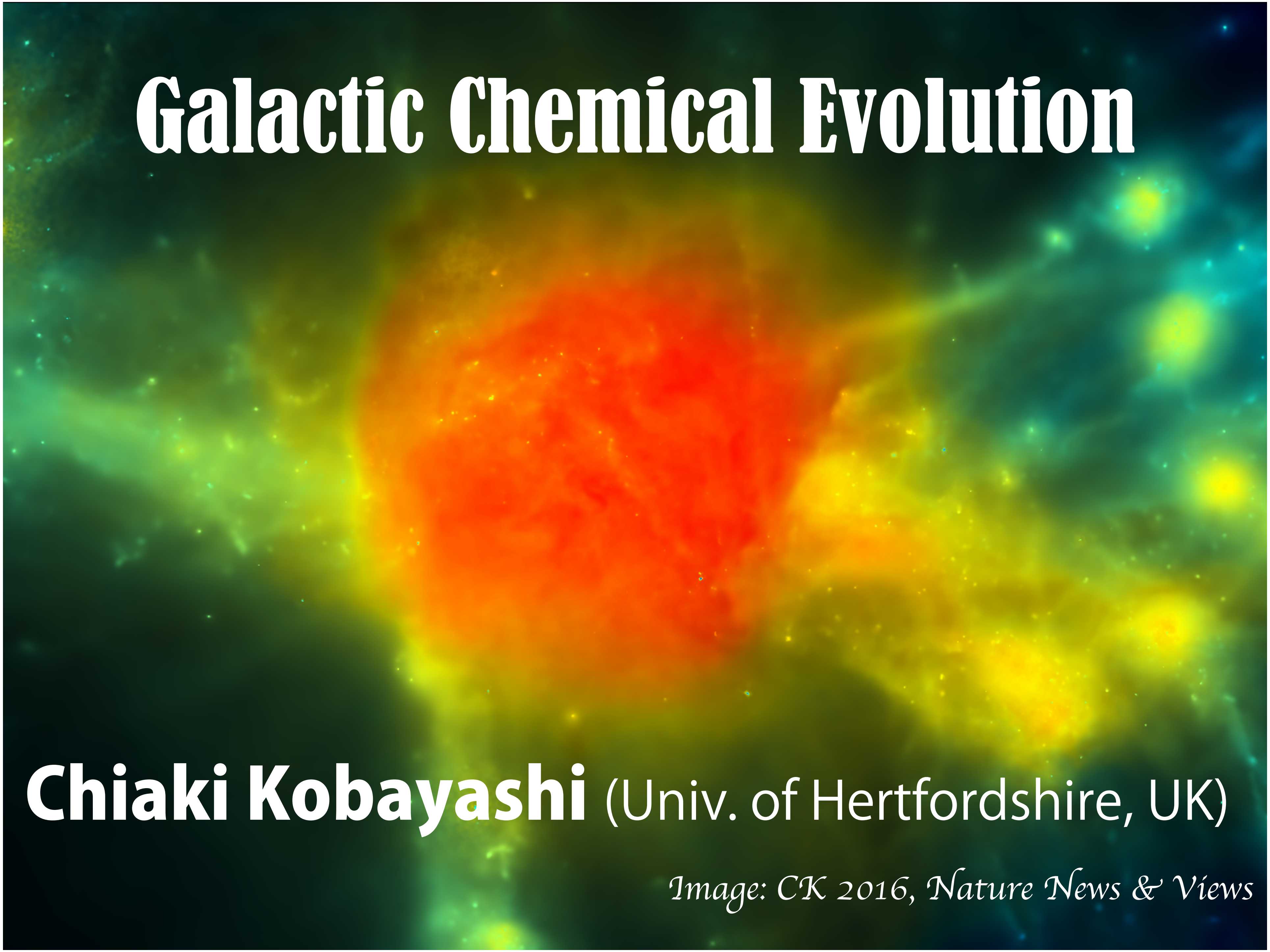


Galactic Chemical Evolution

Chiaki Kobayashi (Univ. of Hertfordshire, UK)

Image: CK 2016, Nature News & Views

Galactic Archaeoloy

2008 Tucson

Galactic Archaeology

of Milky Way and local dwarf galaxies

- ✷ Motions of one billion stars are measured with GAIA.
- ✷ Elemental Abundances (from Li to Eu) of million stars will be measured with
  - ★ **SEGUE** (Resolution~1800) on SDSS
  - ★ **RAVE** (R~7500) on 1.2m UKST
  - ★ **HERMES** on AAT (R~28000/50000)
  - ★ **APOGEE** (R~20000, IR) on SDSS
  - ★ **GAIA-ESO with VLT** (R~20000/40000)
  - ★ ~~WFMOS on Subaru~~
  - ★ **WEAVE** on WHT (R~5000/20000)
  - ★ **4MOST** on VISTA (R~5000/18000)
  - ★ **MSE/ngCFHT**
  - ★ **…**

- ✷ Chemical and dynamical evolution of the Milky Way Galaxy will be revealed!

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

Galactic Chemical Evolution (GCE)

(1) One-zone model: Tinsley 80, Timmes+ 95, Pagel 97, Matteucci 01, Prantzos+ 93, Chiappini+ 97, CK+ 00,06,11, Travaglio+ 01,04,…

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

Inflow Outflow

Metal ejection rates

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

decreased by star formation

to estimate local variations

(2) Stochastic model

Argast+02; Ishimaru+04; Cescutti+08; Wehmeyer+15

given from hydrodynamics in

(3) chemodynamical simulation

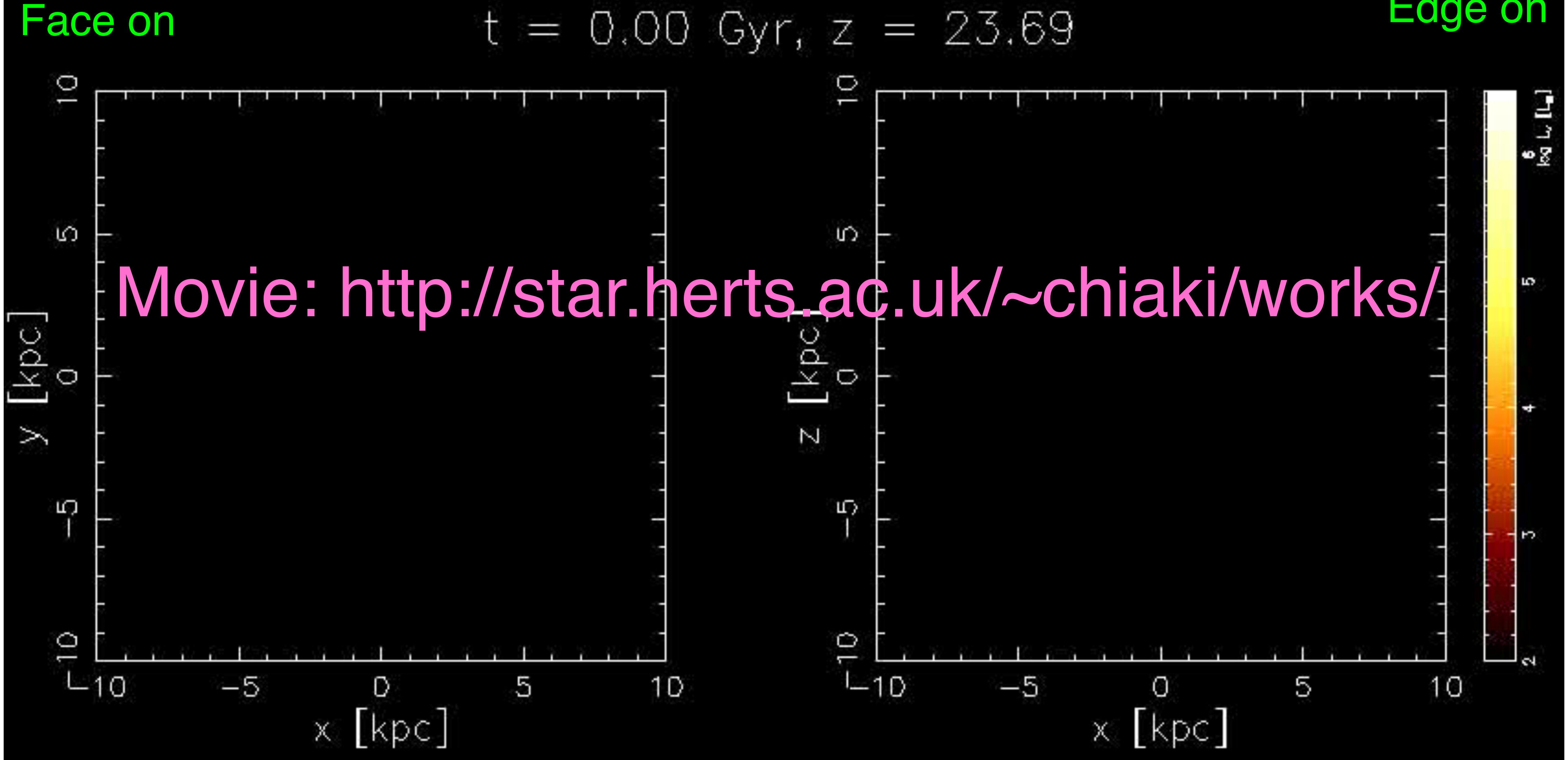
Burkert & Hensler 87, Katz 92, Steinmetz & Müller 94, Mihos & Hernquist 96, CK 04,…

Milky Way-type galaxy

Initial Condition: λCDM fluctuated sphere with $\lambda\sim0.1$, $r\sim3$Mpc,
$M_{tot}\sim10^{12}\,M_\odot$, $N_{tot}\sim120.000$, $M_{gas}\sim10^6\,M_\odot$, $M_{DM}\sim10^7\,M_\odot$
(CK & Nakasato 2011, *ApJ, 729, 16*)

Face on

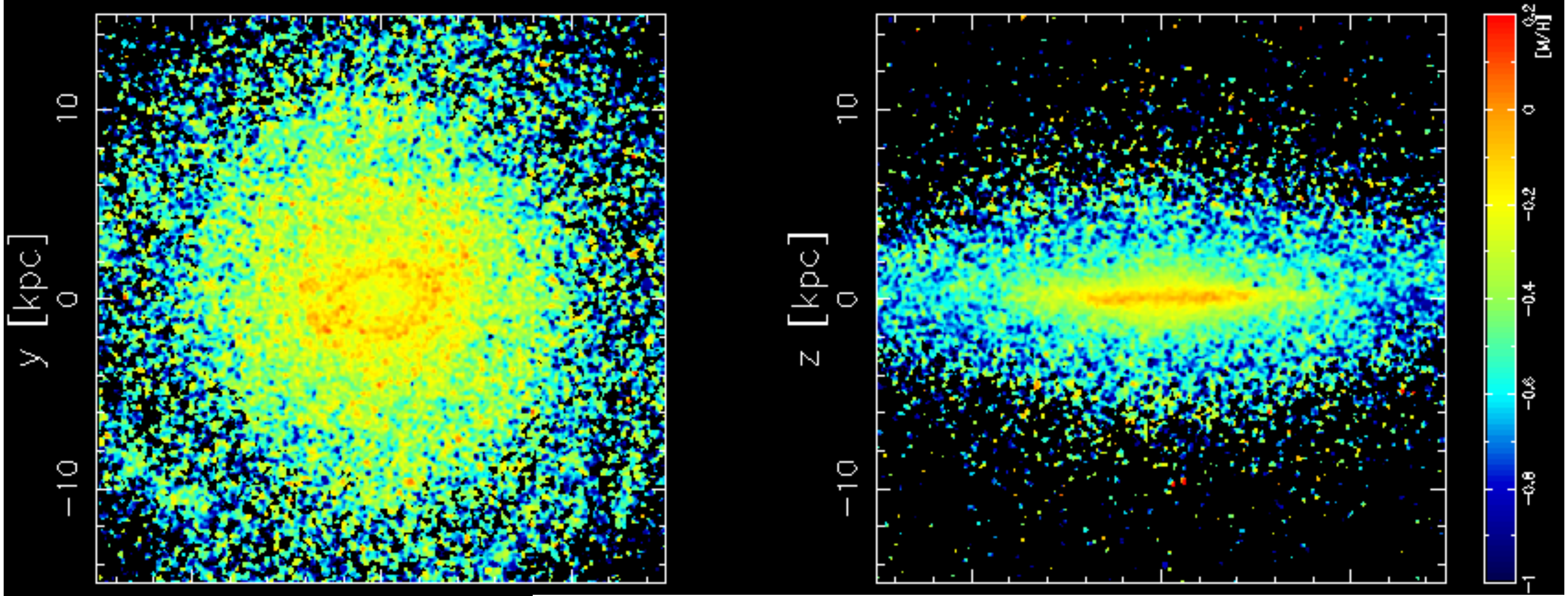
Edge on



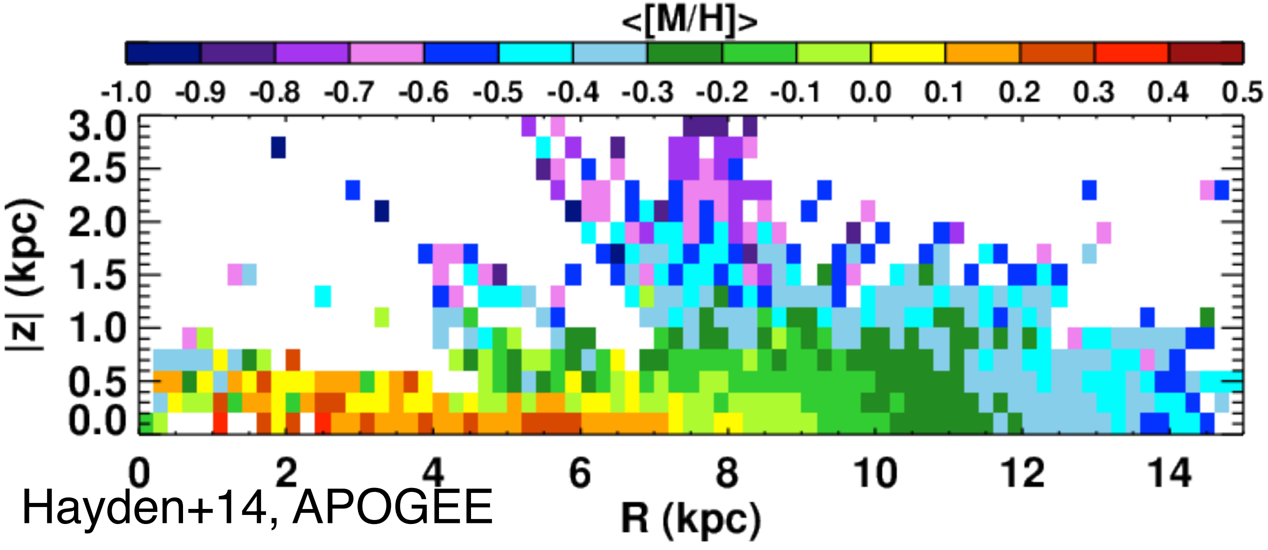
Movie: http://star.herts.ac.uk/~chiaki/works/

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

Metallicity Map

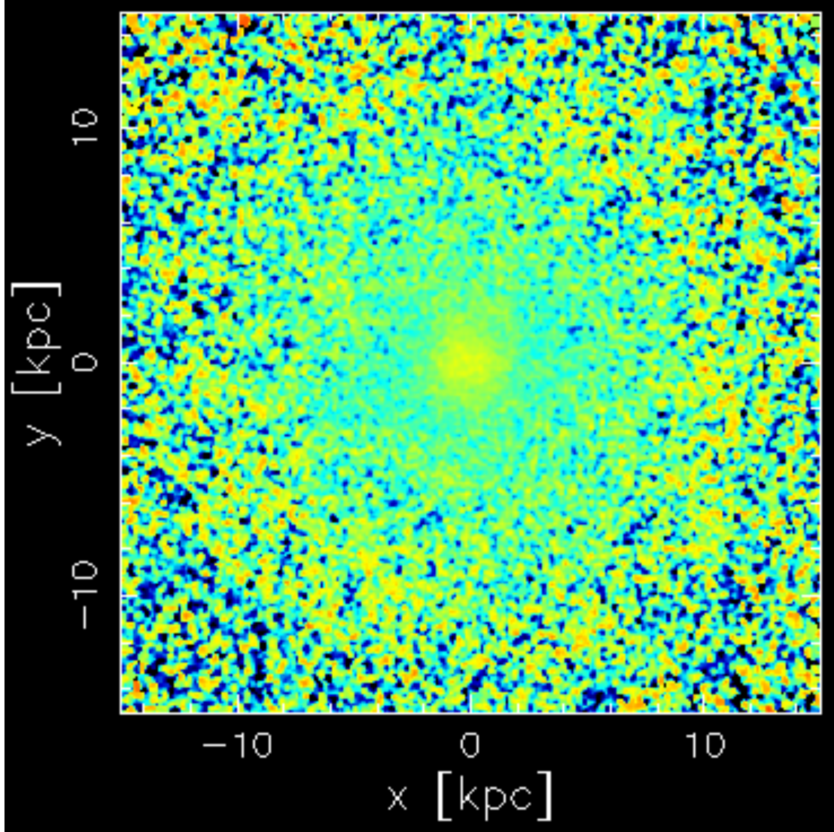


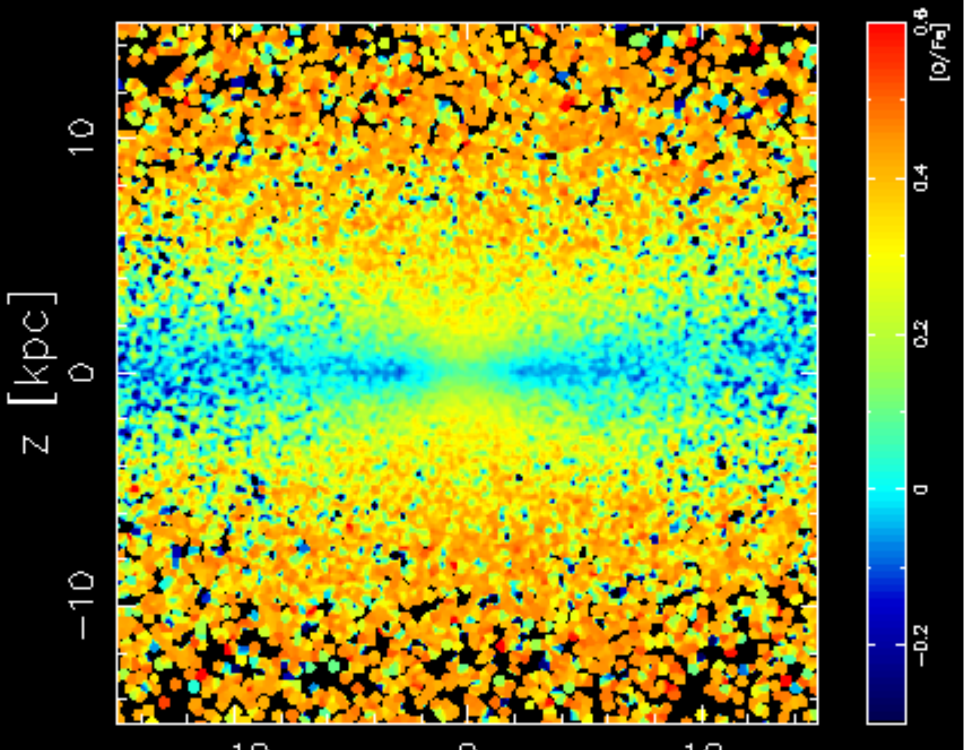
low-mass stellar mass weighted, projected



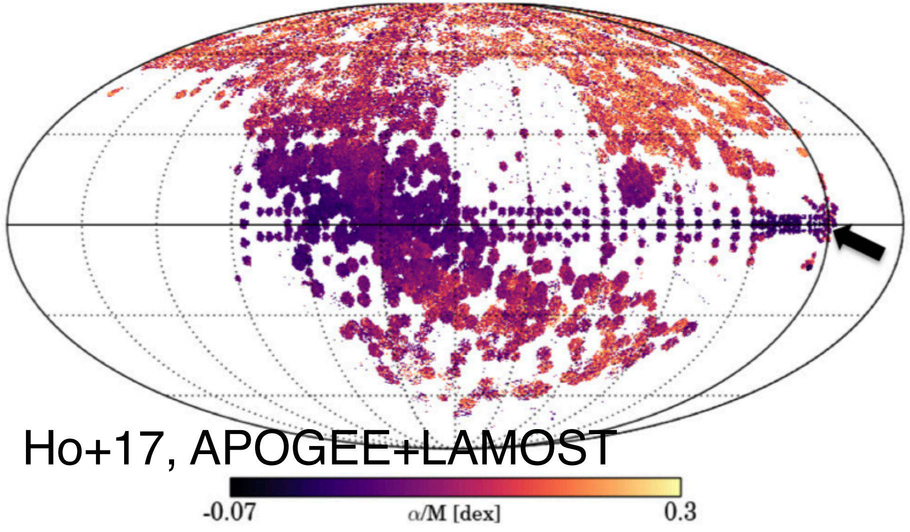
Hayden+14, APOGEE

[O/Fe] Map

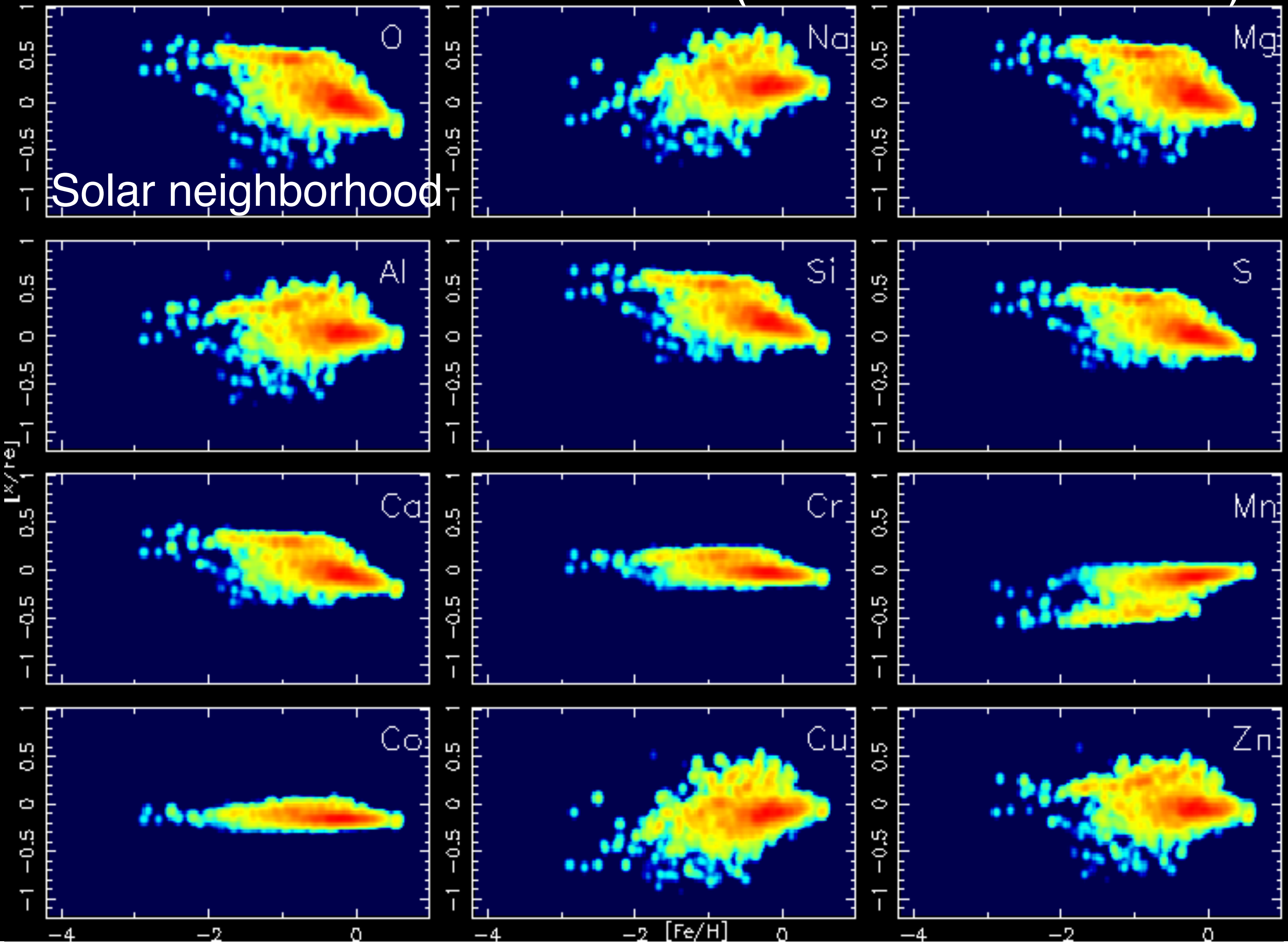




low-mass stellar mass weighted, projected

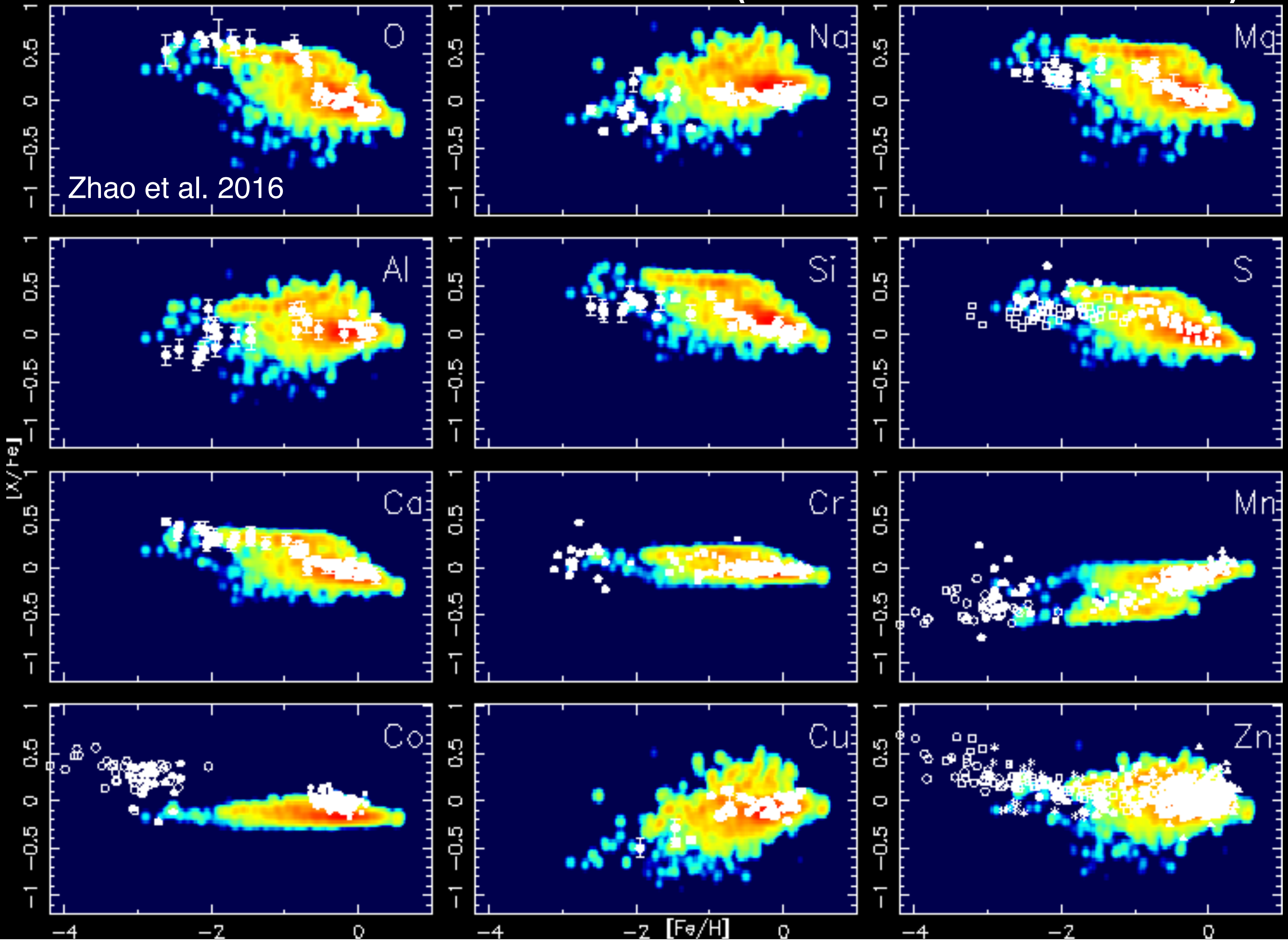

Ho+17, APOGEE+LAMOST

Elemental Abundances (CK & Nakasato 2011+NLTE)

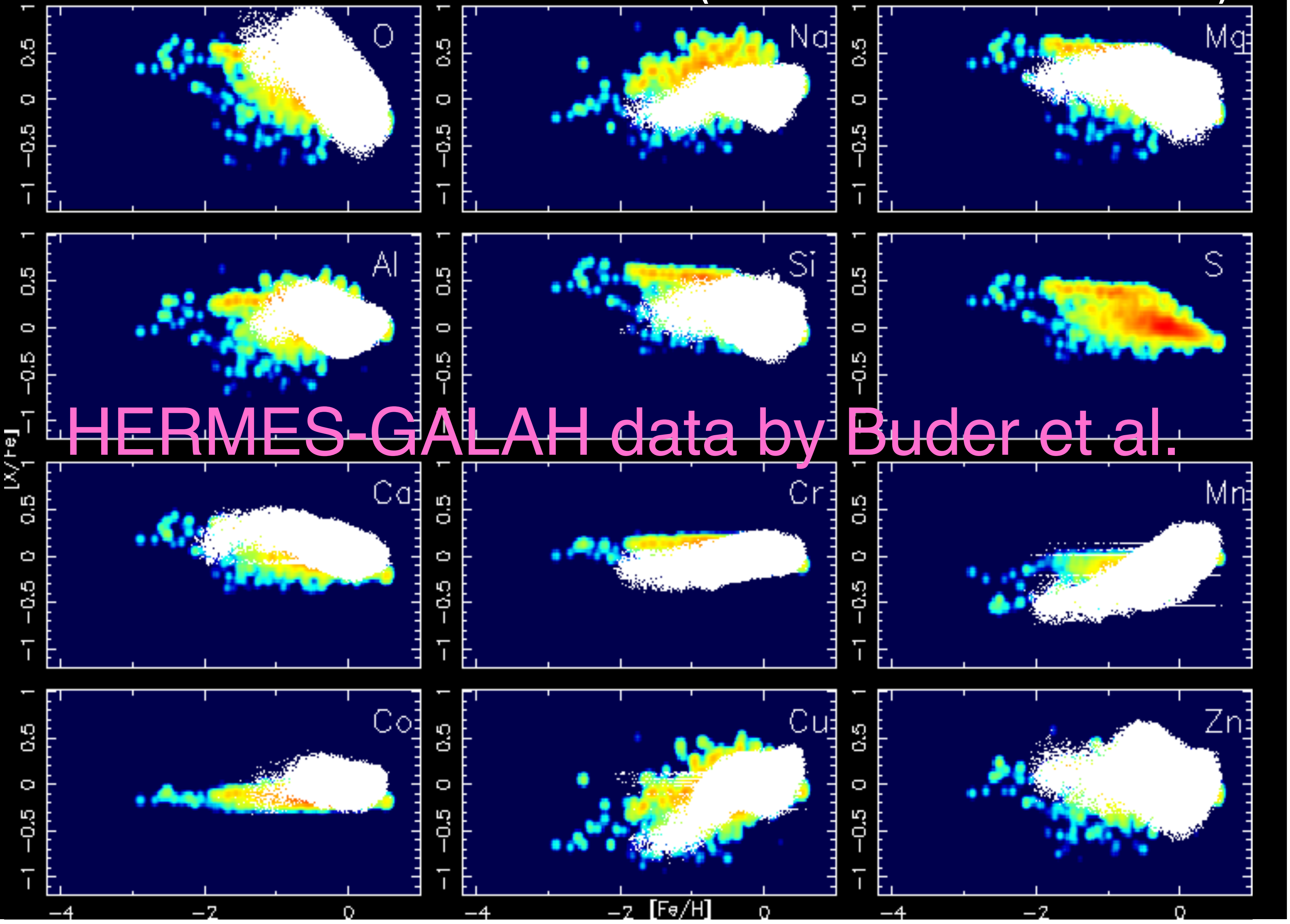


Solar neighborhood

Elemental Abundances (CK & Nakasato 2011+NLTE)



Elemental Abundances (CK & Nakasato 2011+ GALAH)

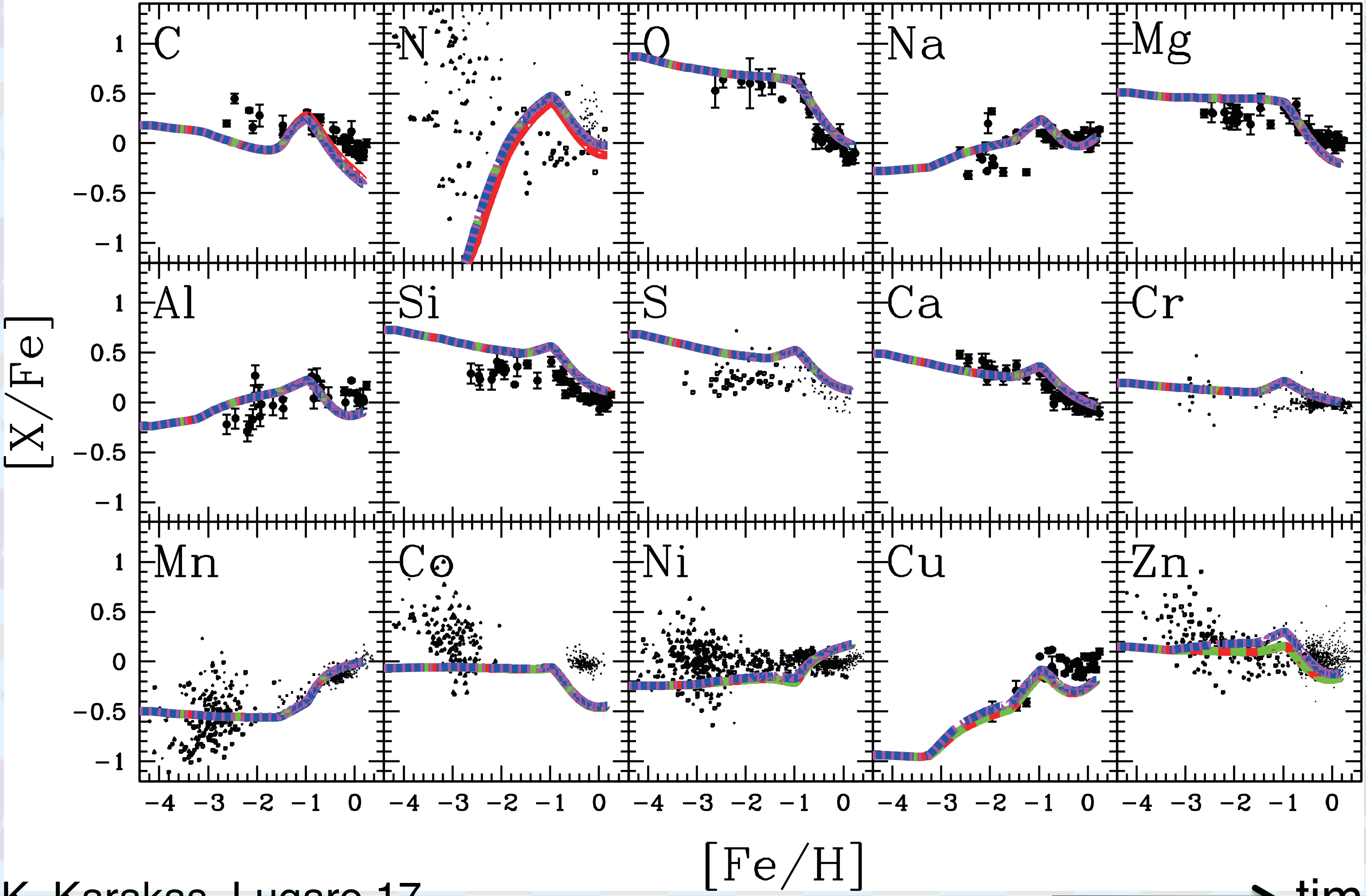


HERMES-GALAH data by Buder et al.

1. Which stellar physics can/should be studied?

Super AGB & ECSN

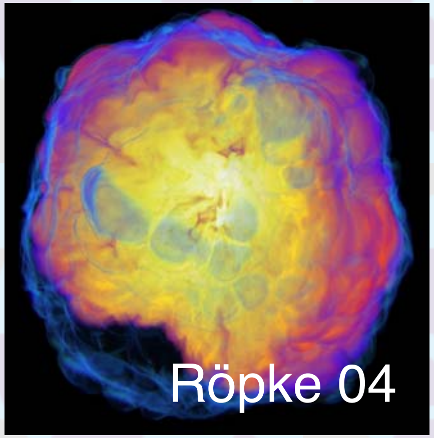
SN+HN+AGB+SNIa(Z), SAGB, ECSN, Iax



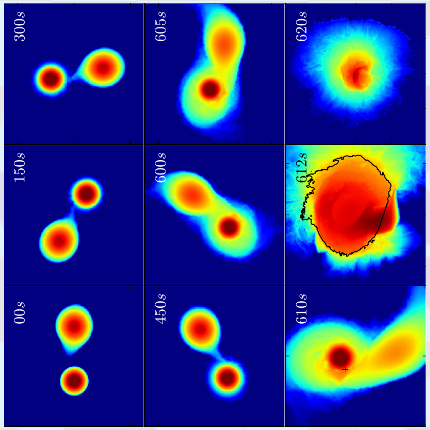
CK, Karakas, Lugaro 17

→ time

SN Ia progenitors / explosions



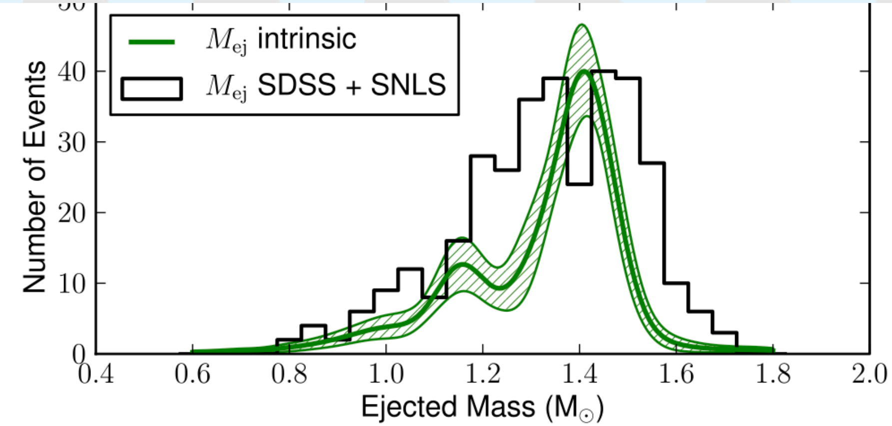
- Ch-mass deflagration or delayed detonation @ **[Fe/H]> -1** (CK, Tsujimoto, Nomoto+ 98)
- sub-Ch double detonation from He-star (Ruiter+14)
- sub-Ch double detonation from H accretion (Yungelson+95, CK+15) @ **low Z**
- Ch-mass deflagration of CONe WD (Meng & Podsiadlowski 14, CK+15, Kromer+15) @ **low Z**



Pakmor+ 11,12

- CO WD+CO WD merger, likely to be sub-Ch
- sub-Ch double detonation from He-WD (Ruiter+14)
- triple merger

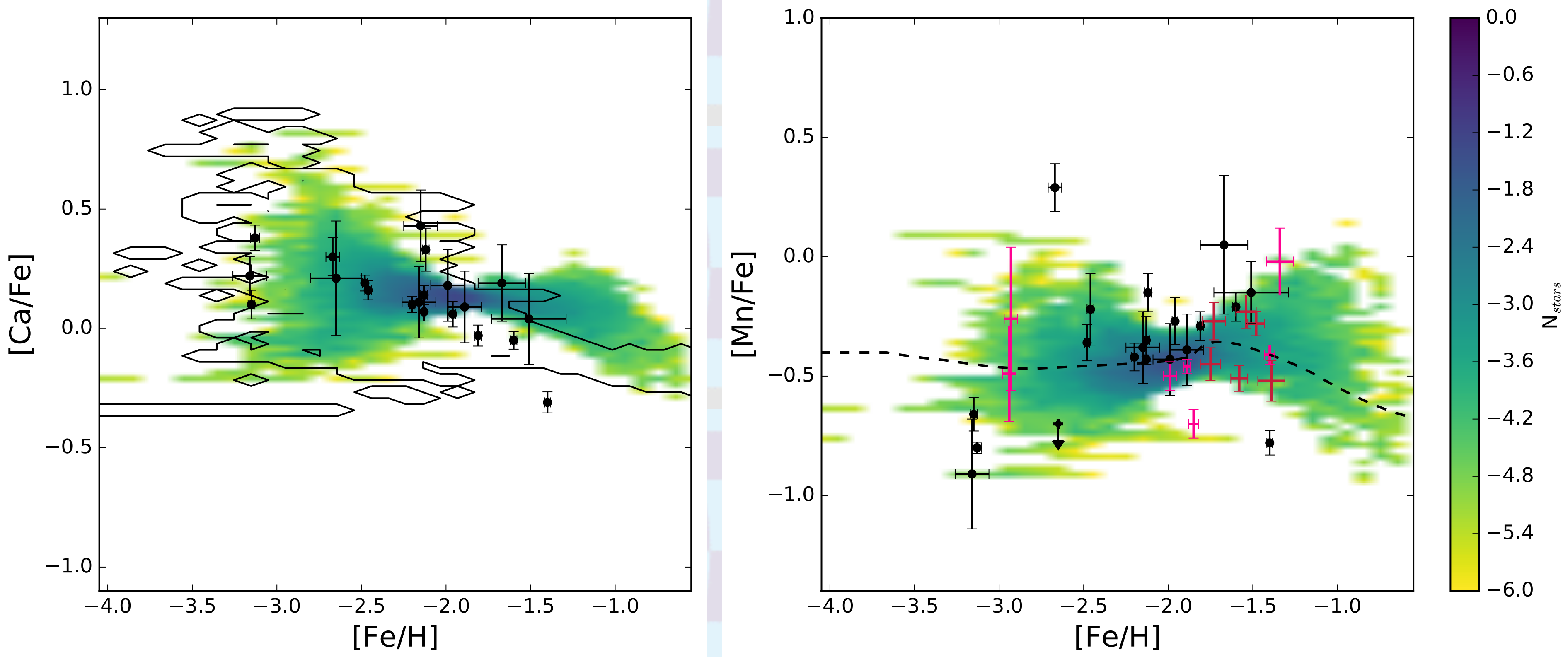
Scalzo et al. 2014



Observations→
The majority of SNe Ia have ~1.4$M_\odot$.

Subclasses of SNIa

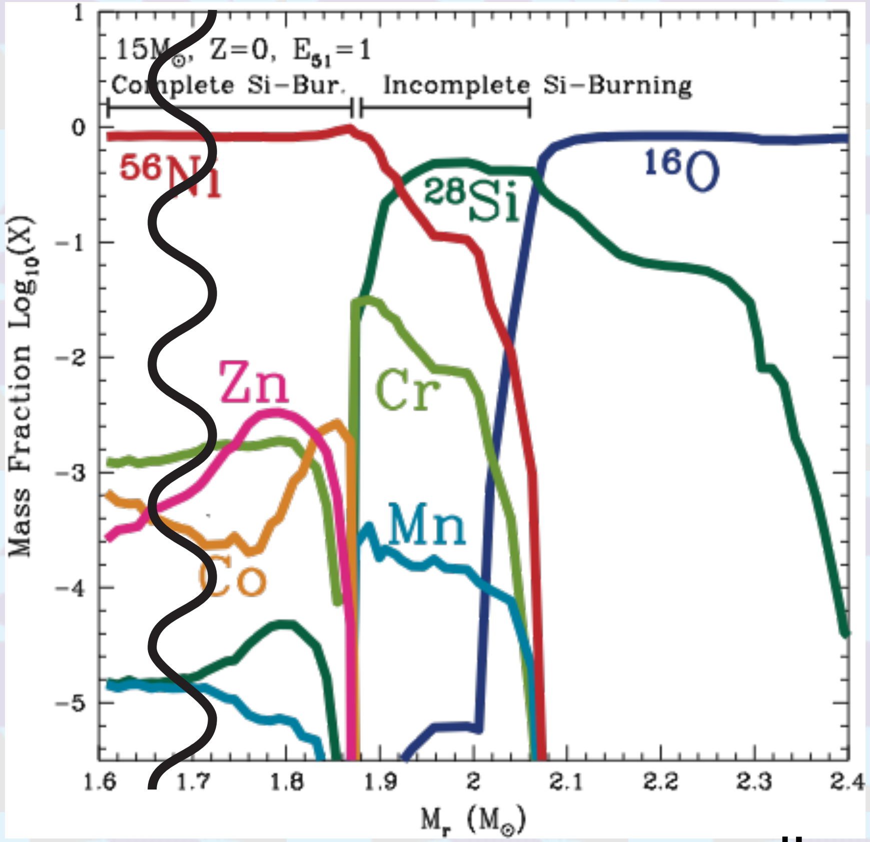
- **Stochastic GCE model** for a dwarf spheroidal galaxy Ursa Minor (Cescutti & CK 2017, ArXiv:1708.09308)
  - SNIax: C deflagration, *possibly* in hybrid CONe WD; Nf5 (Fink+14)
  - sub-Ch SNIa: H accretion in single degenerate system; 1.05 $M_\odot$, (Shigeyama+92) (CK, Nomoto, Hachisu 2015 for details)



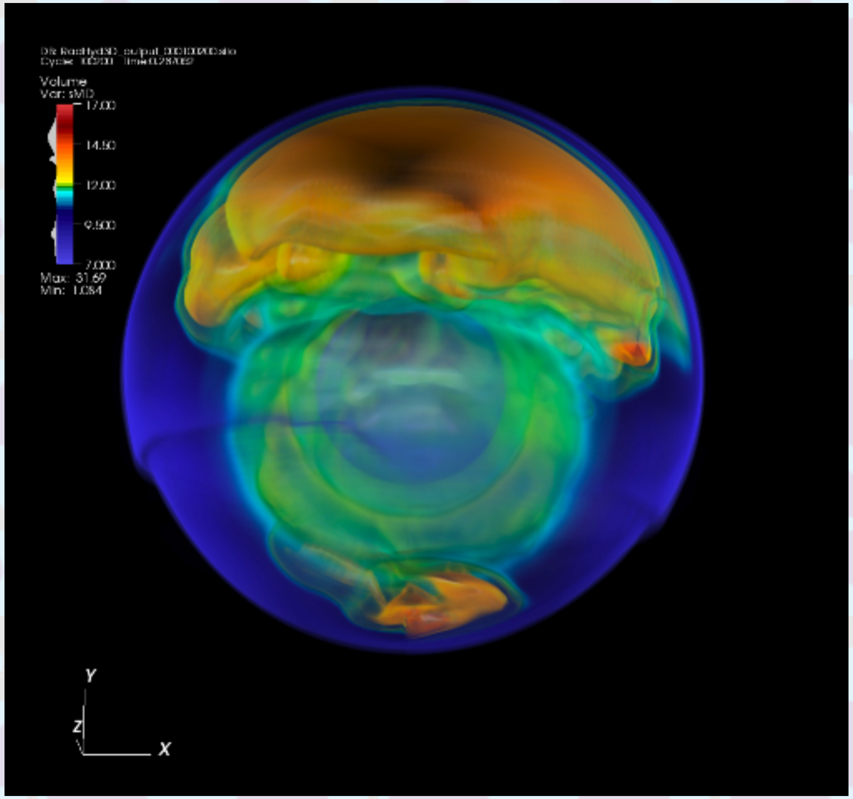
Next generation of SN yields…

- NuGrid
- Limongi+ (rotation)
- Heger+
- PUSH (ν-process)

- 3D yields with ν-process (SN only)

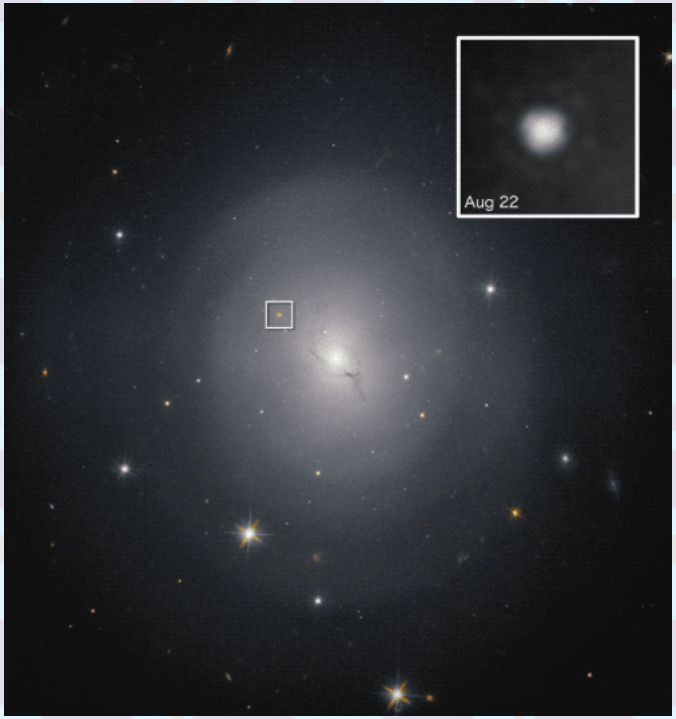


→ radius



Bruenn, Mezzacappa+ 09,13
Also, Marek & Janka 09

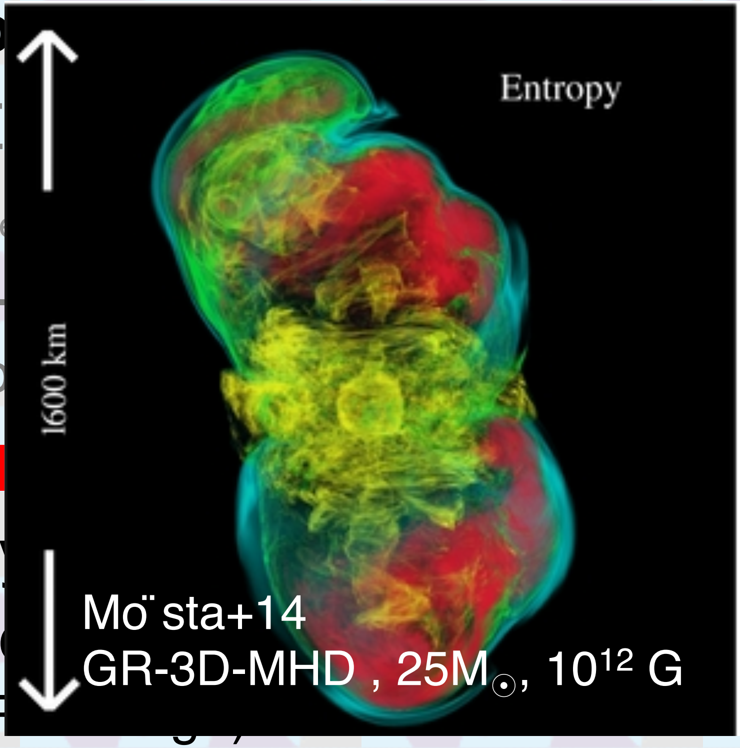
Kilonova



- GW170817
- (short)-GRB
- 2017gfo in NGC4993
- distinct LC and spectra due to lanthanid opacity (open f-shall l=4)

“Go

- E a; Y
- ν- IS (p
- N dy po (F

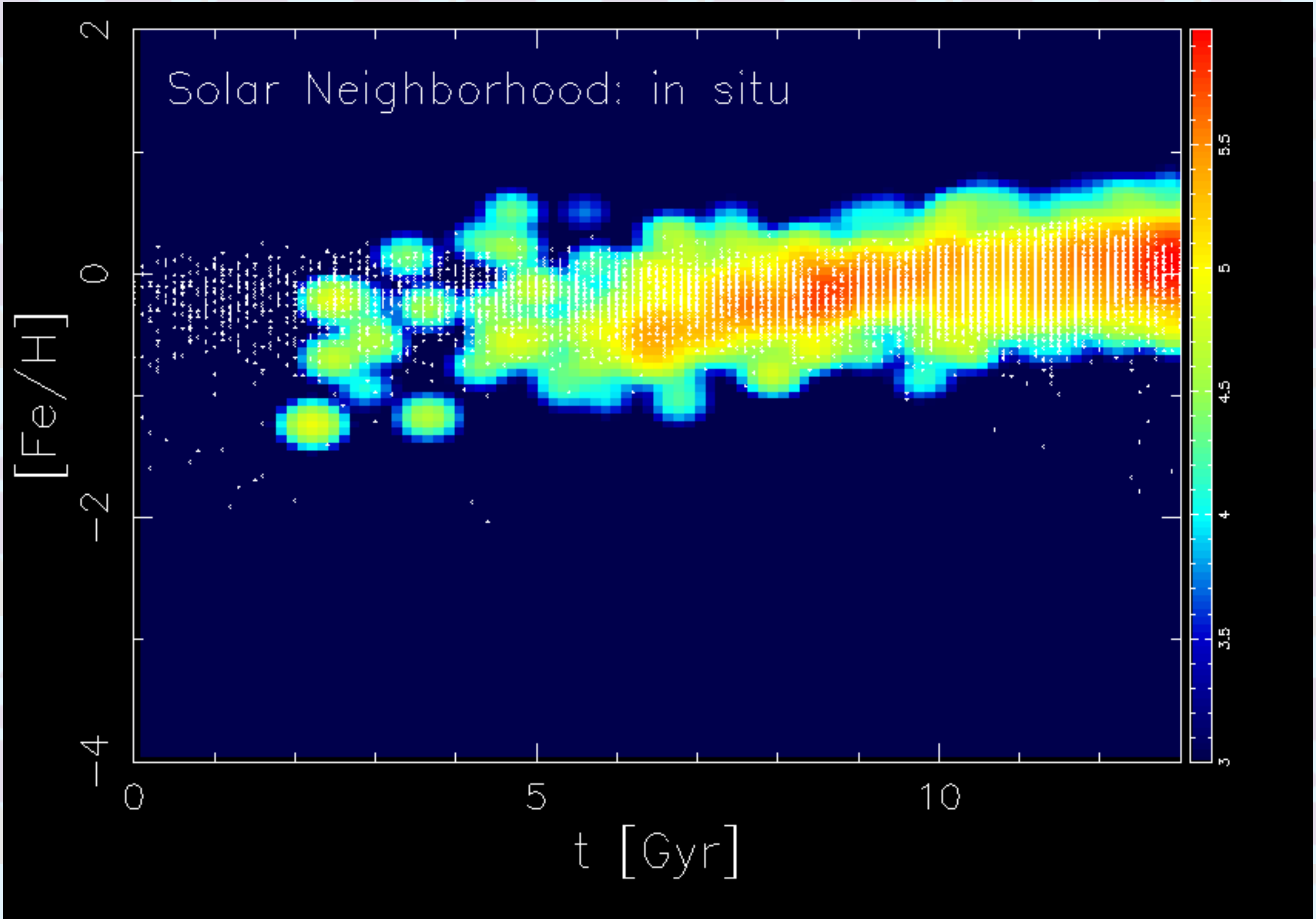


Mösta+14
GR-3D-MHD , 25M$_\odot$, 10^{12} G

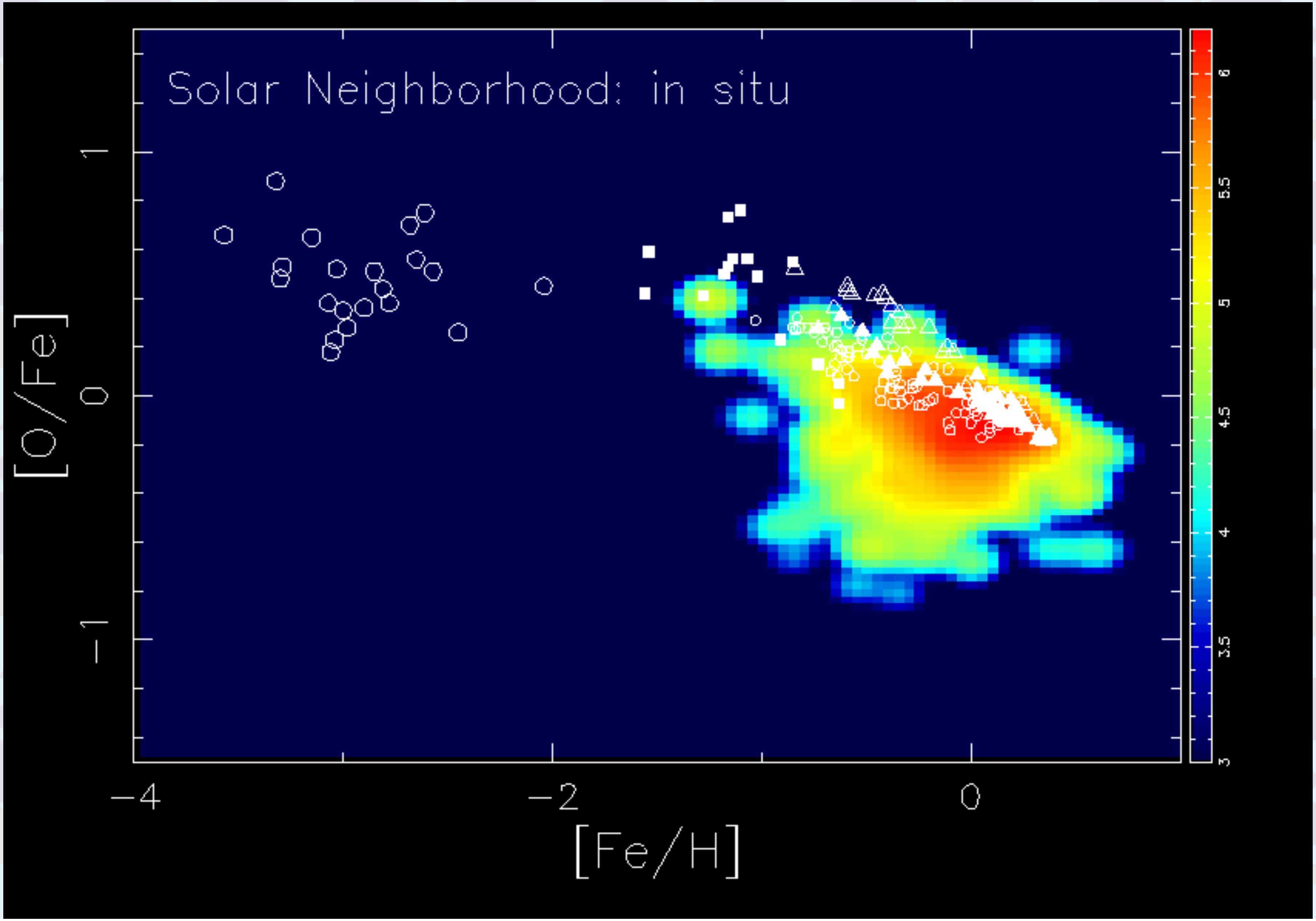
- Magneto-rotational supernova (MRSN), jet or disk – preferred in PCA analysis (Ting, Freeman, CK +12)

2. How Milky Way / disk galaxy formed?

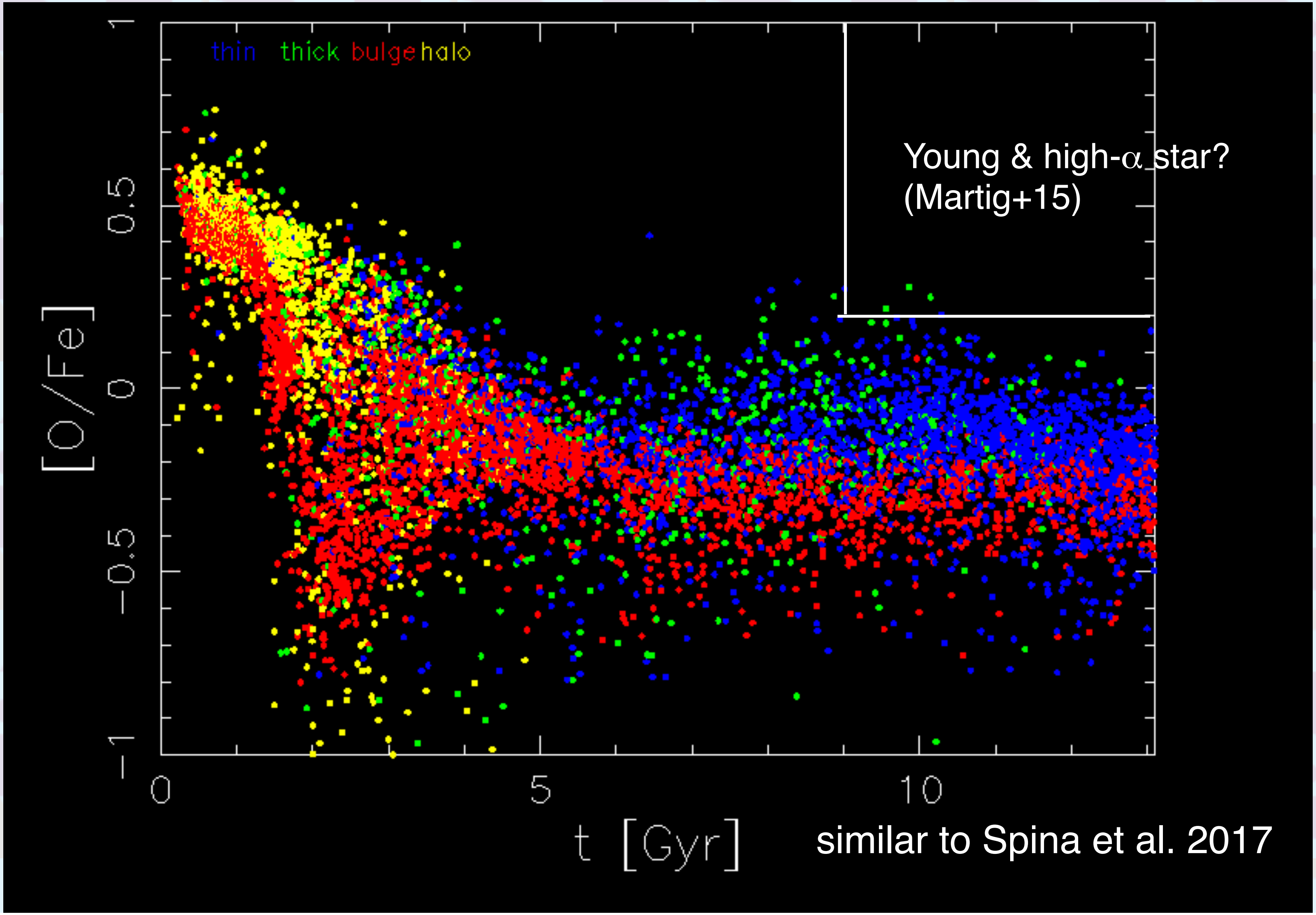
Age-Metallicity Relation



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



[X/Fe] - age

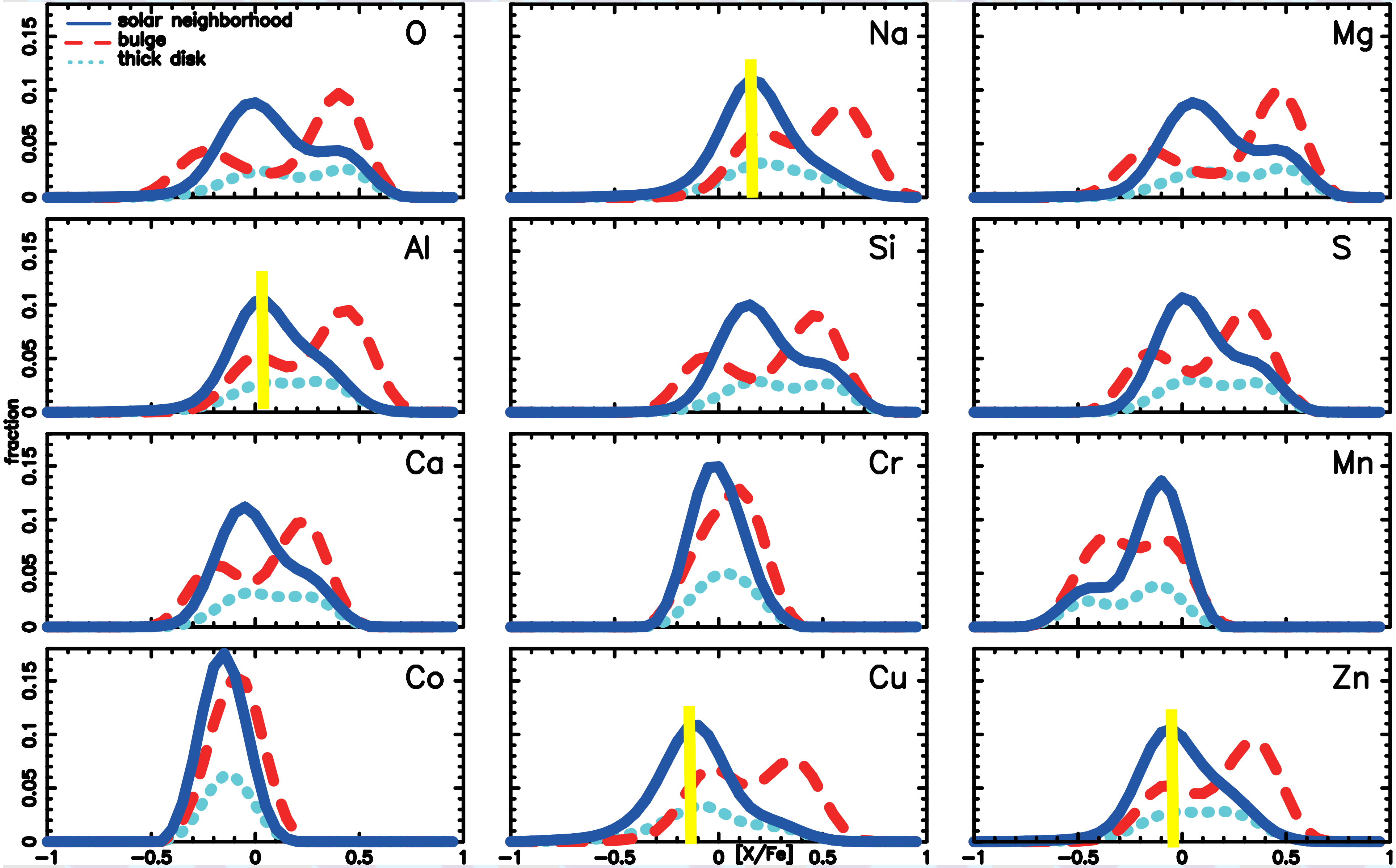


Young & high-α star?
(Martig+15)

similar to Spina et al. 2017

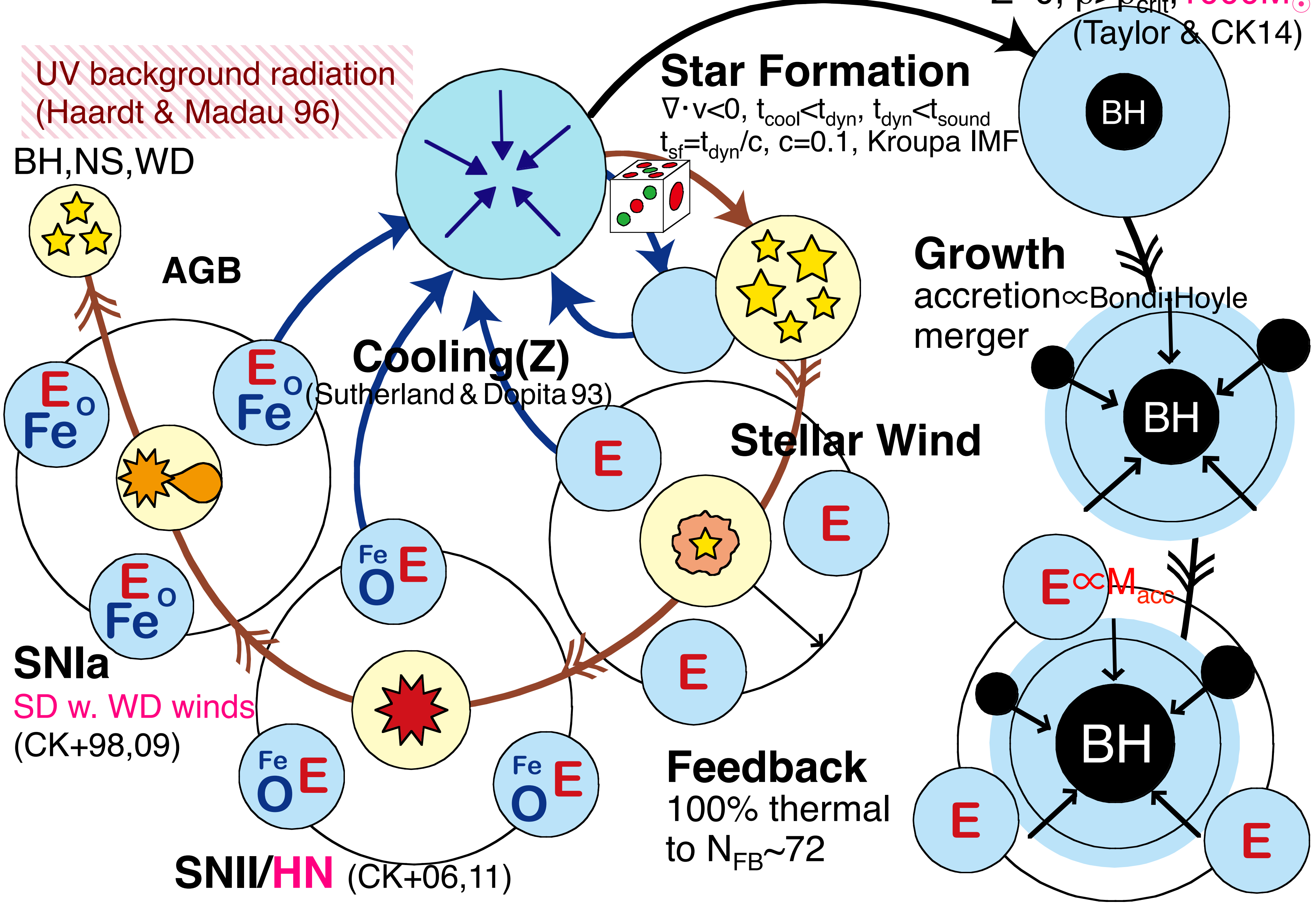
Kinematic thick disk

CK & Nakasato 2011



-1 1 [X/Fe] -1 1

Chemodynamical Simulation



BH Formation
$Z=0$, $\rho>\rho_{crit}$, $1000M_{\odot}$
(Taylor & CK14)

Star Formation
$\nabla\cdot v<0$, $t_{cool}<t_{dyn}$, $t_{dyn}<t_{sound}$
$t_{sf}=t_{dyn}/c$, c=0.1, Kroupa IMF

UV background radiation
(Haardt & Madau 96)

BH,NS,WD

AGB

Cooling(Z)
(Sutherland & Dopita 93)

Stellar Wind

Growth
accretion∝Bondi-Hoyle
merger

$E\propto M_{acc}$

SNIa
SD w. WD winds
(CK+98,09)

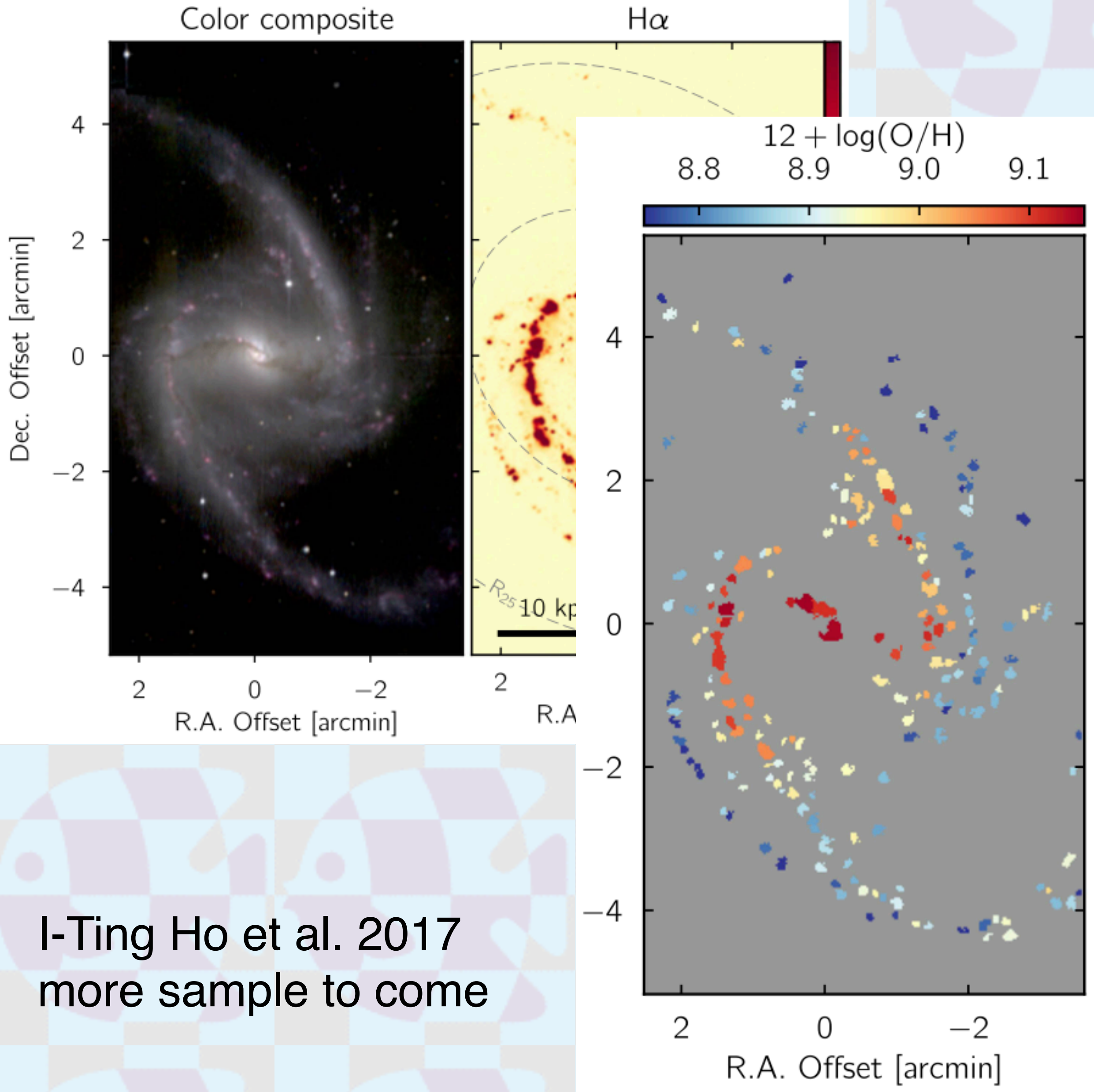
SNII/HN (CK+06,11)

Feedback
100% thermal
to N_{FB}~72

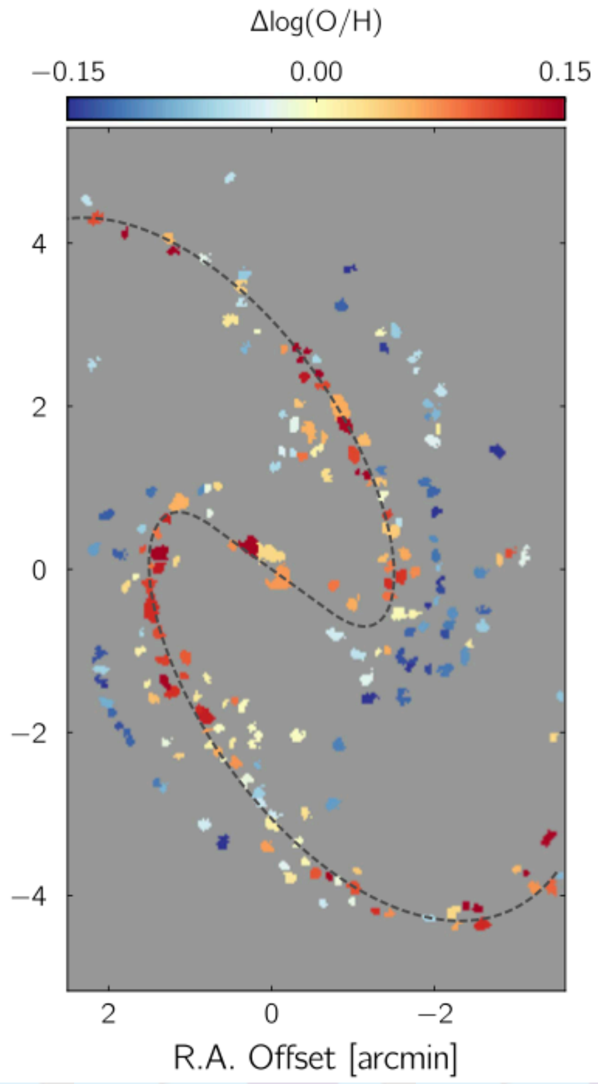
Chemodynamical Simulations

- **Star formation criteria**
  - Katz 92; density only (Stinson+06), Federrath & Klessen 12
- **Feedback modelling**
  - thermal, kinetic, multi-phase (Marrie & White; Scannapieco), stochastic (Dalla Vecchia & Schaye 12); angular momentum (Sminth+); super-bubble (Krause+13; Krumholz)…
- **Mixing**
  - Particle based codes, e.g., SPH (Starkenburg talk)
    - Gas particles get metals from star particles *X(t)* based on *h* (CK 2004; CK & Nakasato 2011) → inhomogeneous enrichment
    - mixing with diffusion equation… (CK priv. comm.)
  - Mesh-based code (RAMSES – Samento talk, Gibson talk)
    - ISM is mixed with grids, depending on the resolution.
  - Real ISM in disk?

Mixing in NGC1365



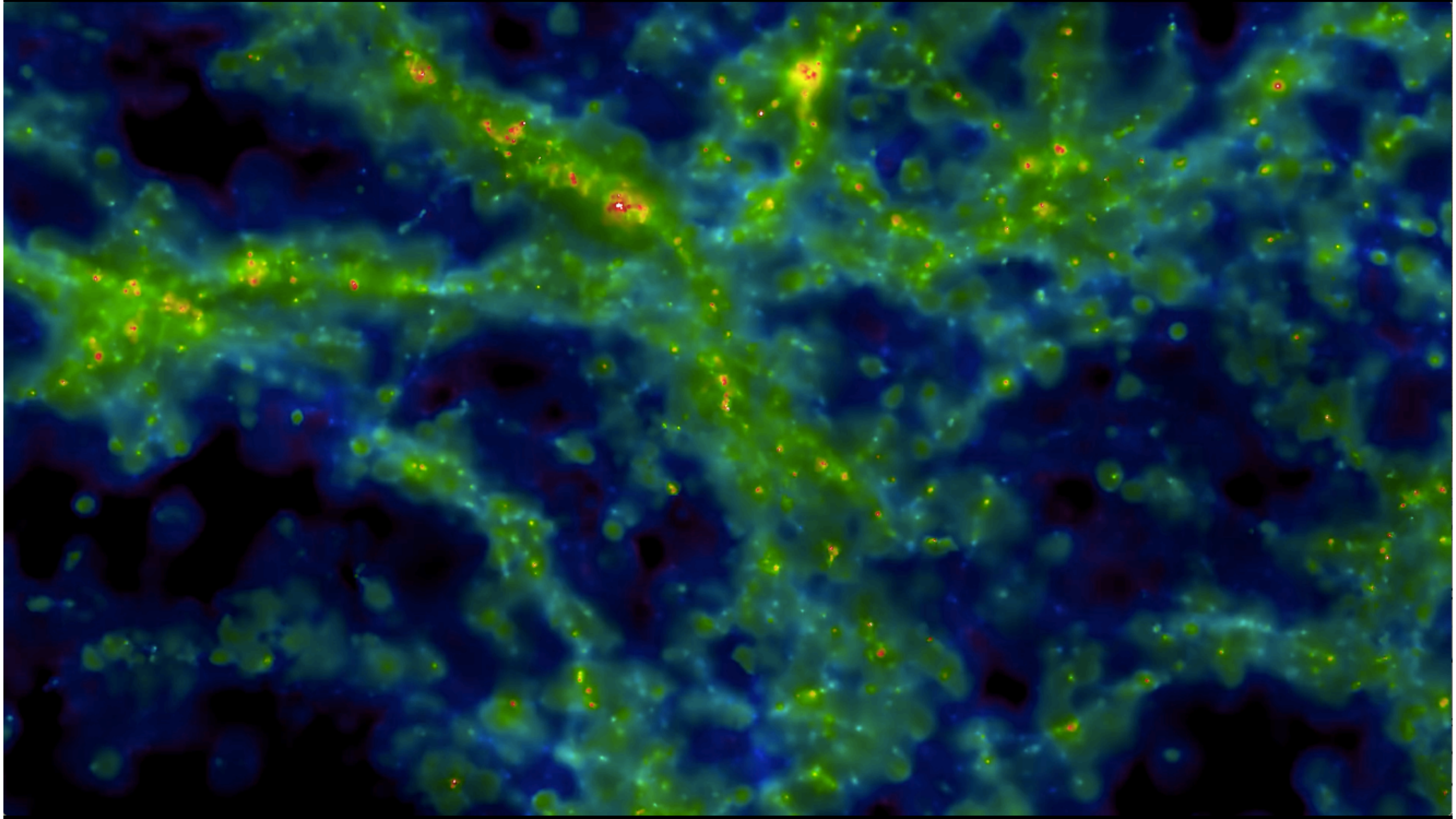
Radial gradient subtracted



I-Ting Ho et al. 2017
more sample to come

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

Summary

- ✓ [X/Fe] trends; K,Sc,V, Ni solved.
- ✓ [α/Fe] trend in Milky Way (radial & vertical gradients)
- ✷ Inhomogeneous chemical enrichment
  - ★ There is no strong Age-Metallicity Relation
  - ★ Most metal-poor stars ≠ Oldest stars
  - ★ Long-lifetime sources (e.g., AGB stars, NS mergers) can contribute at low metallicities.
- ✷ The scatter of [X/Fe] can constrain stellar physics e.g., super-AGB, SNIax, ECSN, NSM, MRSN.
- ✷ Thick disk stars are not just old; formed in merging galaxies, [Na,Al,Cu,Zn] as low as thin disk & lower than bulge.
- ✷ CNO diagnostics at high-z galaxies to constrain star formation history of disk galaxies.