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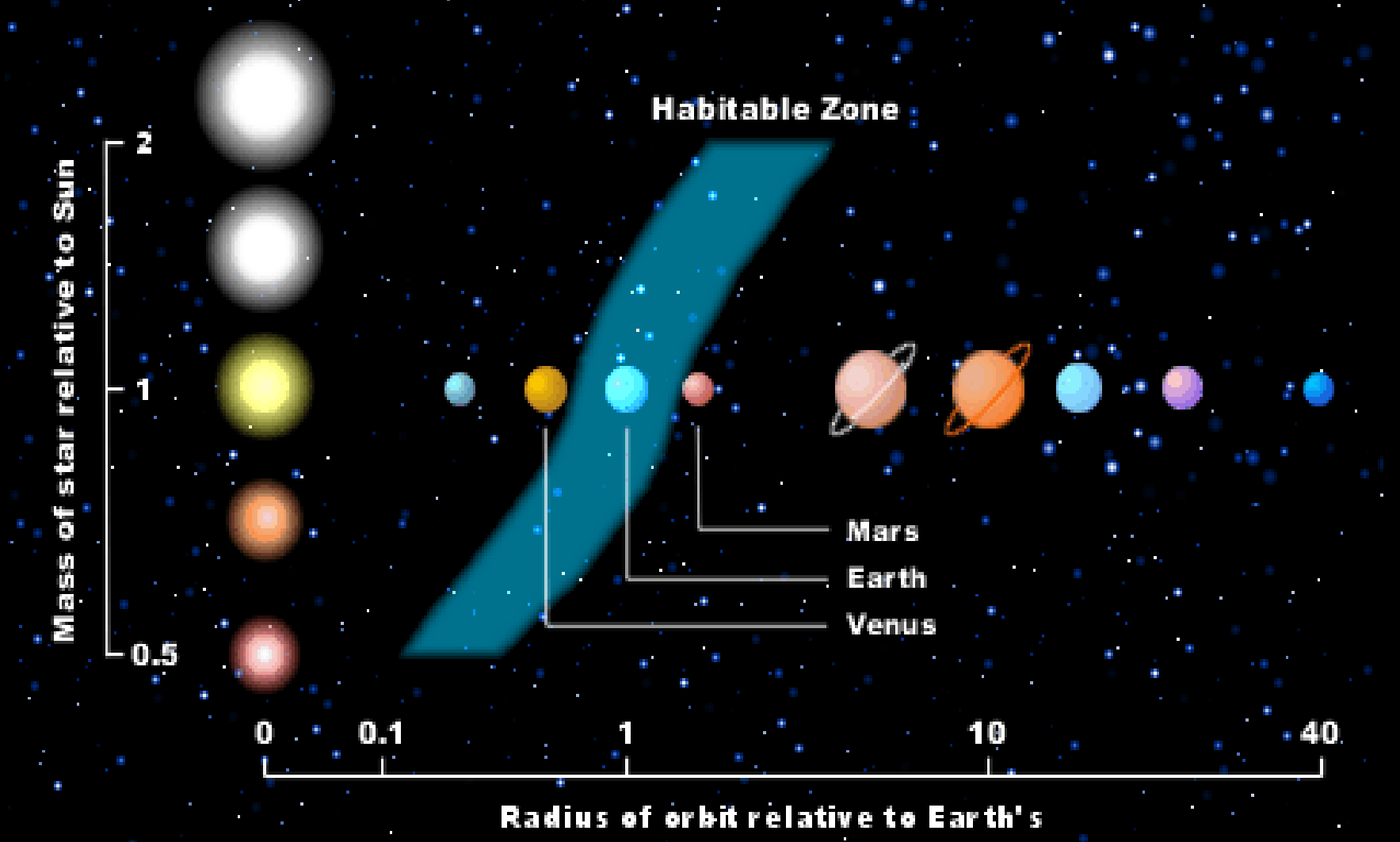
On the Galactic Habitable Zone

(2008) Space Science Reviews, Vol. 135, pp. 313-322

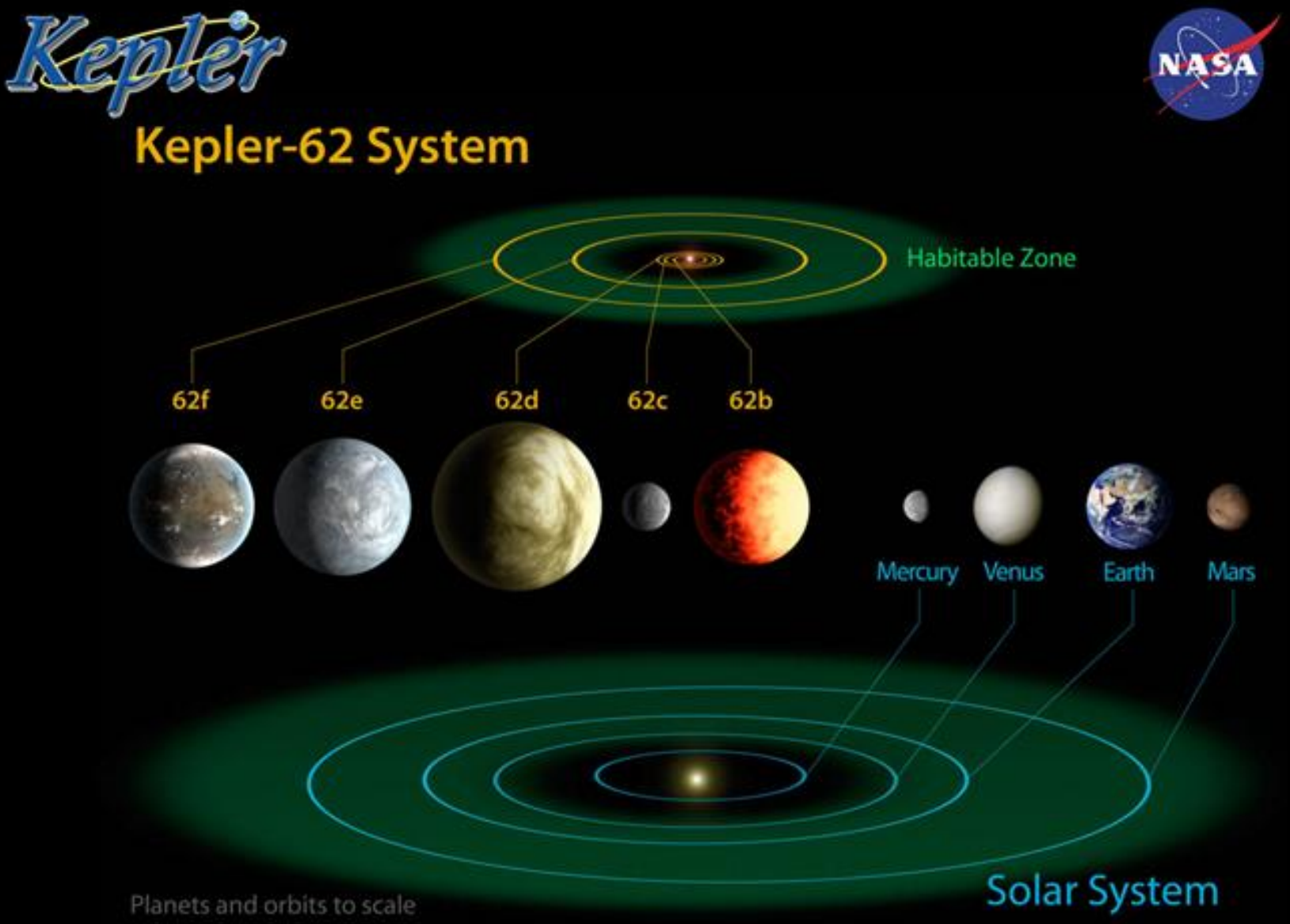
(2012) in Origins and Evolution of Life, Eds. M. Gargaud et al. CUP, pp. 154-166

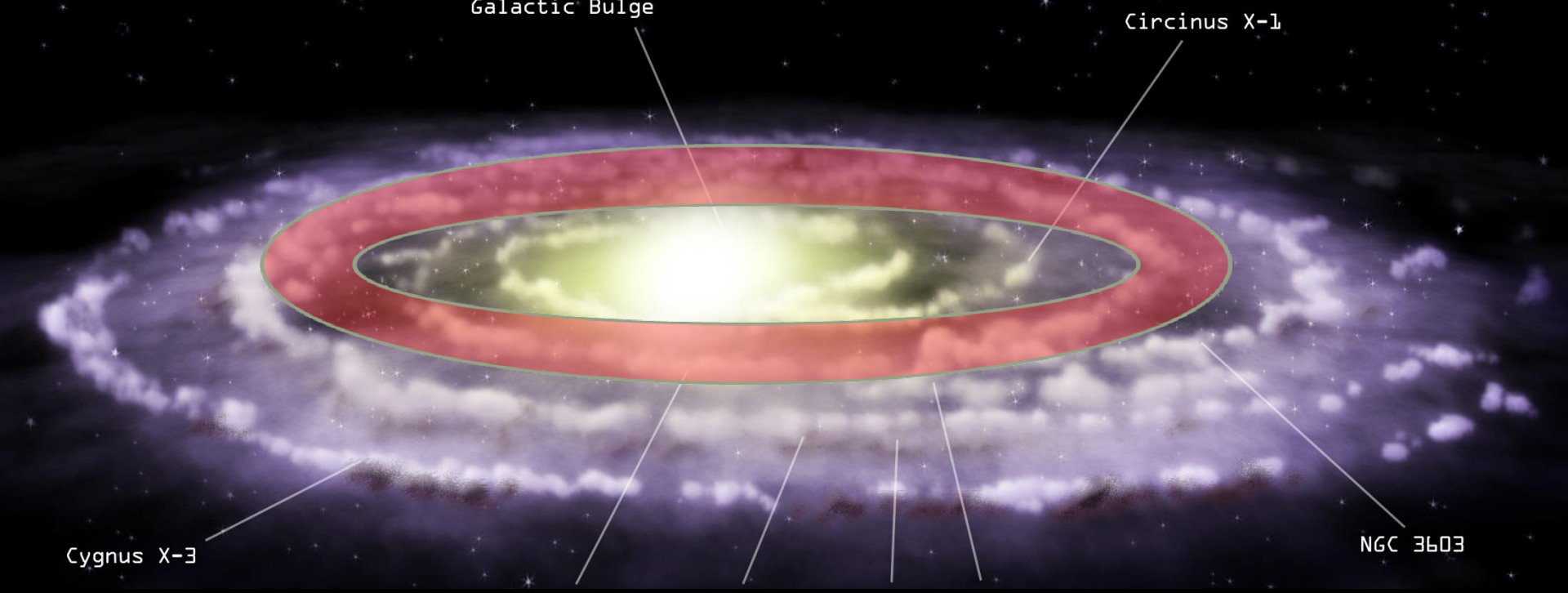
CIRCUMSTELLAR HABITABLE ZONE (*Huang 1959*)



Distance range from the central star corresponds to range of temperatures allowing the presence of liquid water on planetary surface (also: greenhouse effect)

Since stellar luminosity increases (~2) on the Main Sequence, CHZ migrates outwards with time


Kepler
NASA
Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Planets and orbits to scale
Solar System



Several properties of the Milky Way disk vary with radius… and with time

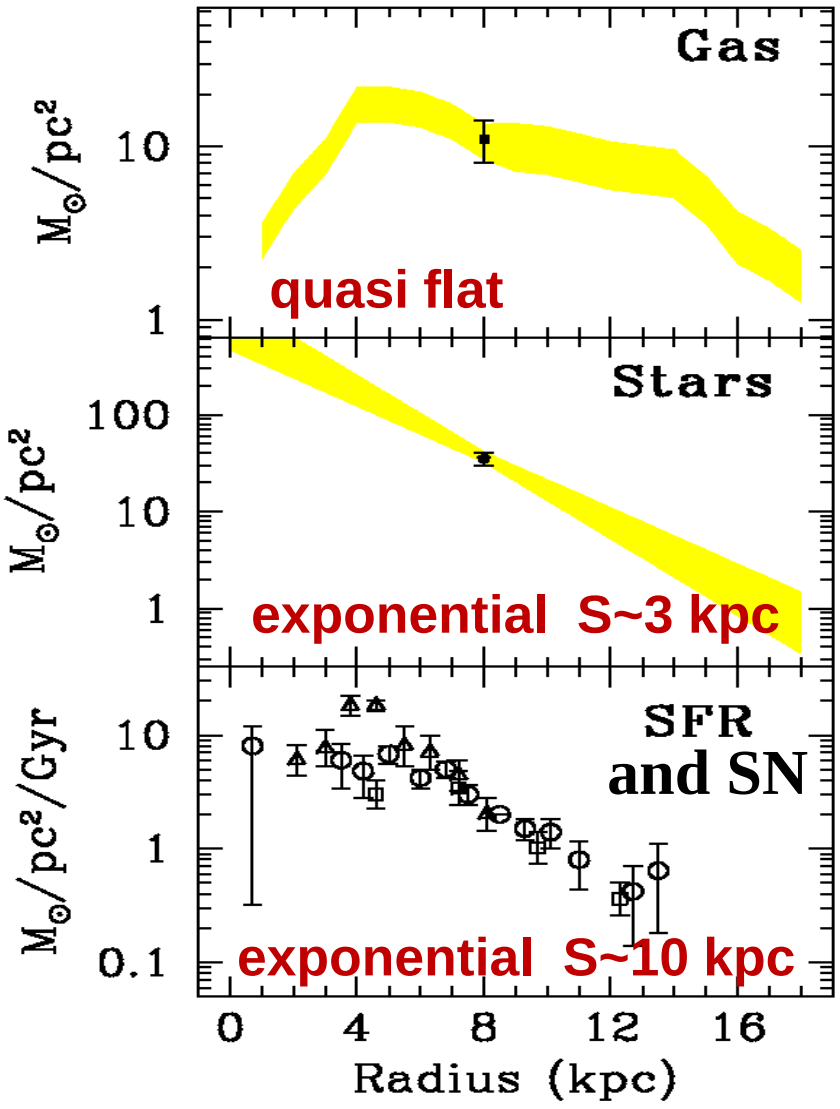
Which one of them *(if any)* are important `for "Galactic habitability"
(=conditions favouring *formation of telluric planets and survival of life*)?

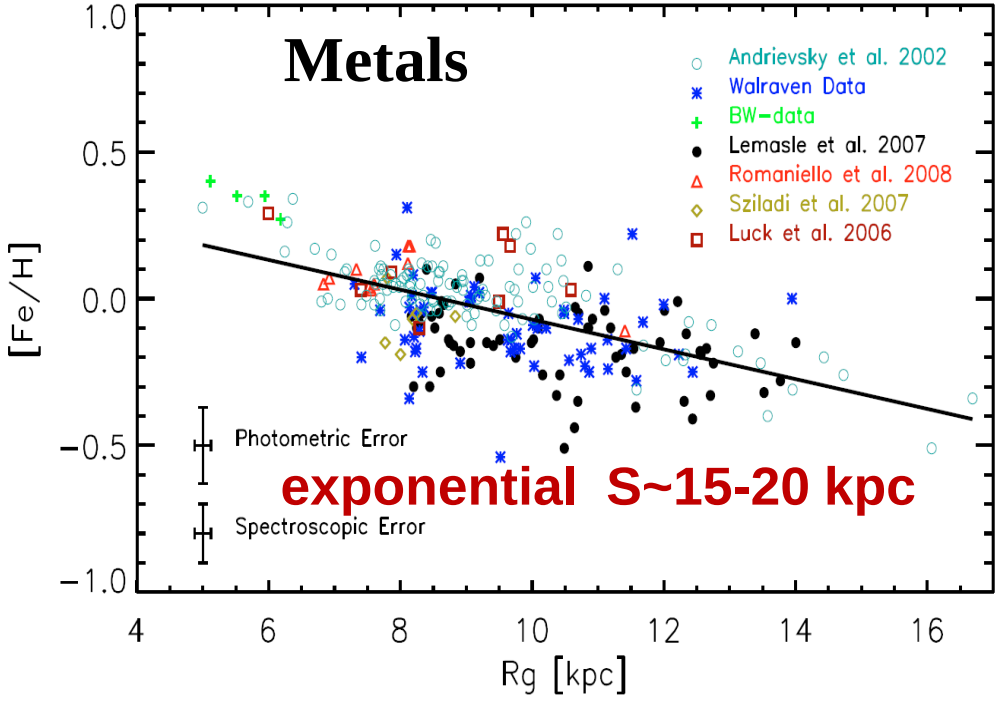
(Perhaps) *metallicity, density of stars, frequency of supernova explosions…*

They may define a "belt of life in the Galaxy"
(Maroshnik and Mukhin 1986; Balazs 1988)

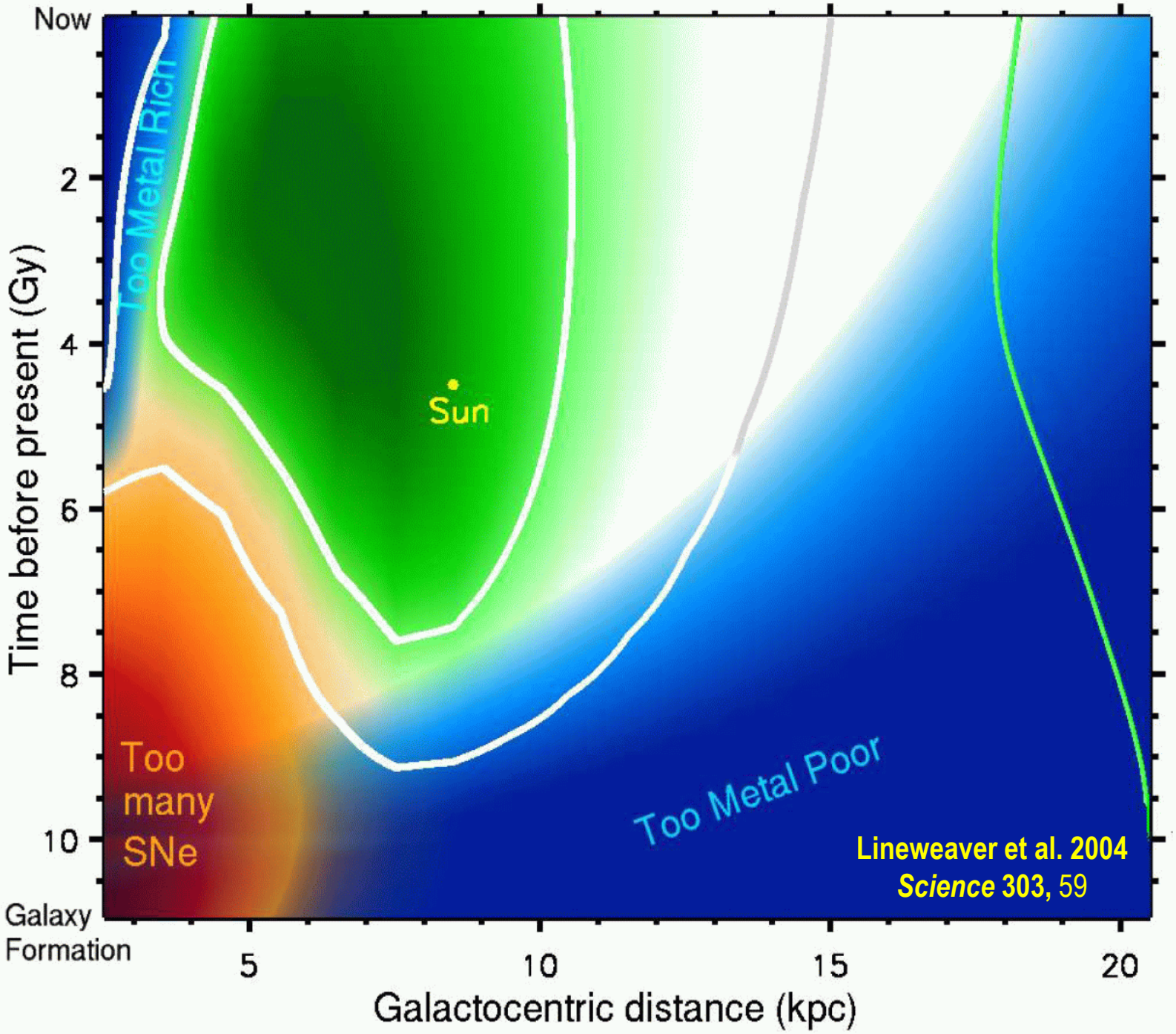
Or a Galactic Habitable Zone
(Gonzalez , Brownlee and Ward 2001, *Icarus, Scientific American*
Lineweaver et al. 2004, *Science*)

The Milky Way disk today





How did those profiles evolve in the past ?


Now
2
4
6
8
10
Galaxy Formation
Time before present (Gy)
Too Metal Rich
Sun
Too many SNe
Too Metal Poor
Lineweaver et al. 2004
Science 303, 59
5
10
15
20
Galactocentric distance (kpc)

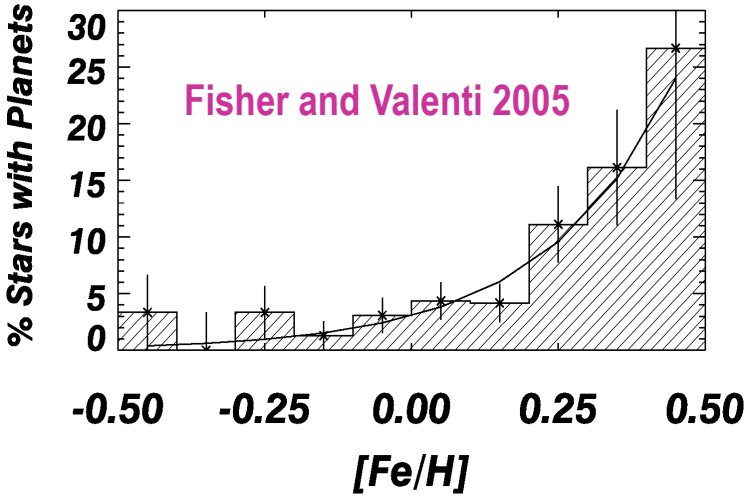
PROBABILITY OF FORMING HOT EXO-JUPITERS

Metallicity dependent:

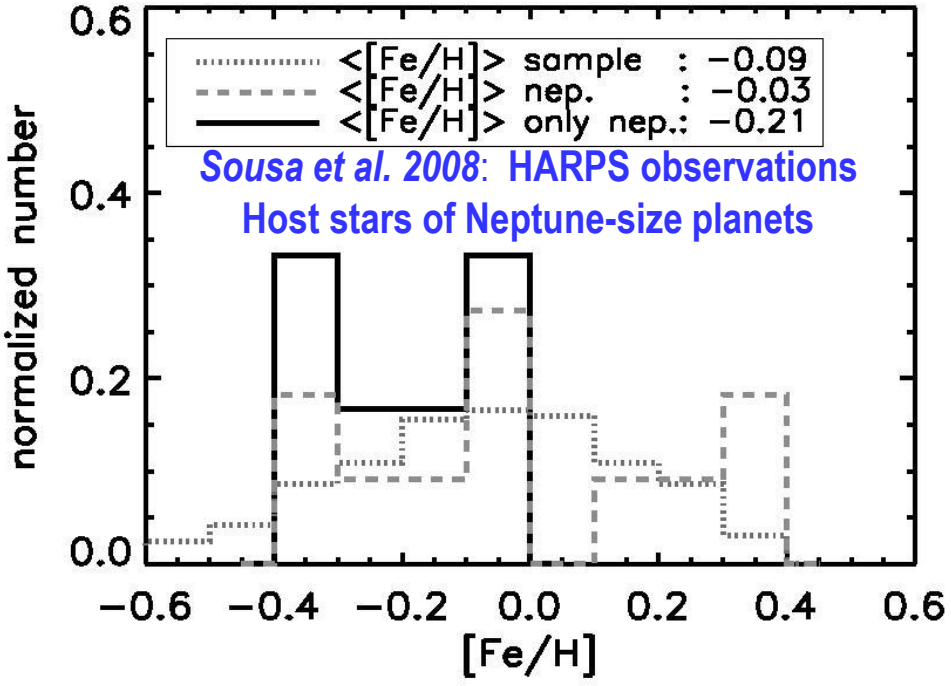
$f_{HJ} = 0.03\ (Fe/Fe_{\odot})^2$

(Fisher and Valenti 2005)

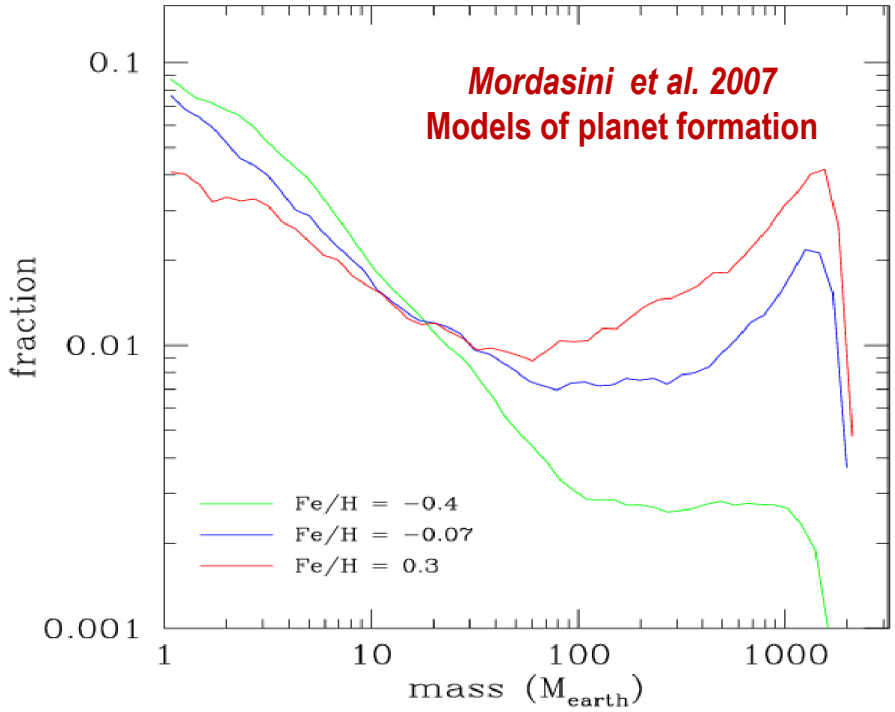
But hot Jupiters destroy Earths in their migration inwards…..



PROBABILITY OF FORMING EXO-EARTHS ?

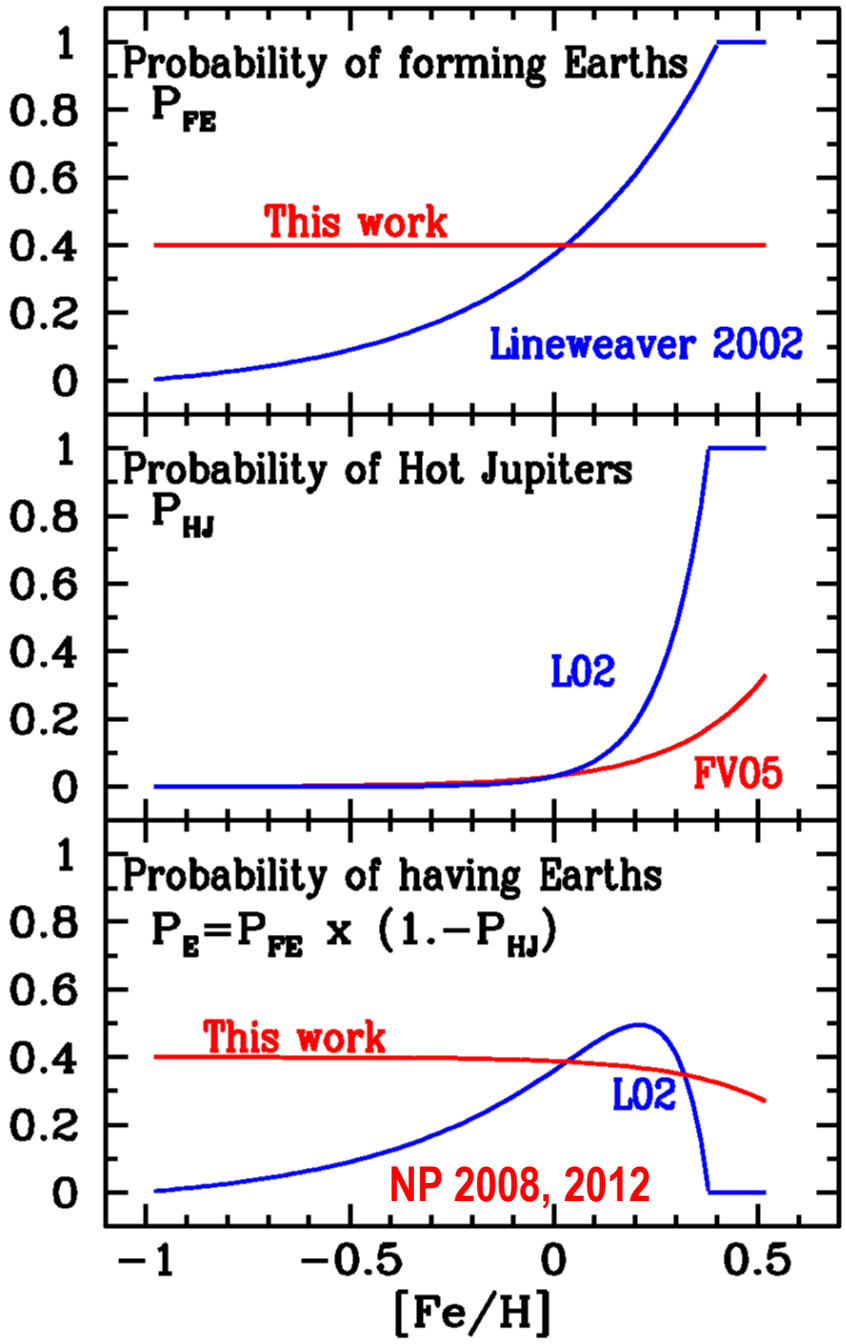


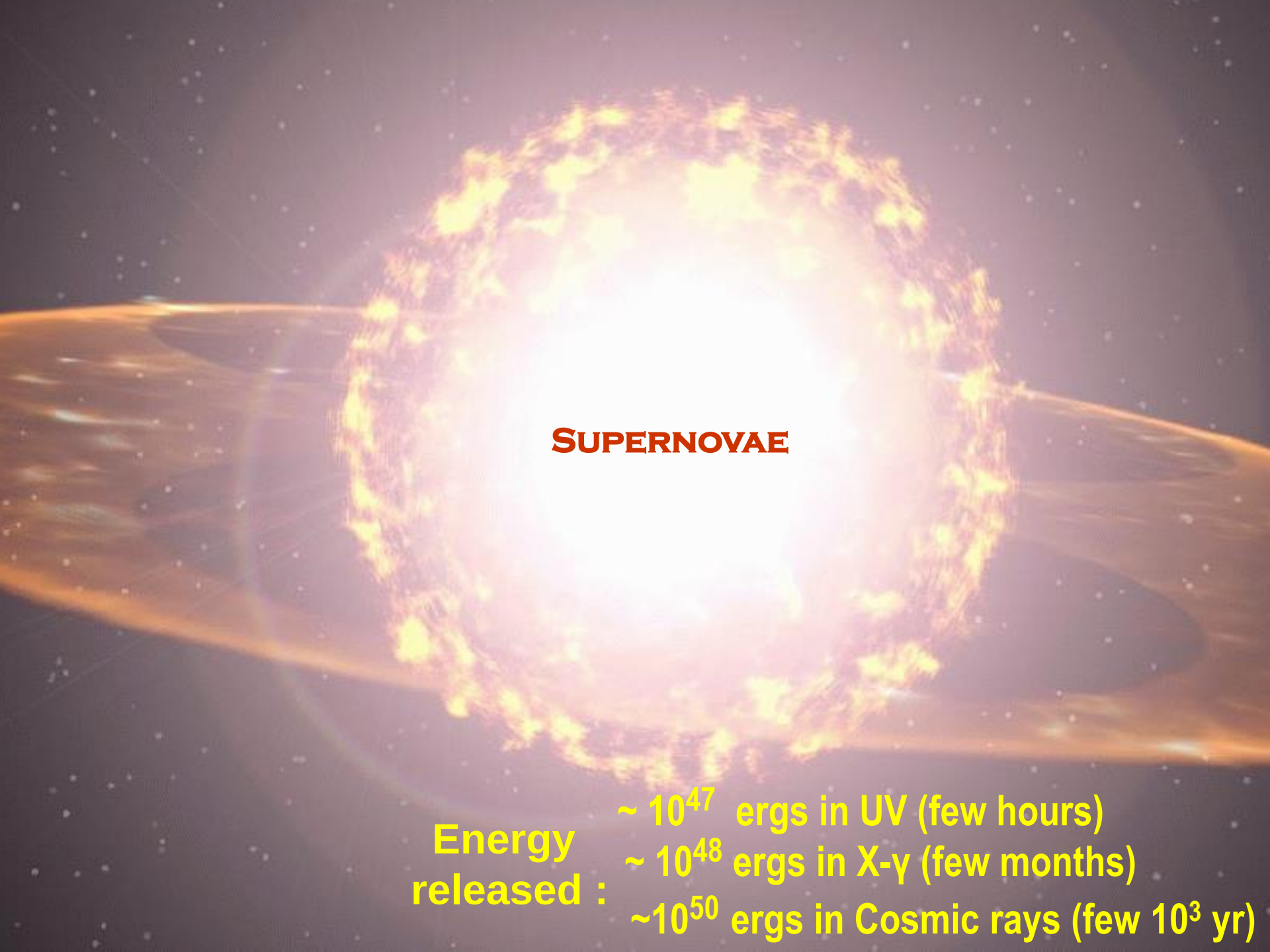
Probably less dependent on metallicity



Probability of having Earths not destroyed by Hot Jupiters

$$P_E = P_{FE} \times (1 - P_{HJ})$$





Energy released :

~ 10^{47} ergs in UV (few hours)

~ 10^{48} ergs in X-γ (few months)

~10^{50} ergs in Cosmic rays (few 10^3 yr)

Ionizing radiation
on
planetary atmospheres

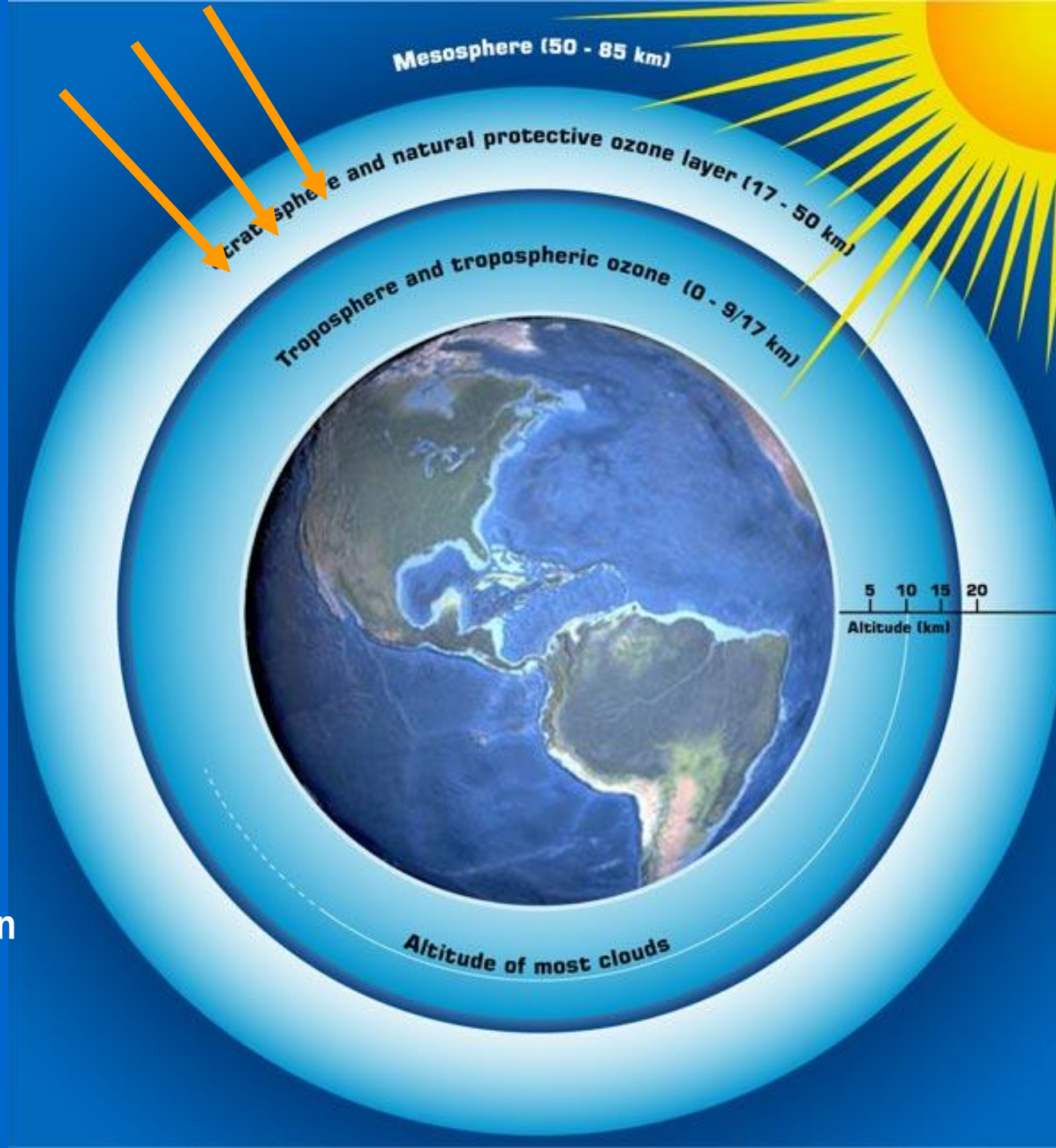
Induces chemical reactions producing NO_X which destroy the protective O_3 layer and increase the solar UV flux on surface

Produces secondary energetic particles and UV reaching the surface

But :

1) Mutations may accelerate and even induce evolution

2) Marine life appears rather immune to such events



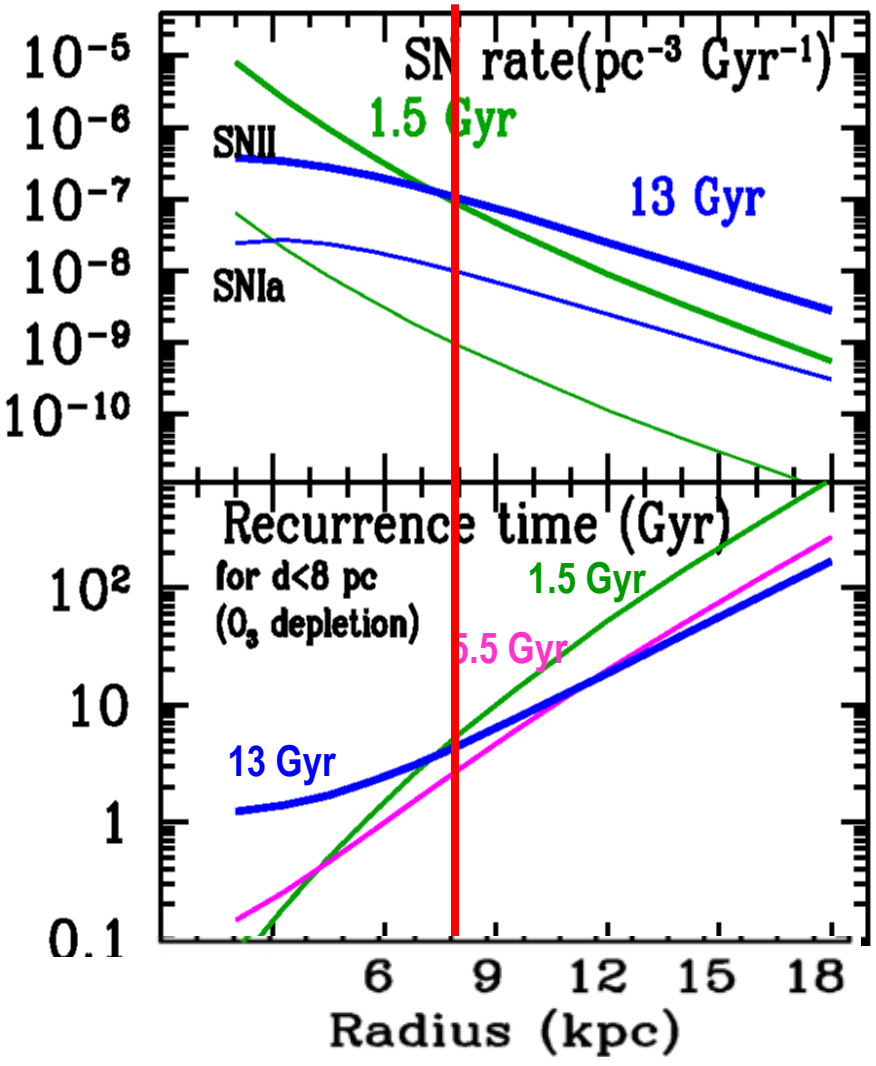
SUPERNOVAE AS A THREAT FOR LIFE (?)

SNII (core collapse of massive stars) are more frequent and closer to the Galactic plane than SNIa (thermonuclear explosions of white dwarfs)

In Milky Way: f_{SN} = 2-3 per century

For depletion of O_3 layer by ~2
d_{SN} < 8 pc (*Gehrels et al. 2003*)

Local recurrence time: ~2. Gyr

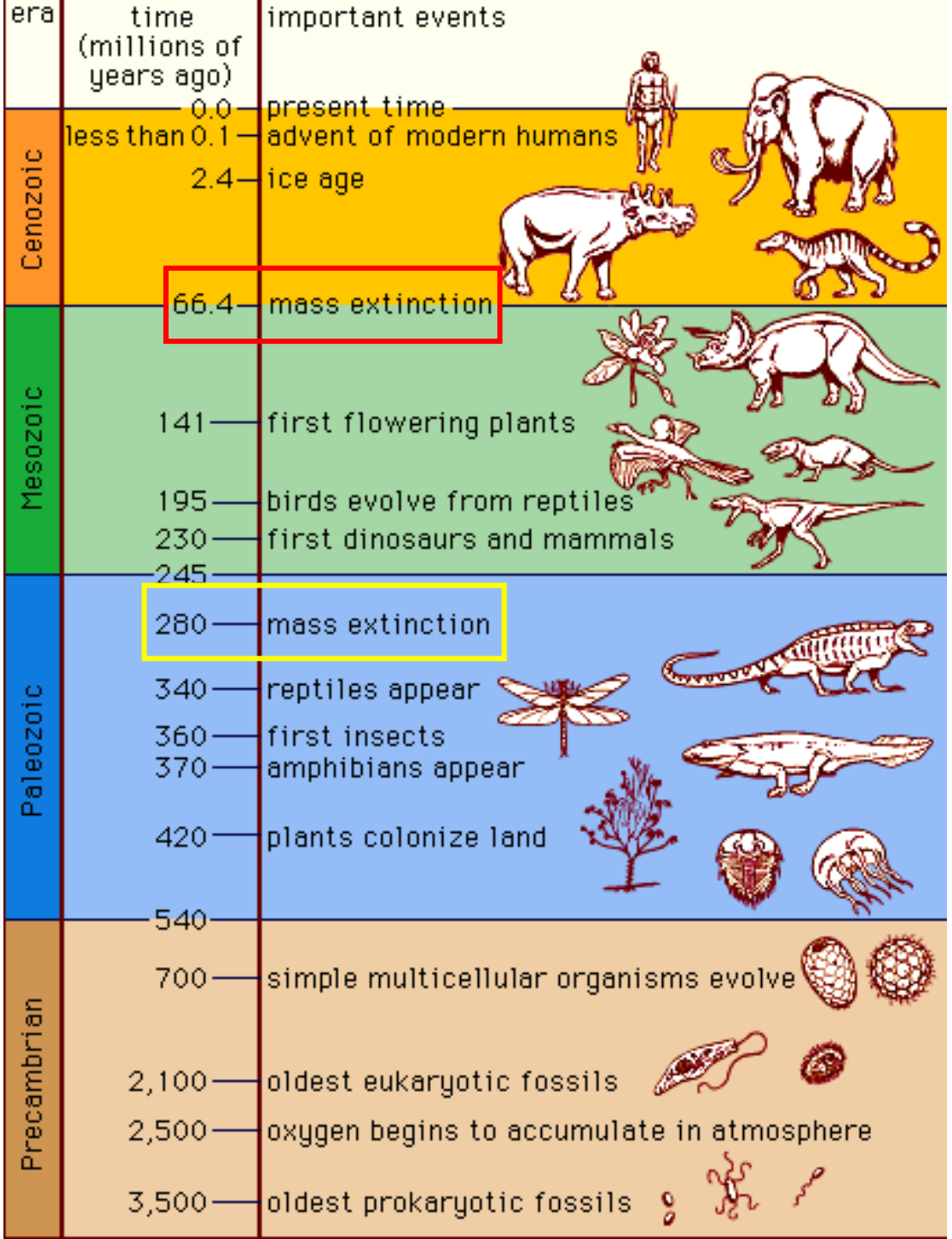


BUT: they concern complex life on land, none of these implies definitive sterilisation…

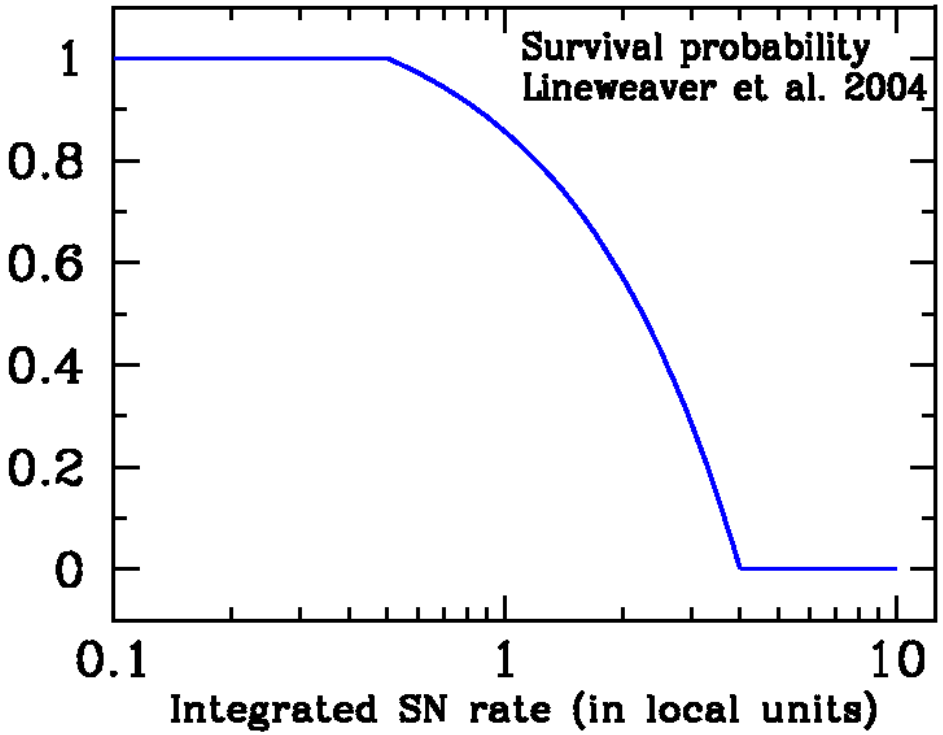
Several major catastrophes occurred in the last 500 million years of multi-cellular life on Earth

But the planet was not sterilized.

Life not only survived, but evolved to higher levels of complexity



How to quantify the SN threat for life ?

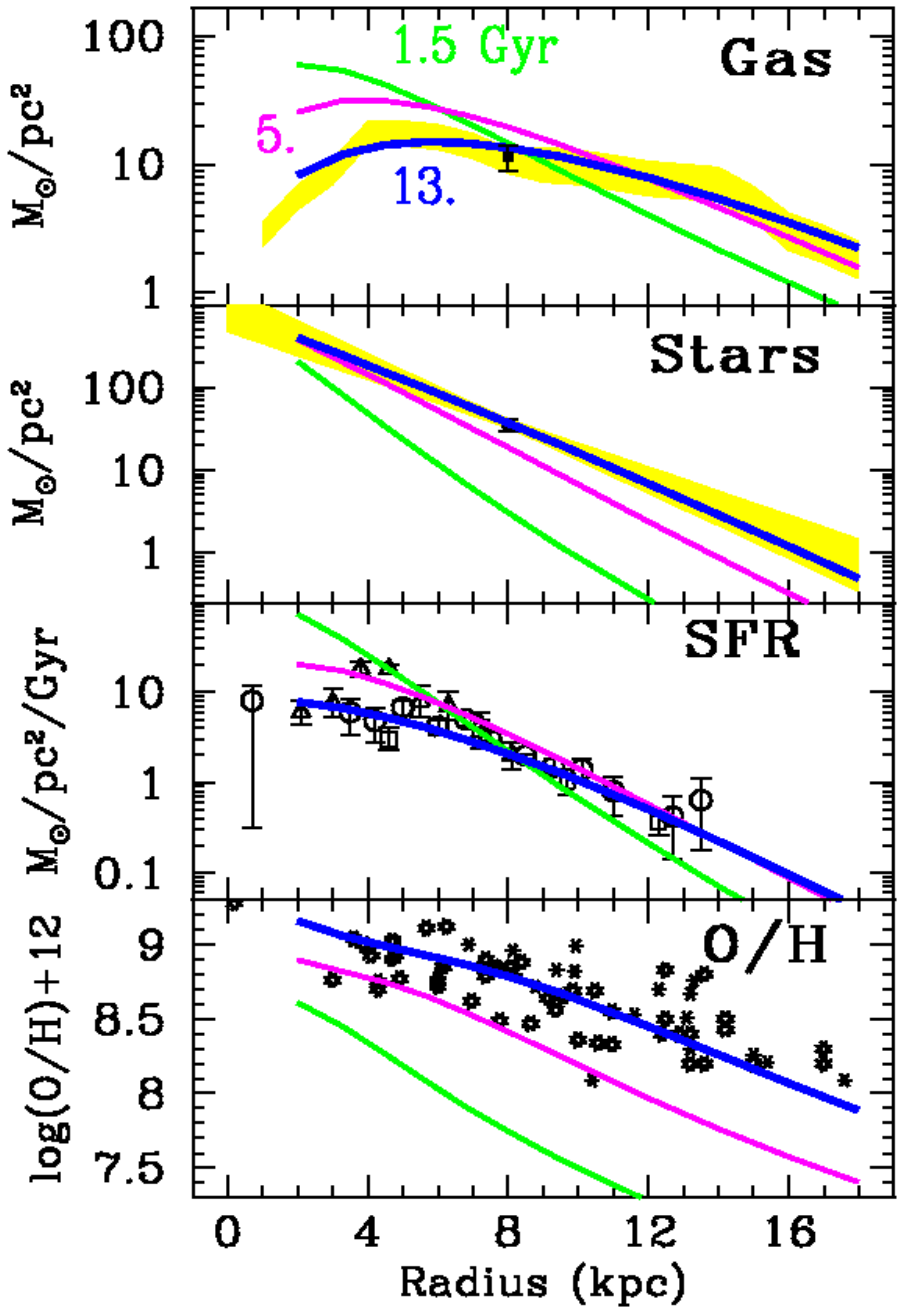


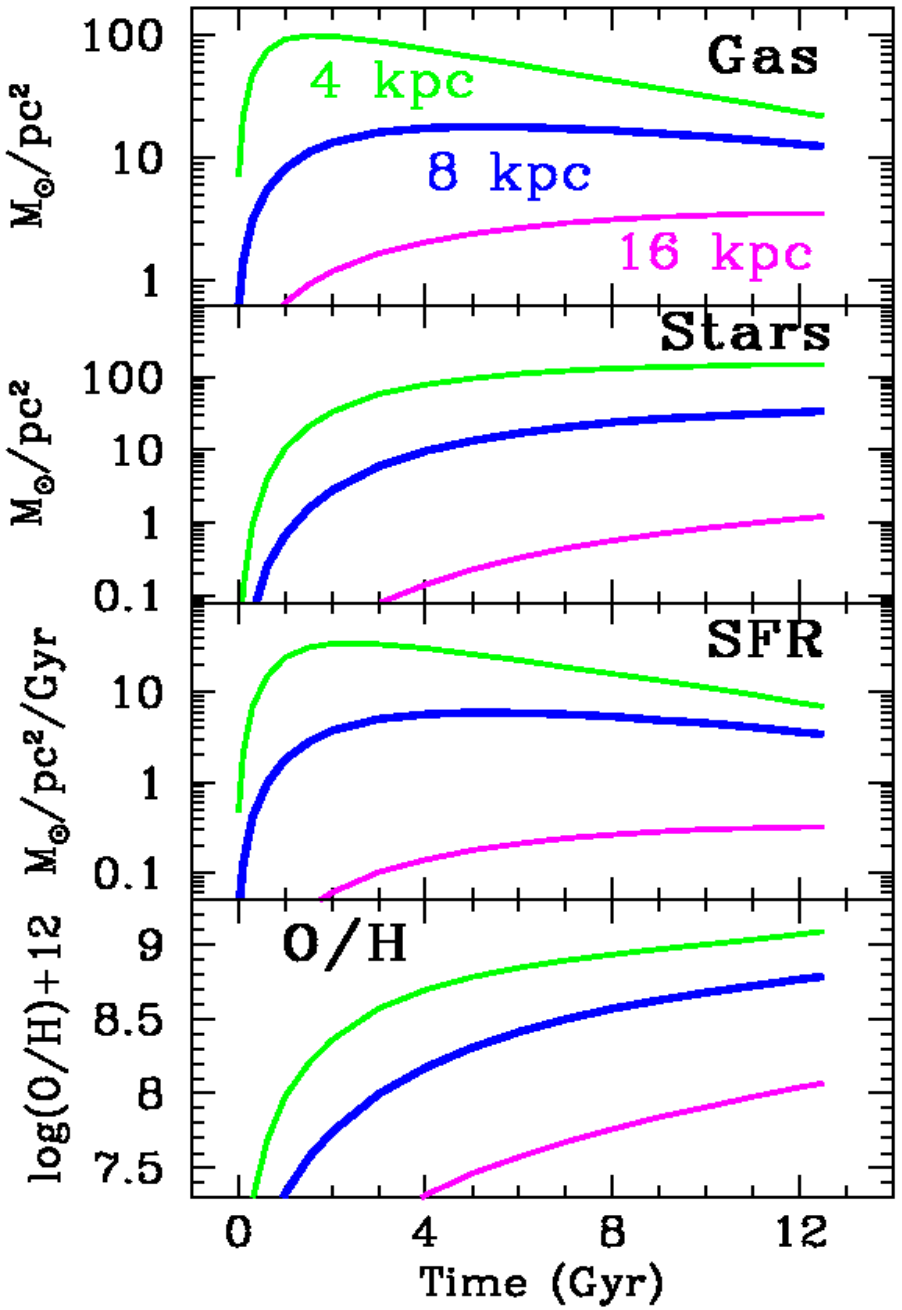
Local unit: $\int_{8\ \mathrm{Gyr}}^{12\ \mathrm{Gyr}} \mathrm{SNR}(t)\,dt = 1$ in Sun's position

Utterly arbitrary quantification

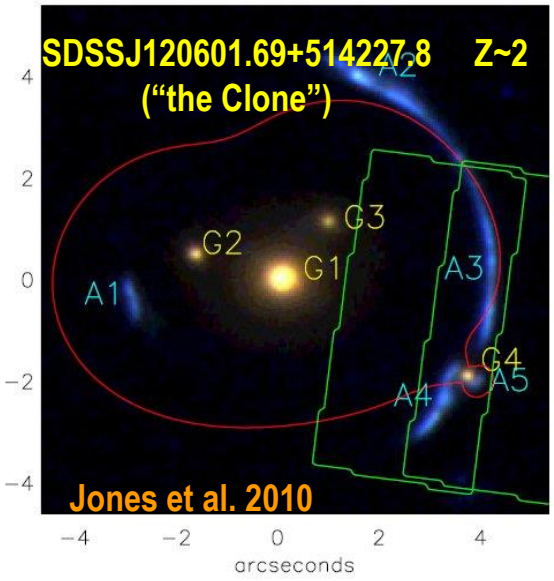
(and even qualification)…

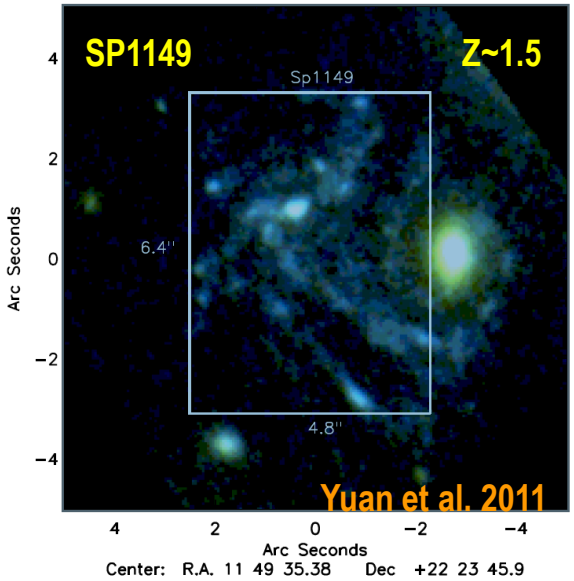
THE EVOLUTION OF THE MILKY WAY DISK (*Boissier and NP 1999*)

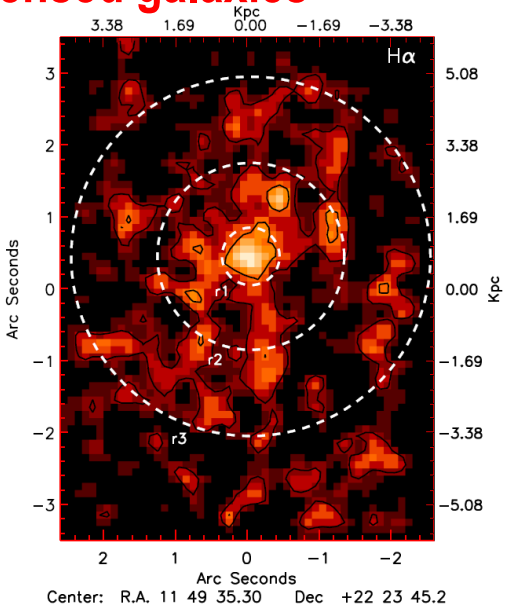


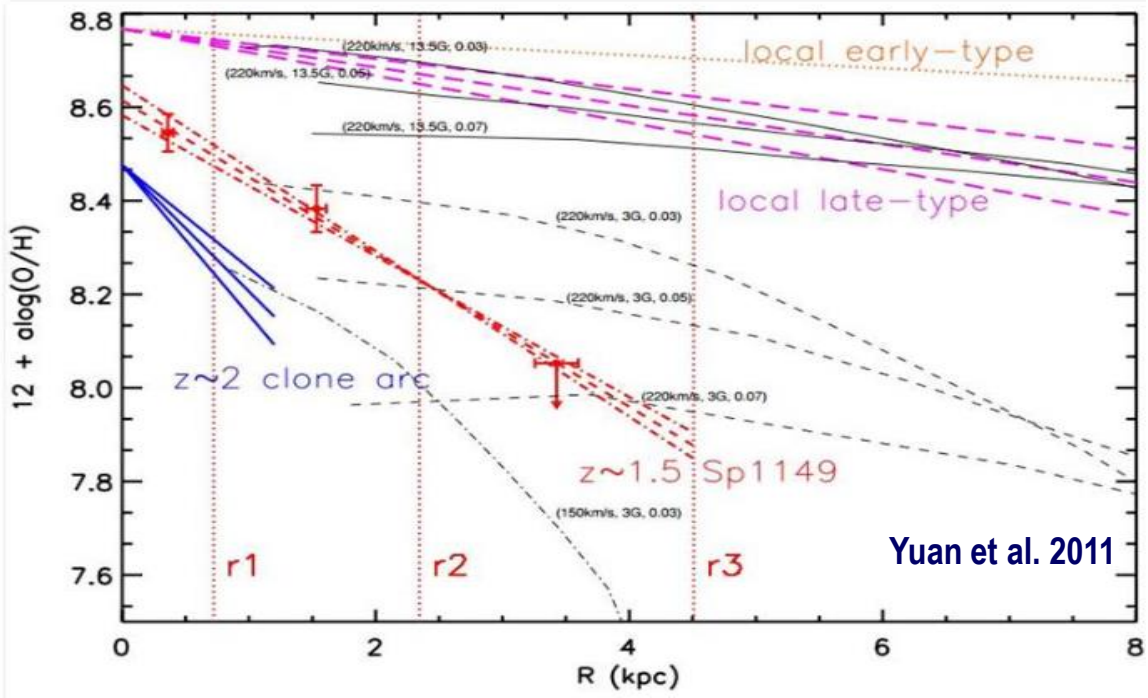


Observation of abundance profiles at high redshift in lensed galaxies



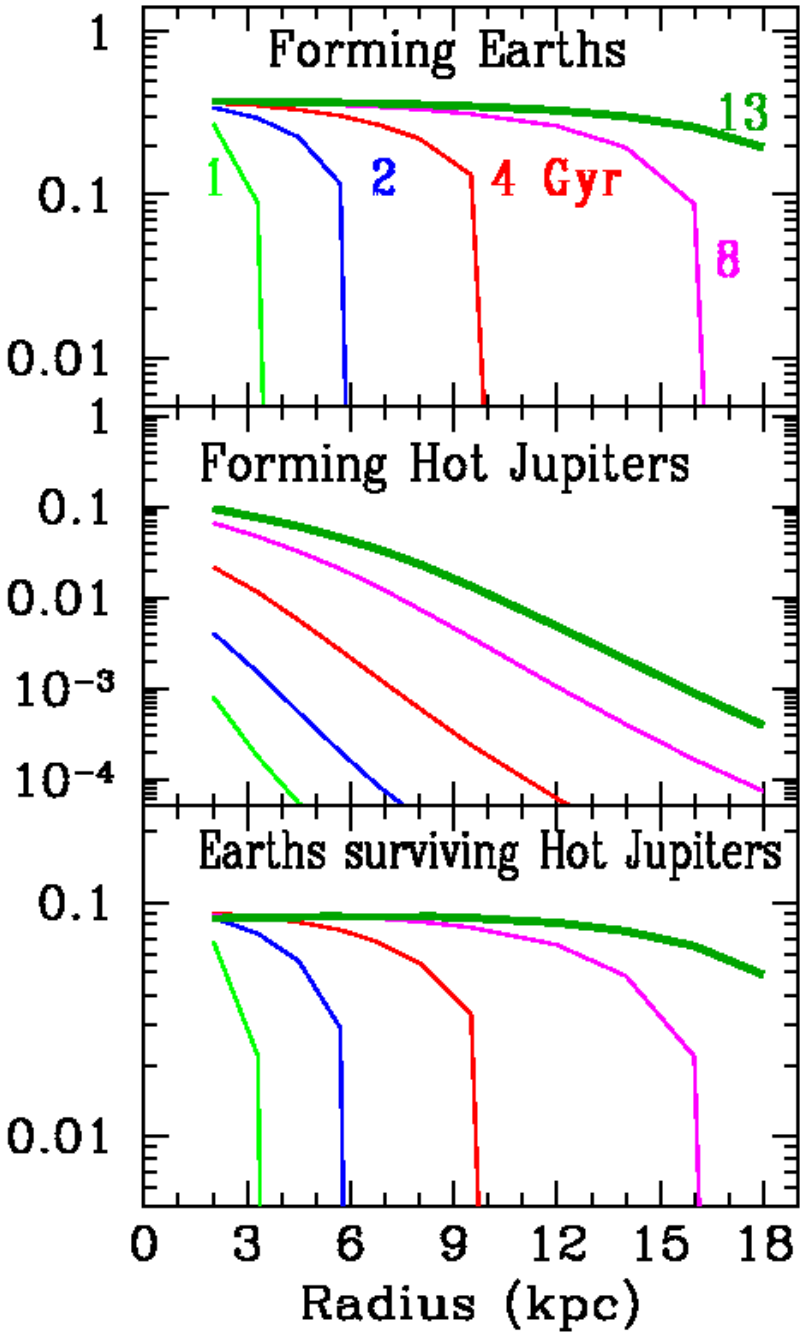


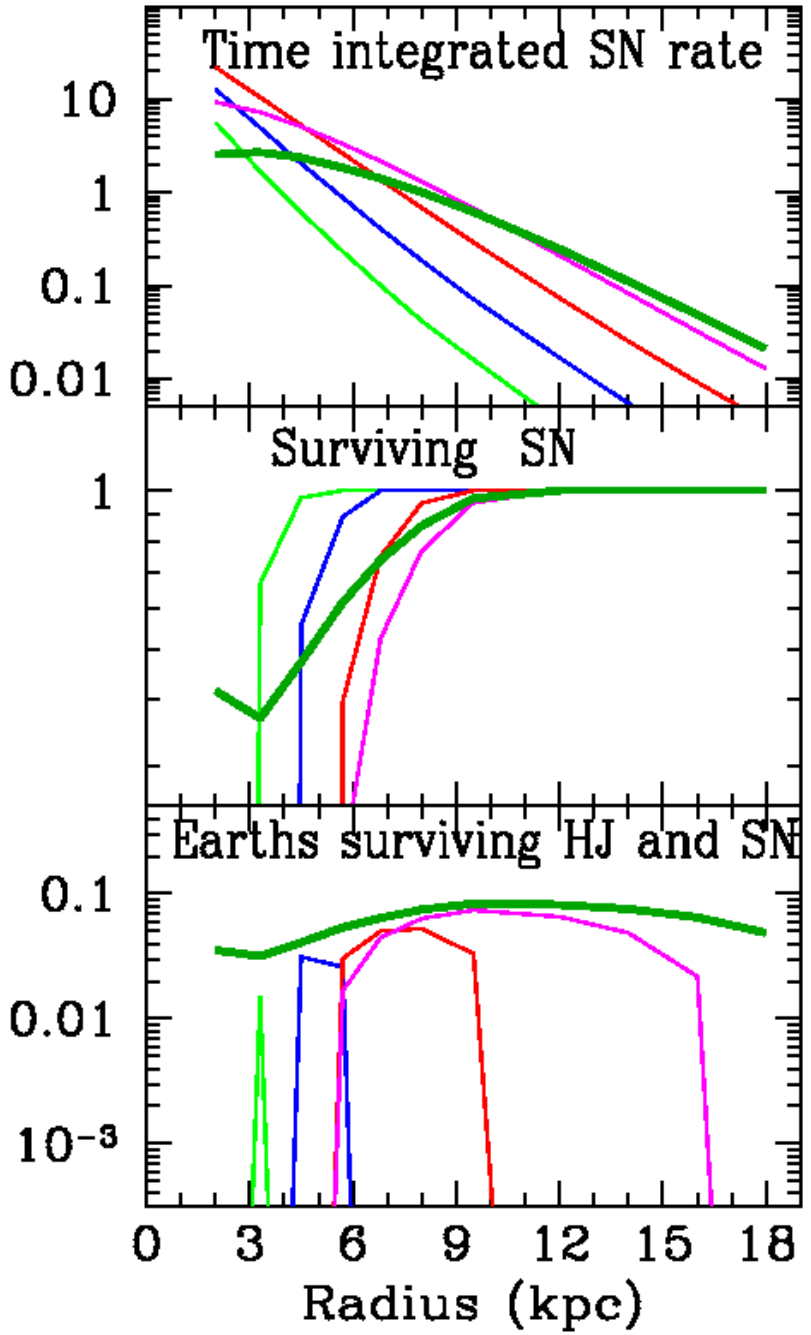




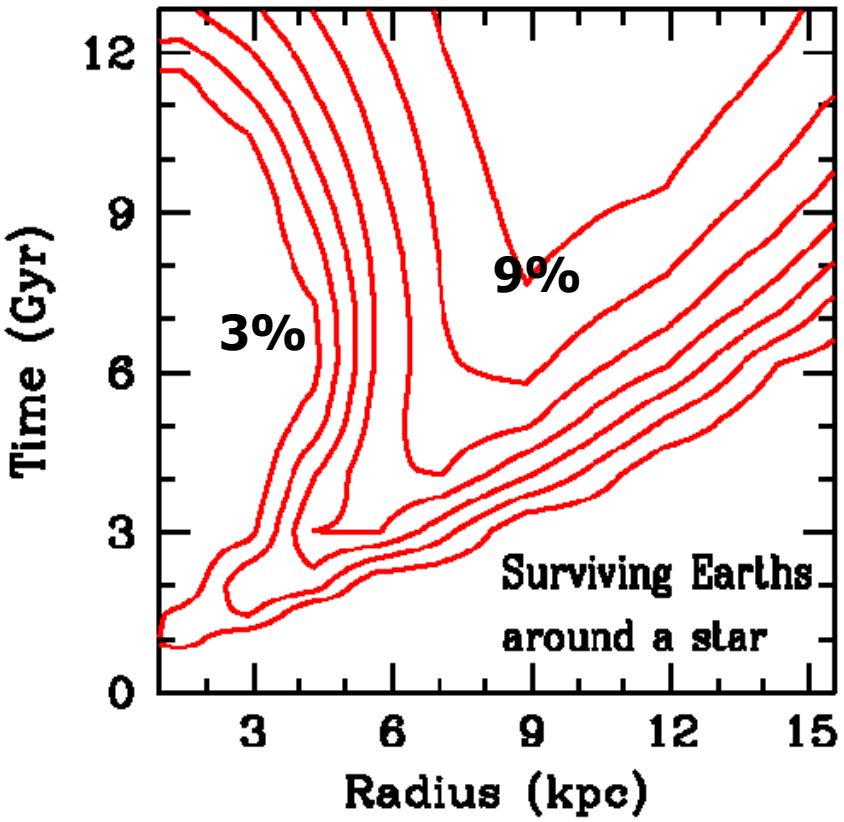
High-z abundance profiles appear to be much steeper than typical profiles of local disks

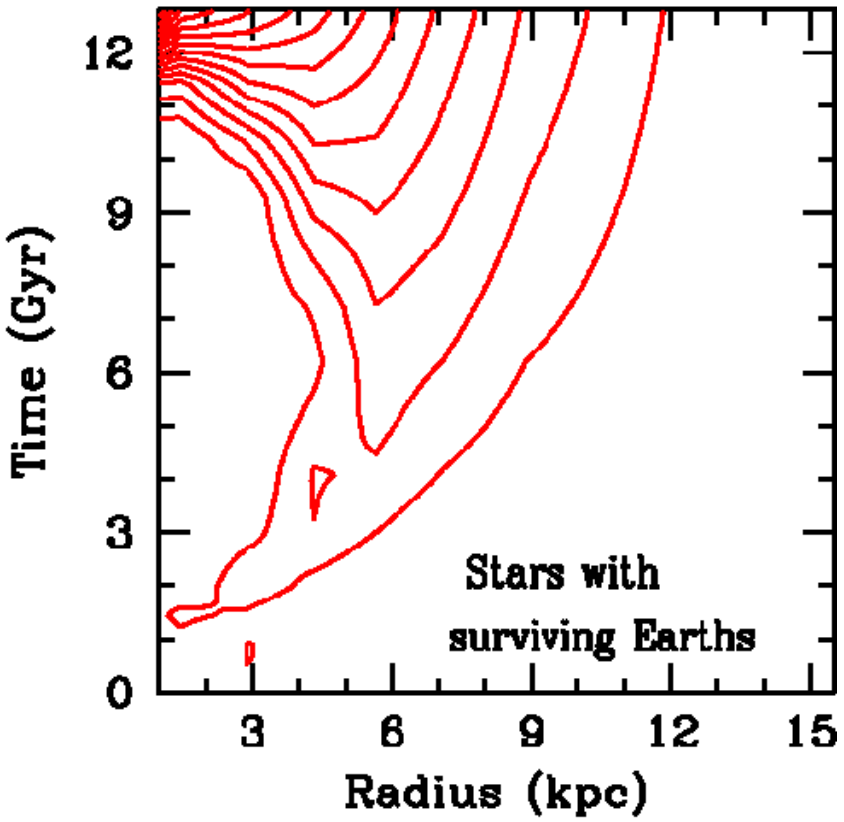
Propabilities…





Stars with Earths having survived threat from Supernovae



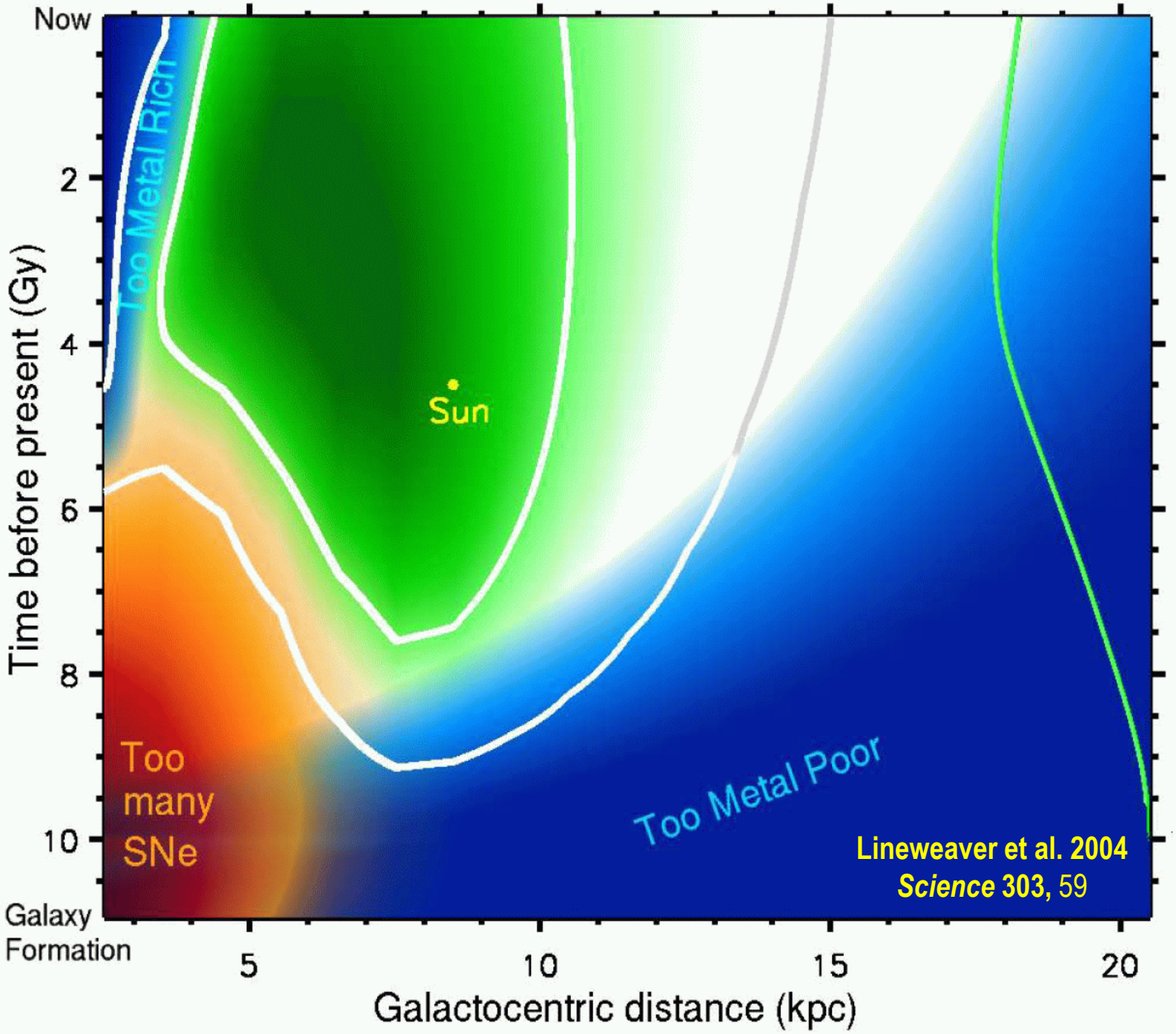


Relative probability to have life *around one star* at a given position,

Probability of having life hosting planets *per unit volume* (or surface density) in a given position

Because the density of stars is higher in the inner disk, the probability of finding a star with Earth-like planets inside a given volume is higher in the inner Galaxy

Similar results obtained in Gowanlock et al. (2011)


Now
2
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Galaxy Formation
Time before present (Gy)
Too Metal Rich
Sun
Too many SNe
Too Metal Poor
Lineweaver et al. 2004
Science 303, 59
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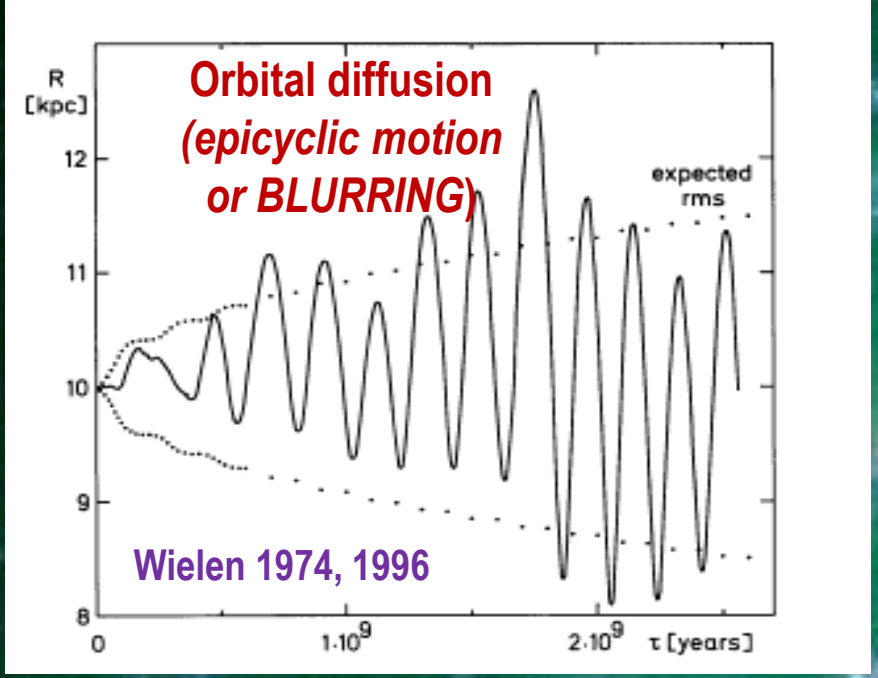
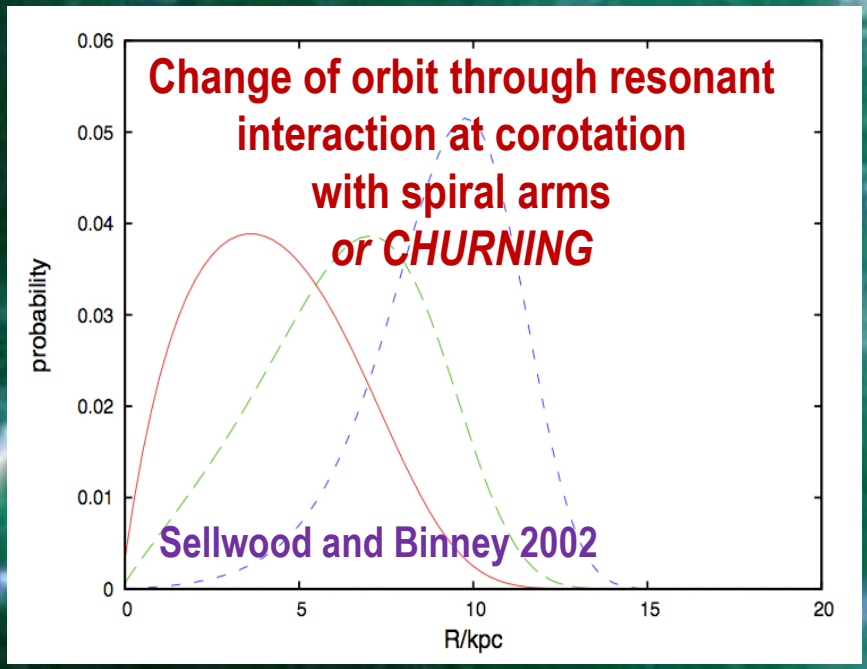
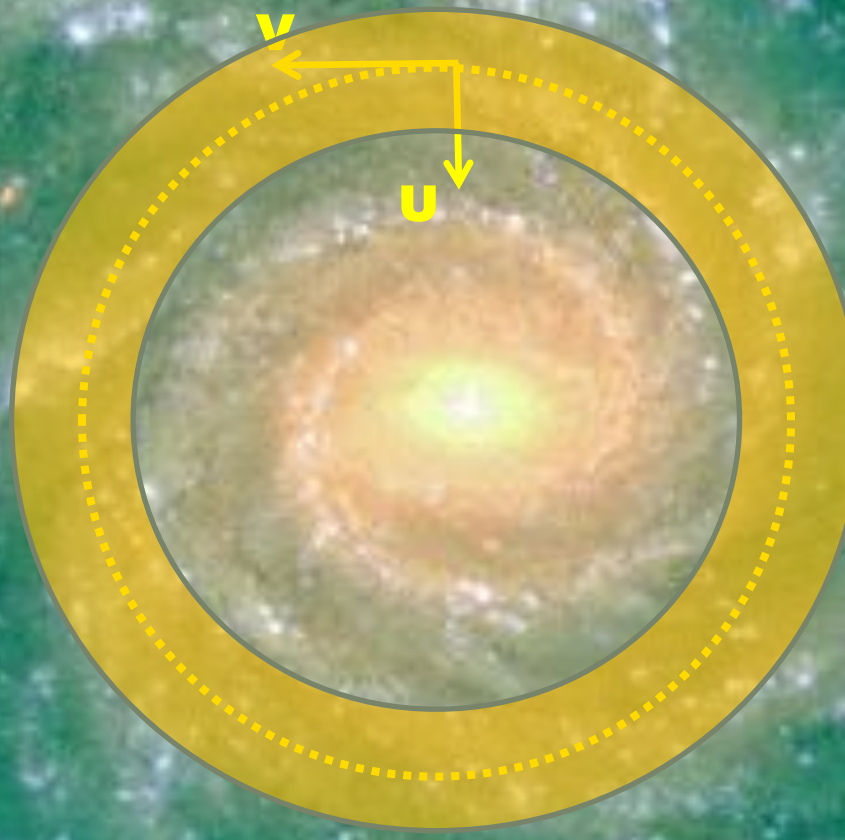
Galactocentric distance (kpc)





Stellar orbits change through interactions with inhomogeneities of gravitational potential (molecular clouds, spiral arms, bar)

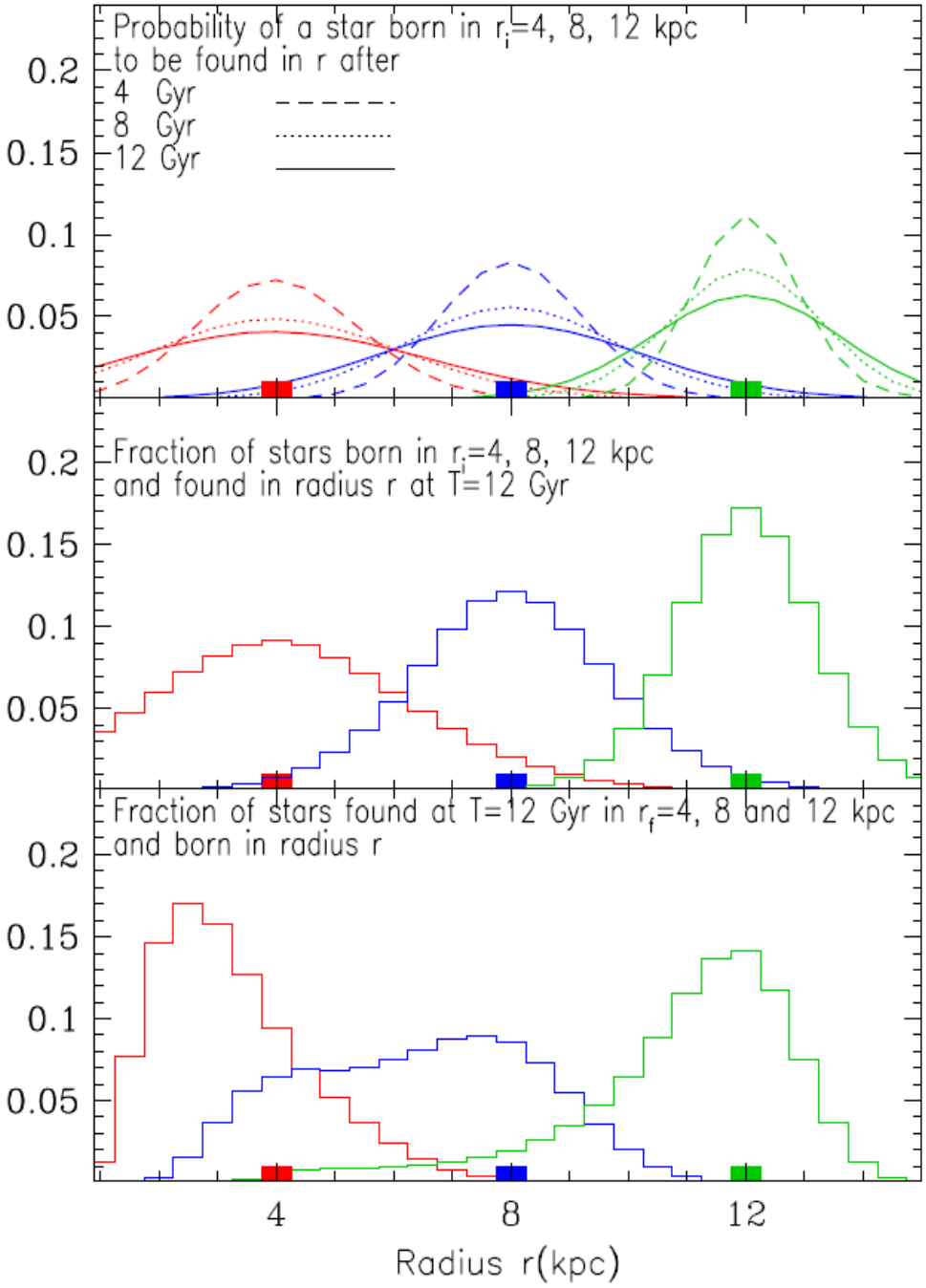


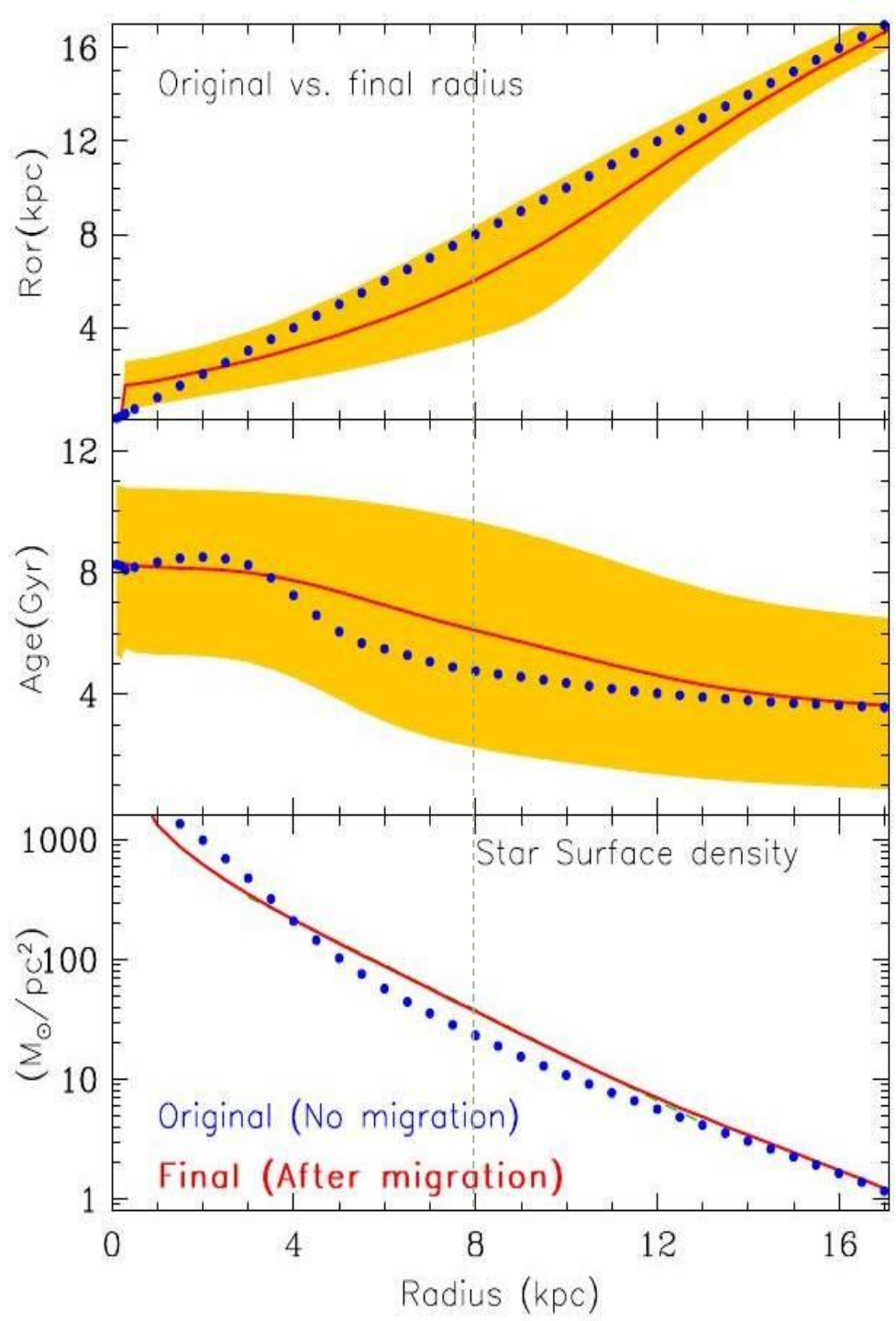
Both effects :

Radial mixing of stars

(Churning much more important than blurring)

Semi-analytical model for the evolution of the MW disk, inspired from N-body+SPH simulations *(Kubryk, NP, Athanassoula 2013, 2015a,b)*





Radial migration affects a large fraction of the disk

In the solar neighborhood it brings stars

mostly from inner regions,, (on average, 1.5 kpc inwards)

mostly older than the locally formed ones (by 1.5 Gyr)

and mostly more metallic than local ones (by 0.15 dex)

SUMMARY : GALACTIC HABITABLE ZONE

GHZ: impossible to define either qualitatively
(probability of creating vs. destroying habitability by various - time and position dependent - factors in the MW disk)
or quantitatively

The more so, since radial migration of stars mixes stellar populations across the MW disk

Also, simple and sea life forms appear to be robust (quasi-immune to cosmic catastrophes)

The concept of GHZ definitively has no explanatory or predictive power
Is it a useless concept?

Perhaps not… it may allow us to structure our thoughts / educated guesses / knowledge about a very complex phenomenon

How philosophical preconceptions can affect physical "theories".

A case in study : G. Gonzalez (*Ball State University, Muncia, Indiana* and *International Society for Complexity, Information and Design* (Intelligent design movement)

We might say, then, that while the Earth is not the physical center of the universe, it seems, paradoxically, that it is the "center" in a more significant sense.

Gonzalez: Yes. If you consider the Earth in the "parameter space" of habitability, then we are very near the "center." Unfortunately, no one else has made this obvious observation. On the contrary, today scientists with anti-religious agendas continue to employ the historically revisionist and empirically discredited metaphysical Copernican Principle as a club to beat down anyone who publicly expresses religious ideas.

These scientists see the extraordinary nature of the Earth as a threat?

Gonzalez: Yes. And they have made public statements denouncing such views as "Pre-Copernican."

How does your work fit into all of this?

Gonzalez: My work, in part, deals with astrobiology from an astronomer's viewpoint. I simply follow the empirical evidence wherever it will lead me, and I try not to let philosophical preconceptions color my interpretations. Over the past decade, I have amassed a body of data that continues to reveal the Earth's uncommon qualities.

And what about our galaxy? Is it extraordinary as well?

Gonzalez: Our galaxy too is atypical. But again, most people are unaware of this, except for a few specialists in extra-galactic astronomy. For example, our galaxy is among the 1 percent most luminous galaxies in the nearby universe.

What effect does luminosity have on the Earth? Why is it important?

Gonzalez: The concentration of heavy elements correlates with the luminosity of a galaxy. More luminous galaxies have more heavy elements, and, thus, are more likely to have Earth-mass planets.

How are others in your field reacting to your arguments? I am assuming that you are challenging scientific orthodoxy, at least in astronomy?

Gonzalez: They don't know what to make of these evidences. They don't deny the data, but they don't quite know how to fit it into their worldviews. A number of my colleagues have congratulated me for my work. Some astronomers who were originally skeptical have moved in my direction as the evidences have continued to accumulate.