

FLORENCE 12-14  
NOVEMBER 2024



**Marco Palla**

University of Bologna & INAF-OAS



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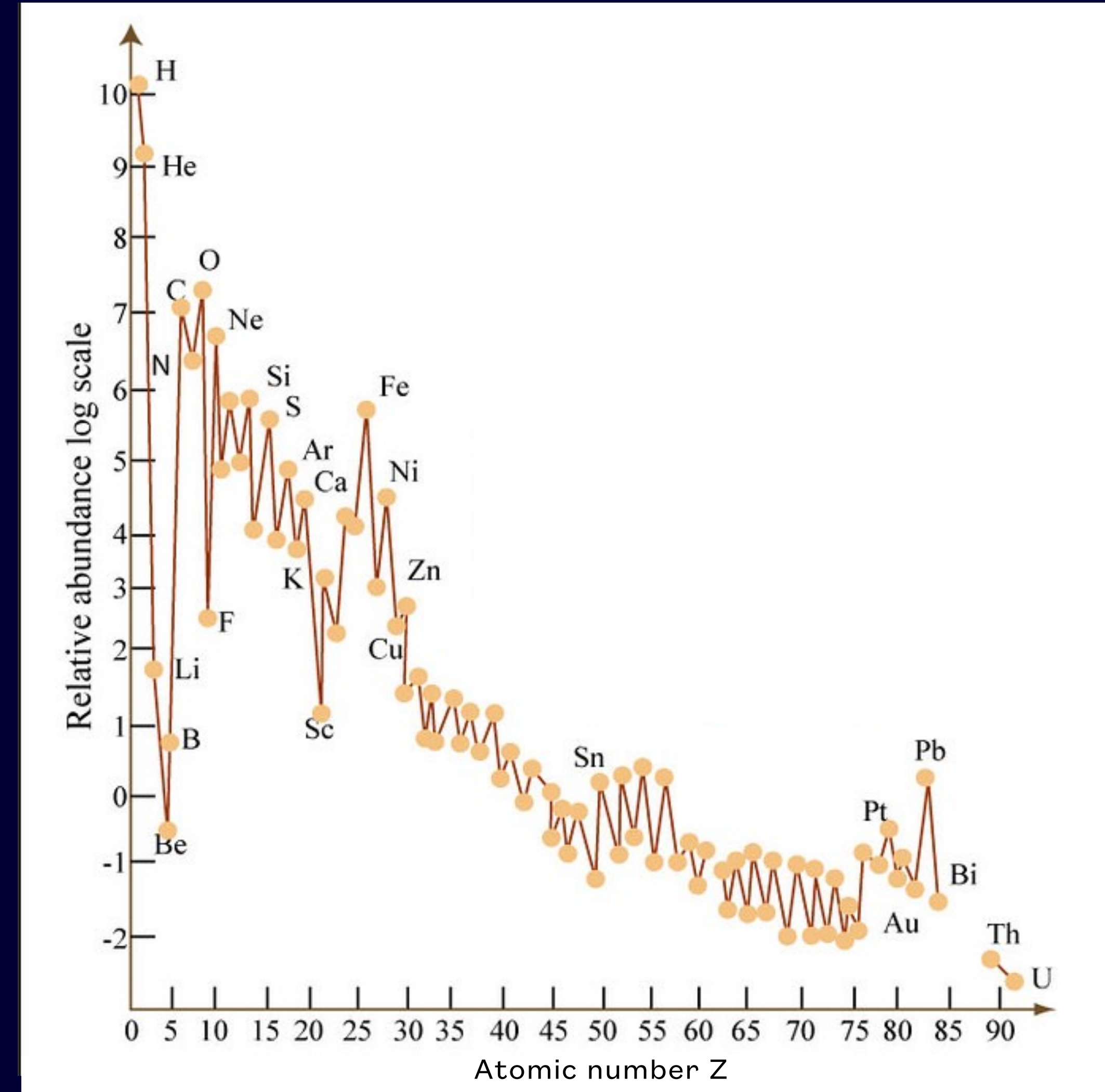
# G(g)alactic Chemical and Dust Gradients: Predictions and Insights from Chemical Evolution Models

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# Chemical evolution in a nutshell

## WHY IS IT SO IMPORTANT?

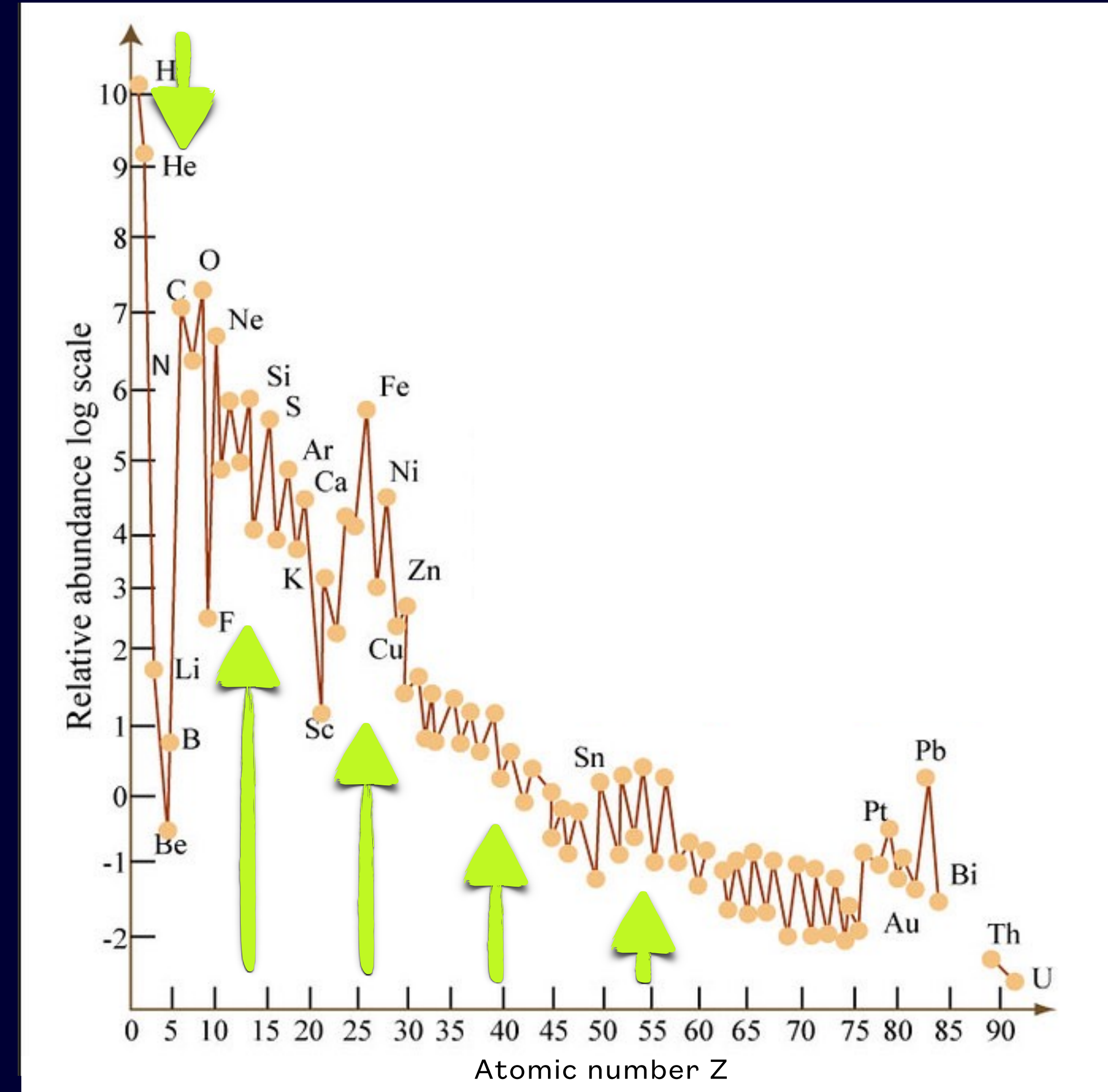
- How chemical abundances evolve through cosmic time ?



# Chemical evolution in a nutshell

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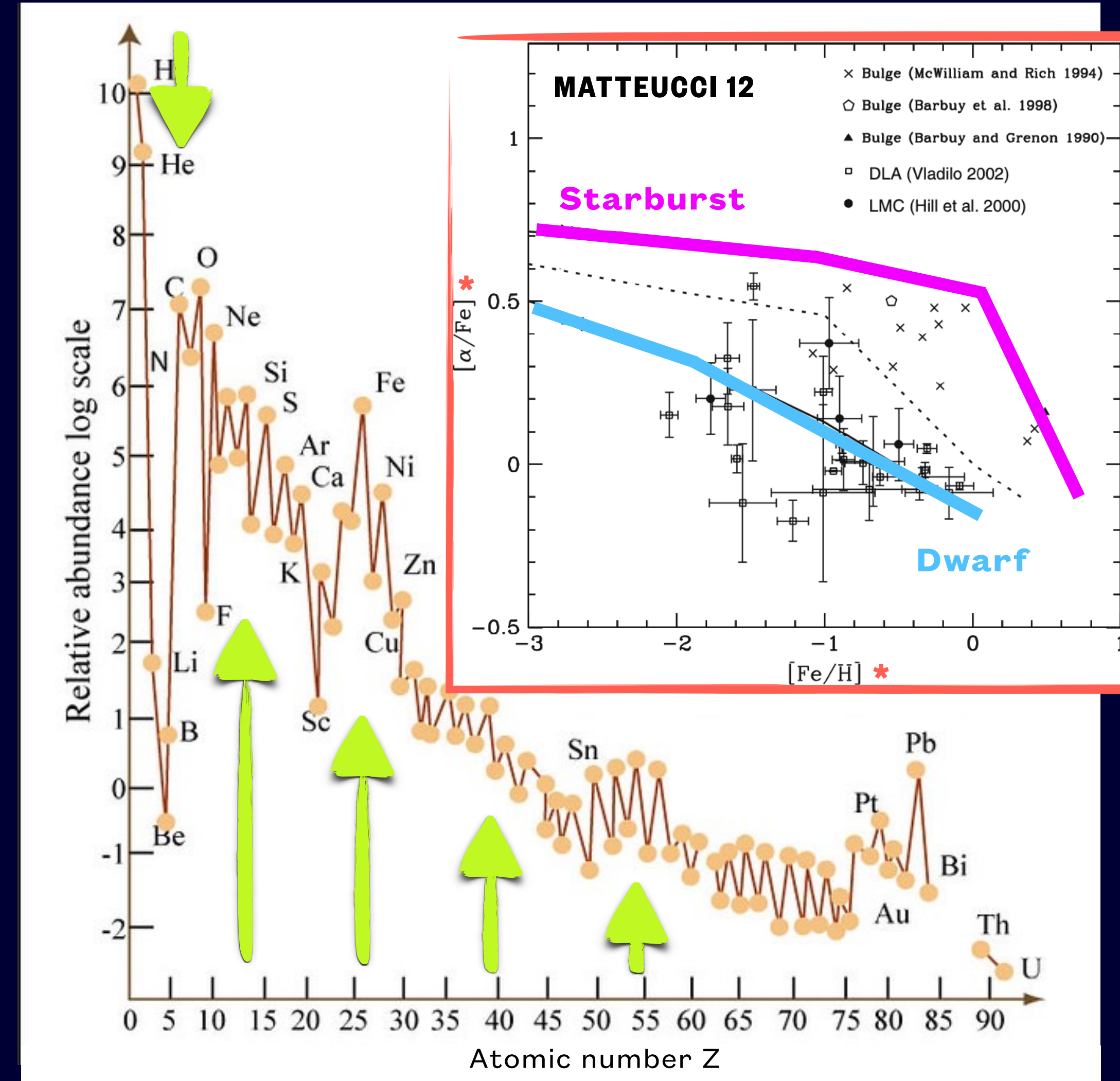
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# Chemical evolution in a nutshell

## WHY IS IT SO IMPORTANT?

- How chemical abundances evolve through cosmic time ?



(stars)

(ISM)

\* Notation:  $- [X/Y] = \log(X/Y) - \log(X_{\odot}/Y_{\odot})$

$- \log(X/H) + 12$

# Chemical evolution in a nutshell

## WHY IS IT SO IMPORTANT?

- How chemical abundances evolve through cosmic time ?

## NEED FOR GALACTIC CHEMICAL EVOLUTION

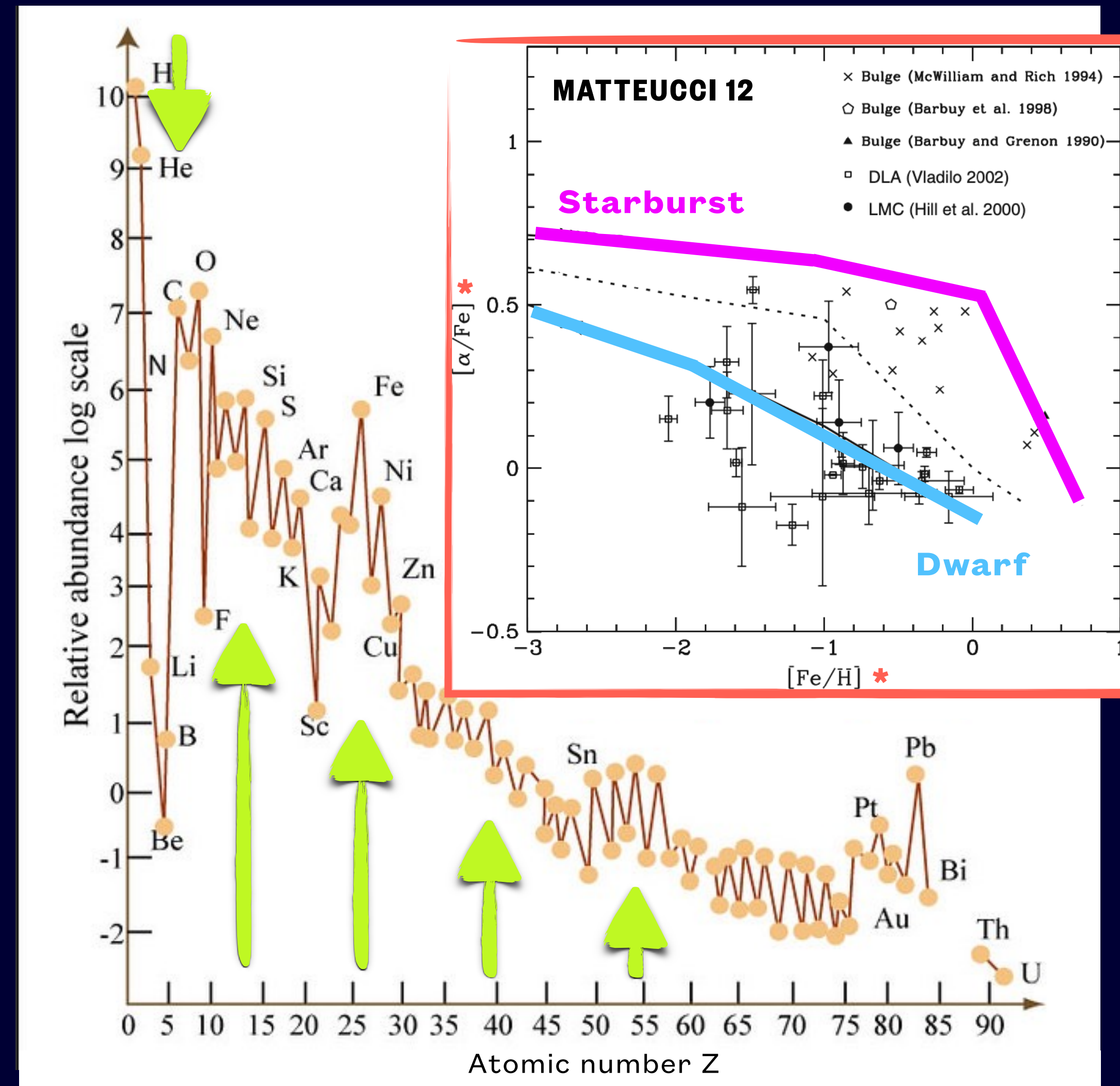
- probes history of star formation in different environments
- Constraints on nucleosynthesis processes

(stars)

(ISM)

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$- \log(X/H) + 12$



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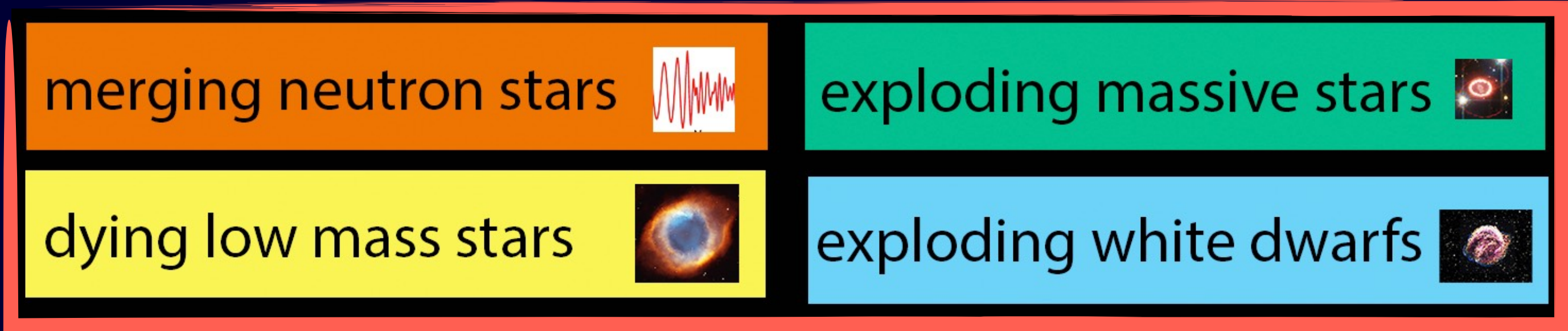
## BASIC INGREDIENTS

$$\dot{M}_i = -\psi(t) X_i(t) + \int_{m(t)}^{m_{max}} Q_{mi}(t - \tau_m) \psi(t - \tau_m) \phi(m) dm + \dot{M}_{i,inf} - \dot{M}_{i,out}$$

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CC-SNe

AGBs

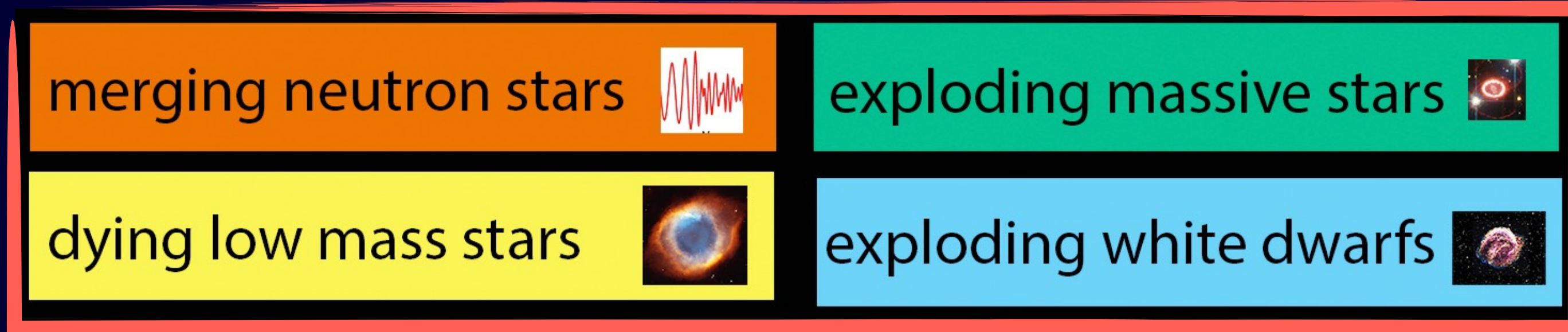
Type Ia SNe

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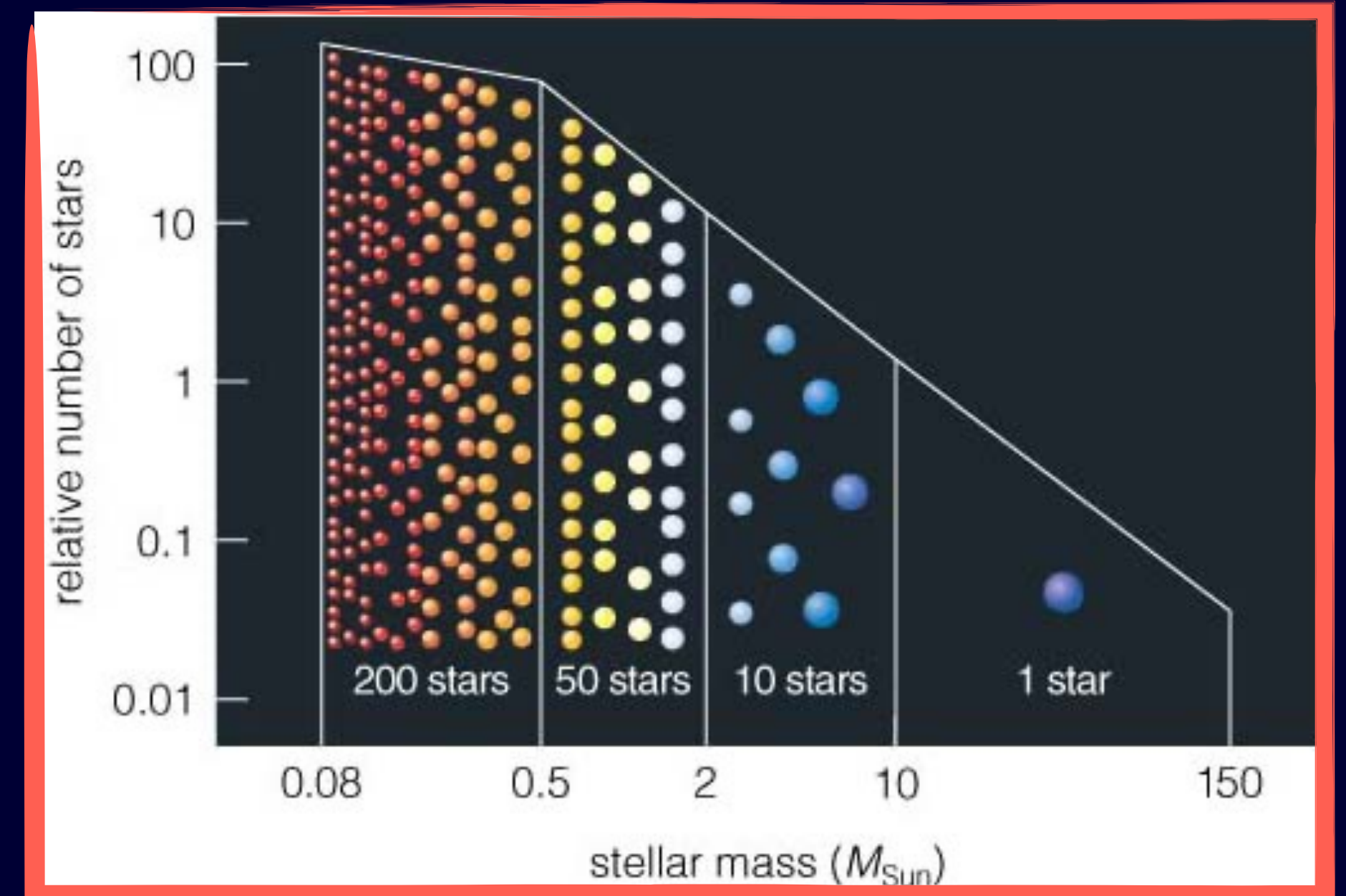
(see Sharda's talk)



CC-SNe

AGBs

Type Ia SNe





# Chemical evolution in a nutshell

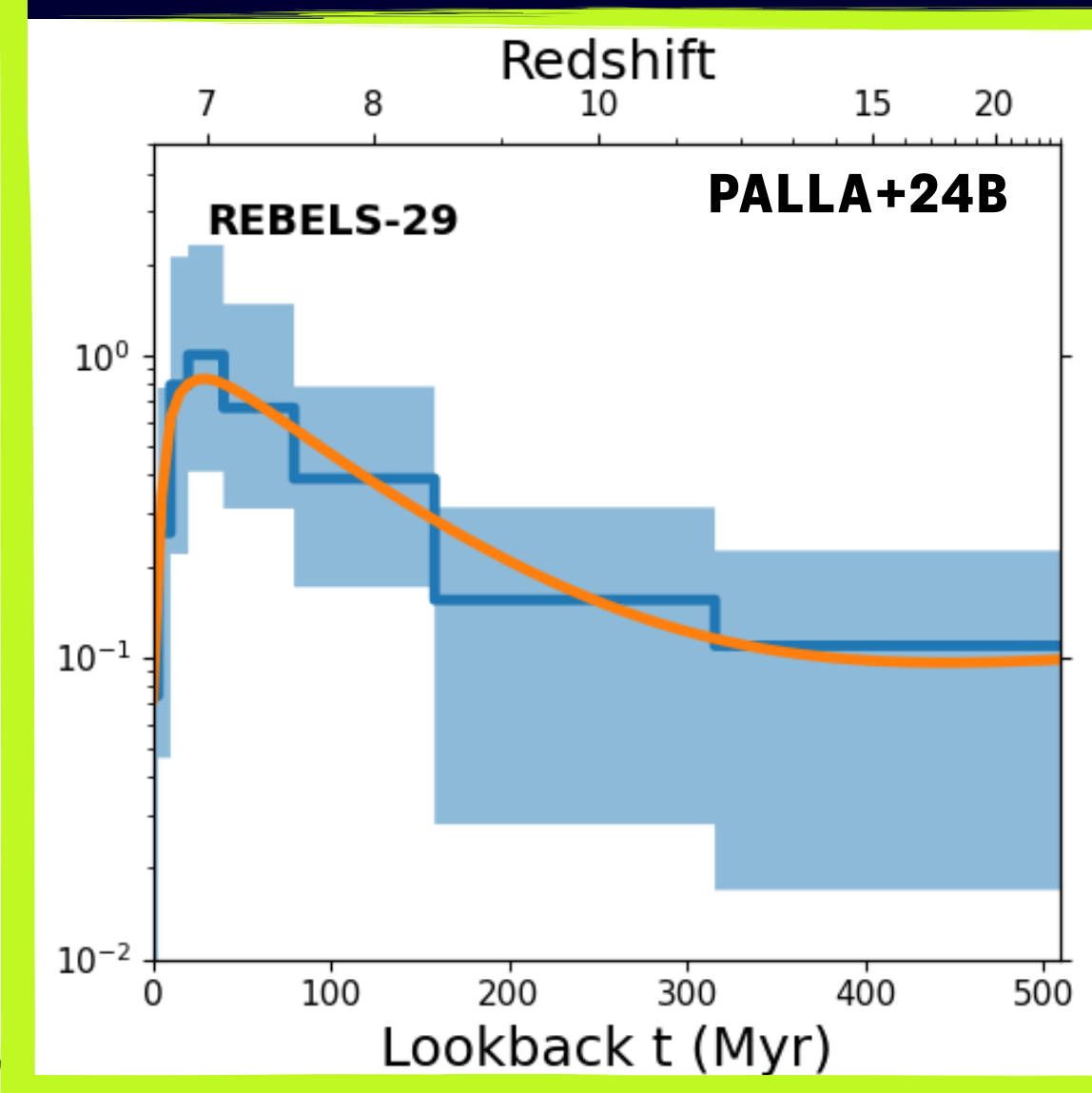
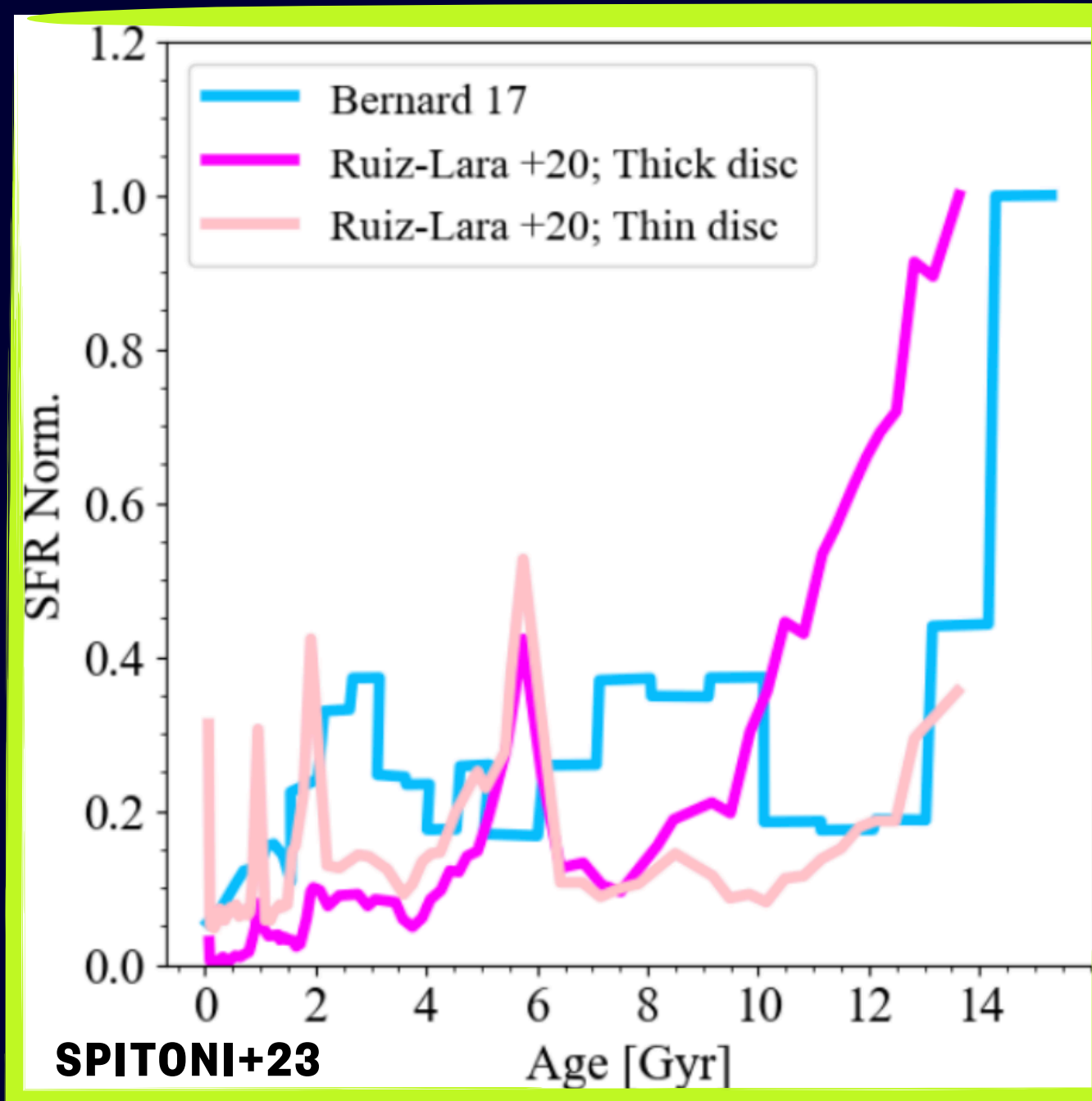
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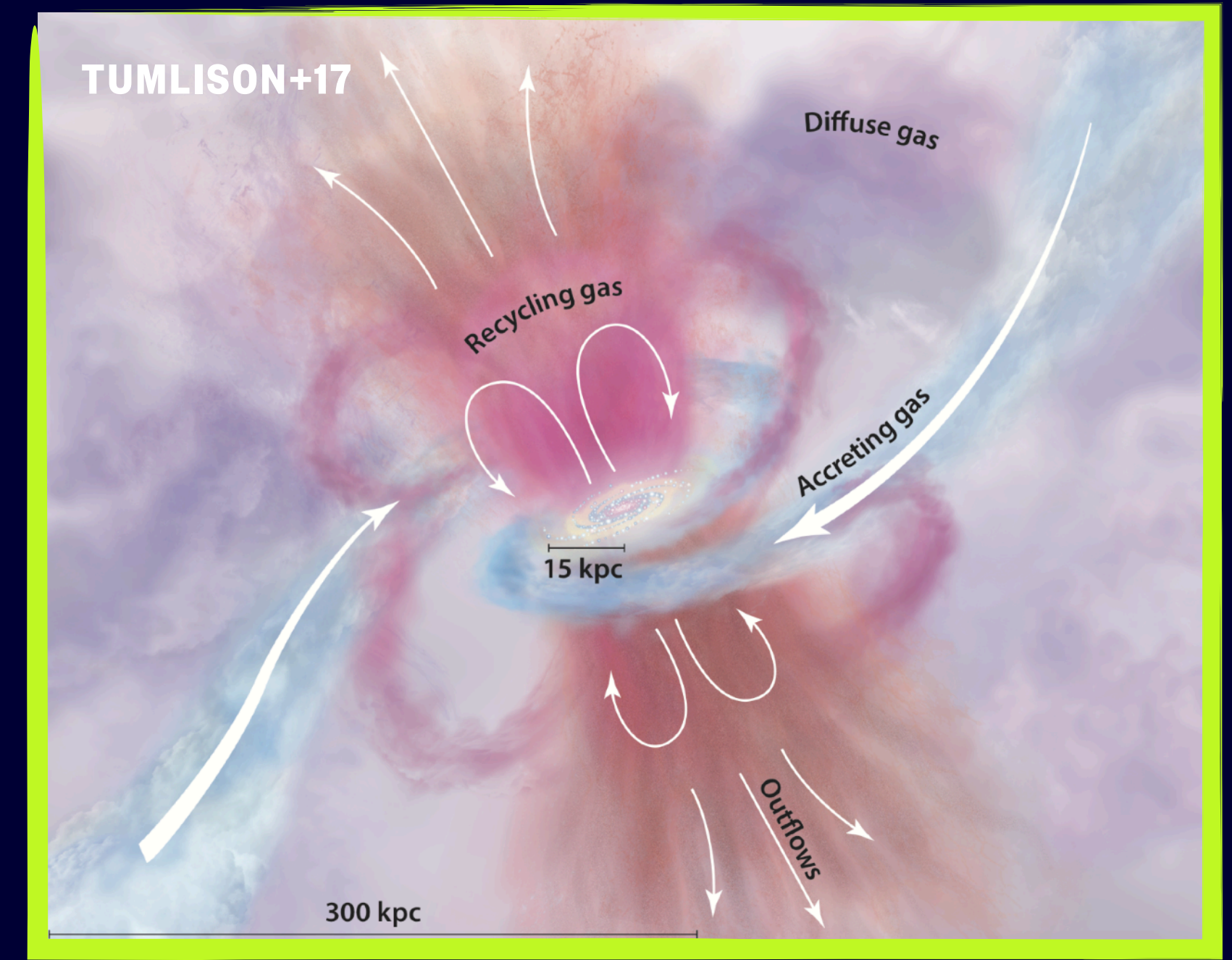
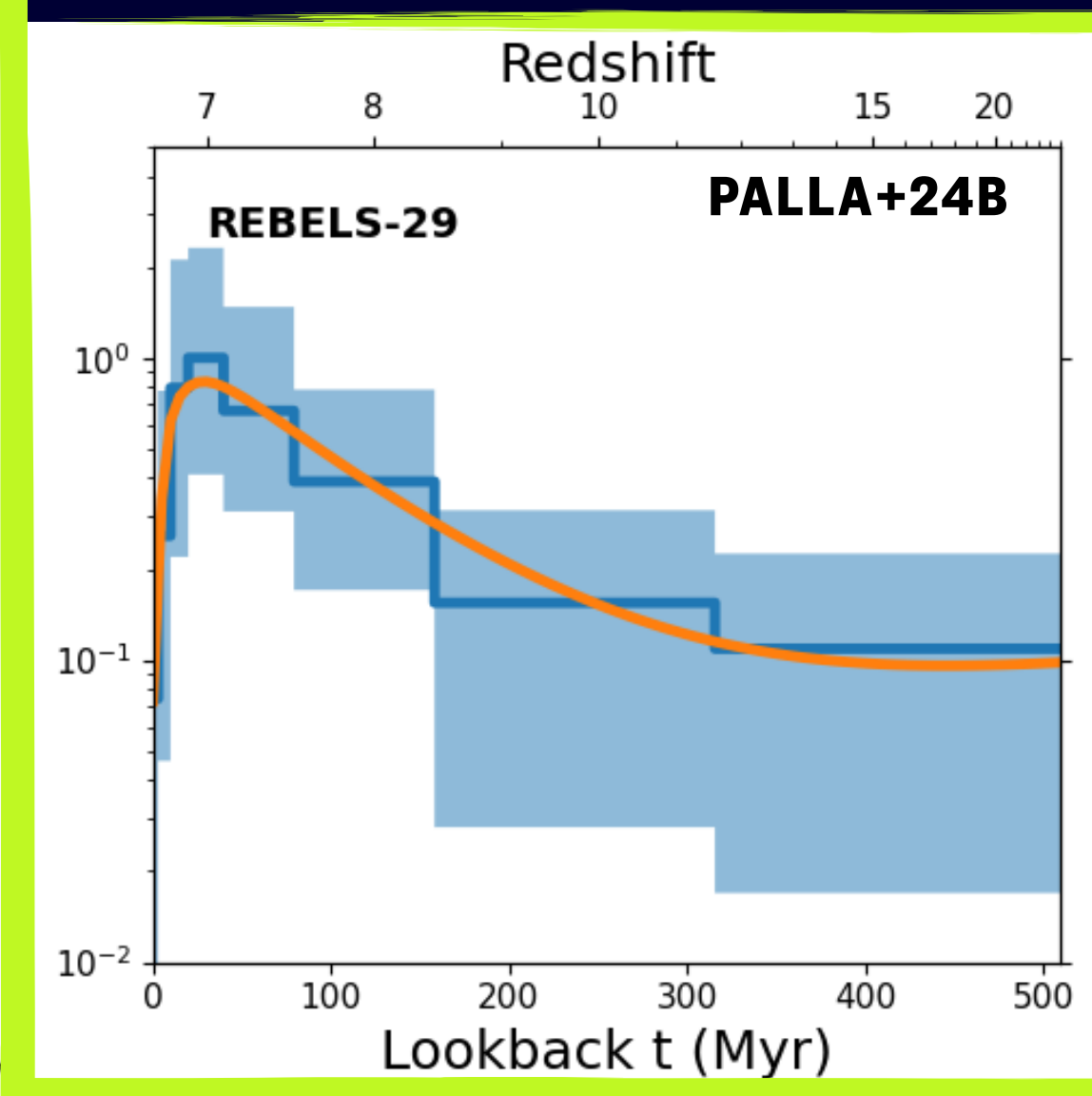
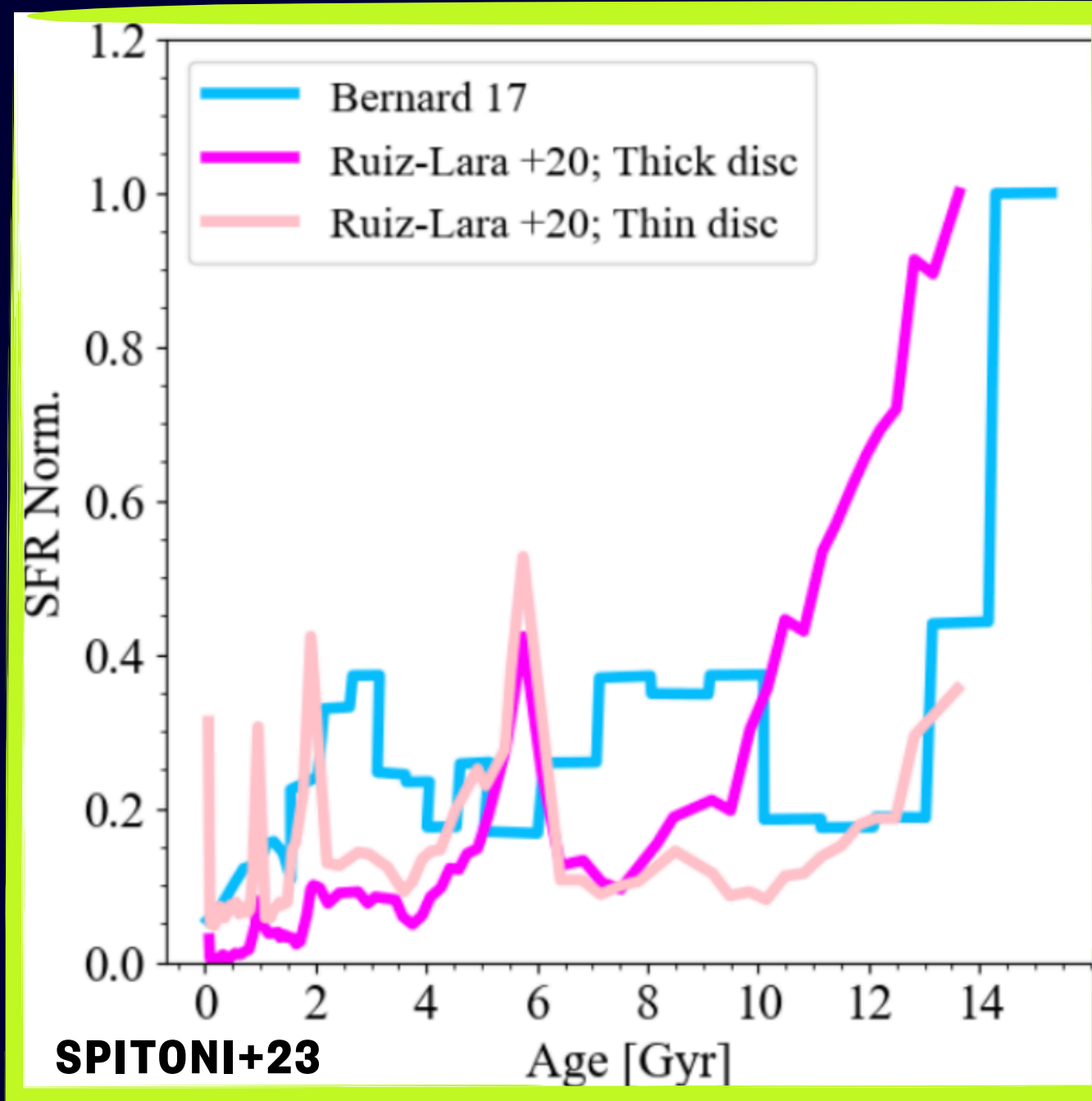
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# 'Tracking' the MW galaxy

Among others ...



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Among others ...



## RADIAL ABUNDANCE GRADIENTS

# 'Tracking' the MW galaxy

Among others ...



## RADIAL ABUNDANCE GRADIENTS

**DIFFERENT TRACERS** availability :

- **HII regions** (e.g. Peimbert+78, Balser+11, Méndez-Delgado+22)
- **Classical Cepheids (CCs)** (e.g. Lemasle+07, Genovali+15, Luck 18)
- **Young OB stars** (e.g. Daflon & Cunha 04, Bragança+19)
- **Planetary Nebulae (PNe)** (e.g. Maciel +03, Stanghellini+10, 18)
- **Open Clusters (OCs)** (e.g. Bragaglia+08, Yong+12, Jacobson+16)
- **Field stars with precise ages** (e.g. Anders+17, Santos-Peral+21)

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**PRESENT-DAY**

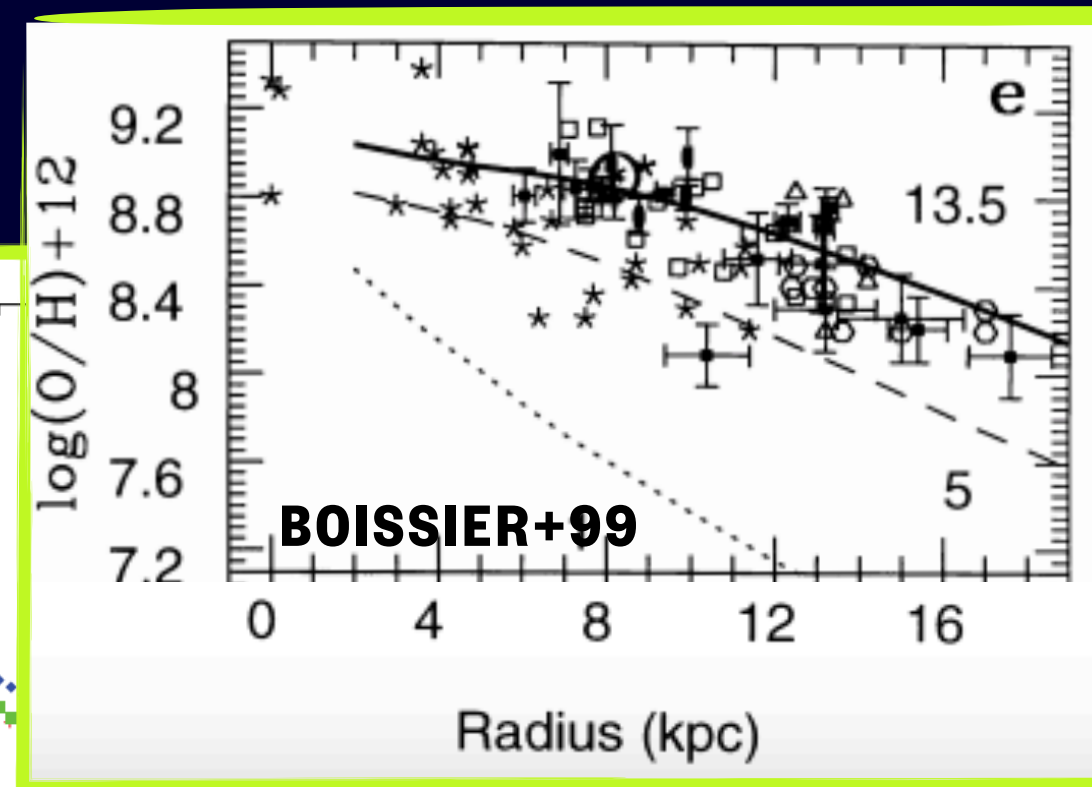
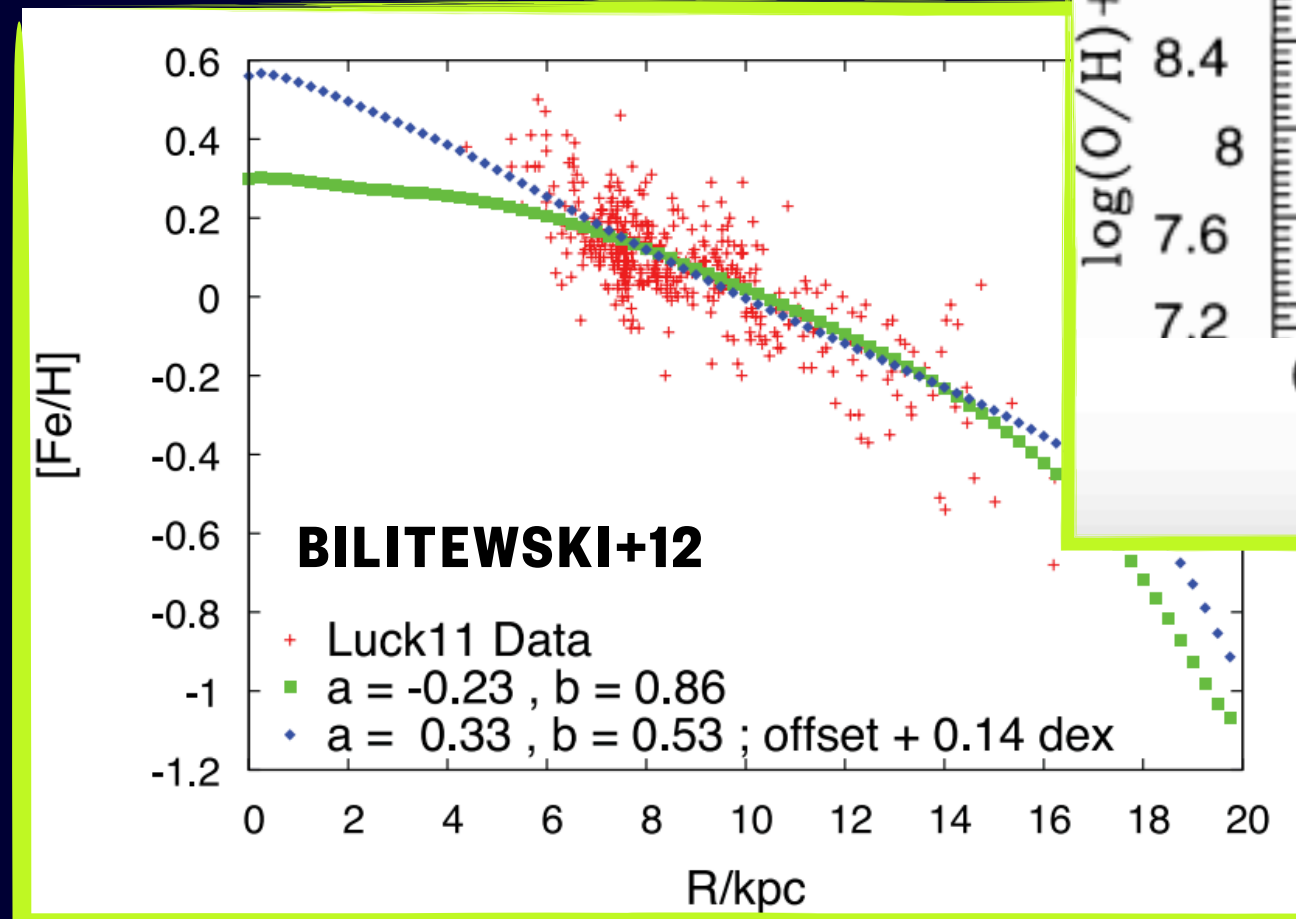
**EVOLUTION**

# 'Tracking' the MW galaxy

Among others ...



## RADIAL ABUNDANCE GRADIENTS



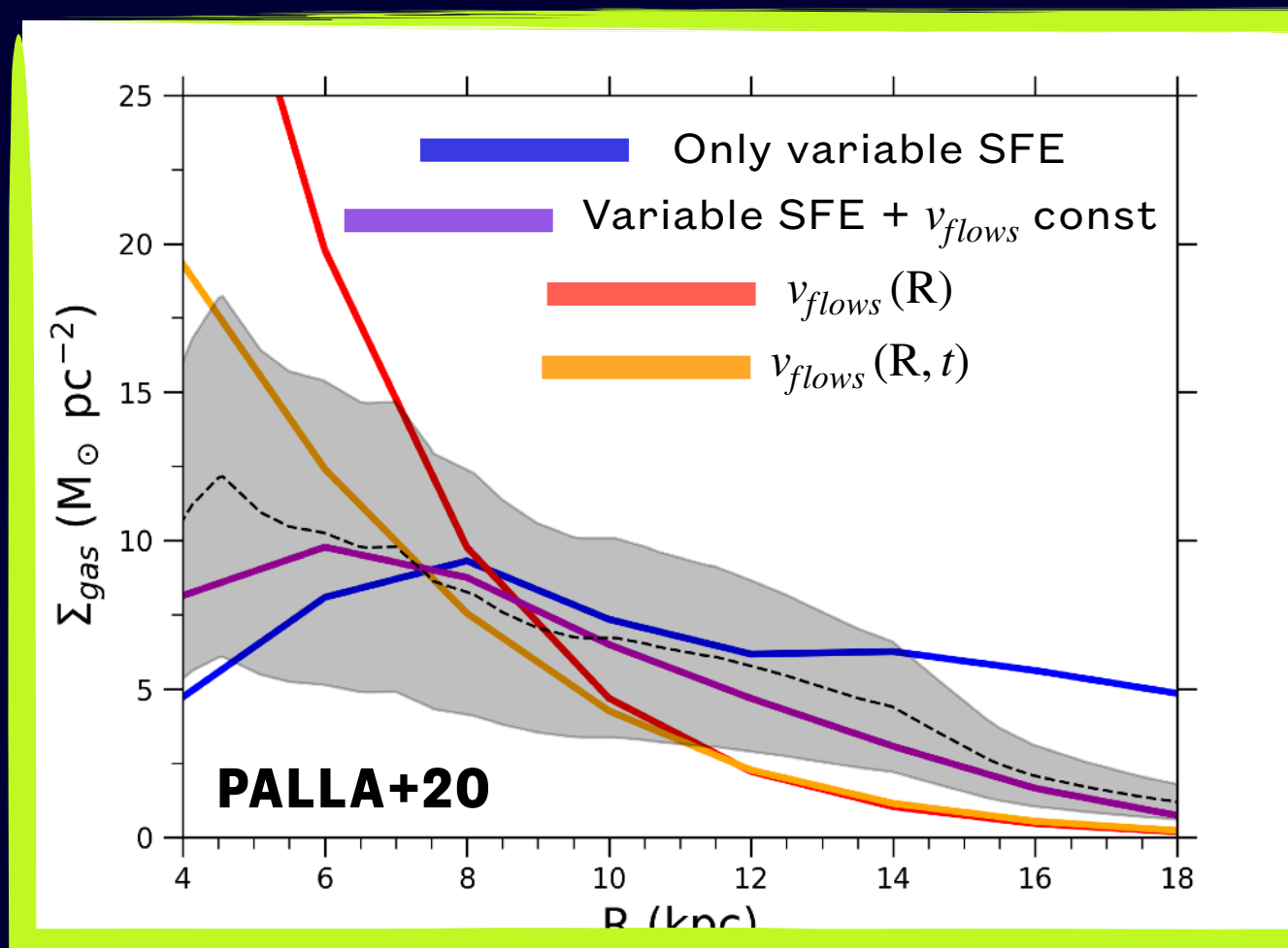
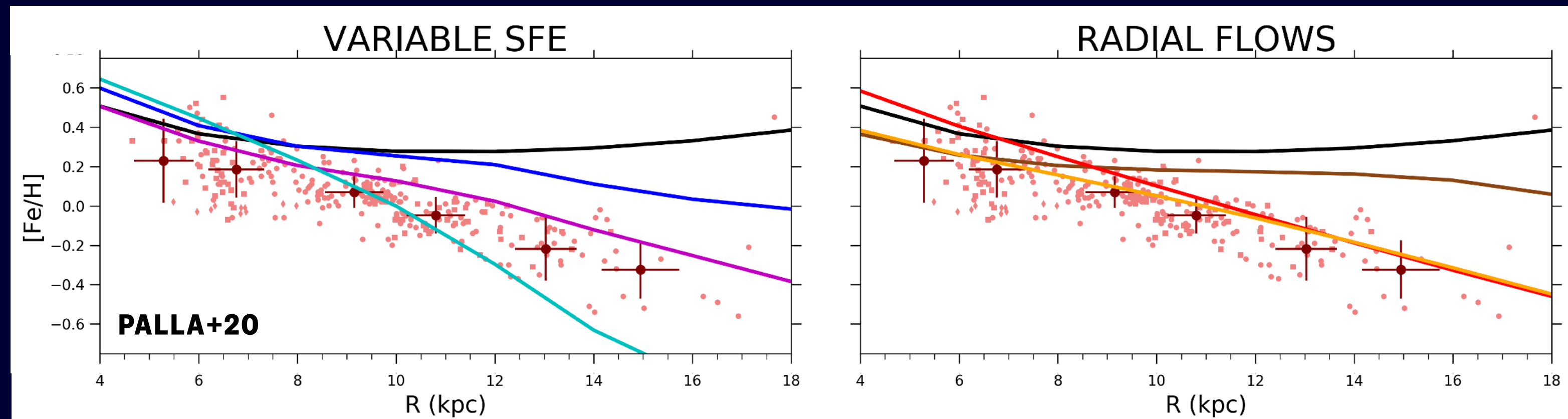
Probing **PROPERTIES** of the **DISC** of our Galaxy:

- **inside-out disc** formation (e.g. Matteucci & François 89, Boissier & Prantzos 99, Bilitewky & Schönrich 12)
- **variable efficiency of SF** (e.g. Colavitti+09, Mott+13, Palla+20)
- **Radial gas flows** (e.g. Portinari & Chiosi 00, Spitoni+11, Bilitewky & Schönrich 12, Grisoni+18)
- **Stellar migration** (e.g. Minchev+13+16, Santos-Peral+21)

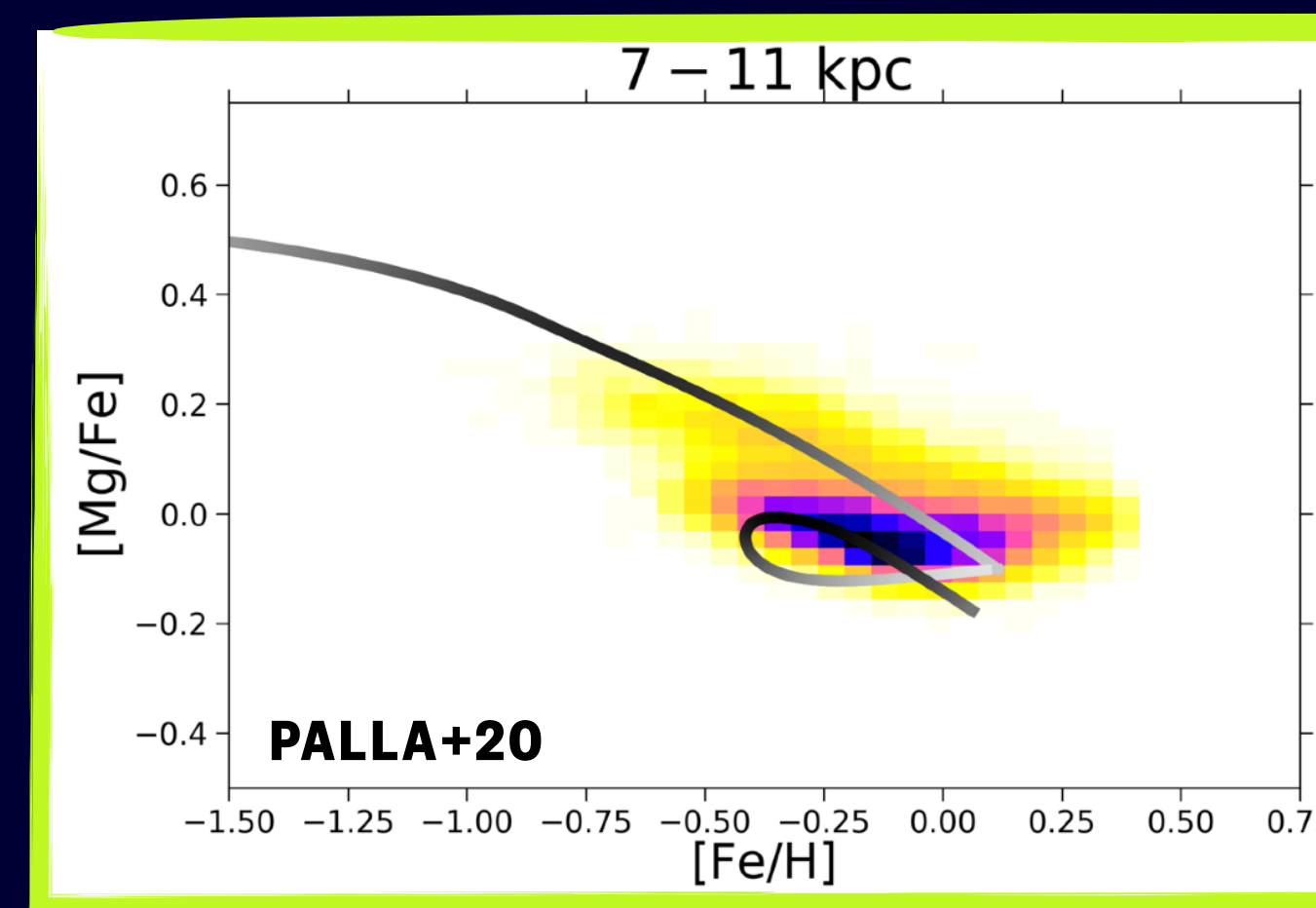


# Modelling radial gradients

NOT ONLY ABUNDANCES



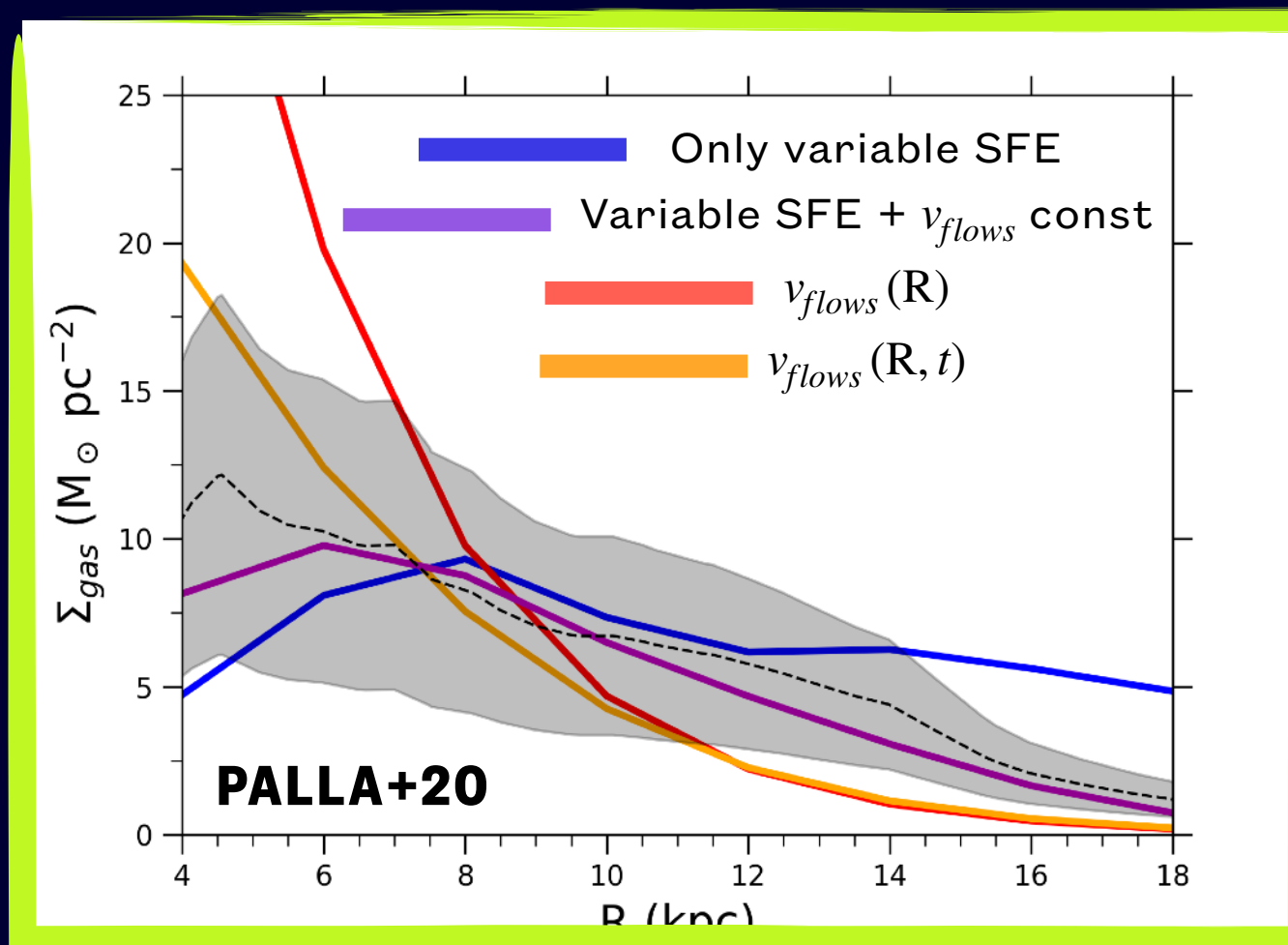
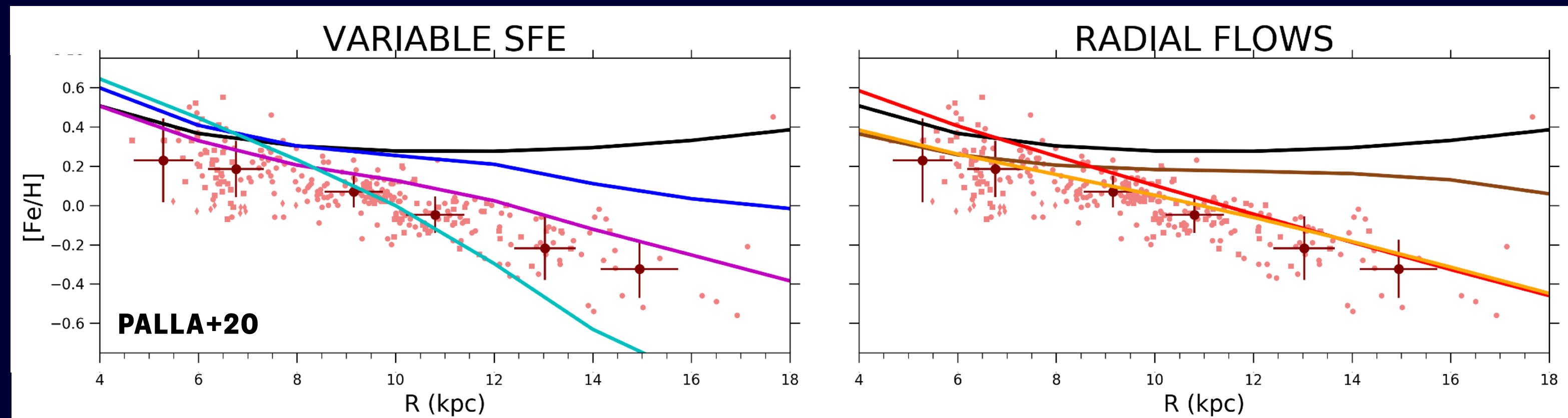
Physical  
Gradients  
(SFR, gas, stars)



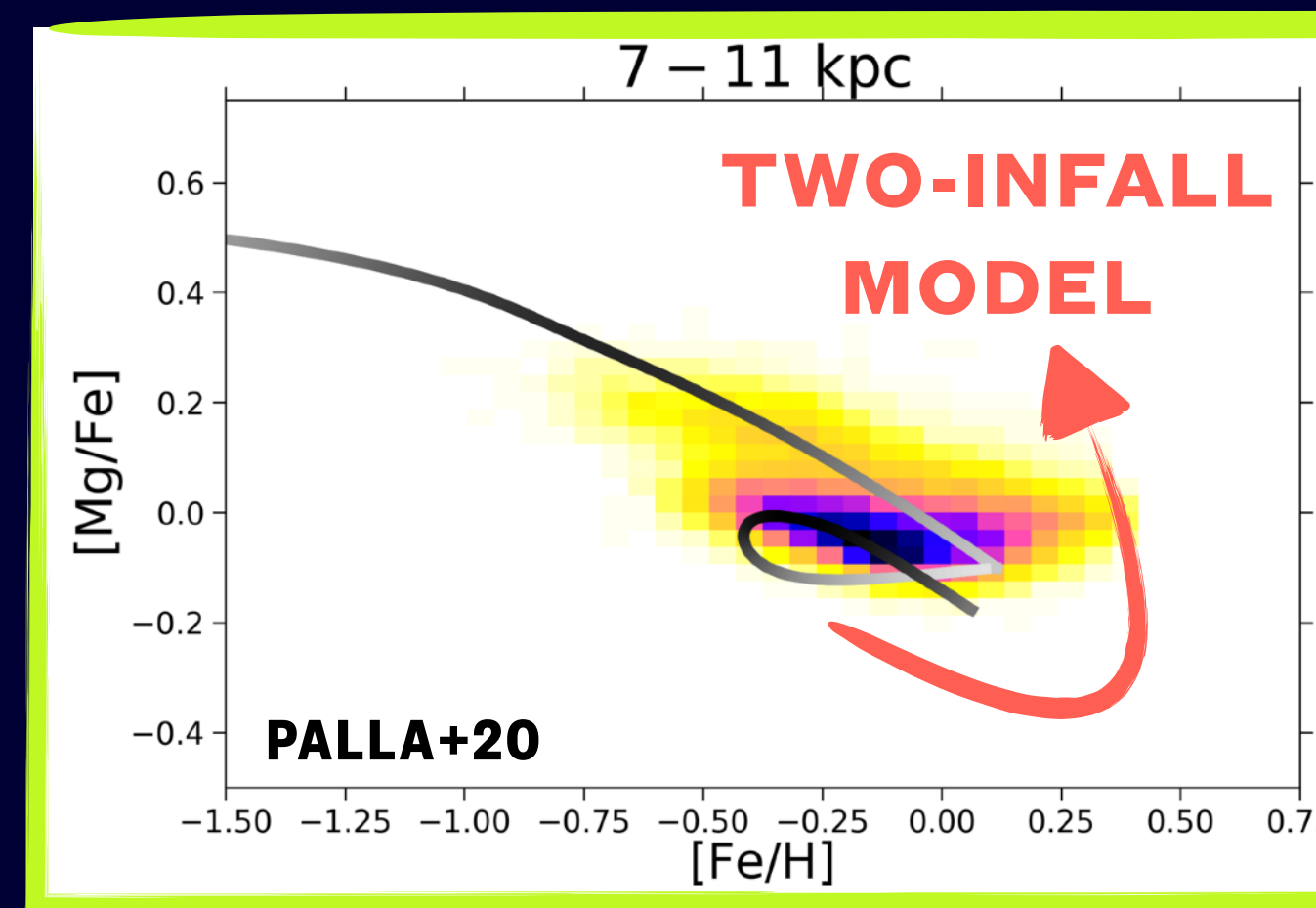
Abundance  
diagrams  
[X/Fe] vs [Fe/H]

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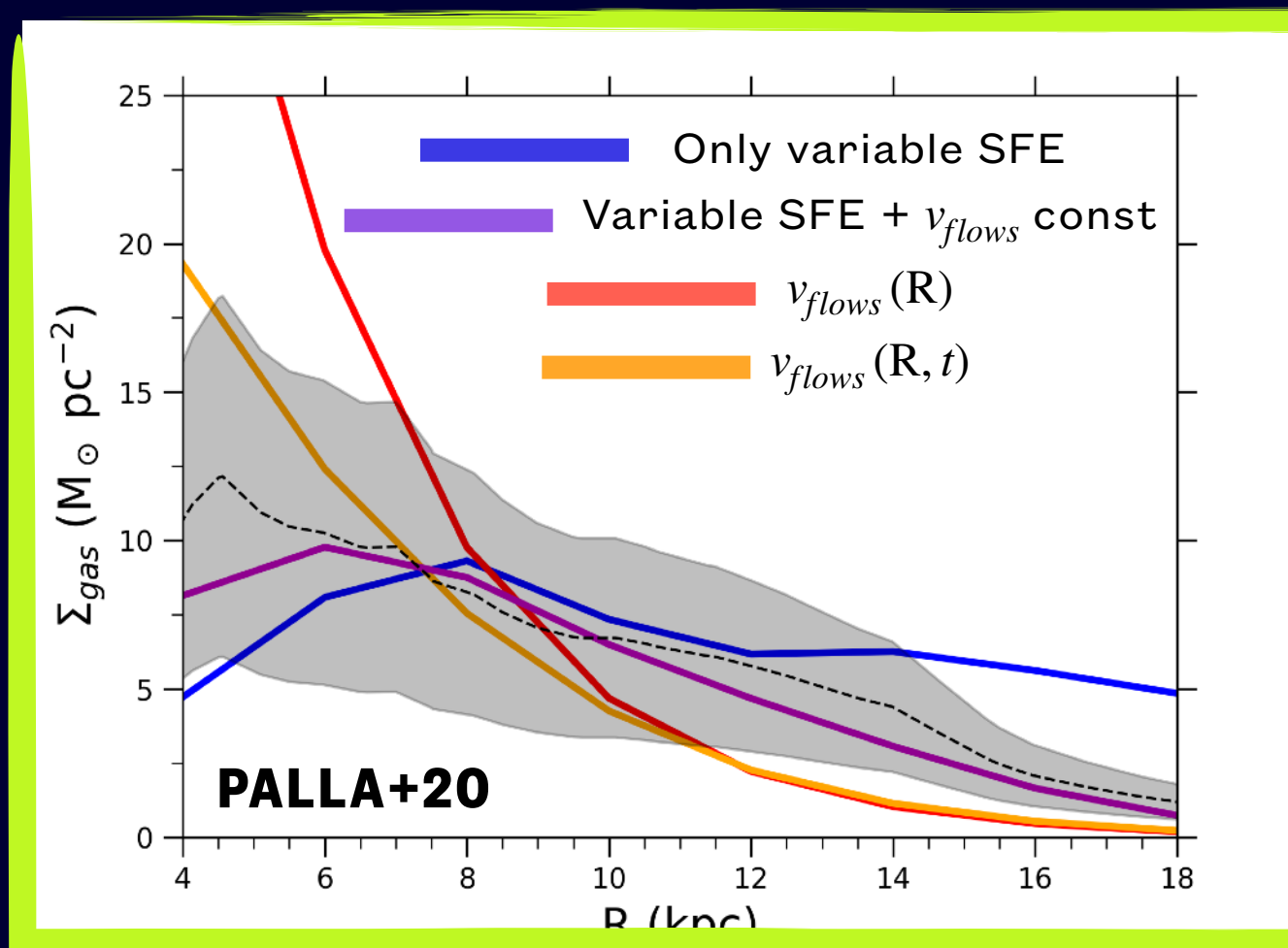
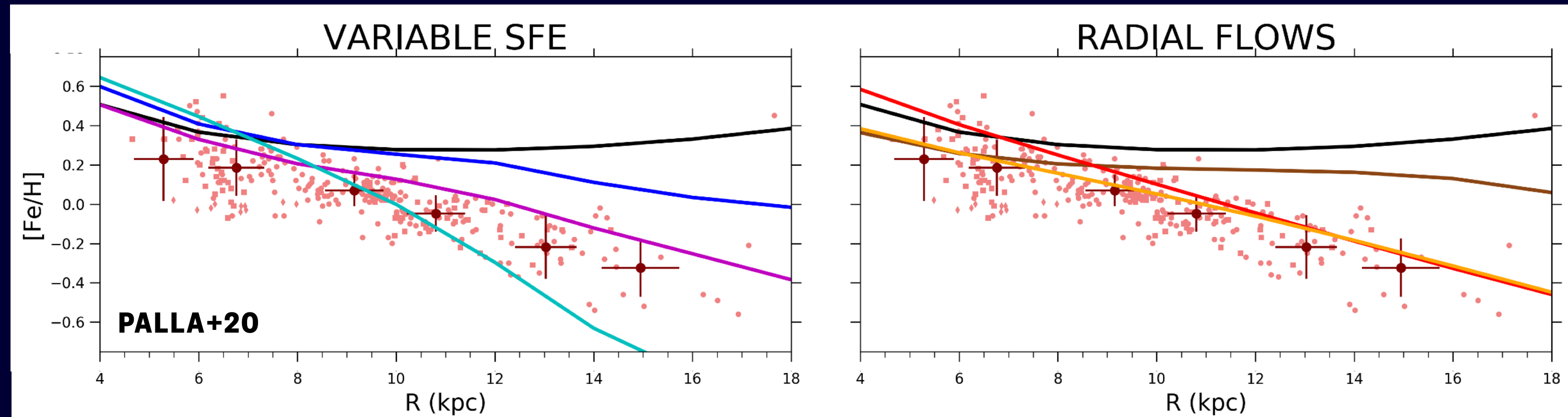
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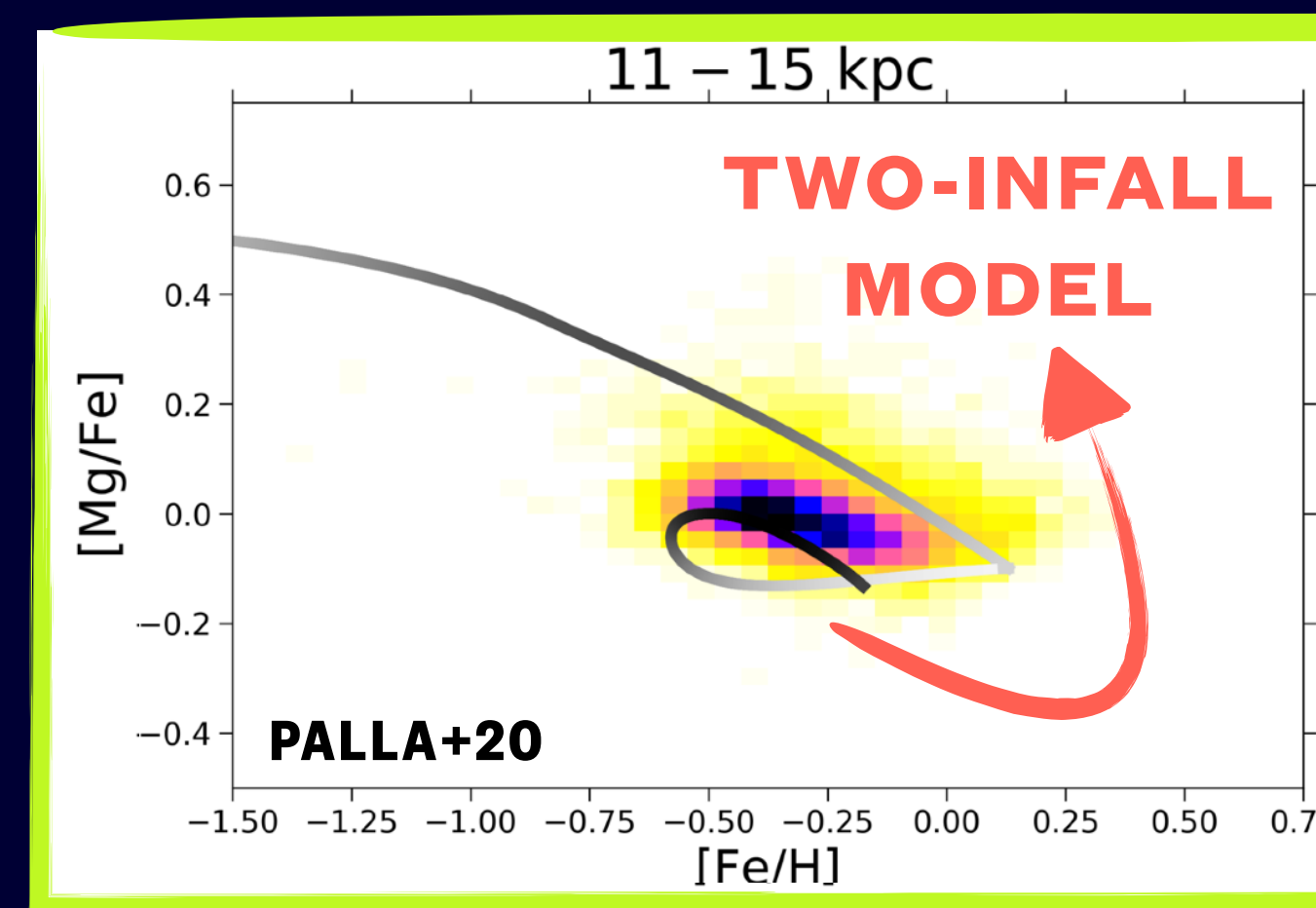
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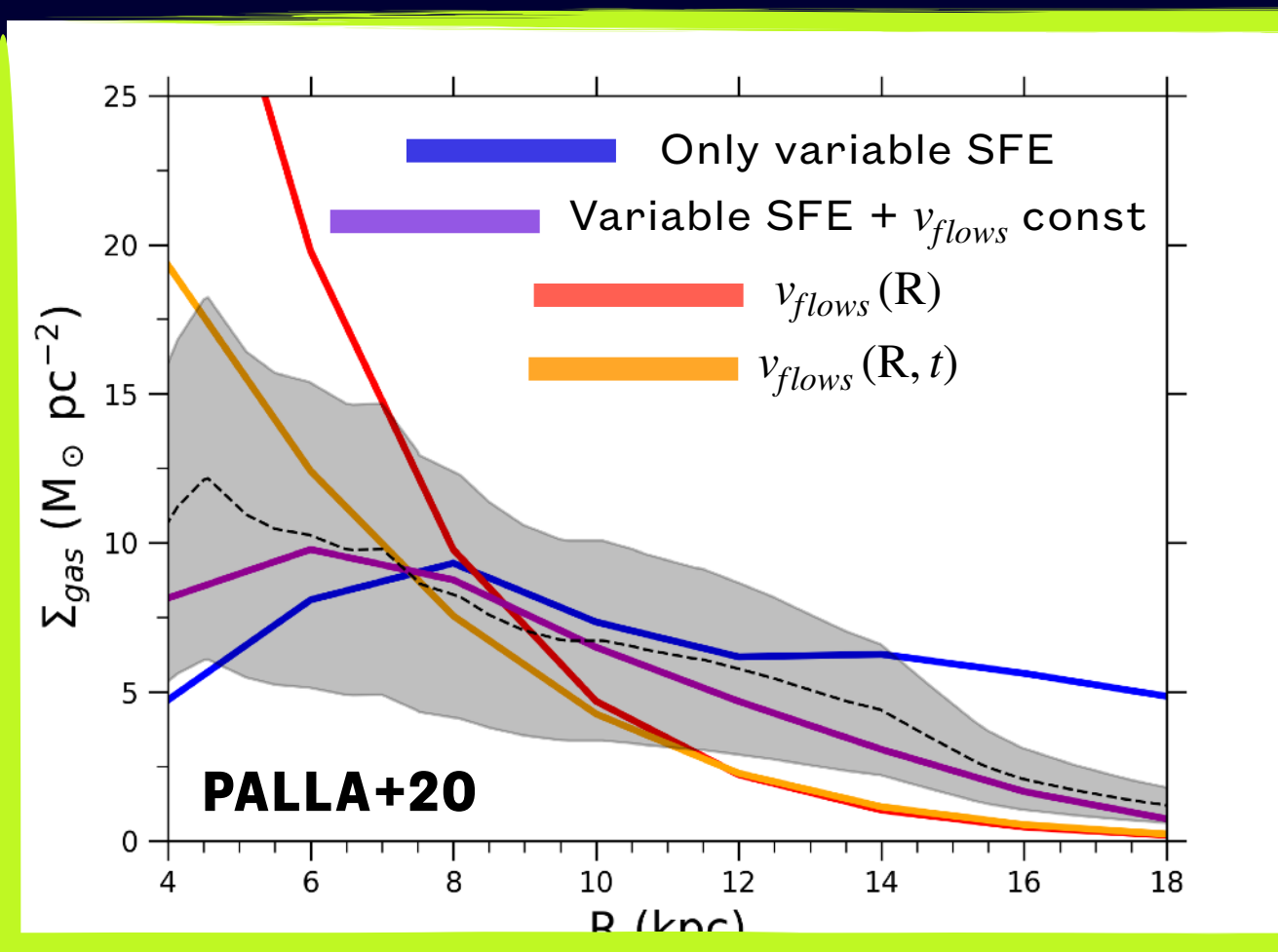
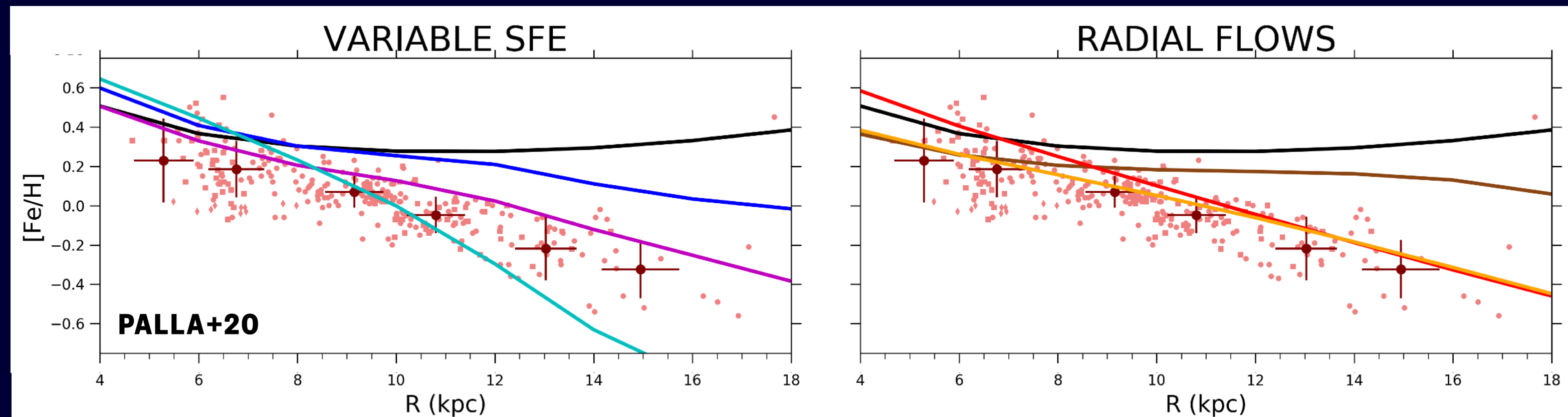
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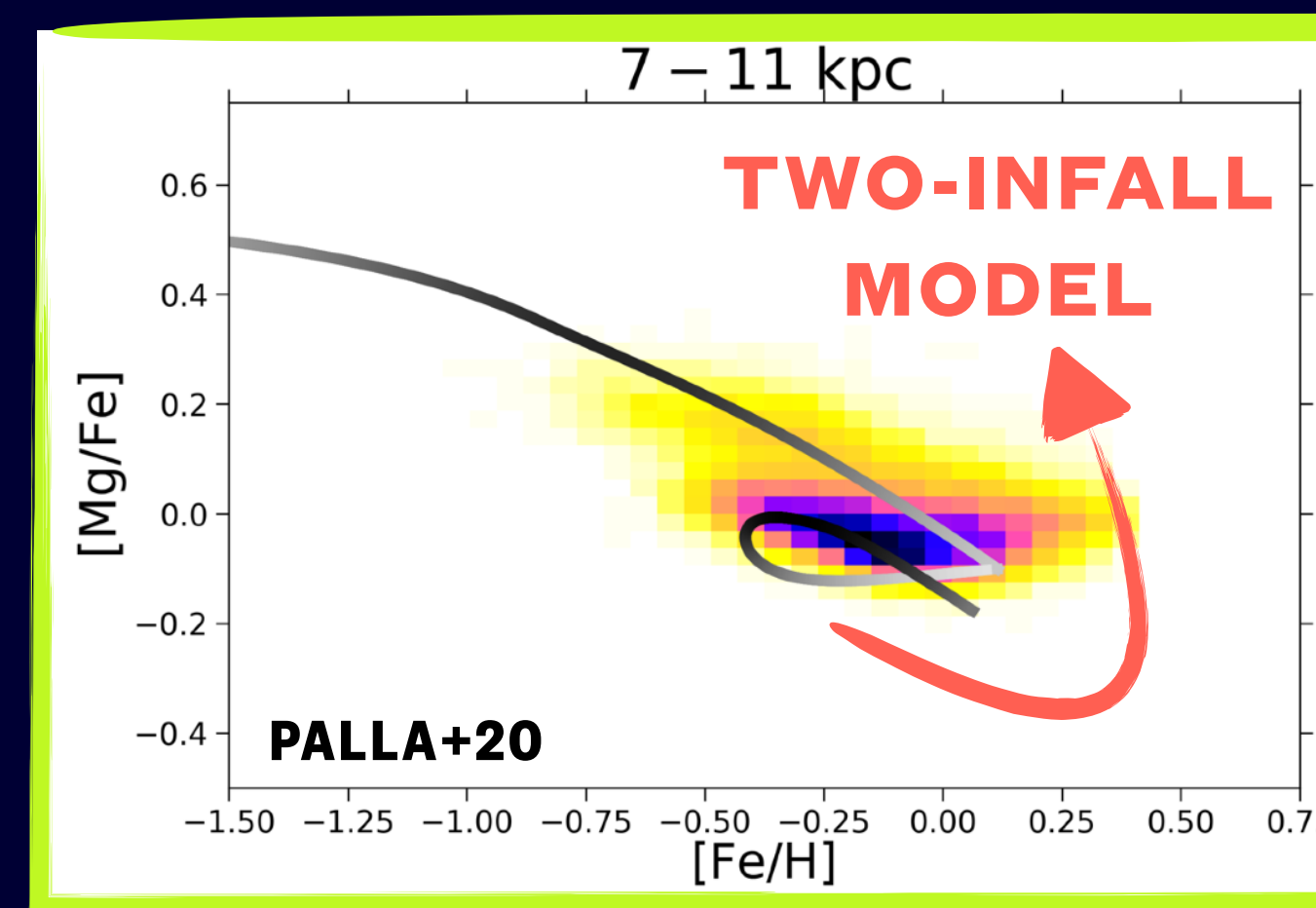
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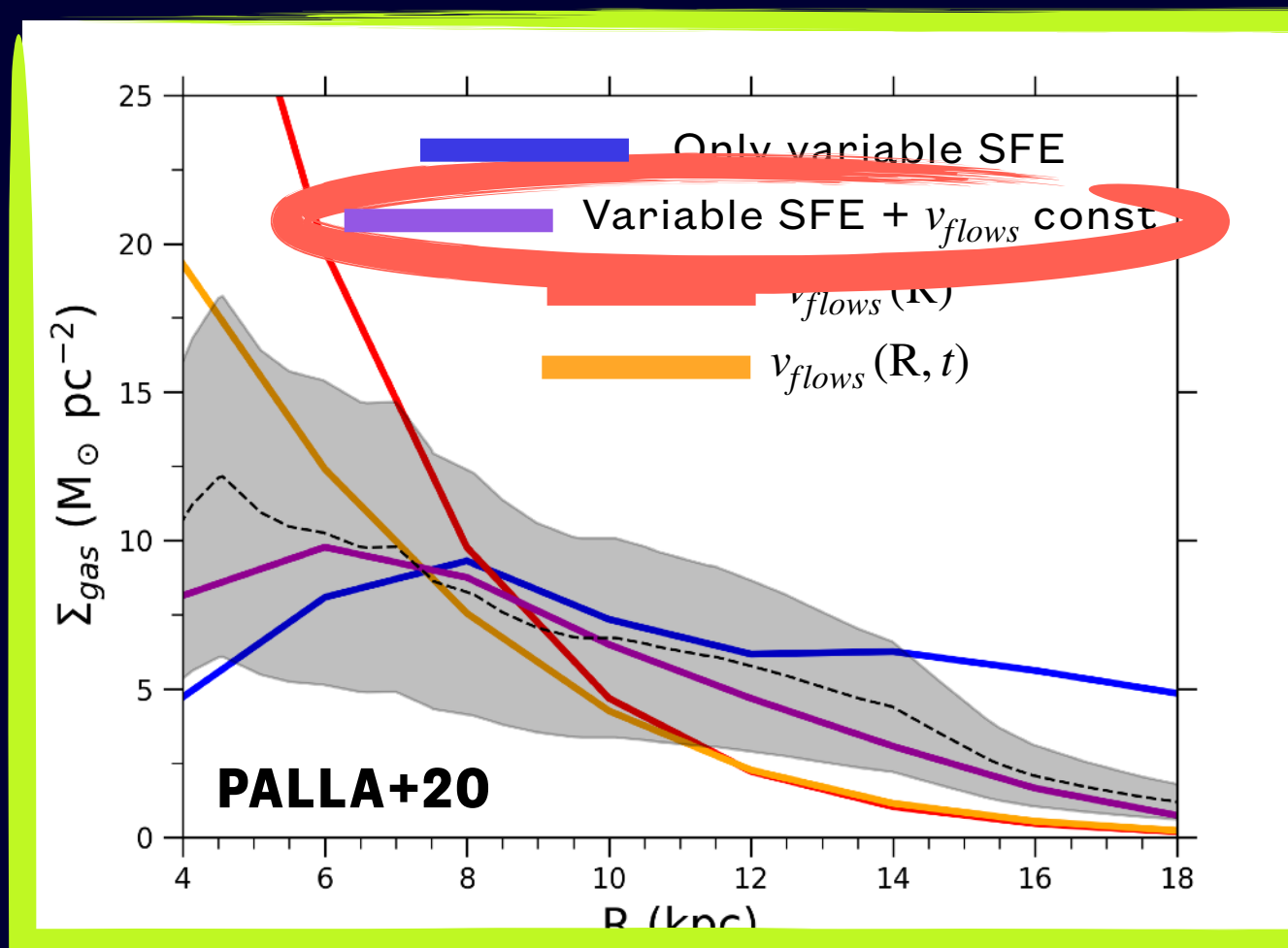
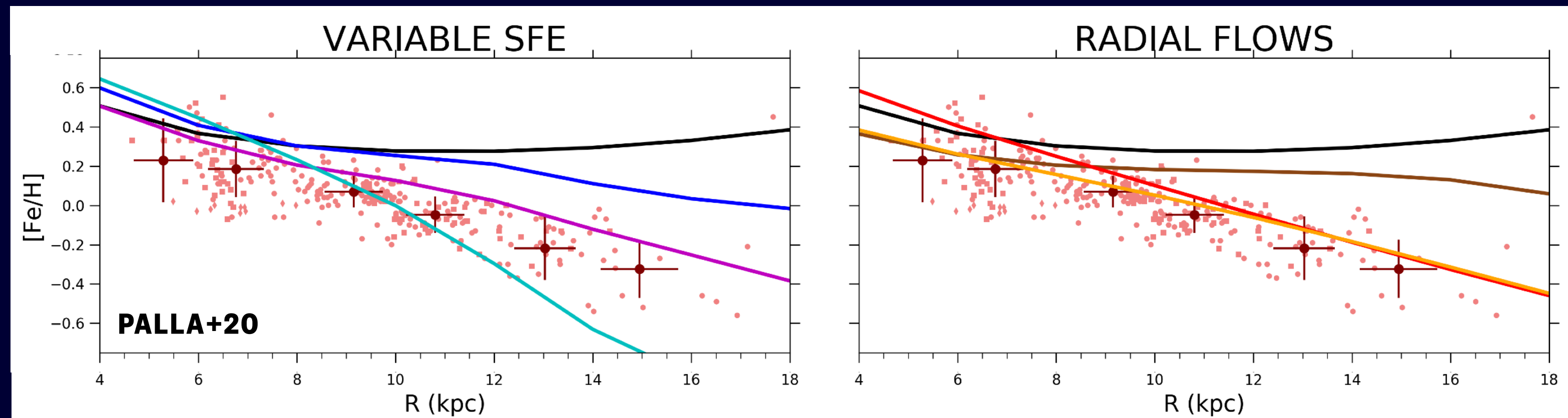
+



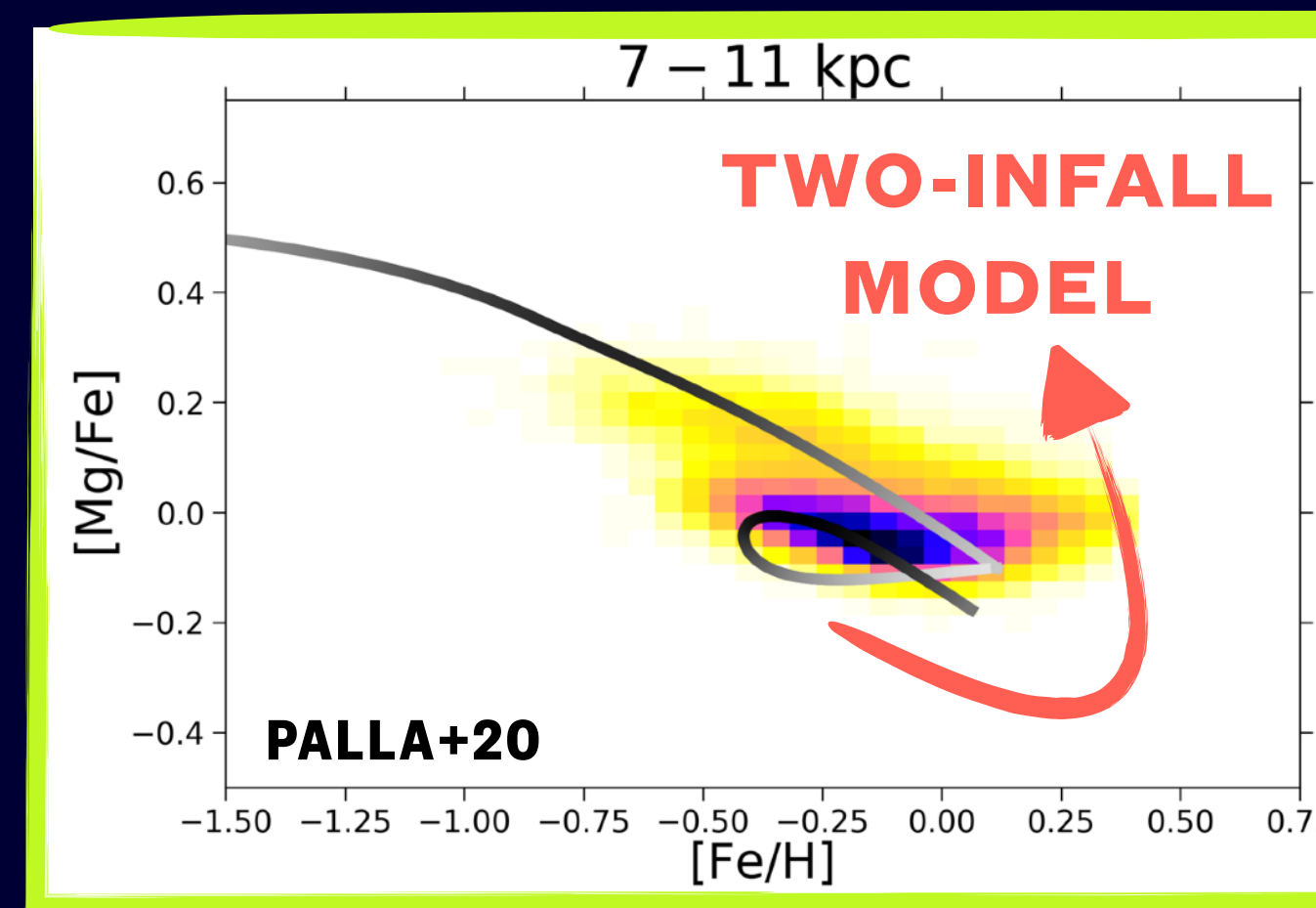
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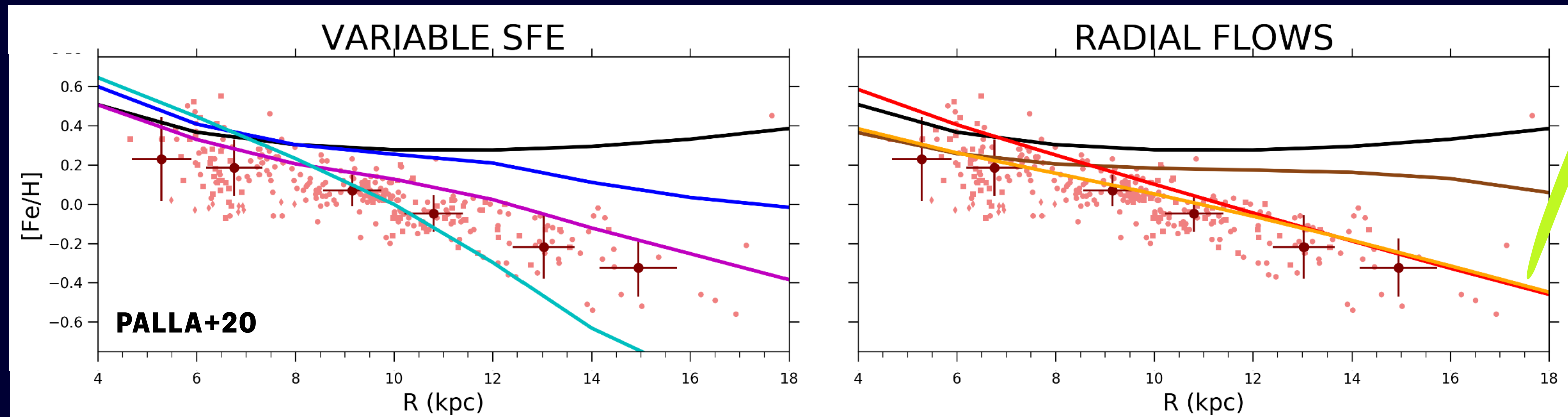
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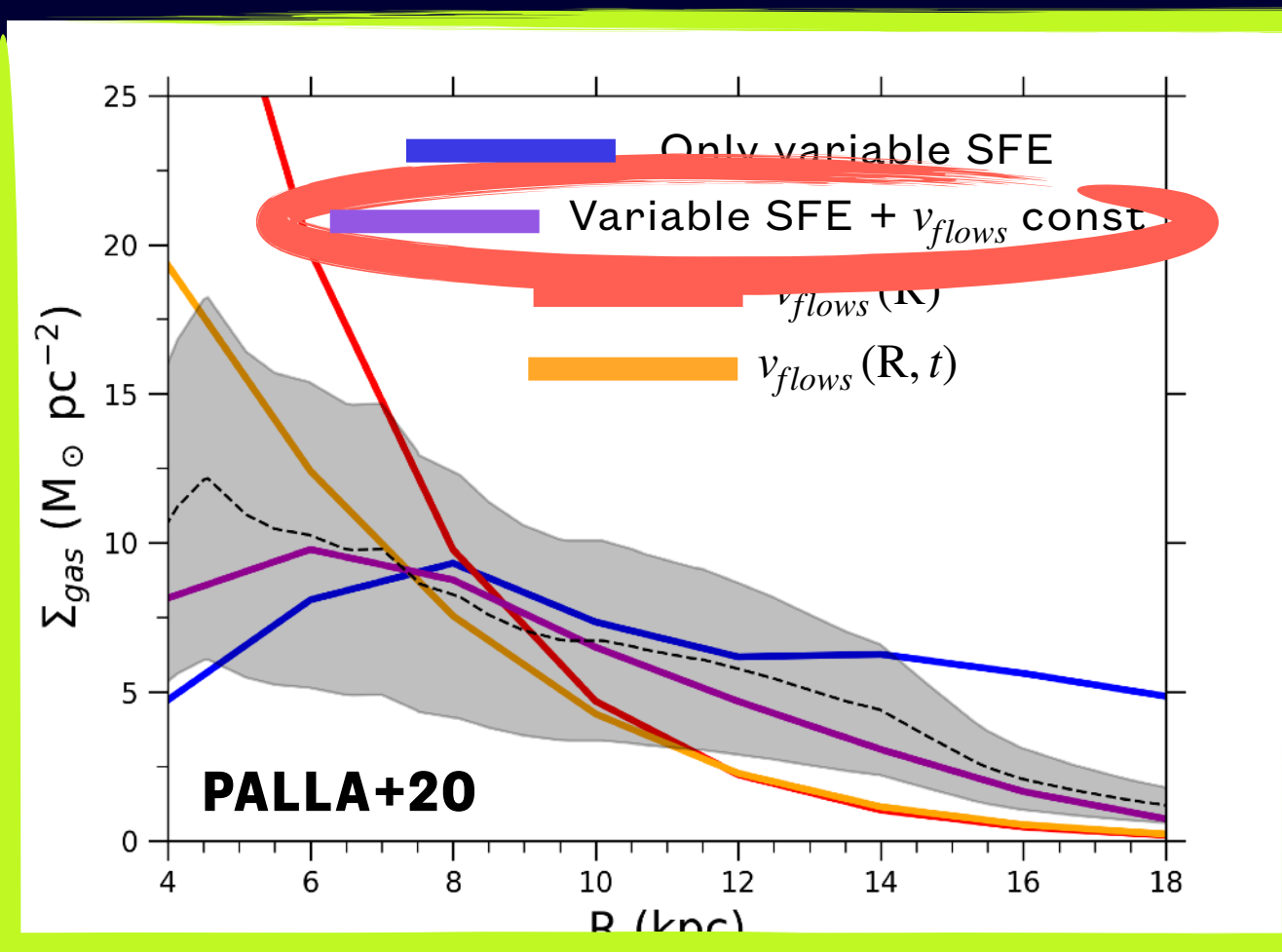
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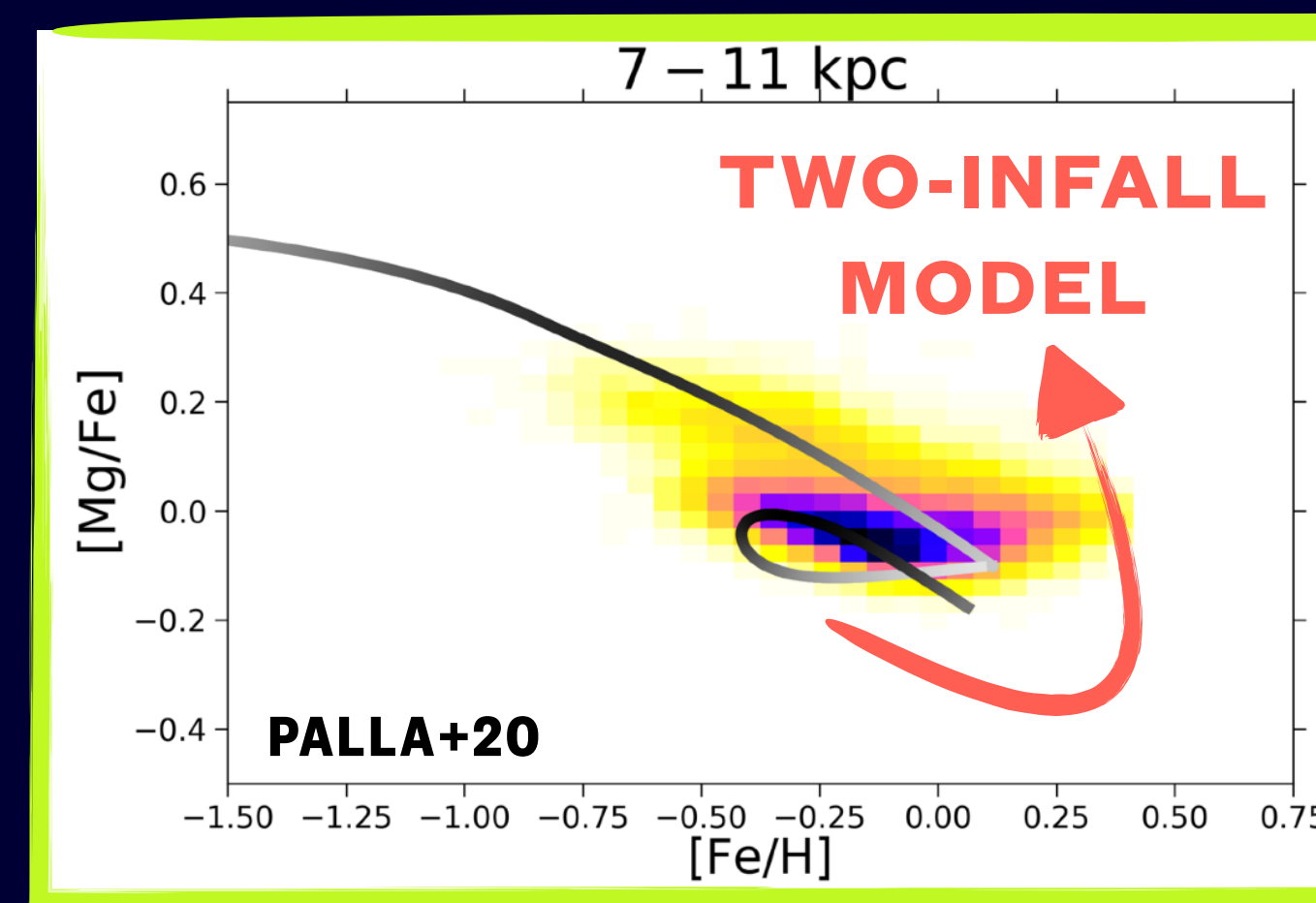


PALLA+20  
 “CLASSICAL” PICTURE

Monotonic decrease  
 in metal abundances  
 with radius



Physical  
 Gradients  
 (SFR, gas, stars)



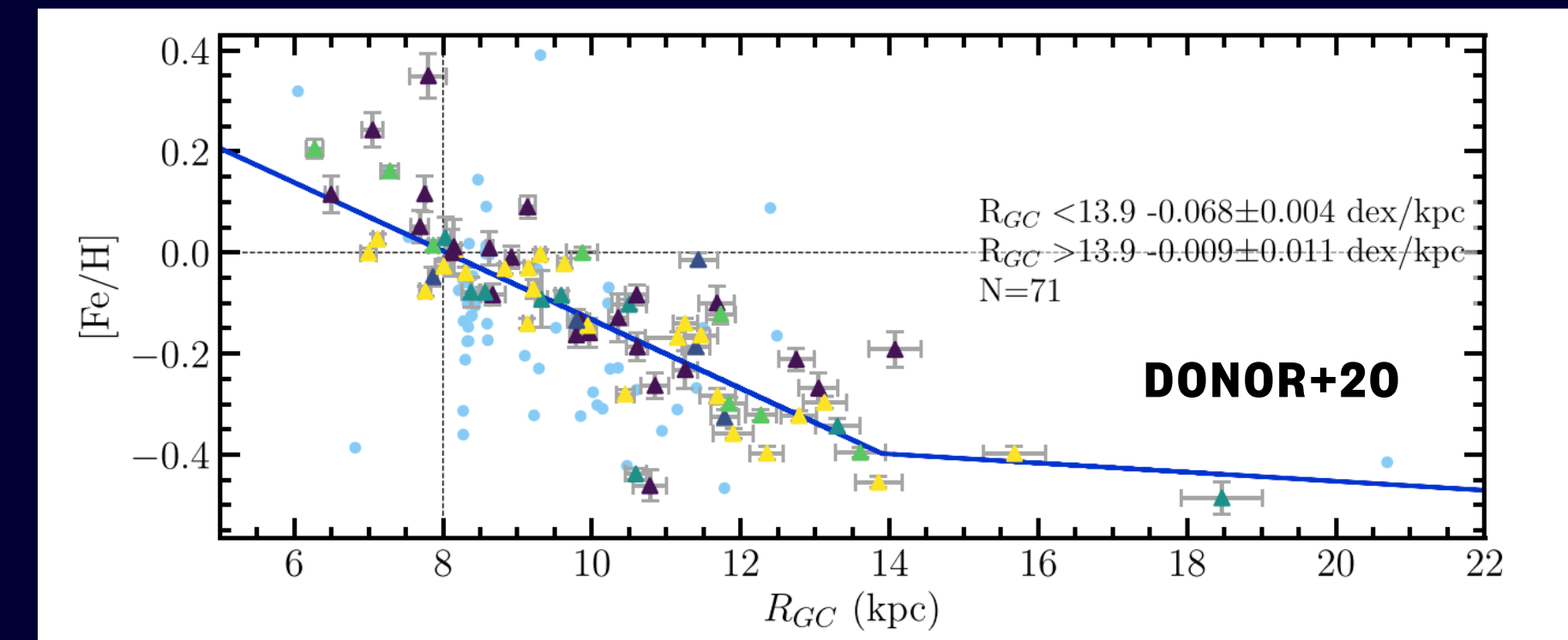
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# Beyond the classical picture

## FLATTENING OF GRADIENT AT LARGE R?

Several indications mostly from OCs studies

(e.g. Sestito+08, Yong+12, Magrini+17, Casamiquela+19, Donor+20, Neptopil+22, Spina+22, Myers+22)



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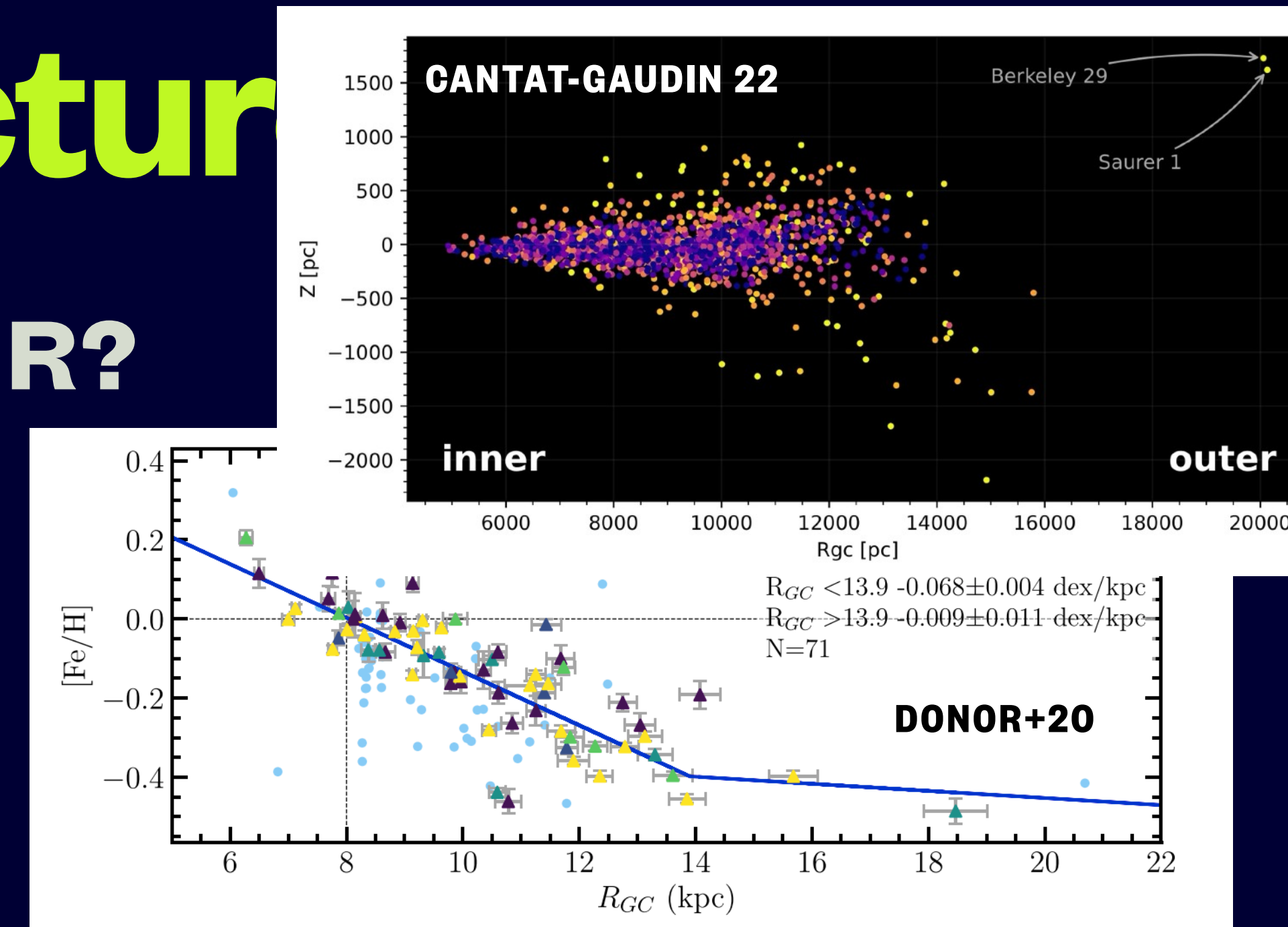
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**BUT too few data**

**BUT SEE ALSO Genovali+14, Lemasle+22**





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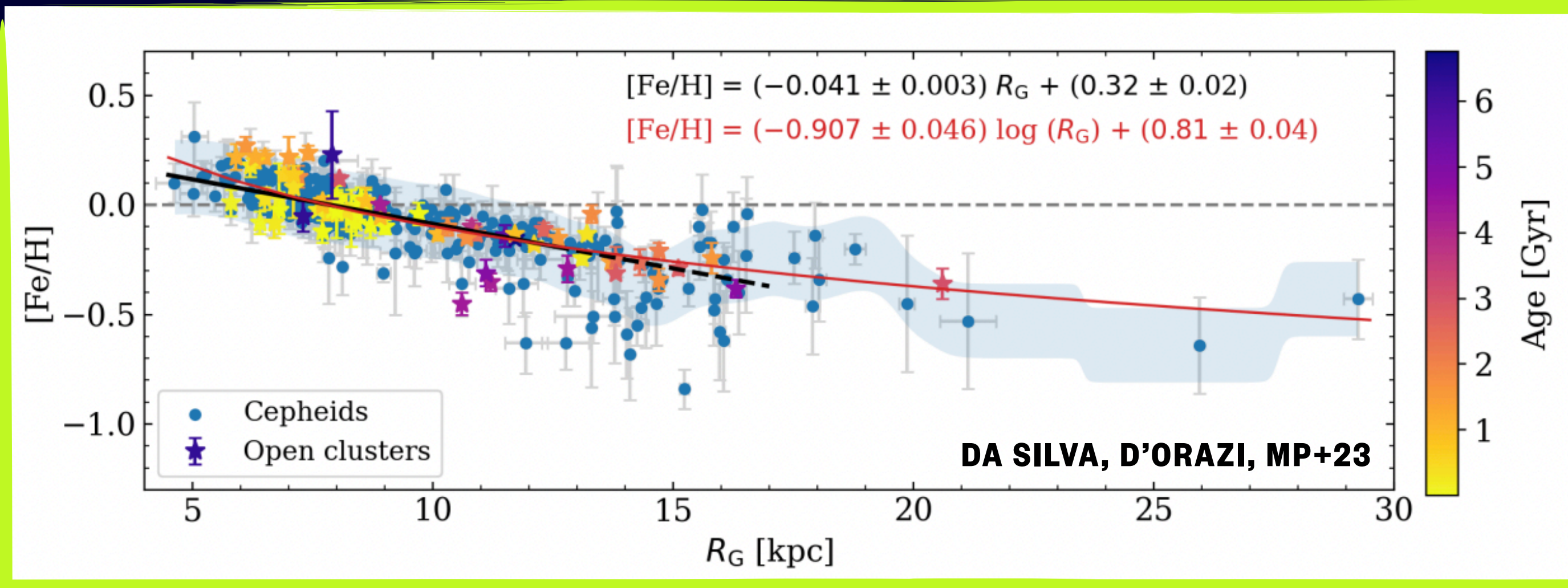
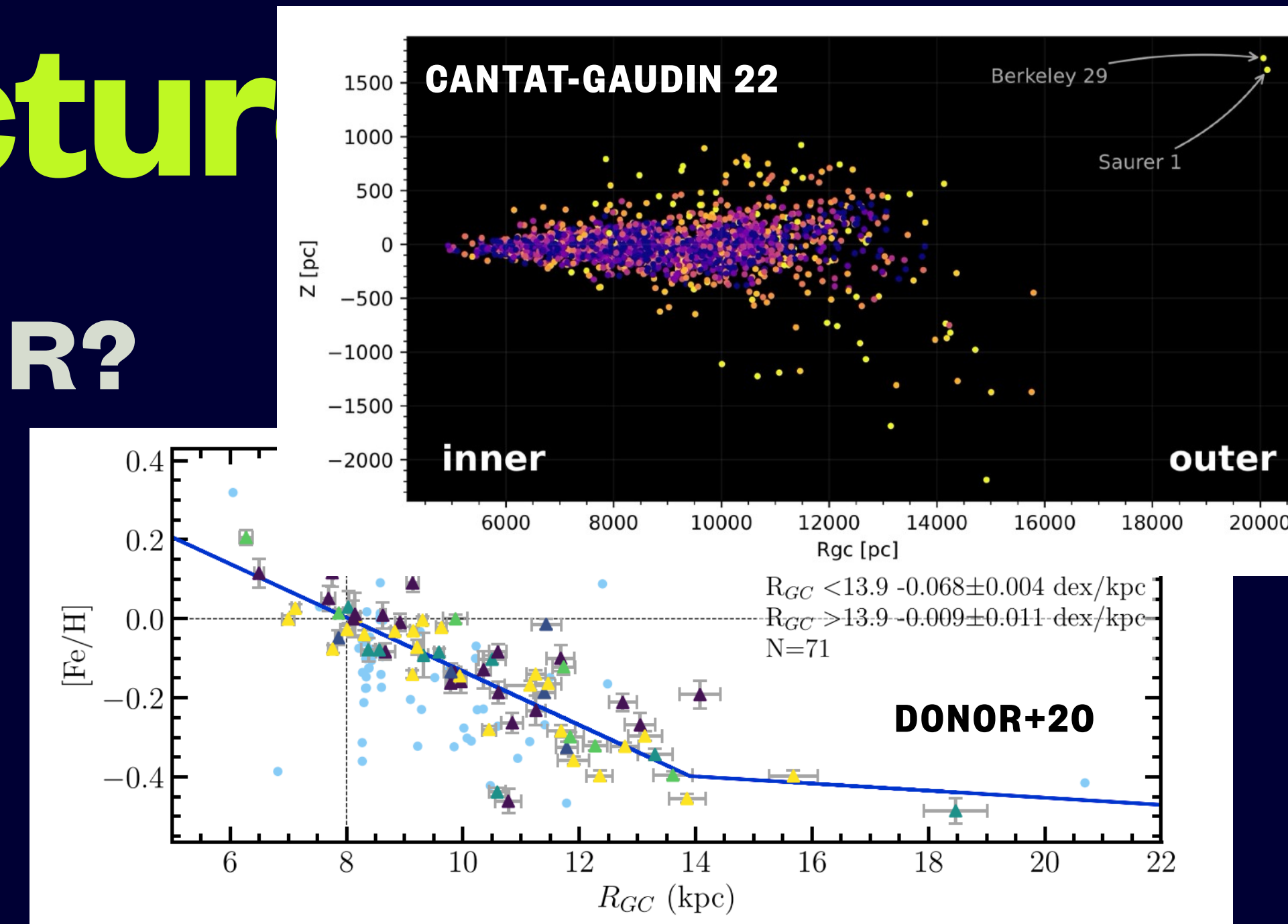
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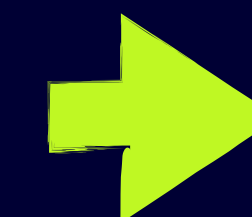
**BUT too few data**

**BUT SEE ALSO Genovali+14, Lemasle+22**



## DA SILVA+23

- Largest homogenous sample of CCs (>350 stars)
- Good radial sampling up to  $R > 16$  kpc

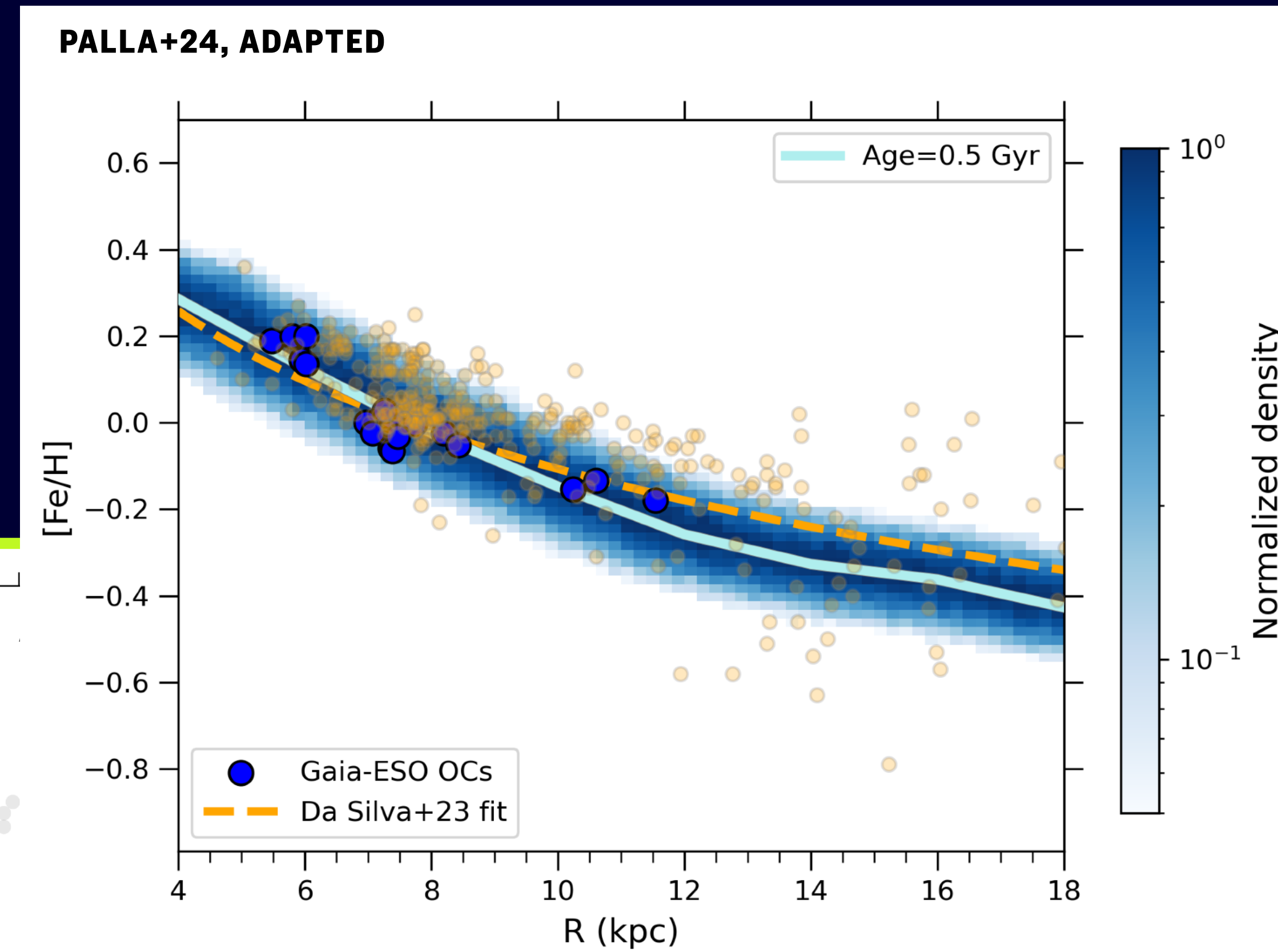
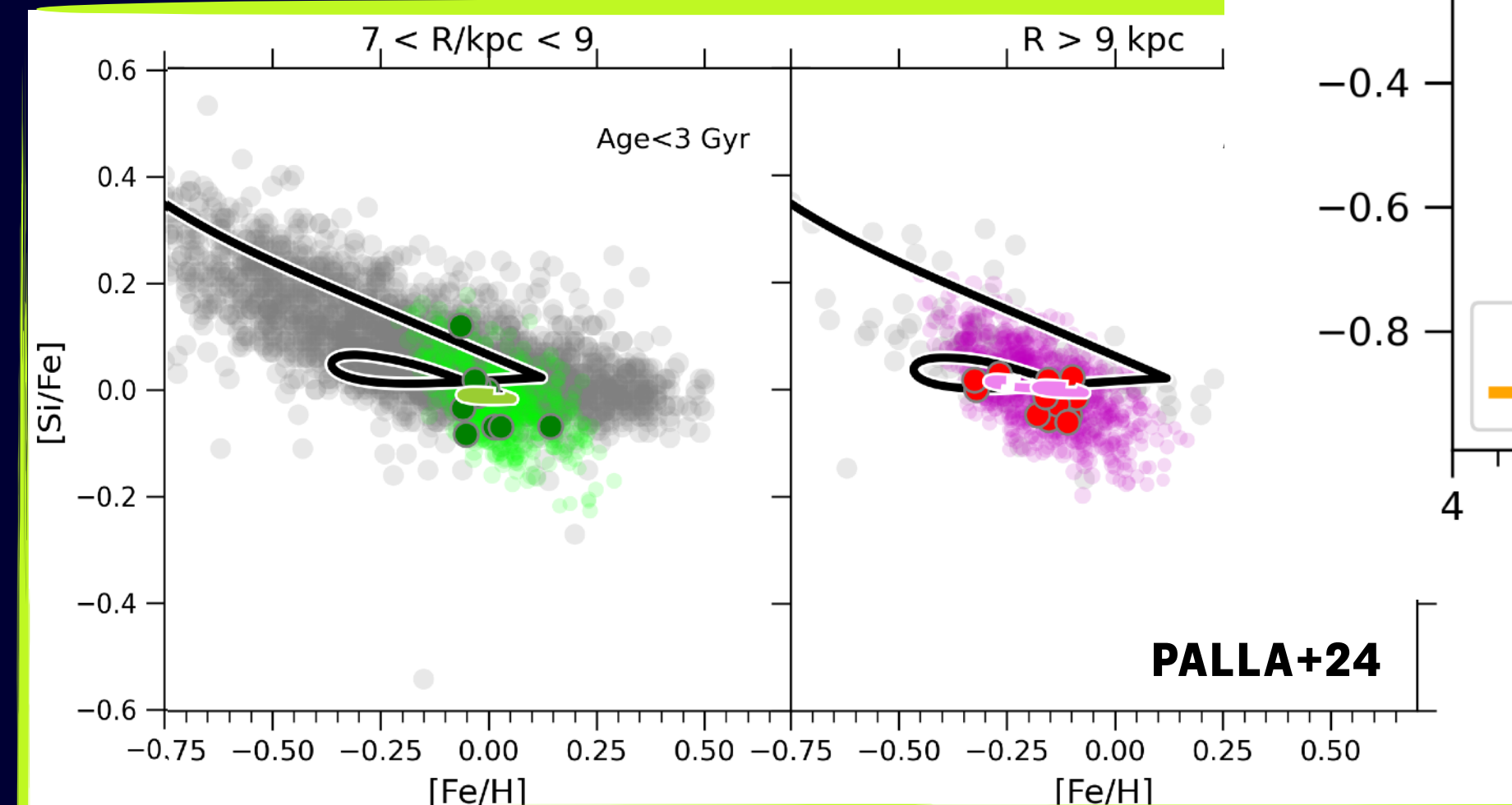
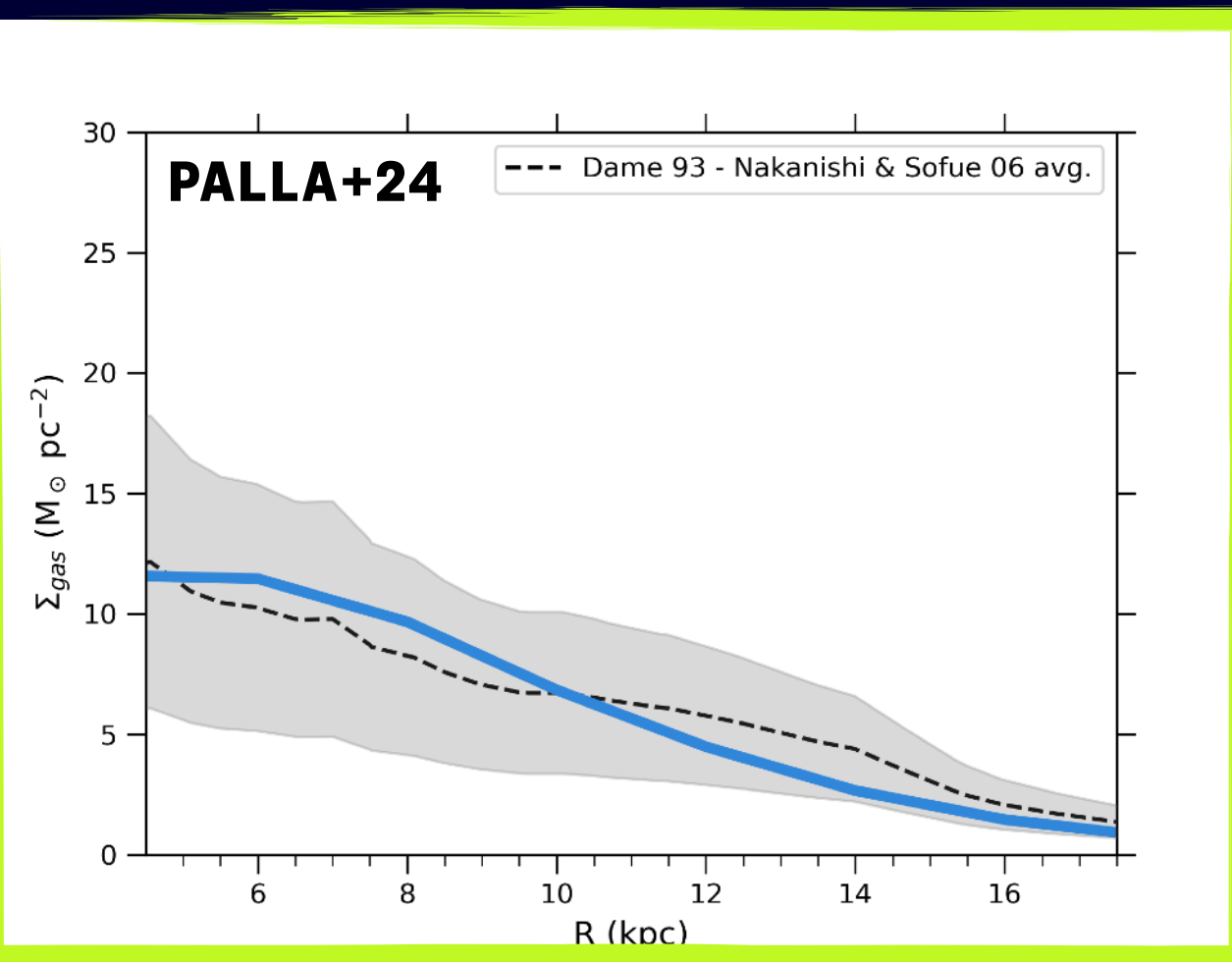


**shallow outer gradient**

# Beyond the classical picture

## UPDATING THE MODELS

- Da Silva+23, Palla+24: revision of the “classical picture”
- **Larger and const efficiency of SF** at large radii + **metal dilution** at late times (3rd infall)

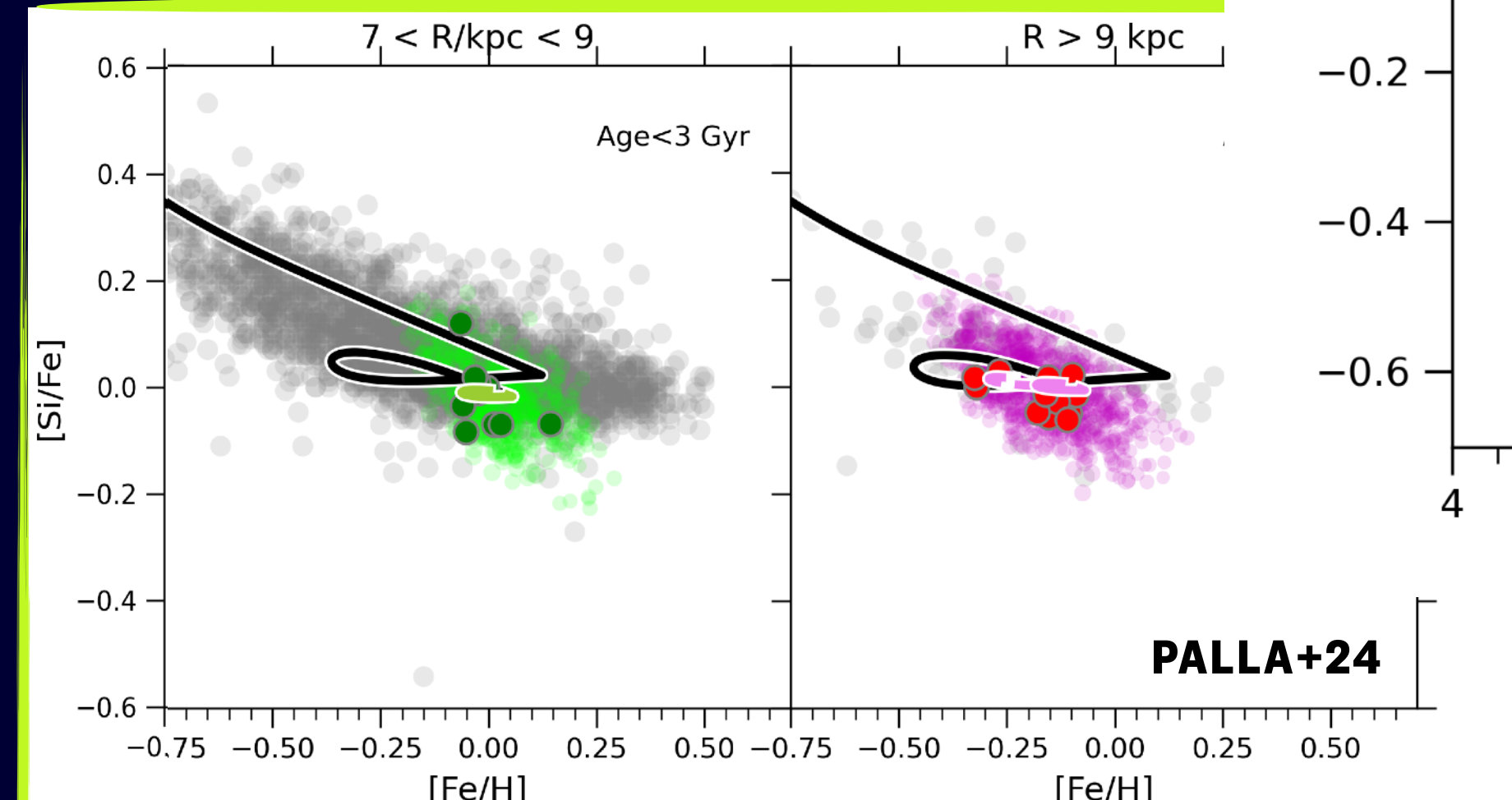
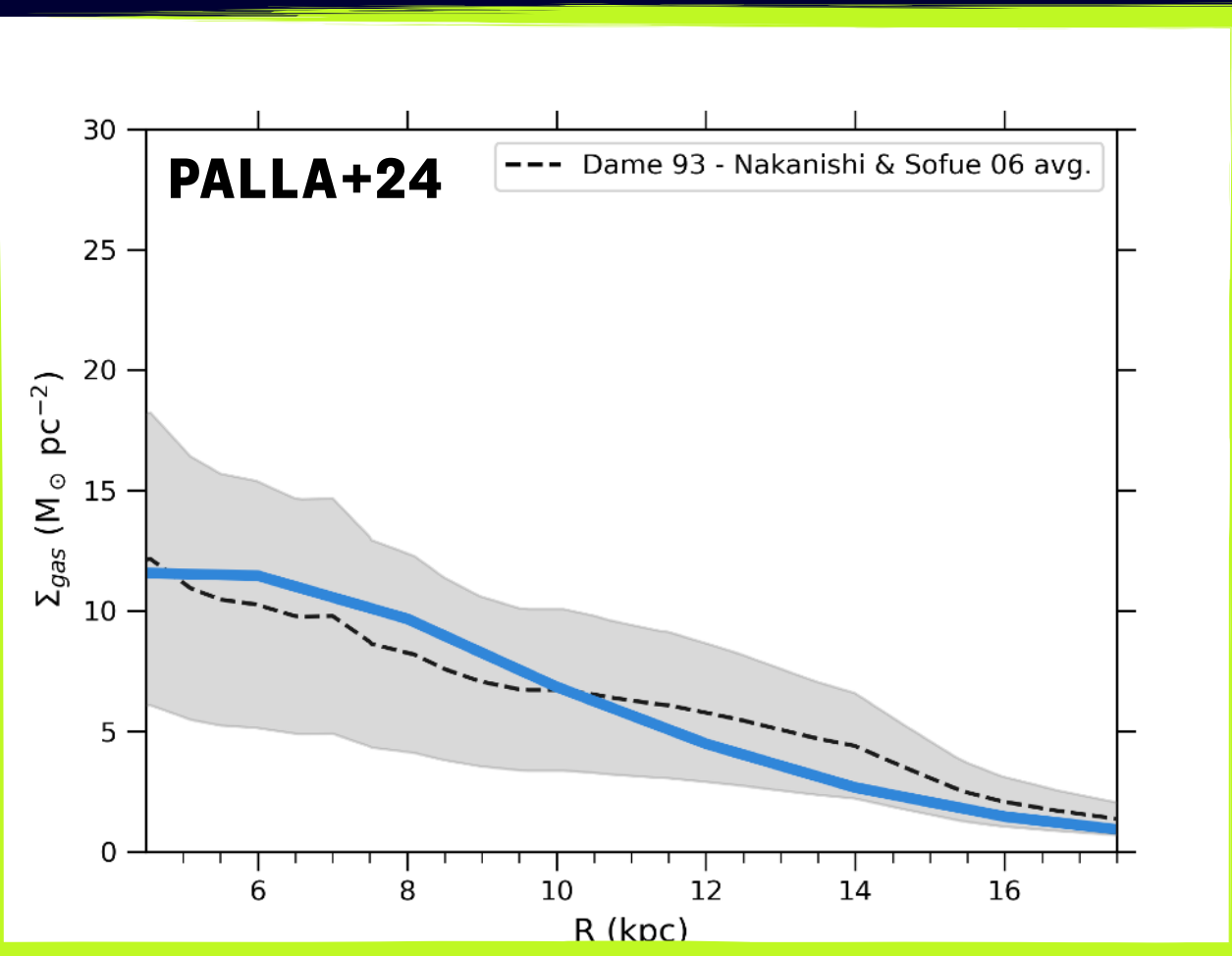
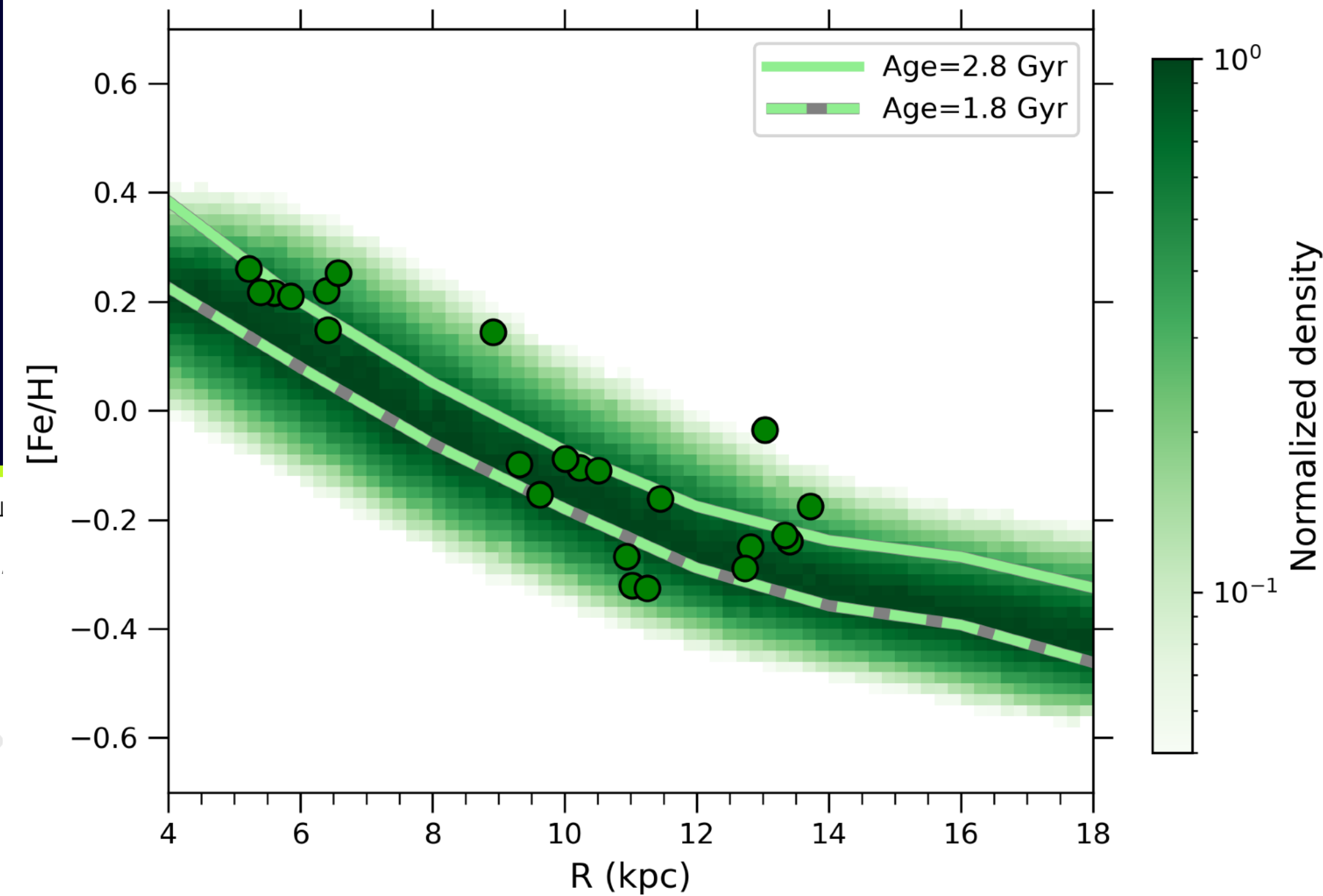


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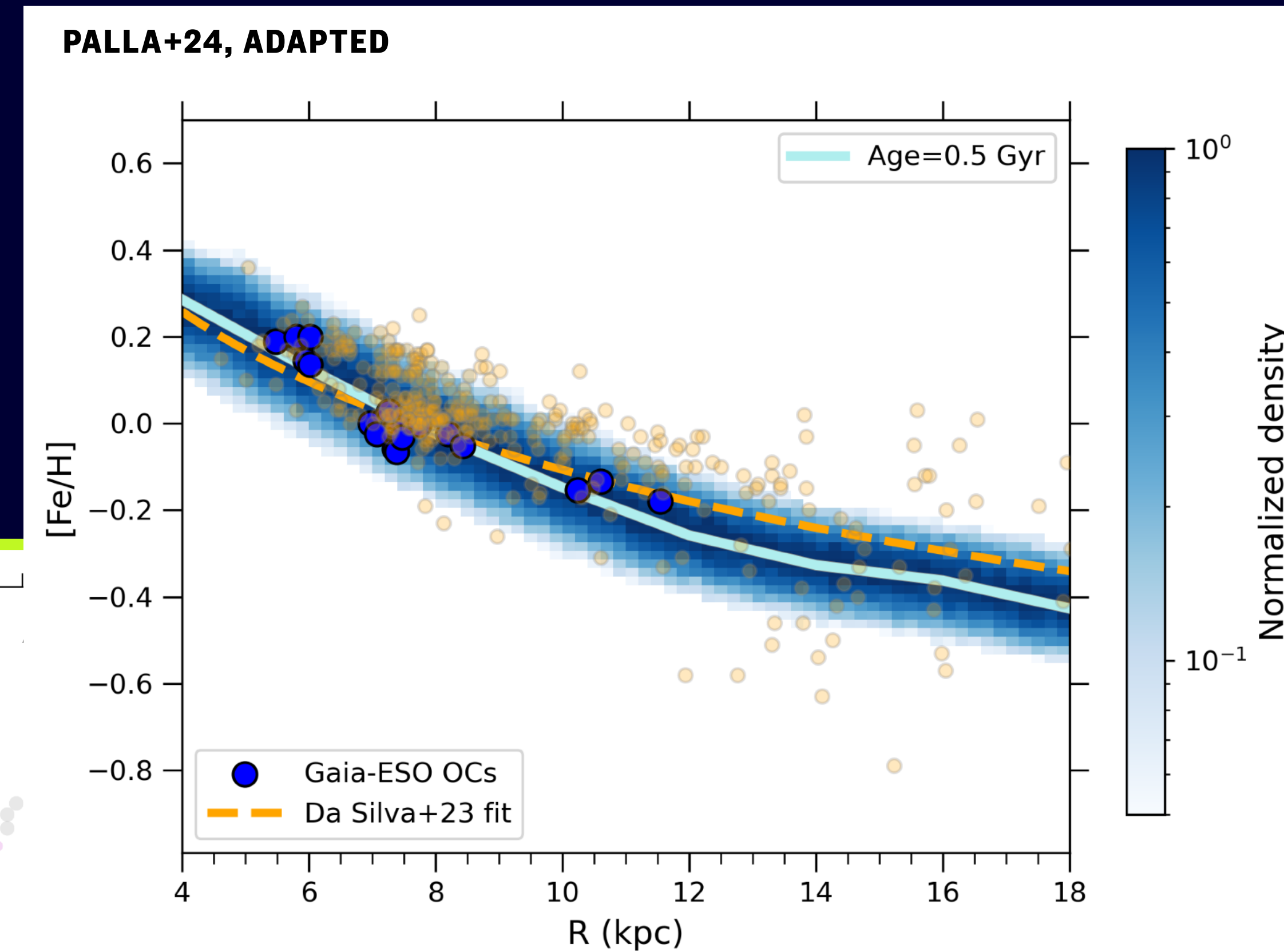
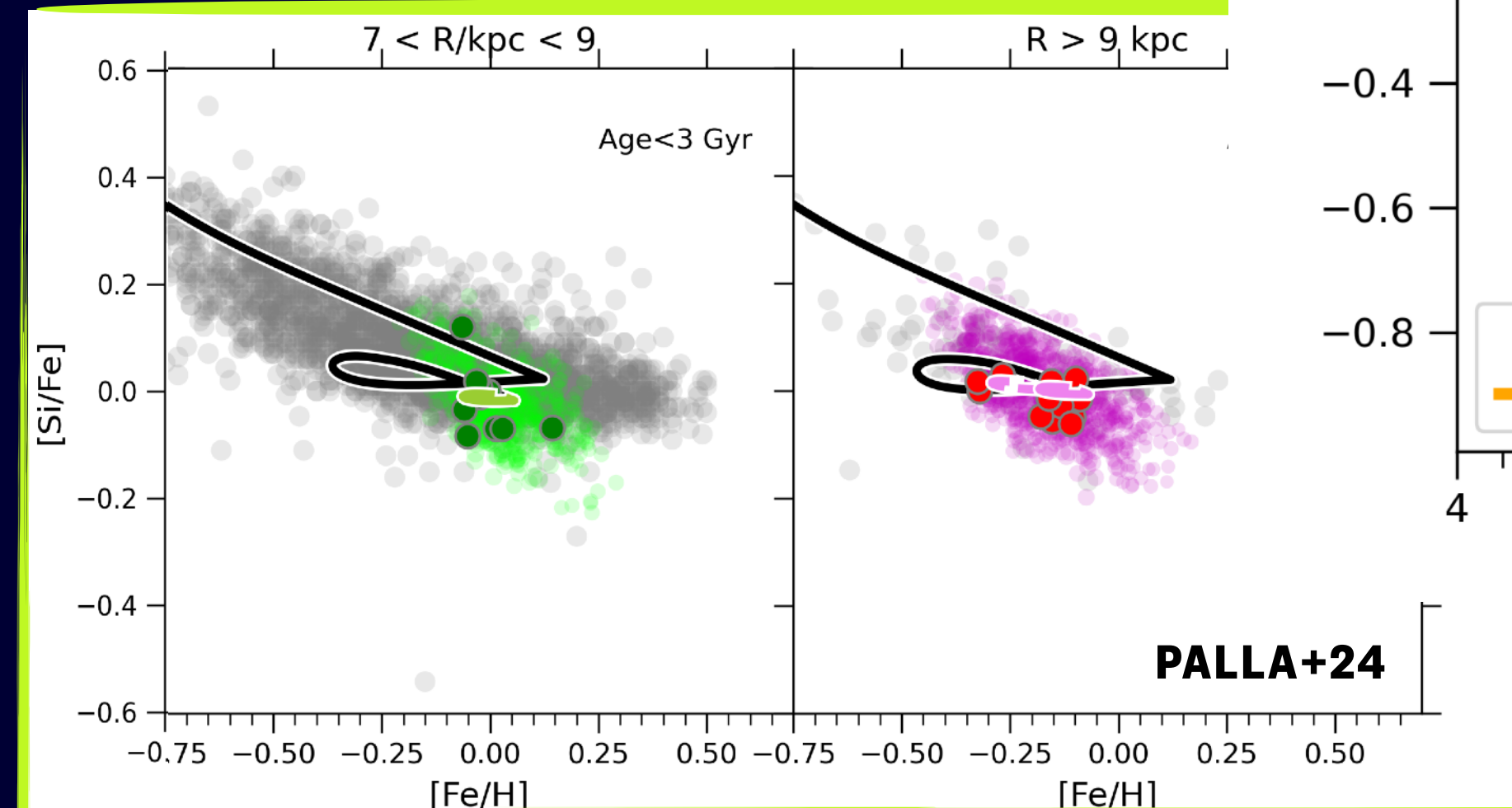
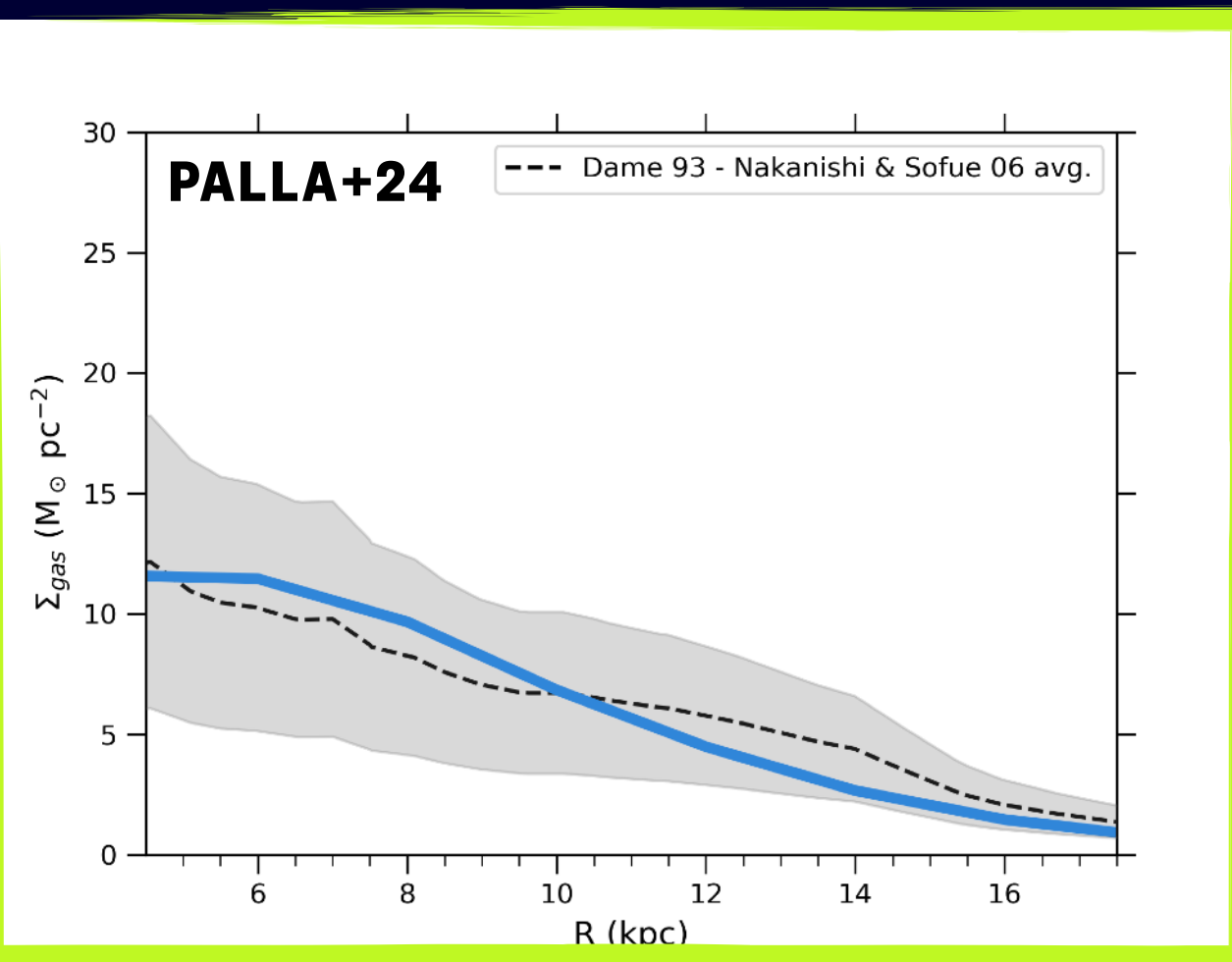
PALLA+24, ADAPTED



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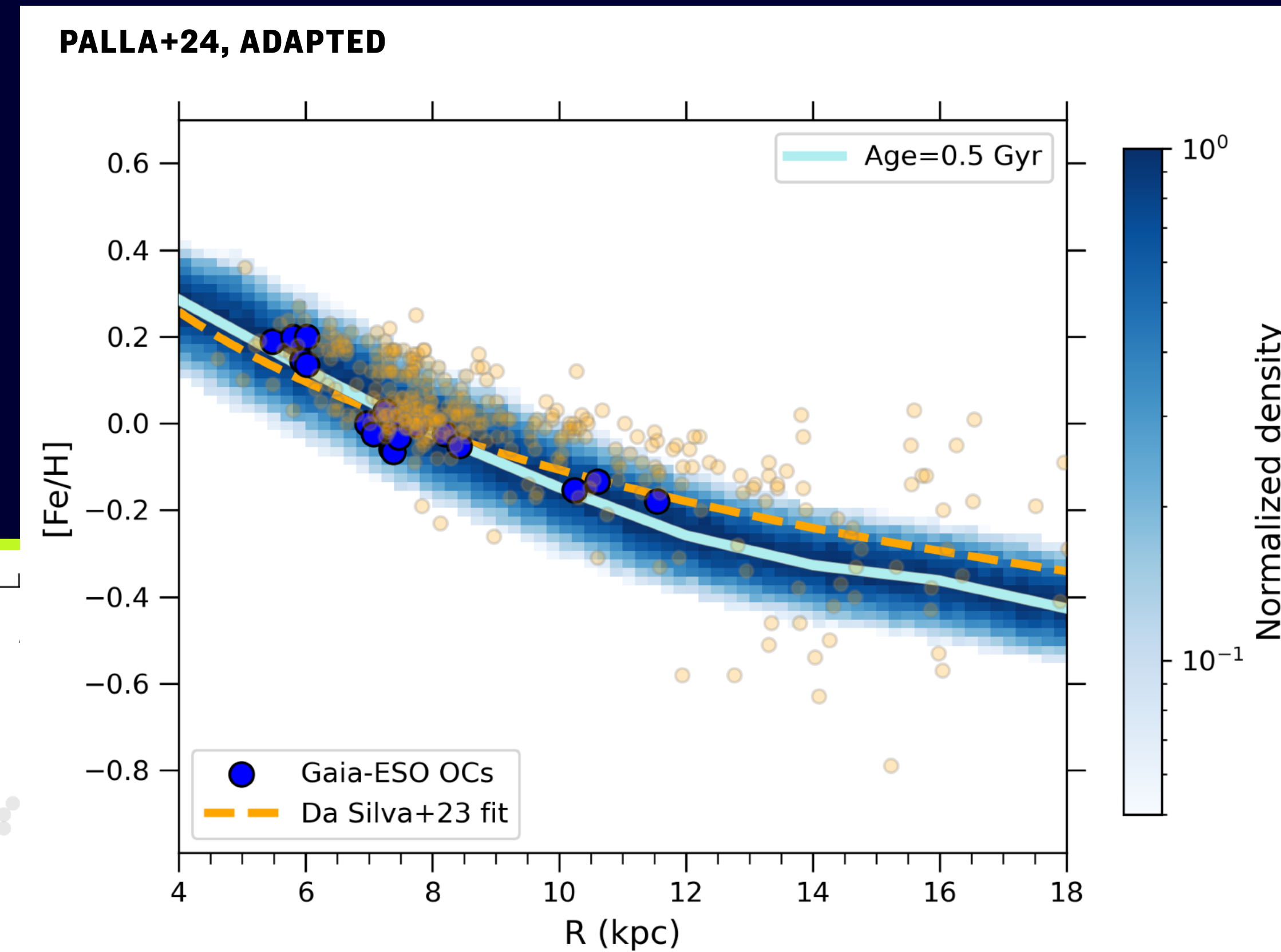
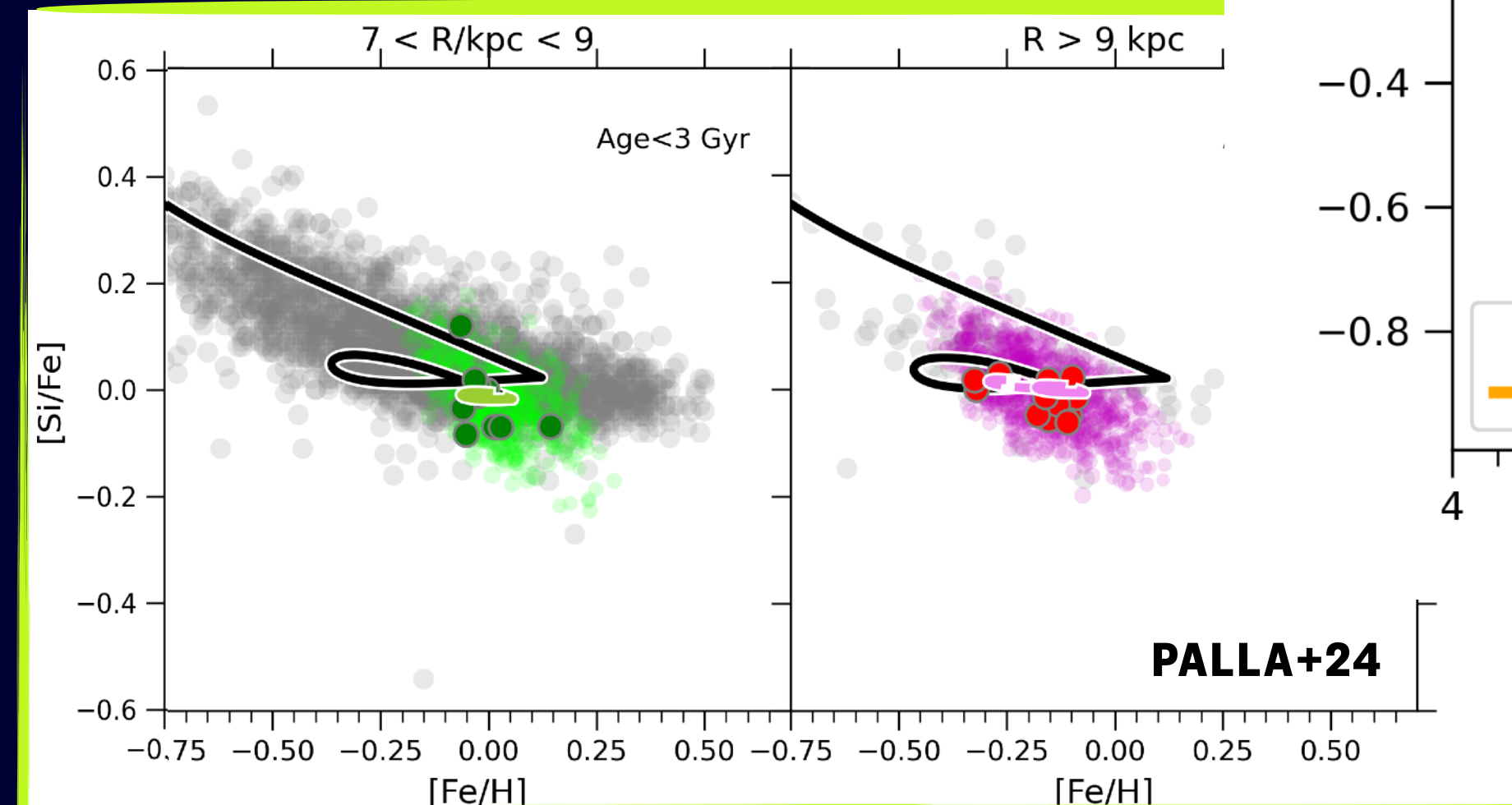
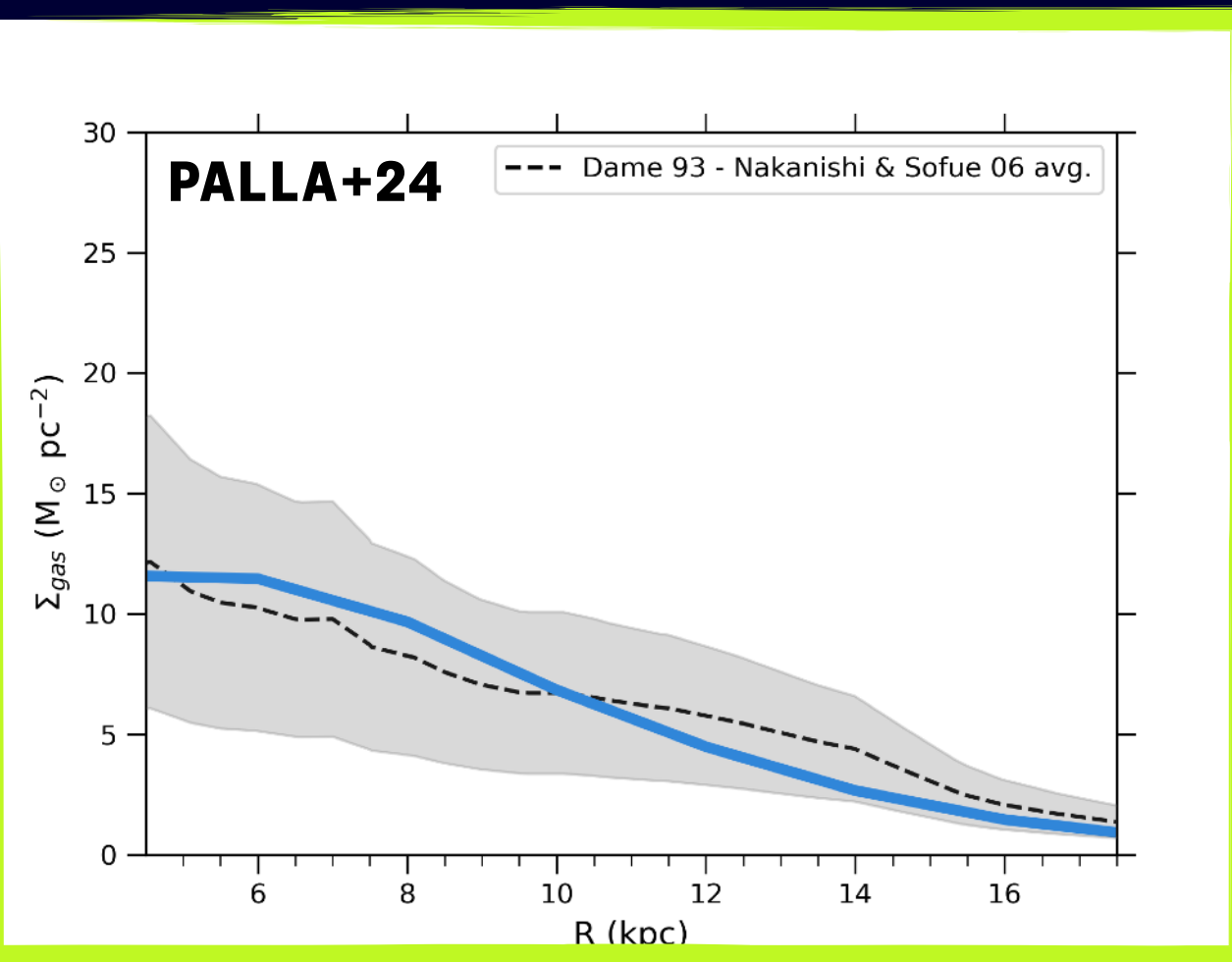


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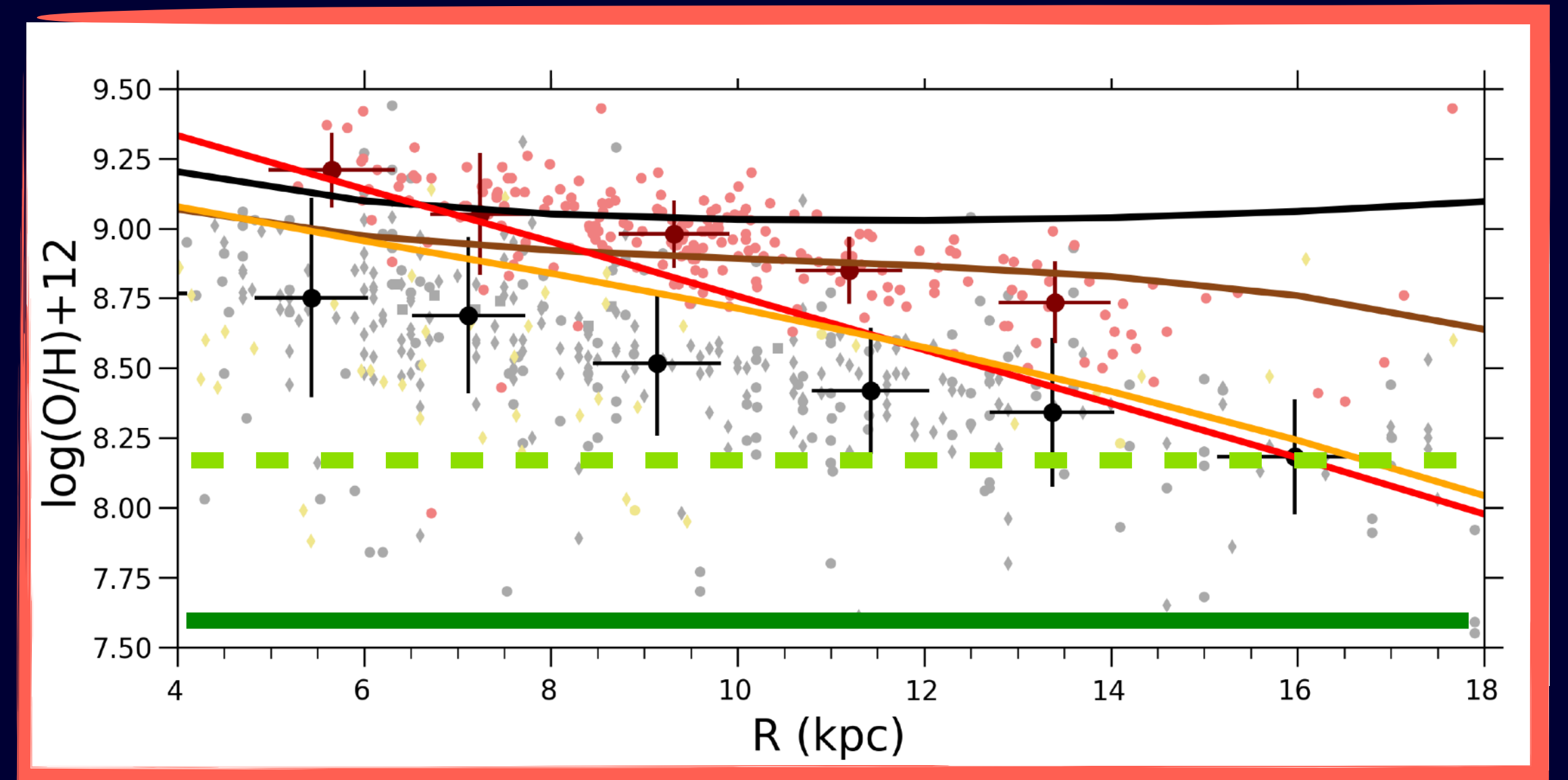
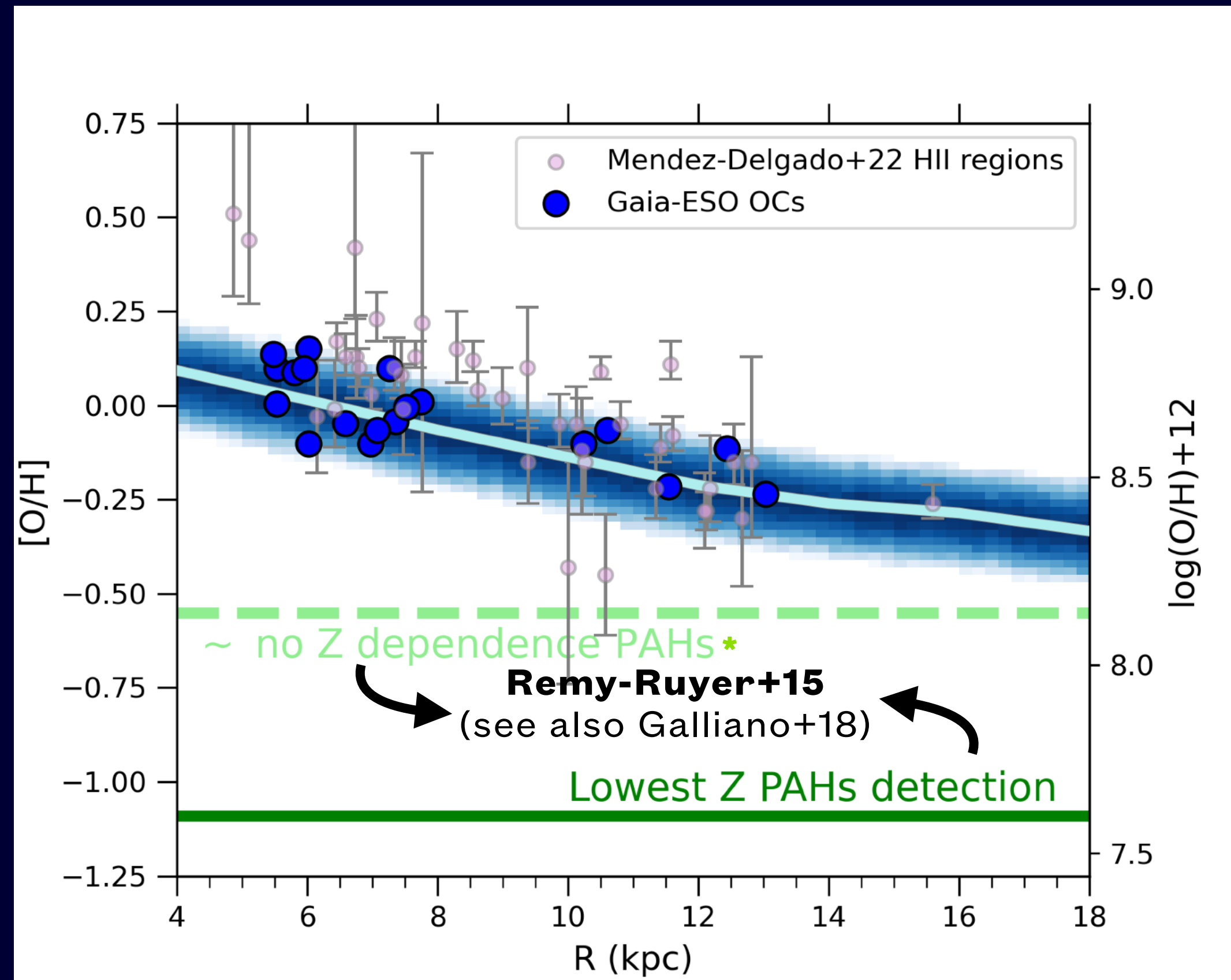
- Da Silva+23, Palla+24: revision of the “classical picture”
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**STILL REPRODUCING THE OTHER QUANTITIES !**



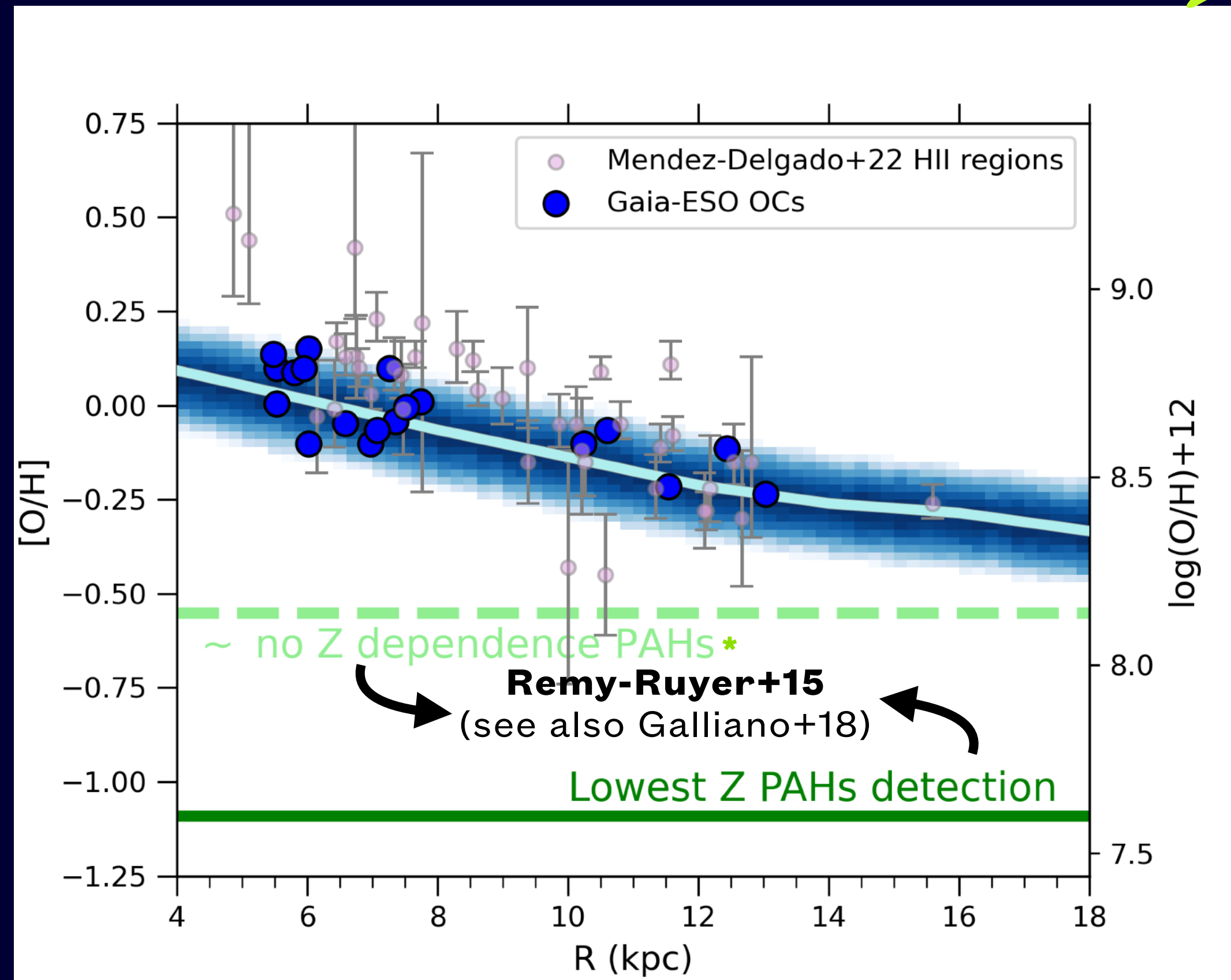
# Other abundances

## CNO ELEMENTS

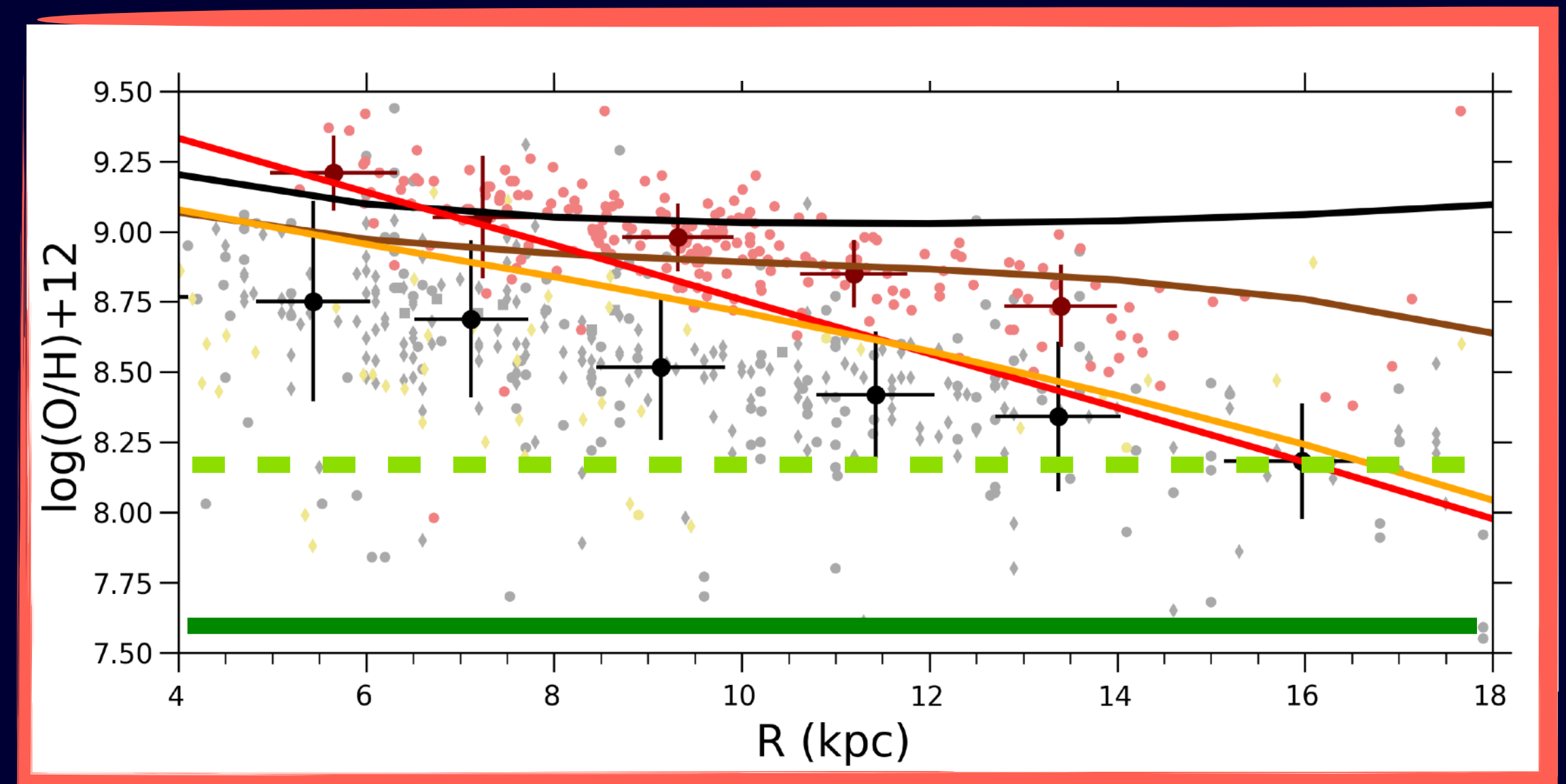
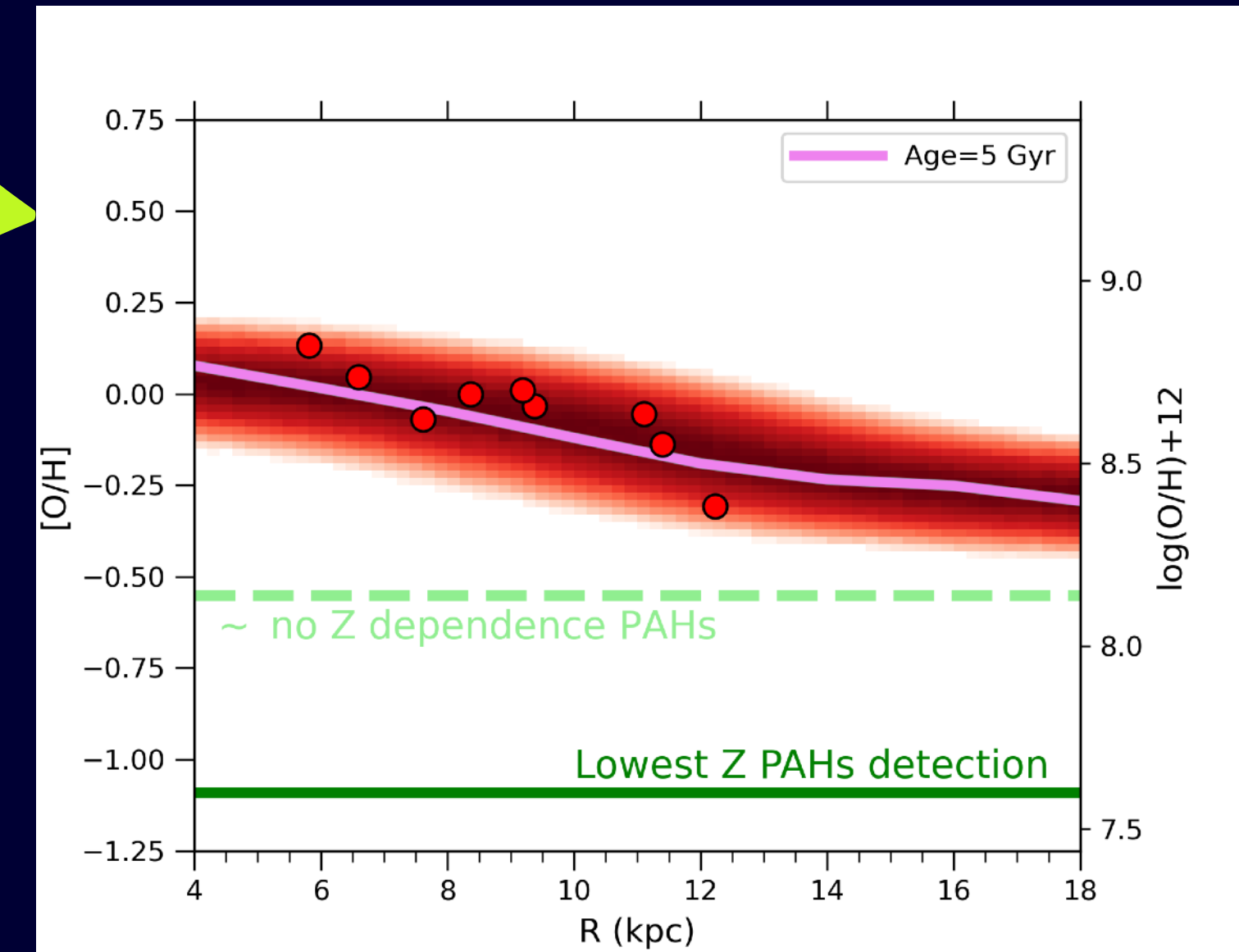


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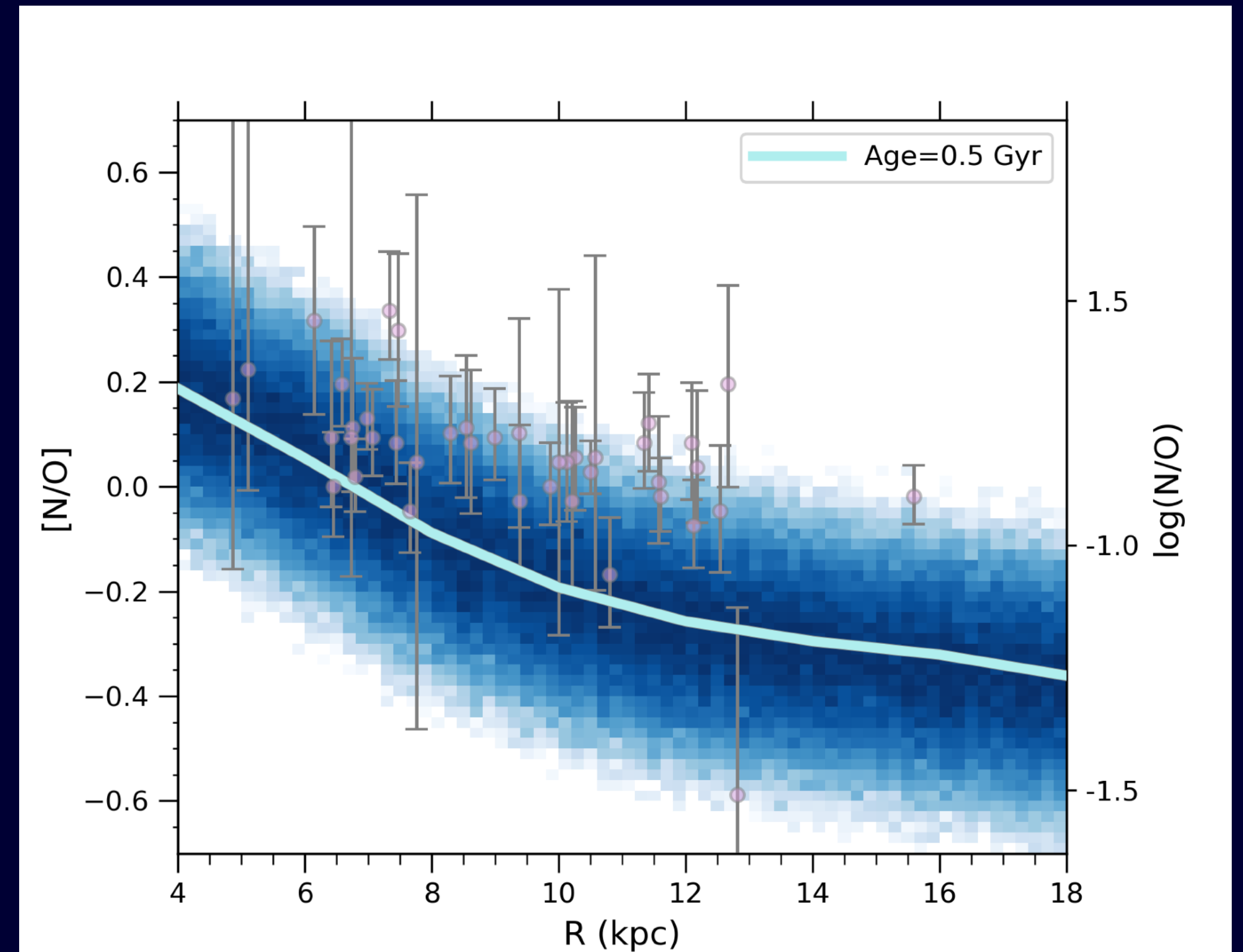
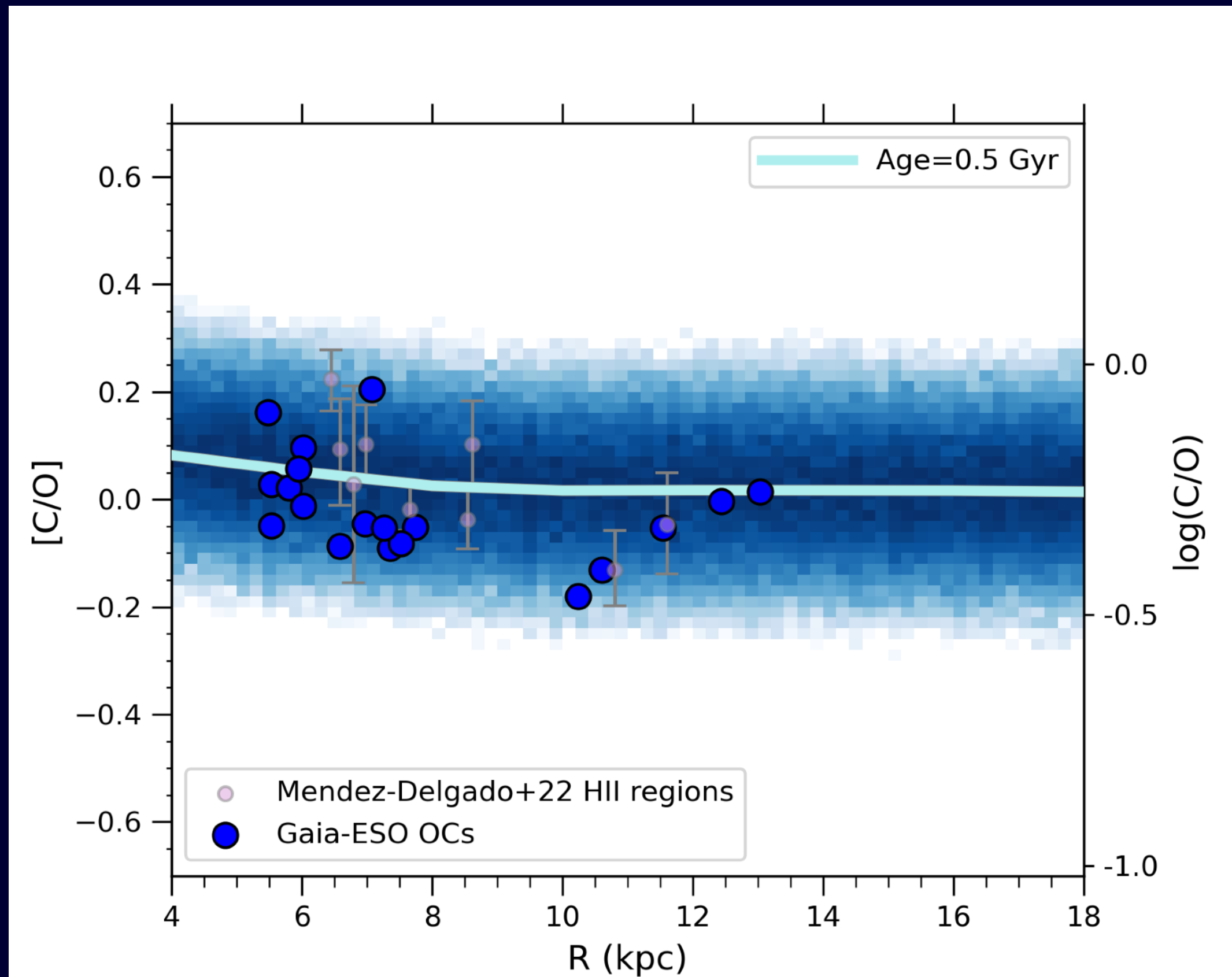


Going backward  
in time ...



# Other abundances

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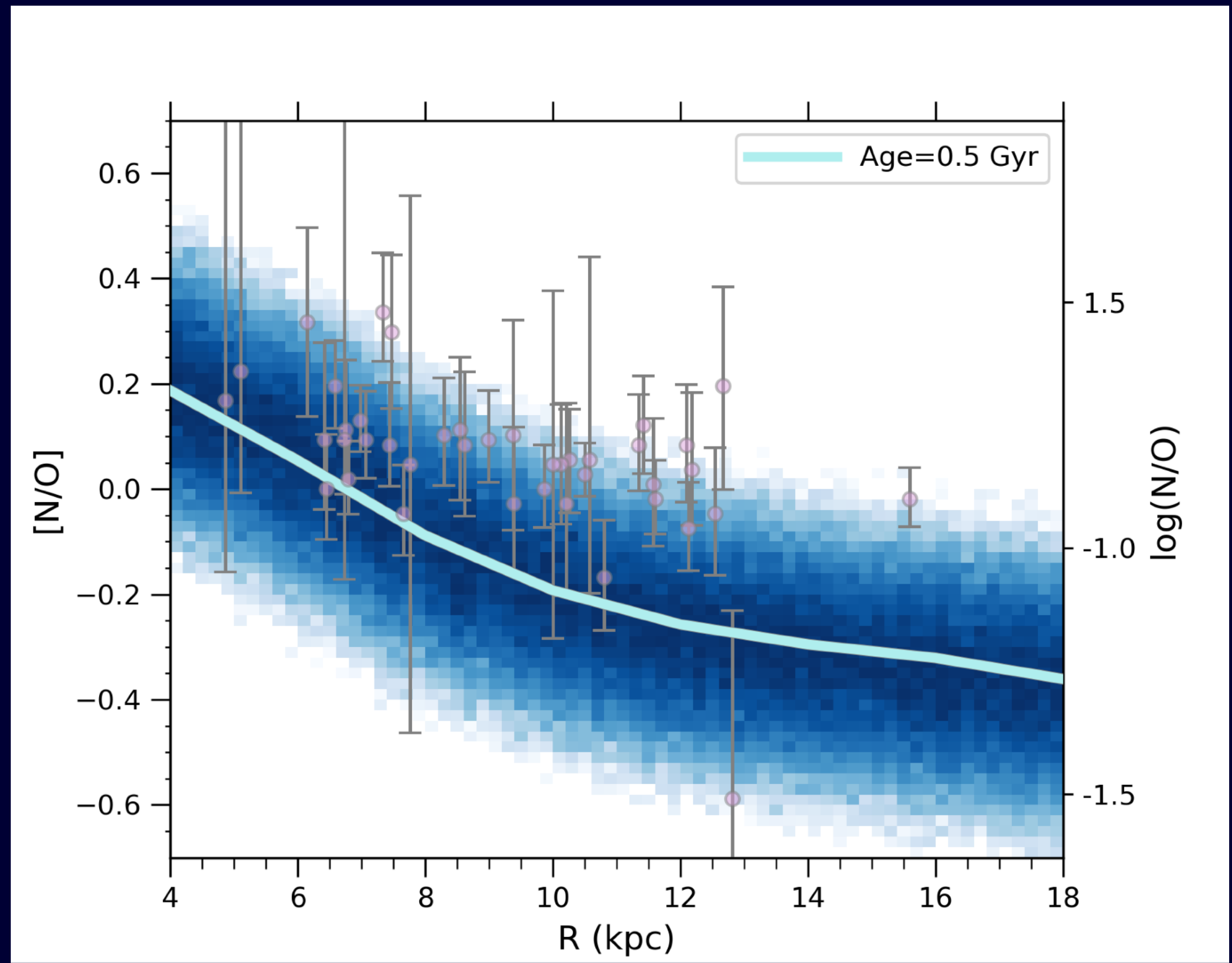
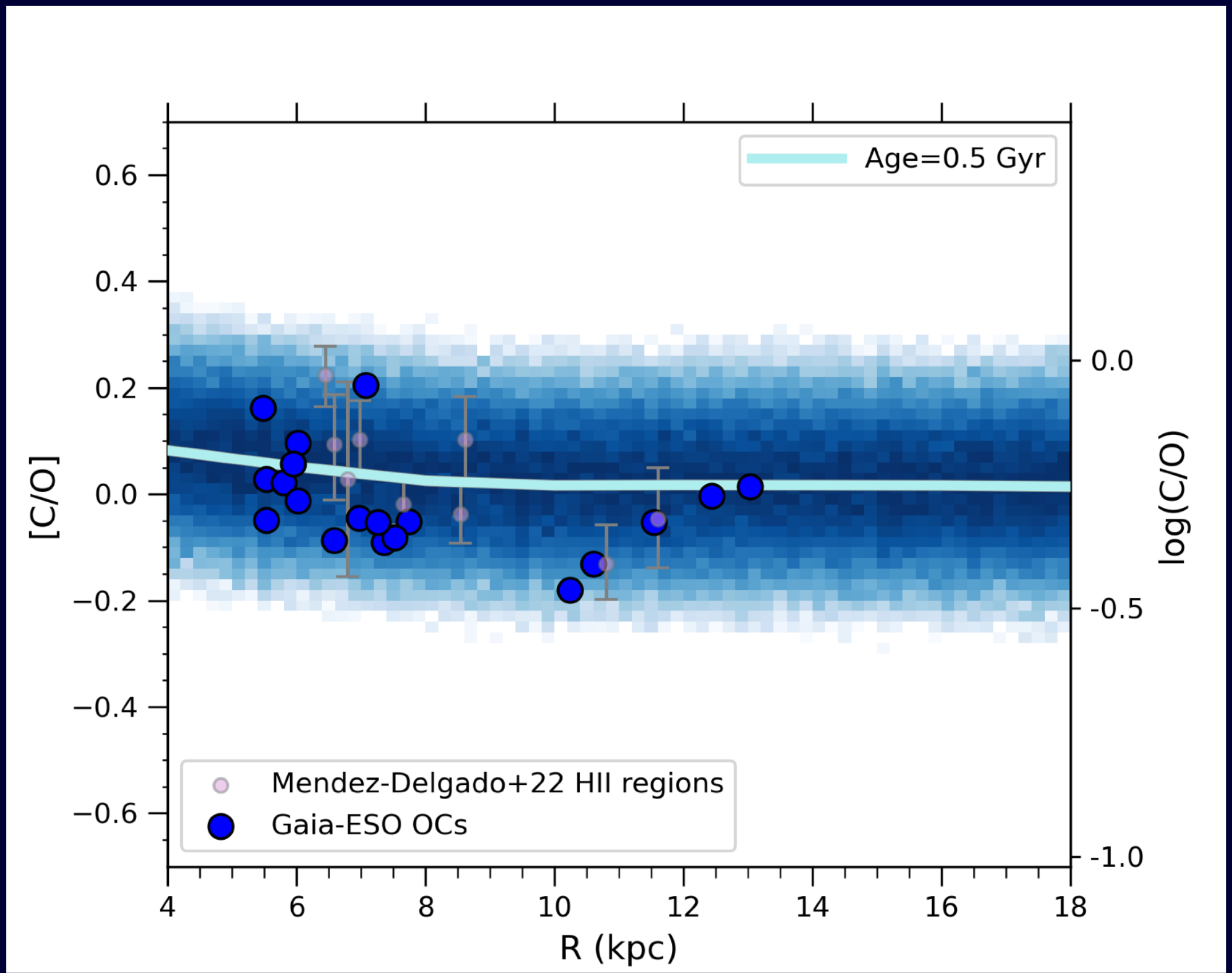




# Other abundances

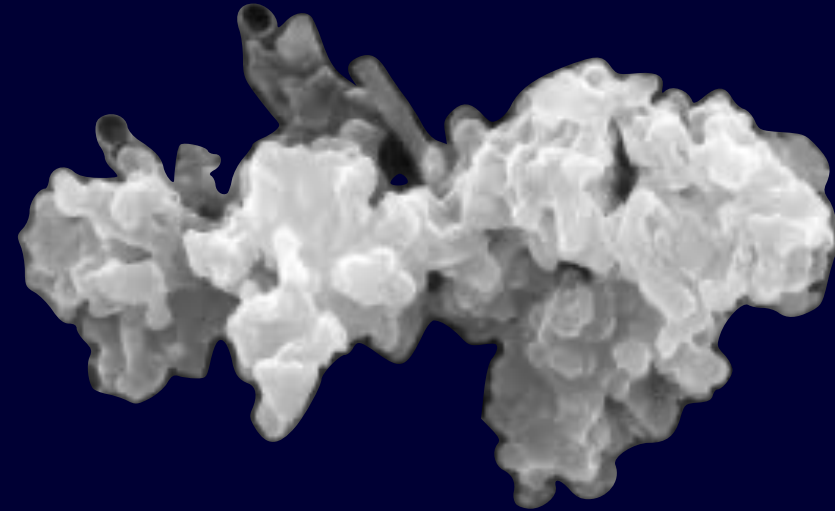
## CNO ELEMENTS


Still to deal with large yield related uncertainties  
(see Pignatari's talk)

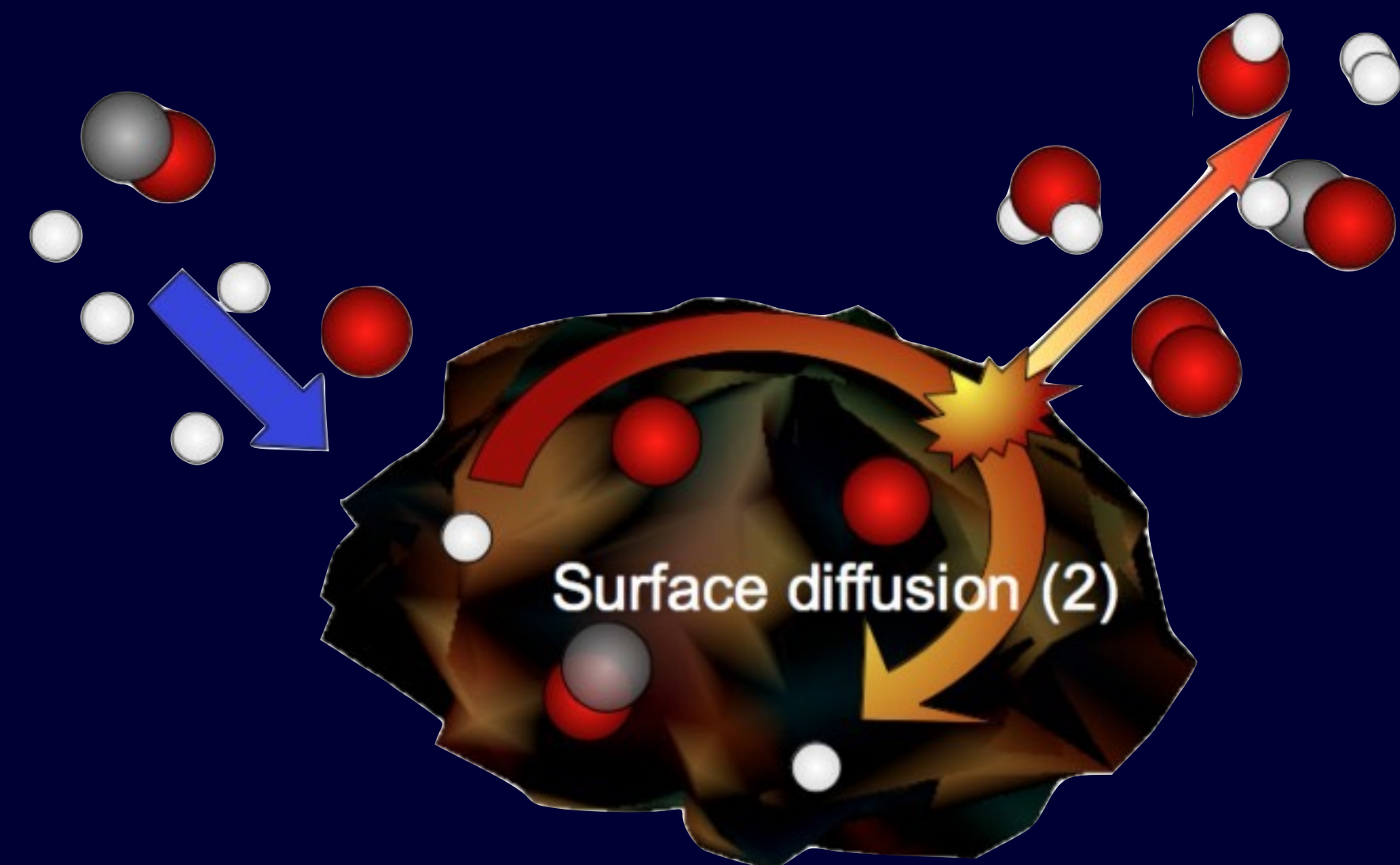
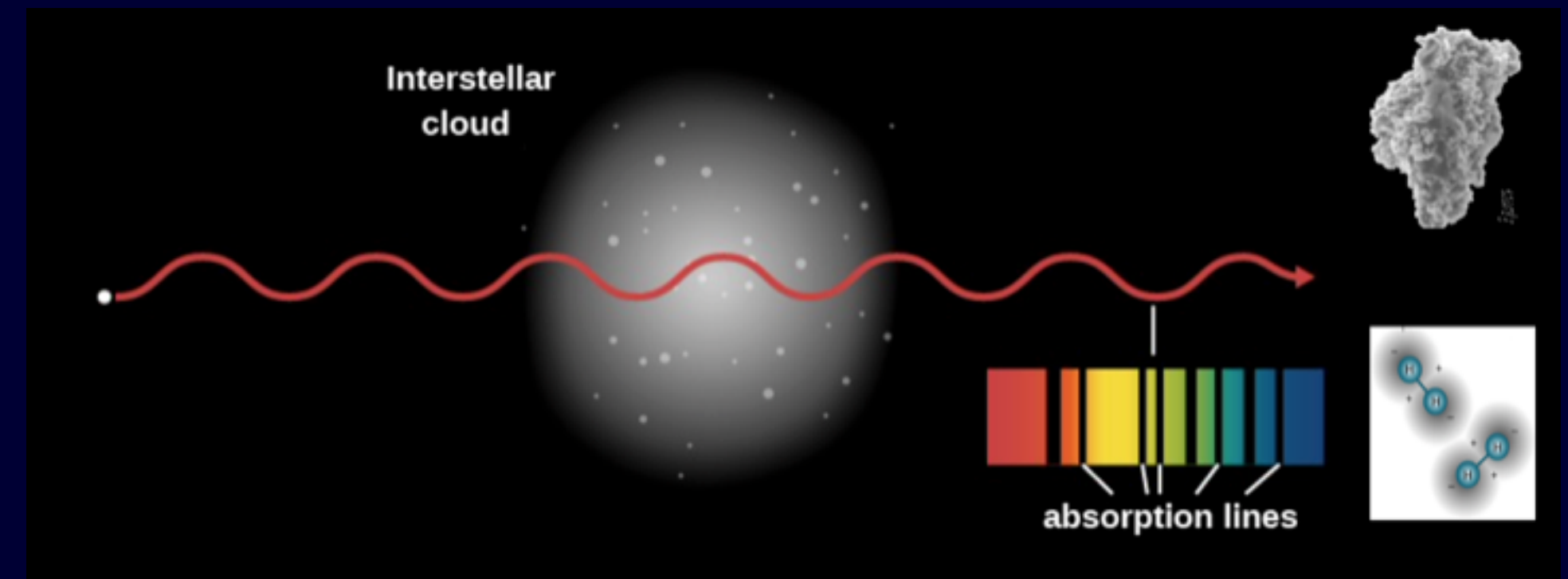


# Not only metals

## DUST IN THE ISM



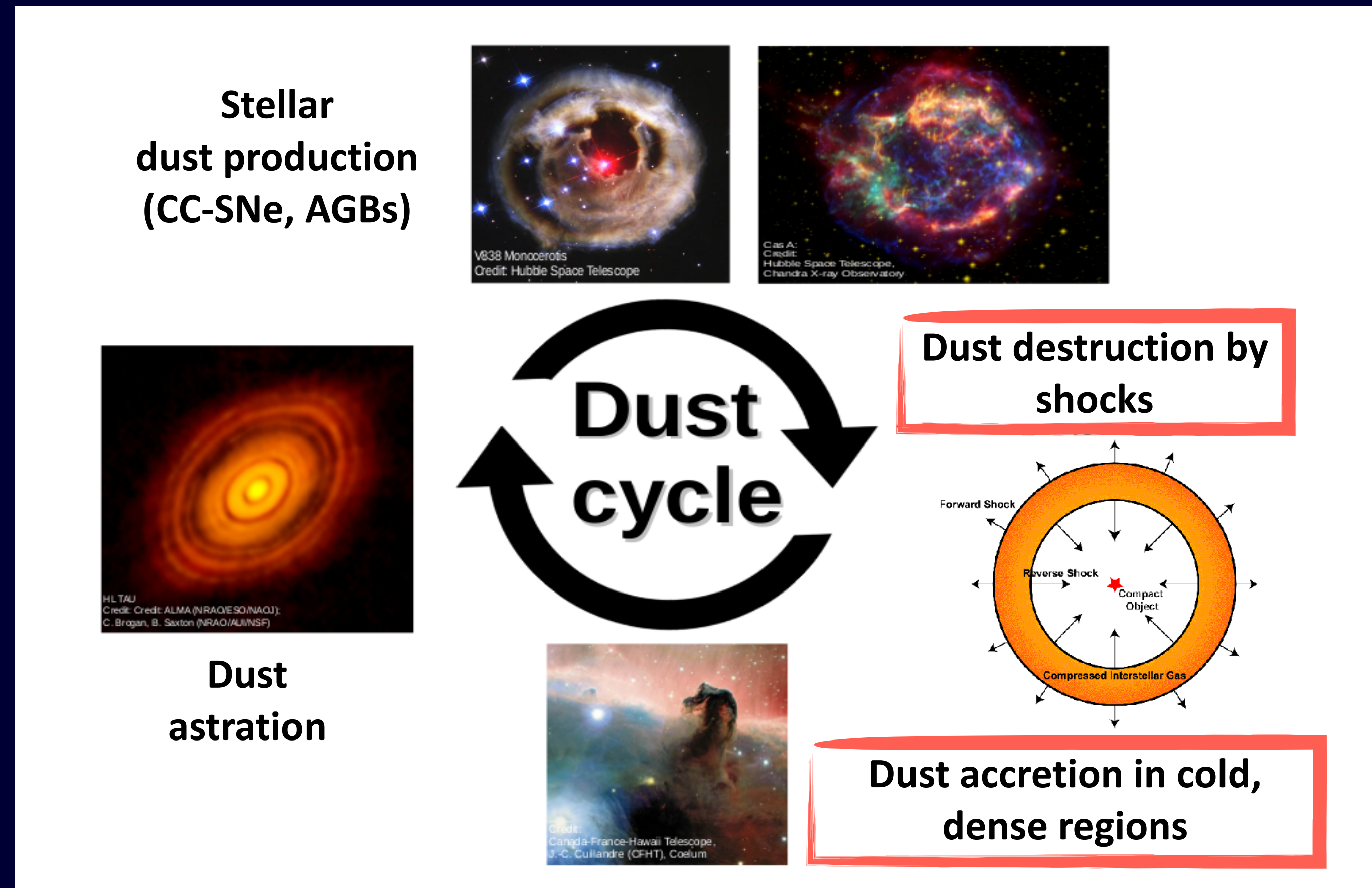
- absorbs, **processes** and re-emits stellar **light**  
(e.g. Popescu & Tuffs 2002; Davies et al. 2017, Galliano+18)
- **depletes metals** from the gas phase  
(e.g. Savage & Sembach 96, Jenkins 09, De Cia+16)
- **catalyst** for the formation of  $\text{H}_2$   
(e.g. Gould & Salpeter 63; Perets+05; Gavilan+14)  
+ other **molecules** ! (e.g. Du+12, Cazaux+16)
- **no dust ... no planets** !  
(No refs. needed )



# Dust evolution in galaxies

(see also Yates' talk)

## DIFFERENT PROCESSES REGULATING DUST AMOUNT



+  
**coagulation,  
fragmentation**

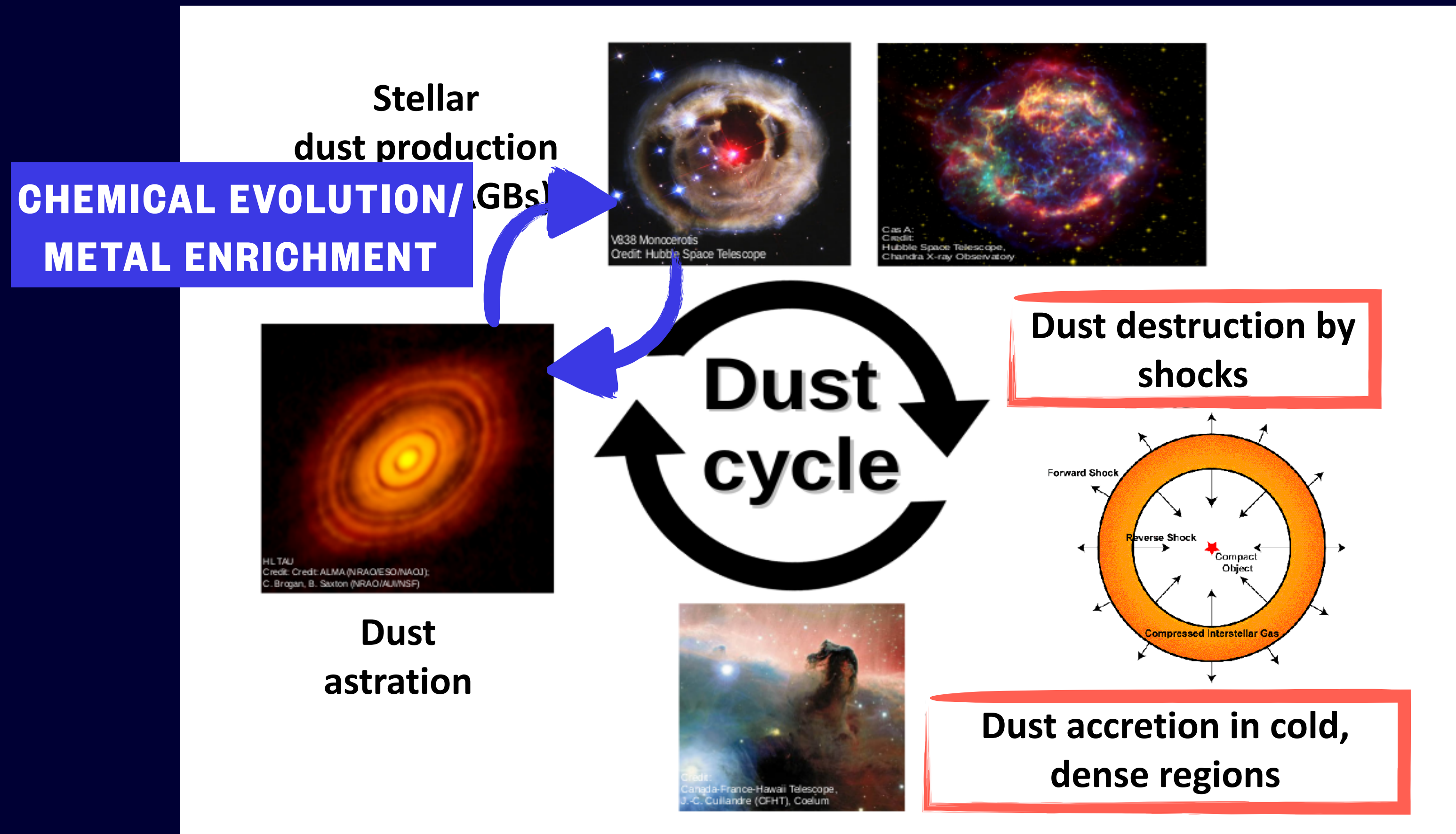
...

(not altering dust mass  
but altering dust properties)

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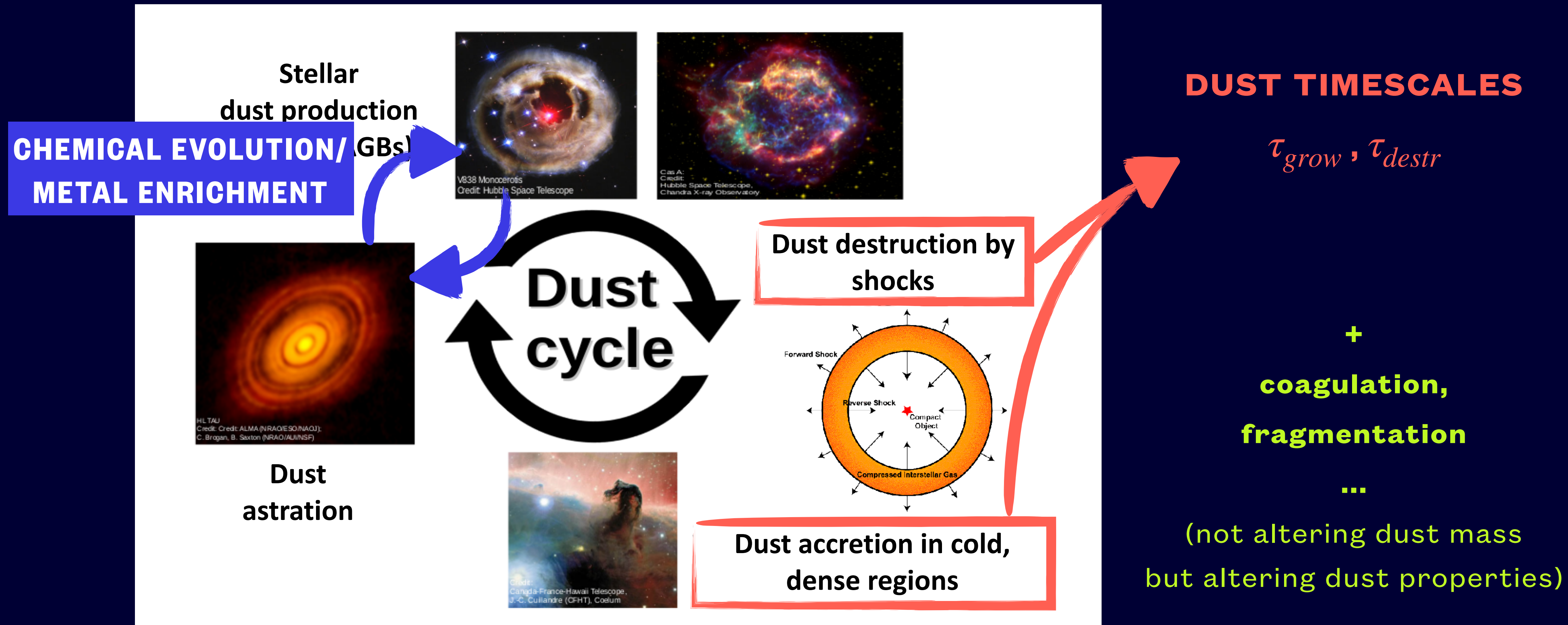
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(not altering dust mass  
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# Dust evolution in galaxies

(see also Yates' talk)

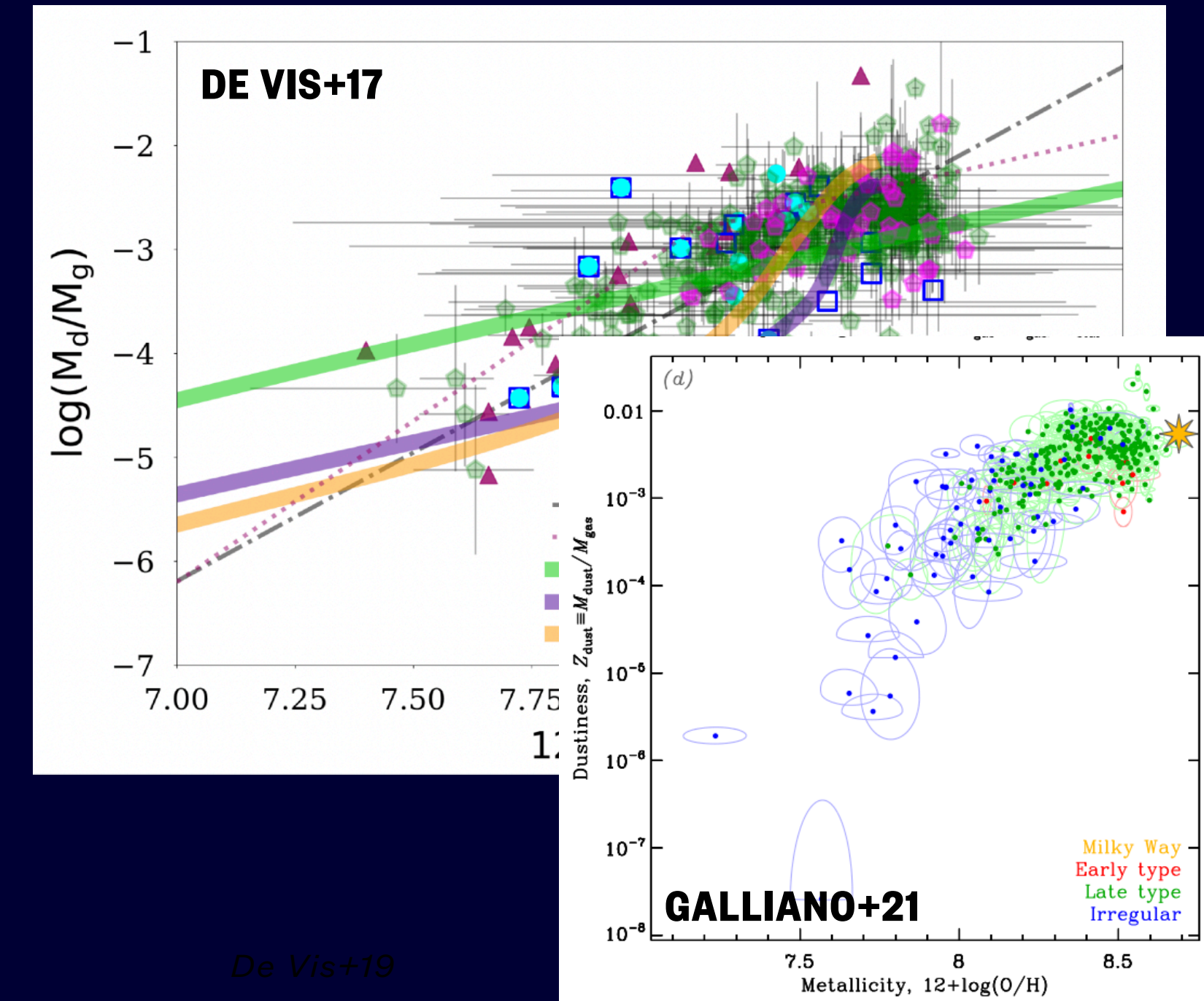
## DIFFERENT PROCESSES REGULATING DUST AMOUNT



# Dust evolution in galaxies

## MODELLING DUST EVOLUTION

- Plethora of **studies about global galactic dust content** (in the local Universe and at high-redshift)



De Vis+19

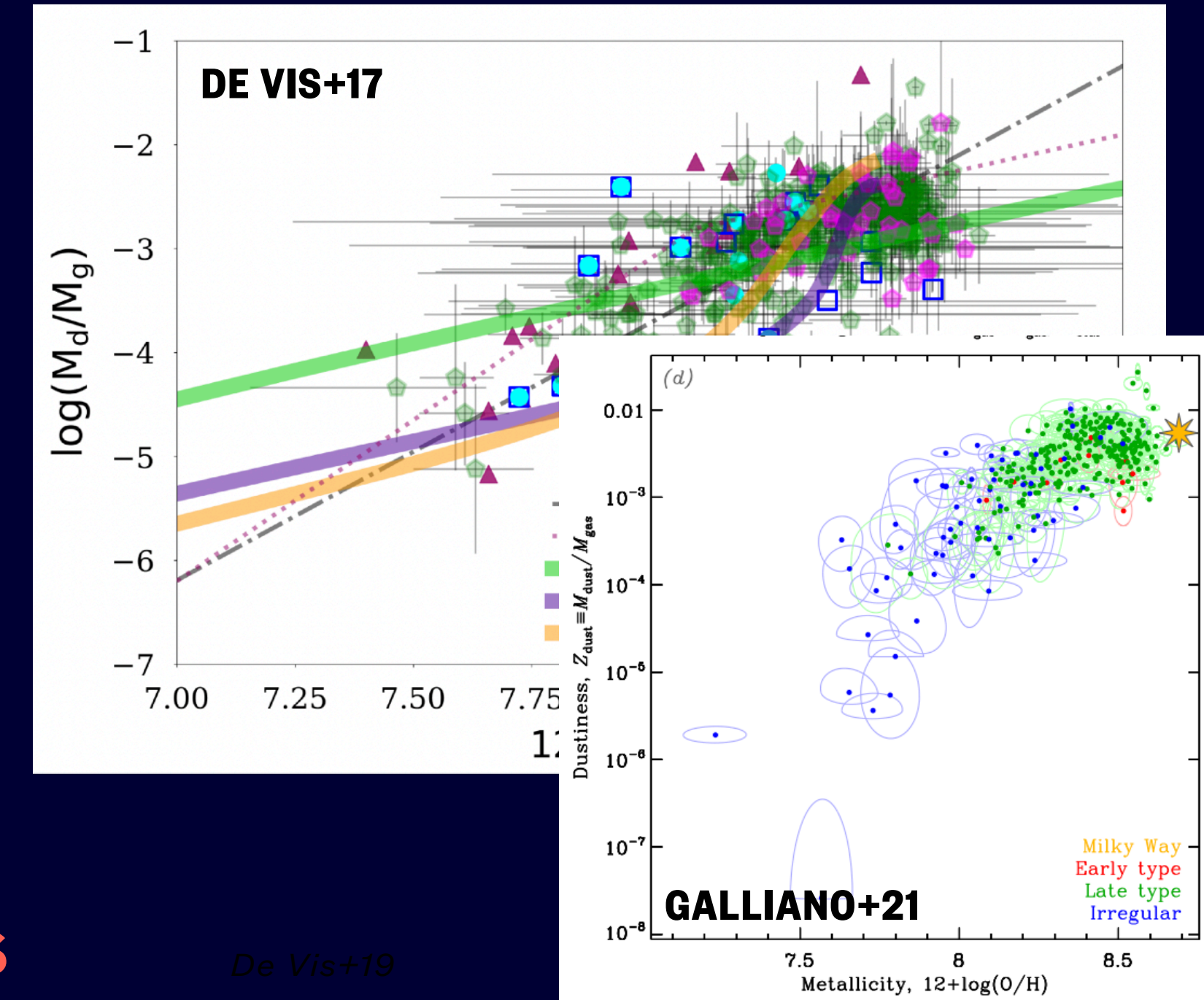
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**BUT**

**very FEW EFFORTS to study  
SUB-GALACTIC PROPERTIES**



*De Vis+19*

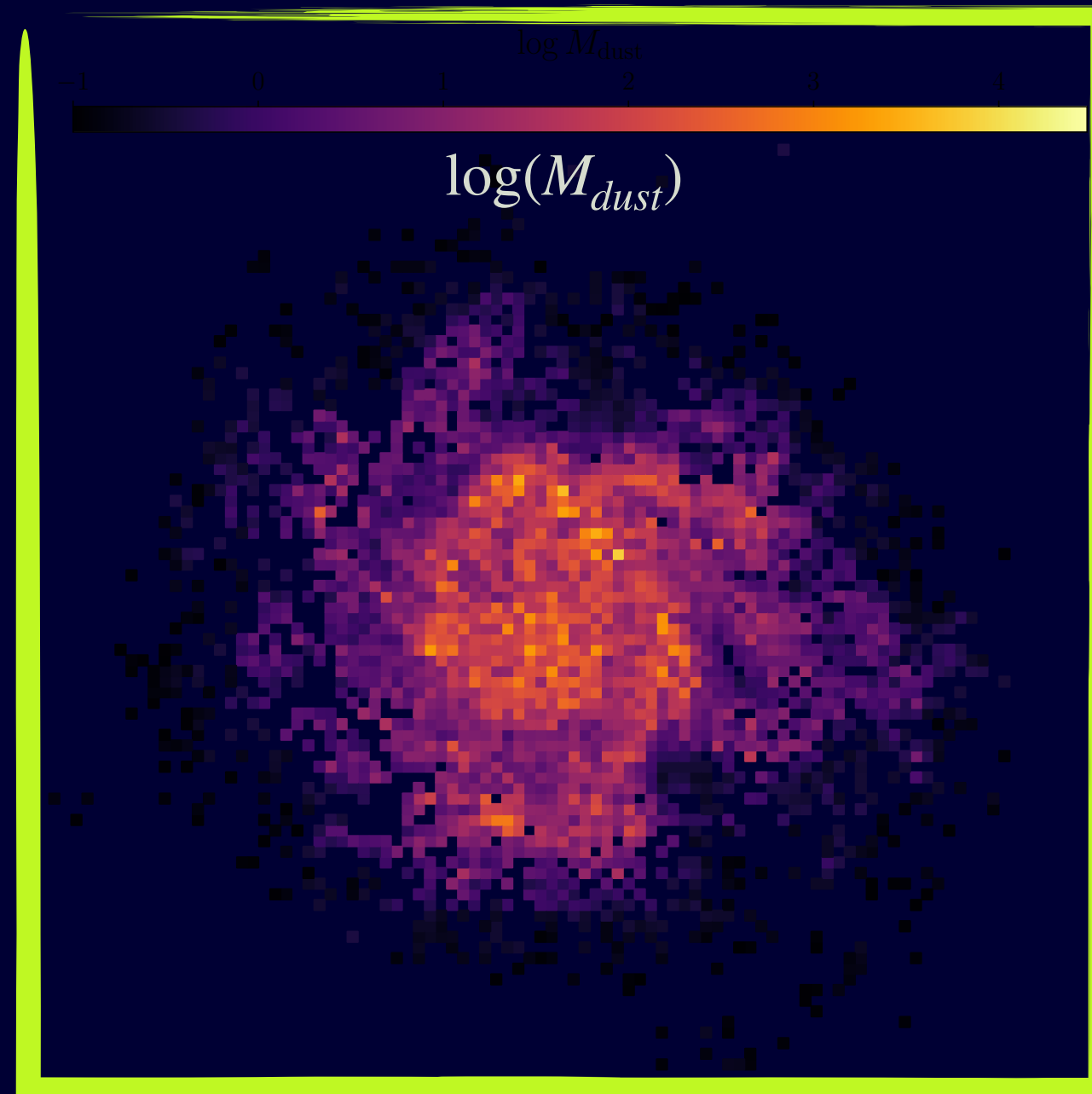
# Dust evolution in galaxies

## MODELLING DUST EVOLUTION

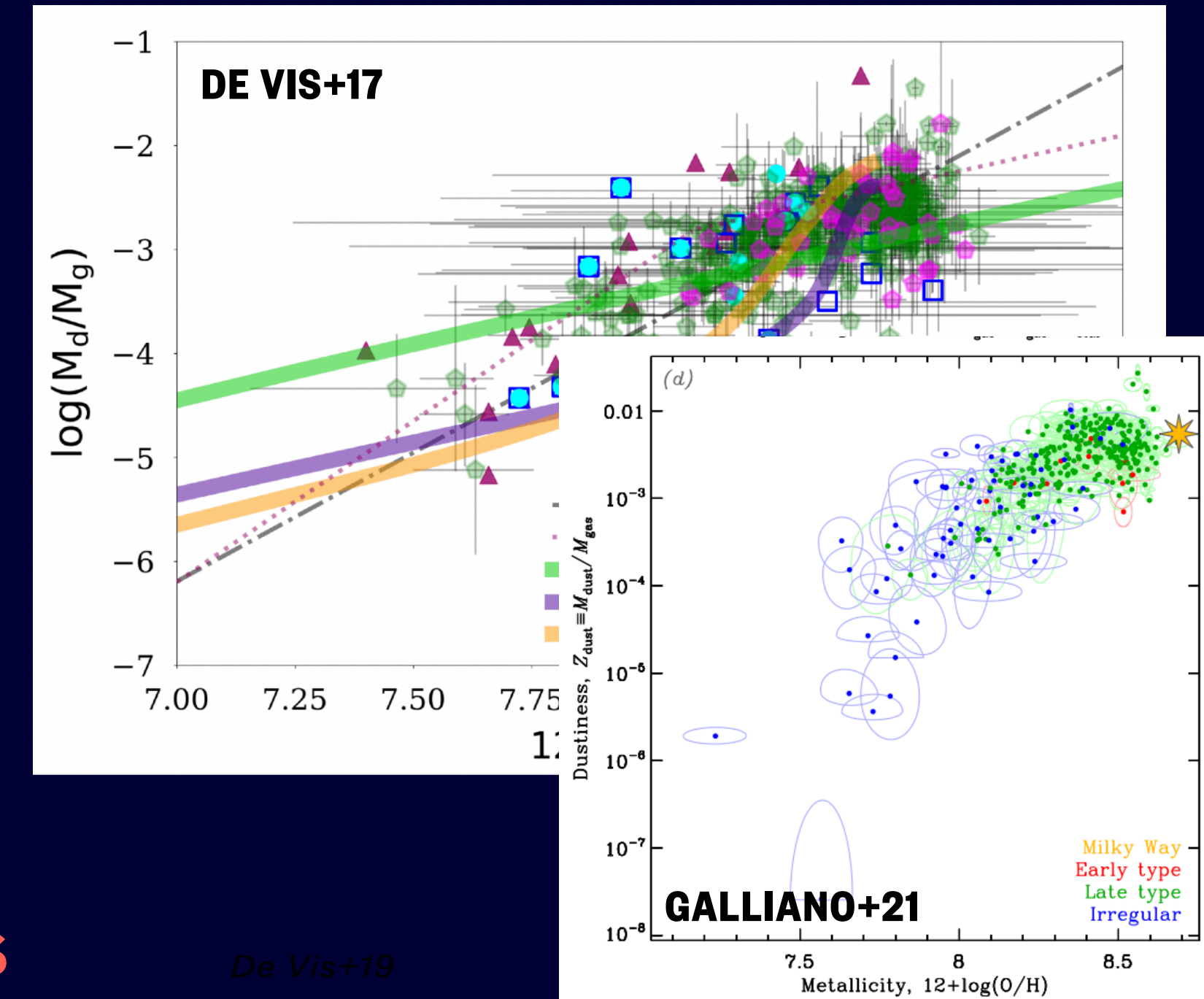
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- NGC 628 / M74: best example for which multi-wavelength, spatially-resolved observations available





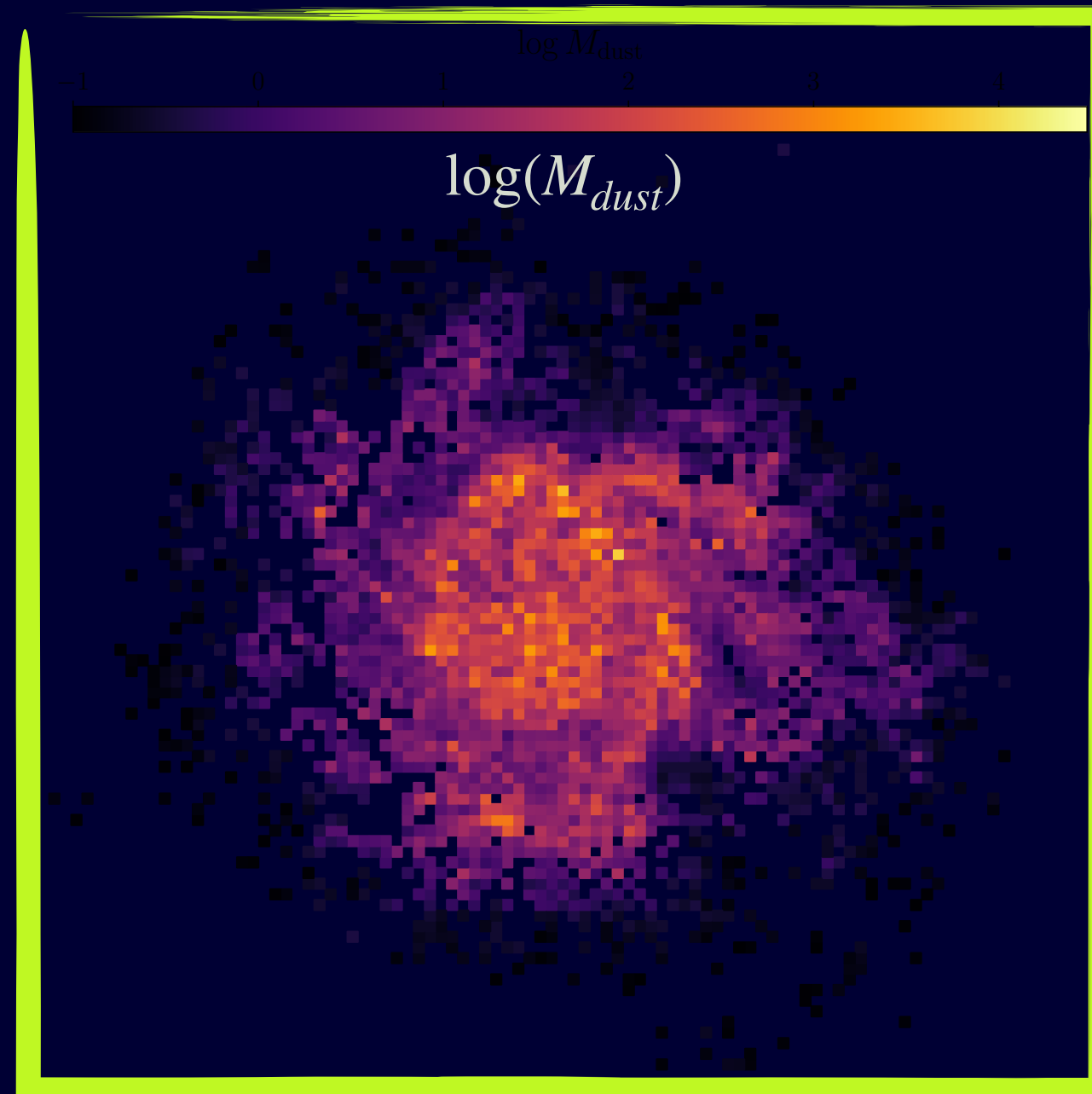
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## MODELLING DUST EVOLUTION

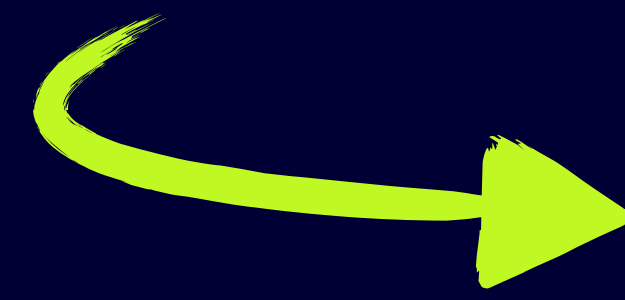
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**BUT**

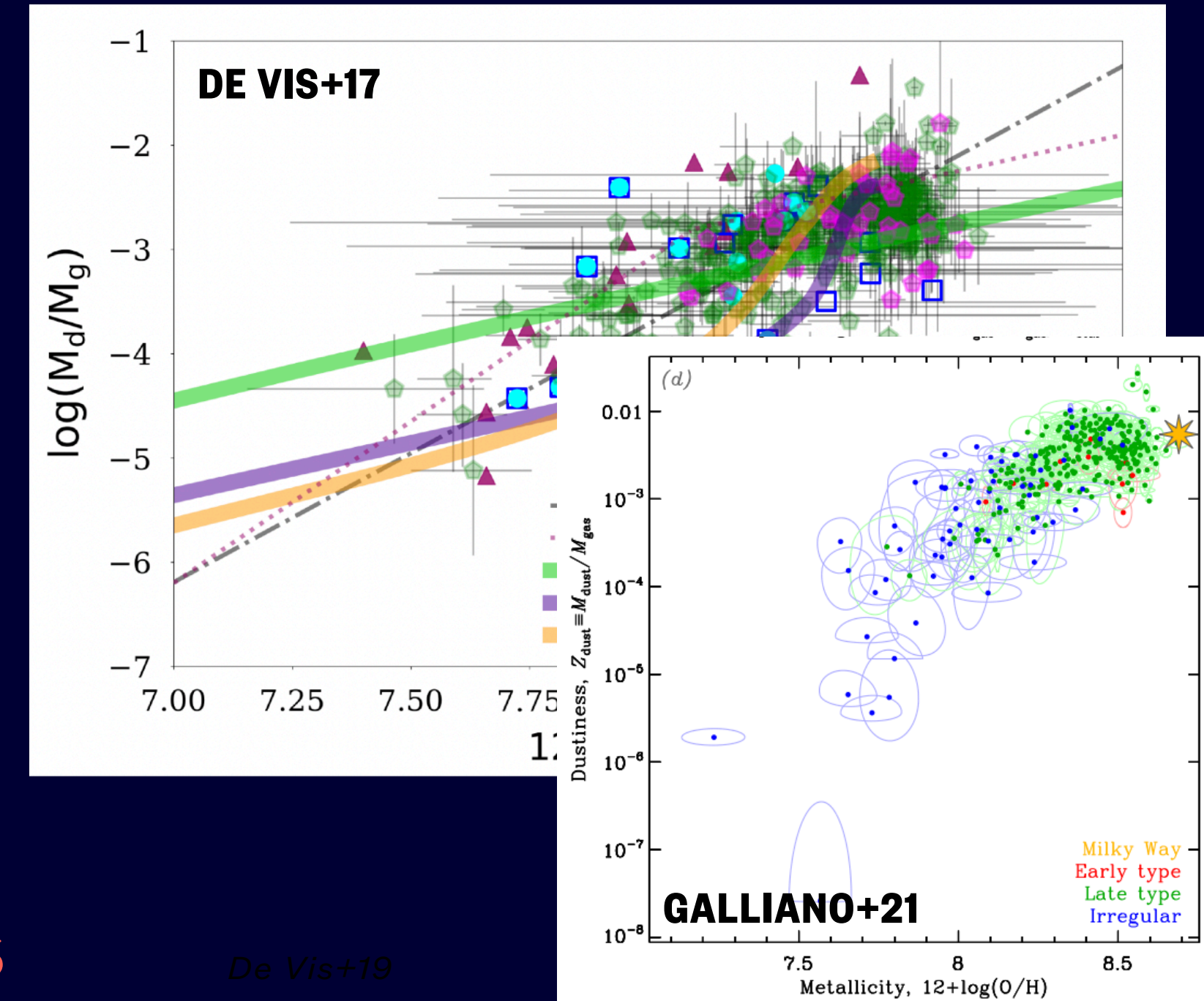
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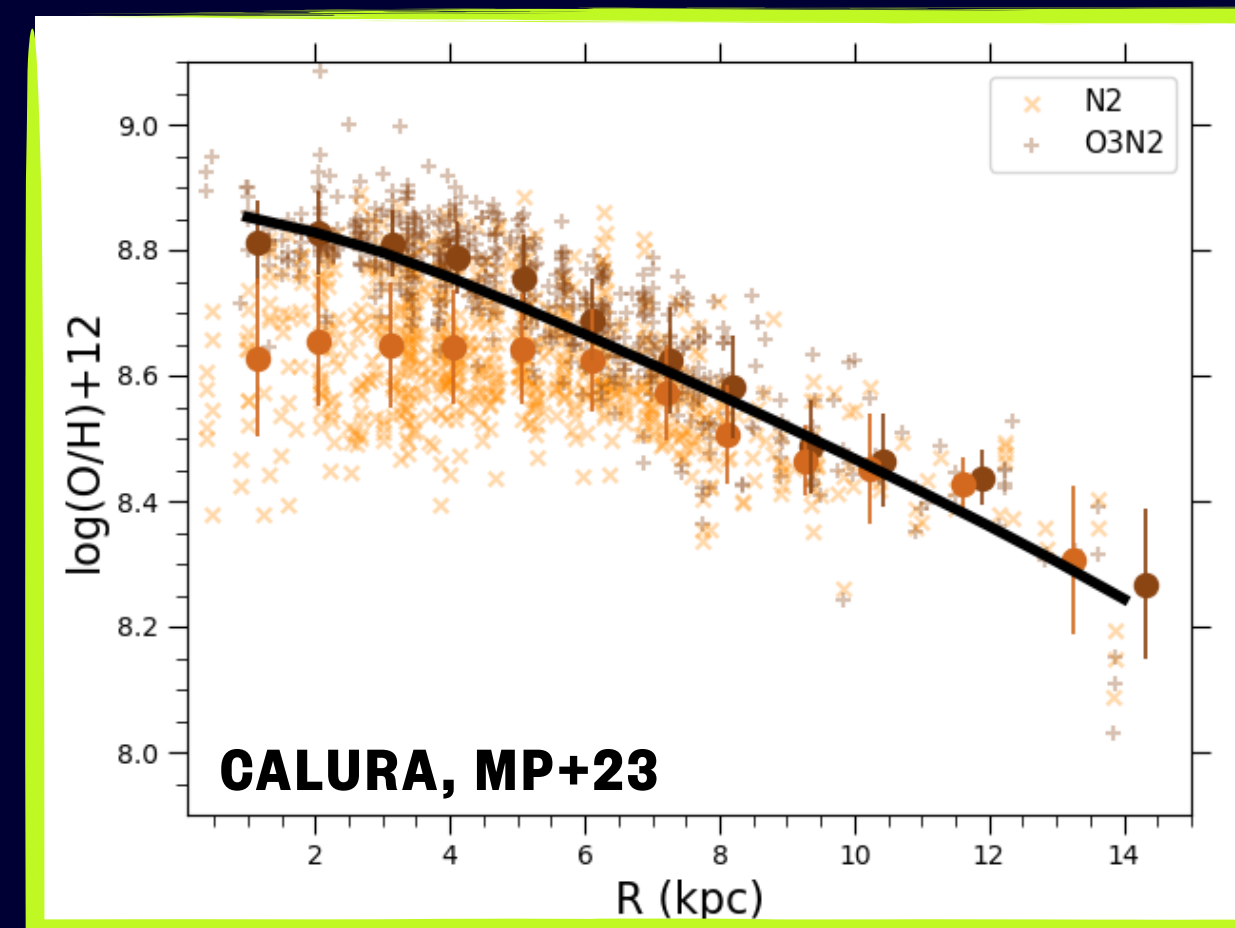
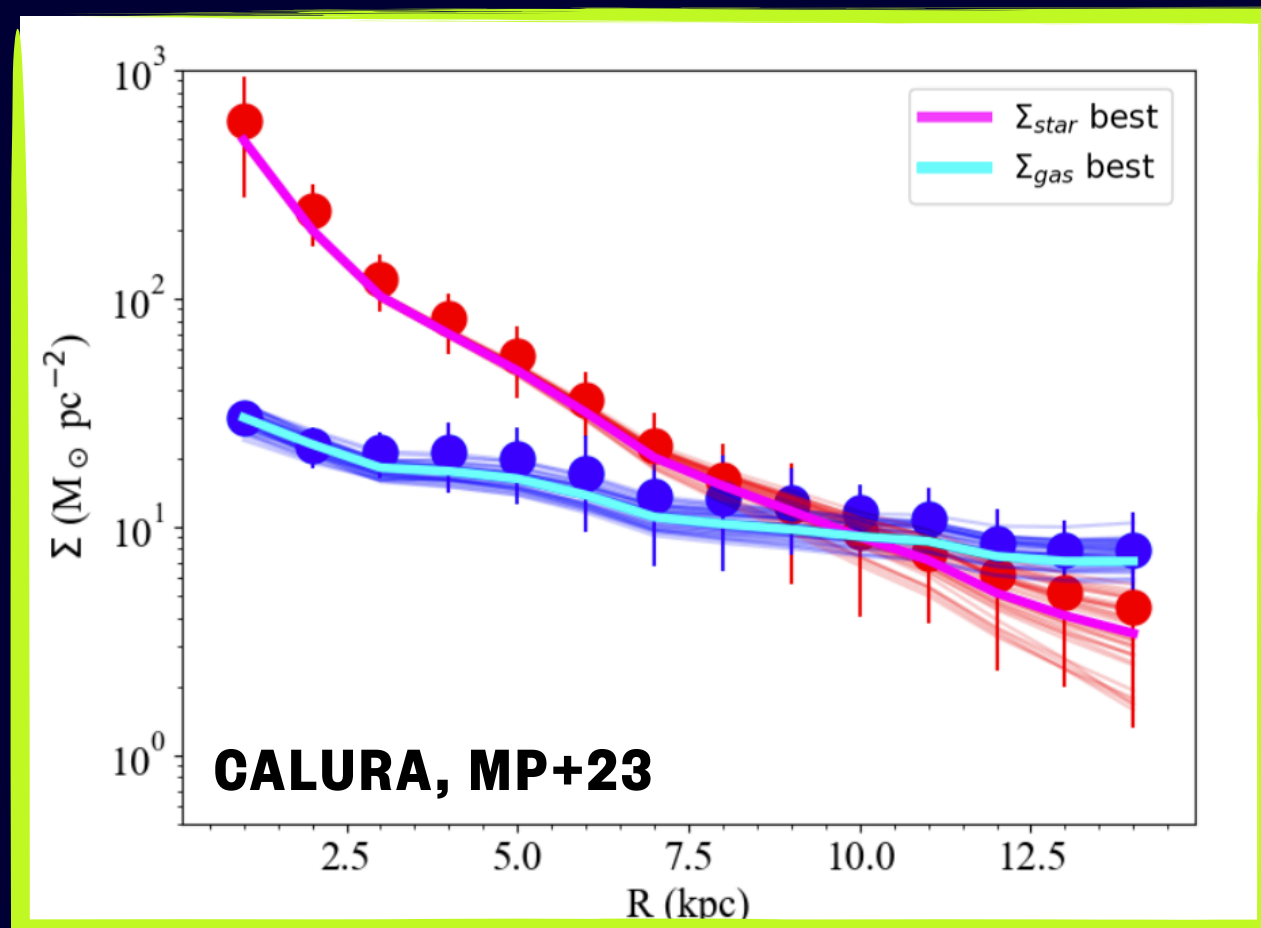
**Optimal COMPARISON for GALAXY EVOLUTION MODELS**



# Dust in M74

## REPRODUCING THE DUST GRADIENT

- Multi-zone chemical evolution model:  
**galaxy divided in 1 kpc wide rings**
- **Fitting model** parameters  
to physical observables **via MCMC**

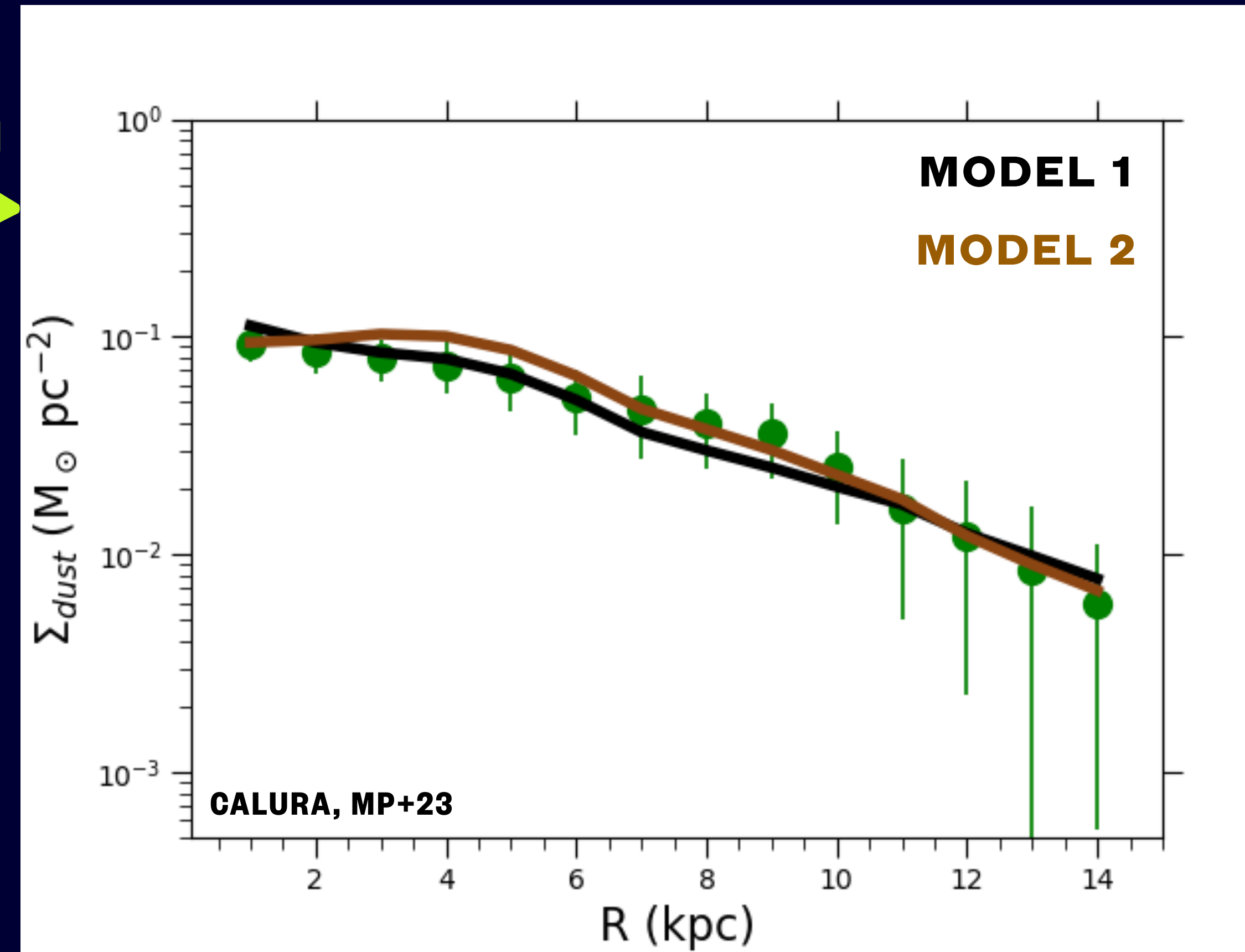
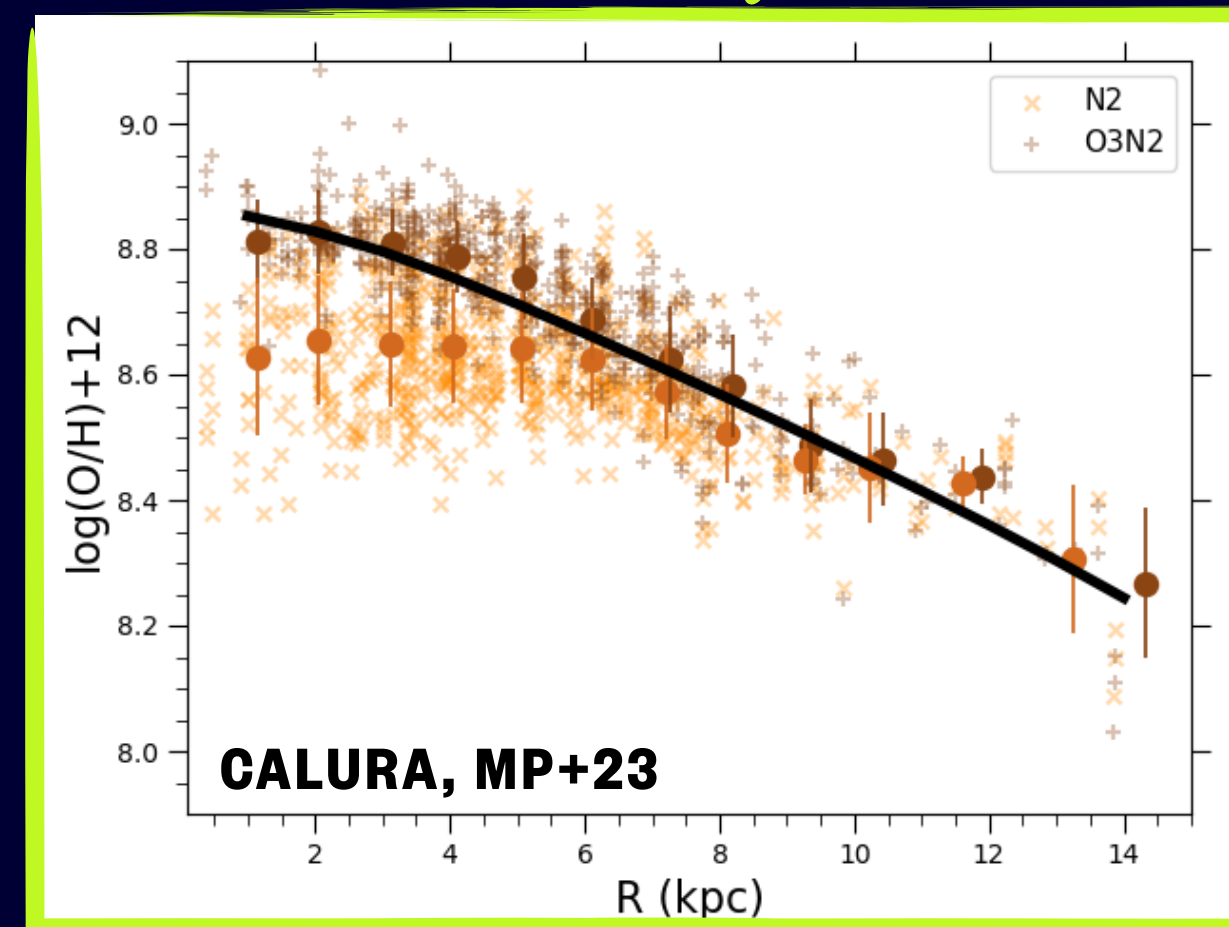
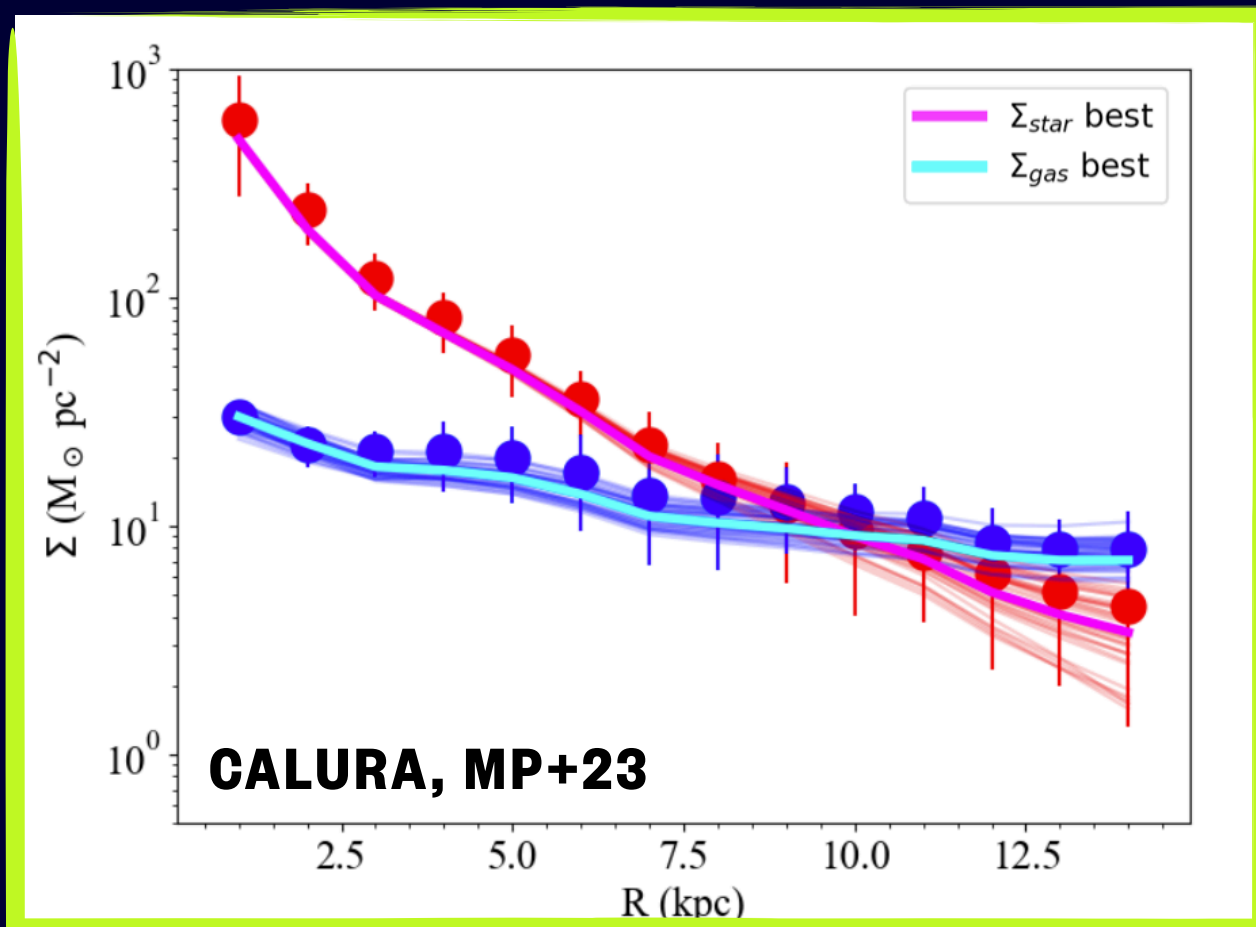
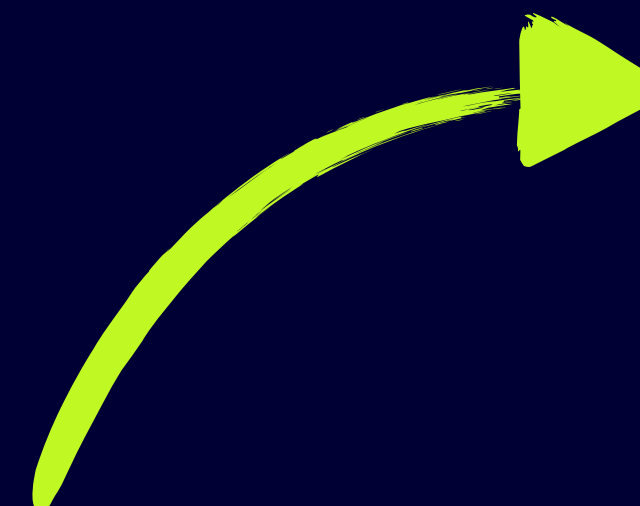


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**DUST EVOLUTION**

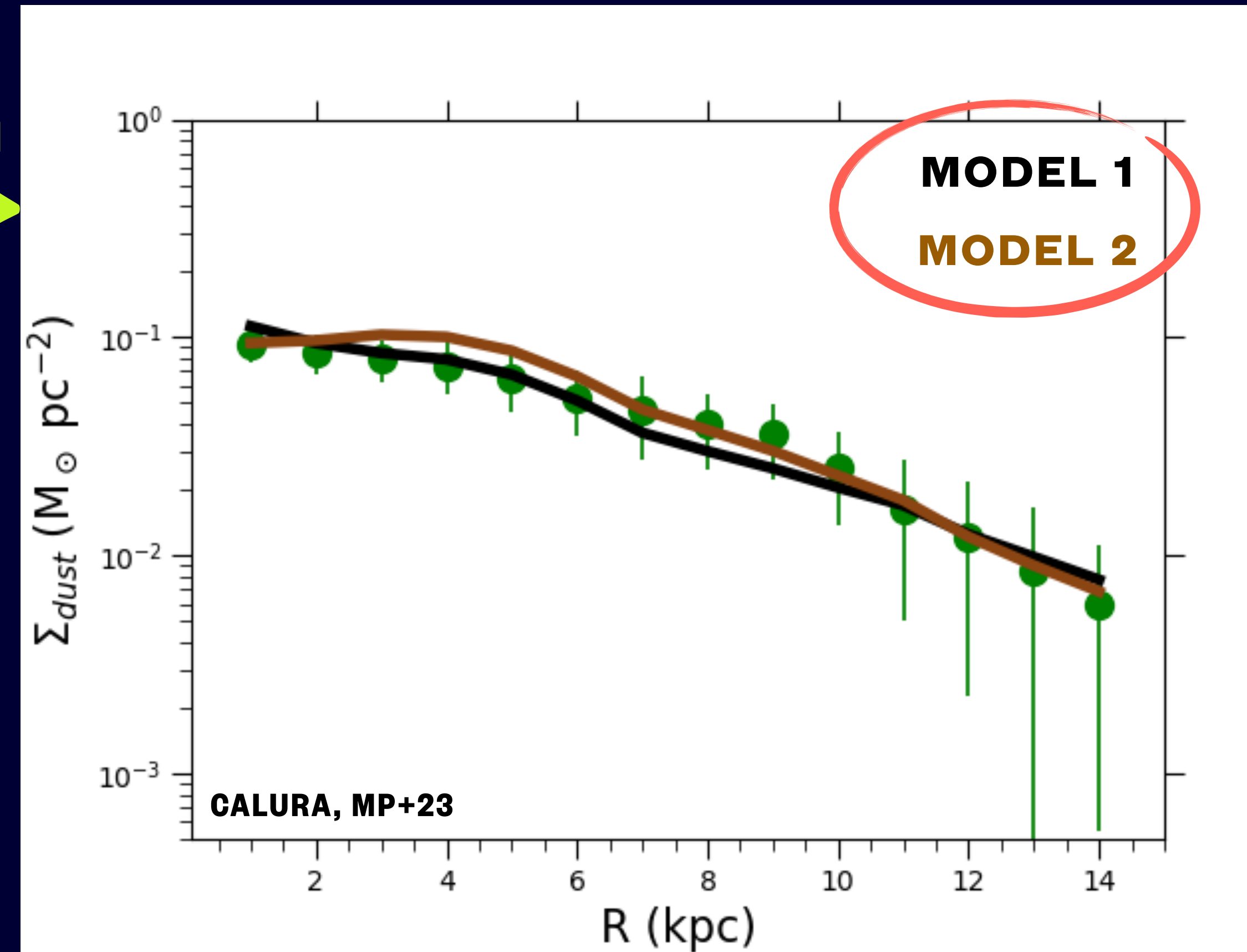
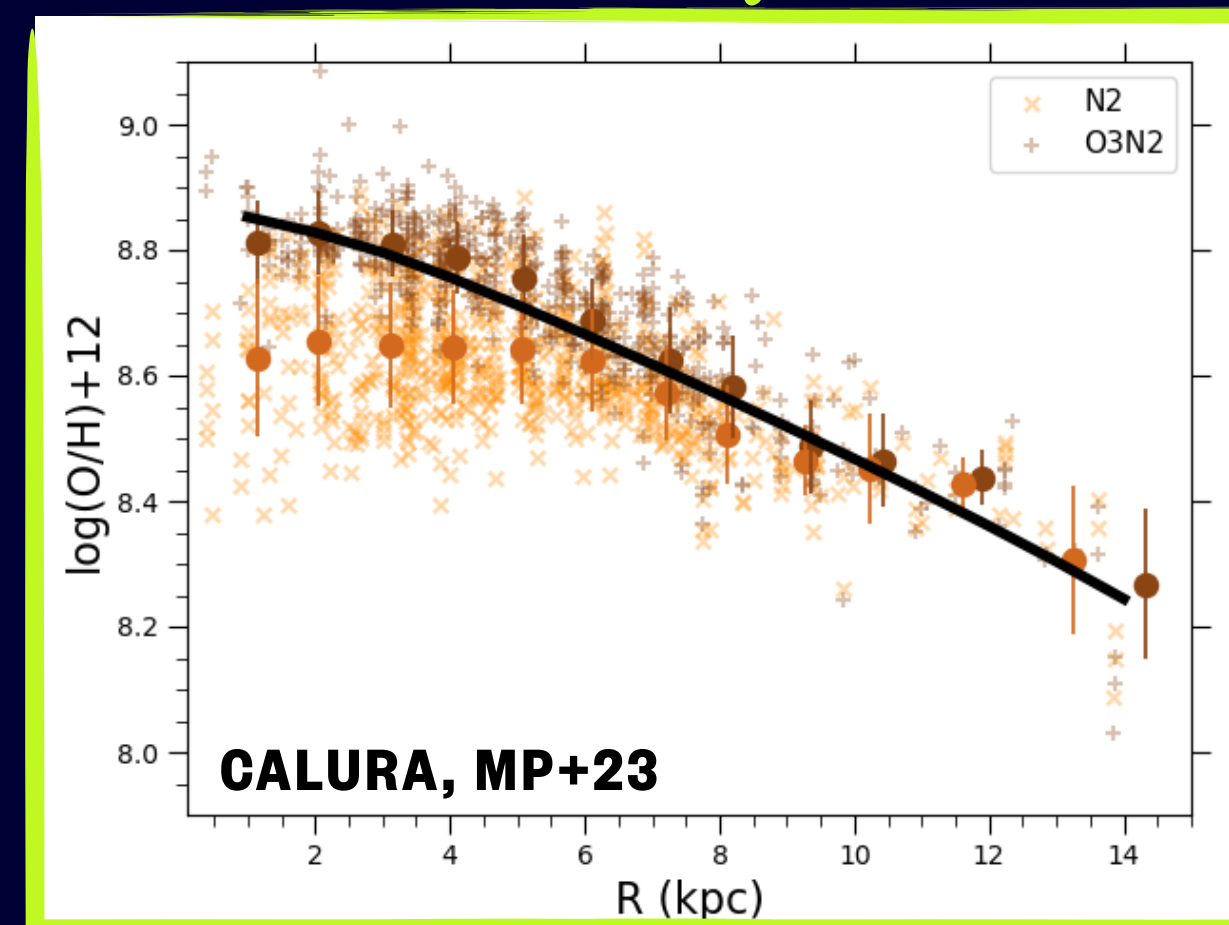
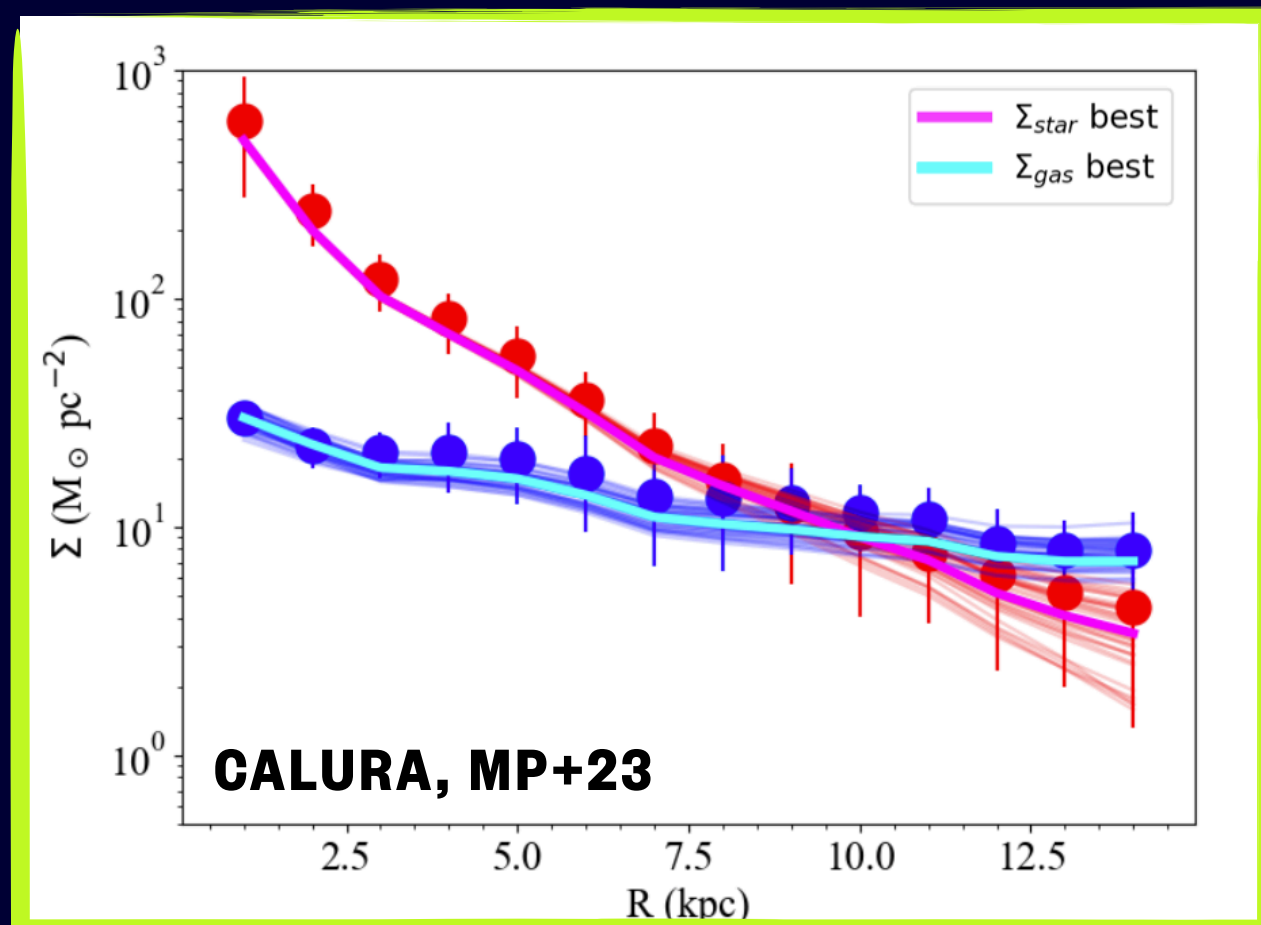
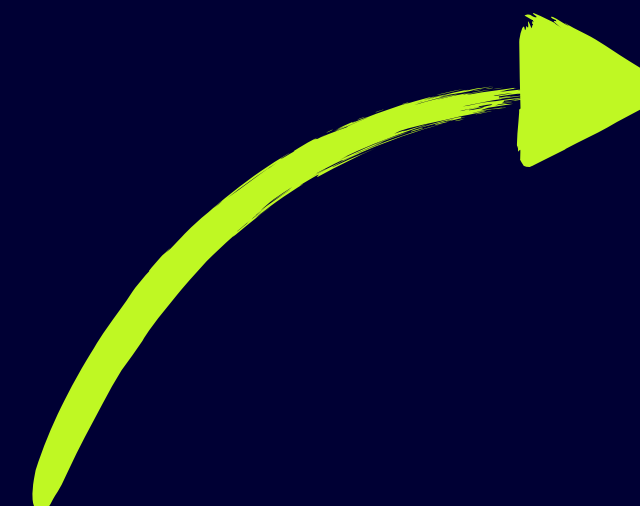


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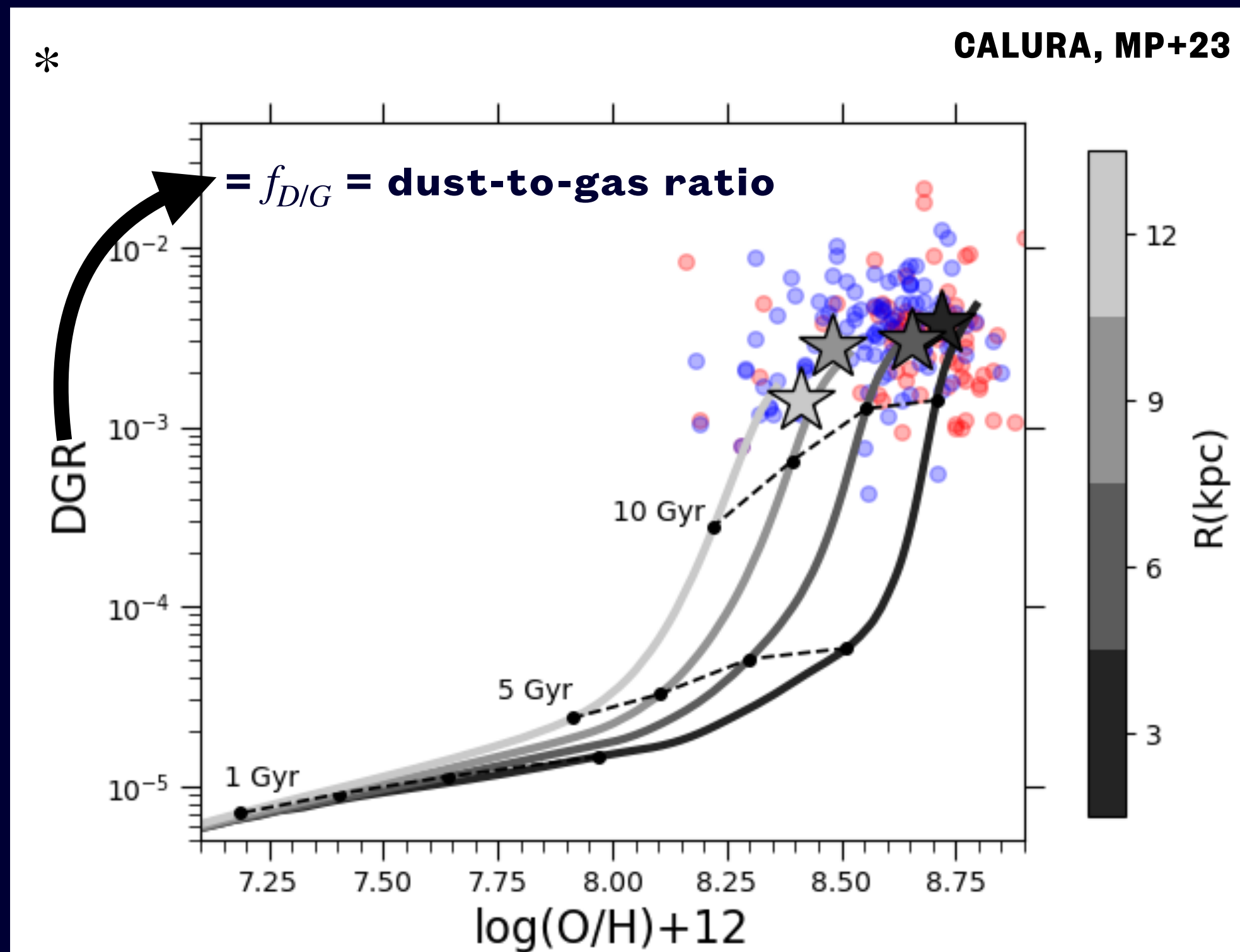
**DUST EVOLUTION**



# Dust in M74

ADIBEKYAN+19

## DUST EVOLUTION AT DIFFERENT RADII

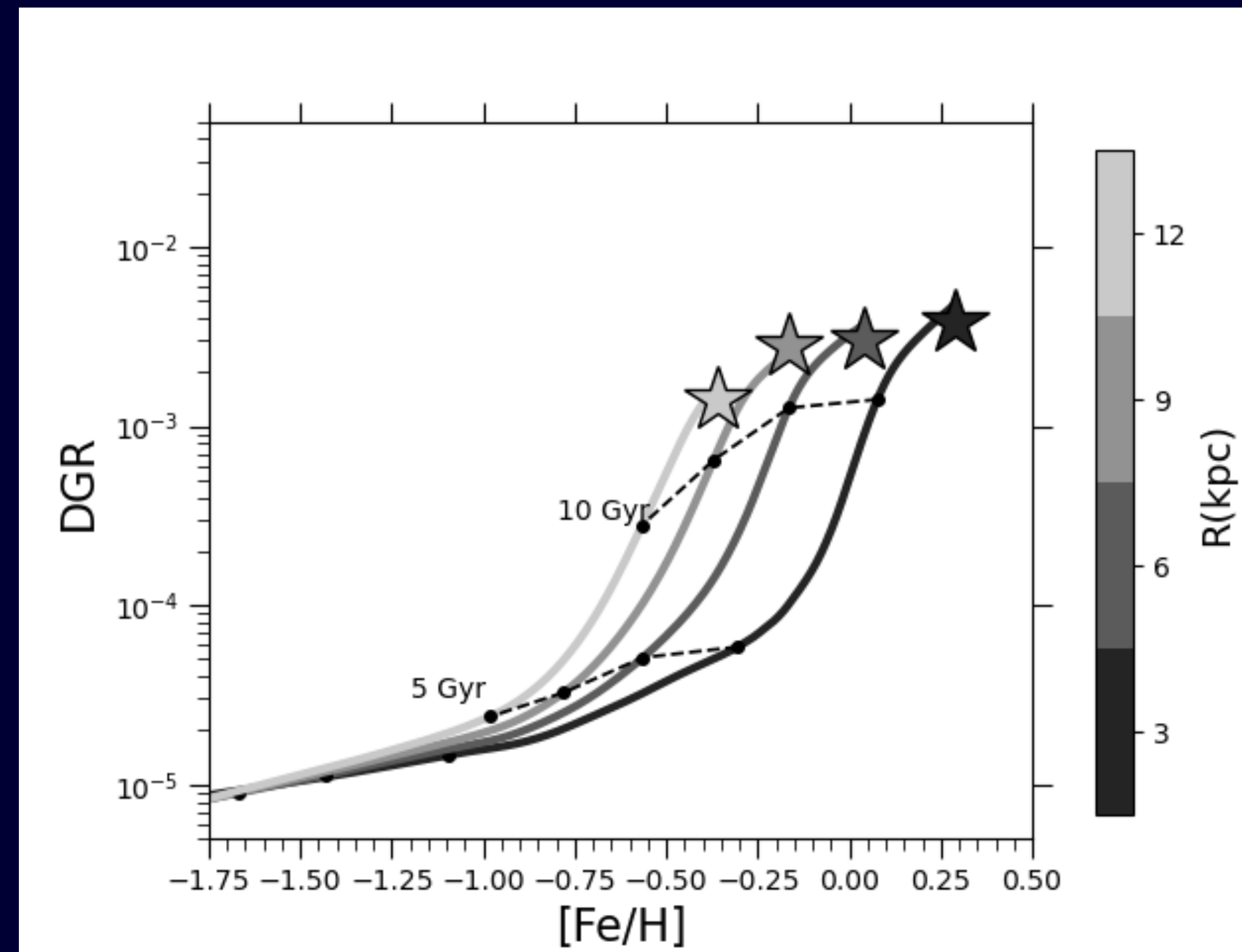
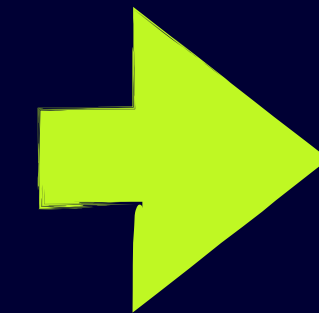
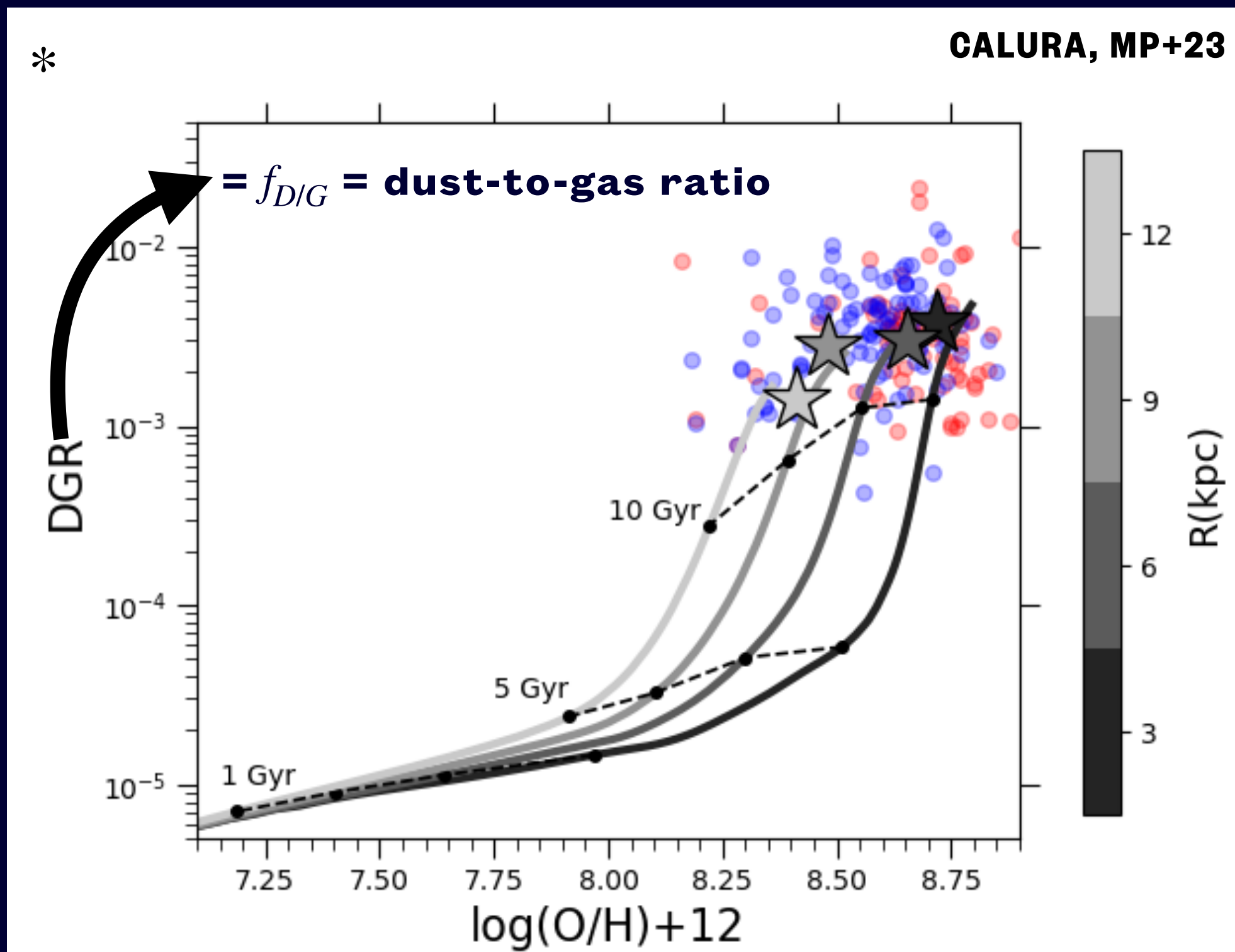


\* DustPedia data of **early-type** and **late-type** non resolved spirals (Casasola+20)

# Dust in M74

ADIBEKYAN+19

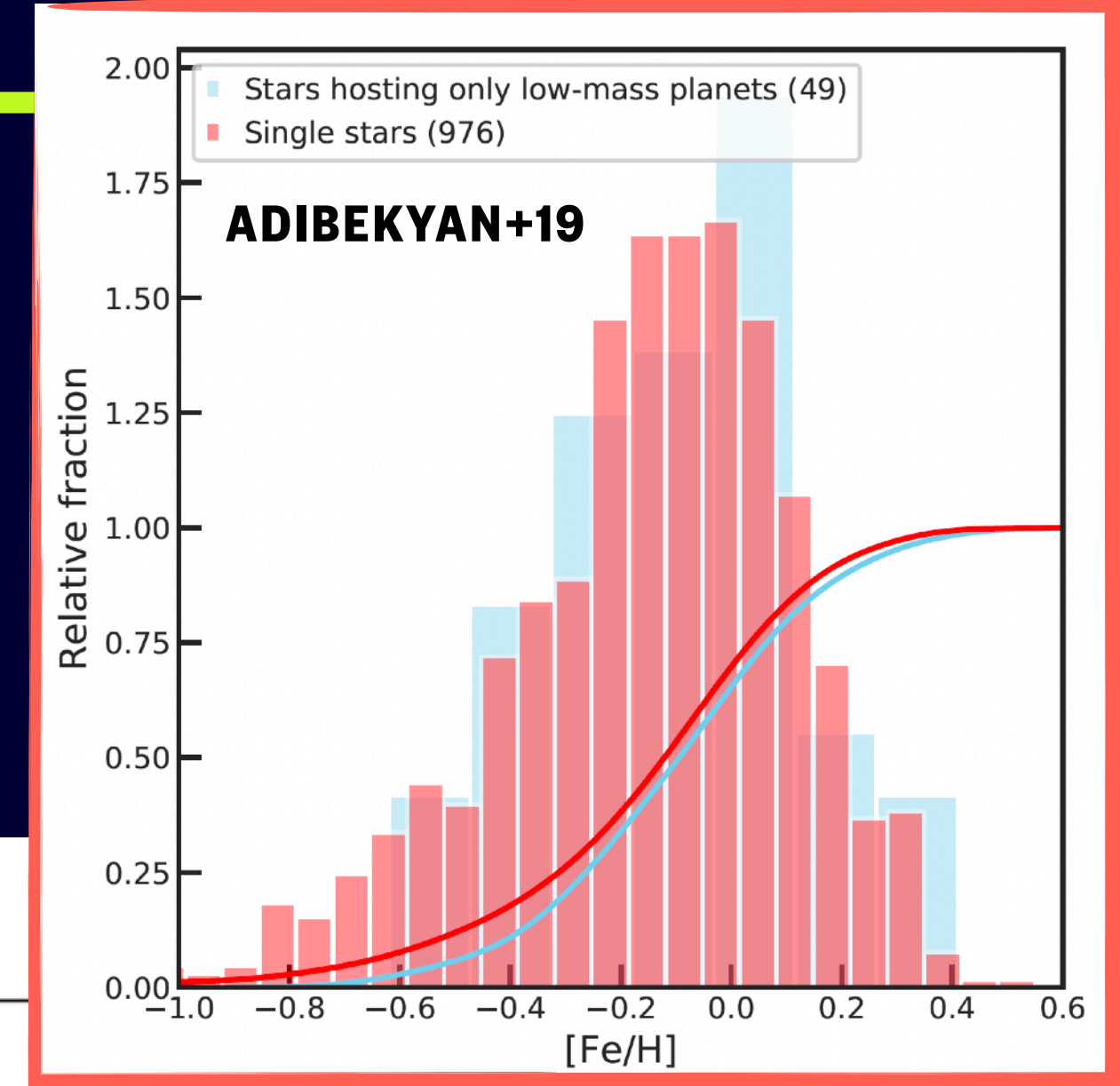
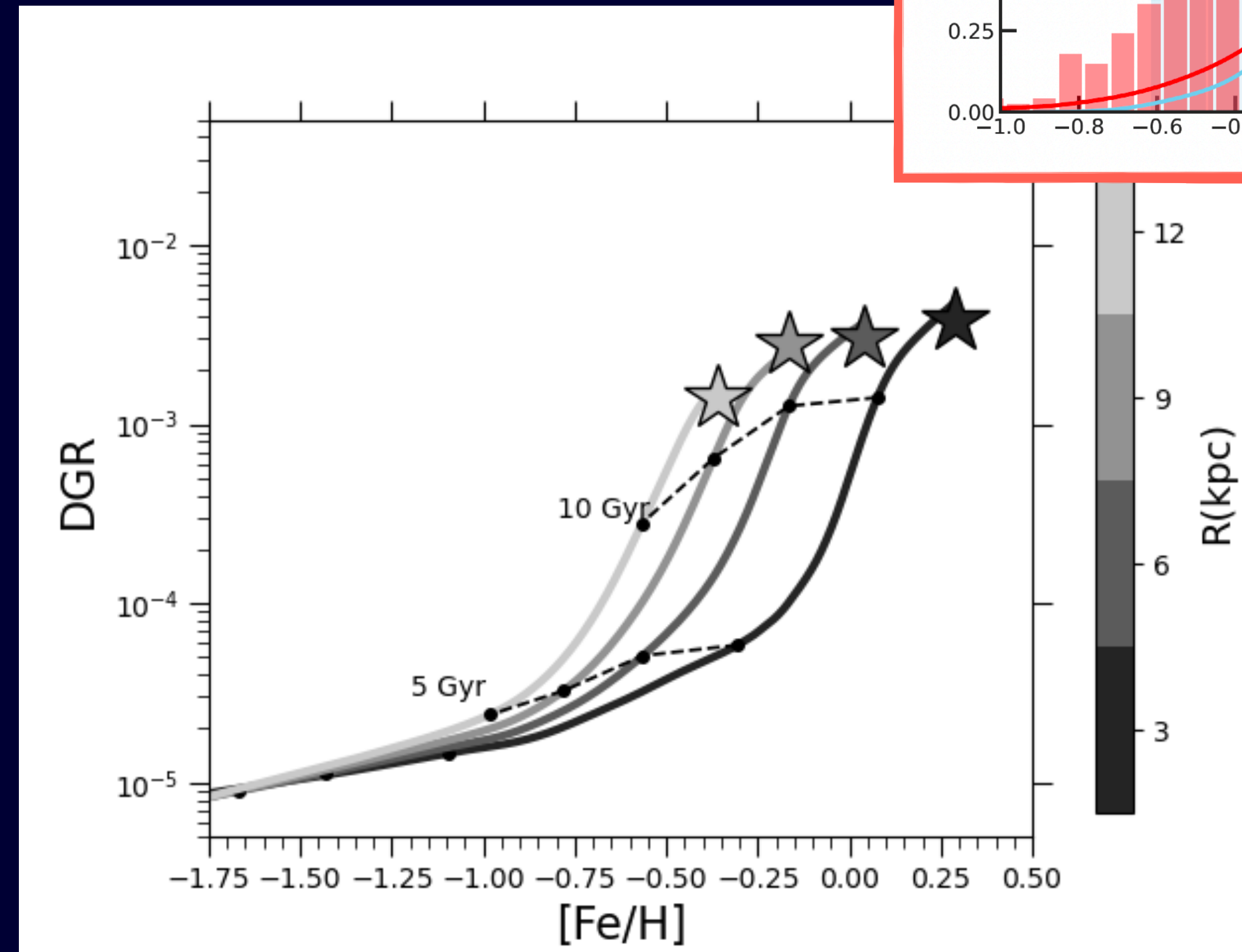
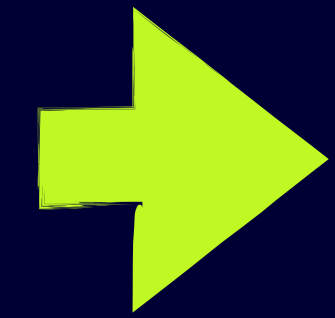
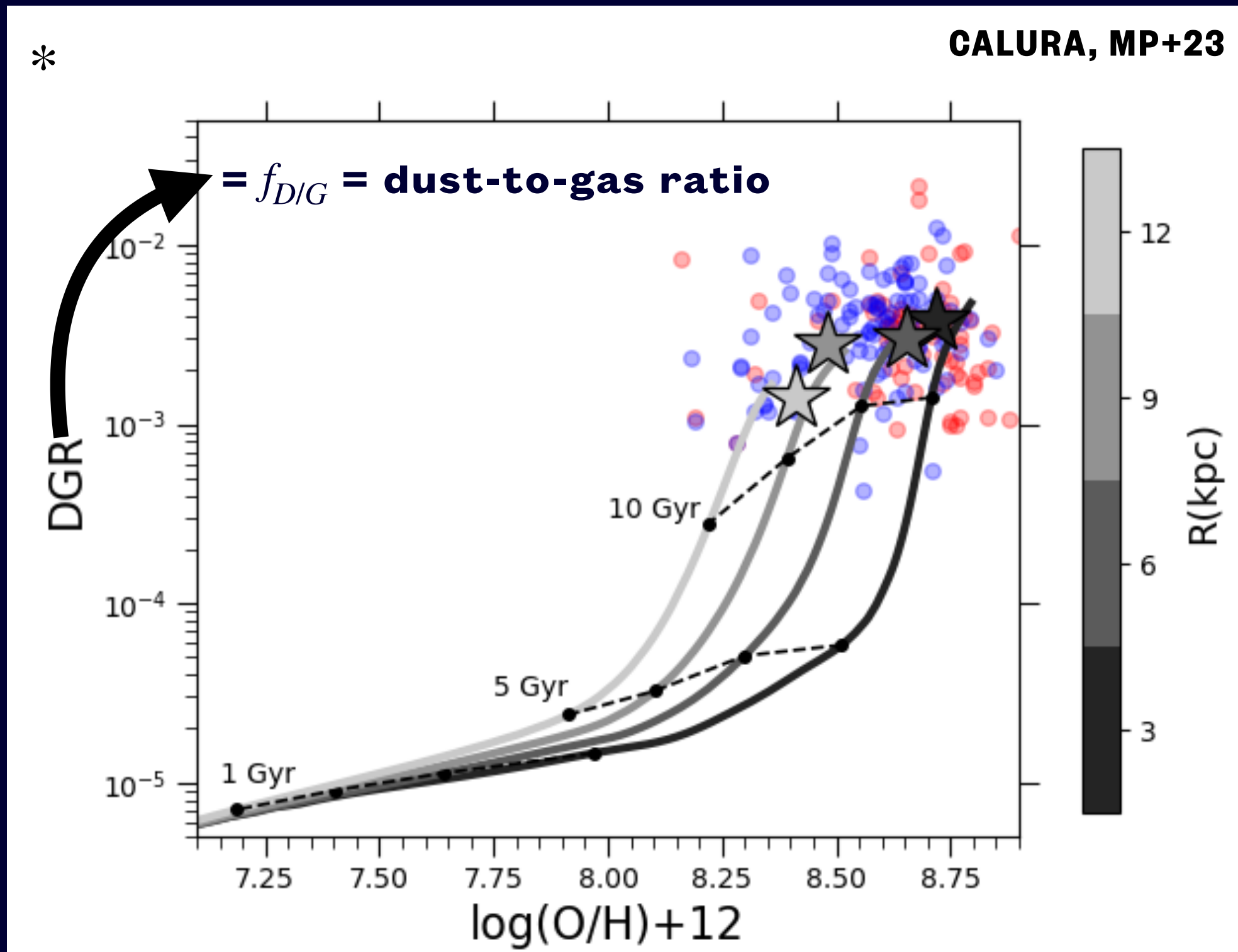
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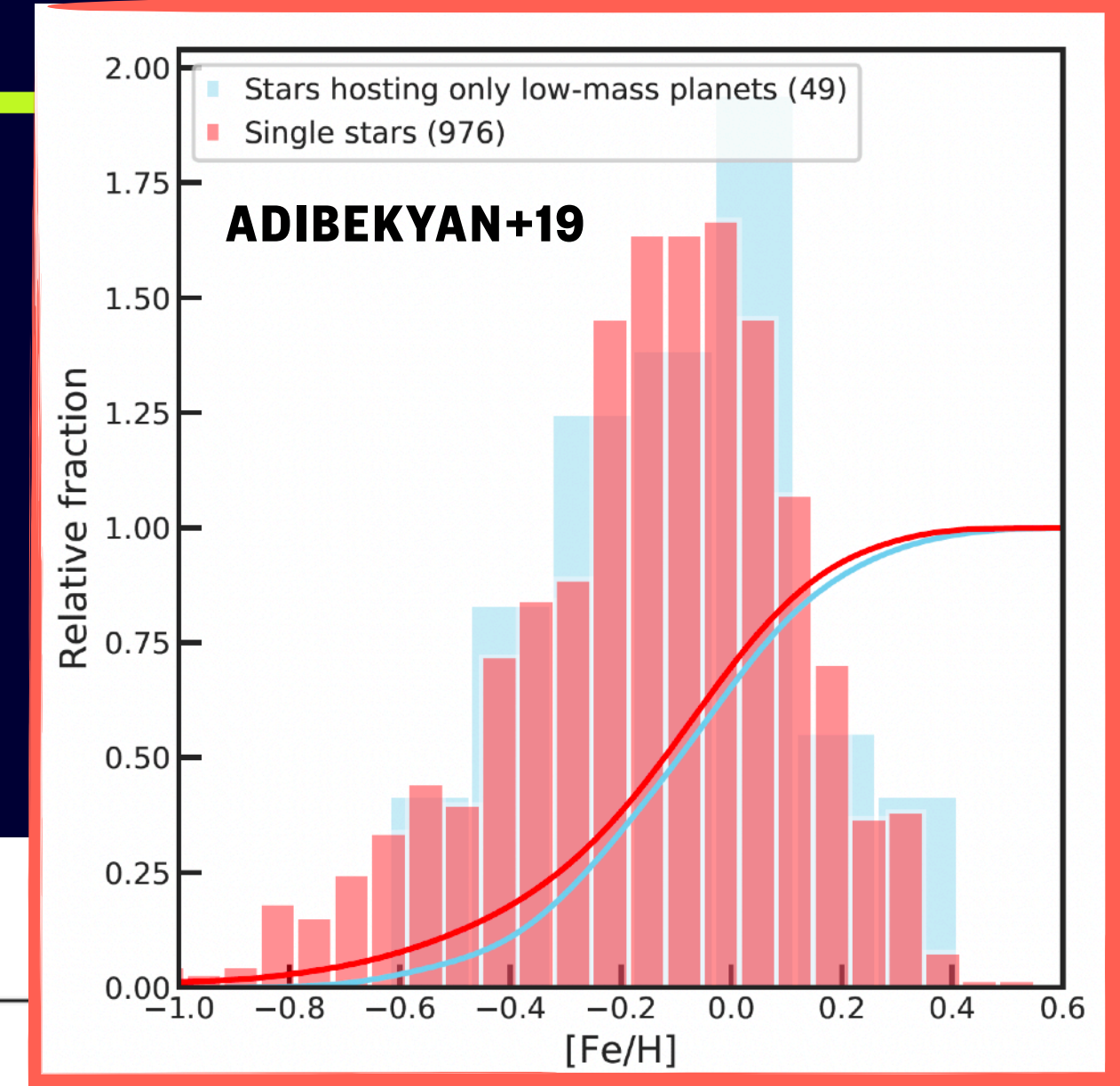
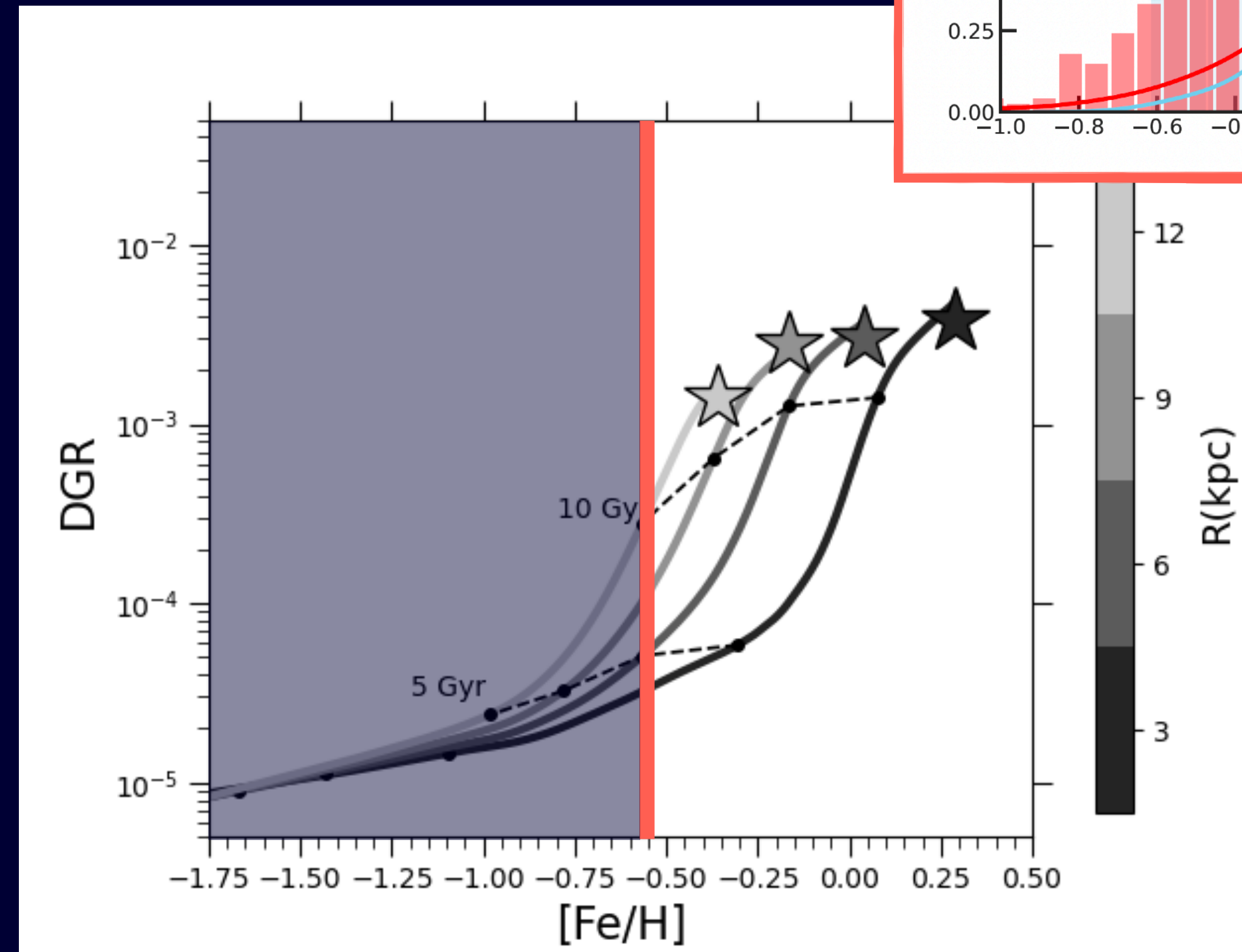
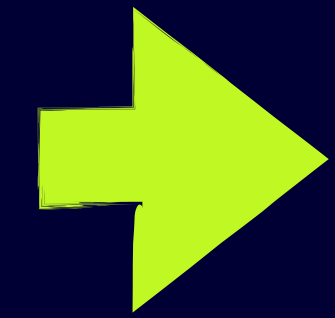
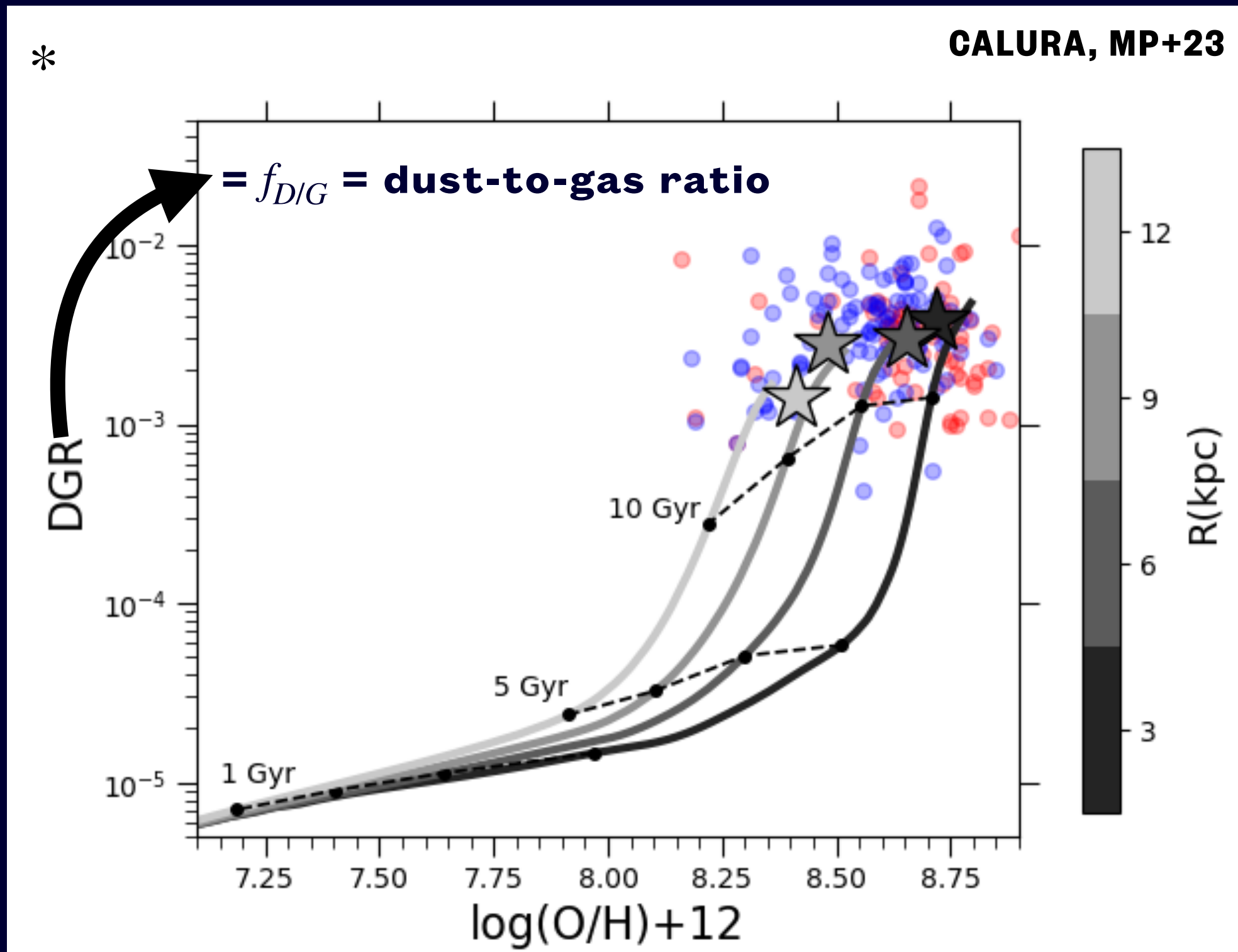
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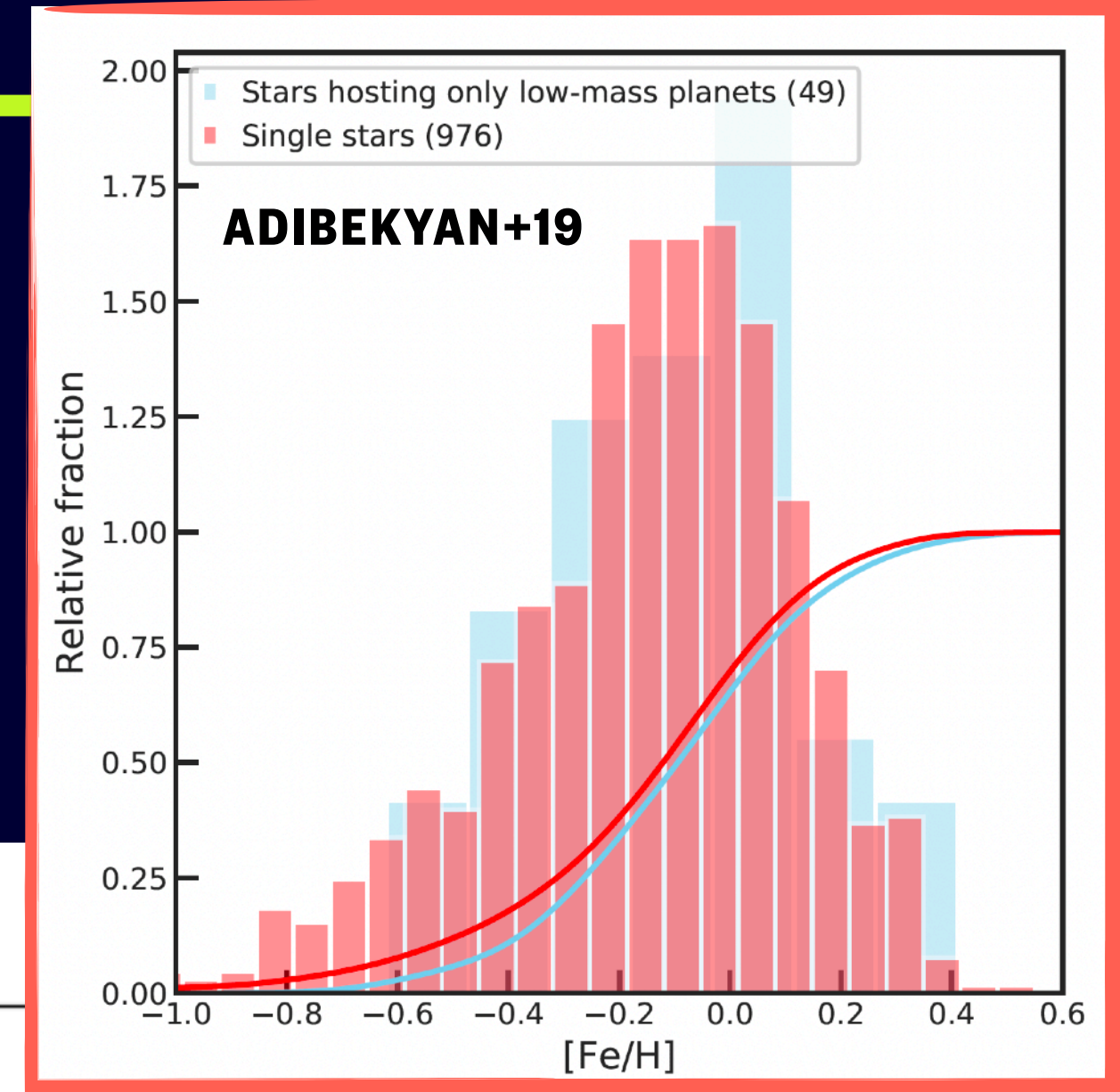
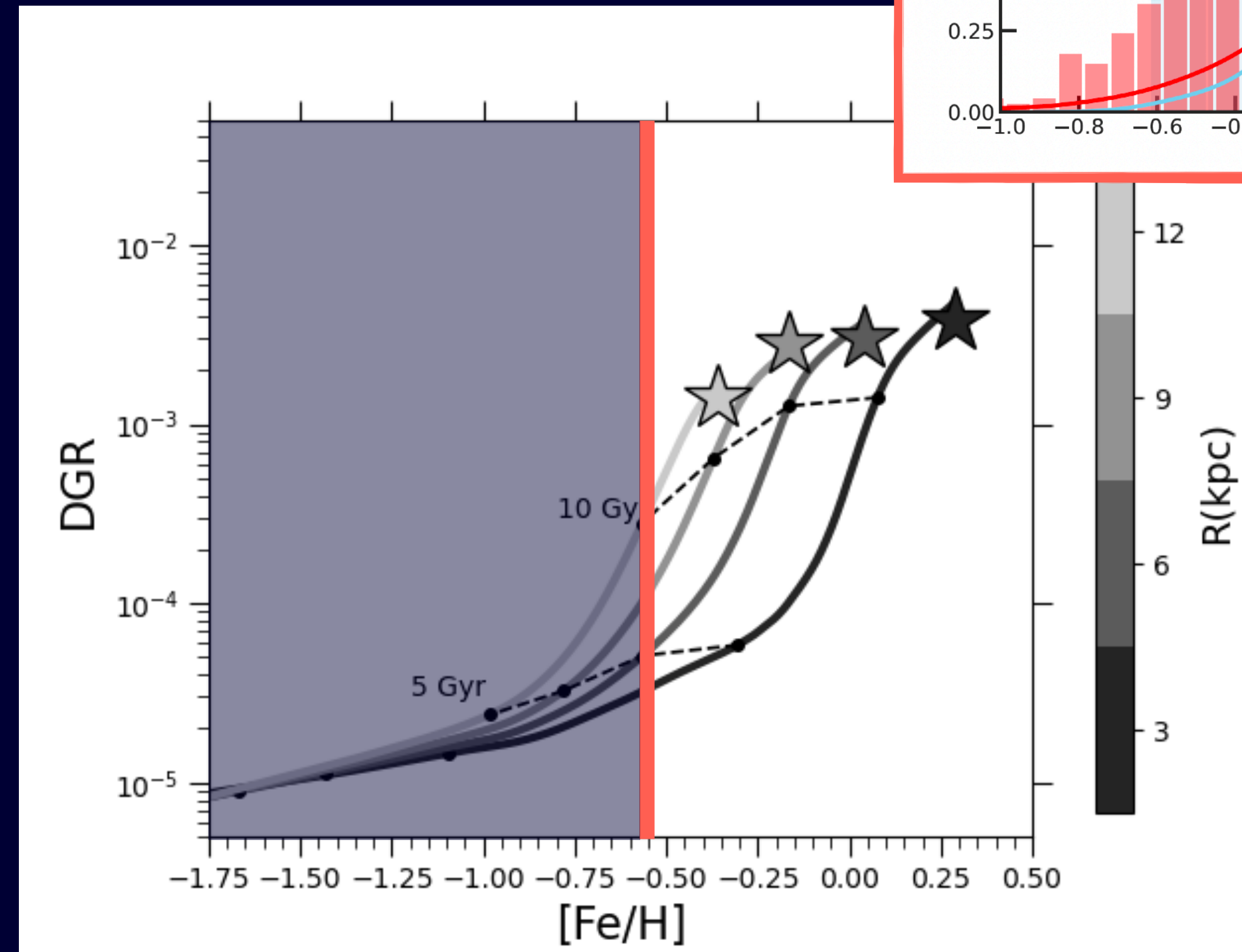
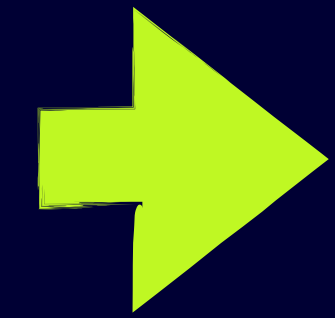
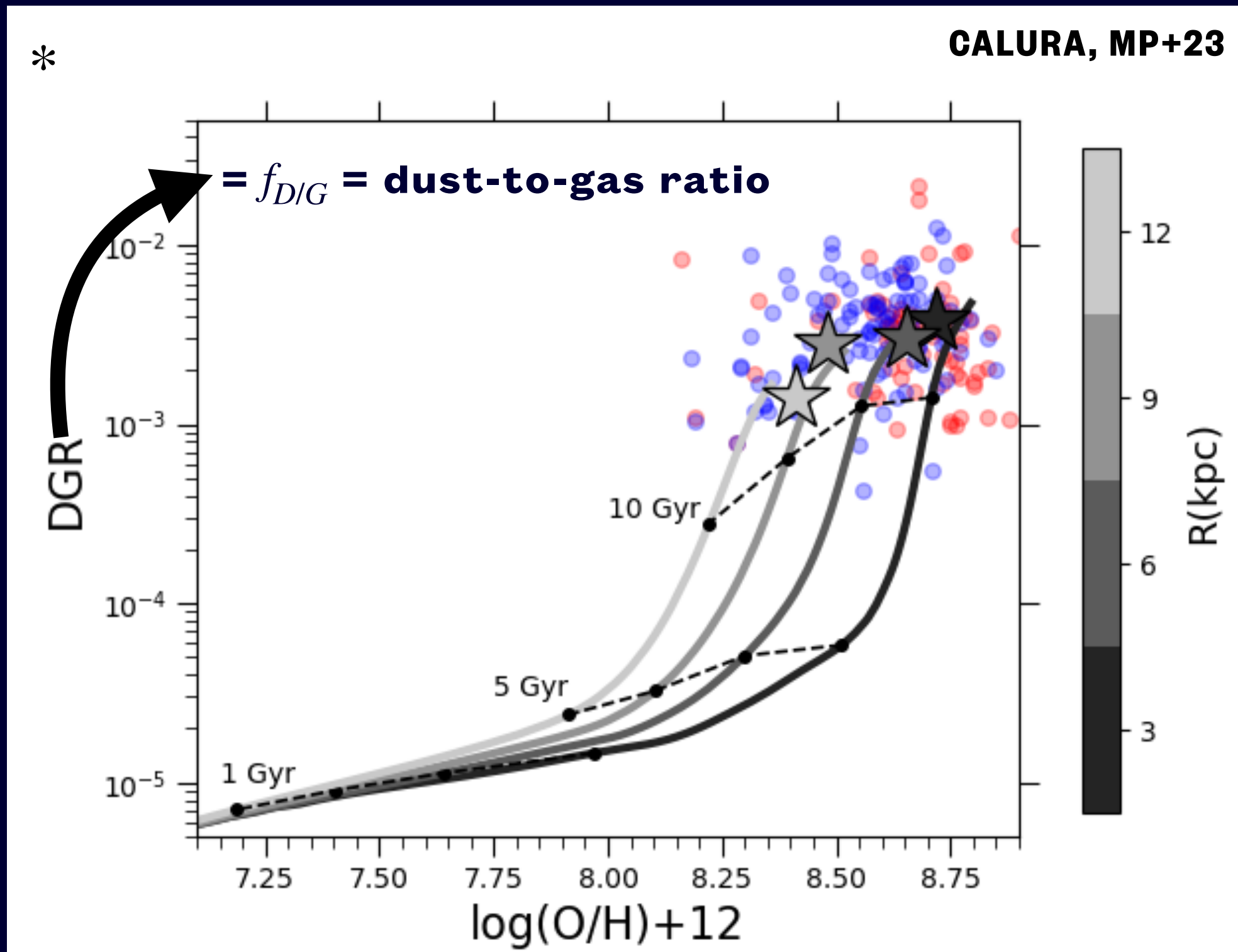


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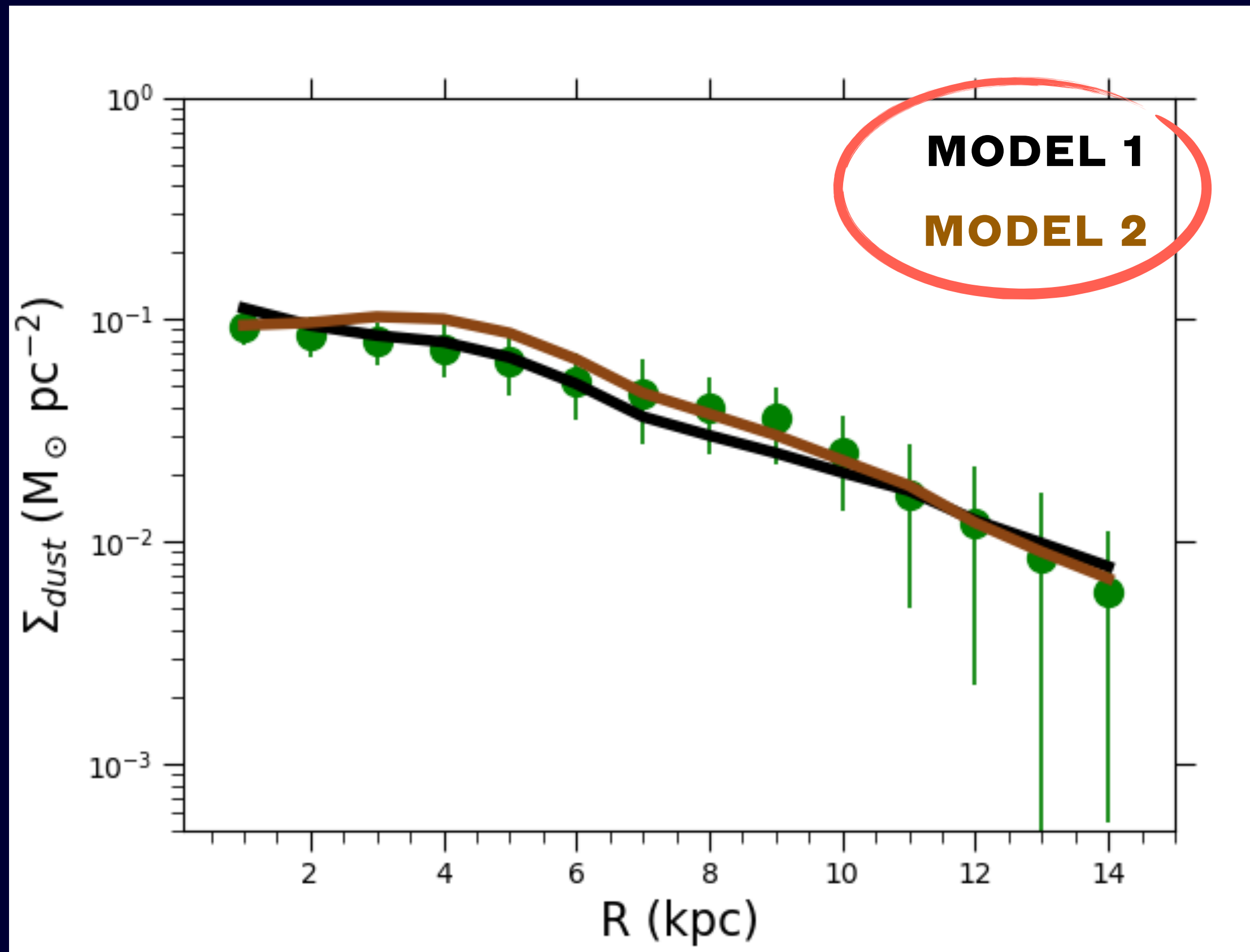
$$\frac{DGR}{DGR_{\odot}} = 10^{[M/H]}$$

(e.g. Lodders+03, Mordasini+09,+18)

\* DustPedia data of early-type and late-type non resolved spirals (Casasola+20)

# Dust in M74 ... and not only !

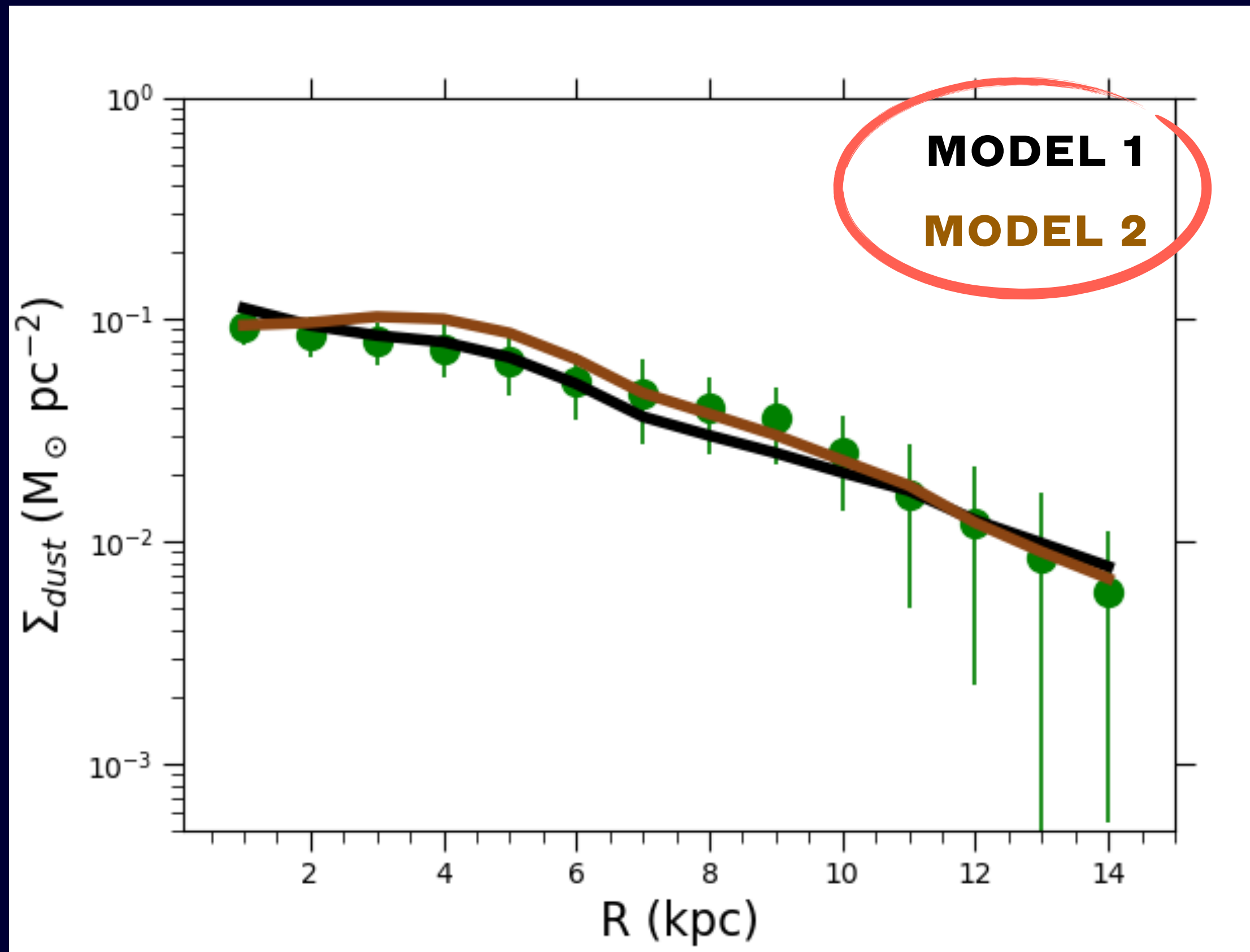
**SAME DUST = DIFFERENT EVOLUTION !**



\* DustPedia data of **early-type** and **late-type** non resolved spirals (Casasola+20)

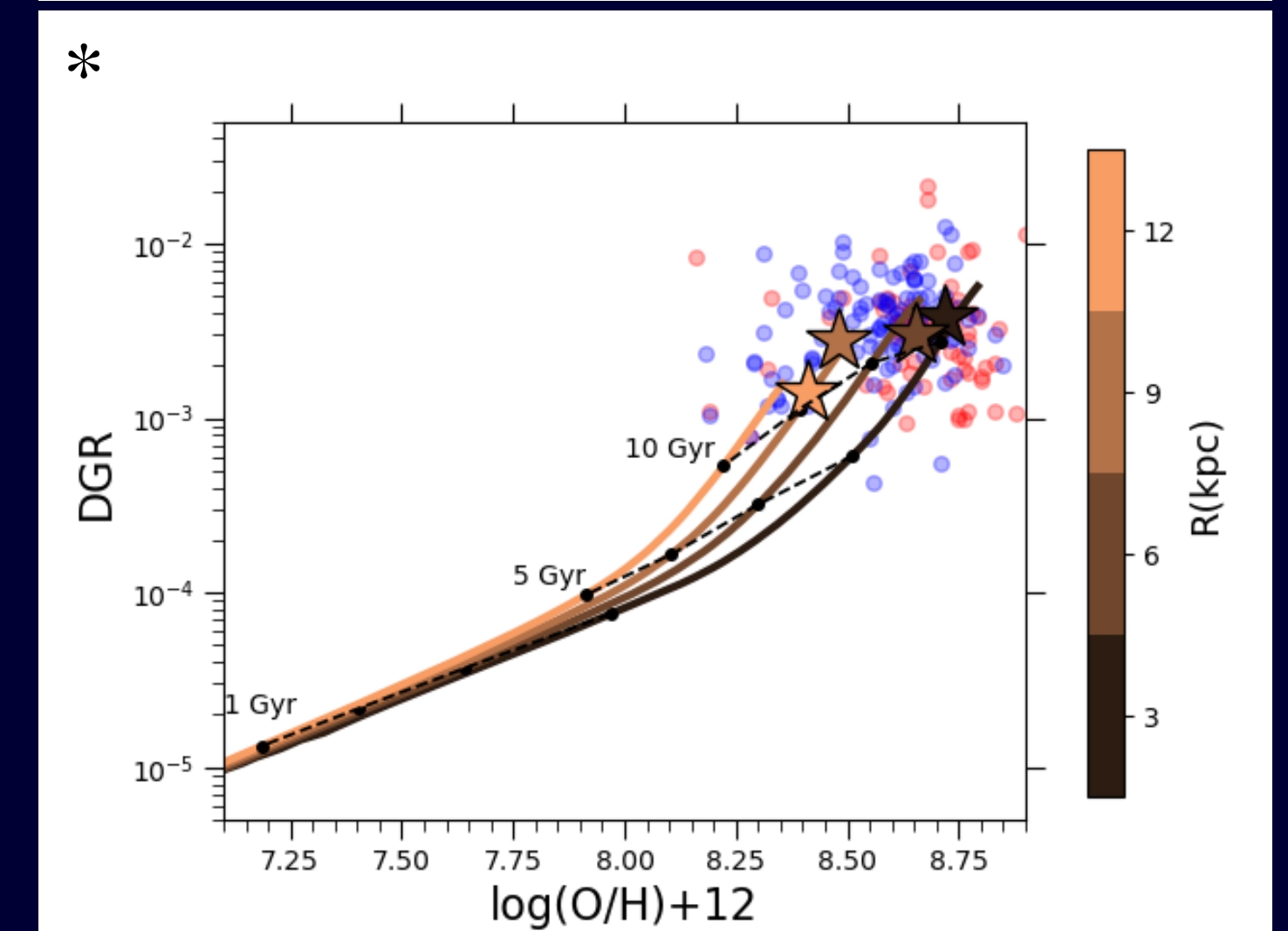
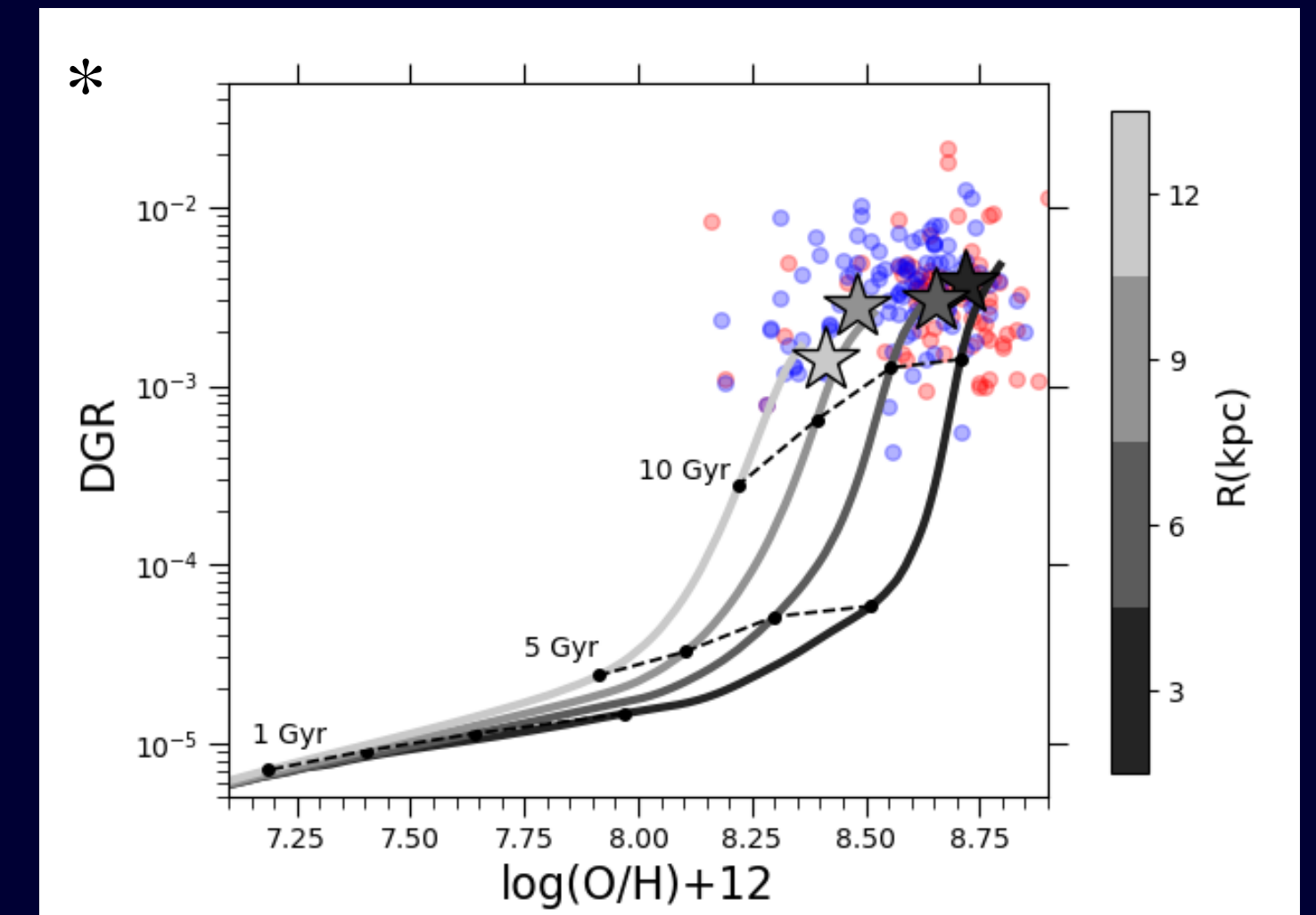
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**SAME DUST = DIFFERENT EVOLUTION!**



**MODEL 1**

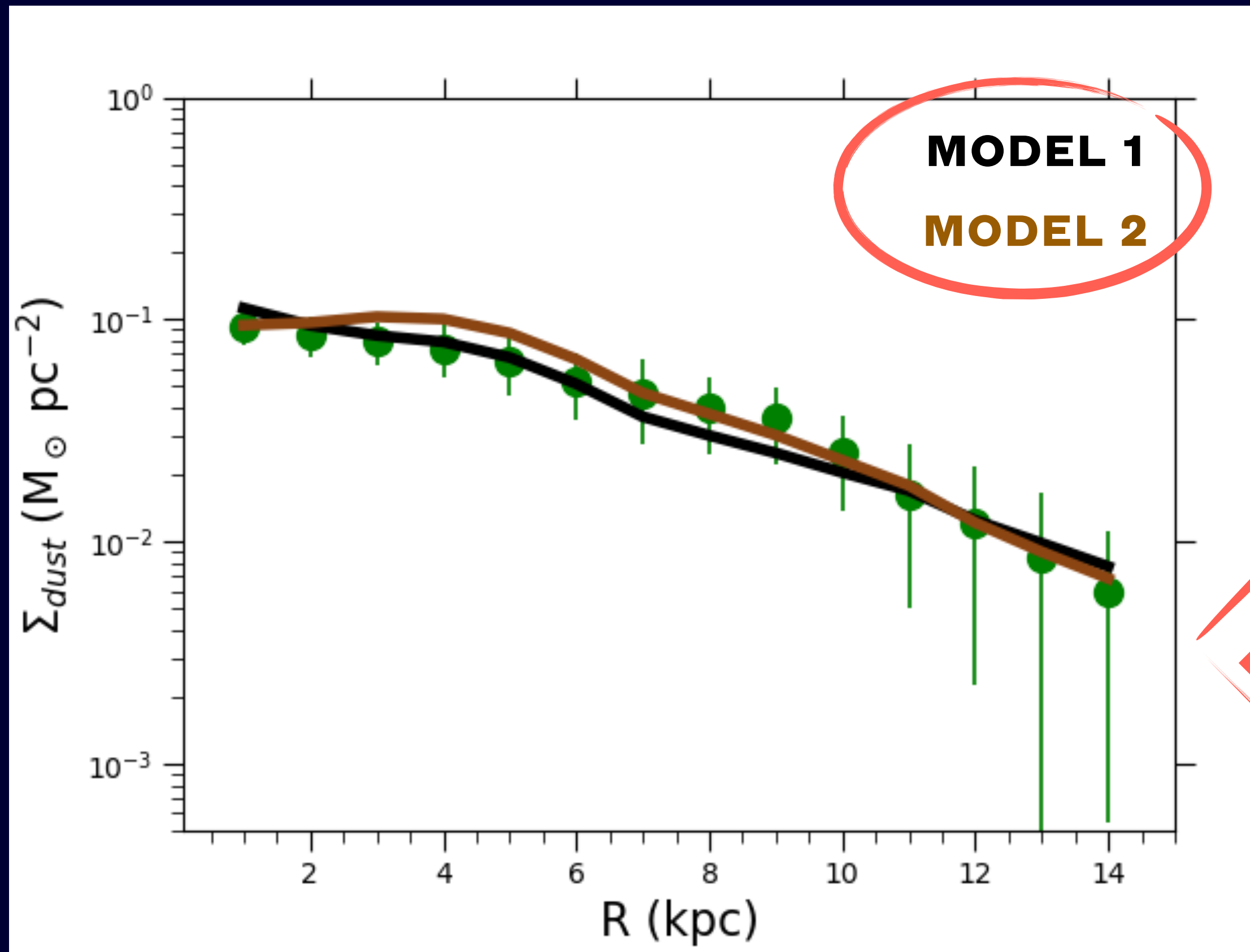
**MODEL 2**



\* DustPedia data of early-type and late-type non resolved spirals (Casasola+20)

# Dust in M74 ... and not only!

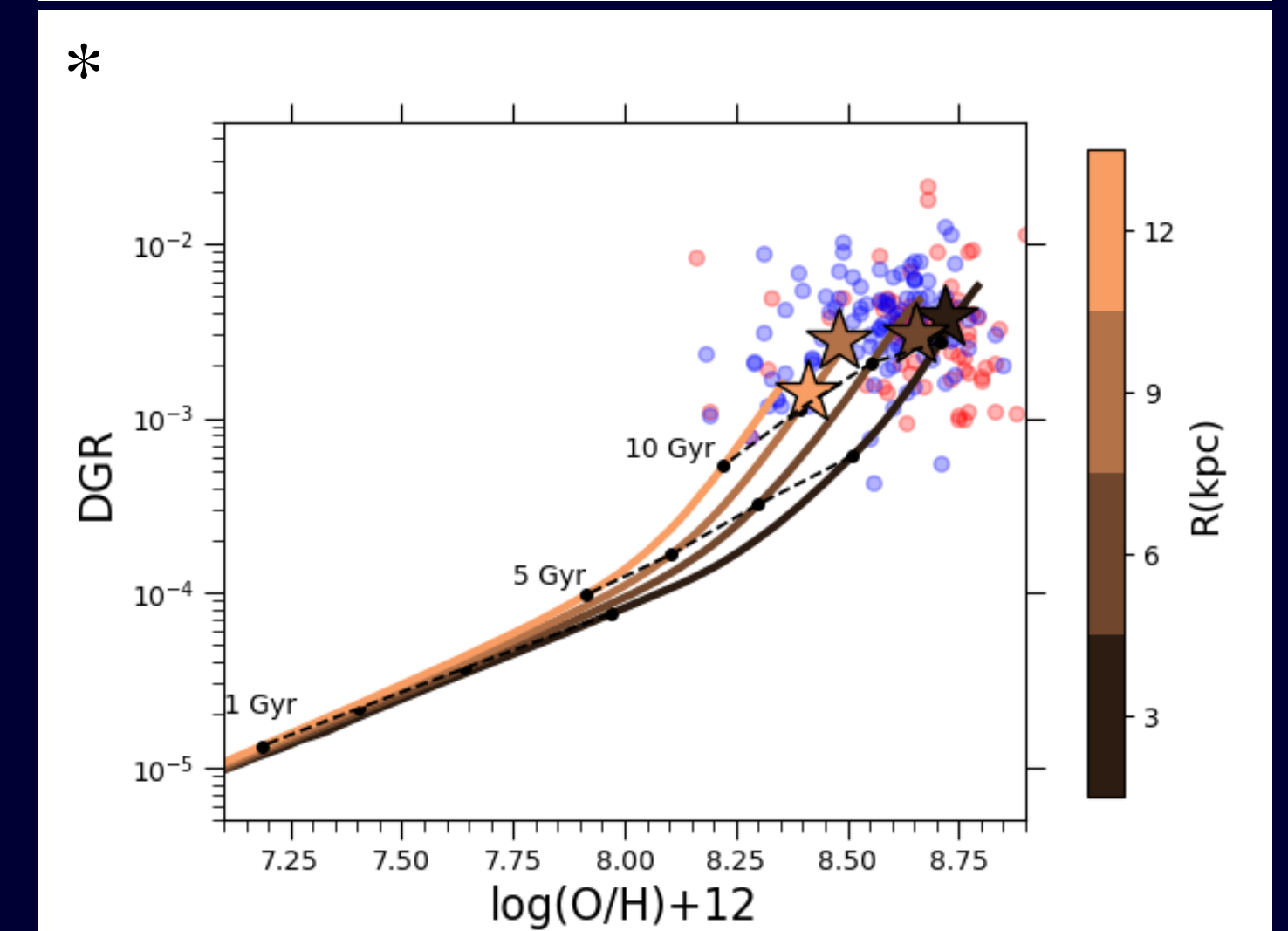
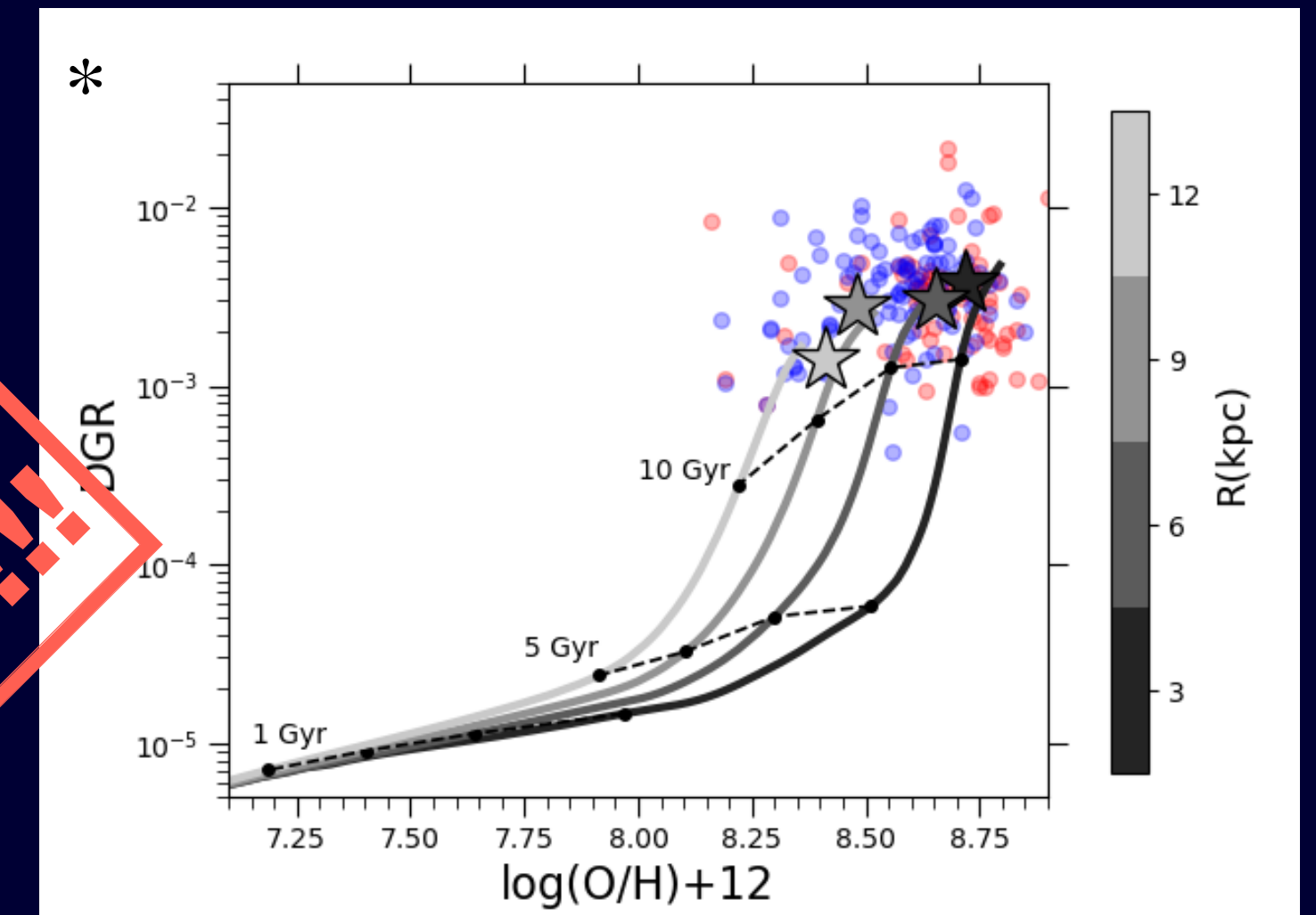
**SAME DUST = DIFFERENT EVOLUTION!**



**MODEL 1**

**DEGENERACY!!!**

**MODEL 2**

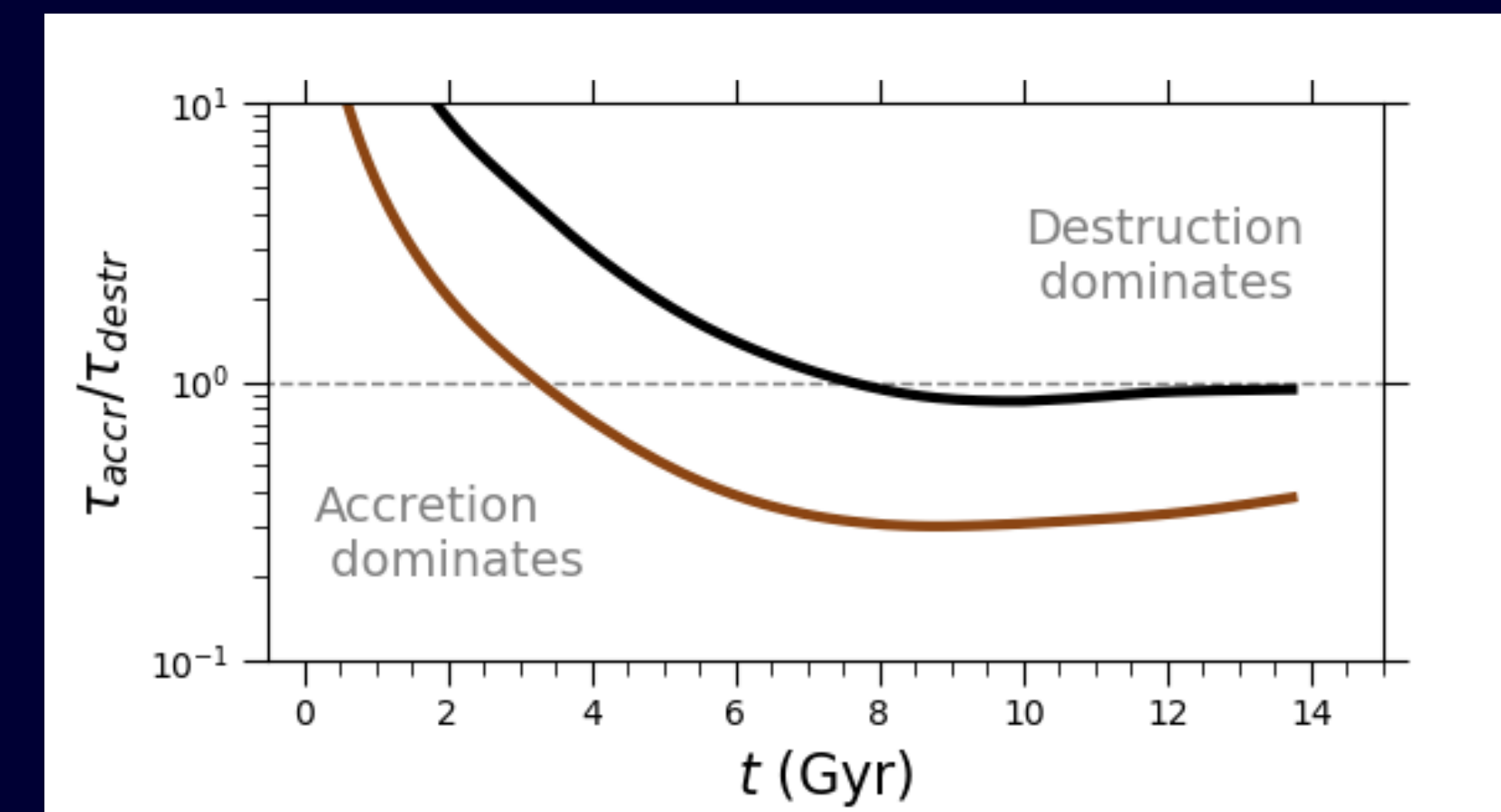
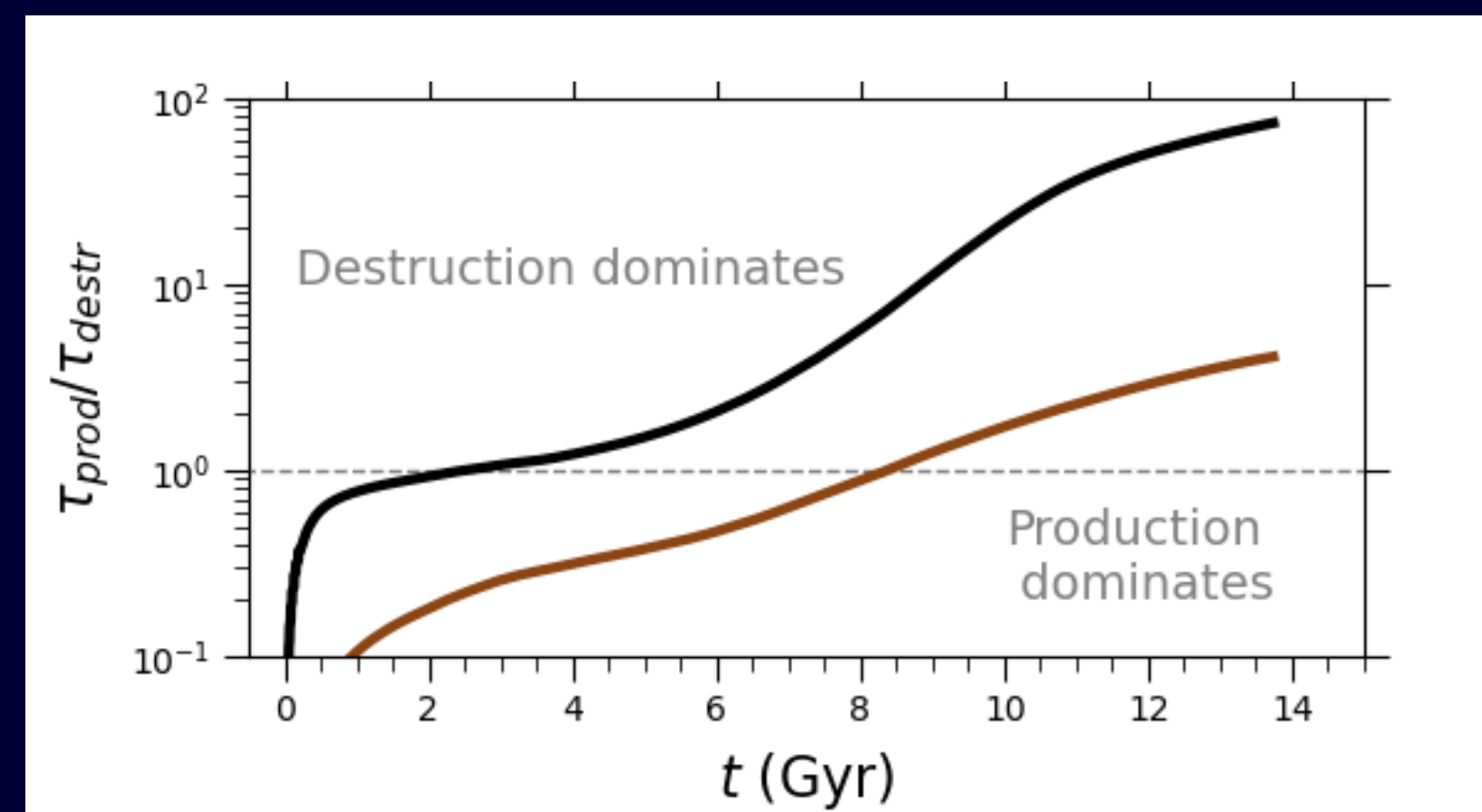
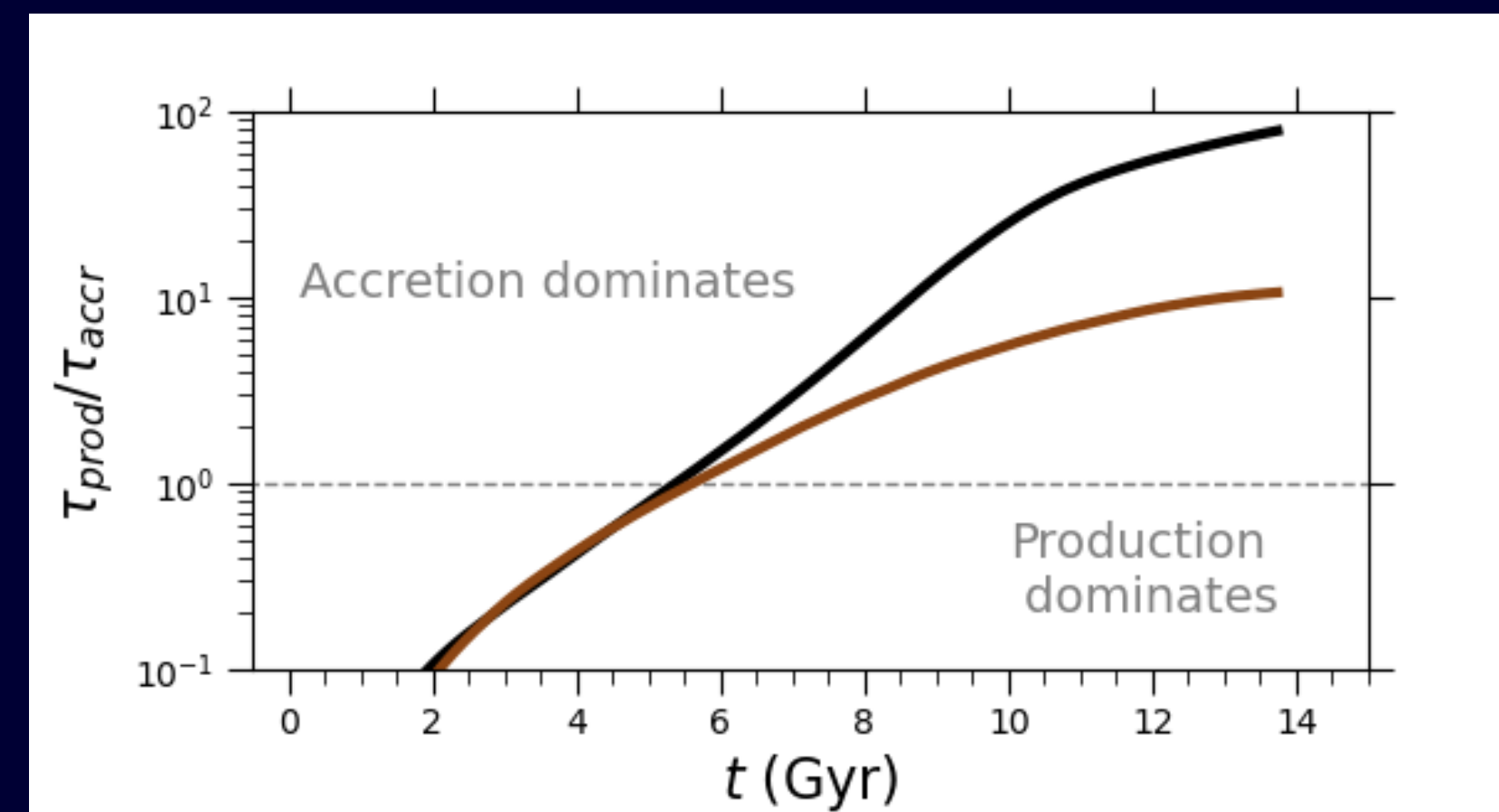


\* DustPedia data of early-type and late-type non resolved spirals (Casasola+20)

# Uncertainties on dust evolution

## THE ROLE OF DUST TIMESCALES

**MODEL 1** smaller growth and destruction timescales



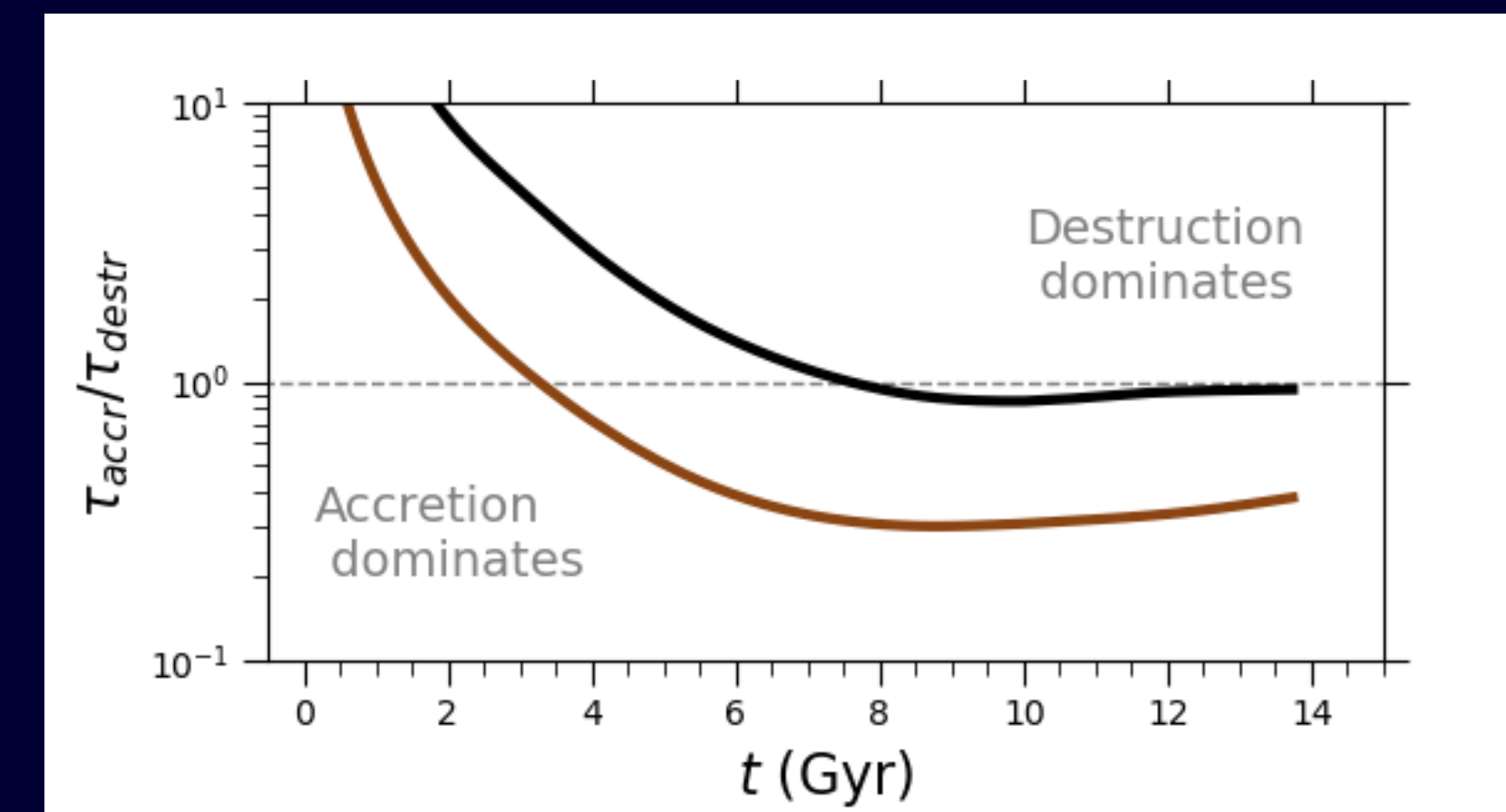
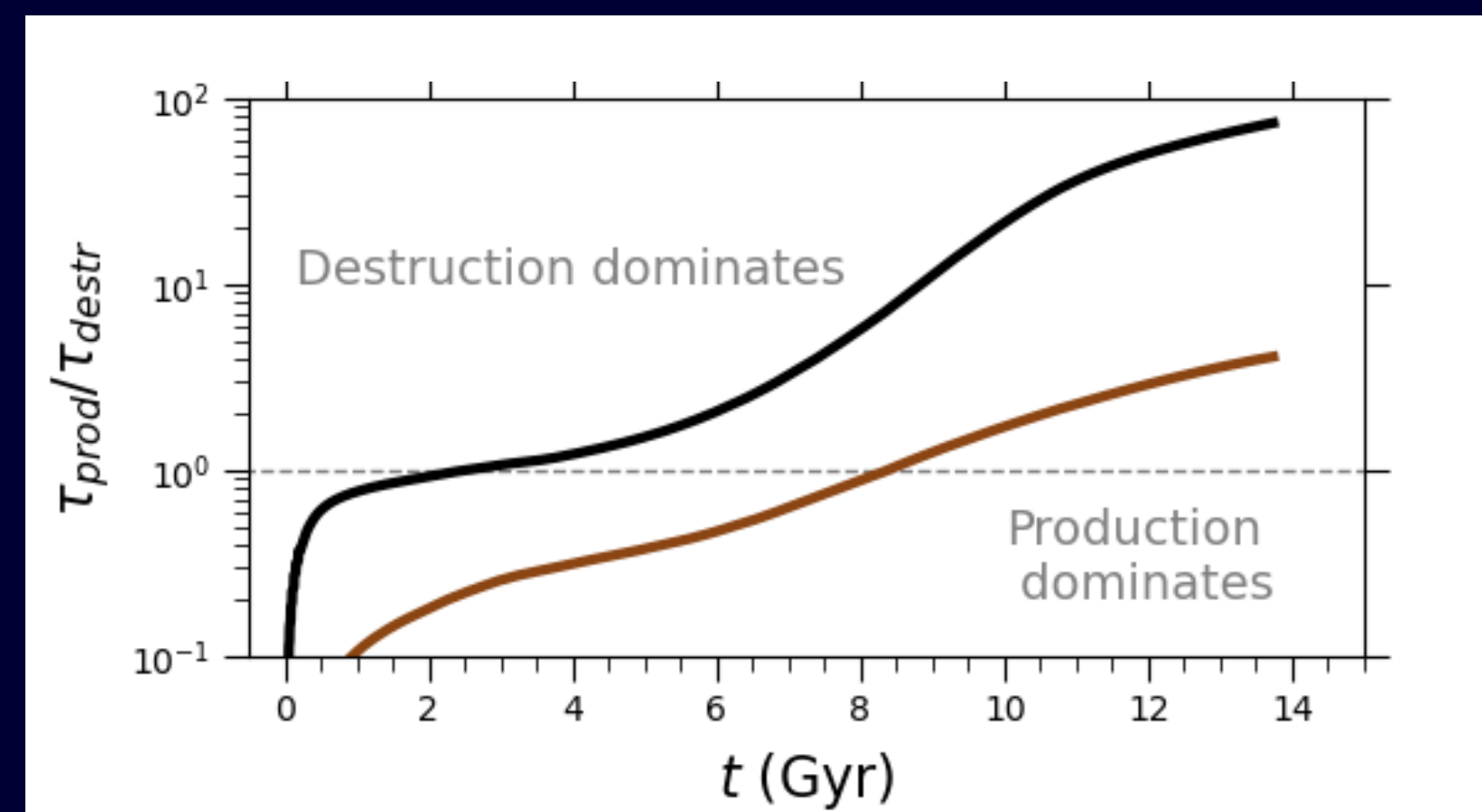
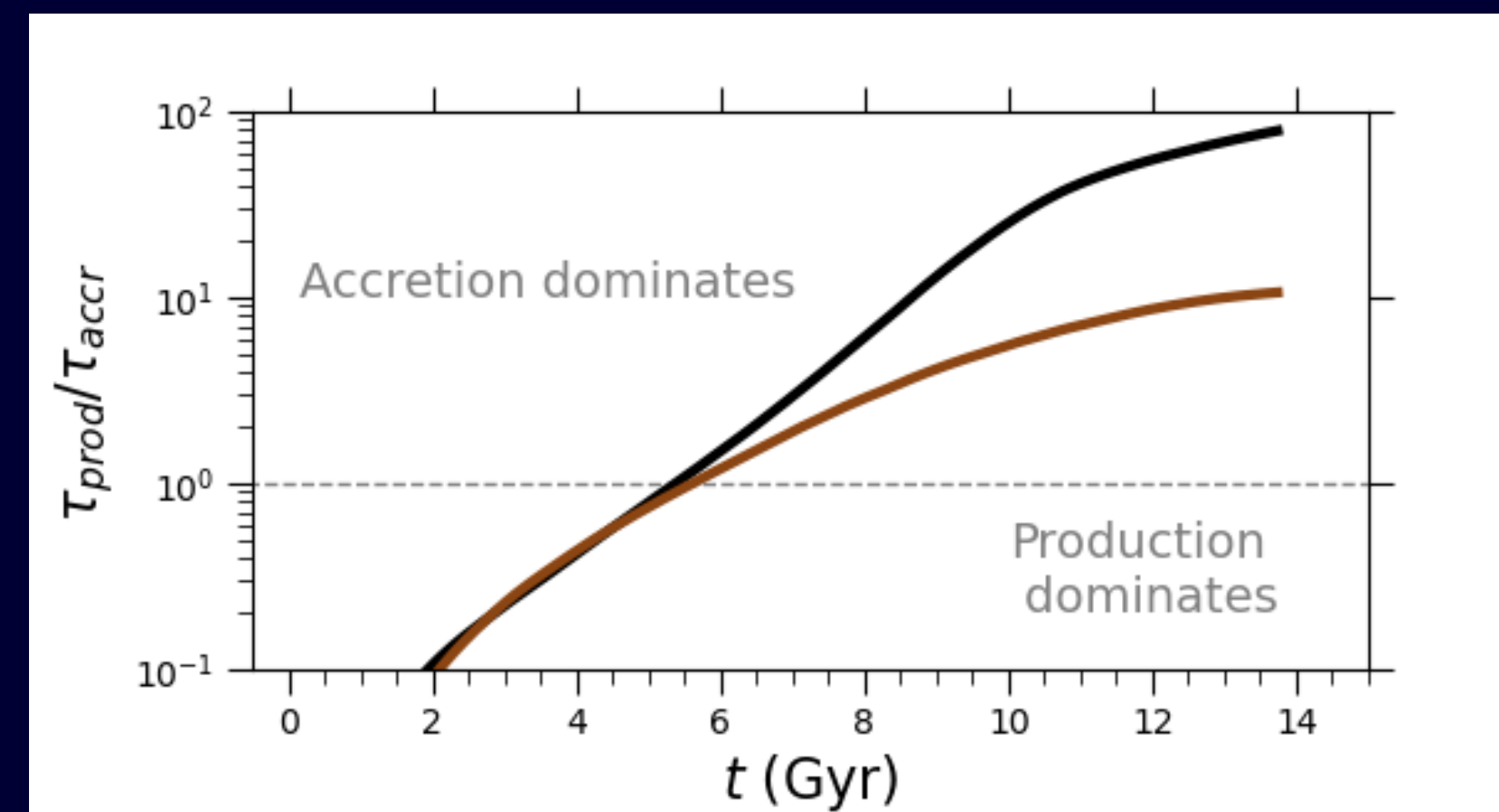
**MODEL 2** larger growth and destruction timescales

# Uncertainties on dust evolution

## THE ROLE OF DUST TIMESCALES

**MODEL 1** smaller growth and destruction timescales

**BALANCE** between  
**GROWTH** and **DESTRUCTION**



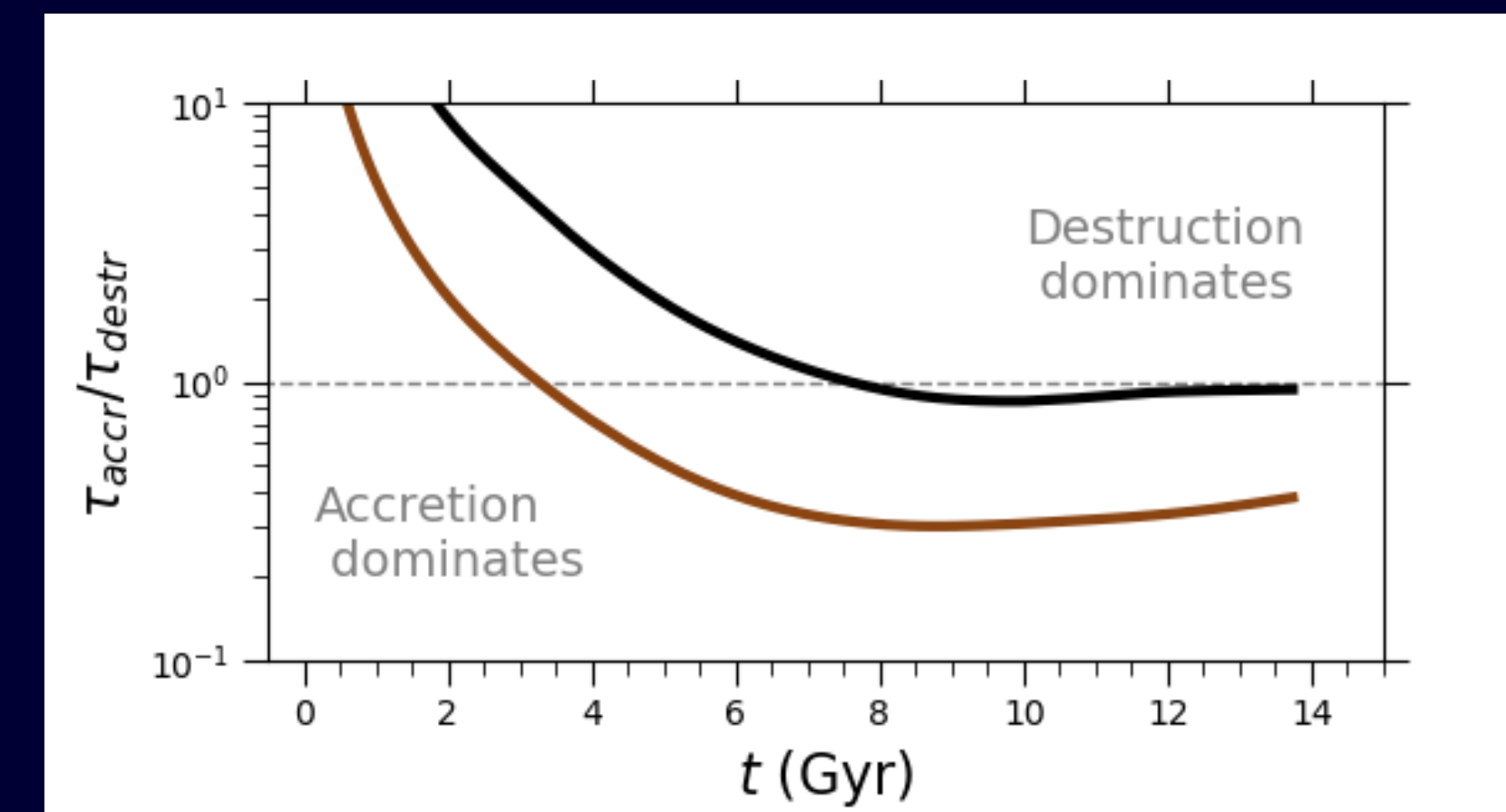
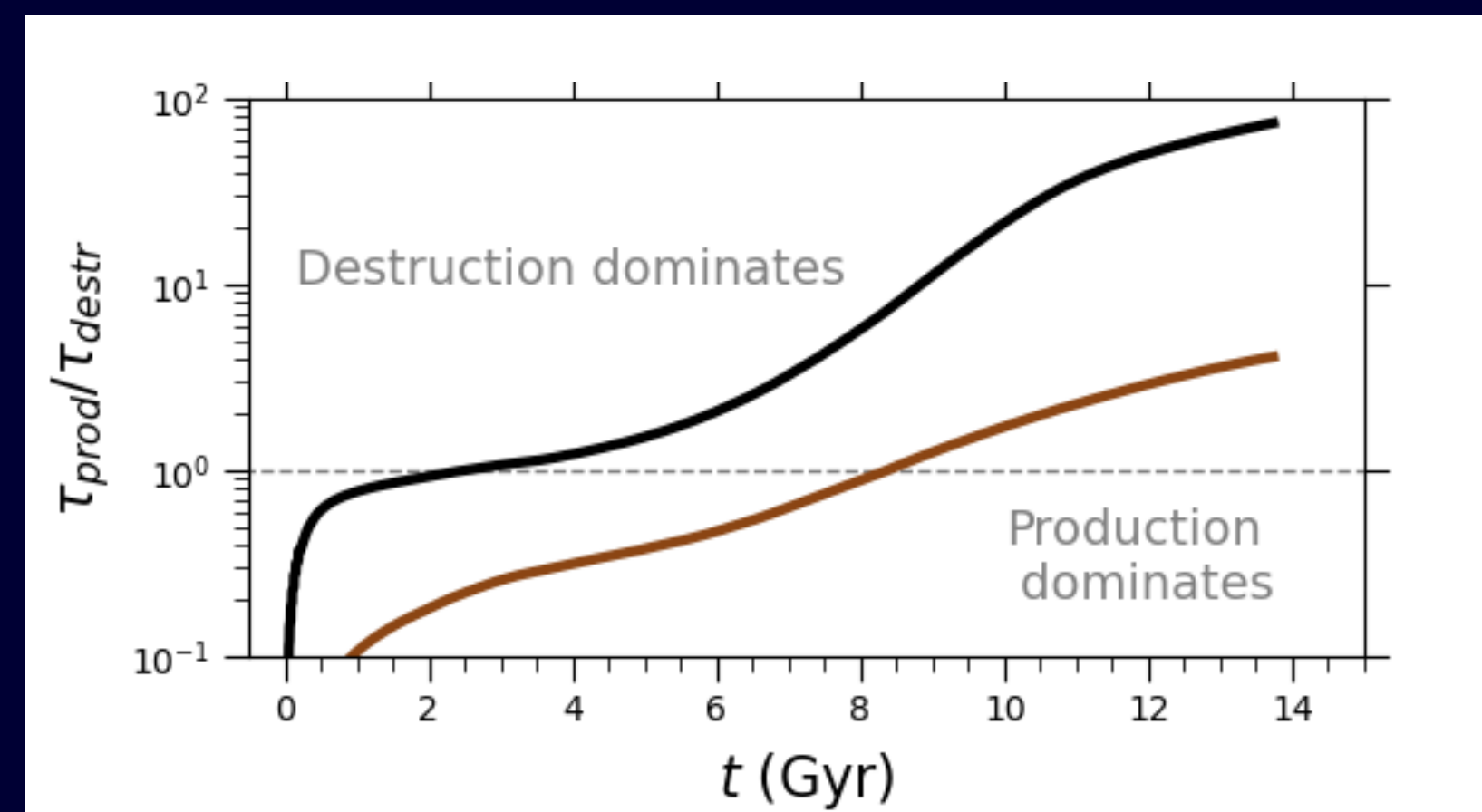
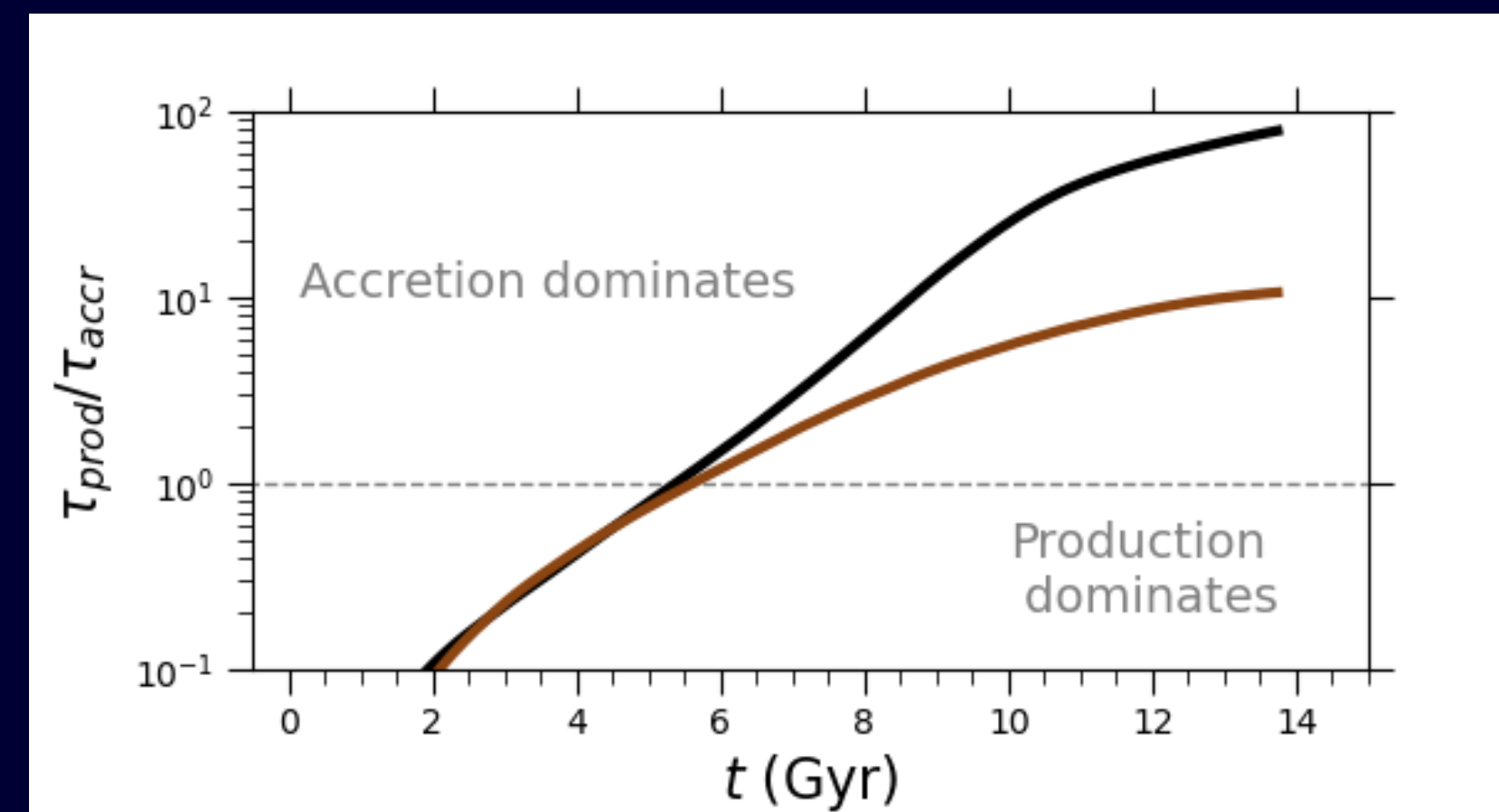
**MODEL 2** larger growth and destruction timescales

# Uncertainties on dust evolution

## THE ROLE OF DUST TIMESCALES

**MODEL 1** smaller growth and destruction timescales

**BALANCE** between  
**GROWTH** and **DESTRUCTION**



**PRODUCTION + GROWTH**  
always **DOMINATE**

**MODEL 2** larger growth and destruction timescales

---

# To take home ...

## Abundance gradients in the Galaxy

- Abundance gradients can be used as powerful keys to “unlock” the properties of the Galactic disc  
**But other observables also needed to break processes degeneracy !**
- evidences of **flat abundance gradients at large Galactocentric radii** from different tracers: change of view with several implications

## Dust in galaxies

- **dust evolution** critically **depends** on the **history of star formation** within its birth environment  
**Limits when locking dust to metallicity (and viceversa) evolution !**
- uncertainties on the **dust evolution modelling: degeneracy** between different **dust processes** (stardust production, dust growth, dust destruction)

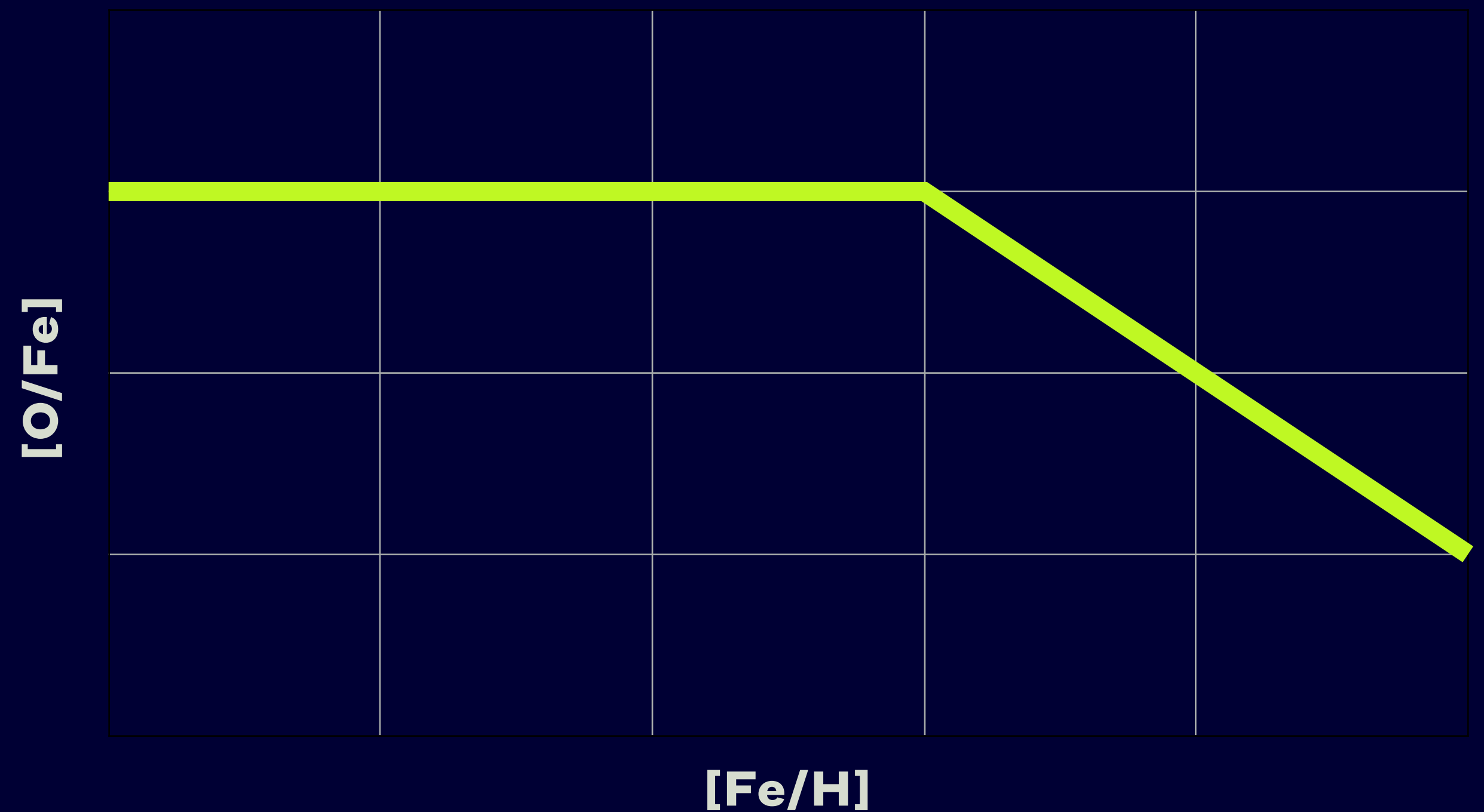


# Bonus

## TIME-DELAY MODEL

**DIFFERENT ROLE by  
DIFFERENT TYPE of STARS in  
CHEMICAL ENRICHMENT !**

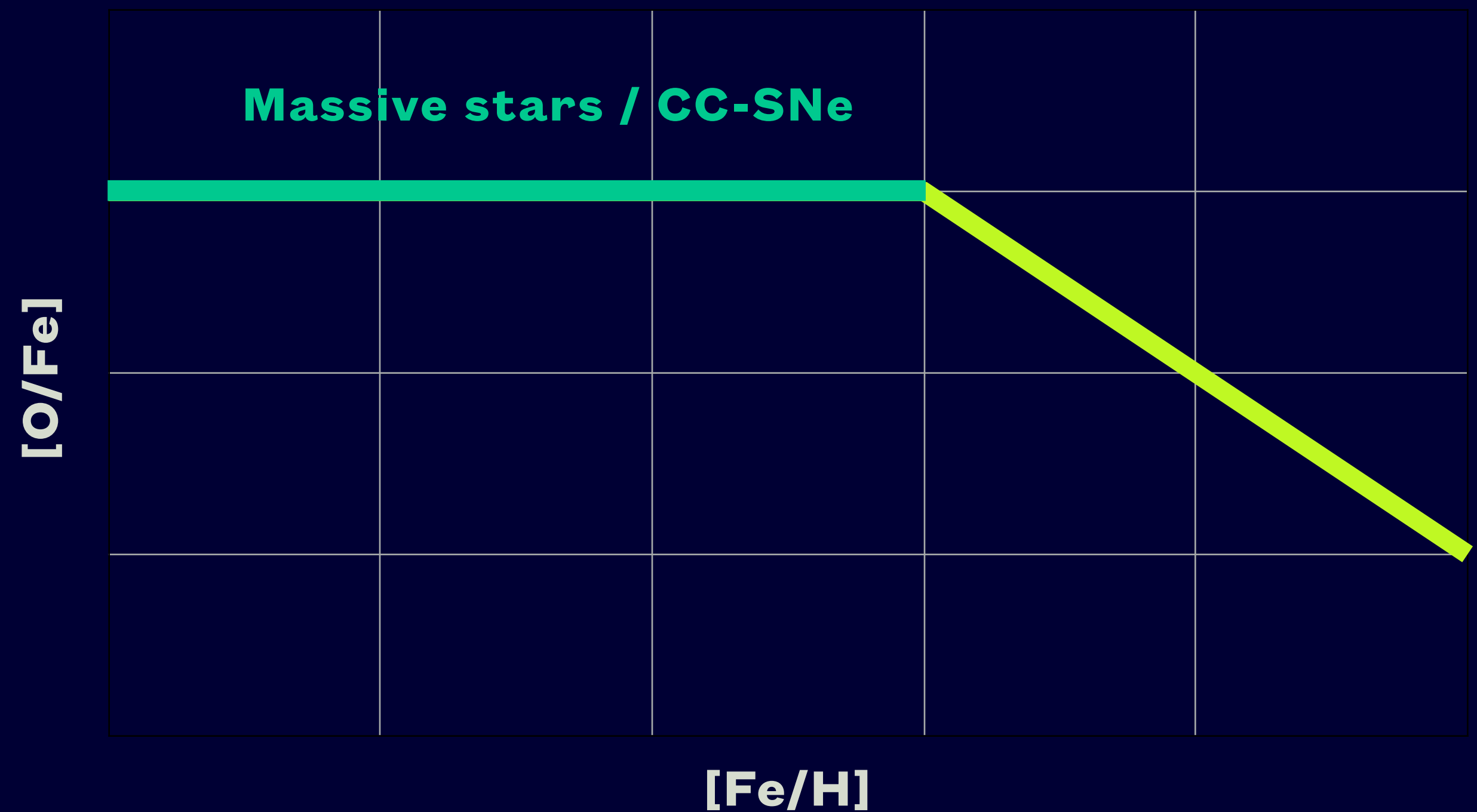
(e.g. Matteucci 01, 12, 21)



# Bonus

## TIME-DELAY MODEL

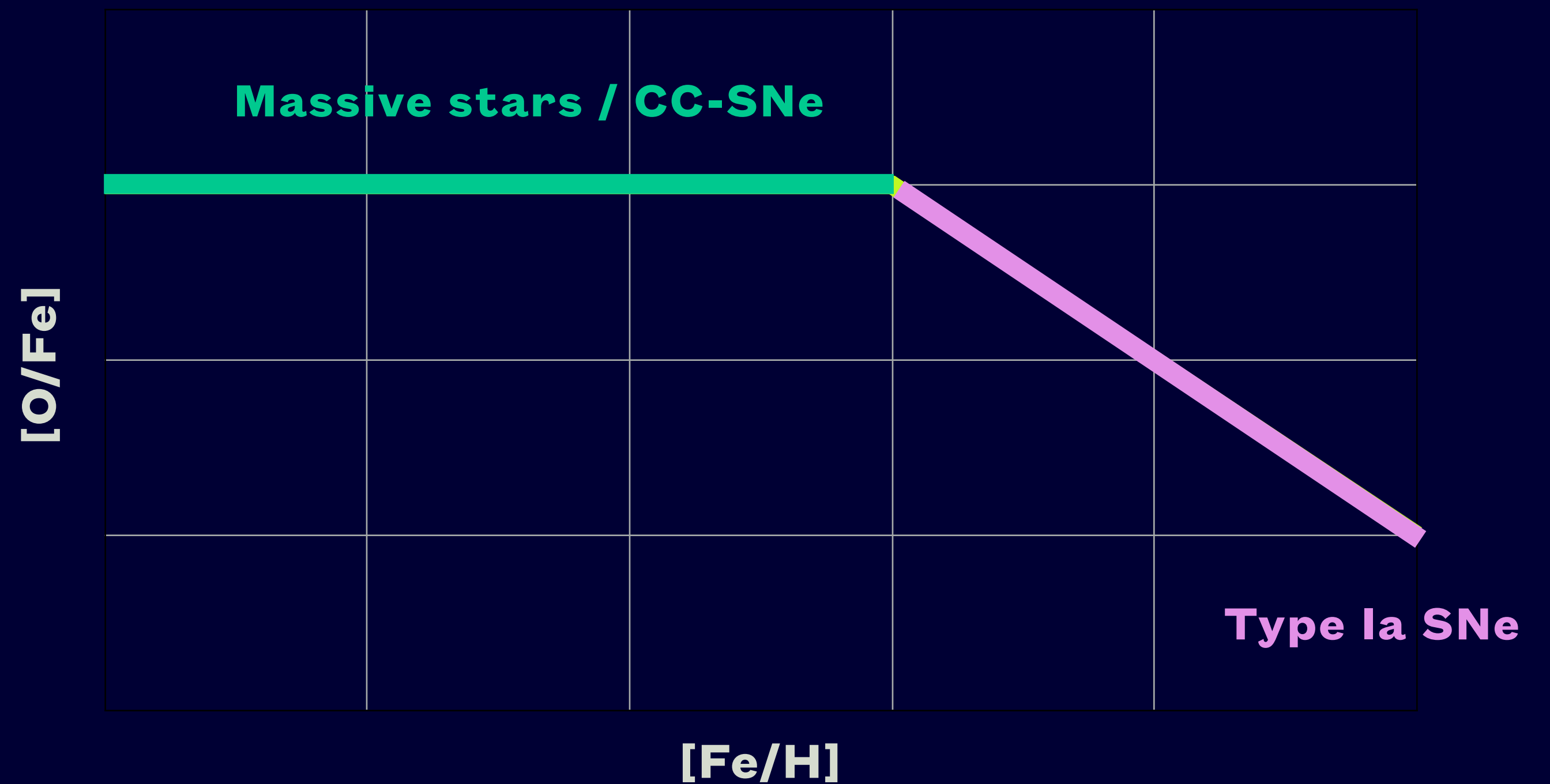
**DIFFERENT ROLE** by  
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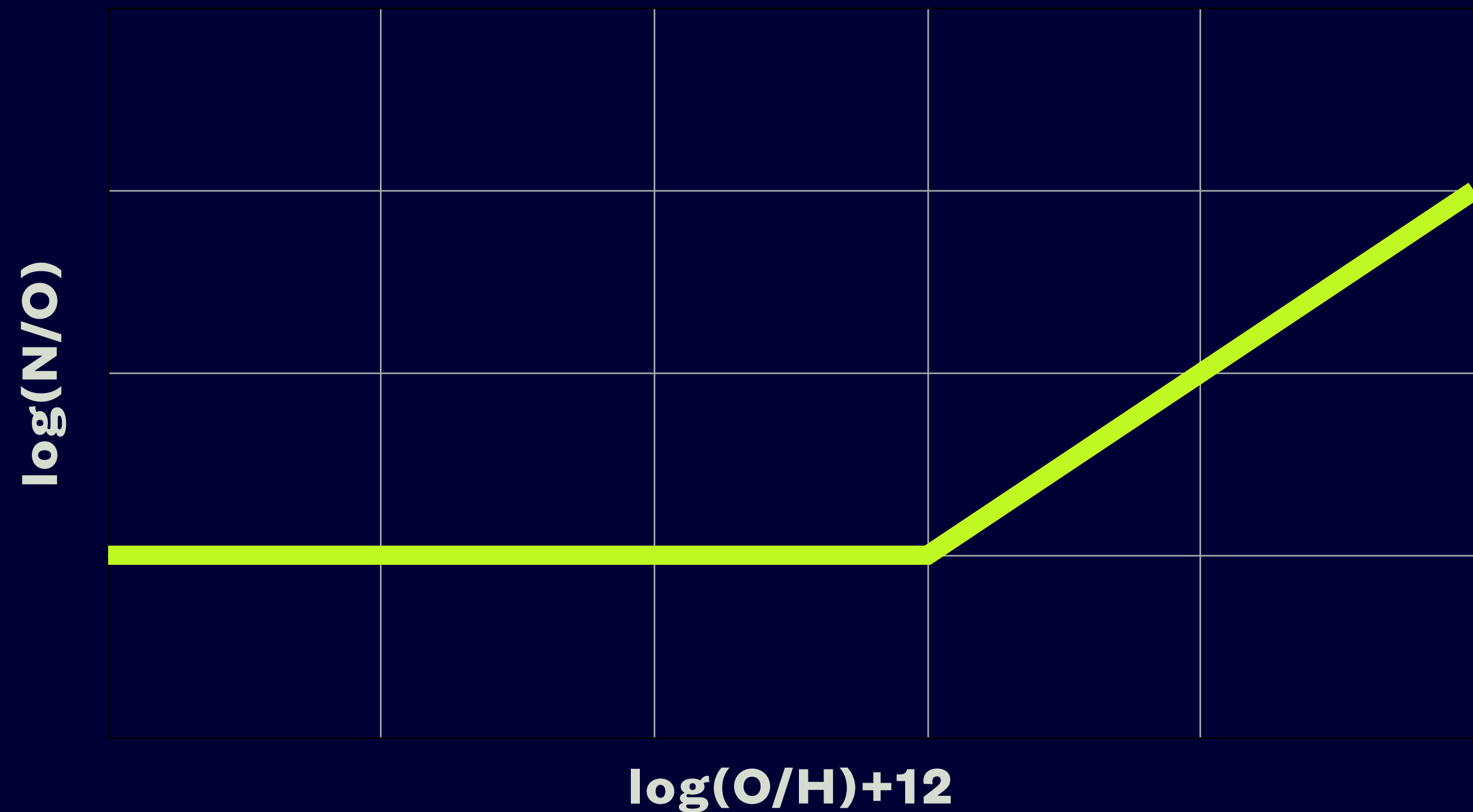
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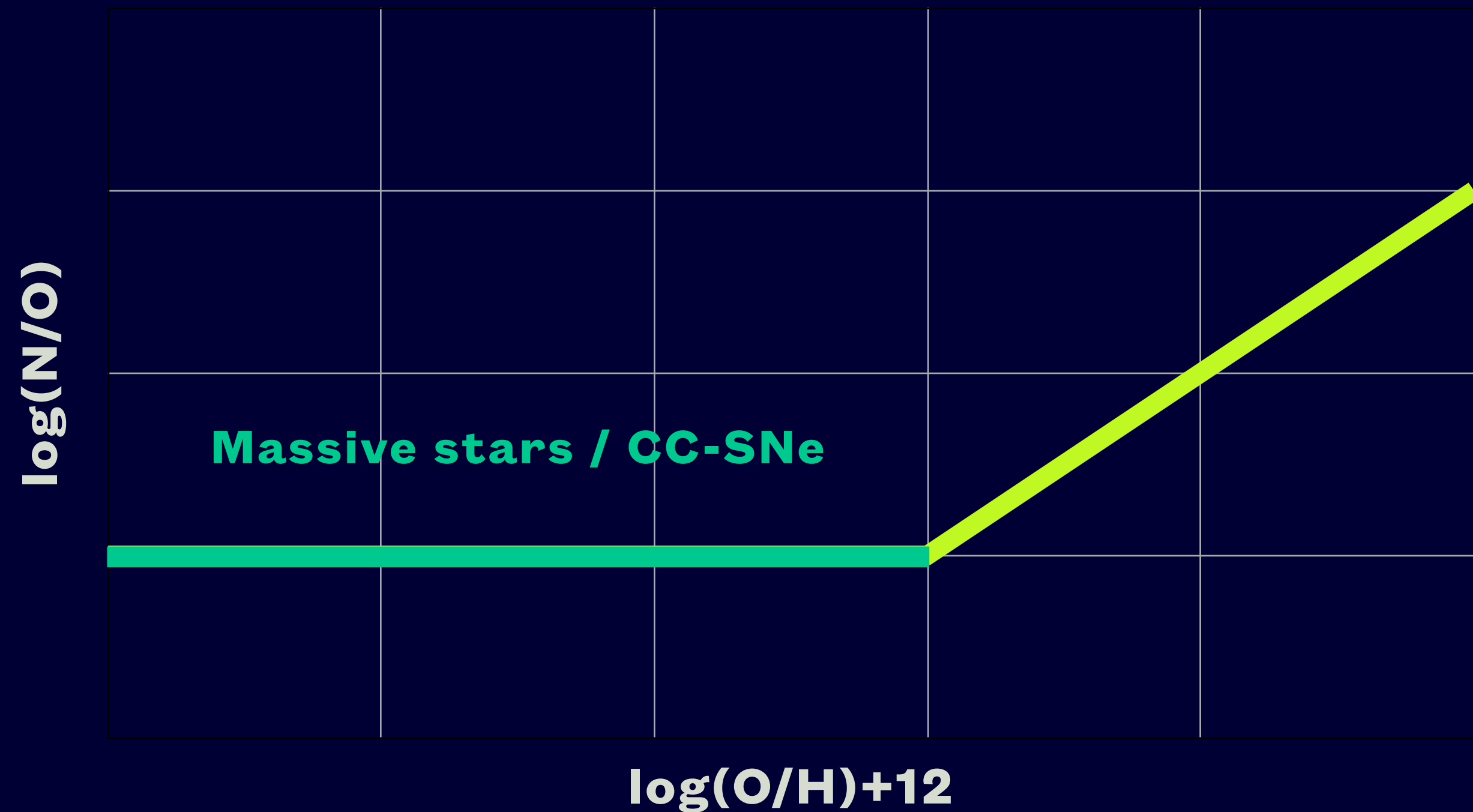


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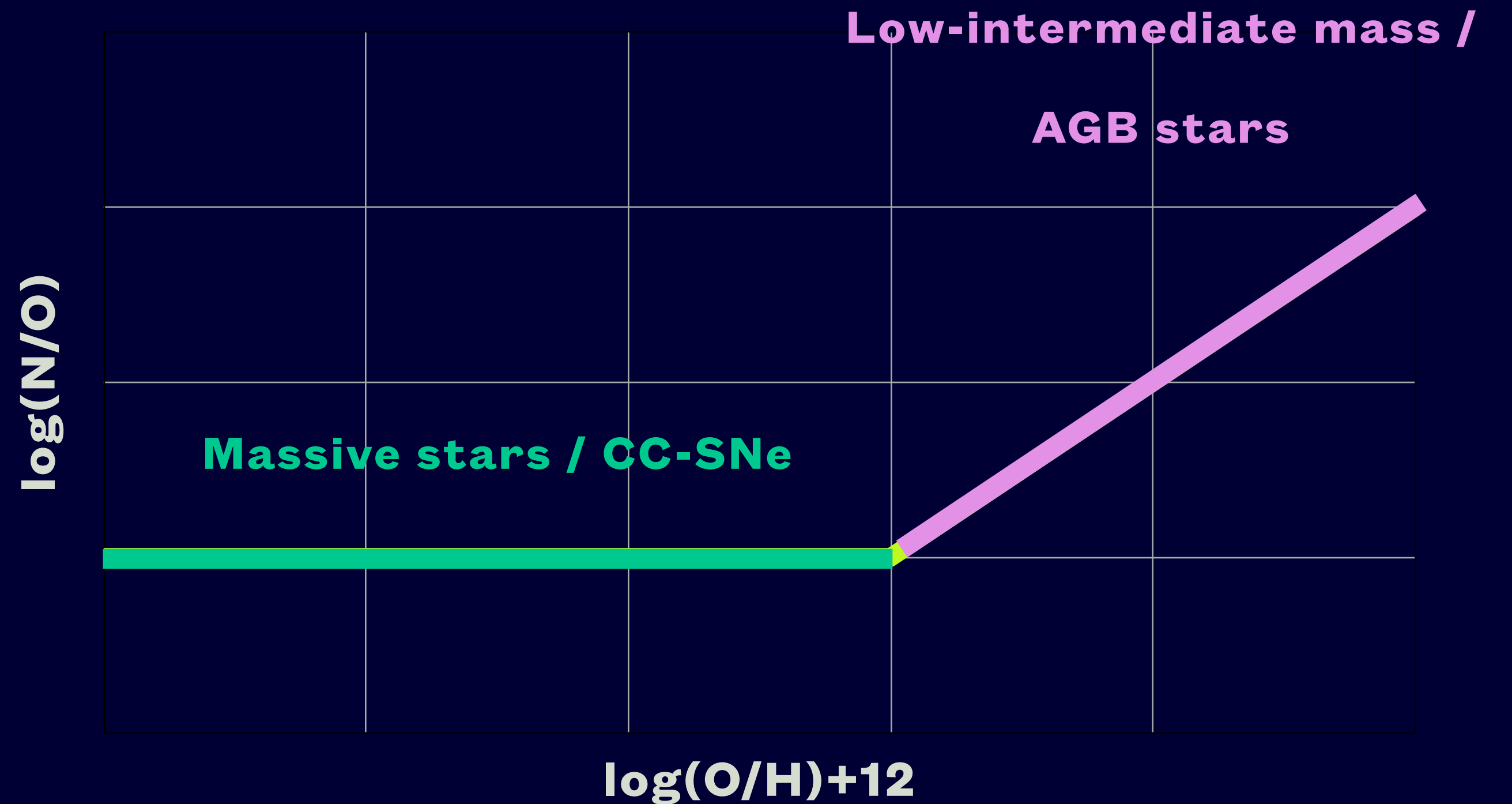
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# Bonus

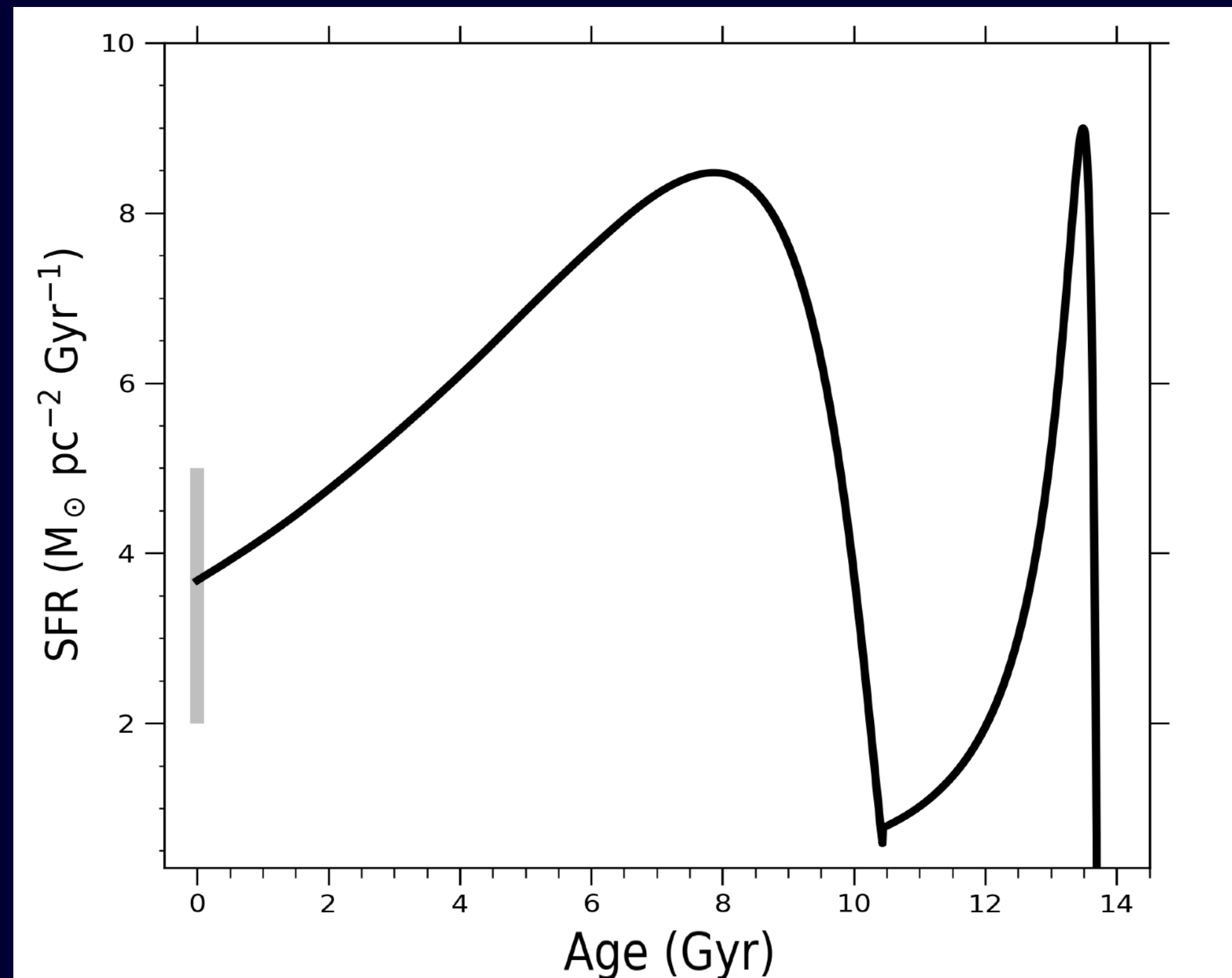
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(e.g. Matteucci 01, 12, 21)



# Bonus

## REVISED TWO-INFALL MODEL

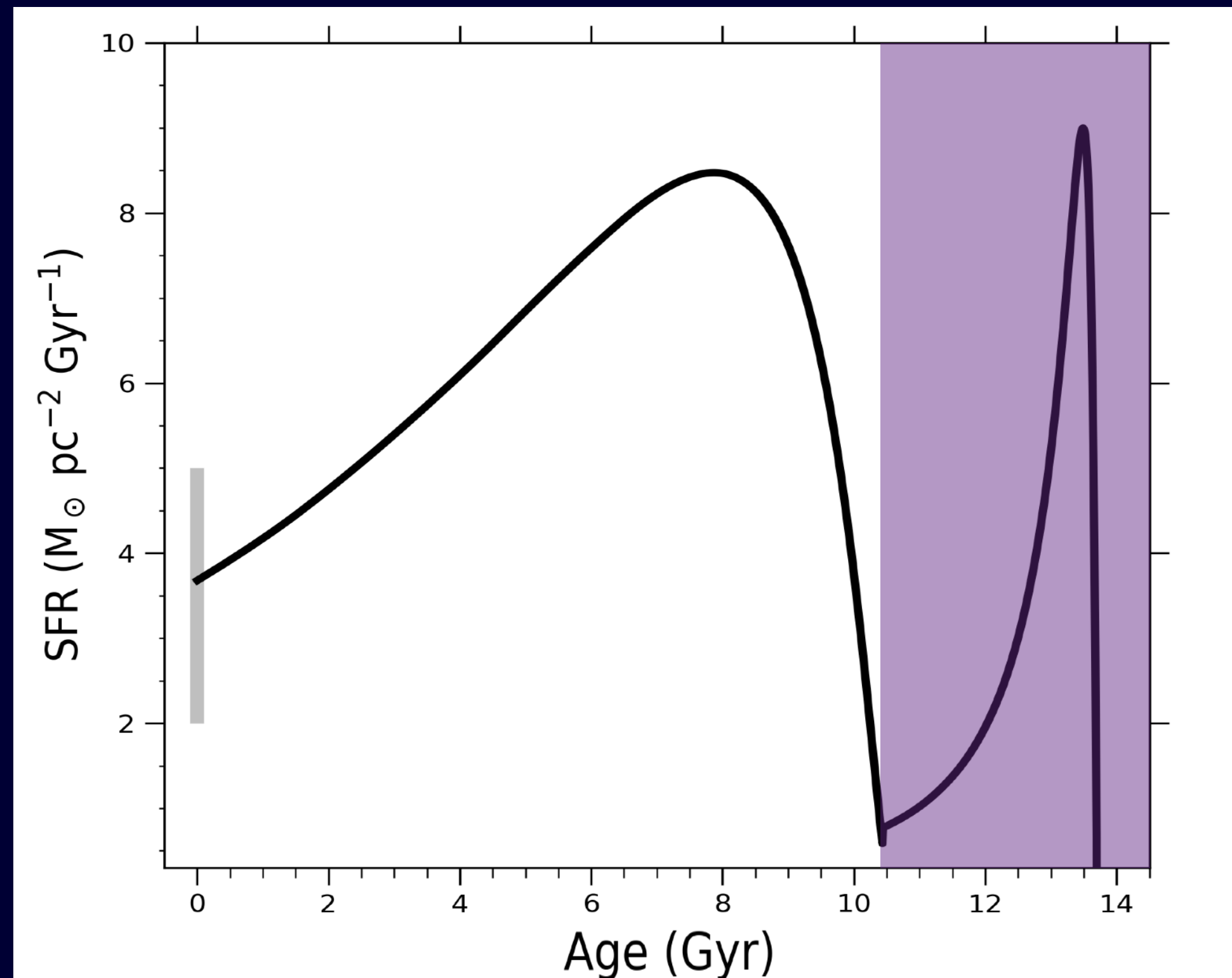


INSIDE - OUT

$$\dot{\Sigma}_{i,inf} = X_{inf} [ A e^{-t/\tau_1} + \theta(t - t_{max}) B e^{-(t-t_{max})/\tau_2} ]$$

# Bonus

## REVISED TWO-INFALL MODEL



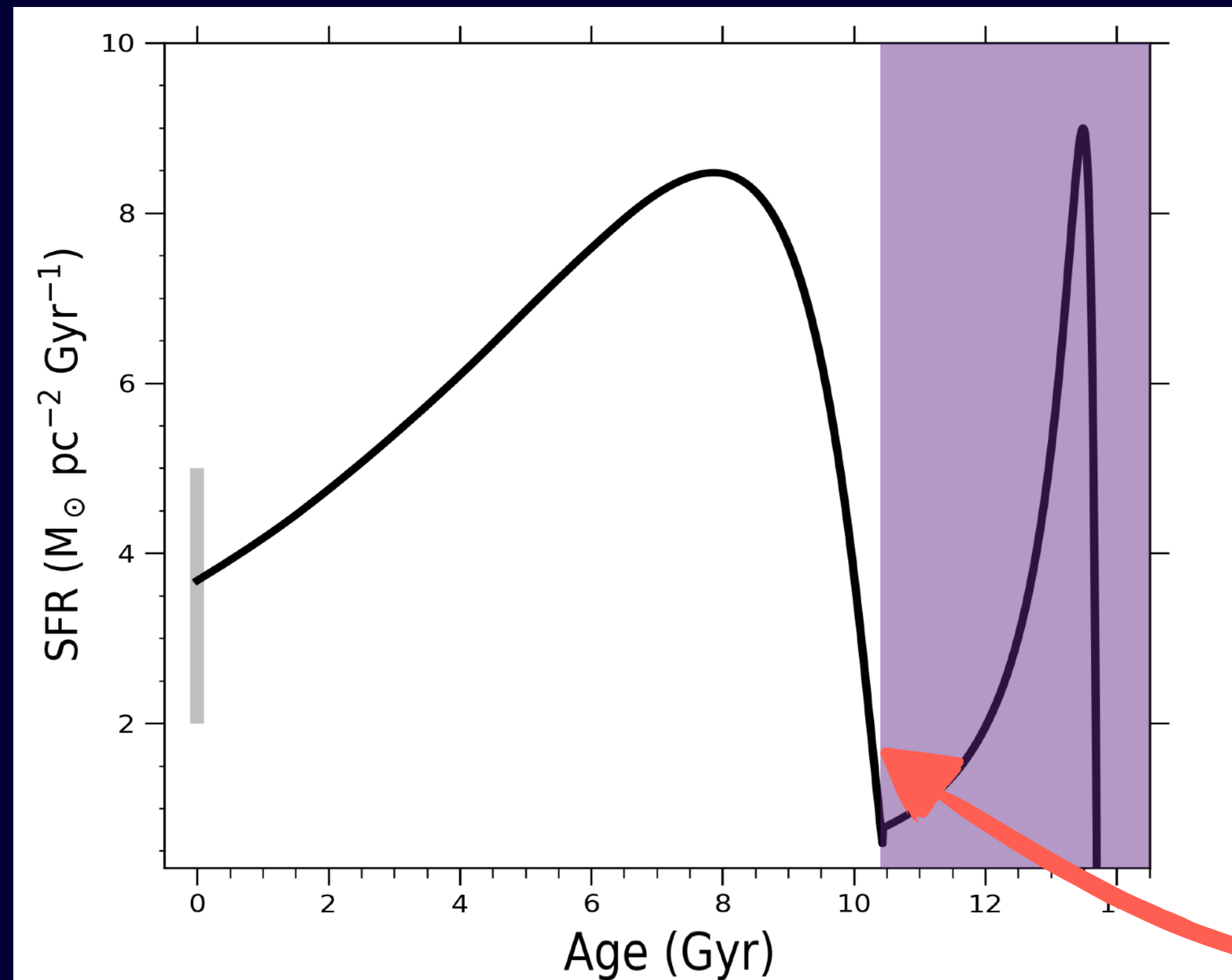
INSIDE - OUT

$$\dot{\Sigma}_{i,inf} = X_{inf} [ A e^{-t/\tau_1} + \theta(t - t_{max}) B e^{-(t-t_{max})/\tau_2} ]$$



# Bonus

## REVISED TWO-INFALL MODEL



(at variance with  
Chiappini+97,  
Romano+10,  
Grisoni+18)

INSIDE - OUT

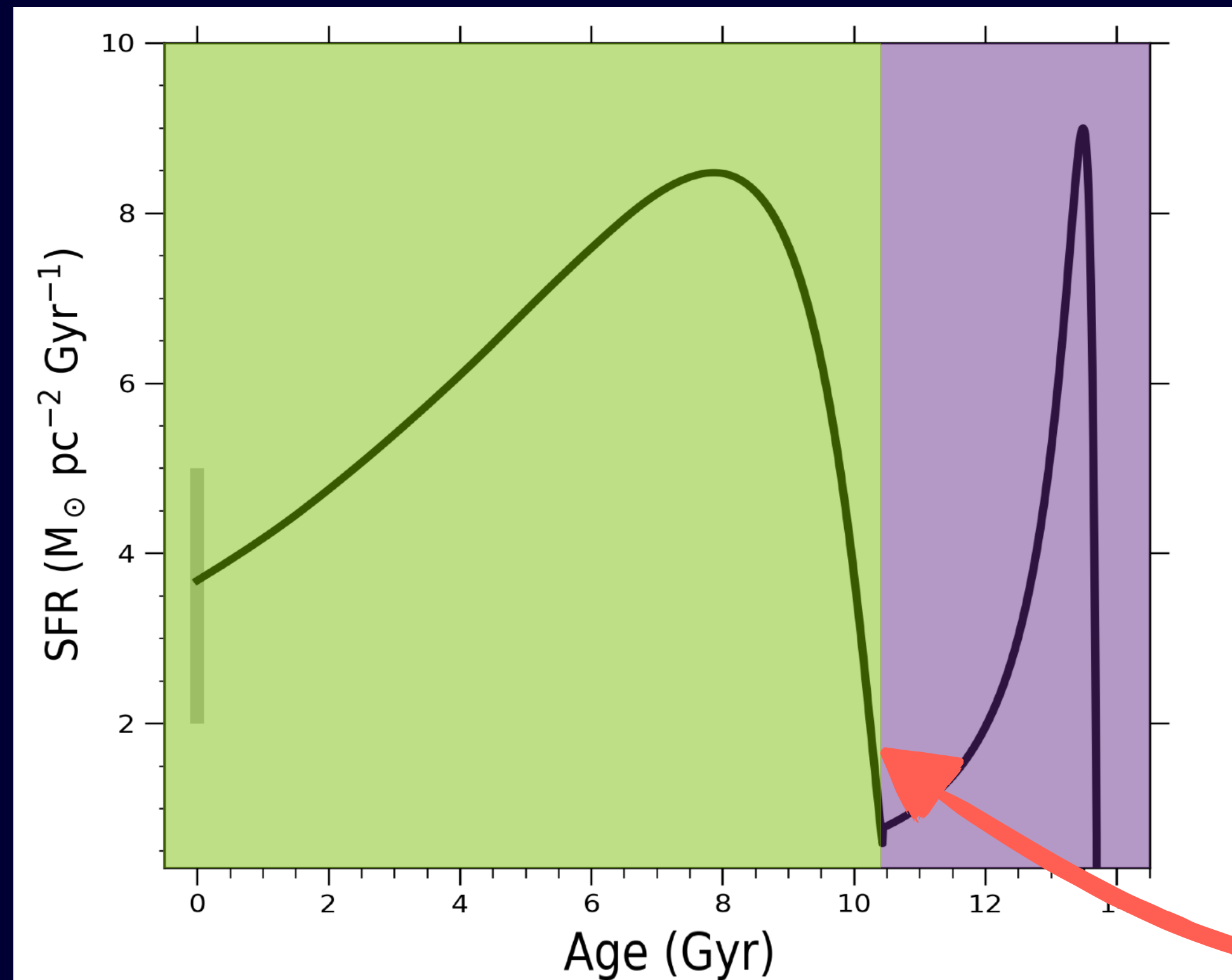
**SPITONI+19:**

$t_{max} > 3 \text{ Gyr}$

$$\dot{\Sigma}_{i,inf} = X_{inf} [ A e^{-t/\tau_1} + \theta(t - t_{max}) B e^{-(t-t_{max})/\tau_2} ]$$

# Bonus

## REVISED TWO-INFALL MODEL



(at variance with  
Chiappini+97,  
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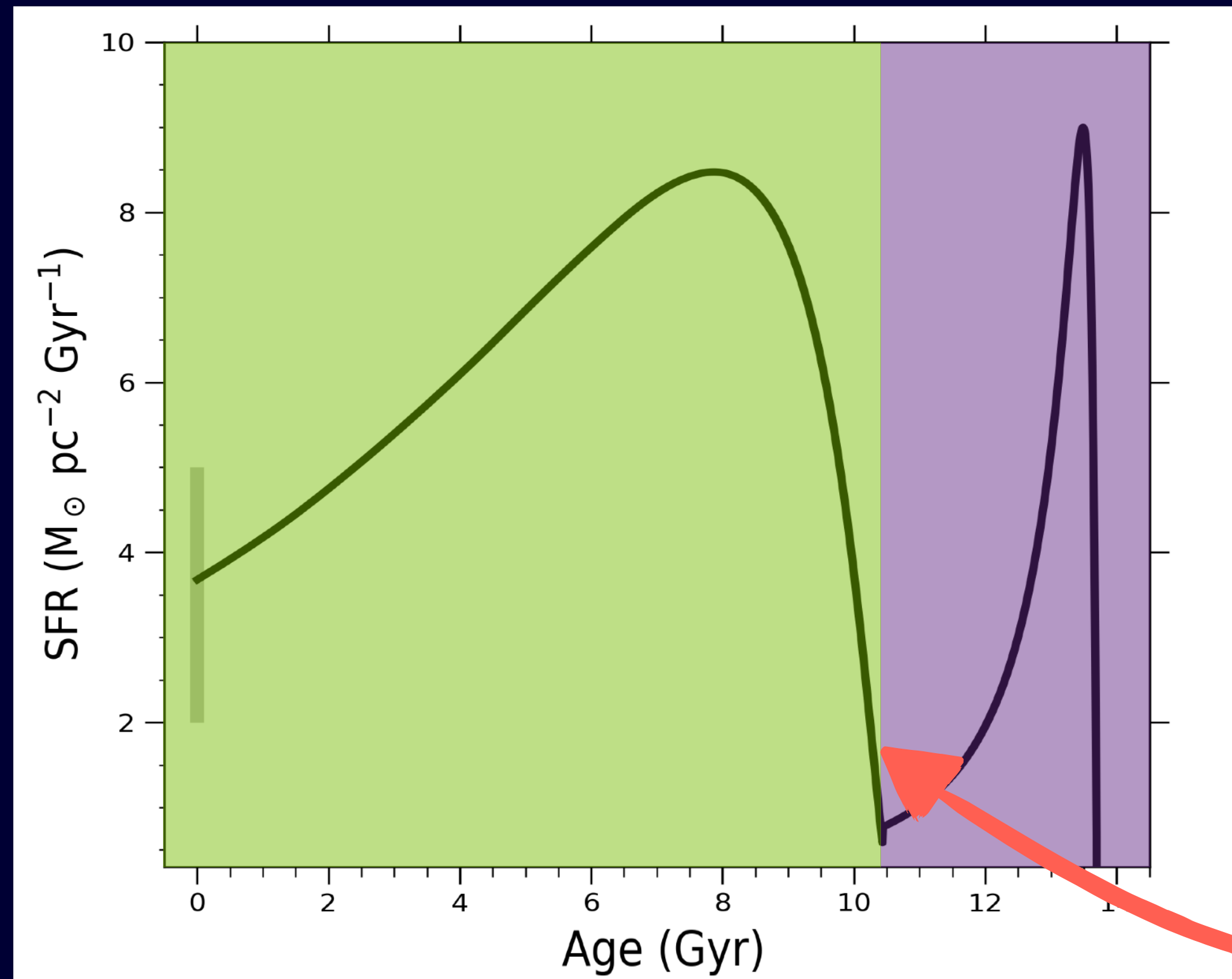
$t_{max} > 3$  Gyr

INSIDE - OUT

$$\dot{\Sigma}_{i,inf} = X_{inf} \left[ A e^{-t/\tau_1} + \theta(t - t_{max}) B e^{-(t-t_{max})/\tau_2} \right]$$

# Bonus

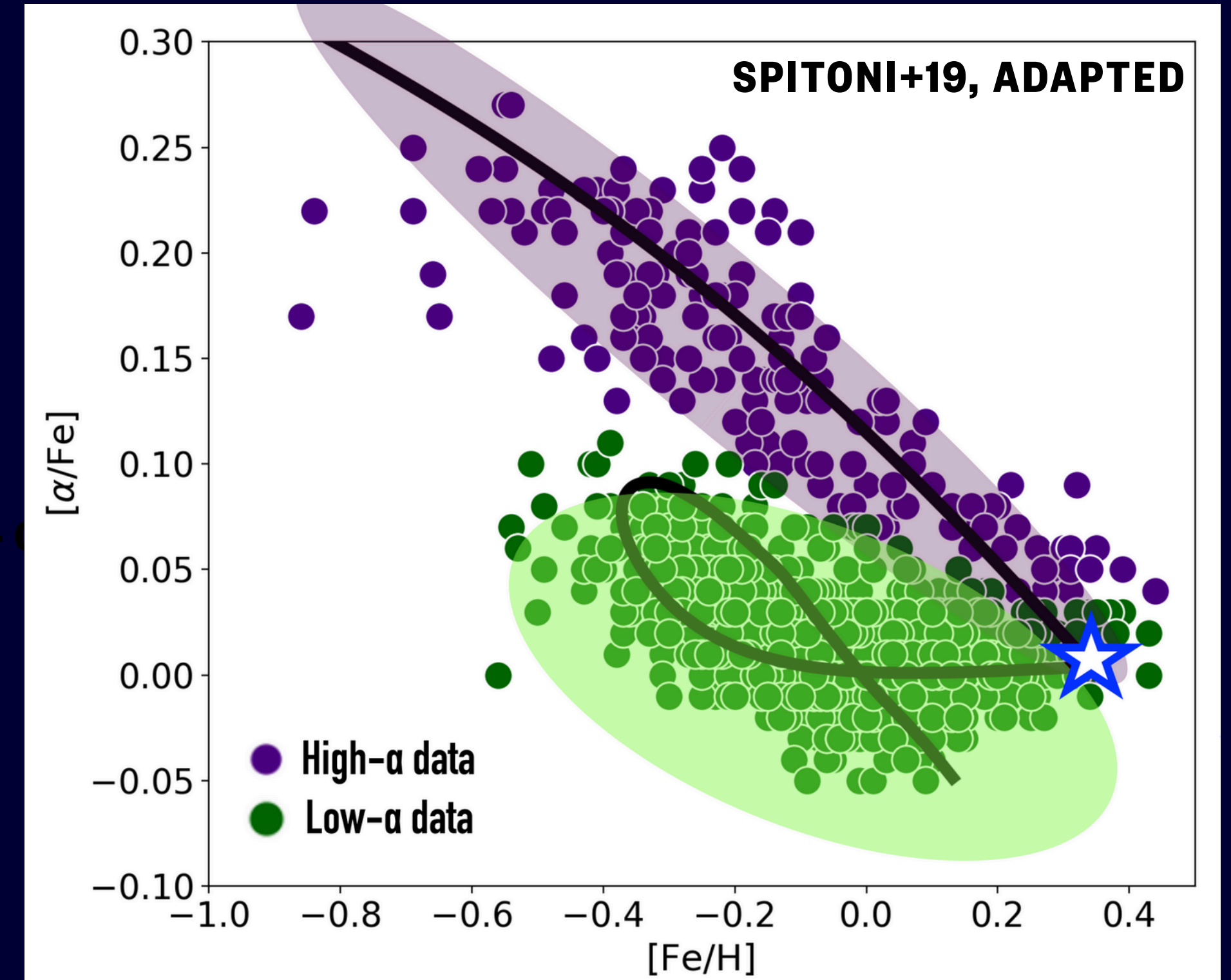
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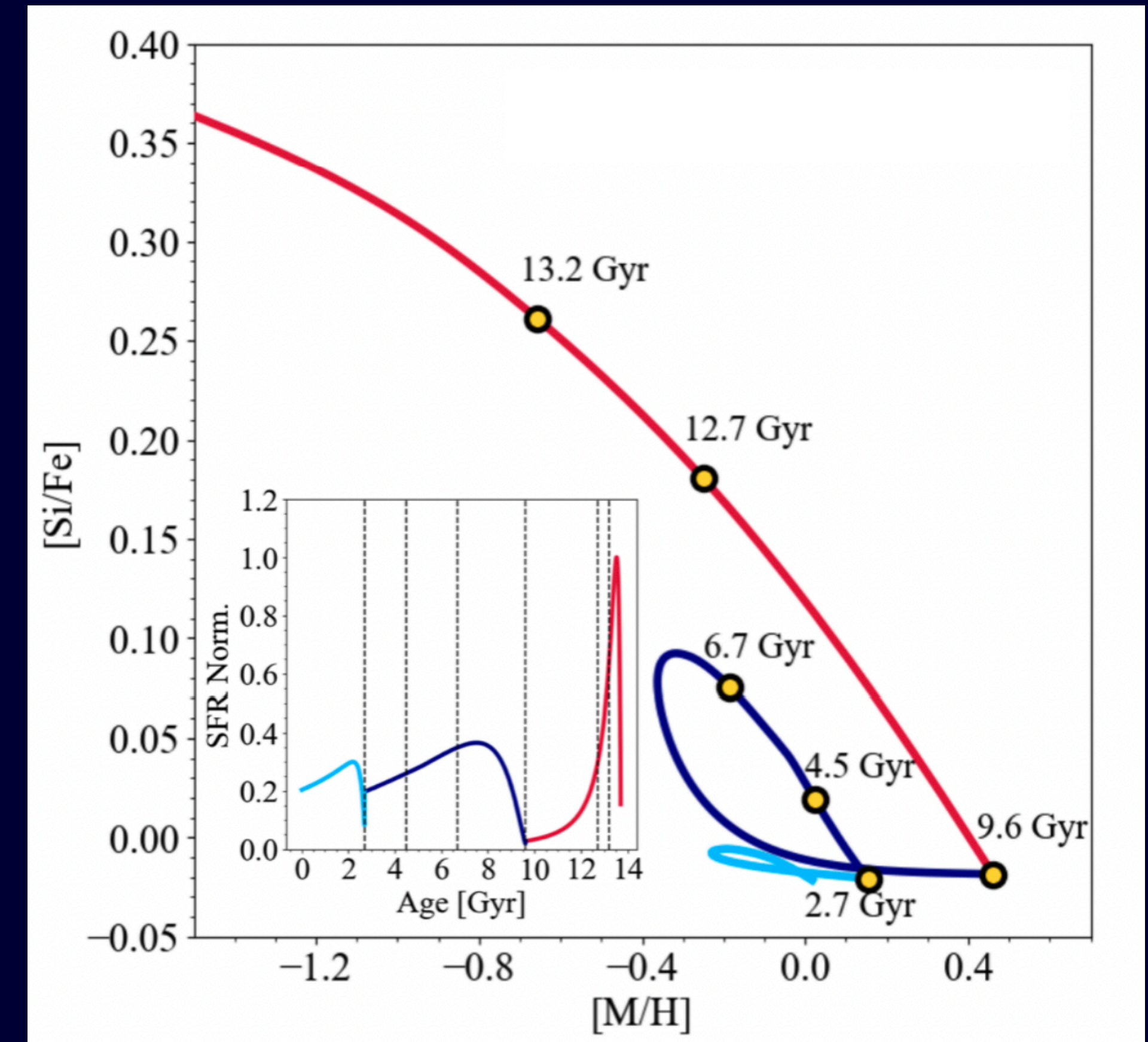
$t_{max} > 3 \text{ Gyr}$



# Bonus

## THREE-INFALL MODEL

- SFH in the solar vicinity from Gaia CMD (and not only!): **peak(s) in SFR in the last 2-3 Gyr** (e.g. Ruiz-Lara+20, Nepal+24)
- Relatively **metal-poor young, massive stars** the low- $\alpha$  disc (e.g. Recio-Blanco+23)

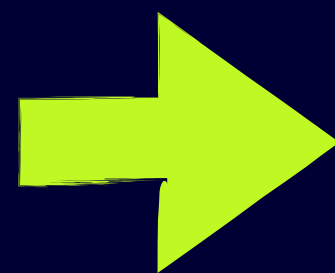


# Bonus

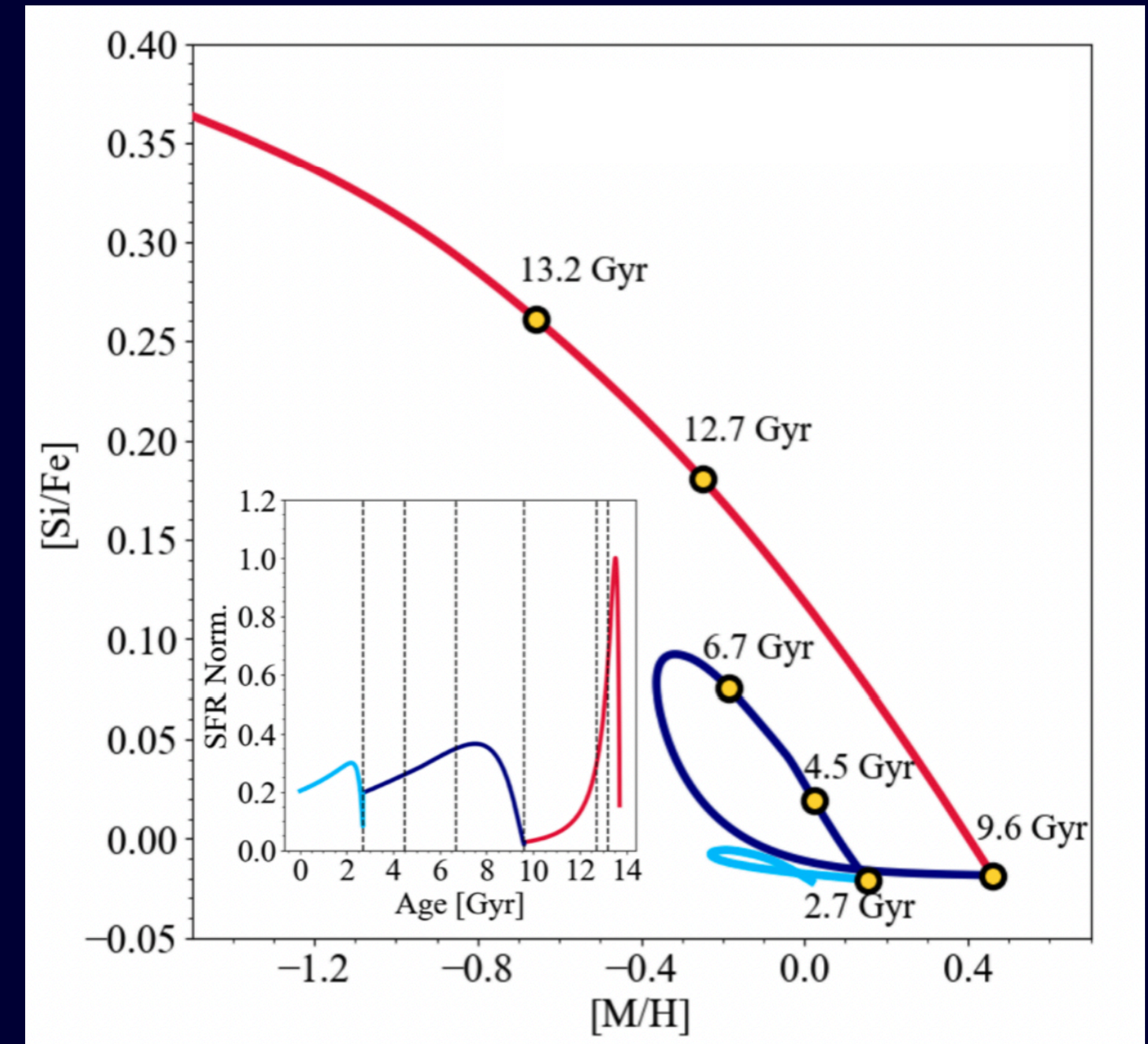
## THREE-INFALL MODEL

- SFH in the solar vicinity from Gaia CMD (and not only!): **peak(s) in SFR in the last 2-3 Gyr** (e.g. Ruiz-Lara+20, Nepal+24)
- Relatively **metal-poor young, massive stars** in the low- $\alpha$  disc (e.g. Recio-Blanco+23)

**BURST IN SF  
TRIGGERED BY  
FRESH GAS**

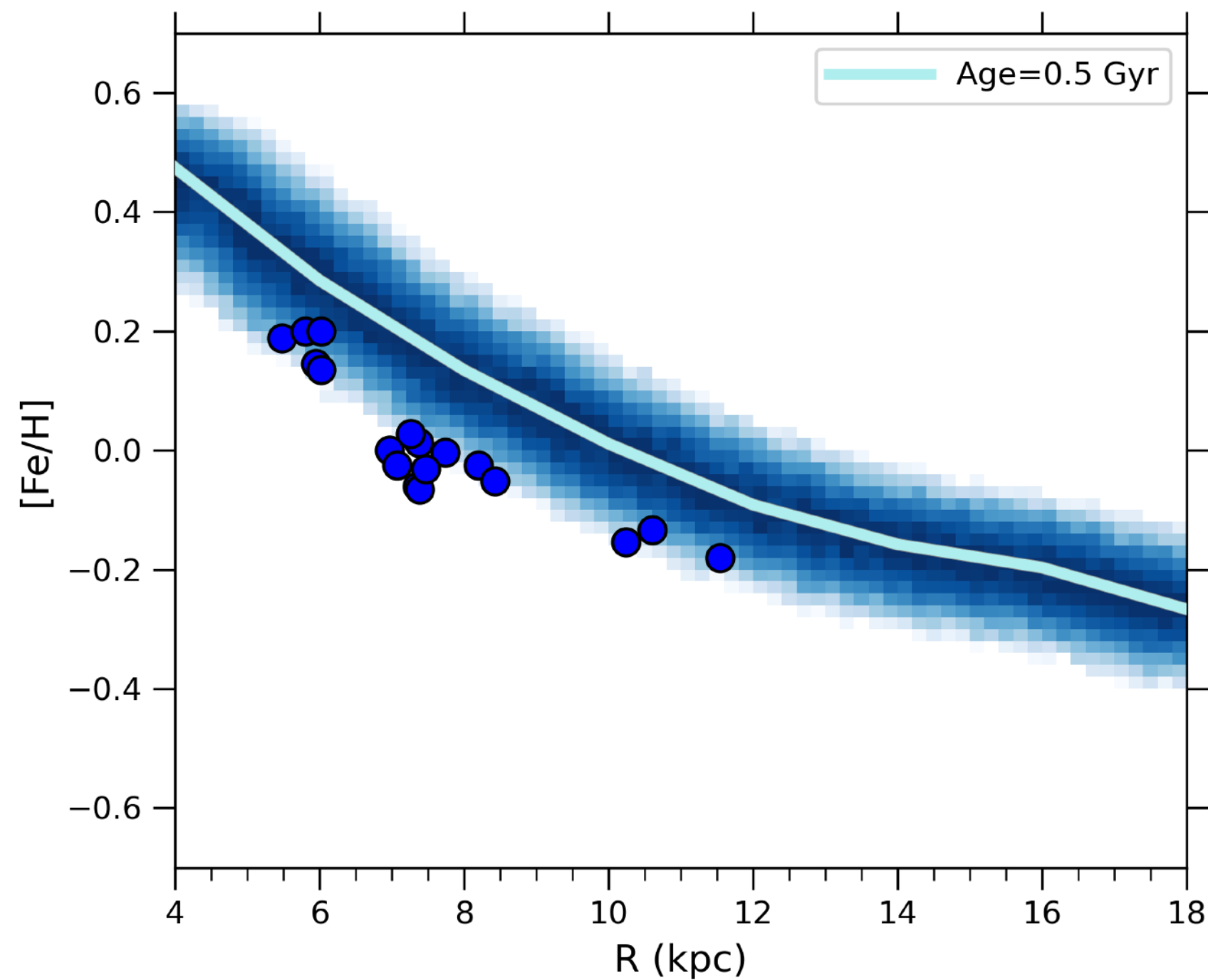


**METAL  
DILUTION**

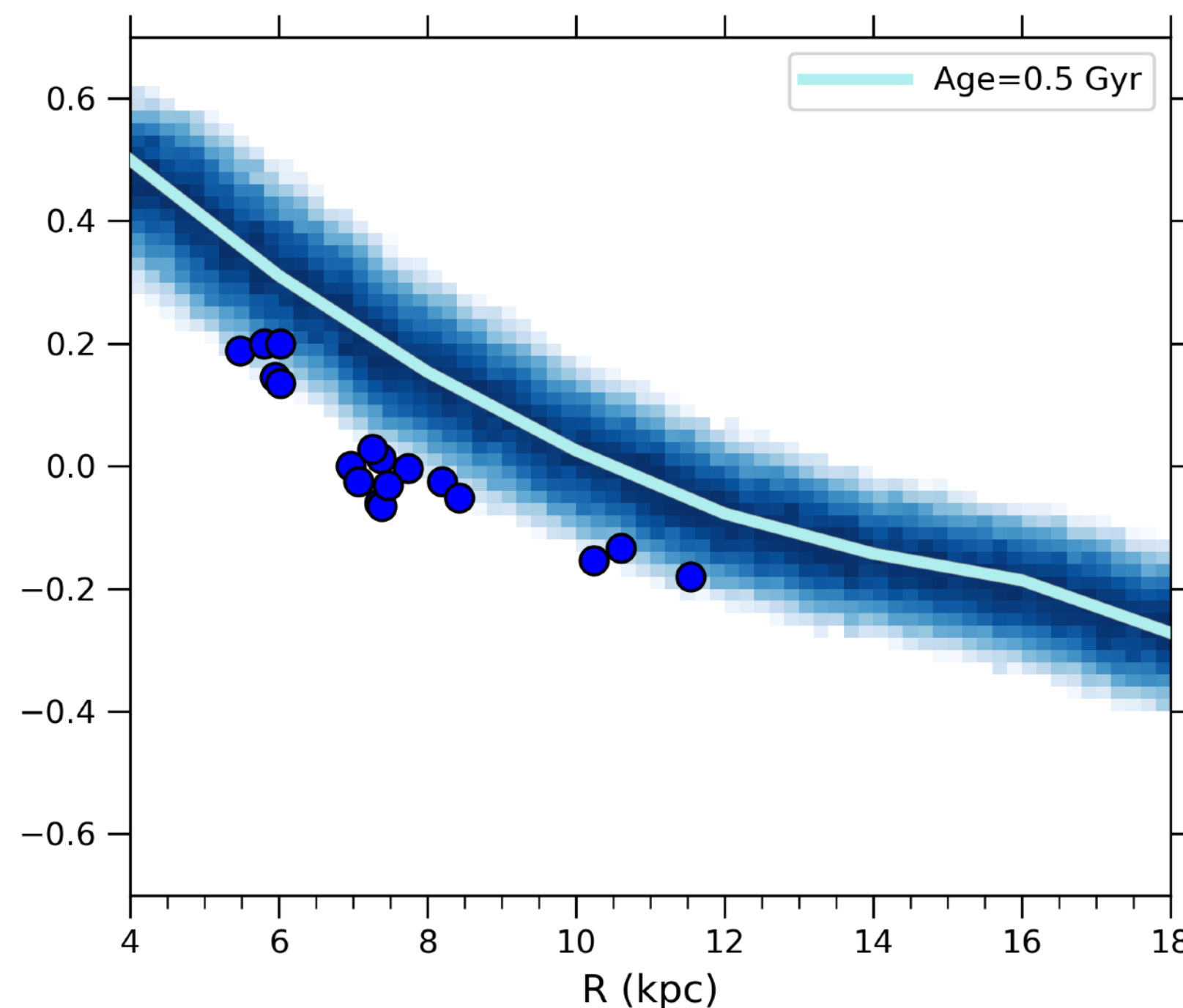


# Bonus

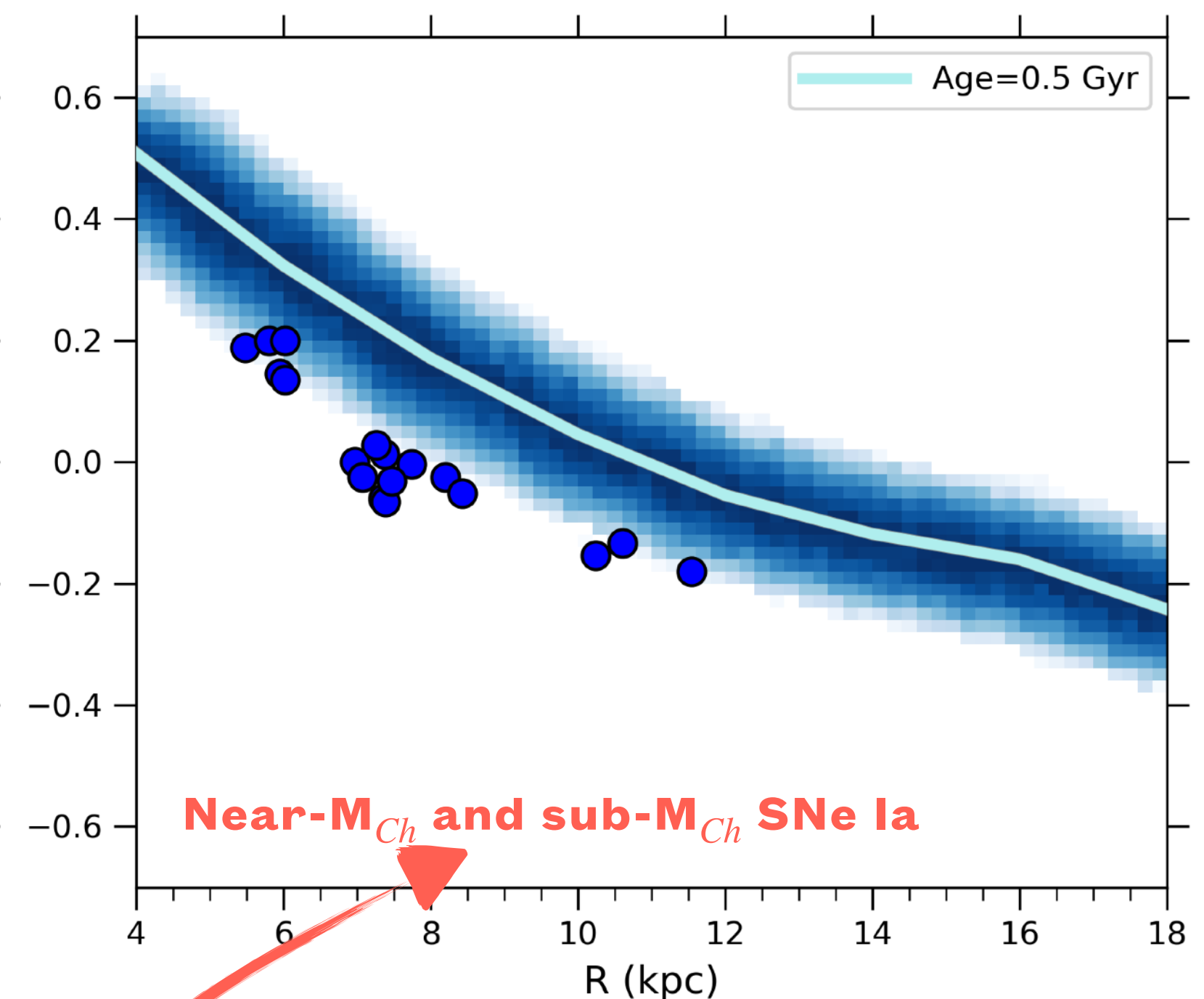
## THREE-INFALL MODEL - NEED FOR METAL DILUTION



Limongi & Chieffi 18  
Iwamoto+99



Kobayashi+11  
Iwamoto+99



Limongi & Chieffi 18  
Leung & Nomoto 18, 20

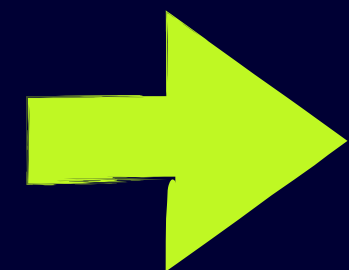
# Bonus

\* DtM = dust-to-metal ratio

## DUST EVOLUTION EQUATION

$$\dot{M}_{d,i} = -\psi(t) X_{d,i} + \int_{m(t)}^{m_{max}} \delta_i Q_{mi}(t - \tau_m) \psi(t - \tau_m) \phi(m) dm + \frac{M_{d,i}}{\tau_{grow}} - \frac{M_{d,i}}{\tau_{destr}} + \dot{M}_{d,i,flows}$$

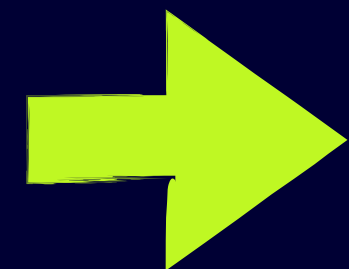
- **Dust production**



yields from stellar models

(CC-SNe: Bianchi & Schneider 07; Marassi+19  
AGB: Nanni+13,+14; Dell'Agli+17, Ventura+18,+20,+21)

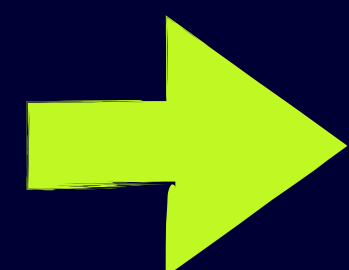
- **Dust growth**



$$\tau_{grow} \propto Z^{-1} (1 - \text{DtM}^*)^{-1}$$

(e.g. Dwek+98; Hirashita+00; Mattson+12; Asano+13)

- **Dust destruction**



$$\tau_{destr} \propto (\text{SN}_{rate})^{-1}$$

(e.g. McKee+89; Jones+94 Asano+13, Priestley+22)

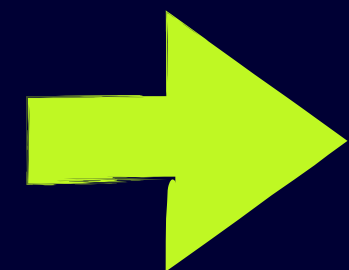
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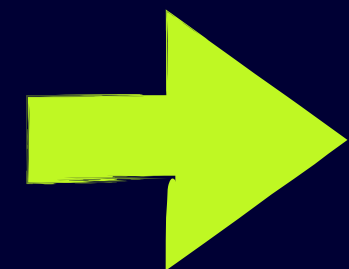
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- **Dust production**



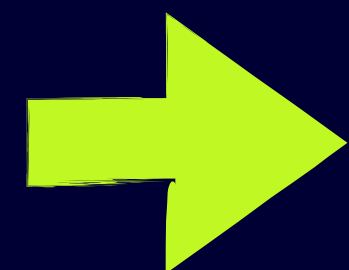
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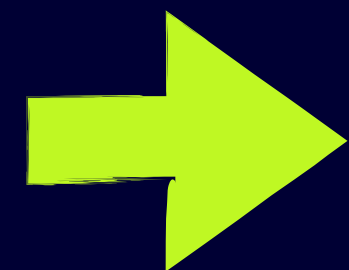
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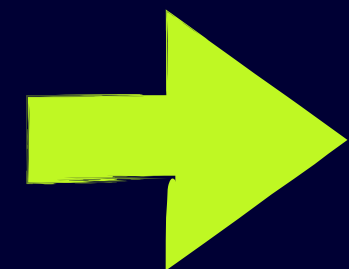
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- **Dust production**



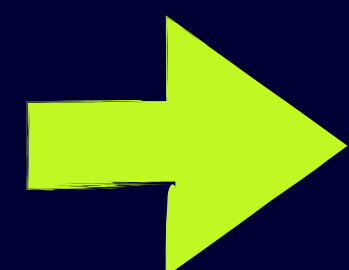
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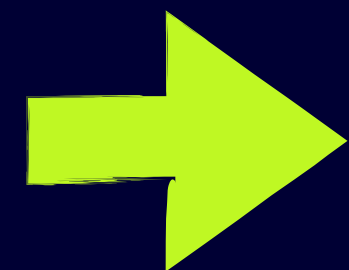
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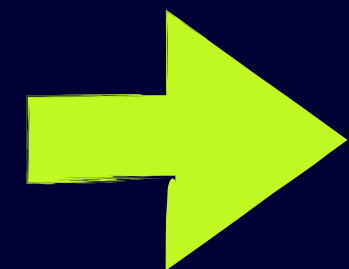
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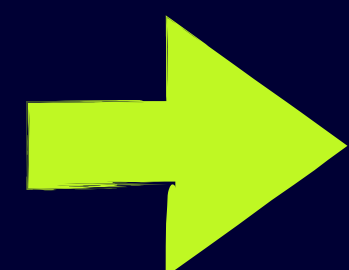
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# Bonus

## MODELLING M74 CHEMICAL EVOLUTION

$$\dot{\Sigma}_i = -\psi(t) X_i(t) + \int_{m(t)}^{m_{max}} Q_{mi}(t - \tau_m) \psi(t - \tau_m) \phi(m) dm + X_{inf,i} \dot{\Sigma}_{inf}$$

# Bonus

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$$\dot{\Sigma}_i = -\psi(t) X_i(t) + \int_{m(t)}^{m_{max}} Q_{mi}(t - \tau_m) \psi(t - \tau_m) \phi(m) dm + X_{inf,i} \dot{\Sigma}_{inf}$$

Gas infall

$$\dot{\Sigma}_{inf} \propto e^{-t/\tau(R)}$$

# Bonus

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Gas infall

$$\dot{\Sigma}_{inf} \propto e^{-t/\tau(R)}$$

SFR

$$\psi(t) = \nu(R) \Sigma_{gas}^k$$

# Bonus

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**Gas infall**

$$\dot{\Sigma}_{inf} \propto e^{-t/\tau(R)}$$

$$\tau(R) = A \times R + B$$

**SFR**

$$\psi(t) = \nu(R) \Sigma_{gas}^k$$

$$\nu(R) = C/R + D$$

# Bonus

## MODELLING M74 CHEMICAL EVOLUTION

$$\dot{\Sigma}_i = -\psi(t) X_i(t) + \int_{m(t)}^{m_{max}} Q_{mi}(t - \tau_m) \psi(t - \tau_m) \phi(m) dm + X_{inf,i} \dot{\Sigma}_{inf}$$

Gas infall

$$\dot{\Sigma}_{inf} \propto e^{-t/\tau(R)}$$

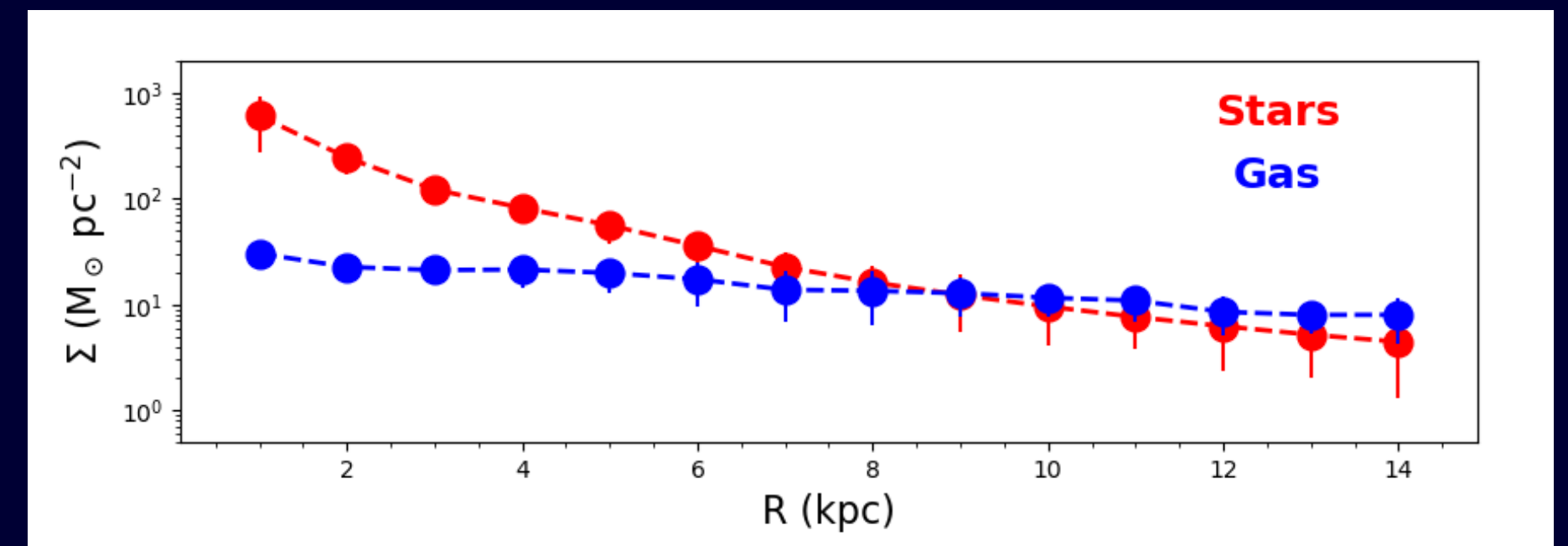
$$\tau(R) = A \times R + B$$

SFR

$$\psi(t) = \nu(R) \Sigma_{gas}^k$$

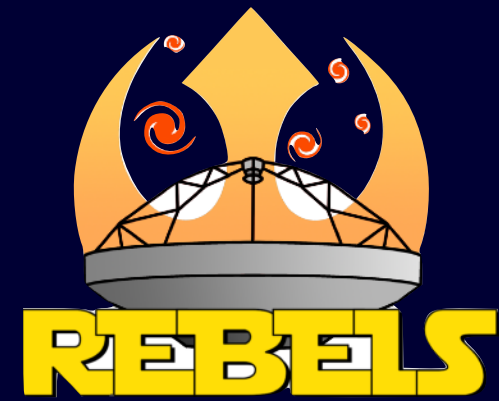
$$\nu(R) = C/R + D$$

MCMC



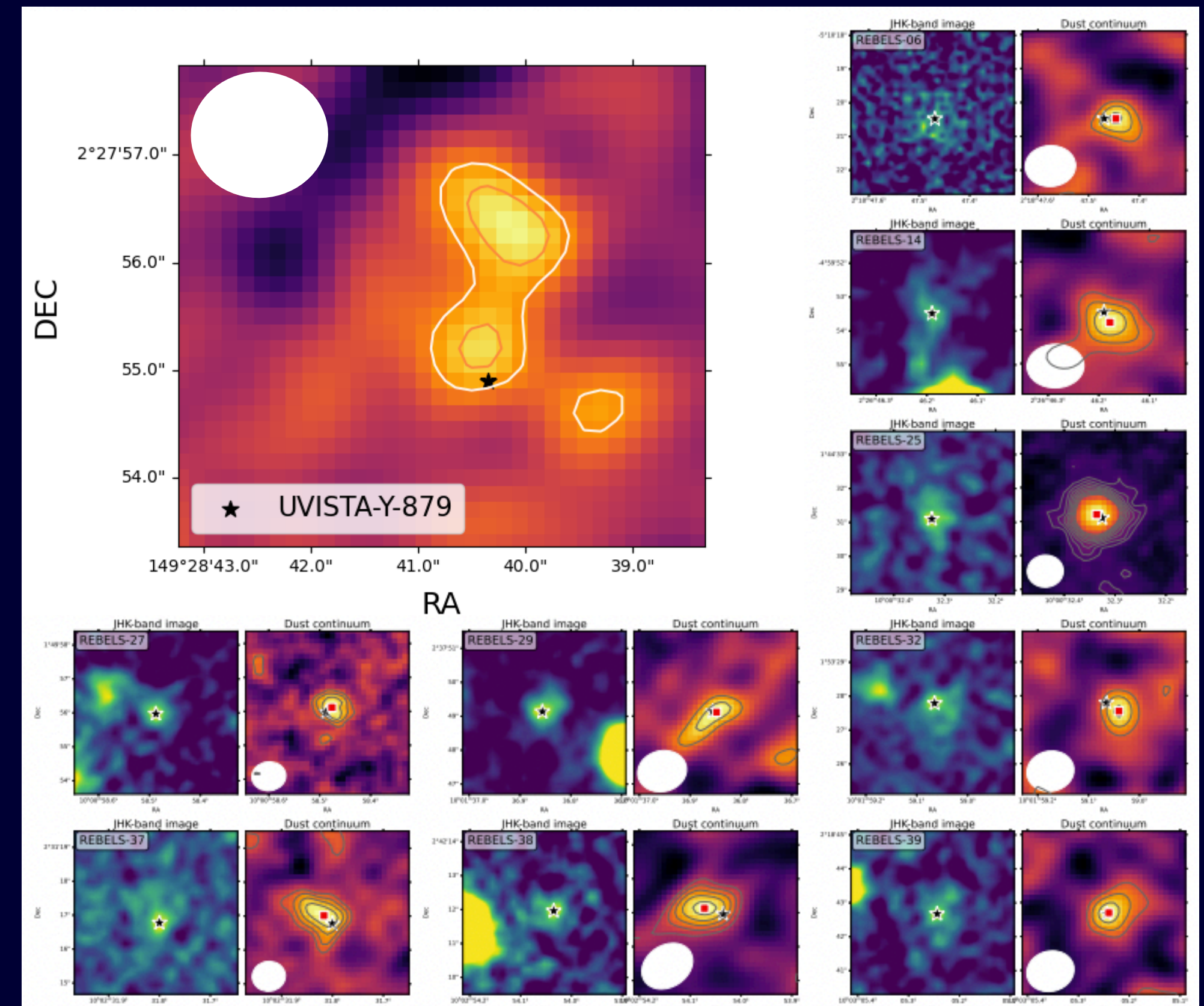
# Bonus

## REBELS GALAXIES



INAMI+22  
(ADAPTED)

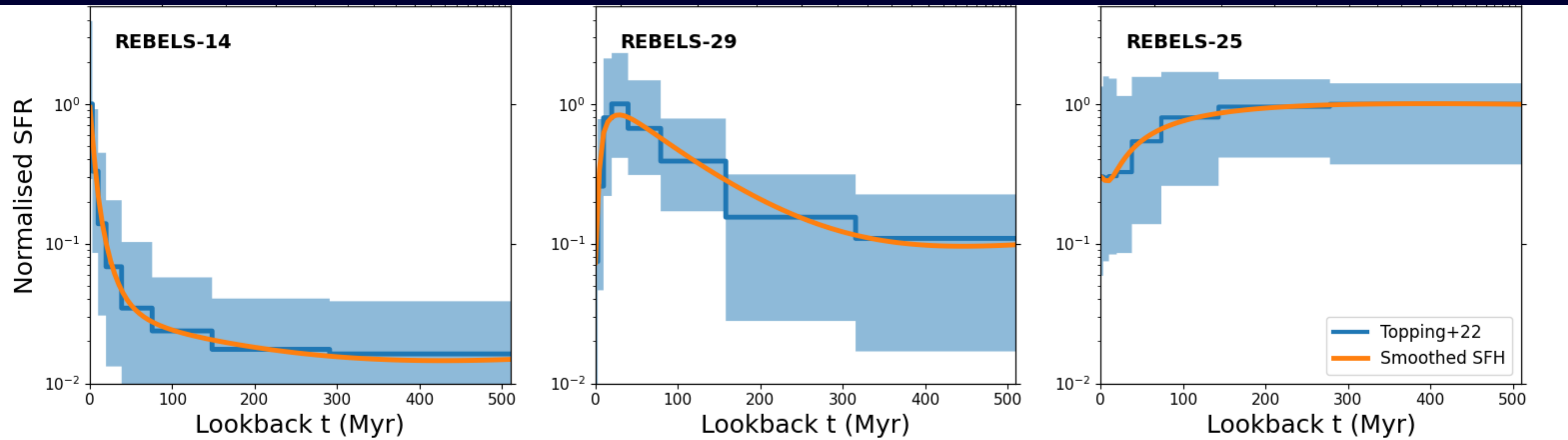
- Cycle-7 ALMA Large Program
- Scanning for:
  - 158  $\mu\text{m}$  [CII] line (band 6 ALMA)
  - **Dust continuum** emission
  - + multi-band observations for several sources
- Dust continuum detected for 16 objects: largest  $z \gtrsim 6$  sample to date
- Serendipitous detections for 2 galaxies (Fudamoto+21)





# Bonus

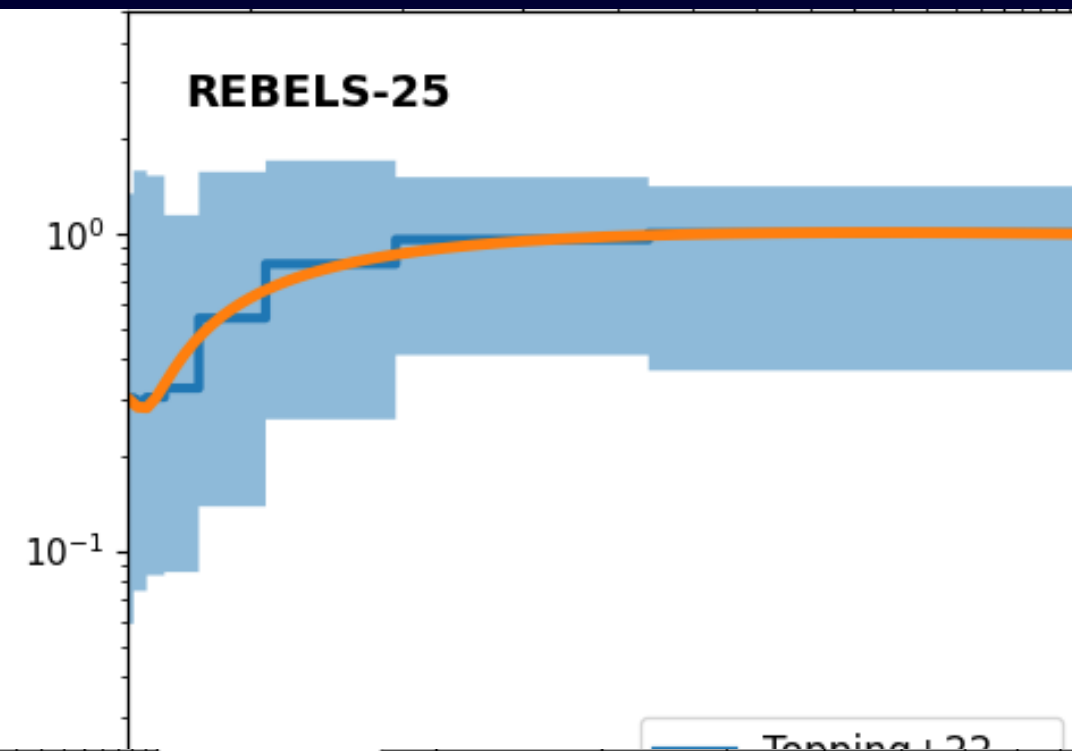
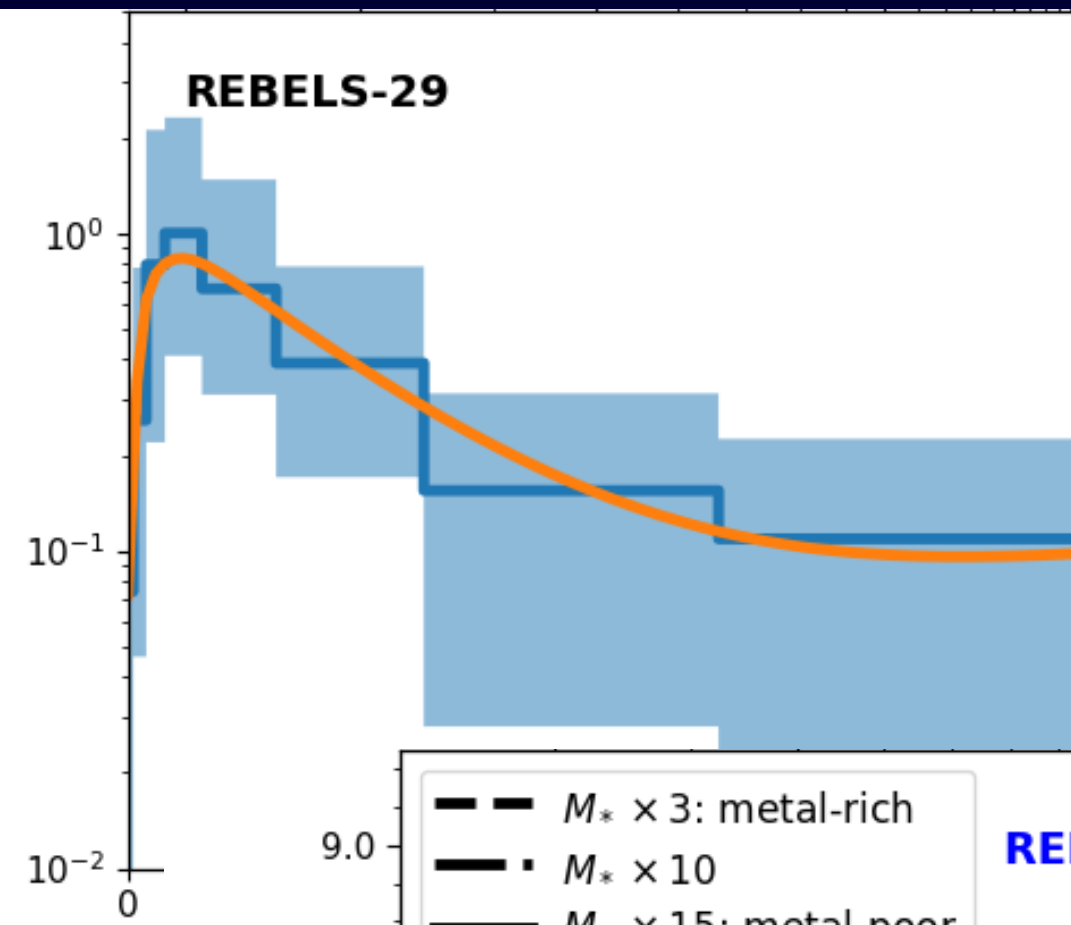
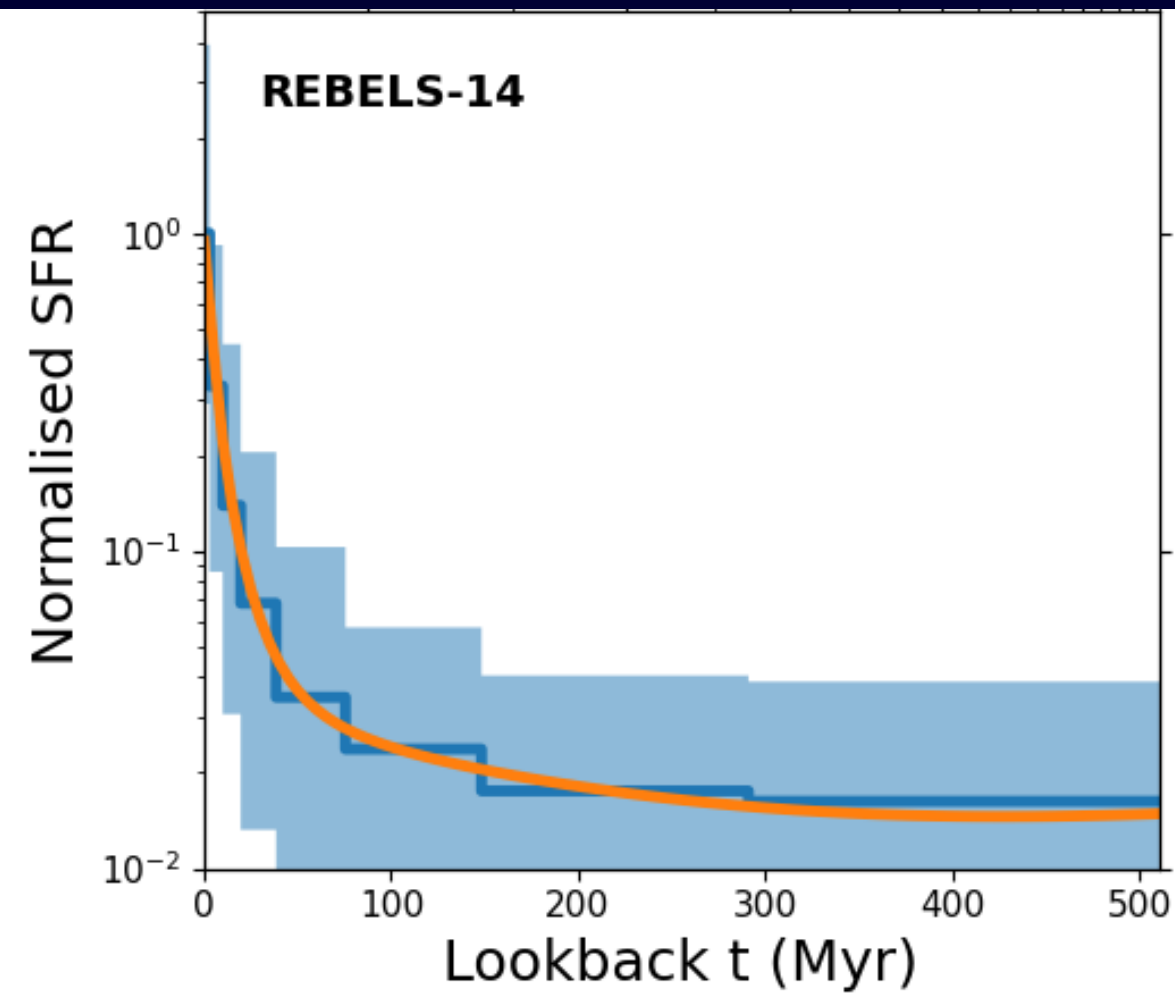
## MODELLING REBELS GALAXIES



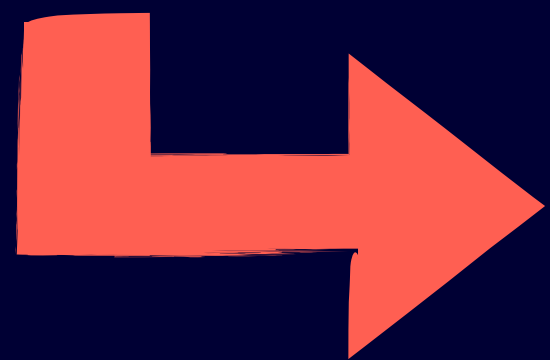
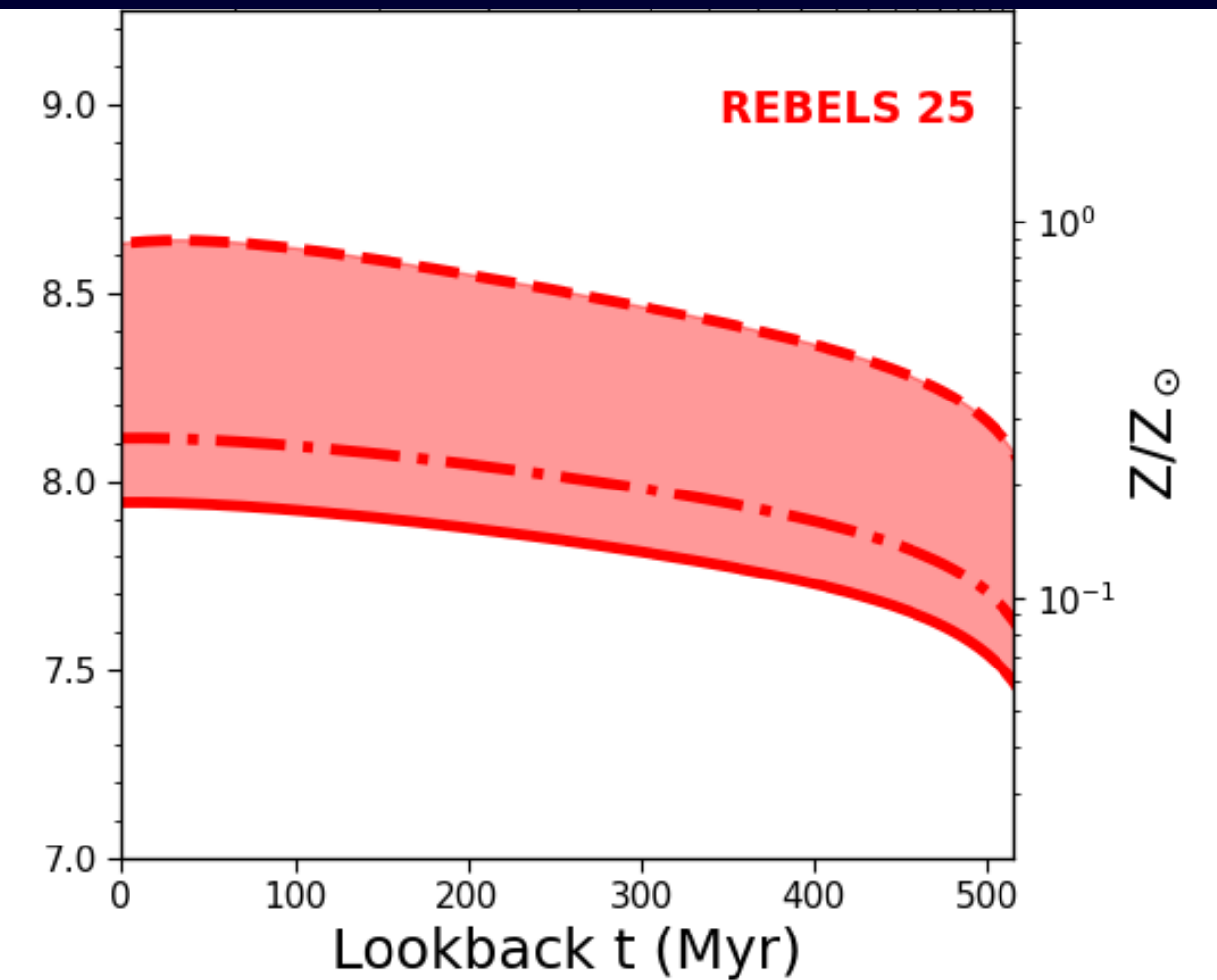
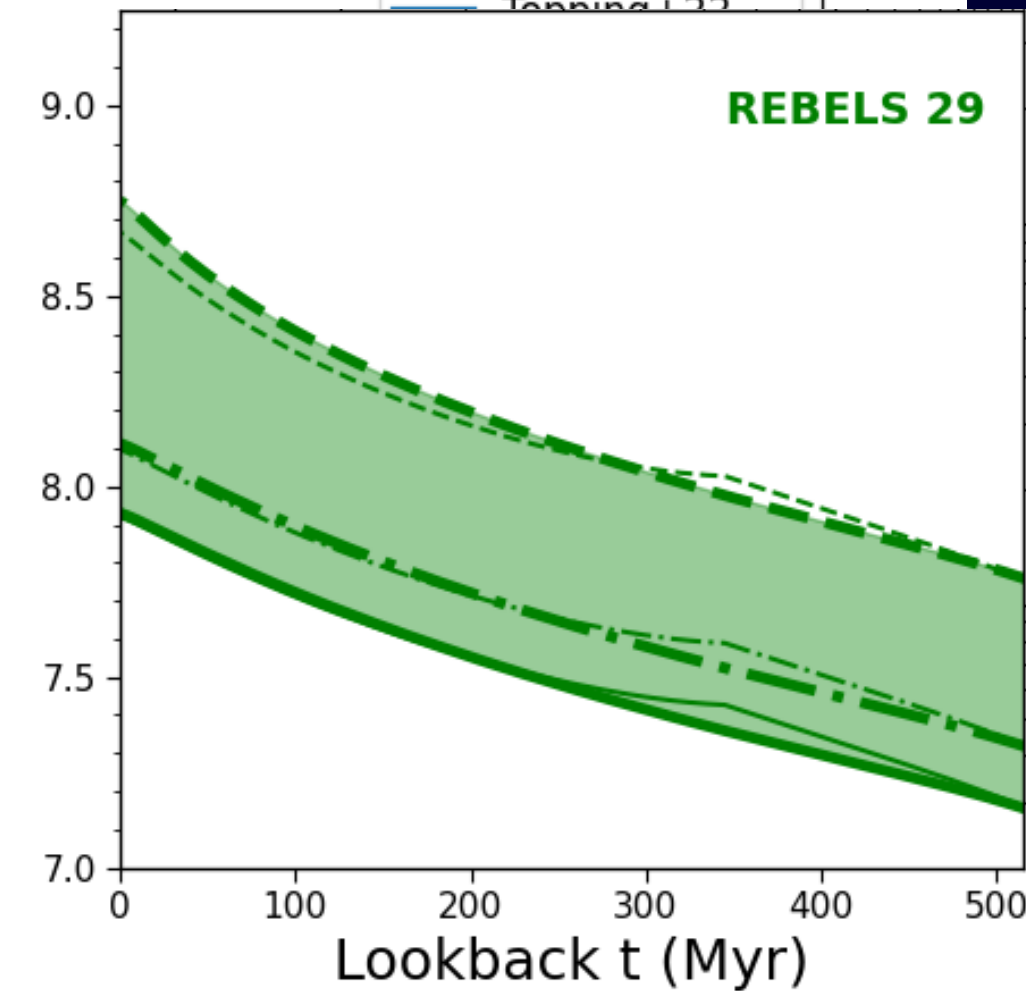
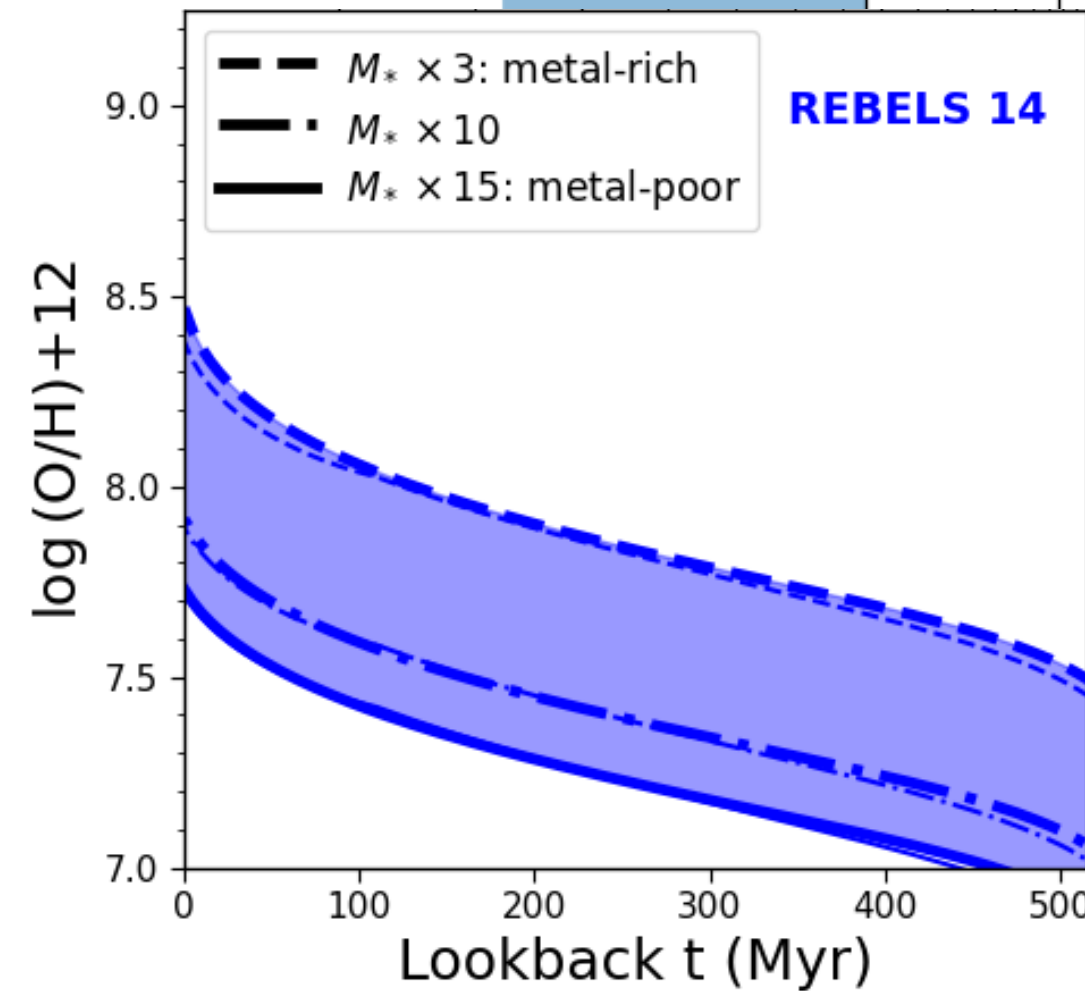
**SFHs** from galaxies'  
non-parametric **SED fitting**  
(Topping+22)

# Bonus

## MODELLING REBELS GALAXIES



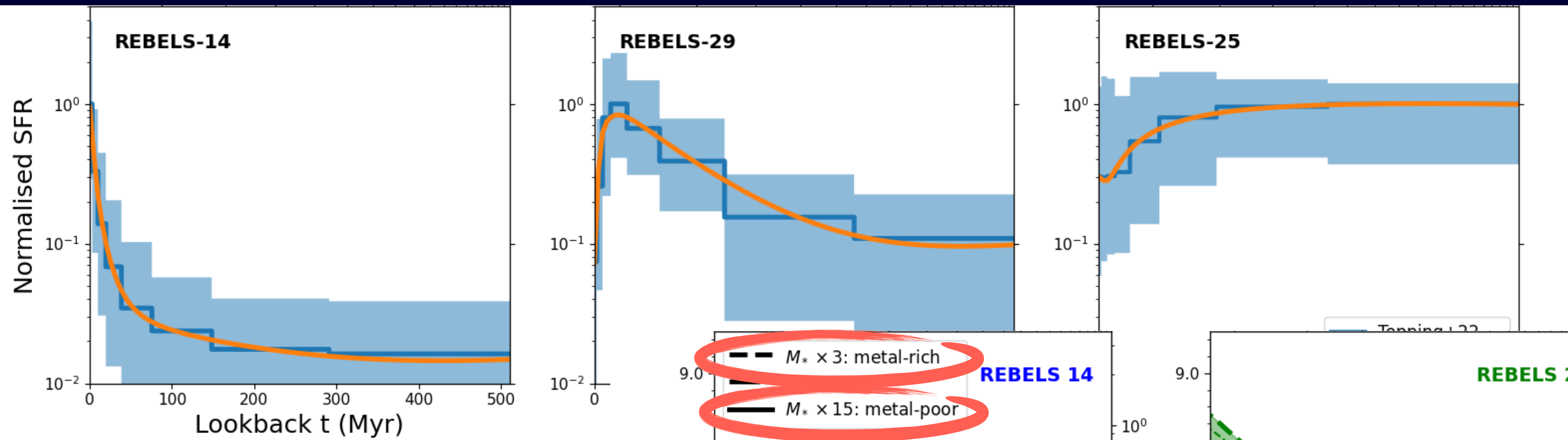
SFHs from galaxies' non-parametric **SED fitting** (Topping+22)



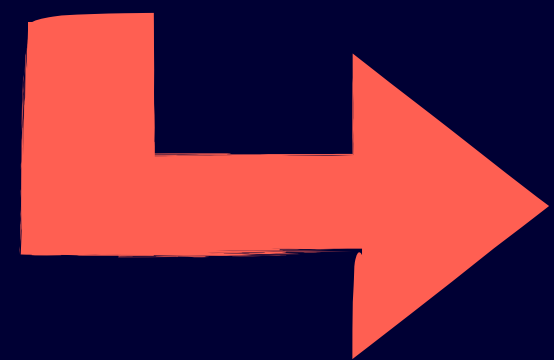
DIFFERENT efficiency of star formation/ gas consumption timescale

# Bonus

## MODELLING REBELS GALAXIES



SFHs from galaxies' non-parametric **SED fitting** (Topping+22)



**DIFFERENT**  
efficiency of star formation/  
gas consumption timescale

