Mantle insights from KamLAND and Borexino results

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Geoneutrinos and geoscience: an intriguing joint-venture
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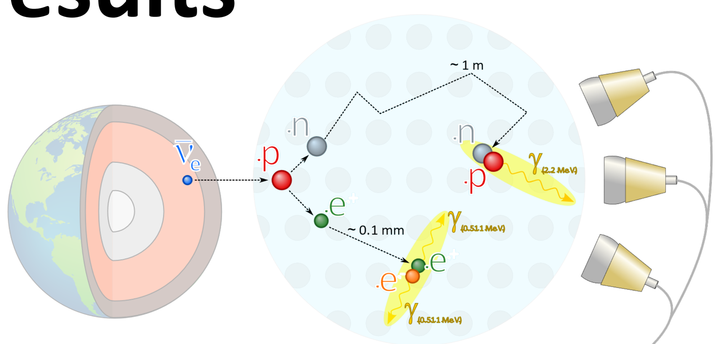
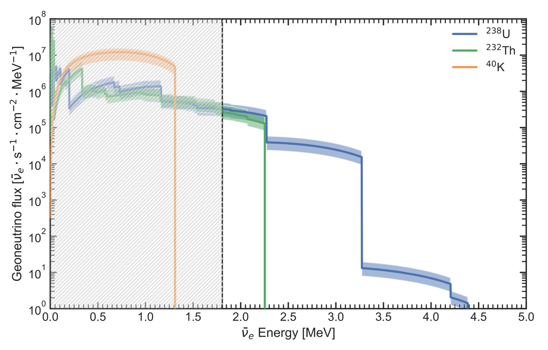
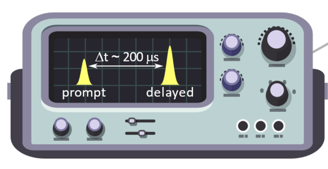
KamLAND and Borexino results

Geoneutrinos, the electron antineutrinos originating from the β^- emitters inside our planet, are a precious tool for exploring the inner Earth. While decaying, the radioisotopes belonging to ^{238}U and ^{232}Th decay chains and ^{40}K release **geoneutrinos** and **energy**, dissipated as heat, in a **well-fixed ratio**.





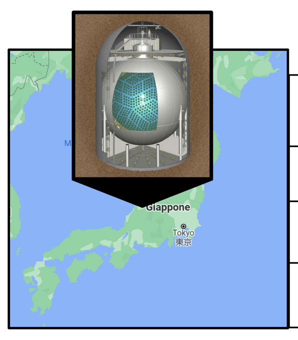


Uranium (U) and thorium (Th) geoneutrinos are detected via **Inverse Beta Decay** on free protons inside big **liquid scintillator detectors**. The measurement of the geoneutrino **flux at surface** permits to estimate the U and Th content of our planet's mantle and in turn to derive its **radiogenic heat production**.

The only two running experiments capable of measuring geoneutrinos are Borexino and KamLAND.

KamLAND is a **1 kton** liquid scintillator detector situated in **Japan**, in the Kamioka mine. It is surrounded by 1325 17" PMTs and 554 20" PMTs.

Borexino is **0.3 kton** liquid scintillator detector situated in **Italy**, at the Laboratori Nazionali del Gran Sasso. It is surrounded by ~2200 8" PMTs.



Data-taking: 2002-2019	
KamLAND (KL)	U+Th
Events [#]	$168.8^{+26.3}_{-26.5}$
Signal [TNU]	$32.1^{+5.0}_{-5.0}$

Data-taking: 2007-2019	
Borexino (BX)	U+Th
Events [#]	$52.6^{+9.6}_{-9.0}$
Signal [TNU]	$47.0^{+8.6}_{-8.1}$

[1] Watanabe, H. *Geo-neutrino Measurement with KamLAND* in Neutrino Geoscience 2019.
1 TNU = 1 antineutrino event measured over 1 year by a detector containing 10^{32} free protons target, assuming 100% detection efficiency.

[2] Agostini, M., *Comprehensive geoneutrino analysis with Borexino*. Physical Review D, 2020

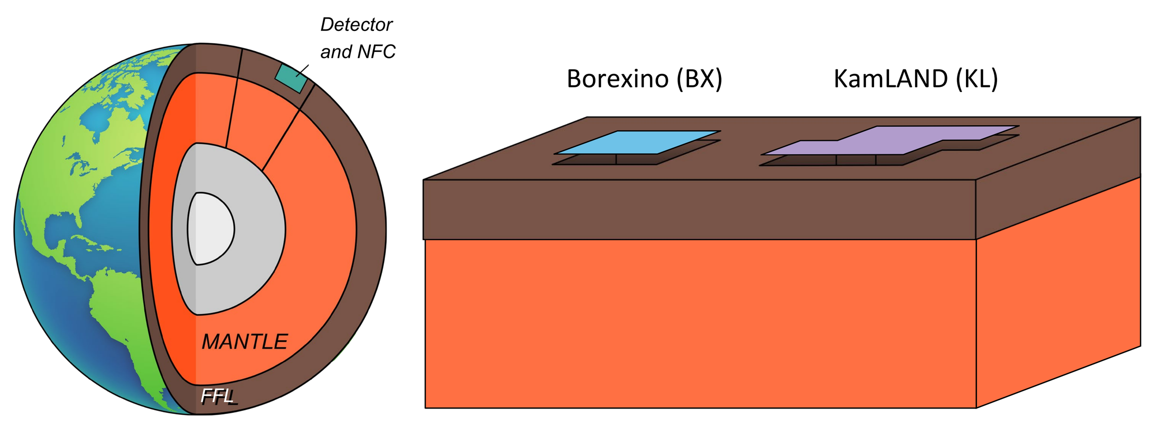
Geophysical and geochemical modelling

The geoneutrino signal can be modeled as the **sum** of **different components:**

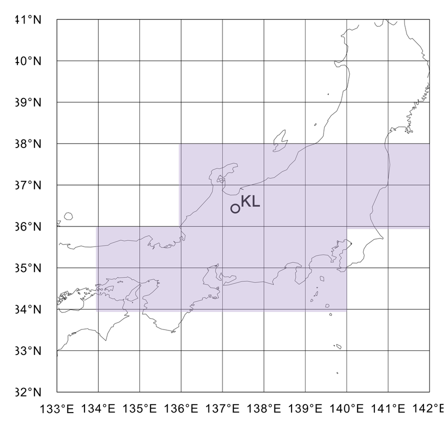
Different for different detectors — Common to detectors

$$S^i_{Exp}(U+Th) = S^i_{NFC}(U+Th) + S^i_{FFC}(U+Th) + S^i_{CLM}(U+Th) + S^i_{M}(U+Th)$$

The **Near Field Crust (NFC)** is the 6°x 4° portion of the crust surrounding the detector. U and Th distributed in the NFC can contribute up to ~ 50% of the total geoneutrino signal.

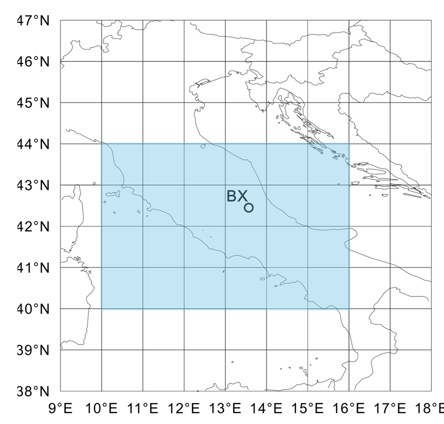


The **Far Field Lithosphere (FFL)** is the superficial portion of the Earth complimentary to the NFC. It includes the Far Field Crust (FFC) and the Continental Lithospheric Mantle (CLM).



KL	S(U+Th) [TNU]
NFC [3]	17.7 ± 1.4
FFC [4]	$7.3^{+1.5}_{-1.2}$
CLM [4]	$1.6^{+2.2}_{-1.0}$

[3] Fiorentini, G., *Mantle geoneutrinos in KamLAND and Borexino*. Physical Review D, 2012



BX	S(U+Th) [TNU]
NFC [2]	9.2 ± 1.2
FFC [4]	$13.7^{+2.8}_{-2.3}$
CLM [4]	$2.2^{+3.1}_{-1.3}$

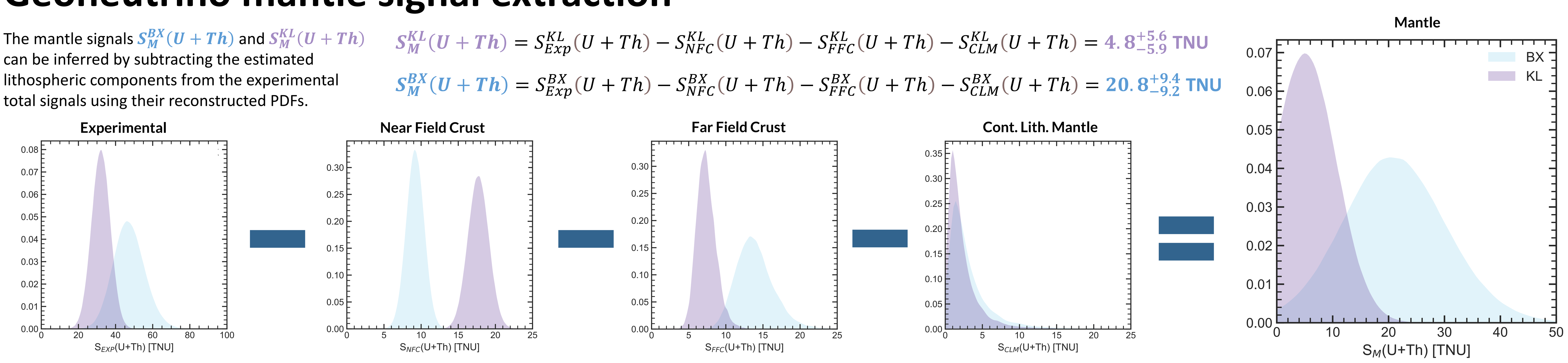
[4] Huang, Y., *A reference Earth model for the heat producing elements [...]*. Geochem Geophys, 2013

Geoneutrino mantle signal extraction

The mantle signals $S^{BX}_M(U+Th)$ and $S^{KL}_M(U+Th)$ can be inferred by subtracting the estimated lithospheric components from the experimental total signals using their reconstructed PDFs.

$$S^{KL}_M(U+Th) = S^{KL}_{Exp}(U+Th) - S^{KL}_{NFC}(U+Th) - S^{KL}_{FFC}(U+Th) - S^{KL}_{CLM}(U+Th) = 4.8^{+5.6}_{-5.9}\ \text{TNU}$$

$$S^{BX}_M(U+Th) = S^{BX}_{Exp}(U+Th) - S^{BX}_{NFC}(U+Th) - S^{BX}_{FFC}(U+Th) - S^{BX}_{CLM}(U+Th) = 20.8^{+9.4}_{-9.2}\ \text{TNU}$$

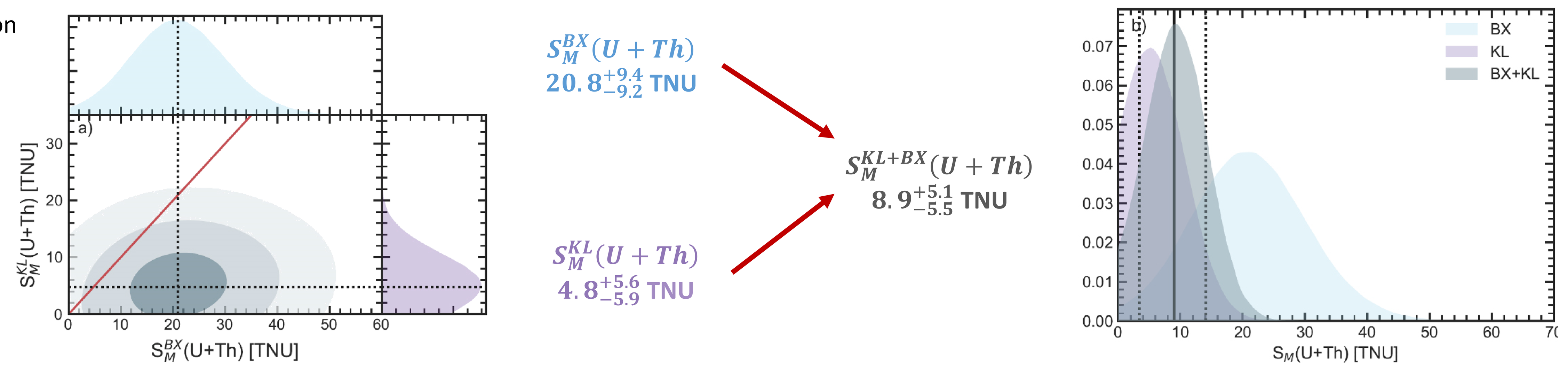


Under the assumption of site-independent mantle signal, the joint distribution $S^{KL+BX}_M(U+Th)$ can be inferred by requiring that the estimated signals $S^{BX}_M(U+Th) = S^{KL}_M(U+Th)$ are two observations of the same underlying quantity $S^{KL+BX}_M(U+Th) = 8.9^{+5.1}_{-5.5}$ TNU.

Correlations need to be properly accounted for:

» $S^{KL}_{FFC}(U+Th) \propto S^{BX}_{FFC}(U+Th)$
» $S^{KL}_{CLM}(U+Th) \propto S^{BX}_{CLM}(U+Th)$

As they are derived from the same geophysical and geochemical model



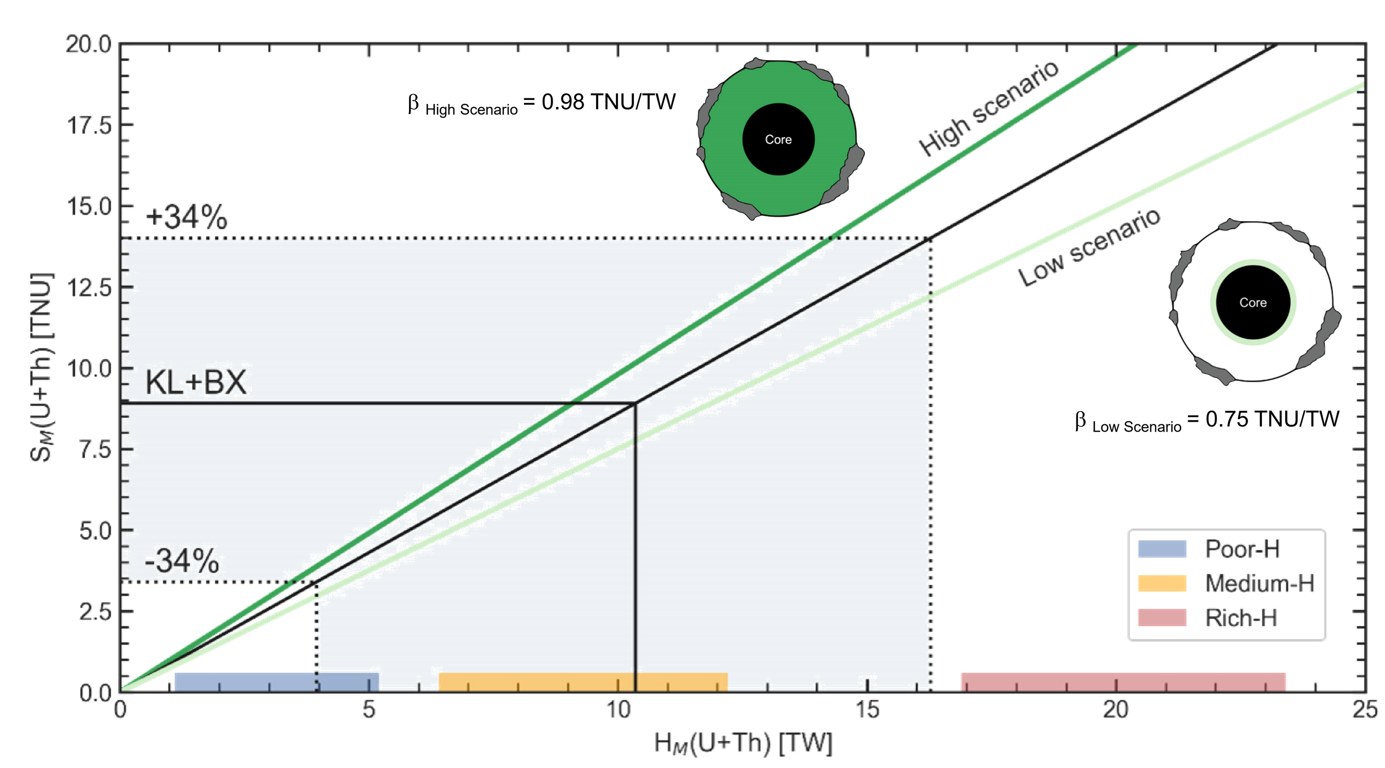
Implications for Earth Science

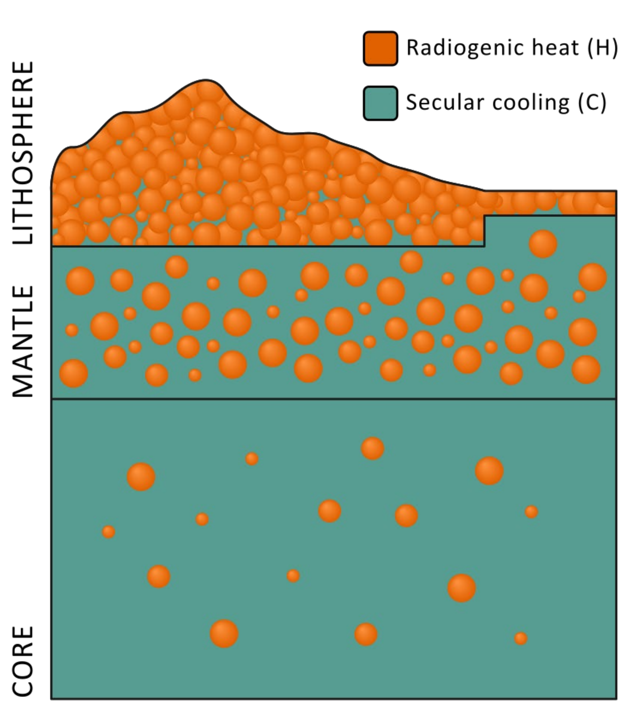
In literature there is a wide range of **Earth compositional models** based on different constraints (composition of meteorites, geochemical and geodynamical observations, etc.). Models can be grouped based on their expected **radiogenic heat production (H)** in **poor-H**, **medium-H** and **rich-H models**.

Assuming that the U and Th abundances in the mantle are radial, non-decreasing function of the depth, the obtained mantle signal $S^{KL+BX}_M(U+Th)$ can be used to estimate the radiogenic heat production of the mantle $H_M(U+Th)$:

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

✓ Our estimate $H_M(U+Th) = 10.3^{+5.9}_{-6.4}$ **TW** falls in the 68% coverage range of the medium-H models and it is compatible at 1σ level with the Poor-H models





Radiogenic heat (H) is not the only source contributing to the well-established total heat power (Q) of the Earth of 47 ± 2 TW [5]. A large contribution to Q comes from the indeterminate slow **secular cooling (C)** of our planet.

✓ By combining our estimate for H_M with the geochemical knowledge on the lithosphere $H_{LS} = 8.1^{+1.9}_{-1.6}$ TW [4] it is possible to derive a picture of the sources of Earth's heat budget:

$C = Q - H$
$C_M = Q - H - C_C$
$H_M = H - H_{LS} - H_C$
$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$

Q [TW]	H_{LS} [TW]	H_M [TW]	H [TW]	C [TW]
47 ± 2	$8.1^{+1.9}_{-1.6}$	$12.5^{+7.1}_{-7.7}$	$20.8^{+7.3}_{-7.9}$	26 ± 8