Galactic habitable zones with chemical evolution models

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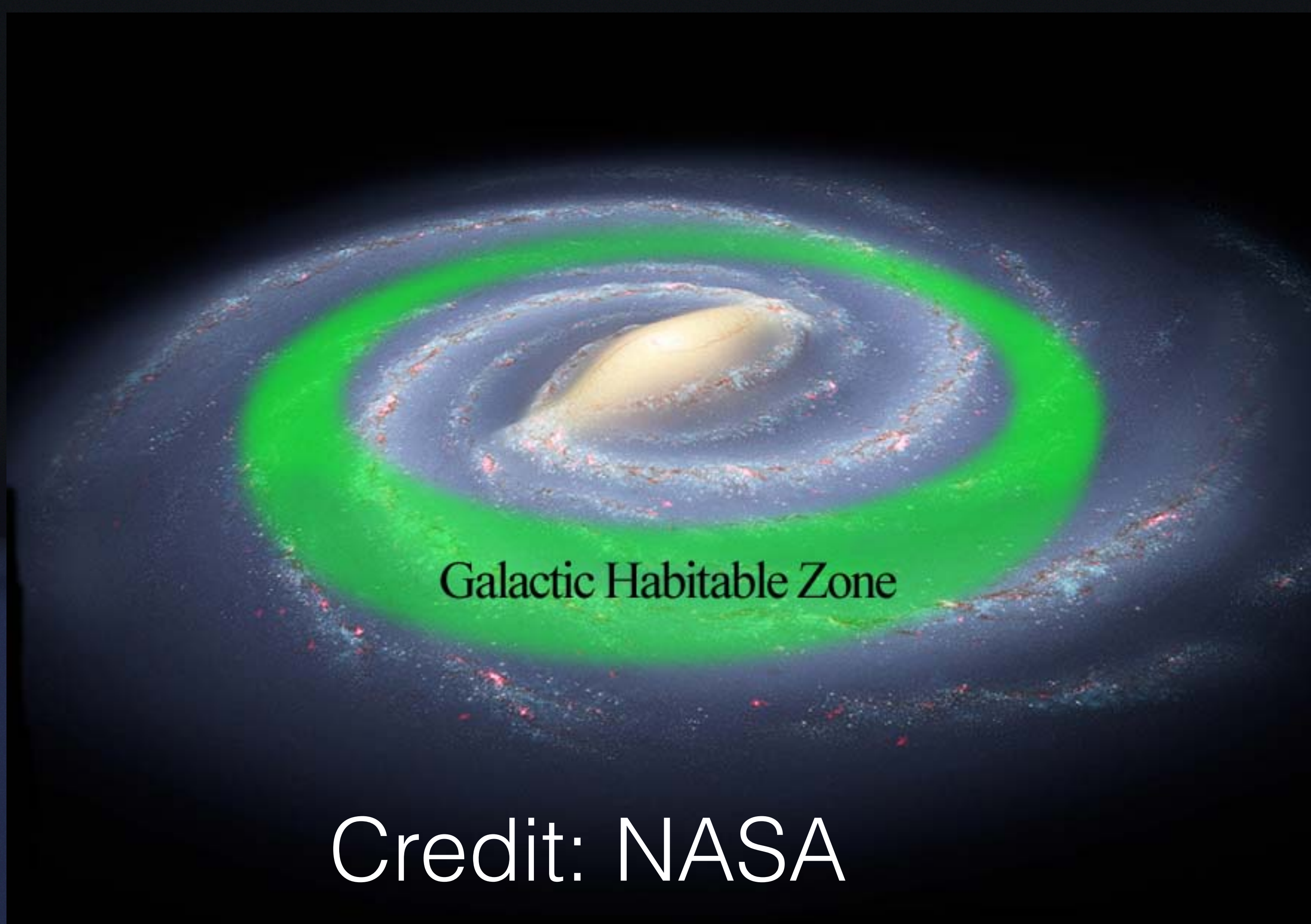
14th November 2024

FLORENCE 12-14 NOVEMBER 2024

The GHZ definition

The Galactic habitable zone is defined as the region with sufficiently high metallicity to form planetary systems in which Earth-like planets could be born and might be capable of sustaining life, after surviving to close supernova explosion events.

(GONZALEZ ET AL. 2001)



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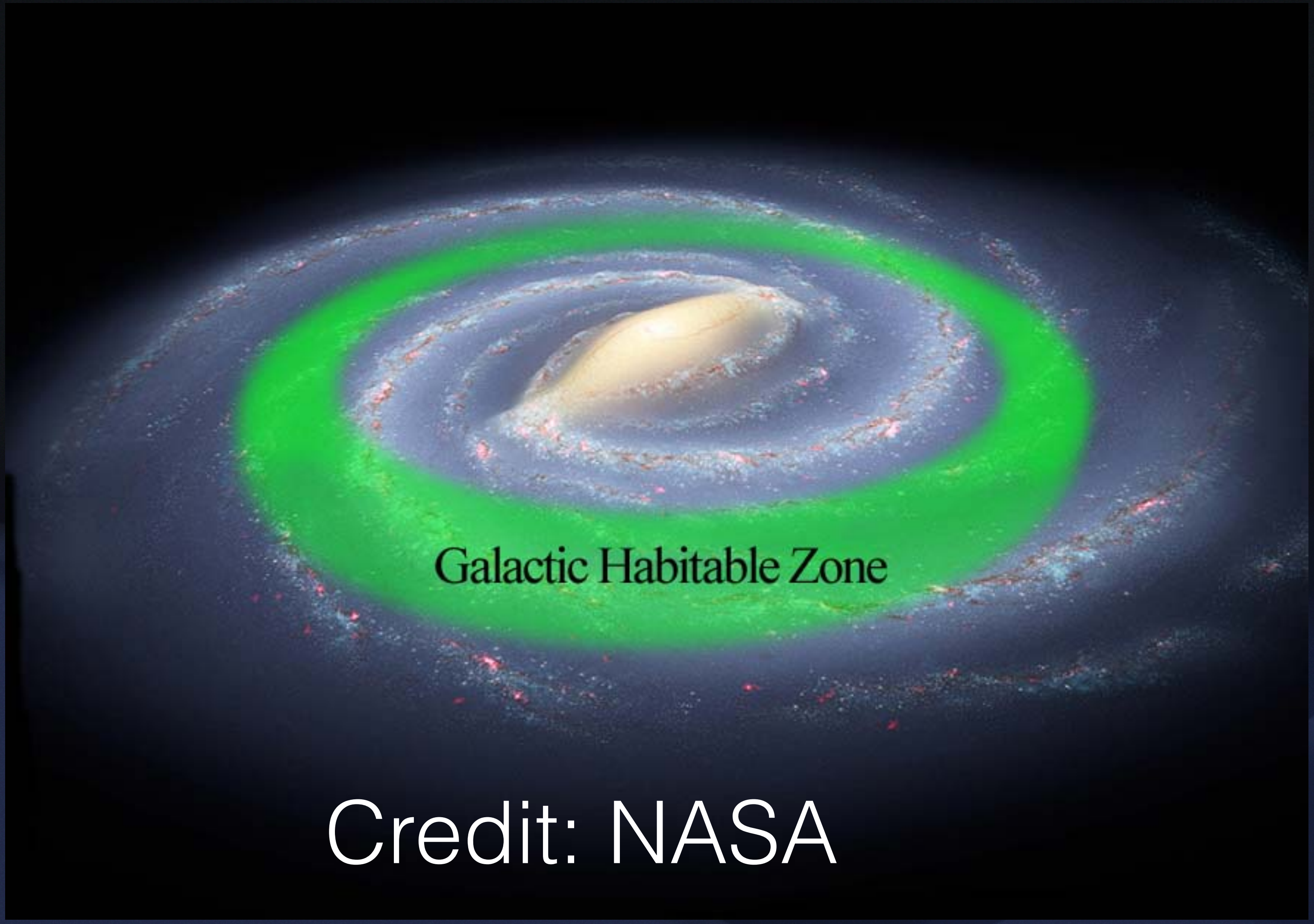
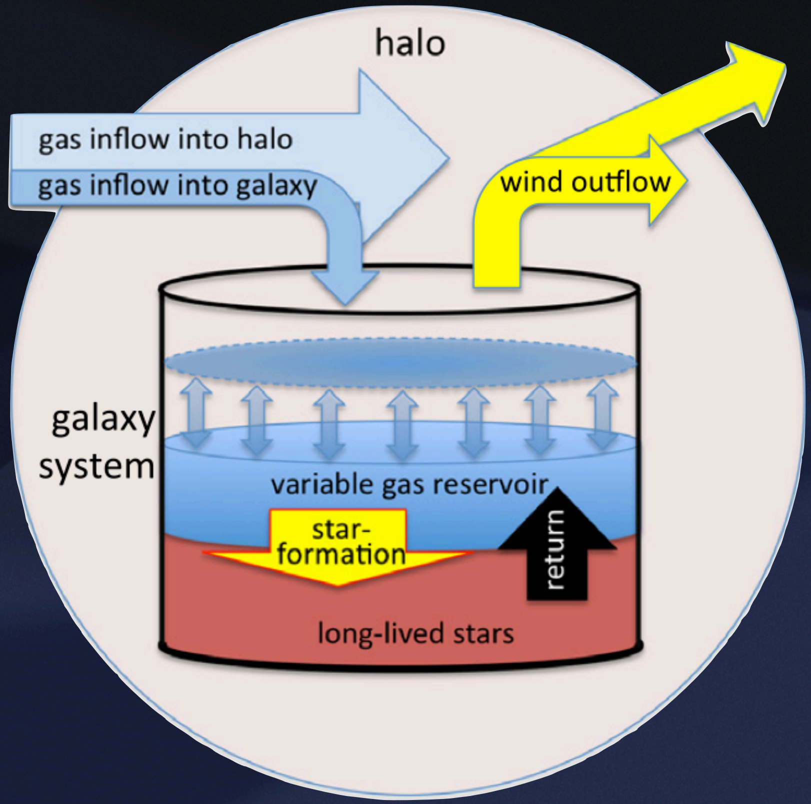
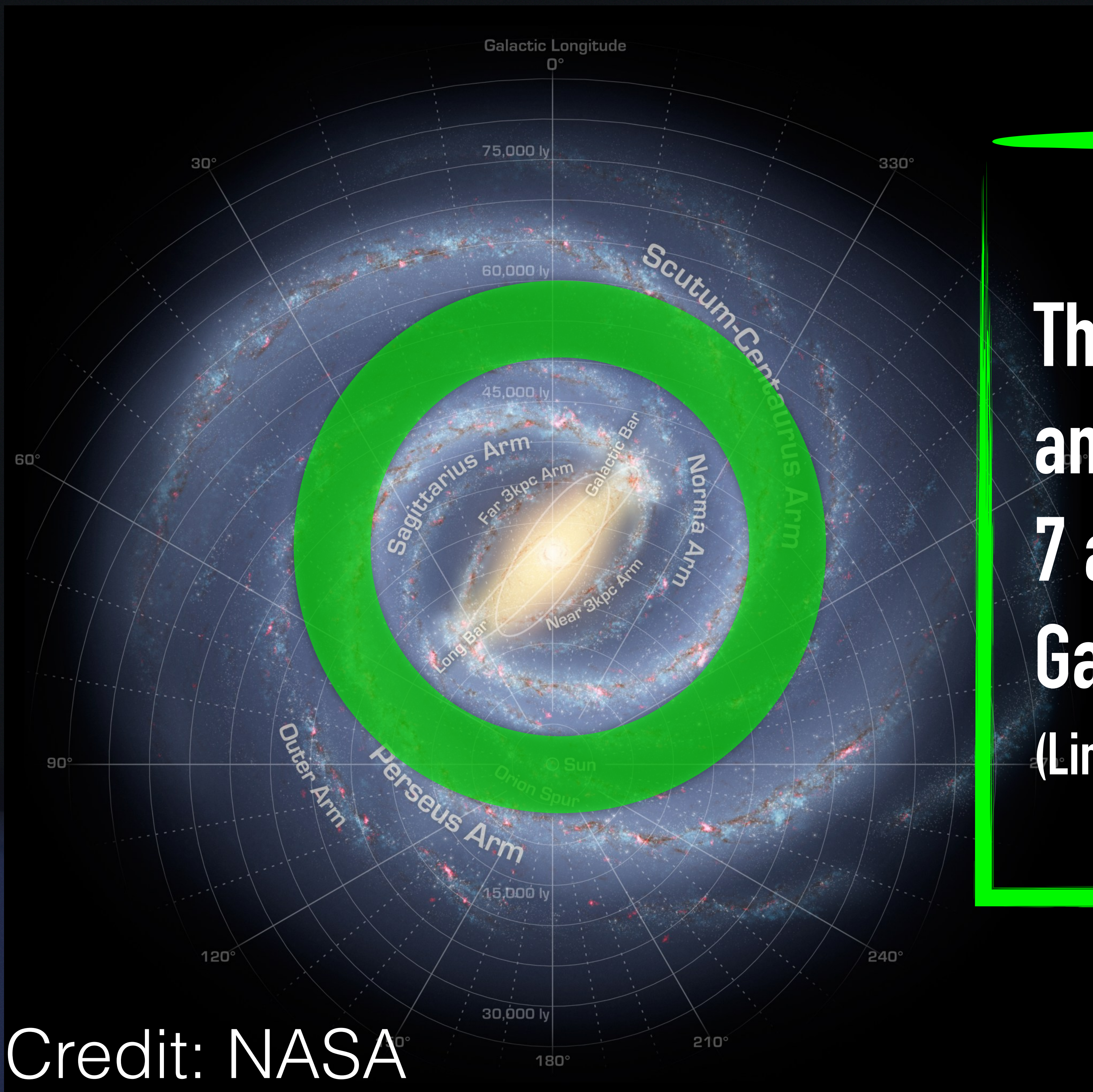




The GHZ definition

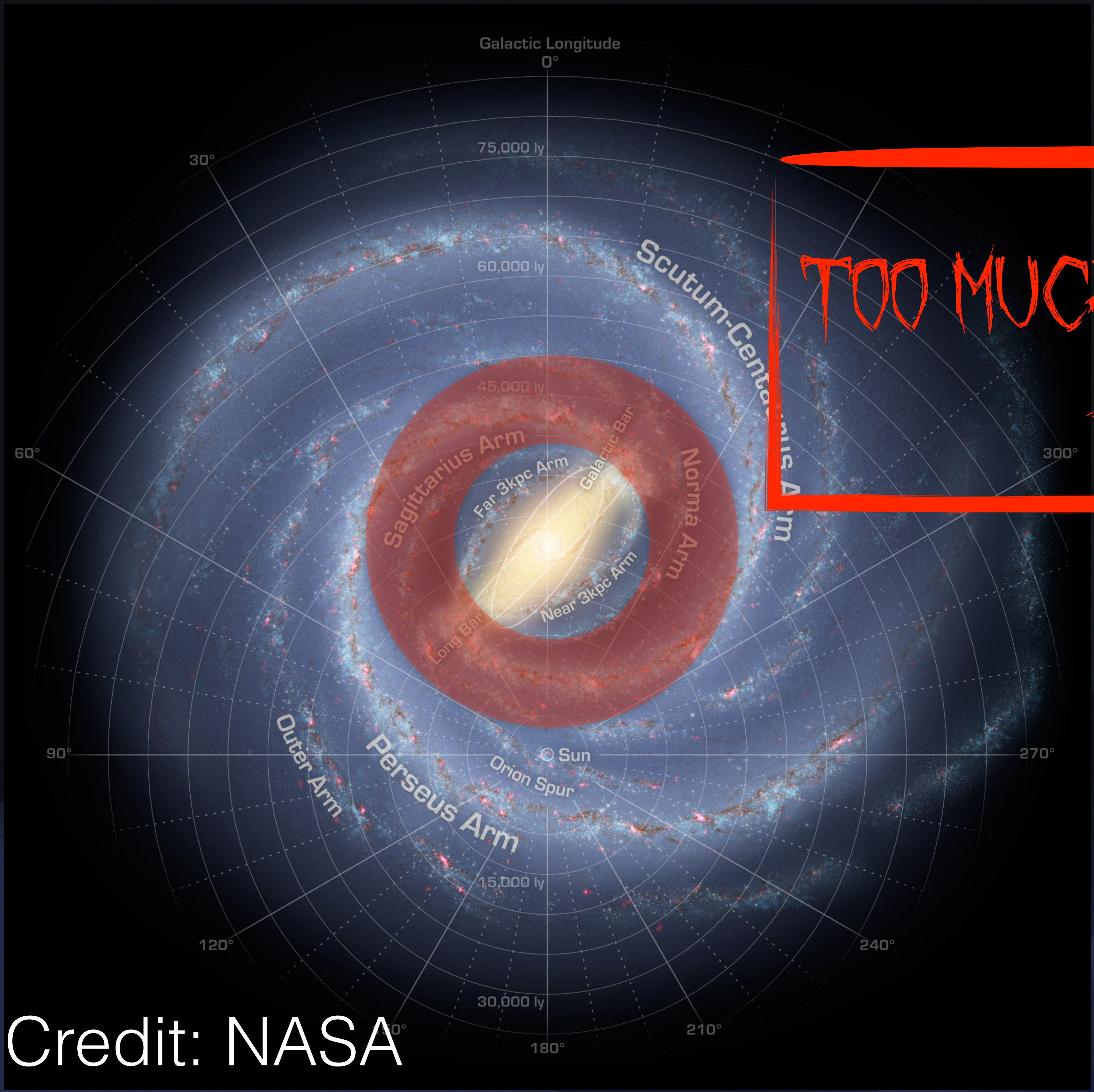


Credit: NASA

The GHZ identified as an annular region between 7 and 9 kpc from the Galactic Centre

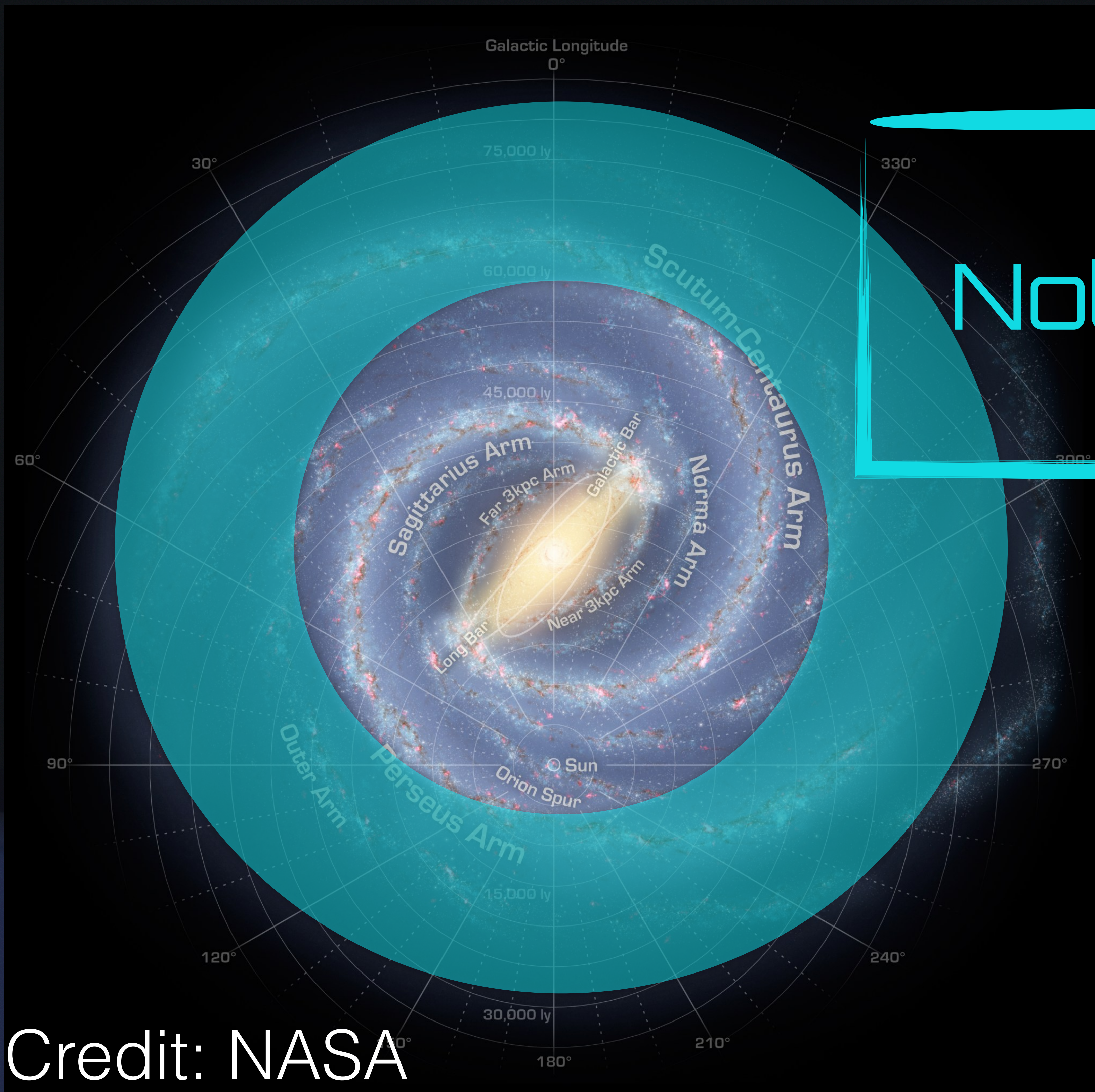
(Lineveawer +04, Spitoni +14,+17).

The GHZ definition



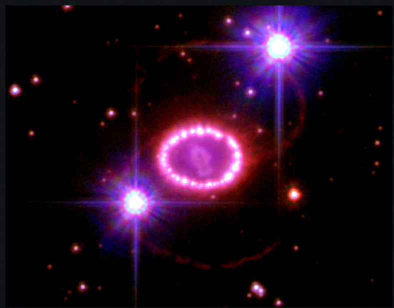
TOO MUCH STAR-FORMATION ACTIVITY

The GHZ definition



Credit: NASA

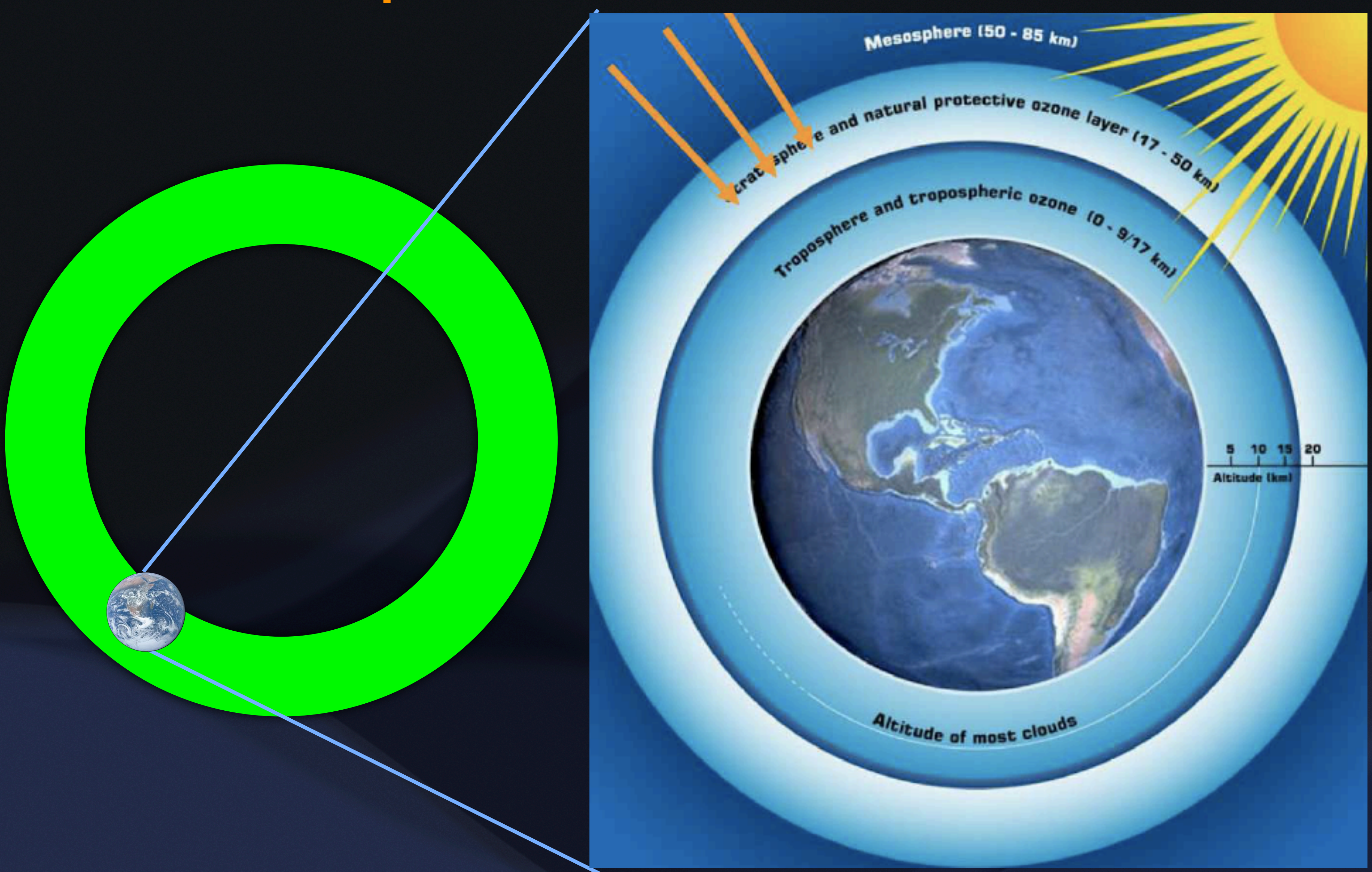
Not many stars



When a SN explodes, it emits STRONG RADIATION that may ionize the planets atmosphere, causing stratospheric ozone depletion.

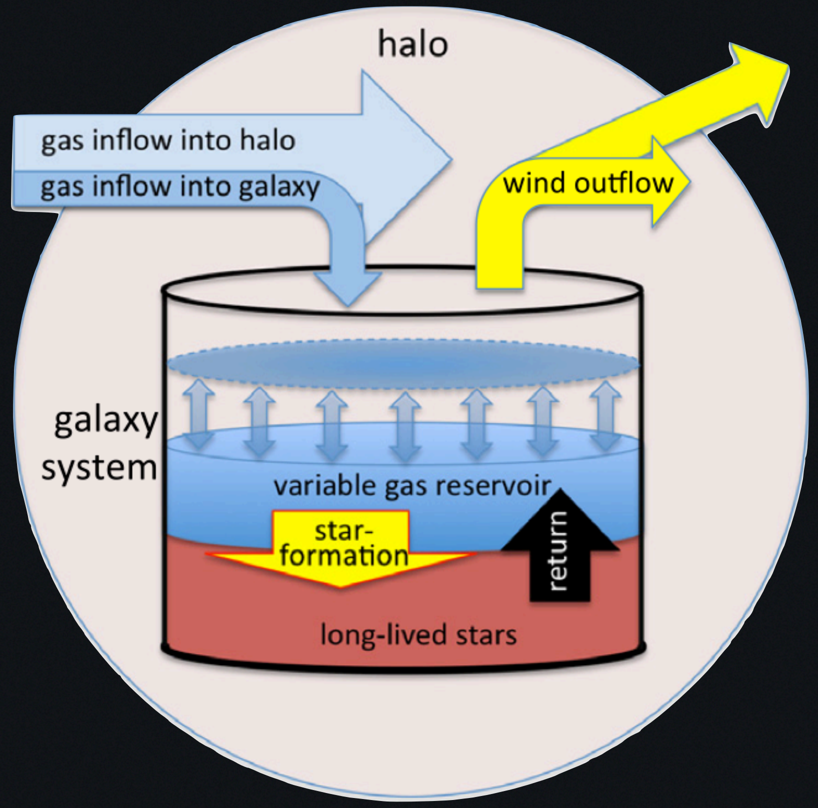
THE ULTRAVIOLET FLUX from the host star can damage genetic material DNA, and consequently the planet sterilization.

(Gehrels +03)



The GHZ map

Galactic chemical evolution model



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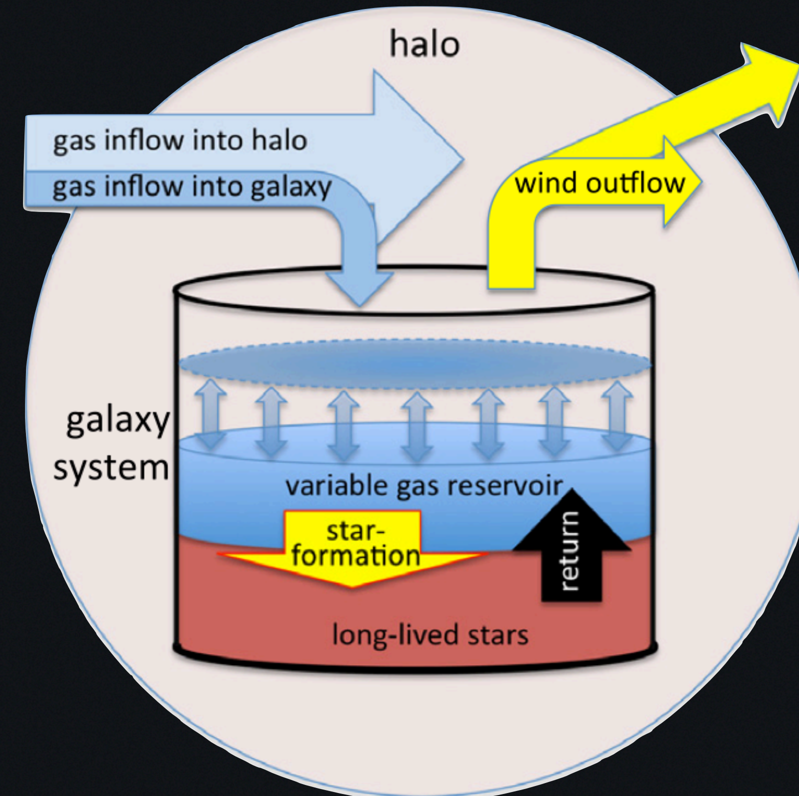

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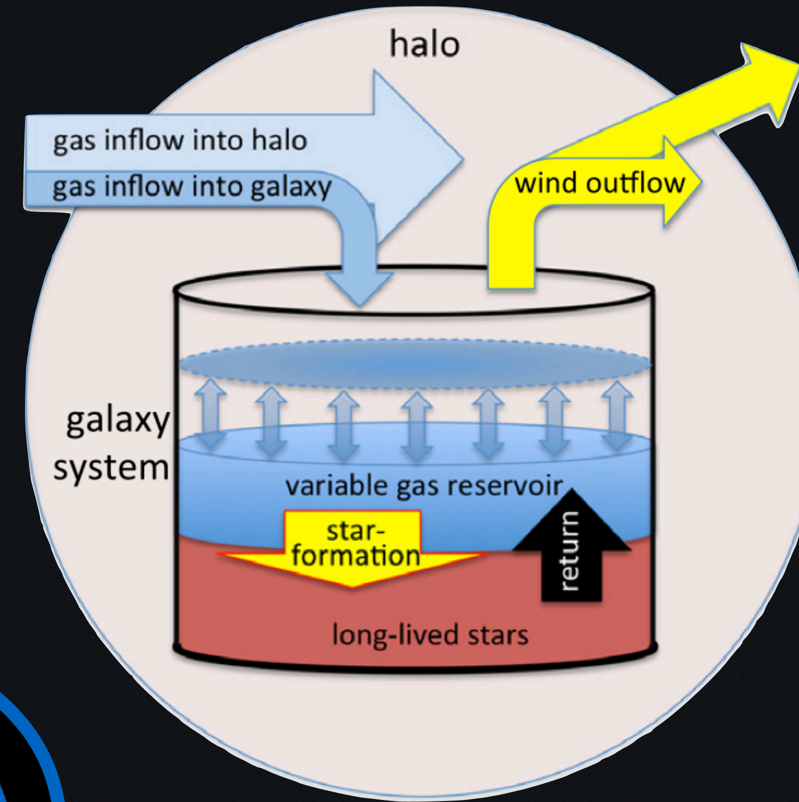

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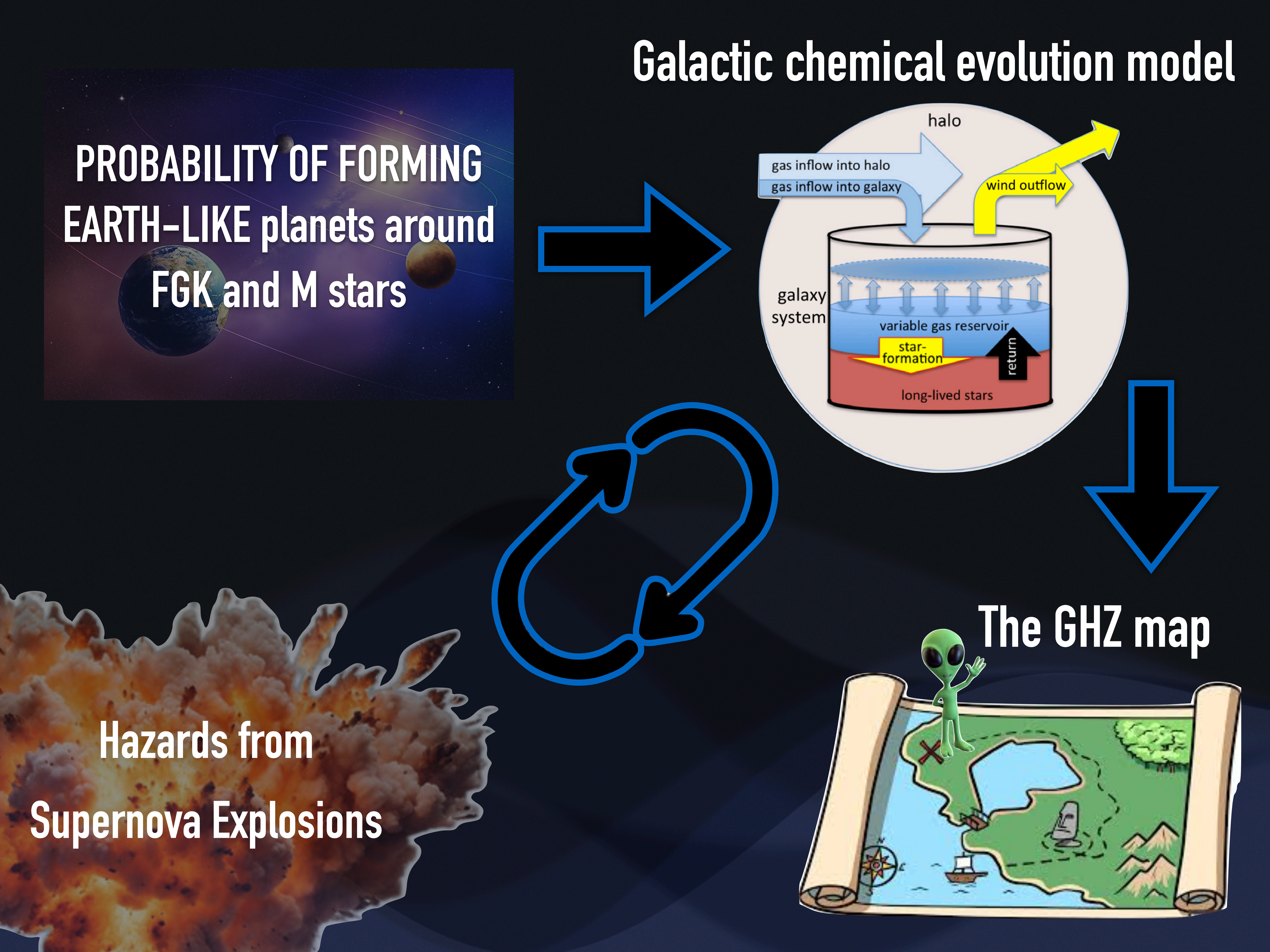
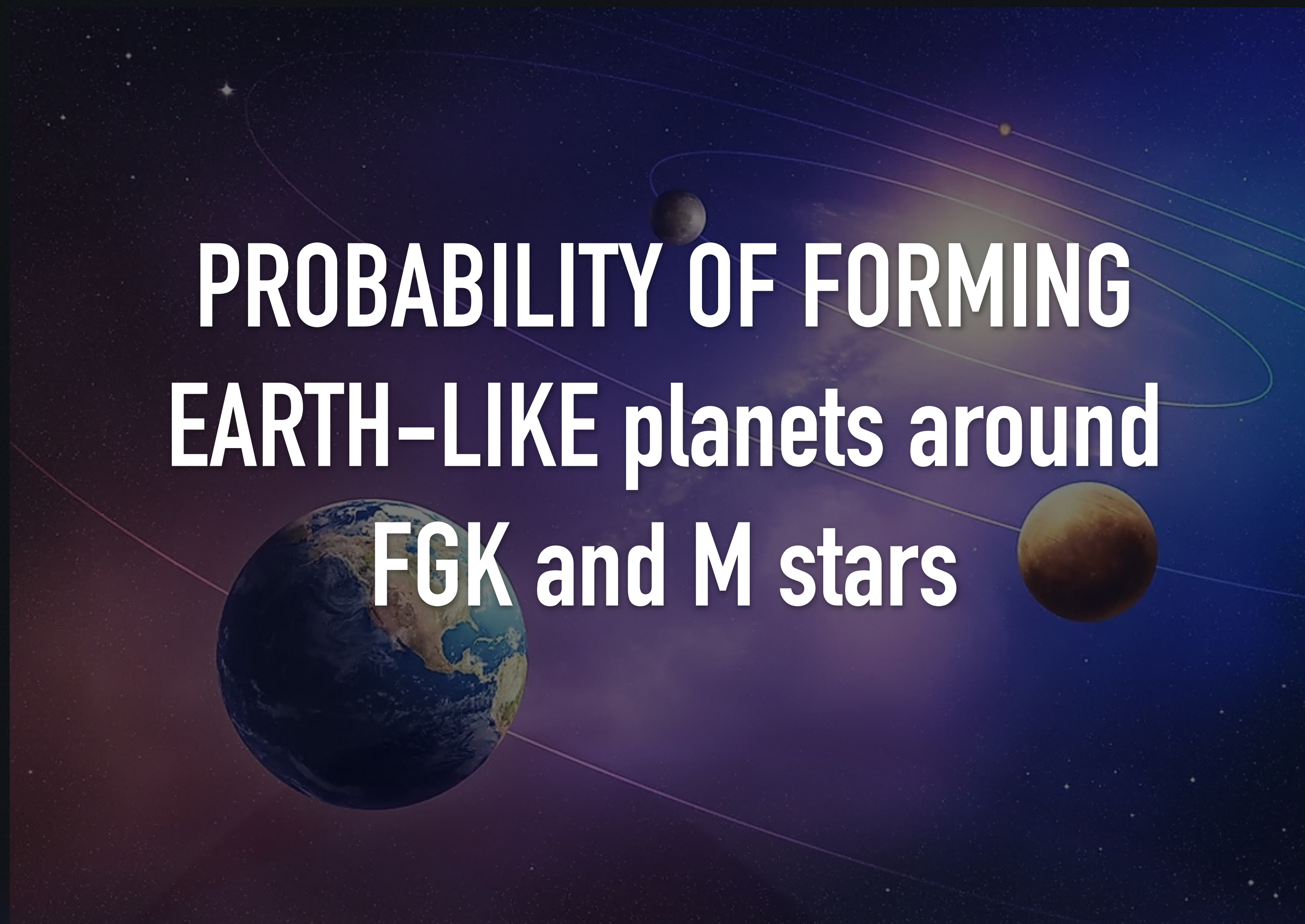


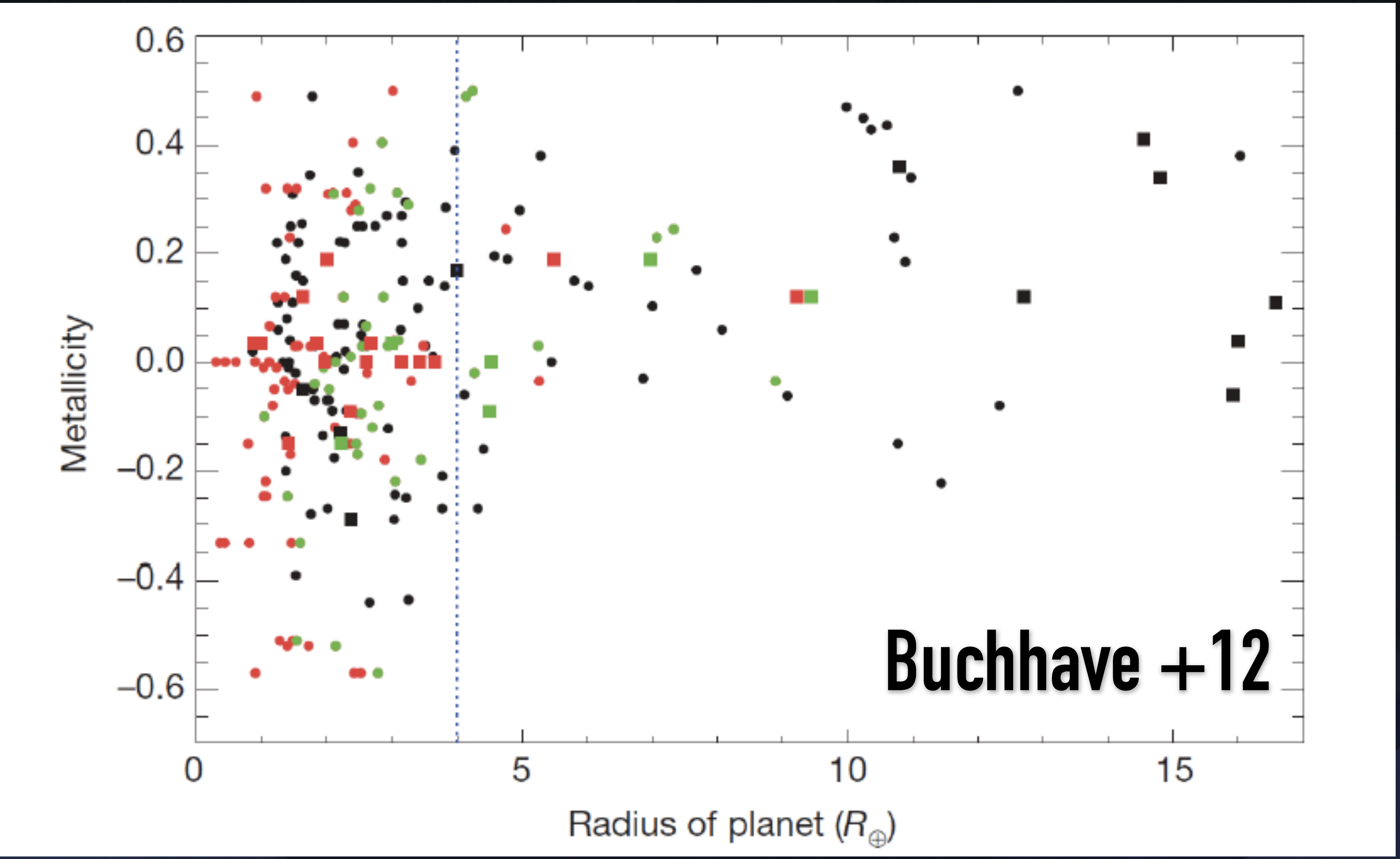
PROBABILITY OF FORMING EARTH-LIKE planets around FGK and M stars
Galactic chemical evolution model
halo
gas inflow into halo
gas inflow into galaxy
wind outflow
galaxy system
variable gas reservoir
star-formation
return
long-lived stars
The GHZ map
Hazards from Supernova Explosions



PROBABILITY OF FORMING EARTH-LIKE planets around FGK and M stars

Spitoni +17

THE PROBABILITY OF FORMING EARTH-LIKE PLANETS FROM OBSERVATIONS

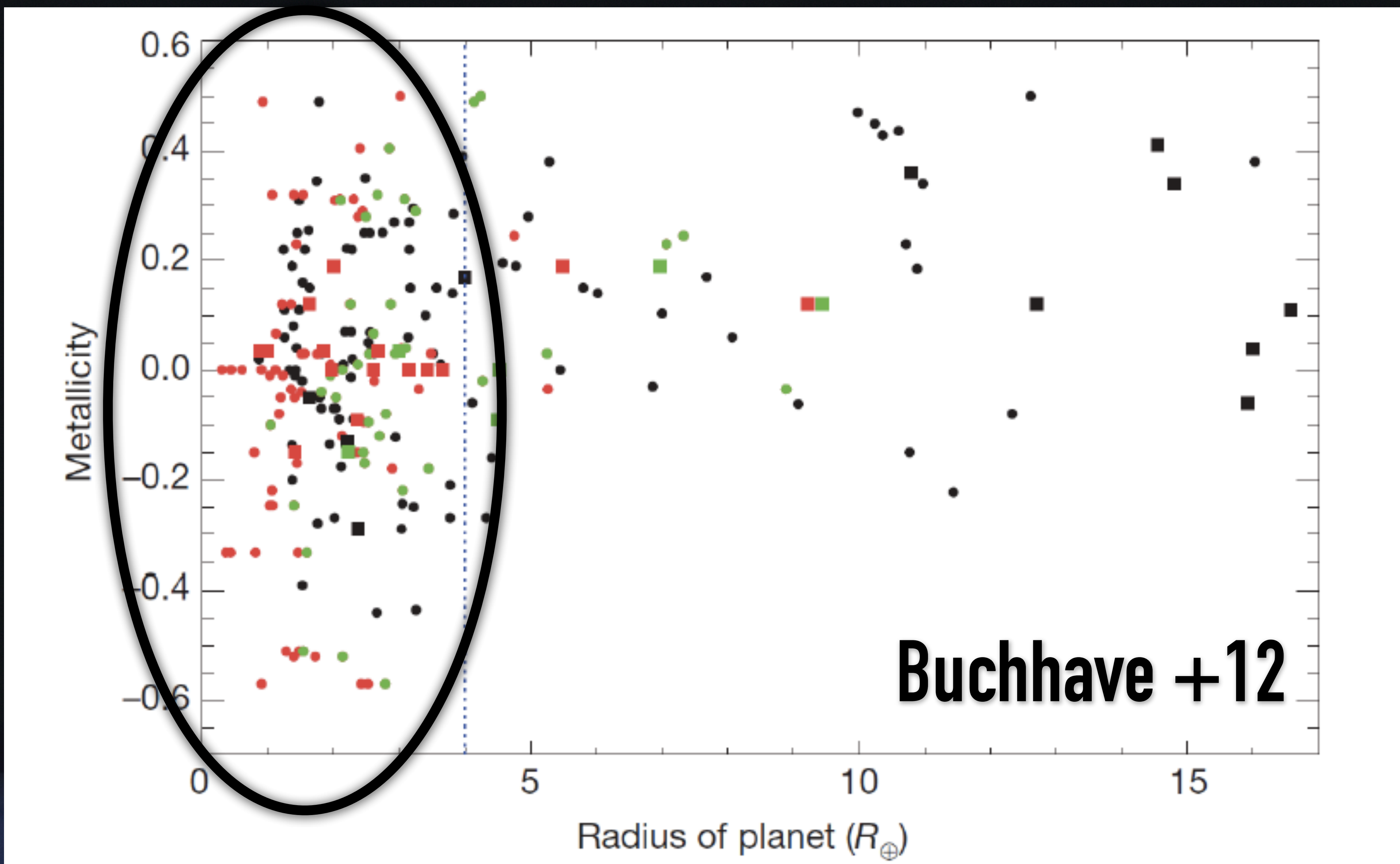


Sistems with one planet

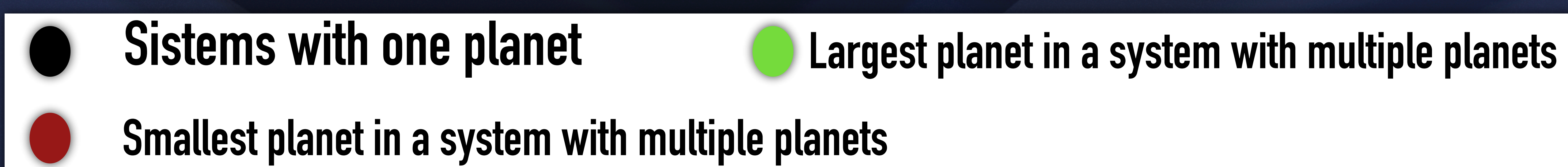
Largest planet in a system with multiple planets

Smallest planet in a system with multiple planets

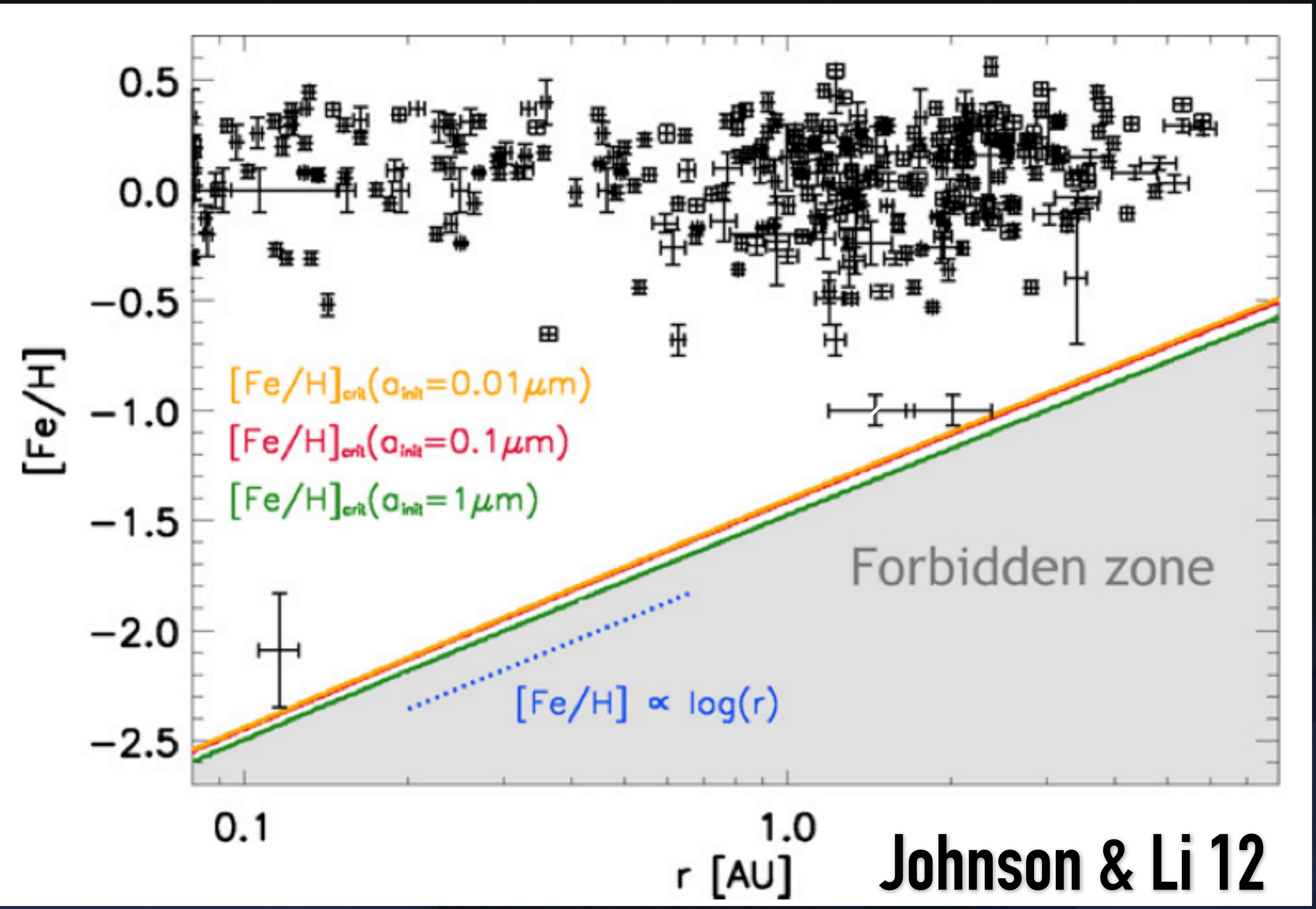
THE PROBABILITY OF FORMING EARTH-LIKE PLANETS FROM OBSERVATIONS



The frequencies of the planets with Earth-like sizes are almost independent of the metallicity,



The First Earth-like Planets from simulations



Johnson & Li 12

Earth-like planets likely formed from circumstellar disks with metallicities Z≥ 0.1 Zsun, i.e [Fe/H]>-1

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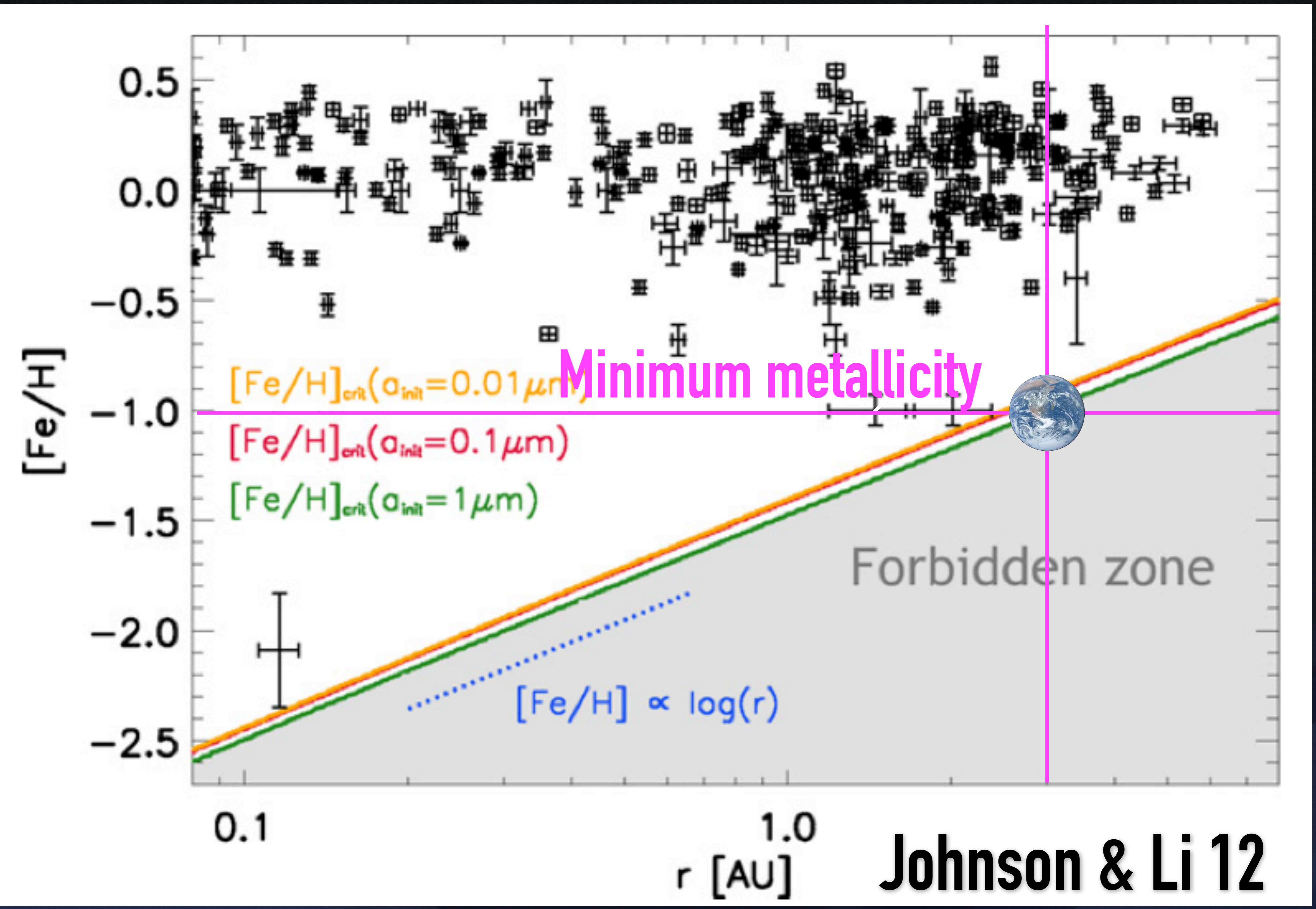


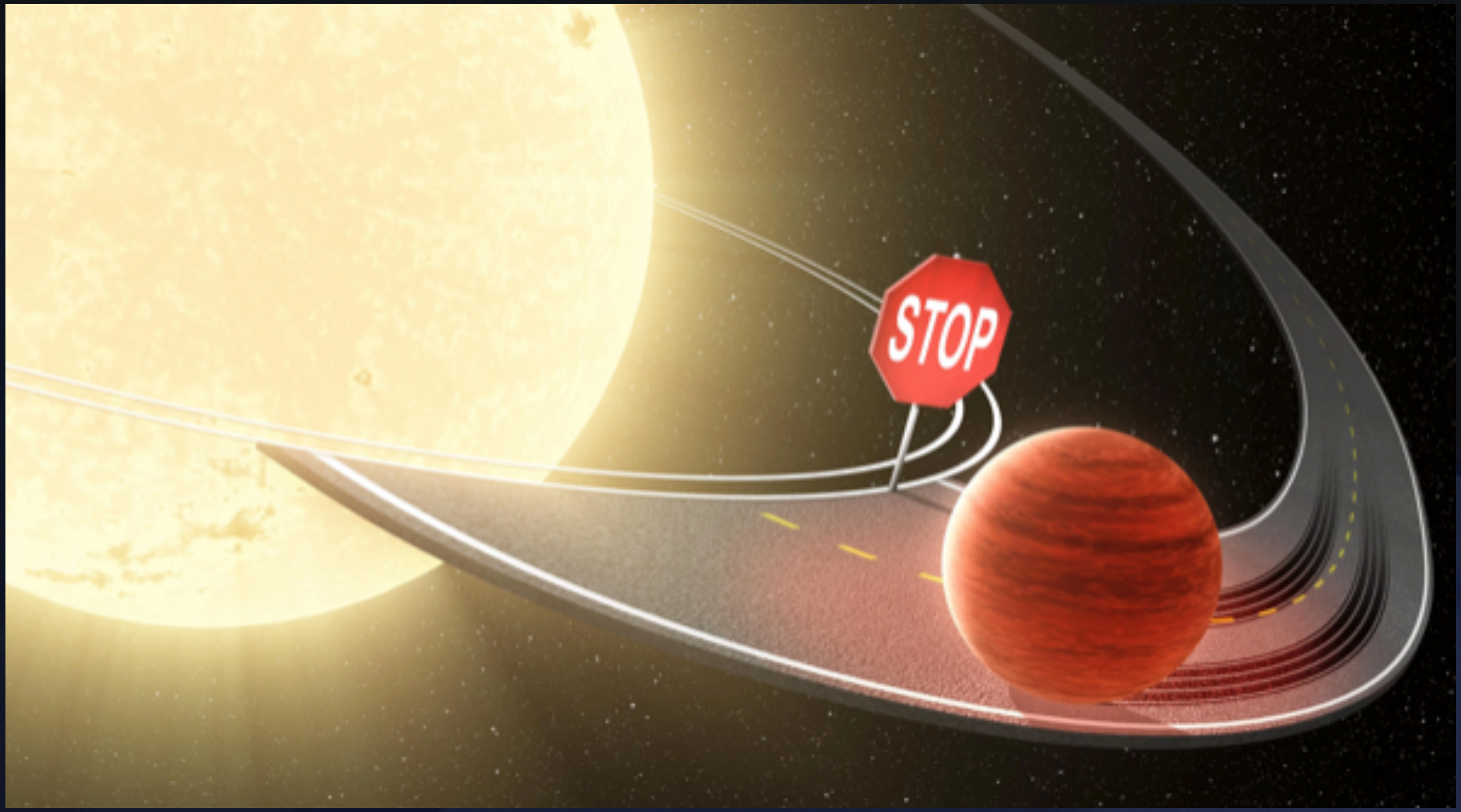
Earth-like planets likely formed from circumstellar disks with metallicities $Z \geq 0.1\,Z_{sun}$,

i.e $[Fe/H] > -1$

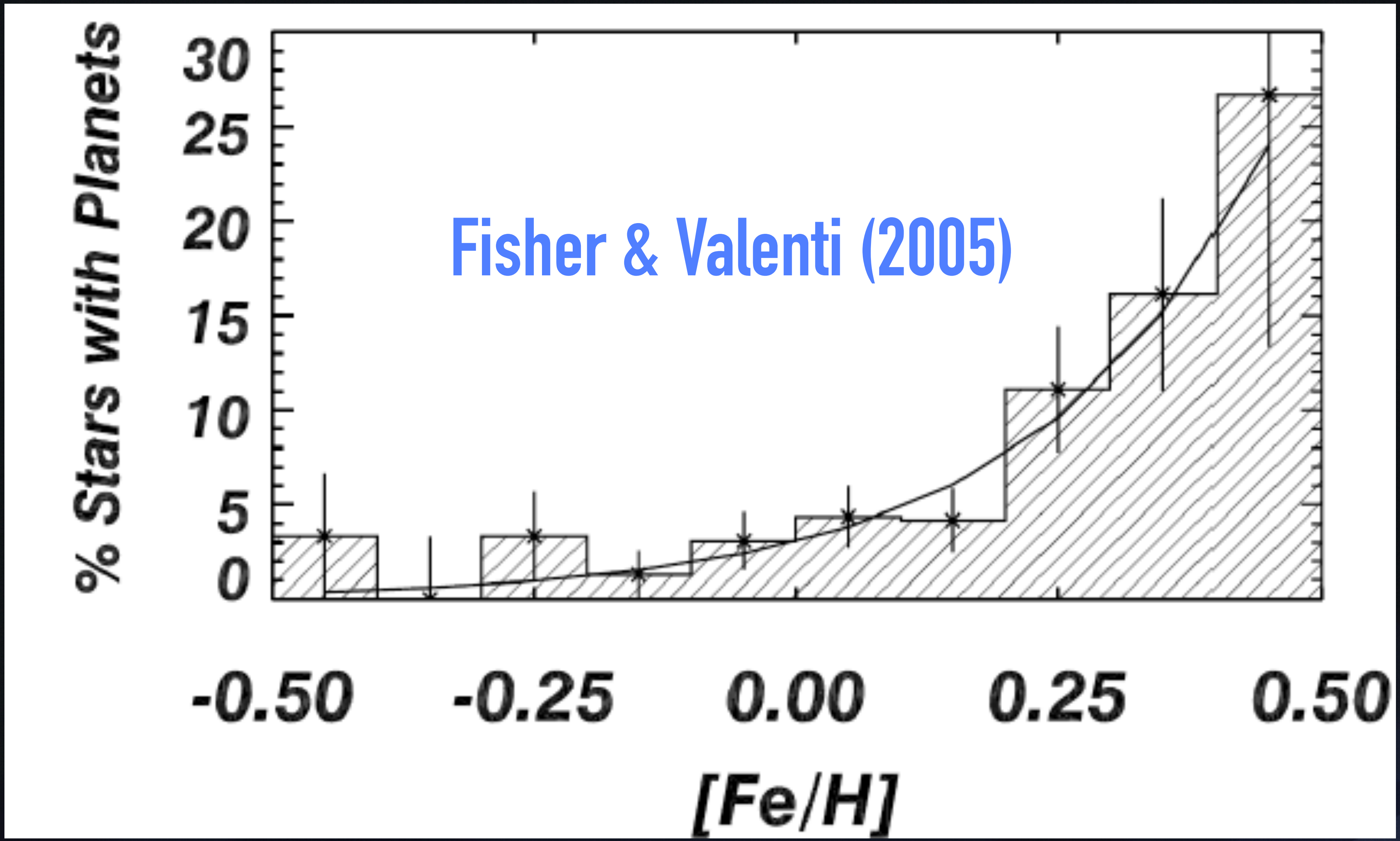
THE PROBABILITY OF FORMING EARTH-LIKE PLANETS

BUT NOT HOT JUPITERS

Migration due to turbulent fluctuations in the disk could destroy the terrestrial planets

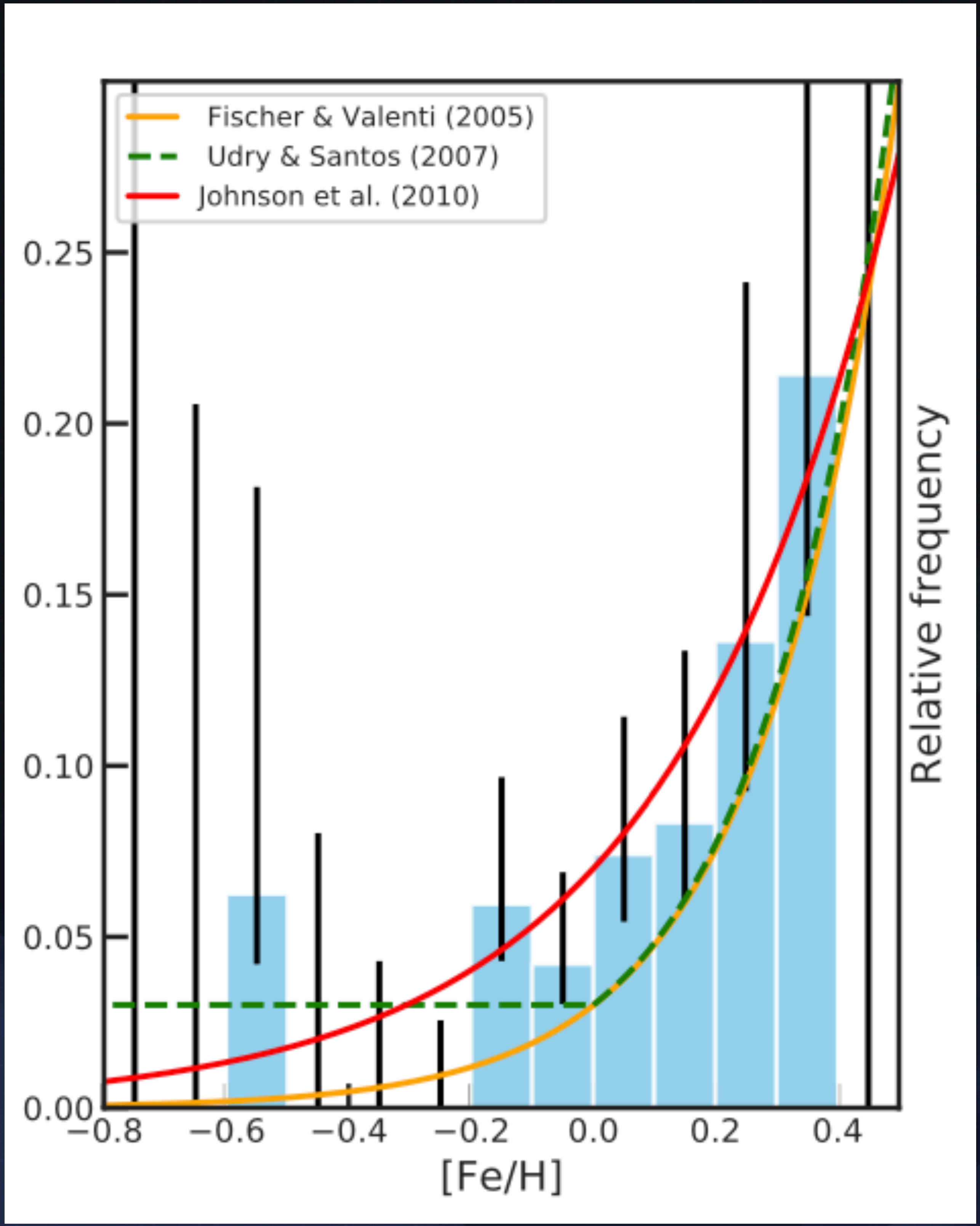


THE PROBABILITY OF FORMING GAS GIANT PLANETS

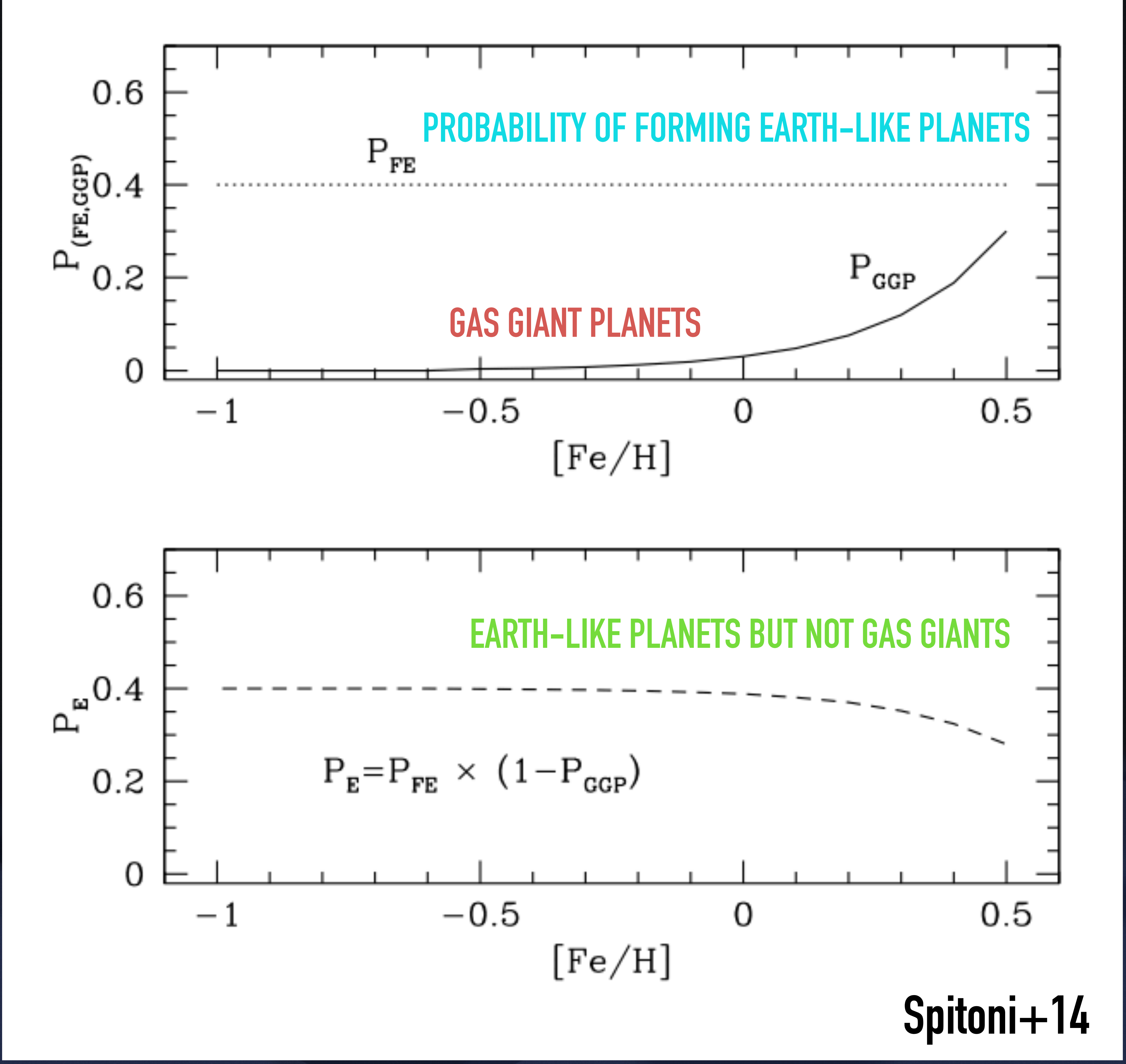


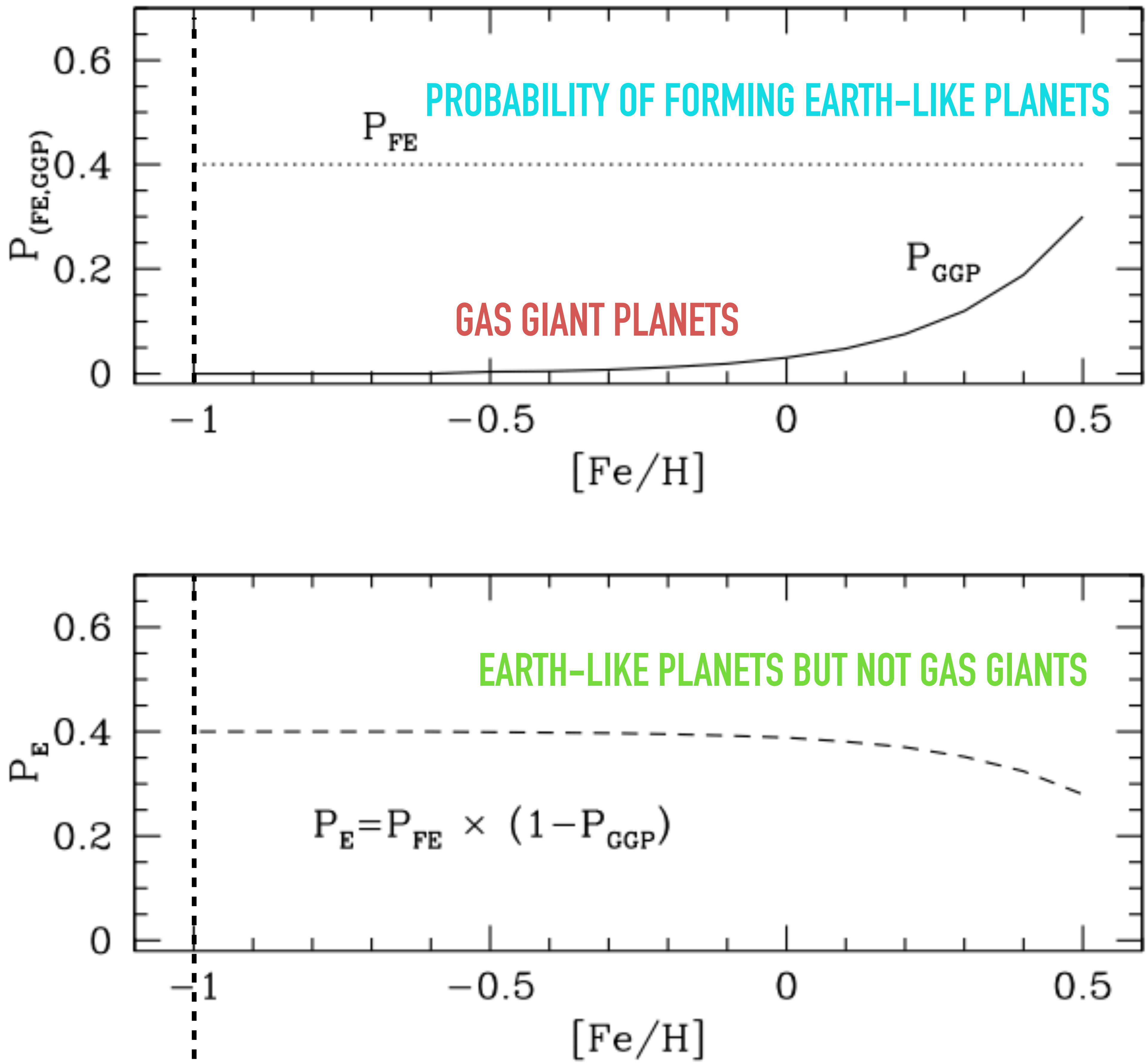
$$P_{GGP}\left([\mathrm{Fe/H}]\right) = 0.03 \times 10^{2.0[\mathrm{Fe/H}]}$$

THE PROBABILITY OF FORMING GAS GIANT PLANETS



Adibekyan +19


PROBABILITY OF FORMING EARTH-LIKE PLANETS
P_{FE}
P_{GGP}
GAS GIANT PLANETS
$P_{(FE,GGP)}$
0.6
0.4
0.2
0
−1
−0.5
0
0.5
[Fe/H]
EARTH-LIKE PLANETS BUT NOT GAS GIANTS
P_E
$P_E = P_{FE} \times (1 - P_{GGP})$
[Fe/H]
Spitoni+14



Minimum [Fe/H] value (Johnson & Li 12)

Spitoni+14

GAS GIANT PLANET PROBABILITIES AROUND:

Gaidos & Mann 14, Zackrisson+16

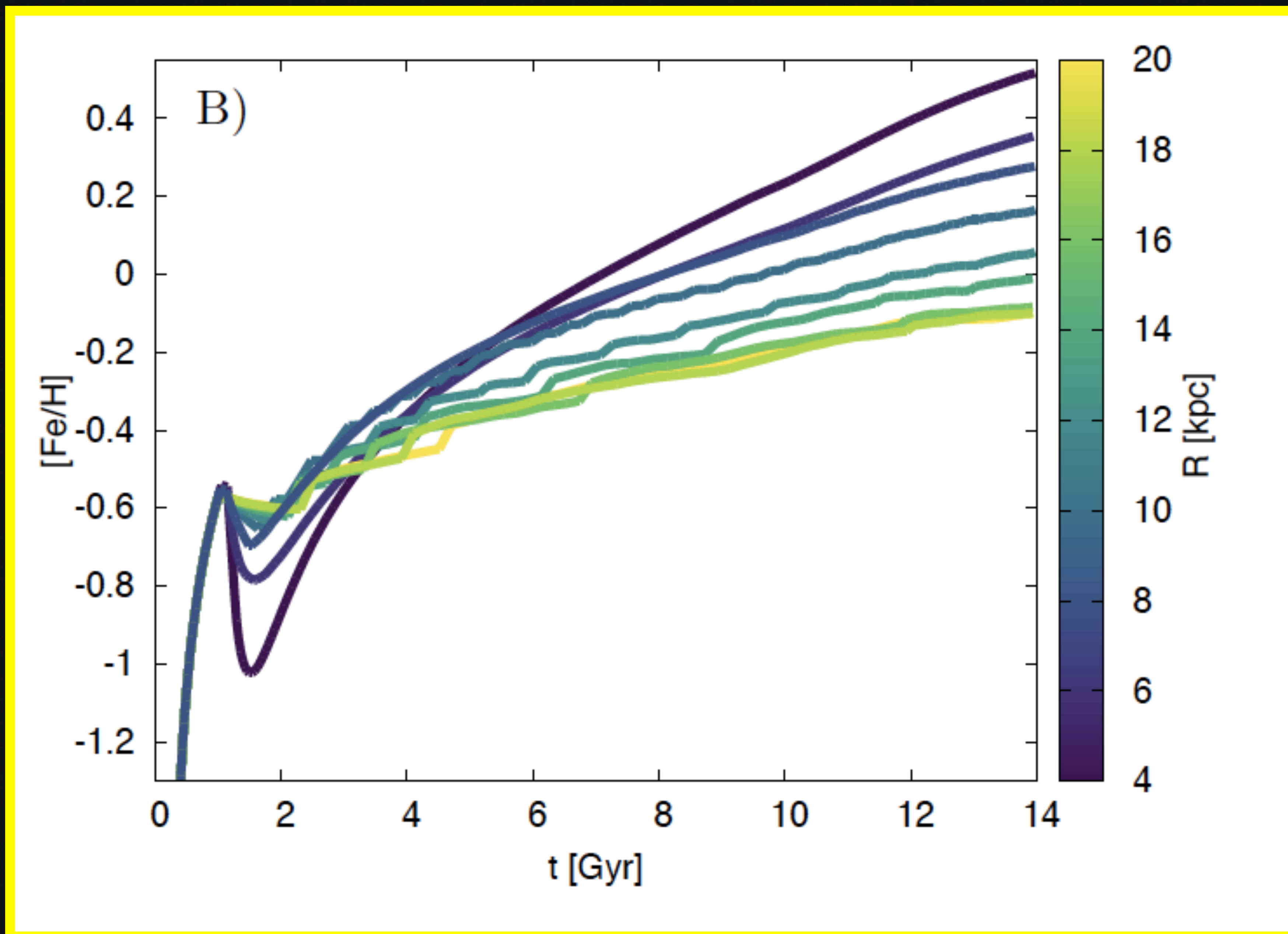
FGK STARS

$$P_{GGP/FGK}\left([\mathrm{Fe/H}], M_\star\right) = 0.07 \times 10^{1.8[\mathrm{Fe/H}]}\left(\frac{M_\star}{M_\odot}\right)$$

M STARS

$$P_{GGP/M}\left([\mathrm{Fe/H}], M_\star\right) = 0.07 \times 10^{1.06[\mathrm{Fe/H}]}\left(\frac{M_\star}{M_\odot}\right)$$

GAS GIANT PLANET PROBABILITIES AROUND:

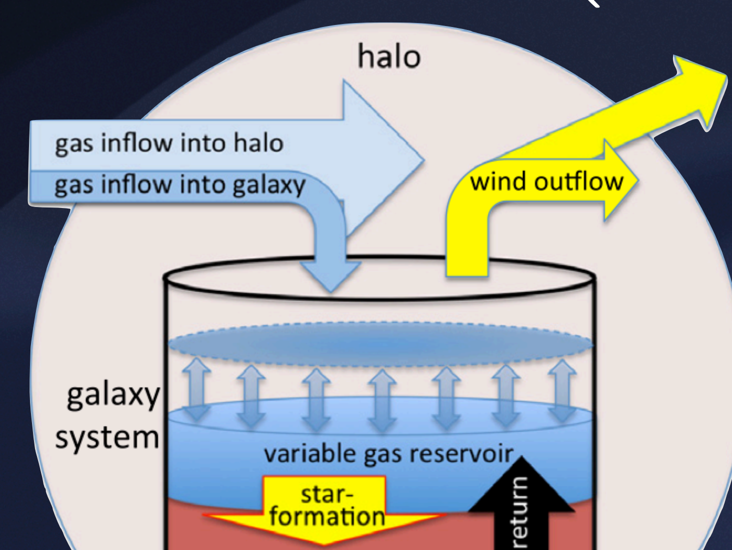


nn 14, Zackrisson+16

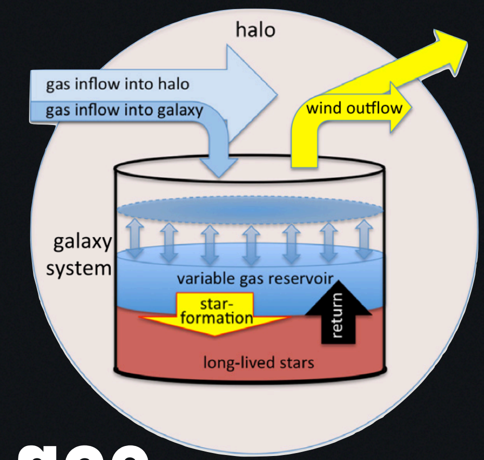
$$.8[\mathrm{Fe/H}]\left(\frac{M_\star}{M_\odot}\right)$$

$$.06[\mathrm{Fe/H}]\left(\frac{M_\star}{M_\odot}\right)$$

CEM predictions for the Galactic disc (Spitoni+17)

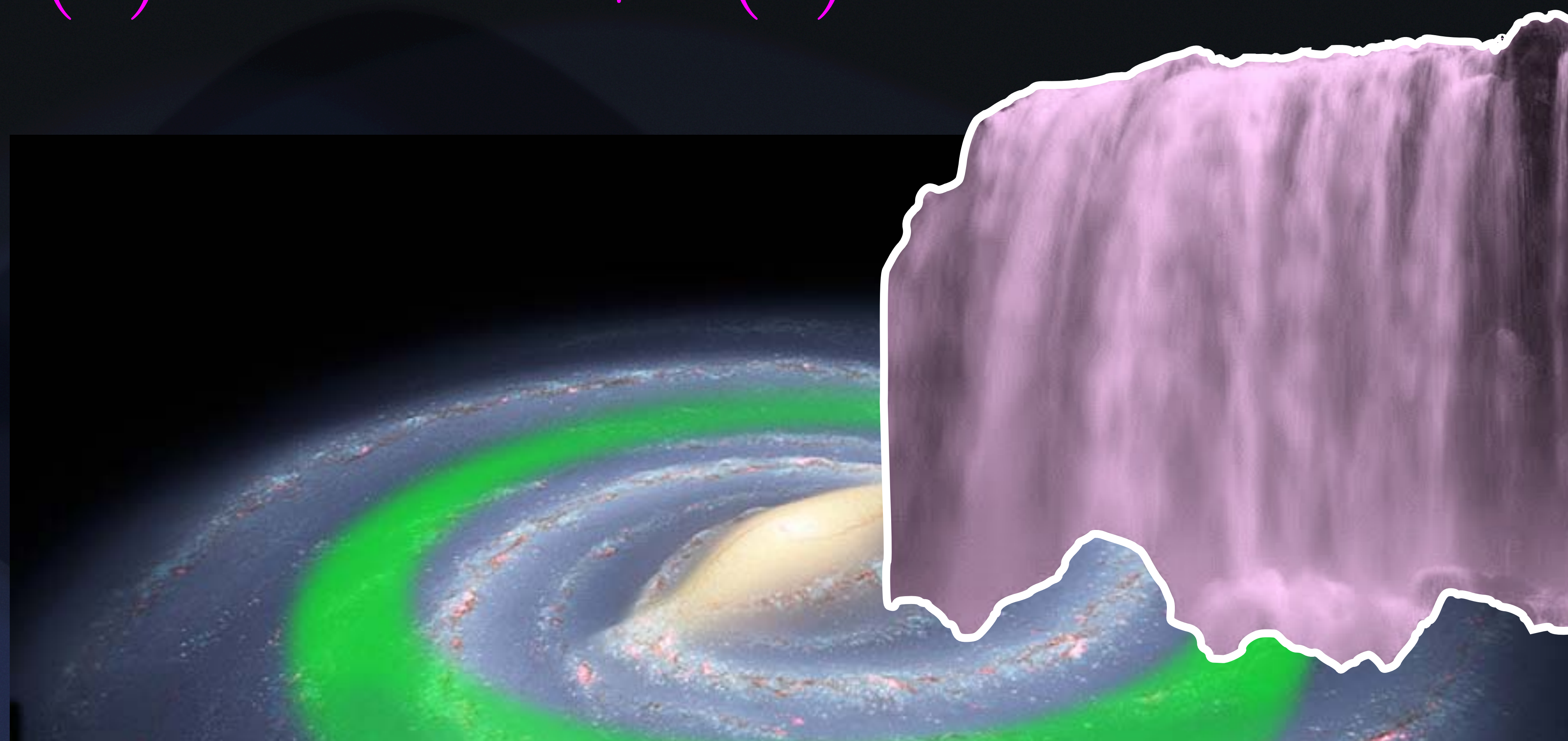


The MW chemical evolution Model



- Two infall model: the halo and thick disk form in a first gas accretion event, while the thin disk forms in a separate event occurring on much longer time-scales

$$A(R,t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{max})/\tau_D(r)}$$



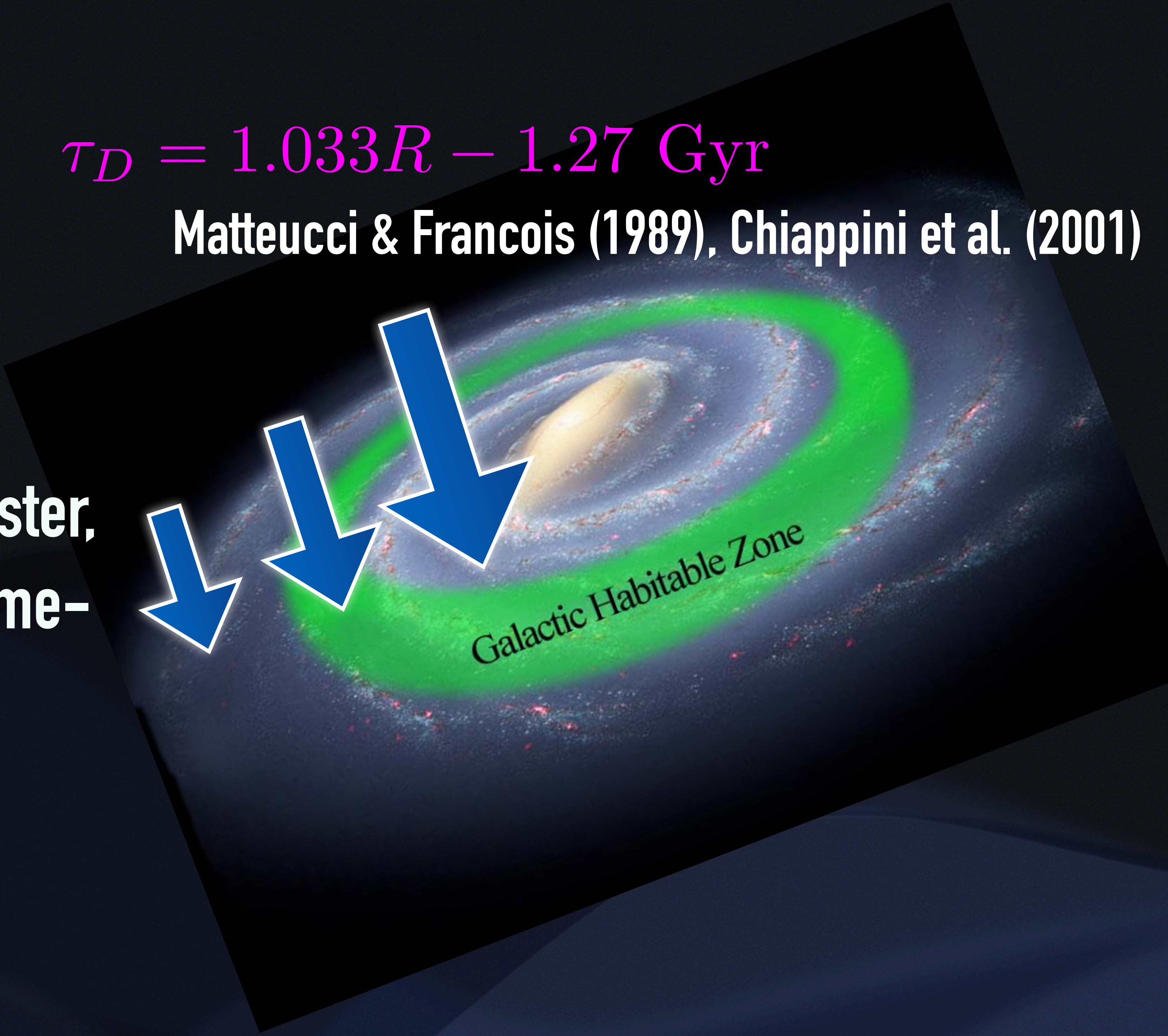
Spitoni +17

Main model assumptions...

- **Inside-out formation** $\tau_D = 1.033R - 1.27\ \mathrm{Gyr}$

Matteucci & Francois (1989), Chiappini et al. (2001)

Larson's (1976) dissipative collapse: spheroidals components are created faster, whereas disks on longer time-scales (see also Cole et al. 2000).



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Larso
colla
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scale
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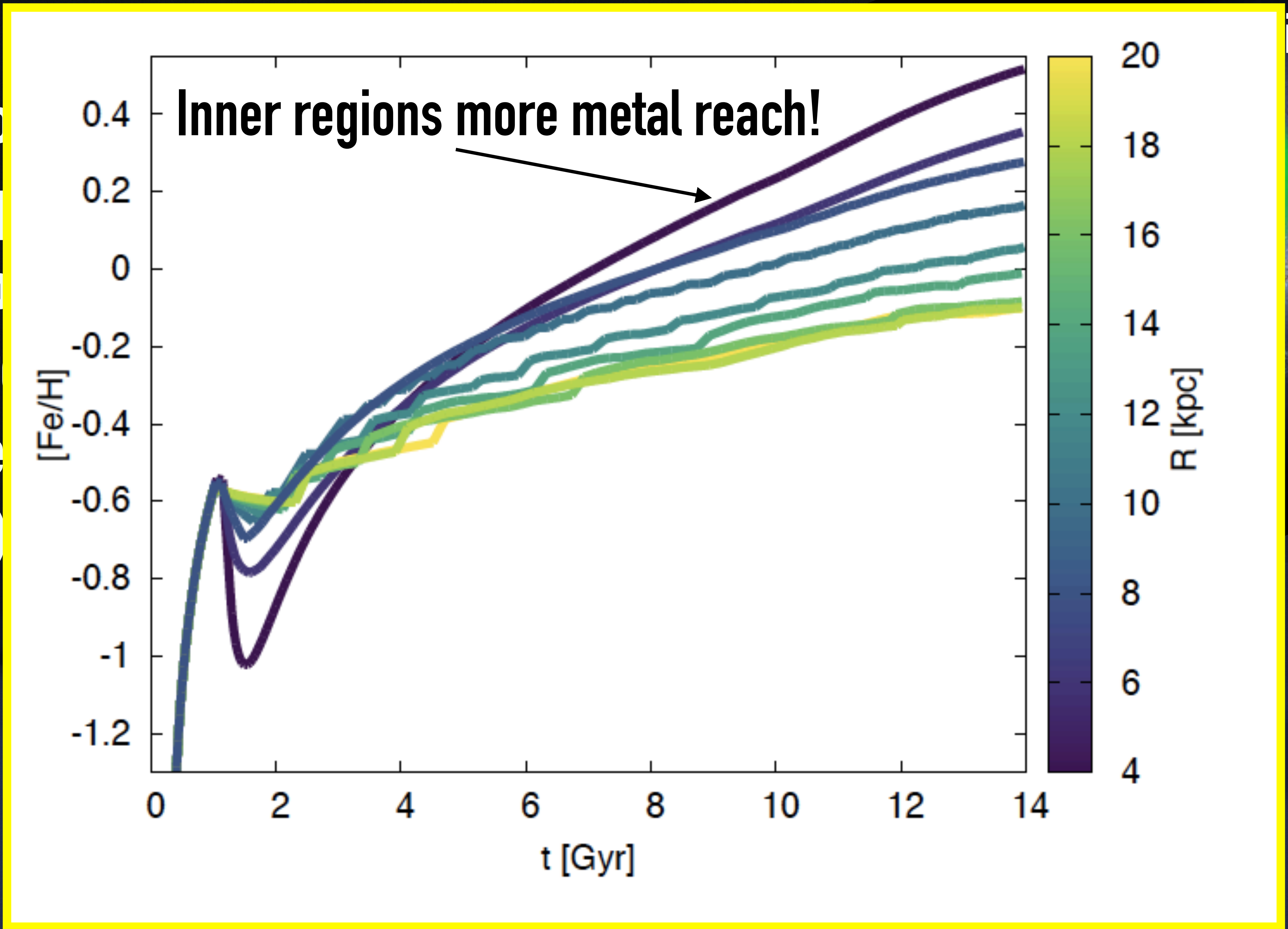
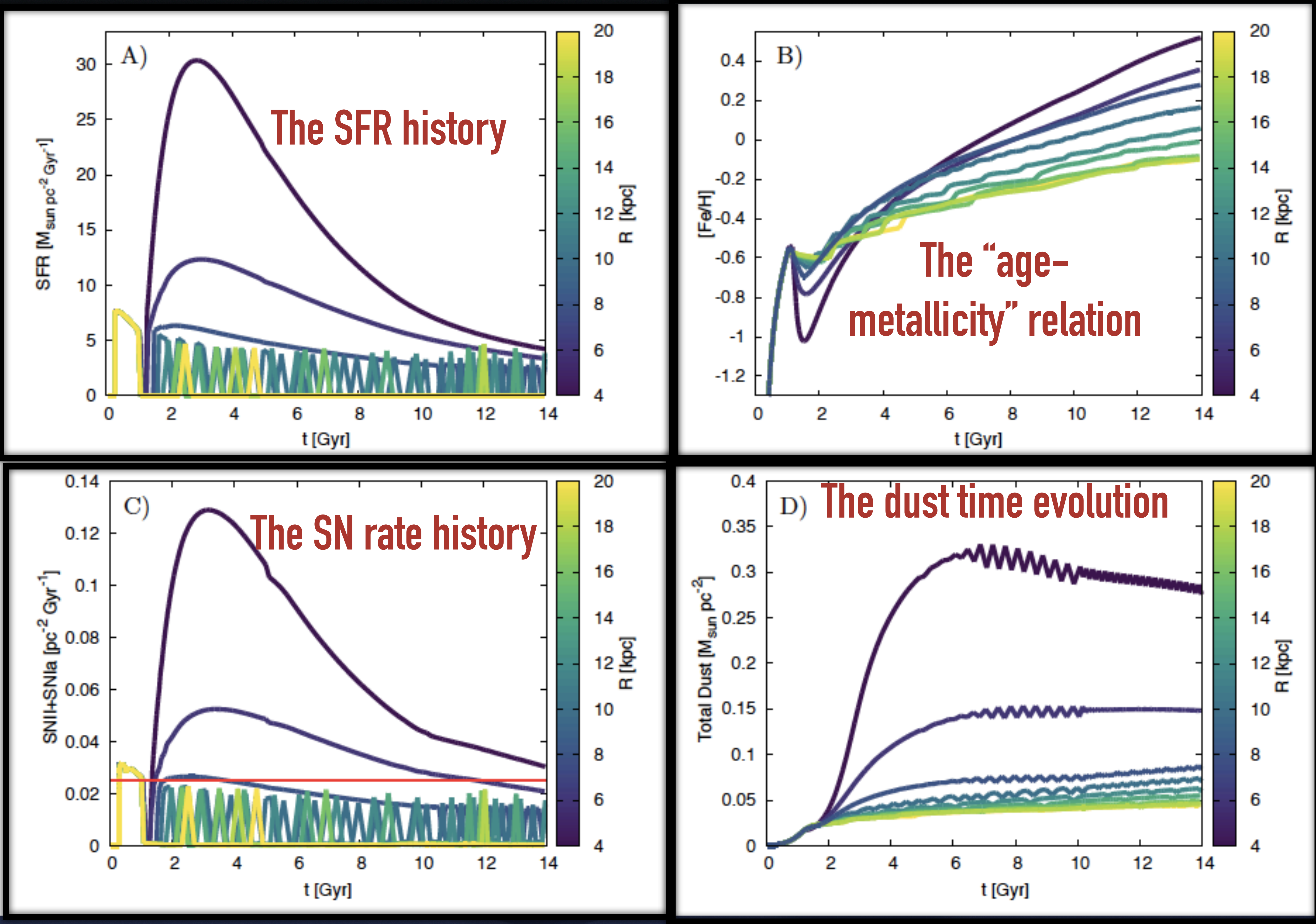


Main model assumptions...

- Inside-out formation
- SFR proportional to the Schmidt (1959) law $\psi(R,t) \propto \nu \sigma_g^k(R,t)$
- Scalo (1986) IMF
- Threshold in the gas surface density for the SF

Kennicutt (1998,1989)
4-7 M_{sun} pc^{-2}

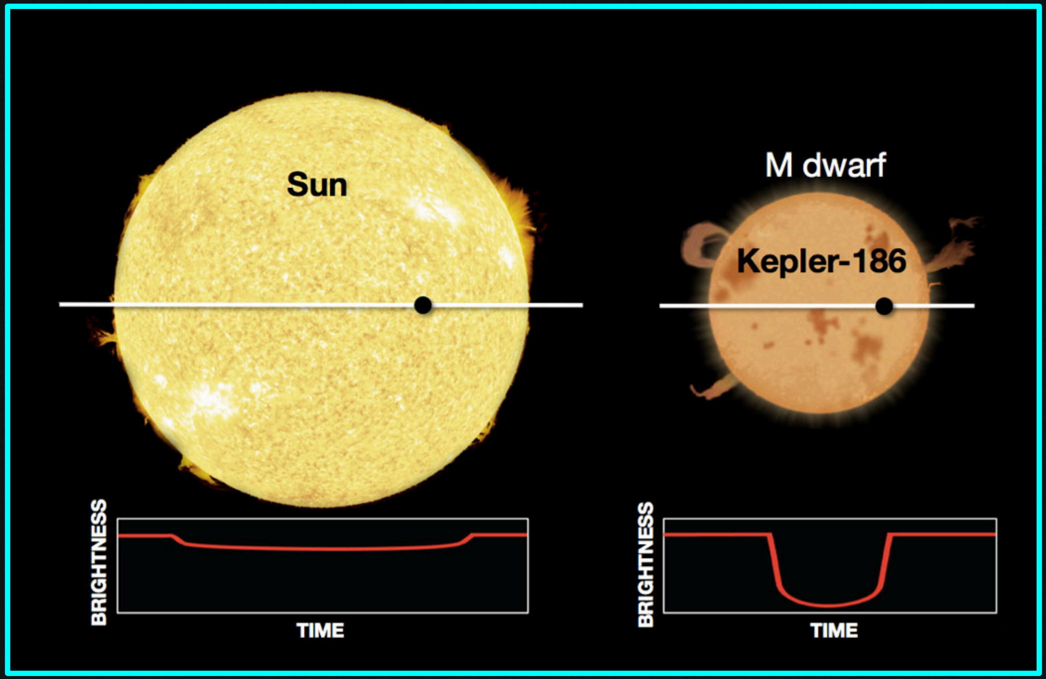
CEM results

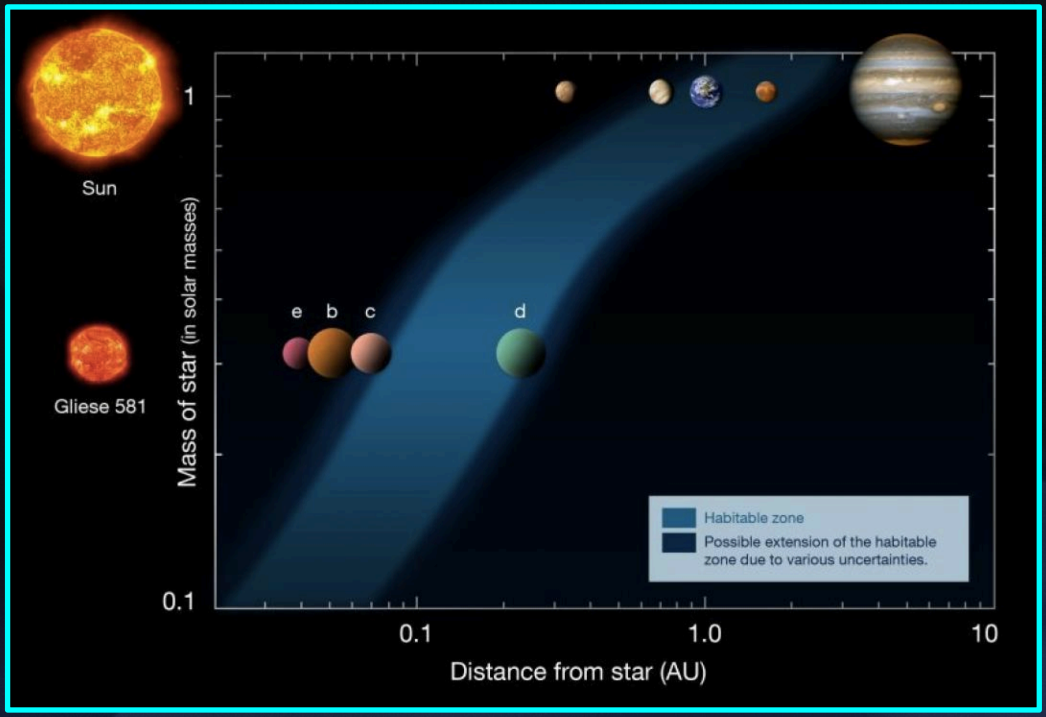


A)
The SFR history
SFR [M$_{sun}$ pc^{-2} Gyr^{-1}]
t [Gyr]
R [kpc]
B)
The "age-metallicity" relation
[Fe/H]
t [Gyr]
R [kpc]
C)
The SN rate history
SNII+SNIa [pc^{-2} Gyr^{-1}]
t [Gyr]
R [kpc]
D)
The dust time evolution
Total Dust [M$_{sun}$ pc^{-2}]
t [Gyr]
R [kpc]

M dwarf stars

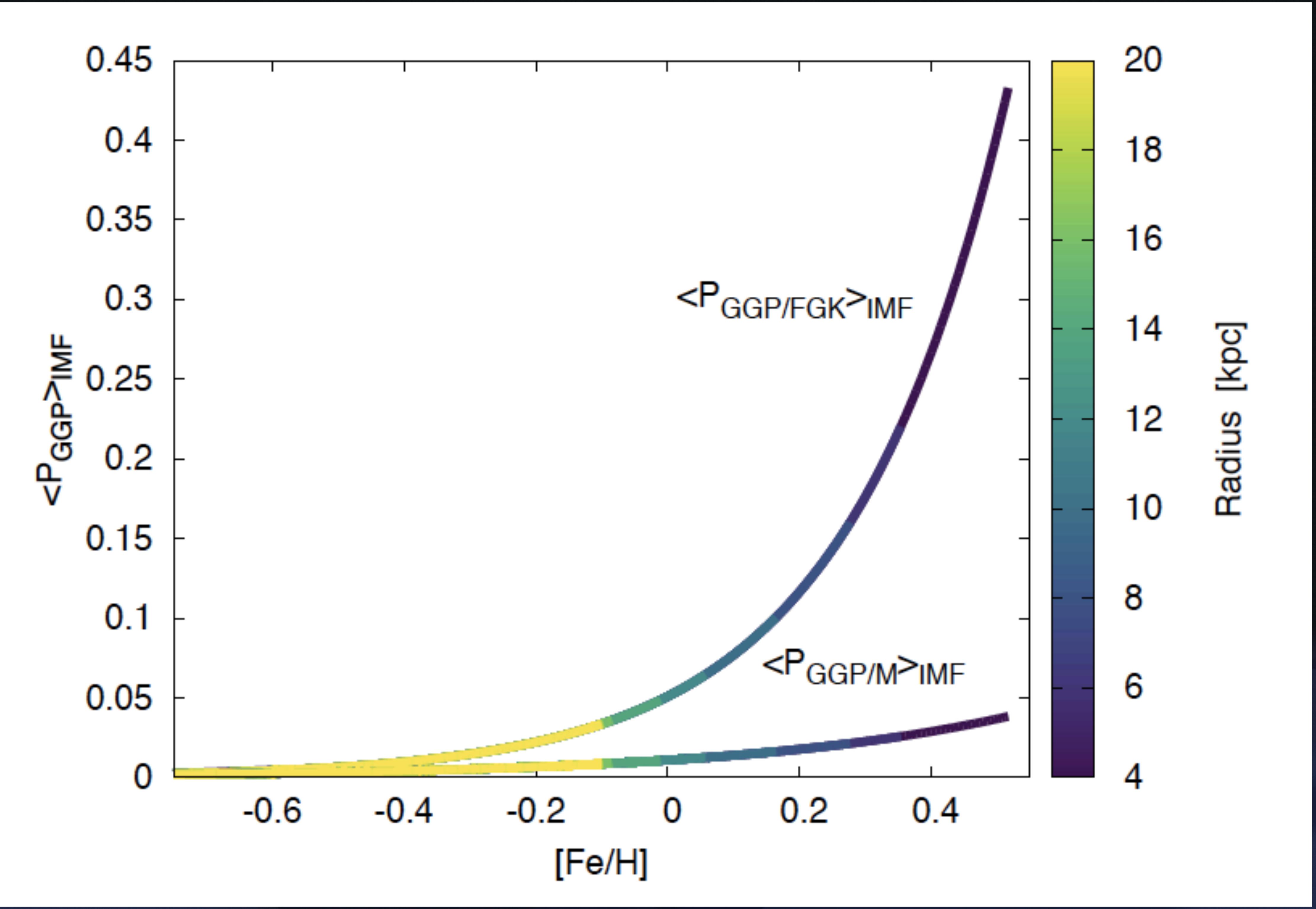
- ✓ M dwarfs comprise ~70% of all stars in the Galaxy
- ✓ Small planets are easier to detect orbiting small stars via the radial velocity and transit techniques, as spectroscopic;
- ✓ Circumstellar Habitable zones are closer to these stars than those of Sun-like stars, increasing the geometric probability of observing a transit;
- ✓ Their extremely long lifetimes ample time for biological development and evolution on orbiting planets





(Credit S. Cassisi)

The probabilities to find gas giant planets around FGK/M stars



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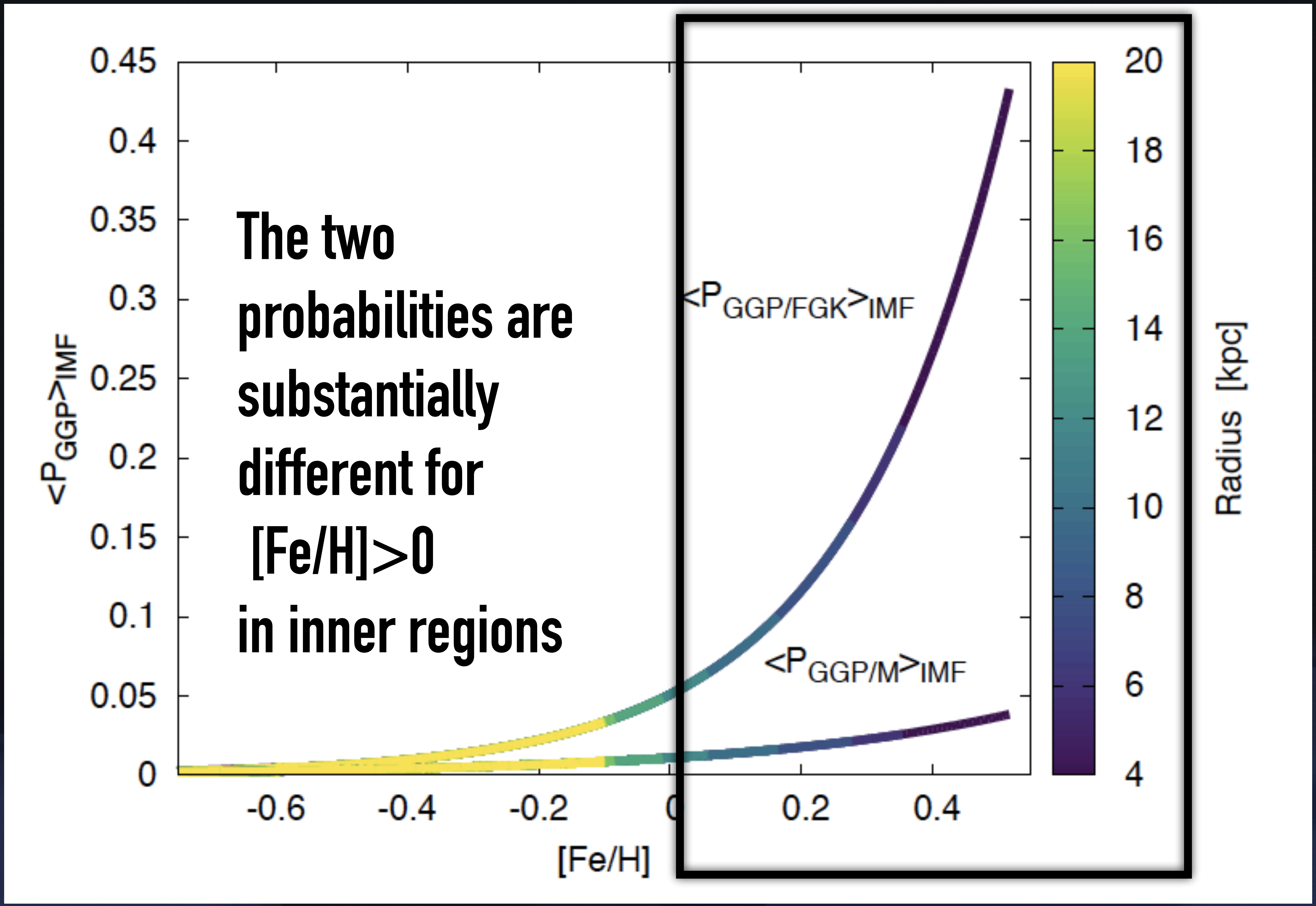
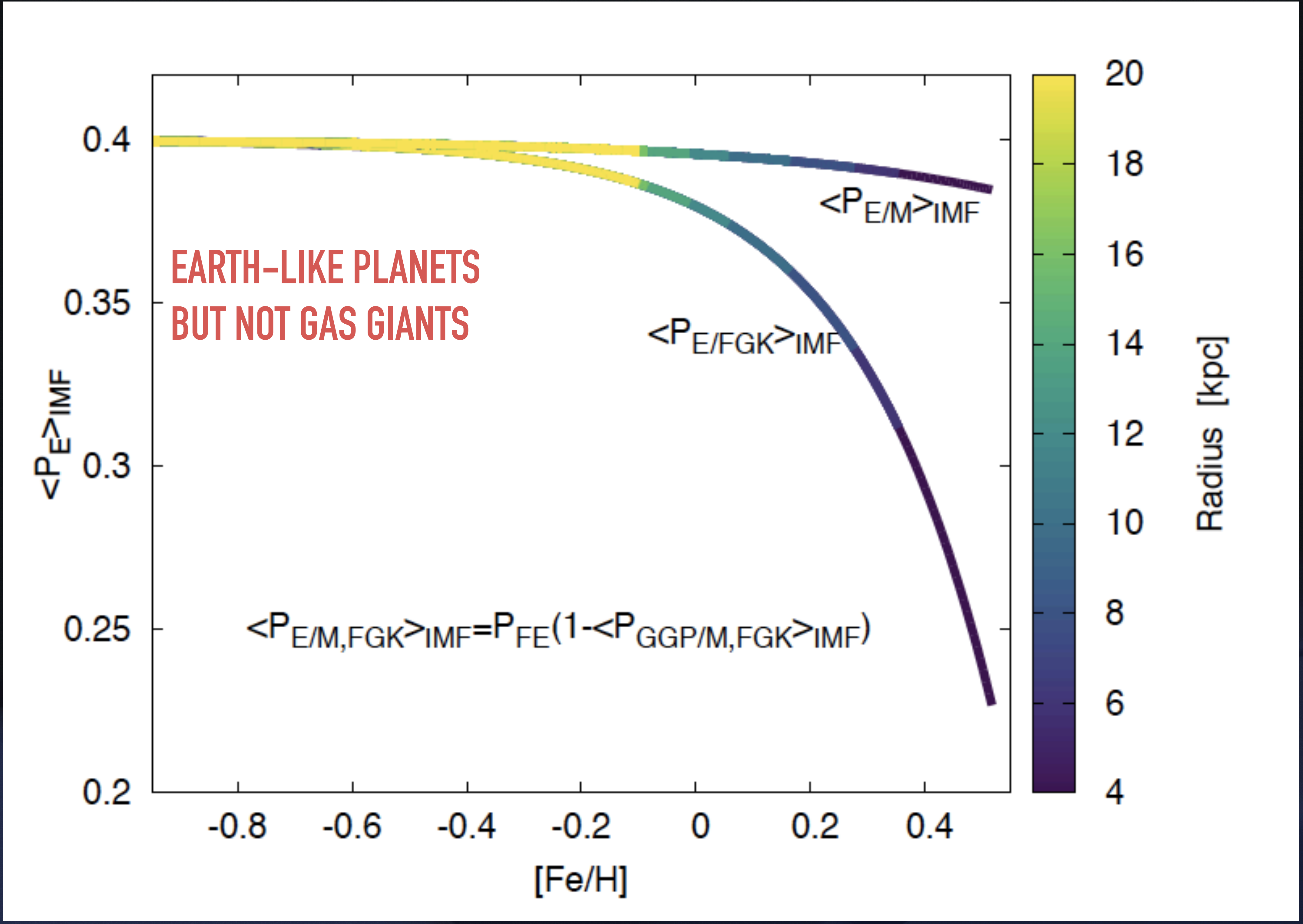


The probabilities to find Earth-like planets without gas giant planets around FGK/M stars



The two probabilities are substantially different for [Fe/H]>0 in inner regions

THE GHZ MAP: TOTAL NUMBER OF FGK/M STARS HOSTING HABITABLE EARTH-LIKE PLANETS (R,t)

$$N_{\star life}(R,t) = P_{GHZ}(R,t) \times N_{\star tot}(R,t)$$

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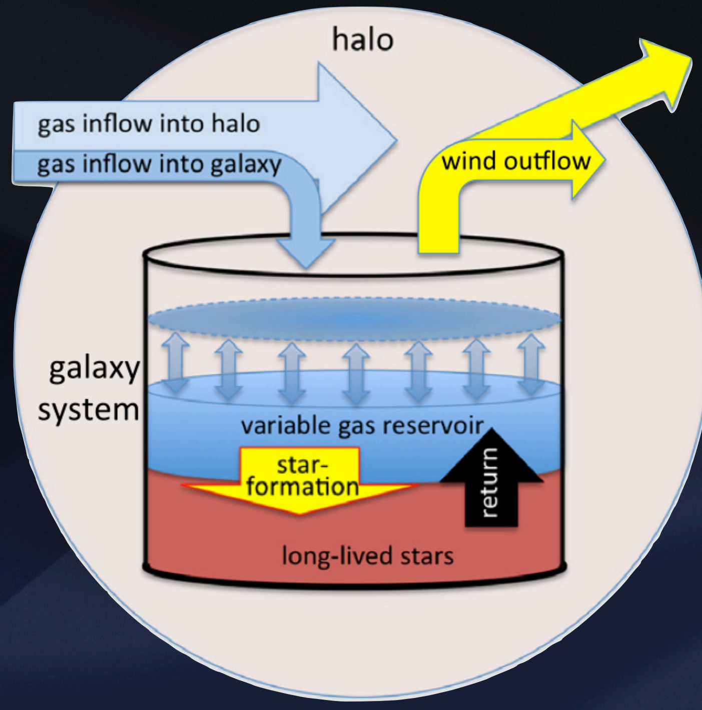
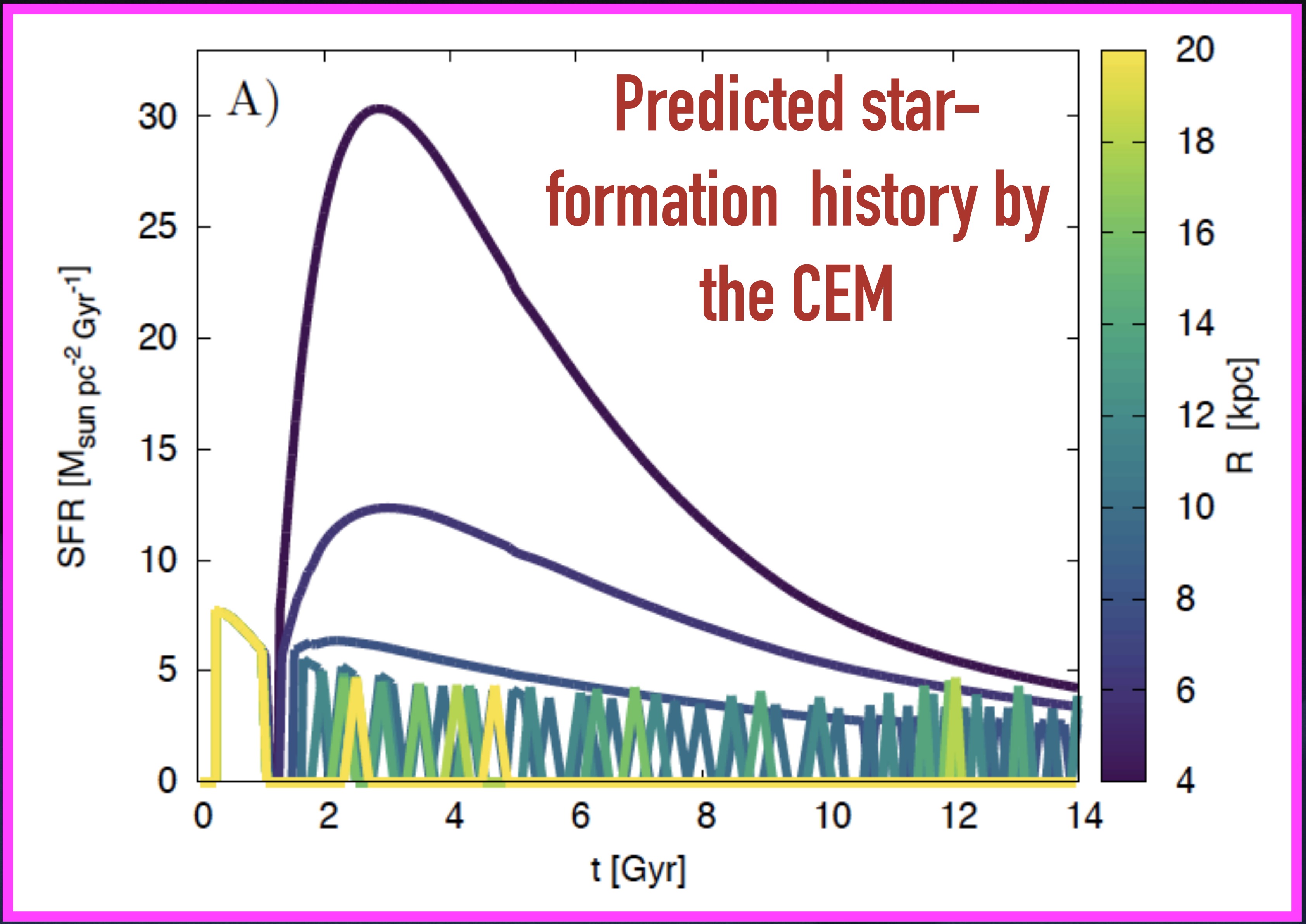


$$P_{GHZ}(FGK/M, R, t) = \frac{\int_0^t SFR(R,t')P_{E/FGK,M}(R,t')P_{SN}(R,t')dt'}{\int_0^t SFR(R,t')dt'}$$

The fraction of all stars having Earths (but no gas giant planets) which survived supernova explosions as a function of the galactic radius and time.

Prantzos 08

$$P_{GHZ}(FGK/M, R, t) = \frac{\int_0^t SFR(R,t') P_{E/FGK,M}(R,t') P_{SN}(R,t') dt'}{\int_0^t SFR(R,t') dt'}$$



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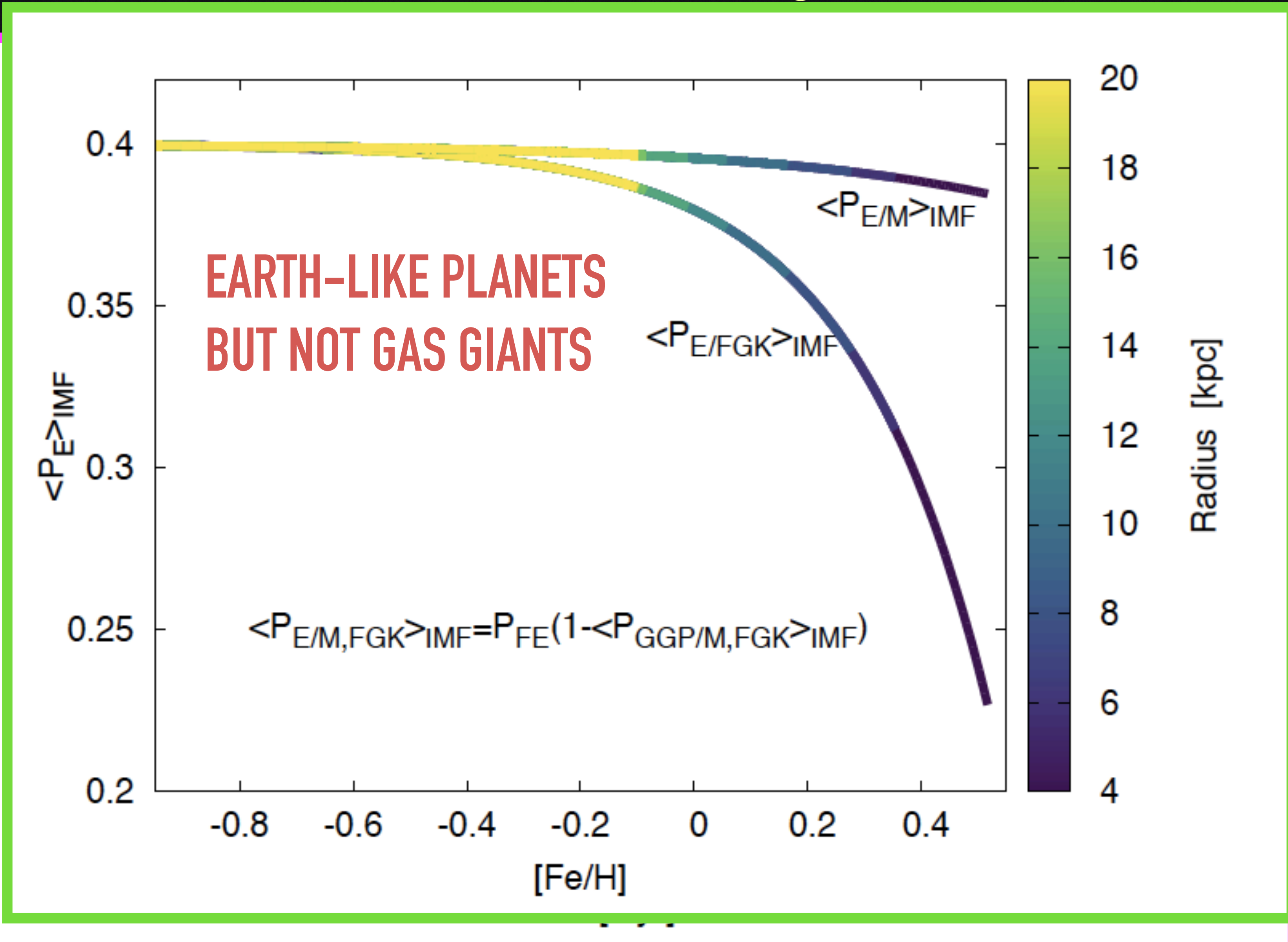

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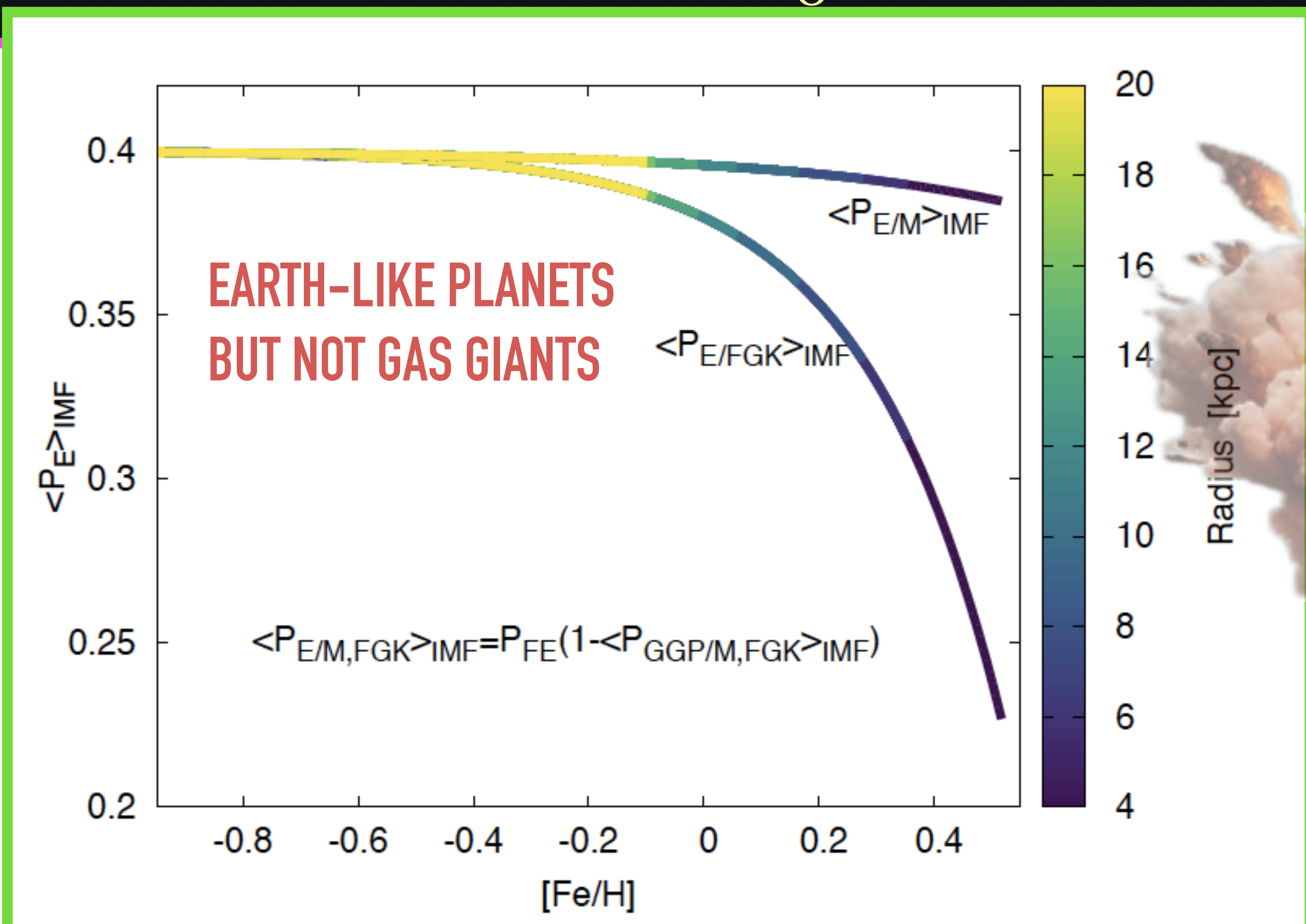

Hazards from Supernova Explosions

If SNR(R,t) has been higher than twice the average SN rate <RSN*> in the solar neighborhood during the last 4.5 Gyr =>NO LIFE

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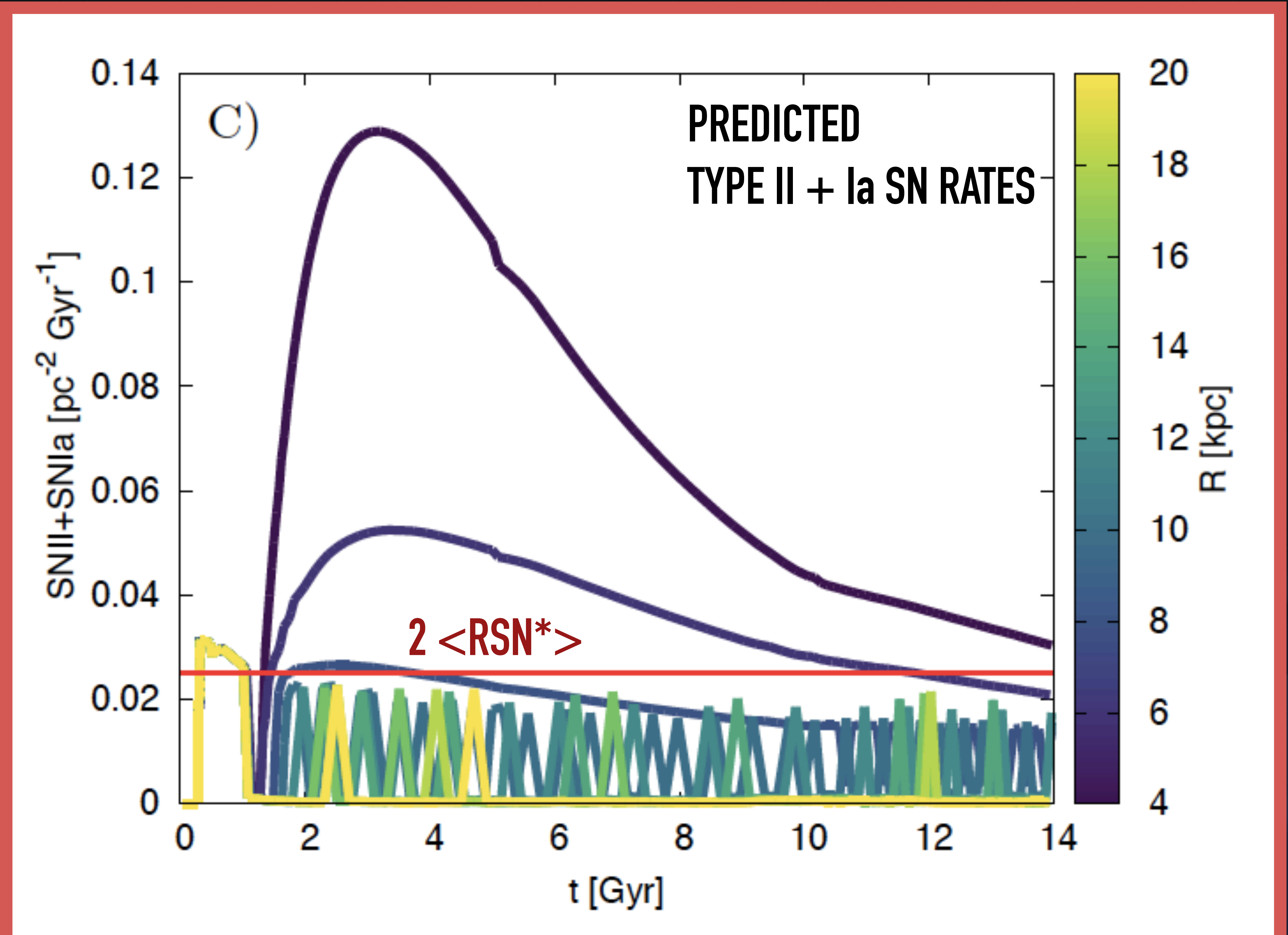
Hazards from Supernova Explosions



if SNR > 2 <RSN*>
then
P_{SN} = 0 else
P_{SN} = 1

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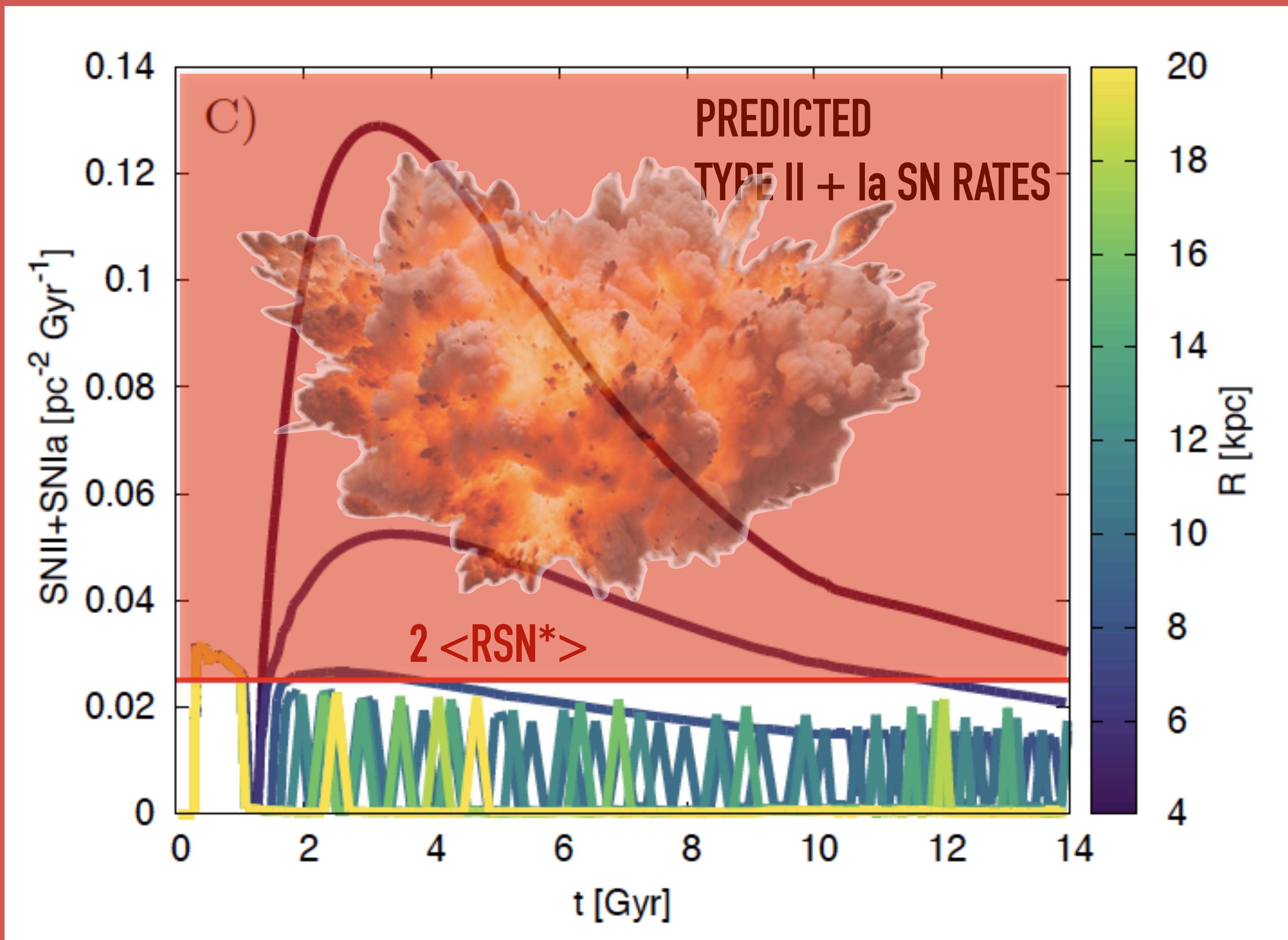

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P_{SN} = 0 else

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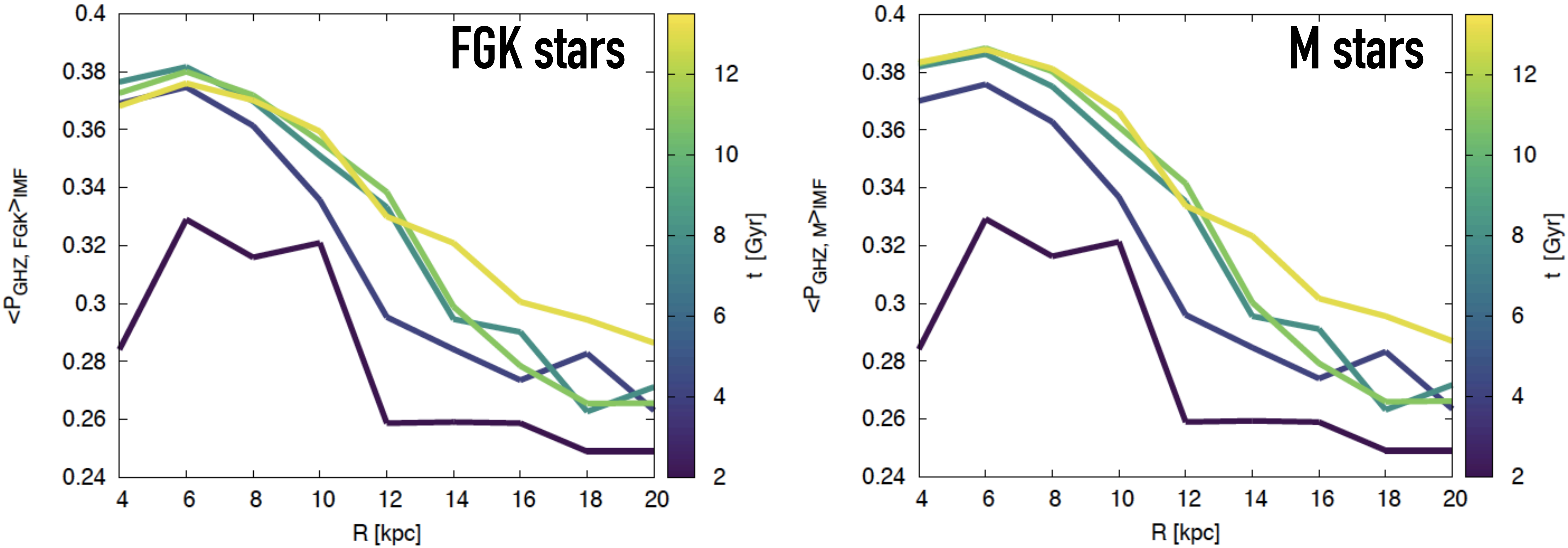
The P_{GHZ} probabilities without SN effects



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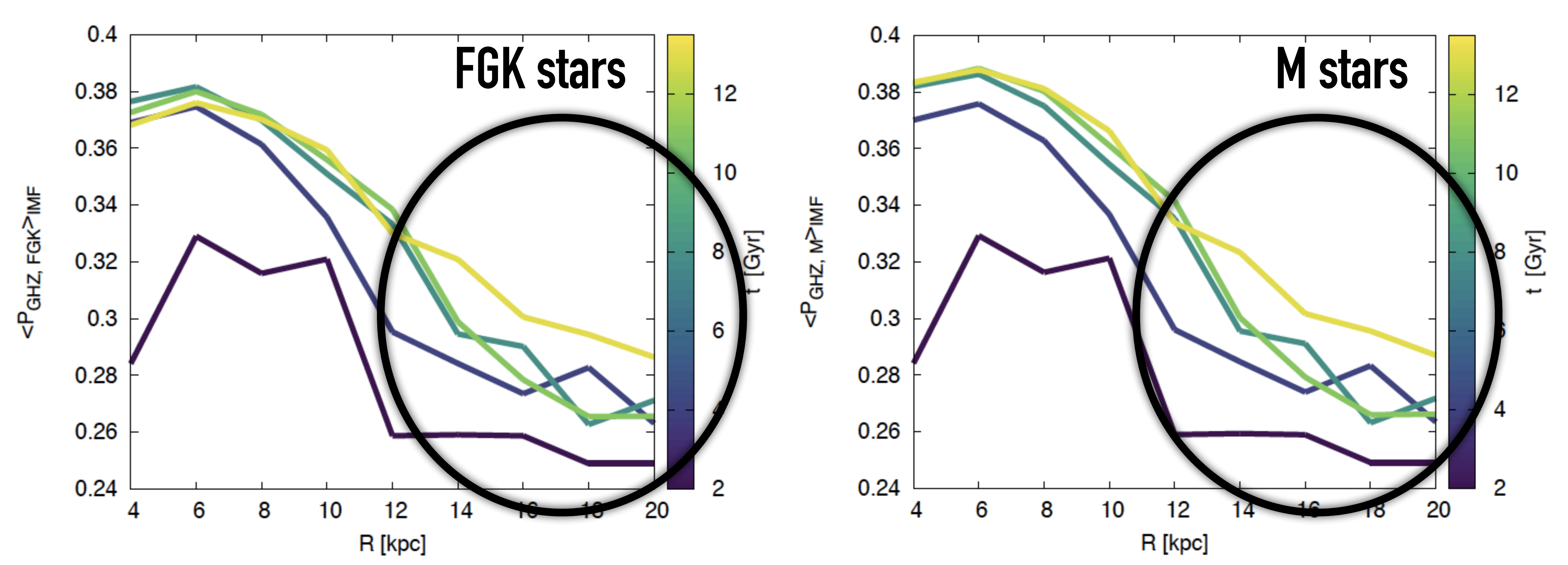
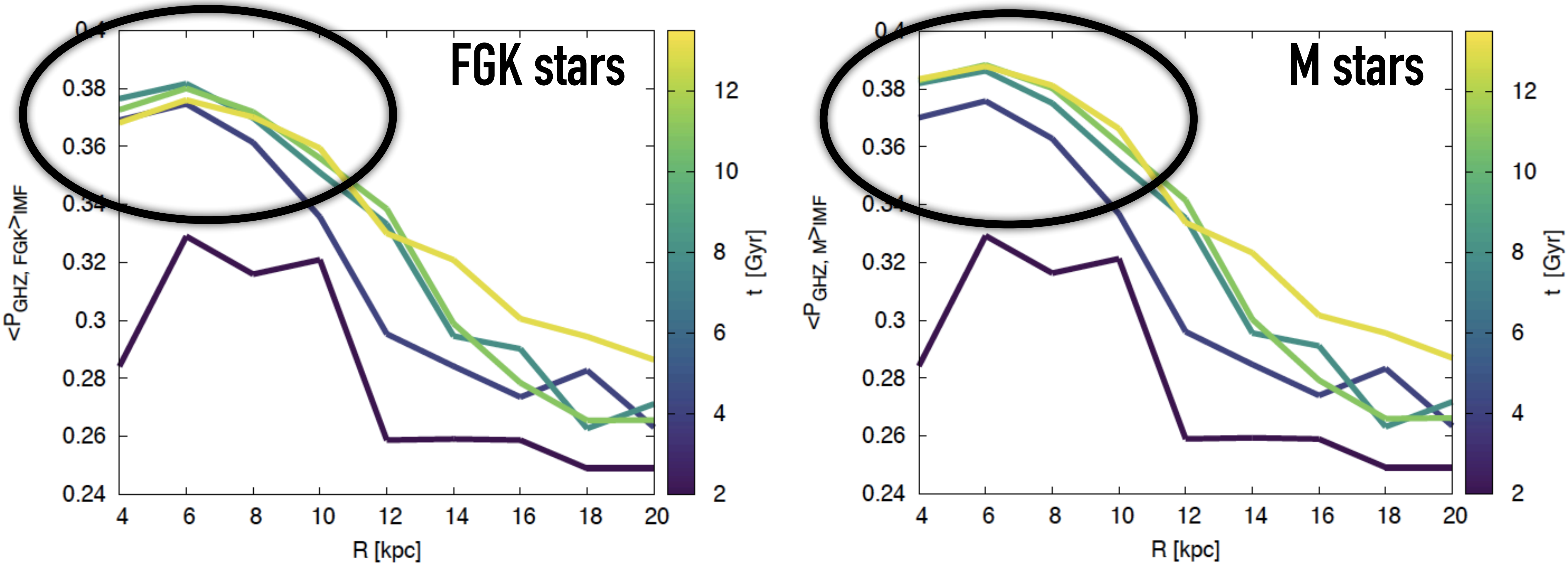


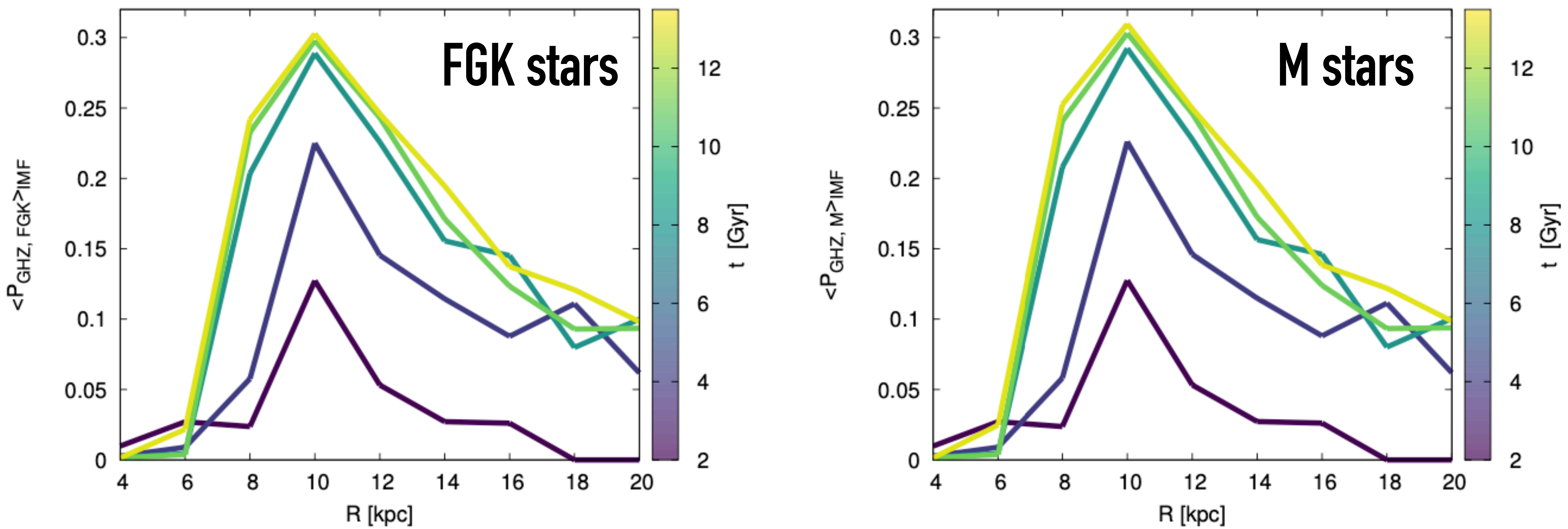
The P_{GHZ} probabilities are identical at large Galactocentric distances. This is due to the fact that, the P_E probabilities are similar for sub-solar values

The P_{GHZ} probabilities without SN effects



The P_{GHZ} probabilities become to be different only for Galactic times larger than 8 Gyr.

The P_{GHZ} probabilities with SN effects



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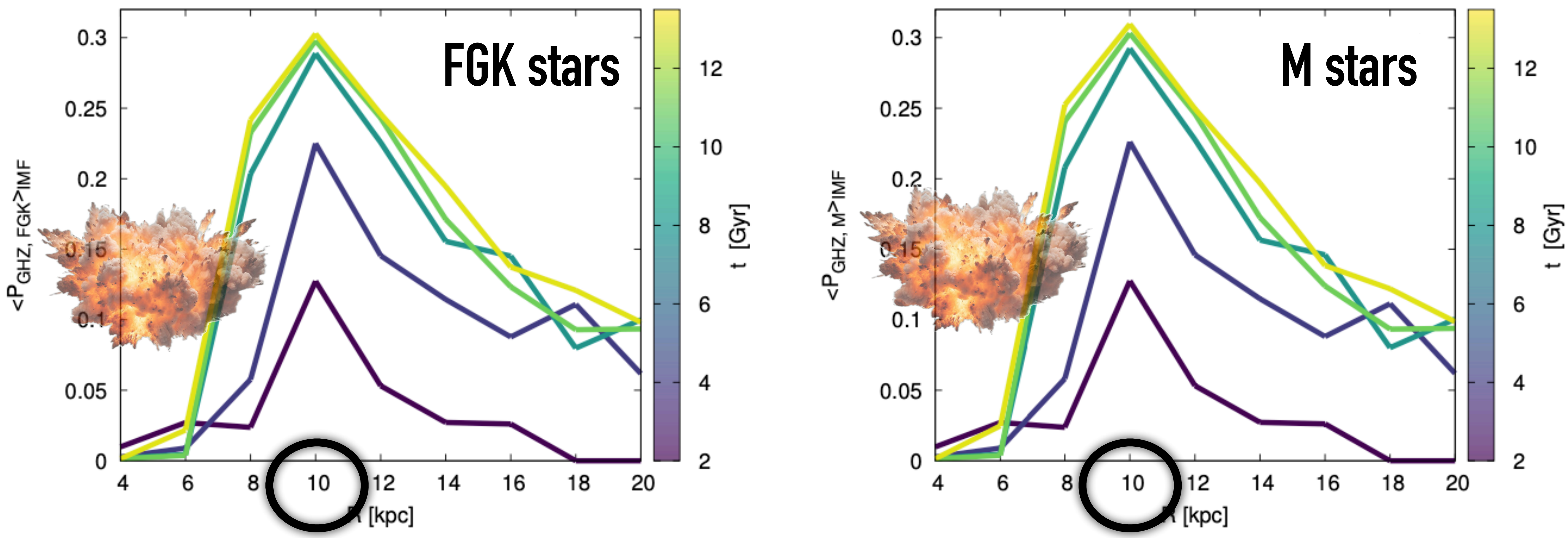
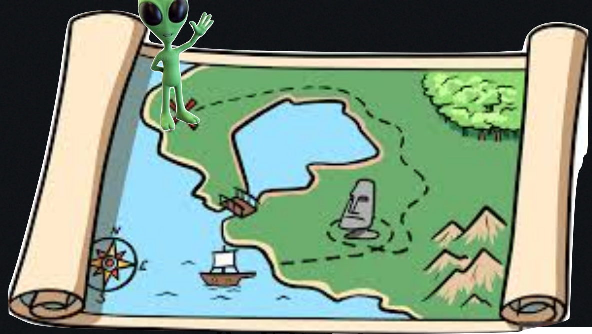
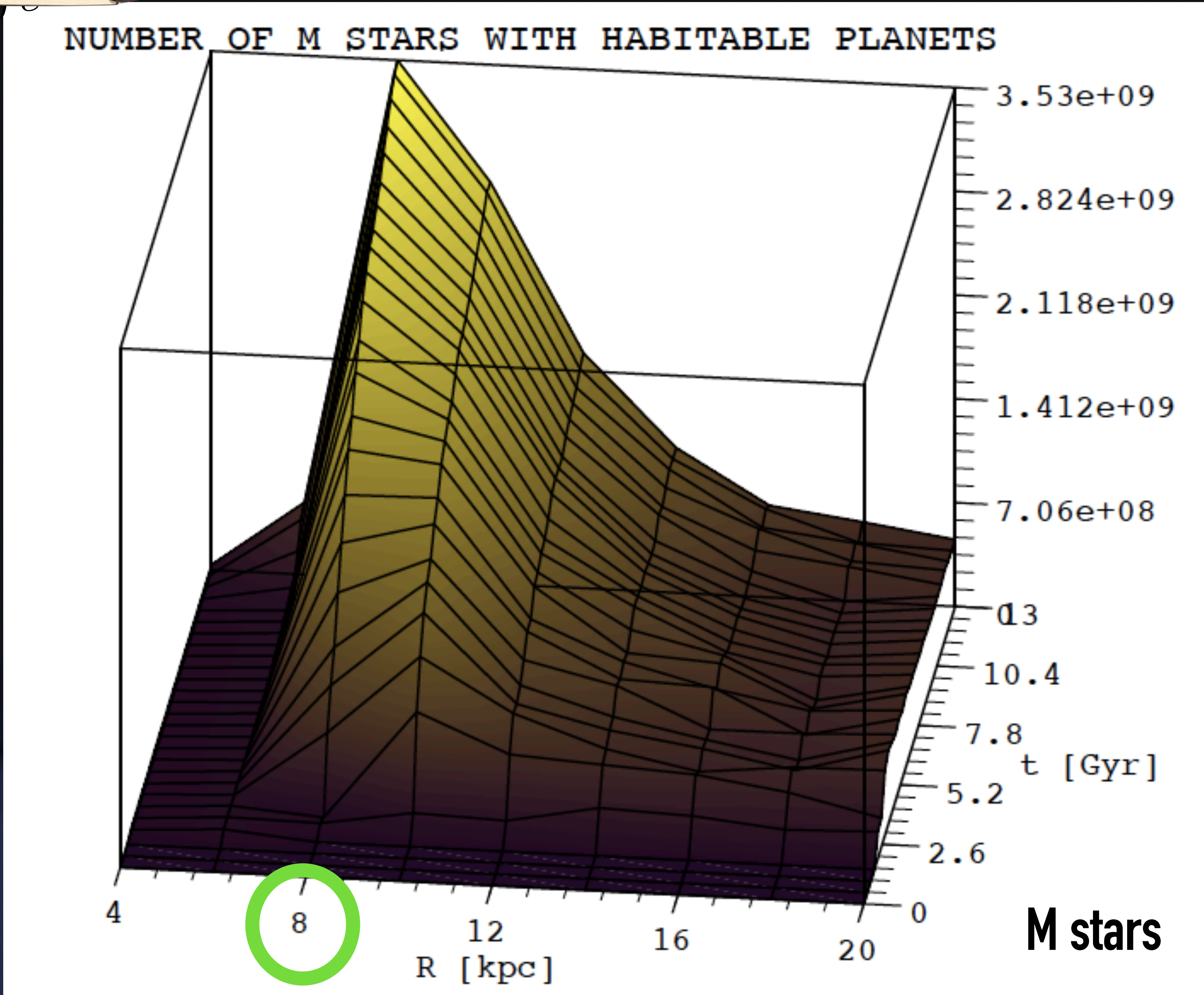


Both P_{GHZ} probabilities peak at 10 kpc



THE GHZ MAP

Spitoni+17



THE GHZ MAP

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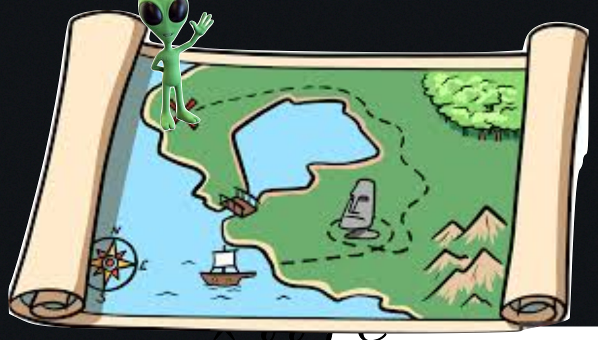
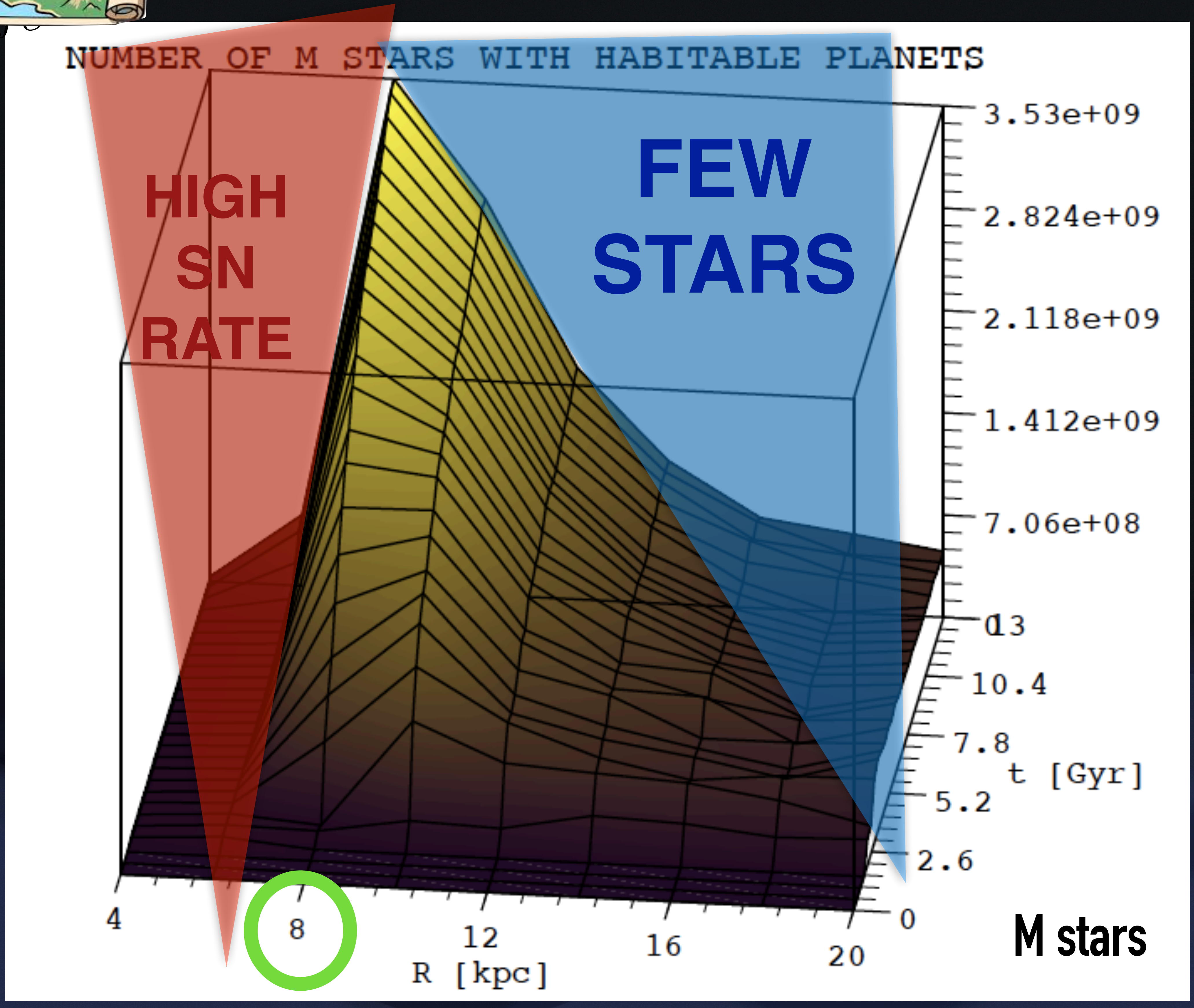
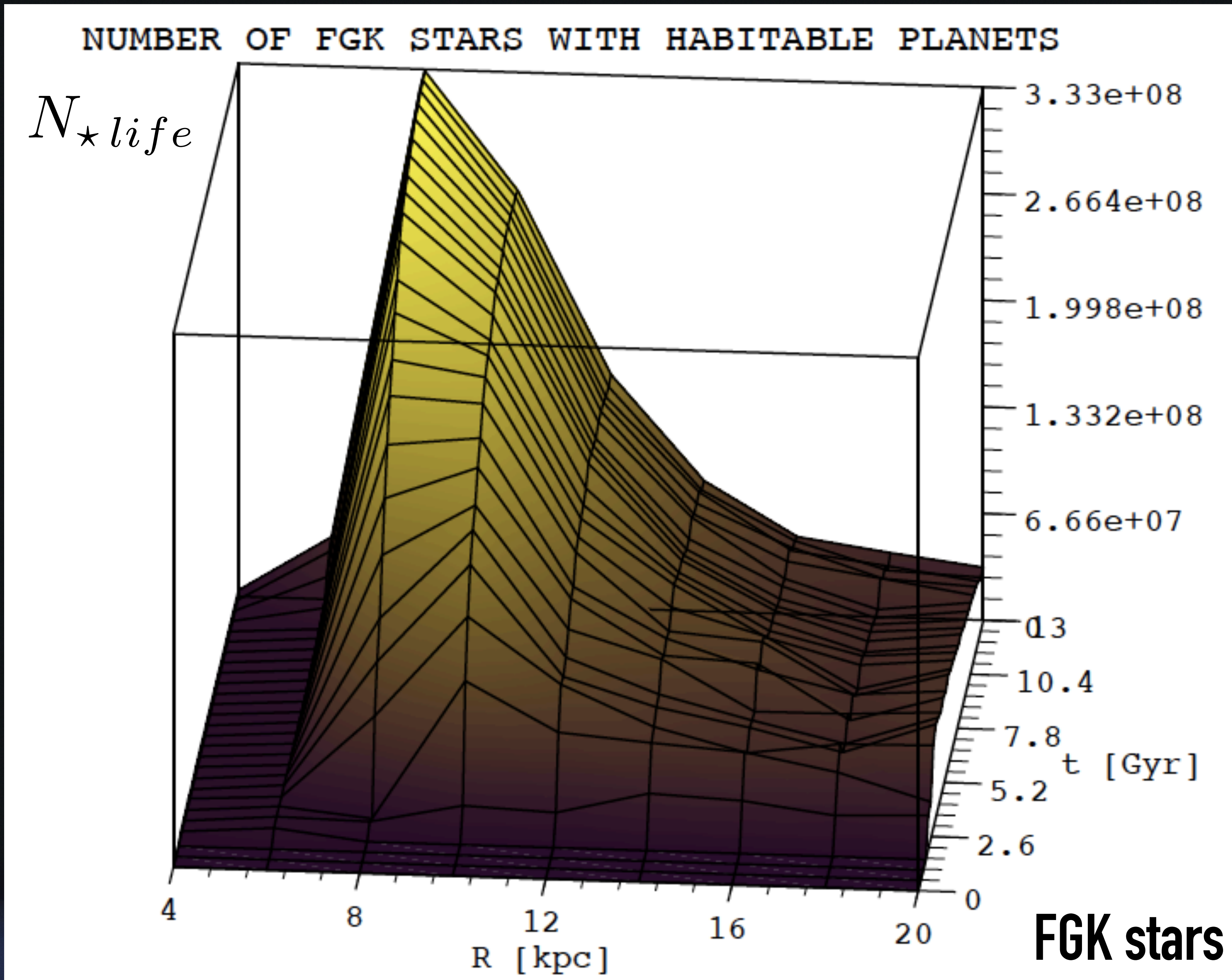
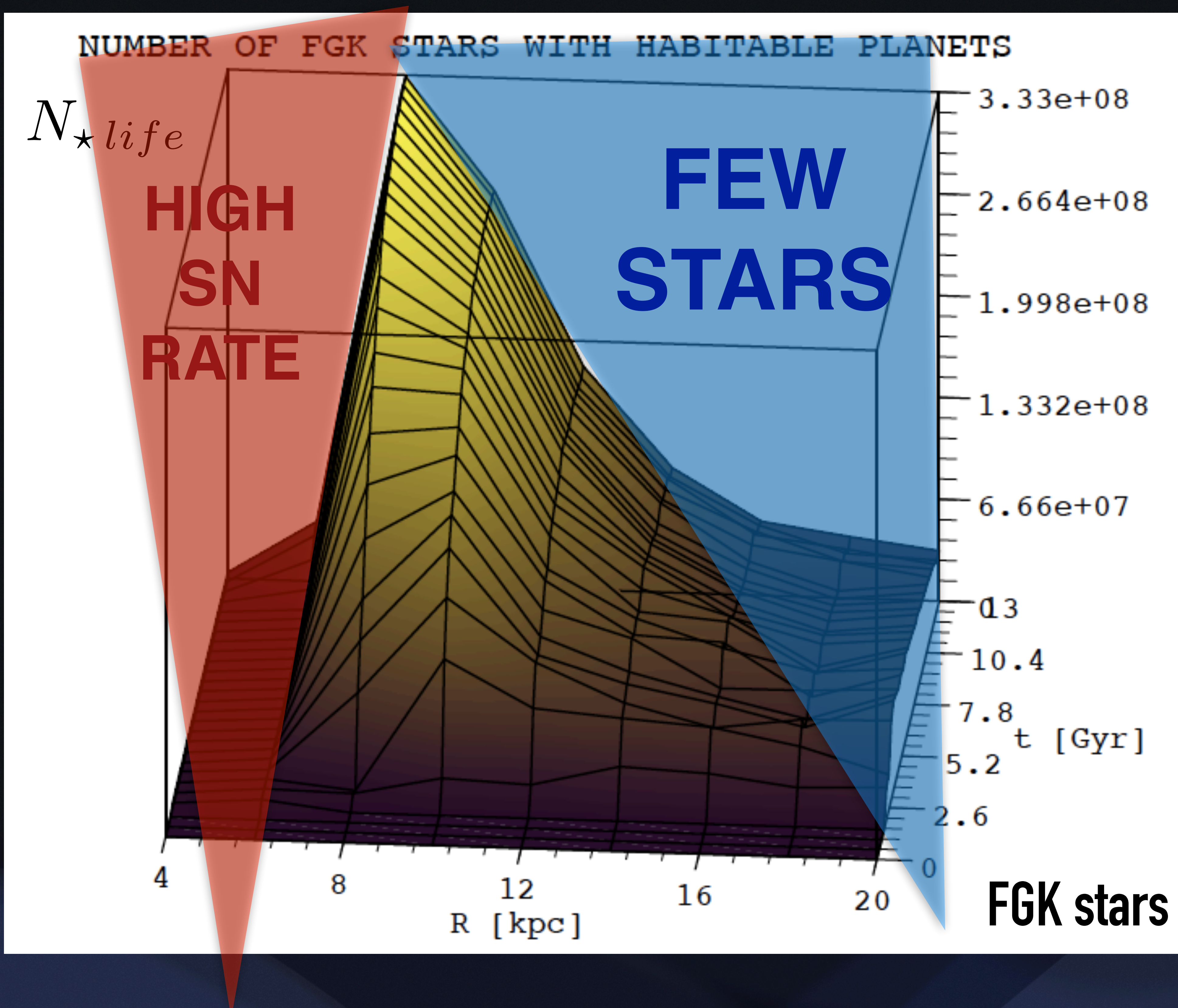






At the peak (8 kpc, at the present day)

$$\frac{N_{\star\, M,life}}{N_{\star\, FGK,life}} = 10.60$$



At the peak (8 kpc, at the present day)

$$\frac{N_{\star\, M,life}}{N_{\star\, FGK,life}} = 10.60$$

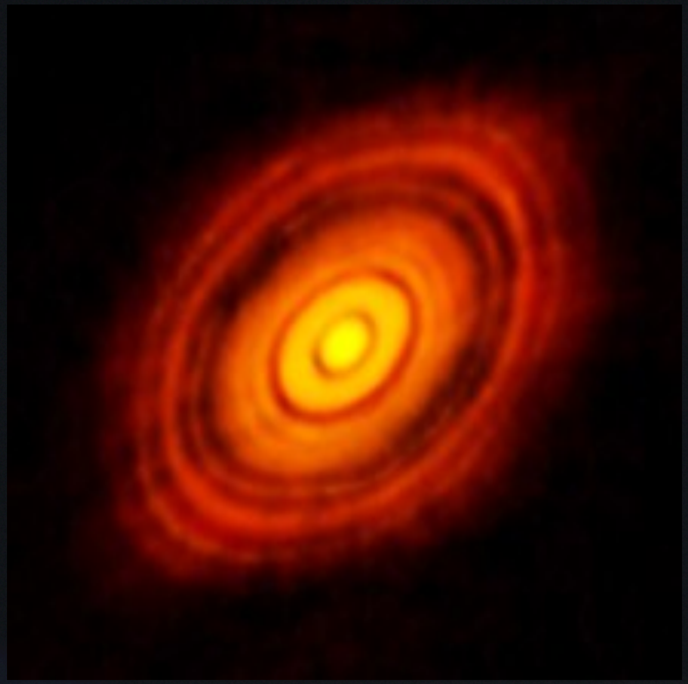
This ratio is consistent with the IMF we adopt in our model.

The ratio between the fraction of M stars over FGK stars (by number) in a newborn population adopting a Scalo IMF is:

$$\left(\frac{M}{FGK}\right)_{\text{Scalo IMF}} = \frac{\int_{0.08\,M_\odot}^{0.45\,M_\odot} m^{-2.35} dm}{\int_{0.45\,M_\odot}^{1.4\,M_\odot} m^{-2.35} dm} = 11.85$$

The role of the dust

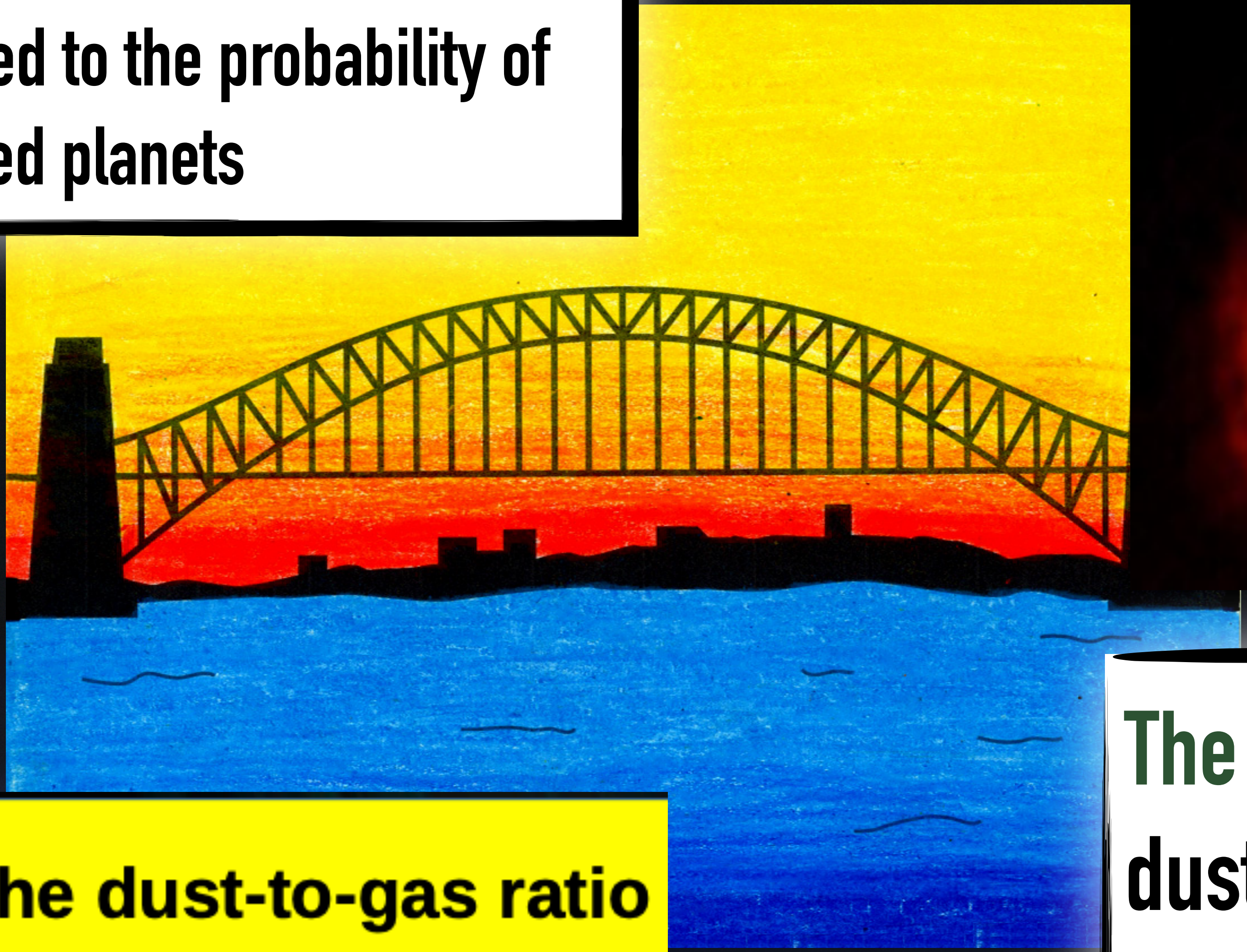
The metallicity of stars, which is observationally related to the probability of the presence of hosted planets

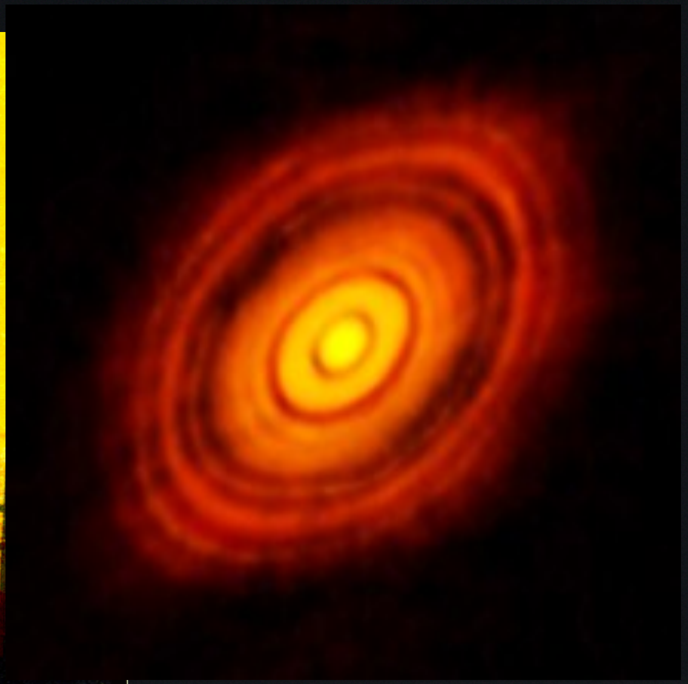


The initial dust-to-gas ratio of the protoplanetary discs

The role of the dust

The metallicity of stars, which is observationally related to the probability of the presence of hosted planets

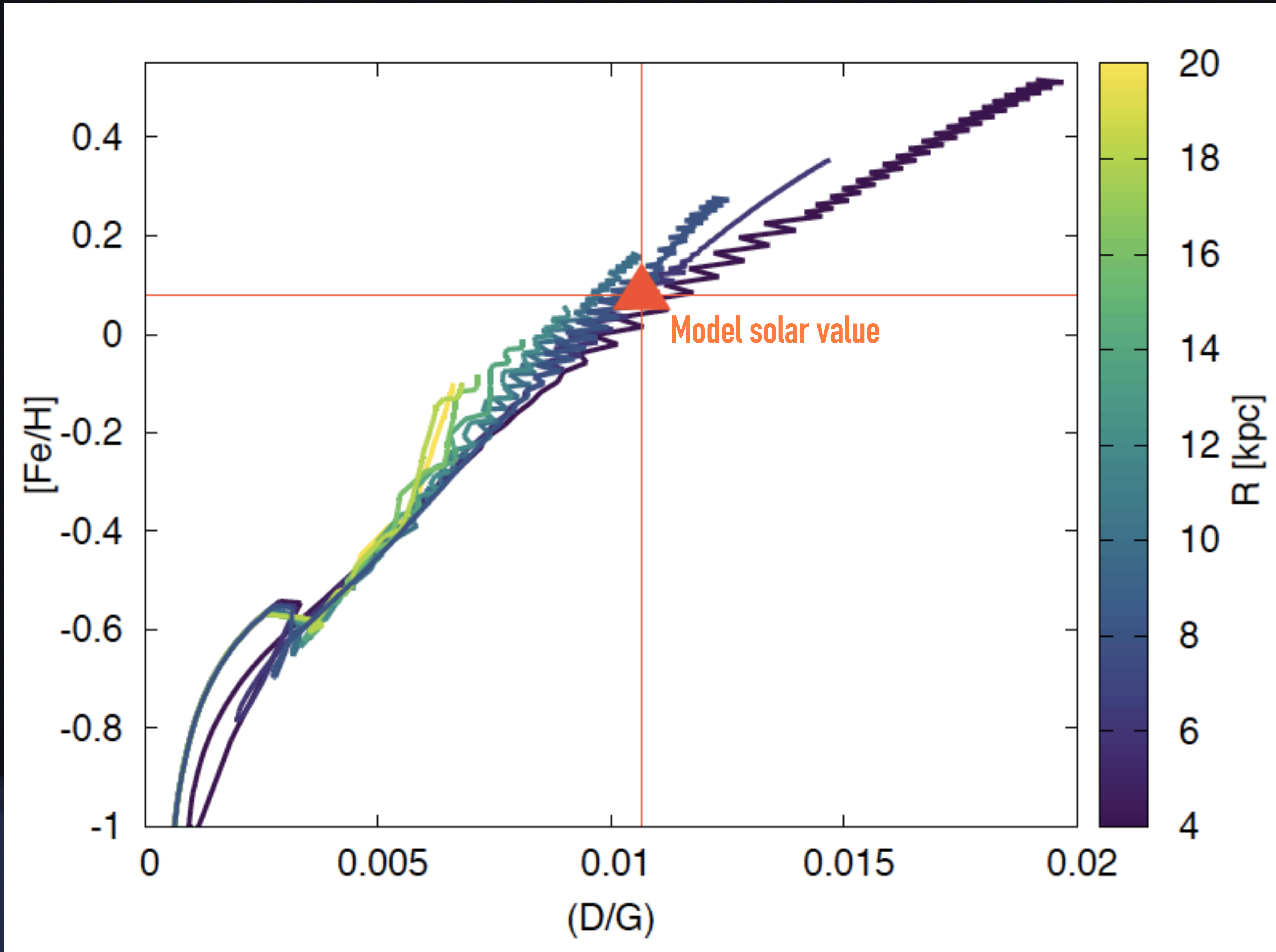


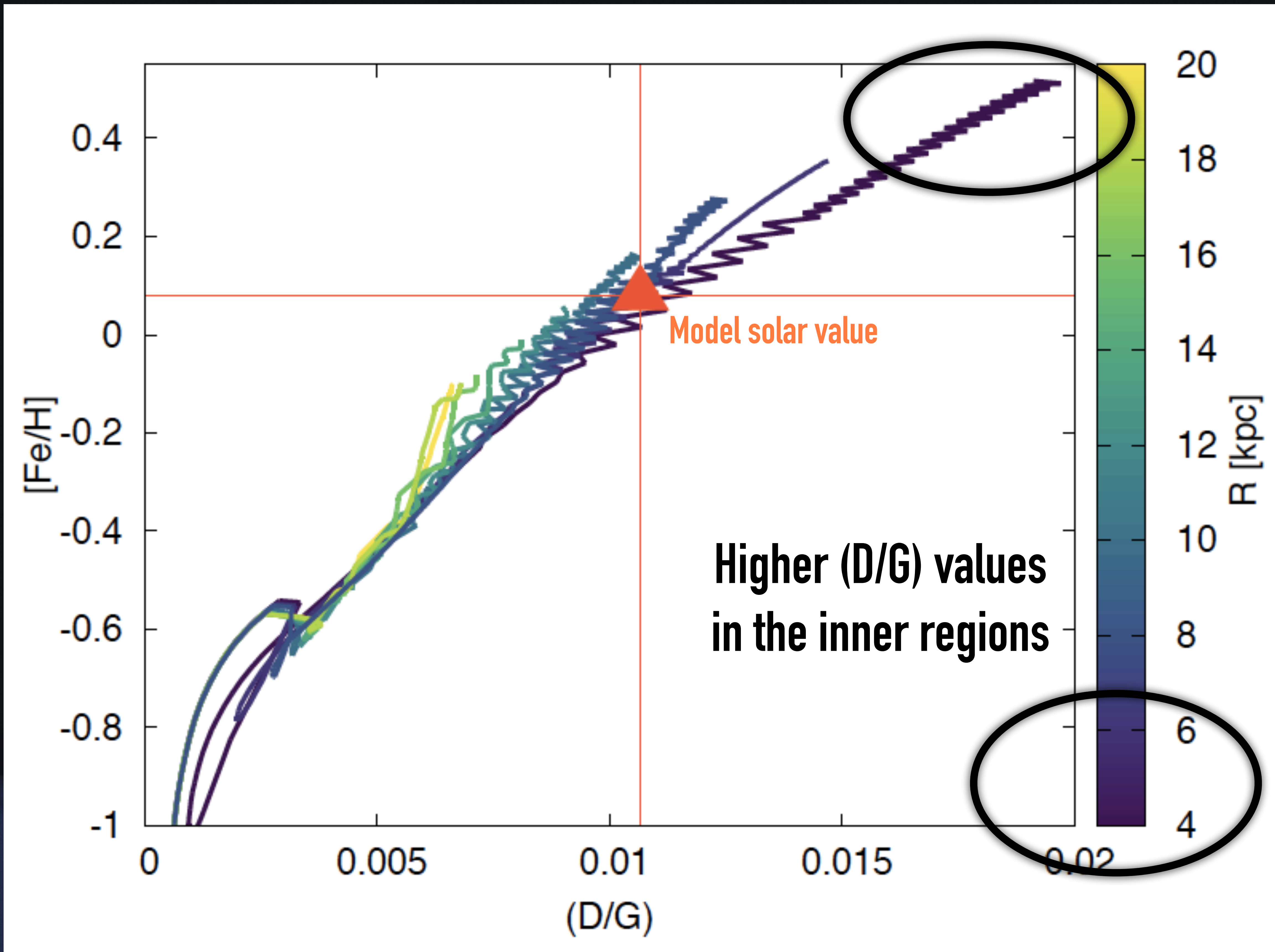


[Fe/H] versus the dust-to-gas ratio

Model of Gioannini et al. (2017)

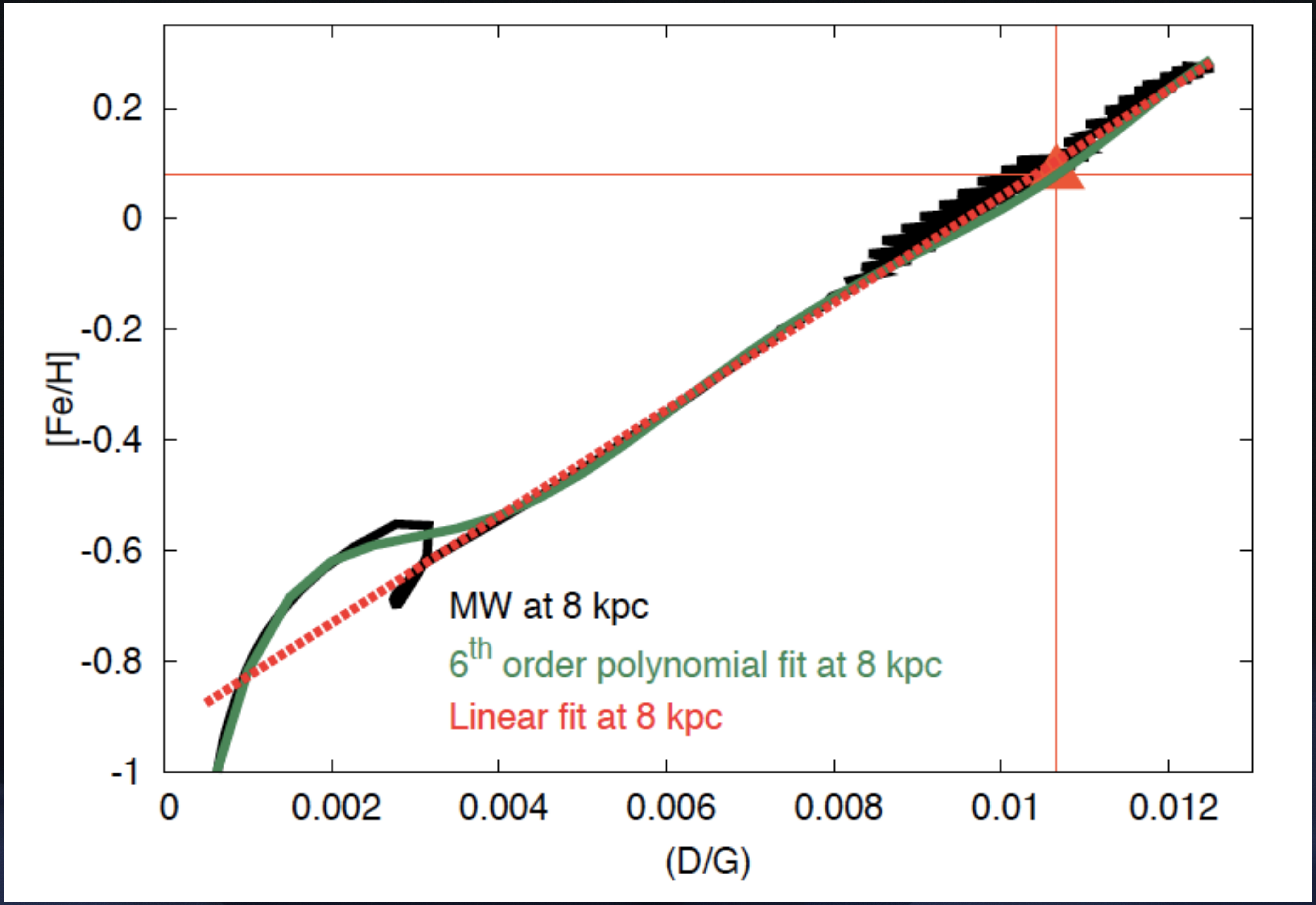
The initial dust-to-gas ratio of the protoplanetary discs


0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
[Fe/H]
0
0.005
0.01
0.015
0.02
(D/G)
Model solar value
20
18
16
14
12
10
8
6
4
R [kpc]



Model solar value
Higher (D/G) values
in the inner regions
[Fe/H]
(D/G)
R [kpc]
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
0.005
0.01
0.015
0.02
20
18
16
14
12
10
8
6
4

MODEL FITS IN THE SOLAR NEIGHBORHOOD



$$[Fe/H] = 96.49\ (D/G) - 0.92$$

GAS GIANT PLANET PROBABILITIES AROUND:

FGK STARS

$$P_{GGP/FGK}\left([\mathrm{Fe/H}], M_\star\right) = 0.07 \times 10^{1.8[\mathrm{Fe/H}]}\left(\frac{M_\star}{M_\odot}\right)$$

M STARS

$$P_{GGP/M}\left([\mathrm{Fe/H}], M_\star\right) = 0.07 \times 10^{1.06[\mathrm{Fe/H}]}\left(\frac{M_\star}{M_\odot}\right)$$

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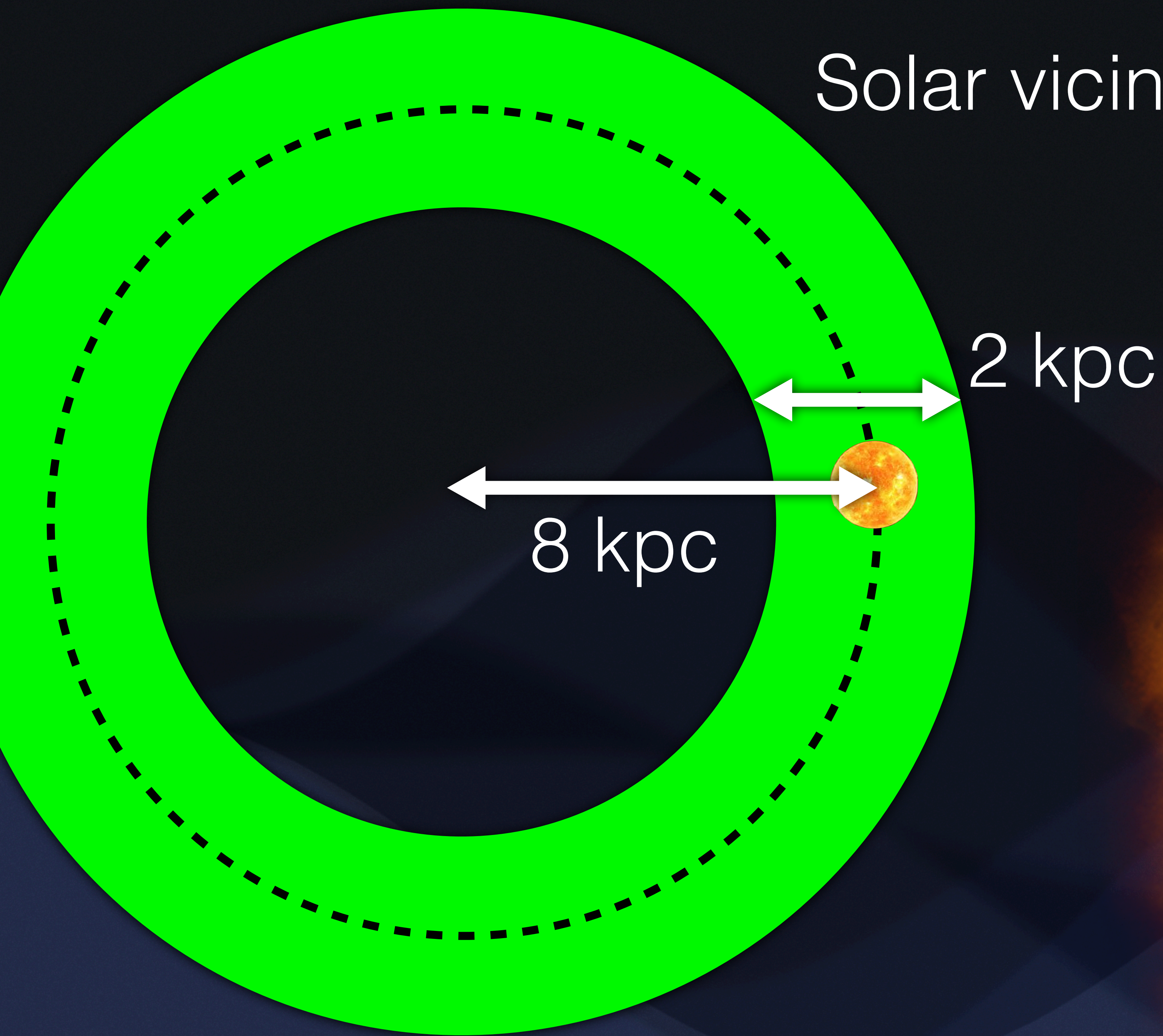
Number of stars similar to Sun born from the beginning up to the formation of the Solar System

$N_{\star life}$

(Fiore.. ES+24)



✓ Same mass as the Sun

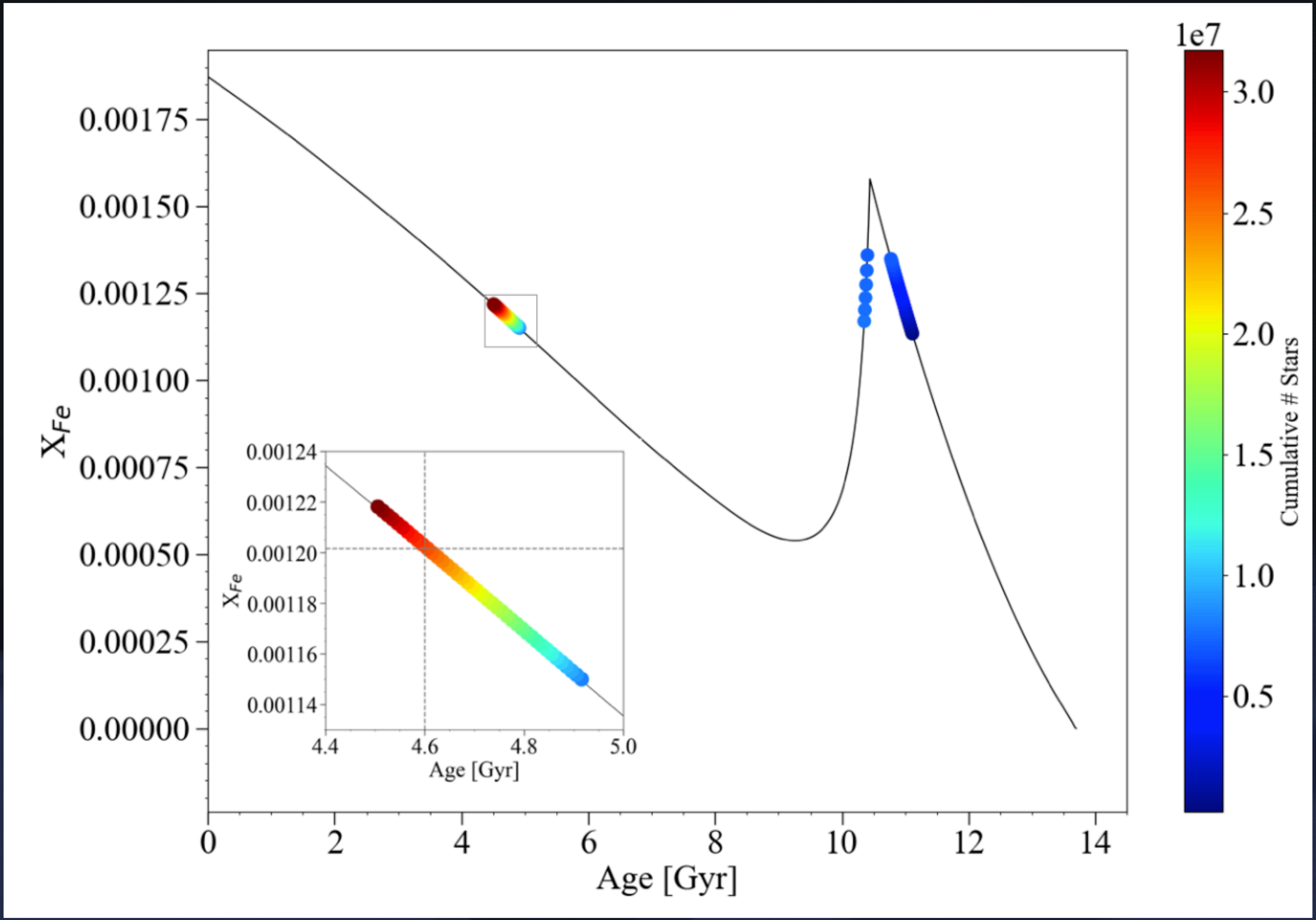
✓ Solar metallicity

12+(Fe/H) = 7.50 ± 0.04 dex

Number of stars similar to Sun born from the beginning up to the formation of the Solar System

$N_{\star life}$

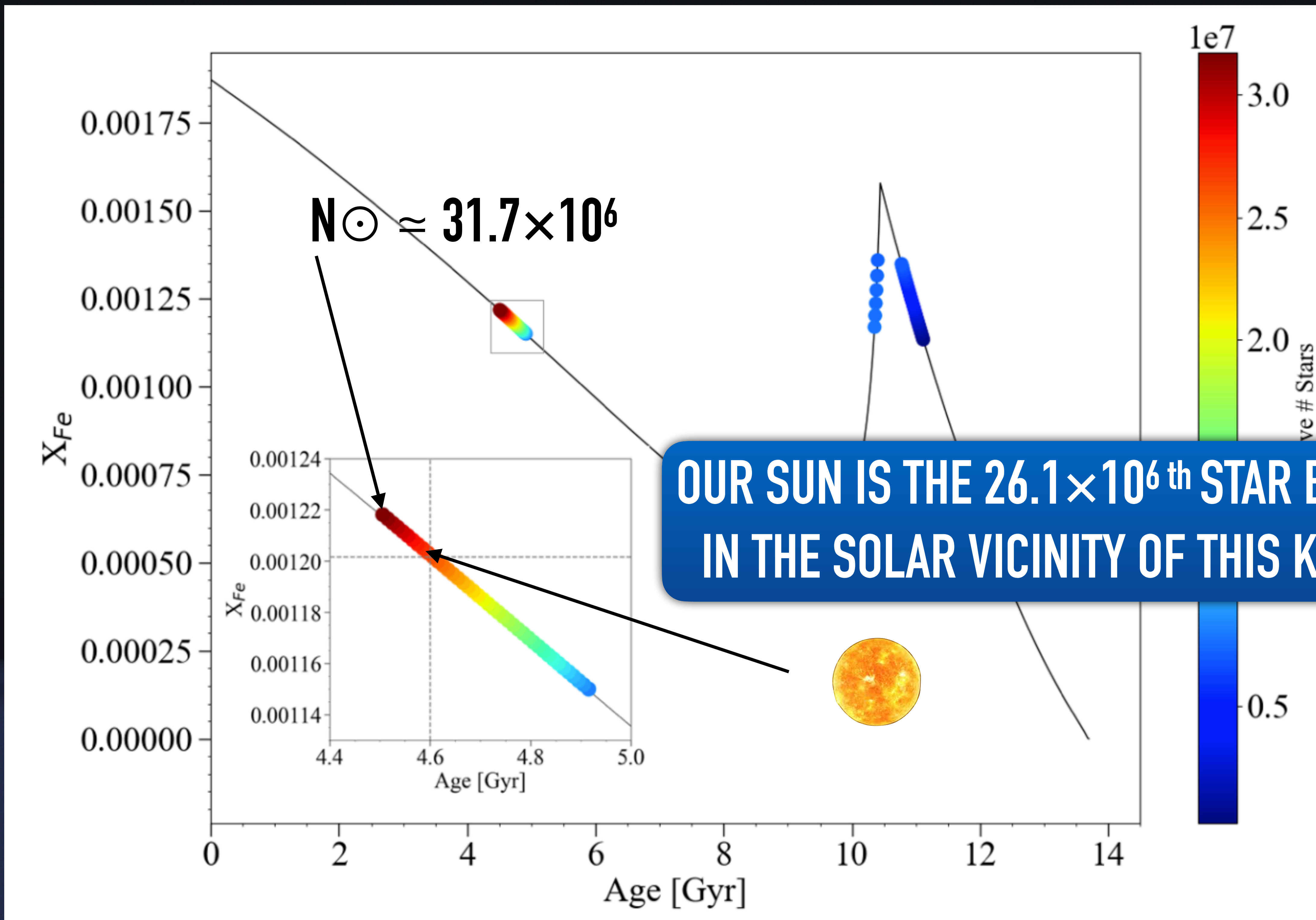
(Fiore.. ES+24)



Number of stars similar to Sun born from the beginning up to the formation of the Solar System

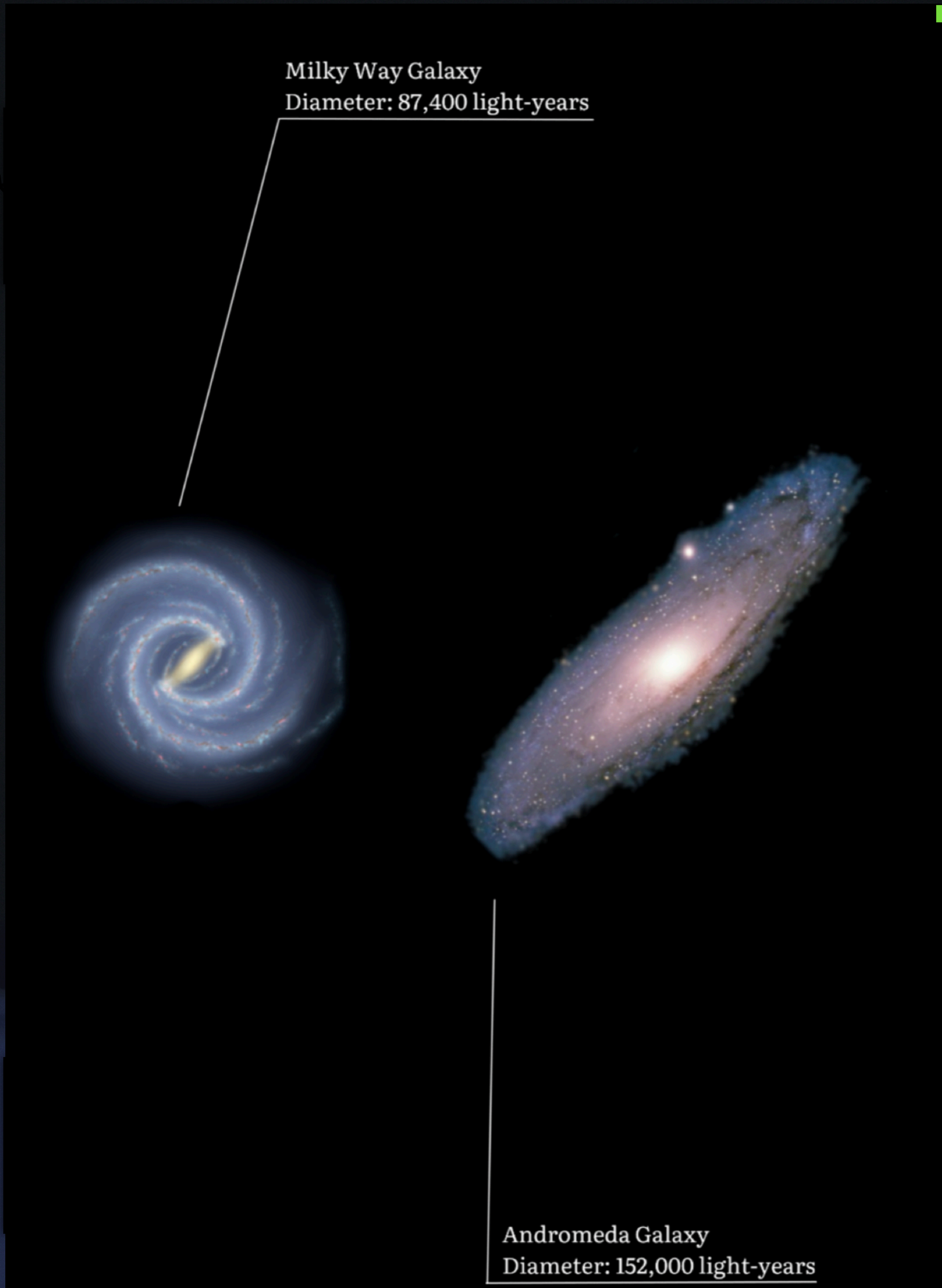
$N_{\star life}$

(Fiore.. ES+24)



OUR SUN IS THE 26.1×10^{6} th STAR BORN IN THE SOLAR VICINITY OF THIS KIND

THE GHZ MAP

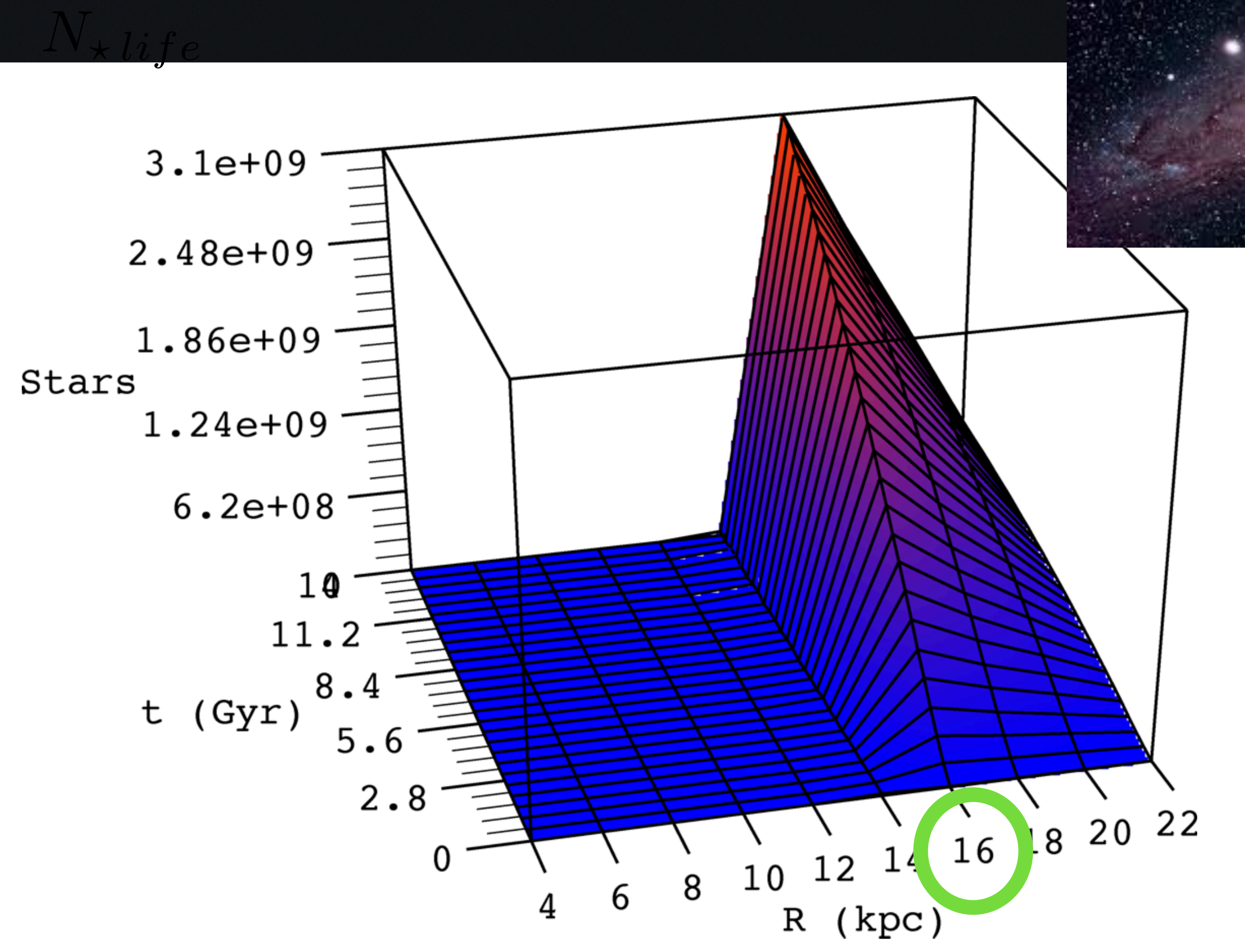


Andromeda Galaxy

Spitoni+14

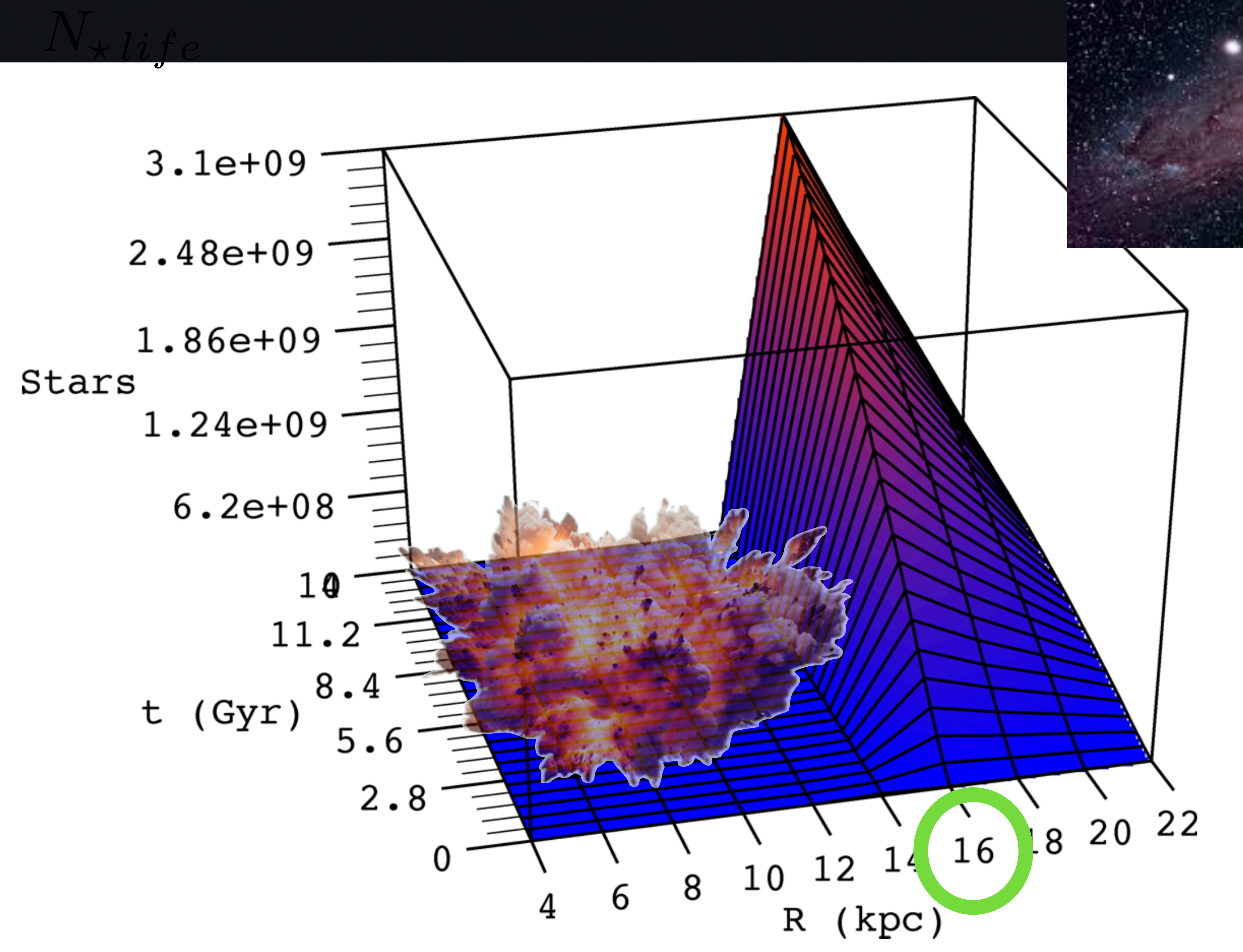
M31 is the largest galaxy of the Local group, more massive and with more stars than the Milky Way

Spitoni+14



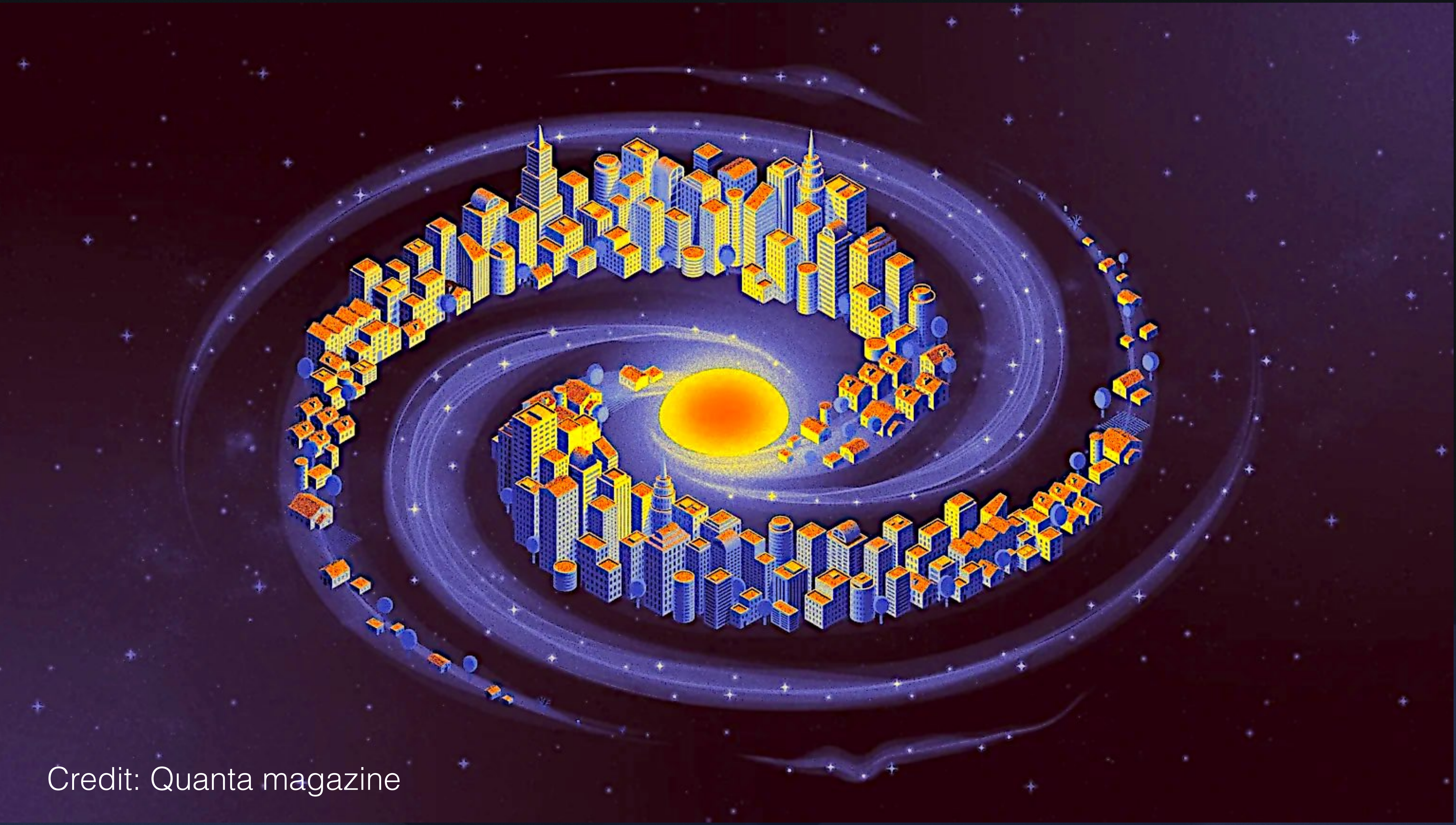
In the region between 4-14 kpc there is a high enough SN rate to annihilate life on formed planets .M 31 was more SF active in the past than the Milky Way (Renda+05, Yin+09)

Spitoni+14



In the region between 4-14 kpc there is a high enough SN rate to annihilate life on formed planets .M 31 was more SF active in the past than the Milky Way (Renda+05, Yin+09)

Future perspective

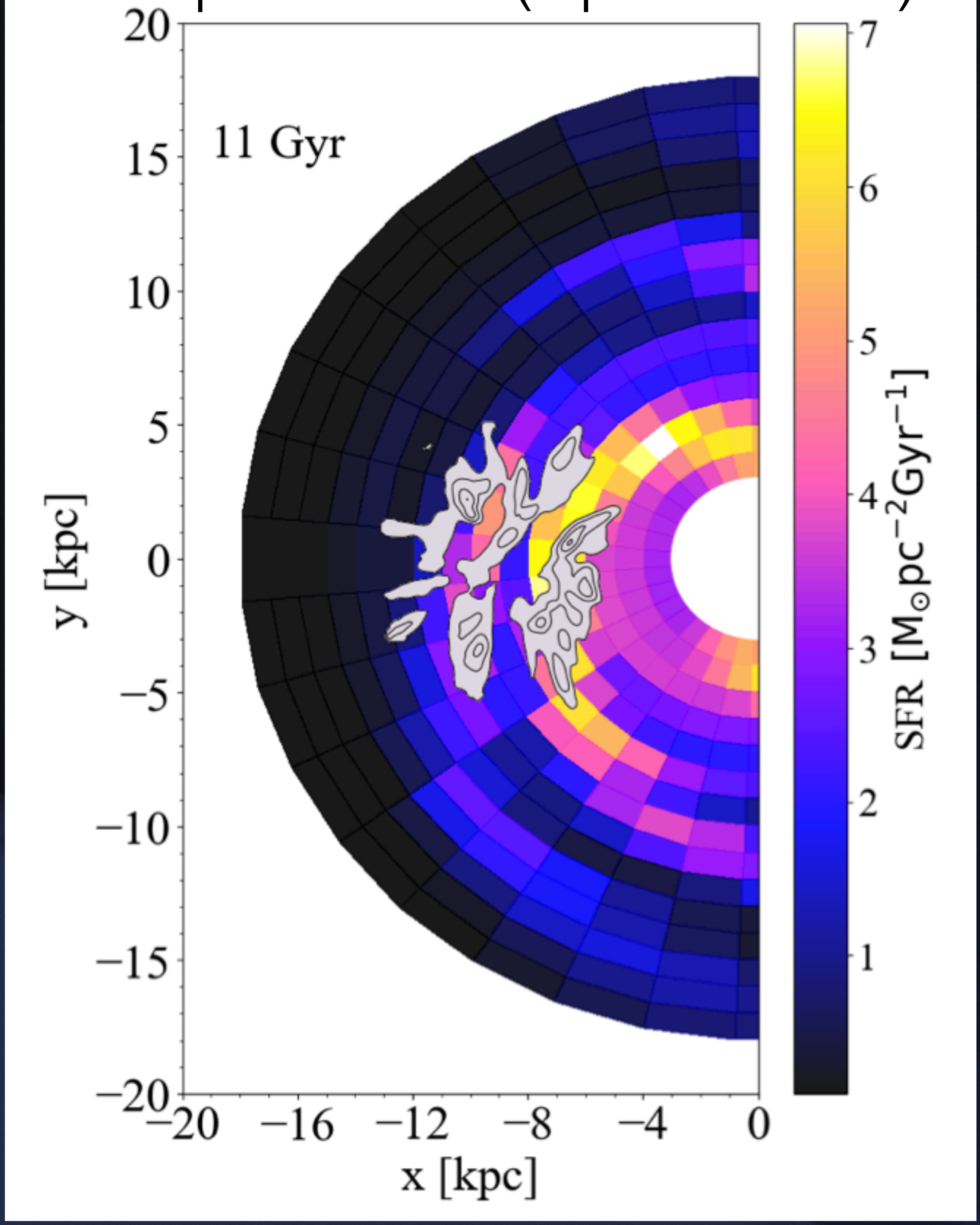


Credit: Quanta magazine

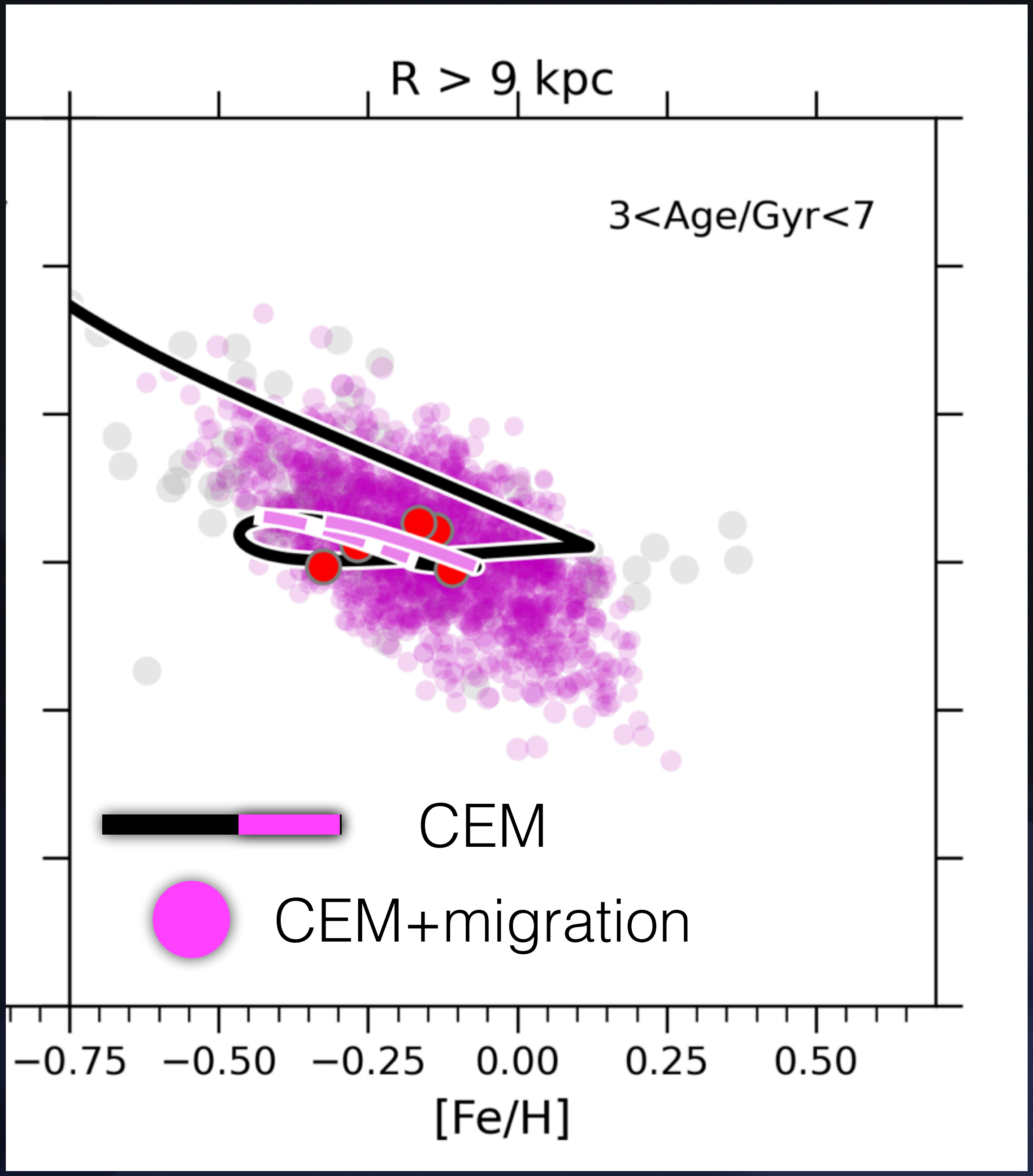
Future perspective

- Effects of spiral arms and stellar migration on the GHZ

Spitoni+23 (Spiral arms)



Palla+24 (migration)



SUMMARY

- Assuming prescriptions for the destructive effect from close-by SN explosions, the larger number of FGK and M stars with habitable planets are in the solar neighborhood.
- At the present time the total number of M stars with habitable terrestrial planets without gas giant ones are $\simeq$ 10 times the number of FGK stars
- The probability of finding gas giant planets can be expressed in terms of the D/G ratio
- Our Sun is the is the 26.1×10^{6} th star born in the solar vicinity of this kind
- In the Andromeda galaxy the GHZ is shifted towards external regions