

XXI SERBIAN ASTRONOMICAL CONFERENCE | INVITED LECTURE

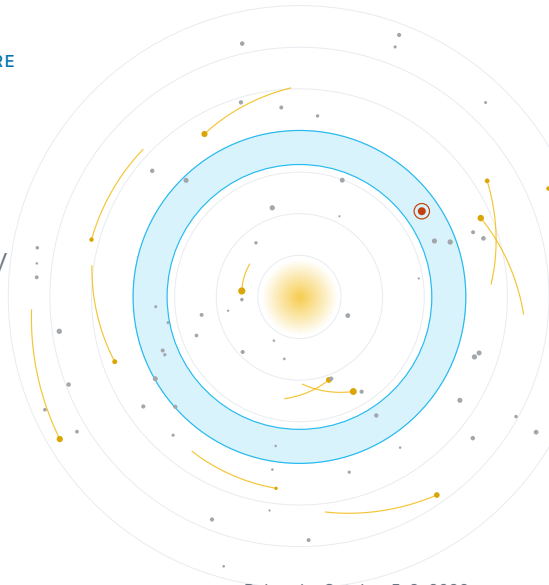
Beyond the Galactic Habitable Zone

A contemporary view of galactic habitability

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The Galactic Habitable Zone: a static annulus

The circumstellar habitable zone, scaled up to a galaxy: the region where

- there are enough **metals** to build terrestrial planets,
- **sterilizing events** (supernovae) are rare enough,
- there has been enough **time** for complex life to evolve.

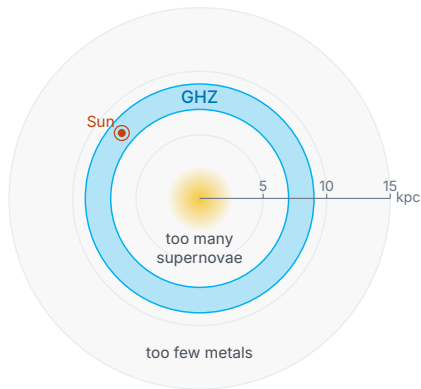
For the Milky Way: an annulus at $R \approx 7\text{--}9\text{ kpc}$, populated by stars born 4–8 Gyr ago and widening with time.

CORE IMPLICIT ASSUMPTIONS

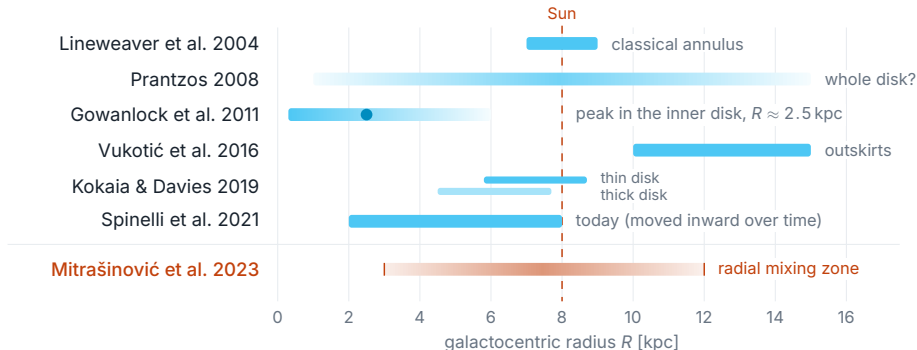
- 1 stars stay where they were born
- 2 chemistry evolves smoothly, in equilibrium
- 3 a present-day snapshot is enough

Gonzalez, Brownlee & Ward 2001, Icarus 152, 185; Lineweaver, Fenner & Gibson 2004, Science 303, 59

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Twenty years of GHZ estimates for the same galaxy



The answer depends on the assumed ingredients and on how the model is built.

Lineweaver et al. 2004; Prantzos 2008, SSRv 135, 313; Gowanlock et al. 2011, AsBio 11, 855; Vukotić et al. 2016, MNRAS 459, 3512; Kokaia & Davies 2019, MNRAS 489, 5165; Spinelli et al. 2021, A&A 647, A41; Mitrašinović et al. 2023, PASA 40, e054

What changed in two decades

01 Simulations

Cosmological and isolated simulations follow assembly, mergers, star formation and chemical enrichment self-consistently, galaxy by galaxy.

Applied to habitability: Vukotić et al. 2016; Forgan et al. 2017; Stanway et al. 2018; Stojković et al. 2019

02 Stellar surveys

APOGEE, Gaia-ESO and Gaia reveal a disk that is dynamically young and perturbed, with stars that **migrate** far from their birth radii.

Hayden et al. 2015, 2018; Antoja et al. 2018; Frankel et al. 2020

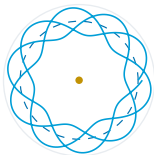
03 Exoplanets

Small planets orbit stars with a wide range of metallicities: the metallicity “threshold” is softer than once assumed.

Buchhave et al. 2012; Wang & Fischer 2015; Padois et al. 2025

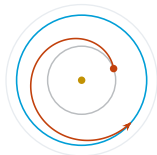
Habitability emerges from chemical evolution, stellar dynamics, star formation history and hazards, and all of them evolve over cosmic time.

Radial migration: blurring and churning



Blurring

orbit becomes eccentric,
guiding radius fixed
(J_R increases)



Churning

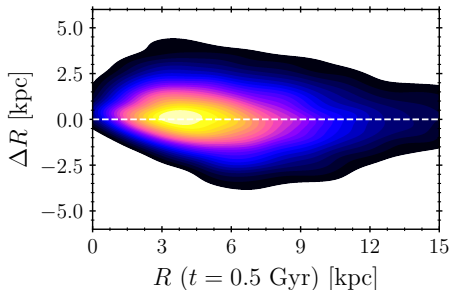
guiding radius changes,
orbit stays circular
(L_z changes)

OUR EXPERIMENT

- Pure N -body Milky Way model: dark halo, exponential disk, bulge (GalactiCs, GADGET-2)
- 2×10^6 particles, evolved for 10 Gyr
- The disk stays **axisymmetric**: no bar, no spiral arms, only mild heating
- 10^4 tracer “stars” mimic the disk; actions (J_R, L_z, J_z) and circularity ξ from AGAMA

A deliberately quiet disk: bars and spirals would only add to the migration we find.

Even a quiet disk mixes

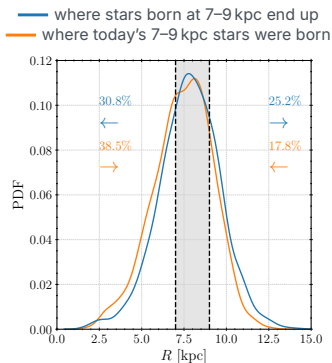


Change in galactocentric radius between 0.5 and 10 Gyr, vs. initial radius

- 54% of stars move outward, 46% inward: a **net outward drift of $\approx 8\%$**
- The largest outward migrations start at $R \approx 4.4$ kpc, the largest inward ones at $R \approx 6.8$ kpc: the central disk is efficiently **mixed**
- ΔR follows $\Delta L_z/L_z$ (Spearman $\rho = 0.40$), barely $\Delta J_R/J_R$ ($\rho = 0.10$), and not J_z : **churning dominates**

No bar or spiral arms needed: mild heating alone redistributes stars over several kpc.

The Solar neighborhood is a crossroads



Within the classical GHZ, $R = 7\text{--}9$ kpc:

- of the stars **born** there, 30.8% end up farther in and 25.2% farther out
- of the stars **living** there today, 38.5% came from the inner disk and only 17.8% from the outer disk
- a quarter of today's residents were born at $R \leq 6.3$ kpc

3–12 kpc

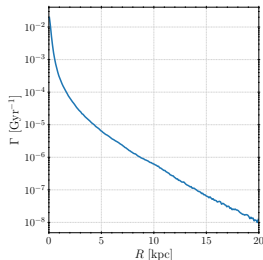
zone of radial mixing that feeds the "GHZ"

The Sun

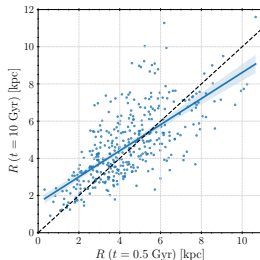
a typical migrant from the metal-rich inner disk, not a rare exception

Mitrašinović et al. 2023, PASA 40, e054; Wielen, Fuchs & Dettbarn 1996, A&A 314, 438; Bird et al. 2012, MNRAS 420, 913; Hayden et al. 2018, A&A 609, A79

Close encounters do not define the inner edge



$$\Gamma = n_* \langle v \rangle \langle \sigma \rangle, \text{ with } \sigma \sim 100 \text{ AU}^2$$



stars evolving onto nearly circular orbits

- $\Gamma(R)$ stays below $\Gamma_{\text{crit}} \simeq 0.22 \text{ Gyr}^{-1}$ (once per age of the Earth) at all radii
- Near the Sun, $\Gamma \sim 10^{-6} \text{ Gyr}^{-1}$, within the range of published estimates
- Even for $\sigma \sim 10^4 \text{ AU}^2$, the inner edge moves only to $R \approx 1 \text{ kpc}$
- Stars settling onto circular orbits mostly migrate **outward** (net 11.5%)

Dynamically, the inner disk is not excluded: encounters matter locally, not for limiting GHZ boundaries.

Mitrašinović et al. 2023, PASA 40, e054; Laughlin & Adams 2000, Icarus 145, 614; Sloan et al. 2017, SciRep 7, 5419; Bojnordi Arbab & Rahvar 2021, IJMPD 30, 2150063

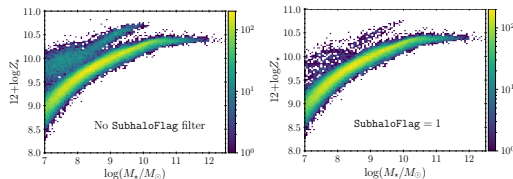
A second peak of habitability? Not quite

GALAXY-SCALE PROXY

$N_p \propto M_\star^2 Z^\alpha / \text{SFR}$ favors massive, metal-rich, quiescent galaxies. In Illustris, a “Cloudlet” of metal-rich dwarfs hinted at a second peak (Stojković et al. 2019).

REVISITED IN ILLUSTRIS-TNG

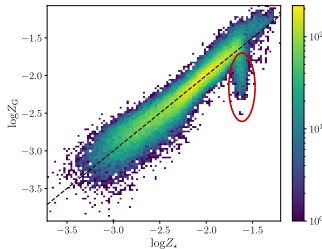
- the Cloudlet is dominated by **non-cosmological** subhalos
- of 616 metal-rich dwarfs, only **97** formed early; 461 appear only at $z = 0$
- genuine ones are compact, **tidally stripped** remnants (most keep $< 5\%$ of their peak mass)



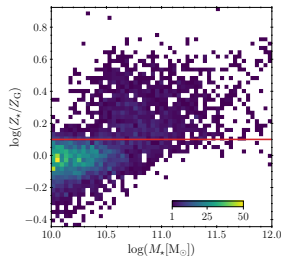
stellar mass–metallicity plane: all subhalos (left)
vs. genuine galaxies only (right)

The bimodality fades under closer scrutiny:
simulated outliers need history-aware
vetting.

Stars and gas can decouple



first hint (PASA 2025): metal-rich stars,
diluted gas



red line: ratio of the asymptotic
stellar and gas MZR levels

4718

massive ($M_* \geq 10^{10} M_\odot$) star-forming
TNG100 galaxies at $z = 0$

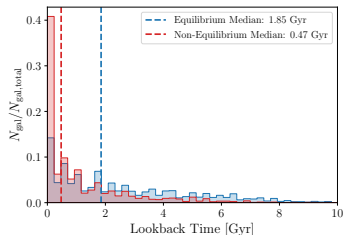
31.5%

chemically decoupled, with
 $\log(Z_*/Z_G) > 0.1$

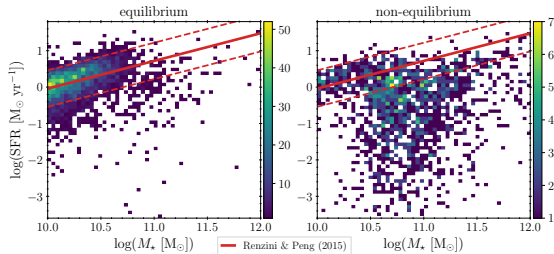
The gas-phase MZR saturates ~ 0.1 dex
below the stellar one: Z_G no longer traces
 Z_* .

In about one in three massive star-forming galaxies, a metal-rich stellar population coexists with a diluted gas reservoir.

Decoupling marks a post-merger, partly quenched phase



time since the last merger, any mass ratio



equilibrium (left) and decoupled (right) galaxies vs. the star-forming main sequence

0.47 Gyr

median time since the last merger
(1.85 Gyr for equilibrium galaxies)

45 vs 19

median number of mergers; major
mergers are similar in both

Below the SFMS

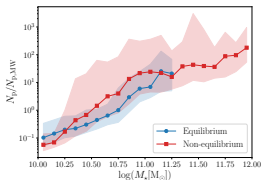
lower SFRs and gas fractions:
a green-valley-like transition

Mitrašinović et al. 2026, *A&A* 710, A257; Rodriguez-Gomez et al. 2017, *MNRAS* 467, 3083; Renzini & Peng 2015, *ApJL* 801, L29; Bustamante et al. 2018, *MNRAS* 479, 3381

The habitability trade-off

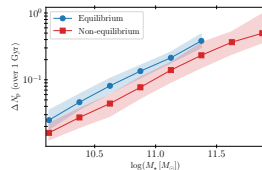
$$\frac{N_p}{N_{p,MW}} = \left(\frac{M_\star}{M_{\star,MW}} \right)^2 \left(\frac{Z_G}{Z_{MW}} \right) \left(\frac{SFR_{MW}}{SFR} \right)$$

TODAY: MORE PLANETS, FEWER HAZARDS



Median $N_p/N_{p,MW}$: **8.6** vs **0.22** ($\approx 40\times$), and still $2-4\times$ higher at fixed $M_\star \gtrsim 10^{10.5} M_\odot$

NEXT GYR: FEWER NEW PLANETS

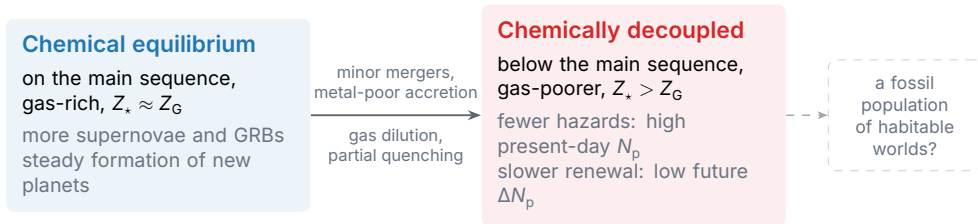


Planets added in 1 Gyr at constant SFR and Z_G : **lower** for decoupled galaxies at every stellar mass

The processes that suppress future terrestrial planet formation also suppress radiation hazards for planets that already exist.

Mitrašinović et al. 2026, A&A 710, A257; Dayal et al. 2015, ApJL 810, L2 (proxy, here with $\alpha = 1$ and gas-phase Z)

Habitability is a phase, not a property



A LOCAL ANALOG: M31

More massive than the Milky Way ($\log M_{\star}/M_{\odot} \approx 11$), well below the main sequence ($\text{SFR} \approx 0.2\text{--}0.4 M_{\odot} \text{ yr}^{-1}$), with a rich accretion history that includes a major merger $\sim 2\text{--}3$ Gyr ago.

Galaxies leaving their peak star-forming phase are a key demographic for galaxy-scale habitability.

How much of the classical GHZ survives?

Survives, as ingredients

- Metallicity matters for building terrestrial planets, with a softer threshold
- Sterilizing events scale with star formation
- The host galaxy is the right context for habitability
- The disk around the Sun is habitable, and our Solar System is typical

Does not survive, as assumptions

- **Sharp boundaries:** radial mixing spans $R \approx 3\text{--}12$ kpc
- **Stars stay put:** birth radius $\neq$ present radius
- **Equilibrium chemistry:** Z_G fails to trace Z_* in $\sim 1/3$ of massive star-forming galaxies
- **One snapshot:** the same galaxy ranks high now and low for the future
- **Outliers at face value:** simulated populations need history-aware information

Toward a time-dependent view of galactic habitability

Habitability as an **emergent, time-dependent property** of galaxy assembly and internal evolution → it is **not** a zone on a map.

ORBITS

Stars, not annuli

birth radius, migration, circularization and vertical motions

CHEMISTRY

Two reservoirs

stars and gas tracked separately: enrichment, dilution...

ASSEMBLY

The time

mergers, accretion and quenching set when a galaxy is favorable

ENVIRONMENT

Beyond the disk

satellites, flybys, clusters, compact remnants and tidal debris

OPEN QUESTIONS

- **Which habitability?** Emergence, persistence and spread of life may favor different environments
- **Which tools?** Cosmological, zoom-in and isolated simulations; Gaia-era surveys and exoplanet demographics (JWST, Roman, PLATO...)

KEY TAKEAWAYS

- 1 **Stars move.** Radial mixing over $R \approx 3\text{--}12$ kpc blurs any sharp GHZ; the Sun is a typical *migrant*.

Mitrašinović, Vukotić, Micic & Ćirković 2023, PASA 40, e054

- 2 **Outliers need scrutiny.** The “Cloudlet” bimodality fades under history-aware selection.

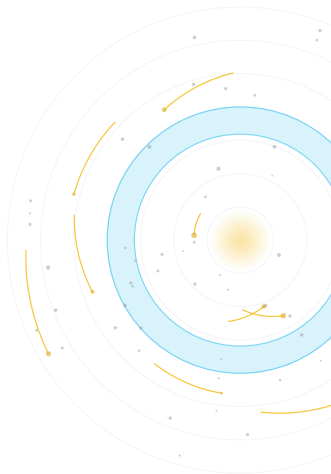
Mitrašinović, Vukotić, Žižak, Micic & Ćirković 2025, PASA 42, e066

- 3 **Chemistry evolves.** Decoupled galaxies trade future planet formation for fewer present-day hazards.

Mitrašinović, Pavlov, Vukotić & Milošević 2026, A&A 710, A257

Thank you!

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