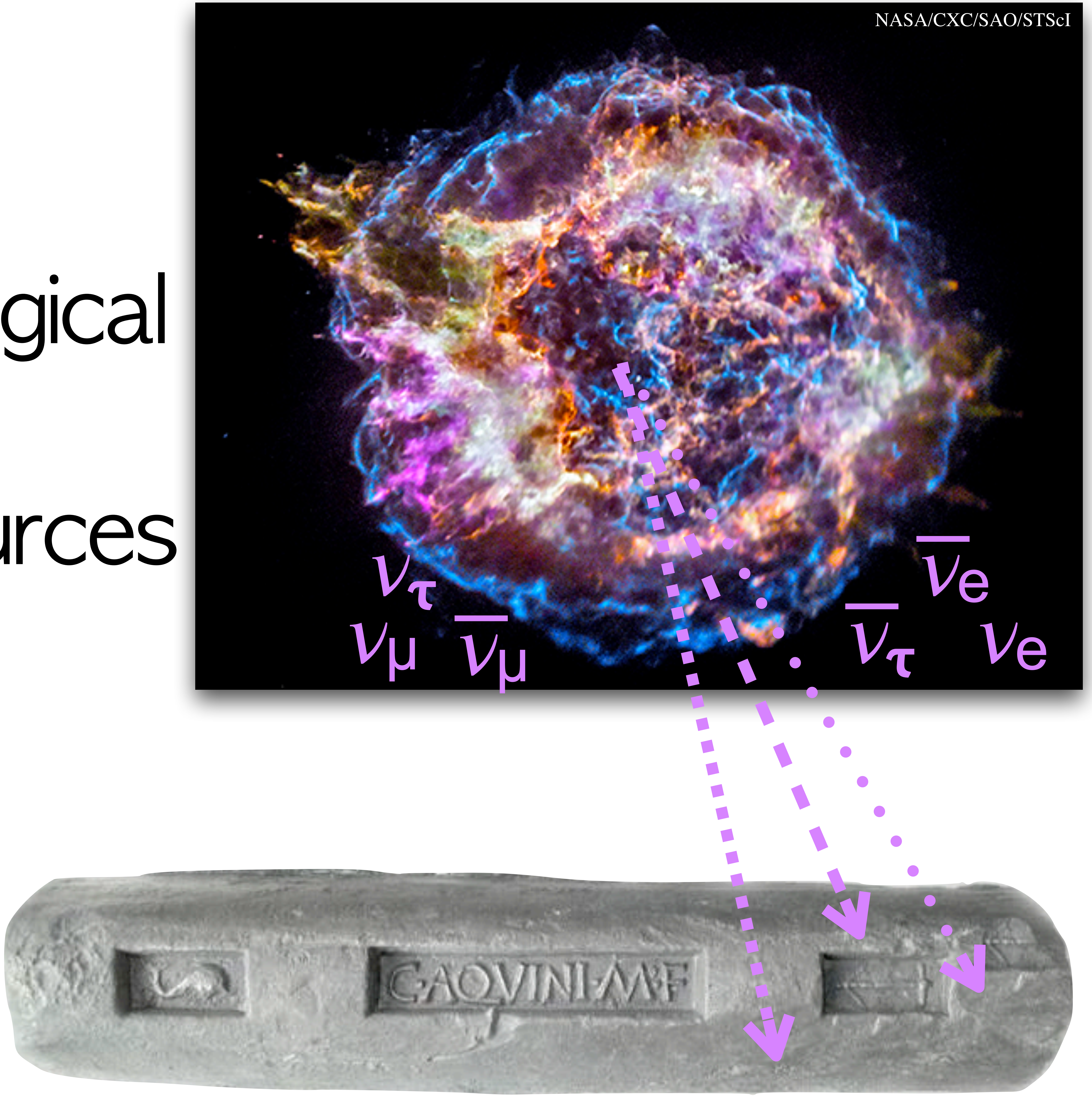
RES-NOVA:
A revolutionary archaeological Pb observatory for astrophysical neutrino sources



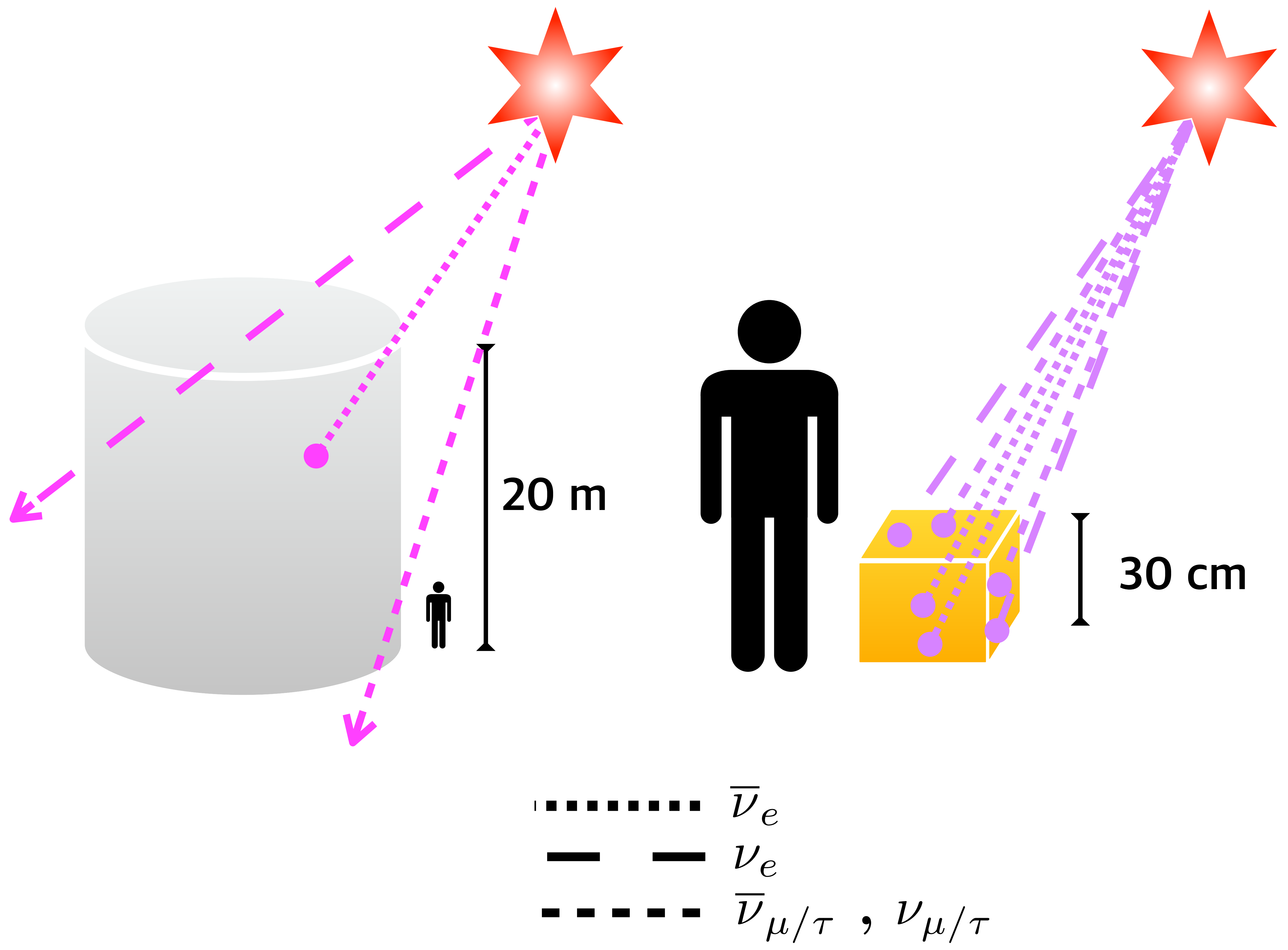
Luca Pattavina
INFN - Laboratori Nazionali del Gran Sasso
Technical University of Munich

29.05.2023 | SNvD 2023 @ LNGS

RES-NOVA IN ONE SLIDE

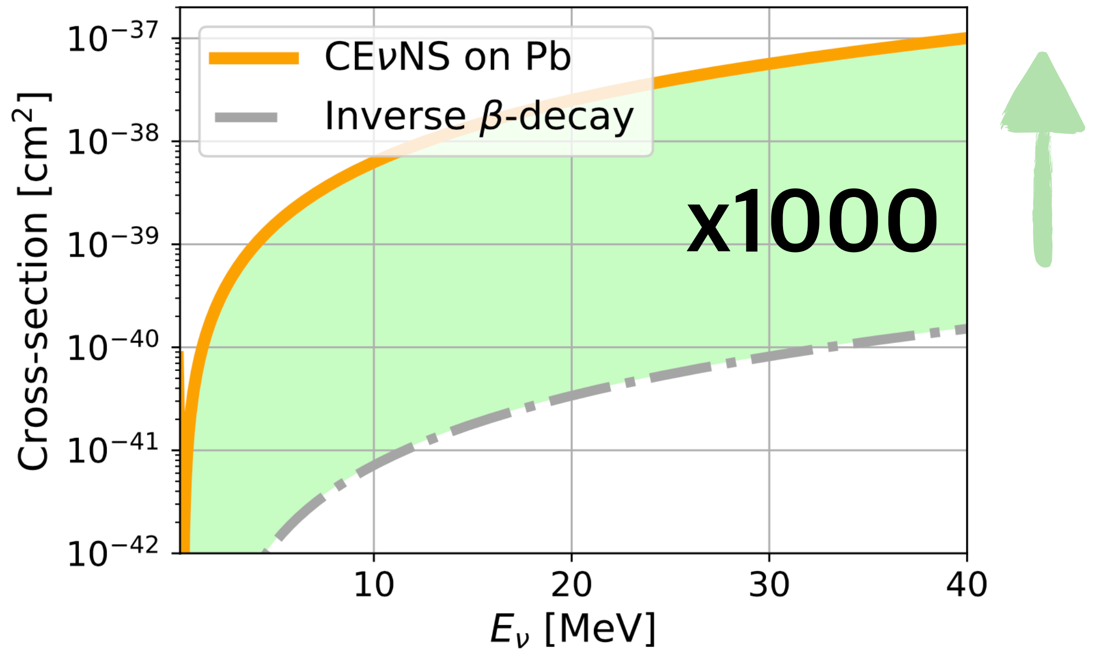
Detecting SuperNova neutrinos

1 SN / 50 years



using an innovative technology for <u>high-statistic</u> and <u>flavor independent</u> 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

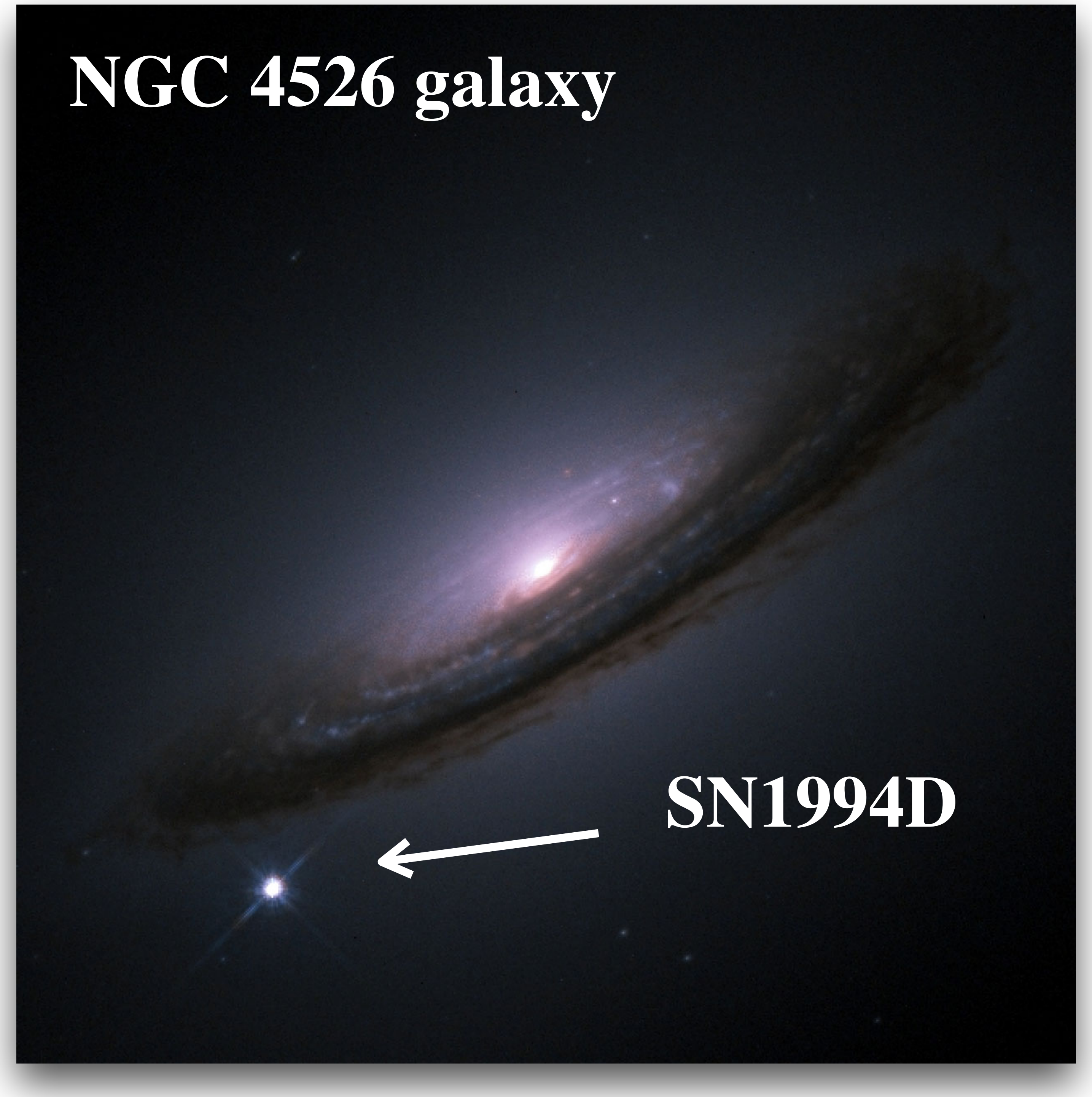
SETTING THE STAGE

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 observation** with underground instrumentation (1987)

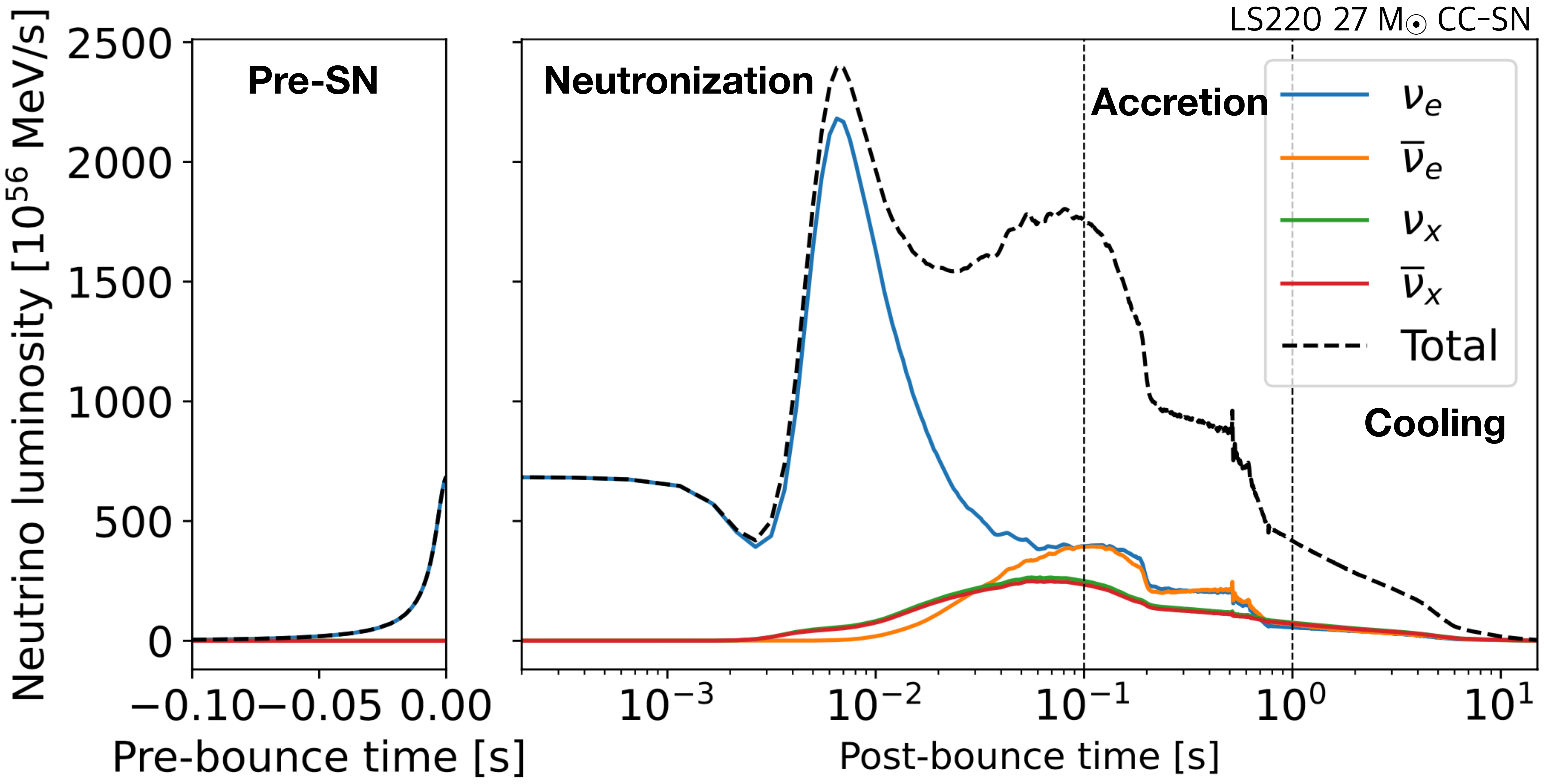


Credit: NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team

NEUTRINOS ARE EMITTED AT ALL TIMES

UNIQUE NEUTRINO SIGNATURE

Neutrino transport simulation of a Core-Collapse SN



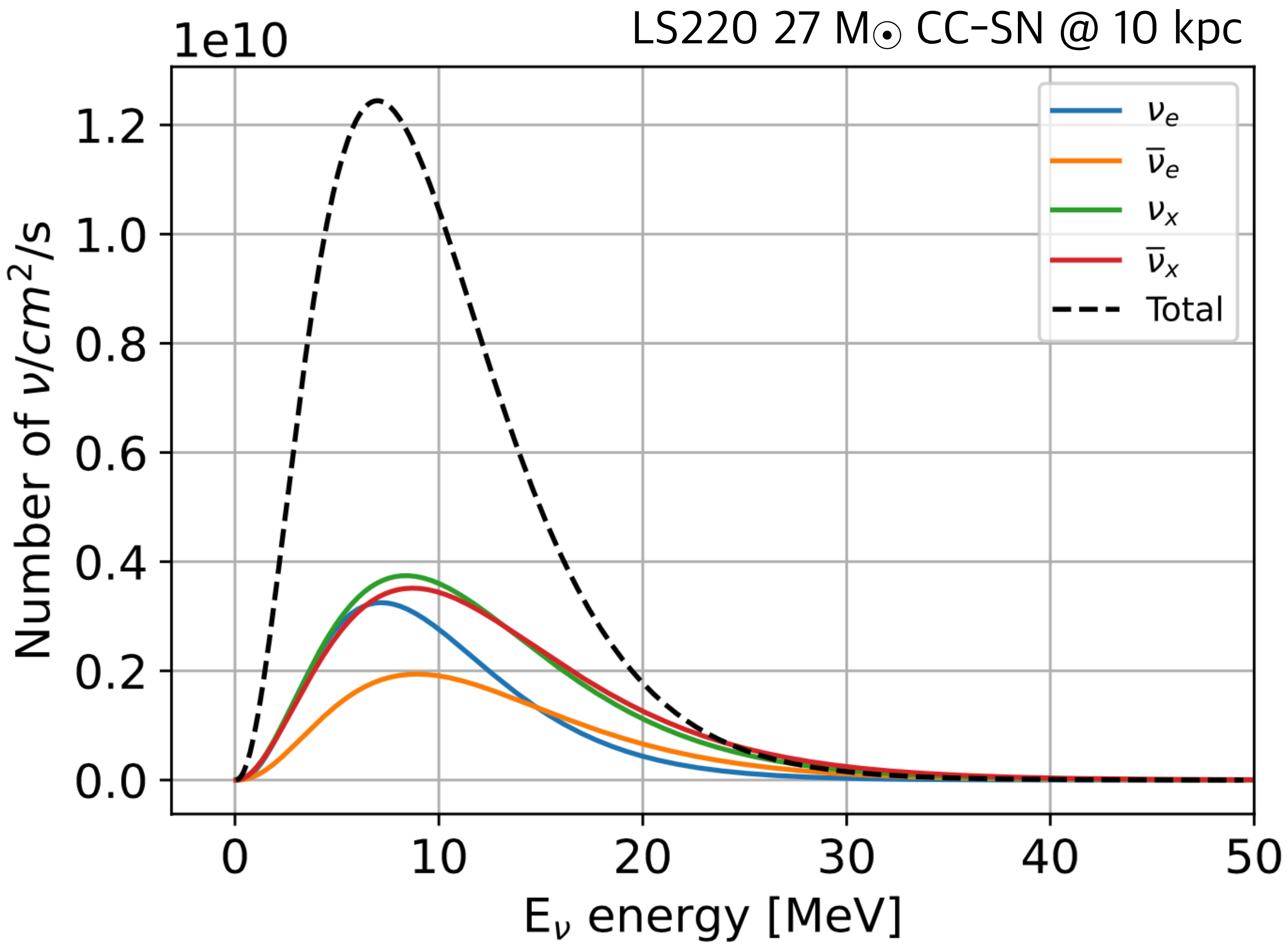
A. Mirizzi et al., Riv. Nuovo Cim.39, 1 (2016) [ArXiv:1508.00785]

Nota Bene: neutrino flavor oscillations not included

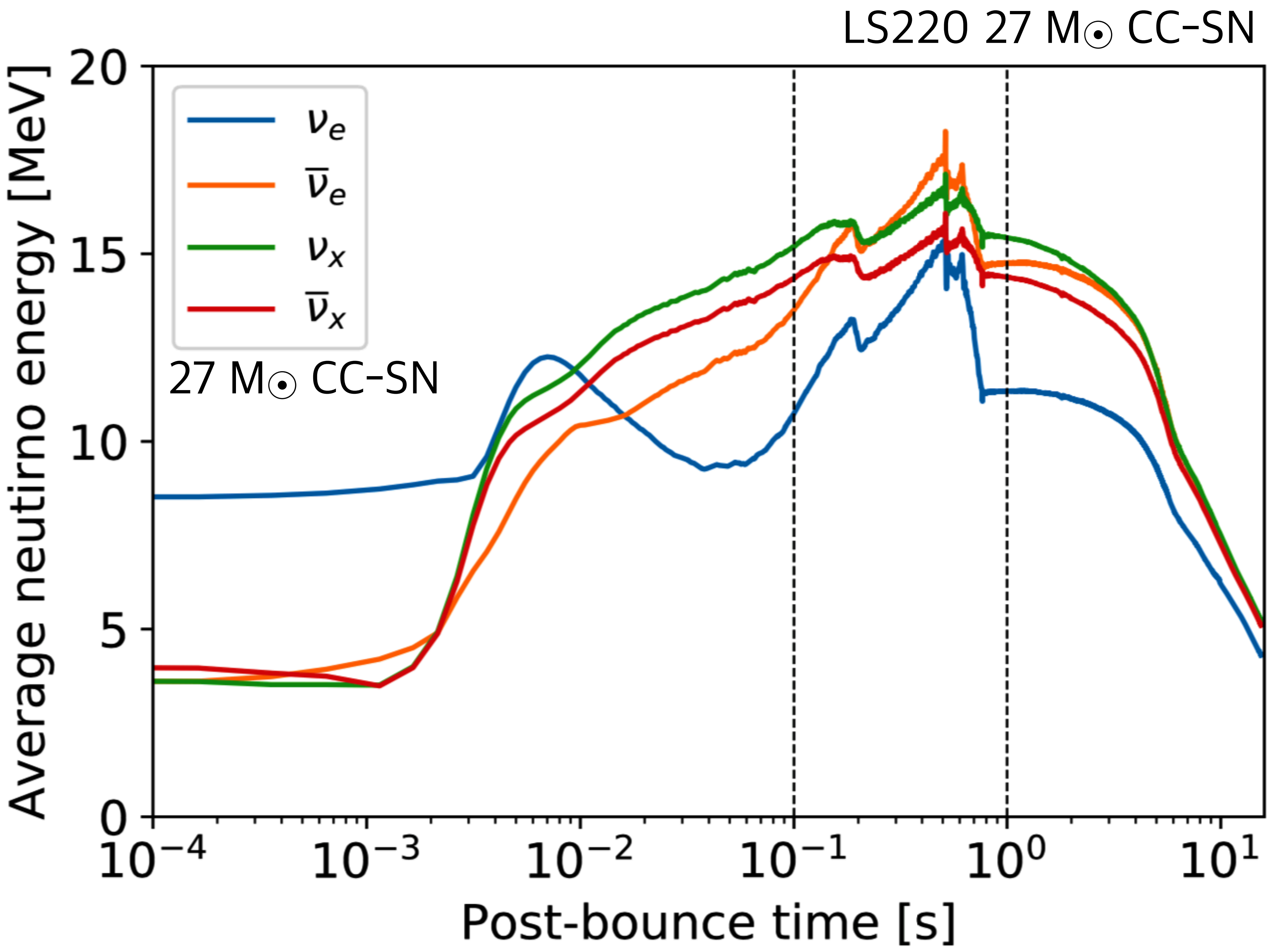
MPA Supernova Archive:
https://wwwmpa.mpa-garching.mpg.de/ccsnarchive

SUPERNOVA NEUTRINO SIGNAL

WHAT IS THE AVERAGE NEUTRINO ENERGY?



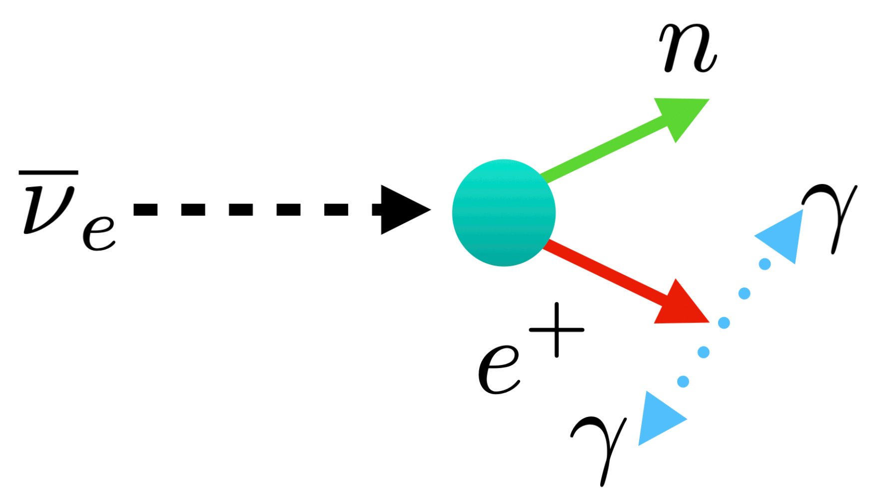
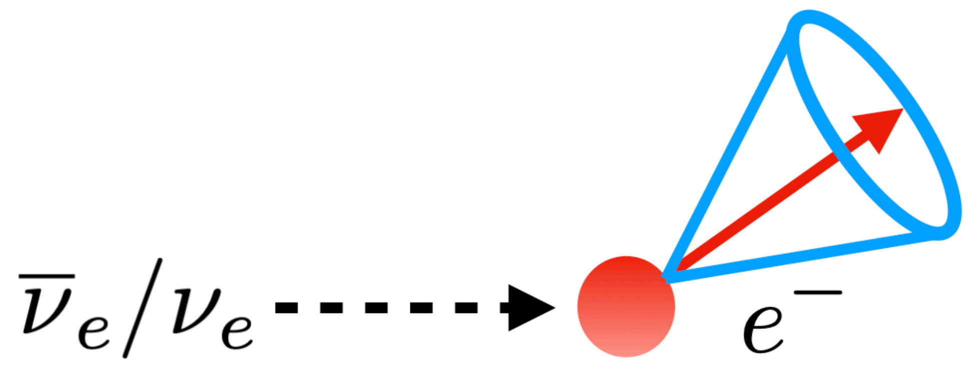
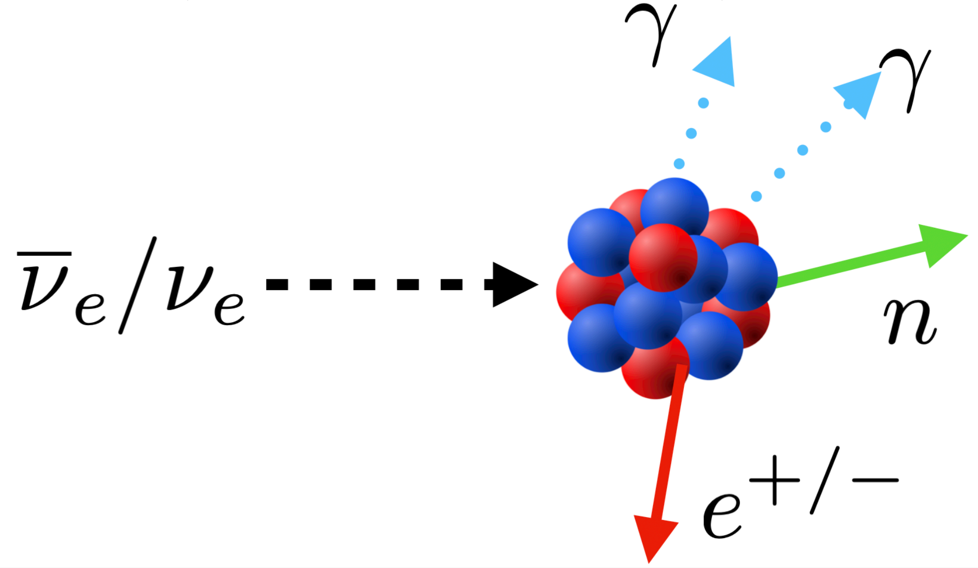
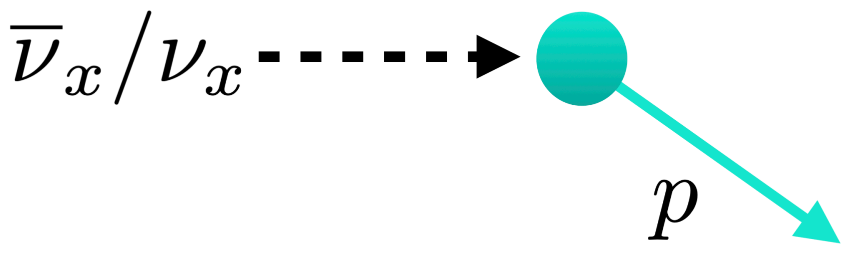
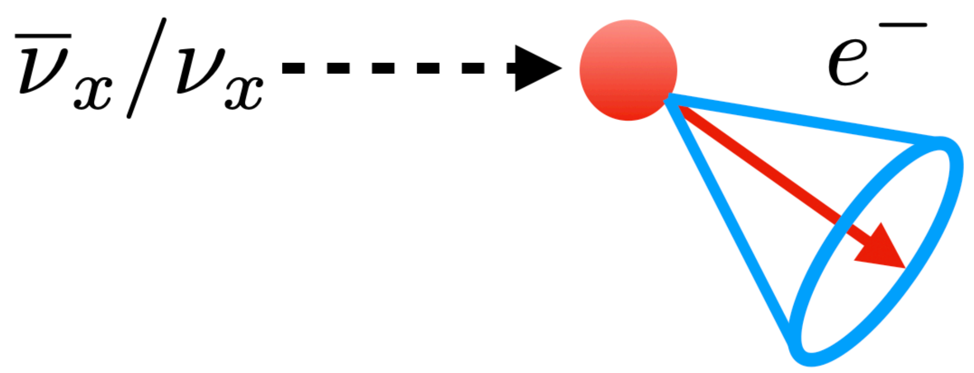
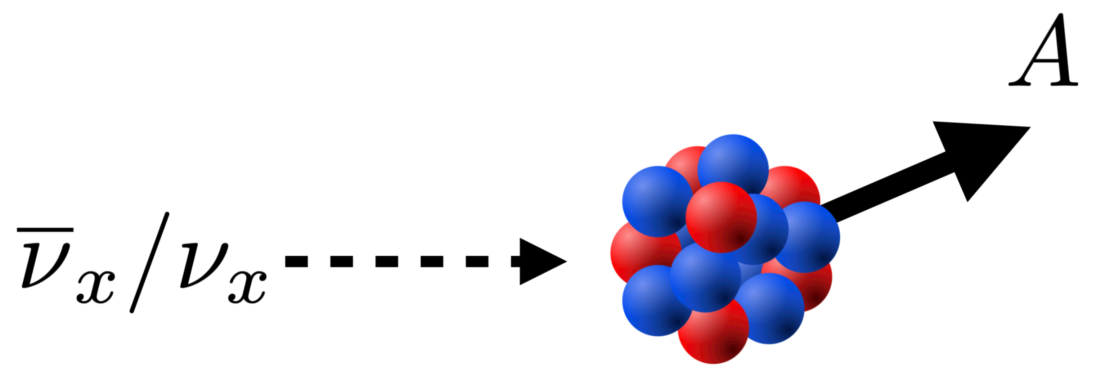
ν_x is the most **intense** component of the flux



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

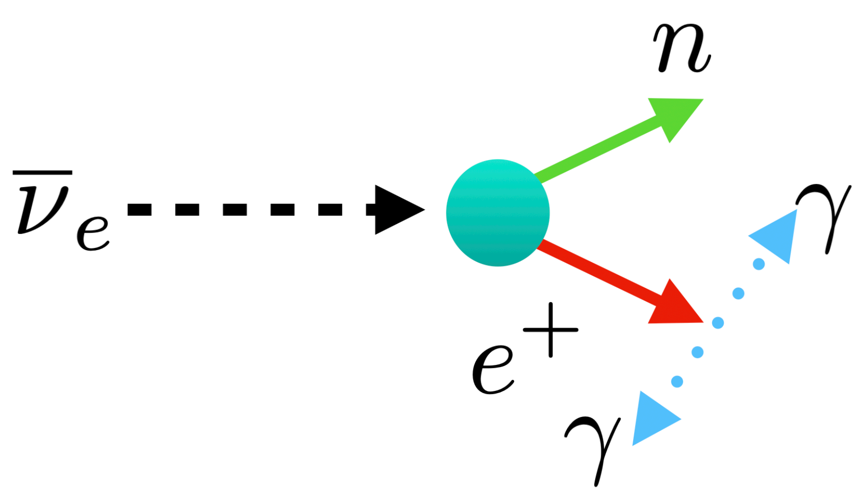
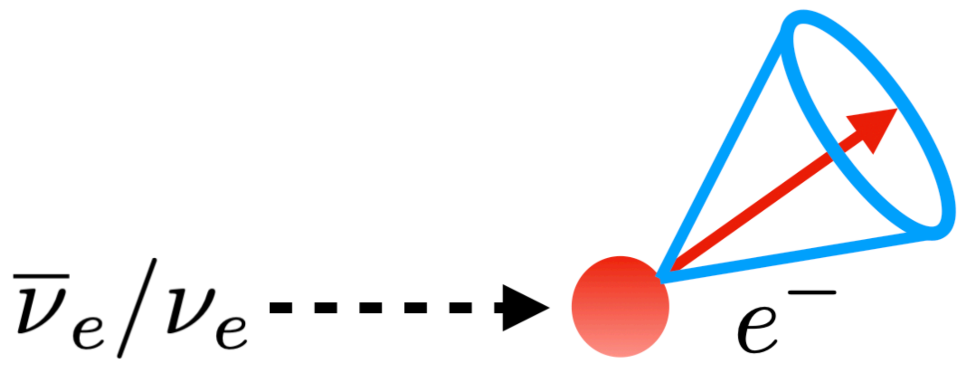
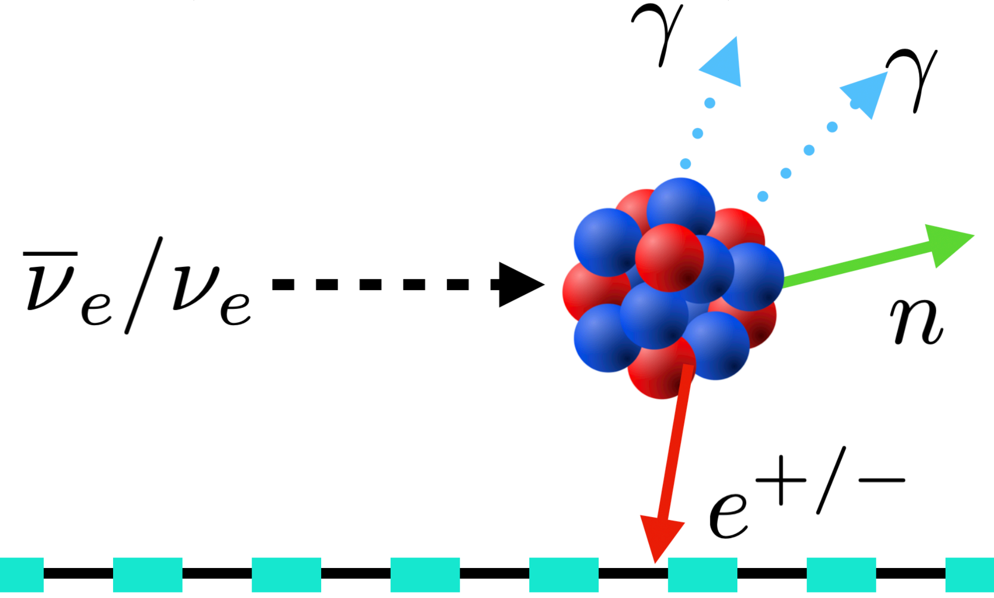
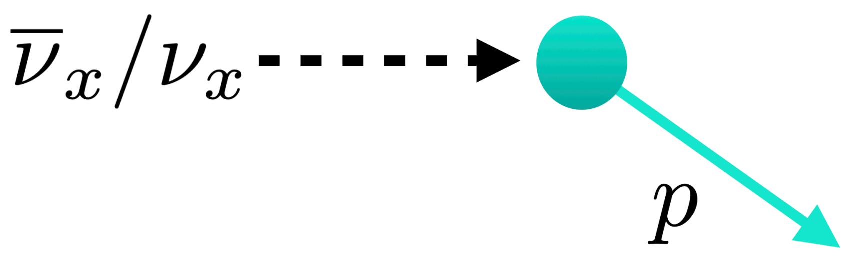
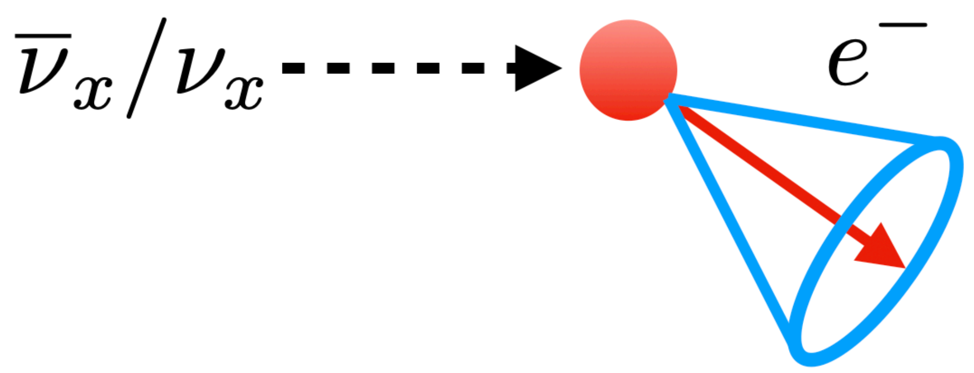
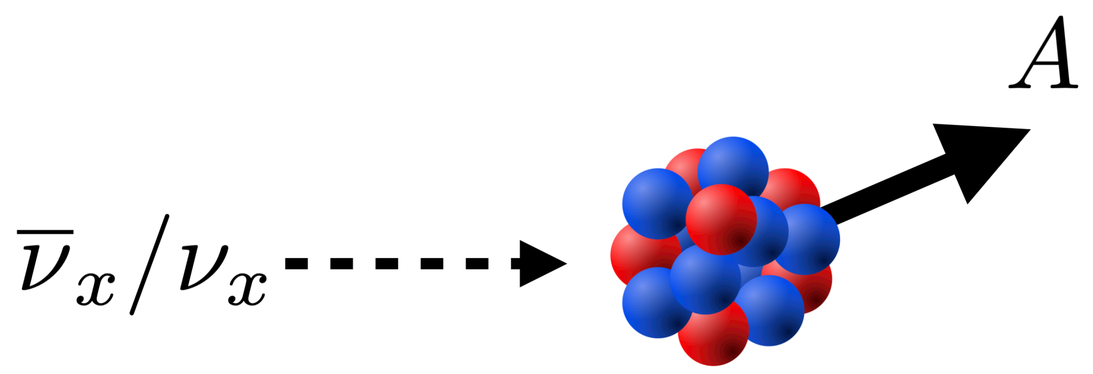
Current SN neutrino detectors are mostly sensitive to anti-ν_e/ν_e

HOW DO WE DETECT SN NEUTRINOS NOWADAYS?

	PROTONS	ELECTRONS	NUCLEI
CHARGE CURRENT	**Inverse beta decay** $\overline{\nu}_e + p \to e^+ + n$ 	**Elastic scattering** $\nu + e^- \to \nu + e^-$ 	**Inelastic scattering** $\nu_e/\overline{\nu}_e + (N,Z) \to e^{-/+} + (N \mp 1, Z \pm 1)$ 
NEUTRAL CURRENT	**Elastic scattering** $\overline{\nu}_x/\nu_x + p \to \overline{\nu}_x/\nu_x + p$ 		**Coherent Elastic neutrino-nucleus scattering (CEvNS)** $\overline{\nu}_x/\nu_x + A \to \overline{\nu}_x/\nu_x + A$ 

From 1987 to nowadays

HOW DO WE DETECT SN NEUTRINOS NOWADAYS?

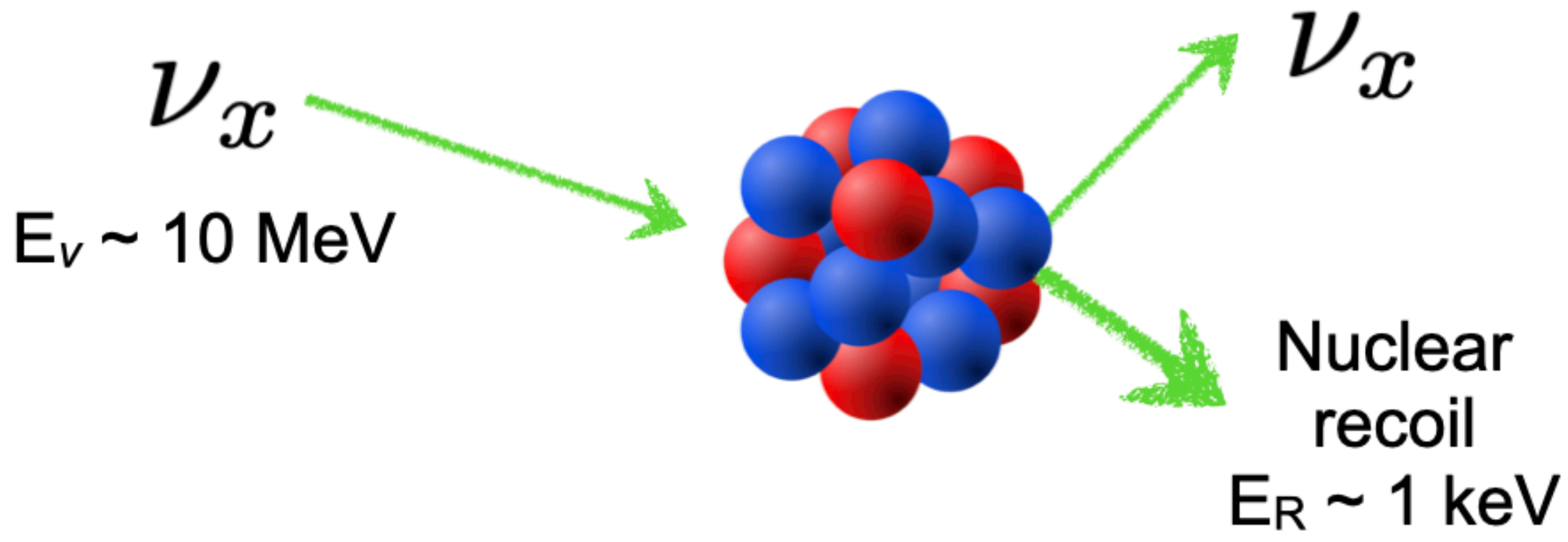
	PROTONS	ELECTRONS	NUCLEI
CHARGE CURRENT	**Inverse beta decay** $\overline{\nu}_e + p \to e^+ + n$ 	**Elastic scattering** $\nu + e^- \to \nu + e^-$ 	**Inelastic scattering** $\nu_e/\overline{\nu}_e + (N, Z) \to e^{-/+} + (N \mp 1, Z \pm 1)$ 
NEUTRAL CURRENT	**Elastic scattering** $\overline{\nu}_x/\nu_x + p \to \overline{\nu}_x/\nu_x + p$ 		**Coherent Elastic neutrino-nucleus scattering (CEvNS)** $\overline{\nu}_x/\nu_x + A \to \overline{\nu}_x/\nu_x + A$ 

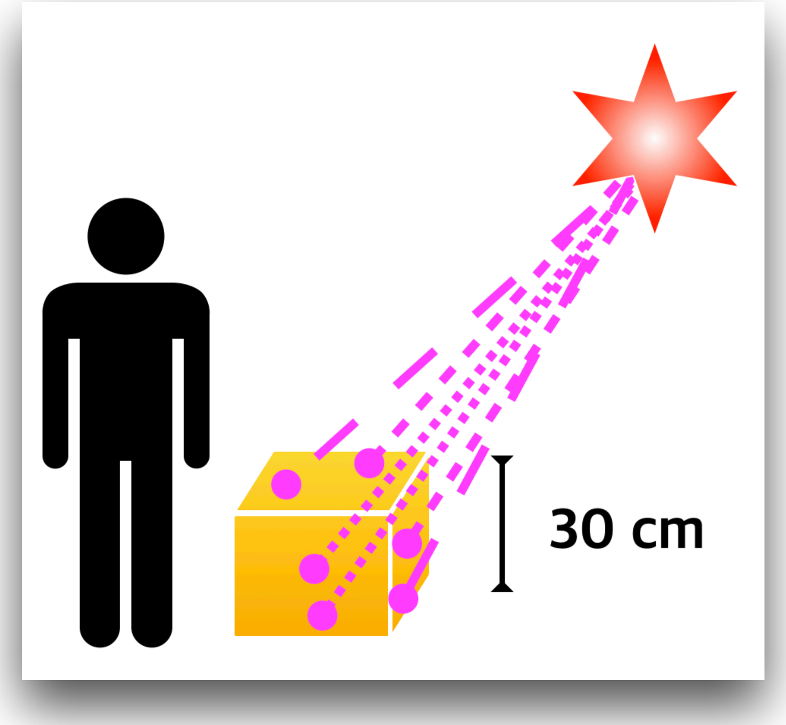
Since 2017

COHERENT Coll., *Science* 357 (2017) 6356, 1123

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

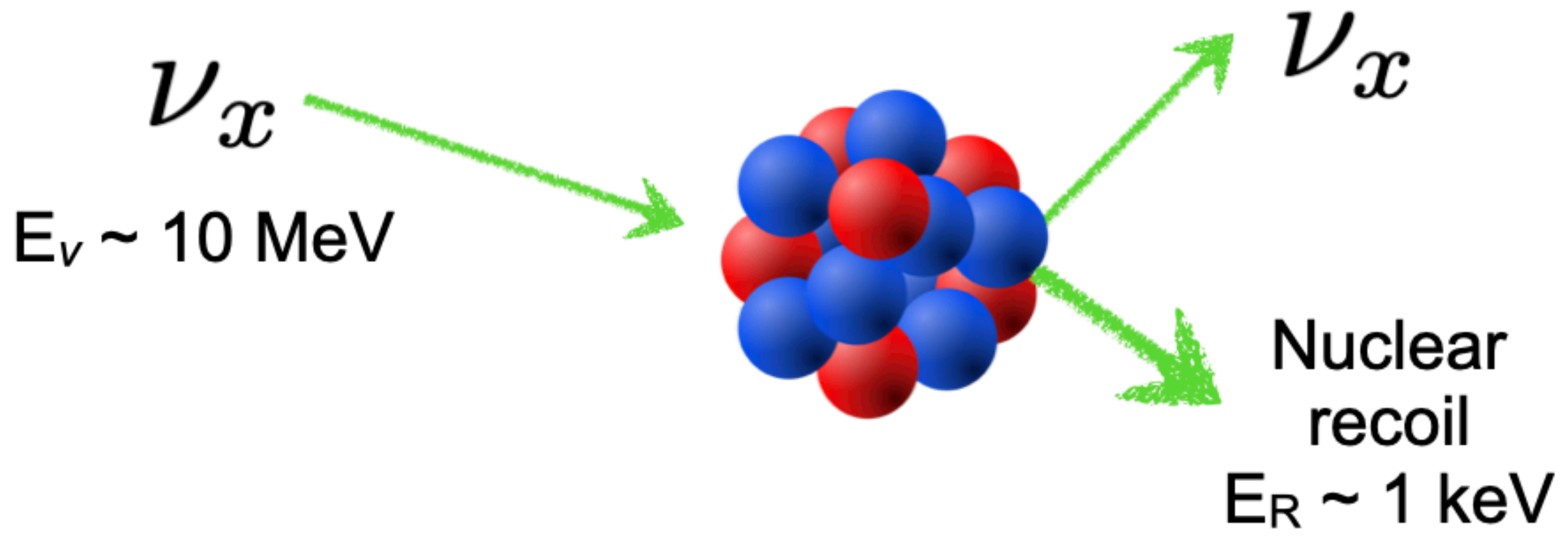
Nuclear Form factor

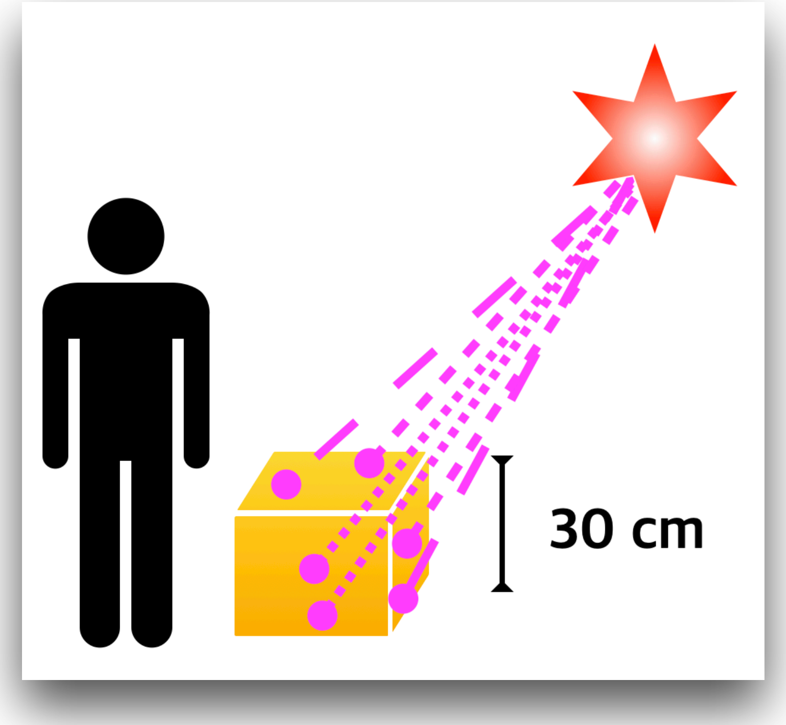
Neutrino energy

Weak nuclear charge

ALL NEUTRINO FLAVORS ARE DETECTED

COHERENT NEUTRINO-NUCLEUS SCATTERING





> Equally sensitive to all ν-flavors

> High interaction cross-section

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

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

cross-section

Nuclear Form factor

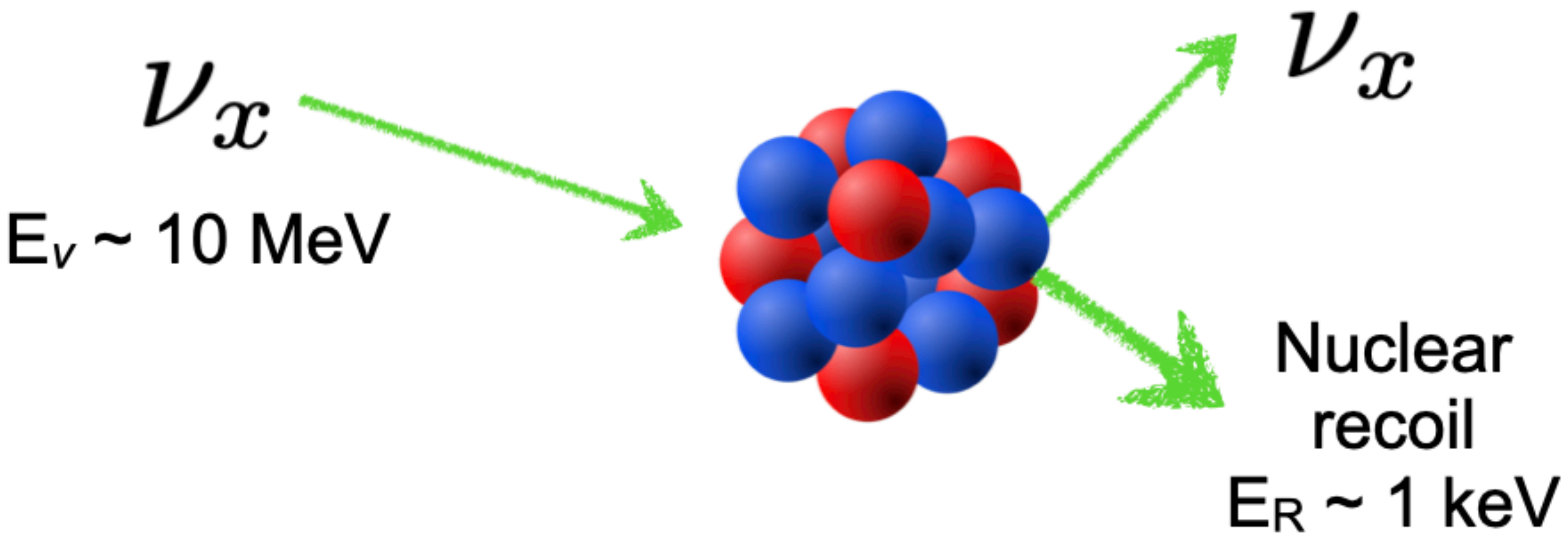
Neutrino energy

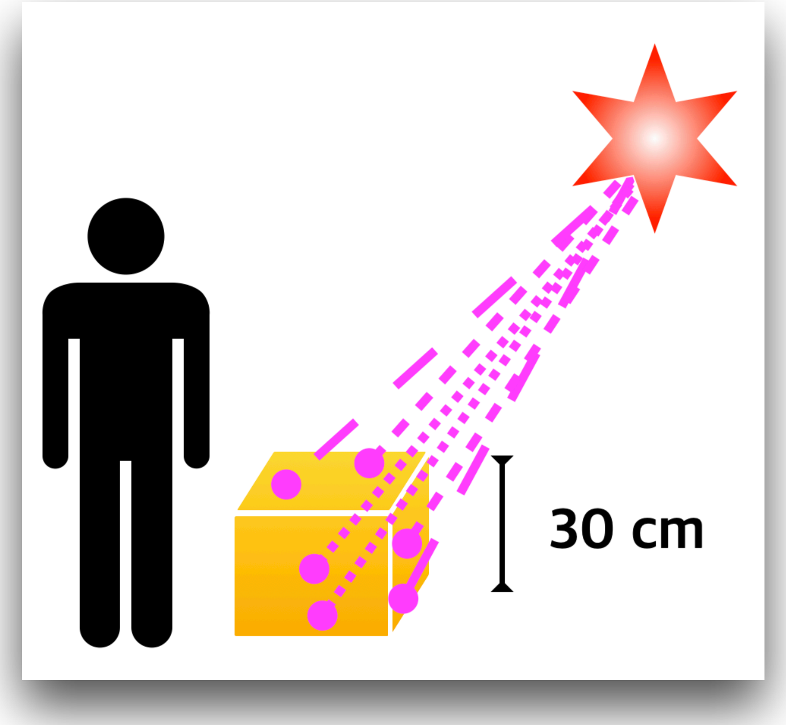
Weak nuclear charge

* 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

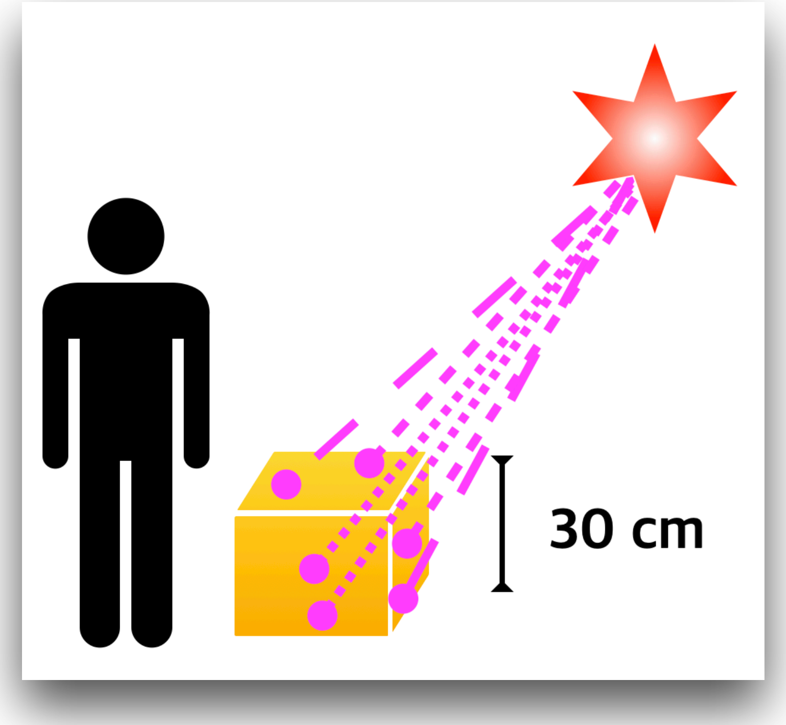
ALL NEUTRINO FLAVORS ARE DETECTED

COHERENT NEUTRINO-NUCLEUS SCATTERING

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

cross-section

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

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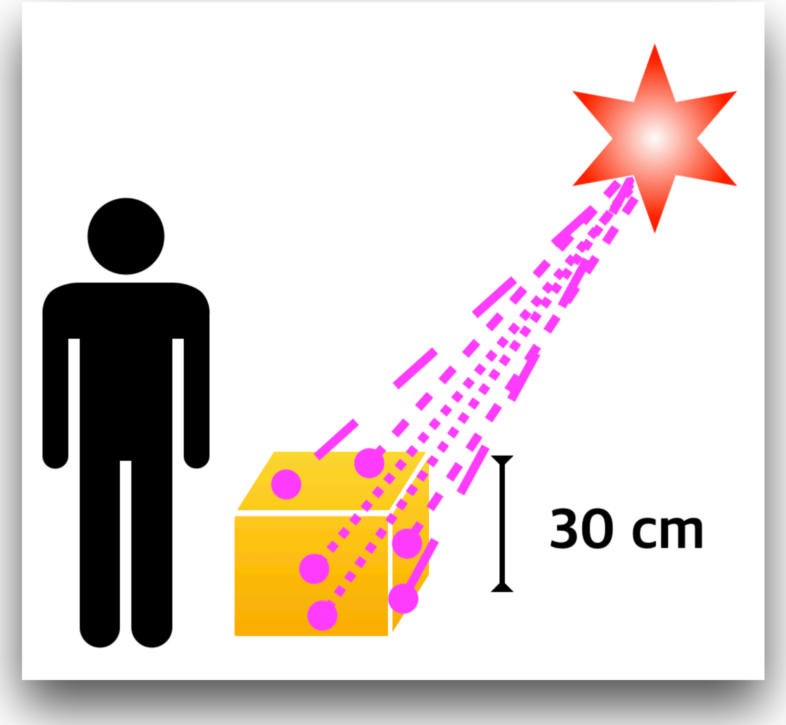
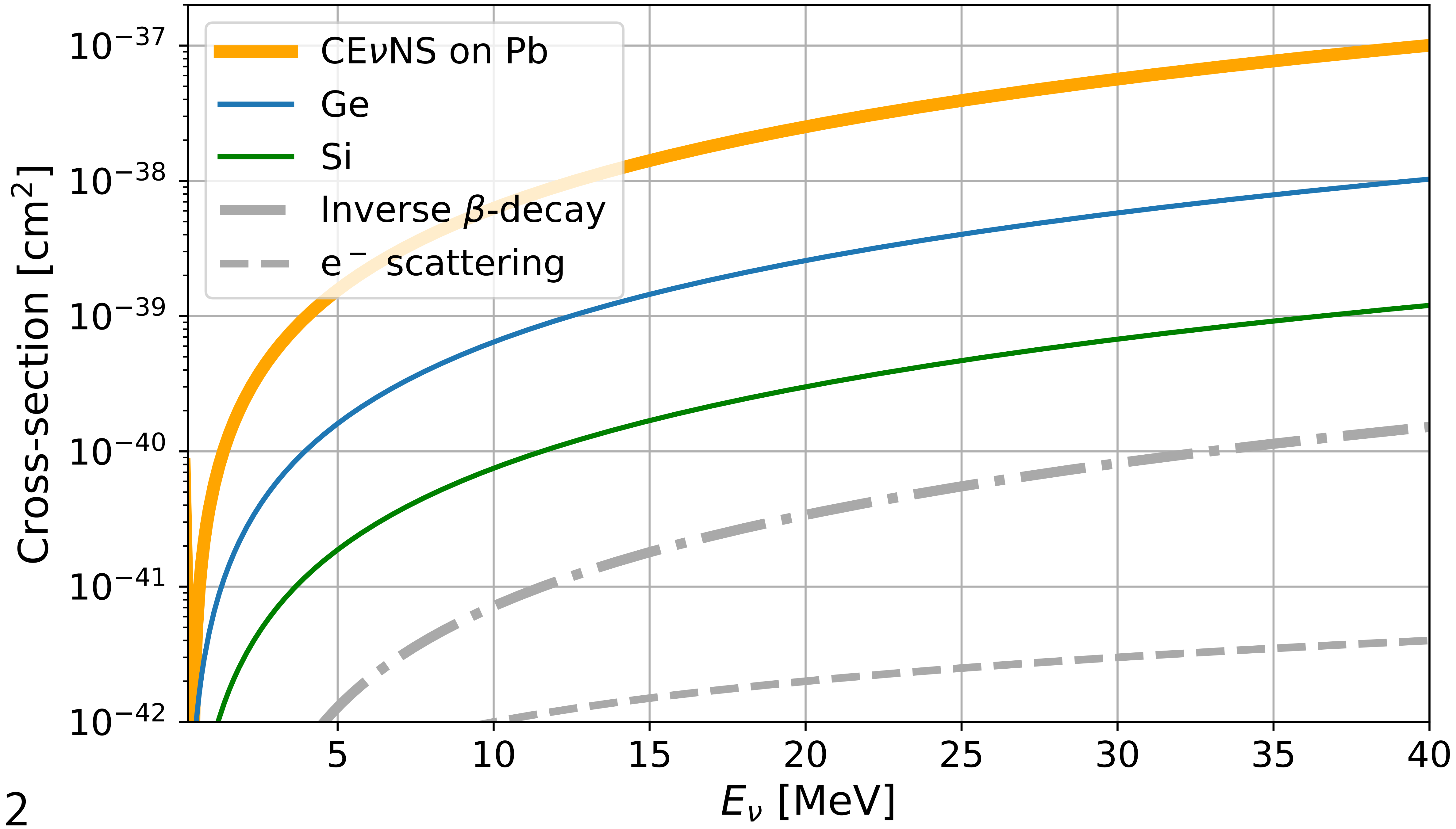




All neutrino flavors are detected

Coherent neutrino-nucleus scattering

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

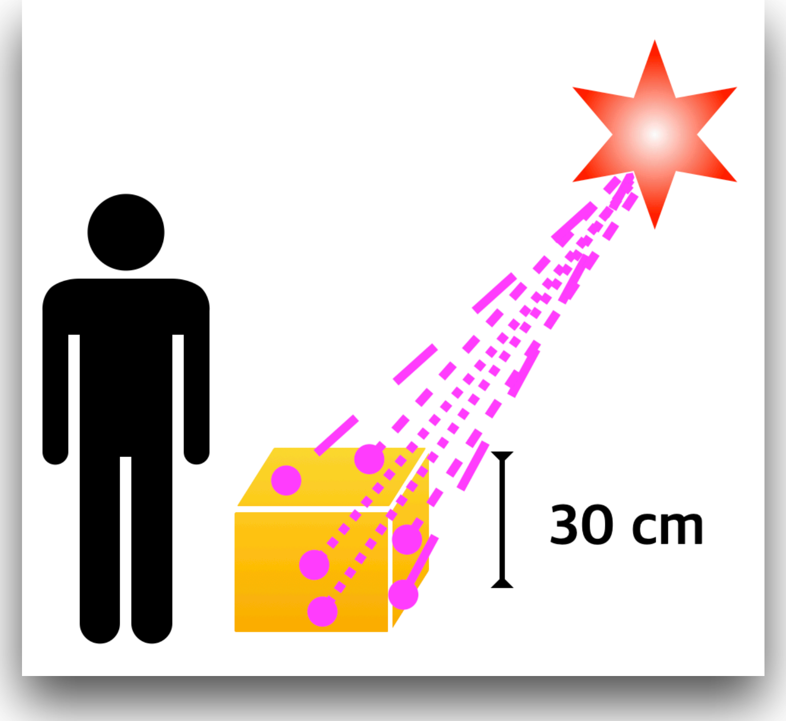
cross-section

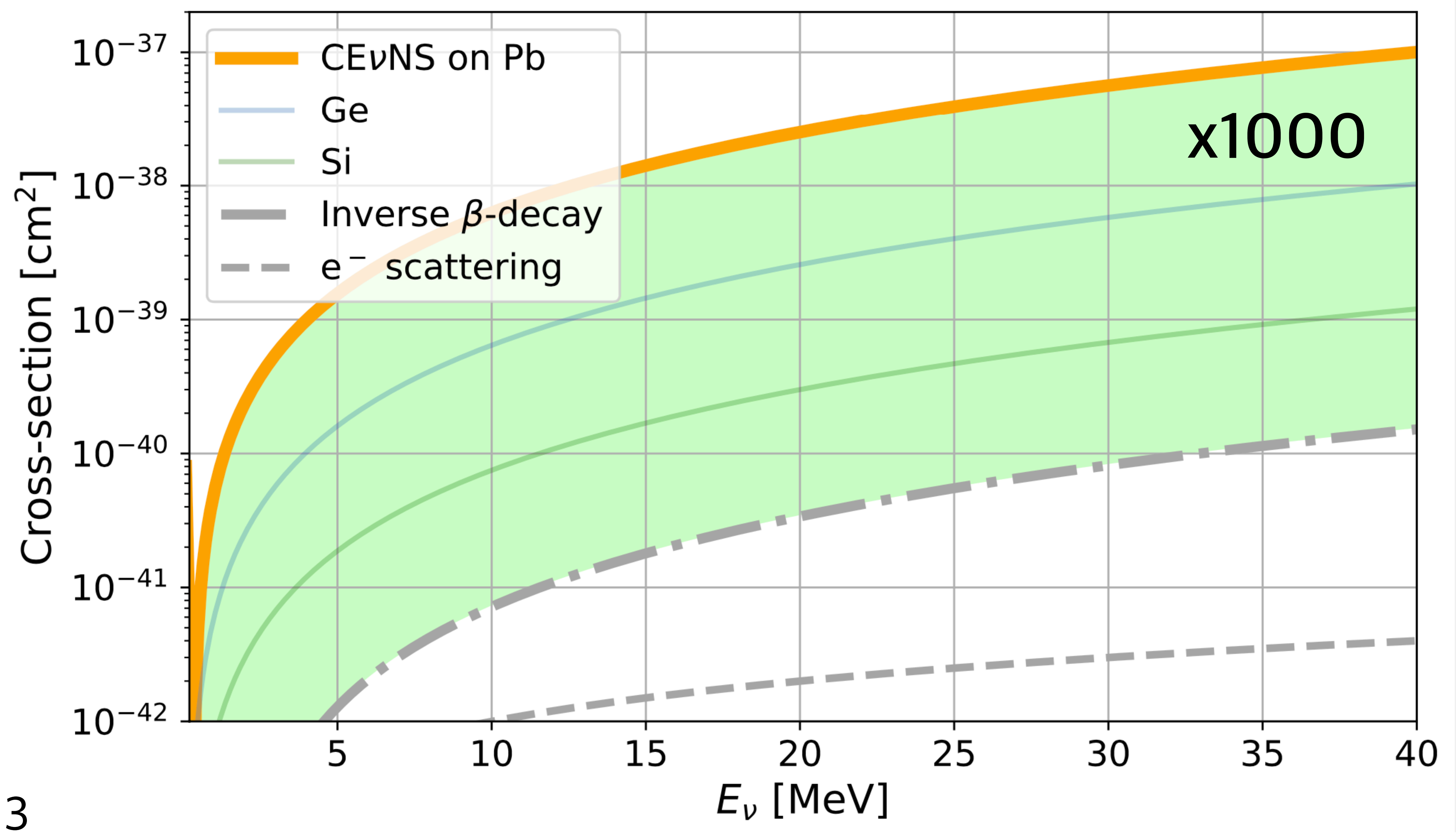
Neutron number

Pb ideal target

Highest neutron number

Highest nuclear stability





ALL NEUTRINO FLAVORS ARE DETECTED

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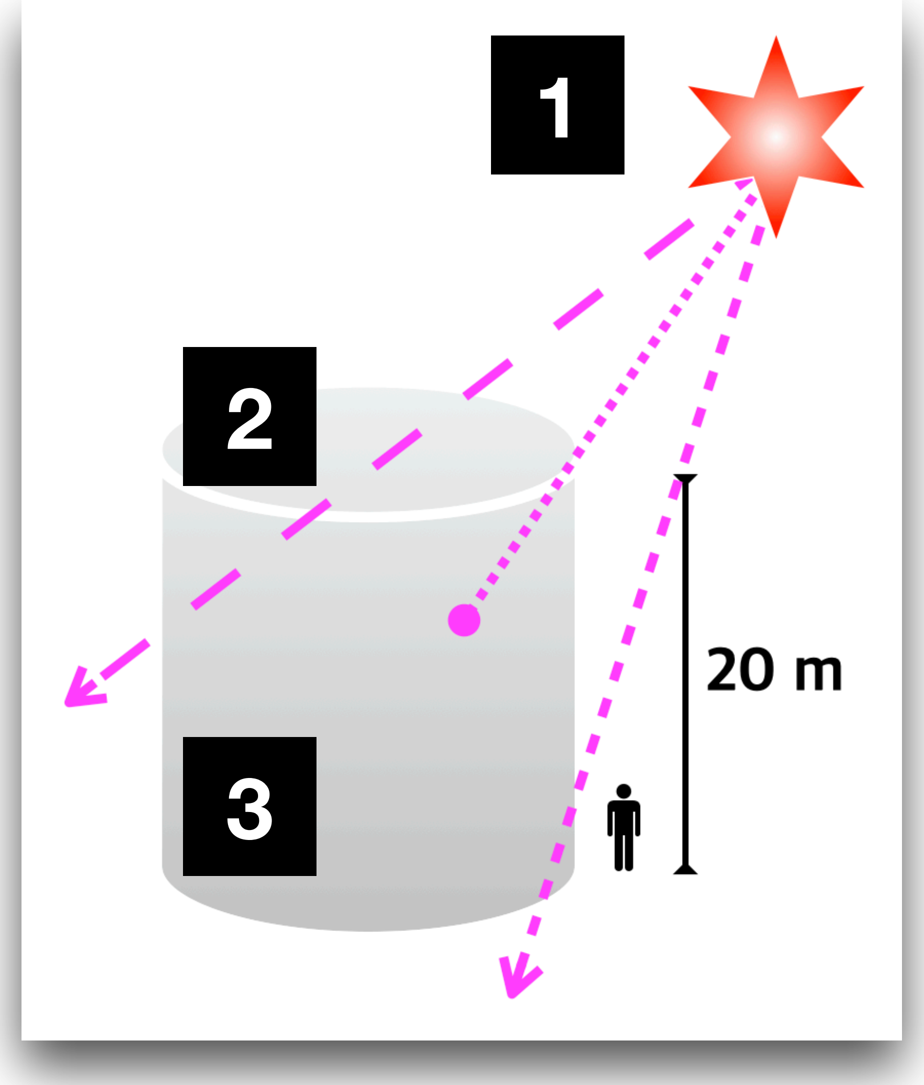


N^2

Neutron number

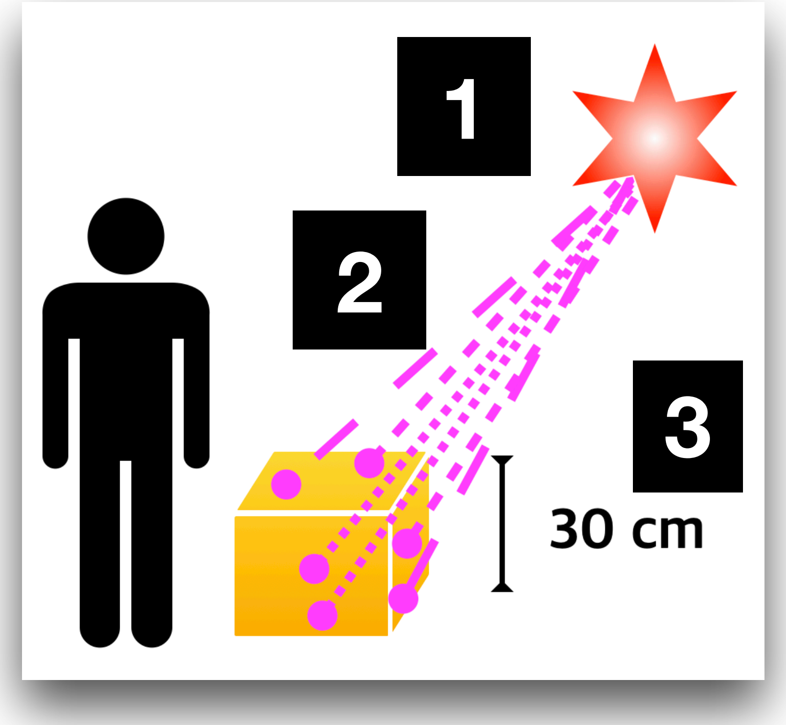
Status quo:

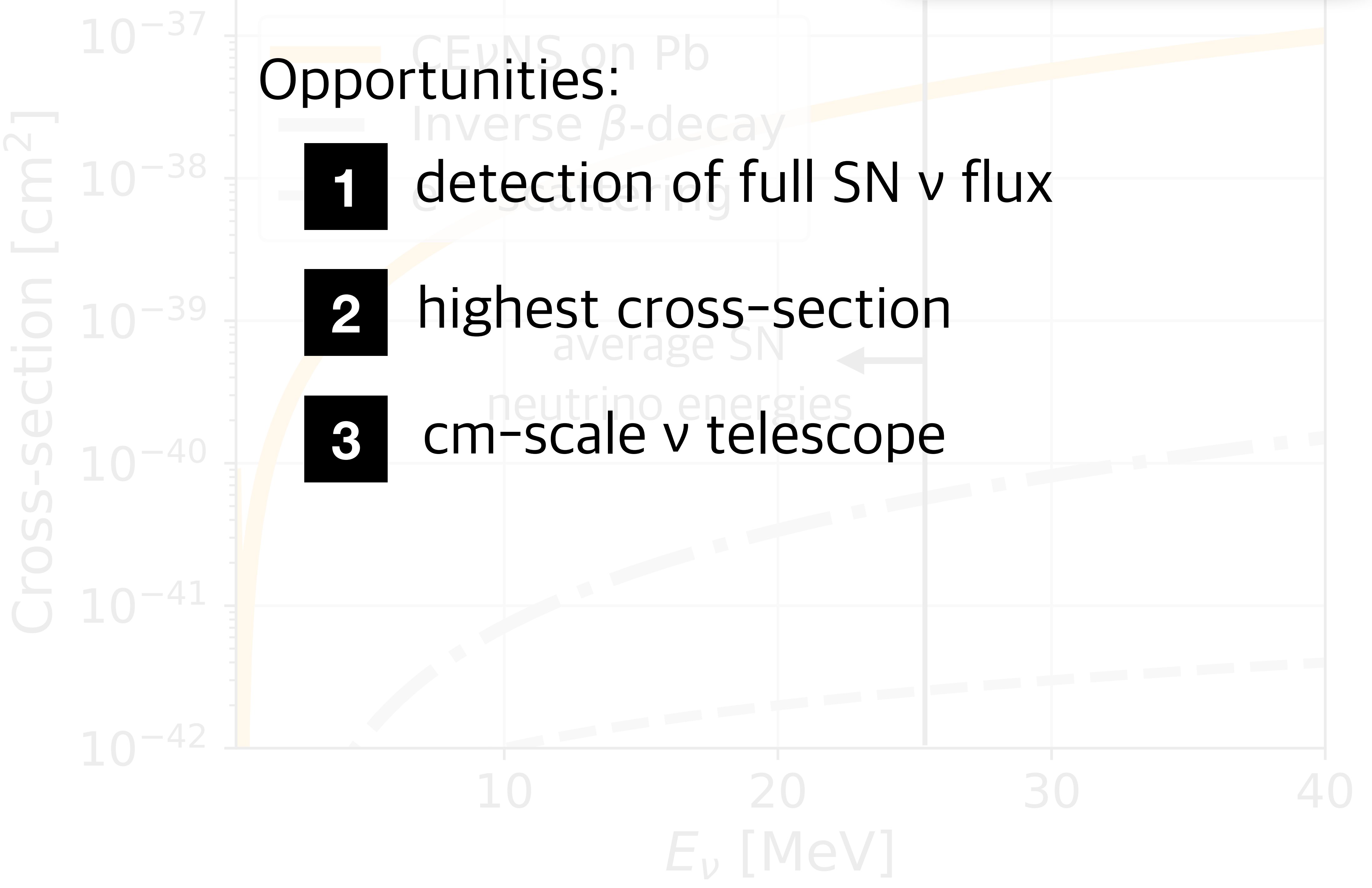
- **1** detection of ~1/6 SN flux
- **2** small cross-section
- **3** large volume detectors

Pb ideal target

Highest neutron number

Highest nuclear stability





Opportunities:

- **1** detection of full SN ν flux
- **2** highest cross-section
- **3** cm-scale ν telescope

RES-NOVA gives unique insights into SNe

Innovative experimental approach

Detection channel

Coherent neutrino-nucleus scattering

Technology

Cryogenic detectors

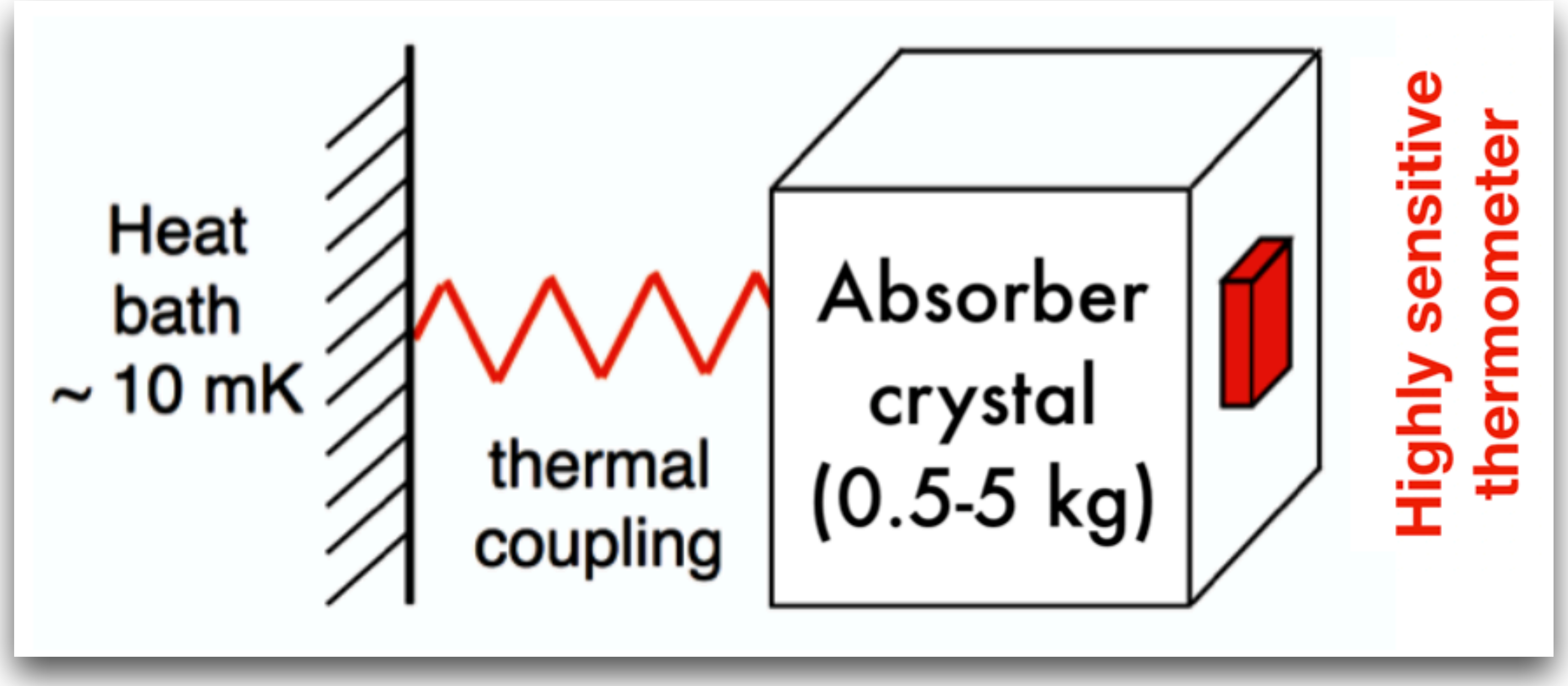
Target material

$PbWO_4$ from archaeological-Pb

RES-NOVA DETECTOR TECHNOLOGY

ADVANCED CRYOGENIC DETECTORS

Cryogenic calorimeters made from Pb



- ↑ Wide choice of compounds
- ↑ Easily scalable technology (modularity)
- ↑ Excellent energy resolution/threshold

- ⬇ Fully active detectors ➔ low bkg

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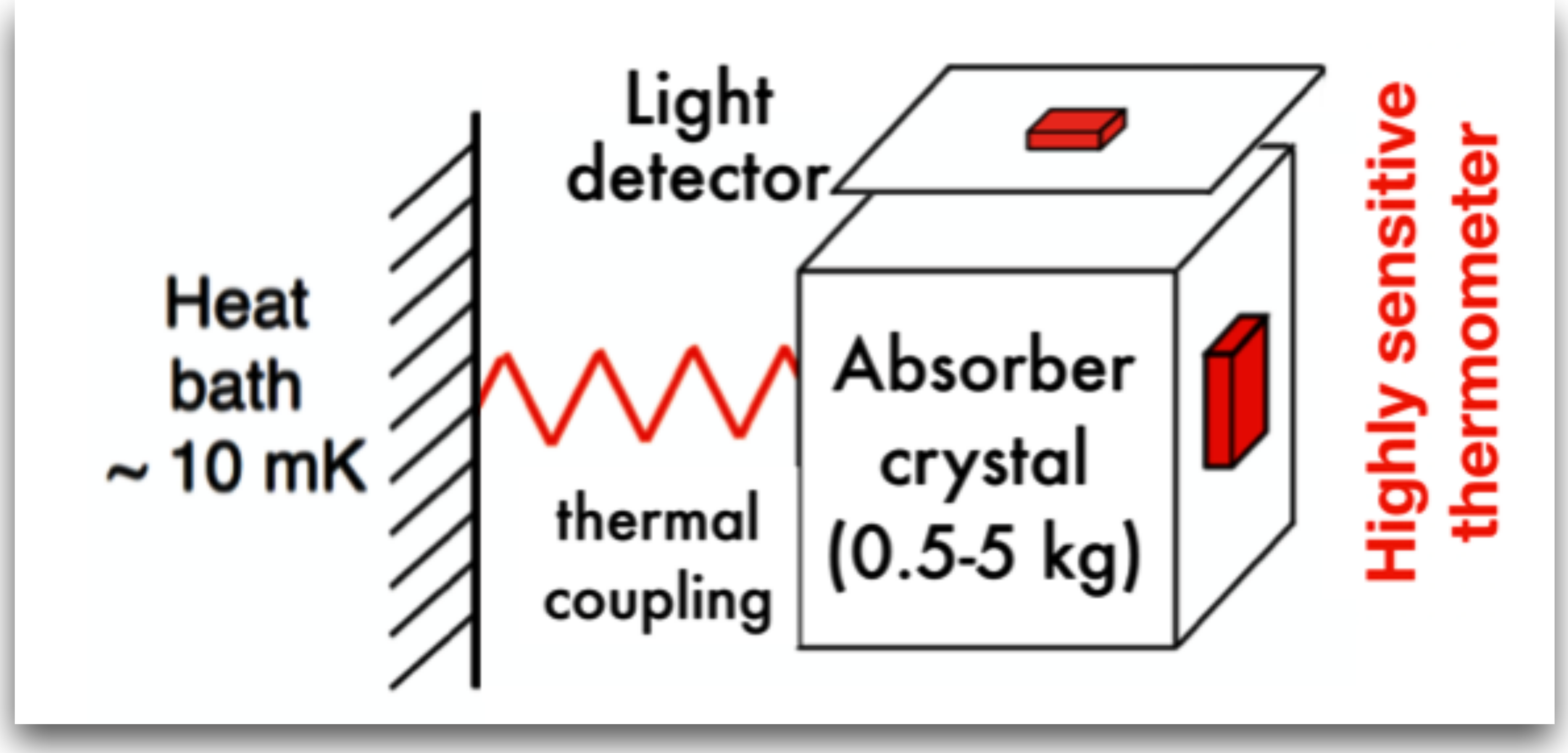
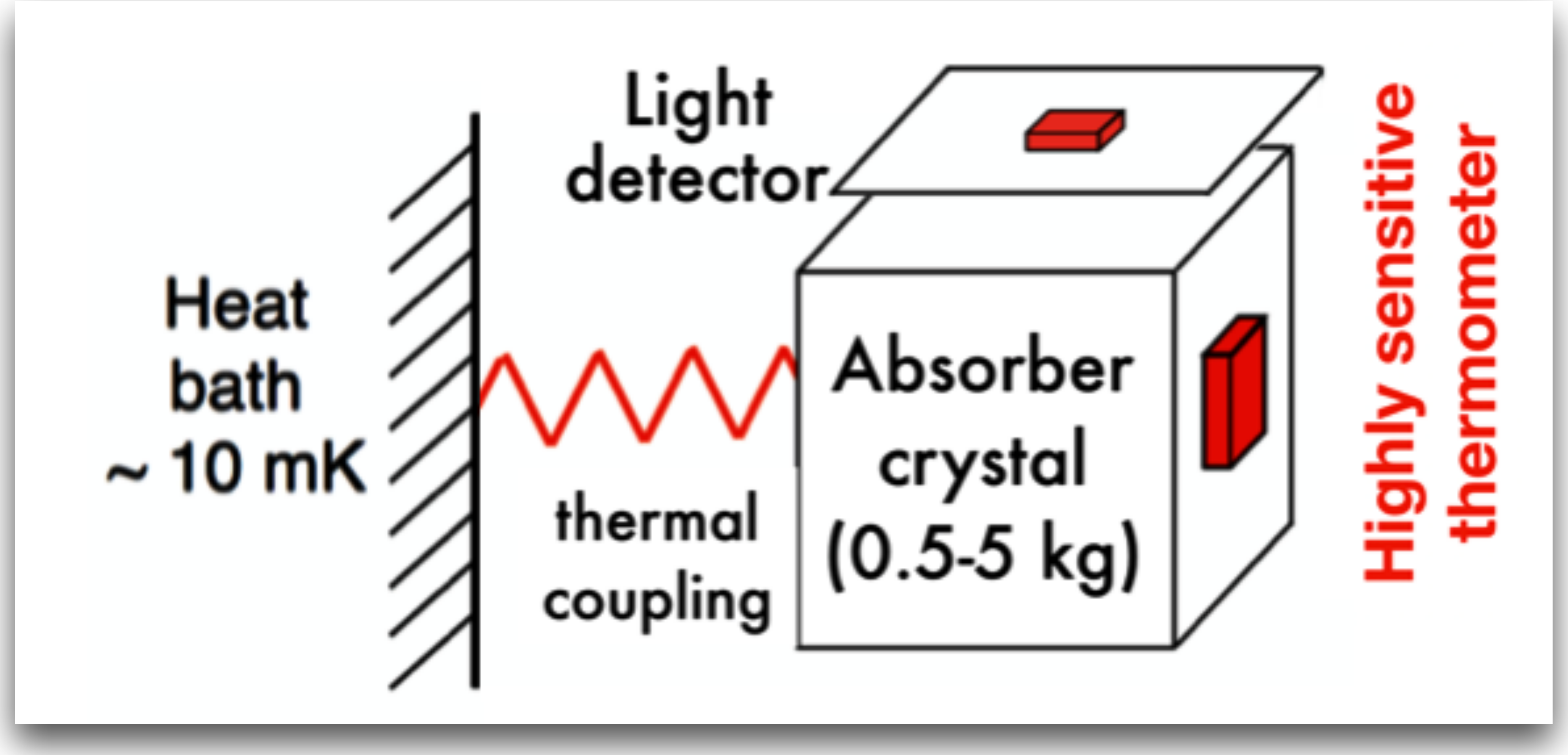


- ↑ Wide choice of compounds
- ↑ Easily scalable technology (modularity)
- ↑ Excellent energy resolution/threshold
- ↑ Particle ID for scintillating cryogenic detectors
- ⬇ Fully active detectors ➔ low bkg

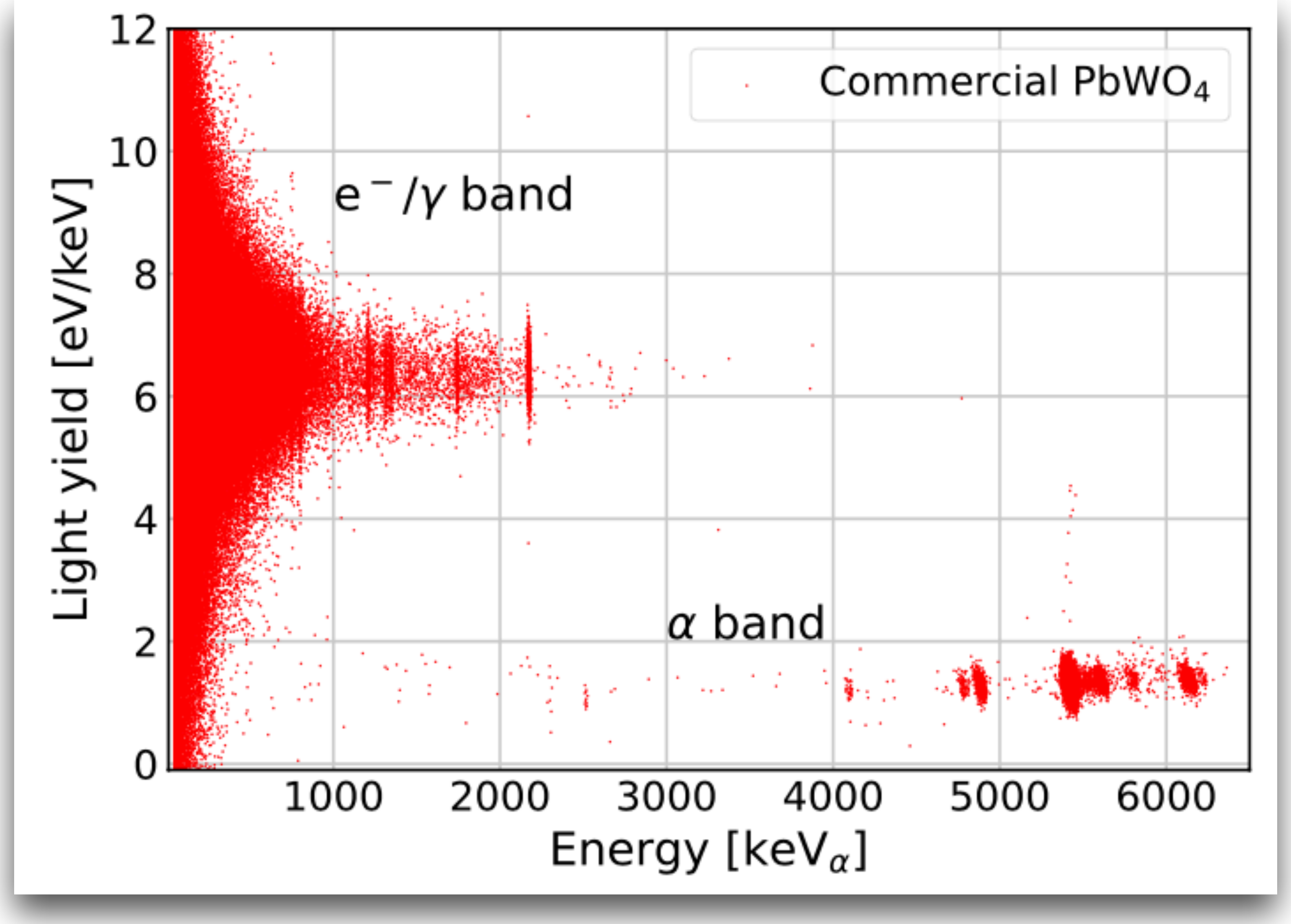
RES-NOVA DETECTOR TECHNOLOGY

ADVANCED CRYOGENIC DETECTORS

Cryogenic calorimeters 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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ADVANCED CRYOGENIC DETECTORS

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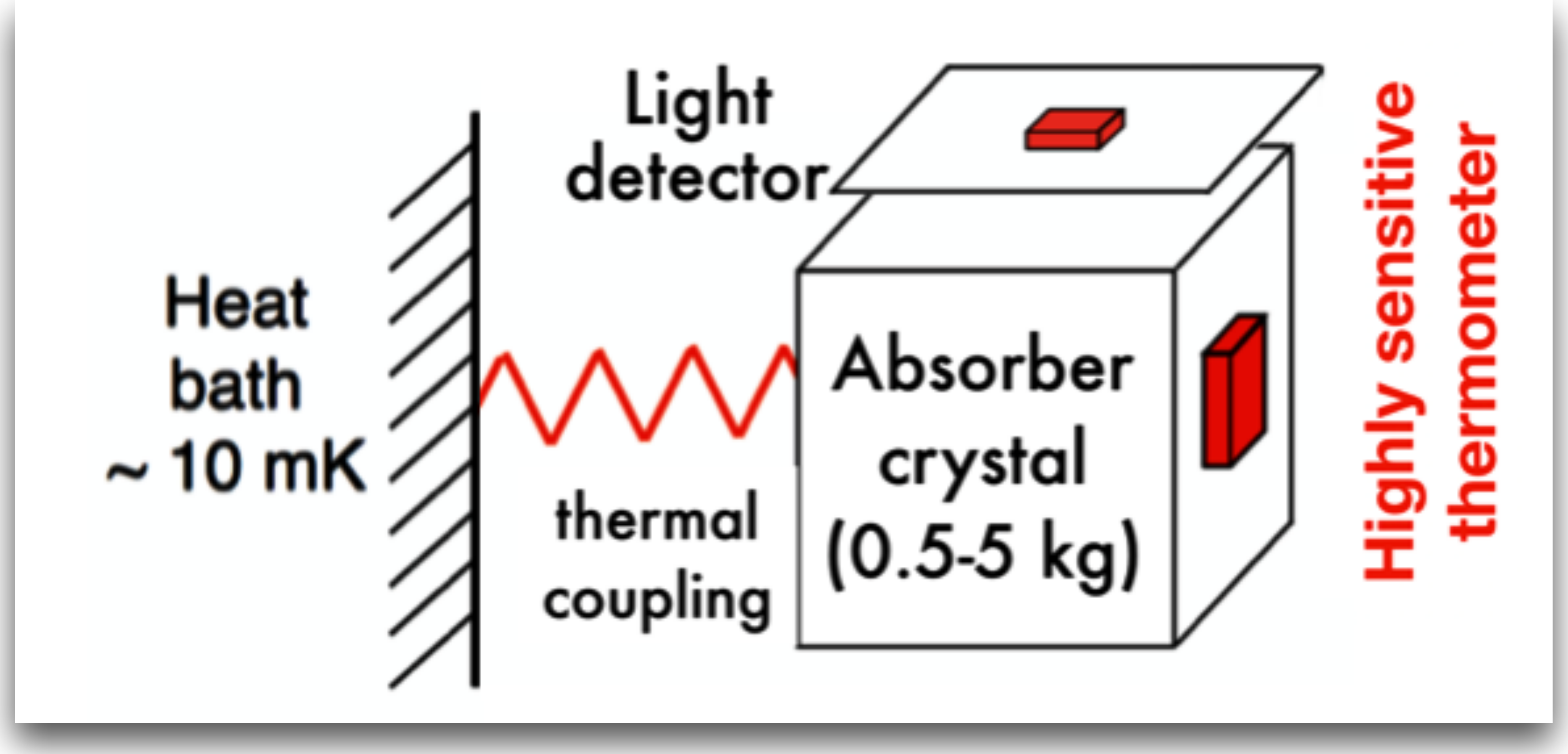


High-radiopurity crystal

$PbWO_4$ crystals

Low-background neutrinoless double-beta decay technology

Thermometer at mK

Transition Edge Sensor

Low-threshold Dark Matter technology

RES-NOVA GIVES UNIQUE INSIGHTS INTO SNE

INNOVATIVE EXPERIMENTAL APPROACH

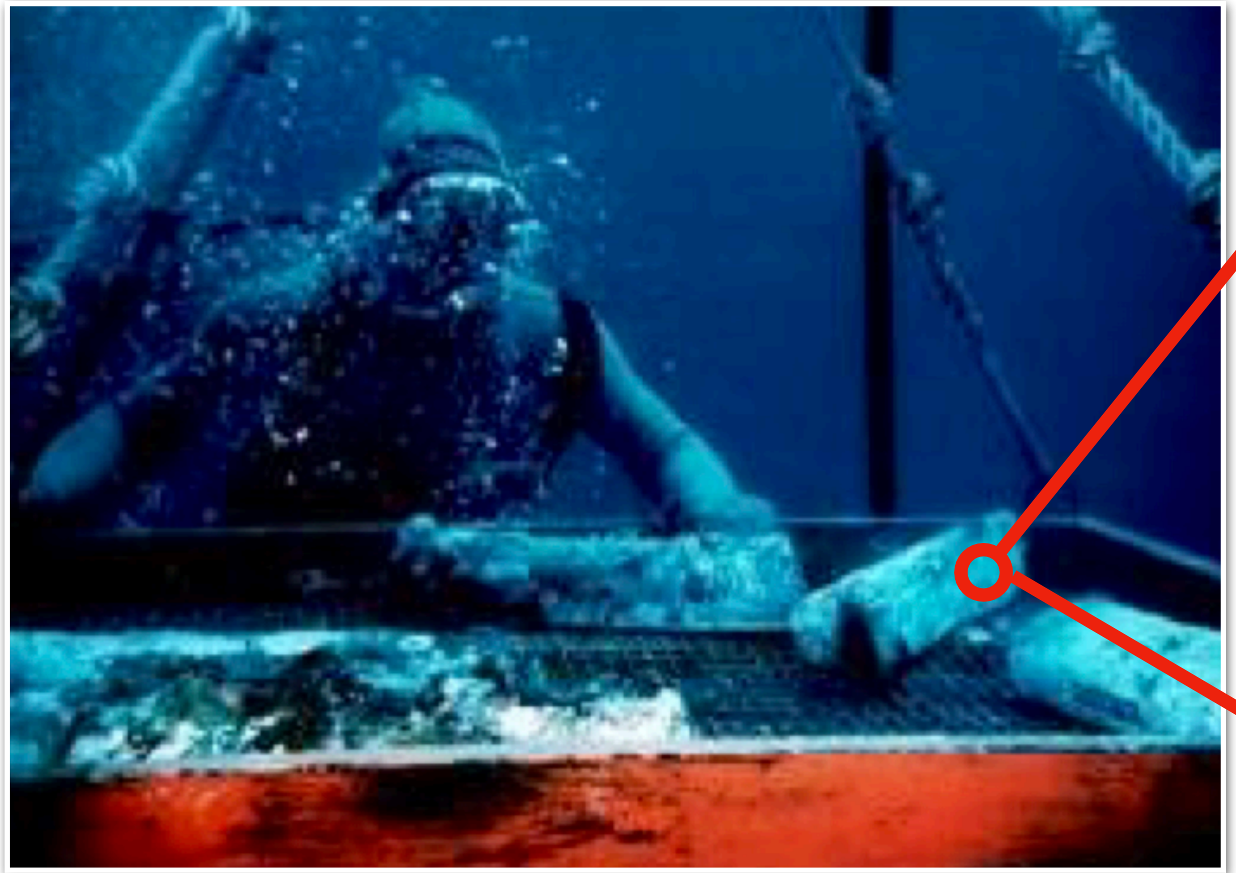
RES-NOVA

Detection channel
Coherent neutrino-nucleus scattering

Technology
Cryogenic detectors

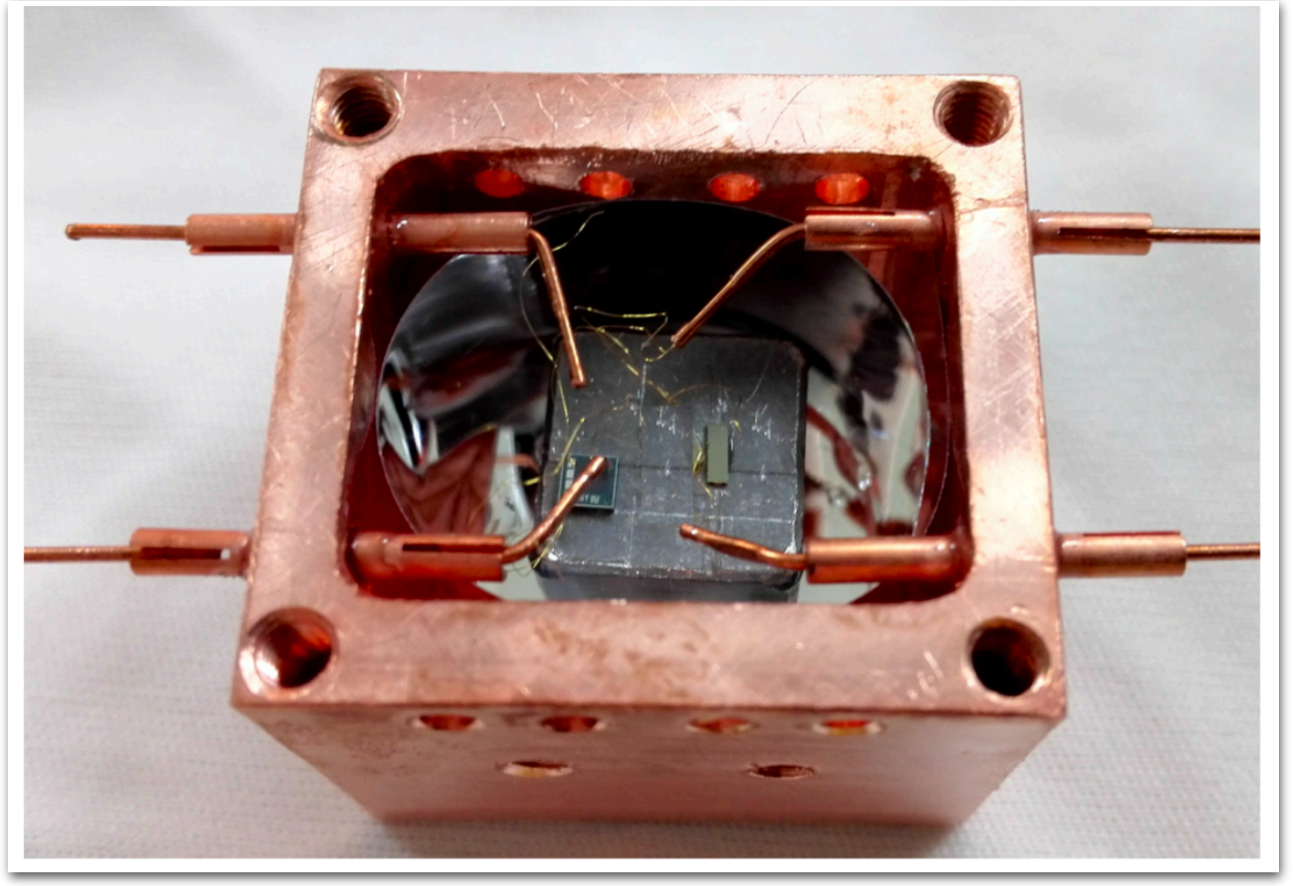
Target material
$PbWO_4$ from archaeological-Pb

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 mBq/kg

x10^4 better than commercial low-background Pb

Several tons of Archaeo-Pb @ INFN

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

RES-NOVA GIVES UNIQUE INSIGHTS INTO SNE

INNOVATIVE EXPERIMENTAL APPROACH

RES-NOVA

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Coherent neutrino-nucleus scattering

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$PbWO_4$ from archaeological-Pb

RES-NOVA GIVES UNIQUE INSIGHTS INTO SNE

INNOVATIVE EXPERIMENTAL APPROACH

RES-NOVA →

Detection channel
Coherent neutrino-nucleus scattering

Technology
Cryogenic detectors

Target material
$PbWO_4$ from archaeological-Pb

What can we learn?

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

Galactic SN neutrino signal:

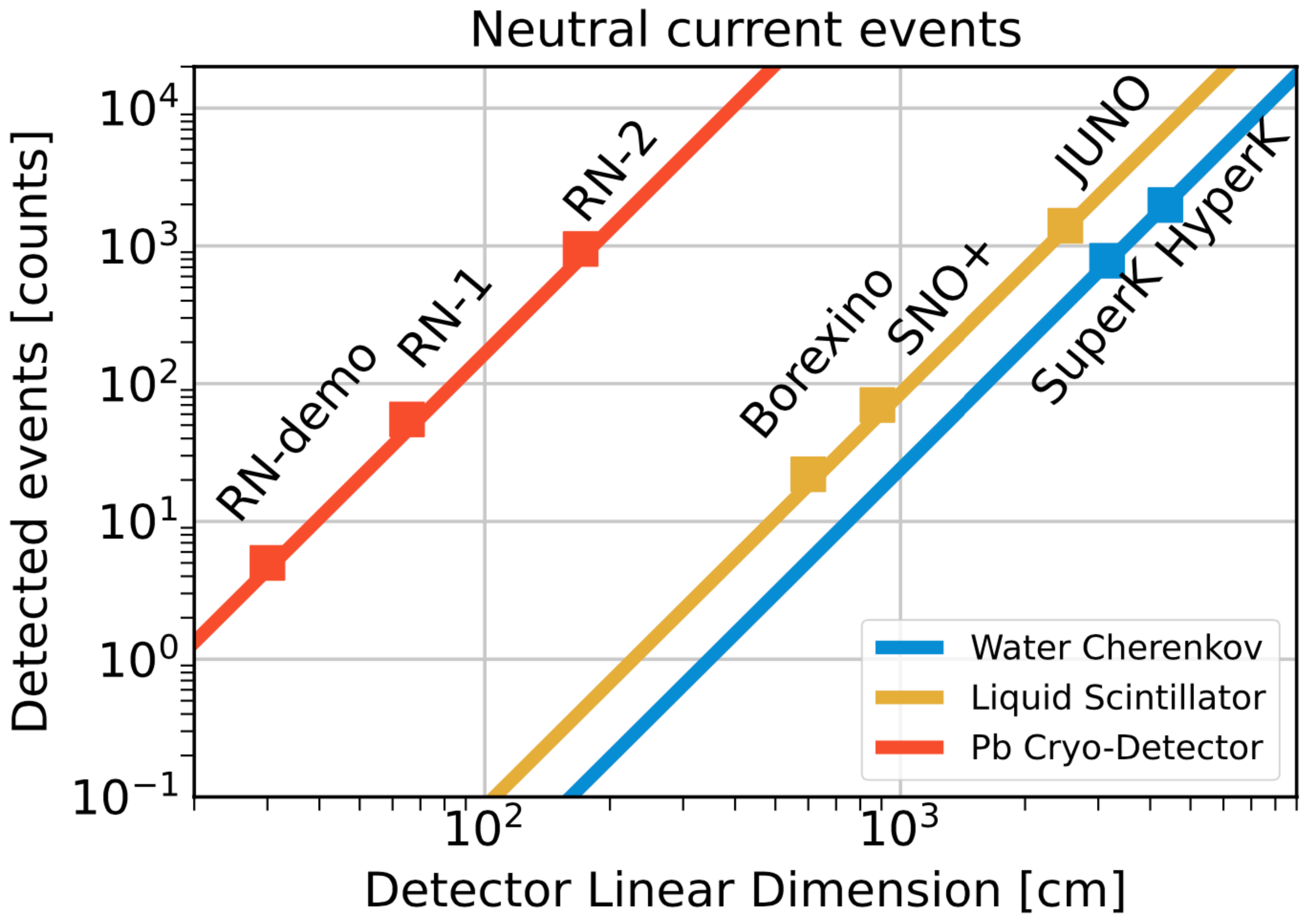
Water Cherenkov (SuperK): 0.2 ev./m^3

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

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

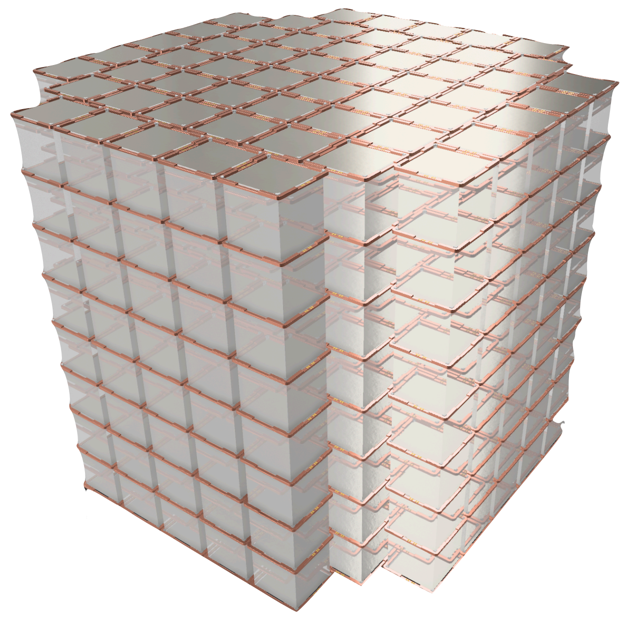
NEUTRINO OBSERVATORY AT THE CM-SCALE

AN ARRAY OF $PbWO_4$ CRYSTALS

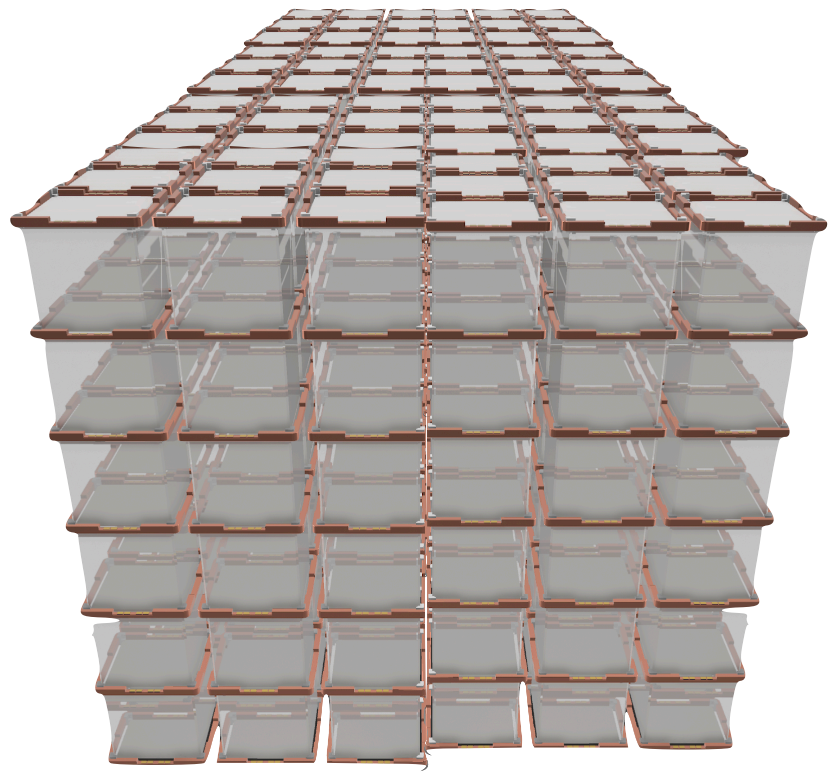


	RN-demo @ LNGS
Size:	(30 cm)^3
Threshold:	1 keV
SN @ 10 kpc:	~10 counts

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

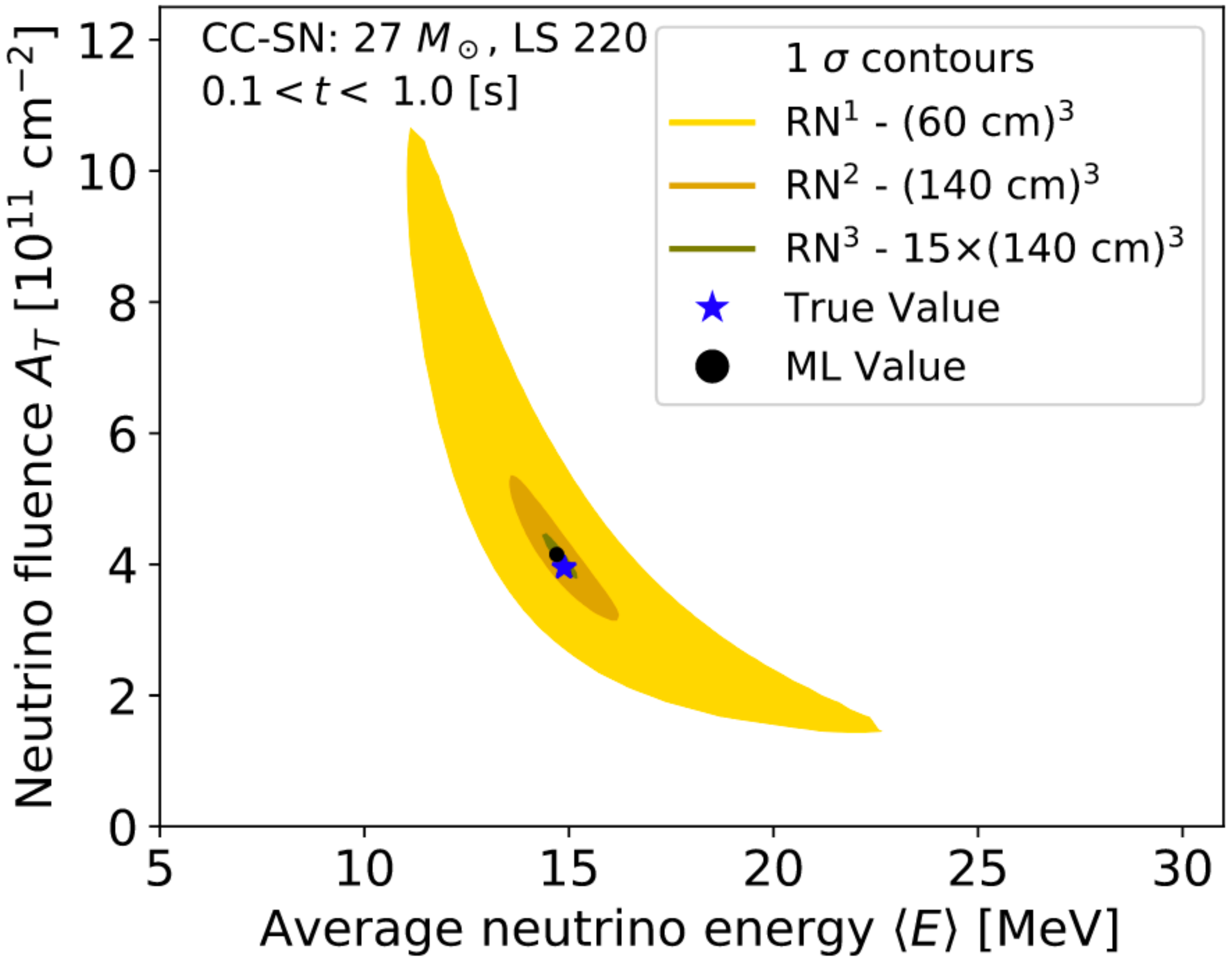


	RN-2
Size:	(140 cm)^3
Threshold:	1 keV
SN @ 10 kpc:	~900 counts



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	
RN-I	30%
RN-2	8%
RN-3	4%

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

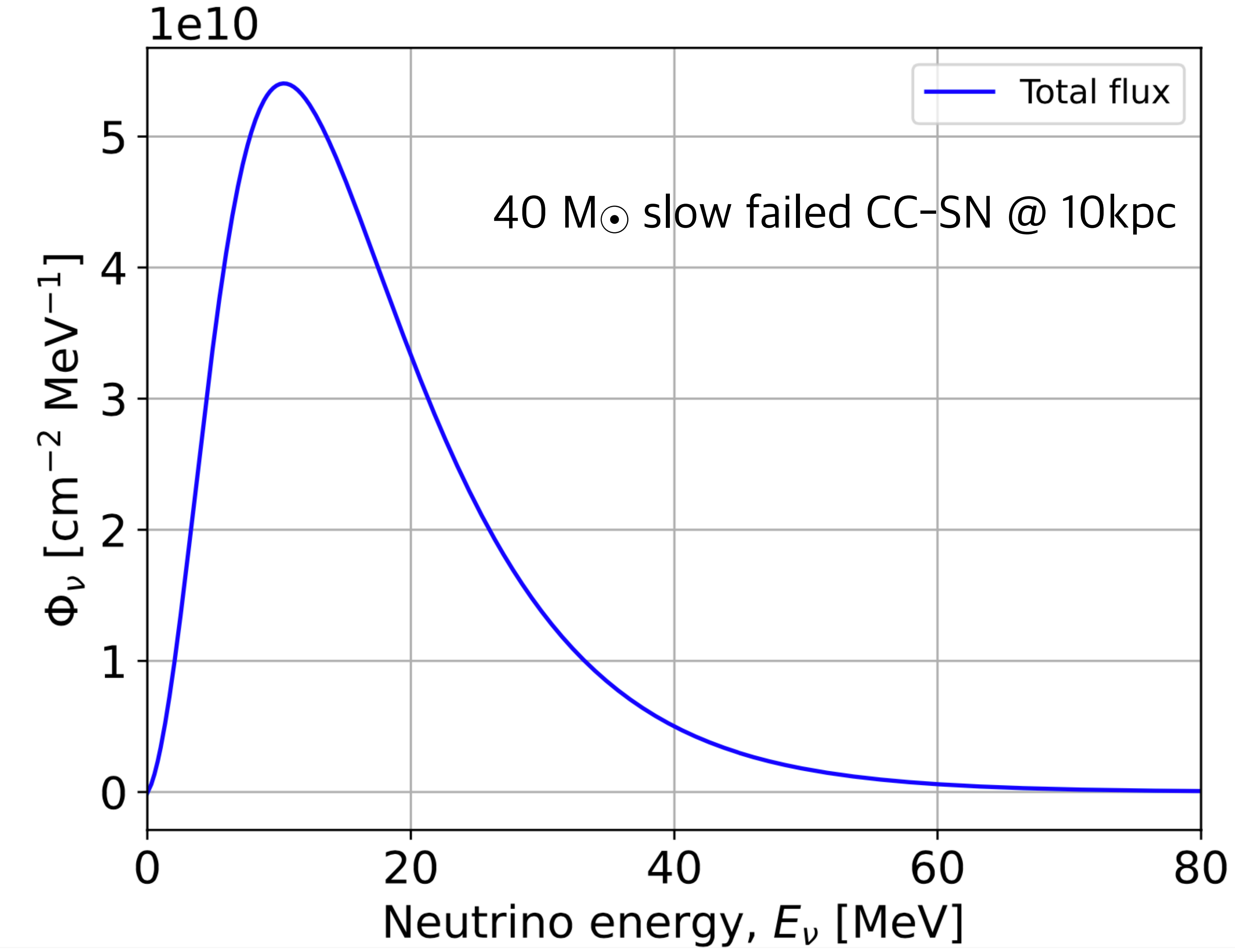
ν_e/anti-ν_e	
SK-Gd (IBD)	25%

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

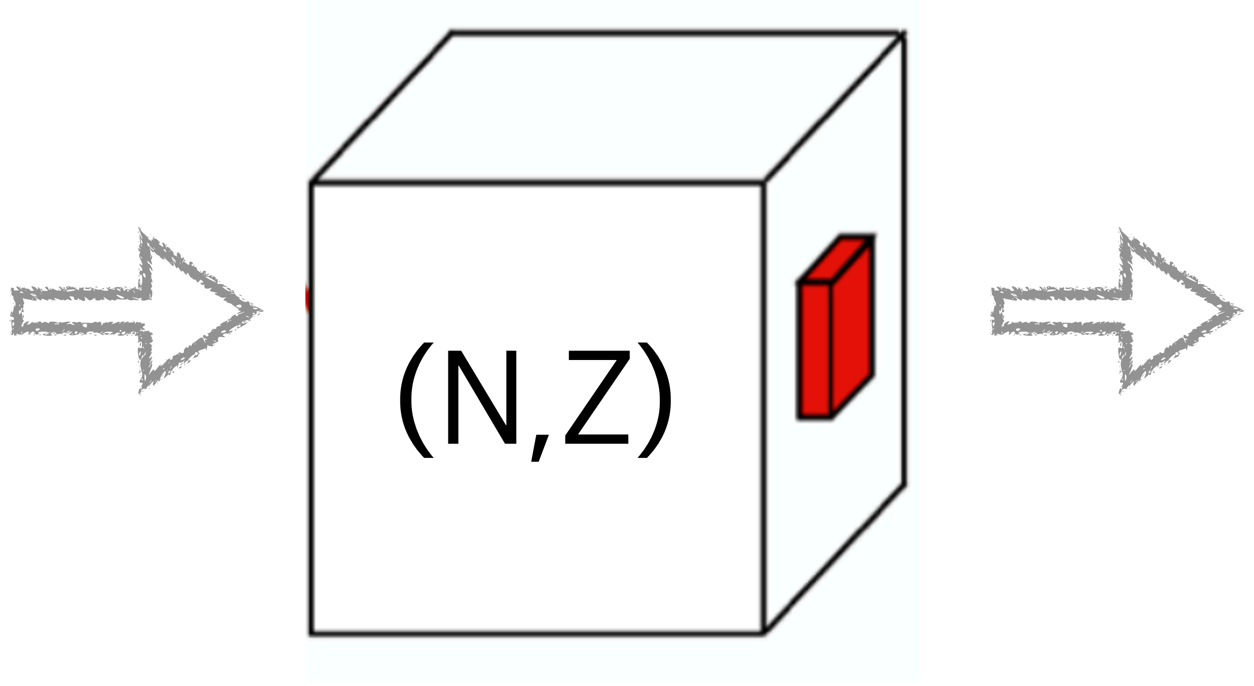
IS PB THE BEST TARGET FOR SN NEUTRINOS

LET'S HAVE A LOOK AT THE PERIODIC TABLE

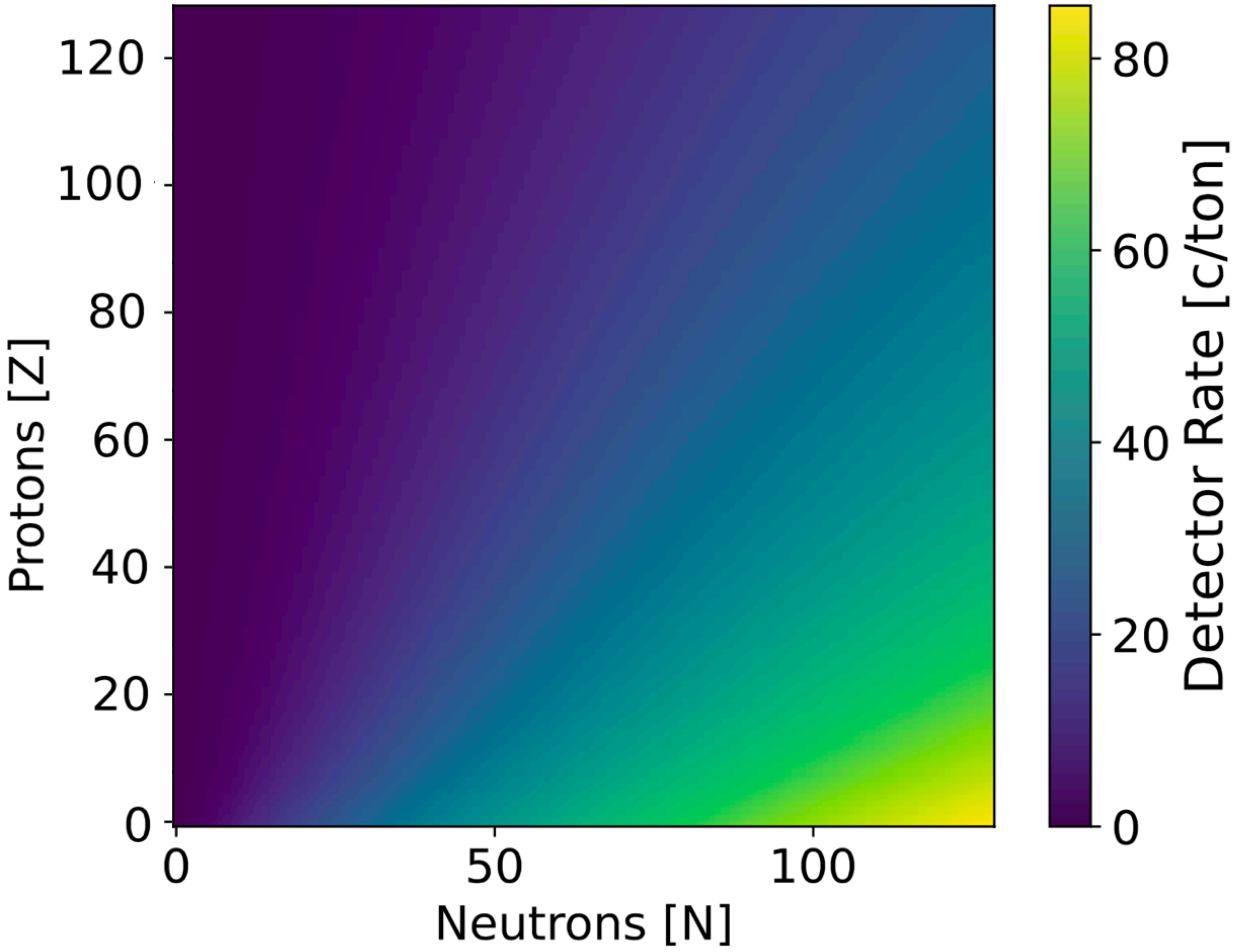
SN neutrino **source**



Cryogenic **detector**



Detector **counting rate** for E_{th} = 1 keV



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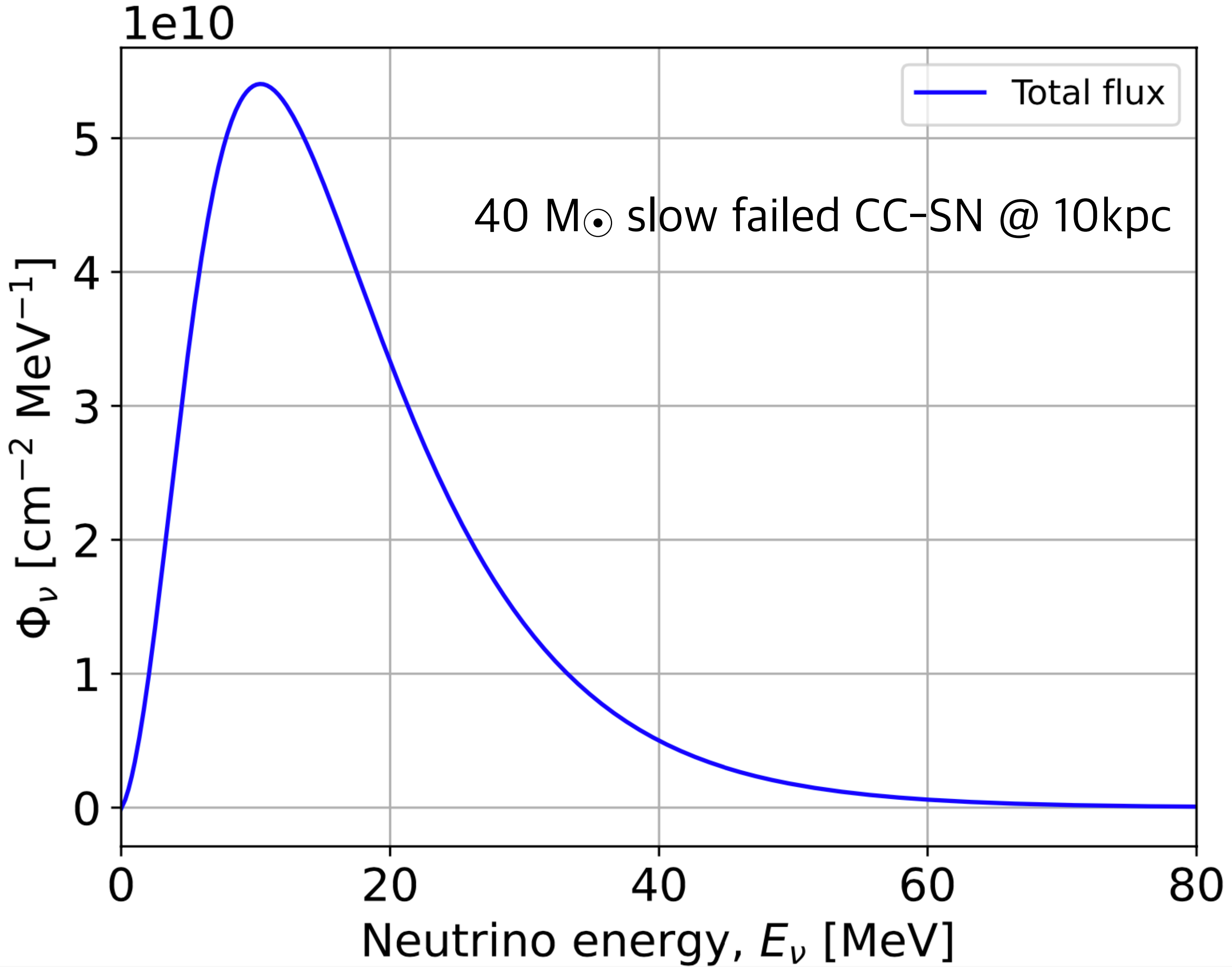

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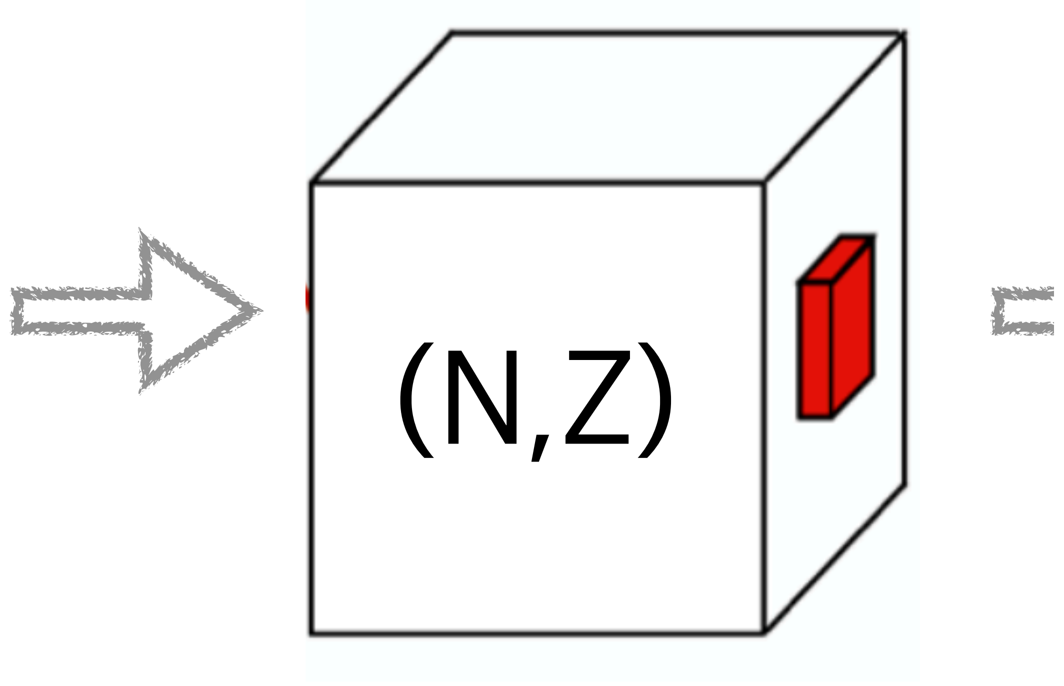
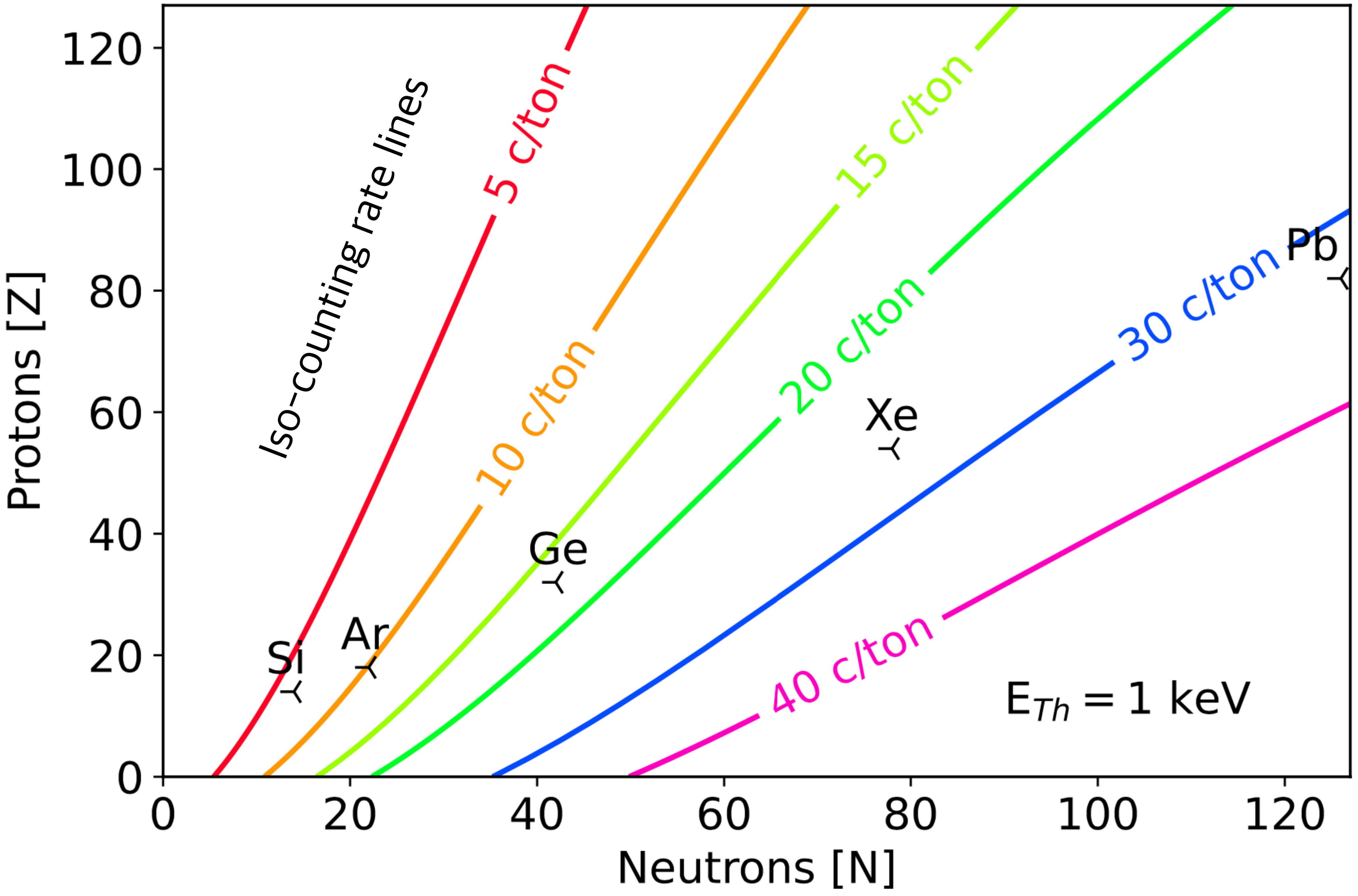
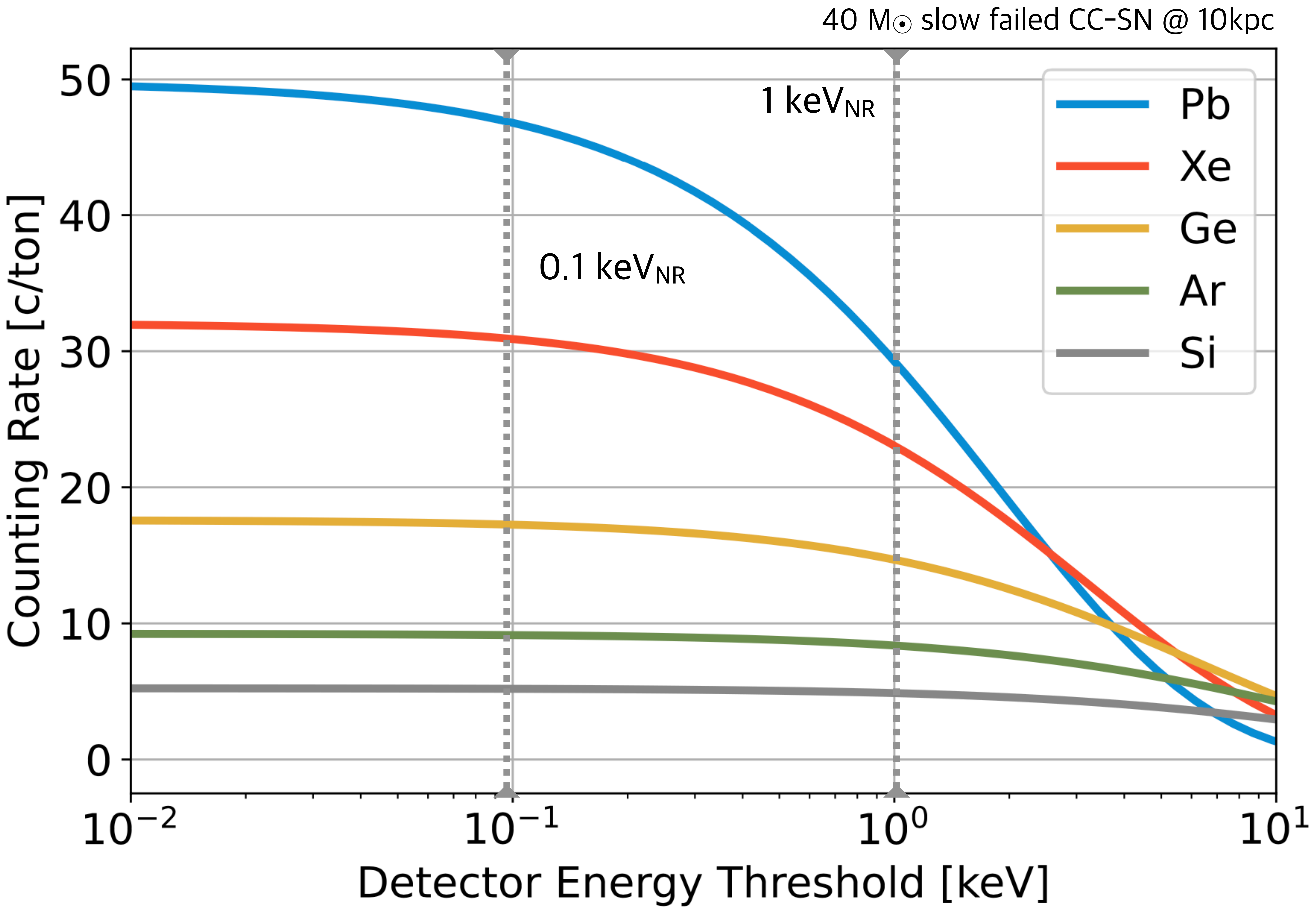


Detector **counting rate** for E_{th} = 1 keV



HOW LOW SHOULD THE THRESHOLD BE ?

ULTRA-LOW ENERGY THRESHOLD ARE NOT NEEDED

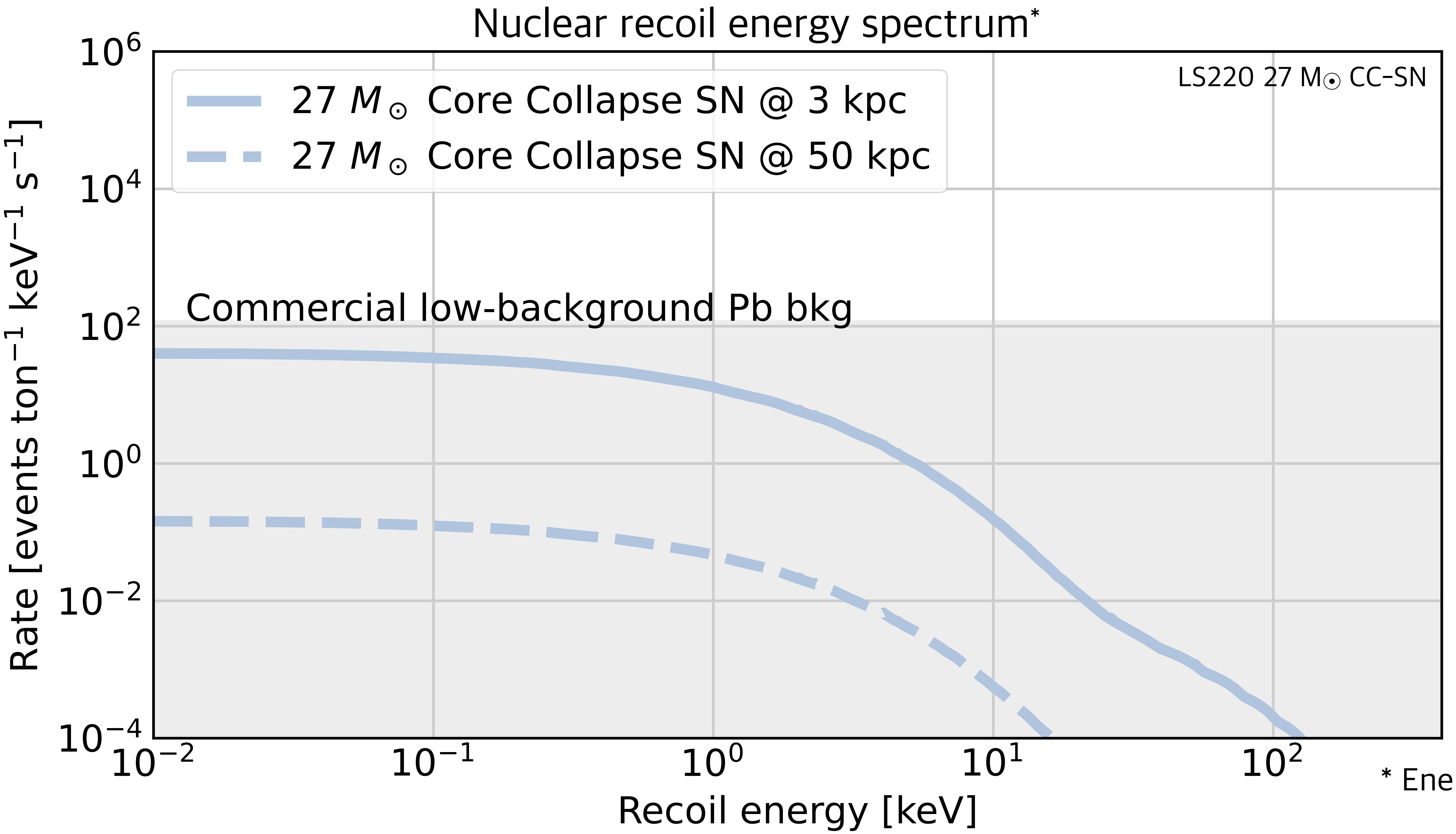


Lower threshold is beneficial

Lower threshold is not mandatory

The threshold is not limiting the statistics

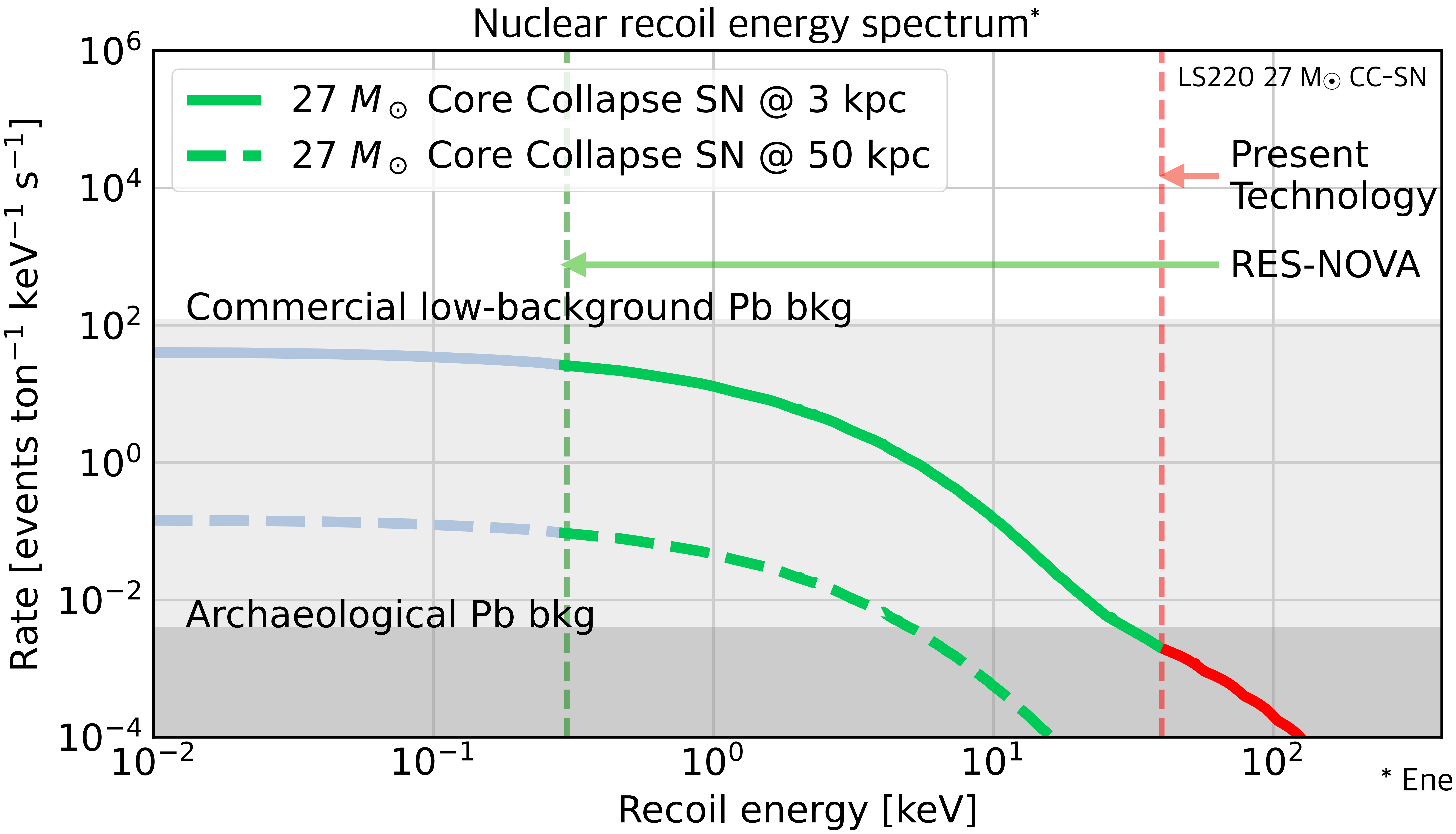
RES-NOVA DETECTS SN NEUTRINOS



* Energy resolution 0.2 keV

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

RES-NOVA DETECTS SN NEUTRINOS



* Energy resolution 0.2 keV

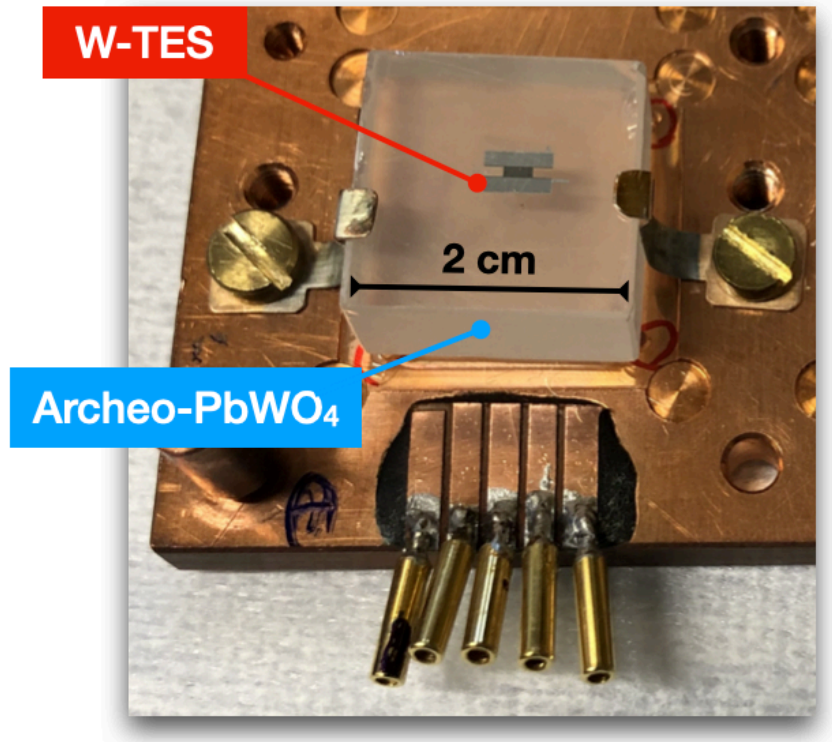
L. Pattavina et al., *Phys. Rev. D* 102, 063001 (2020)

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)

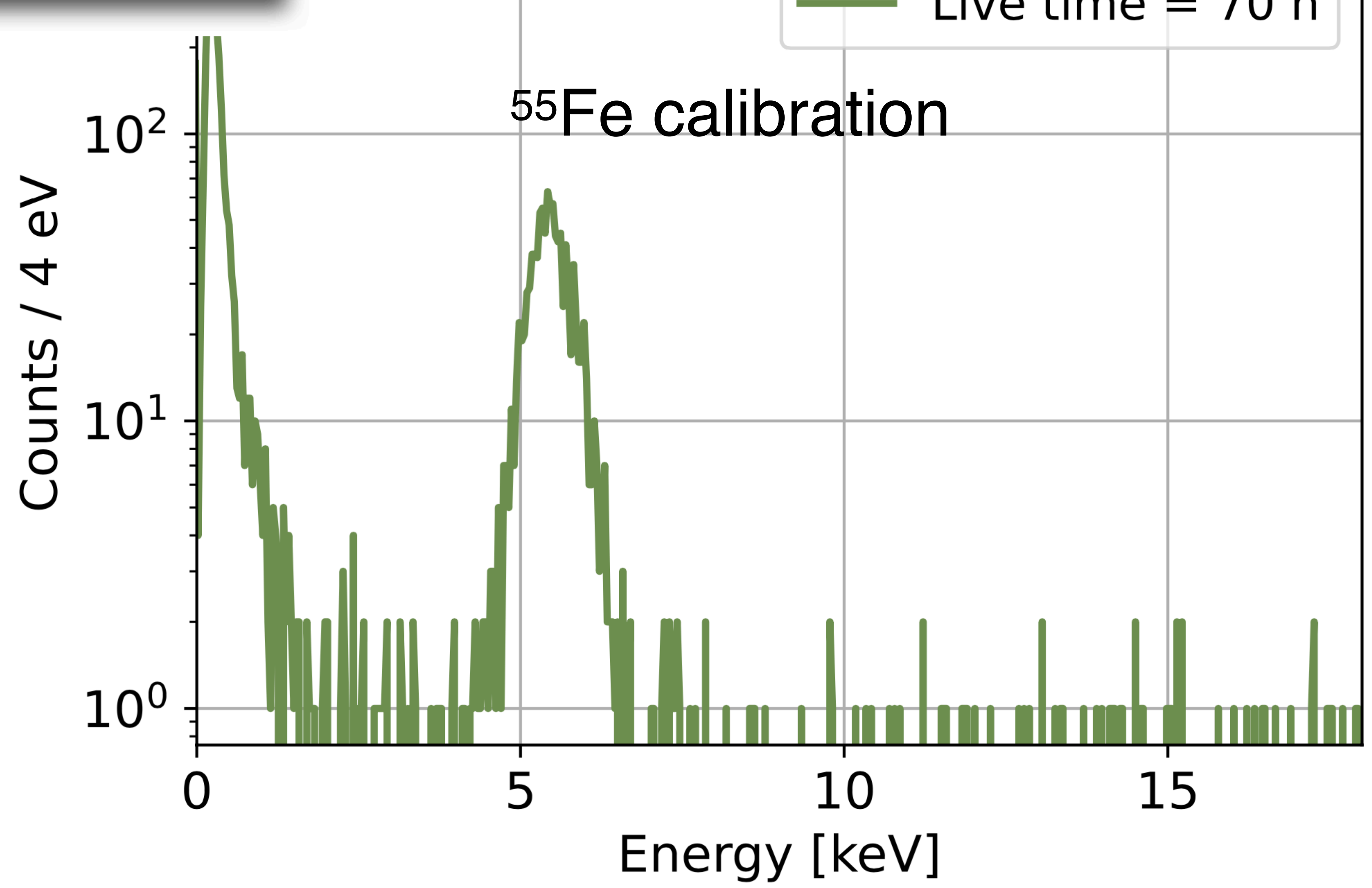
RES-NOVA PROOFS OF PRINCIPLE

ACHIEVEMENT OF LOW THRESHOLD AND LOW BACKGROUND



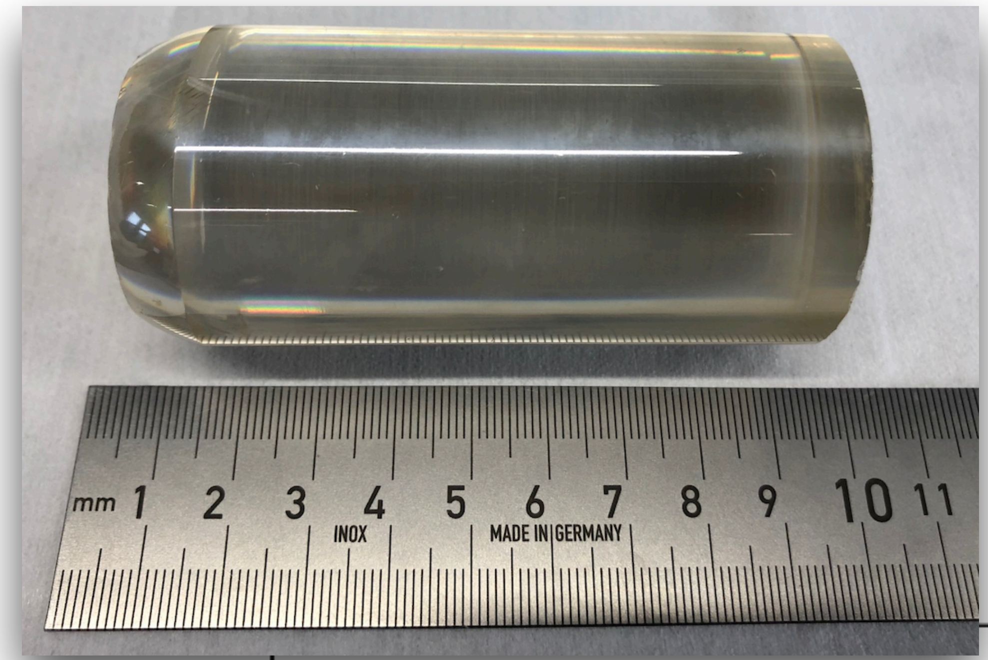
N. Ferreiro Iachellini et al.,
J. Low Temp. Phys. 11, 184 (2022)

TOTAL ENERGY SPECTRUM



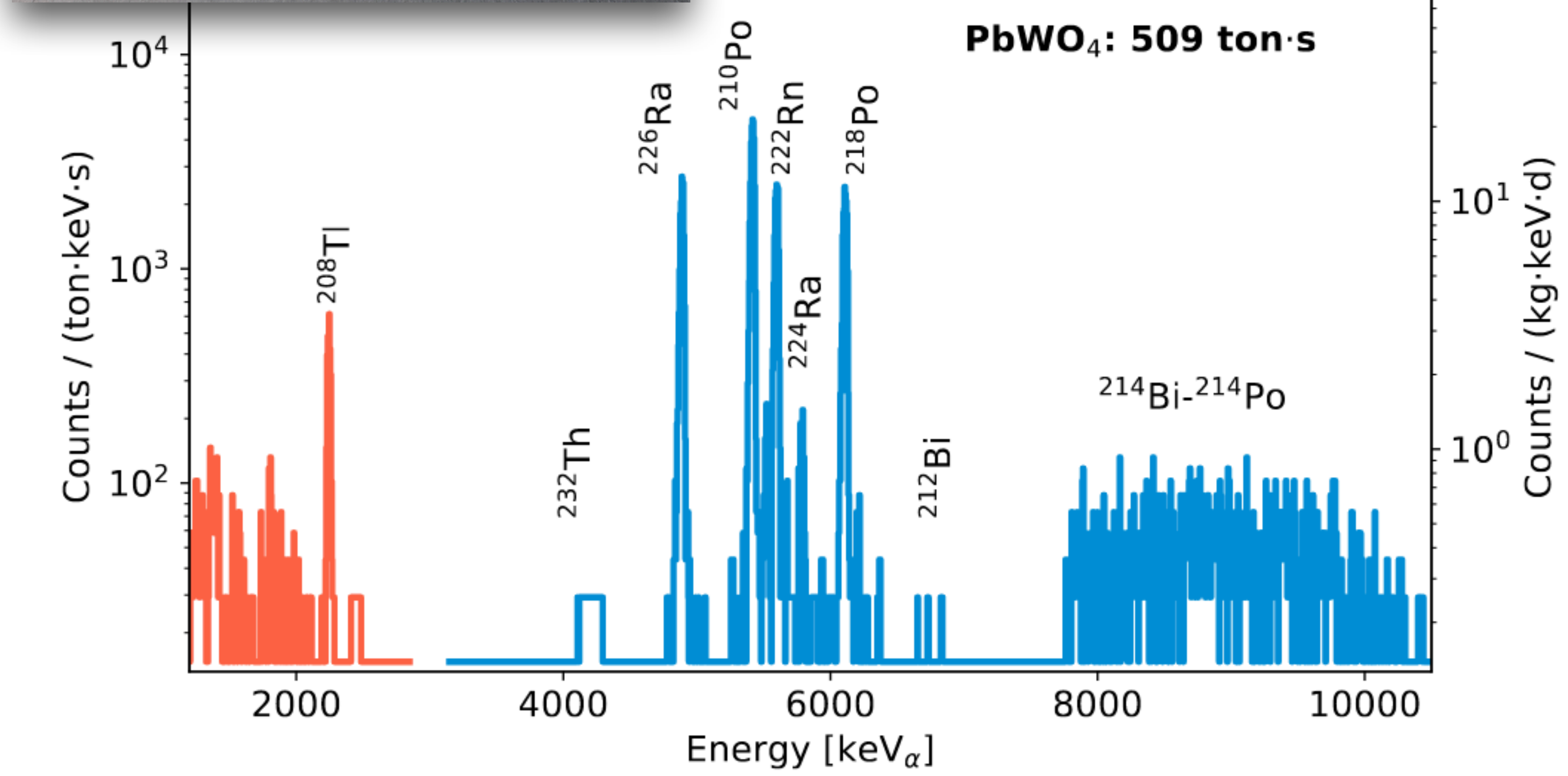
Above ground @ Max Planck Munich (DE)

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



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

TOTAL ENERGY SPECTRUM

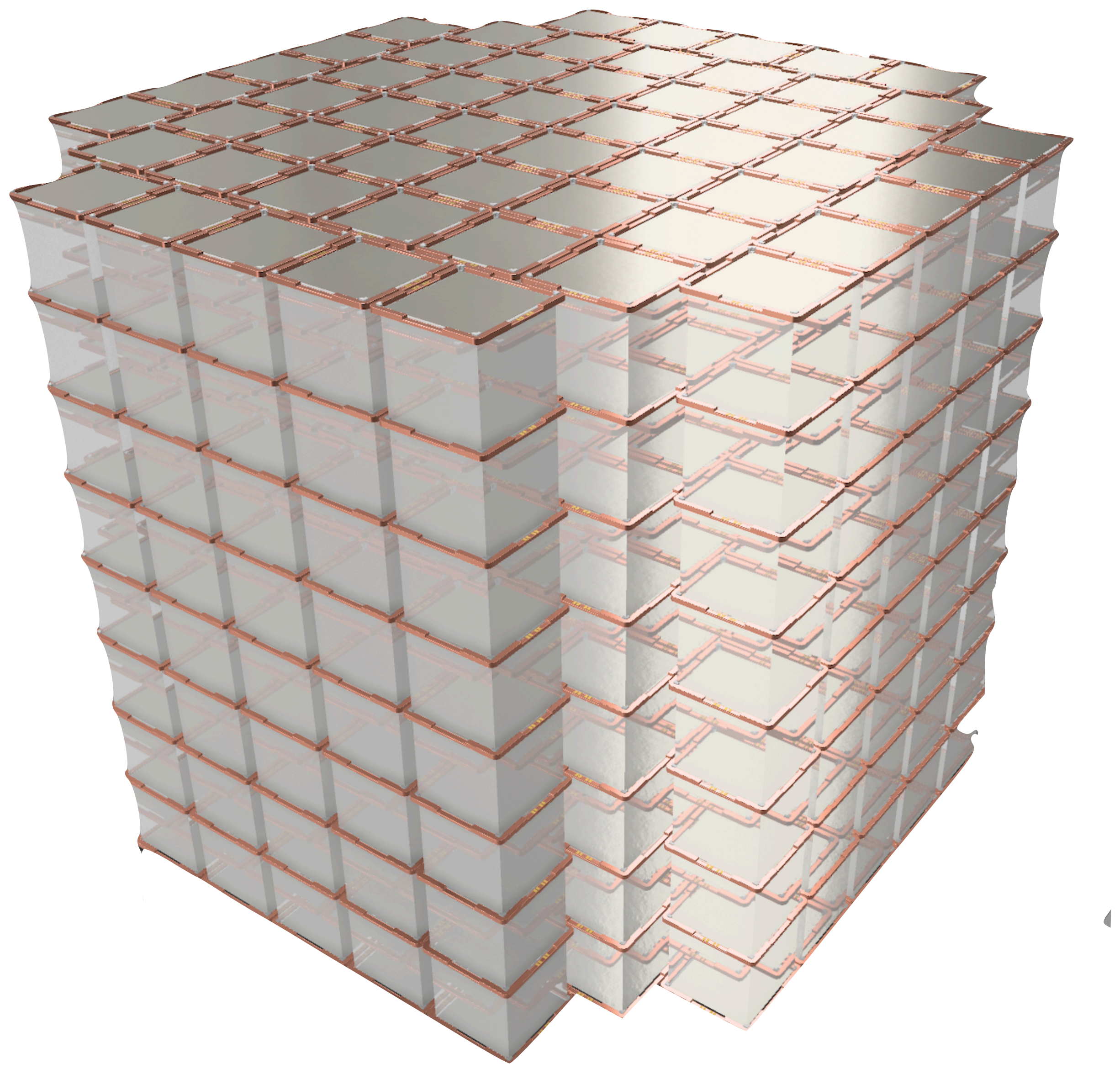


Under ground @ LNGS (IT)

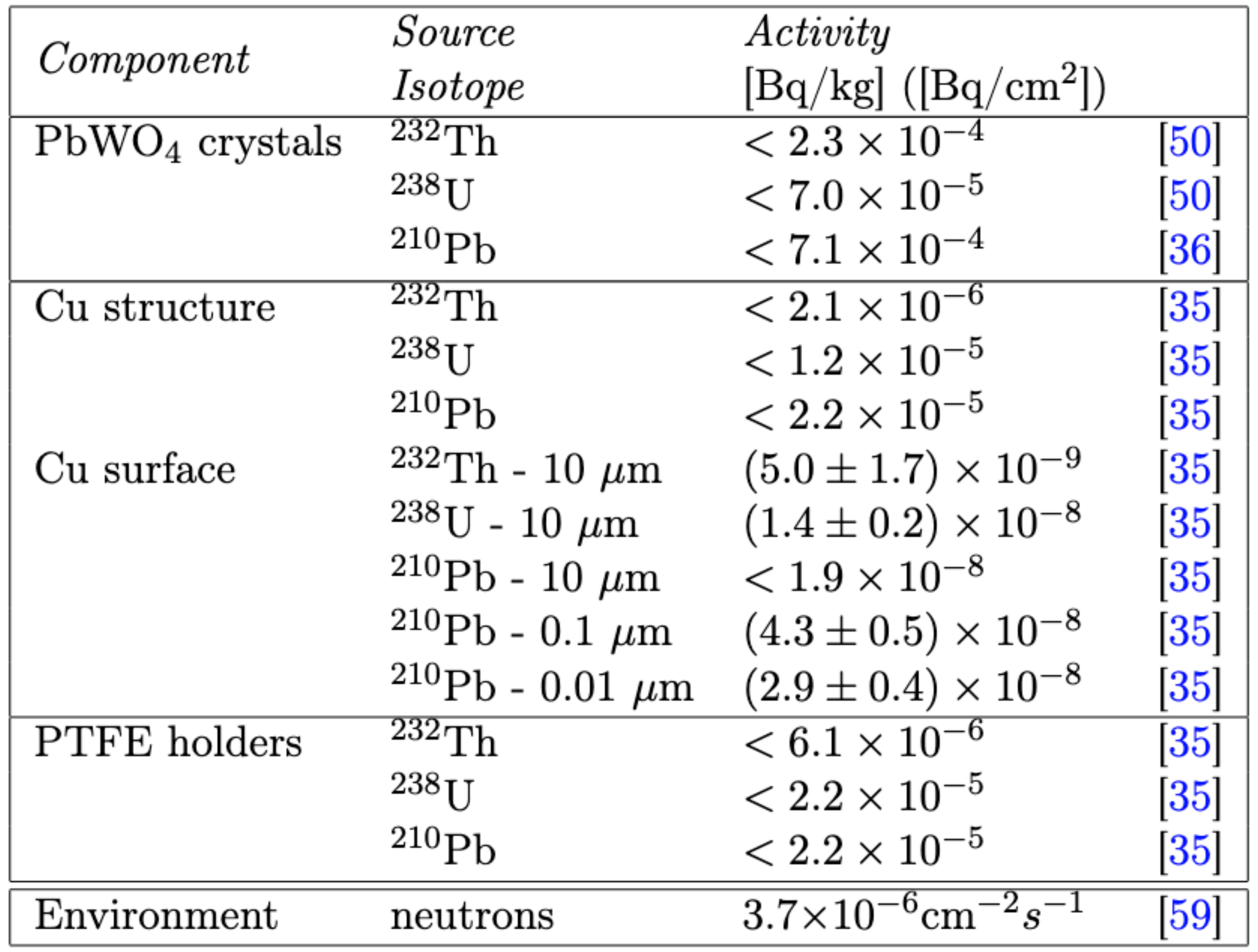
Radiopurity @ μBq/kg scale ($PbWO_4$ - 0.9 kg)

RES-NOVA BACKGROUND MODEL

Detector response studies to radioactive background sources – MC simulations

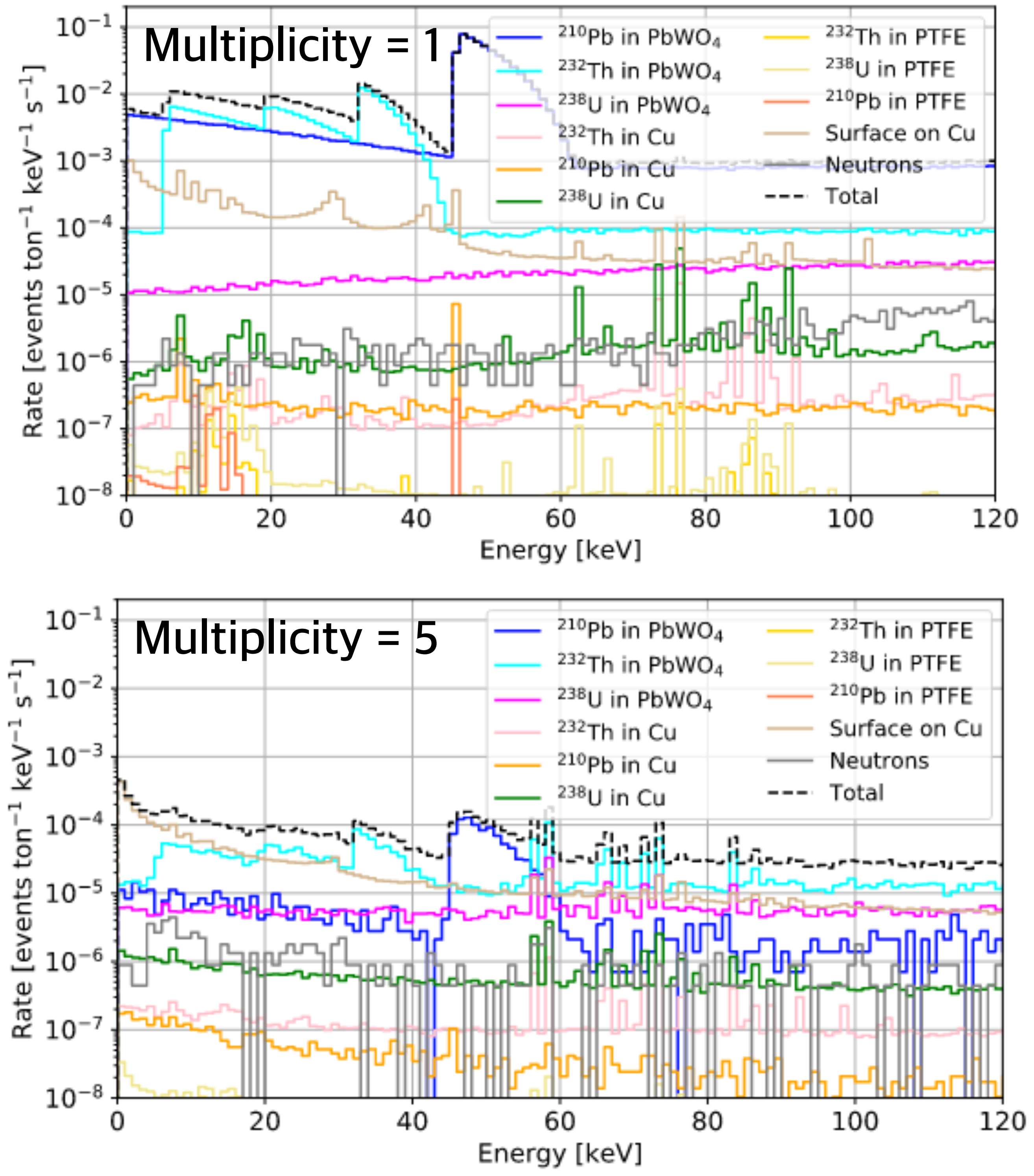


Modular detector



Component	*Source* *Isotope*	*Activity* [Bq/kg] ([Bq/cm^2])	
PbWO$_4$ crystals	^{232}Th	$< 2.3 \times 10^{-4}$	[50]
	^{238}U	$< 7.0 \times 10^{-5}$	[50]
	^{210}Pb	$< 7.1 \times 10^{-4}$	[36]
Cu structure	^{232}Th	$< 2.1 \times 10^{-6}$	[35]
	^{238}U	$< 1.2 \times 10^{-5}$	[35]
	^{210}Pb	$< 2.2 \times 10^{-5}$	[35]
Cu surface	^{232}Th - 10 μm	$(5.0 \pm 1.7) \times 10^{-9}$	[35]
	^{238}U - 10 μm	$(1.4 \pm 0.2) \times 10^{-8}$	[35]
	^{210}Pb - 10 μm	$< 1.9 \times 10^{-8}$	[35]
	^{210}Pb - 0.1 μm	$(4.3 \pm 0.5) \times 10^{-8}$	[35]
	^{210}Pb - 0.01 μm	$(2.9 \pm 0.4) \times 10^{-8}$	[35]
PTFE holders	^{232}Th	$< 6.1 \times 10^{-6}$	[35]
	^{238}U	$< 2.2 \times 10^{-5}$	[35]
	^{210}Pb	$< 2.2 \times 10^{-5}$	[35]
Environment	neutrons	3.7×10^{-6}cm$^{-2}s^{-1}$	[59]

Radioactive background sources



Detector energy response

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

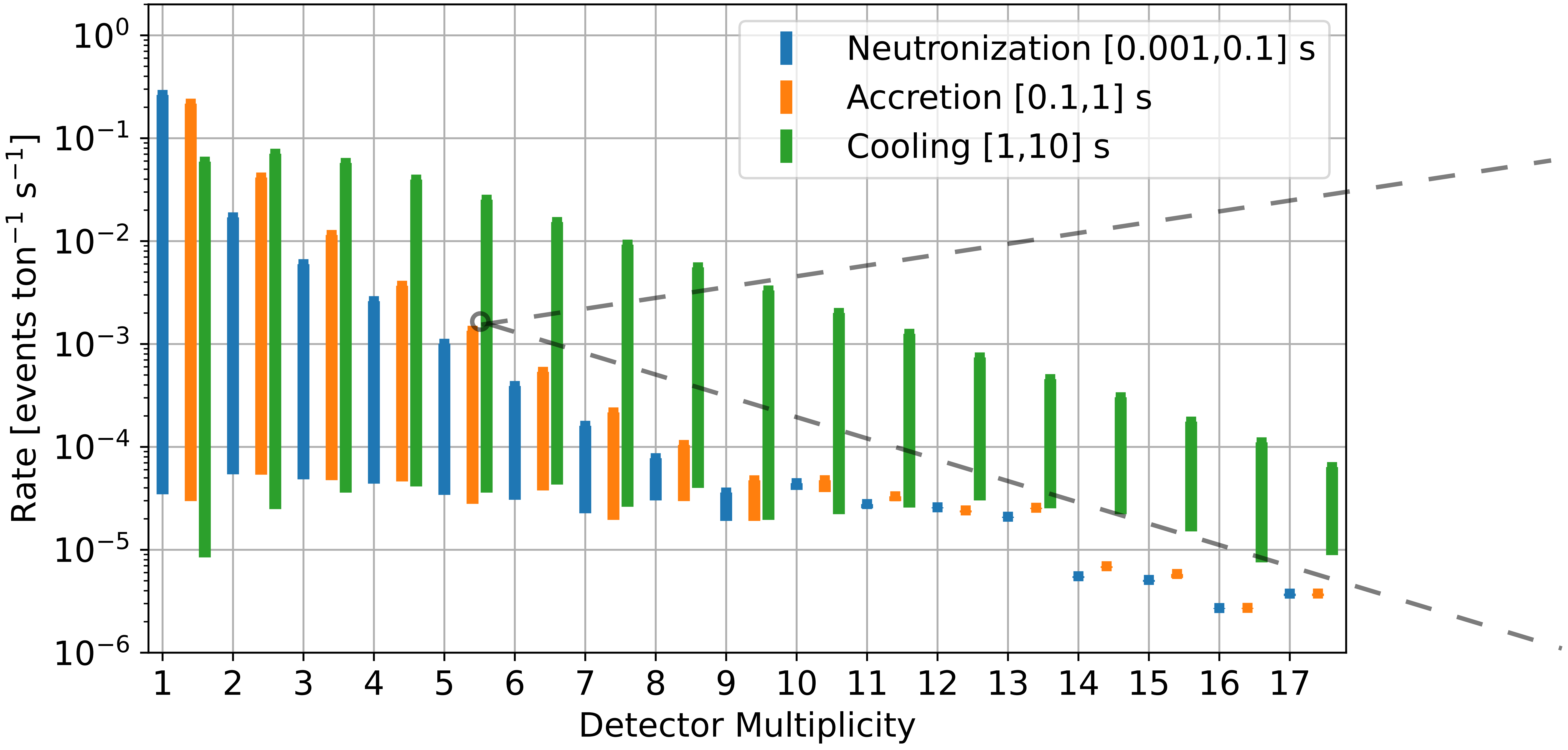
RES-NOVA BACKGROUND MODEL

High multiplicity SN signal → High multiplicity bkg → Low-background

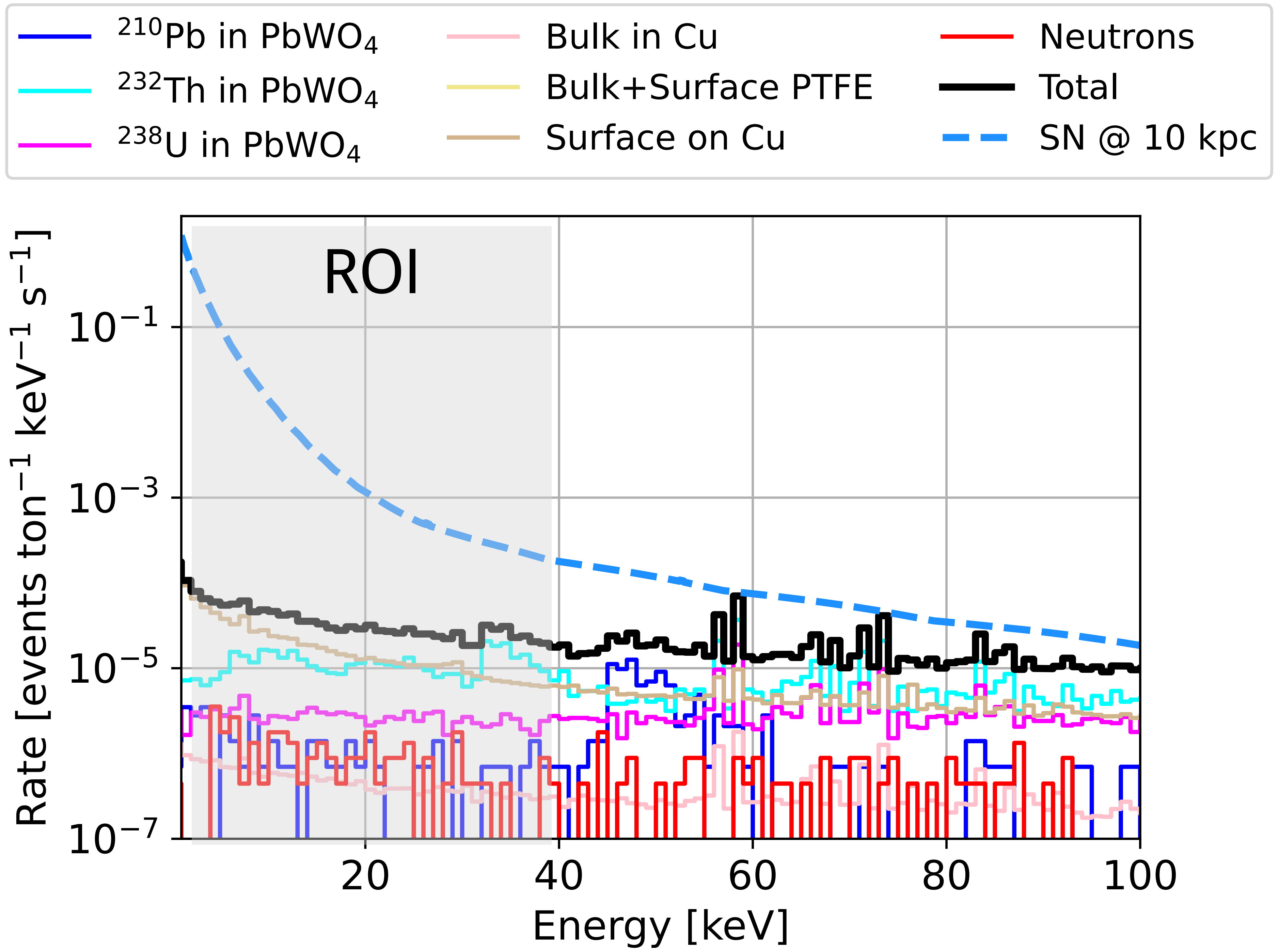
Bkg goal: <10^{-3} ev/ton/keV/s in coincidence mode (no particle ID)

<0.086 c/keV/kg/d

Background rate in the ROI



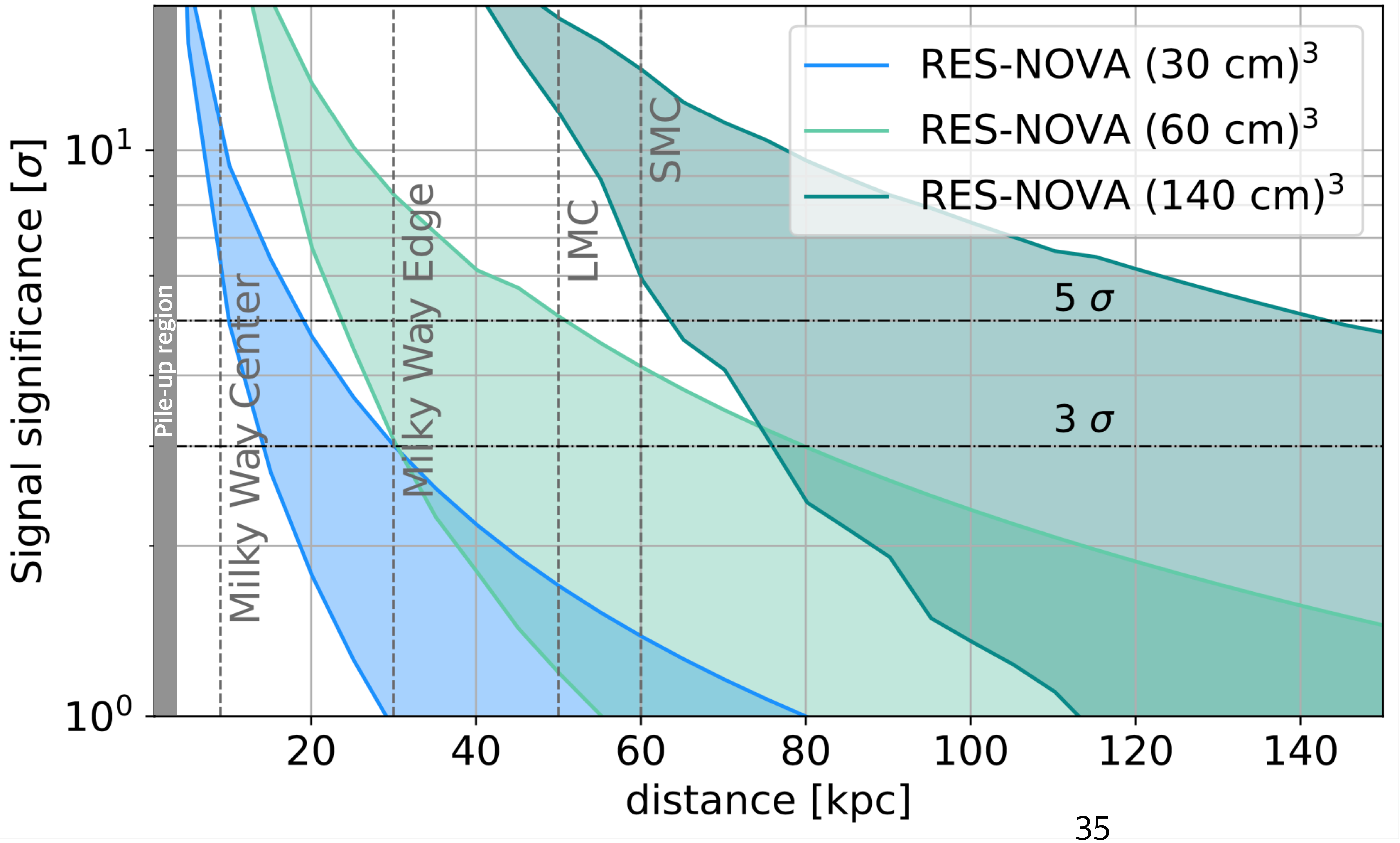
Detector energy spectrum for a SN @ 10 kpc



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

RES-NOVA SENSITIVITY

SMALL DETECTOR GREAT POTENTIAL



Target: **archaeo-$PbWO_4$**

Energy threshold: **1 keV**

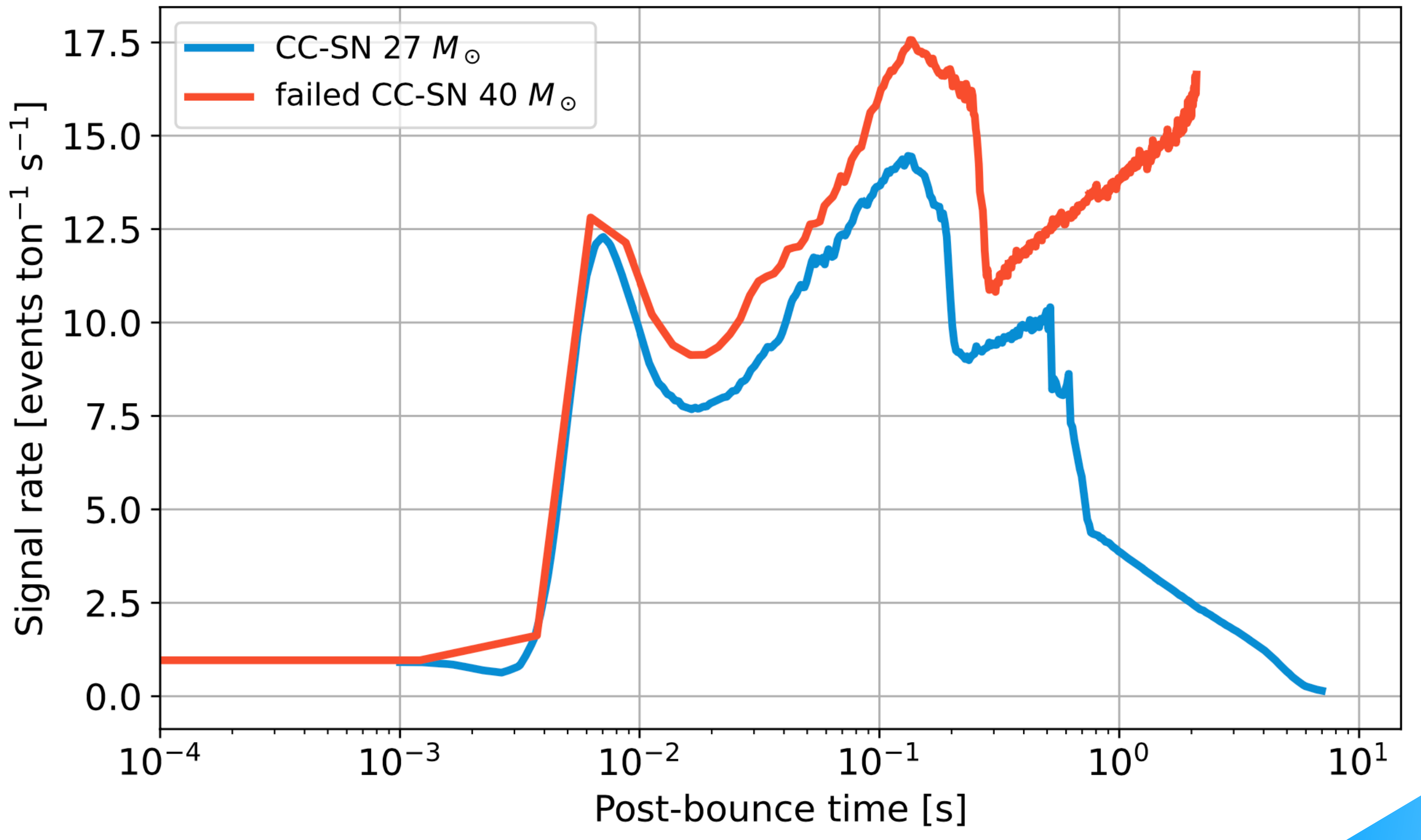
Bkg @ ROI: **10^{-3} c/keV/ton/s/**

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

RES-NOVA IMPACT

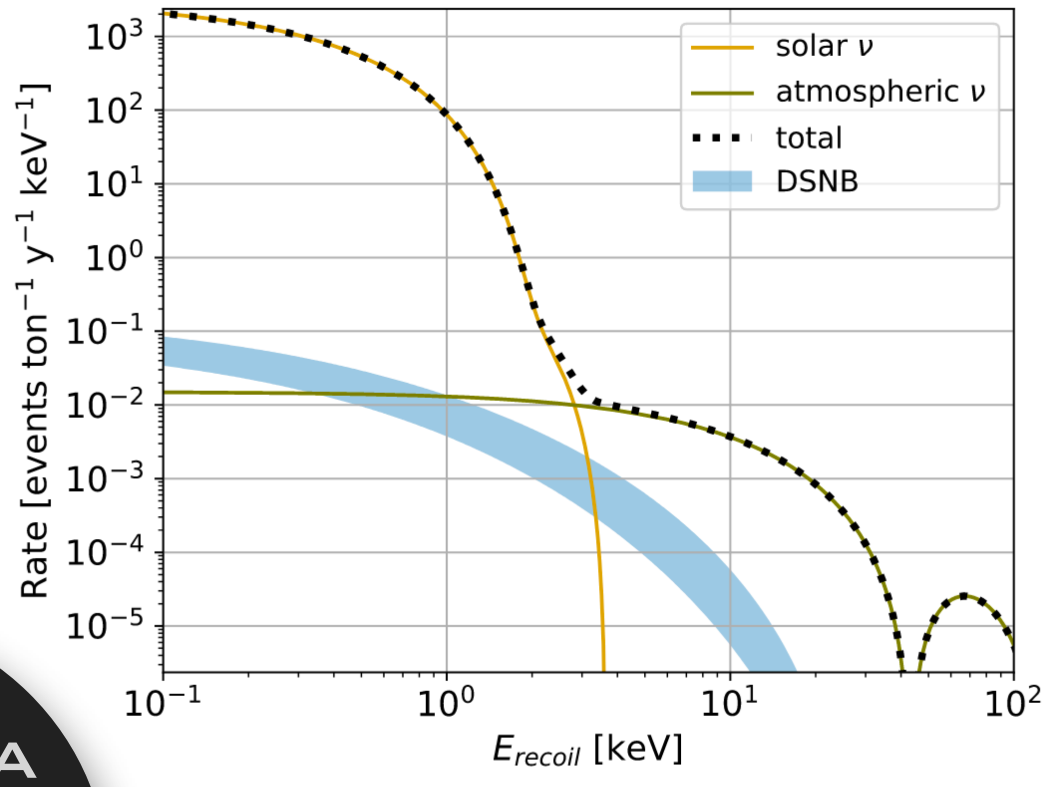
MULTI-DISCIPLINARITY

Core Collapse model discrimination

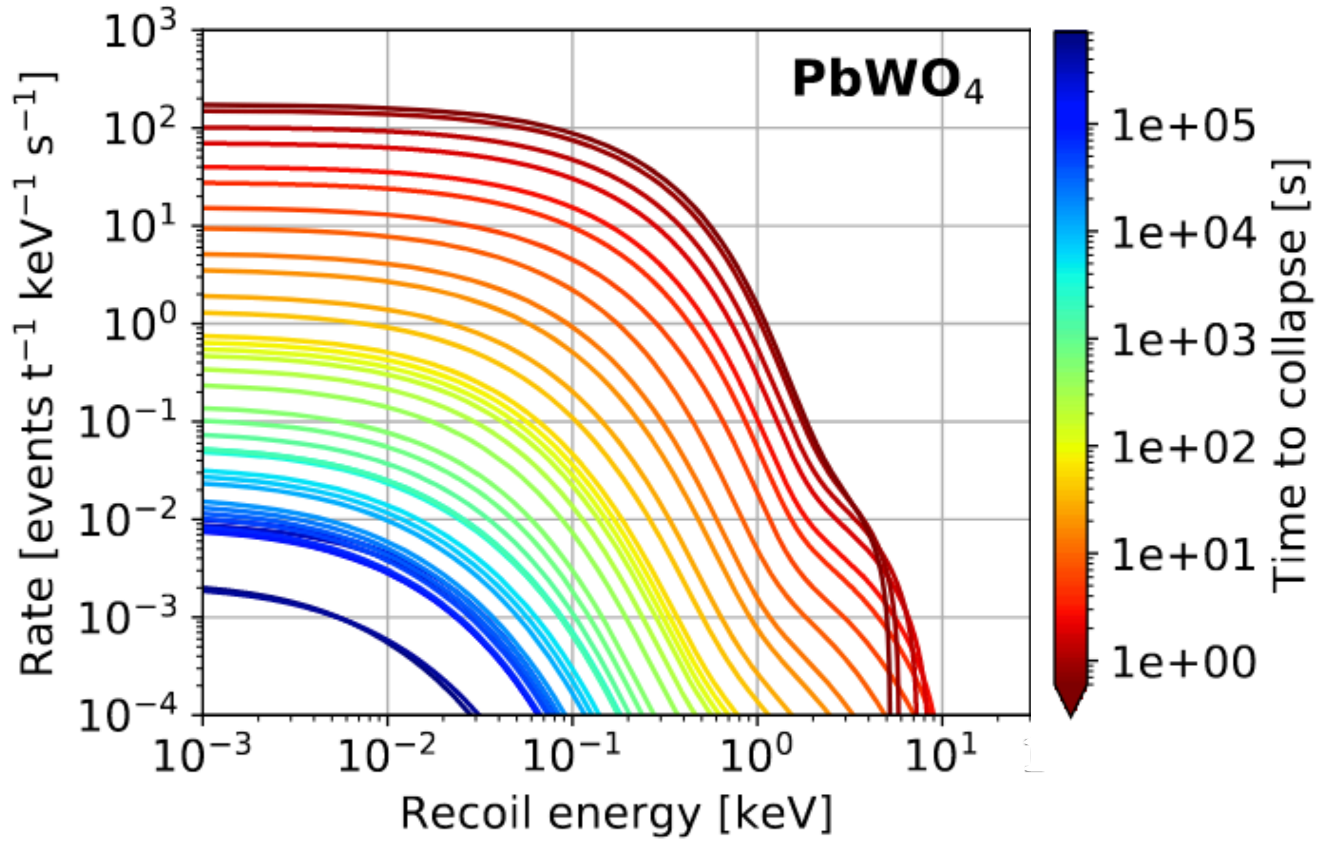


RES-NOVA

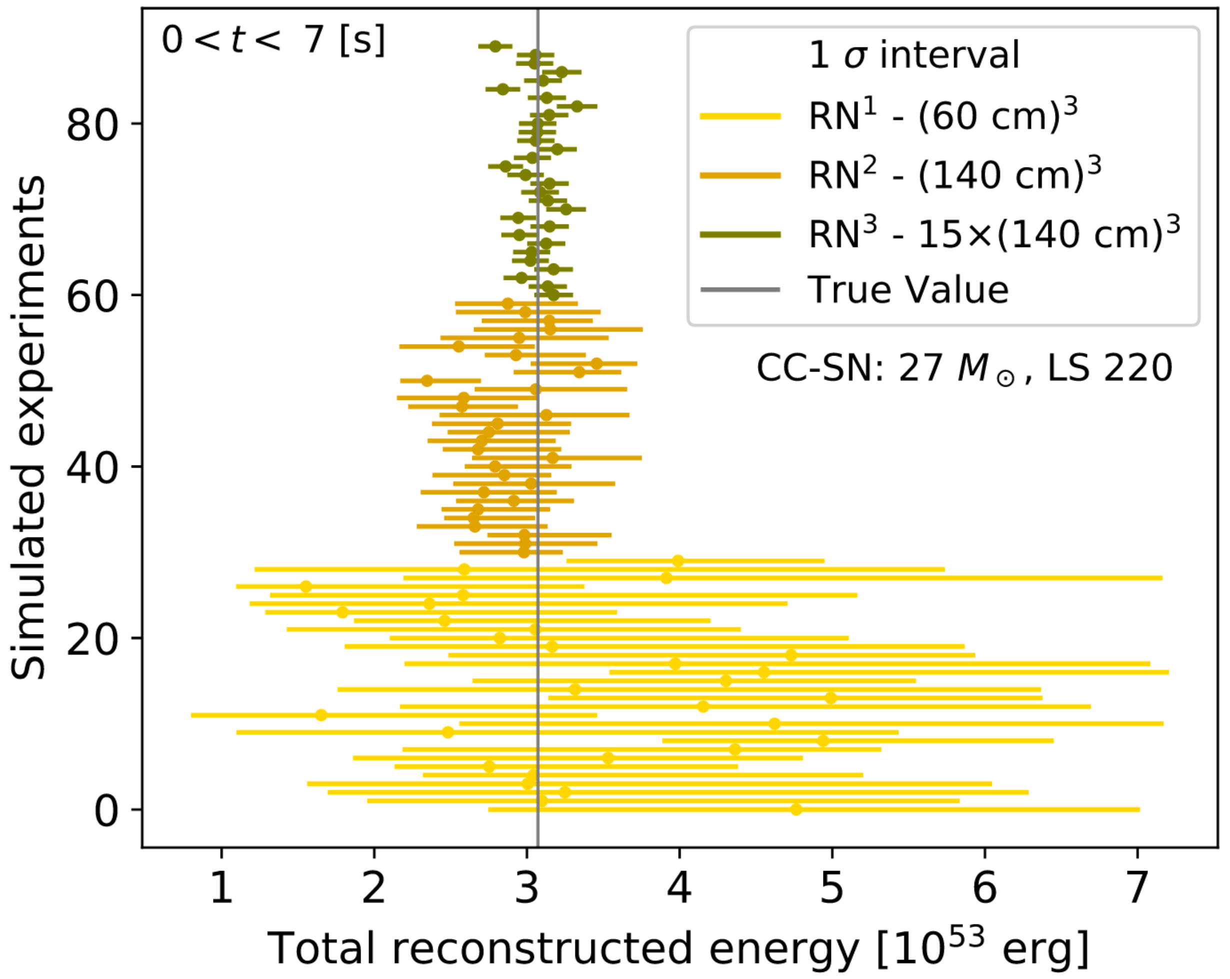
Diffuse SN neutrino Background



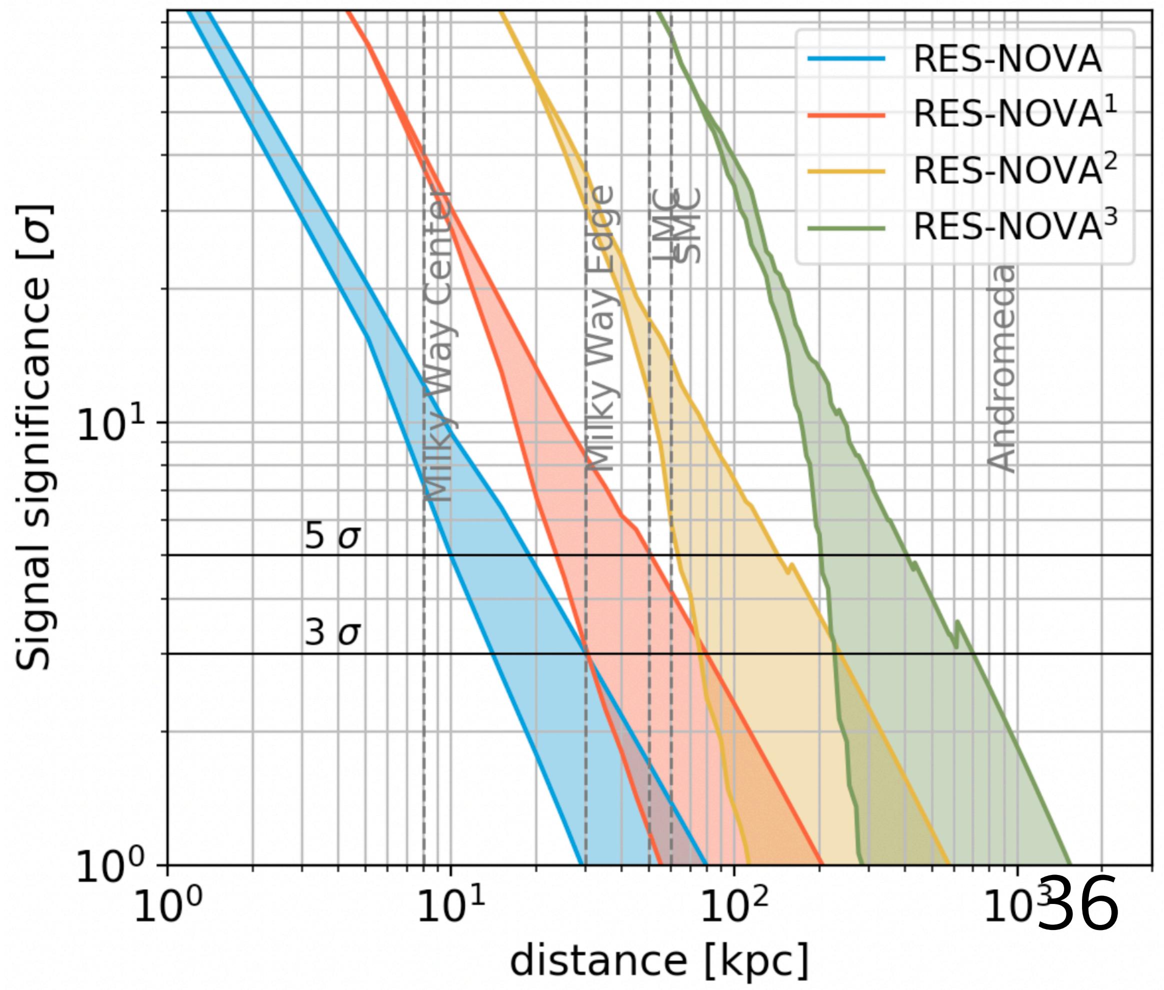
Pre-SN neutrino detection



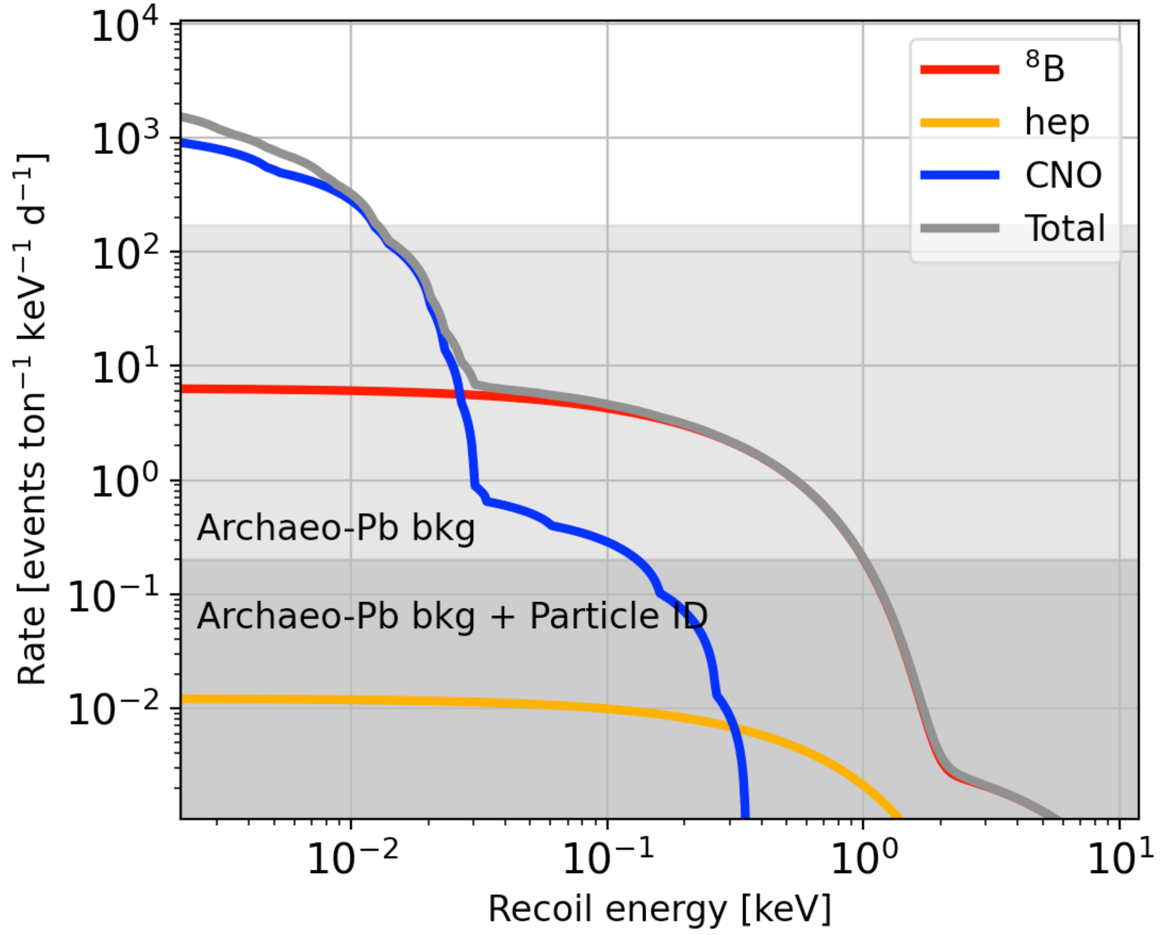
Precise ε_{tot} reconstruction



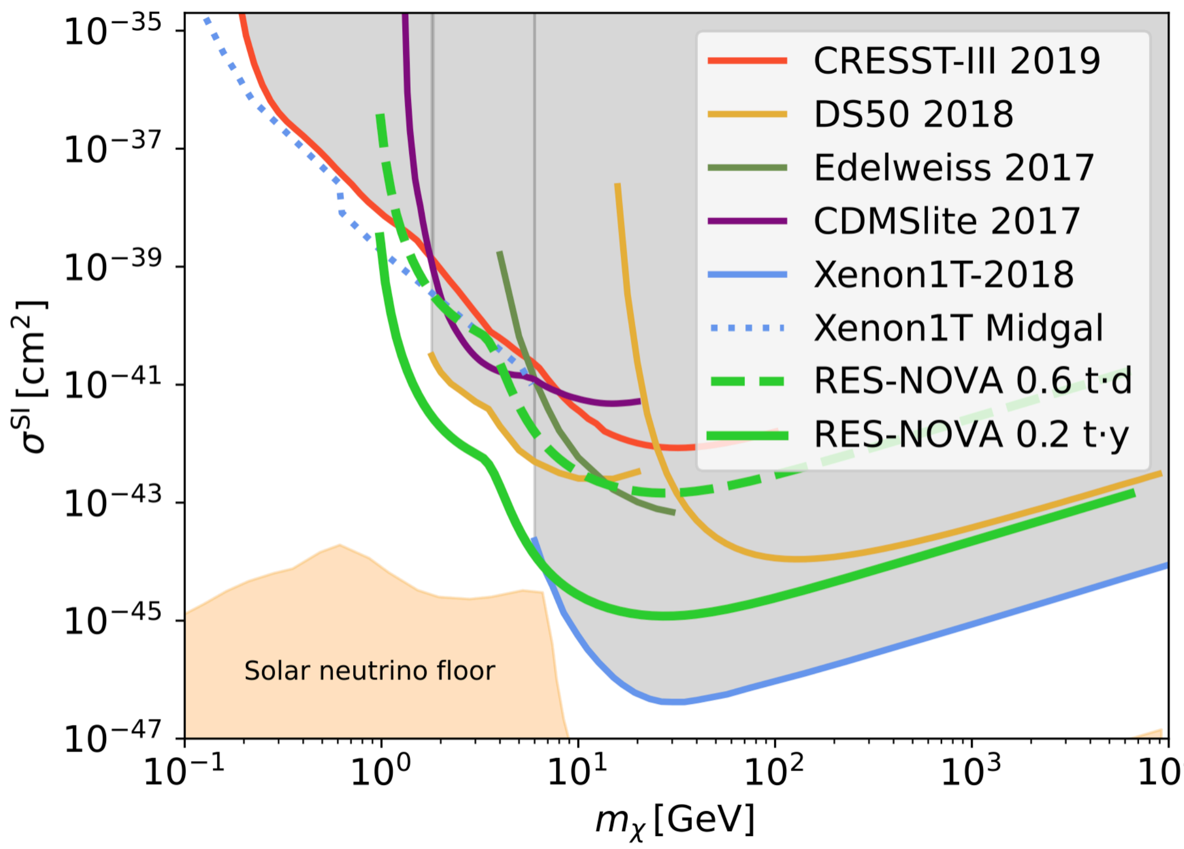
Deep space exploration



Solar neutrinos



Direct DM searches

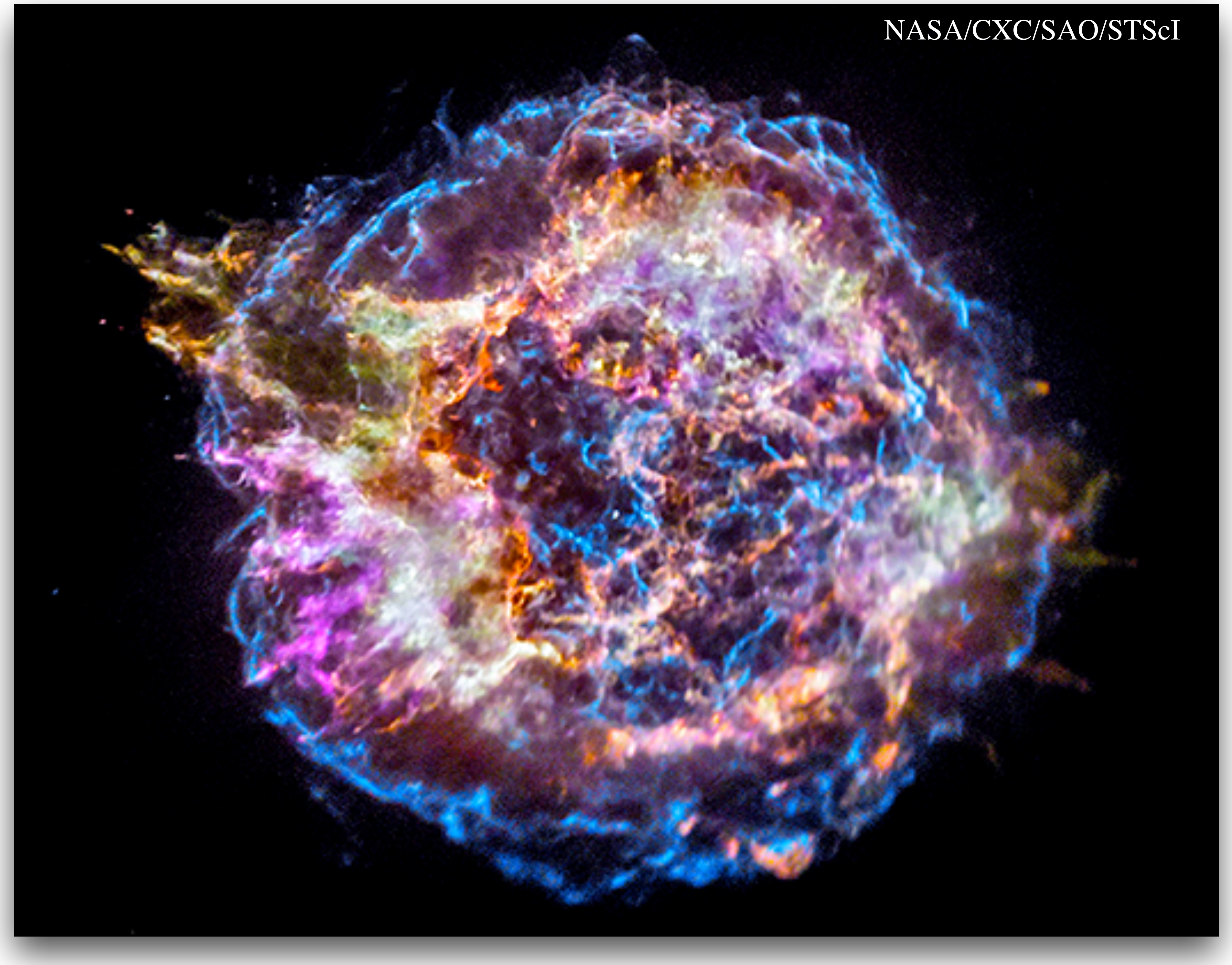


P. Eller, LP et al JCAP 10 (2022) 024
LP et al., JCAP 10 (2021) 064
LP et al., Phys. Rev. D 102, 063001 (2020)

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


NASA/CXC/SAO/STScI

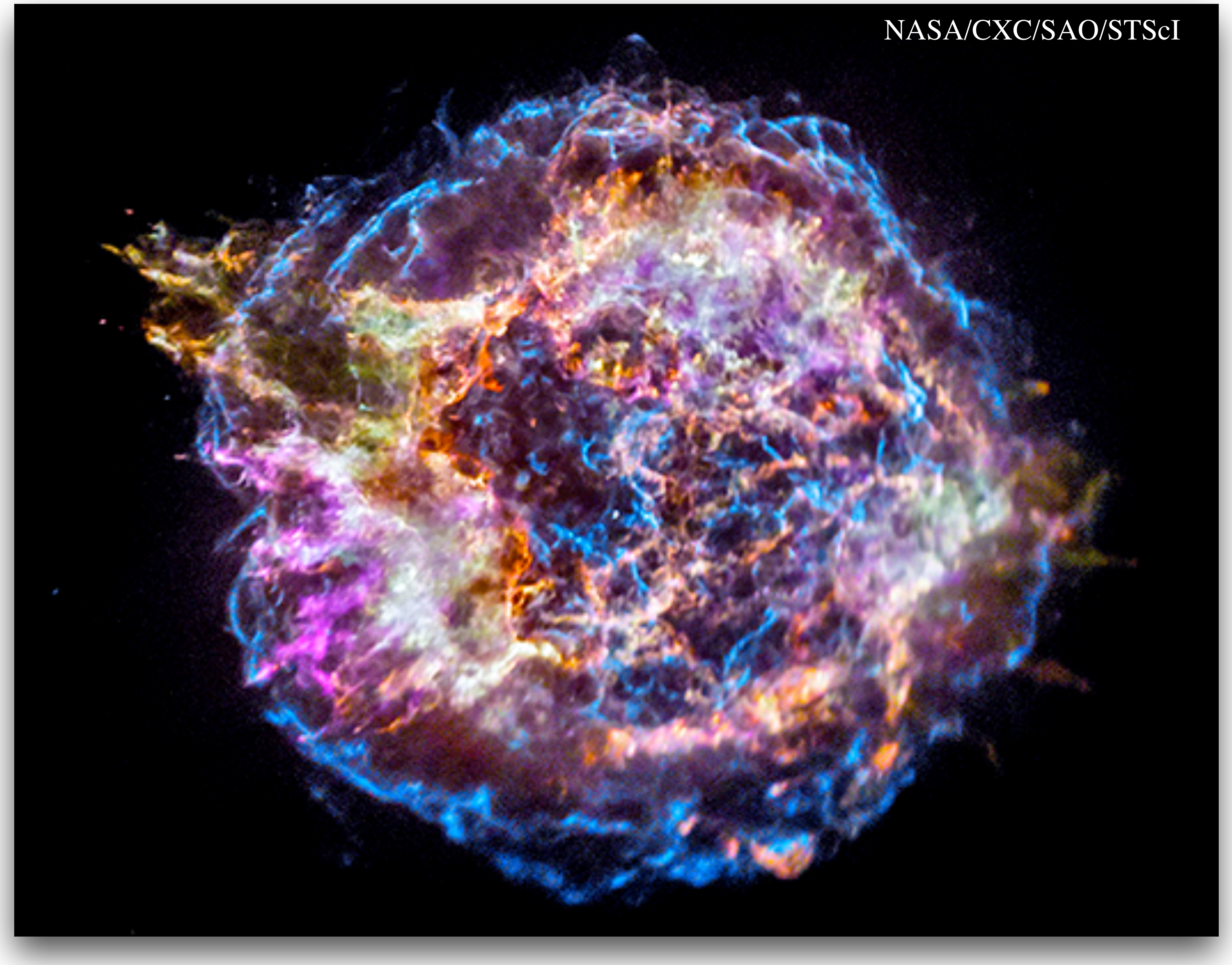
ARE WE READY FOR THE NEXT SN ?

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

Innovative experimental approach
Multi-disciplinarity

Feasibility
Proof of principle detectors gave promising results

Timeliness
In the next 5 y there is ~10% of probability to observe a SN


NASA/CXC/SAO/STScI