SUMMER INSTITUTE: USING PARTICLE PHYSICS
TO UNDERSTAND AND IMAGE THE EARTH

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Argon, geoneutrinos

Ondřej Šrámek
Department of Geophysics
Charles University in Prague
ondrej.sramek@gmail.com
geo.mff.cuni.cz/~sramek

High mantle Urey ratio?

$$\text{Urey ratio} = \frac{\text{radiogenic power}}{\text{surface heat loss}}$$

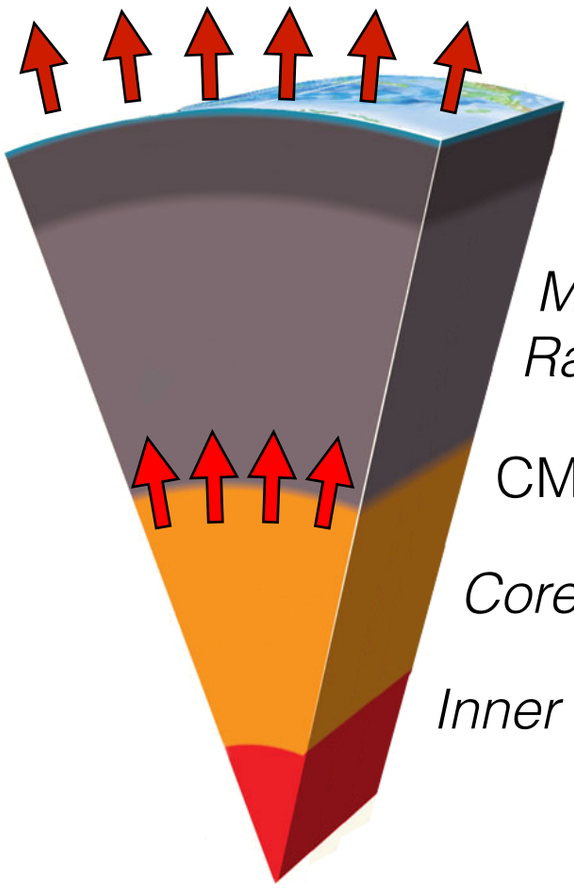
20 TW radiogenic power in BSE ↔ Mantle Ur ~ 0.3

- Deschamps et al. 2010, *Nu–Ra* scaling based on 3-D spherical shell numerical simulations of convection: *"Applied to the Earth's mantle, the mixed heating scaling predicts a Urey ratio between 0.4 and 0.6, depending on the Rayleigh number."* (between 23 and 31 TW radiogenic power in BSE)

- Nakagawa & Tackley 2012: *"The Urey ratio that is calculated purely from convective heat flow is always higher than 0.5* [19 TW in BSE]*. When magmatic heat flow is included, the Urey ratio is slightly lower at the present day"*

- Lenardic et al. 2011: Including continents is important. Results from numerical models relax the tension between classical convection models and lower Urey ratio estimated from geochemical models.

Earth energy budget



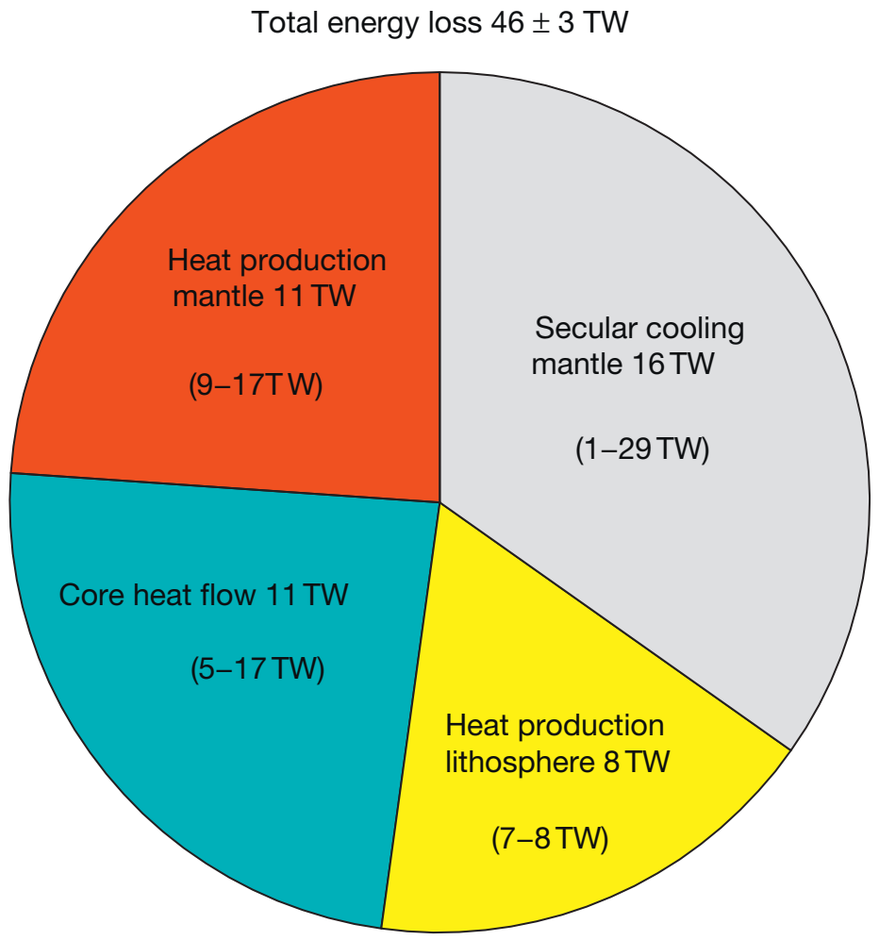
Surface heat flux

Mantle secular cooling
Radiogenic heat production

CMB heat flux

Core cooling

Inner core growth



Jaupart et al. 2015 in Treatise on Geophysics

Argon

^{40}Ar … radiogenic, stable
^{36}Ar … primordial, stable
^{39}Ar … radioactive, $t_{1/2}$ = 269 y

Atmosphere
^{40}Ar from degassing of Earth
^{39}Ar produced cosmogenically: $^{40}Ar(n,2n)^{39}Ar$
$^{40}Ar/^{36}Ar = 295$
$^{39}Ar/^{40}Ar = 8\times10^{-16}$

Underground
^{40}Ar produced by electron capture on ^{40}K

Dark matter WIMP search and underground argon

- DarkSide-50 experiment (darkside.lngs.infn.it)

- Dark matter detectors looking for Weakly Interacting Massive Particles (WIMPs) require low radioactivity argon

- Atmospheric level ($^{39}Ar/^{40}Ar = 8\times10^{-16}$) is too high (~1 decay per sec per kg)

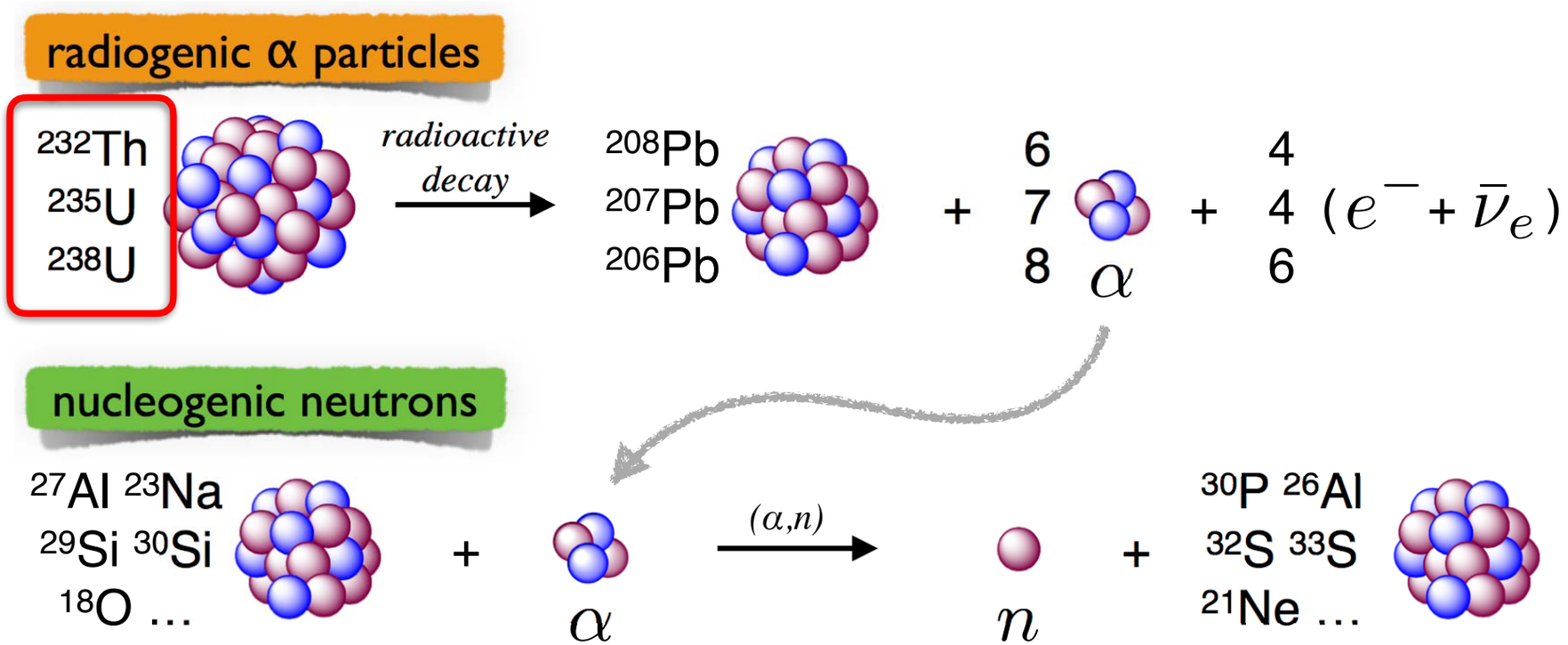
- Gas from deep CO_2 wells shows lower level of ^{39}Ar,
  e.g., Doe Canyon near Cortez Colorado

- Xu et al. 2015: ^{39}Ar activity a factor of 150 below atmospheric
- Agnes et al. (DarkSide) 2016: ^{39}Ar activity a factor of 1400 below atmospheric

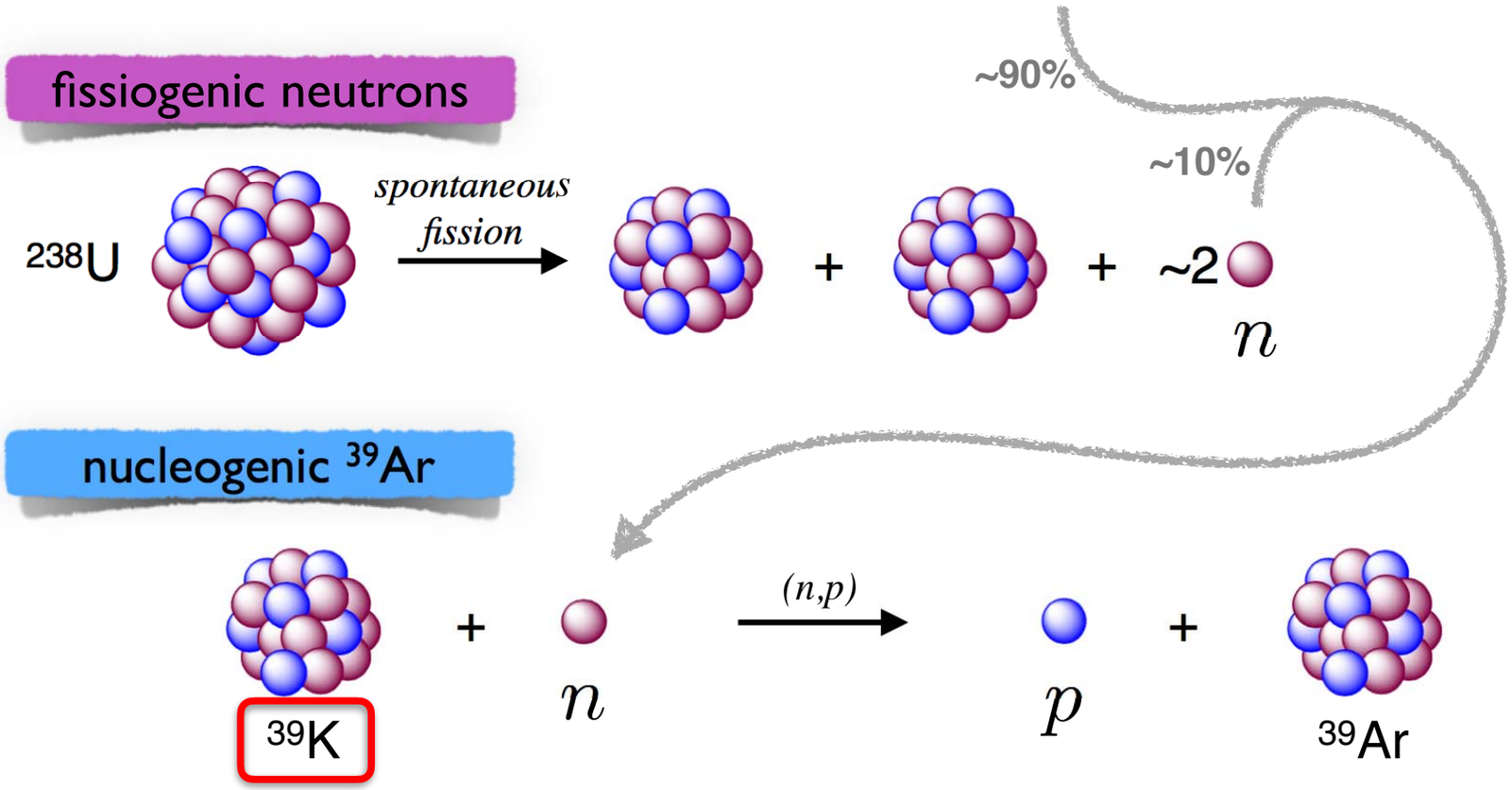
- Cosmogenic production attenuated with depth in the Earth.
  At depths > 700 m, nucleogenic production of ^{39}Ar dominates.

Underground production of noble gases

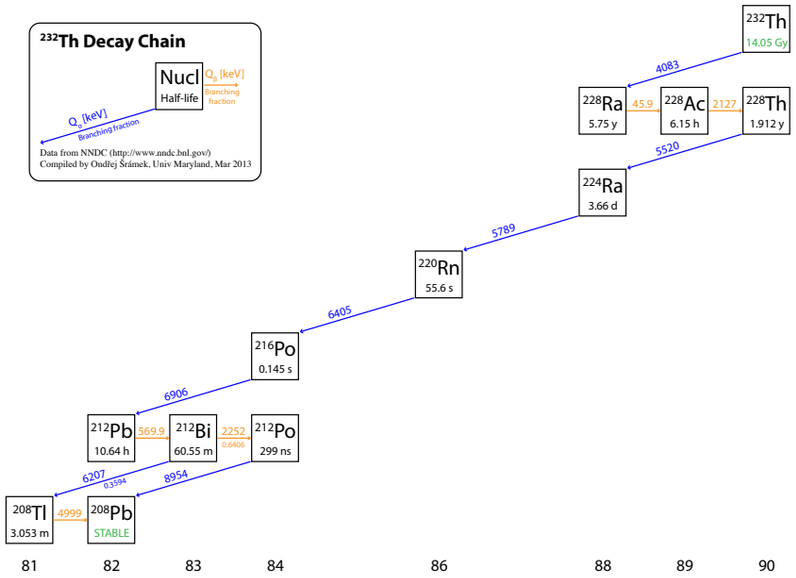
Th, U

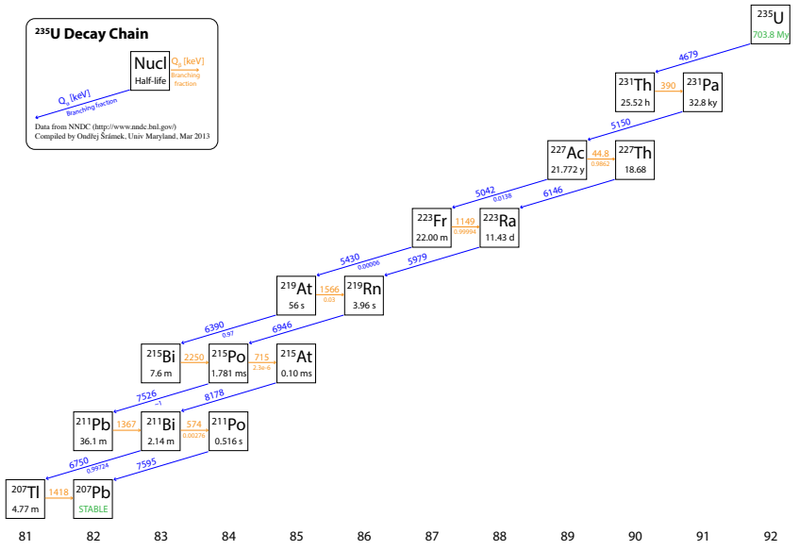


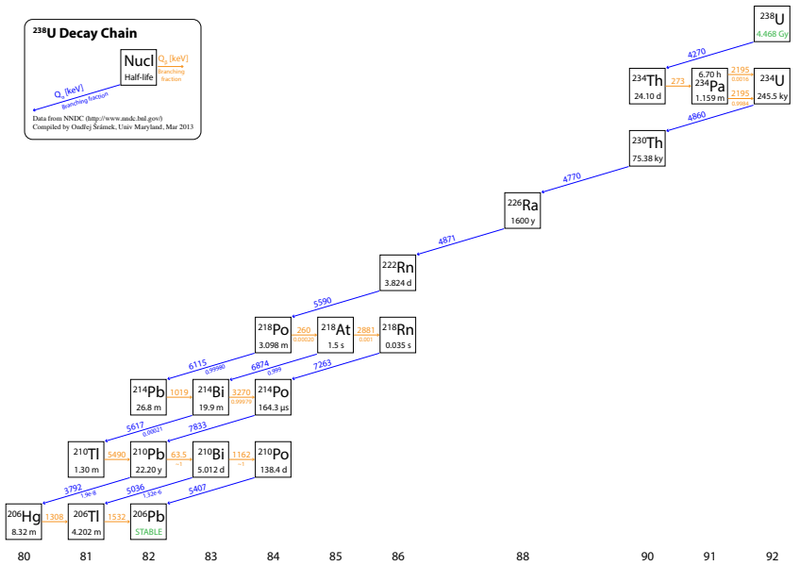
K

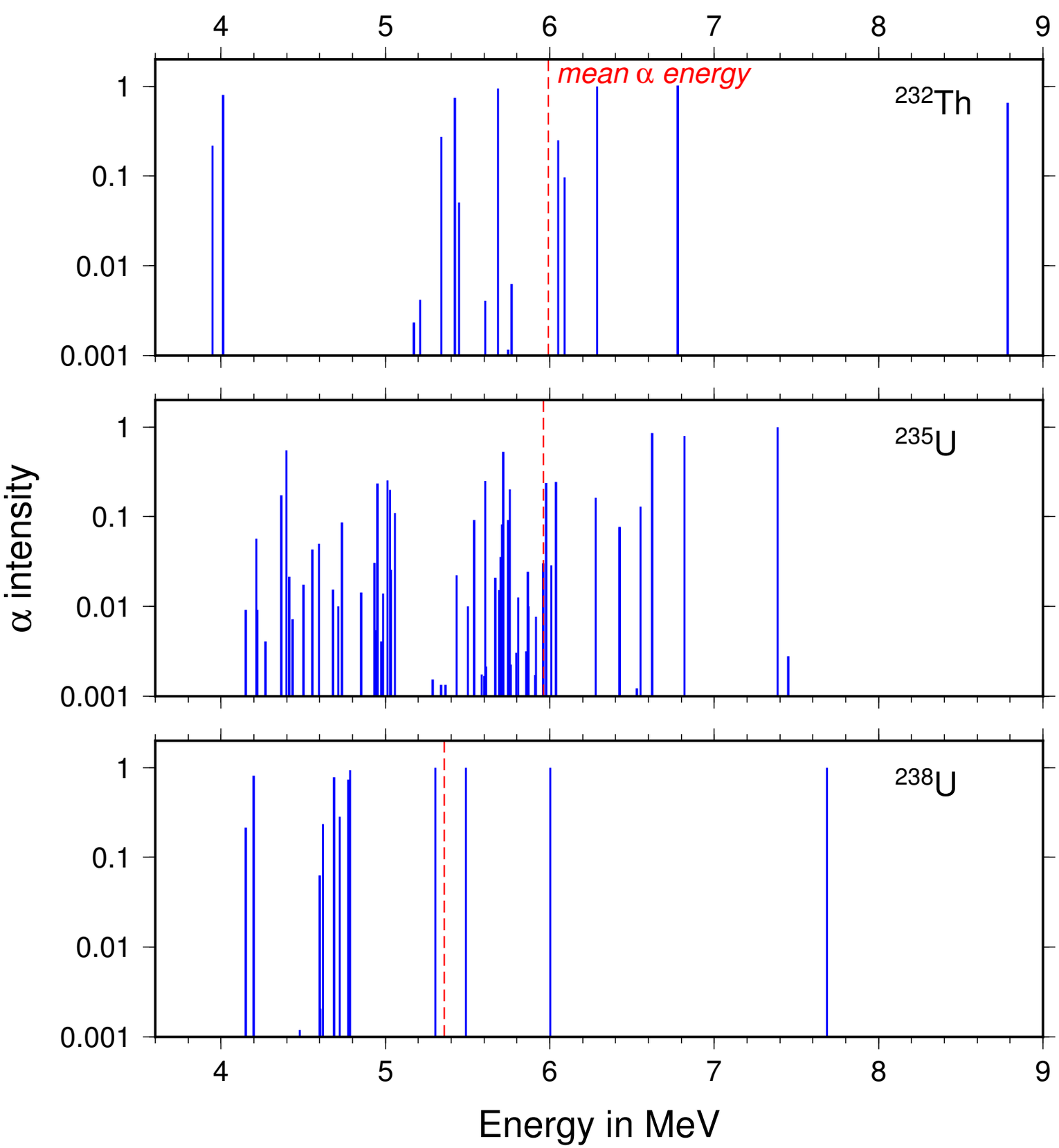


Producing α particles

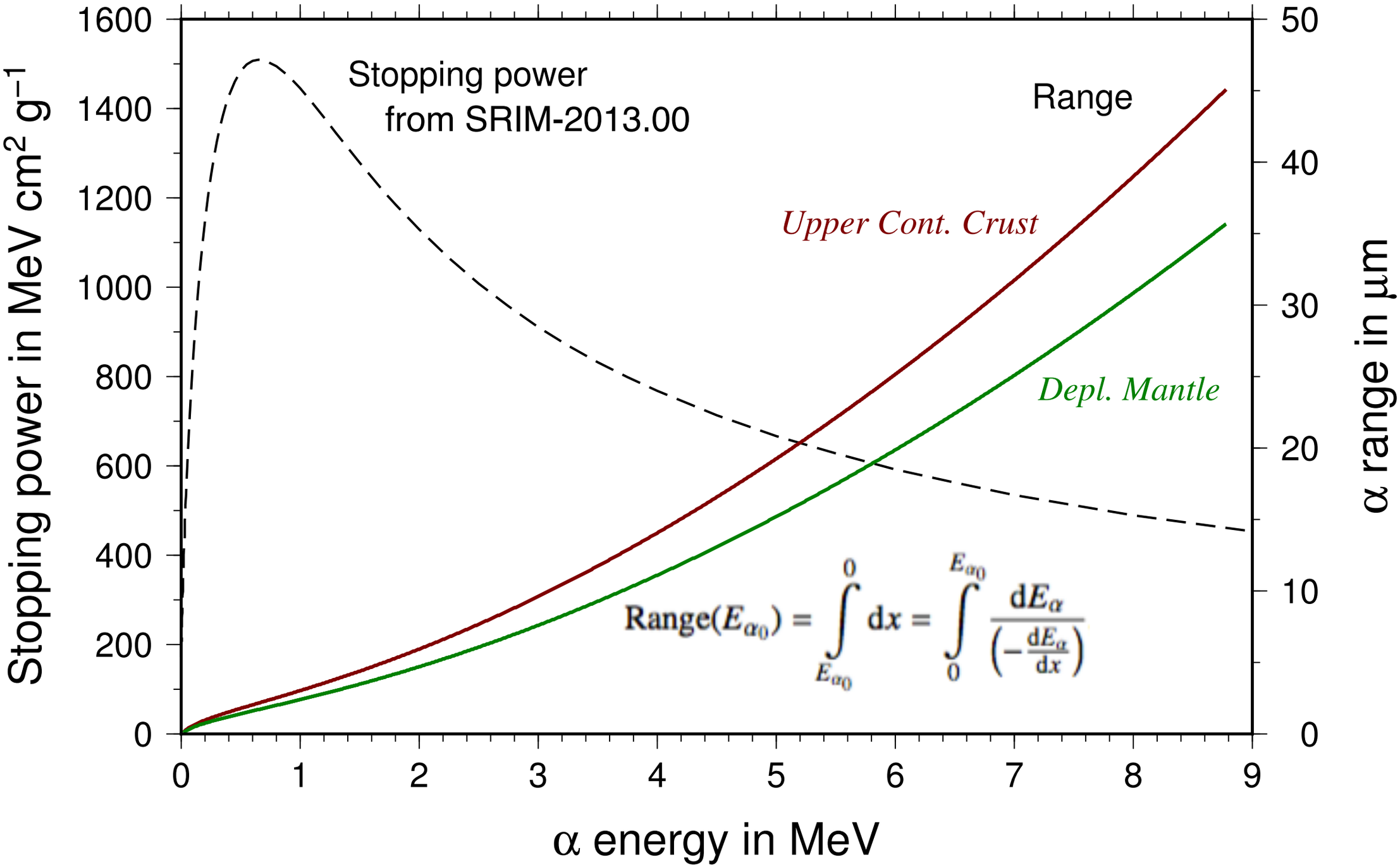








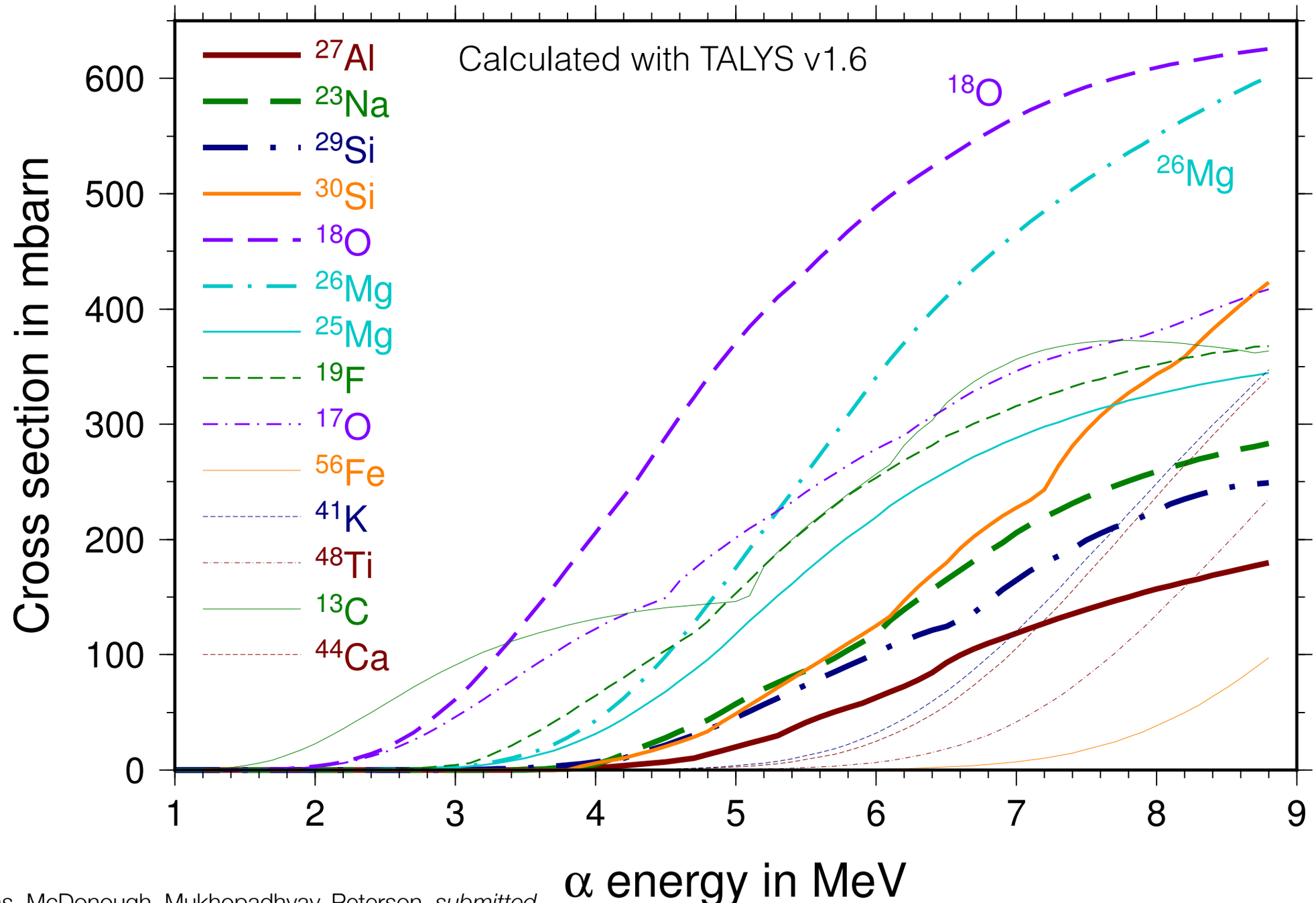
Travel distance of α particle in rock



O.Š., Stevens, McDonough, Mukhopadhyay, Peterson, *submitted*

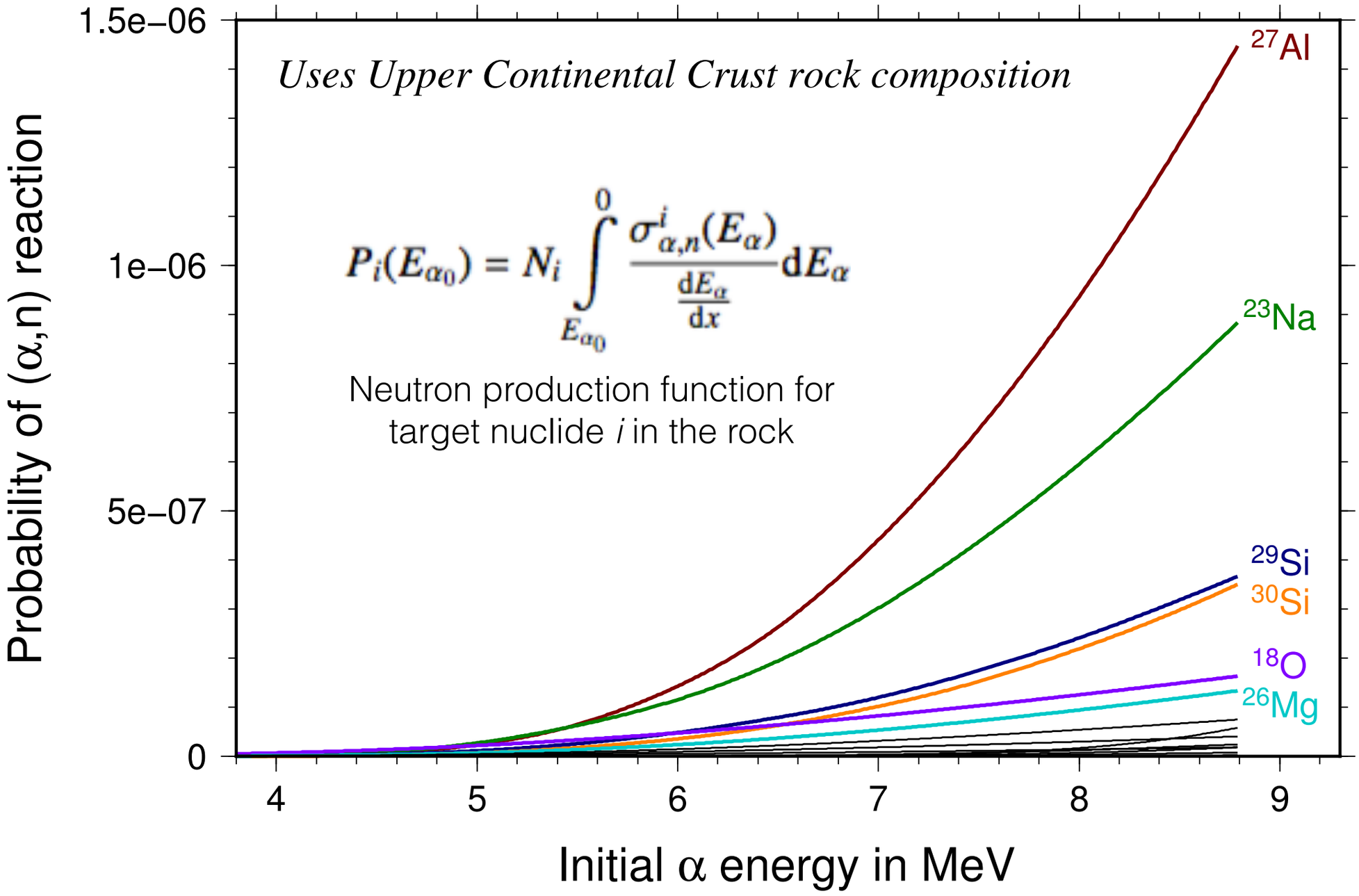
Cross section of (α,n) reaction

Threshold energy E_{th} + overcoming Coulomb barrier V_c $\quad E_{th} = -\frac{m_1 + m_2}{m_2} Q \quad V_C = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r}$



O.Š., Stevens, McDonough, Mukhopadhyay, Peterson, *submitted*

Probability of neutron production



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Neutron yield and neutron energy

Following α-decays down the decay chain

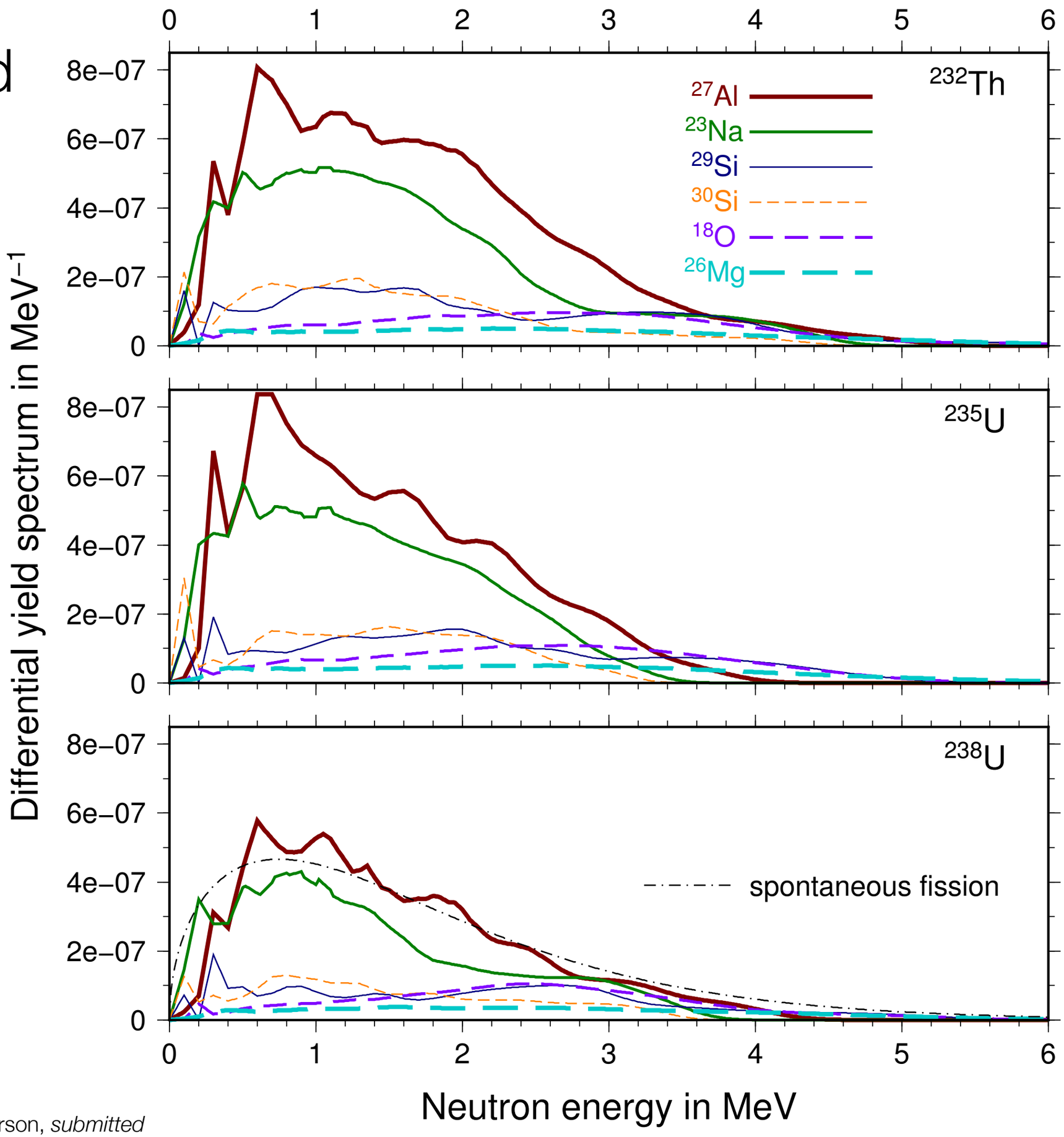
Neutron yield

$$Y^i_{\alpha,n} = \sum_{k=1}^{\text{decays}} b_k \sum_{l=1}^{\text{levels}} f_{kl} P_i(E_{kl})$$

Neutron yield spectrum

$$\frac{\mathrm{d}P_i}{\mathrm{d}E_n}(E_{\alpha_0}, E_n) = N_i \int_{E_{\alpha_0}}^{0} \frac{\frac{\mathrm{d}\sigma^i_{\alpha,n}}{\mathrm{d}E_n}(E_\alpha, E_n)}{\frac{\mathrm{d}E_\alpha}{\mathrm{d}x}} \mathrm{d}E_\alpha$$

$$\frac{\mathrm{d}Y^i_{\alpha,n}}{\mathrm{d}E_n} = \dots$$



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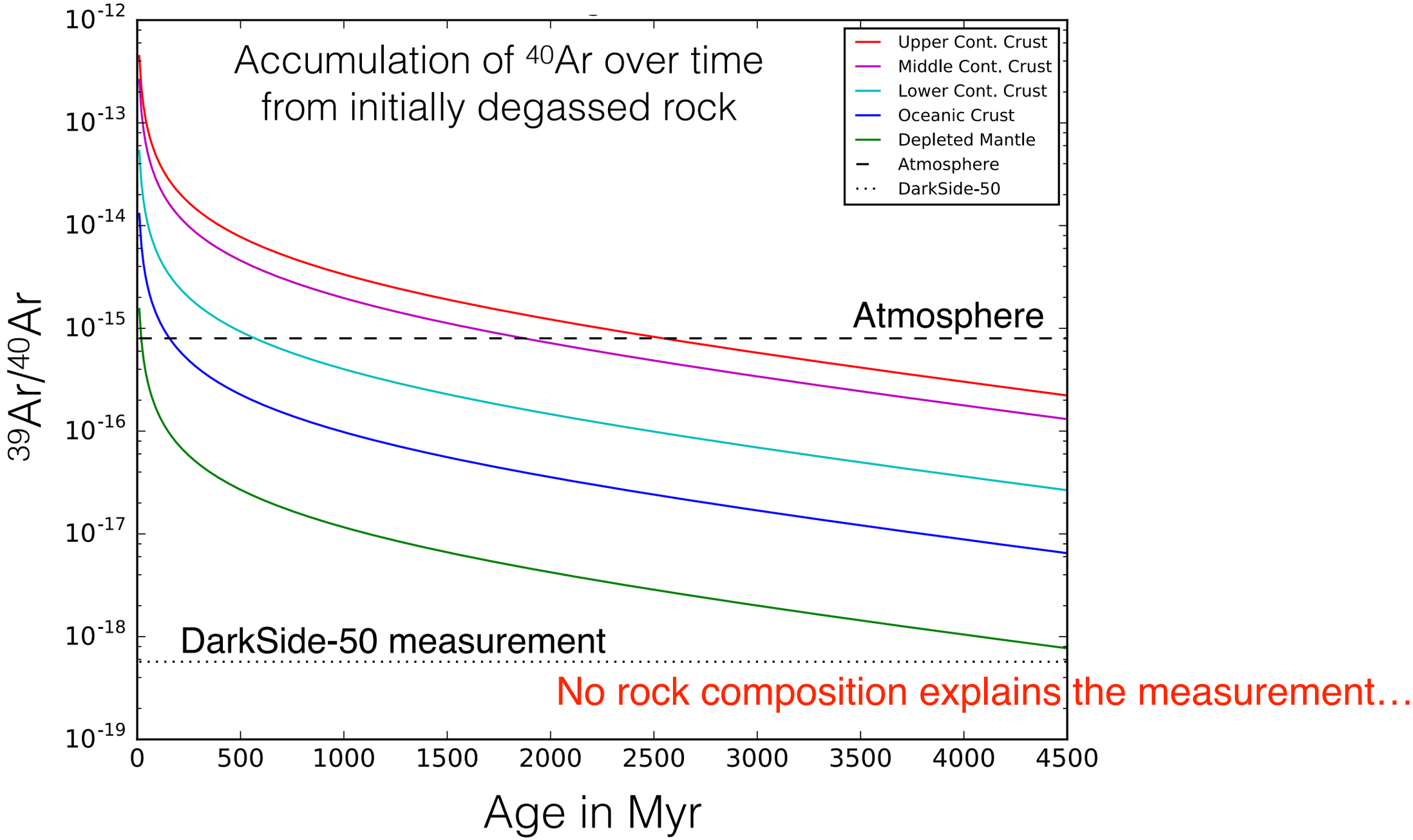
Calculated production rates

Neutron energy spectra are input into MCNP6 simulation to calculate ^{39}Ar yields from ^{39}K(n,p)^{39}Ar

Composition	^{4}He	neutrons	^{21}Ne	^{39}Ar
Upper Continental Crust	1.64×10^{10}	10680	753	28.7
Middle Continental Crust	8.98×10^{9}	6114	416	13.9
Lower Continental Crust	1.53×10^{9}	1129	70.2	0.749
Bulk Oceanic Crust	3.79×10^{8}	260	15.8	0.0235
Depleted Upper Mantle	2.51×10^{7}	22.4	1.06	0.000257

Predicting $^{39}Ar/^{40}Ar$ produced underground

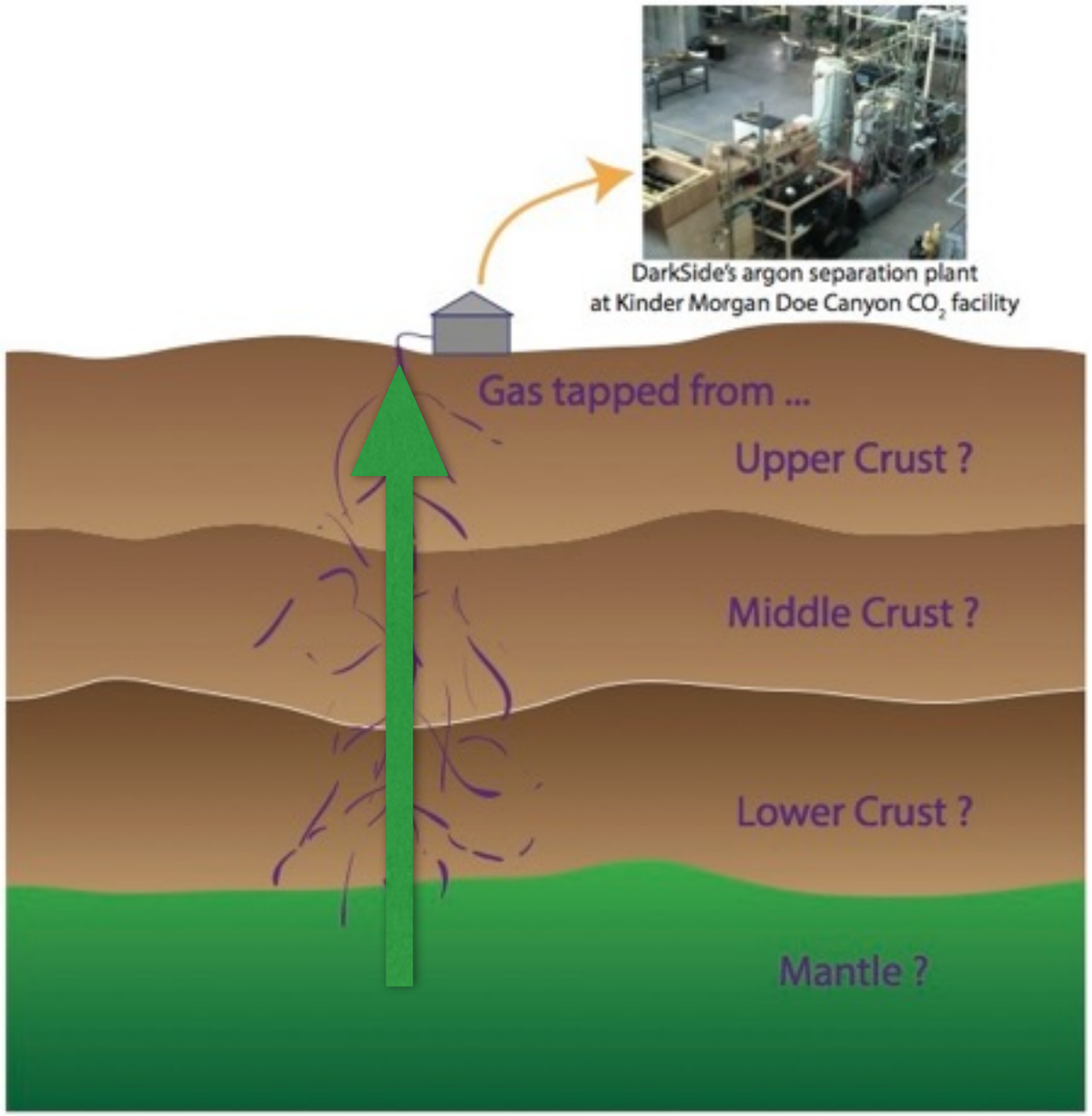


Source rock has even lower K, Th, U?

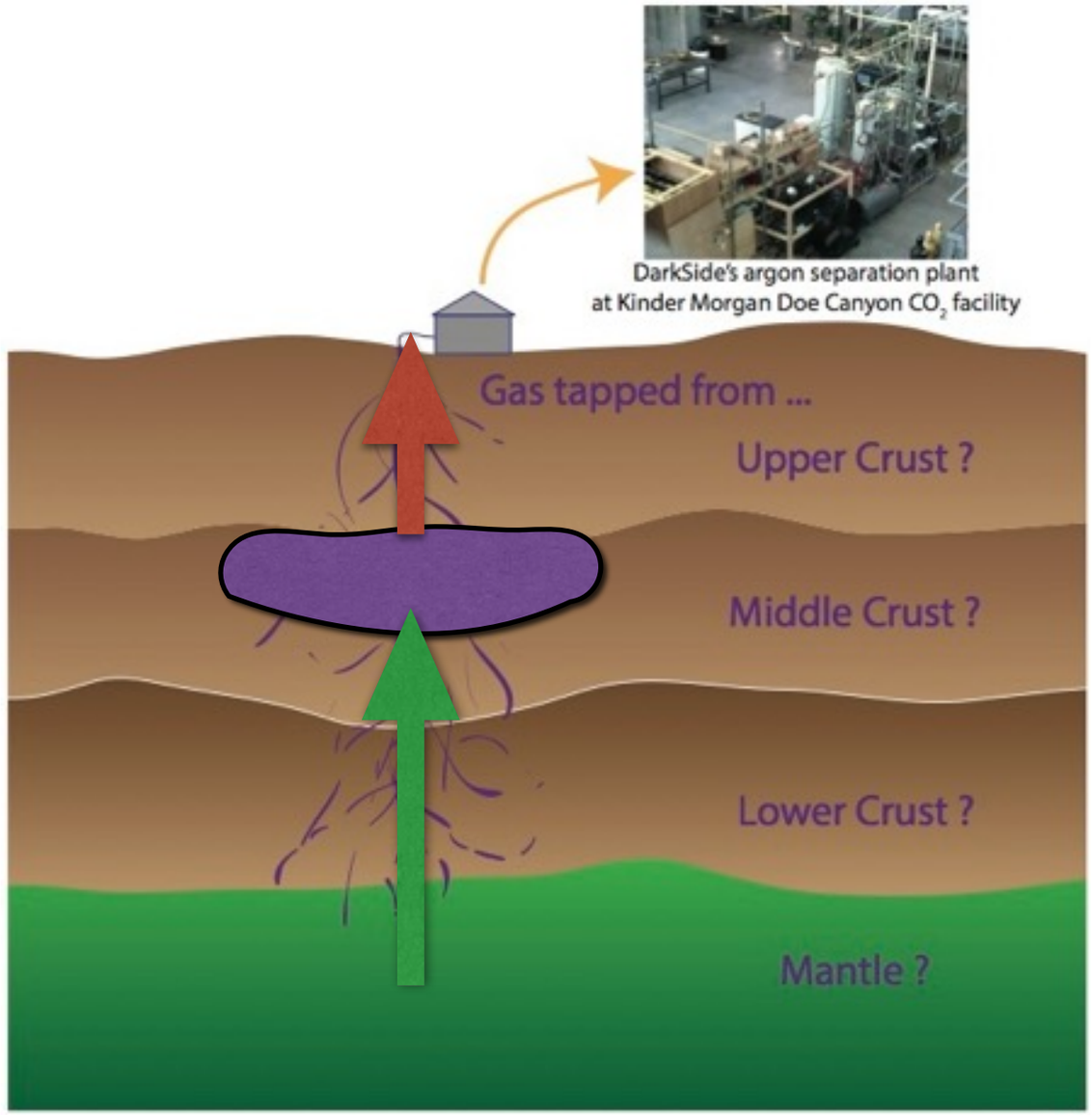
Initially degassed rock assumption no good?

Accumulation of gas in isolated reservoir in the crust?

Message from the mantle?



Or story of the crust?



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Initially degassed rock assumption no good?
Accumulation of gas in isolated reservoir in the crust?

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/distance^2 from source

Predicting geoneutrino flux from geological models

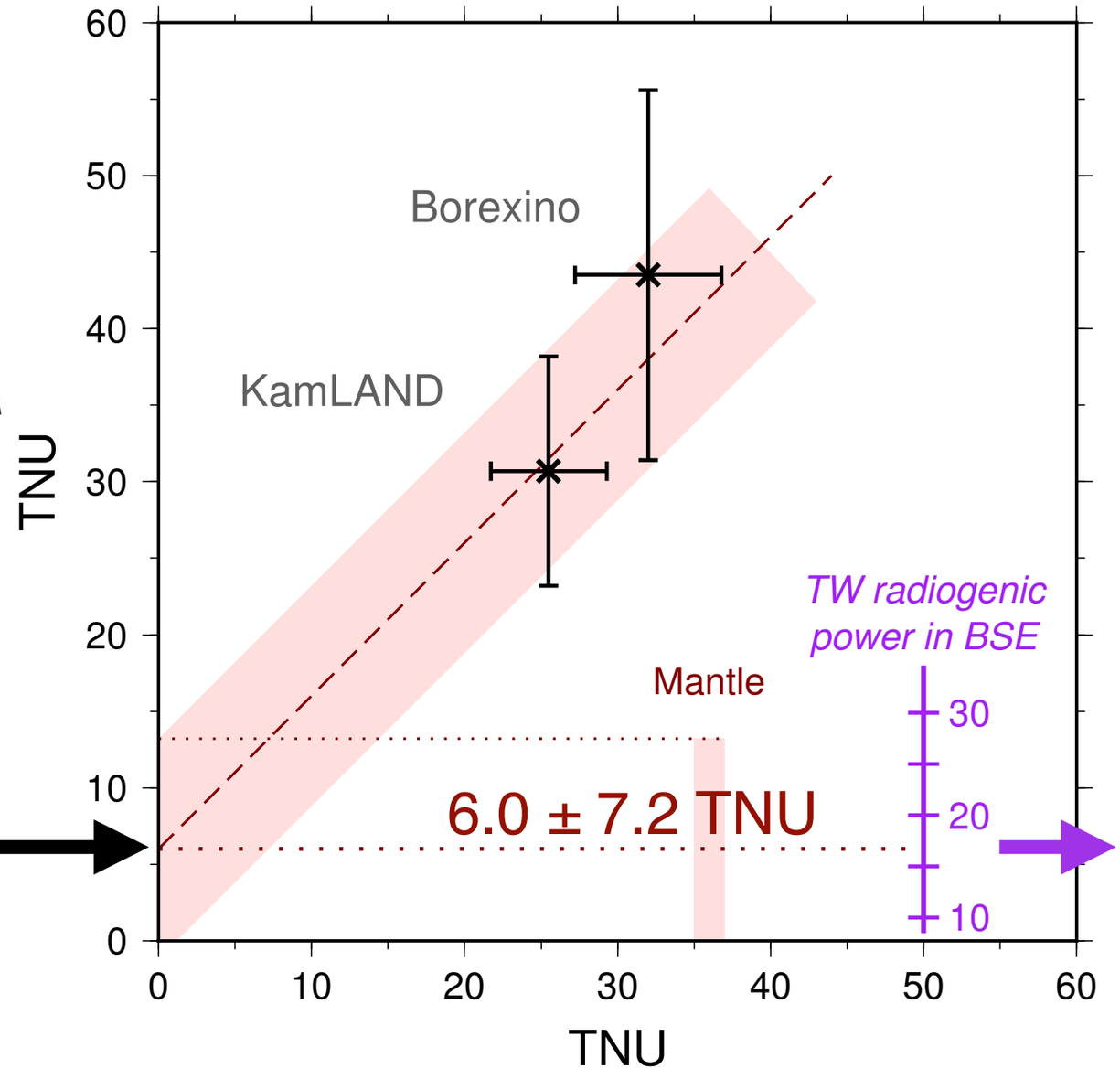
$$\phi(\vec{r}) = \frac{X\lambda N_A}{\mu} n_\nu \langle P_{ee} \rangle \iiint \frac{A(\vec{r}')\rho(\vec{r}')}{4\pi|\vec{r} - \vec{r}'|^2} \mathrm{d}\vec{r}'$$

ρ … material density [kg/m^3]

A … abundance of Th, U [g/g]

Geoneutrino measurements: current status

Measurement by physics:
Total geoneutrino flux
(lithosphere + mantle)



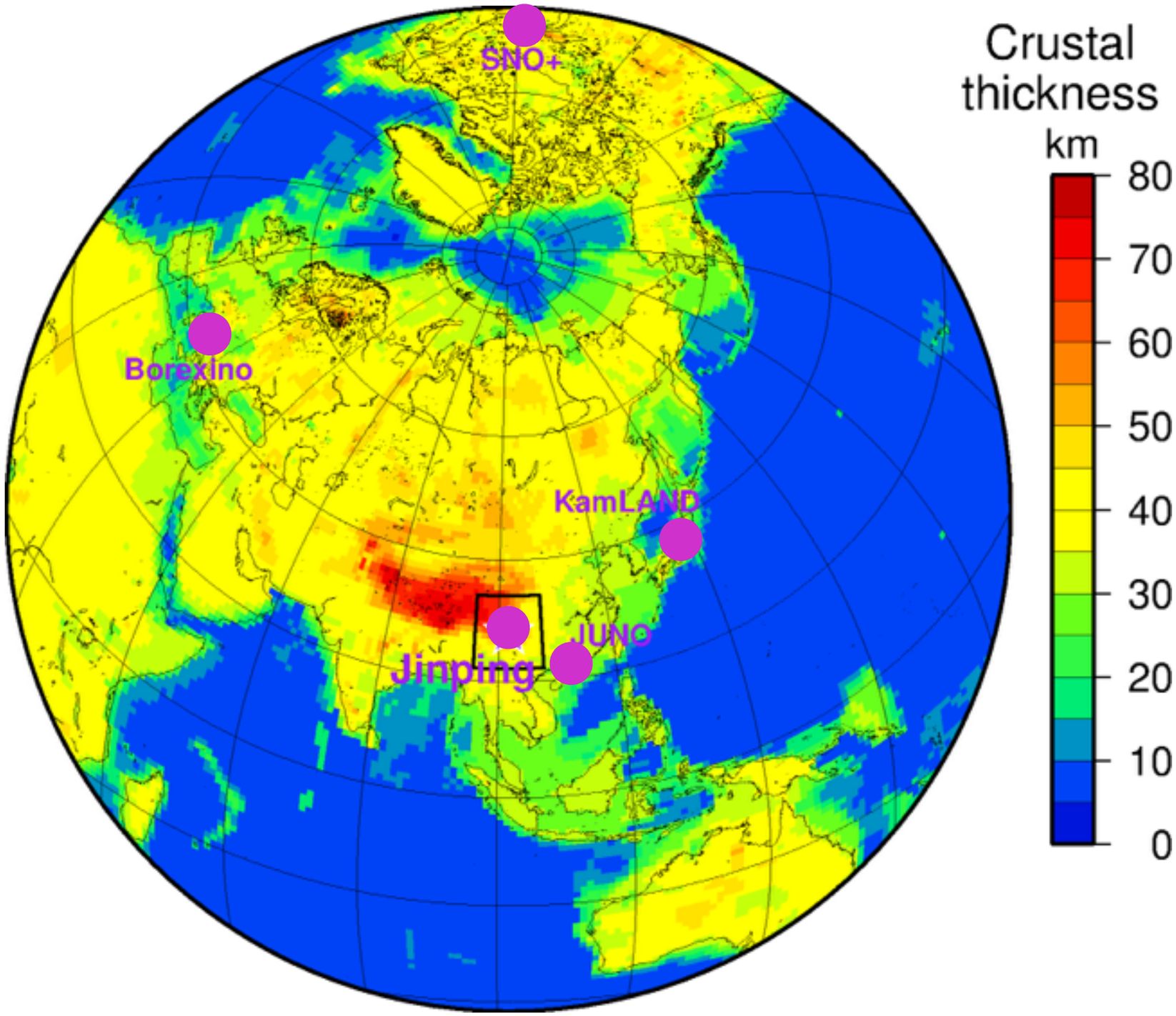
Mantle geoneutrino flux

17 ± 11 TW
in BSE

Prediction from geology:
Lithospheric geoneutrino flux

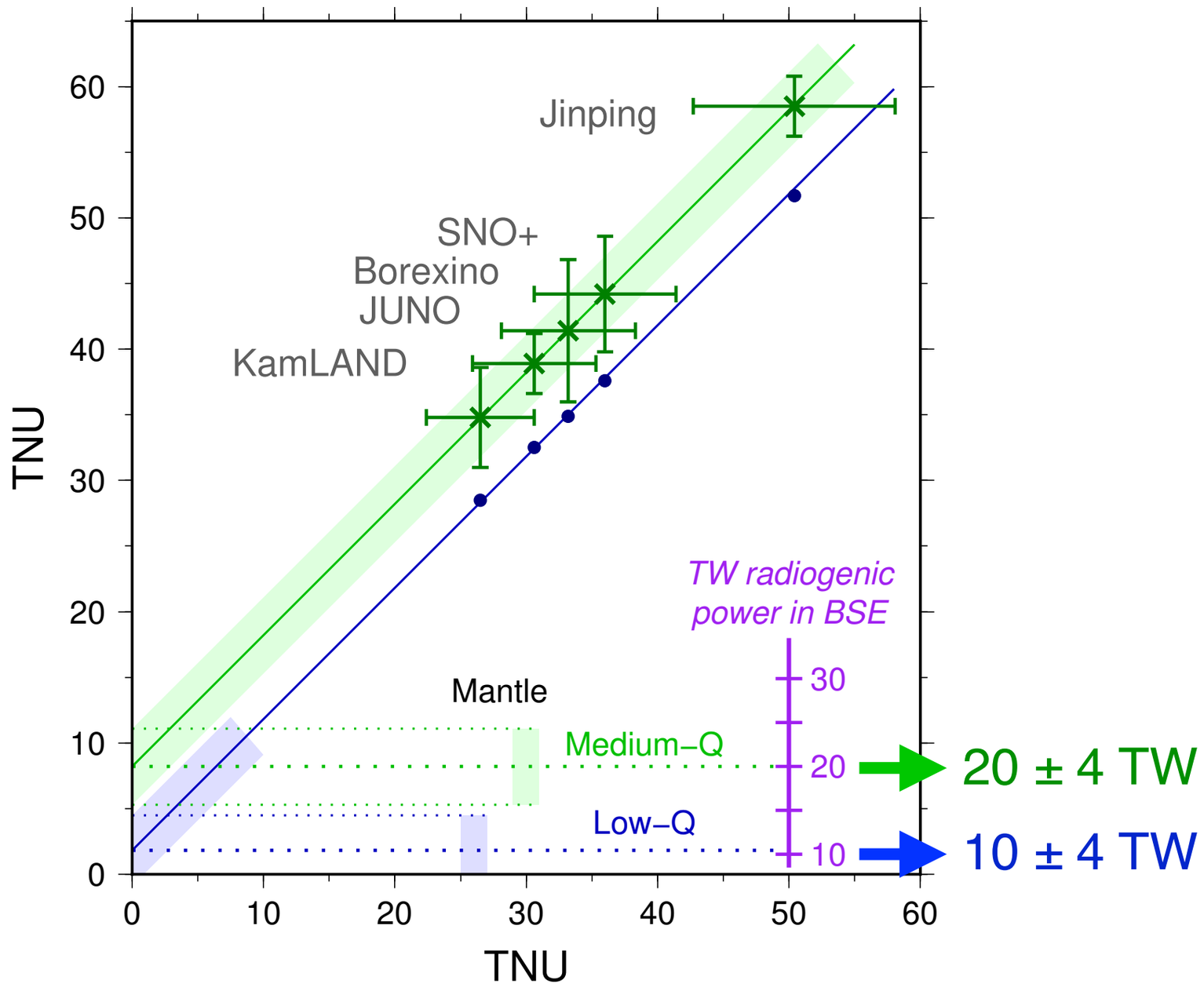
OŠ, Roskovec, Wipperfurth, Xi, McDonough, *submitted*

Geoneutrino detecting experiments by 2025(?)



Geoneutrino measurements by 2015 (?)

Simulated measurement by physics:
Total geoneutrino flux
(lithosphere + mantle)



Prediction from geology:
Lithospheric geoneutrino flux

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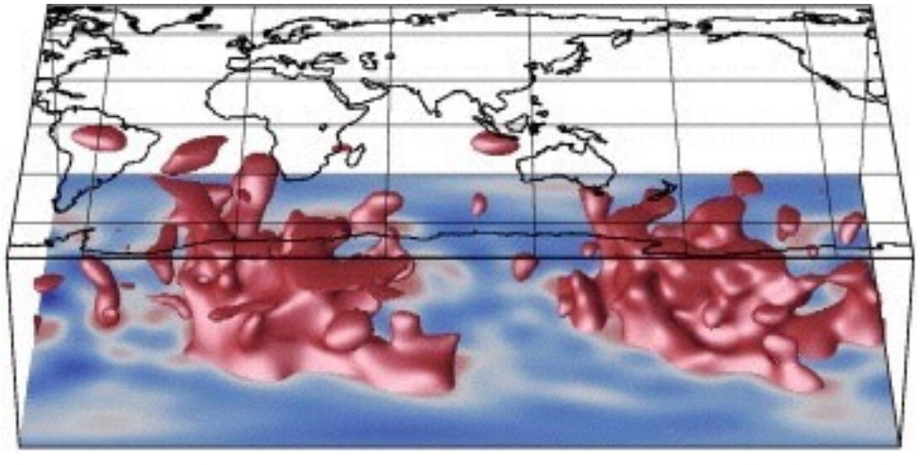
Interrogate mantle structure?

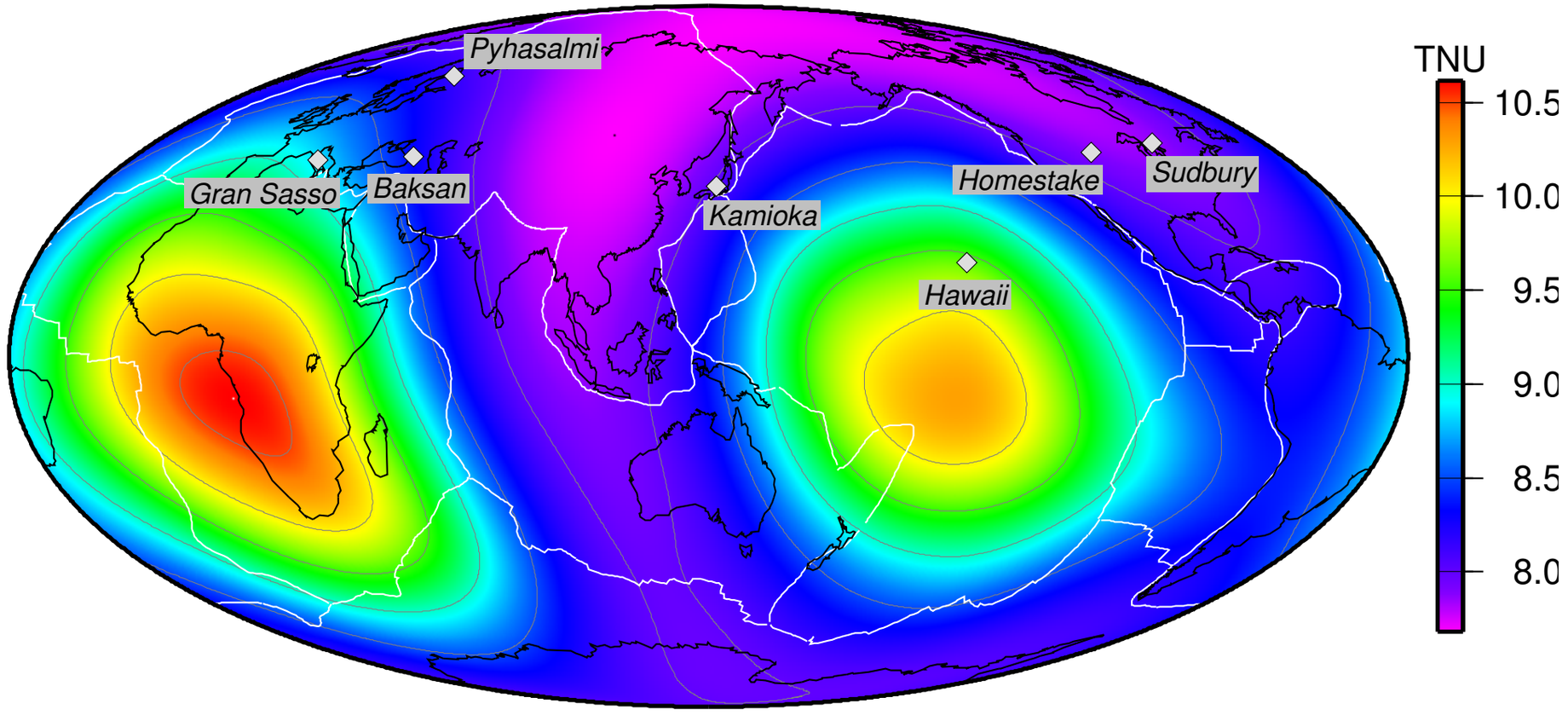


LLSVPs

$\delta \ln V_s < 0$

Assume these piles represent an enriched reservoir.

Mantle geoneutrino flux prediction

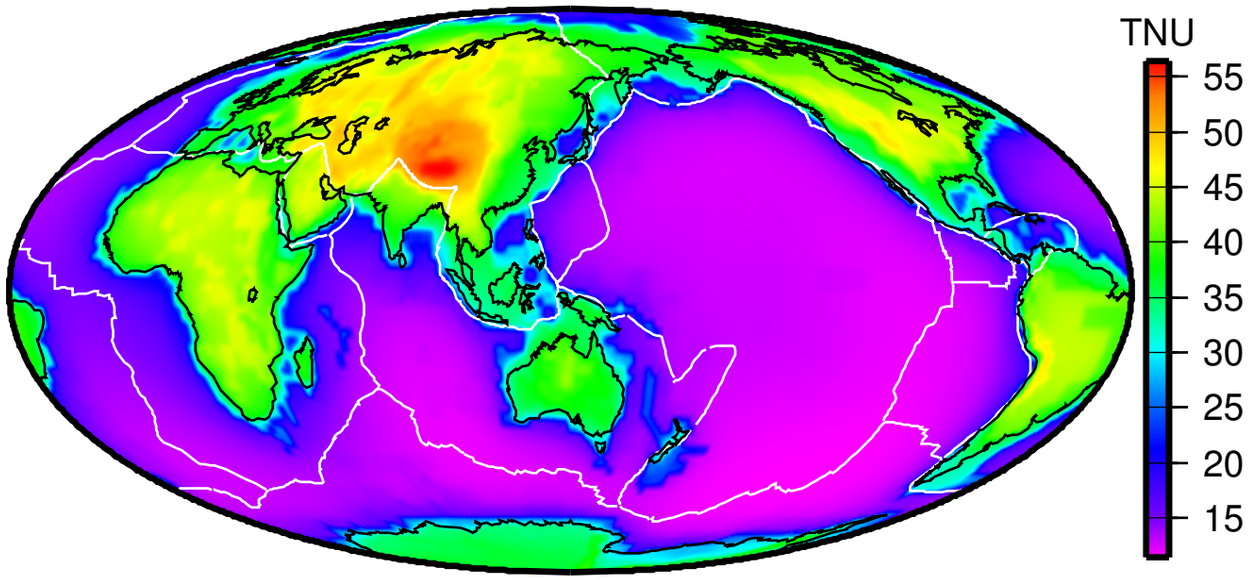


Detectable?

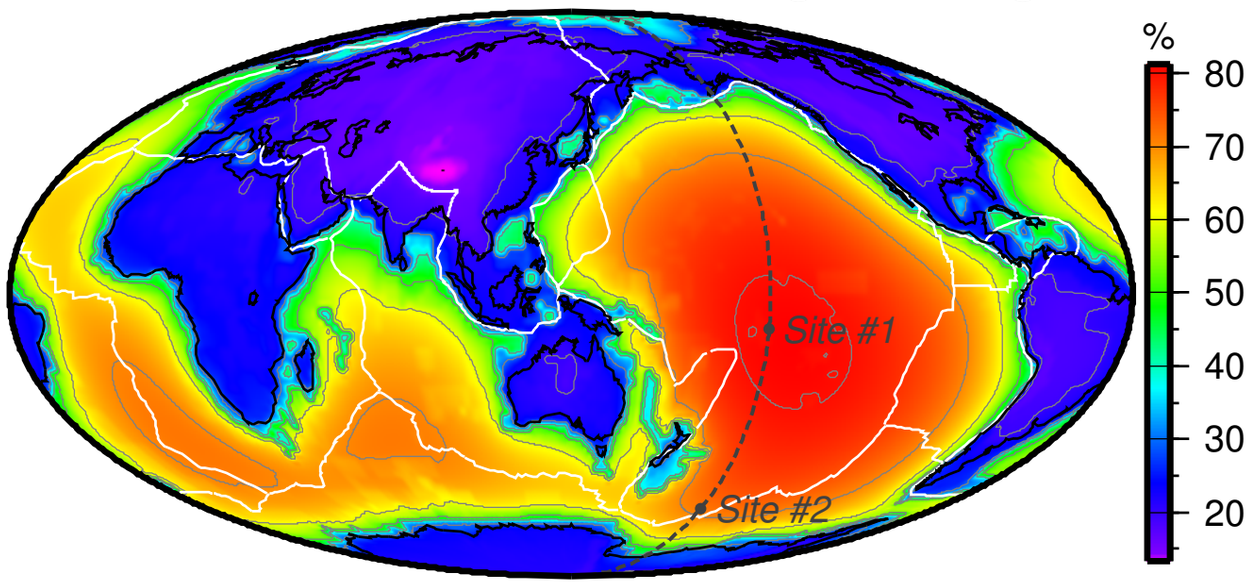
O.Š., McDonough, Kite, Lekić, Dye, Zhong, EPSL 2013

Detecting mantle structure

Lithosphere + mantle prediction



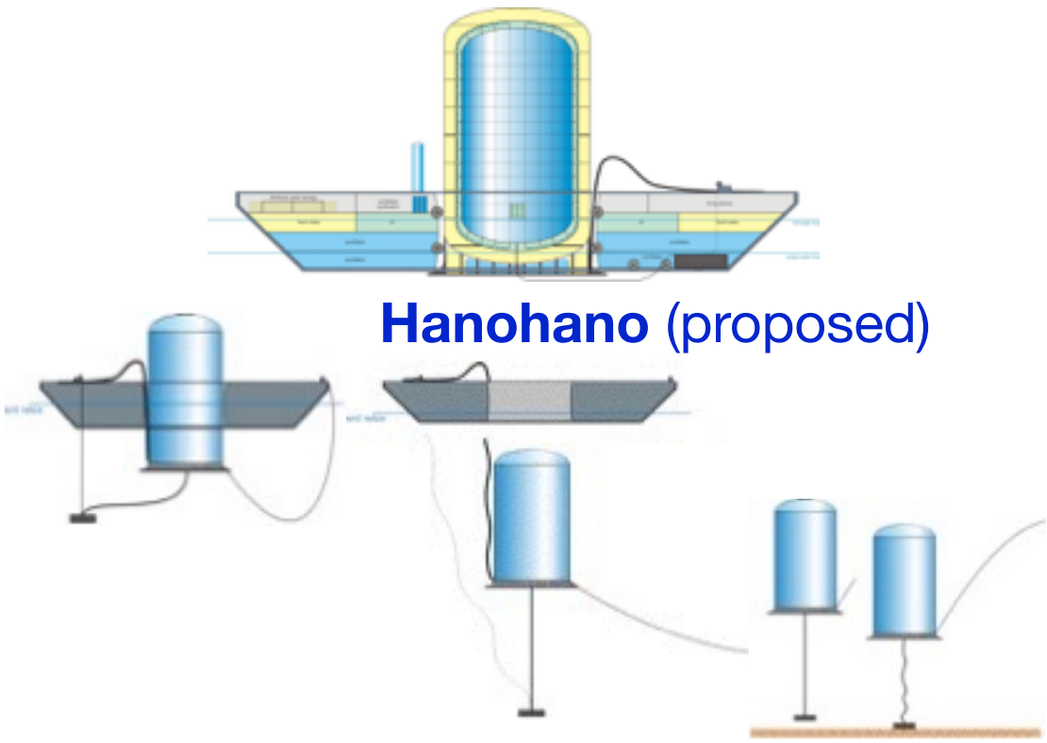
Mantle contribution to total geonu signal



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

O.Š., McDonough, Kite, Lekić, Dye, Zhong, EPSL 2013

Get away from continents and away from reactors



Hanohano (proposed)