



University of  
Zurich<sup>UZH</sup>



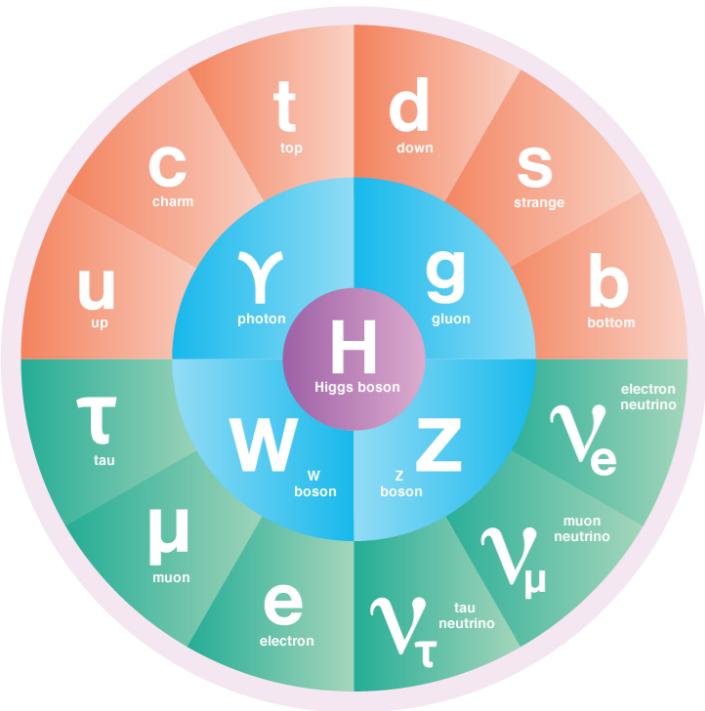
# Looking for wild neutrinos with XLZD

XLZD@Boulby open community meeting

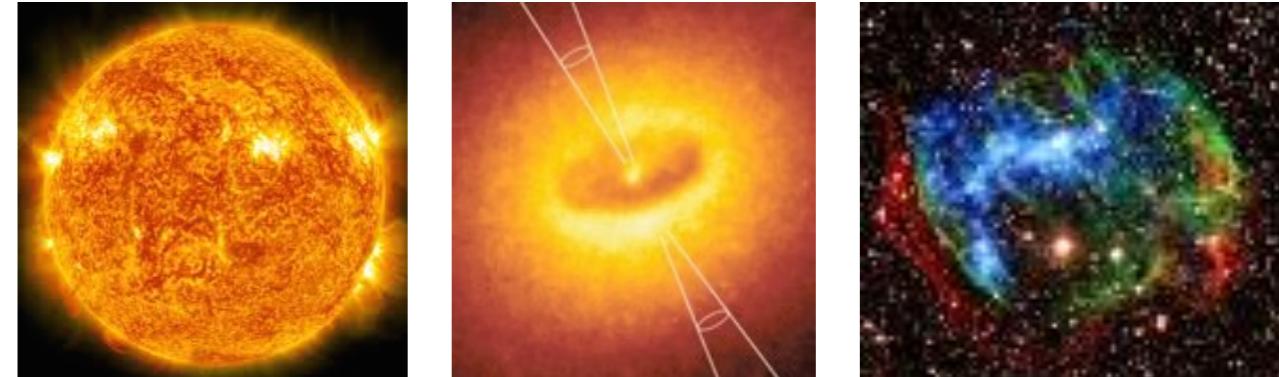
Laura Baudis  
University of Zurich  
July 4, 2023



# Neutrinos matter!

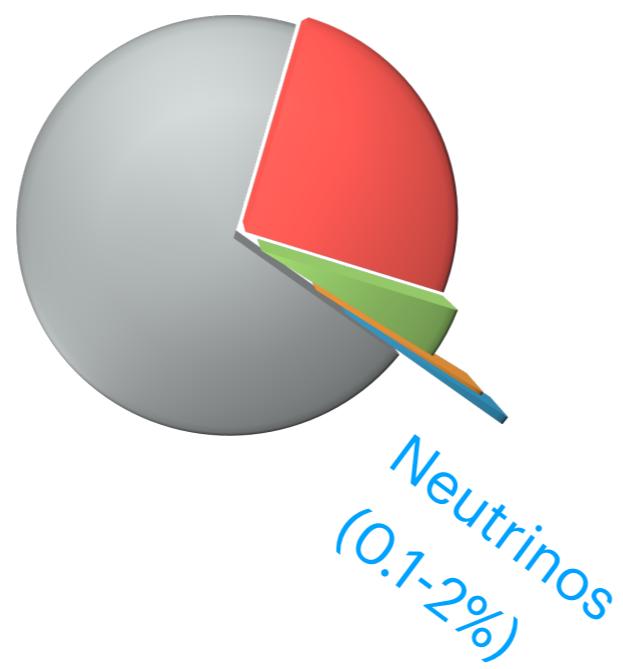
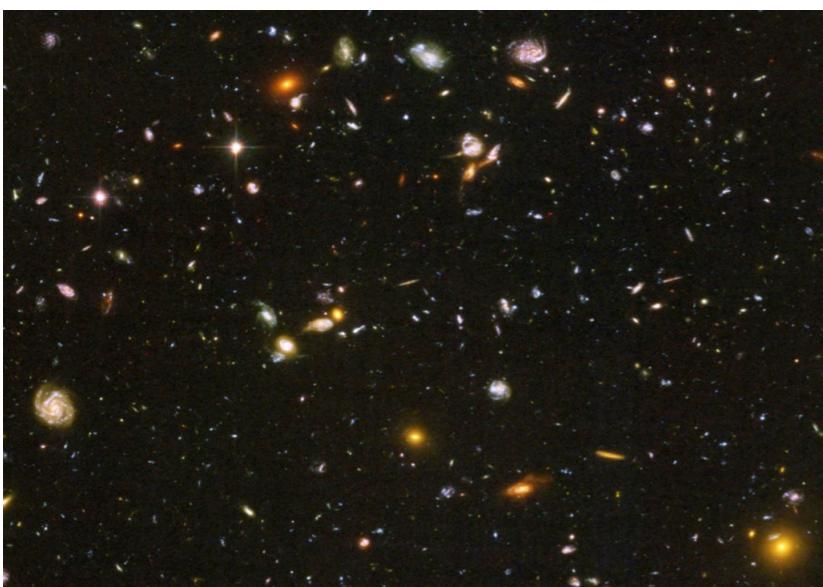


Fundamental  
particles and  
interactions



Astrophysical systems

Cosmology and  
early Universe



The Earth



Nuclear reactors

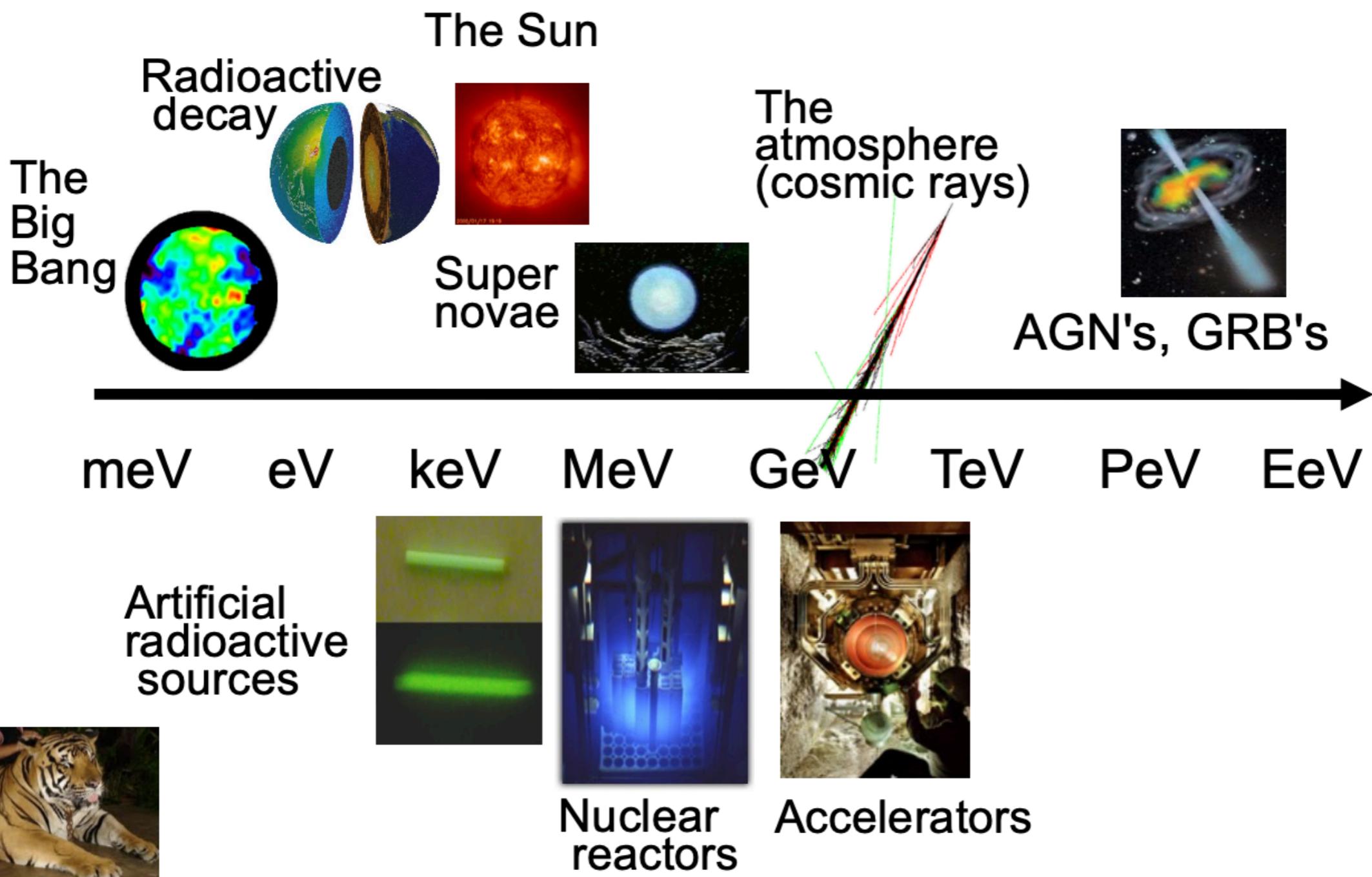


for many reasons....

# Two kinds: wild and tame v's



Kate Scholberg  
Zurich Physics  
Colloquium 2022

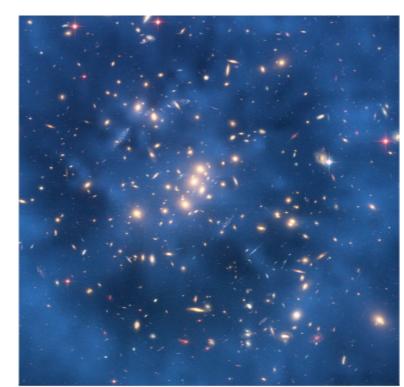
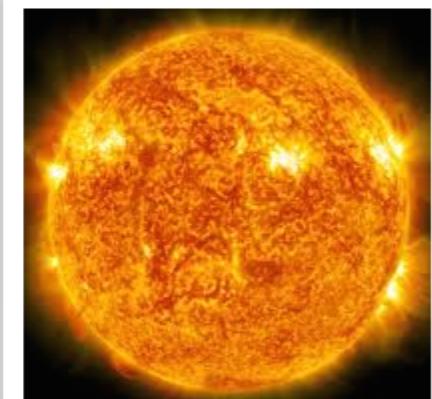


# XLZD: a wild neutrino observatory

Wild

Solar  
neutrinos  
(pp +  ${}^8\text{B}$ )

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

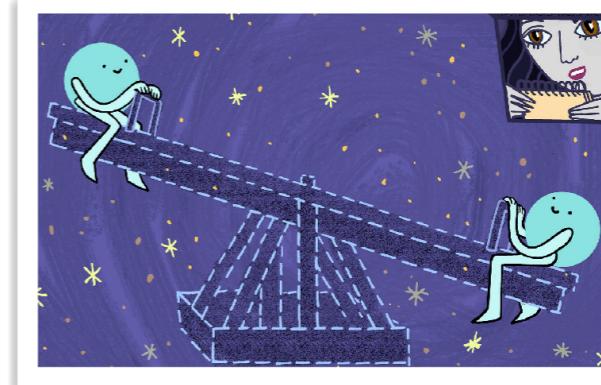


Dark matter

JCAP 10, 016 (2015)

Supernova  
neutrinos

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



Neutrino  
nature

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

Wild

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



Atmospheric  
neutrinos

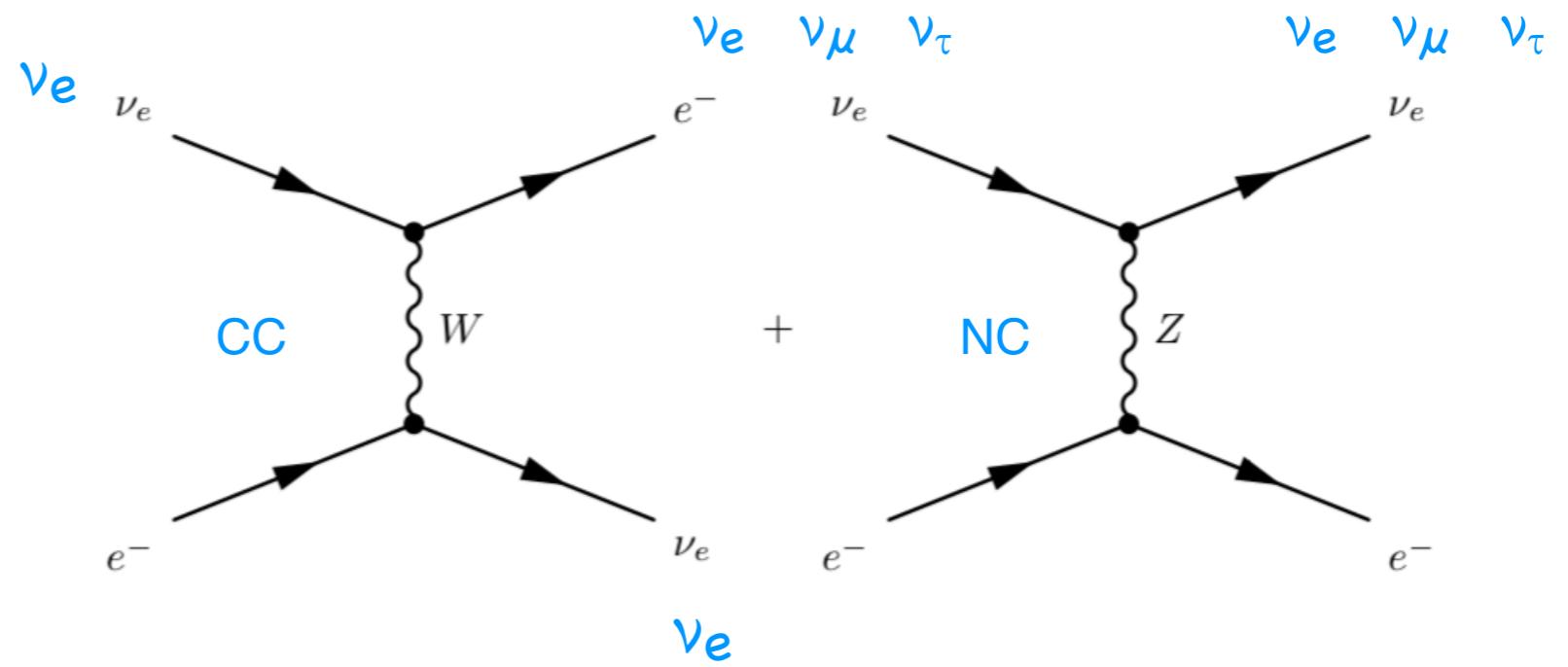
PRD 104 (2021)

Wild

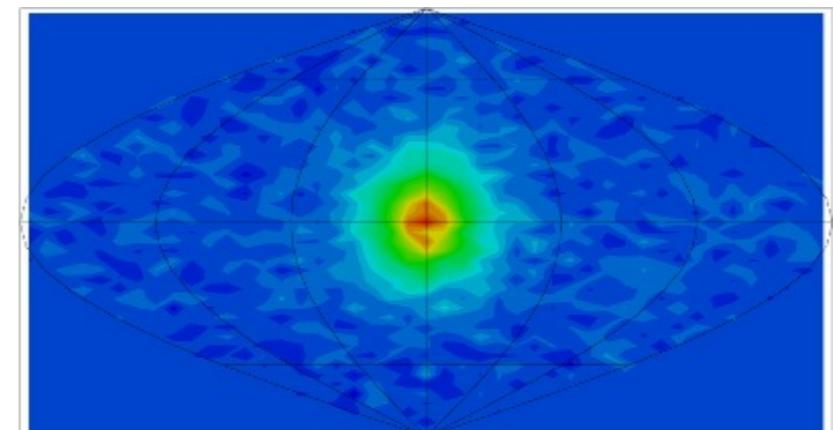
# (Wild) Neutrino interactions

## Elastic neutrino-electron scattering

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

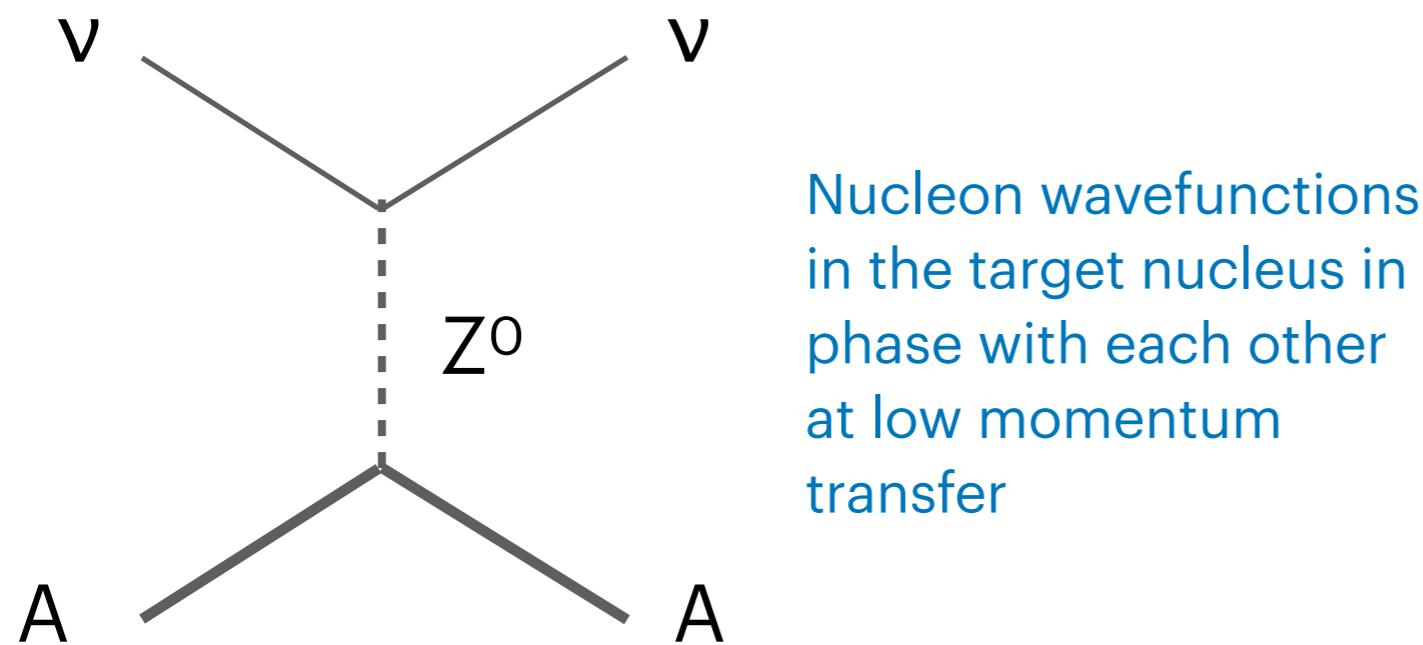
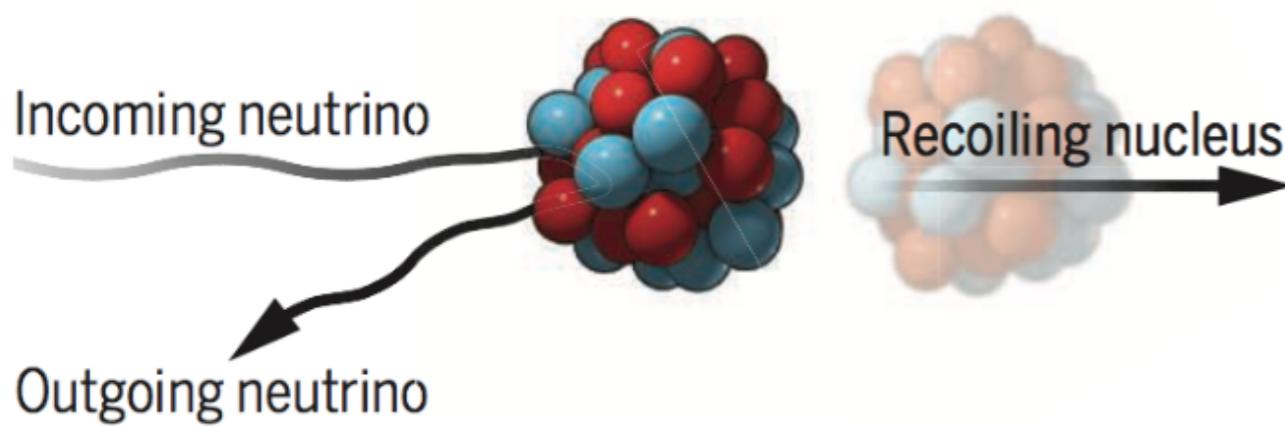


- $\nu_e$  interactions: CC & NC
- $\nu_\mu$  and  $\nu_\tau$  interactions: only via NC  
( $\sigma_{\text{tot}} \approx 10^{-43} \text{ cm}^2$ , solar  $\nu$  have low energies and the CC reactions involving  $\nu_\mu$  and  $\nu_\tau$  are kinematically not allowed )



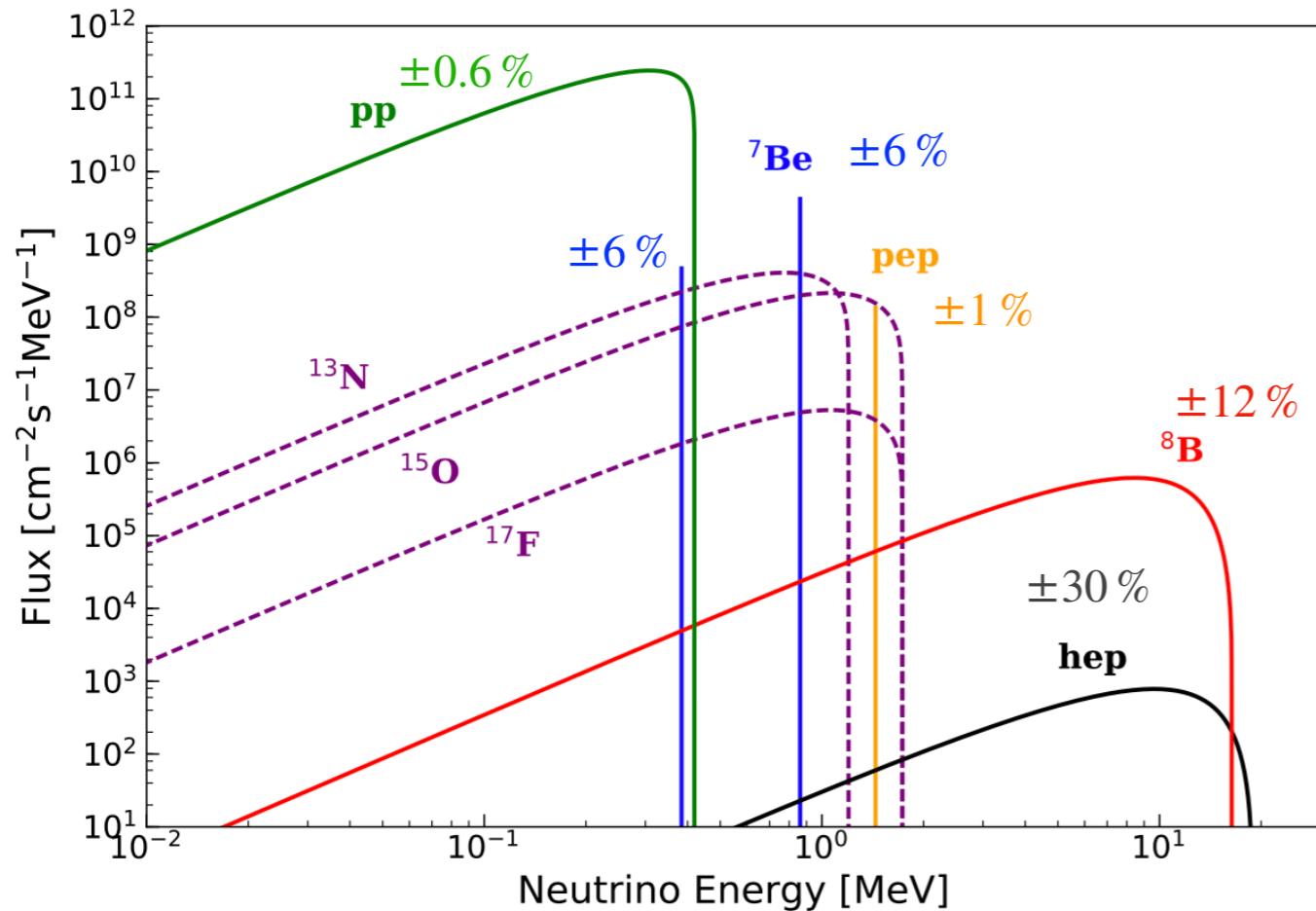
# (Wild) Neutrino interactions

**CEvNS:**  $\nu + A \rightarrow \nu + A$



- A neutrino hits a nucleus via Z-exchange
- The nucleus recoils as a whole
- The process is coherent up to neutrino energies of ~50 MeV

# Low-energy solar neutrinos

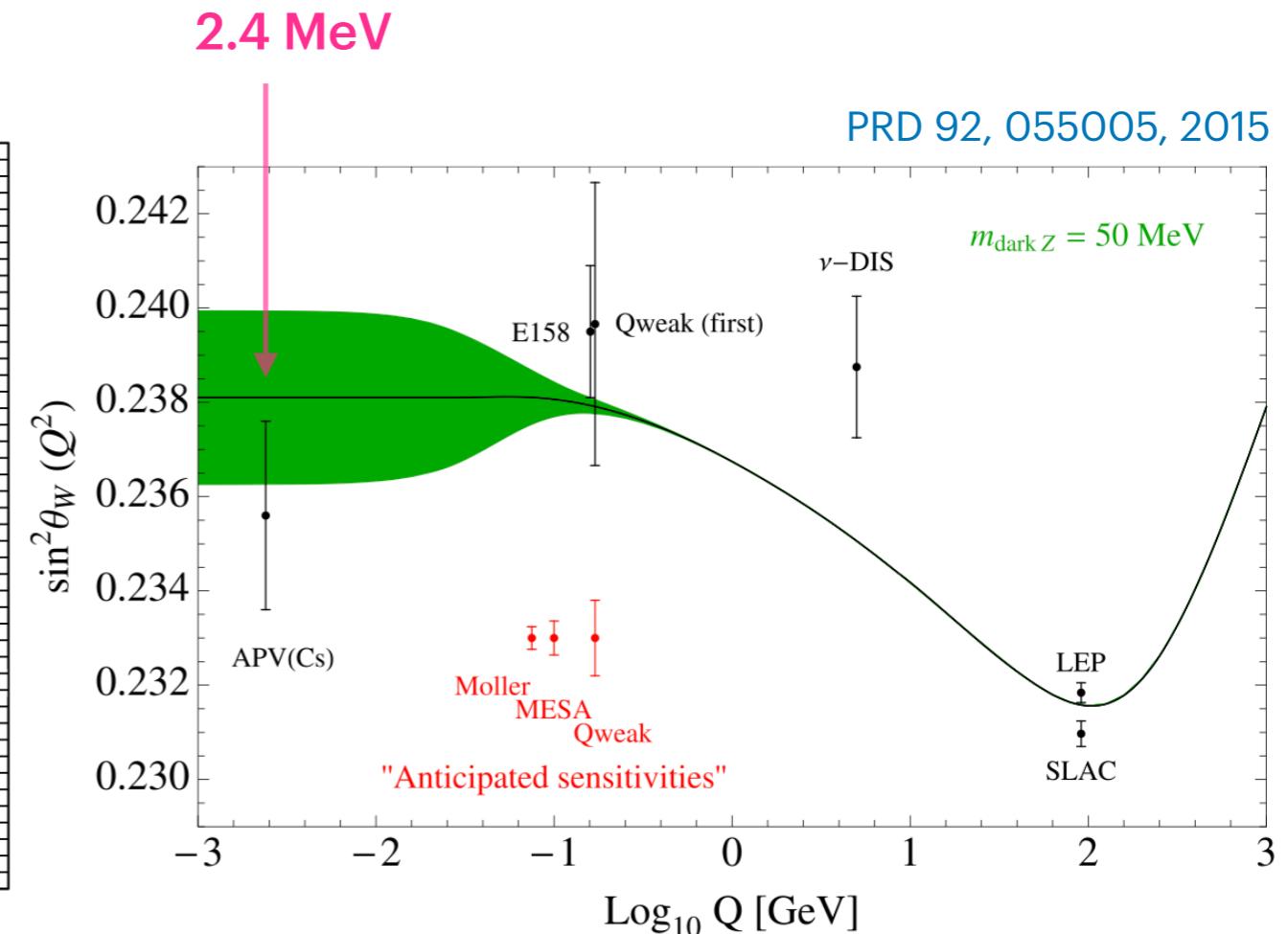
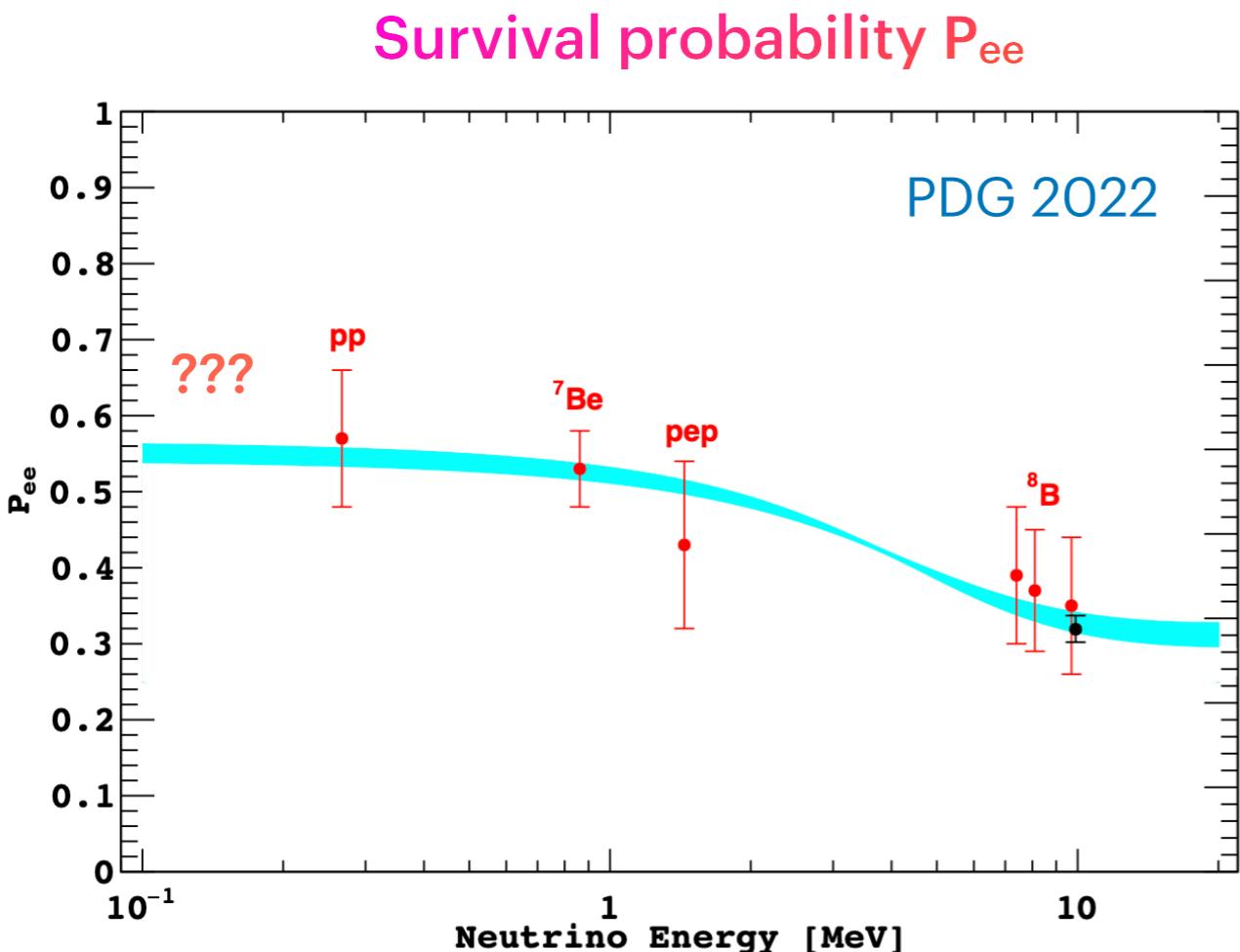


**Table 1** The characteristic values of the flux scales [50], their relative uncertainties, the maximum neutrino energies, and the MSW-LMA  $\nu_e$  survival probability [51] used in this study

Component	$\Phi$ (cm $^{-2}$ s $^{-1}$ )	$\sigma$ (%)	$Q$ (keV)	$P_{ee}$
pp	$5.98 \times 10^{10}$	0.6	420	0.55
$^7\text{Be}$	$4.93 \times 10^9$	6	862, 384	0.52
$^{13}\text{N}$	$2.78 \times 10^8$	15	1200	0.52
$^{15}\text{O}$	$2.05 \times 10^8$	18	1732	0.50
pep	$1.44 \times 10^8$	1	1442	0.50

$$\frac{dR}{dT} = N_e \int \frac{d\Phi}{dE_\nu} \left( P_{ee} \frac{d\sigma_e}{dT} + (1 - P_{ee}) \frac{d\sigma_{\nu,\tau}}{dT} \right) dE_\nu$$

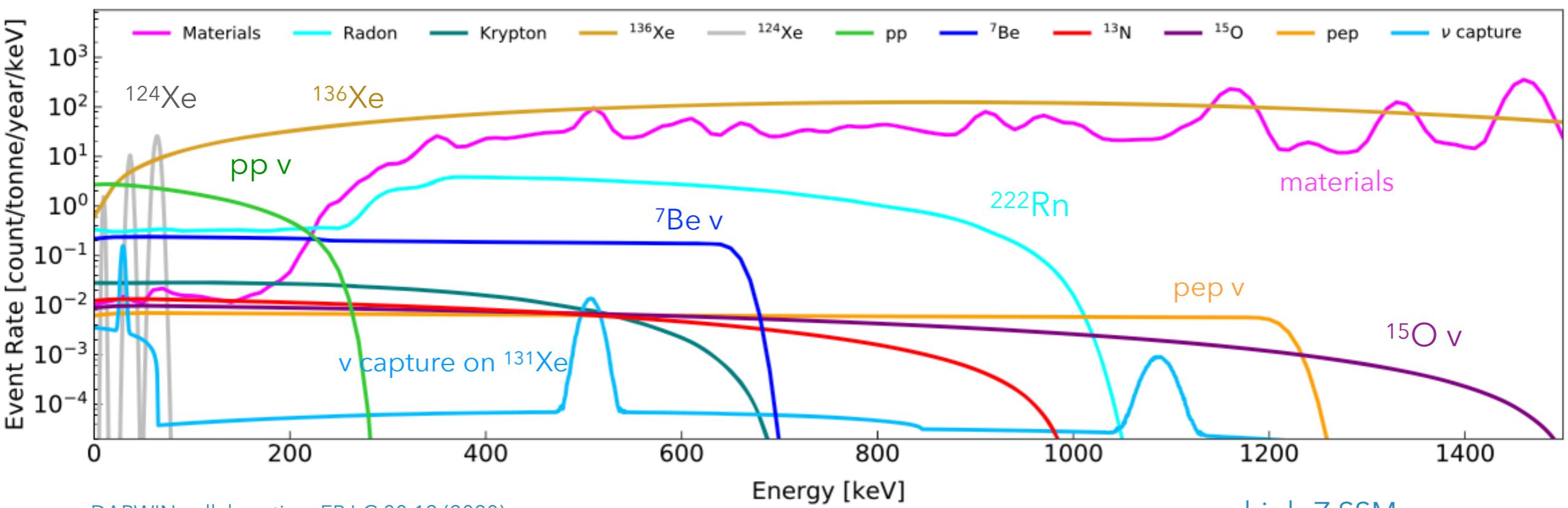
# Low-energy solar neutrinos



- What is the  $\nu_e$  survival probability ( $P_{ee}$ ) below 200 keV?
- What is the value of the weak mixing angle ( $\sin^2 \theta_w$ ) at low energies?

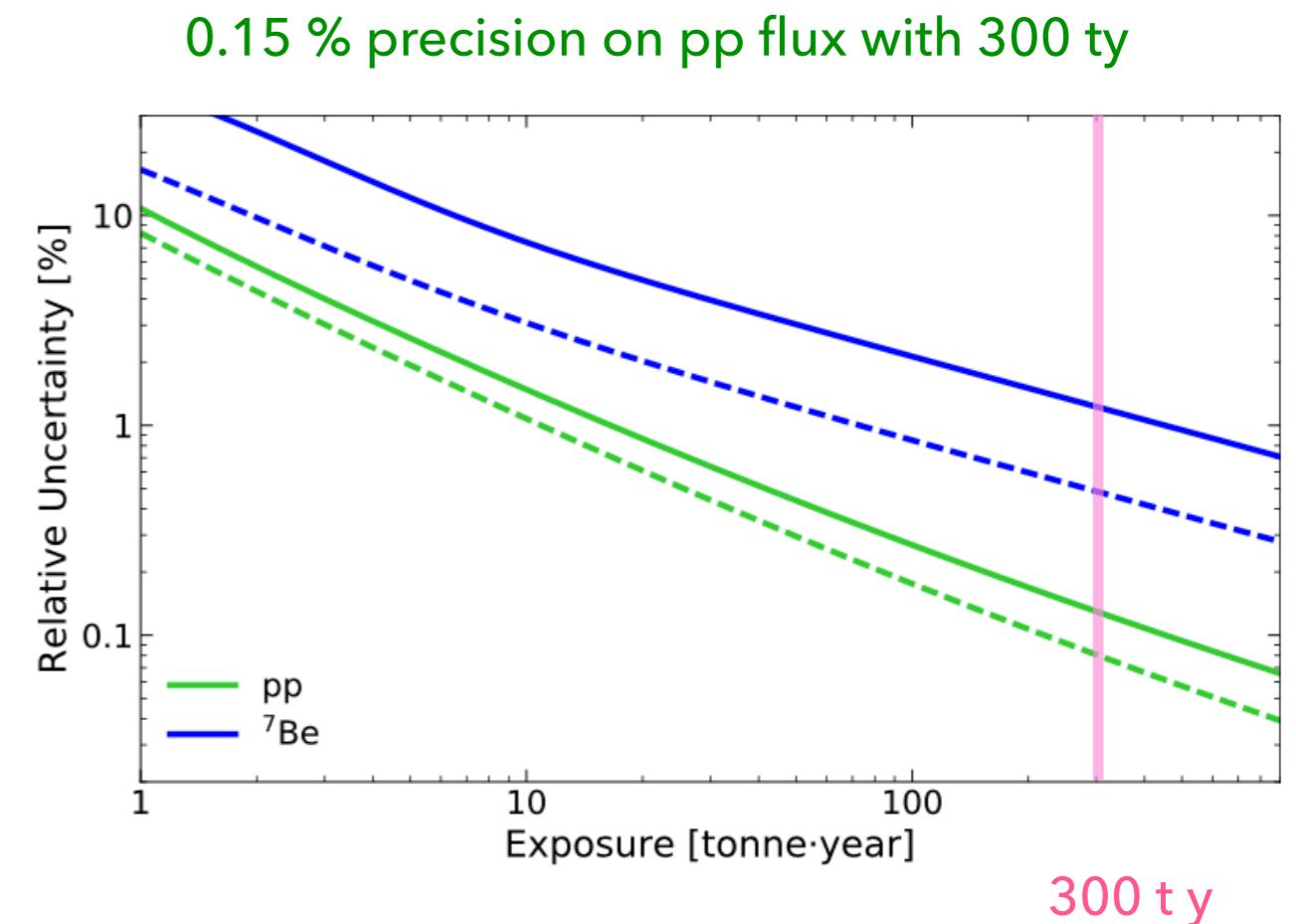
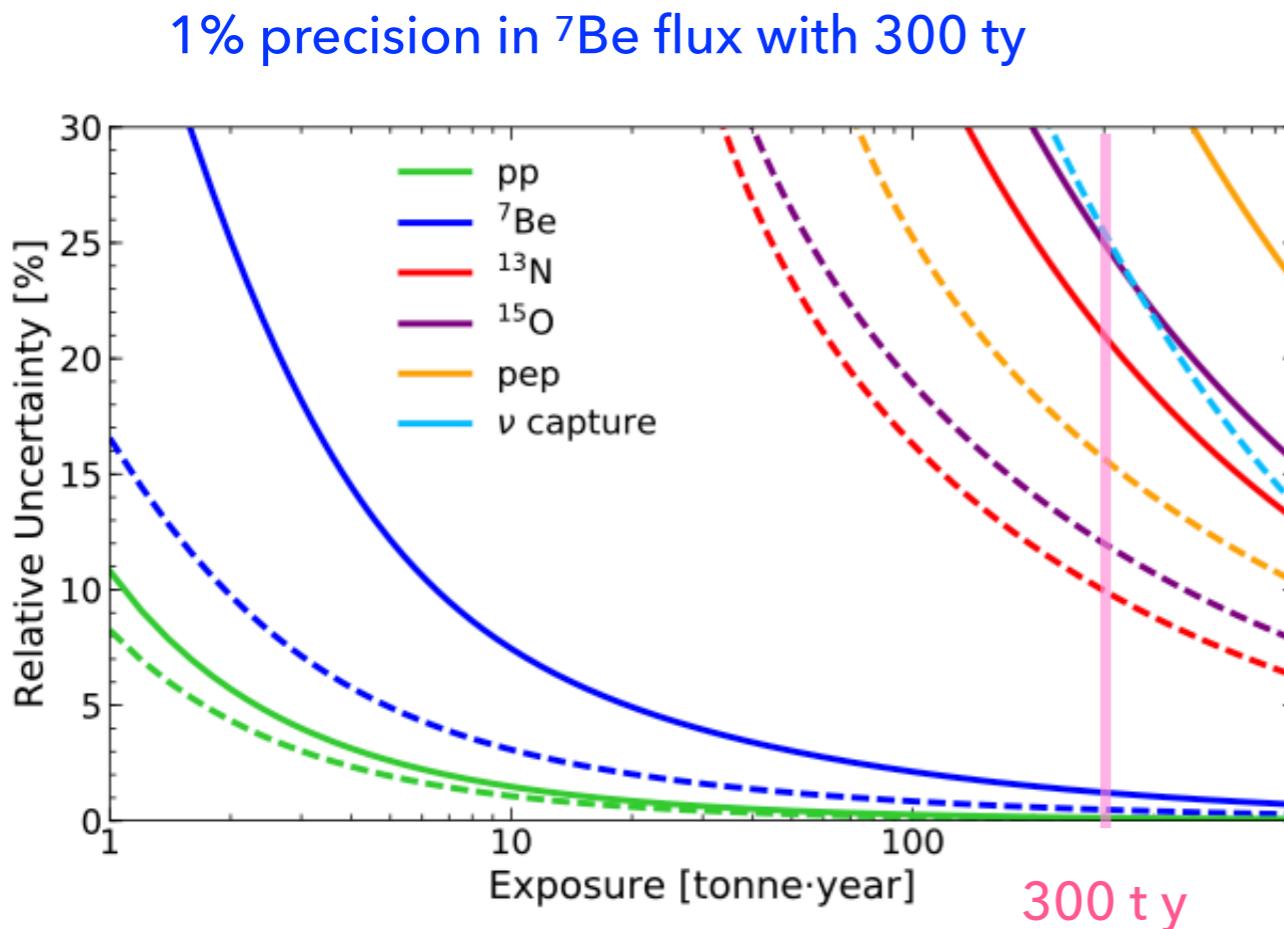
# Low-energy solar neutrinos

- Signals: five solar  $\nu$  components +  $\nu$  capture on  $^{131}\text{Xe}$  (Q-value = 0.355 MeV)
- Backgrounds: five components up to 3 MeV; 1 keV energy threshold for ERs
- Multivariate spectra fit of all 11 components (30 t fiducial mass)



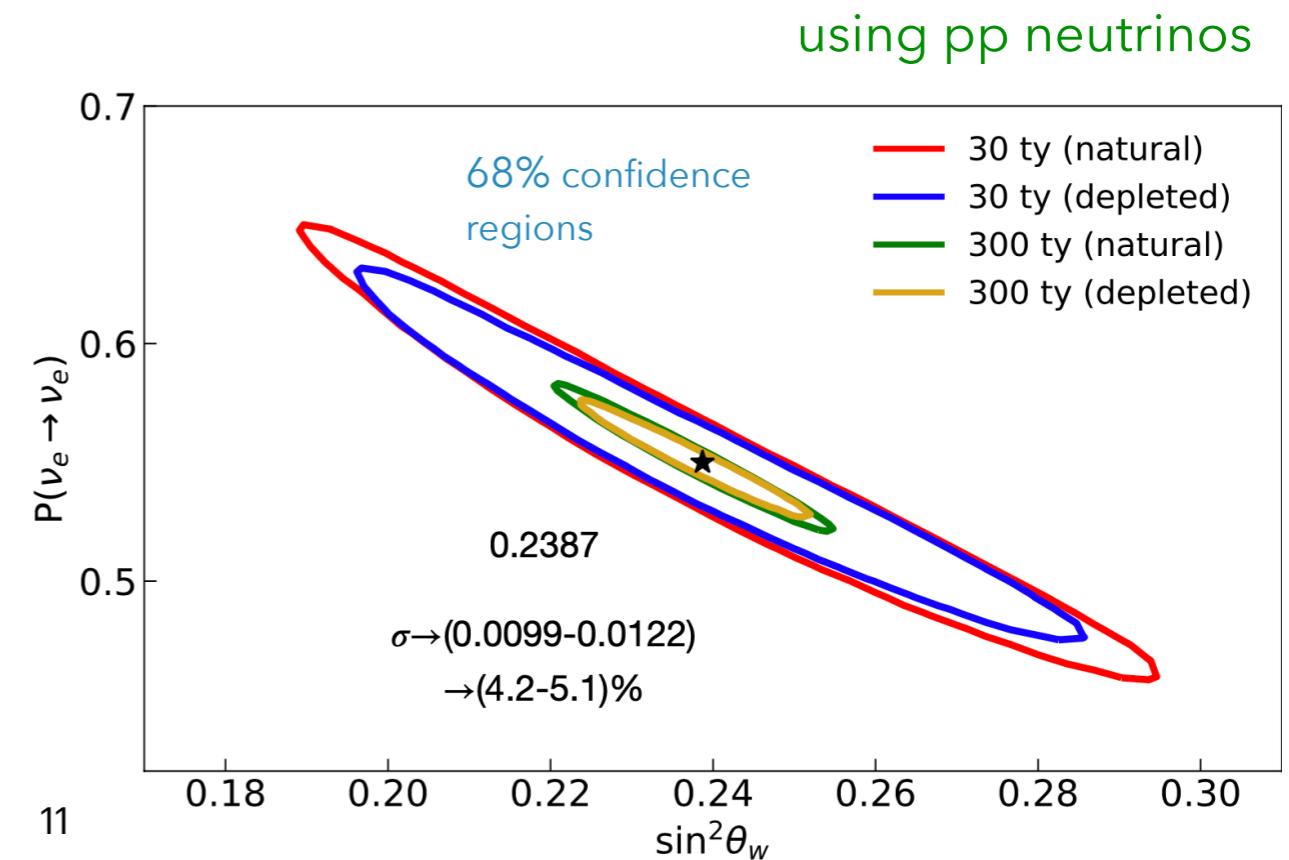
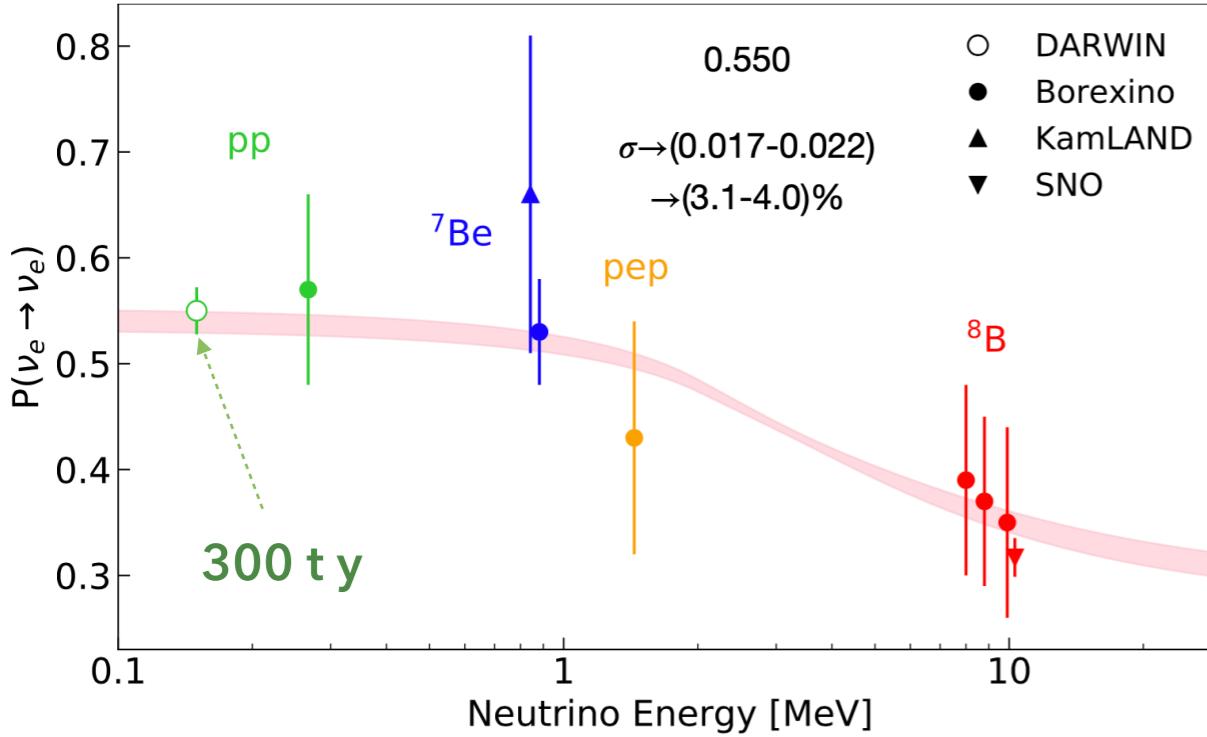
# Low-energy solar neutrinos

- Determined relative uncertainty of each solar  $\nu$  component vs exposure
- Solid: natural xenon target; dashed: target depleted in  $^{136}\text{Xe}$



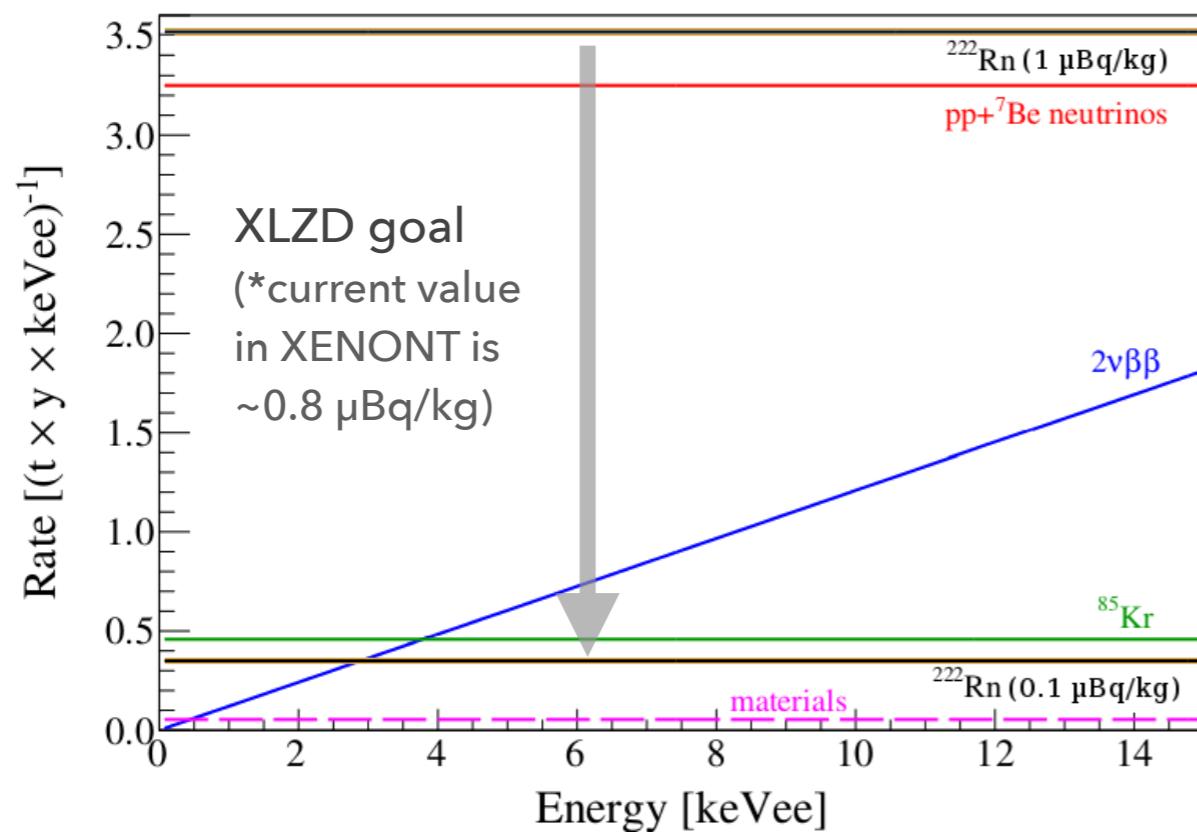
# Low-energy solar neutrinos

- Rates: 365 events/(t y) from pp ν and 140 events/(t y) from  ${}^7\text{Be}$  ν;  ${}^{13}\text{N}$ : 6.5/(t y),  ${}^{15}\text{O}$ : 7.1/(t y)
- **pp-flux: 0.15% statistical precision with 300 t y exposure** (sub-percent after 10 t y)
- $\nu_e$  survival probability & weak mixing angle < 300 keV
- $P_{ee}$ : ~4% relative uncertainty;  $\sin^2\theta_W$ : ~5% relative uncertainty

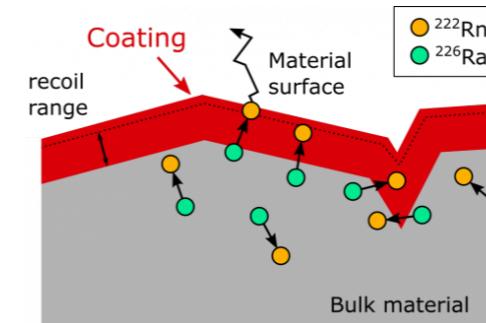


# Some challenges for XLZD

- Achieve a  $^{222}\text{Rn}$  concentration of  $\sim 0.1 \mu\text{Bq/kg}$  (distillation column, "radon-free" circulation pumps, coating techniques to avoid radon emanation, radio-pure materials)
- Achieve a low energy threshold (background from  $^{123}\text{Xe} 2\nu\beta\beta$  decay)



Example: Rn distillation column for XENONnT (reduce  $^{222}\text{Rn}$  - hence also  $^{214}\text{Bi}$  - from pipes, cables, cryogenic system)

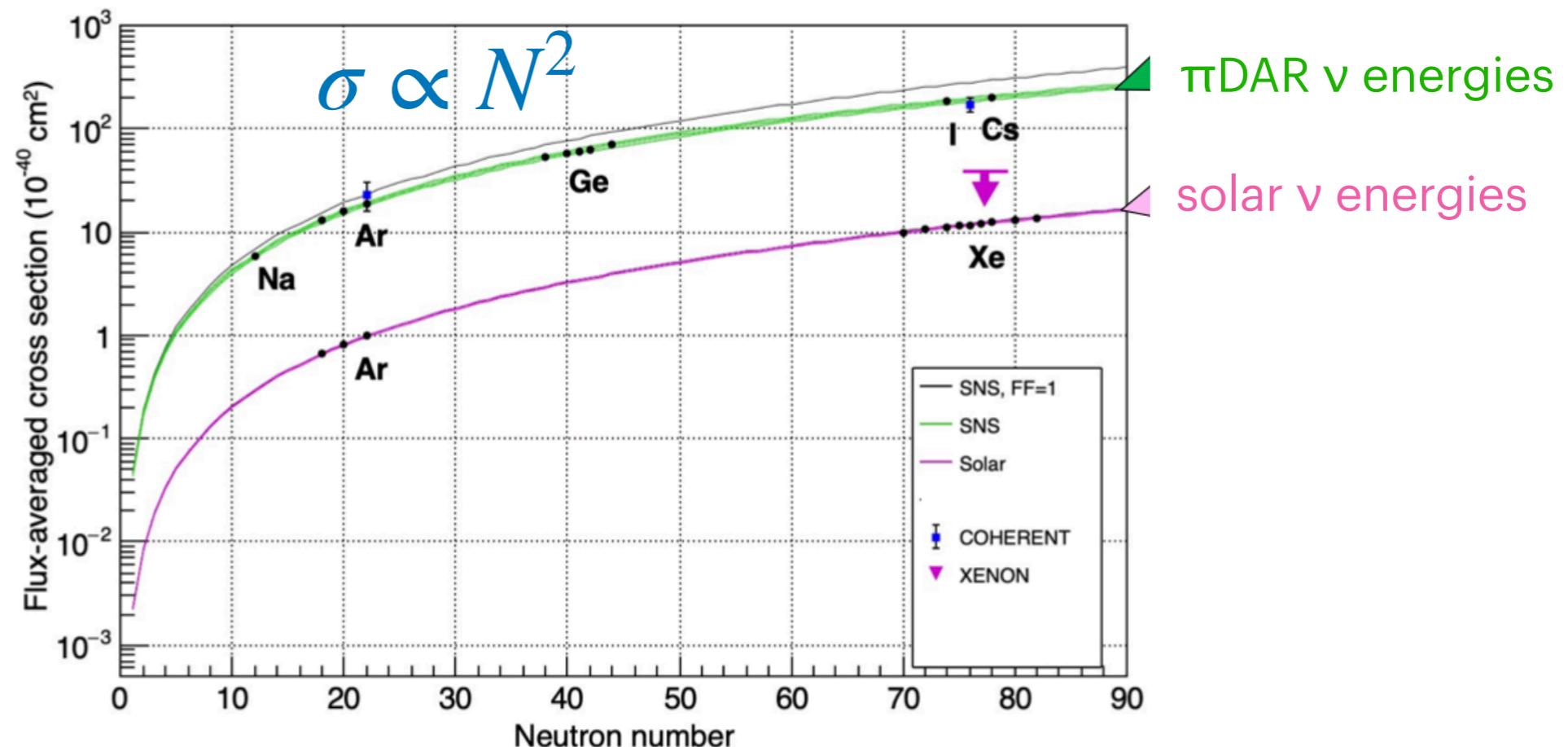


# CEvNS

- Proposed almost 50 years ago (Daniel Z. Freedman PRD 9, March 1974)
- Observed by COHERENT (CsI & LAr detectors), 43 y later, with  $\nu$ 's from  $\pi$ DAR
- **Never observed on xenon & never observed using wild neutrinos**
- For  $^8\text{B}$  solar neutrinos, the process is fully coherent (even for heavy nuclei)



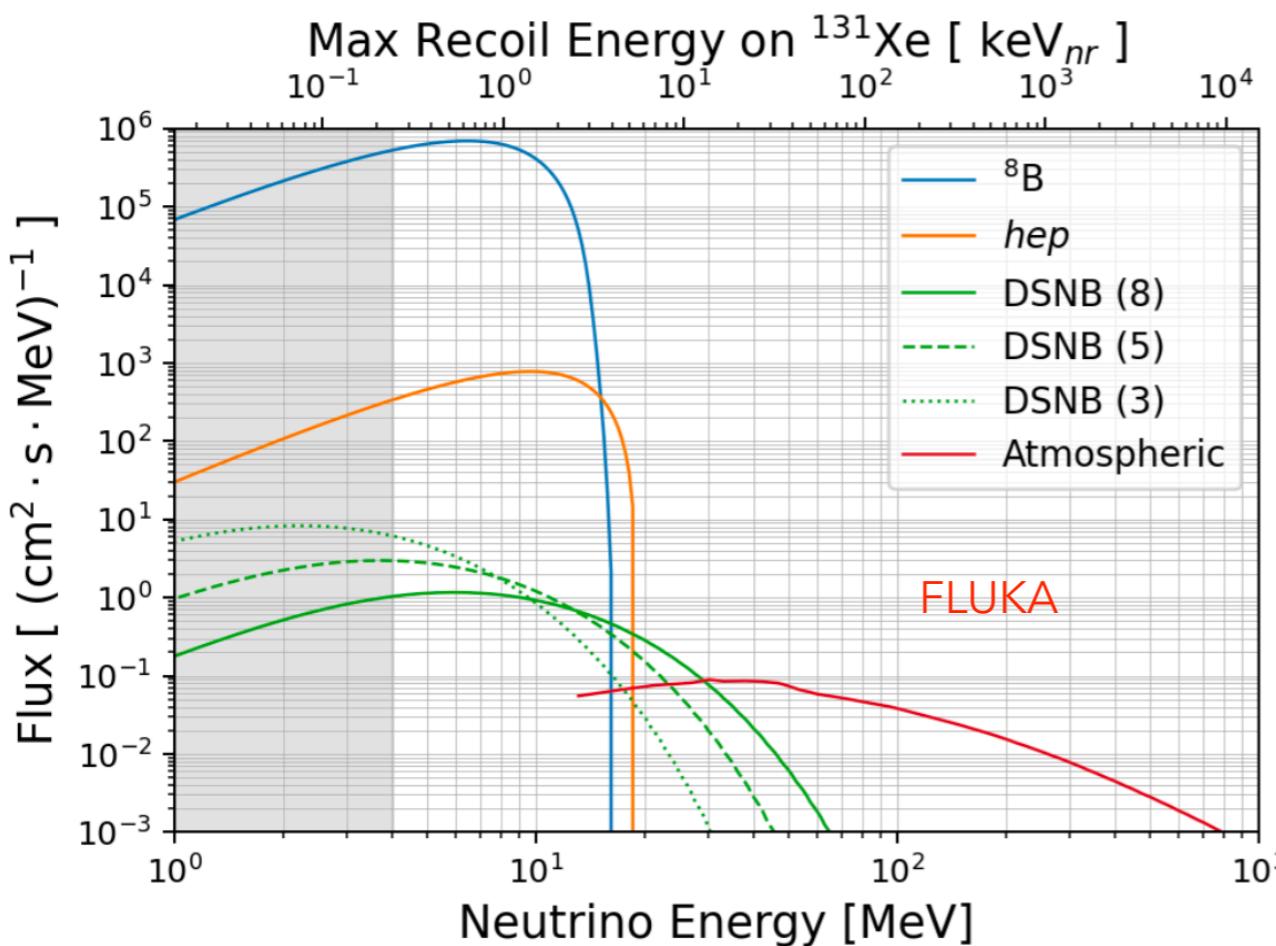
Figure by Kate Scholberg



# CEvNS in XLZD

- Sources: solar  $^8\text{B}$  and hep  $\nu$ 's; core-collapse SN; DSNB and atmospheric  $\nu$ 's

$$T_{\max} \propto \frac{2E_\nu^2}{M}$$



X. Xiang et al., 2304.06142

$$\sin^2 \theta_W = 0.231$$

$$Q_W = (1 - 4 \sin^2 \theta_W) Z - N$$

weak nuclear charge

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left( 2 - \frac{MT}{E_\nu^2} \right)$$

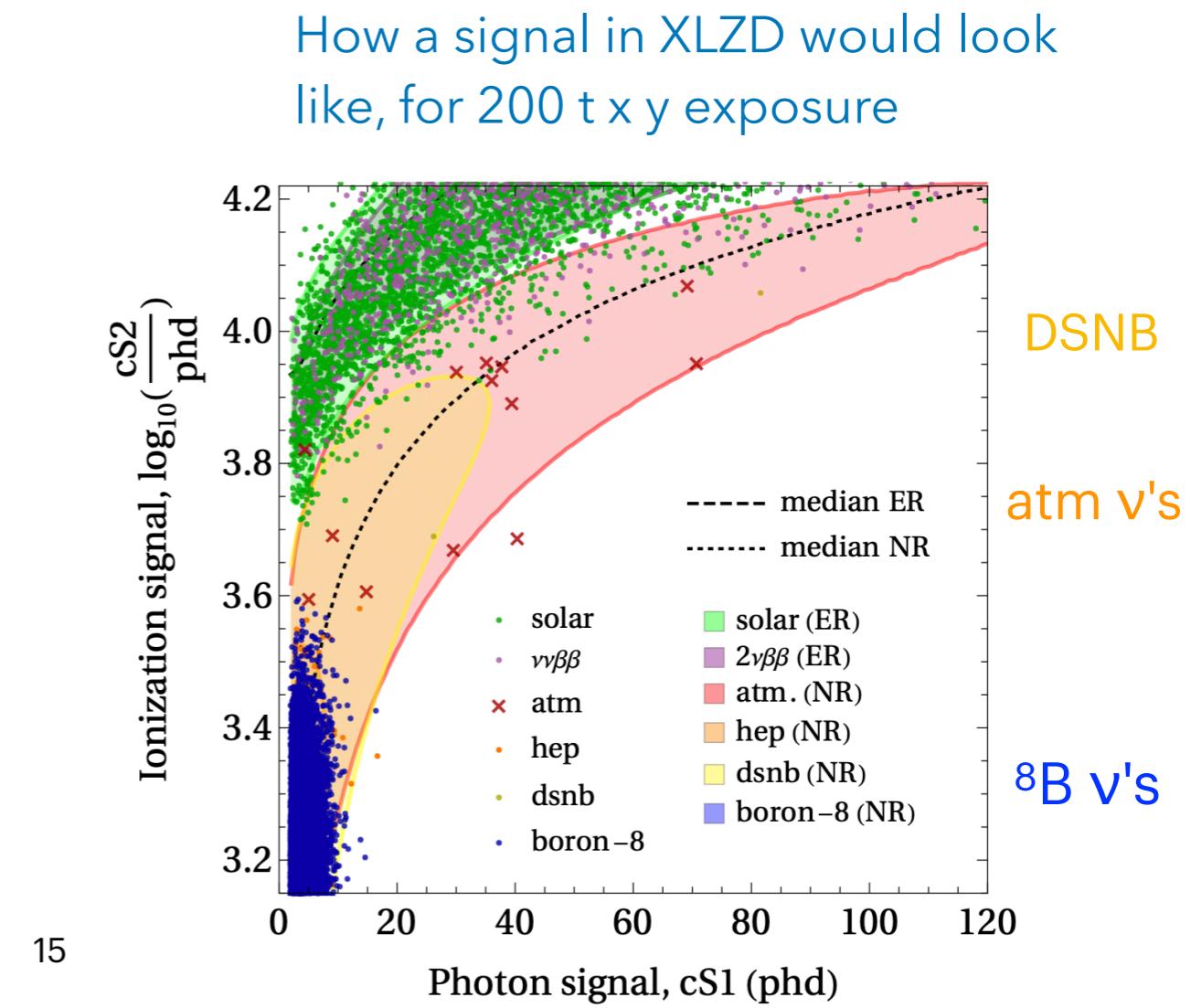
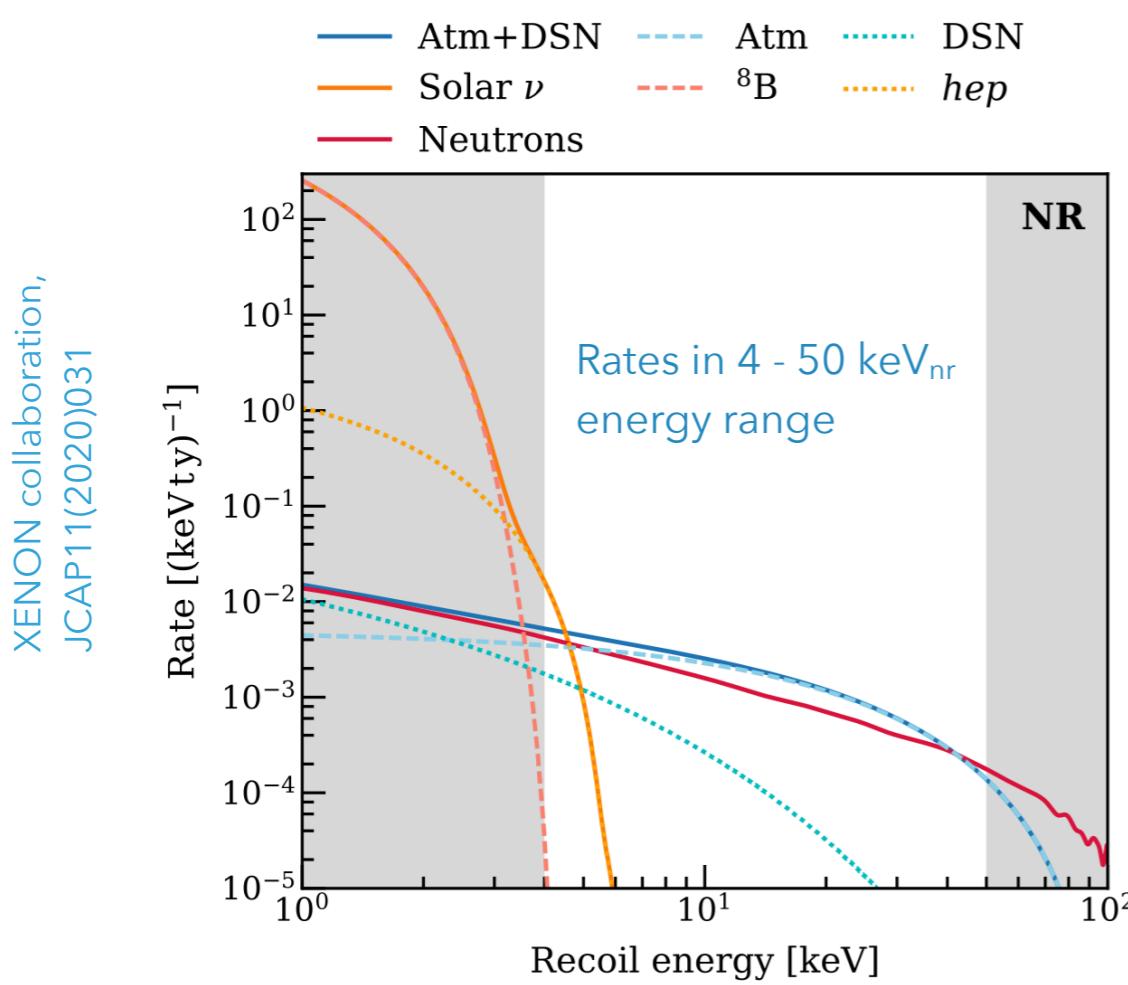
kinematics

form factor  $F = 1$  full coherence

$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$

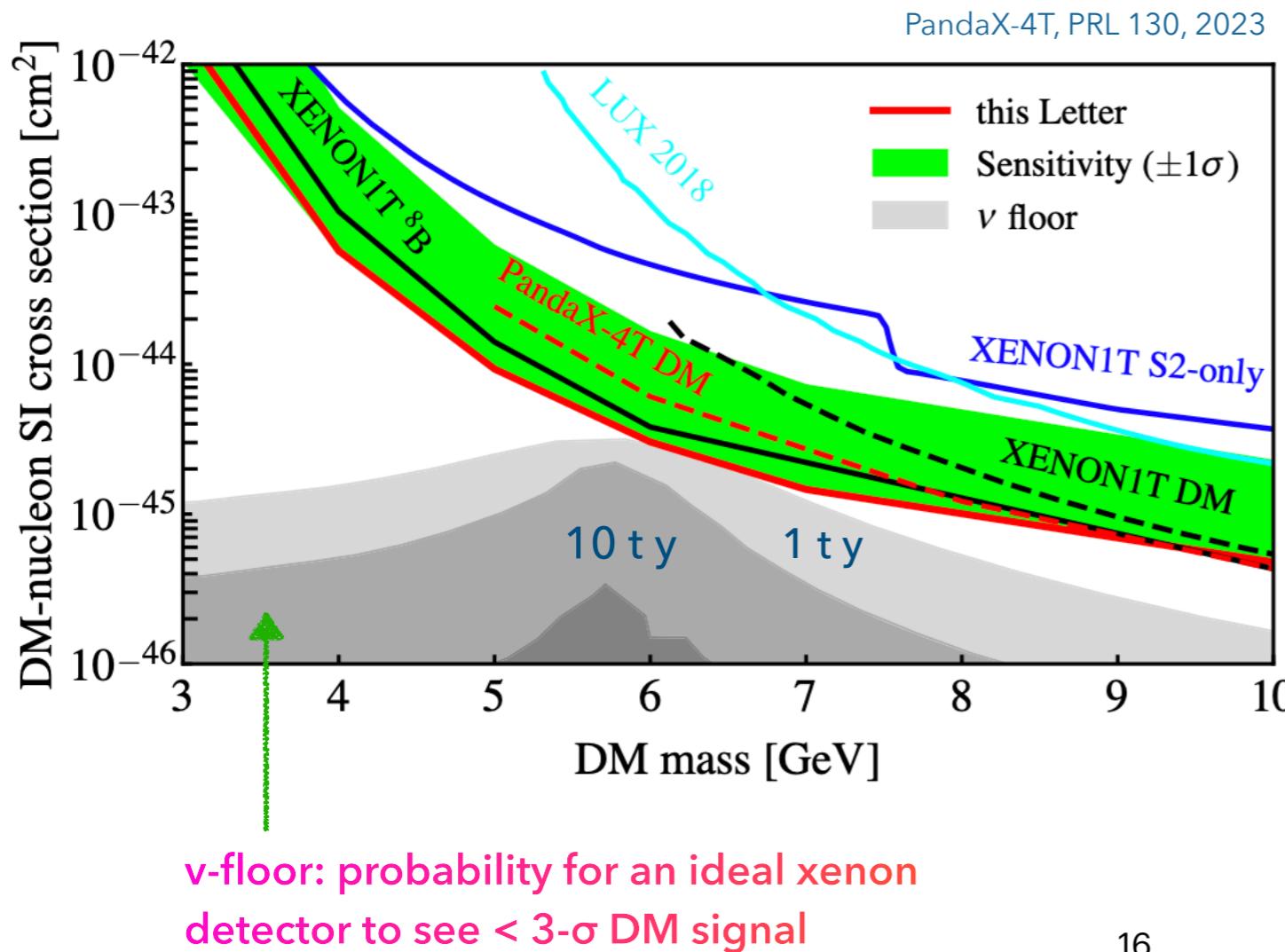
# CEvNS with ${}^8\text{B}$ neutrinos

- ~99% of CEvNS-induced events expected  $< 3 \text{ keV}_{\text{nr}}$
- ~ $10^4$  events/(200t y) for 2-fold S1 and 5  $n_e$  S2 (see X. Xiang et al., 2304.06142)

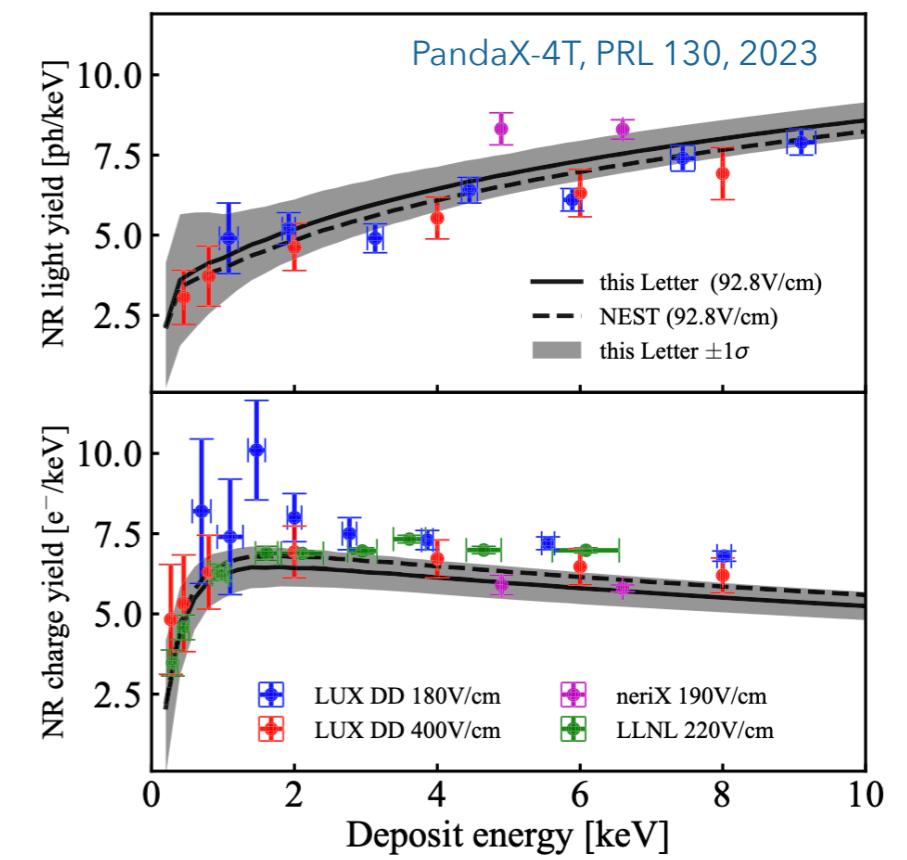
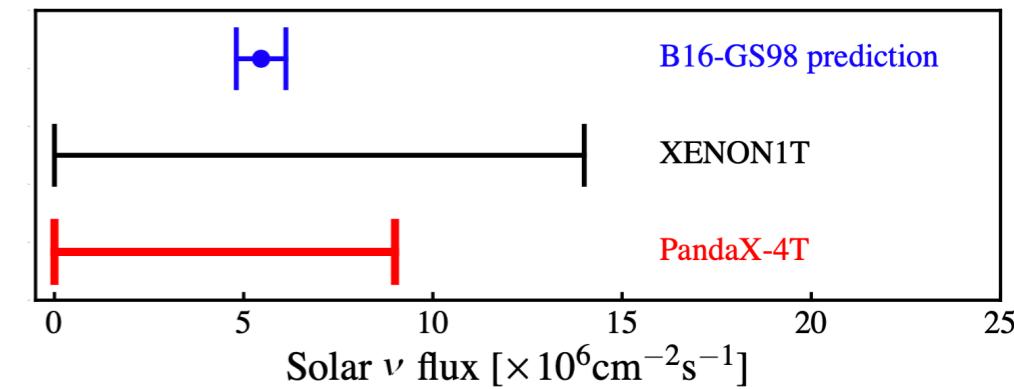


# Existing ${}^8\text{B}$ $\nu$ constraints

- XENON1T, PandaX-4T
- Searches ongoing in LZ, PandaX-4T, XENONnT

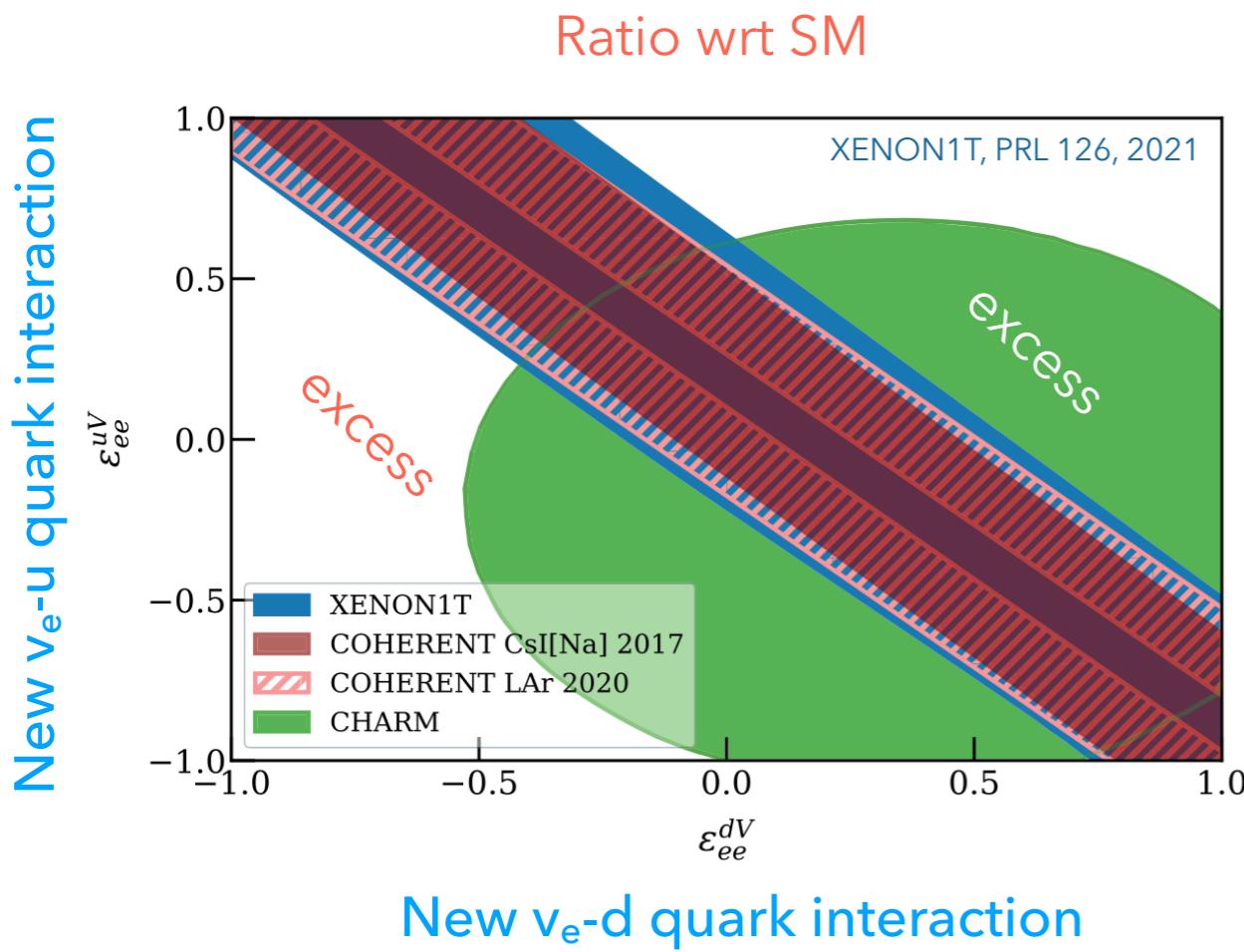


${}^8\text{B}$  flux prediction and constraints from XENON1T and PandaX-4T

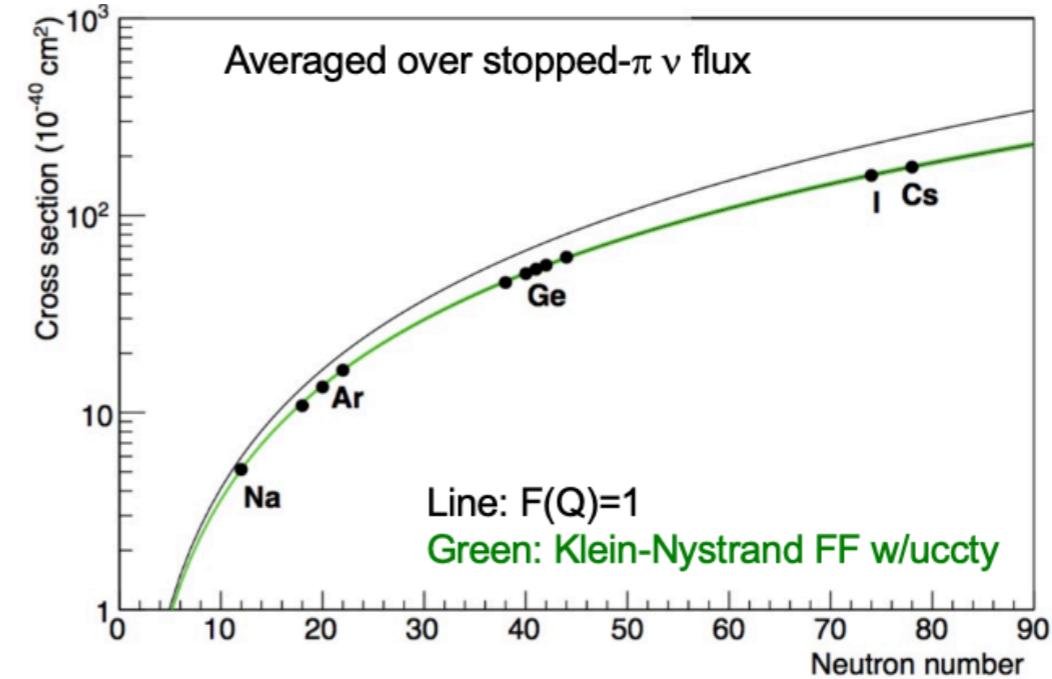


# Non-standard $\nu$ interactions

- New physics specific to  $\nu$ -nucleon interactions poorly constrained
- In general: *model-independent parametrisation* of non-standard contributions to  $\nu$ -q interaction cross sections (with vector and axial-vector couplings)
- Presence of NSI results in enhancement or suppression of CEvENS rate

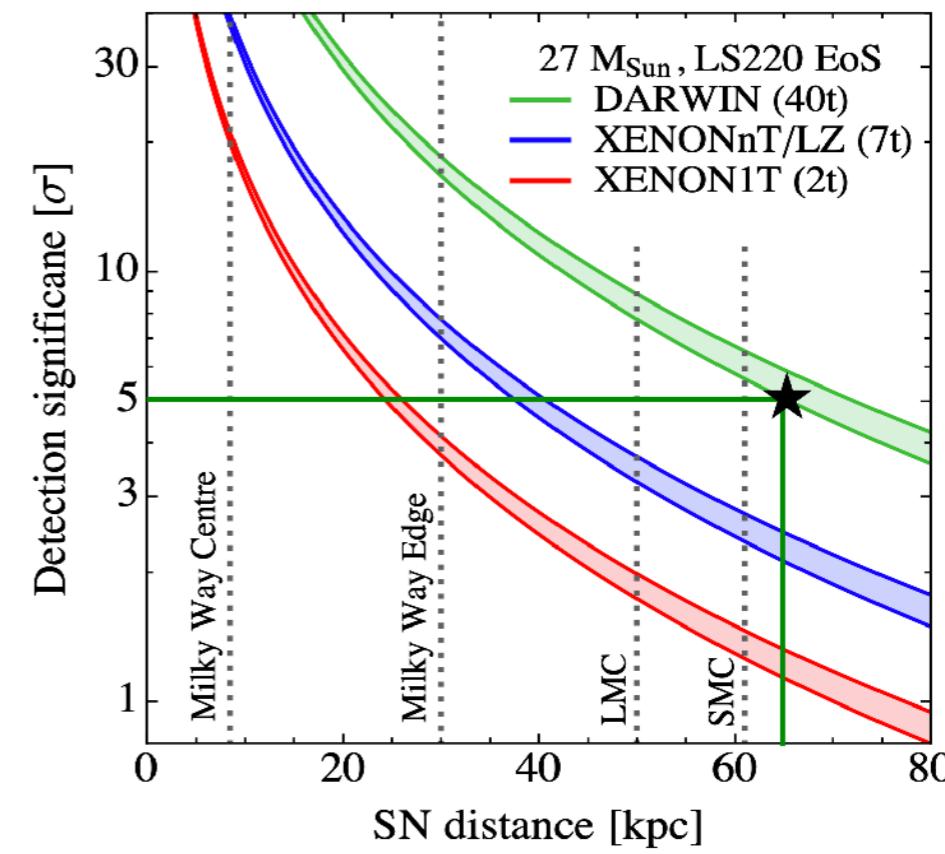
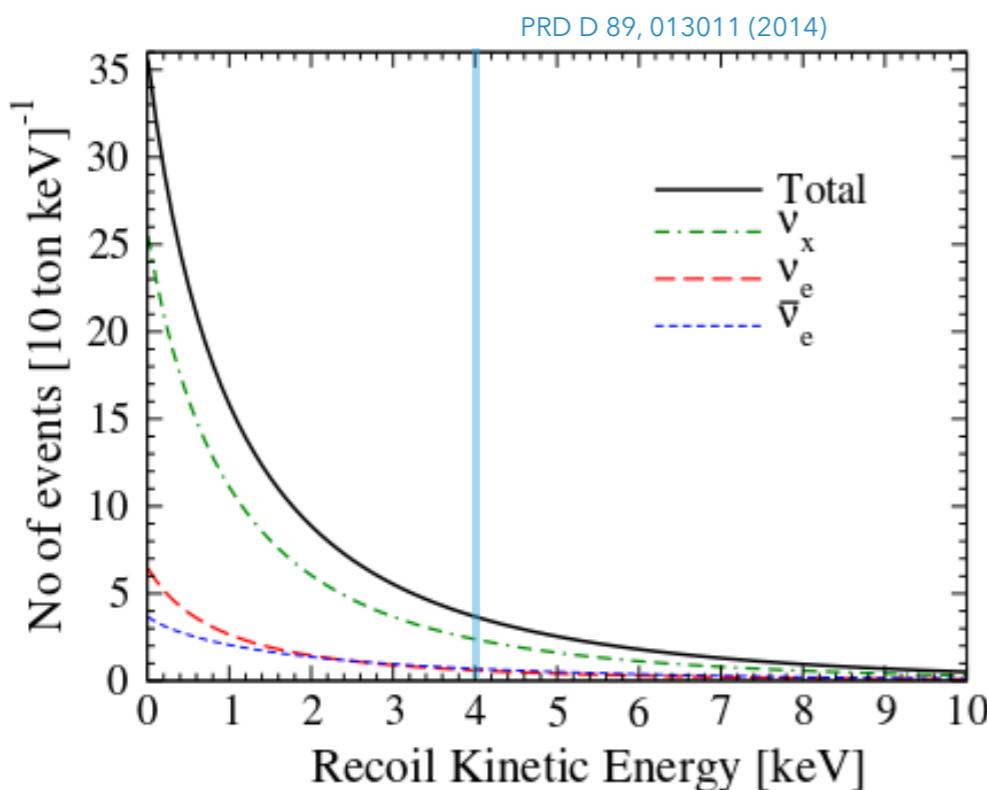


If we see additional or fewer CEvNS than expected in XLZD: could be BSM physics!



# CEvNS with SN neutrinos

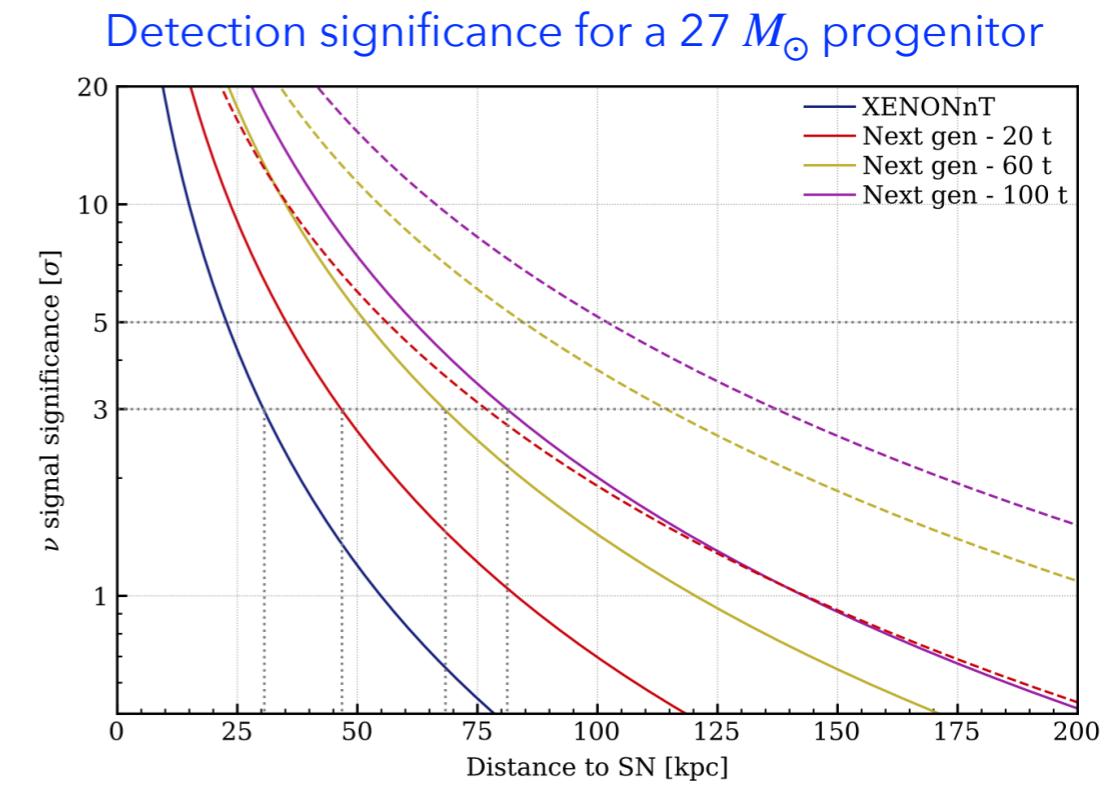
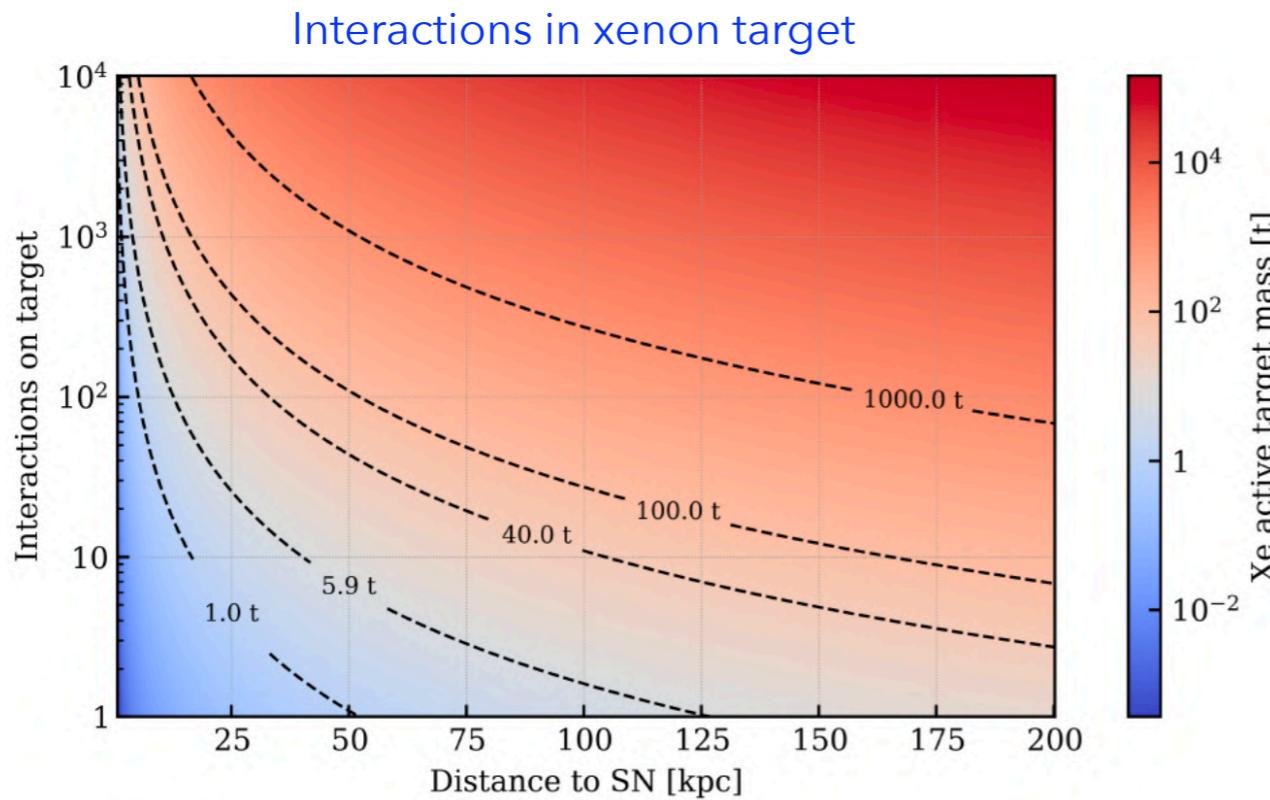
- Collapse of a star: ~99% of gravitational binding energy of proto-neutron star goes into  $\nu$ 's of all flavours, ~ 10s of MeV  $\nu$  energies
- XLZD: sensitivity to all neutrino flavours from a core-collapse SN
  - few events/tonne expected for SN at 10 kpc
  - 700 events (in 40 t) from SN with  $27 M_{\odot}$  at 10 kpc



R. Lang et al., PRD  
94, 103009

# CEvNS with SN neutrinos

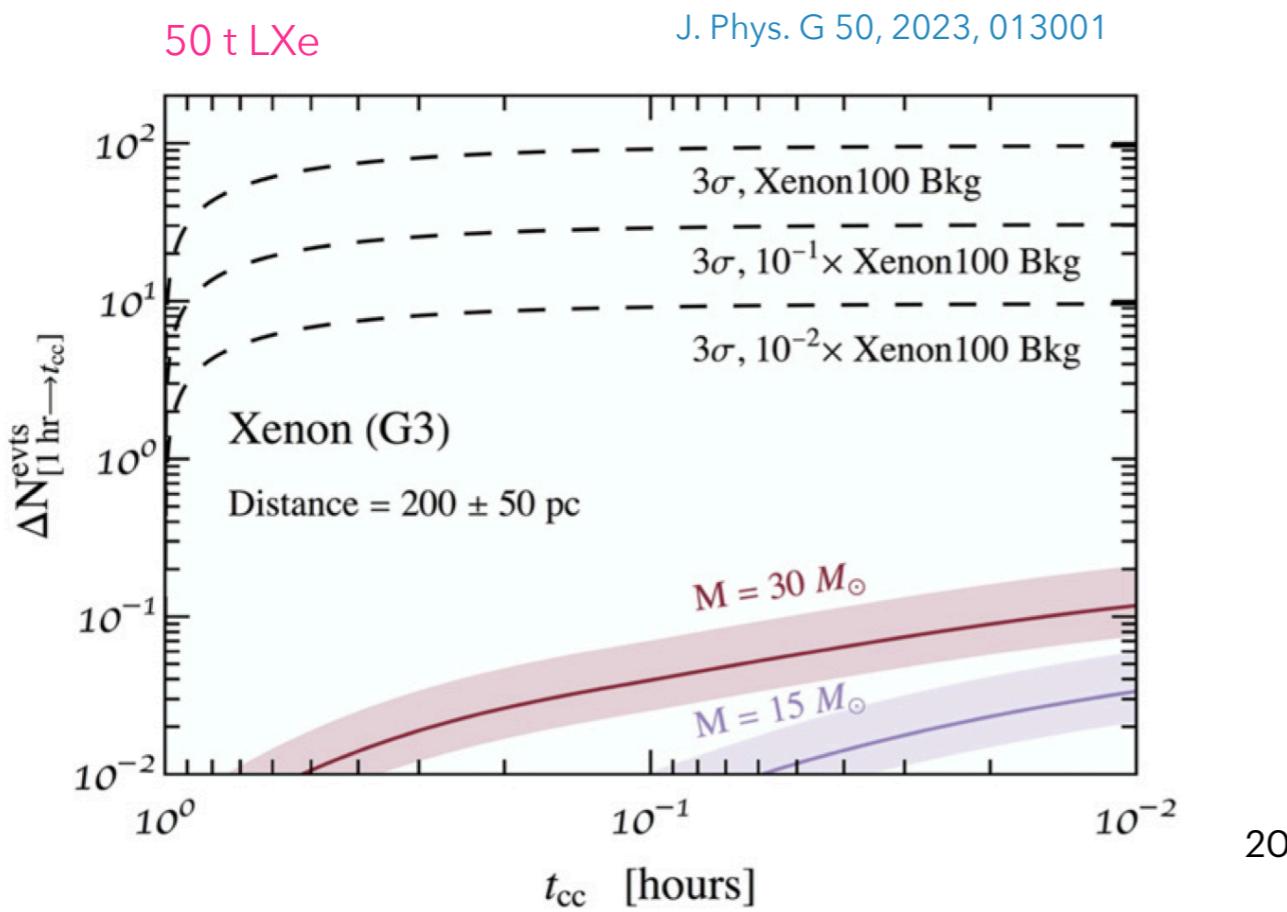
- Collapse of a star: ~99% of gravitational binding energy of proto-neutron star goes into  $\nu$ 's of all flavours, ~ 10s of MeV  $\nu$  energies
- XLZD: sensitivity to all neutrino flavours
  - few events/tonne expected for SN at 10 kpc
  - 700 events (in 40 t) from SN with  $27 M_\odot$  at 10 kpc



Plots by Ricardo Peres

# CEvNS with SN neutrinos

- SN close to Earth ( $d < \text{kpc}$ , e.g., Betelgeuse)
  - XLZD: sensitivity to neutrinos emitted prior to core collapse, in Si-burning stage
    - "pre-SN" neutrinos have lower energies ( $\sim 10 \text{ MeV}$ ), lower threshold necessary
    - $O(100)$  pre-SN neutrinos expected in 12 h window, 0.1 keV energy threshold

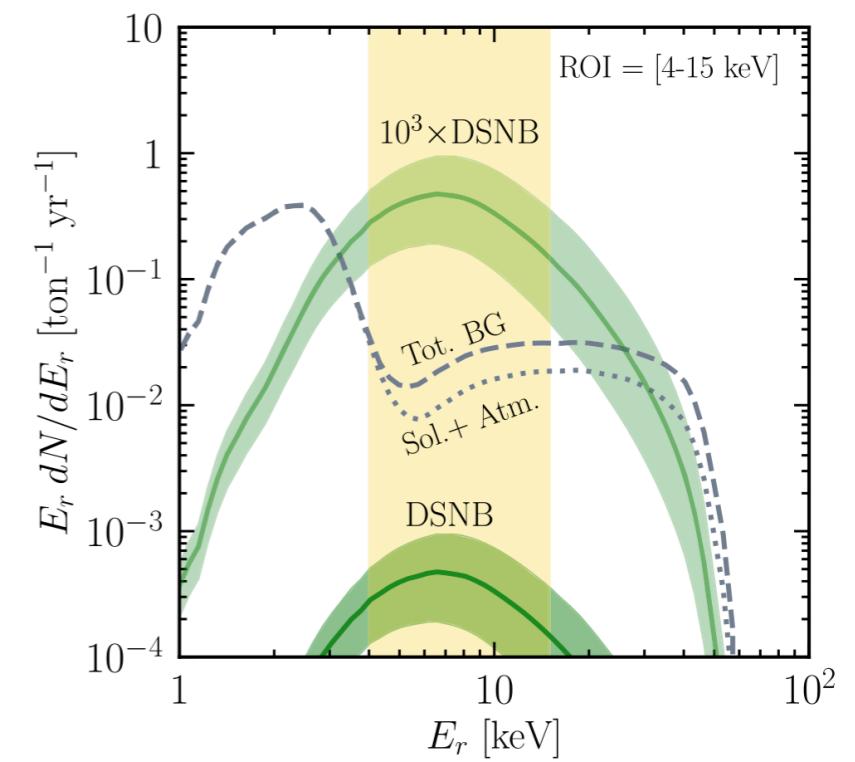
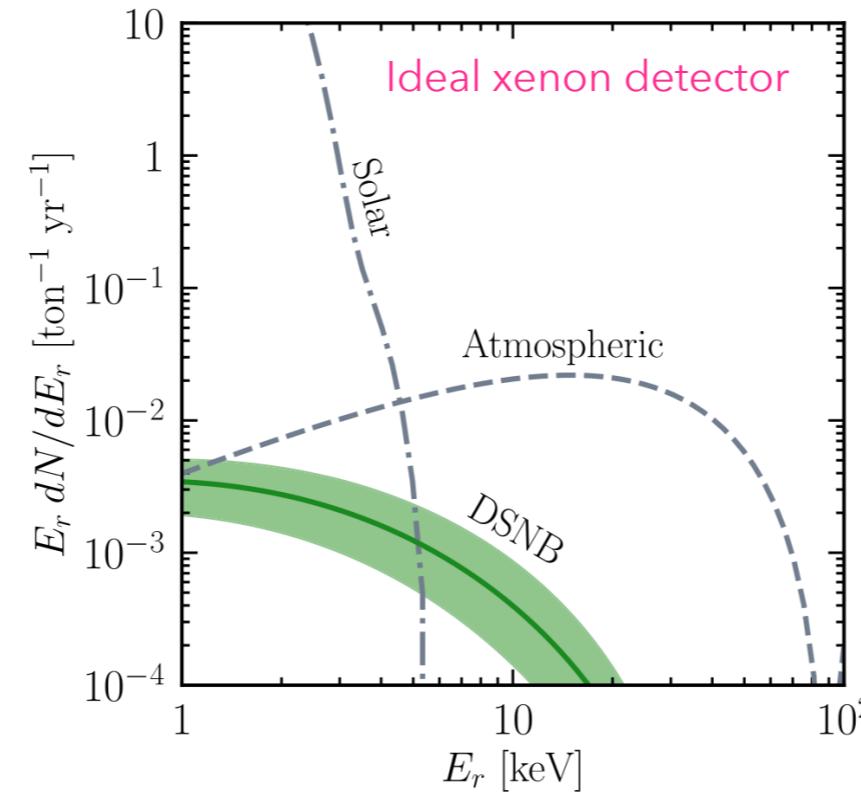
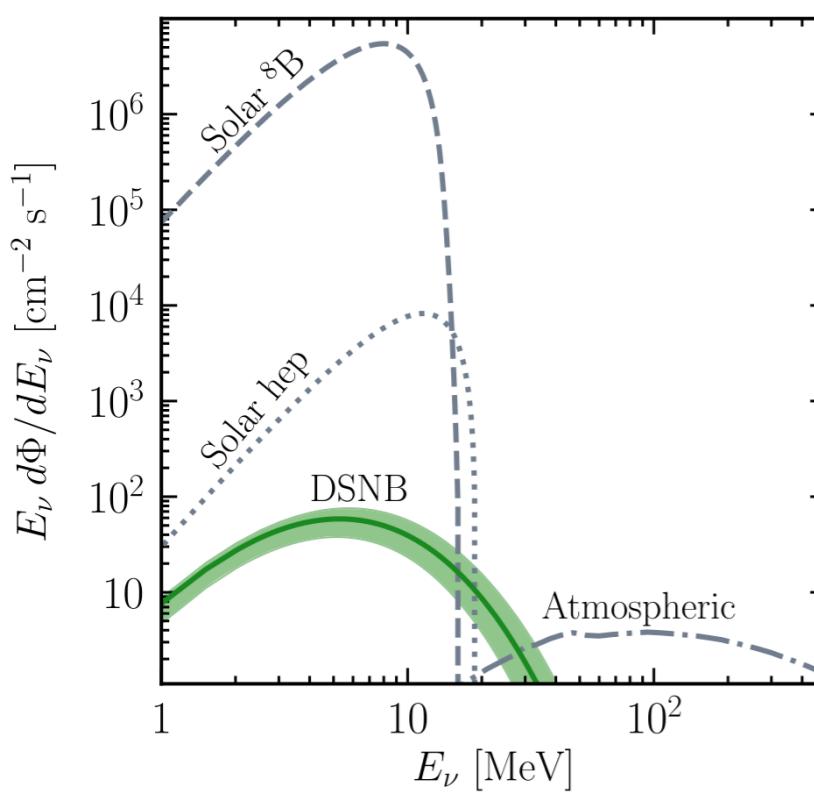


*Also: planned participation in supernova  
early warning system  
(SNEWS) network (<https://snews.bnl.gov>)*

*SNEWS: prepares and provides early warning system for galactic SN => early alert to facilitate observation of optical counterpart*

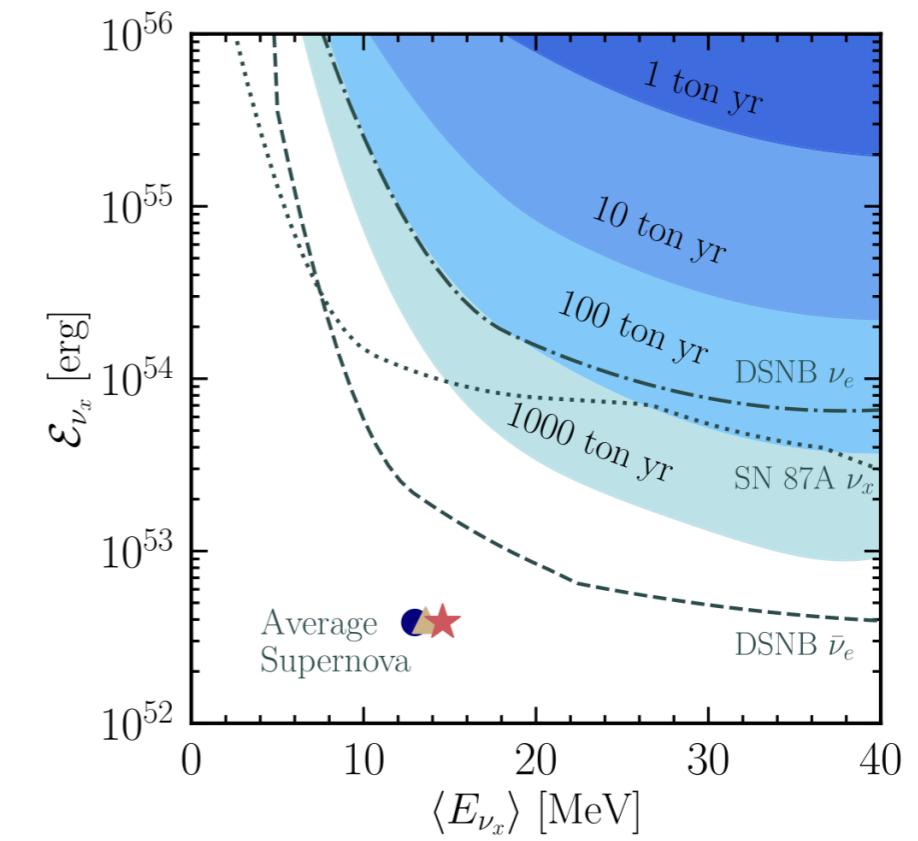
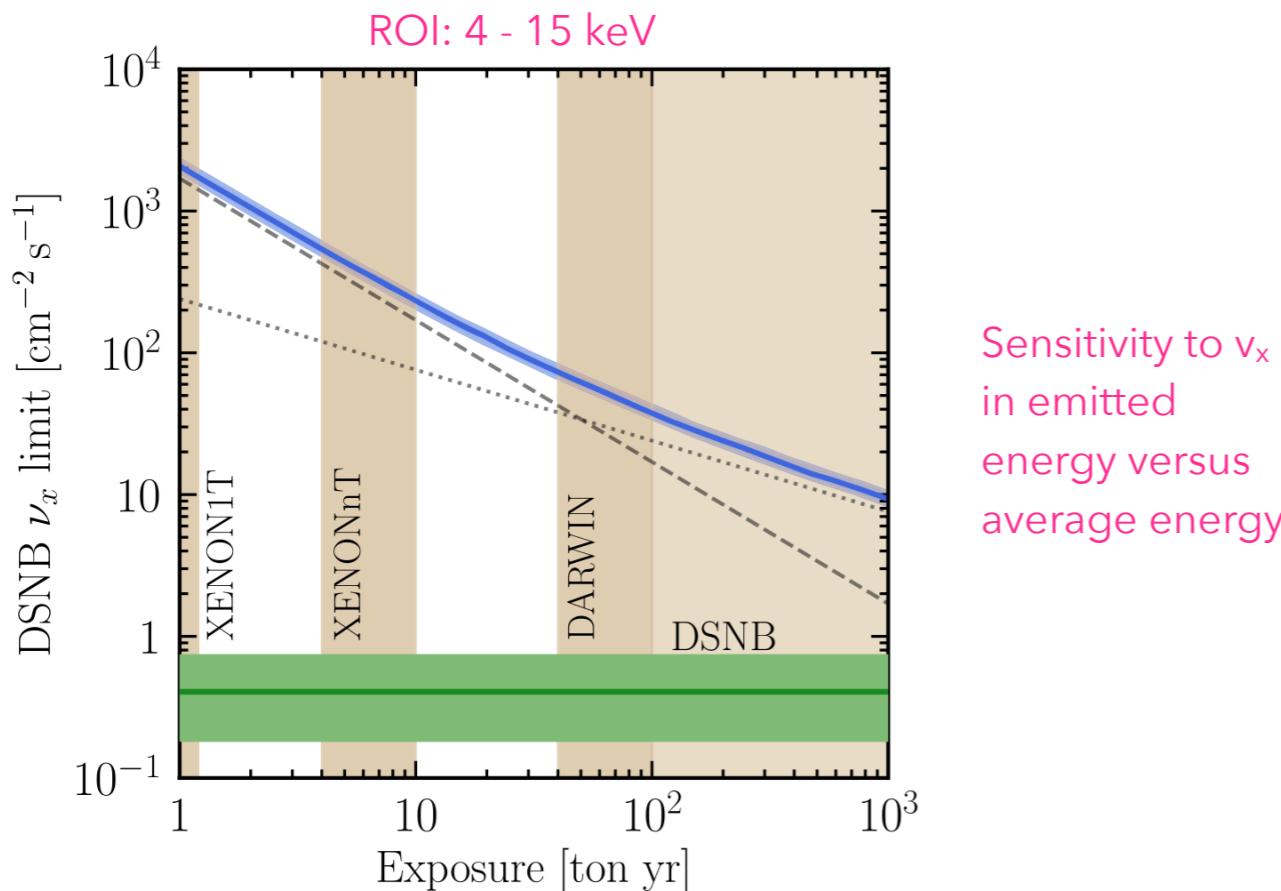
# CEvNS with DSNB

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



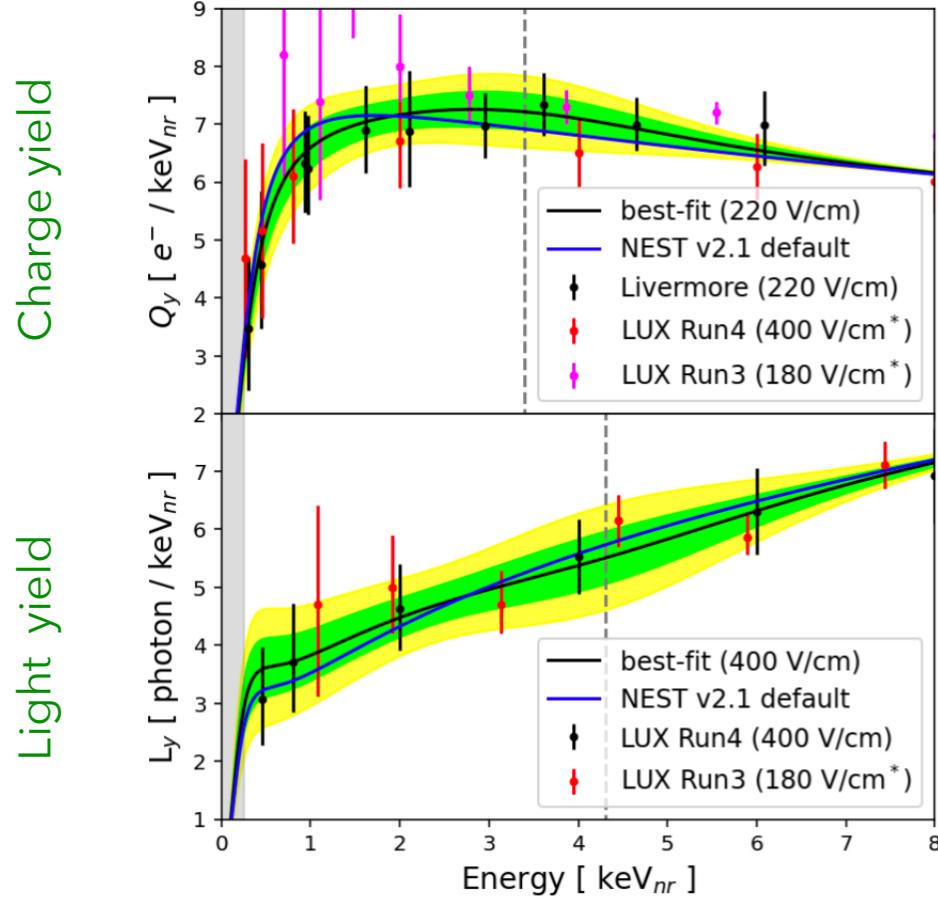
# CEvNS with DSNB

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



# Some challenges

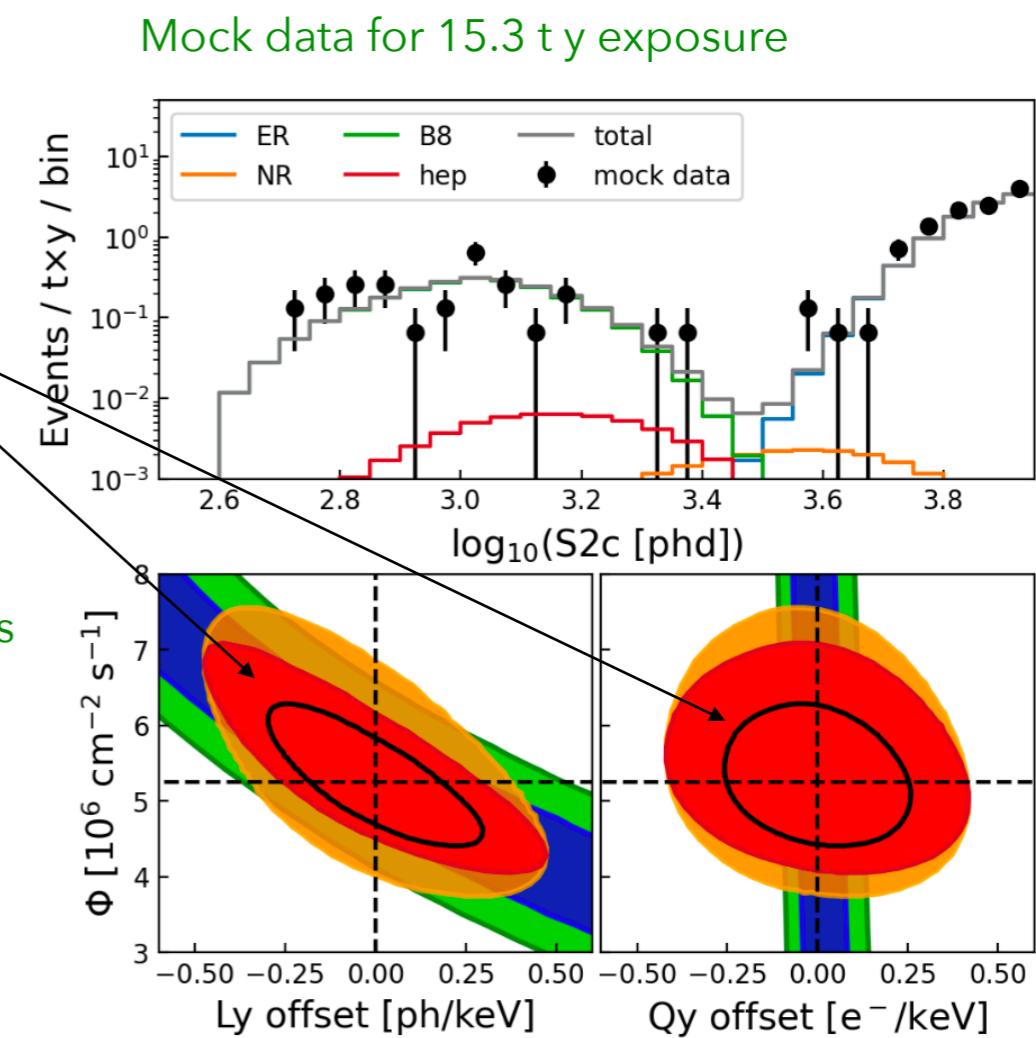
- Light and charge yields at lowest energies & their uncertainties: dominate systematics (especially in constraining NSI); in situ and special calibrations needed
- Accidental coincidence rate (due to isolated S1 and isolated S2 signals; R&D programme and modelling (semi-empirical code) in place for XLZD



50 t y with  $Q_y$ ,  
 $L_y$  uncertainties  
reduced by 1/2

Bands: no constraints  
on  $Q_y$ ,  $L_y$

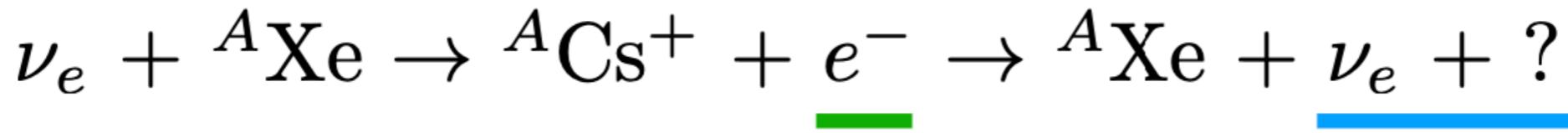
Contours:  $Q_y$ ,  $L_y$   
constrained to calib  
data



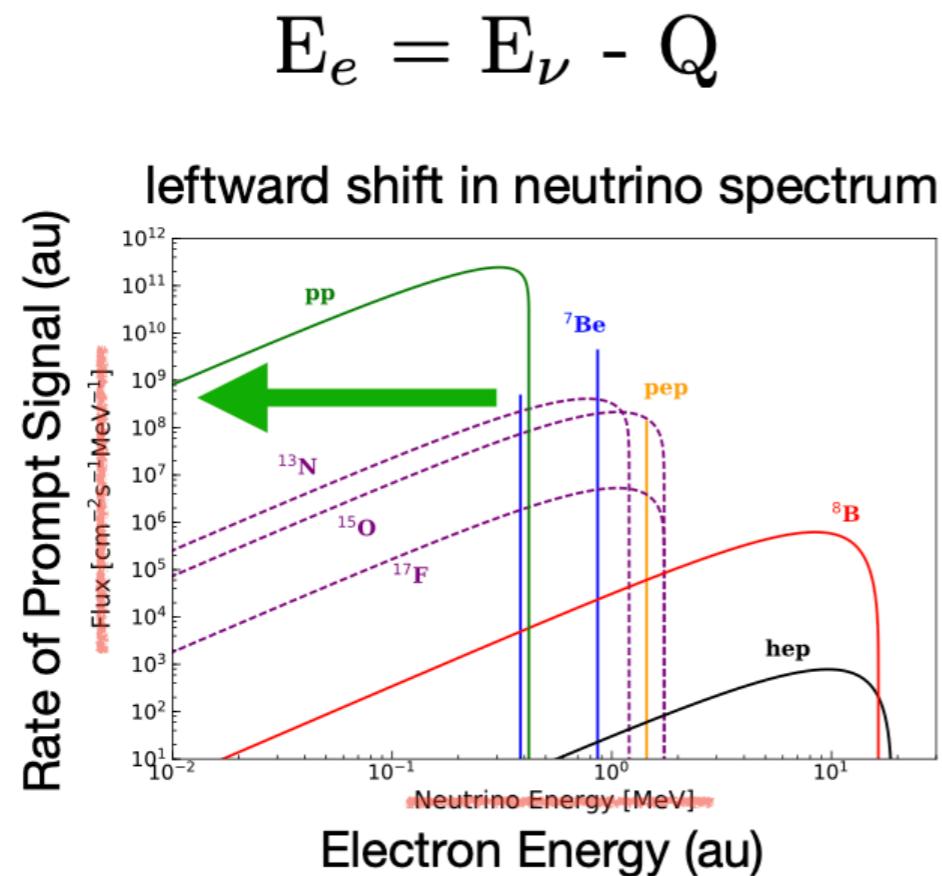
The end

# Additional slides

# Neutrino capture



## Prompt Signature



## Delayed Signature

follows half-life  $\tau$

$\beta^-$  electrons

spectrum

?

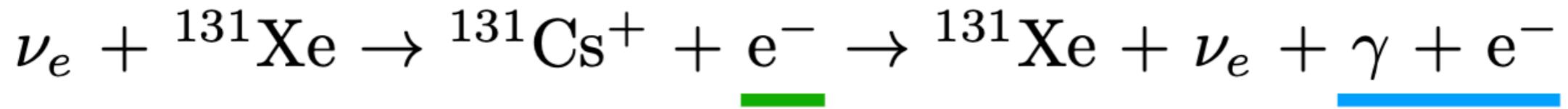
EC

Combination of X-rays and Auger electrons

peak @

$$E = Q - E_\nu$$

# Neutrino capture



A	% > Q	R [SNU]	R <sub>PS</sub> [ty <sup>-1</sup> ]	R <sub>DS</sub> [ty <sup>-1</sup> ]
pp	17.2	9.7	0.78	0.78
Be	100	17.8	1.42	1.42
N	90.8	1.6	0.13	0.13
O	96.2	1.8	0.14	0.14
pep	100	1.6	0.13	0.13
B	99.98	12.7	0.11*	1.00
			<b>2.71</b>	<b>3.60</b>

Georgadze et al.

<https://www.sciencedirect.com/science/article/pii/S0927650597000170>

$$Q = 355 \text{ keV}$$

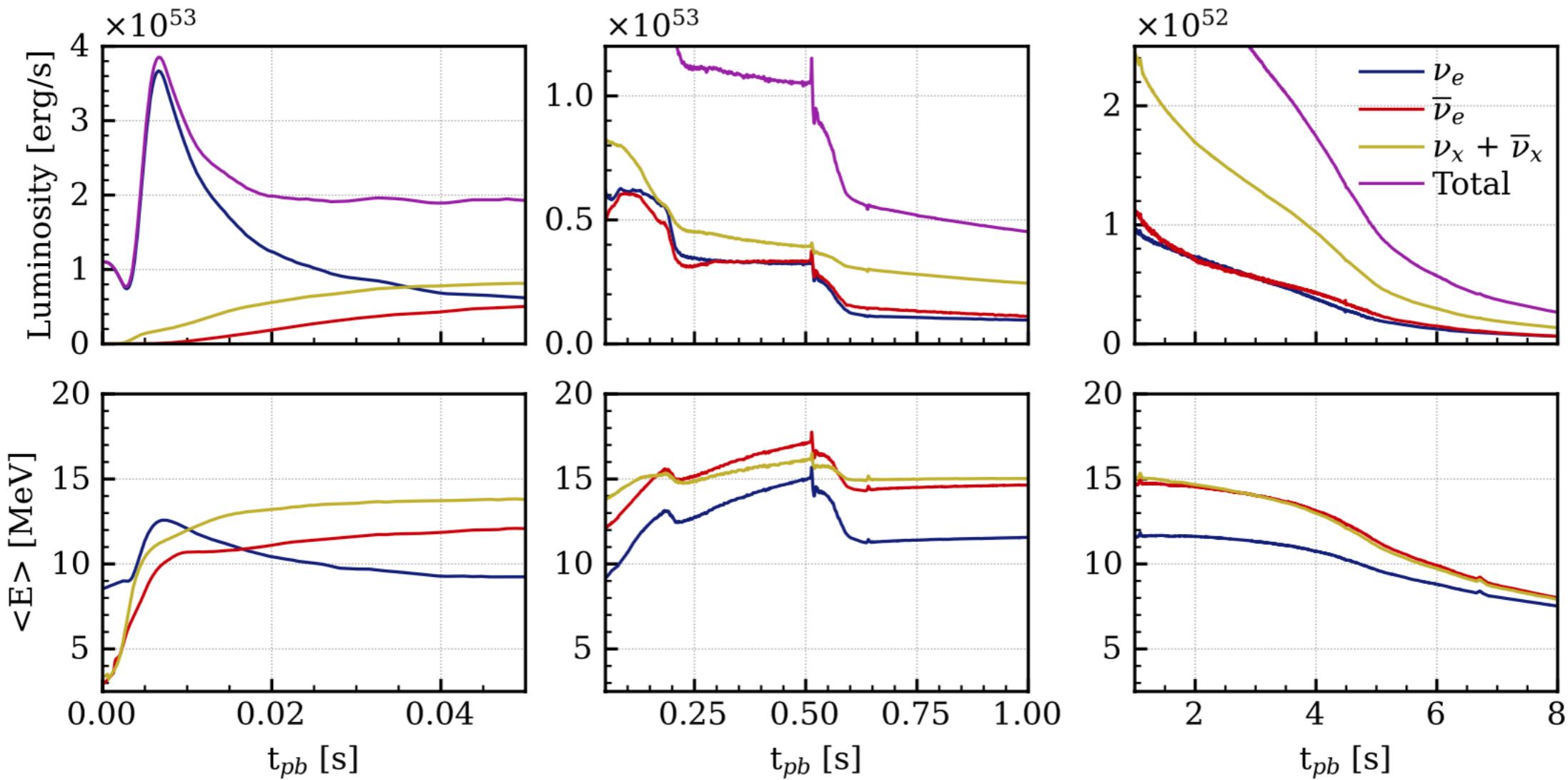
$$E_\nu = 325.5 \text{ keV}$$

$$E_{NC} = 29.5 \text{ keV}$$

\* only 11.4% in [0,3] MeV

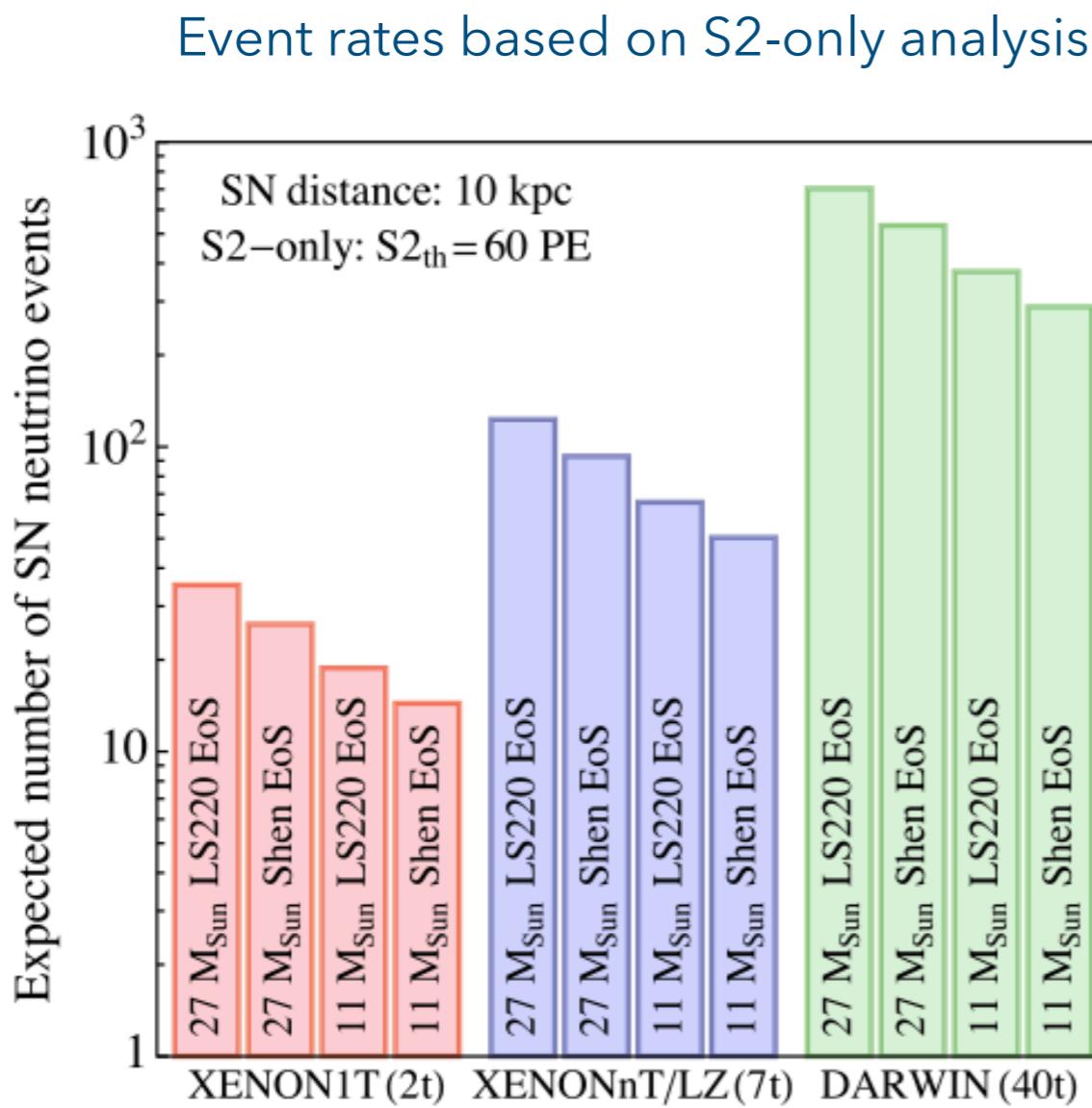
# SN v luminosity and energy

For a  $27 M_{\odot}$  progenitor, as a function of time after bounce

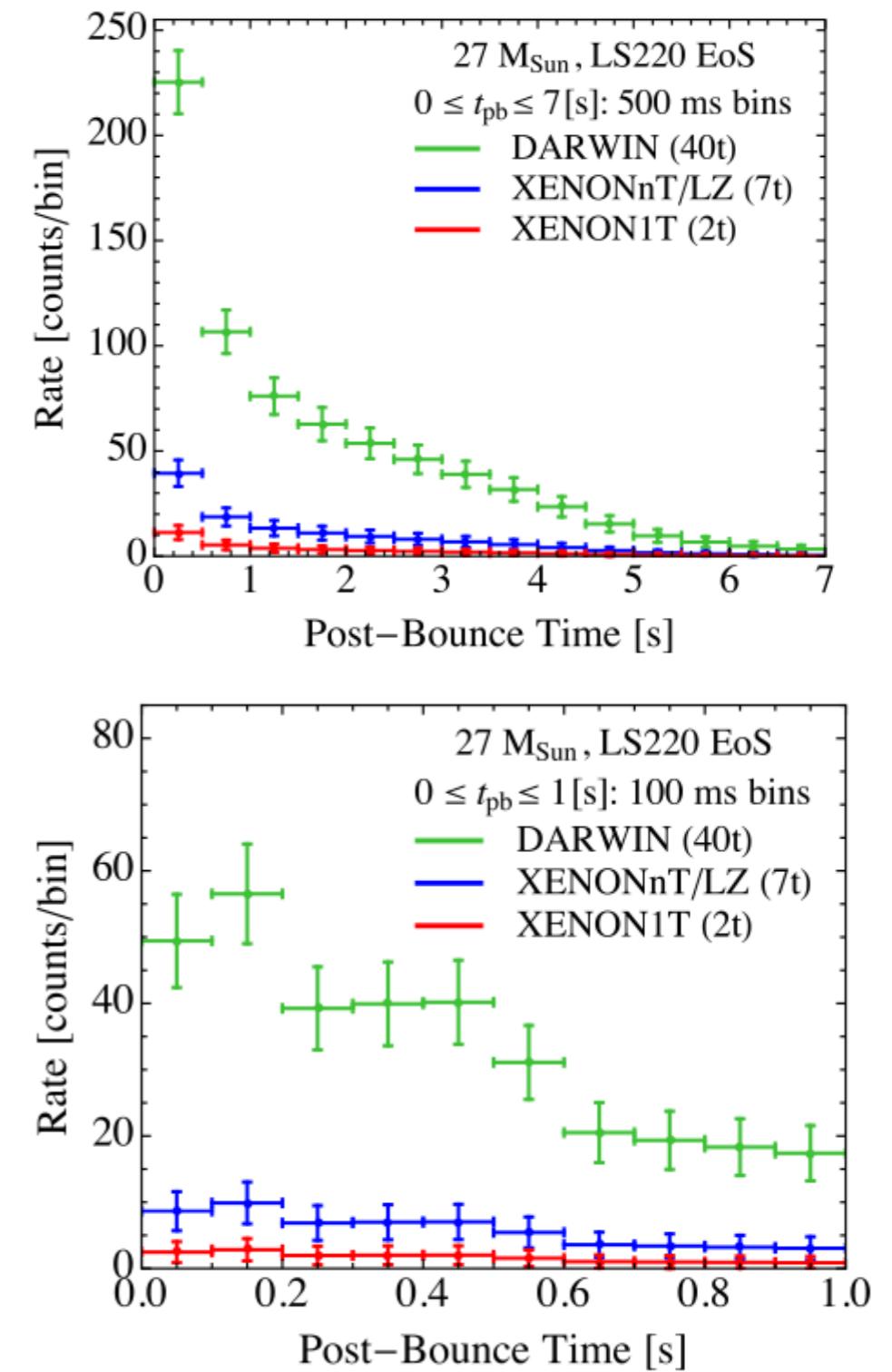


Plot by Ricardo Peres, model from the Garching SN archive

# SN ν events



Event rates from S2-only analysis



# CEvNS

- The process was first proposed almost 50 years ago (Daniel Z. Freedman PRD volume 9, number 5, March 1974)

PHYSICAL REVIEW D

VOLUME 9, NUMBER 5

1 MARCH 1974

## Coherent effects of a weak neutral current

Daniel Z. Freedman<sup>†</sup>

*National Accelerator Laboratory, Batavia, Illinois 60510*

*and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790*

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process  $\nu + A \rightarrow \nu + A$  should have a sharp coherent forward peak just as  $e + A \rightarrow e + A$  does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about  $10^{-38} \text{ cm}^2$  on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes  $\nu + A \rightarrow \nu + A^*$  provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

# AC studies

## Toy semi-empirical accidental code (Tina)

Traditionally, ACs are not considered in sensitivity projections, but are significant.

Three of the Largest Contributors are not yet considered.

- S1s
  - Pile-up Dark Counts
    - Number of channels
  - Charge-Insensitive Regions
    - Detector Geometry
    - Electron Lifetime
  - **Delayed Photons?**
- S2s
  - Bulk xenon S2-only events
    - Detector Radioactivity
    - Neutrinos
  - **Delayed Electrons?**
  - **Electrode Events?**

