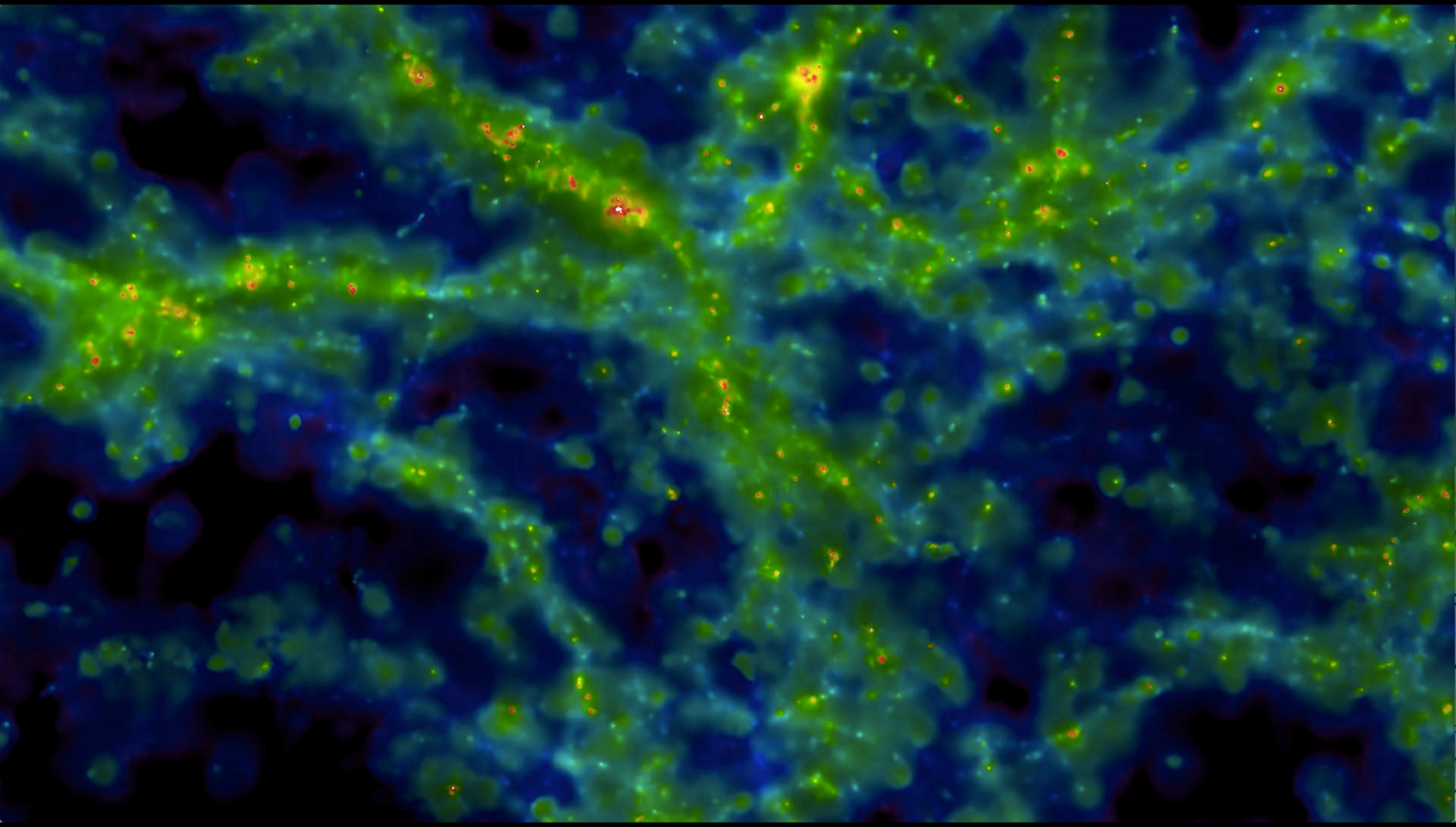
Cosmological Simulations

from z=5 to 0



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

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

Galactic Chemical Evolution (GCE) models

(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+16

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

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

Inflow Outflow

decreased by star formation

given from hydrodynamics in
(3) chemodynamical simulation

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

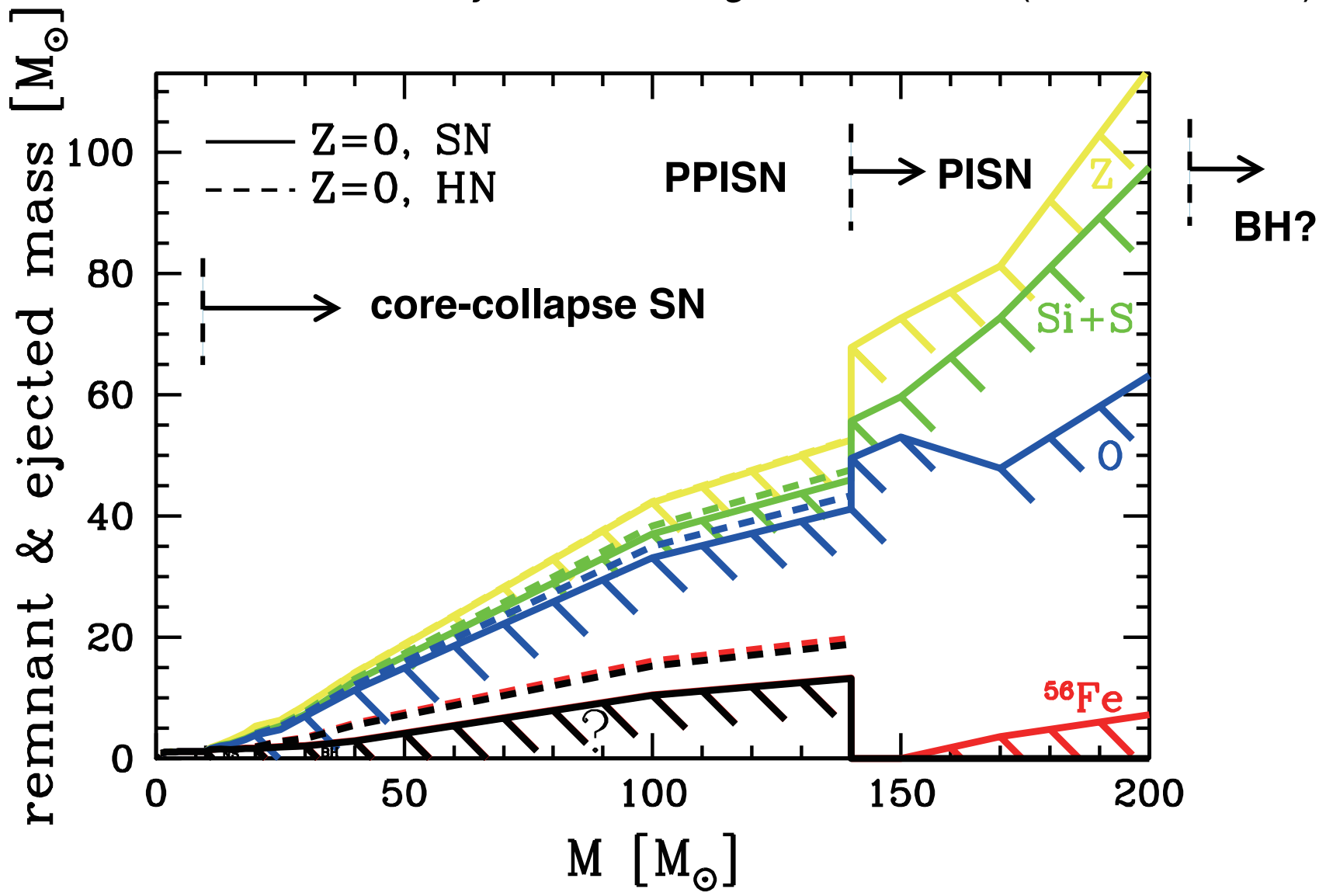
→ **inhomogeneous enrichment**

(2) Stochastic model

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

Nucleosynthesis Yields

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



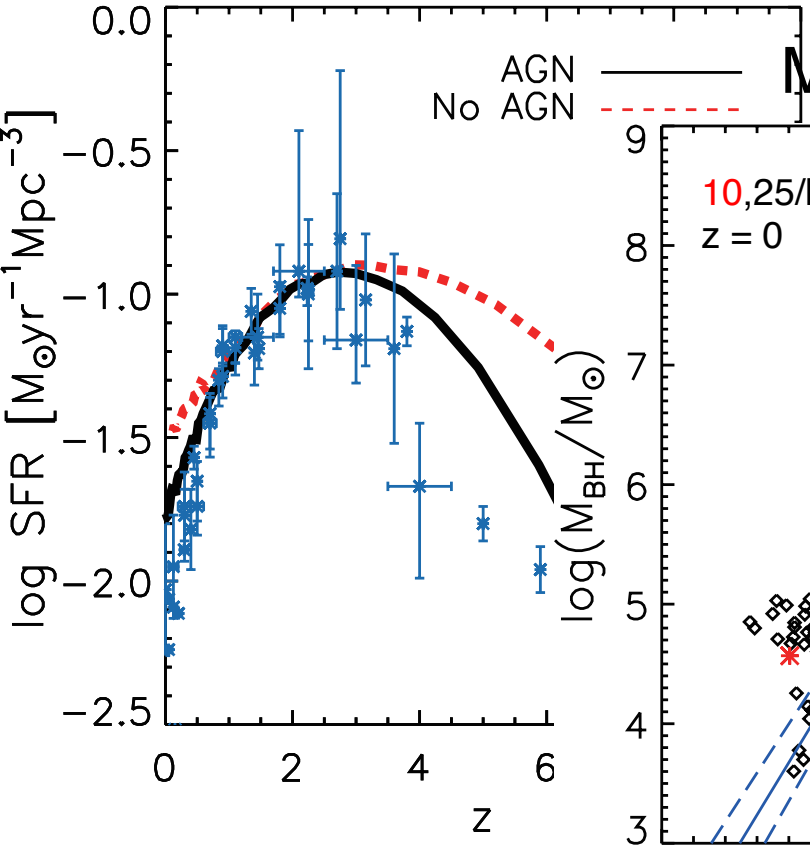
Also, Woosley & Heger

Cosmic Evolution

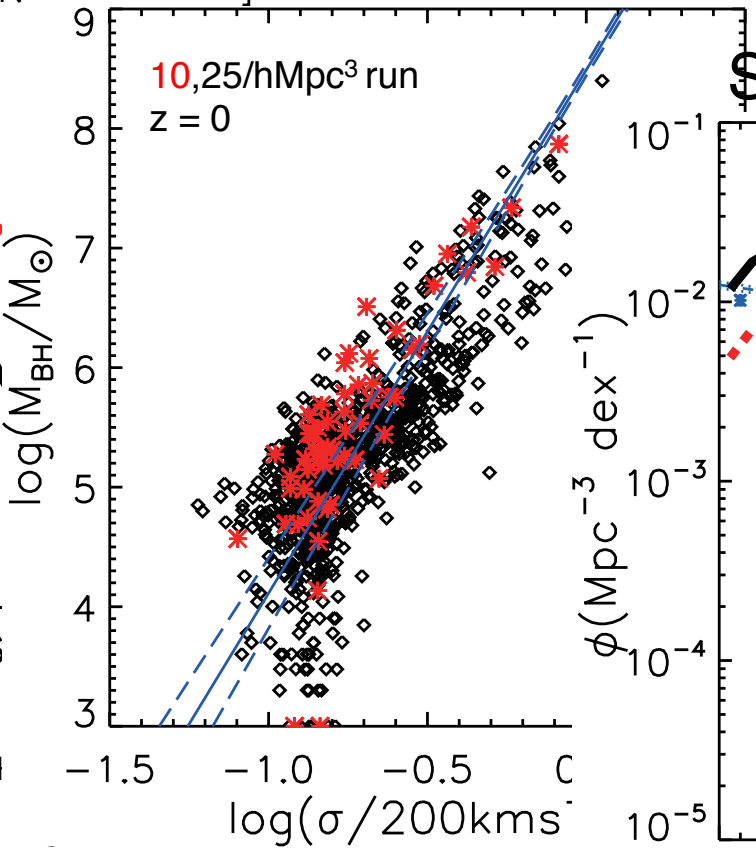
$M_{BH\ seed}$~100-1000$M_\odot$ better than 10, $10^{4\text{-}5}M_\odot$ – First Star origin

Taylor & CK 2014, MNRAS, 442, 2751;
Taylor & CK 2015, MNRAS, 448, 1835

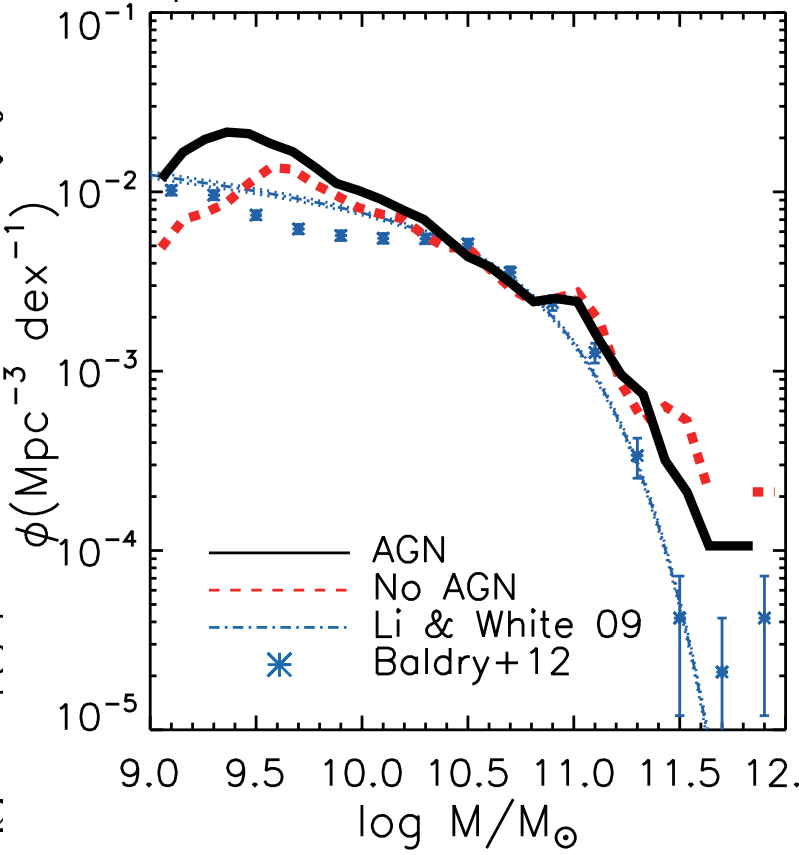
Cosmic SFR



Magorrian relation



Stellar Mass Function



obs: Bouwens+11, Karim+ Cucciati+12, Oesch+12, B +13, Gunawardhana+13, Sobral+13

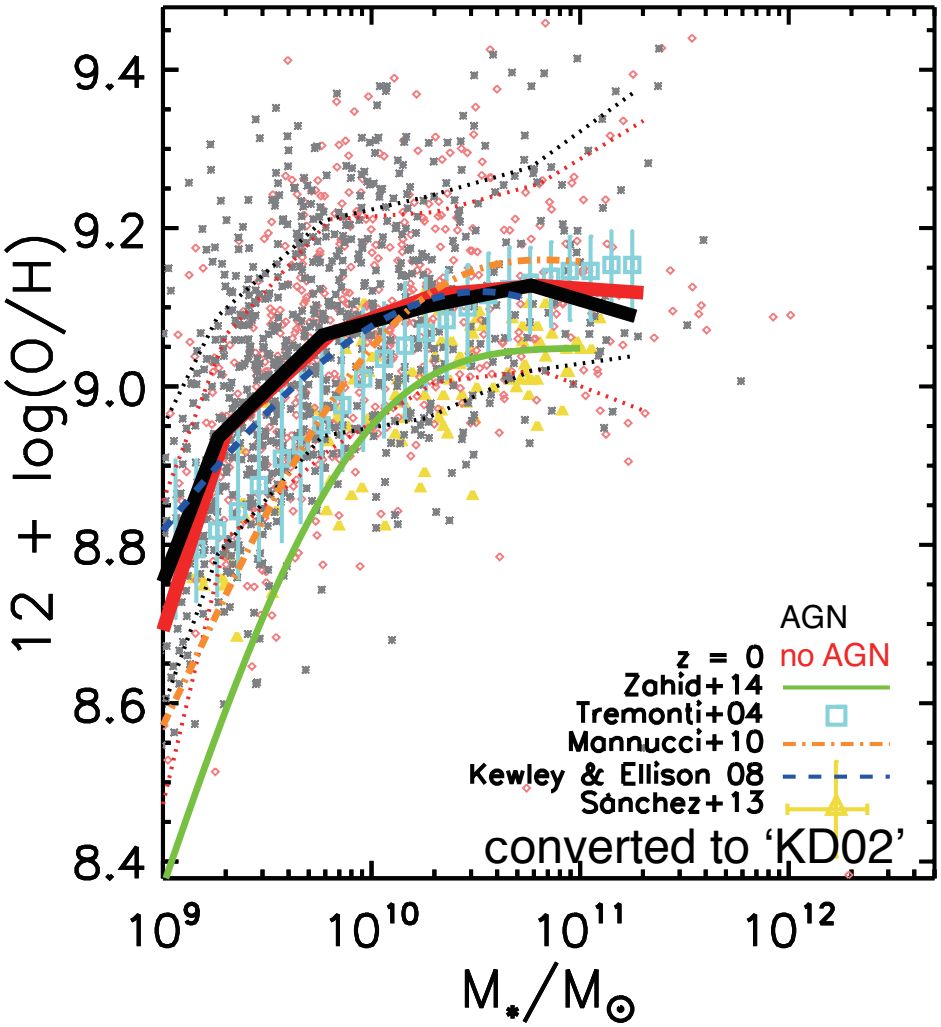
obs: Kormendy & Ho 2

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

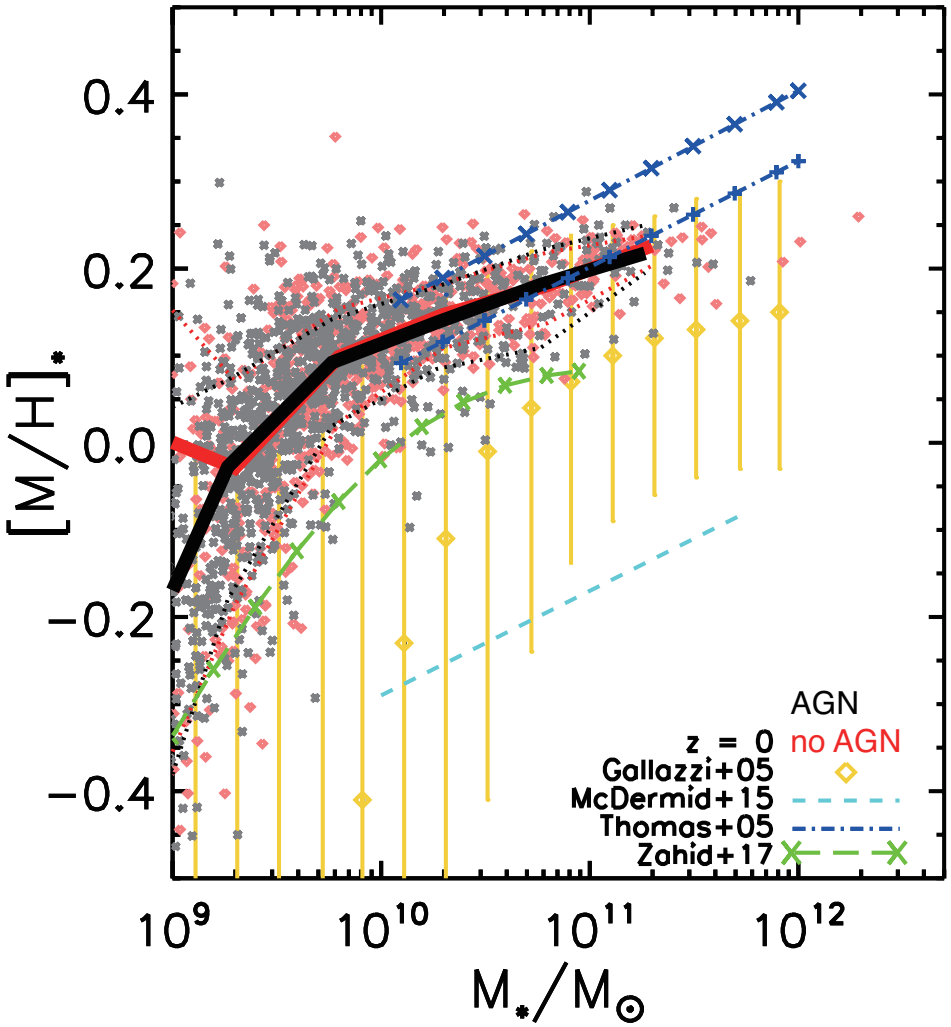
Mass Metallicity Relations (MZR)

Taylor & CK 2015a

Gas-phase Oxygen Abundance, SFR weighted



Stellar Metallicity, luminosity weighted



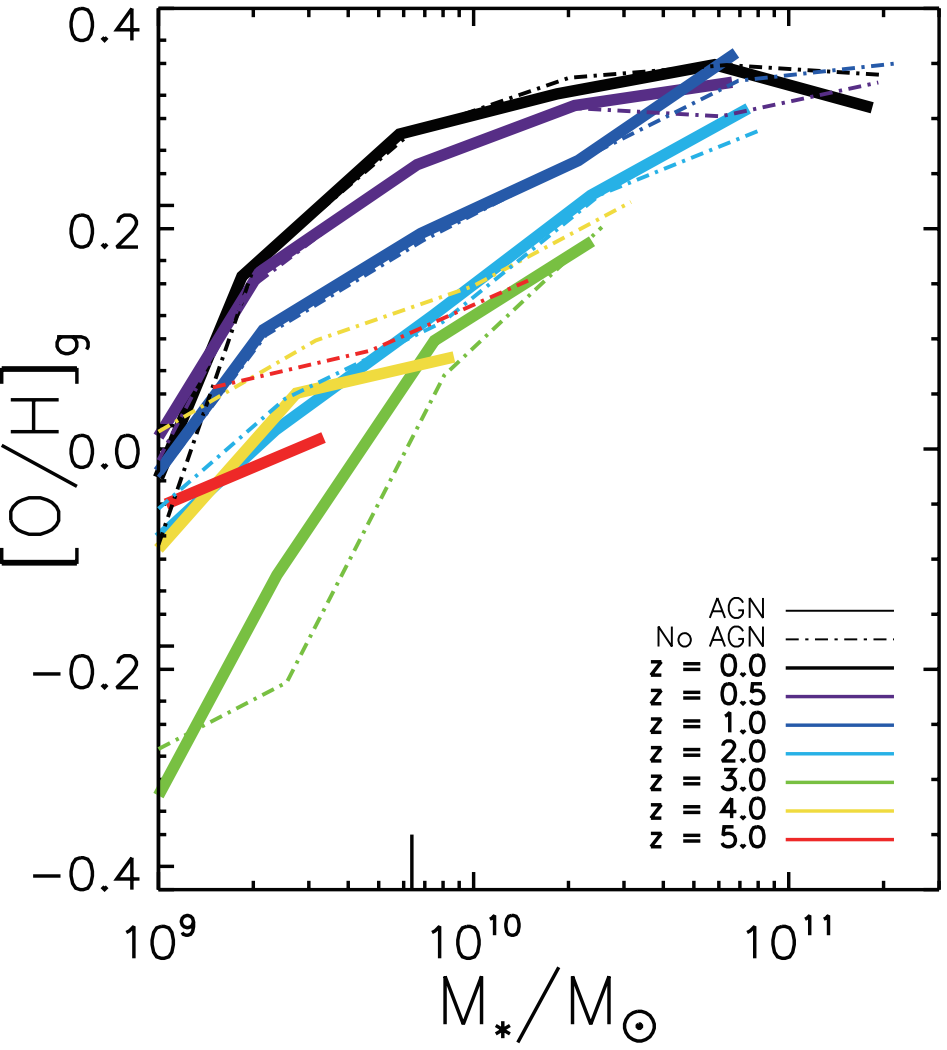
Mostly SN-driven metal-loss; AGN eject only ~2% of metals.

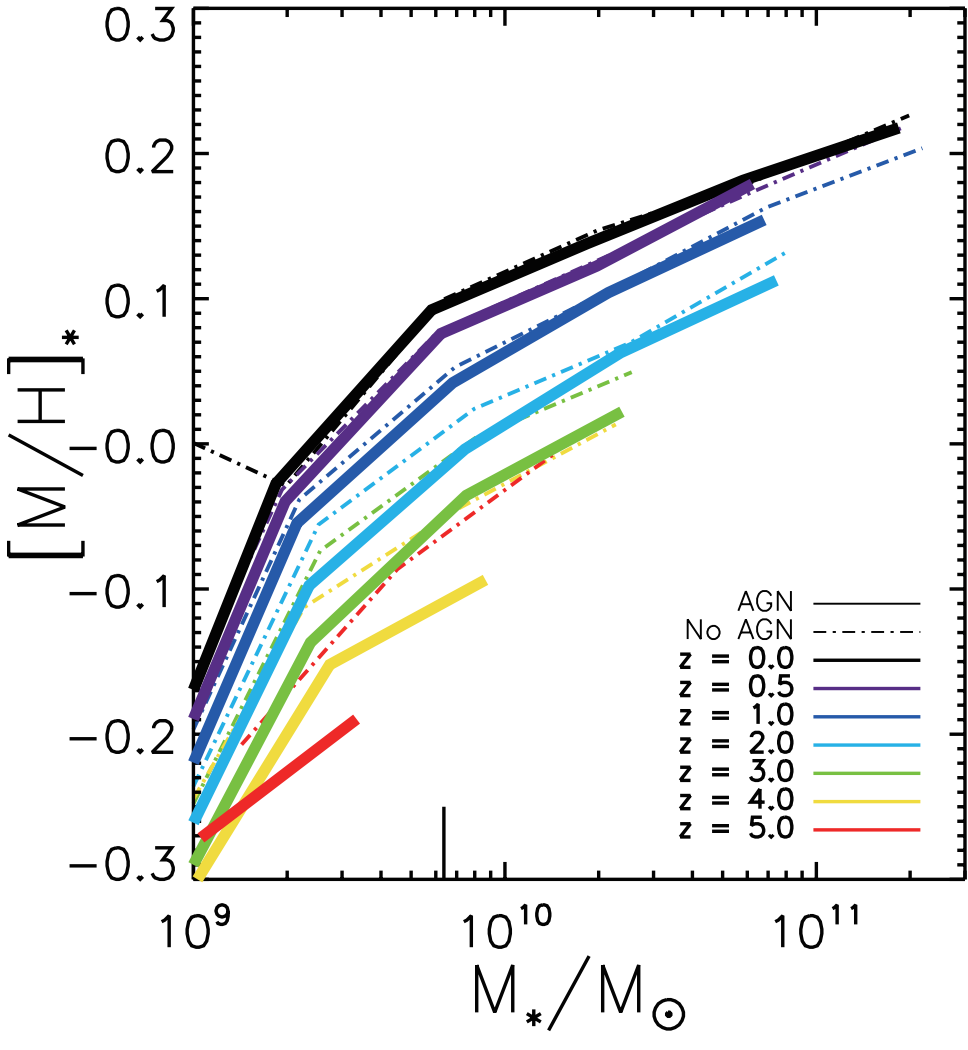
Time evolution of MZR

Taylor & CK 2016

✷ Gas: Steeper slope at higher-z. ✷ Stars: Normalization shift.

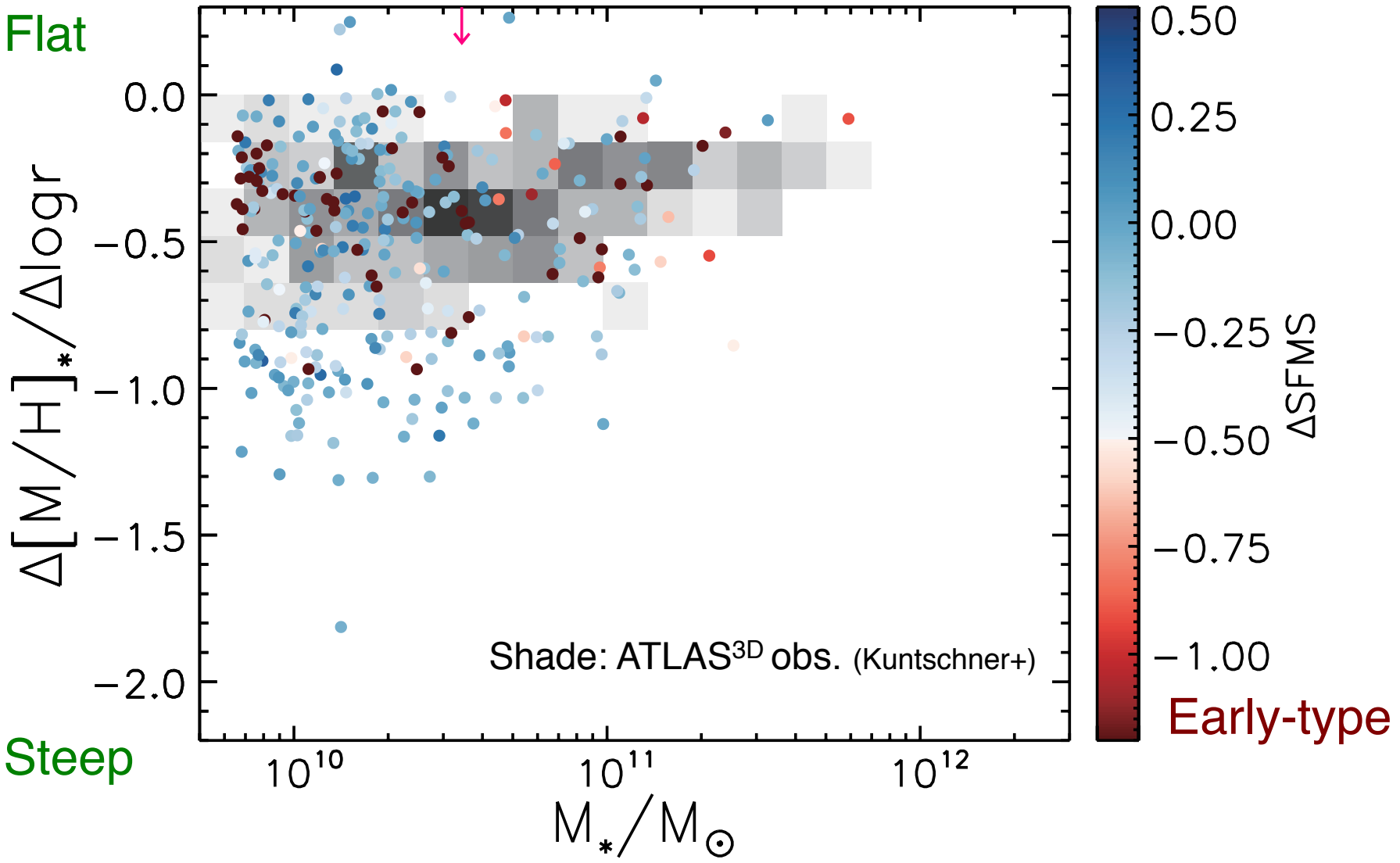
← Inflow at low-M, z~3 ← Outflow at low-M, all z





Metallicity Radial Gradients

Taylor & CK 2017

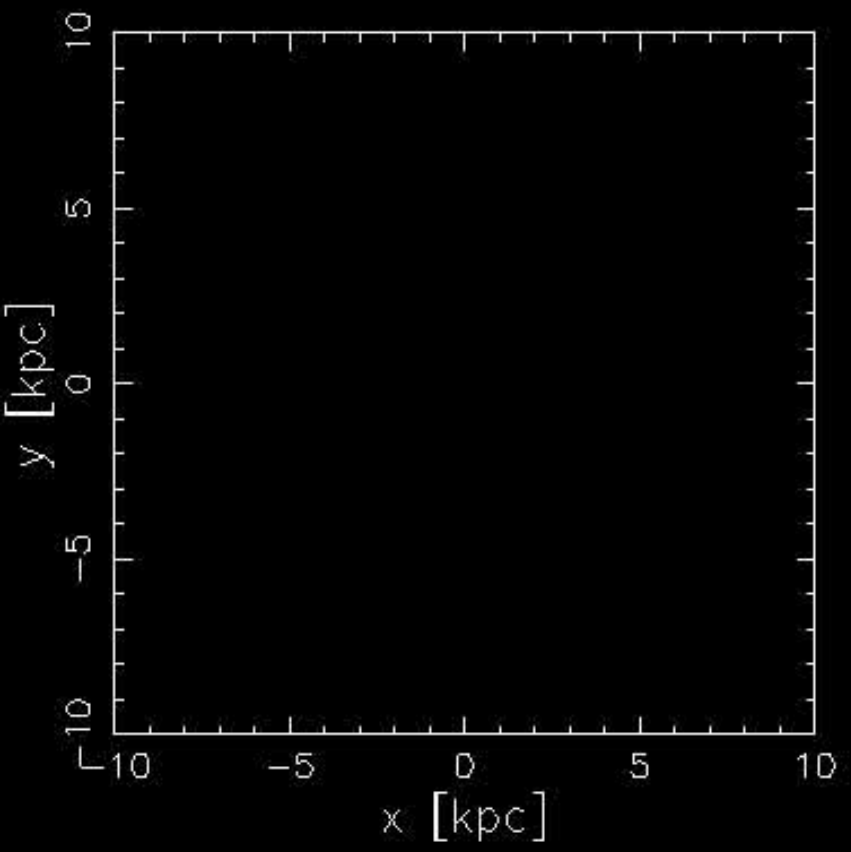


"Inside-out" formation + flattening by major mergers

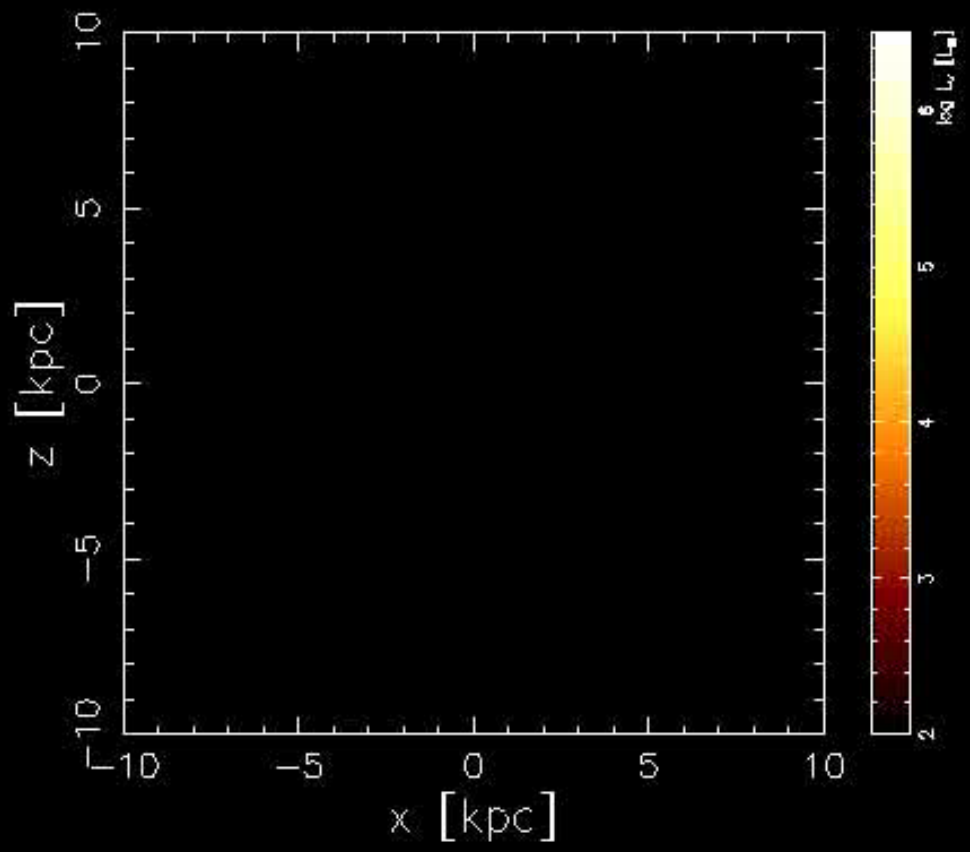
Milky Way-type galaxy

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

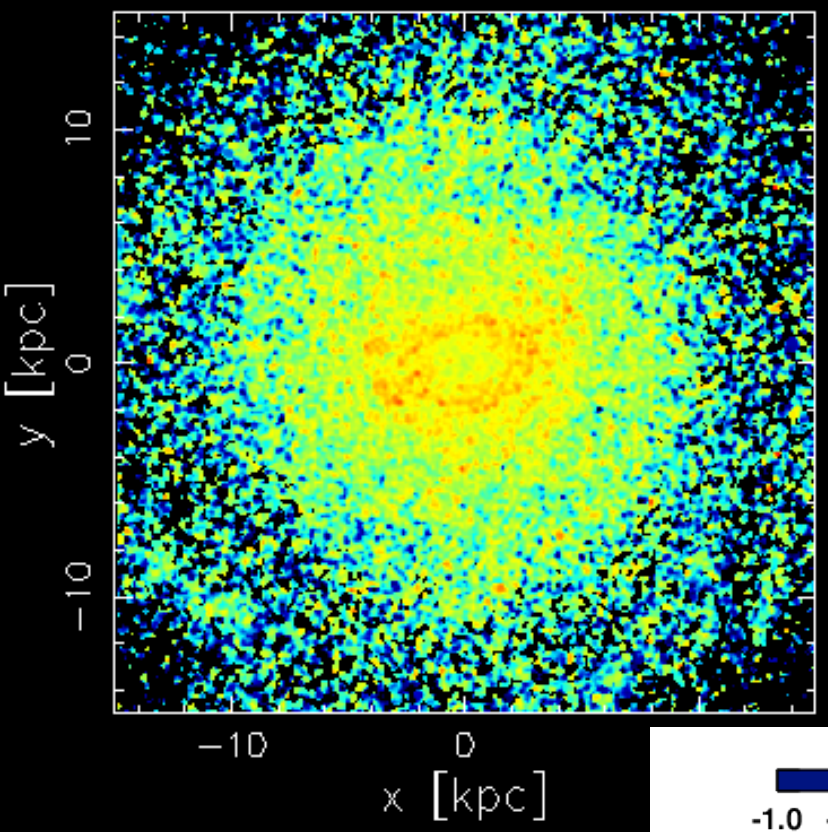


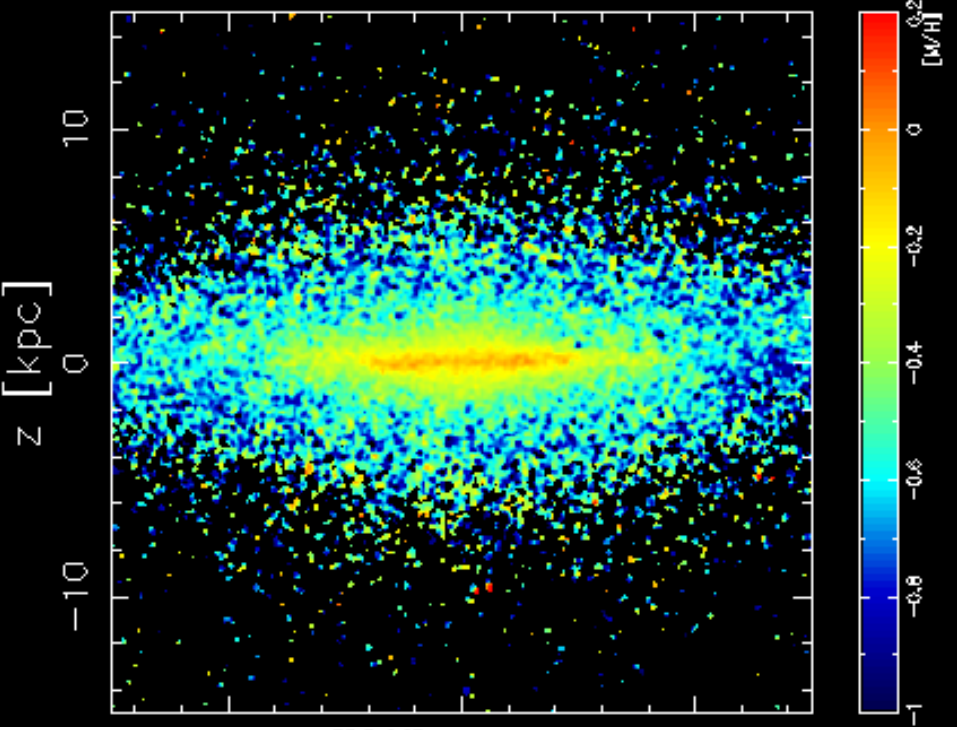
Edge on



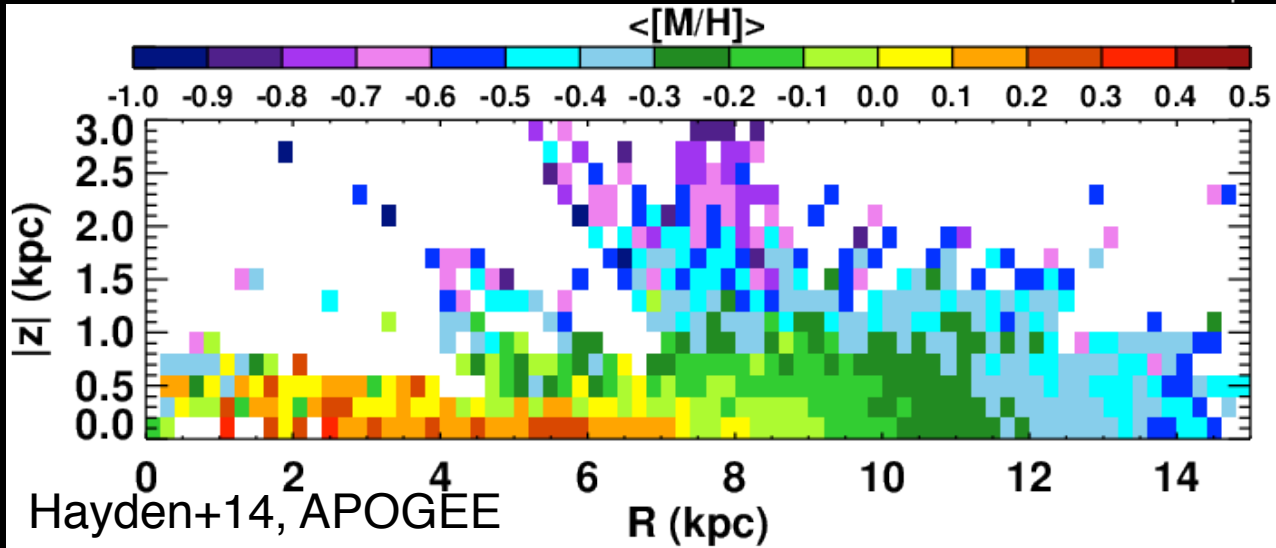
Similar results obtained also with Aquarius Initial Condition (CK 2015).

Metallicity Map



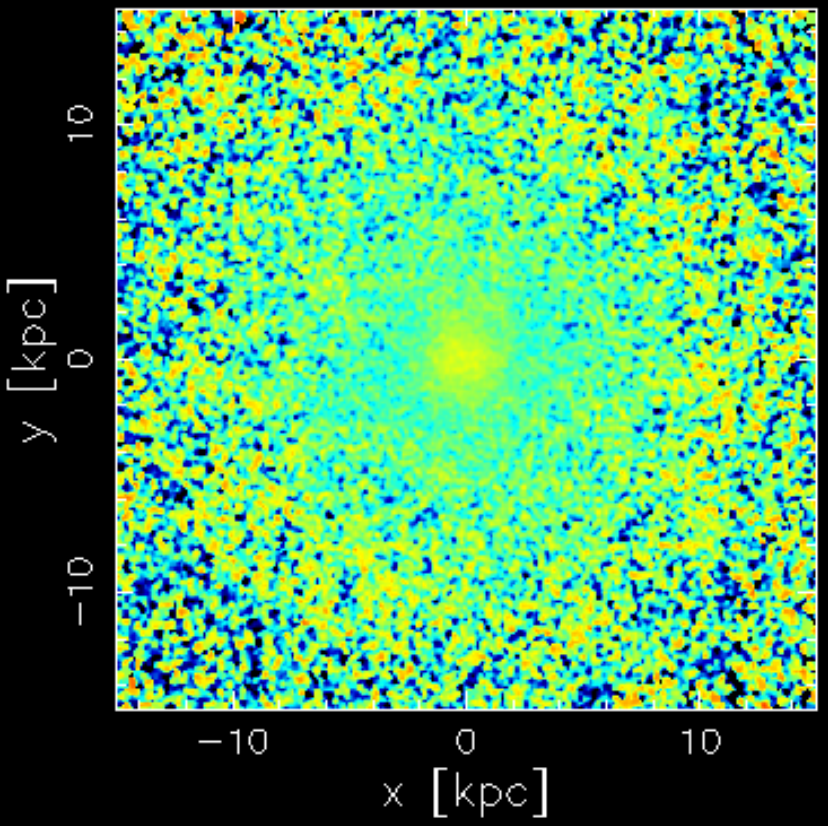


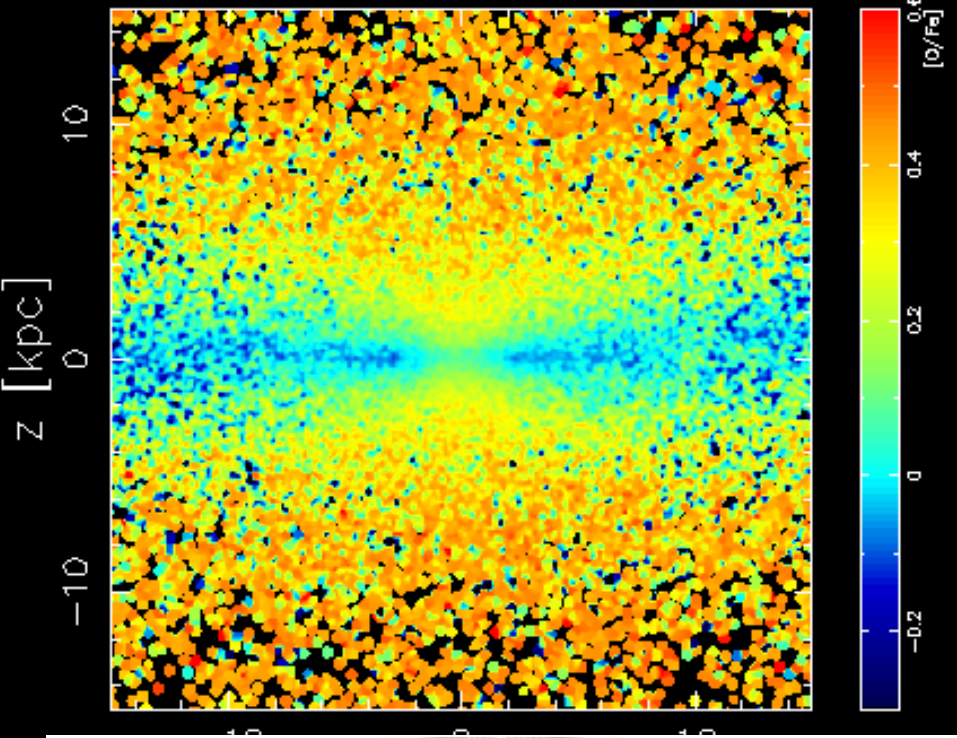
low-mass stellar mass weighted, projected



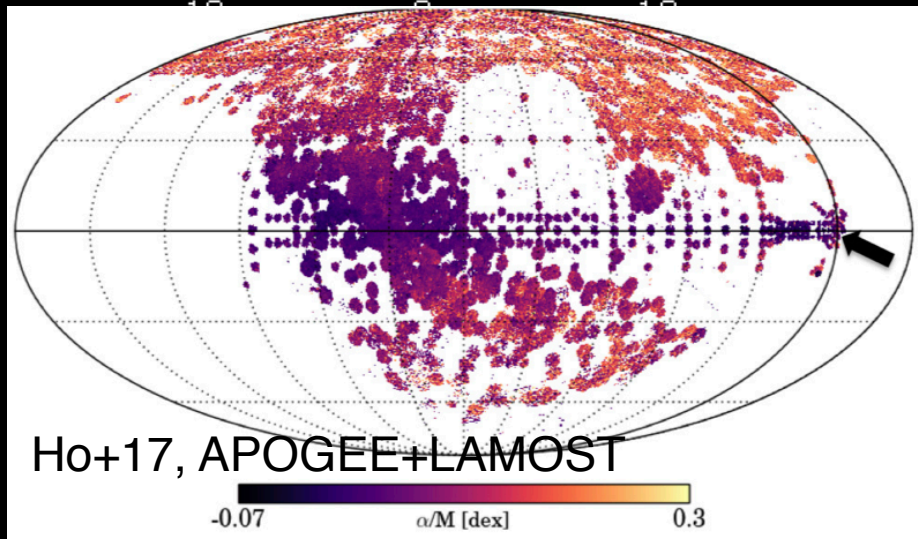
Hayden+14, APOGEE

[O/Fe] Map



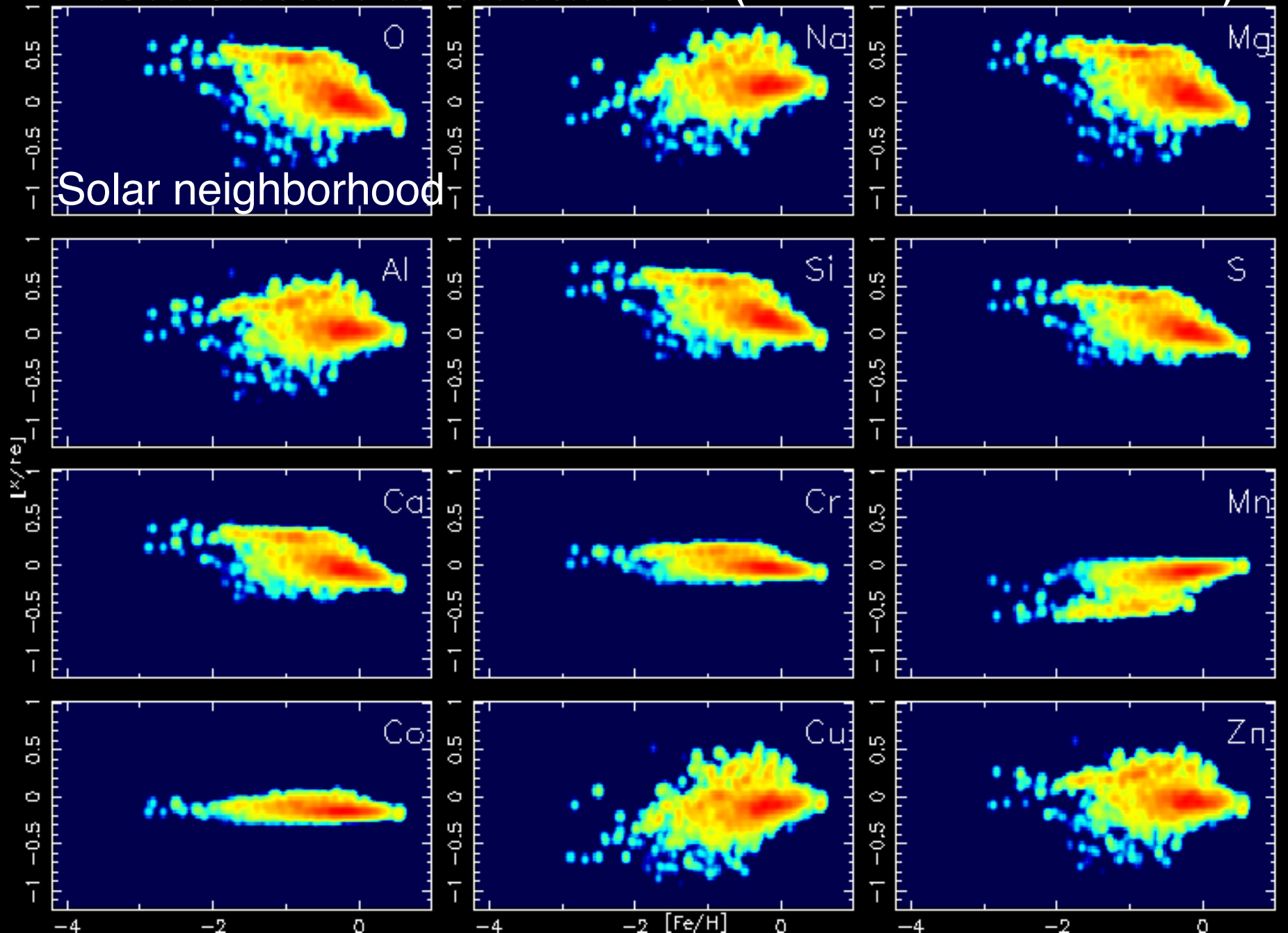


low-mass stellar mass weighted, projected

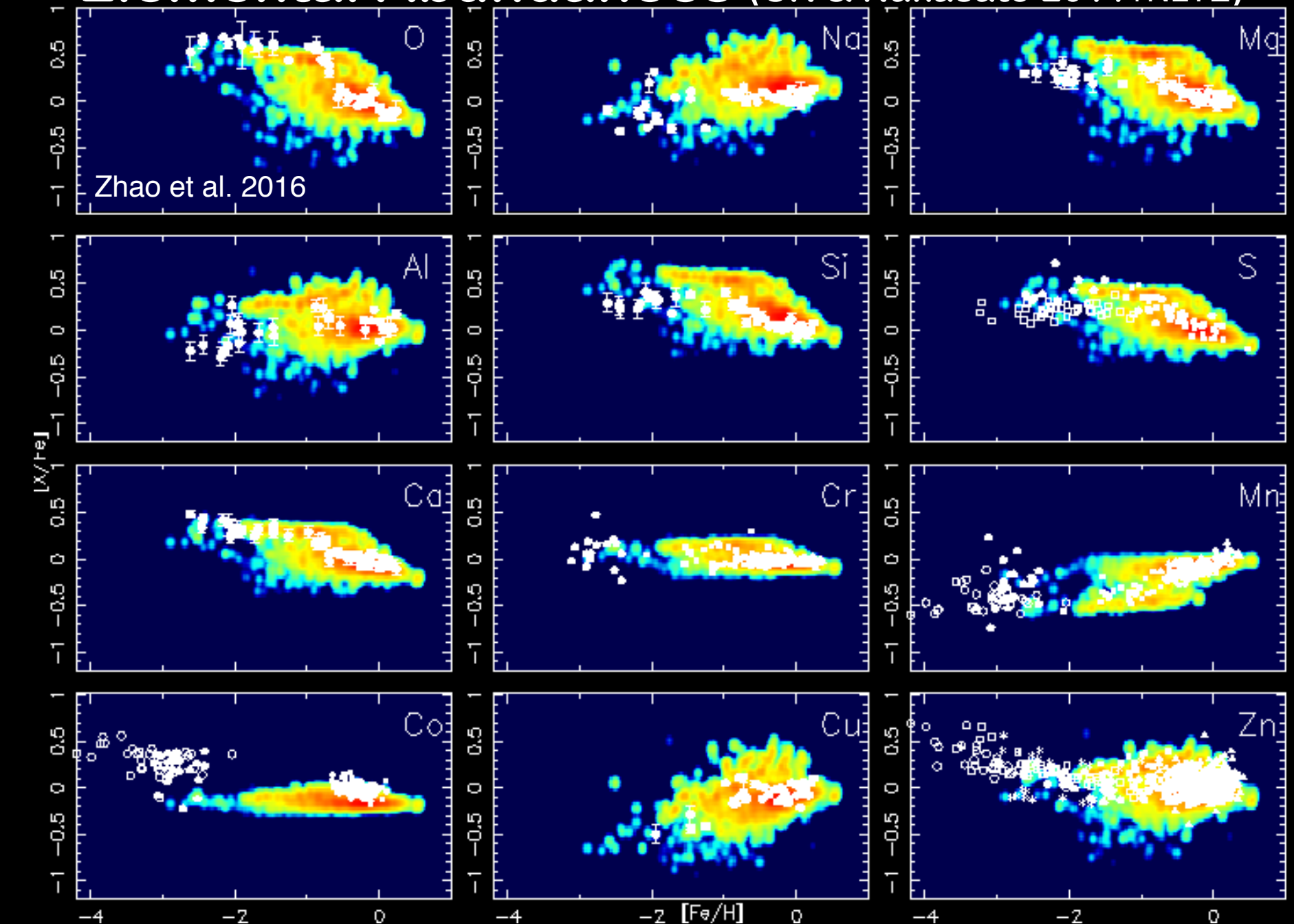


Ho+17, APOGEE+LAMOST

Elemental Abundances (CK & Nakasato 2011+NLTE)

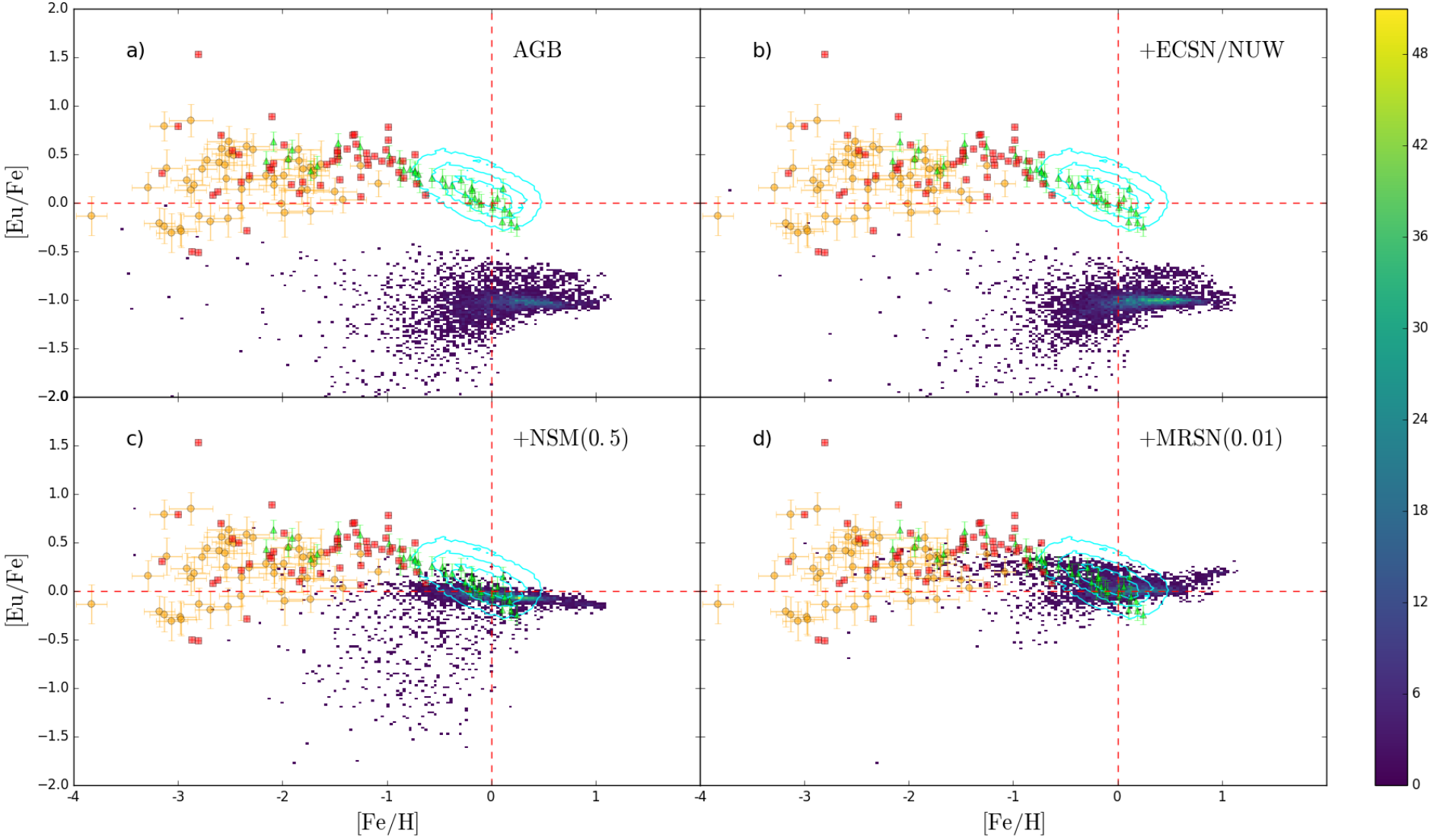


Elemental Abundances (CK & Nakasato 2011+NLTE)



[Eu/Fe]-[Fe/H]

Chris Haynes & CK 2018



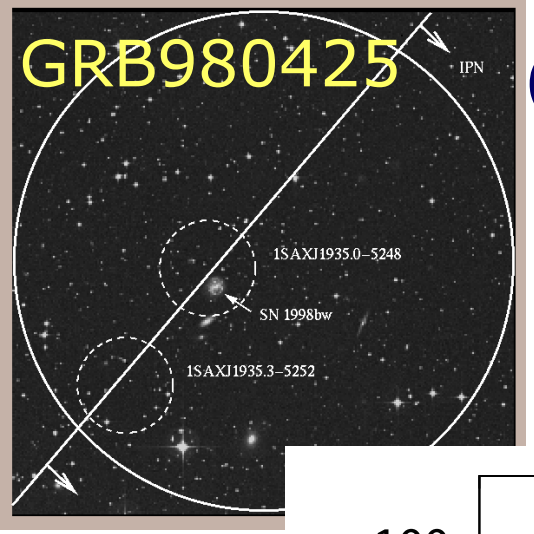
Neutron star mergers alone cannot reproduce the observations.

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

Summary

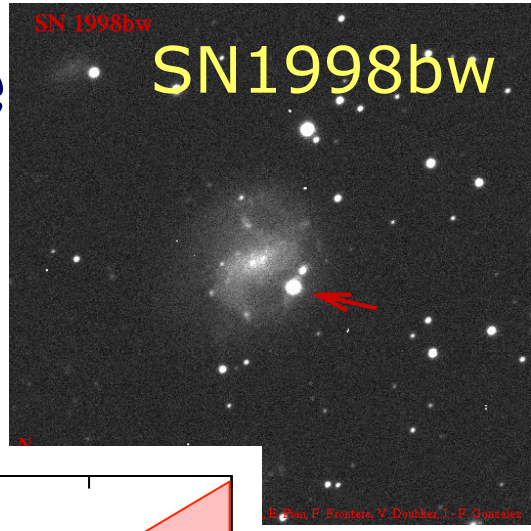
- Metallicity is not a single value at a given time in the Universe.
  - Mass-metallicity(-SFR) relations of galaxies
  - Metallicity radial gradients within galaxies
  - Internal structures of galaxies (bulge/disk, spiral etc)

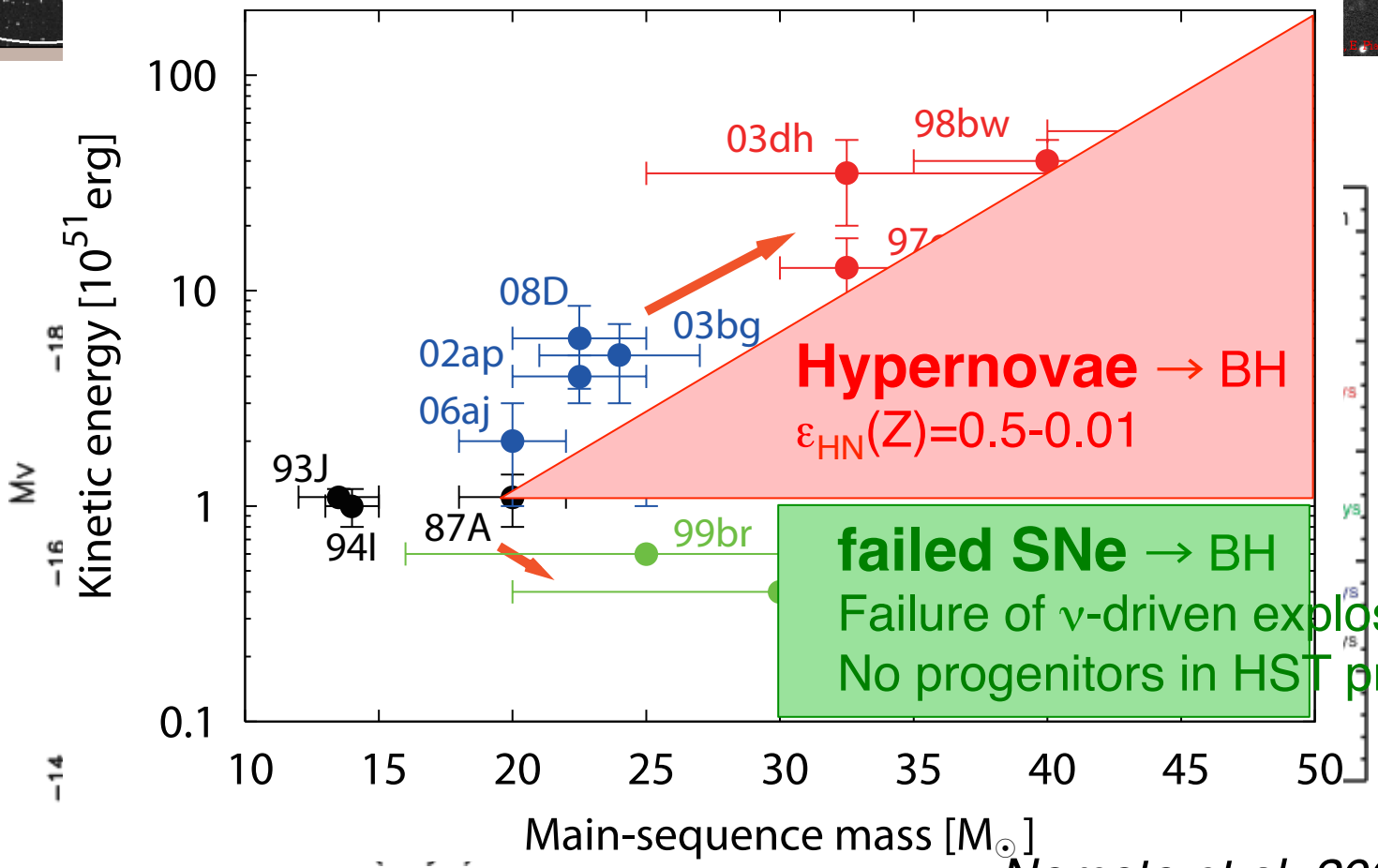
- Even in the solar neighbourhood (1<kpc), inhomogeneous enrichment is “observed”.
  - There is no tight age-metallicity relations (AMR) of stars.
  - There is a large scatter of [X/Fe] in
  - Long-lifetime sources (eg NSMs) can contribute at low metallicities.
  - However, NSM timescale in BPS models seem to be too long (Haynes & Kobayashi 2019).
- and O/Fe is not constant (observed).



Core-collapse SNe

- SN light curves & spectra fitting → M, E_{kin}, M(Fe)
- Mixing-fallback model





Nomoto et al. 2002, 2013

Chemical Evolution in Solar Neighborhood

CK+17, in prep.

DTDs provided by A. Ruiter; D. Vanbeveren

SD (KN09 based on HK winds(Z)); 2D DDT(Z) (Leung & Nomoto 17)

SD+DD+double.det (Ruiter+09&14); 3D DDT N100(Z) (Seitenzahl+12) + 1.1+0.9$M_\odot$ (Pakmor+12) + 1.06$M_\odot$ (Sim +10)

Shen+17?

SD+DD(Z) (Mennekens+12); 3D DDT N100(Z) (Seitenzahl+12) + 1.1+0.9$M_\odot$ (Pakmor+12)