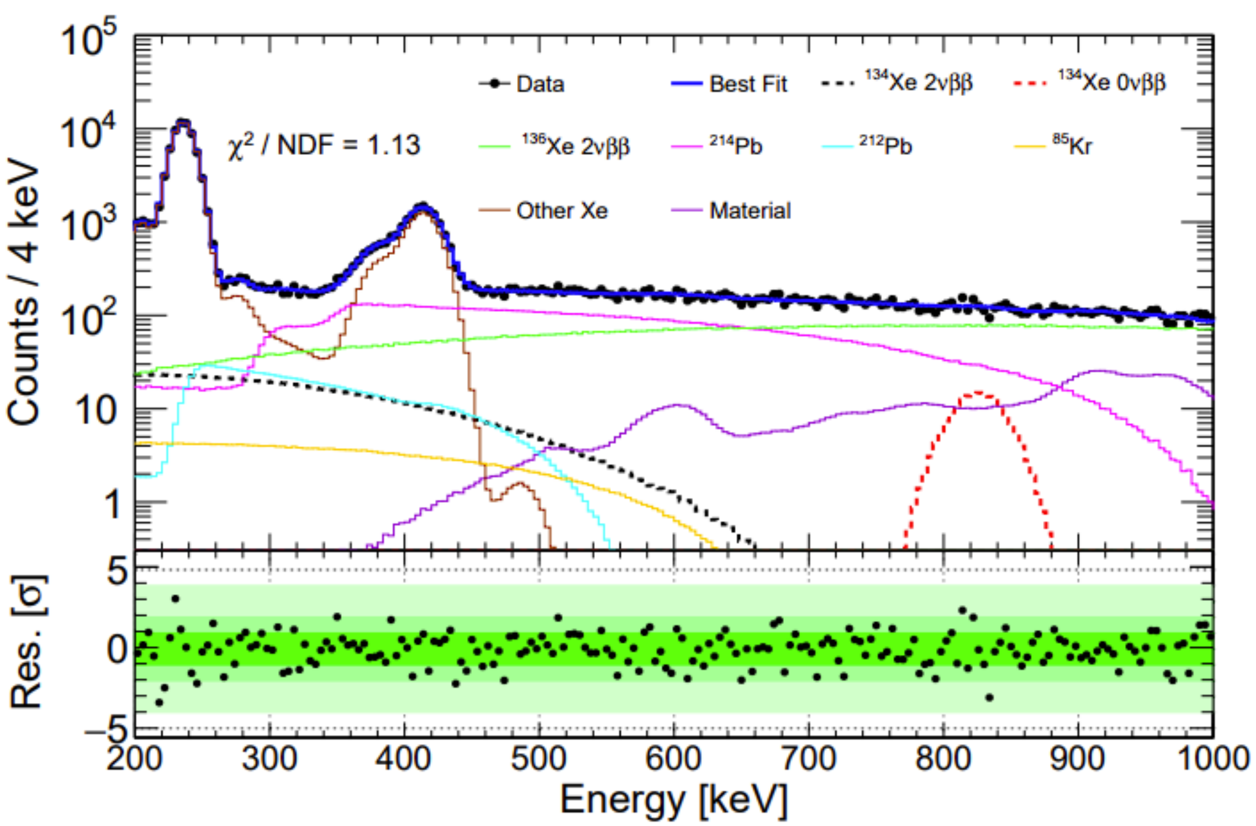


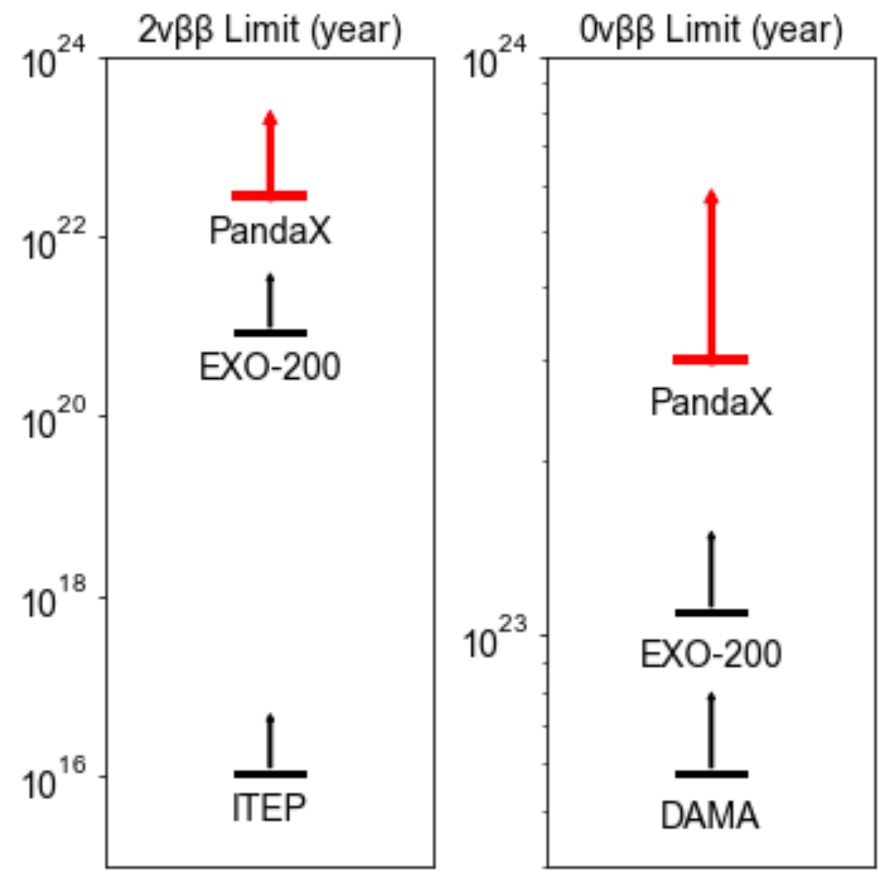
$$^{124}\mathrm{Xe} + 2\mathrm{e}^- \rightarrow {}^{124}\mathrm{Te} + 2\nu_e$$

XENON, Nature 568, 2019

Other 2nd order weak decays

- ^{36}Ar, ^{124}Xe, ^{126}Xe, ^{134}Xe (10.4% in ^{nat}Xe)
- First results on ^{134}Xe from PandaX-4T
- Lower limits: $T_{1/2}^{2\nu\beta\beta} > 2.8 \times 10^{22}\, y$, $T_{1/2}^{0\nu\beta\beta} > 3 \times 10^{23}\, y$ (90% CL)



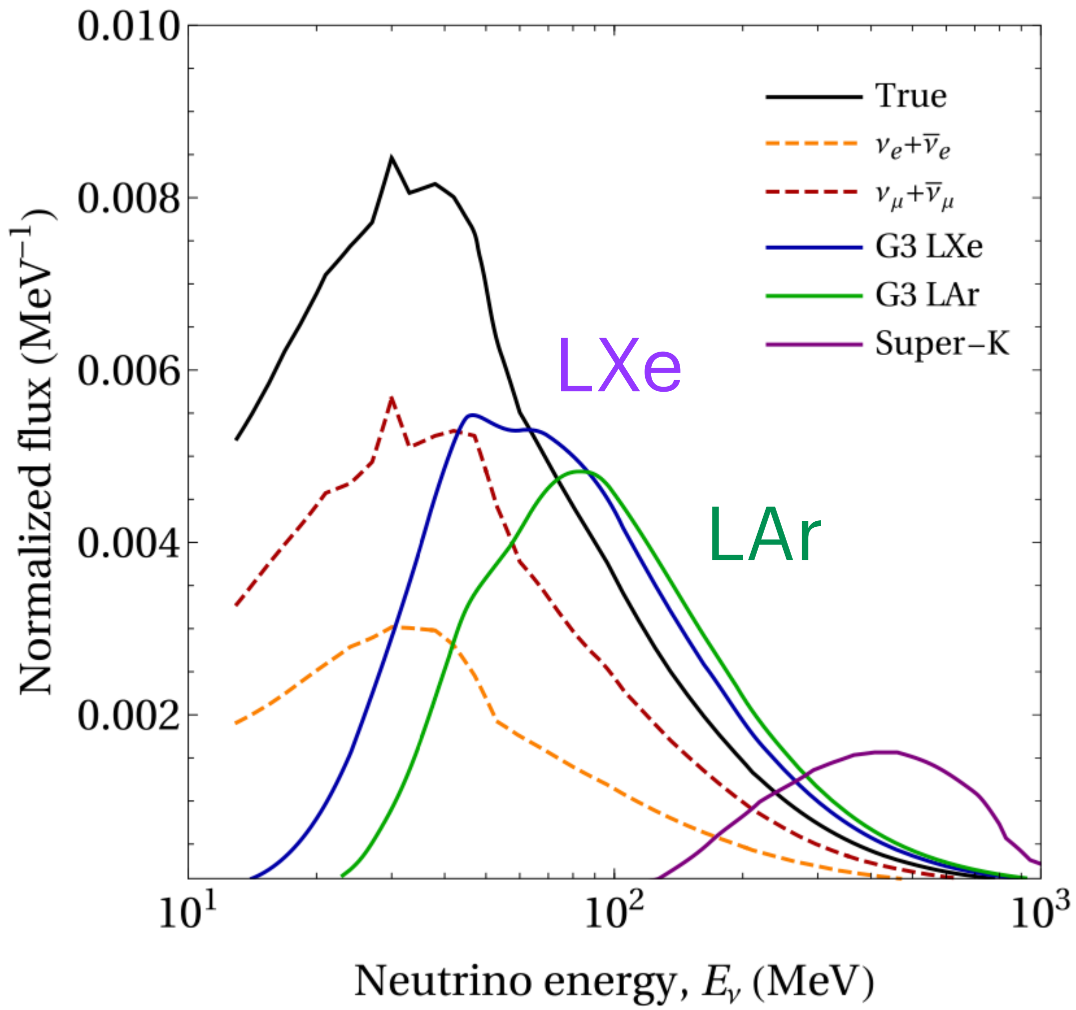


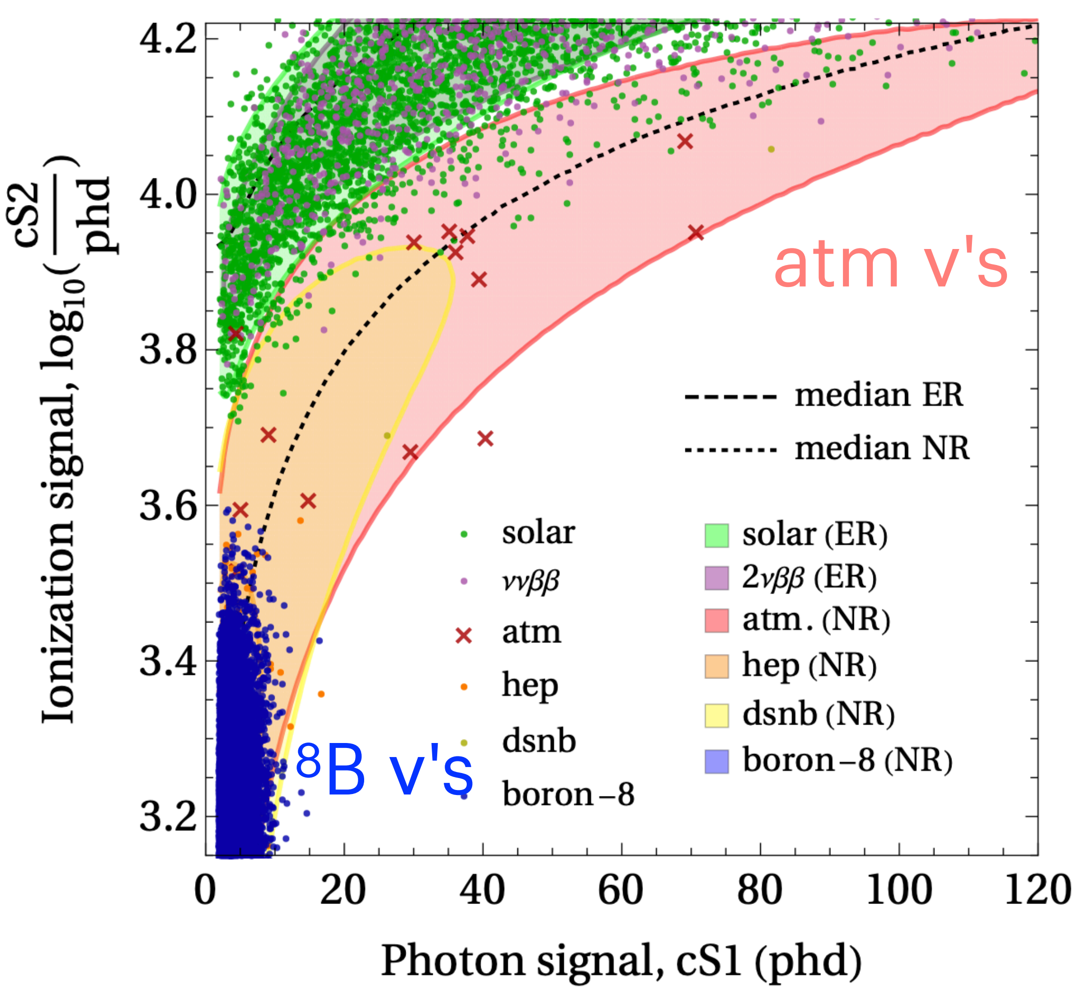
PandaX, PRL 132, 2024

HAN, Ke (Shanghai Jiao Tong University)

Atmospheric neutrinos

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

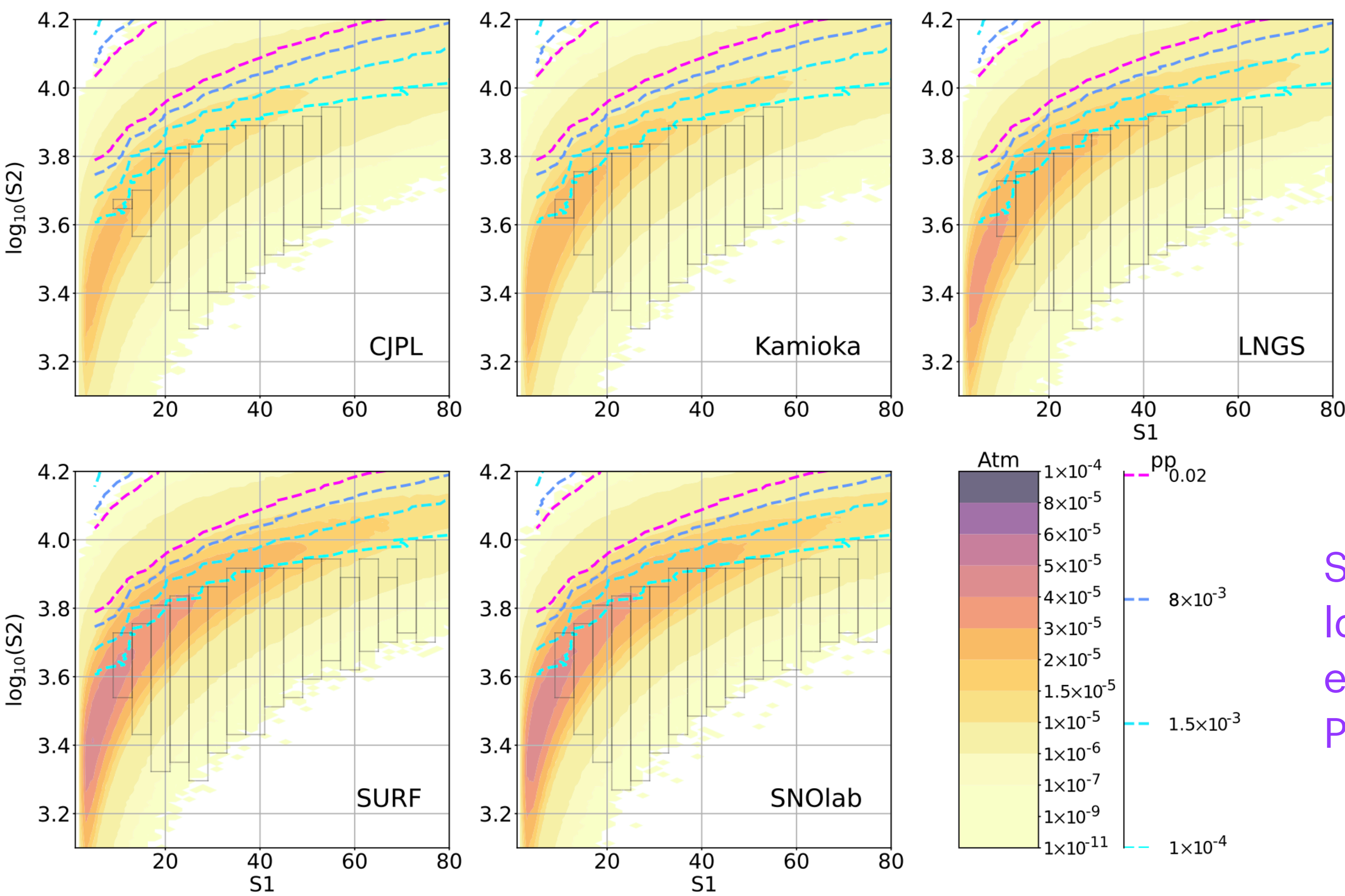




Newstead, Lang, Strigari, PRD 104, 2021

Atmospheric neutrinos

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



See study at different labs (for Ar and Xe exp): Y. Zhuang et al., PRD109, 2024

Conclusions & Outlook

- Dark matter detectors: ultra-low backgrounds & low energy thresholds
- Backgrounds for the dark matter search: soon to be dominated by ν's
- Competitive sensitivity to ν's from a variety of sources and to second order weak decays with & without ν's
- Complementary measurements to dedicated ν experiments
- Next months: new results expected from ongoing experiments
- Future: higher stats measurements from next-generation detectors

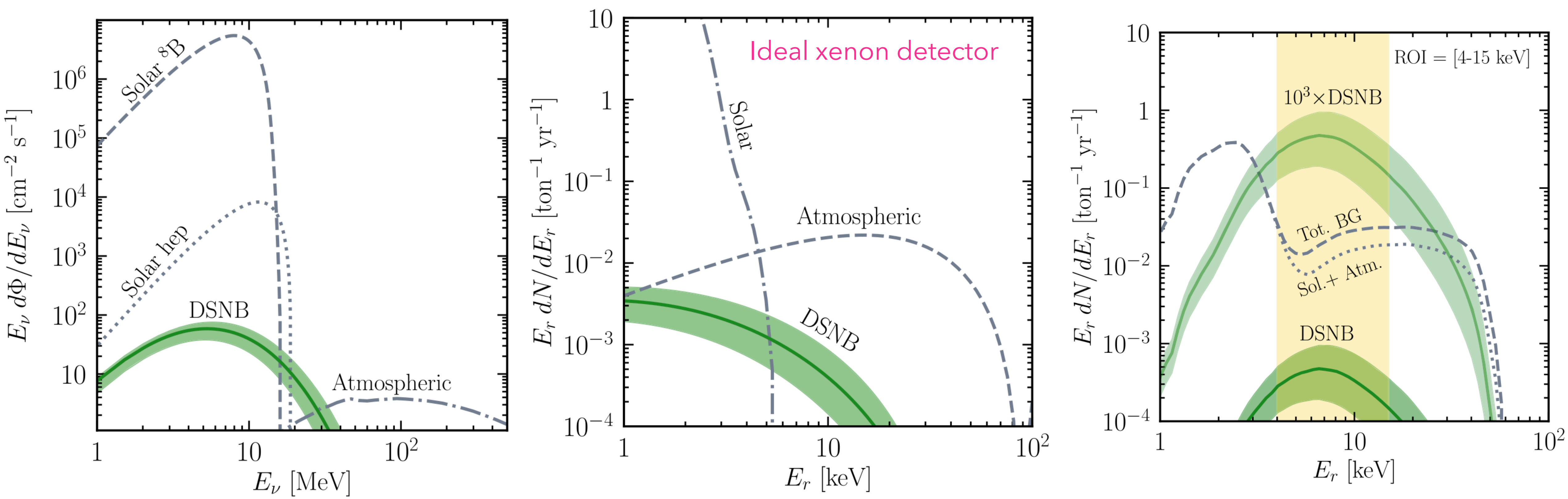
Thank you

Additional material

DSNB with CEvNS

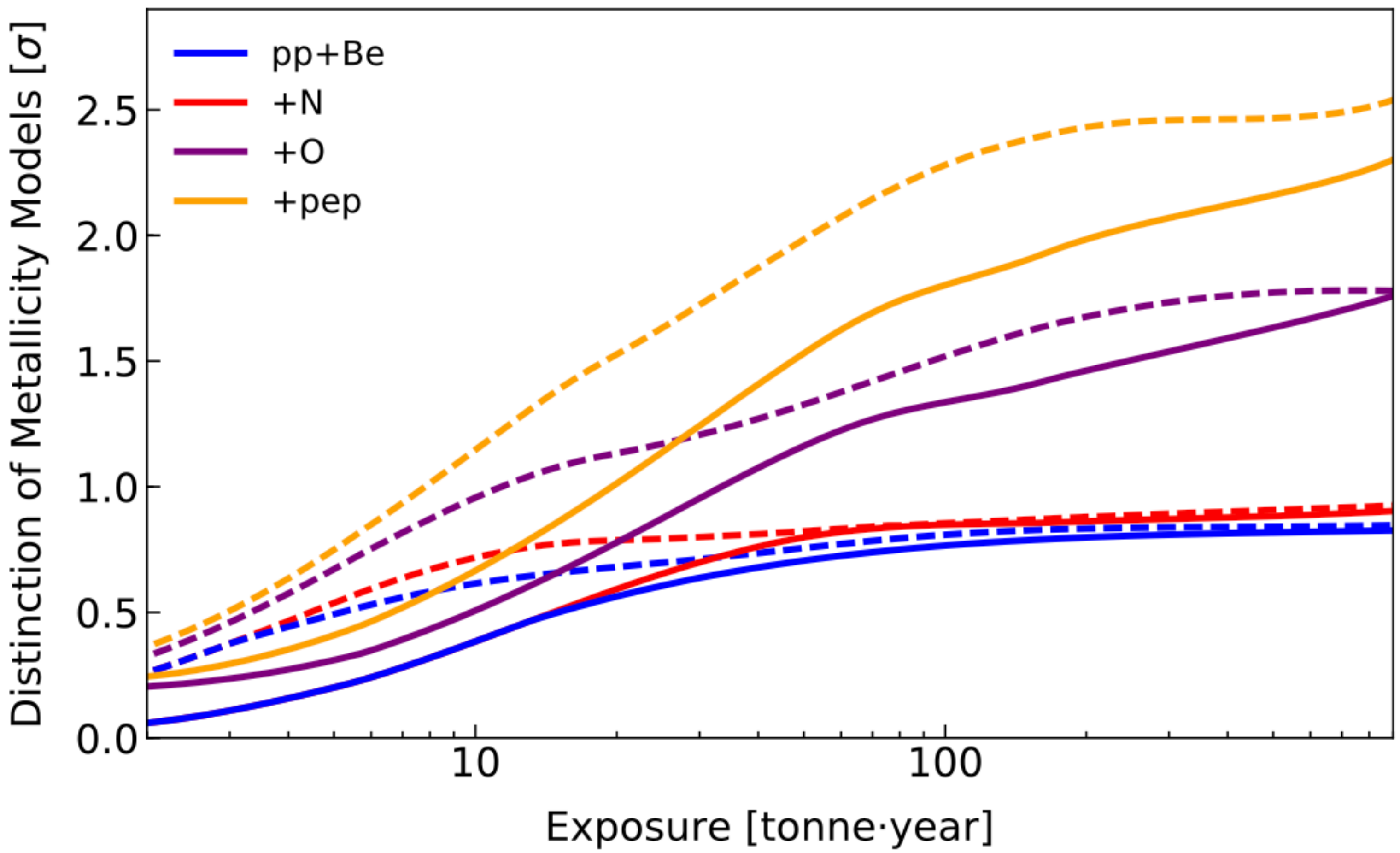
- Understanding of core-collapse SN depends on probing DSNB with all flavours
- So far, only upper limits in ν_e and $\bar{\nu}_e$ flux by SNO and SuperK (19 $cm^{-2}s^{-1}$, 2.7 $cm^{-2}s^{-1}$), limits on in $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ fluxes much weaker (per flavour, ~10^3 $cm^{-2}s^{-1}$),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

Suliga, Beacom, Tambora, PRD 105, 2022



Solar neutrinos

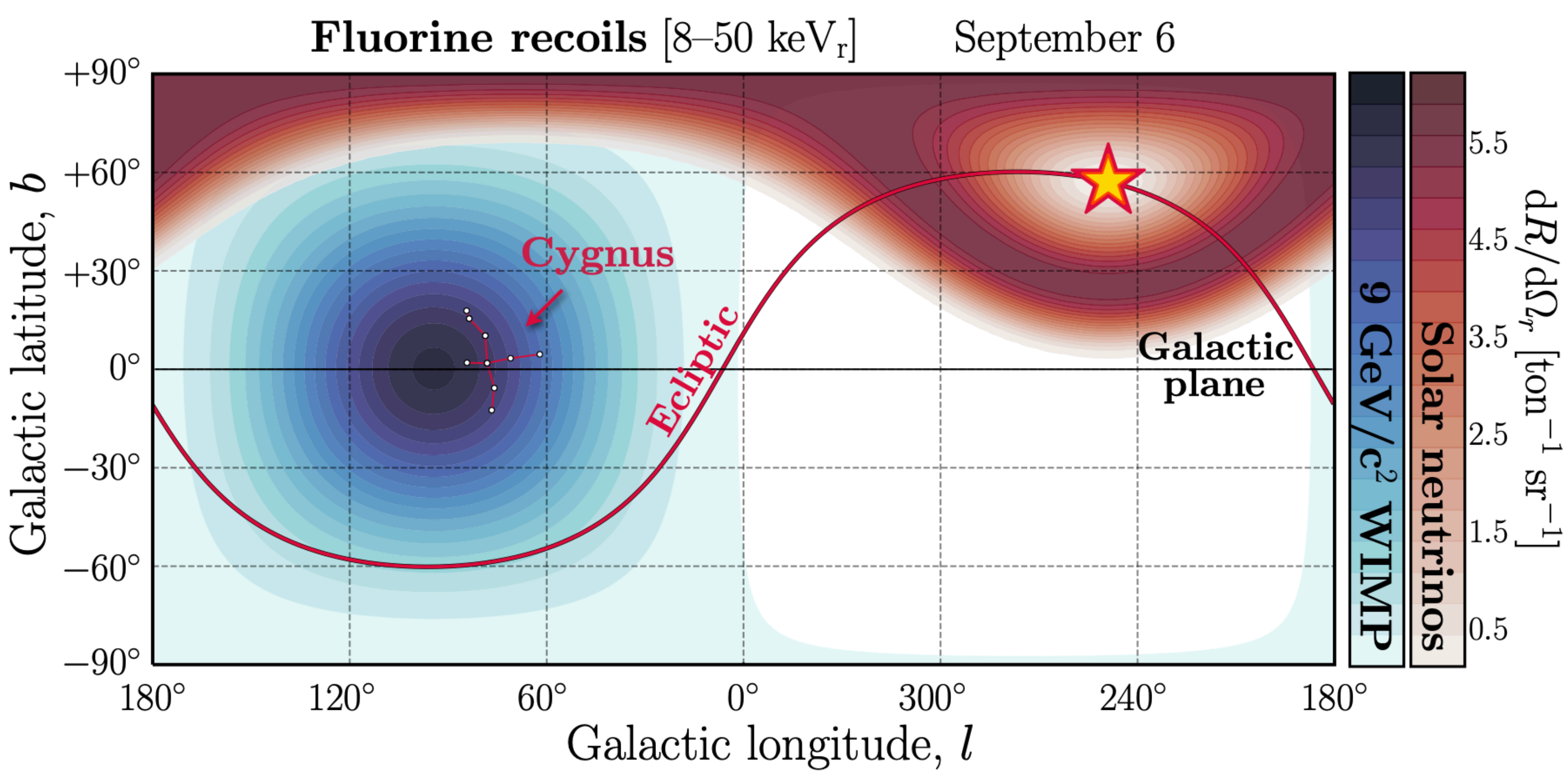
- High-Z versus low-Z models in LXe
- Target depleted in ^{136}Xe needed to distinguish between HZ and LZ up to theoretical uncertainties

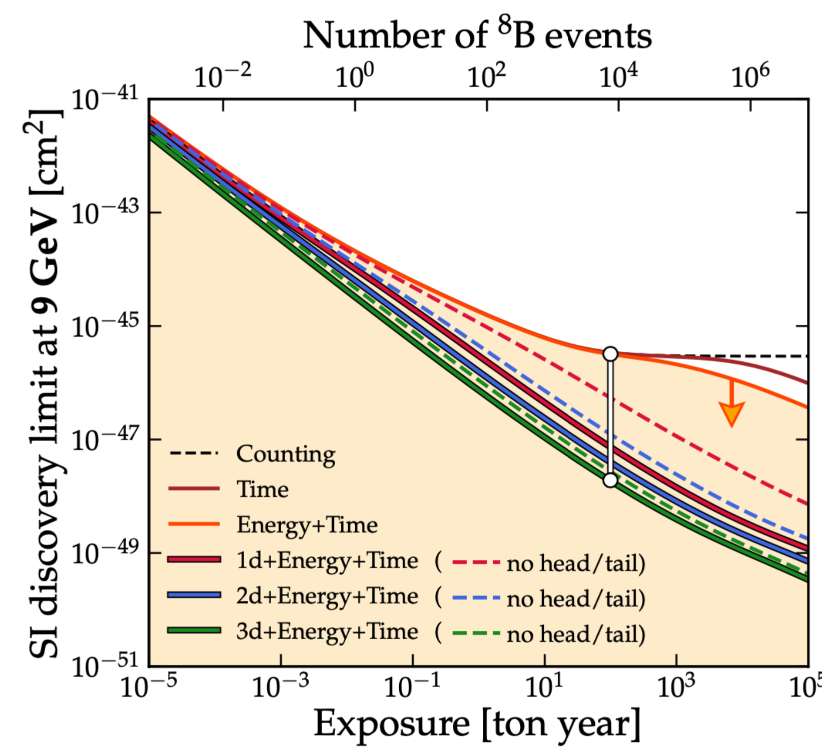


DARWIN collaboration, EPJ-C 80 12 (2020)

Directional detectors

- The incoming direction of WIMPs and solar neutrinos differs: this can be exploited to overcome the solar "neutrino fog"





Directional Recoil Detection

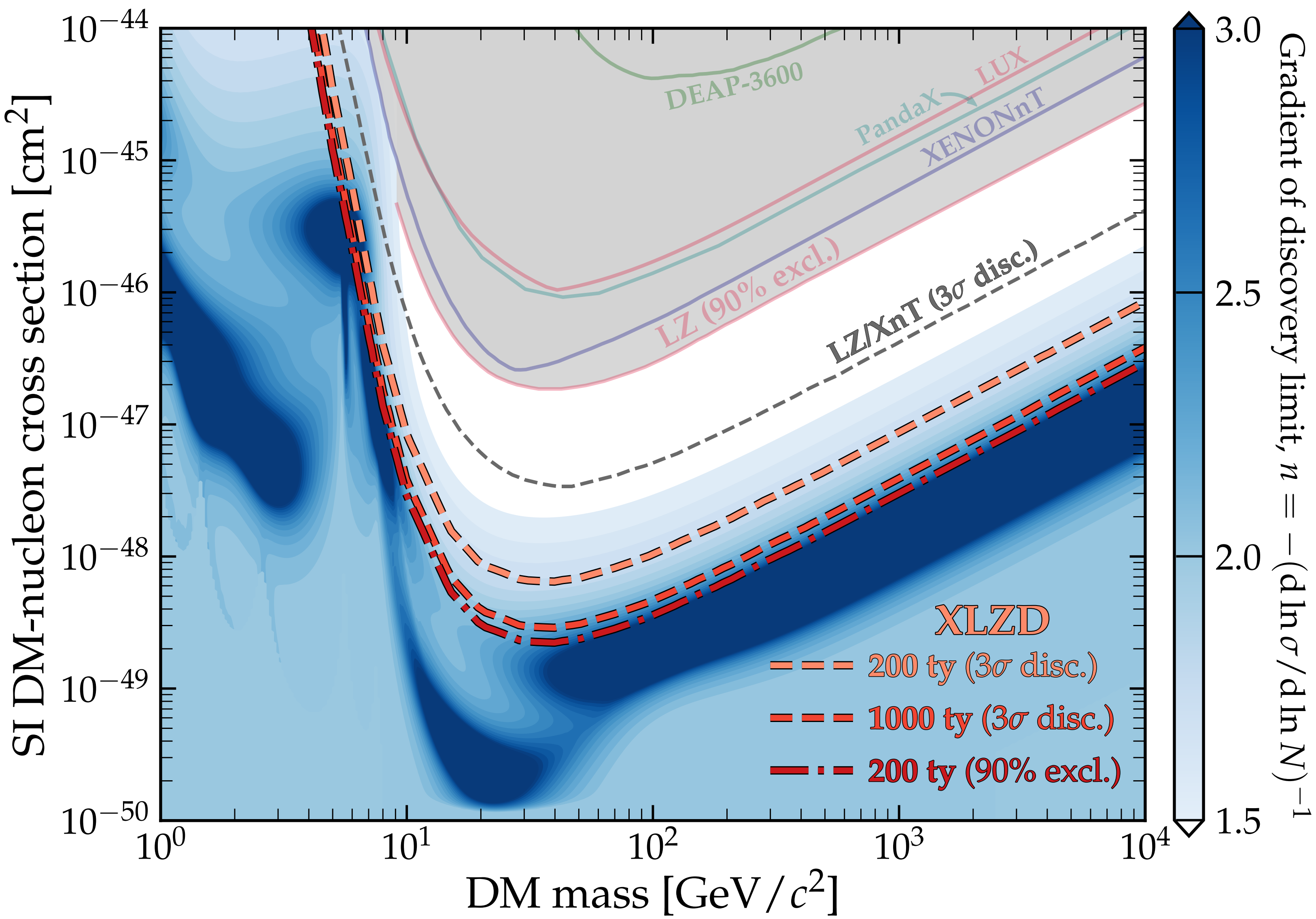
Sven E. Vahsen,[1] Ciaran A. J. O'Hare,[2] and Dinesh Loomba[3]

[1]Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA; email: sevahsen@hawaii.edu
[2]ARC Centre of Excellence for Dark Matter Particle Physics, The University of Sydney, School of Physics, NSW 2006, Australia; email: ciaran.ohare@sydney.edu.au
[3]Department of Physics and Astronomy, University of New Mexico, NM 87131, USA, email: dloomba@unm.edu

Annual Review of Nuclear and Particle Science
2021. 71:1–41

This article's doi:
10.1146/annurev-nucl-020821-035016

The neutrino fog



Credit Ciaran O'Hare

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

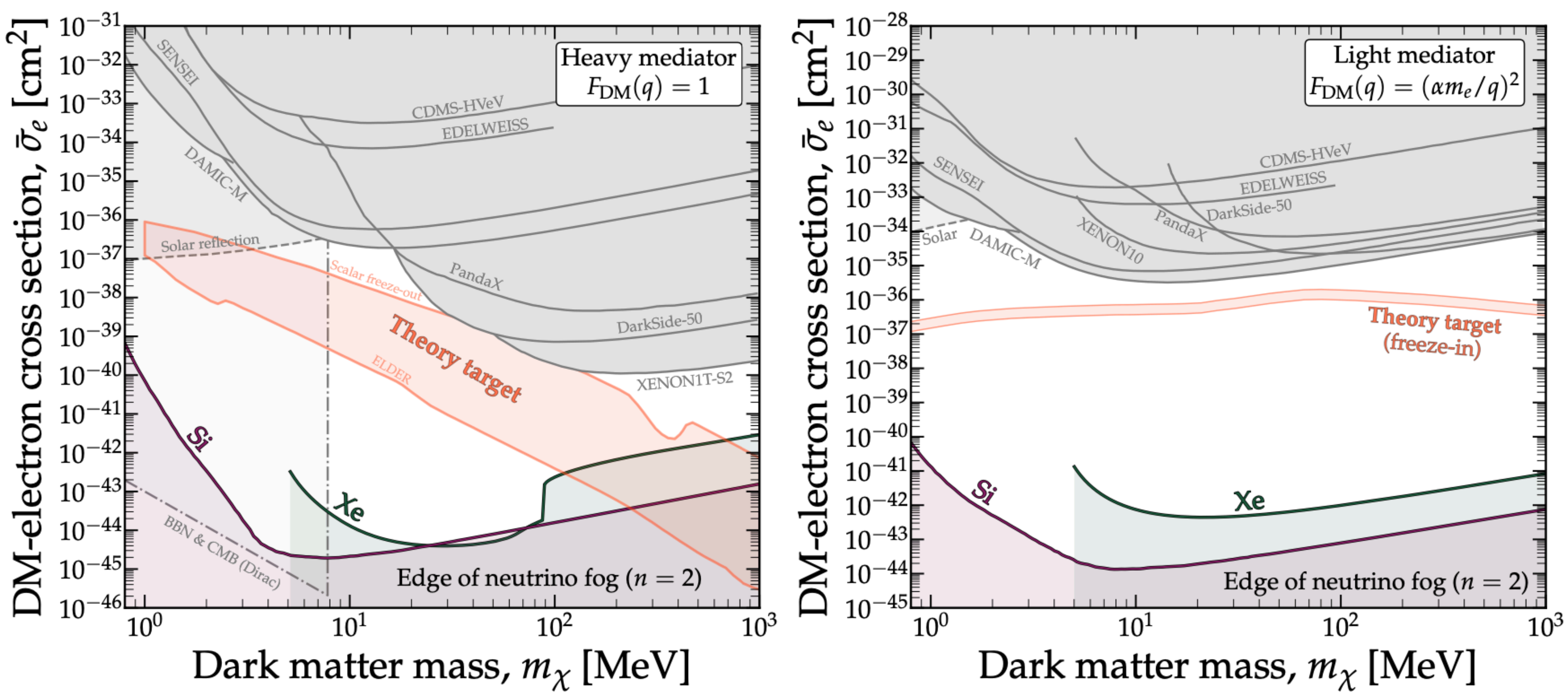
Here ν fog for a Xe target: blue contour map

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

Approaching the neutrino fog

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

The "fog" for Si and Xe targets, for 2 mediators



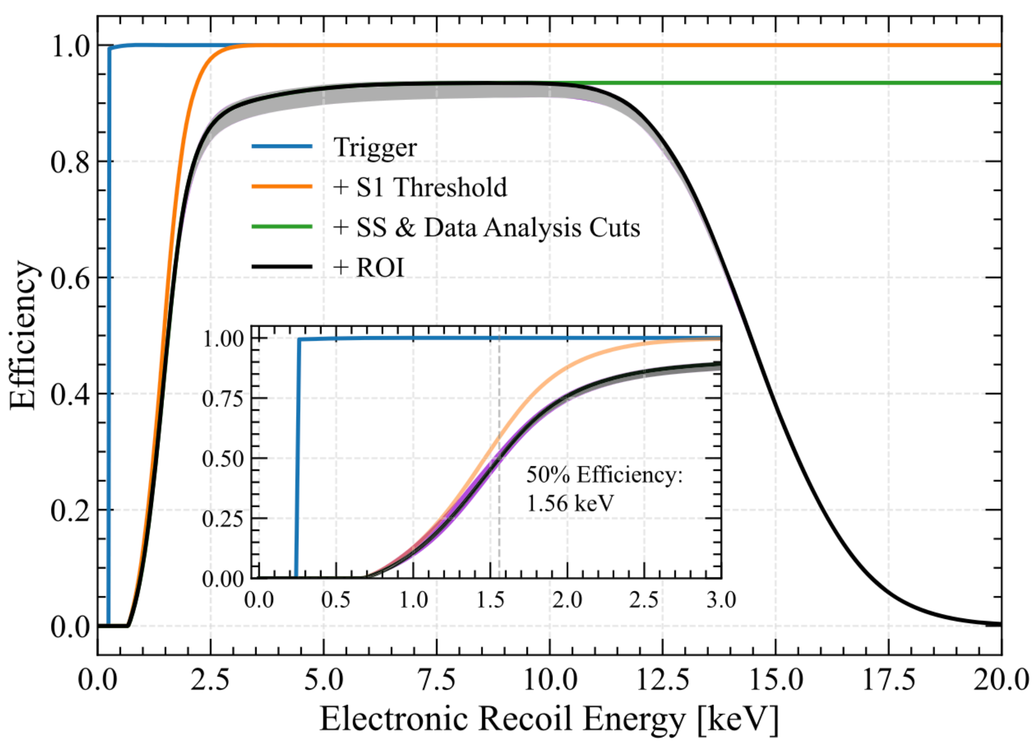
B. Carew at al, 2312.04303

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

Energy thresholds in Xe TPCs

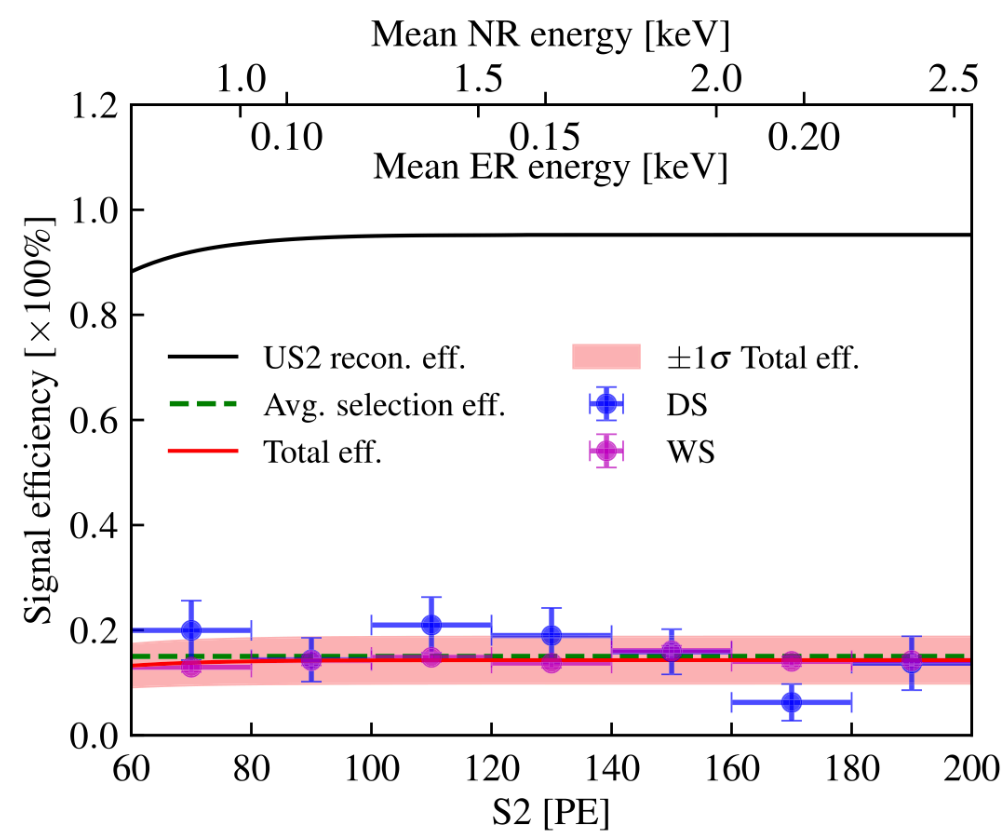
- S1 + S2: ~ 1 keV with 3-fold coincidence (ER) (hits in ≥ 3 PMTs within ~50-100 ns); lower threshold (< 1 keV) with 2-fold coincidence (with lower signal efficiency)
- S2-only: ~ 0.2 keV, with 5 e^- - 100 e^- detected (probe ER and NR interactions), down to W-value, with 1 e^- - 5 e^- signal (mostly 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

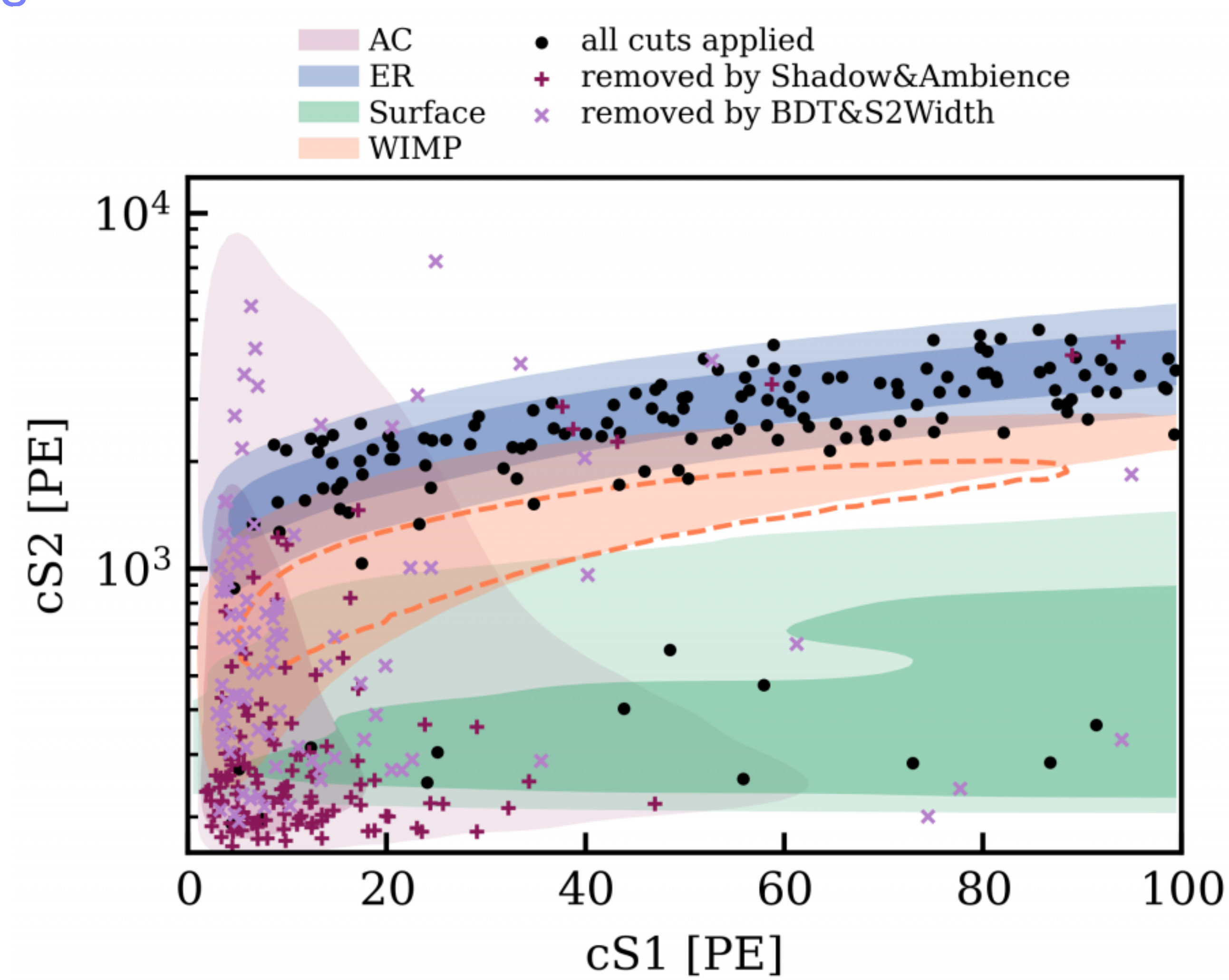
PandaX-4T, PRL 130, 2023



AC backgrounds in TPCs

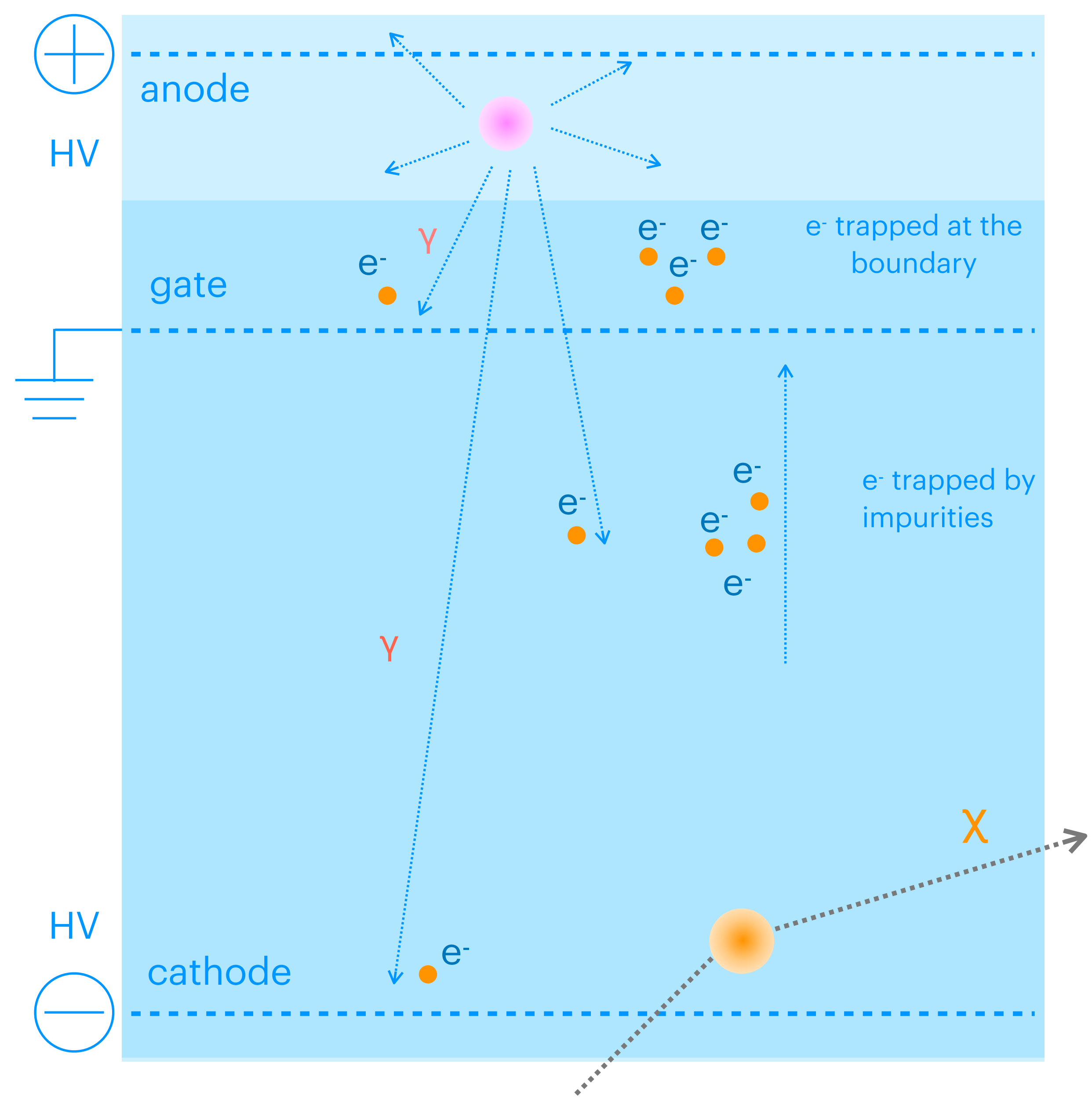
- Combinatorial background at low energies can be significant
- Main sources for isolated S1 and isolated S2 signals
  - Primary scintillation (S1s)
    - Dark counts (pile-up) ∝ nr. channels
    - Charge-insensitive regions
    - Delayed photons
  - Electroluminiscence (S2s)
    - Bulk xenon S2-only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

Example from XENONnT



Ionisation only backgrounds

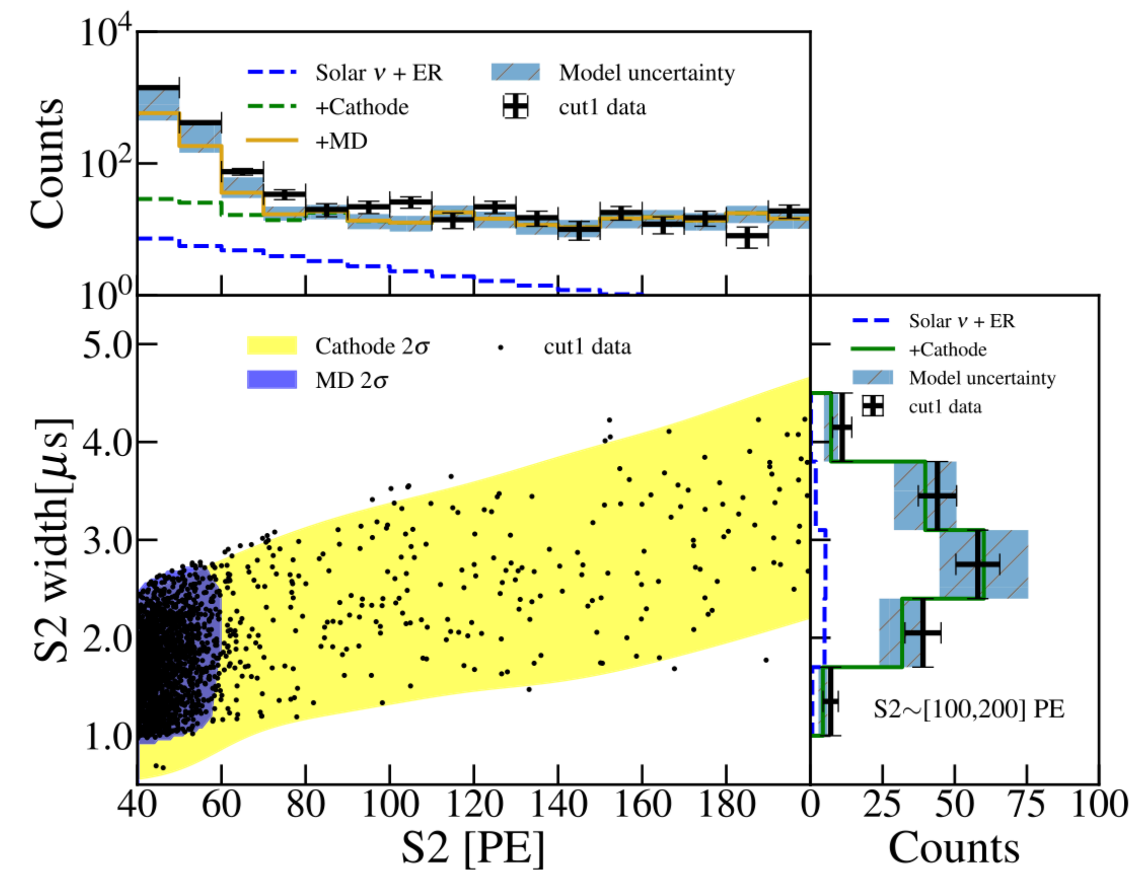
- Radioactivity
- Solar neutrinos
- Instrumental
    - Spurious emission of single and few electrons from the cathode
    - Delayed e- after large S2 signals: trapped e- at the liquid/gas interface; e- emitted from impurities, etc
- Important to understand & mitigate origin, develop background models

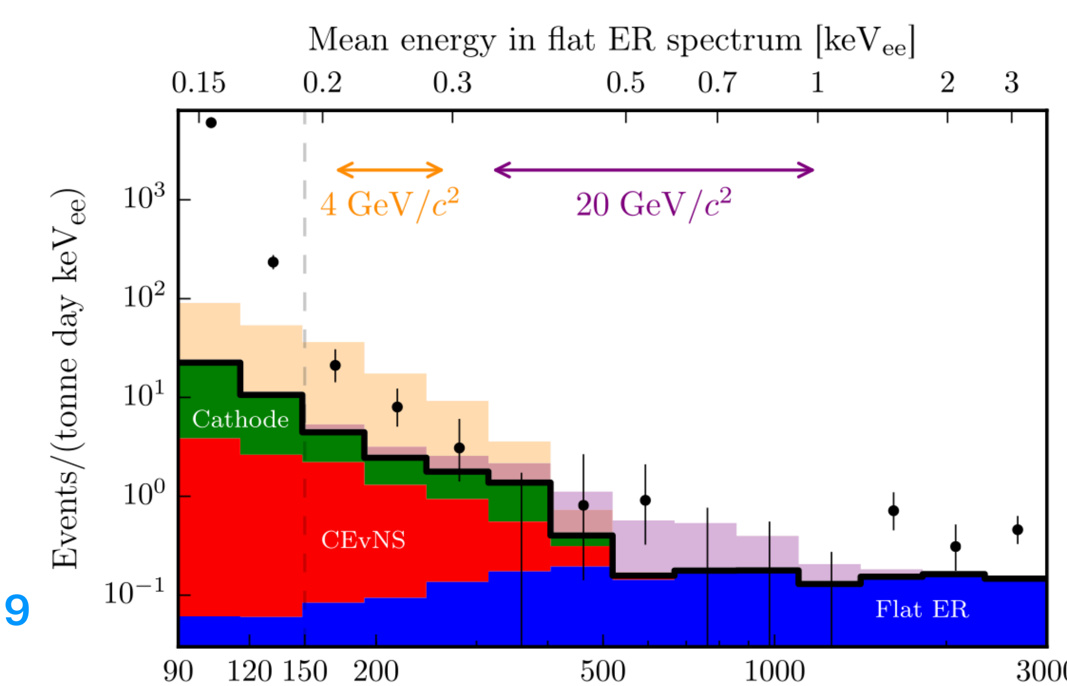


Ionisation only backgrounds

- 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

PandaX-4T, PRL 130, 2023





XENON1T, PRL 123, 2019

Other 2nd order weak decays

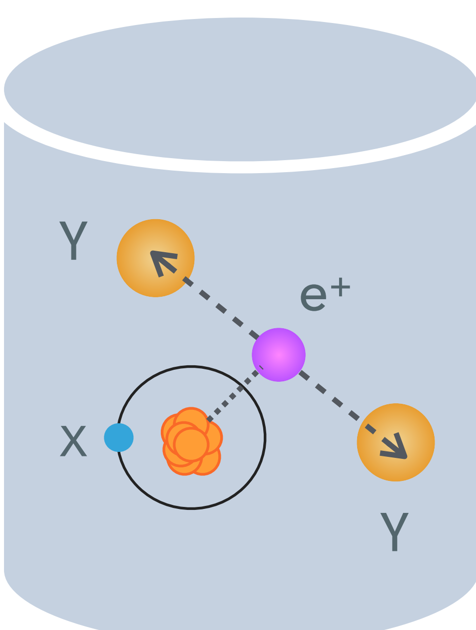
- ^{36}Ar (0.33%), ^{124}Xe (0.095%), ^{126}Xe (0.089%), ^{134}Xe (10.4%)

$$^{36}\text{Ar} \rightarrow ^{36}\text{S} + \gamma + X_K + X_L$$

0.23 keV

430 keV

2.5 keV



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

1.8 MeV

31.8 keV

Geoneutrinos

- $\bar{\nu}_e$ from the Earth: low energies $\Rightarrow$ ERs (via ES) needed for detection
- Low fluxes: large exposures (100 - 1000 t y) needed
- A measurement of ^{40}K $\bar{\nu}_e$: can help constrain its radioactive contribution to the Earth's surface hear flow
- Directional detectors: could suppress the solar neutrino background

AGM2015: Antineutrino Global Map 2015 (geo-ν flux due to ^{238}U & ^{232}Th decay in the Earth's crust and mantle)