s, i & r Element Nucleosynthesis (sirEN)
Giulianova June 9-14 2025

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

Emanuele Spitoni

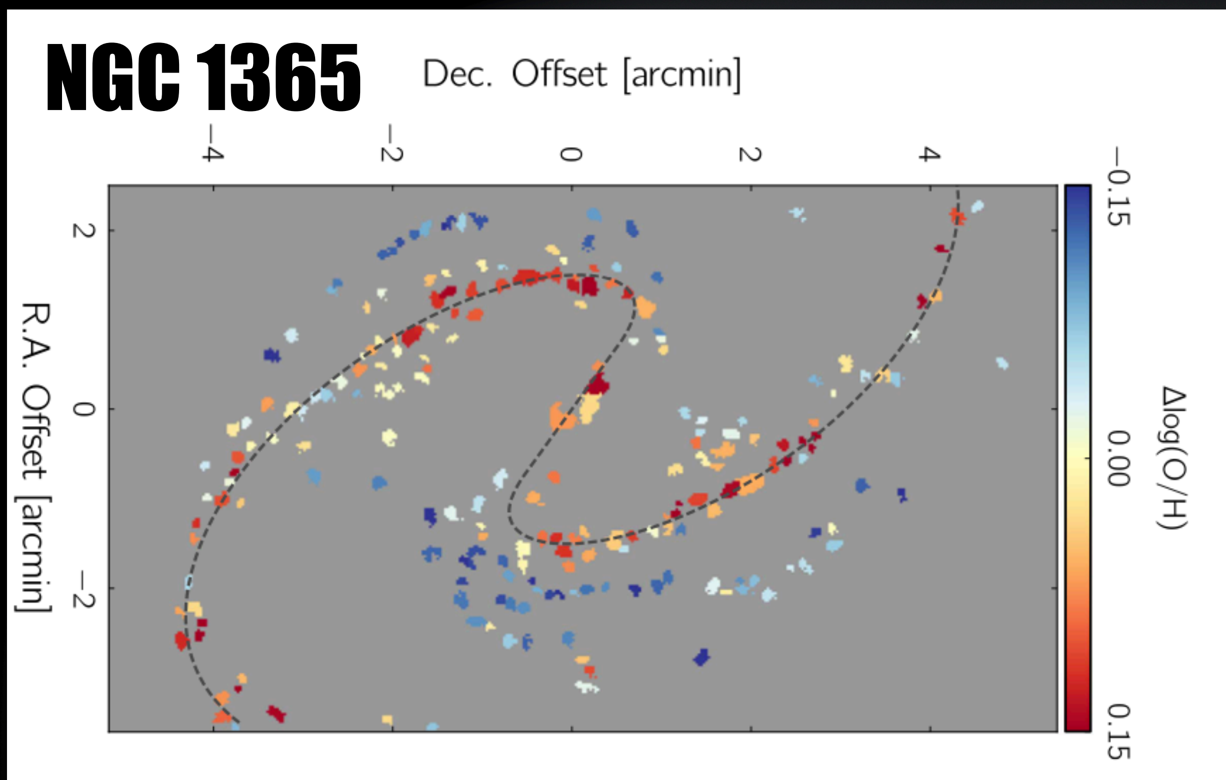
(In collaboration with G. Cescutti and I. Minchev)

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

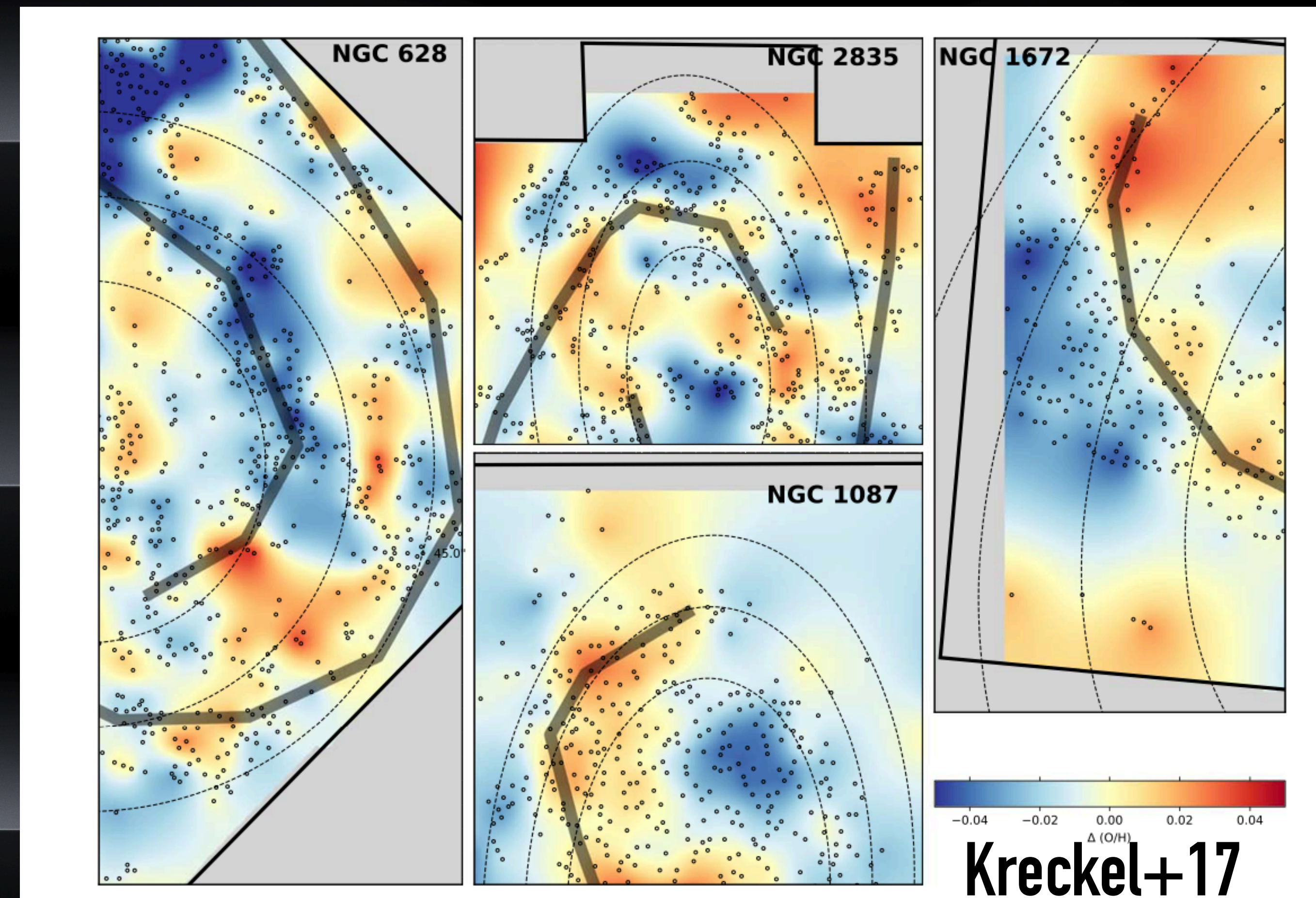
June 12th 2025

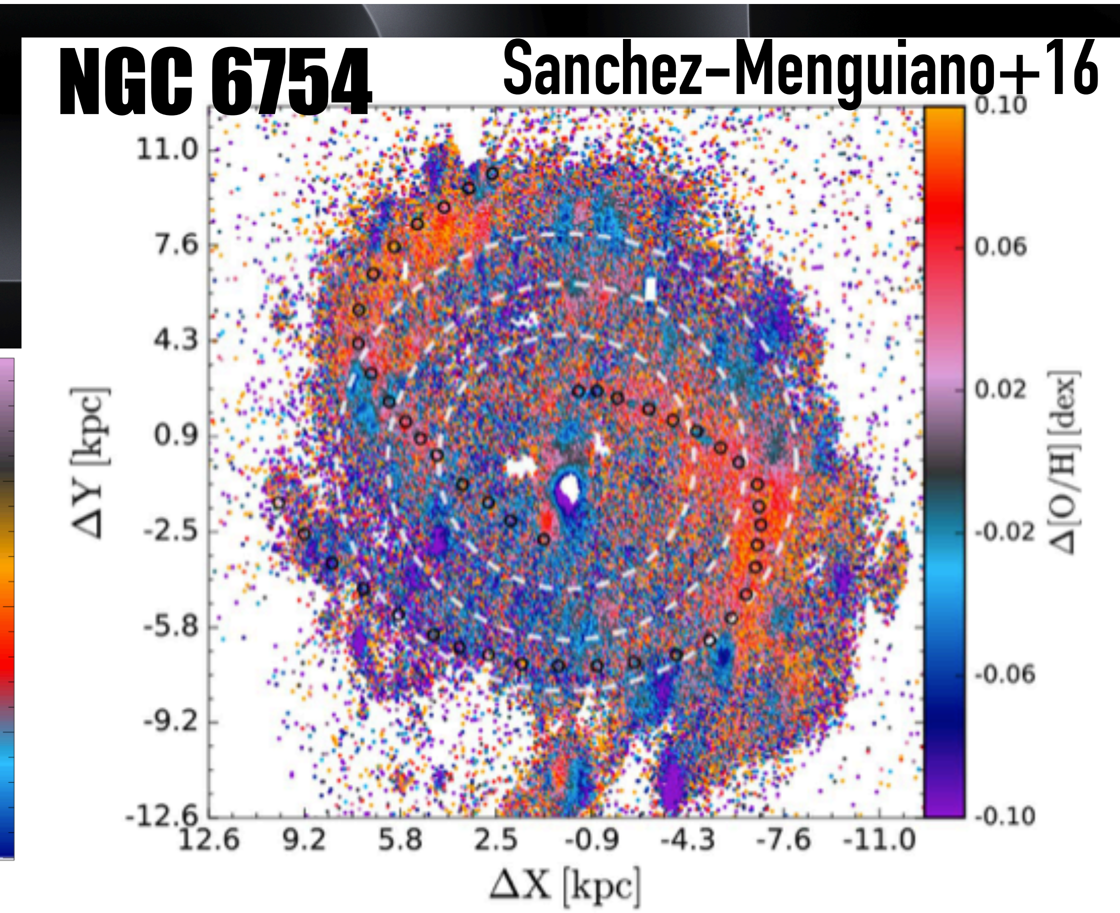
Chemical abundance azimuthal variations

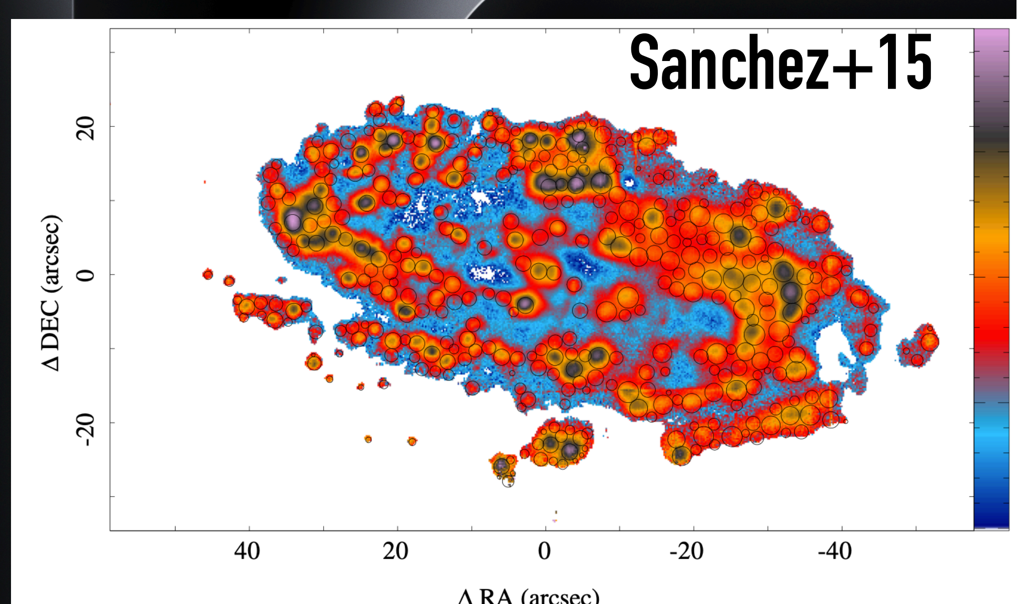
External galaxies



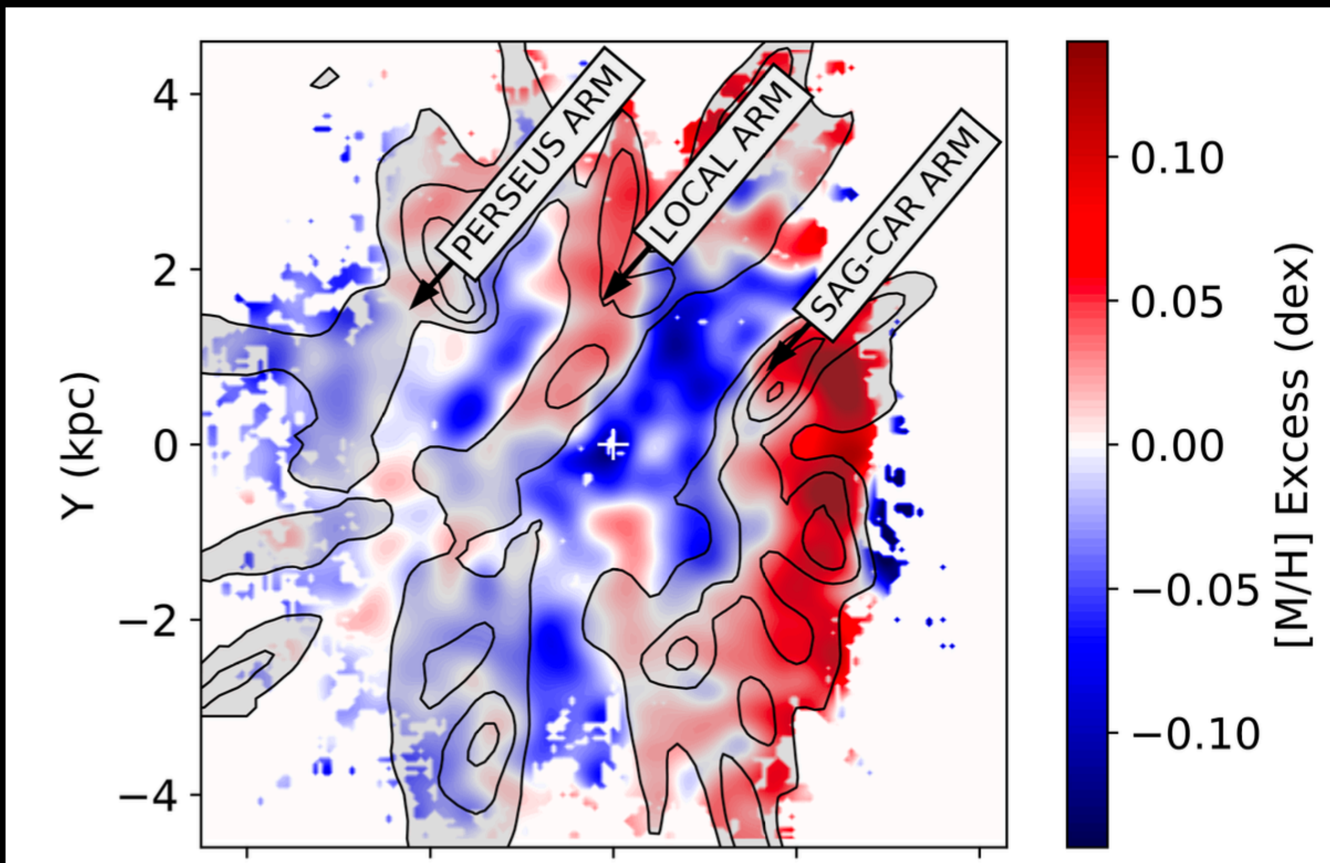
Ho+17





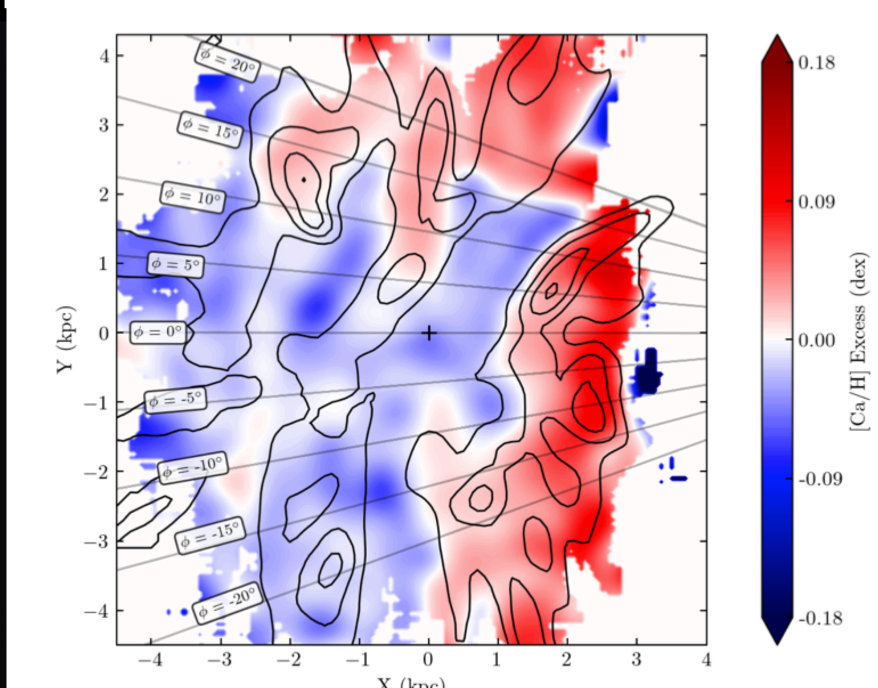


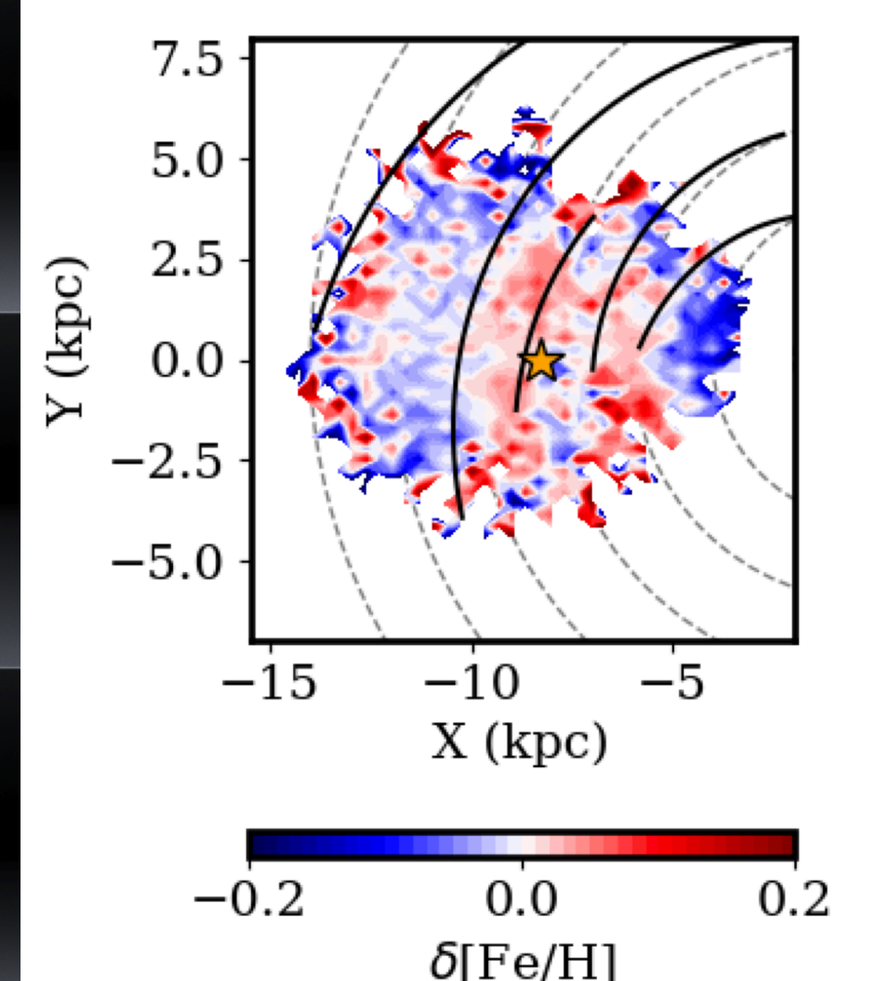
Milky Way



Poggio+ES 22 Gaia DR3

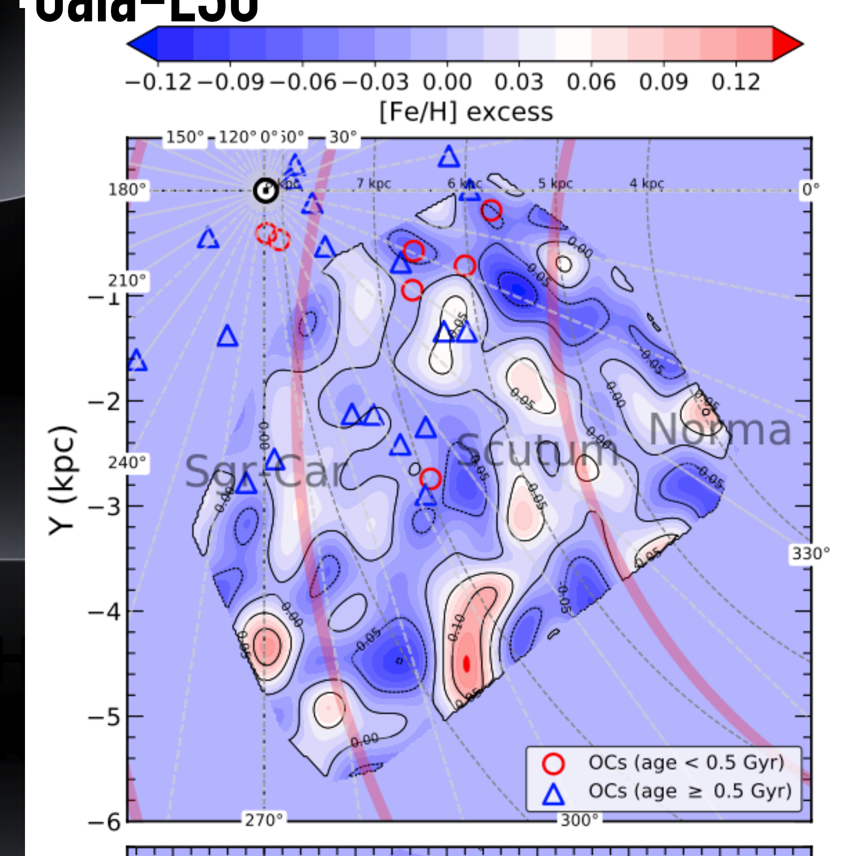
Barbillon+ES 25





Hackshaw+24
APOGEE

Viscasillas, Magrini, ES+25
Gaia-ESO



A 2D Galactic disk chemical evolution (Spitoni+19,23; Vasini,ES +25)

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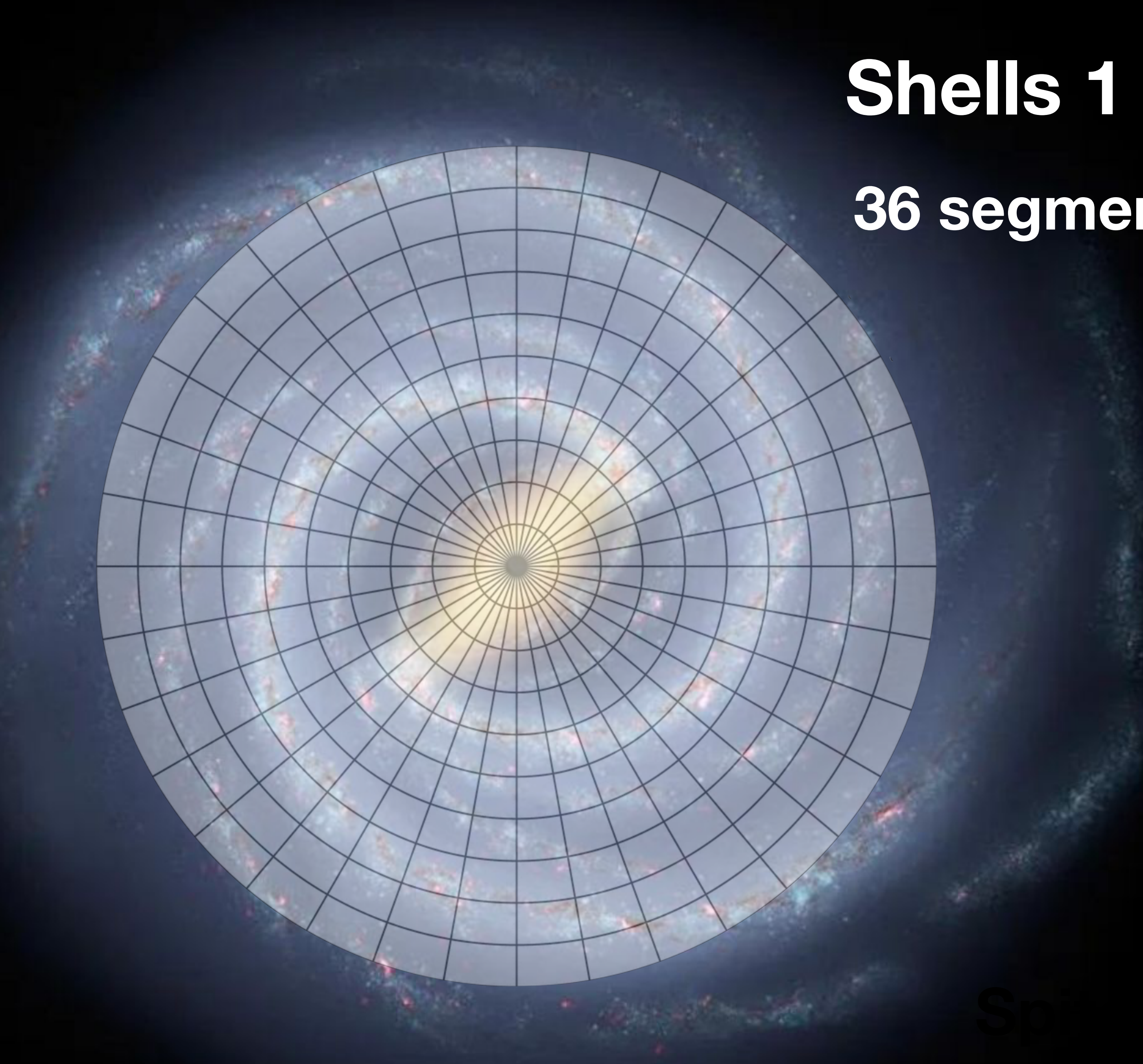

Shells 1 kpc-wide

36 segments of 10° width.

Spiral arms prescriptions

Spitoni+19

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

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

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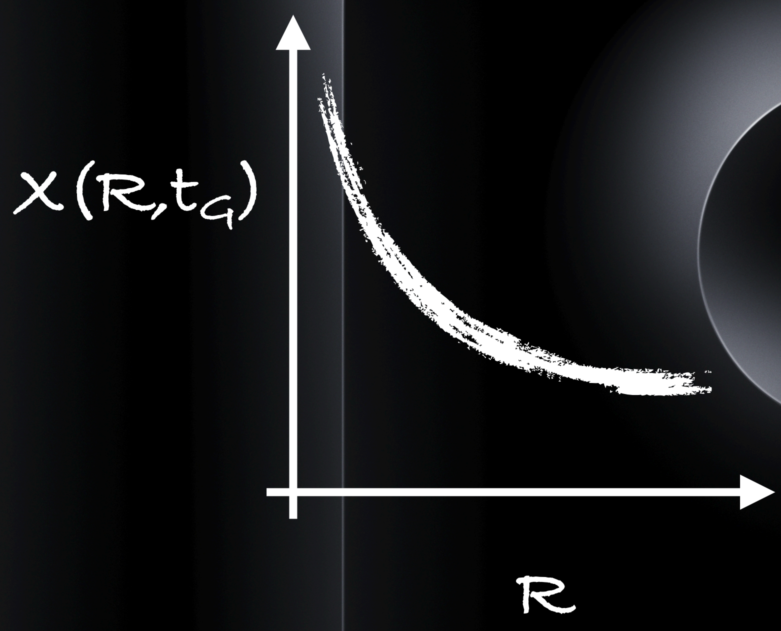
AMPLITUDE OF THE SPIRAL DENSITY



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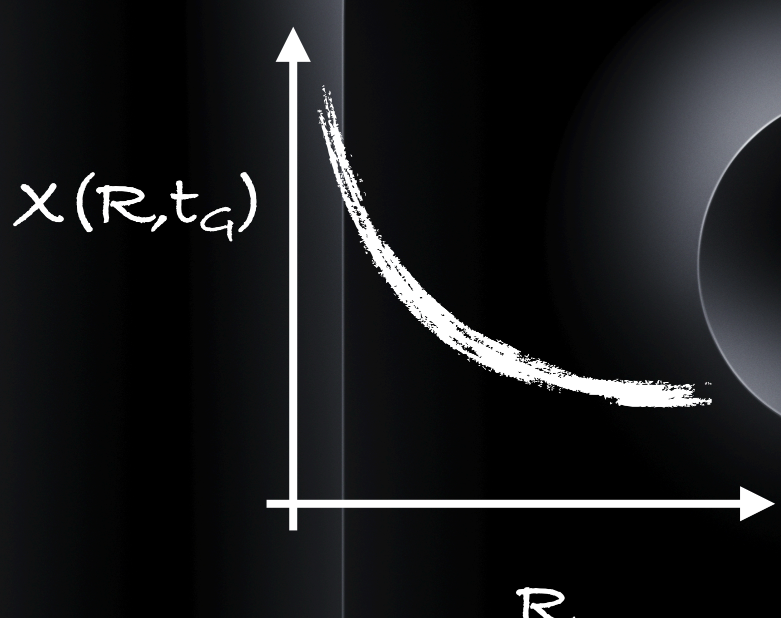


MODULATION FUNCTION

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

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

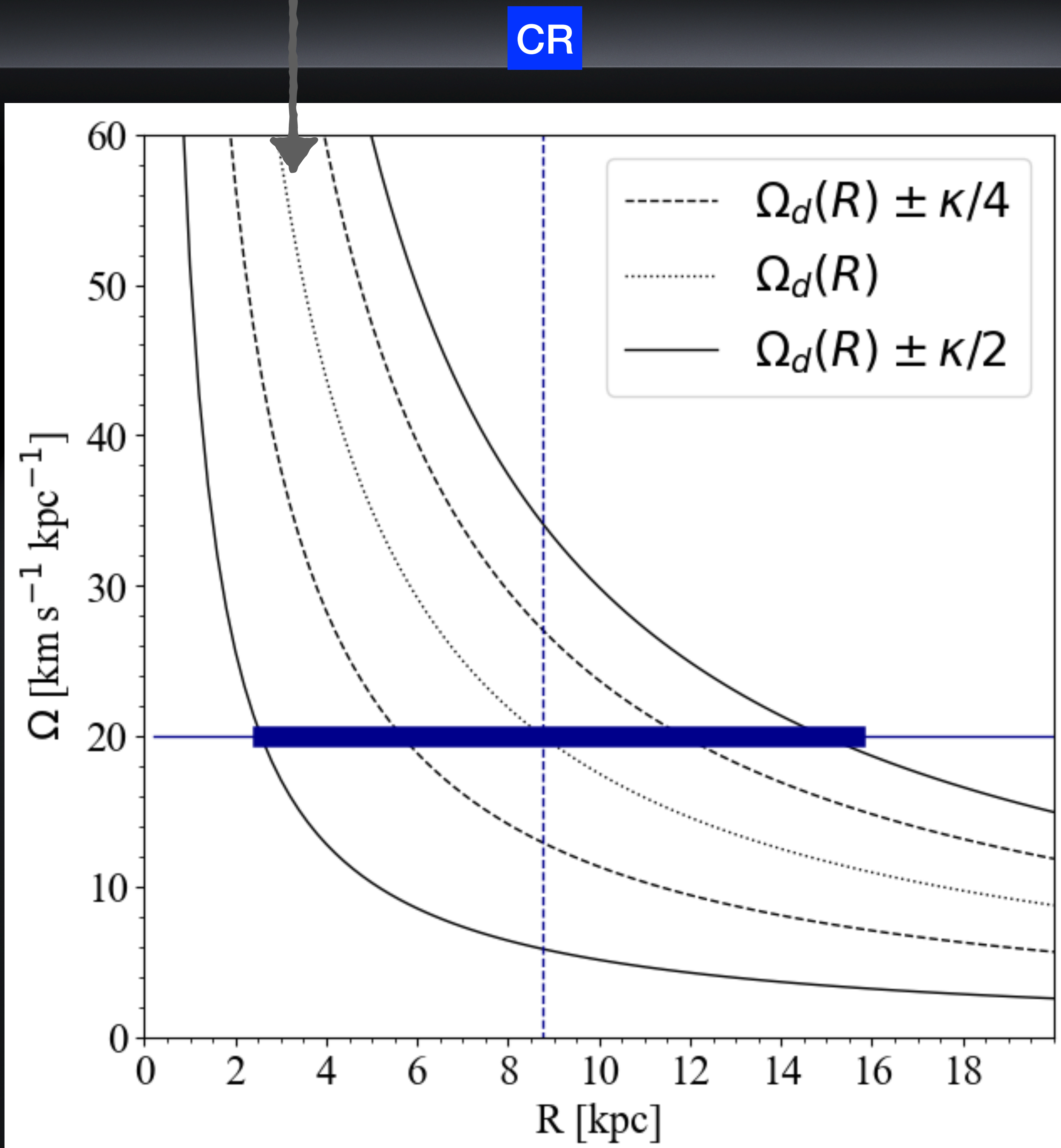
Cox & Gomez (2002)

m multiplicity (e.g. the number of spiral arms)

Ω_S angular velocity of the spiral pattern

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

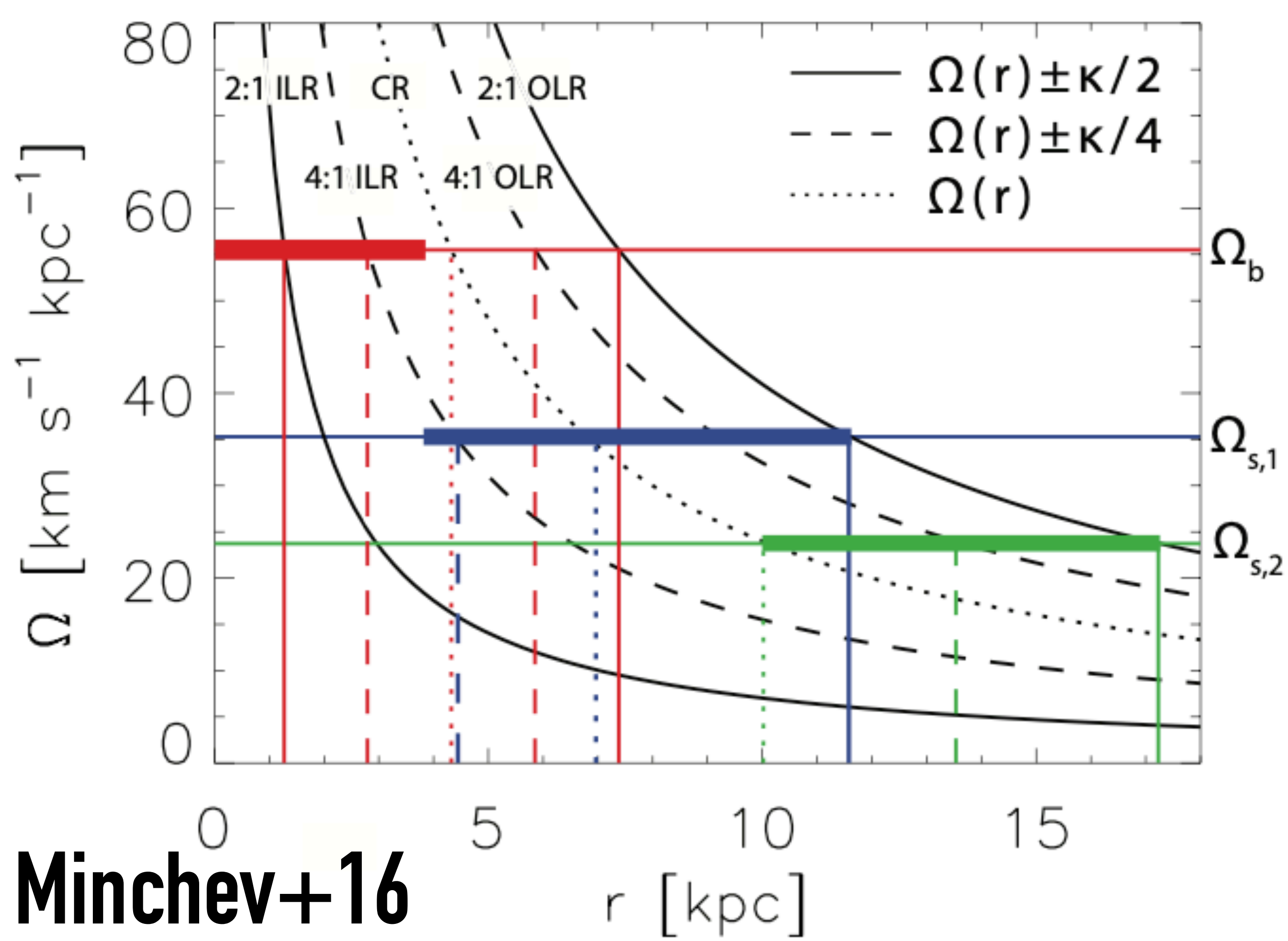
Spitoni+19



Spiral structure with multiplicity m = 2 with a single pattern

Modelings side: why multiple spiral modes?

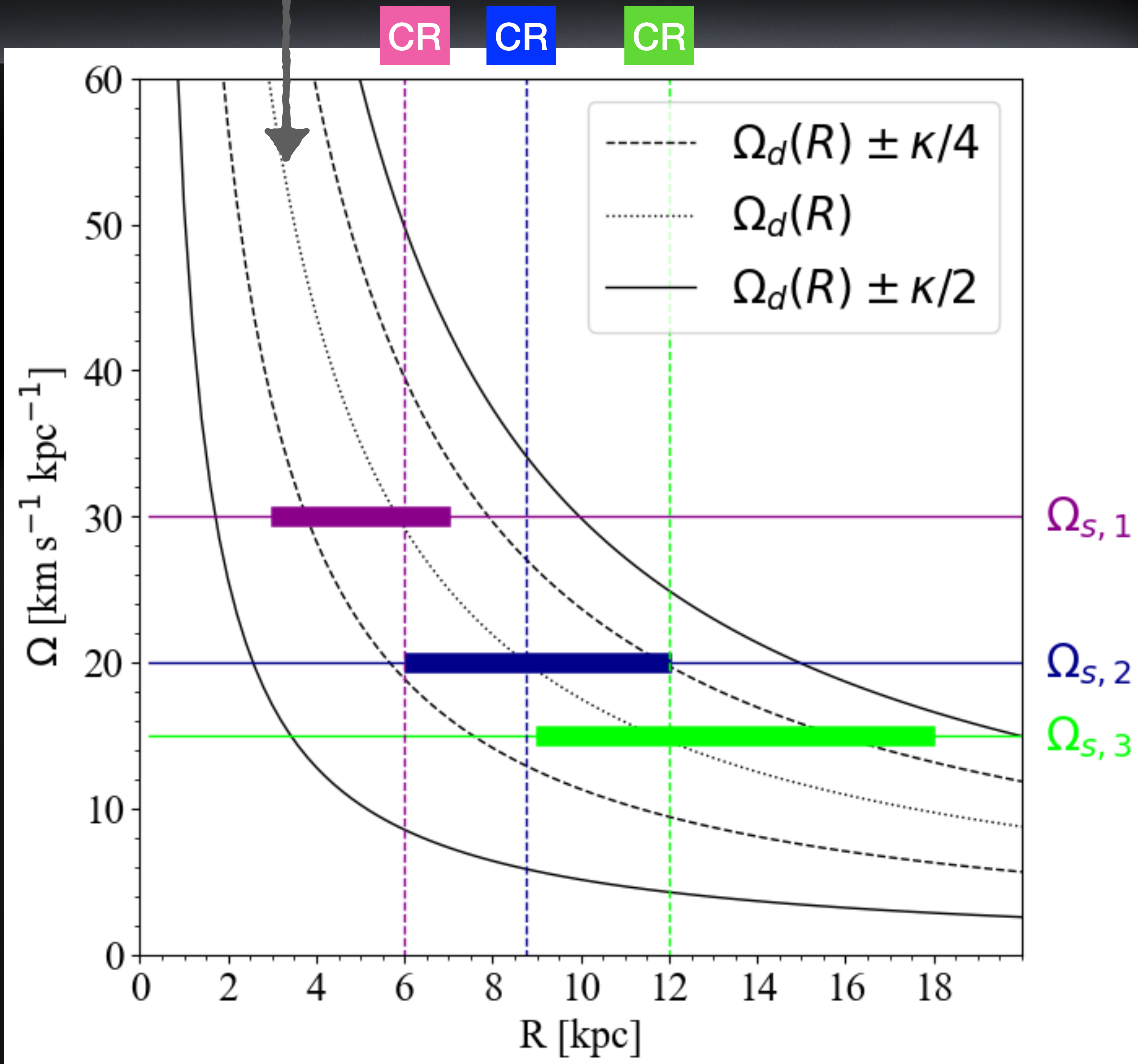
Presence of multiple spiral modes moving at different pattern speeds in galactic discs including our own Milky Way (Minchev & Quillen 2006 Quillen et al. 2011)



Minchev+16

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

Spitoni+23

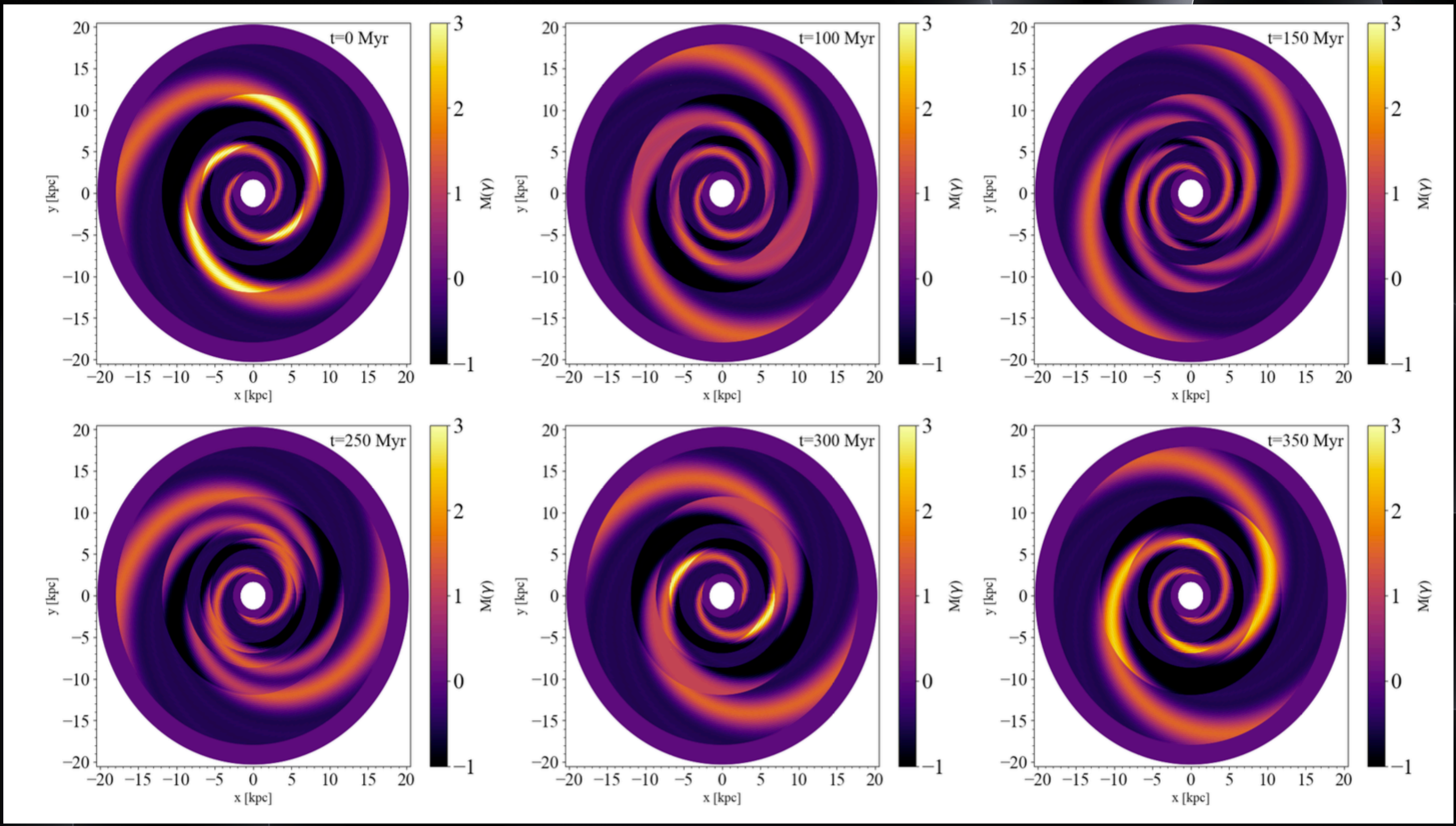


Spiral structure with multiplicity m = 2 composed by three chunks moving at different pattern speeds

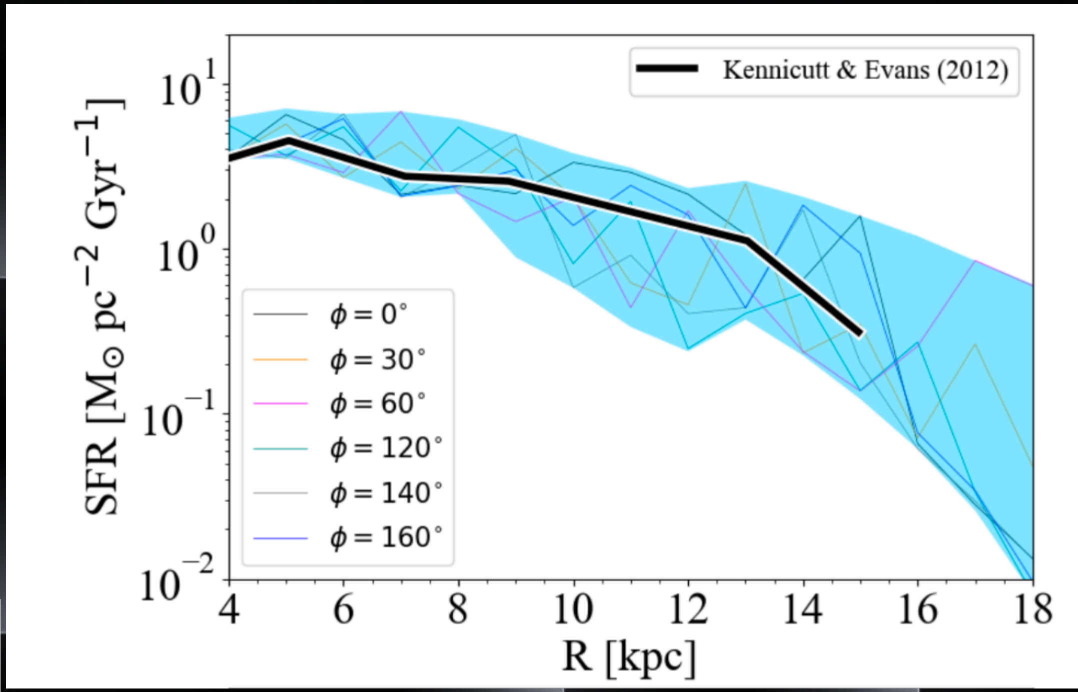
MODEL

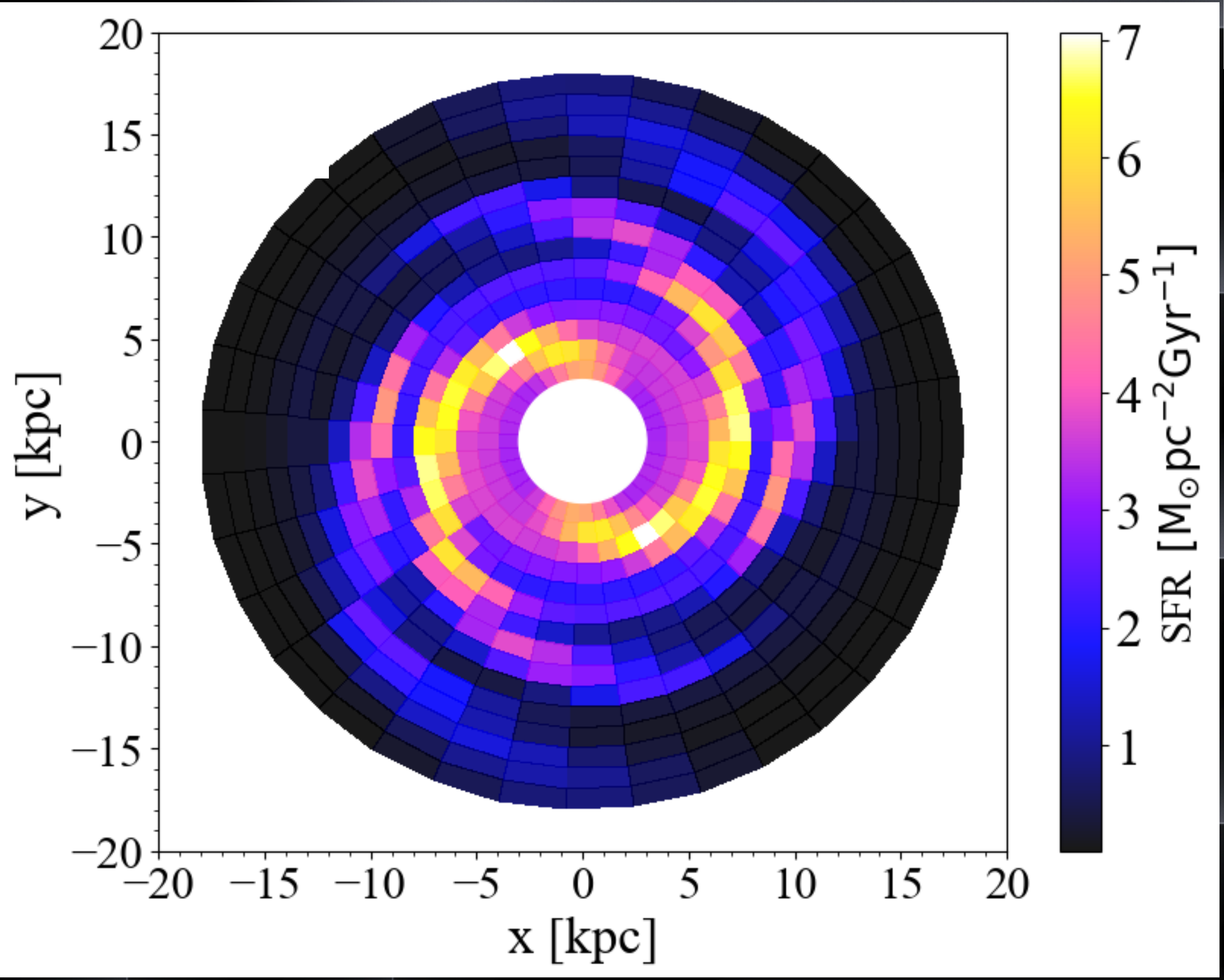
For a m=2 spiral arms structure

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



The present-day star formation rate

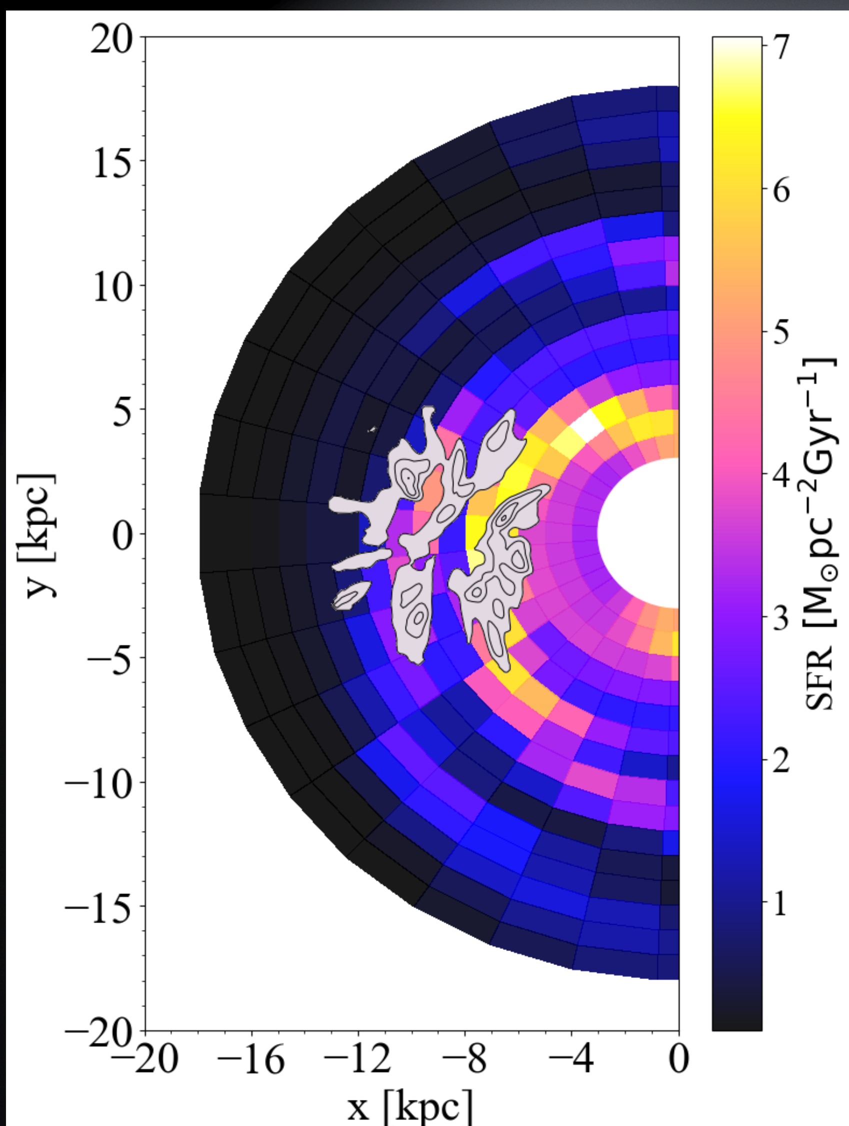




Spitoni+23

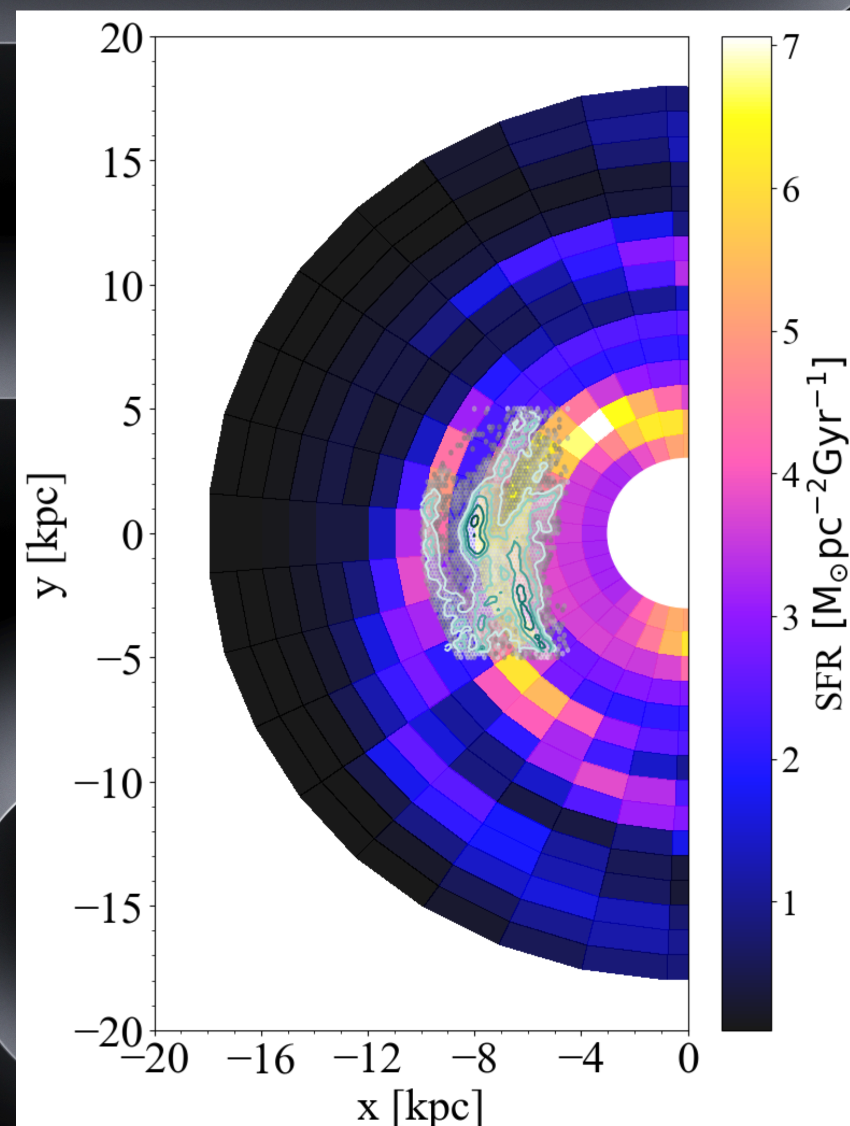
Poggio+21

UPM stars



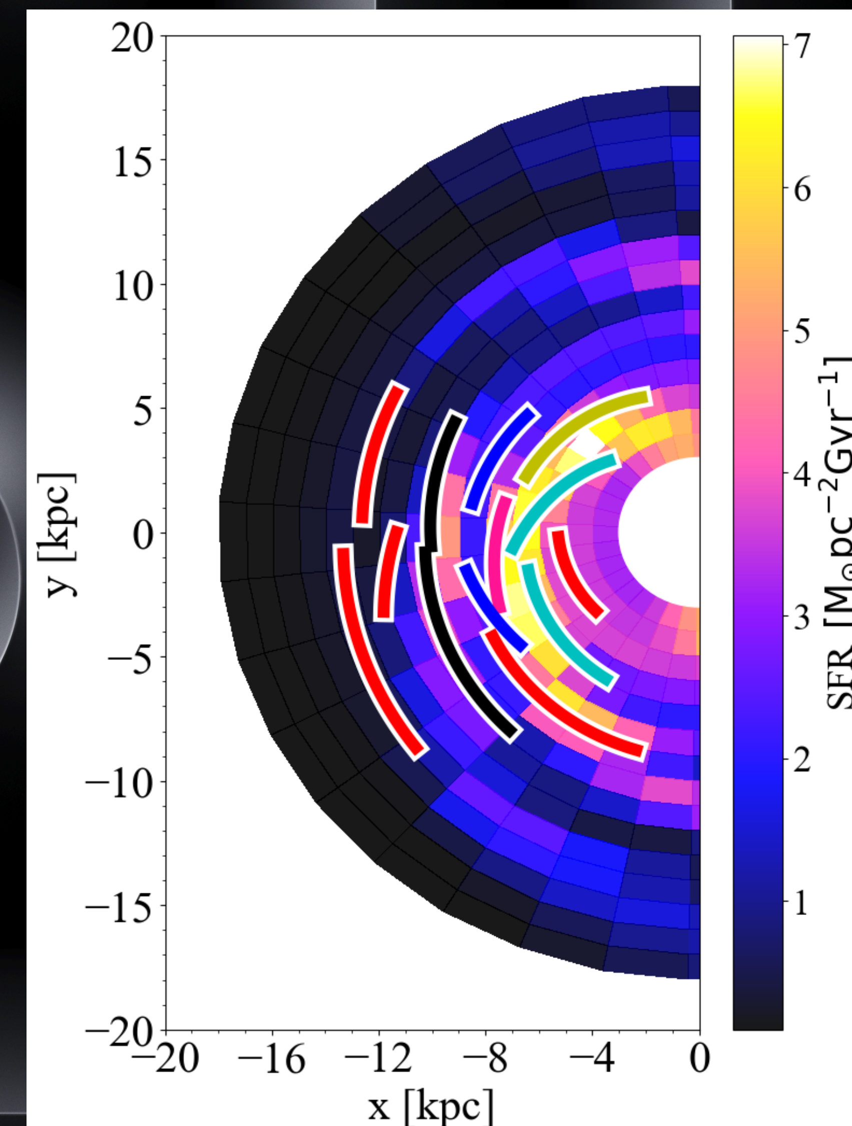
Palicio+ES 23

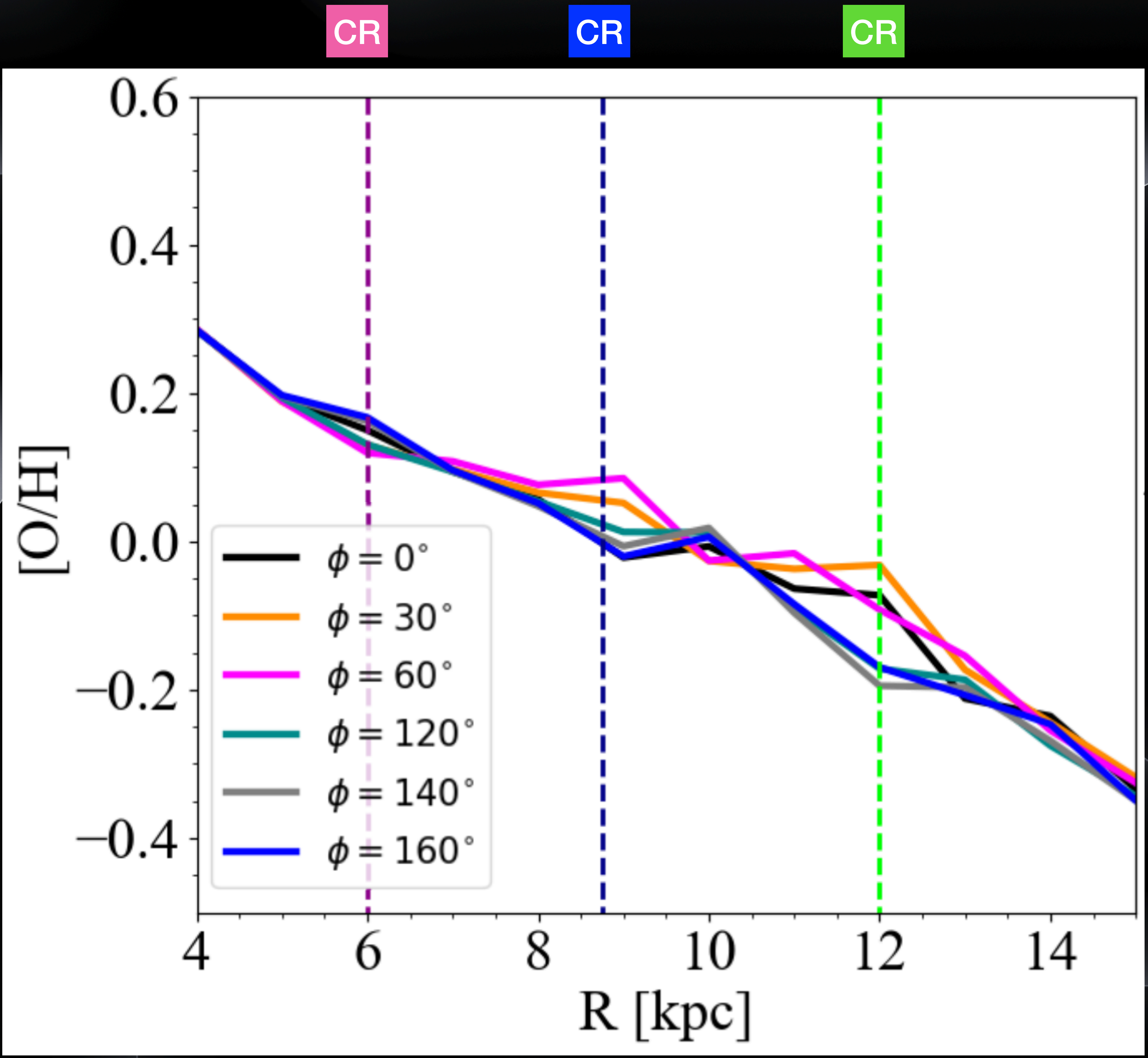
Radial actions, $J_R < 0.01\ R_\odot V_\odot$



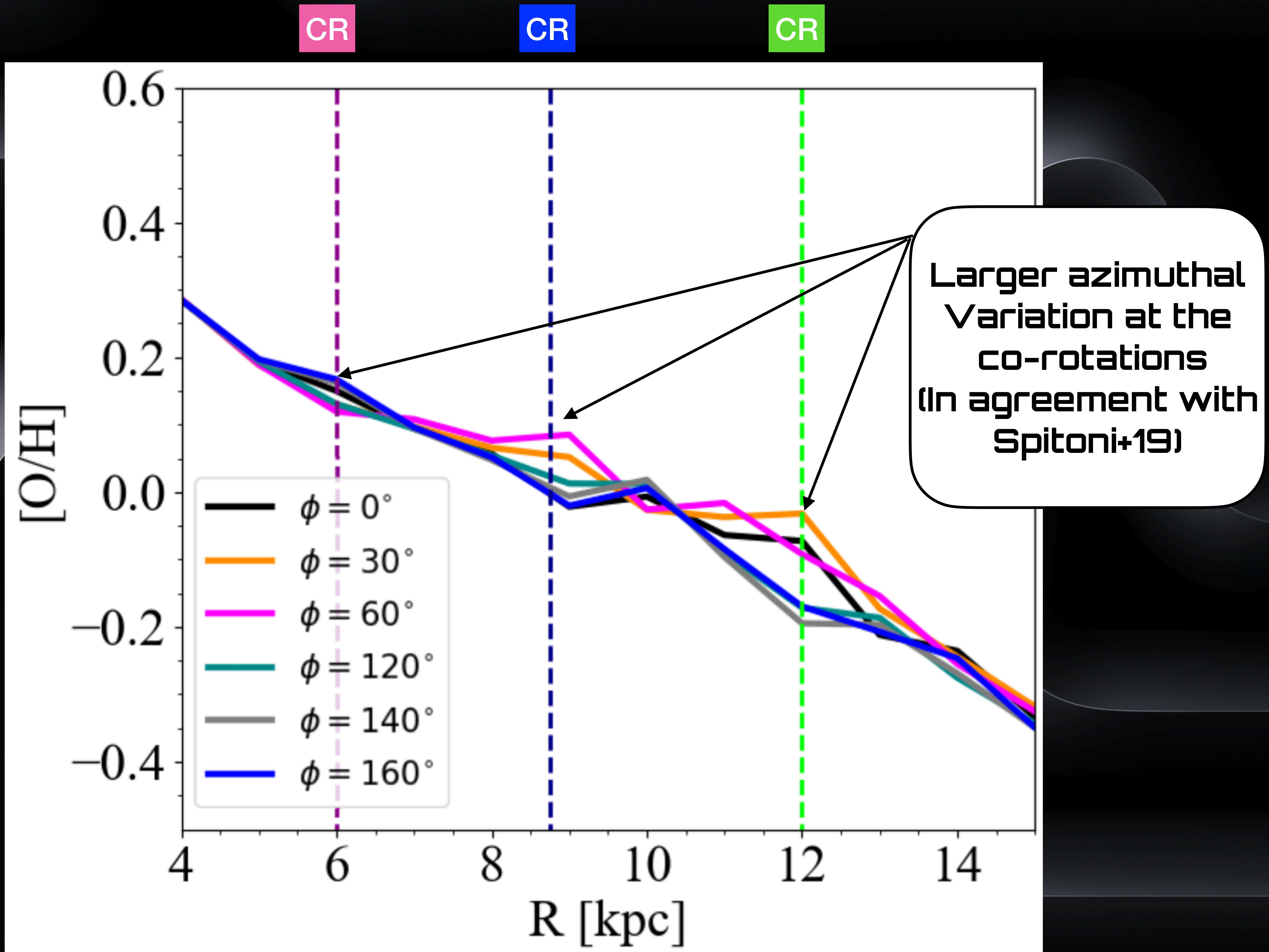
Lemasle+22

Cepheids

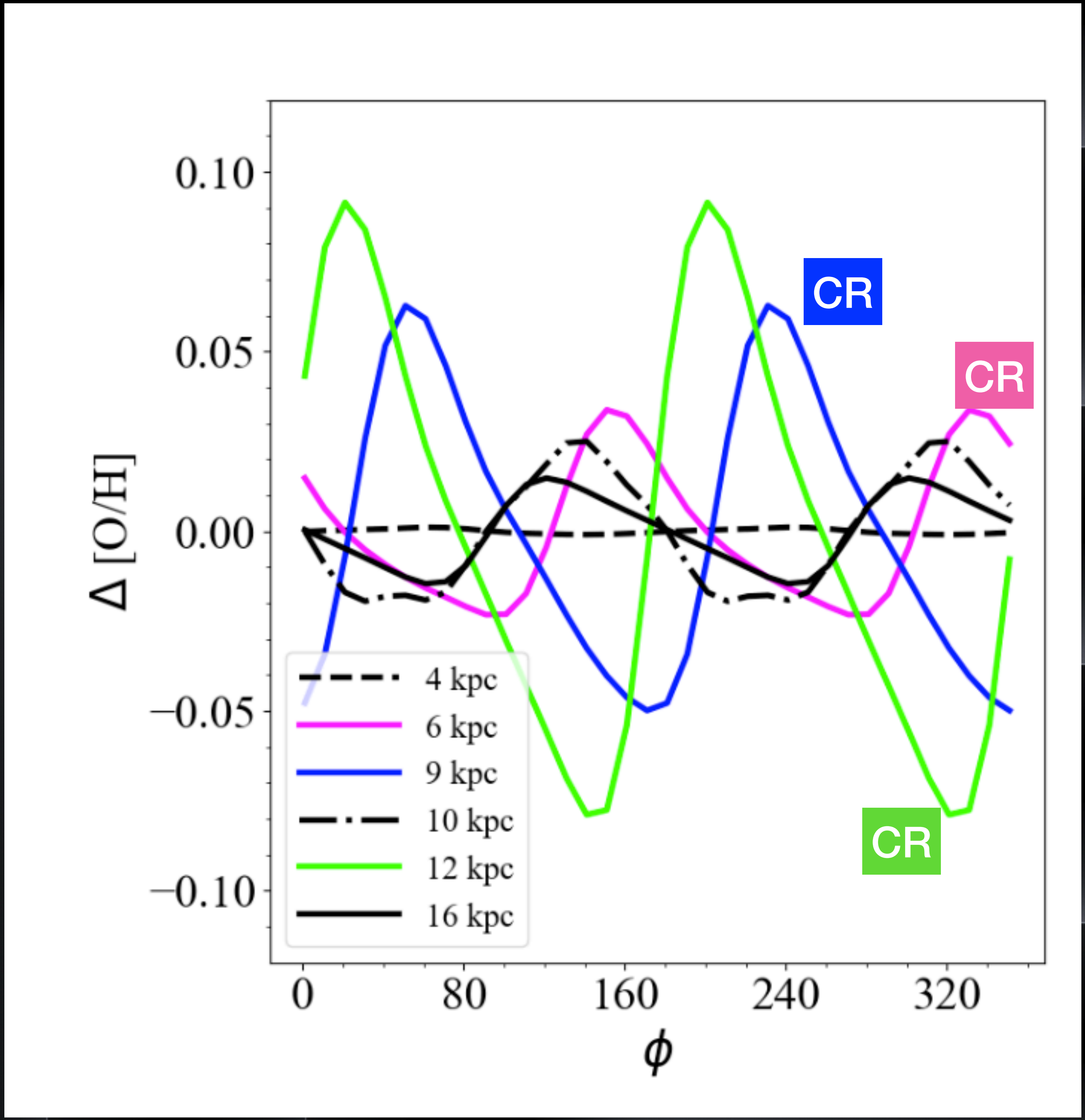




CR
CR
CR
0.6
0.4
0.2
0.0
−0.2
−0.4
[O/H]
$\phi = 0^\circ$
$\phi = 30^\circ$
$\phi = 60^\circ$
$\phi = 120^\circ$
$\phi = 140^\circ$
$\phi = 160^\circ$
4
6
8
10
12
14
R [kpc]


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]
ϕ = 0°
ϕ = 30°
ϕ = 60°
ϕ = 120°
ϕ = 140°
ϕ = 160°
Larger azimuthal Variation at the co-rotations (In agreement with Spitoni+19)

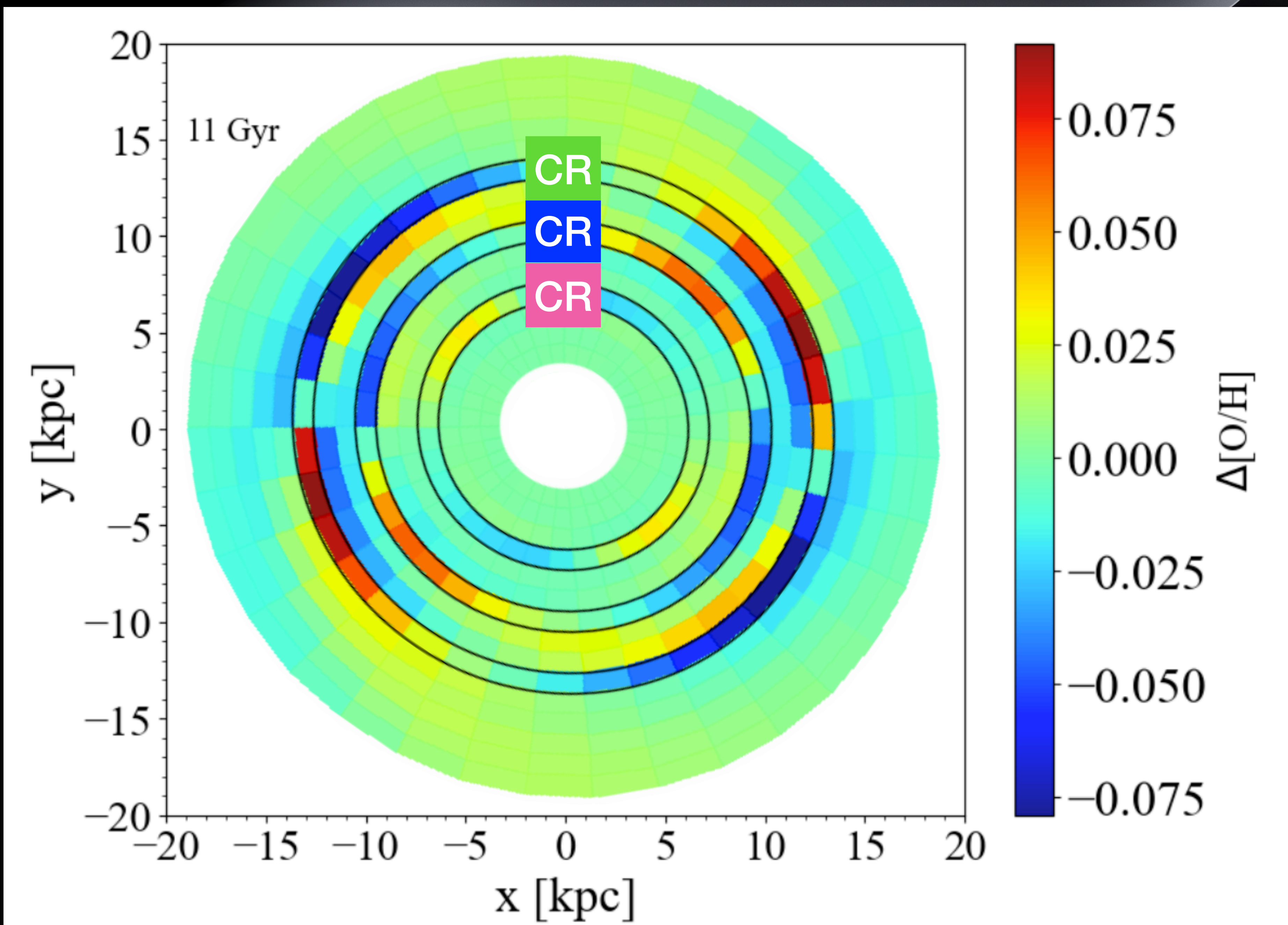
Present day residual azimuthal variations



Larger azimuthal Variation at the co-rotations (In agreement with Spitoni+19)

Spitoni+23

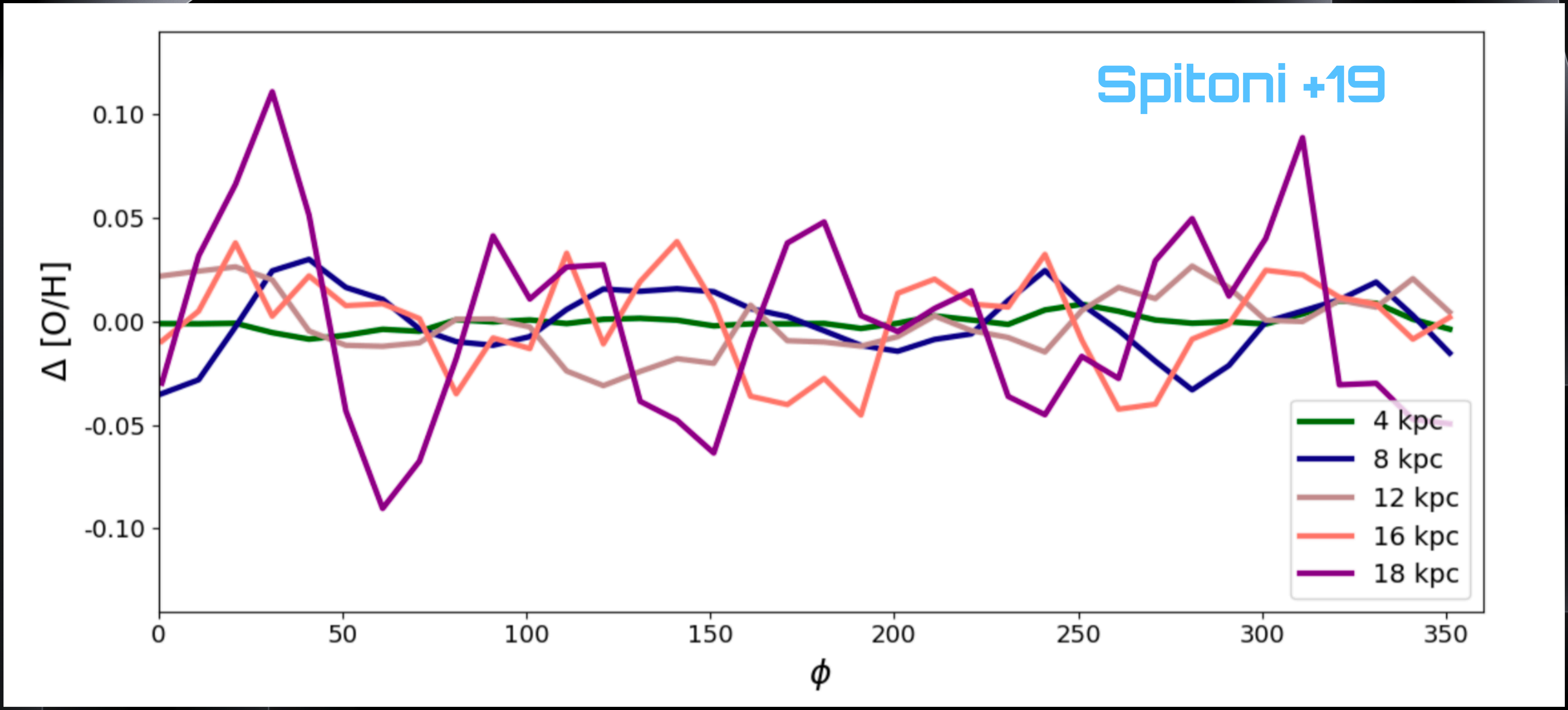
Present day residual azimuthal variations



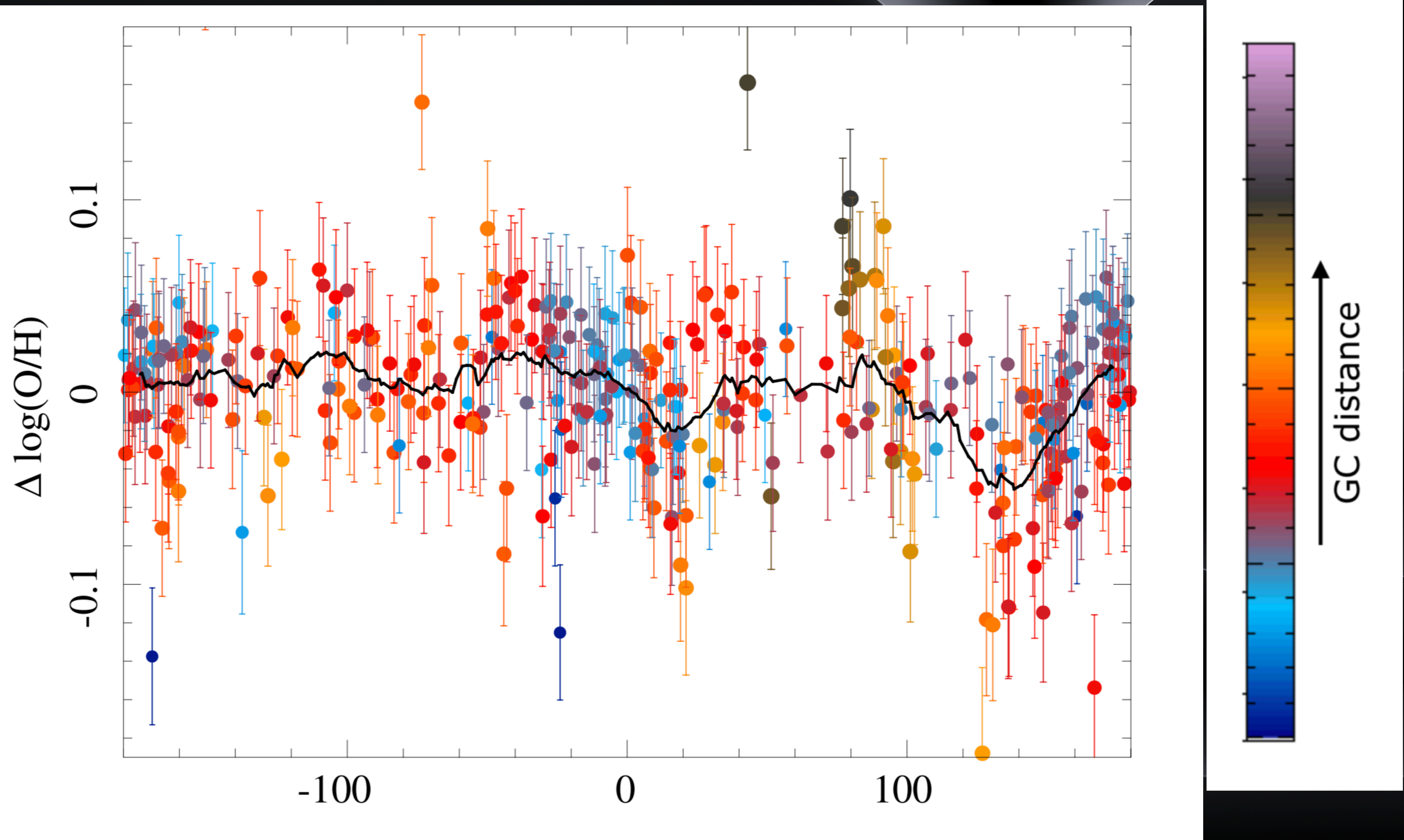
Larger azimuthal Variation at the co-rotations (In agreement with Spitoni+19)

Spitoni+23

... Results in agreement with the chemical evolution model in which we consider the density fluctuation by the chemo-dynamical model by Minchev+13

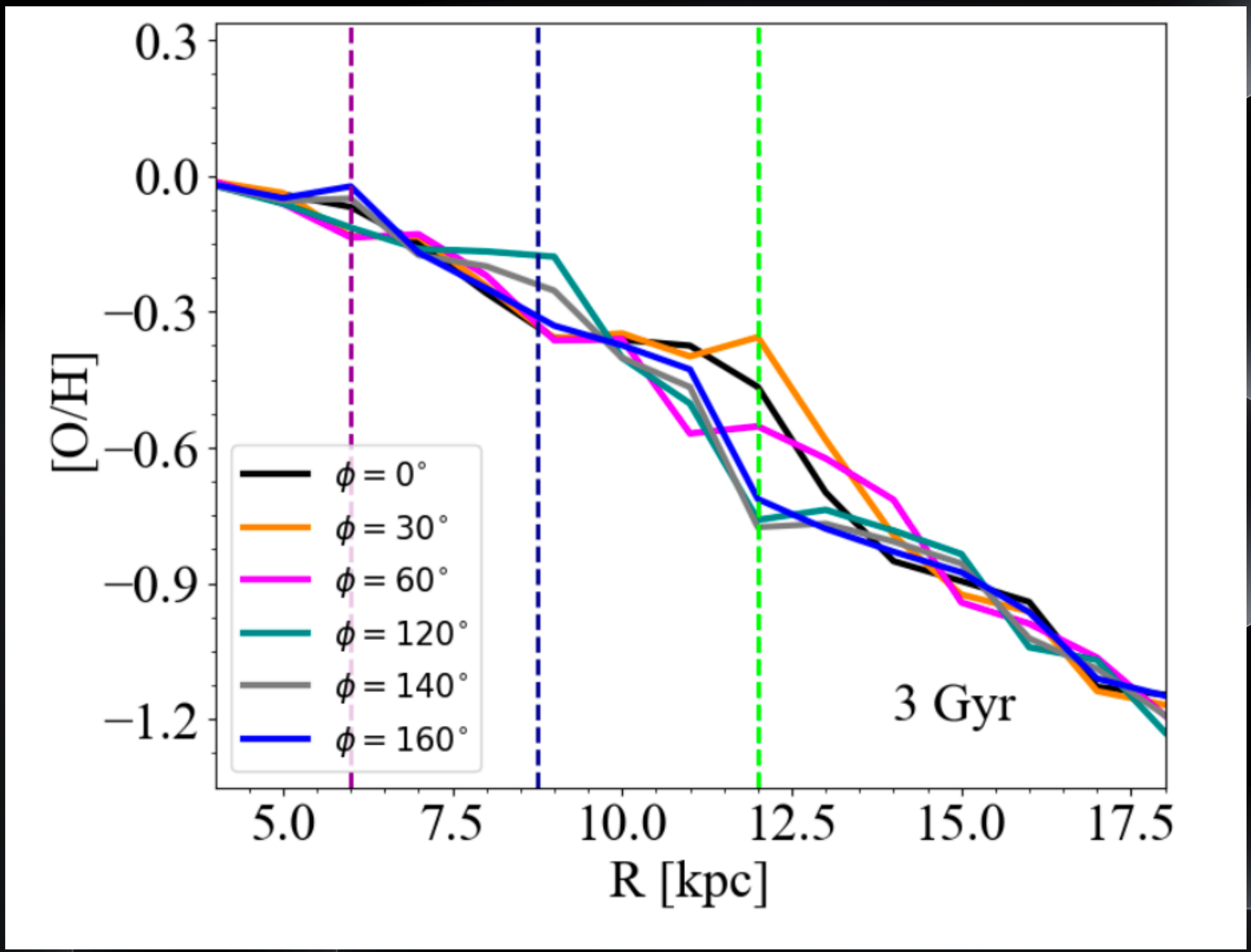


NGC 6754



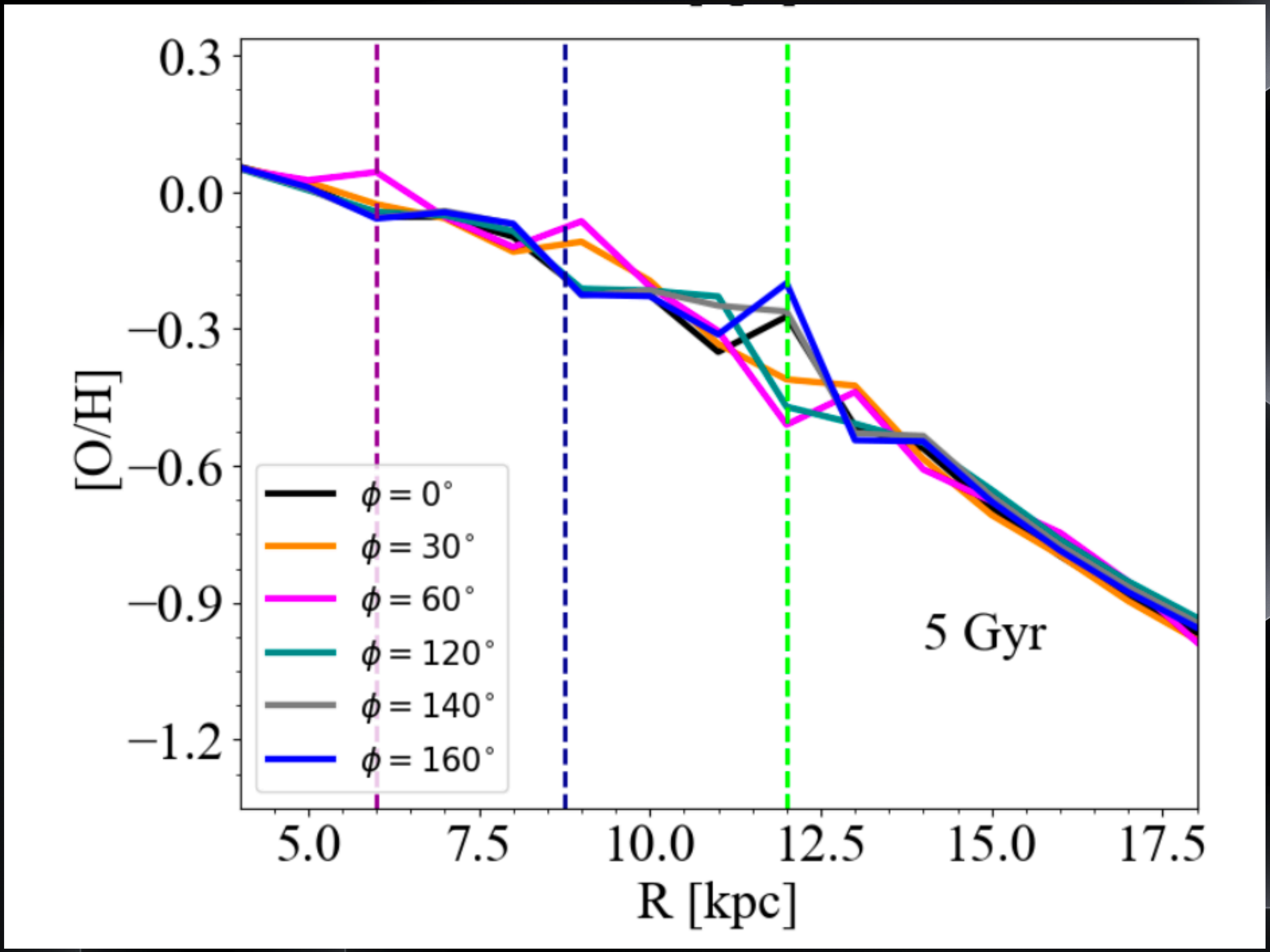
Sanchez et al. (2015)

Temporal evolution of the oxygen gradient



As the oxygen abundance increases (i.e. closer to the "satura- tion" level of the chemical enrichment), the chemical variations due to perturbations of the SFR become smaller.

Temporal evolution of the oxygen gradient



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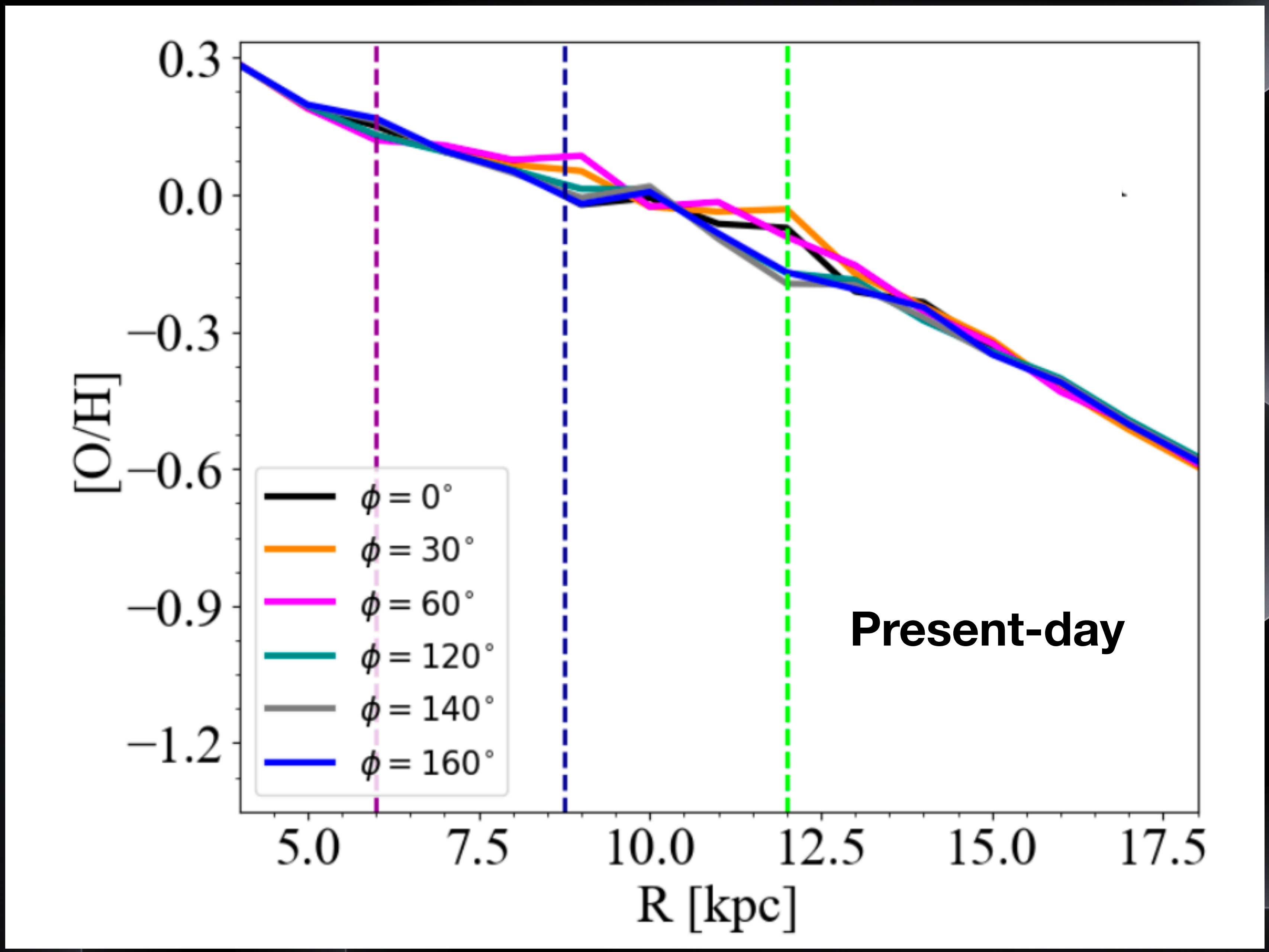

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What about other -s and -r process elements?

Ba Eu

Ba

Modified yields of Cristallo et al. (2009, 2011) for nucleosynthesis by the s-process in low-mass AGB stars +rotating massive stars (Frischknecht+16)

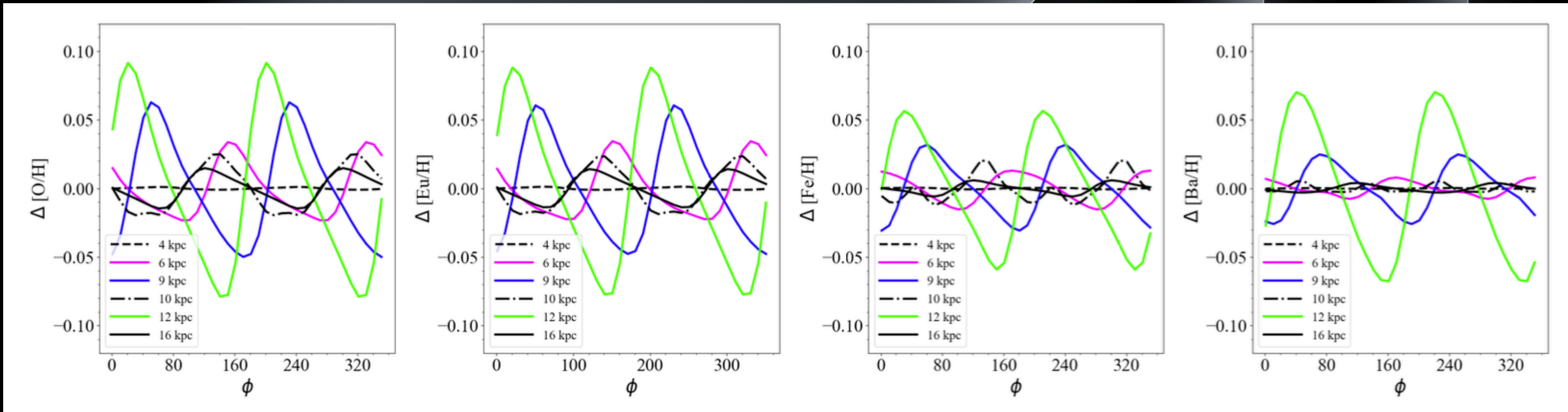
Eu

NSM fixed time delay of 1 Myr for the coalescence (the scenario is also compatible with other sources of r-process material such as MRD SNe)

(see Cescutti +15, Rizzuti+19)

Present day residual azimuthal variations

Oxygen Europium Iron Barium



Present day residual azimuthal variations

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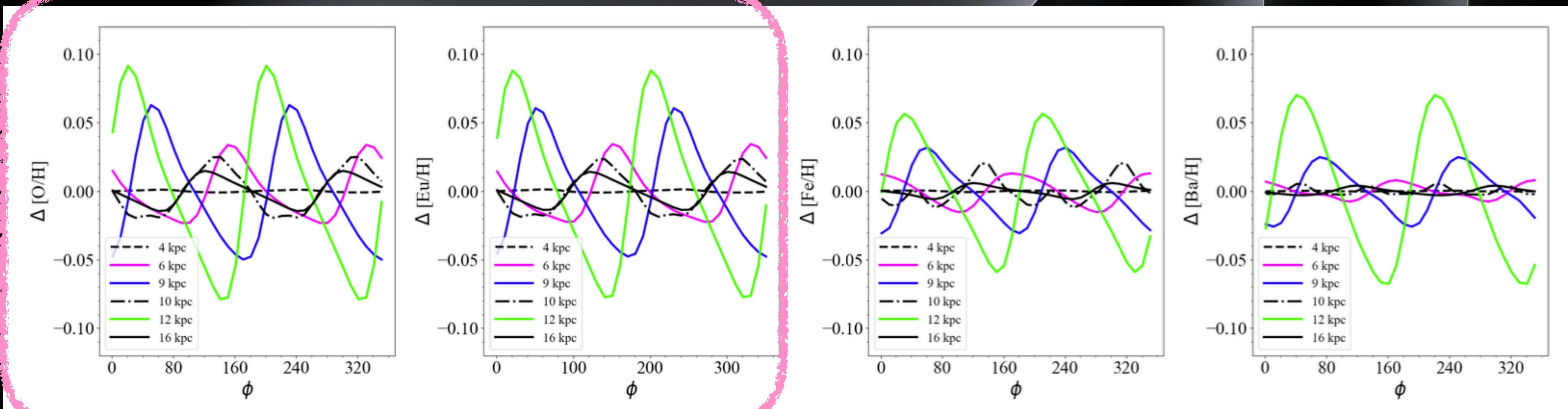
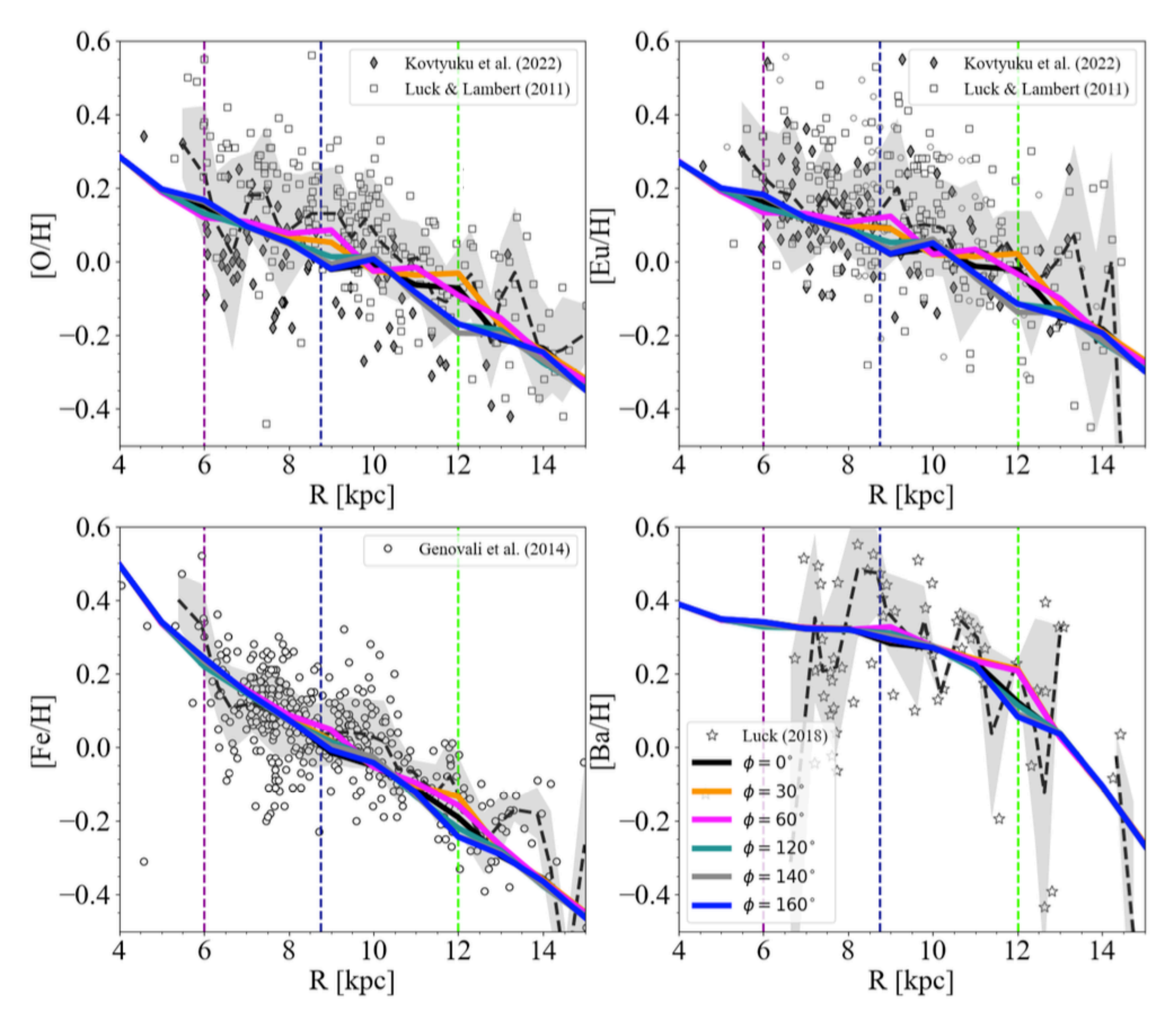


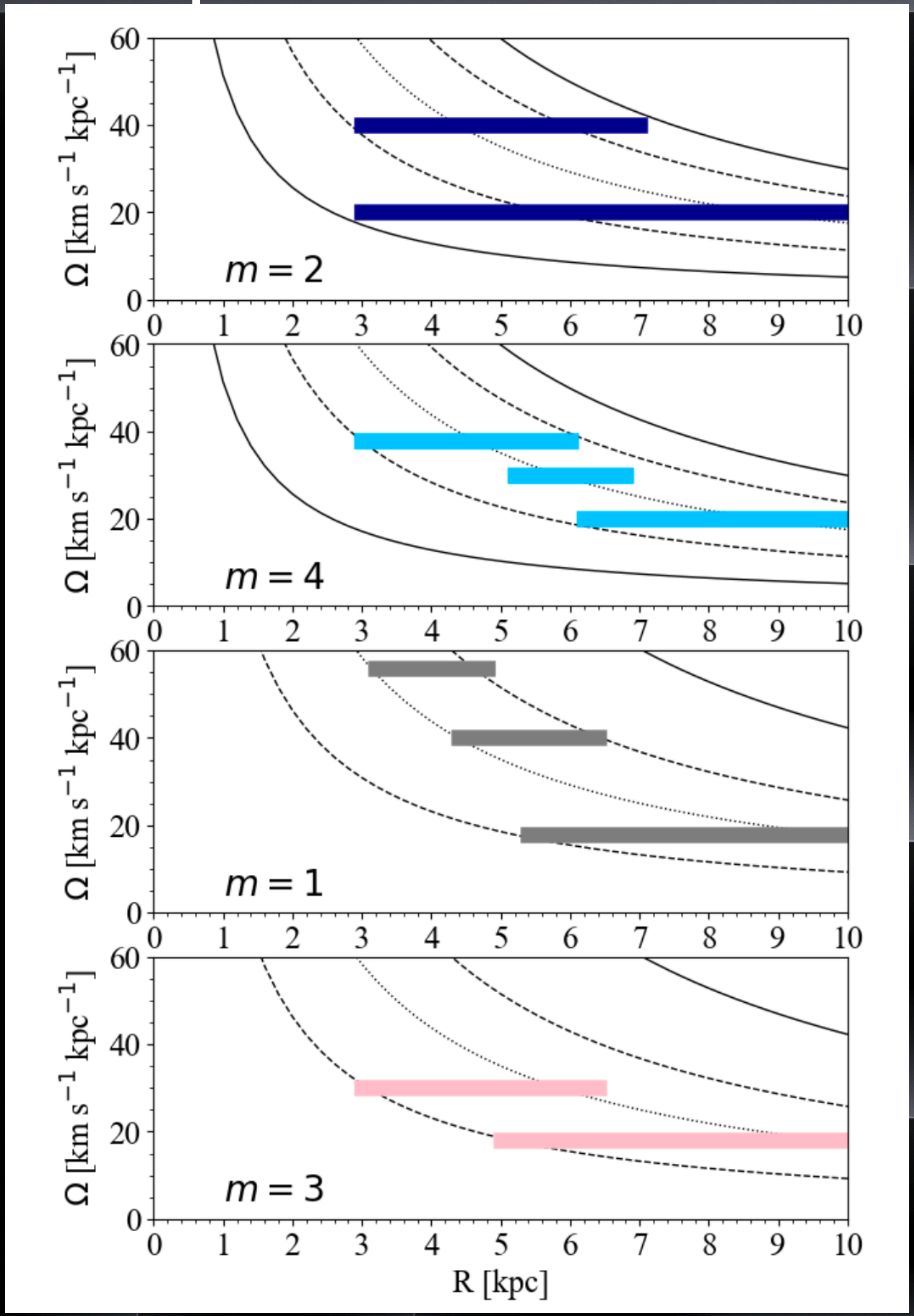
Larger azimuthal variations for elements produced on shorter time-scales

Spitoni+23



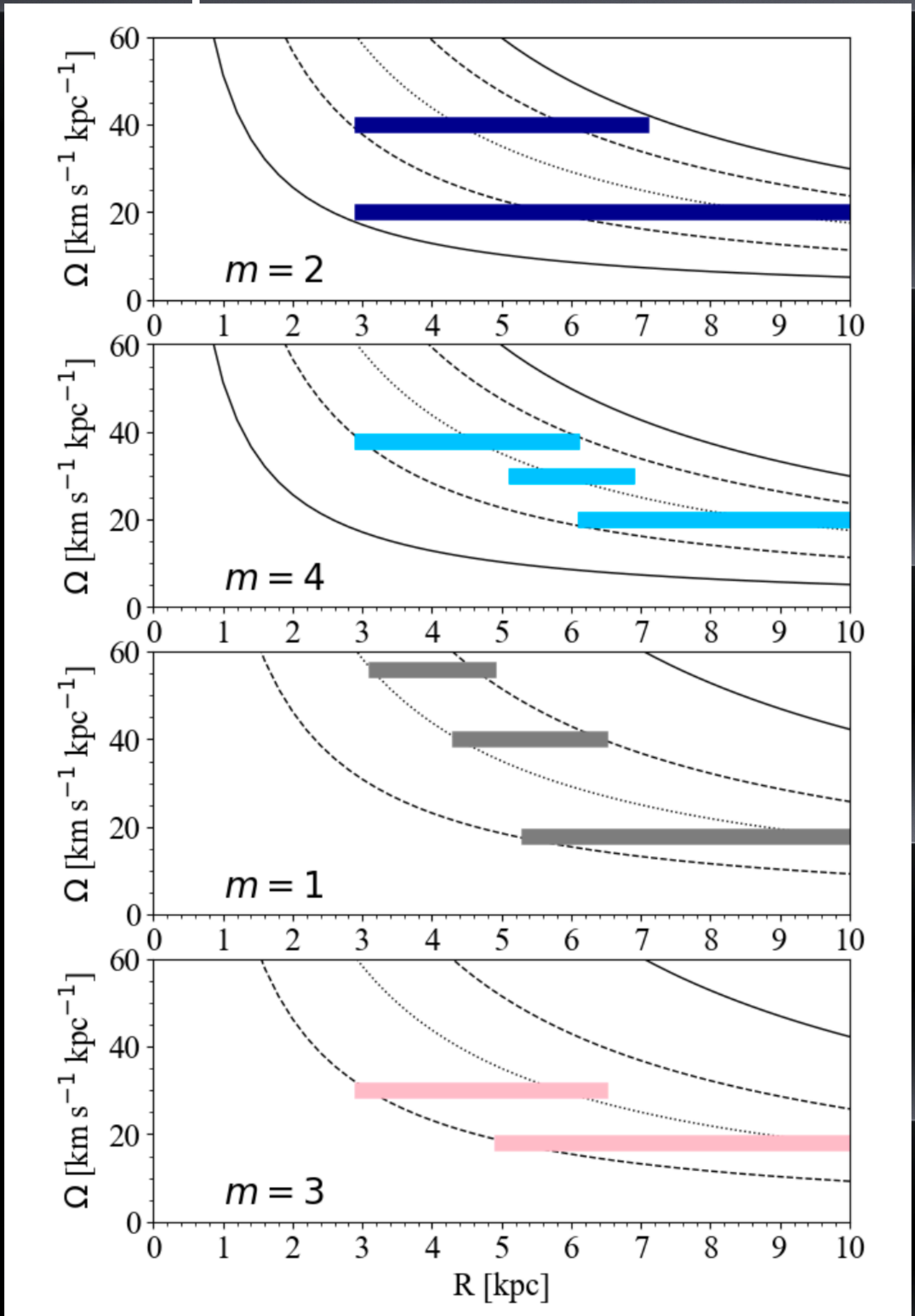
Kovtyuku et al. (2022)
Luck & Lambert (2011)
[O/H]
R [kpc]
[Eu/H]
Genovali et al. (2014)
[Fe/H]
[Ba/H]
Luck (2018)
$\phi = 0^\circ$
$\phi = 30^\circ$
$\phi = 60^\circ$
$\phi = 120^\circ$
$\phi = 140^\circ$
$\phi = 160^\circ$

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)

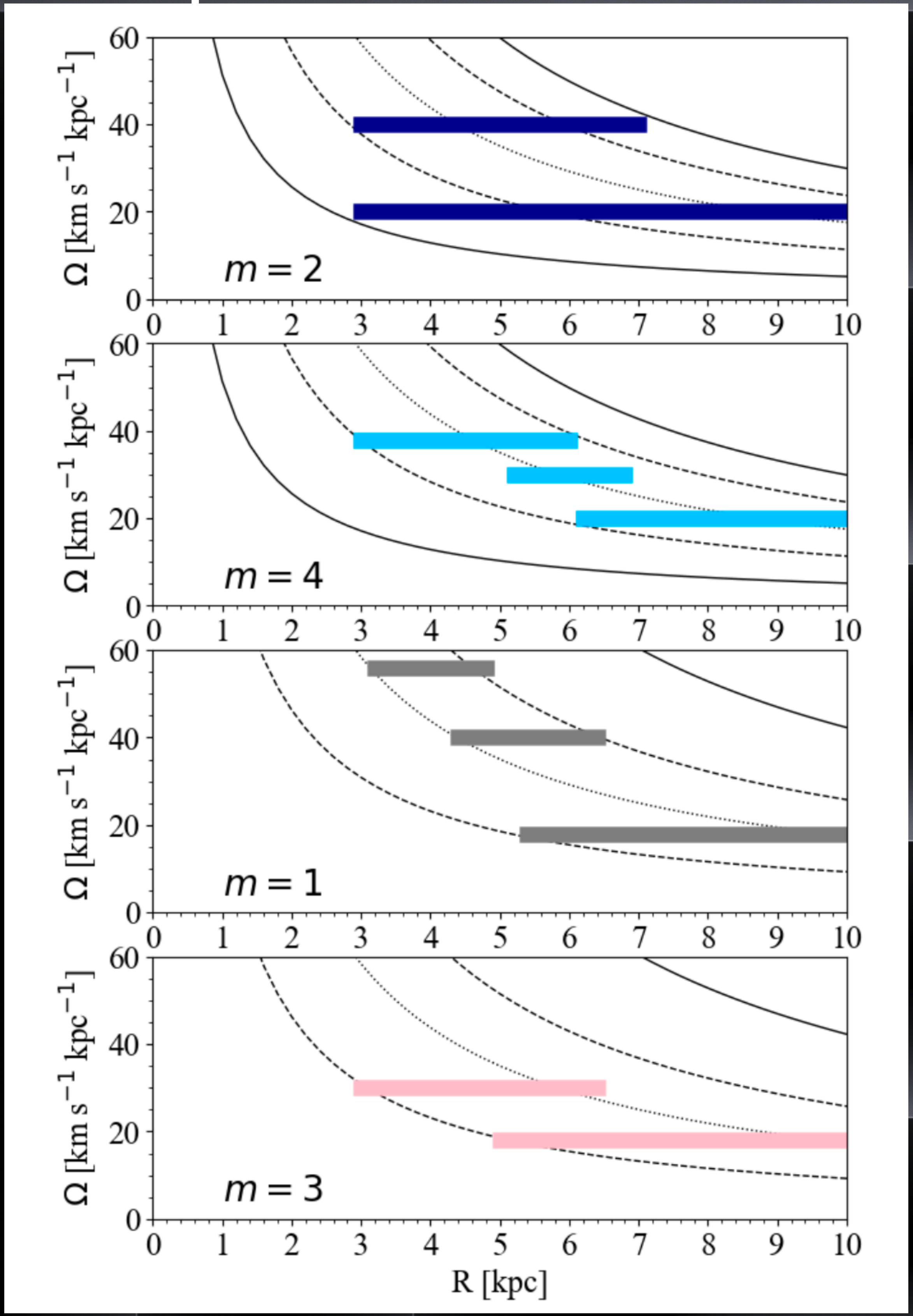
Spiral arms with different pattern speeds Ω_s and modes m



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



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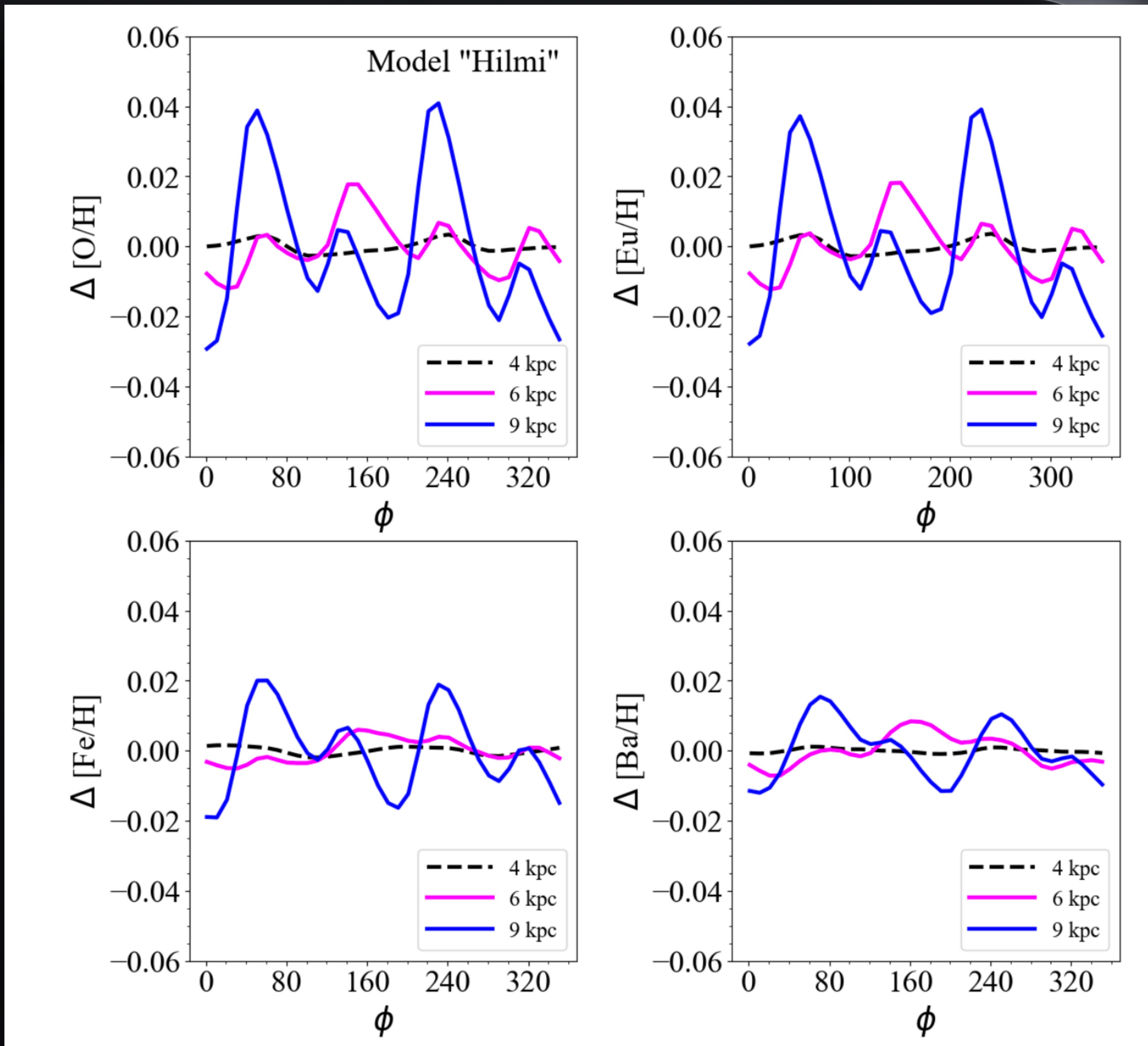
$A_1 + A_2 + A_3 + A_4 = 1$

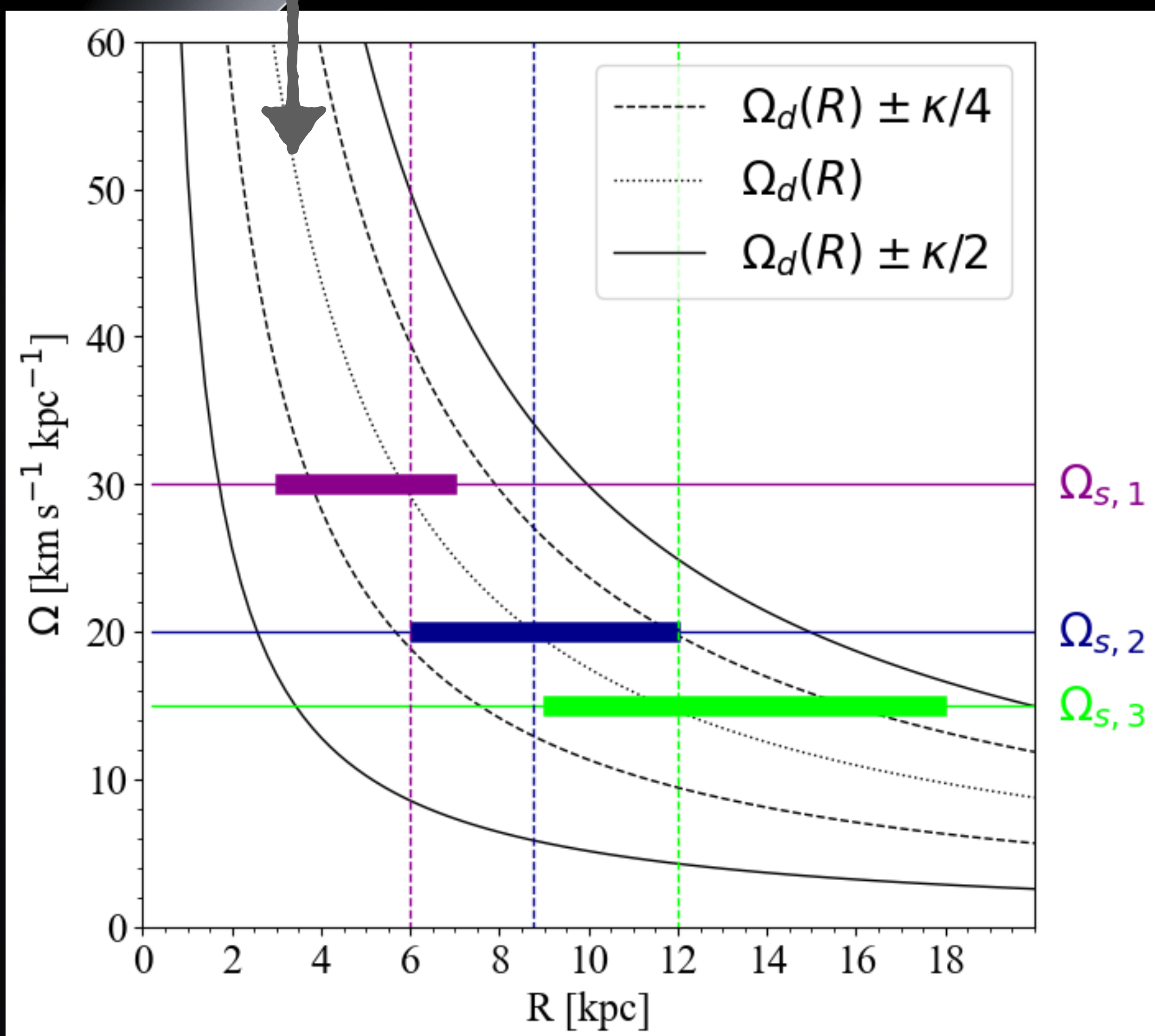
Spiral arms with different pattern speeds Ω_s and modes m extracted from Hilmi+20



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

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).

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



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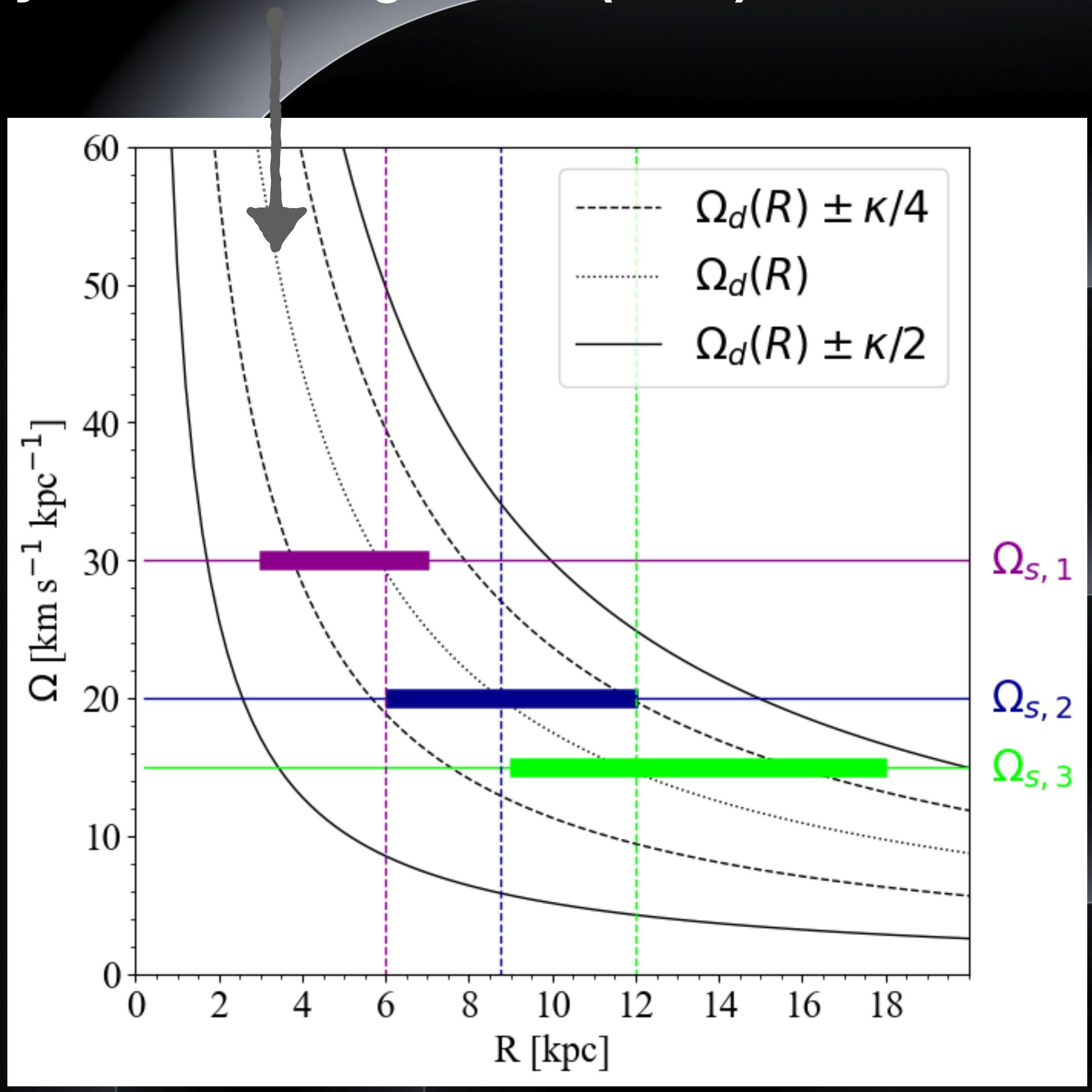
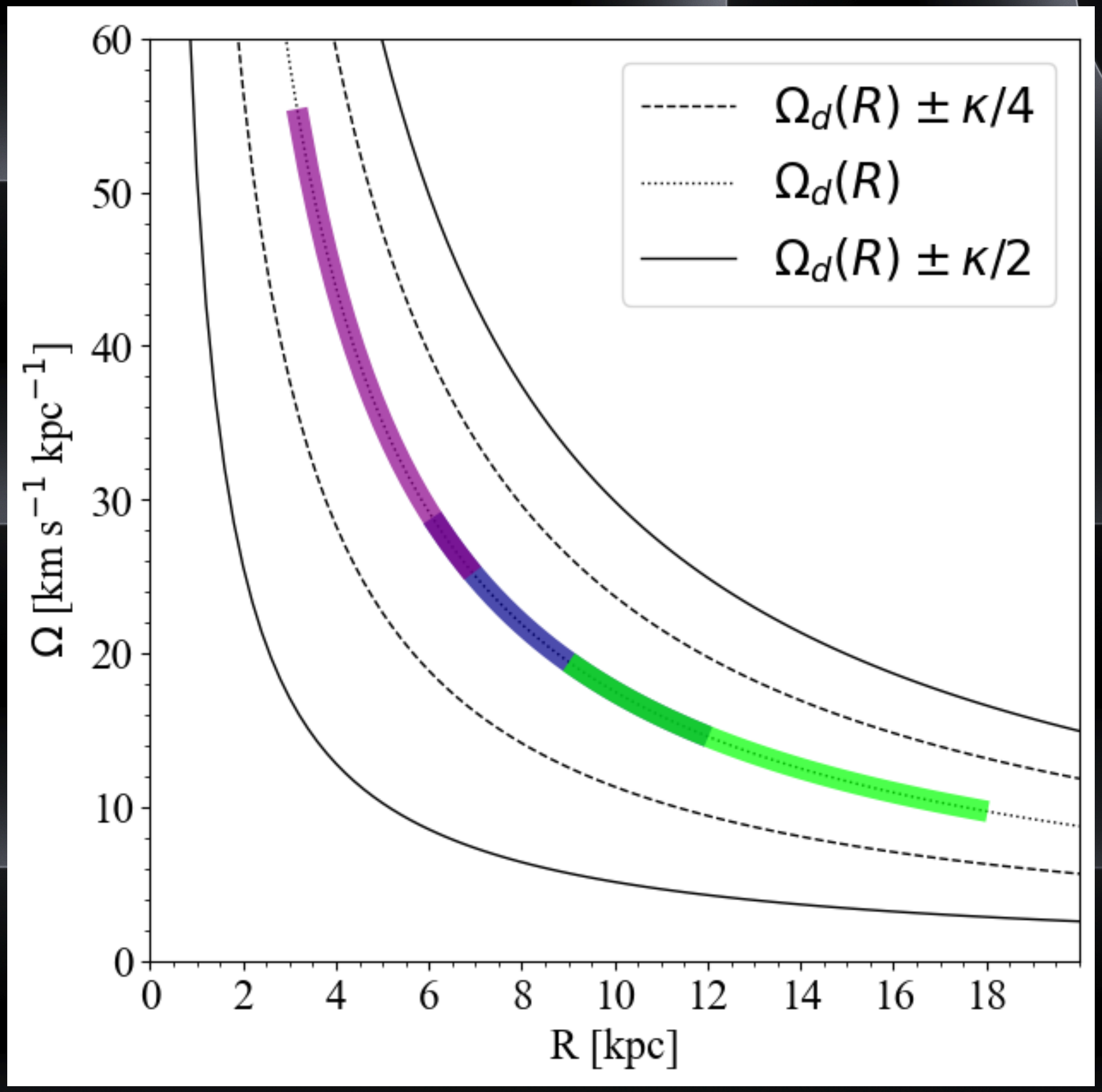
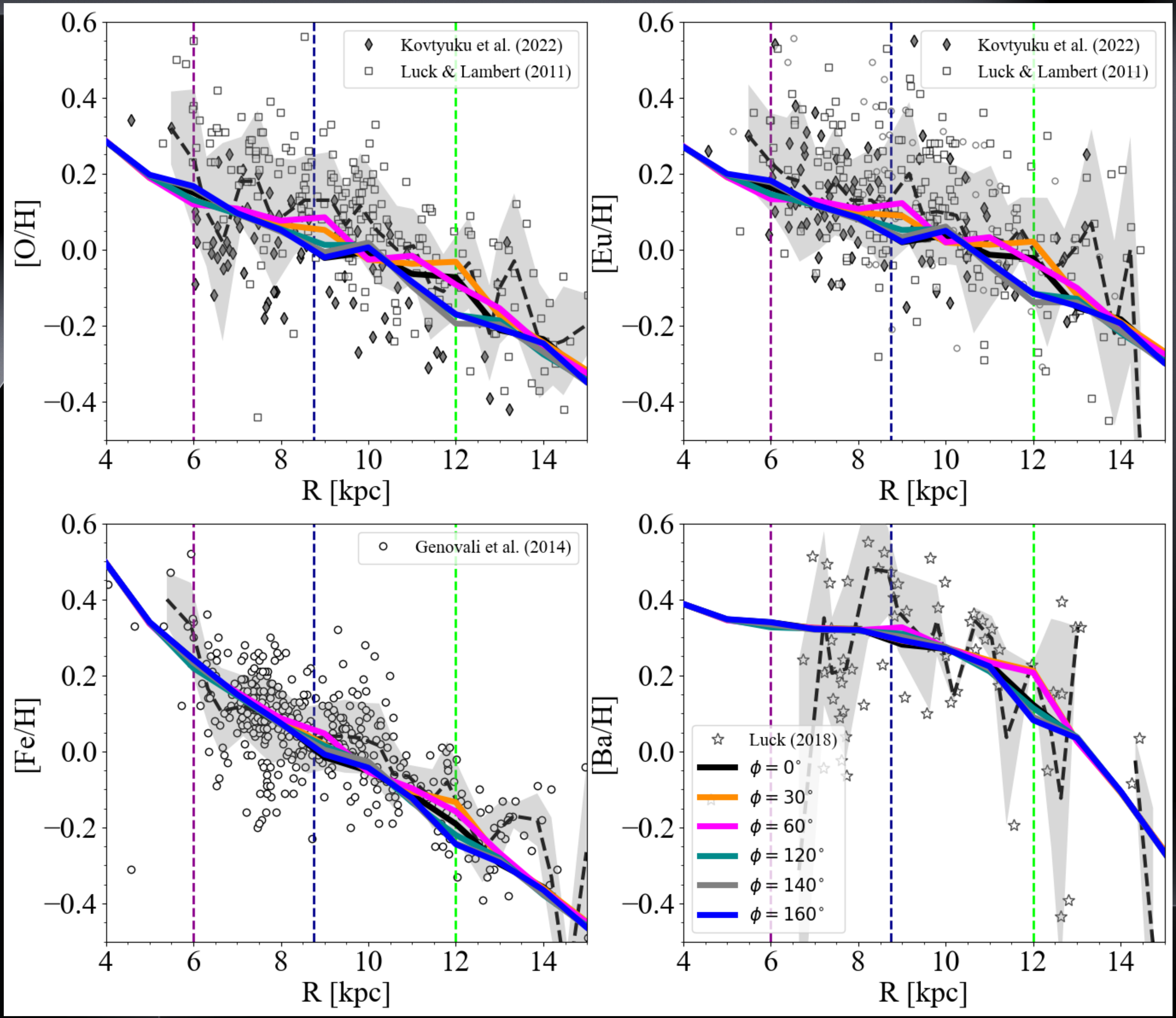


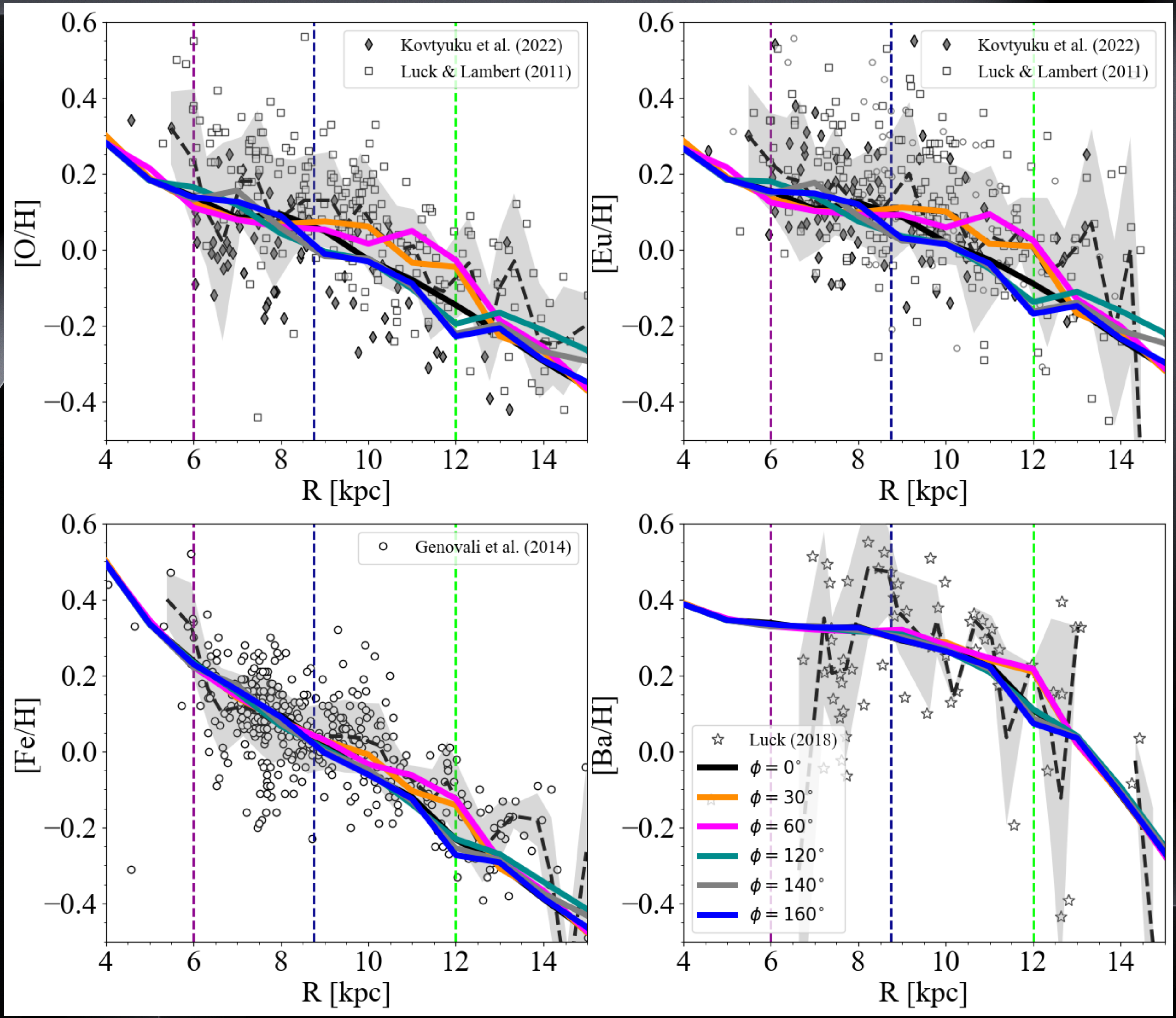
EVOLUTION AT MORE RECENT TIMES



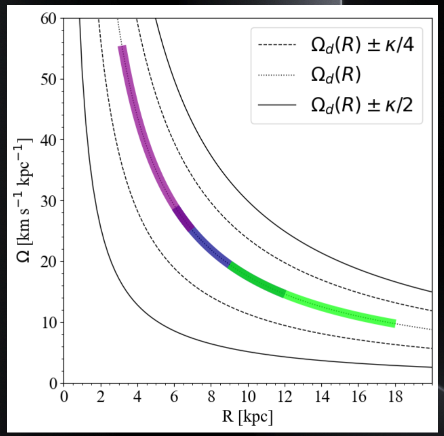
REFERENCE MODEL



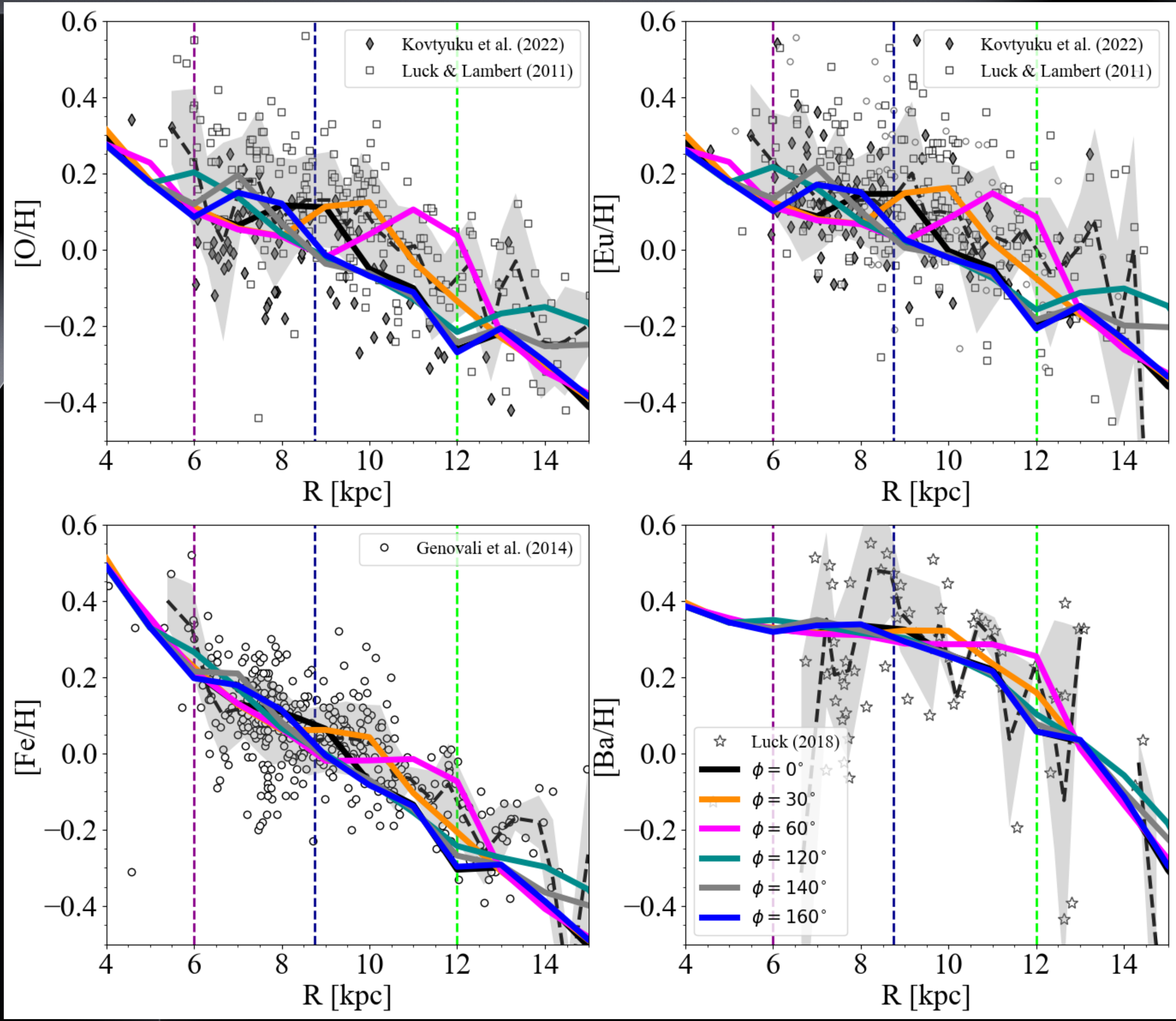
Extending the co-rotation to all Galactocentric distances



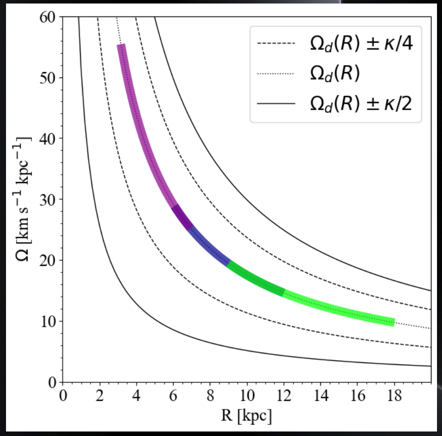
Last 0.3 Gyr



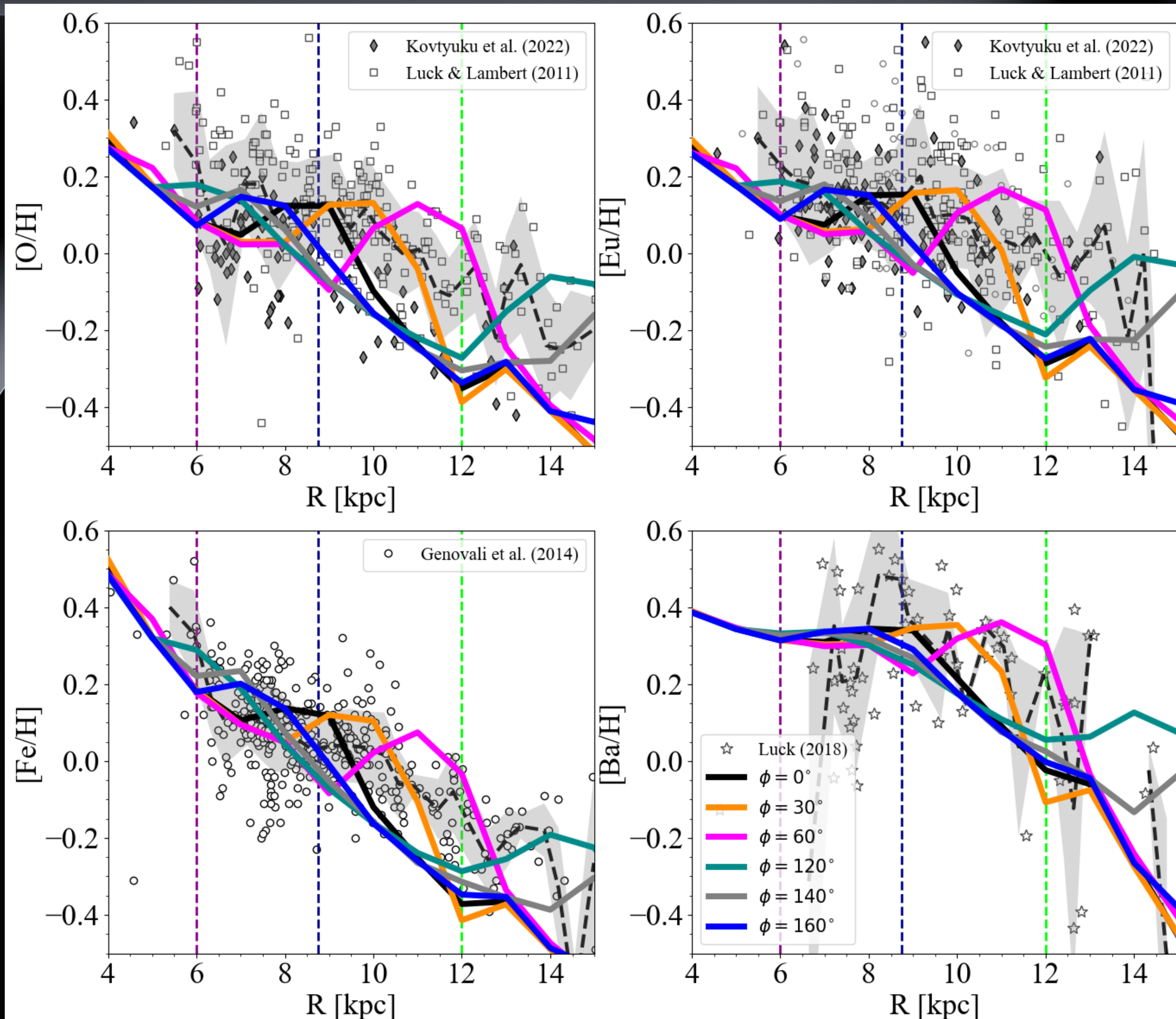
Extending the co-rotation to all Galactocentric distances



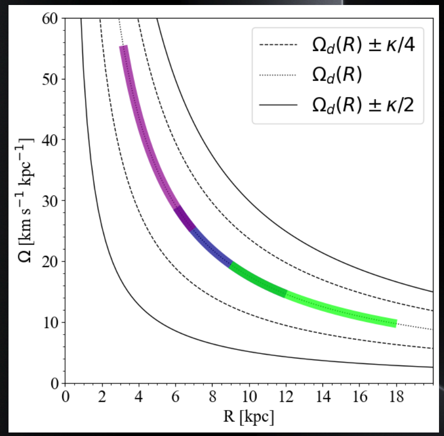
Last 1 Gyr



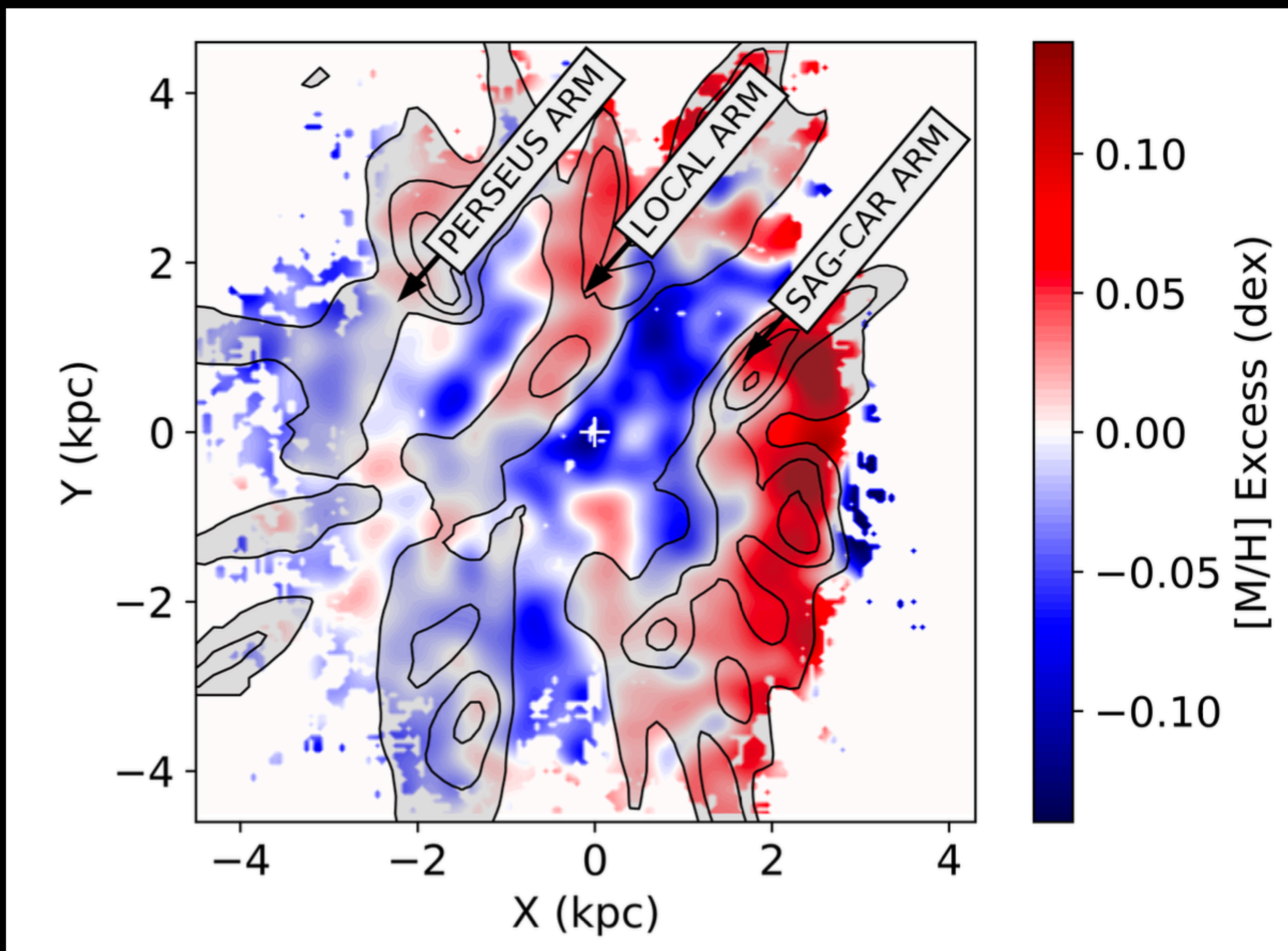
Extending the co-rotation to all Galactocentric distances



Last 3 Gyr

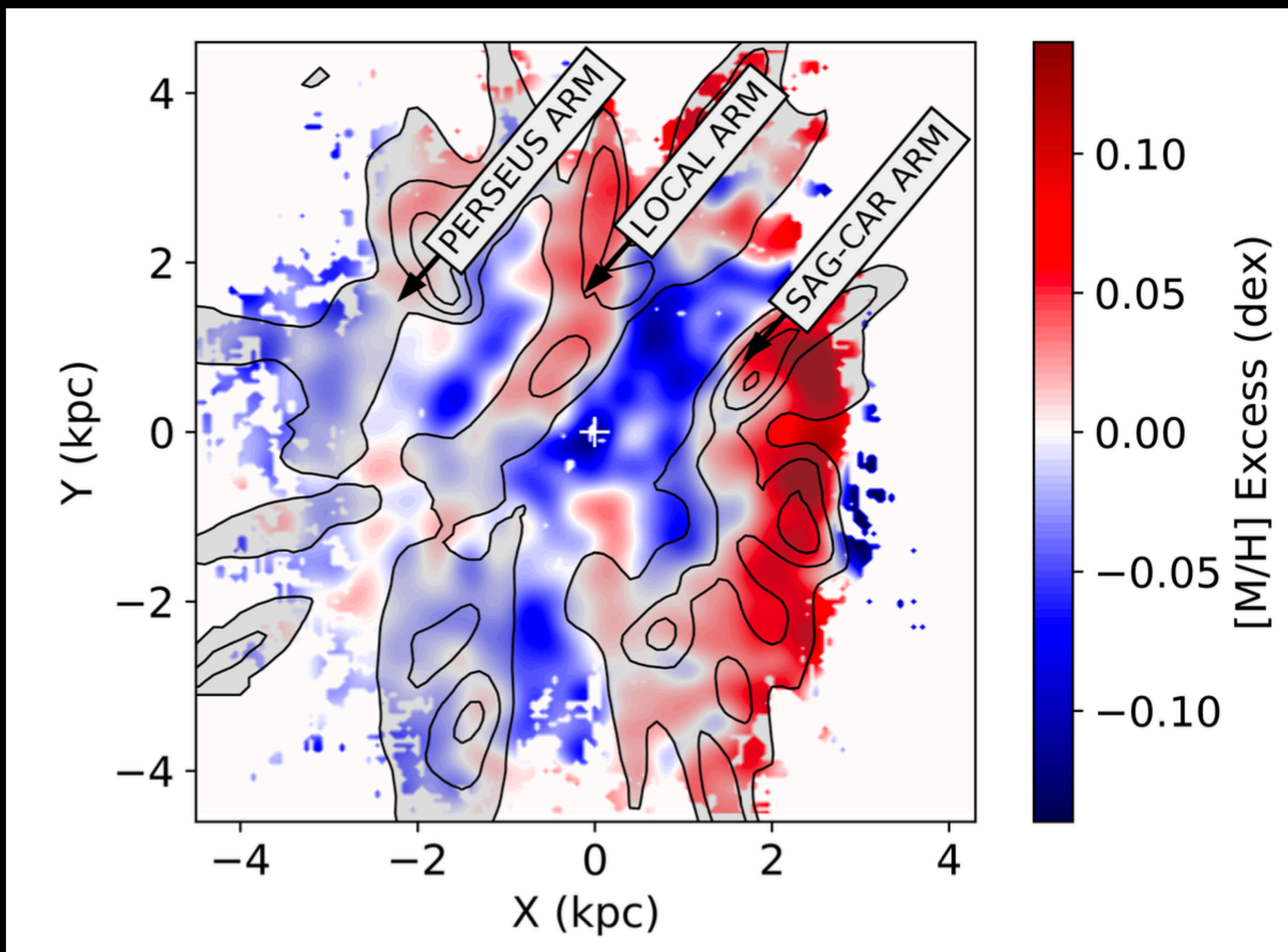


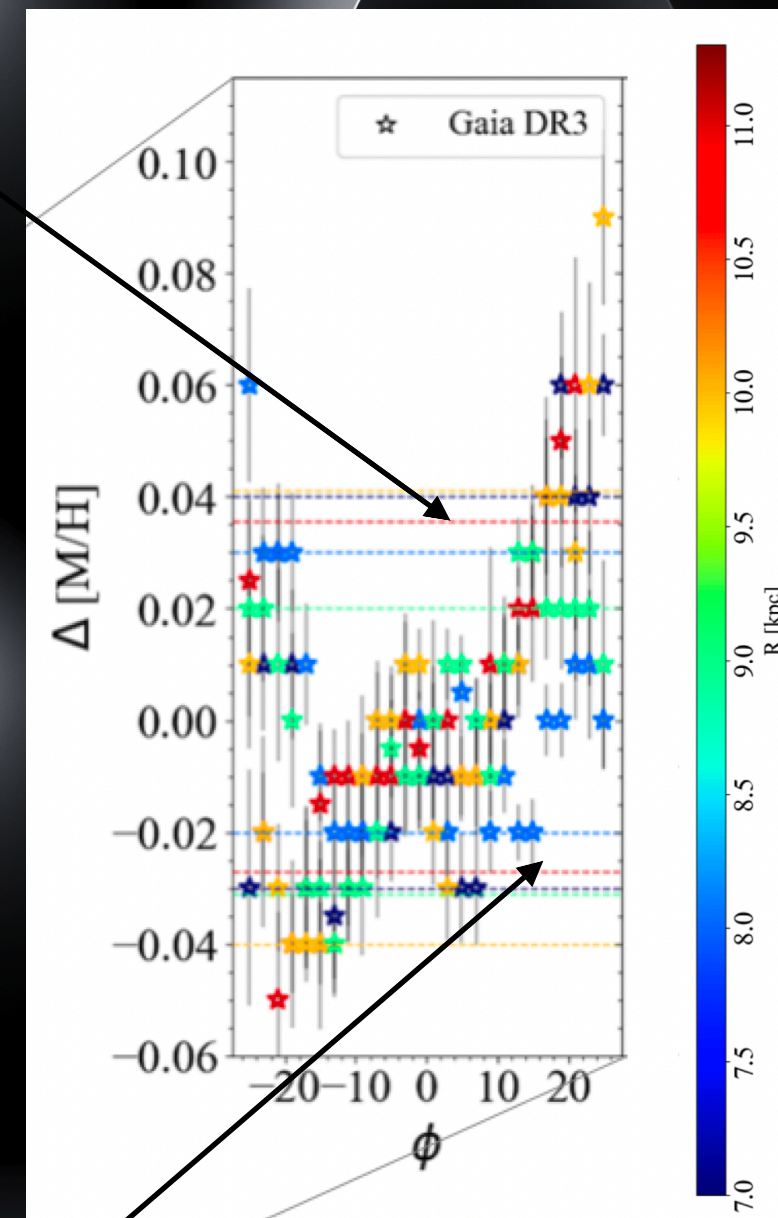
Comparison with Poggio+ES 22 (Gaia DR3)



Comparison with Poggio+ES 22 (Gaia DR3)

Percentile 90%

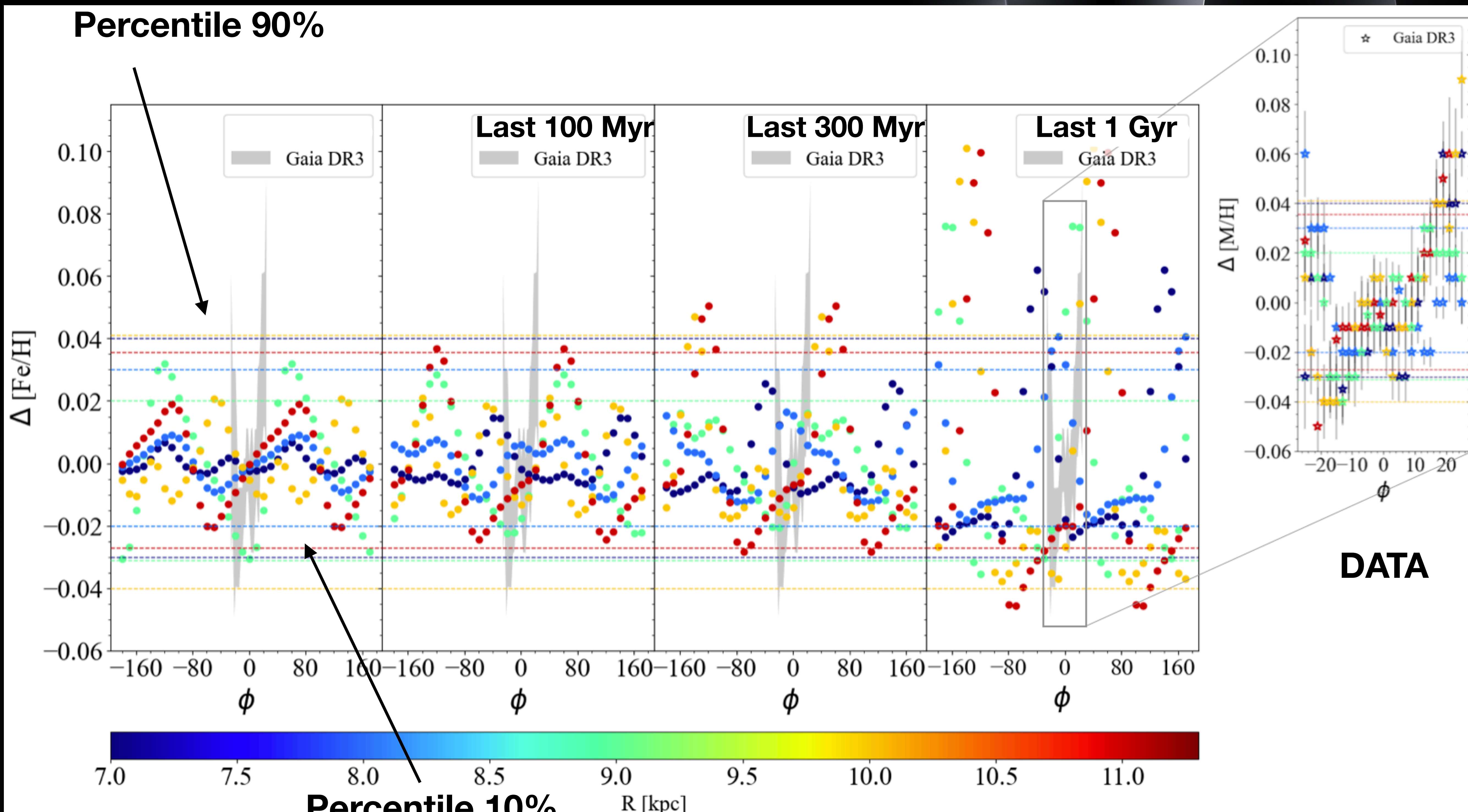


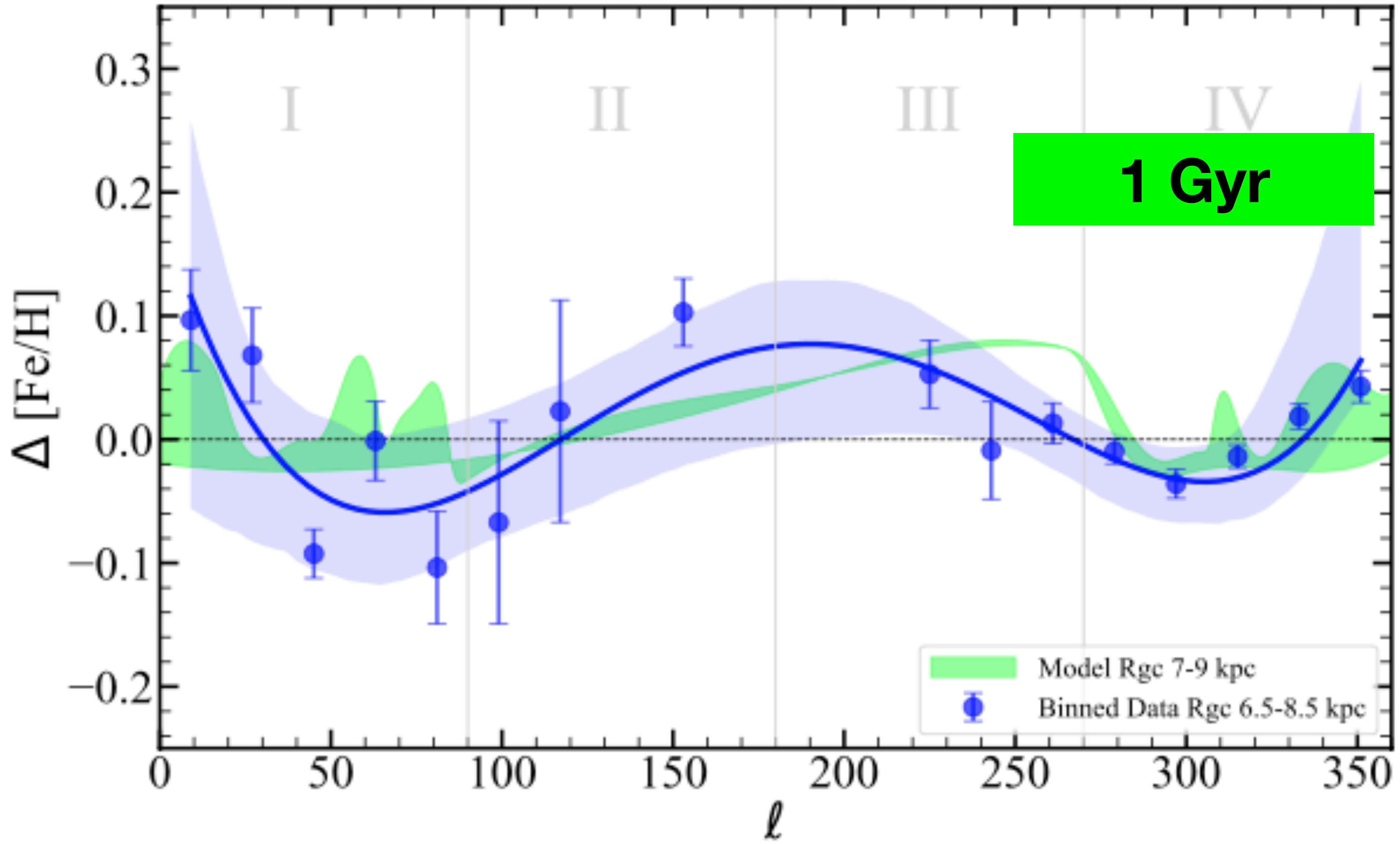


Residual azimuthal variations

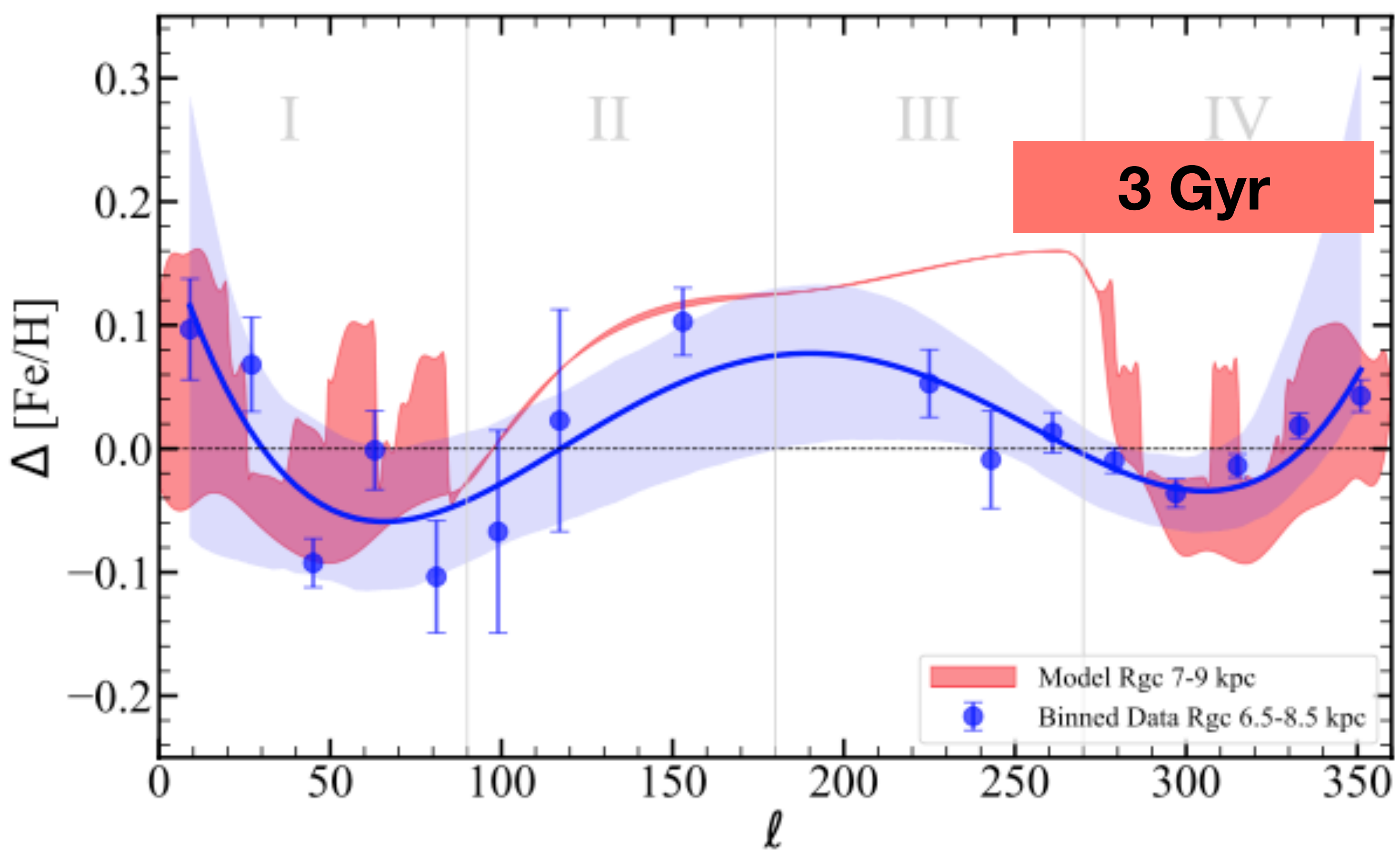
Percentile 10%

Comparison with Poggio+ES 22 (Gaia DR3)





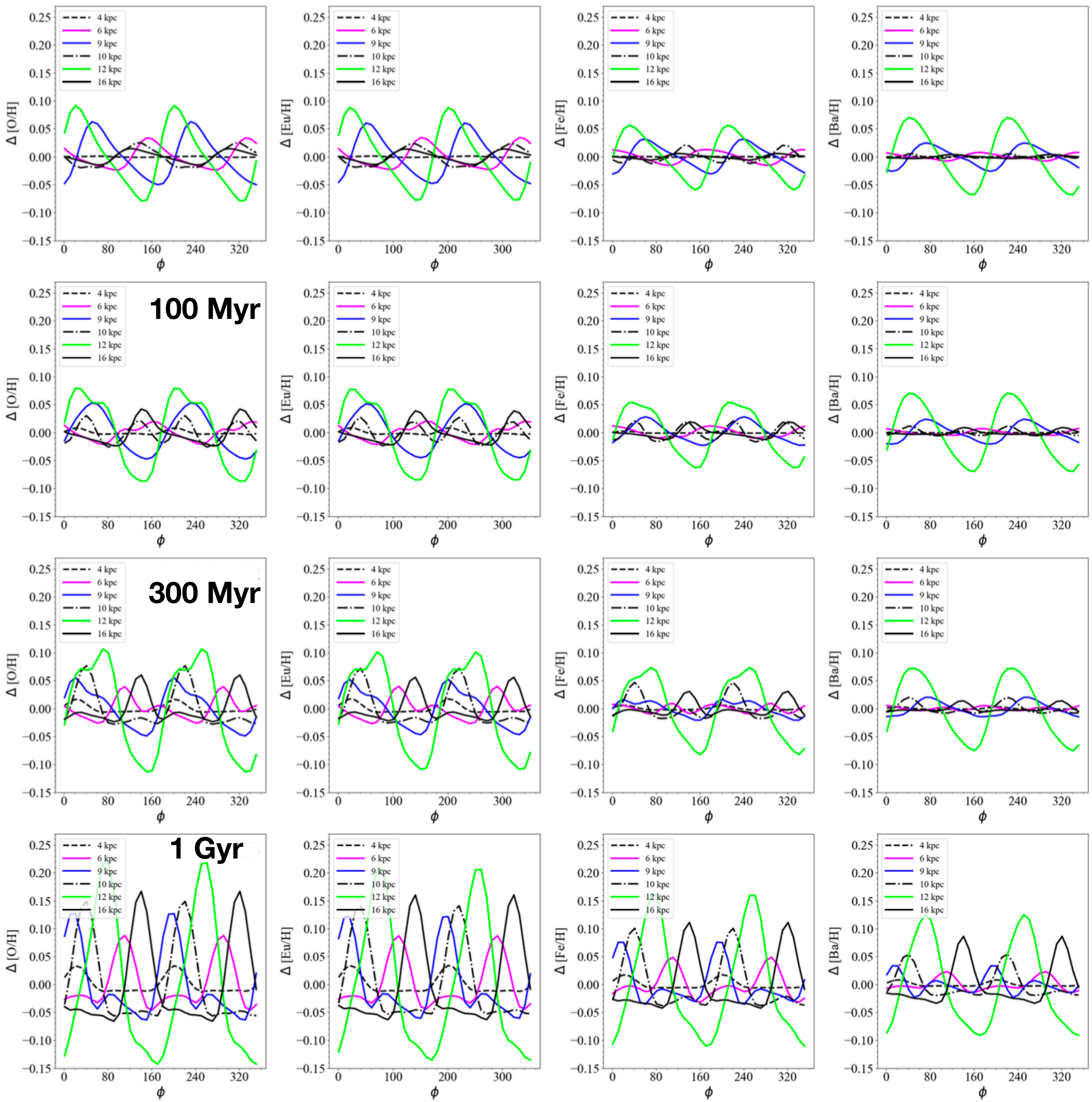
Viscasillas, Magrini, ES+25

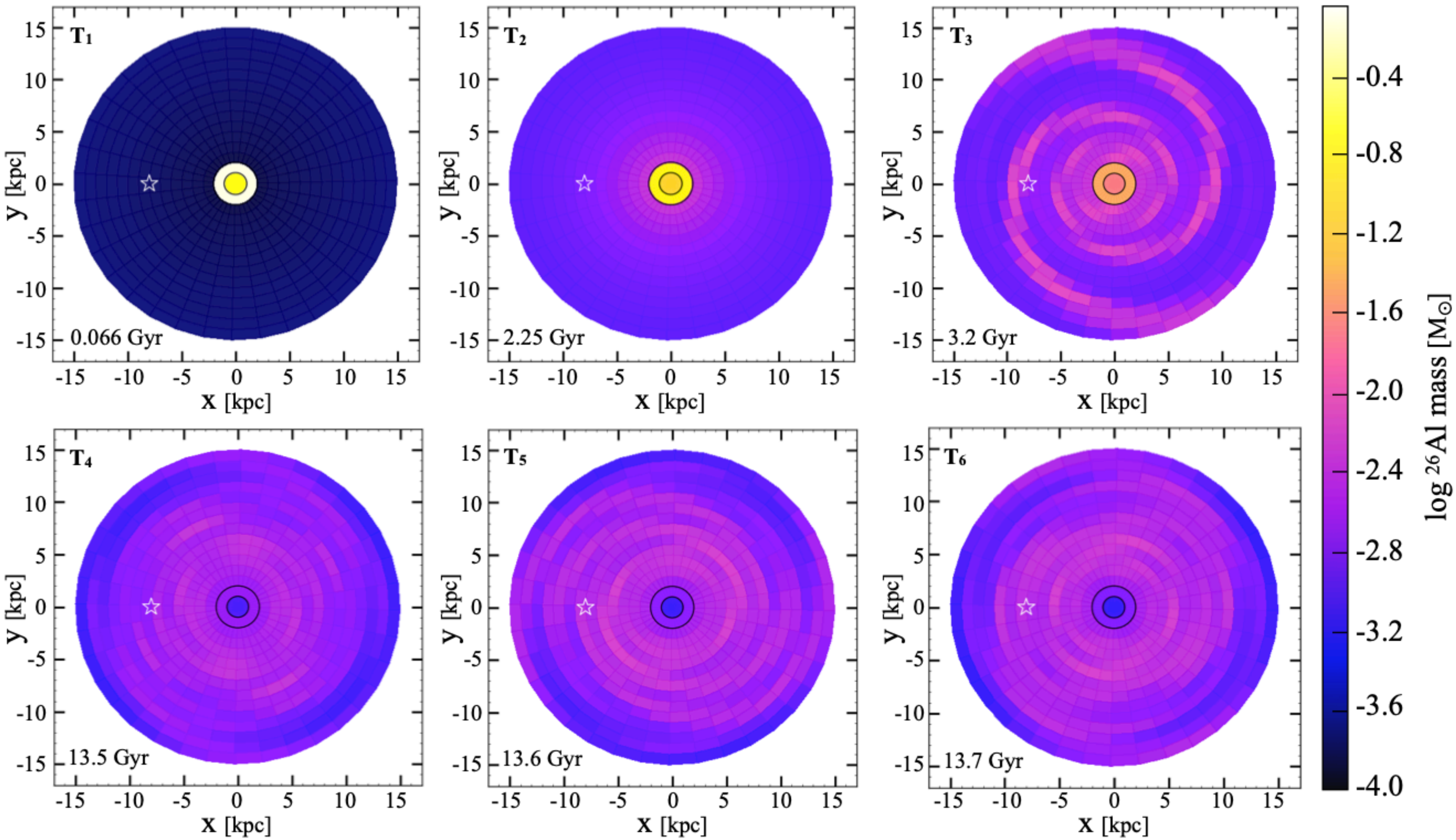


Agreement between the inner spiral arms traced chemical abundance patterns in Gaia ESO and our model predictions.

Conclusions

- 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+ES22), Gaia-ESO (Viscasillas, Magrini, ES+25), if co-rotation is extended to all radii at recent evolutionary times.


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


T1
0.066 Gyr
T2
2.25 Gyr
T3
3.2 Gyr
T4
13.5 Gyr
T5
13.6 Gyr
T6
13.7 Gyr
x [kpc]
y [kpc]
-15 -10 -5 0 5 10 15
log ^{26}Al mass [$M_\odot$]
-0.4
-0.8
-1.2
-1.6
-2.0
-2.4
-2.8
-3.2
-3.6
-4.0

Vasini, ES +25

Spiral arms analytical prescriptions

Spitoni+19

- Analytical spiral structure by Cox & Gomez (2002).

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

MODULATION FUNCTION

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

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

- Coeval evolution between the amplitude of the spiral density perturbation $\chi(R, t)$ and the total surface density $\Sigma_D(R, t)$ computed at the same Galactic distance R.

$$\frac{d}{dt}\left[\chi(R,t)/\Sigma_D(R,t)\right]=0.$$

Spiral arms analytical prescriptions

Spitoni+19

$$\delta_{\mathrm{S}}(R,\phi,t) = \frac{\Sigma_{\mathrm{S}}(R,\phi,t) + \Sigma_{\mathrm{D}}(R,t)}{\Sigma_{\mathrm{D}}(R,t)} = 1 + \frac{\Sigma_{\mathrm{S}}(R,\phi,t)}{\Sigma_{\mathrm{D}}(R,t)}$$

$$\delta_{\mathrm{S}}(R,\phi,t) = 1 + M(\gamma)\frac{\chi(R,t_G)}{\Sigma_{\mathrm{D}}(R,t_G)}$$

COEVAL EVOLUTION CONDITION

$$\mathrm{SFR} = \nu\Sigma_g(R,t)^k\delta_{\mathrm{S}}(R,\phi,t)^k$$