Pristine Th in solar twins: habitability in rocky planets

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to look for planets around solar twins

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Pristine Th in solar twins:
habitability in rocky planets

- ^{232}**Th**: unstable isotope of a *r*-process element
- Rocky planets
  - connection 'internal energy budget' – 'habitability'
- Sample of solar twins
- Reading Th abundance from a multispecies blend
- $[Th/X]_{obs}$ transformation to $[Th/X]_{ZAMS}$ (X: H, Fe and Si)
  - two corrections: radioactive decay & *gravitational settling*
- $[Th/X]_{ZAMS}$ *vs*. [Fe/H] and stellar age
- **Conclusions**

Botelho, Milone, Meléndez et al. 2019 MNRAS 482, p. 1690

Pristine Th in solar twins: **Thorium**

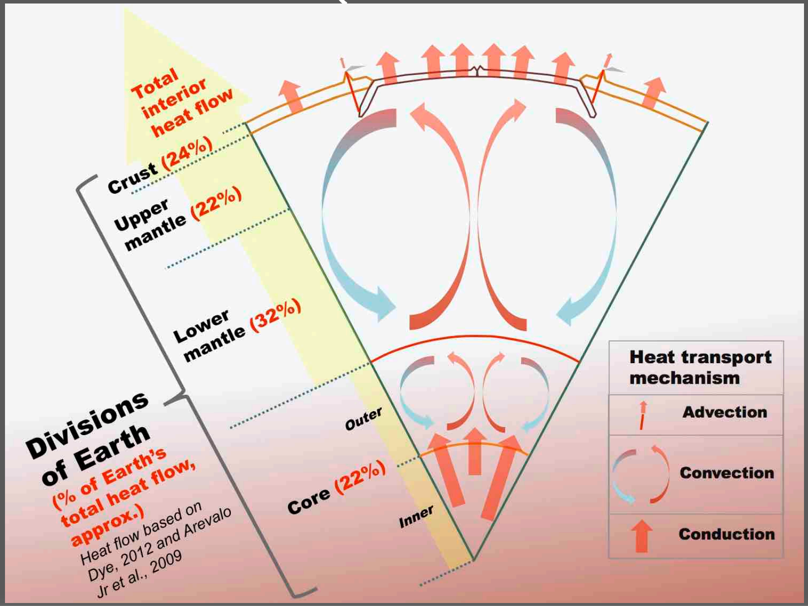
- Th is a *r*-process element synthetized in core collapse supernovae and mergers of compact objects
  - neutron star – neutron star
  - neutron star – black hole

- ^{232}Th: its most abundant unstable isotope (99.98% in SS)
  - Half-life of 14.05 Gyr !
  - Th Series/Cascade down to ^{208}Pb: 42.6 Mev!
  - Th in G-dwarfs by Butcher (1987) ➔ Galaxy's age (cosmochronology)

Pristine Th in solar twins:
rocky planets &
connection 'internal energy budget' – 'habitability'

- structure 🡐 formation process & internal heat
- internal heat 🡐 secular cooling of core-mantle & radioactive decay of Th-U-K isotopes in the core-mantle over long periods of time (Huang et al. 2013, for Earth)
  - Earth as a geologically active rocky planet: ~43% radiogenic of the current total flow of 47 TW in the surface

(<surface flux> ~ 92 mW/m^2 << 1361 W/m^2, solar constant)



crust: "rigid" rocks

upper mantle: "rigid"/plastic silicates, ~1000 K

lower mantle: Mg-Si oxides, ~3000 K

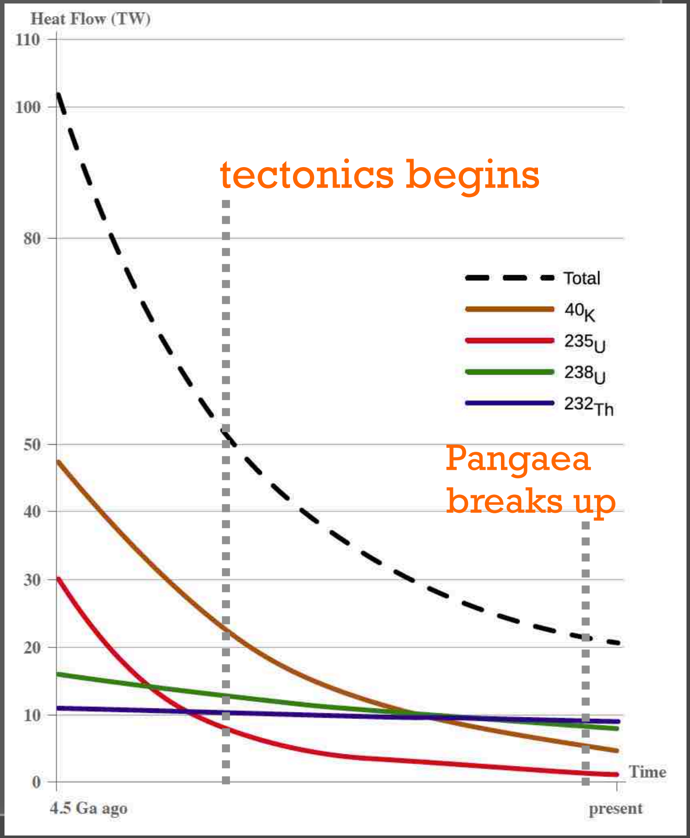
outer core: plastic alloy of Fe-Ni-S-(O), ~5000 K

inner core: rigid alloy of Fe-Ni-S-(O) under crystallization, ~10000 K

Pristine Th in solar twins: Earth

- mantle thickness ← Si, Mg & O abundances (McDonough 2003)
- mantle convection ← pristine abundances of ^{232}Th, ^{238}U, ^{40}K (16:4:1)
- plate tectonics → geological Carbon cycle (CO_2) → atmospheric greenhouse effect → life emergence and evolution (Walker et al. 1981, Misra et al. 2015)
  - $\log(Th)_{Earth} = \log(Th)_{\odot}$ + 0.04-0.11 dex: +10-29%
  - Earth has ≈ 80% of its initial Th
  - (^{232}Th, ^{238}U, ^{40}K, ^{235}U) =

(%-$\tau_{1/2}$: 99.98–14Gyr, 99.3–4.5Gyr, 0.01–1.2Gyr, 0.7–1Gyr)



Pristine Th in solar twins: *questions arise*

- What is the evolution of Th abundance in the ISM at the solar neighbourhood ?
  - Why do not precisely derive the pristine Th abundance in solar twins spanning different ages ?
- Is the Sun deficient or enhanced in Th in comparison with solar twins ? (Unterborn+2015 measured Sun as deficient against just 10 twins)
- What would the internal energy budget be in potential rocky planets unveiled by the Th content in possible hosting-planet solar twins ?

Pristine Th in solar twins:
the sample

- 67 solar twins: ESO large observing program, led by Jorge Meléndez, to hunt for planets around solar twins ($d \leq 94$ pc)
- photospheric parameters, abundances of *n*-elements, masses and isochrone ages (Spina et al. 2018)
  - errors in T_{eff}, log *g*, [Fe/H], ξ : 4 K, 0.012, 0.004 *dex*, 0.011 *km/s*
  - 0.4 Gyr as typical error in age
  - Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd and Dy
- other elements (Bedell et al. 2018)
  - C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Cu and Zn
- V_{macro} & v.sin(i) (dos Santos et al. 2016)
- 53 twins:

$-0.126 \leq [Fe/H] \leq +0.132$, $0.96 \leq m \leq 1.08\ M_{\odot}$ & $0.5 \leq age \leq 8.6$ Gyr

Pristine Th in solar twins:
spectral synthesis of a multispecies blend

- HARPS spectra (R=115,000), FWHM ≅ 0.035 Å at the blend
- HOMOGENEOUS ANALYSIS -x- Spina+18, Bedell+18 & dos Santos+16
- MOOG handled through a Python script
- Fe-Ni-Mn-**Th**-Co-CN-Ce-CH 4019Å multispecies blend
- chi^2 minimization
  - to estimate the error in abundance directly from the spectral noise
- VALD atomic lines + Kurucz molecular lines + Castelli & Kurucz (2004) model atmospheres (ATLAS9)
- differential chemical analysis to Sun
- *gf* solar calibration
- 53 stars: σ [Th/H] ≅ σ [Th/Fe], 0.012-0.049 dex, <0.025 dex>
  - error propagation of star parameters included

Botelho et al. (2019)

Pristine Th in solar twins:
tiny abundance of Th in the Sun!!!

Nearly **1 atom of Fe or Si** for each **30 thousand atoms of H**

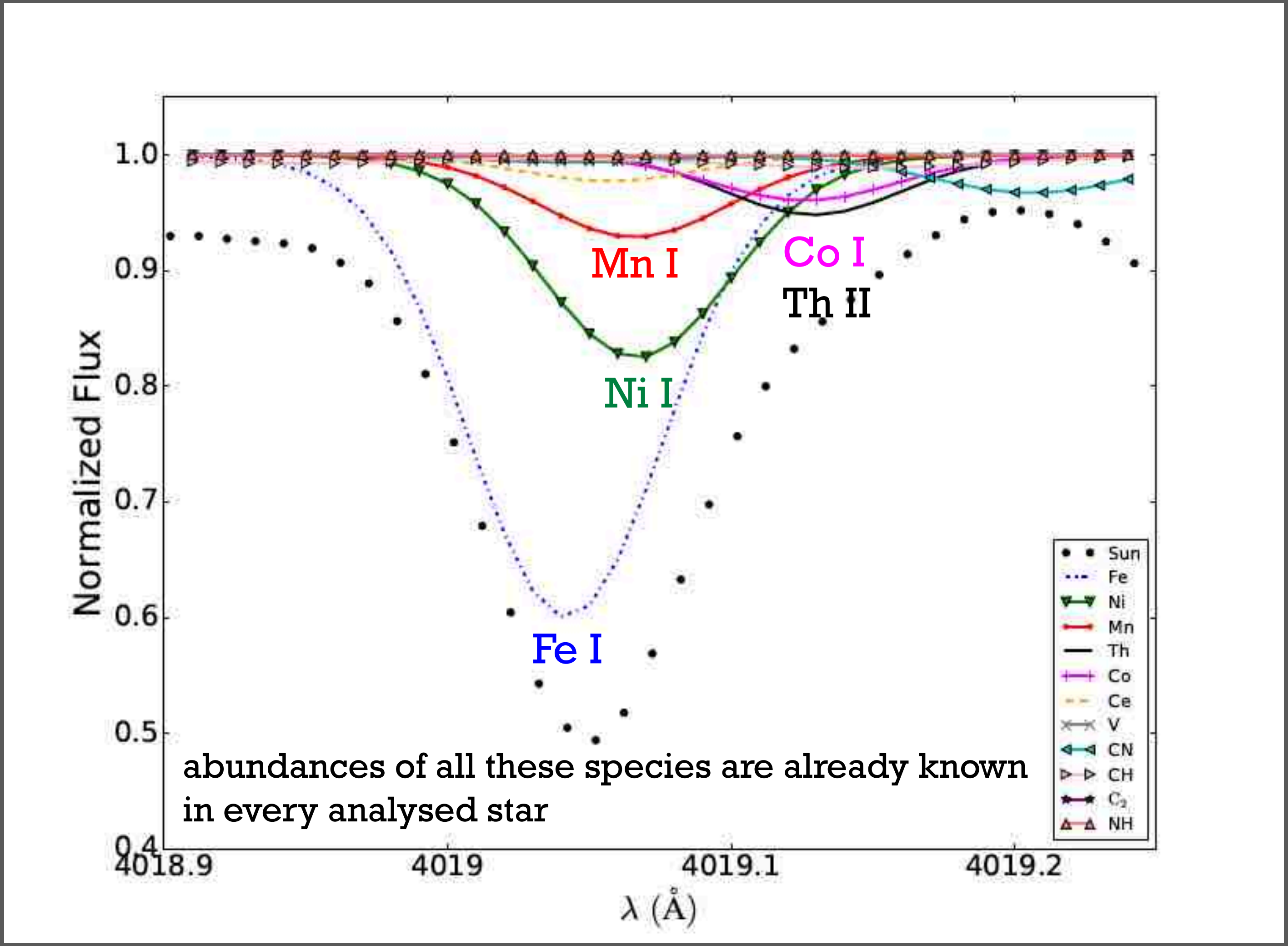
&

1 atom of Th for about each **1 trillion atoms of H**

+ there are two spectral lines of ^{232}Th in the optical range
(one 4.5 weaker than another in a complex blend)

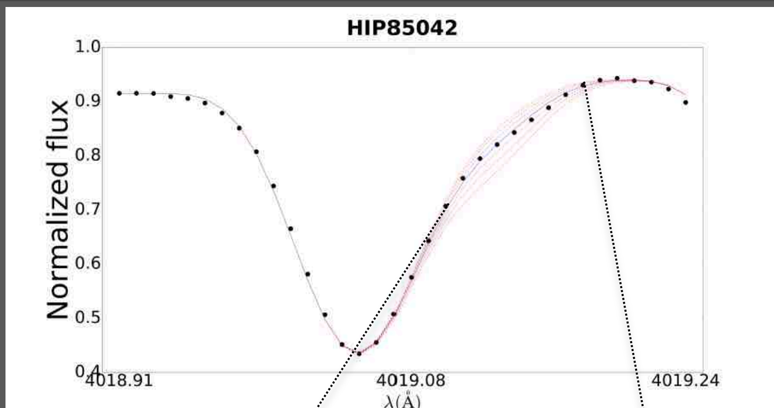
→ a real CHALLENGE,
but not impossible at high-resolution !!!

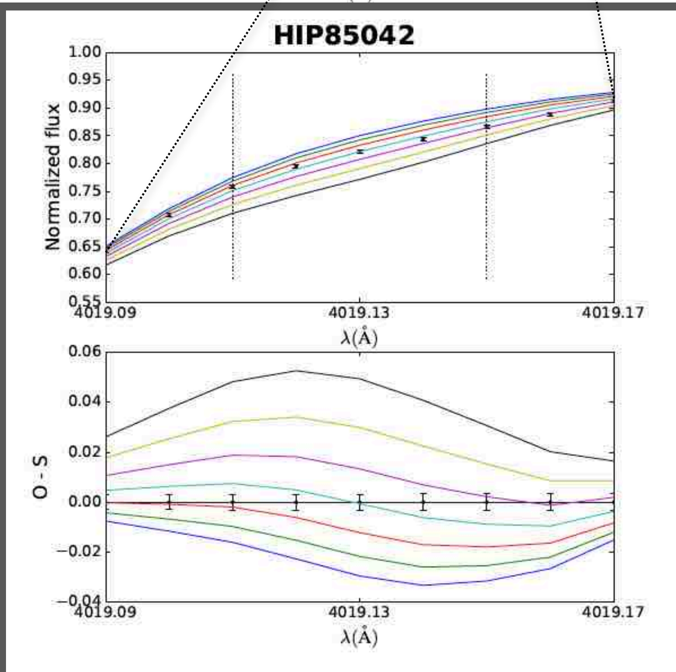
Pristine Th in solar twins:
spectral synthesis of a multispecies blend



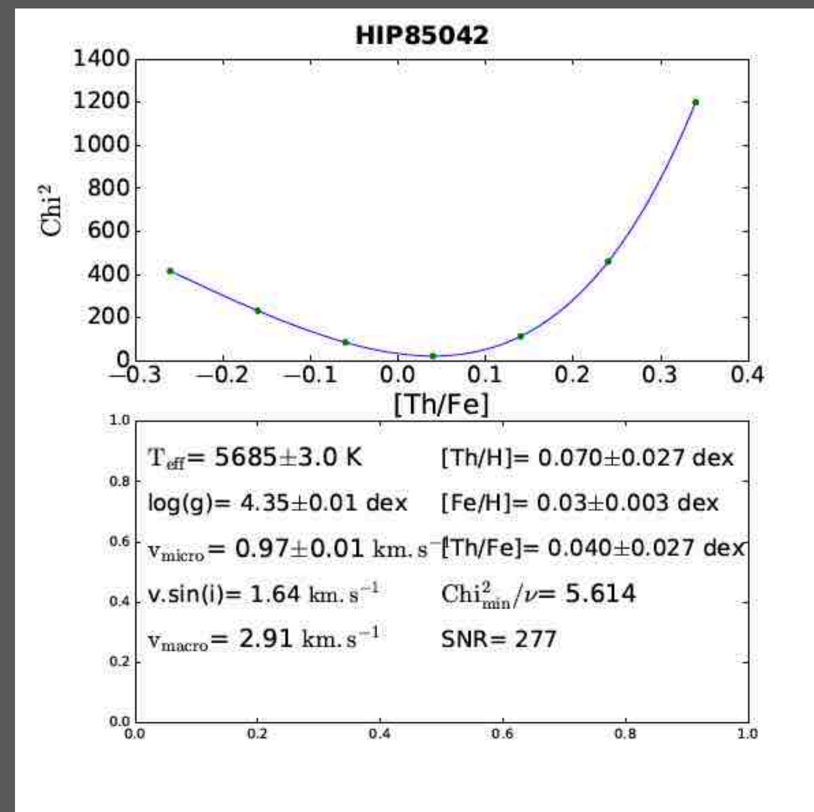
Botelho et al. (2019)

Pristine Th in solar twins:
spectral synthesis of a multispecies blend





$$\chi^2 = \sum_{i\ 1,5} (O_i - S_i)^2 / \sigma(O_i)^2$$



Botelho et al. (2019)

Pristine Th in solar twins: *results*

[Th/X] & [Th/Fe] for 53 + 5 solar twins (58 stars in total)

53 thin disc (9 stars were excluded)
+ 4 α–rich old
+ 1 anomalously rich in *s*-elements

53 thin disc solar twins: observed abundances of Th

- -0.117≤ [Th/H] ≤ +0.257 dex (76% to 181% of solar value)
- -0.085 ≤ [Th/Fe] ≤ +0.235 dex (82% to 172% of solar ratio)
- σ [Th/H] ≅ σ [Th/Fe]: 0.025 dex as average value

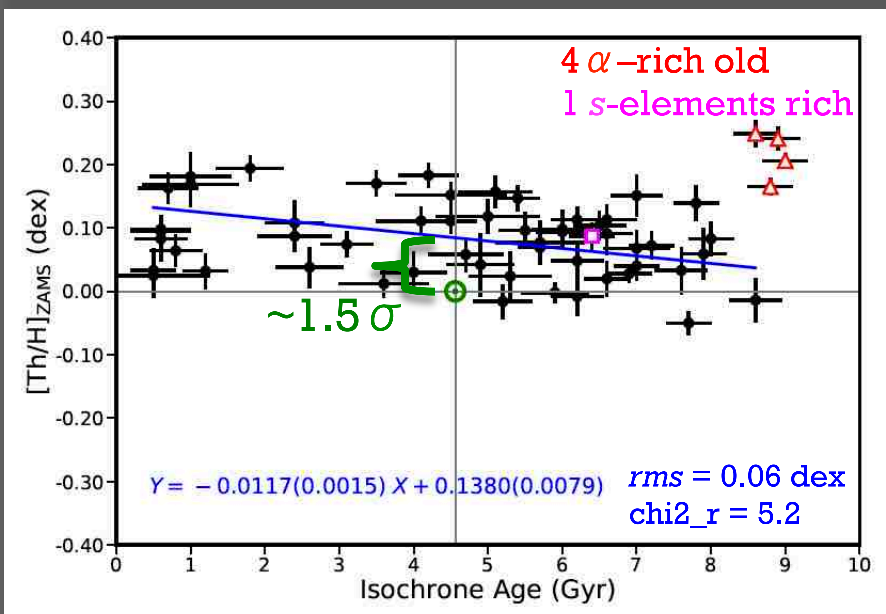
$$Error_{[X/Fe]} = \sqrt{(\Delta[X/Fe]_{T_{eff}})^2 + (\Delta[X/Fe]_{\log g})^2 + (\Delta[X/Fe]_{v_{mic}})^2 + (\Delta[X/Fe]_{[Fe/H]})^2 + (\Delta[X/Fe]_{x}}$$

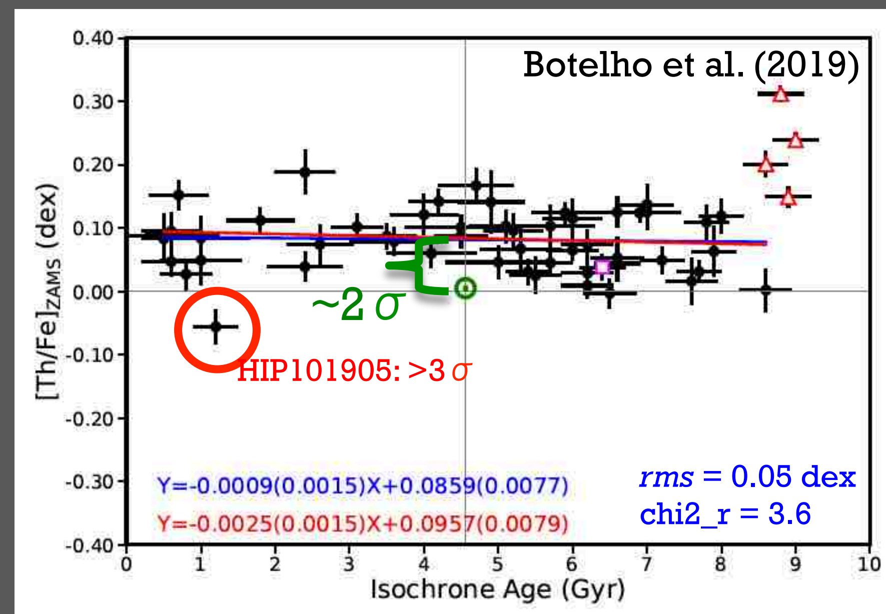
Botelho et al. (2019)

[Th/Fe] = [Th/H] – [Fe/H] = log(n(Th)/n(Fe))$_*$ - log(n(Th)/n(Fe))$_\odot$

Pristine Th in solar twins:
Th decay-corrected abundance (ZAMS)

- $[Th/H]_{ZAMS}$ *vs*. isochrone age & $[Th/Fe]_{ZAMS}$ *vs*. isochrone age





time

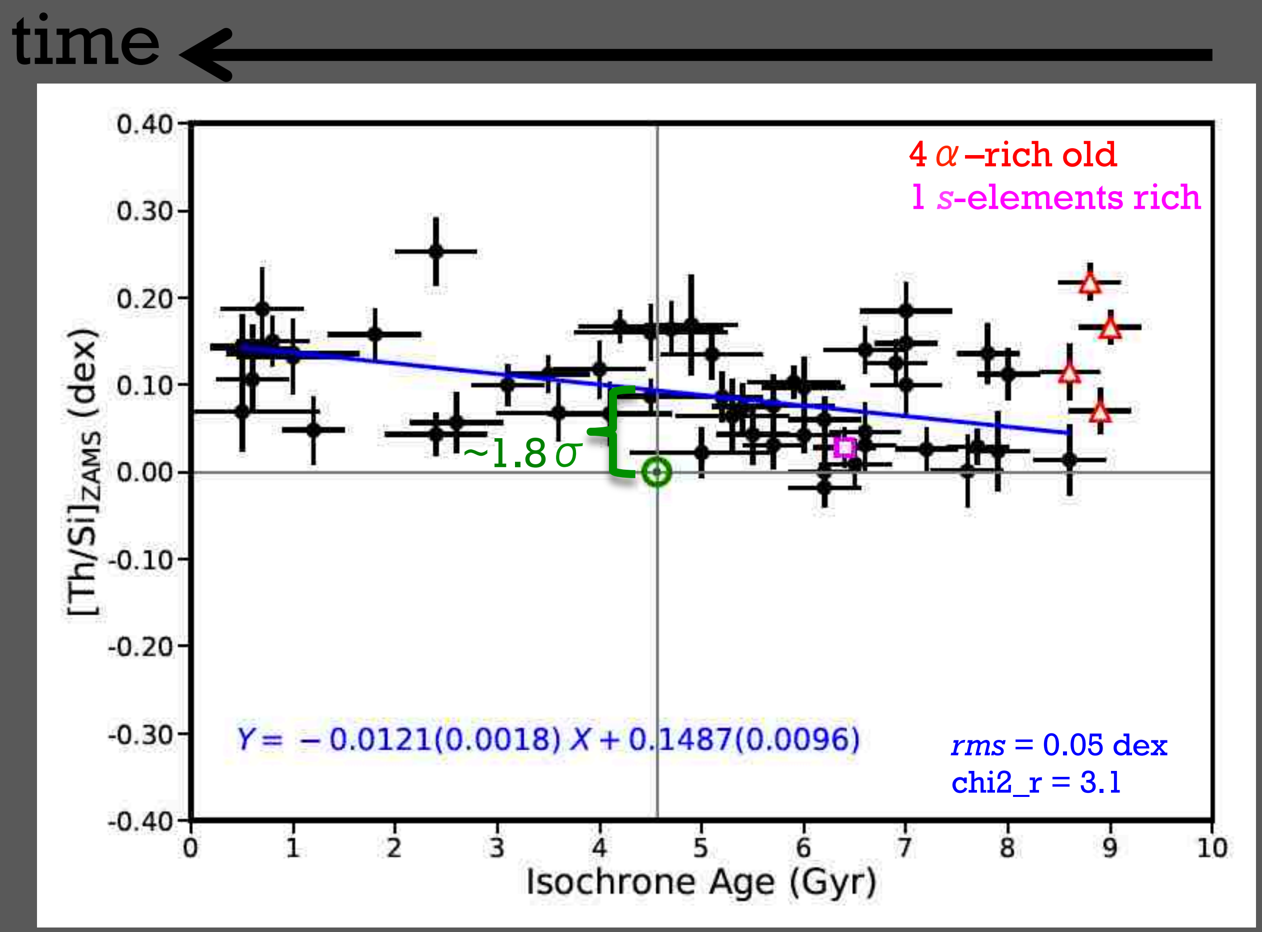
time

$[Th/H]_{ZAMS} = \log(n(Th)/n(H))_{*,ZAMS} - \log(n(Th)/n(H))_{\odot,ZAMS}$

$[Th/Fe]_{ZAMS} = \log(n(Th)/n(Fe))_{*,ZAMS} - \log(n(Th)/n(Fe))_{\odot,ZAMS}$

Th in solar twins:
results – ZAMS abundance

- **$[Th/Si]_{ZAMS}$ *vs*. isochrone age**

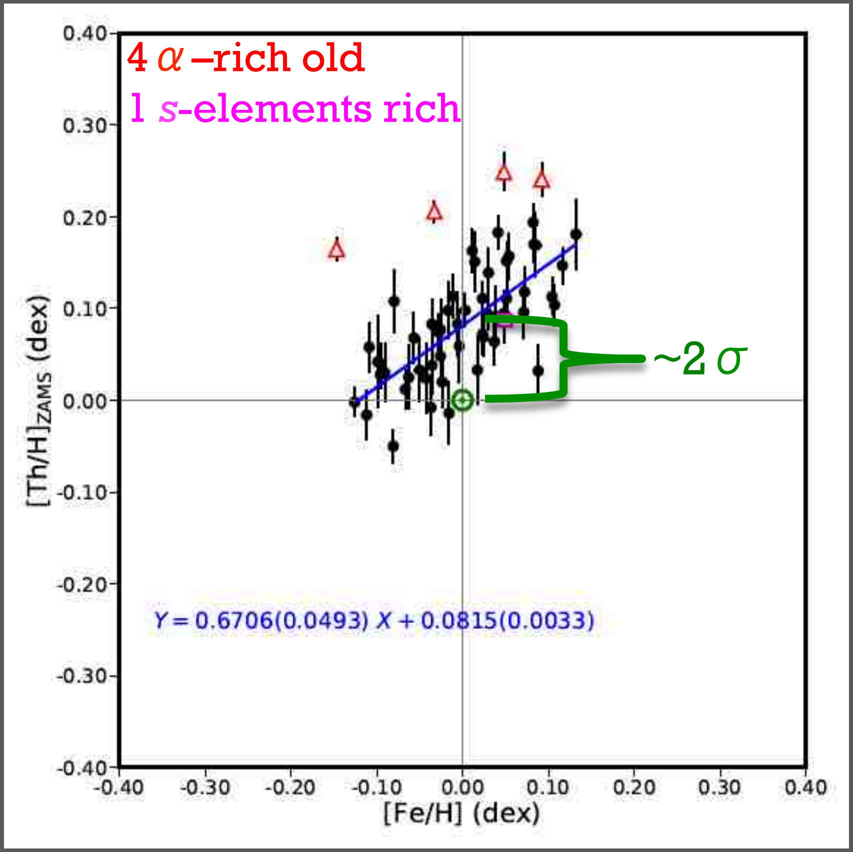


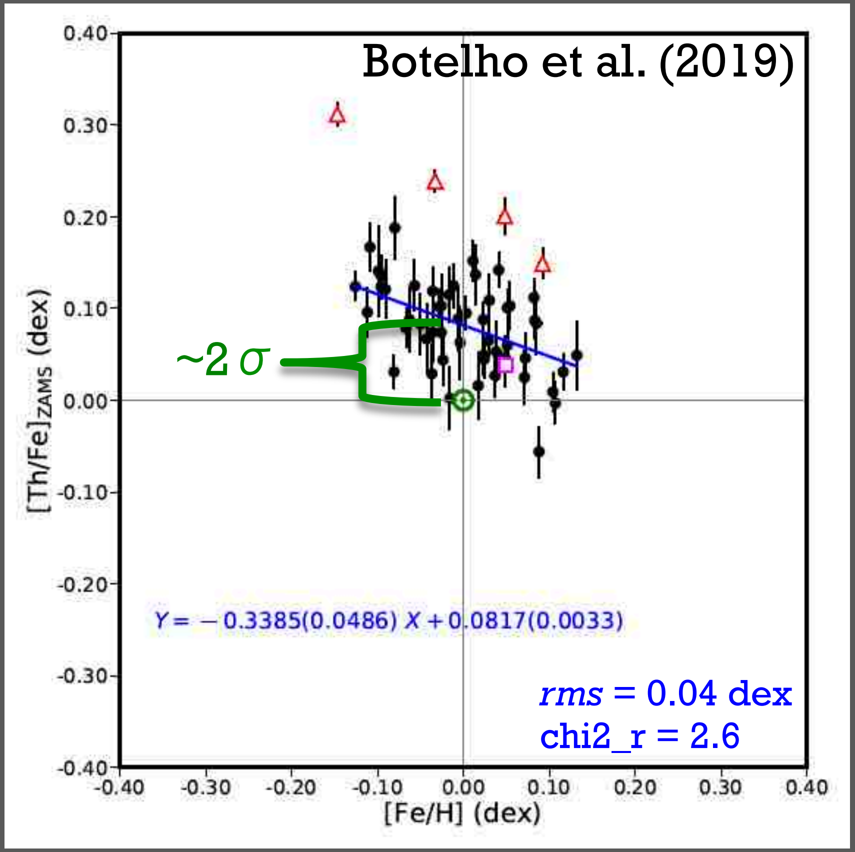
Botelho et al. (2019)

$[Th/Si]_{ZAMS} = \log(n(Th)/n(Si))_{*,ZAMS} - \log(n(Th)/n(Si))_{\odot,ZAMS}$

Pristine Th in solar twins:
Th decay-corrected abundance (ZAMS)

- $[Th/H]_{ZAMS}$ *vs*. [Fe/H] & $[Th/Fe]_{ZAMS}$ *vs*. [Fe/H]





$[Th/H]_{ZAMS} = \log(n(Th)/n(H))_{*,ZAMS} - \log(n(Th)/n(H))_{\odot,ZAMS}$

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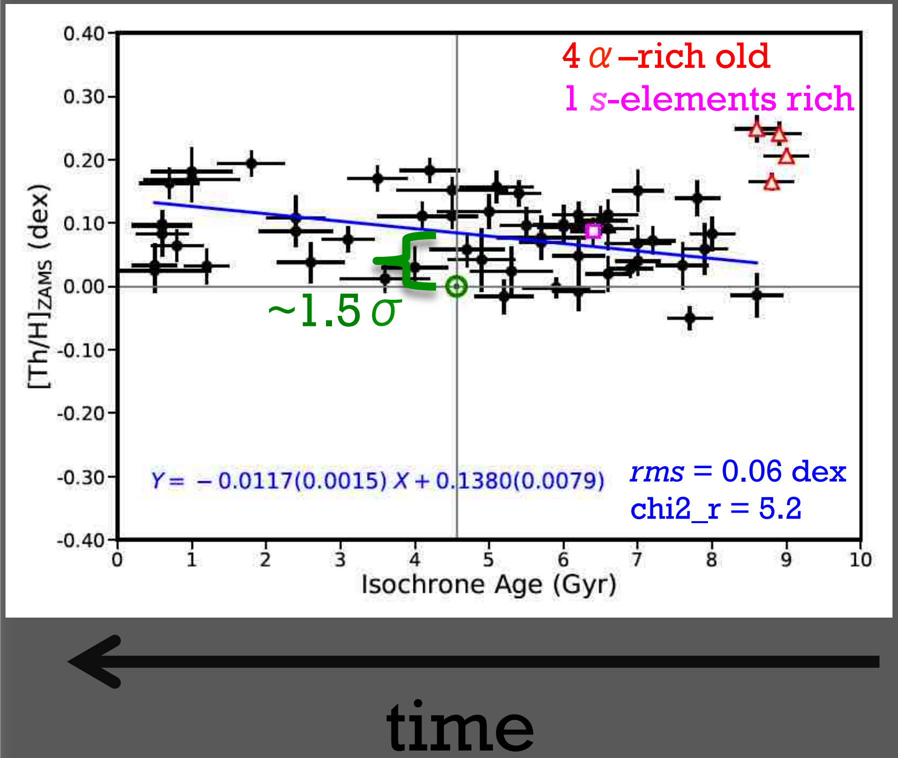
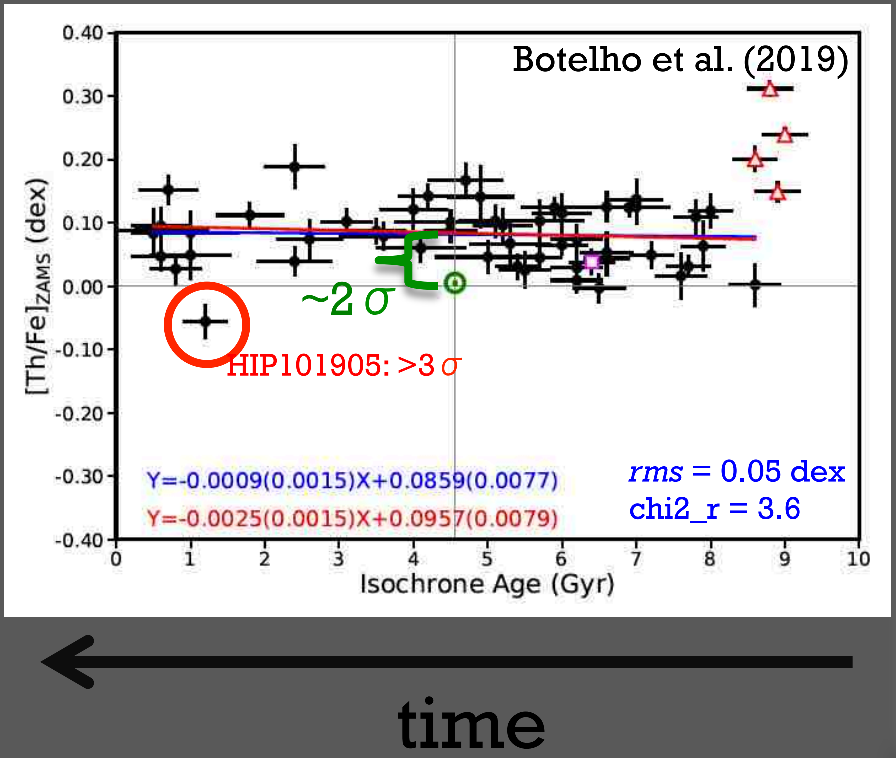
Pristine Th in solar twins:
Th decay-corrected abundance (ZAMS)

- $[Th/H]_{ZAMS}$ *vs*. isochrone age & $[Th/Fe]_{ZAMS}$ *vs*. isochrone age





$[Th/H]_{ZAMS} = \log(n(Th)/n(H))_{*,ZAMS} - \log(n(Th)/n(H))_{\odot,ZAMS}$

$[Th/Fe]_{ZAMS} = \log(n(Th)/n(Fe))_{*,ZAMS} - \log(n(Th)/n(Fe))_{\odot,ZAMS}$

Pristine Th in solar twins:
correction by internal atomic diffusion

- Microscopic effects <---> changes in abundances: 4 kinds of diffusion

- Concentration: negligible in the Sun & solar twins ($\tau \approx 10^{13}$ years)
- Temperature: negligible in the Sun & solar twins ($\tau \approx 10^{13}$ years)
- Pressure diffusion or gravitational settling (sedimentation): heavier atoms migrate towards regions of higher pressure (inwards), important in dwarfs on decreasing photospheric abundances
- Radiative levitation/acceleration: opposite to sedimentation and important for elements with more complex energy levels

- Michaud et al. (2004): diffusive and non-diffusive stellar models (0.6–1.4 $M_{\odot}$), $Z_{\odot}$, applied to M67 and NGC188, 28 elements (Th not investigated), Sun as calibrator (temperature diffusion, sedimentation and radiative acceleration taken into acount)
- surface elemental abundances are decreased in dwarfs up to MS turn-off: Δlog(E) = - few to tenhs of milidex (≈0.010 dex/Gyr, e.g. Fe & Mg, both clusters)

Pristine Th in solar twins:
correction by internal atomic diffusion

- $[Th/X]_{ZAMS,GSC}$: inclusion of a correction for the gravitational settling for both stellar and solar pristine values

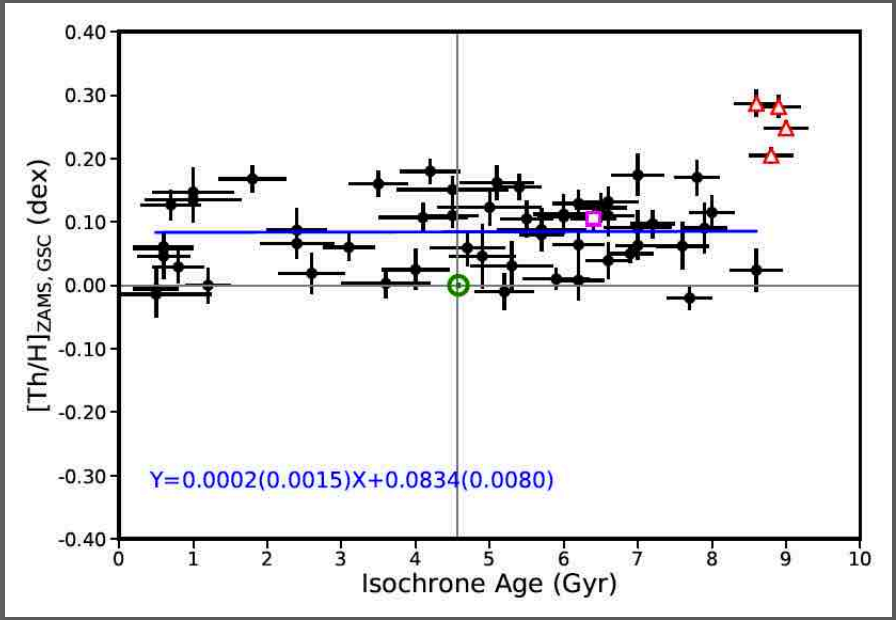
- Two approaches to estimate based on Michaud et al. (2004)
- 1) overall rate of photospheric abundance decreasing for each element by adopting the predictions for 1 $M_\odot$ models in M67 with 3.7 Gyr, and NGC188 with 6.4 Gyr – extrapolated for Thorium! (less precise, theoretical-empirical):

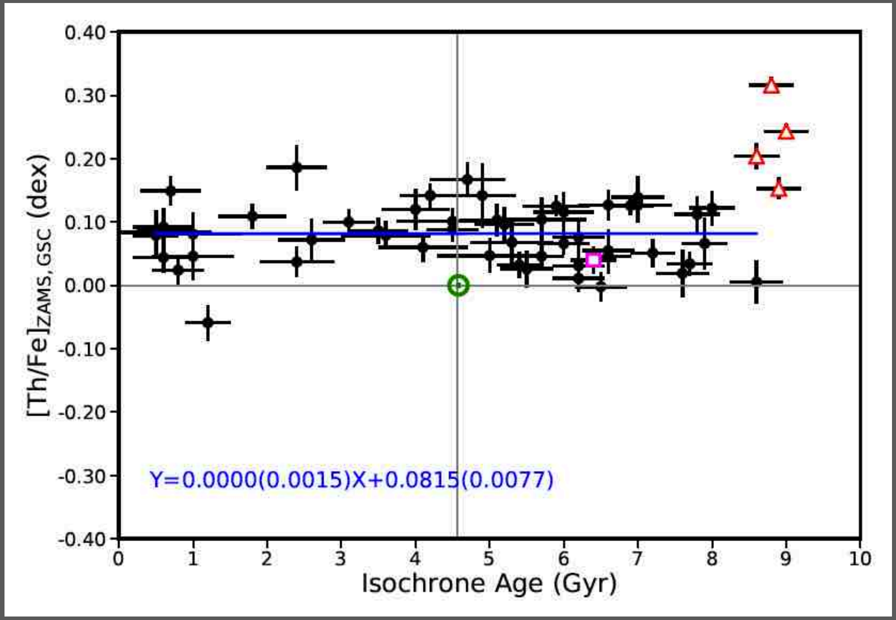
  -0.0095 dex/Gyr for Th, -0.0086 dex/Gyr for Fe & Si
- 2) exponential decreasing for the photospheric abundance based on the diffusion time of each element and adding a dependence on the stellar mass – approximation for Thorium! (theoretical):

  diffusion time of Helium rescaled to Mercury (Hg) for representing Thorium (estimation 1.45 x 10^{11} years) and to Manganese for representing Iron & adopting interpolations and tiny extrapolations with 1 $M_\odot$ and 1.1 $M_\odot$ models

Pristine Th in solar twins:
correction by gravitational settling too

- $[Th/H]_{ZAMS,GSC}$ & $[Th/Fe]_{ZAMS,GSC}$ vs. Age: inclusion of a correction for the gravitational settling for both star's and Sun's pristine values ---> FIRST APPROACH



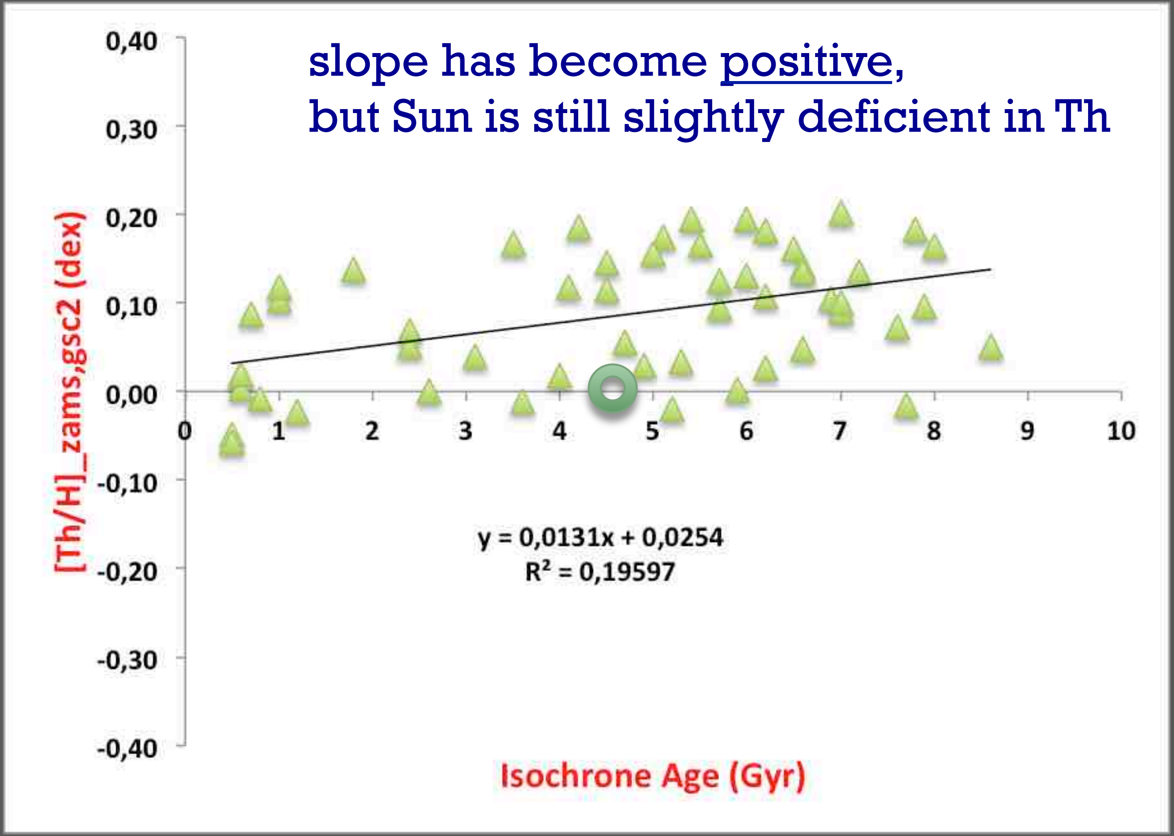


slope has changed in 4 sigma, becoming null now!

slope has kept equal to zero!

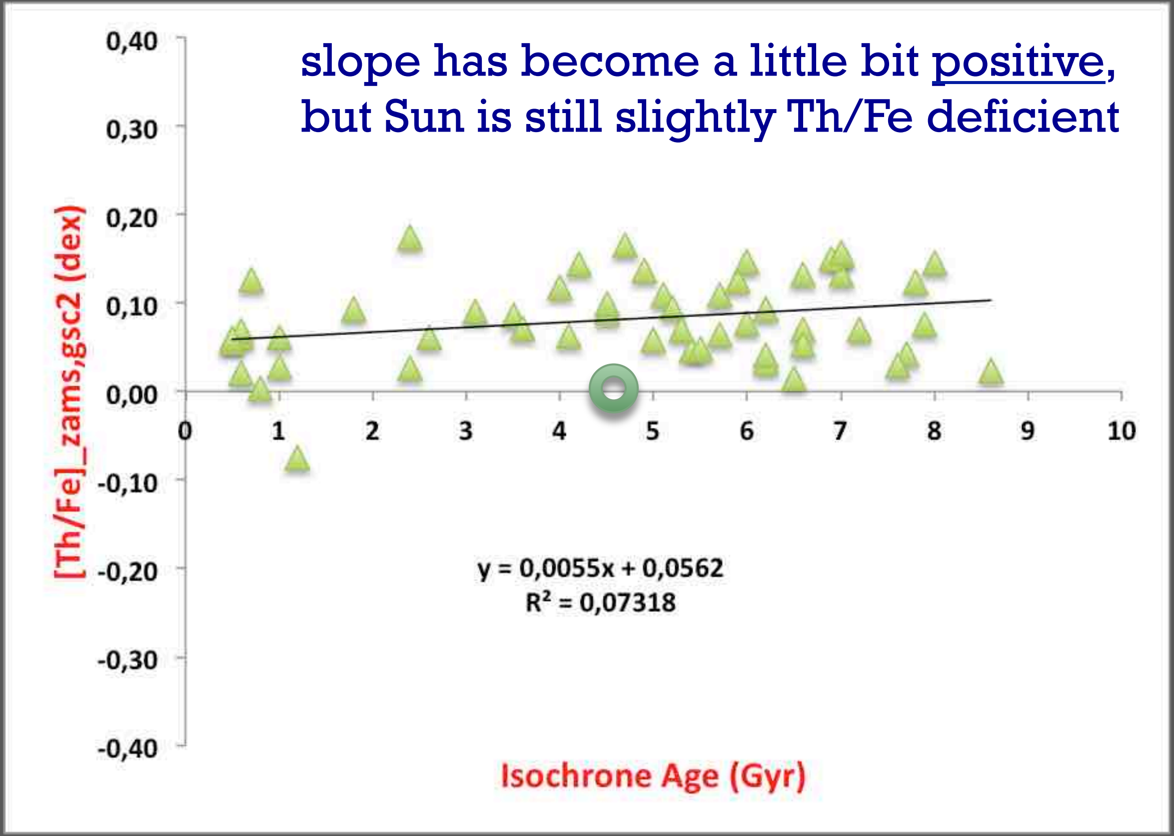
Pristine Th in solar twins:
correction by gravitational settling

- $[Th/H]_{ZAMS,GSC}$ & $[Th/Fe]_{ZAMS,GSC}$ vs. Age: inclusion of a correction for the gravitational settling for both star's and Sun's pristine values ---> SECOND APPROACH



Pristine Th in solar twins:
correction by gravitational settling

- $[Th/H]_{ZAMS,GSC}$ & $[Th/Fe]_{ZAMS,GSC}$ vs. Age: inclusion of a correction for the gravitational settling for both star's and Sun's pristine values ---> SECOND APPROACH



Pristine Th in solar twins: conclusions (ZAMS-decay only)

$[Th/X]_{ZAMS}$ *vs.* [Fe/H]

- Th/H nearly follows Fe/H (~0.08 dex enhanced relatively to Sun), but not under a 1:1 relation (slope < 1)

- $[Th/Fe]_{ZAMS}$ is super-solar and decreases with [Fe/H] then!

- sites of Th formation like Eu (but not like Nd)
  - core-collapse SNs
  - neutron star mergers
  - black hole–neutron star mergers

Botelho et al. (2019)

Pristine Th in solar twins: conclusions (ZAMS-decay only)

[Th/X]$_{ZAMS}$ *vs.* isochrone age

- [Th/H]$_{ZAMS}$ increased over time from 8.6 Gyr ago until now
  - from +0.04 up to +0.14 dex, linear fit: 110 to 138% of solar value!
  - from -0.05 up to +0.19 dex, individually: 89-155% of solar value
  - Sun slightly deficient in Thorium (≈0.10 dex, ≈2 sigma)
  - current values: from 76 up to 181% (more dispersion!)
- [Th/Fe]$_{ZAMS}$ ≈ super-solar and constant over time ~ +0.09 dex (*rms* = 0.047 dex)
- [Th/Si]$_{ZAMS}$ increased from +0.045 dex 8.6 Gyr ago to +0.149 dex now
  - *Si is the 3rd-4th most abundant element in rocky planets*
  - comparisons among rocky planets with different mantle thicknesses
  - higher ratios ➔ higher internal energy budget

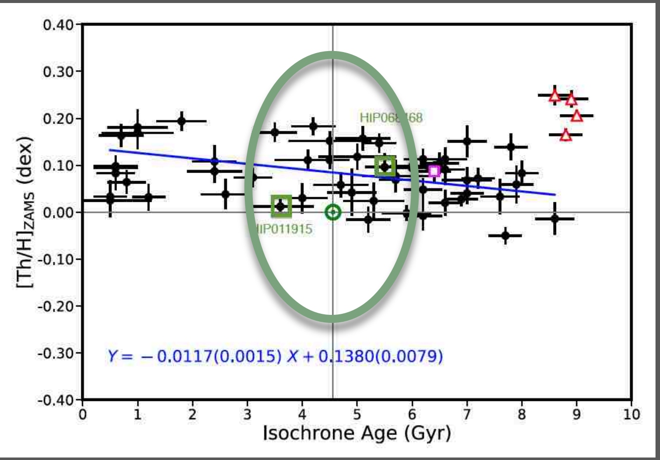
Botelho et al. (2019)

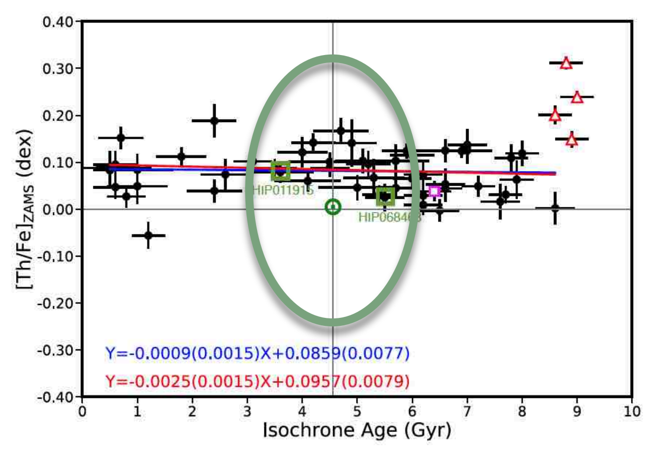
Pristine Th in solar twins: **conclusions & speculations**

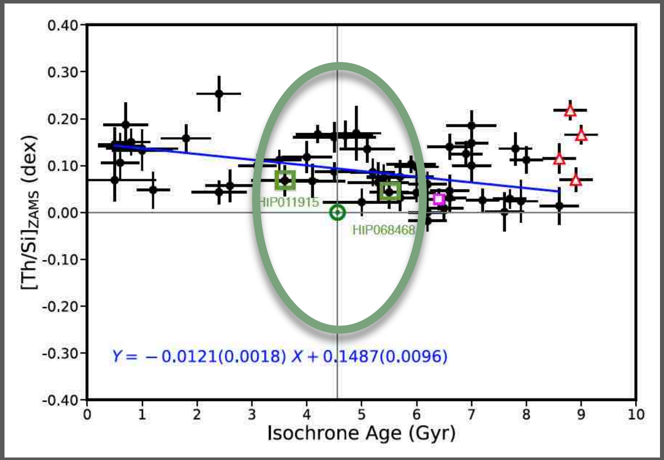
- high probability of having plate tectonics in any potential rocky planet around any solar twin in the Galaxy's thin disc, making possible the habitability on the planetary surface (as probable as the Sun, or more)
- speculation 1: *the life could be widespread in the Galaxy's (thin) disc in time and space too!*
- speculation 2: since that Sun is slightly deficient in Thorium in comparison with solar twins (~0.1 dex or ~2 σ), *the more probable solar twins with potential rocky planets could be those ones also deficient in Th like Sun* (Th is a refractory element & Sun is deficient in refractories relatively to volatiles in comparison with solar twins without rocky planets)

Pristine Th in solar twins:
speculation 2

the more probable solar twins with potential rocky planets
could be those ones deficient in Th like Sun and 2 other hosting-planet twins







Th in solar twins: **planet habitability**

- **mantle convection – plate tectonics – C cycle – greenhouse effect:** ~~It is not the unique criterion of habitability on a rocky planet !!!~~

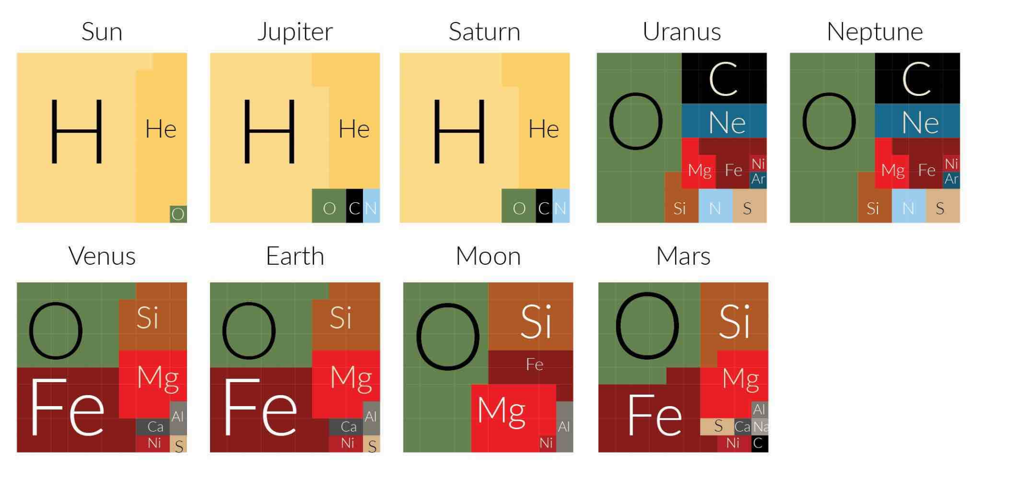
Other (~related) criteria

- planet intrinsic properties
  - enough surface gravity to hold an atmosphere (α M/R^2)
  - minimum mass to have internal structure + long-term magnetic field (threshold rotation)
  - threshold metal abundance (Mg, Si, O, Fe, Ni, S, C,…)

- planet orbit and planetary system dynamics
  - orbit in the habitable zone
  - low eccentric orbit, no tidal locked rotation, stable moderate axial inclination
  - dynamically stable planetary orbits

- host star properties
  - late F – G – mid K (and perhaps M type)
  - threshold metal abundance (Mg, Si, O, Fe, Ni, S, C,…)
  - no excessive magnetic activity

Th in solar twins: Solar System

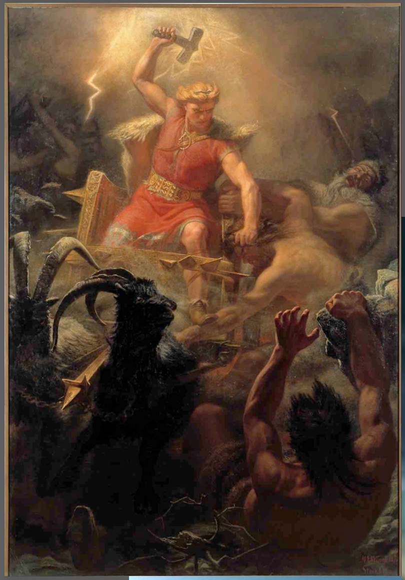


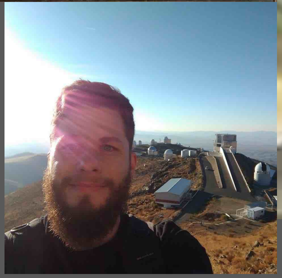
- Rocky bodies of Solar System with internal differentiation (mantle made of silicate rocks too)
  - Venus (some volcanic activity, no magnetic field, size/gravity comparable to Earth, irreversible greenhouse effect)
  - Mars (single crust plate, no magnetic field, small size/gravity)
  - Mercury (weak magnetic field, small size/gravity)

  ➔ ***Earth is the only planet currently with subduction and plate tectonics!***
  - Moon (single crust plate)
  - Jupiter's moons: Io (aduction/volcanoes) and Europa
  - asteroid Vesta

Pristine Th in solar twins:
habitability in rocky planets

internal energy budget – convective mantle – plate tectonics – geological Carbon cycle – greenhouse effect – habitability on the surface

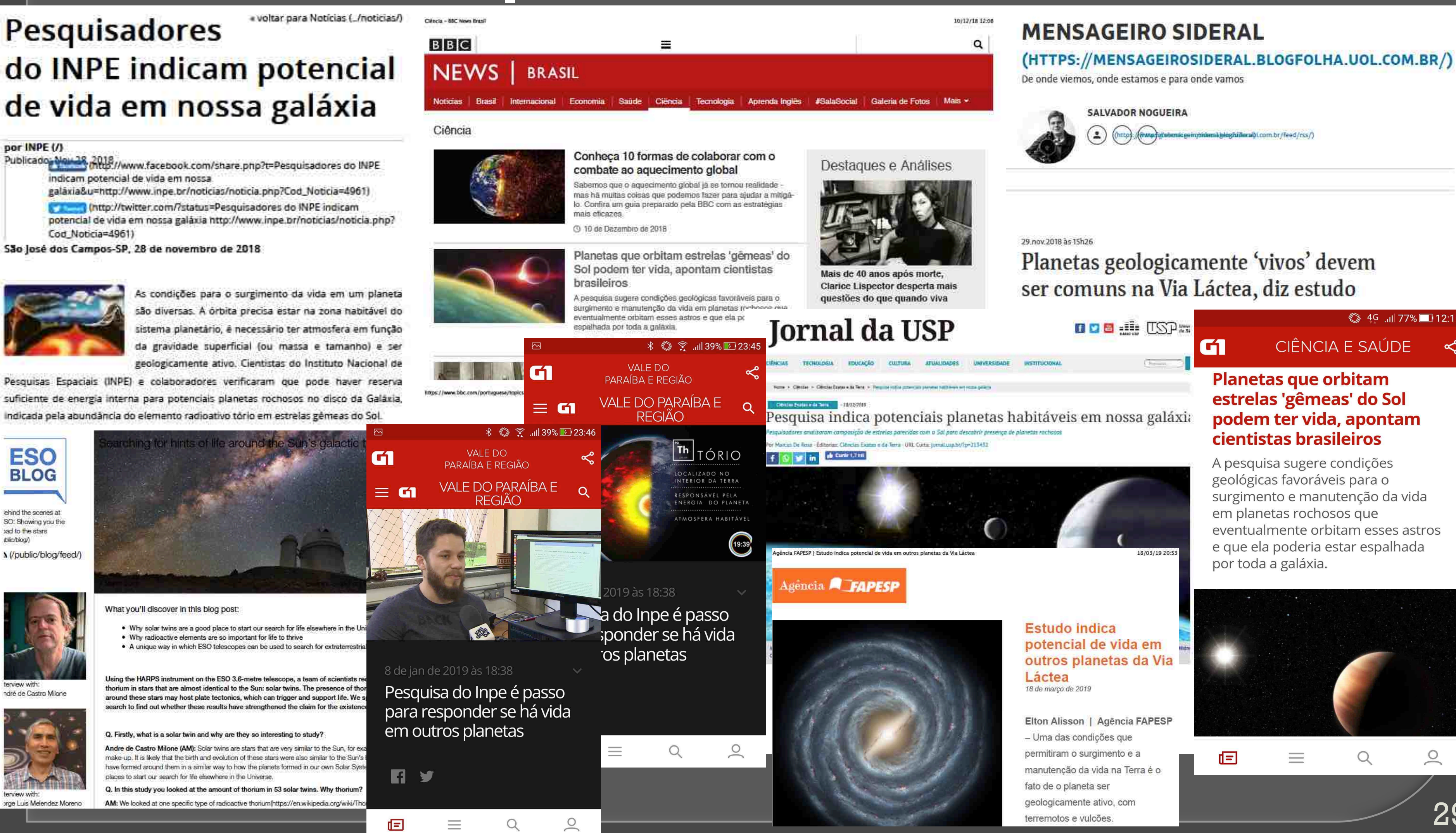




Thorium is named after the Nordic god Thor

Th in solar twins: impact in the press at Brazil & ESO blog

INPE's press release and our own contacts



Thank you
OBRIGADO

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