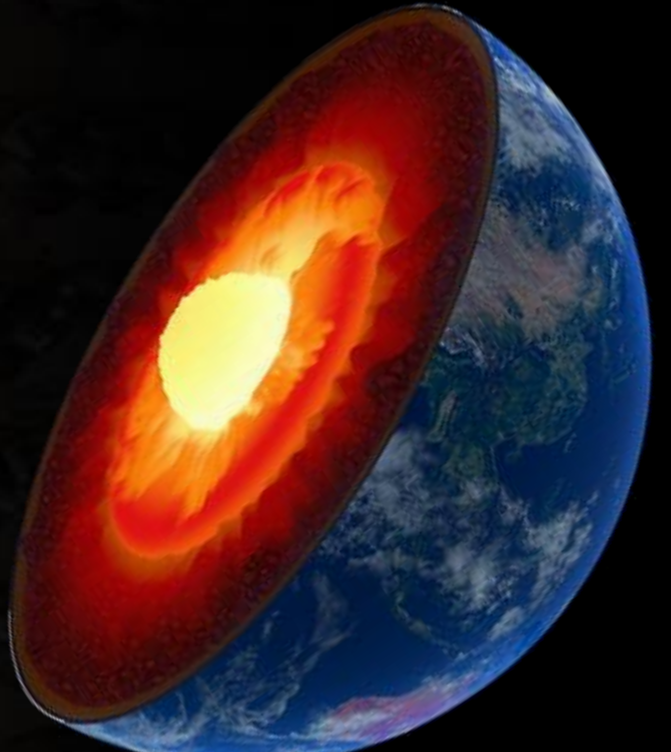
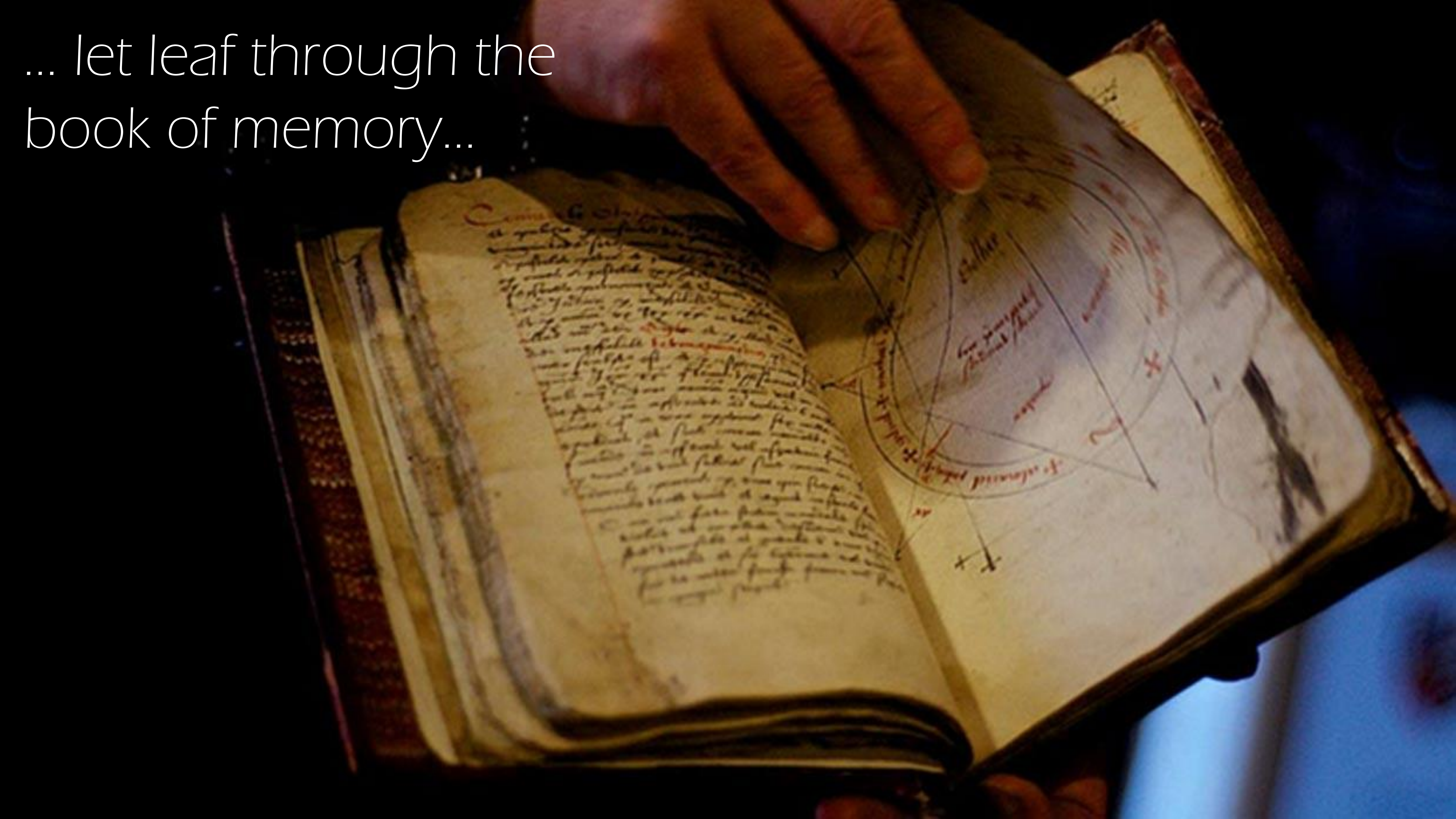
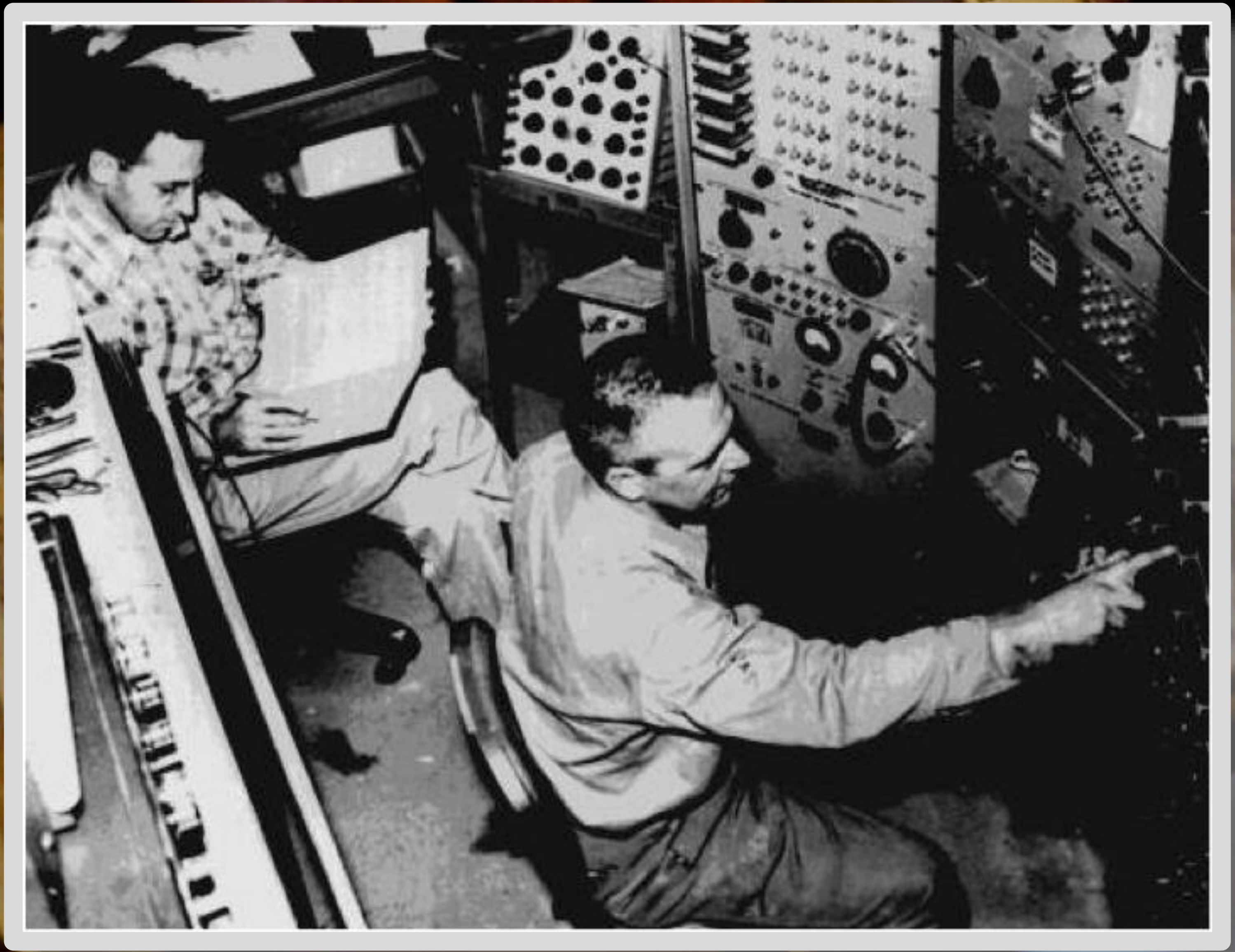


The role of Borexino in geoneutrino physics

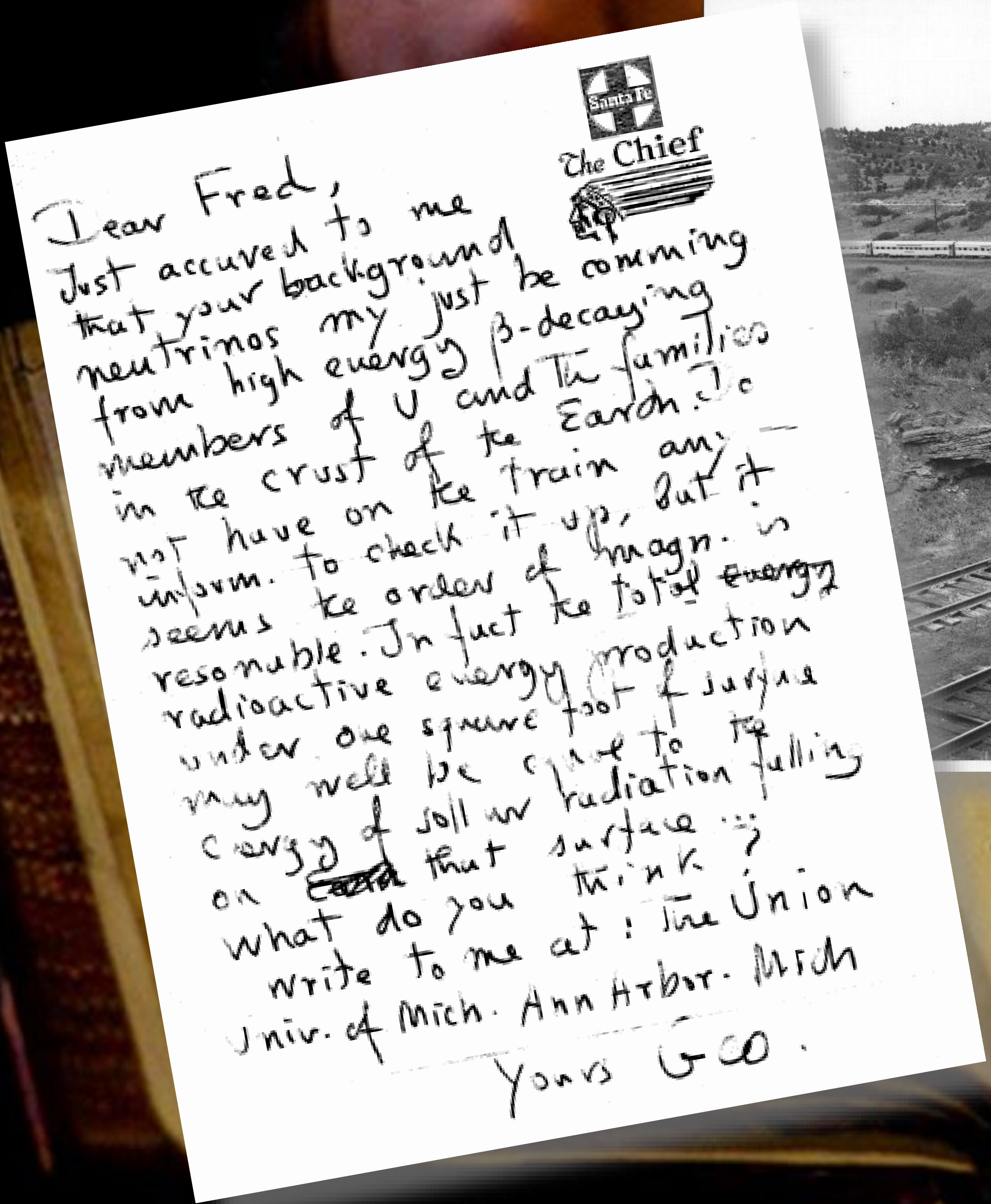
Fabio Mantovani – mantovani@fe.infn.it – www.fe.infn.it/radioactivity/
University of Ferrara – INFN Ferrara


… let leaf through the
book of memory…

…1953…

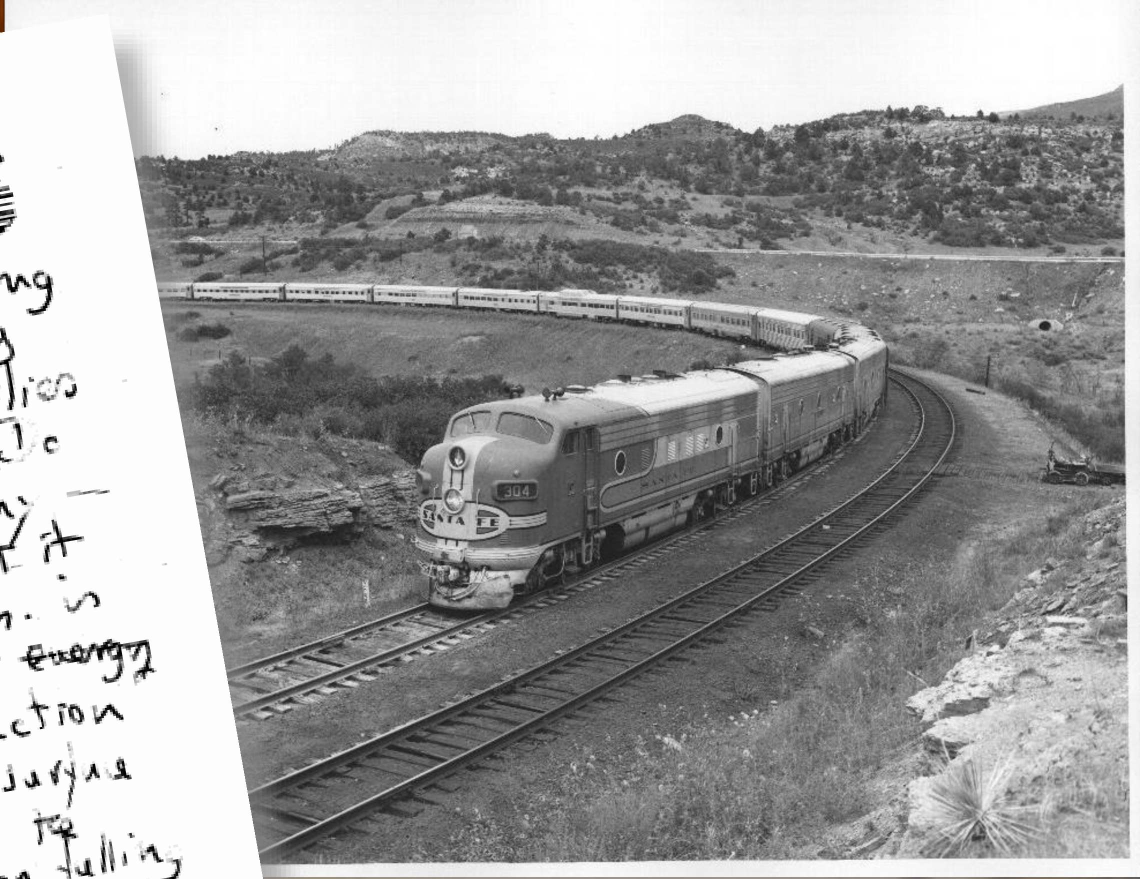


In 1953 G. Gamow wrote to F. Reines: "It just occurred to me that your background may just be coming from high energy beta-decaying members of U and Th families in the crust of the Earth."


Santa Fe
The Chief

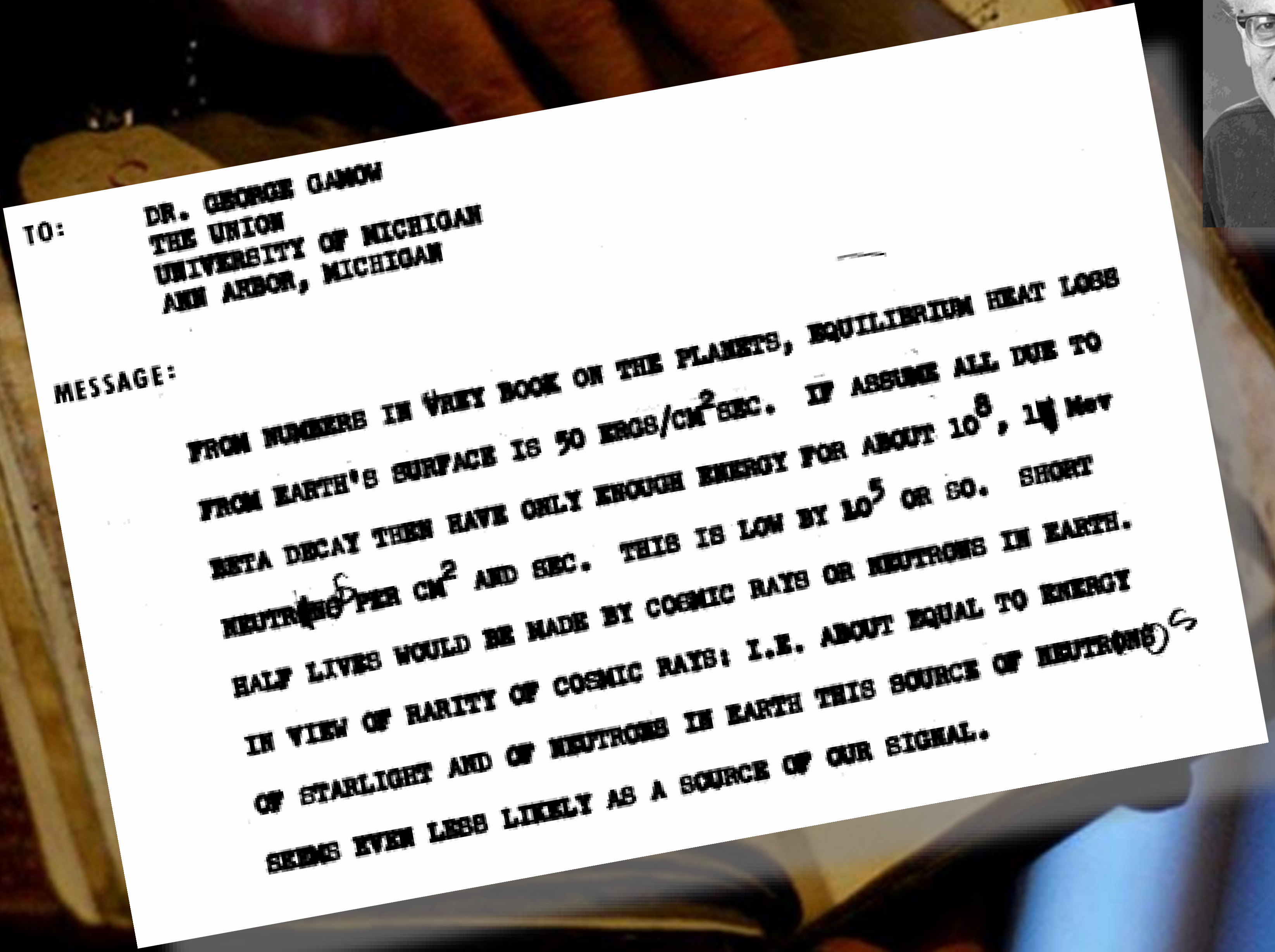
Dear Fred,
Just occured to me
that your background
neutrinos my just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. I do
not have on the train any
inform. to check it up, but it
seems the order of magn. is
resonable. In fuct the total ~~energy~~
radioactive energy production
under one square foot of surface
may well be equal to the
energy of solar radiation falling
on ~~earth~~ that surface.
what do you think?
write to me at: The Union
Univ. of Mich. Ann Arbor. Mich

Yours Geo.



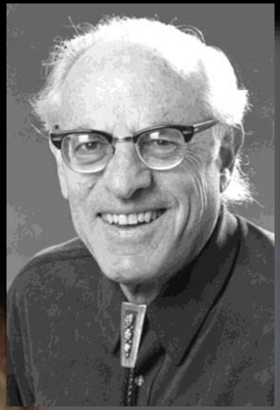
F. Reines answered to G. Gamow:

“Heat loss from Earth’s surface is 50 erg cm^{-2} s^{-1}.
If assume all due to beta decay than have only enough energy for about 10^8 one-MeV neutrinos cm^{-2} and s.”

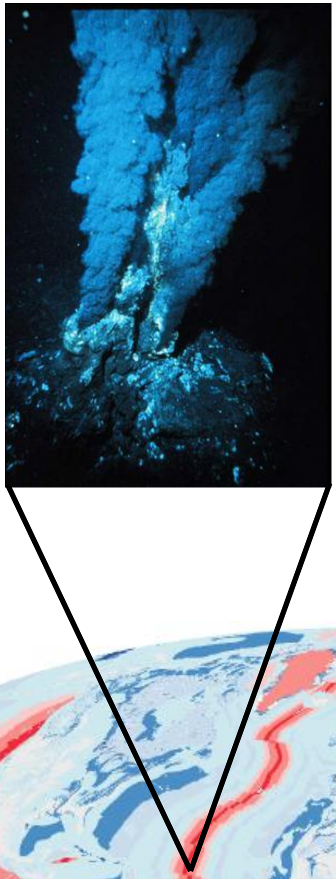

TO: DR. GEORGE GAMOW
THE UNION
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

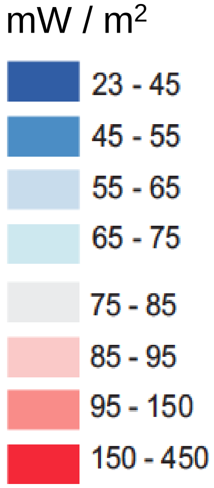
MESSAGE:

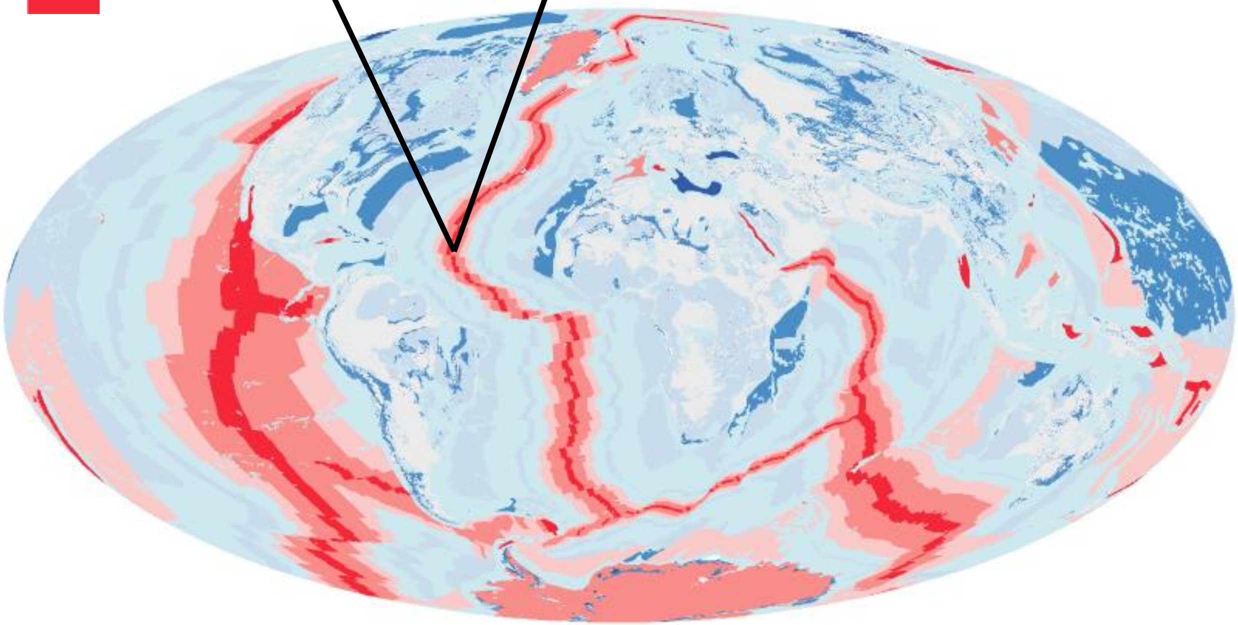
FROM NUMBERS IN VREY BOOK ON THE PLANETS, EQUILIBRIUM HEAT LOSS FROM EARTH'S SURFACE IS 50 ERGS/CM^2 SEC. IF ASSUME ALL DUE TO BETA DECAY THEN HAVE ONLY ENOUGH ENERGY FOR ABOUT 10^8, 1 Mev NEUTRINOS PER CM^2 AND SEC. THIS IS LOW BY 10^5 OR SO. SHORT HALF LIVES WOULD BE MADE BY COSMIC RAYS OR NEUTRONS IN EARTH. IN VIEW OF RARITY OF COSMIC RAYS; I.E. ABOUT EQUAL TO ENERGY OF STARLIGHT AND OF NEUTRONS IN EARTH THIS SOURCE OF NEUTRONS SEEMS EVEN LESS LIKELY AS A SOURCE OF OUR SIGNAL.



Heat power of the Earth







- Heat power of the Earth Q [30-49 TW] is the equivalent of ~ 10^4 nuclear power plants.
- The conduction is not the only way of Earth’s cooling: convective motions are responsible for significant fraction of surface heat loss.
- The quantitative assessment of heat transport by hydrothermal circulation remains a difficult task.
- Heat flow observations are sparse, non-uniformly distributed and not reliable in the oceans.

REFERENCE	Continents	Oceans	Total
	q_{CT} [mW m^{-2}]	q_{OCS}[mW m^{-2}]	Q (TW)
Williams et al., 1974	61	92	43 ± 6
Davies, 1980	55	95 ± 10	41 ± 4
Sclater et al., 1980	57	99	42
Pollack et al., 1993	65 ± 2	101 ± 2	44 ± 1
Hofmeister and Criss, 2005	61	65	31 ± 1
Jaupart et al., 2015	65	107	46 ± 2
Davies and Davies, 2010	**71**	**105**	**47 ± 2**
Davies, 2013	65	96	45
Lucazeau, 2019	66.7	89.0	44

Geo-neutrinos: anti-neutrinos from the Earth

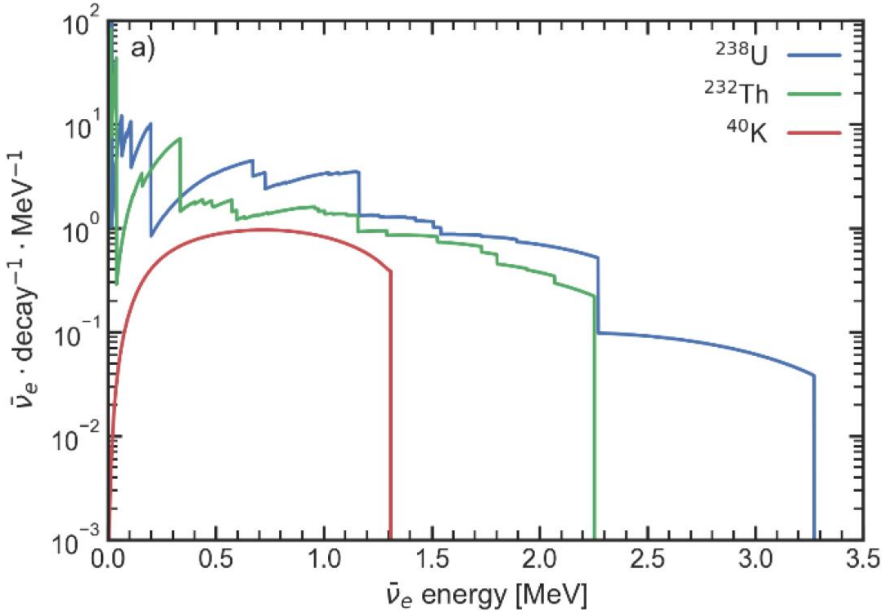
U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well-fixed ratio:

Decay	$T_{1/2}$ [10^9 yr]	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]	ε_H [W/kg]
$^{238}U \to {}^{206}Pb + 8\,{}^4He + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}Th \to {}^{208}Pb + 6\,{}^4He + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}K \to {}^{40}Ca + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

- Earth emits (mainly) antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,cm^{-2}s^{-1}$ whereas Sun shines in neutrinos
- A fraction of geo-neutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons:

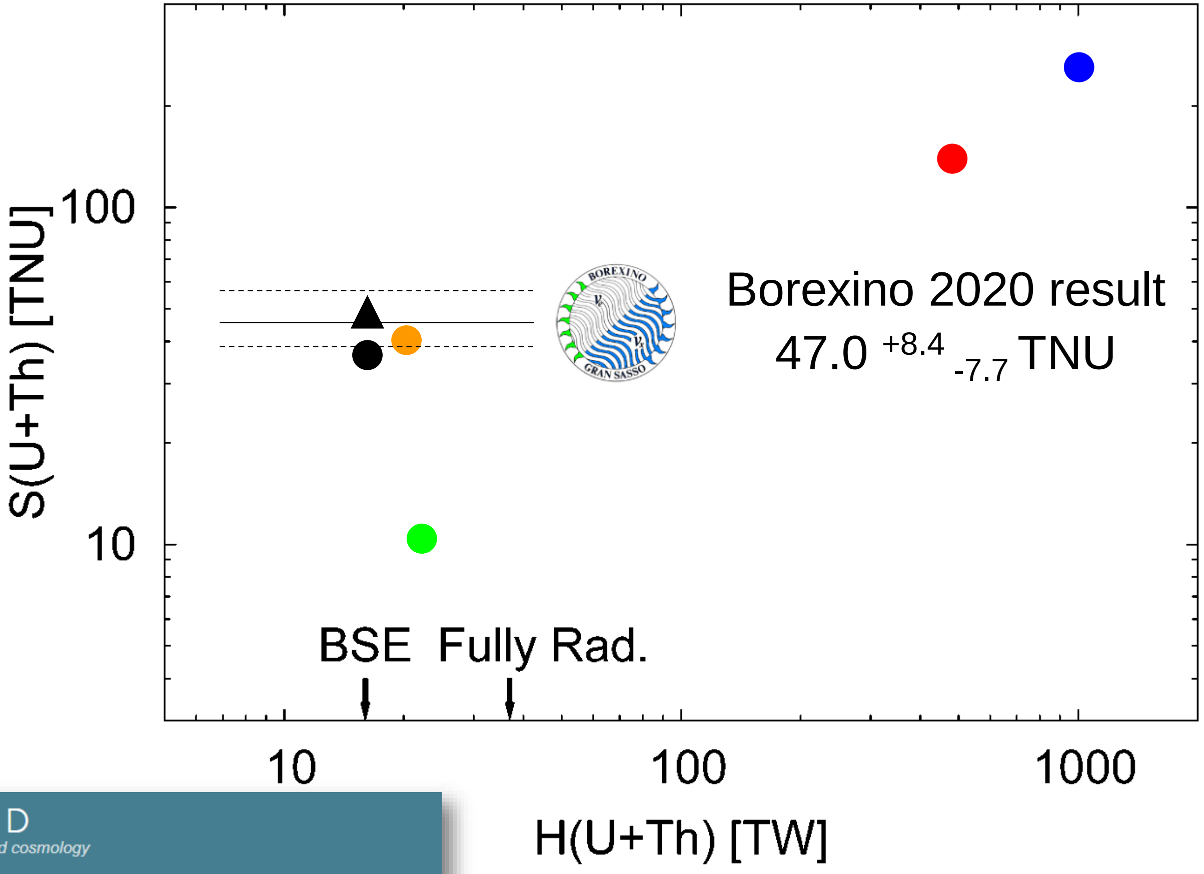
$$\bar{\nu} + p \to e^+ + n - 1.8\ \text{MeV}$$

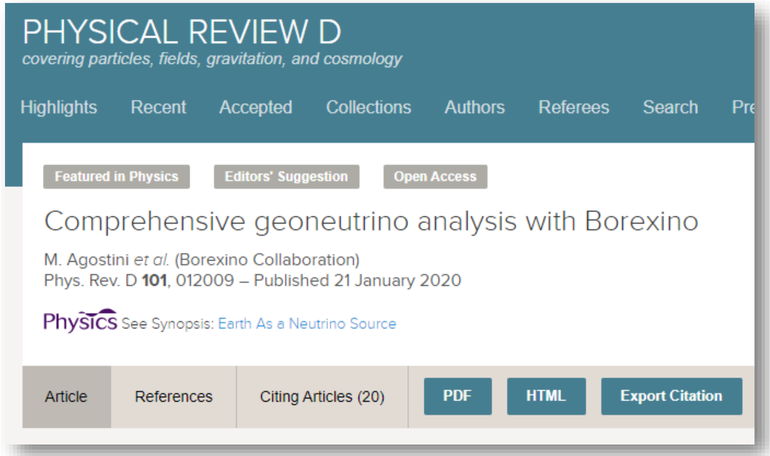
- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from U
- Signal unit: **1 TNU** = one event per 10^{32} free protons/year



First calculations of geoneutrino signal

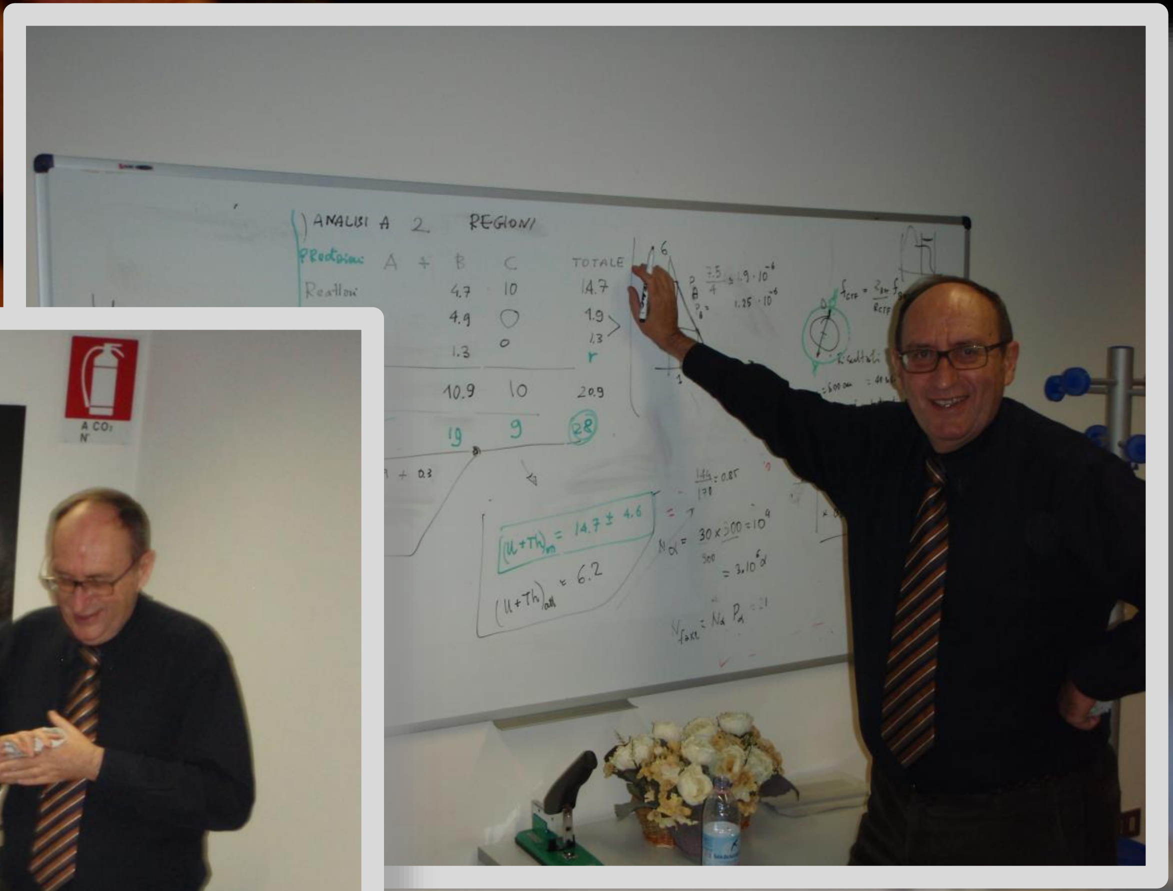
- Models assuming uniform U and Th distribution in the Earth:
  - Eder (Nucl. Phys. 1966)
  - Marx (Cz. J. Phys 1969)
  - Kobayashi (GRL 1991)
- Model with a uniform distribution of U in the continental crust:
  - Krauss et al. (Nature 1984)
- BSE model with different U distribution between crust and mantle:
  - ● Rothschild et al. (1998)
  - ▲ Raghavan et al. (1998)



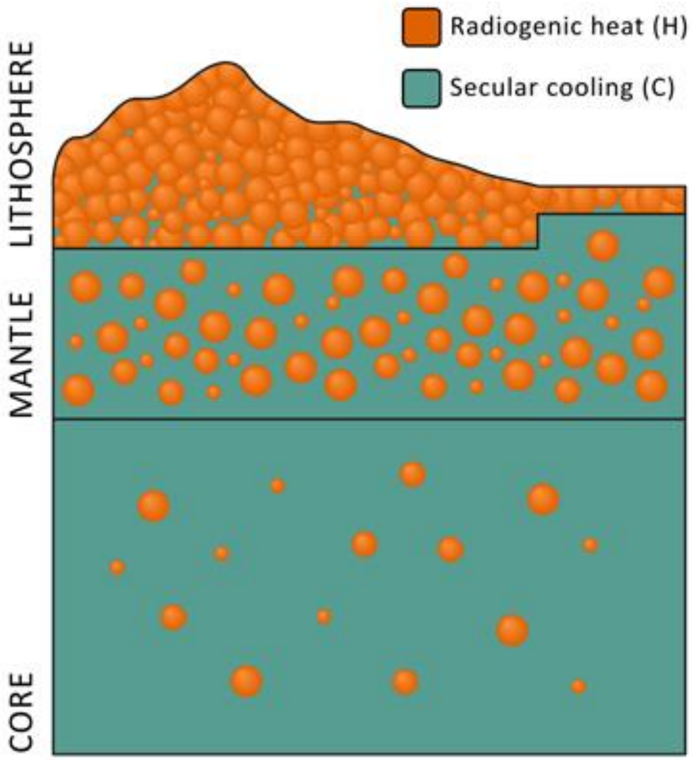


2003 – 2008

… discussing geoneutrinos and energetics of the Earth…



Earth's heat budget



- H_{CC} = radiogenic power of the continental crust
- H_{CC} = radiogenic power of the continental crust
- H_{CLM} = radiogenic power of the continental lithospheric mantle

$$C = Q - H$$

$$C_M = Q - H - C_C$$

$$H_M = H - H_{LS} - H_C$$

$$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$$

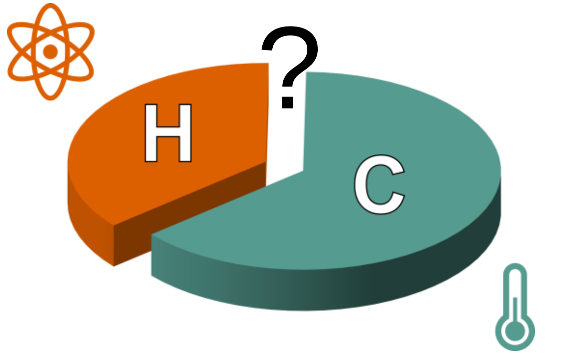
$$U_R = \frac{H - H_{CC}}{Q - H_{CC}}$$

	Range [TW]	Adopted [TW]
H	[10 ; 37]	19.3 ± 2.9
H_{LS}	[6 ; 11]	$8.1^{+1.9}_{-1.4}$
H_M	[0 ; 31]	$11.0^{+3.3}_{-3.4}$
H_C	[0 ; 5]	0

	Range [TW]	Adopted [TW]
C	[8 ; 39]	28 ± 4
C_{LS}	~ 0	0
C_M	[1 ; 29]	17 ± 4
C_C	[5 ; 17]	11 ± 2

Neglecting tidal dissipation and gravitation contraction (<0.5 TW), the two contributions to the total heat loss (Q) are:

- Secular Cooling (C): cooling down caused by the initial hot environment of early formation's stages
- Radiogenic Heat (H) due to naturally occurring decays of Heat Producing Elements, HPEs (U, Th and K) inside our planet.



- The mass of the lithosphere (~ 2% of the Earth's mass) contains ~ 40% of the total estimated HPEs and it produces H_{LS} ~ 8 TW.
- Radiogenic power of the mantle H_M and the contributions to C from mantle (C_M) and core (C_C) are model dependent.

2005 – 2010

… meanwhile the experimental results were starting to be published…

Physics Letters B 687 (2010) 299–304

Contents lists available at ScienceDirect

Physics Letters B

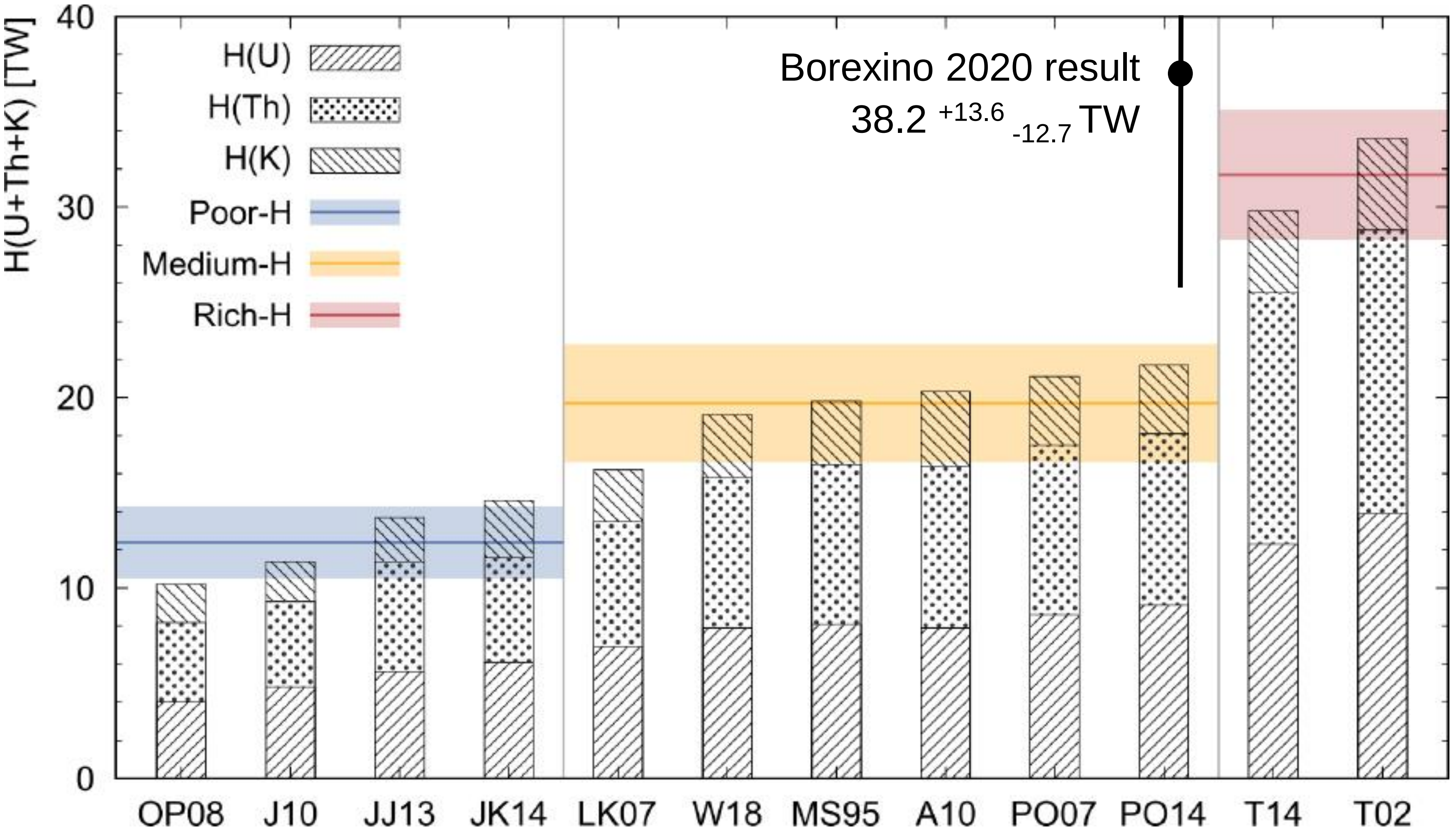
www.elsevier.com/locate/physletb

Observation of geo-neutrinos

Borexino Collaboration

Bulk Silicate Earth Models and radiogenic heat

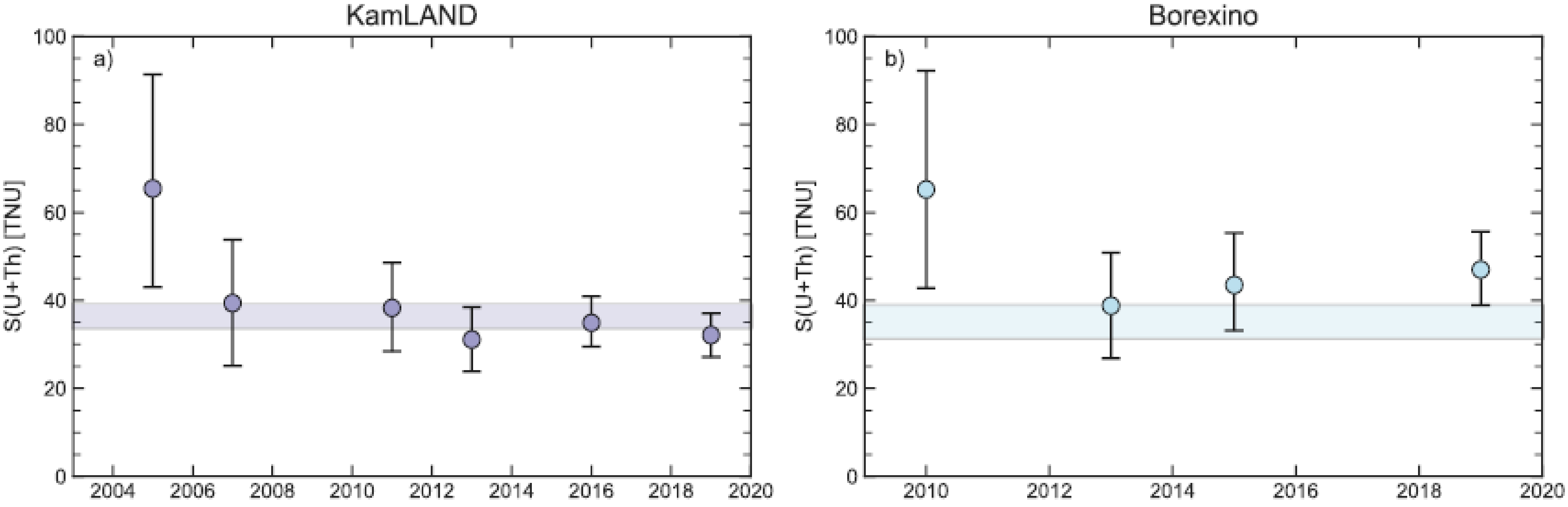
- The BSE describes the primordial, non-metallic Earth condition that followed planetary accretion and core separation, prior to its differentiation into a mantle and lithosphere.
- Different authors* proposed a range of BSE models based on different constraints (enstatite chondrites, carbonaceous chondrites, undepleted mantle, etc.)



	Poor	Medium	Rich
H(U+Th+K) [TW]	12.4 ± 1.9	19.7 ± 3.1	31.7 ± 3.4

** The codes reported in the plot are explicitly indicated in the back slide.*

Timeline of KamLAND and Borexino geoneutrino results

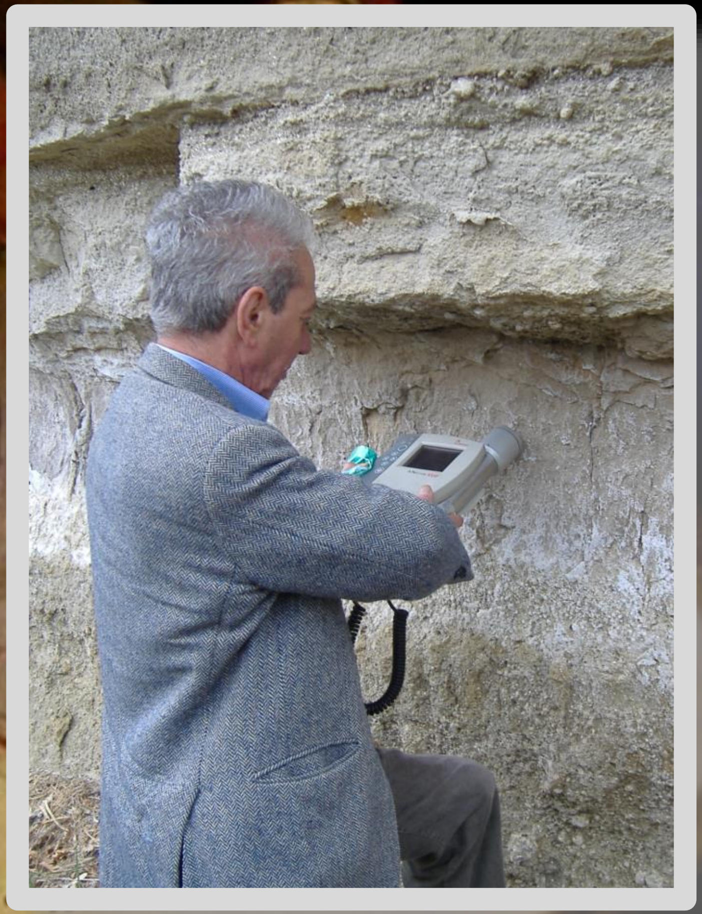


- Horizontal bars traces the expected signal at 1σ C.L.
- Borexino has always been the protagonist of Neutrino Geoscience conferences…

- 2005 Honolulu (Hawaii - US)
- 2008 Sudbury SNOLab(Canada)
- 2010 Gran Sasso Lab (Italy)
- 2013 Takayama (Japan)
- 2015 Paris (France)
- 2019 Prague (Czech Republic)

2008-2010

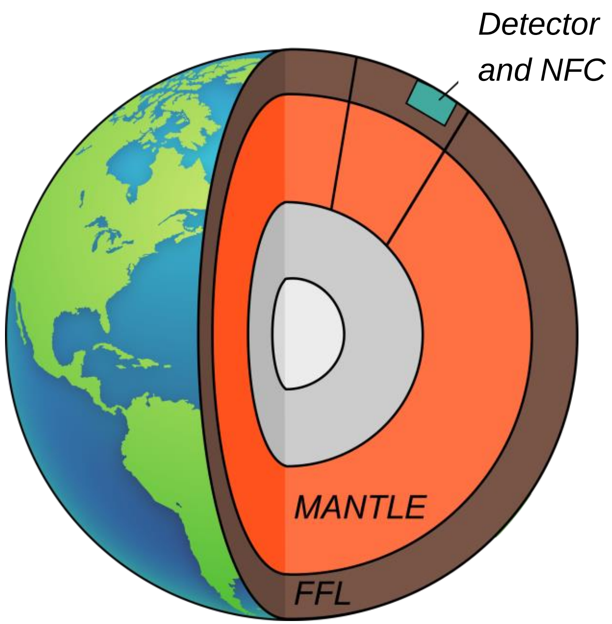
..."you will never fully understand Borexino results, if you don't know the radioactivity of surrounding rocks..."

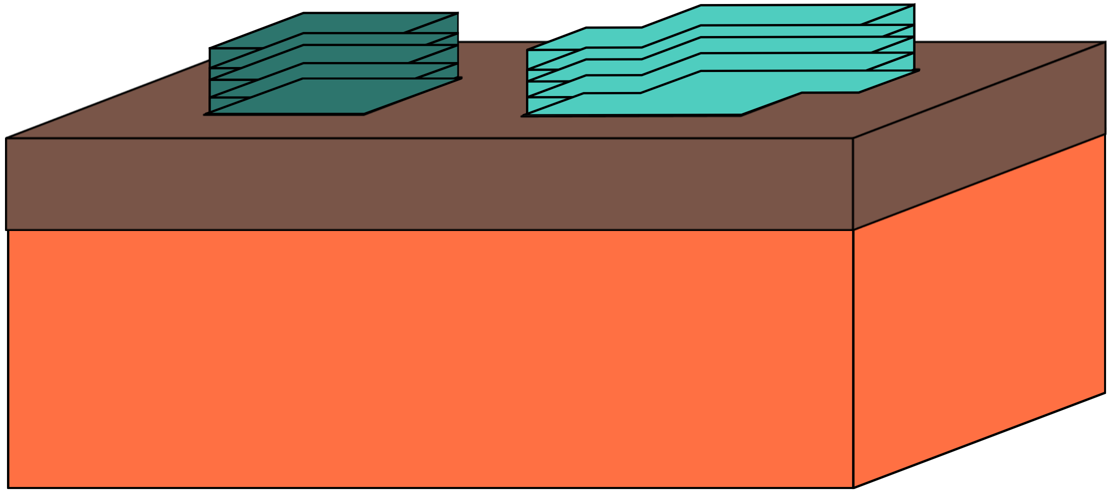


Mantle geoneutrino signals from multi-site detection

The **Far Field Lithosphere (FFL)** is the superficial portion of the Earth including the Far Field Crust (FFC) and the Continental Lithospheric Mantle (CLM).

U and Th distributed in the **Near Field Crust (NFC)** gives a significant contribution to the signal (~ 50% of the total).





$$S_M^i(U+Th) = S_{Exp}^i(U+Th) - S_{FFC}^i(U+Th) - S_{CLM}^i(U+Th) - S_{NFC}^i(U+Th)$$

The geological models need to comply with the following constraints:

- **FFC** model needs to be unique for *i* detectors for avoiding systematic biases.
- **NFC** should be built with geochemical and/or geophysical information typical of the local regions.
- **NFC** must be geometrically complementary to the FFC.
- All geoneutrino signal contributions should be separately reported together with their uncertainties.

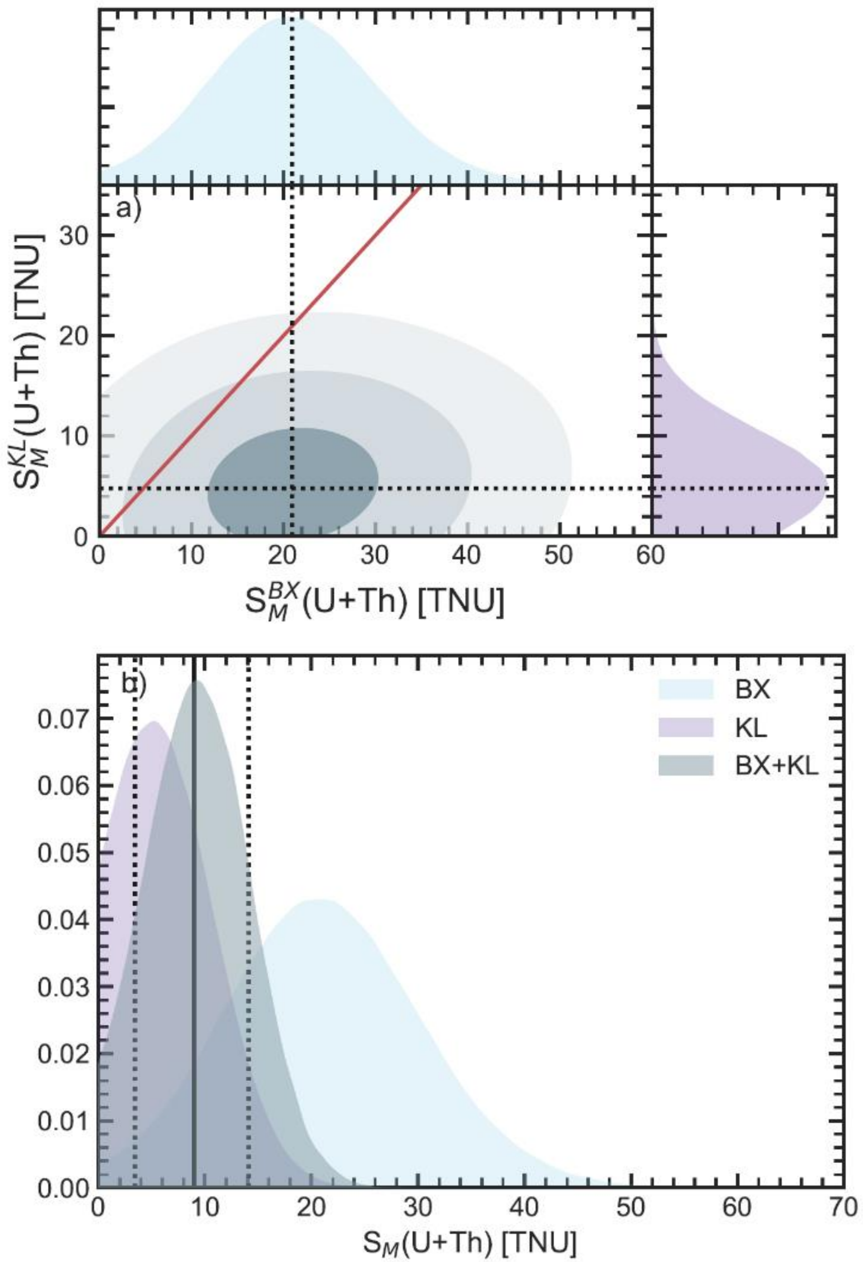
Mantle geoneutrinos from KamLAND and Borexino*

- The FFC and the CLM signals of KL and BX are fully correlated, since they are derived from the same geophysical and geochemical model.
- S_{NFC}^{BX}(U+Th) and S_{NFC}^{KL}(U+Th) are considered uncorrelated.
- Using only the experimental signals published by BX and KL collaborations without any spectral information, the PDFs of experimental KL and BX signals are reconstructed.

	S_{Exp}(U+Th) [TNU]	S_{NFC}(U+Th) [TNU]	S_{FFC}(U+Th) [TNU]	S_{CLM}(U+Th) [TNU]	S_M(U+Th) [TNU]
KL	32.1 ± 5.0	17.7 ± 1.4	$7.3^{+1.5}_{-1.2}$	$1.6^{+2.2}_{-1.0}$	$4.8^{+5.6}_{-5.9}$
BX	$47.0^{+8.6}_{-8.1}$	9.2 ± 1.2	$13.7^{+2.8}_{-2.3}$	$2.2^{+3.1}_{-1.3}$	$20.8^{+9.4}_{-9.2}$
KL+BX	-	-	-	-	$8.9^{+5.1}_{-5.5}$

- The joint distribution S_M^{KL+BX}(U+Th) can be inferred from the PDFs by requiring that S_M^{KL}(U+Th) = S_M^{BX}(U+Th), obtaining the combined mantle geoneutrino signal:

$$S_M^{KL+BX}(U+Th) = 8.9^{+5.1}_{-5.5}\ \text{TNU}$$

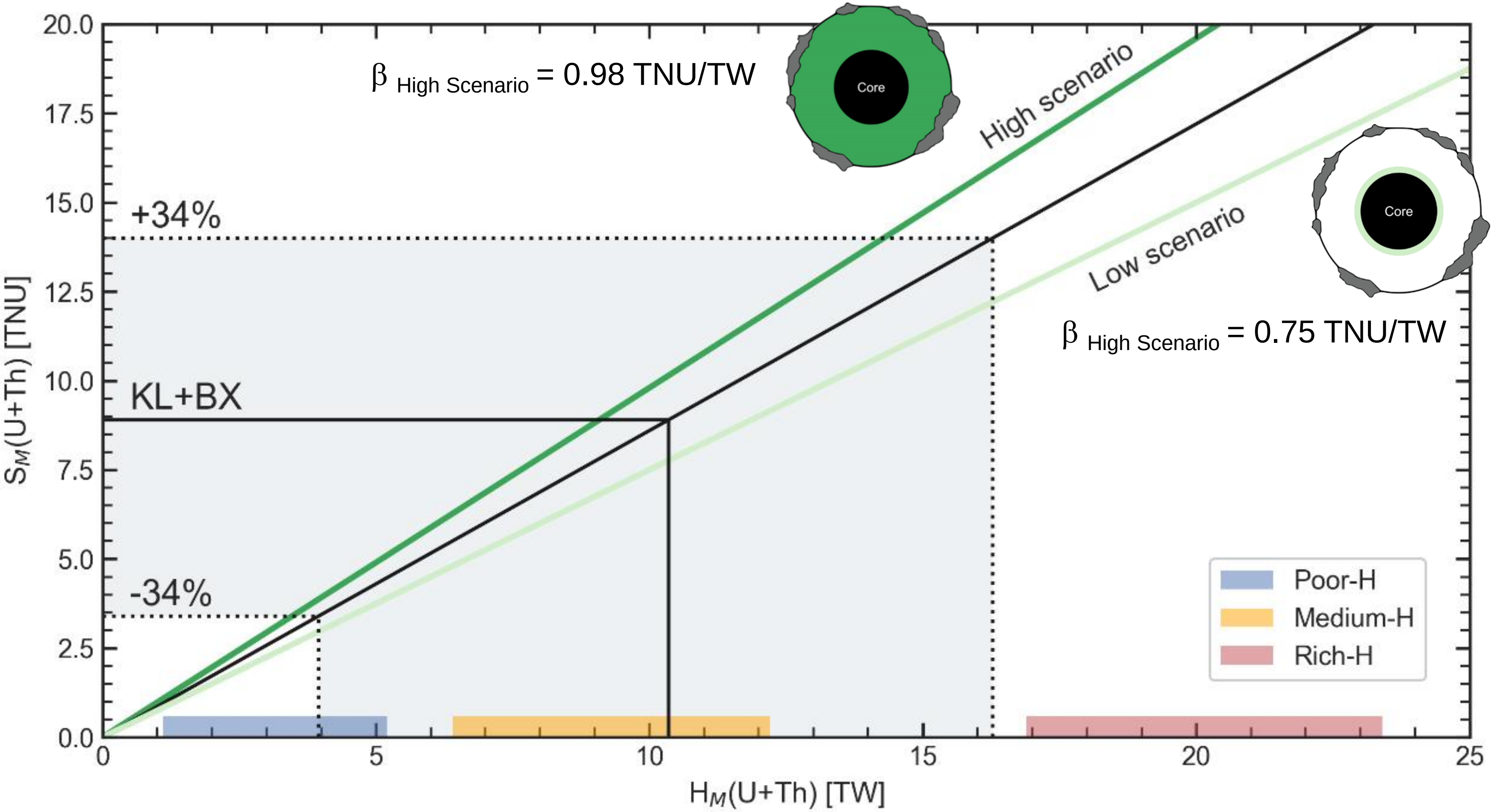


* Bellini et al. 2021 - https://arxiv.org/abs/2109.01482v1

Mantle radiogenic power from U and Th

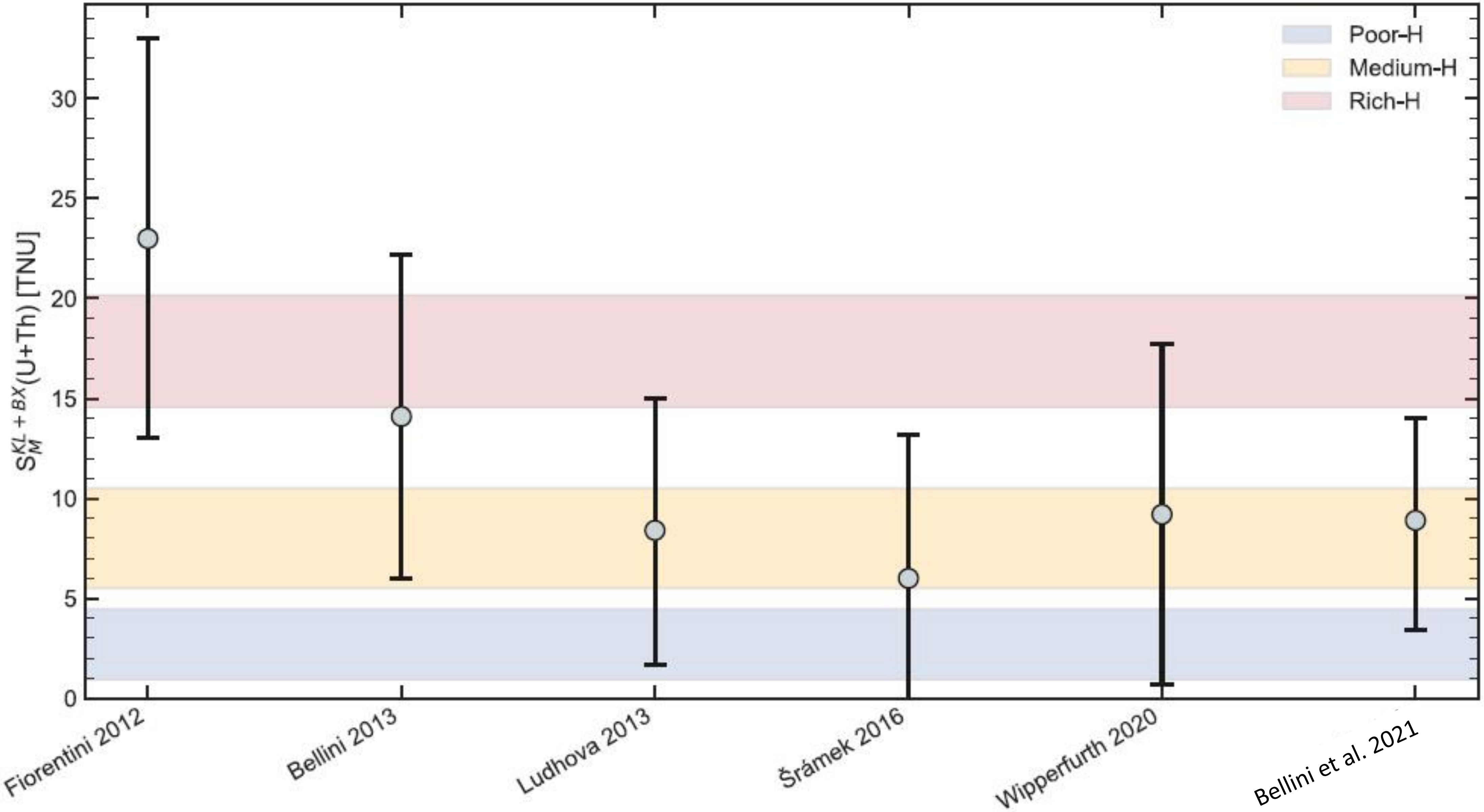
Since H_{LS} (U+Th)= $6.9_{-1.2}^{+1.6}$ TW is independent from the BSE model, the discrimination capability of the combined geoneutrino measurement among the different BSE models can be studied in the space S_M(U+Th) vs H_M(U+Th):

$$S_M(U+Th) = \beta \cdot H_M(U+Th)$$

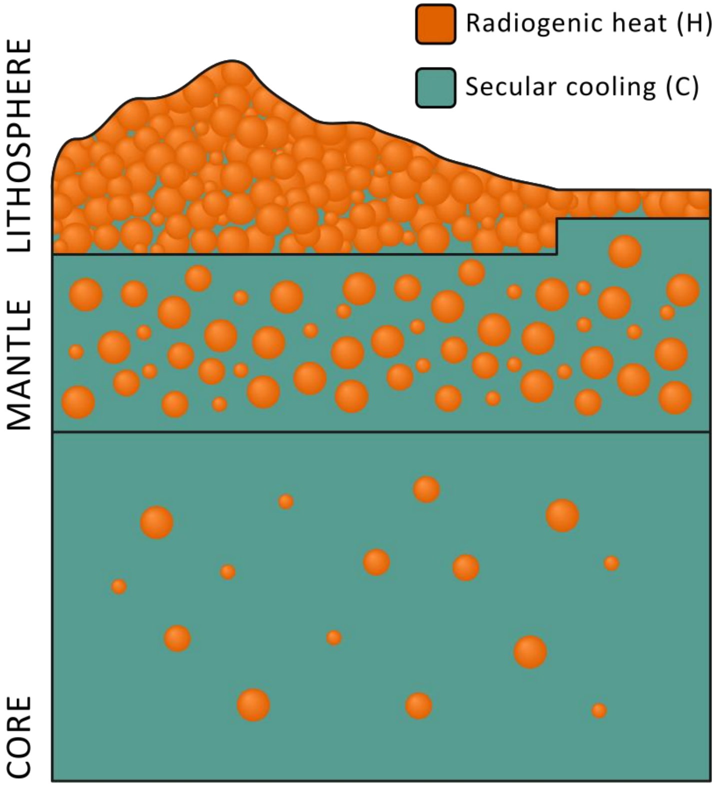


	Poor	Medium	Rich	KL+BX
H_M(U+Th) [TW]	$3.2^{+2.0}_{-2.1}$	9.3 ± 2.9	$20.2^{+3.2}_{-3.3}$	$10.3^{+5.9}_{-6.4}$

Collection of the geoneutrino mantle signals



Understanding the Earth's heat budget with geoneutrinos



$$C = Q - H$$

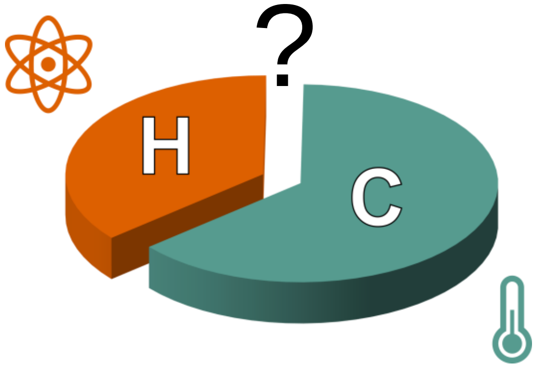
$$C_M = Q - H - C_C$$

$$H_M = H - H_{LS} - H_C$$

$$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$$

$$U_R = \frac{H - H_{CC}}{Q - H_{CC}}$$

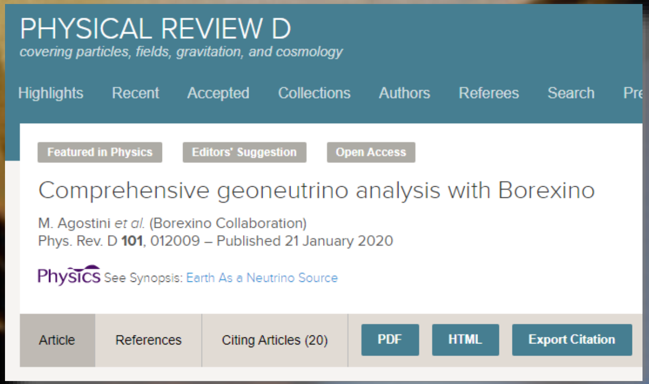
- We know from direct measurements
  - $Q = 47 \pm 2$ TW
  - $H_{LS}(U+Th+K) = 8.1^{+1.9}_{-1.4}$ TW



	Reference values from published models	Combining KL + BX experimental results
H_M(U+Th+K) [TW]	**$11.3^{+3.3}_{-3.4}$**	**$12.5^{+7.1}_{-7.7}$**
H [TW]	**19.3 ± 2.9**	**$20.8^{+7.3}_{-7.9}$**
C [TW]	**28 ± 4**	**26 ± 8**

... and the future?

... the future belongs to women



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Comprehensive geoneutrino analysis with Borexino

M. Agostini *et al.* (Borexino Collaboration)
Phys. Rev. D **101**, 012009 – Published 21 January 2020

Physics See Synopsis: Earth As a Neutrino Source

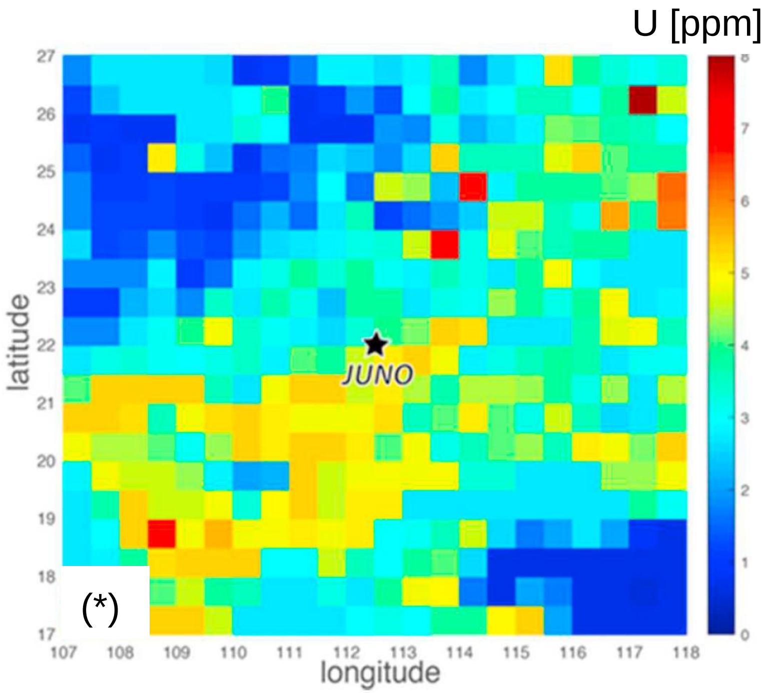
Article | References | Citing Articles (20) | PDF | HTML | Export Citation

Expected geoneutrino signal at JUNO

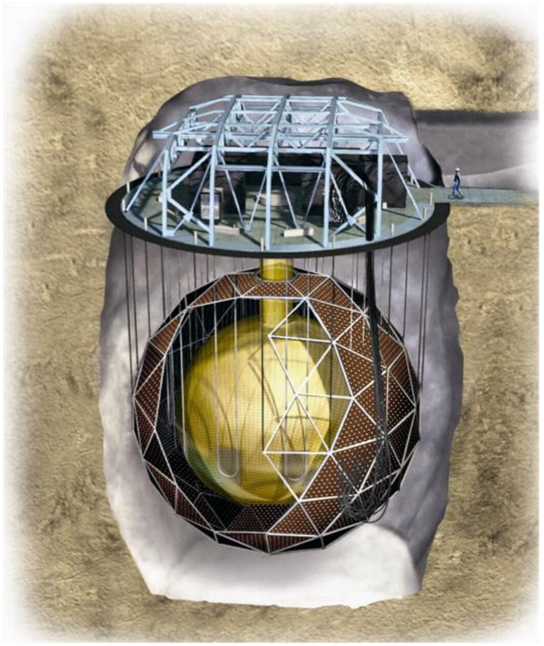
- JUNO is a 20 kton LS detector surrounded by ~18.000 20” PMT
- Expected geo-ν ~ 400 events/year (~ 40 TNU)
- Expected react-ν in [1.8-3.3 MeV] ~ 260 TNU (S_{rea} / S_{geo} ~ 7)

	N° of cores	Thermal power/core
Yangjiang	6	2.9 GW
Taishan	2	4.6 GW

	S(U+Th) [TNU]
Strati et al., 2015 (using global crustal model)	$39.7^{+6.5}_{-5.2}$
Wipperfurth et al., 2020 (using global crustal models)	$41.3^{+7.5}_{-6.3}$ $41.2^{+7.6}_{-6.4}$ $40.05^{+7.4}_{-6.2}$
Gao et al., 2020 (*) (combining global crustal model and local geological data)	$49.1^{+5.6}_{-5.0}$

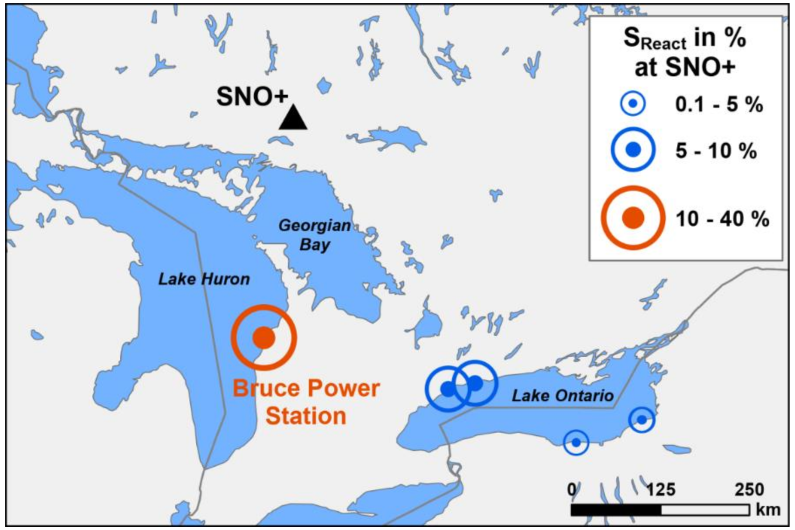


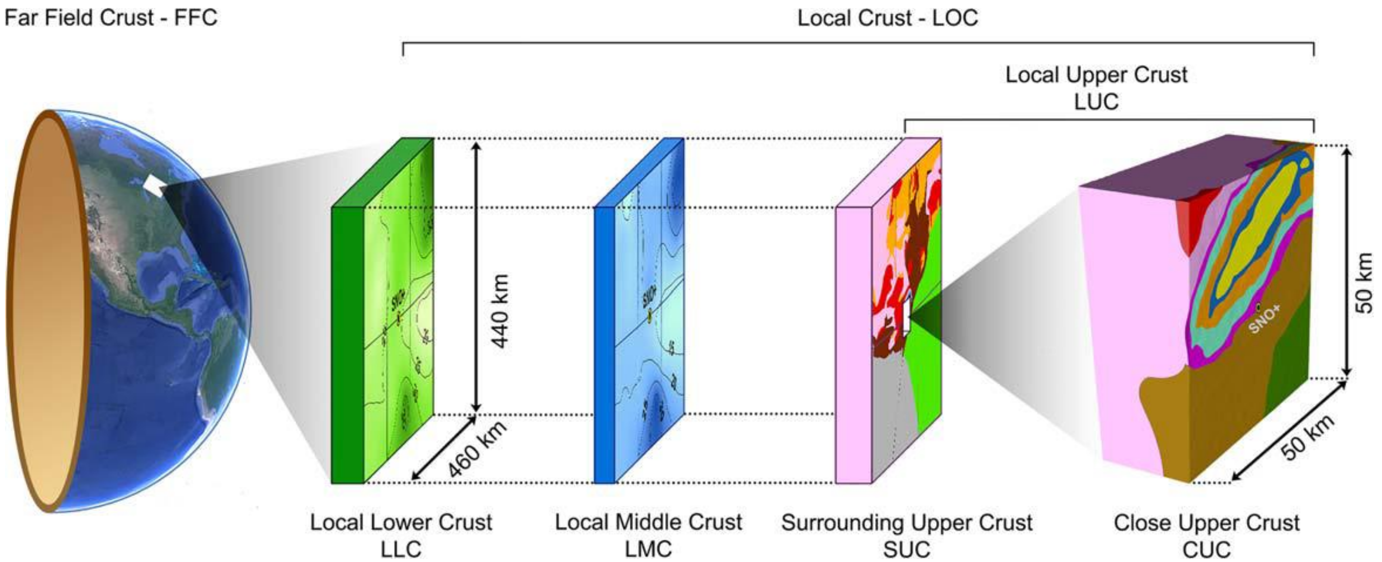
Expected geoneutrino signal at SNO+



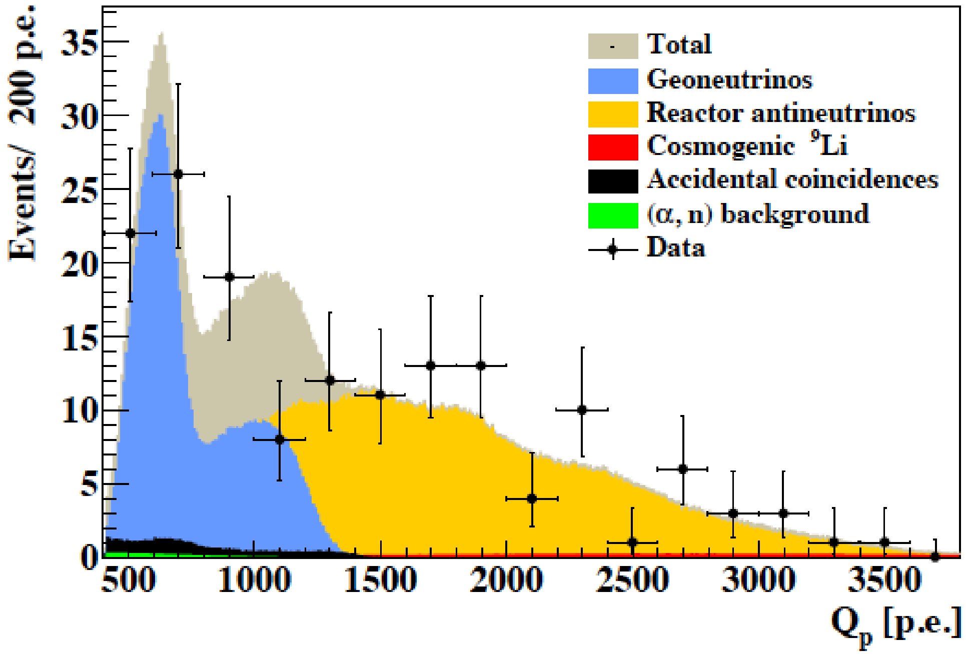
- Deepest underground detector (~ 5800 mwe)
- 780 tons of LS detector with ~ 9300 PMTs
- Expected react-ν in [1.8-3.3 MeV] = $48.5^{+1.8}_{-1.5}$ TNU (S_{rea} / S_{geo} ~ 1.2)

	S(U+Th) [TNU]
Wipperfurth et al., 2020 (using global crustal models)	$50.2^{+9.7}_{-8.1}$
	$46.2^{+9.3}_{-7.7}$
	$46.8^{+9.3}_{-7.8}$
Strati et al., 2017 (combining global crustal model and local geological data)	$41.8^{+9.6}_{-6.2}$



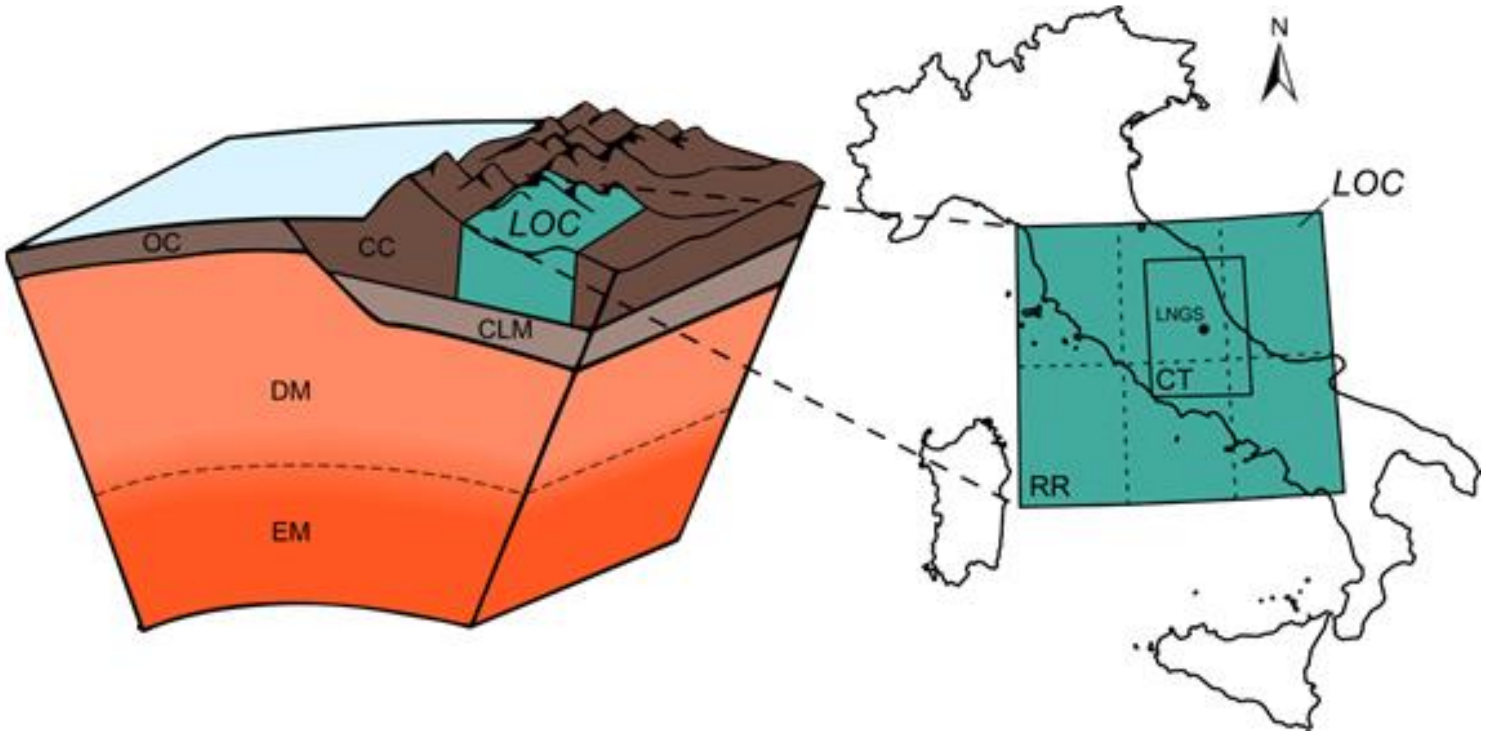


Borexino and geoneutrinos: what's in the future?



Data taking	2007-2019
Reactors events	39.5 ± 0.7
Tot bkg events	8.3 ± 1.0
Geo-ν events (U+Th)	$52.6^{+9.6}_{-9.0}$
S(U+Th) [TNU]	$47.0^{+8.6}_{-8.1}$

- Analysis of data between 2019 and 2021: we expect ~ +10% more events
- An update geochemical local model*: from 57 rock samples to 10^3 (U + Th) measurements



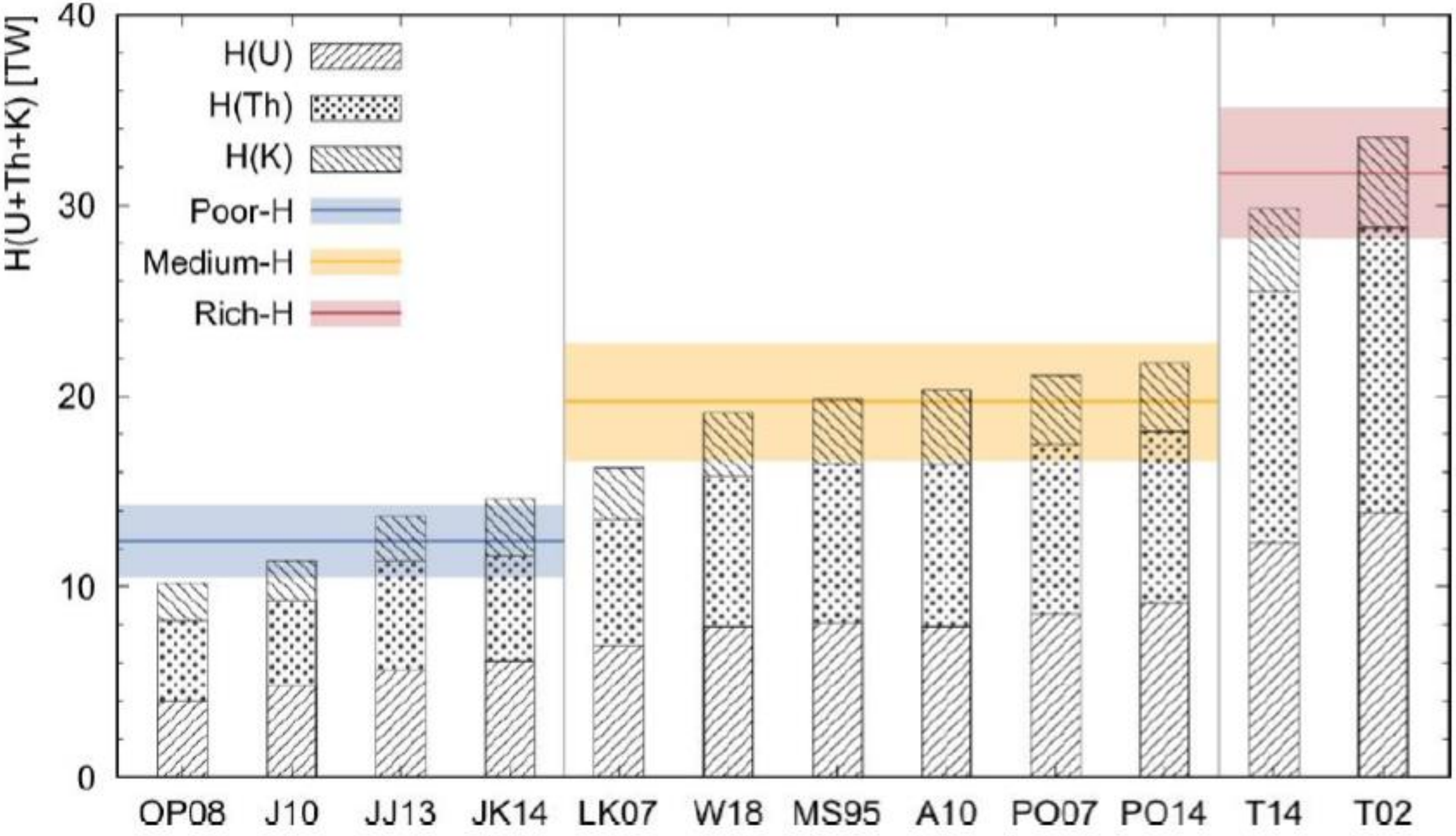
* Virginia is going to apply for Starting Grant of FIS (Fondo Italiano per la Scienza)

Thank you, Borexino!

You wrote an outstanding page in the book of Earth science

Back up slide

Reference	Code
Jackson and Jellinek, 2013	JJ13
O'Neill and Palme, 2008	OP08
Javoy and Kaminski, 2014	JK14
Javoy et al., 2010	J10
McDonough and Sun, 1995	MS95
Lyubetskaya and Korenaga, 2007	LK07
Palme and O'Neill, 2007	PO07
Arevalo, 2010	A10
Wang et al., 2018	W18
Palme and O'Neill, 2014	PO14
Turcotte, 2002*	T02
Turcotte, 2014	T14



	Poor	Medium	Rich
H(U+Th+K) [TW]	12.4 ± 1.9	19.7 ± 3.1	31.7 ± 3.4