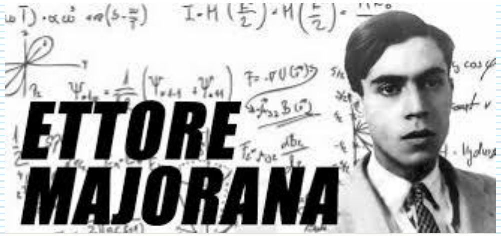
Symposium on Science at PAUL
(Paarl Africa Underground Laboratory)
Du Kloof Lodge, Du Toitskloof Mountains, South Africa
Beijing, China – January 15-18, 2024

A request for a study of β-decays and the ENIGMA project

Fedor Šimkovic

ARE NEUTRINOS THEIR OWN ANTIPARTICLES?



3[rd] SOUTH AFRICA - JINR SYMPOSIUM

Few to Many Body Systems: Models, Methods and Applications

November 27 - 30, 2012, Stellenbosch University, South Africa

- main
- General info
- Important dates
- Circular
- Programme
- Schedule
- Registration
- Participants
- Visa
- Accomodation

Welcome! November 27 - 30, 2012

The Symposium program will cover new experimental and theoretical developments in the field of nuclear physics, applied nuclear physics, condensed matter physics and physics of underground laboratories in the context of the South Africa - JINR collaboration.

Main topics:

- Dense matter in heavy ion collisions and astrophysics
- Nuclear reactions, beams and facilities, techniques and applications
- Nuclear structure, clusters, modern microscopical methods
- Physics of few-body, atomic and molecular systems
- Computational and mathematical methods in many-body physics
- Nonlinear phenomena in condensed matter
- Towards the underground laboratory and particle astrophysics

Symposiums JINR – South Africa

2. Dubna (2010)
3. Blaauwklippen wine farm (2012)
4. Dubna (2015)
5. Sommerset West (2018)

Among participants:

S. Wyngaardt, R. Newman, R. de Meijer I. Štekl, F.Š

International Symposium on Exciting Physics Makutsi Safari Farm, South Africa (2011)

Dubna 2015

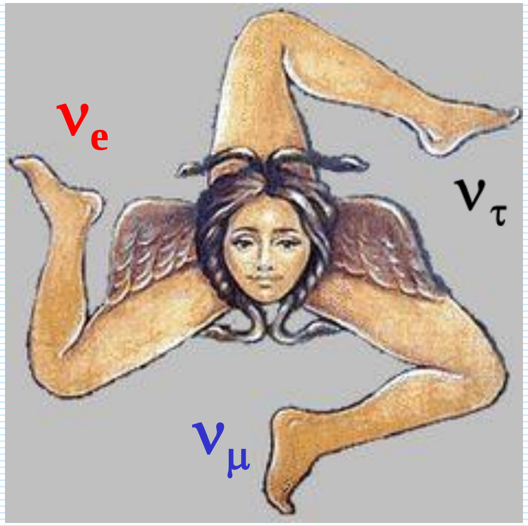
Session(s): *Physics at Underground Laboratory*
Conveners: F. Šimkovic, S. Wyngaardt

Chairman: F. Šimkovic
14:30 D. Naumov (DLNP, JINR) 25'+5'
Neutrino Physics program at the JINR
15:00 R. Newman (Stellenbosch U.) 18'+2'
Towards SAUL - perspectives, progress and prospects for establishing enhanced low-level radioactivity measurement capability
15:20 O. Smirnov (DLNP, JINR) 18'+2'
Neutrino geophysics
15:40 A. Zakharov (ITEP Moscow) 18'+2'
Possible alternatives for models of the Galactic Centre

Conference on Neutrino and Nuclear Physics (CNNP 2020), Arabella Hotel & Spa, (2020)

Symposium on Science at PAUL (Paarl Africa Underground Laboratory) Du Kloof Lodge (2024)

OUTLINE



I. Introduction - Being too ambitious ($0\nu\beta\beta$ decay)?
(not for PAUL now)

II. Being less ambitious - $2\nu\beta\beta$ decay
(nuclear structure, beyond SM physics)

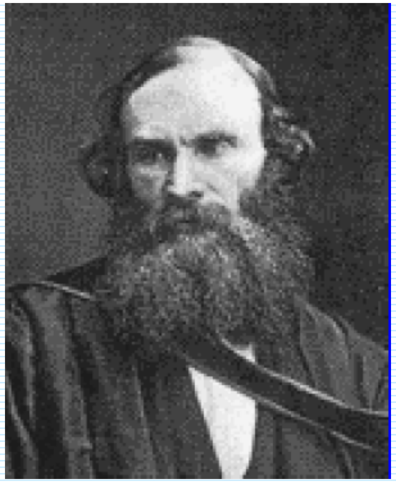
III. Atomic effects in single-β decay, EC
(electron-exchange effect)

IV. Direct Neutrino mass measurements
(^{187}Re, ^{115}In)

V. Detection of reactor antineutrinos – towards geoneutrino detection (ENIGMA – prototype of a detector)

V. Neutrino telescope in South Africa
(a new challenge)?

Physics at the beginning of 20th century



„There is nothing new to be discovered in physics now, all that remains is more and more precise measurements“

Kelvin. 1900

In vino veritas

(Western Cape is a good location for PAUL)

Physics at the beginning of 21th century

ν-physics can answer many of these fundamental questions:

+ Origin of the Universe – relic neutrinos
+ Dominance of matter over antimatter in Universe
+ Dark matter, dark energy of Universe
+ Understanding Sun, stars, supernova explosion
+ cosmic rays, cosmic accelerators
+ collisions of black holes and neutron stars
+ Look inside the Earth - geoneutrinos
+ beyond Standard model physics, GUTs
+ monitoring nuclear reactor
+ etc.

Like most people, physicists enjoy a good mystery.

When you start investigating a mystery you rarely know where it is going

Majorana fermions

Ettore Majorana

Teoria simmetrica dell'elettrone e del positrone (A symmetric theory of electrons and positrons).

Il Nuovo Cimento, 14: 171–184, 1937.) 171

ν is its own antiparticle

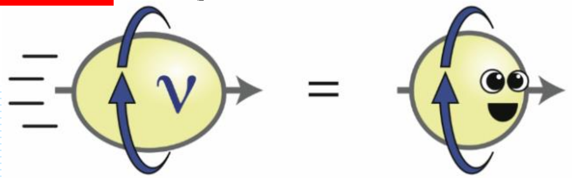
Bruno Pontecorvo

Inverse beta processes and nonconservation of lepton charge

Zhur. Eksptl'. i Teoret. Fiz. 34, 247 (1958)

It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are "mixed" particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different combined parity.[5]

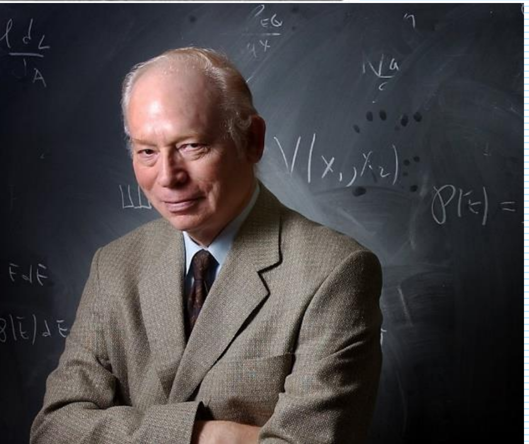
ν ↔ anti-ν oscillation



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 57 NUMBER 9 NOVEMBER 2017



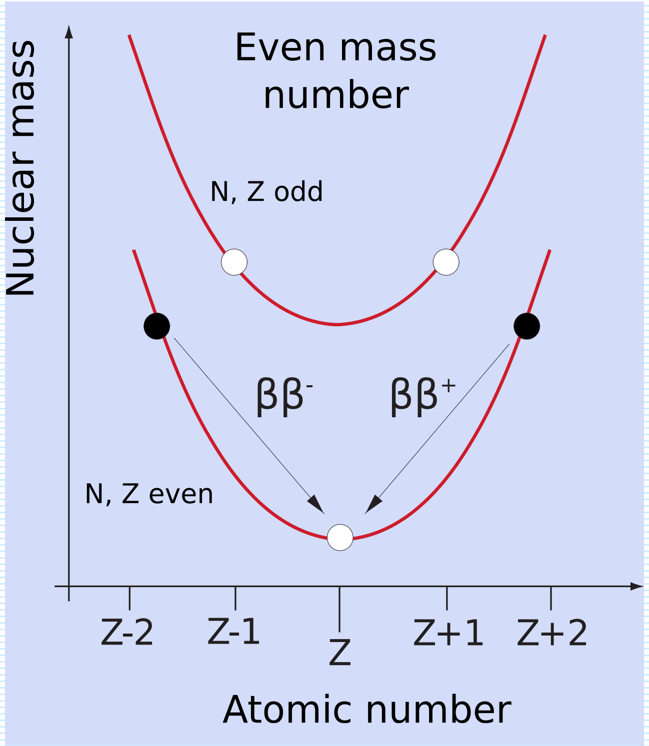
Steve Weinberg

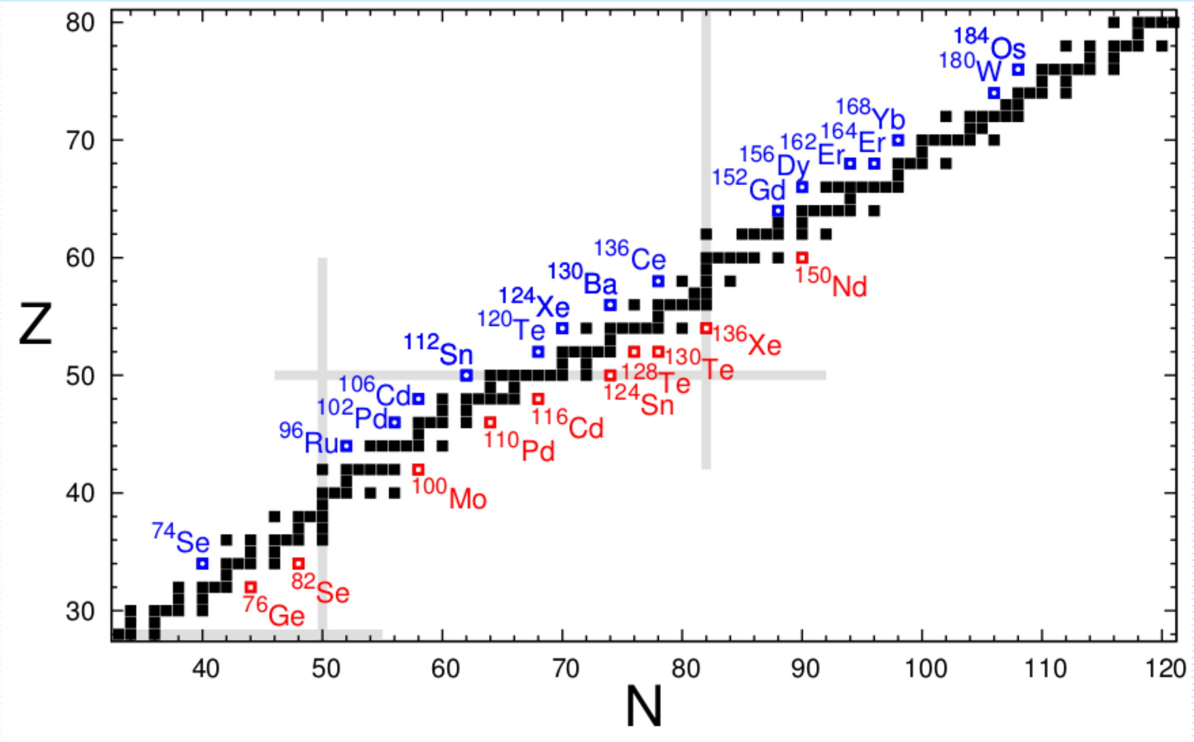
ν-mass generation via d=5 eff. oper. related to unknown high energy scale (GUT?)

thought massless back in 1979. Weinberg does not take credit for predicting neutrino masses, but he thinks it's the right interpretation. What's more, he says, the non-renormalisable interaction that produces the neutrino masses is probably also accompanied with non-renormalisable interactions that produce proton decay and other things that haven't been observed, such as violation of baryon-number conservations. "We don't know anything about the details of those terms, but I'll swear they are there."

Nuclear double-β decay

(even-even nuclei, pairing int.)





Phys. Rev. 48, 512 (1935)

Two-neutrino double-β decay – LN conserved

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^- + \nu_e + \nu_e$$

Goepert-Mayer – 1935. 1st observation in 1987

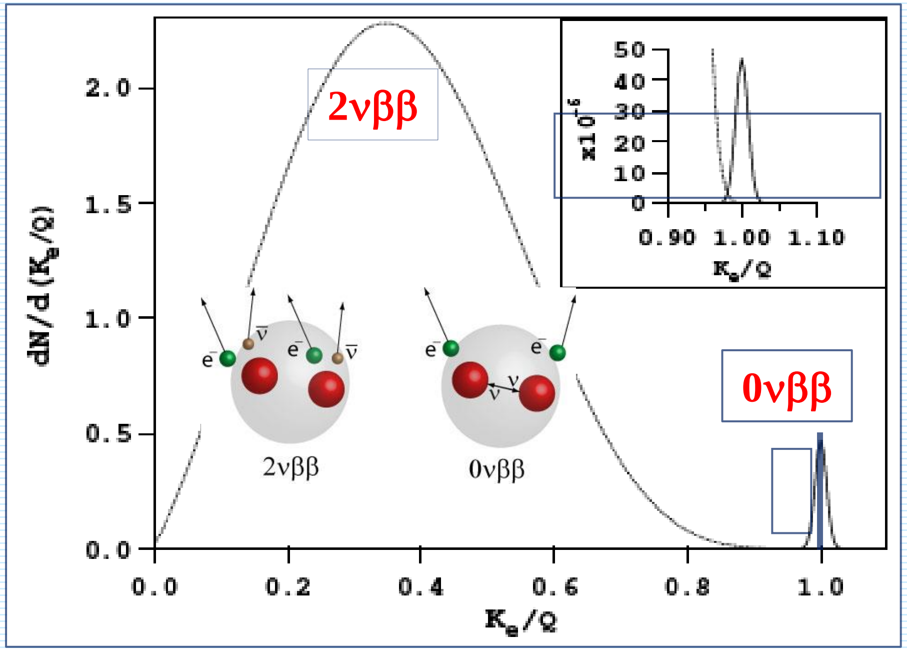
Nuovo Cim. 14, 322 (1937)

Phys. Rev. 56, 1184 (1939)

Neutrinoless double-β decay – LN violated

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^- \quad \text{(Furry 1937)}$$

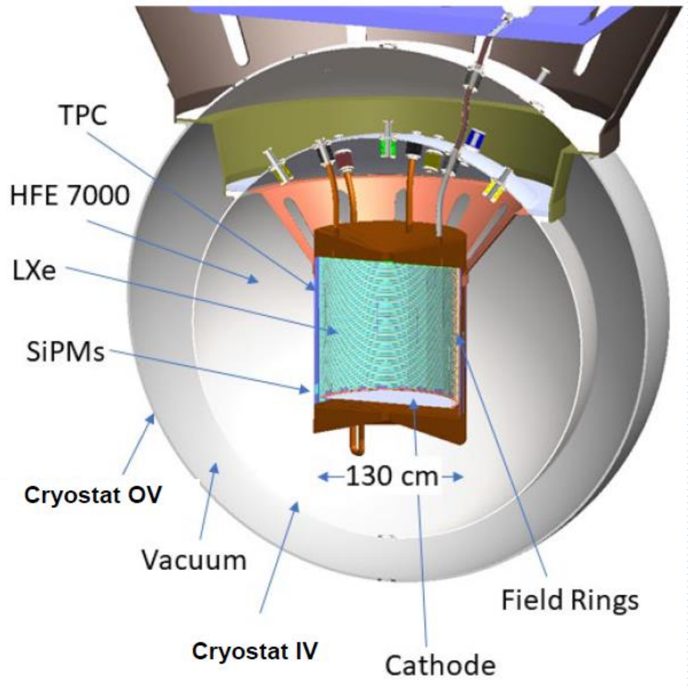
Not observed yet. Requires massive Majorana ν's

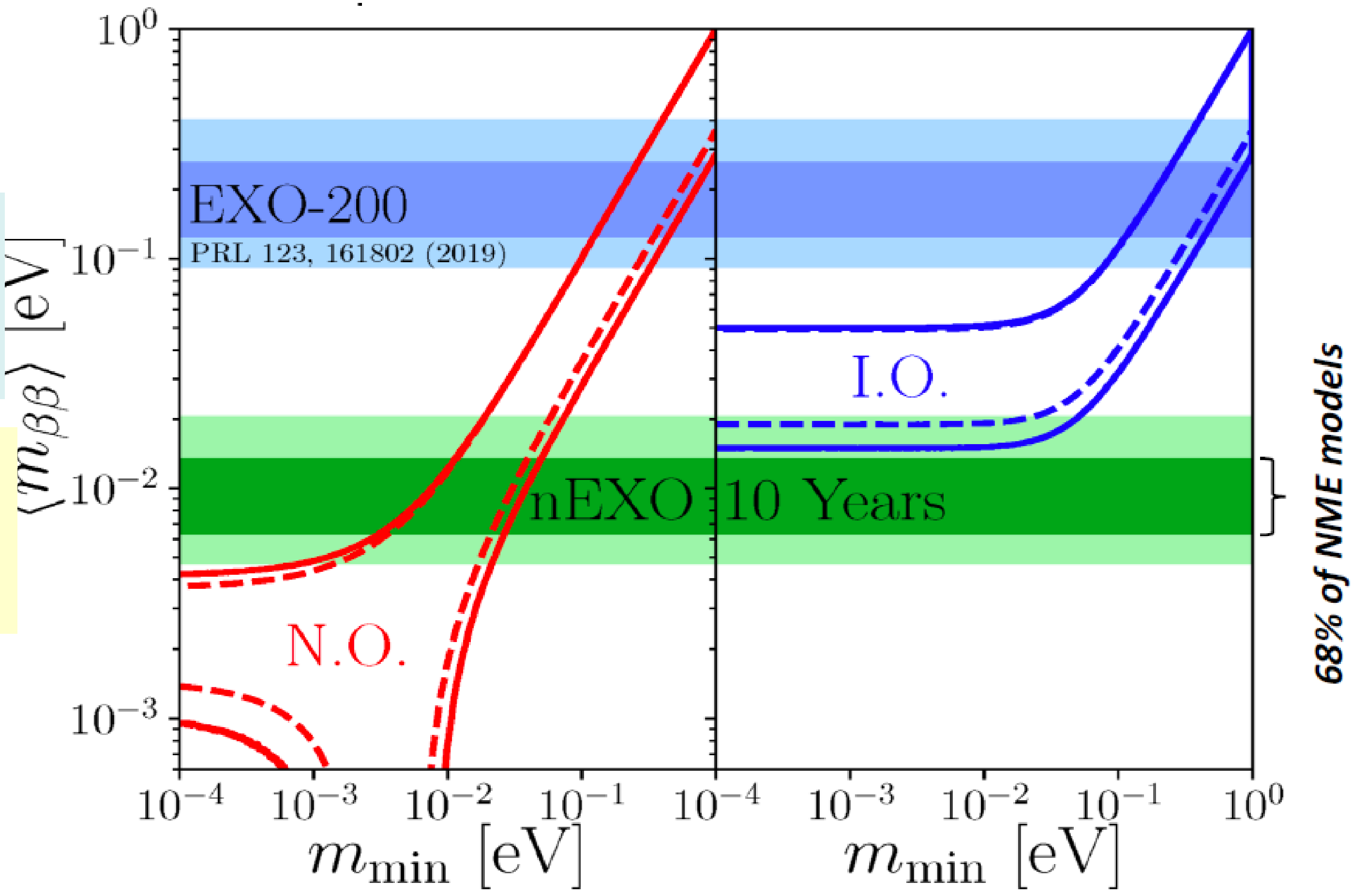


nEXO
5 ton-class ^{136}Xe 0νββ experiment

EXO-200, 1st 100 kg-class 0νββ-experiment, excellent background-essential for nEXO design, Sensitivity increased linearly with exposure.

nEXO, discovery 0νββ experiment, reaches sensitivity of 10^{28} yr in 6.5 yr data taking, probes $m_{\beta\beta}$ down to 15 meV, scalable experiment.



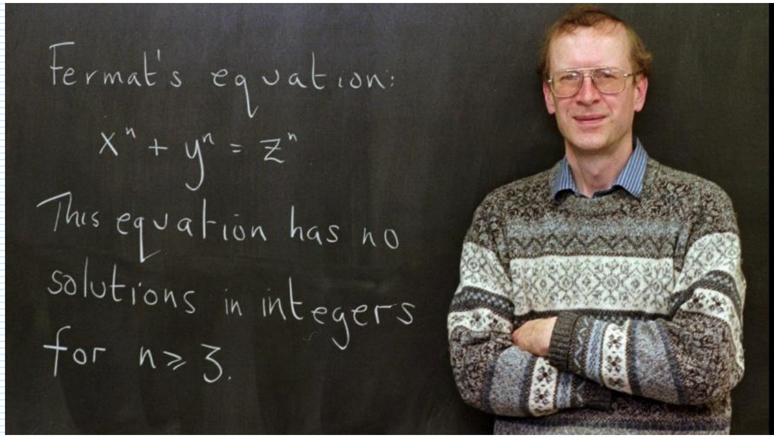


	isotope	$m_{\beta\beta}$ [meV] 90% excl. sensitivity	$m_{\beta\beta}$ [meV] 3 σ discovery potential
Legend	^{76}Se	8.2	11.1
CUPID	^{100}Mo	11.1	12.0
nEXO	^{136}Xe	12.9	15.0

Around **1637**, Pierre de Fermat wrote in the margin of a book that the more general equation

$$a^n + b^n = c^n$$

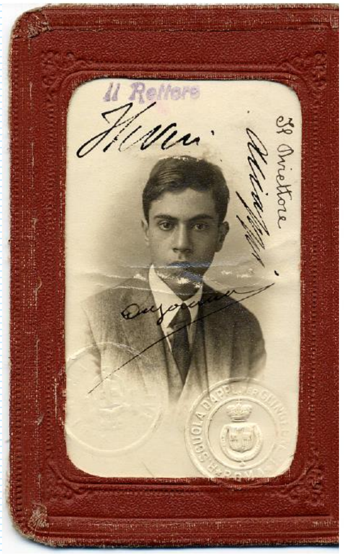
had no solutions in positive integers if n is an integer greater than **2**.



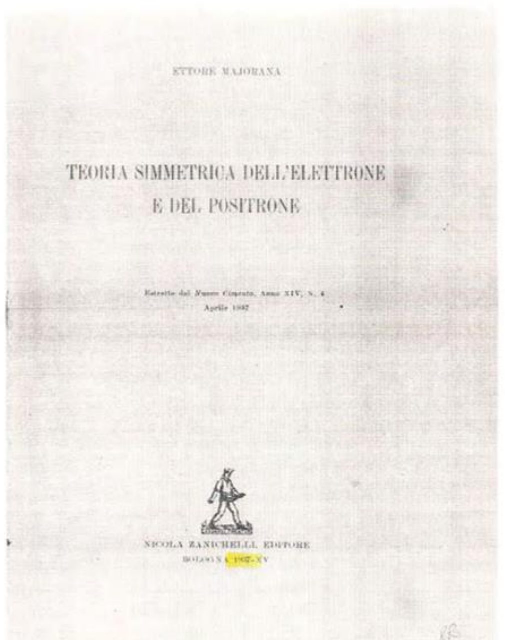
After **358** years

The proof was published by Andrew Wiles in **1995**.

Some long-standing tasks of humanity …



1937



After **85** years

n-ton-class $0\nu\beta\beta$ exp. with discovery potential

- KamLAND-Zen 800
- SNO+
- LEGEND
- nEXO
- NEXT
- CUPID
- etc

After **?** years

If $m_{\beta\beta}$ < 1 meV, what technology is needed for observation of $0\nu\beta\beta$?

2νββ is sensitive to New Physics

All 100 kg- and ton-class 0νββ experiments can also study a diverse range of exotic phenomena, e.g. through spectral distortion in $2\nu\beta\beta$.
Future searches will probe the $2\nu\beta\beta$ with high statistics about 10^5-10^6 events.

Common subjects:

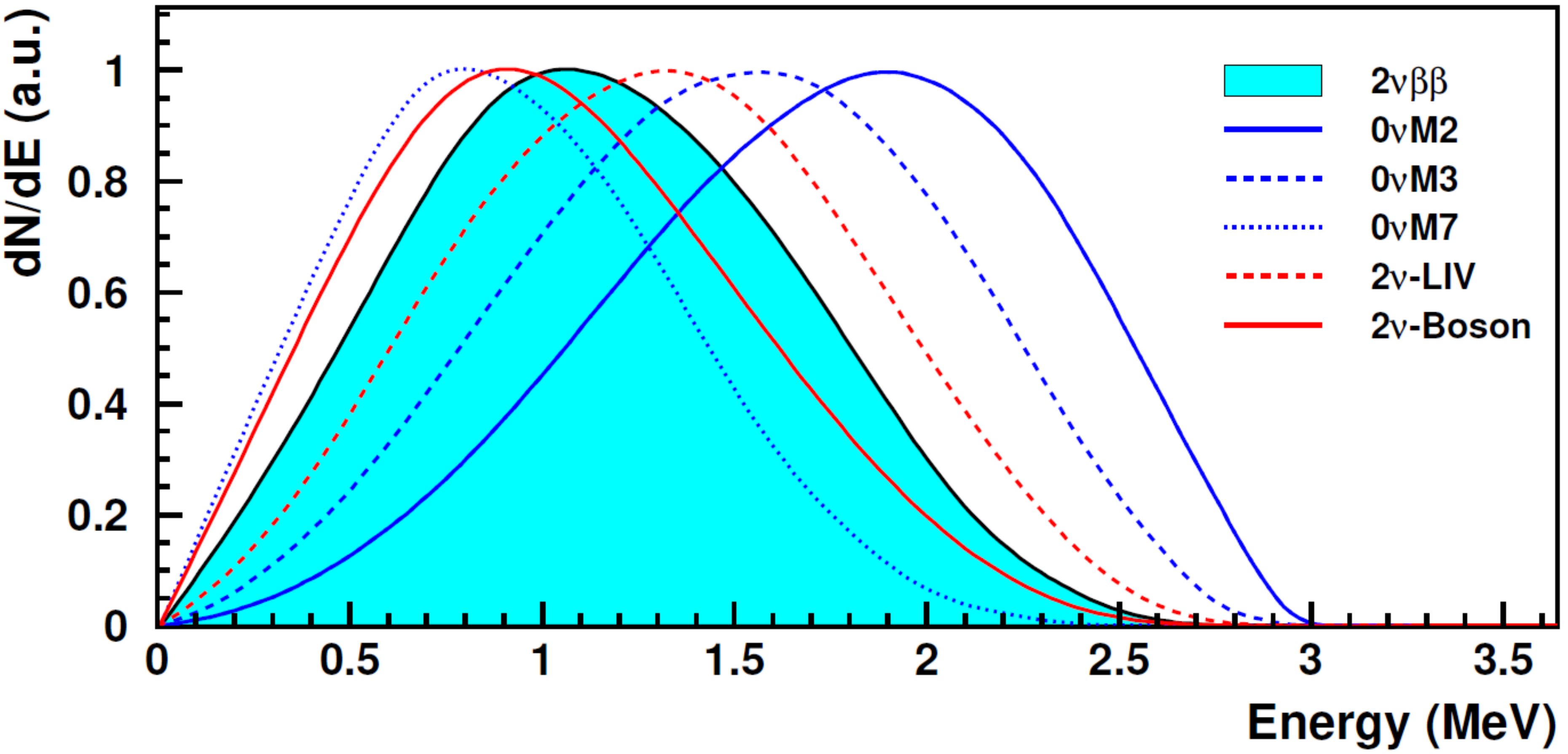
Majoron(s) emission
(partly)bosonic neutrinos,
Lorentz invariance violation

Recent subjects:

Lepton-number conserving right-handed currents
(PRL 125 (2020) 17, 171801)

Neutrino self-interactions
(PRD 102 (2020) 5, 051701)

Sterile neutrino and light fermion searches through energy end point
(PRD 103 (2021) 5, 055019;
PLB 815 (2021) 136127)



$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n \left[p_1 \varepsilon_1 F(\varepsilon_1)\right] \left[p_2 \varepsilon_2 F(\varepsilon_2)\right]$$

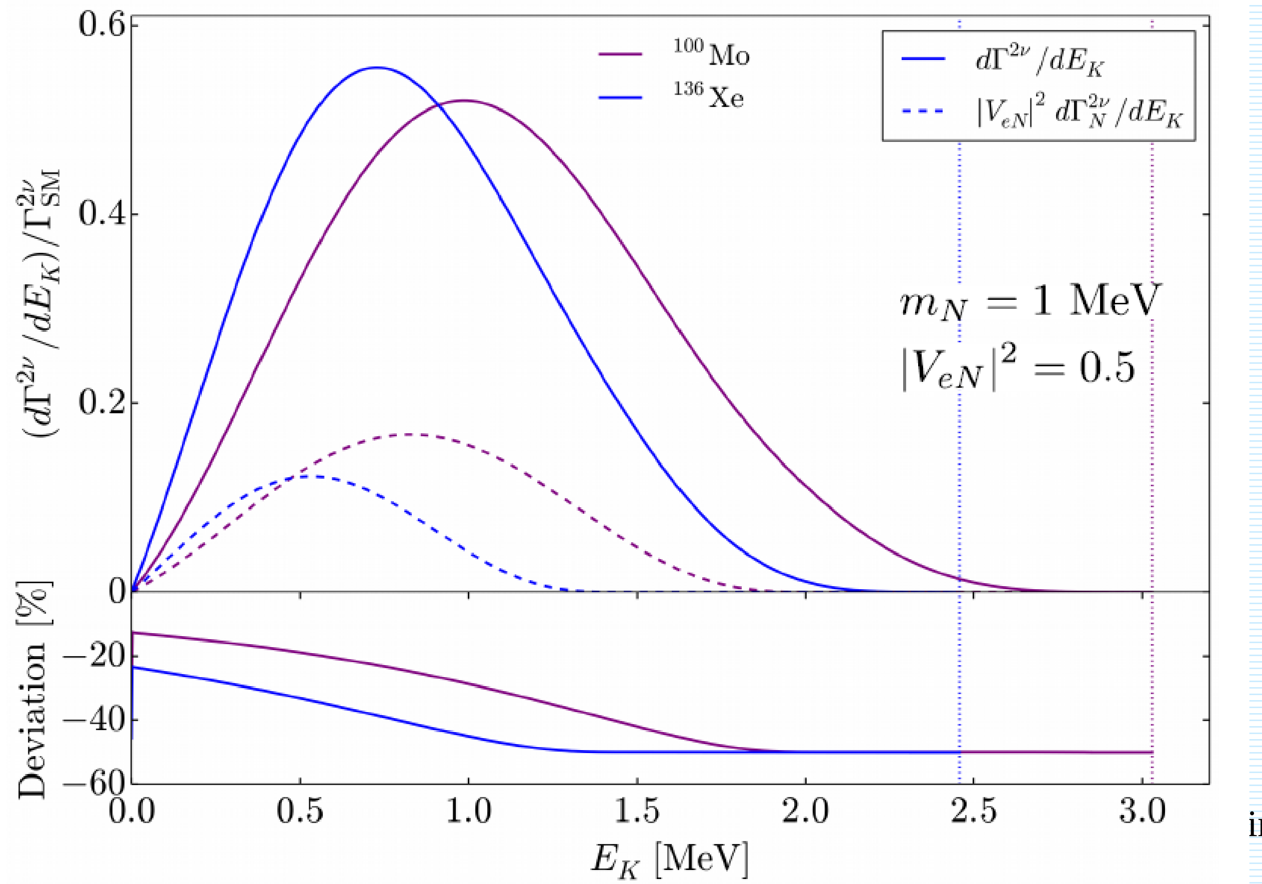
Spectral index n

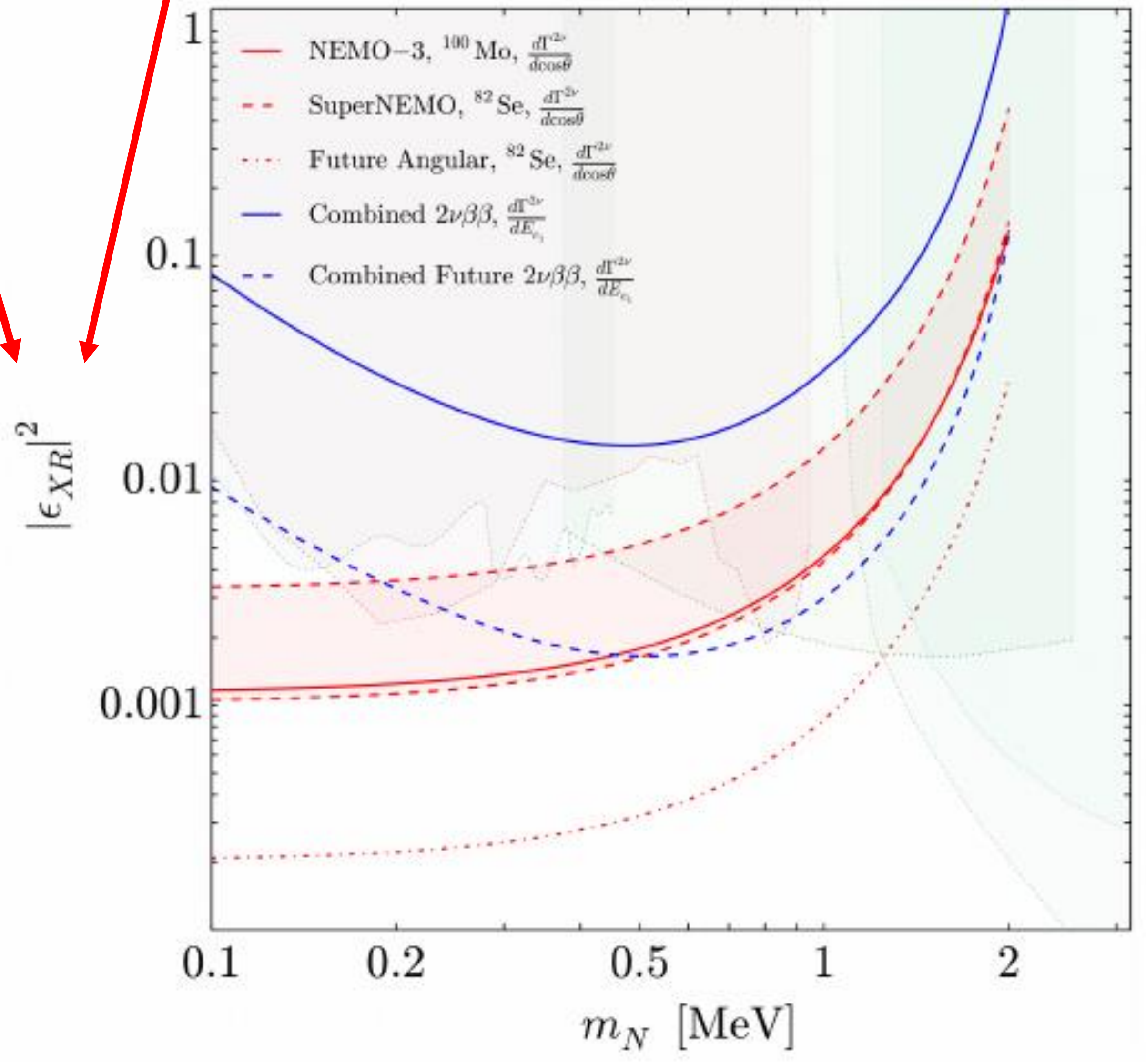
$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left[(1+\delta_{\mathrm{SM}}) j_L^{\mu} J_{L\mu} + V_{eN} j_L^{N\mu} J_{L\mu} + \epsilon_{LR} j_R^{N\mu} J_{L\mu} + \epsilon_{RR} j_R^{N\mu} J_{R\mu} \right] + \mathrm{h.c.}$$

Exotic 2νββ Sterile Neutrino (or HNL)

Consider either mixing of sterile ν with active ν, or right-handed currents

Phys.Rev.D 103 (2021) 055019





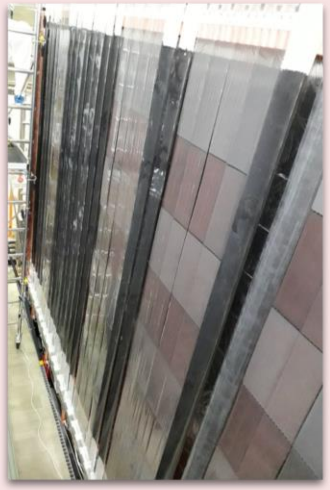
SuperNEMO Double-Beta Decay Experiment

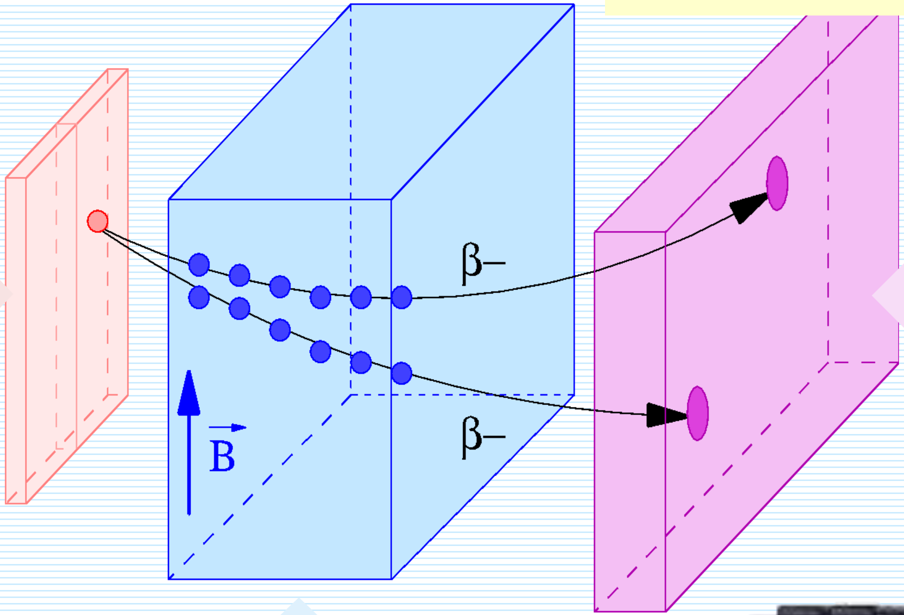
Unique tracker -calorimeter technology

- **Excellent background rejection**
- Disentangle $0\nu\beta\beta$ **mechanisms:** V+A, sterile ν…
- Nuclear physics: constrain g_A in $2\nu\beta\beta$

Source foil

^{82}Se or any $\beta\beta$ isotope





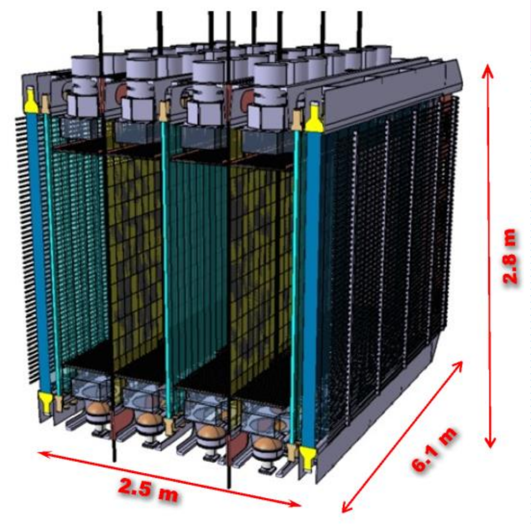
Segmented calorimeter

Individual e^- & γ energies

Tracker

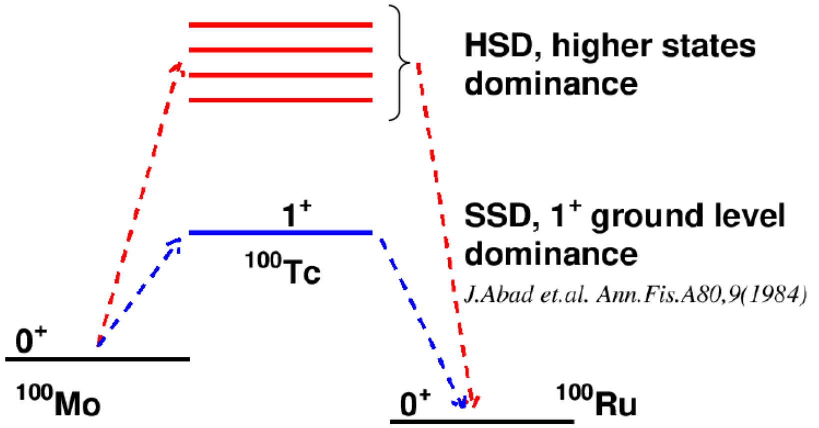
Identification of e^-, e^+, γ and α

Full $\beta\beta$ kinematics & topology

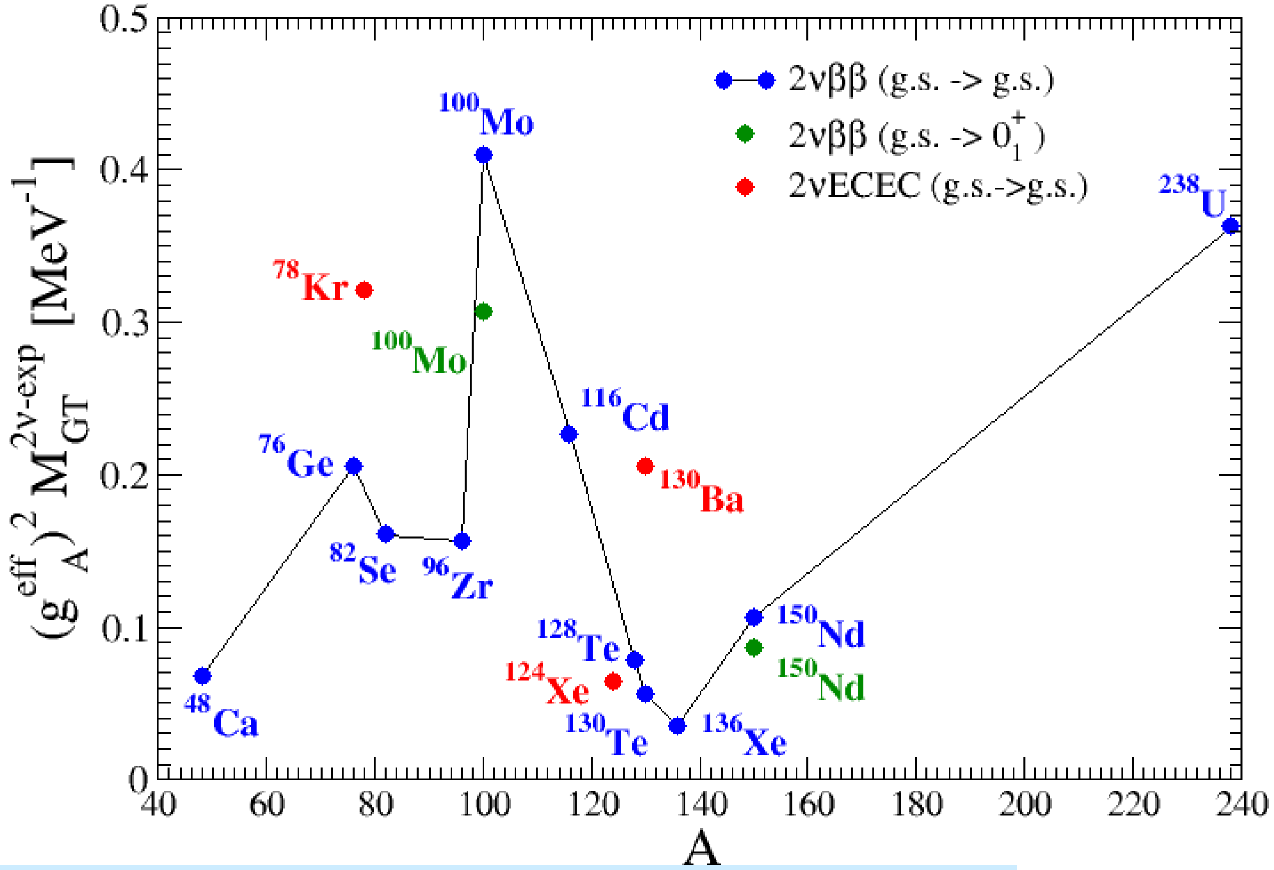


Understanding of the 2νββ-decay NMEs is of crucial importance for correct evaluation of the 0νββ-decay NMEs

There is no reliable calculation of the *2νββ-decay NMEs yet*



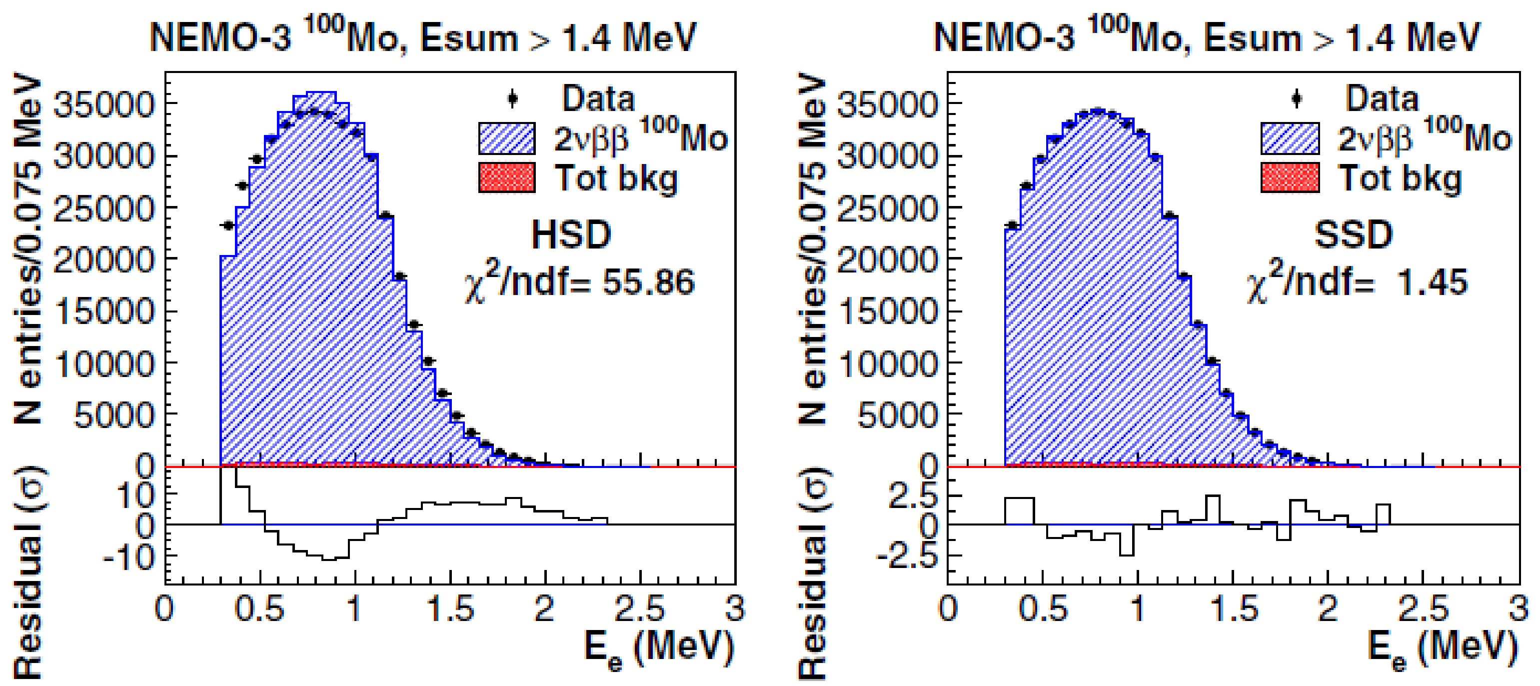
$$M_{GT}^{2\nu} = \sum_m \frac{< 0_f^+ || \tau^+ \sigma || 1_m^+ >< 1_m^+ || \tau^+ \sigma || 0_i^+ >}{E_m - E_i + \Delta}$$



The spread of 2νββ and 0νββ NMEs is large and small, respectively.
Reasons:

- **2νββ NMEs governed by contribution from single (1^+) multipole unlike 0νββ NMEs by contributions from all multipoles (J^π) of int. nucl.**
- **Neutrino potential vs 2νββ potential**

Both 2νββ and 0νββ operators connect the same states. Both change two neutrons into two protons. Explaining 2νββ-decay is necessary but not sufficient



Looking for SSD/HSD effect

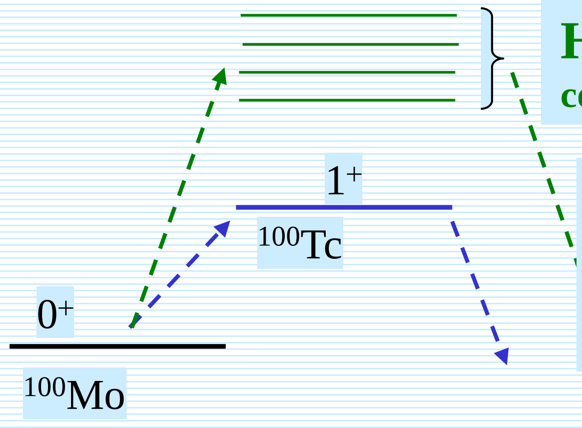
SSD favored

$\Rightarrow$

Strong trans. through low lying states of (A,Z+1);

$M_F^{2\nu} \approx 0$

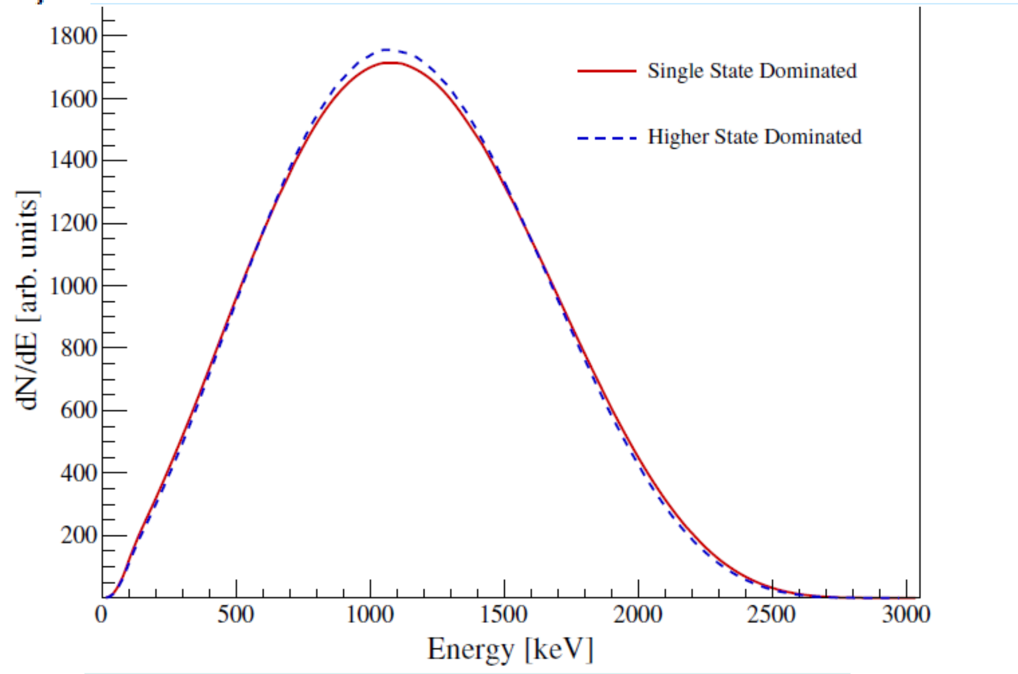
NEMO3 Collaboration, Eur. Phys. J. C79, 440 (2019)



HSD, higher levels contribute to the decay

SSD, 1^+ level dominates in the decay

(Abad et al., 1984, Ann. Fis. A 80, 9)



CUPID-0 Coll., PRL 123, 262501 (2019)

Improved description of the 0νββ–decay rate (a way to fix g_A^{eff})

F. Š, R. Dvornický, D. Štefánik, A. Faessler, PRC 97, 034315 (2018).

$$M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i+E_f)/2]^2 - \varepsilon_{K,L}^2}$$

$$\epsilon_K = (E_{e_2} + E_{\nu_2} - E_{e_1} - E_{\nu_1})/2$$
$$\epsilon_L = (E_{e_1} + E_{\nu_2} - E_{e_2} - E_{\nu_1})/2$$

Taylor expansion

$$\frac{\varepsilon_{K,L}}{E_n - (E_i+E_f)/2}$$

$$\epsilon_{K,L} \in \left(-\frac{Q}{2}, \frac{Q}{2}\right)$$

$$M_{GT-1}^{2\nu} = \sum_n M_n \frac{1}{(E_n - (E_i+E_f)/2}$$

$$M_{GT-3}^{2\nu} = \sum_n M_n \frac{4\, m_e^3}{(E_n - (E_i+E_f)/2)^3}$$

We get

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq \left(g_A^{\rm eff}\right)^4 \left|M_{GT-3}^{2\nu}\right|^2 \frac{1}{|\xi_{13}^{2\nu}|^2} \left(G_0^{2\nu} + \xi_{13}^{2\nu} G_2^{2\nu}\right)$$

$$\xi_{13}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$$

$$\xi_{15}^{2\nu} = \frac{M_{GT-5}^{2\nu}}{M_{GT-1}^{2\nu}}$$

The g_A^{eff} can be deterimed with measured half-life and ratio of NMEs and calculated NME dominated by transitions through low lying states of the intermediate nucleus (ISM)

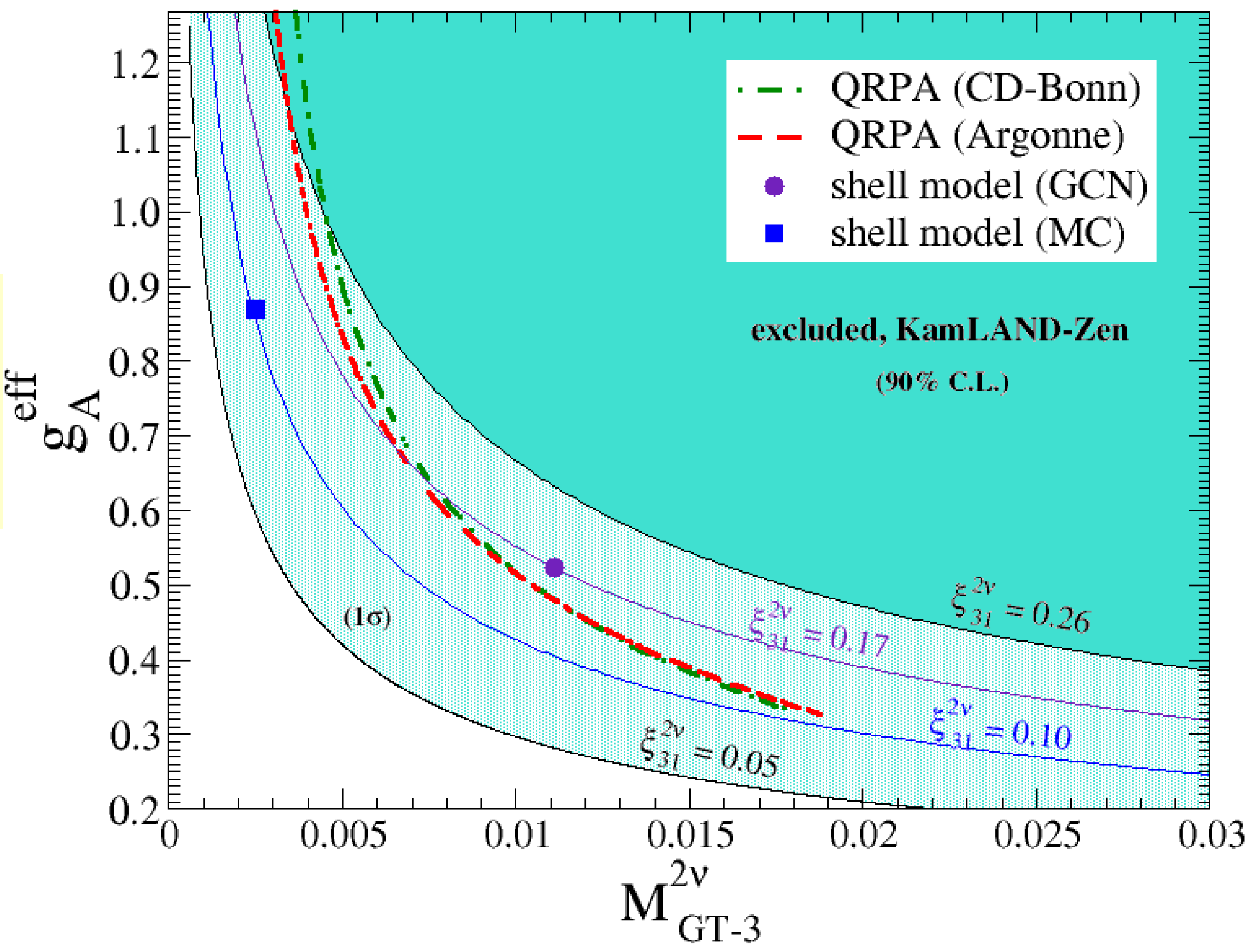
KamLAND-Zen Exp. : ξ_{13}<0.26 (^{136} Xe)

ξ_{13} can be determined phenomenologically from the shape of energy distributions of emitted electrons

The g_A^{eff} can be deterimed with measured half-life, ratio of NMEs ξ_{31} and calculated NME, dominated by transitions through low lying states of the intermediate nucleus.

$$\left(g_A^{\rm eff}\right)^2 = \frac{1}{\left|M^{2\nu}_{GT-3}\right|} \frac{\left|\xi^{2\nu}_{13}\right|}{\sqrt{T^{2\nu-exp}_{1/2}\left(G^{2\nu}_0 + \xi^{2\nu}_{13} G^{2\nu}_2\right)}}$$

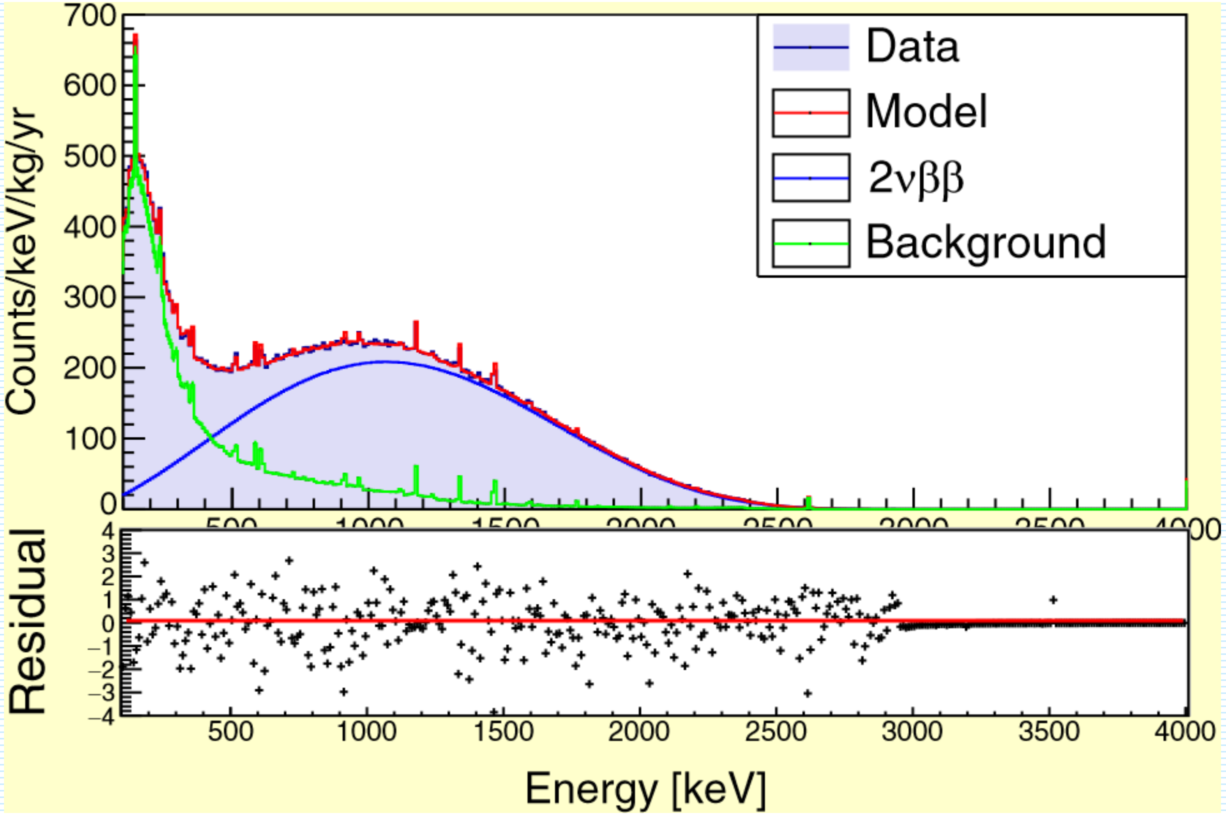
M_{GT-3} have to be calculated by nuclear theory - ISM



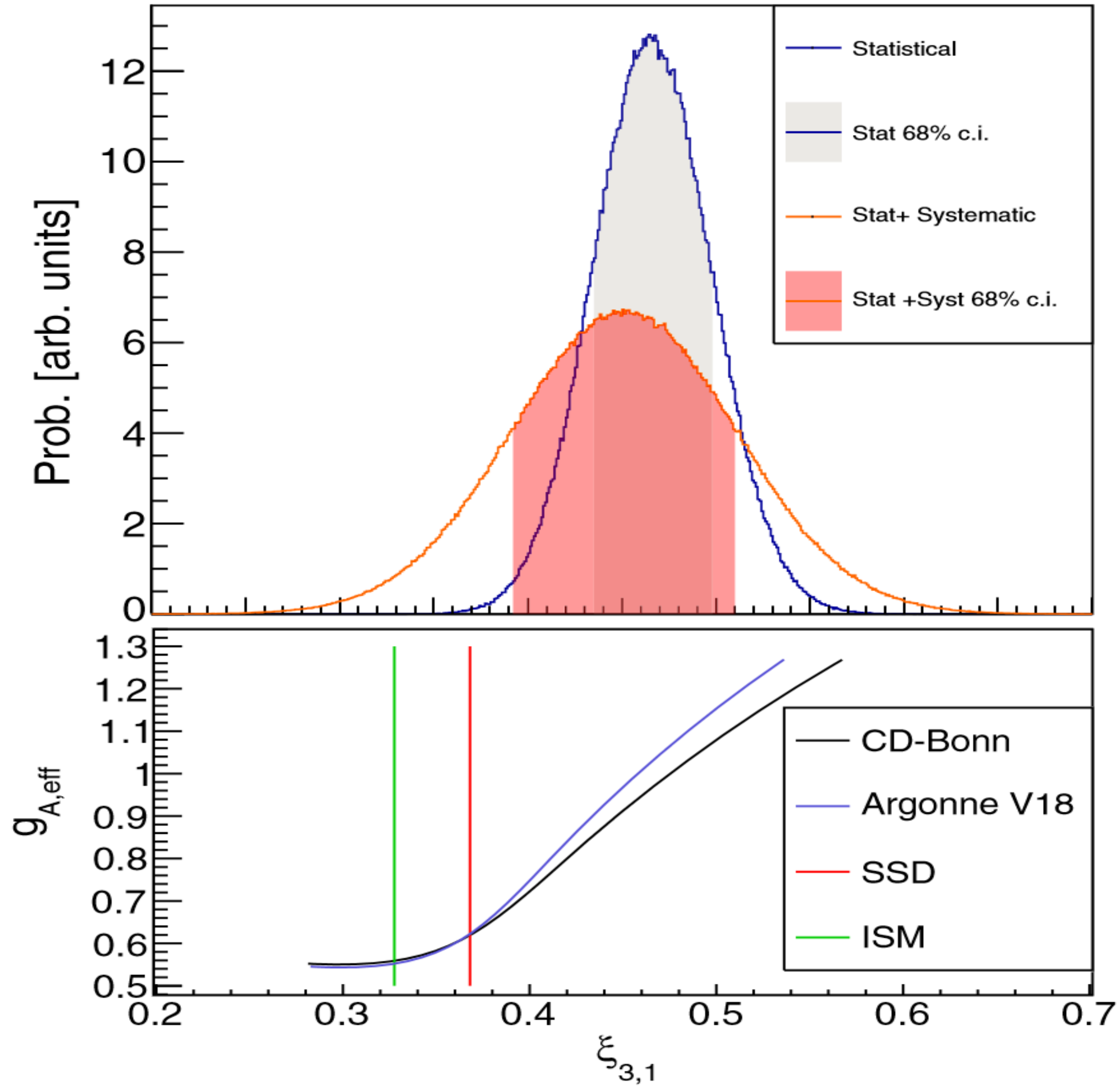
KamLAND-Zen Coll. (+J. Menendez, F.Š.), Phys.Rev.Lett. 122, 192501 (2019)

CUPID-Mo Exp. : ξ_{13}=0.45±0.03 (stat) ±0.05 (syst) (^{100} Mo)

CUPID-Mo Coll. (+F.Š.), Phys.Rev.Lett. 131, 162501 (2023)



$T_{1/2}$ = [7.07±0.02(stat)±0.11(syst)] x 10^{18} yr



ξ_{51}/ξ_{31} = 0.364-0.368 (QRPA), 0.367 (SSD), 0.349 (ISM)

g_A^{eff} (pnQRPA) = 1.0 ±0.1(stat)±0.2(syst)

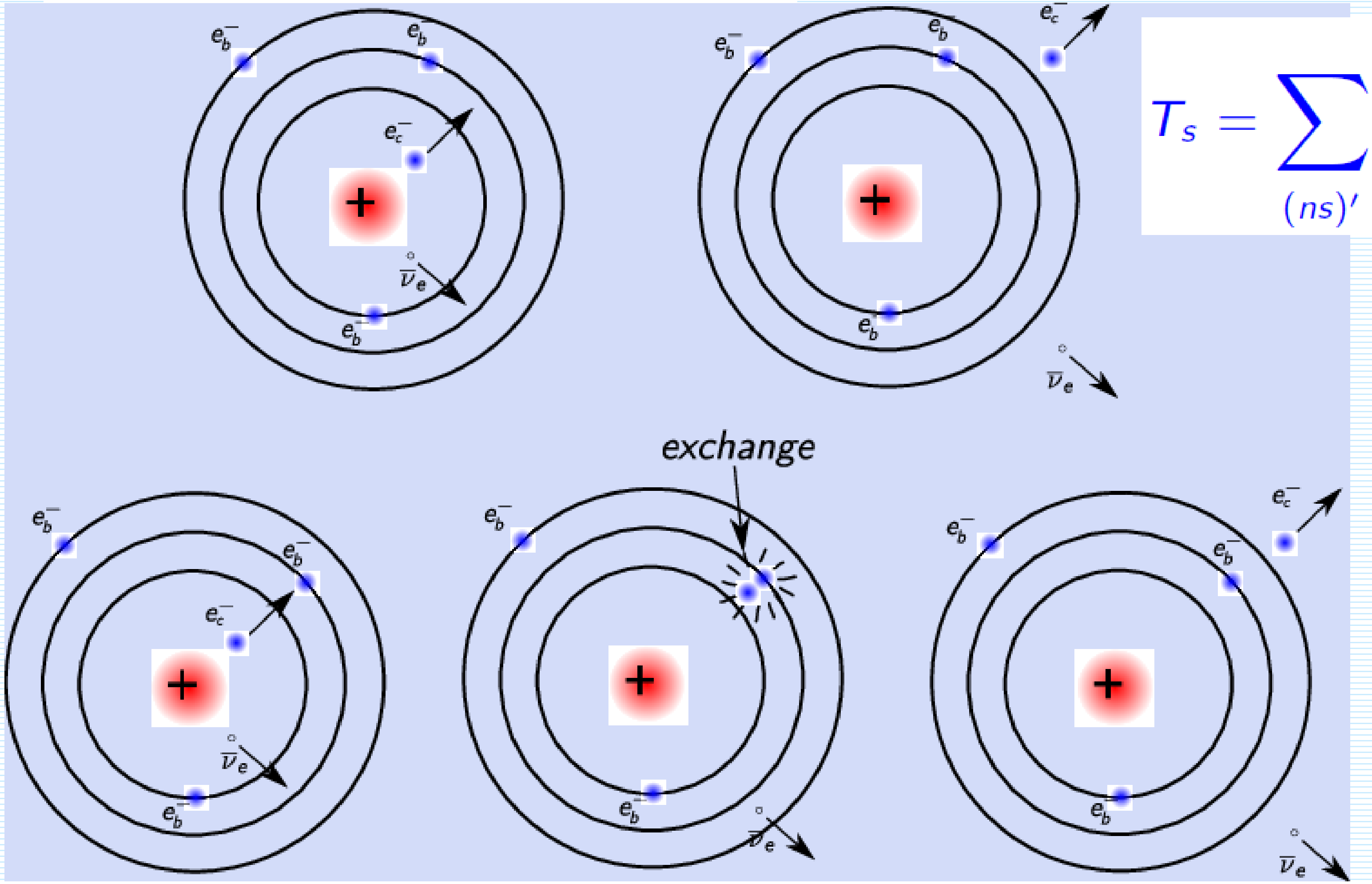
g_A^{eff} (ISM) = 1.11 ±0.03(stat)±0.05(syst)

Atomic effects in β-decay
(electron exchange effect)

$$\frac{d\Gamma}{dE_e} \Rightarrow \frac{d\Gamma}{dE_e} \times \left[1 + \eta^T(E_e)\right]$$

$$\eta^T(E_e) = f_s(2T_s + T_s^2) + (1 - f_s)(2T_{\bar{p}} + T_{\bar{p}}^2) = \eta_s(E_e) + \eta_{\bar{p}}(E_e)$$

Overlap of (A, Z) bound and (A, Z+1) continuum e-states



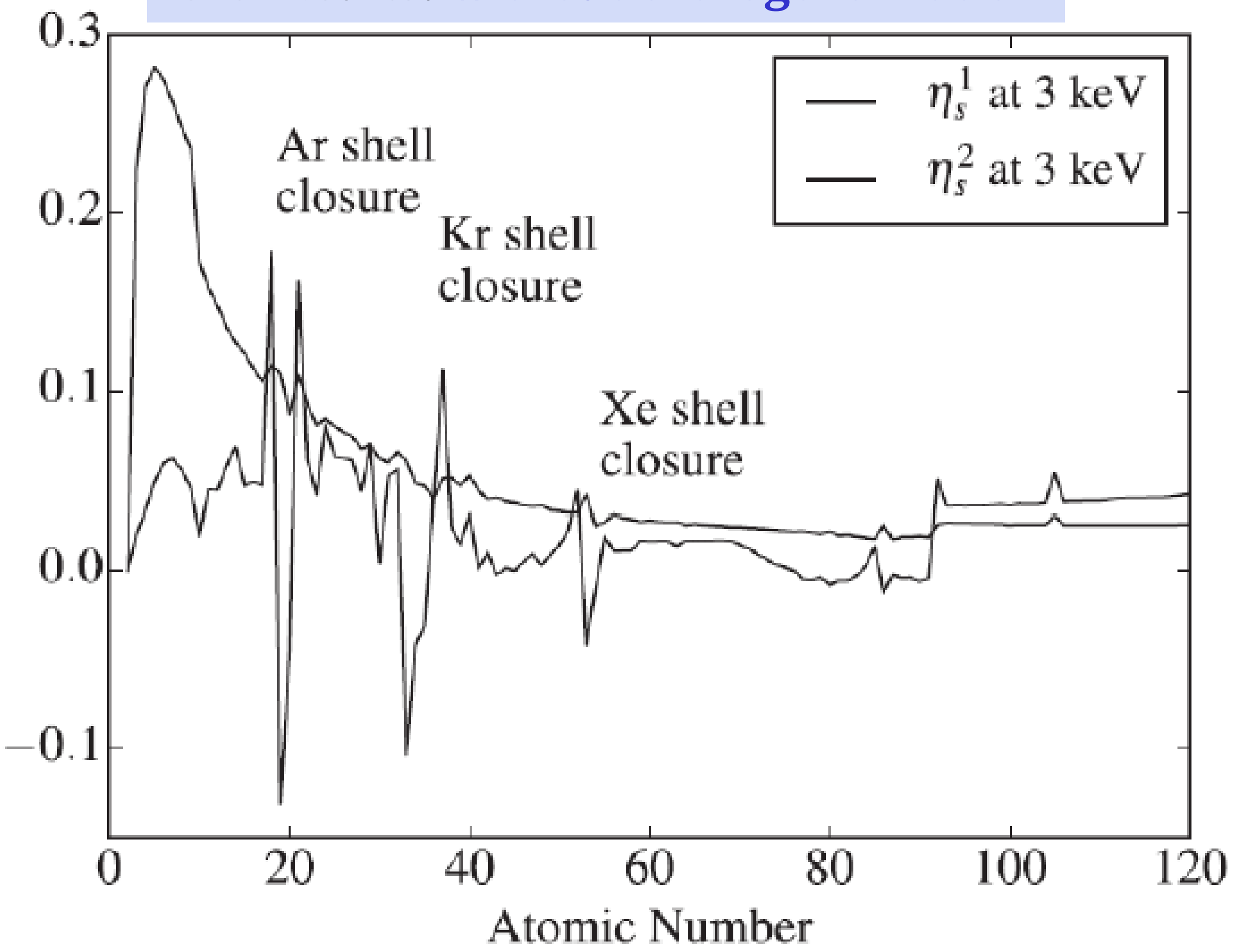
$$T_s = \sum_{(ns)'} T_{ns} = -\sum_{(ns)'} \frac{\langle \psi'_{E_e s} | \psi_{ns} \rangle}{\langle \psi'_{ns} | \psi_{ns} \rangle} \frac{g'_{n,-1}(R)}{g'_{-1}(E_e, R)}$$

$$f_s = \frac{g'^2_{-1}(E_e, R)}{g'^2_{-1}(E_e, R) + f'^2_{+1}(E_e, R)}$$

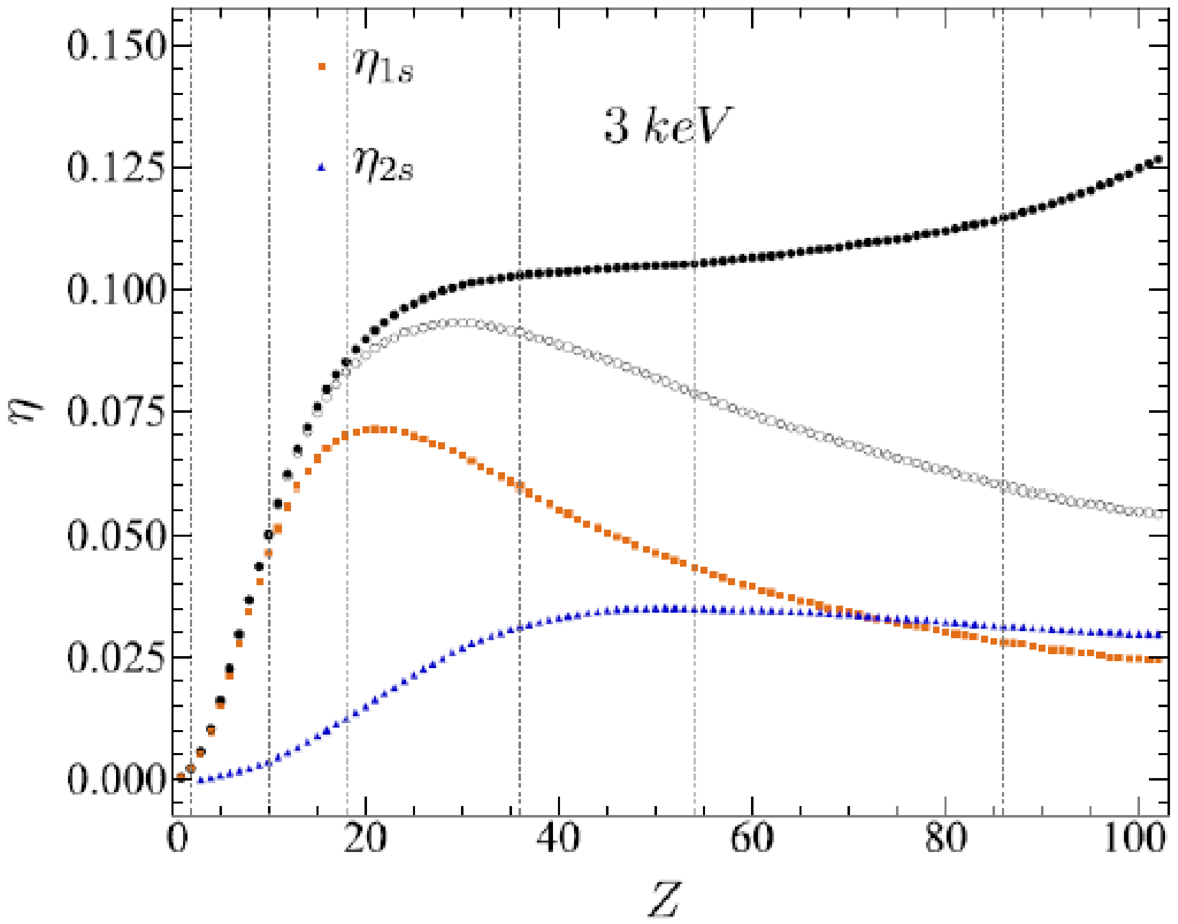
Transition	L	|ΔJ|	Δπ
allowed	0	0,1	0
first-forbidden	1	0,1,2	1
second-forbidden	2	1,2,3	0
third-forbidden	3	2,3,4	1
fourth-forbidden	4	3,4,5	0

Orthogonalization of bound and continuum states

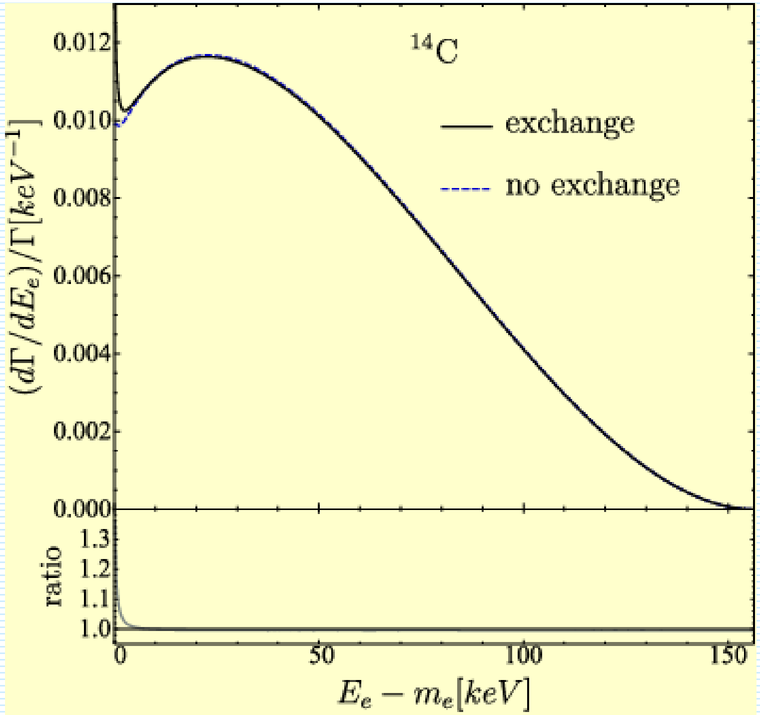
Old results: **without orthogonalization**

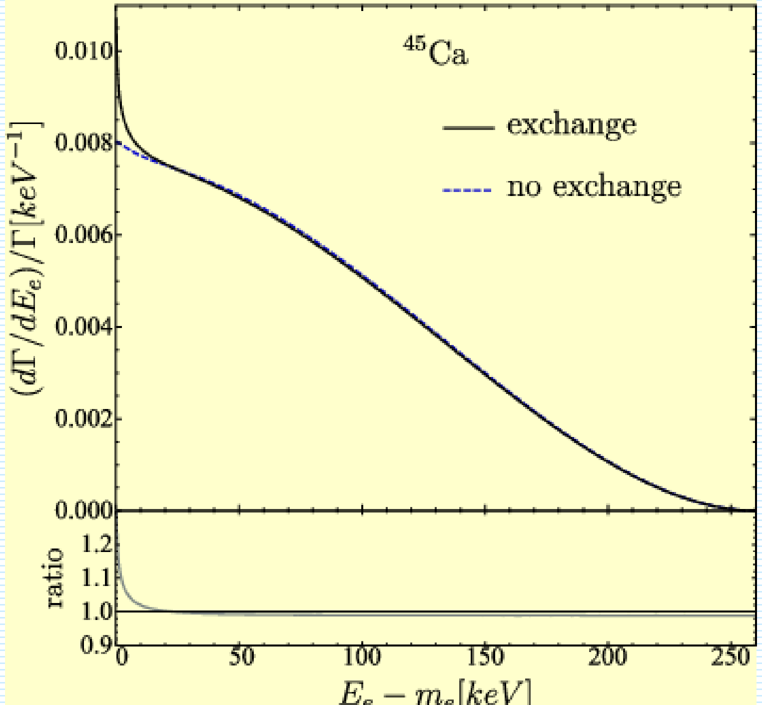


with orthogonalization



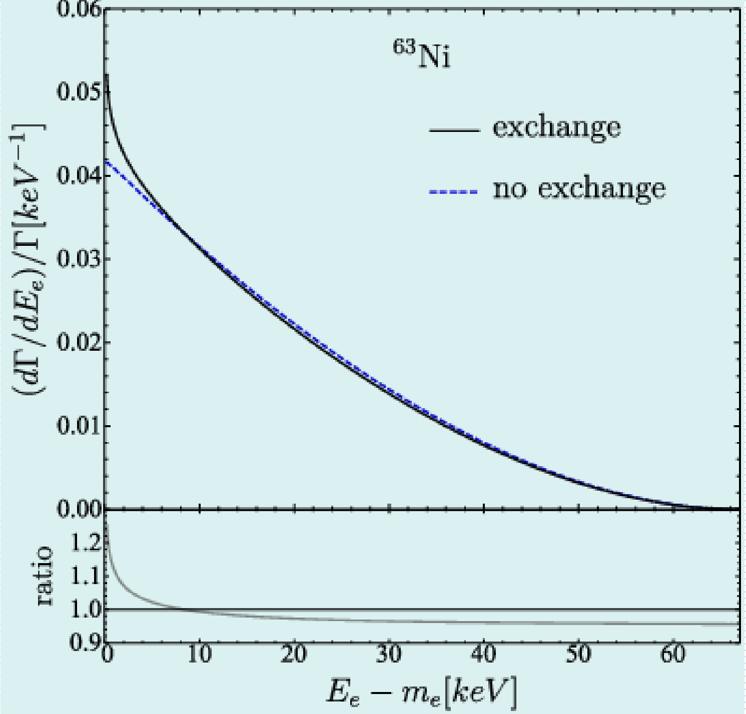
O. Nitescu, S. Stoica, F.Š., PRC 107, 025501 (2023)

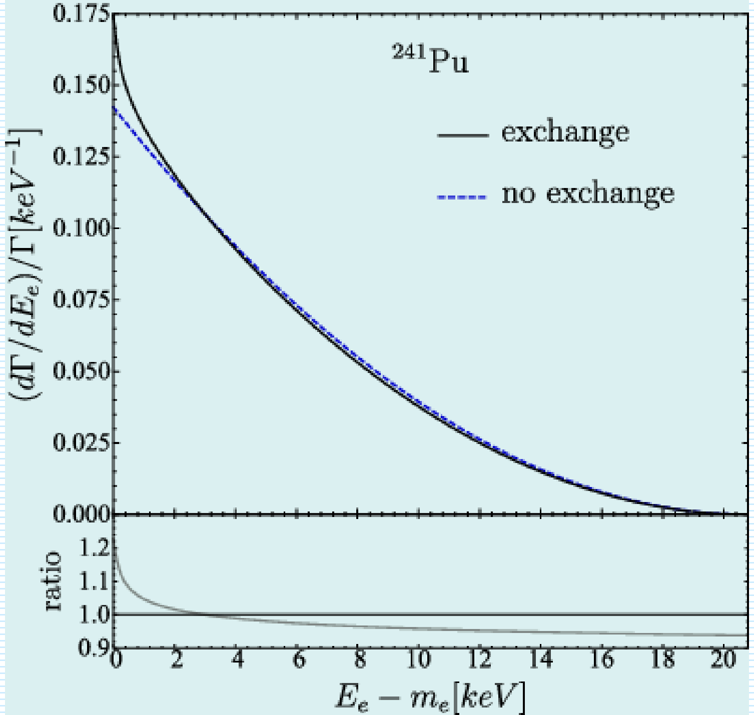




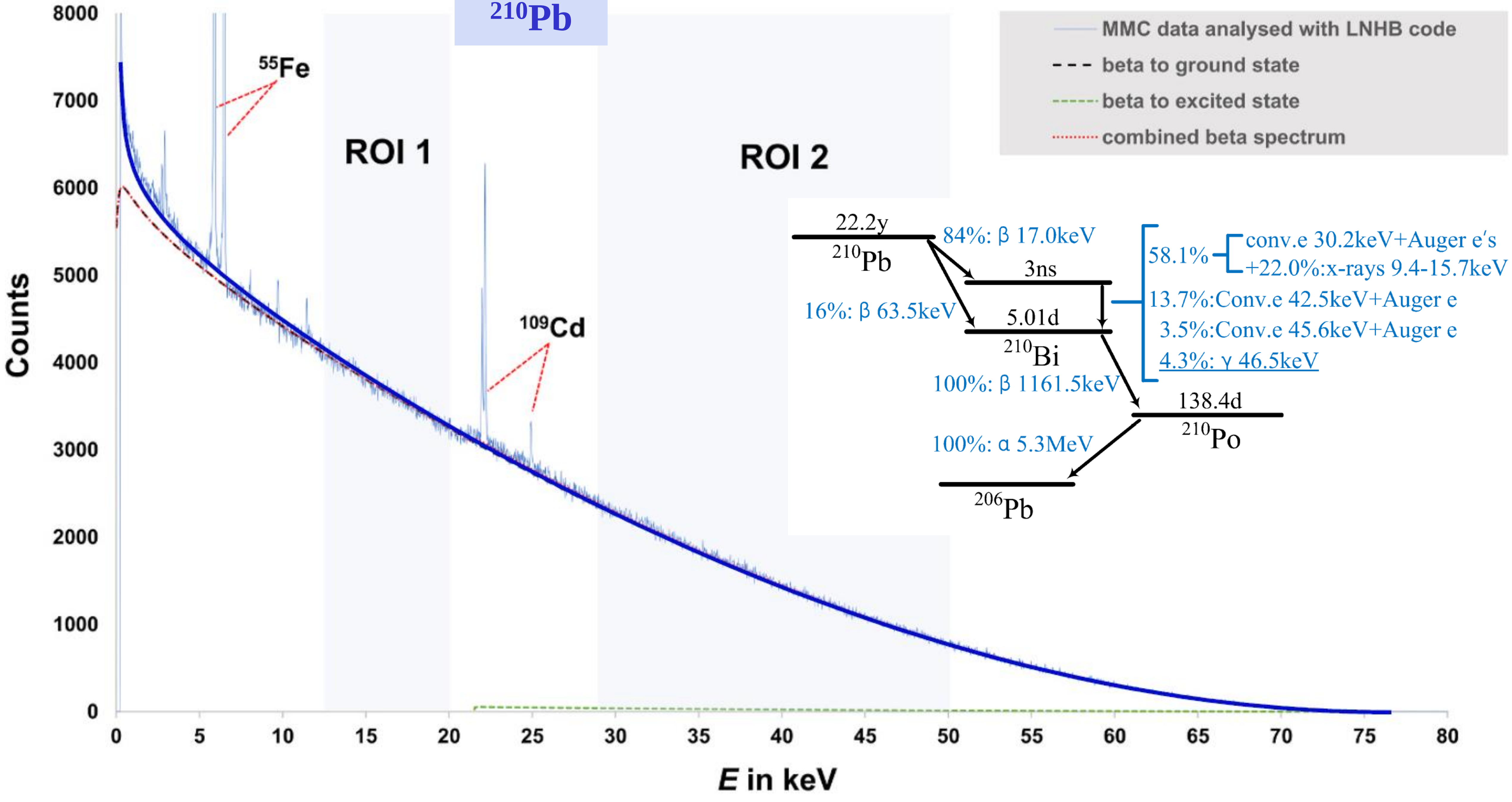
β-decay of
^{14}C ,^{45}Ca,
^{63}Ni, and ^{241}Pu
(with
electron exchange effect)

O. Nitescu, S. Stoica,
F.Š., PRC 107, 025501 (2023)





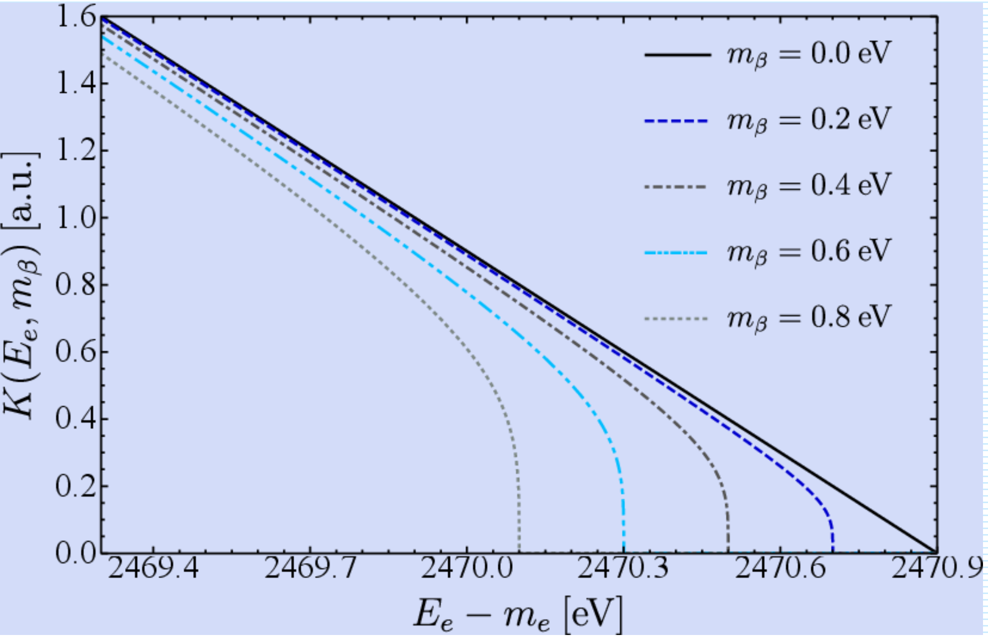
^{210}Pb



MMC data analysed with LNHB code
beta to ground state
beta to excited state
combined beta spectrum
55Fe
109Cd
ROI 1
ROI 2
Counts
E in keV
22.2y
210Pb
84%: β 17.0keV
16%: β 63.5keV
3ns
5.01d
210Bi
100%: β 1161.5keV
138.4d
210Po
100%: α 5.3MeV
206Pb
58.1%
conv.e 30.2keV+Auger e's
+22.0%:x-rays 9.4-15.7keV
13.7%:Conv.e 42.5keV+Auger e
3.5%:Conv.e 45.6keV+Auger e
4.3%: γ 46.5keV

β-decay of ^{187}Re
(with electron exchange effect)

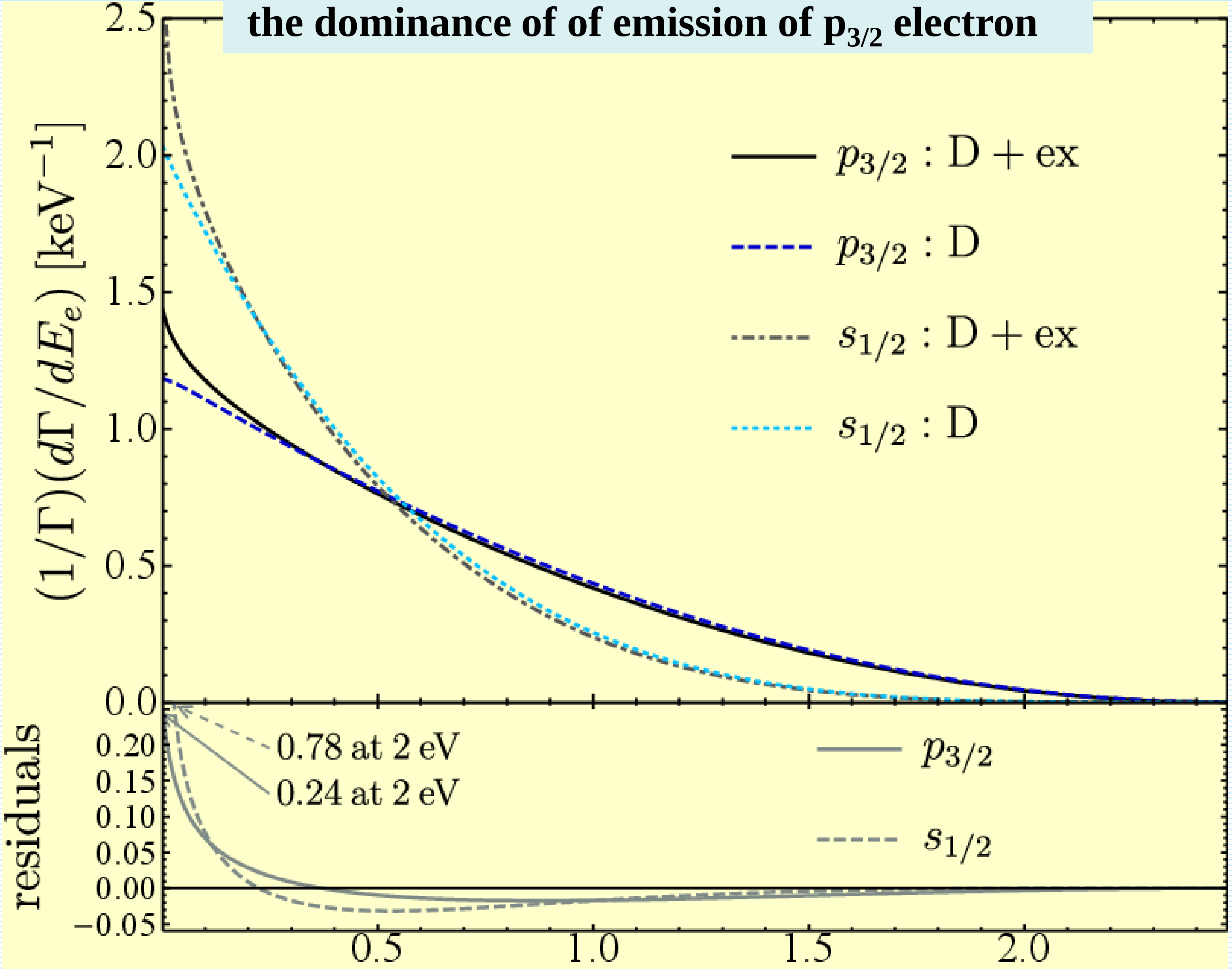
$$^{187}_{85}Re \rightarrow ^{187}_{86}Os + e^- + \bar{\nu}_e$$



^{187}Re: unique 1st	
E_0	2.47 keV
$t_{1/2}$	4.35 10^{10} y

^{187}Re (62.8 % abund.)

5/2$^+$ → 1/2$^-$ ´unique´ 1st forbidden transition, the dominance of of emission of $p_{3/2}$ electron



O. Nitescu, R. Dvornický, F.Š., to be published in PRC)

MARE project

Precursors (MANU, MIBETA)

Semiconductors	Single element Array of 10 elements Statistics: $N = 10^6$ events	$\sigma(\langle M_\beta \rangle) \sim 20$ eV

MARE-1 – commissioning in Milan – $\Delta E \sim 10 - 30$ eV – $\tau_R \sim 100\ \mu s$

Transition Edge Sensors Semiconductors	Arrays of 300 elements Statistics: $N = 10^{10}$ events	$\sigma(\langle M_\beta \rangle) \sim 2$ eV

MARE-2 –R&D in Genoa – $\Delta E \sim 5$ - 10 eV – $\tau_R \sim 1 - 10\ \mu s$

Transition Edge Sensors Magnetic calorimeters Kinetic Inductance Det.	Arrays of 50000 elements Statistics: $N = 10^{13}$ events	$\sigma(\langle M_\beta \rangle) \sim 0.2$ eV

Alternative to ^{187}Re : ^{163}Ho EC source to be implanted in the detector

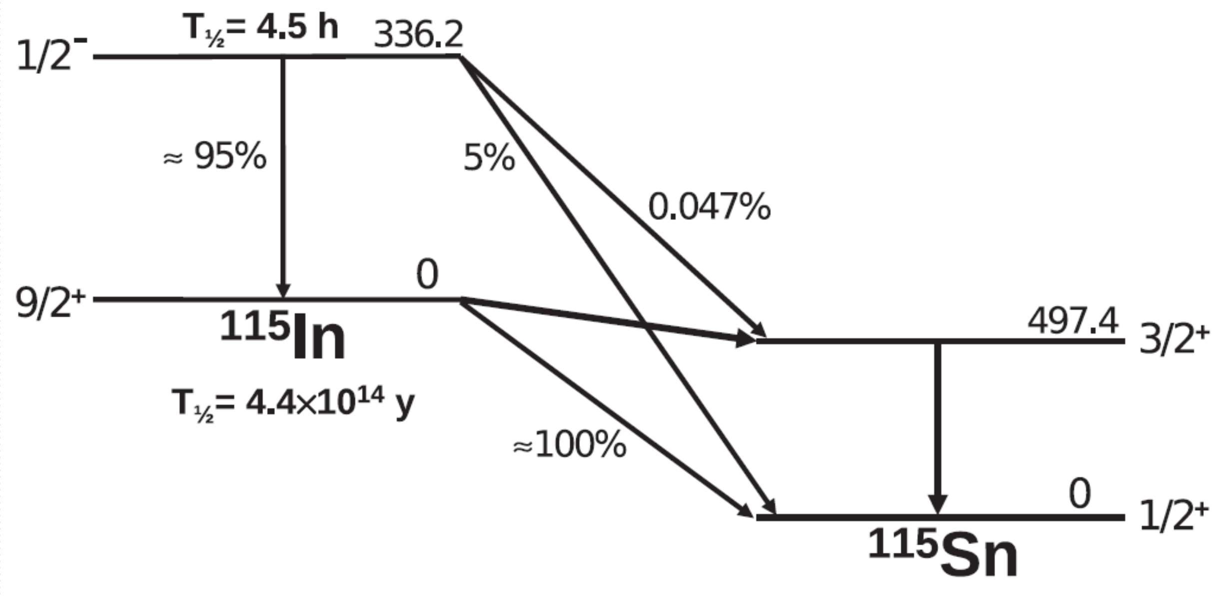
Sensitivity to ~1 keV sterile neutrinos

Possible composition of the passive shielding and muon veto structure

!
What about MARE exp. at PAUL?
!

Measuring od neutrino mass with ^{115}In
(spectrum not measured yet)

$5/2^+ \rightarrow 1/2^-$ ´unique´ 2^{nd} forbidden transition, the dominance of emission of $d_{5/2}$ electron



^{115}In: unique 2^{nd}	
E_0	0.35(17) keV
$t_{1/2}$	$4.1(6)\ 10^{20}$ y

^{115}In (%: 95.7)

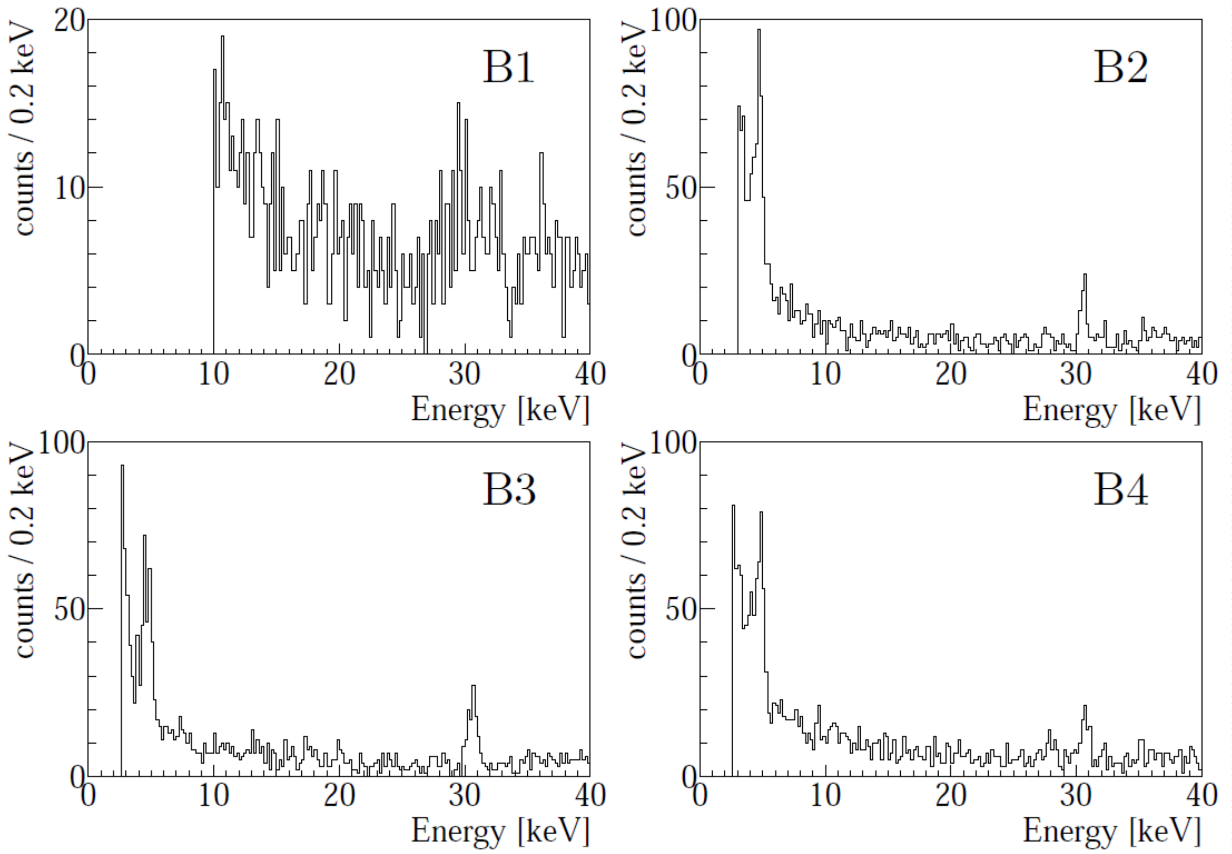
PRL **103**, 122501 (2009) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2009

Smallest Known Q Value of Any Nuclear Decay: The Rare β^- Decay of $^{115}\mathrm{In}(9/2^+) \rightarrow {}^{115}\mathrm{Sn}(3/2^+)$

J. S. E. Wieslander,[1,2] J. Suhonen,[2] T. Eronen,[2] M. Hult,[1,‡] V.-V. Elomaa,[2] A. Jokinen,[2] G. Marissens,[1] M. Misiaszek,[3] M. T. Mustonen,[2] S. Rahaman,[2,*] C. Weber,[2,†] and J. Äystö[2]

Ettore Fiorini task – EC of ^{123}Te

^{123}Te is a naturally occurring isotope of Tellurium (abundance **0.908±0.002%**) which may decay via EC to ^{123}Sb with a Q-value of **52.2 ± 1.5 keV**. Since the transition is 2nd-forbidden unique, it has been estimated that very little **K** capture actually occurs and that the majority of EC decays take place from the **L3** shell. Several searches for Sb K lines from EC of ^{123}Te have been performed. Positive evidence, $T_{1/2} = (1.24 \pm 0.10) \cdot 10^{13}$ y, was claimed but subsequently ruled out.



In **F. Alessandria et al., JCAP 01 (2013) 038** an energy spectrum down to the L energy region. was shown. The observed line, however, cannot be attributed to ^{123}Te, since the energy is compatible with the **L1** shell (**4.6983 keV**) and not with the **L3** one (**4.1322 keV**).

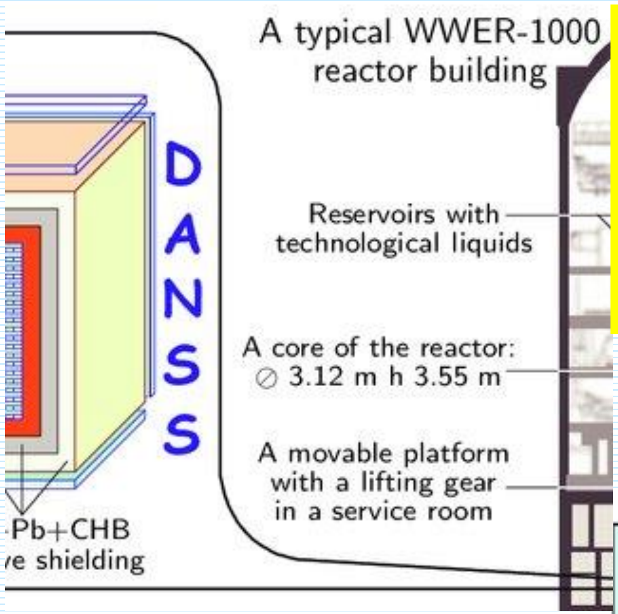
^{115}In: unique 2nd	
Q	52.2 ±1.5 keV
$t_{1/2}$	unknown

in ^{123}Te (%: 0.908±0.002)

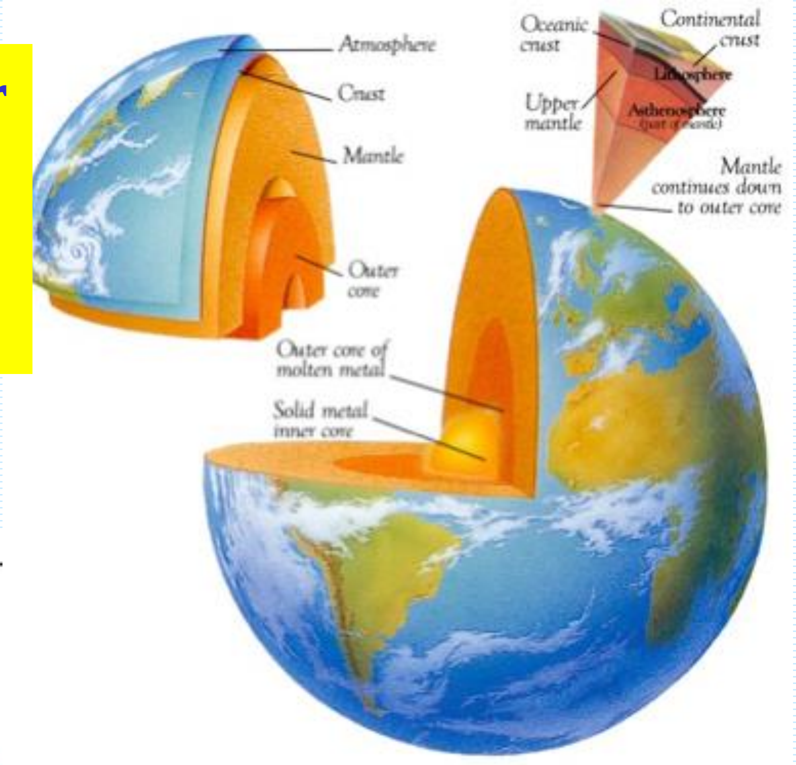
$T_{1/2}$(L1)/$T_{1/2}$(L3) = 0.04 (theory)

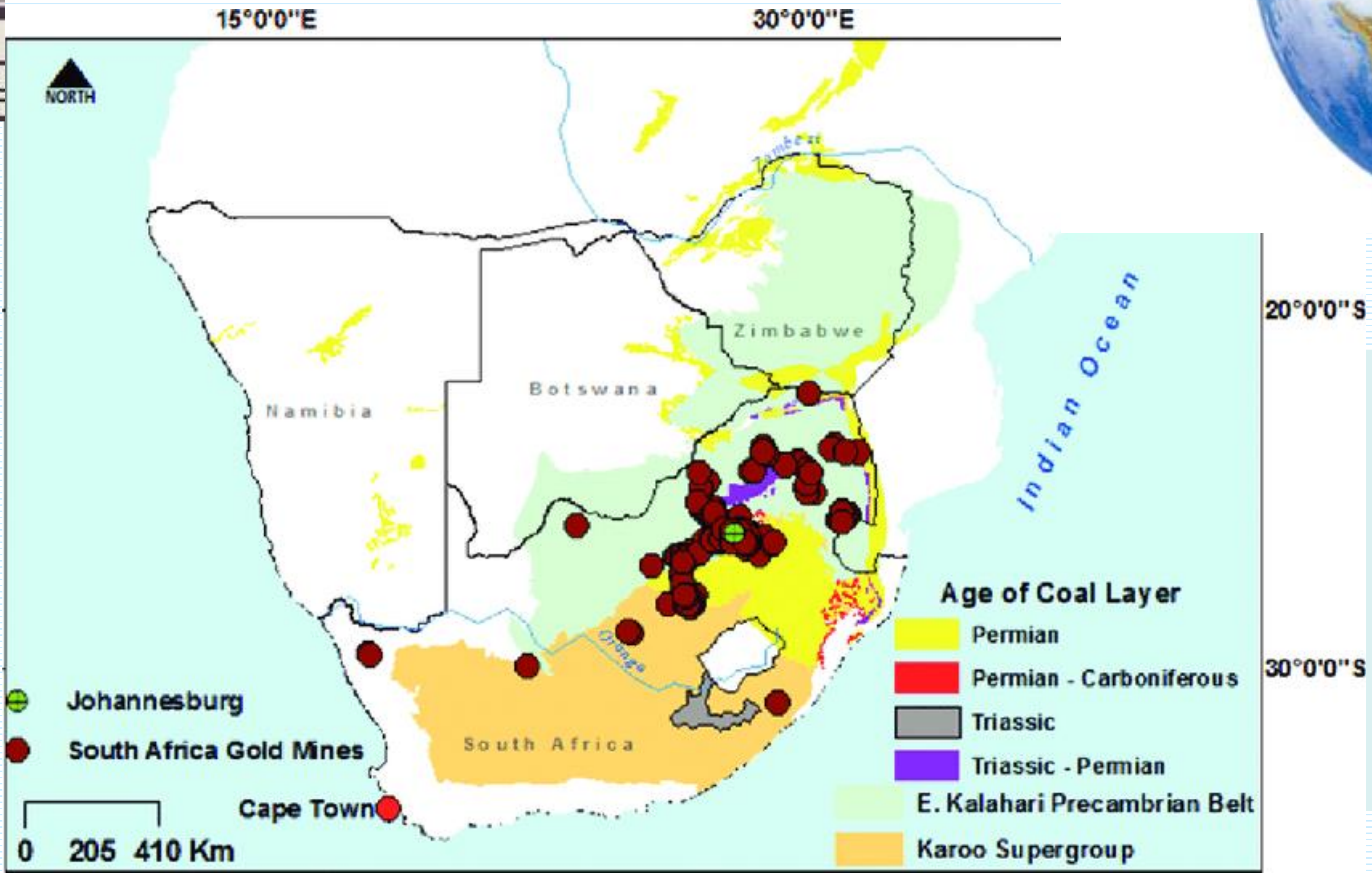
Being ambitious – Geoneutrino detector

From prototype detector to Geoneutrino detector (ENIGMA prototype detector)



SoLiđ





Gold mine:
Plastic scintillator detector instead of liquid scintillator detector
(KamLAND, Borexino)

Applied Antineutrino Physics Workshop 2023

18-21 September 2023
The Guildhall York
Europe/London timezone

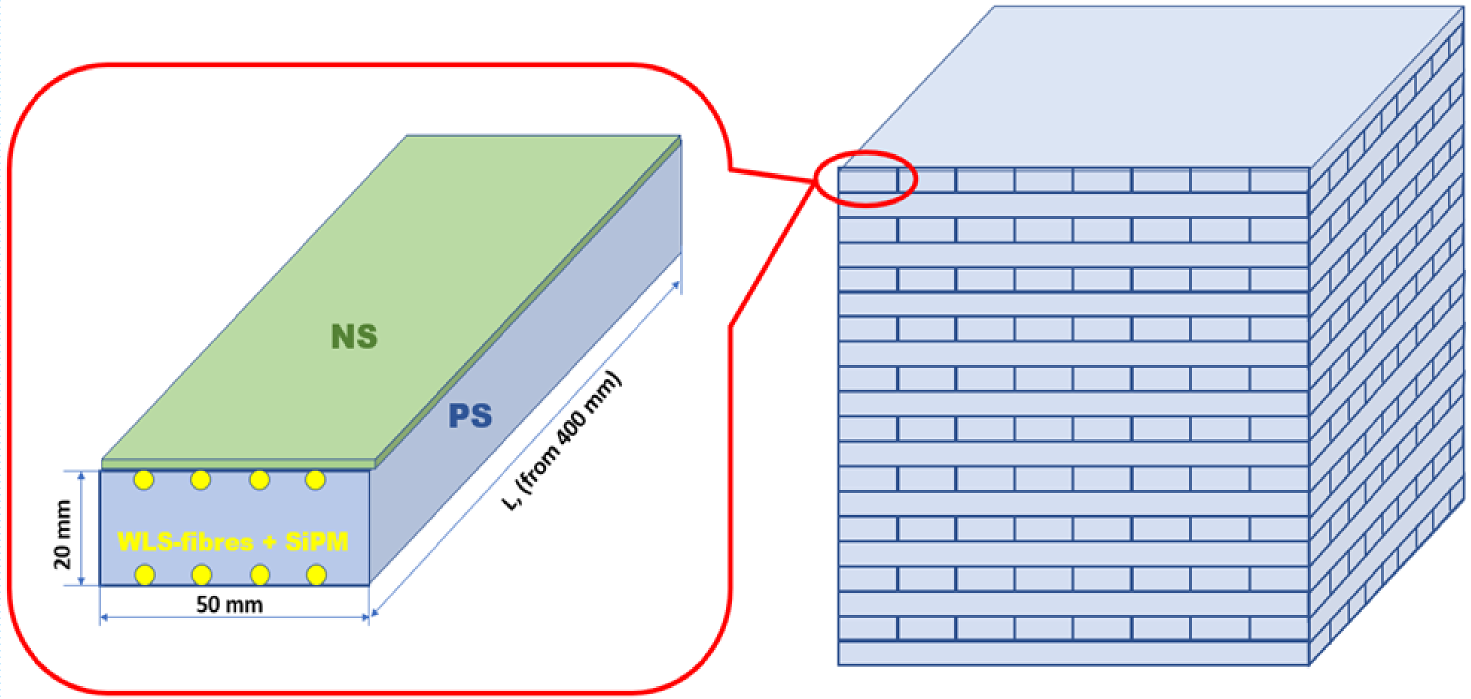
- Overview
- Useful information
  - Getting there
  - Accommodation
  - Visas
- Conference agenda
- Call for Abstracts
- Registration
- Participant List
- Organising committee
- Conference Proceedings

Antineutrino detectors are developed and constructed worldwide

The Applied Antineutrino Physics (AAP) workshops provided an engaging and lively forum for the review and discussion of antineutrino detection and technology R&D for applications including reactor monitoring, safeguards, and geophysics.

Enigma detector
(Call of the Recovery and Resilience Plan of the Slovak Republic)

The detector will be assembled from 360 strips of polystyrene-based plastic scintillator (PS, 60 x 5 x 2 cm^3) assembled into a cube with an edge of 60 cm

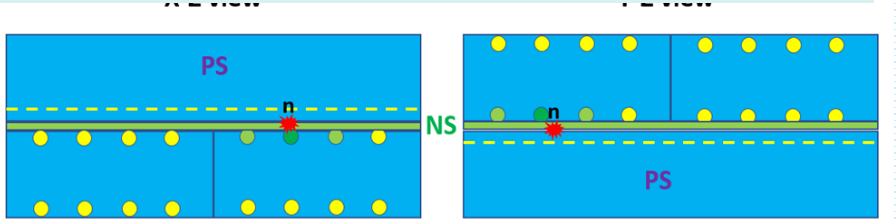


Concept of the ENIGMA detector (configuration 40x40x40 cm^3): left - the base cell (strip) - an elementary optical element, right - the assembled detector without passive shielding.

Between layers, there is a thin sheet of ZnS scintillator doped with Lithium-6 to tag neutron captures.

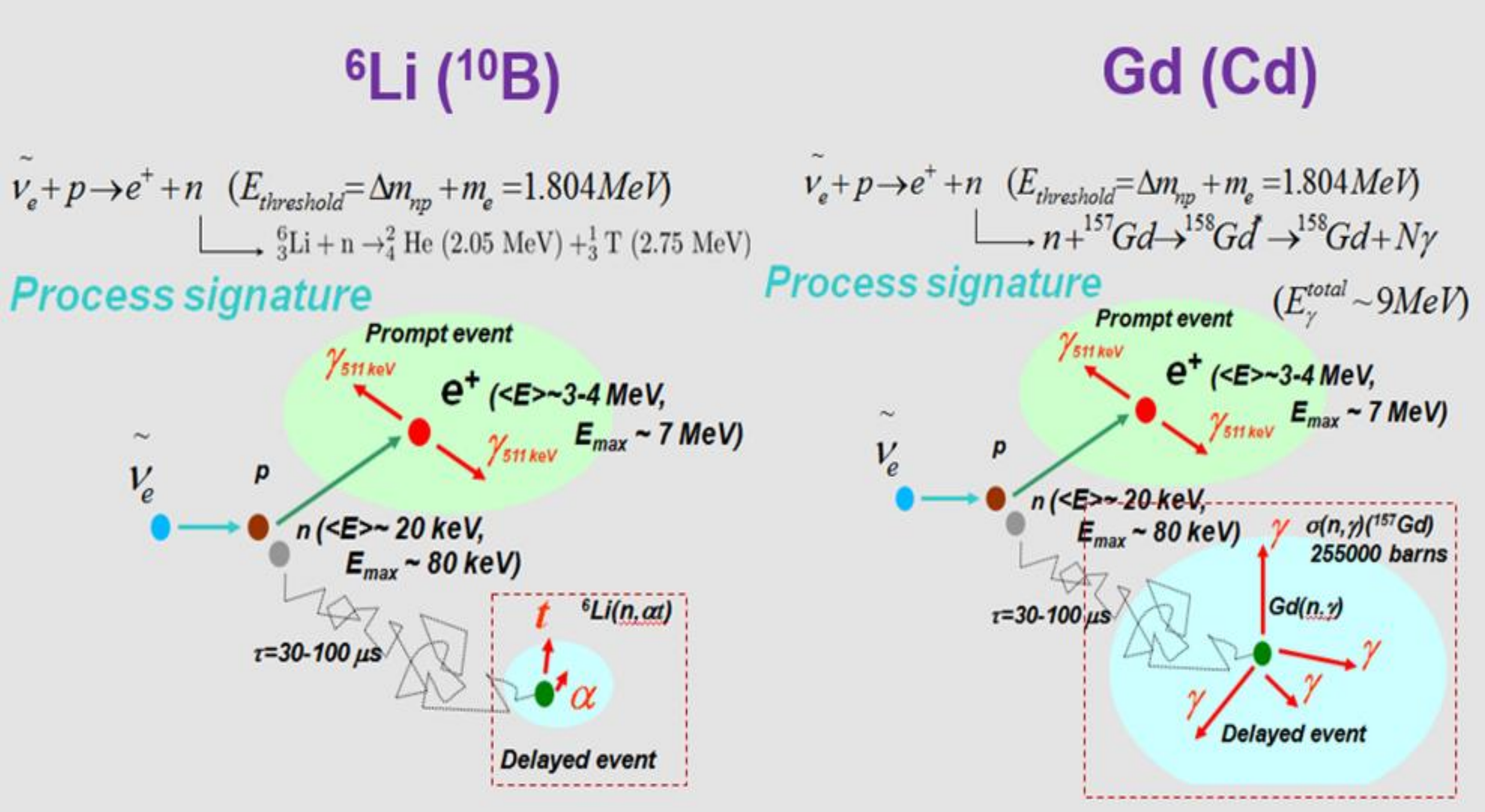
Being inspired by DANSS and SOLID detectors.

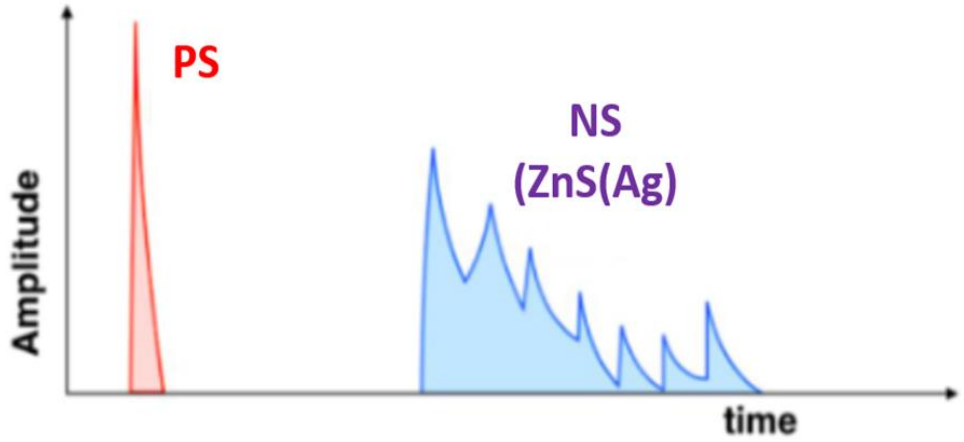
We expect improved energy resolution on the level of 6-8% FWHM@1 MeV, which is comparable with liquid scintillators!!!



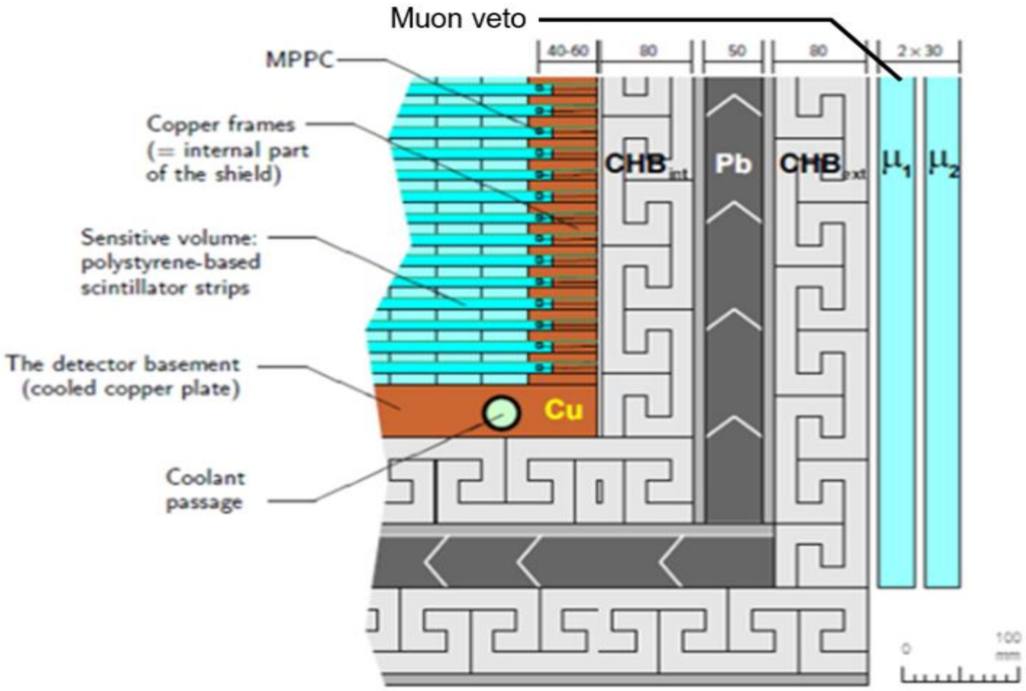
Configuration of two adjacent PS layers connected through optically glued NS. The neutron signal is localized through the geometry of the triggered fibers from two adjacent orthogonal layers.

Comparison of neutron capture parameters in ^{6}Li and Gd .





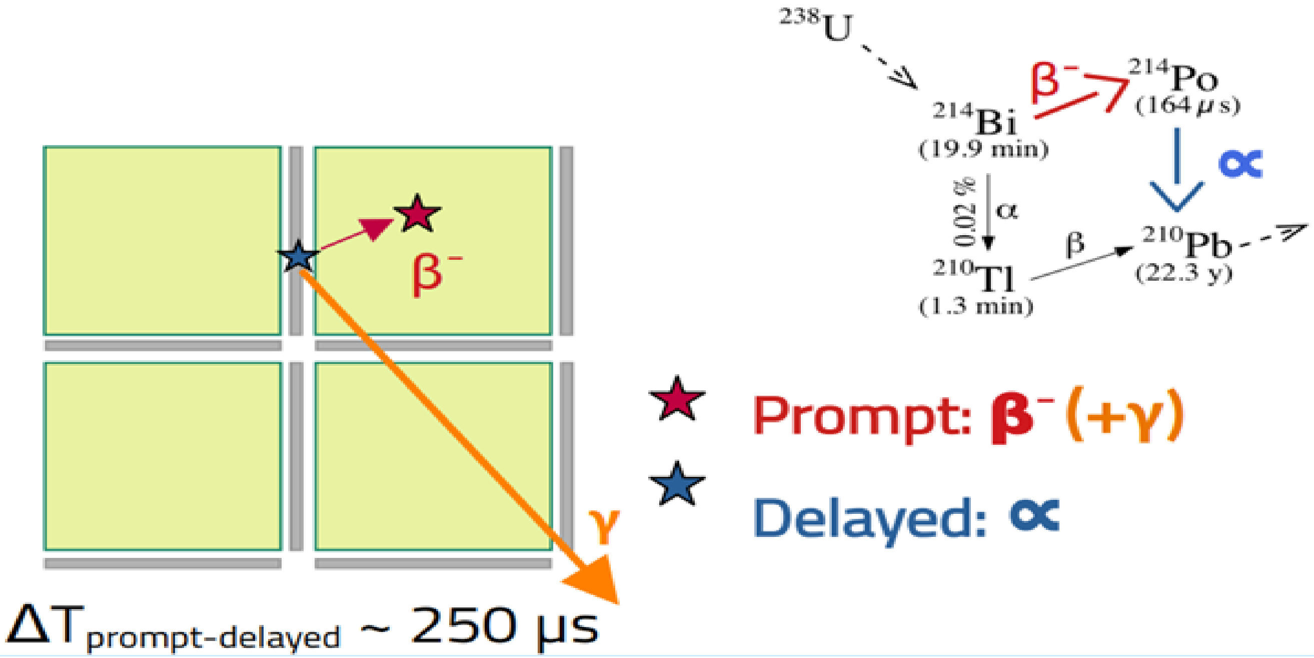
Time waveform of the signal from the Plastic Scintillator (PS) and from the Neutron Scintillator (NS)



BiPo background

Internal radioactivity from ZnS layers contamination

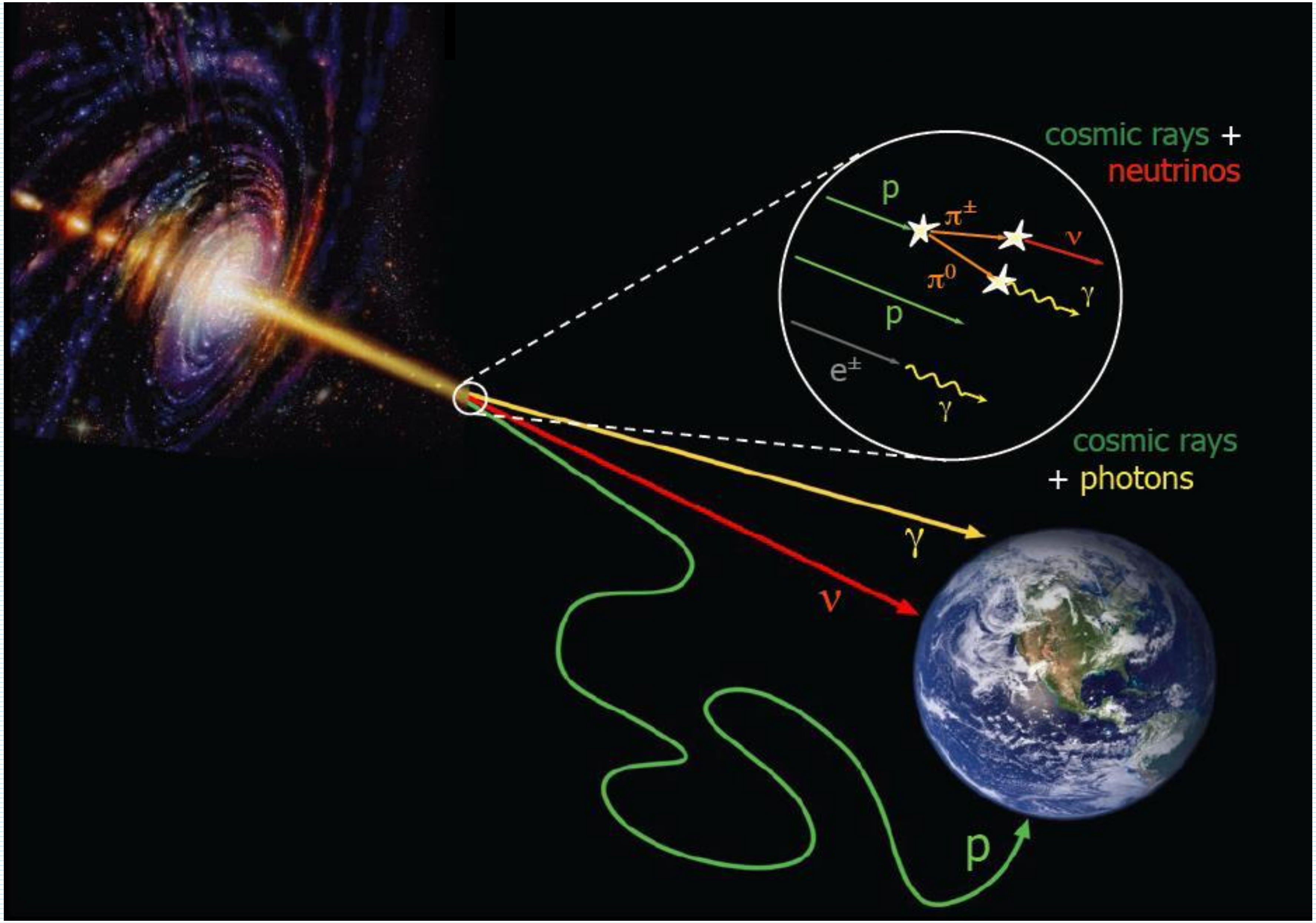
External Radon decay.



BiPo background (picture is given for the SOLID detector).

Possible composition of the passive shielding and muon veto structure

South African Neutrino Telescope. Why not?



Location: Current and Future Neutrino Telescopes

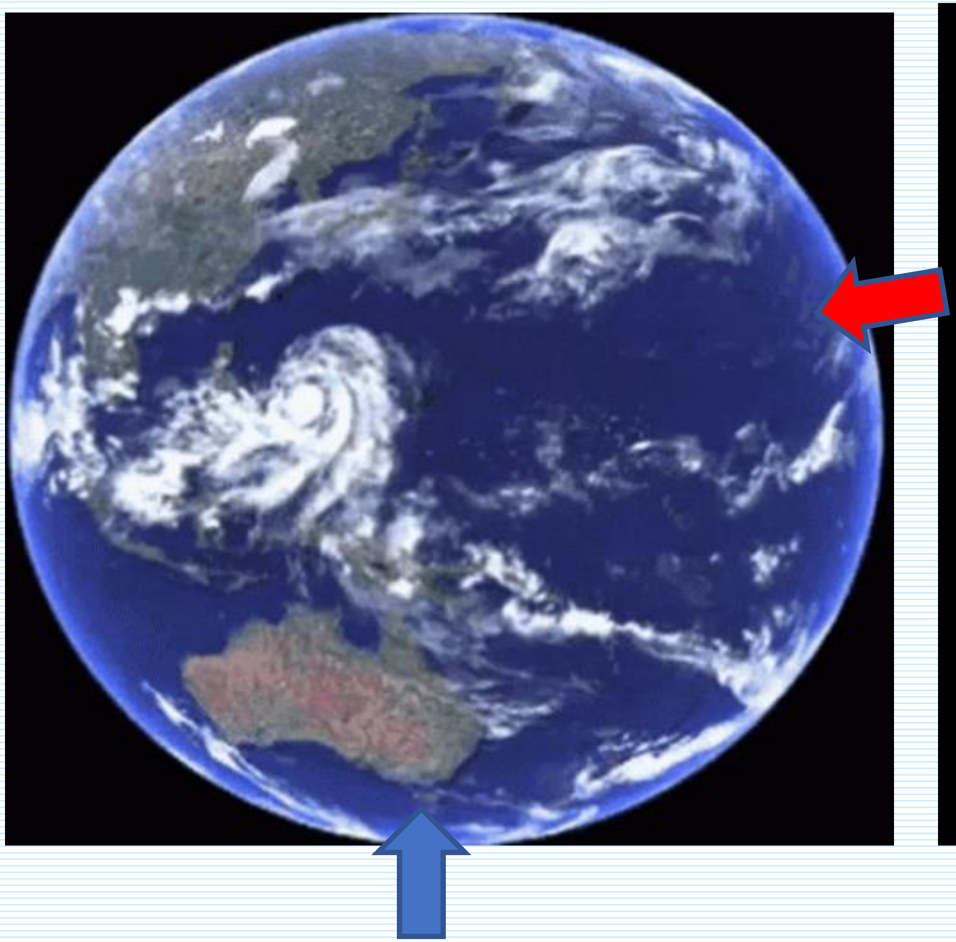
IceCube-Gen2

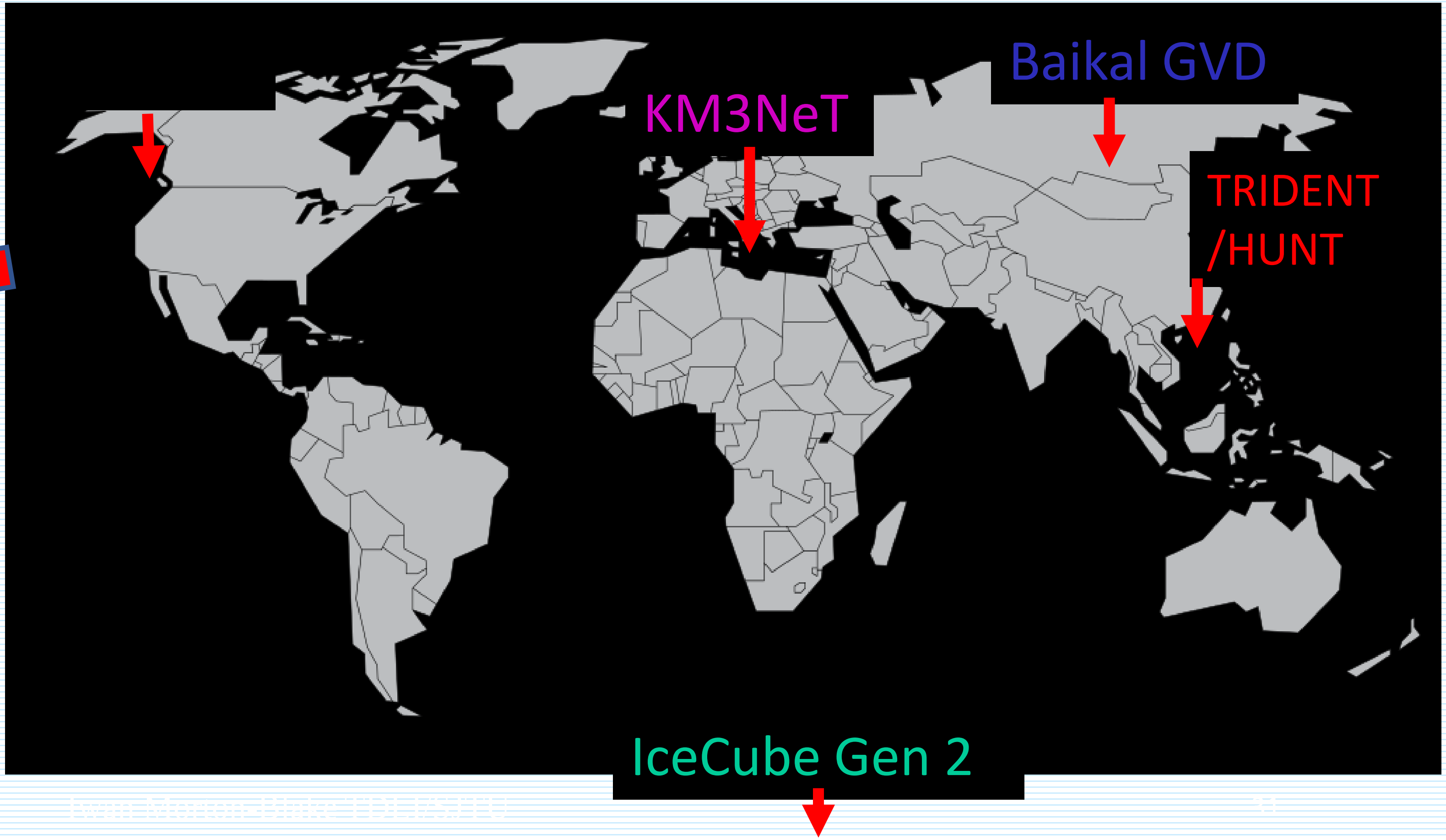
Baikal GVD

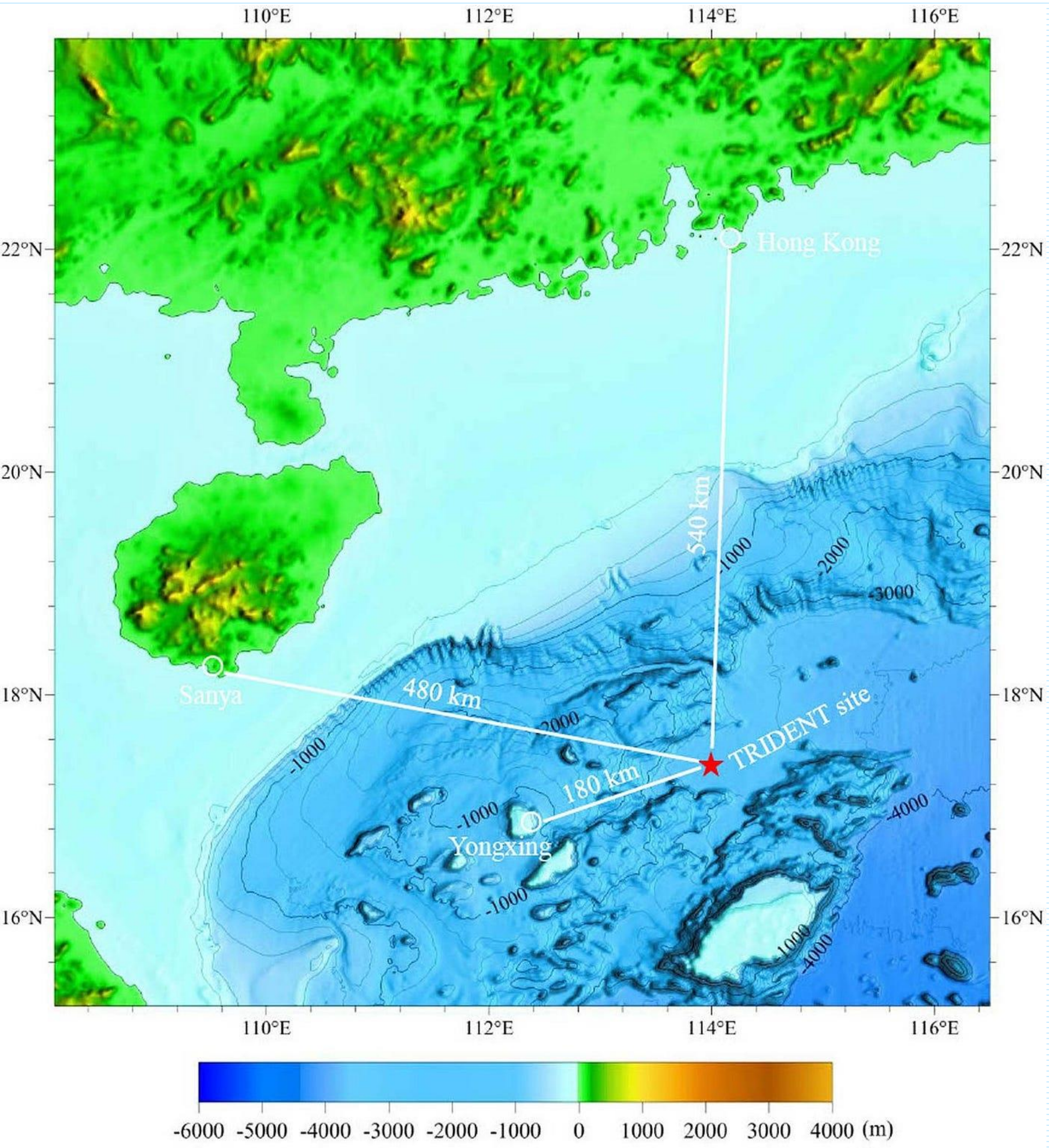
KM3NeT

P-ONE

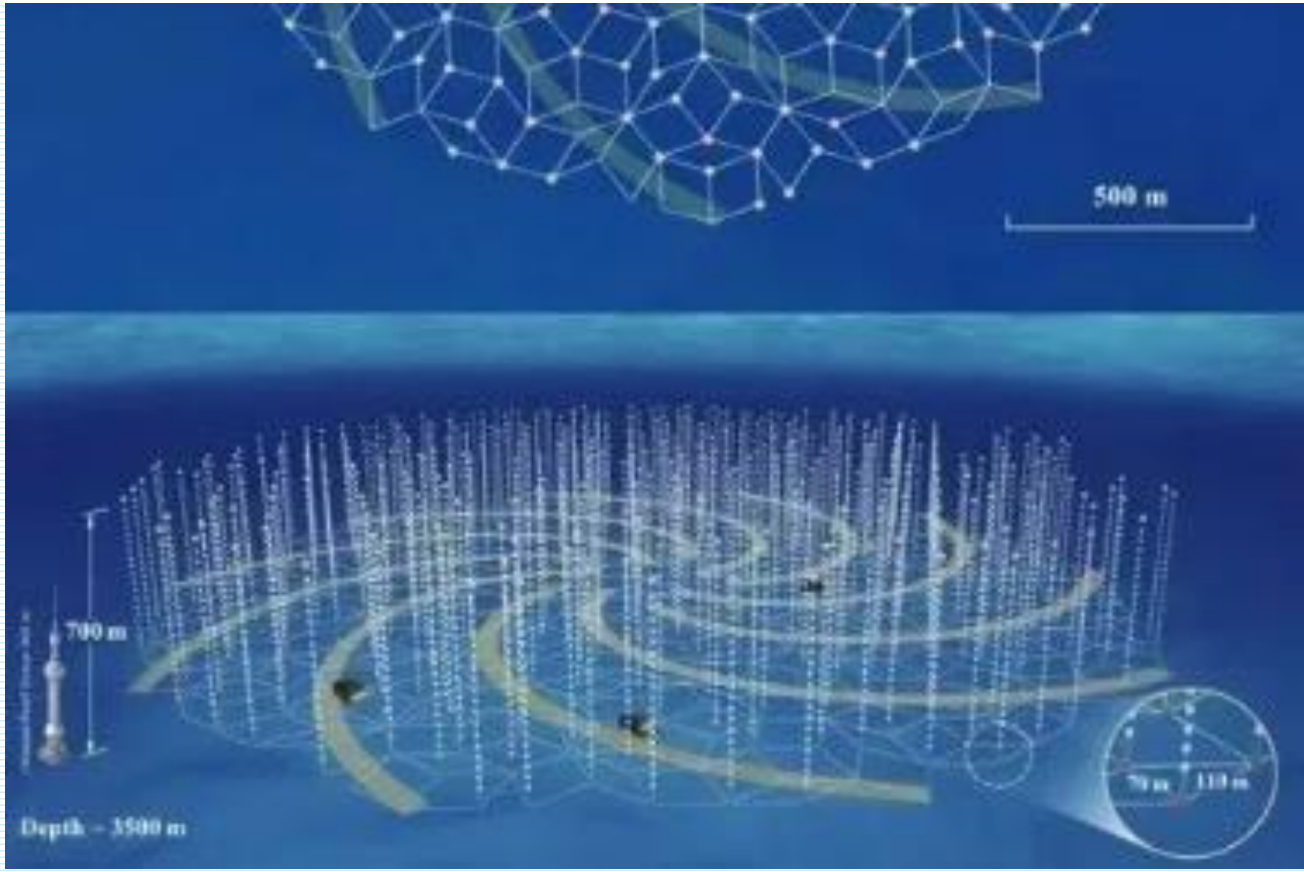
TRIDENT







The Tropical Deep-sea Neutrino Telescope - TRIDENT
(nicknamed Hai-Ling in Chinese = ocean bell)
Shanghai University

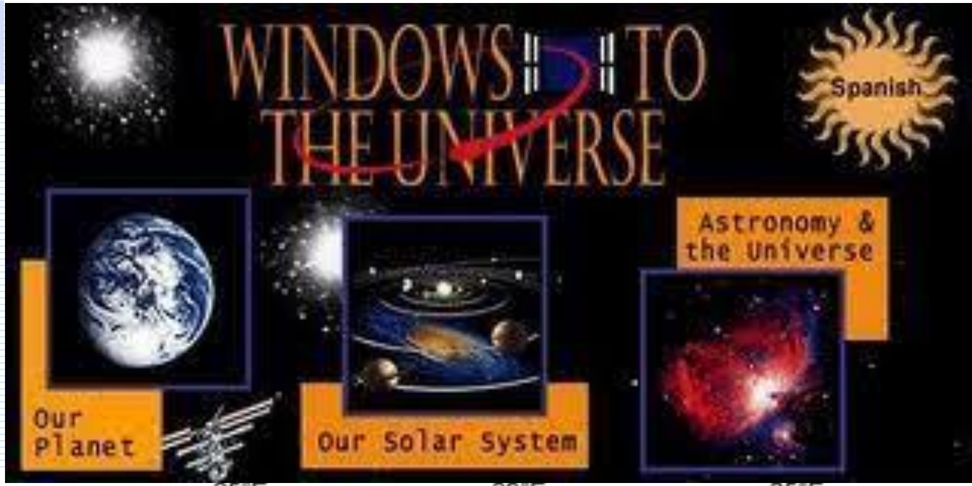


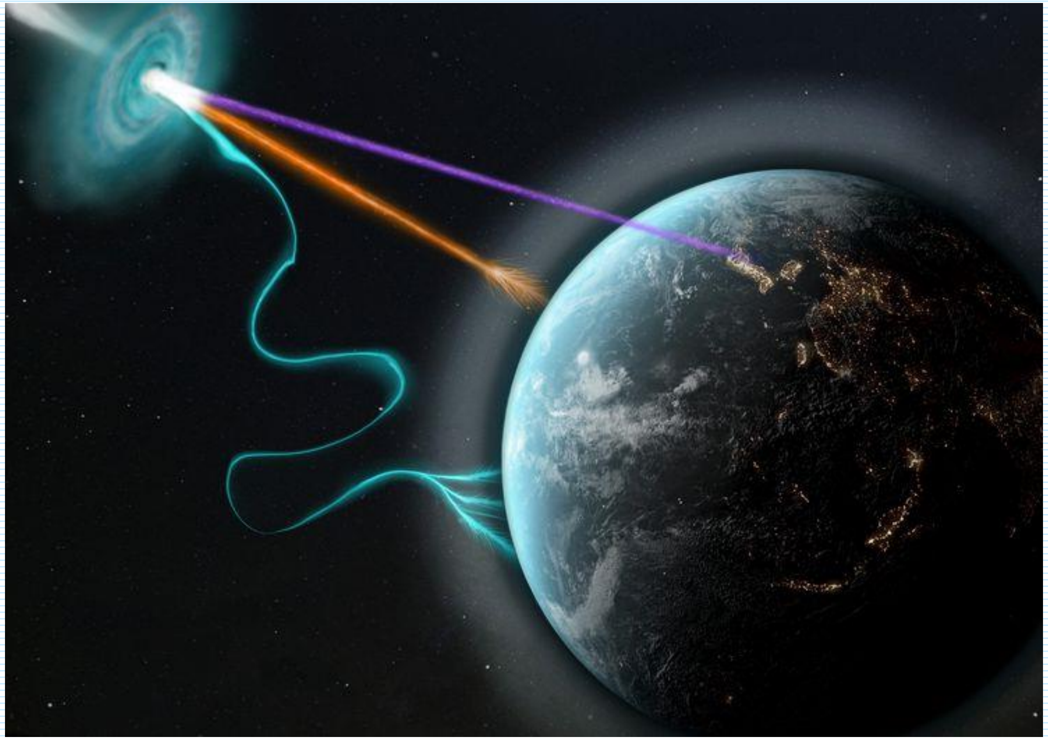
Huge Underwater high-energy Neutrino Telescope - HUNT
IHEP Beijing

Multimessenger astronomy

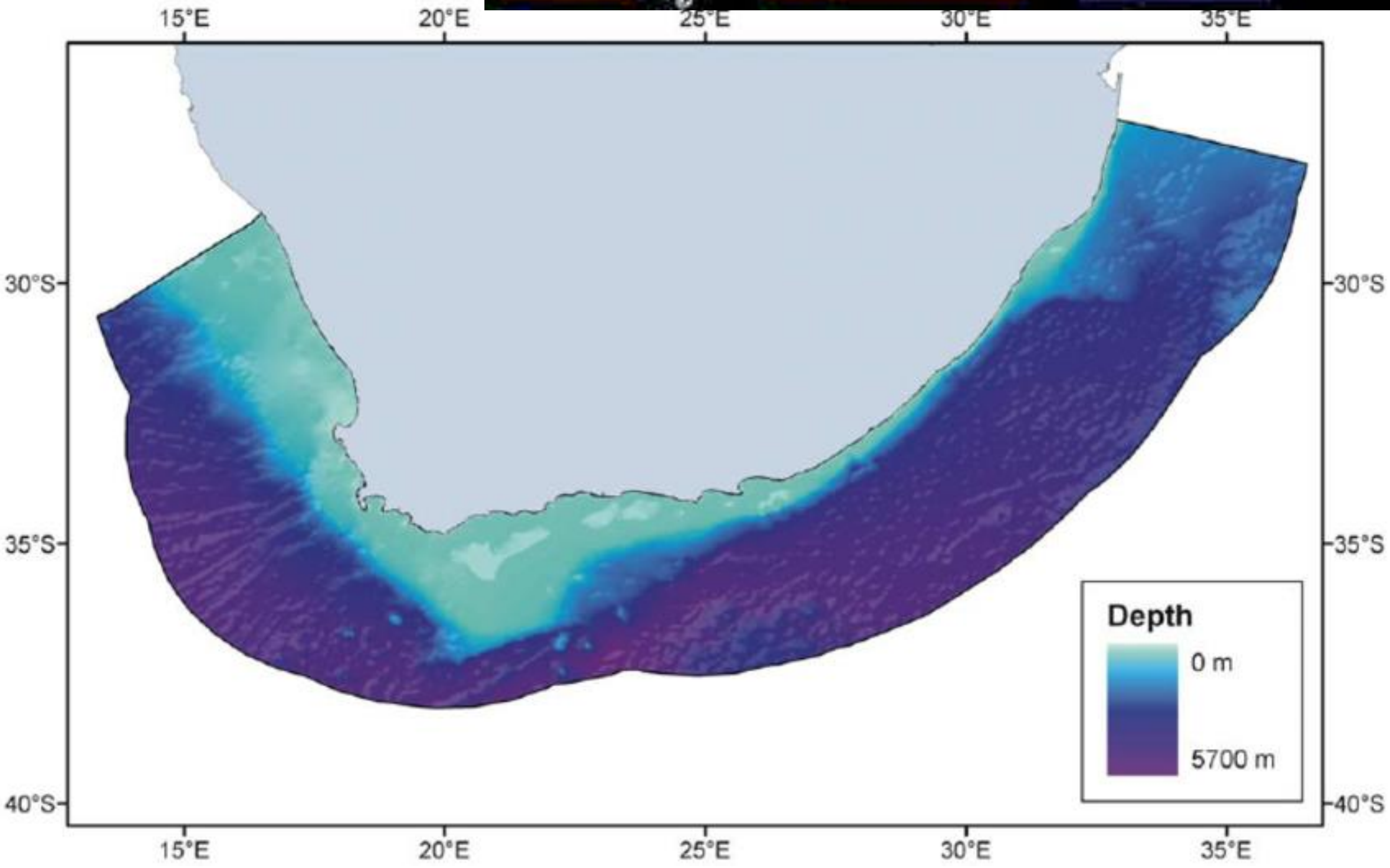
South Africa =
Astrophysical Superpower?
(SKA, PAUL, "SA ν-telescope")

From radio km^2 detector
to neutrino km^3 detector

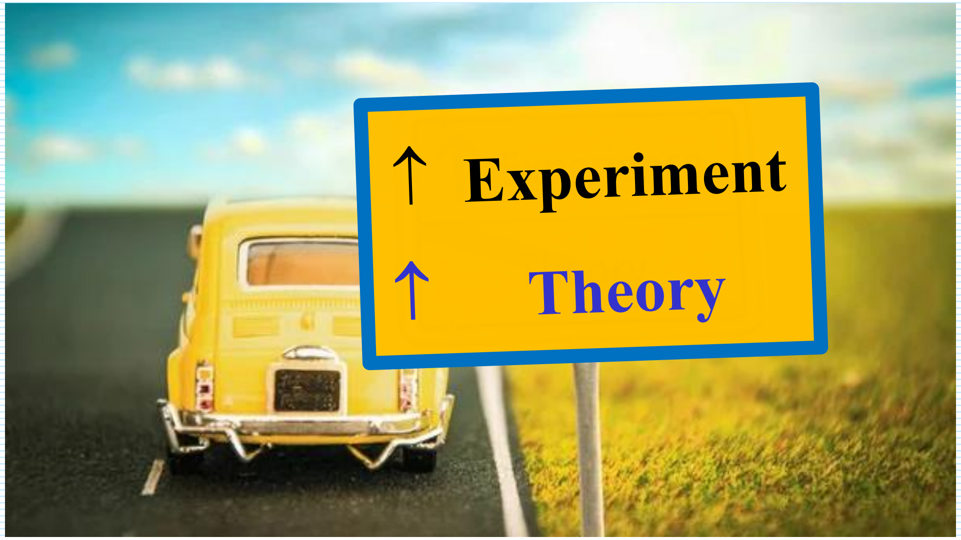




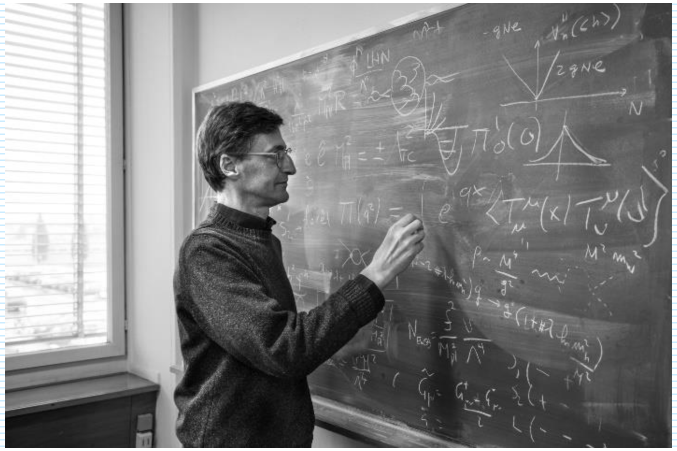
Messengers from space: Cosmic objects emit neutrinos (violet), gamma rays (orange) and protons (green).



AI can not solve ν-physics problems!



ν-physics problems can be solved only by ν-experiments (and ν-theory), i.e., by skilled experimentalists and theorists



Thank you for your attention!

Sterkte, Paul!

Ngikufisela inhlanhla enhle, Paul!

Ngikufisela inhlanhla, Paul!

Mahlatse, Paul!

Good Luck, PAUL!

Mashudu mavhuya, Paul!

Ke o lakaletsa mohlohonolo, Paul

Tsela tsweu, Paul!

Ndzi ku navelela mikateko, Paul!

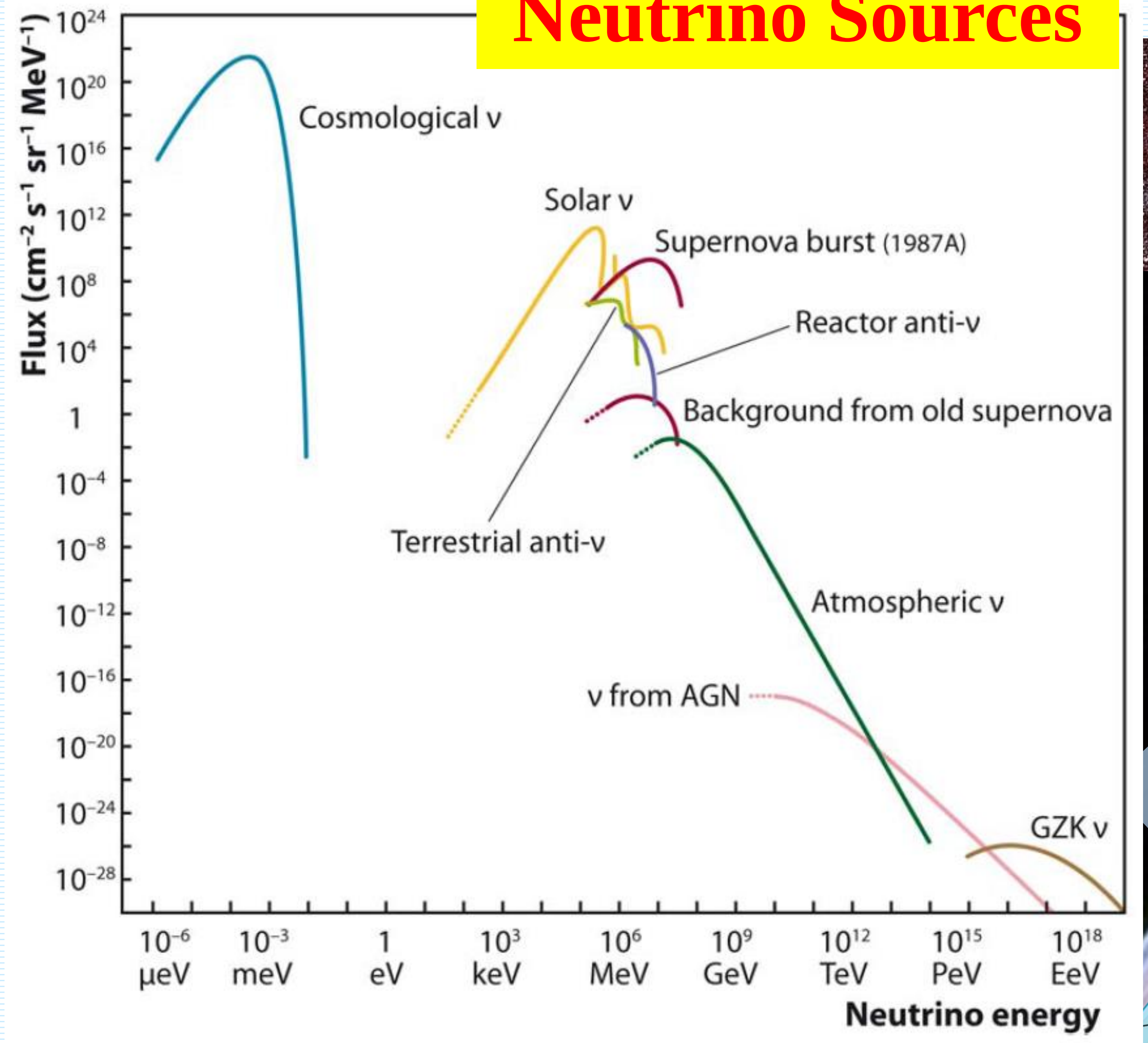
Umnqweno omhle, Paul!

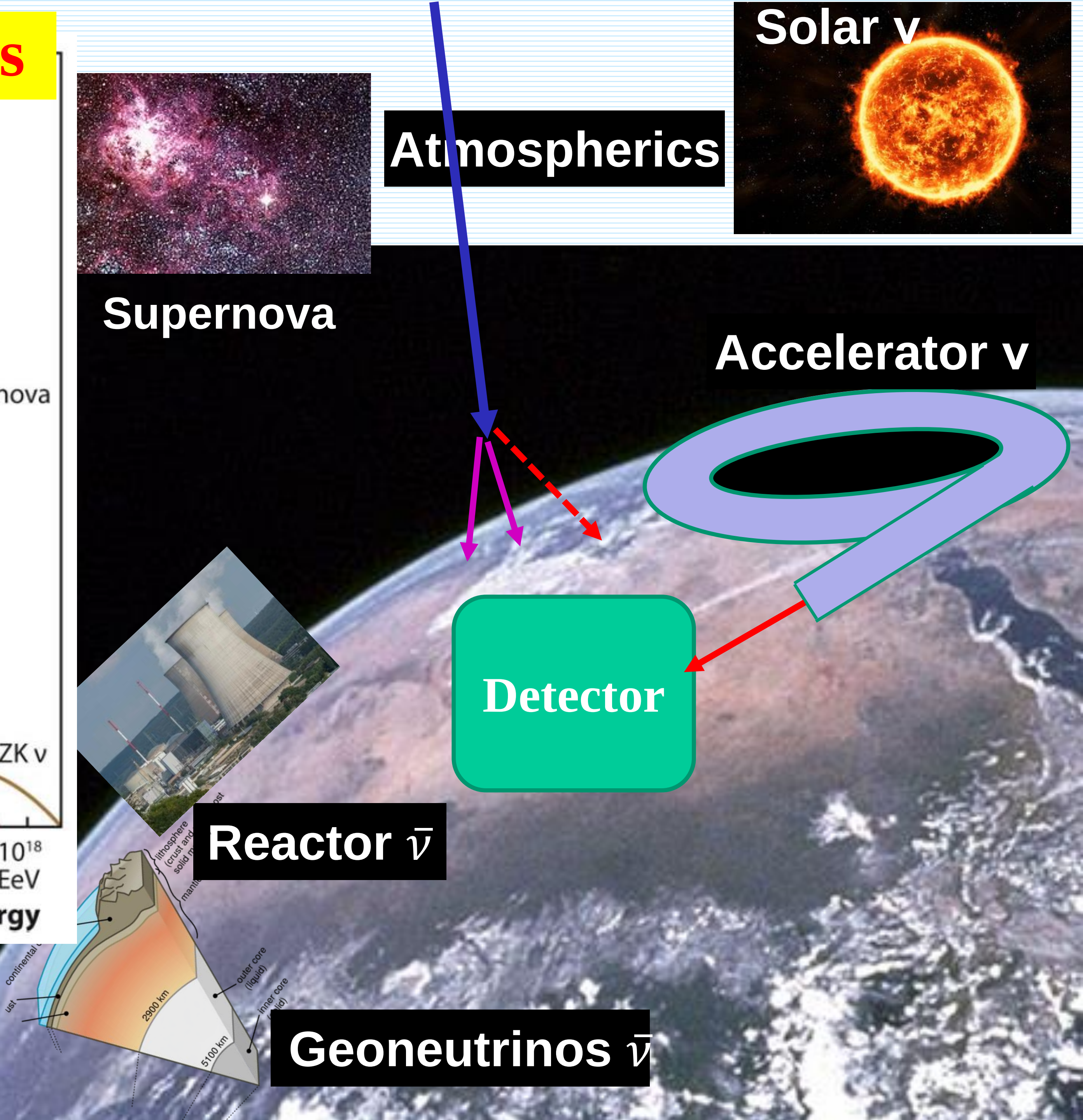
Nqwenelela impumelelo, Paul!

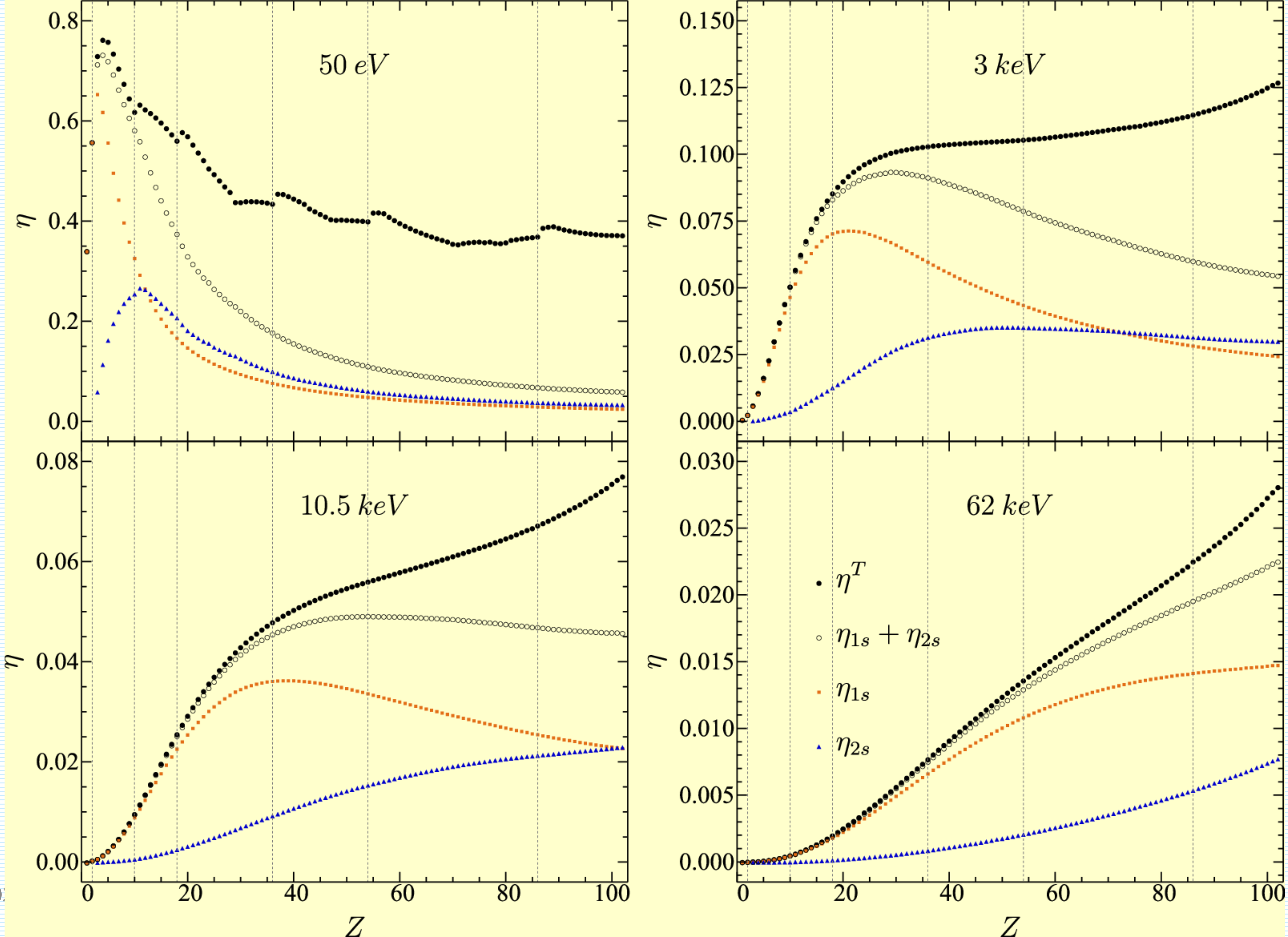
See you later!

Backup slides

Neutrino Sources

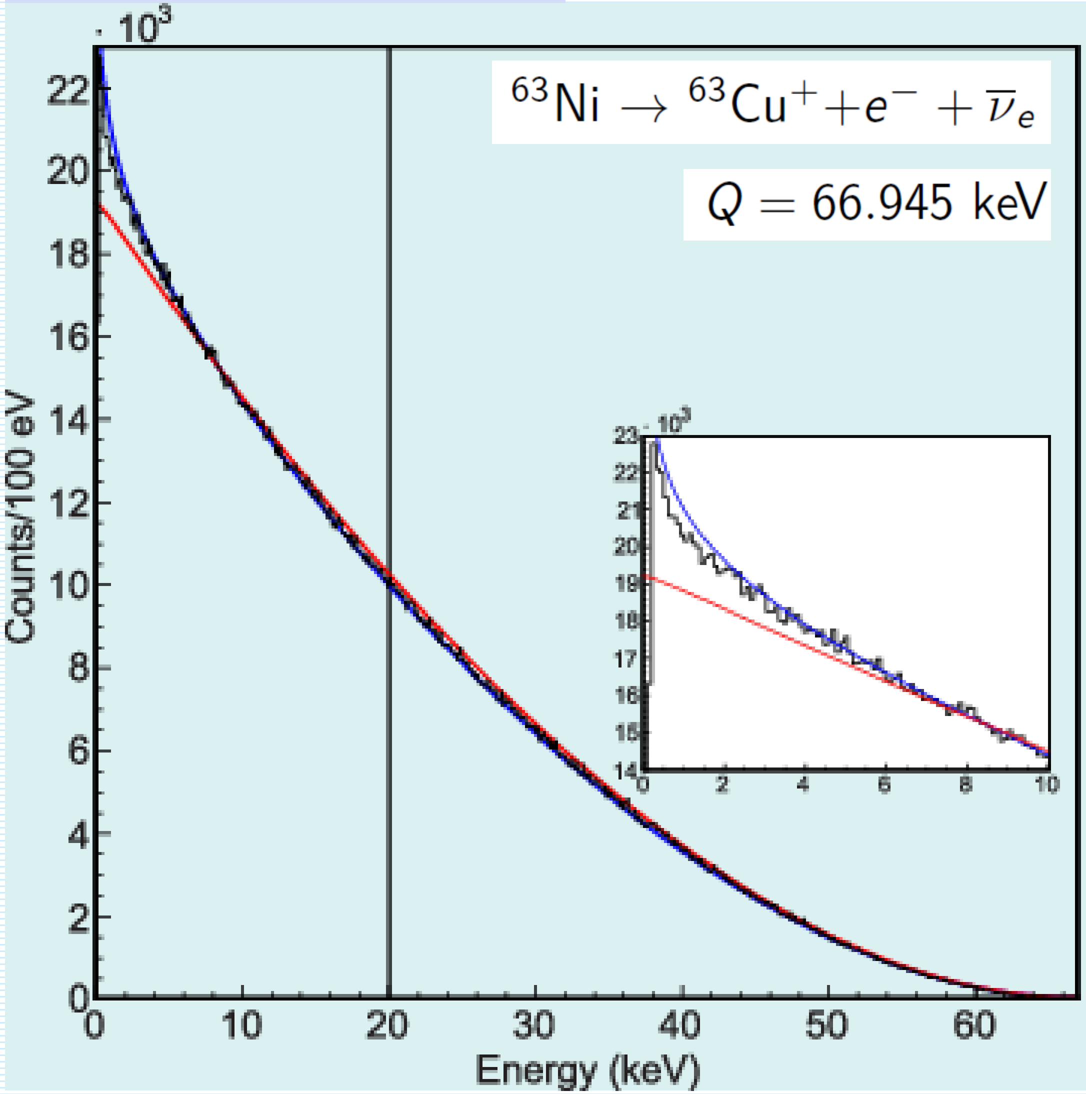




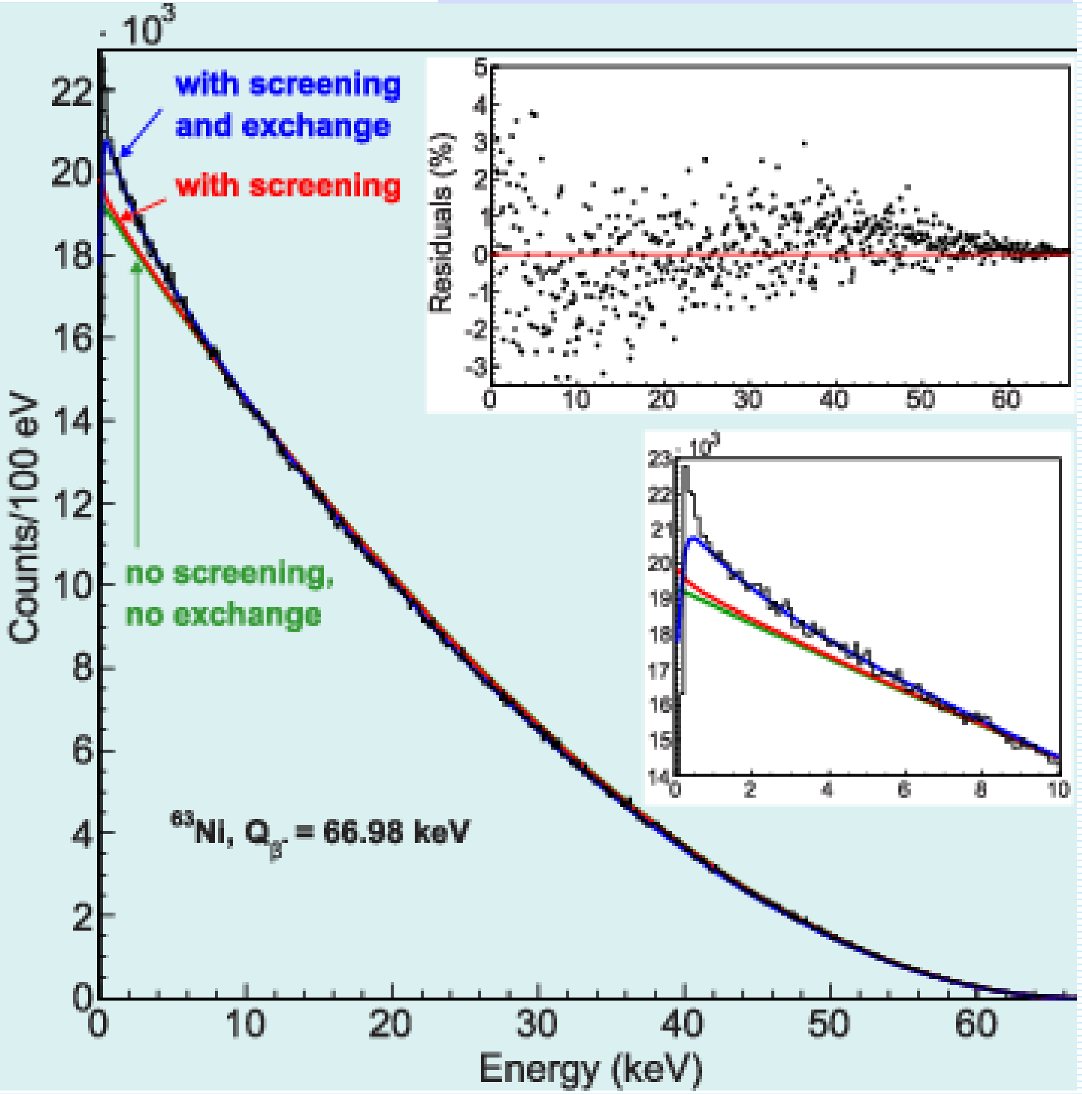

50 eV
3 keV
10.5 keV
62 keV
η
Z
η^T
$\eta_{1s} + \eta_{2s}$
η_{1s}
η_{2s}

β-decay of ^{63}Ni
(with electron exchange effect)

with orthogonalization



without orthogonalization



O. Nitescu, S. Stoica, F.Š., PRC 107, 025501 (2023)