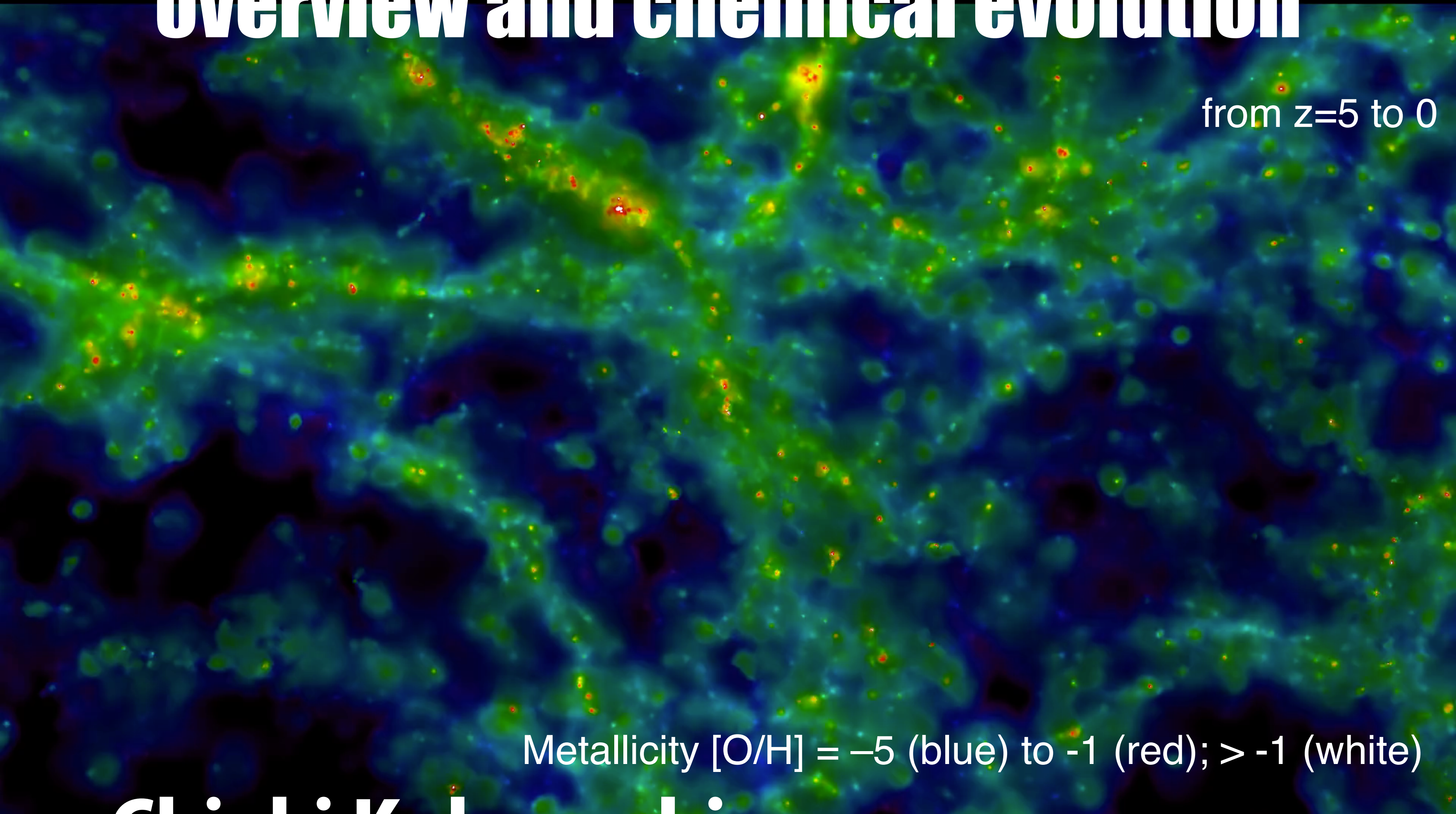
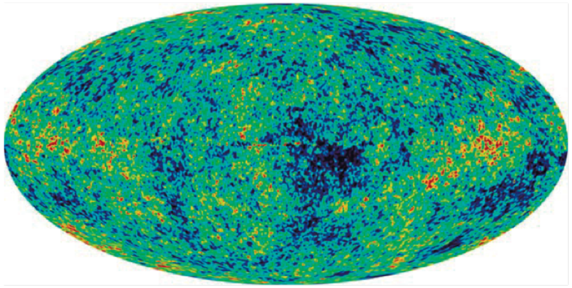
Galactic archeology: overview and chemical evolution



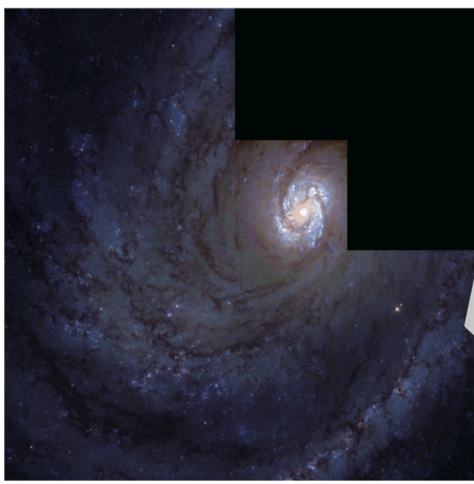
Chiaki Kobayashi
(Univ. of Hertfordshire, UK)

LEVERHULME TRUST

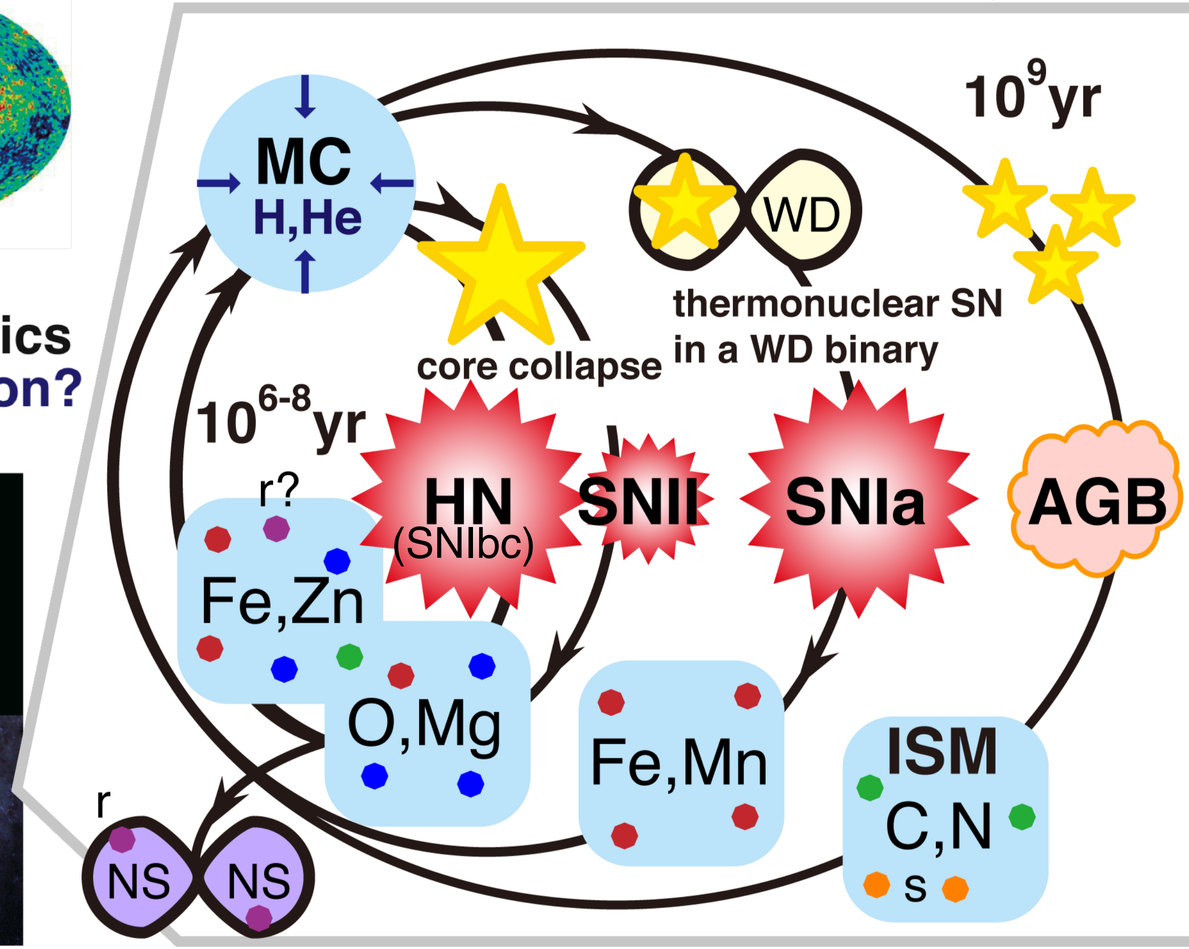
Galactic Archaeology



Gravity
Hydrodynamics
Star Formation?
Feedback?



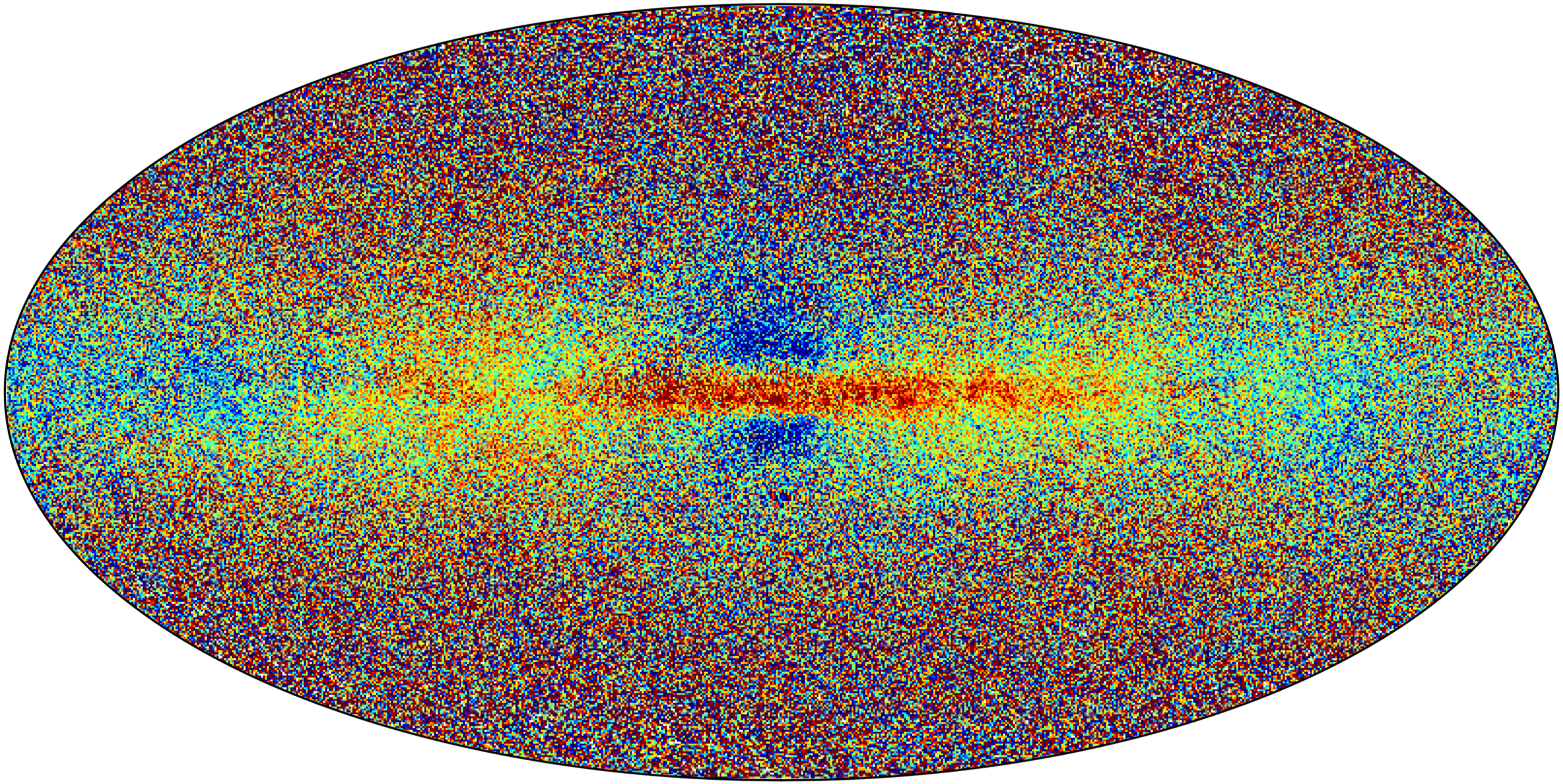
Nomoto, CK, Tominaga 2013 ARAA



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

Gaia DR3 Metallicity Map

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

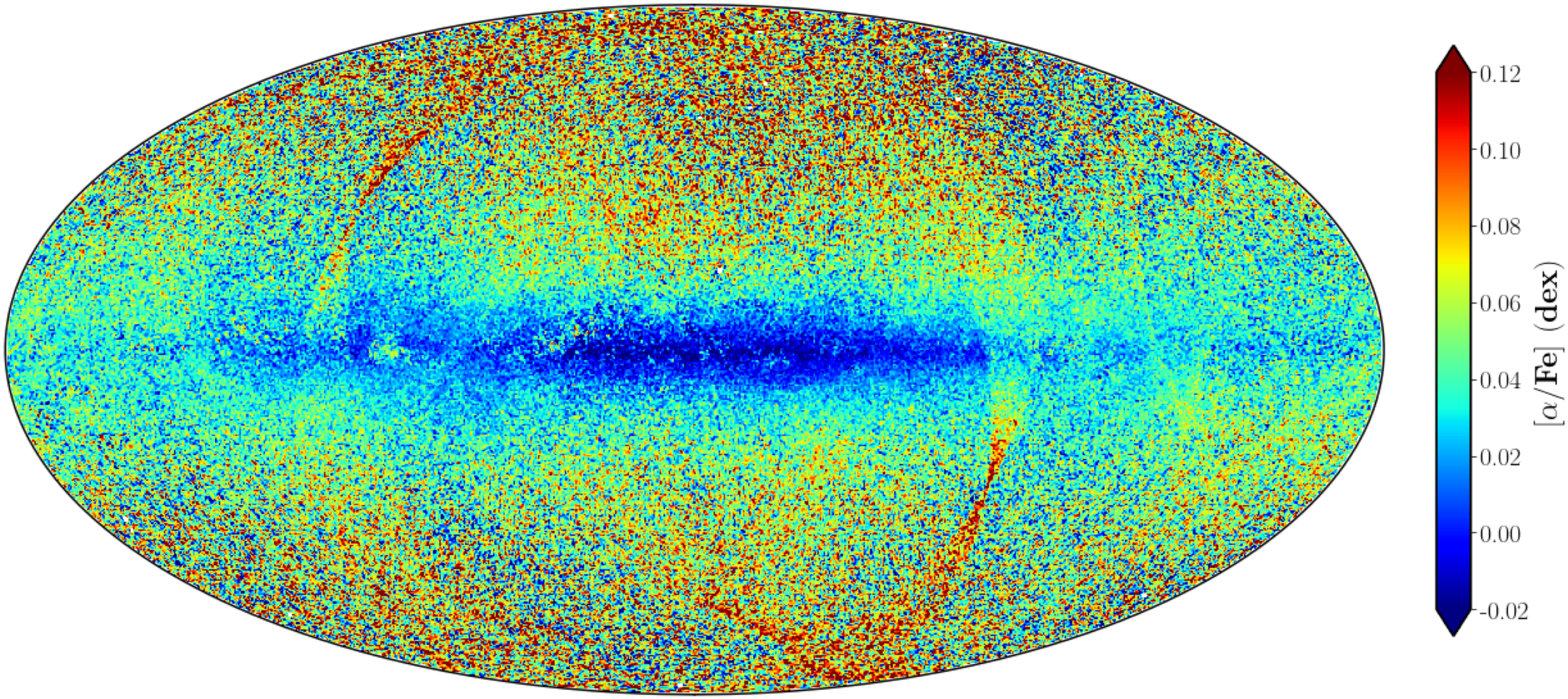


1.59 billion sources with G<21 mag
470 million objects have astrophysical parameters
https://www.cosmos.esa.int/web/gaia/dr3

13 June 2022

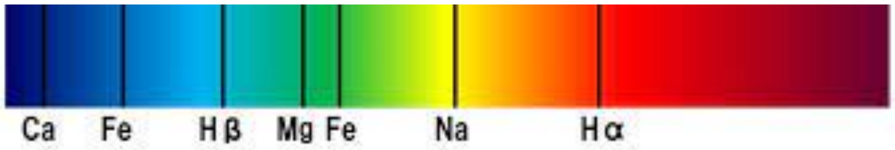
Gaia DR3 [α/Fe] Map

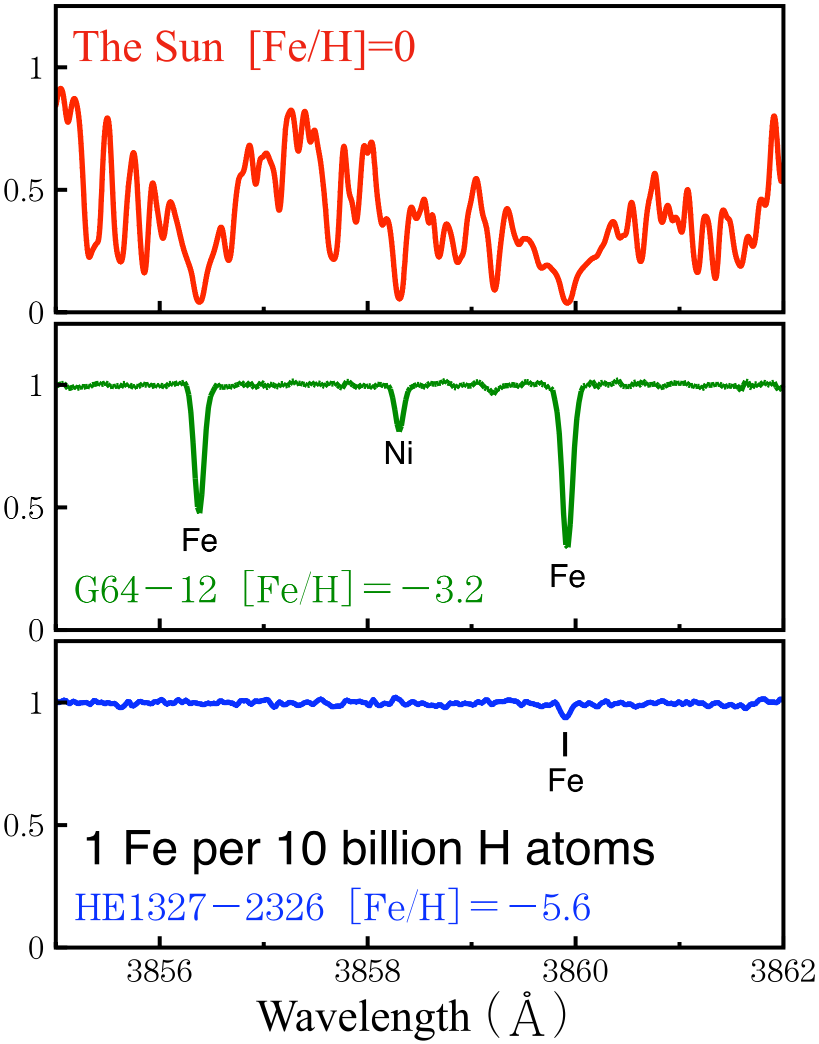
Abundance $[X/Y]=\log(X/Y)-\log(X/Y)_{\odot}$

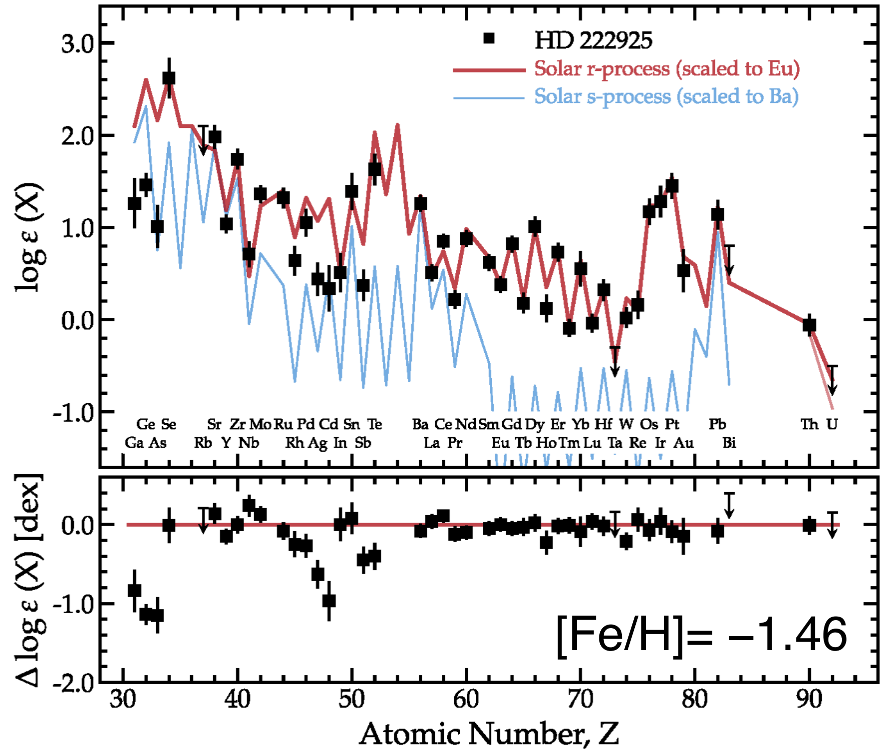


The patterns close to the Ecliptic Poles are artefacts caused by the Gaia scanning law.

Elemental Abundances

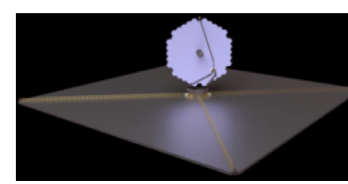






R-process Alliance, Roederer+22
UV: HST/STIS, R=114,000
optical: Magellan, R=61,000-68,000

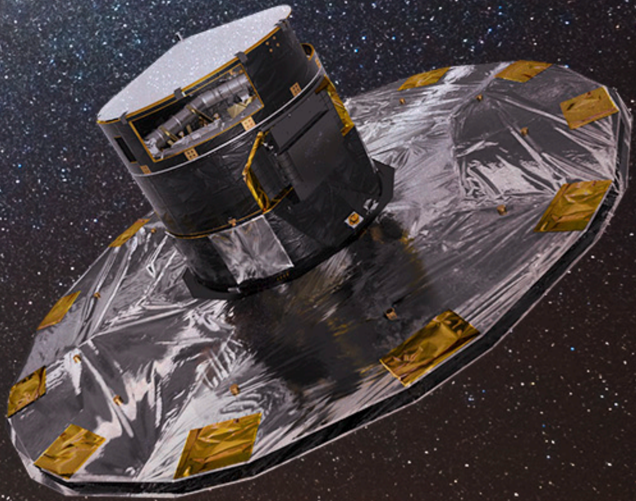
Needs **LUVOIR**
(ArXiV:2207.04271)



Galactic Archaeology surveys

of Milky Way and local dwarf galaxies

- Motions of <u>one 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)
- Chemodynamical evolution is being revealed.



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

Galactic Chemical Evolution (GCE)

(1) One-zone model (instantaneous mixing): Tinsley 80, Timmes+95, Pagel 97, Matteucci 01, Prantzos+93, Ferrini+92 (Molla, Travaglio, Magrini), Chiappini+97, CK+ 00…, Vincenzo+14, Cote+16

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

Metal ejection rates

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

decreased by star formation

Inflow Outflow

given from hydrodynamics in

(3) Chemodynamical simulation

Burkert & Hensler 87, Katz 92, Steinmetz & Müller 94, Mihos & Hernquist 96, CK 04,…, FIRE, EAGLE, Horizon, Illustris

→ **inhomogeneous enrichment**

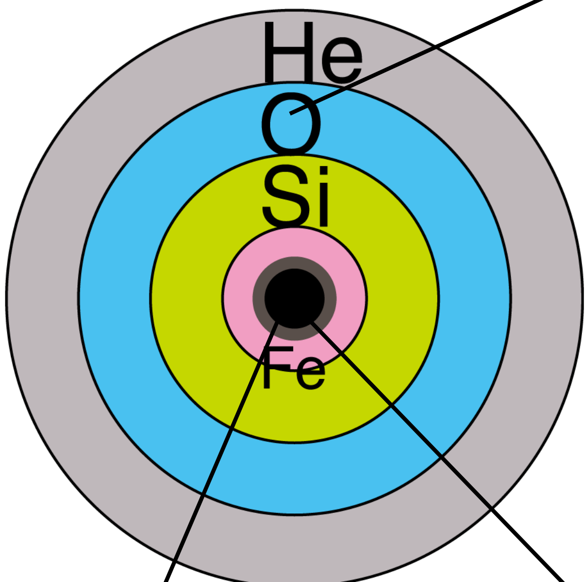
(2) Stochastic model

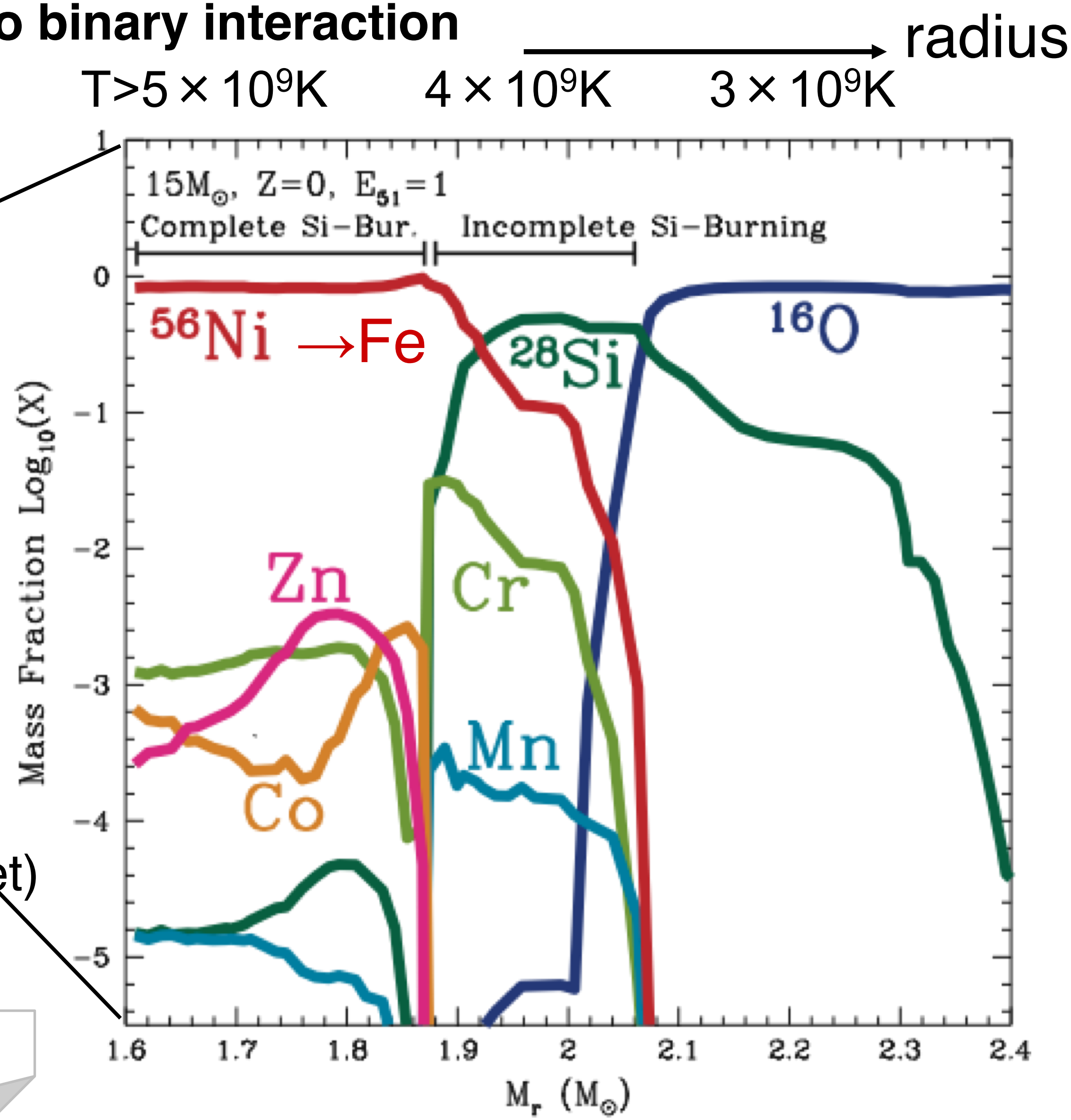
Ishimaru+99; Argast+02; Cescutti+08; Wehmeyer+15

Stellar Evolution and Nucleosyntheis

>10$M_\odot$, 1D, w/wo rotation, no binary interaction

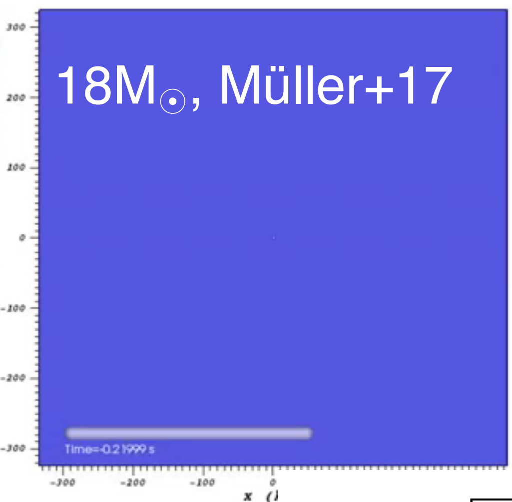
Woosley, Heger+ 95, 07
Nomoto, Umeda+ 97, 06
Limongi, Chieffi+ 00, 12, 18





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

Three groups give fairly similar results (Fig.5 of Nomoto+13).



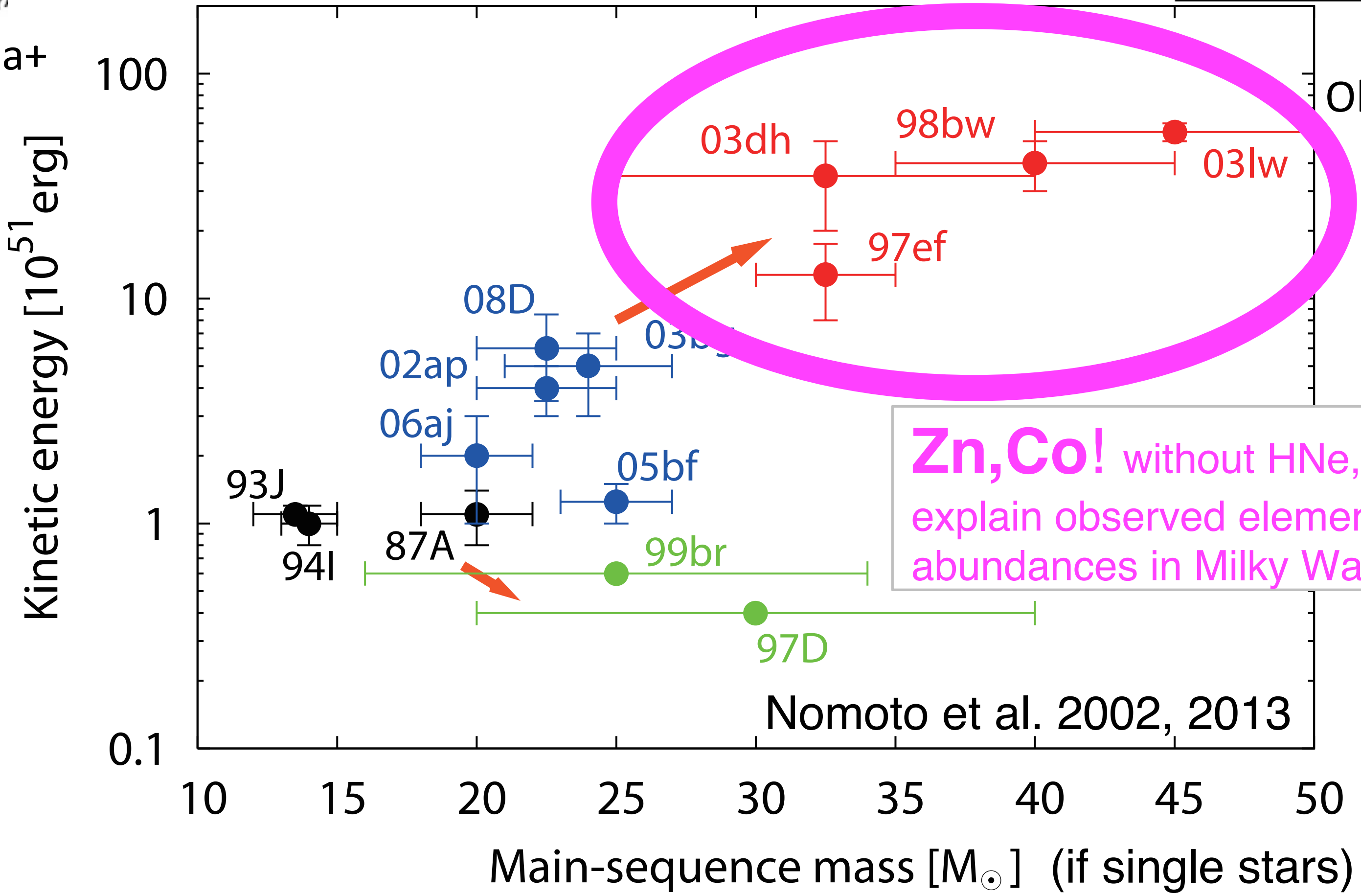
Core-collapse SNe

← ν-driven SNII & failed SN

Hypernovae (mechanism?) →

In GCE, 50-1% at >20M⊙

Mezzacappa+
Burrows+
Kotake+



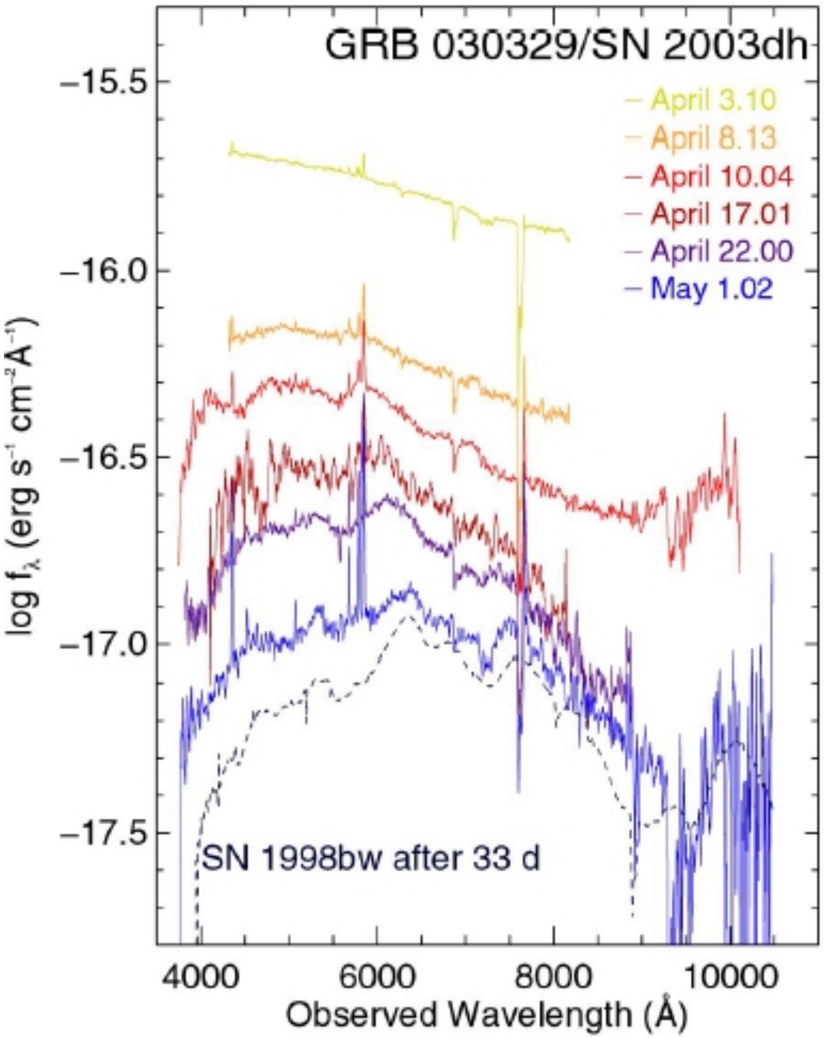
Takiwaki+
Obergaulinger
& Aloy

Zn,Co! without HNe, can't explain observed elemental abundances in Milky Way (CK+06).

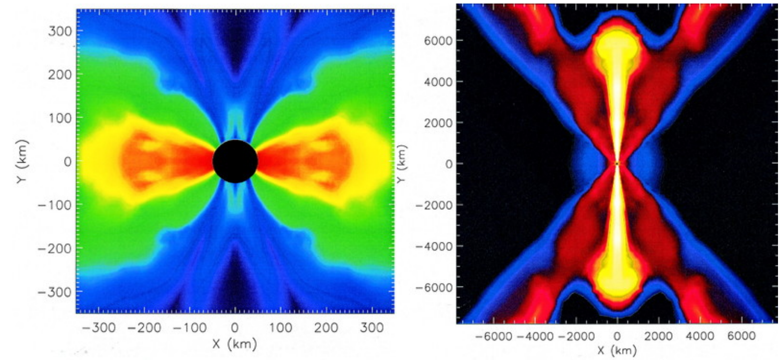
Hypernova-long GRB connection

1998bw/980425, 2003dh/030329, 2003lw/031203, 2012bz/12422A, ...

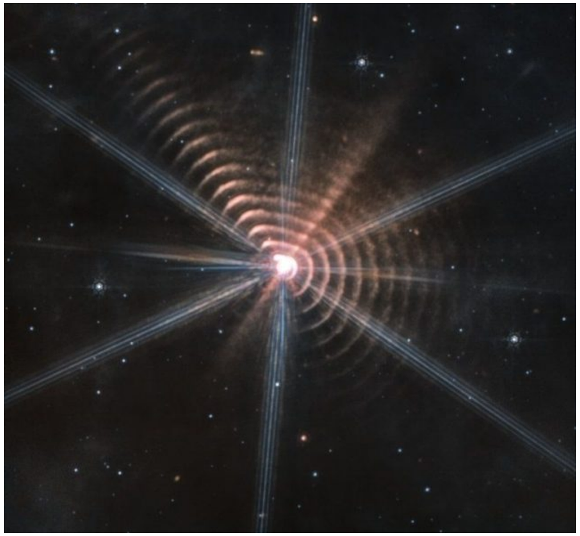
but 060505, 060614



- ❖ Collapsar? (MacFadyen & Woosley 99)



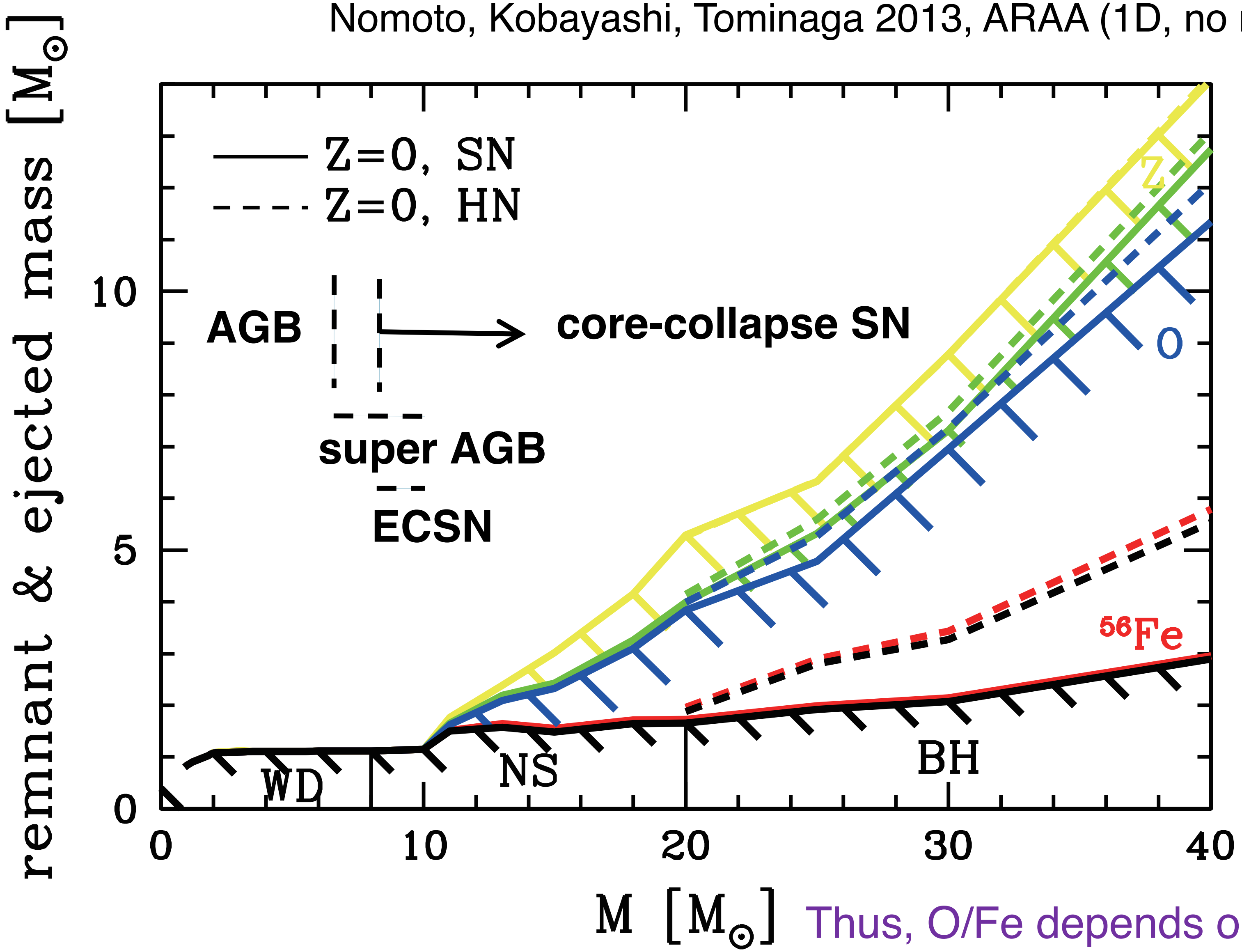
- ❖ Rotating massive star?



WR 140
JWST/MIRI
dust
binary

Nucleosynthesis Yields

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

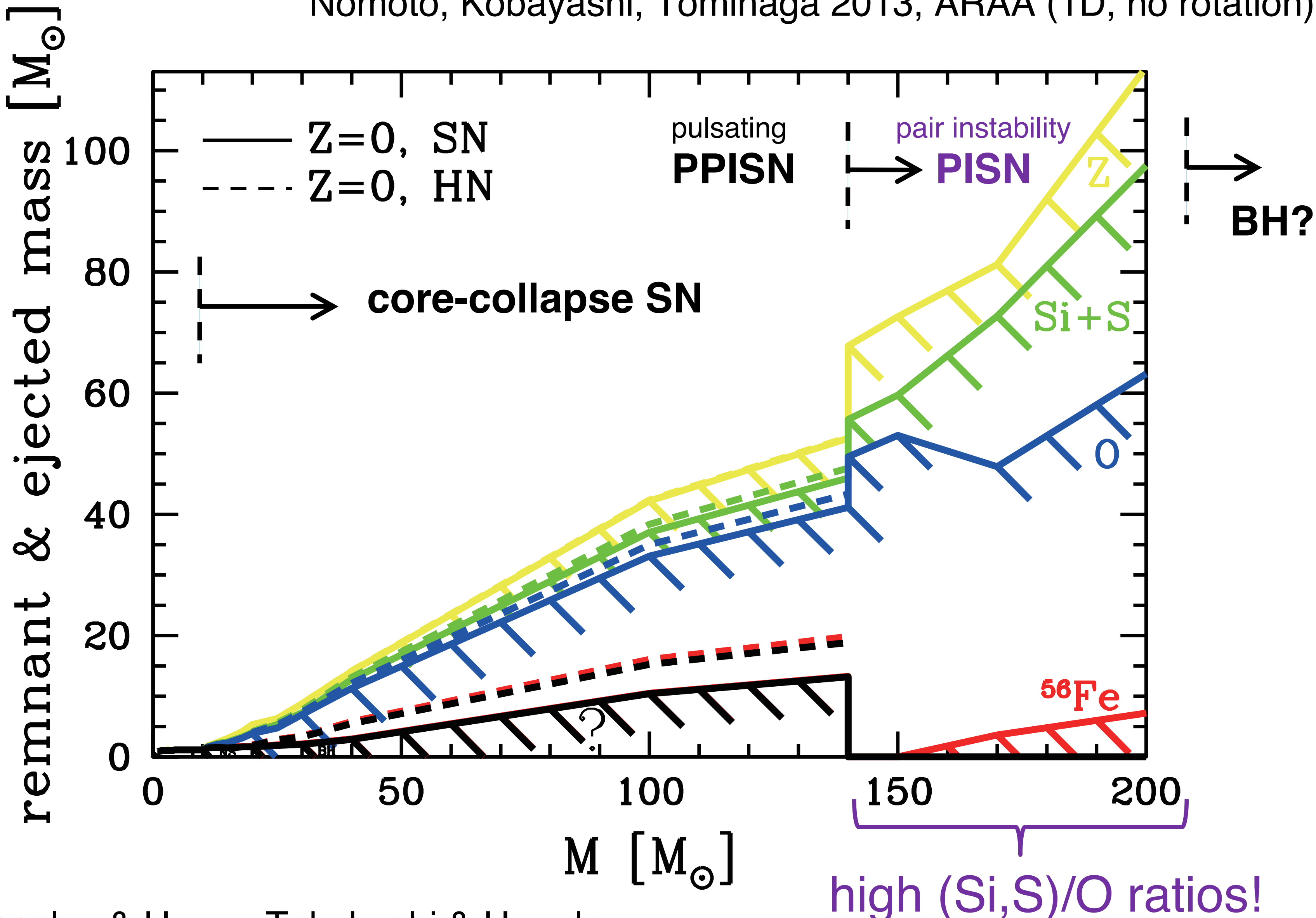


Thus, O/Fe depends on IMF

Also, Woosley & Heger; Limongi & Chieffi; NuGrid

Nucleosynthesis Yields

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



Also, Woosley & Heger; Takahashi & Umeda

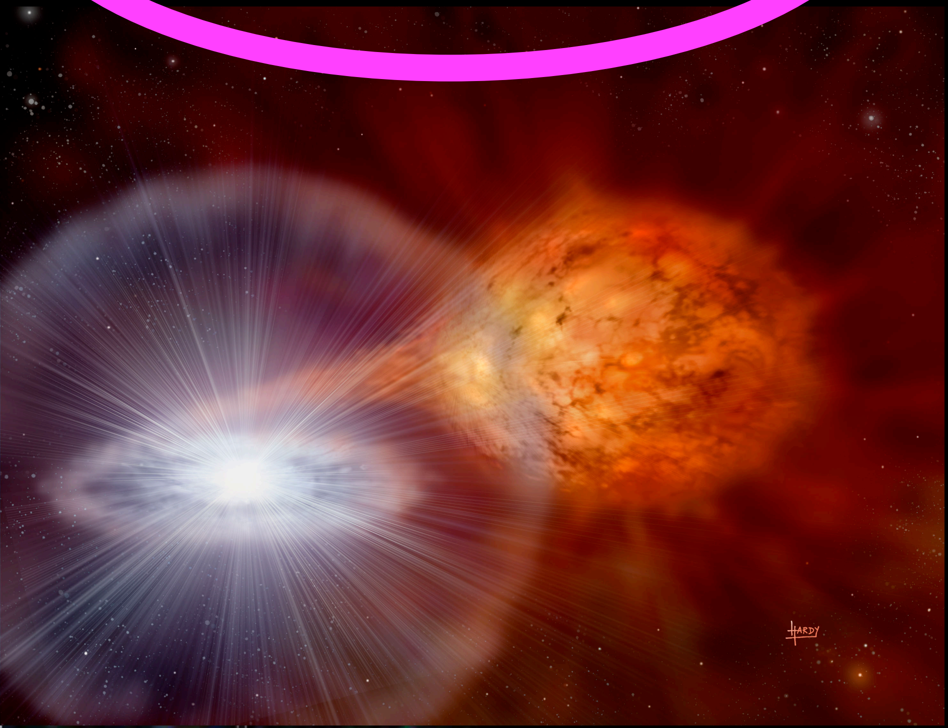
Thermonuclear (Type Ia) Supernovae

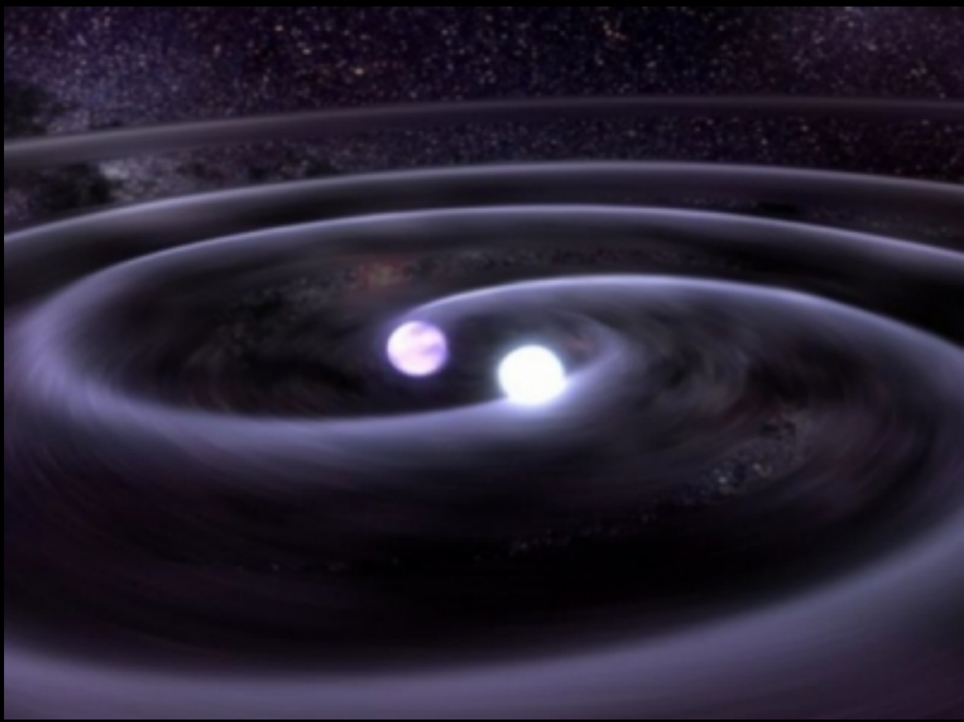
Thermonuclear explosion in a binary with C+O white dwarf

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

vs

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

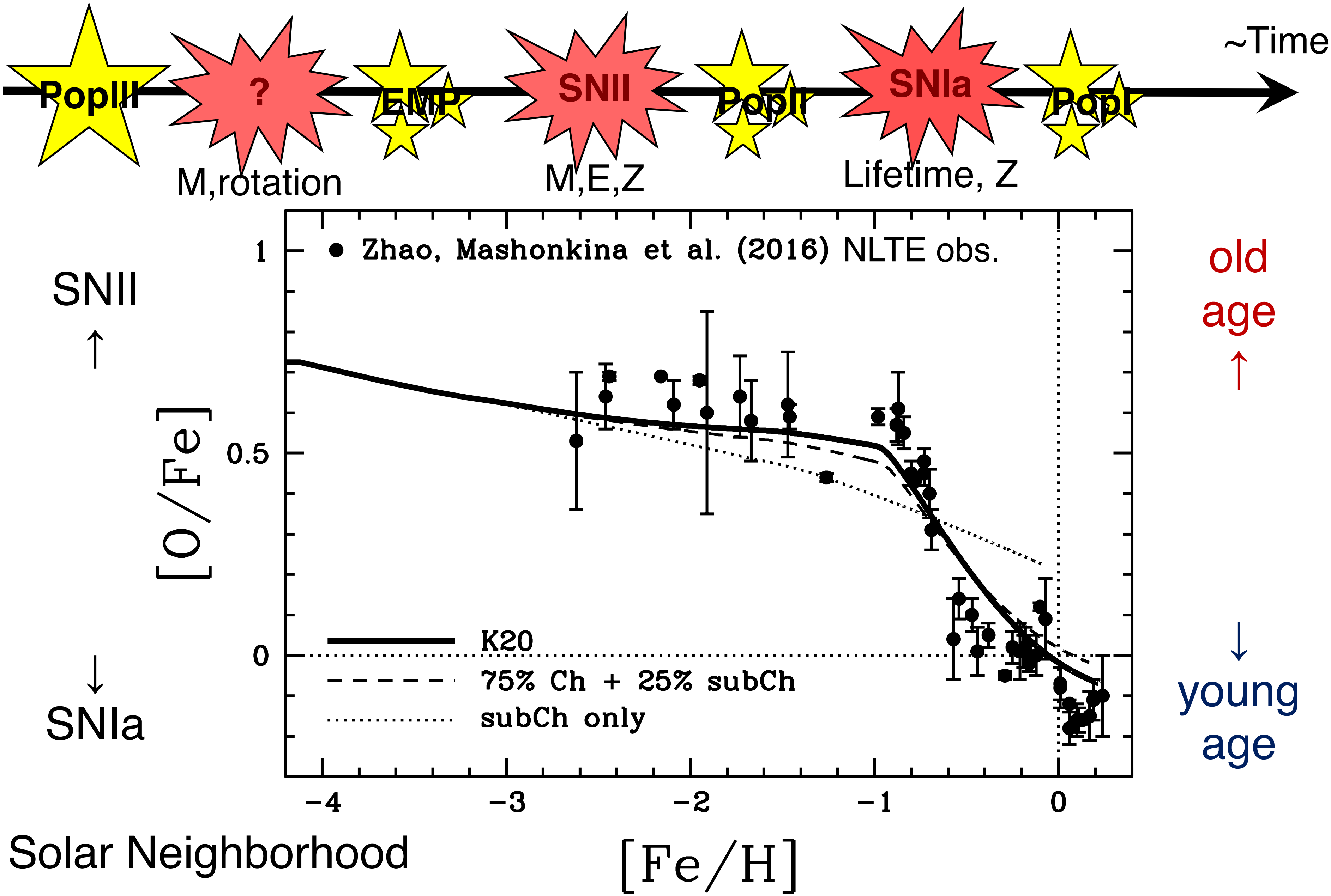




← a companion star observed! (McCully+14)

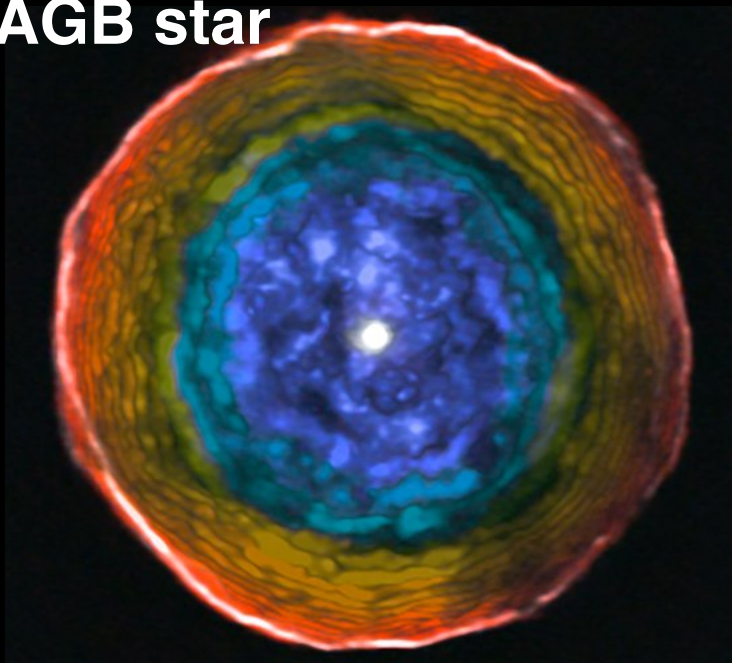
For Mn! 75% Ch needed for the elemental abundances in Milky Way (CK, Leung, Nomoto 2020)

The [α/Fe]-[Fe/H] relation



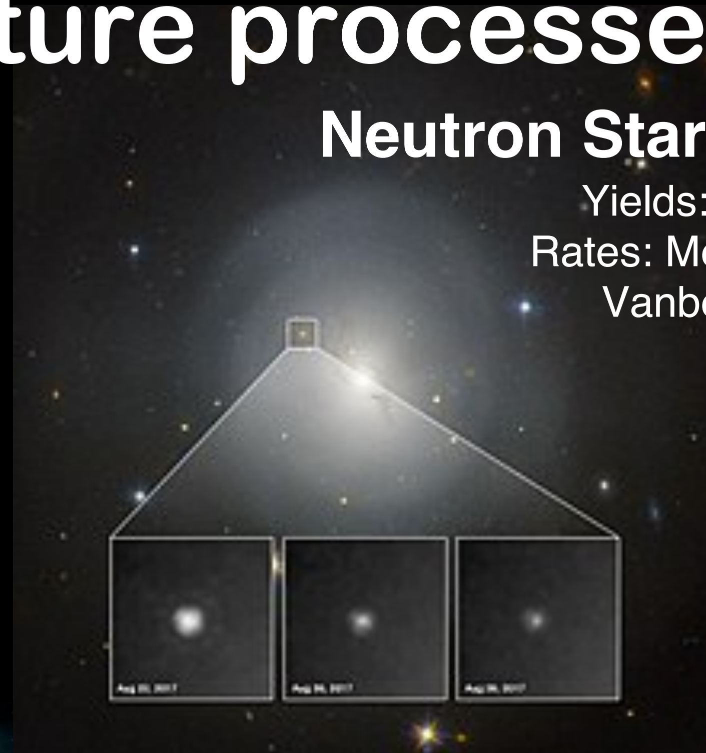
Neutron-capture processes

AGB star



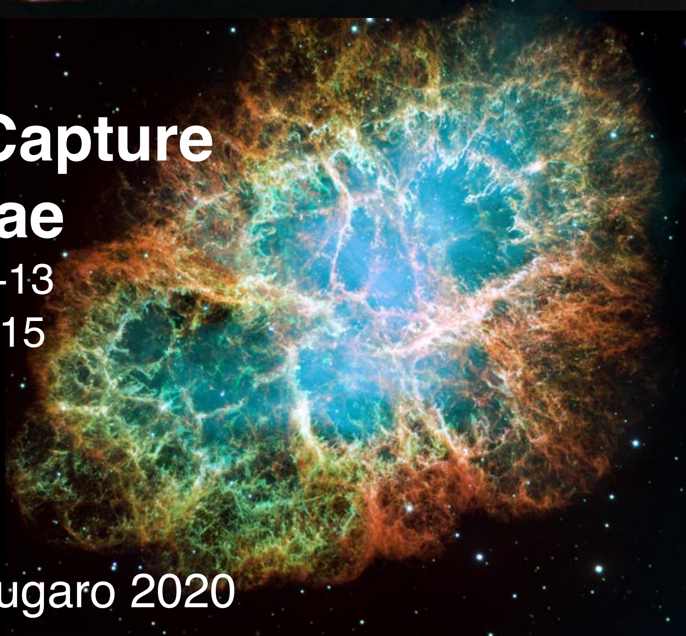
Neutron Star Merger

Yields: Wanajo+14
Rates: Mennekens & Vanbeveren 2014



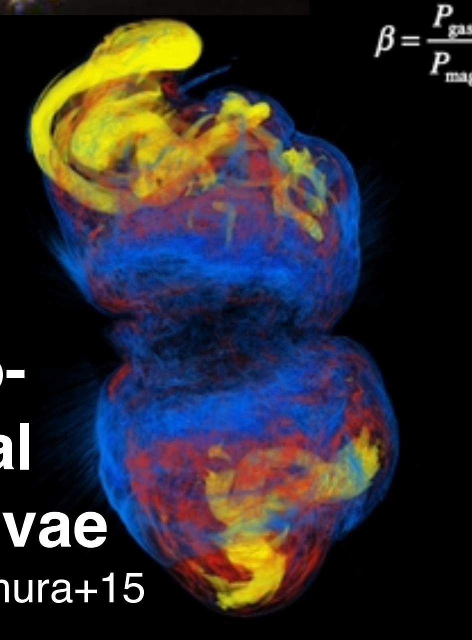
Electron Capture Supernovae

Yields: Wanajo+13
Mass: Doherty+15



Magneto-rotational Supernovae

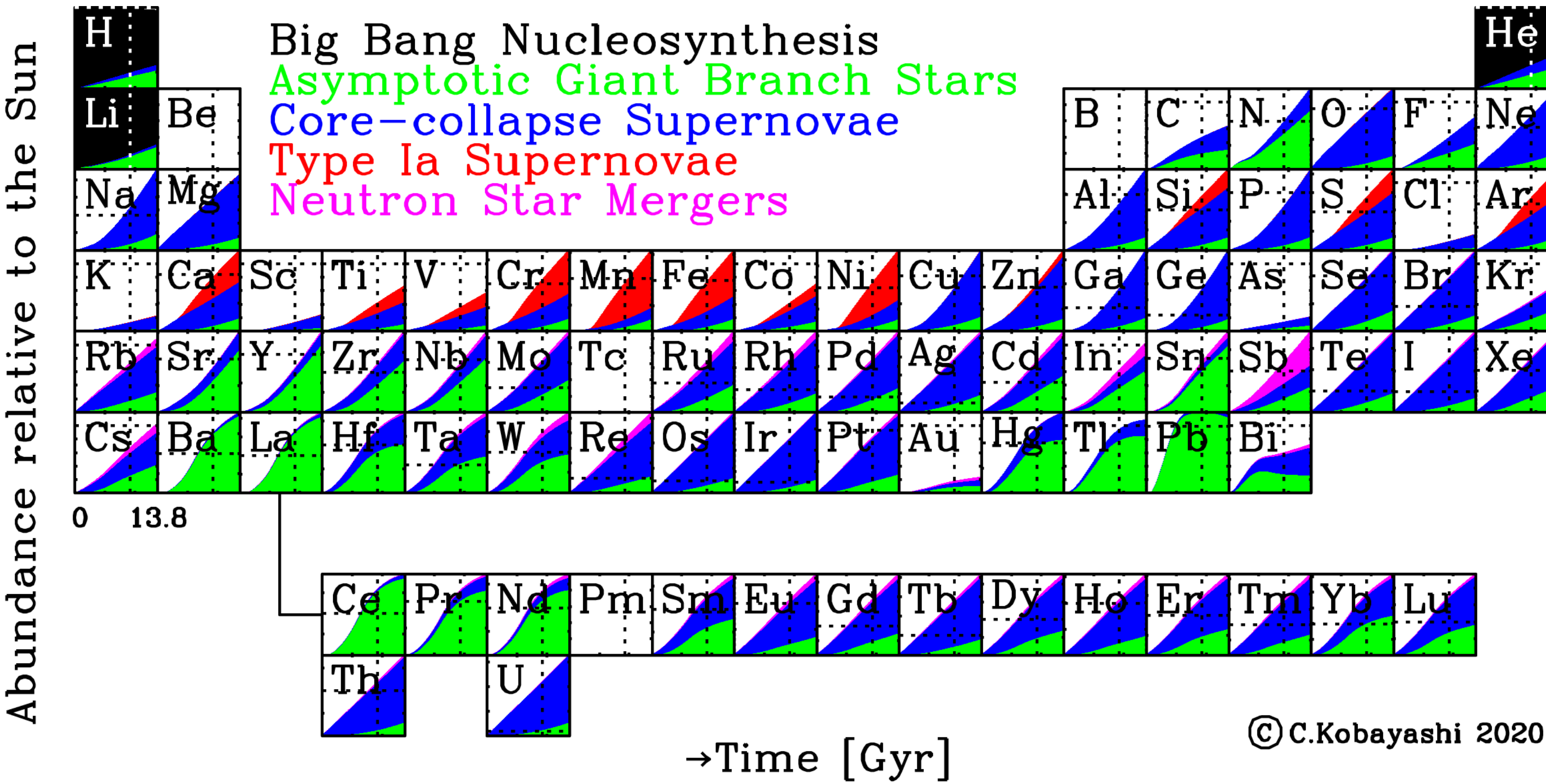
Yields: Nishimura+15



CK, Karakas, Lugaro 2020

The Origin of Elements

CK, Karakas, Lugaro 2020, ApJ



※Purely theoretical, no empirical equations.

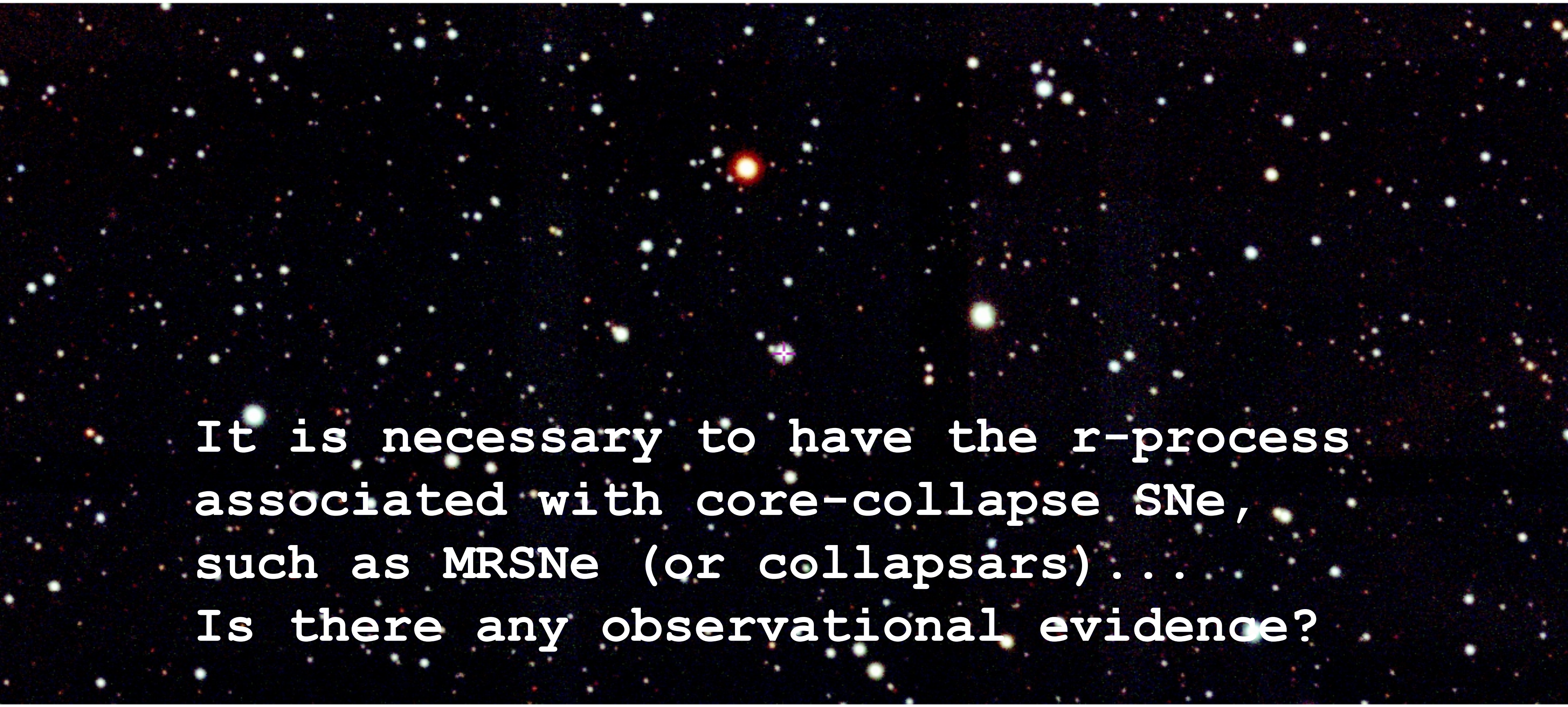
※Mass-loss is counted toward AGB or ccSN.

dotted lines: solar values

Article
Nature | Vol 595 | 8 July 2021 | 223

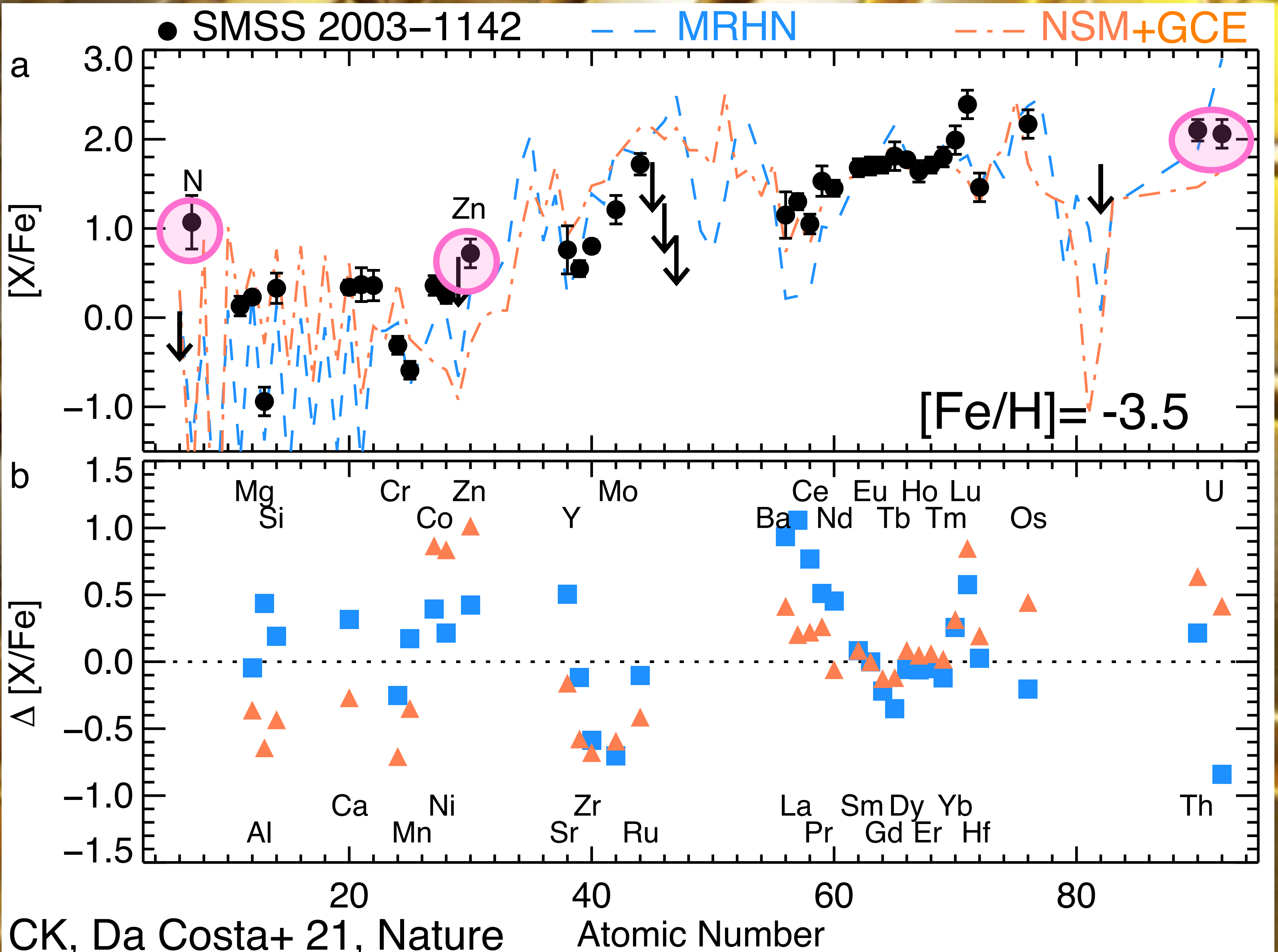
r-Process elements from magnetorotational hypernovae

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]



- 26000 SkyMapper photometric candidates
- 2618 EMP candidates with ANU 2.3m spectra (Da Costa+19)
- 479 stars in SkyMapper DR1.1 (Yong+21b) with Magellan/VLT/Kech
- SMSS J200322.54-114203.3, [Fe/H]= -3.5, 2.3kpc away, Halo orbit

Magneto-rotational Hypernova!

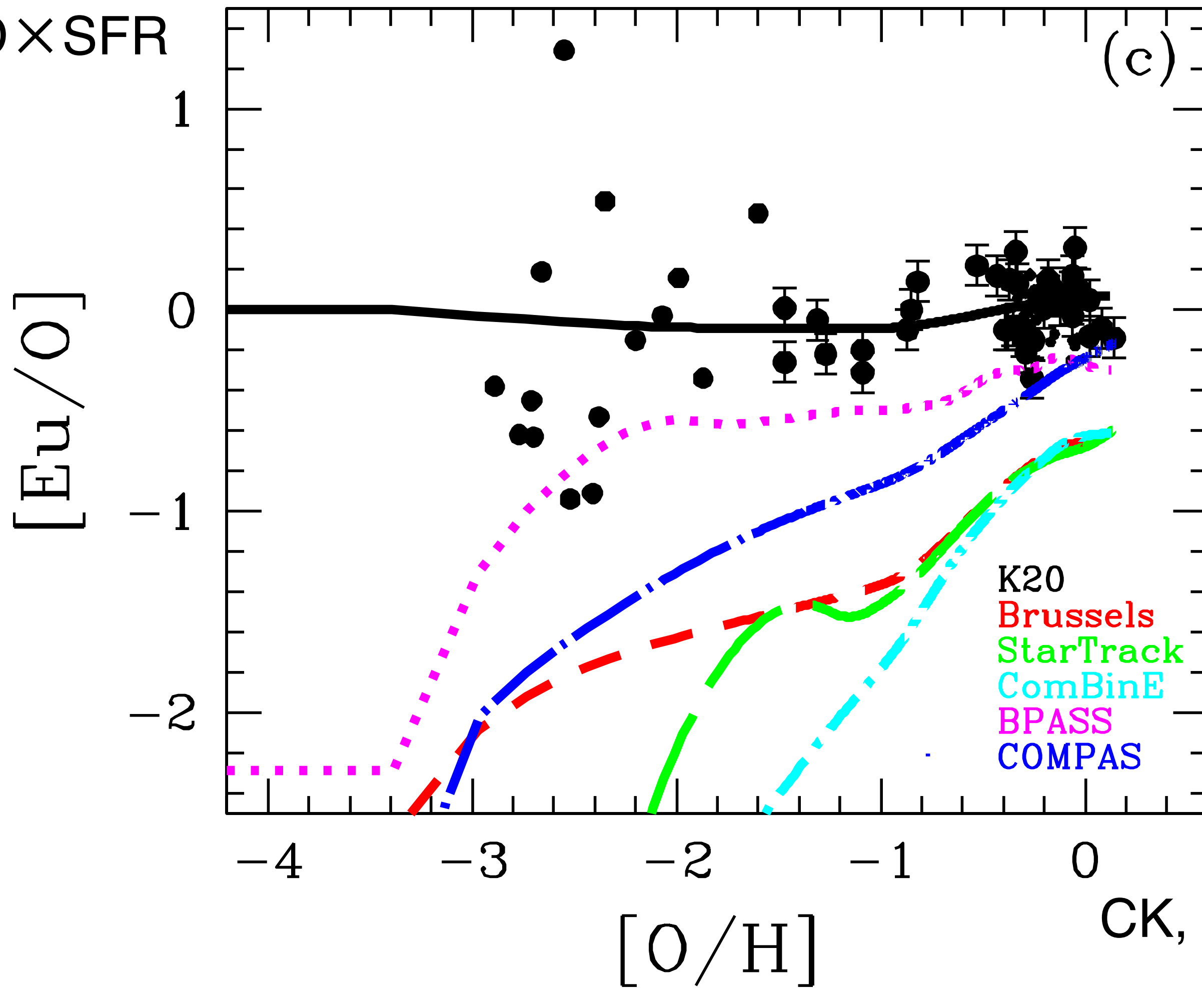


Yong, CK, Da Costa+ 21, Nature

Can NSMs be the major r-process site?

- In binary population synthesis (BPS, colours), timescales become shorter at lower metallicity, but still too long and the rates are also too low...

$R_{NSM} \neq DTD \times SFR$
but DTD(Z)



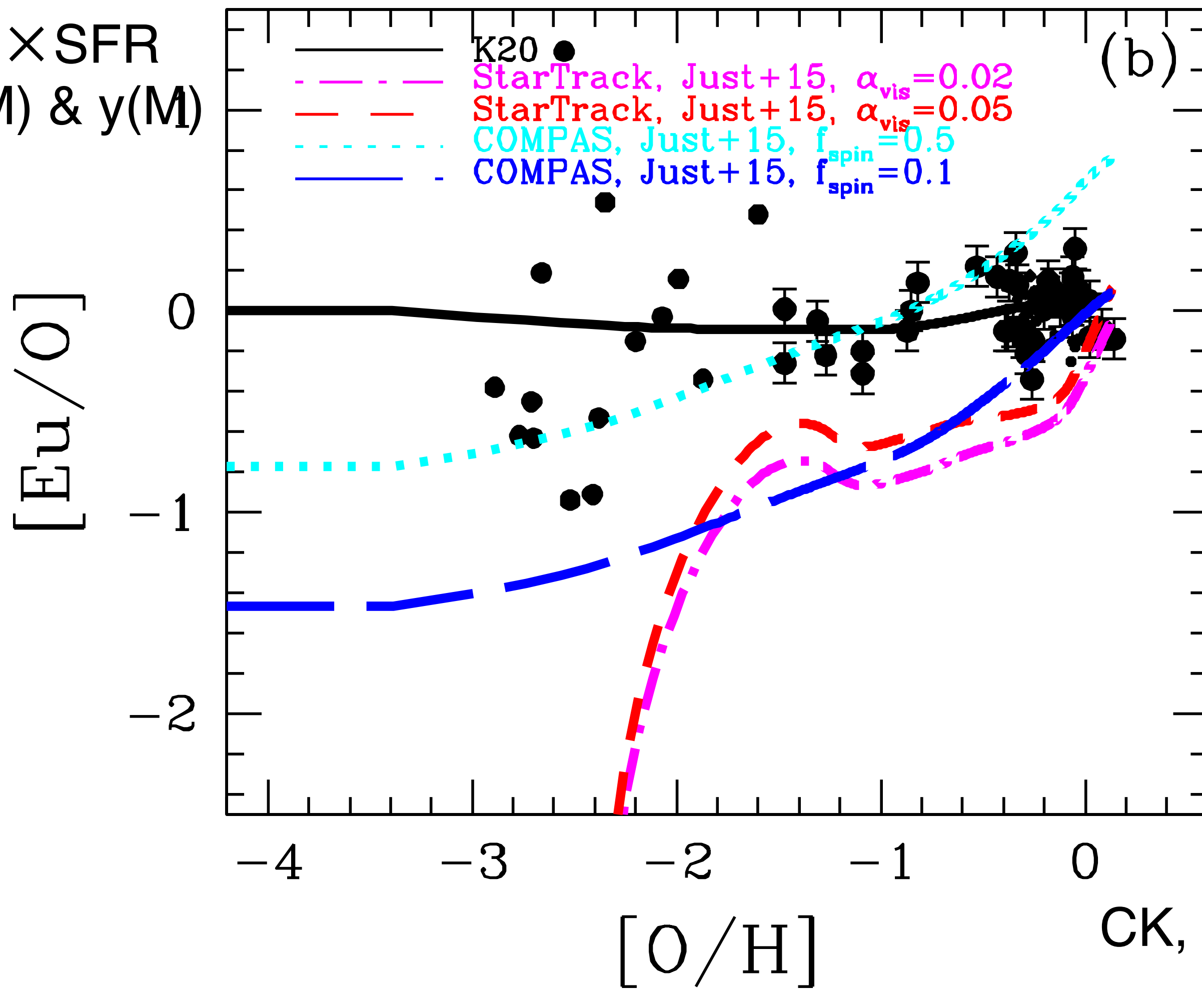
incl. MRSNe
used in K20

CK, Mandel+ 22

Can NSMs be the major r-process site?

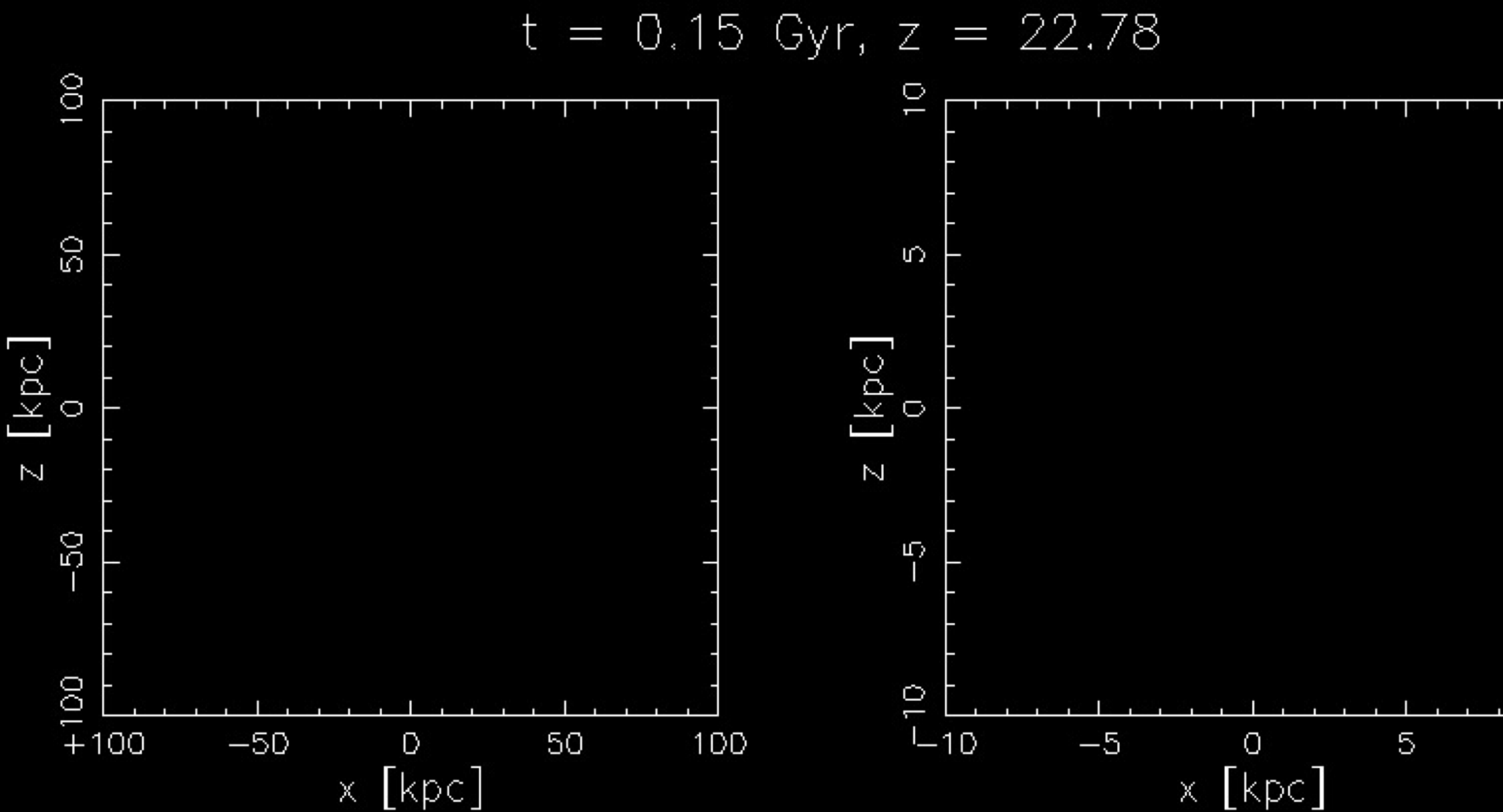
❖ BH-NS mergers may be important in early Universe, but depends on mass, EoS, viscosity of winds (α_{vis}), spin (f_{spin}). Timescales are still an issue.

$R_{NSM} \not\approx DTD \times SFR$
but DTD(Z,M) & y(M)



CK, Mandel+ 22

MW-type galaxy zoom-in simulation

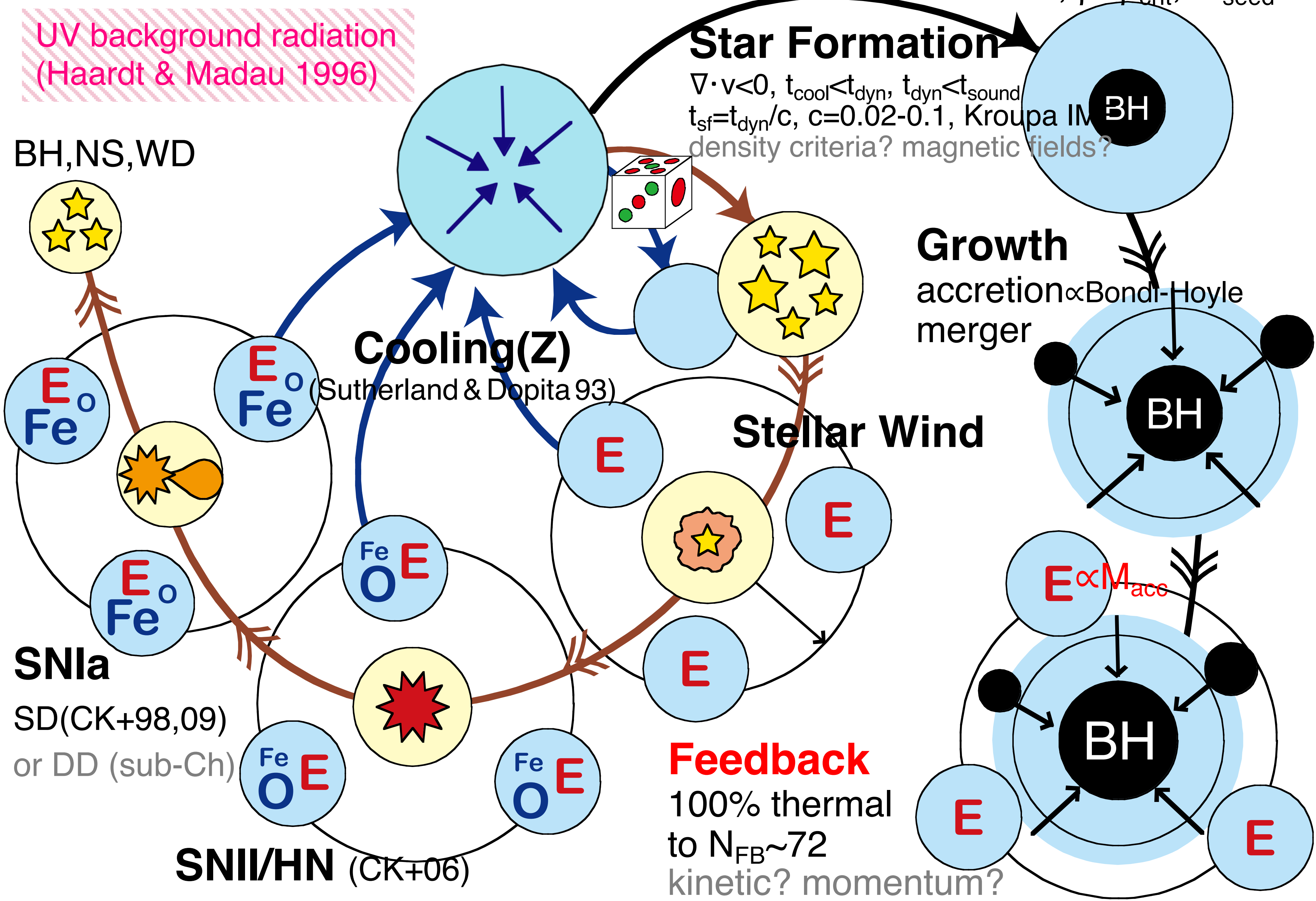


Gadget3-based code (CK+ 2007)

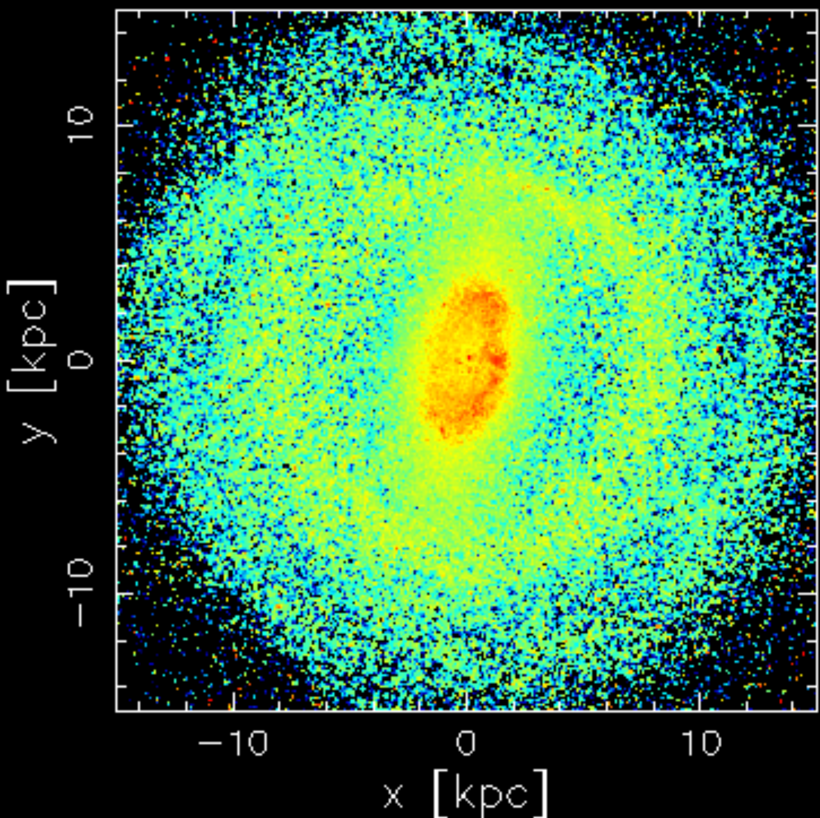
Aquila Initial Condition (Scannapieco+12), $3\times10^5 M_\odot$, 0.5kpc

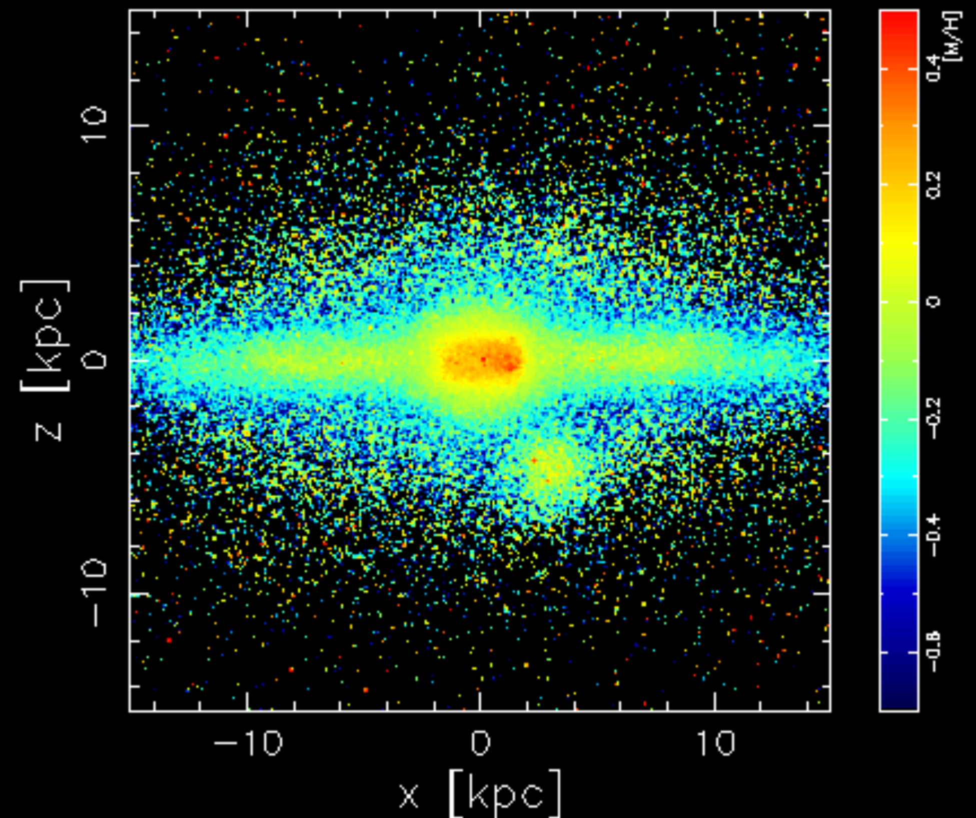
https://star.herts.ac.uk/~chiaki/works/Aq-C-5-kro2.mpg

Chemodynamics



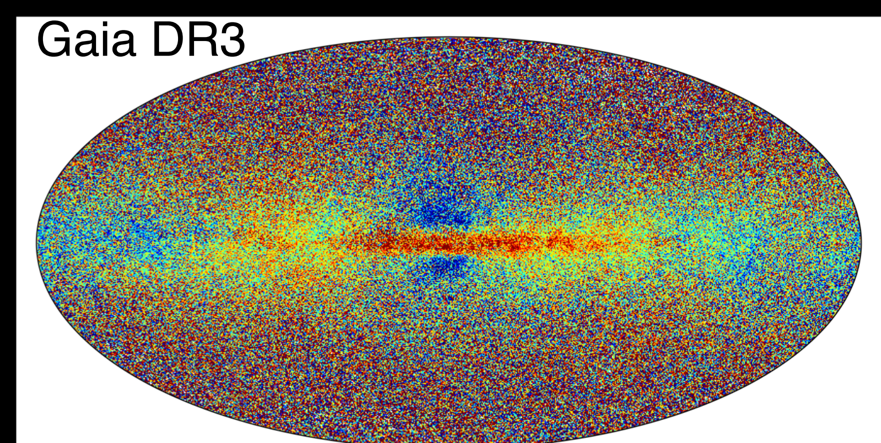
Metallicity Map (K22)



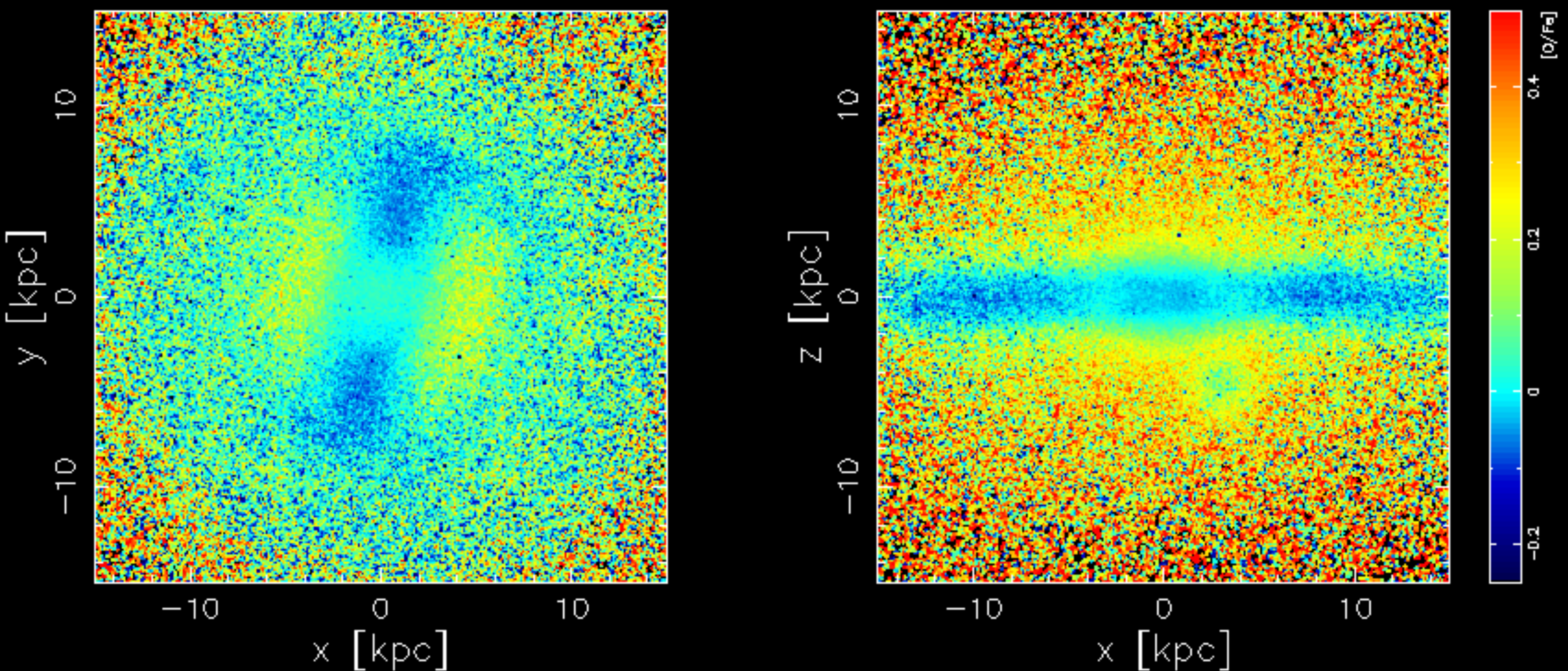


- ✓ Radial gradient
- ✓ Vertical gradient

low-mass stellar mass weighted, projected

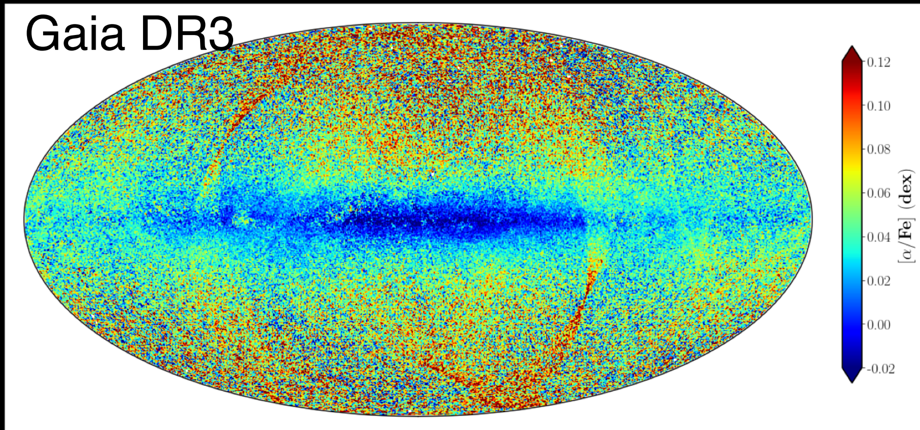


[O/Fe] Map (K22)



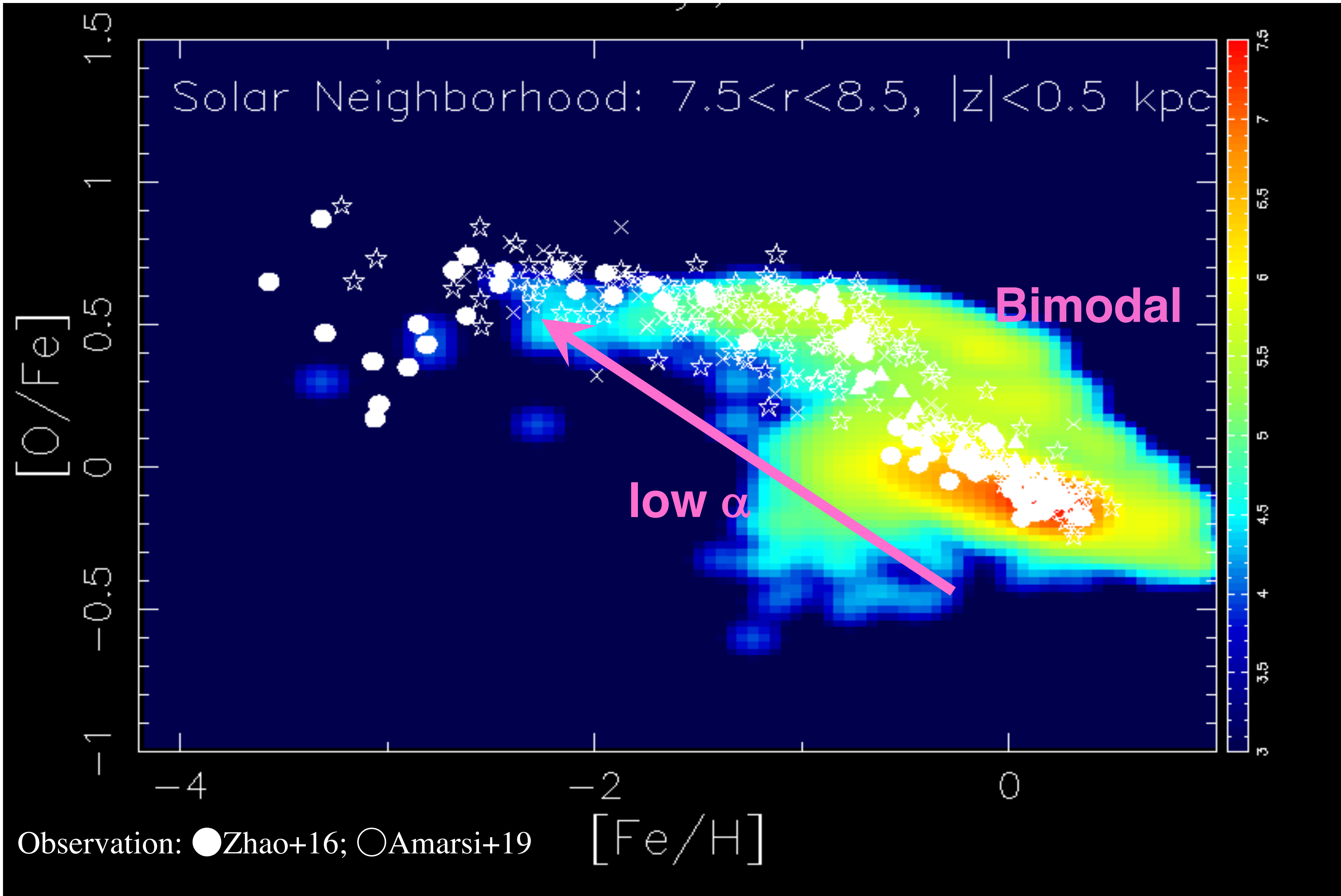
✗ Radial gradient
✓ Vertical gradient

low-mass stellar mass weighted, projected



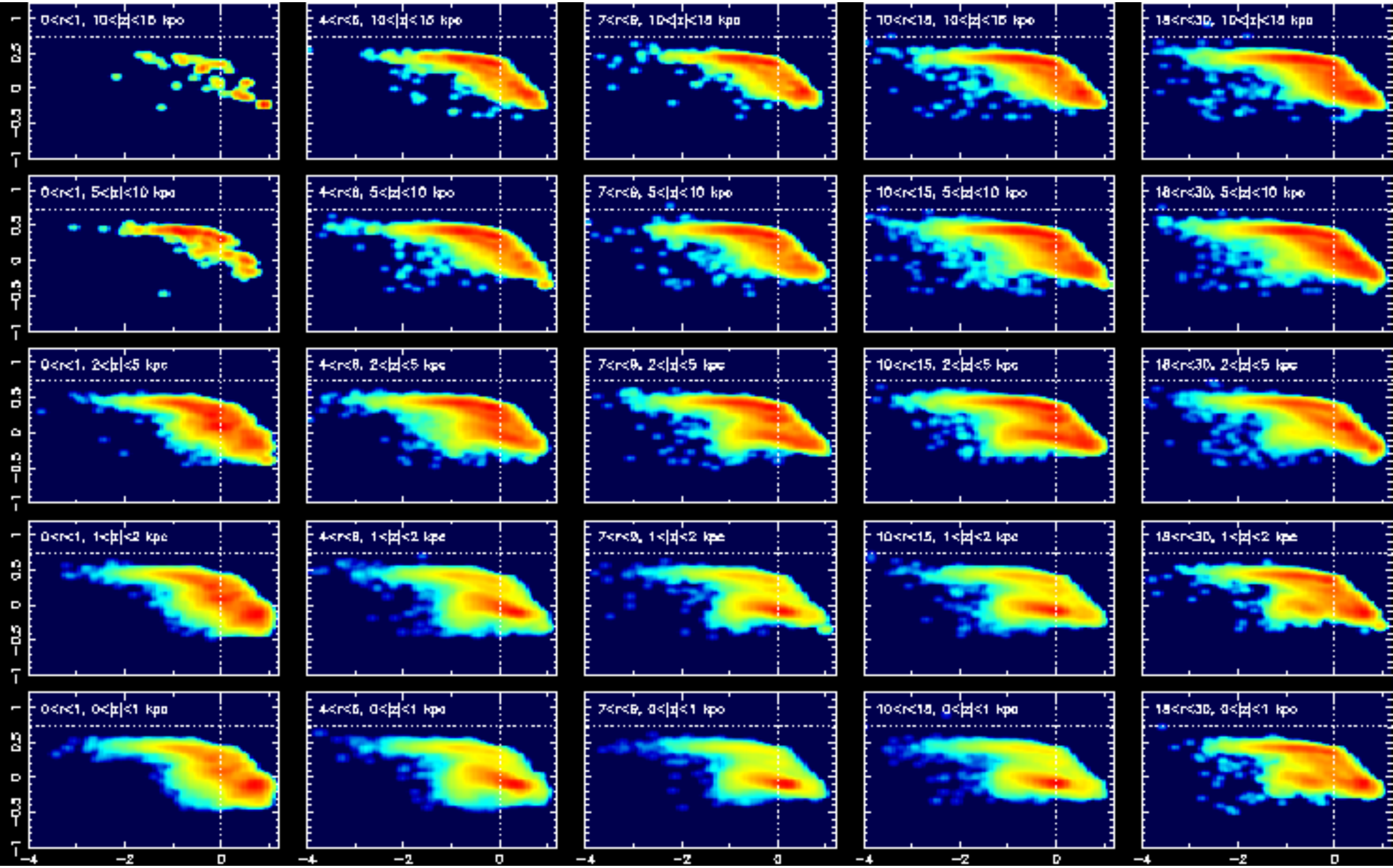
The [O/Fe]-[Fe/H] Relation

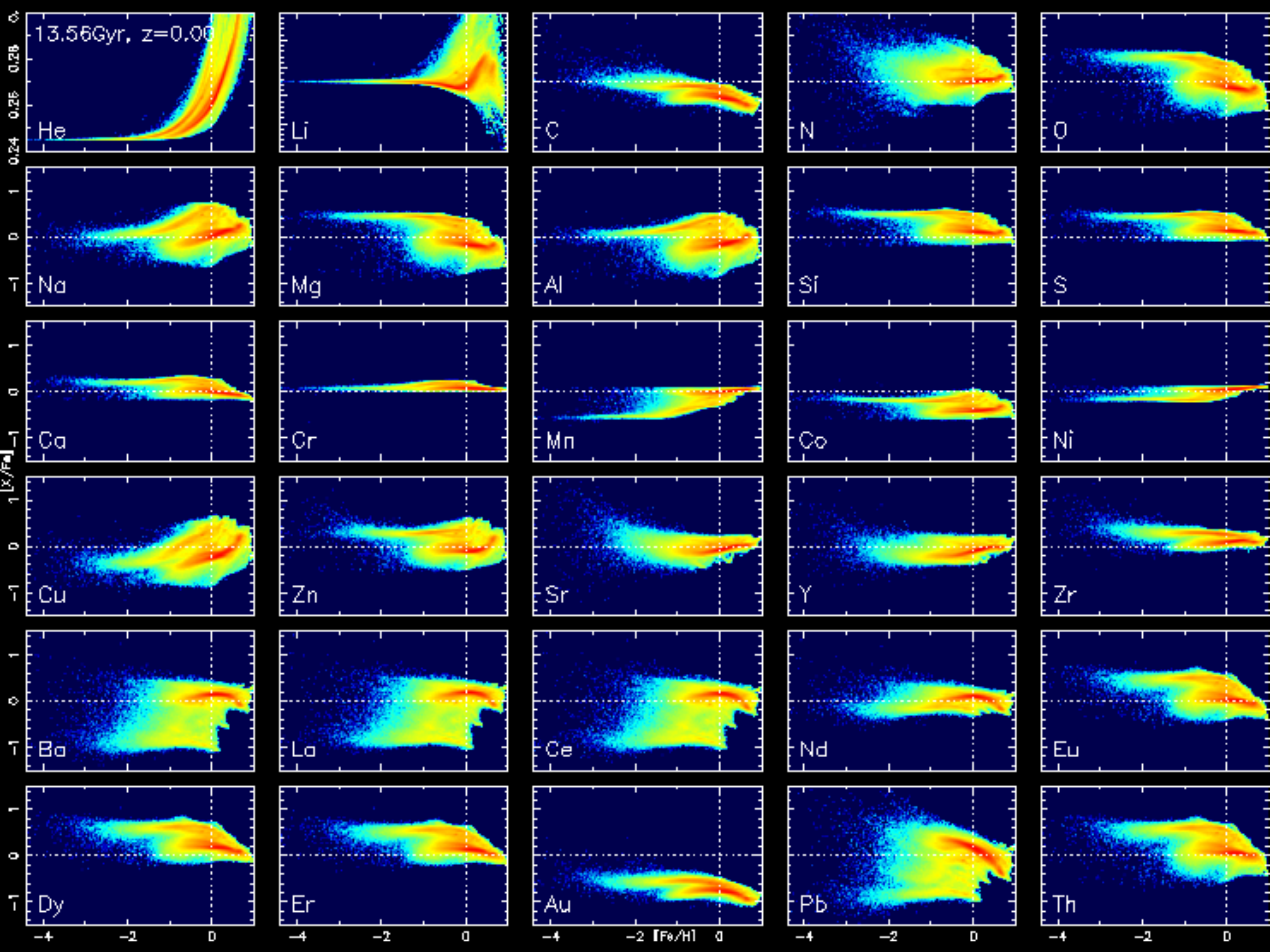
Also CK & Nakasato 2011



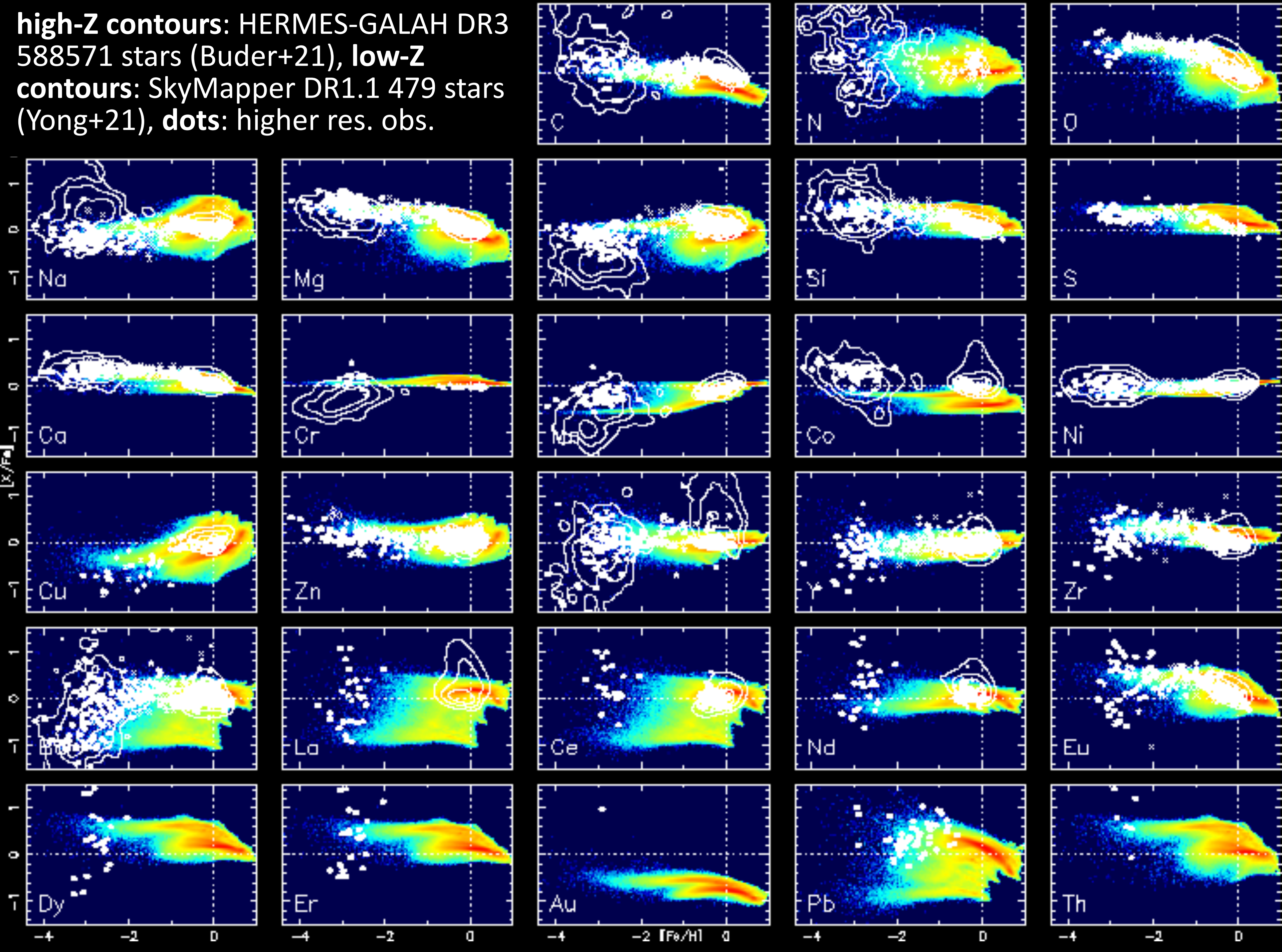
The α/Fe bimodality

Also Fig 1 of CK 2016




13.56Gyr, z=0.00
He
Li
C
N
O
Na
Mg
Al
Si
S
Ca
Cr
Mn
Co
Ni
Cu
Zn
Sr
Y
Zr
Ba
La
Ce
Nd
Eu
Dy
Er
Au
Pb
Th
[X/Fe]
[Fe/H]

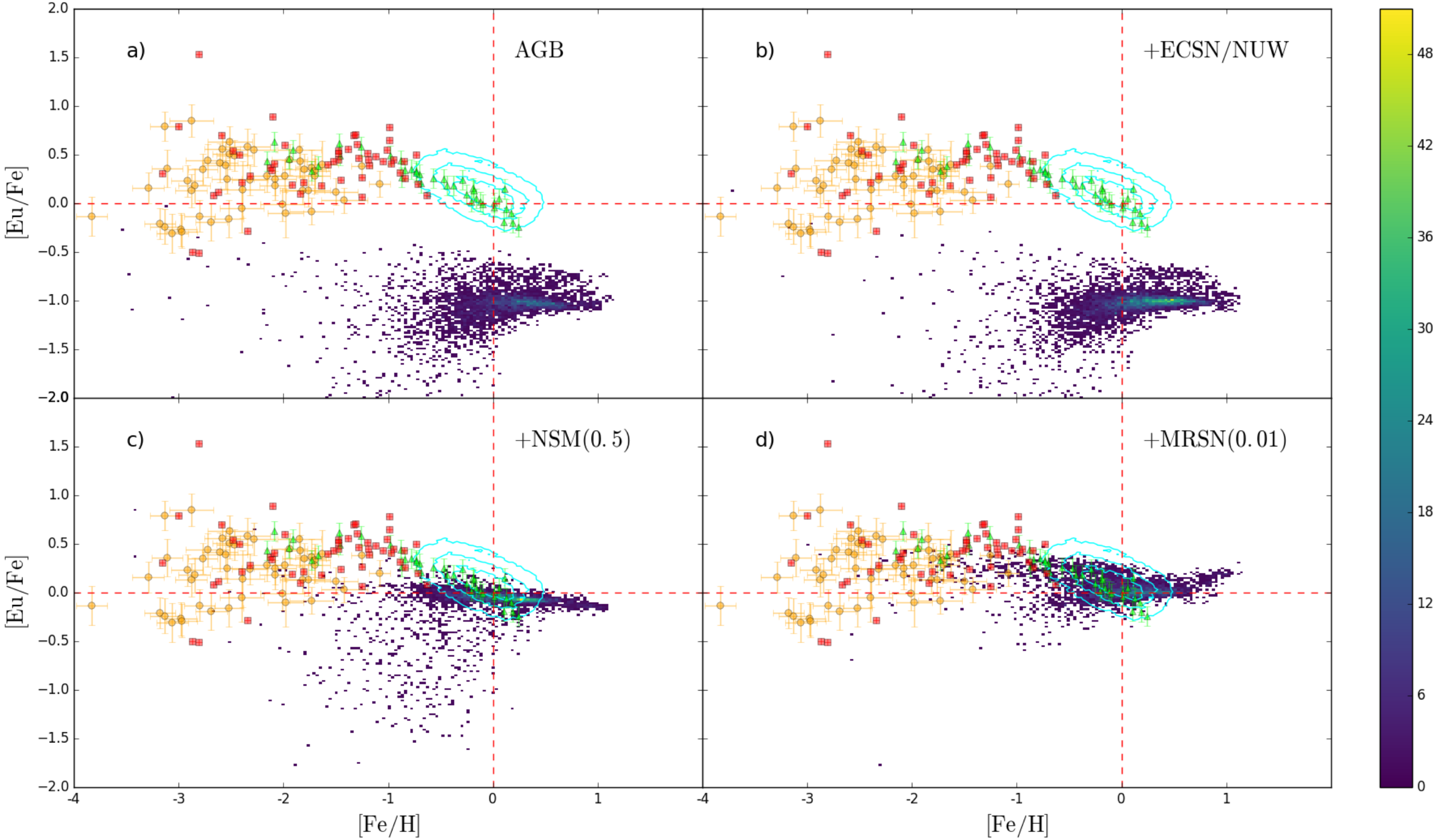
high-Z contours: HERMES-GALAH DR3 588571 stars (Buder+21), **low-Z contours**: SkyMapper DR1.1 479 stars (Yong+21), **dots**: higher res. obs.



[Eu/Fe]-[Fe/H]

Chemo-hydrodynamical Simulation

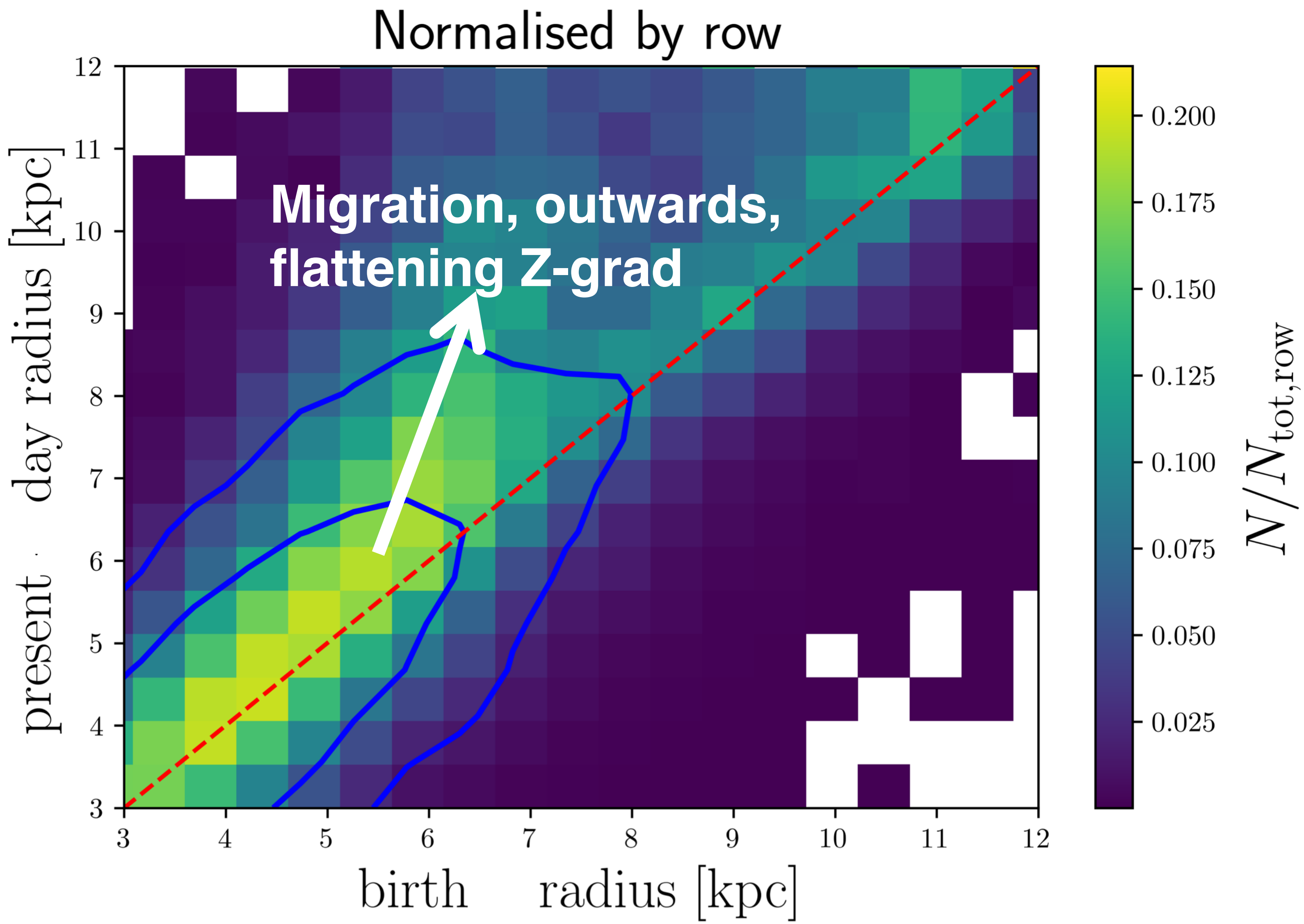
Haynes & CK 2019



Neutron star mergers alone cannot reproduce the observations.

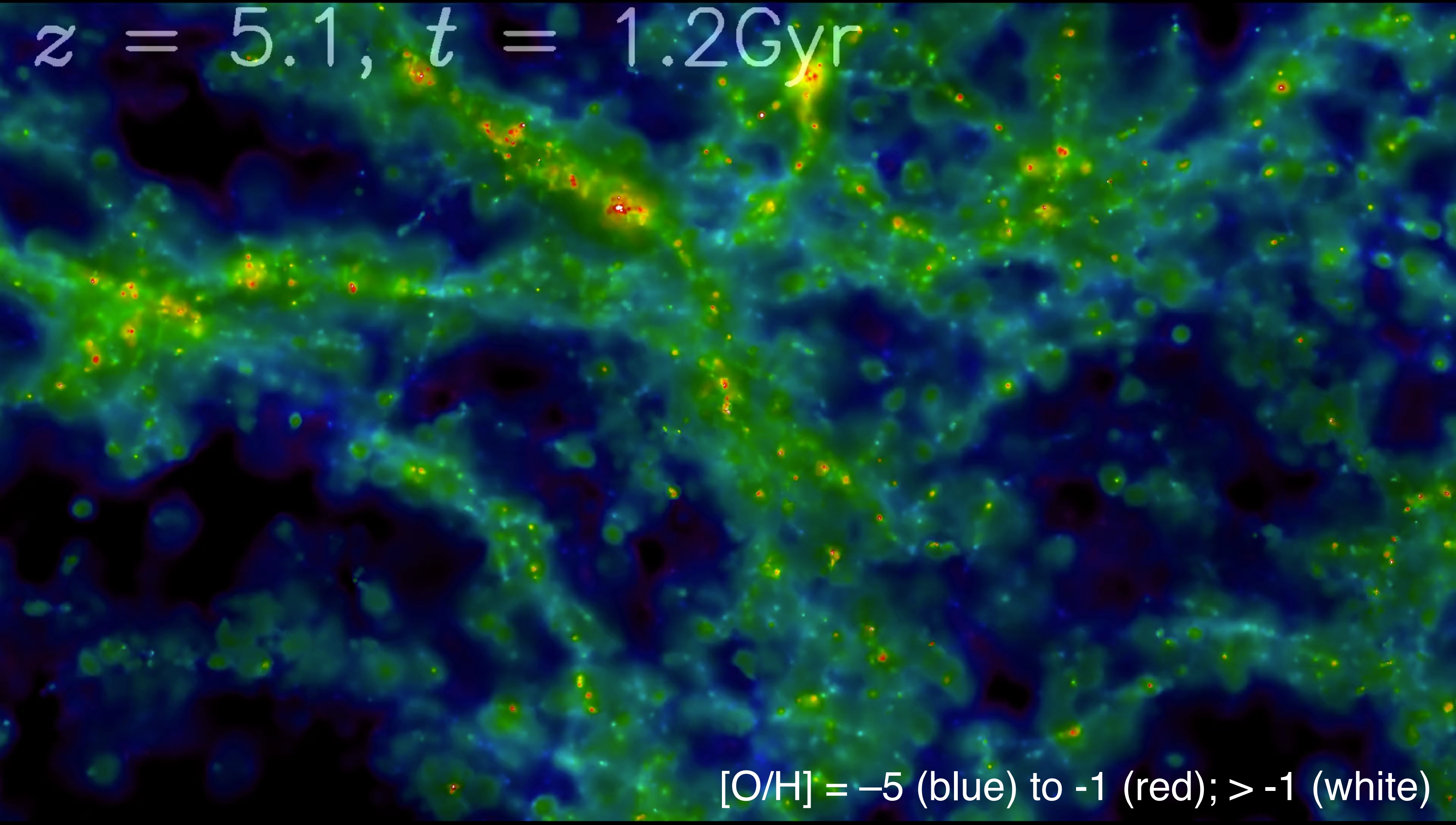
Hansen+17; Roederer+16; NLTE Zhao+16; HERMES-GALAH

Migration – tracing the stellar birth place



Vincenzo & CK 2020, also for gas flows

Cosmological Simulations

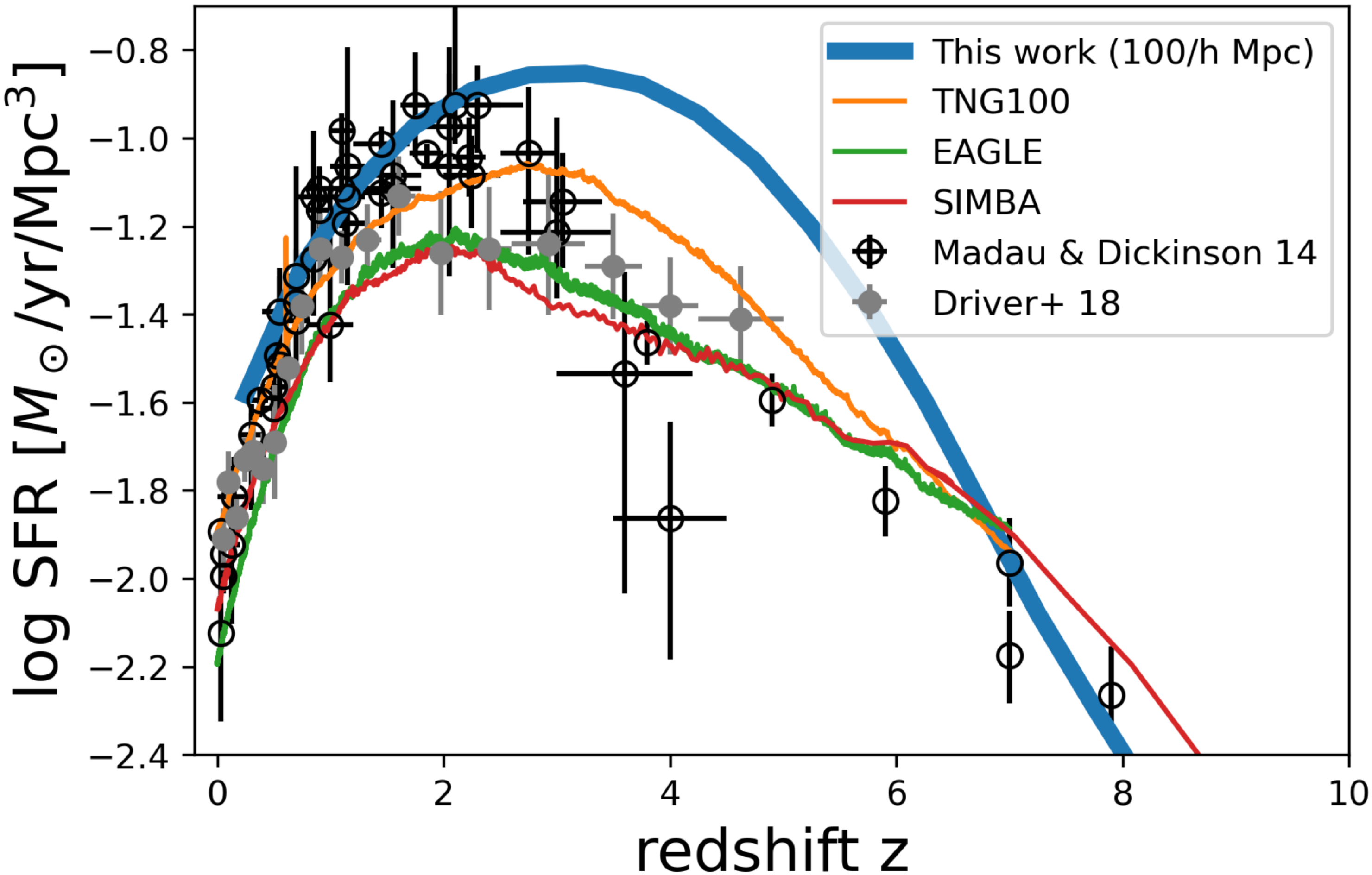


25Mpc, $1.4 \times 10^7 M_\odot$, 1.6kpc resolution

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

Cosmic Star Formation Rate

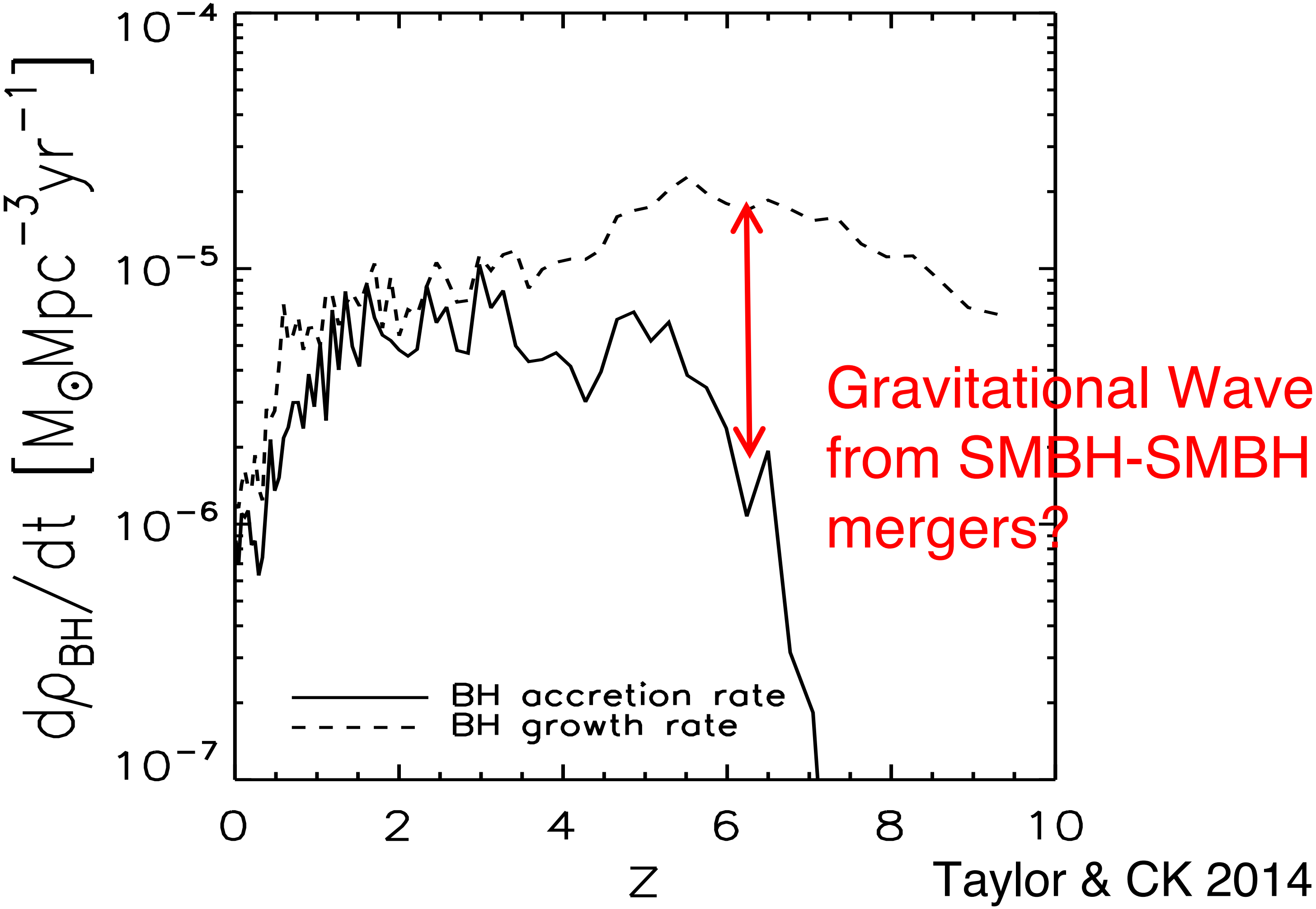
CK 2022 in prep.



Data provided by Yates et al. 2021, and C. Lovell for SIMBA

SMBH Growth Rate

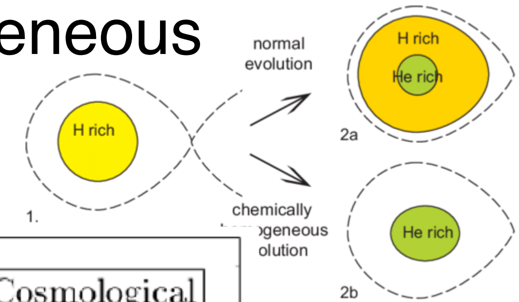
- Our SMBHs originate from the first stars, $M_{seed} = 1000 M_\odot$, smaller than in other simulations ($\sim 10^5 M_\odot$).
- $M_{BH}(<10^7 M_\odot)$–bulge mass relation@z=0 reproduced.

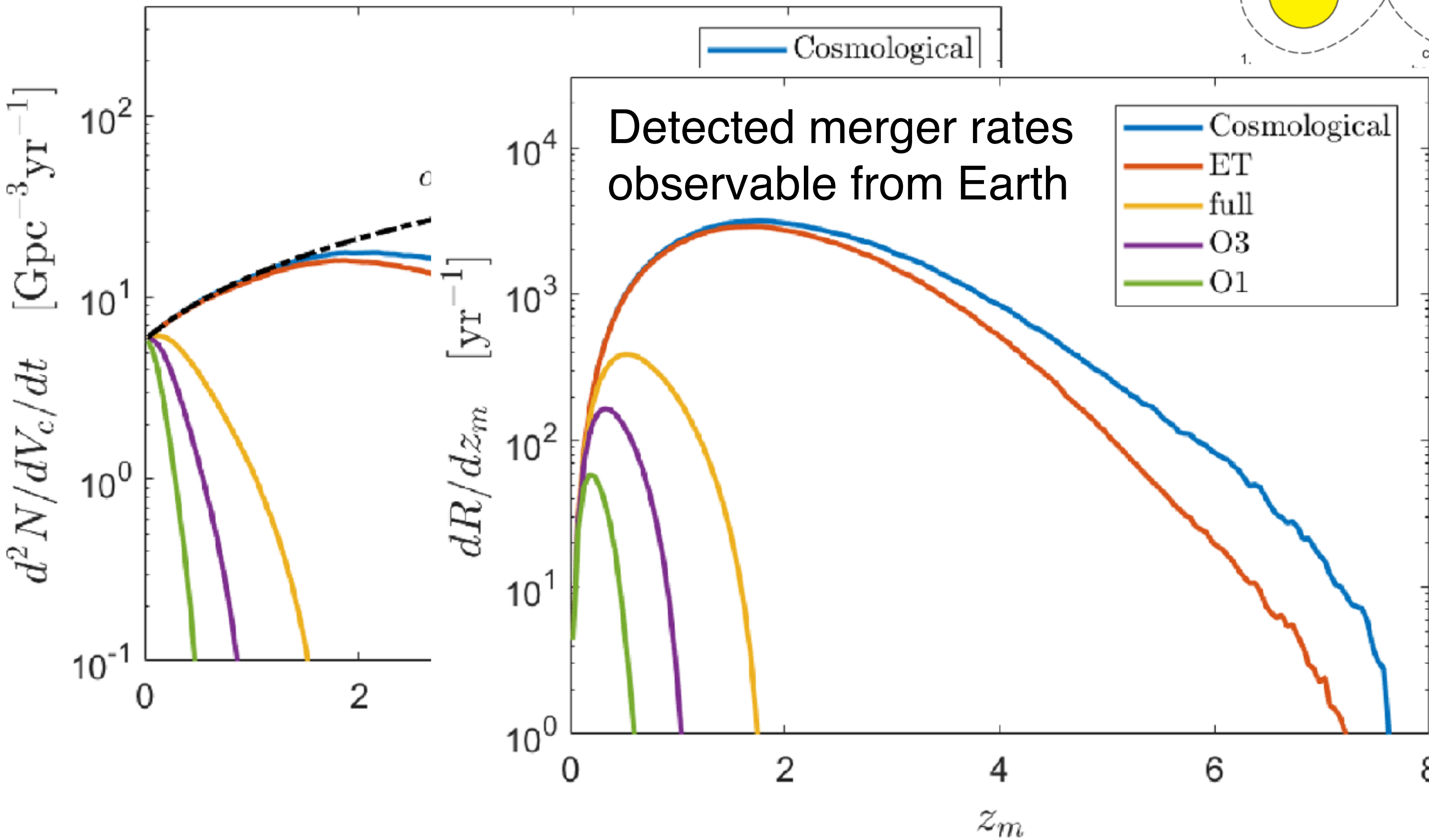


Taylor & CK 2014

BH-BH Merger Rate

- BH-BH mergers from chemically homogeneous evolution; M_{BH} = 17-43,124-338$M_\odot$



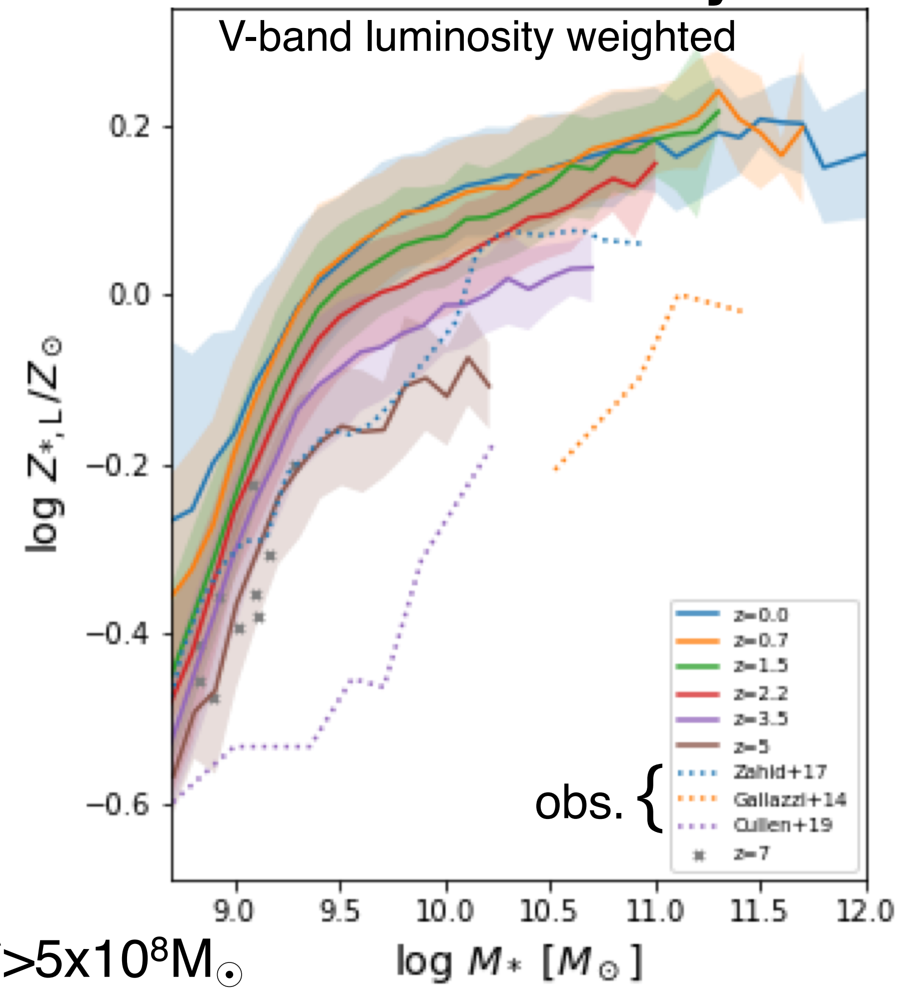


du Buisson, Marchant, Podsiadlowski, CK et al. 2020 (post process)

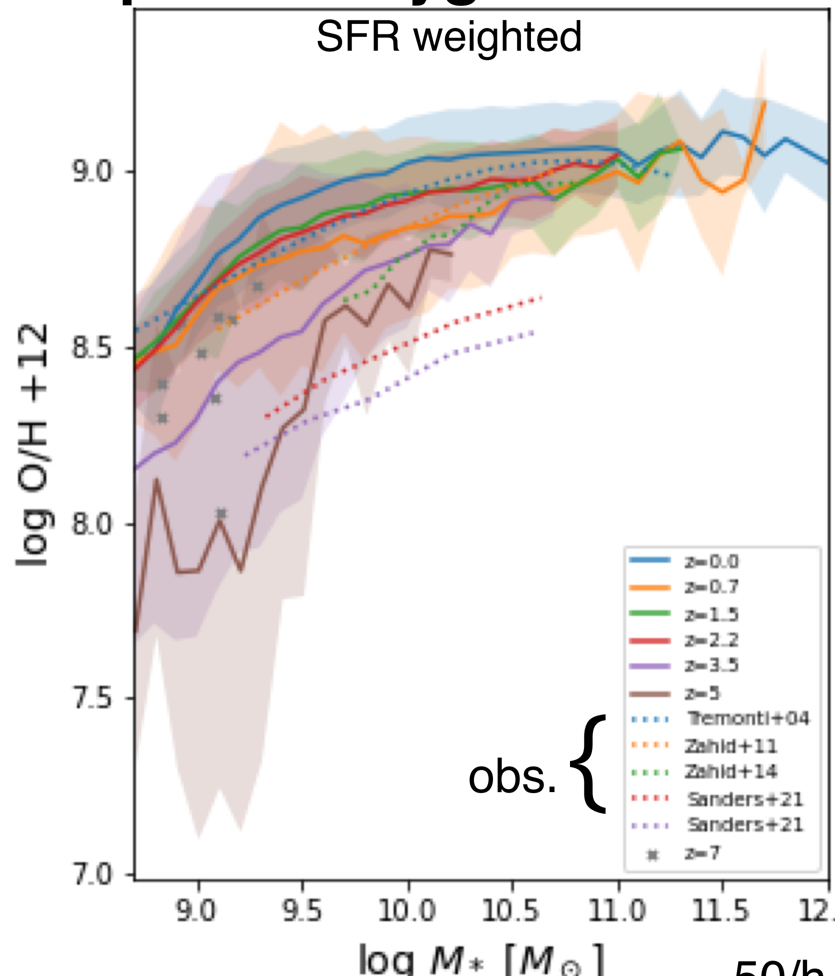
Mass Metallicity Relations

- Massive galaxies are more metal-rich because of the mass-dependent winds by SN feedback (CK, Springel, White 07; Taylor et al. 2020)
- No dependence on AGN feedback (Taylor & CK 2015a; 2016)

Stellar Metallicity



Gas-phase Oxygen Abundance



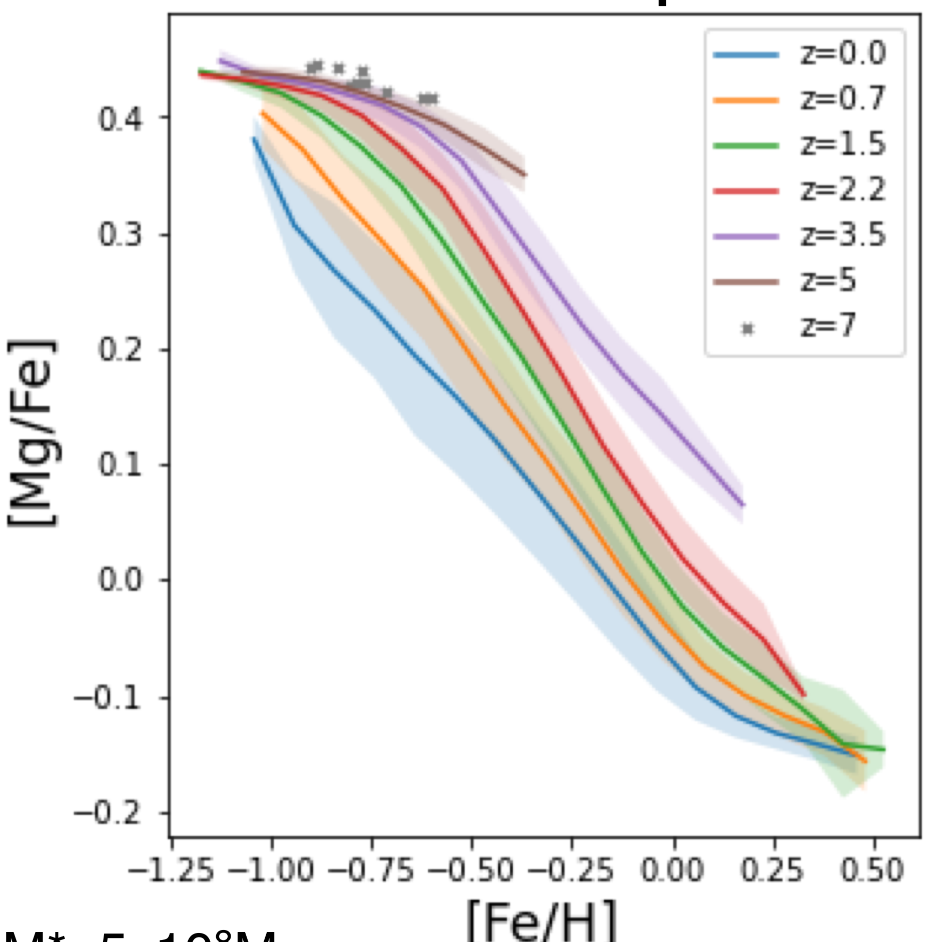
$M^* > 5 \times 10^8 M_\odot$

50/h Mpc

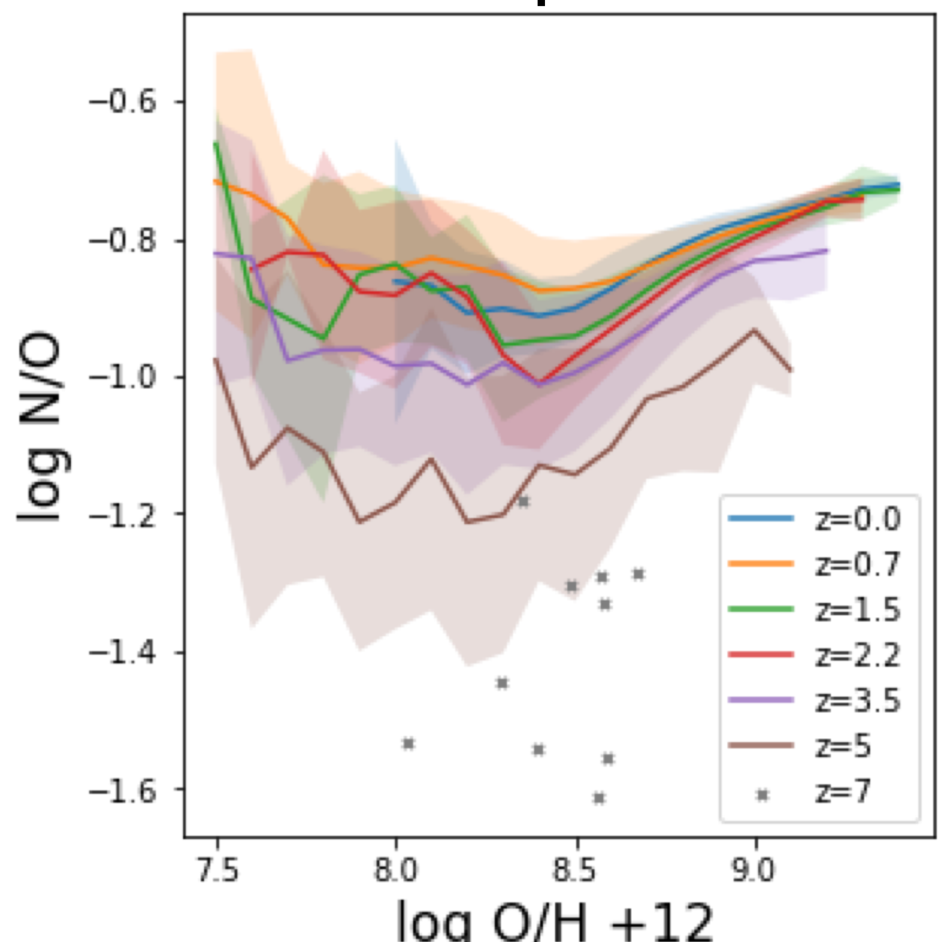
Elemental Abundance Ratios

- O, Mg come from >10M$_\odot$ stars, N from 4-7M$_\odot$, Fe from Type Ia SNe
- At higher-z, stellar [α/Fe] higher at a given [Fe/H] (Vincenzo+2018); gas-phase N/O does not evolve (Vincenzo & CK 2018).

Stellar Pop.



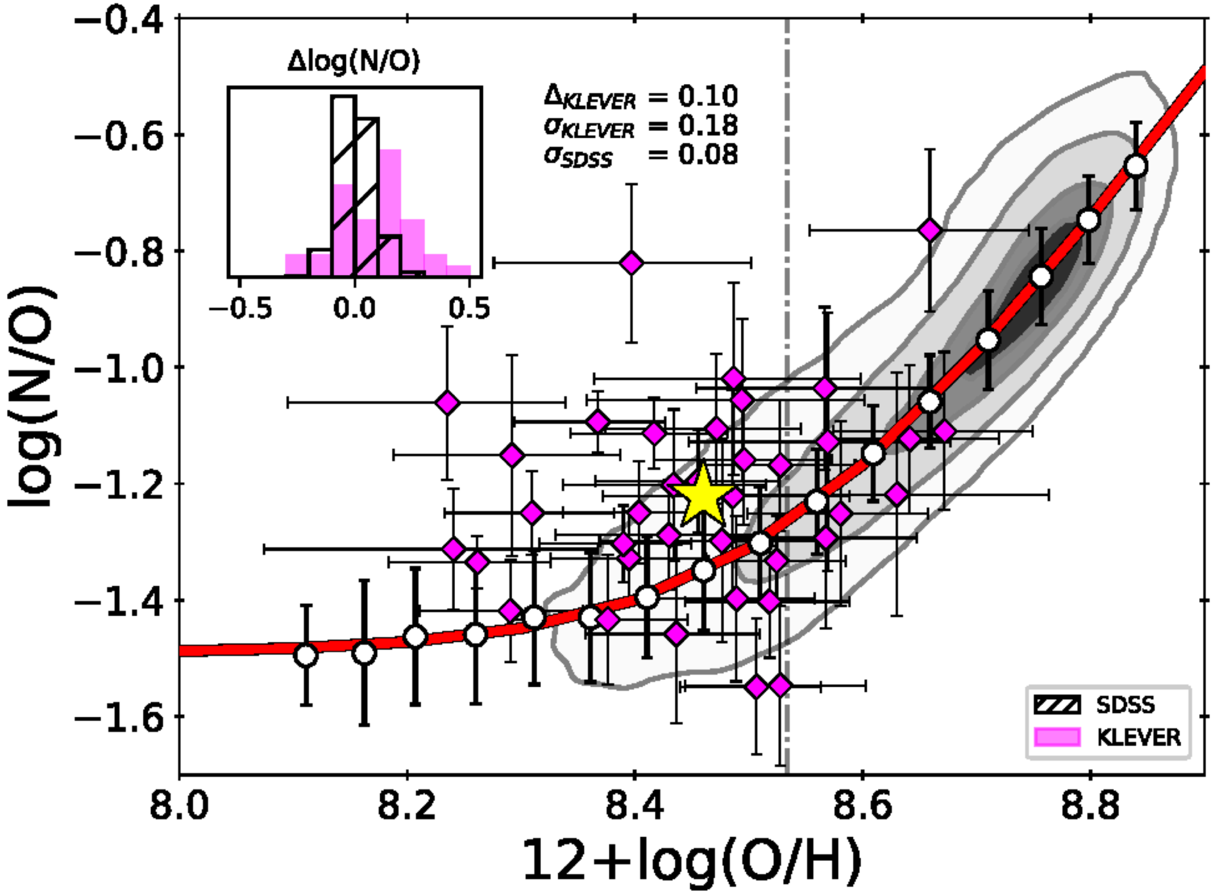
Gas-phase



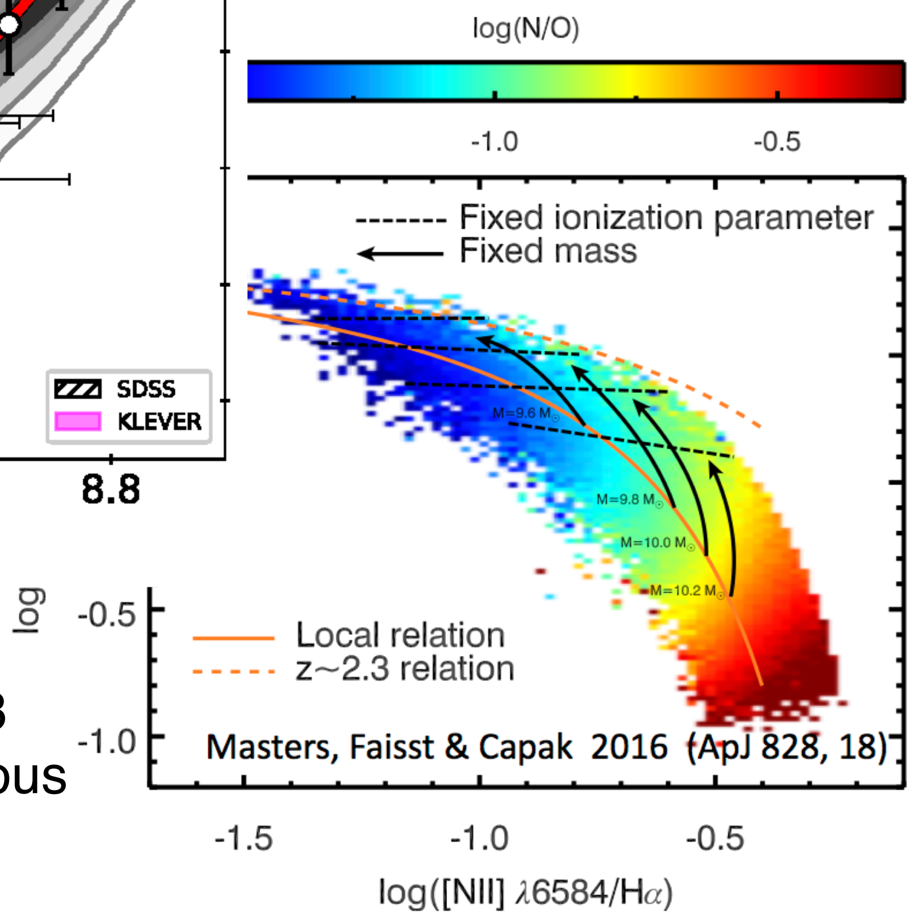
M*>5x10^{8}M$_\odot$

50/h Mpc

The N/O-O/H relation @ z~2



BPT diagram



VLT/KMOS KLEVER survey (Hayden-Pawson+ 22), see Vincenzo & CK 2018 for theoretical prediction - inhomogeneous enrichment from AGB stars

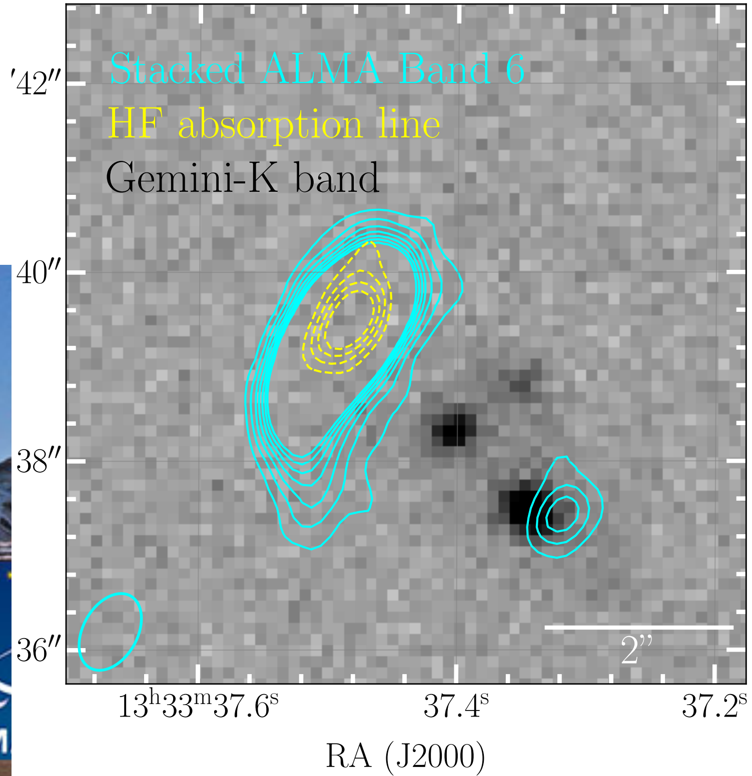
nature astronomy
4 Nov 2021
LETTERS
https://doi.org/10.1038/s41550-021-01515-9

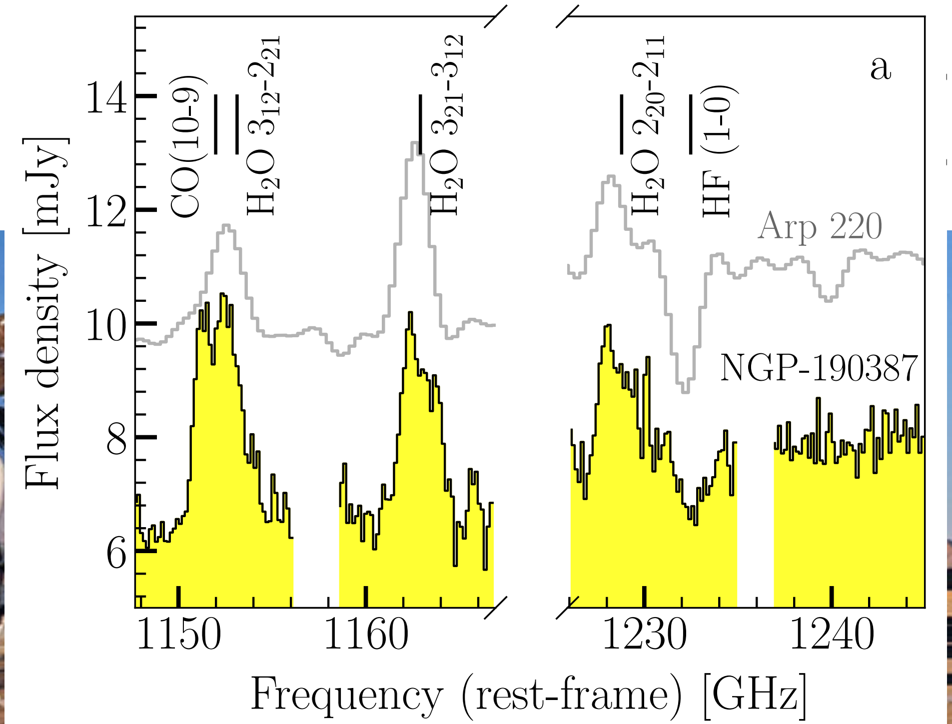
The ramp-up of interstellar medium ^ enrichment at z > 4 (z=4.420)

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]

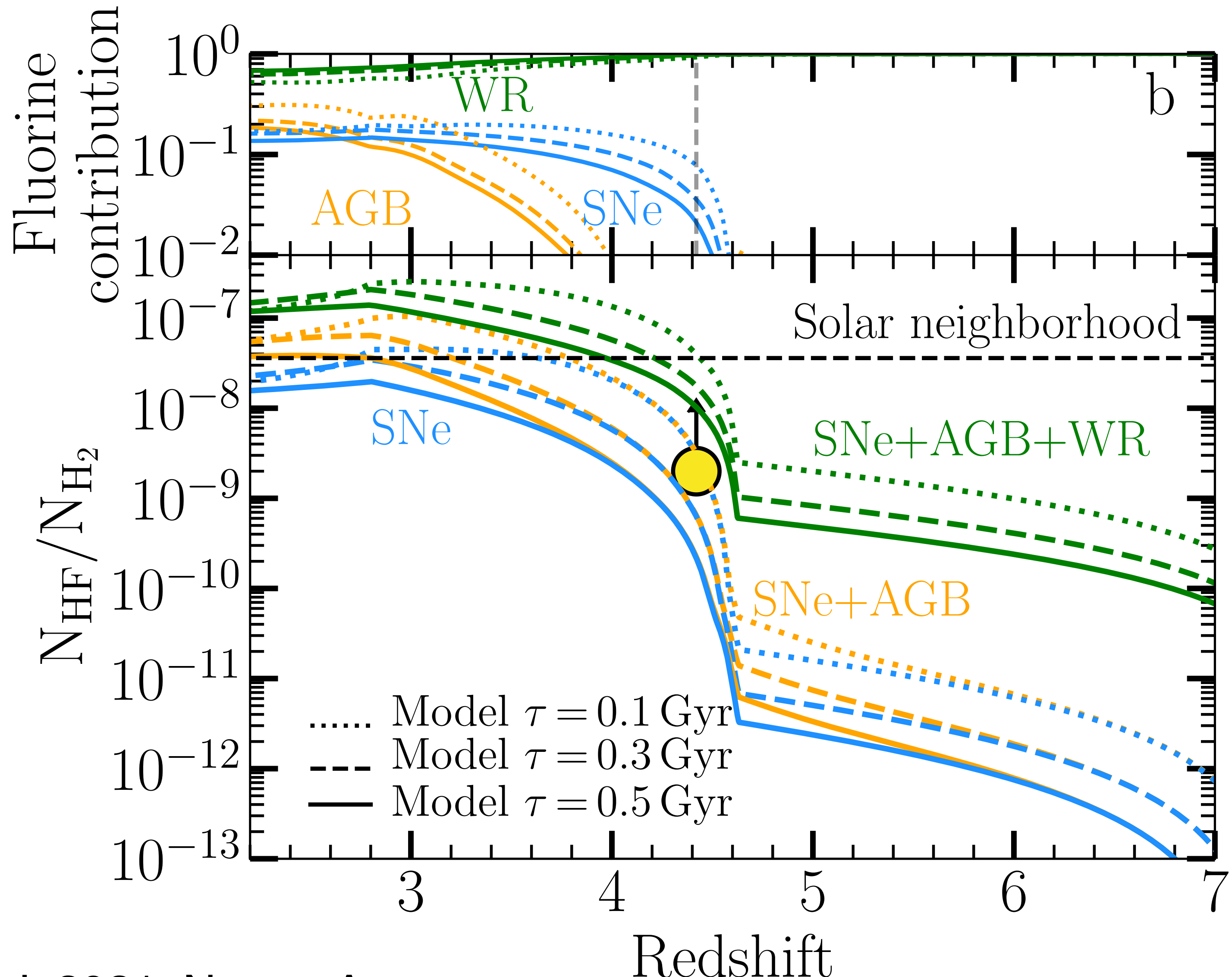
- Lensed dusty star-forming galaxy **NGP-190387** at z = 4.420
- $N(H_2)=2.1\pm0.4\ 10^{24}$ cm^2 (from [C I])
- $H_2 + F \rightarrow H + HF$ (stable, dominant)





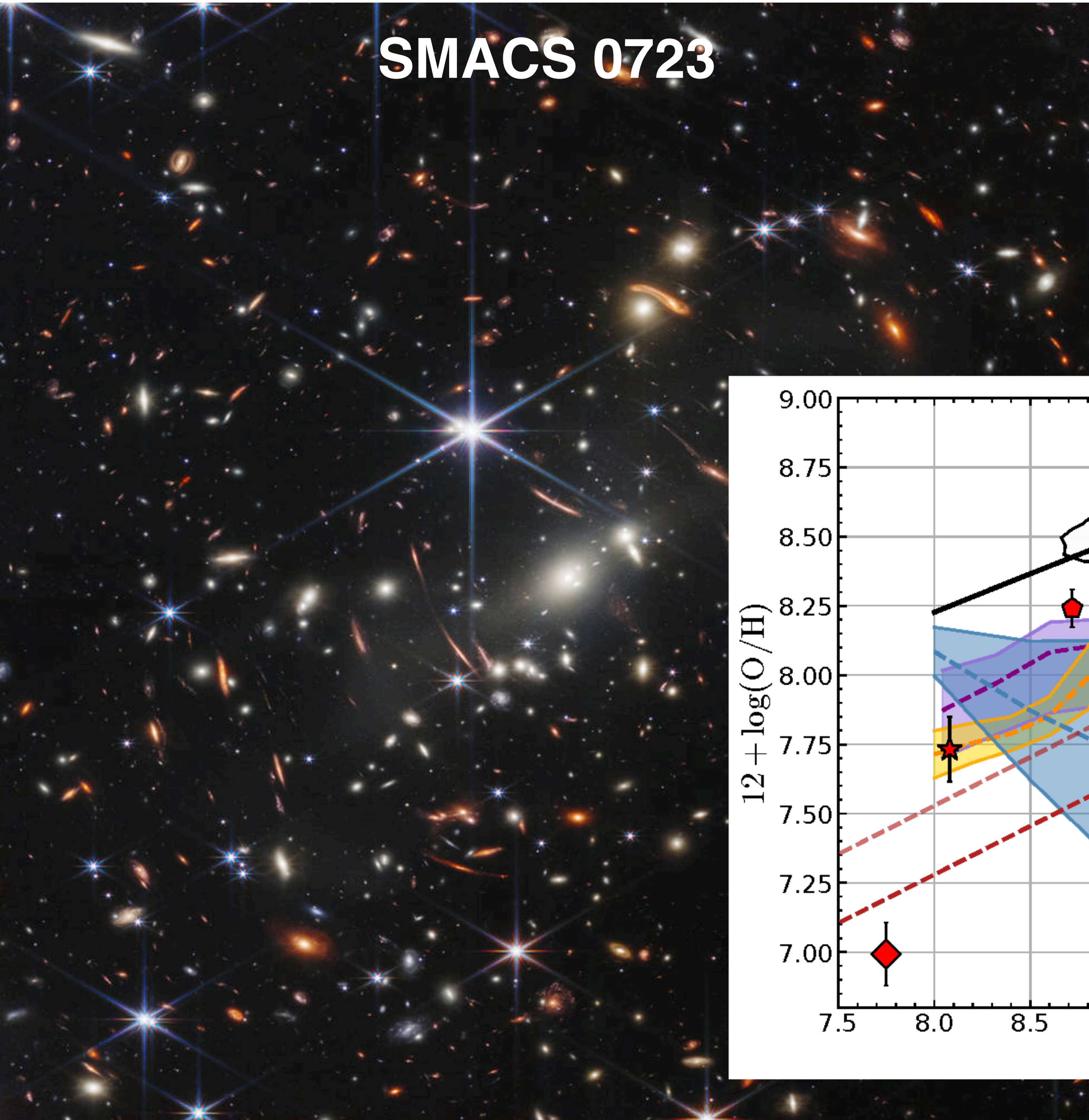
Rapid enrichment by Wolf-Rayet stars

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

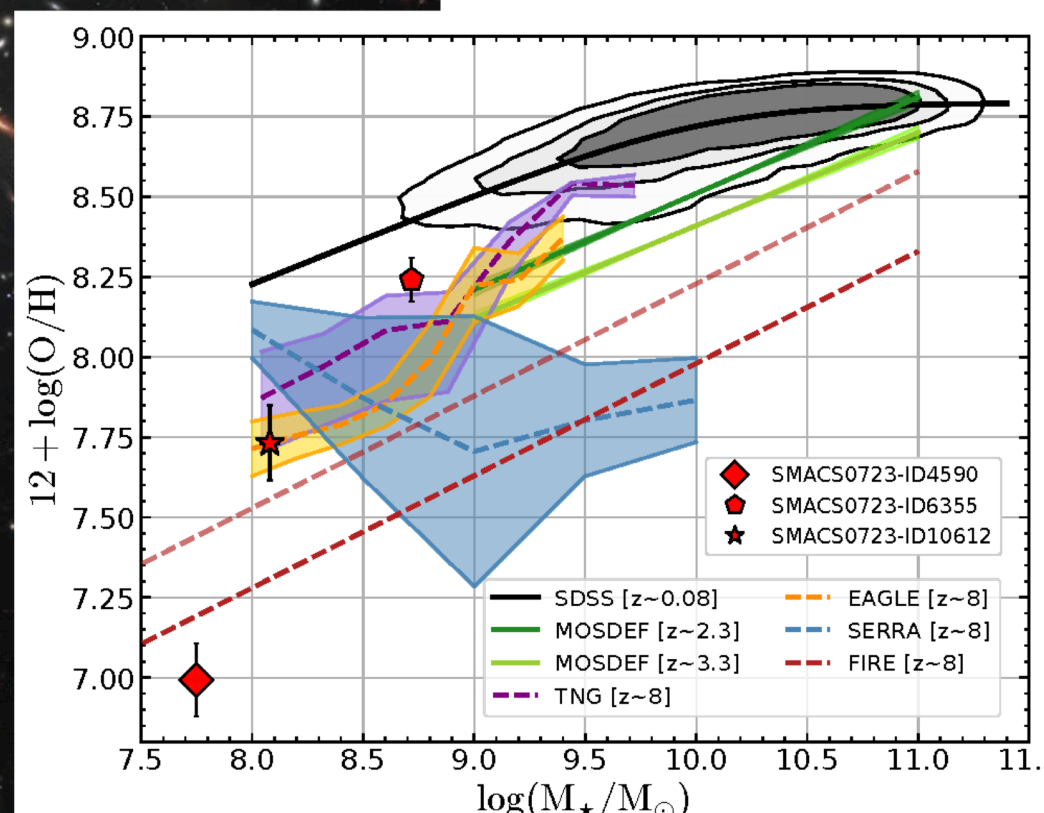


Franco et al. 2021, Nature Astronomy

Mass Metallicity Relation @ z~8



JWST/NIRSpec:
Curti+22,
also Brinchmann 22,
Stiavelli's talk



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). Fluorine (F) may be enhanced by rotating massive stars ($>20M_\odot$).

- **Galactic archaeology** – Map of elements in the Milky Way is being observed, and well reproduced with **chemodynamical simulations** that includes inhomogeneous enrichment, gas flows, stellar migration.

- **Extra-galactic archaeology** – Elemental abundances can also be measured in distant galaxies with JWST & ALMA, comparable to cosmological simulations with AGN feedback.

- By reproducing observed chemical evolution, cosmological chemodynamical simulations can provide robust predictions of **gravitational wave events** (e.g., WD-WD, NS, SMBH mergers).