Chemical evolution models with Gaia DR3

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INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

ifpU

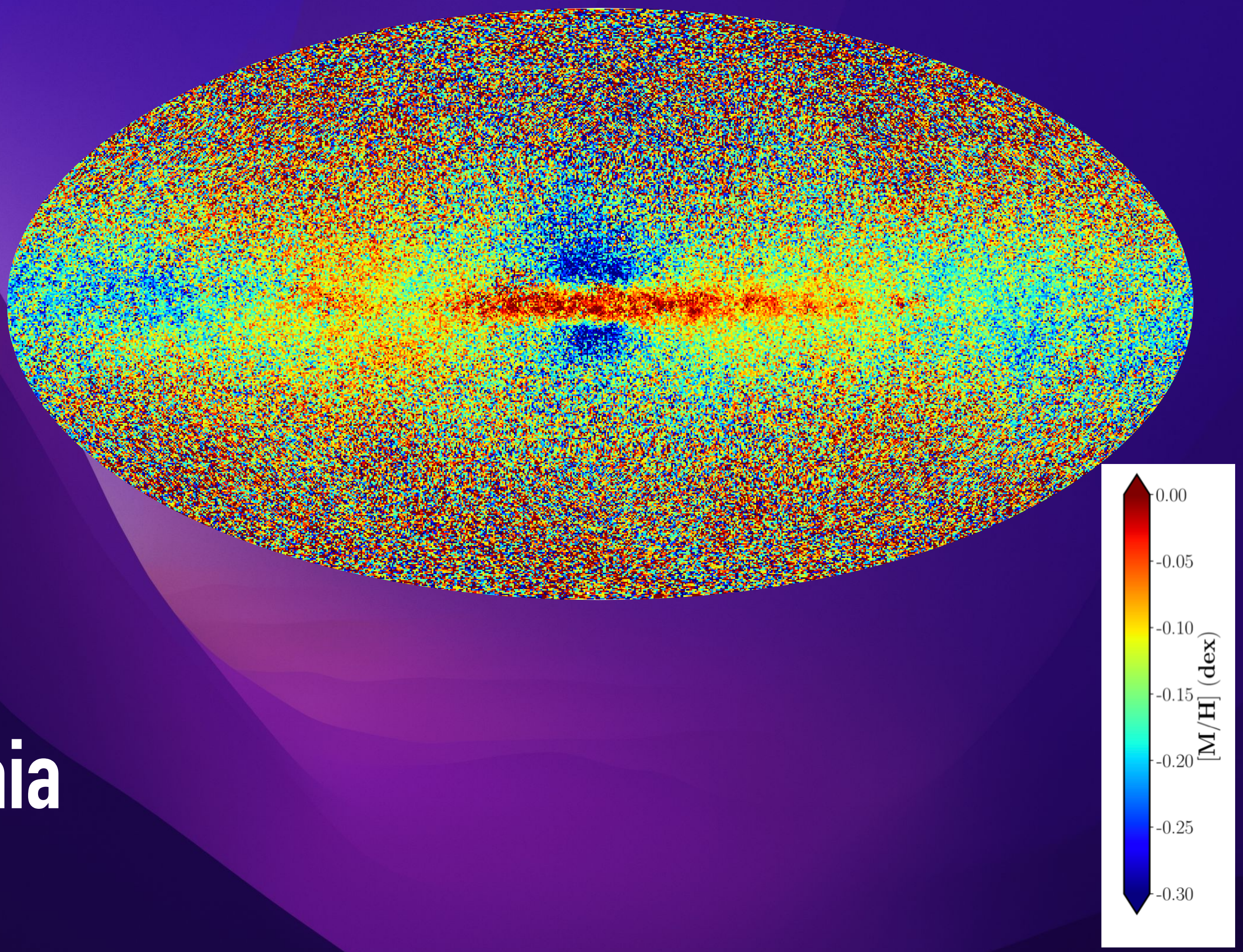
Focus week "Galactic Archaeology: reconstructing the history of galaxies"

Gaia DR3

- Gaia DR3 has brought a truly and unprecedented revolution opening a new era of all-sky spectroscopy and chemo-physical characterisation of Galactic stellar populations

- About 5.6 million stars with chemical abundances with Gaia DR3 GSP-Spec module (R ∼11 500)

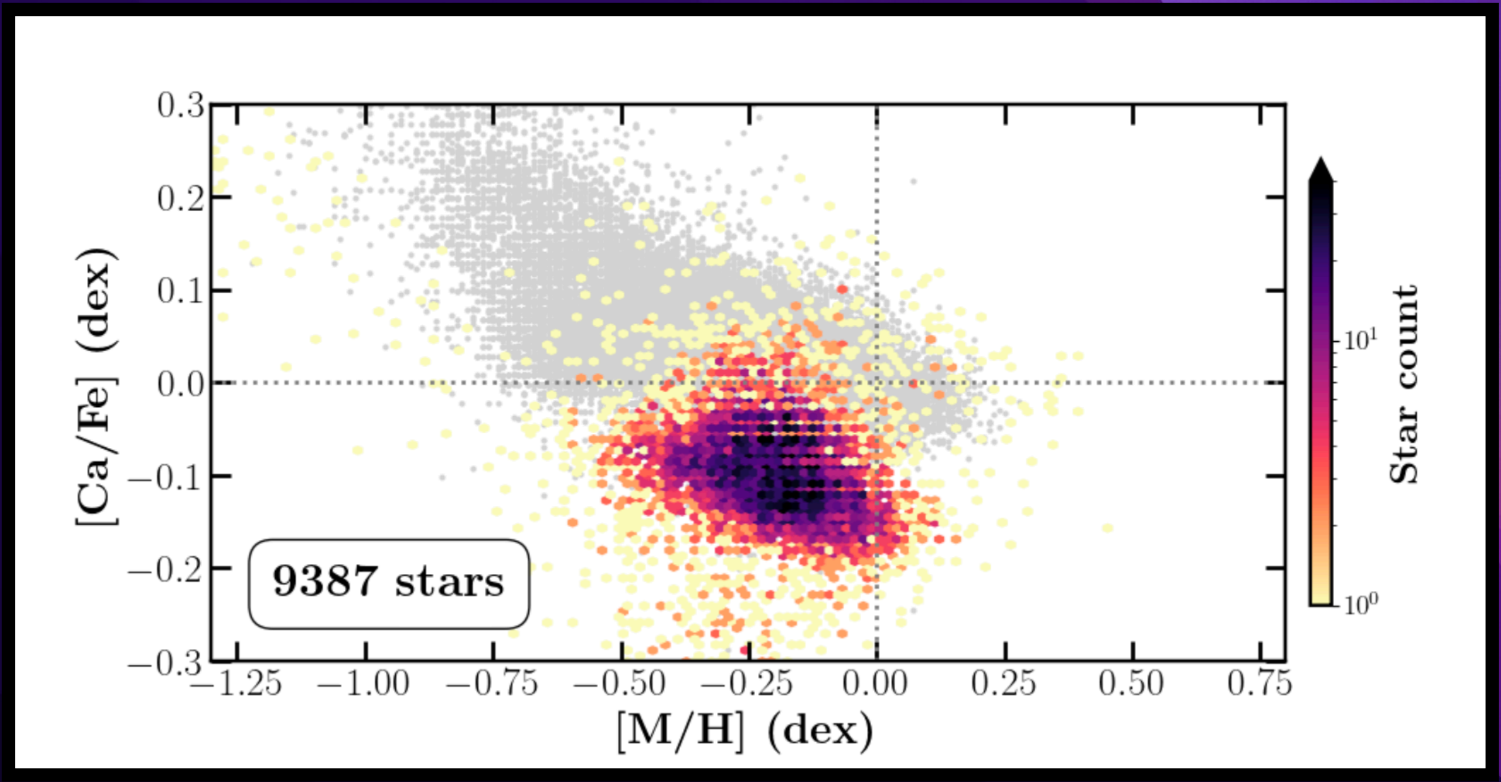
Stellar metallicity

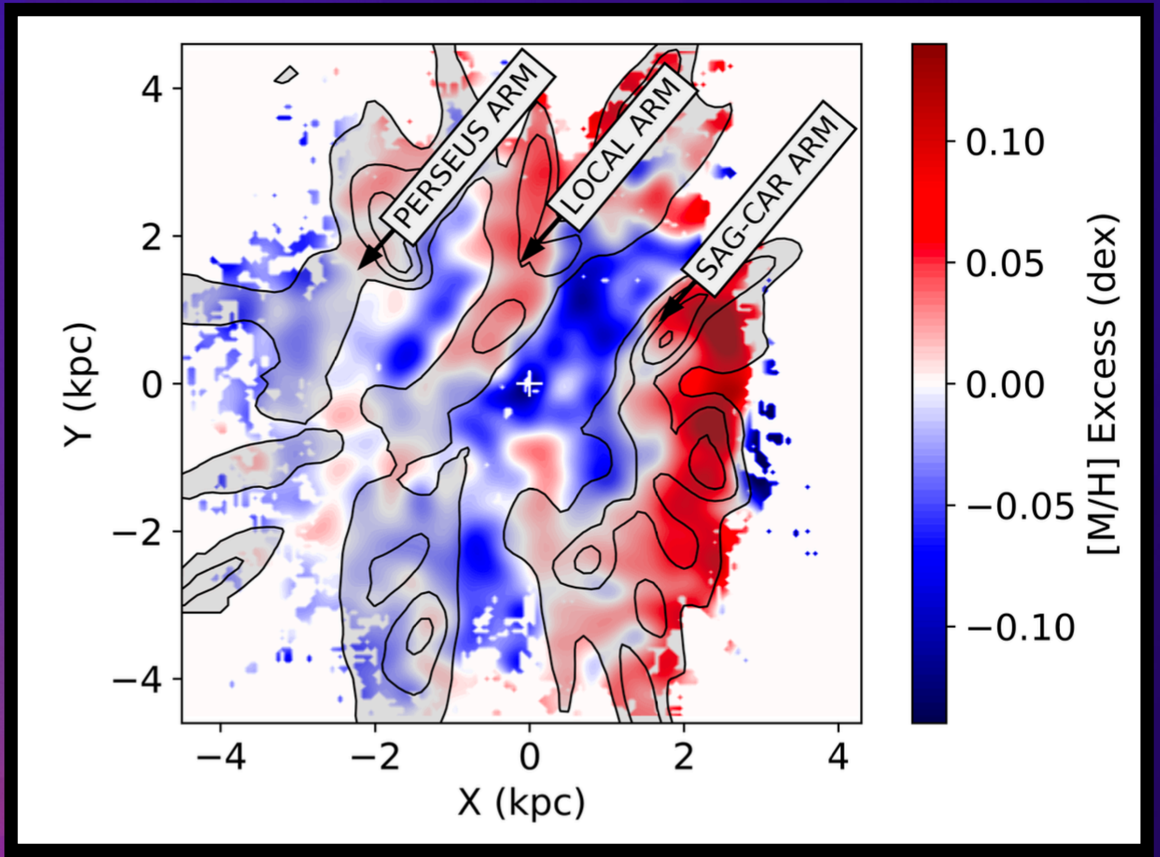


Main motivations:

2) Spiral arm signatures

1) Recent chemical impoverishment in several Gaia DR3 elements



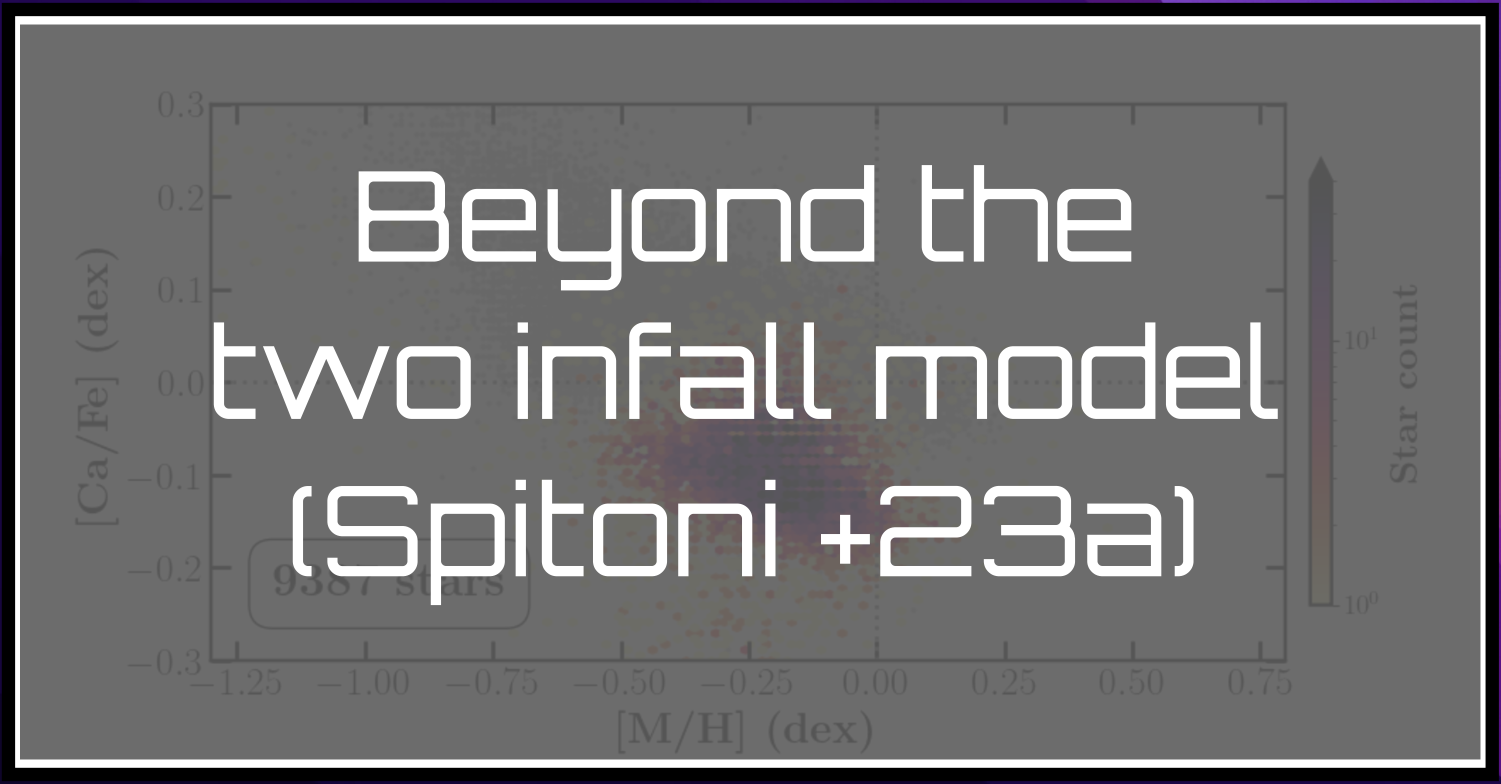


Poggio et al.+ES 22

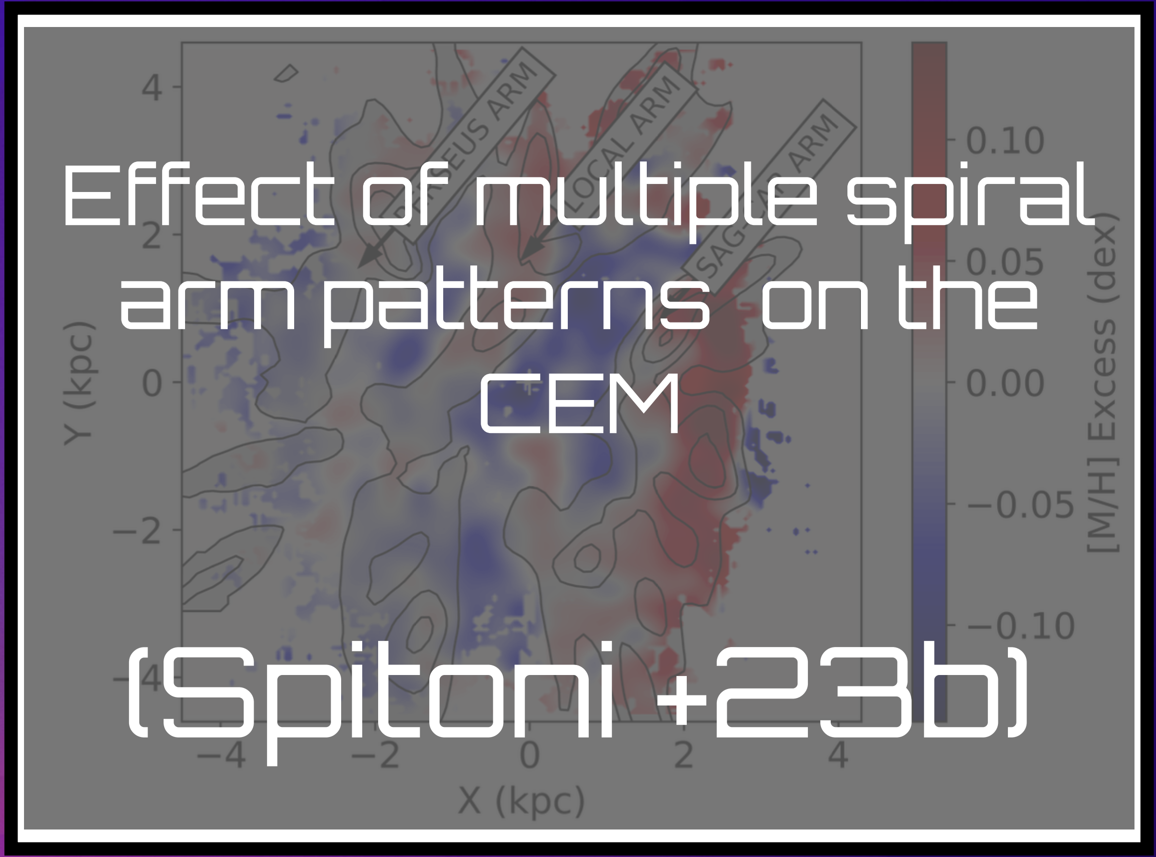
Gaia Collaboration, Recio Blanco +23

Main motivations:

1) Recent chemical impoverishment in several Gaia DR3 elements



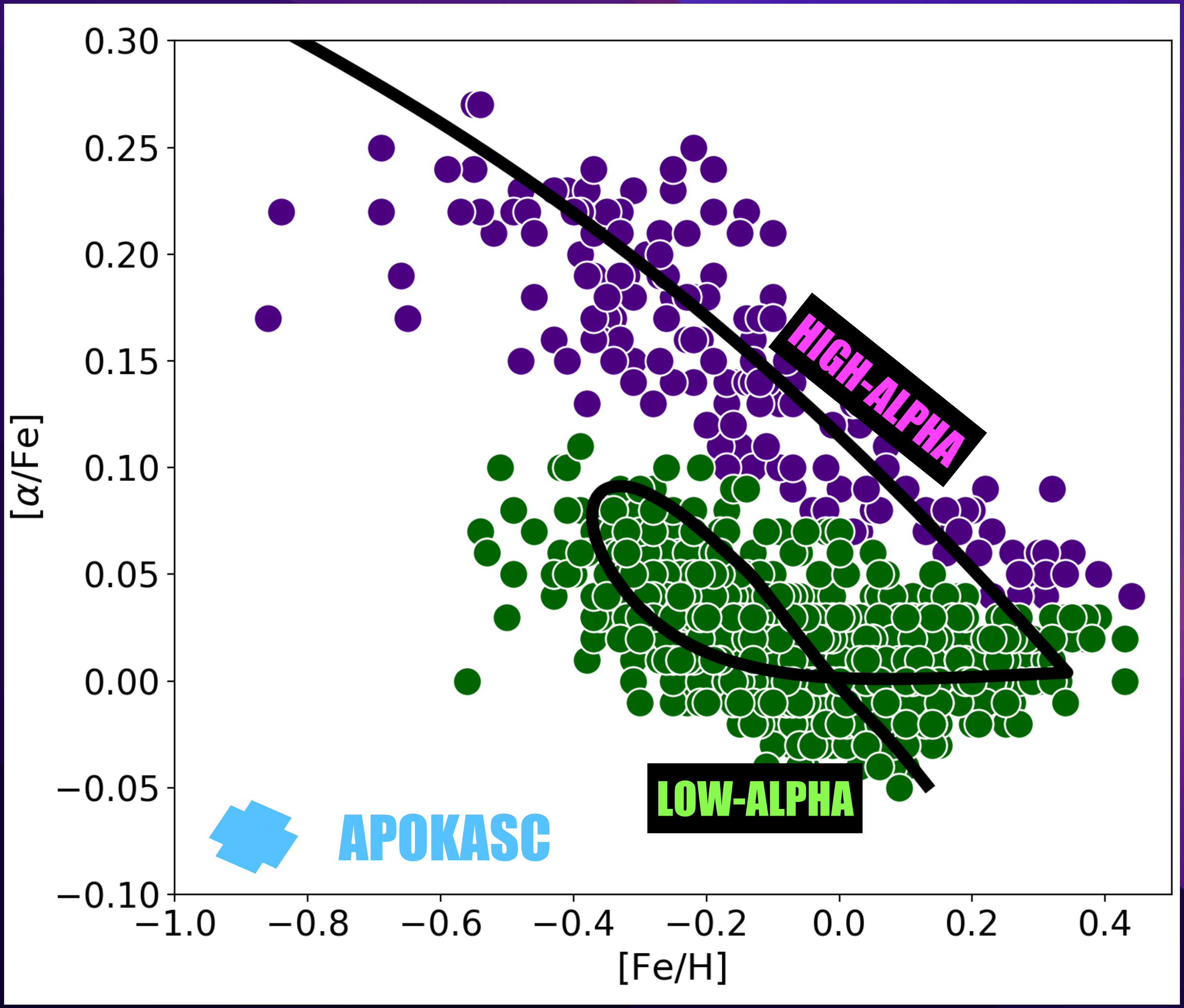
2) Spiral arm signatures

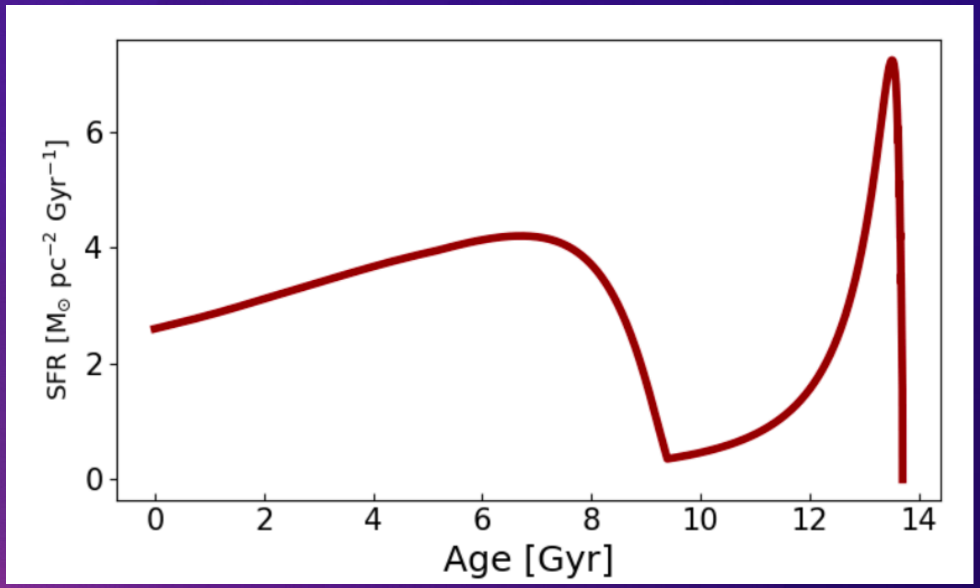


The two-infall model

(see Valeria's talk)

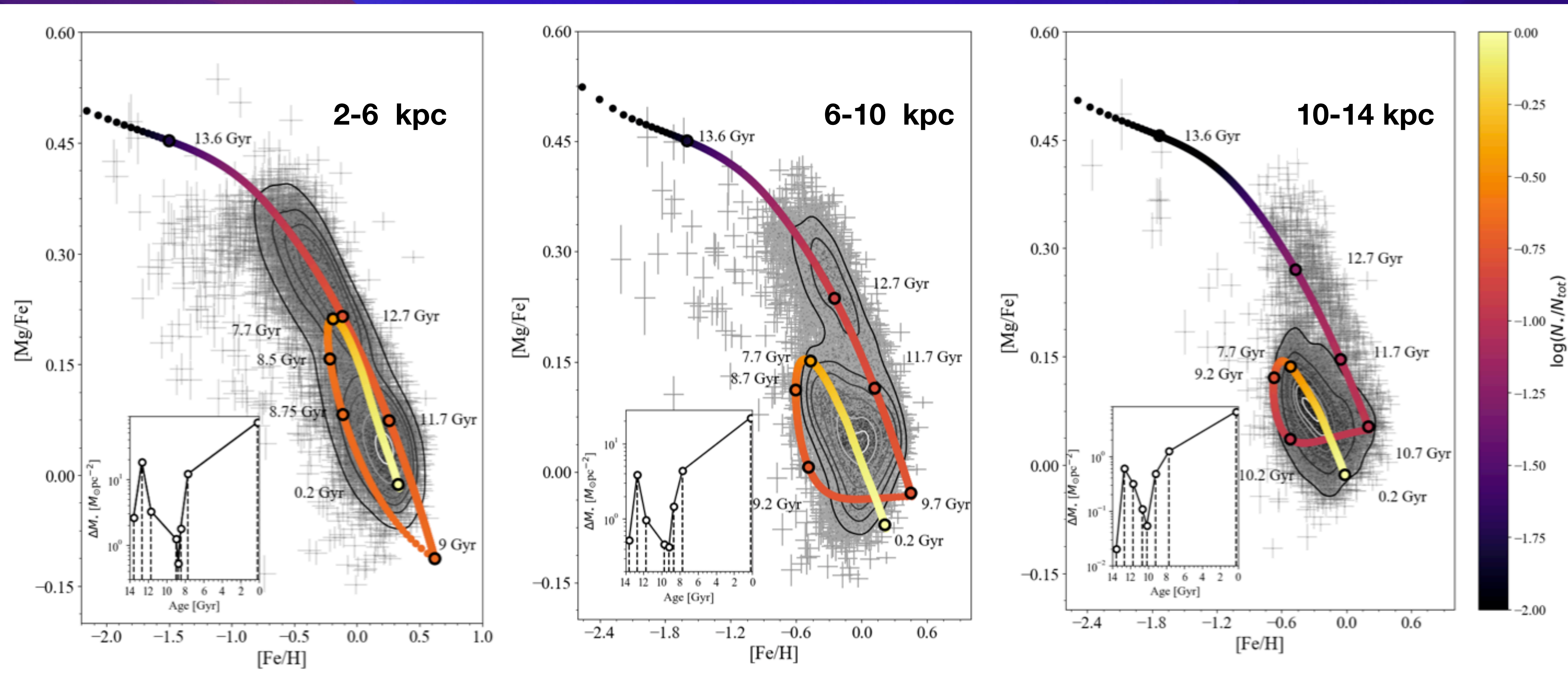
a) Solar Vicinity





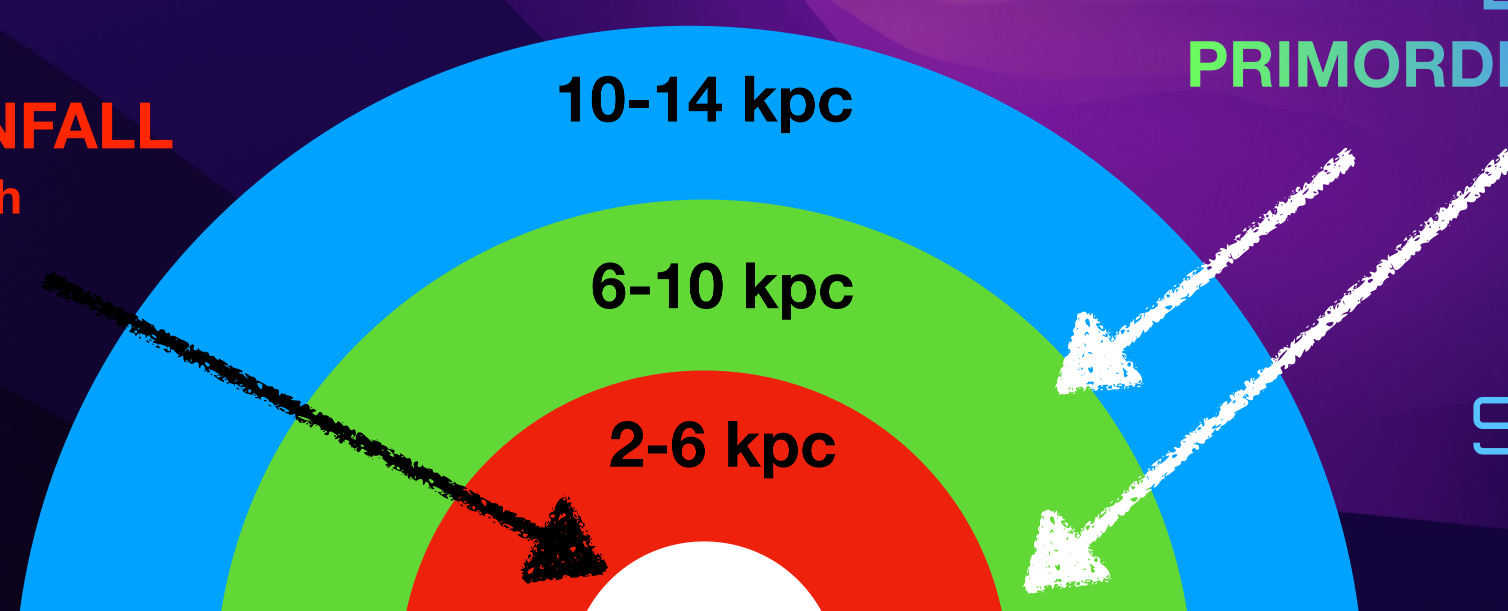
Spitoni +19a,+20

b) The whole Galactic disc



LOW-α
ENRICHED GAS INFALL
(in agreement with
Palla+20,
Agertz+21)

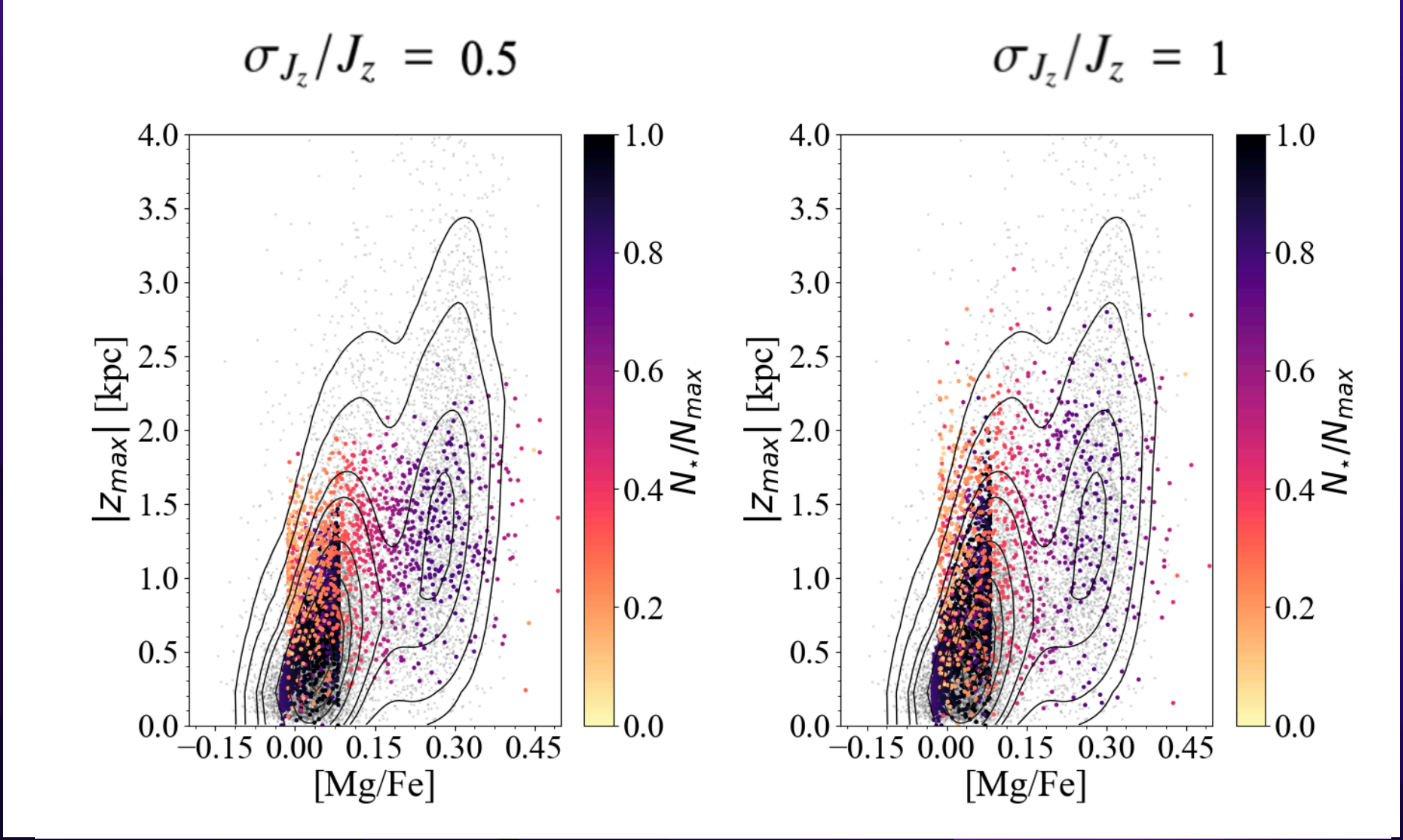
LOW-α
PRIMORDIAL GAS INFALL



Spitoni +21

c) The vertical distribution

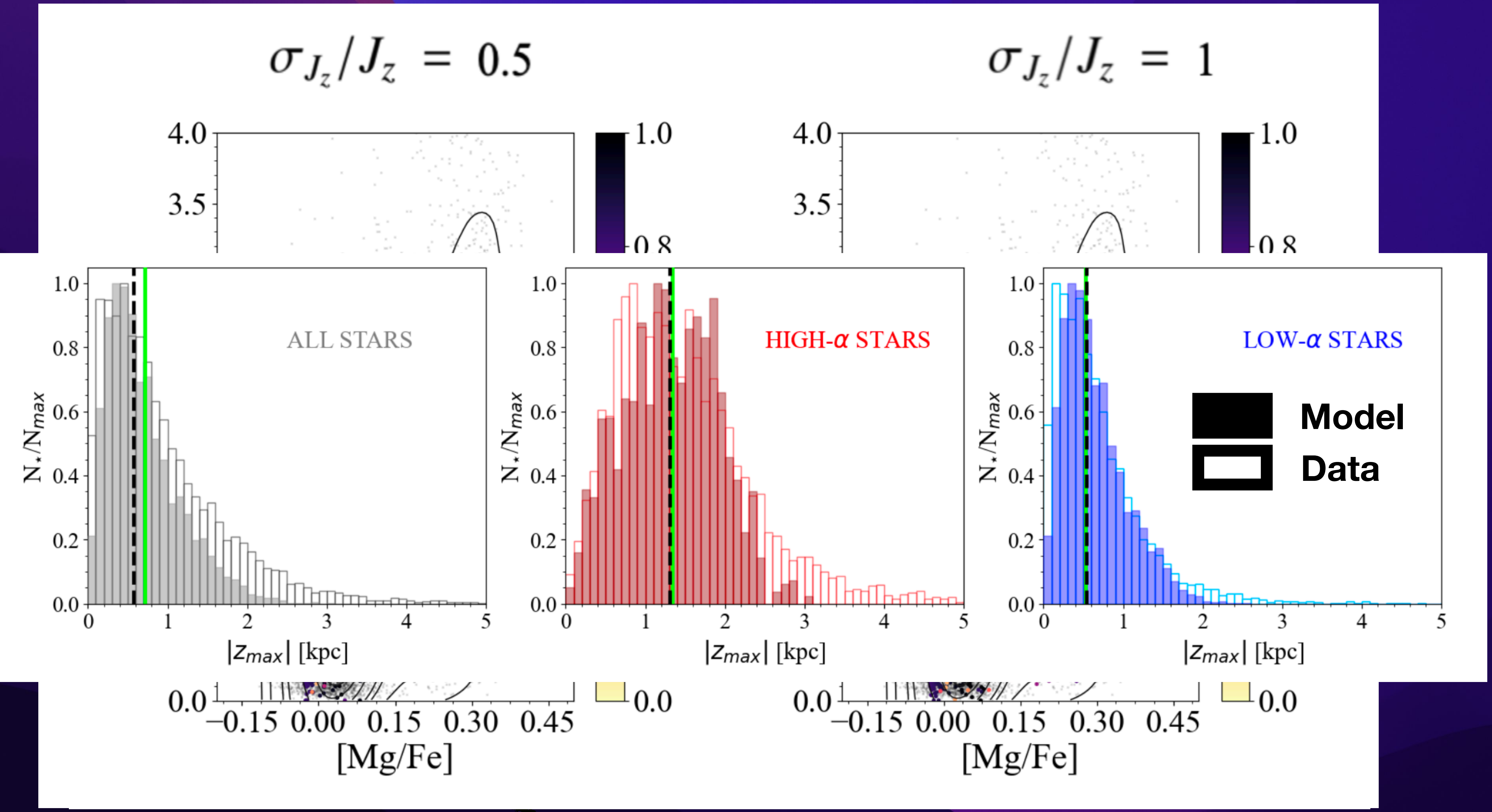
(using the Jz vs. Age rel. by Ting & Rix 19)



Spitoni +22

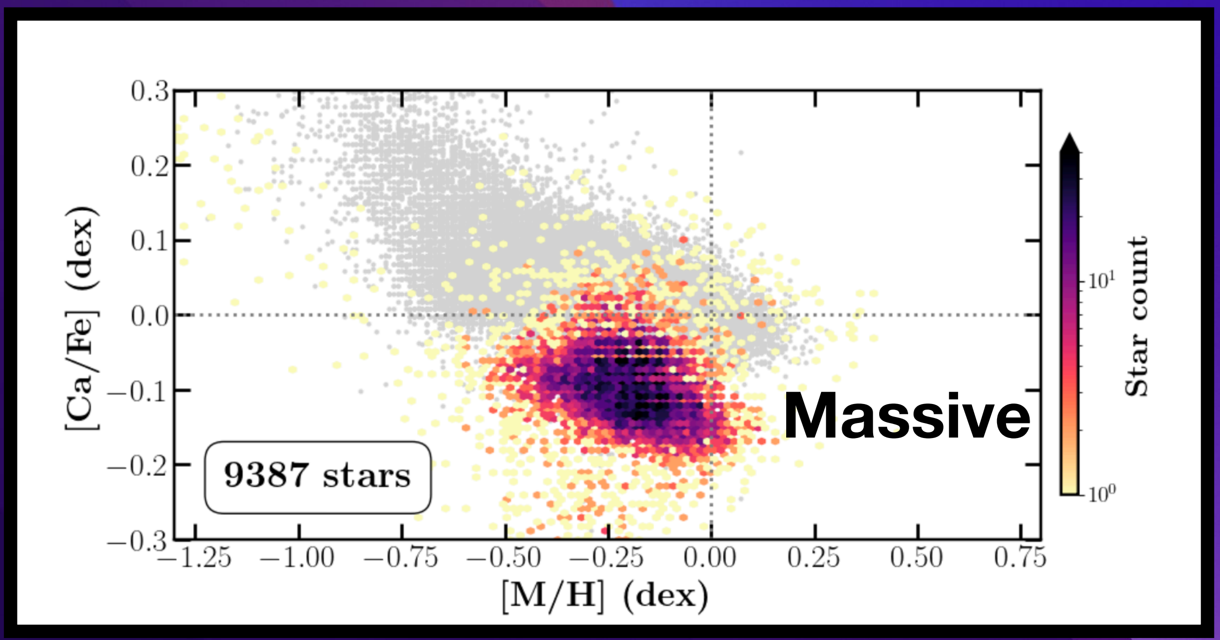
c) The vertical distribution

(using the Jz vs. Age rel. by Ting & Rix 19)



Spitoni +22

Massive stars population

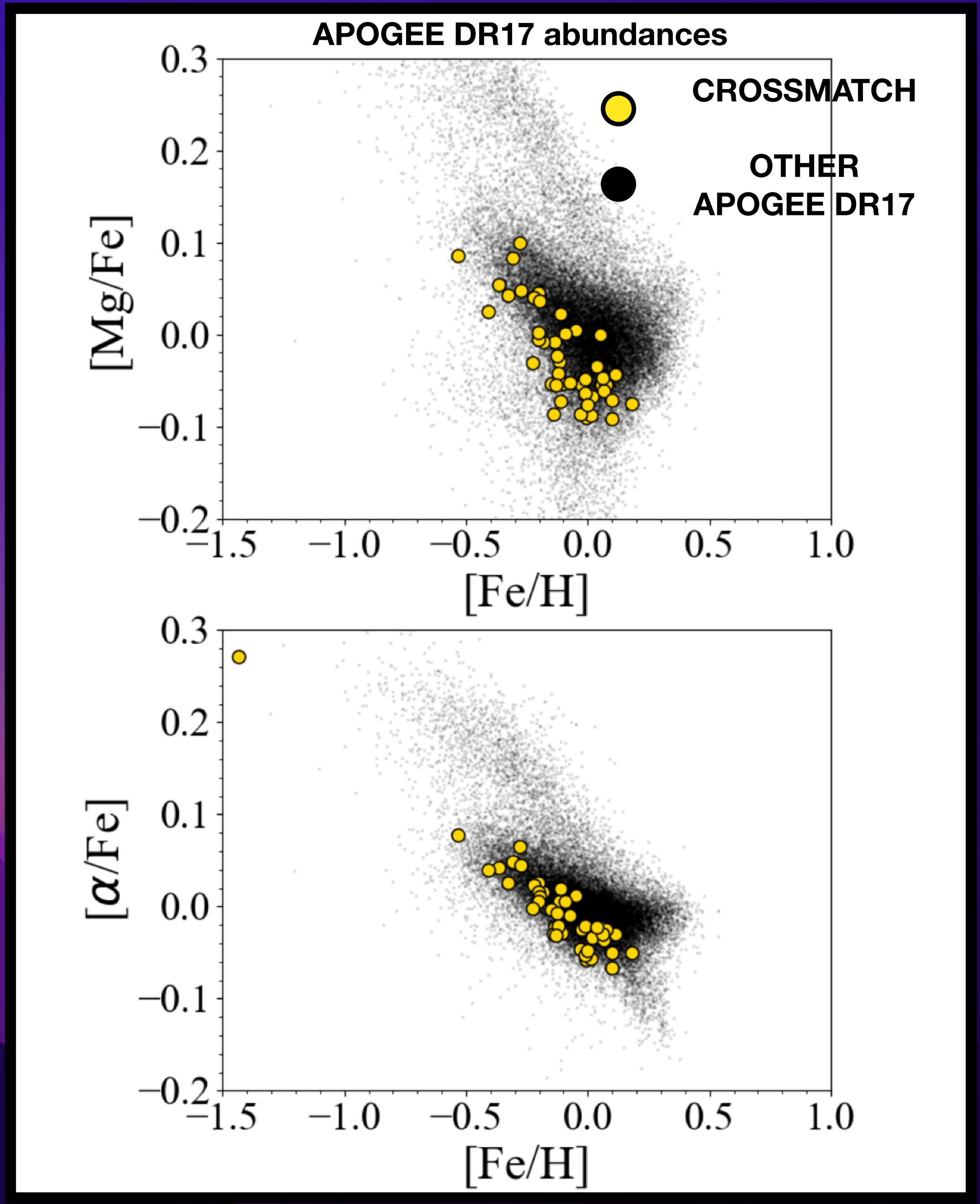


Gaia Collaboration, Recio Blanco +22

All the cross-matched stars are part of the low-α sequence in APOGEE DR17 and the majority of them present sub-solar values in metallicity.

● CROSSMATCH APOGEE DR17

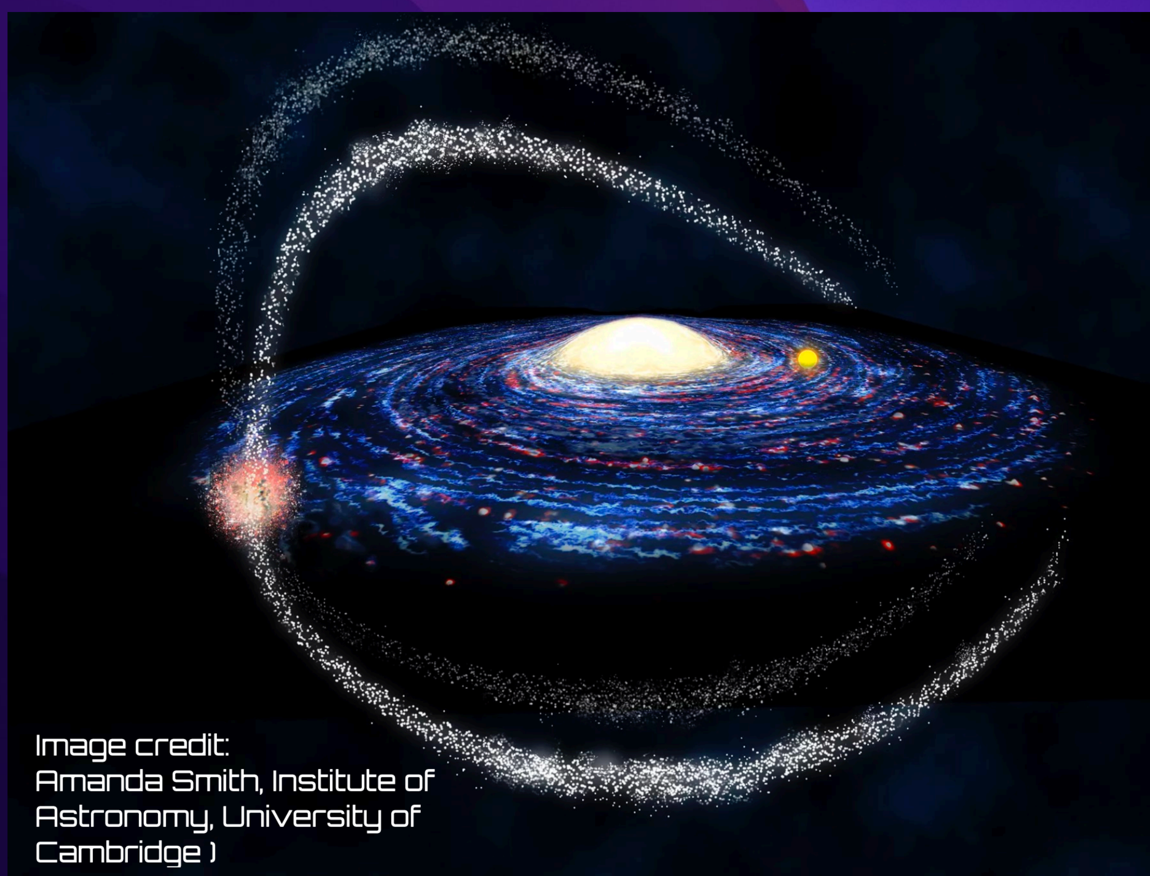
Abdurro'uf et al. (2022)

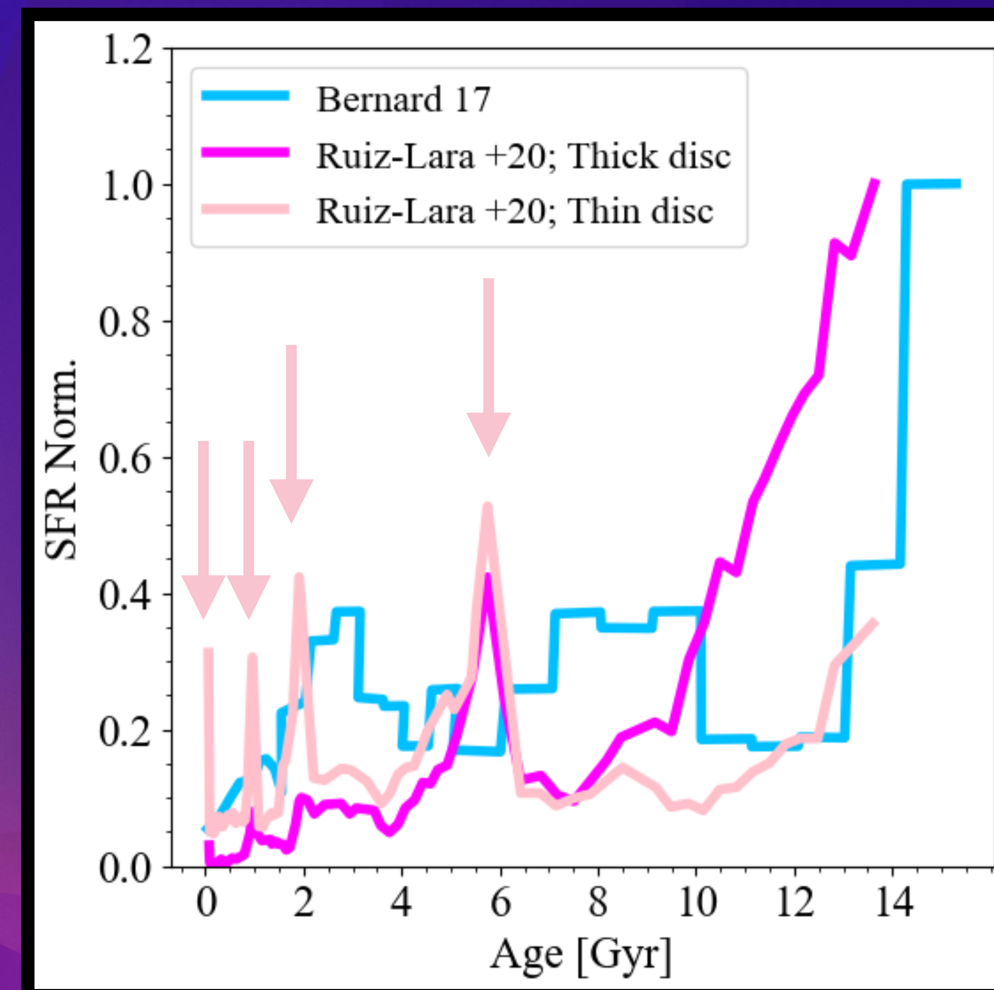


Spitoni +23a

Beyond the two infall model (Spitoni +23a)

Star formation history



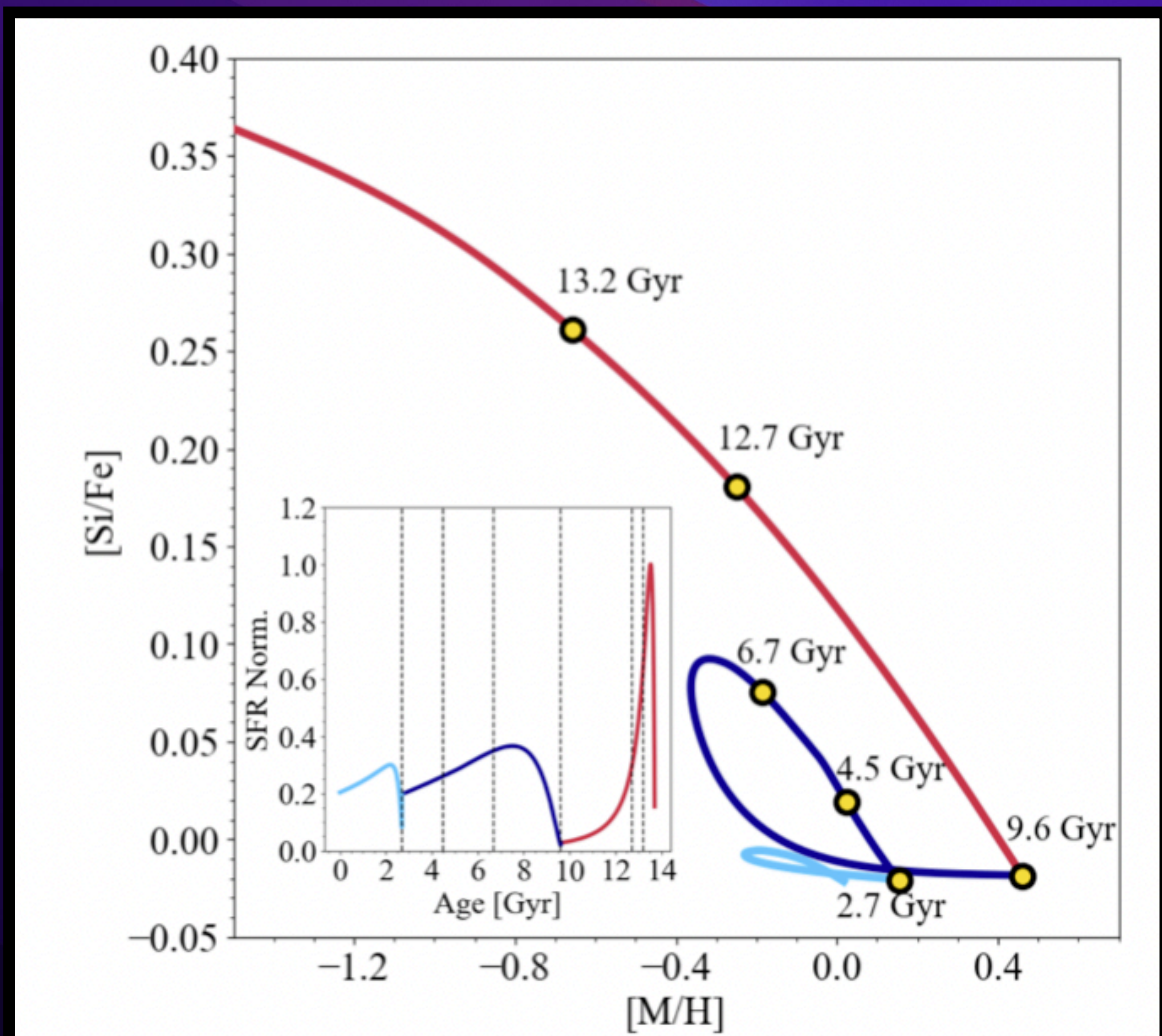


Sagittarius dwarf spheroidal galaxy pericentre passages which triggered formation of new stars in the Galactic disc.

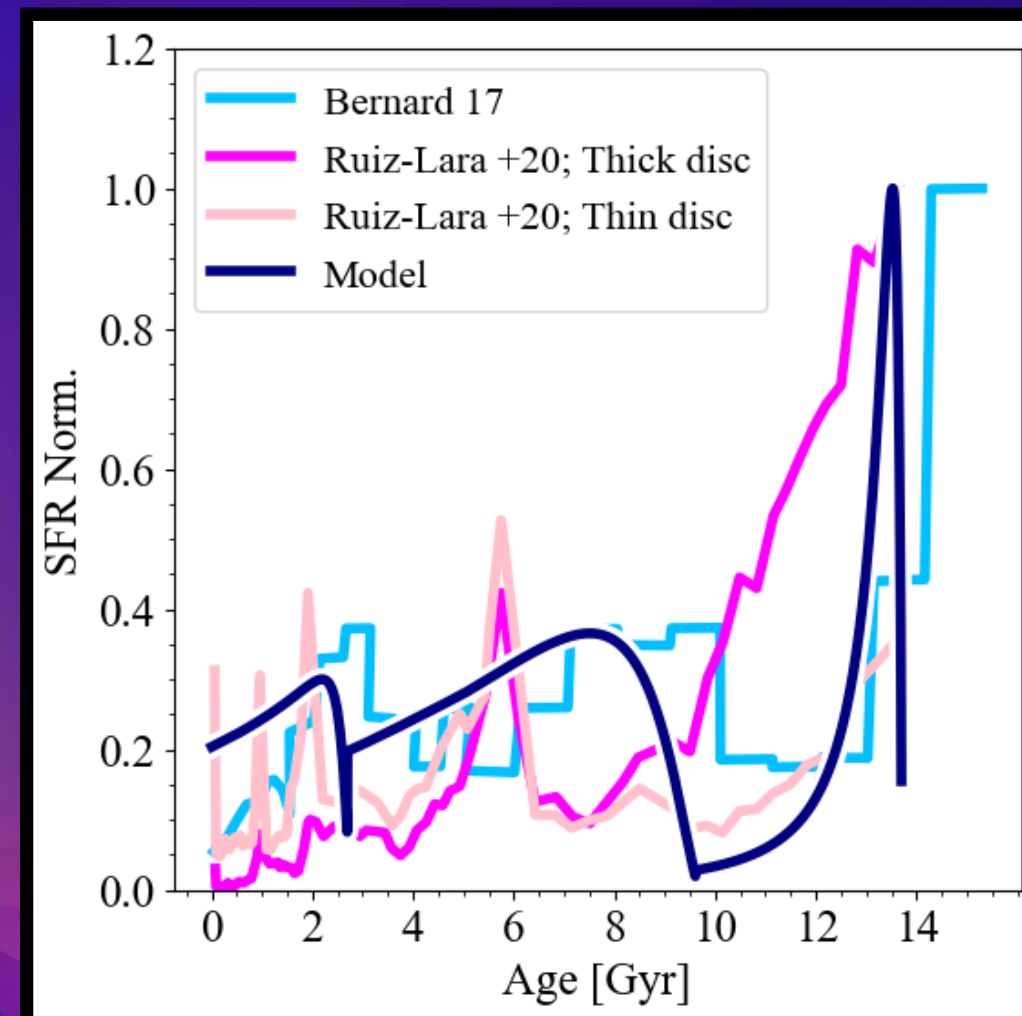
Gaia DR2 and DR1

http://staff.astro.lu.se/~florent/vintergatan.php

Beyond the two infall model (Spitoni +23a)

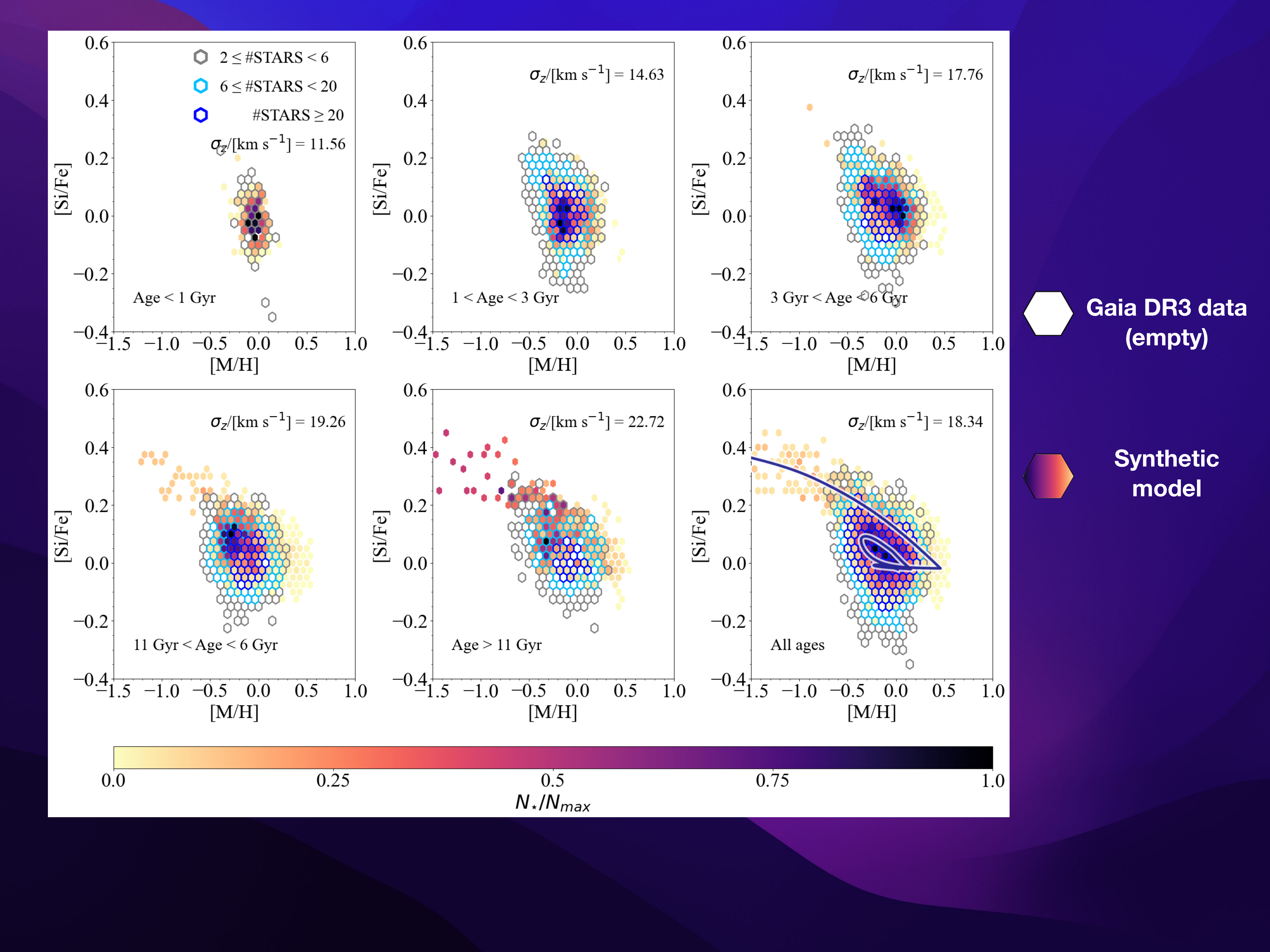


Star formation history

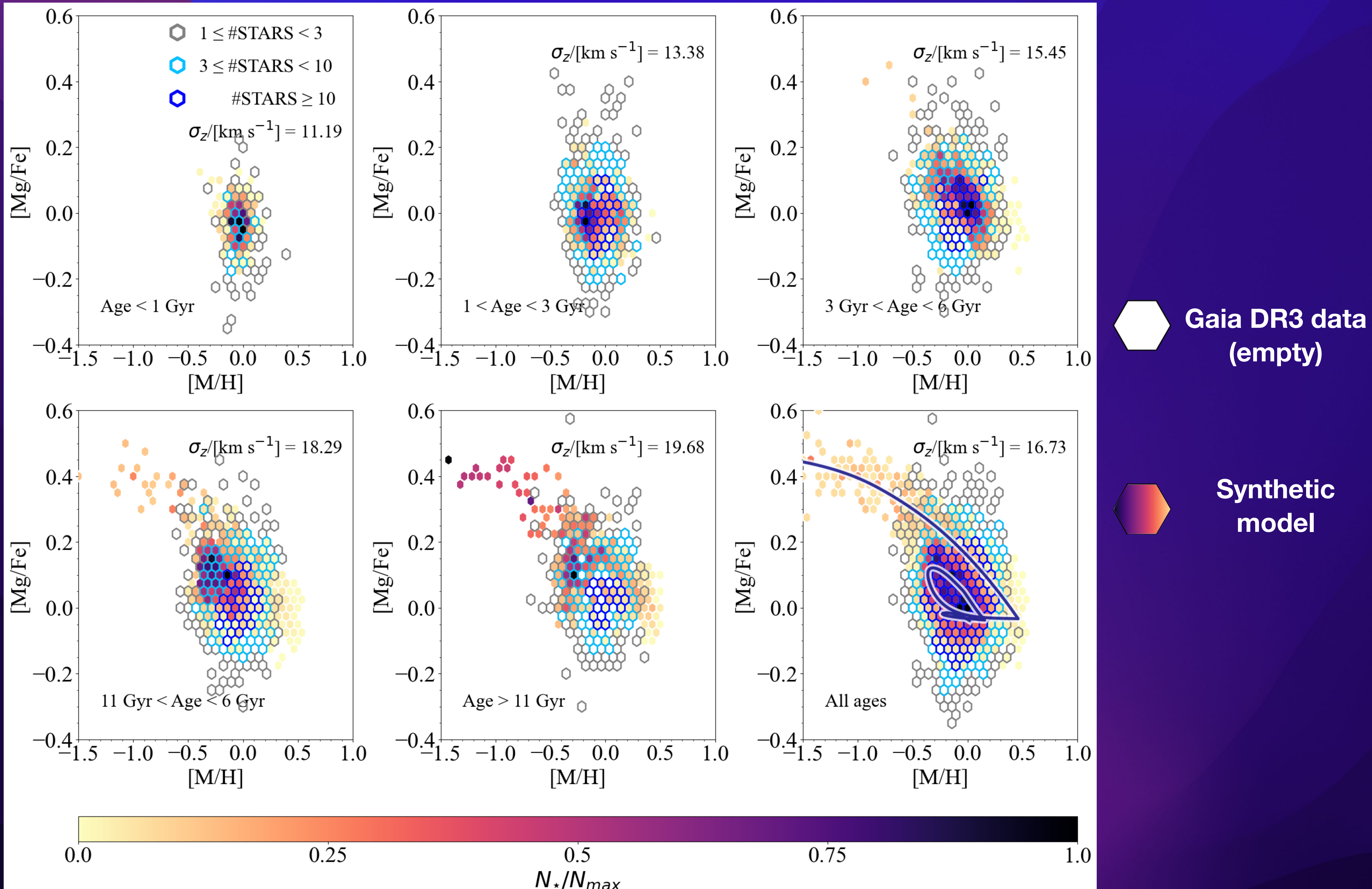


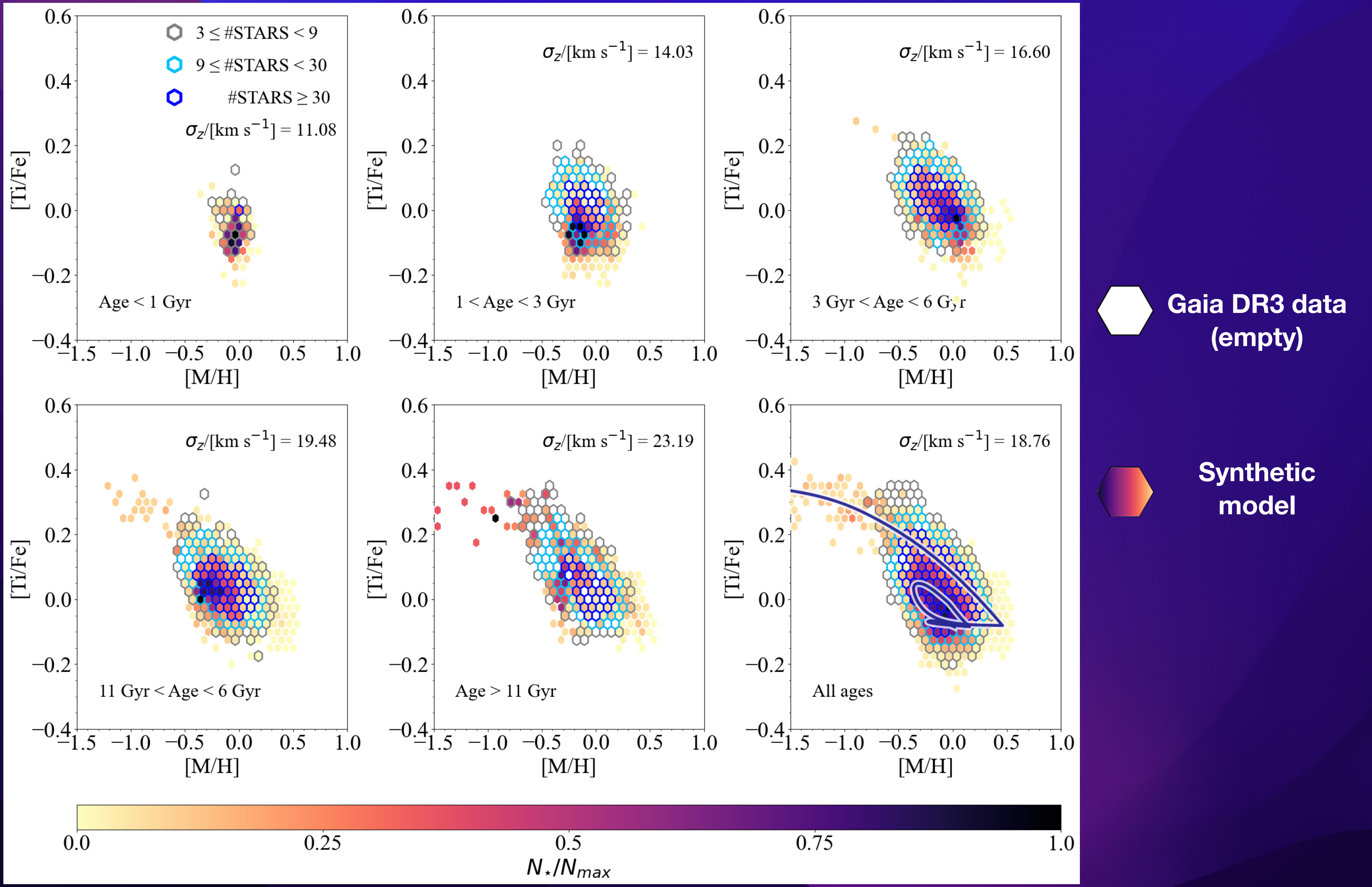
Gaia DR2 and DR1

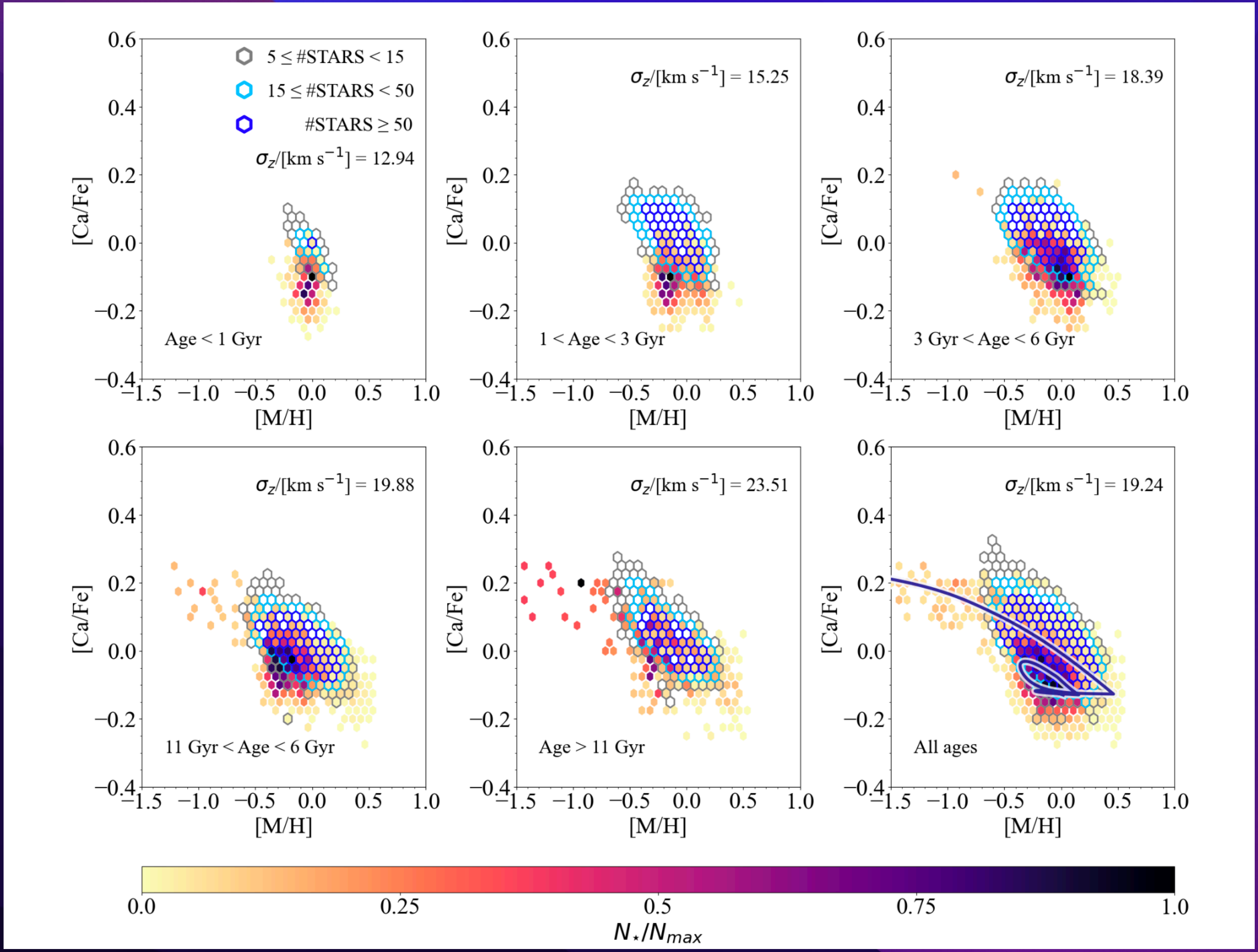
http://staff.astro.lu.se/~florent/vintergatan.php



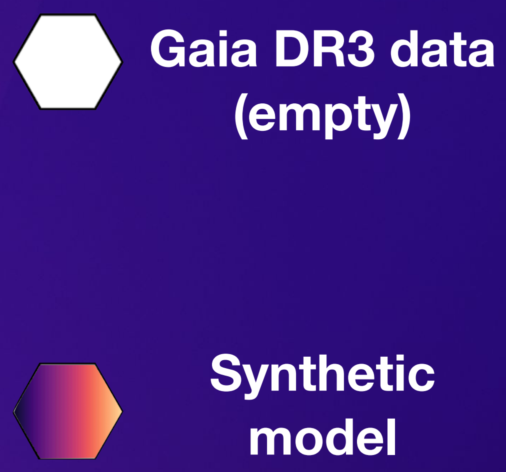
2 ≤ #STARS < 6
6 ≤ #STARS < 20
#STARS ≥ 20
σ_z/[km s^{-1}] = 11.56
Age < 1 Gyr
σ_z/[km s^{-1}] = 14.63
1 < Age < 3 Gyr
σ_z/[km s^{-1}] = 17.76
3 Gyr < Age < 6 Gyr
σ_z/[km s^{-1}] = 19.26
11 Gyr < Age < 6 Gyr
σ_z/[km s^{-1}] = 22.72
Age > 11 Gyr
σ_z/[km s^{-1}] = 18.34
All ages
[Si/Fe]
[M/H]
$N_\star/N_{max}$
Gaia DR3 data (empty)
Synthetic model


1 ≤ #STARS < 3
3 ≤ #STARS < 10
#STARS ≥ 10
σz/[km s−1] = 11.19
Age < 1 Gyr
σz/[km s−1] = 13.38
1 < Age < 3 Gyr
σz/[km s−1] = 15.45
3 Gyr < Age < 6 Gyr
σz/[km s−1] = 18.29
11 Gyr < Age < 6 Gyr
σz/[km s−1] = 19.68
Age > 11 Gyr
σz/[km s−1] = 16.73
All ages
[Mg/Fe]
[M/H]
N⋆/Nmax
Gaia DR3 data (empty)
Synthetic model


3 ≤ #STARS < 9
9 ≤ #STARS < 30
#STARS ≥ 30
σz/[km s−1] = 11.08
Age < 1 Gyr
σz/[km s−1] = 14.03
1 < Age < 3 Gyr
σz/[km s−1] = 16.60
3 Gyr < Age < 6 Gyr
σz/[km s−1] = 19.48
11 Gyr < Age < 6 Gyr
σz/[km s−1] = 23.19
Age > 11 Gyr
σz/[km s−1] = 18.76
All ages
[Ti/Fe]
[M/H]
N⋆/Nmax
Gaia DR3 data (empty)
Synthetic model



5 ≤ #STARS < 15
15 ≤ #STARS < 50
#STARS ≥ 50
σz/[km s−1] = 12.94
Age < 1 Gyr
σz/[km s−1] = 15.25
1 < Age < 3 Gyr
σz/[km s−1] = 18.39
3 Gyr < Age < 6 Gyr
σz/[km s−1] = 19.88
11 Gyr < Age < 6 Gyr
σz/[km s−1] = 23.51
Age > 11 Gyr
σz/[km s−1] = 19.24
All ages
[Ca/Fe]
[M/H]
N⋆/Nmax

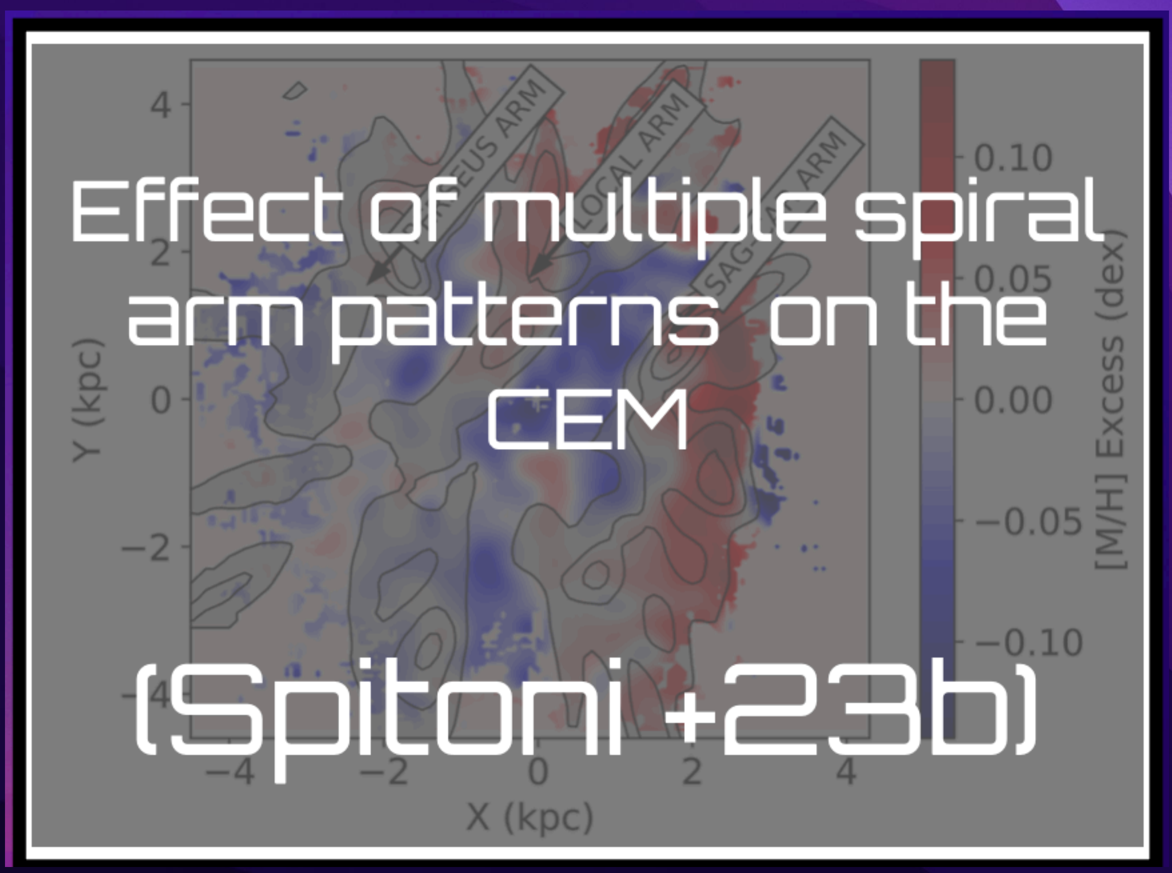


Gaia DR3 data (empty)
Synthetic model

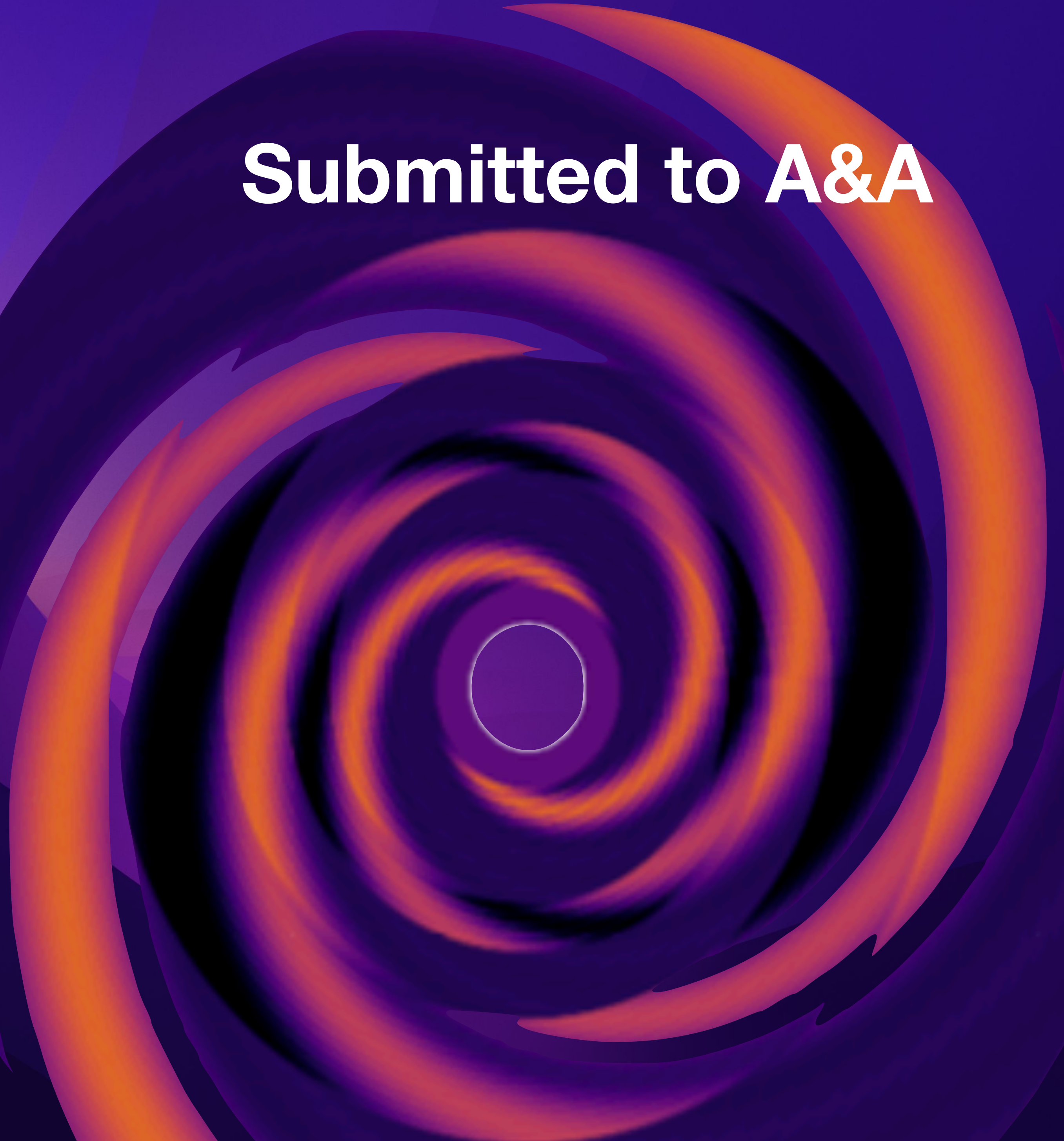
2D chemical evolution models II.

Effects of multiple spiral arm patterns on O, Eu, Fe and Ba abundance gradients

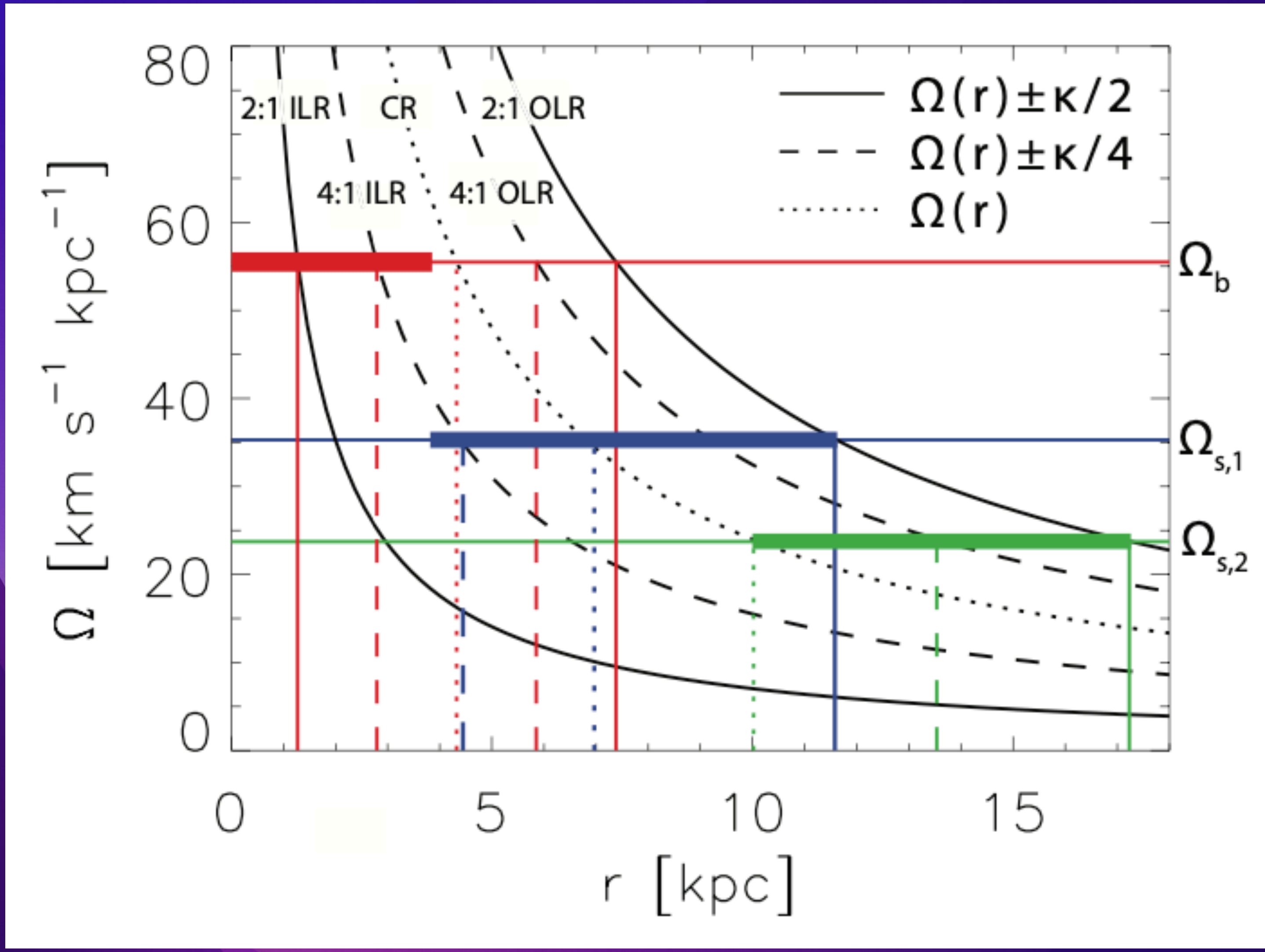
E. Spitoni[1,2 ⋆], G. Cescutti[1,3,4], A. Recio-Blanco[2], I. Minchev[5], E. Poggio[2,6], P. A. Palicio[2], F. Matteucci[1,3,4], S. Peirani[2], M. Barbillon[2], and A. Vasini[3]



Submitted to A&A



Presence of multiple spiral modes moving at different pattern speeds in galactic discs including our own Milky Way (Minchev & Quillen 2006; Quillen et al. 2011)



Minchev+16

Spiral arms prescriptions

Spitoni+19b

- ISM density fluctuations from an analytical spiral arms model with a single pattern

$$\Sigma_S(R,\phi,t) = \chi(R,t_G)M(\gamma).$$

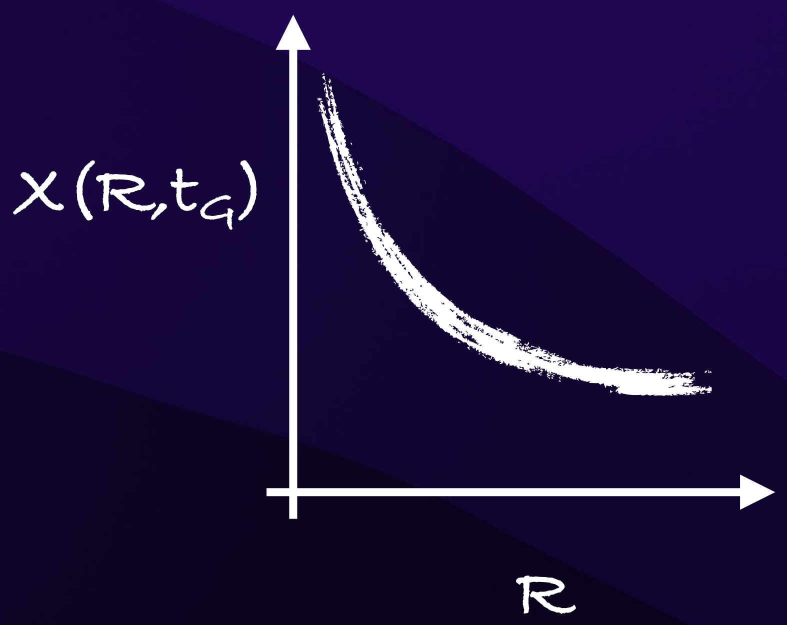
MODULATION FUNCTION

$$M(\gamma) = \left(\frac{8}{3\pi}\cos(\gamma) + \frac{1}{2}\cos(2\gamma) + \frac{8}{15\pi}\cos(3\gamma)\right),$$

$$\gamma(R,\phi,t) = m\left[\phi + \Omega_s t - \phi_p(R_0) - \frac{\ln(R/R_0)}{\tan(\alpha)}\right].$$

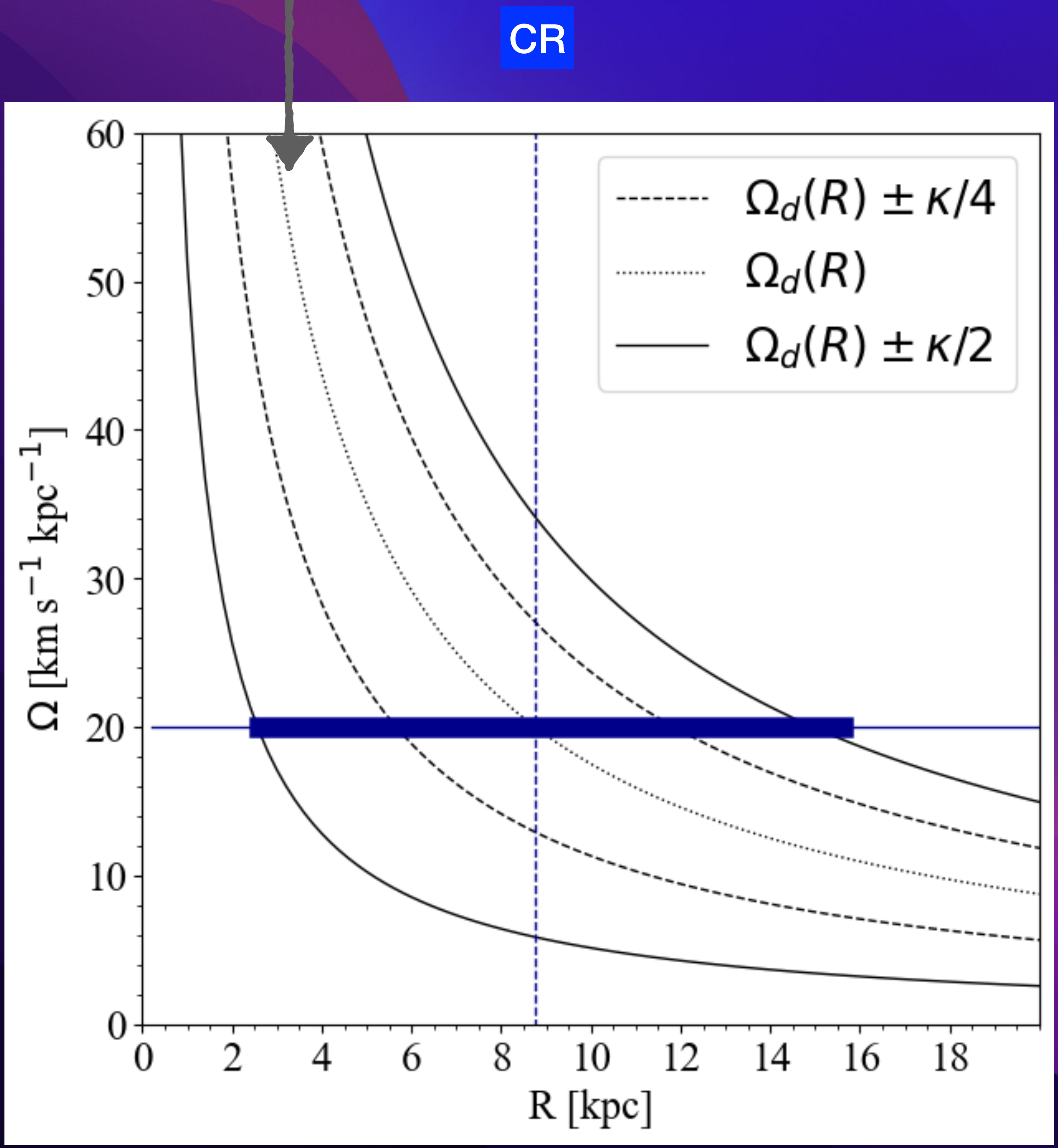
Cox & Gomez (2002)

AMPLITUDE OF THE SPIRAL DENSITY



Spitoni +19b

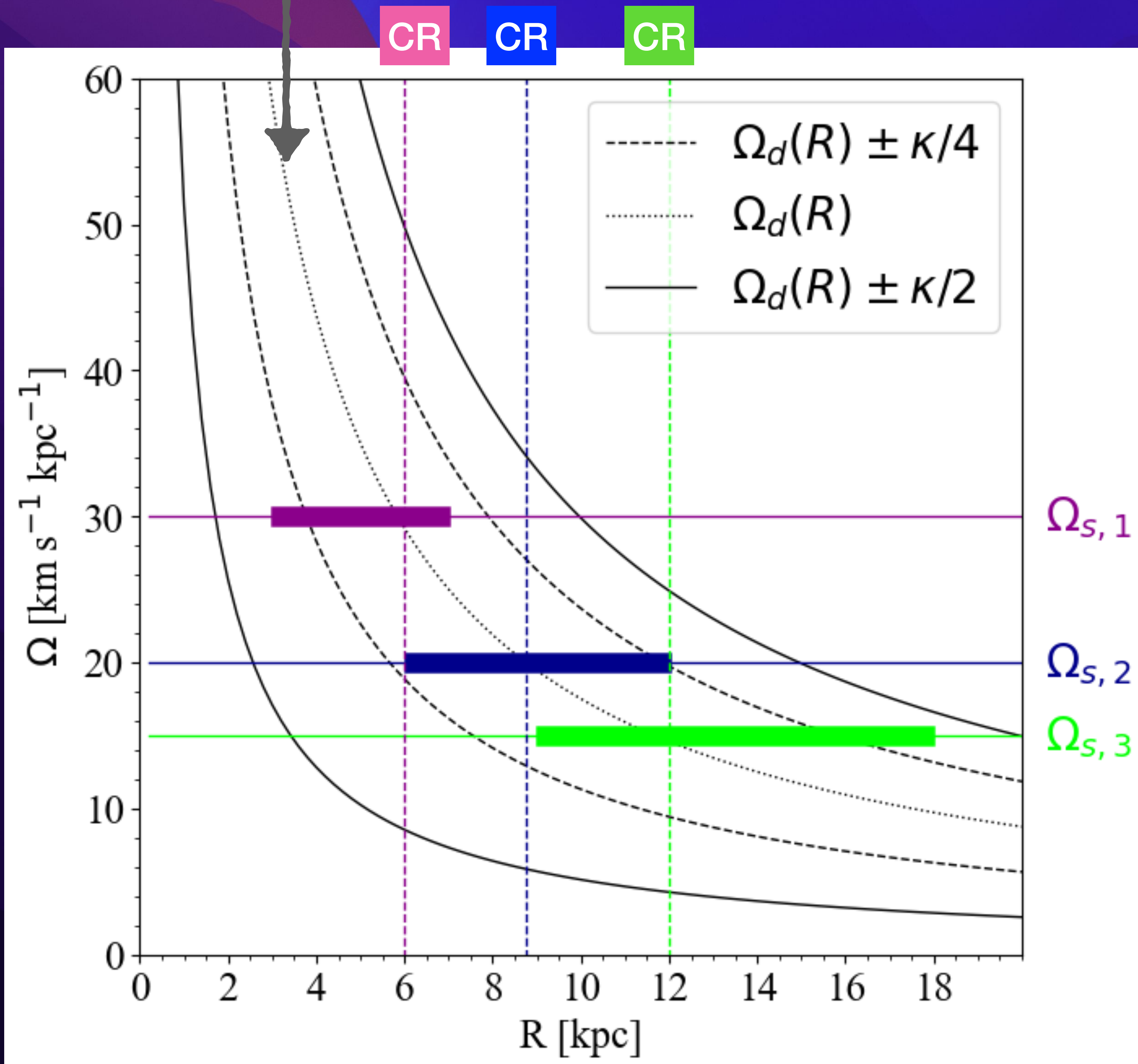
Disc angular velocity by Roca-Fàbrega et al. (2014)



MODEL A

Spiral structure with multiplicity m = 2 with a single pattern

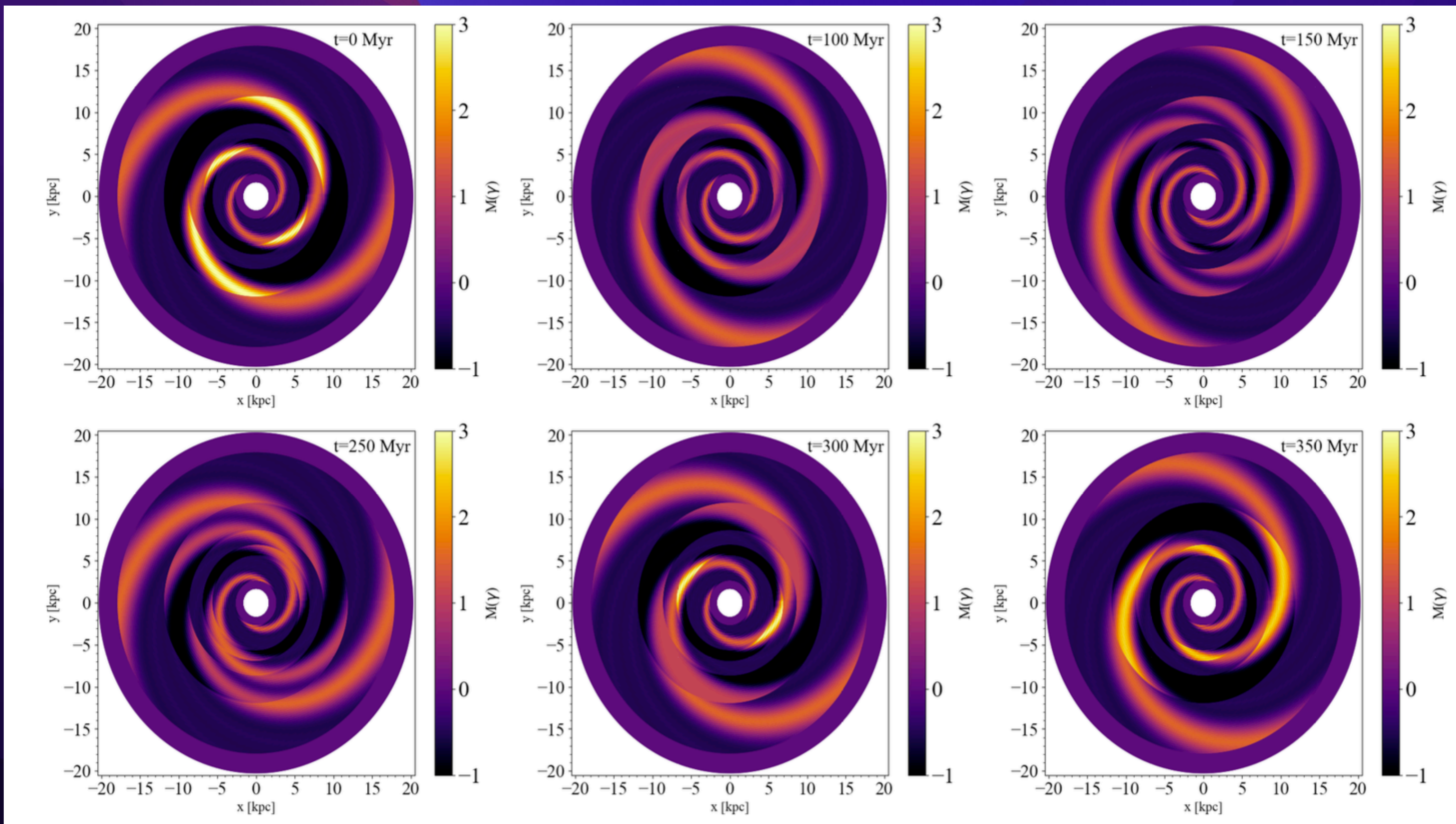
Disc angular velocity by Roca-Fàbrega et al. (2014)



MODEL A

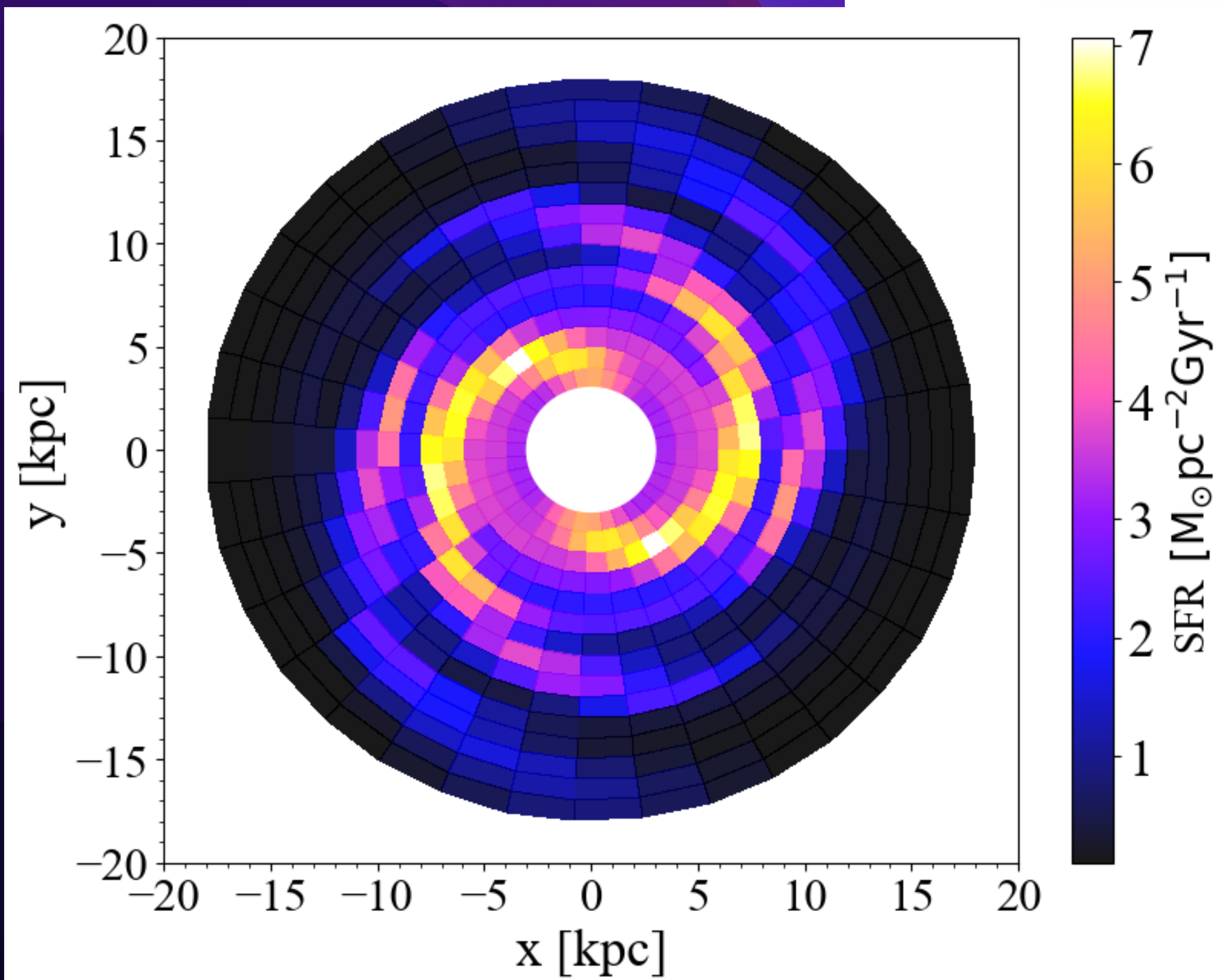
Spiral structure with multiplicity m = 2 composed by three chunks moving at different pattern speeds

$$M(\gamma) = \sum_{j=1}^{N} M_{MS,j}(\gamma_j)$$

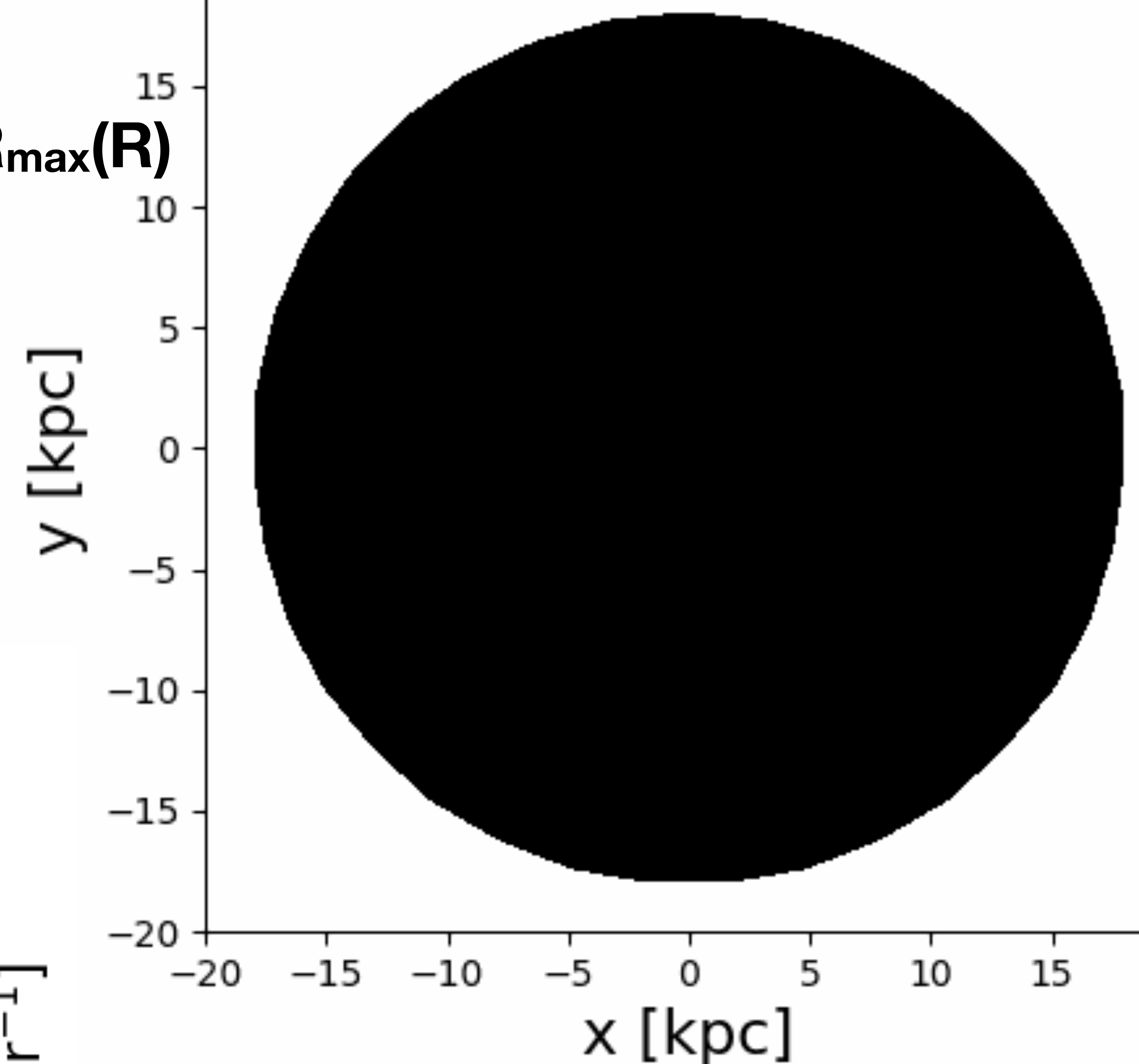


For a m=2 spiral arms structure

The star formation rate

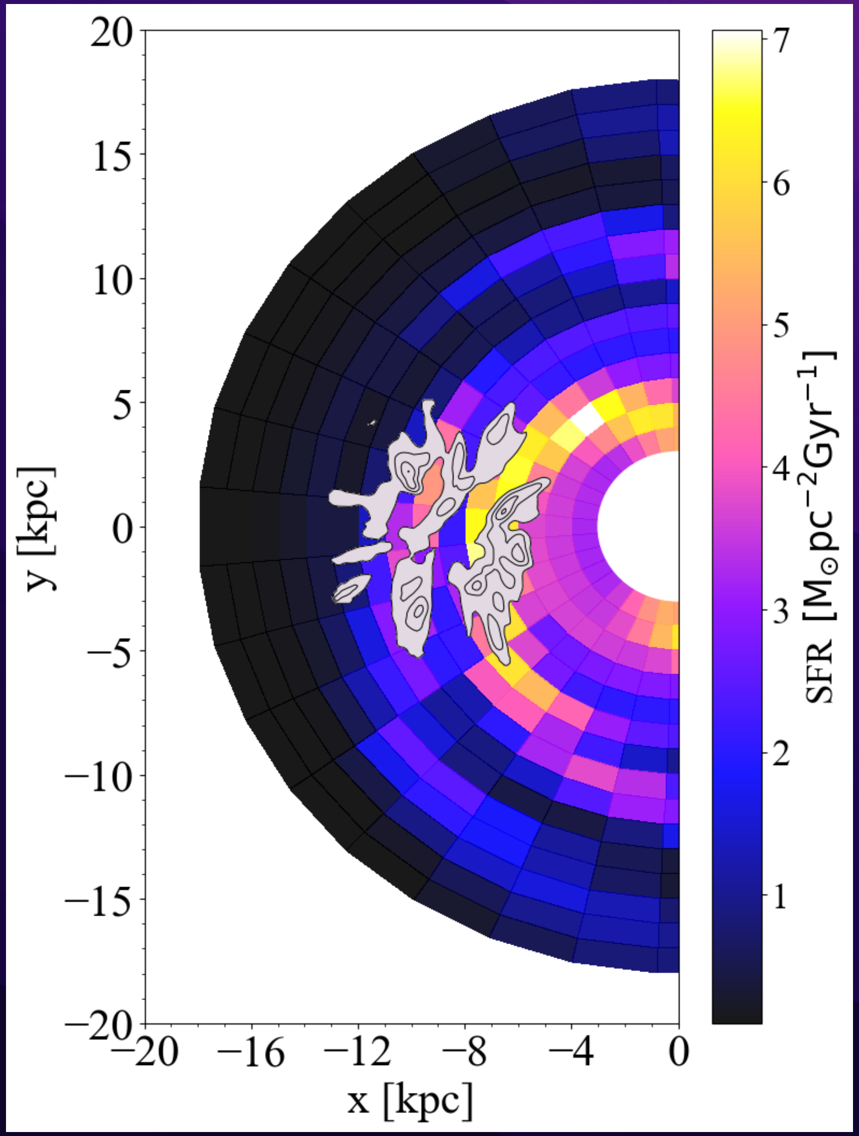


SFR(R,ϕ)/SFR$_{max}$(R)



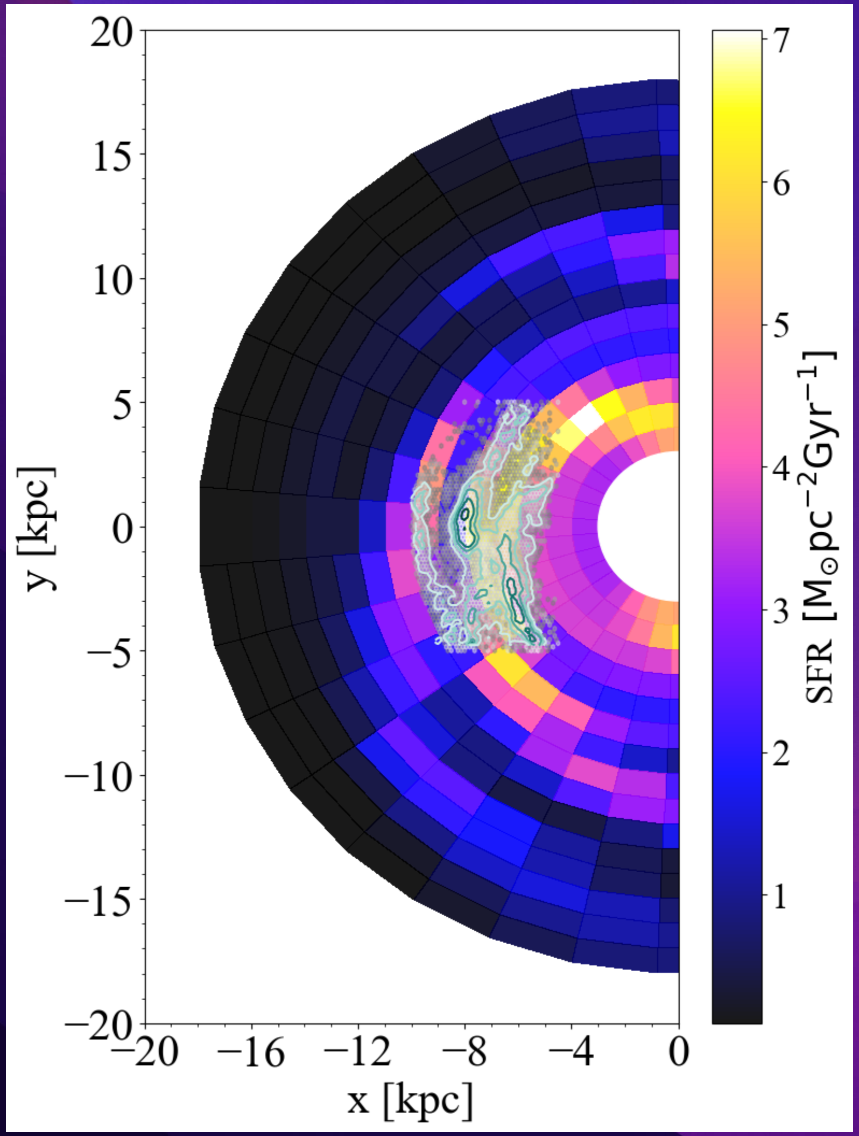
Poggio+21

UPM stars



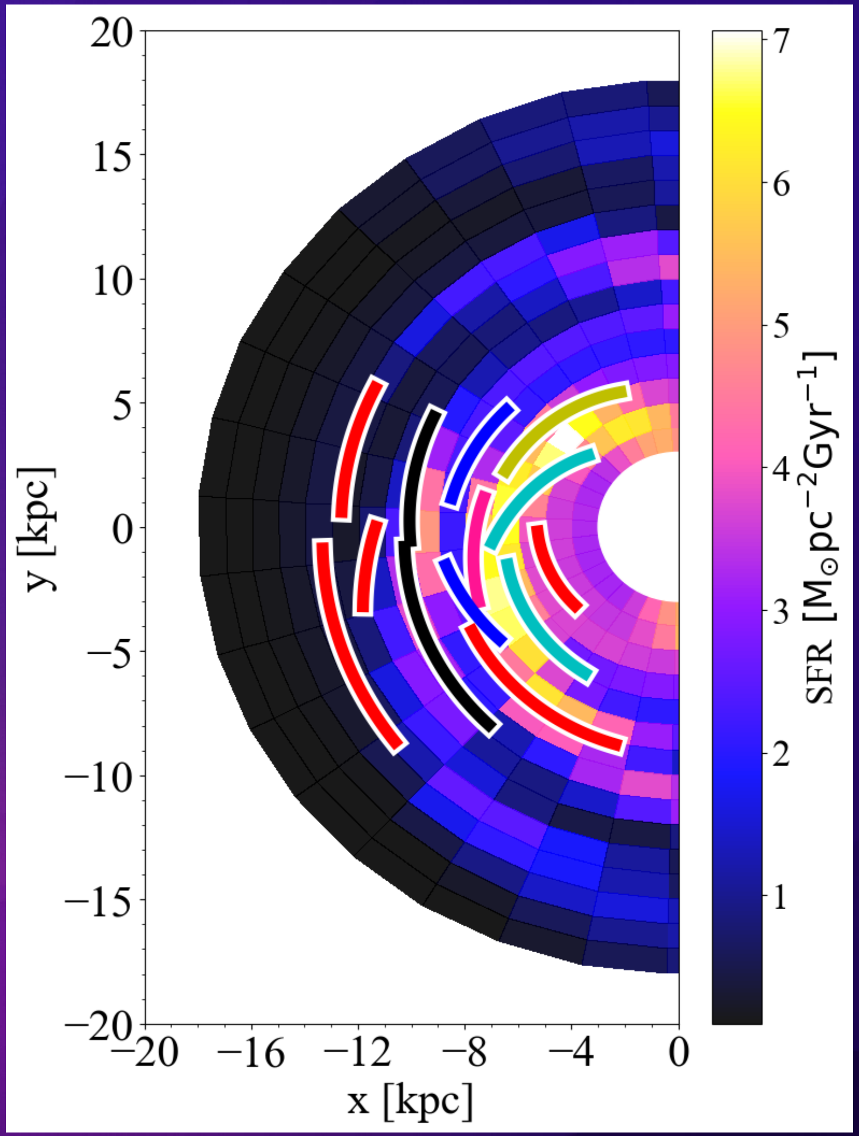
Palicio+ES 23

Radial actions, $J_R < 0.01 R_\odot V_\odot$

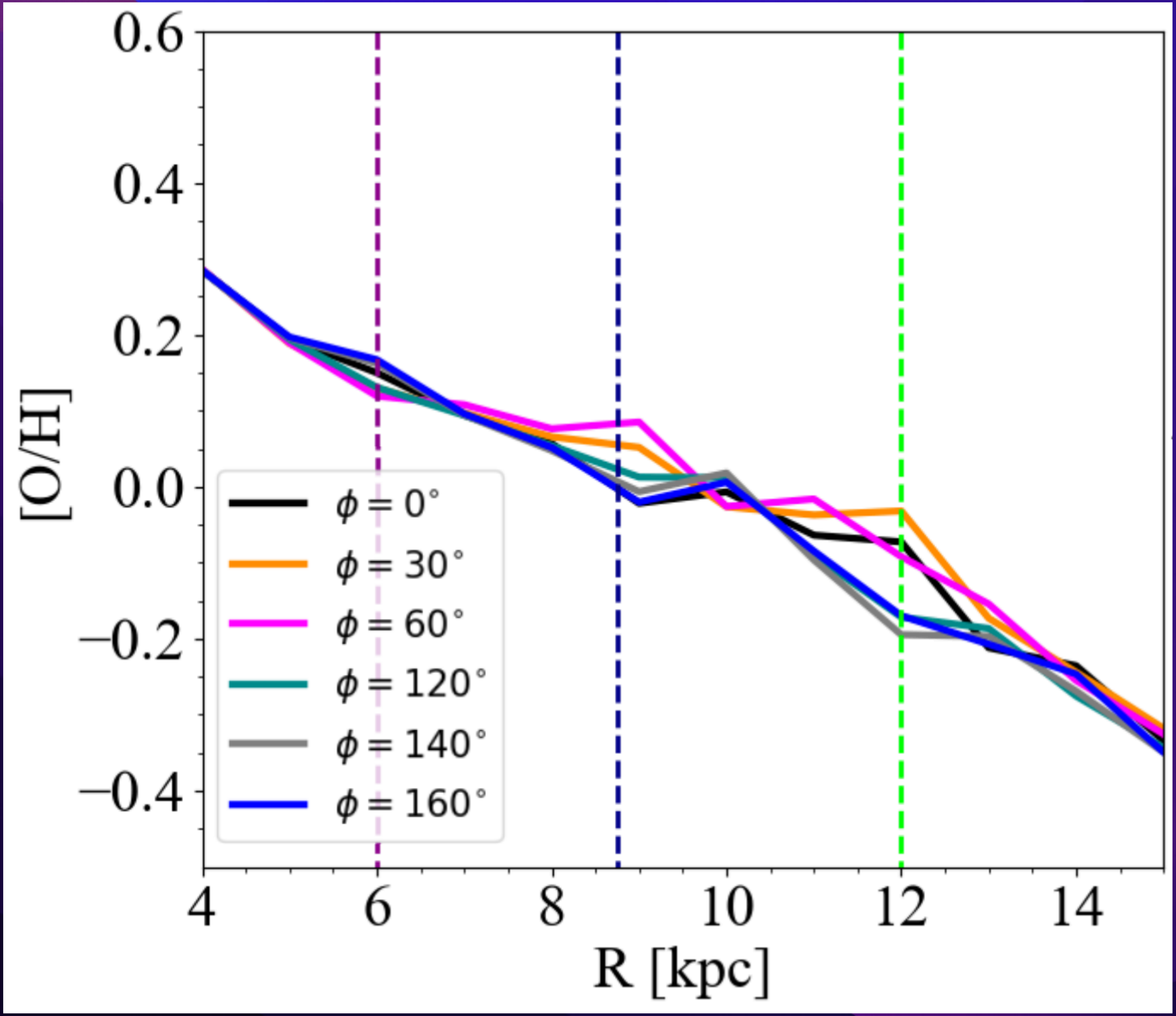


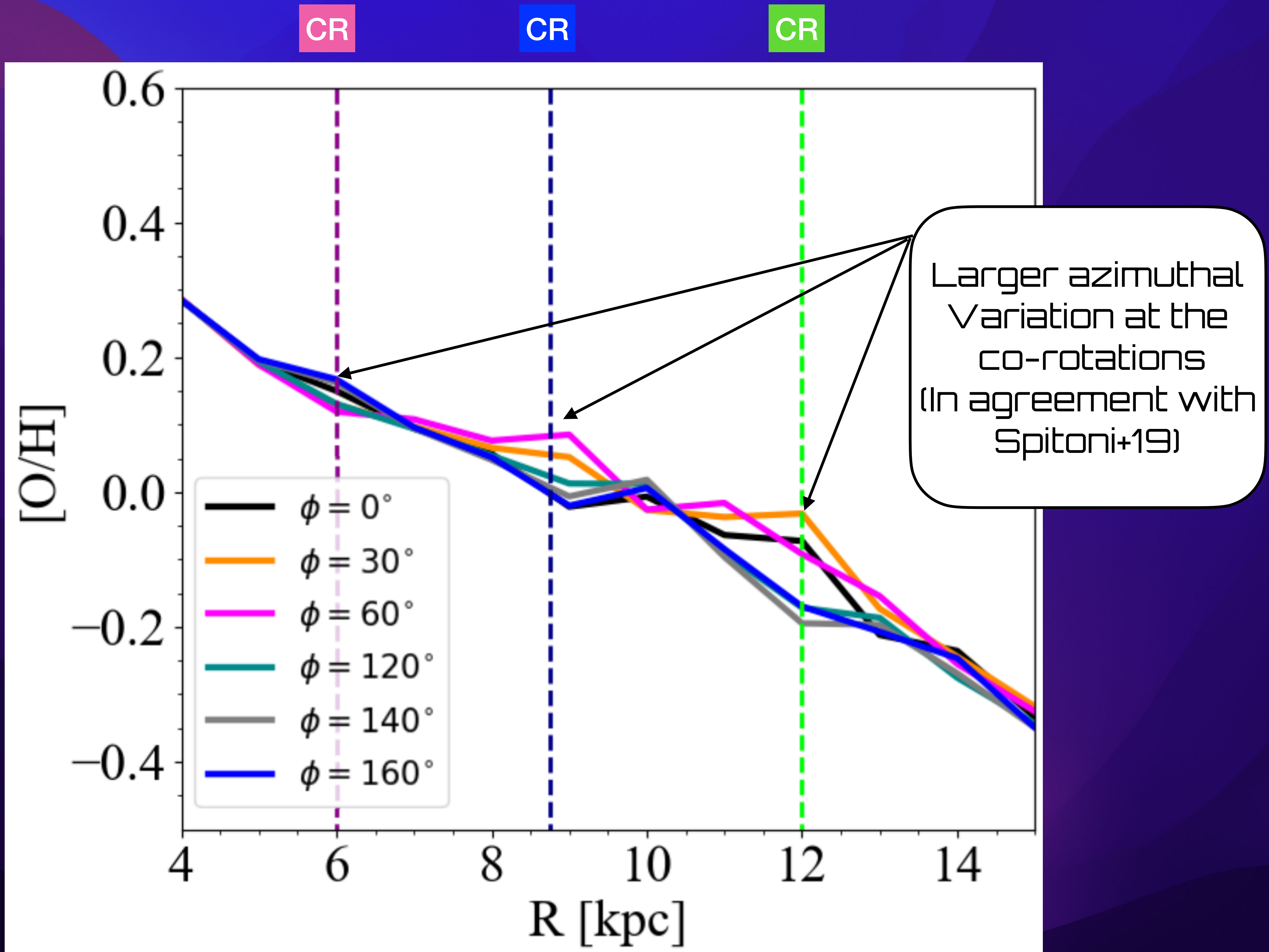
Lemasle+22

Cepheids



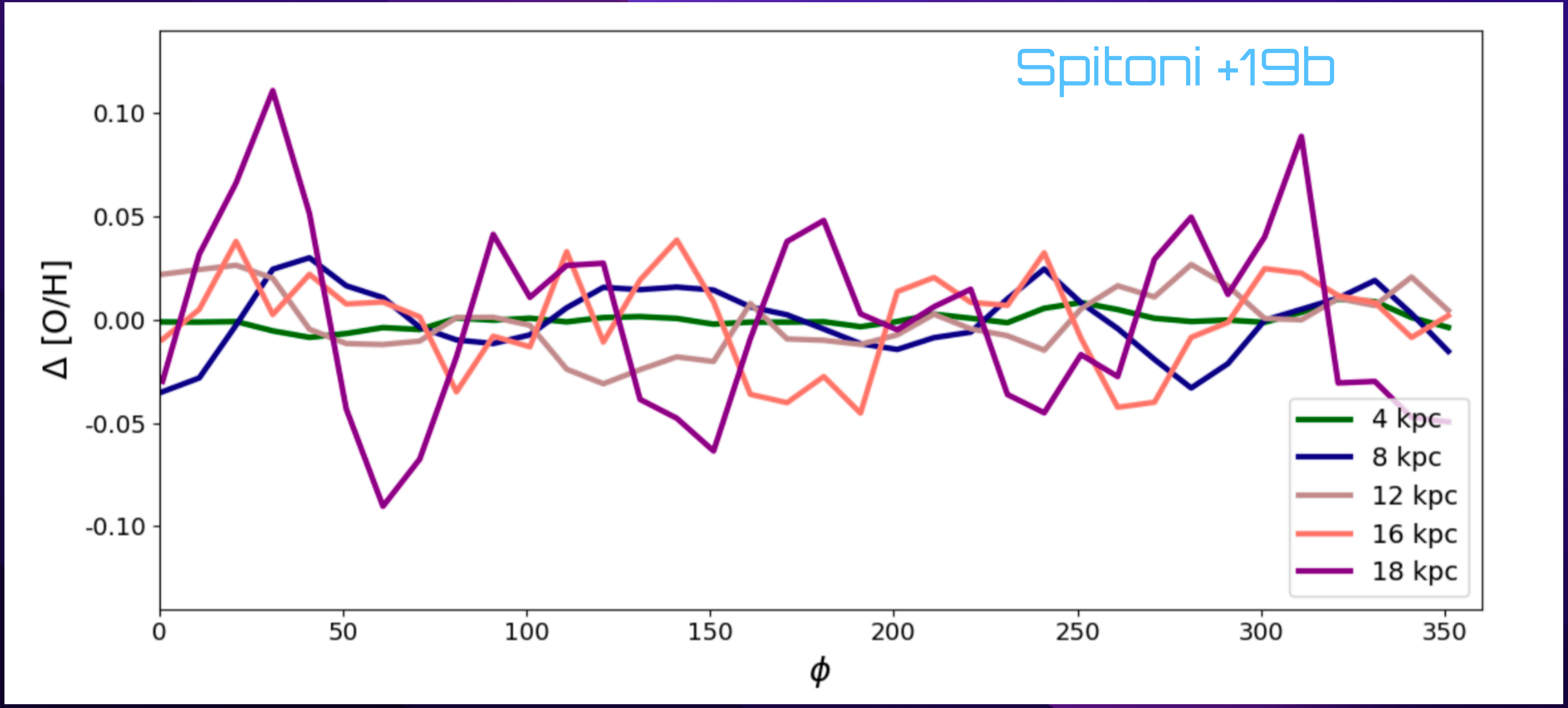
CR CR CR





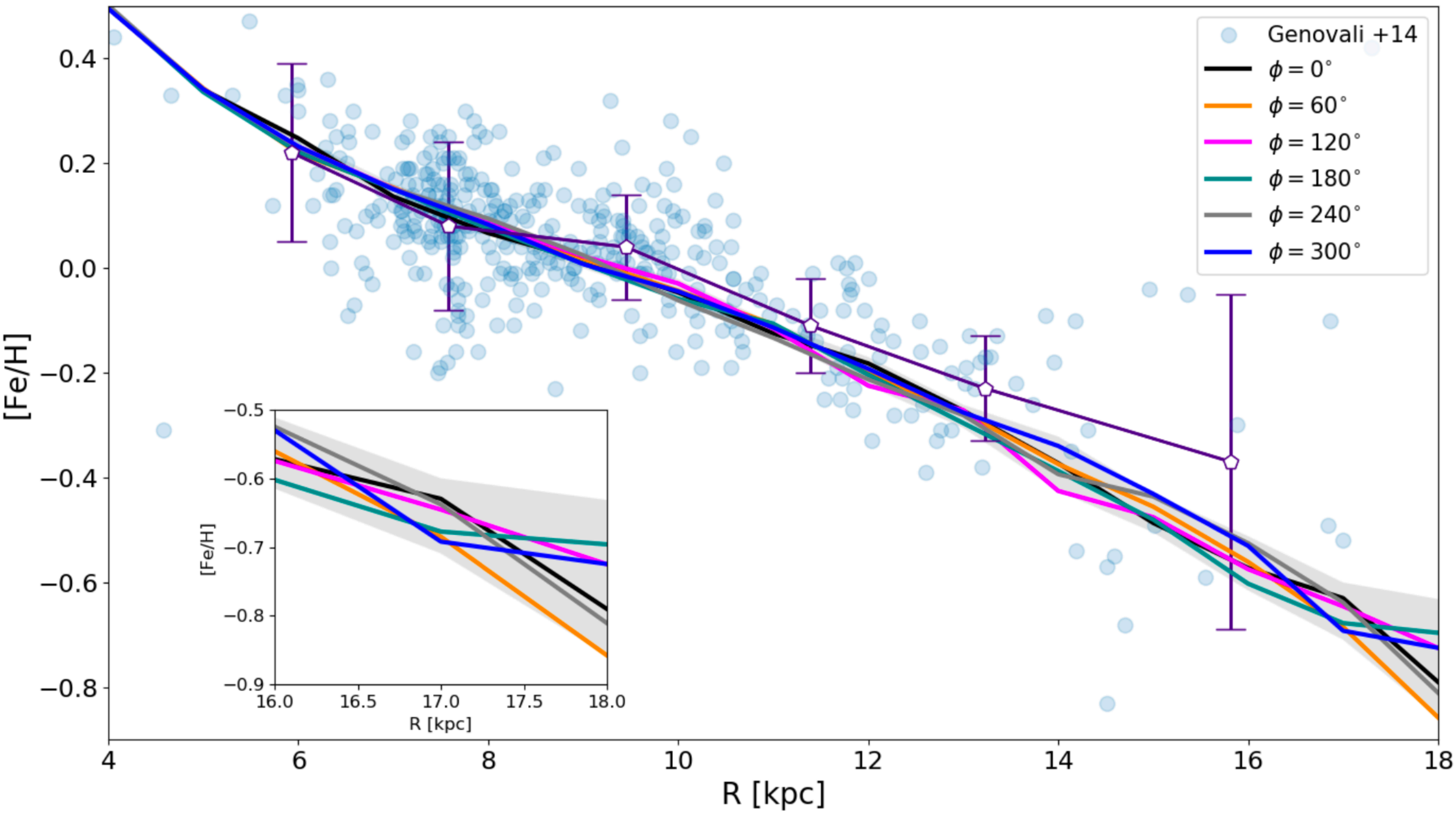
CR
CR
CR
0.6
0.4
0.2
0.0
−0.2
−0.4
[O/H]
4
6
8
10
12
14
R [kpc]
$\phi = 0^\circ$
$\phi = 30^\circ$
$\phi = 60^\circ$
$\phi = 120^\circ$
$\phi = 140^\circ$
$\phi = 160^\circ$
Larger azimuthal Variation at the co-rotations (In agreement with Spitoni+19)

... Results in agreement with the chemical evolution model in which we consider the density fluctuation by the chemo-dynamical model by Minchev+13 (see Ivan's talk, MCM model)

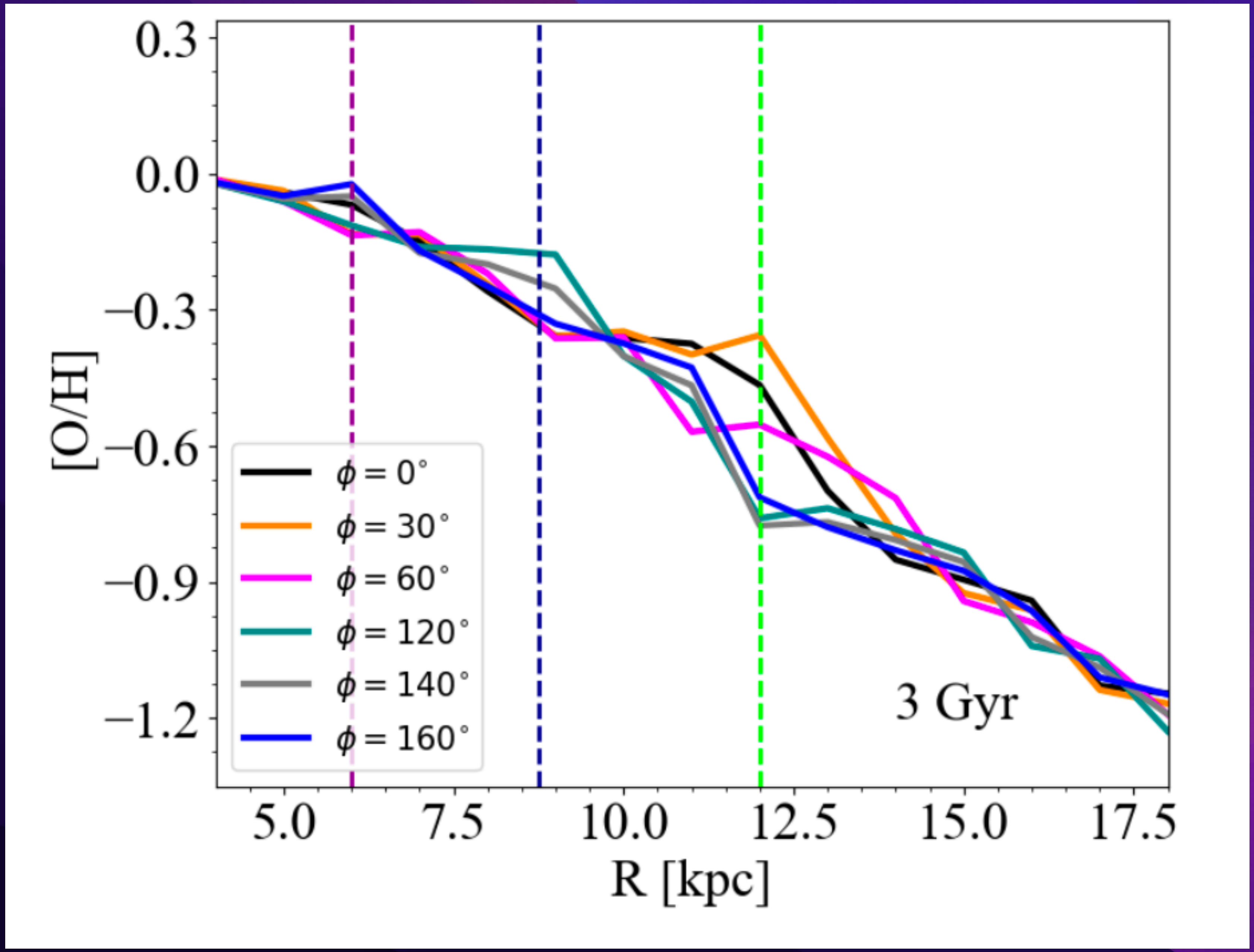


[Fe/H] abundance gradient considering the density fluctuation by the chemo-dynamical model by Minchev+13

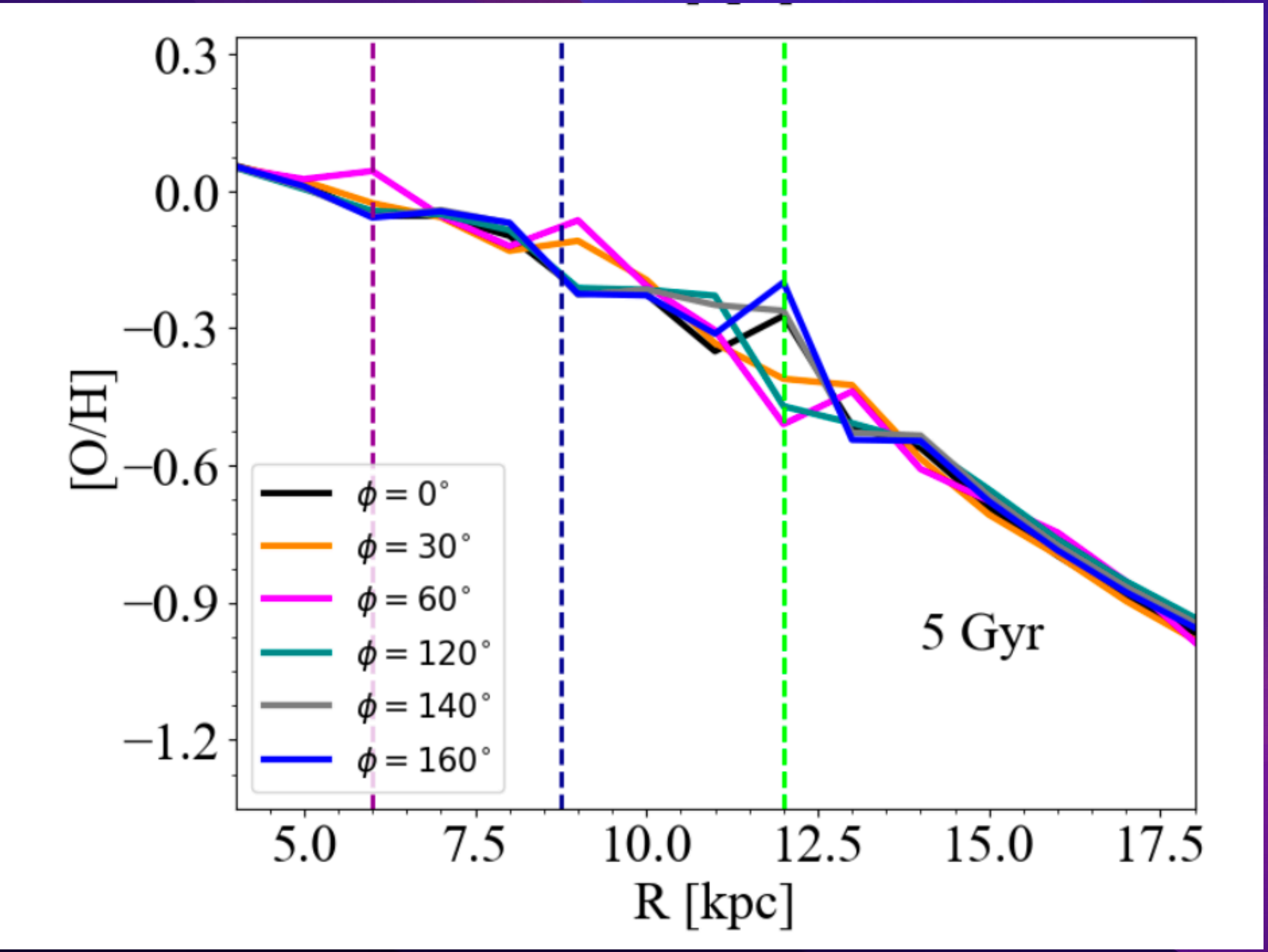
Spitoni +19b



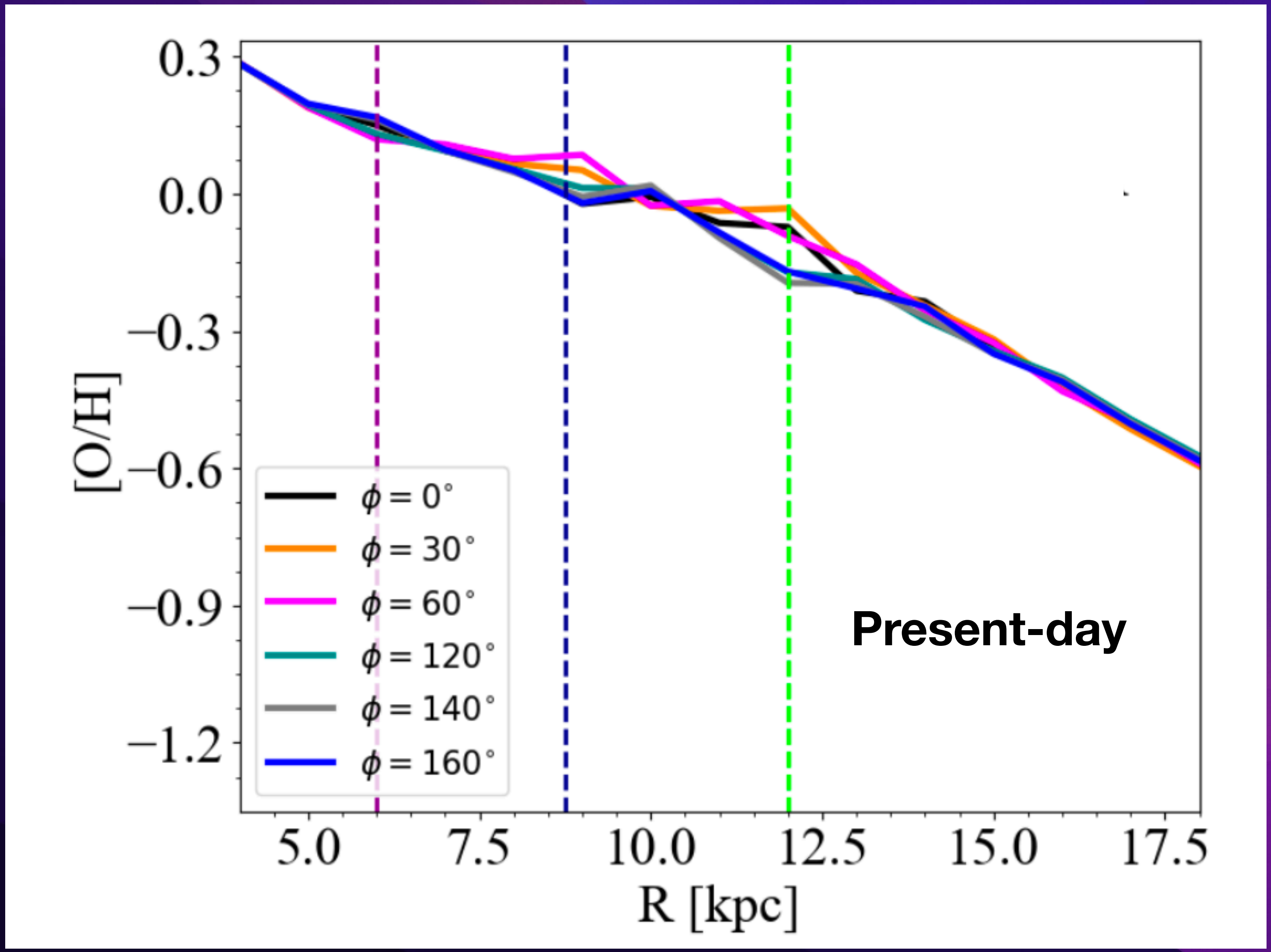
Temporal evolution of the oxygen gradient



Temporal evolution of the oxygen gradient



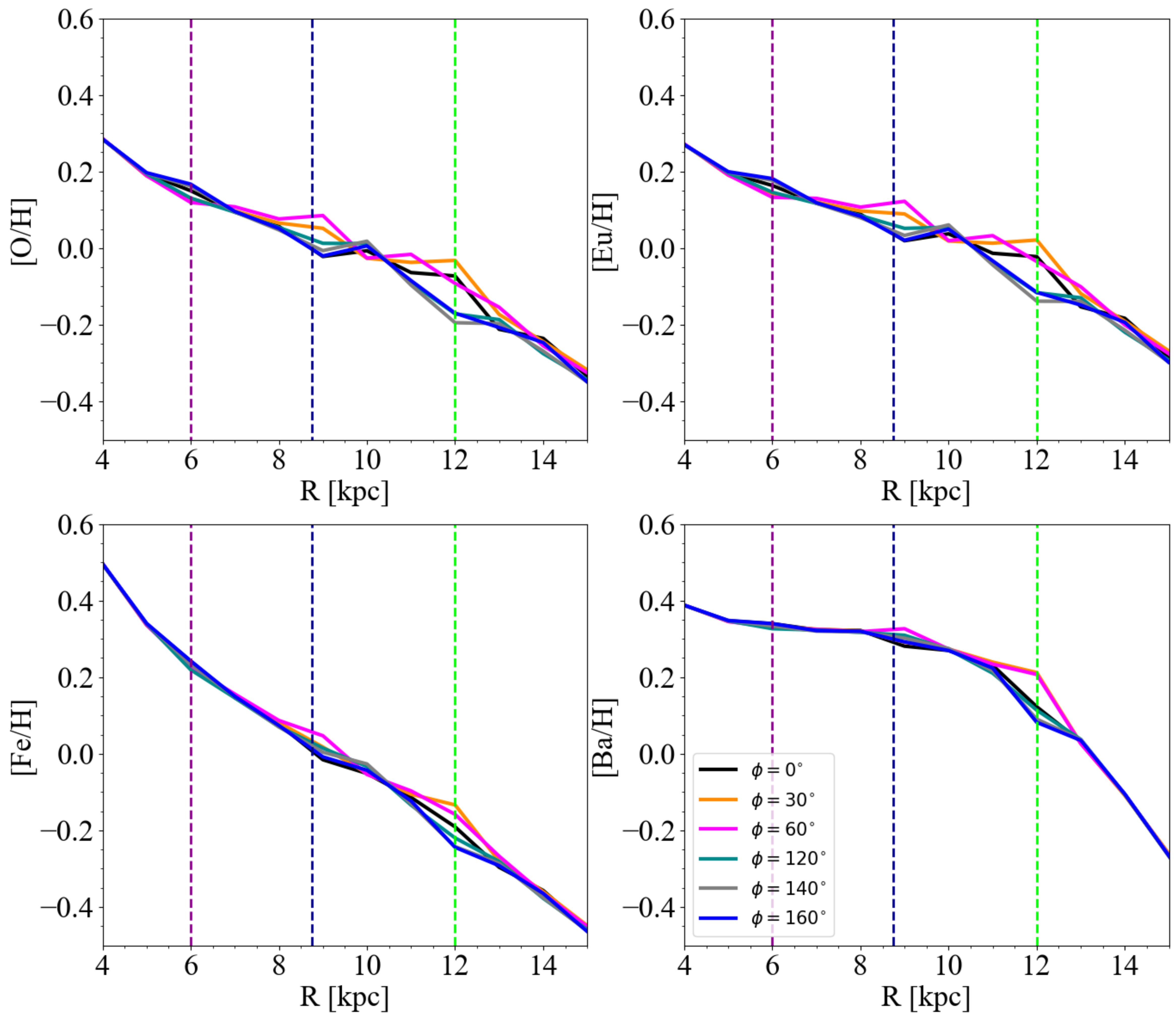
Temporal evolution of the oxygen gradient



What about other elements?

What about other elements?

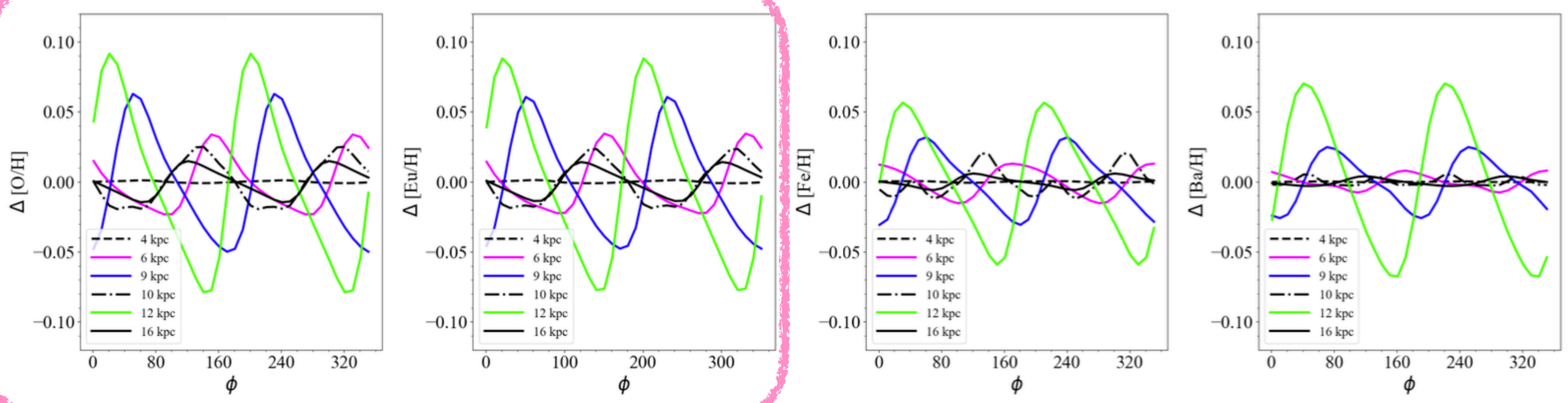
O Fe Ba Eu



[O/H]
[Eu/H]
[Fe/H]
[Ba/H]
R [kpc]
0.6
0.4
0.2
0.0
−0.2
−0.4
4
6
8
10
12
14
$\phi = 0^\circ$
$\phi = 30^\circ$
$\phi = 60^\circ$
$\phi = 120^\circ$
$\phi = 140^\circ$
$\phi = 160^\circ$

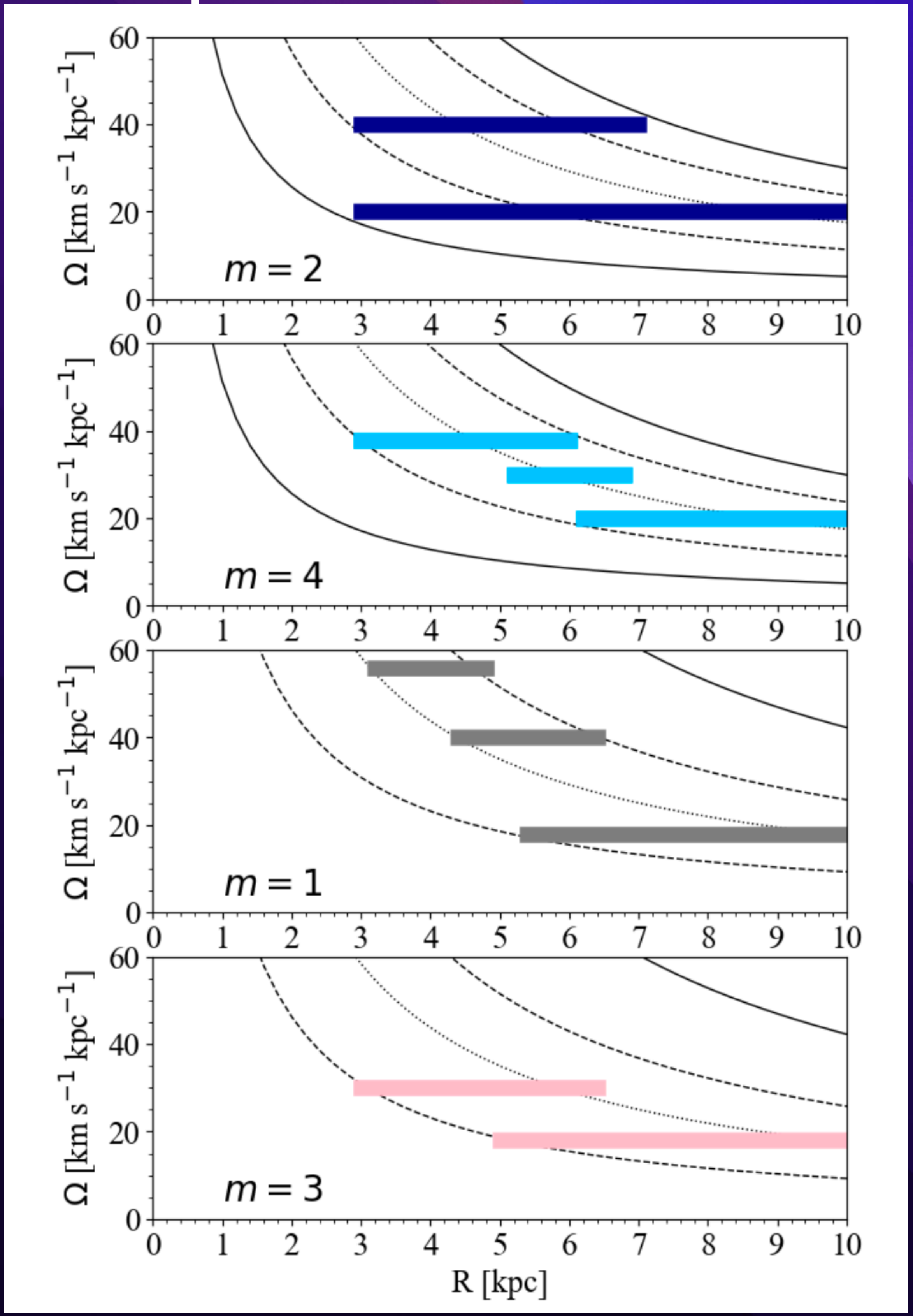
Present day residual azimuthal variations

Oxygen Europium Iron Barium



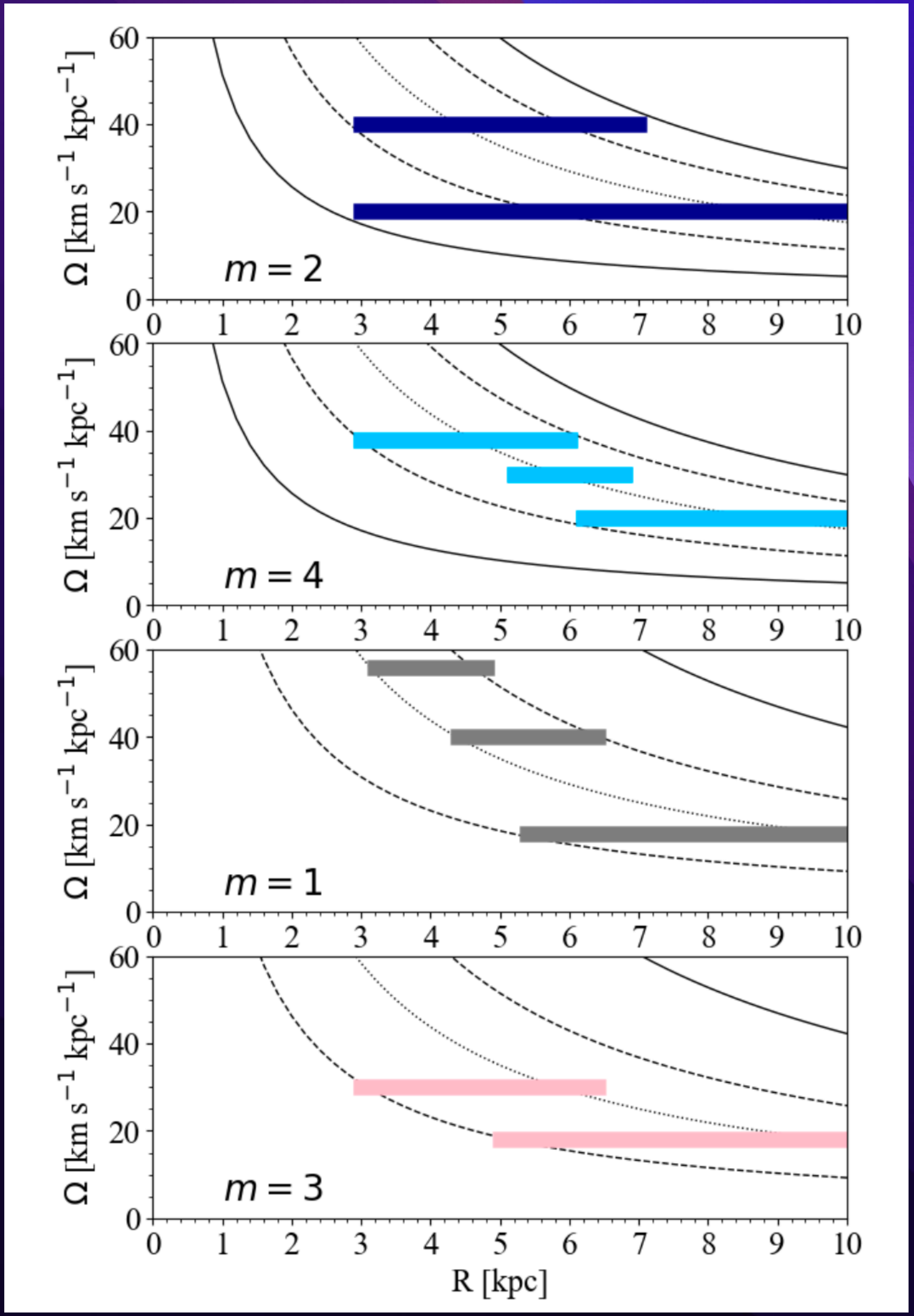
Larger azimuthal variations for elements produced on shorter time-scales

Spiral arms with different pattern speeds Ω_s and modes m



Ω_s and m extracted from Hilmi+20 high- resolution hydrodynamical simulations of MW-sized galaxies from the NIHAO-UHD project of Buck et al. (2020)

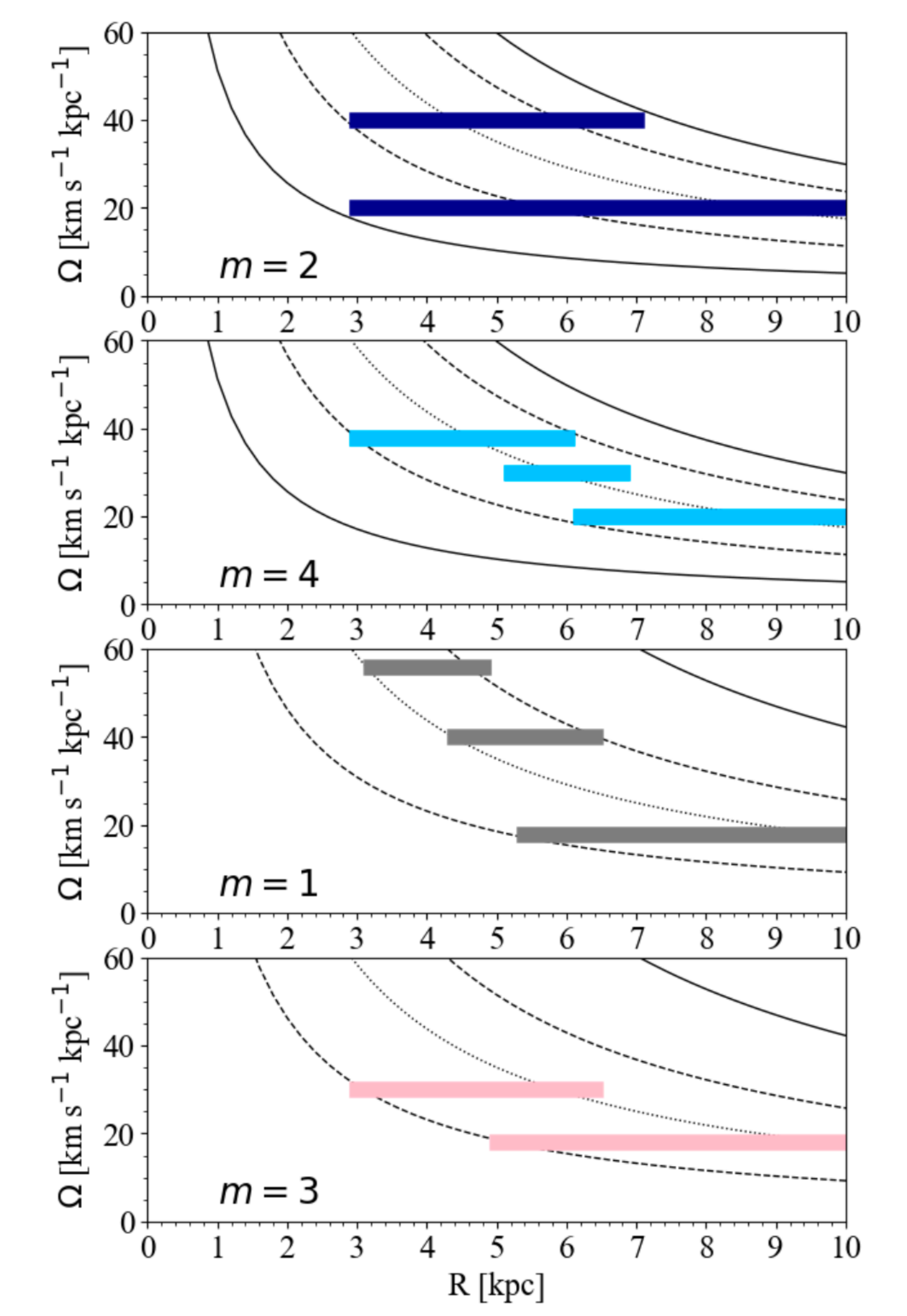
Spiral arms with different pattern speeds Ω_s and modes m



The new ISM density fluctuation is...

$$\Sigma_{MS}(R,\phi,t) = \chi(R,t_G)\sum_{m=1}^{4}\left(A_m \sum_{j=1}^{N_m} M_{MS_{m,j}}(\gamma_j)\right)$$

Spiral arms with different pattern speeds Ω_s and modes m

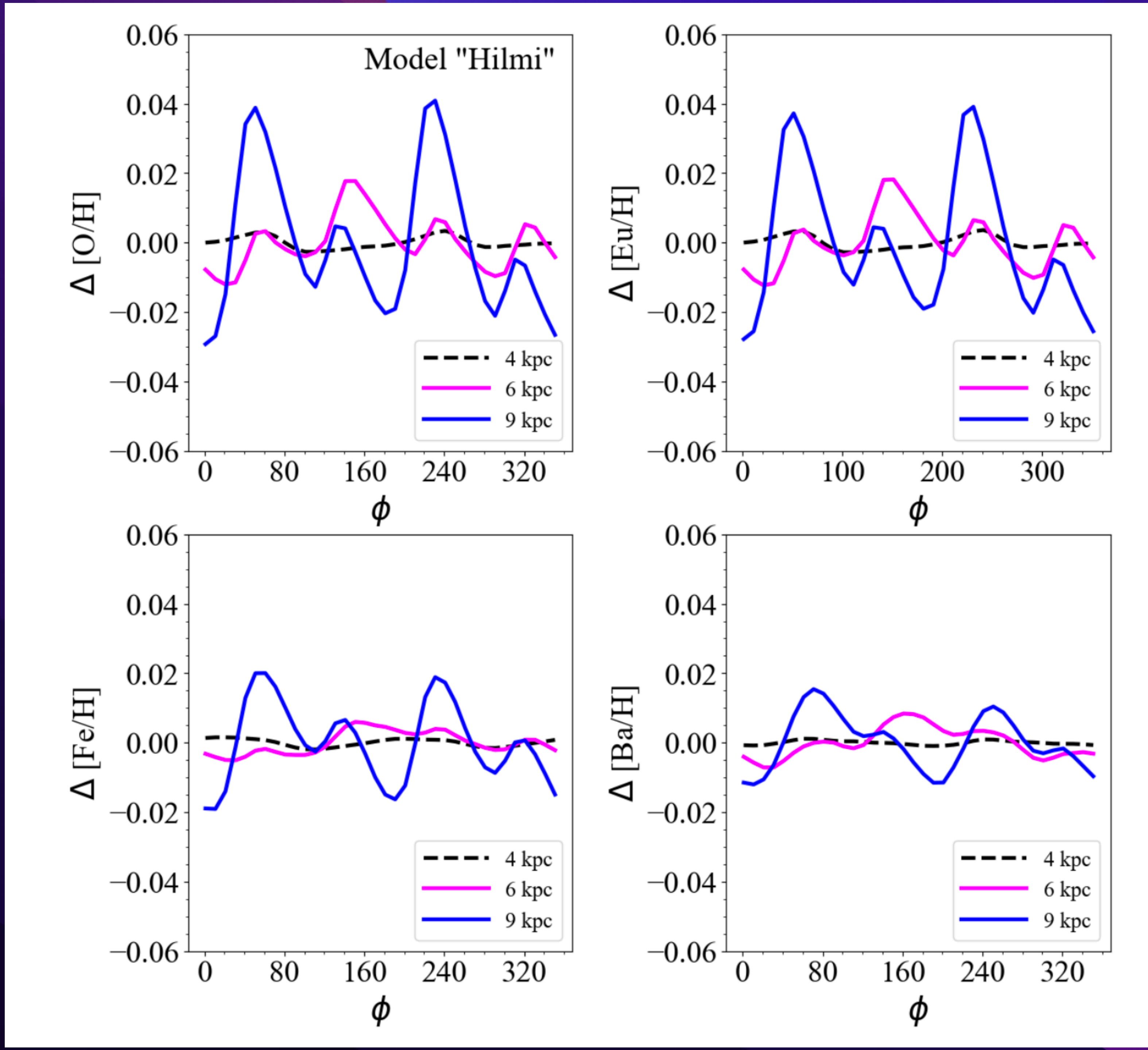


The new ISM density fluctuation is…

$$\Sigma_{MS}(R,\phi,t) = \chi(R,t_G)\sum_{m=1}^{4}\left(A_m \sum_{j=1}^{N_m} M_{MS_{m,j}}(\gamma_j)\right)$$

$A_1 + A_2 + A_3 + A_4 = 1$

Spiral arms with different pattern speeds Ω_s and modes m extracted from Hilmi+20



Presence of additional wiggles in the azimuthal variations compared to the results

Dynamics of stars around spiral arms in an N-body/SPH simulated barred-spiral galaxy

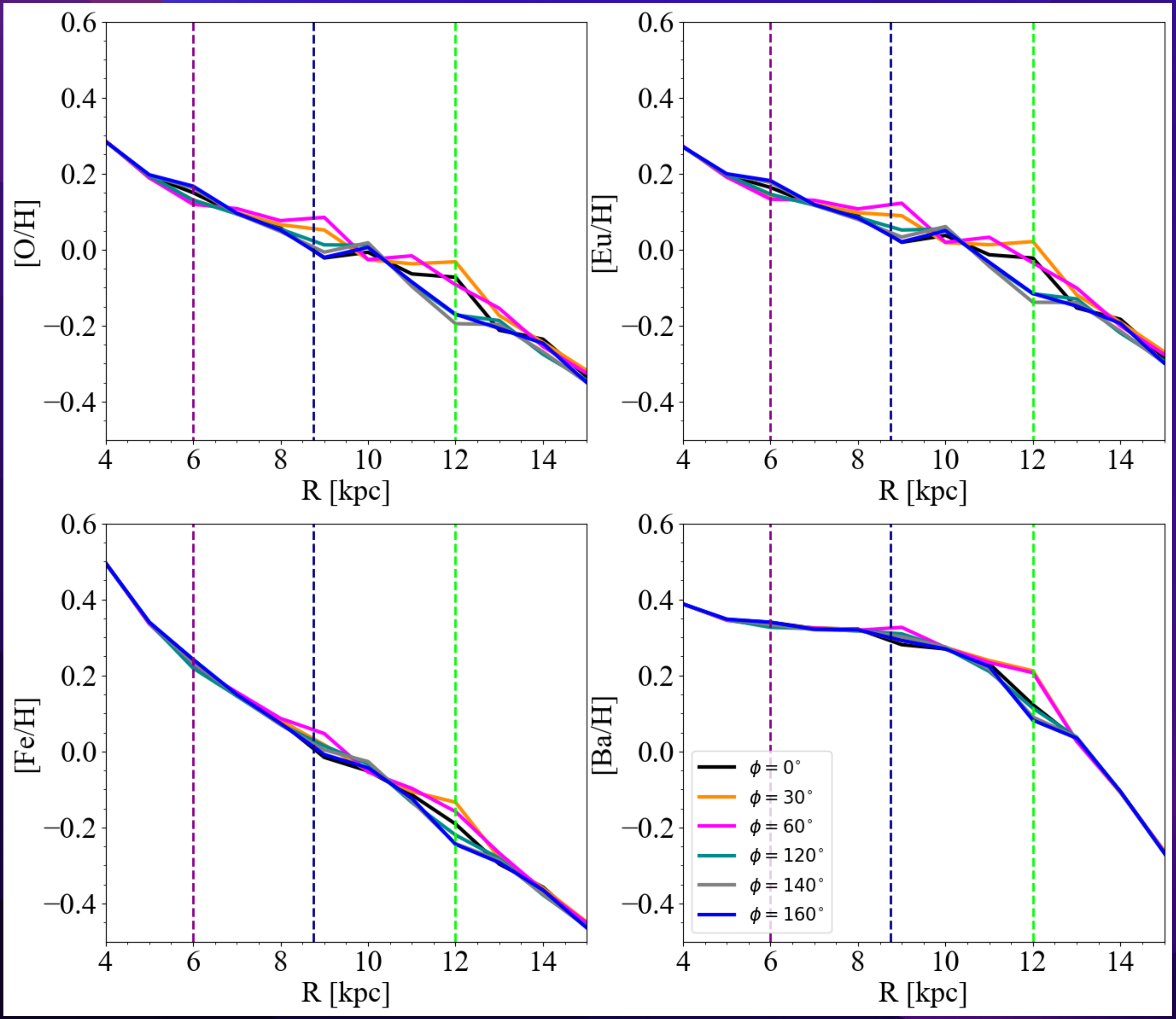
Robert J.J. Grand [1]*, Daisuke Kawata [1], Mark Cropper [1]
[1] *Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT*

3 June 2021

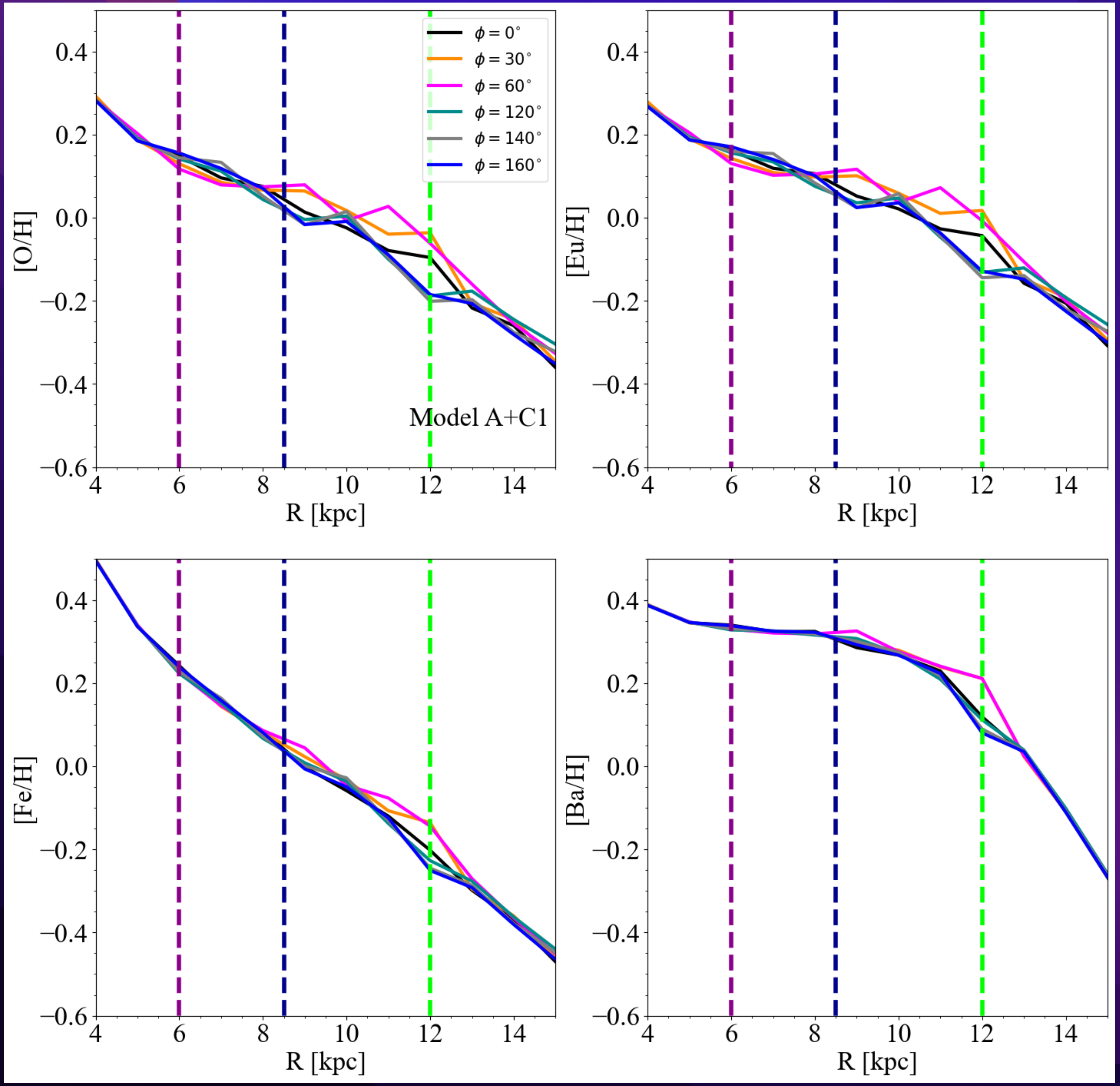
ABSTRACT
We run N-body smoothed particle hydrodynamics (SPH) simulations of a Milky Way sized galaxy. The code takes into account hydrodynamics, self-gravity, star formation, supernova and stellar wind feedback, radiative cooling and metal enrichment. The simulated galaxy is a barred-spiral galaxy consisting of a stellar and gas disc, enveloped in a static dark matter halo. Similar to what is found in our pure N-body simulation of a non-barred galaxy in Grand et al. (2012), we find that the spiral arms are transient features whose pattern speeds decrease with radius, in such a way that the pattern speed is similar to the rotation of star particles. Compared to the non-barred case, we find that the spiral arm pattern speed is slightly faster than the rotation speed of star particles: the bar appears to boost the pattern speed ahead of the rotational velocity. We trace particle motion around the spiral arms at different radii, and demonstrate that there are star particles that are drawn towards and join the arm from behind (in front of) the arm and migrate toward the outer (inner) regions of the disc until the arm disappears as a result of their transient nature. We see this migration over the entire radial range analysed, which is a consequence of the spiral arm rotating at similar speeds to star particles at all radii, which is inconsistent with the prediction of classical density wave theory. The bar does not prevent this systematic radial migration, which is shown to largely preserve circular orbits. We also demonstrate that there is no significant offset of different star forming tracers across the spiral arm, which is also

Material spiral arms, propagating near the co-rotation at all galactic radii, have been described by a number of recent numerical work with different interpretations (see Grand et al. 2012; Comparetta & Quillen 2012; Hunt et al. 2019).

Reference model

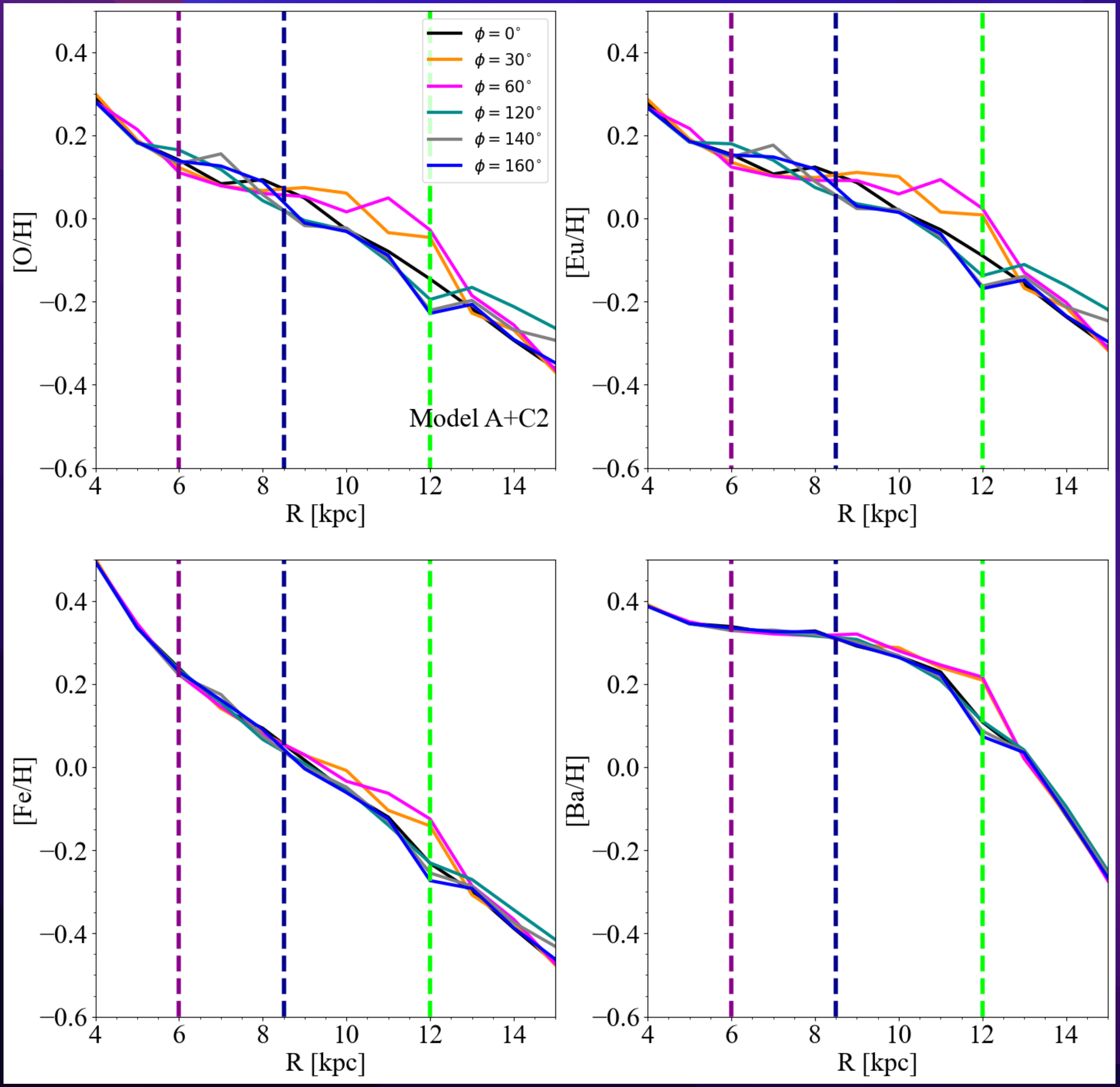


Extending the co-rotation to all Galactocentric distances



Last 100 Myr

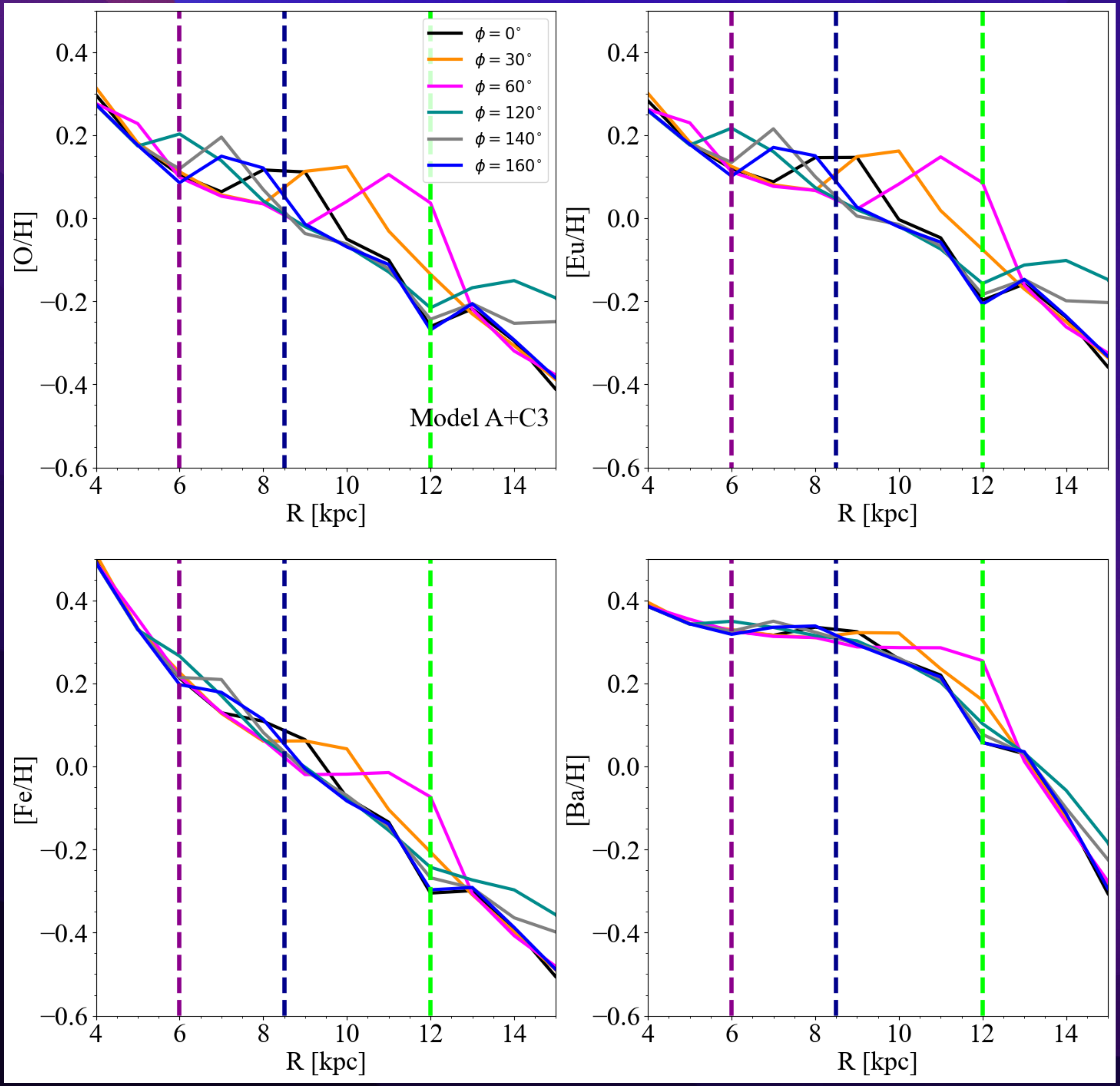
Extending the co-rotation to all Galactocentric distances

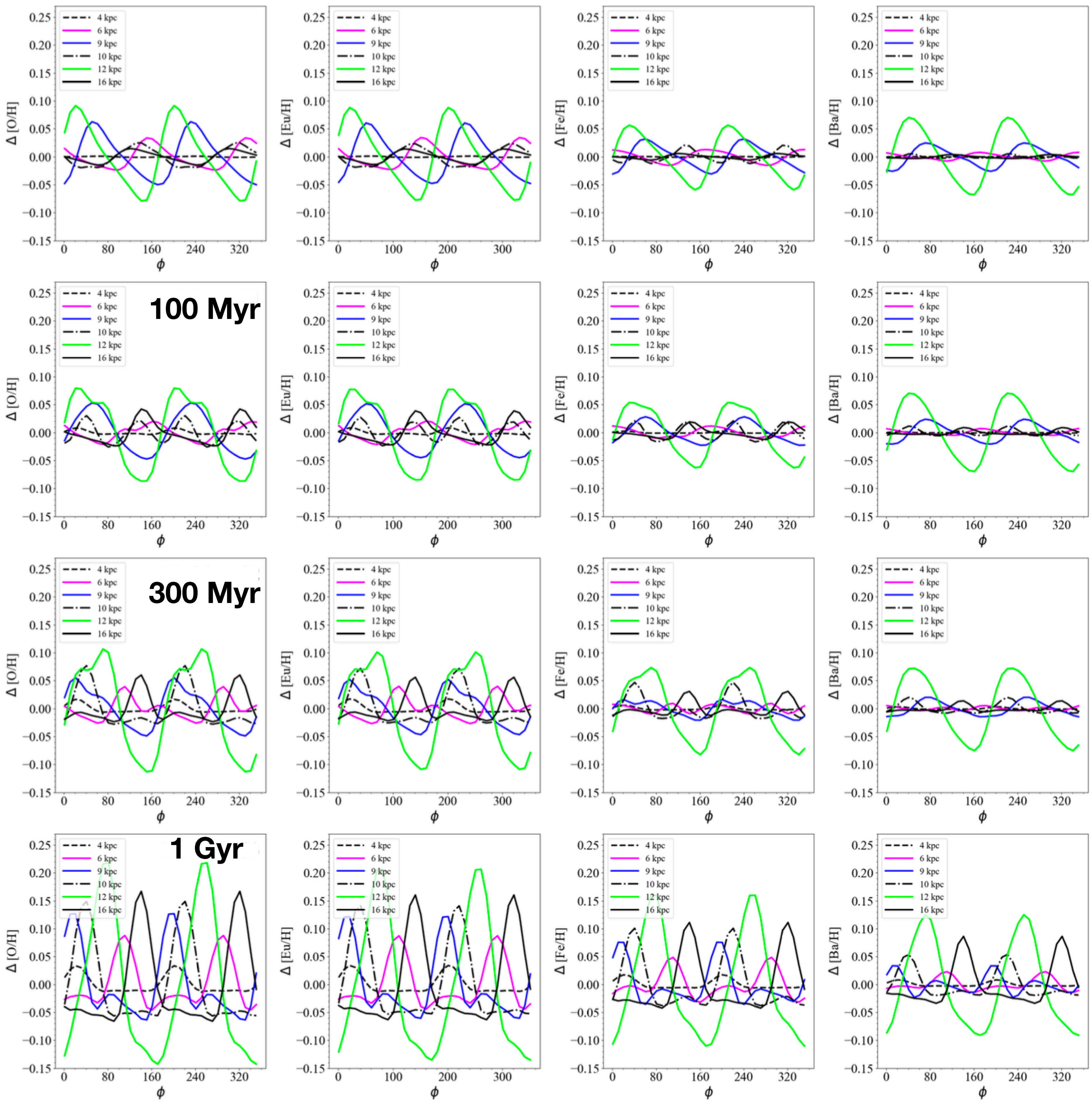


Last 300 Myr

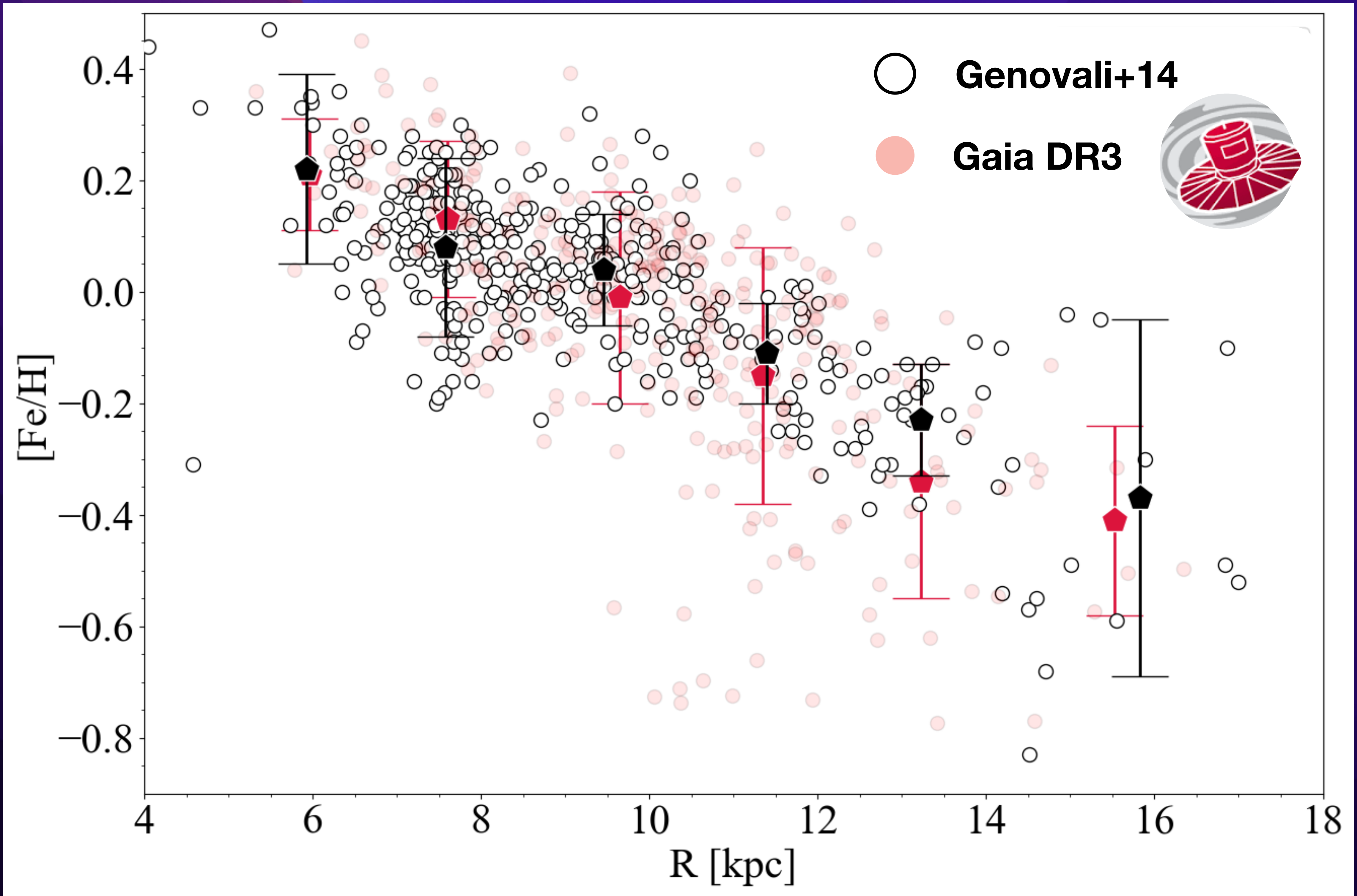
Extending the co-rotation to all Galactocentric distances

Last 1 Gyr

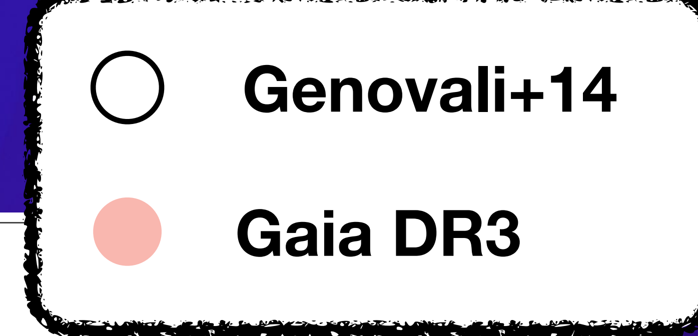


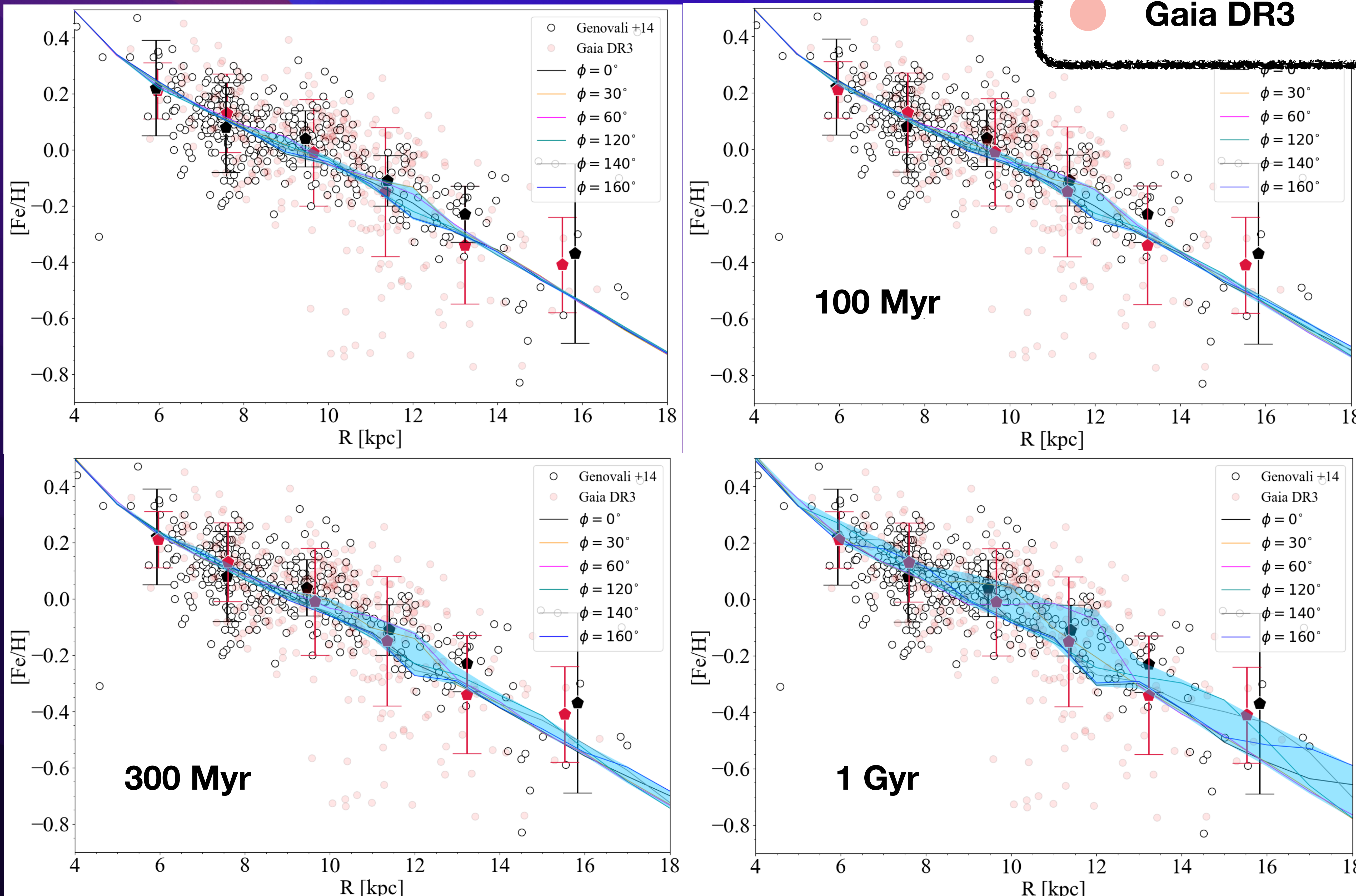

100 Myr
300 Myr
1 Gyr
4 kpc
6 kpc
9 kpc
10 kpc
12 kpc
16 kpc
Δ [O/H]
Δ [Eu/H]
Δ [Fe/H]
Δ [Ba/H]
ϕ

Cepheids with Gaia DR3



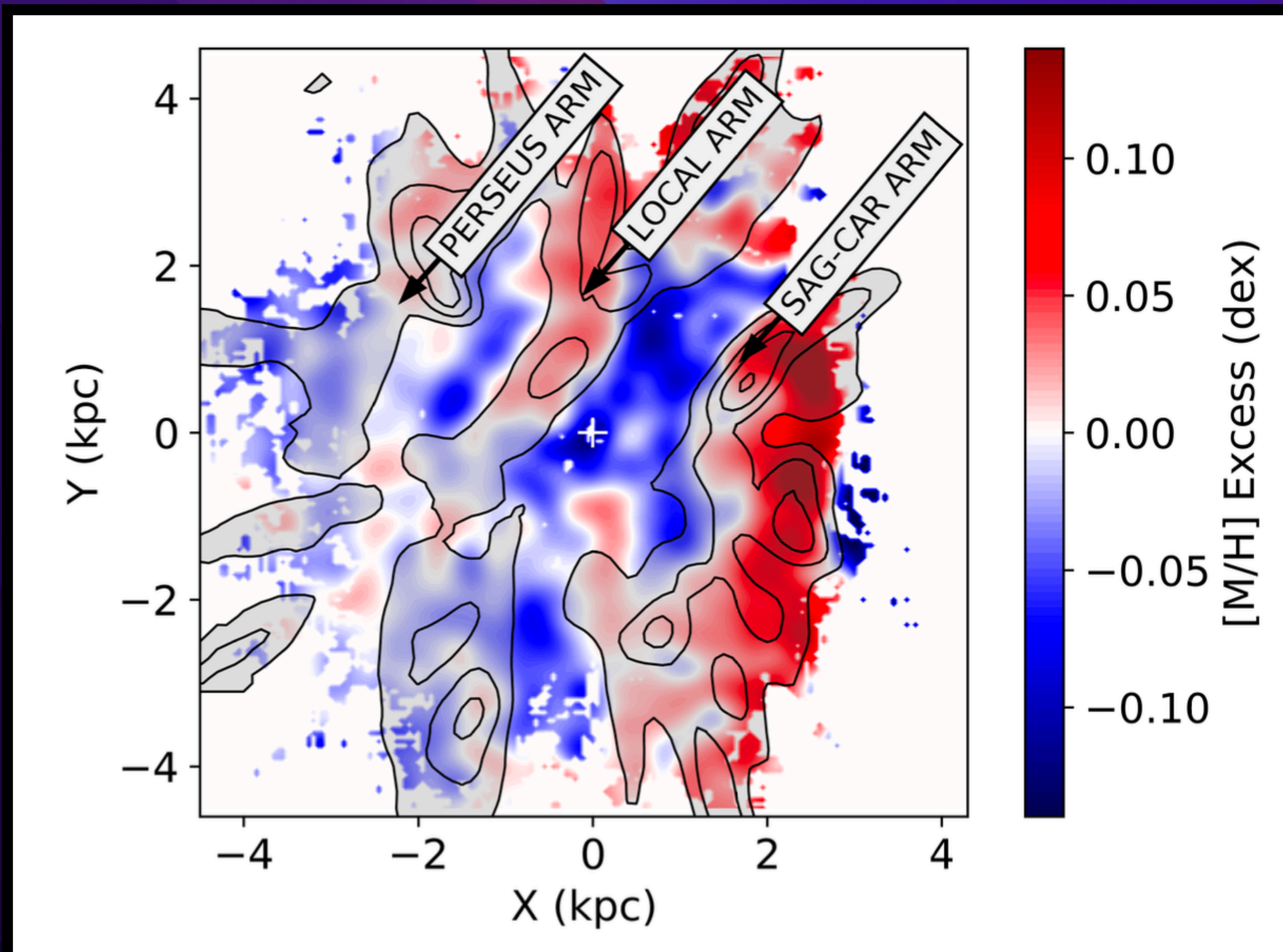
Comparison with Cepheids

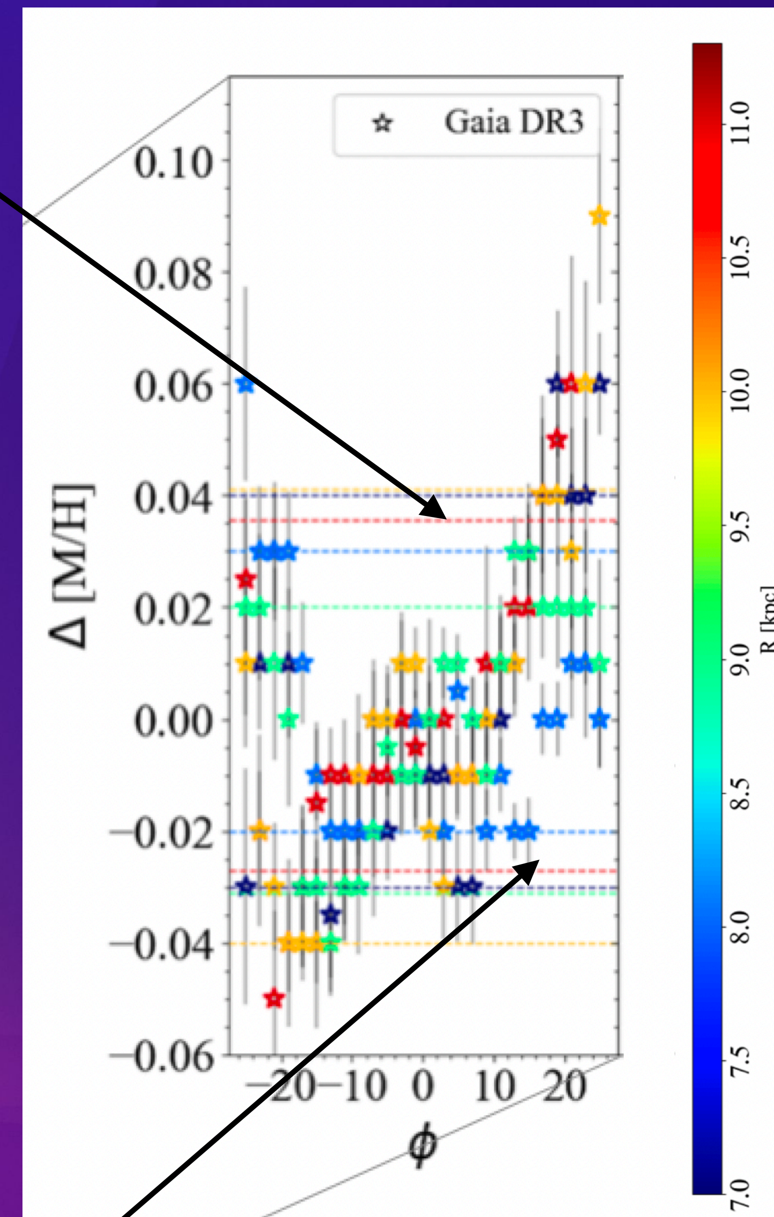




Comparison with Poggio+ES 22 (Gaia DR3)

Percentile 90%

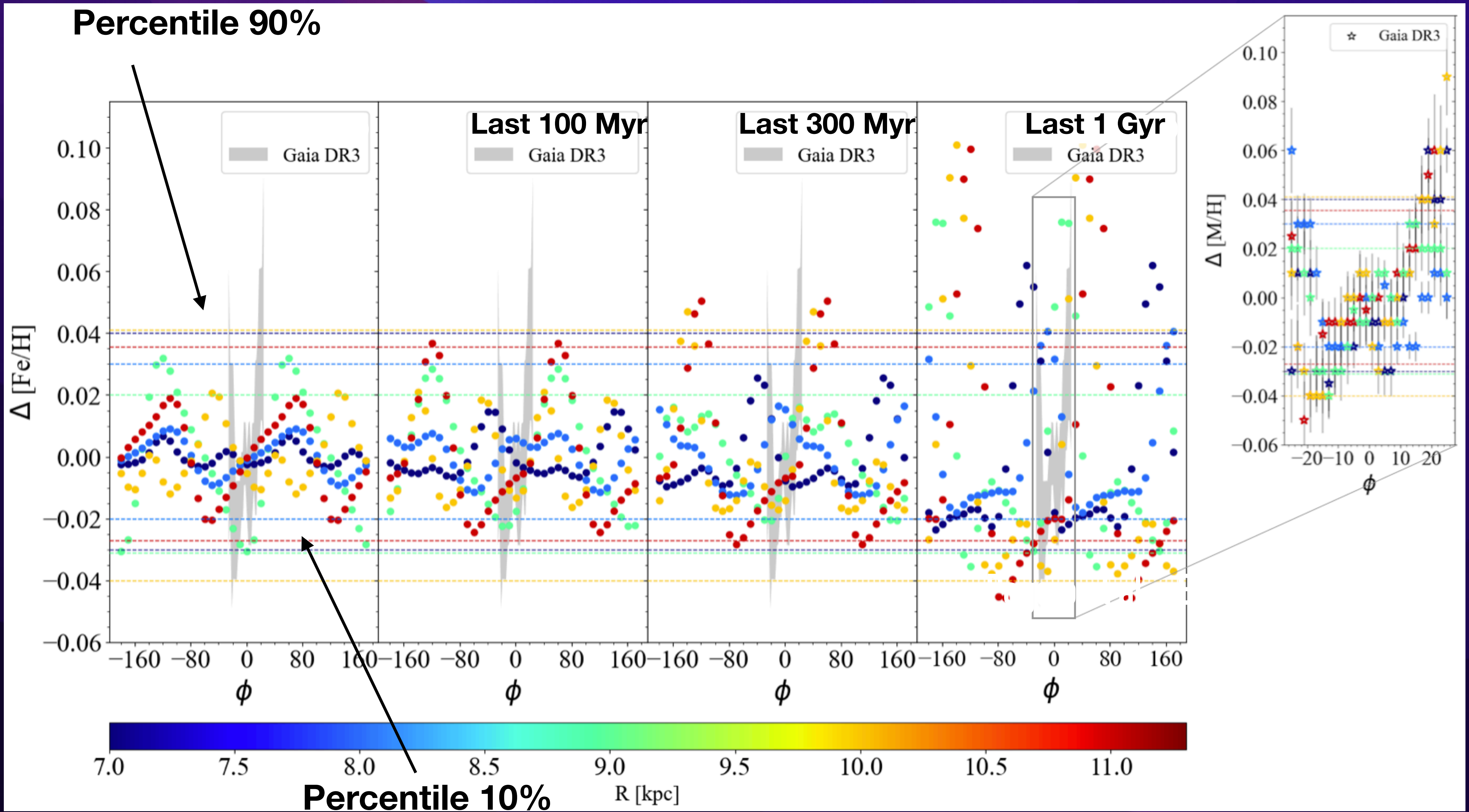




Percentile 10%

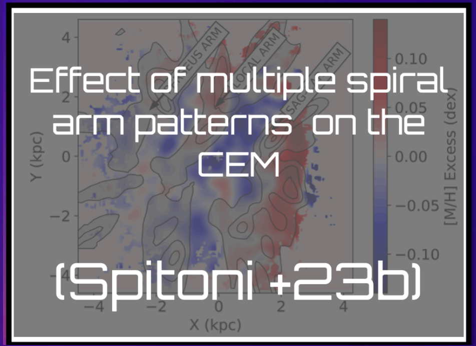
Percentile 10%

Comparison with Poggio+22 (Gaia DR3)



Conclusions

- The most recent gas infall - which started 2.7 Gyr ago - allows us to predict well the Gaia DR3 young population which has suffered a recent chemical impoverishment.



- Elements synthesised on short time scales (i.e., oxygen and europium in this study) exhibit larger abundance fluctuations.

- Predicted azimuthal variations are consistent with metallicity variations found by Gaia DR3 (Poggio et al. 2022), if co-rotation is extended to all radii at recent evolution times (during the last $\simeq$ 300 Myr).

Image credit: Giuliana Fiorentino

ABUNDANCE GRADIENTS IN THE LOCAL UNIVERSE (ADONIS)

Registration open

(Deadline 15 October 2023)

25 March - 19 April 2024

Giuseppe Bono, Antonela Monachesi, Laura Sánchez-Menguiano, Emanuele Spitoni, Rolf-Peter Kudritzki

Discussions will be organised to maximise the interaction between different communities and will be focussed on these themes:

Week 1 (25/3 to 29/3): Abundance gradients: Nature or Nurture?
Main topics: Galactic chemical enrichment: Halo, Bulge, Thin/Thick disk; Chemical evolution models for gas-poor and gas-rich stellar systems; Numerical simulations for MW/M31-like galaxies.

Week 2 (1/4 to 5/4): What is driving the azimuthal variations across the galactic thin disk?
Main topics: Numerical simulations and the mass content of the galaxies, mass-metallicity relation, metallicity distribution across the Bar and in stellar streams.

Week 3 (8/4 to 12/4): Are the radial abundance gradients universal?
Main topics: Chemo-dynamical models the impact of stellar migrations, spiral structure and resonances, chemical enrichment in classical and pseudo-bulges, kinematics and spectroscopy with Integral Field Spectrographs.

Week 4 (15/4 to 19/4): What has been the chemical enrichment of nearby stellar systems?
Main topics: Chemical enrichment in the zoo of dwarf galaxies, abundances based on optical/NIR diagnostics, new frontiers for theory and observations.

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