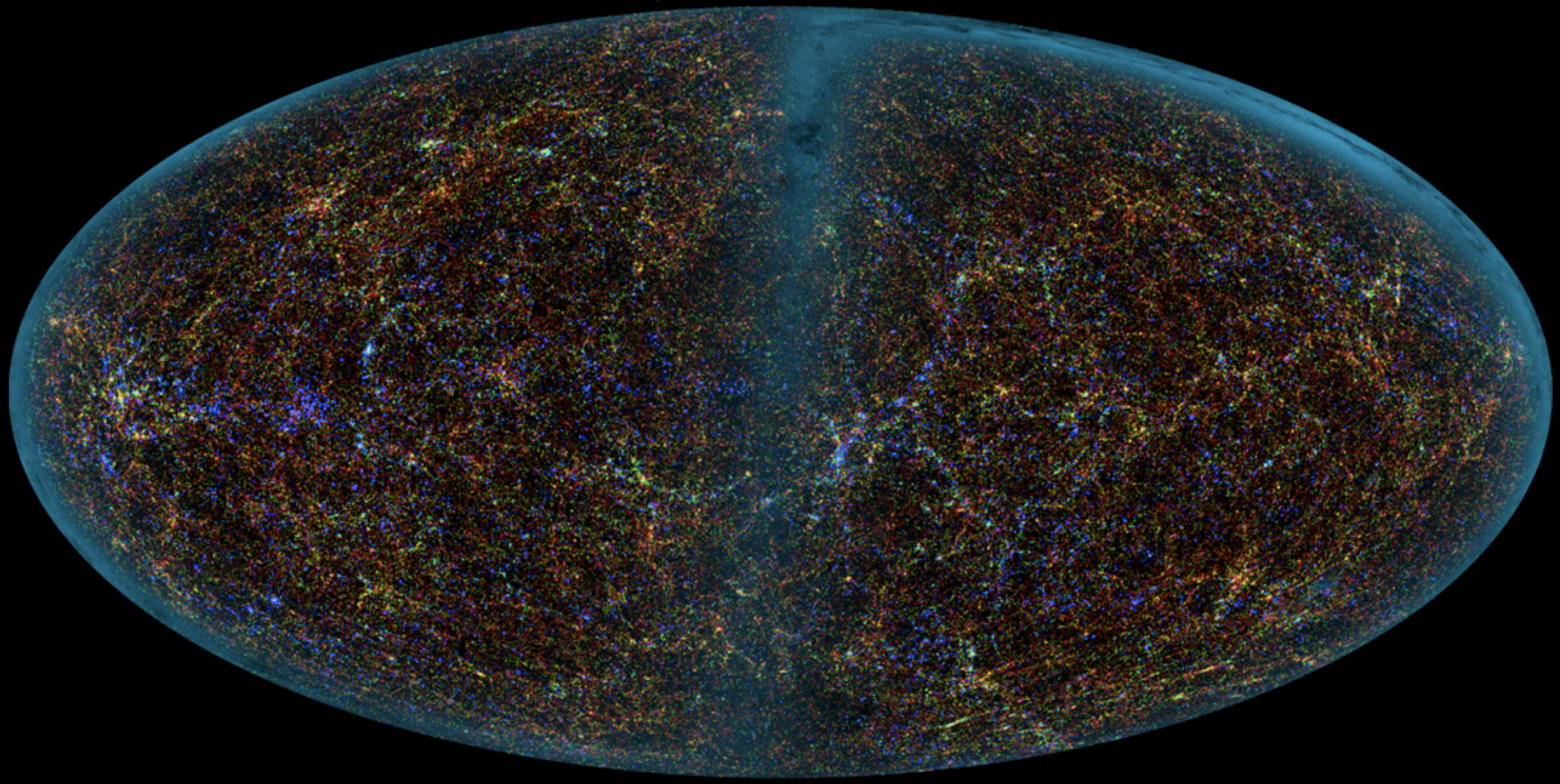
Cosmology

and Large Scale Structure



Today

Age constraints

homework due

13 October 2022

http://astroweb.case.edu/ssm/ASTR328/

Age of the Universe

- Oldest stars
  - Globular clusters
- White dwarfs
  - cooling curves & luminosity function
- Radioactive chronometers
  - Thorium/Europium ratio
- Interstellar dust grains
  - Oxygen isotope ratios

Expansion time scale set by the Hubble time H_0^{-1}.
What about the ages of observed objects?
The contents of the universe should not be older than the universe itself!

Age of the Universe

- Oldest stars
  - Globular clusters

$\langle t_{GC} \rangle = 17 \pm 2$ Gyr (Chaboyer et al 1992)

Globular cluster ages are an ancient and venerable constraint. Were important in encouraging belief in Sandage's $H_0 = 50$ in preference to de Vaucouleurs's $H_0 = 100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Then the Hipparcos satellite changed the local distance scale:

$\langle t_{GC} \rangle = 11.5 \pm 1.3$ Gyr (Chaboyer et al 1998)

Estimates continue to be refined:

$\langle t_{GC} \rangle = 13.32 \pm 0.1$ (stat) $\pm\ 0.5$ (sys) Gyr (Valcin et al 2020)

Age of the Universe

- Oldest stars
  - Globular clusters

$$L \sim M^a$$

in solar units
with

$$a = 3.5 - 4$$

the exponent is mass dependent;
that $a > 1$ means that more
massive stars burn out faster.

To first order, the age can be estimated from the luminosity of the main sequence turn-off point. It follows simply from the available energy supply (the hydrogen mass in core) and the rate of energy use (the luminosity).

$$E_{\text{MS}} = f_{core}\, \epsilon_H\, M_*\, c^2$$

where f_{core} is the mass fraction in the star's core (~12%)

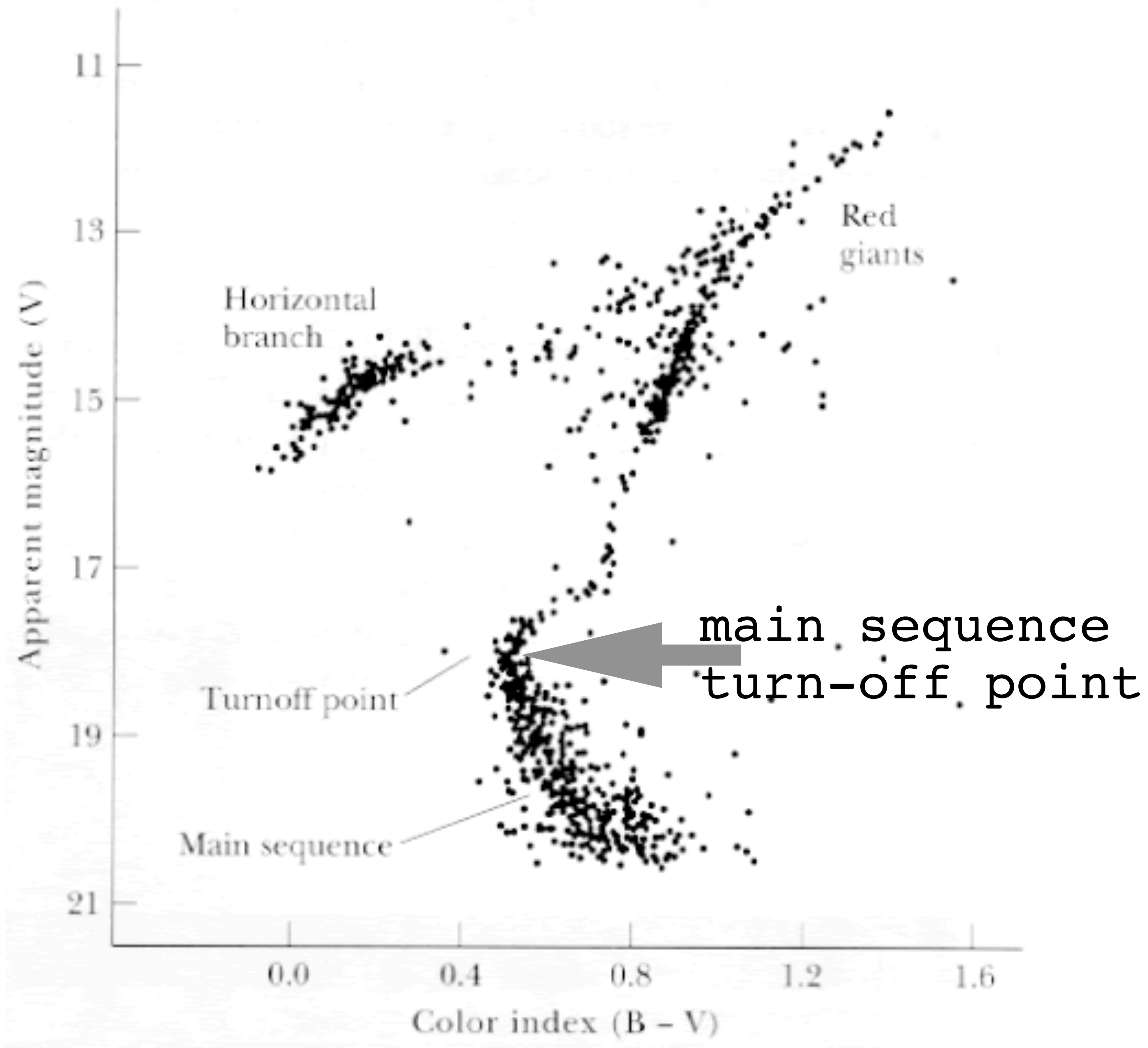
ϵ_H is the conversion efficiency of fusion (0.7%)

M_* is the mass of the star.

$$t_{\text{TO}} = \frac{E_{\text{MS}}}{L_{\text{TO}}}$$

$$L_{\text{TO}} \sim M_{\text{TO}}^a$$

where L_{MS} is the luminosity of a star at the main sequence turn off point.
This depends on the distance through $L = 4\pi d^2 F$ where F is the observed flux.



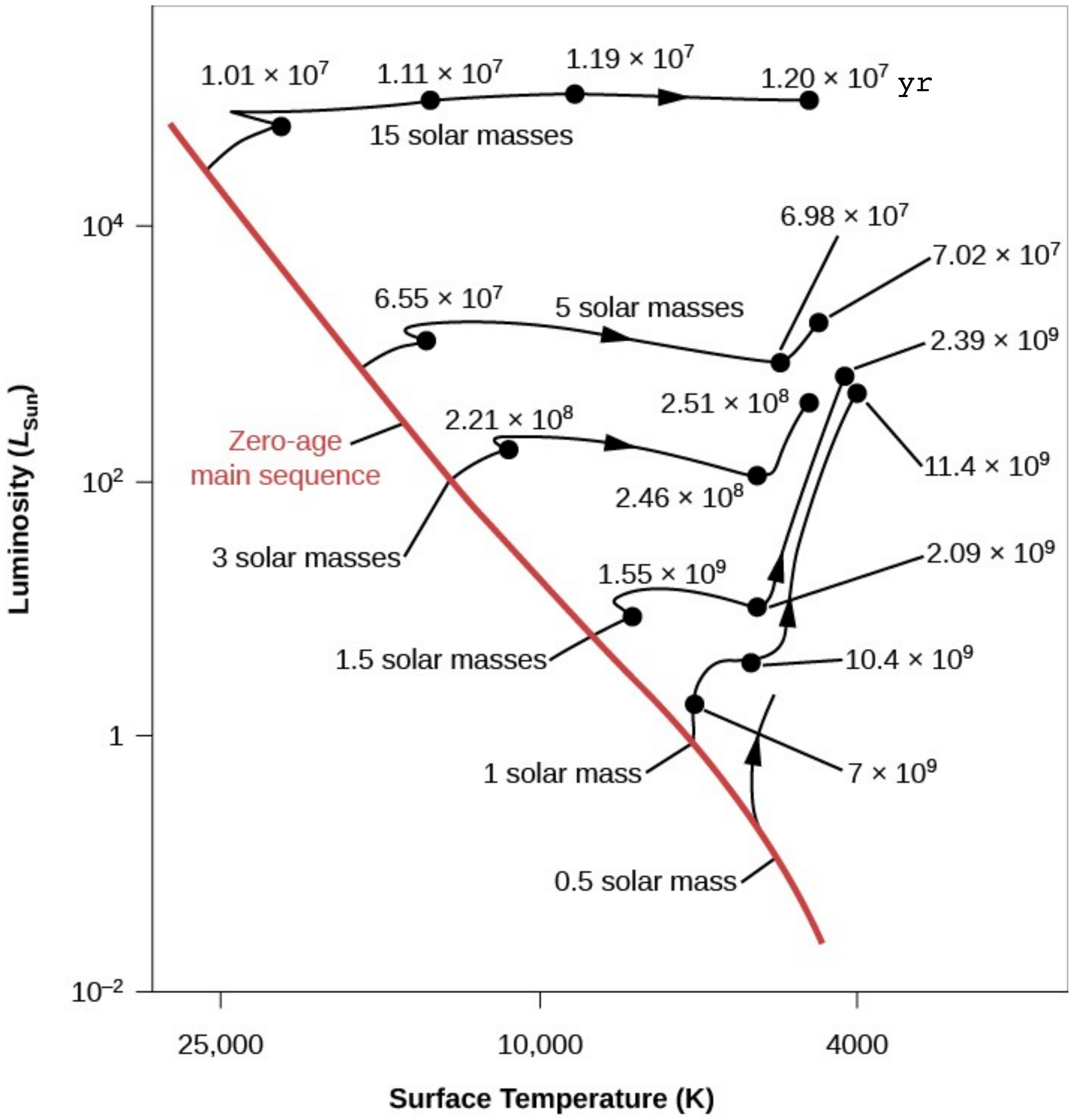
Age of the Universe

- Oldest stars
  - Globular clusters

More accurately, one can build models of stellar evolution that track the changes in a star's luminosity and surface temperature/color as a function of time.

One then fits these evolutionary tracks to HR diagrams.

Evolutionary tracks for stars of various masses



Gontcharov et al. (2020)

Age of the Universe

- Oldest stars
  - Globular clusters

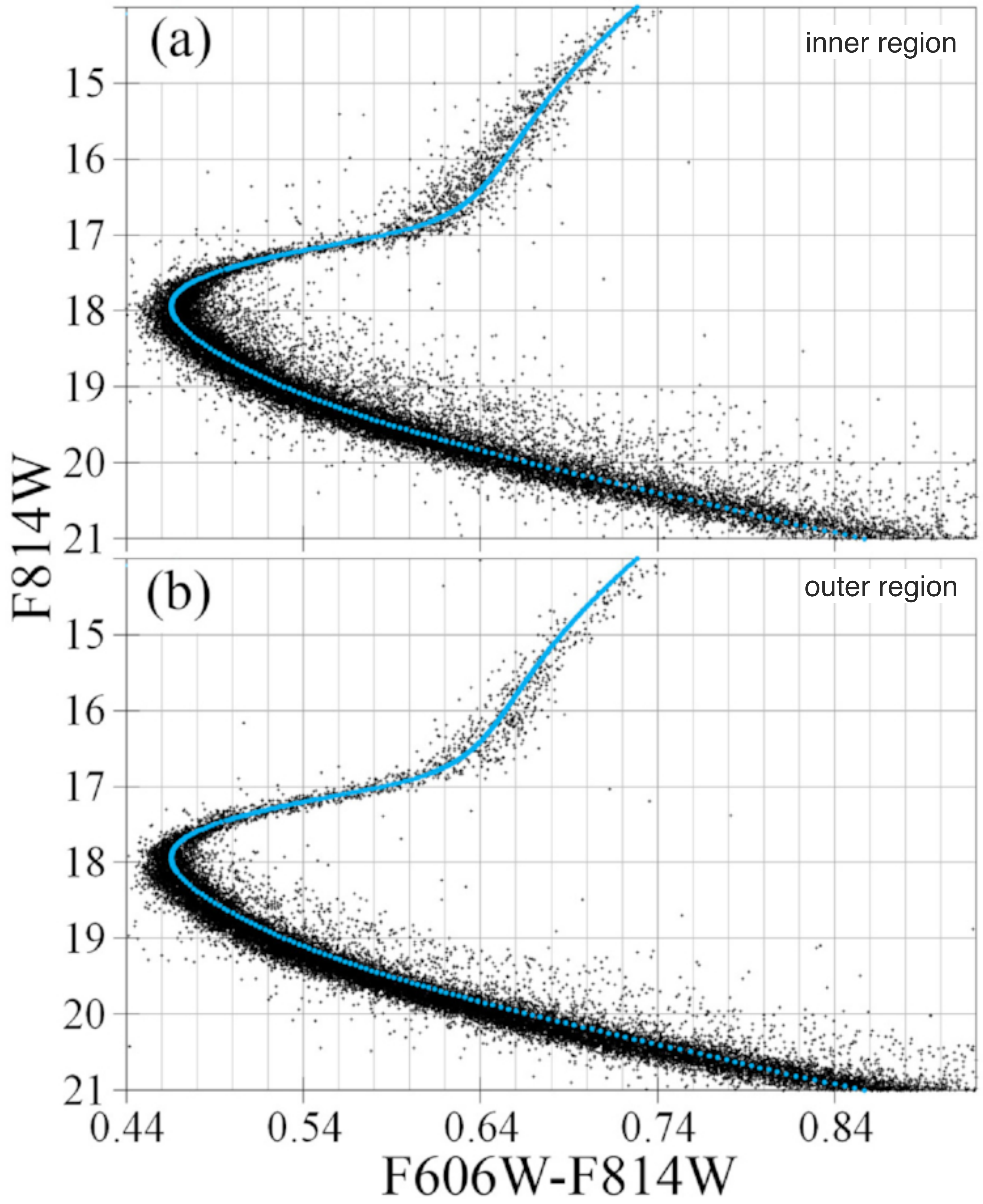
More accurately, one can build models of stellar evolution that track the changes in a star's luminosity and surface temperature/color as a function of time.

One then fits these evolutionary tracks to HR diagrams.
The physics is well understood, but the details of the models does matter, as does the composition ([Fe/H], [α/Fe]) of the stars.

"the derived ages are different for the different models/isochrones, e.g. in the optical range from 12.3 ± 0.7 Gyr for He-α-enhanced DSEP to 14.4 ± 0.7 Gyr for MIST."
(Gontcharov et al. 2020)

Never see stars with ages clearly exceeding ~14 Gyr.

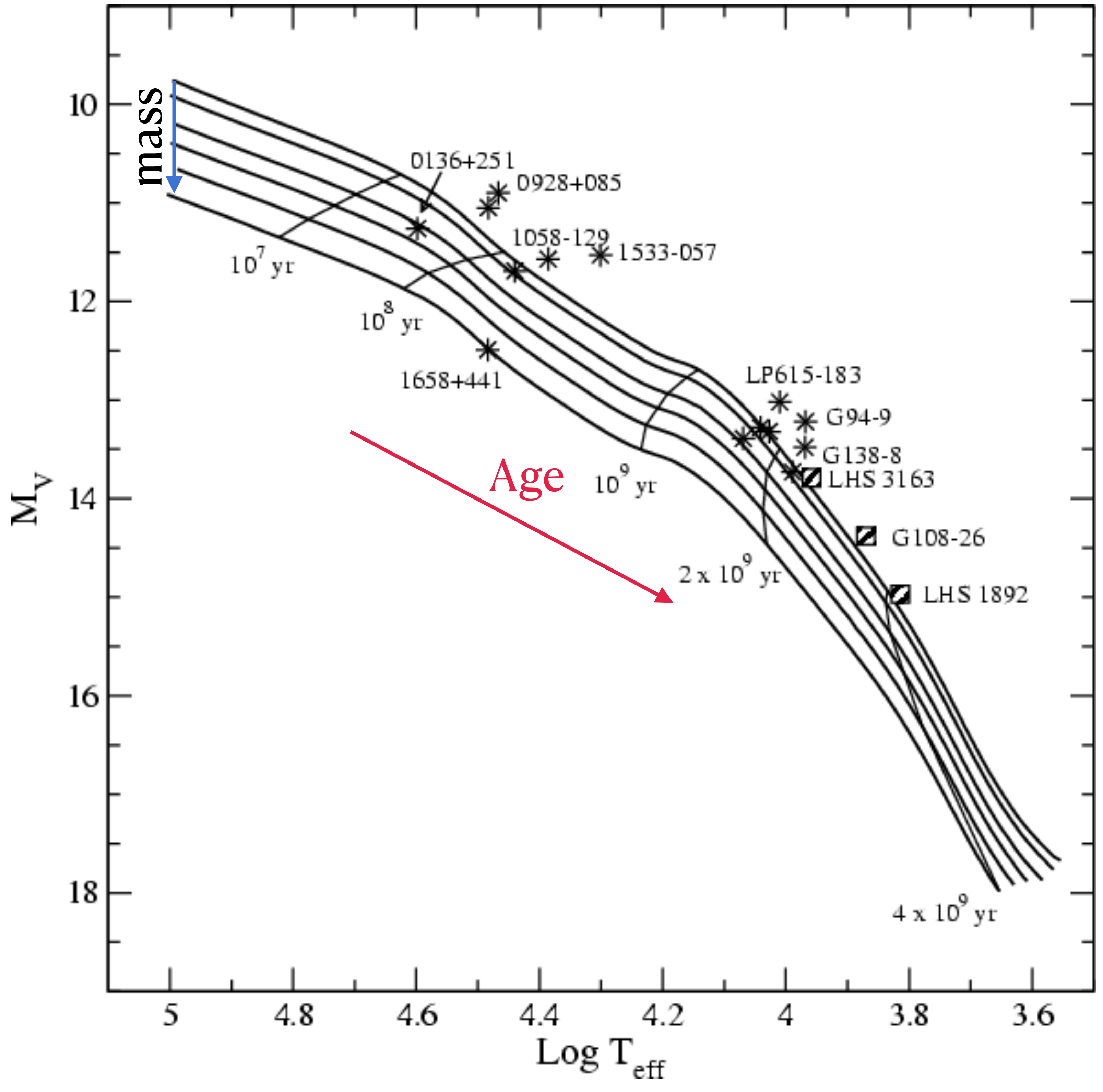
Best fitting isochrone for globular cluster NGC 6205



*F*606*W* – *F*814*W* versus *F*814*W* CMD of NGC 6205 based on the *HST* ACS data for (a) 25 231 stars within and (b) 24 958 stars outside the 1.14 arcmin radius from the cluster's centre. The best-fitting IAC-BaSTI isochrone is shown by the curve as a reference.

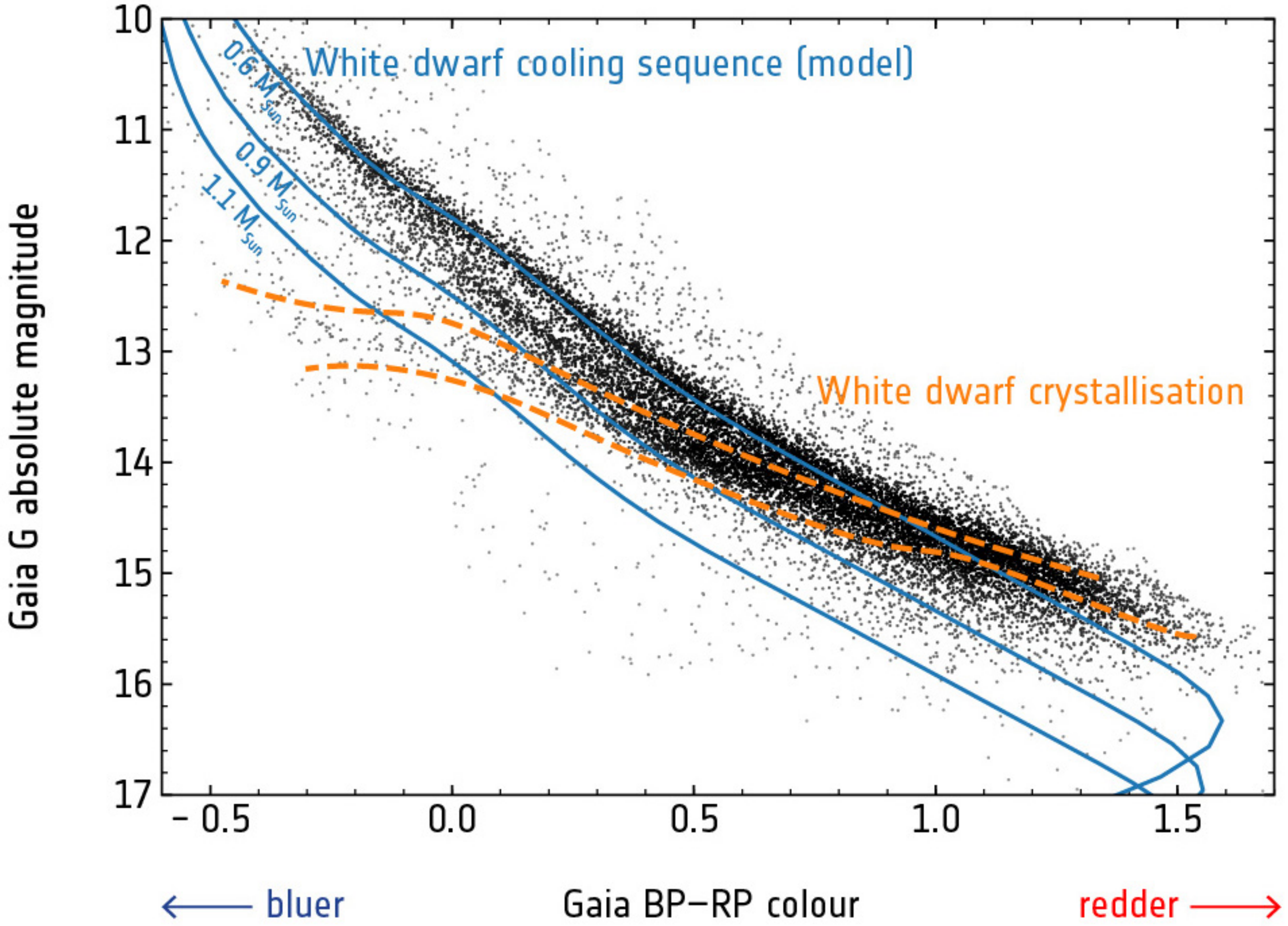
Age of the Universe

- White dwarfs
  - cooling curves & luminosity function



White dwarfs follow a simple radiative cooling curve — these cores of former stars fade as they cool in a predictable way. One therefore expects a truncation of the white dwarf luminosity function at the lowest luminosity to which they have had time to cool. That, plus the lifetime of the star that gave them birth, gives an age limit.

$$L_{WD} = 4\pi R_{WD}^2 \sigma_{SB} T^4 \quad = \frac{dE}{dt} = \frac{d}{dt}\left(\frac{3}{2} N k_B T\right) \rightarrow \quad \frac{dT}{dt} \approx \frac{\sigma_{SB} T^4 m_p}{2\pi R_{WD}^2 k_B M_{WD}}$$



Age of the Universe

- White dwarfs
  - cooling curves & luminosity function

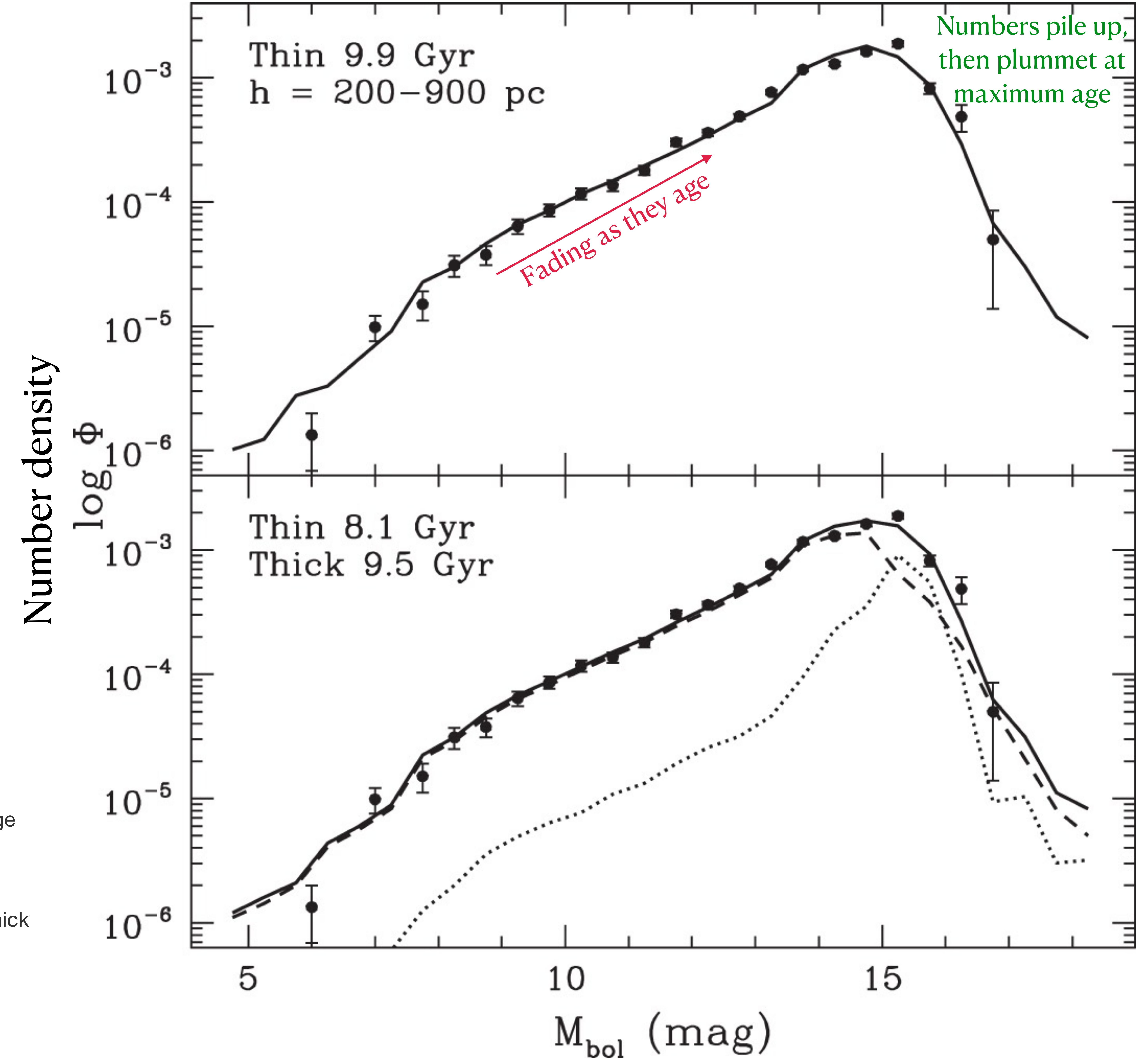
Can distinguish the age of the thin and thick disk …

$$t_{WD}^{max} = 12.5^{+1.4}_{-3.5}\ \text{Gyr}$$

For halo white dwarfs

Figure 6. The white dwarf luminosity function from the deep proper motion survey (points with error bars, Munn et al. 2017) using a disk scale height range of 200–900 pc. The top panel shows the model fits assuming a population of 100% thin disk stars, whereas the bottom panel shows the fits using a composite population where the ratio of thick disk to thin disk white dwarfs is 35%. Dashed and dotted lines show the contribution from the thin disk and thick disk white dwarfs, respectively.

Kilic et al (2017)



Age of the Universe

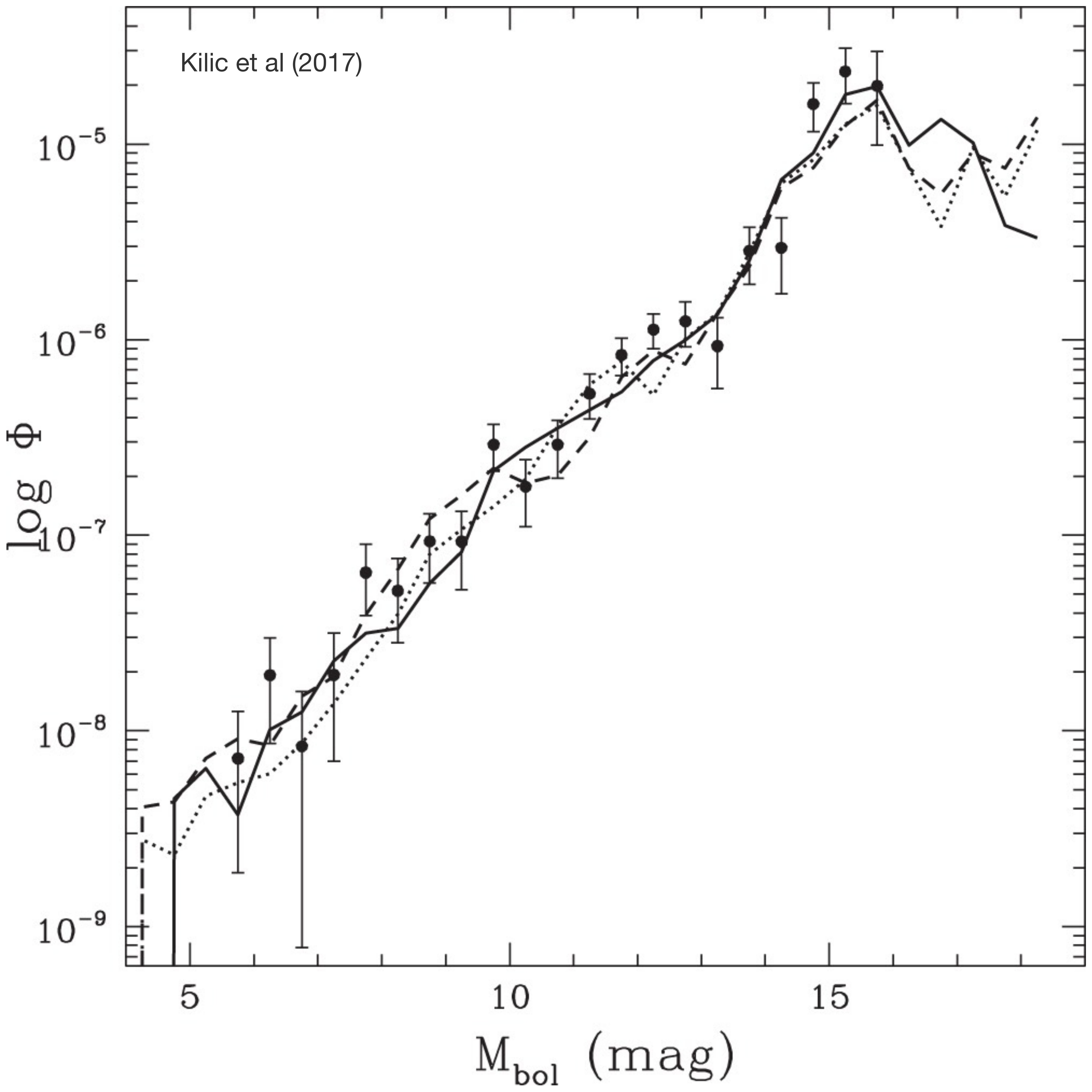
- White dwarfs
  - cooling curves & luminosity function

... the age of the stellar halo ...

$$t_{WD}^{max} = 12.5^{+1.4}_{-3.5}\ \mathrm{Gyr}$$

For halo white dwarfs

Figure 9. Munn et al. (2017) luminosity function for the km s–1 halo white dwarf sample. Solid, dashed, and dotted lines show model luminosity functions for 12.5, 13.9, and 15.0 Gyr old halo samples, respectively. This luminosity function implies a halo age of $12.5^{+1.4}_{-3.5}$ Gyr.



Age of the Universe

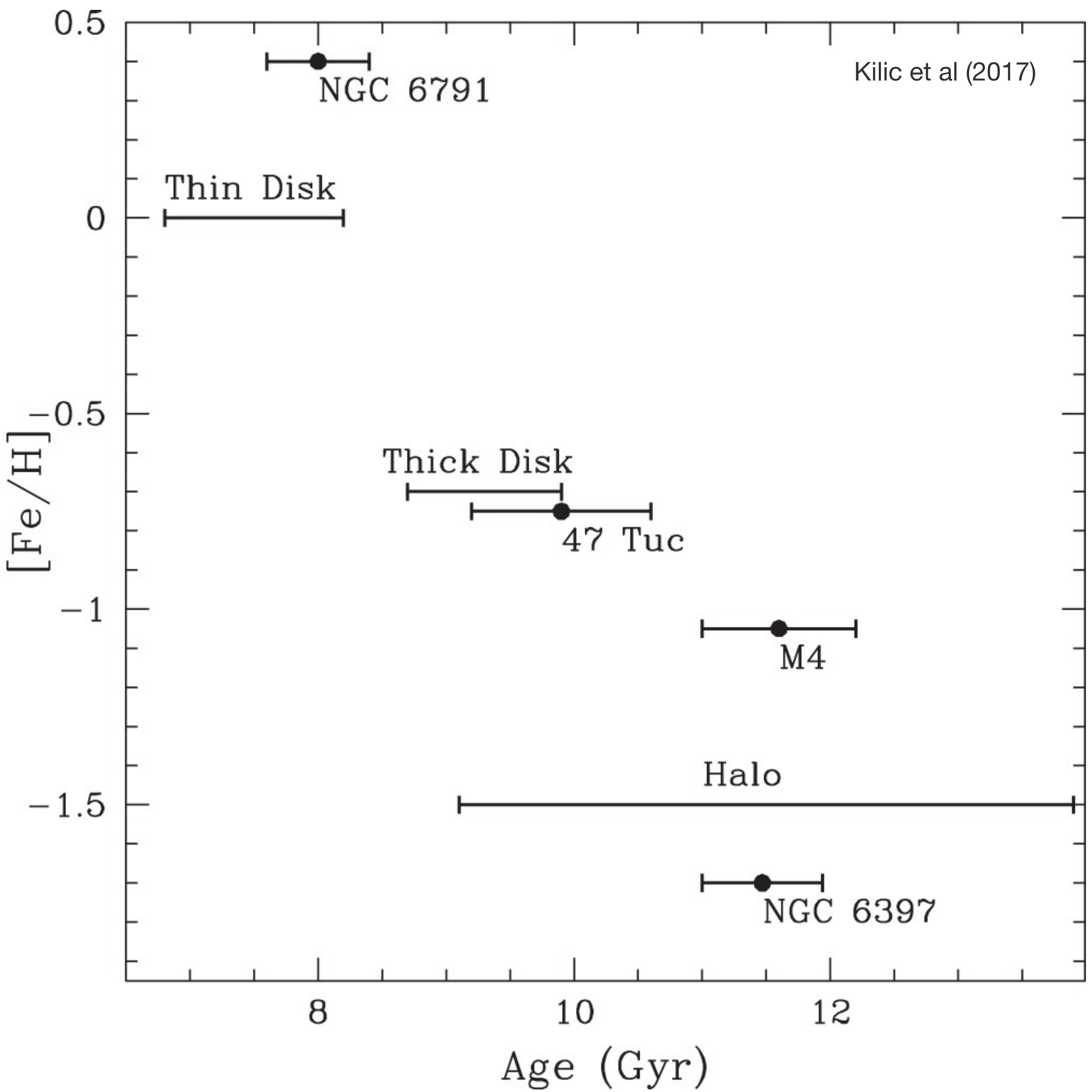
- White dwarfs
  - cooling curves & luminosity function

... and the age-metallicity relation.

$$t_{WD}^{max} = 12.5^{+1.4}_{-3.5}\ \mathrm{Gyr}$$

For halo white dwarfs

Figure 10. Age–metallicity relation based on the white dwarf luminosity functions for the open cluster NGC 6791, globular clusters 47 Tuc, M4, and NGC 6397 (Hansen et al. 2013, and references therein), and field thin disk, thick disk, and halo stars from this study. The error bars cover the age ranges estimated from both the 40 pc local sample and the Munn et al. (2017) deep proper motion survey sample.



Age of the Universe

- Radioactive chronometers
  - Uranium/Europium ratio
  - Thorium/Europium ratio

r-process elements heavier than iron are created in SN explosions and/or neutron star collisions. Some are radioactive and decay with a half-life that is well-known from the laboratory. **^{232}Thorium has a half-life of 14.05 Gyr**, so makes a good cosmochronometer. ^{238}Uranium has a half-life of 4.5 Gyr so is also useful, but is even harder to measure in stars. These are typically referenced to stable elements like Europium.

Stellar age dating with thorium, uranium and lead 451

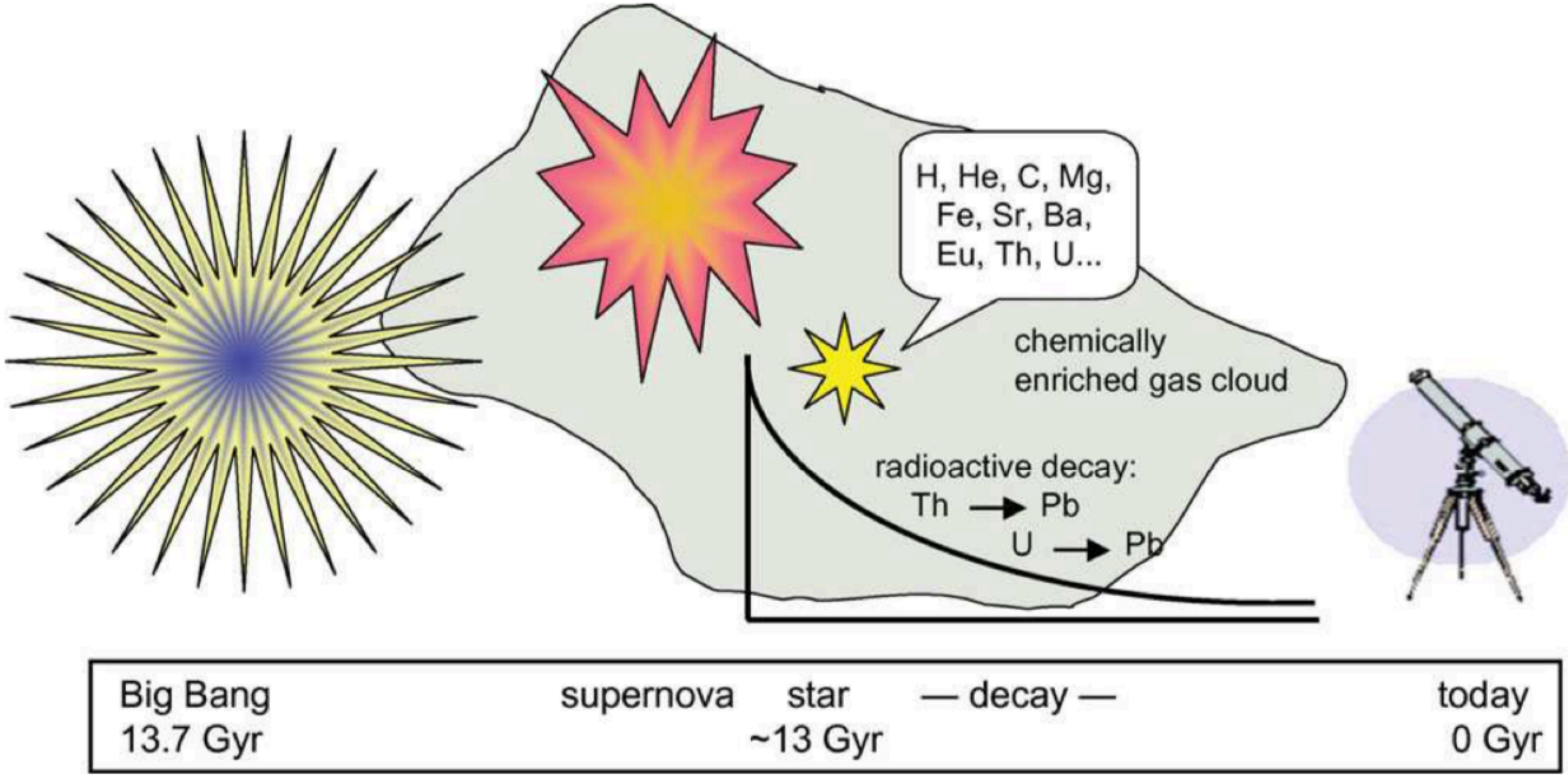


Figure 1. Formation process of r-process-enhanced metal-poor stars. They inherit the "chemical fingerprint" of a previous-generation supernova. Taken from Frebel (2009).

Age of the Universe

SN explosions provide neutron-rich environments that generate neutron-rich nuclei at high atomic number through the “r-process.” These isotopes are highly unstable and quickly decay to the nuclear valley of stability.

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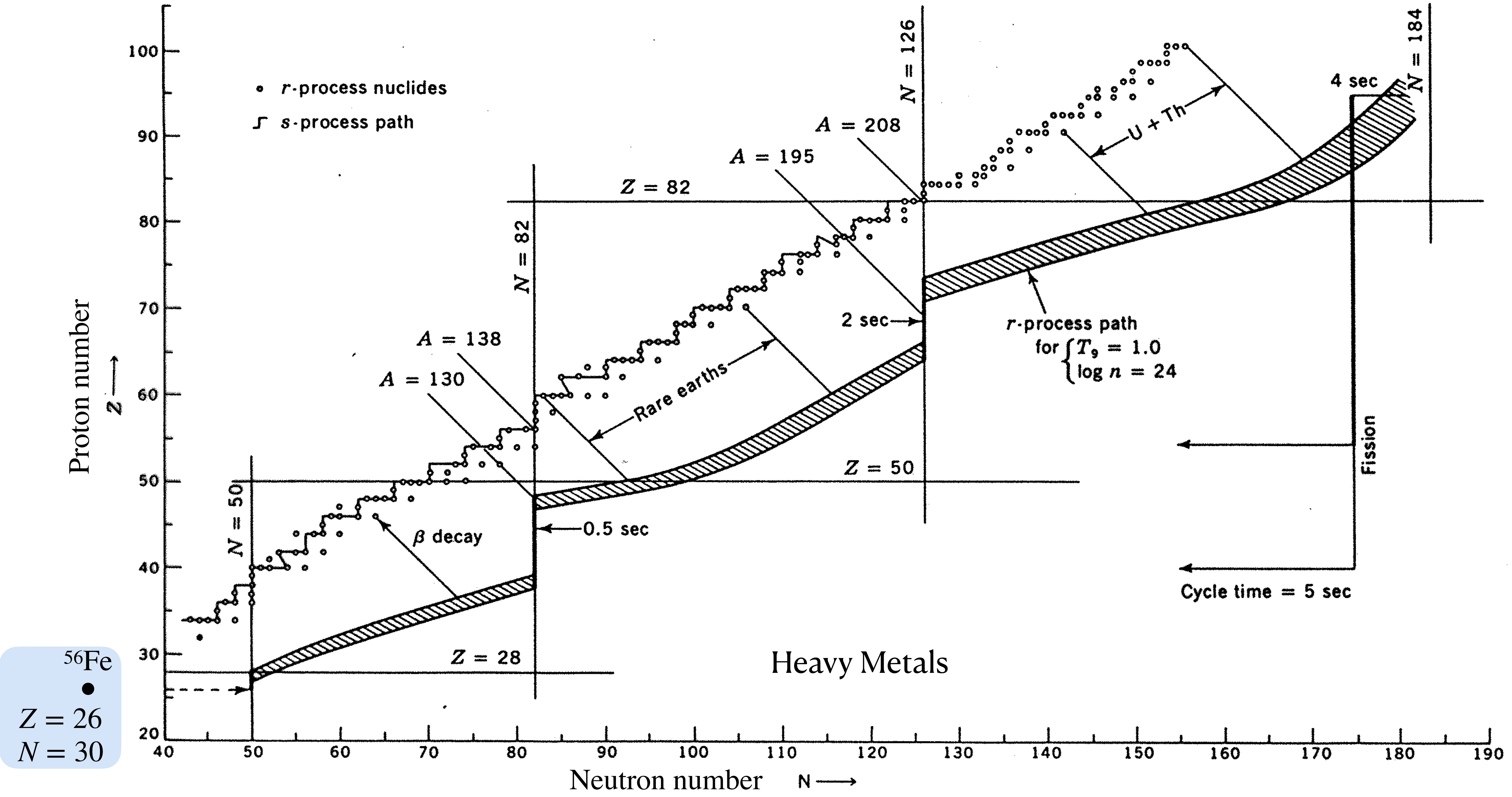

Fig. 7-30 Neutron-capture paths for the *s* process and the *r* process. The *s* process follows a path in the *NZ* plane along the line of beta stability. The neutron-rich progenitors to the stable *r*-process nuclei, which are here shown as small circles, are formed in a band in the neutron-rich area of the *NZ* plane, such as the shaded area shown here. This *r*-process path was calculated for the case $T_9 = 1.0$ and $\log n_n = 24$. After the synthesizing event the nuclei in this band beta-decay to the stable *r*-process nuclei. The abundance peaks at $A = 80$, 130, and 195 are attributed to abundance peaks in the neutron-rich progenitors having $N = 50$, 82, and 126. Neutron capture flows upward from the lower left-hand corner along the shaded band until neutron-induced fission occurs near $A = 270$. [*P. A. Seeger, W. A. Fowler, and D. D. Clayton, Astrophys. J. Suppl.,* **11**:121 (1965). *By permission of The University of Chicago Press. Copyright* 1965 *by The University of Chicago.*]

Age of the Universe

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A. Frebel & K.-L. Kratz

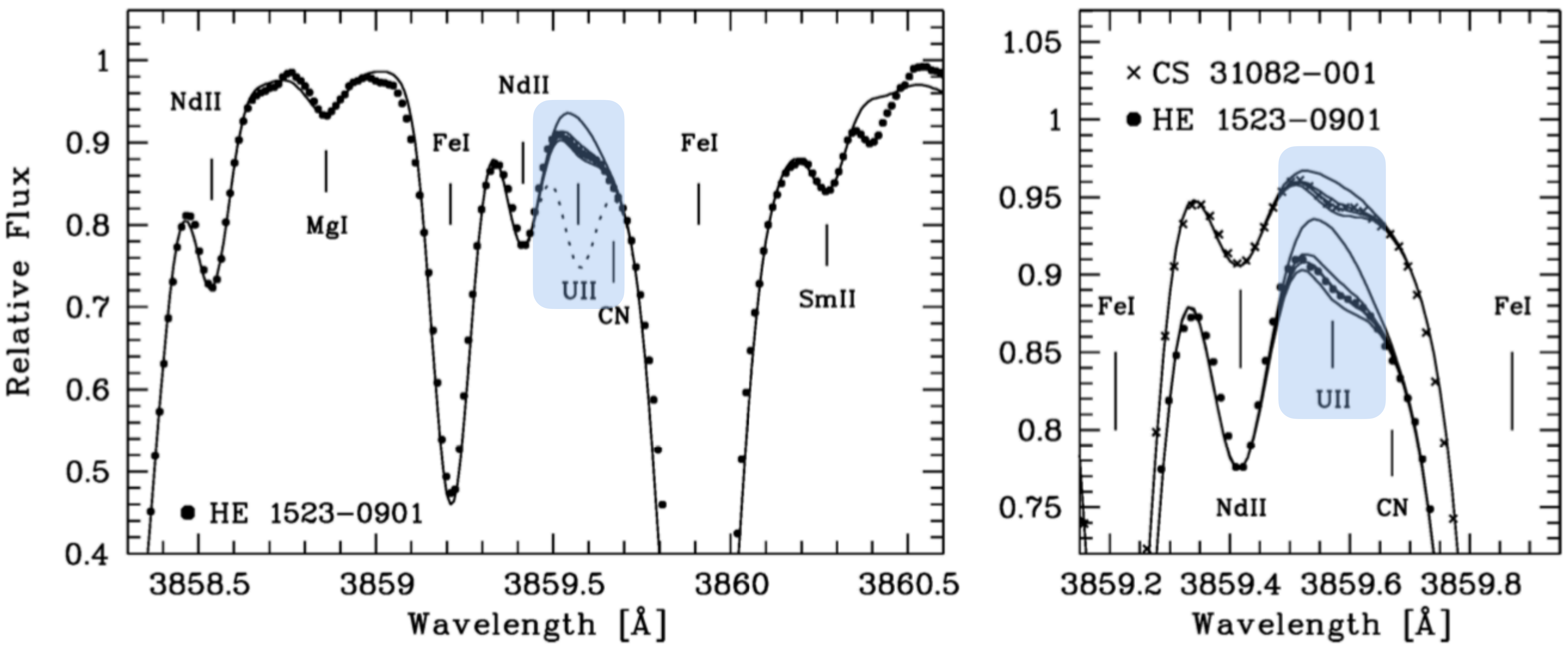


Figure 2. Spectral region around the U II line in HE 1523−0901 (*filled dots*) and CS 31082-001 (*crosses*; right panel only). Overplotted are synthetic spectra with different U abundances. The dotted line in the left panel corresponds to a scaled solar r-process U abundance present in the star if no U were decayed. Figure taken from (Frebel *et al.* 2007a).

Age of the Universe

- Radioactive chronometers
  - Thorium/Europium ratio

$$N_{\rm Th} = N_{\rm Th}(t_0)\, e^{-t/\tau_{\rm Th}}$$

Theoretically expect initial Th/Eu = 0.48.

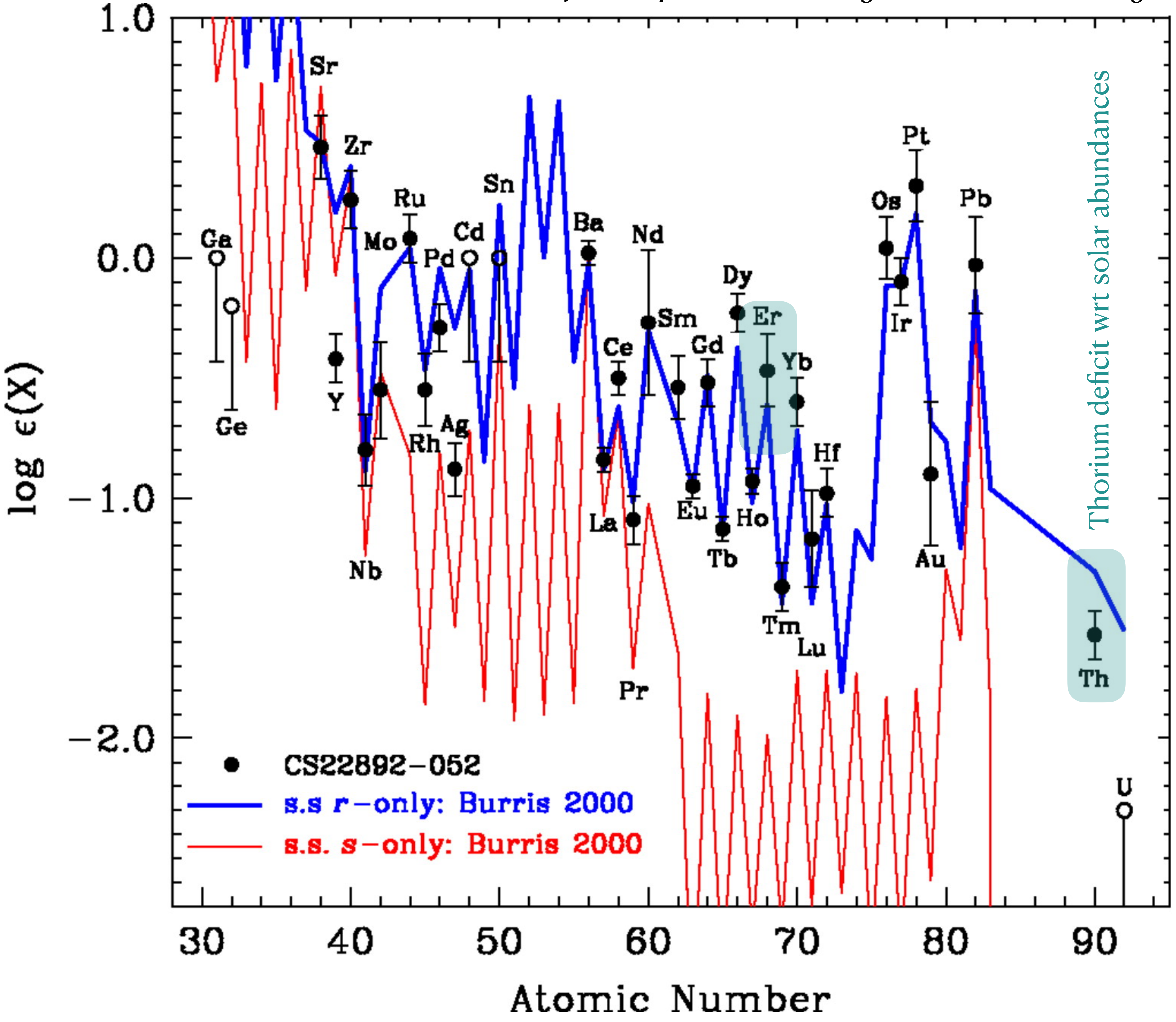
In the solar system, Th/Eu = 0.46.

In CS 22892-052, Th/Eu = 0.24.

$$t_{*,\rm Th} = 12.8 \pm 3 \text{ Gyr}$$

Old stars are everywhere, not just in globular clusters.
However, they are hard to identify in the field.

Sneden's star: CS 22892-052 very metal poor: [Fe/H] = −3.1 (Sneden et al. 2003)



Nittler et al (2008)

Age of the Universe

- Interstellar dust grains
  - Oxygen isotope ratios

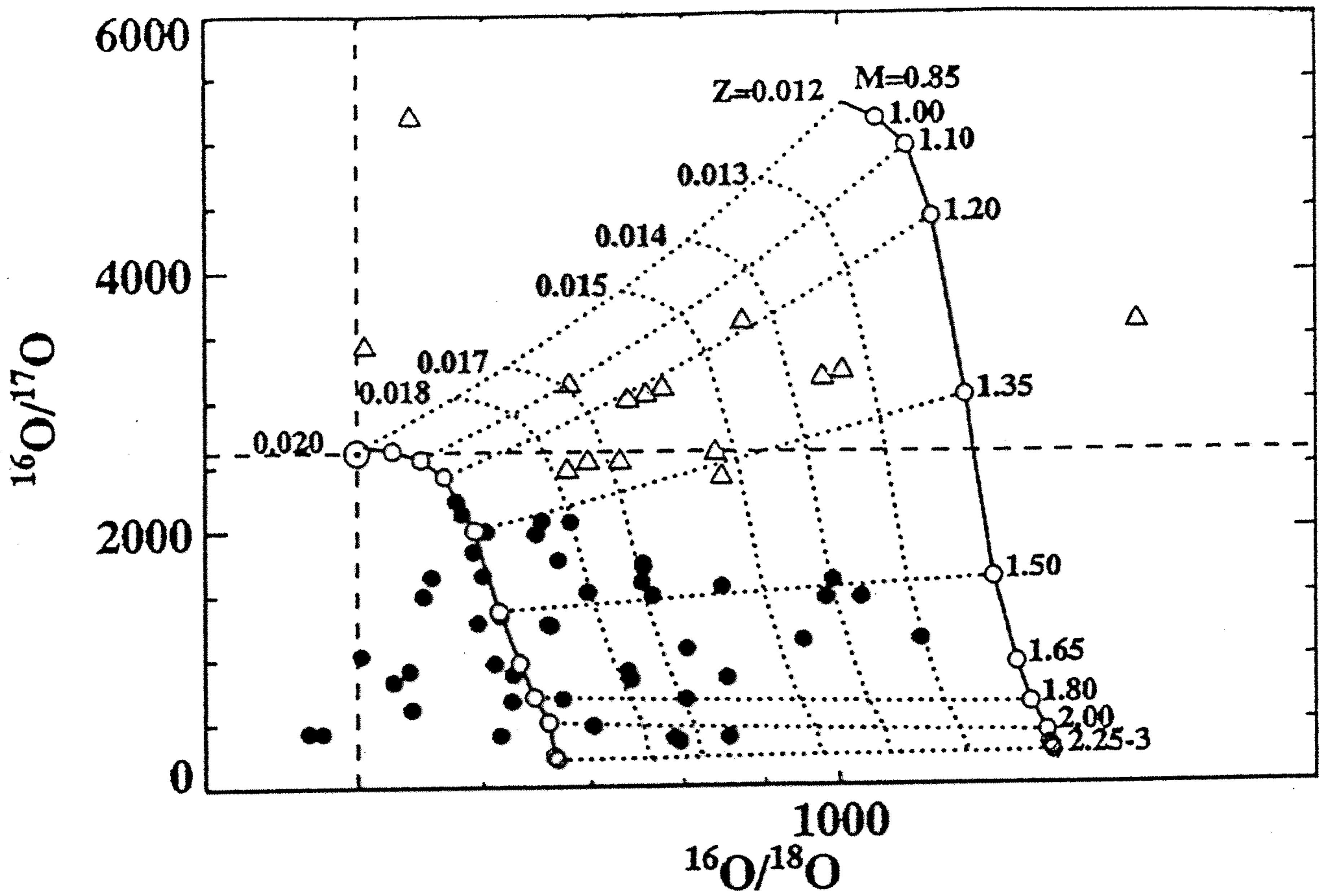


FIG. 2. Comparison of oxide grain data for groups 1 and 3 (see Fig. 1 for symbol definitions) with predictions of O-isotopic ratios following first dredge-up in red giant stars of initial mass $(0.85-3)M_{\odot}$ and metallicity $Z = 0.012-0.02$ [22]. For the sake of clarity, error bars on grain measurements are not shown. Each open circle corresponds to predictions for a distinct star. The dotted lines indicate interpolated values for masses and metallicities intermediate to those calculated. Oxide grains belonging to groups 1 and 3 have isotopic compositions consistent with these predictions, provided that they come from several different stars with distinct masses and initial compositions.

Some dust grains have been captured from hyperbolic orbits: they have an origin external to the solar system. Such grains have isotopic ratios of oxygen indicating dredge-up during the red giant phase prior to the birth of the sun. Some grains with similar isotopic ratios were captured into meteorites at the dawn of the solar system. The required chain of events implies a minimum age:

$$t_{MW} = t_{\odot} + t_{mix} + t_{*} + t_{Z}$$

$t_{\odot} = 4.55$ Gyr   age of solar system

$t_{mix} \approx 0.1$ Gyr   mixing time in ISM

$t_{*} = f(M_{*}, Z) \approx 5 \pm 1$ Gyr   evolution of star that made the grain

$t_{Z} \approx 4$ Gyr   evolution of the stars that made the metals in the star than made the grain

$$t_{MW} = 13.7 \pm 1.3 \text{ Gyr}$$

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- Interstellar dust grains
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Expansion time scale set by the Hubble time H_0^{-1}.
What about the ages of observed objects?
The contents of the universe should not be older than the universe itself!

Independent age estimates are pretty consistent

$$t_{GC} = 13.32 \pm 0.1 \text{ (stat)} \pm 0.5 \text{ (sys) Gyr}$$

$$t_{WD}^{max} = 12.5^{+1.4}_{-3.5} \text{ Gyr}$$

$$t_{*,\mathrm{Th}} = 12.8 \pm 3 \text{ Gyr}$$

$$t_{MW} = 13.7 \pm 1.3 \text{ Gyr}$$

Sets lower limit on the age of the universe that is [just barely] consistent with the Hubble time H_0^{-1}.