Radiogenic Element Abundances

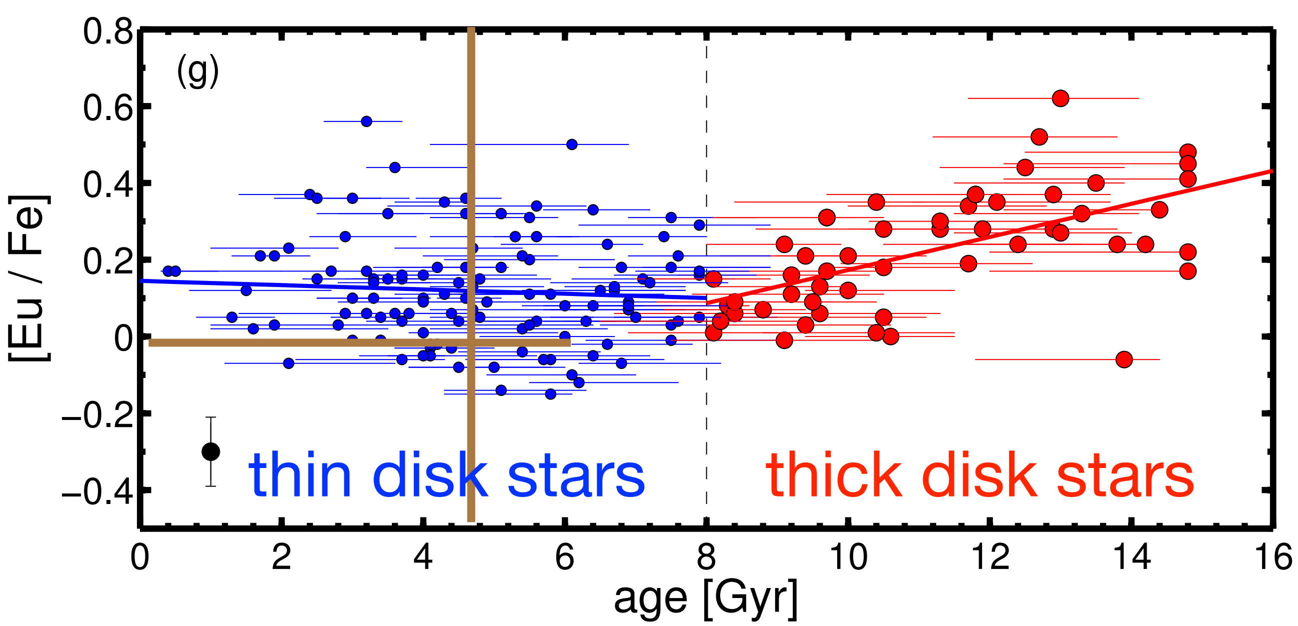
Summary by Joel Primack
May 20, 2020

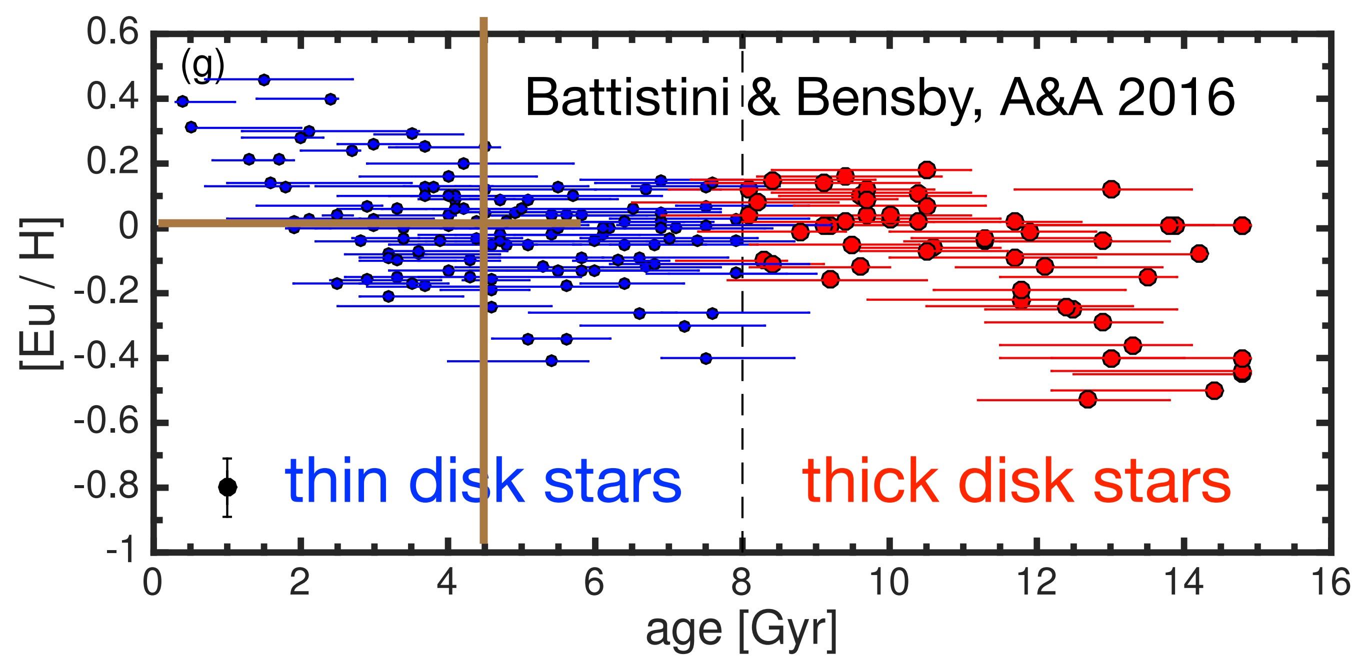
The sun is about 0.1 dex low in [Eu/Fe], which ranges from -0.25 to +0.3.
The sun is about 0.1 dex high in [Eu/H], which ranges from -0.5 to +0.5.
Which is more important for planetary dynamos and plate tectonics?

Borexino geoneutrino data favor higher Earth Th and U abundance than chondrites or the sun.

Radiogenic Heating of Planets — Main points:

- The sun is about 0.1 dex low in [Th/Fe] and [Th/Si] compared with solar twin stars with [Fe/H] ~ 0. [Eu/Fe] is even larger for [Fe/H] < 0. [Th/Eu]_ZAMS is flat => Eu traces Th.
- Terrestrial planets (R_P ≤ R_Earth) are observed around stars with [Fe/H] ≳ - 0.5 (Wang & Fisher 2015), for which median [Eu/Fe] ~ +0.25 (Battistini & Bensby 2016, Delgado Mena+2018).
- Most planets with [Fe/H] ≤ 0 will therefore have higher [Eu/Fe] than Earth, but whether they are more likely to have a dynamo-generated magnetic field, convective mantle, and possibly plate tectonics may depend more on [Eu/Si] and [Eu/Mg]. The dependence on [Fe/H] of [Eu/Fe] is much like that of [O/Fe], [Mg/Fe], and [Si/Fe] — all increase as [Fe/H] decreases below 0 (Delgado Mena+2019).
- In [Eu/H] the sun is a bit high compared with other thin disk stars, and higher than most thick disk stars:



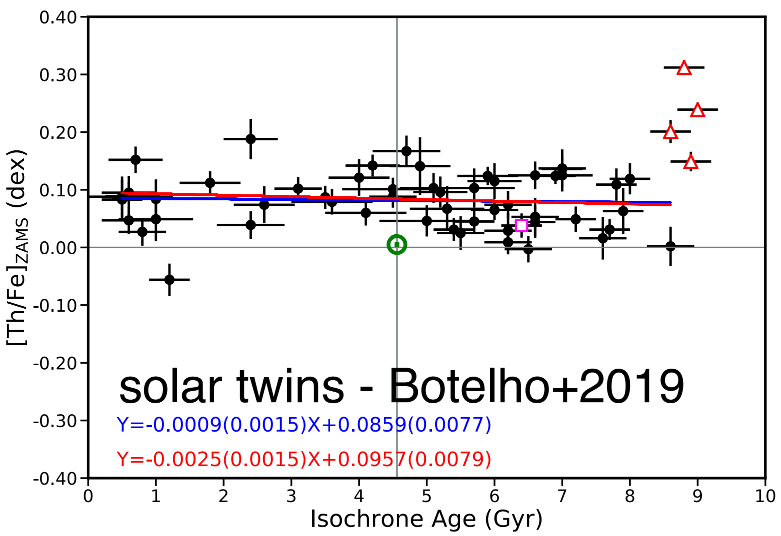


- The [Eu/H] range in the thin disk is about from -0.4 to +0.5, i.e. from 0.4x solar to 3x solar. Thick disk stars have even lower [Eu/H], down to about -0.5, i.e. ⅓ solar. Old planets around such old stars would have even less radiogenic heating because of radioactive decay of U and Th.
- The [Eu/Mg] range is from about -0.26 to +0.3 in the Battistin & Bensby2016 and Delgado Mena+2015 samples (Griffith, Johnson Weinberg 2019).
- Francis's model shows that Earth may have borderline Th abundance required for a permanent dynamo, if its Eu and Th abundance is solar or chondritic. Younger (older) thin disk stars have higher (lower) [Eu/Fe], so their younger (older) planets are more (less) likely to have higher radiogenic heat and dynamos.
- Geoneutrino data favors a higher Earth Th and U abundance than chondrites or the sun.

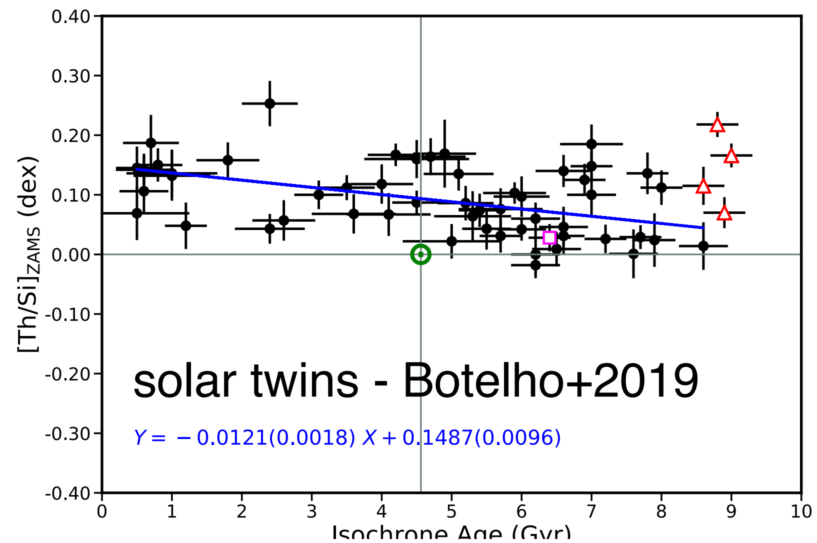
[Eu/Fe] and [Th/Fe]

- The sun is about 0.1 dex low in [Th/Fe] and [Th/Si] compared with solar twin stars with [Fe/H] ~ 0.
[Th/Eu]_ZAMS is flat => Eu traces Th (Botelho 2019). [Eu/Fe] is larger for [Fe/H] < 0 (Battistini&Bensby 2016).

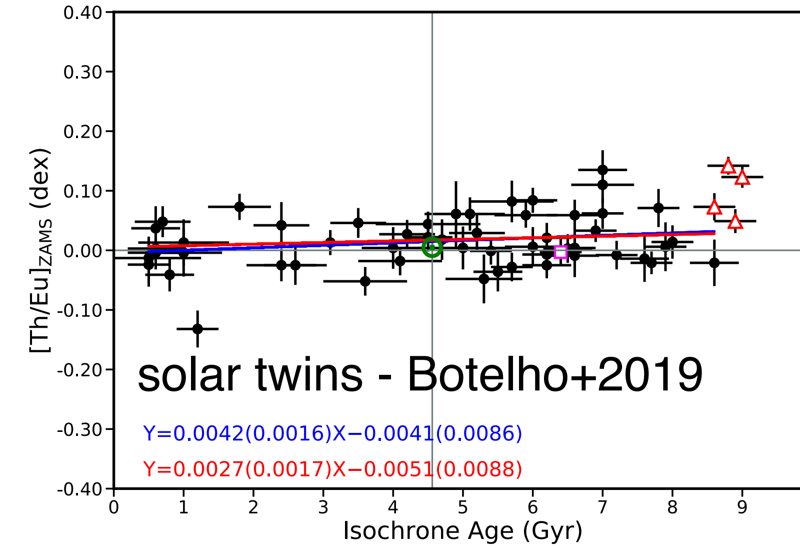
$[Th/Fe]_{ZAMS}$

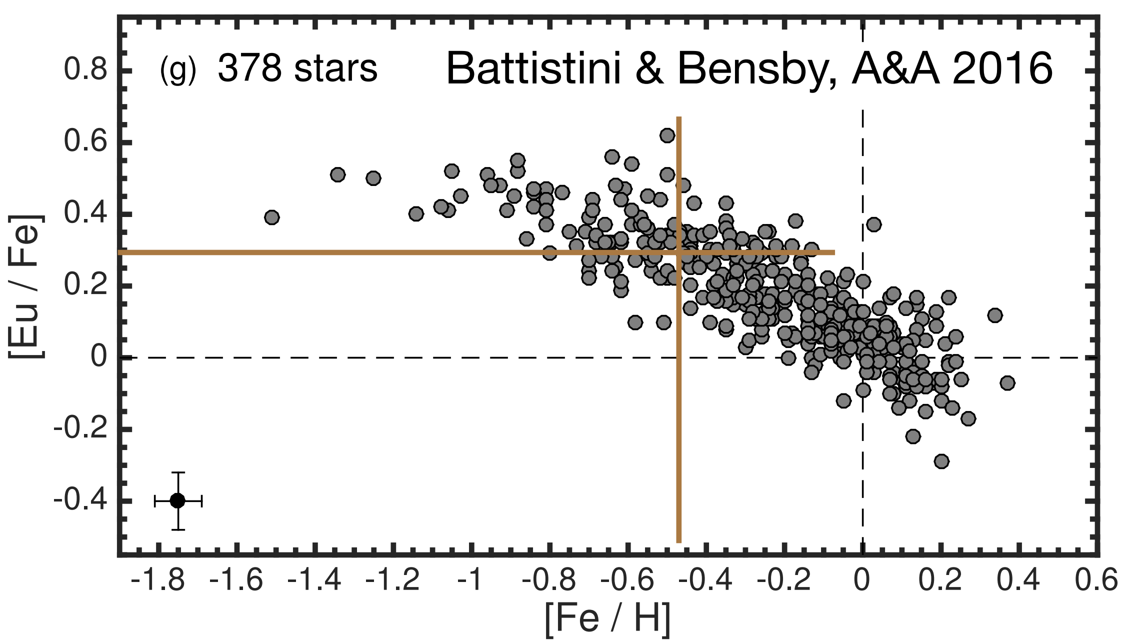


$[Th/Si]_{ZAMS}$



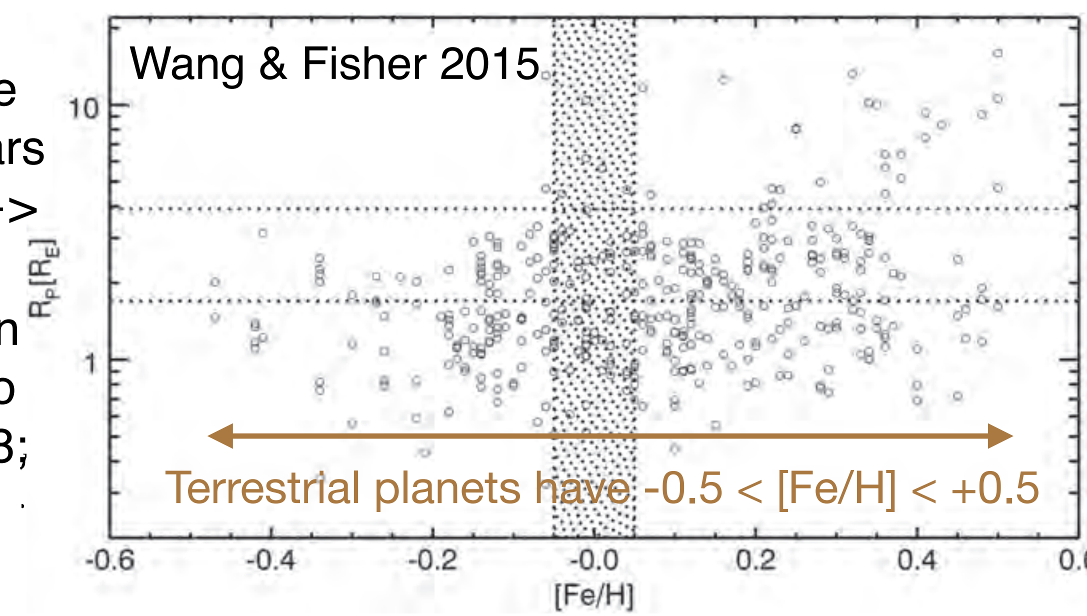
$[Th/Eu]_{ZAMS}$





- Terrestrial planets (R_P ≤ R_Earth) are observed around stars with [Fe/H] ≳ - 0.5 —>

<— for which median [Eu/Fe] ~ +0.25 (also Delgado Mena+2018; GALAH)



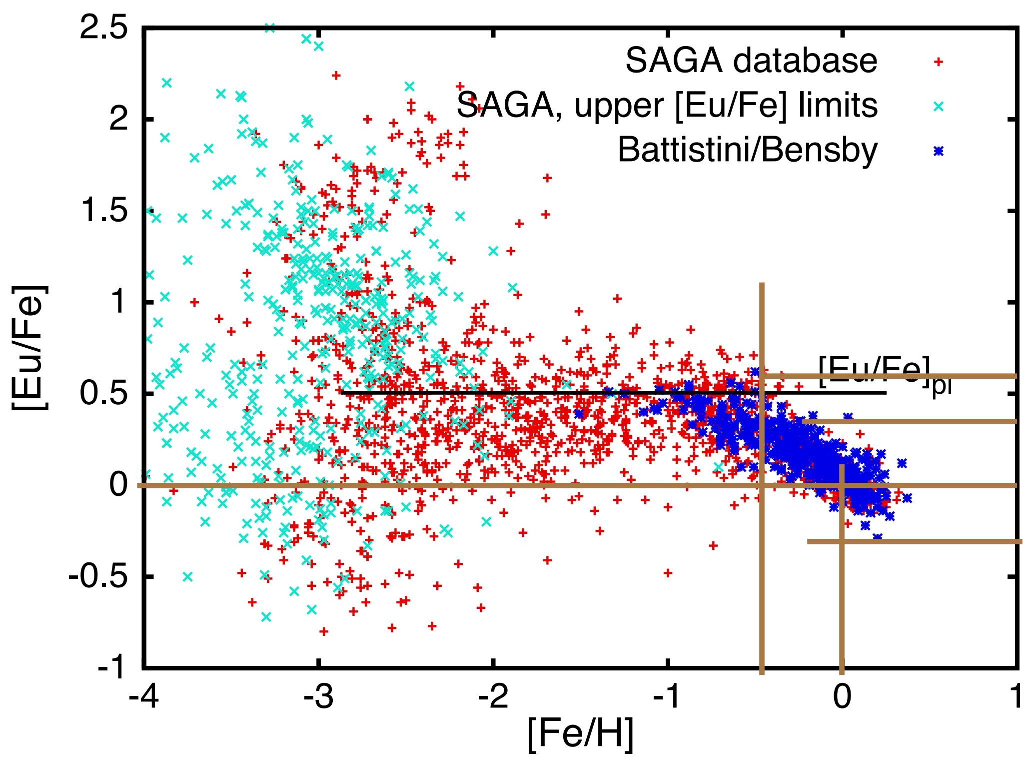
- The GALAH survey (LinAsplund+2019) of over 160,000 stars finds [Eu/Fe] ranging from < -0.25 to > +0.3 at the era of solar system formation (possibly a wider range than that), and for older thick disk stars a narrower spread in [Eu/Fe] from -0.1 to > +0.3, with [Fe/H] from -0.6 to +0.3. At all stellar ages, lower [Fe/H] correlates with higher [Eu/Fe].

The chemical evolution of r-process elements from neutron star mergers: the role of a 2-phase interstellar medium - Ralph A. Schönrich and David H. Weinberg - MNRAS 487, 580–594 (2019)

ABSTRACT Neutron star mergers (NM) are a plausible source of heavy r-process elements such as Europium, but previous chemical evolution models have either failed to reproduce the observed Europium trends for Milky Way thick disc stars (with [Fe/H] ≈ −1) or have done so only by adopting unrealistically short merger time-scales. Using analytic arguments and numerical simulations, we demonstrate that models with a single-phase interstellar medium (ISM) and metallicity-independent yields cannot reproduce observations showing [Eu/α] > 0 or [Eu/Fe] > [α/Fe] for α-elements such as Mg and Si. However, this problem is easily resolved if we allow for a 2-phase ISM, with hot-phase cooling times τ cool of the order of 1 Gyr and a larger fraction of NM yields injected directly into the cold star-forming phase relative to α-element yields from core-collapse supernovae (ccSNe). We find good agreement with observations in models with a cold phase injection ratio fc,NM/fc,ccSN of the order of 2, and a characteristic merger time-scale τNM = 150 Myr. We show that the observed supersolar [Eu/α] at intermediate metallicities implies that a significant fraction of Eu originates from NM or another source besides ccSNe, and that these non-ccSN yields are preferentially deposited in the star-forming phase of the ISM at early times.

We will argue in this paper that the essential ingredient for resolving this problem is proper accounting for enrichment into different phases of the ISM. While discussions of the ISM often distinguish three or more phases – e.g. cold, warm, and hot – for our purposes we need only distinguish (cold) gas that can immediately form stars from (hot) gas that must first cool on a ~ Gyr time-scale before entering the star-forming phase.

SAGA = Stellar Abundances for Galactic Archaeology - for low [Fe/H]



B&B A&A 2016 - Eu in 378 F & G dwarf stars in solar nbh

For [Fe/H] > -0.5 (for stars with planets), [Eu/Fe] range is -0.3 to +0.6, (½ to 4x solar). At [Fe/H] ~ 0 [Eu/Fe] range is -0.3 to +0.4 (½ to 2.5x solar)

7 CONCLUSIONS

We should take three main points from this analysis:

(i) Modelling the different phases of the interstellar medium (hot versus cold star-forming gas) is vital to understand chemical evolution on time-scales smaller than ∼1 Gyr.

(ii) In contrast to 1-phase chemical evolution models, we find that neutron star mergers as source of r-process elements with reasonable DTDs (delay times of the order of 100 Myr) can explain the observed abundance patterns, provided that the fraction of NM yields delivered directly to the cold star-forming phase of the ISM is higher than that of ccSN yields.

(iii) The only other significant sources of r-process elements are (possibly) ccSNe, but we can only explain the [Eu/Si] > 0 and [Eu/Mg] > 0 values in the thick disc if there is a source of r-process elements that differs from a constant ccSN contribution. This implies a significant source of r-process elements besides ccSNe – most naturally neutron star mergers.

The main problem is not as much explaining r-process abundances at the very metal-poor end, where stochastic chemical evolution and the superposition of stellar populations from different accreted dwarf galaxies complicate the picture (and provide freedom in parameter choice). Instead, the challenge is the relatively high-metallicity edge of the high [Eu/Fe] sequence, near the 'knee' of the [Mg/Fe] versus [Fe/H] distribution.

- Most planets with [Fe/H] < 0 will therefore have higher [Eu/Fe] than Earth, but whether they are more likely to have a dynamo-generated magnetic field, convective mantle, and possibly plate tectonics may depend more on [Eu/Si] and [Eu/Mg]. The dependence on [Fe/H] of [Eu/Fe] is much like that of [O/Fe], [Mg/Fe], and [Si/Fe] — all increase as [Fe/H] decreases below 0 (Delgado Mena+2019 HARPS-GTO sample: > 1000 FGK stars with R ~ 115000 spectra).

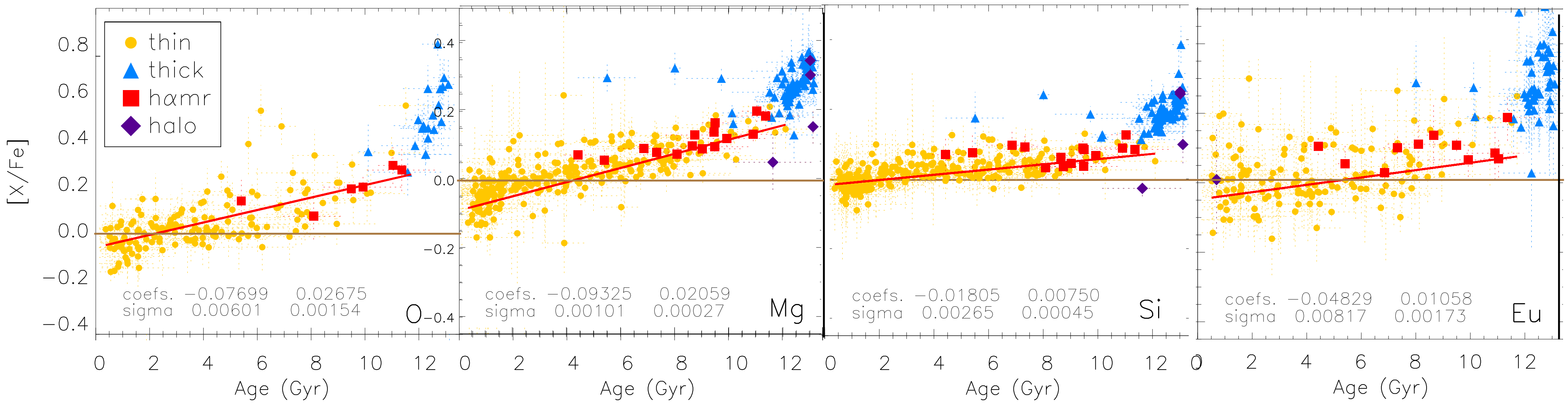


Fig. 7. [X/Fe] as a function of age for stars with an error in age smaller than 1.5 Gyr. The different stellar populations are depicted with different colors and symbols as explained in the legend. We note the different size of y axis for oxygen with respect to the rest of elements. The red line is a weighted linear fit to the thin disk stars to guide the eye on the general behavior of the trends. The *coefs.* values in each panel are the abscissa origin and the slope of the fit, respectively, together with the error (σ) of each coefficient.

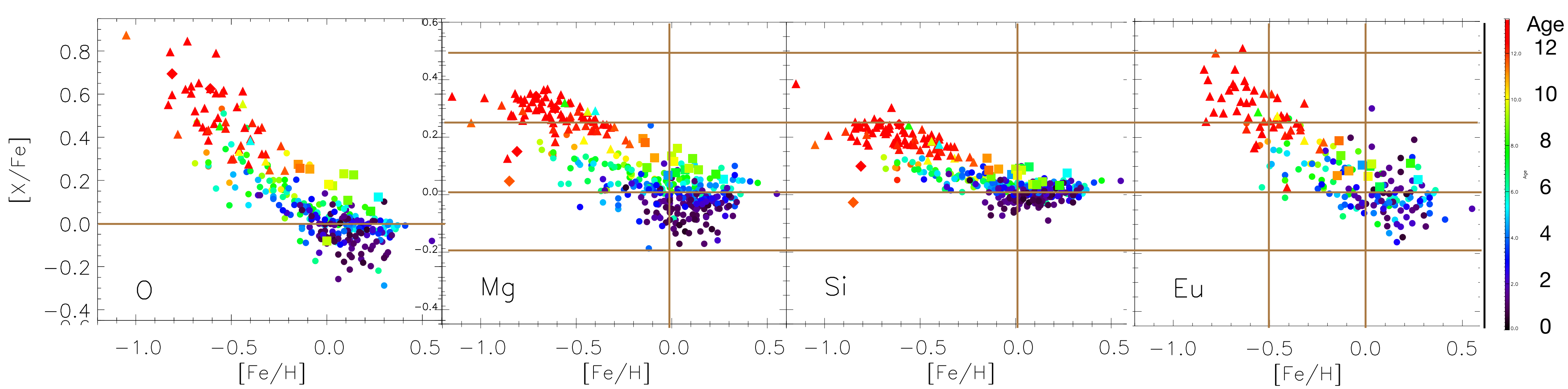


Fig. 8. [X/Fe] as a function of [Fe/H] for stars with an error in age smaller than 1.5 Gyr. We note the different size of *y* axis for oxygen with respect to the rest of elements. The circles, triangles, squares and diamonds are the stars from the thin disk, thick disk, hαmr and halo.

- Whether planets are more likely to have a dynamo-generated magnetic field, convective mantle, and possibly plate tectonics may depend more on [Eu/Si] and [Eu/Mg].

- The [Eu/Mg] range is from about -0.26 to +0.3 in the Battistini & Bensby 2016 and Delgado Mena+2015 samples (Griffith, Johnson, & Weinberg 2019). The solar values look pretty typical.

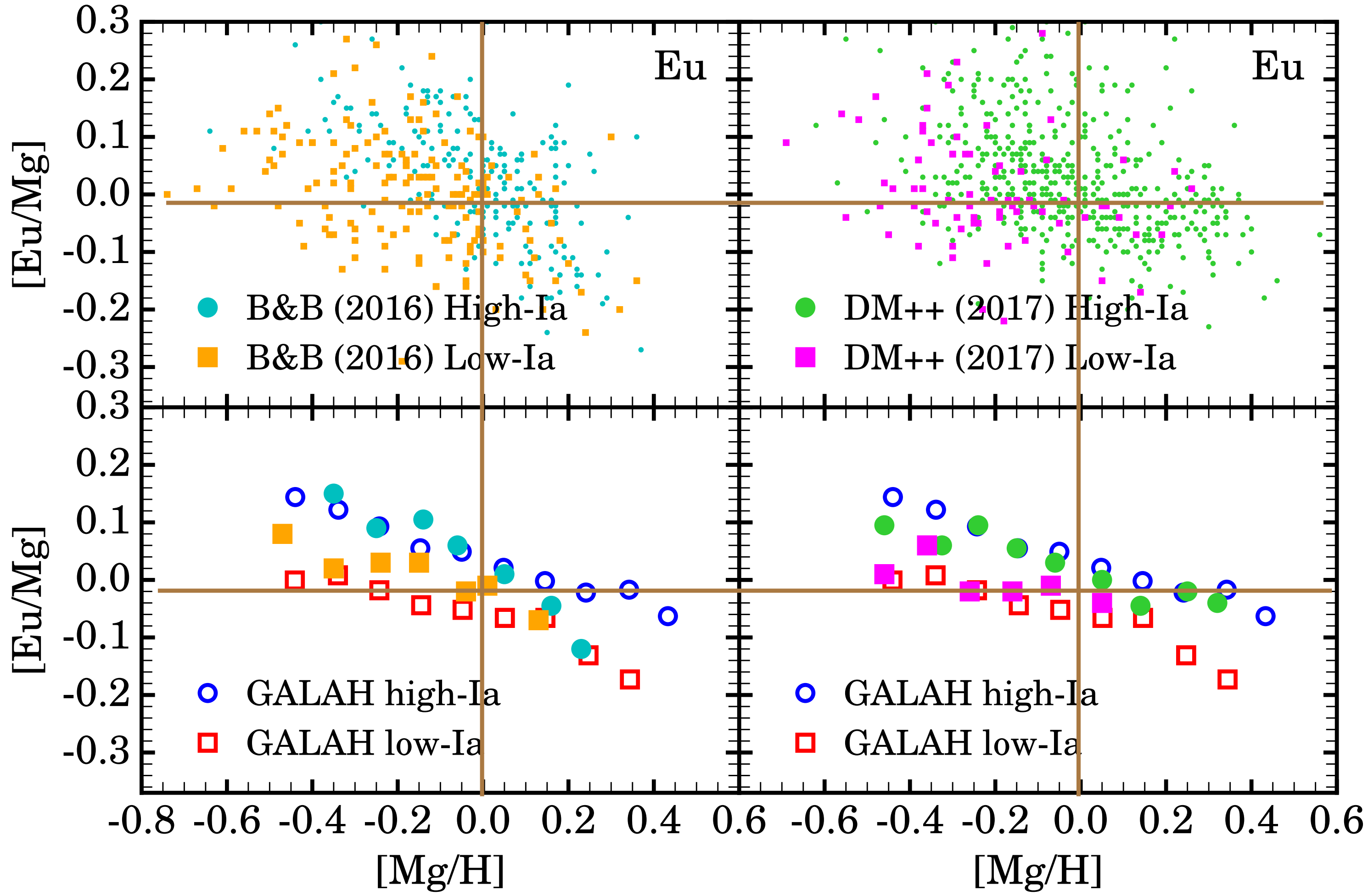
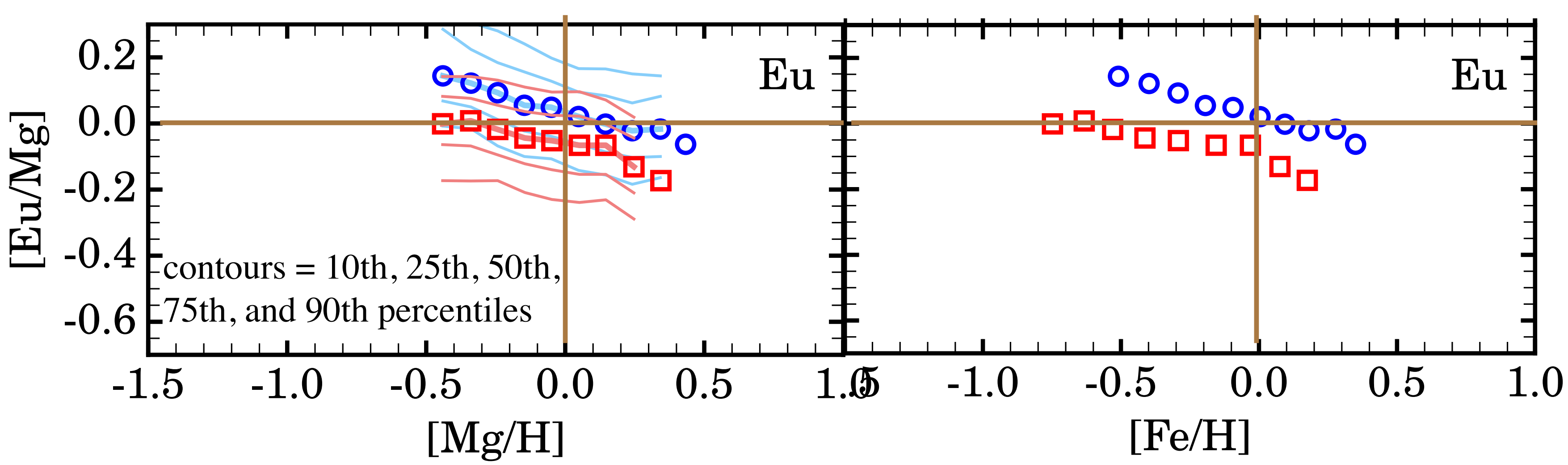
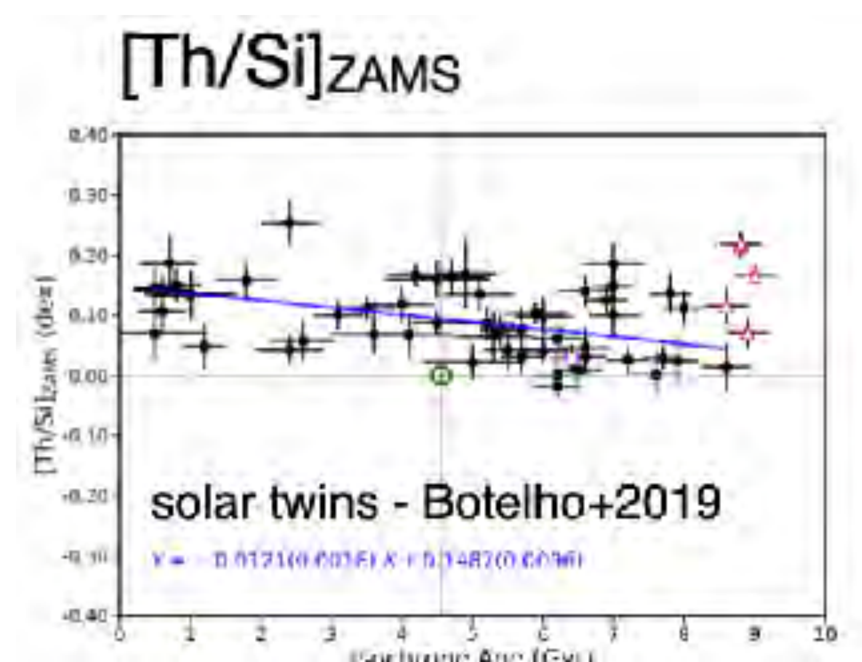


Figure 9. Top left: distribution of Eu abundances in 378 dwarf stars from Battistini & Bensby (2016). Stars classified as high-Ia and low-Ia are colored teal and orange, respectively. Top right: distribution of Eu abundances in 570 FGK stars from Delgado Mena et al. (2017) with green high-Ia and magenta low-Ia stars. Bottom left and right: median abundances of the high-Ia (filled teal/green circles) and low-Ia (filled orange/magenta squares) populations. GALAH median trends (bottom left panel of Figure 8) are added for comparison.



GALAH and APOGEE data from Griffith, Johnson, Weinberg 2019. The 10 to 90 percentile range in [Eu/Mg] is -0.3 to + 0.3 for [Mg/H] > -0.3



- Francis's model shows that Earth may have borderline Th & U abundance required for a permanent dynamo, if its Eu and Th abundance follows that of the sun and chondrites. Younger (older) thin disk stars have higher (lower) [Eu/Fe], so their younger (older) planets are more (less) likely to have higher radiogenic heat and dynamos.

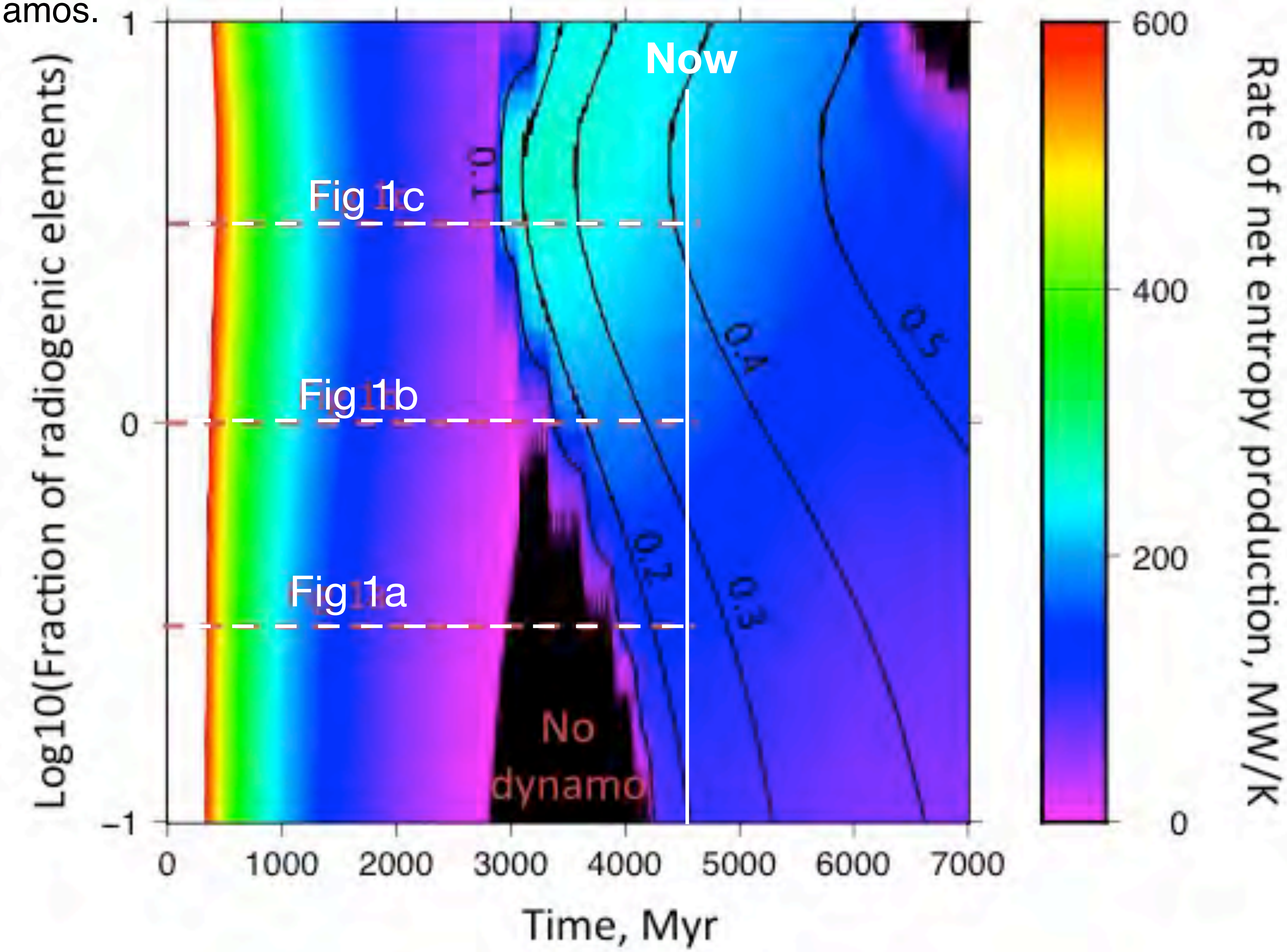


Figure 2. Sensitivity of evolution of core parameters to different radiogenic element concentrations. The colors show the rate of net entropy production, with black indicating a negative value (no dynamo). The contours denote the inner core radius relative to the total core radius. The three dashed red lines show the trajectories of the three evolution scenarios shown in Fig 1. I've added a vertical white line at 4540 Myr, labeled "Now" and changed the red dashed lines to white, for visibility.

- Borexino geoneutrino data favors a higher Earth Th and U abundance than chondrites or the sun.

Borexino Radiogenic Heat Flux and Convective Urey Ratio vs. BSE Models

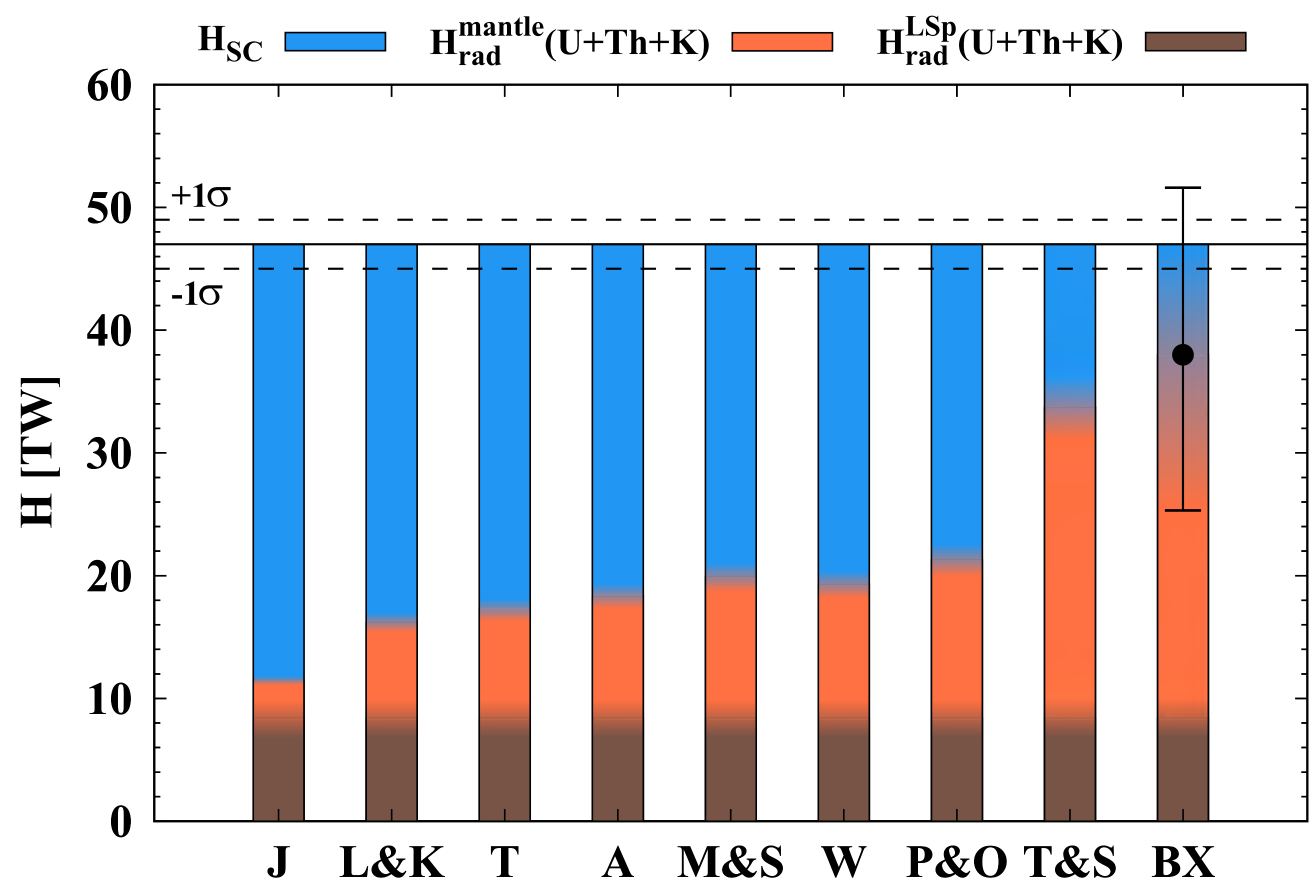


FIG. 55. Decomposition of the Earth's total surface heat flux $H_{tot} = (47 \pm 2)$ TW (horizontal black lines) into its three major contributions—lithospheric (brown) and mantle (orange) radiogenic heat H_{rad}^{LSp} and H_{rad}^{mantle}, respectively, and secular cooling H_{SC} (blue). The labels on the x axis identify different BSE models (Table VII), while the last bar labeled BX represents the Borexino measurement. The lithospheric contribution $H_{rad}^{LSp} = 8.1^{+1.9}_{-1.4}$ TW (Table V) is the same for all bars. The amount of HPEs predicted by BSE models determines the mantle radiogenic heat (Table VII), while for Borexino the value of $30.0^{+13.5}_{-12.7}$ TW is inferred from the extracted mantle signal. The difference between H_{tot} and the respective total radiogenic heat is assigned to the heat from secular cooling of the Earth.

$$UR_{CV} = \frac{H_{rad} - H_{rad}^{CC}}{H_{tot} - H_{rad}^{CC}},$$

where H^{CC} is the radiogenic heat produced in the continental crust.

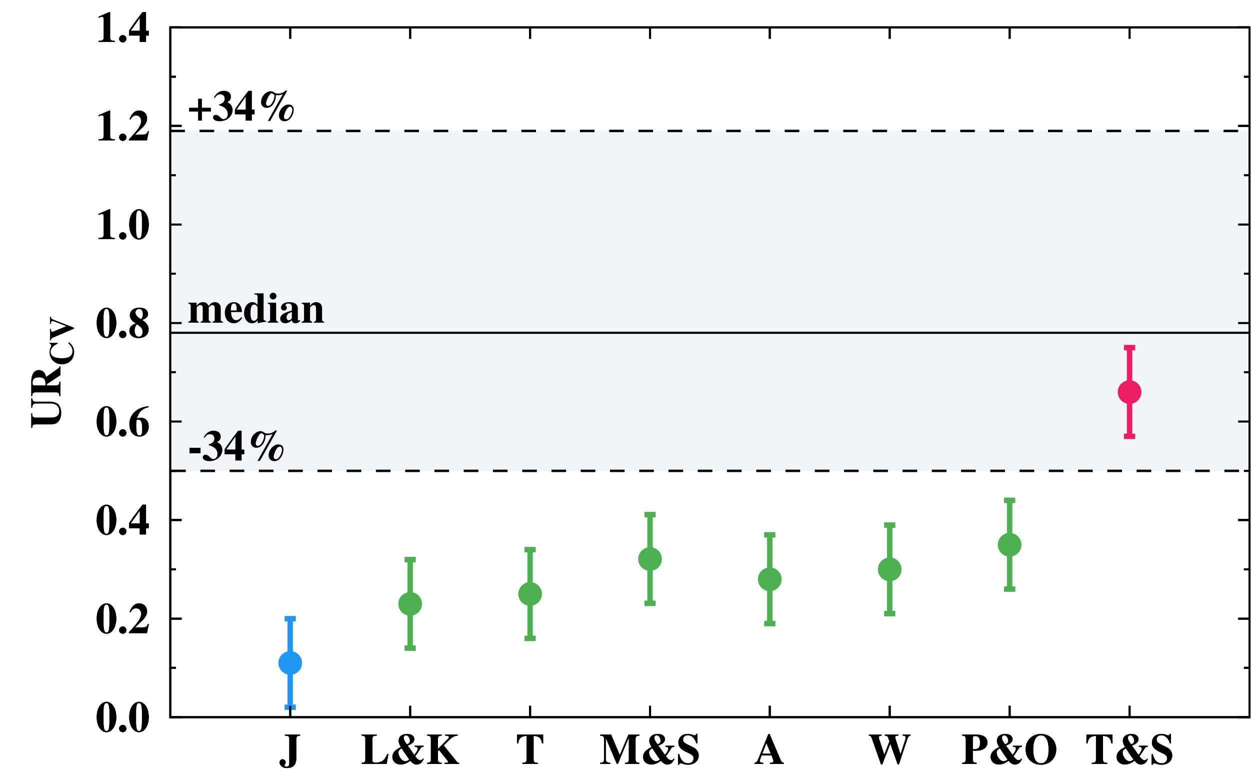


FIG. 56. Comparison of Borexino constraints (horizontal band) with predictions of the BSE models (points with $\pm 3\sigma$ error bars, Table VII) for the convective Urey ratio UR_{CV} [Eq. (6)], assuming the total heat flux $H_{tot} = (47 \pm 2)$ TW and the radiogenic heat of the continental crust $H_{rad}^{CC} = 6.8^{+1.4}_{-1.1}$ TW (Table V). The blue, green, and red colors represent different BSE models (CC, GC, and GD; Table VII, respectively).

- J: Javoy at al., 2010
- L&K: Lyubetskaya and Korenaga, 2007
- T: Taylor, 1980
- A: Anderson, 2007
- M&S: Mc Donough and Sun, 1995
- W: Wang, 2018
- P&O: Palme and O'Neil, 2003
- T&S: Turcotte and Schubert, 2002

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On the Distribution and Variation of Radioactive Heat Producing Elements Within Meteorites, the Earth, and Planets

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Some key excerpts: The balance between contemporaneous heat production, and total heat loss, has previously been expressed in terms of the Urey ratio, which is defined as the ratio of internal heat generation, to total system heat loss (Christensen 1985; Lenardic et al. 2011). The most recent estimate for Earth's heat loss is 47 ± 1 TW (Davies and Davies 2010), and for its radiogenic heat production, about 21.5 TW, assuming a geochemical model for the Bulk Silicate Earth (BSE) based on chondrite meteorites (O'Neill 2016). This value gives a planetary Urey ratio of 0.45, implying that less than half of Earth's heat comes from contemporaneous heat production. Non-chondritic BSE models for the concentrations of the HPEs predict even lower values for the Urey ratio (O'Neill and Palme 2008; Jackson and Jellinek 2013).

Both U and Th are "Refractory Lithophile Elements" (RLEs), which comprise a group of 28 elements that are calculated to condense from the canonical solar nebula at higher temperatures than the main constituents of the rocky planets (i.e. Mg, Si (and associated O) and Fe, the latter initially condensing as metal). The RLEs occur in approximately the same ratios to each other in most undifferentiated meteorites ("chondrites") and, within uncertainty, the solar composition. This observation is assumed to also apply to the Bulk Silicate Earth (known as the "chondritic model" of the Earth's composition), enabling its concentrations of U and Th to be estimated. … By contrast K is not a RLE, but behaves cosmochemically as a moderately volatile element. Therefore, its abundance in the Bulk Silicate Earth is not constrained by the chondritic model, but must be estimated empirically.

Gando et al. (2011) combined results from Borexino and KamLAND to estimate that mantle ^{232}Th and ^{238}U contribute 20.0 +8.8/-8.6 TW to Earth's heat flux. **Results from Borexino alone have tended towards higher values, and recently, the Borexino team (Agostini et al. 2019) estimated the total radiogenic heat of the Earth at 38.2 +13:6/-12:7 TW (confidence intervals are ±34%), and the total mantle heat contribution of 24.6 TW +11.1/-10.4 from ^{238}U and ^{232}Th. Therefore, even at the 95% confidence interval this estimate would only just be compatible with the largest radiogenic heat production values deduced from geochemistry.** We can convert these contributions to mantle concentrations as follows. If we assume the mass of the mantle is 4×10^{24} kg, then a flux of 24.6 TW gives us a mantle heat production from these isotopes of 6.15×10^{-12} W/kg (range of $3.55–8.93 \times 10^{-12}$ W/kg). … **Although argued by Agostini et al. (2019) to be marginally consistent with a geodynamic model for mantle heat generation, these values are not consistent with published chondritic or non-chondritic BSE compositions (Table 4). In particular, these results exclude the enstatite-chondrite or non-chondritic Earth models at a high degree of confidence and, thus, more work is required before geoneutrino constraints can be regarded as reliable.**