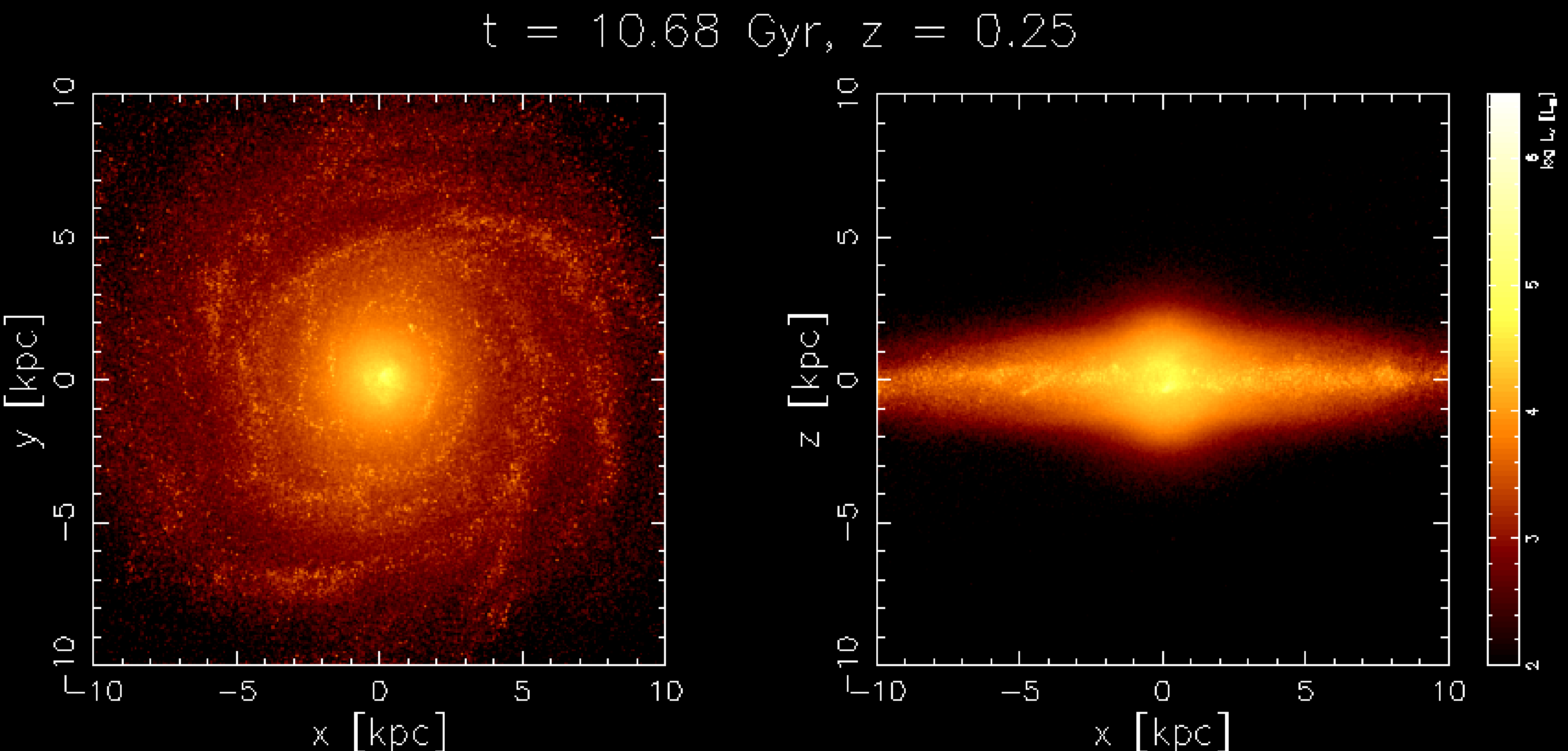
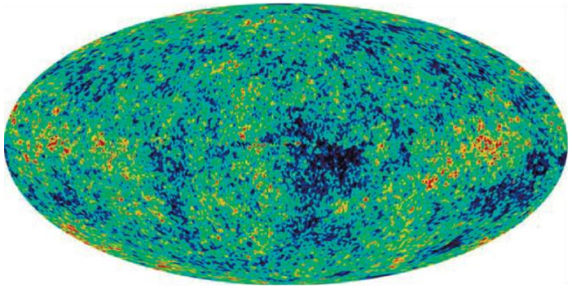
Chemical evolution with hydrodynamical cosmological simulations



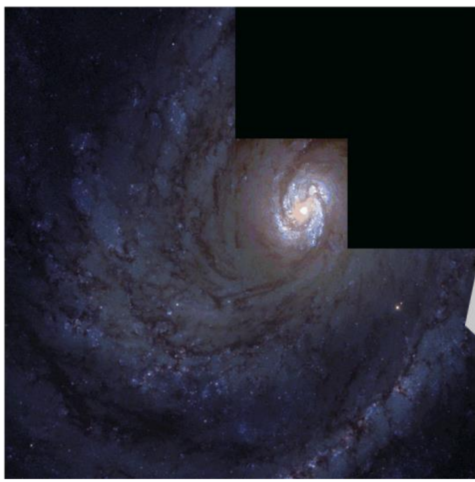
Chiaki Kobayashi (Univ. of Hertfordshire, UK)
George Darwin Lecturer, Royal Astronomical Society

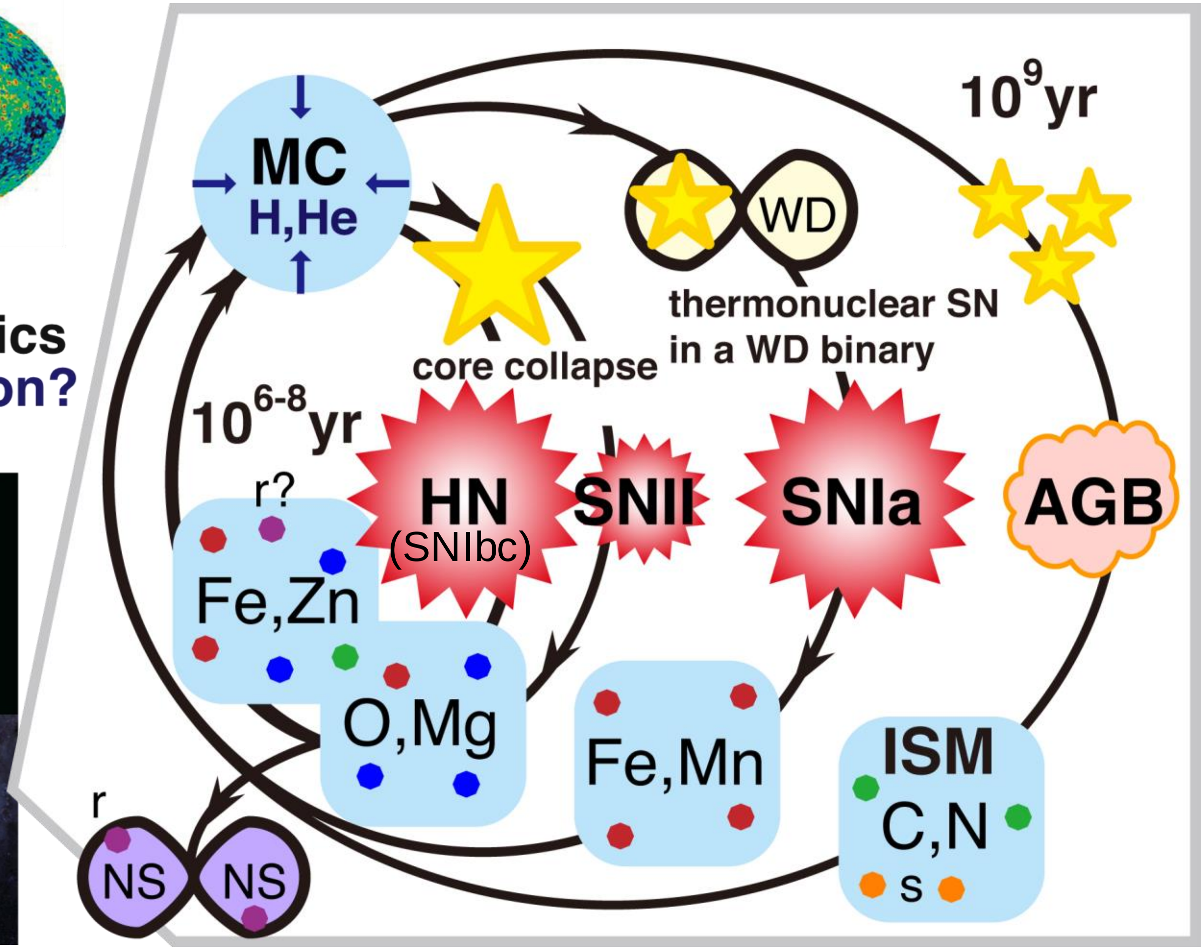
Galactic Chemical Evolution (GCE)

Nomoto, CK, Tominaga 2013 ARAA



Gravity
Hydrodynamics
Star Formation?
Feedback?





- [Fe/H] and [X/Fe] evolve in a galaxy: fossils that retain the evolution history of the galaxy → **Galactic Archaeology**

Galactic Chemical Evolution (GCE)

CK & Taylor 2023, ArXiv: 2302.07255

$$\frac{d(Zf_{\mathrm{g}})}{\mathrm{dt}} = E_{\mathrm{SW}} + E_{\mathrm{SNcc}} + E_{\mathrm{SNIa}\atop\mathrm{NSM}} - Zy + Z_{\mathrm{inflow}}R_{\mathrm{inflow}} - ZR_{\mathrm{outflow}}$$

Metal ejection rates

- nucleosynthesis yields
- initial mass function (IMF)
- binaries, SNIa/NSM progenitors
- nuclear reaction rates

Nuclear Astrophysics

decreased by star formation

Inflow   Outflow

Galaxy Evolution

① One-zone models

(Tinsley 80, Pagel 97, Matteucci 01...)

- instantaneous mixing approximation

② Semi-analytic models

- cosmological mass assembly

③ Hydrodynamical simulations

- inhomogeneous enrichment
- internal structures
- metallicity gradients
- comparison to IFU!

Cosmological box, or "zoom-in" for MW

Nuclei in the Cosmos XIII, Debrecen 2014

Galactic Chemical Evolution (GCE)

CK & Taylor 2023, ArXiv: 2302.07255

$$\frac{d(Zf_g)}{dt} = E_{SW} + E_{SNcc} + E_{\substack{SNIa \\ NSM}} - Zy + Z_{inflow}R_{inflow} - ZR_{outflow}$$

Inflow

- ❖ Cosmological flow (Z=0)
- ❖ Galaxy mergers (Z>0)
- ❖ Fountain (Z>0, low-α)
- ❖ Radial flow (high Z, high-α)

(Vincenzo & CK 2020)

Outflow

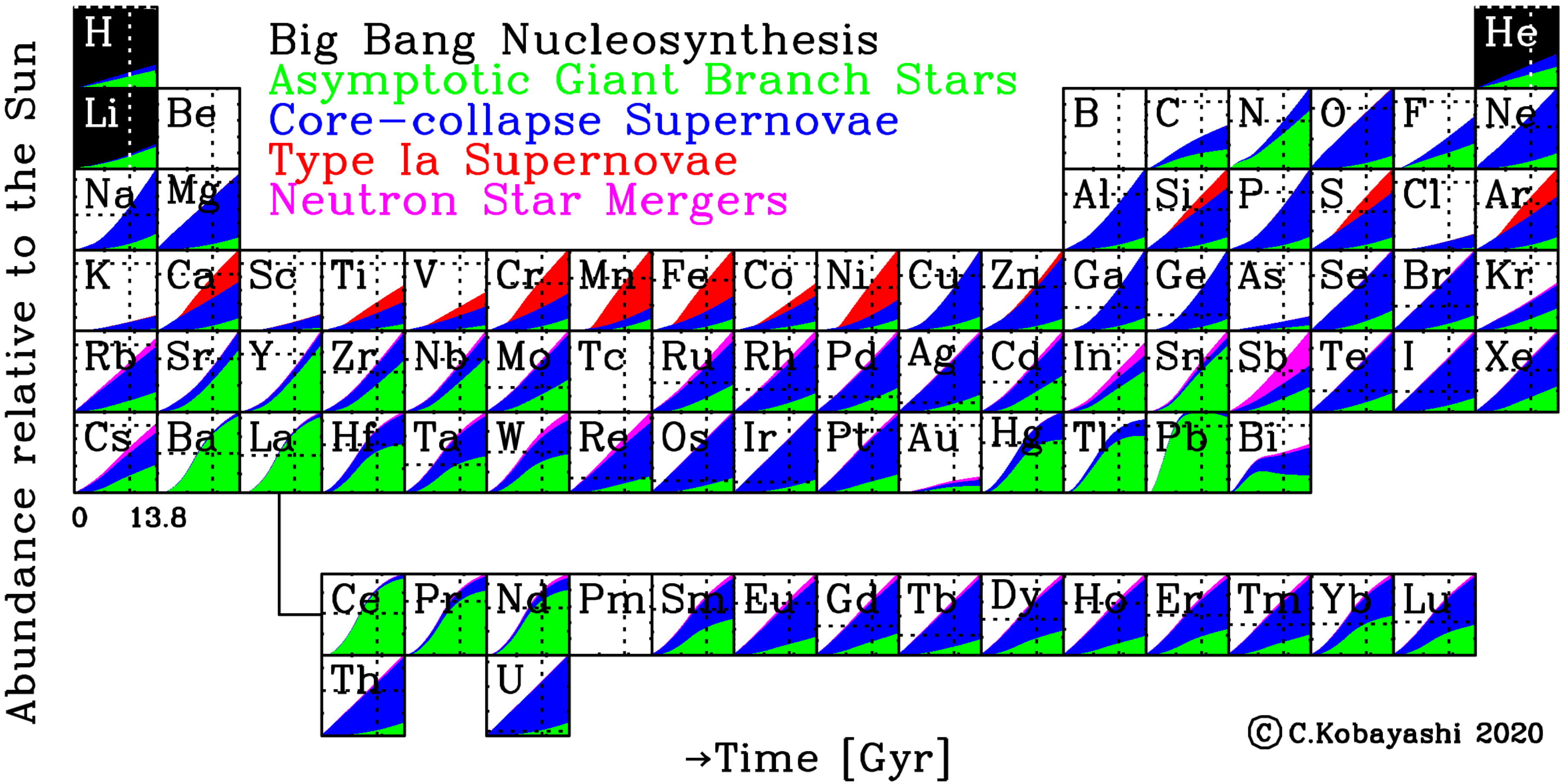
- ❖ Supernova driven winds ($M_{tot}<10^{10}M_\odot$)
- ❖ AGN driven winds ($M_{tot}>10^{11}M_\odot$)
- ❖ Tidal/ram pressure stripping

(Taylor, CK, Kewley 2020)

- ✓ All included in cosmological hydrodynamical simulations (subject to numerical resolution), as well as **stellar migration**.
- ✓ Constrained from: Evolution of (1) Metallicity radial gradients, (2) Elemental abundance ratios

The Origin of Elements

CK, Karakas, Lugaro 2020, ApJ



※Purely theoretical, no empirical equations.

※Mass-loss is counted toward AGB or ccSN.

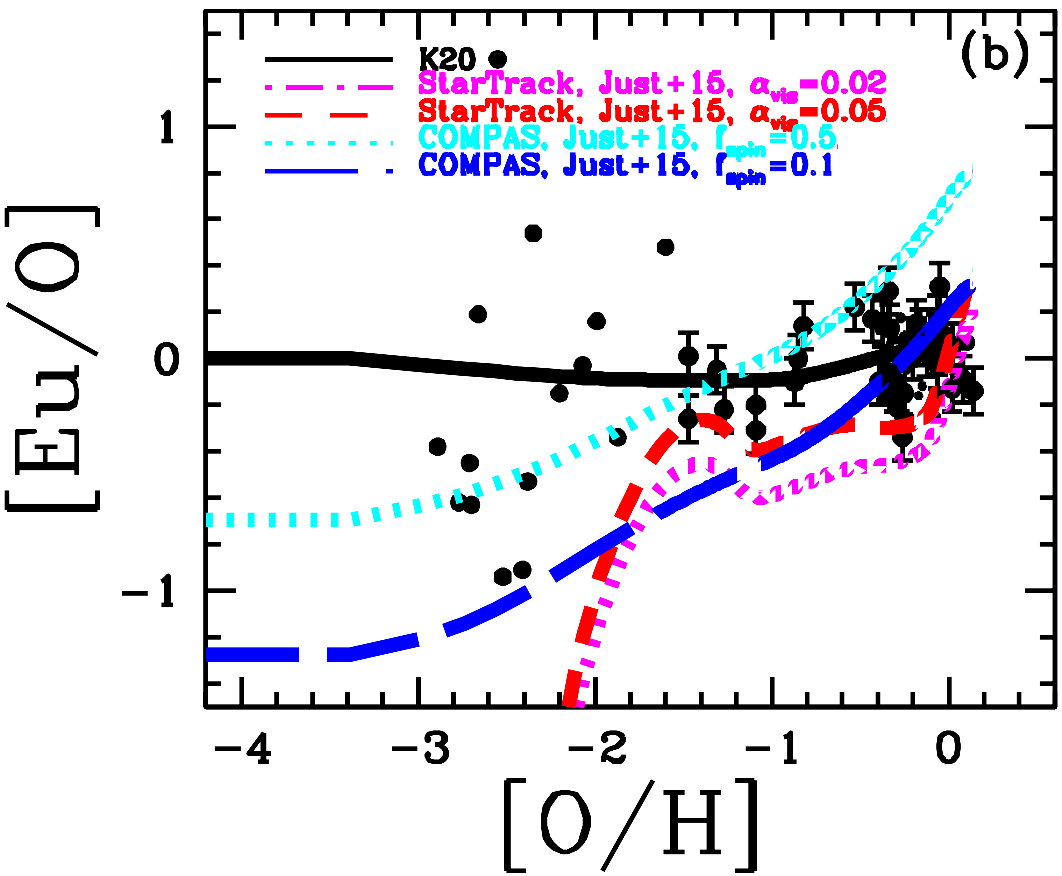
dotted lines: solar values

The Astrophysical Journal Letters, 943:L12 (11pp), 2023 February 1 https://doi.org/10.3847/2041-8213/acad82

Can Neutron Star Mergers Alone Explain the r-process Enrichment of the Milky Way?

Chiaki Kobayashi[1], Ilya Mandel[2,3], Krzysztof Belczynski[4], Stephane Goriely[5], Thomas H. Janka[6], Oliver Just[7,8], Ashley J. Ruiter[9], Dany Vanbeveren[10], Matthias U. Kruckow[11], Max M. Briel[12], Jan J. Eldridge[12], and Elizabeth Stanway[13]

NSM contribution will be higher, but MRSNe are still needed

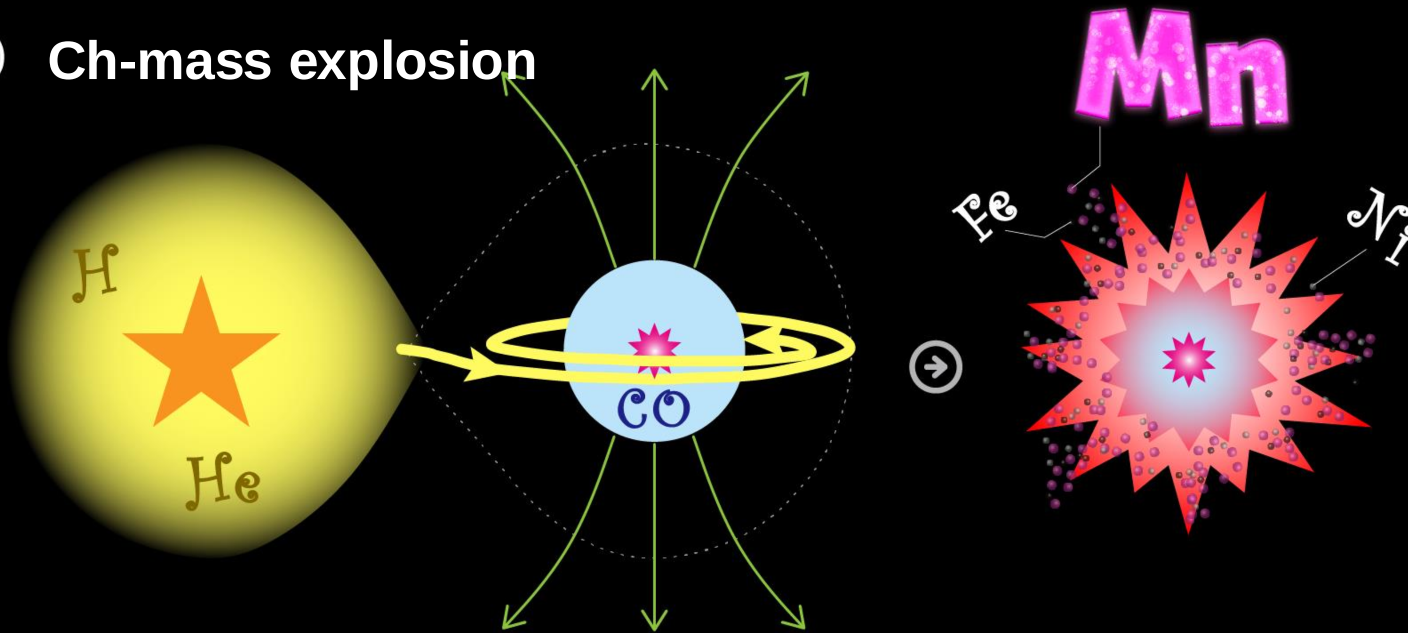


- **NS-BH** improved
- **Yieds** for both dynamical ejecta (Ye<0.1) and ν-driven winds from torus (Ye~0.2).
- **Higher rates** depending on binary population synthesis.

Points: observations of nearby stars

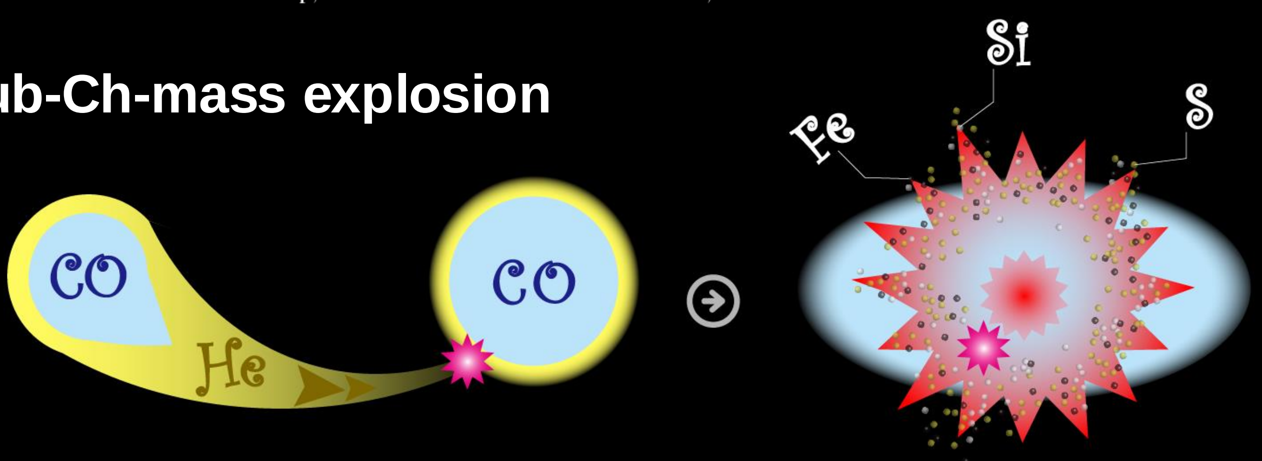
Thermonuclear (Type Ia) Supernovae

(a) **Ch-mass explosion**



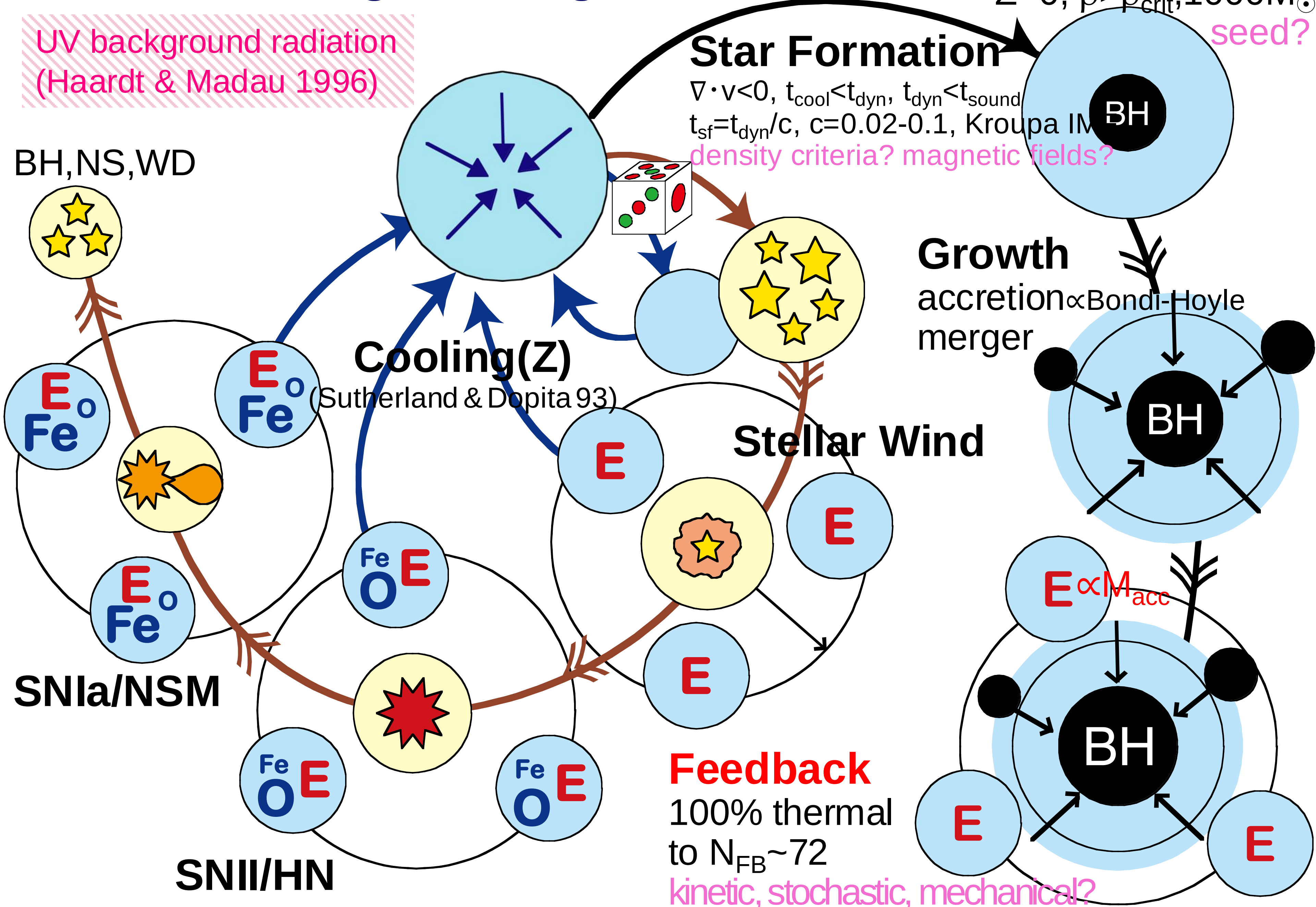
$$\mathscr{R}_{t,\mathrm{Ia}} = b \int_{\max[m_{\mathrm{p},\ell}, m_t]}^{m_{\mathrm{p},u}} \frac{1}{m} \phi(m)\, dm \int_{\max[m_{\mathrm{d},\ell}, m_t]}^{m_{\mathrm{d},u}} \frac{1}{m} \psi(t-\tau_m)\, \phi_{\mathrm{d}}(m)\, dm.$$

(b) **Sub-Ch-mass explosion**



CK, Leung, Nomoto 2020, also Seitenzahl+2013

Chemo-hydrodynamics



THE ASTROPHYSICAL JOURNAL, 729:16 (16pp), 2011 March 1 doi:10.1088/0004-637X/729/1/16

CHEMODYNAMICAL SIMULATIONS OF THE MILKY WAY GALAXY

CHIAKI KOBAYASHI[1] AND NAOHITO NAKASATO[2,3,4]

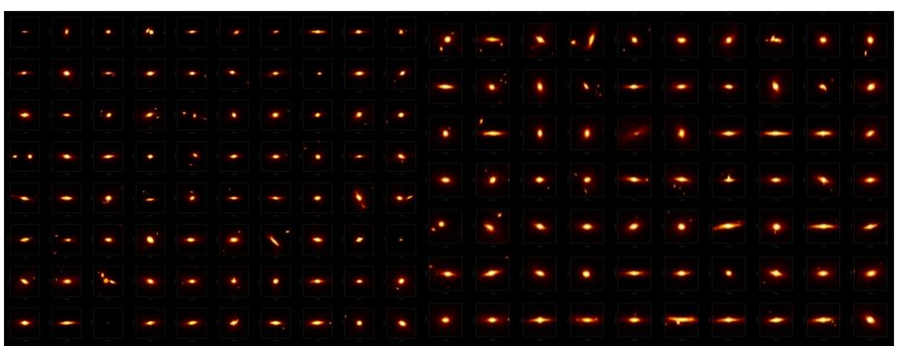
2011

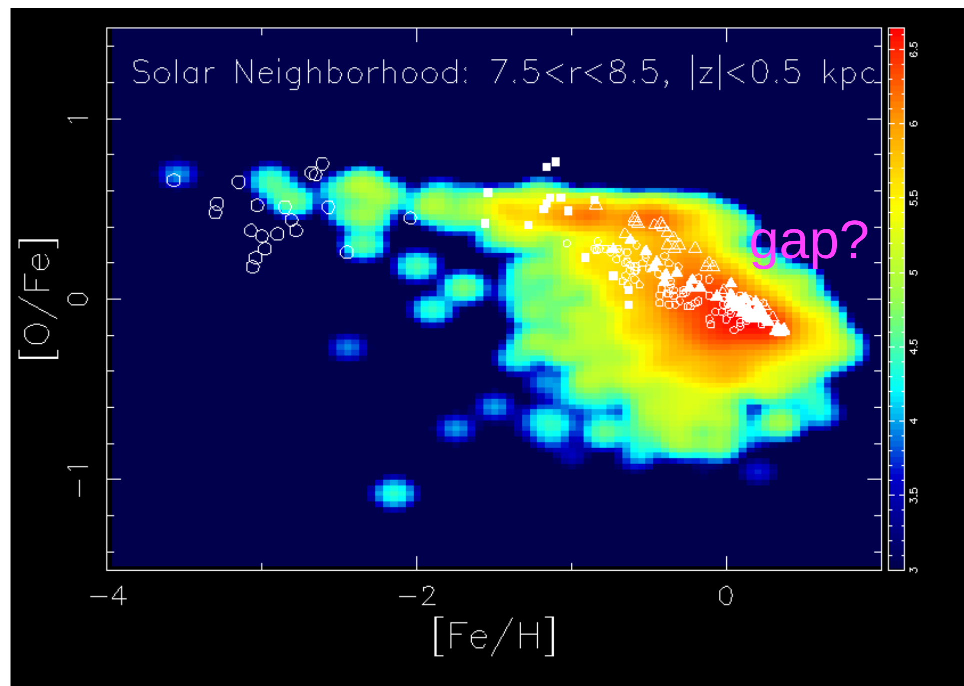
ABSTRACT

We present chemodynamical simulations of a Milky-Way-type galaxy using a self-consistent hydrodynamical code that includes supernova feedback and chemical enrichment, and predict the spatial distribution of elements from oxygen to zinc. In the simulated galaxy, the kinematical and chemical properties of the bulge, disk, and halo are consistent with the observations. The bulge formed from the assembly of subgalaxies at $z \gtrsim 3$, and has higher $[\alpha/Fe]$ ratios because of the small contribution from Type Ia supernovae. The disk formed with a constant star formation over 13 Gyr, and shows a decreasing trend of $[\alpha/Fe]$ and increasing trends of [(Na,Al,Cu,Mn)/Fe] against [Fe/H]. However, the thick disk stars tend to have higher $[\alpha/Fe]$ and lower [Mn/Fe] than thin disk stars. We also predict the frequency distribution of elemental abundance ratios as functions of time and location, which can be directly compared with galactic archeology projects such as HERMES.

i.e. higher [Mg/Mn]

- GRAPE-SPH code (CK 2004)
- Chosen from 150 initial conditions with 3σ top-hat λCDM fluctuation generated in 8Mpc
- Disk: 48, Sb galaxy: 5 cases





Astron. Astrophys. 214, 239–248 (1989) 1989

Oxygen in old and thick disk stars *

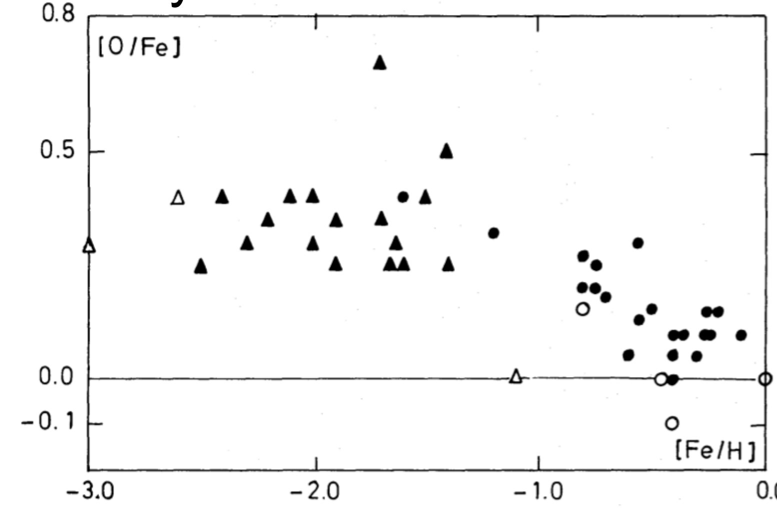
B. Barbuy[1,2] and **M. Erdelyi-Mendes**[1]

[1] Universidade de Sao Paulo, Depto. de Astronomia, C.P. 30627
[2] Observatoire de Paris, Section de Meudon, F-92195 Meudon C

Received May 25, accepted September 5, 1988

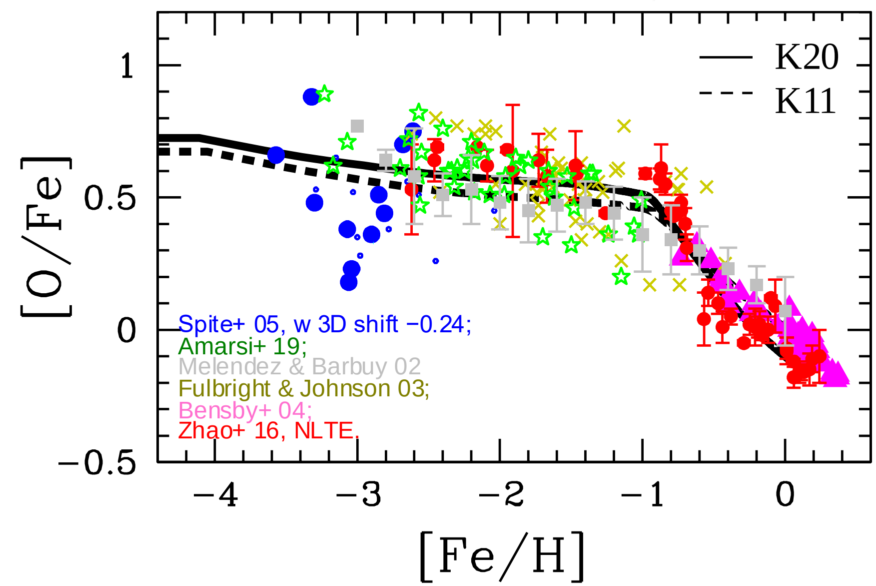
Summary. High resolution Reticon and CCD spectra comprehending the |O I| λ6300.311 line were obtained for old and thick disk stars. The space velocities were studied in order to classify the stars in the different population groups. The atmospheric parameters were examined to be as accurate as possible and used to determine the oxygen abundance with synthetic spectrum calculations. The present results show that (a) oxygen seems to be overabundant relative to iron for metallicities [Fe/H] = −0.8; (b) for metallicities in the range −0.8 < [Fe/H] < −0.5, there seems to be a spread in the [O/Fe] ratios. This spread could be an indication of a thick disk phase in the chemico-dynamical evolution of the Galaxy. The scatter is however within the error bars of the determinations. Finally, it must be pointed out that a difference seems to appear between oxygen-to-iron ratios derived from the forbidden and the permitted lines.

Barbuy didn't need APOGEE☺



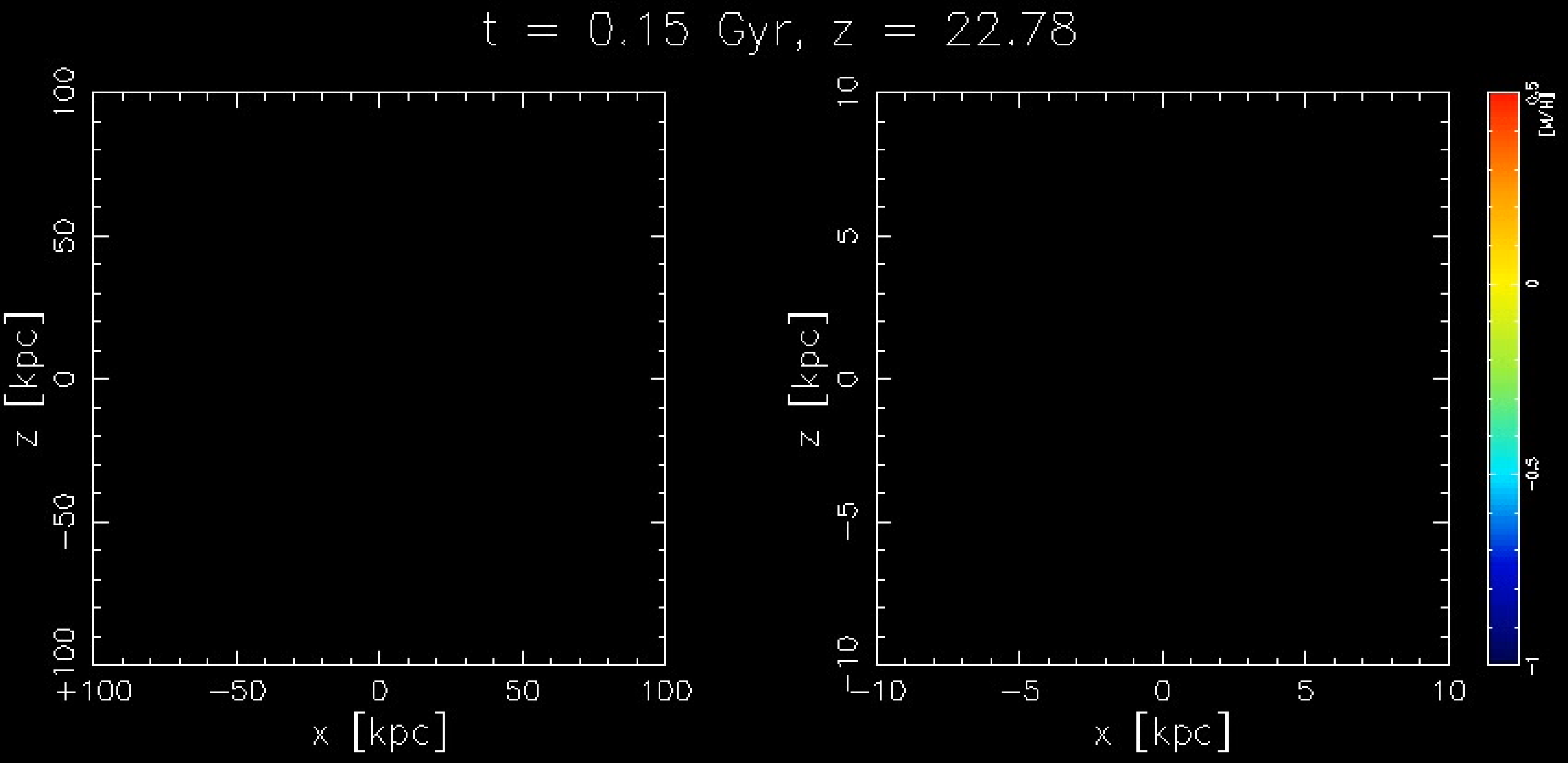
b

Fig. 4a and b. [O/Fe] versus [Fe/H]. **a** Present results for the range −1.0 < [Fe/H] < 0.0, where error bars are shown. The line drawn corresponds to predictions by Matteucci and Greggio (1986). **b** Present results and those of Barbuy (1988), given in the range −3.0 < [Fe/H] < 0.0. Symbols: ● and ○: present work; ▲ and △: Barbuy (1988), where ○, △ represent uncertain results due to the weakness of the |O I| line. ⊙ represents the solar value



Melendez & Barbuy didn't need NLTE☺

Cosmological ‘zoom-in’ simulation

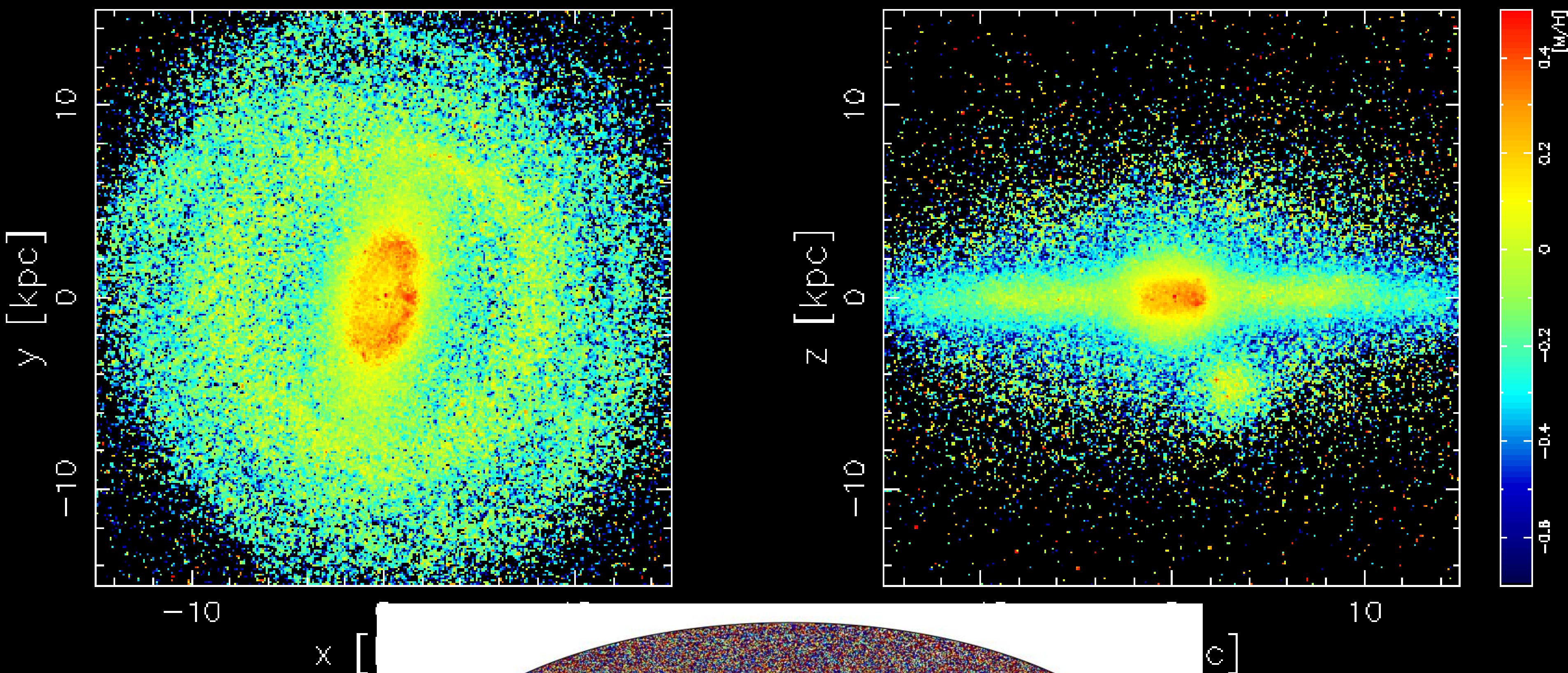


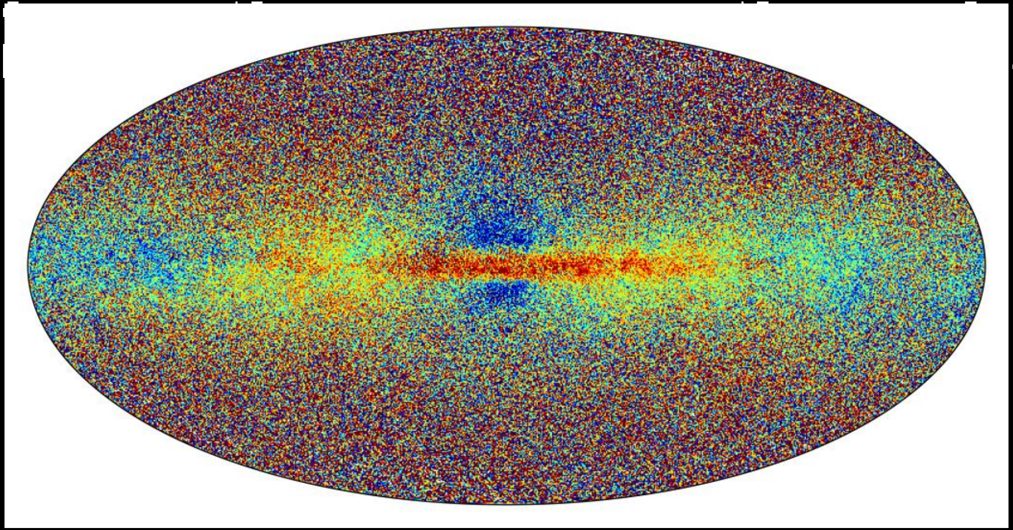
Gadget3-based code (CK+ 2007), Aquila IC (Scannapieco+12), $3x10^5 M_\odot$, 0.5kpc

https://star.herts.ac.uk/~chiaki/works/Aq-C-5-kro2.mpg

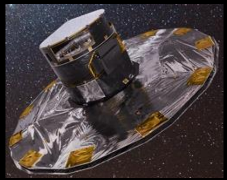
Basic features are the same in CK & Nakasato 11, Brook+12, Scannapieco+12, Auriga, FIRE-2, ARTEMIS, VINTERGATAN... but input stellar physics matters!

Metallicity Map

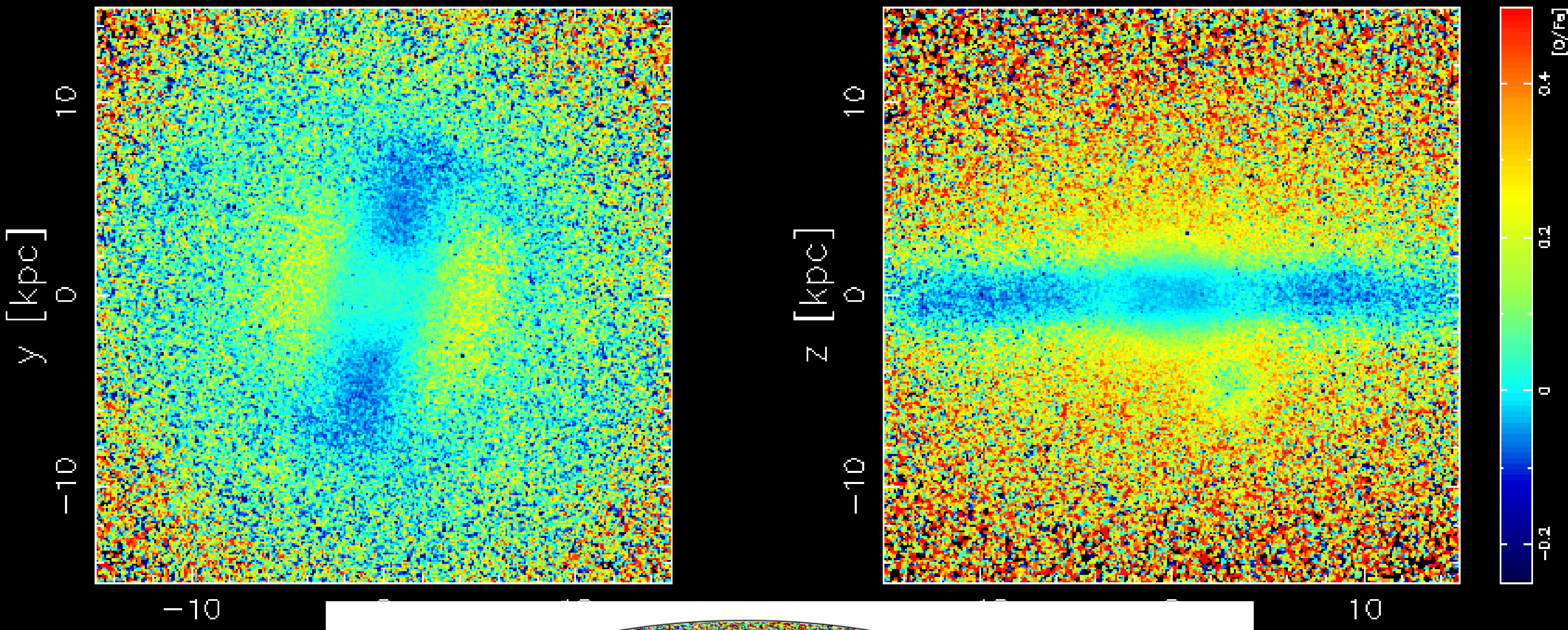


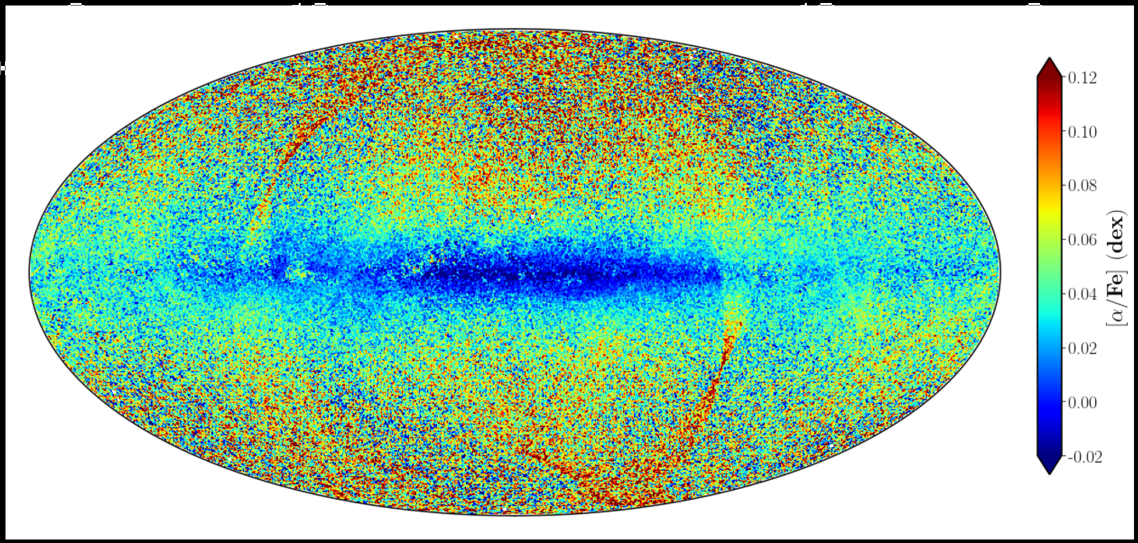


Metallicity
low to high
Gaia DR3

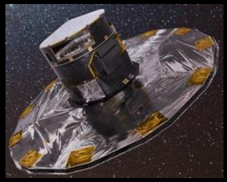


[O/Fe] Map

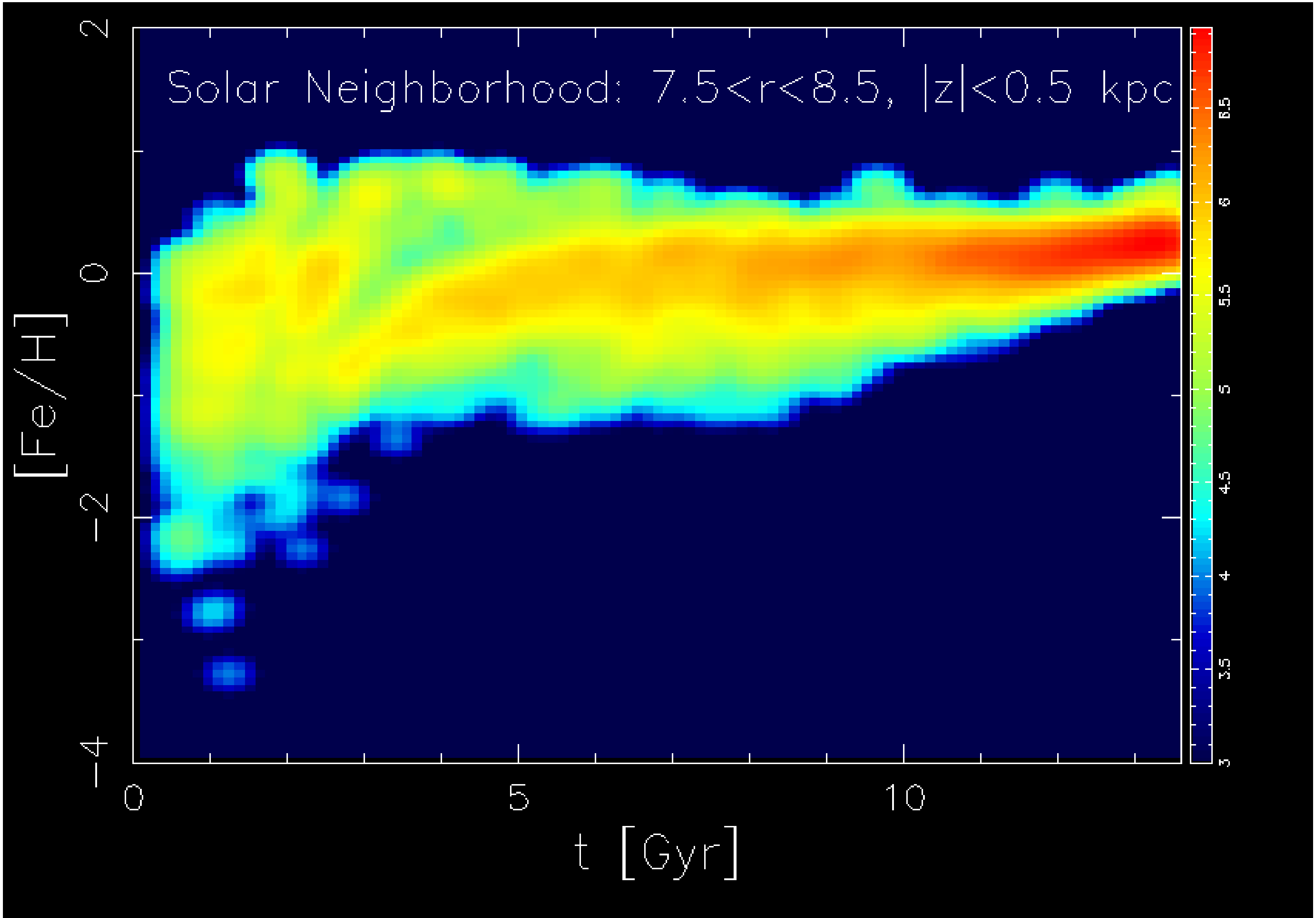




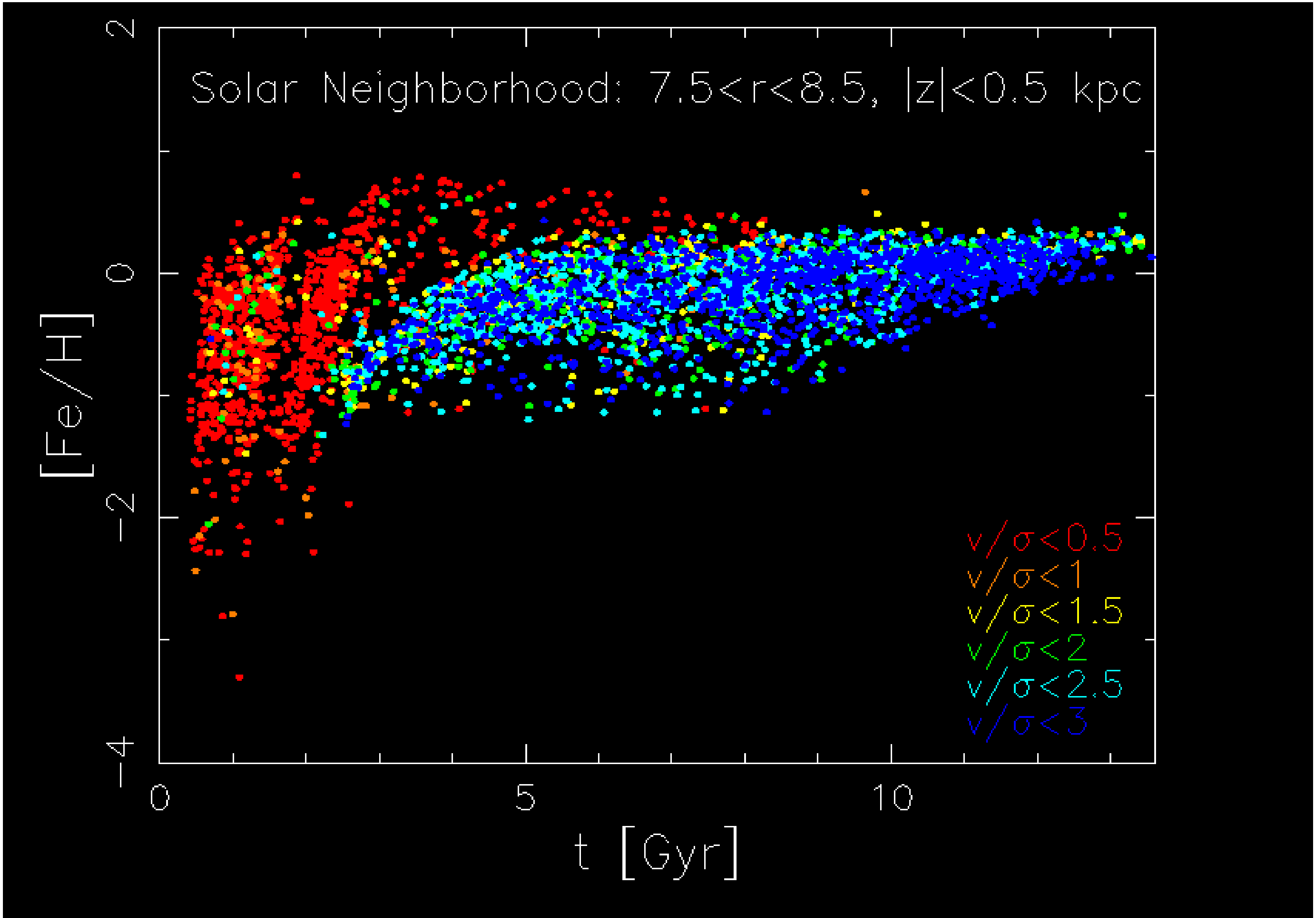
[α/Fe]
low to high
Gaia DR3



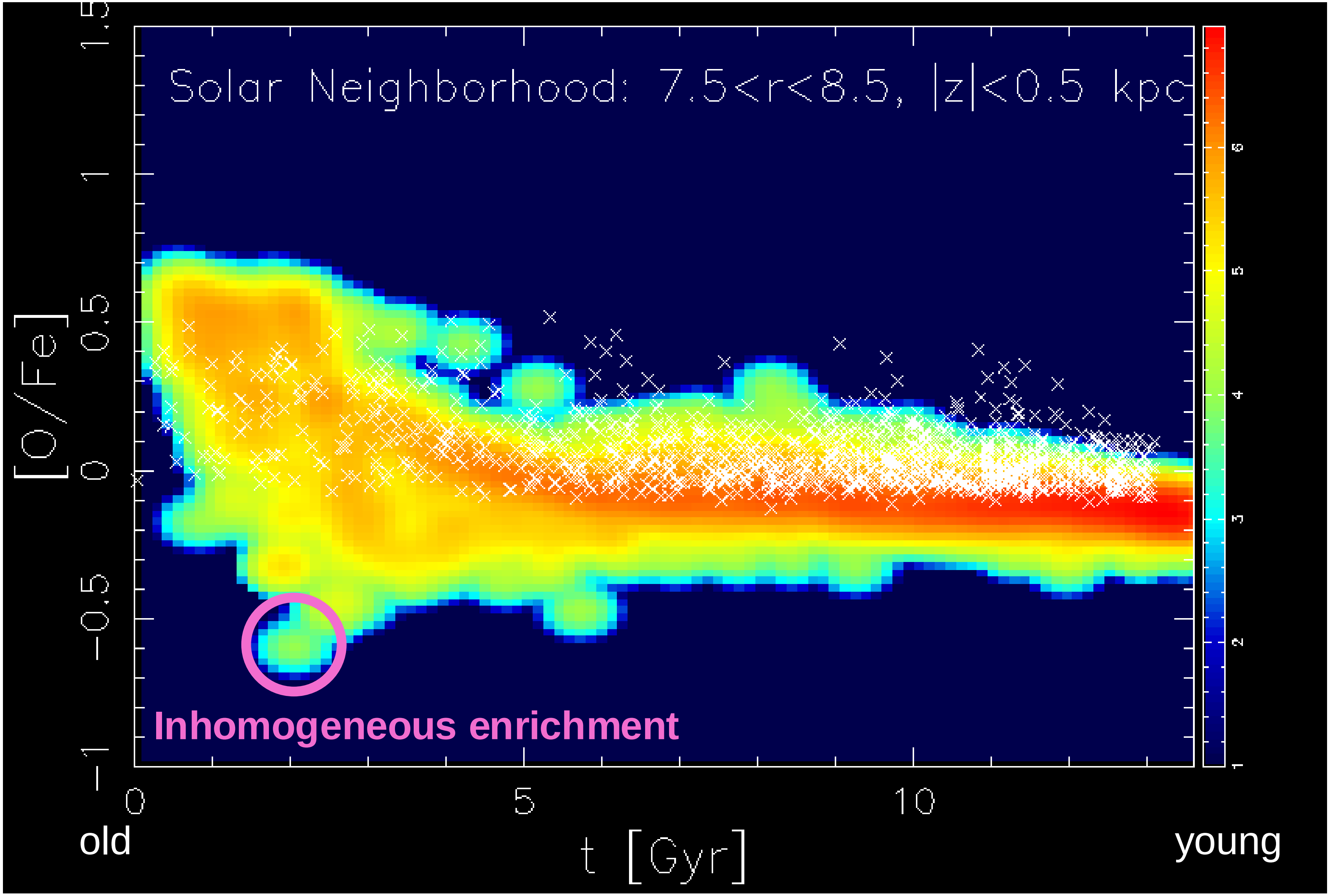
Age-Metallicity Relation



Age-Metallicity Relation

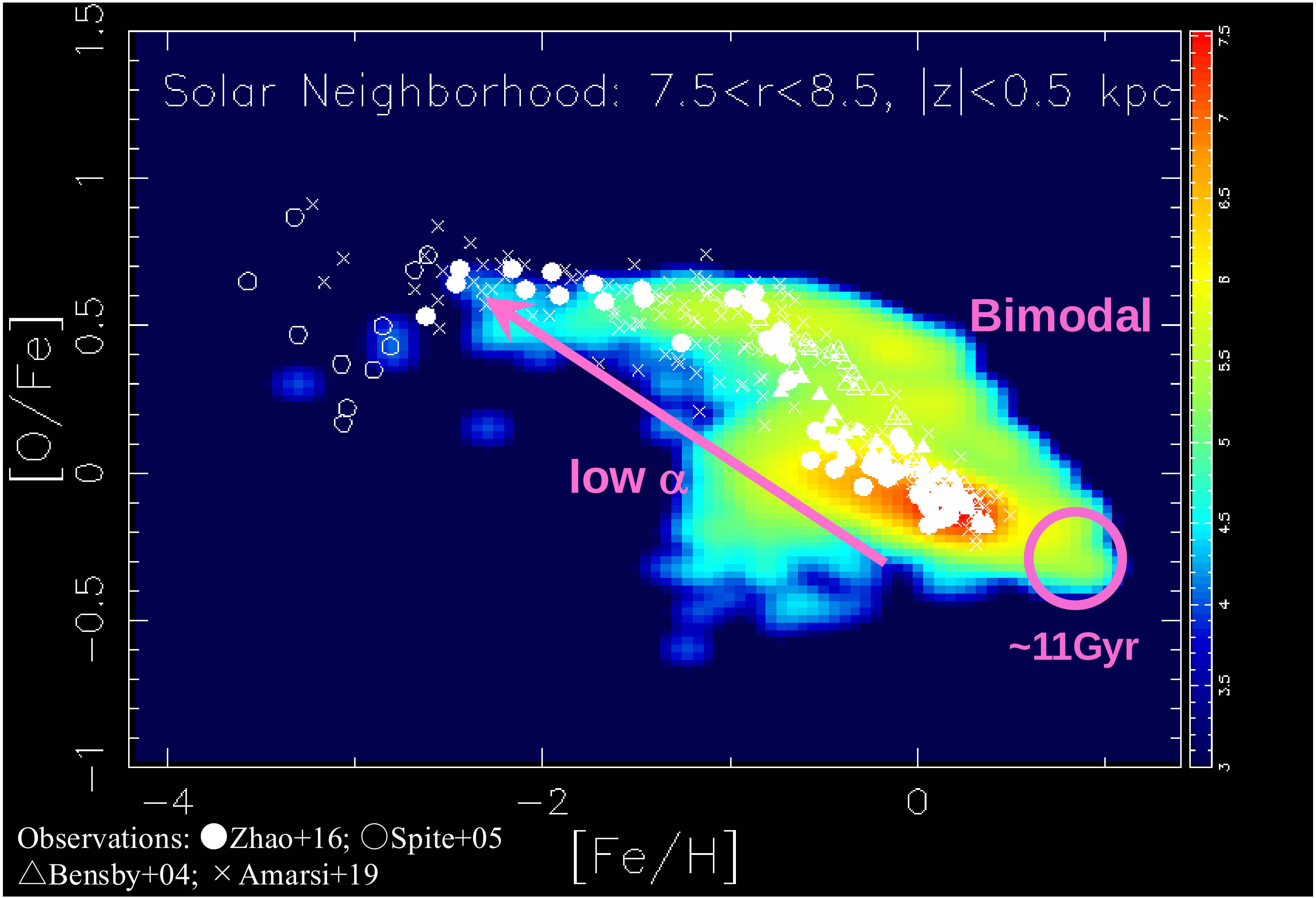


[O/Fe]-Age evolution

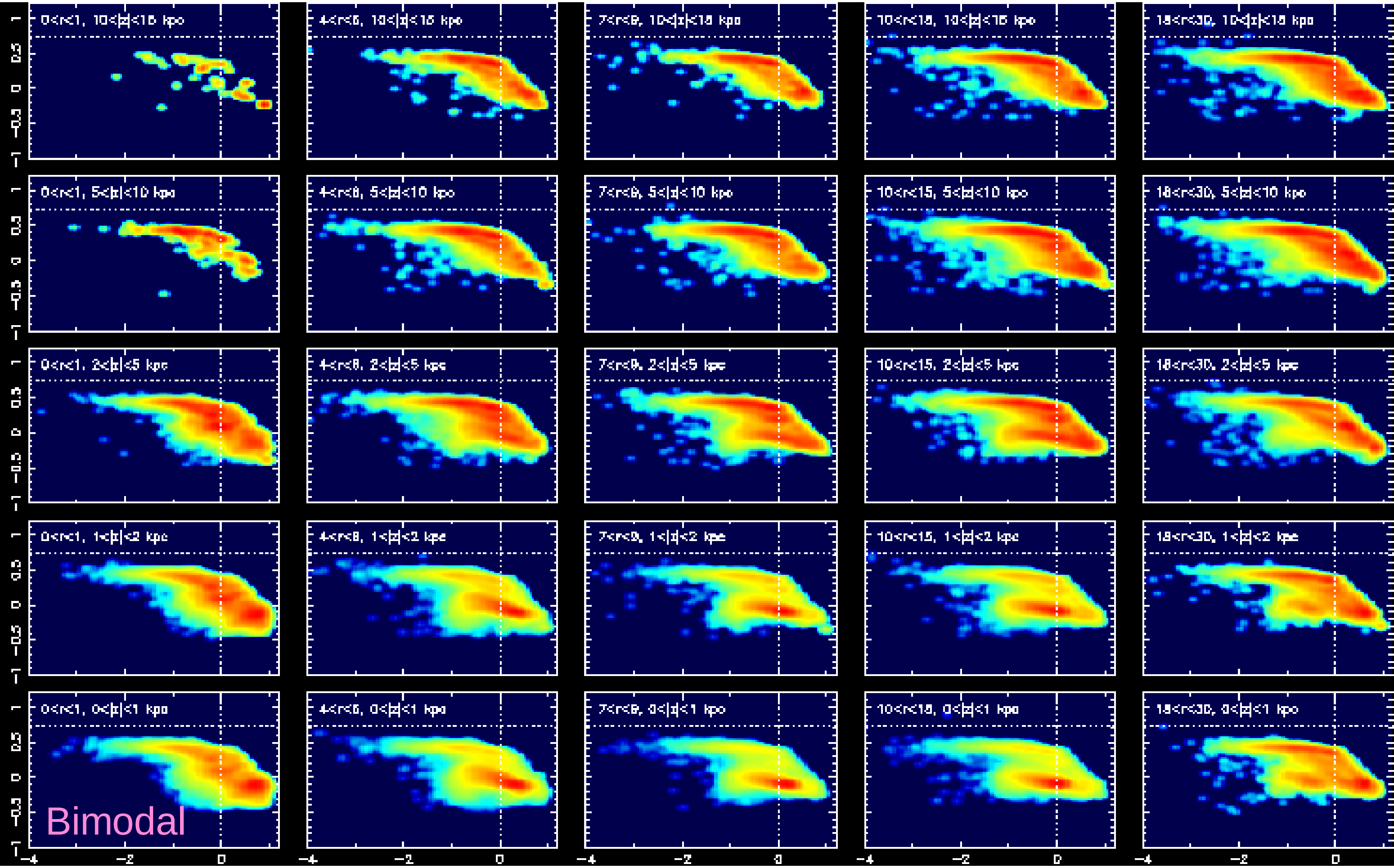


The [O/Fe]-[Fe/H] Relation

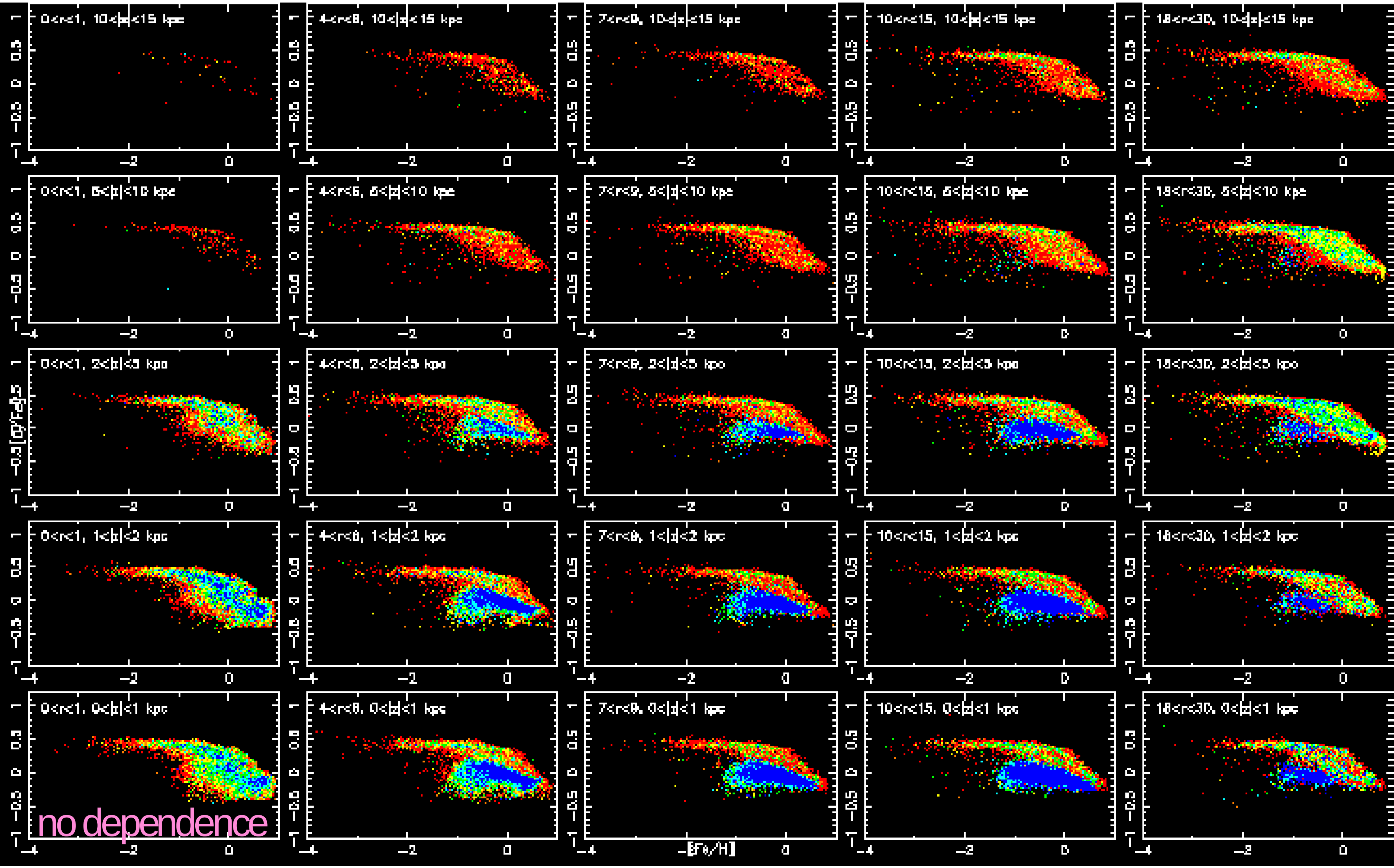
First shown in CK & Nakasato 2011



α/Fe bimodality in simulated MW



v/σ dependence

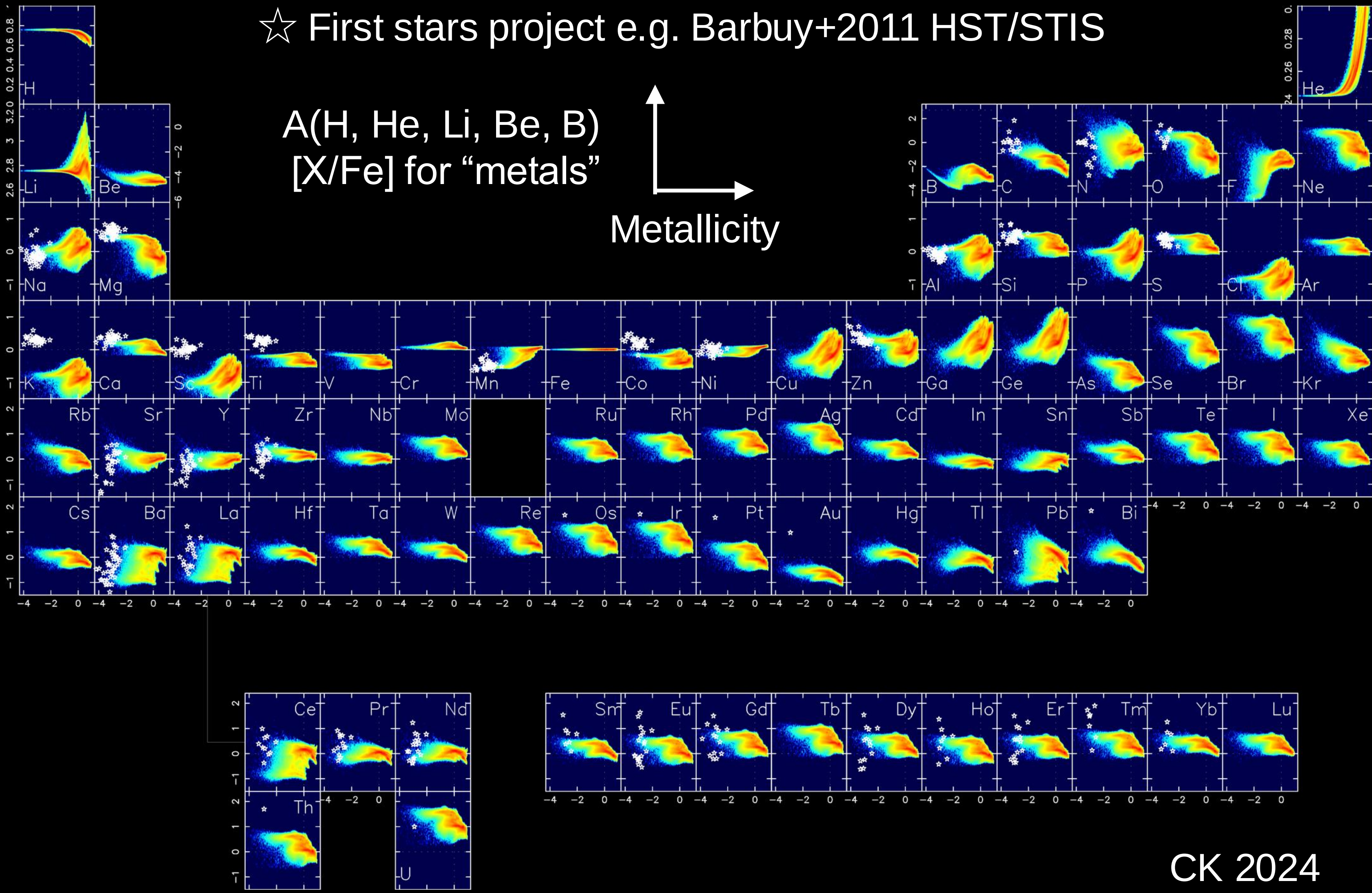


[X/Fe]-[Fe/H] relations in MW

☆ First stars project e.g. Barbuy+2011 HST/STIS

A(H, He, Li, Be, B)
[X/Fe] for "metals"

Metallicity

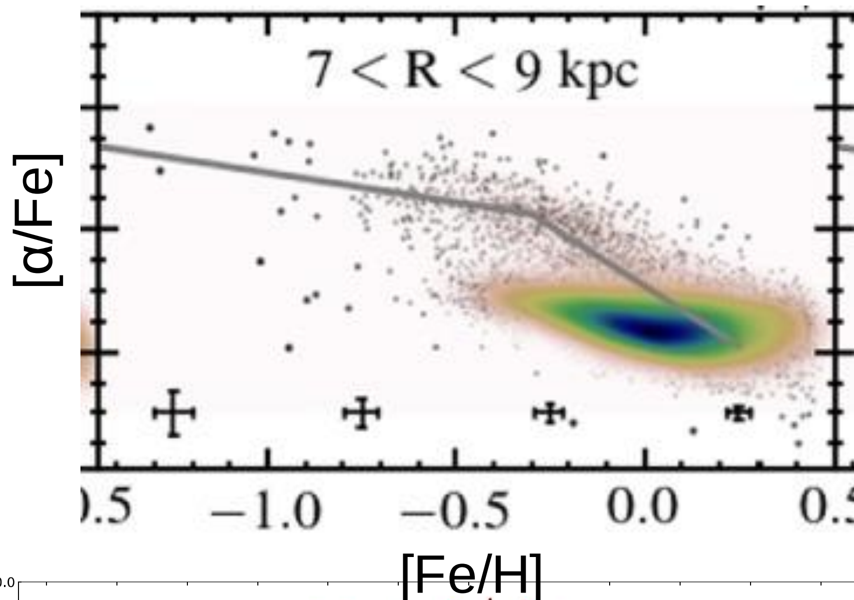


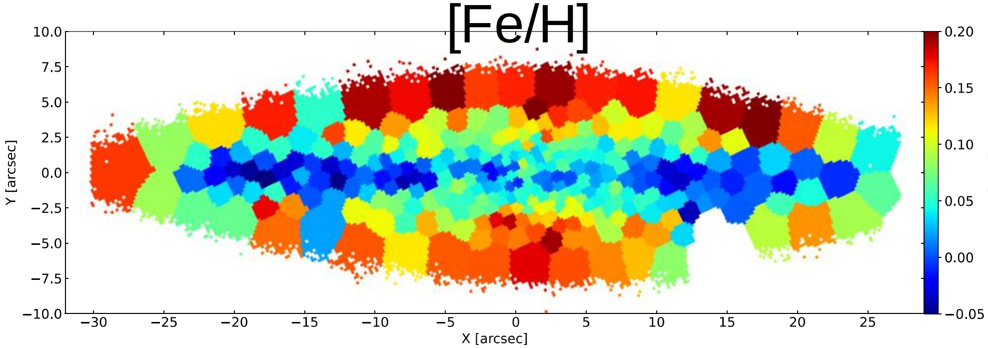
CK 2024

The α/Fe bimodality universal?

α element: O, Ne, Mg, Si, S, Ar, Ca

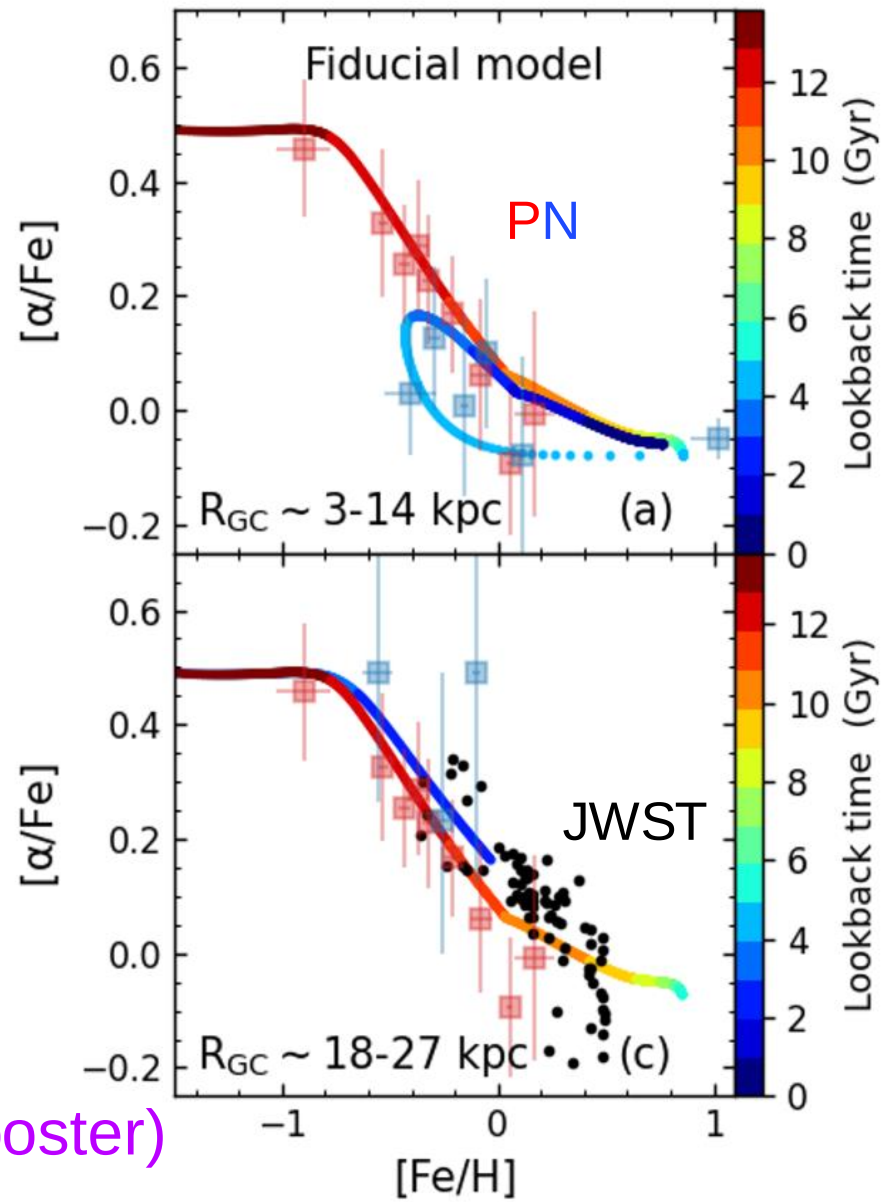
MW e.g. Hayden+ 2015





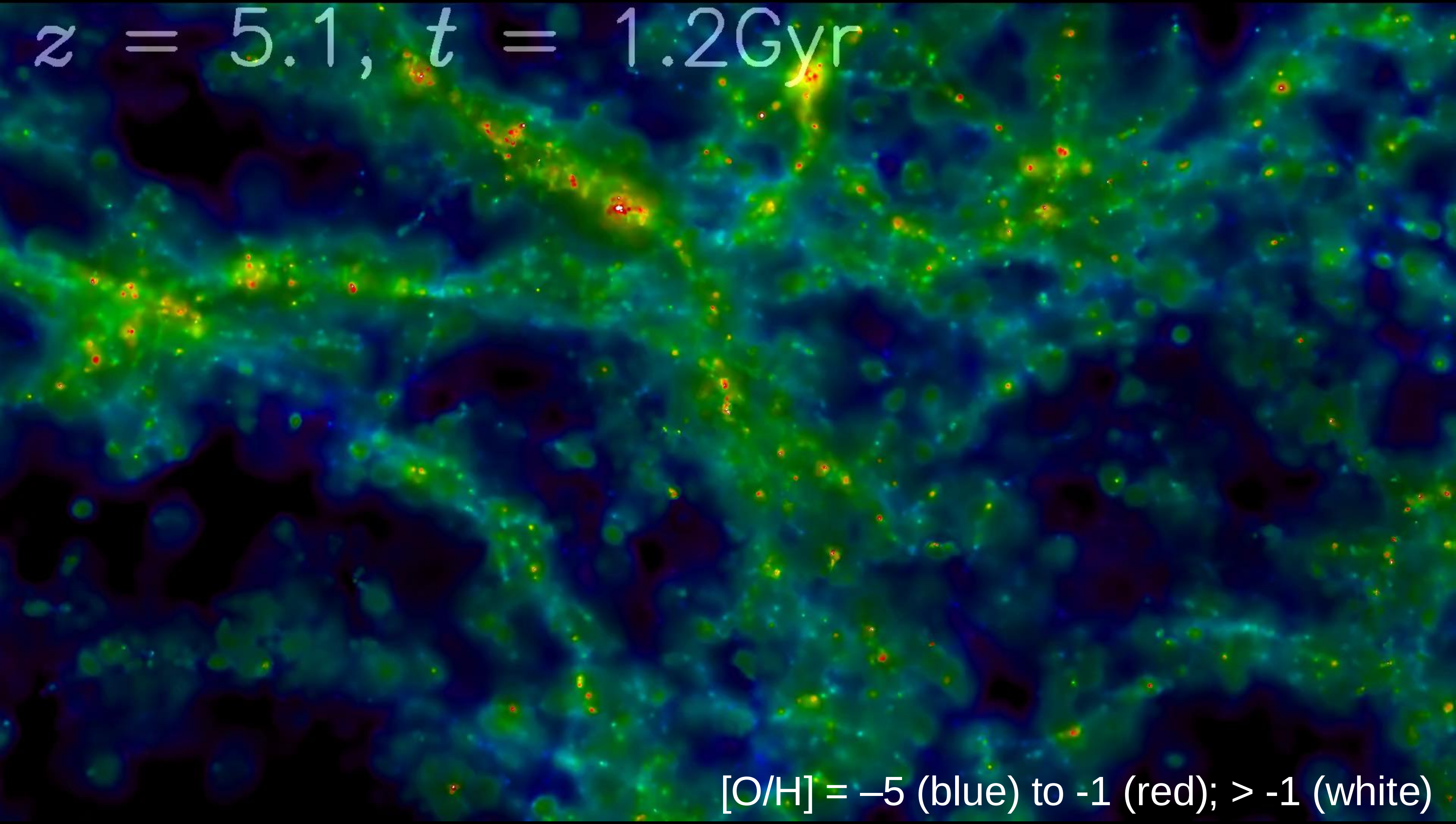
S0 Somawanshi,...CK+ 2024

M31 CK, Bhattacharya+ 2023



Subaru PFS will map M31 (Kirby poster)

Cosmological box simulations



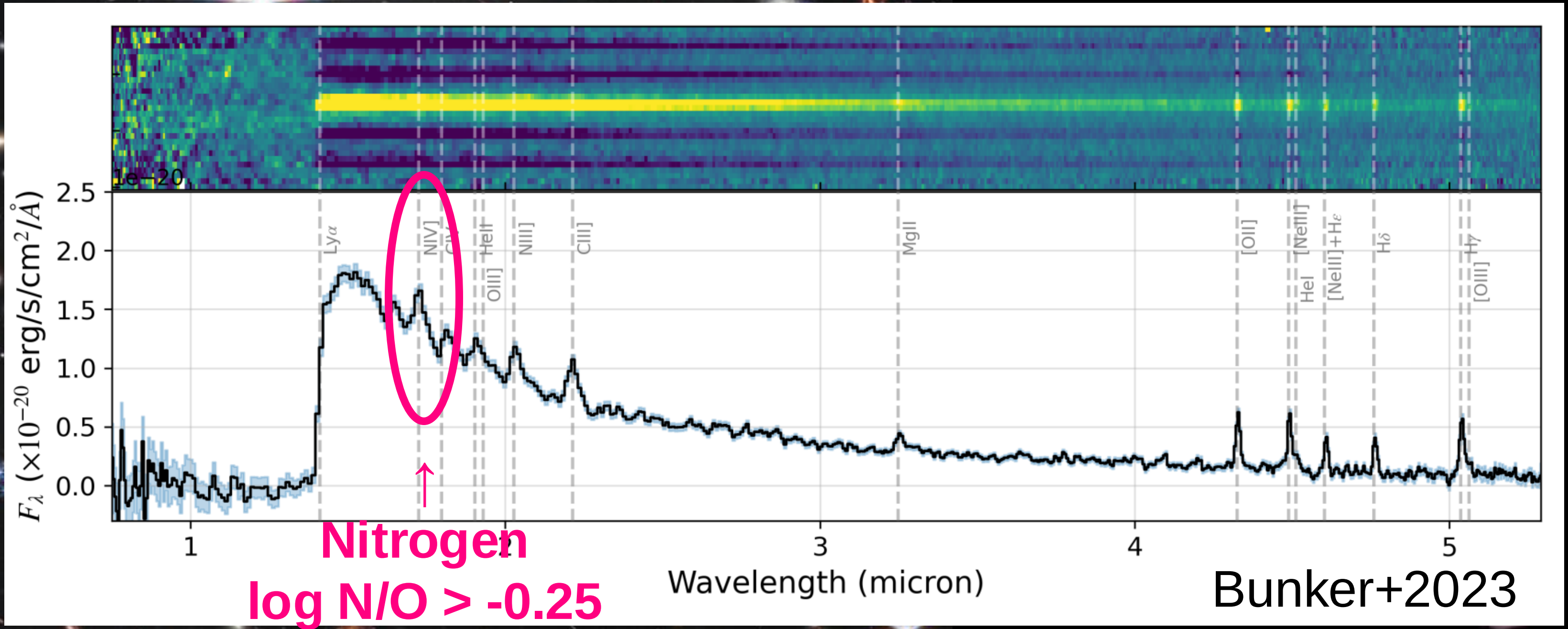
Taylor & CK (2015), 25Mpc, 1.4x$10^7$$M_\odot$, 1.6kpc resolution https://www.youtube.com/watch?v=jk5bLrVI8Tw

See also, Steinmetz & Navarro 94, Cen & Ostriker 99, ... CK+07, EAGLE, IllustrisTNG, HORIZON-AGN, Magneticum, SIMBA-C...

Extra-galactic Archaeology!

25 Dec 2021 launch
11 July 2022

NIRSpec/JWST
R = 100 (MOS)
R = 1000 (MOS + fixed Slits)
R = 2700 (fixed Slits + IFU)
CNO, Ne, Ar, S, Fe



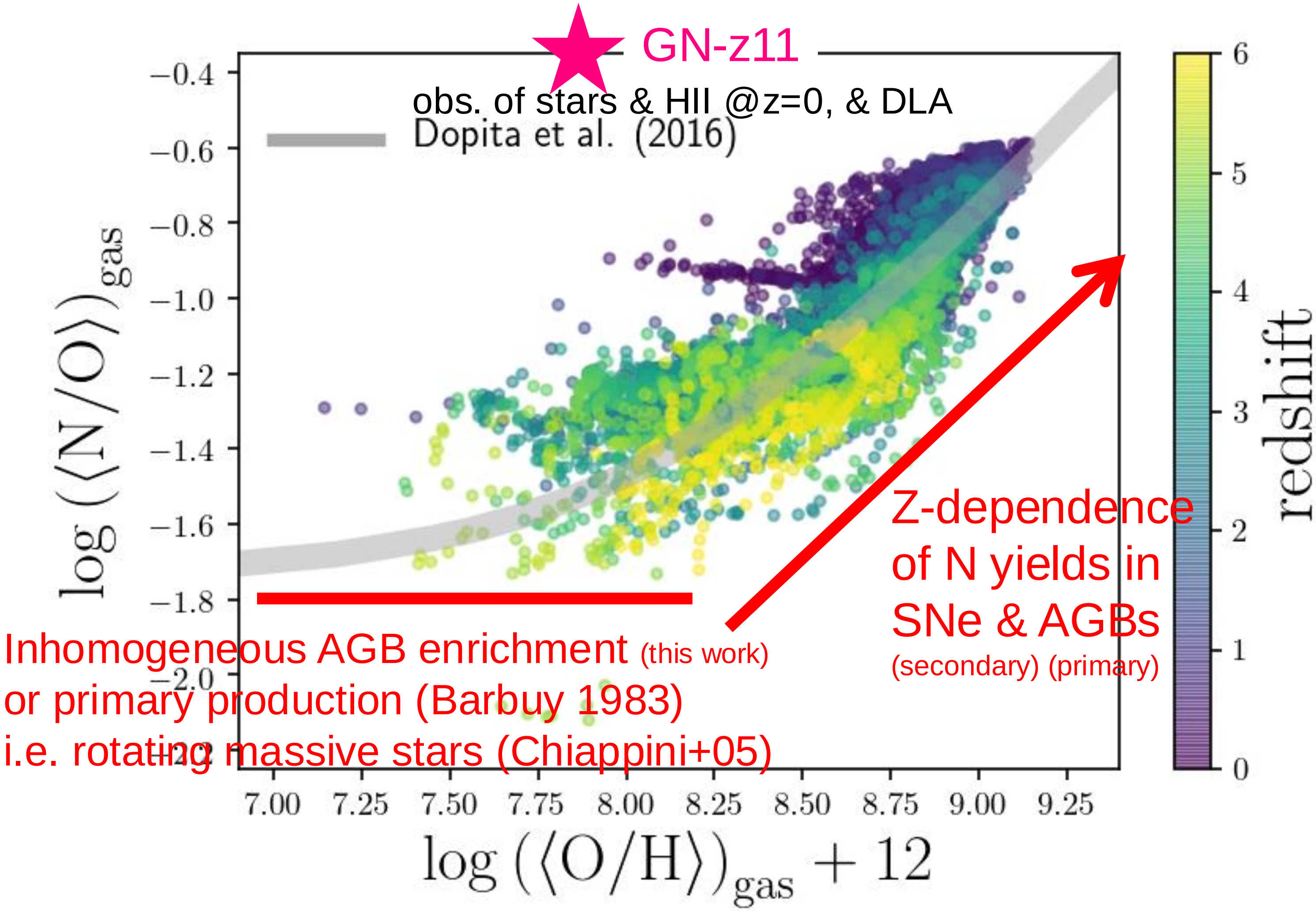
Nitrogen
log N/O > -0.25

Bunker+2023

CK & Ferrara 2024 for a GCE model

The N/O-O/H relation of SFGs

Fiorenzo Vincenzo & CK 2018b, MNRAS, 478, 155
33 star-forming galaxies in cosmological simulation



Summary

- We have good understanding on **the origin of elements** in the universe, except for the elements around Ti and some n-capture elements (Au).
- **Zoom-in simulations** – Spatial distribution of elements (from C to U) in the Milky Way are in good agreement with observations. Bimodality/trimodality are predicted for many elements, e.g. α, odd-Z, Mn, r-process elements in all disk galaxies (if my SNIa model is correct).
- **Cosmological box simulation** – Self-regulated galaxies follow the similar O/Ar-O/H relation, equivalent to the α/Fe-Fe/H relation. Observed Low-α galaxies can be explained intermittent star formation as for the N-rich galaxy GN-z11 (with Wolf-Rayet stars; CK & Ferrara 24), while MW's satellites are likely affected by strong SN feedback & sub-Ch-mass SNe Ia.

Book Chapter in Handbook of Nuclear Physics, ArXiv: 2302.07255
Data Release (incl. *all* elements with K20 yields) in 2025