RES-NOVA

A revolutionary archaeological Pb observatory for astrophysical neutrino sources

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INFN - Laboratori Nazionali del Gran Sasso

European Research Council
Established by the European Commission

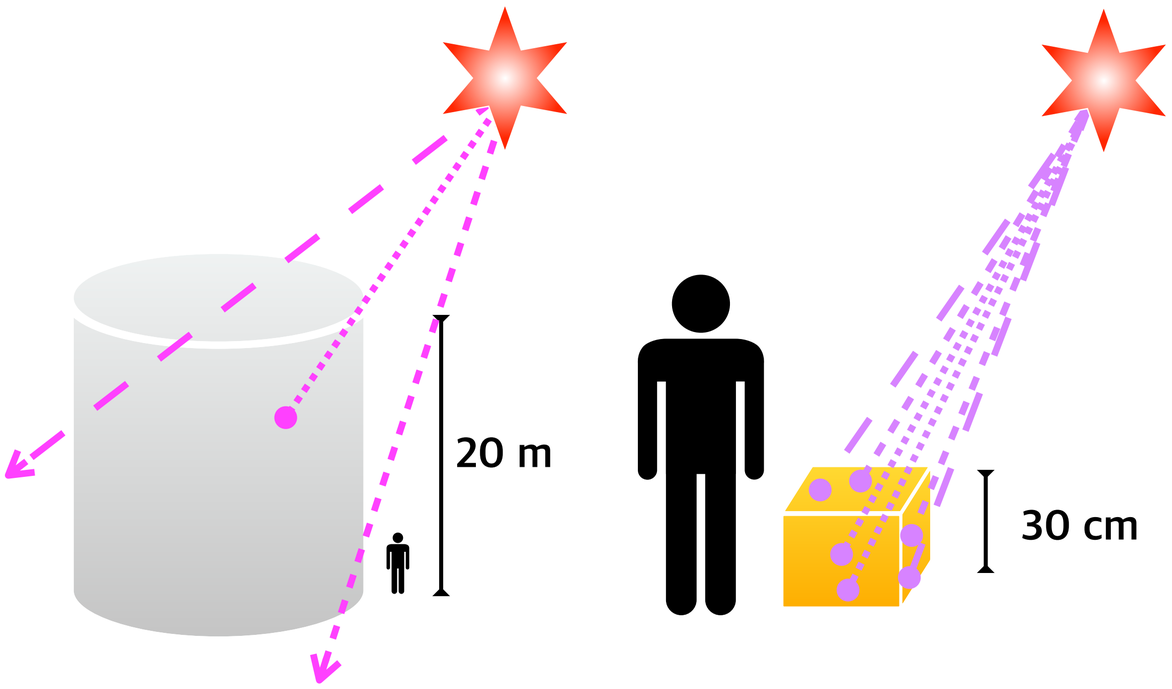
Funded by the European Union

LNGS LX Scientific Committee - 16.10.2023

RES-NOVA IN ONE SLIDE

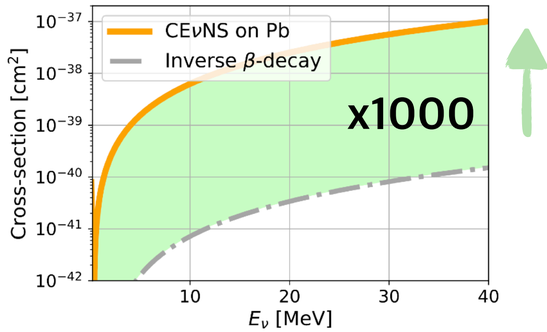
Detecting SuperNova neutrinos

1 SN / 50 years



using an innovative technology for high-statistic and flavor independent studies

Coherent neutrino-nucleus scattering on Pb



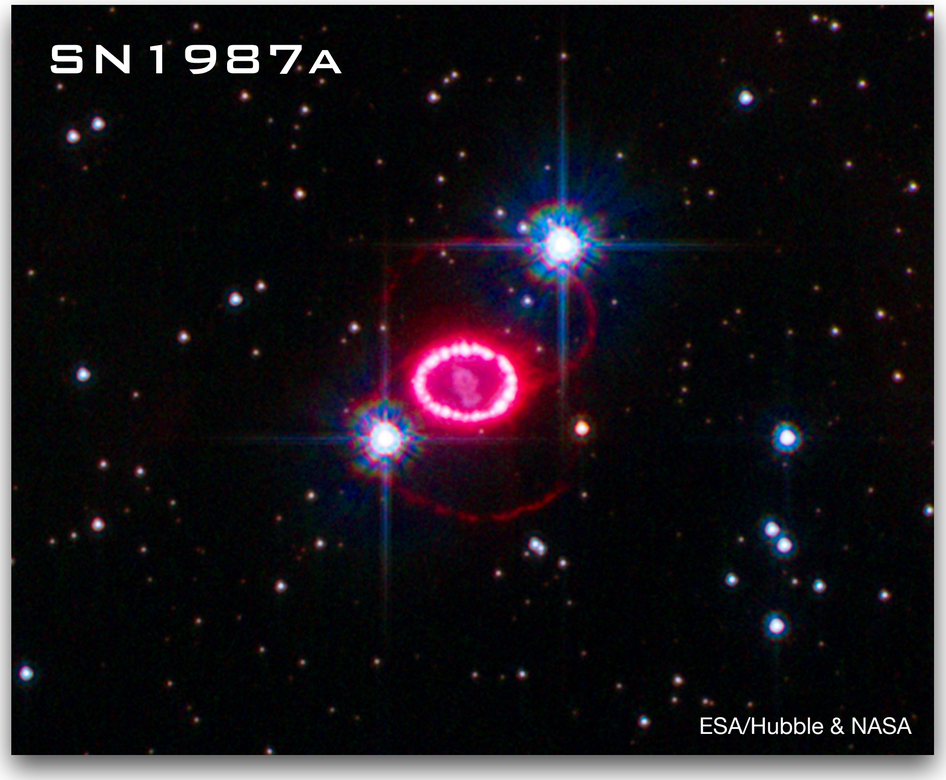
Archaeo-Pb-based neutrino telescope

Total detector volume (30 cm)³

Survey 90% of SN in Milky Way

Supernovae: cosmic fireworks

Setting the stage



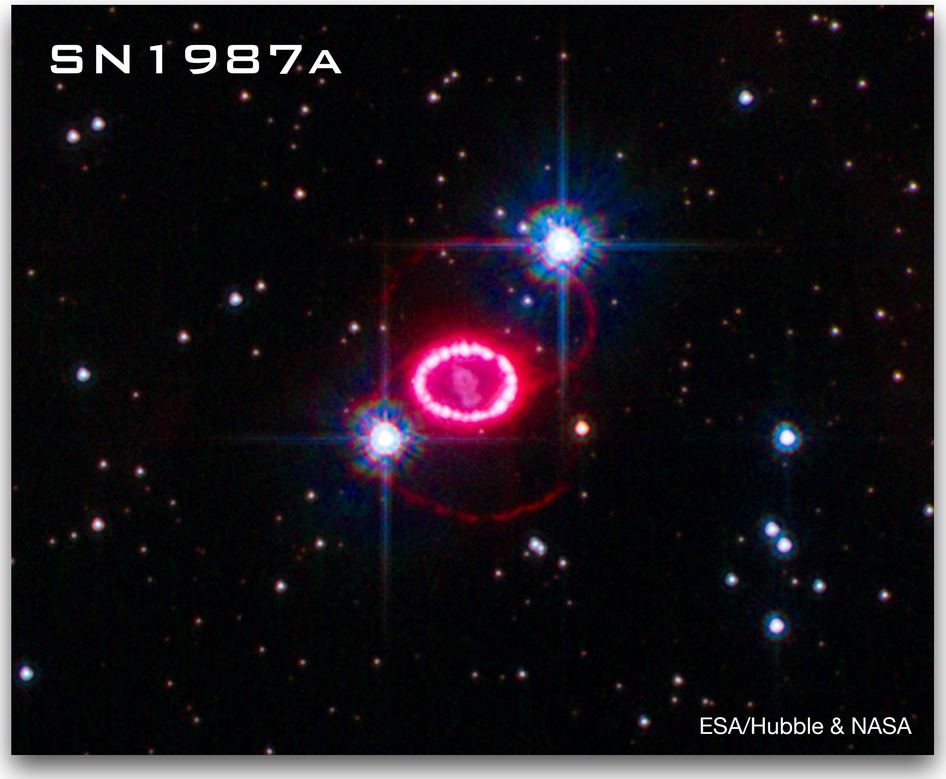
High-energy **explosions of massive stars**

Star binding energy is converted into:
all flavor-neutrinos, GW, EM radiation

Why neutrinos are interesting?

Supernovae: cosmic fireworks

Setting the stage



High-energy **explosions of massive stars**

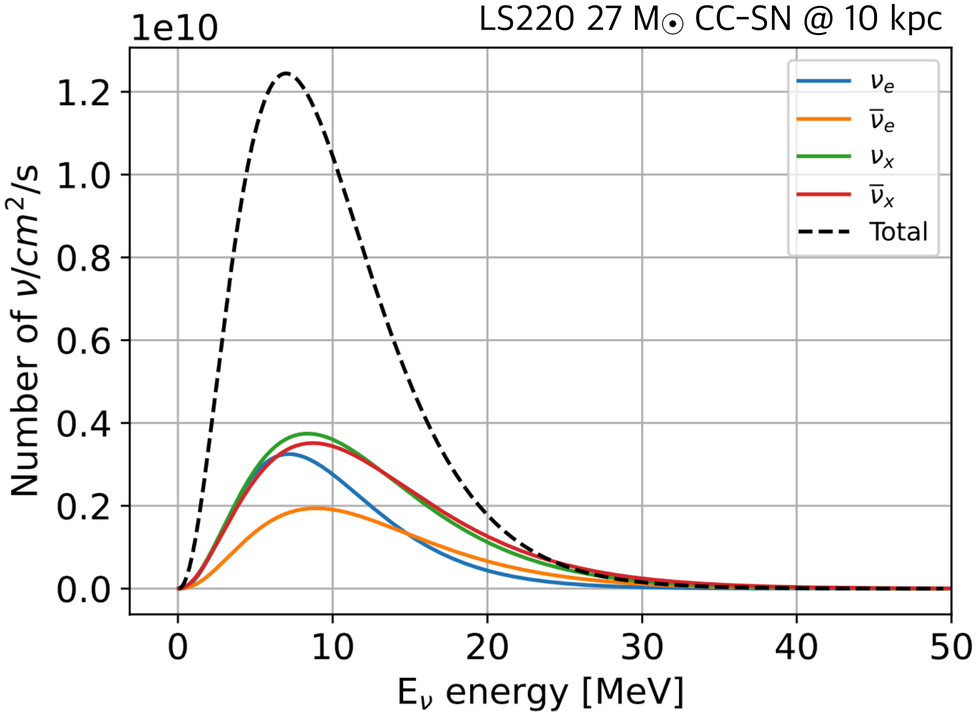
Star binding energy is converted into:
all flavor-neutrinos, GW, EM radiation

Why neutrinos are interesting?

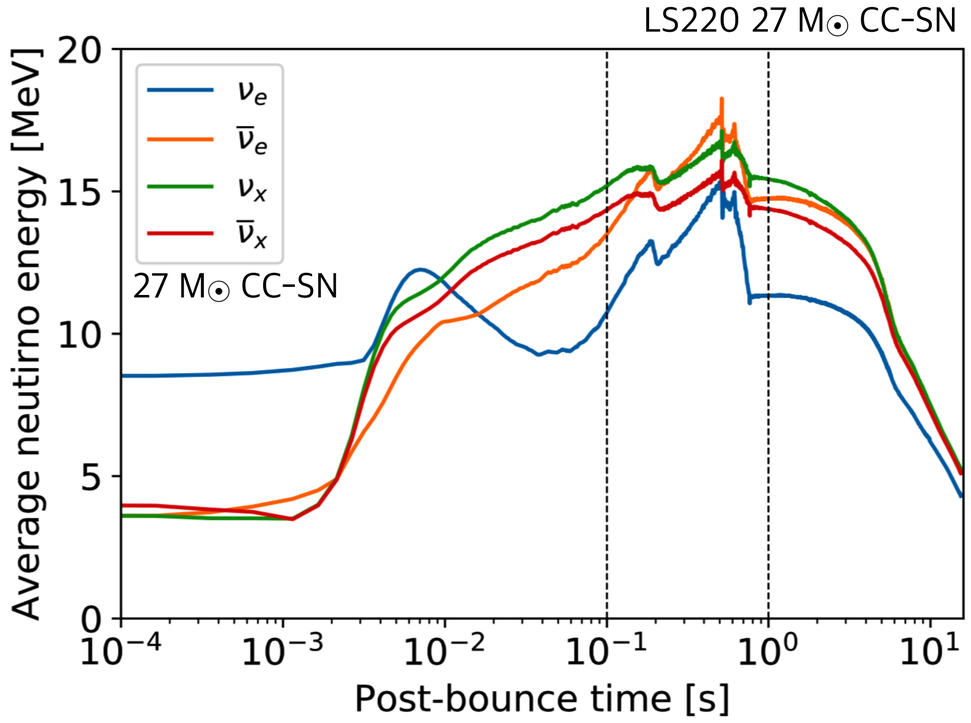
- Direct **probes** and **messengers** of SN dynamics
- Highest luminosity
- Neutrinos provide **early alerts** of the explosion

Supernova Neutrino signal

What is the average neutrino energy?



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

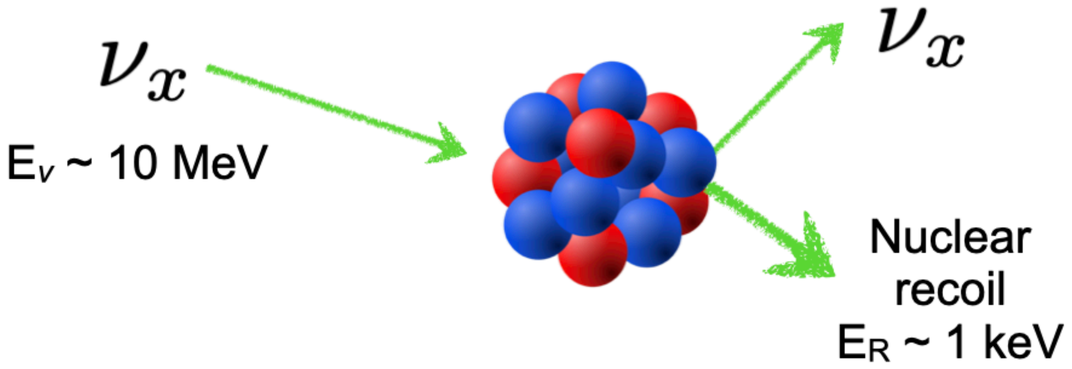


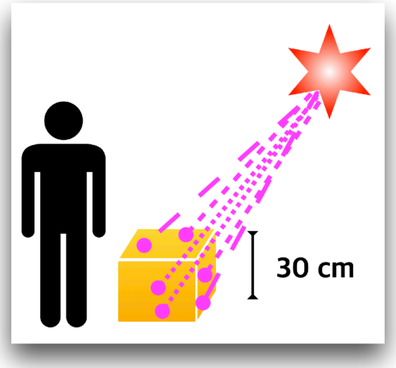
v_x is the most **energetic** component of the flux

Current SN neutrino detectors are mostly sensitive to anti-v_e/v_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

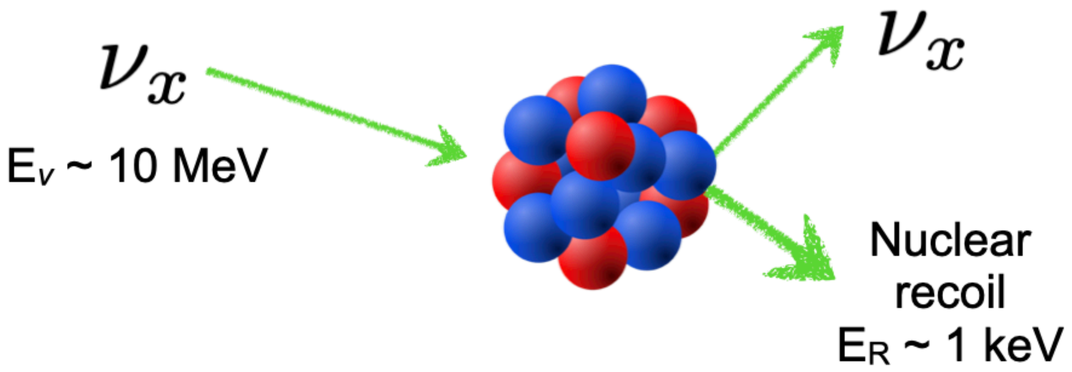
Nuclear Form factor

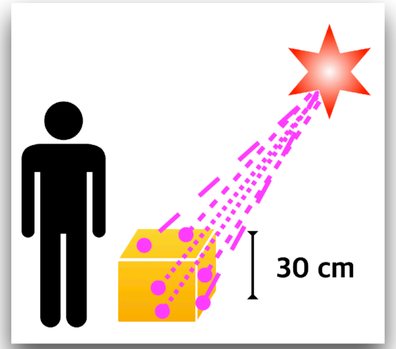
Neutrino energy

Weak nuclear charge

All neutrino flavors are detected

Coherent neutrino-nucleus scattering





> Equally sensitive to all ν-flavors

> High interaction cross-section

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

~5%

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

cross-section

Nuclear Form factor

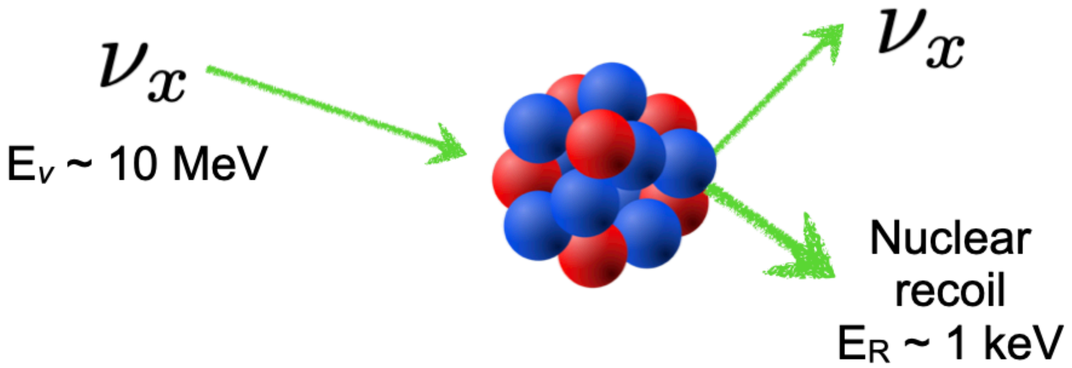
Neutrino energy

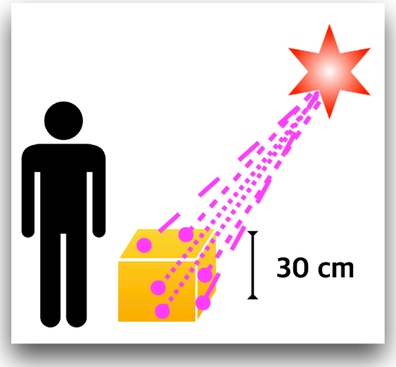
Weak nuclear charge

* 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

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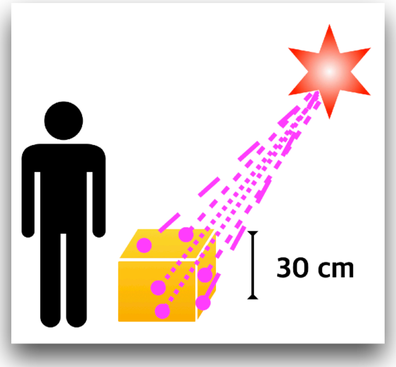
cross-section

Neutron number



Pb ideal target

Highest neutron number

Highest nuclear stability

* Nuclear Weak Form Factor measured!

All neutrino flavors are detected

Coherent neutrino-nucleus scattering

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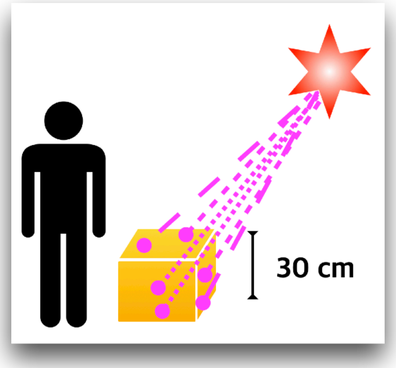
cross-section

Neutron number



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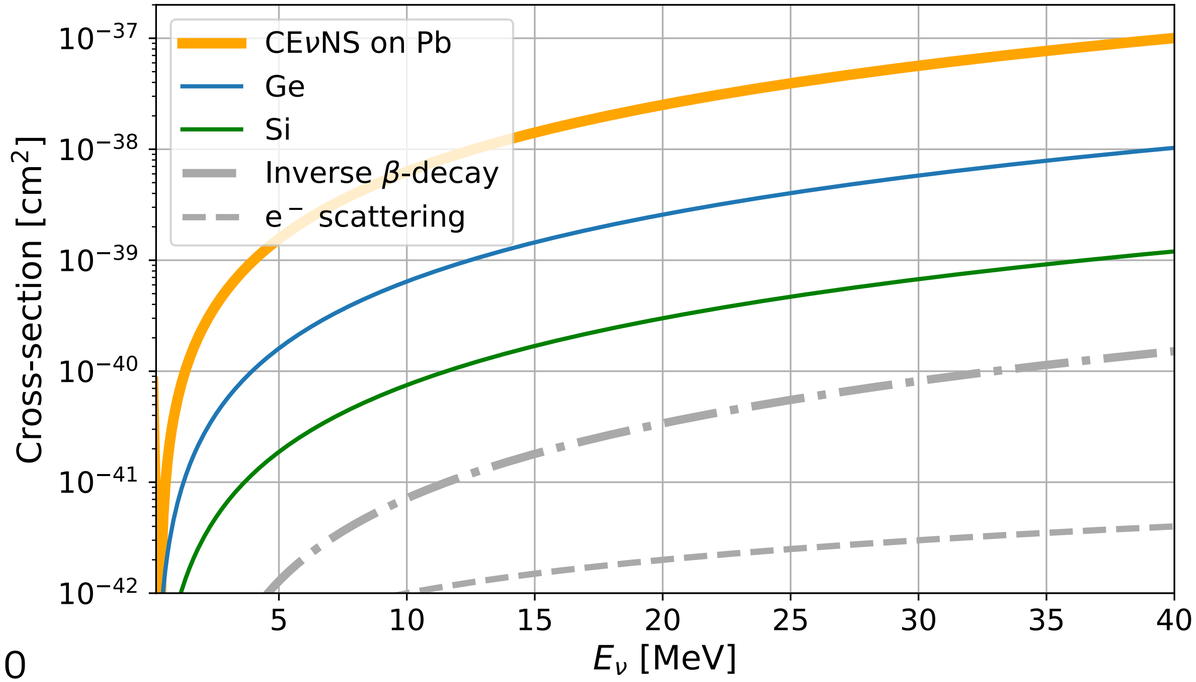

All neutrino flavors are detected

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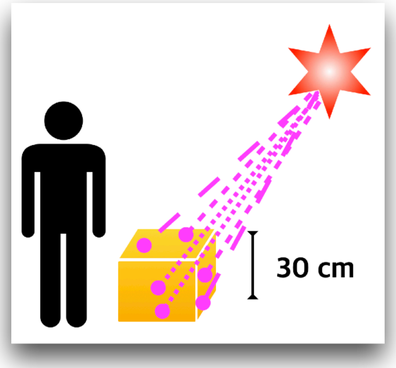
$$\sigma_{CE\nu NS} \propto N^2$$

cross-section

Neutron number



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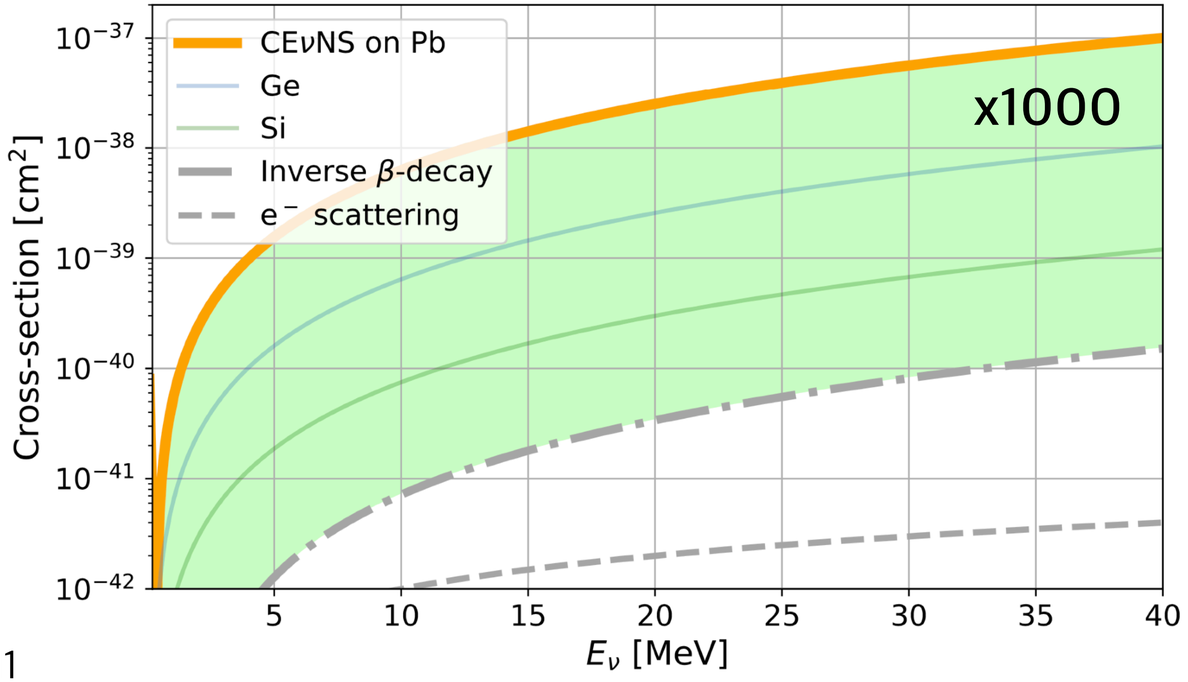
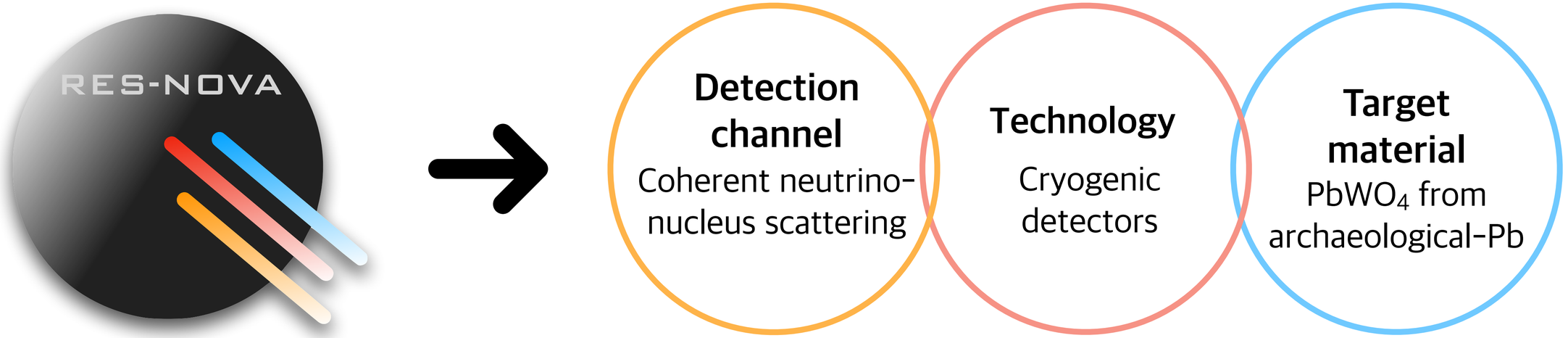


RES-NOVA gives unique insights into SNe

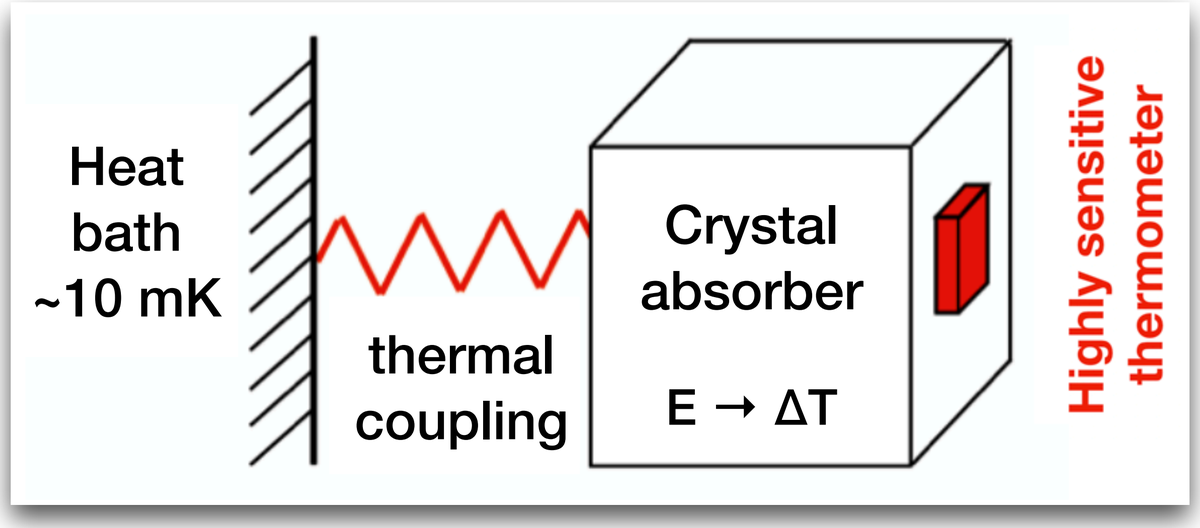
Innovative experimental approach



RES-NOVA detector technology

Advanced Cryogenic Detectors

Cryogenic detectors made from Pb



High-radiopurity crystal

$PbWO_4$ crystals

Commercial crystal (HEP applications)
Good cryogenic performance
High density crystal

Thermometer at mK

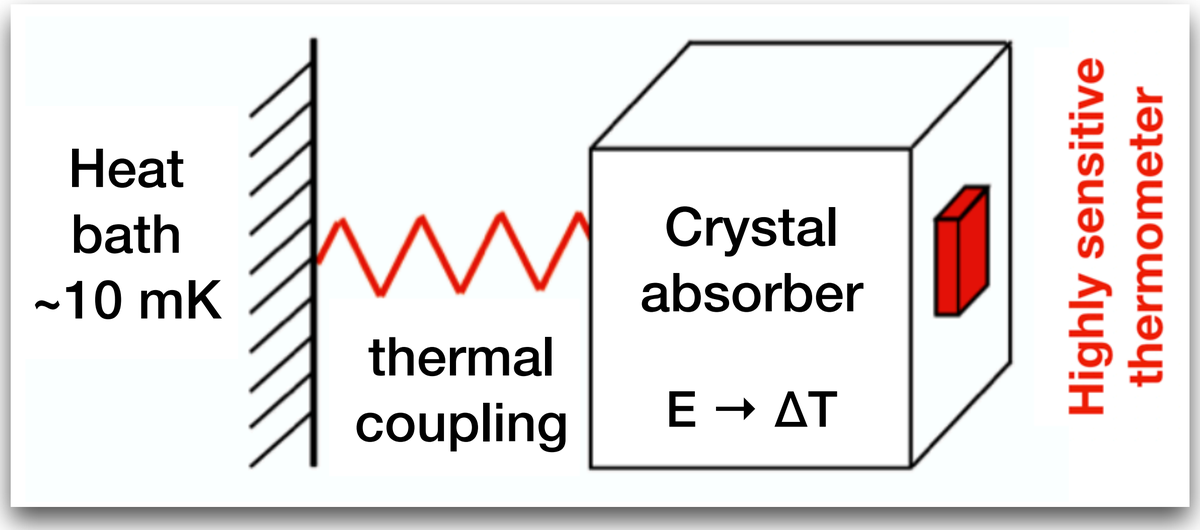
Transition Edge Sensor

Top tech for light-DM searches
Production + operation scalability

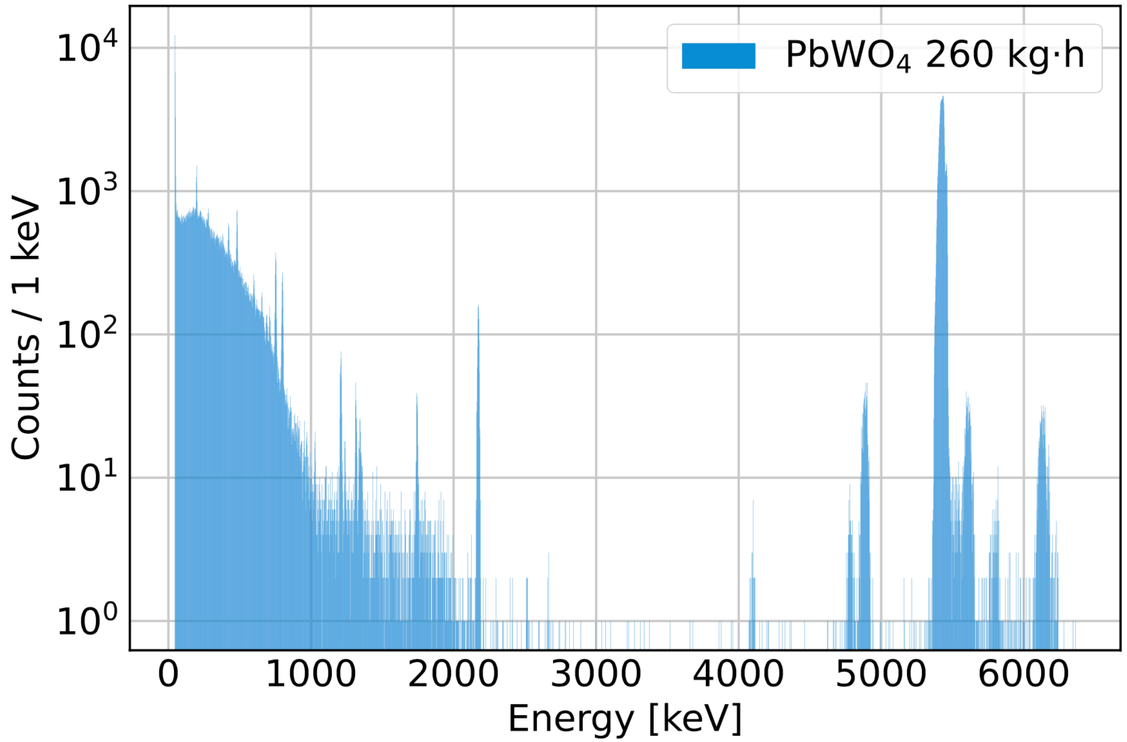
RES-NOVA detector technology

Advanced Cryogenic Detectors

Cryogenic detectors made from Pb



Cryogenic measurement of "commercial" $PbWO_4$



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

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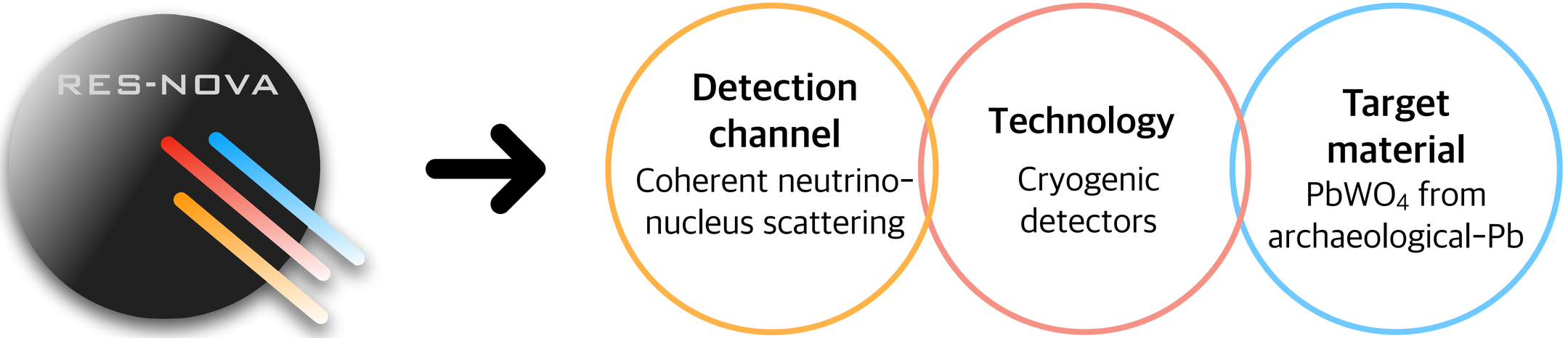
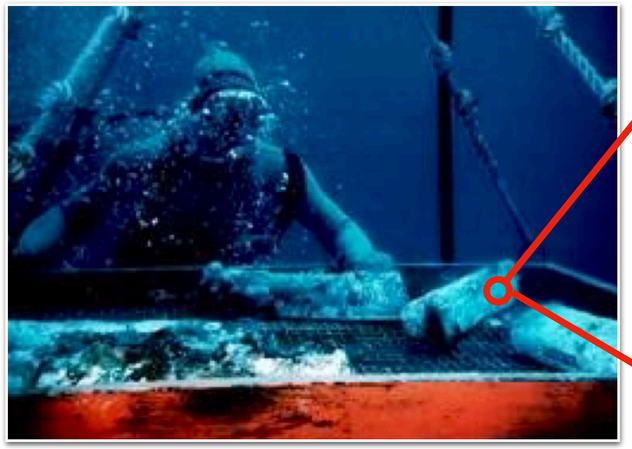
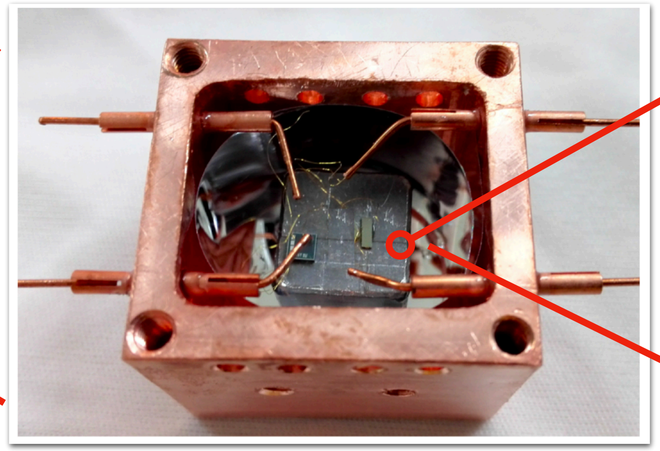


Cryogenic detectors built from Archaeological Pb

from passive material to active detector component

taken from N. Nosengo (2010)





Nuclide	Low background Pb (Boliden®) [1]	Archaeological Pb [2, 3]
^{232}Th	<46 μBq/kg	<45 μBq/kg
^{238}U	<31 μBq/kg	<46 μBq/kg
^{210}Pb	$(2.3\pm0.4)\cdot 10^{7}$ μBq/kg	<715 μBq/kg

Archaeological Pb:

- ★ from underwater shipwreck
- ★ 2000 years old

Archaeo-Pb cryogenic detector

High radiopurity: < 1 mBq/kg

^{210}Pb **x10^{4}** lower than commercial low-background Pb

(Q_{β^-}-value: 63 keV, $T_{1/2}$= 22.3 y)

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

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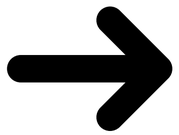

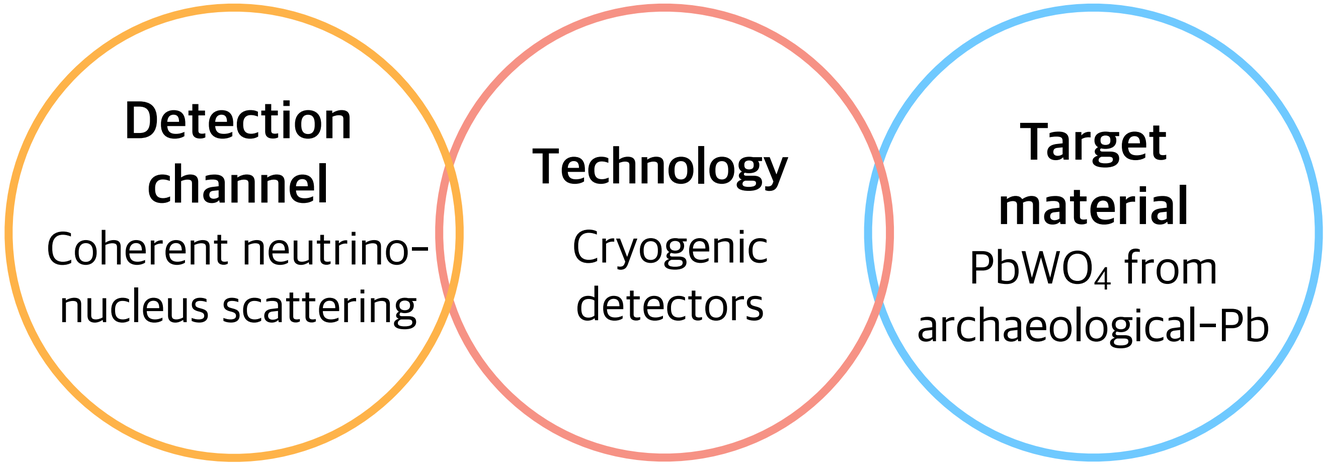

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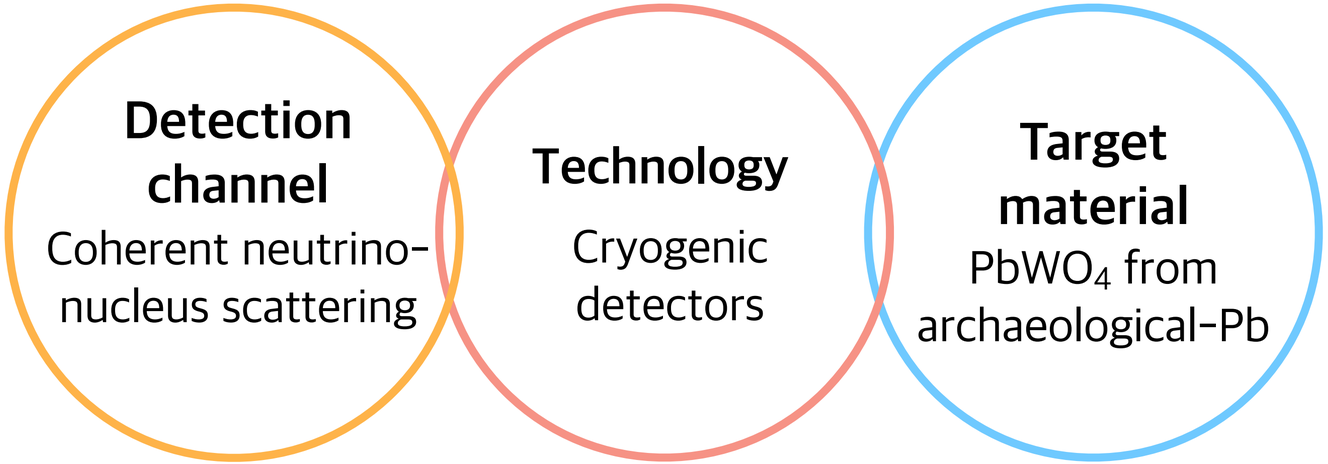


Galactic SN neutrino signal:

Water Cherenkov (SuperK): 0.2 ev./m^3

Liquid Scintillator (SNO+): 0.4 ev./m^3

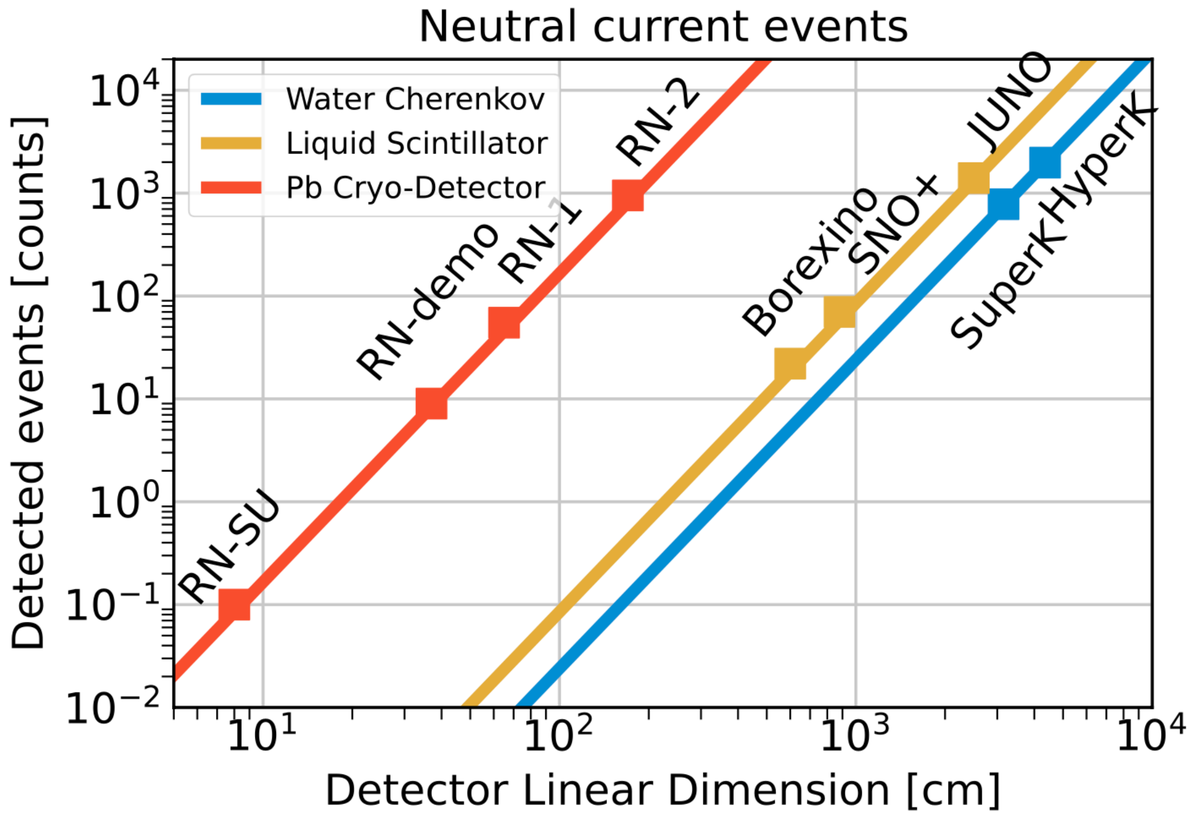
RES-NOVA: ~200 ev./m^3

What can we learn?

- Core-collapse physics studies
- Characterization of SN remnants
- Neutrino mass properties
- Multi-messenger Astronomy

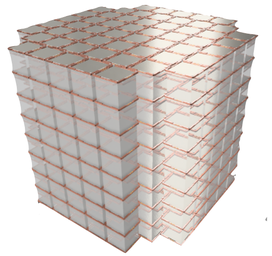
Neutrino observatory at the cm-scale

an array of $PbWO_4$ crystals

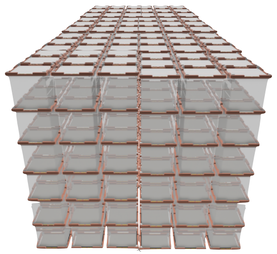


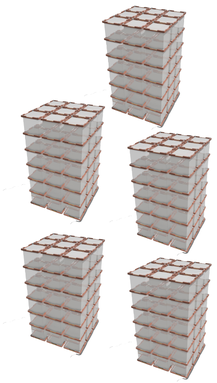
Size: **RN-demo @ LNGS** **$(30\ cm)^3$**
Threshold: **1 keV**
SN @ 10 kpc: **~10 counts**

Size: **RN-1** **$(60\ cm)^3$**
Threshold: **1 keV**
SN @ 10 kpc: **~50 counts**



Size: **RN-2** **$(140\ cm)^3$**
Threshold: **1 keV**
SN @ 10 kpc: **~900 counts**

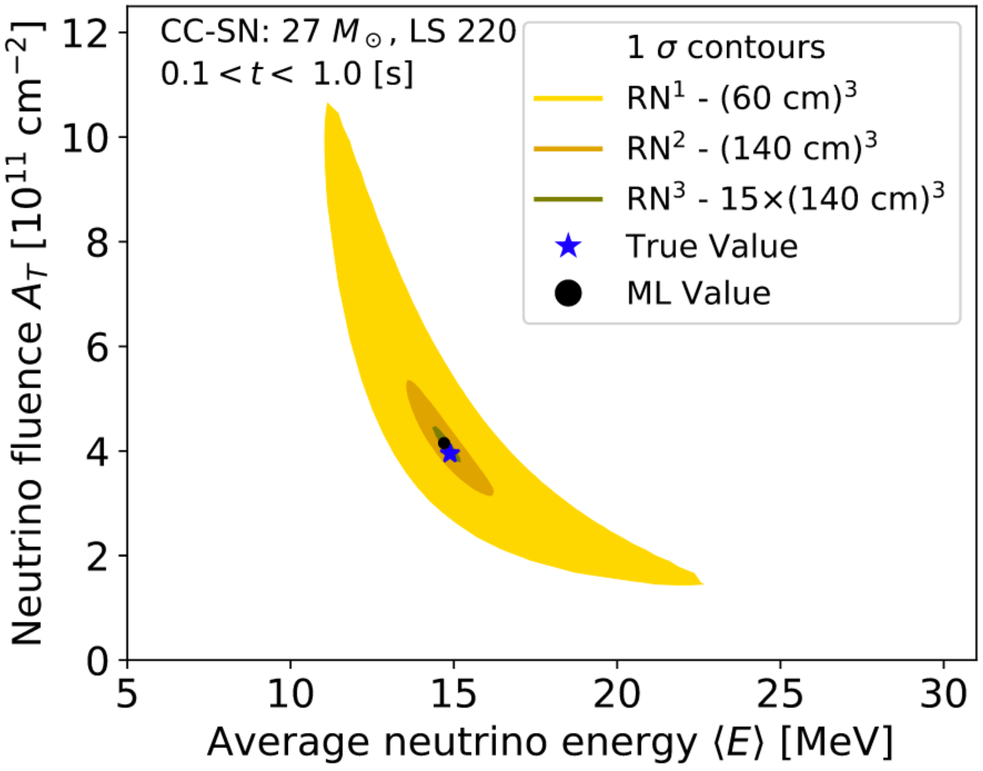




Triangulation

SN ENERGY RECONSTRUCTION IN RES-NOVA

Reconstruction of A_T and <E> by likelihood analysis



$$\mathcal{E}_{\rm tot} = 4\pi d^2 A_T \langle E \rangle$$

Neutrino fluence

Average neutrino energy

Precision in total SN energy reconstruction

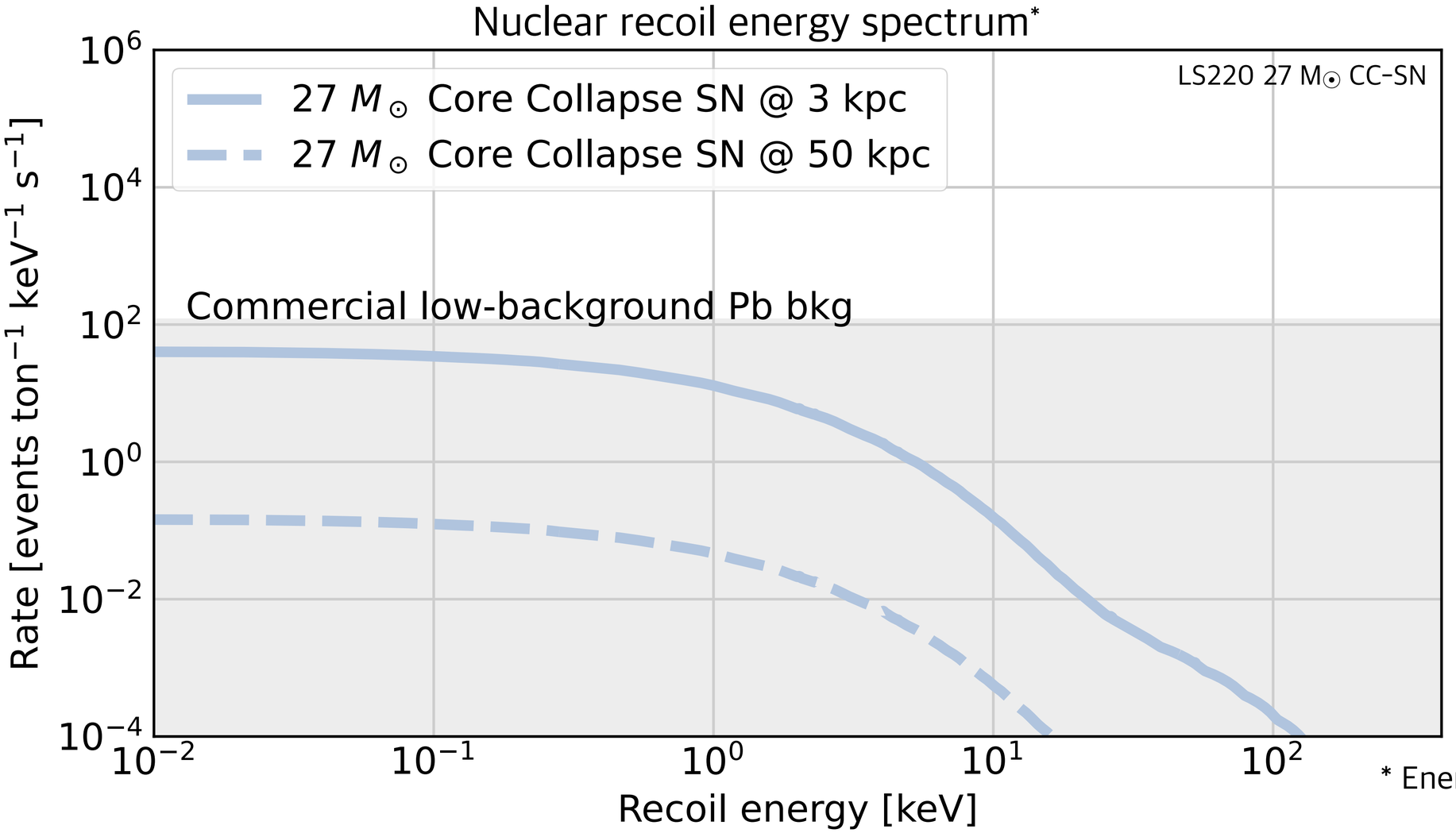
ν_x/anti-ν_x		ν_e/anti-ν_e	
RN-I	30%		
RN-2	8%	SK-Gd* (IBD)	25%
RN-3	4%		

L. Pattavina et al., Phys. Rev. D 102, 063001 (2020)

A. Gallo Rosso et al., JCAP 04 (2018) 040

* >90% Gd loading

RES-NOVA detects SN neutrinos



* Energy resolution 0.2 keV

L. Pattavina et al., *Phys. Rev. D* 102, 063001 (2020)

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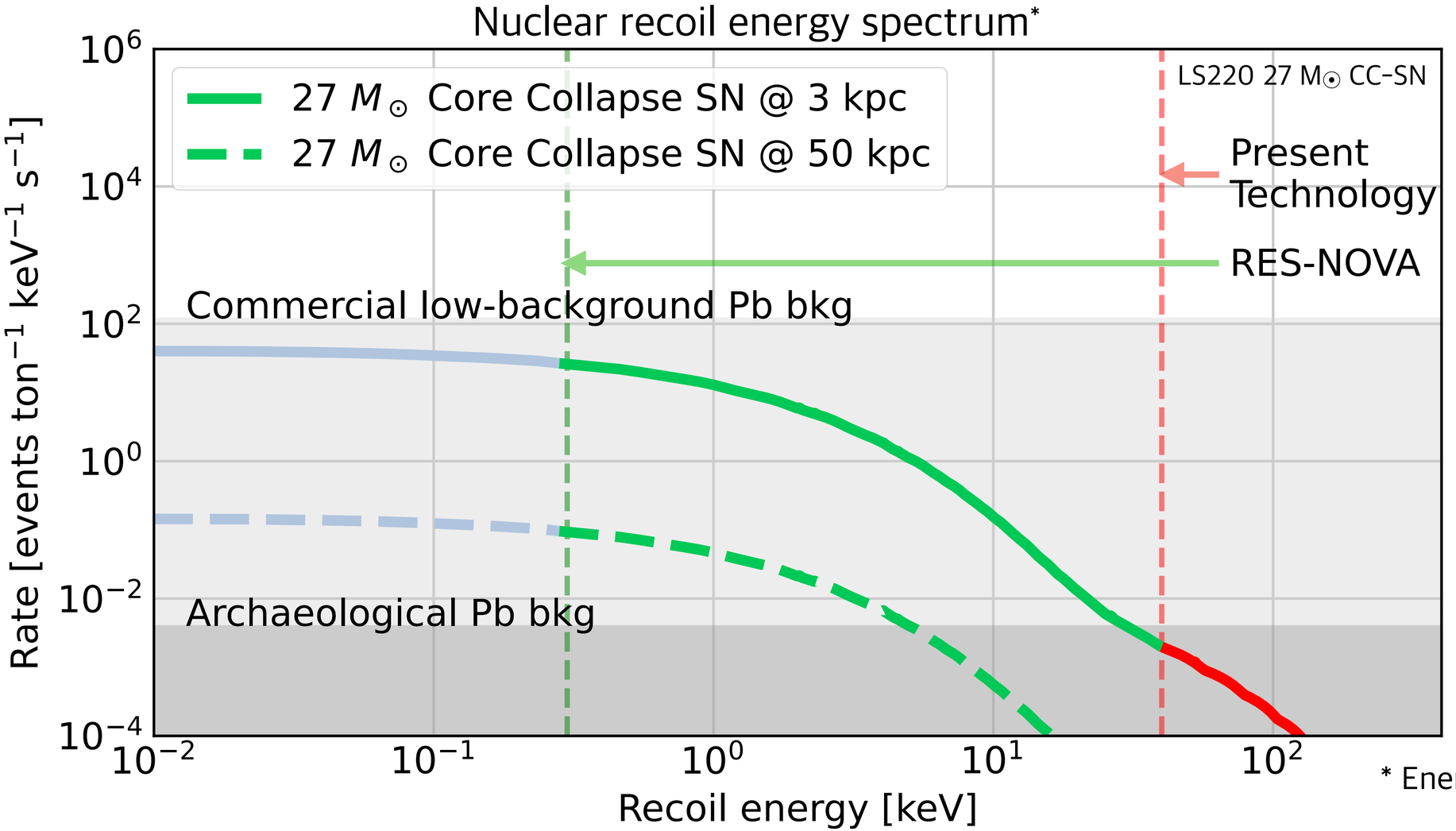

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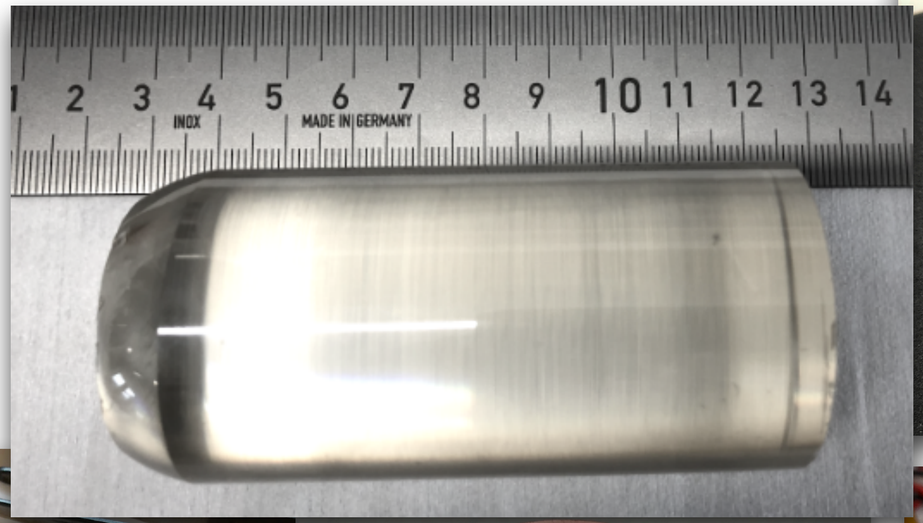
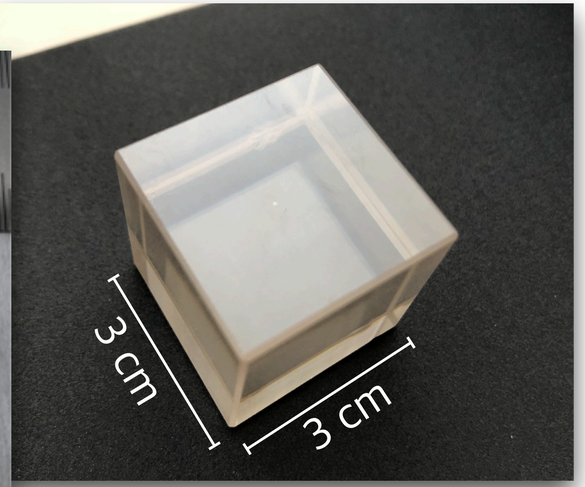
L. Pattavina et al., *Phys. Rev. D* 102, 063001 (2020)

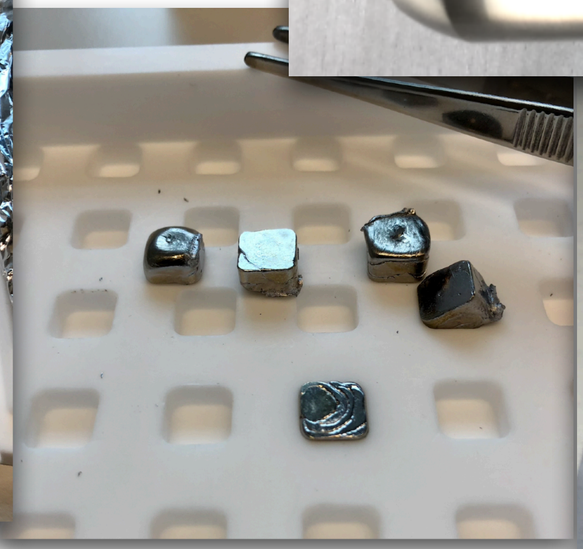
RES-NOVA Group of Interest, *Eur. Phys. J. C* 82, 692 (2022)

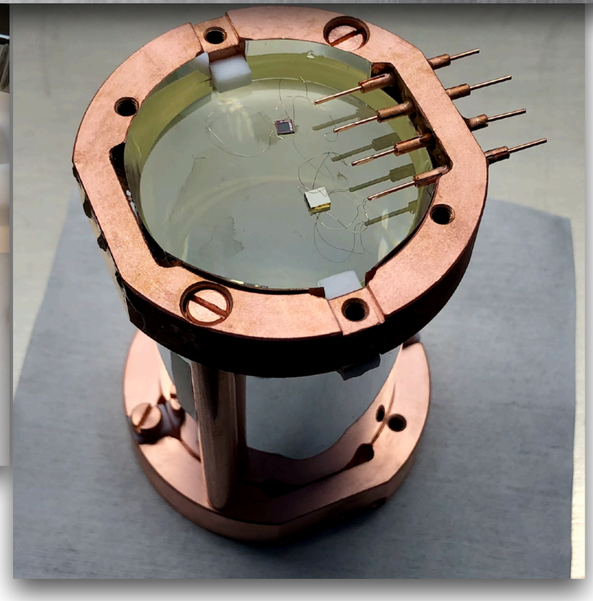
N. Ferreiro, L. Pattavina et al., J. Low Temp. Phys. 11, 184 (2022)

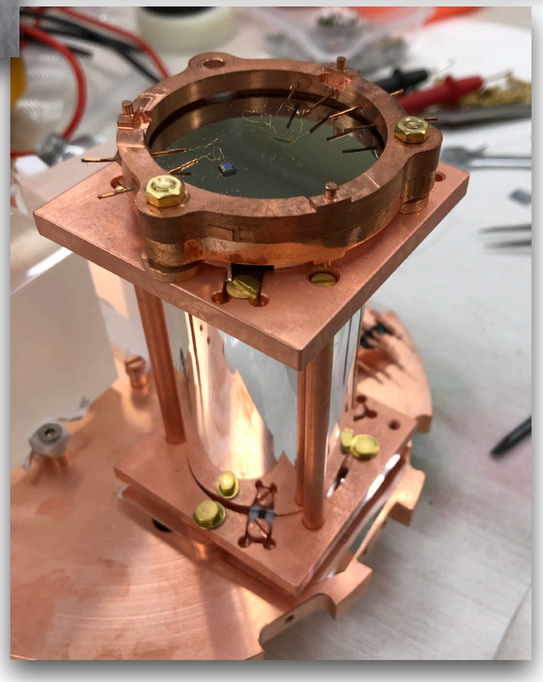
Preliminary work





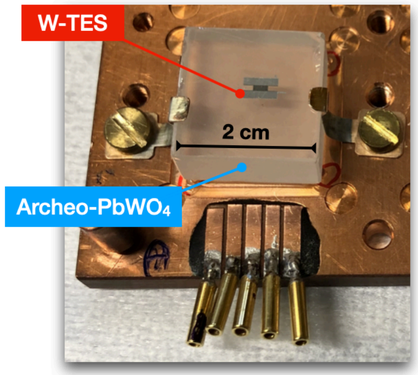






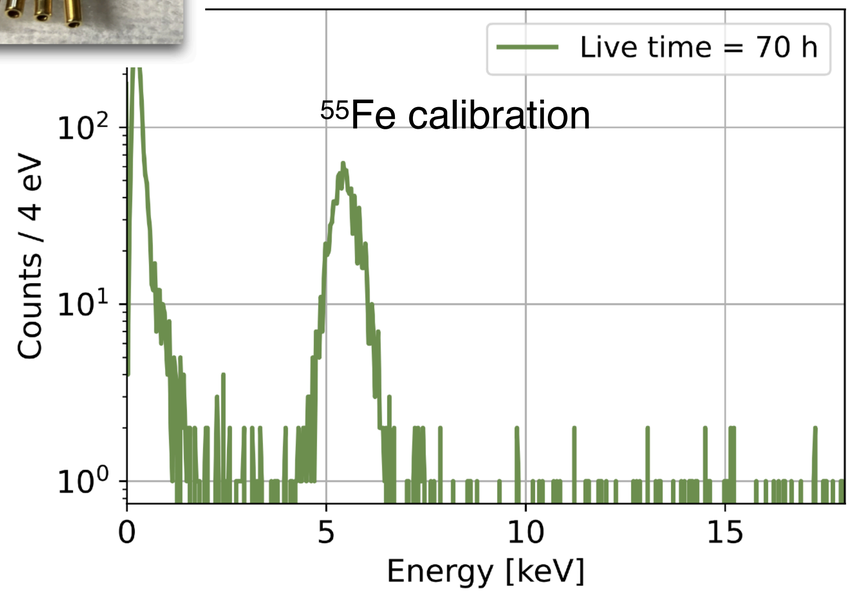
RES-NOVA PROOFS OF PRINCIPLE

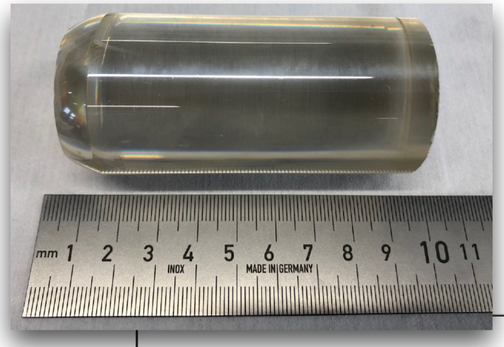
ACHIEVEMENT OF LOW THRESHOLD AND LOW BACKGROUND



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

TOTAL ENERGY SPECTRUM





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

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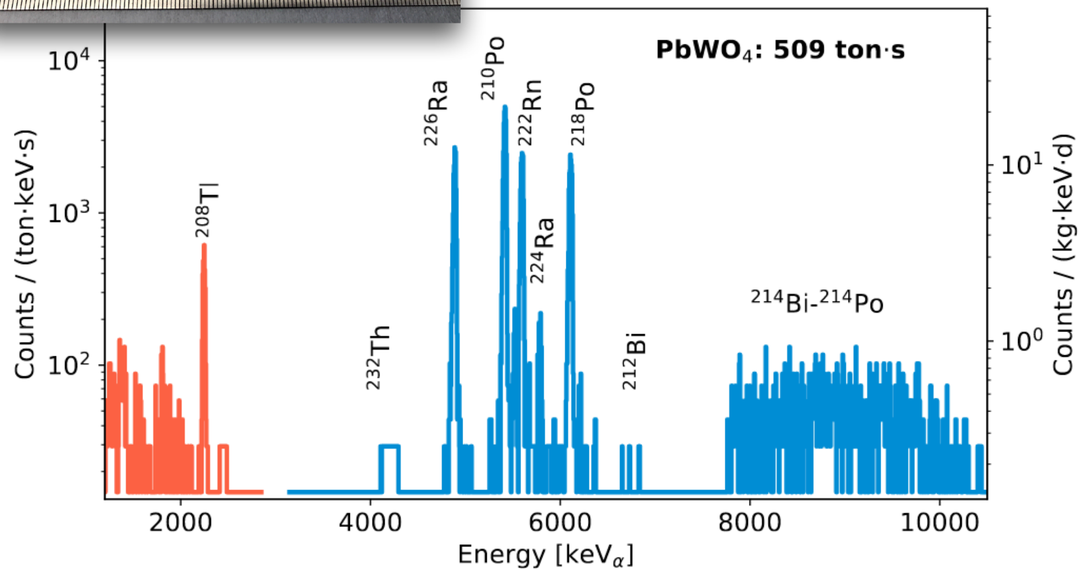


Above ground @ Max Planck Munich (DE)

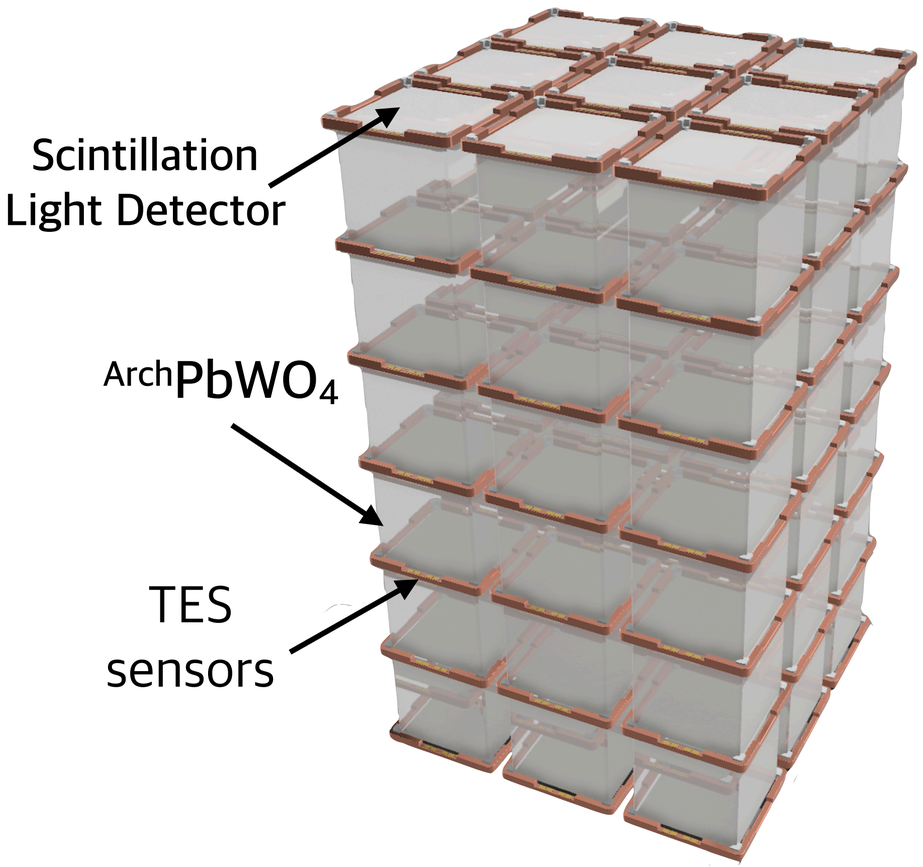
Nuclear recoil threshold – 300 eV ($PbWO_4$ – 20 g)

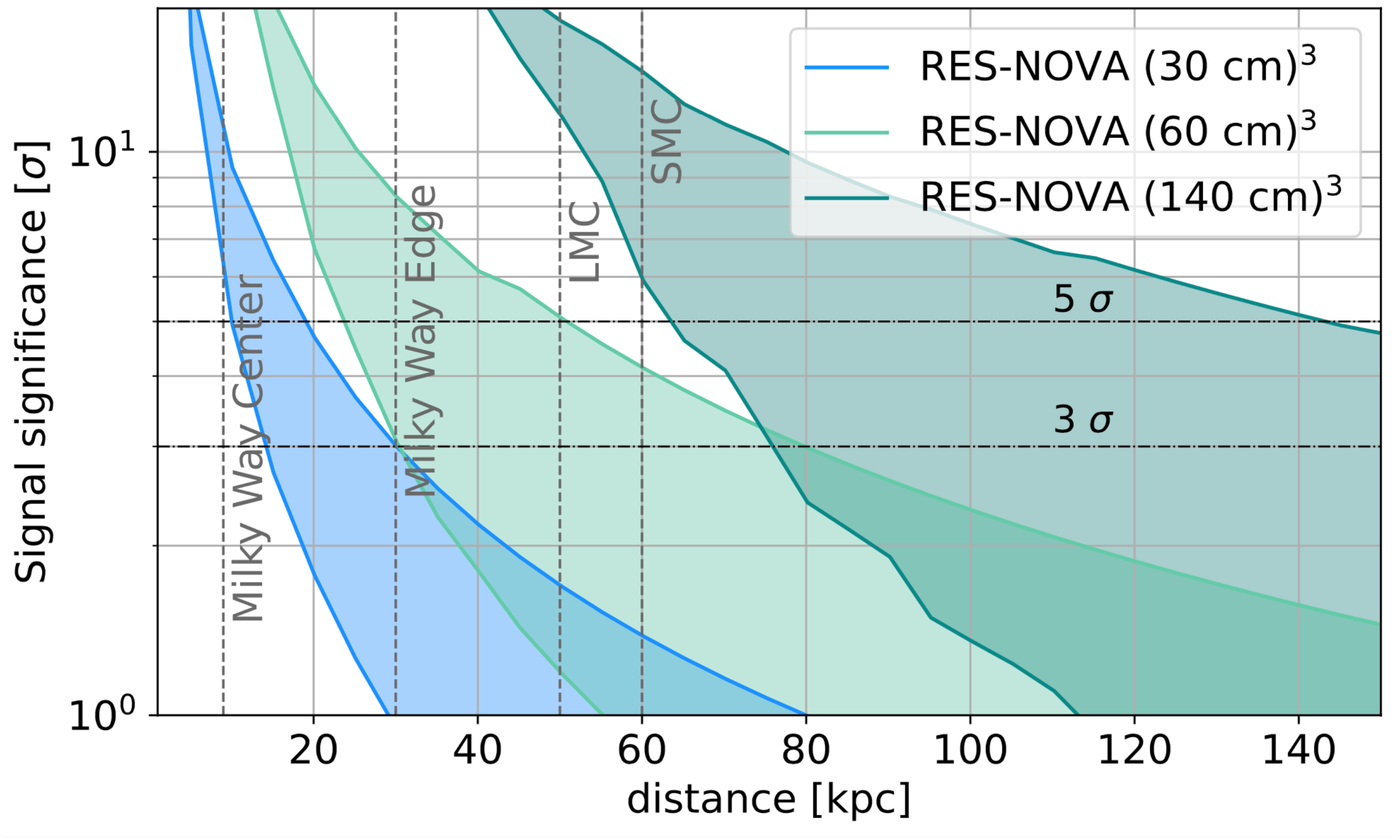
Under ground @ LNGS (IT)

Radiopurity @ μBq/kg scale ($PbWO_4$ – 0.9 kg)

RESNOVA TECHNOLOGY DEMONSTRATOR

Target performance:
Threshold 1 keV
Bkg in RoI 10^{-3} c/keV/ton/s



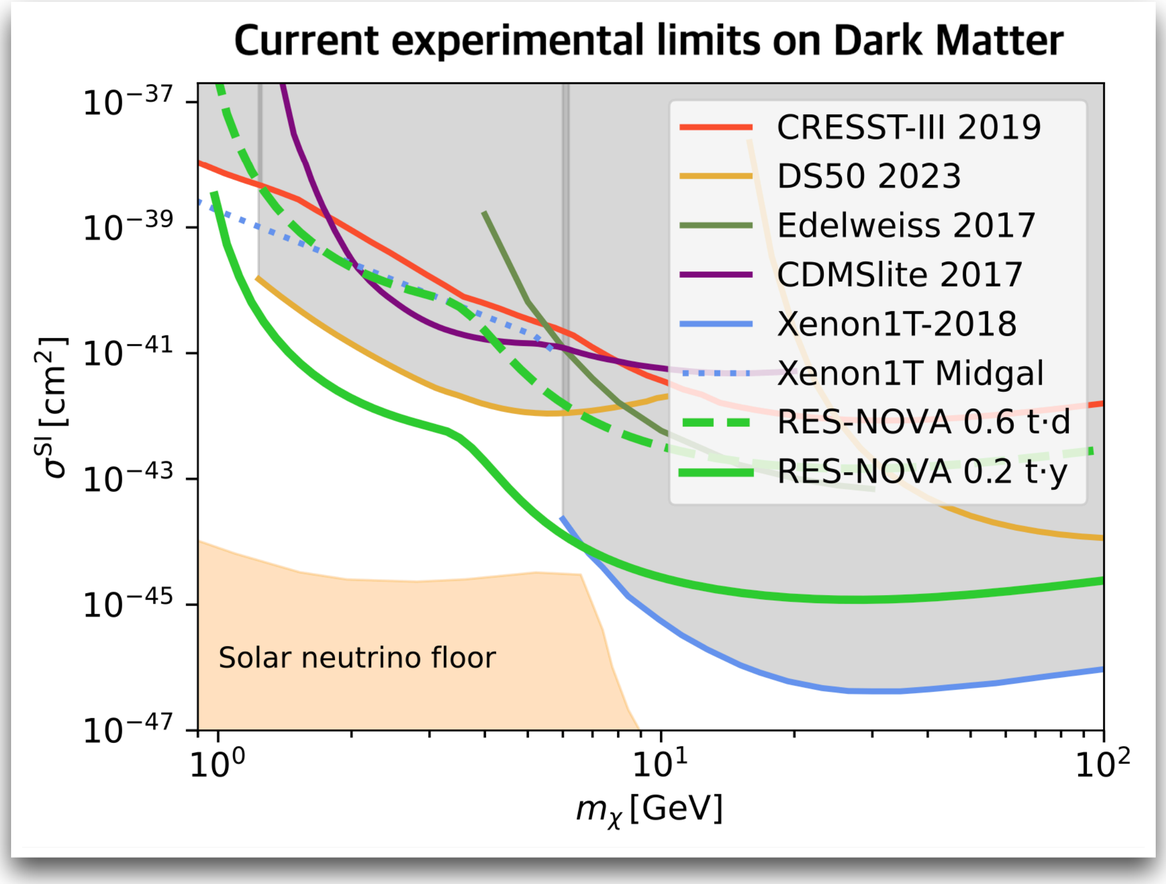


<15 kpc 90% of Galactic SNe are included

L. Pattavina et al., *JCAP* 10 (2021) 064

RES-NOVA produces knowledge

Cross-disciplinary



Secure physics results:

- Direct Dark Matter search
  Physics results during the R&D phase
- Solar neutrino detection
- Solar axion searches
- Neutrino-mass via 2EC decay of ^{180}W

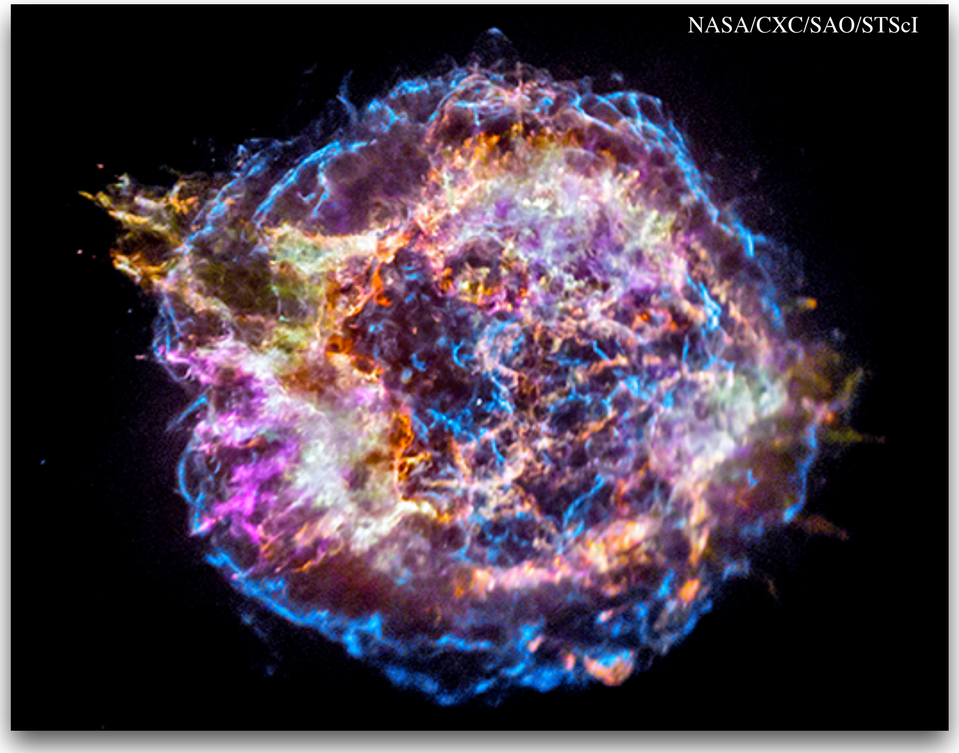
Already big resonance in the community:

- Non-standard neutrino interactions
- Primordial black-holes
- Supermassive black-hole formation
- Neutron skin measurement

[JCAP 11 (2021) 020, New J. Phys. 23 (2021) 031201,
Phys. Rev. D 103 (2021) 083002, JCAP 08 (2021) 019, Phys. Rev.D 106 (2022) 12,
123034, Nucl. Phys.B 977 (2022) 115737, Phys. Lett.B 829 (2022) 137050]

Are we ready for the next SN ?

- SN1987A neutrinos took 160,000 y to reach our detectors
- In 2022 the most advanced EU neutrino detector went off-line



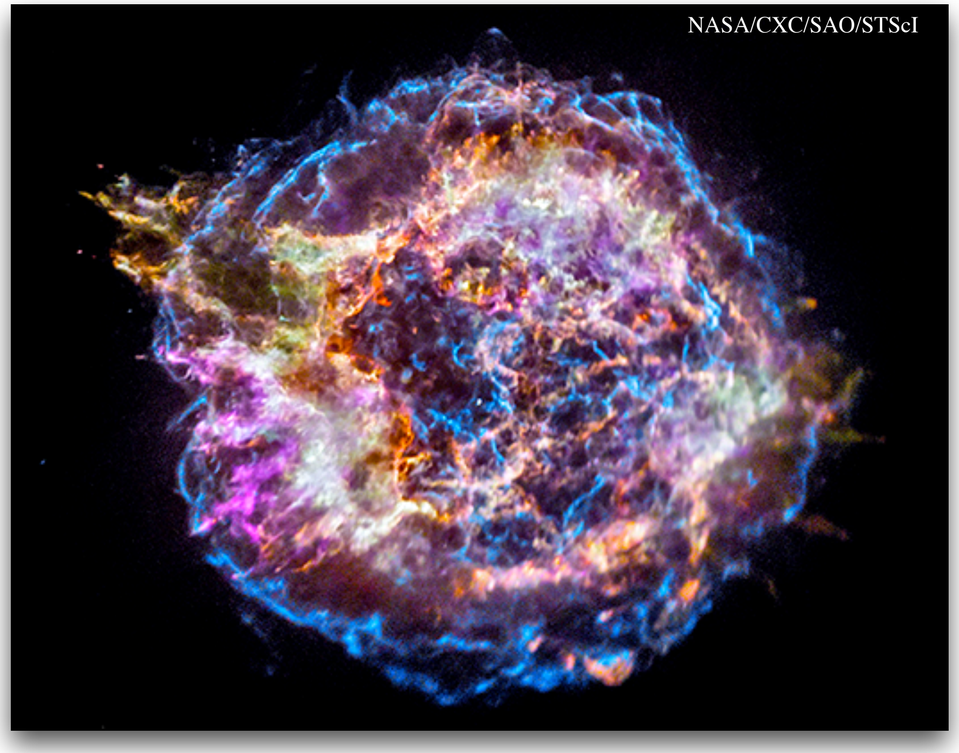
Are we ready for the next SN ?

Timeliness
A unique window of opportunity for a new technology

Experimental approach
Multi-disciplinarity

Feasibility
Proof of principle detectors gave promising results

RES-NOVA demo is funded
Long-term science program on neutrino physics



Back-up slides