

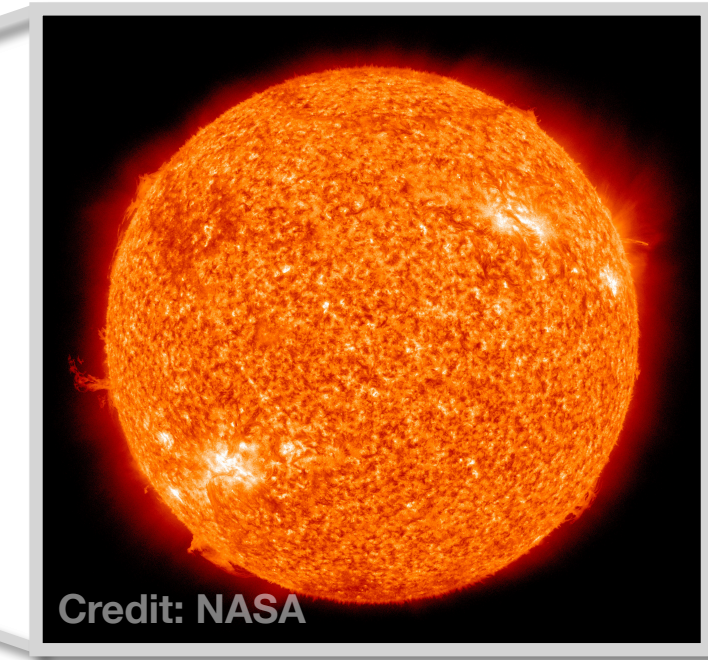
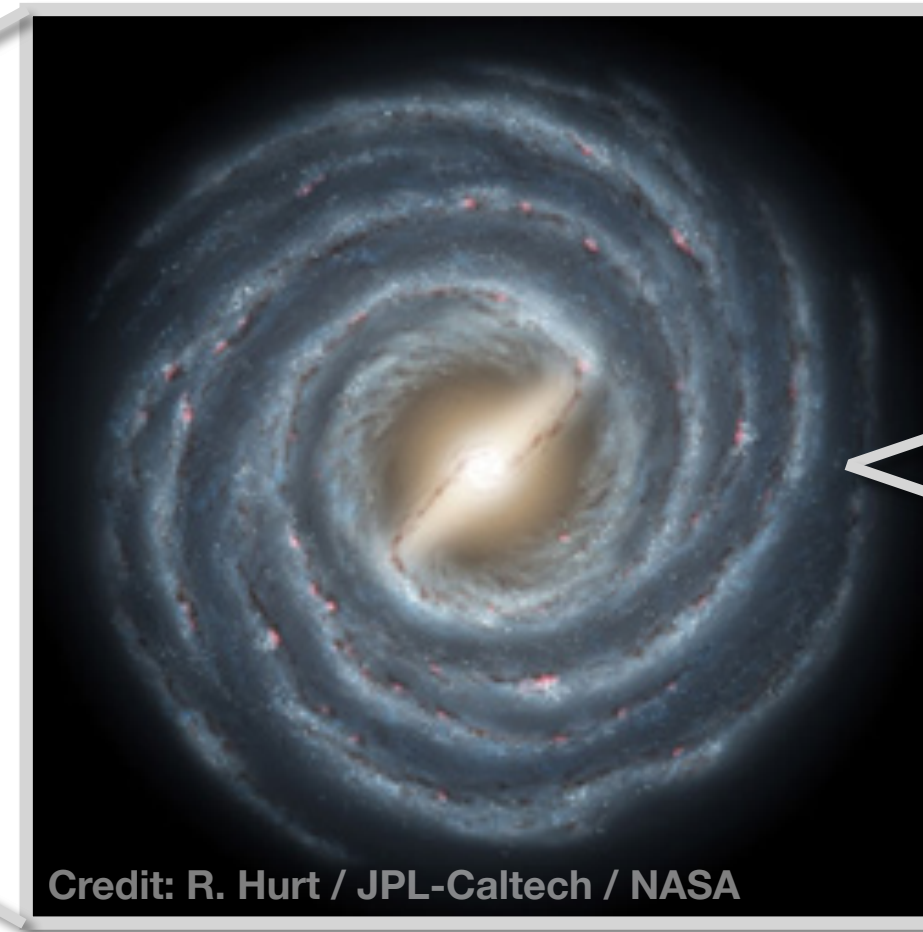
# Order in Chaos: Decoding the age-chemical structure of the Milky Way disk



**Aarya Patil** (she/her)

LSST-Discovery Alliance Catalyst Fellow,  
Max-Planck-Institut für Astronomie





# Order in Chaos: Decoding the age-chemical structure of the Milky Way disk



**Aarya Patil** (she/her)

Astronomy & Astrophysics PhD & Data Sciences Institute Fellow,  
University of Toronto

# Science



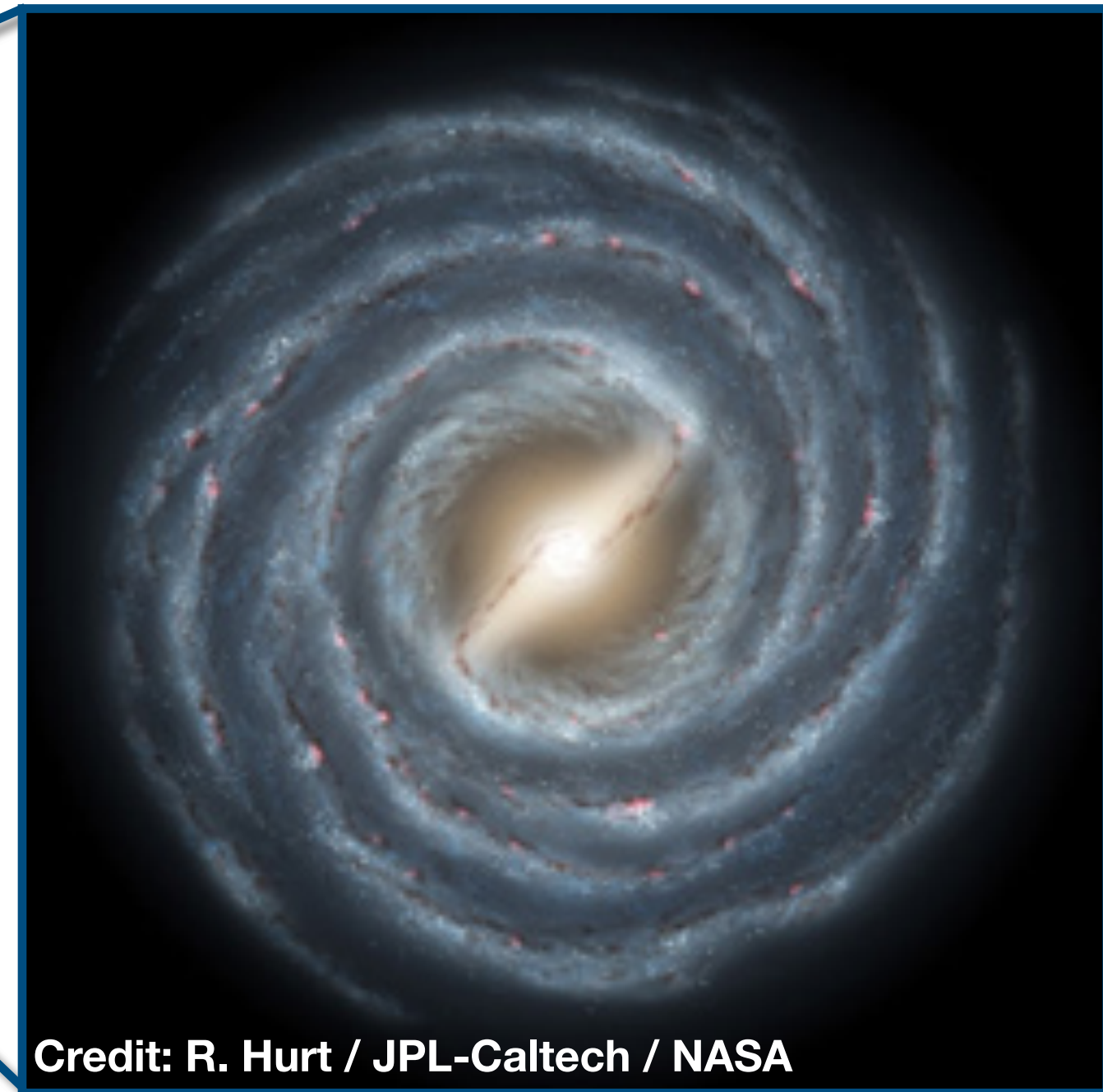
## Galaxy formation and evolution

# Science



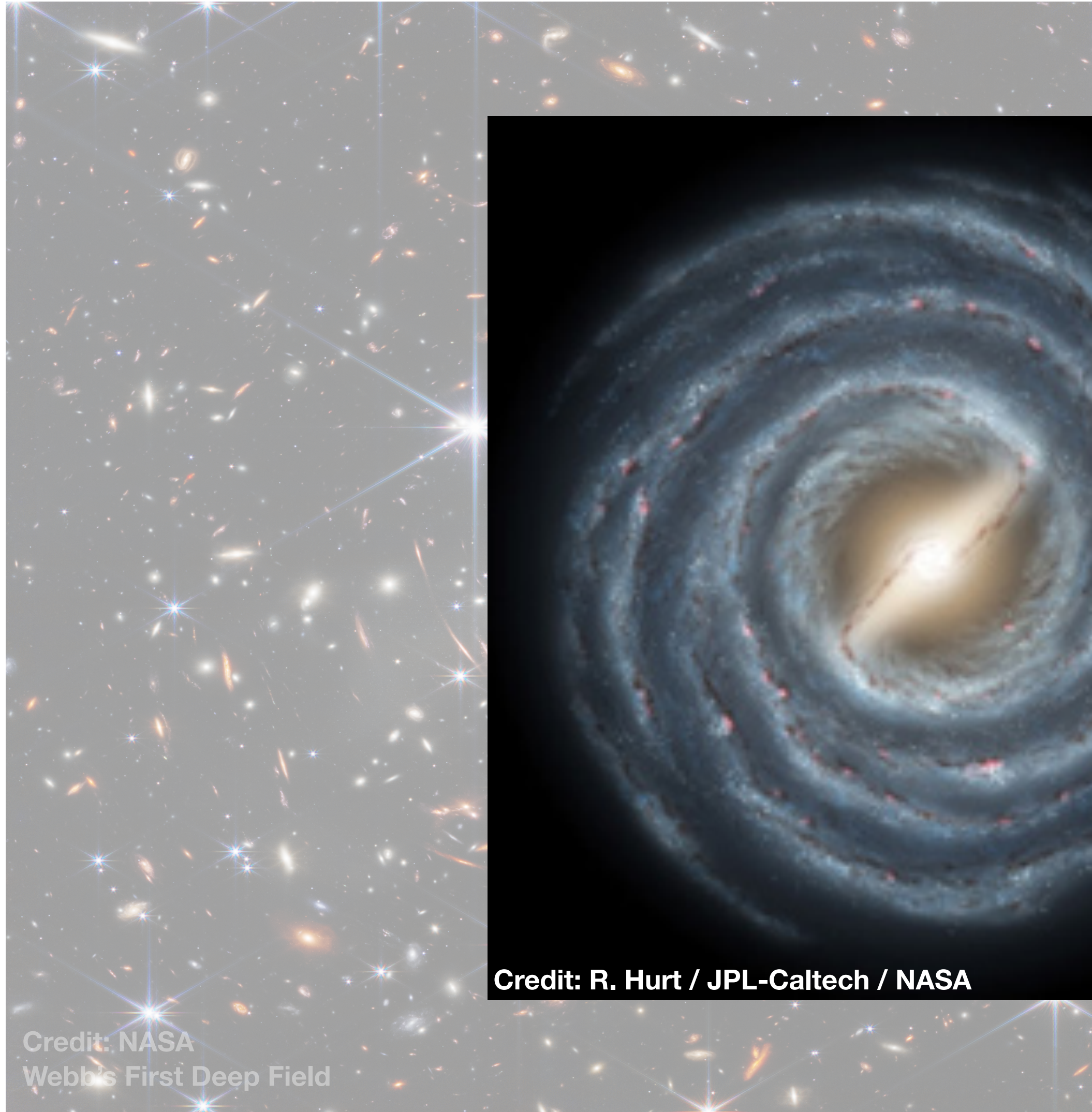
Credit: NASA  
Webb's First Deep Field

**Milky Way** as a *typical* galaxy

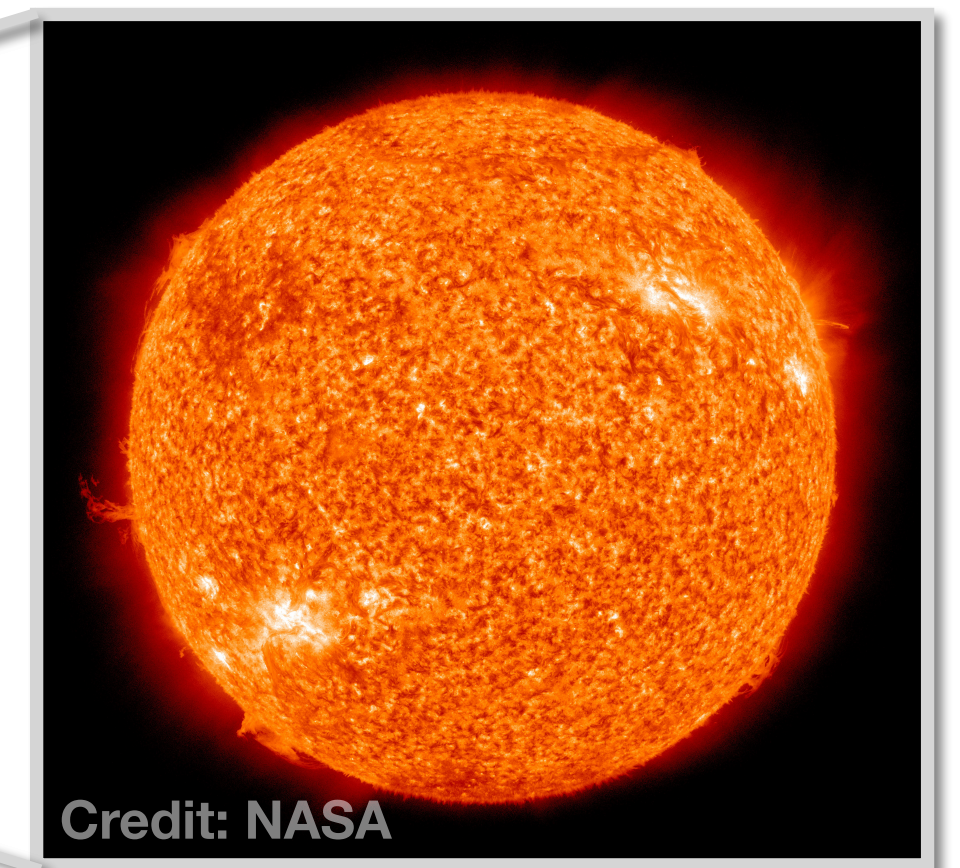


Credit: R. Hurt / JPL-Caltech / NASA

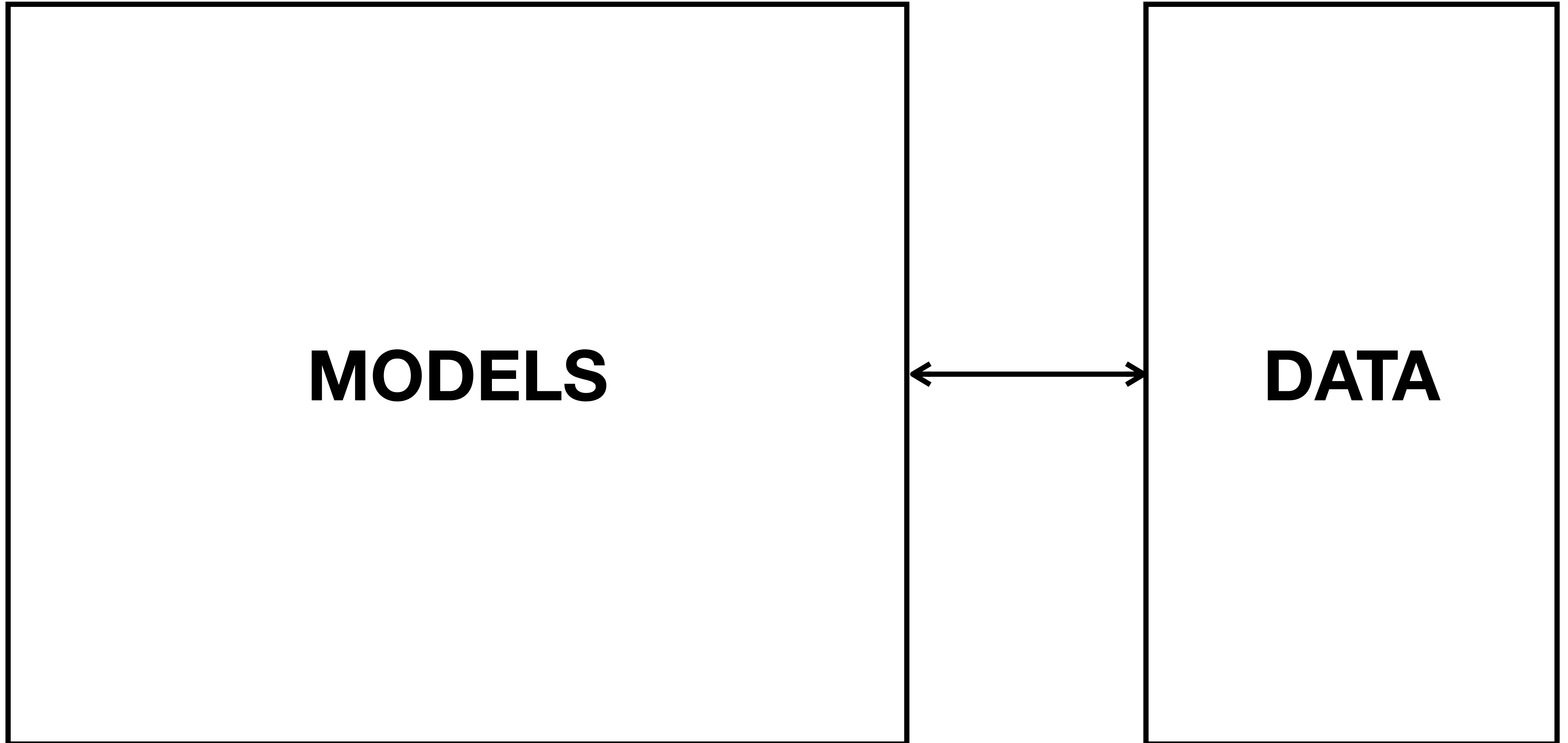
# Science



- Age
- Chemistry
- Orbits

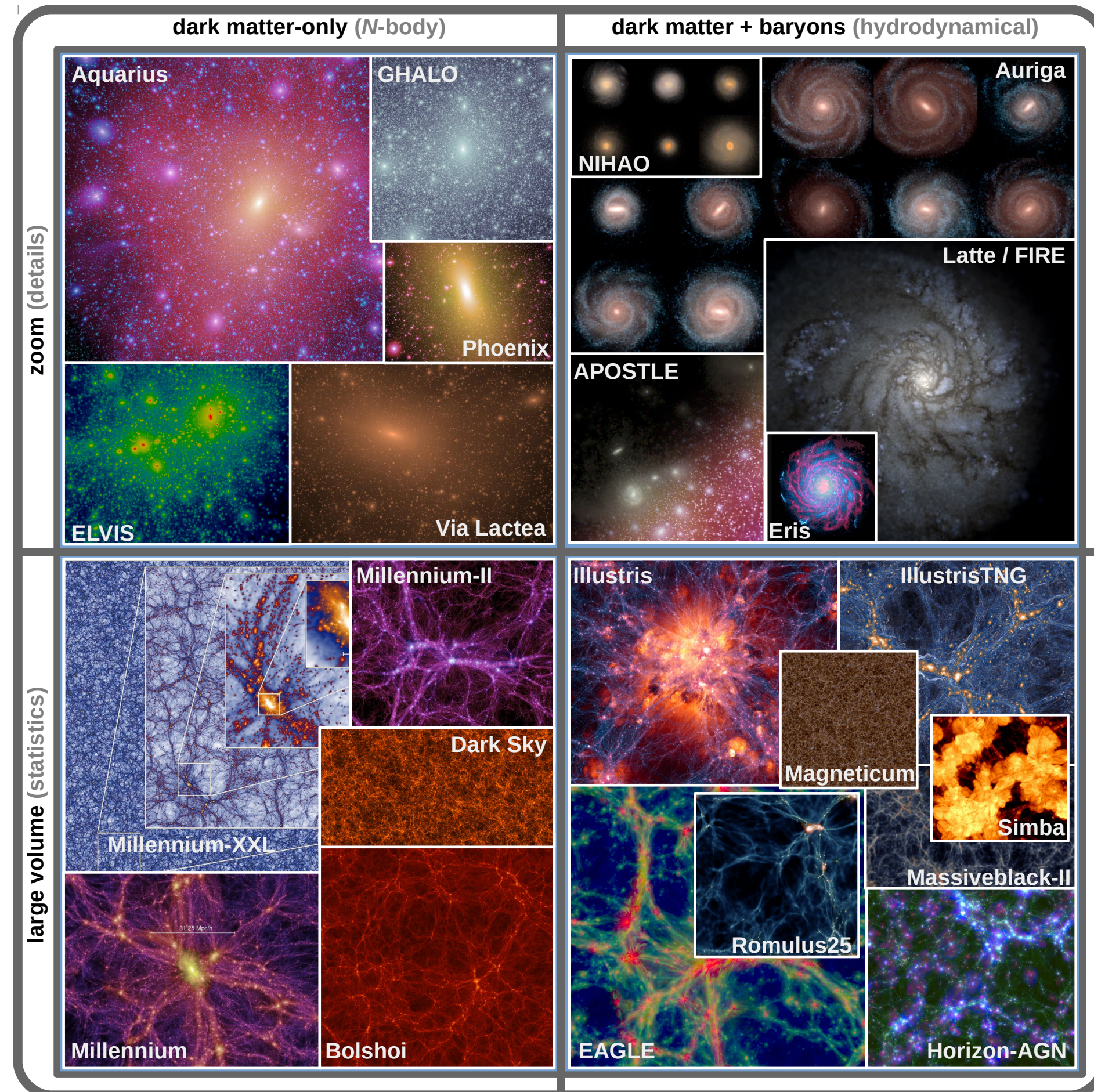


# Science



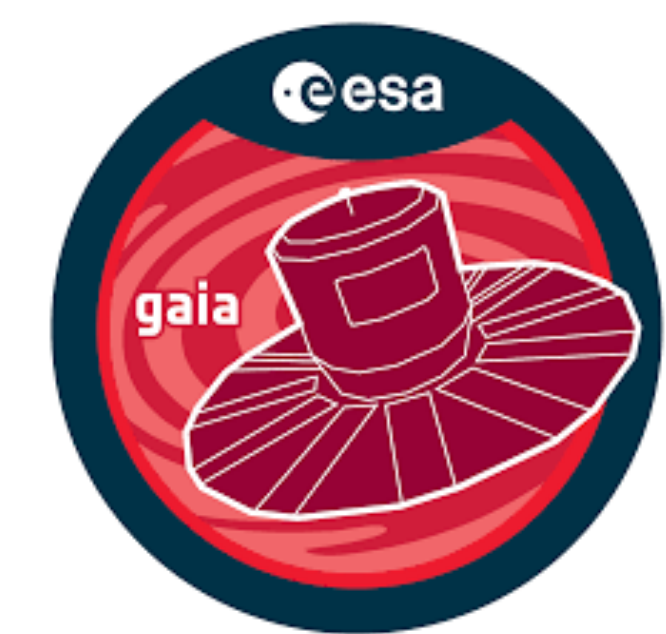
# Science

## Cosmological simulations of MW-like galaxies



Credit: Vogelsberger et al. 2020, *Nat Rev Phys* 2, 42–66

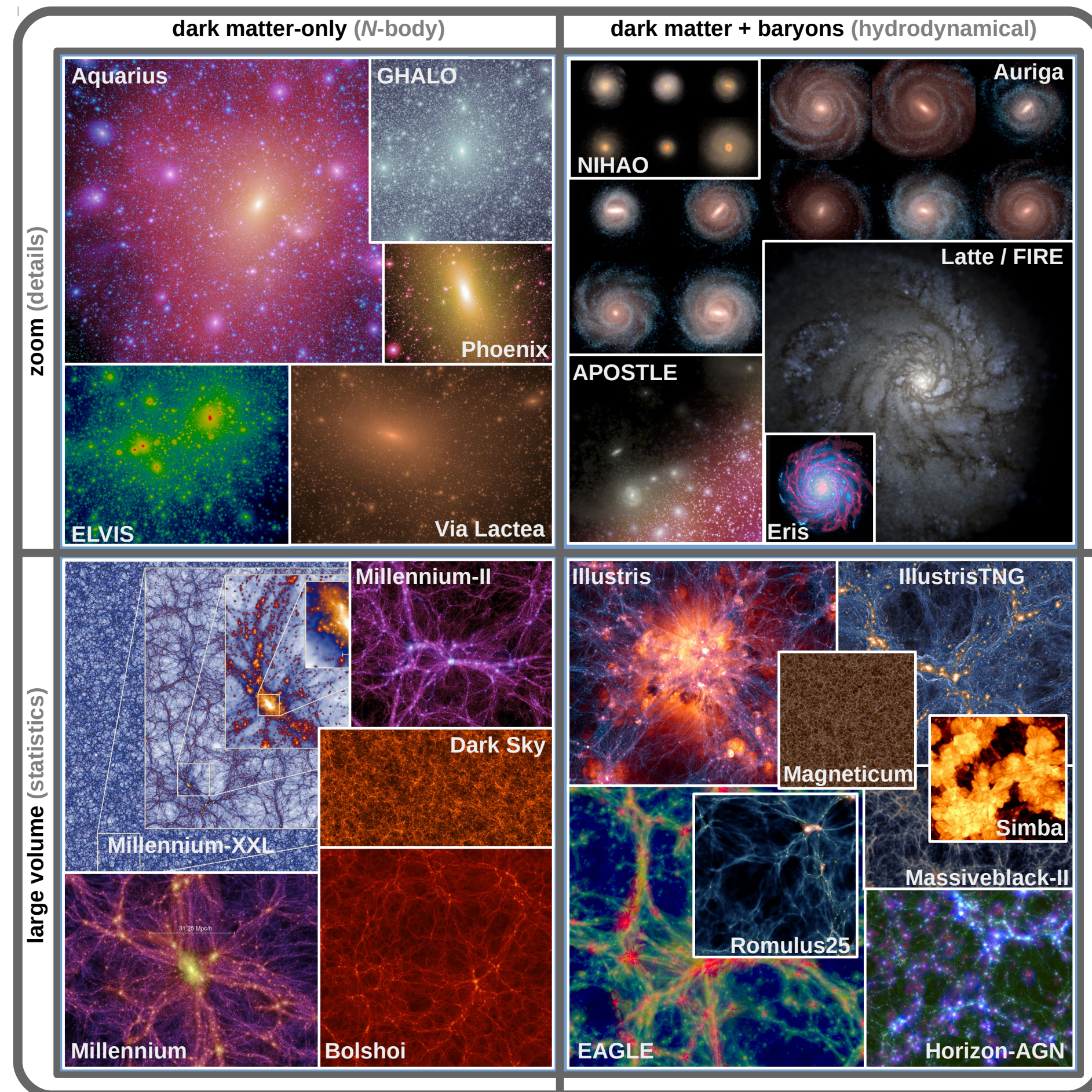
$\approx 10^9$  stellar observations  
of different varieties



*GAP*

# Science

## Cosmological simulations of MW-like galaxies



Credit: Vogelsberger et al. 2020, *Nat Rev Phys* 2, 42–66

$>10^9$  stellar observations  
6 colors over space & time



**LSST**  
Discovery  
Alliance

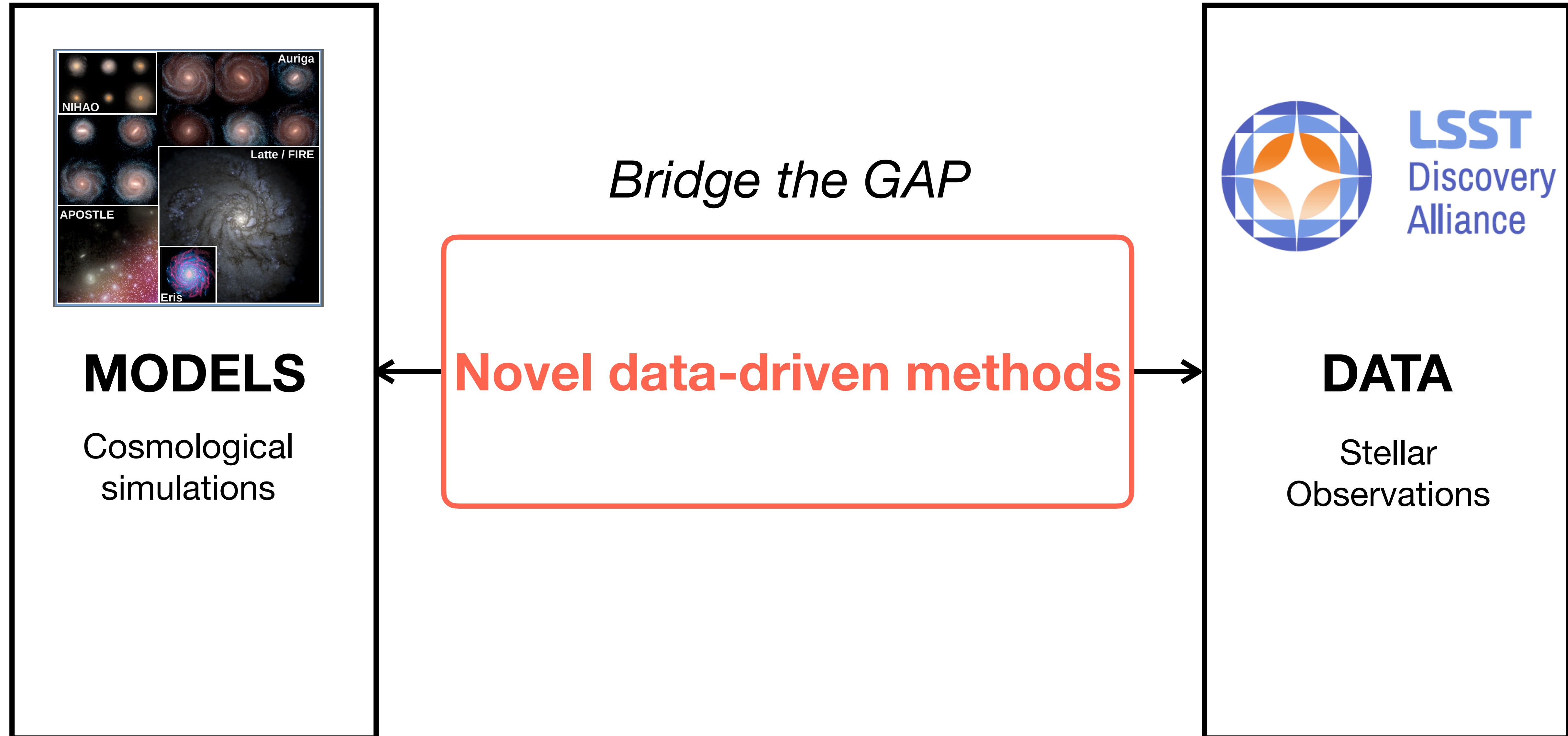
*GAP*



**VERA C. RUBIN**  
OBSERVATORY



# Interdisciplinary challenges



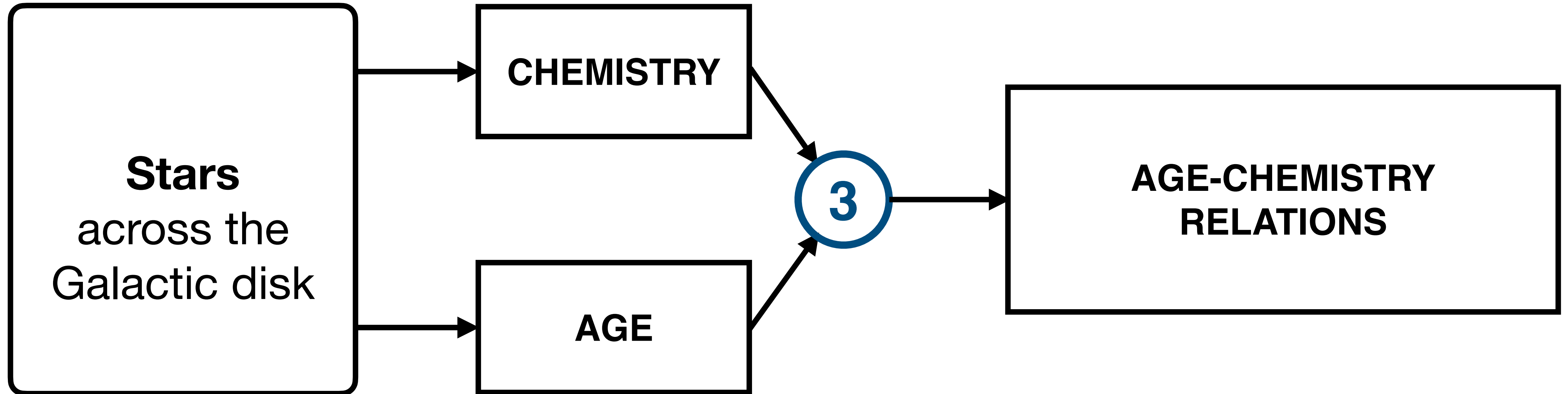
# Interdisciplinary challenges



# PhD thesis

Patil et al. 2022

①

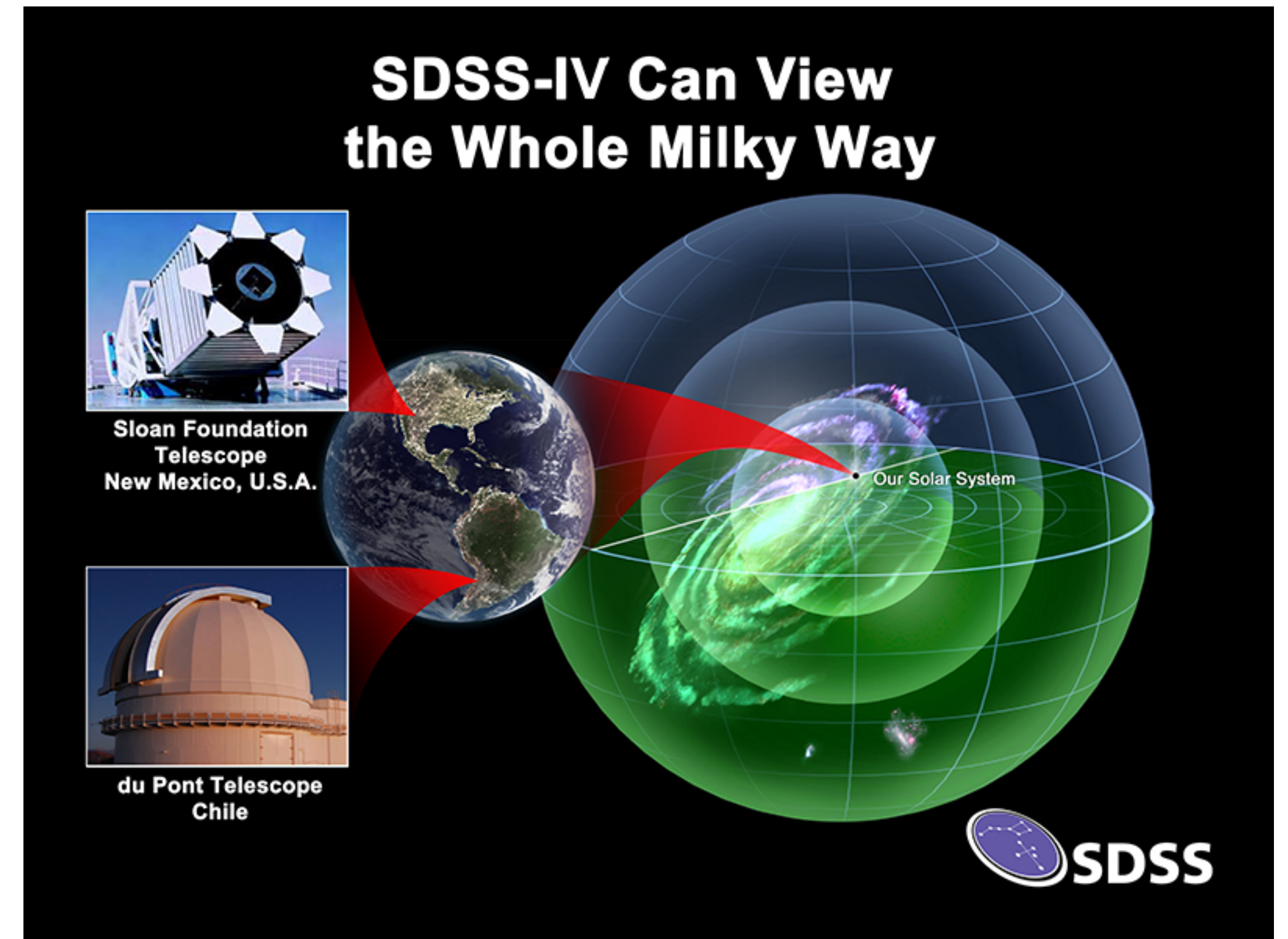
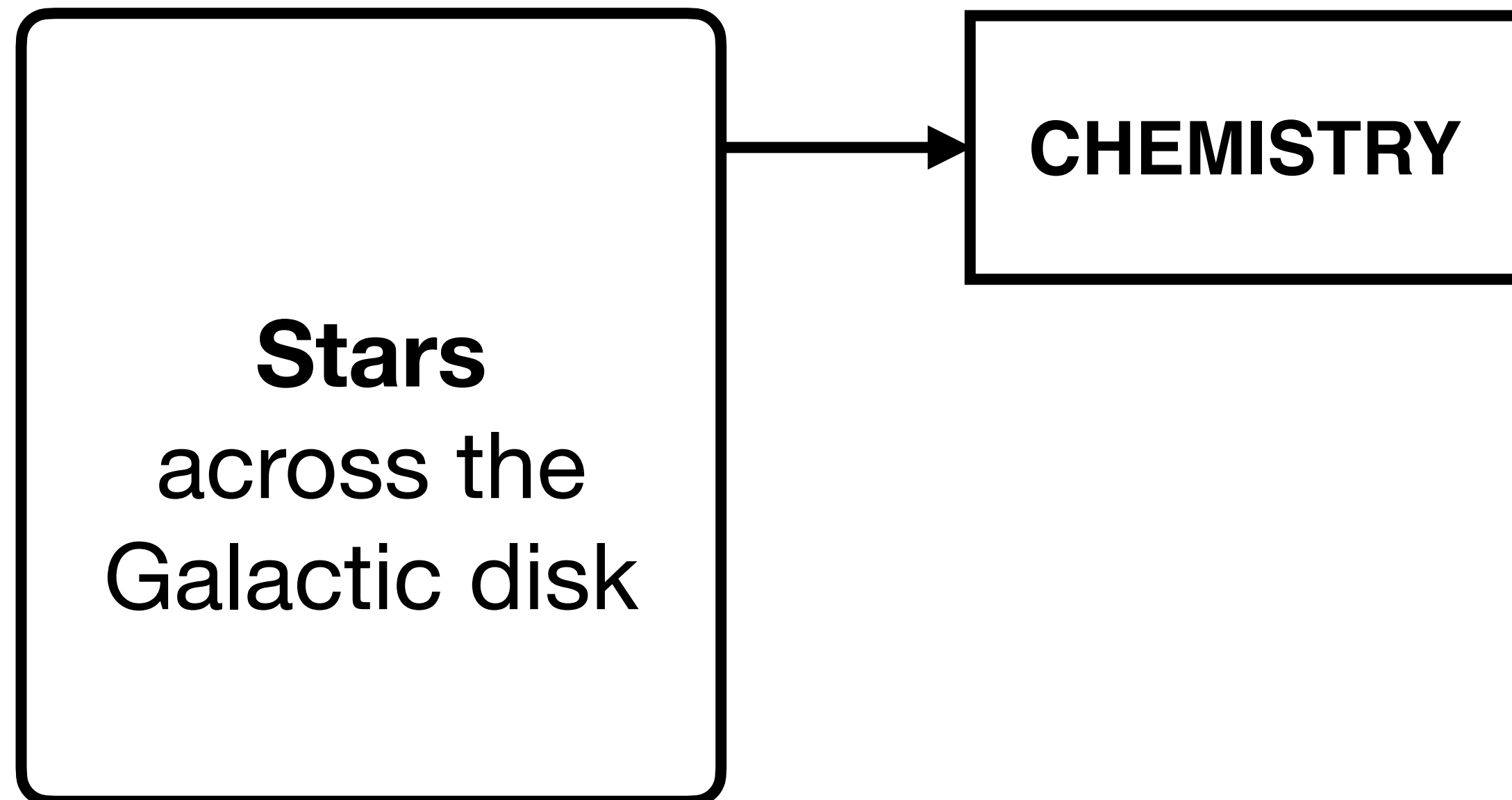


②

Patil et al. (under review)

Patil et al. 2023

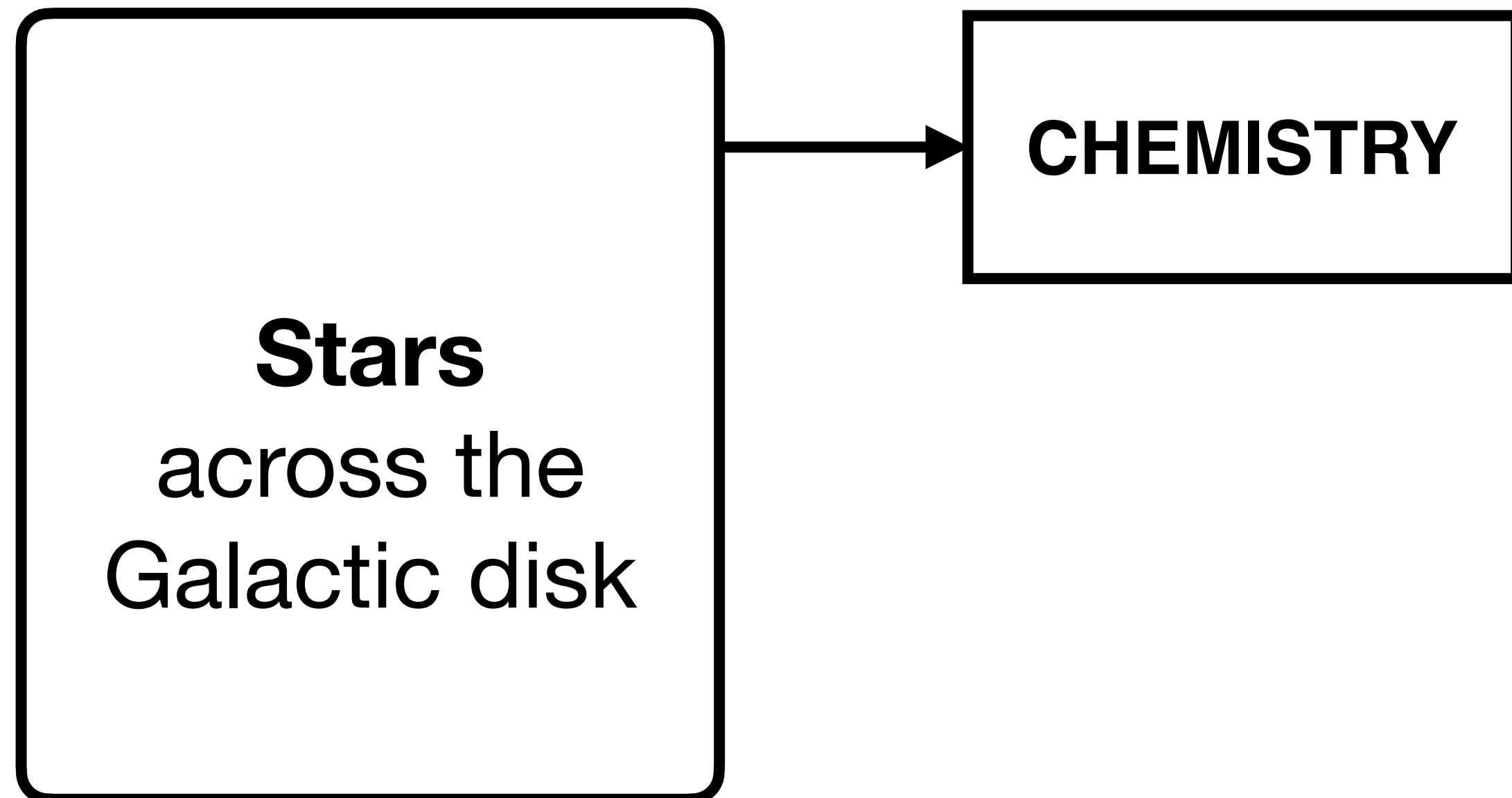
# ① Precise chemical compositions of stars



## APOGEE spectroscopy

Majewski et al. 2017

# ① Accurate & precise chemistry of stars



SDSS-IV Can View  
the Whole Milky Way

**Functional data analysis**  
**Likelihood-free inference**

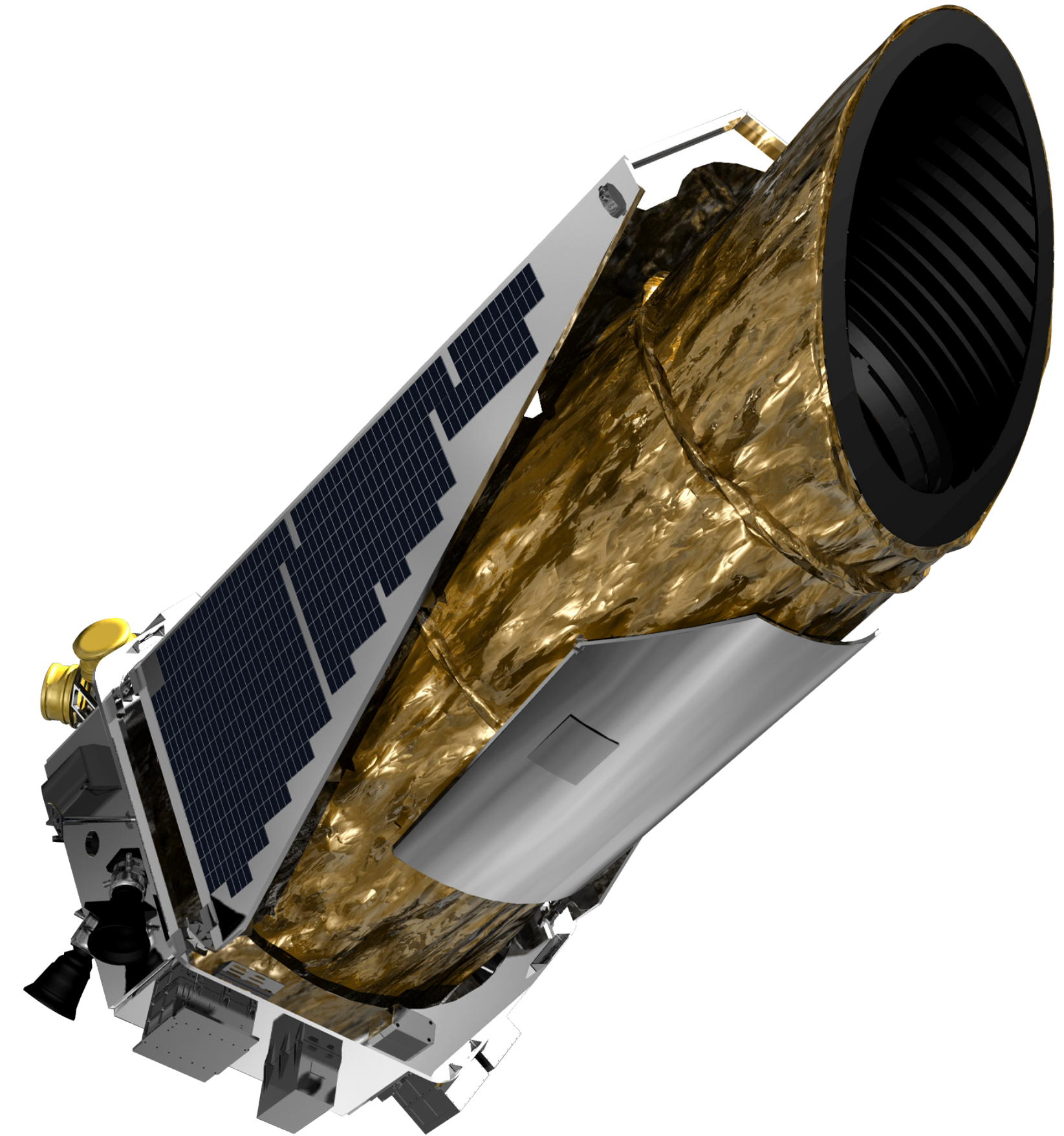
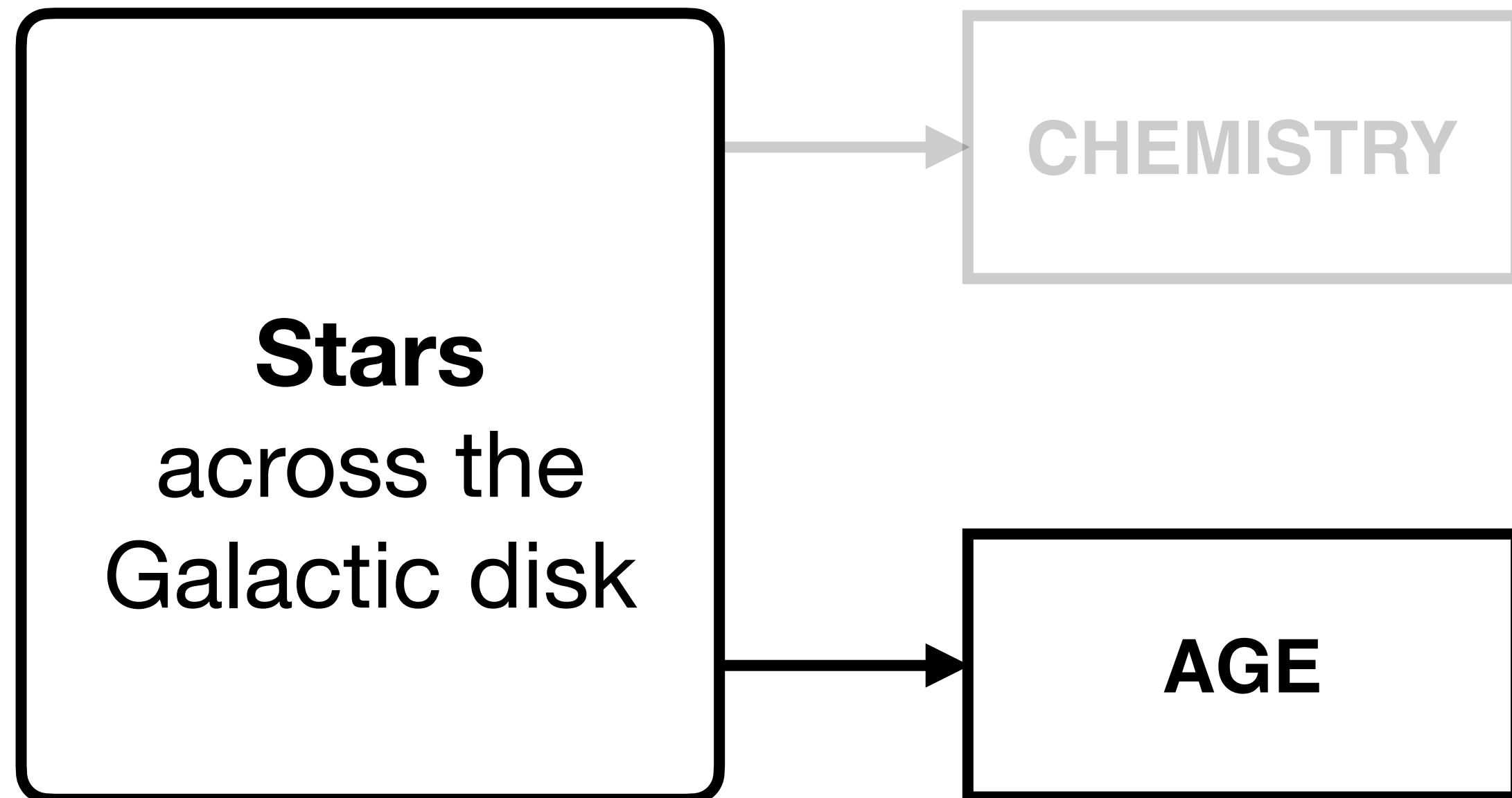
du Pont Telescope  
Chile

SDSS

APOGEE spectroscopy

Majewski et al. 2017

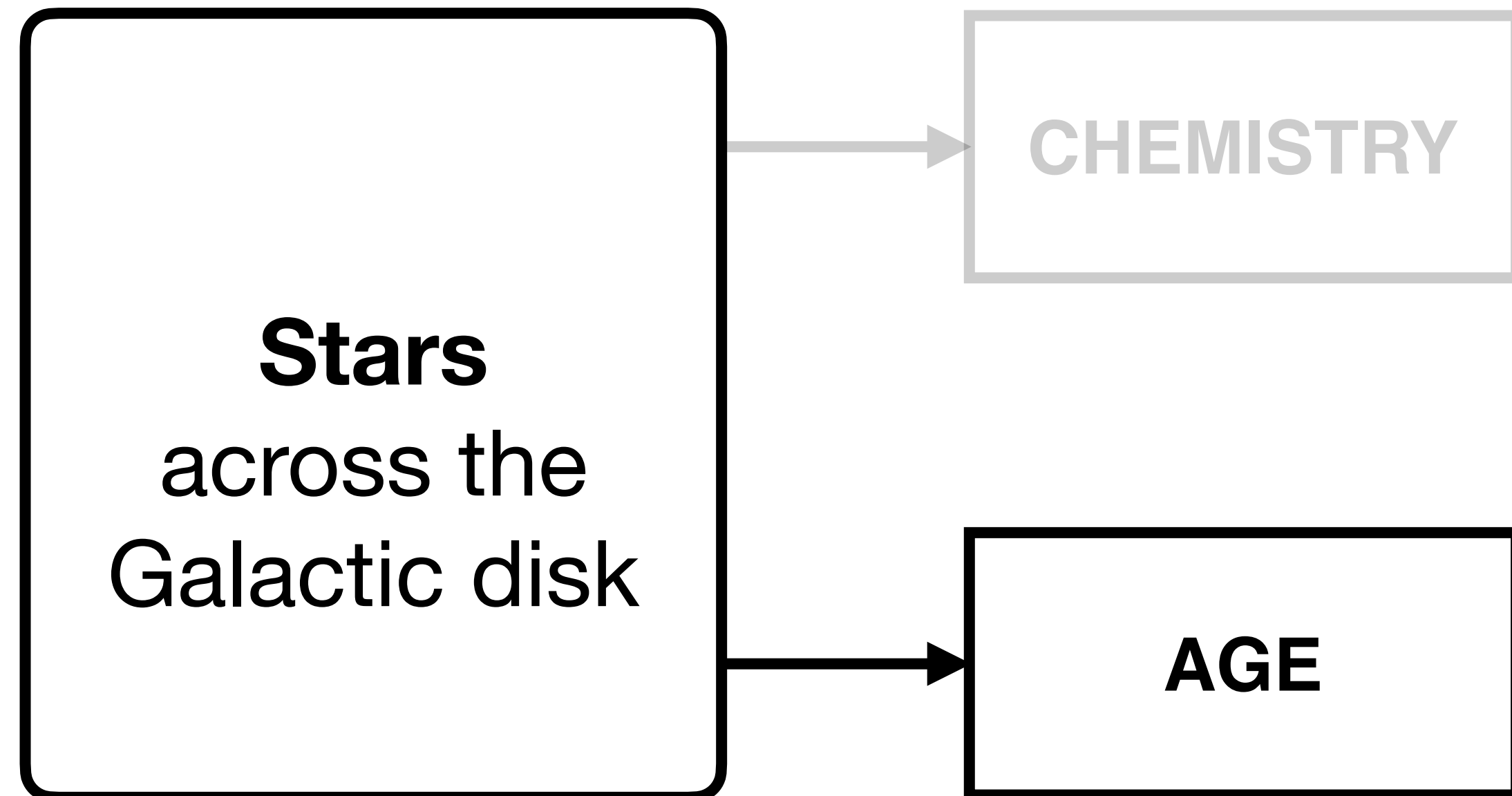
## ② Accurate & precise ages of stars



**Kepler time-series**

Borucki et al. 2010

## ② Accurate & precise ages of stars



### Multitaper power spectrum analysis



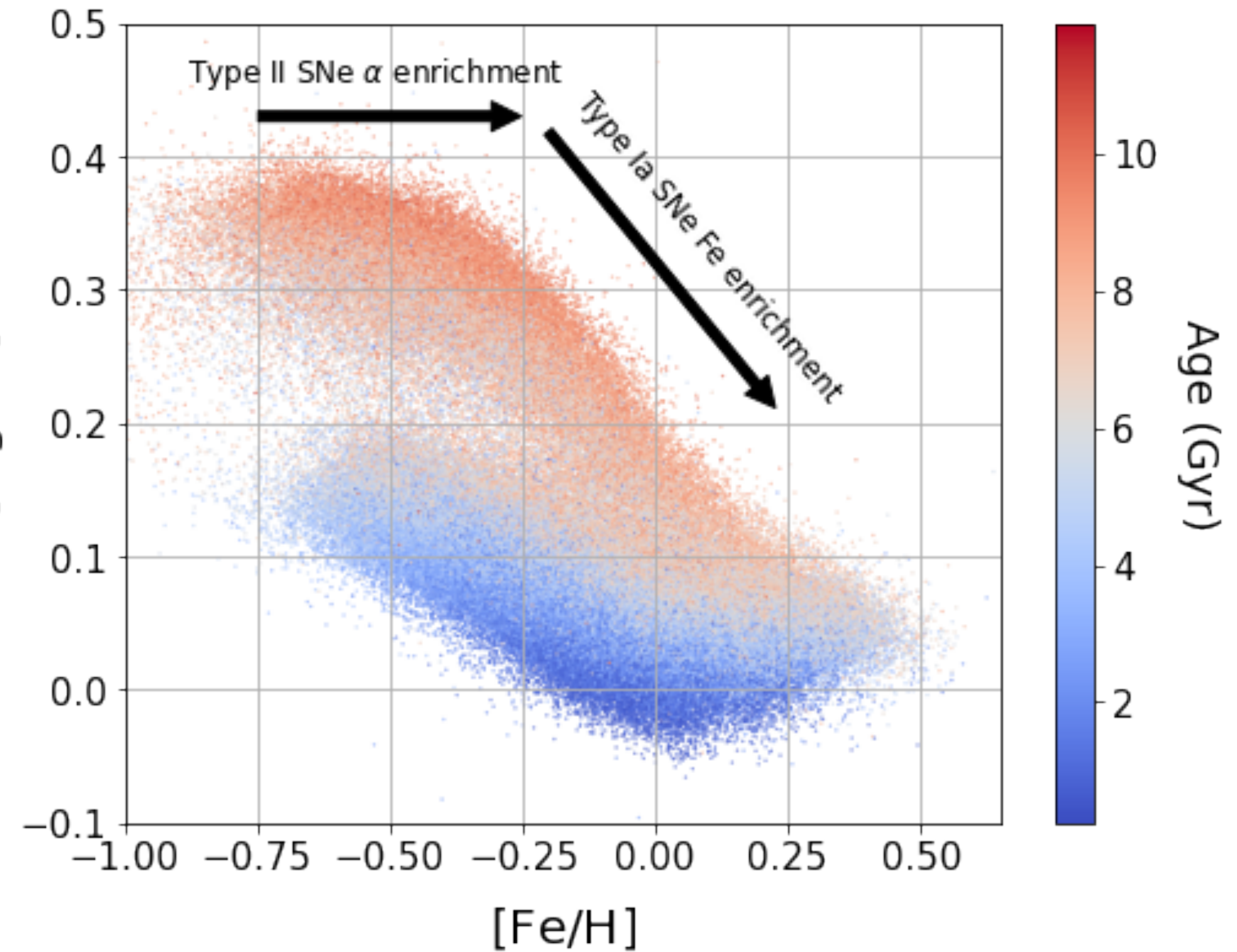
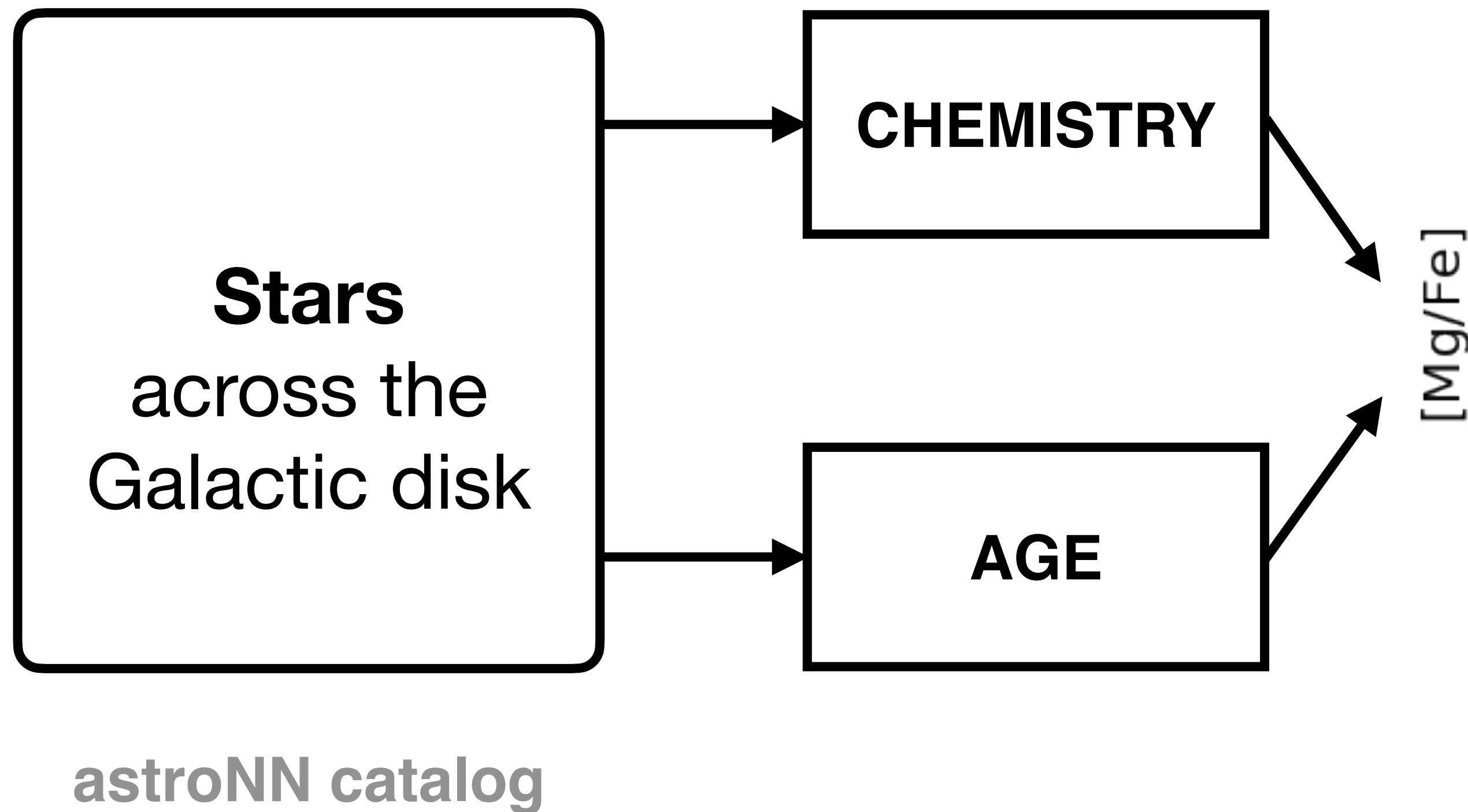
Kepler



es

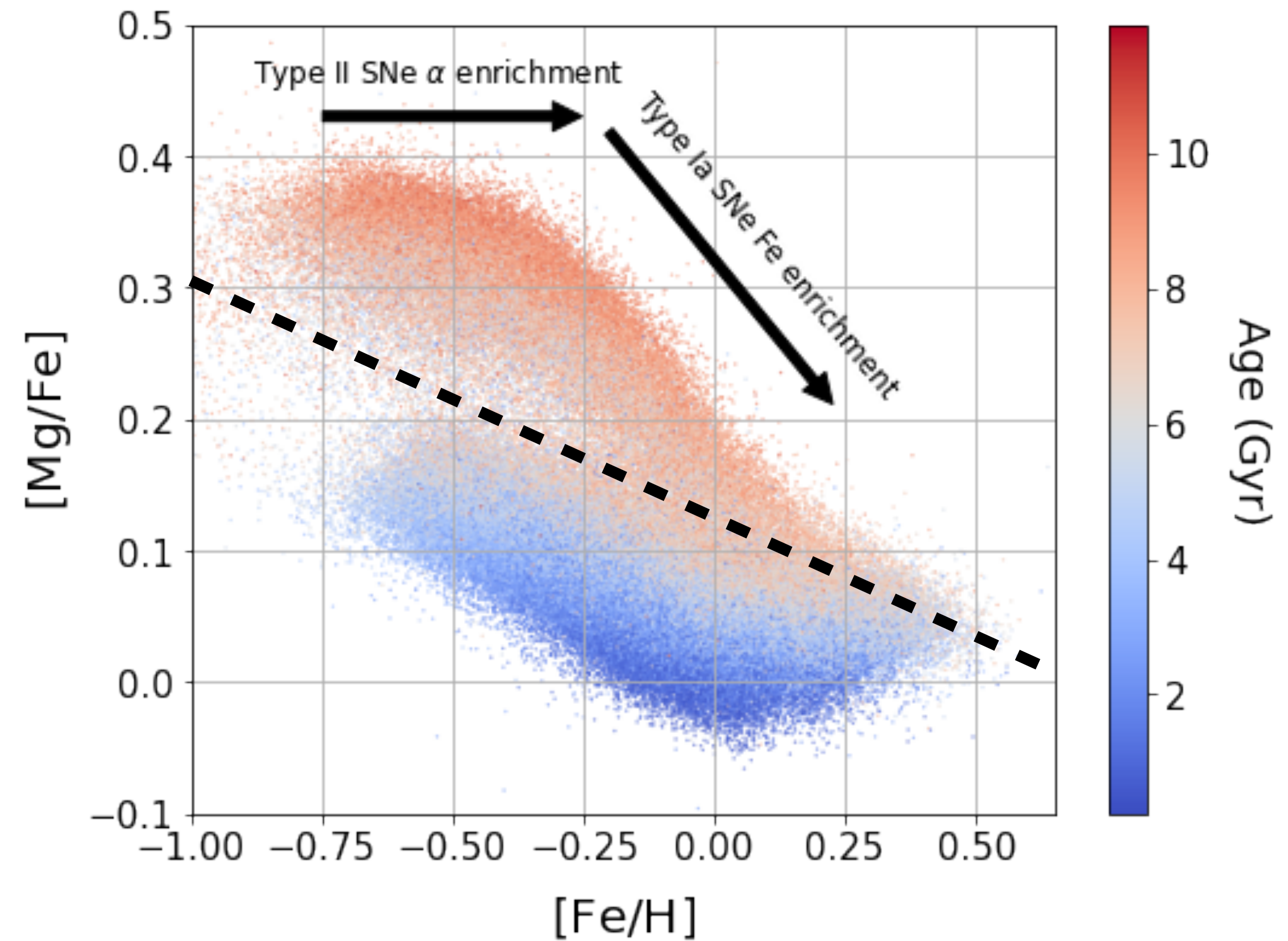
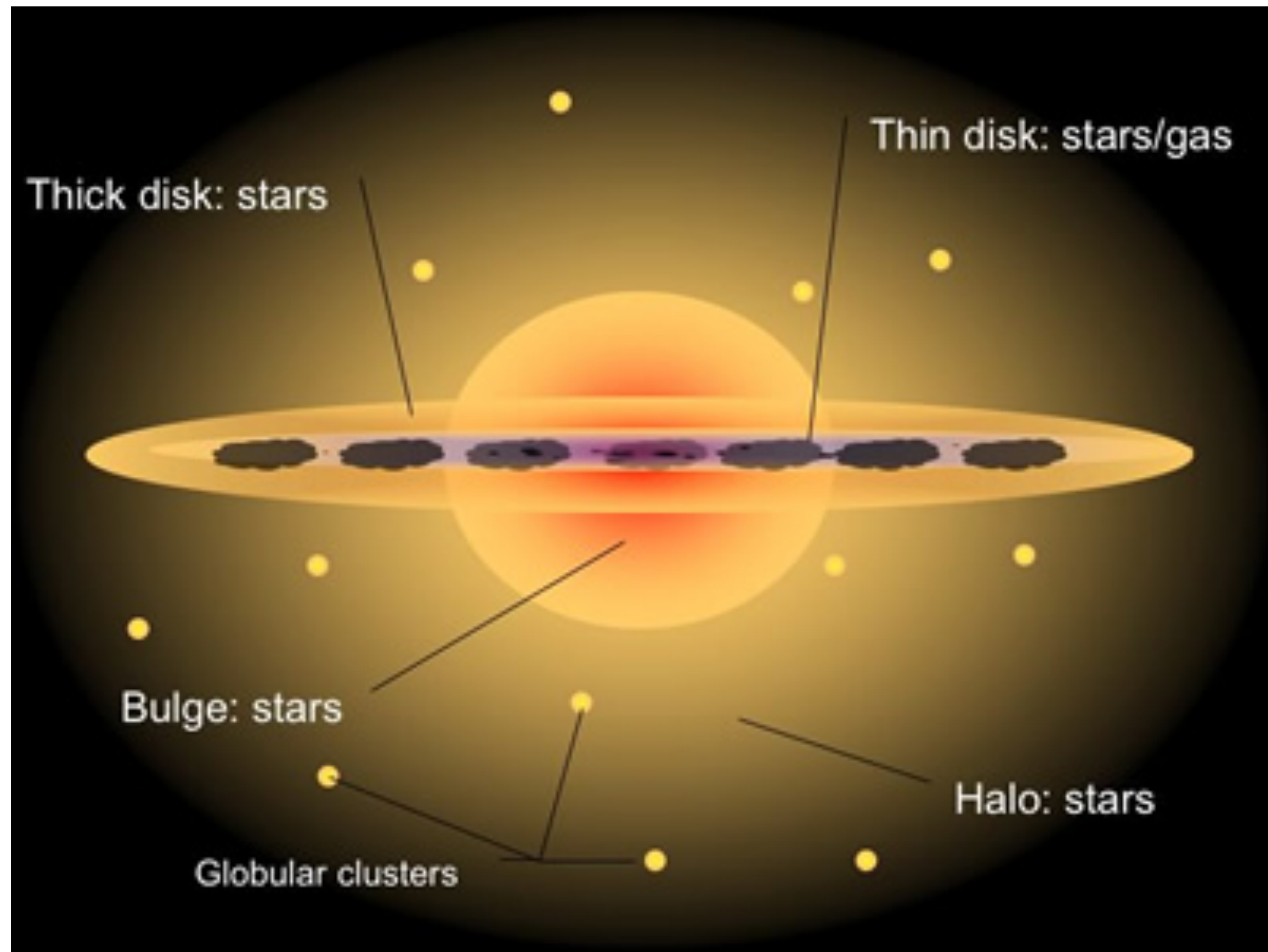
Borucki et al. 2010

# ③ Precise age-chemical relation of the disk



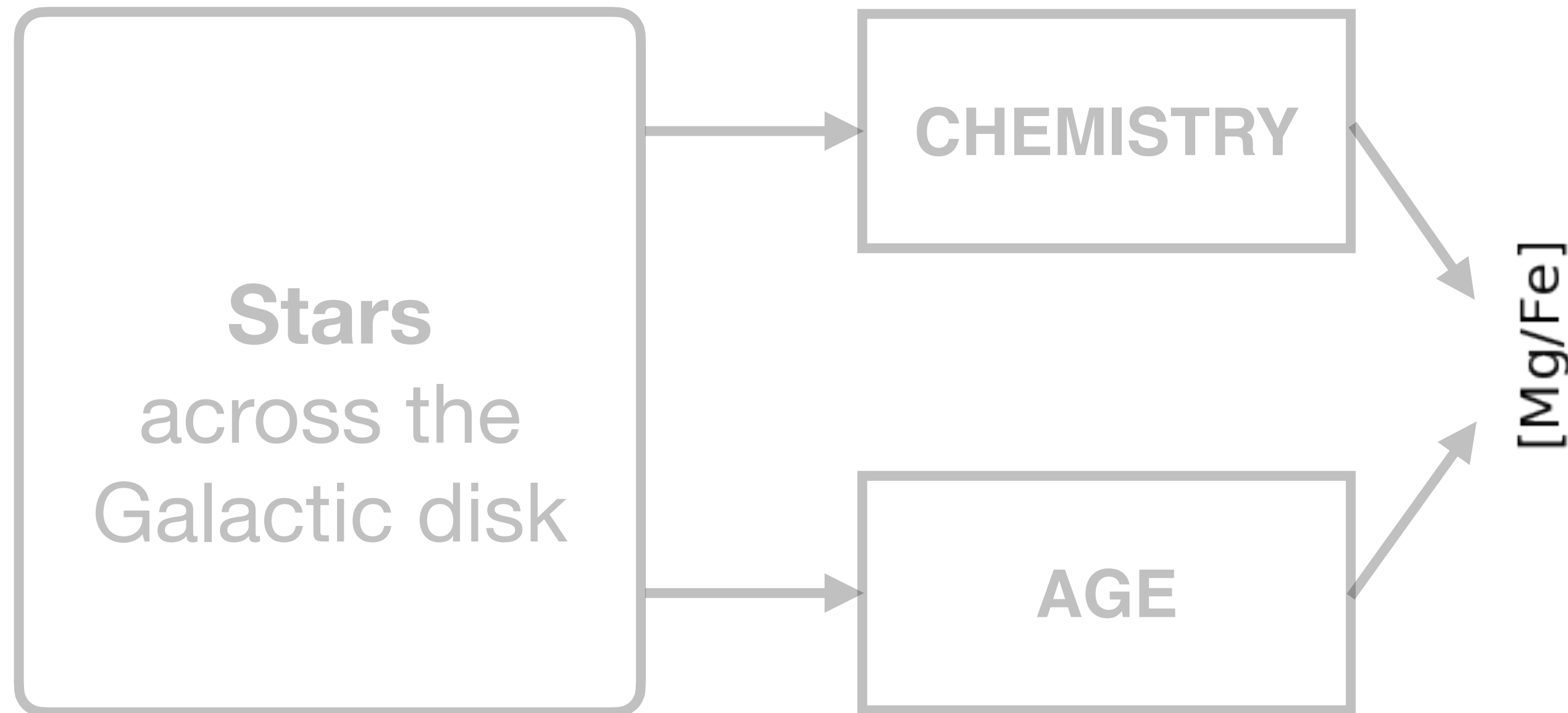


# ③ Precise age-chemical relation of the disk

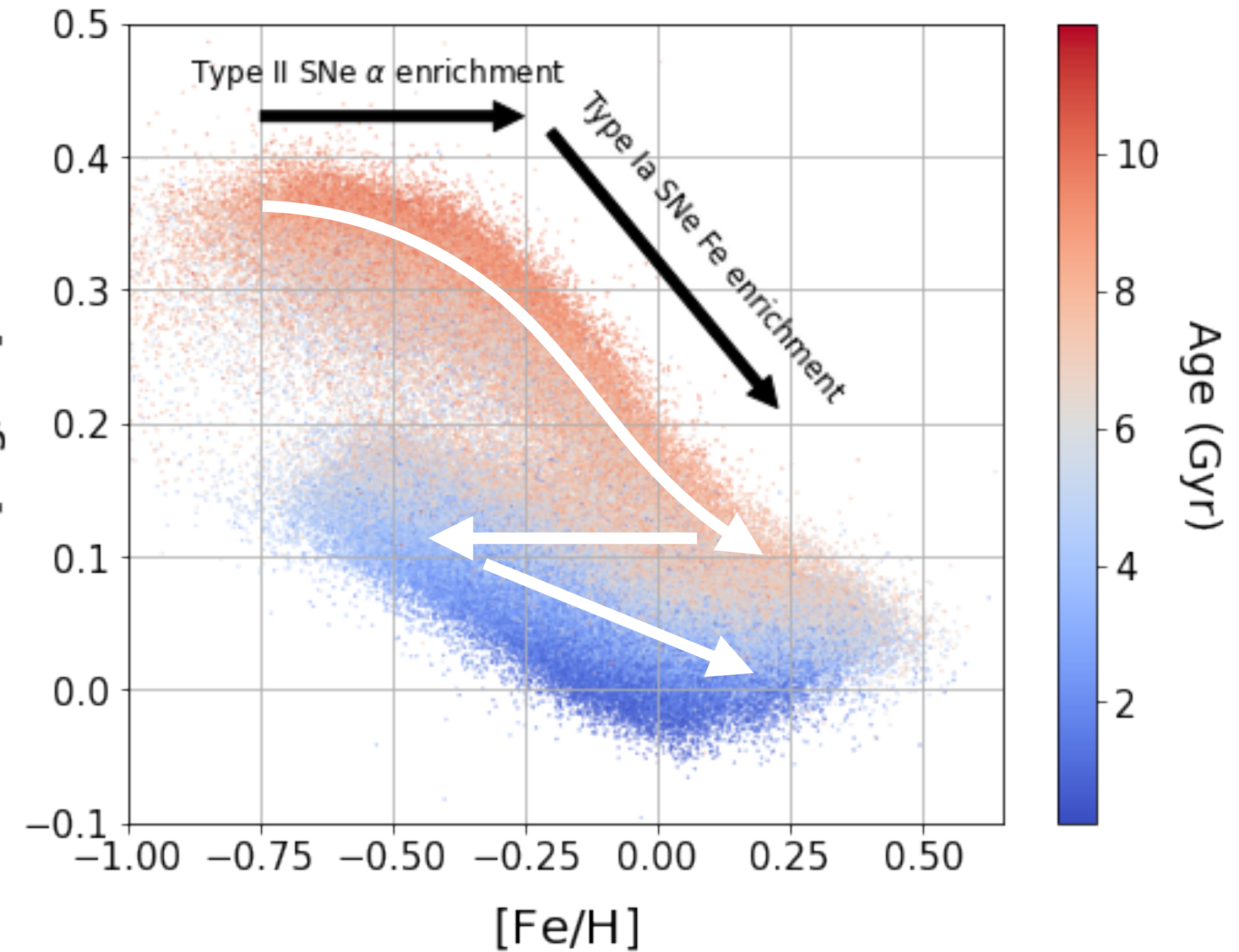


Credit: <https://astronomy.swin.edu.au/cosmos>

# ③ Precise age-chemical relation of the disk

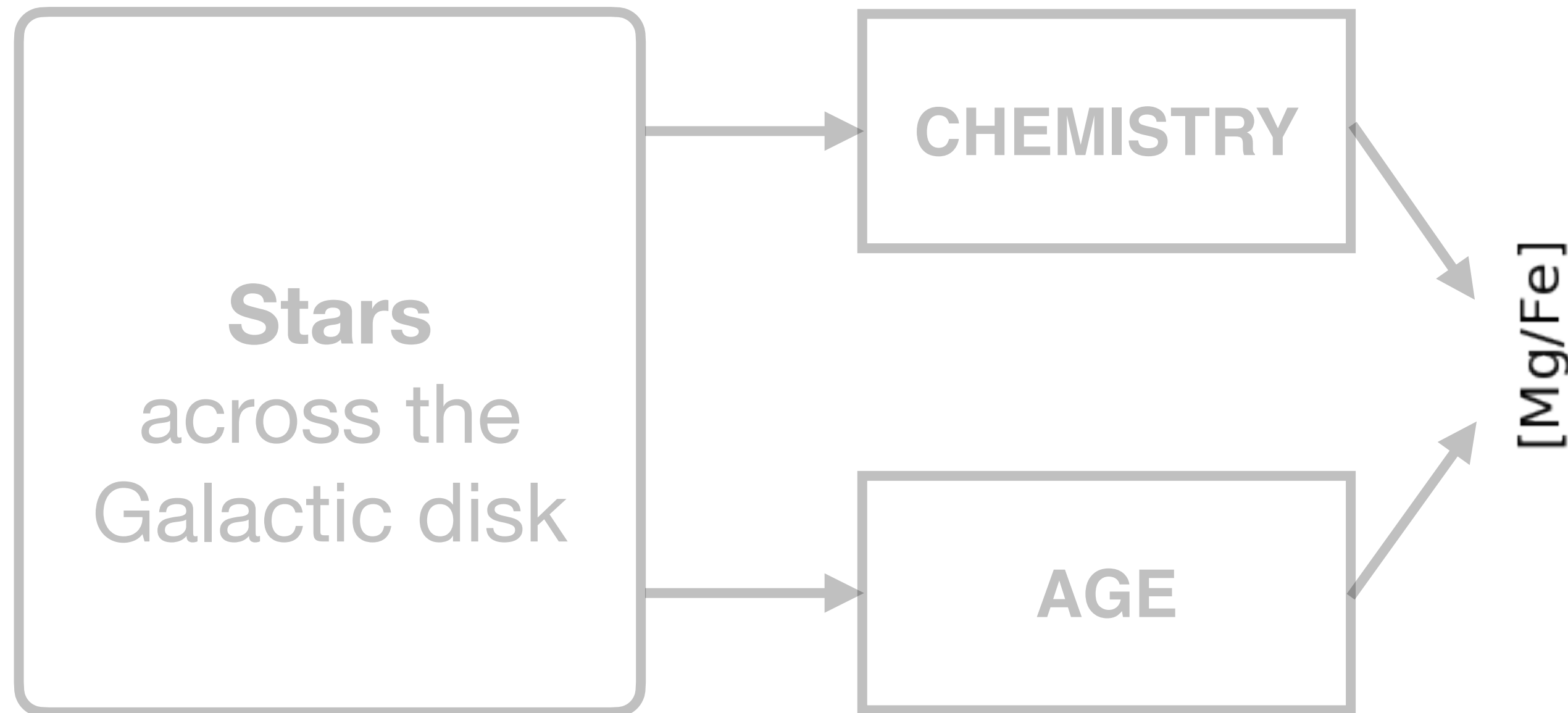


## Ex-situ scenarios

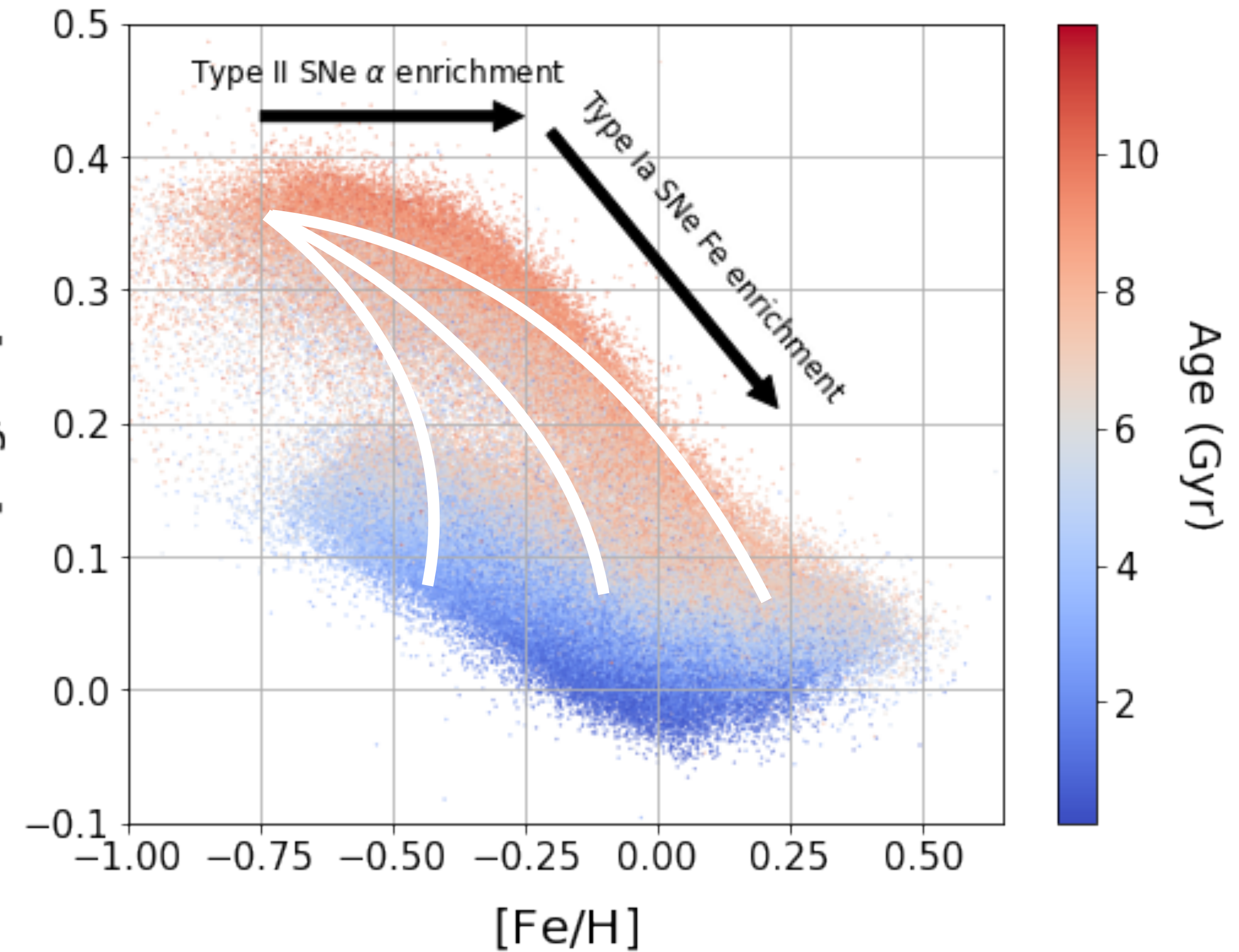


Chiappini, 2001

# ③ Precise age-chemical relation of the disk

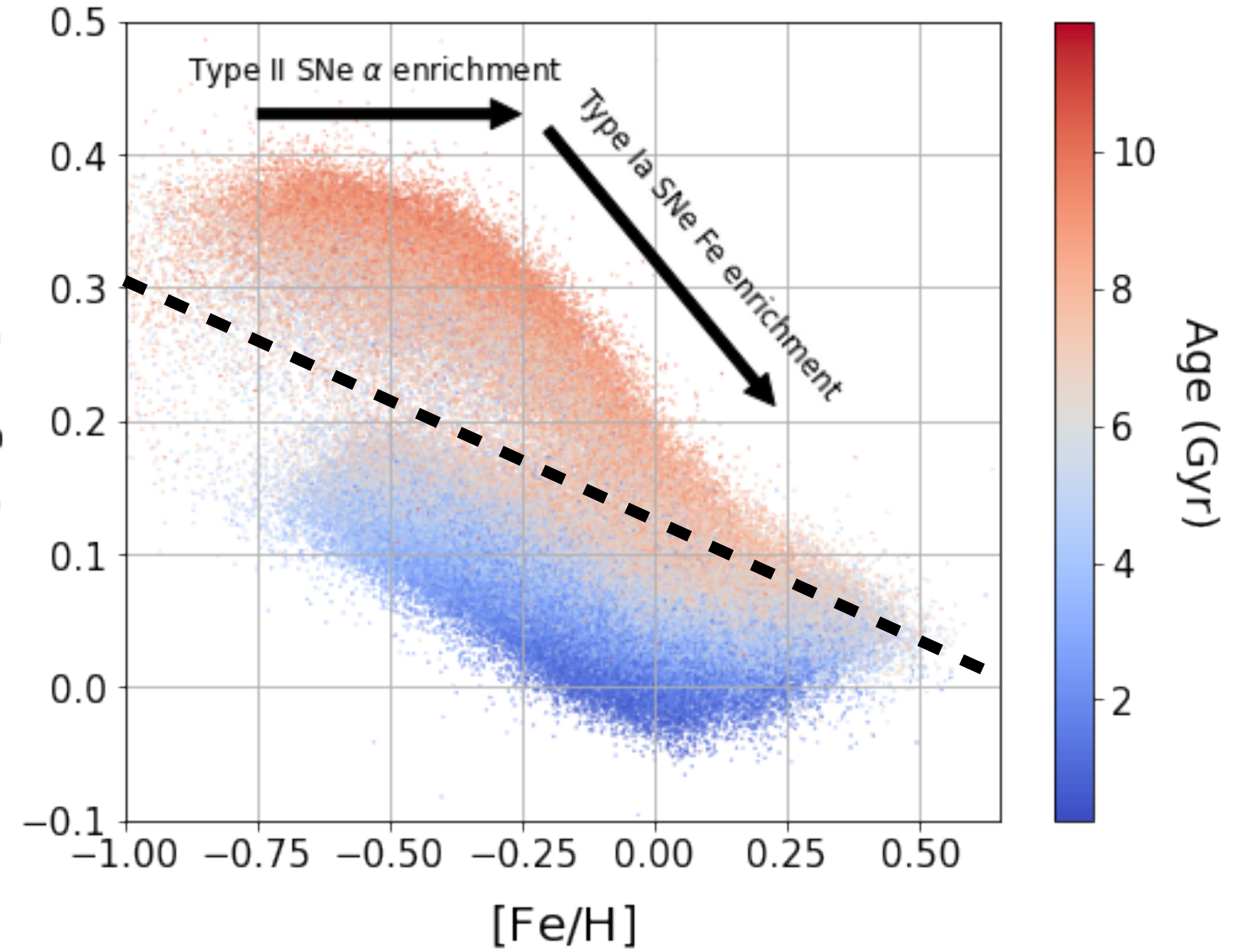
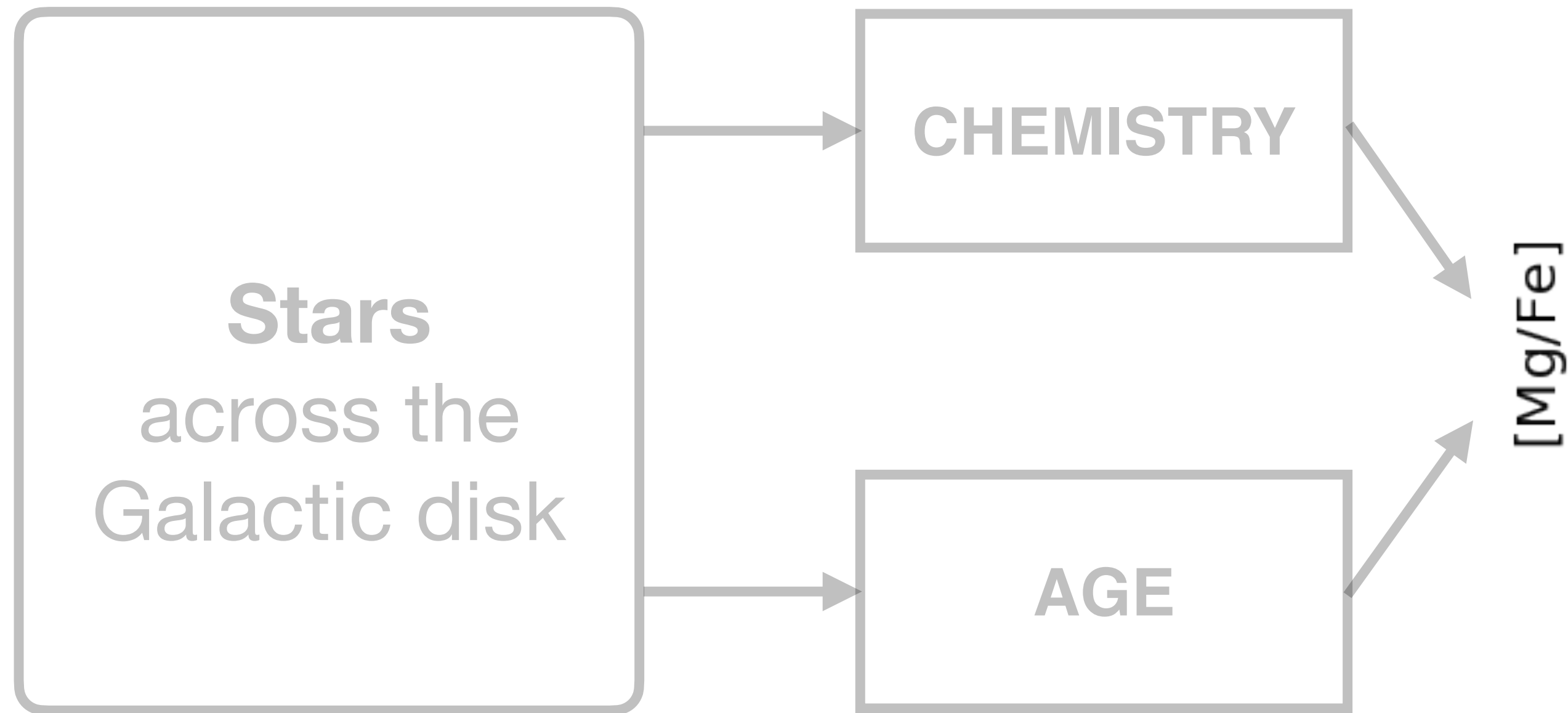


## In-situ scenarios



Sellwood & Binney, 2002

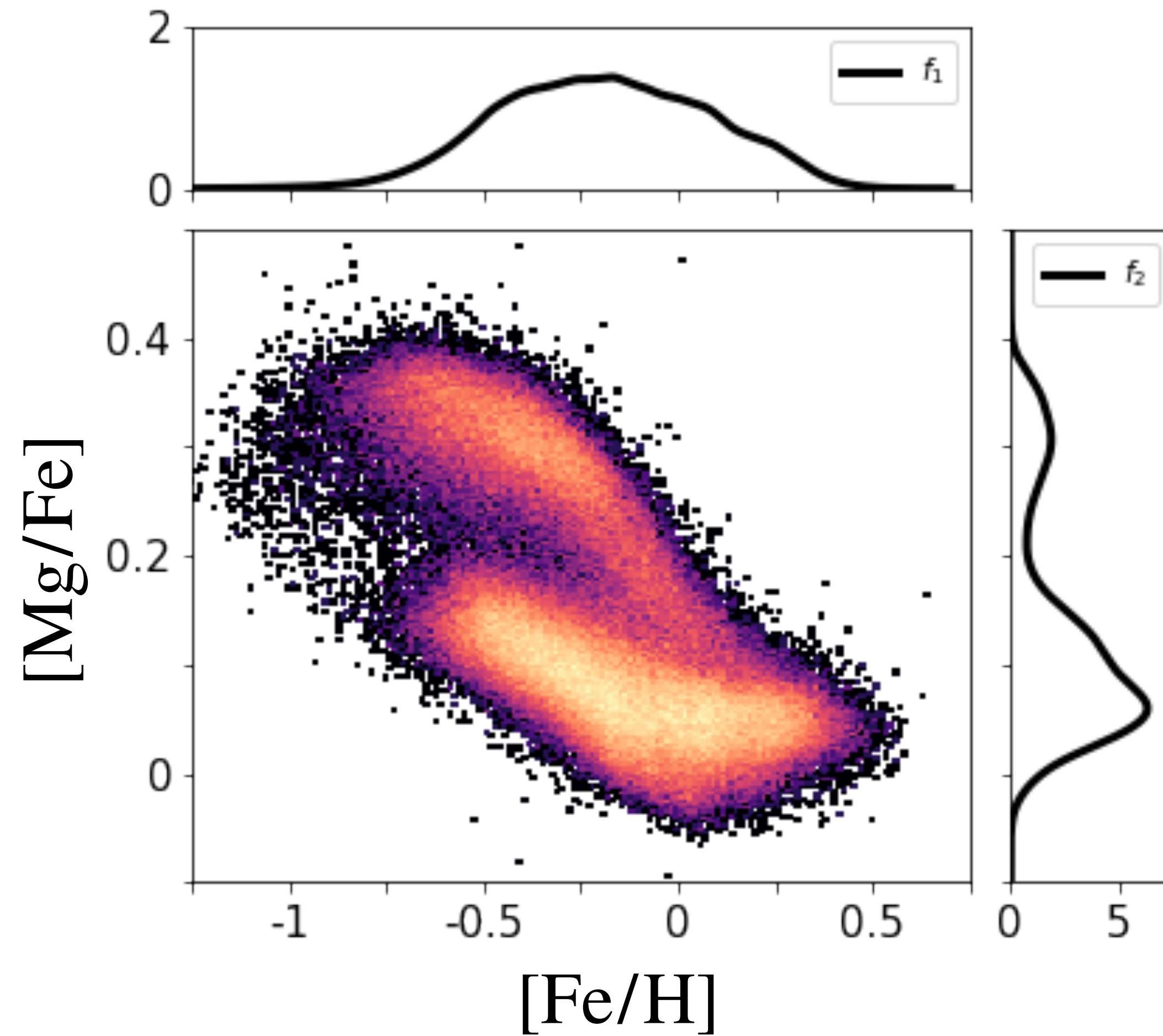
# PhD thesis



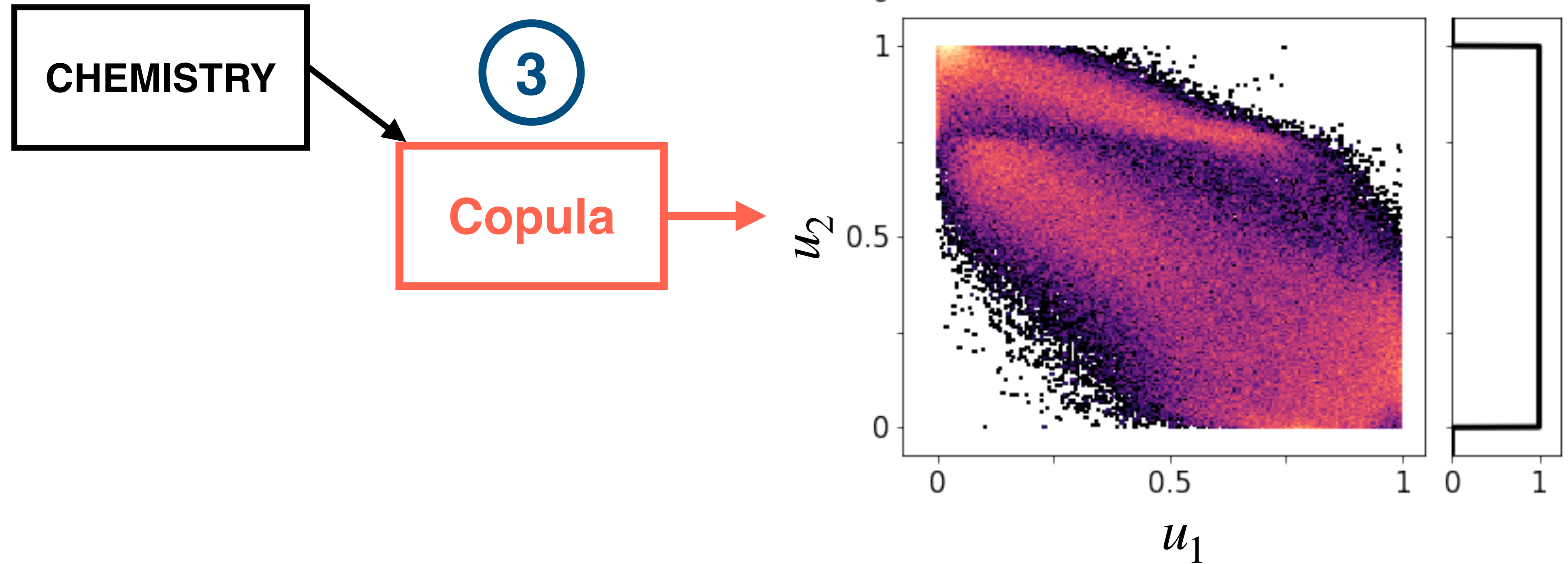
**Manual?**

# ③ Precise age-metallicity relation of the disk

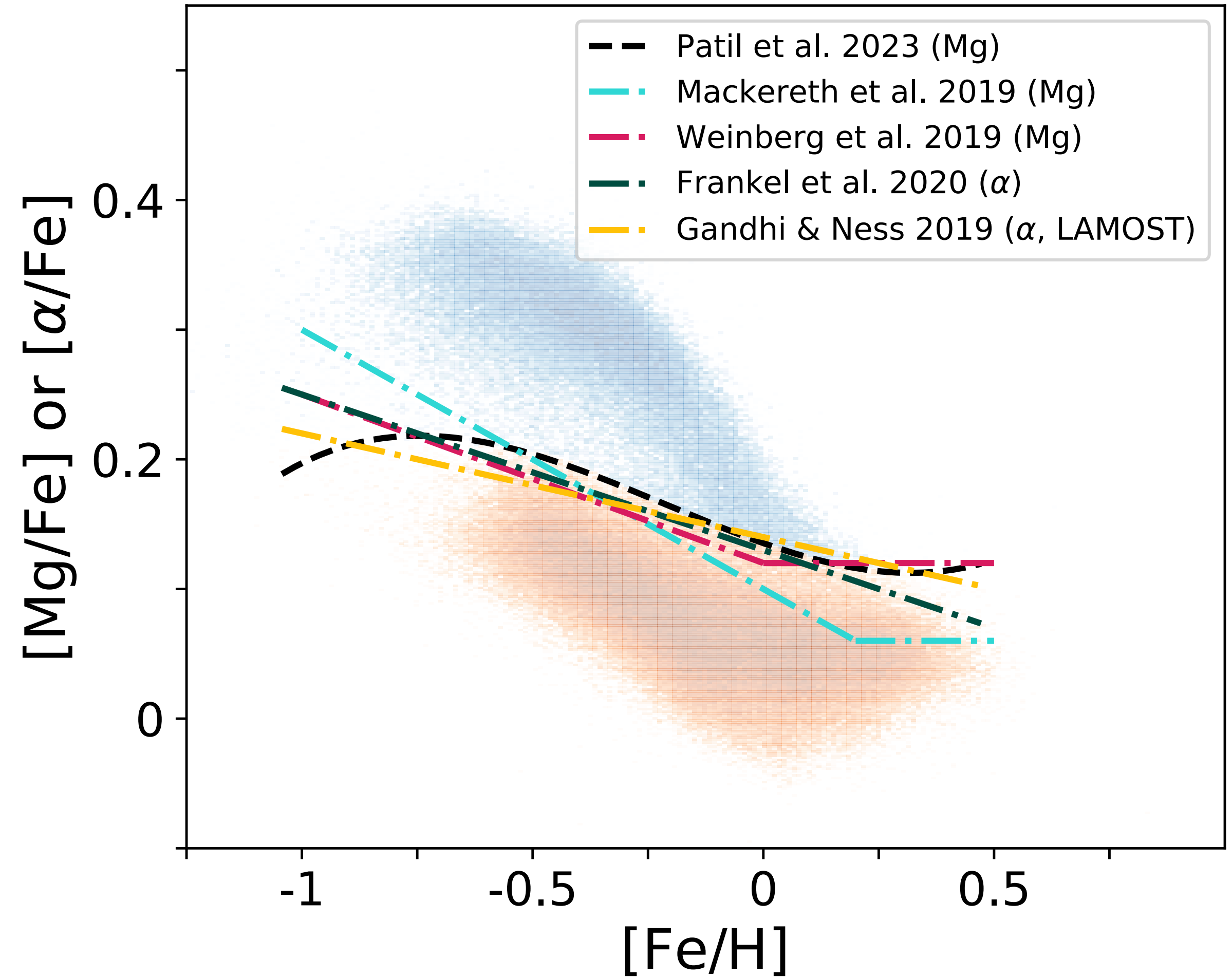
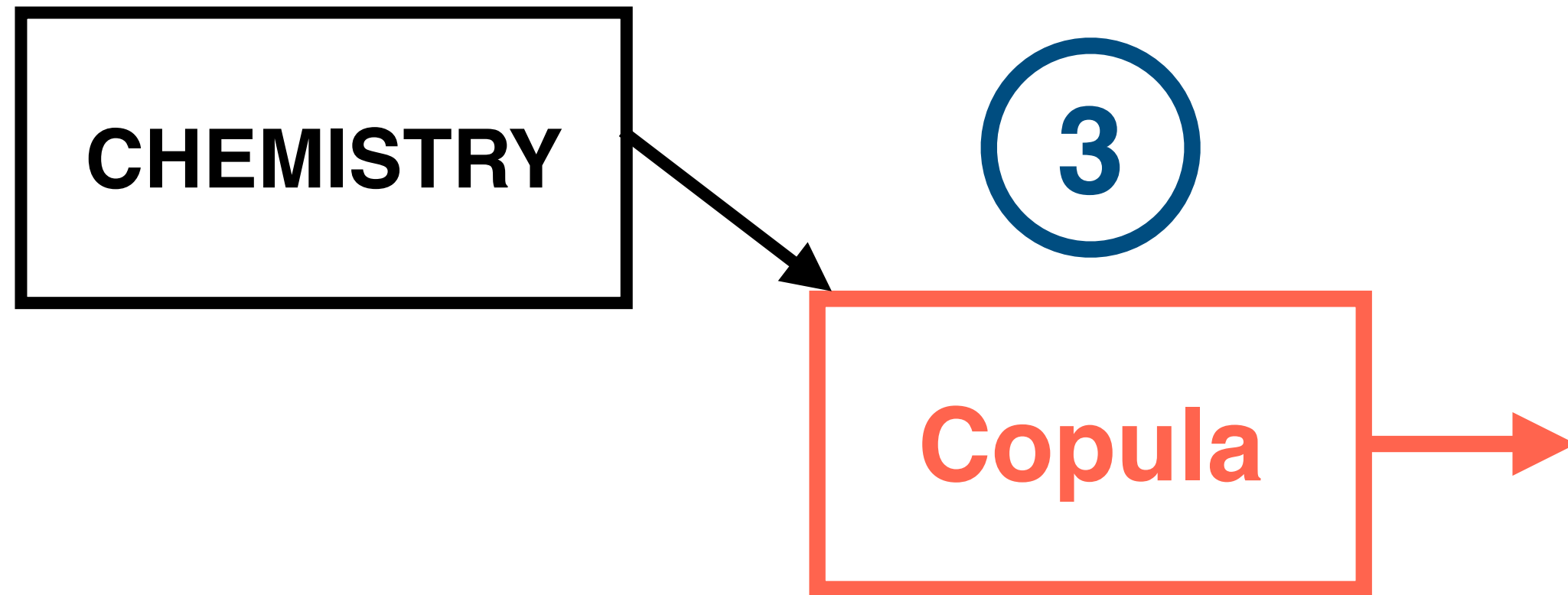
CHEMISTRY →



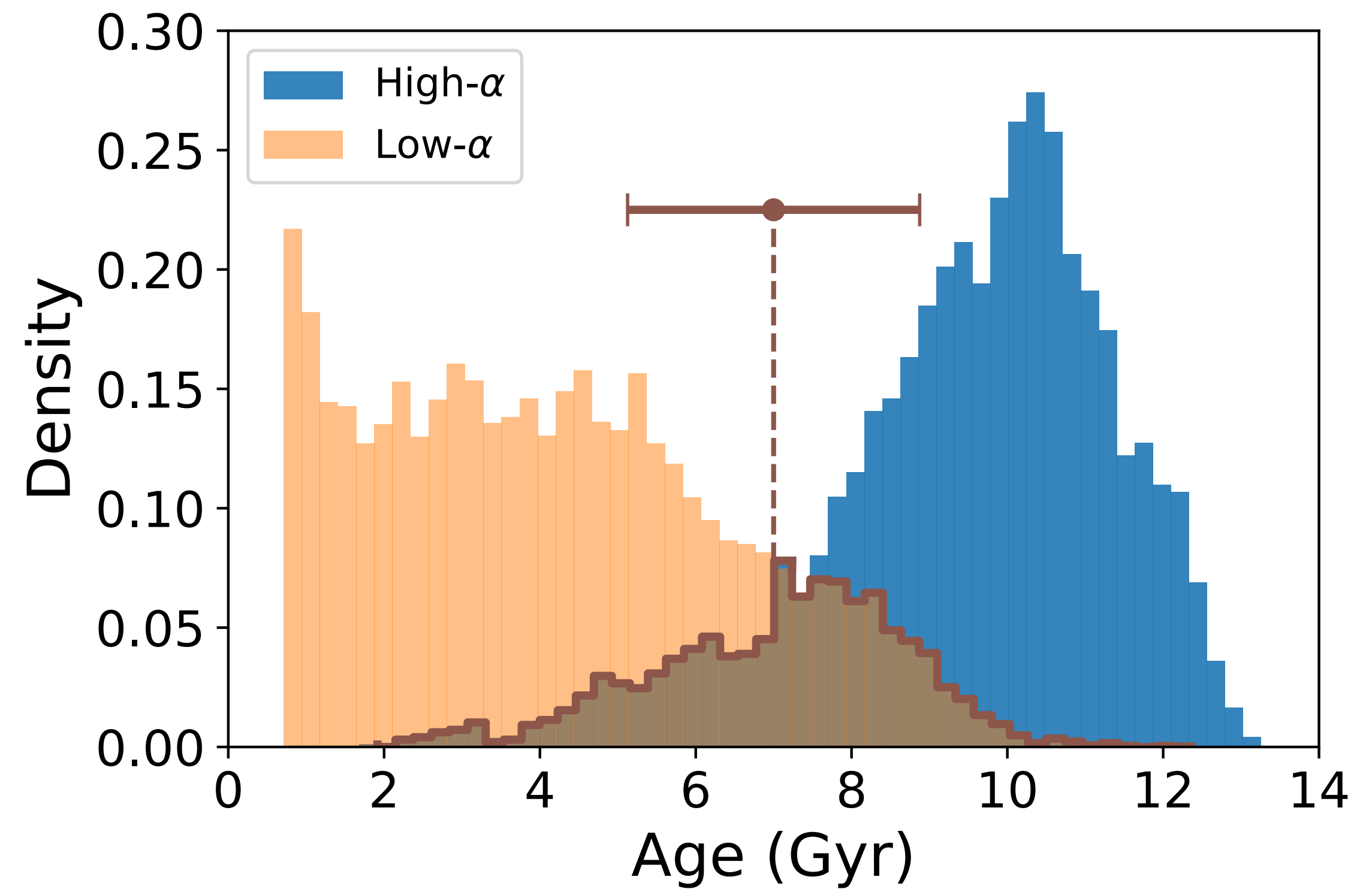
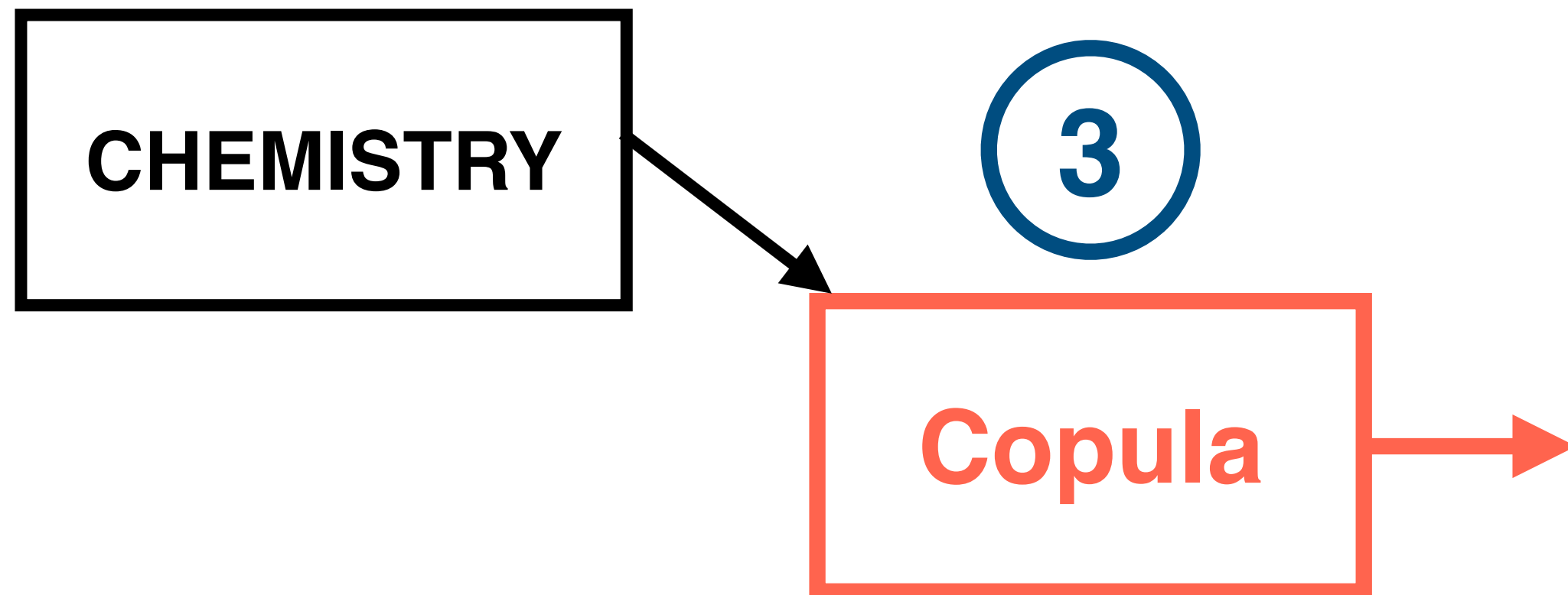
# ③ Precise age-metallicity relation of the disk



# ③ Precise age-metallicity relation of the disk

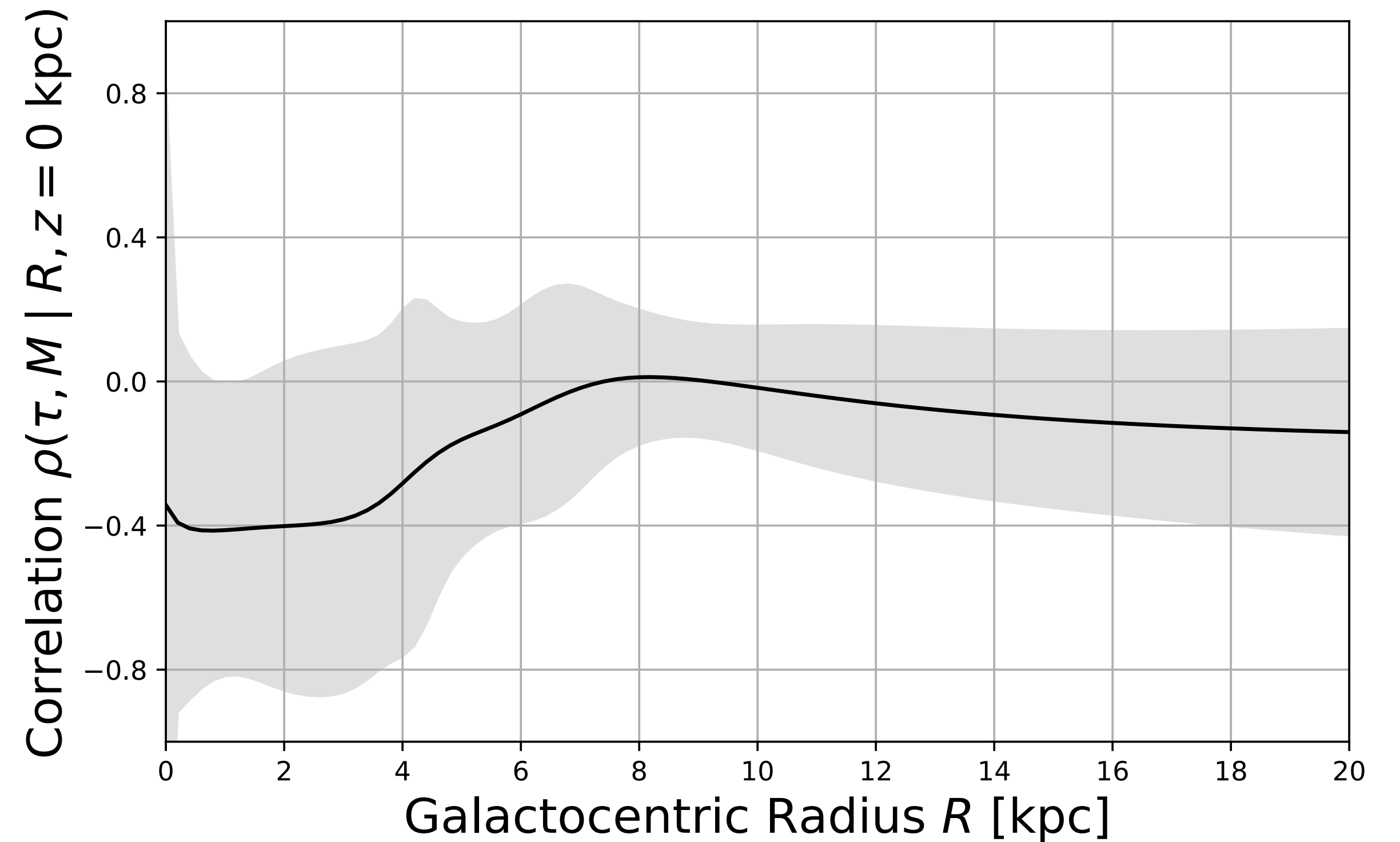
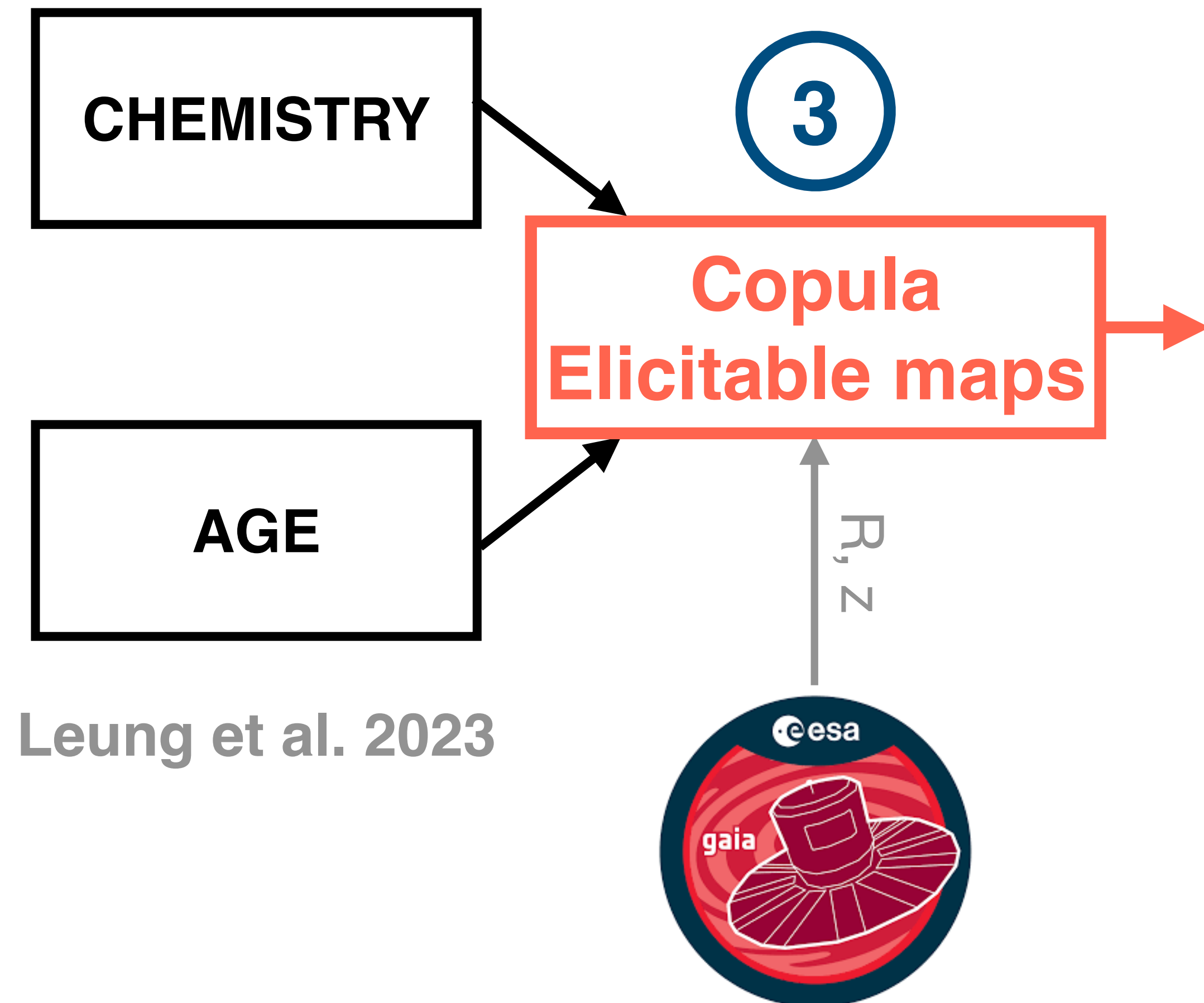


# ③ Precise age-metallicity relation of the disk





# ③ Precise age-metallicity relation of the disk



### ③ Elicitable maps

$$T : Y \rightarrow \mathbb{R}$$

Elicitable map is a map such that  $\exists S : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$   
where  $S$  is a score (loss) function

$$\arg \min_{x \in \mathbb{R}} \mathbb{E}[S(x, Y)] = T(Y)$$

### ③ Elicitable maps

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where  $S$  is a score (loss) function

$$\arg \min_{x \in \mathbb{R}} \mathbb{E}[S(x, Y)] = T(Y)$$

$$T[Y] = \mathbb{E}[Y]$$

$$S(x, Y) = (x - Y)^2$$

$$\arg \min_{x \in \mathbb{R}} \mathbb{E}[(x - Y)^2] = \mathbb{E}[Y]$$

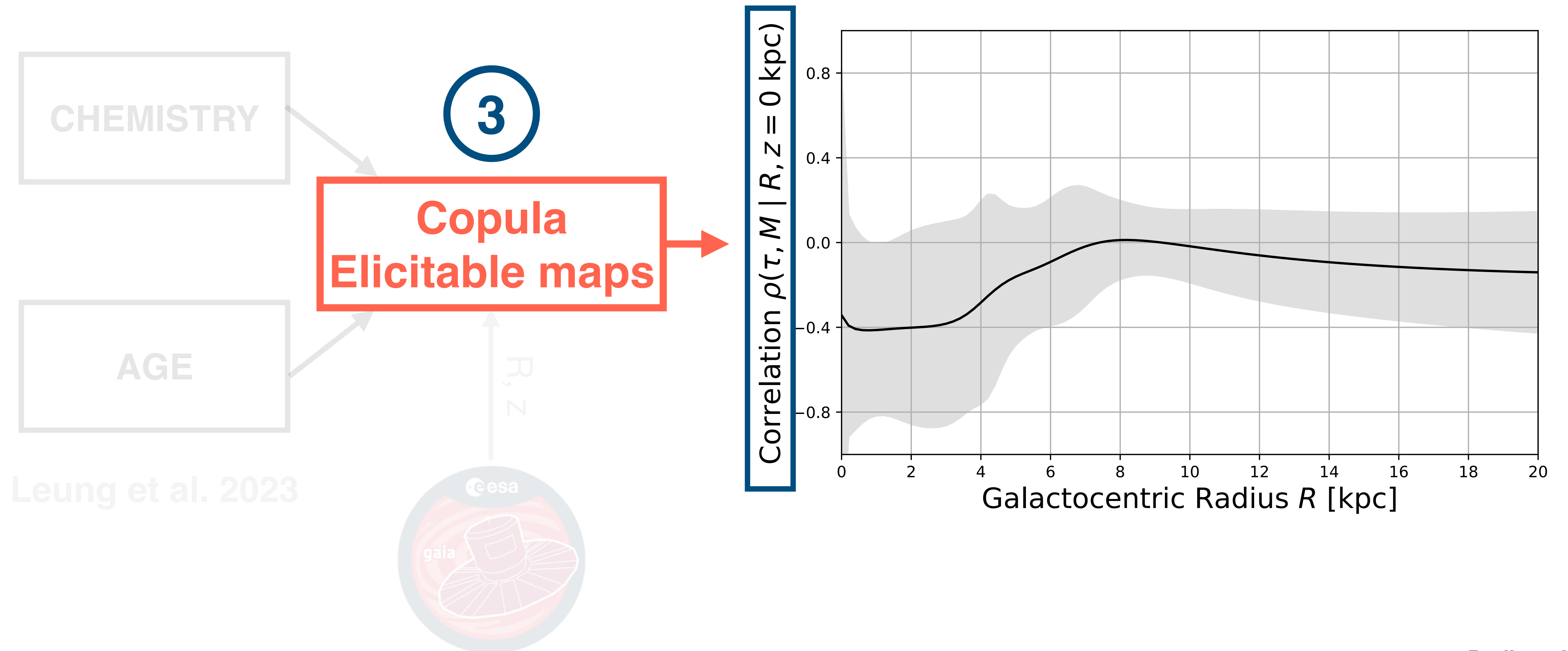
### ③ Conditional elicatability

$$T : Y \rightarrow \mathbb{R}$$

$$\arg \min_{g \in \mathbb{G}} \mathbb{E}[S(g(X), Y)] = T[Y | X = x]$$

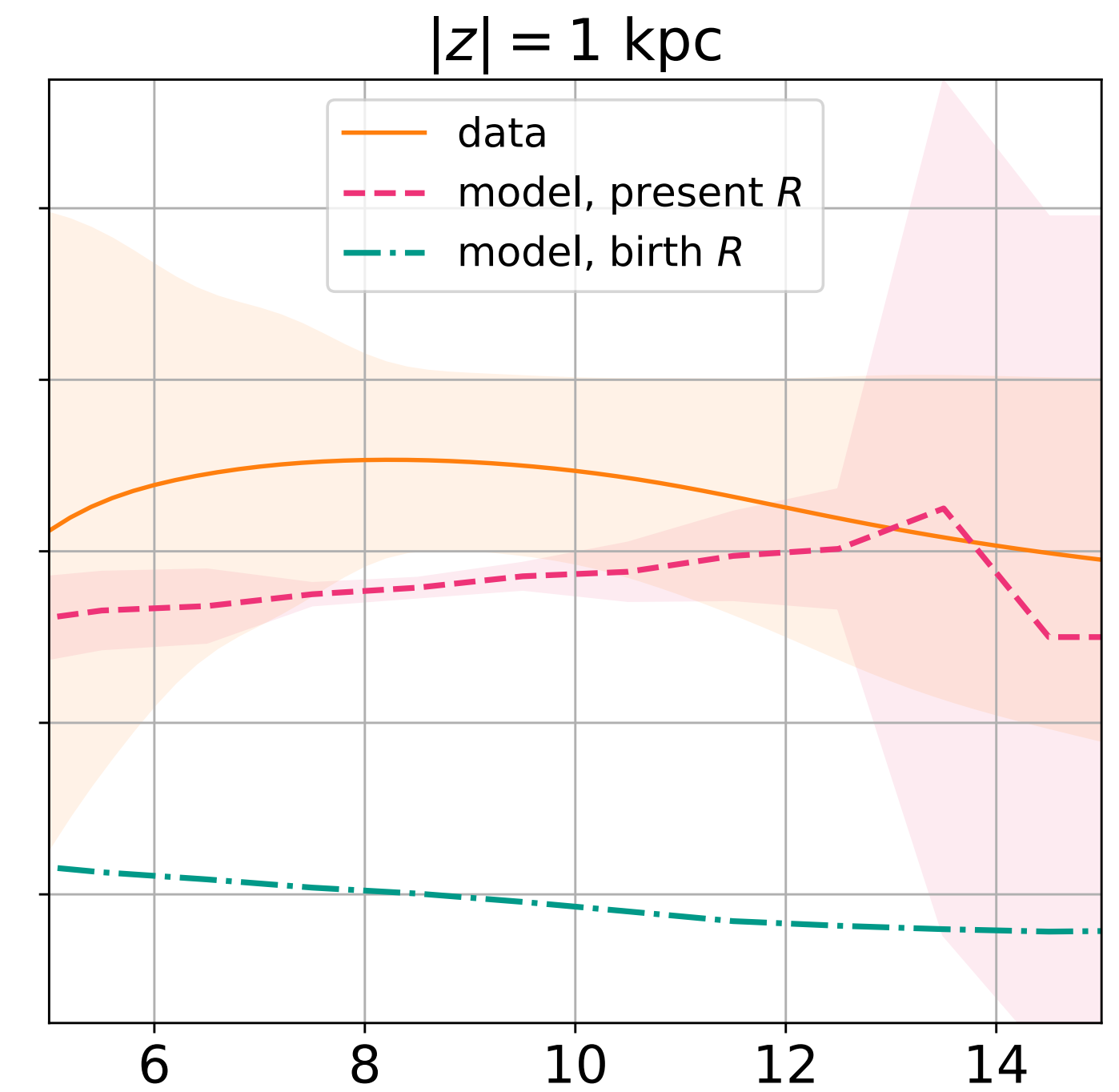
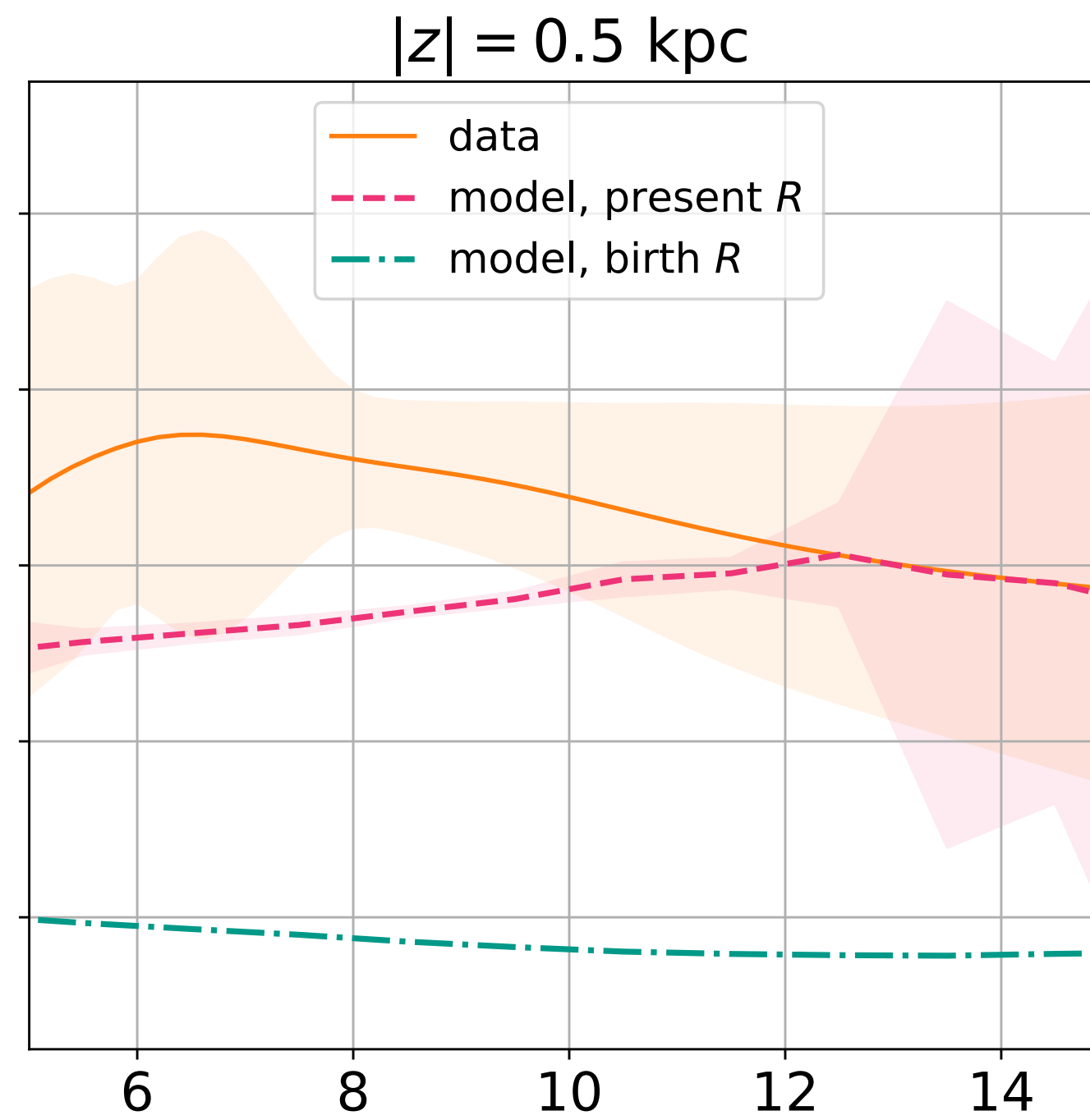
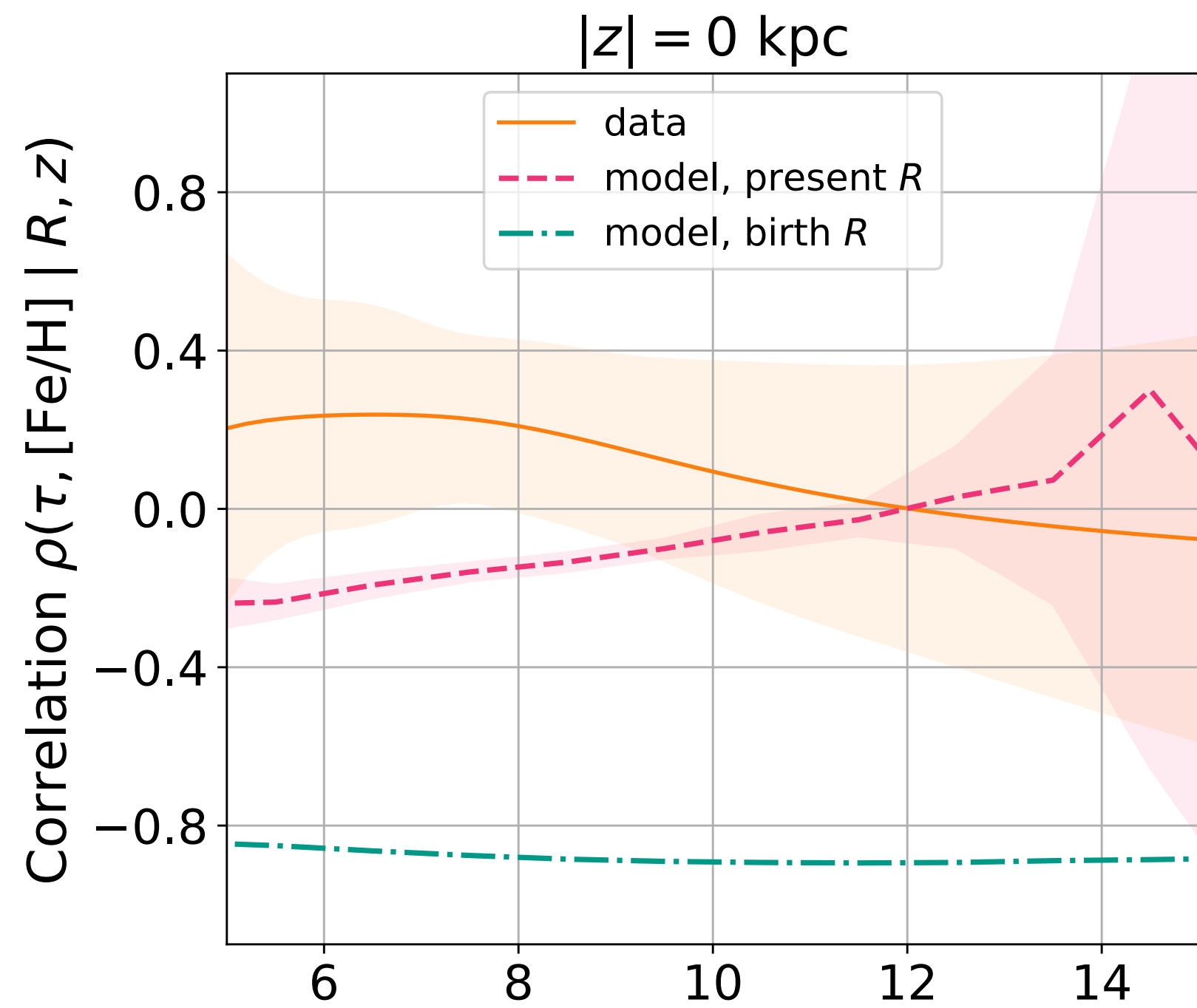
$$g(x) = a_0 + a_1x + a_2x^2 \dots$$

# ③ Precise age-metallicity relation of the disk



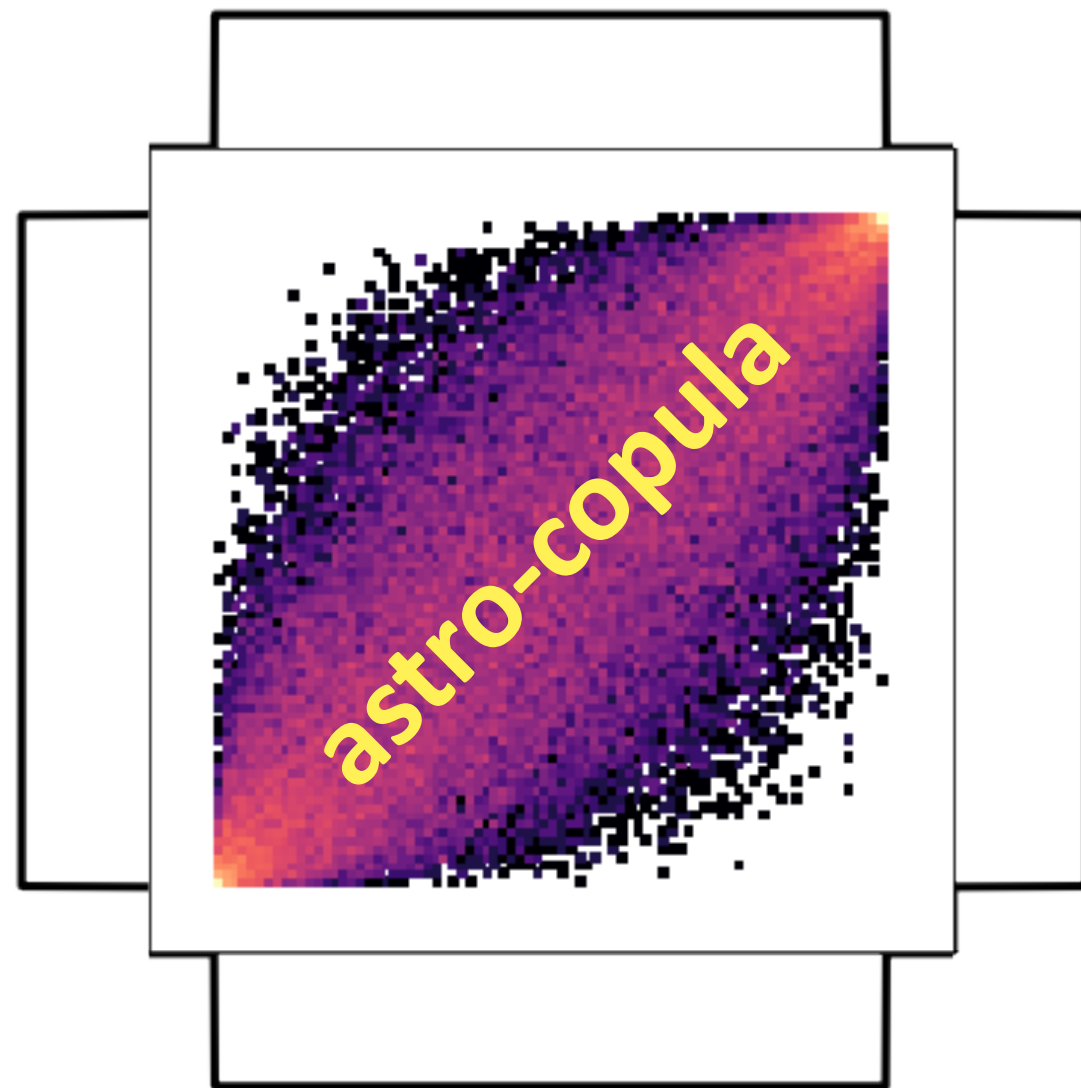
# ③ Comparison with radial migration models

## Data: Low- $\alpha$ disk



Model: Frankel et al. 2020

# ③ Dependence modeling



Galactic astronomy

Extragalactic astronomy

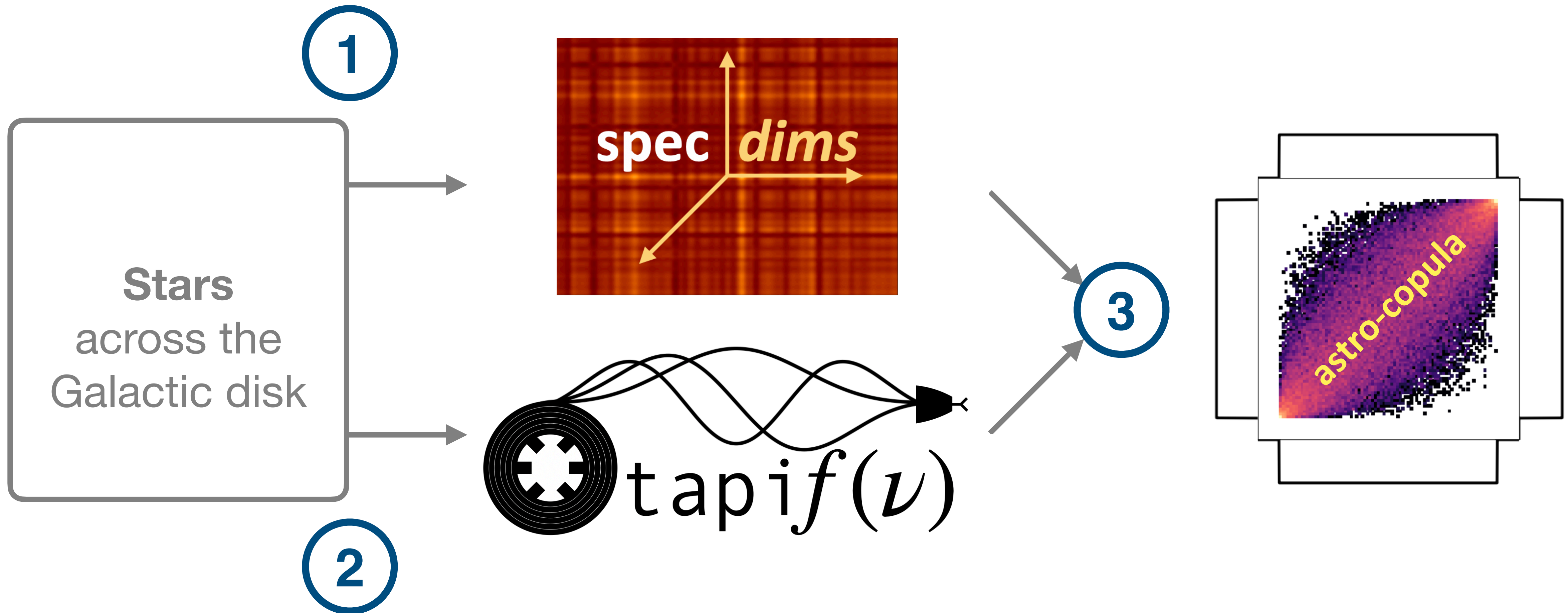
Cosmology

<> Code Issues Pull requests Actions Projects Wiki

```
from copula import Copula

model = Copula(data)
model.generate_copula_kde()
model.plot_copula()
```

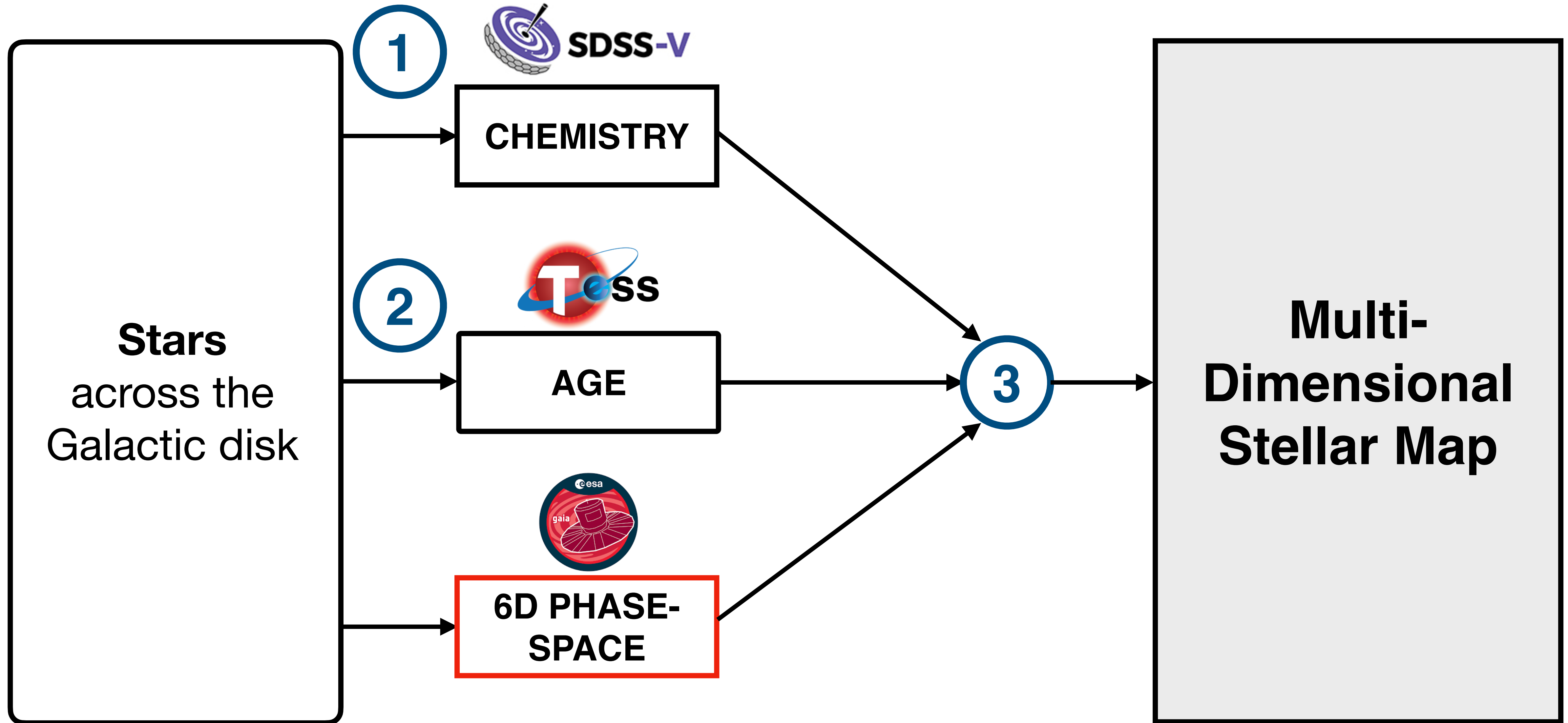
# Open-source software



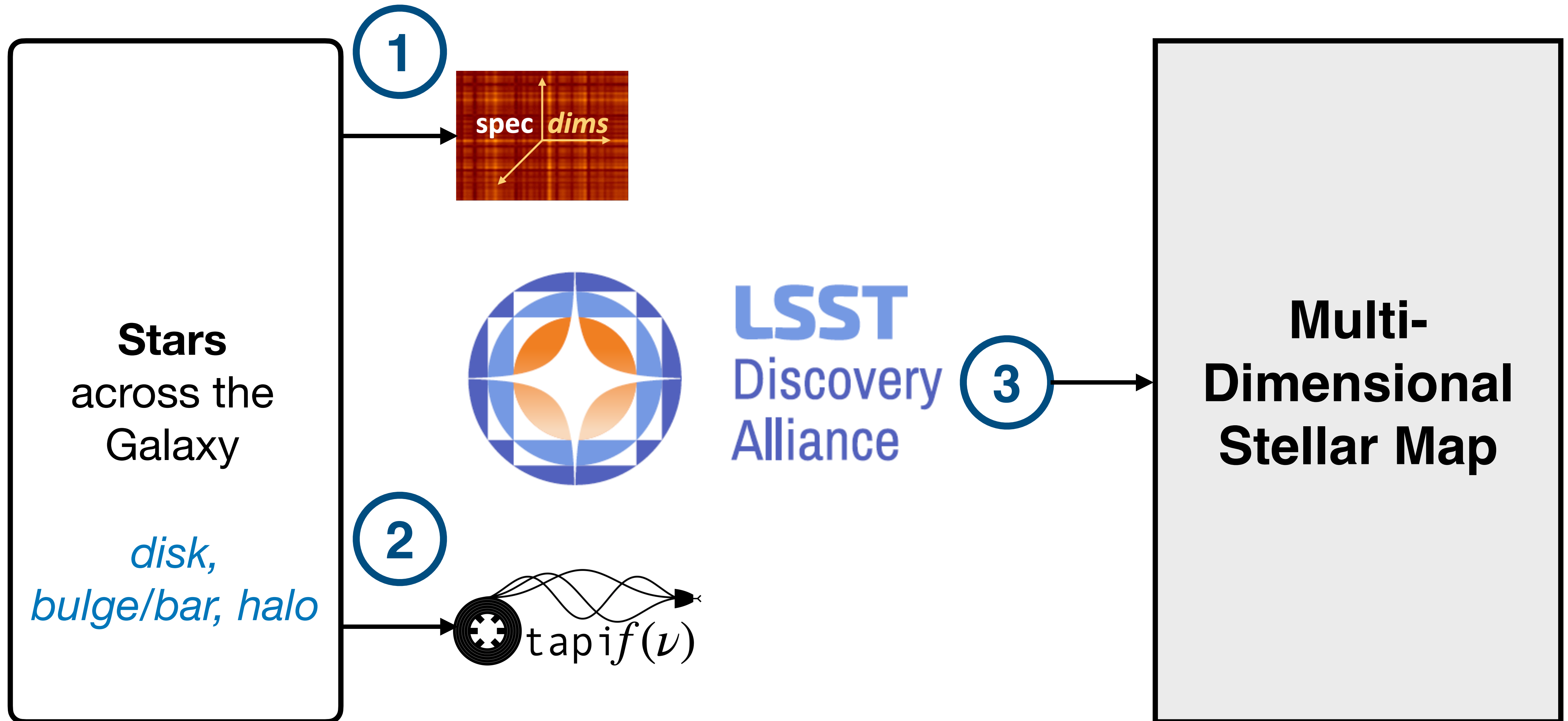
<https://github.com/aaryapatil>



# Ongoing



# Postdoctoral Plan





# Thank you!

Email: [patil@mpia.de](mailto:patil@mpia.de)

Website: <https://aaryapatil.github.io/>