TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften, Institut für Kern- und Teilchenphysik

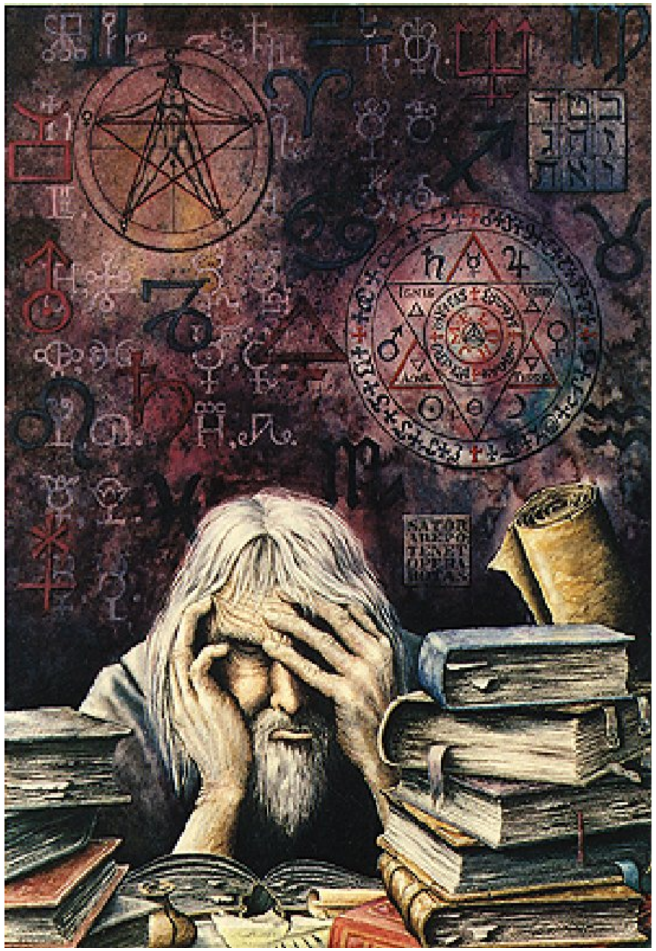
Overview of THEIA physics 2025- Low energy

23.10. 2016, FROST Workshop Mainz

Kai Zuber, TU Dresden

DRESDEN concept

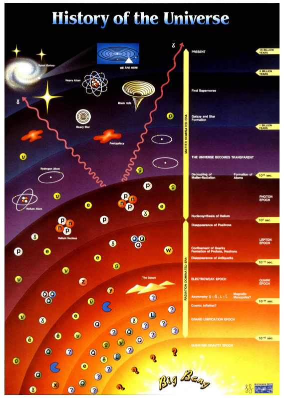
Contents



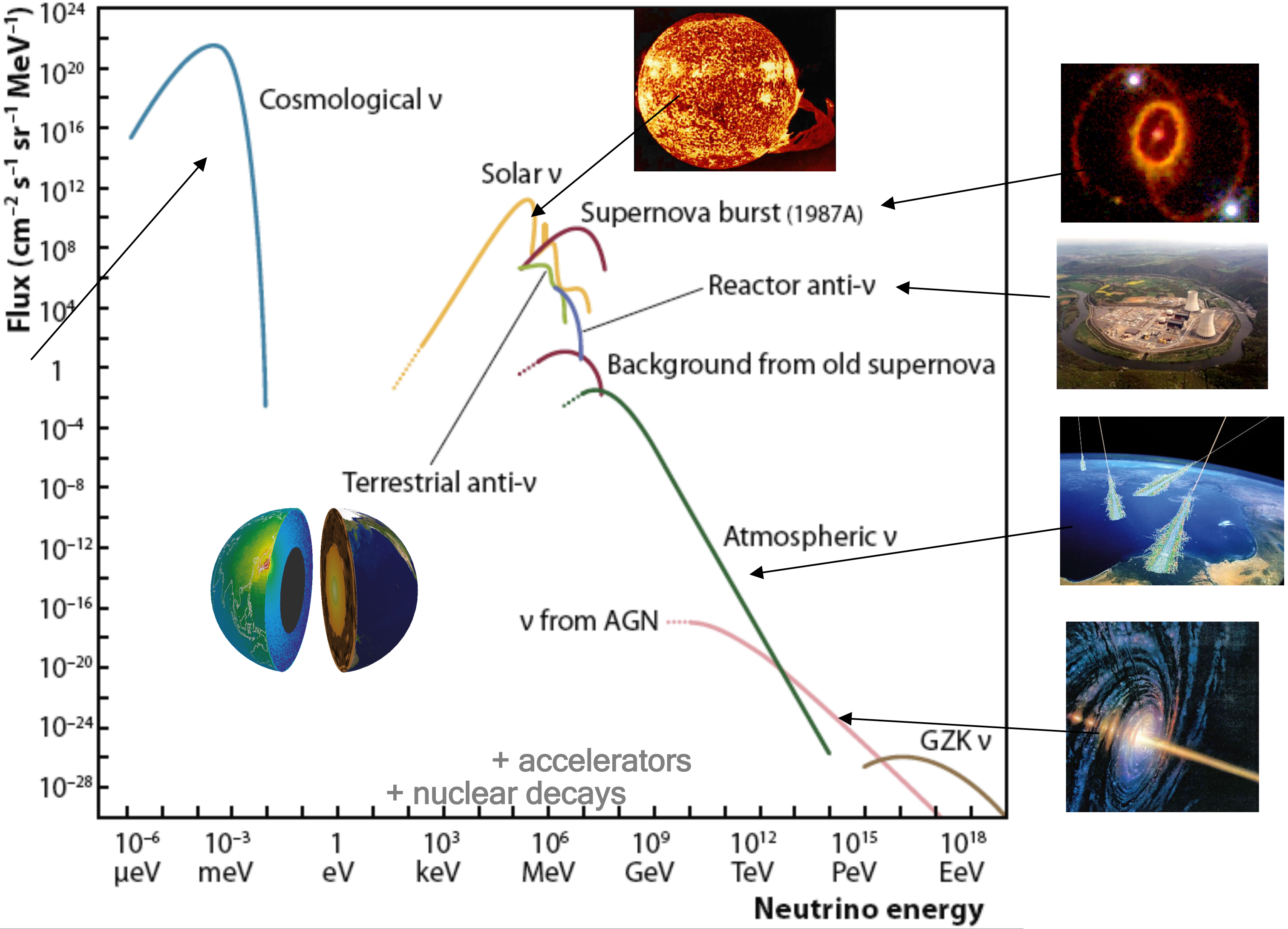
- Introduction
- Double beta decay and related issues
- Solar neutrinos
- Supernova neutrinos and DSNB
- Geo-neutrinos
- Summary

I will ignore sterile neutrinos, NSI,....,

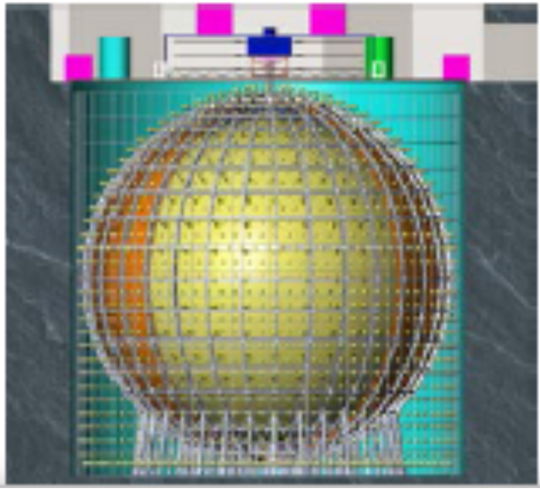
Universal neutrino spectrum

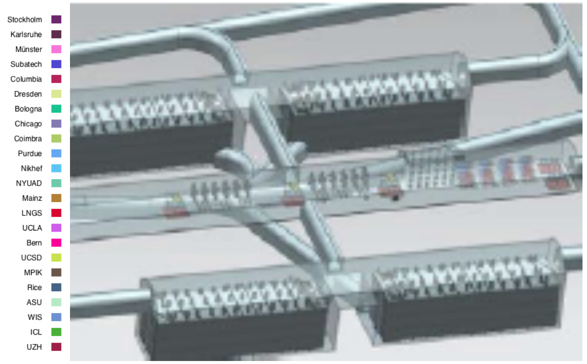


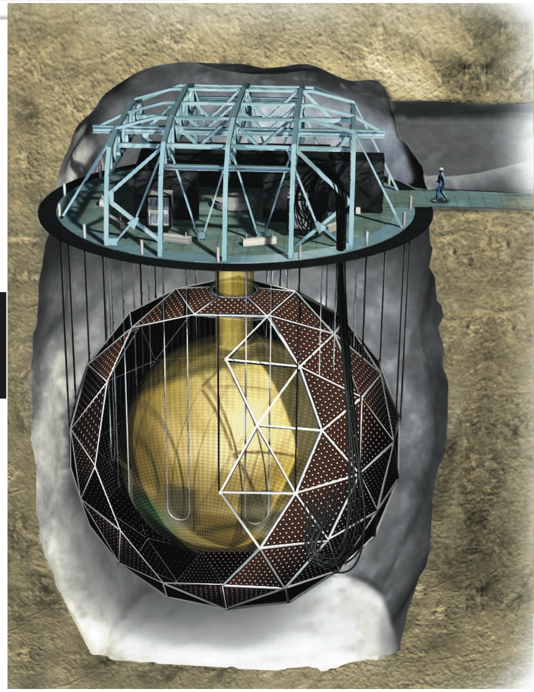
1.95 K neutrino background

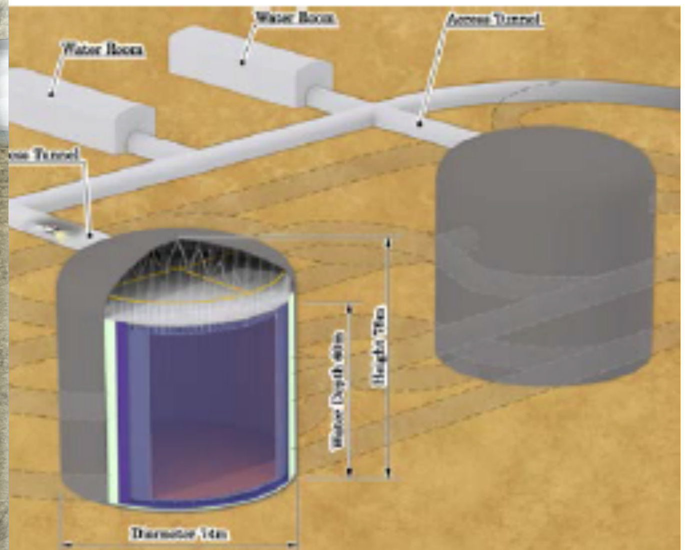


New detectors









+ more

Conservation laws

Not all conserved numbers are linked to fundamental symmetries

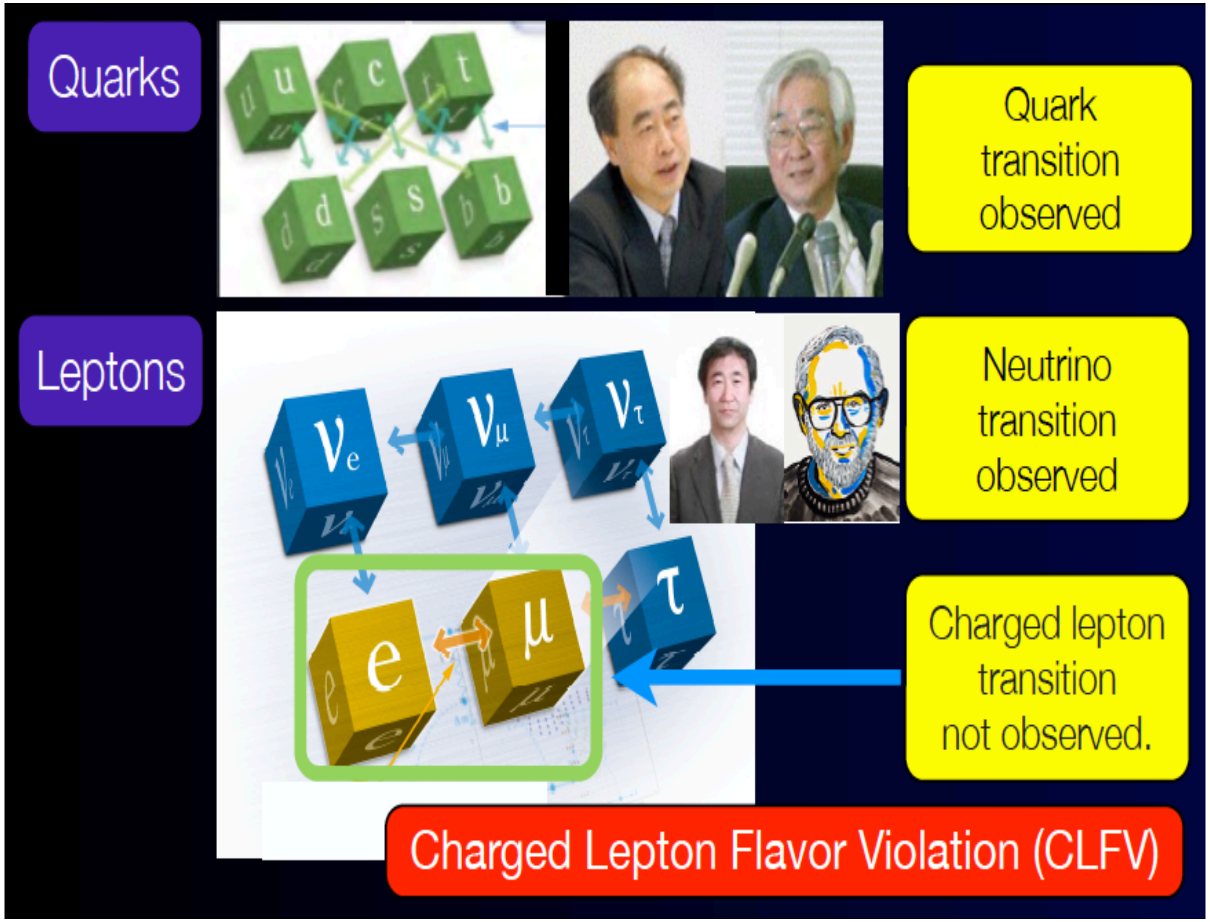
- $0\nu\beta\beta$ $\Delta L = 2, \Delta B = 0$
- Proton decay (Talk H. Tanaka) $\Delta L = 1, \Delta B = 1$
- Neutron-Antineutron Osc. $\Delta L = 0, \Delta B = 2$

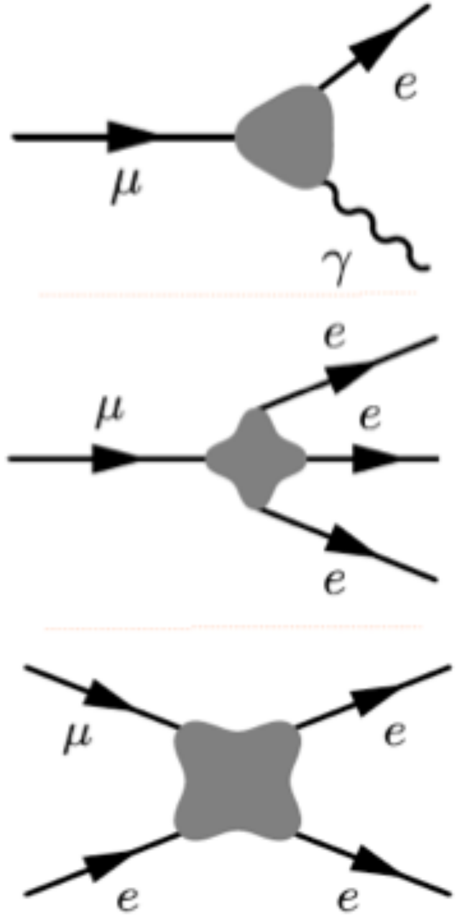
(Nnbar at ESS)

Only gauge anamoly free combination is B-L $\Delta(B - L) = 0$

Electroweak phase transition $\Delta(B + L) = 2 \times N_F$

Charge lepton number violation

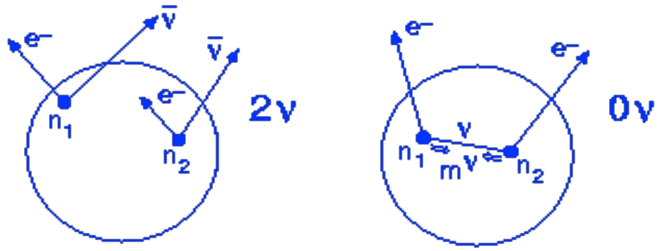




MEG (+ upgrade) and mu ->3 e at PSI,
mu-e conversion COMET (J-PARC), Mu2e (Fermilab)
4 orders of magnitude improvement in the next 8 years

Double beta decay

- $(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$ 2νββ
- $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ 0νββ



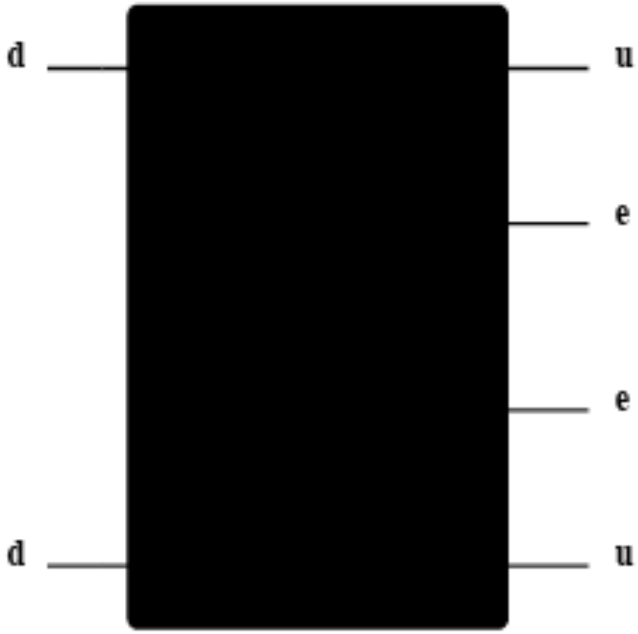
Unique process to measure character of neutrino

The smaller the neutrino mass the longer the half-life

Neutrino mass measurement via half-life measurement

Requires half-life measurements well beyond 10^{20} yrs!!!!

Any ΔL=2 process can contribute to 0νββ

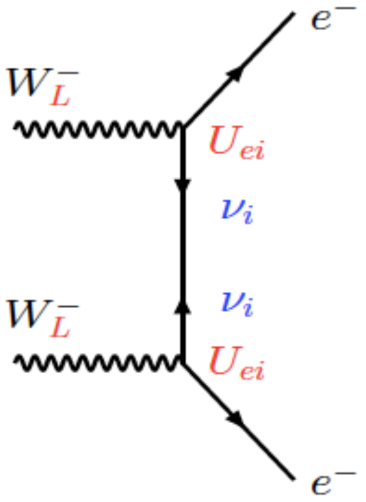


- R_p violating SUSY
- V+A interactions
- Extra dimensions (KK- states)
- Leptoquarks
- Double charged Higgs bosons
- Compositeness
- Heavy Majorana neutrino exchange
- Light Majorana neutrino exchange
- ...

$$1 / T_{1/2} = PS * NME^2 * \varepsilon^2$$

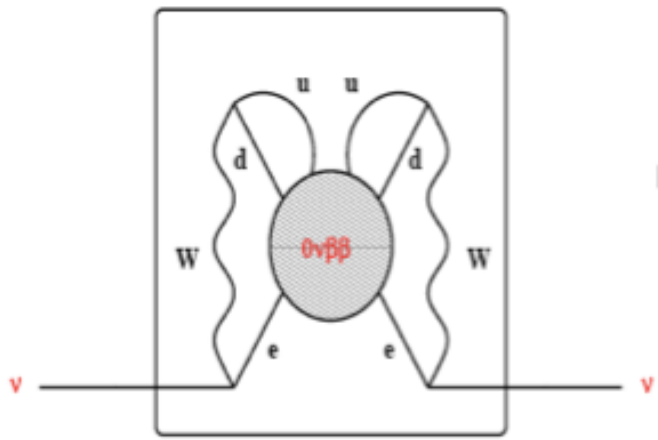
Nice interplay with LHC

Light Majorana neutrinos



$$\varepsilon \equiv \langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$$

$1 / T_{1/2} = PS * NME^2 * (<m_\nu> / m_e)^2$



Schechter and Valle 1982:

Independent of mechanism for neutrinoless DBD
Majorana neutrino mass will appear in higher order!

Observe $0\nu\beta\beta$ aecay

$\equiv$

Neutrinos are Majorana particles

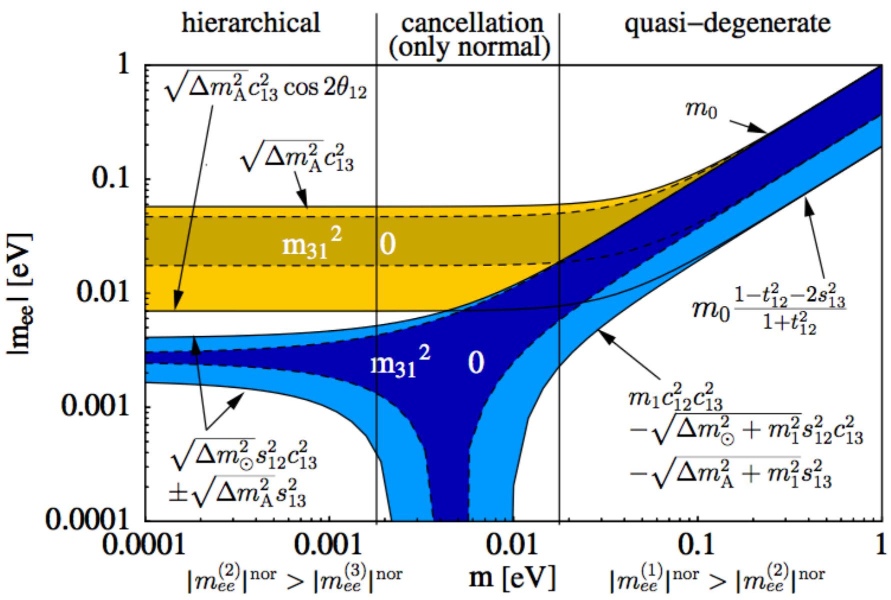
Mass hierarchies and DBD

With the known oscillation results everything is fixed

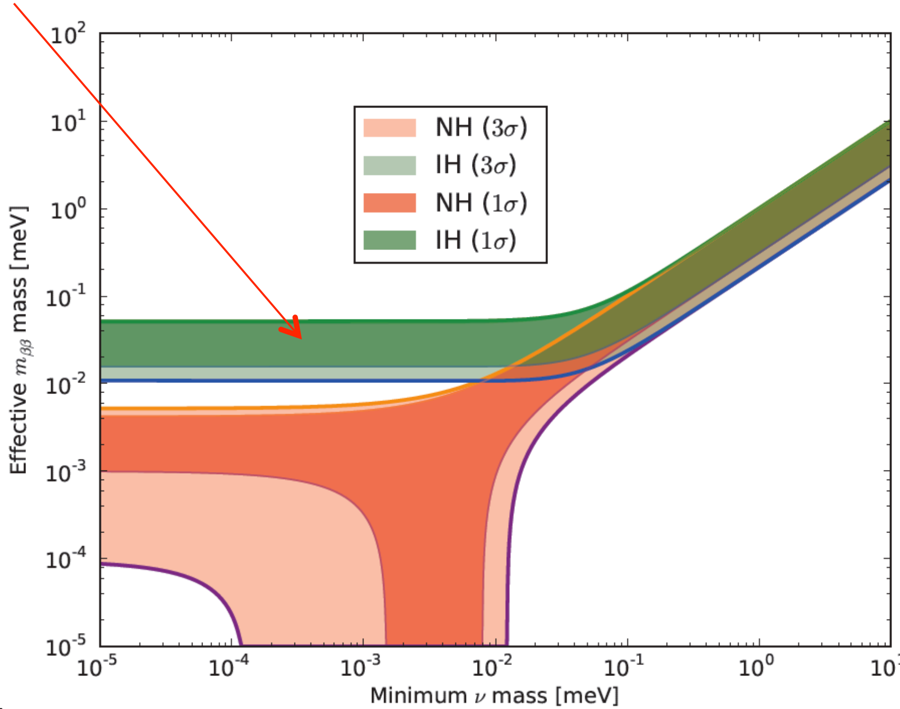
General dependence

Touch this by 2025

Current data



M. Lindner, A.. Merle, W. Rodejohann, Phys. Rev. D 73, 053005 (2006)



Back of an envelope

This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

$$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta} \quad (\tau >> T) \quad \text{(Background free)}$$

For half-life measurements of 10^{26-27} yrs

1 event/yr you need 10^{26-27} source atoms

This is about 1000 moles of isotope, implying about 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...

Perfect world experiment

- No background
- δ function as peak
- 100 % abundance
- 100% detection efficiency
- Infinite measuring time
- Infinite mass

$$T_{1/2}^{-1} \propto a\varepsilon\sqrt{\frac{Mt}{\Delta E B}}$$

Life is easy, the rest is just details

Experimental approaches

0νββ decay rate scales with Q^5 → only those with Q>2000 keV

11 isotopes of interest

Isotope	Nat. abund. (%)	Q-values 2012
Ca-48	0.187	4262.96 ± 0.84
Ge-76	7.44	2039.006 ± 0.050
Se-82	8.73	2997.9 ± 0.3
Zr-96	2.80	3356.097 ± 0.086
Mo-100	9.63	3034.40 ± 0.17
Pd-110	11.72	2017.85 ± 0.64
Cd-116	7.49	2813.50 ± 0.13
Sn-124	5.79	2292.64 ± 0.39
Te-130	33.80	2527.518 ± 0.013
Xe-136	8.9	2457.83 ± 0.37
Nd-150	5.64	3371.38 ± 0.20

Candles

GERDA, Majorana

SuperNEMO, LUCIFER

MOON, AMore

COBRA

Tin.Tin

CUORE, SNO+

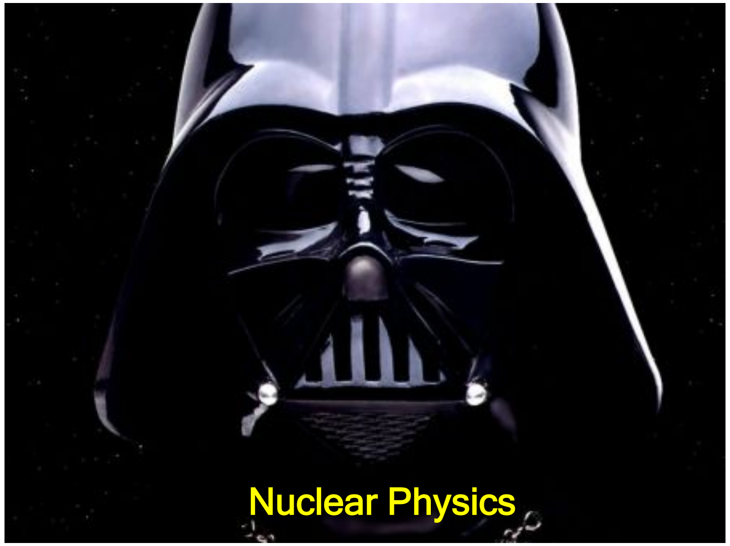
nEXO, KamLAND-Zen, NEXT, XMASS

MCT, SuperNEMO(?)

There is no super-isotope!

Master equation

$$1 / T_{1/2} = PS * NME^2 * (<m_\nu> / m_e)^2$$



Measurement

Exact calculation

J. Kotila, F. Iachello, PRC 034316 (2012)
S. Stoica, M. Mirea, arXiv:1307.0290

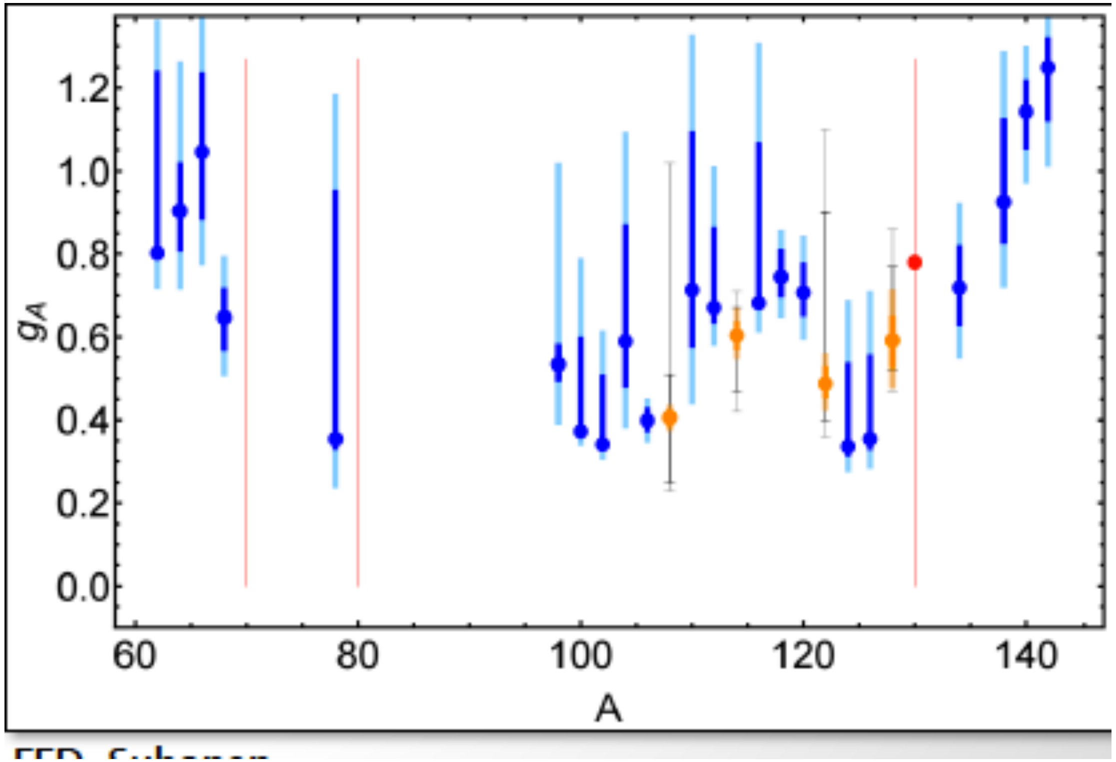
Complex calculations

Severe nuclear structure issue

Quantity of interest

Quenching of g_A

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} g_A^4 \mid M^{0\nu} \mid^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$



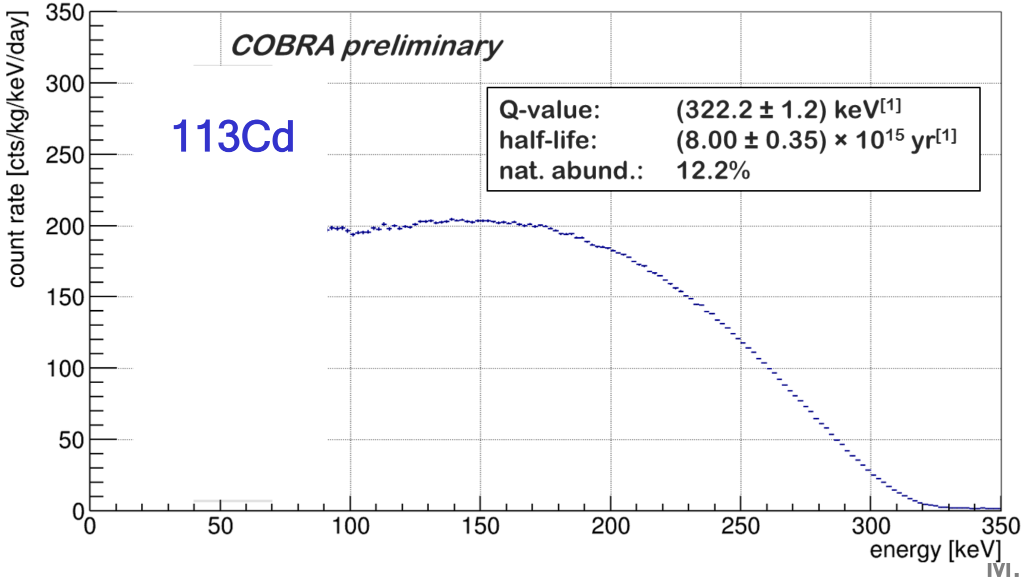
Deppisch, Suhonen, arXiv:1606.02908

The case of ^{113}Cd

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} g_A^4 \mid M^{0\nu} \mid^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

4-fold forbidden non-unique beta decay ($1/2^+ \rightarrow 9/2^+$)

COBRA experiment (CdZnTe detectors)



Q-value:

$$322 \pm 0.3(stat.) \pm 0.9(sys.) \text{ keV}$$

J. V. Dawson et al., Nucl. Phys. A 818,264 (2009)

AME 2012 value: 322.6 0.8 keV

Penning trap value: 323.89 (27) keV

N. D. Gamage et al., Phys. Rev. C 94,025505 (2016)

Shape depends on g_A

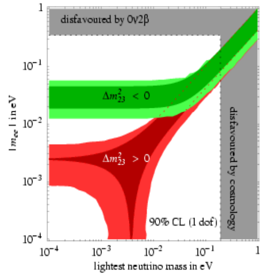
T. Mustonen, M. Aunola, J. Suhonen , PRC 73,054301 (2006)

M. T. Mustonen, J. Suhonen,, PLB 657,38 (2007)

Tackling 50 meV (IH)

Inverse hierarchy:

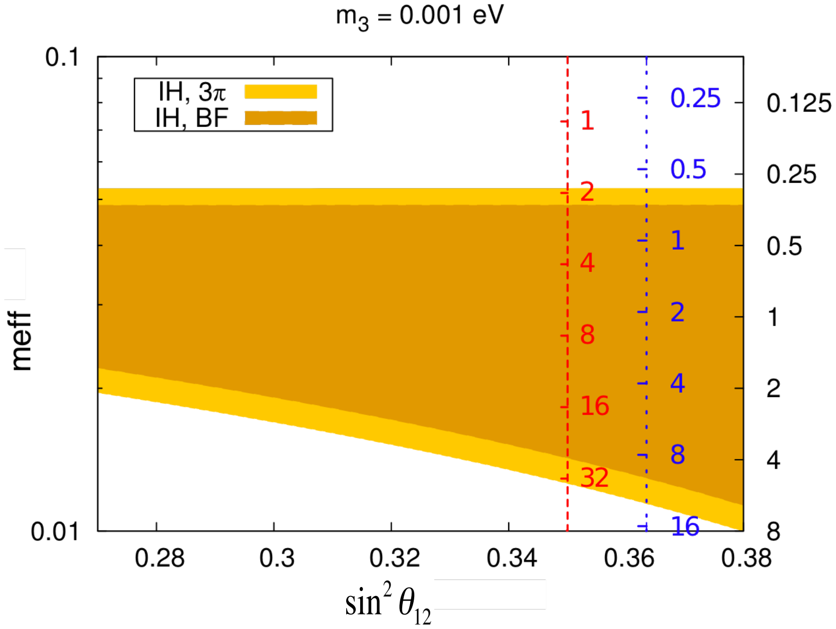
$$
\begin{aligned}
\langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\
&\simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 \\
&\sim (c_\odot^2 - s_\odot^2)\sqrt{\Delta m^2_{Atm}} \\
&\simeq 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}}\ \mathrm{eV} \ \simeq 19\ \mathrm{meV}
\end{aligned}
$$

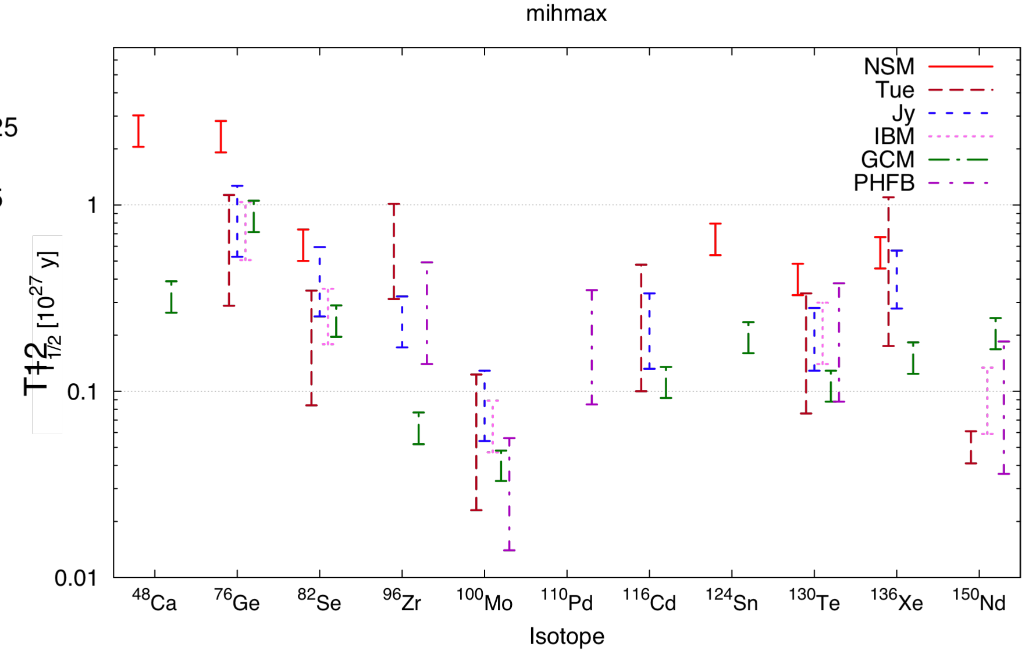


Just to touch the IH

^{100}Mo and ^{150}Nd seems most promising

Dependence on solar mixing angle

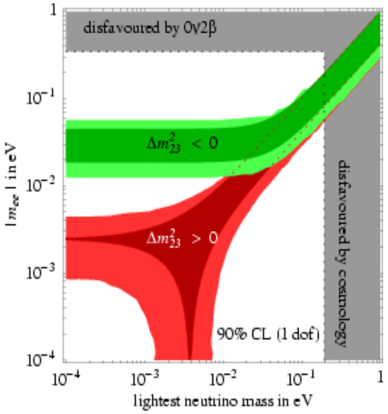




A. Dueck, W. Rodejohann, K. Zuber, PRD 83, 113010 (2011)

Reminder: Factor 2 in mass implies factor 16 in experimental parameters ➔ better solar measurement
➔SNO+??? Reactors (JUNO , RENO-50)???

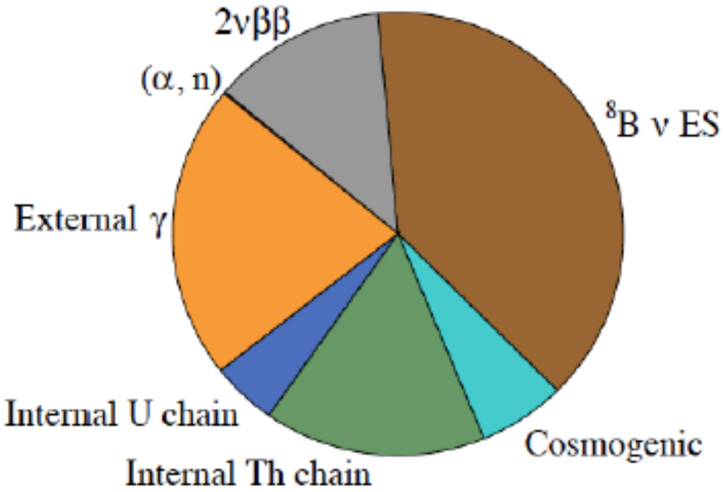
Tackling the IH/normal hierarchy

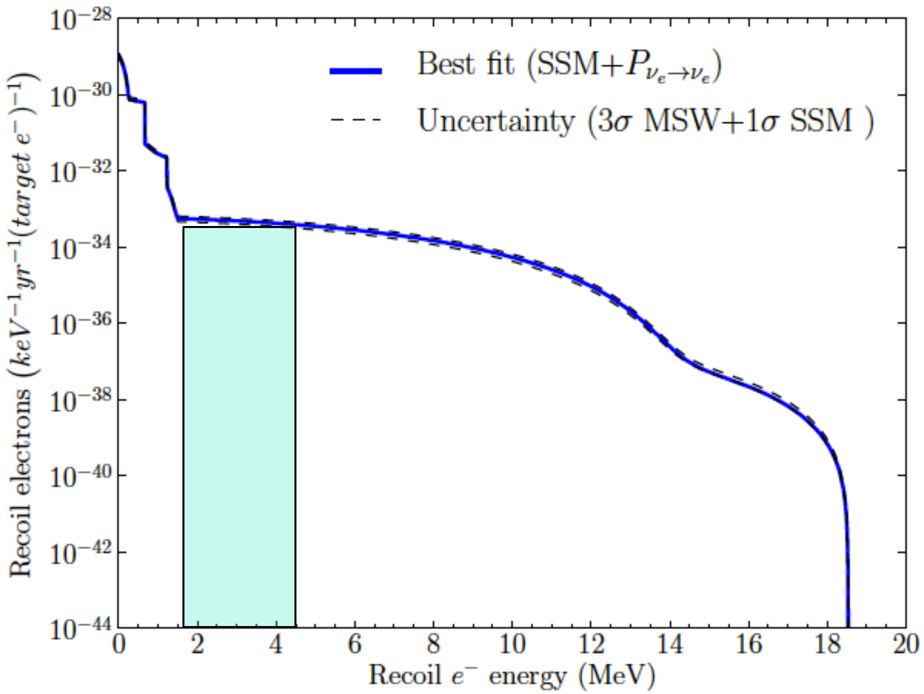


Effects described will already appear if in IH

- Will be tough and expensive
  >> tonne scale detectors
- Needs more precise data
  from oscillations

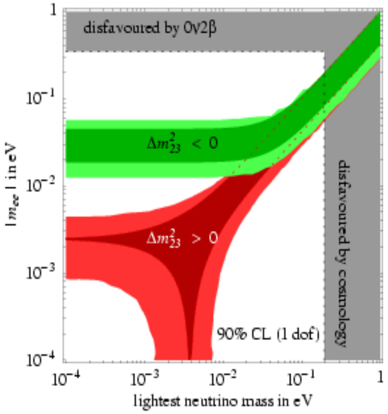
SNO+ background budget





N. deBarros, K. Zuber, JPG 38, 105201 (2011)

Tackling the normal hierarchy

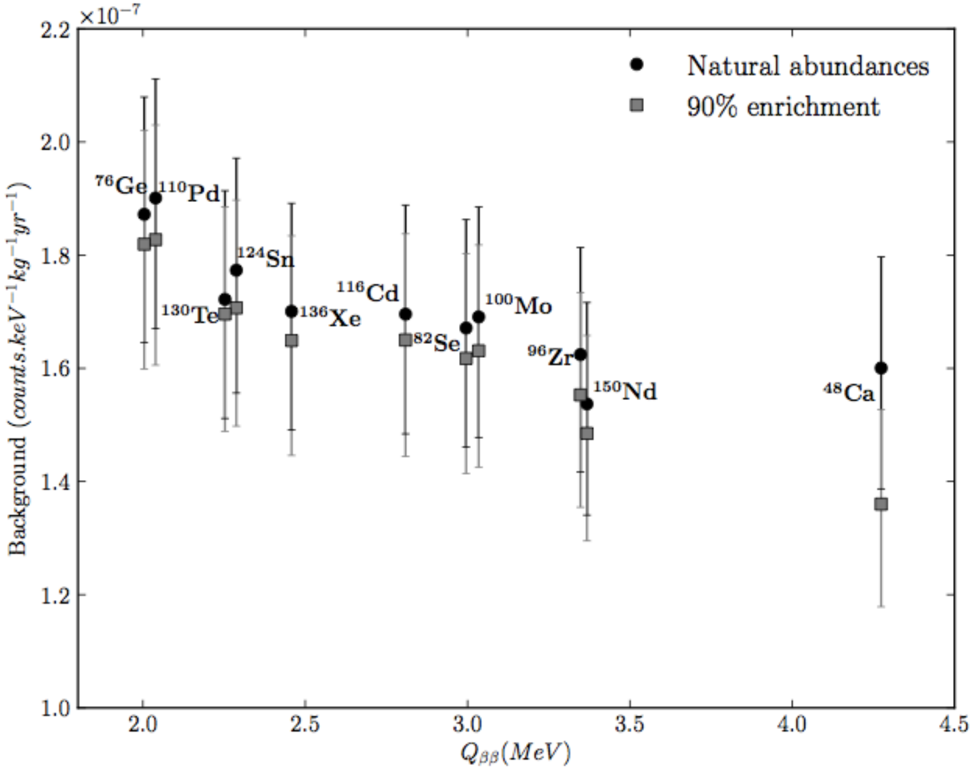


Effects described will already appear if in IH

- Will be tough and expensive
  >> tonne scale detectors
- Needs more precise data
  from oscillations

- New background components (f.e. solar neutrino-electron elastic scattering, CC reactions on DBD nuclide)

N. deBarros, K. Zuber, JPG 38, 105201 (2011)
H. Ejiri, K. Zuber, J. Phys. G. 43,045201 (2016)
H. Ejiri, S. Elliott, Phys. Rev. C 89,055501(2014

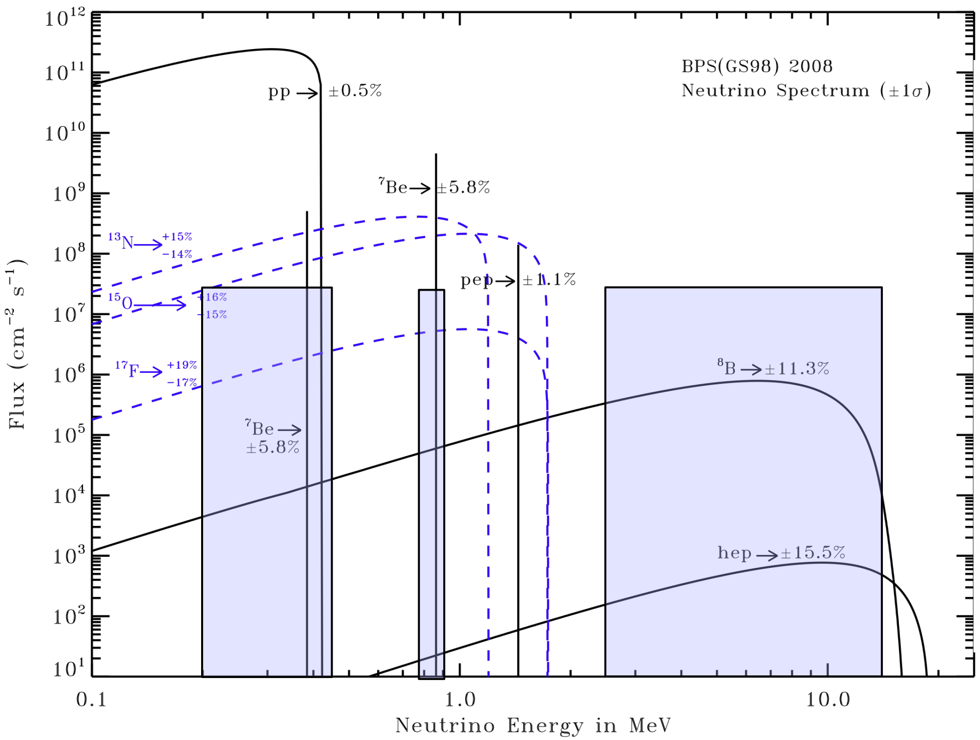


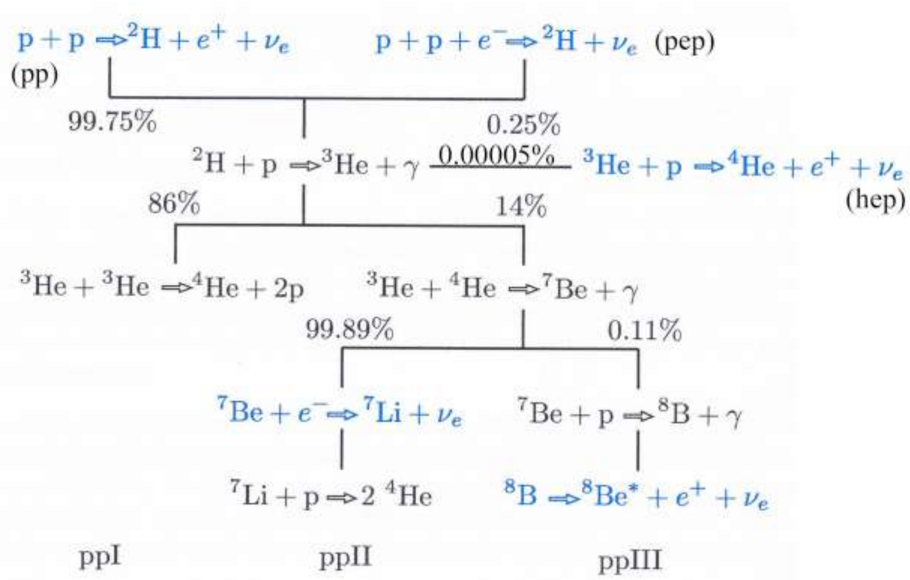
Experiments which work for IH might not work for NH

Standard solar models

Assumption: The Sun is producing energy via nuclear fusion

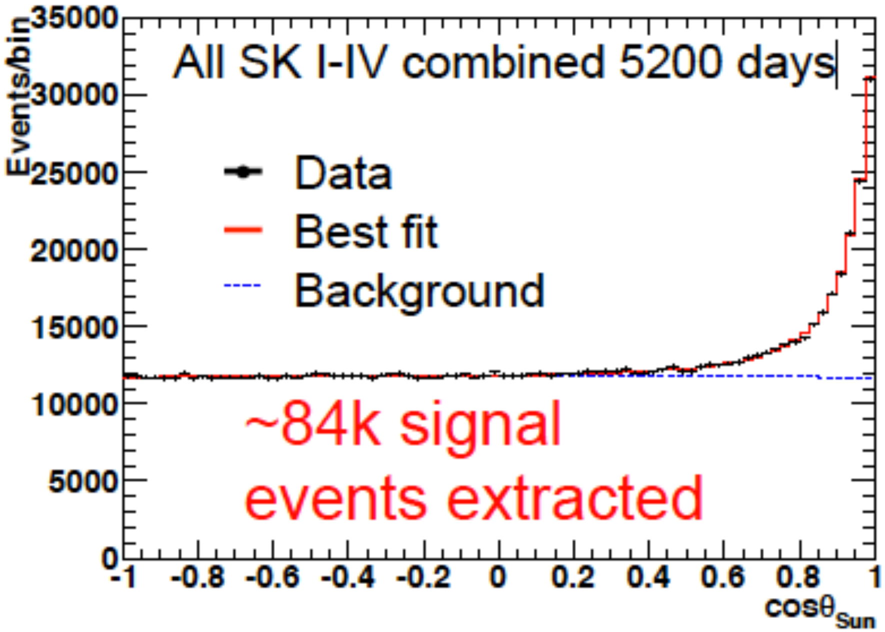
$$2e^- + 4p \rightarrow {}^4He + 2\nu_e + 26.73\ MeV$$





Ultimate goal: Measure full spectrum in real time

Super-K solar

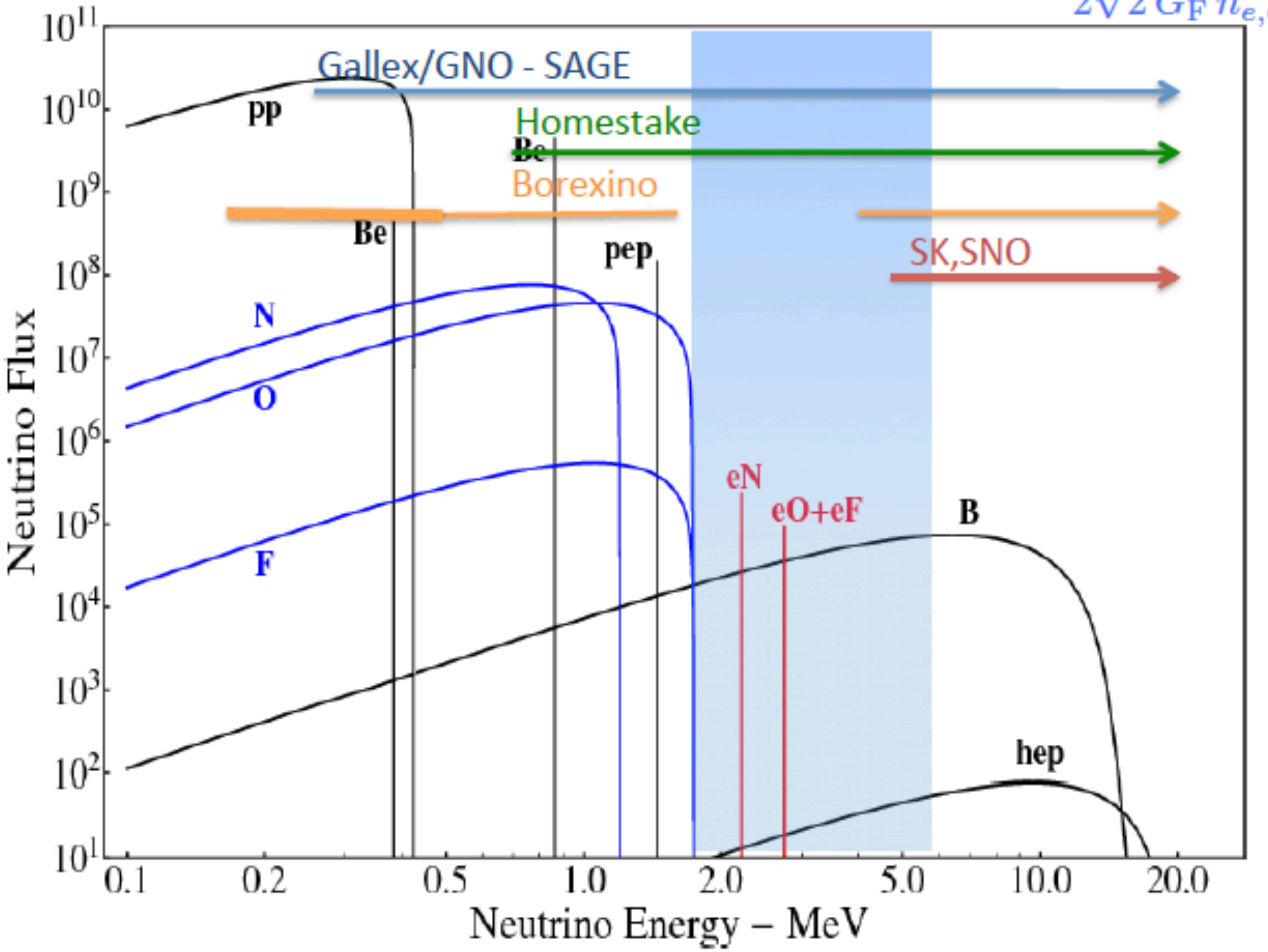


Earth matter effects!!!
Regeneration

^{8}B flux
DATA/MC = 0.4486±0.0062
Flux = 2.355±0.033 [10^6/cm^2/sec]

Solar neutrino measurements

"Transition" at: $E^* = \frac{\Delta m^2_{21} \cos(2\theta_{12})}{2\sqrt{2}\, G_F\, n_{e,\odot}}$

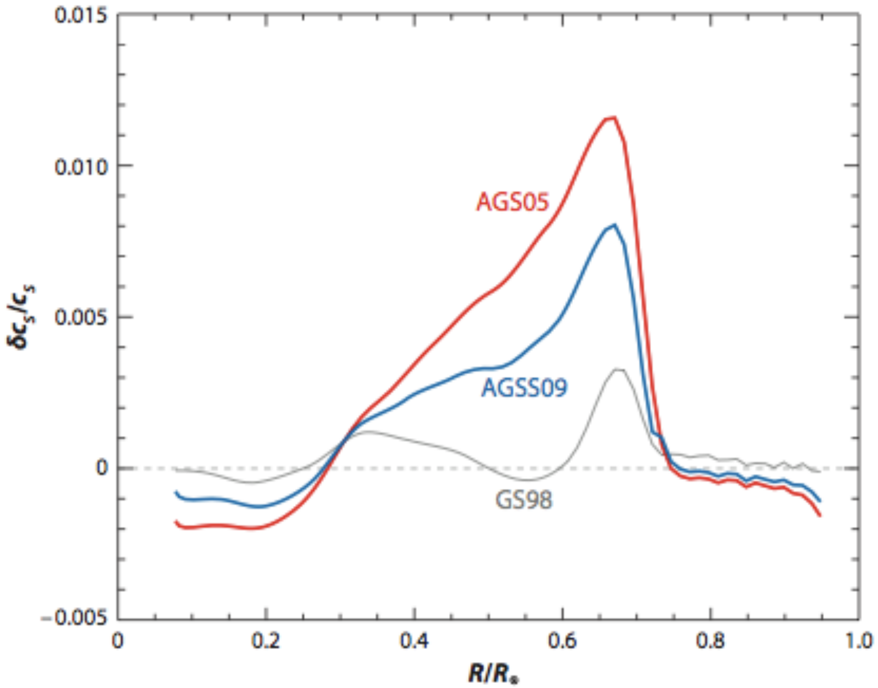


J.N. Bahcall, PRD 1990
L.C. Stonehill et al., PRC 2004
F.L. Villante, PLB 2015

Measurement of CNO-neutrinos

First prove of the existence of the CNO-fusion cycle

The solar abundance problem



Asplund et al.
Ann. Rev. Astr. Astrophys. 47, 481 (2009)

Two paradigmatic sets

Element	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

$\log \varepsilon_X = \log (N_X/N_H) + 12$

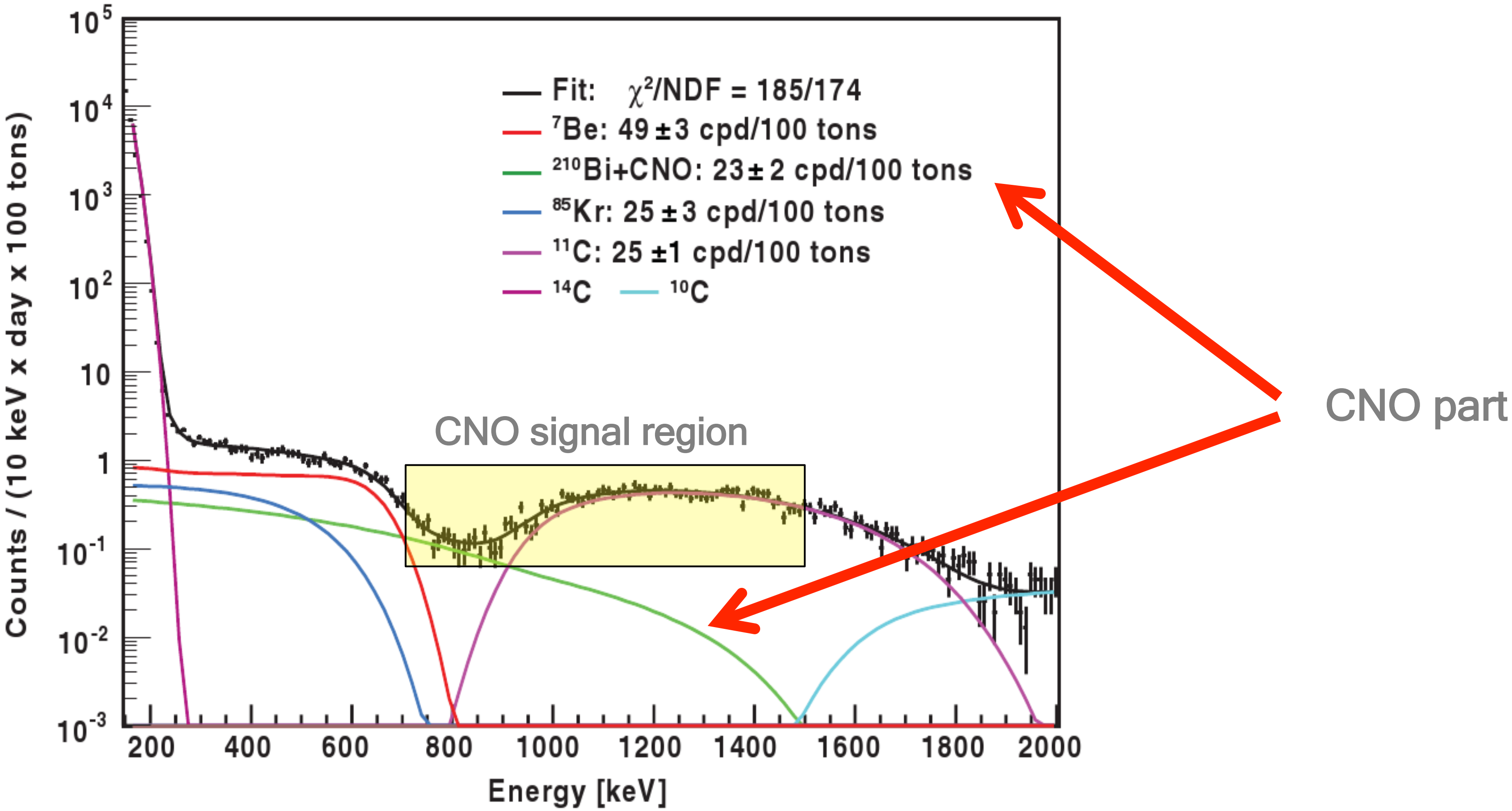
GS98: Grevesse & Sauval (1998)
AGSS09: Asplund et al. (2009)

Reduction of CNO(Ne) ≈30-40%

Borexino spectrum

Are metals homogeneously distributed in stars?

Pallavicini, Neutrino 2012



Measure CNO neutrinos (very tough), Jinping proposal , arXiv:1602.01733

Uncertainties

Nuclear reaction rates

	S_{11}	S_{33}	S_{34}	S_{17}	$S_{1,14}$	Opac	Diff
pp	0.1	0.1	0.3	0.0	0.0	0.2	0.2
pep	0.2	0.2	0.5	0.0	0.0	0.7	0.2
hep	0.1	2.3	0.4	0.0	0.0	1.0	0.5
^{7}Be	1.1	2.2	4.7	0.0	0.0	3.2	1.9
^{8}B	2.7	2.1	4.5	7.7	0.0	6.9	4.0
^{13}N	2.1	0.1	0.3	0.0	5.1	3.6	4.9
^{15}O	2.9	0.1	0.2	0.0	7.2	5.2	5.7
^{17}F	3.1	0.1	0.2	0.0	0.0	5.8	6.0

^{3}He(α,γ)^{7}Be

^{7}Be(p,γ)^{8}B

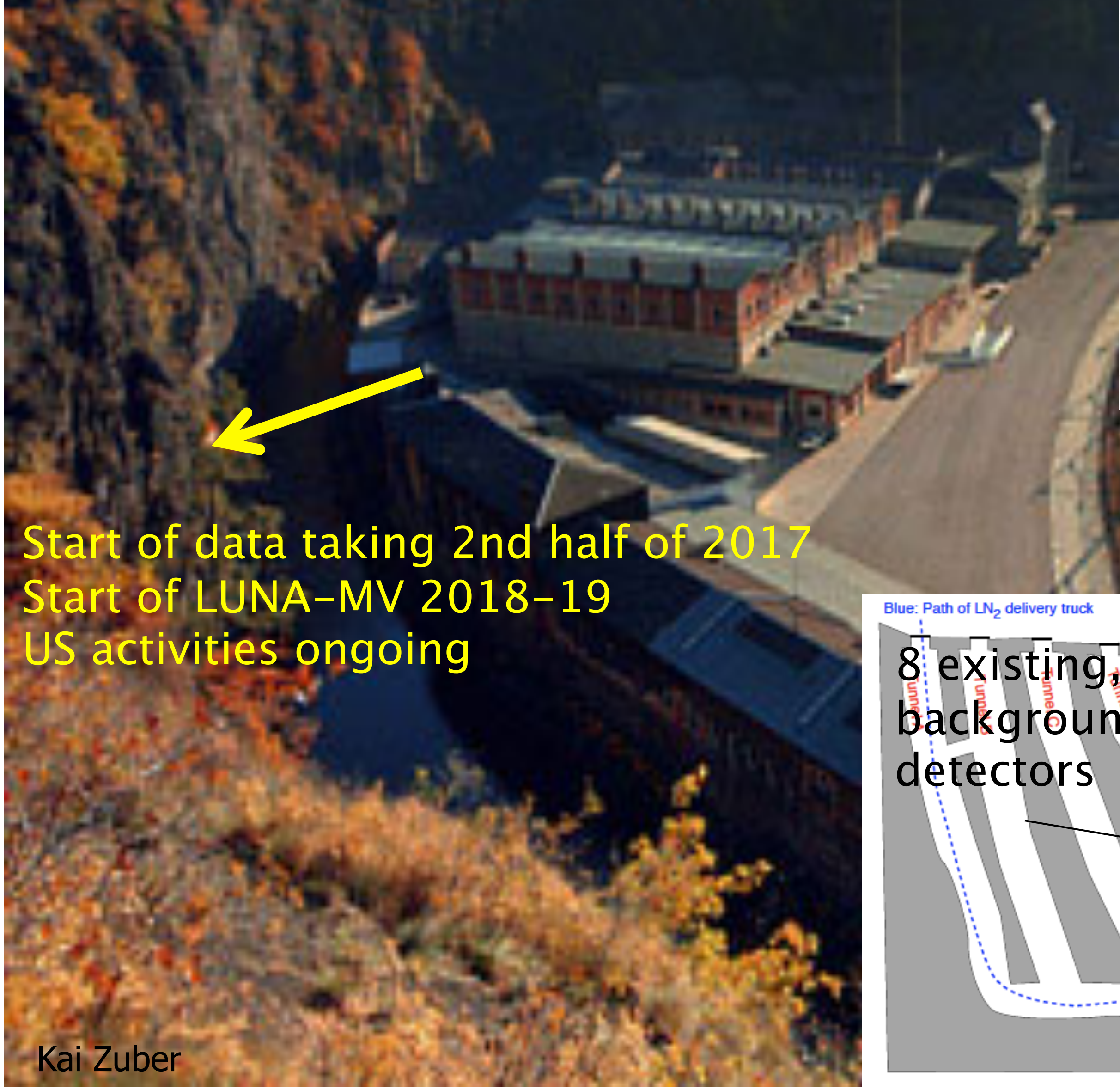
^{14}N(p,γ)^{15}O

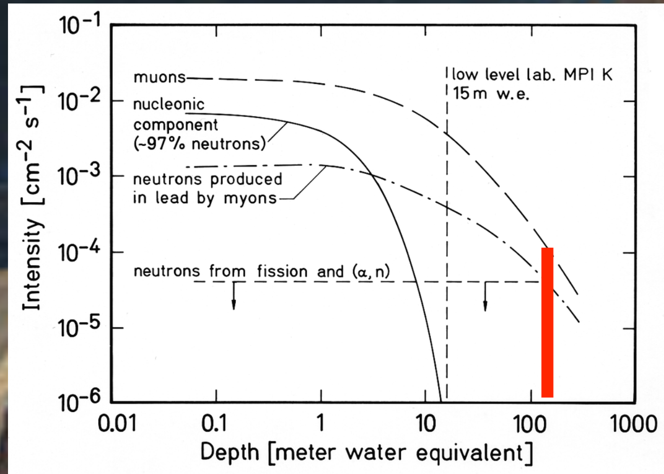
Unsicherheit im vorhergesagten Neutrinofluss, in Prozent

Antonelli et al., 1208.1356

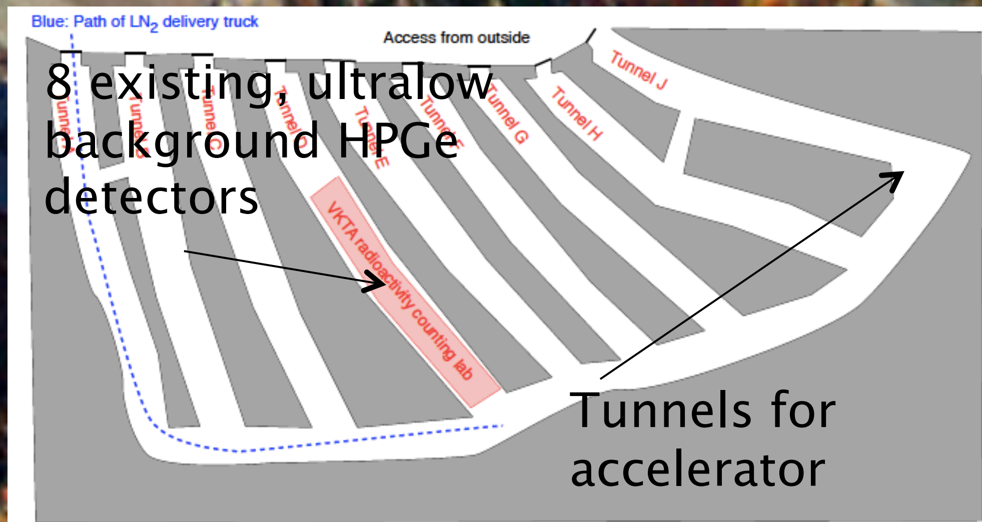
Felsenkeller Laboratory Dresden

T. Szücs et al., Eur. Phys. J. A 48,8 (2012)

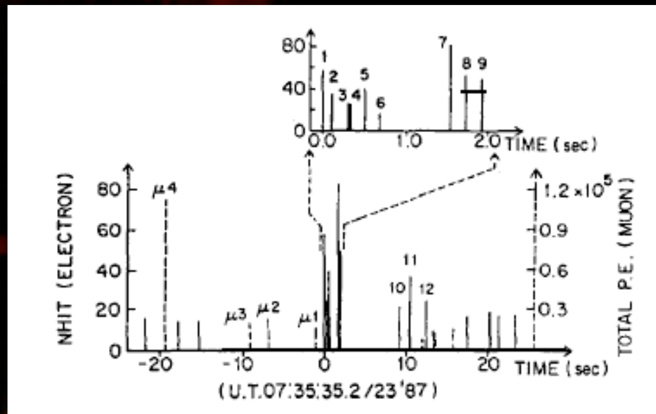




Start of data taking 2nd half of 2017
Start of LUNA-MV 2018-19
US activities ongoing



Supernova 1987A

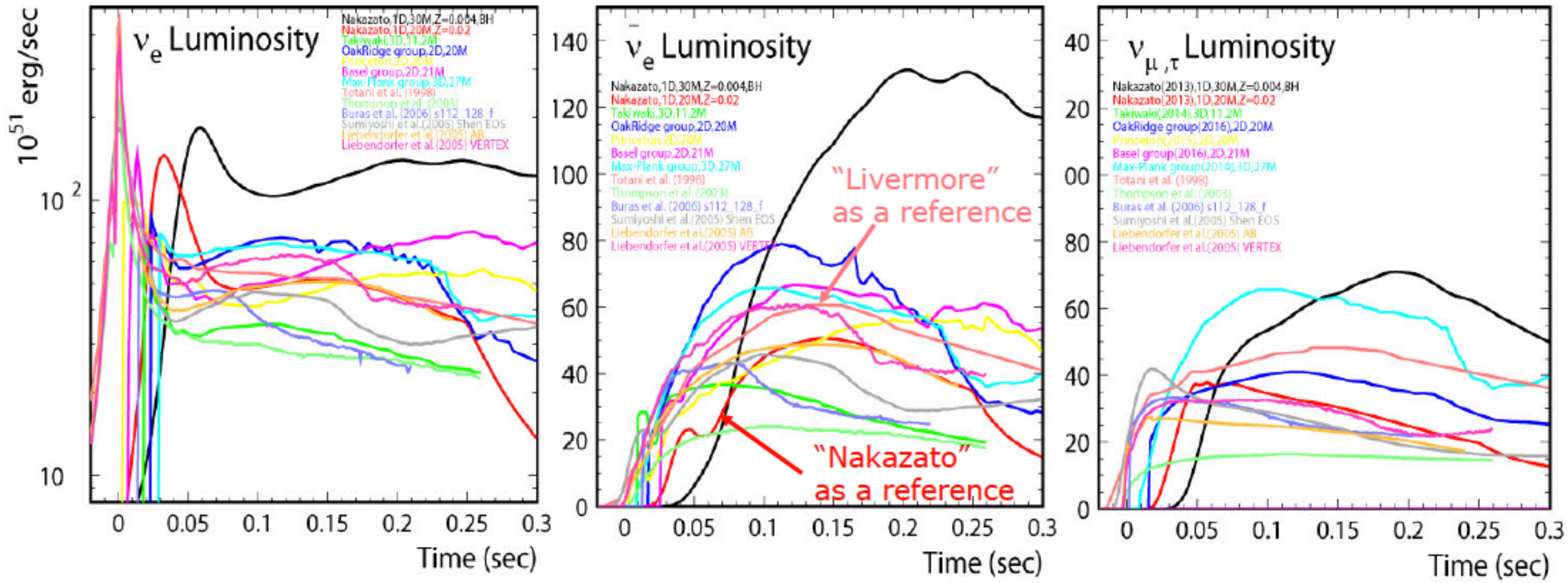


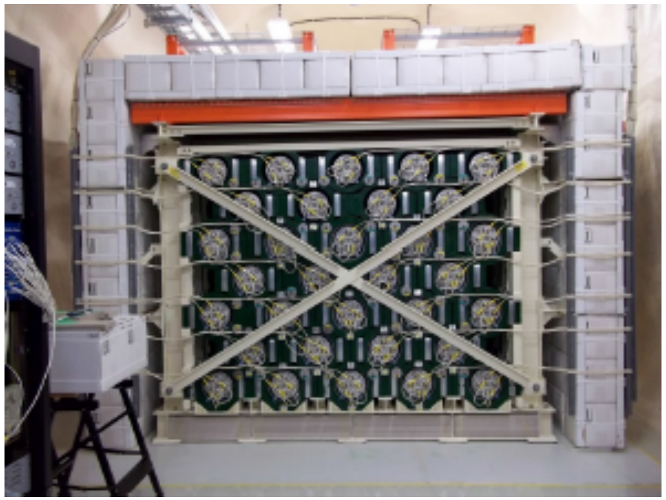
Desperately waiting for the next one

SN neutrino spectra

We are not short on simulated data, but on experimental data...

Figures: H.Suzuki, M. Nakahata

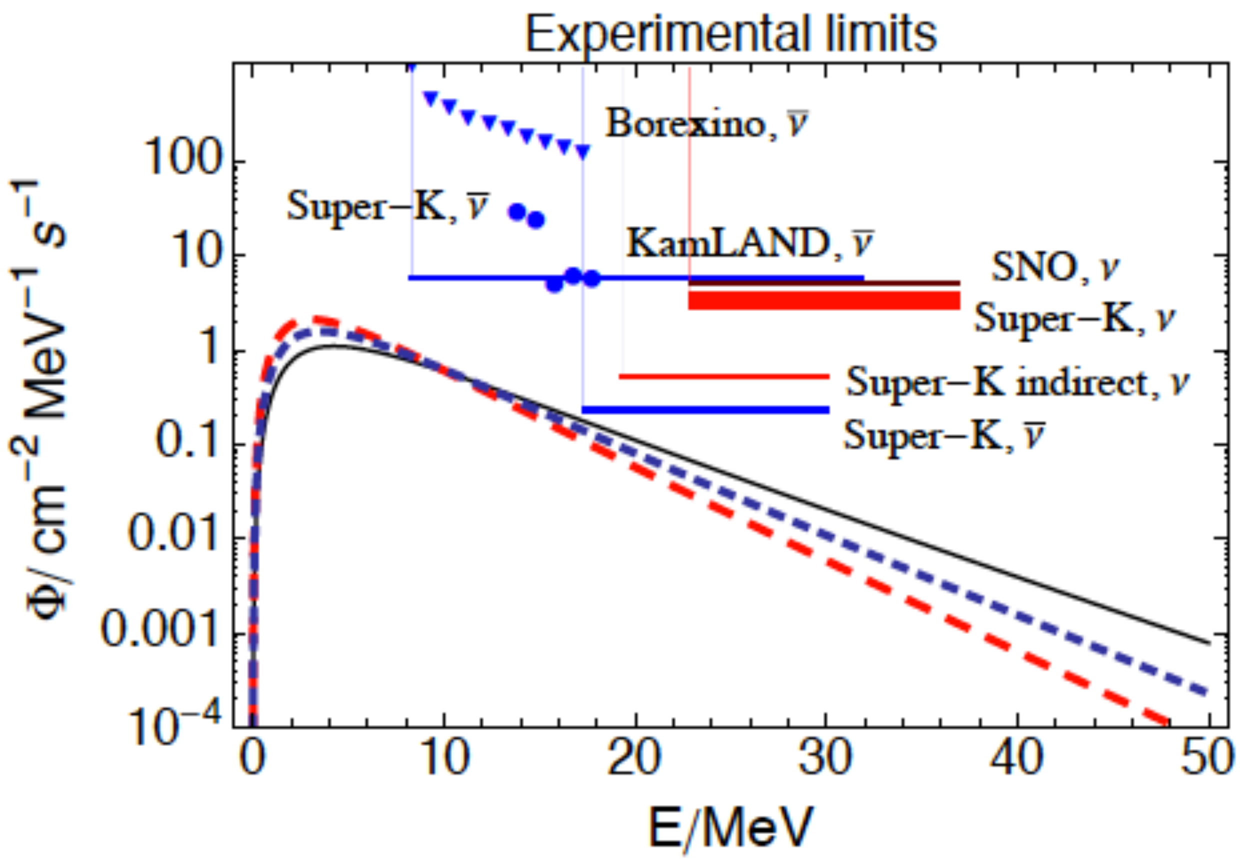




1 kt HALO-2 at LNGS?

Diffuse SN background

Summing up SN neutrinos from the history of the Universe



Geoneutrinos

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV},$$

$$^{235}_{92}\mathrm{U} \longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV},$$

$$^{232}_{90}\mathrm{Th} \longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV},$$

$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV},$$

$$^{40}_{19}\mathrm{K} + e^- \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}.$$

U and Th decays produce detectable antineutrinos

Geoneutrino flux proportional to U, Th concentration

Scales as 1/distance² from source

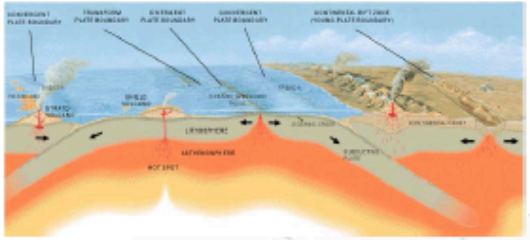
Predicting geoneutrino flux from geological models

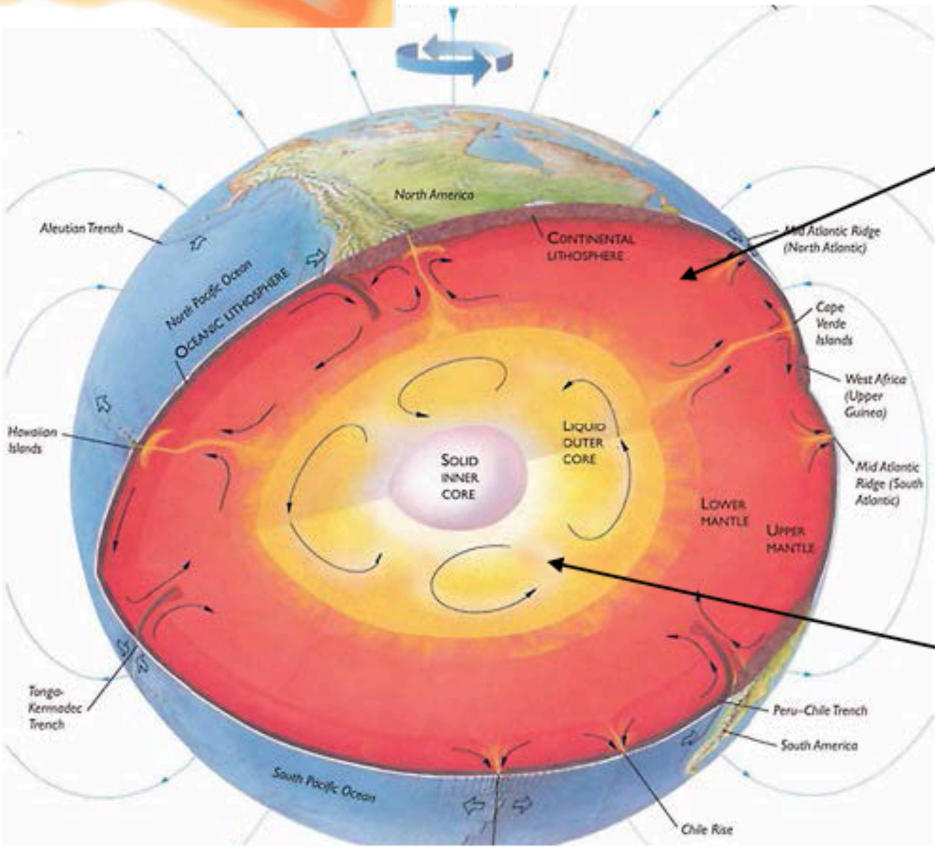
$$\phi(\vec{r}) = \frac{X\lambda N_A}{\mu} n_\nu \langle P_{ee}\rangle \iiint \frac{A(\vec{r}\,')\rho(\vec{r}\,')}{4\pi|\vec{r}-\vec{r}\,'|^2} d\vec{r}\,'$$

ρ … material density [kg/m³]

A … abundance of Th, U [g/g]

Plate tectonics ⇔ Mantle convection

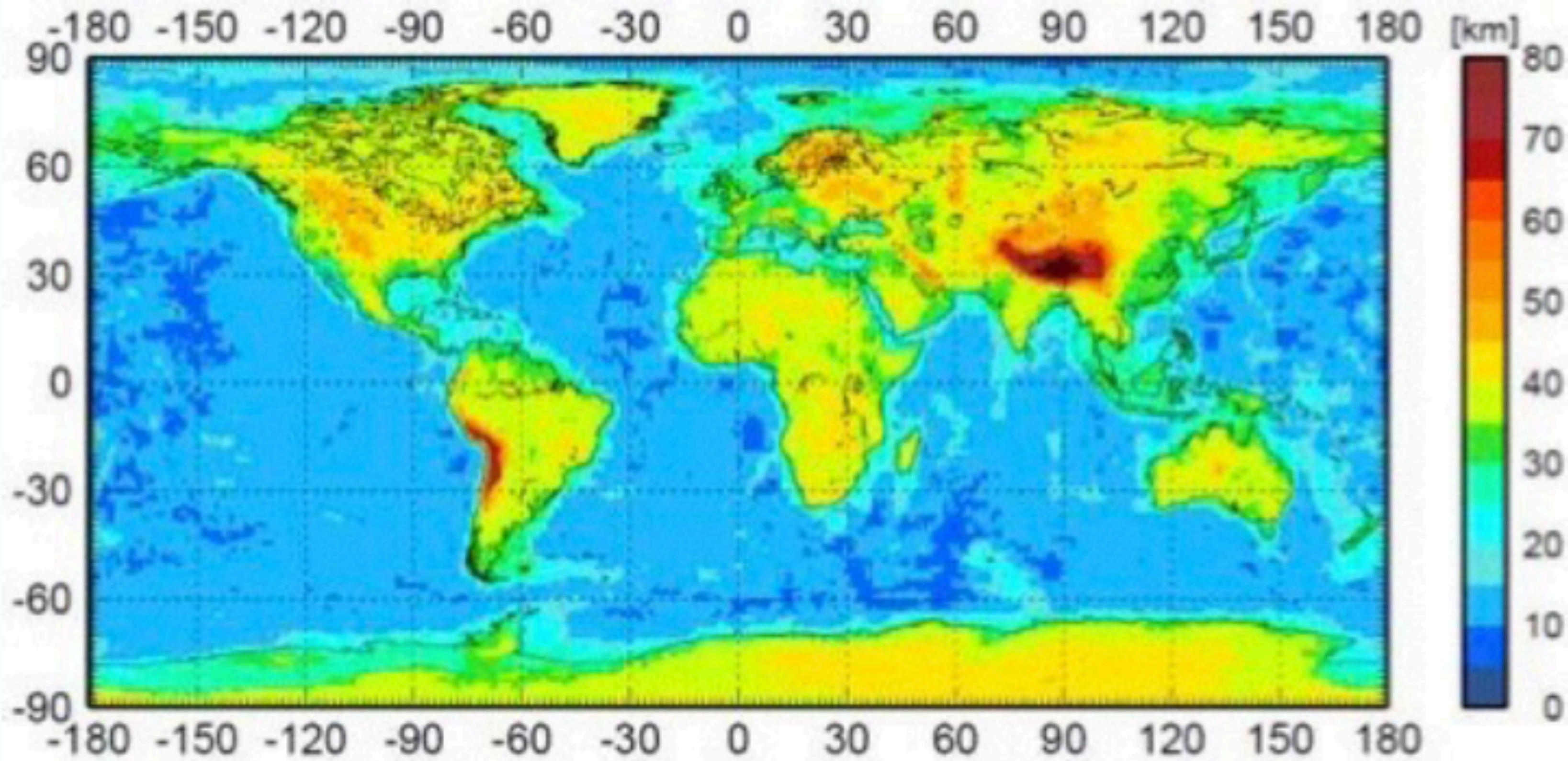




Convection
in the mantle

Convection
in the outer core

Thickness and density of Earth's crust



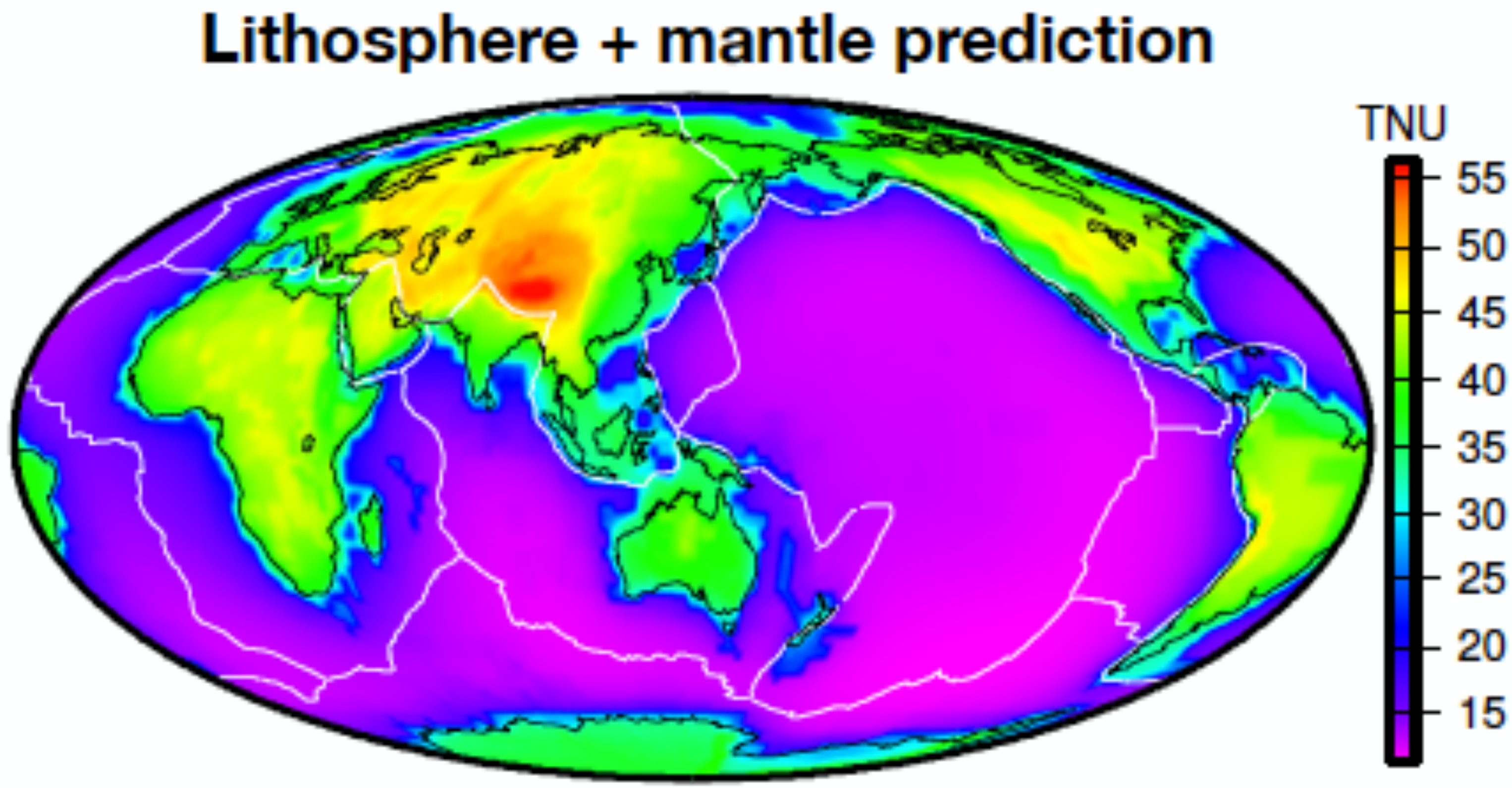
+ model of chemical composition in the crust

⇒ model of heat production in the crust

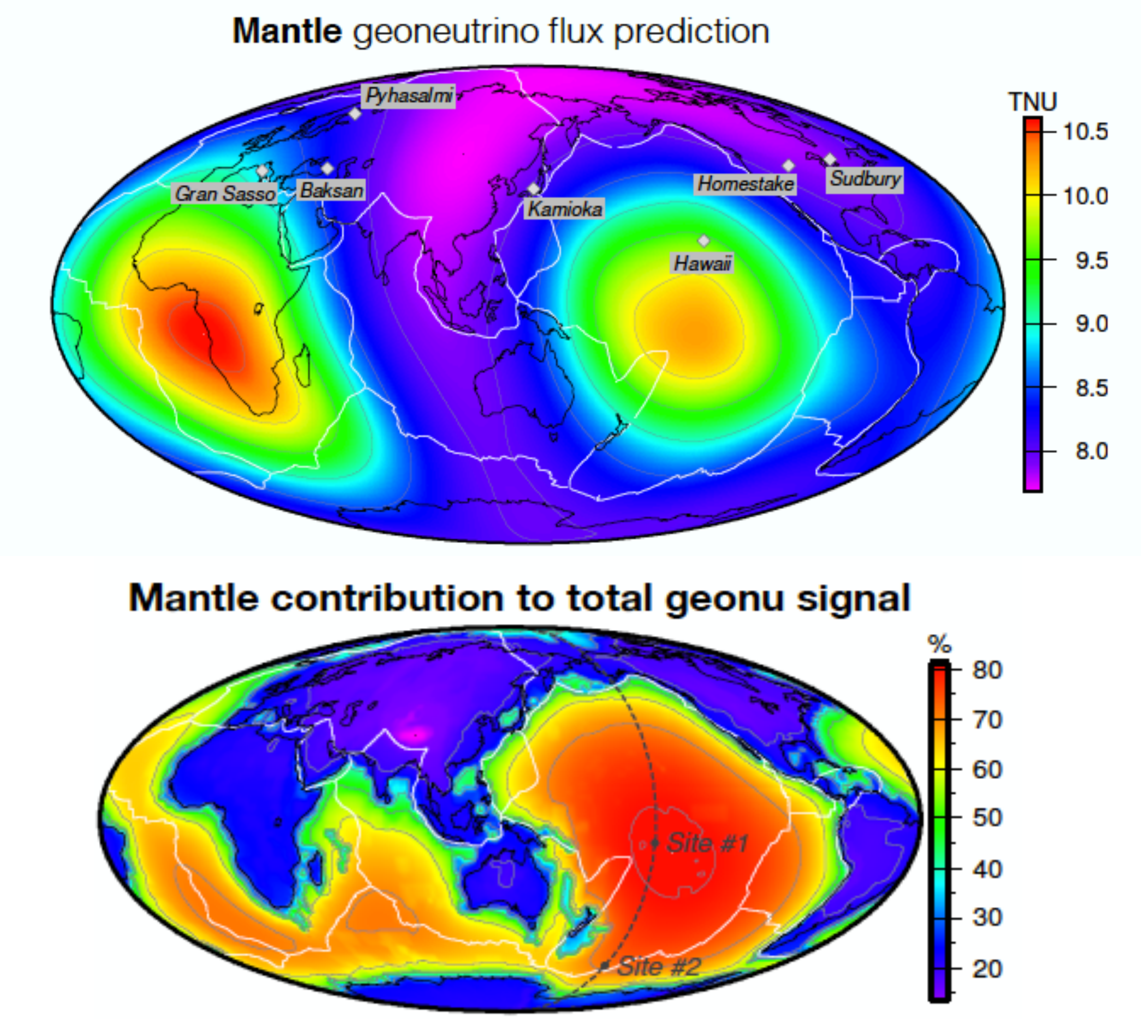
Continental Crust	**Oceanic Crust**
6.8 (+1.4/–1.1) TW	**0.22 ± 0.03 TW**

Model by Yu Huang et al. 2013

Terrestrial neutrinos



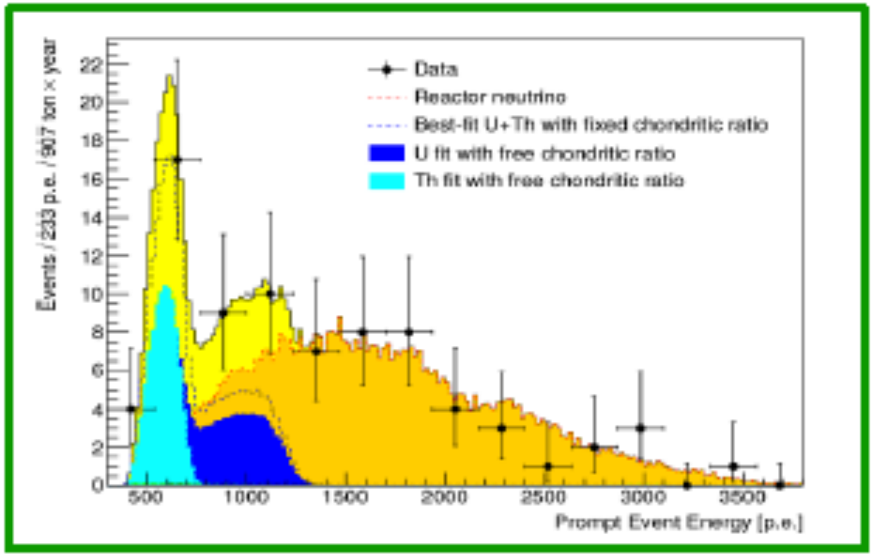
Geoneutrinos - mantle



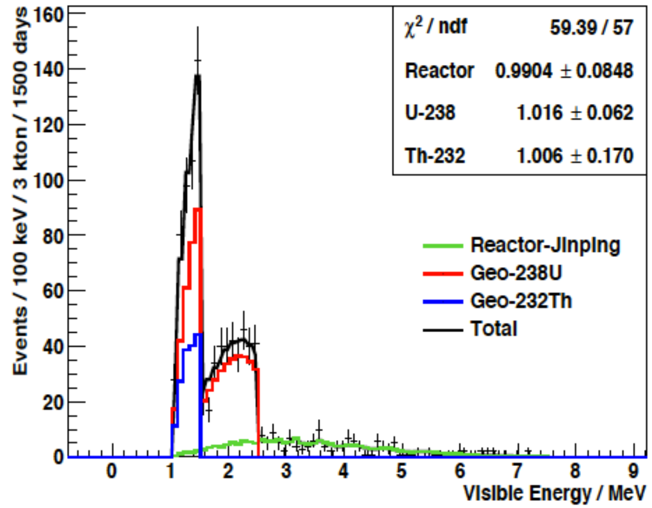
Continental locations: not more than ~25% of geonu signal coming from mantle

Geoneutrinos

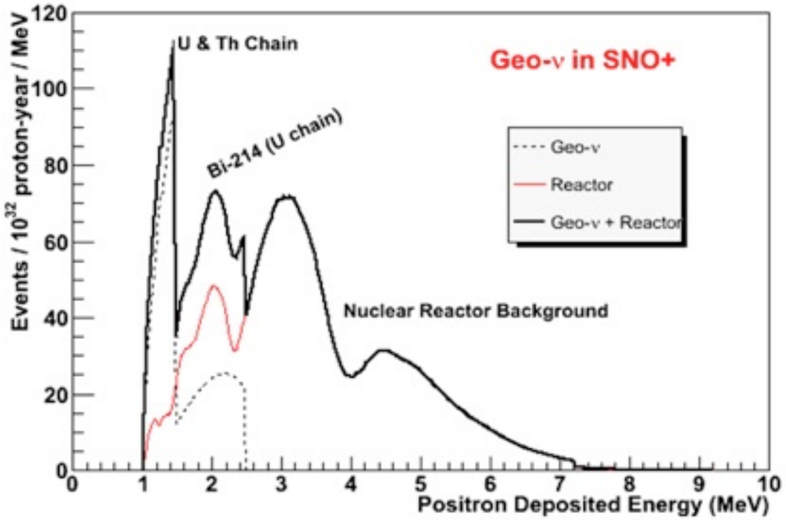
Borexino



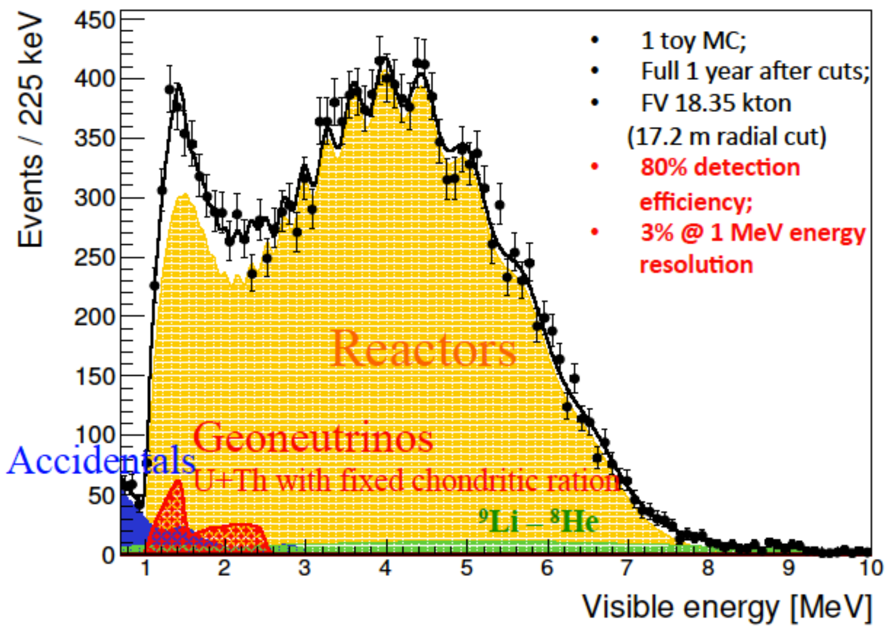
Jingping



SNO+



JUNO



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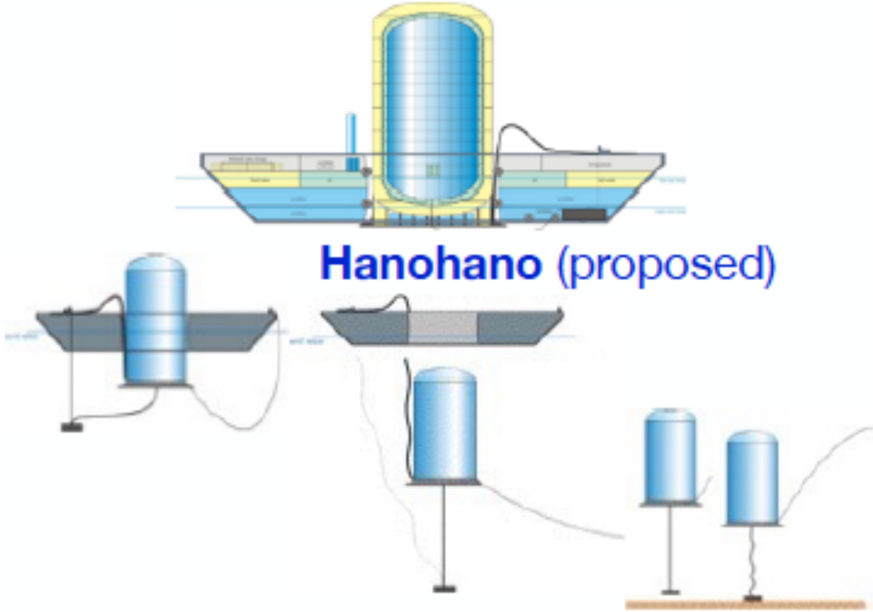
Hanohano



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Earth project

Towards Earth AntineutRino TomograpHy (EARTH)

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Summary

- A lot of new results and experiments will appear in the next decade

- It must be the aim of double beta decay to reach the IH, however the understanding of the nuclear matrix elements and quenching of g_A is mandatory if you want to get a neutrino mass

- The detection of CNO neutrinos would be the first prove of the existence of this fusion cycle and is the only way to study fundamental astrophysical assumptions.

- The detection of the DSNB is in reach for the next generation experiment.

- Having the LHC running, improving dark matter detectors and various other experiments (g-2 at Fermilab, CLV, Neutron - Antineutron Oscillations) hopefully new things will appear.

- Geoneutrinos developed their own charm and are an established research field.