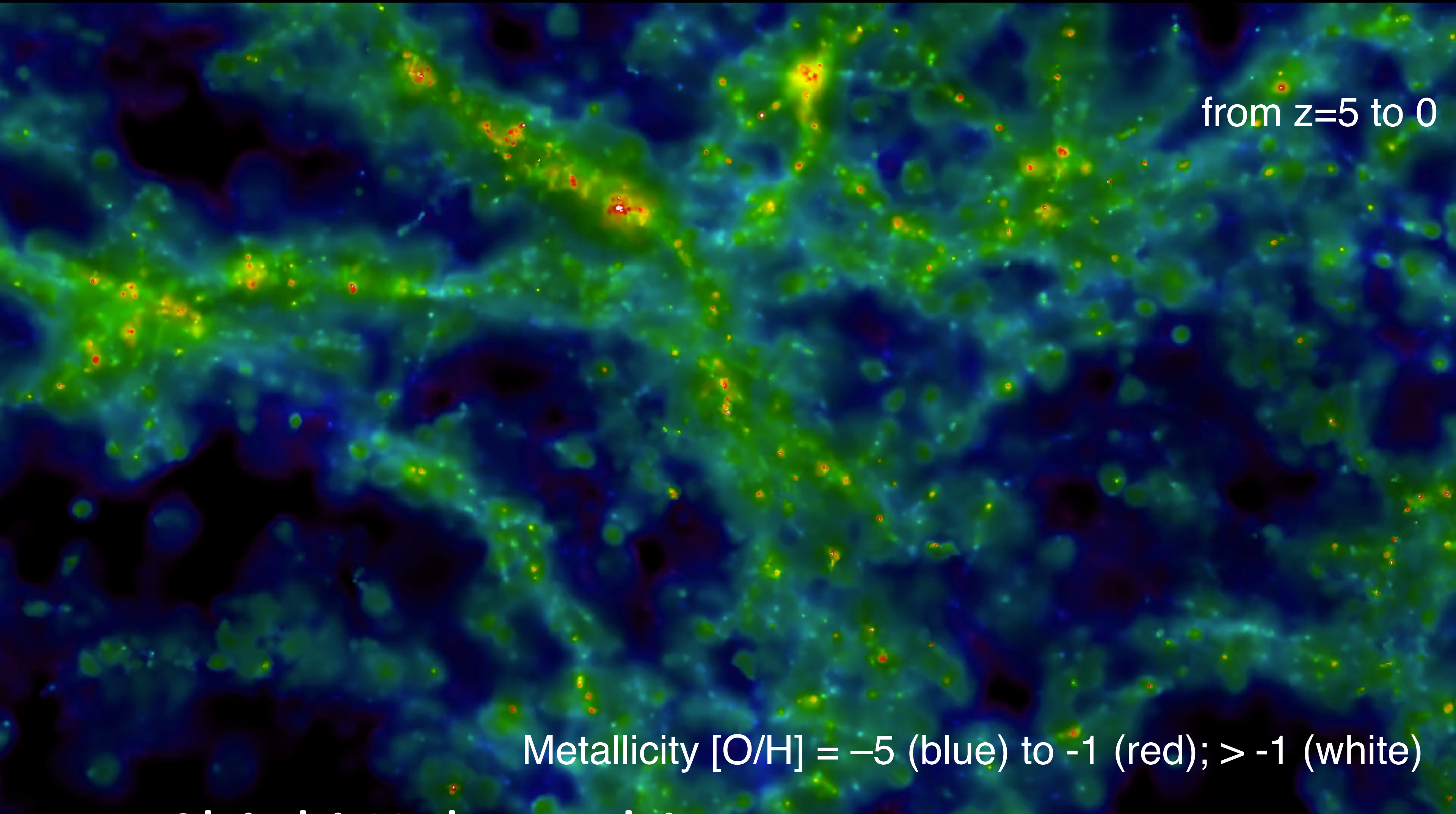
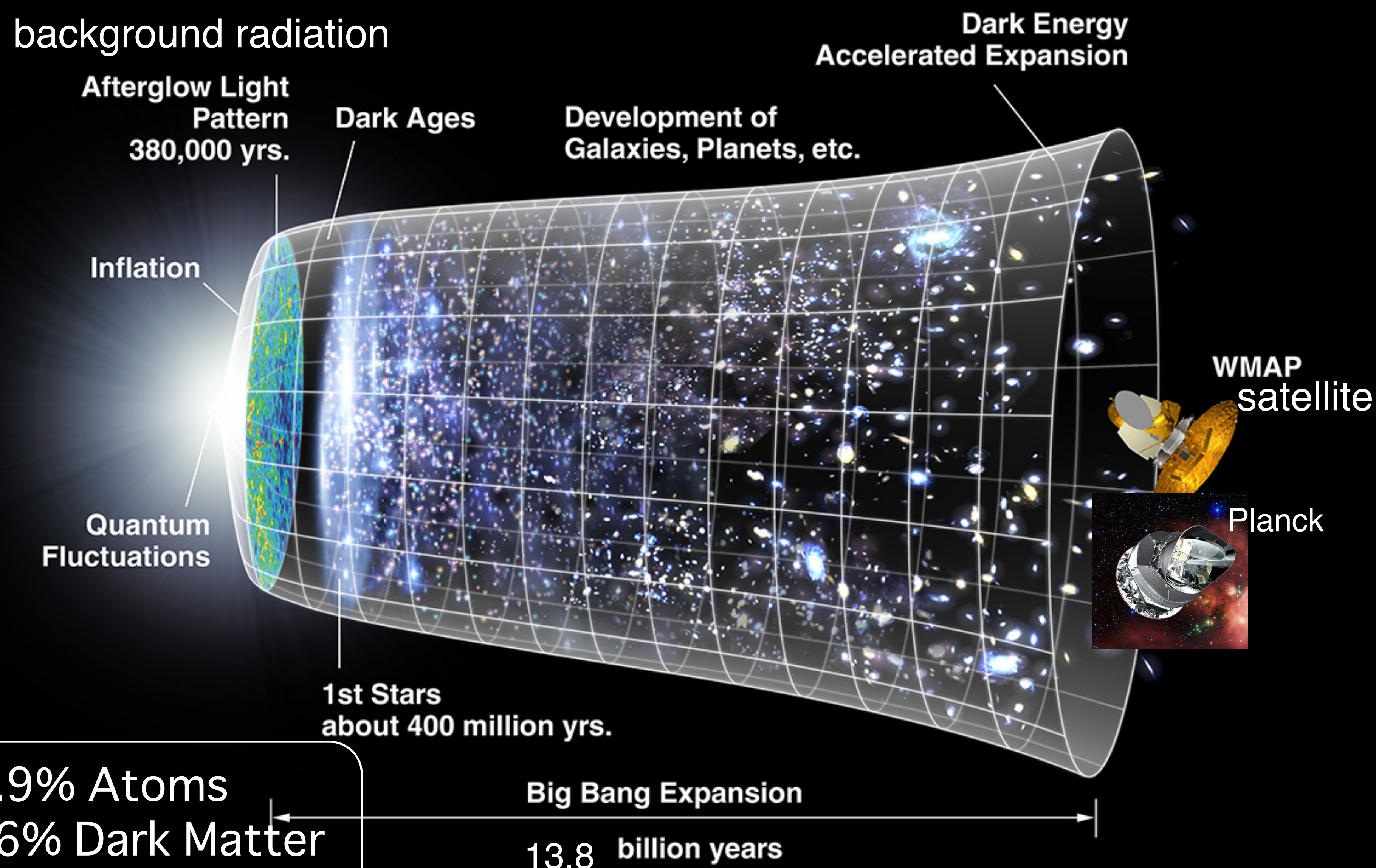
Chemical Evolution of Galaxies



Chiaki Kobayashi
(Univ. of Hertfordshire, UK)

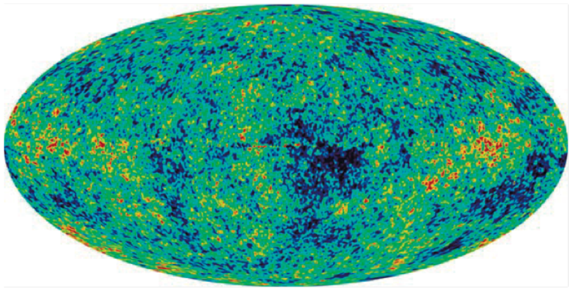
LEVERHULME TRUST

History of the Universe

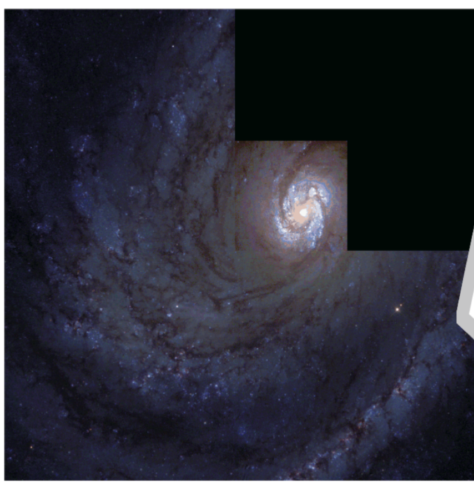


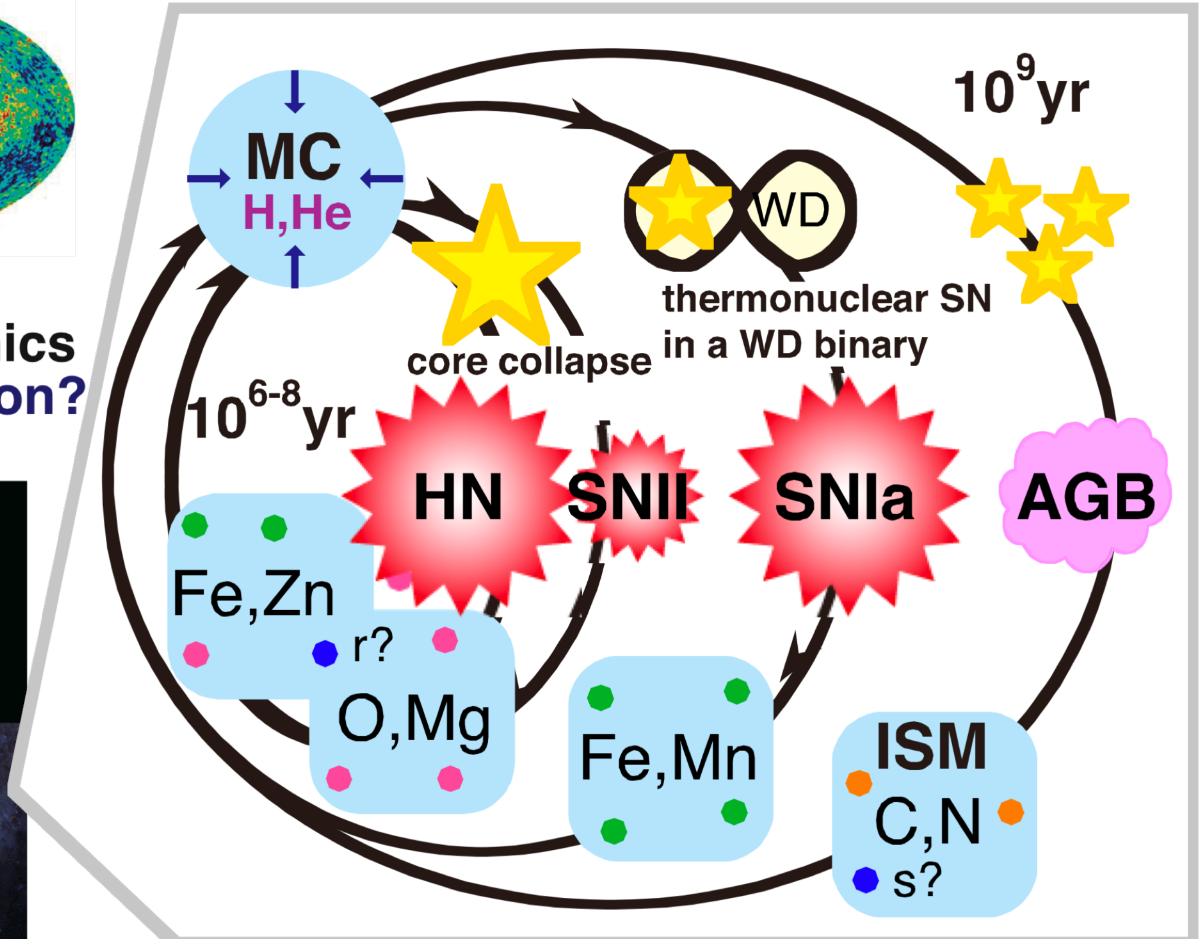
4.9% Atoms
26% Dark Matter
69% Dark Energy

Galactic Chemical Evolution (GCE)



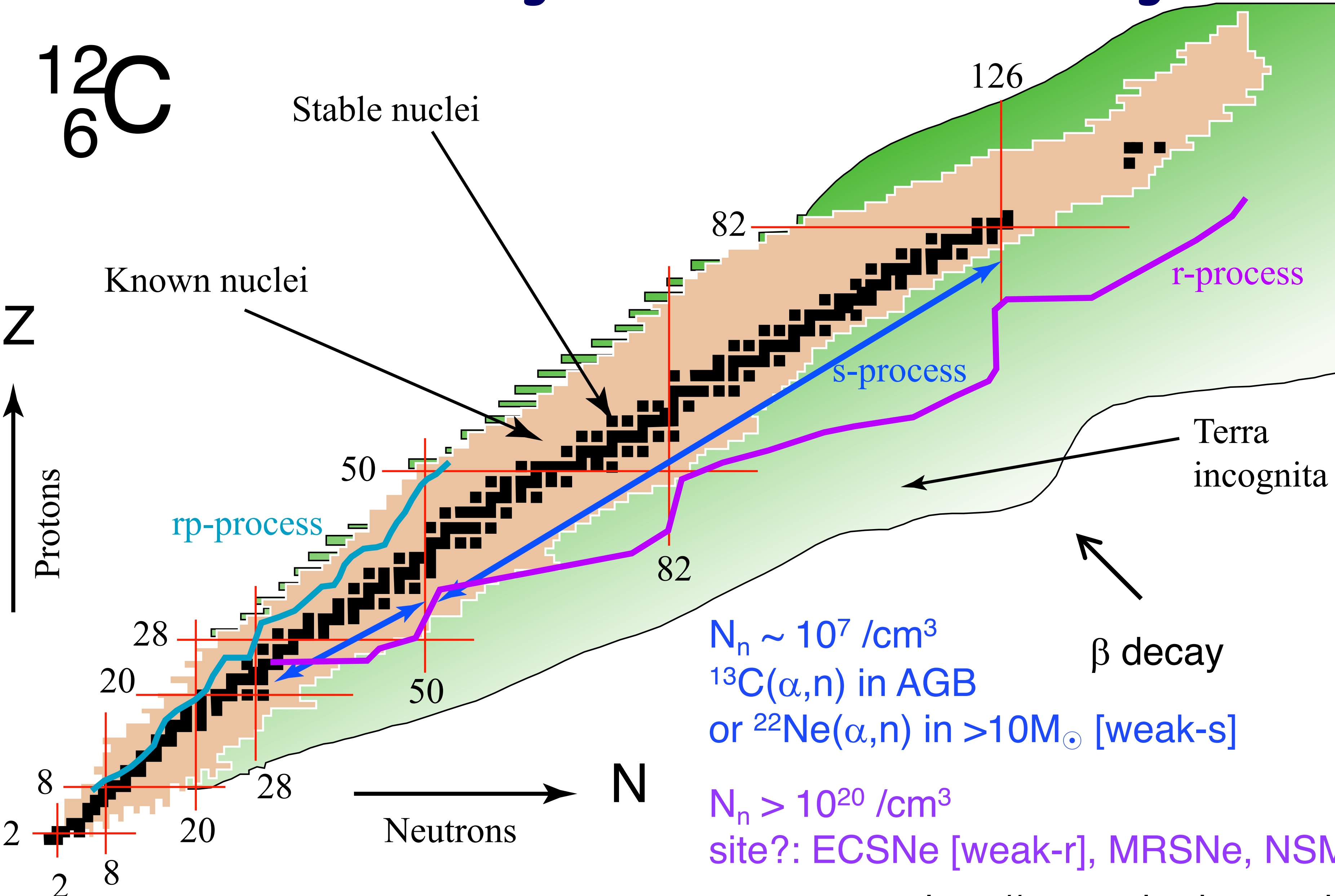
Gravity
Hydrodynamics
Star Formation?
Feedback?





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

Not Chemistry but Nuclear Physics



$N_n \sim 10^7$ /cm^3
$^{13}C(\alpha,n)$ in AGB
or $^{22}Ne(\alpha,n)$ in $>10M_\odot$ [weak-s]

$N_n > 10^{20}$ /cm^3
site?: ECSNe [weak-r], MRSNe, NSM

http://cococubed.asu.edu

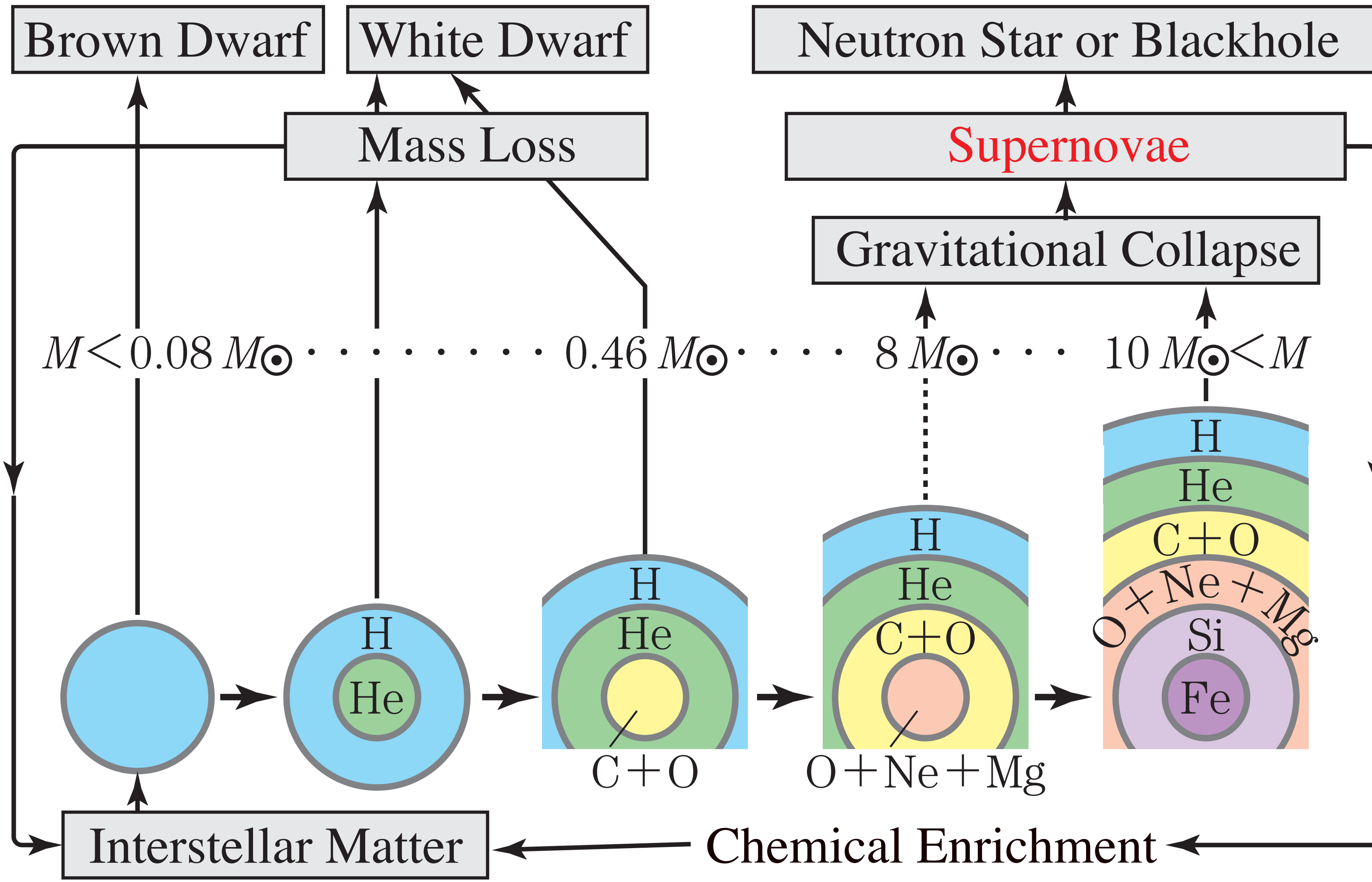
1/6
Stellar Yields

D. Arnett 1996, Supernovae and Nucleosynthesis

Nomoto, CK, Tominaga 2013, ARAA

CK, Karakas, Lugaro 2020, ApJ, 900, 179

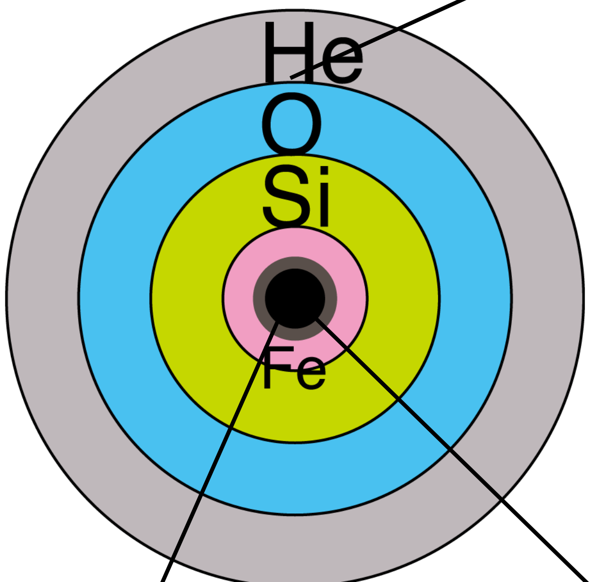
Fate of Stars

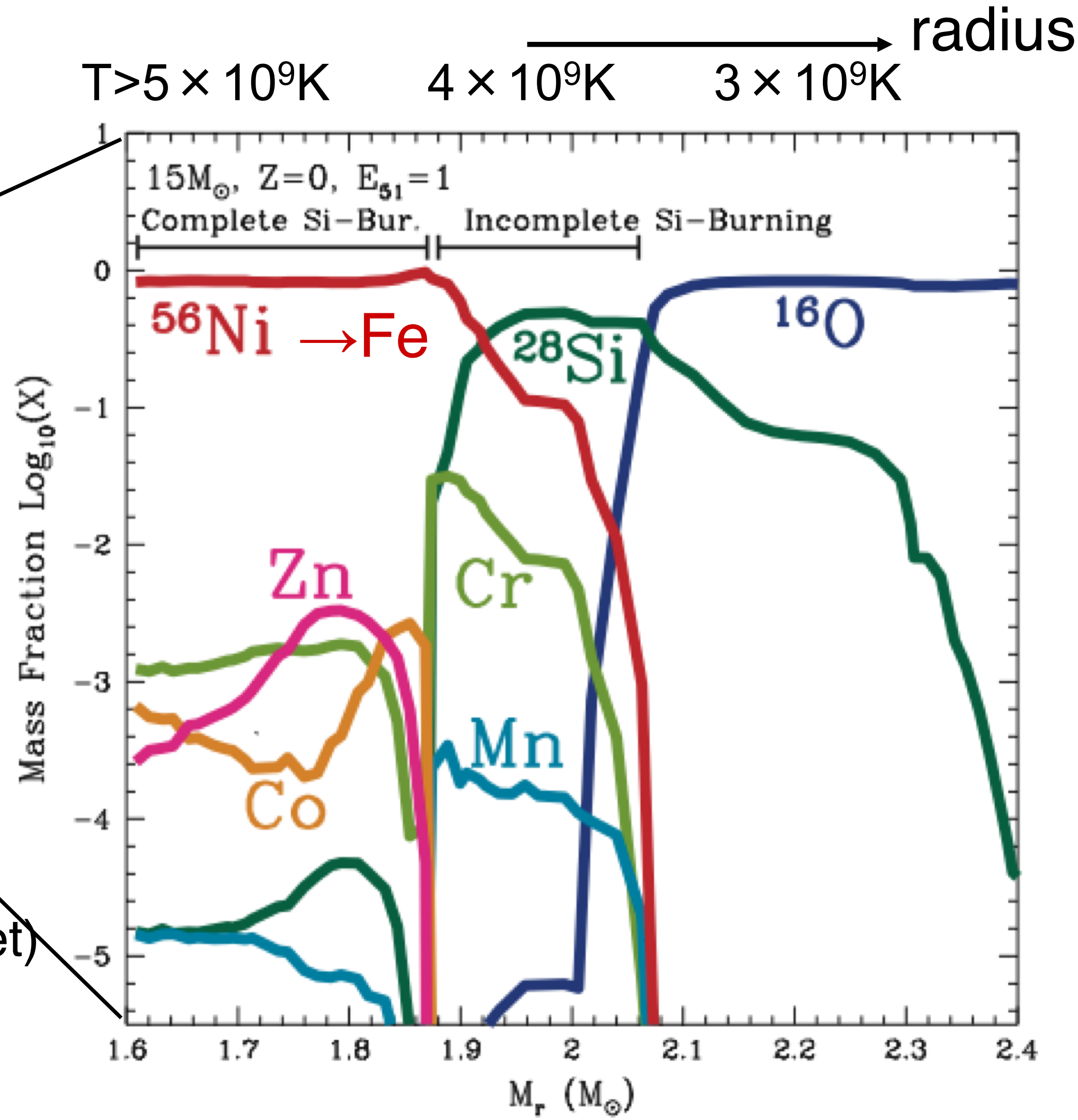


※ Solar Mass $M_{\odot}=2\times10^{33}$g

Explosive Nucleosyntheis

Woosley, Heger+ 95, 08
Nomoto, Umeda+ 97, 06
Limongi, Chieffi+ 00, 12





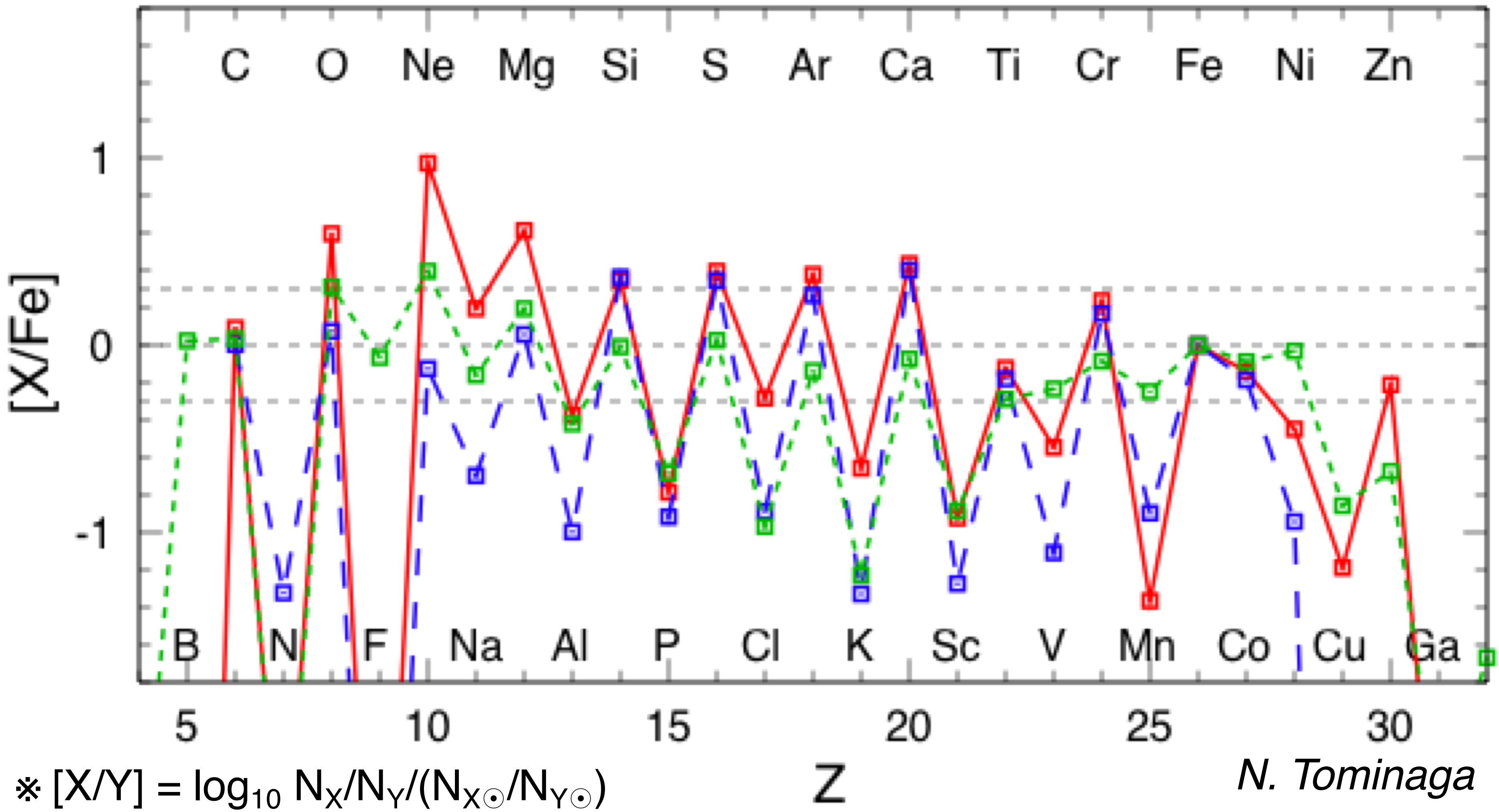
Mixing (Rayleigh-Taylor or jet)
and Fallback (BH or NS)

Also, dust yields (Gen Chiaki+ in prep.)

SN Yields from different groups

$20M_\odot$ Z=0 E=1foe

Tominaga, Umeda, Nomoto 2007
Heger & Woosley 2008
Limongi, Straniero, Chieffi 2000

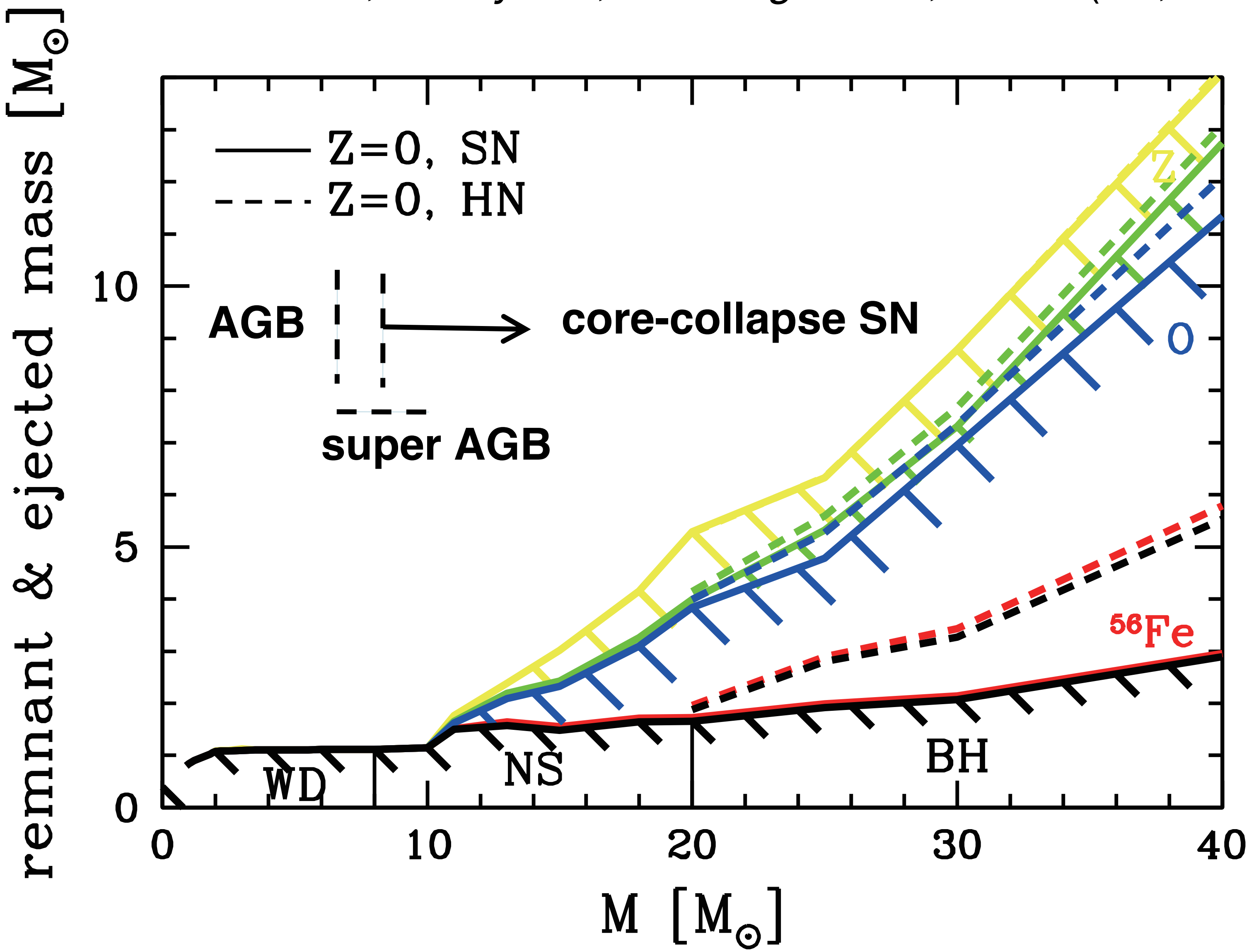


※ $[X/Y] = \log_{10} N_X/N_Y/(N_{X\odot}/N_{Y\odot})$

N. Tominaga

Stellar Yields

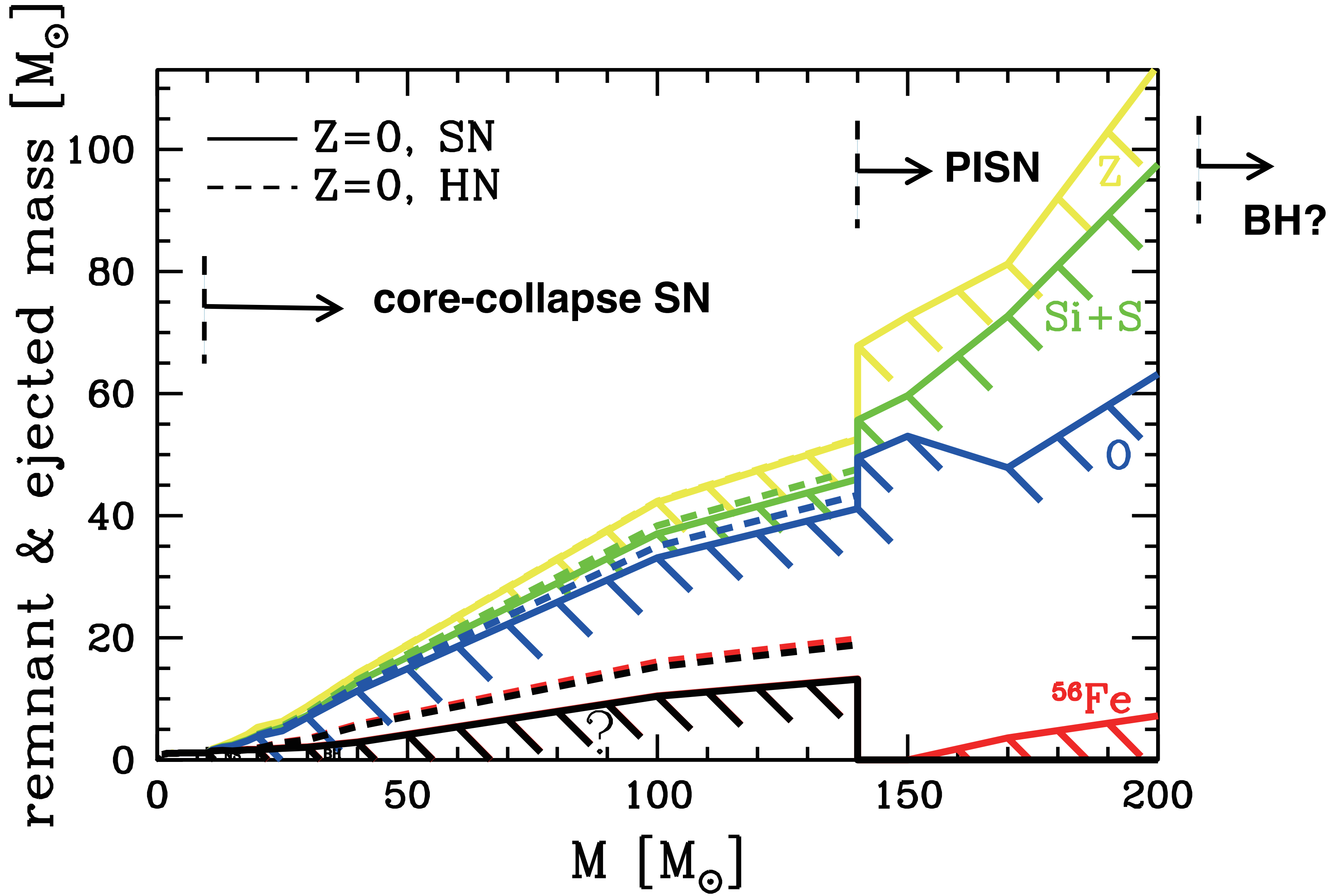
Nomoto, Kobayashi, Tominaga 2013, ARAA (1D, no rotation)



Also, Woosley & Heger; Limongi & Chieffi

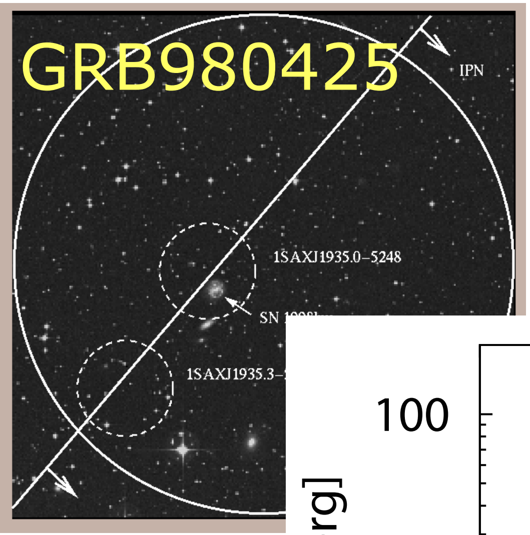
Stellar Yields

Nomoto, Kobayashi, Tominaga 2013, ARAA (1D, no rotation)



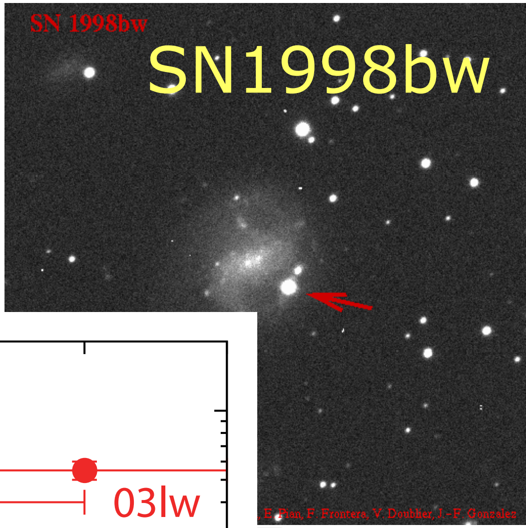
Also, Woosley & Heger

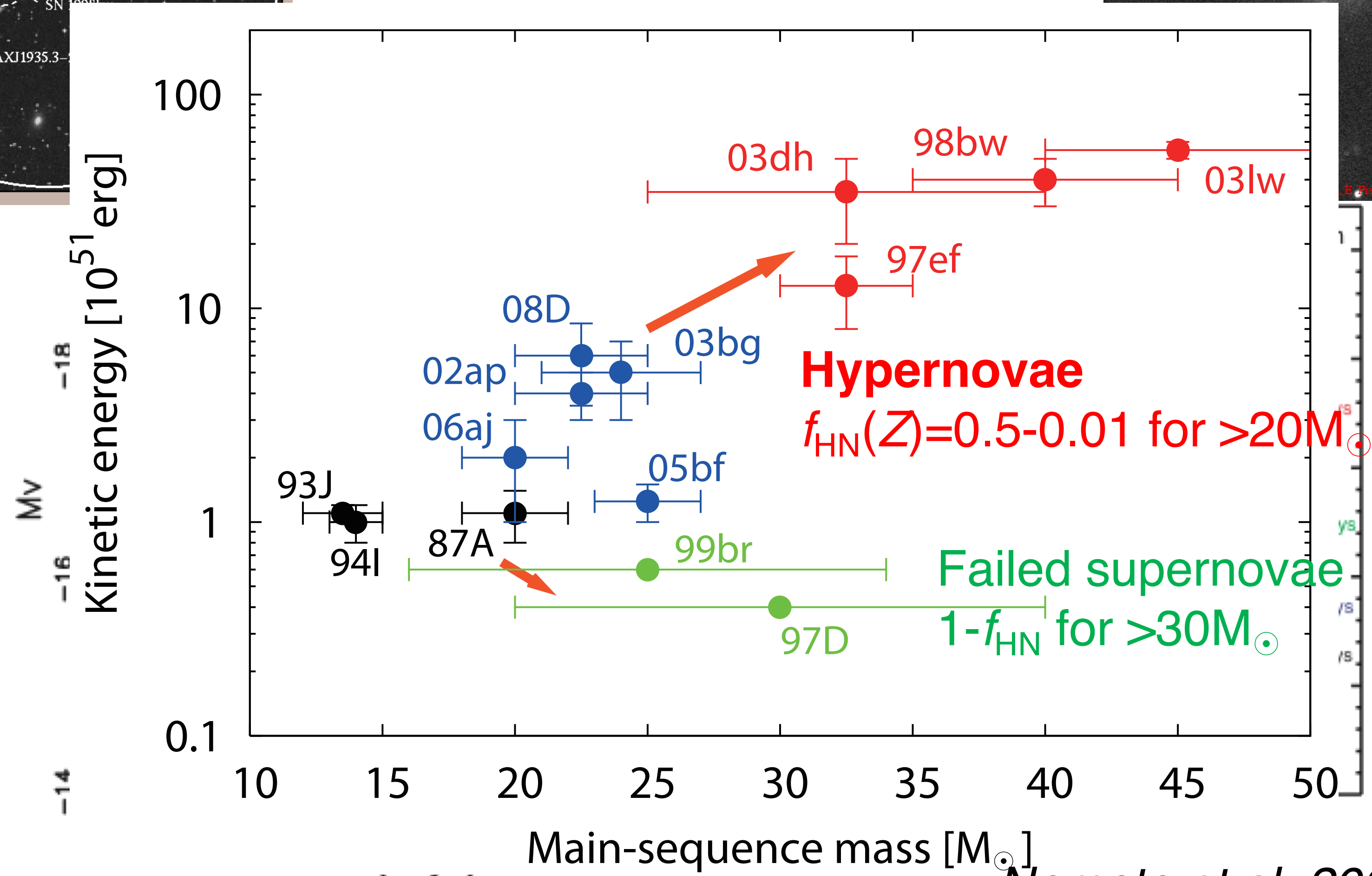
Hypernovae



- SN light curves & spectra fitting

→ M, E_{kin}, M(Fe)

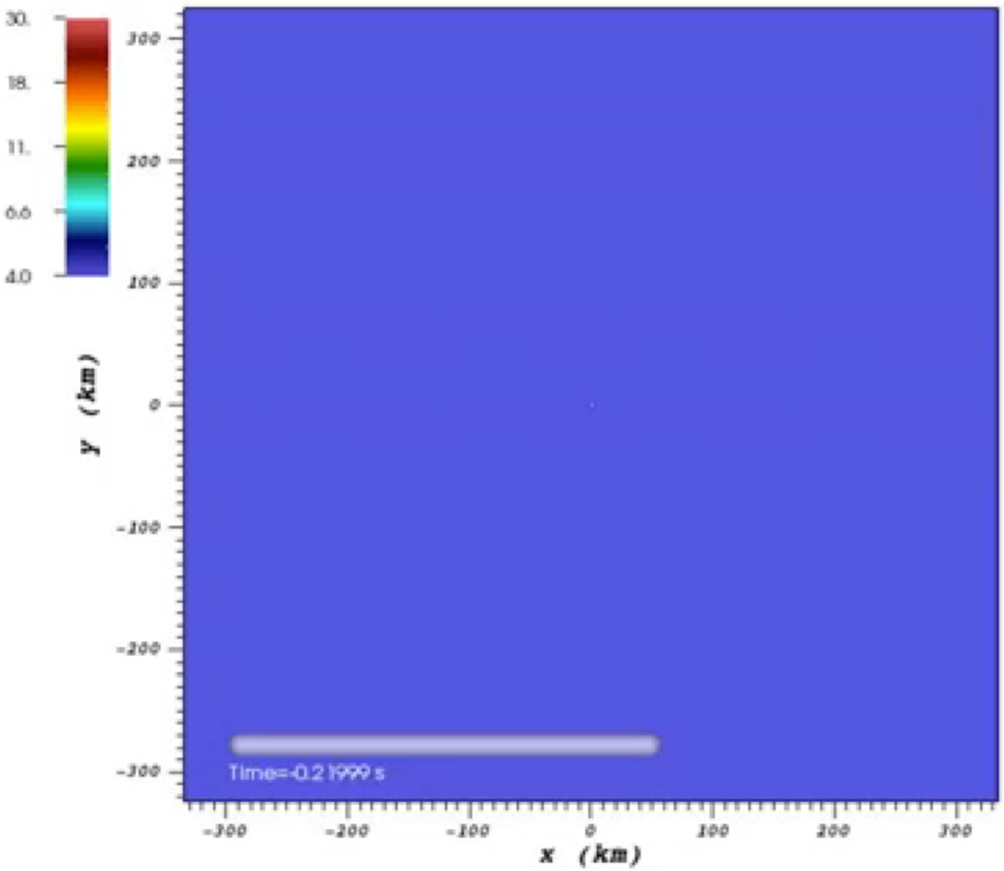


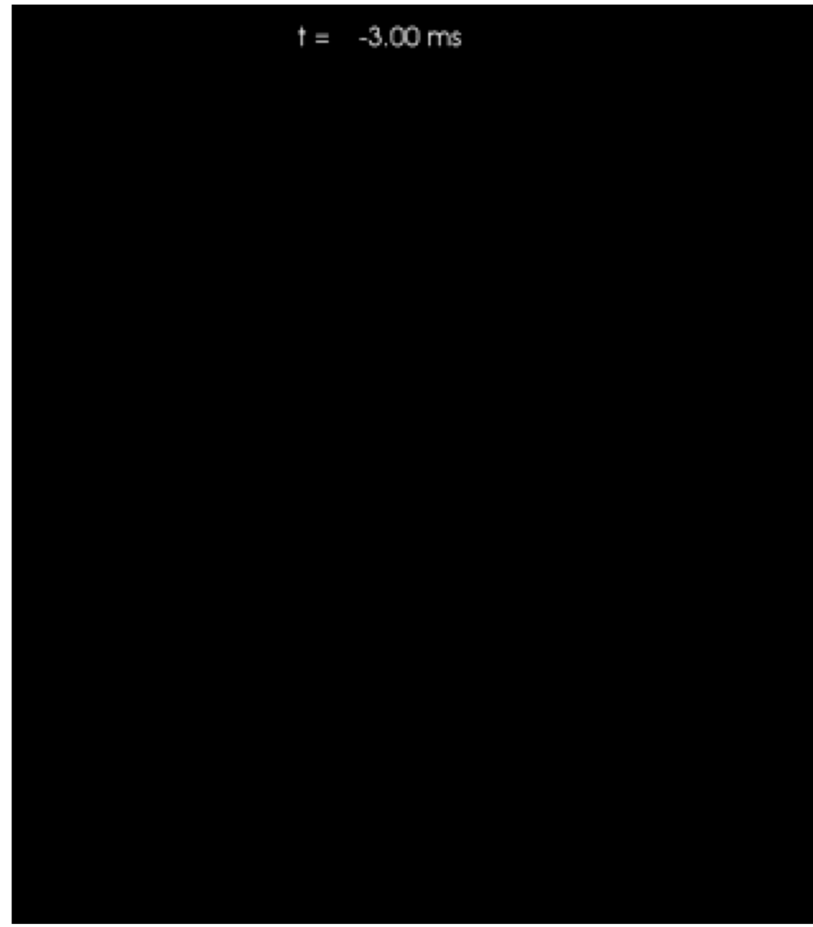


Nomoto et al. 2002, 2013

Supernova Explosions

- Neutrino-driven ($18M_{\odot}$, type II)
- Magneto-rotational ($25M_{\odot}$, type Ic)





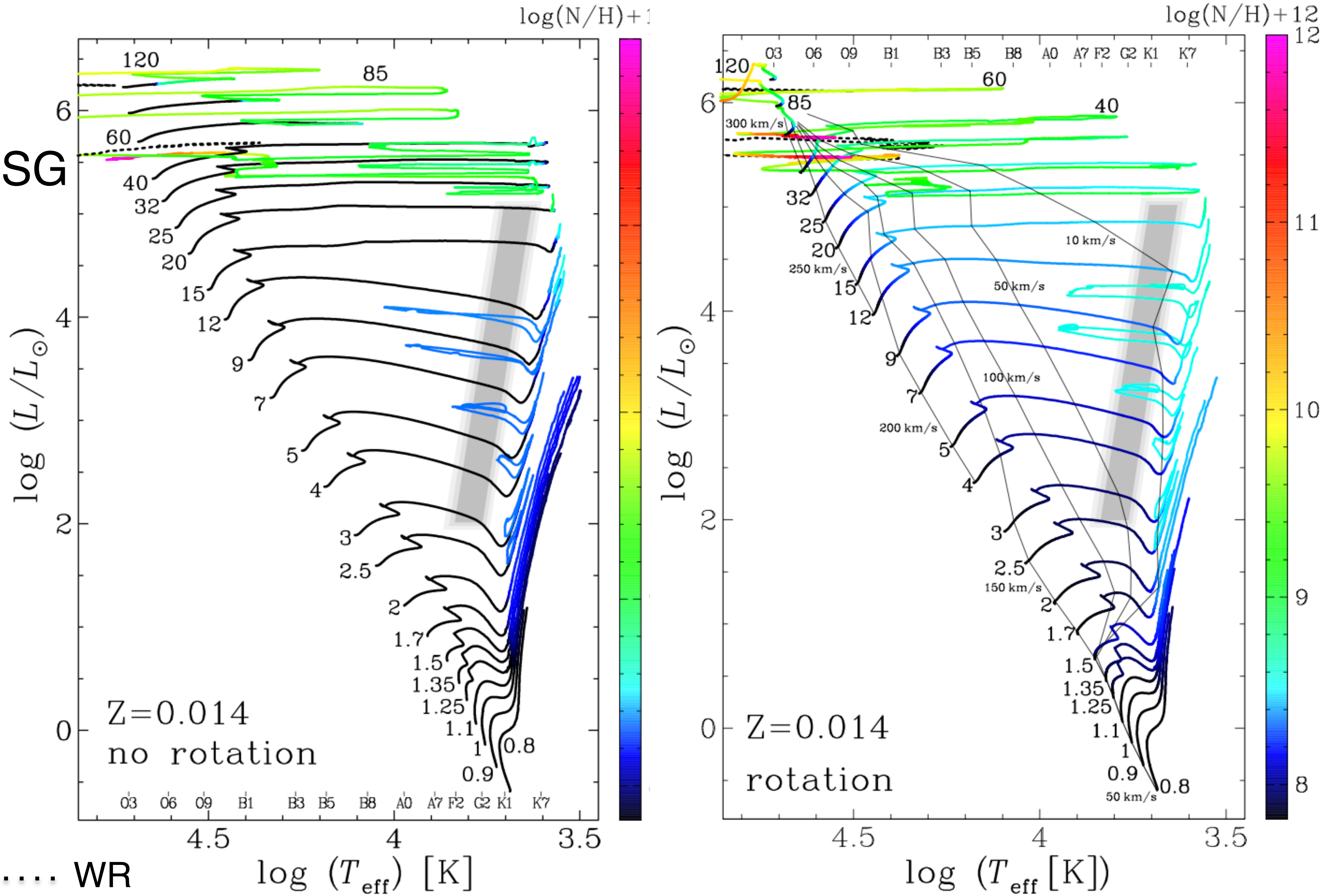
Müller+17; Mezzacappa+; Burrows+; Kotake+

Mösta+14; Takiwaki+; Obergaulinger & Aloy

Meynet & Maeder 02

Rotation effect

Ekström+12



BSG

...... WR

Cepheid instability strip

more in CK22, 2203.01980

Binary effect

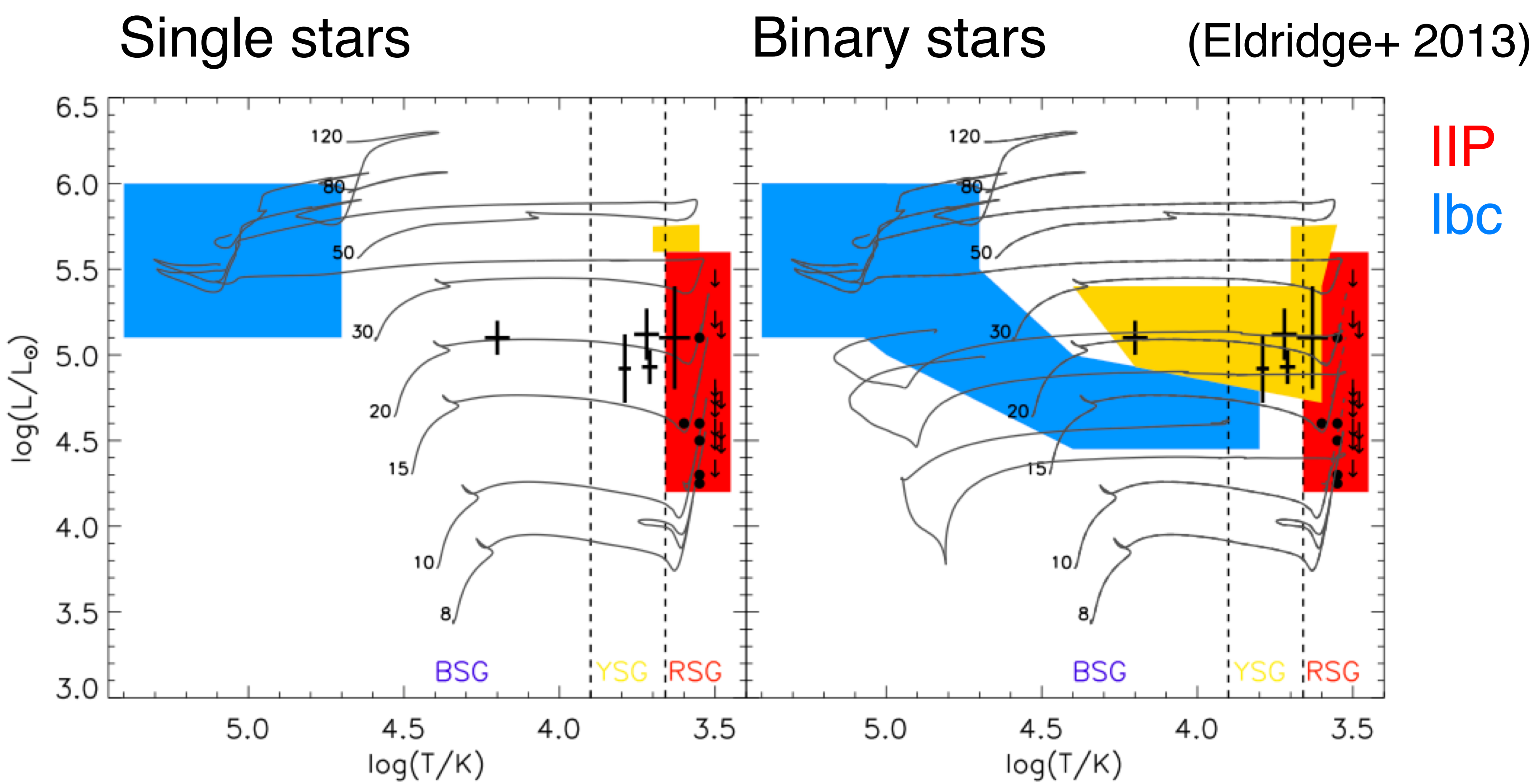


Figure 12. Cartoon HR diagrams of SN progenitors, the red, yellow and blue regions show the expected location of progenitors for type IIP, other type II and type Ib/c SNe. The left panel shows the single-star scenario. The solid lines show the evolution tracks for stars with masses given at their initial location. The right panel shows the binary scenario with the solid tracks at 10, 15 and 20$M_\odot$ showing binary evolution tracks and the dashed lines the single star tracks. In both plots the points with error bars show the locations of SNe 1987A, 1993J, 2008cn, 2009kr and 2011dh (Podsiadlowski 1992; Maund et al. 2004; Elias-Rosa et al. 2009a, 2010; Fraser et al. 2010b; Maund et al. 2011) respectively. The circles show the progenitor locations of observed type IIP progenitors and the arrows the upper limits for these progenitors (Smartt et al. 2009).

more in CK+23, 2211.04964

2/6
The One-Zone Model

Tinsley 1980, Fundamentals of Cosmic Physics, 5, 287

Pagel 1997, Nucleosynthesis and Chemical Evolution of Galaxies

Matteucci 2001, The Chemical Evolution of the Galaxy

CK, Tsujimoto, Nomoto 2000, ApJ, 539, 26

Matteucci 2021, A&ARv

Galactic Chemical Evolution (GCE)

Tinsley 80, Pagel 97, Matteucci 01...

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

Metal ejection rates

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

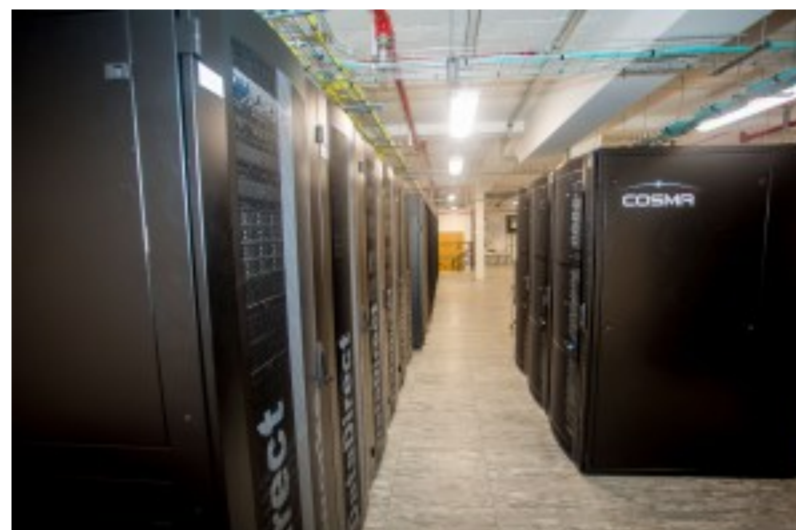
Nuclear Astrophysics

decreased by star formation

Inflow Outflow

Galaxy Evolution

Nuclei in the Cosmos XIII, Debrecen 2014



Initial Mass Function (IMF)

- $\phi(m)$: the *mass* of stars formed in the mass interval (m, $m+dm$). Approximated with a power law, time-independent.

$$\phi(m) \propto m^{-x}$$

- normalized between the lower limit $m_\ell \sim 0.1 M_\odot$ and upper limit $m_u \sim 120 M_\odot$

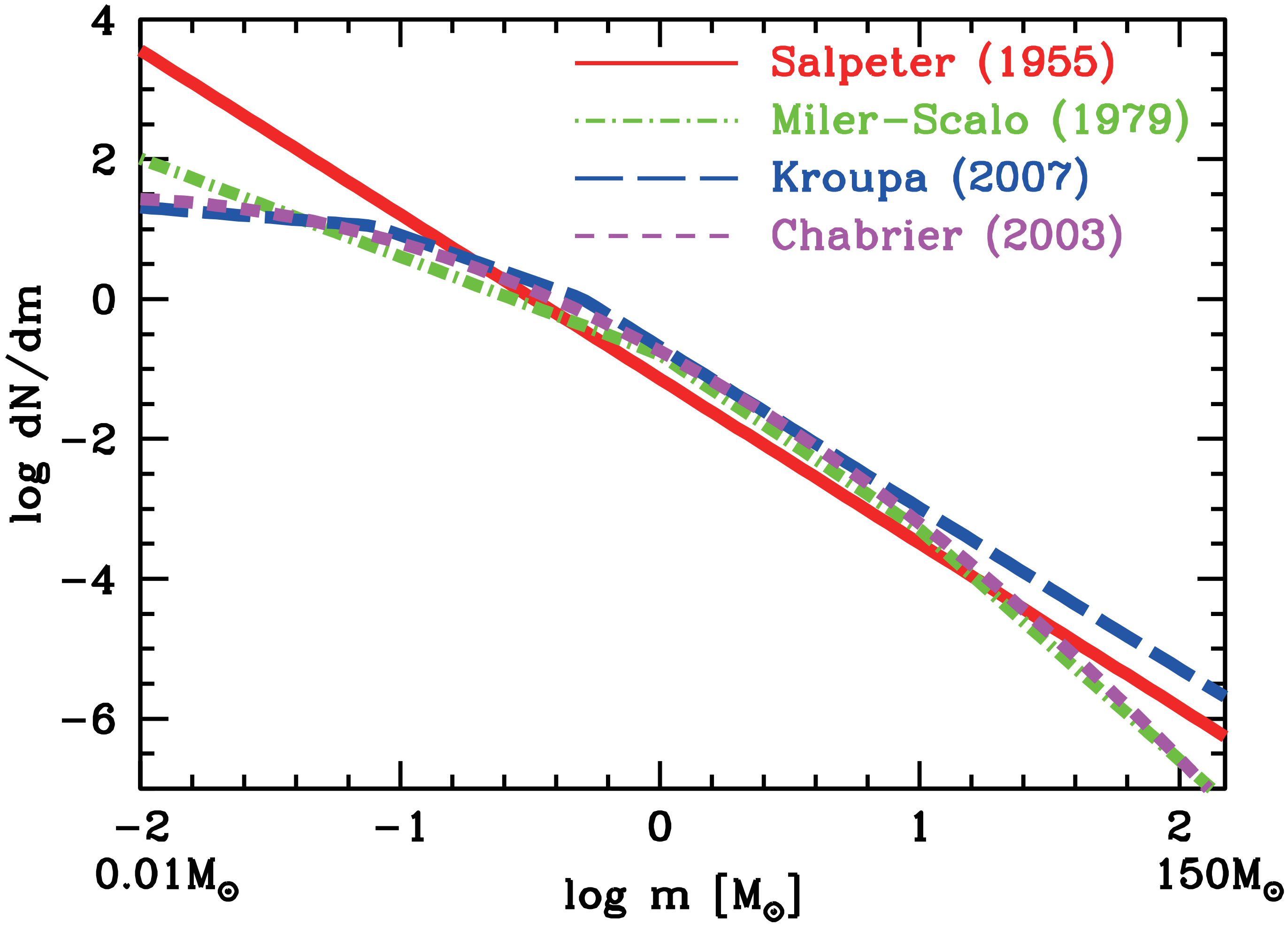
$$\int_{m_\ell}^{m_u} m^{-x} dm = \frac{1}{1-x}(m_u^{1-x} - m_\ell^{1-x}) = 1$$

$$\phi(m) = m^{-x} \frac{1-x}{m_u^{1-x} - m_\ell^{1-x}}$$

- Observed IMF has x=1.35 (Salpeter 1955), but universal?

※ If the IMF is defined for the *number* of stars, x=2.35.

Initial Mass Function (IMF)



In GCE models, Salpeter IMF with a suitable m_ℓ can give similar results with Kroupa IMF.

One-zone model: basic equations

- Assumption: the interstellar medium (ISM) in a system we consider is well mixed with uniform composition.
- Gas fraction f_g, star formation rate ψ, ejection rate E, E_{Ia}, infall rate R_{in}, outflow rate R_{out}

$$\frac{d\,f_{\rm g}}{dt} = -\psi + E + E_{\rm Ia} + R_{\rm in} - R_{\rm out}$$

- Stellar fraction f_s

$$\frac{d\,f_{\rm s}}{dt} = \psi - E - E_{\rm Ia}$$

- Metallicity Z: mass fraction of C and heavier elements

$$\frac{d\,(Z\,f_{\rm g})}{dt} = -Z\,\psi + E_Z + E_{Z,\rm Ia} + Z_{\rm in}\,R_{\rm in} - Z\,R_{\rm out}$$

Ejection rates from SWs and SNe

- A star with initial mass *m*, Lifetime τ_m, and Remnant mass fraction w_m, was born at time ($t - \tau_m$) and dies at *t*.
- Turnoff mass m_t is the mass with $\tau_m = t$.

$$E = \int_{m_t}^{m_u} (1 - w_m)\, \psi(t - \tau_m)\, \phi(m)\ dm \tag{1}$$

- Metals newly synthesized during AGB and core-collapse SNe are given by Nucleosynthesis yields p_{zm}

$$E_{Z,\rm cc} = \int_{m_t}^{m_u} p_{zm}\, \psi(t - \tau_m)\, \phi(m)\ dm \tag{2}$$

- Metals that are in the star from its birth and are returned by stellar winds (SWs), called `*unprocessed*' metals

$$E_{Z,\rm sw} = \int_{m_t}^{m_u} (1 - w_m - p_{zm})\, Z(t - \tau_m)\, \psi(t - \tau_m)\, \phi(m)\ dm \tag{3}$$

mass fraction of SWs x metallicity at birth

Galactic terms

- Star formation rate (SFR)

$$\psi \propto f_g$$

- Inflow rate

$$R_{in} \propto \exp(-t/\tau)$$

$$\text{or} \quad t \exp(-t/\tau)$$

- Outflow rate

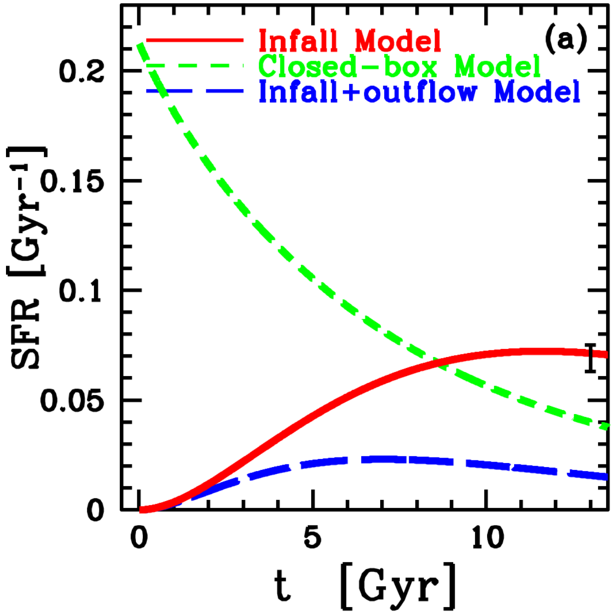
$$R_{out} \propto \psi \qquad : \text{ SN-driven}$$

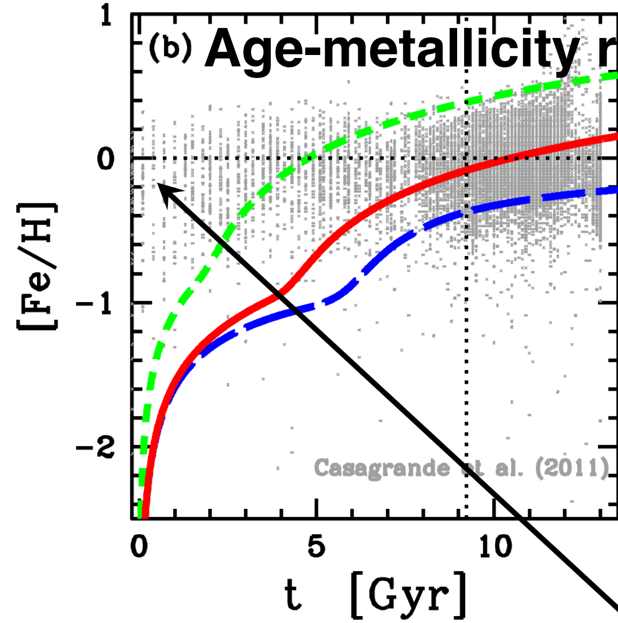
$$\text{or} \quad \psi = 0 \text{ for } t > t_w \quad : \text{ AGN-driven}$$

- With instantaneous recycling approximation, there are analytic solutions, see Tinsley 1980 etc.
- In the following, numerical models without it. (Note some galaxy simulations still assume IRA.)

Closed, infall, outflow models

$f_{g,0}$=1





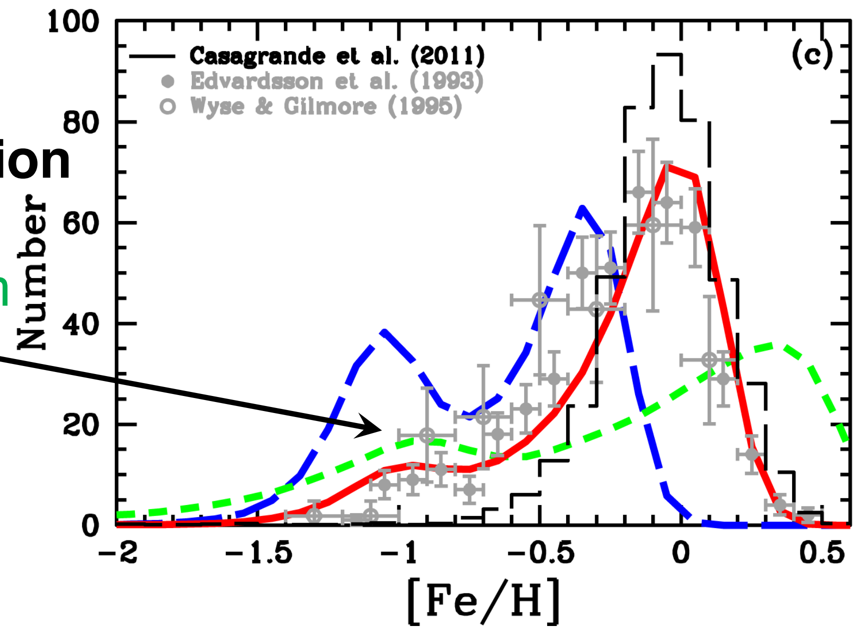
Age-metallicity relation AMR

Obs. uncertain here

Stellar migration

Metallicity distribution function MDF

The G-dwarf problem



also exists in bulge, ellipticals, dwarf gals

Observations are for the solar neighbourhood.

3/6
SNIa Model in GCE

Greggio 2005, A&A, 441, 1055

CK et al. 2015, ApJ, 804, 24 for the subclasses of SNe Ia

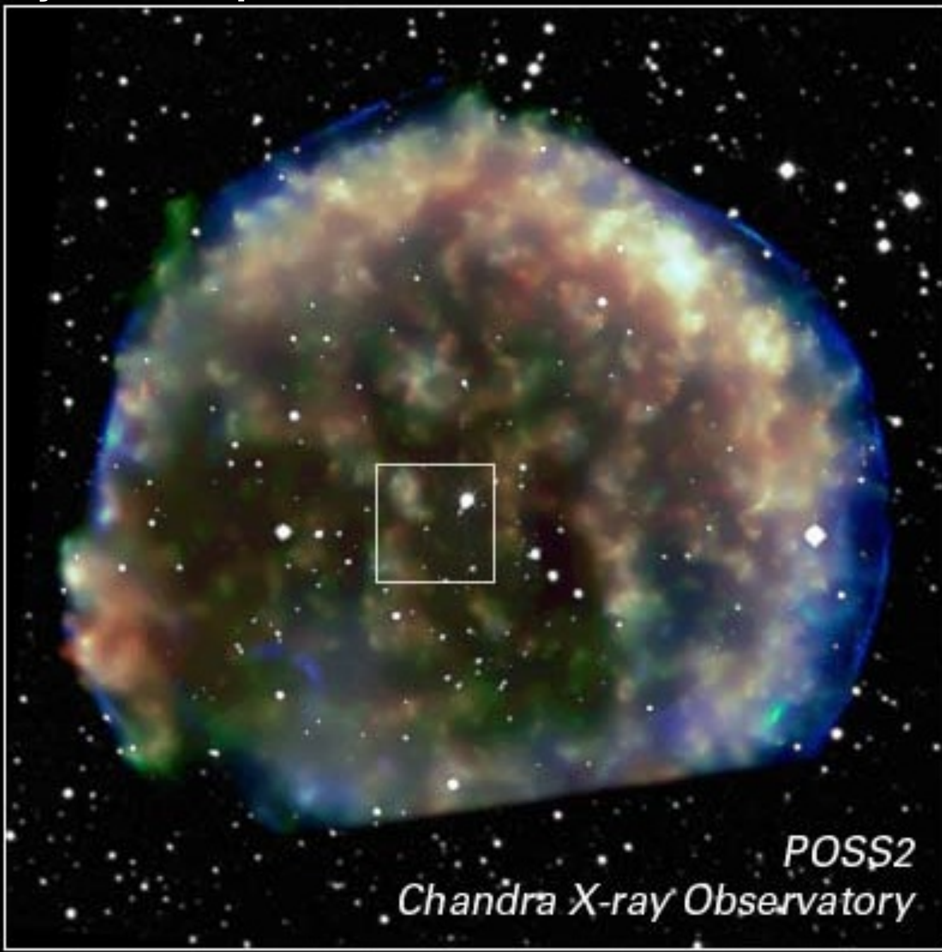
Jha et al. 2019; Soker 2019; Ruiter 2020 for recent reviews

CK, Leung, Nomoto 2020, ApJ, 895, 138

Type Ia Supernovae

※ No H, strong Si line

Tycho's Supernova Remnant SN 1572



NASA, ESA and P. Ruiz-Lapuente (University of Barcelo

Kepler's Supernova Remnant ▪ SN 1604

Tycho Brahe (1546-1601, Denmark)   Johannes Kepler (1571-1630, Germany)

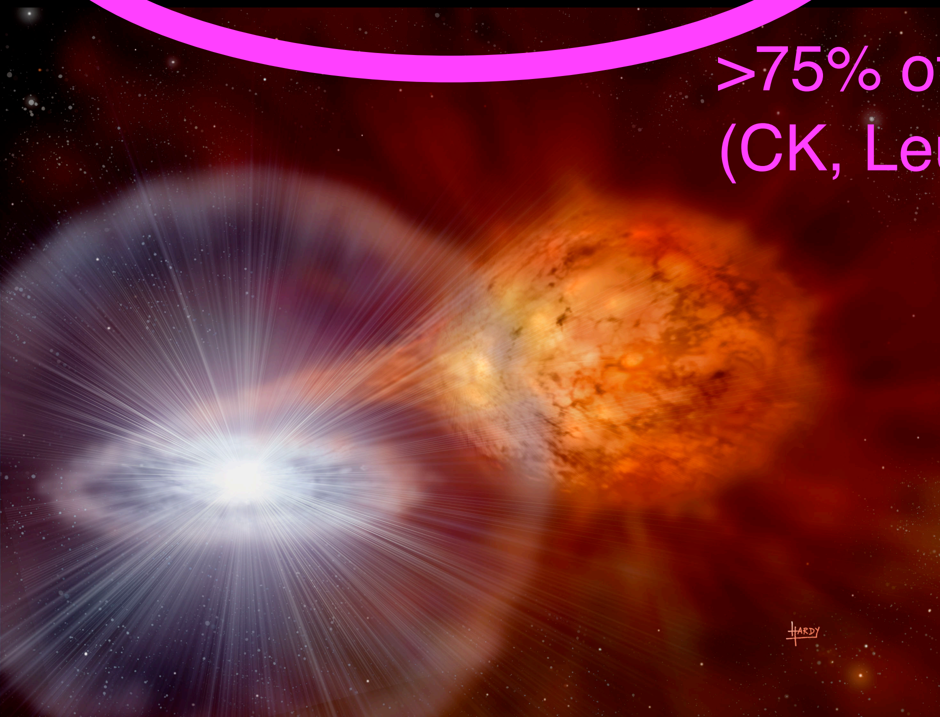
Thermonuclear Supernovae

Thermonuclear explosion in a binary with C+O white dwarf

Chandrasekhar (Ch) mass explosion, expected in Single Degenerate (SD)

vs

Sub-Ch mass explosion, showed in Double Degenerate (DD) simulations, also possible in SD



>75% of SNIa contribution for **Mn** (CK, Leung, Nomoto 20)

← a companion star observed! (McCully+14)

Type Ia Supernovae

- Mass ejection,

$$E_{\rm Ia} = m_{\rm CO}\,\mathcal{R}_{\rm Ia}$$

- Metal ejection, Nucleosynthesis yields $p_{zm,\rm Ia}$

$$E_{Z,\rm Ia} = m_{\rm CO}\,p_{zm,\rm Ia}\,\mathcal{R}_{Ia}$$

- SN Ia Rate, see Kobayashi & Nomoto (2009) for comparison
  - Kobayashi et al. (1998)'s formula, depends on *Z*

primary stars x secondary stars

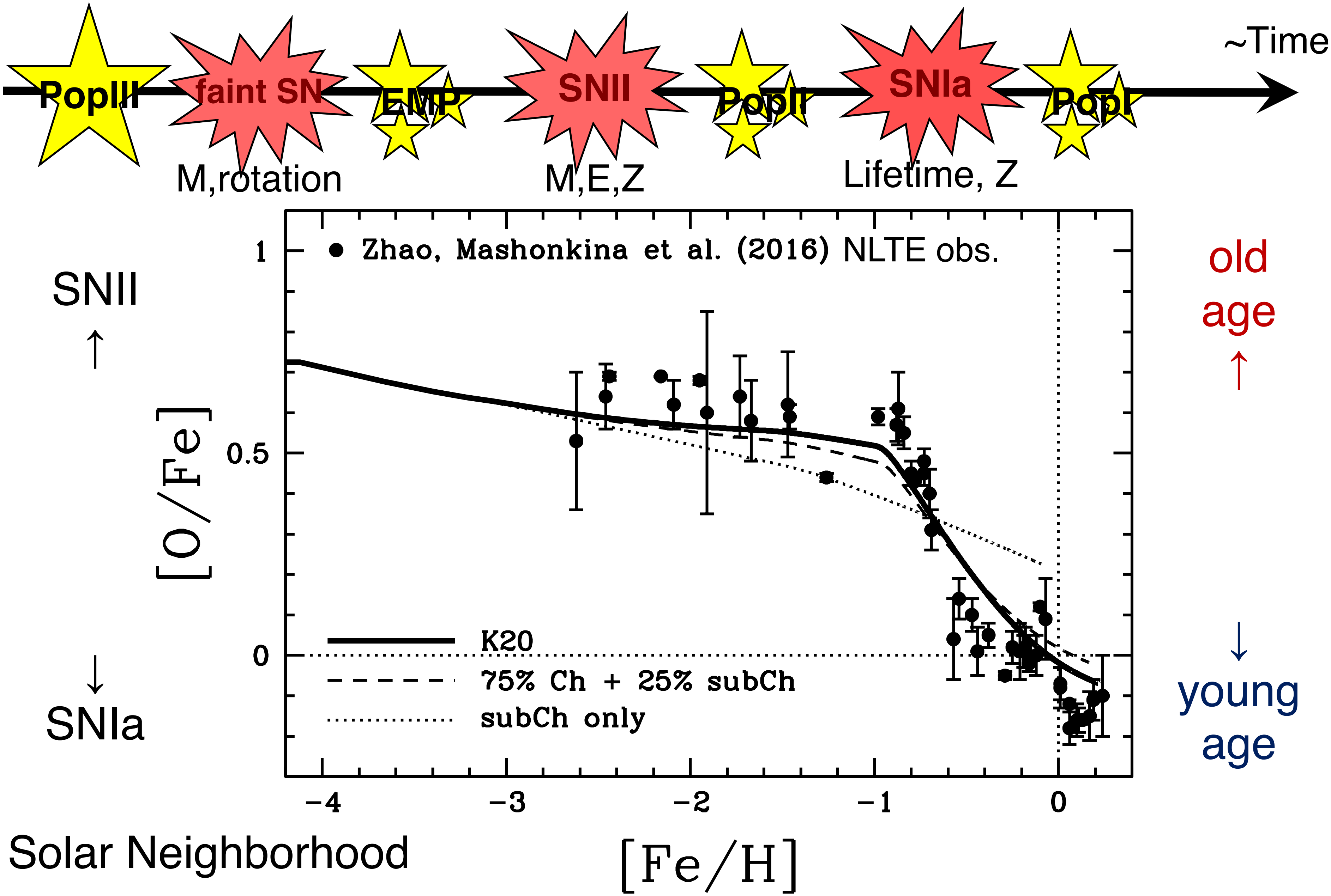
$$\mathcal{R}_{\rm Ia} = b\left[\int_{\max[m_{\rm p,\ell},\,m_t]}^{m_{\rm p,u}} \frac{1}{m}\,\phi(m)\;dm\right]\left[\int_{\max[m_{\rm d,\ell},\,m_t]}^{m_{\rm d,u}} \frac{1}{m}\,\psi(t-\tau_m)\,\phi_{\rm d}(m)\;dm\right]$$

  - Greggio & Renzini (1983)'s formula, also in Matteucci's works

$$\mathcal{R}_{\rm Ia} = A\int_{\max[2m_2(t),m_{\rm B,\ell}]}^{m_2(t)+m_{\rm B,u}/2} \phi(m_{\rm B})\left[\int_{\max[\frac{m_2(t)}{m_{\rm B}},\,\frac{m_{\rm B}-m_{\rm B,u}/2}{m_{\rm B}}]}^{0.5} \psi(t-\tau_{m_2})f(\mu)d\mu\right]dm_{\rm B}$$

mass ratio

The [α/Fe]-[Fe/H] relation



Solar Neighborhood

4/6
The Origin of Elements

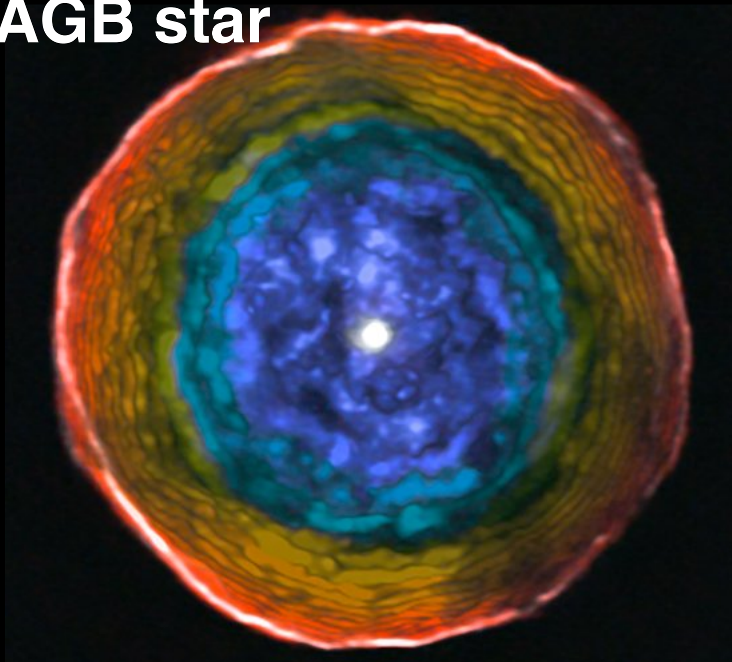
CK, Umeda, Nomoto et al. 2006

CK, Karakas, Umeda 2011

CK, Karakas, Lugaro 2020, ApJ, 900, 179

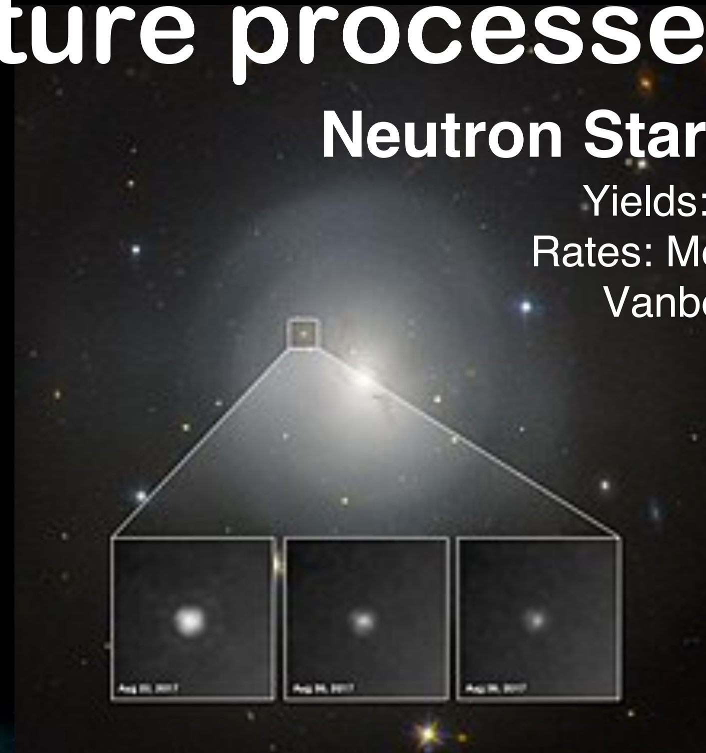
Neutron-capture processes

AGB star



Neutron Star Merger

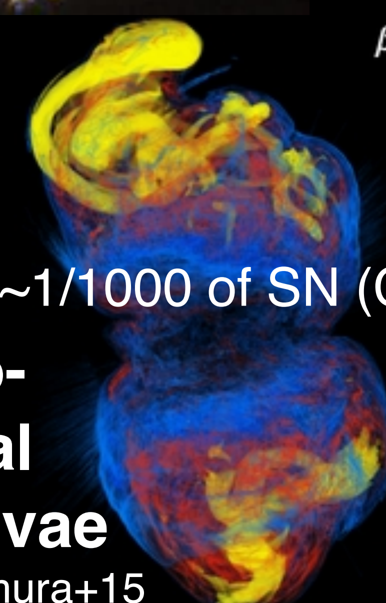
Yields: Wanajo+14
Rates: Mennekens & Vanbeveren 2014



Electron Capture Supernovae

Yields: Wanajo+13
Mass: Doherty+15

$$\beta = \frac{P_{gas}}{P_{mag}}$$



3% of HN, ~1/1000 of SN (CK+20)

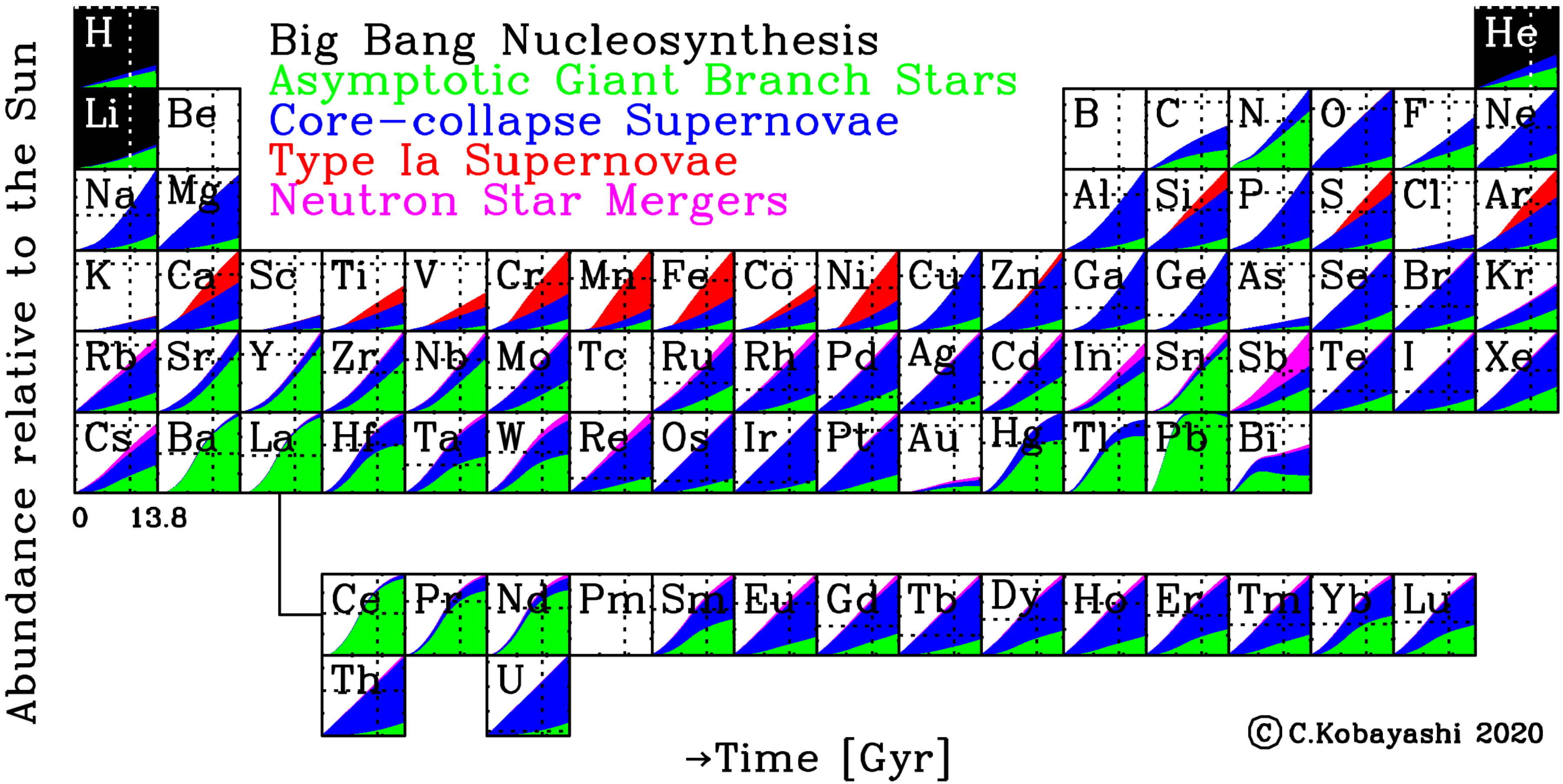
Magneto-rotational Supernovae

Yields: Nishimura+15

CK, Karakas, Lugaro 2020

The Origin of Elements

CK, Karakas, Lugaro 2020, ApJ



※Purely theoretical, no empirical equations.

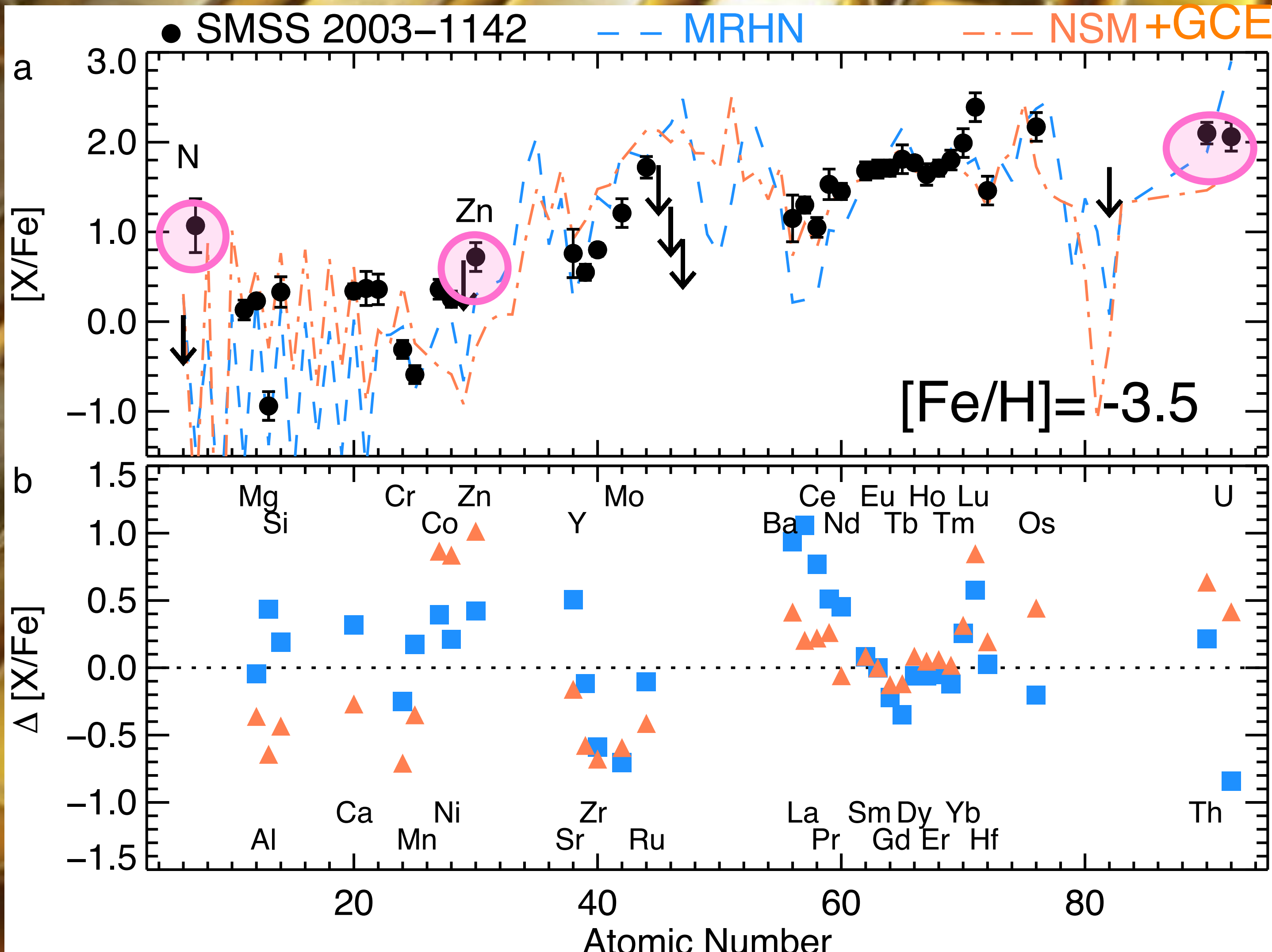
※Mass-loss is counted toward AGB or ccSN.

dotted lines: solar values

Article
Nature | Vol 595 | 8 July 2021 | 223

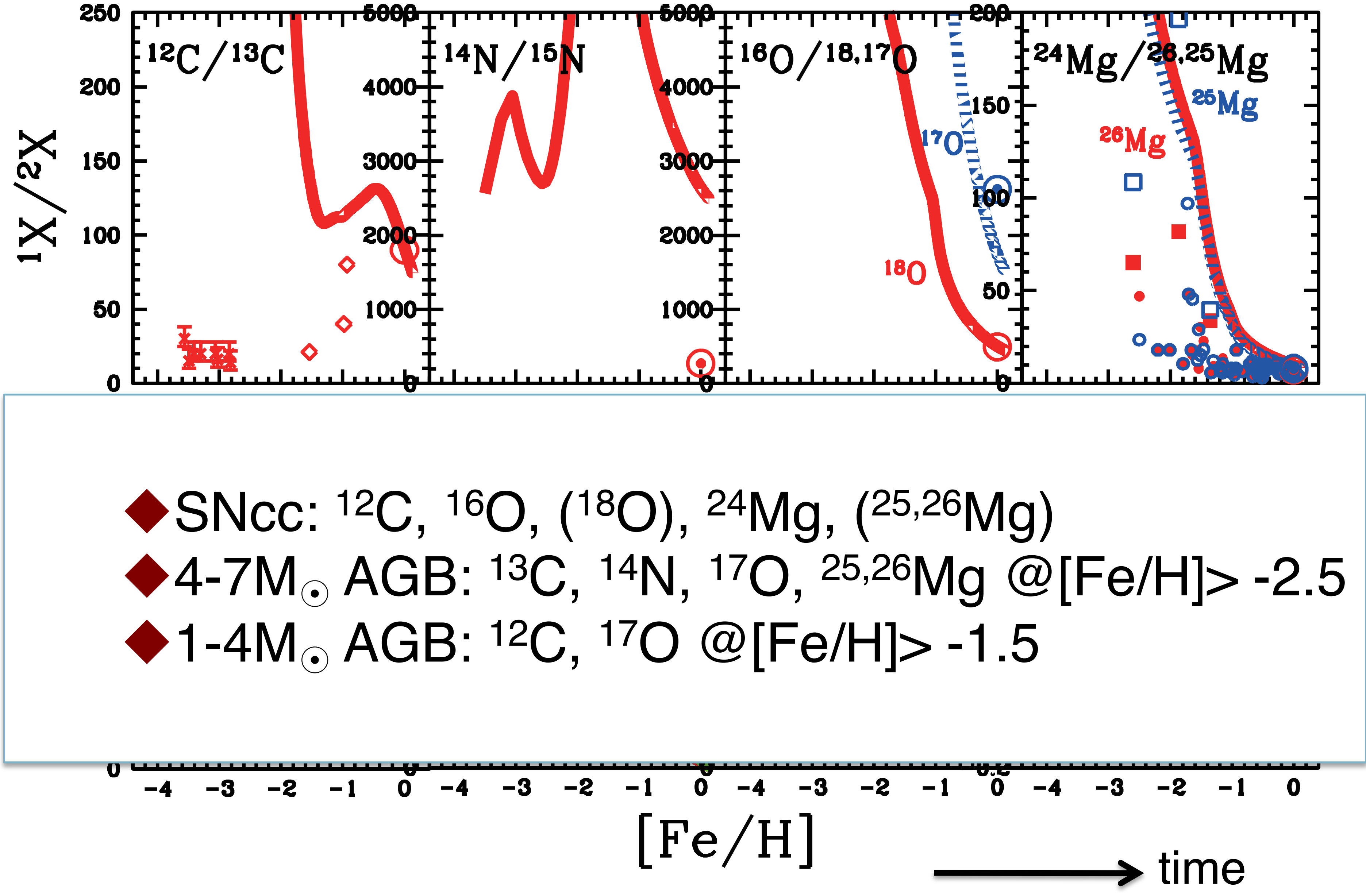
r-Process elements from magnetorotational hypernovae

D. Yong[1,2]✉, C. Kobayashi[2,3], G. S. Da Costa[1,2], M. S. Bessell[1], A. Chiti[4], A. Frebel[4], K. Lind[5], A. D. Mackey[1,2], T. Nordlander[1,2], M. Asplund[6], A. R. Casey[2,7], A. F. Marino[8], S. J. Murphy[1,9] & B. P. Schmidt[1]



Isotope Ratios

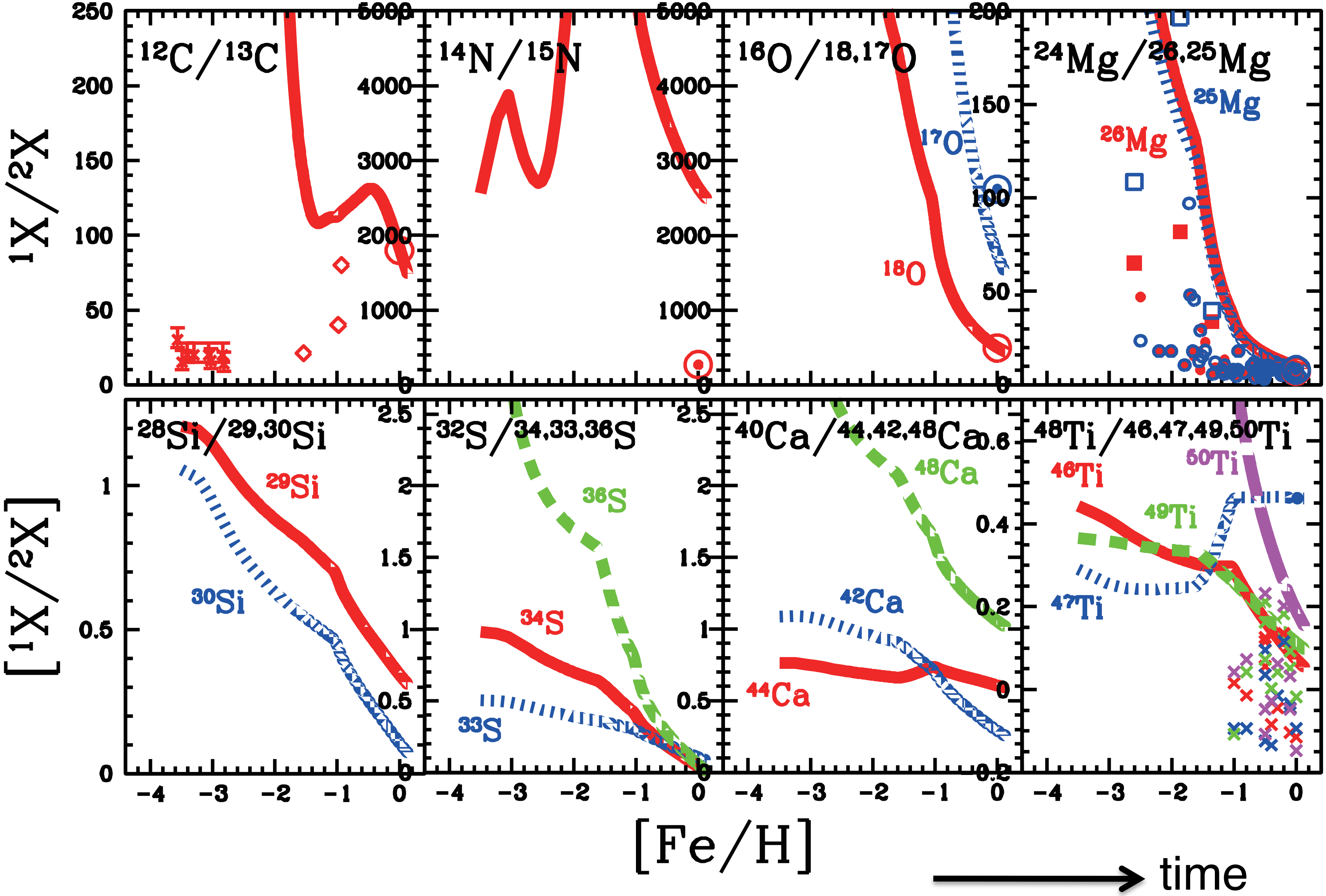
CK, Karakas, Umeda (2011)



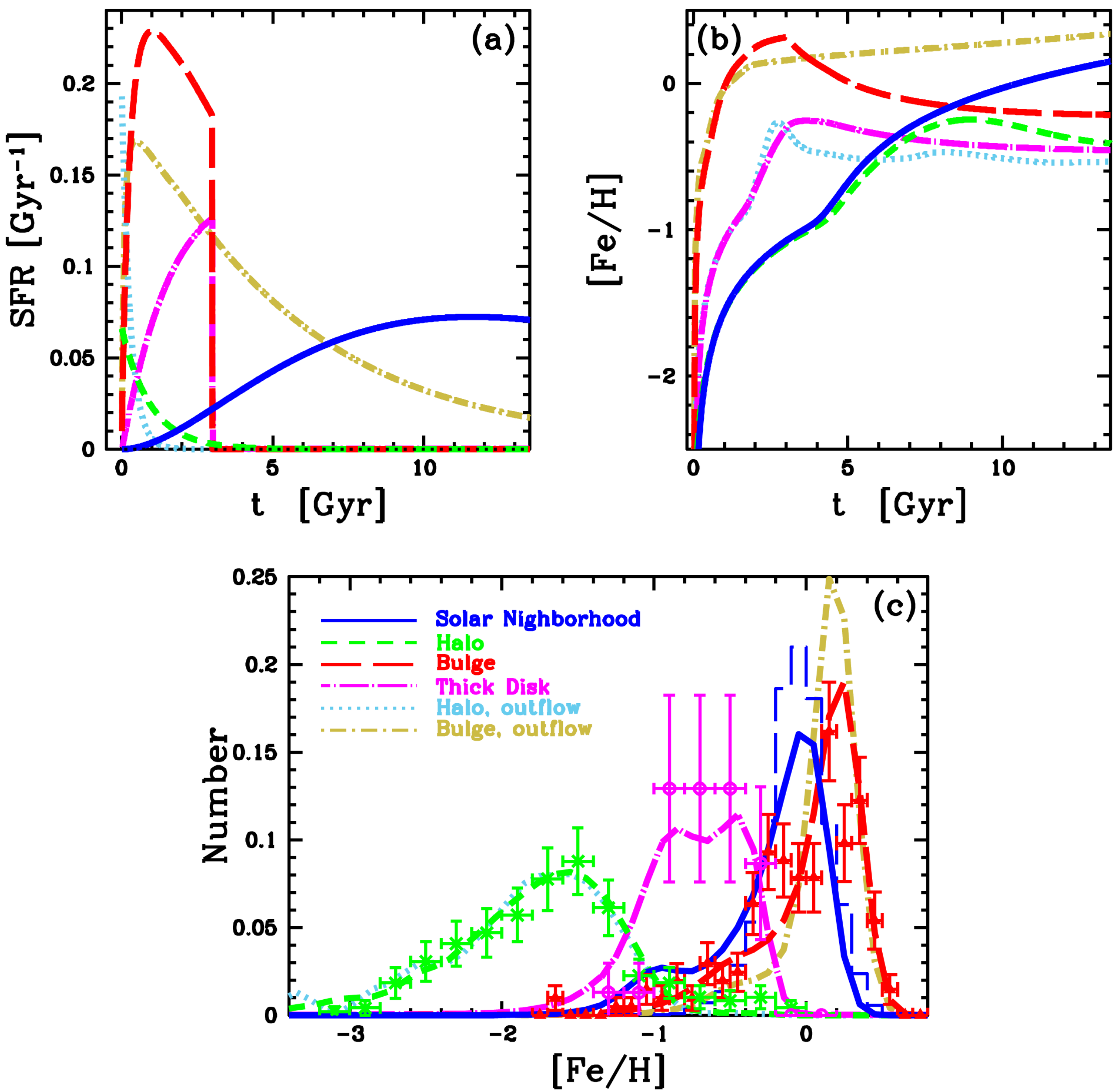
- SNcc: ^{12}C, ^{16}O, (^{18}O), ^{24}Mg, ($^{25,26}Mg$)
- 4-7$M_{\odot}$ AGB: ^{13}C, ^{14}N, ^{17}O, $^{25,26}Mg$ @[Fe/H]> -2.5
- 1-4$M_{\odot}$ AGB: ^{12}C, ^{17}O @[Fe/H]> -1.5

Isotope Ratios

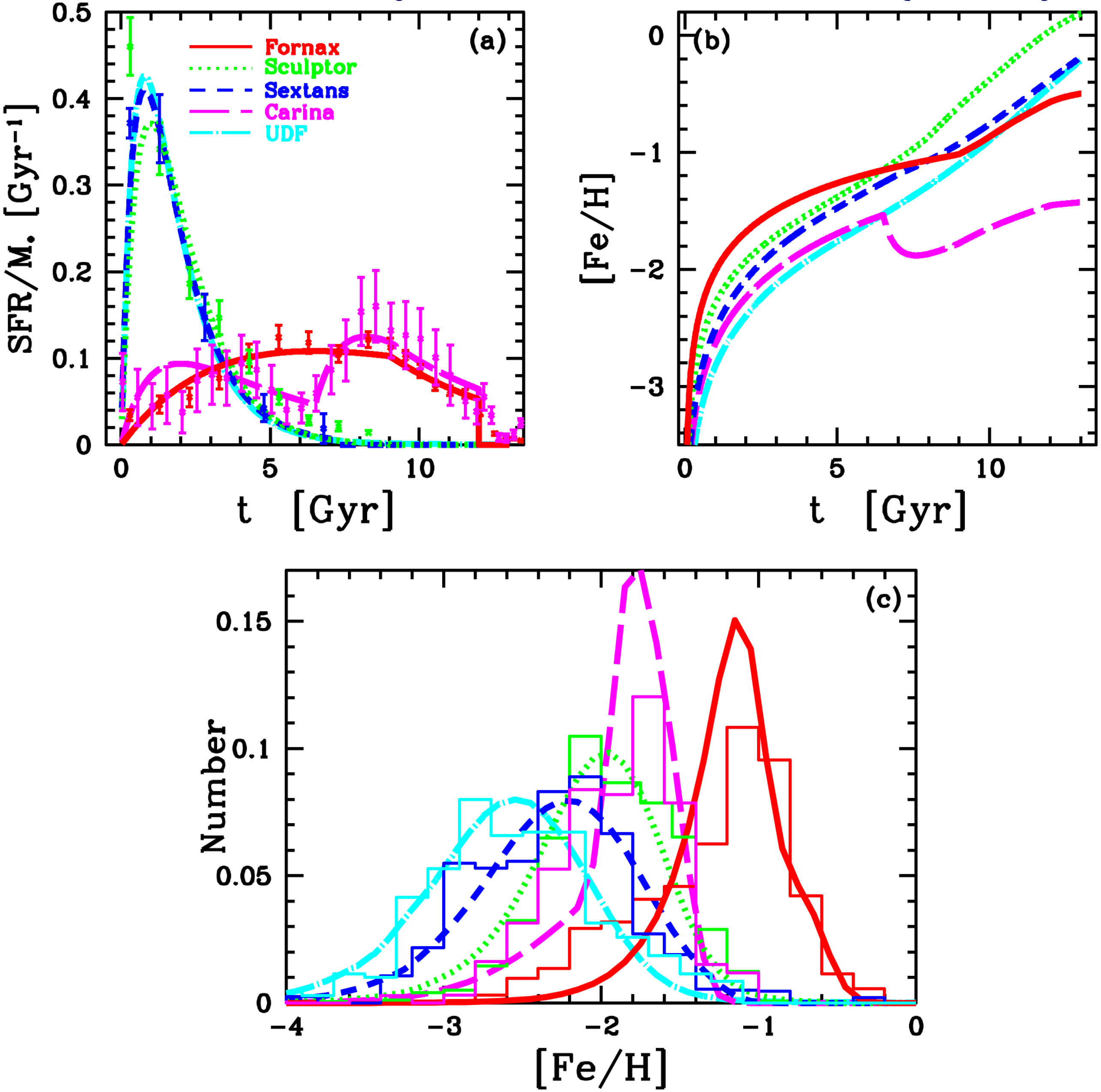
CK, Karakas, Umeda (2011)



MW solar, thick disk, bulge, halo



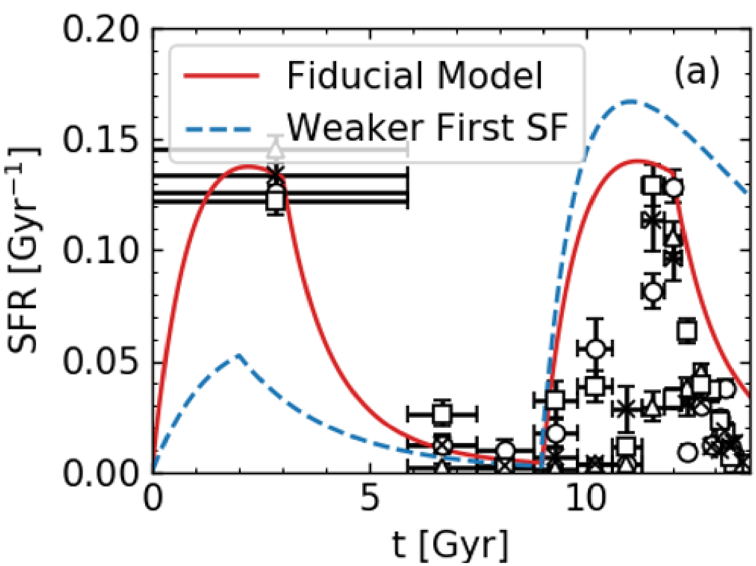
MW dwarf spheroidals (dSphs)



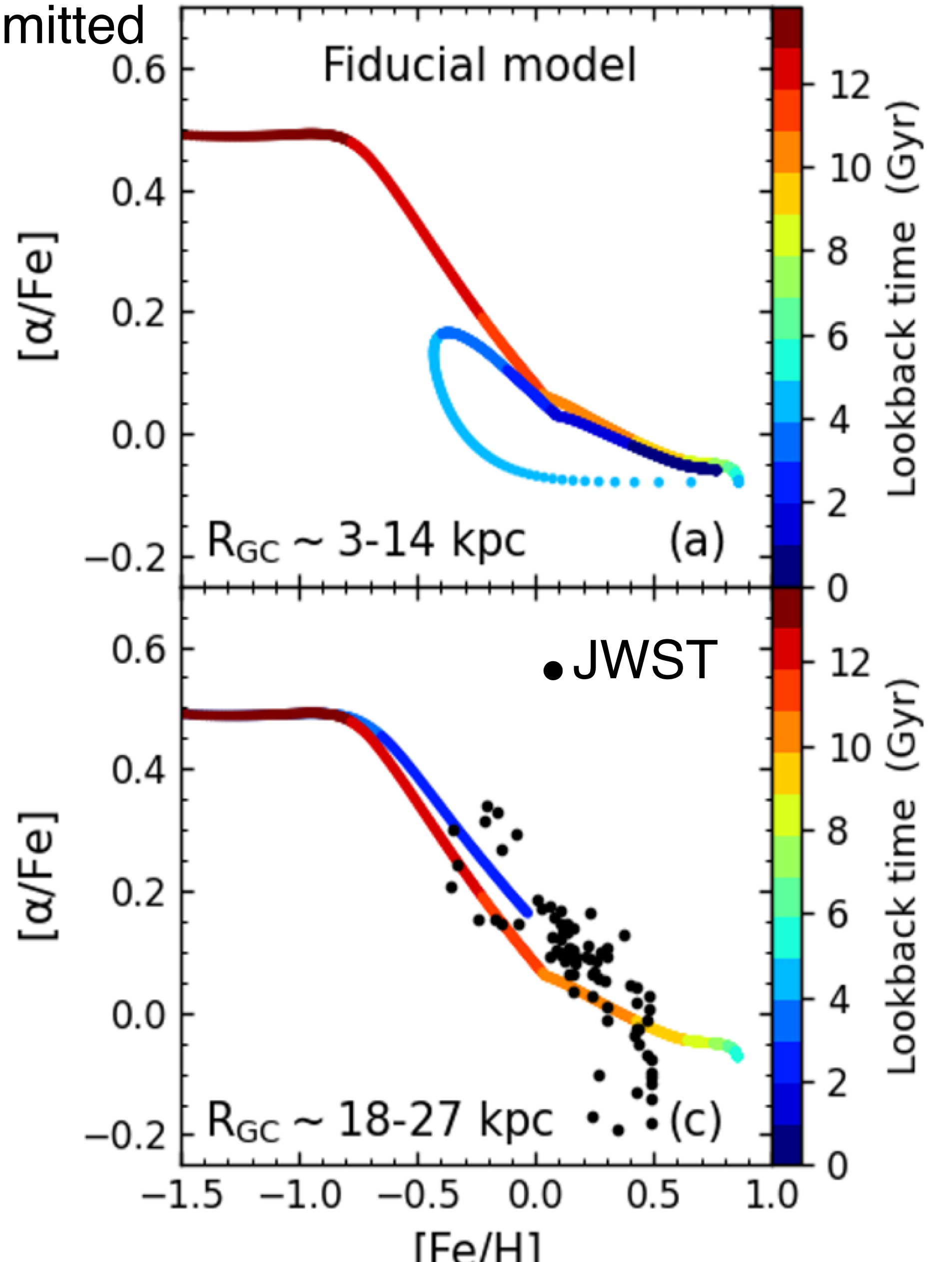
A model of Andromeda Galaxy M31

CK, Bhattacharya+ 2023, to be submitted

- Dual inflow model, to match age and metallicity distribution with HST (Williams+17) and O/Ar of PNe



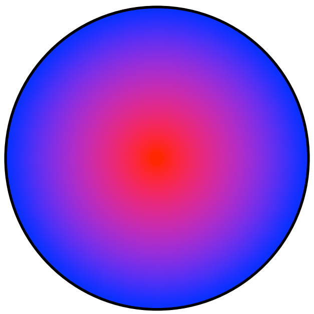
Arnaboldi +22

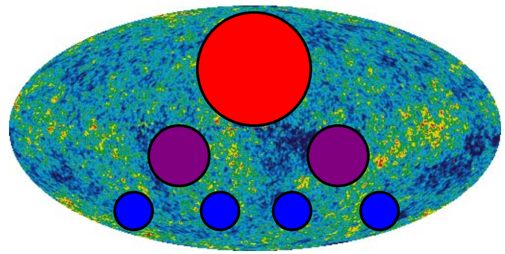


Part-2

Chemodynamical Simulations
&
Inhomogeneous enrichment

3 types of galaxy models





One-zone (monolithic) models

- Instantaneous mixing approximation
- SFR/inflow/outflow with analytic formula
- Average evolution of a galaxy (or a shell of galaxy)

Semi-analytic (hierarchical) models

- Mass assembly history based on λCDM scenario
- Global properties of galaxies in a large scale

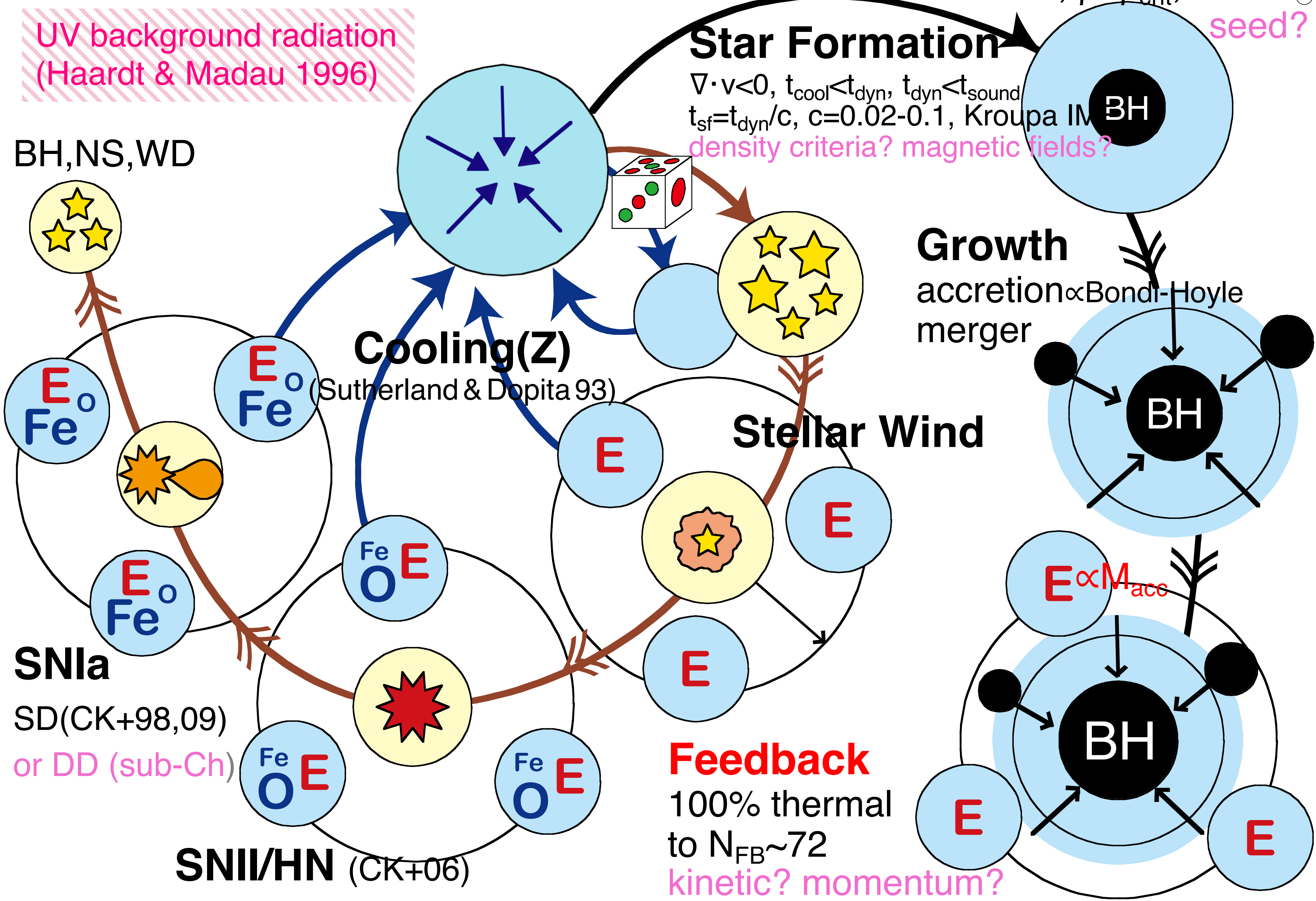
Chemo-dynamical simulations

- Inhomogeneous chemical enrichment
- Internal structures - kinematics of stars/gas, spatial distribution of elements

other types of models

- Stochastic models (Argast+02; Ishimaru & Prantzos; Cescutti+; Wehmeyer+)
- Chemodynamical models without hydro (e.g., Minchev & Chiappini)

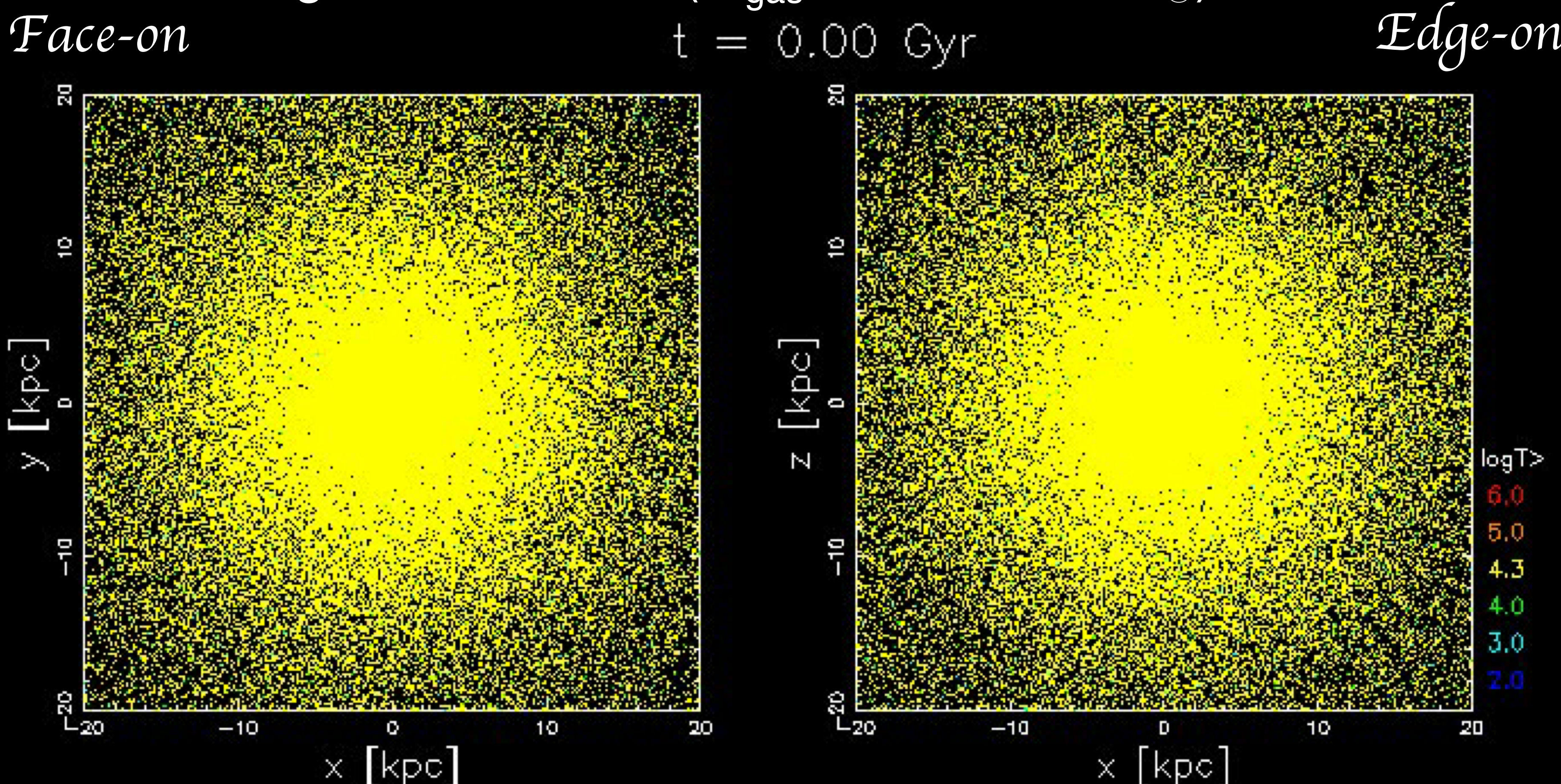
Chemodynamics



Galactic winds

CK+07

- Isolated disk, fixed NFW halo $M_{tot}=10^{10}$ /h $M_\odot$
- 10% gas, N=160000 ($m_{gas}=6.3\times10^3$ /h $M_\odot$), $\lambda=0.1$



Colors: Gas Temperature, White: Stars

https://star.herts.ac.uk/~chiaki/works/diskold160000z.mpg

5/6
The Milky Way Galaxy

CK & Nakasato 2011

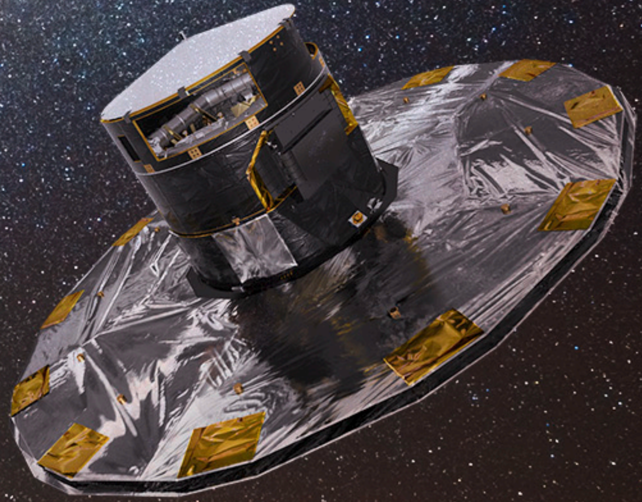
Vincenzo & CK 2020

Grand et al. 2017; Font et al. 2020; FIRE-2

Galactic Archaeology surveys

of Milky Way and local dwarf galaxies

- ❖ Motions of one <u>billion</u> stars are measured with Gaia.
- ❖ Ages from asteroseismology COROT, Kepler, K2, TESS…
- ❖ Elemental Abundances (from Li to Eu) of one <u>million</u> stars will be measured with multi-object spectrographs:
  - ◆ **SEGUE** (Resolution~1800) on SDSS
  - ◆ **RAVE** (R~7500) on 1.2m UKST
  - ◆ **APOGEE** (R~20000, IR) on SDSS
  - ◆ **HERMES** on AAT (R~28000/50000)
  - ◆ **GAIA-ESO** with VLT (R~20000/40000)
  - ~~◆ WFMOS on Subaru~~
  - ◆ **DESI** on Mayall (R~2000-5000)
  - ◆ **WEAVE** on WHT (R~5000/20000)
  - ◆ **4MOST** on VISTA (R~4000/21000)
  - ◆ **MOONS** on VLT (R~4000-6000/20000)
  - ◆ **PFS** on Subaru (R~2300-5000)
  - ◆ **MSE** (R~5000/30000)
- ❖ For Au, U etc, target survey of EMP stars w higher res./ UV

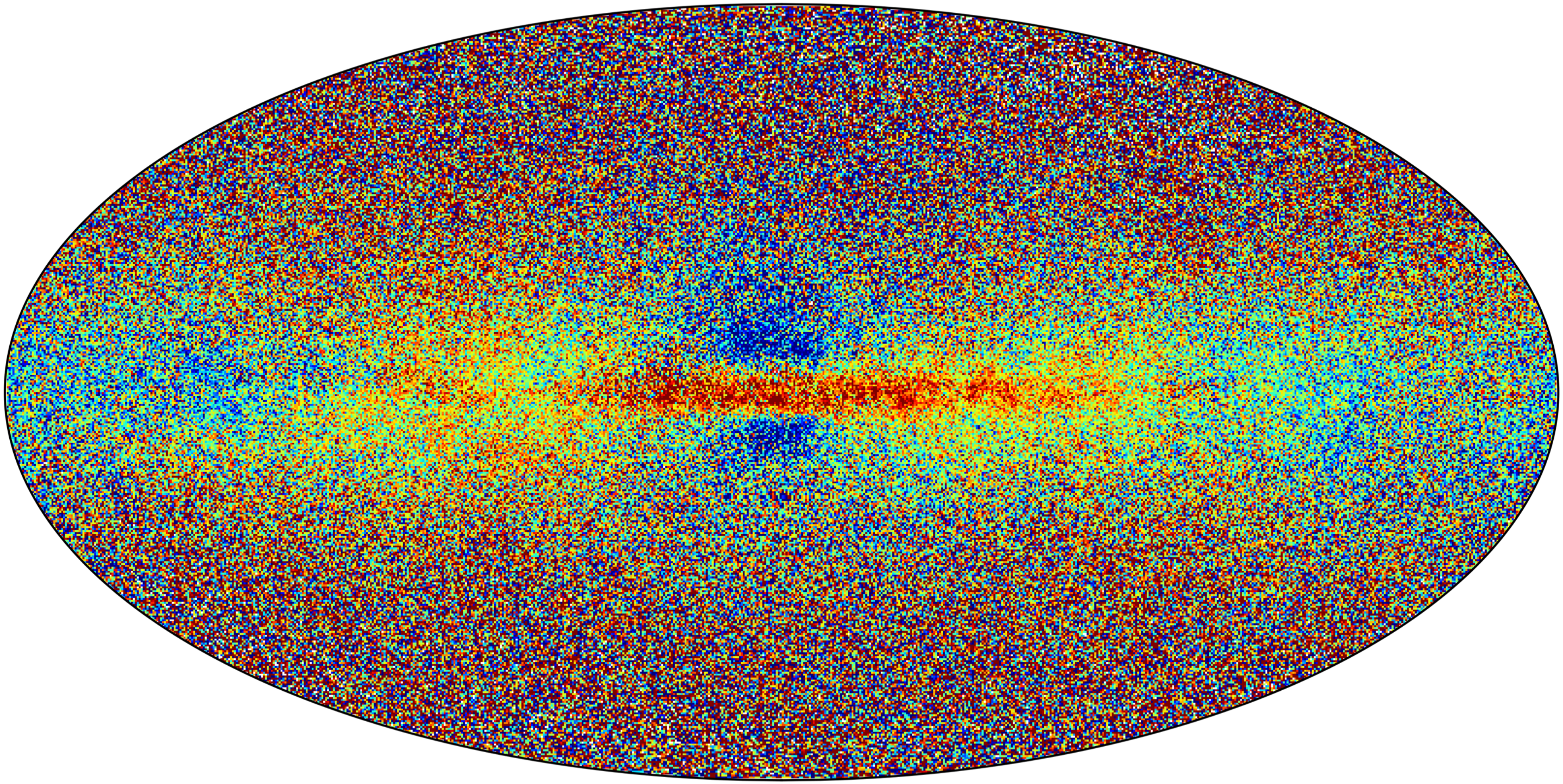


Gaia spacecraft http://sci.esa.int/gaia/

Gaia DR3 Metallicity Map

13 June 2022

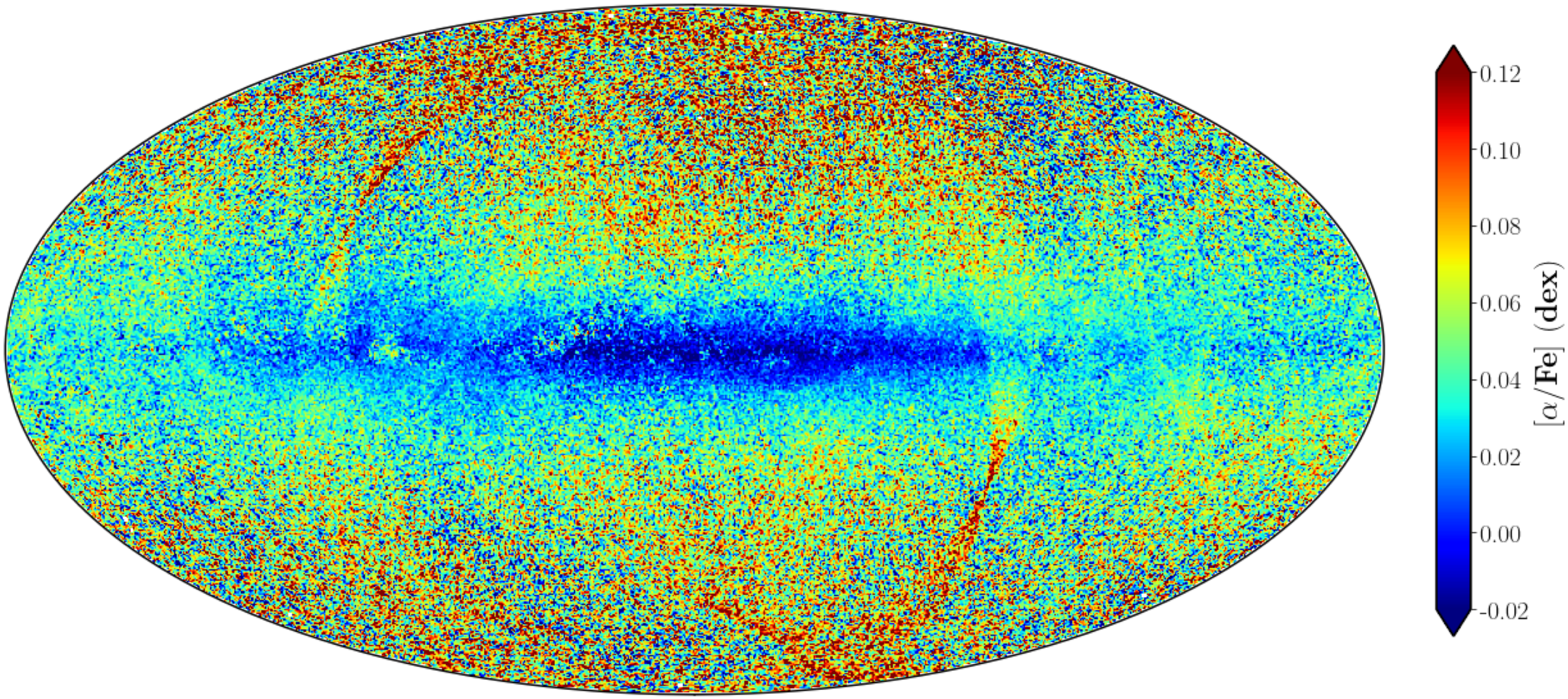
Metallicity $Z=\Sigma X_i(\geq C)$, low to high



1.59 billion sources with G<21 mag
470 million objects have astrophysical parameters
https://www.cosmos.esa.int/web/gaia/dr3

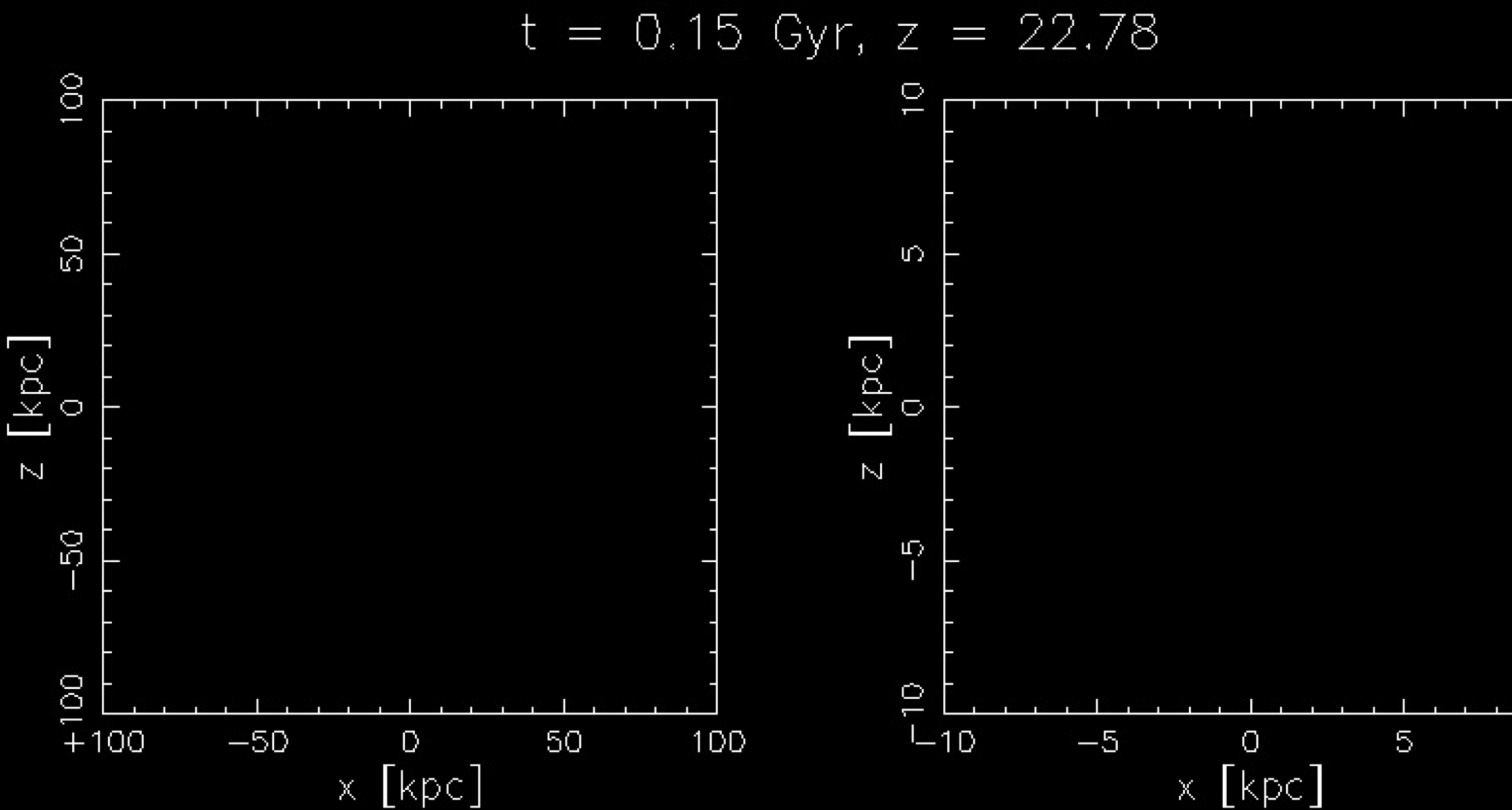
Gaia DR3 [α/Fe] Map

Abundance $[X/Y]=\log(X/Y)-\log(X/Y)_\odot$



The patterns close to the Ecliptic Poles are artefacts caused by the Gaia scanning law.

MW-type galaxy zoom-in simulation

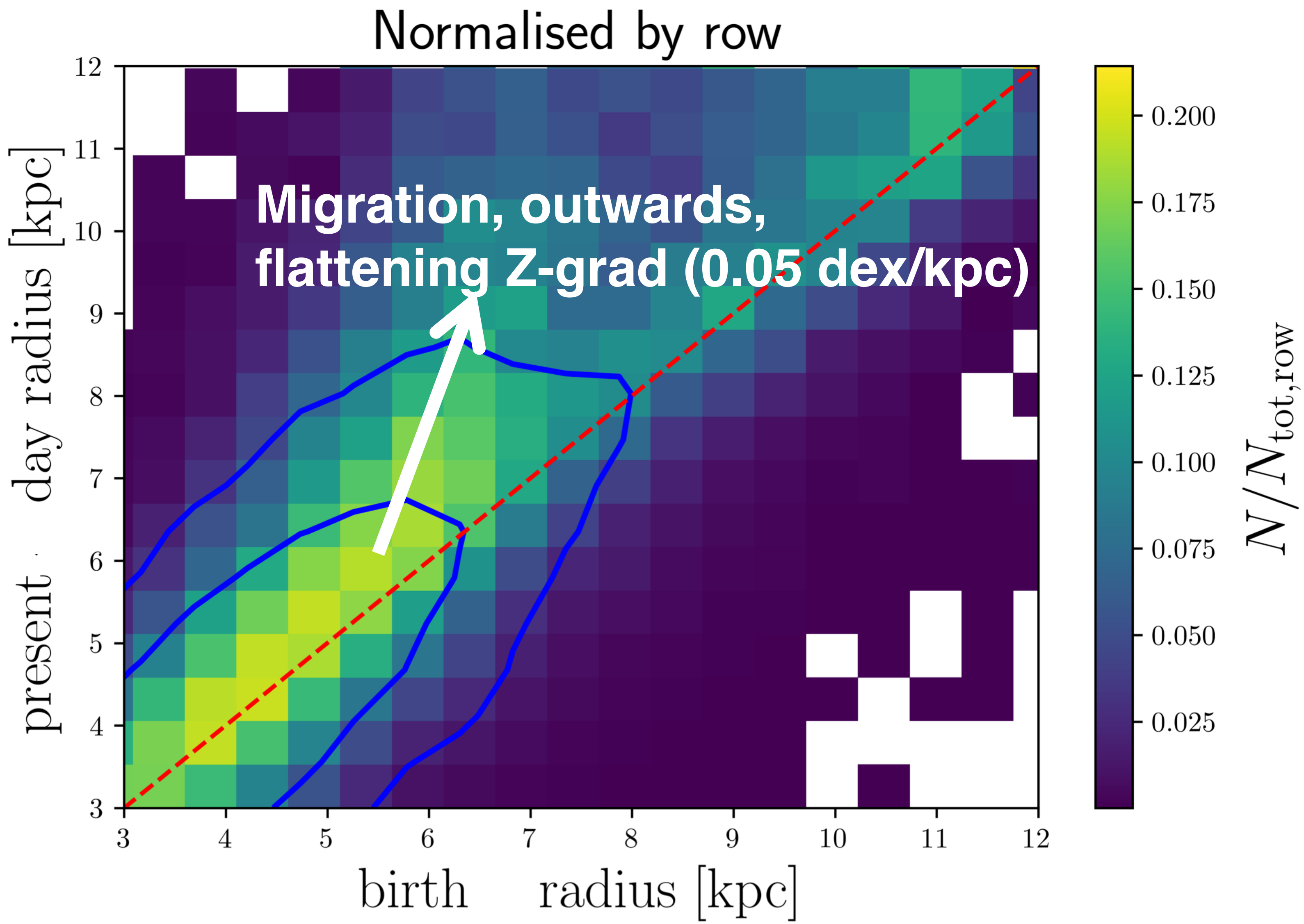


Gadget3-based code (CK+ 2007)

Aquila Initial Condition (Scannapieco+12), 3x10^{5}M$_\odot$, 0.5kpc

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

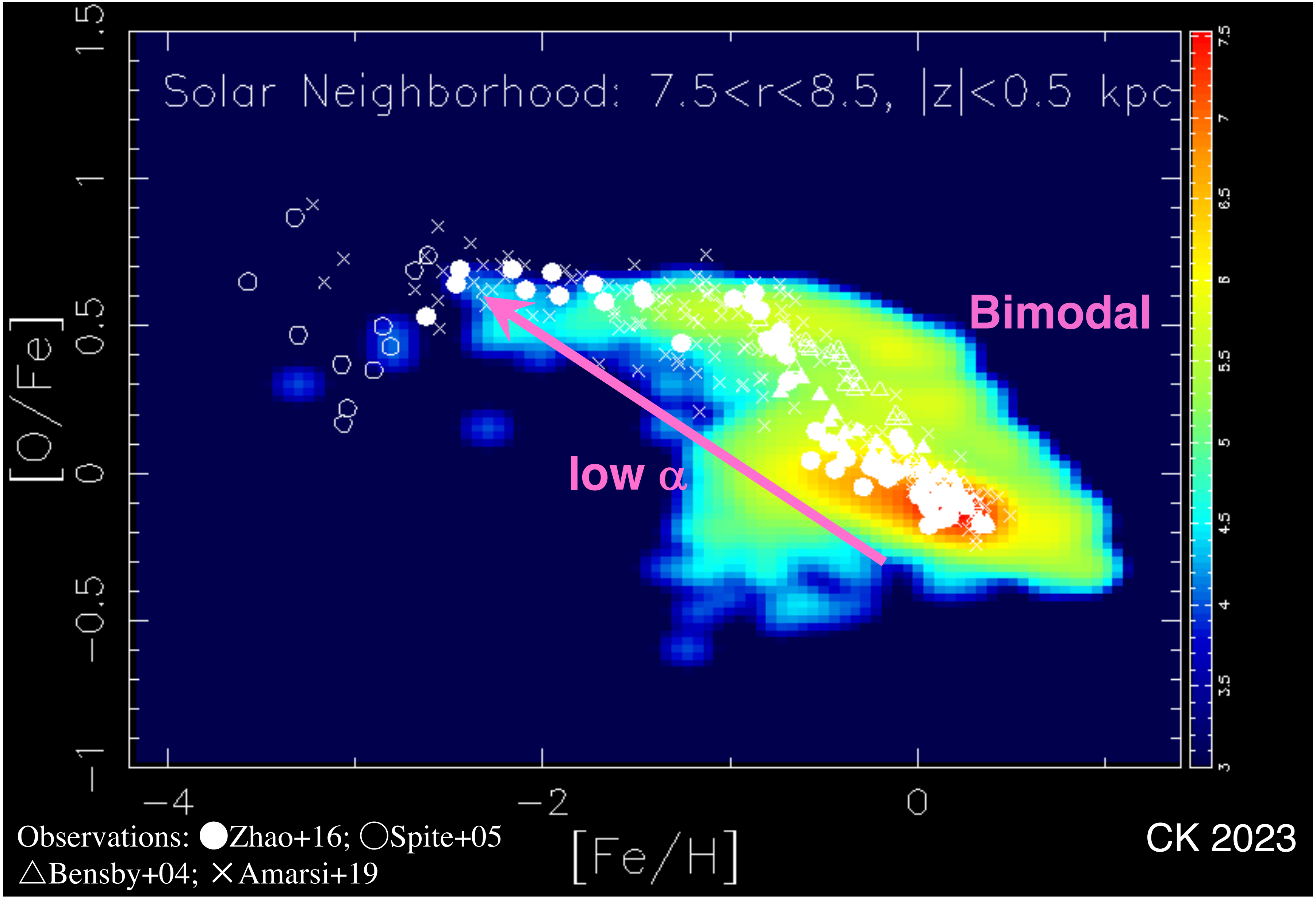
Migration – tracing the stellar birth place



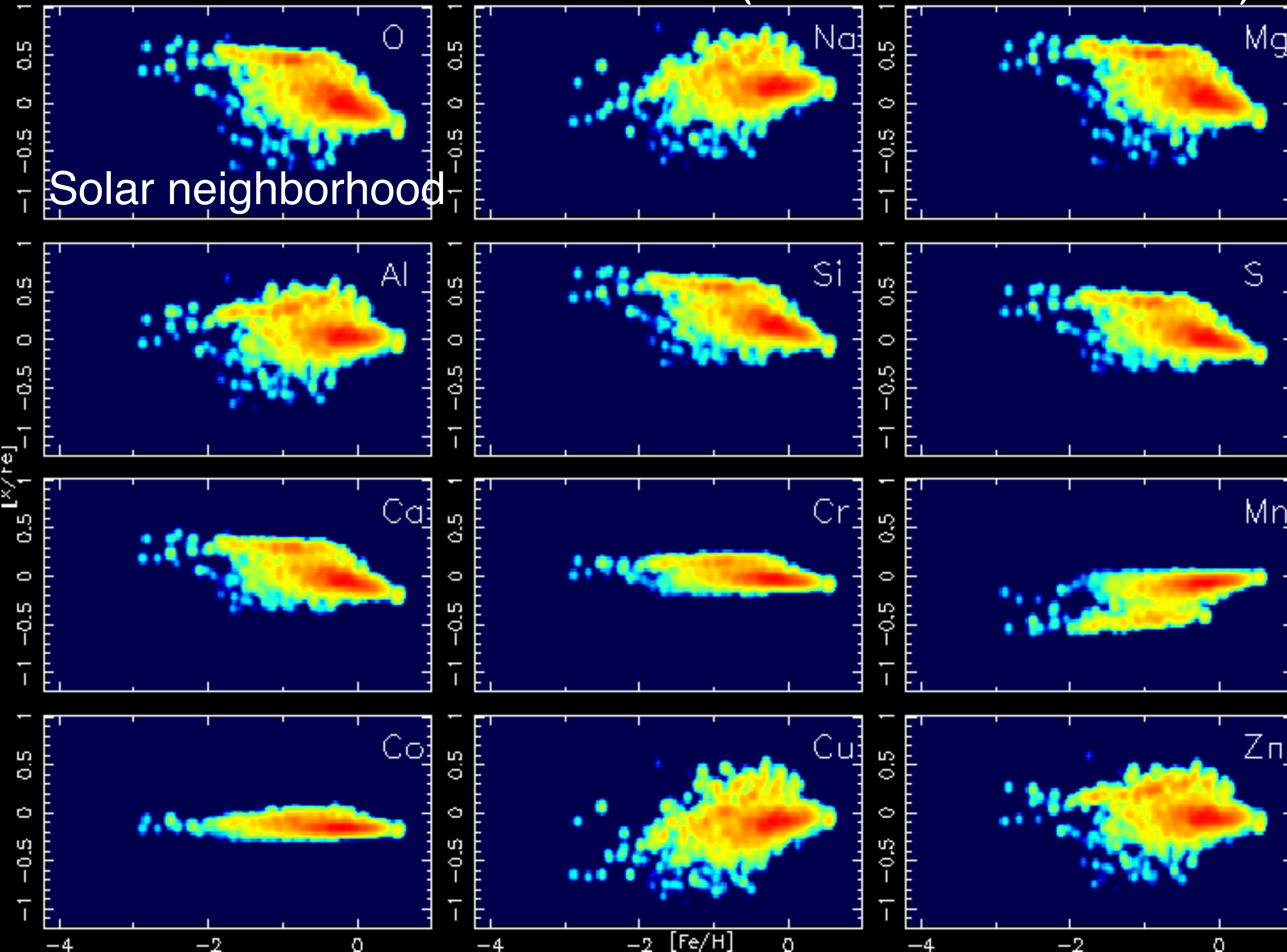
Vincenzo & CK 2020

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

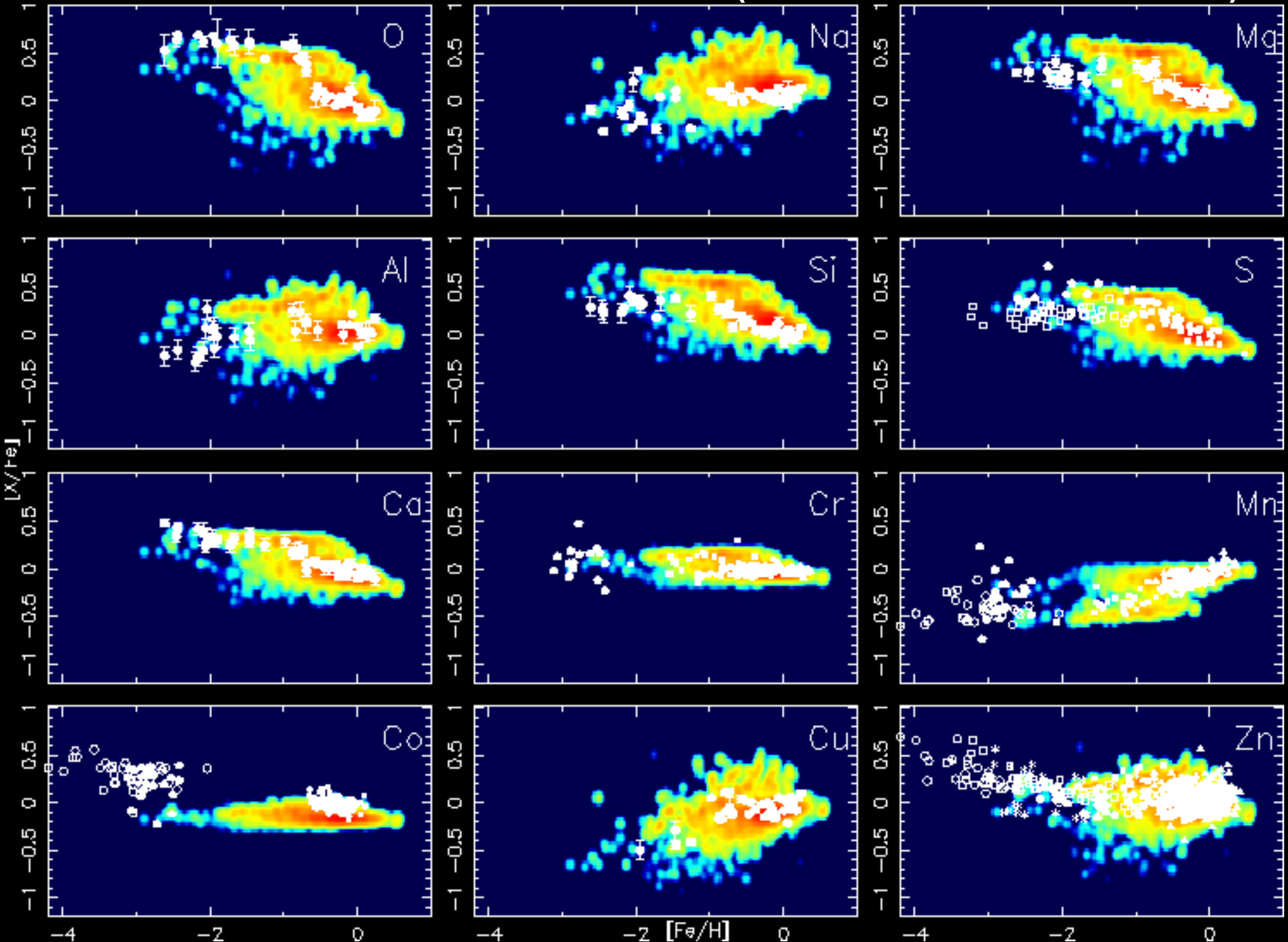
Also CK & Nakasato 2011



Elemental Abundances (CK & Nakasato 2011+NLTE)



Elemental Abundances (CK & Nakasato 2011+NLTE)



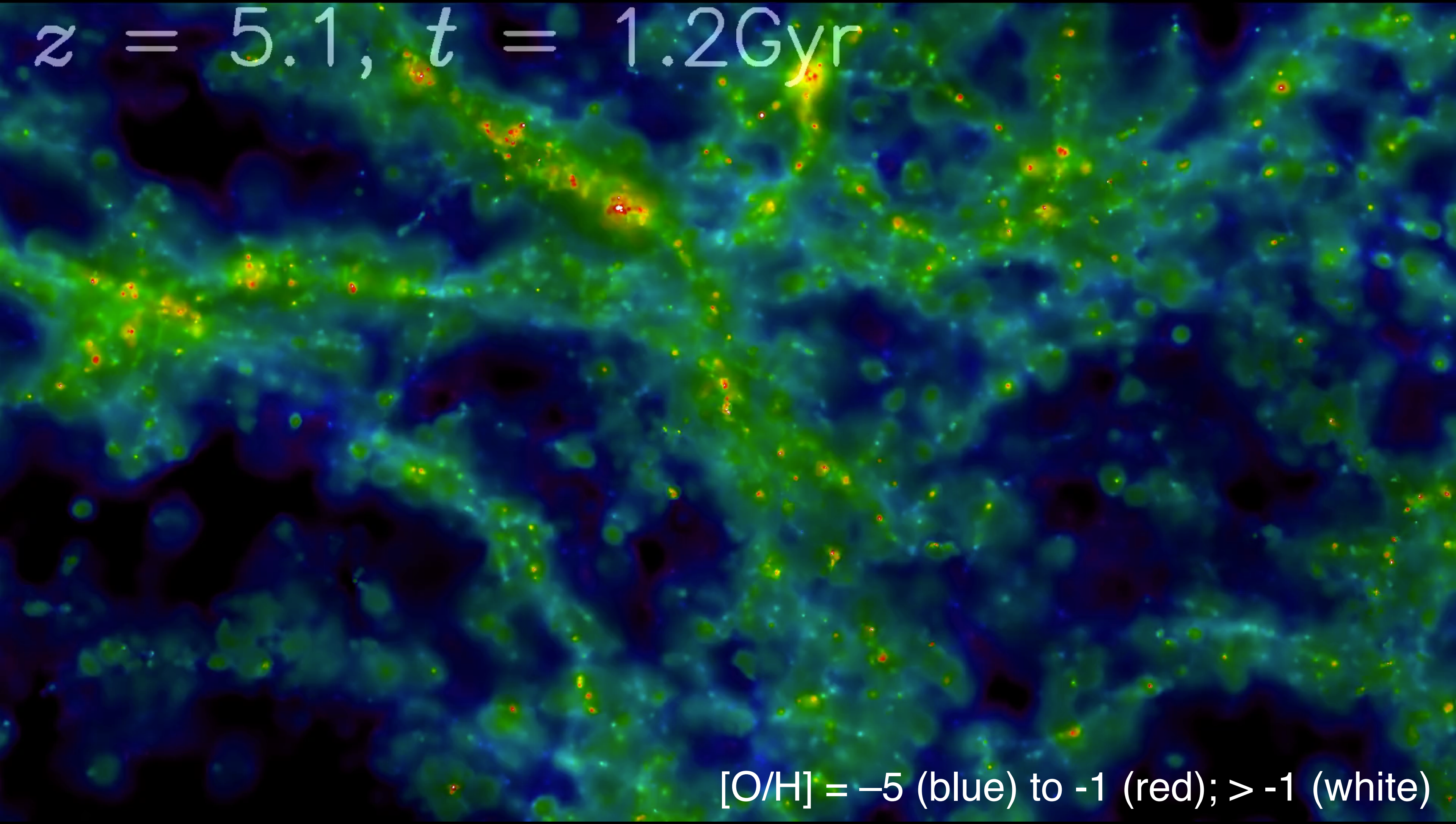
6/6
Cosmic Chemical Enrichment

CK, Springel, White 2007, MNRAS

Taylor & CK 2014, 15ab, 16, 17

EAGLE, HORIZON-AGN, Magneticum, IllustrisTNG, SIMBA

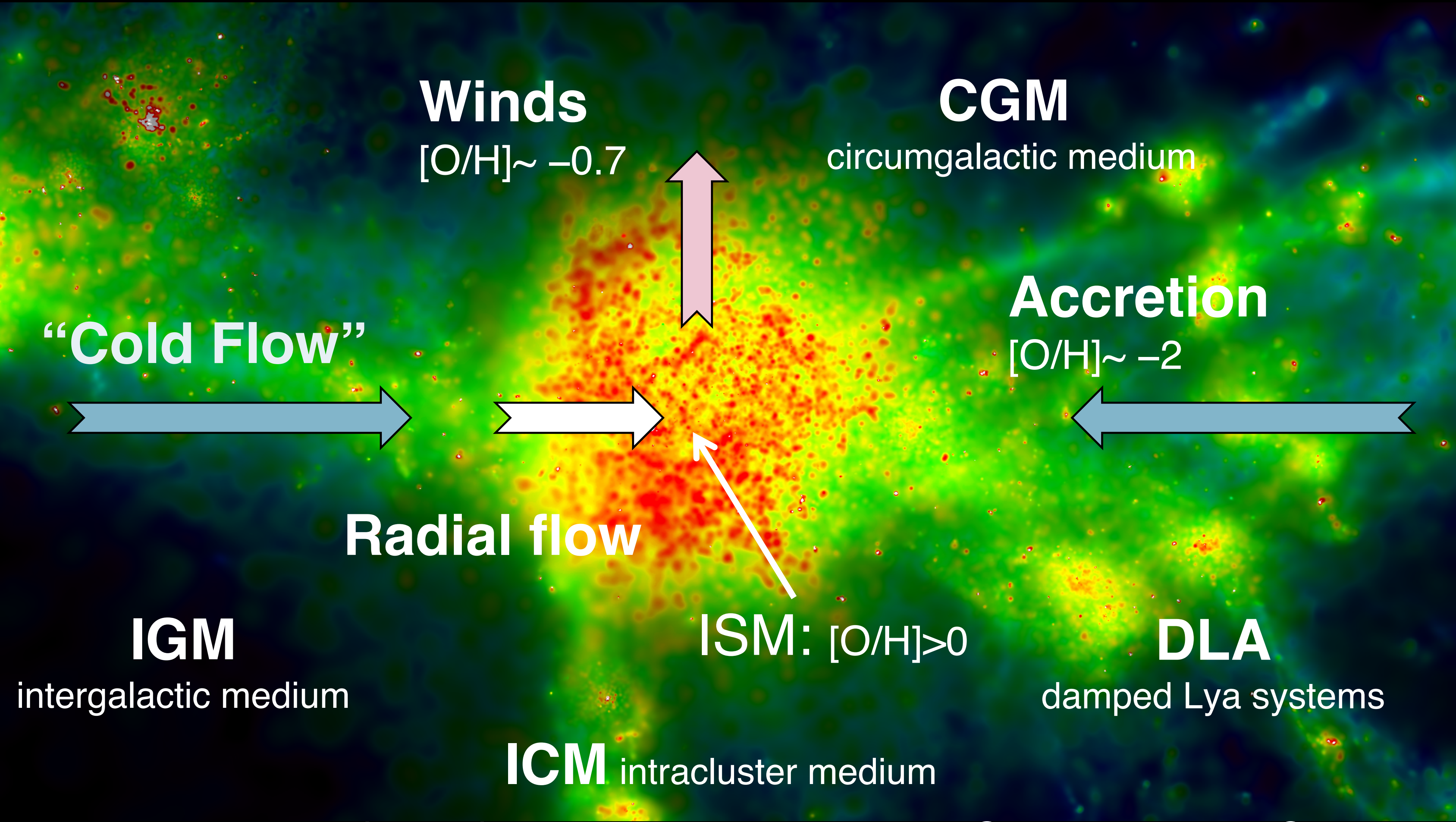
Cosmological Simulations



25Mpc, $1.4 \times 10^7 M_\odot$, 1.6kpc resolution

Philip Taylor (ANU), https://www.youtube.com/watch?v=jk5bLrVI8Tw

Metal Flows during galaxy evolution

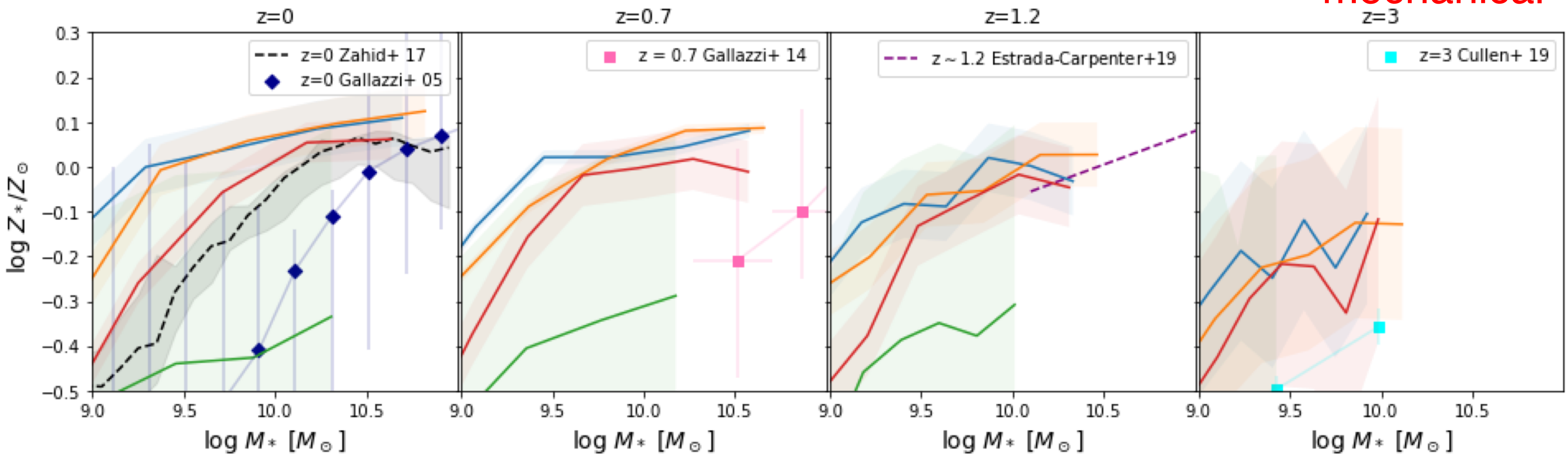


in cosmological, chemodynamical simulations, e.g., CK+07, Taylor & CK 15; see also Illustris, EAGLE, HORIZON-AGN, Magneticum, SIMBA...

Mass-Metallicity Relations

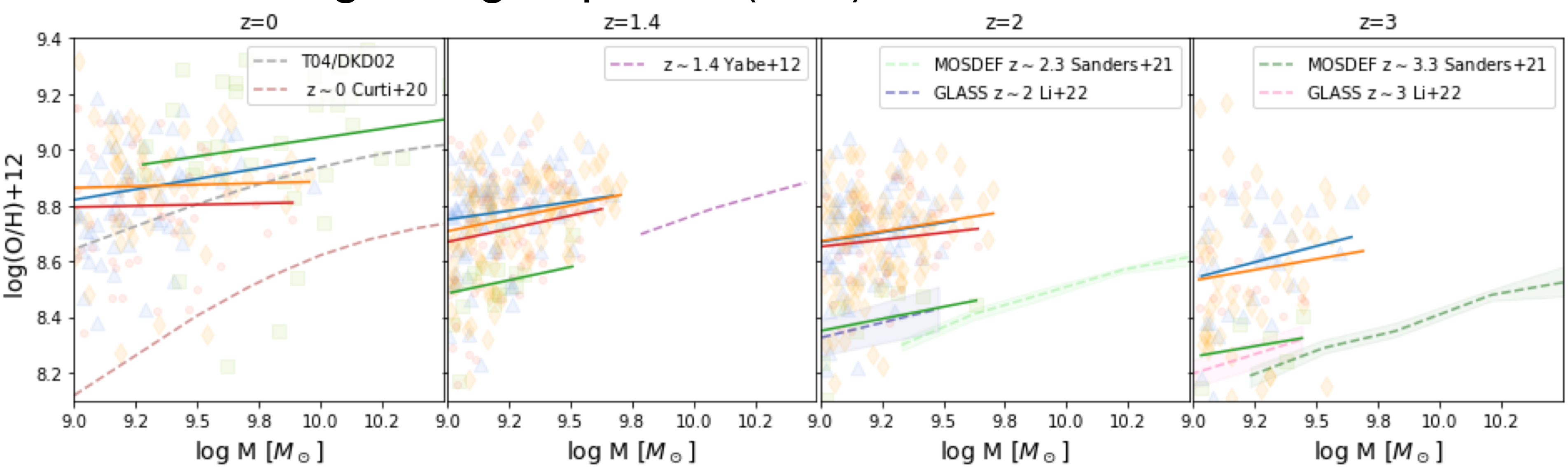
thermal
kinetic
stochastic
mechanical

- Luminosity-weighted Stellar Populations



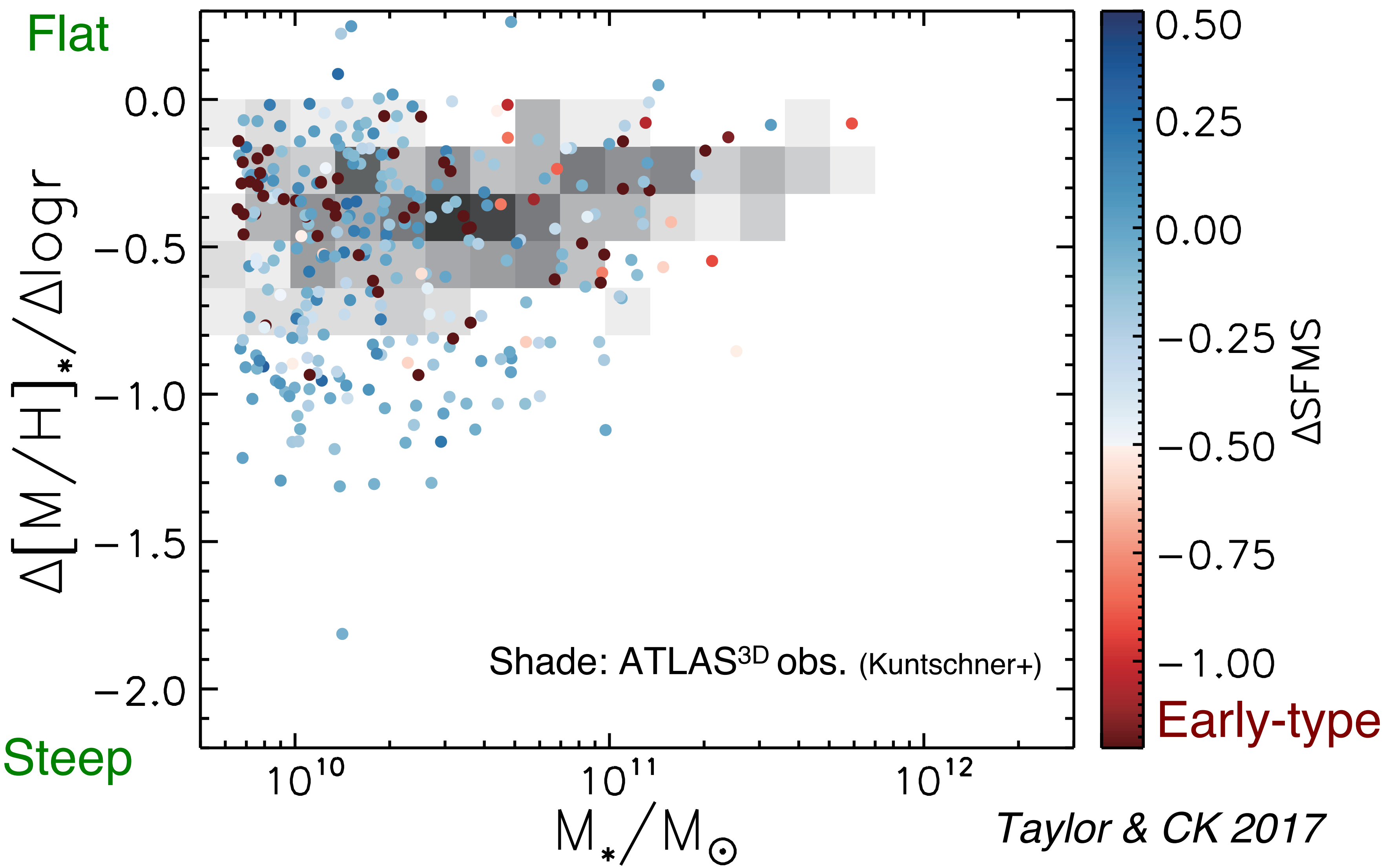
- SFR-weighted gas-phase (ISM)

Ibrahim & CK 2023, 2307.11595



Metallicity Radial Gradients

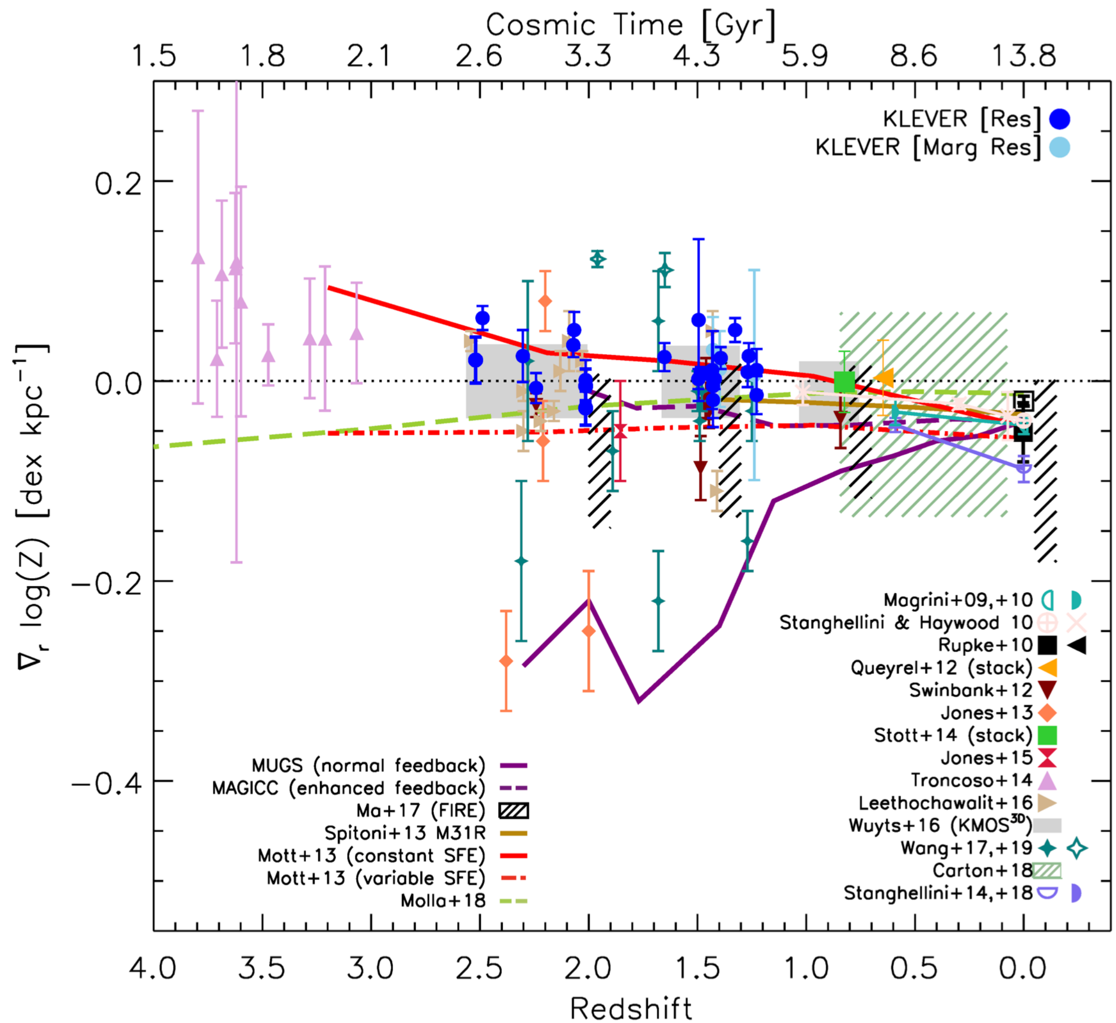
"Inside-out" formation + flattening by major mergers (CK04)



Taylor & CK 2017

Evolution of Gradients

See Pilkington+12 for more models/simulations.



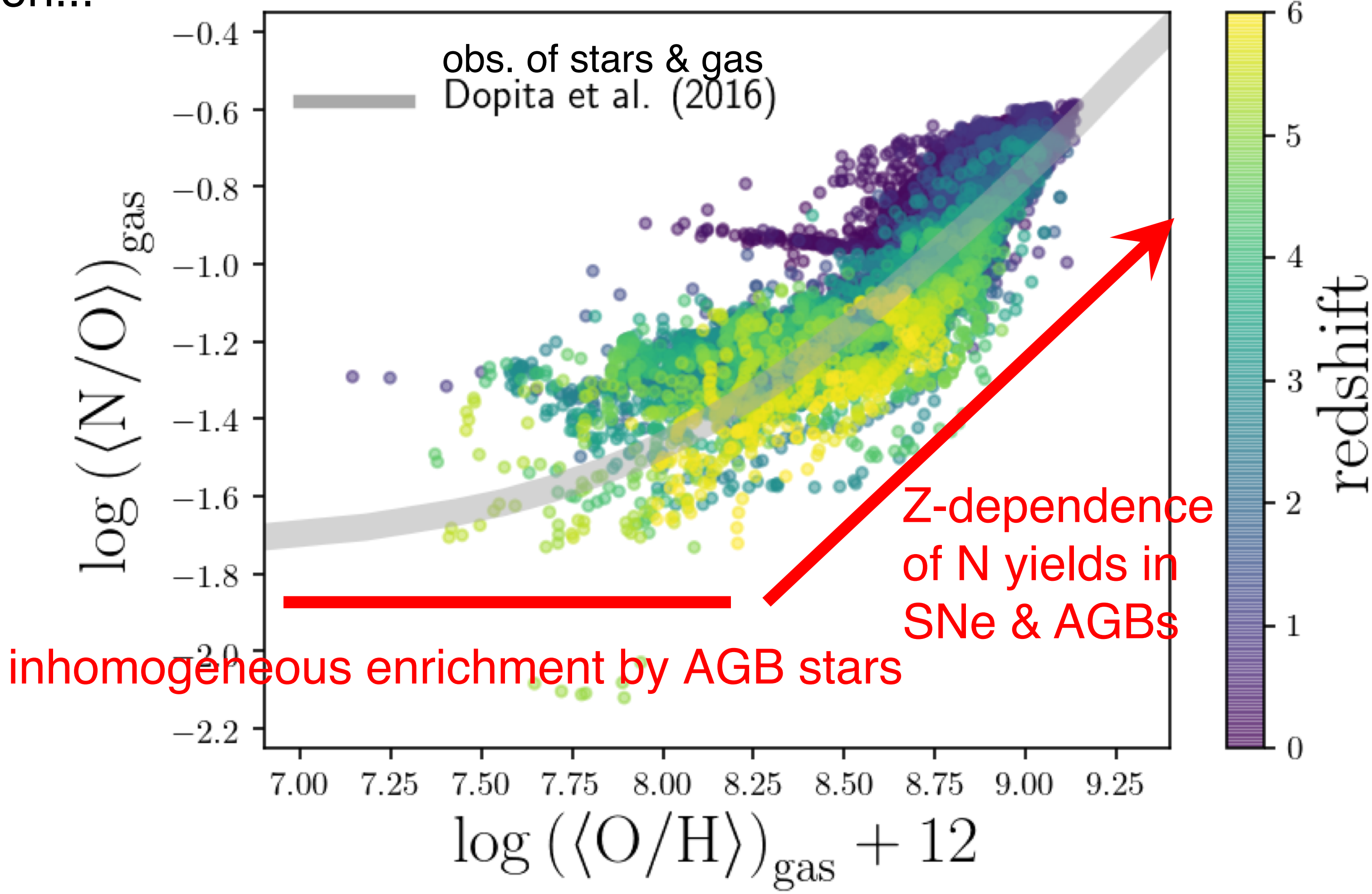
KMOS, KLEVER Survey, lenzed galaxies@1.2<z<2.5 Curti+20

The N/O-O/H relation

Unlike one-zone GCE (Chiappini+05) with rotation...

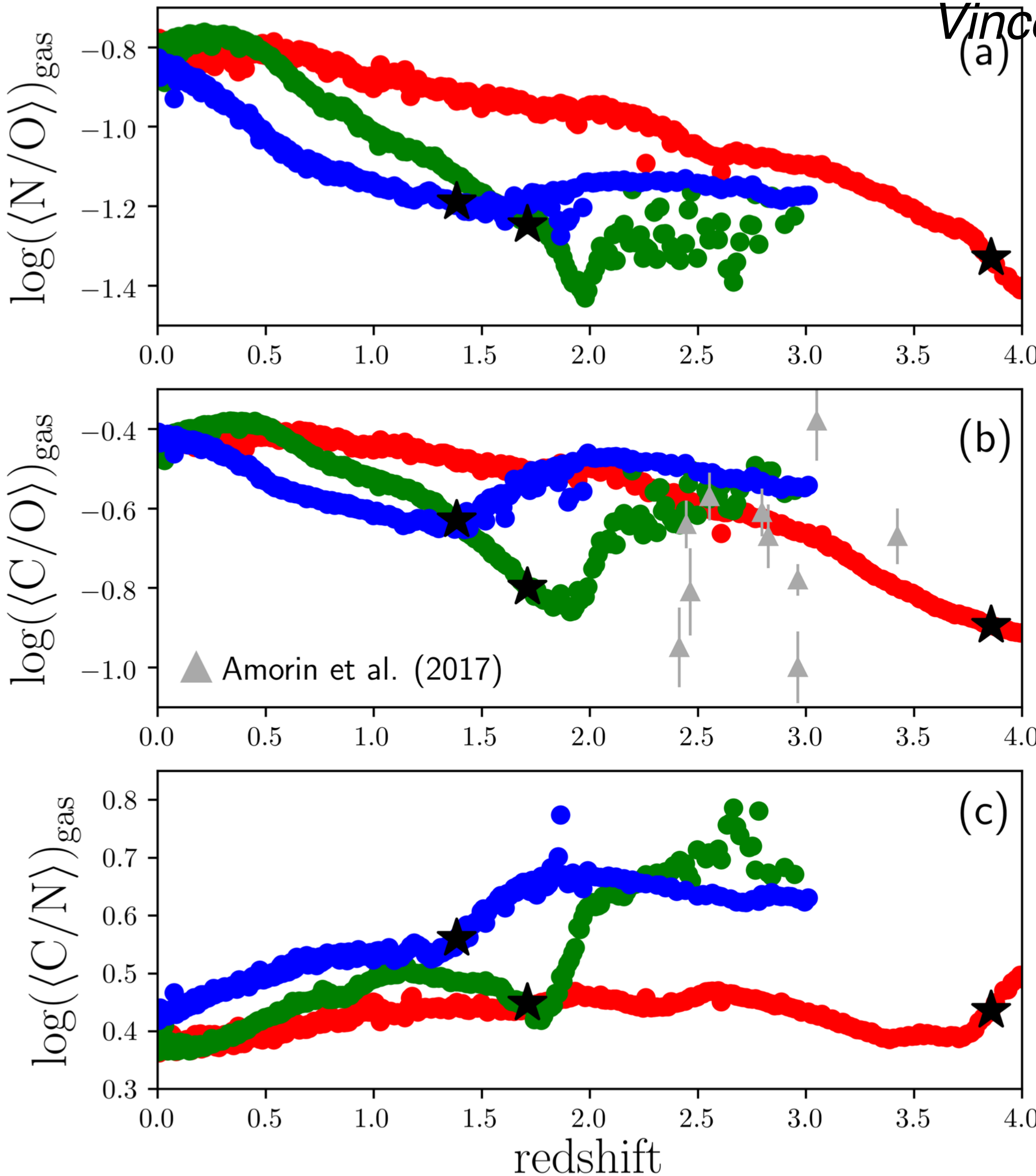
Vincenzo & CK 2018b, MNRAS, 478, 155

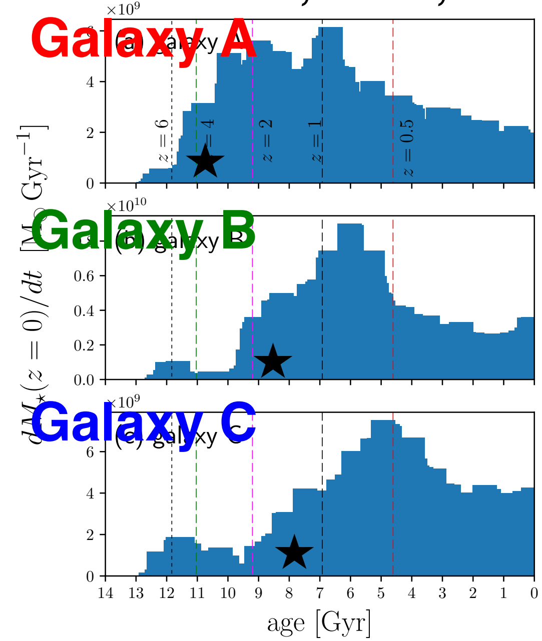
33 star-forming galaxies in cosmological simulation



CNO abundance ratios

Vincenzo & CK 2018a, A&A, 610, 16





C: low-mass AGB, <4M$_\odot$
N: massive AGB, >4M$_\odot$
O: core-collapse SNe

Currently, N/O (z<2.5), C/O (z>2), but C/N with JWST/NIRSpec!

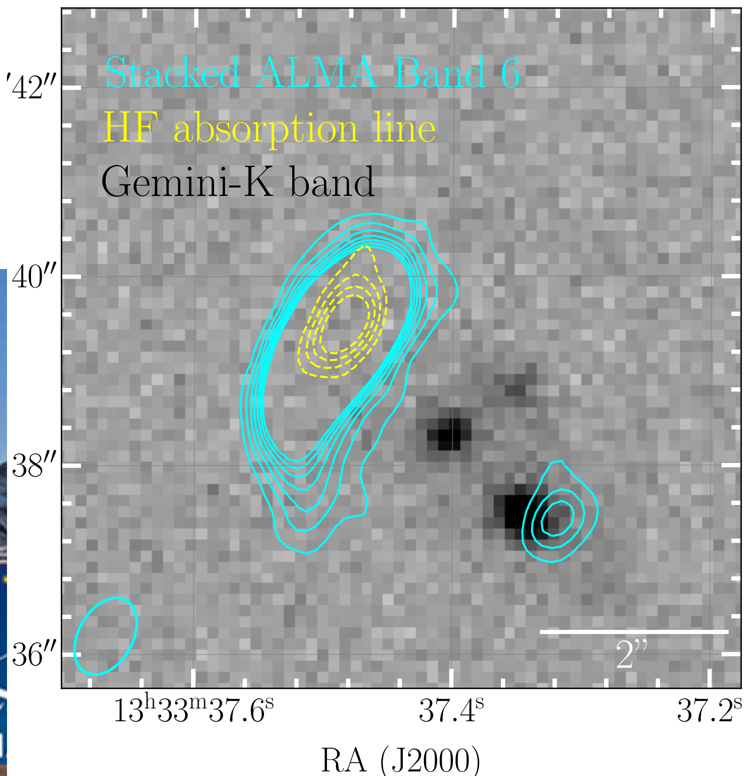
nature astronomy
4 Nov 2021
LETTERS
https://doi.org/10.1038/s41550-021-01515-9

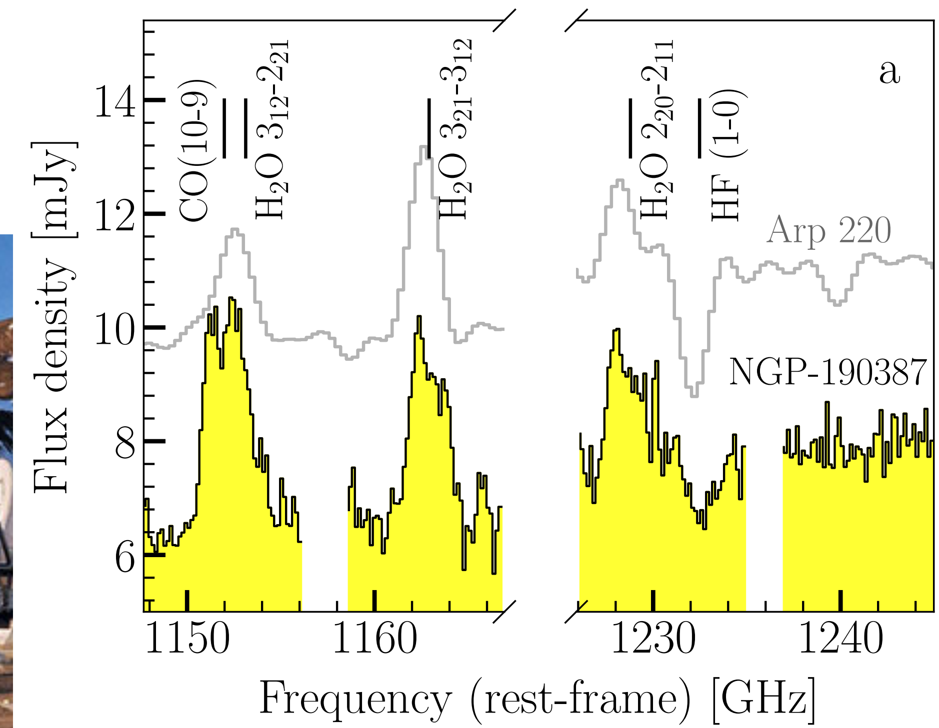
The ramp-up of interstellar medium enrichment at z > 4 (z=4.420)

^ Fluorine

M. Franco[1]✉, K. E. K. Coppin[1], J. E. Geach[1], C. Kobayashi[1], S. C. Chapman[2,3], C. Yang[4], E. González-Alfonso[5], J. S. Spilker[6], A. Cooray[7] and M. J. Michałowski[8]

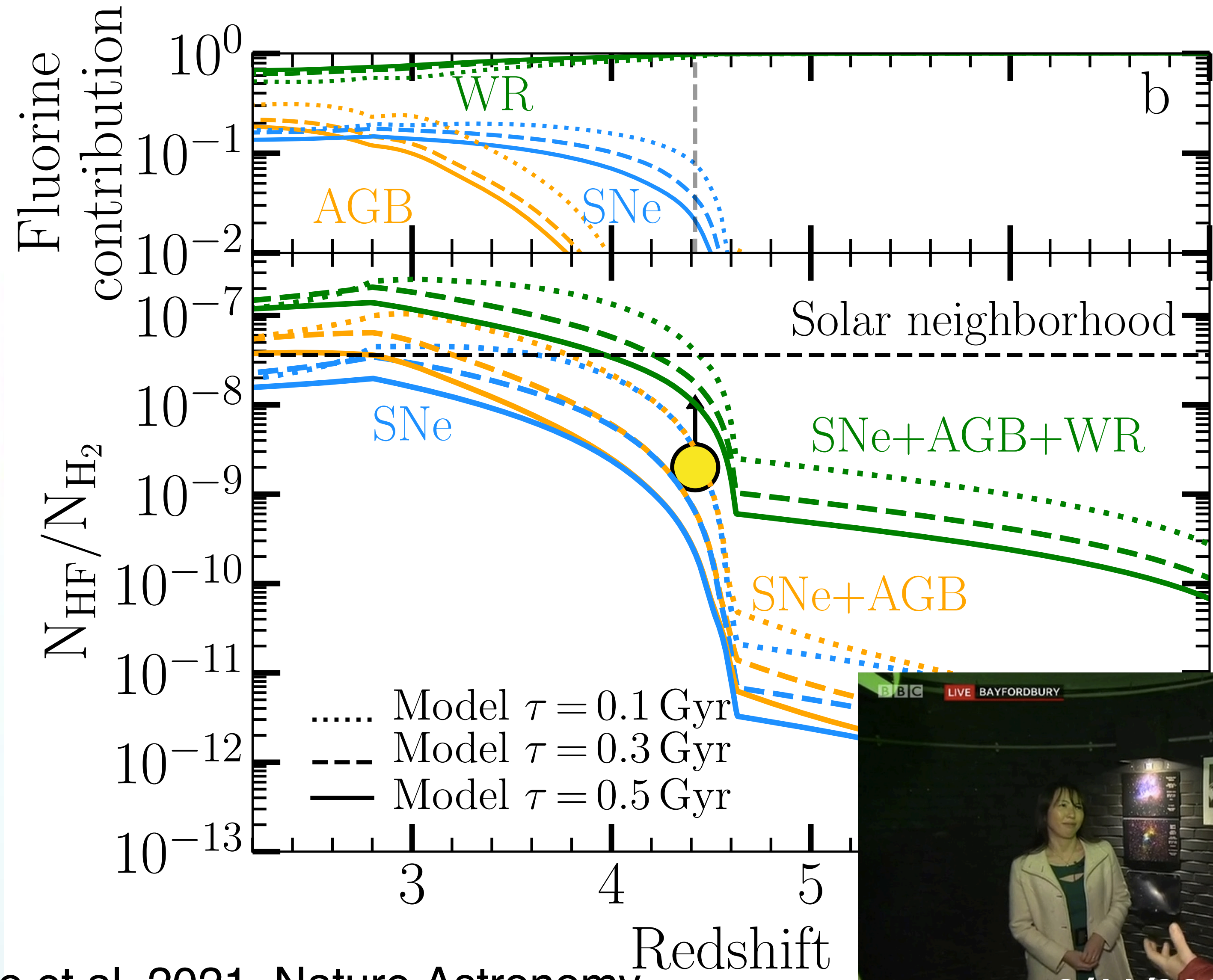
- Lensed dusty star-forming galaxy **NGP-190387** at z = 4.420
- $N(H_2)=2.1\pm0.4\ 10^{24}$ cm^2 (from [C I])
- $H_2 + F \rightarrow H + HF$ (stable, dominant)





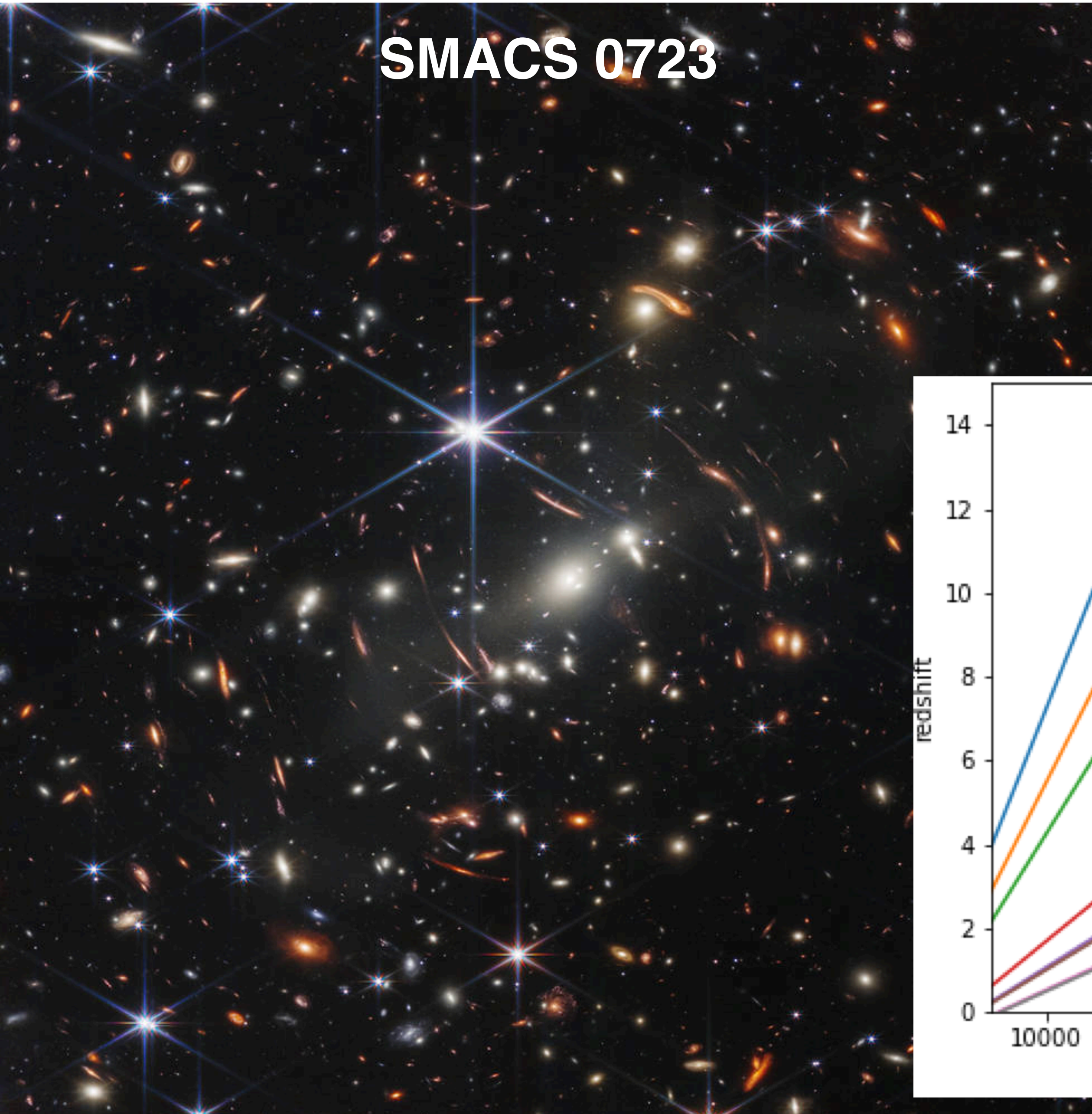
Rapid enrichment by Wolf-Rayet stars

1.4 Gyrs after Big Bang, 0.7 Gyrs after re-ionization



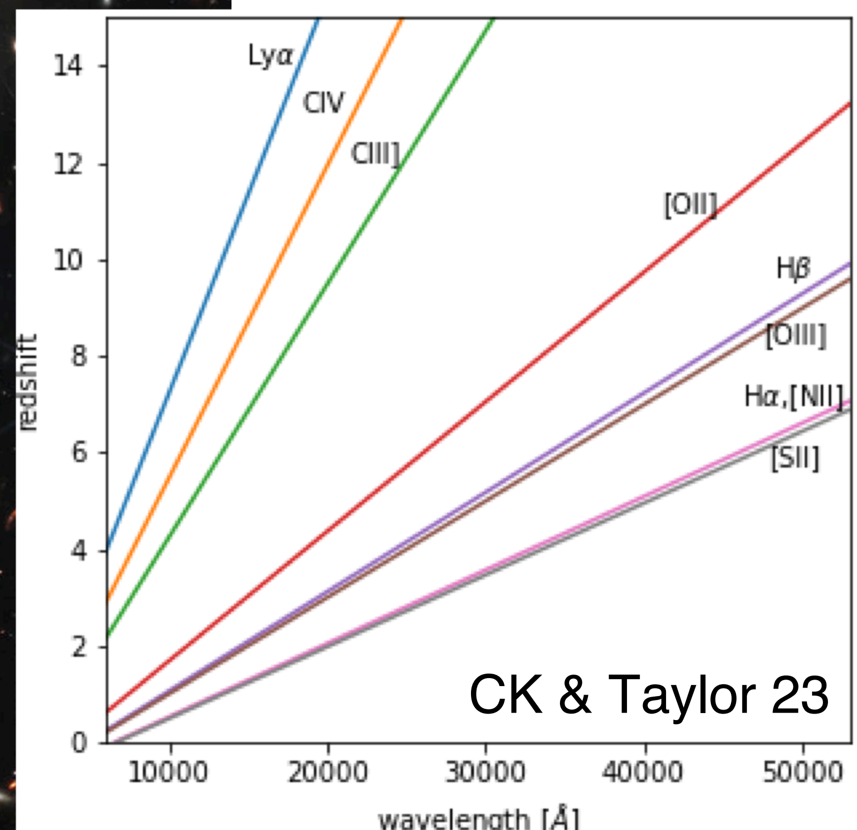
Franco et al. 2021, Nature Astronomy

James Webb Telescope



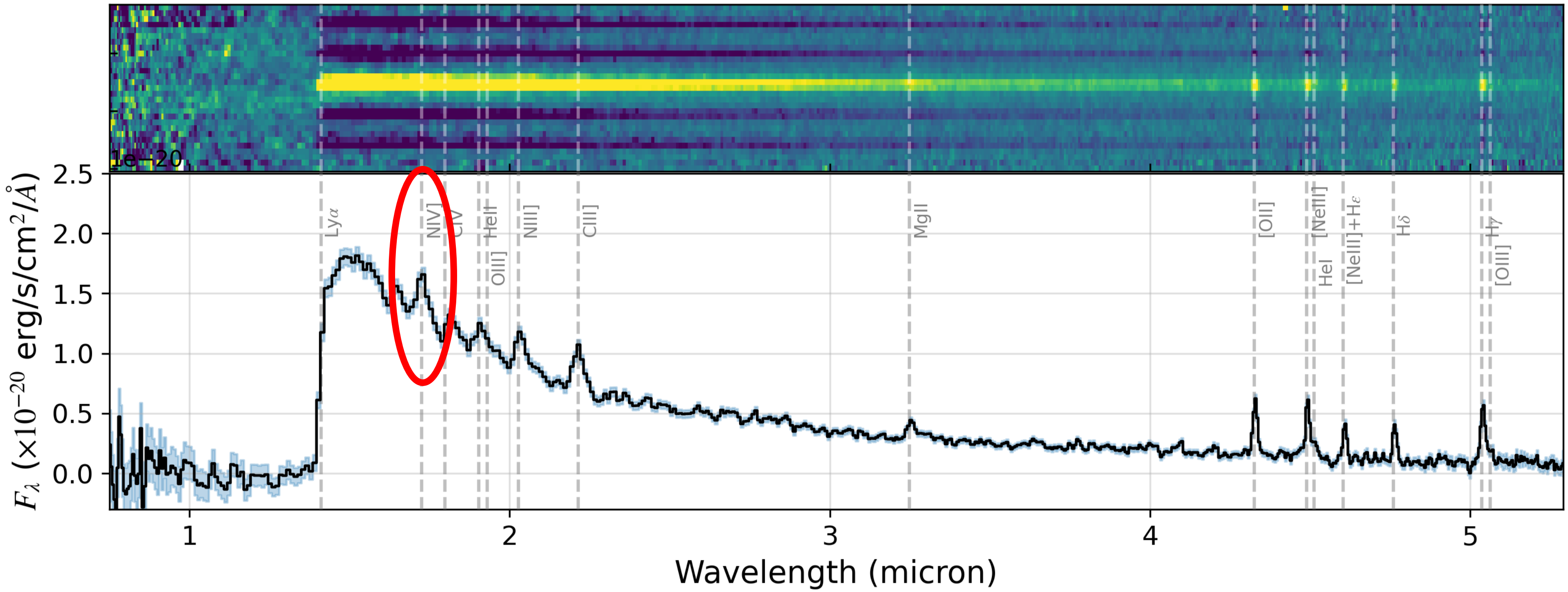
25 Dec 2021 launch
11 July 2022

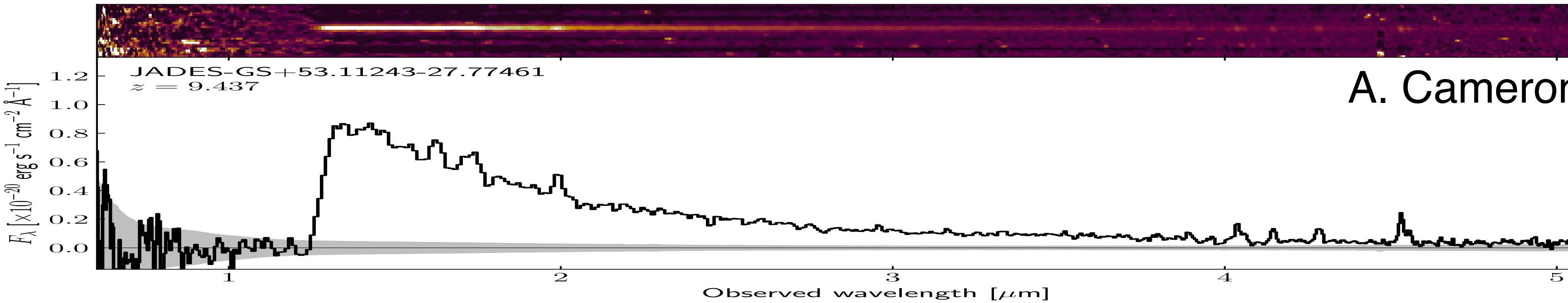
NIRSpec/JWST
R = 100 (MOS)
R = 1000 (MOS + fixed Slits)
R = 2700 (fixed Slits + IFU)



GN-z11 @ z=10.6, 430 Myr after Big Bang

Bunker+2023, PRISM/CLEAR (R~100)

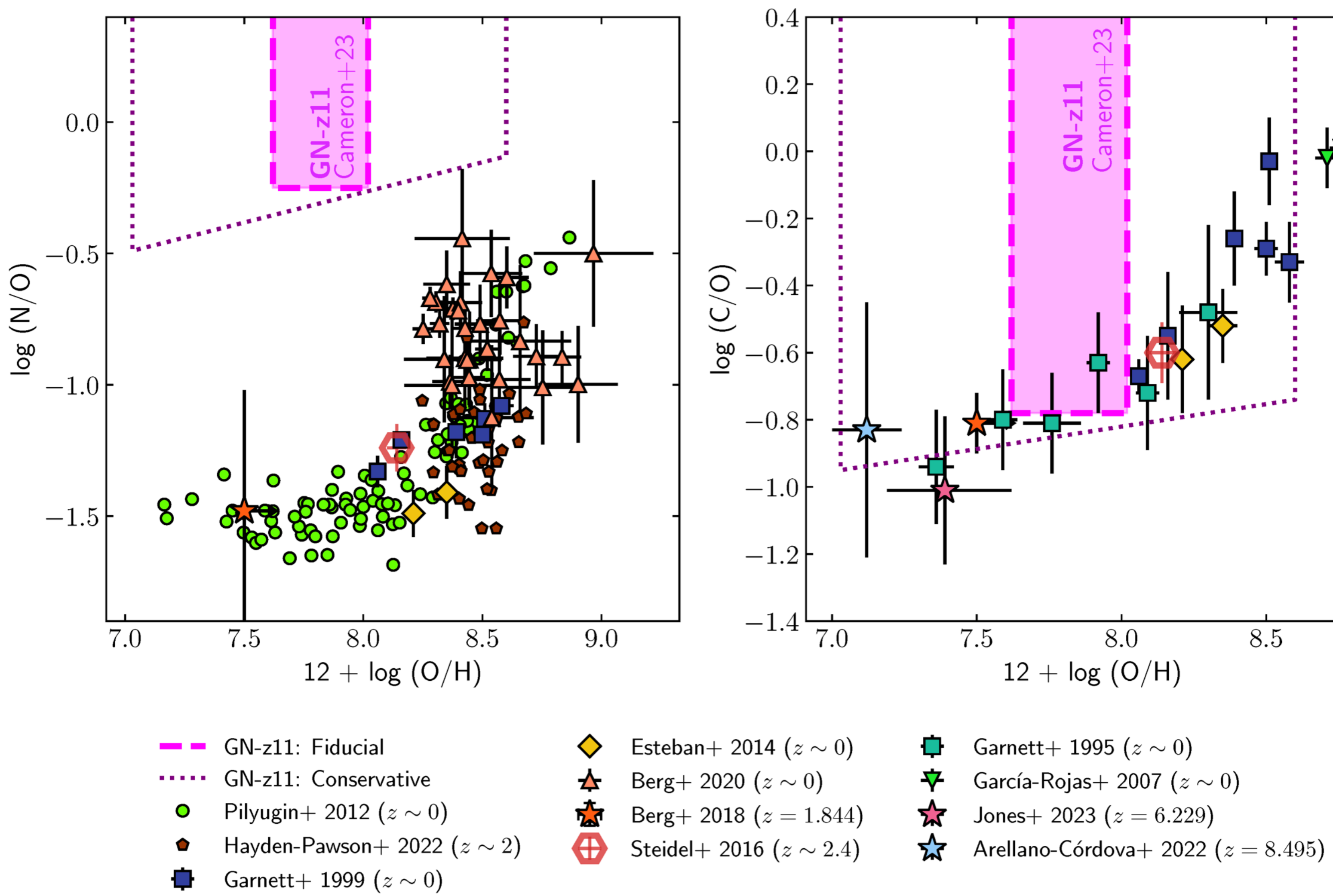




A. Cameron

CNO ratios of GN-z11 !?!?

- log(N/O) > –0.25, log(C/O) > –0.78, 12 + log(O/H)≈7.82
- Not AGBs. WR stars, or very massive star (>1000$M_\odot$)???



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).

- ❖ **Galactic archaeology** – 6D map of elements (from Li to Eu) in the Milky Way is being observed with multi-object spectrographs (MOS; e.g. APOGEE, HERMES-GALAH, WEAVE, 4MOST, MOONS, PFS), and is well reproduced with **chemodynamical simulations** that includes inhomogeneous enrichment, gas flows, stellar migration.

- ❖ **Extra-galactic archaeology** – Projected map of elemental abundances (CNO, F,Mg,Fe) can be estimated with integral field unit (IFU; e.g, MaNGA, CALIFA, SAMI, MUSE), also in distant galaxies with JWST & ALMA, and are fairly consistent with **cosmological simulations** with feedback from super-massive BHs, but more WR (^{13}C, N, F) !?

Book Chapter in Handbook of Nuclear Physics, ArXiv: 2302.07255