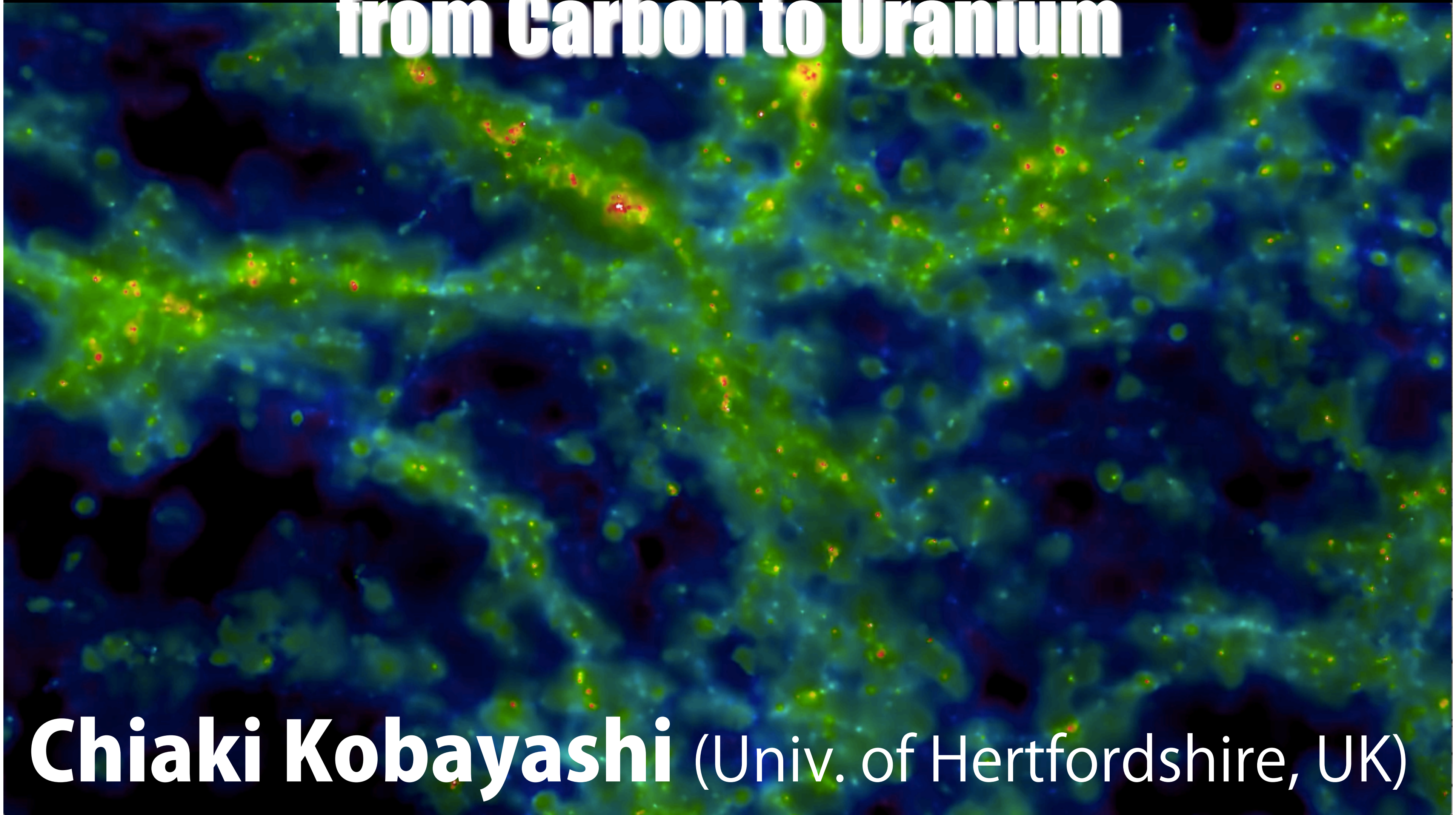
Galactic and cosmic chemical evolution from Carbon to Uranium



Chiaki Kobayashi (Univ. of Hertfordshire, UK)

Central massive galaxy in 25Mpc^3, from z=5 to 0, [O/H] = –5 (blue) to -1 (red); > -1 (white)

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

Models for r-process(es)

- **(1) Galactic Chemical Evolution (GCE)**
  - Mennekens & Vanbeveren 14, with binaries
  - Ishimaru+ 15 (subhalos, only NSM ok)
  - Côté+ 18
  - Kobayashi, Karakas, Lugaro 18
- **(2) Stochastic Chemical Evolution Model**
  - Ishimaru & Wanajo 99 (either 8-10 or >30$M_\odot$ SN)
  - Argast+ 04
  - Cescutti+ 15
  - Wehmeyer+ 15
- Post-processing Chemical Enrichment does not work
- **(3) Chemo-hydrodynamical Simulation (SPH)**
  - van de Voort+ 15
  - Hirai+ 15, 17, isolated dwarf galaxies
  - Haynes & Kobayashi 18, arXiv1809.10991

Galactic Chemical Evolution (GCE)

(1) One-zone model (instantaneous mixing): Tinsley 80, Timmes+ 95, Pagel 97, Matteucci 01, Prantzos+ 93, Chiappini+ 97, CK+ 00,06,11,… Vincenzo+14, Cote+

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

Metal ejection rates
- **nucleosynthesis yields**
- initial mass function (IMF)
- SNIa progenitor model
- 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,…

→ **inhomogeneous enrichment**

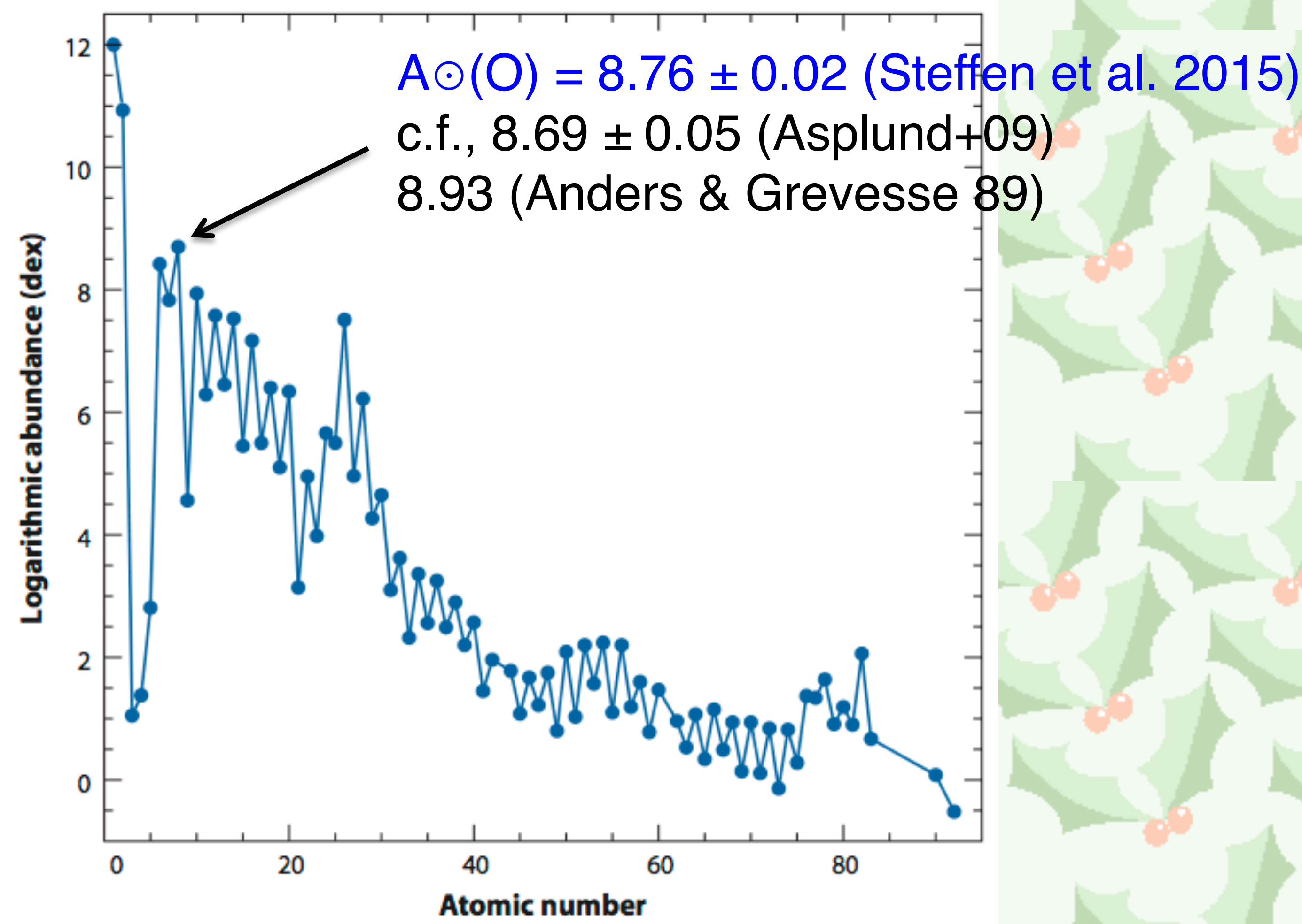
(2) Stochastic model
; Ishimaru+99; Argast+02; Cescutti+08; Wehmeyer+15

KKL18 GCE Model

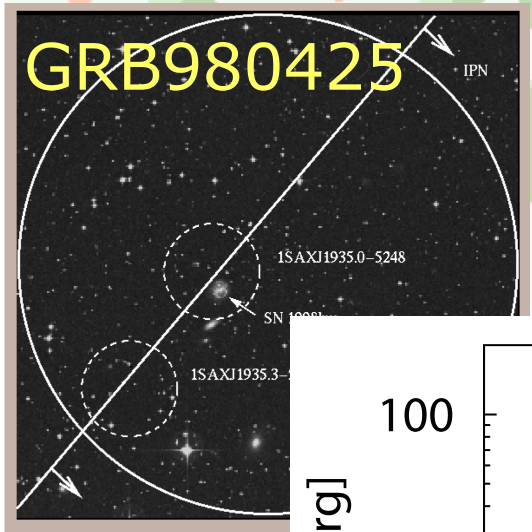
Nuclei in the Cosmos XIII conference, Debrecen, Hungary, Jul 2014

The Solar Abundance

- Photosphere values from Asplund+ 09, except for O (AG89 was used in K06,K11). This is a matter only when we compare with observations.

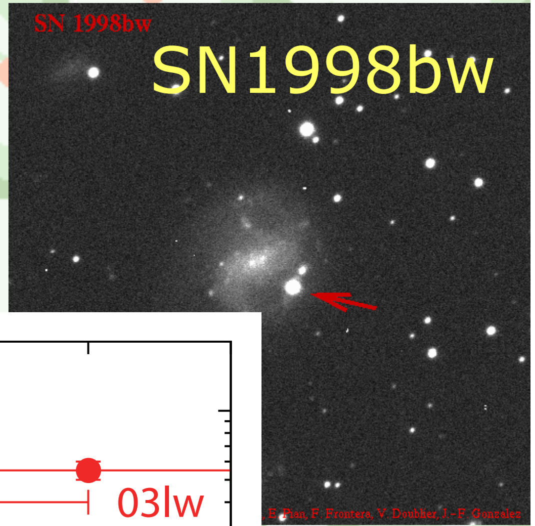


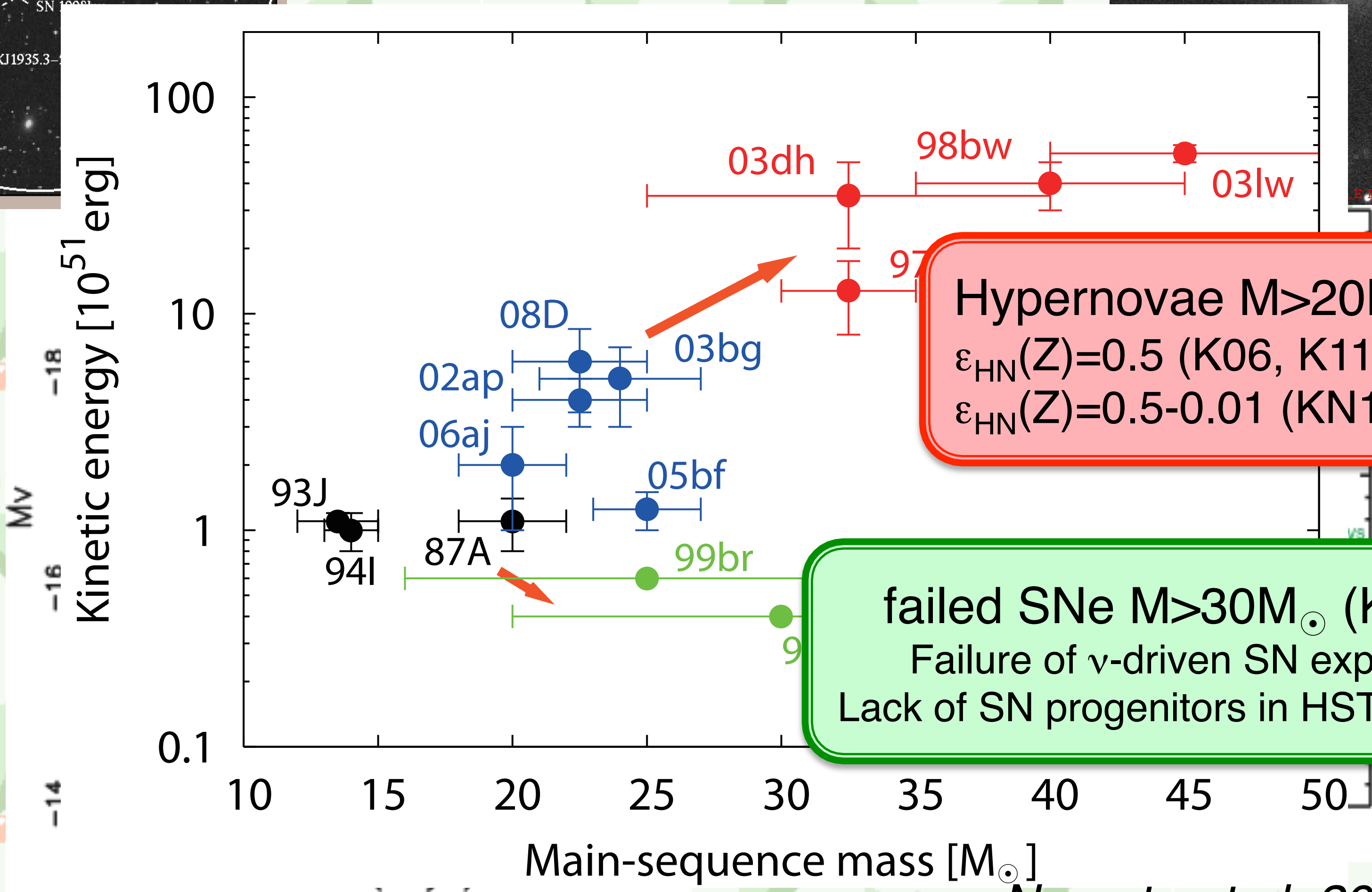
Hypernovae



- SN light curves & spectra fitting

→ M, E_{kin}, M(Fe)





Hypernovae M>20$M_\odot$

ε_{HN}(Z)=0.5 (K06, K11)

ε_{HN}(Z)=0.5-0.01 (KN11,KKL18)

failed SNe M>30$M_\odot$ (KKL18)

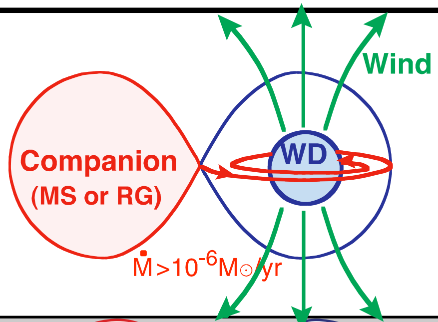
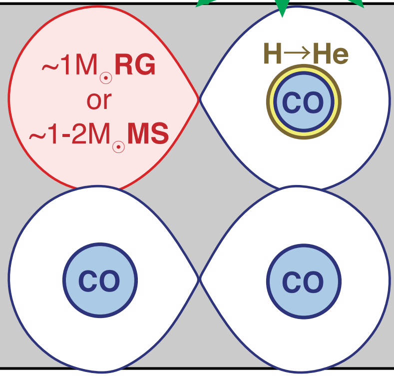
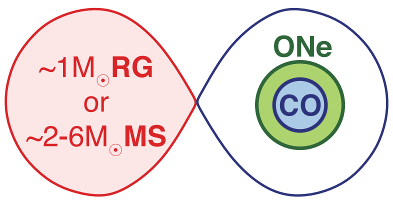
Failure of ν-driven SN explosions

Lack of SN progenitors in HST pre-image

Nomoto et al. 2002, 2013

Type Ia Supernovae

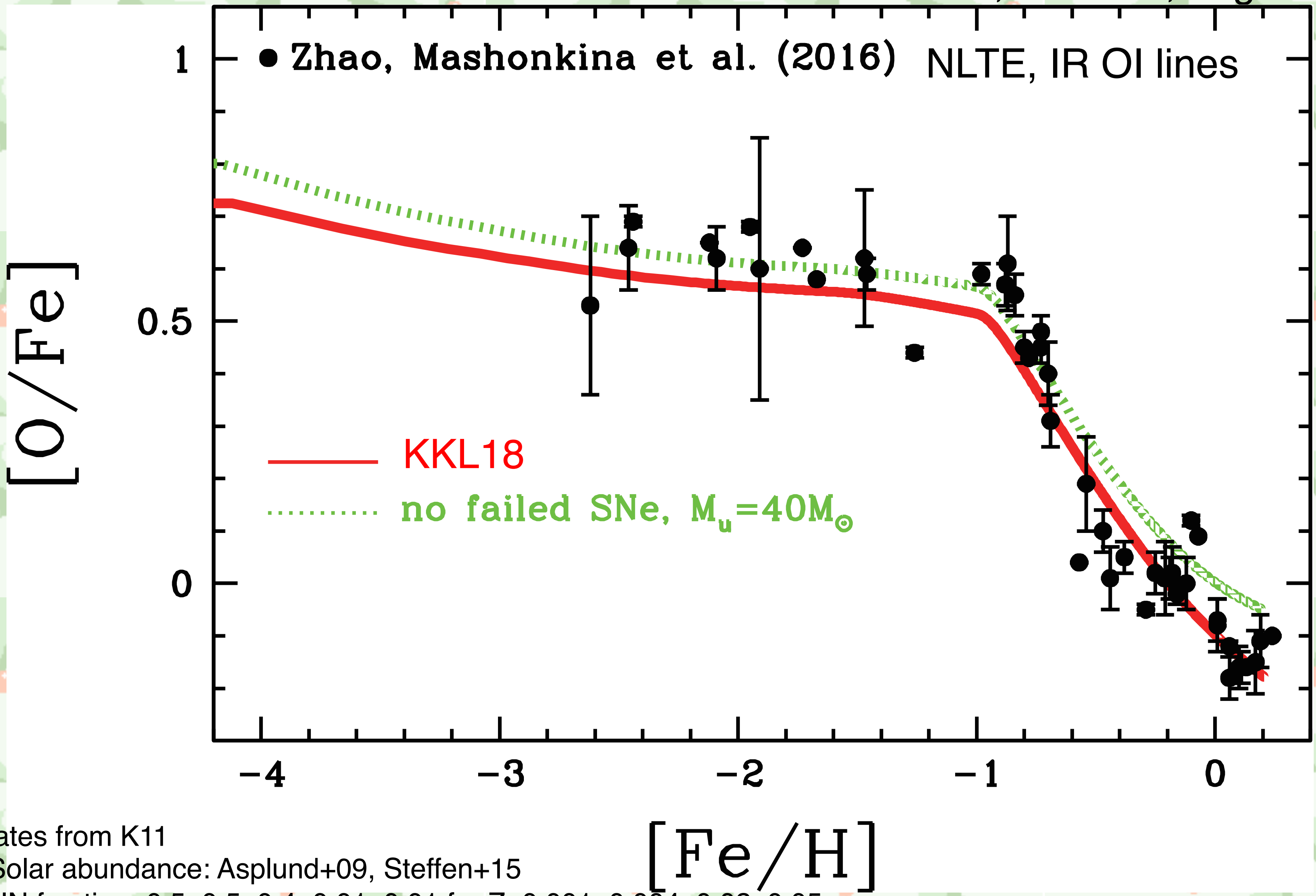
CK, Nomoto, Hachisu 2015, ApJL, 804, 24

Progenitor System	Progenitor	Explosion	Yields
	Ch mass (Nomoto 82; Röpke 04; CK & Nomoto 09)	deflagration or delayed detonation (Leung & Nomoto 18)	M(Fe)=0.7$M_\odot$ high [Mn/Fe]
	sub-Ch mass (Pakmor+12; Ruiter+14, Shen +18)	double detonation	M(Fe)~0.6$M_\odot$ low [Mn/Fe]
	Ch mass (Foley+13; McCully+14; Kromer+15)	deflagration	M(Fe)~0.2$M_\odot$ high [Mn/Fe]

N.B. Very simplified.

New GCE model

CK, Karakas, Lugaro 18

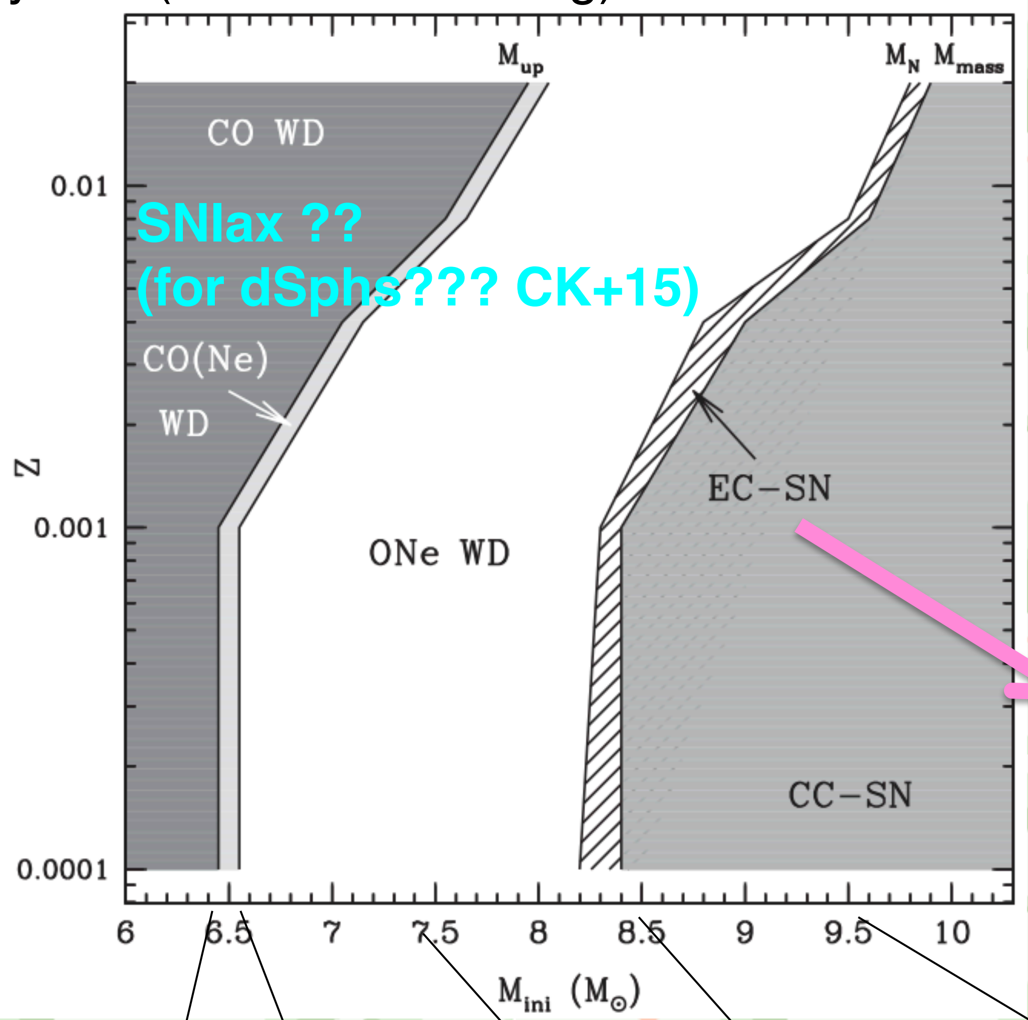


Updates from K11

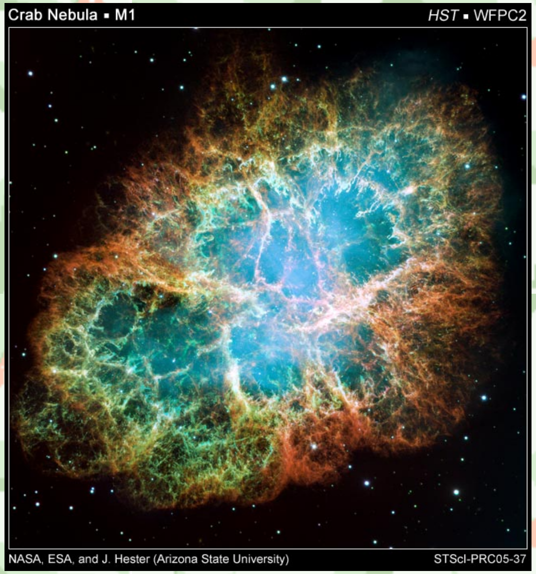
- Solar abundance: Asplund+09, Steffen+15
- HN fraction=0.5, 0.5, 0.4, 0.01, 0.01 for Z=0.001, 0.004, 0.02, 0.05
- SNIa yields: Z-dependent, 2D delayed detonation

Super AGB

Doherty +15 (before Ne burning)



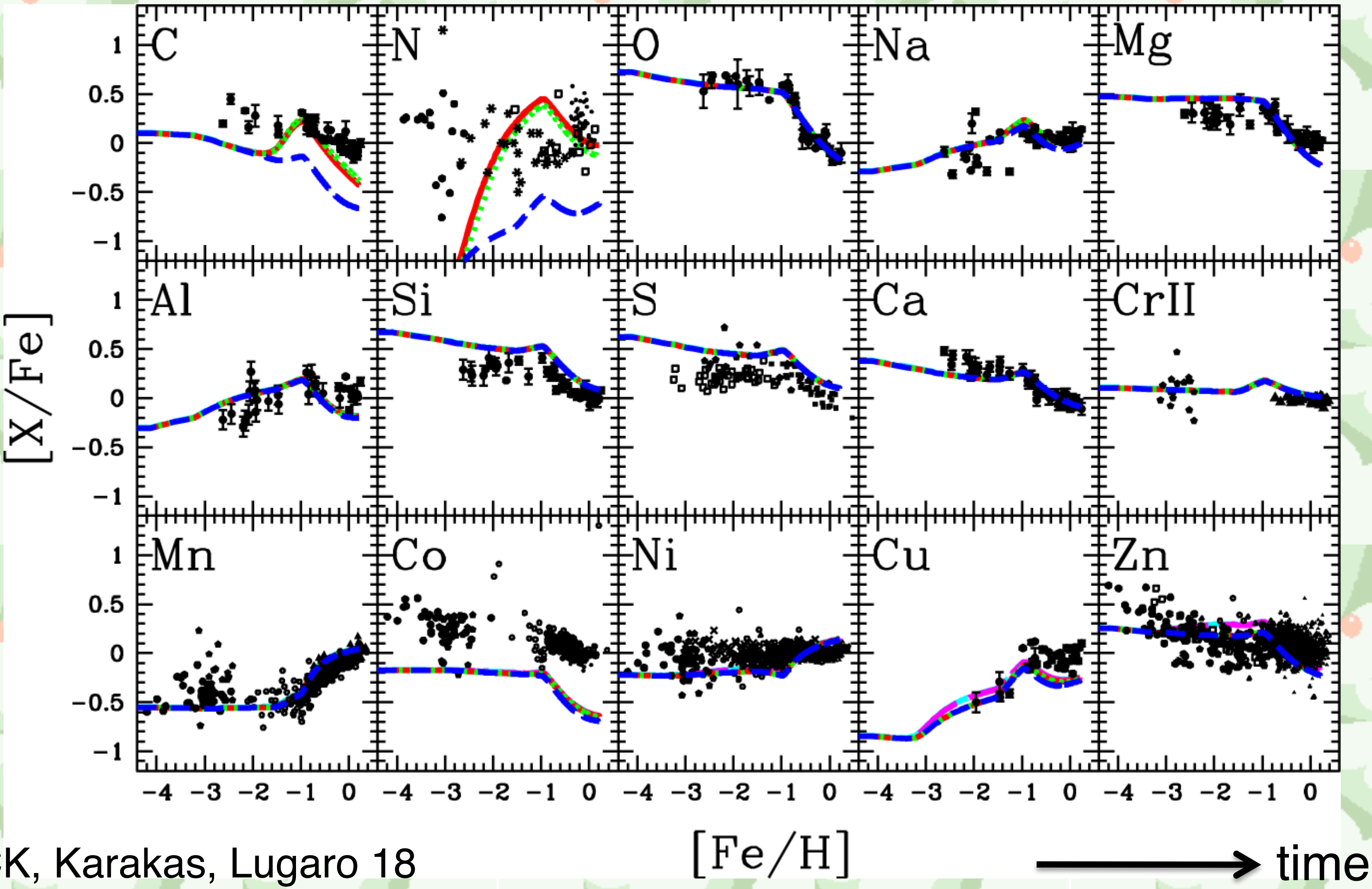
- But, highly depends on overshoot, mass-loss, reaction rates, & binary. URCA?
- In GCE, these event rates can vary x1.5



Karakas 10   Fink+14   Doherty+14   Wanajo+11   CK+06(=N06),11(=NKT13)

Super AGB

SN+HN+SNIa(Z), AGB, SAGB, ECSN, lax



CK, Karakas, Lugaro 18

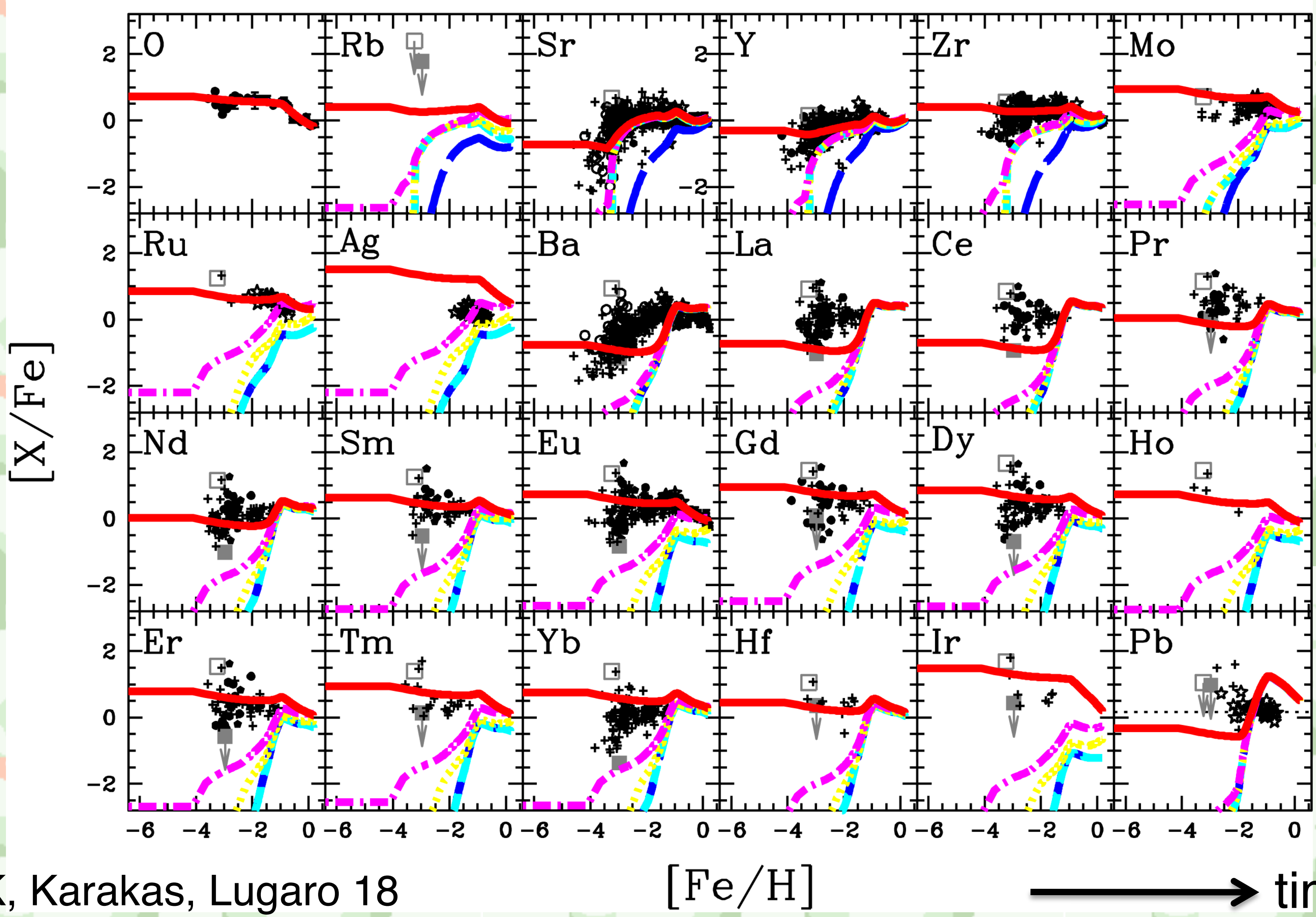
Neutron-capture processes

- s-process in AGB
- Electron-capture supernova (ECSN)
- ν-driven wiands from proto NS (p-rich)
- Neutron Star Merger (NSM), dynamical ejecta (<1%) +post-merger disk winds
  - GW170817, GRB 170817A, AT 2017gfo in NGC 4993
- Magneto-rotational supernova (MRSN)
  - preferred in PCA analysis (Ting, Freeman, CK+ 12)

- Karakas & Lugaro 16
- Wanajo+11, 8.8$M_\odot$ 2D sim. (Janka+08), but see Pllumbi+15
- Wanajo 13, 1.4-2.0$M_\odot$ semi-analytic, but see Arcones & Montes 11, 1D sim.
- Wanajo+14, 1.3+1.3$M_\odot$, 3D GR sim. (Sekiguchi+14); **delay-time from binary pop. synthesis** (Mennekens & Vanbeveren 16)
- Nishimura+15, 25$M_\odot$, 10^{11}G, SR MHD sim. (Takiwaki+09); ~1% of ≥25$M_\odot$, but see Winteler +12; Mösta+14 for 3D.

n-capture processes

s-process, ECSN, ν-winds, NS+NS&NS+BHM, MRSN

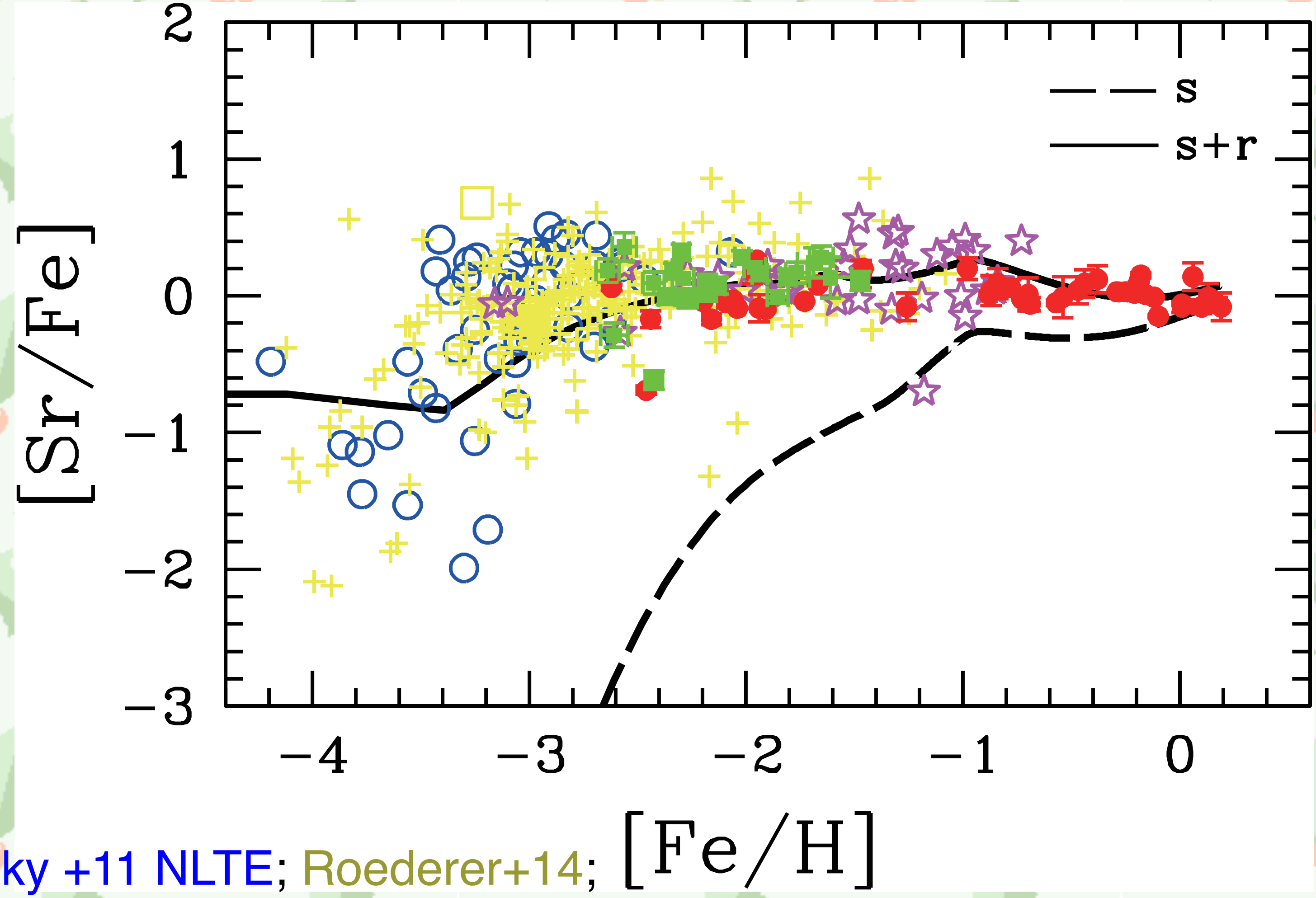


CK, Karakas, Lugaro 18

time

[(Sr,Y,Zr)/Fe]-[Fe/H]

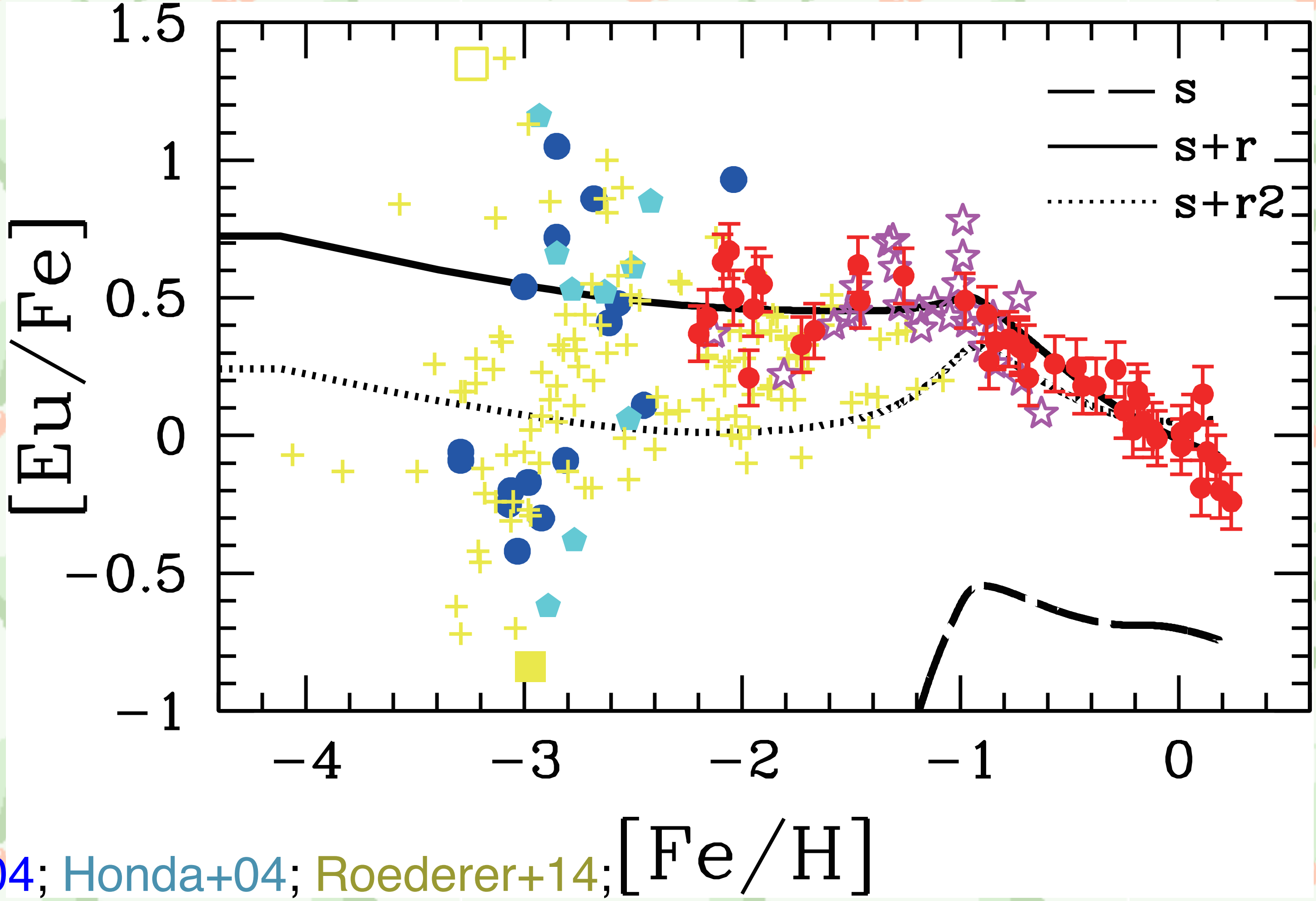
r: ECSN + NSM*(0.5-1) + MRSN (1-3% of HN)
No additional LEPP required! (no fine tuning)



Andrievsky +11 NLTE; Roederer+14;
Zhao+16 NLTE; Hansen+16; Reggiani+17

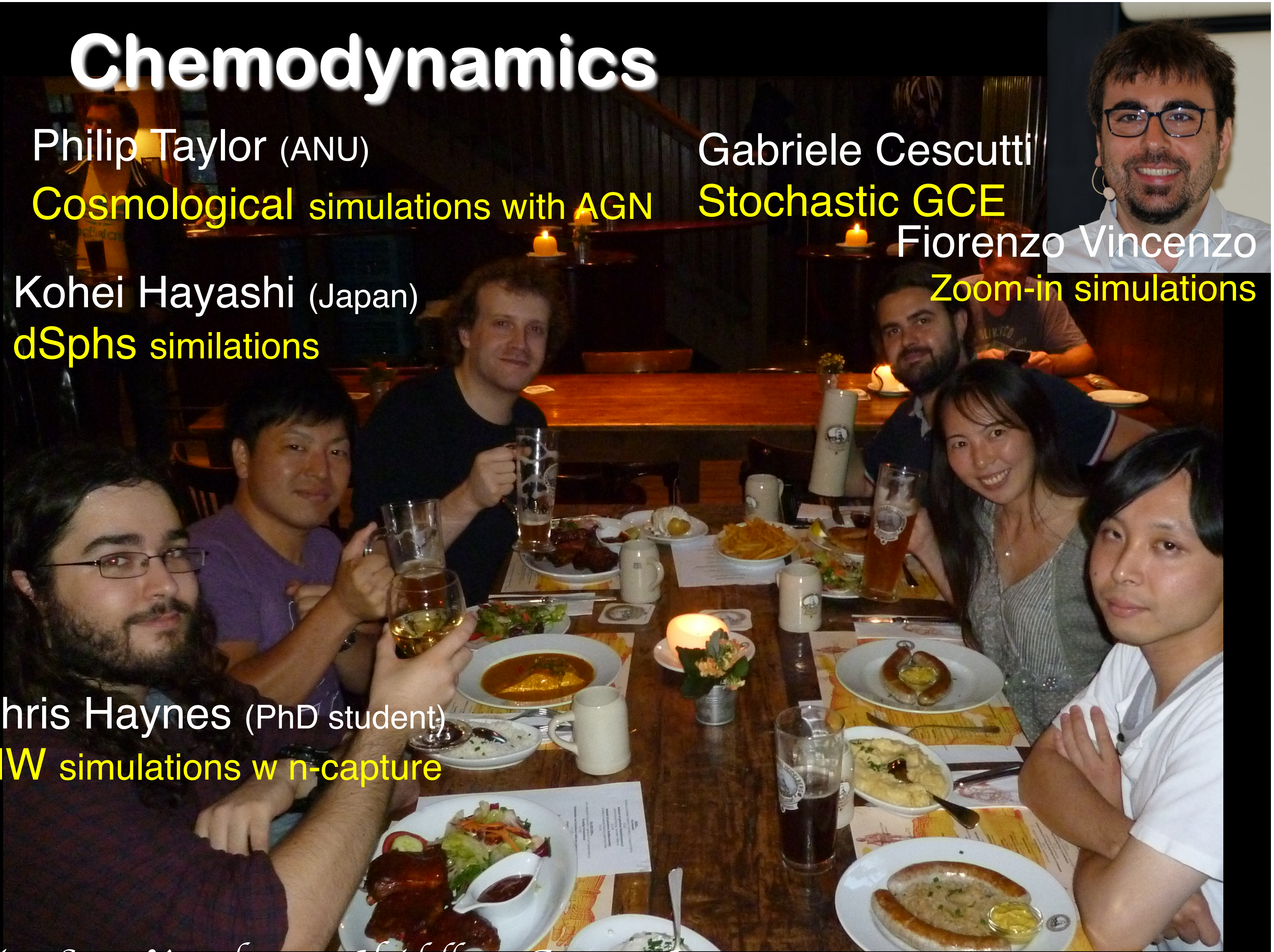
[Eu/Fe]-[Fe/H]

r: ECSN + NSM*0.5 + MRSN (3% of HN)
r2: ECSN + NSM + MRSN (1% of HN)



Cayrel+04; Honda+04; Roederer+14;
Zhao+16 NLTE; Hansen+16

Chemodynamics



Philip Taylor (ANU)
Cosmological simulations with AGN

Gabriele Cescutti
Stochastic GCE

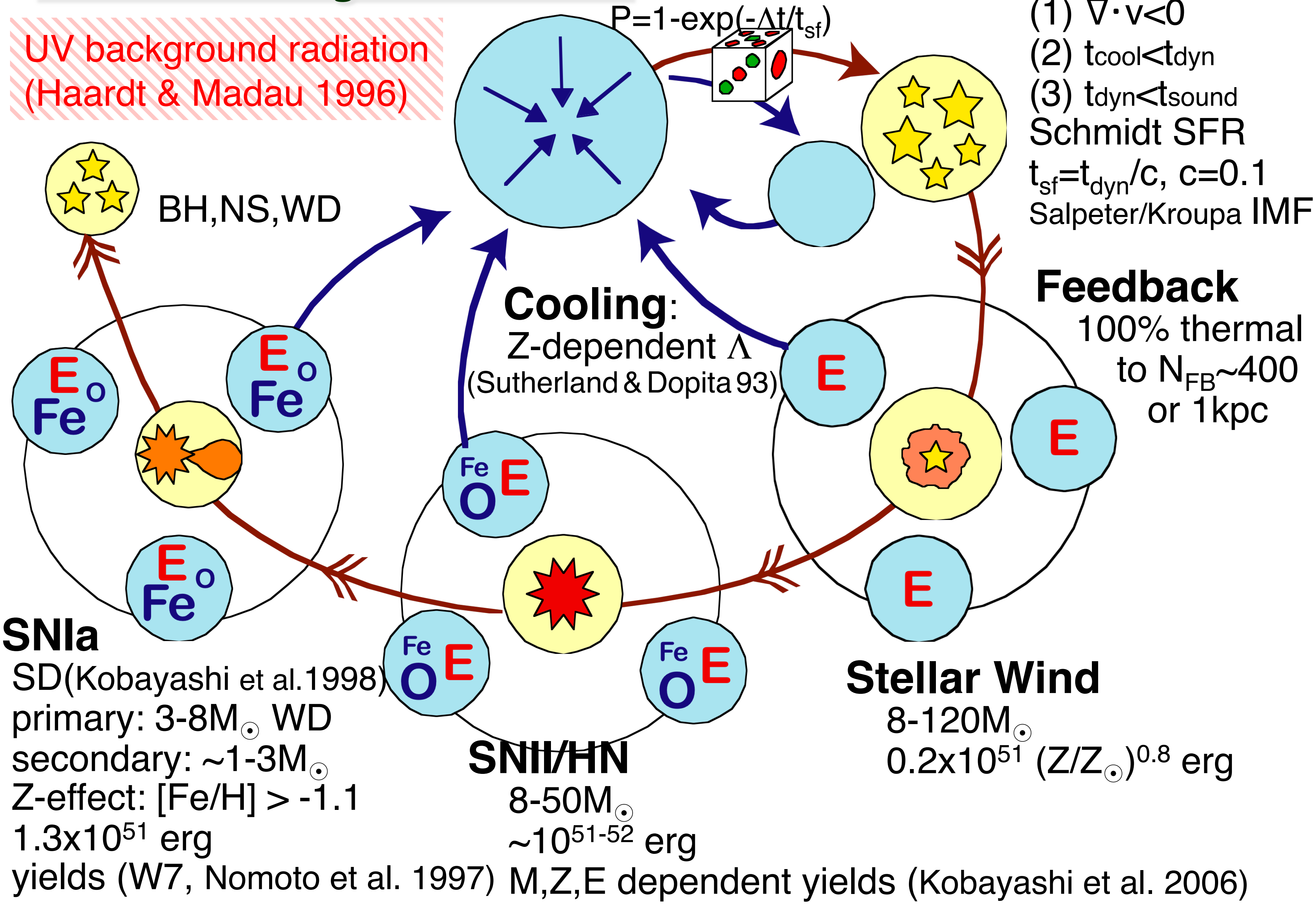
Fiorenzo Vincenzo
Zoom-in simulations

Kohei Hayashi (Japan)
dSphs similations

Chris Haynes (PhD student)
MW simulations w n-capture

First Stars V conference, Heidelberg, Aug 2016

Chemodynamics

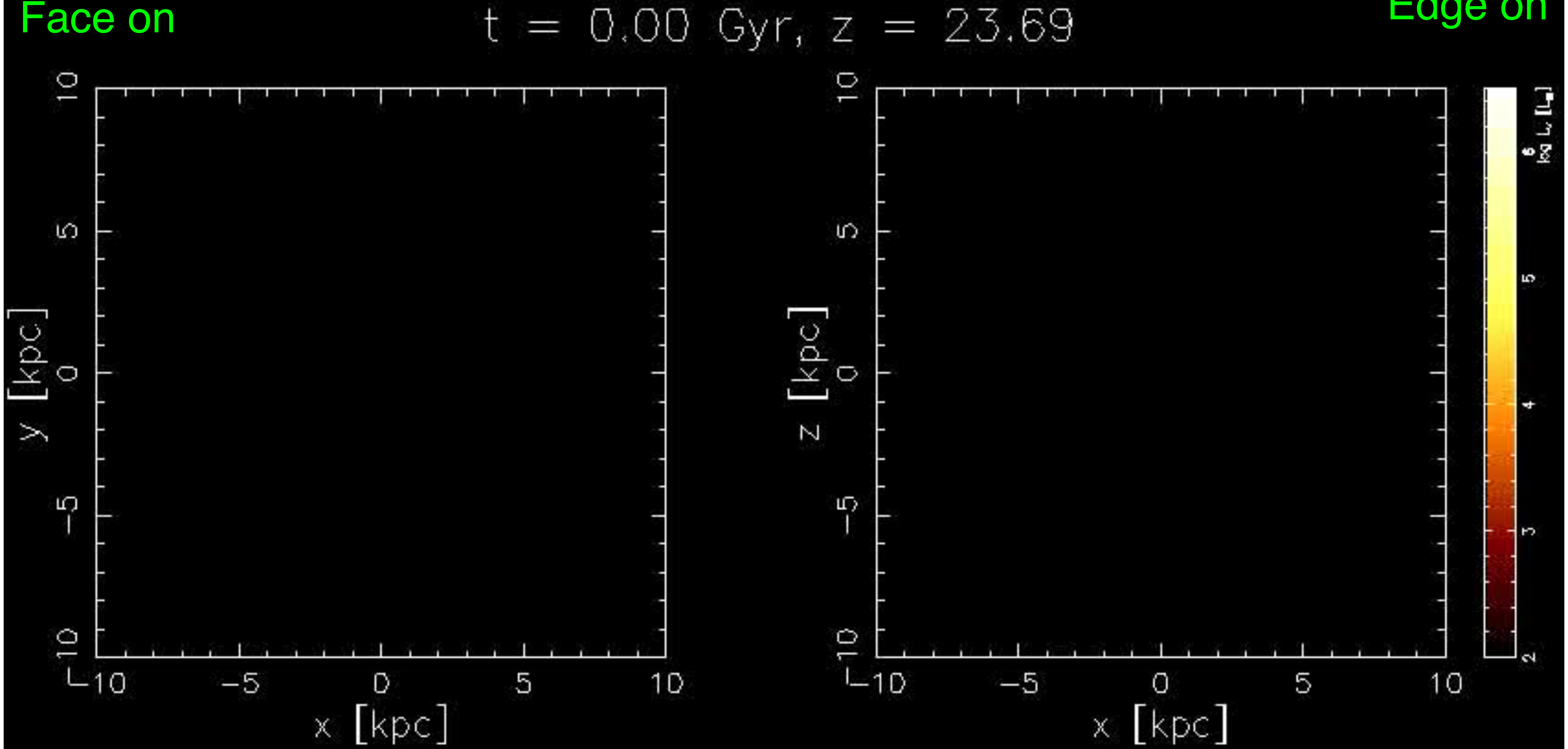


Milky Way-type galaxy

Initial Condition: λCDM fluctuated sphere with λ~0.1, r~3Mpc,
M_{tot}~10^{12} $M_\odot$, N_{tot}~120.000, M_{gas}~10^6 $M_\odot$, M_{DM}~10^7 $M_\odot$
(CK & Nakasato 2011, *ApJ, 729, 16*)

Face on

Edge on



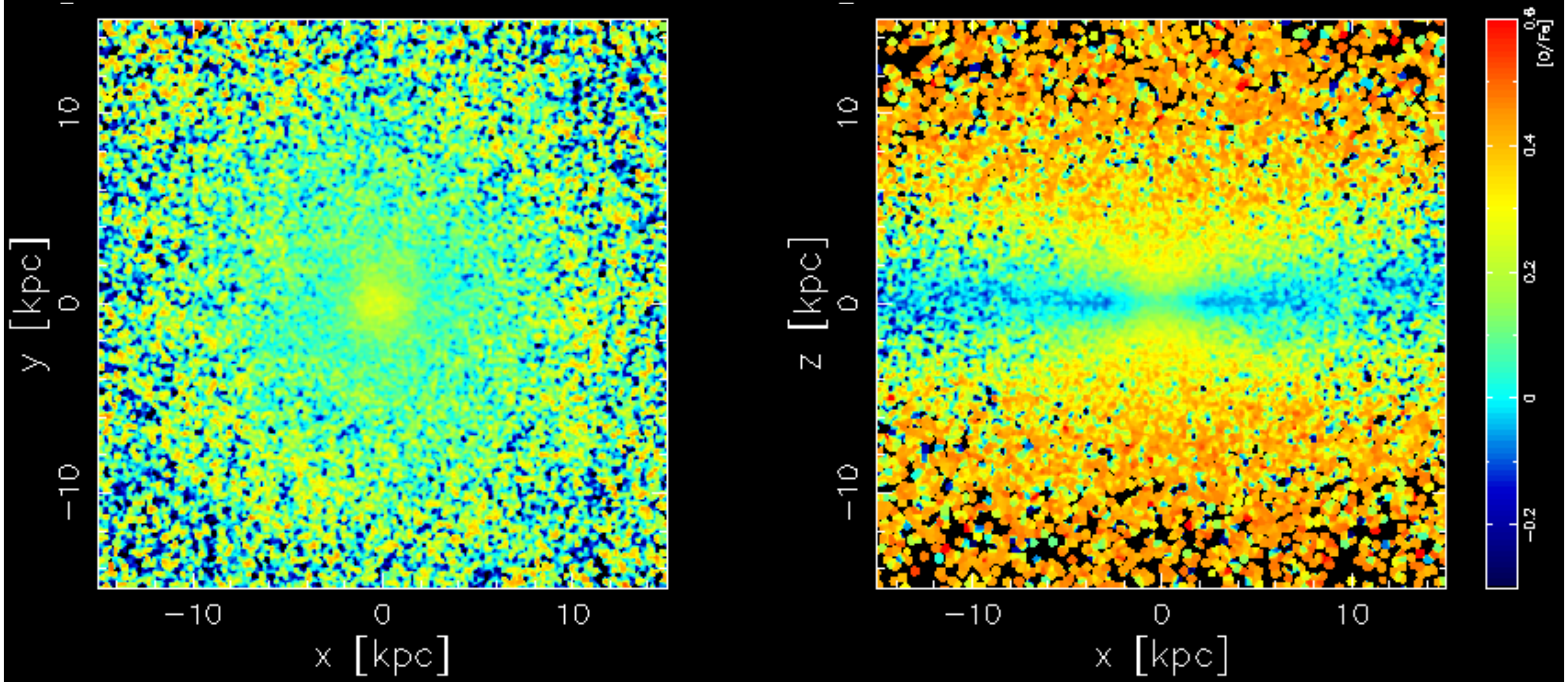
Similar results obtained also with Aquarius Initial Condition (CK 2015).

Milky Way simulation

- CK & Nakasato 2011: GRAPE-SPH, m_{gas}~10^6 $M_{\odot}$, 400 CPU hrs
- CK 2015, HK18:, Gadget-3, Aquarius IC, $3x10^5$ $M_{\odot}$, 1M CPU hrs

Face on

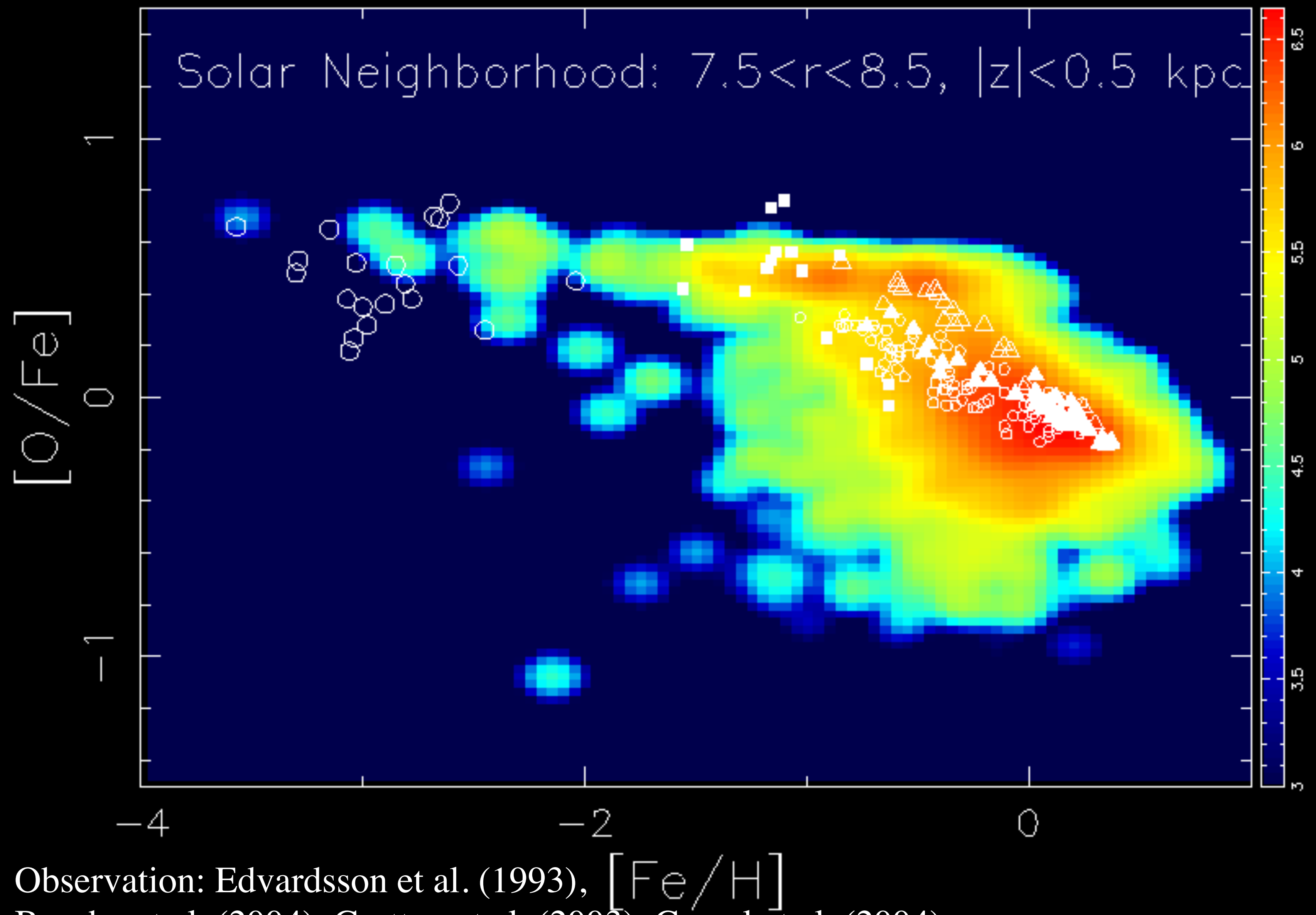
Edge on



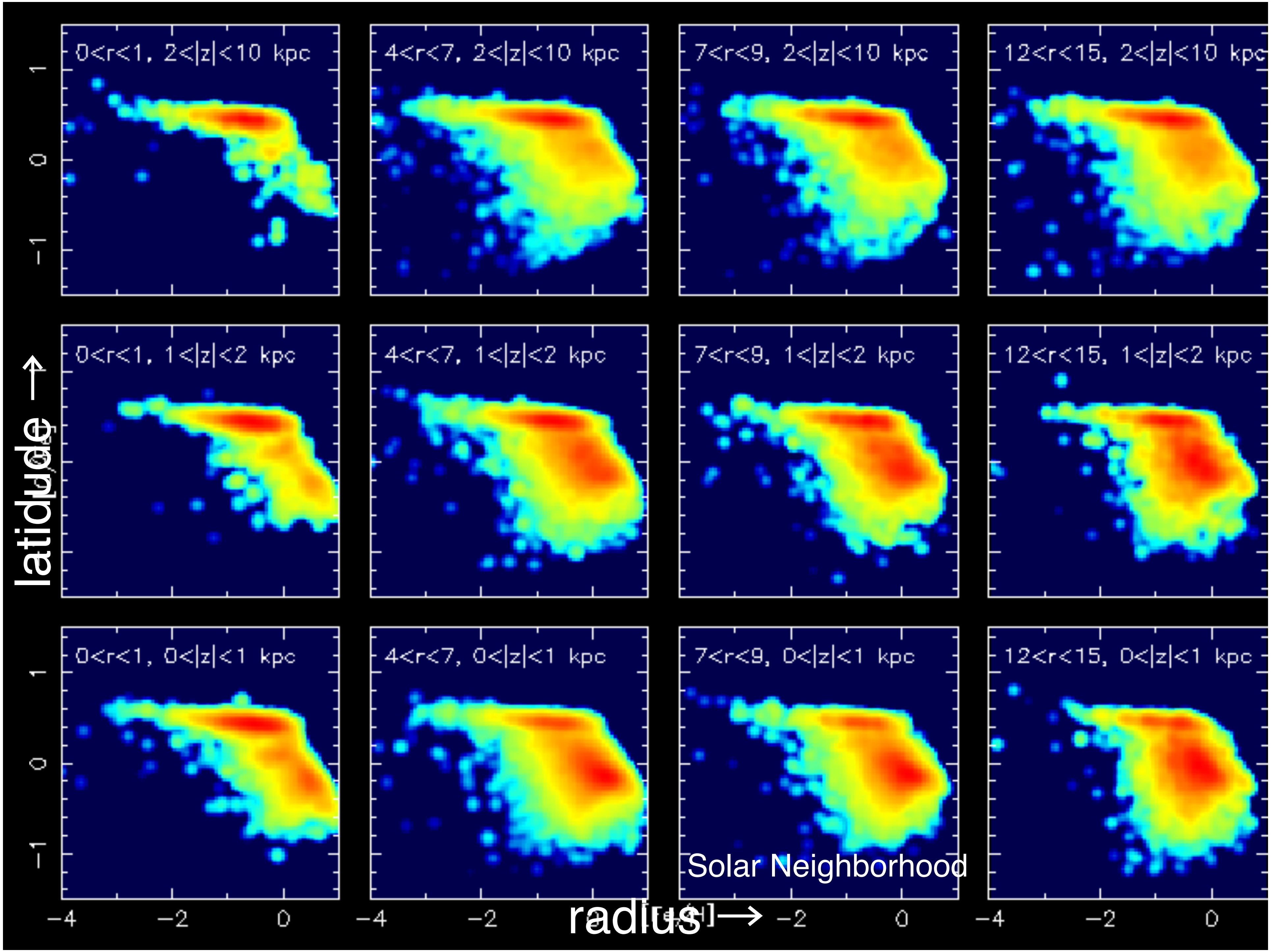
Similar to GA survey maps, e.g., APOGEE

[O/Fe]-[Fe/H] bimodarity

Kobayashi & Nakasato 2011, GRAPE-SPH



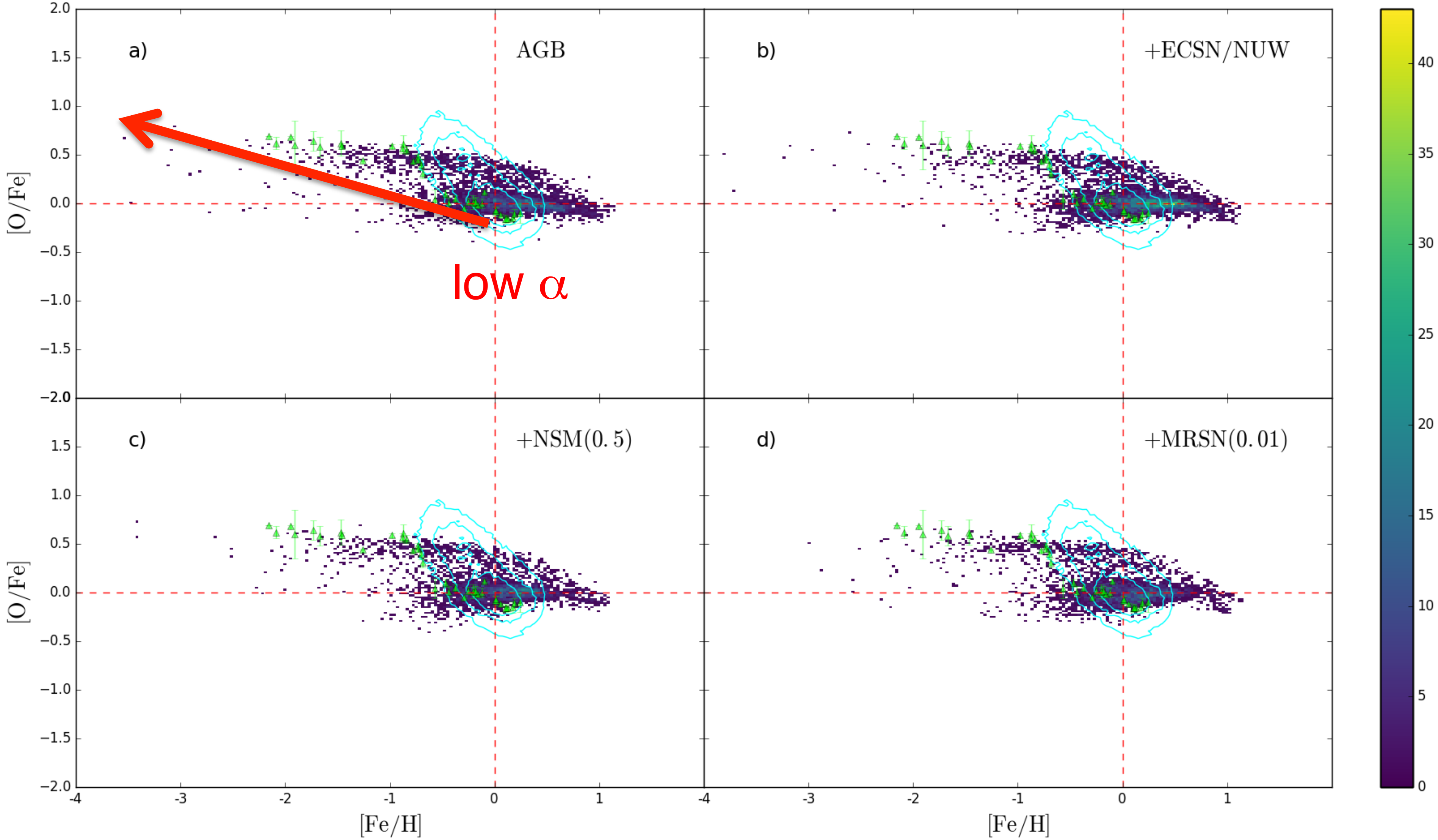
Observation: Edvardsson et al. (1993), Bensby et al. (2004), Gratton et al. (2003), Cayrel et al. (2004)



0<r<1, 2<|z|<10 kpc
4<r<7, 2<|z|<10 kpc
7<r<9, 2<|z|<10 kpc
12<r<15, 2<|z|<10 kpc
0<r<1, 1<|z|<2 kpc
4<r<7, 1<|z|<2 kpc
7<r<9, 1<|z|<2 kpc
12<r<15, 1<|z|<2 kpc
0<r<1, 0<|z|<1 kpc
4<r<7, 0<|z|<1 kpc
7<r<9, 0<|z|<1 kpc
12<r<15, 0<|z|<1 kpc
latidude →
Solar Neighborhood
radius →

[O/Fe]-[Fe/H]

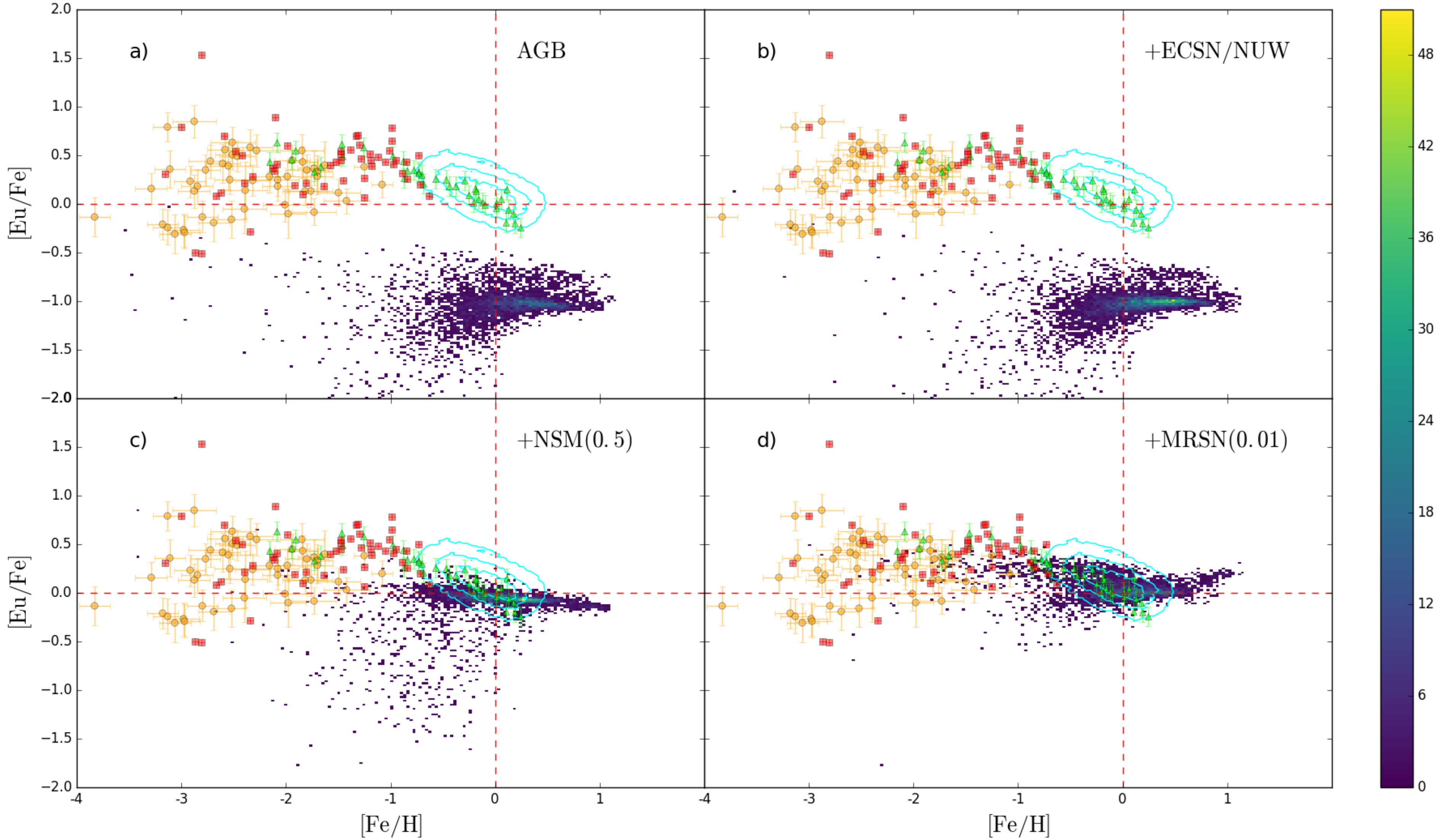
Chris Haynes & CK 2018, 2019



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

[Eu/Fe]-[Fe/H]

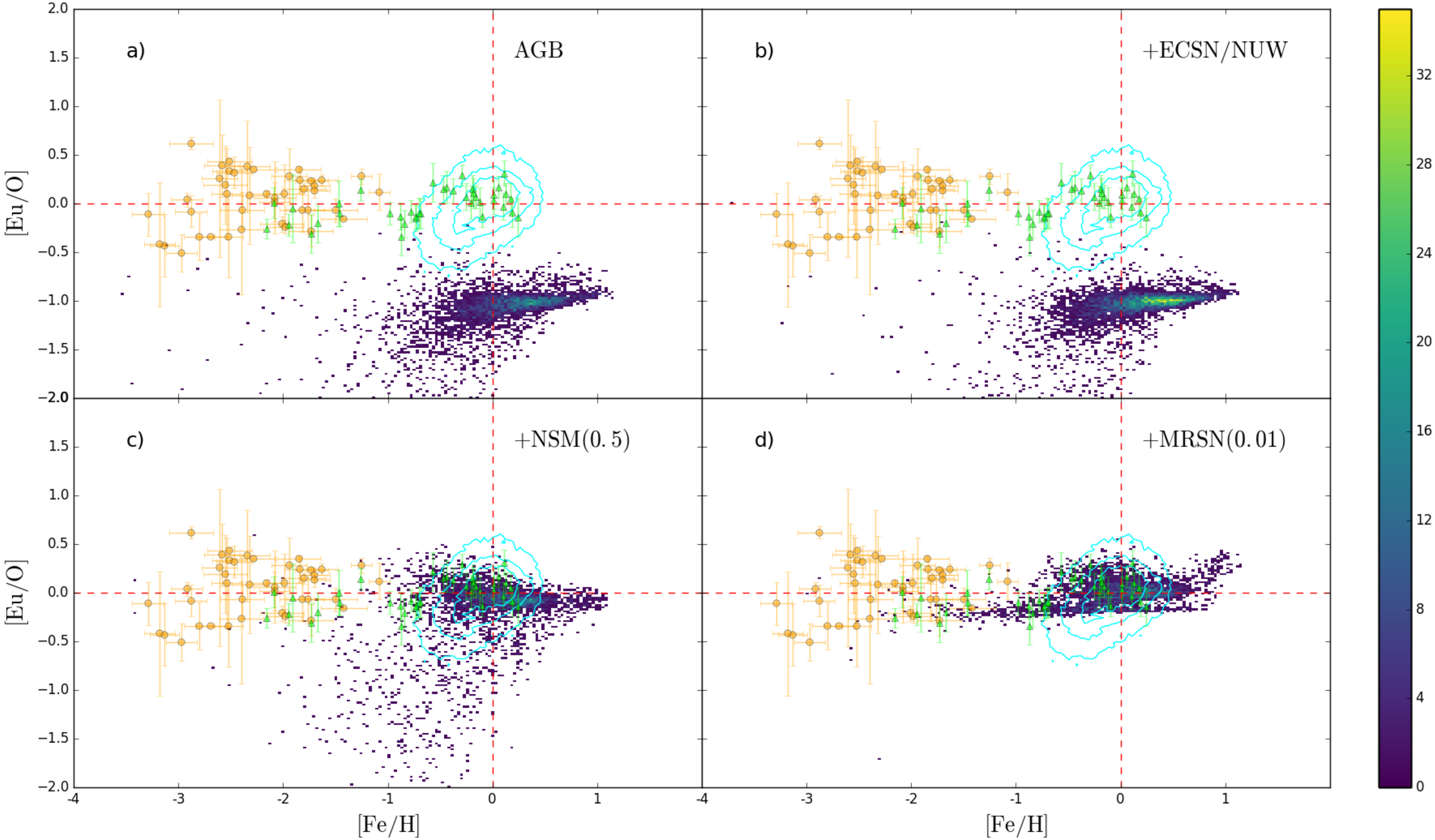
Chris Haynes & CK 2018



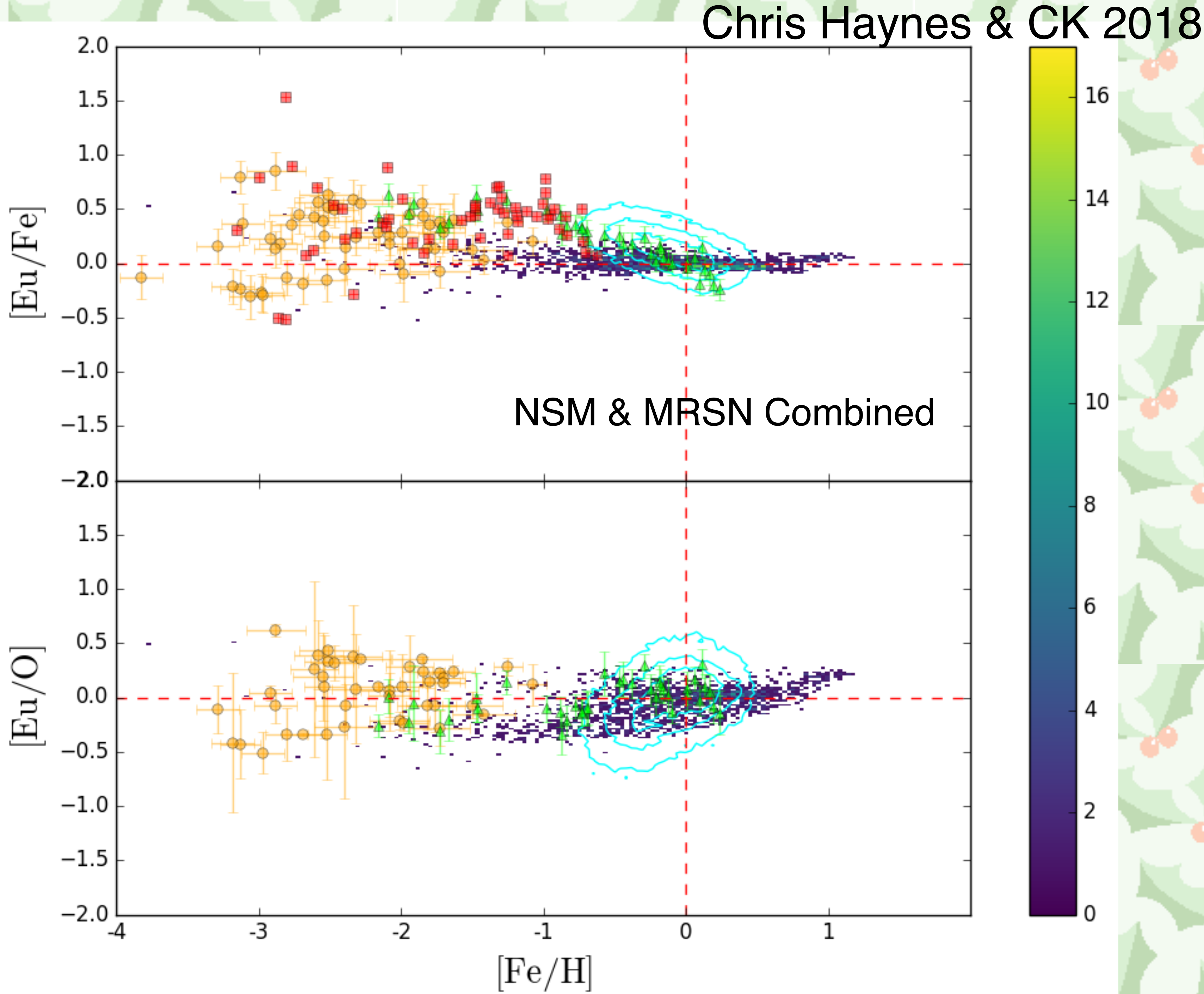
Hansen+17; Roederer+16; NLTE Zhao+16; HERMES-GALAH

[Eu/O]-[Fe/H]

Chris Haynes & CK 2018

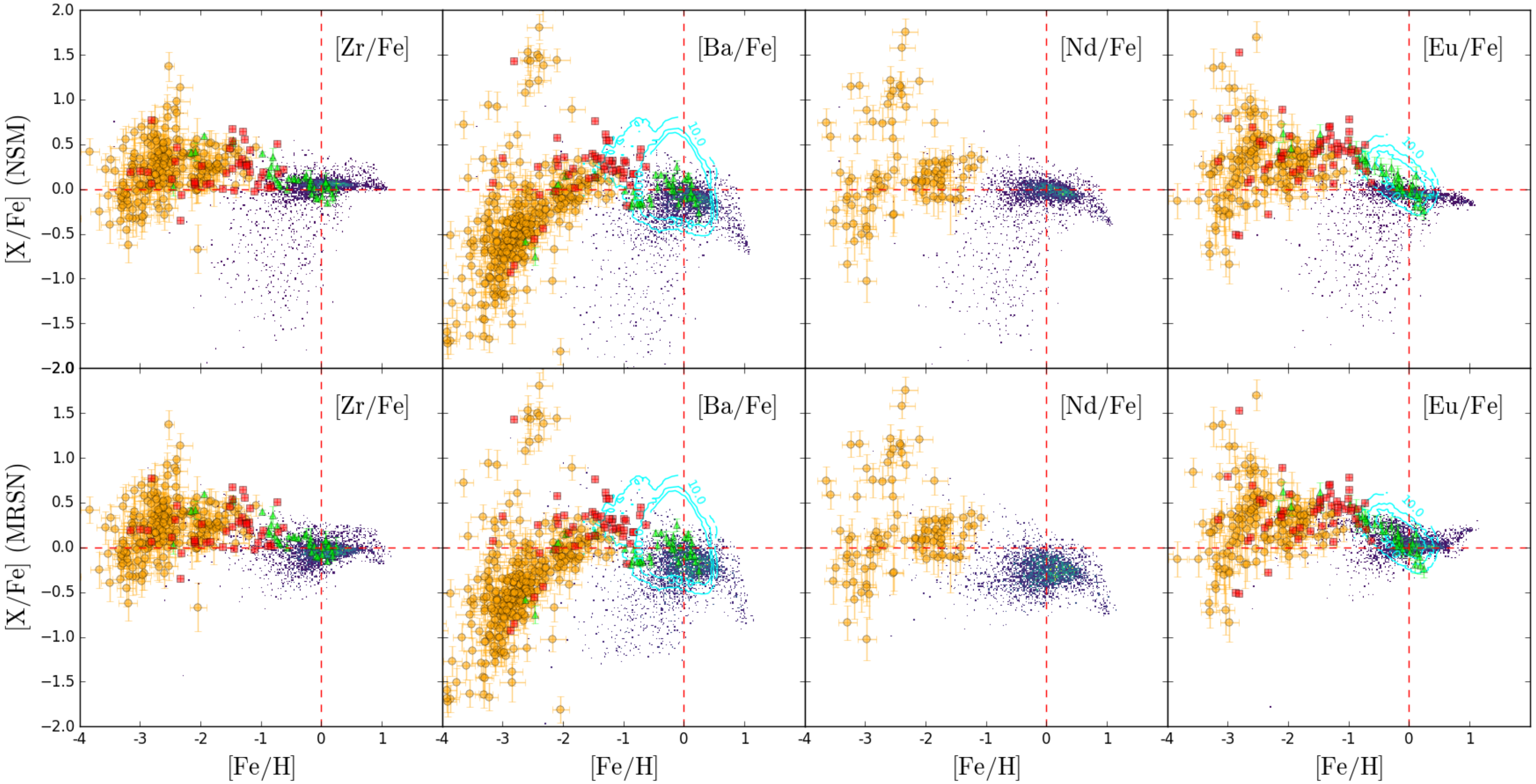


Hansen+17; Roederer+16; NLTE Zhao+16; HERMES-GALAH


Chris Haynes & CK 2018
NSM & MRSN Combined
[Eu/Fe]
[Eu/O]
[Fe/H]
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
-4
-3
-2
-1
0
1
16
14
12
10
8
6
4
2
0

[(Zr,Ba,Nd,Eu)/Fe]

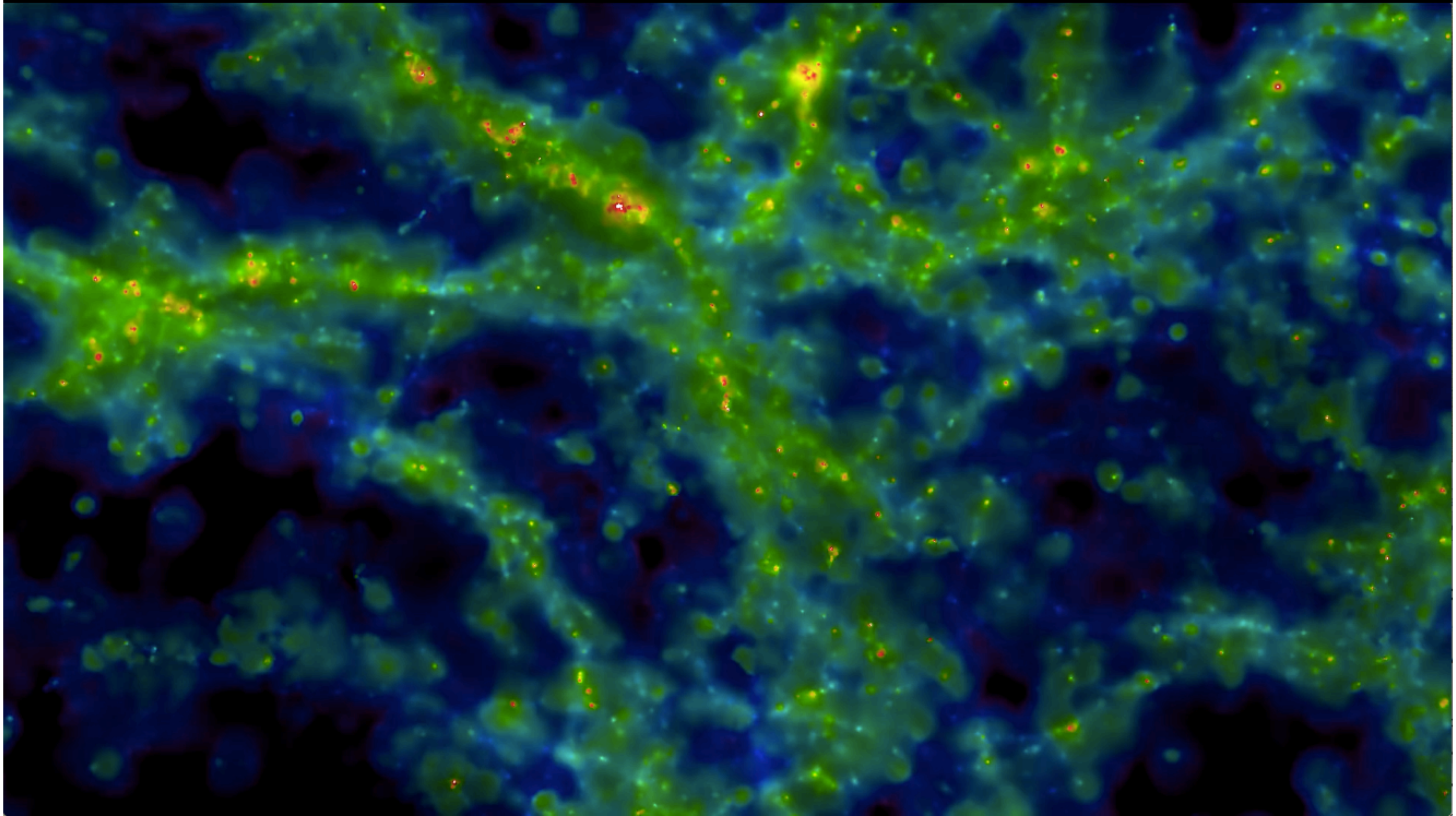
Chris Haynes & CK 2019, in prep



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

Cosmic Chemical Enrichment

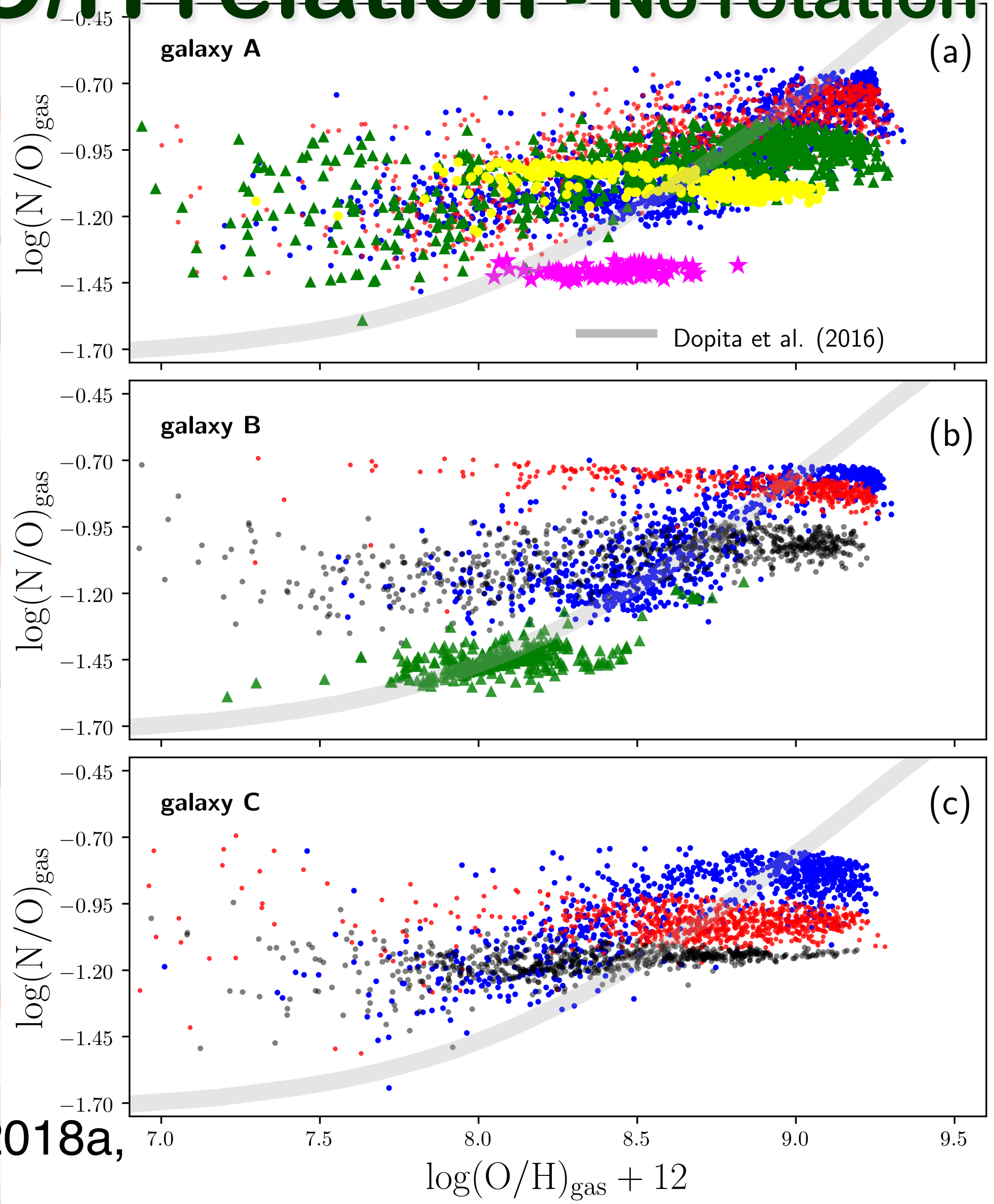
from z=5 to 0



[O/H] = –5 (blue) to -1 (red); > -1 (white)

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

N/O-O/H relation - No rotation needed



individual ISM within a galaxy

z=0

z=0.5

z=1

z=2

z=3

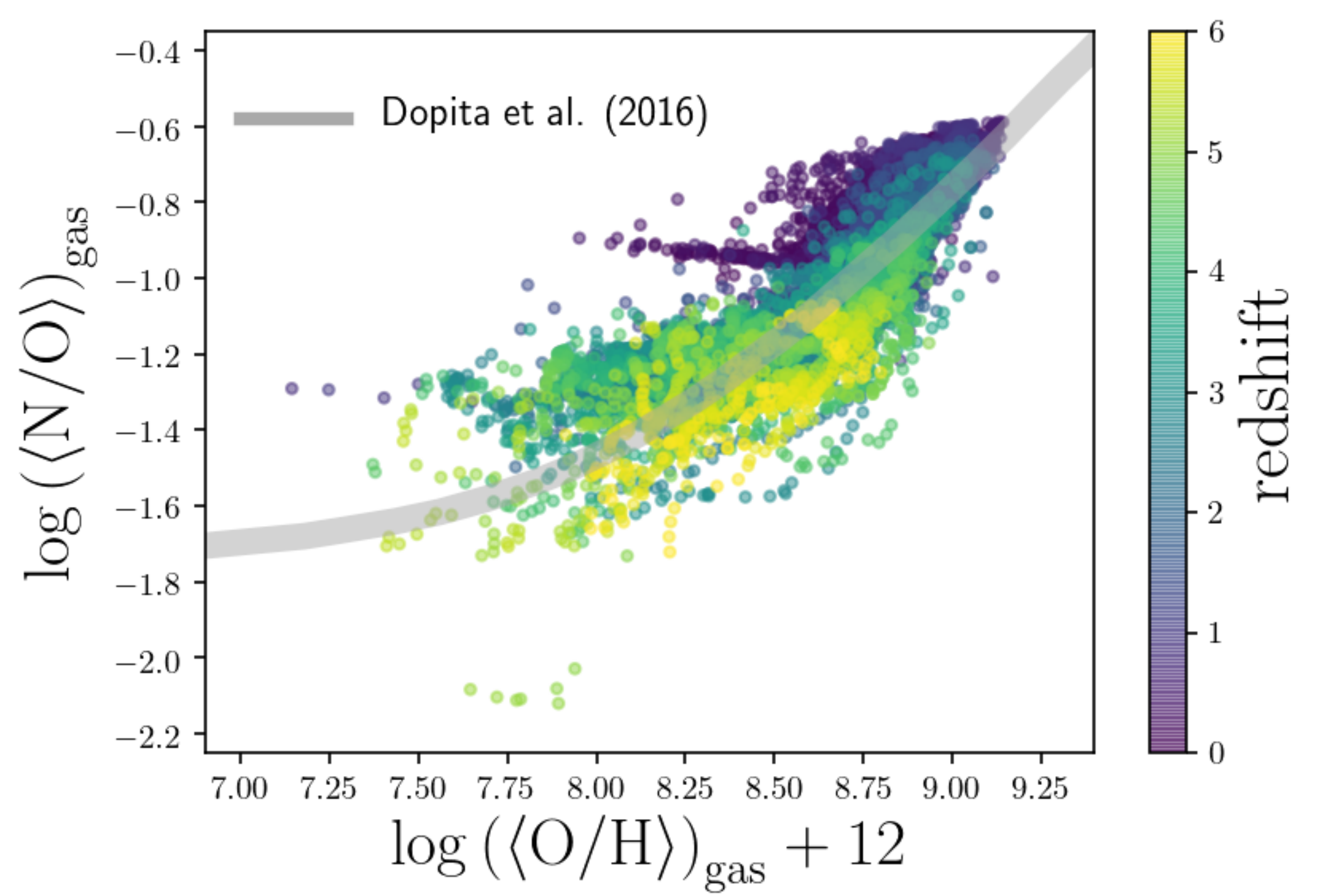
z=4

Grey bar: Compilation of observations at local Universe (Dopita+16)

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

N/O-O/H relation - No rotation needed

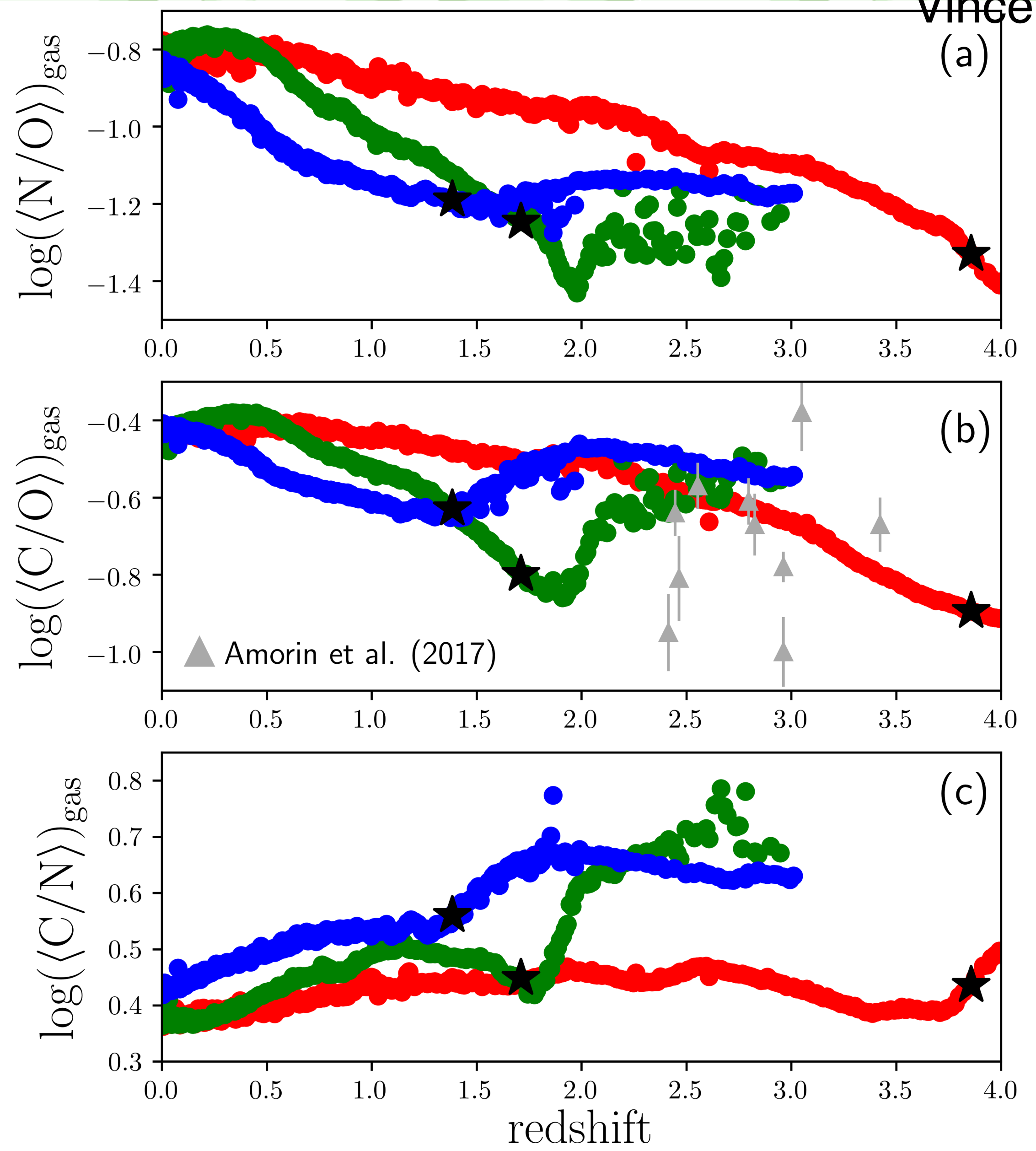
Vincenzo & CK 2018b, MNRAS, 478, 155

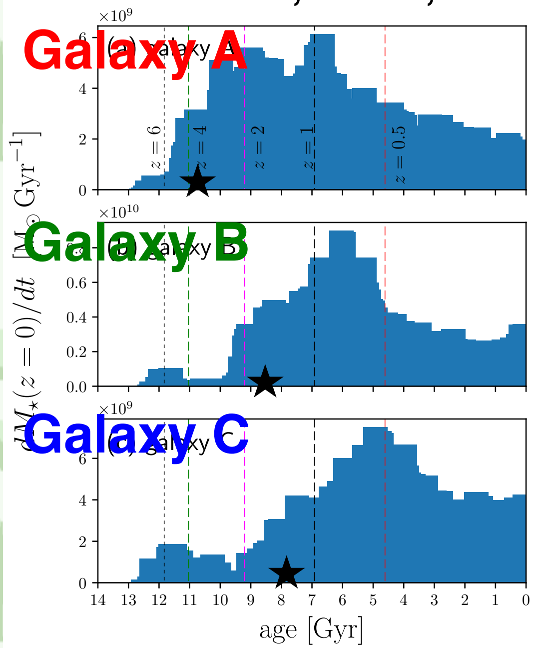


- SFR-weighted ISM of 33 galaxies in cosmological simulation
- *Local* relation reflects metallicity radial gradients.
- *Global* relation is caused by the mass-metallicity relation.

Redshift evolution of CNO 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 is possible with **JWST**!

Conclusions

- GCE model is updated, including n-capture processes from AGB stars, ECSN, ν-driven winds, NS mergers, and magneto-rotational supernovae (MRSNe, ~3% of HNe). No additional LEPP (e.g., weak-s) is required.
- With inhomogeneous enrichment, contributions from long time-delay sources (AGB, NSM) appear at low metallicities. (i.e., No tight age-metallicity relation.)
- However, NSM timescales seem to be too **long** to explain the distribution of [Eu/(Fe,O)]-[Fe/H]. MRSNe greatly reduce the scatters at [Fe/H]<0.
- Simple combination of NSM and MRSN does not work, and metallicity dependence seems to be necessary.
- Inhomogeneous enrichment could also explain dSphs.
- With AGB, we do NOT need *stellar* rotation for ^{14}N/O-O/H relation, different from Chiappini+ 05. We do need *core* rotation+B-fields for HNe and MRSNe.