

RES-NOVA

Detecting Supernova neutrinos with archaeological Pb-based cryogenic detectors

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Supernovae: cosmic fireworks

setting the stage

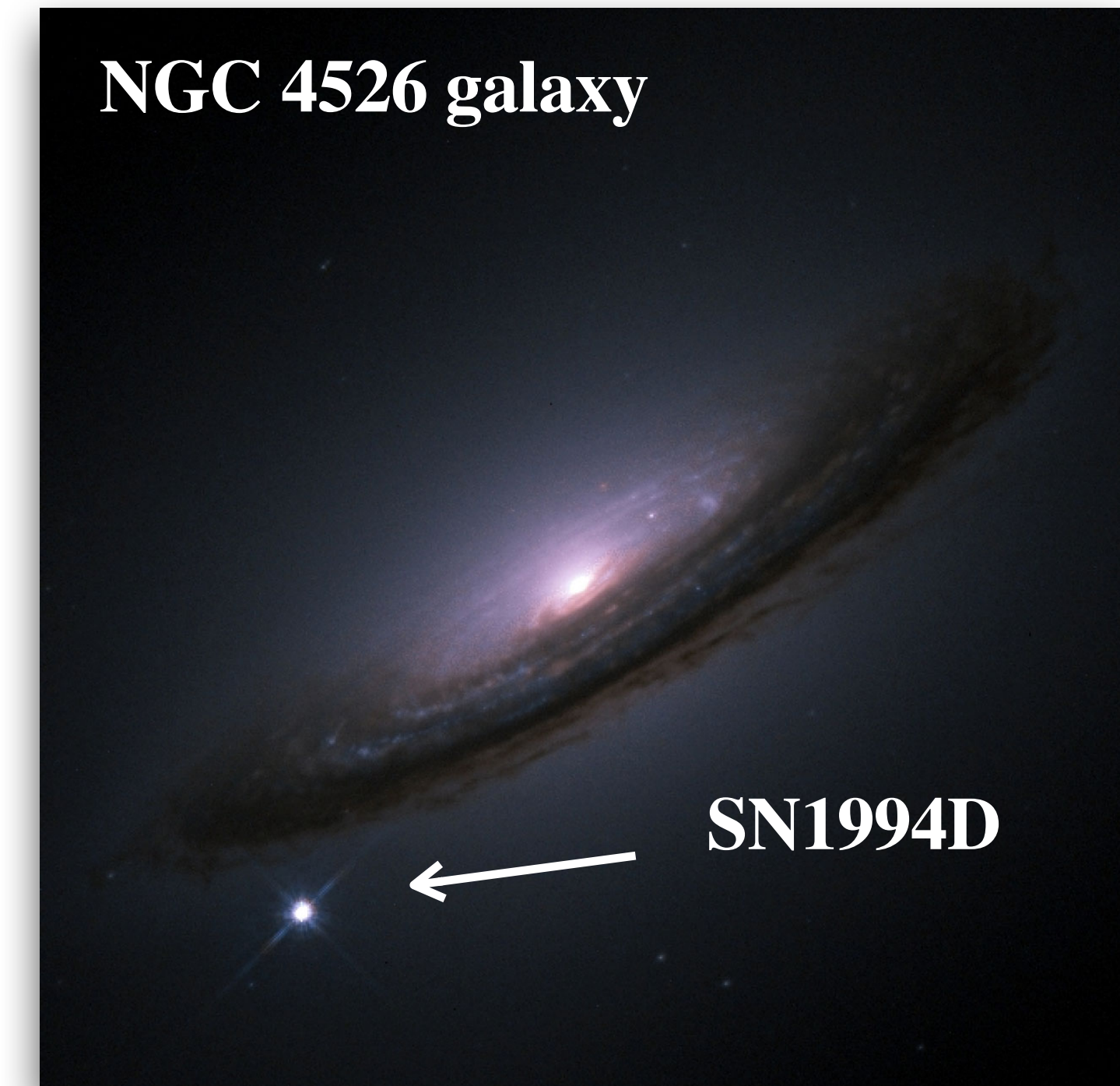
Supernovae (SN): high-energy **explosions of massive stars**

Almost total star binding energy converted into **all flavor-neutrinos**
but also **GW** and **EM** radiation

Neutrinos: direct **probes** and **messengers** of SNe hidden dynamics

Rare event (~ 1.6 SN/100 y): **1 observation** with underground instrumentation

*1987 Birth of
Neutrino Astronomy*

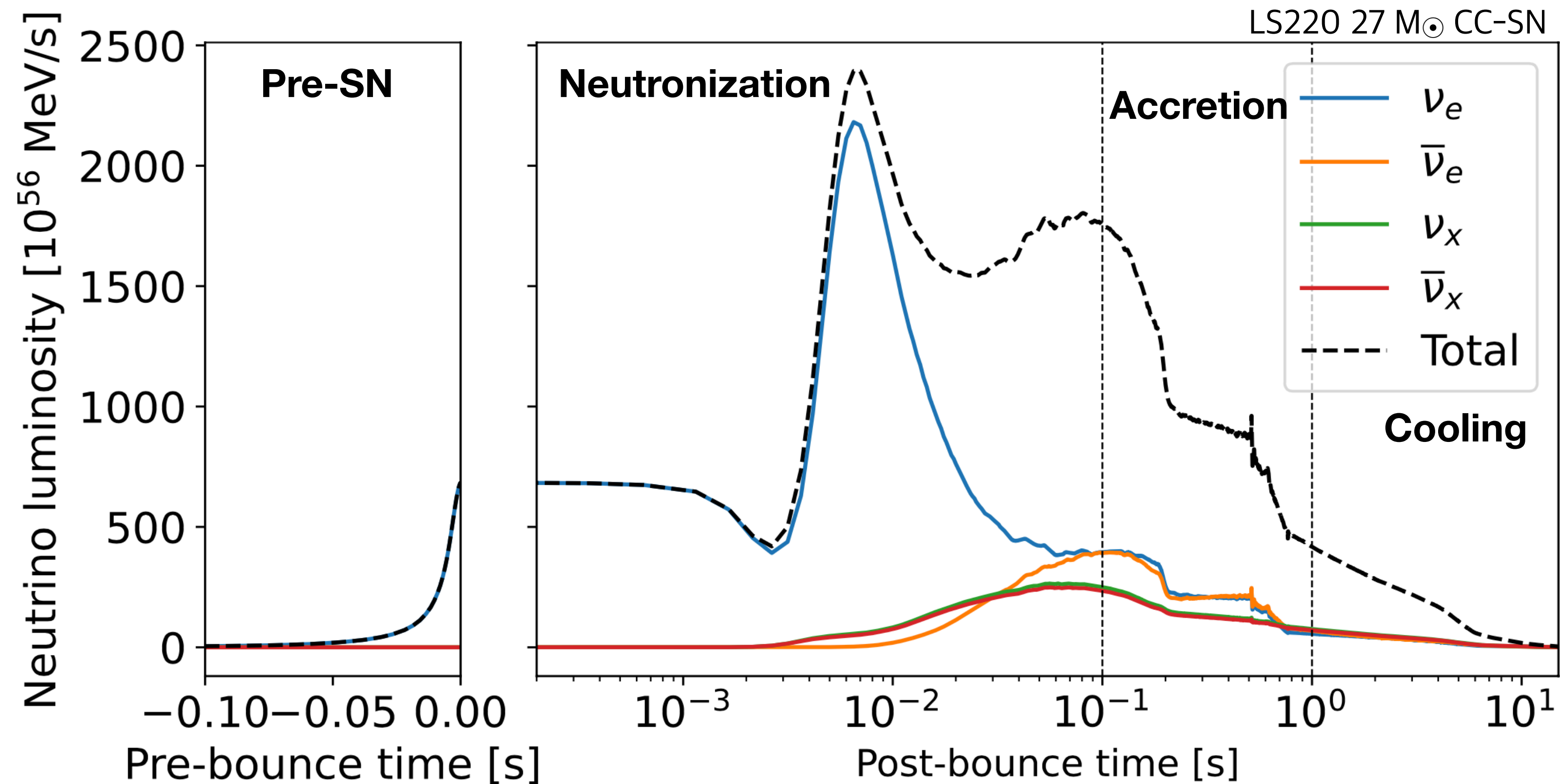


Credit: NASA/ESA, The Hubble Key Project Team and
The High-Z Supernova Search Team

Neutrinos are emitted at all times

Unique neutrino signature

Neutrino transport simulation of a Core-Collapse SN



A. Mirizzi et al., Riv. Nuovo Cim.39, 1 (2016)

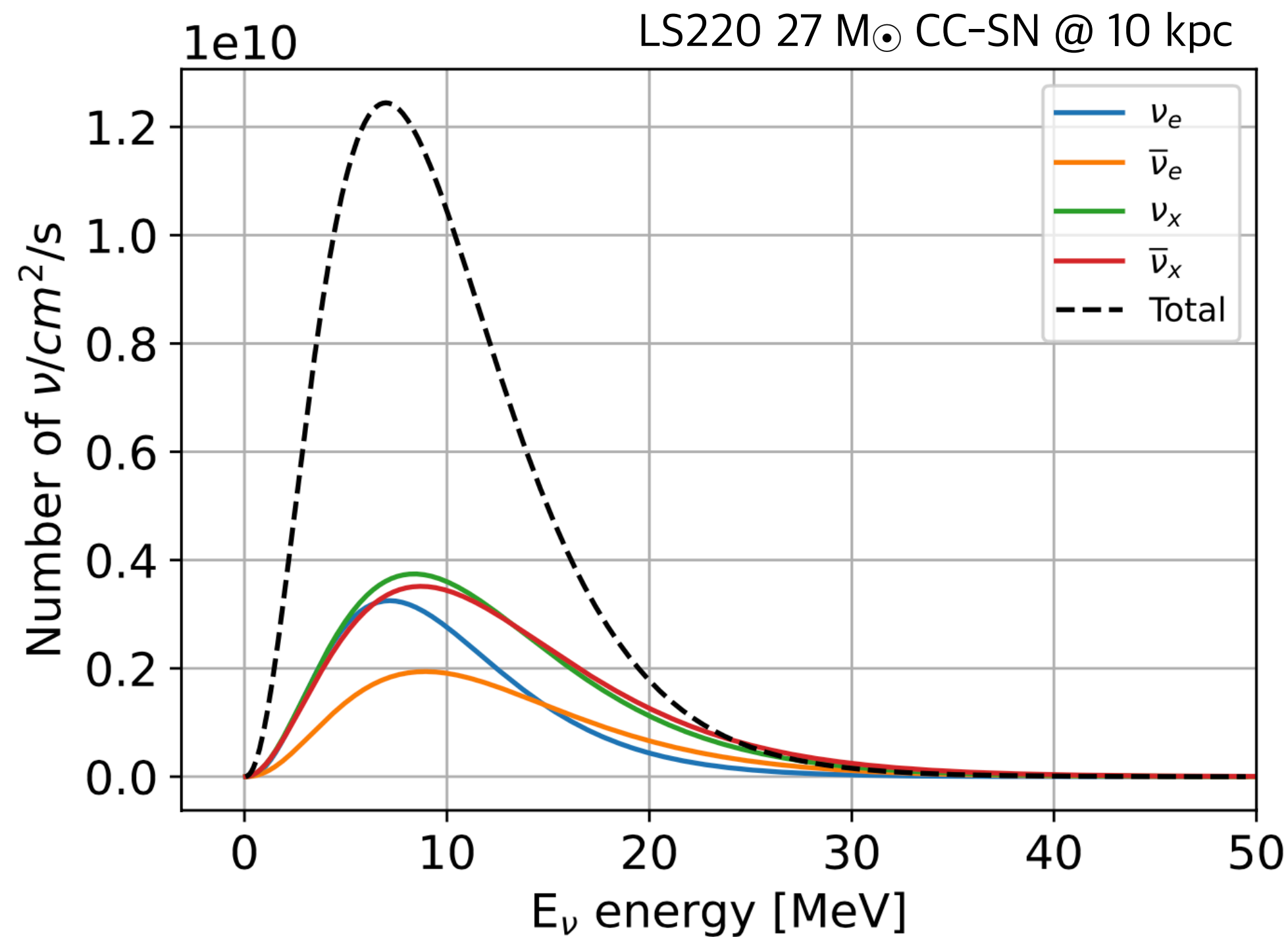
Nota Bene: neutrino flavor oscillations not included

MPA Supernova Archive:

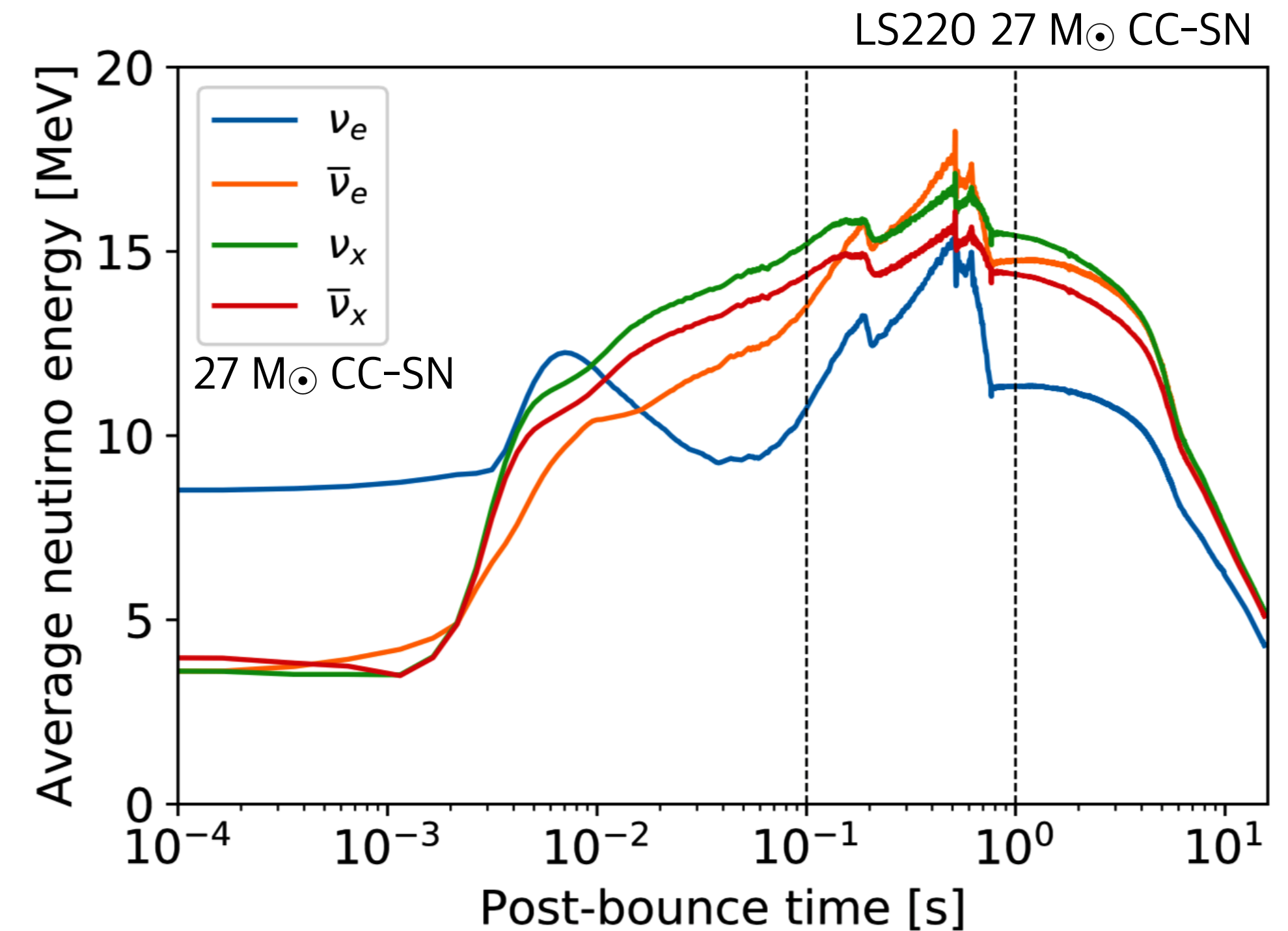
<https://wwwmpa.mpa-garching.mpg.de/ccsnarchive>

Supernova Neutrino signal

What is the average neutrino energy?



ν_x is the most **intense** component of the flux

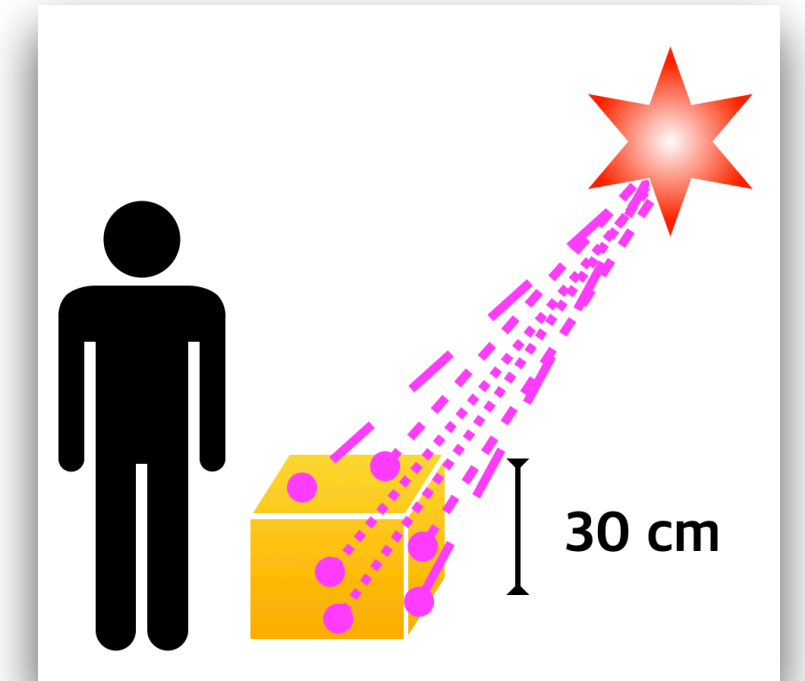
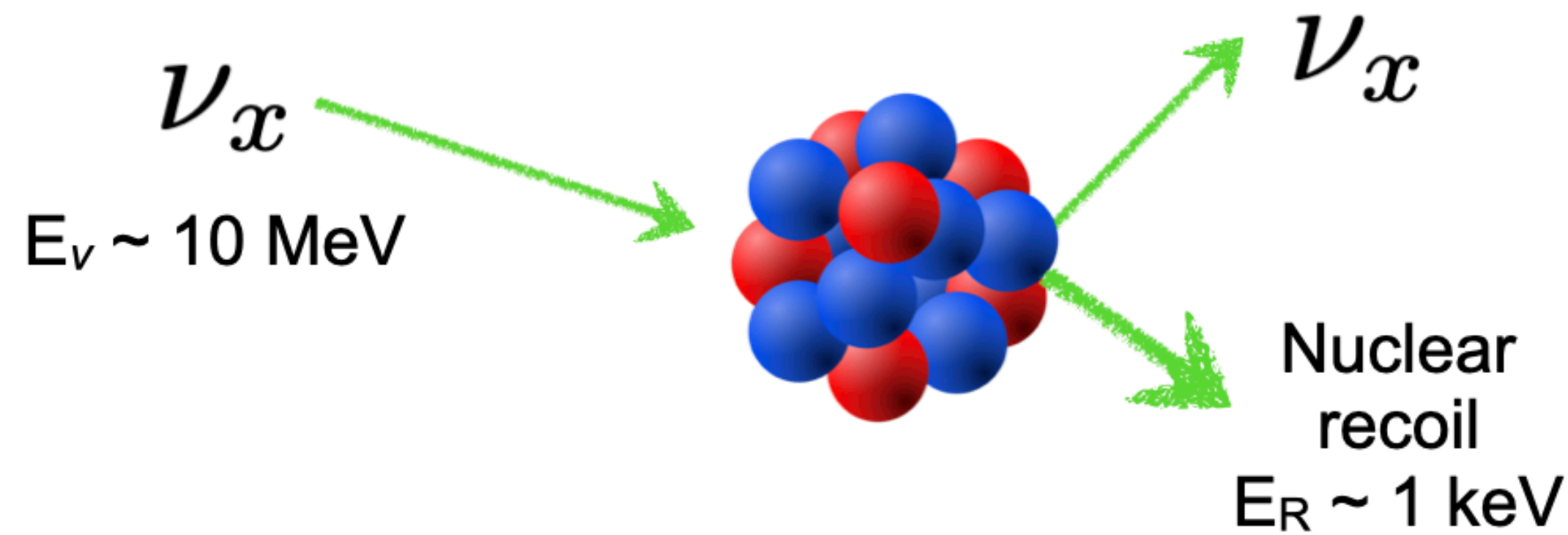


ν_x is the most **energetic** component of the flux

Current SN neutrino detectors are mostly sensitive to anti- ν_e/ν_e

All neutrino flavors are detected

Coherent neutrino-nucleus scattering



- > Equally sensitive to all ν -flavors
- > High interaction cross-section

$$\sigma_{CE\nu NS^*} = \frac{G_F^2}{4\pi} F^2(q^2) E_\nu^2 Q_W^2$$

cross-section

Nuclear Form factor

Neutrino energy

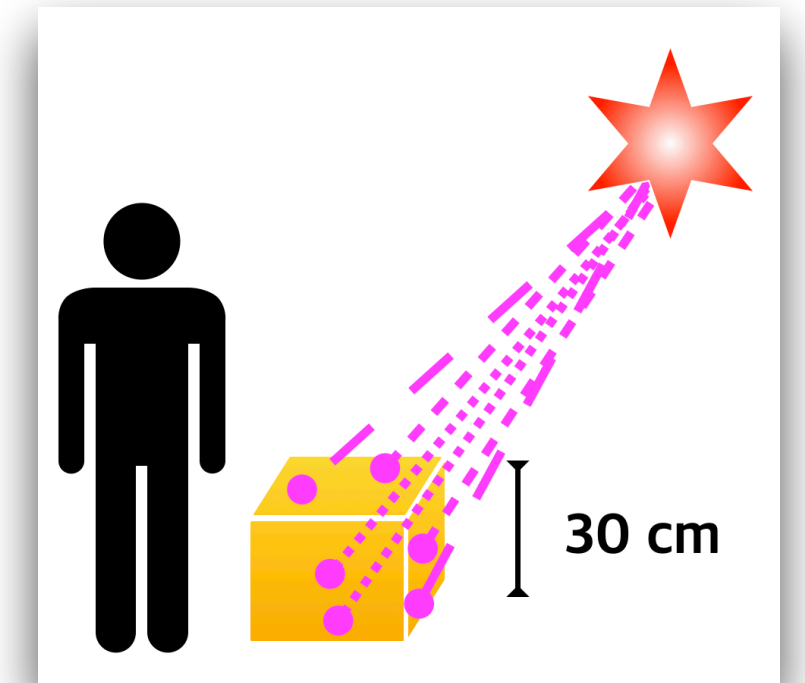
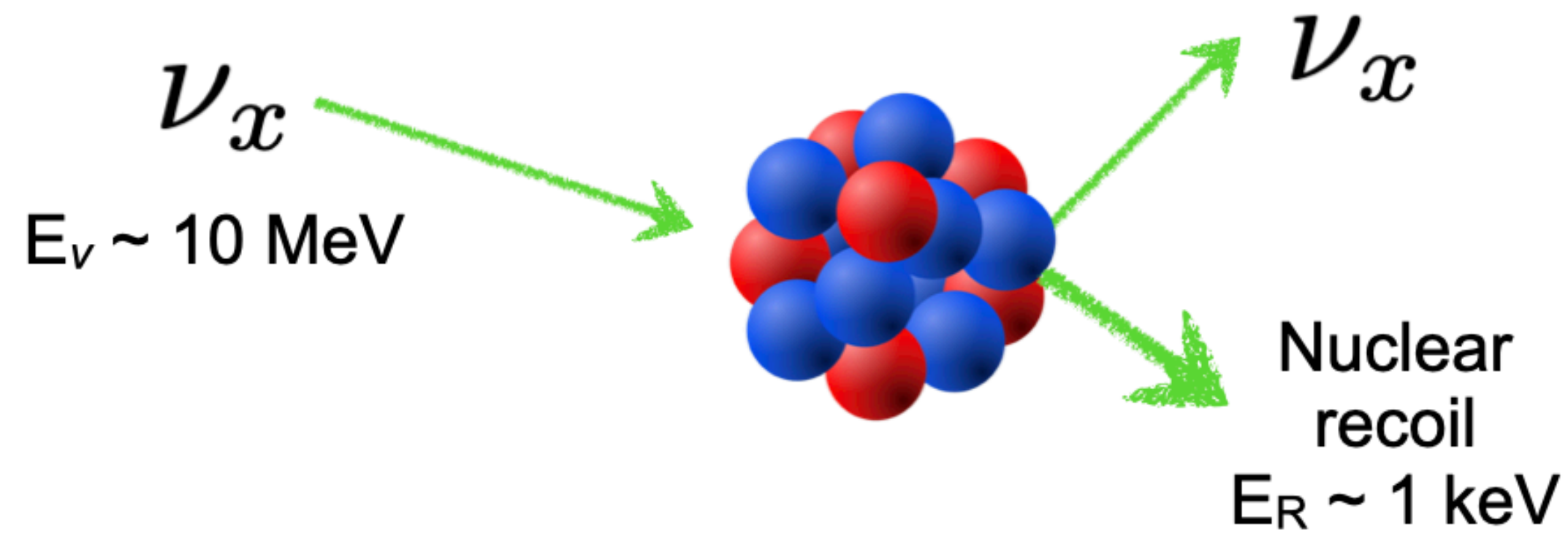
$$Q_W = N - Z \overbrace{(1 - 4 \sin^2 \theta_W)}^{\sim 5\%}$$

Weak nuclear charge

* Spin 0 interaction

All neutrino flavors are detected

Coherent neutrino-nucleus scattering



- > Equally sensitive to all ν -flavors
- > High interaction cross-section

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section Neutron number

All neutrino flavors are detected

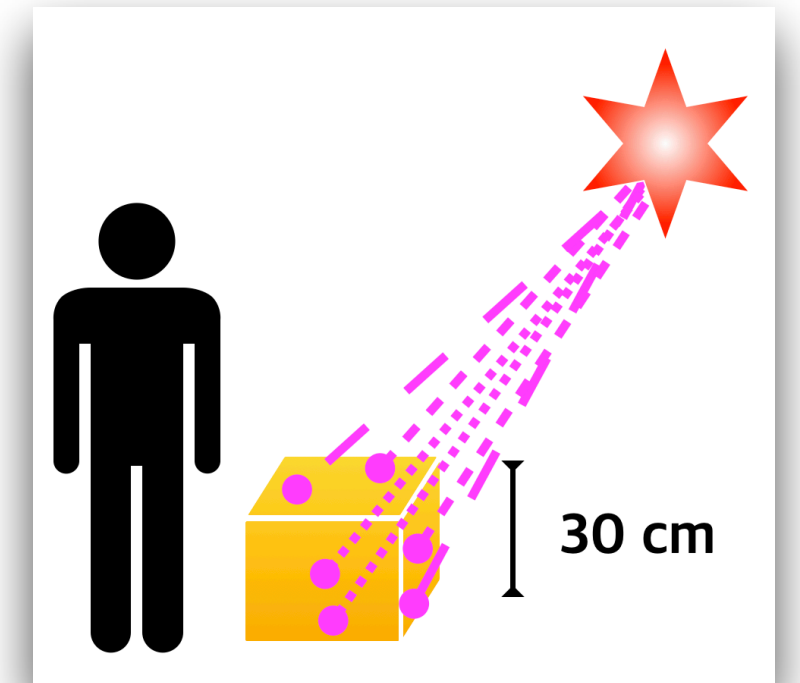
Coherent neutrino-nucleus scattering

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section $\nearrow$ Neutron number

Pb ideal target

Highest neutron number
Highest nuclear stability



All neutrino flavors are detected

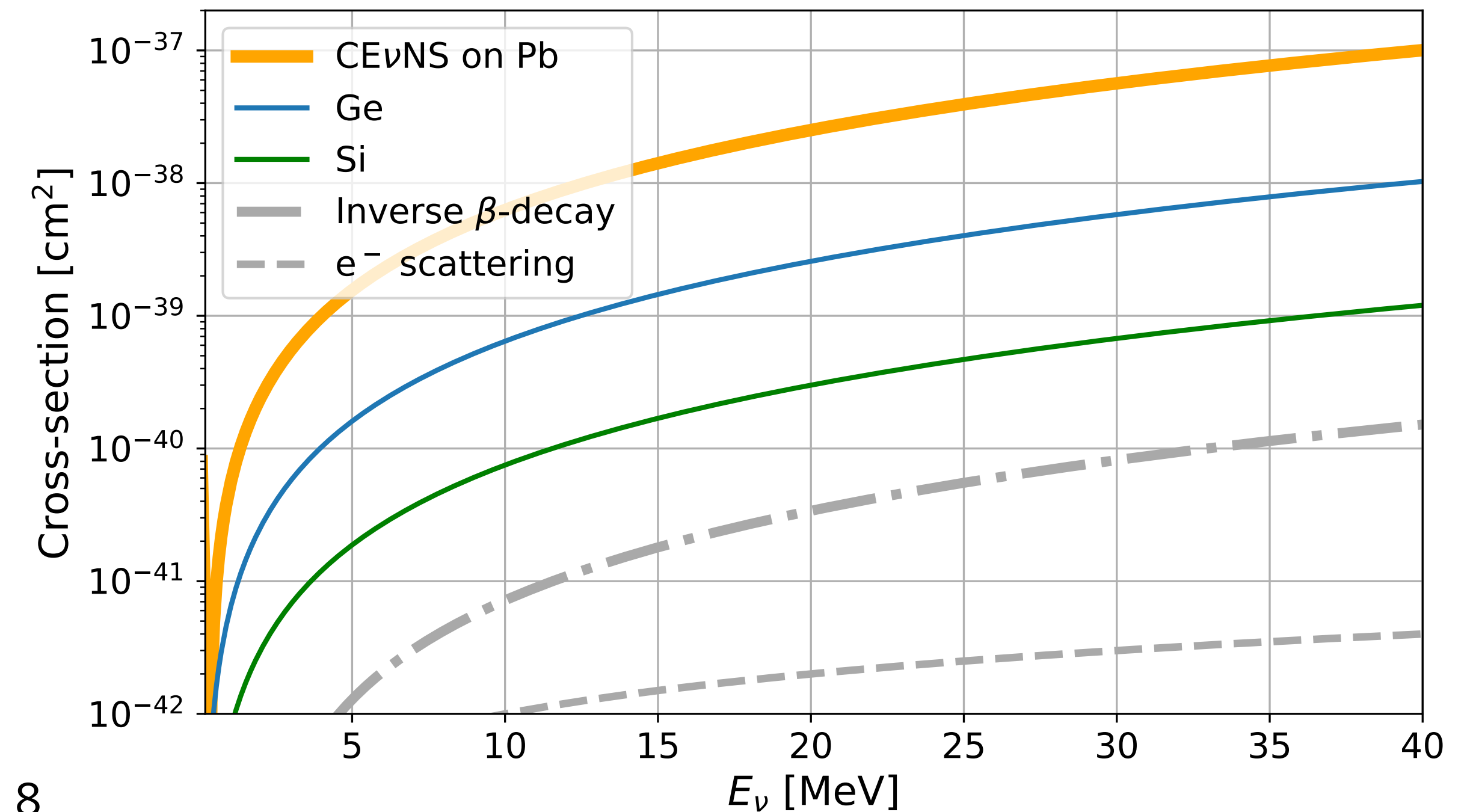
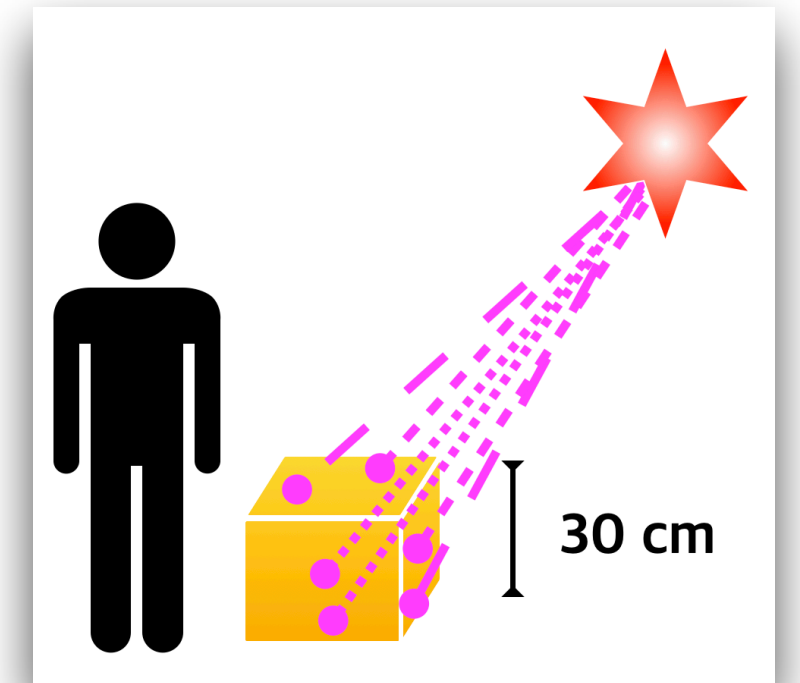
Coherent neutrino-nucleus scattering

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section $\nearrow$ Neutron number

Pb ideal target

Highest neutron number
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All neutrino flavors are detected

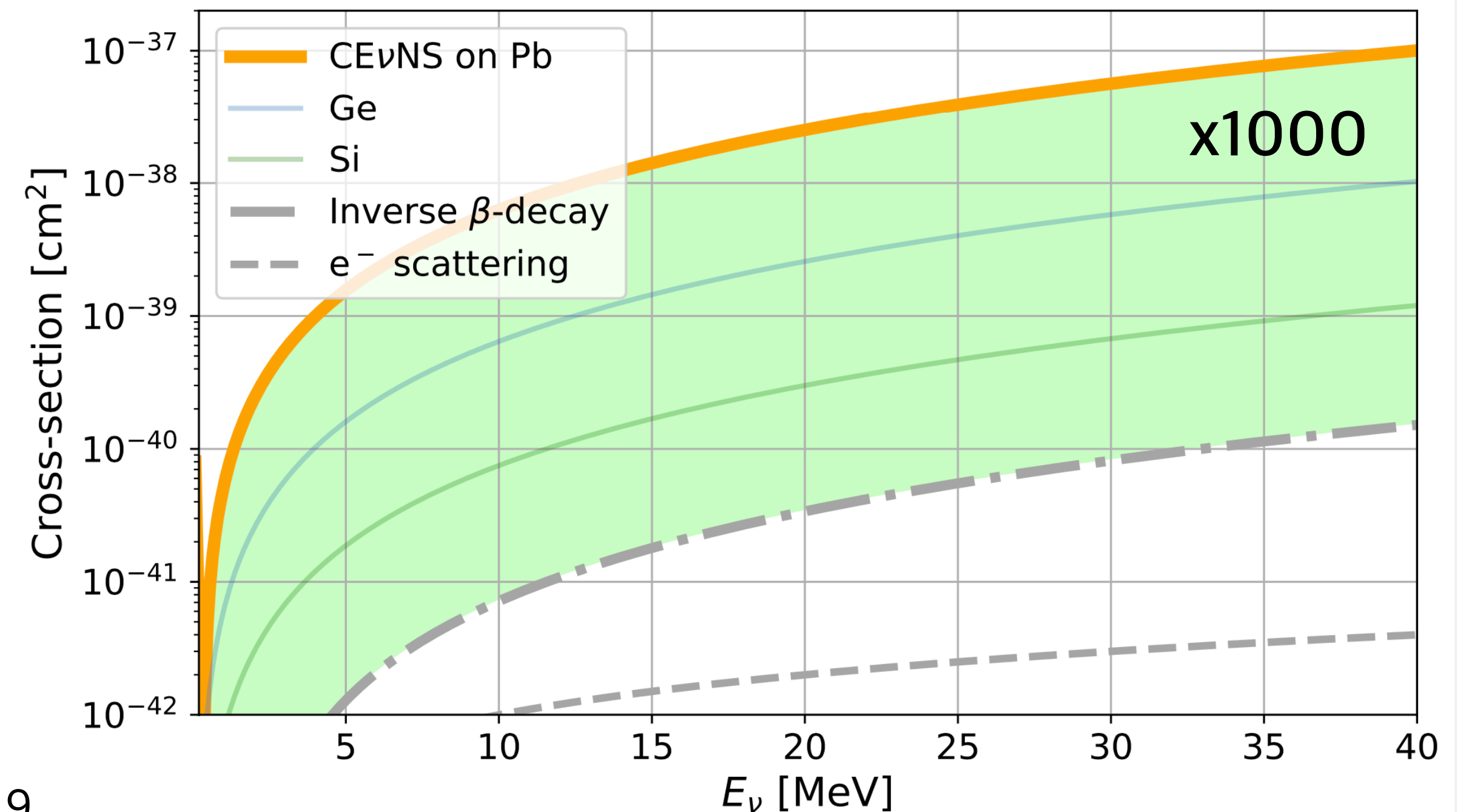
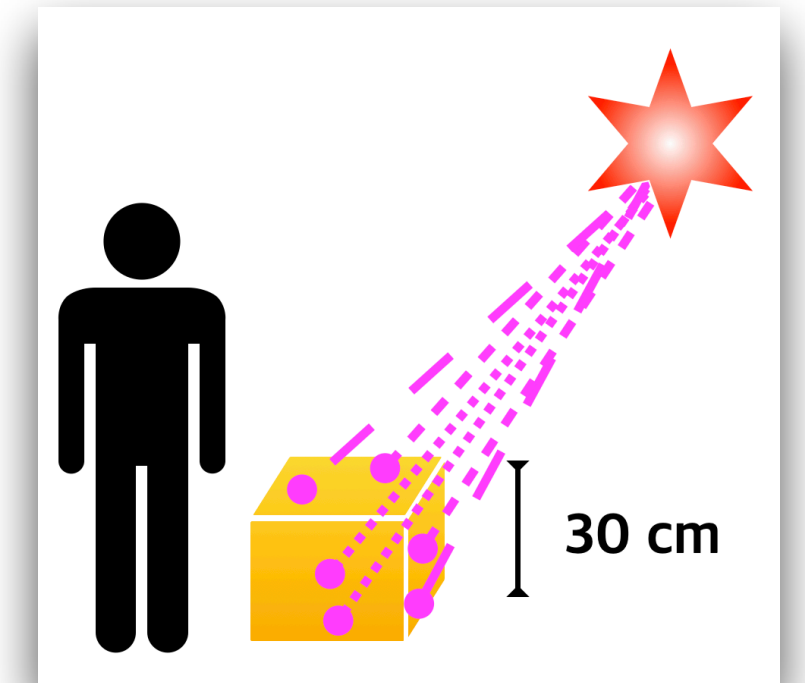
Coherent neutrino-nucleus scattering

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section $\nearrow$ Neutron number

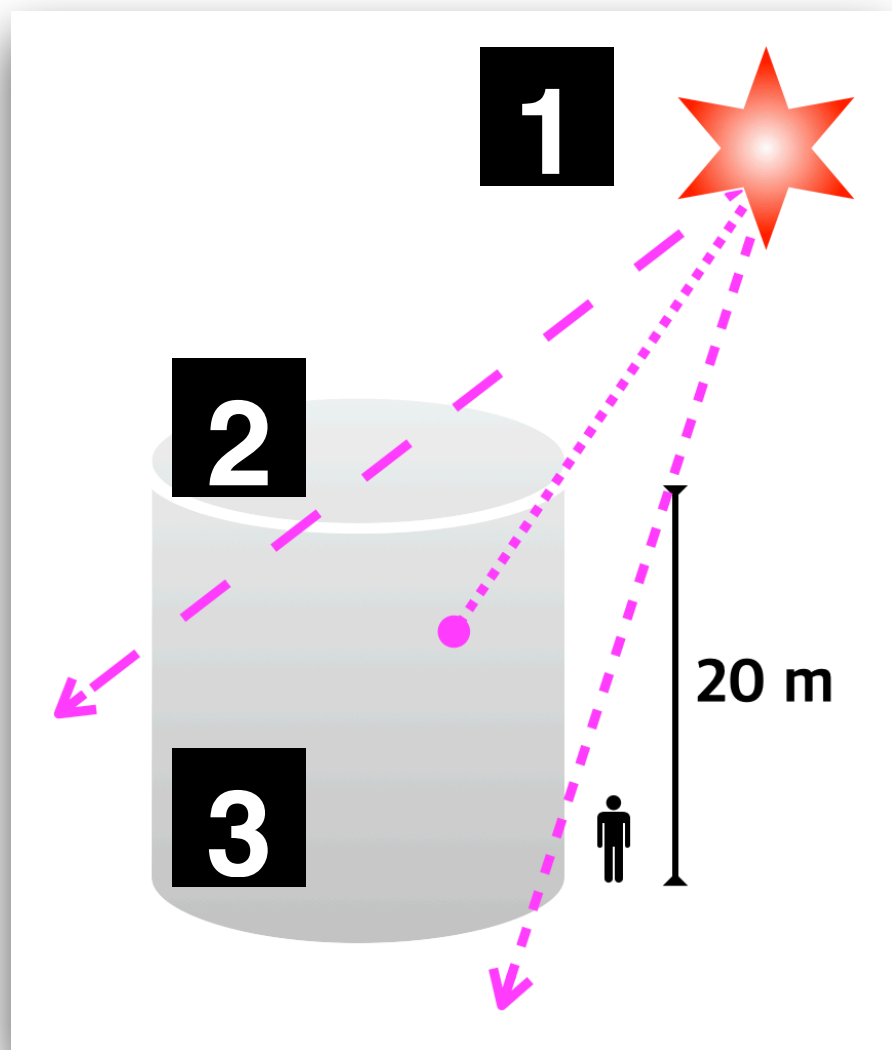
Pb ideal target

Highest neutron number
Highest nuclear stability



All neutrino flavors are detected

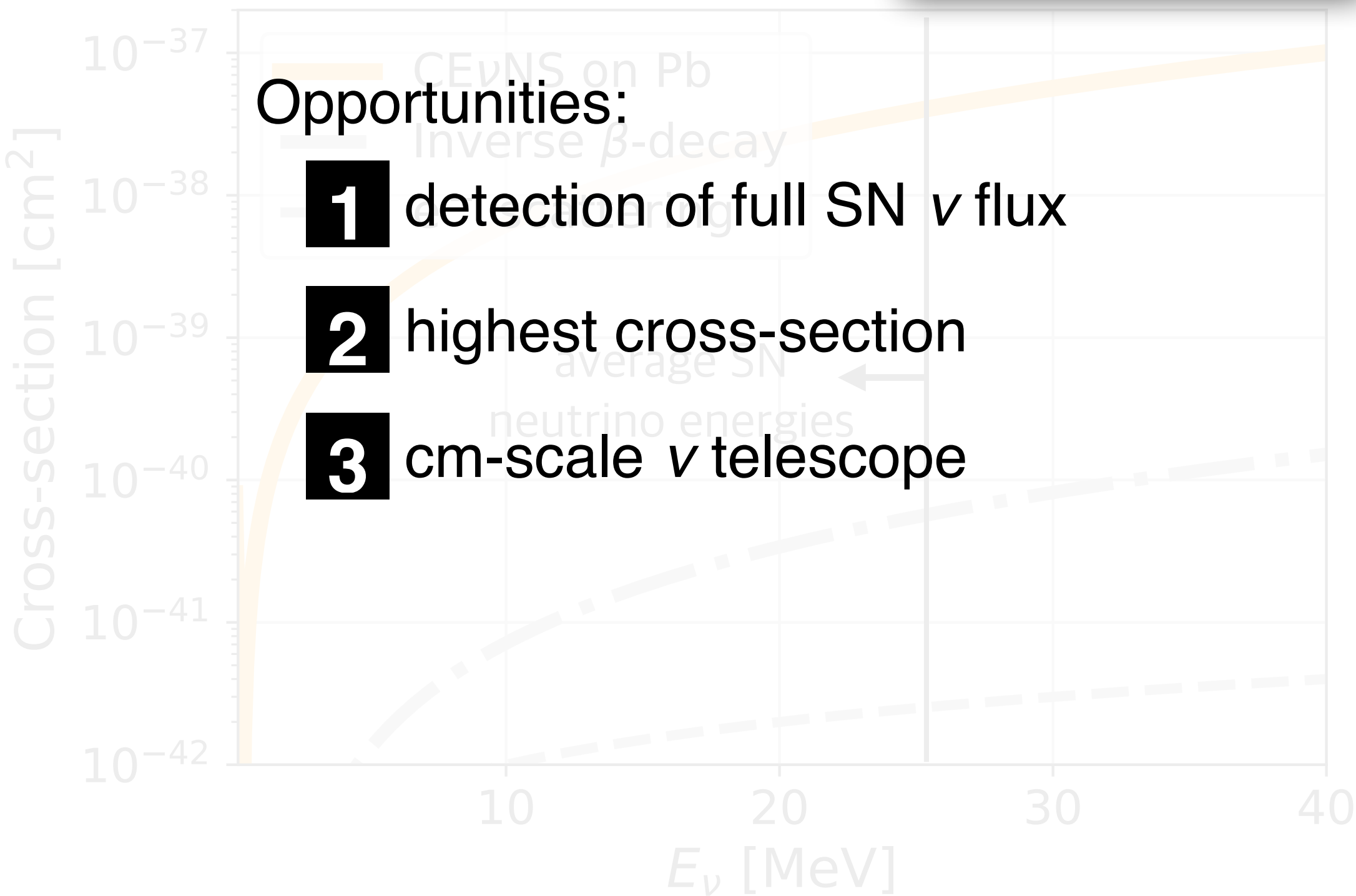
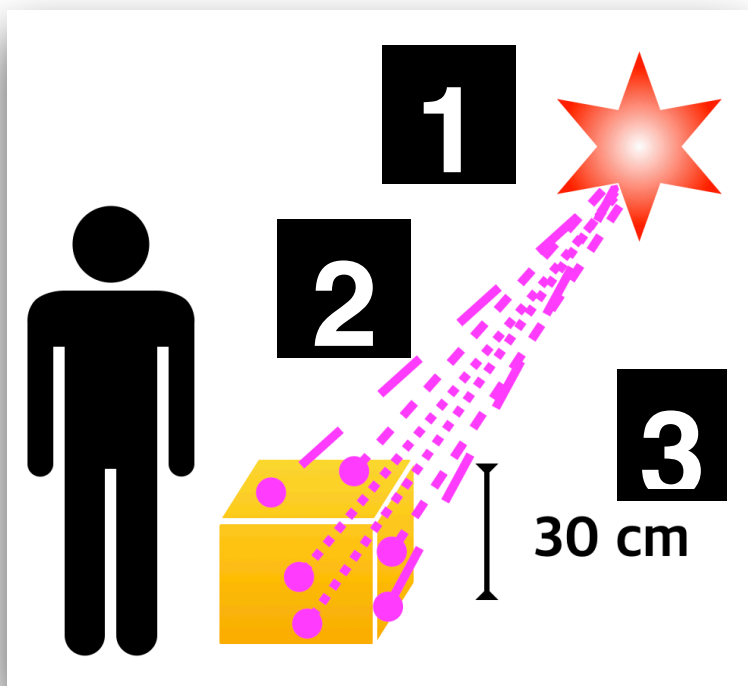
Coherent neutrino-nucleus scattering



N^2
Neutron
number

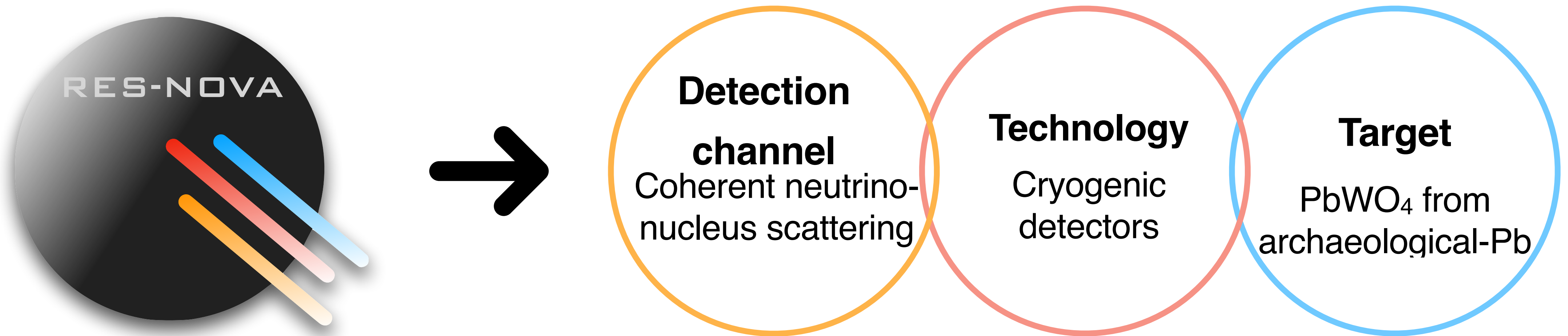
Status quo:

- 1** detection of $\sim 1/6$ SN flux
- 2** small cross-section
- 3** large volume detectors



RES-NOVA gives unique insights into SNe

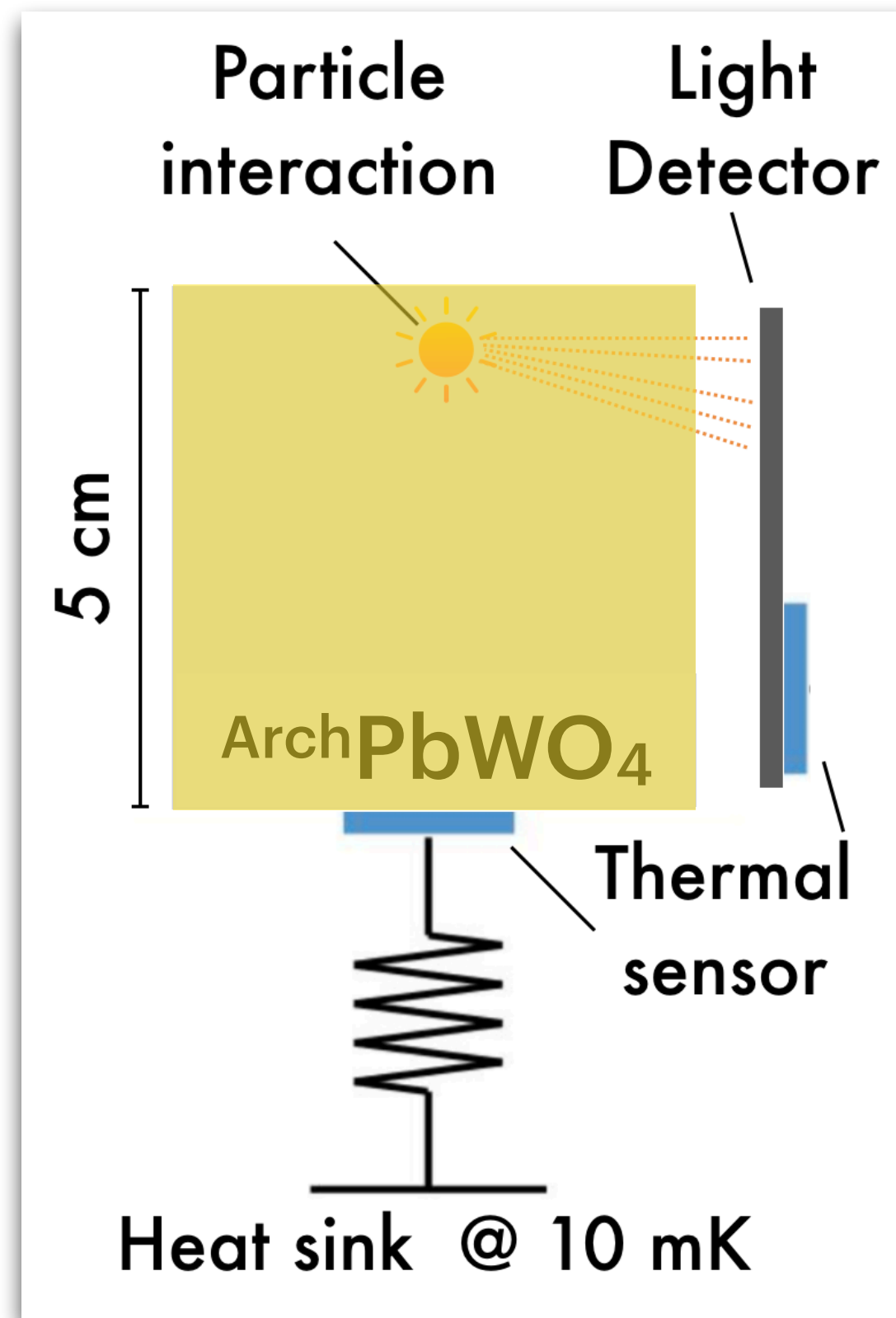
Innovative experimental approach



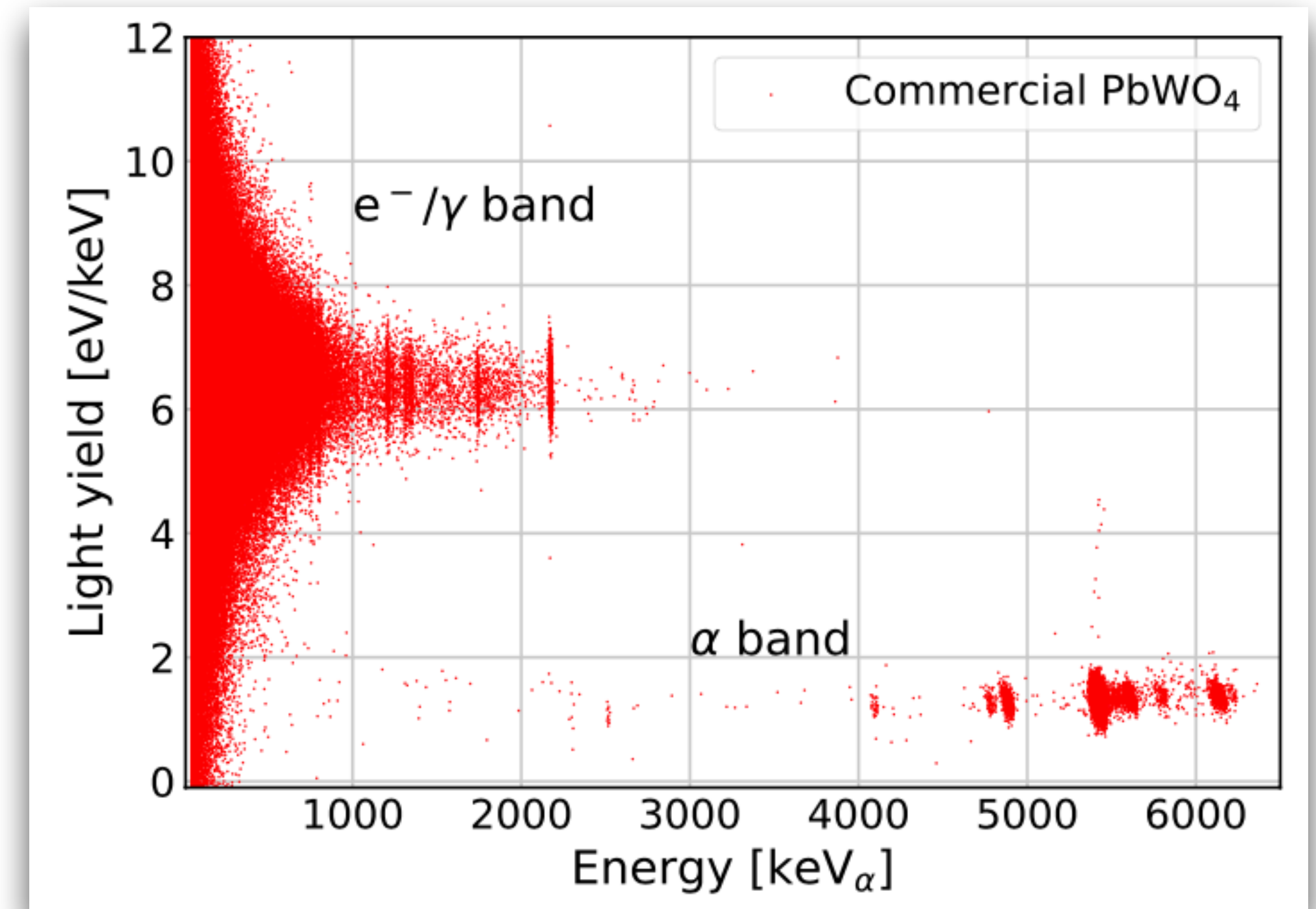
RES-NOVA detection technique

Cryogenic Calorimeters with Transition Edge Sensors

Cryogenic calorimeters based on PbWO₄ crystals



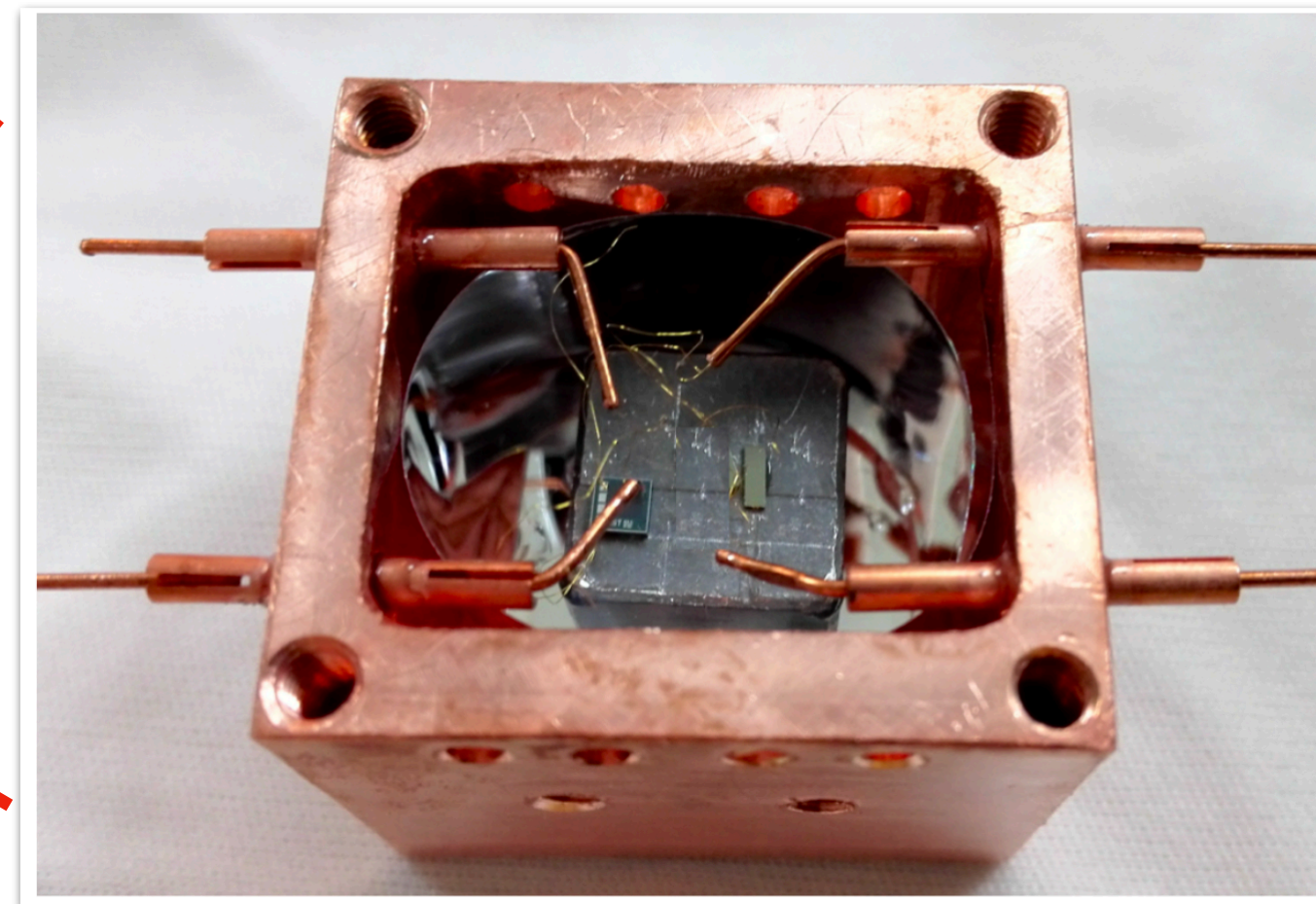
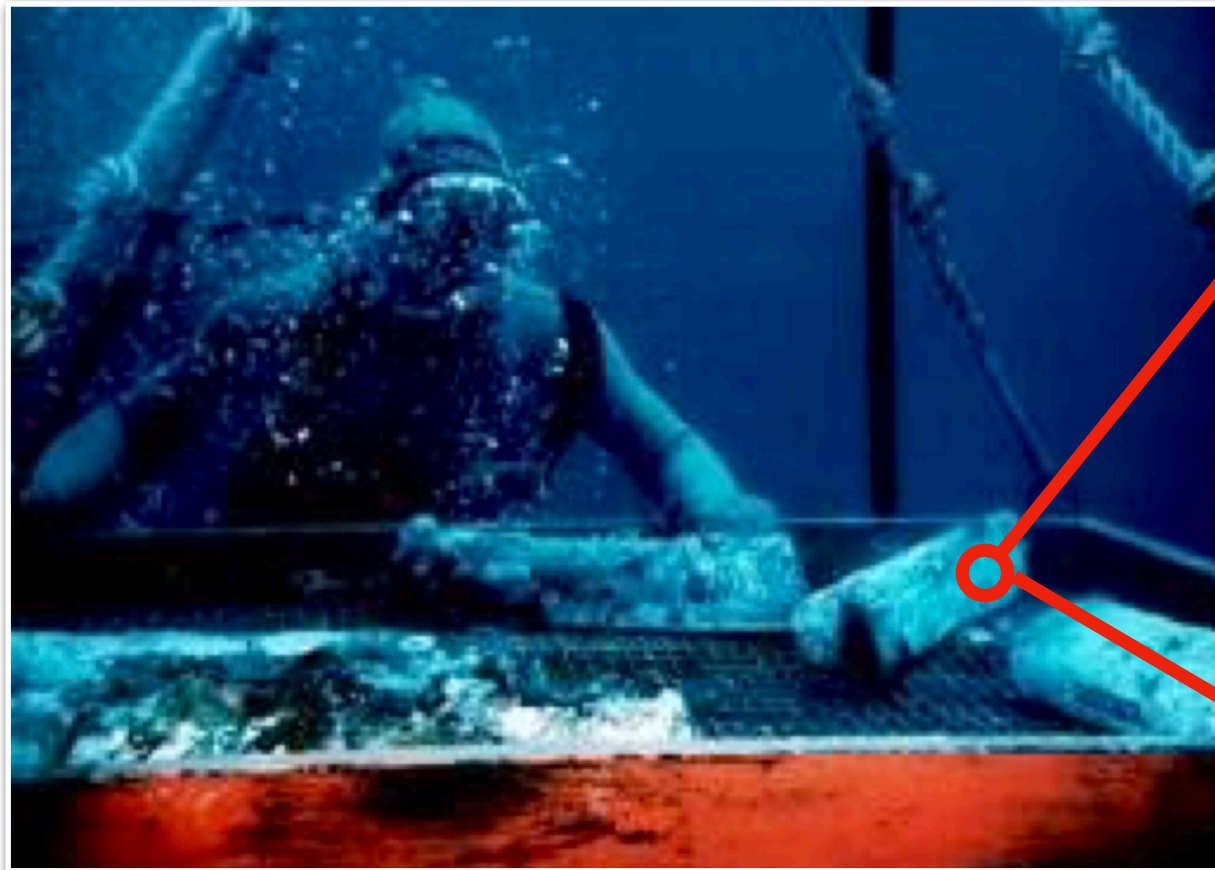
Cryogenic measurement of commercial PbWO₄



J.W. Beeman, LP et al., Eur. Phys. J. A 49, 50 (2013)

Cryogenic detectors built from Archaeological Pb

taken from N. Nosengo (2010)



Archaeological Roman Pb:

- ★ from underwater shipwreck
- ★ 2000 years old

Archaeo-Pb cryogenic detector

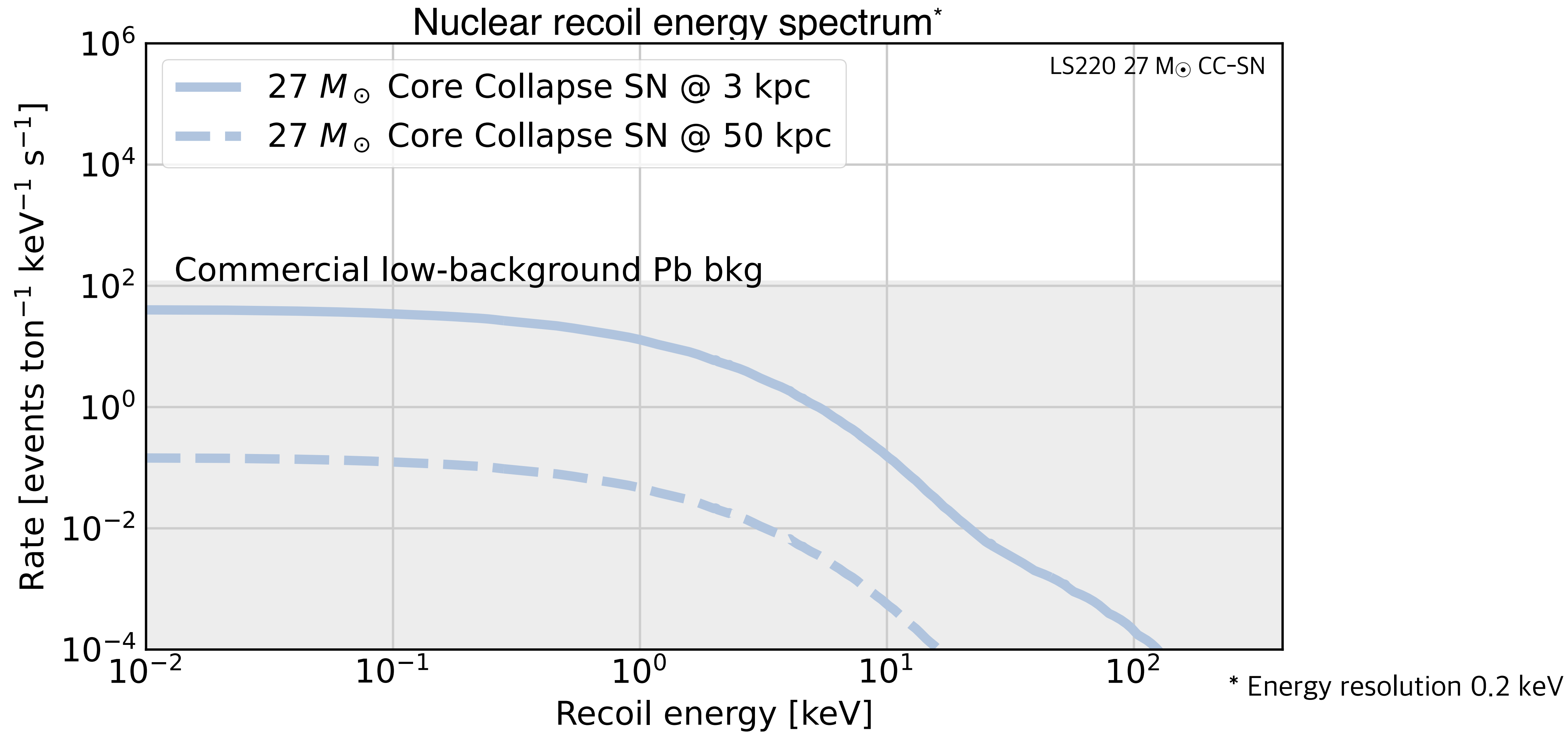
High radiopurity: $< 1 \text{ mBq/kg}$

**$\times 10^4$ better than commercial
low-background Pb**

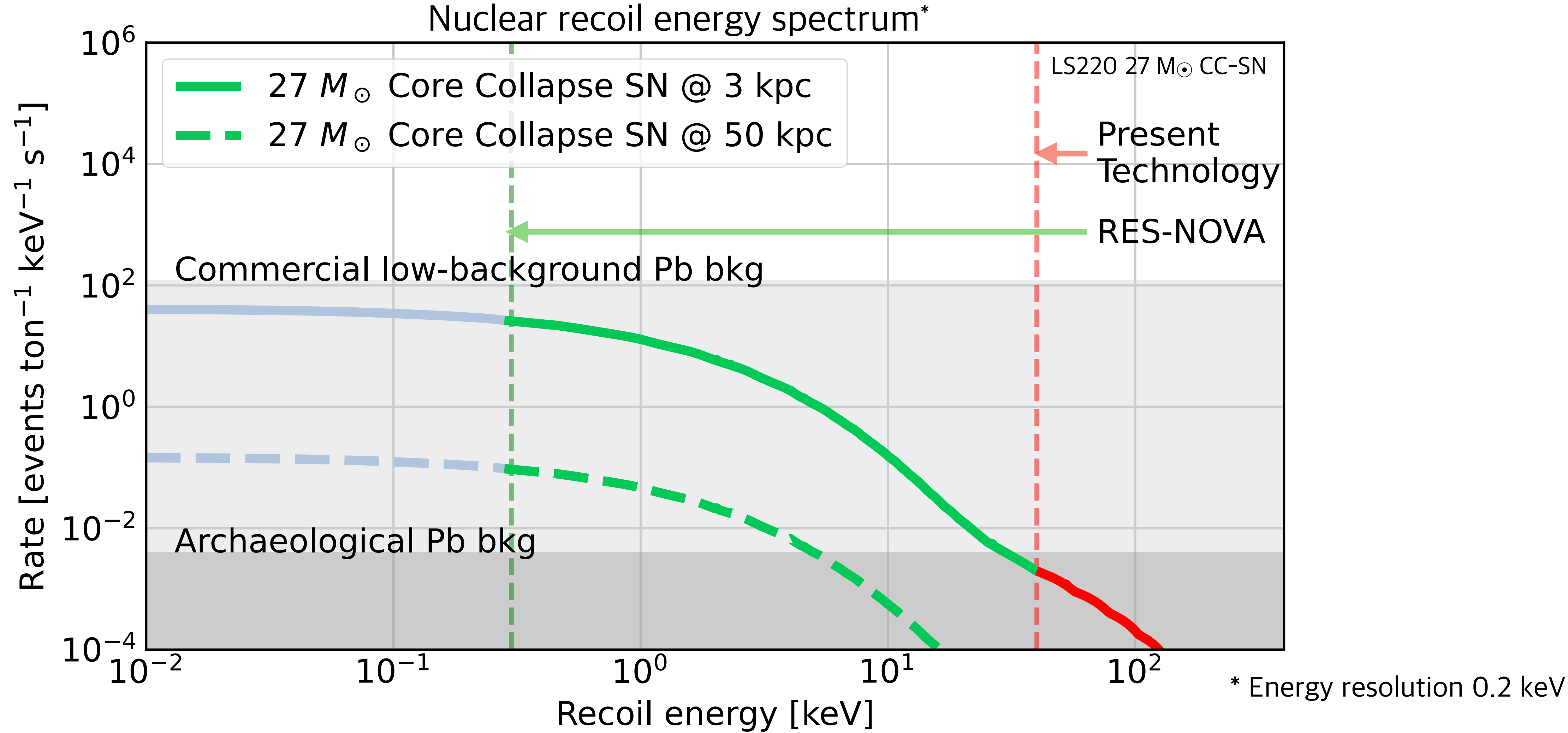
Several tons of ArchPb available

L. Pattavina et al., Eur. Phys. J. A 55, 127 (2019)

RES-NOVA detects SN neutrinos

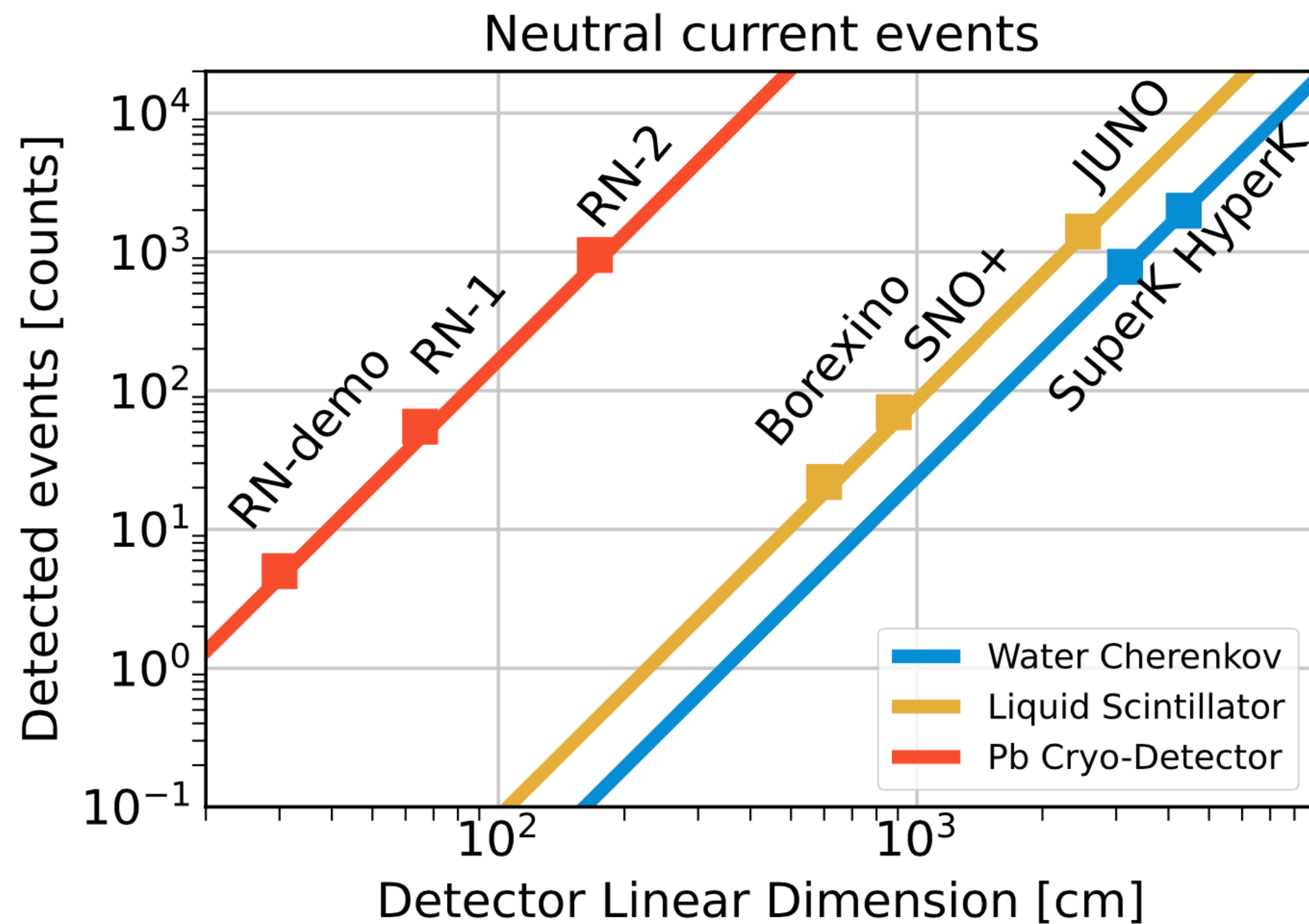


RES-NOVA detects SN neutrinos



Neutrino observatory at the cm-scale

an array of PbWO_4 crystals



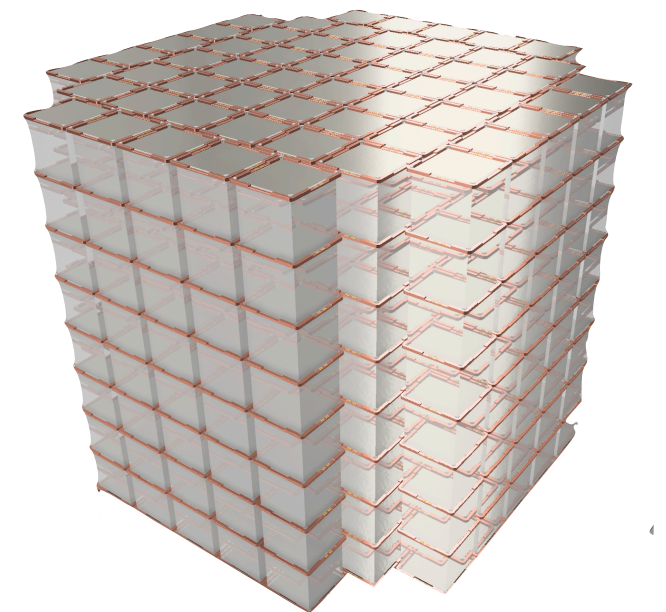
Size:
Threshold:
SN @ 10 kpc:

RN-demo @ LNGS
(30 cm)³
1 keV
~10 counts



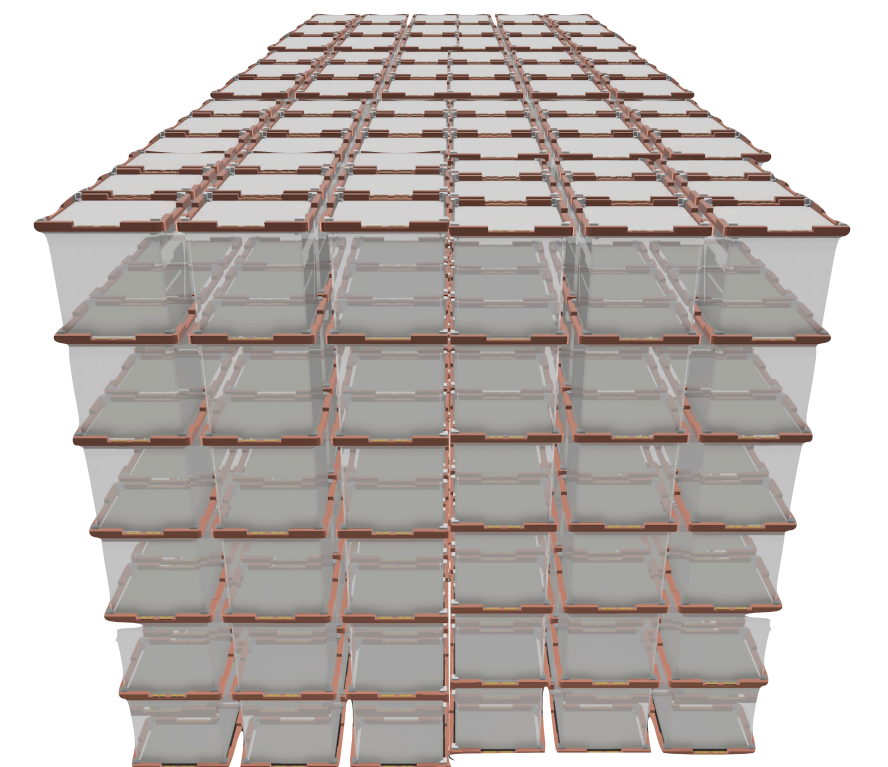
Size:
Threshold:
SN @ 10 kpc:

RN-1
(60 cm)³
1 keV
~50 counts



Size:
Threshold:
SN @ 10 kpc:

RN-2
(140 cm)³
1 keV
~900 counts



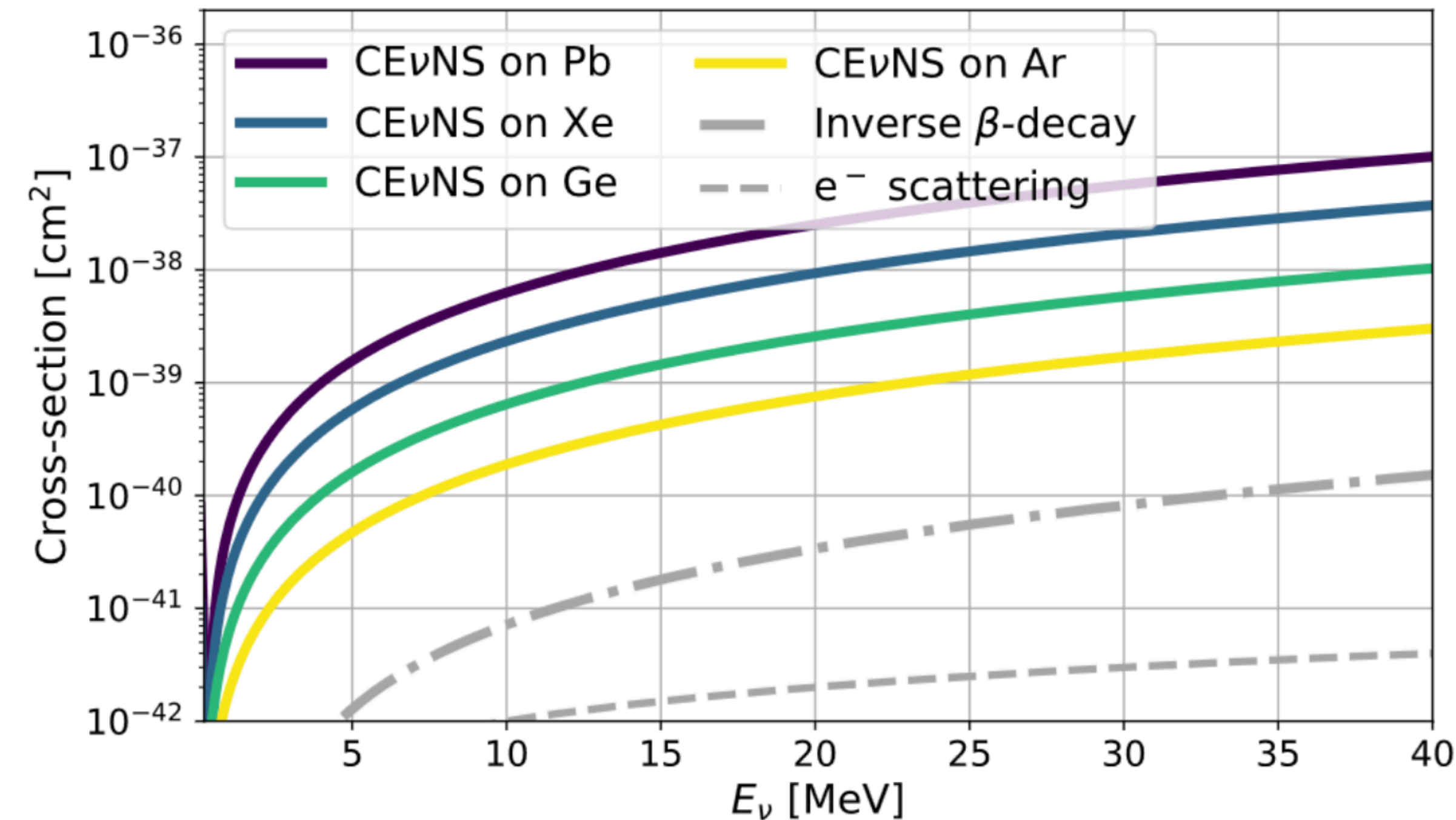
Not only neutrinos

Dark matter studies

Assuming that the time-integrated DM-induced event rate equals the CEvNS rate from SN neutrinos, we obtain:

$$\begin{aligned} R_{CE\nu NS} &\sim \sigma_{CE\nu NS} \cdot T(10 \text{ s}) \sim N^2 \cdot 10 \text{ s} \\ R_{DM} &\sim \sigma_{DM} \cdot T(1 \text{ y}) \sim A^2 \cdot 3 \times 10^7 \text{ s} \sim (2N)^2 \cdot 3 \times 10^7 \text{ s} \\ R_{DM} &\simeq R_{CE\nu NS} \rightarrow \sigma_{DM} \sim 10^{-7} \cdot \sigma_{CE\nu NS} \end{aligned}$$

This simplified scaling argument suggests that RES-NOVA can probe SI DM cross-section to the 10^{-45} cm^2 scale



RES-NOVA dark matter sensitivity

DM differential cross-section:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2 \mu_n^2} \sigma_{\text{DM-N}} \cdot A^2 \cdot |F(q)|^2$$

The diagram illustrates the components of the DM differential cross-section formula. Arrows point from the following terms in the equation to their physical meanings:

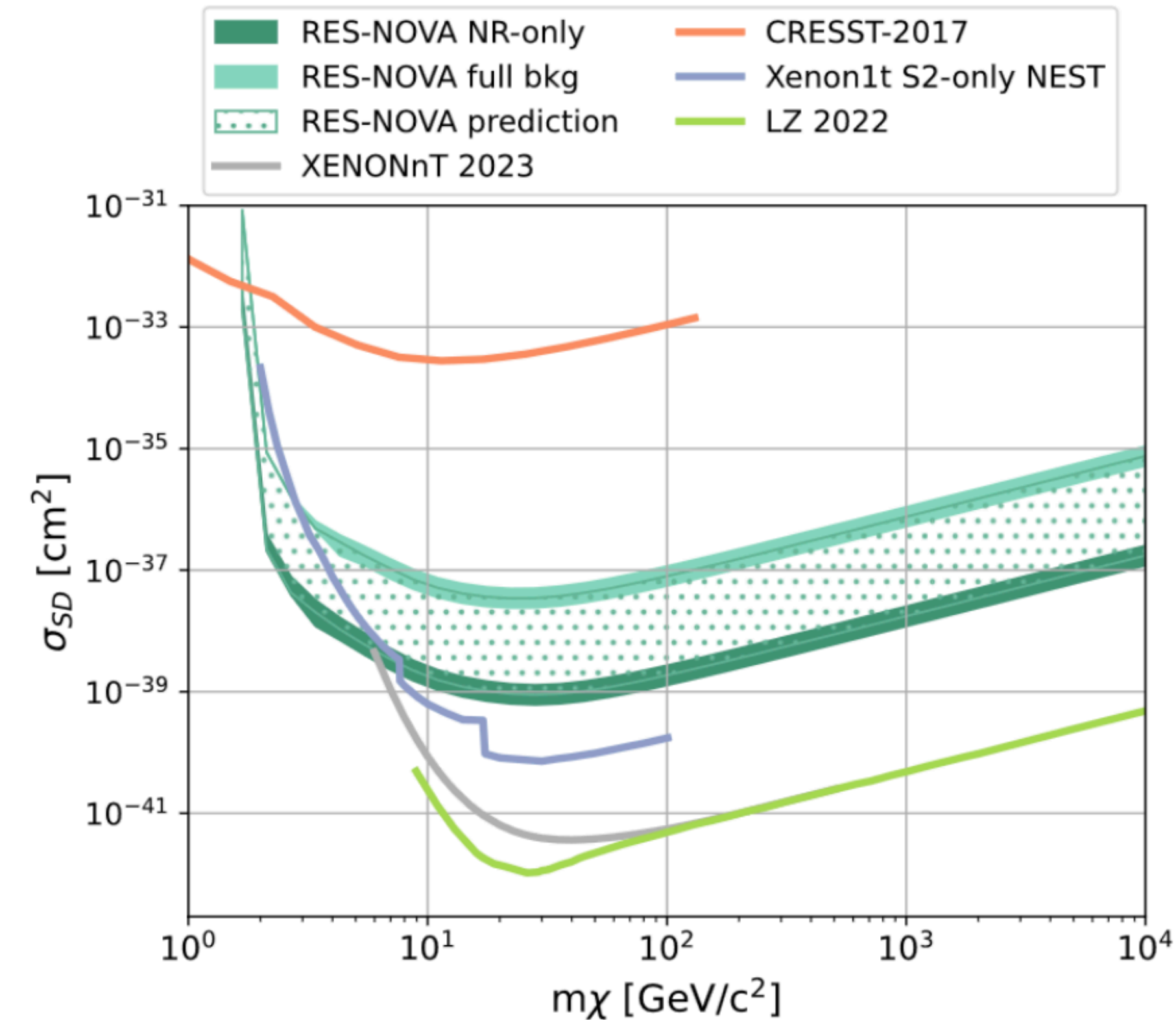
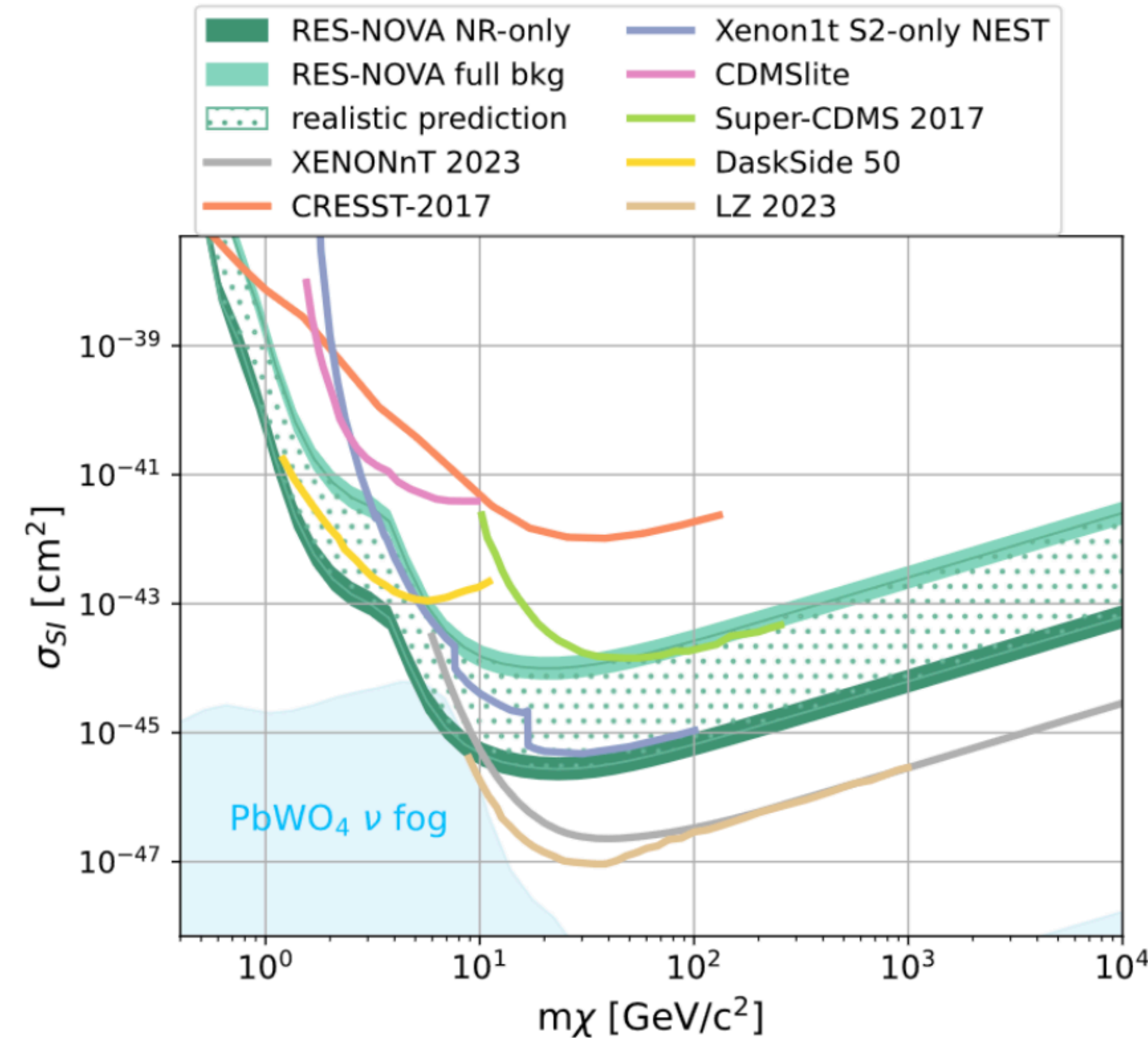
- v : relative velocity
- μ_n : DM-nucleus reduced mass
- $\sigma_{\text{DM-N}}$: DM-nucleon cross-section
- A : Atomic number
- $F(q)$: Nuclear form factor

Using arch-PbWO as a target, makes RES-NOVA sensitive to a broader range of dark matter masses

RES-NOVA dark matter sensitivity

projection for:

- spin-independent (left)
- spin-dependent (right)
- Input bkg model: >40 bkg sources
- Exposure of 170 kg·y

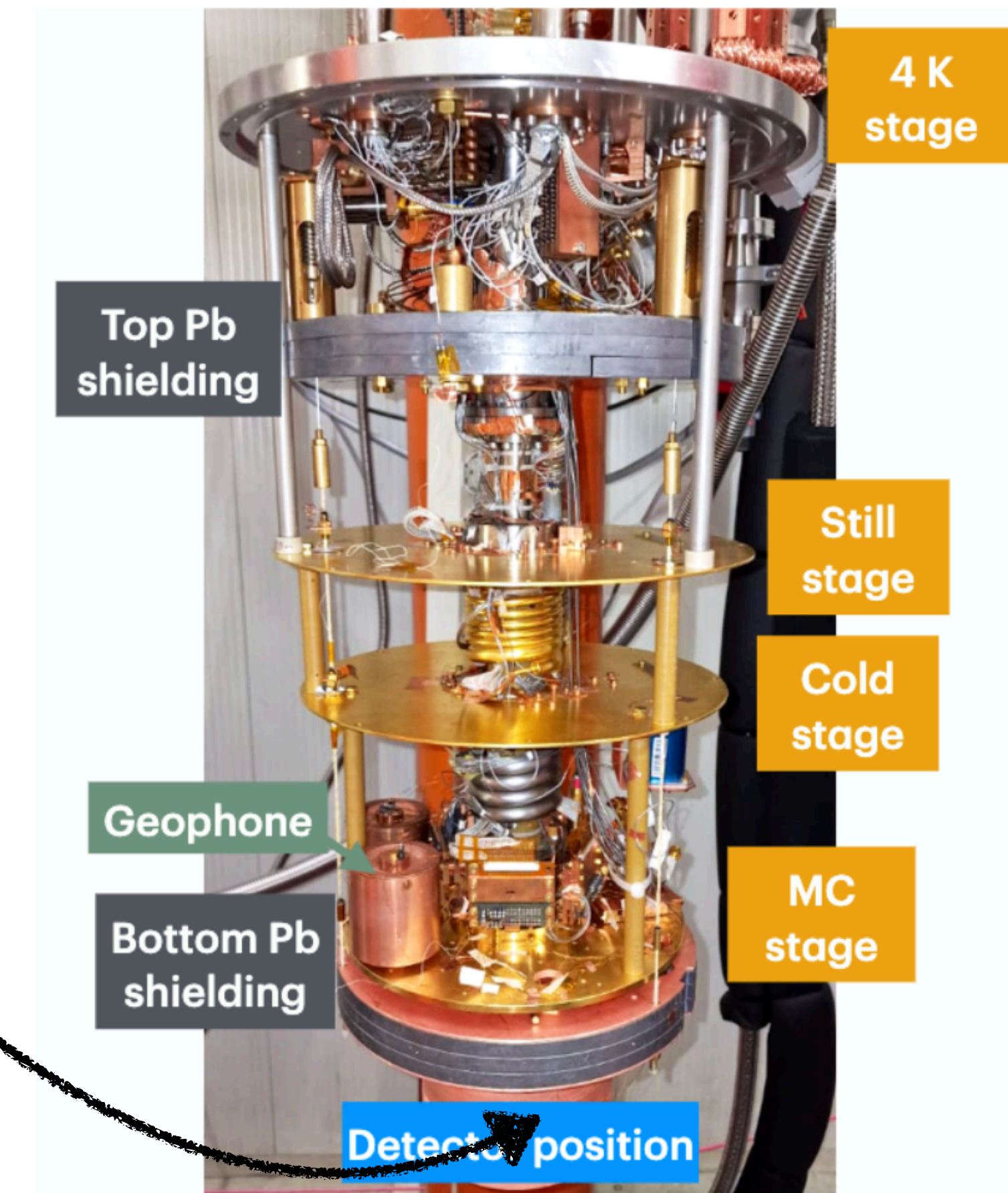
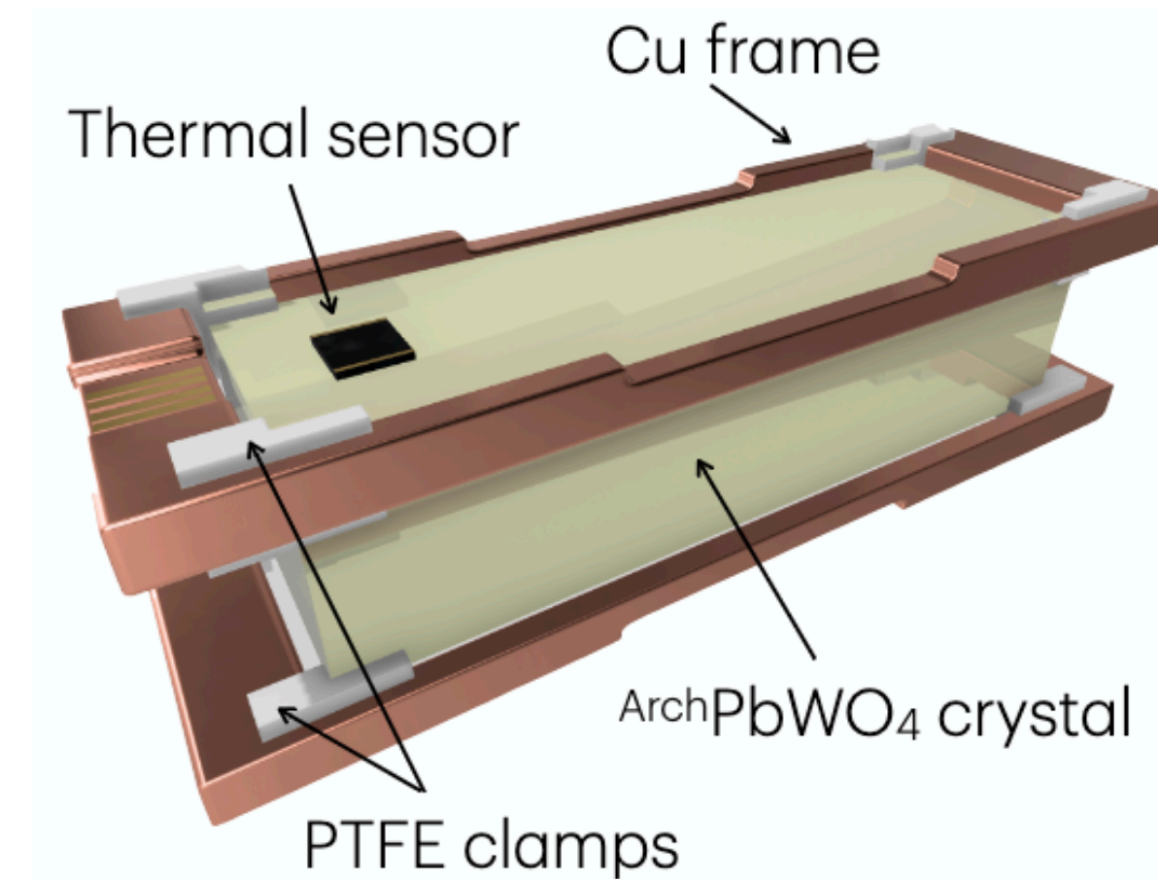


RES-NOVA Coll., Phys. Rev. D 111, 103050 (2025)

Dark matter preliminary measurement

13 g archPbWO crystal at LNGS

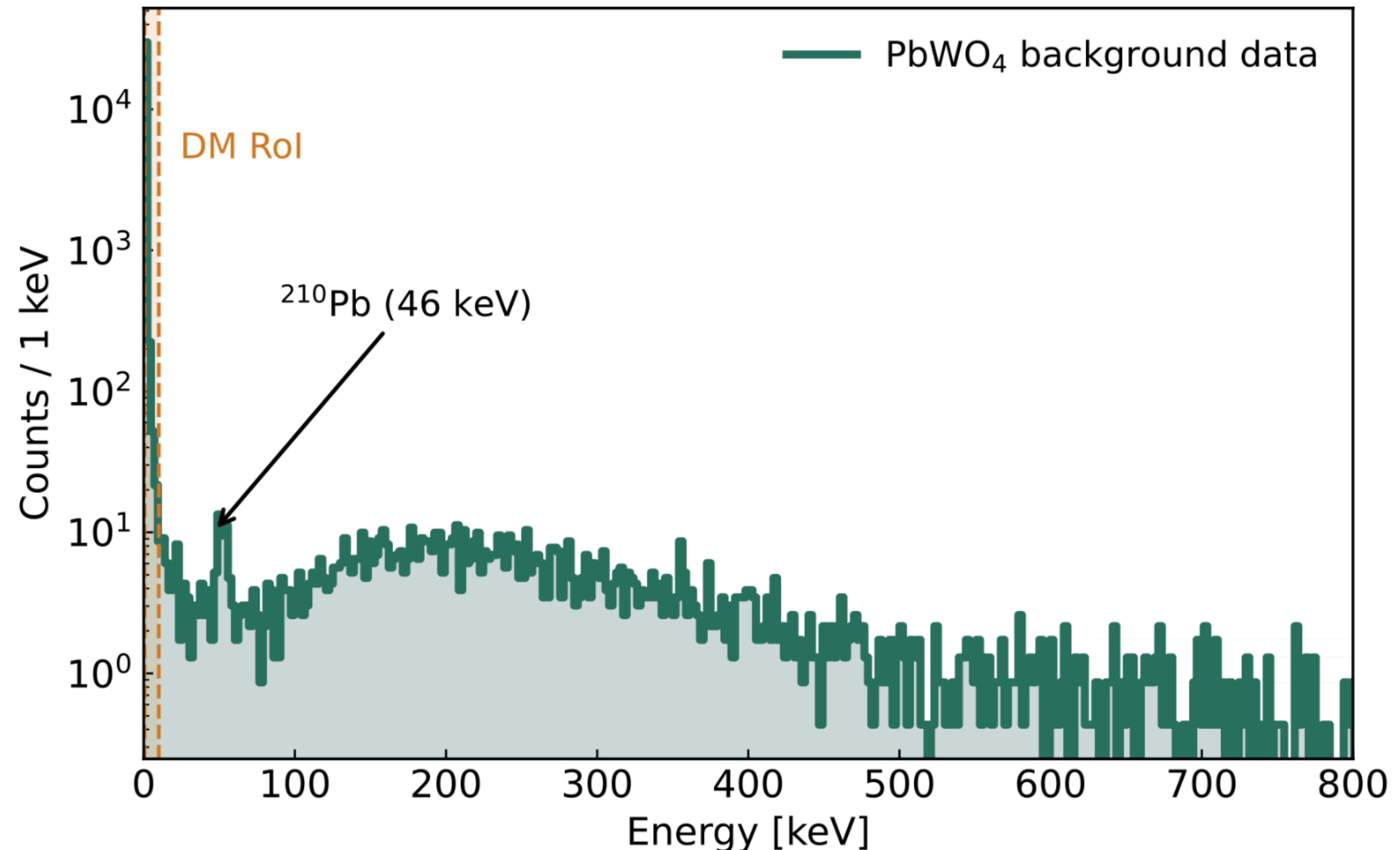
- The crystal had a mass of **13 g** and dimensions of **$0.7 \times 0.7 \times 4 \text{ cm}^3$**
- The measurement was performed in IETI a **pulse-tube** assisted dilution refrigerator at **LNGS**
 - Not optimized for ultra-low-background measurements
 - Optimized for mechanical stability and vibrational isolation
- **NTD** as a thermal sensor (energy reconstruction)



Detector calibration

Energy resolution and performance

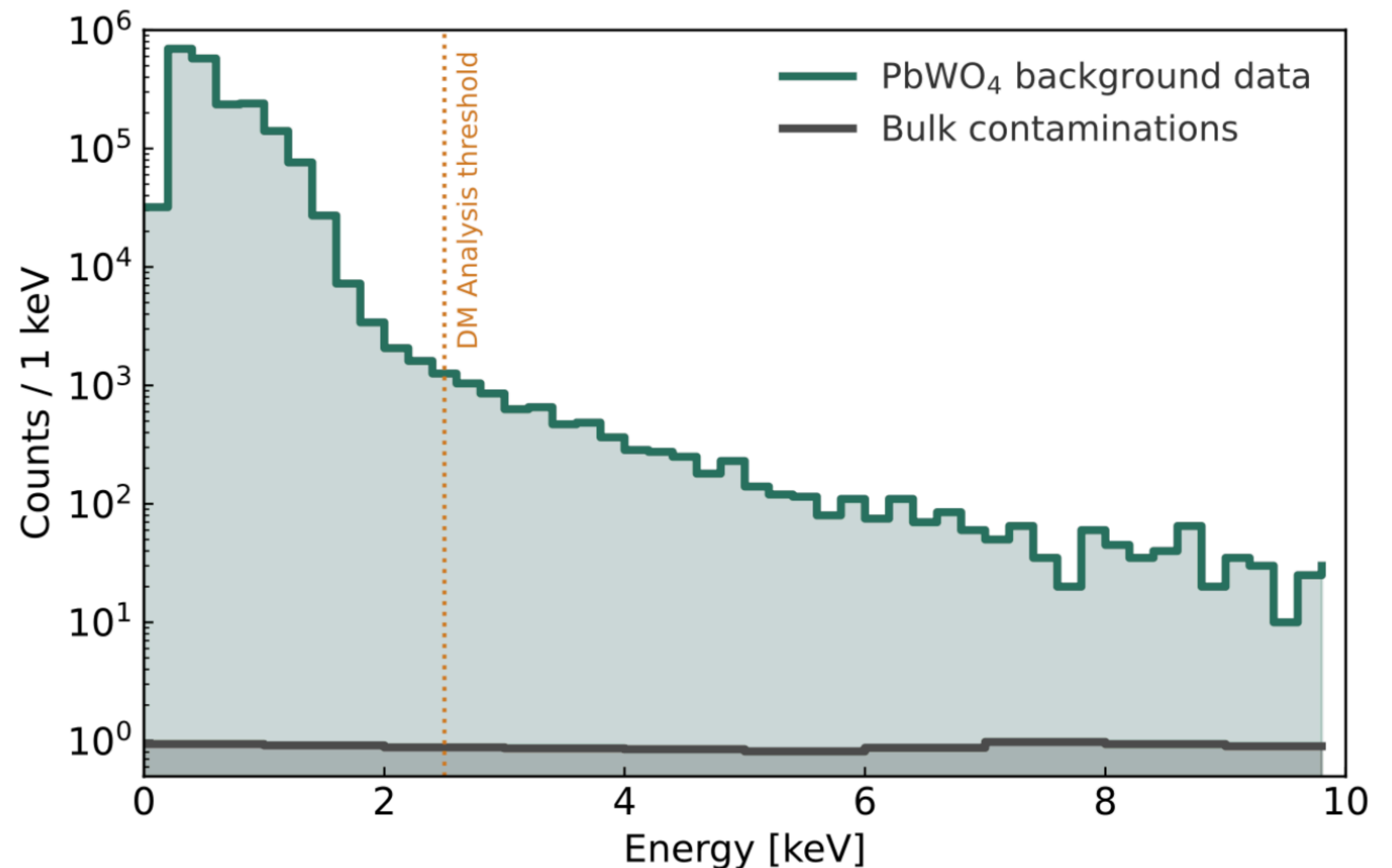
- Energy estimation through Optimum Filter
- Energy calibration performed using the **2615 keV γ line** from ^{208}Tl
- Calibration validated through the **46 keV feature** from ^{210}Pb observed in background data
- Measured detector response: 112 $\mu\text{V}/\text{MeV}$
- Energy resolution at 0 keV: 239 eV - baseline resolution



Dark matter sensitivity

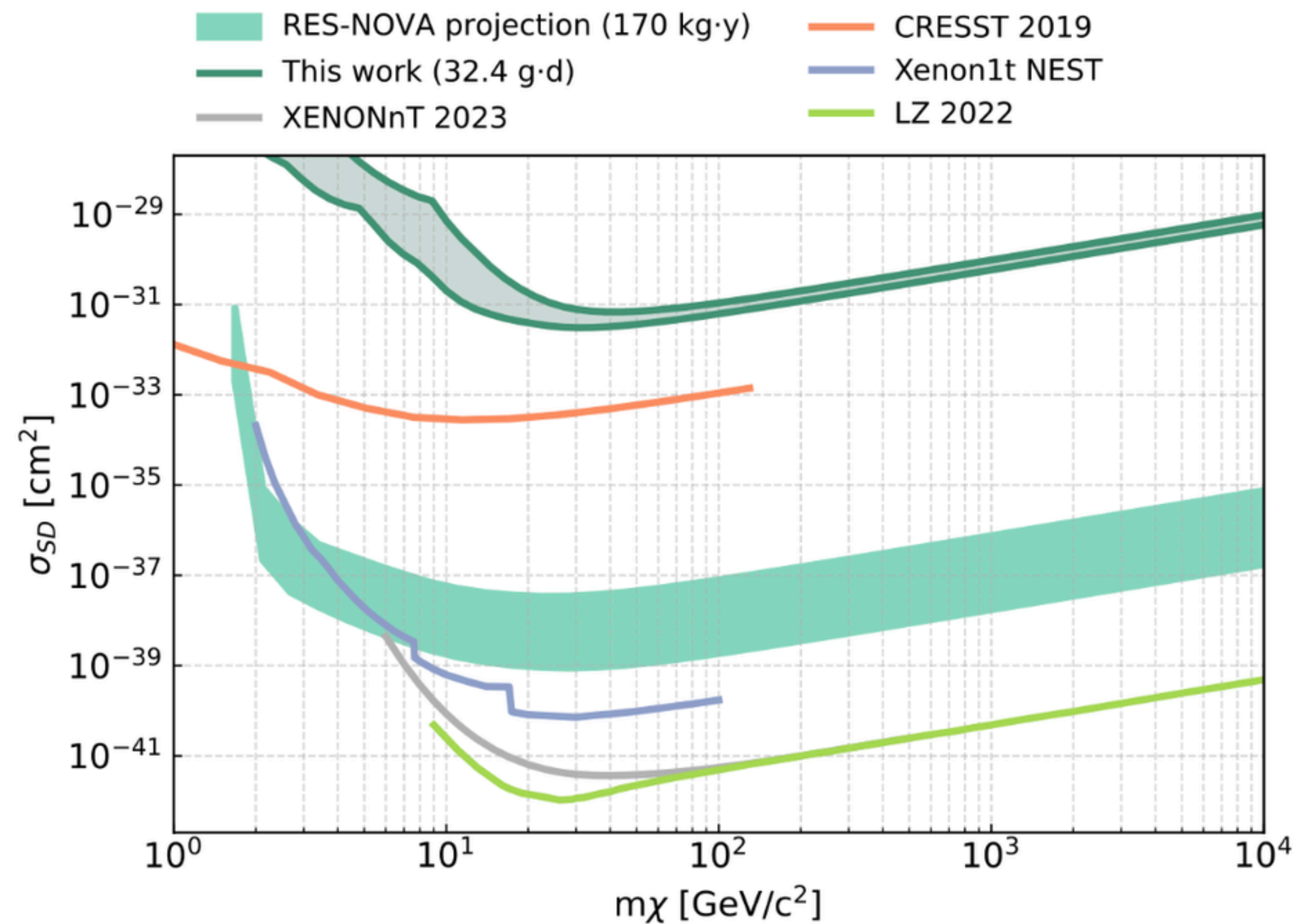
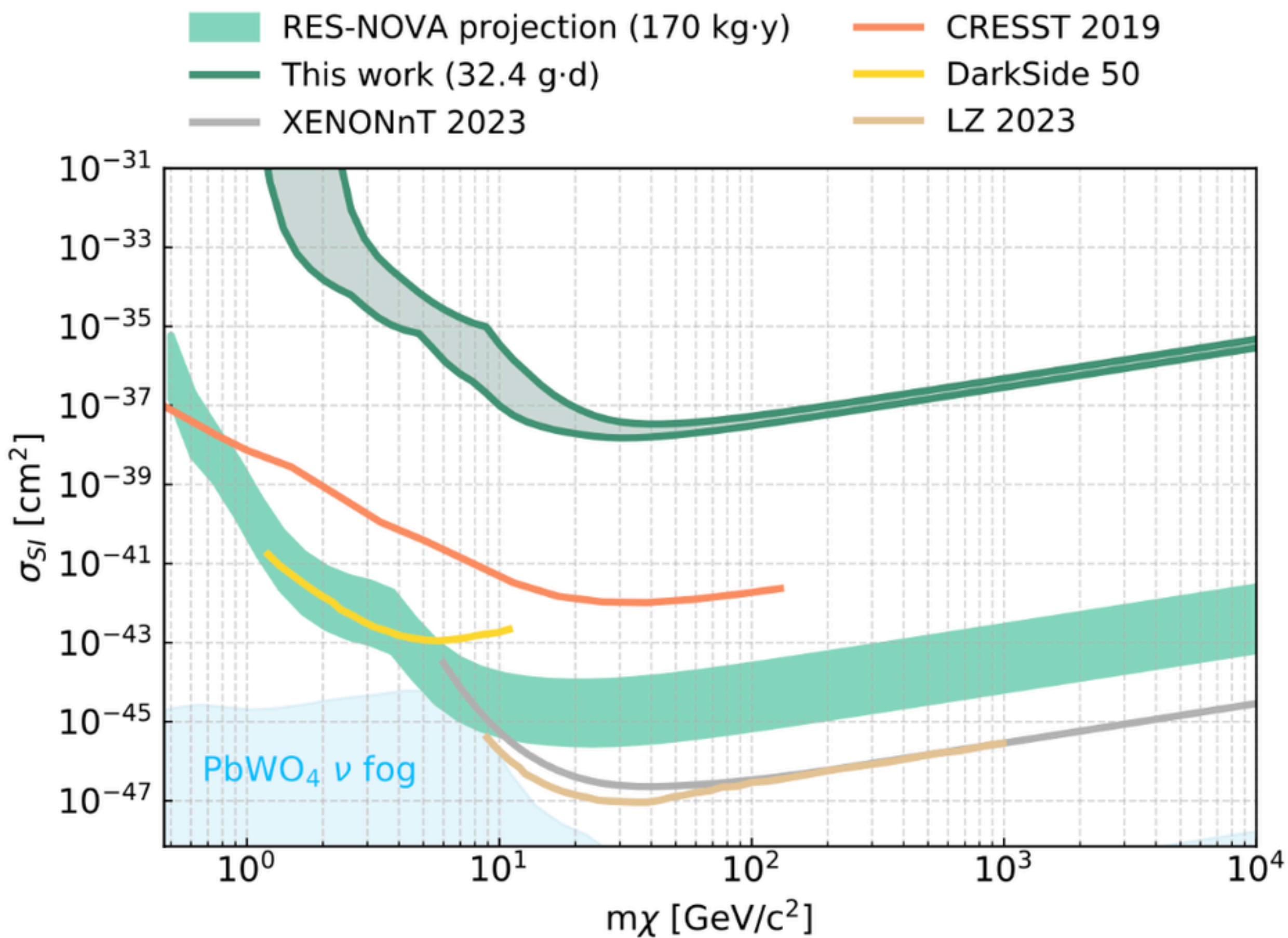
Data analysis

- DM sensitivity derived by comparing the observed spectrum with the expected recoil spectrum in PbWO_4
- Expected spectra include detector efficiency and energy resolution effects
- Since no reliable background model is available in the ROI (2.5 keV - 10 keV), limits are obtained using the **Yellin optimum interval method**
- Sensitivity evaluated at **90% CL**



Dark matter limit

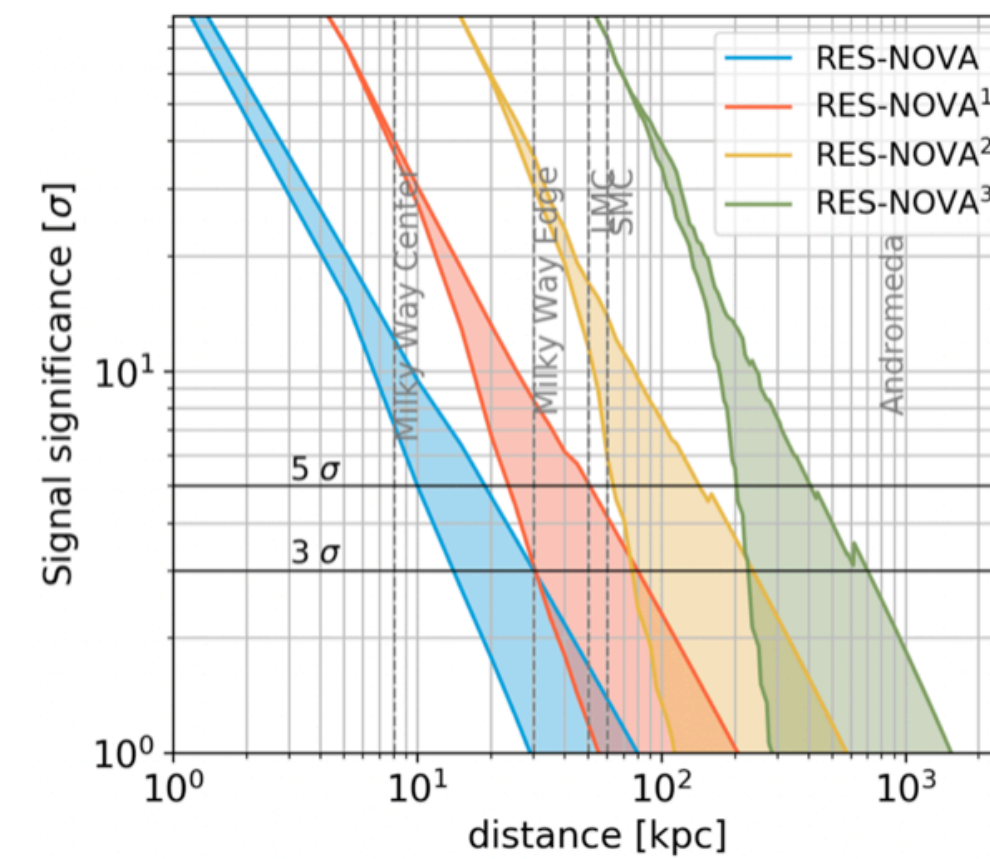
32.4 g*day



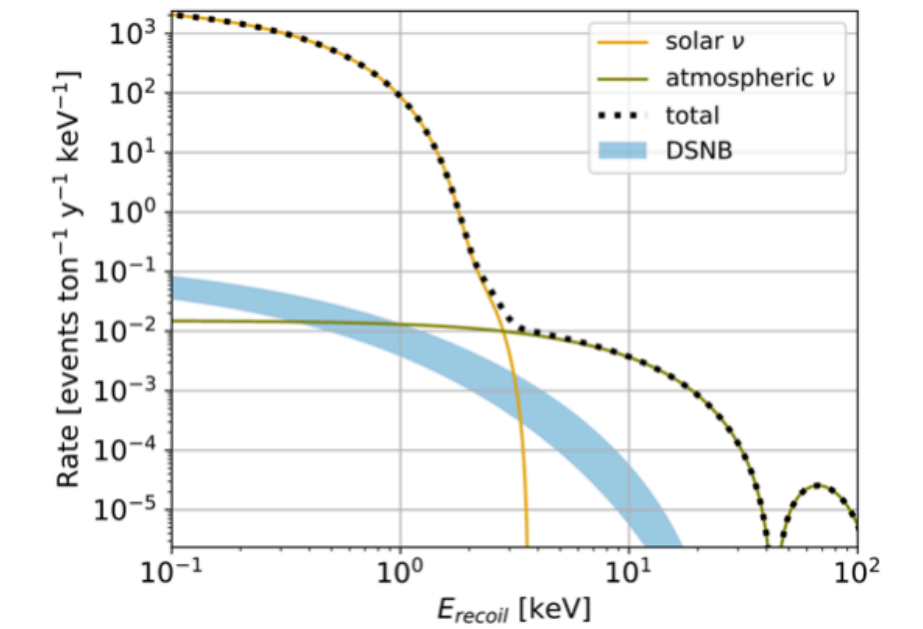
Conclusions

- ◆ RES-NOVA is a new neutrino observatory at cm-scale
 - ◆ *broad physics program*
- ◆ RES-NOVA technology is already established
 - ◆ Archaeological Pb can be embedded in PbWO₄
 - ◆ Preliminary results exceed expectations ($E_{\text{th}} = 300 \text{ eV}$)
- ◆ RES-NOVA provides a complementary approach to the current SN neutrino observatories

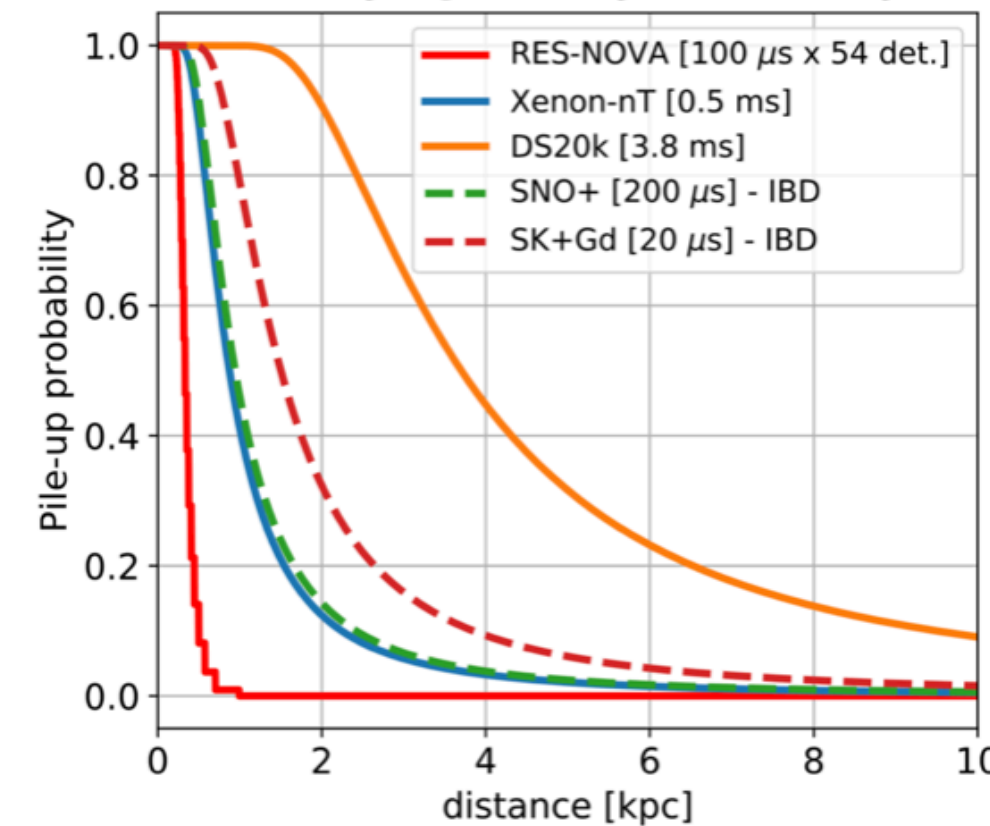
Deep space exploration



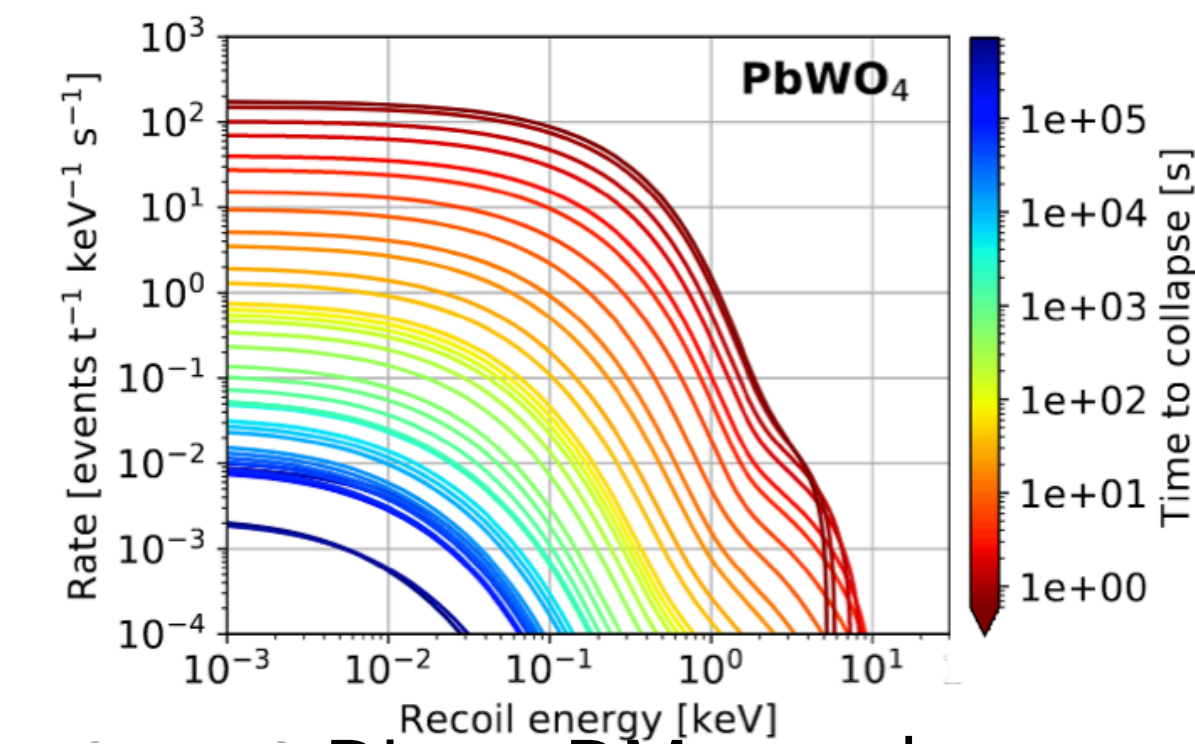
Diffuse SN neutrino Background



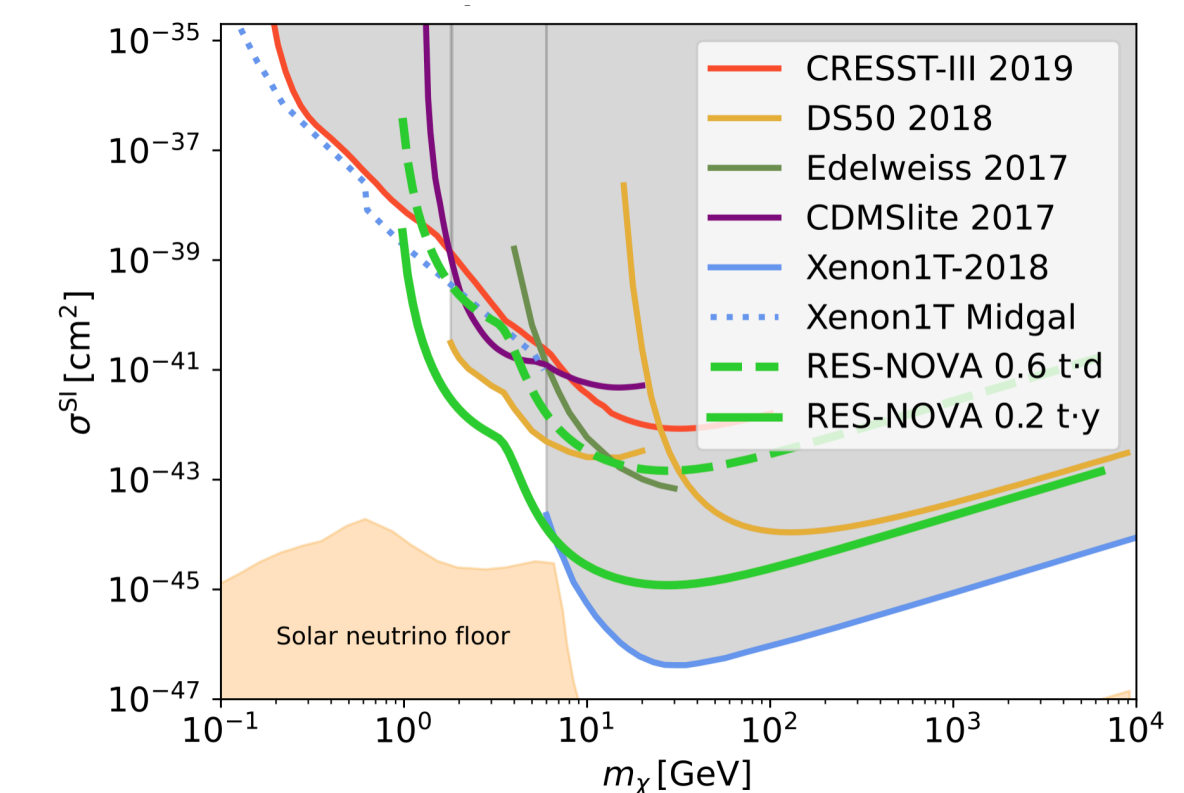
Nearby galaxy survey



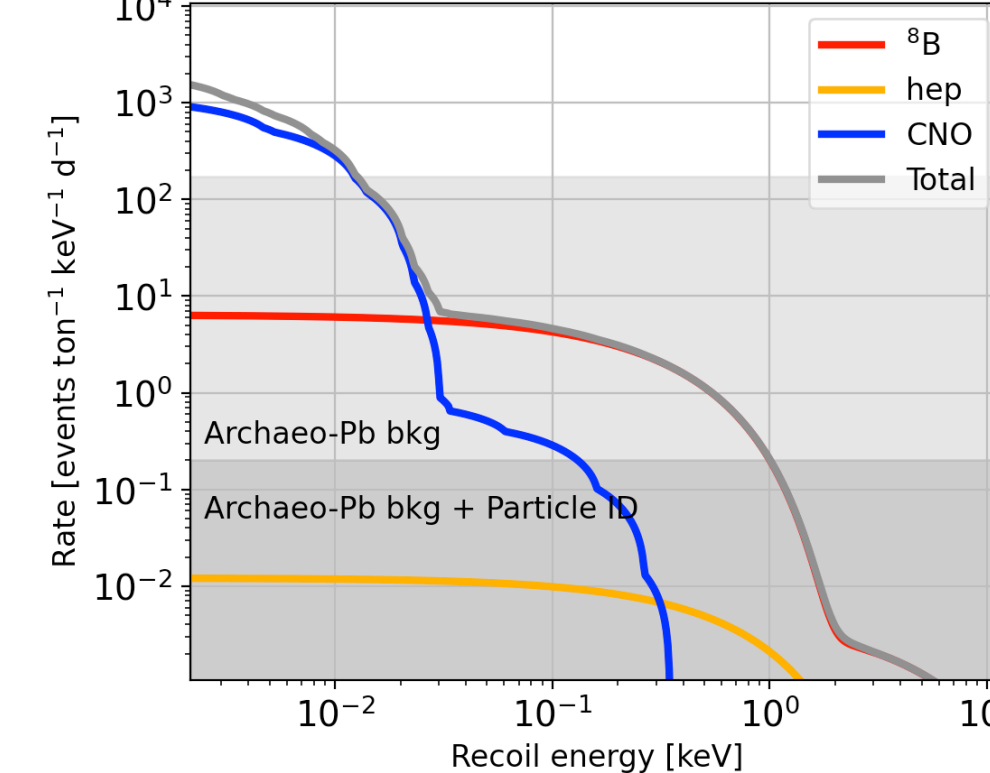
Pre-SN neutrino detection



Direct DM searches



Solar neutrinos



RES-NOVA BACKGROUND MODEL

High multiplicity SN signal



High multiplicity bkg

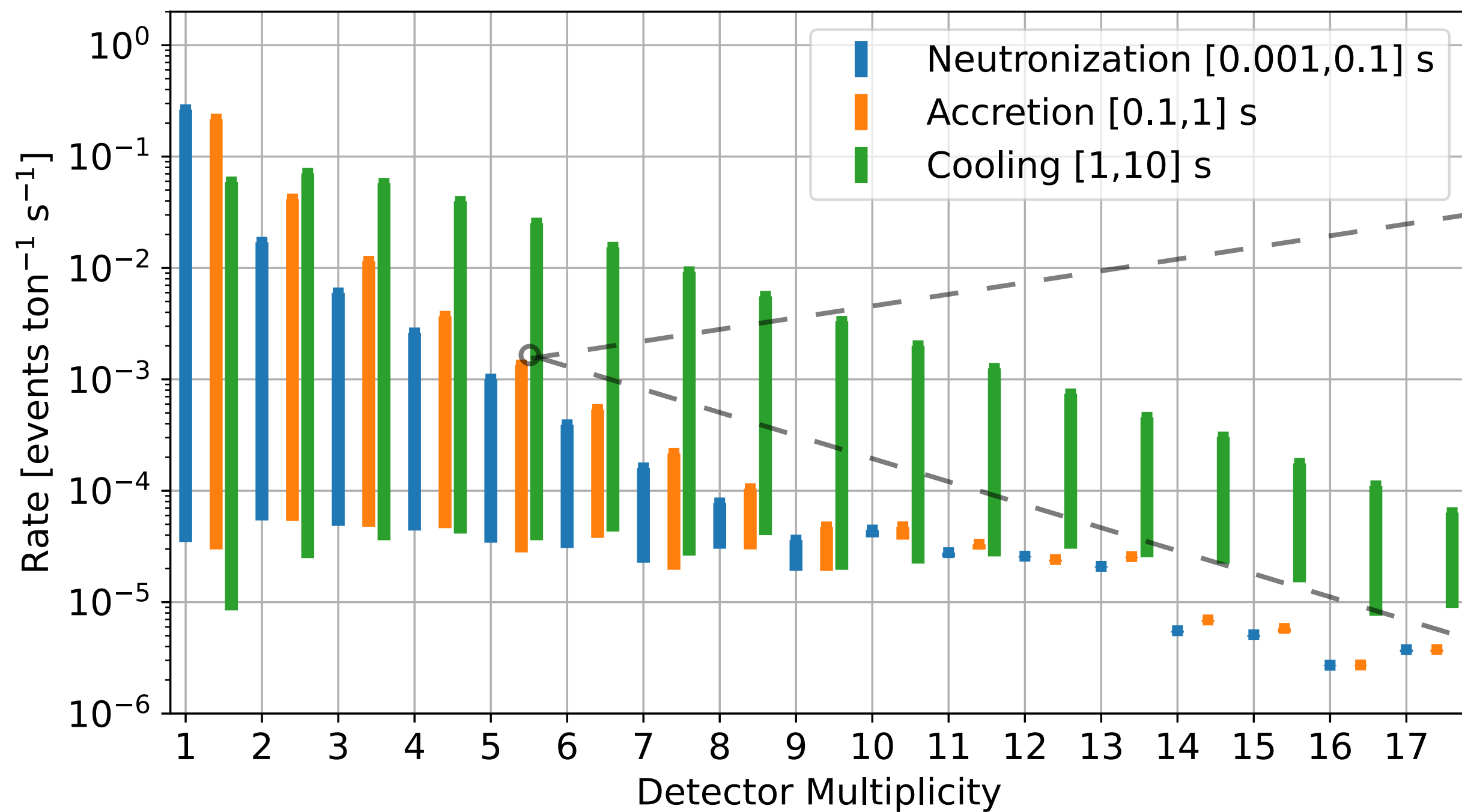


Low-background

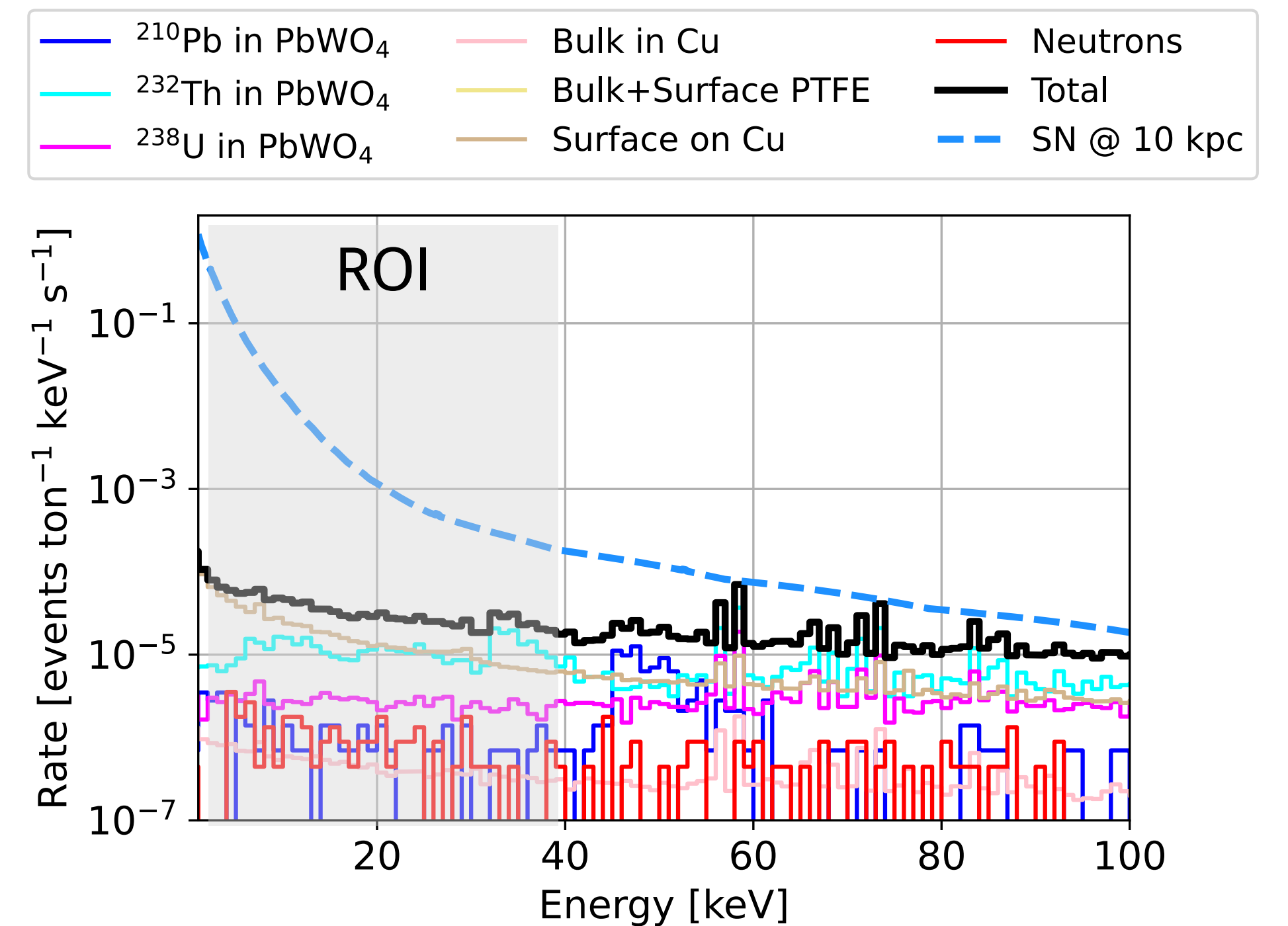
Bkg goal: $<10^{-3}$ ev/ton/keV/s in coincidence mode (no particle ID)

<0.086 c/keV/kg/d

Background rate in the ROI

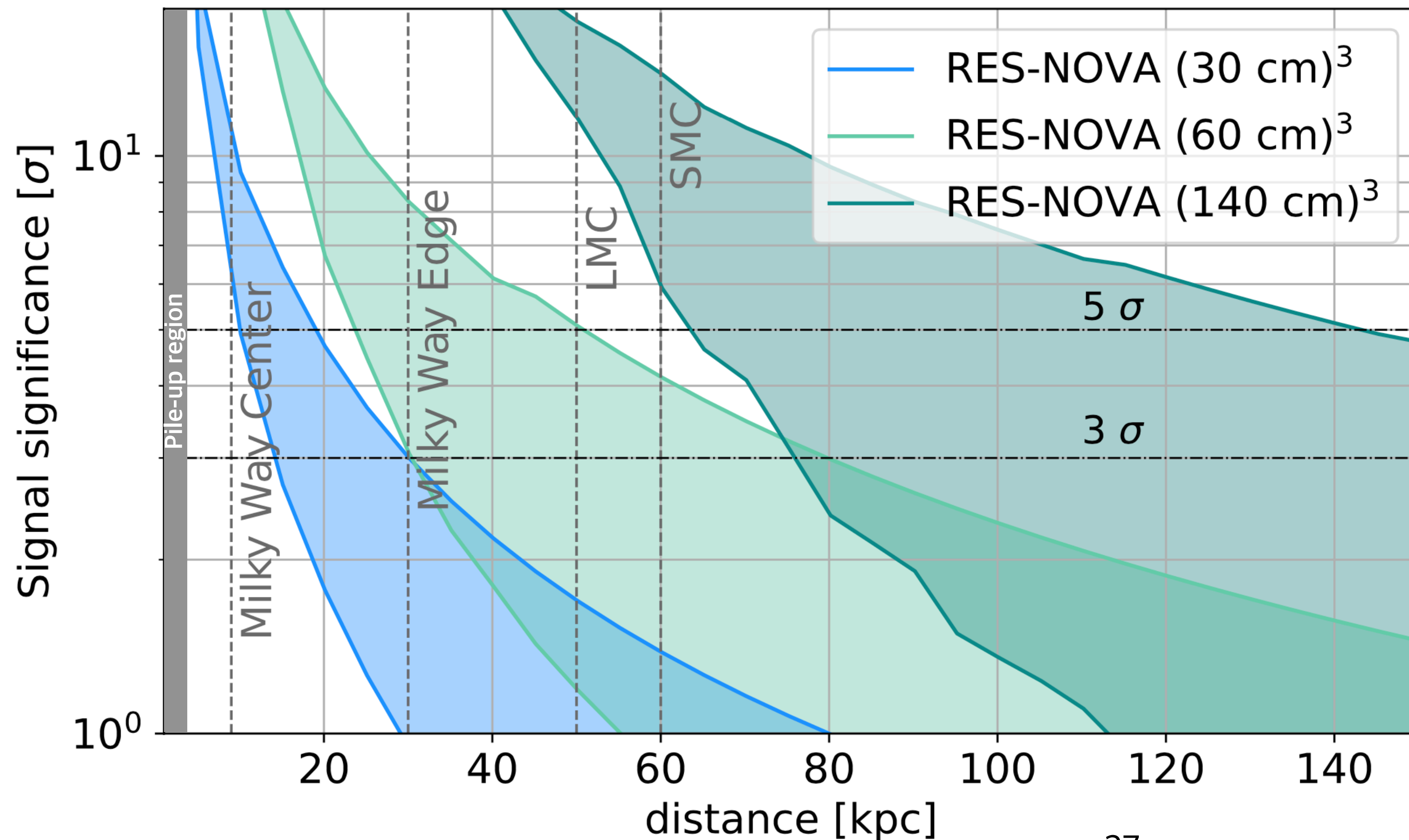


Detector energy spectrum for a SN @ 10 kpc



RES-NOVA sensitivity

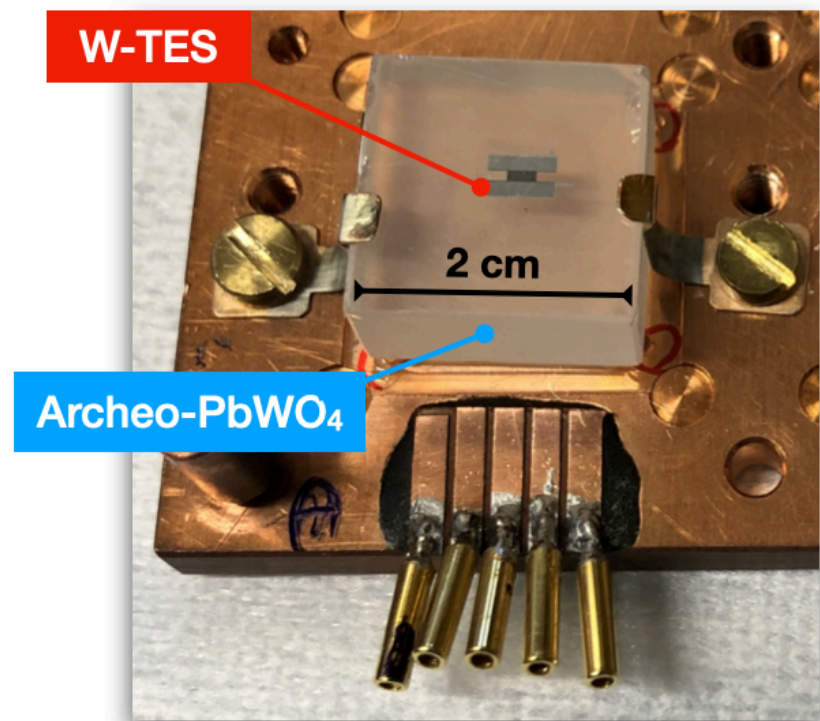
small detector great potential



Target: archaeo-PbWO₄
Energy threshold: 1 keV
Bkg @ ROI: 10⁻³ c/keV/ton/s/

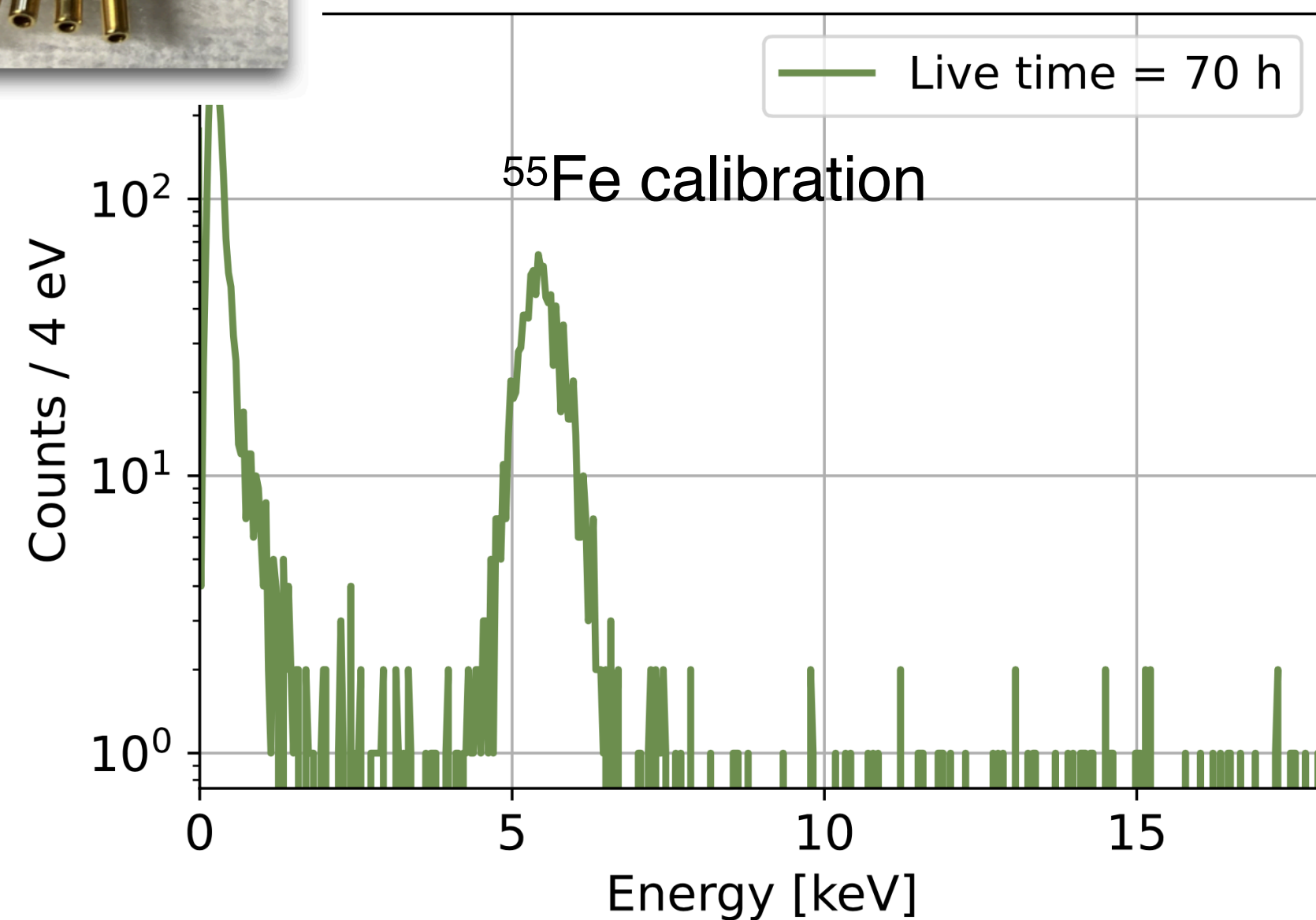
RES-NOVA proofs of principle

achievement of low threshold and low background



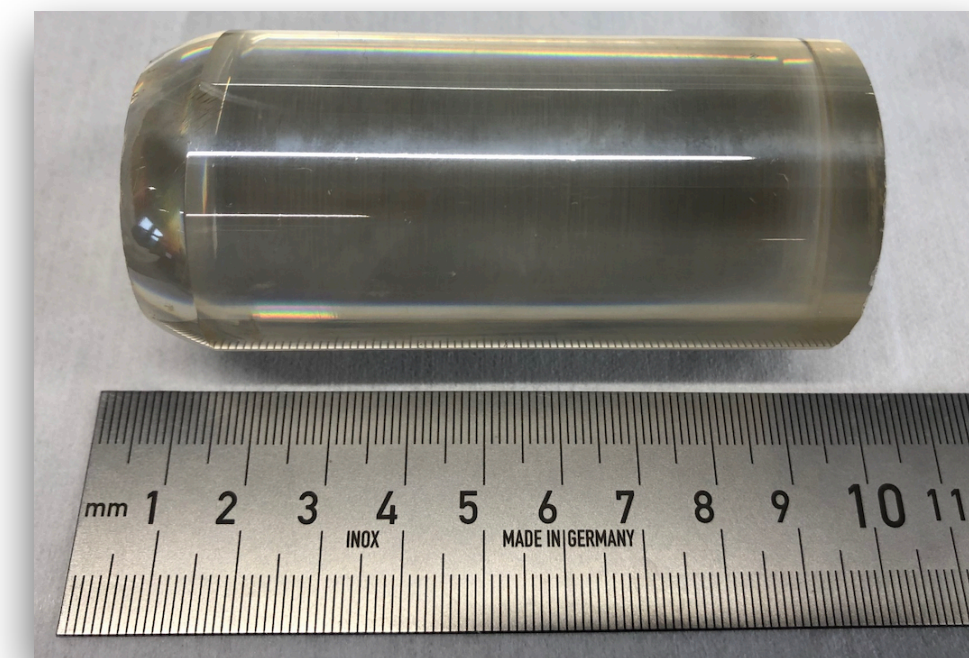
N. Ferreiro Iachellini et al.,
J. Low Temp. Phys. 11, 184 (2022)

TOTAL ENERGY SPECTRUM



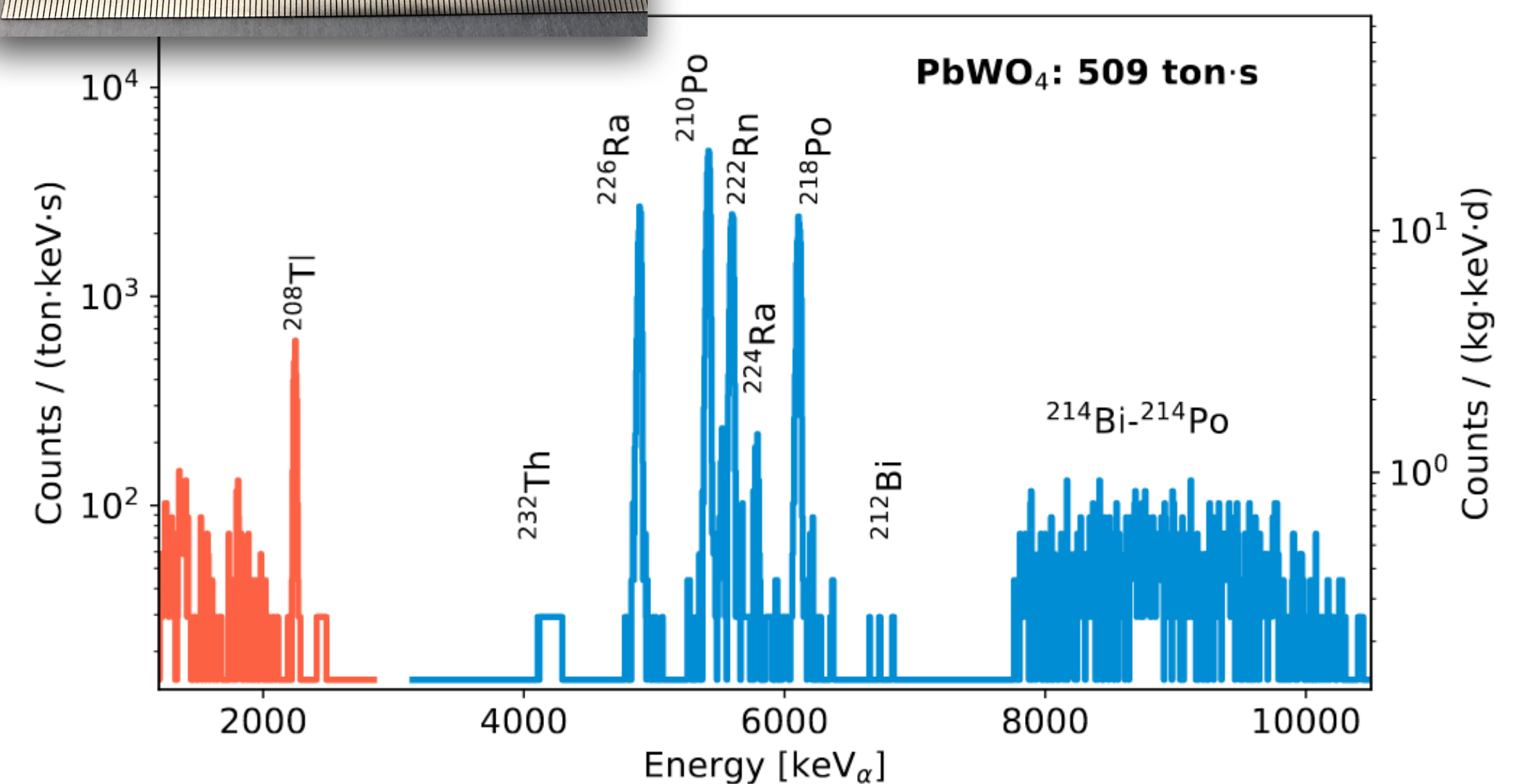
Above ground @ Max Planck Munich (DE)

Nuclear recoil threshold - 300 eV (PbWO₄ - 20 g)



RES-NOVA group of interest
Eur. Phys. J. C 82, 692 (2022)

TOTAL ENERGY SPECTRUM



Under ground @ LNGS (IT)

Radiopurity @ μBq/kg scale (PbWO₄ - 0.9 kg)