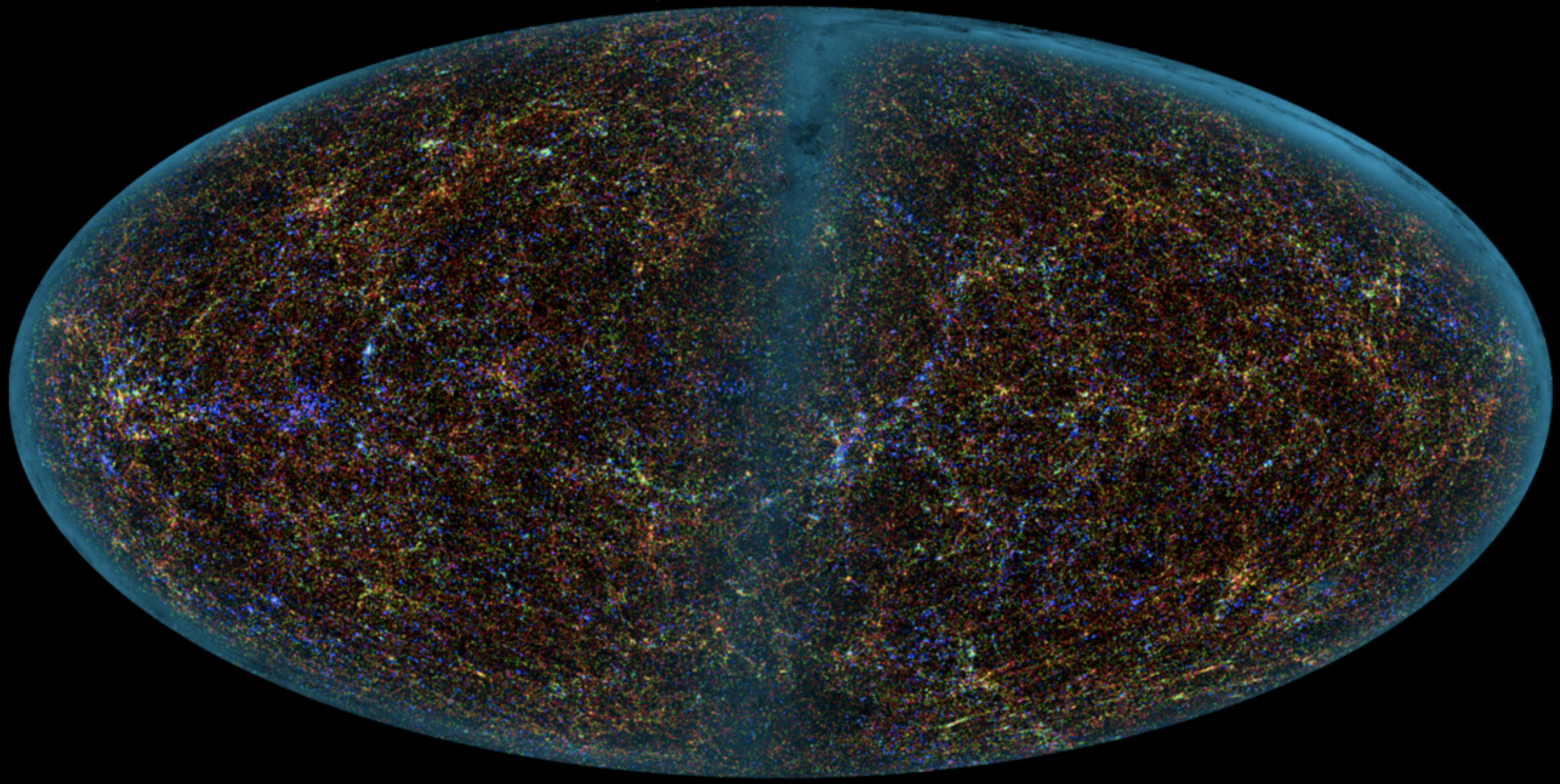
Cosmology

and Large Scale Structure



<u>Today</u>
Age constraints
Early Universe

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!

Independent age estimates are pretty consistent

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

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

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

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

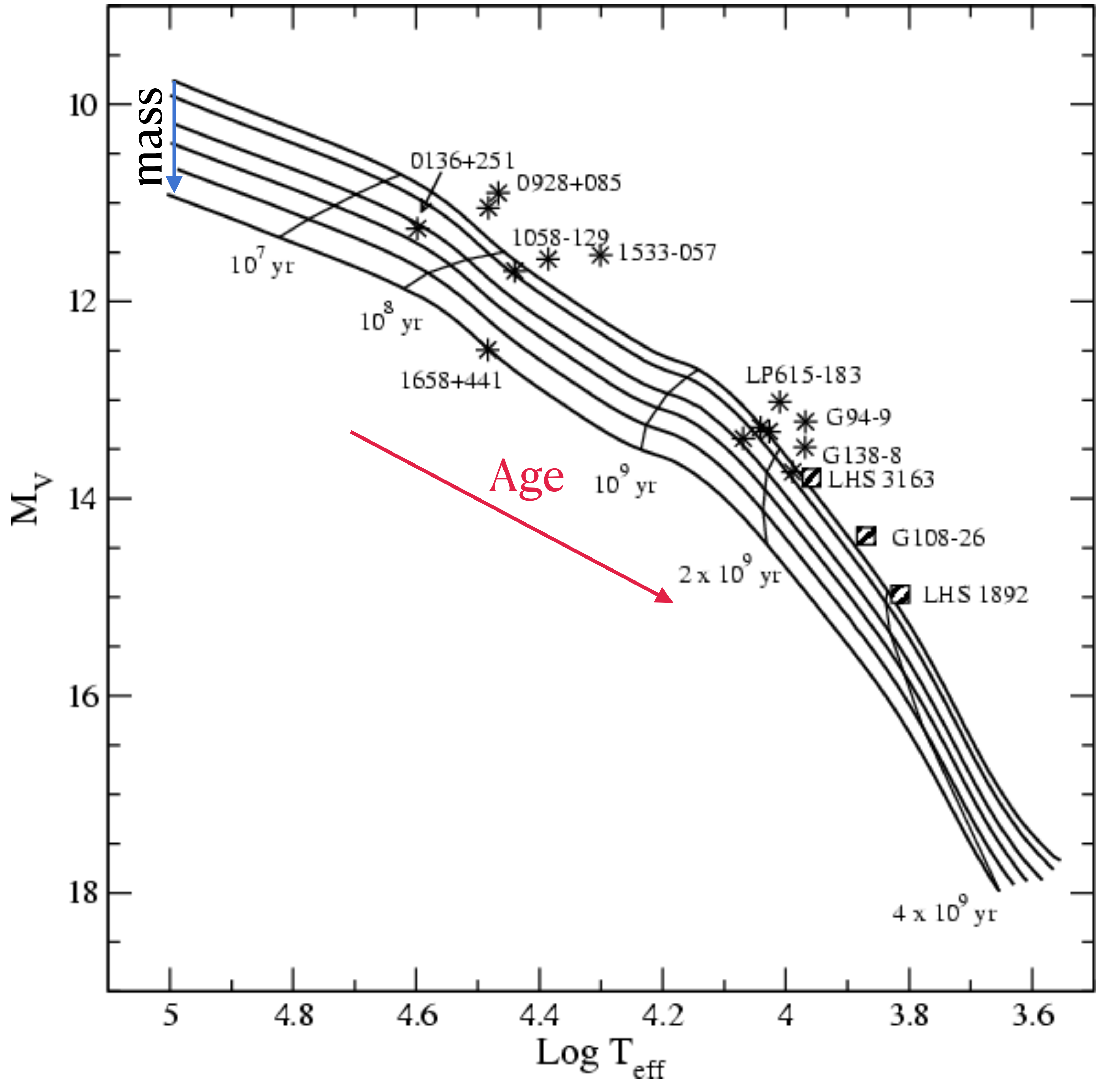
Sets lower limit on the age of the universe that is [just barely] consistent with the Hubble time H_0^{-1}.

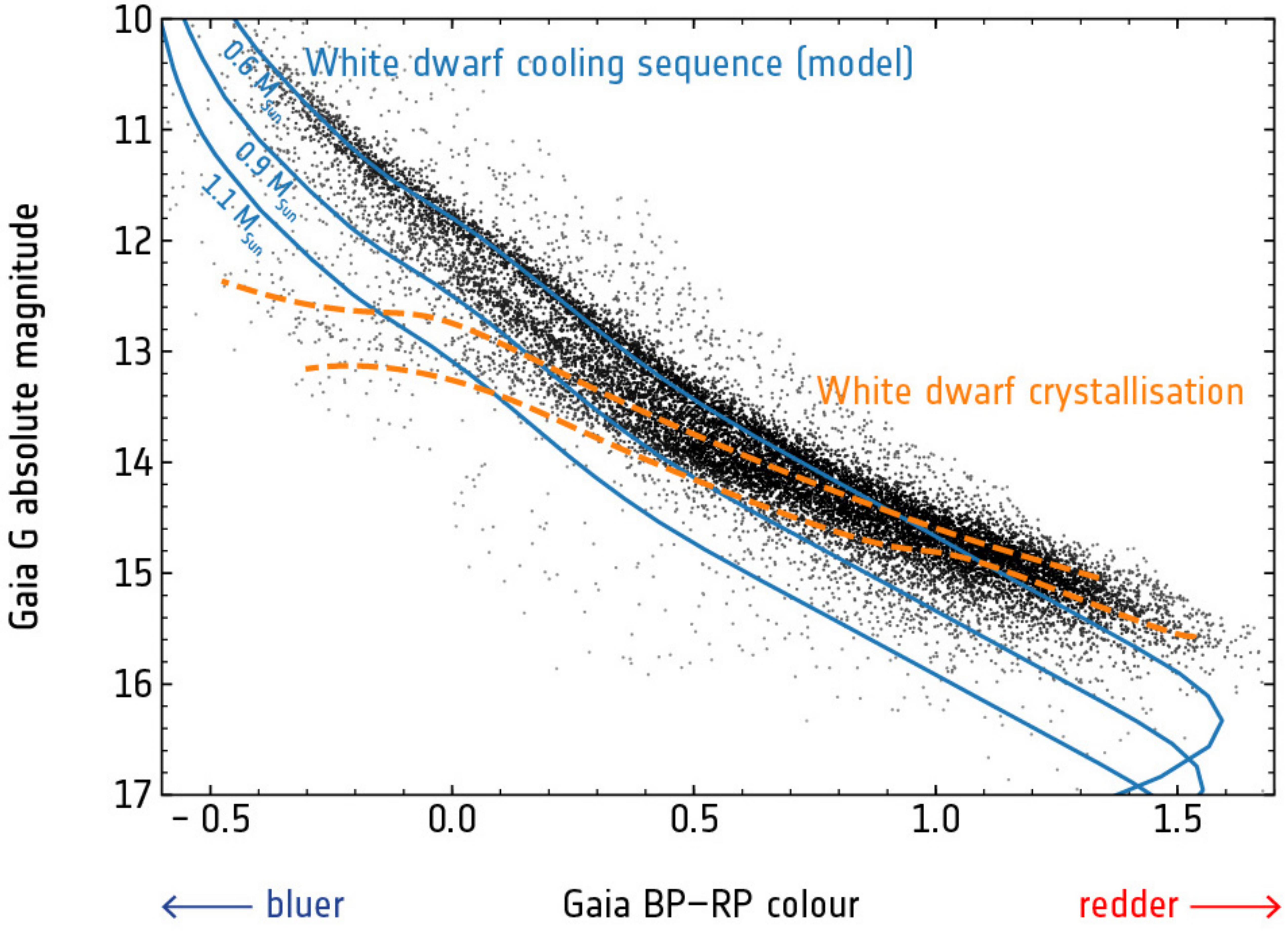
Age of the Universe

- 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

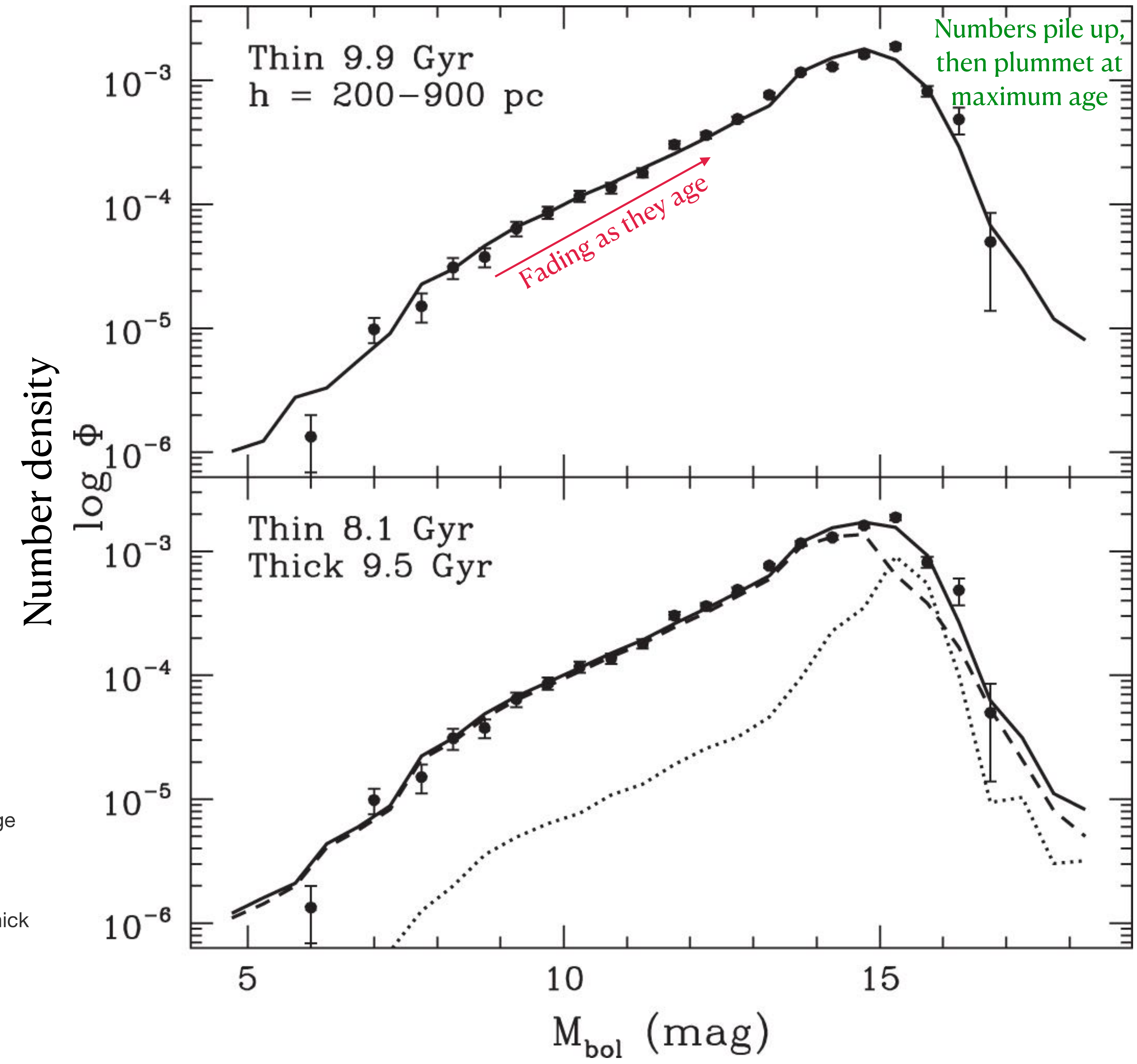
Can distinguish the age of the disk …

$$t_{WD}^{max} \approx 10 \text{ Gyr}$$

For white dwarfs in the disk of the Milky Way

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

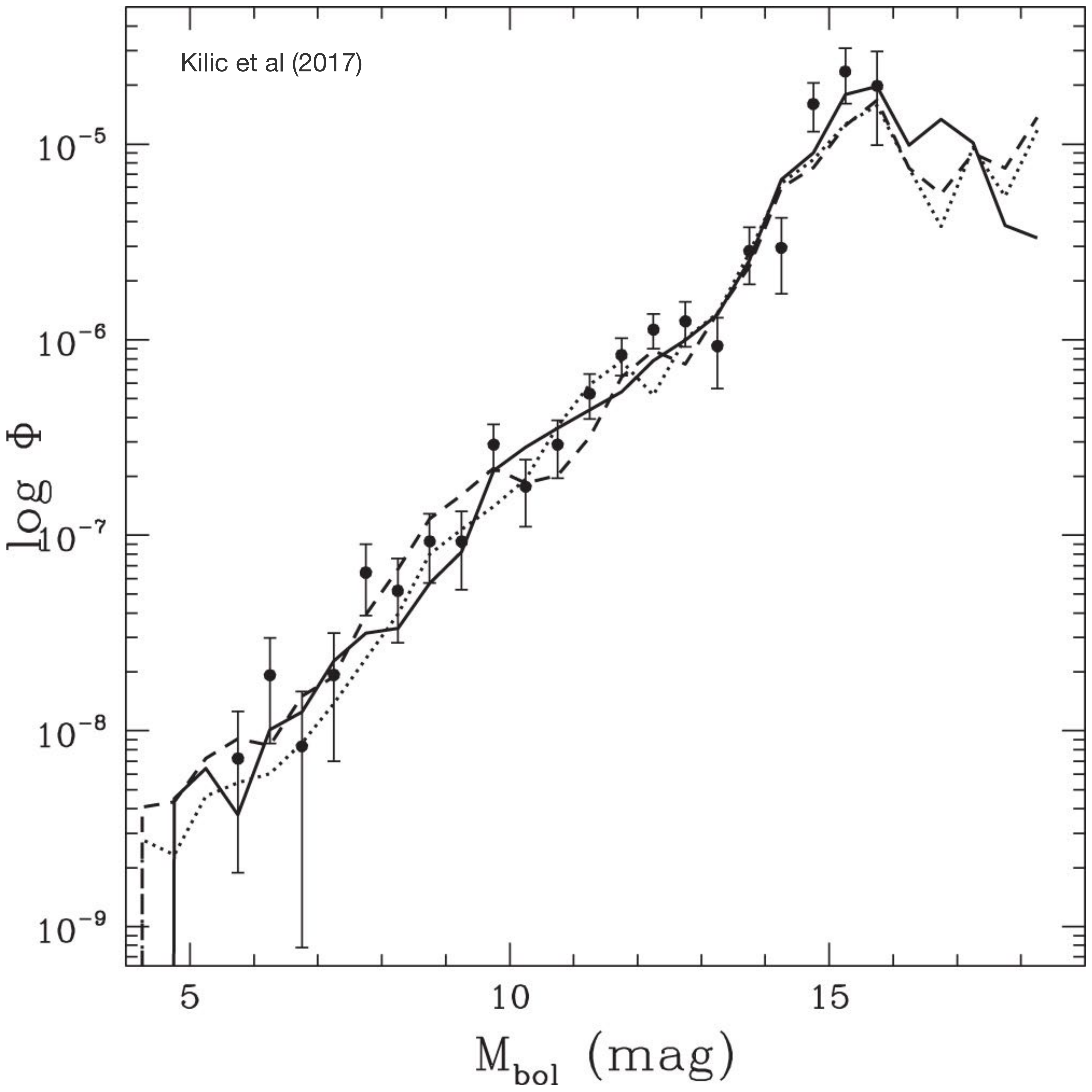
- White dwarfs
  - cooling curves & luminosity function

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

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

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

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.

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

r-process elements created in SN explosions. 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.

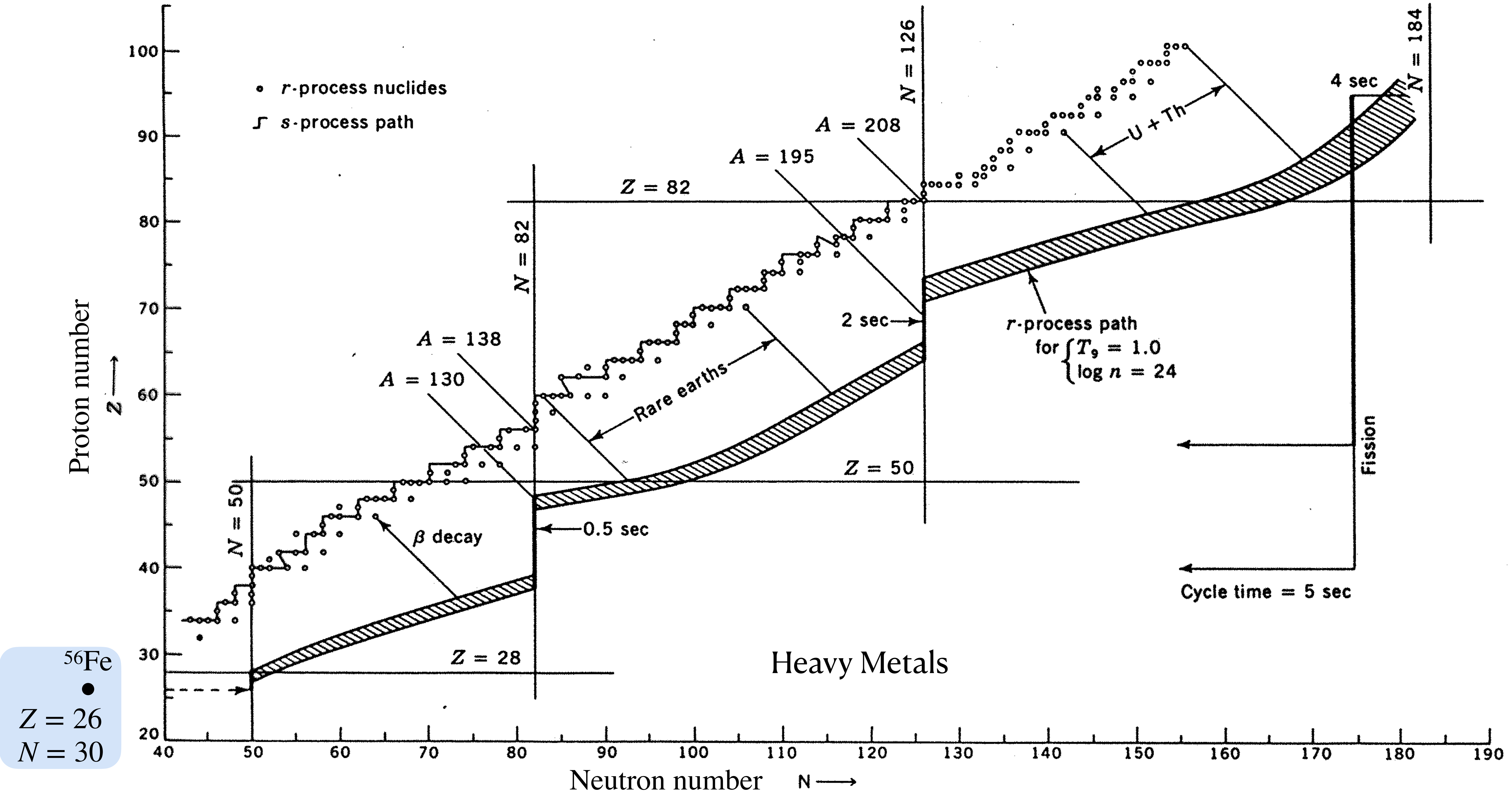


Fig. 7-30 Neutron-capture paths for the *s* process and the *r* process. The *s* process follows a path in the *NZ* plane along the line of beta stability. The neutron-rich progenitors to the stable *r*-process nuclei, which are here shown as small circles, are formed in a band in the neutron-rich area 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

- Radioactive chronometers
  - Uranium/Europium ratio

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A. Frebel & K.-L. Kratz

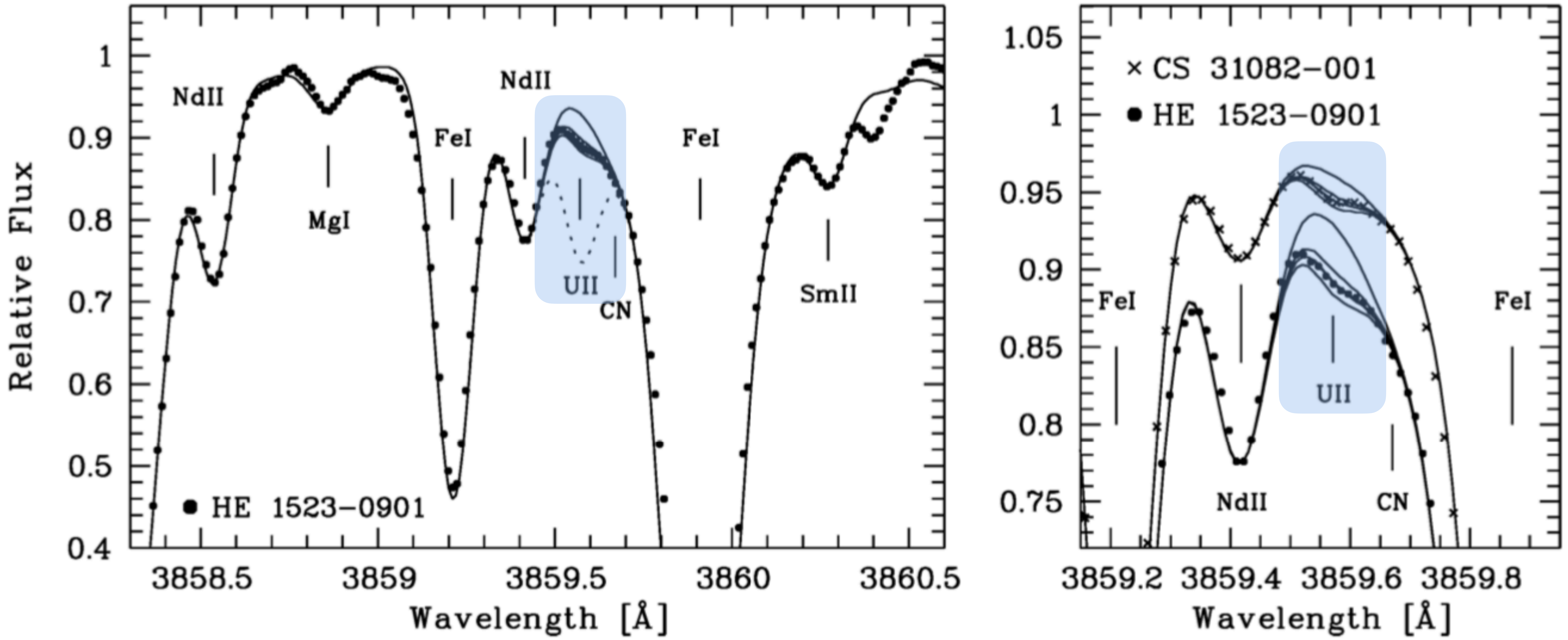


Figure 2. Spectral region around the U II line in HE 1523−0901 (*filled dots*) and CS 31082-001 (*crosses*; right panel only). Overplotted are synthetic spectra with different U abundances. The dotted line in the left panel corresponds to a scaled solar r-process U abundance present in the star if no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

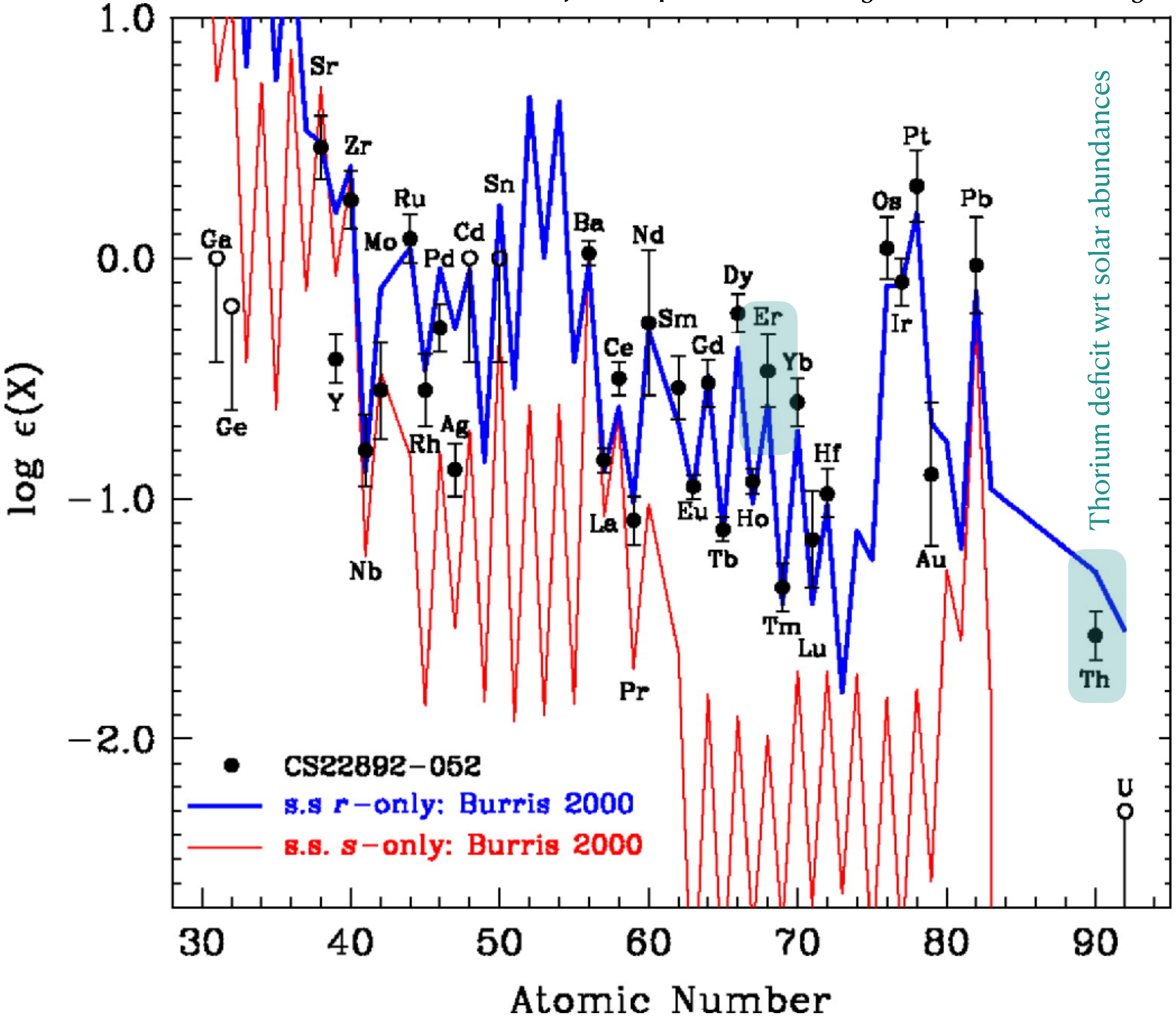
In the solar system, Th/Eu = 0.46.

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

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

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

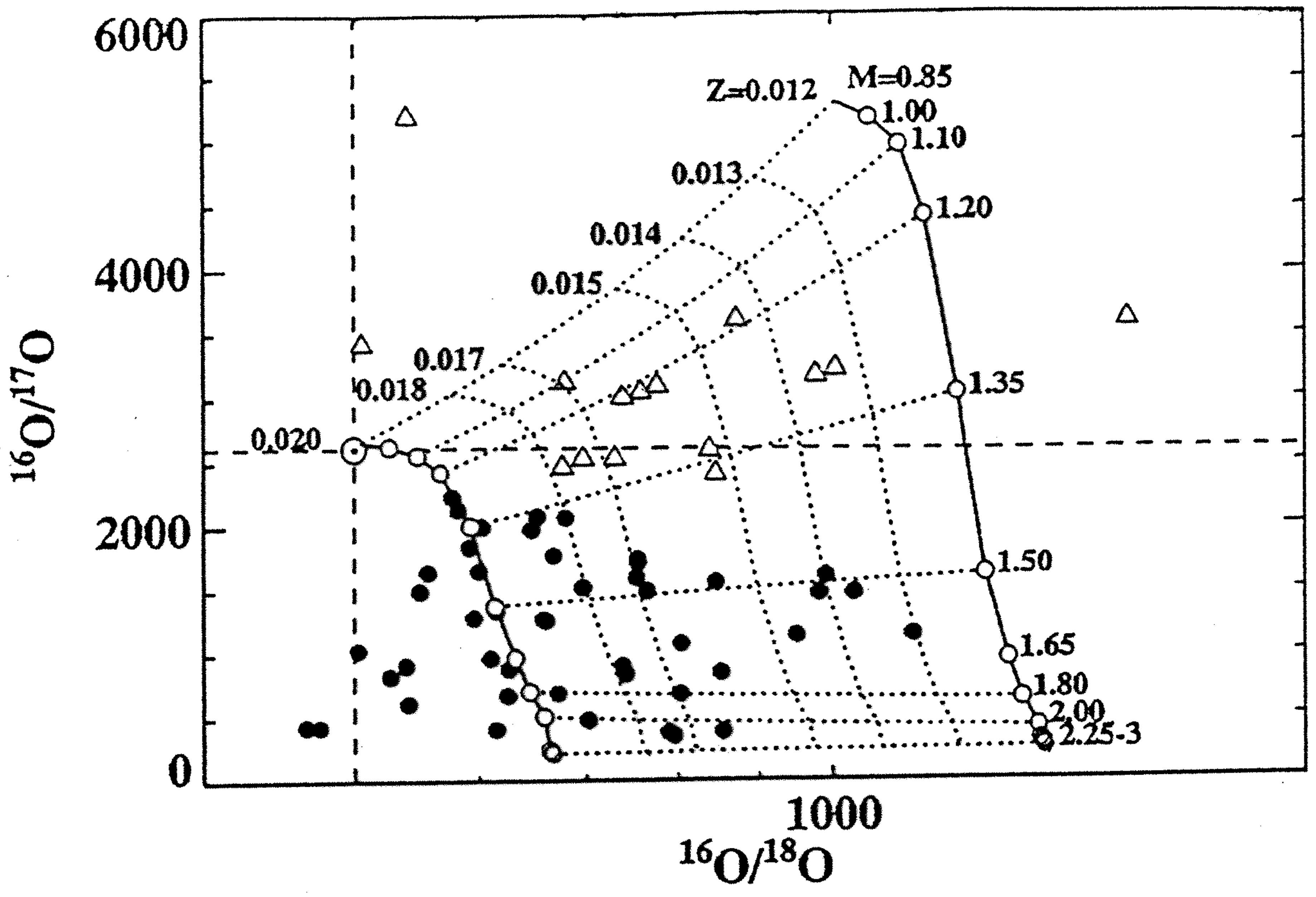
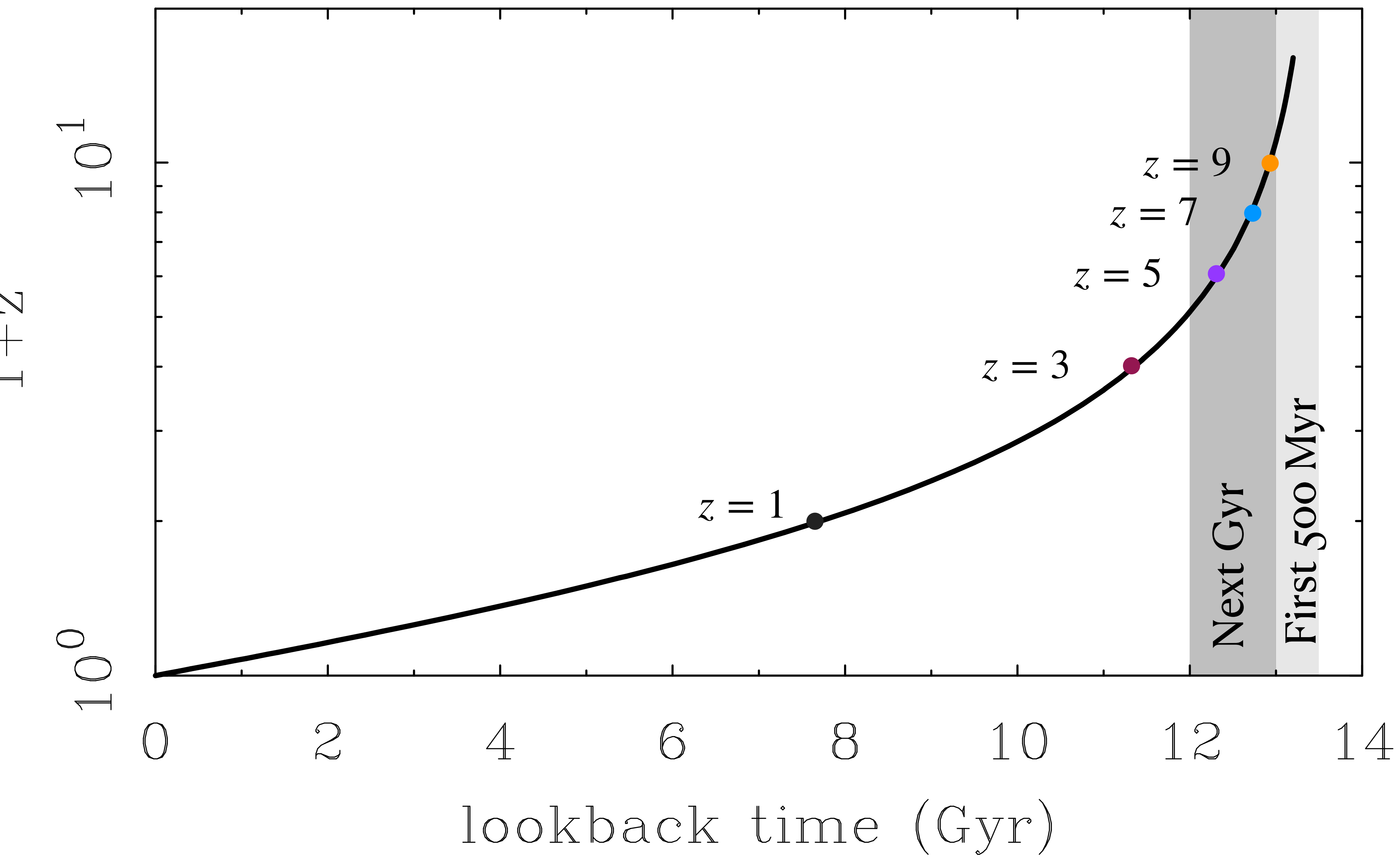


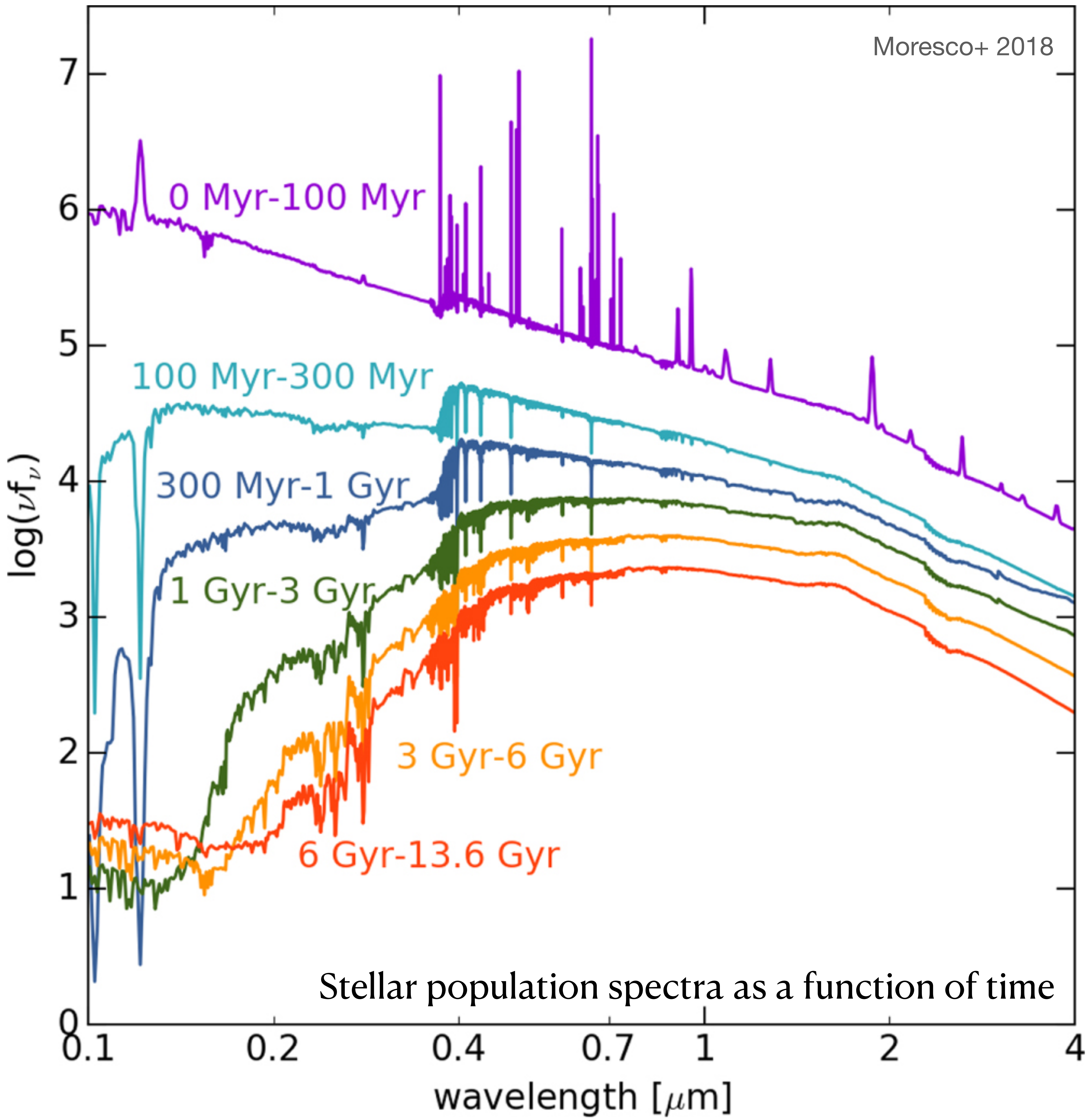
FIG. 2. Comparison of oxide grain data for groups 1 and 3 (see Fig. 1 for symbol definitions) with predictions of O-isotopic ratios following first dredge-up in red giant stars of initial mass $(0.85-3)M_{\odot}$ and metallicity $Z = 0.012-0.02$ [22]. For the sake of clarity, error bars on grain measurements 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.

Cosmic Chronometers

In principle, we can age date the stars in galaxies observed over a range of redshifts to empirically reconstruct the age-redshift relation.

LCDM age-redshift relation ($H_0 = 70$, $\Omega_m = 0.3$; $t_0 = 13.5$ Gyr)





Stellar population spectra as a function of time

Early Universe

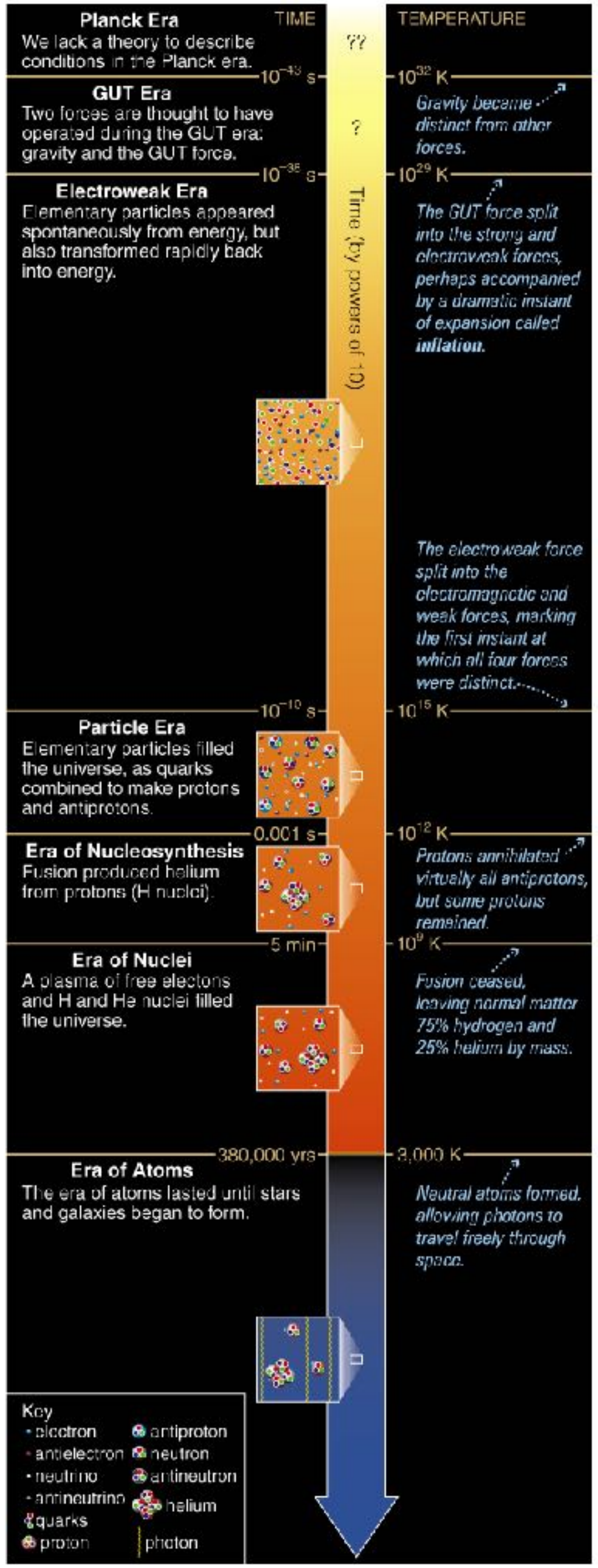


Figure 17.4 This timeline summarizes conditions and transitions that marked the early eras of the universe.

time ↓ Temp ↑

Cosmic Timeline

Time	Event
$t \sim 10^{-43}$ s	Planck scale (*speculative*)
$t \sim 10^{-38}$ s	GUT scale (*speculative*)
$t \sim 10^{-35}$ s	Inflation (*speculative*)
$t \sim 10^{-12}$ s	Standard Model forces emerge
$t \sim 10^{-8}$ s	WIMPs decouple (*speculative*)
$t \sim 10^{-5}$ s	quarks condense into baryons (*baryogenesis*)
$t \sim 10^{-4}$ s	proton-antiproton annihilation ends
$t \sim 1$ s	neutrinos decouple
$t \sim 4$ s	electron-positron annihilation ends
$t \sim 10^{2}$ s	Big Bang Nucleosynthesis
$t \sim 10^{5}$ yr	Matter-radiation equality
$t \sim 4 \times 10^{5}$ yr	Atoms form, CMB emerges
$t \sim 5 \times 10^{6}$ yr	Gas temperature decouples from radiation
$t \sim 10^{7}$ yr	Dark Ages
$t \sim 5 \times 10^{8}$ yr	Cosmic dawn (first stars)
$t \sim 10^{9}$ yr	Galaxies form
$t \sim 4 \times 10^{9}$ yr	Peak star formation
$t \sim 9 \times 10^{9}$ yr	Sun forms
$t \sim 13 \times 10^{9}$ yr	Multicellular life on earth
$t \sim 13.7 \times 10^{9}$ yr	You are now

Early U radiation dominated

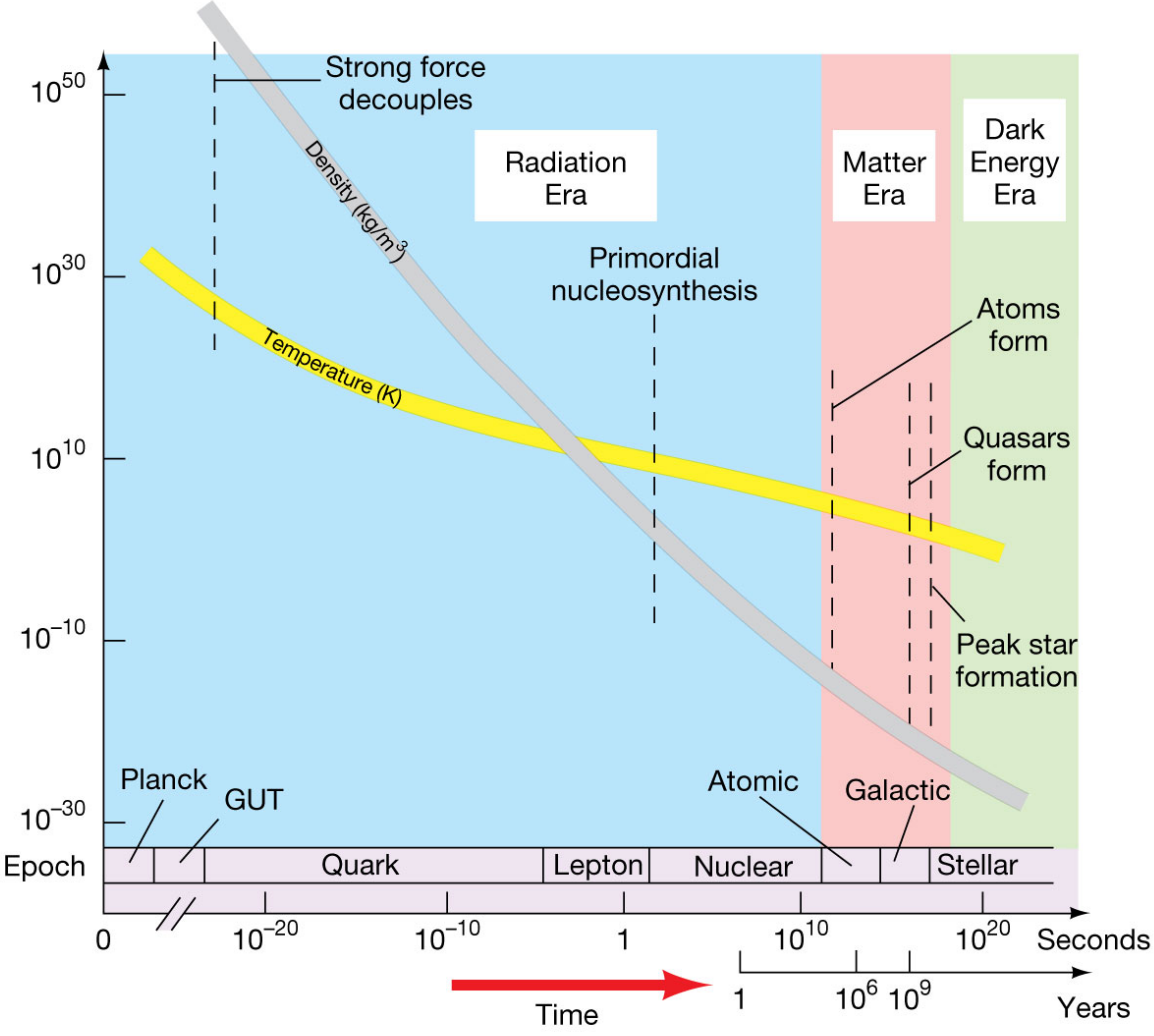
$$t \lesssim 10^5 \text{ yr}$$

$$a \sim t^{1/2}$$

$$T \sim a^{-1}$$

$$Tt^2 \sim \text{constant}$$

Decoupling means to fall out of thermal equilibrium - i.e., when it becomes impossible for the radiation field to spontaneously create particle-antiparticle pairs.



Time	Event
$t \sim 10^{-43}$ s	Planck scale (*speculative*)

Known physics breaks down at the Planck scale

$$m_P = \sqrt{\frac{\hbar c}{G}} = 1.22 \times 10^{19} \text{ GeV c}^{-2} \approx 2 \times 10^{-5} \text{ g}$$

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35} \text{ m}$$

$t_P = \dfrac{\ell_P}{c}$; need a theory of quantum gravity.

$t \sim 10^{-38}$ s GUT scale (*speculative*)

GUT stands for Grand Unified Theory; this is the hypothetical scale at which the strong nuclear force becomes indistinguishable from the electroweak force.

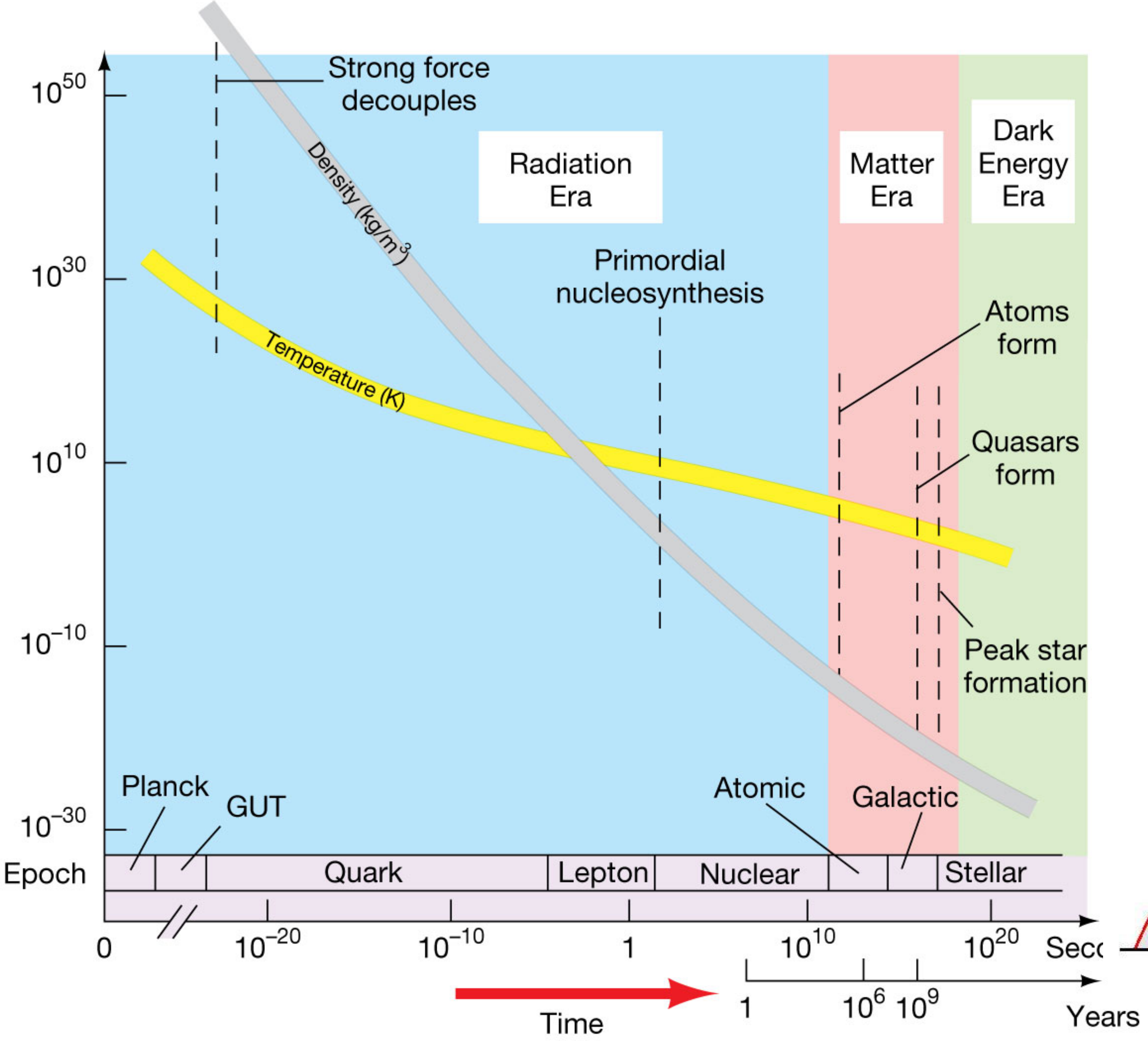
$t \sim 10^{-35}$ s Inflation (*speculative*)

Period of exponential growth: $a \sim e^{Ht}$
Must revert to radiation $a \sim t^{1/2}$ after $t \sim 10^{-24}$ s.

$t \sim 10^{-12}$ s Standard Model forces emerge

The four forces become distinct; one can begin to recognize "ordinary" particles that one might find in high energy particle accelerators: $T \sim 10^{15}$ K $\sim$ 150 GeV.

Nb.: The LHC probes ~ 7 GeV, roughly equivalent to 10^{-16} s



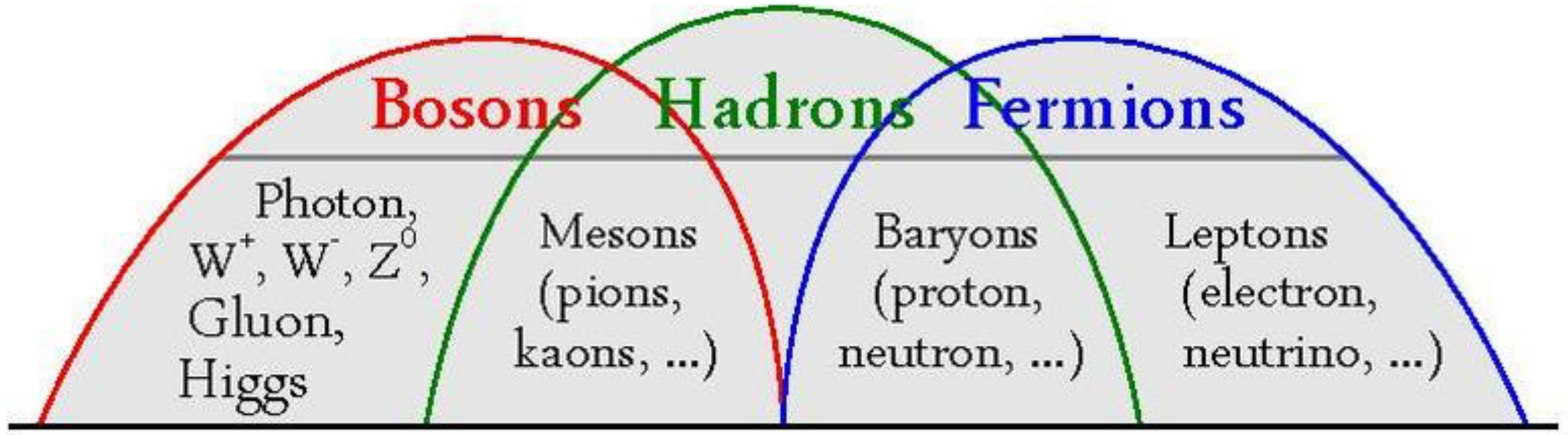
Time	Event
$t \sim 10^{-8}$ s	WIMPs decouple (*speculative*)

Weakly Interacting Massive Particles (WIMPs) freeze out around this time, depending on their mass ($M_\chi \sim 100$ GeV with huge uncertainty).
It is not clear that these supersymmetric particles exist.

$t \sim 10^{-5}$ s	quarks condense into baryons (*baryogenesis*)

The quark-gluon plasma coalesces into hadrons (baryons and mesons); no more free quarks. This must have happened, but we do not understand the resulting matter-antimatter asymmetry.
Why is there more matter than antimatter?

Baryons have an odd number of quarks (usually 3: e.g., protons & neutrons)
Mesons have an even number of quarks (usually 2: e.g., pions)



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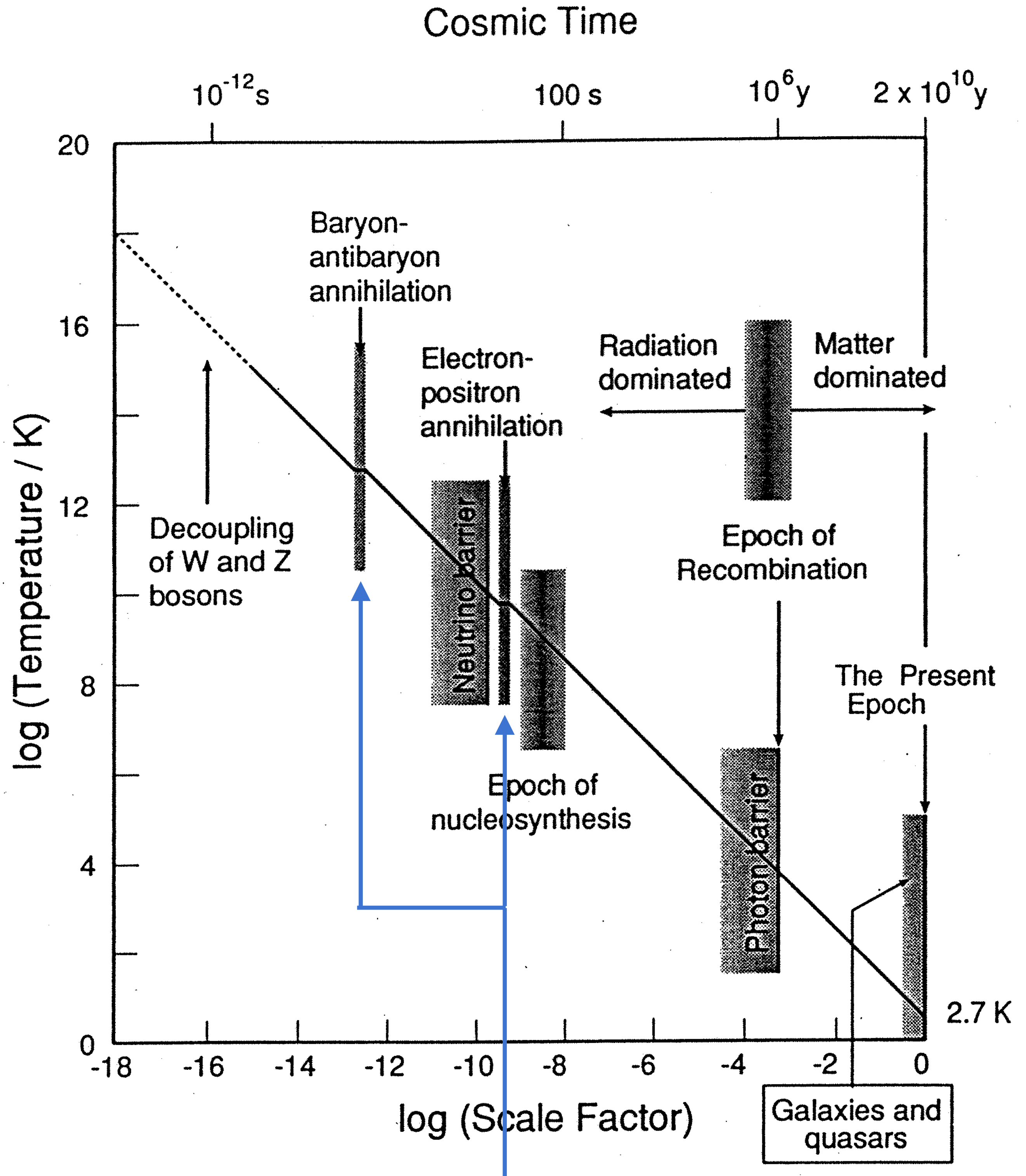


Fig. 6.1 The thermal history of the standard Hot Big Bang. The radiation temperature decreases as $T_r \propto R^{-1}$ except for abrupt jumps as different particle-antiparticle pairs annihilate at $kT \approx mc^2$. Various important epochs in the standard model are indicated. An approximate time scale is indicated along the top of the diagram. The neutrino and photon barriers are indicated. In the standard model, the Universe is optically thick to neutrinos and photons prior to these epochs.

Time	Event
$t \sim 10^{-4}$ s	proton-antiproton annihilation ends

This energy is deposited in the radiation field (which becomes the CMB). Only about one proton is left over for every billion proton-antiproton pairs (this is the matter-antimatter asymmetry).

There are $10^9 + 1$ protons for every 10^9 antiprotons

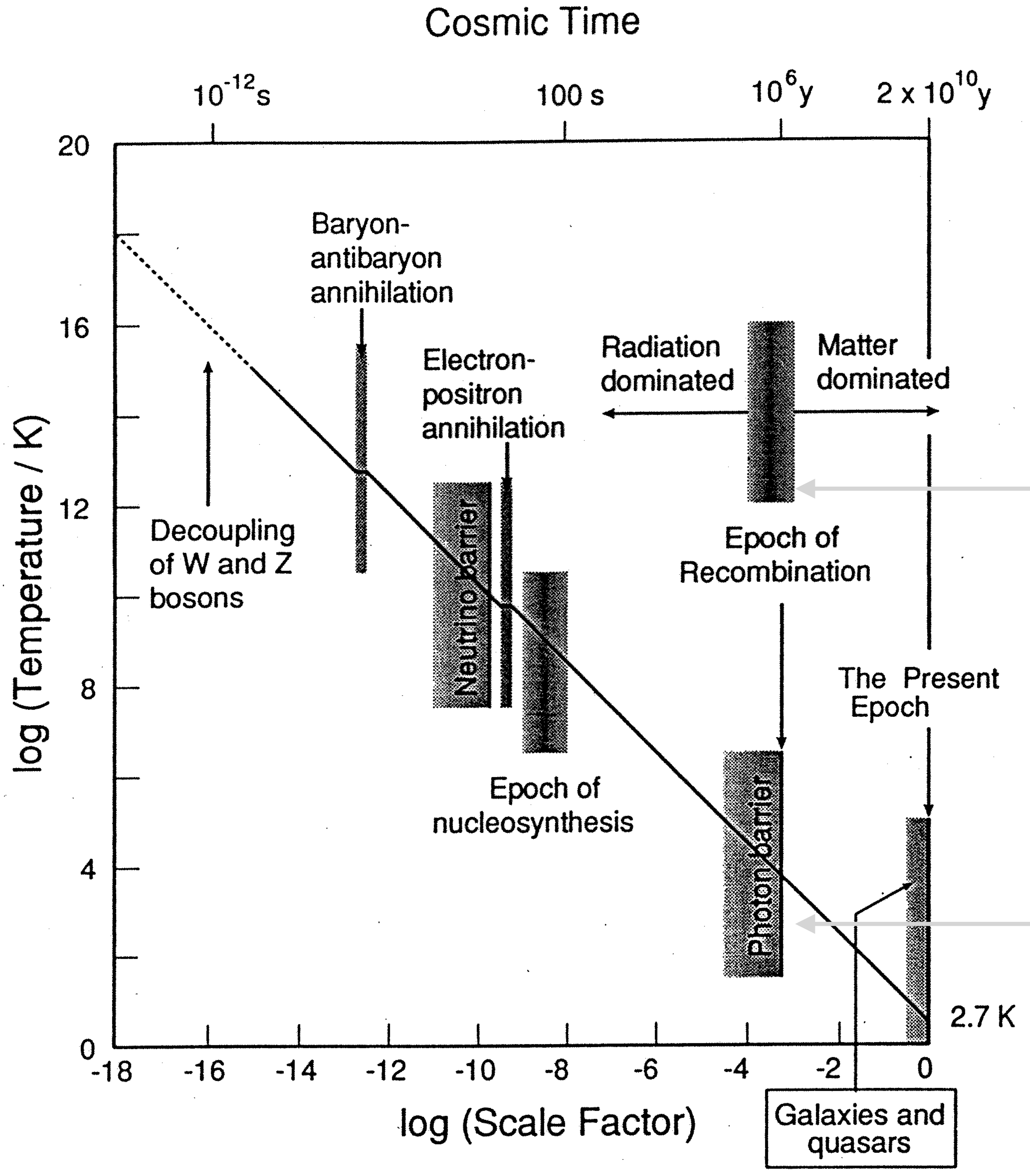
$t \sim 1$ s — neutrinos decouple

Neutrinos drop out of equilibrium. They lose energy with expansion the same as the radiation field, $T_\nu \sim a^{-1}$, with an initial energy density $\varepsilon_\nu \sim T_\nu^4$ fixed at this point.

$t \sim 4$ s — electron-positron annihilation ends

Being less massive than protons, electrons freeze out from positrons at this later time. The excess energy feeds the radiation background but not the neutrino background.

- Note the brief pause in the decline of the temperature of the radiation field as first proton-antiproton annihilation, then later electron-positron annihilation dump energy into radiation.



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Called the "photon barrier" here because of the sudden change in opacity.

Time	Event
$t \sim 10^2$ s	Big Bang Nucleosynthesis

Surviving neutrons fuse with protons to make the isotopes of hydrogen, helium, and lithium. These exist as free nuclei in an opaque plasma until recombination.

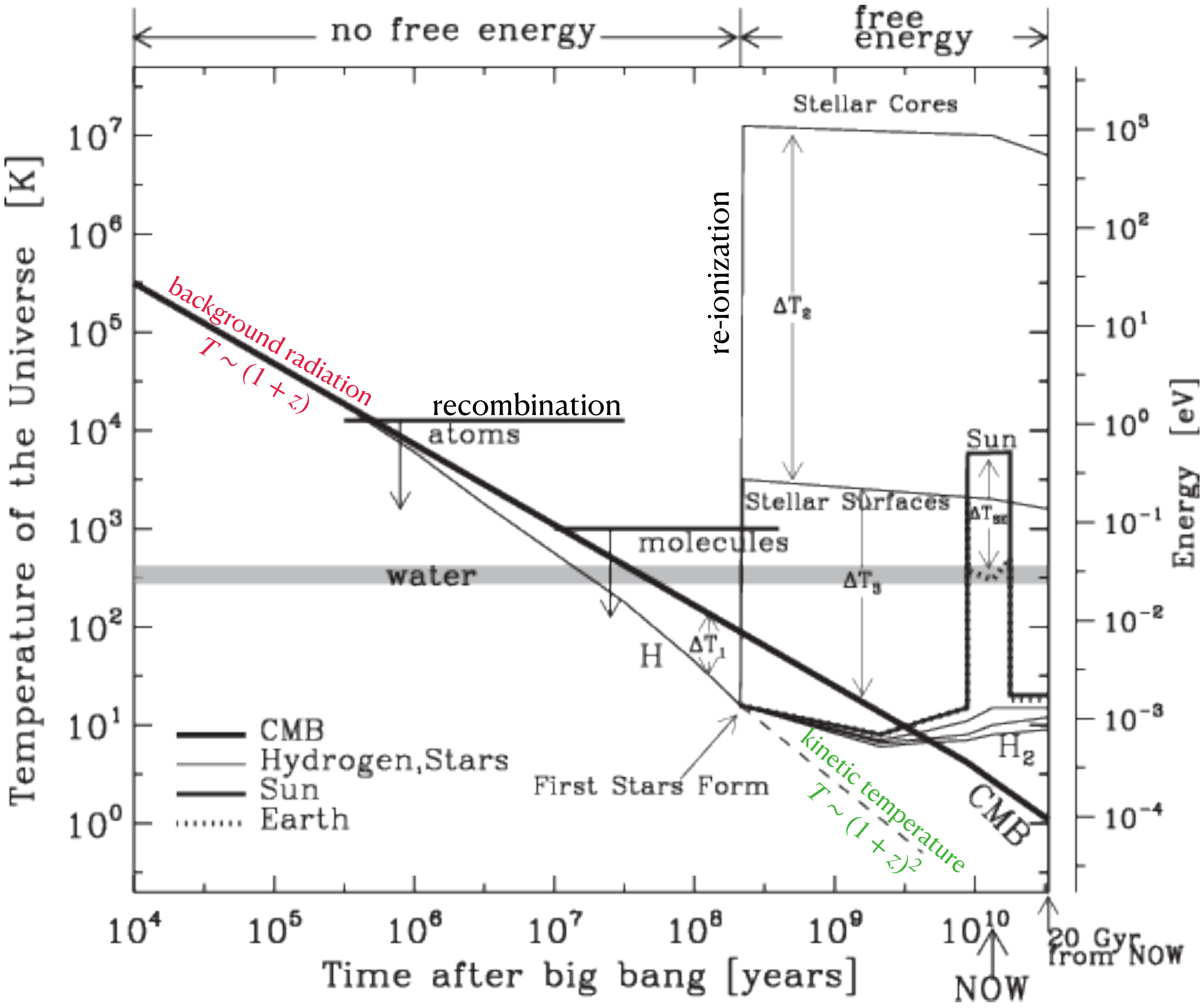
^{1}H ^{2}H ^{3}He ^{4}He ^{6}Li ^{7}Li

$t \sim 10^5$ yr — Matter-radiation equality

Must happen at some point since $\varepsilon_r \sim a^{-4}$ while $\rho_m \sim a^{-3}$. Exactly when depends sensitively on the matter density.

$t \sim 4 \times 10^5$ yr — Atoms form, CMB emerges

Electrons and protons combine to form hydrogen: the universe transitions from an opaque plasma to a transparent, neutral gas. The opacity drops to near zero; the photons of the radiation field propagate freely without further interactions.



Time	Event
$t \sim 5 \times 10^6$ yr	Gas temperature decouples from radiation

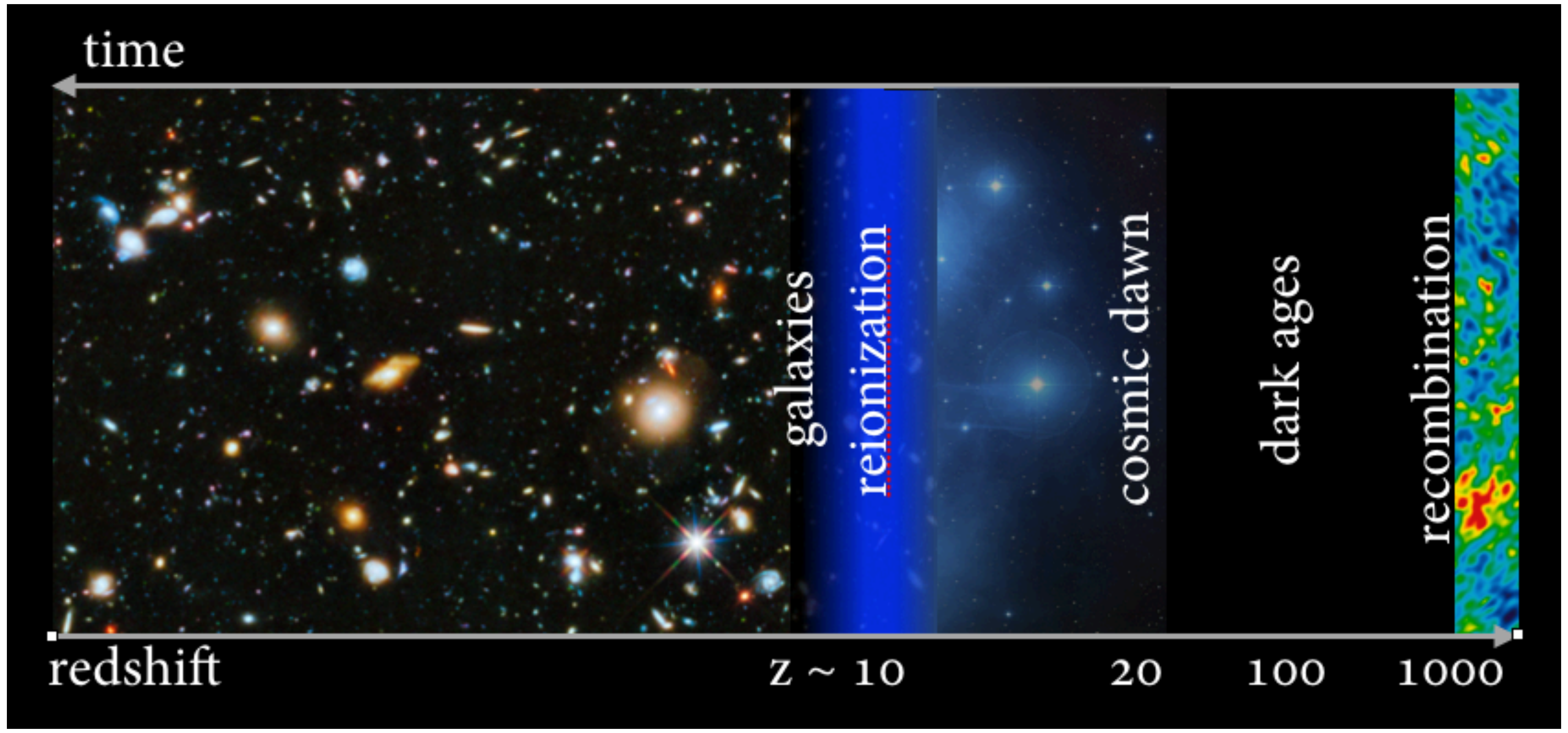
After recombination, the kinetic temperature of matter departs from that of the radiation field. They start out identical, and it takes a while for the matter to relax to fall as $T_{mat} \sim a^{-2} \sim (1+z)^2$ after $z \approx 200$.

$t \sim 10^7$ yr Dark Ages (no stars)

From $z \approx 1000$ to $z \approx 20$, the universe is composed of neutral, primordial gas. Sources of light have yet to form, so this period is known as the Dark Ages.

$t \sim 5 \times 10^8$ yr Cosmic dawn / re-ionization

Formation of the first stars (and maybe quasars?) These flood the universe with UV radiation that re-ionizes the universe. The gas in the intergalactic medium remains hot and highly ionized to this day.



Empirical Pillars of Hot Big Bang

- Hubble expansion
- Big Bang Nucleosynthesis
- Relic Radiation (CMB)

Time	Event
$t \sim 4 \times 10^5$ yr	Atoms form, CMB emerges
$t \sim 5 \times 10^6$ yr	Gas temperature decouples from radiation

Baryons can only begin to gather together and form structures after decoupling from the radiation

$t \sim 10^7$ yr	Dark Ages
$t \sim 5 \times 10^8$ yr	Cosmic dawn / reionization
$t \sim 10^9$ yr	Galaxies form

Free fall time for Milky Way mass ~ 1 Gyr
Probably a messy process involving the merger of smaller protogalactic fragments that can collapse more quickly.

$t \sim 4 \times 10^9$ yr Peak star formation

The star formation rate of the universe peaked at $z \approx 2$; declines precipitously after $z < 1$

$t \sim 9 \times 10^9$ yr Sun forms

A relative late comer, merely 4.5 Gyr old.

$t \sim 13 \times 10^9$ yr multicellular life on earth

Singe-celled life appeared fairly early, but the Cambrian explosion didn't occur until 0.6 Gyr ago