The impact of stellar migration and gas giants on Galactic habitability

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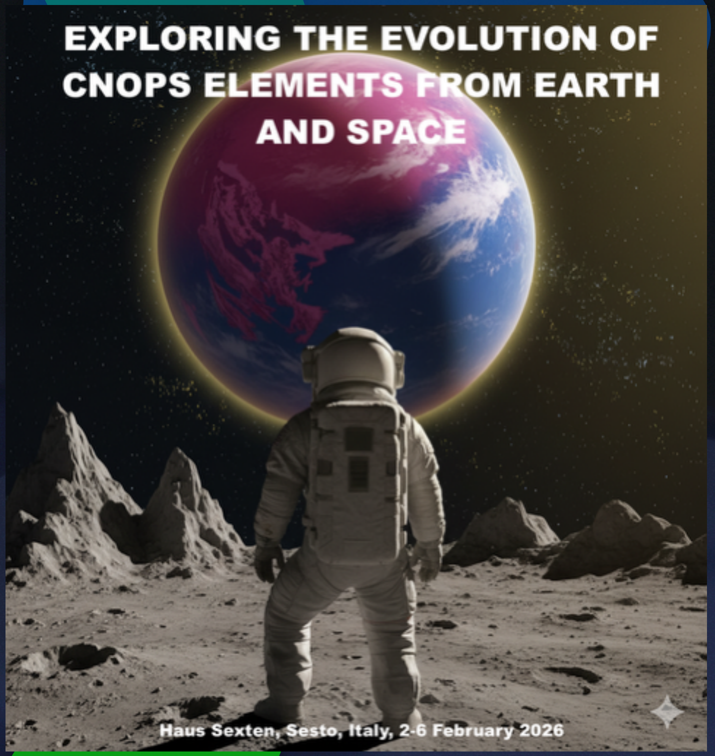


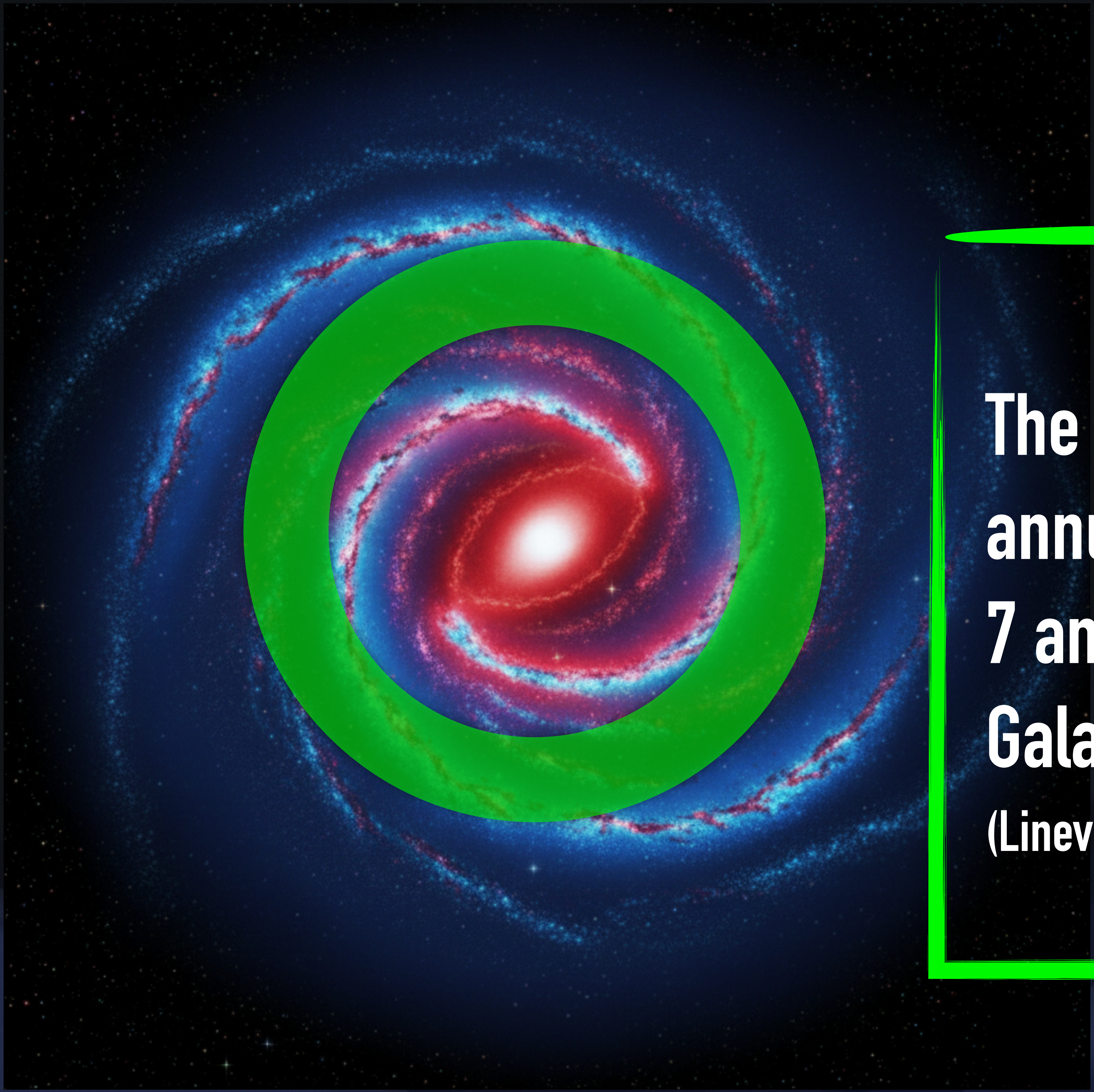
Emanuele Spitoni

In collaboration with: M. Palla, L. Magrini, F. Matteucci
C. Danielski, M. Tsantaki, A. Sozzetti, M. Molero, F. Fontani,
D. Romano, G. Cescutti, L.Silva

The GHZ definition

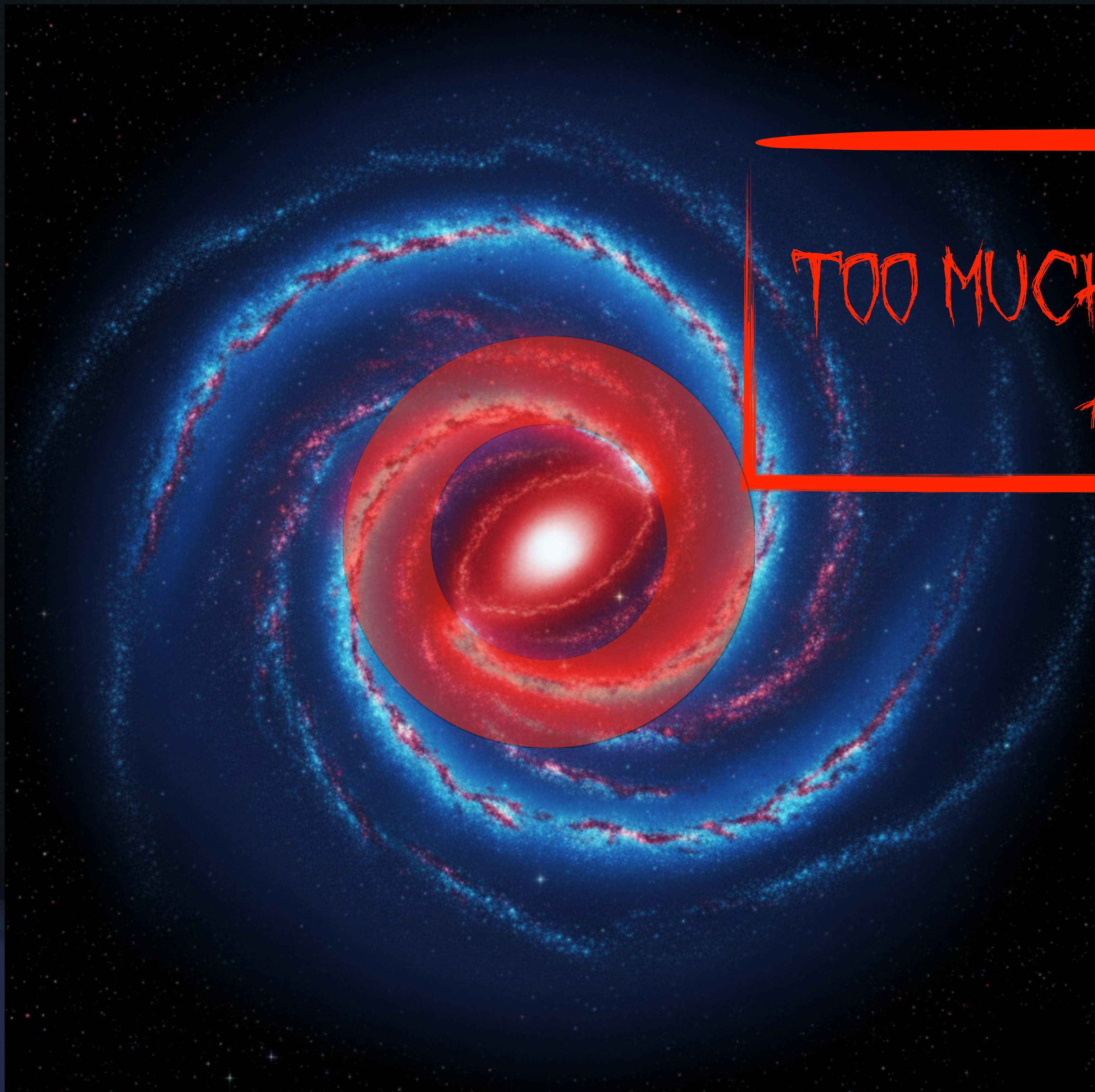
The Galactic habitable zone is defined as the region with sufficiently high metallicity to form planetary systems in which Earth-like planets could be born and might be capable of sustaining life, after surviving to close supernova explosion events.

(GONZALEZ ET AL. 2001)

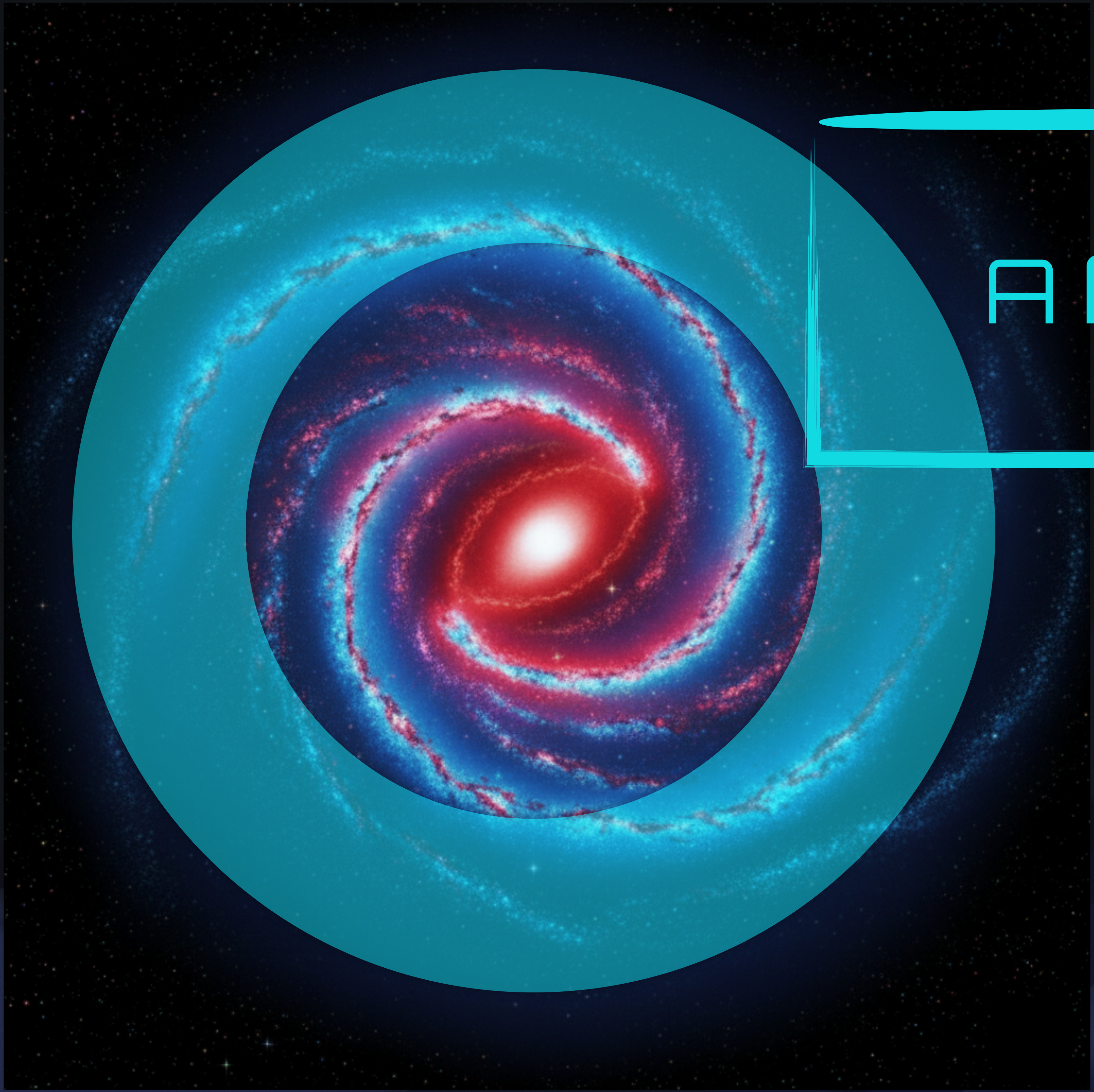


The GHZ identified as an annular region between 7 and 9 kpc from the Galactic Centre

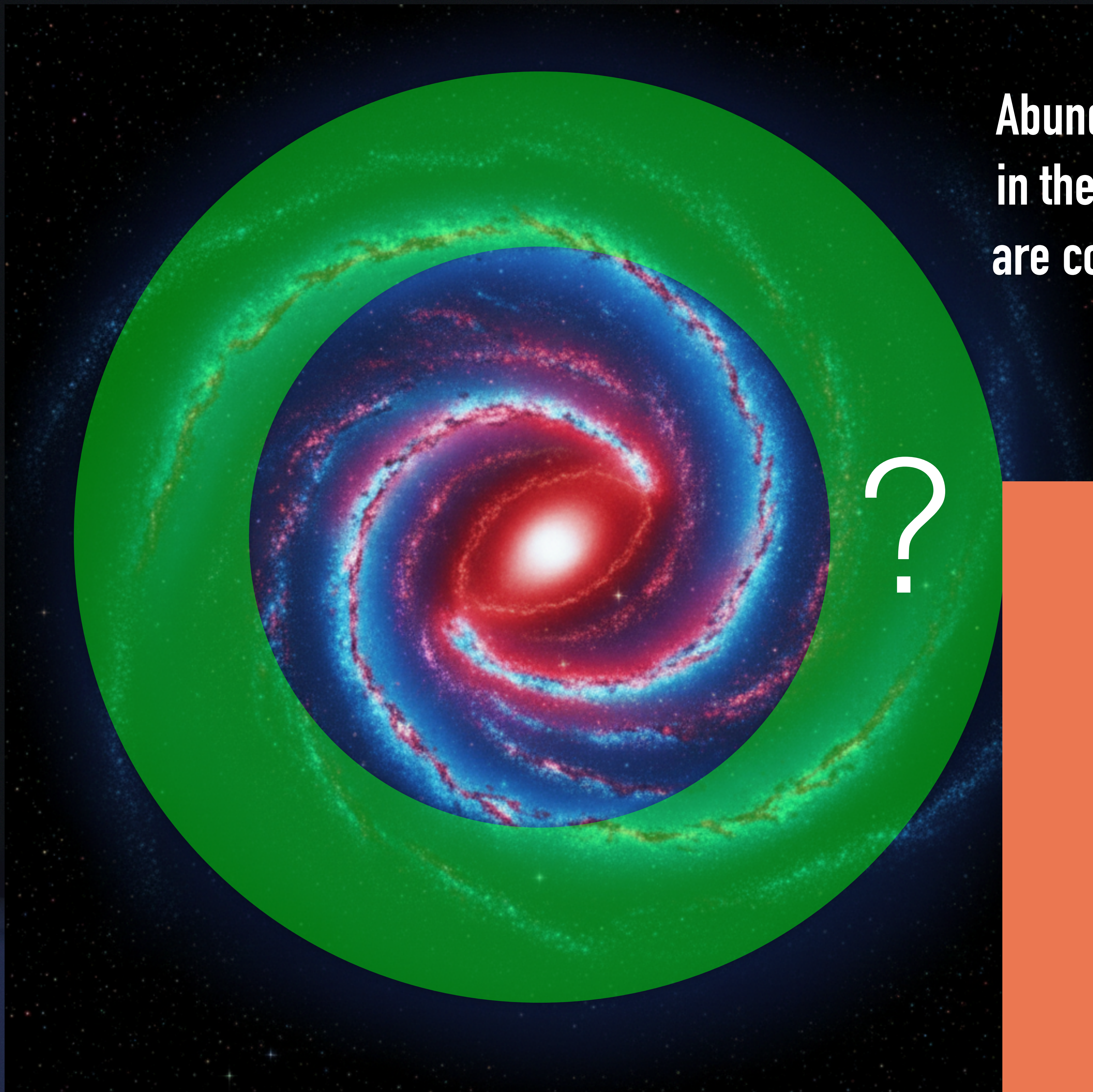
(Lineveawer +04, Spitoni +14,+17).



TOO MUCH STAR-FORMATION ACTIVITY



A few stars



Abundances of organic molecules found in the outer Galaxy star-forming regions are comparable to those measured near the Sun (Fontani +24)

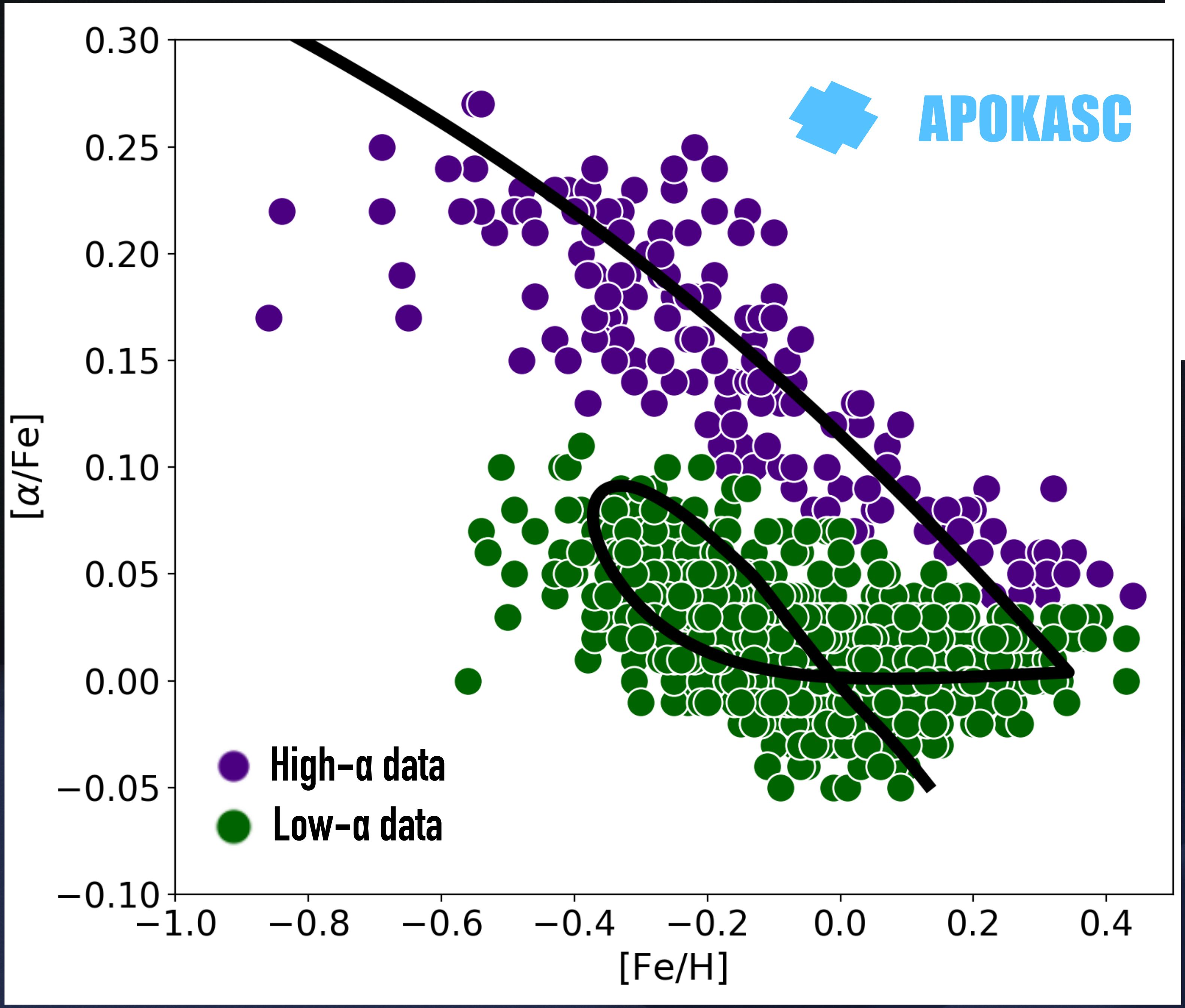
Including the effect of stellar migration on the GHZ

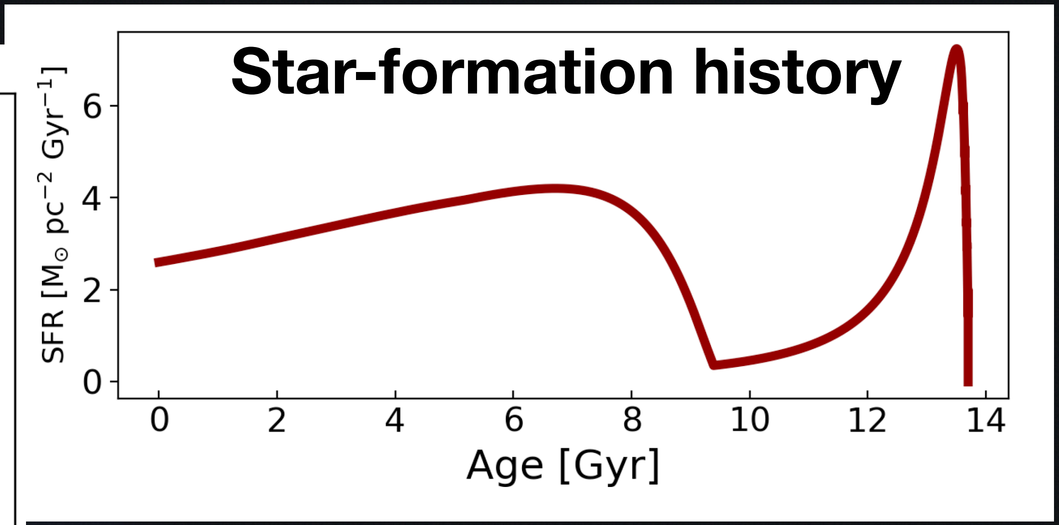
Spitoni+25

The two-infall model at 8 kpc

$$\mathcal{I}_i(t,i) = (\mathcal{X}_i)_{inf}\left[\mathcal{N}_1\, e^{-t/\tau_1} + \theta(t - t_{\max})\mathcal{N}_2\, e^{-(t-t_{\max})/\tau_2}\right]$$

Infall gas rate





Spitoni+19

The two-infall model at 8 kpc

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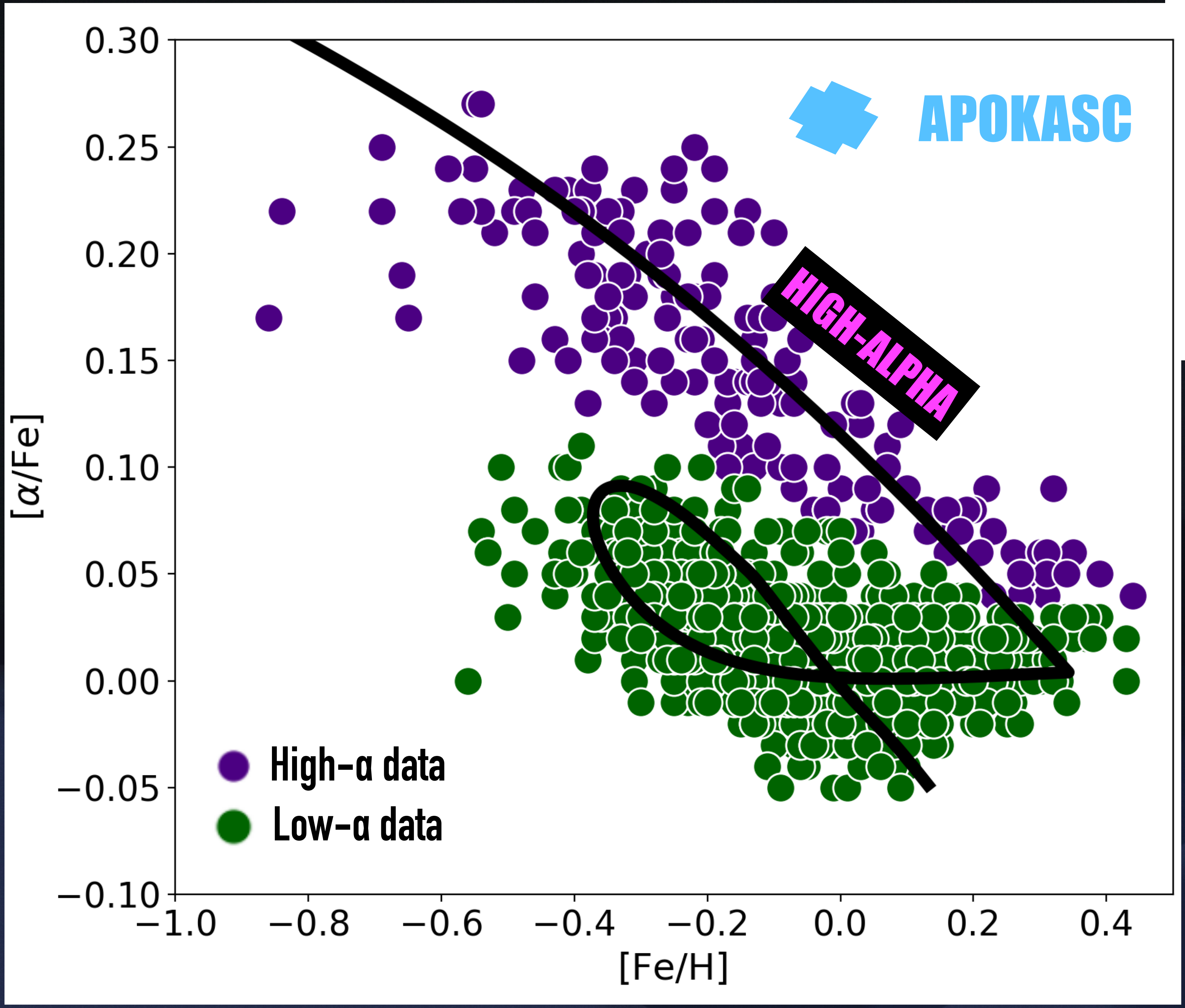

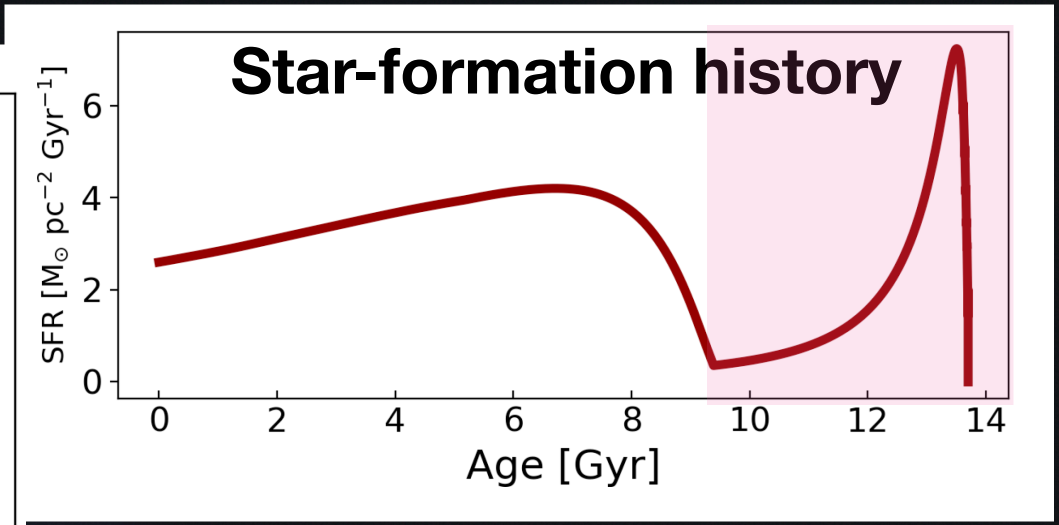

Spitoni+19

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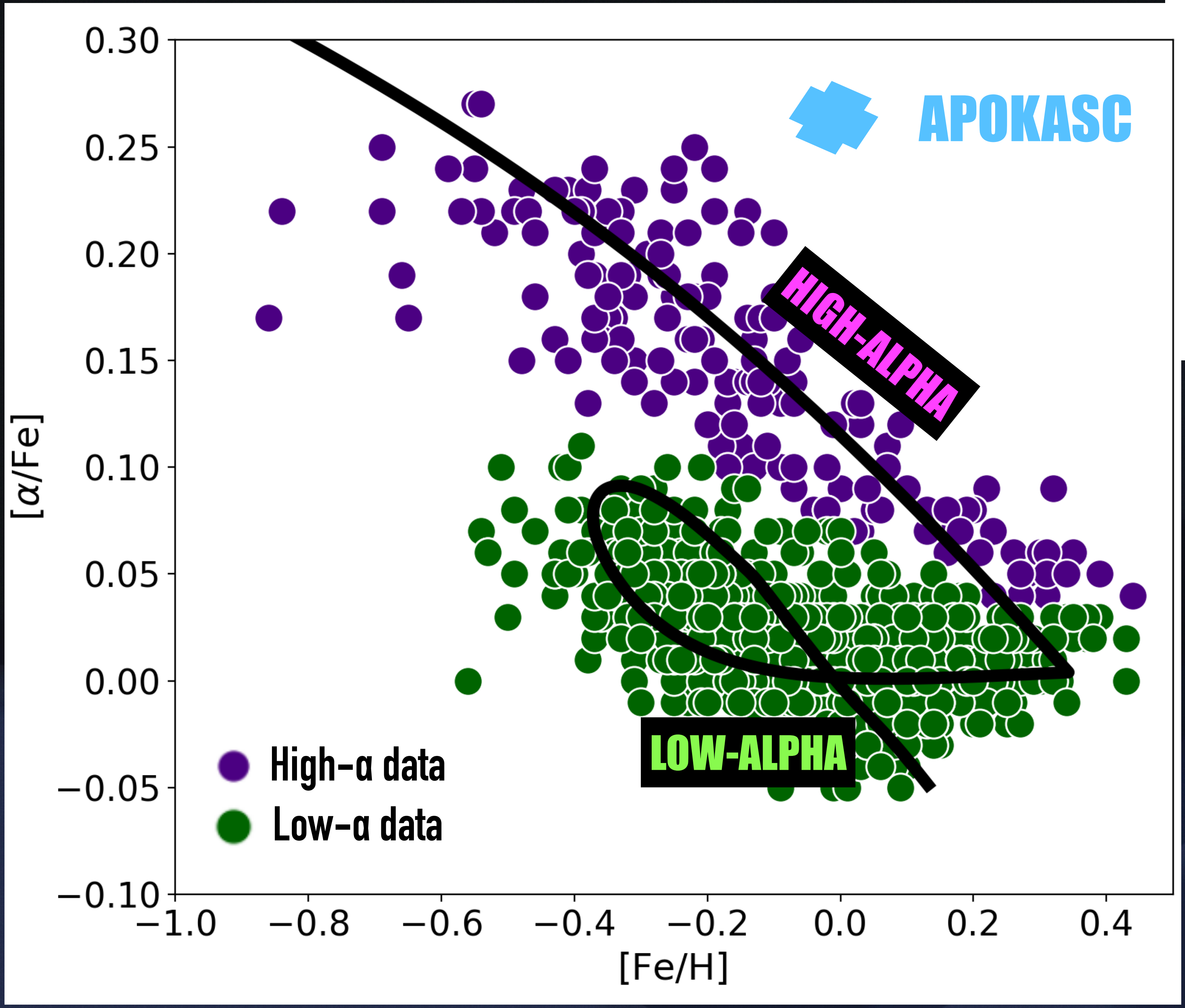
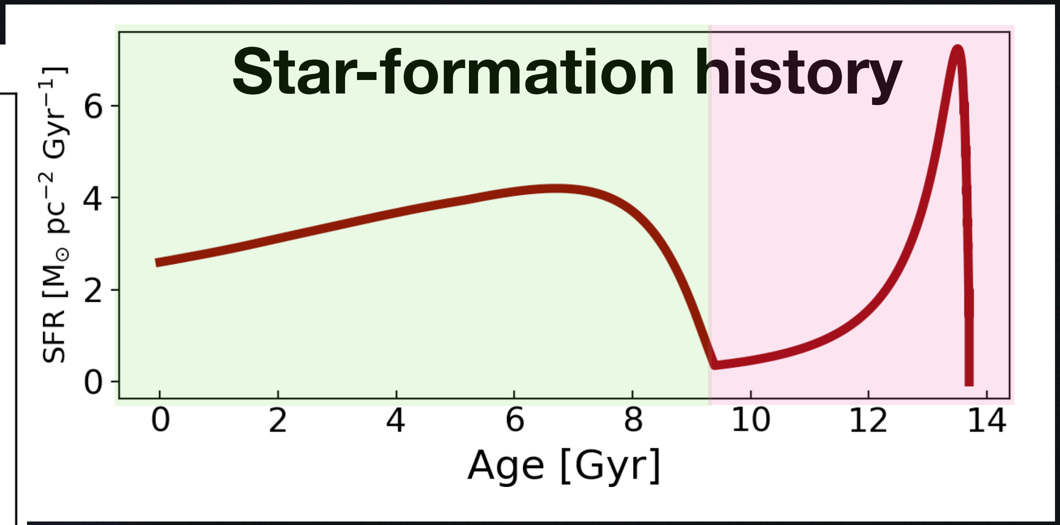
Infall gas rate



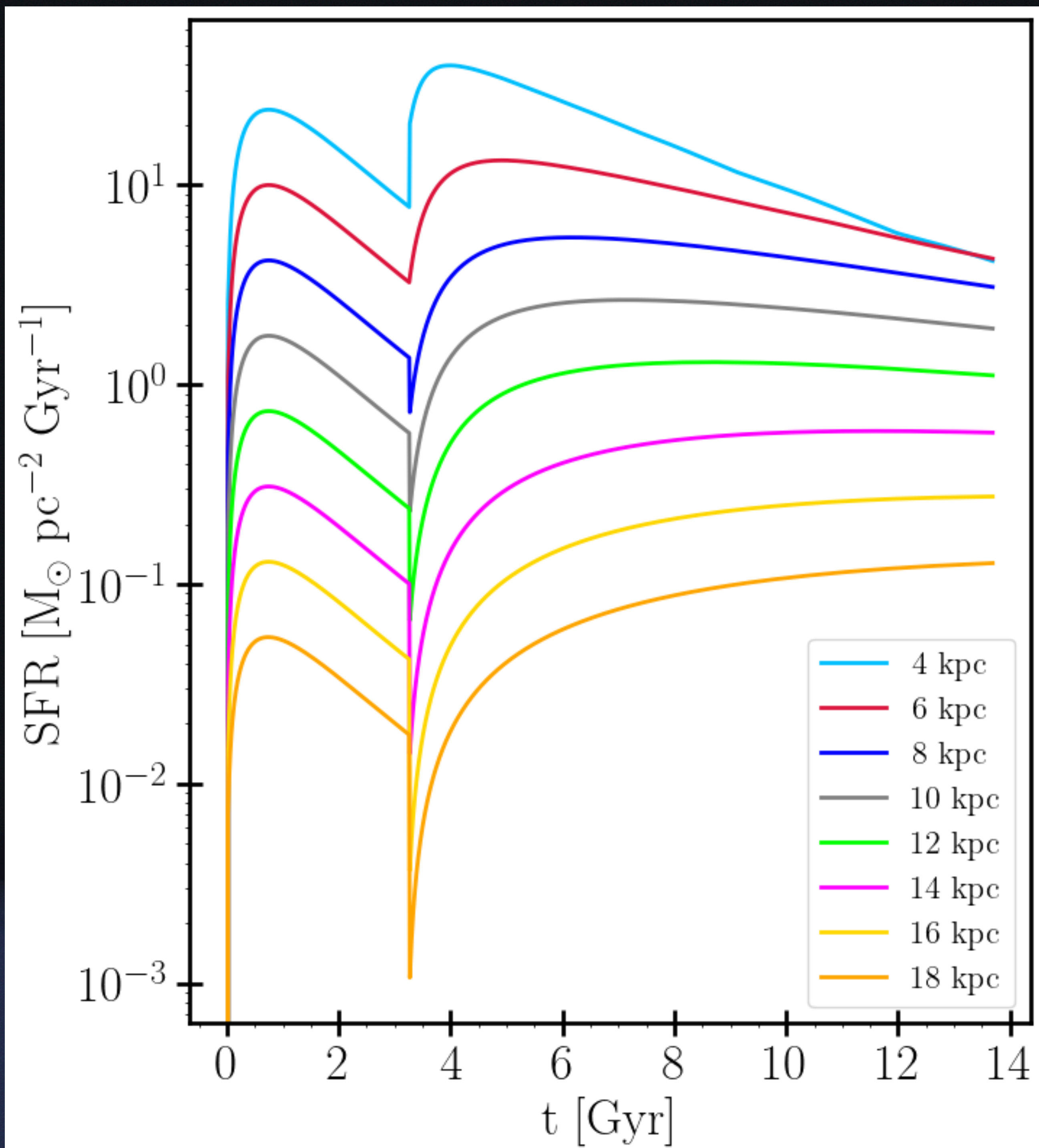


Spitoni+19

Reference multi-zone CEM

GG BAD

Predicted star formation history at different radii

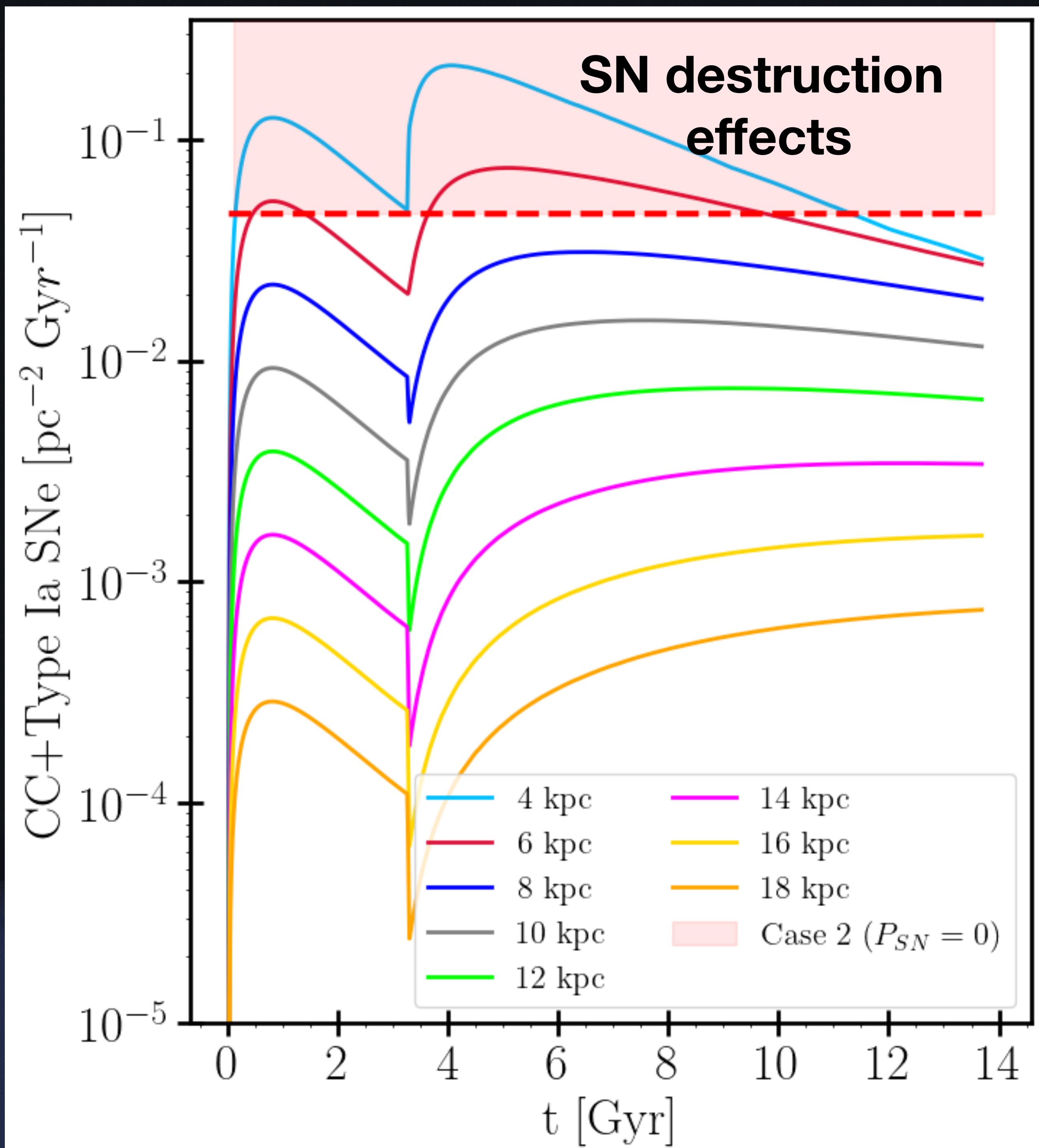


Spitoni+25

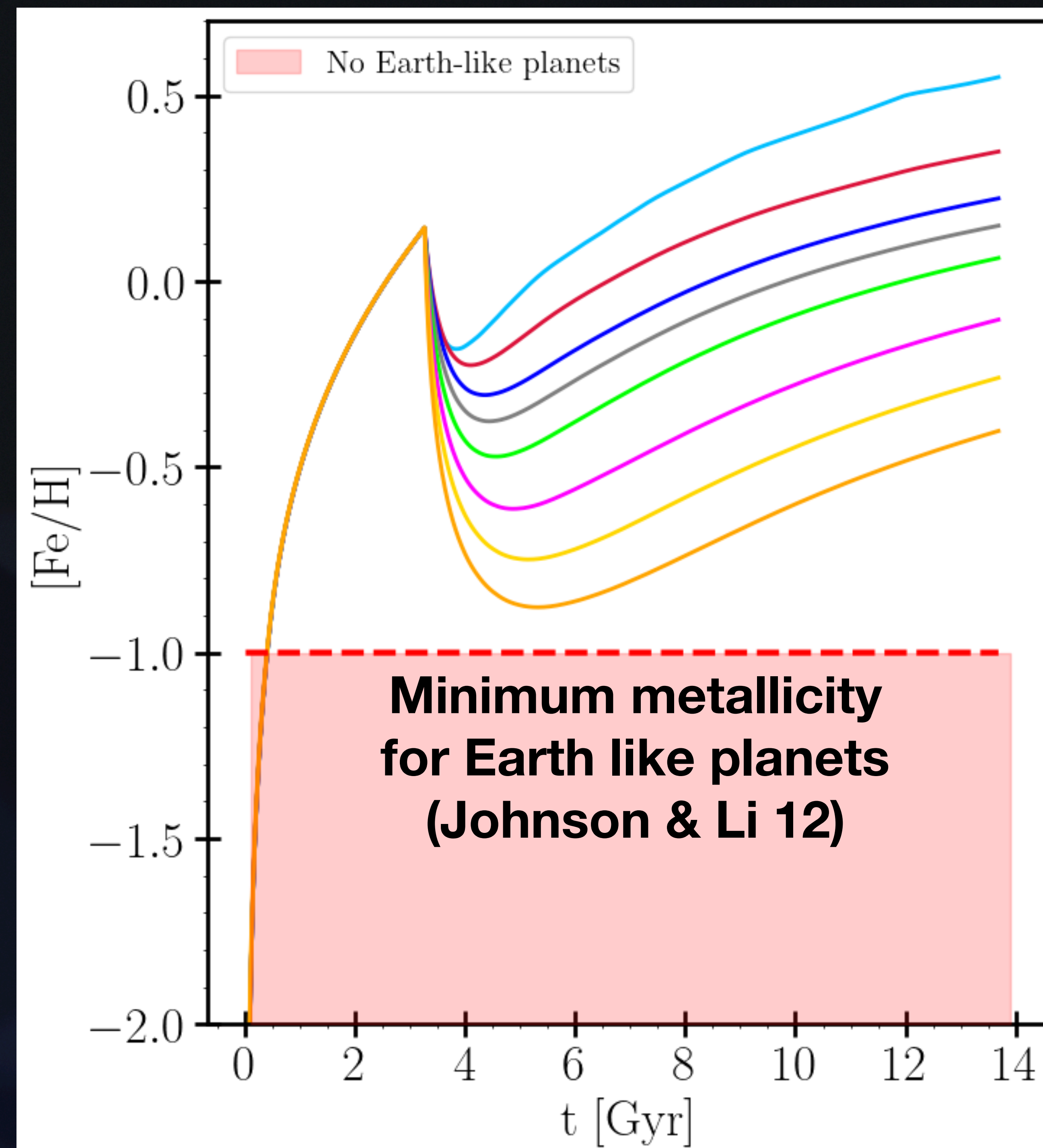
Reference multi-zone CEM

GG BAD

Computed SN rates



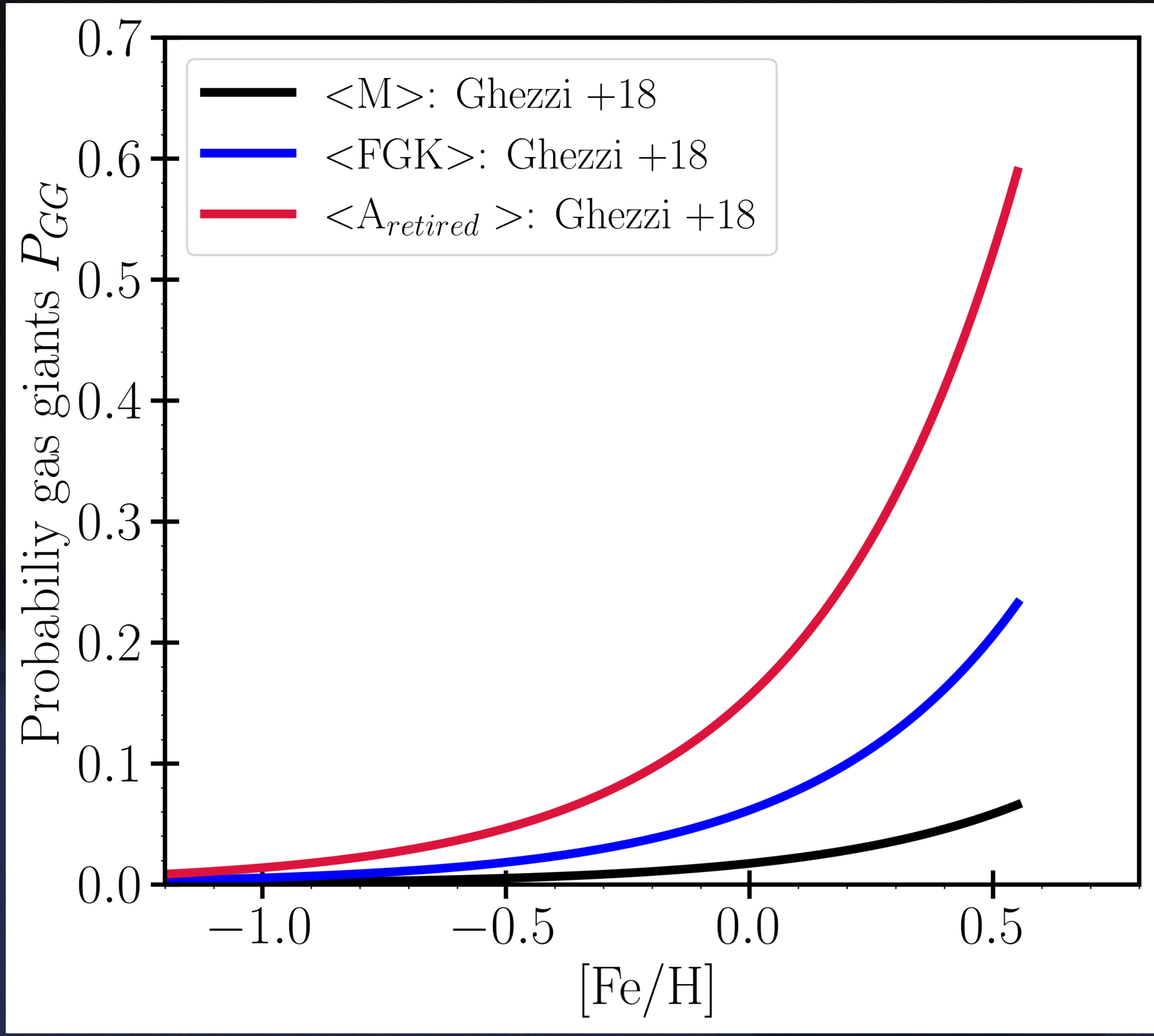
Age-metallicity relation



Spitoni+25

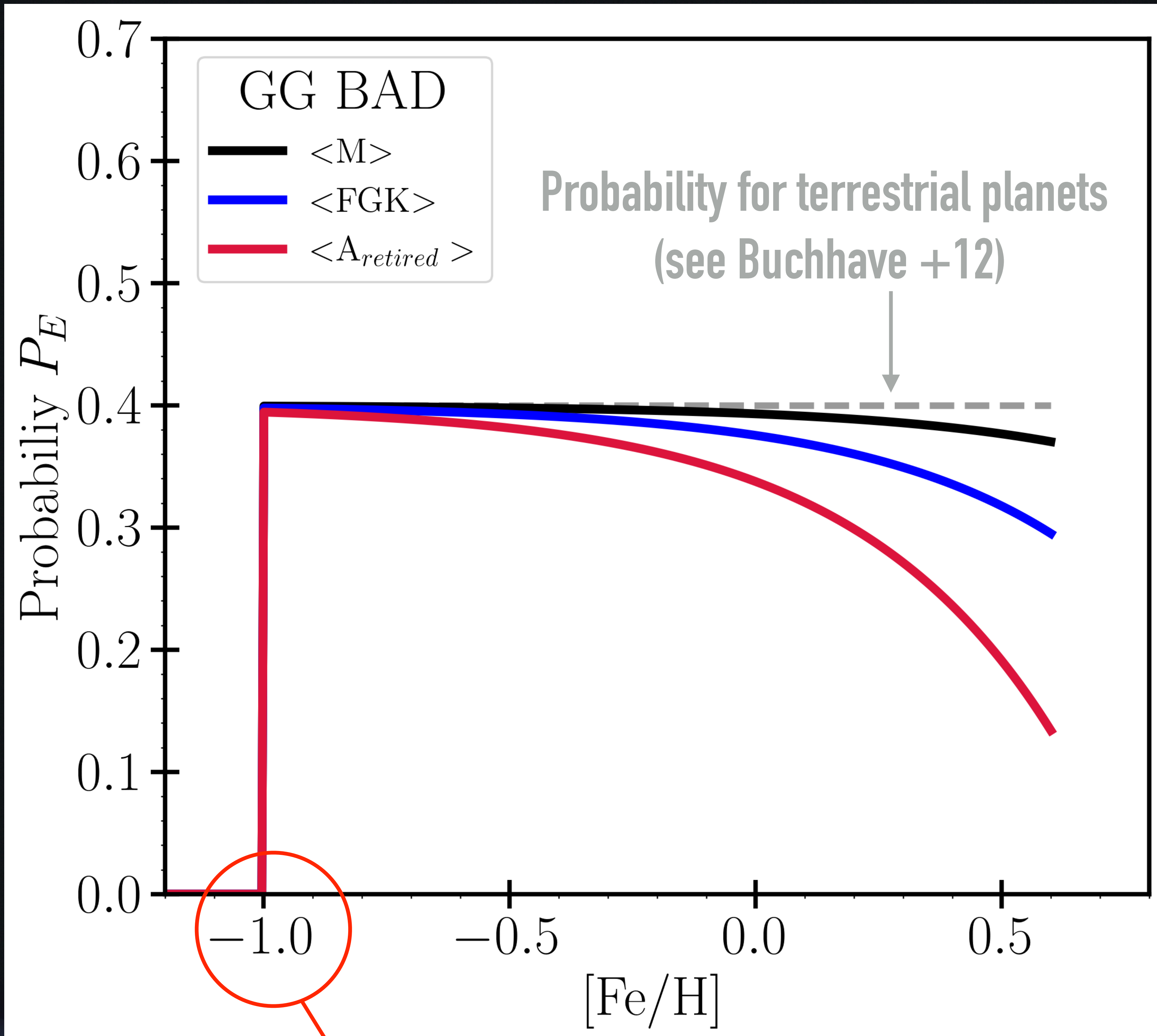
PROBABILITY OF FORMING gas giants

(potential dangers posed by gas giant migration: Jupiter's migration sculpt the inner solar system, limiting material available for terrestrial planets)



Probability of finding gas giants around different stellar types (Ghezzi+18)

$$P_{GGP}\,(M_\star, [\mathrm{Fe/H}]) = 0.085^{+0.008}_{-0.010} \left(\frac{M_\star}{M_\odot}\right)^{1.05^{+0.28}_{-0.24}} 10^{1.05^{+0.21}_{-0.17}[\mathrm{Fe/H}]}$$

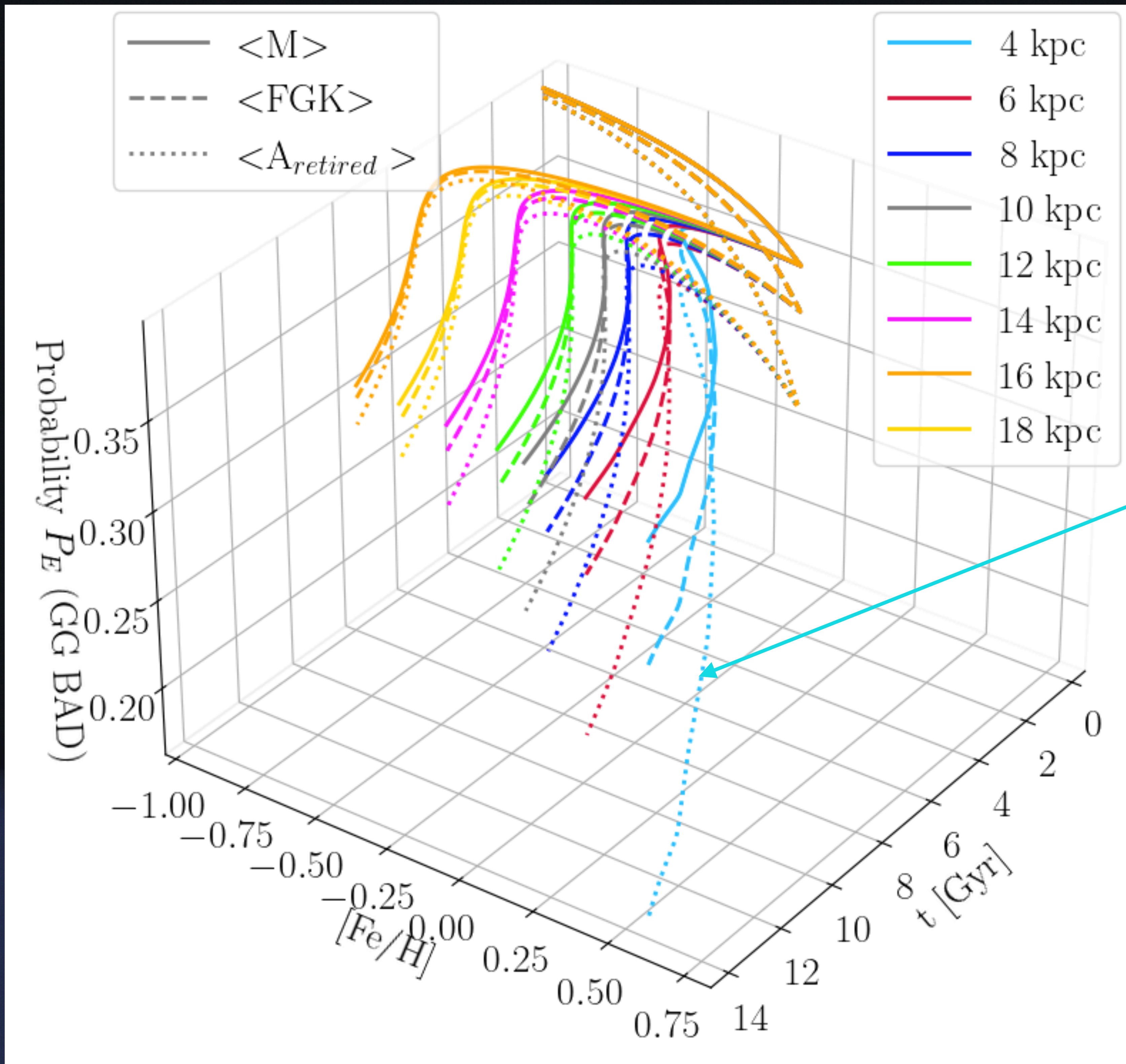


Probability of finding terrestrial planets but not gas giants ones (following Prantzos+08, Spitoni, +14+17)

$$P_E\,([\mathrm{Fe/H}]) = 0.4 \times (1- < P_{GGP}\,(M_\star, [\mathrm{Fe/H}]) >_{IMF})$$

Minimum metallicity for Earth like planets (Johnson & Li 12)

PROBABILITY OF EARTH-like with CEM models in a the 3D space



The inner regions achieve lower values of P_E due to the higher metallicities reached during the thin disc evolution phase. This effect is more evident for retired A stars.

THE GHZ MAP

$N_{\star\, mHC}$: **TOTAL NUMBER OF STARS hosting Earth-like planets with minimum Habitability Conditions**

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

$$P_{GHZ}(R,t) = \frac{\int_0^t \psi(R,t') P_E(R,t') P_{SN}(R,t') \ dt'}{\int_0^t \psi(R,t') \ dt'}$$

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

$$P_{GHZ}(R,t) = \frac{\int_0^t \psi(R,t') P_E(R,t') P_{SN}(R,t')\ dt'}{\int_0^t \psi(R,t')\ dt'}$$

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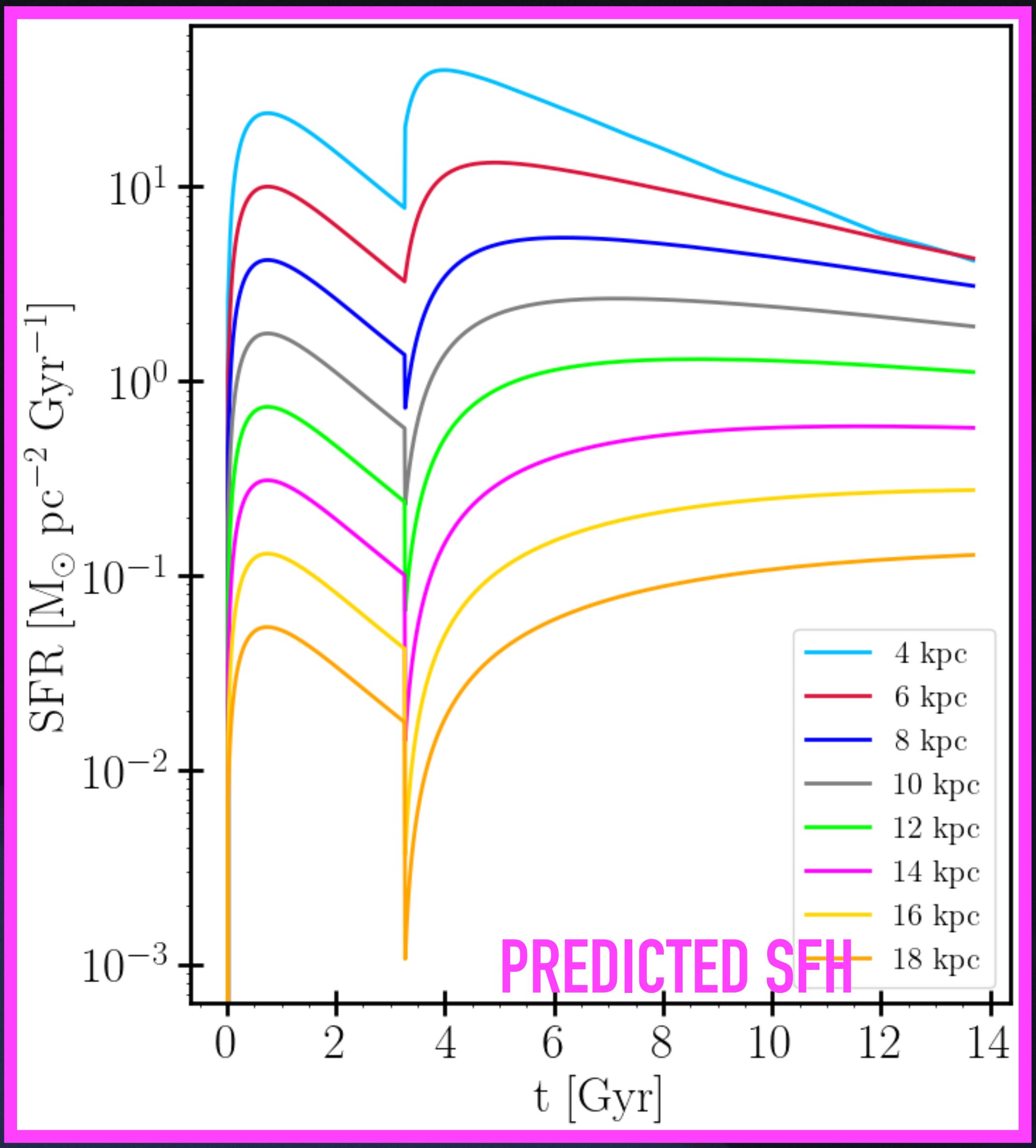

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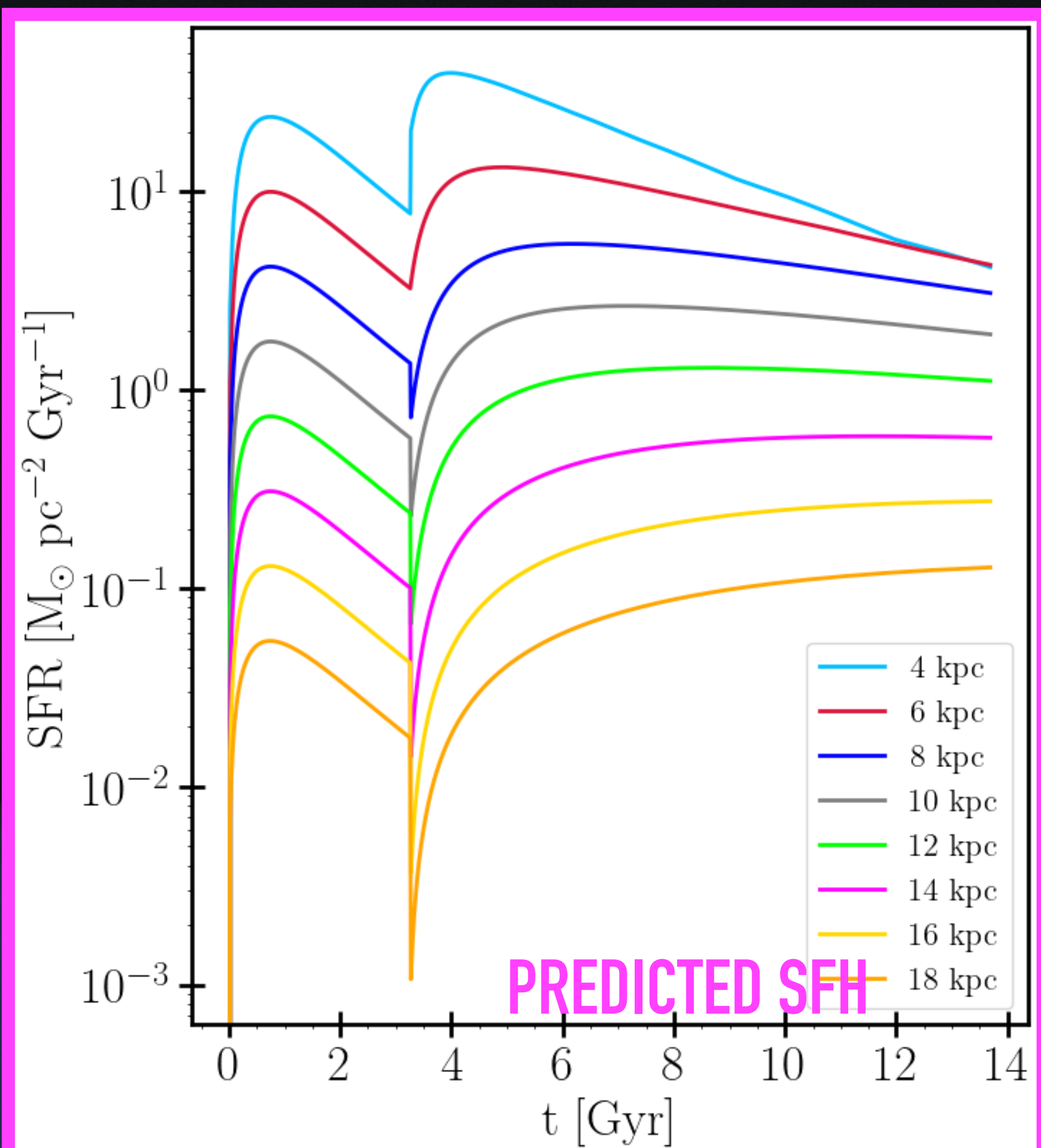
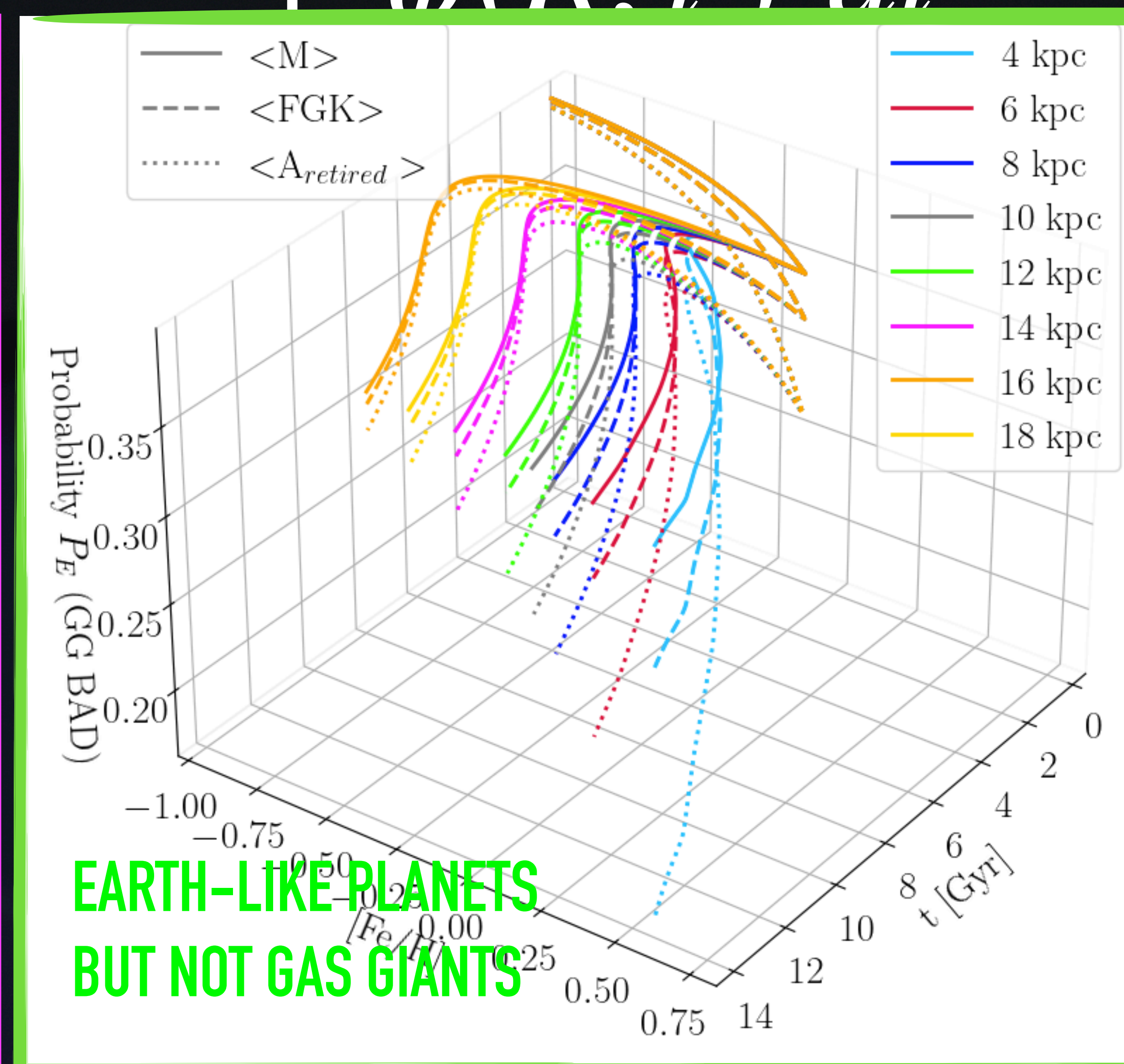
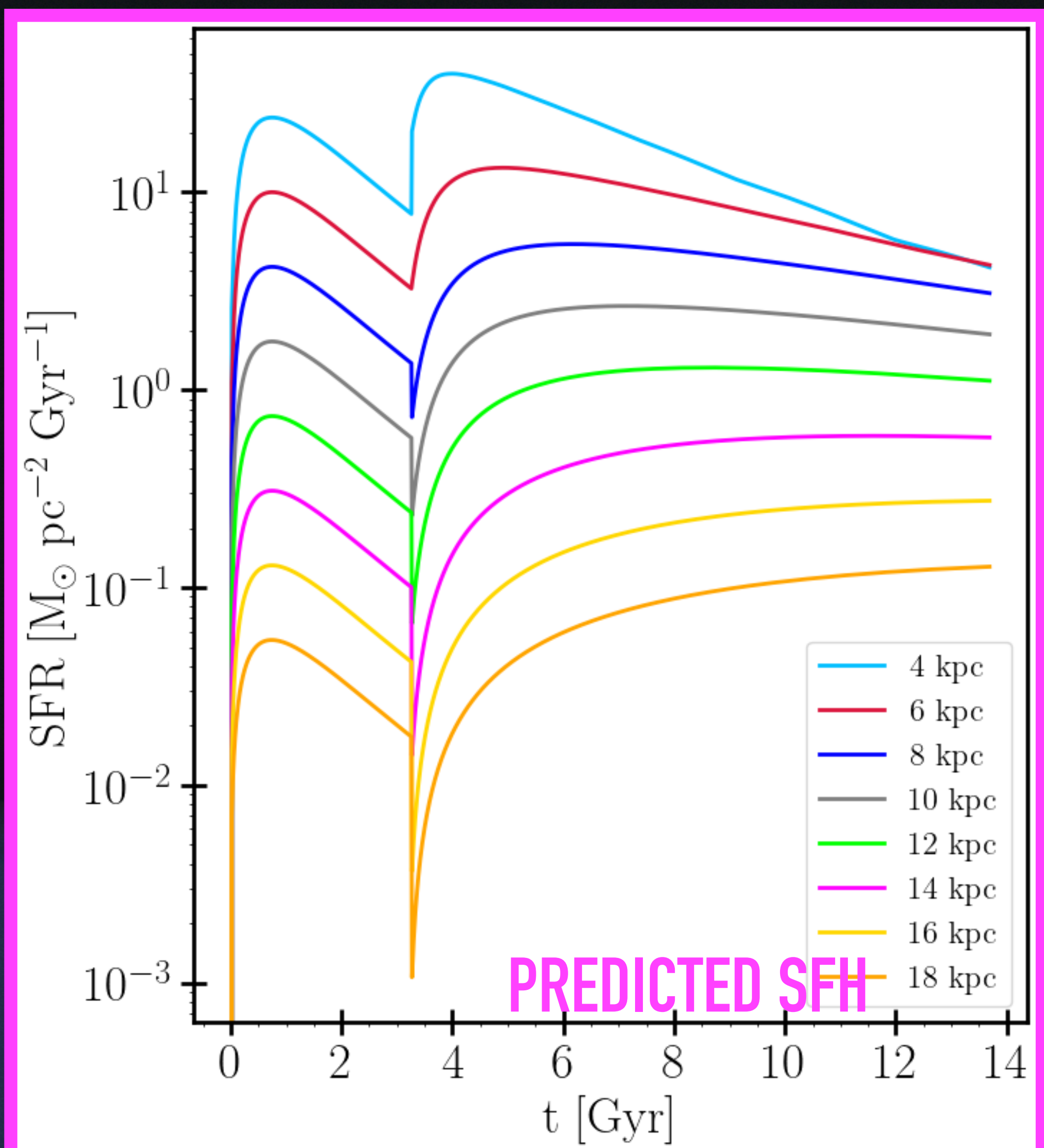
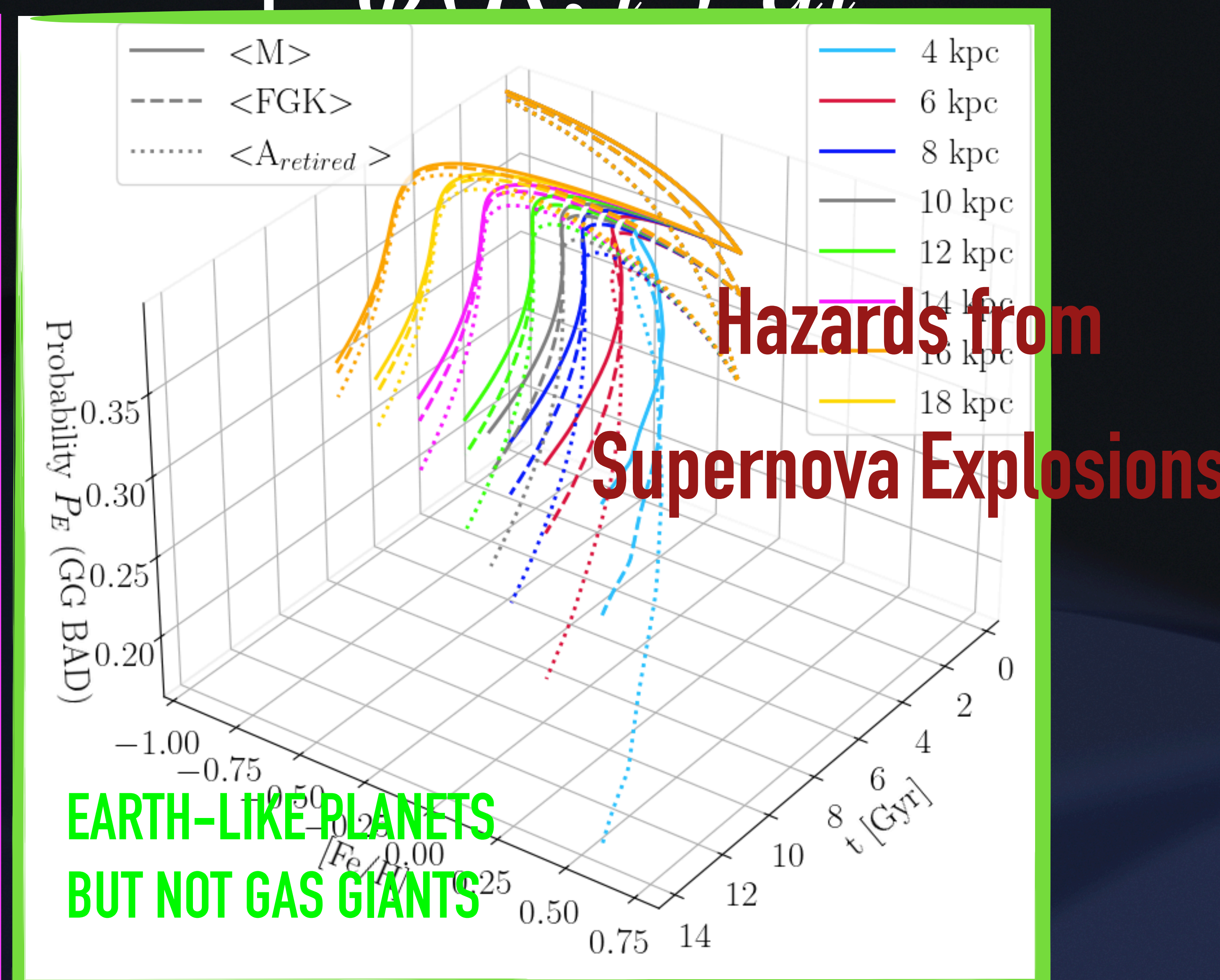




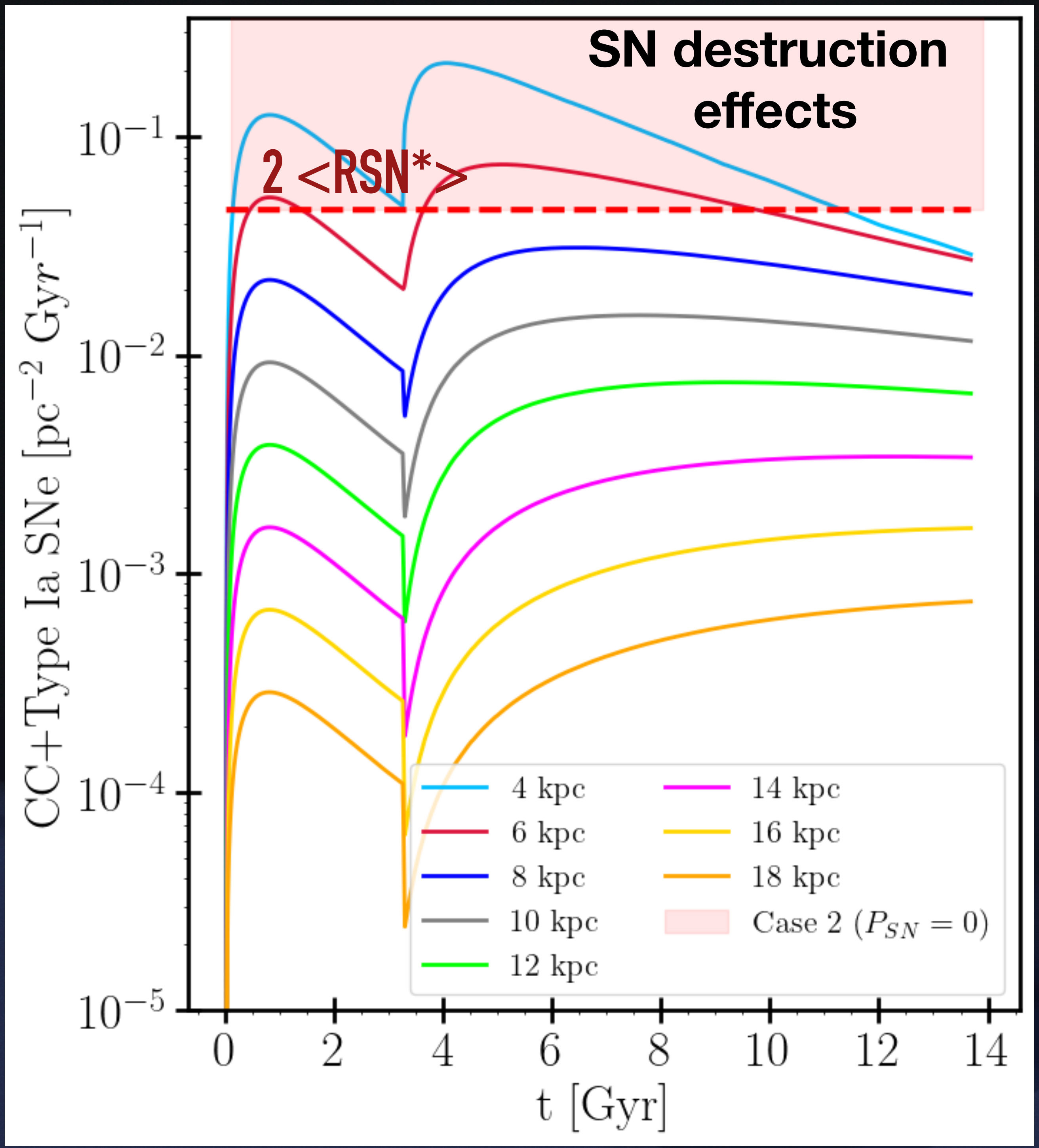
$$P_{GHZ}(R,t) = \frac{\int_0^t \psi(R,t') P_E(R,t') P_{SN}(R,t')\, dt'}{\int_0^t \psi(R,t')\, dt'}$$



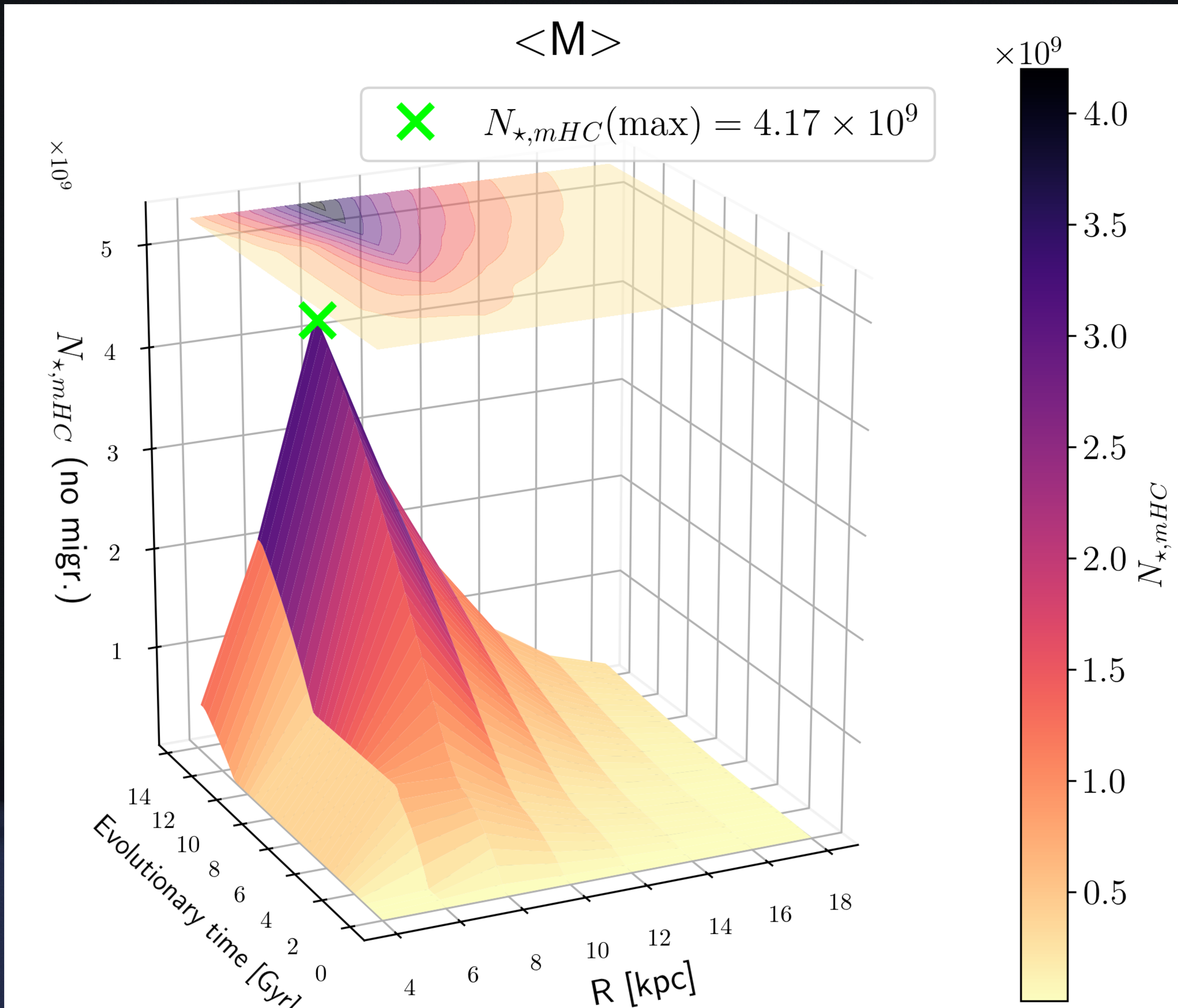


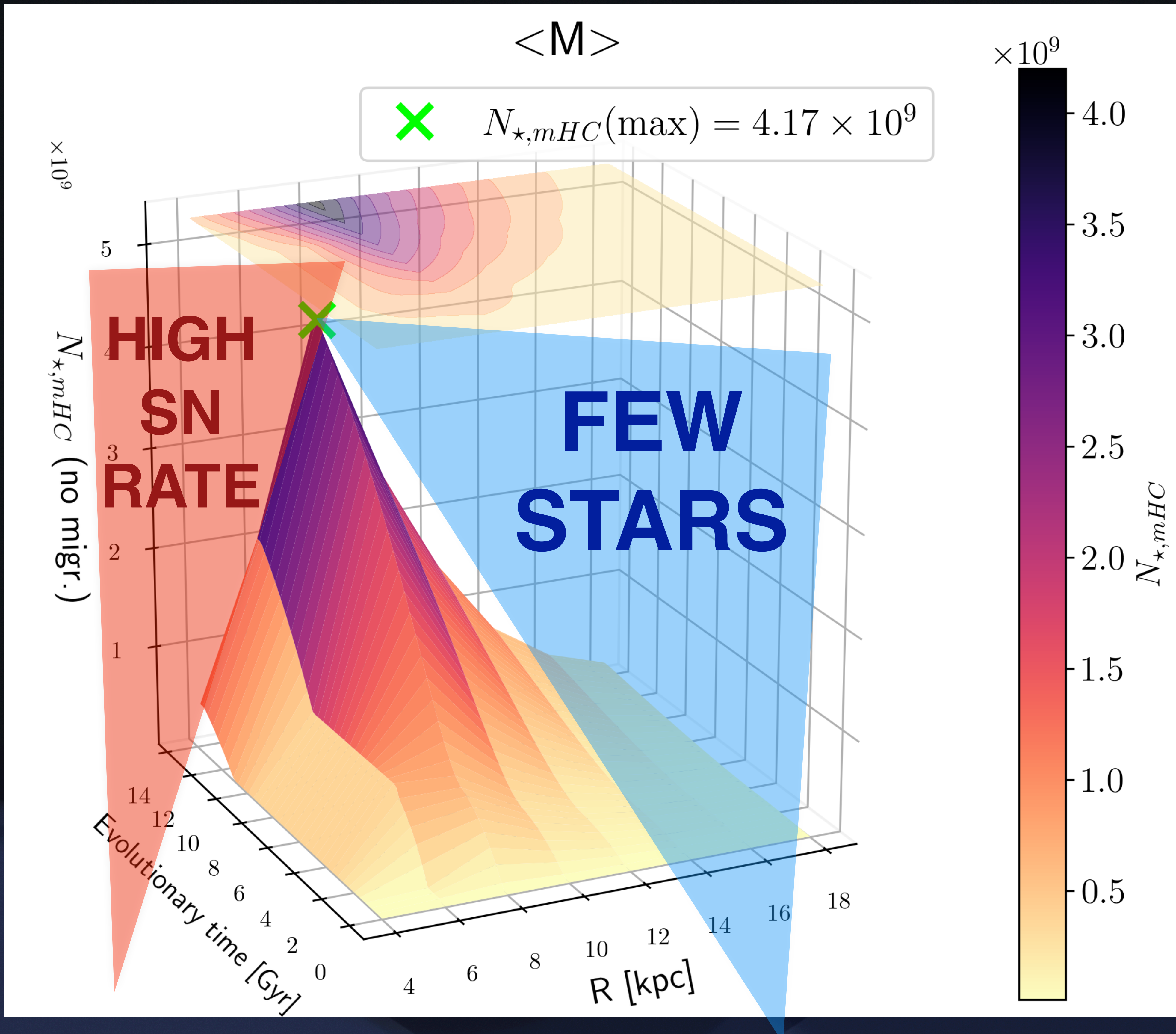
If SNR has been higher than twice the average SN rate <RSN*> in the solar neighborhood during the last 4.5 Gyr => NO minimum condition for life

Hazards from Supernova Explosions

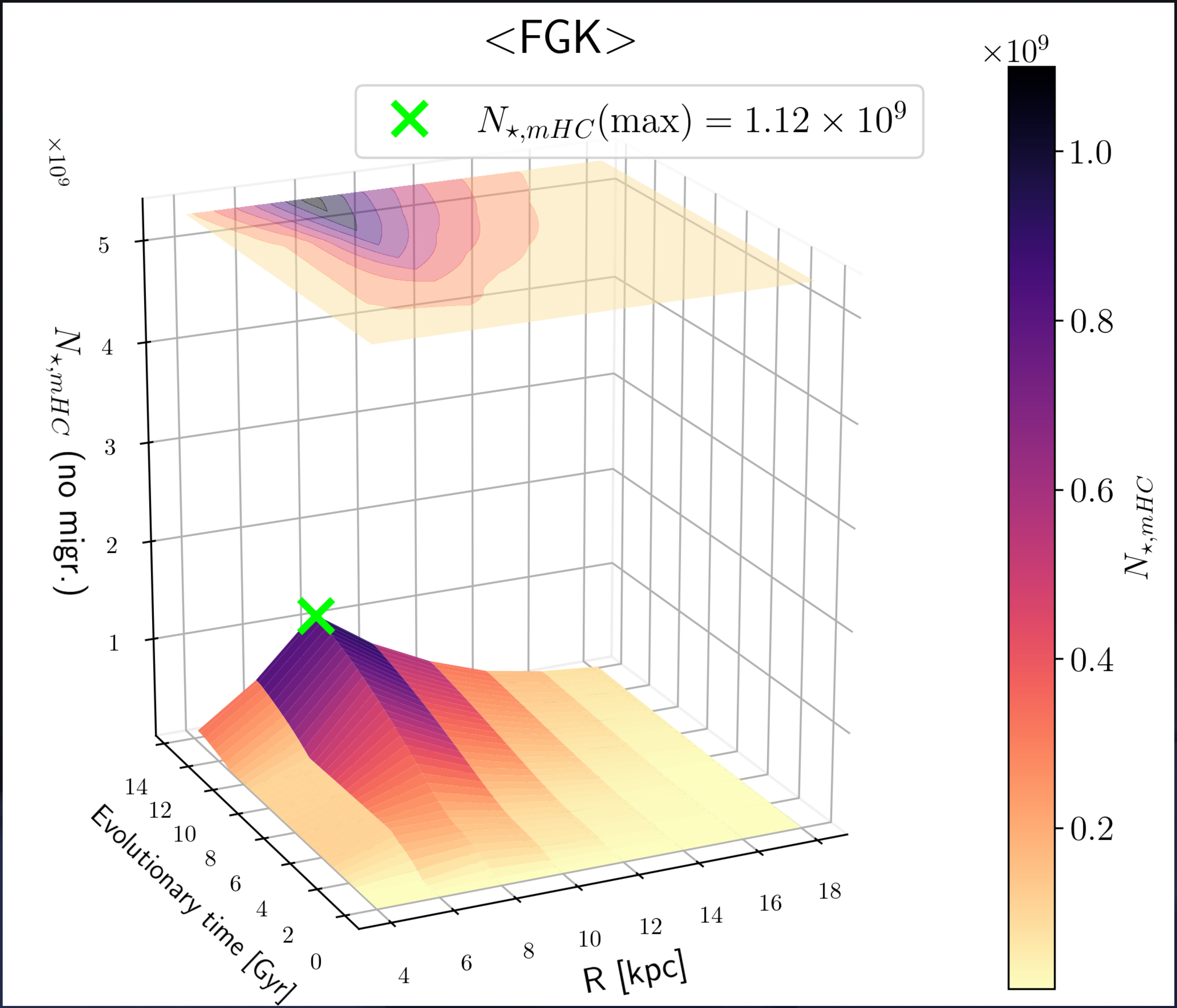


if SNR > 2 <RSN*>
then
P_{SN} = 0 else
P_{SN} = 1

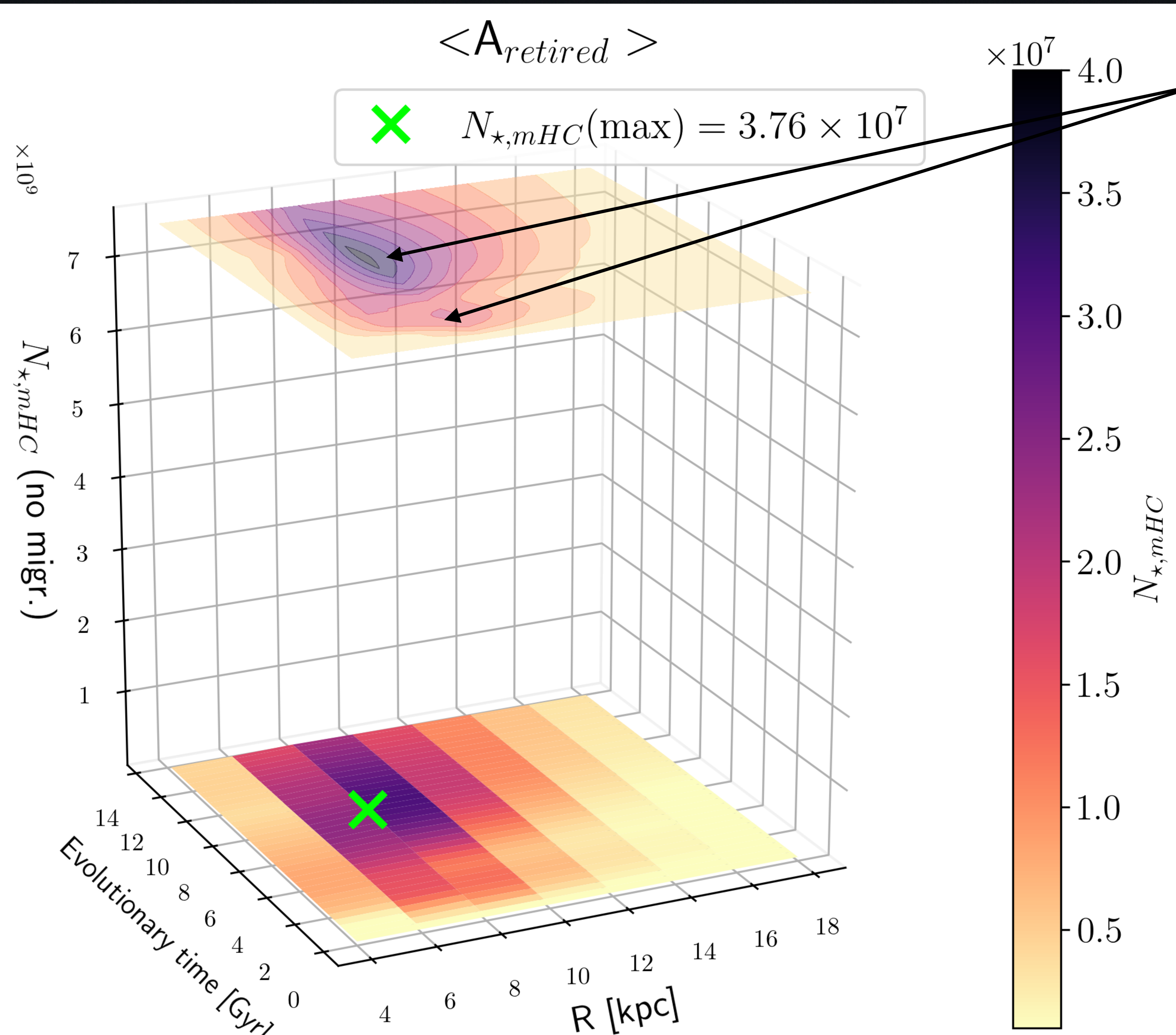

<M>
$N_{\star,mHC}(\max) = 4.17 \times 10^9$
$N_{\star,mHC}$ (no migr.)
$\times 10^9$
Evolutionary time [Gyr]
R [kpc]
$N_{\star,mHC}$
$\times 10^9$



<M>
$N_{\star,mHC}(\max) = 4.17 \times 10^9$
HIGH SN RATE
FEW STARS
$\times 10^9$
$N_{\star,mHC}$ (no migr.)
Evolutionary time [Gyr]
R [kpc]
$N_{\star,mHC}$



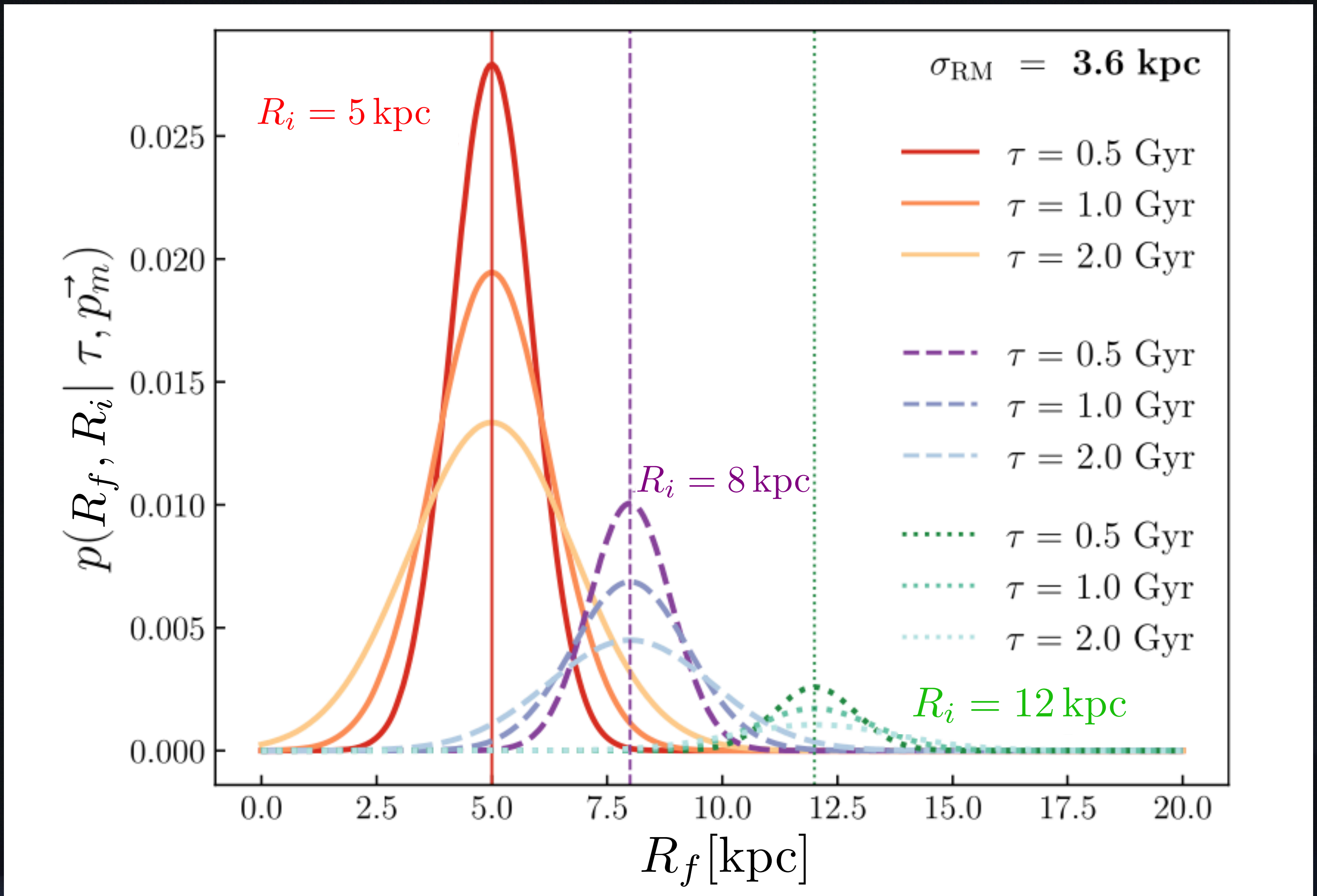
<FGK>
$N_{\star,mHC}(\max) = 1.12 \times 10^9$
$\times 10^9$
$N_{\star,mHC}$ (no migr.)
1
2
3
4
5
Evolutionary time [Gyr]
0
2
4
6
8
10
12
14
R [kpc]
4
6
8
10
12
14
16
18
$\times 10^9$
1.0
0.8
0.6
0.4
0.2
$N_{\star,mHC}$



Retired A start, shorter lifetimes.

The stellar distribution follows the star formation history, revealing two distinct clumps associated with the peak gas infall rates during the thick and thin disk phases

Stellar migration using a parametric approach



$$\ln p(R_f \,|\, R_i, \tau) = \ln(c_3) - \frac{(R_f - R_i)^2}{2\,\sigma_{RM}\,\tau/10\,\mathrm{Gyr}}$$

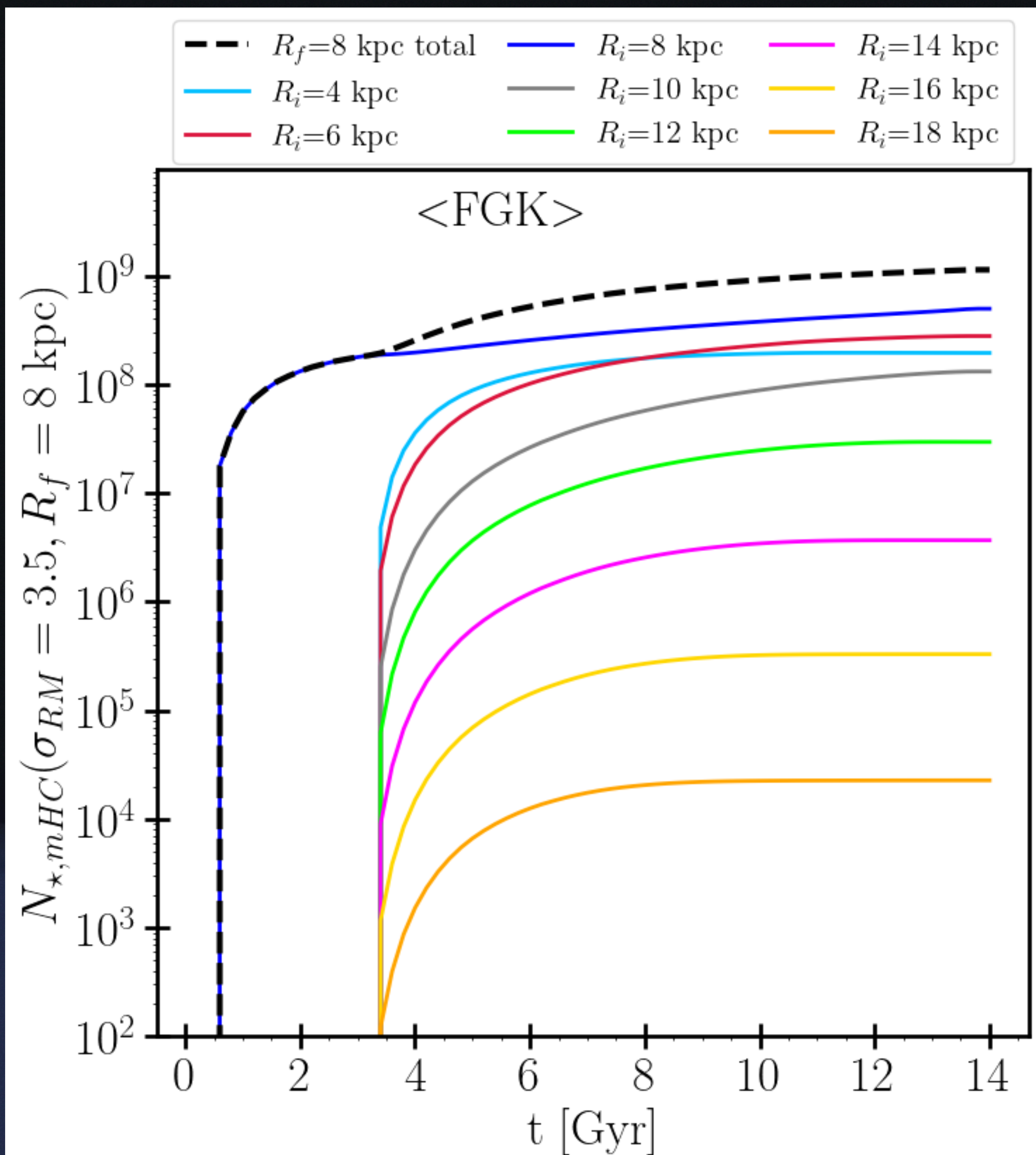
Frankel+18

Migration is seen as a result of a diffusion process and treated in a parametric way

Temporal evolution of the total number of FGK stars hosting habitable planets with "Frankel" MIGRATION

minimum conditions for life ($N_{\star,mHC}$) in the solar vicinity

$\sigma_{RM} = 3.5\,\mathrm{kpc}$



Stellar migration leads to a redistribution of stars in solar vicinity.

43.78% were formed in situ

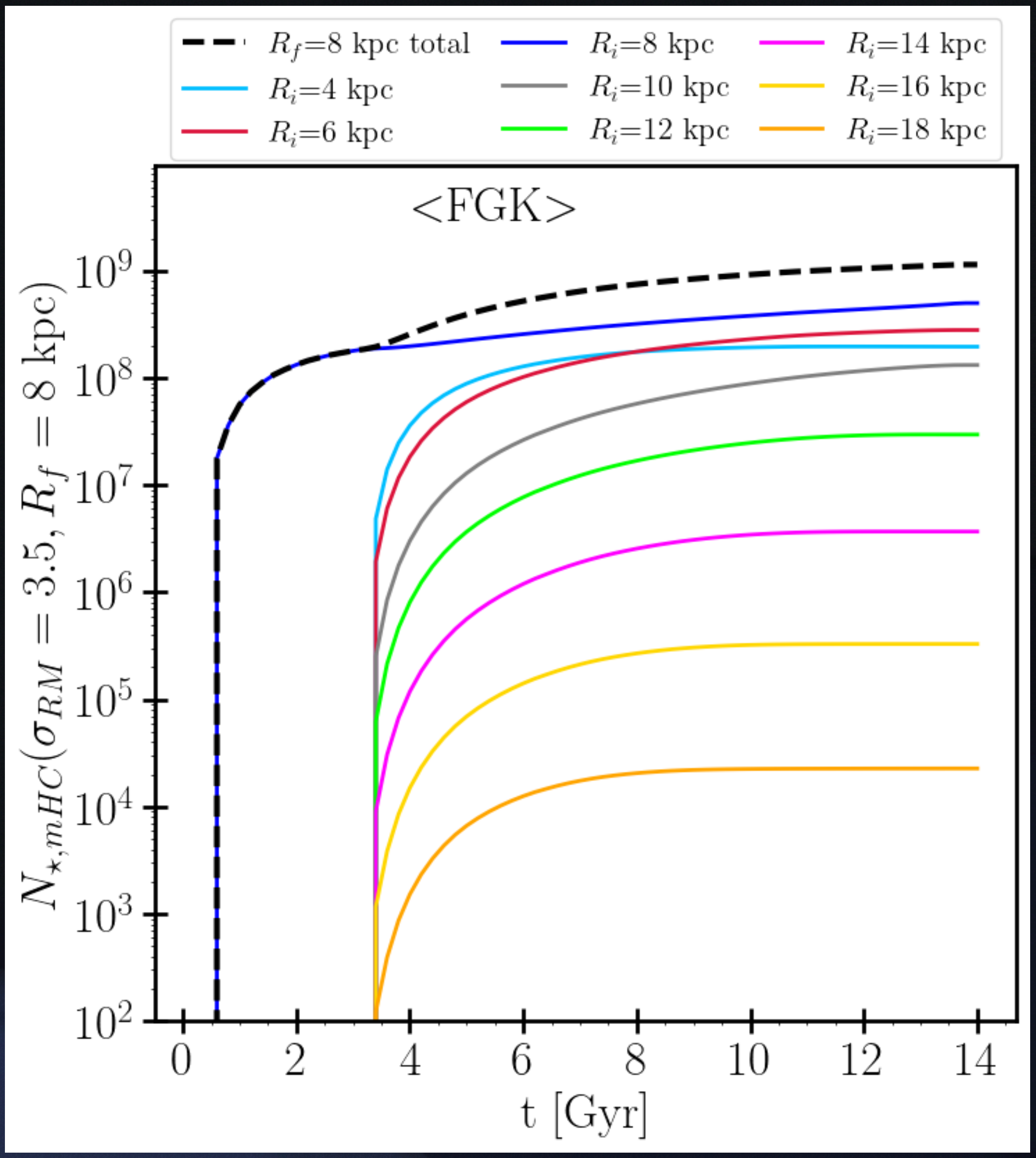
17.16% originated from 4 kpc

24.53% from 6 kpc

11.57% from 10 kpc

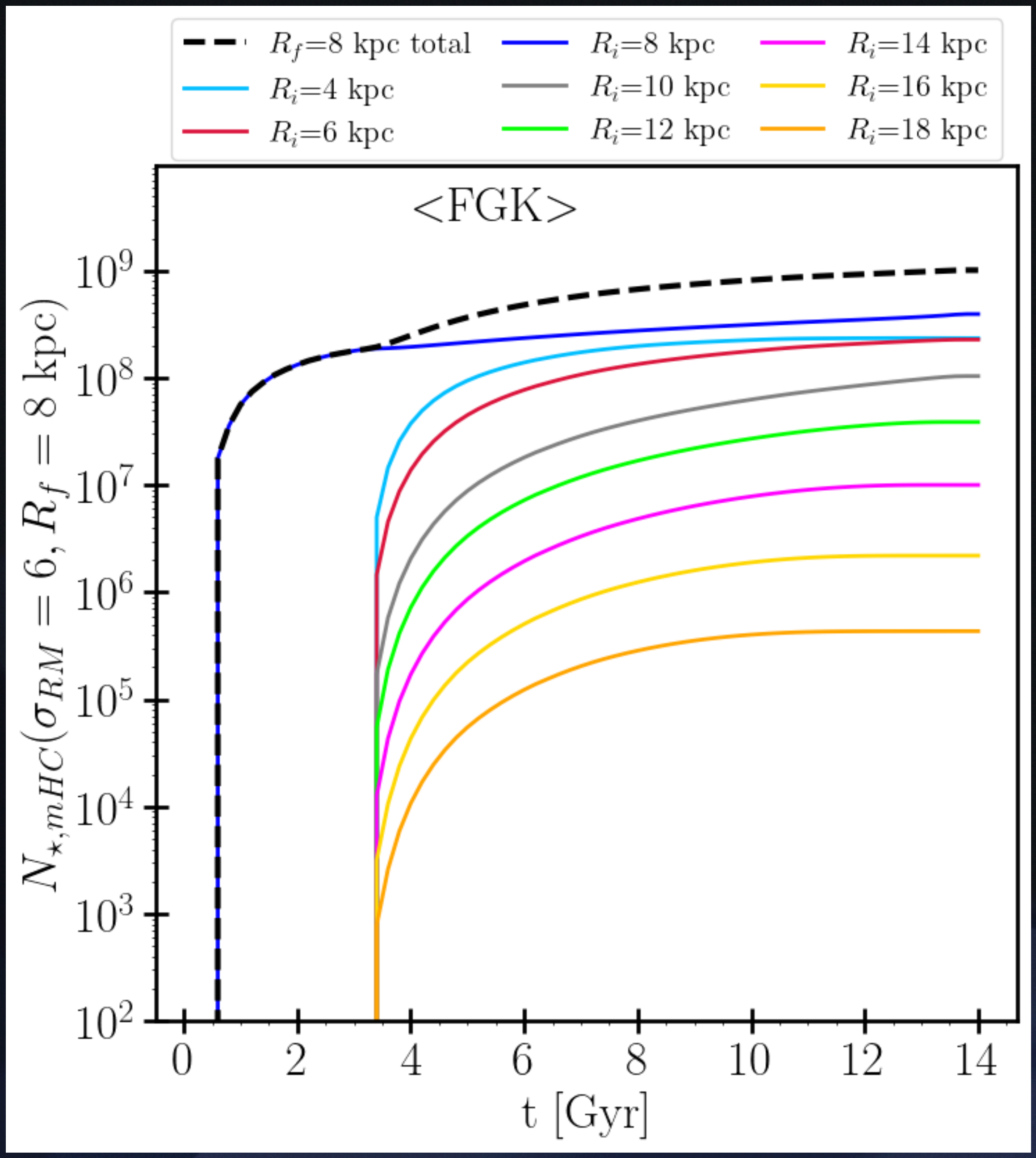
“Frankel” MIGRATION

$\sigma_{RM} = 3.5\,\mathrm{kpc}$



STRONG MIGRATION

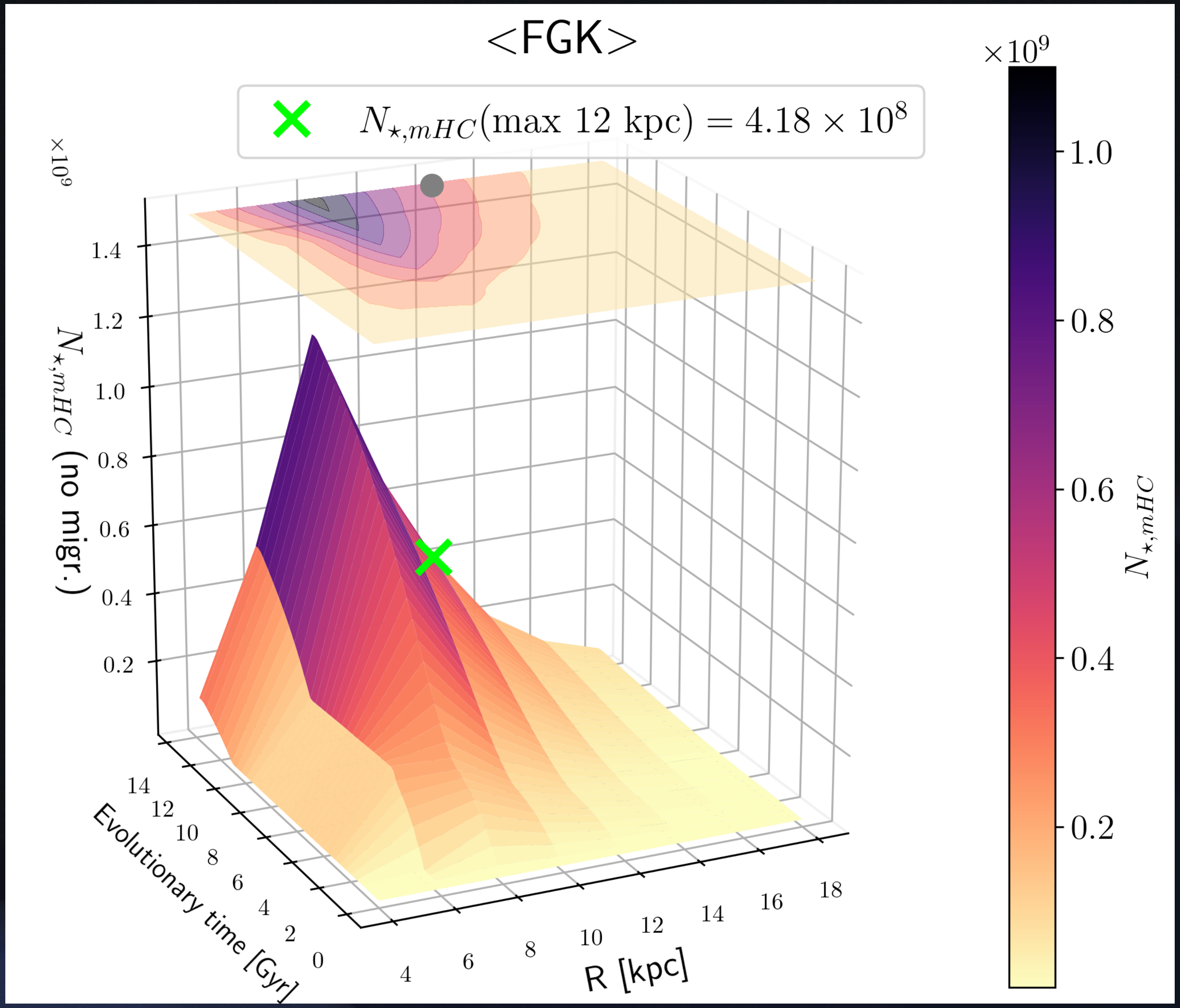
$\sigma_{RM} = 6\,\mathrm{kpc}$

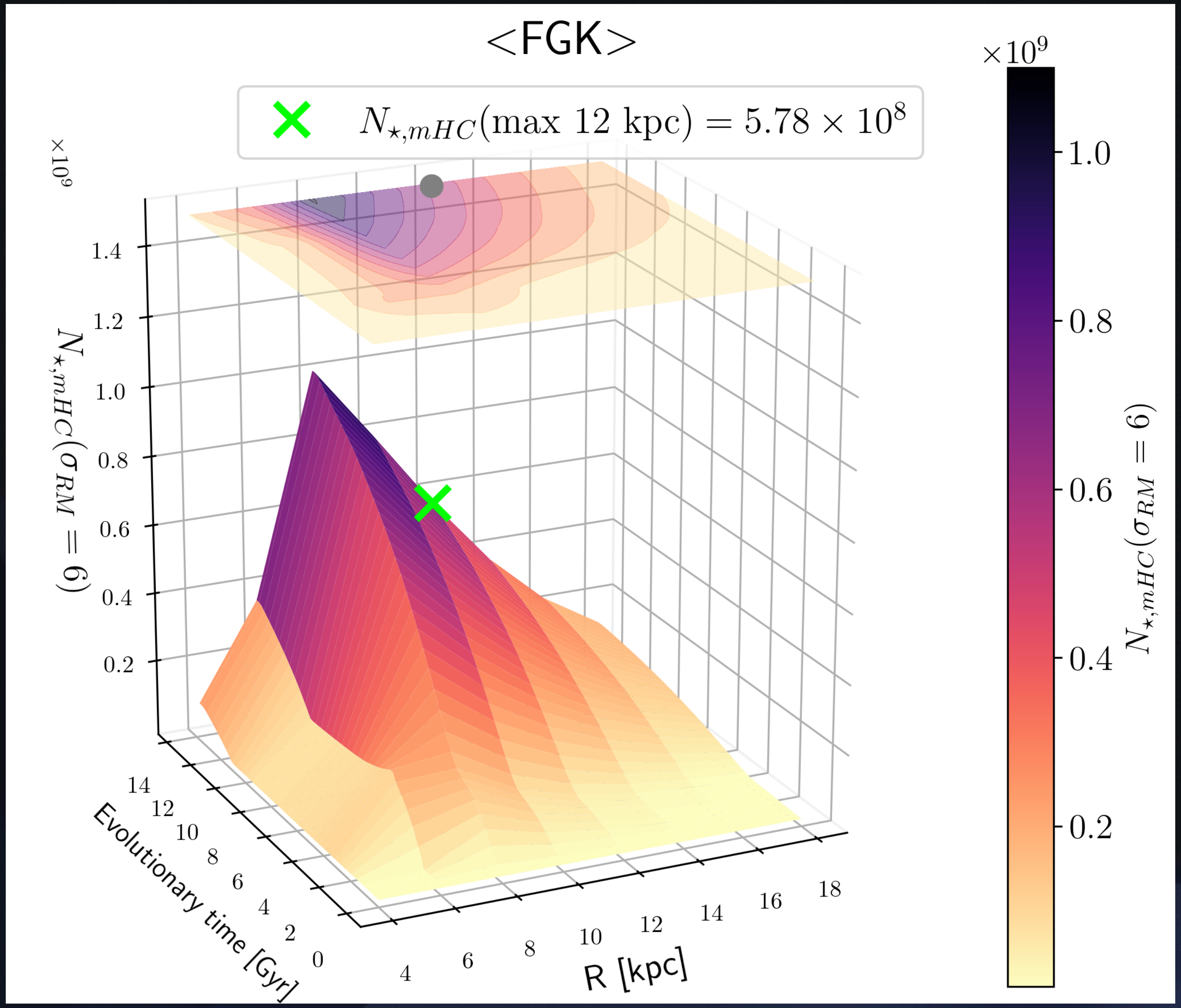


No stellar migration

Strong migration

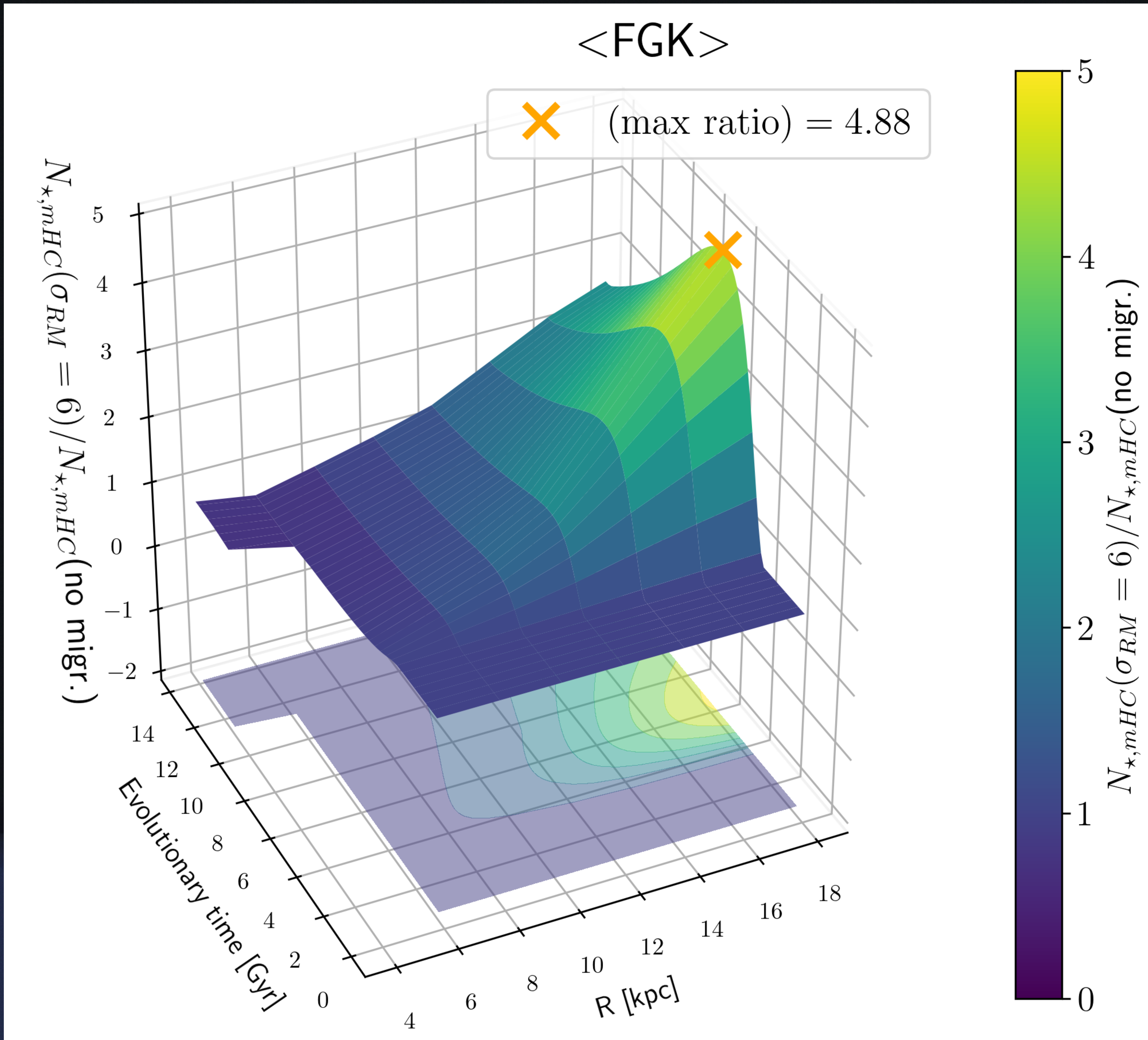
$$\sigma_{RM} = 6\,\mathrm{kpc}$$





FGK stars

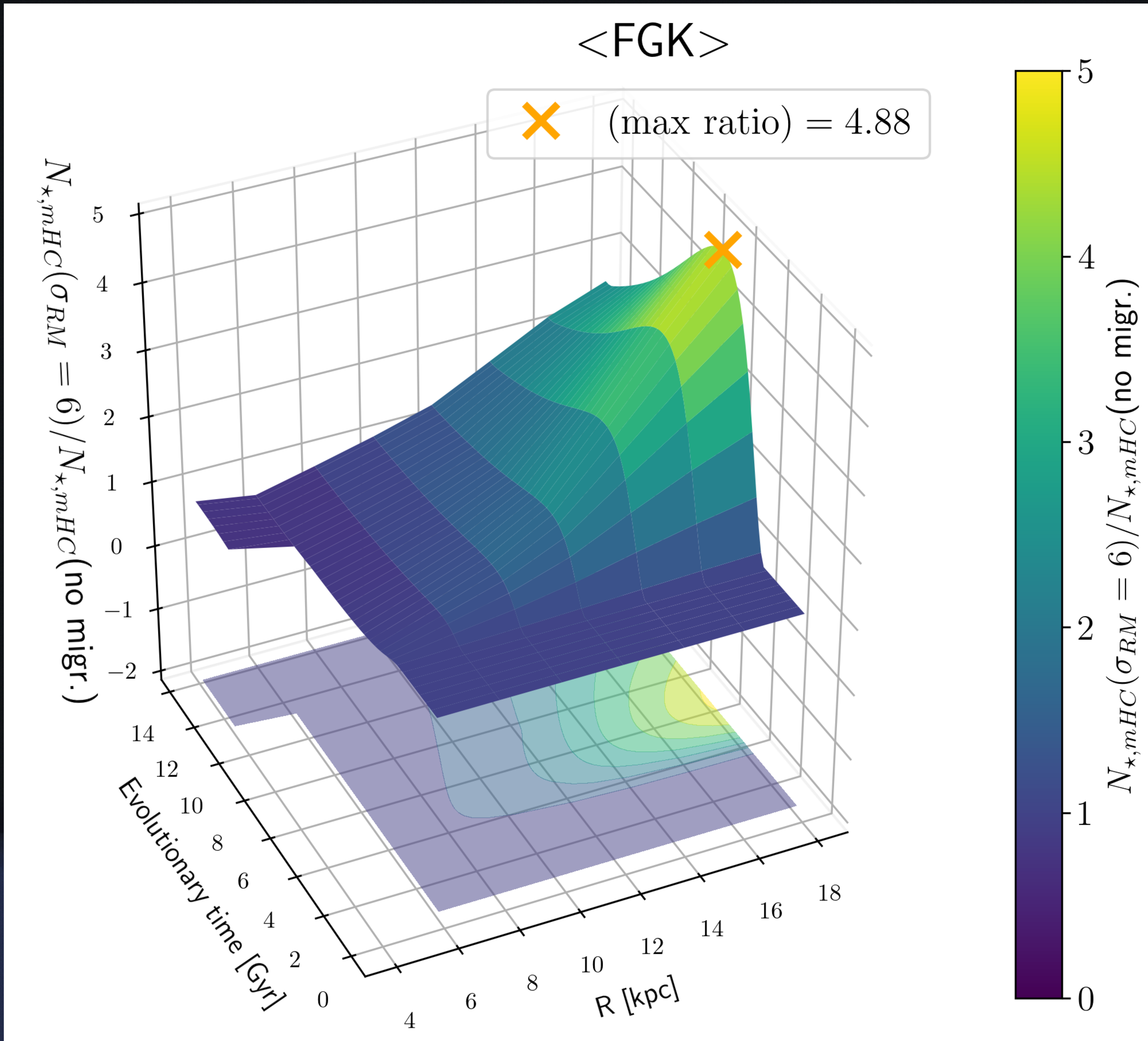
Number of Star Ratio



STRONG MIGRATION

NO MIGRATION

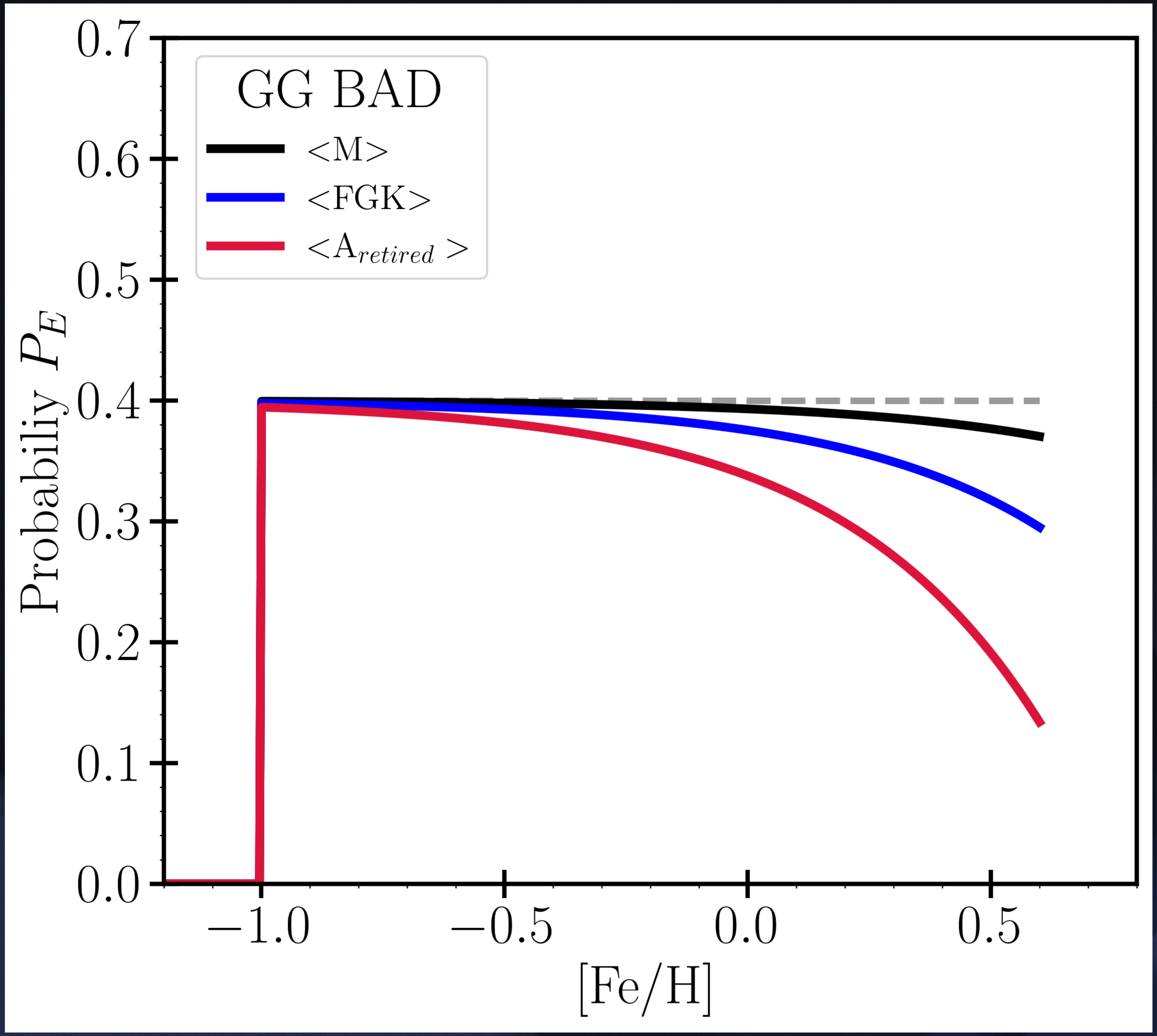
Substantial increase in the number of stars hosting habitable planets in the outer Galactic regions. This occurs because stellar migration enables stars to move towards more external parts



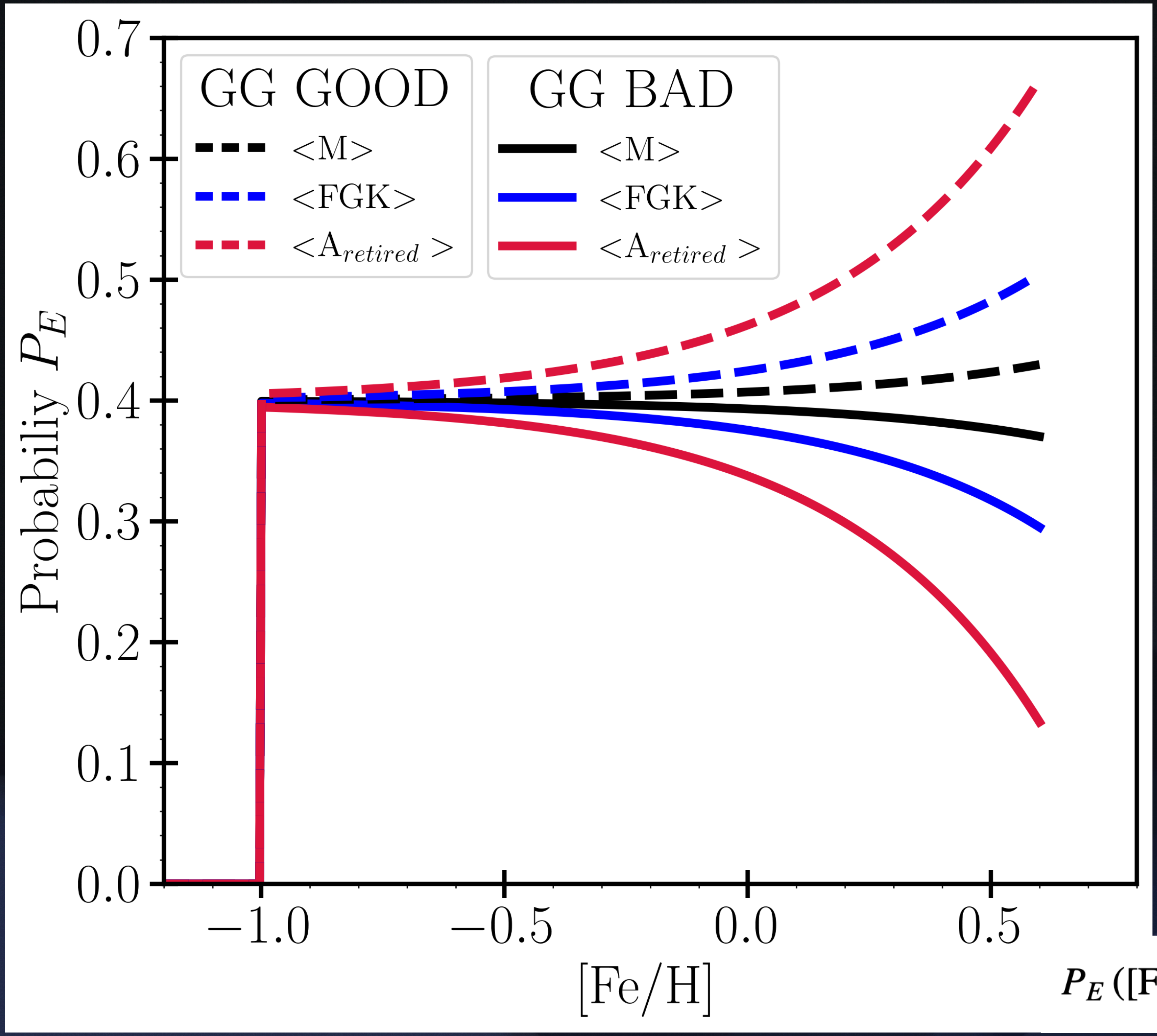
Star Ratio

$$\frac{\text{STRONG MIGRATION}}{\text{NO MIGRATION}}$$

Gas giants as catalysts for terrestrial planet formation?



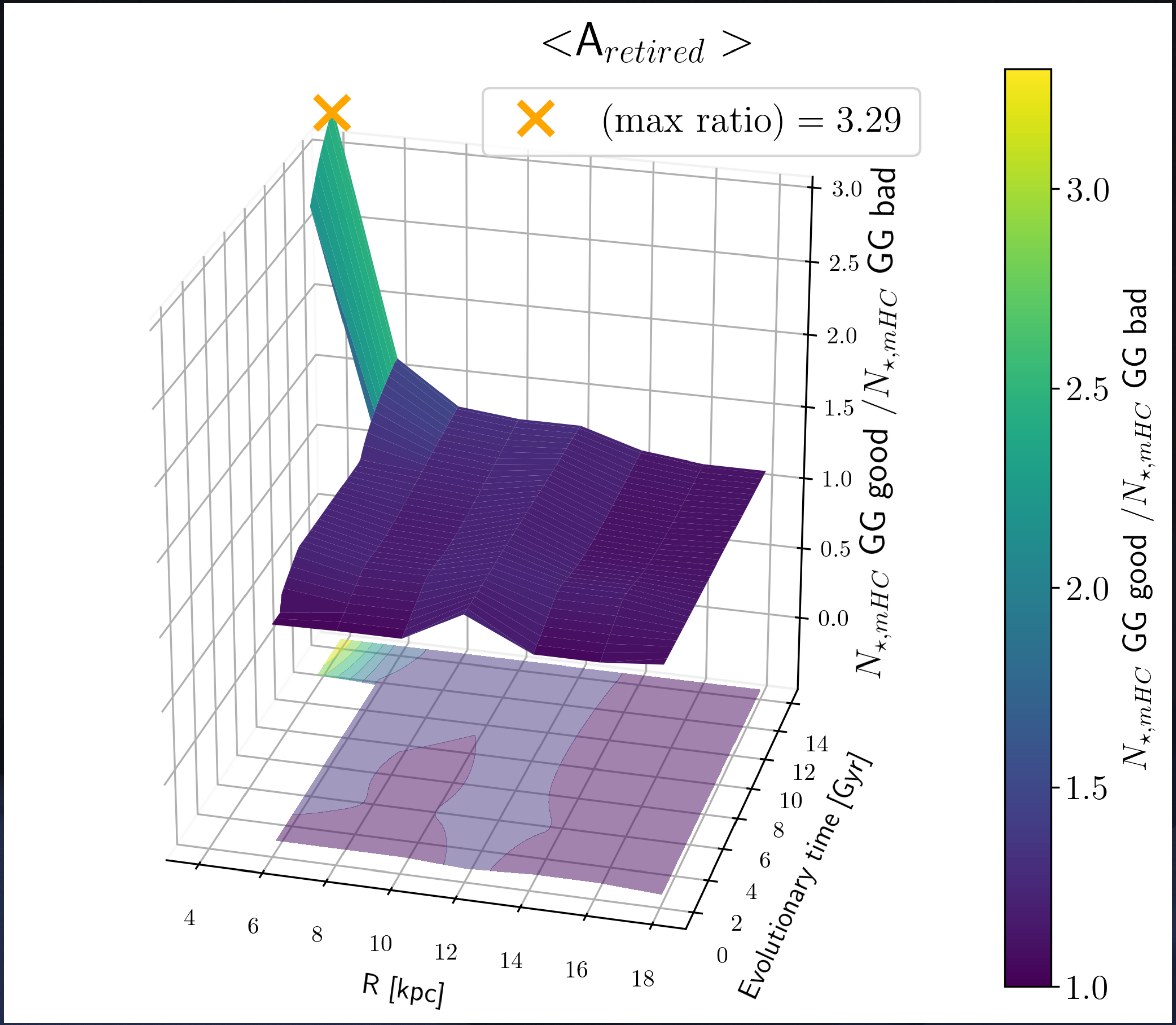
Gas giants as catalysts for terrestrial planet formation



Gas giants clear material in their orbital vicinity, creating gaps in the protoplanetary disk. This can enhance planet formation by concentrating planetesimals and embryos into specific regions, as described in the 'Nice Model' and similar frameworks (Tsiganis et al. 2005).

$$P_E\,([\mathrm{Fe/H}]) = 0.4 \times (1+ < P_{GGP}\,(M_\star, [\mathrm{Fe/H}]) >_{IMF})$$

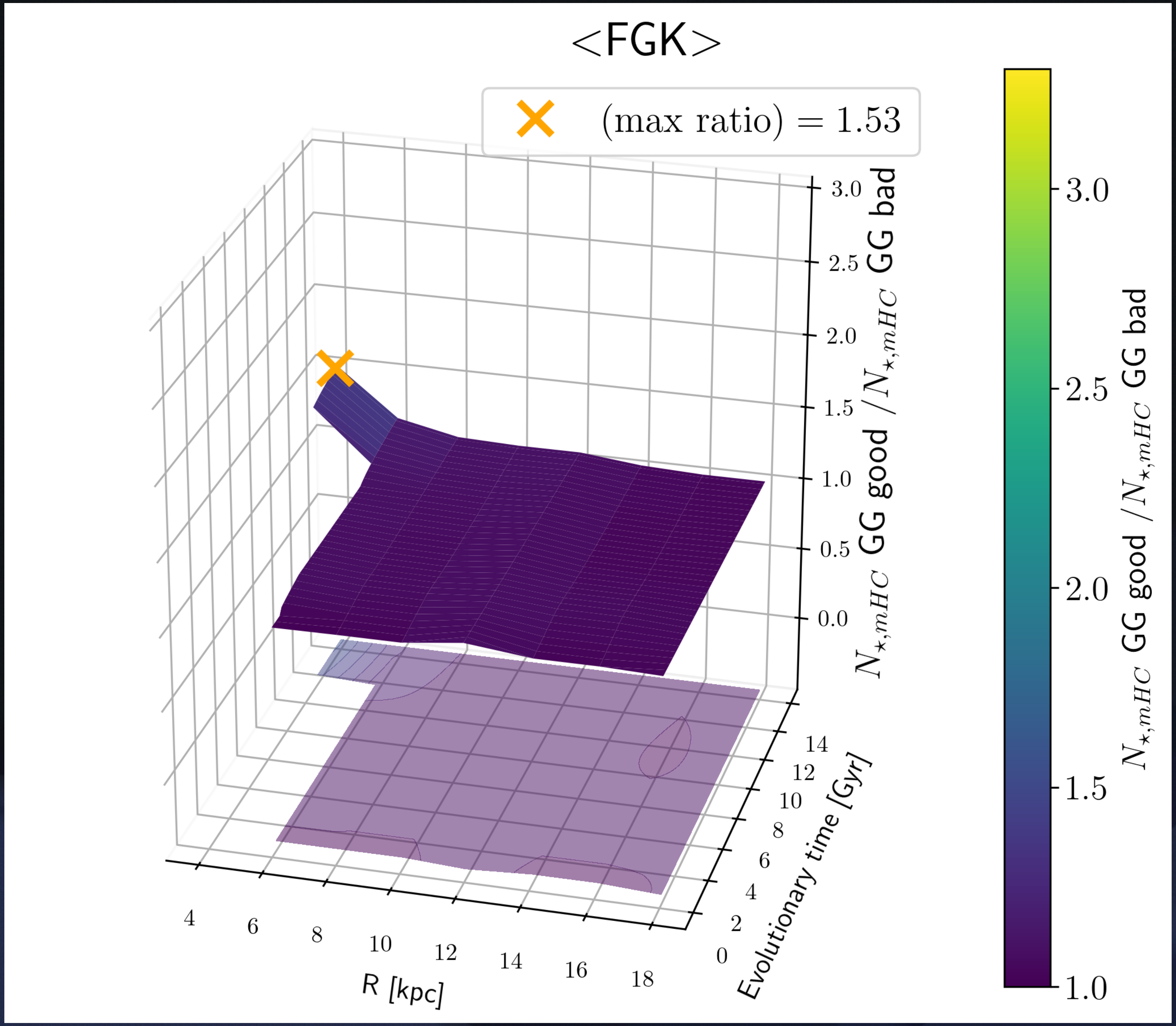
NO MIGRATION
RATIO BETWEEN GG GOOD/GG BAD



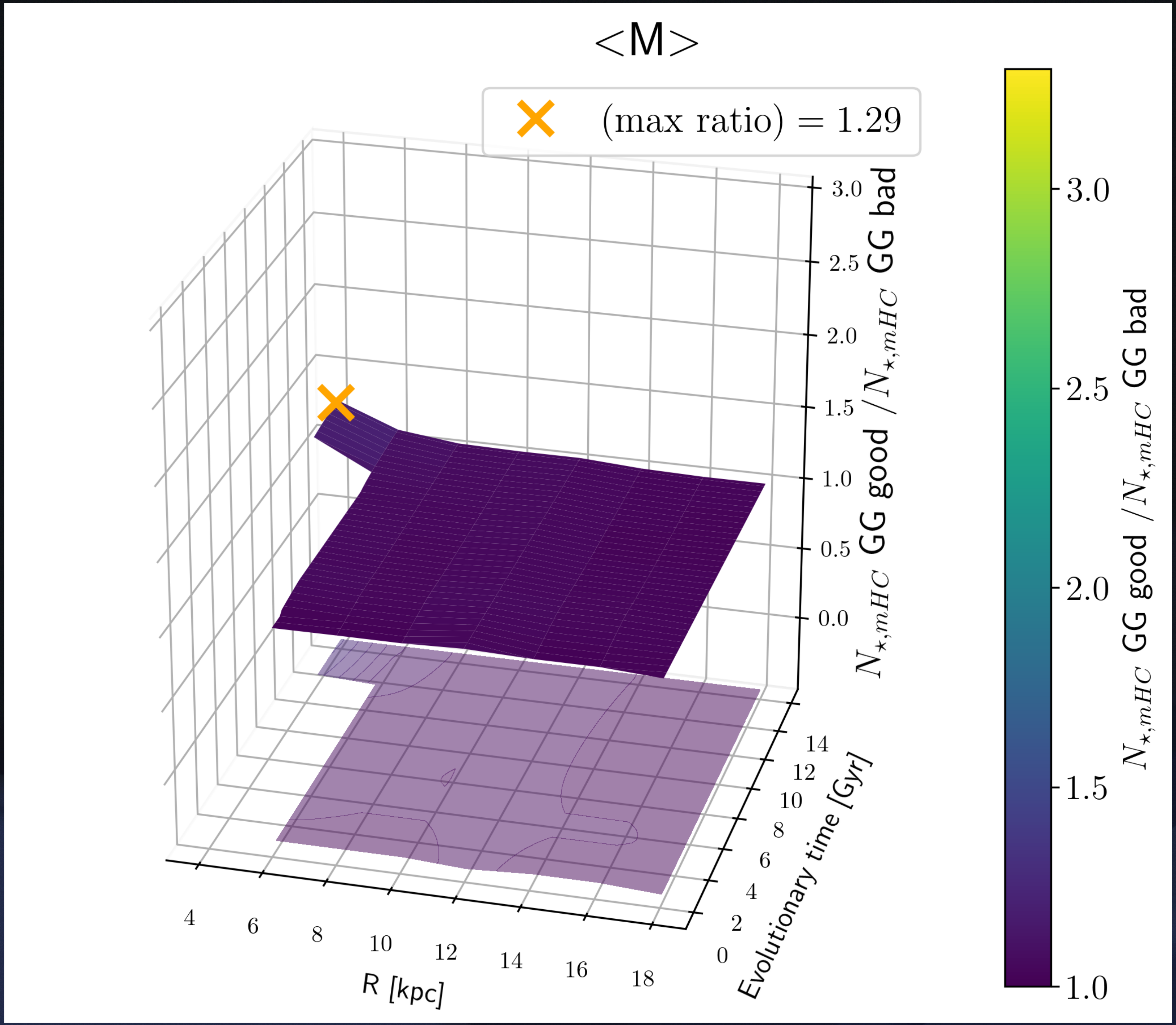
GG GOOD

GG BAD

NO MIGRATION
RATIO BETWEEN GG GOOD/GG BAD



NO MIGRATION
RATIO BETWEEN GG GOOD/GG BAD



SUMMARY

- Assuming prescriptions for the destructive effect from close-by SN explosions, the larger number of stars with habitable planets are in the solar neighborhood also in presence of stellar migration.
- Stellar migration has a larger impact in the outskirts of the Galactic disc. In the annular region centred at 18 kpc, the number of stars hosting habitable planets is increased by a factor of $\sim$5 compared to the reference model without stellar migration.
- The hypothesis that gas giant planets facilitate the formation of terrestrial planets has the most pronounced effect in the inner Galactic disc (in the annular region centred at 4 kpc from the Galactic centre)

arXiv > astro-ph > arXiv:2601.21032

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[Submitted on 28 Jan 2026]

The LEGARE Project. I. Chemical evolution model of the Nuclear Stellar Disc in a Bayesian framework

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Spitoni+26