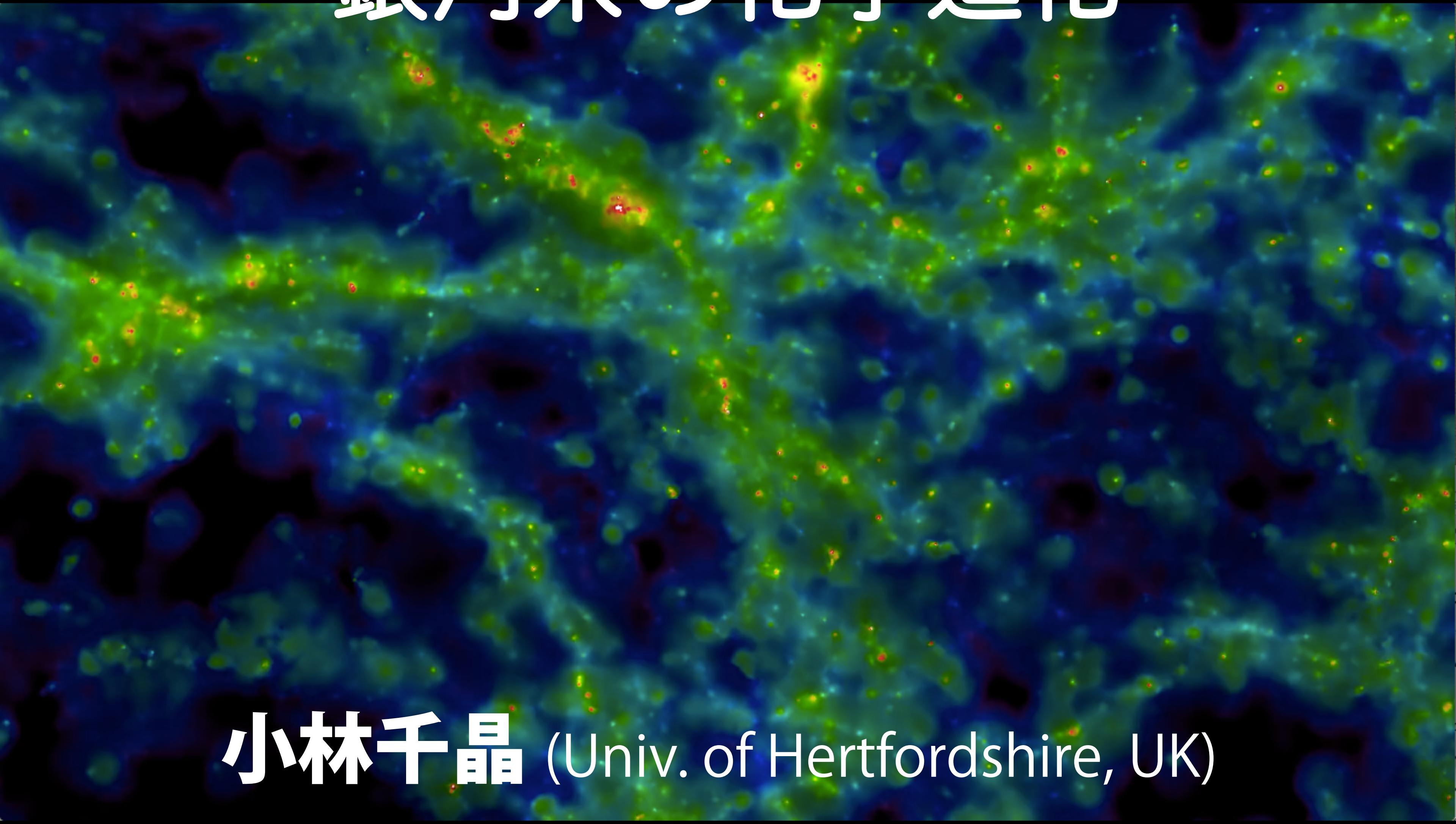
銀河系の化学進化



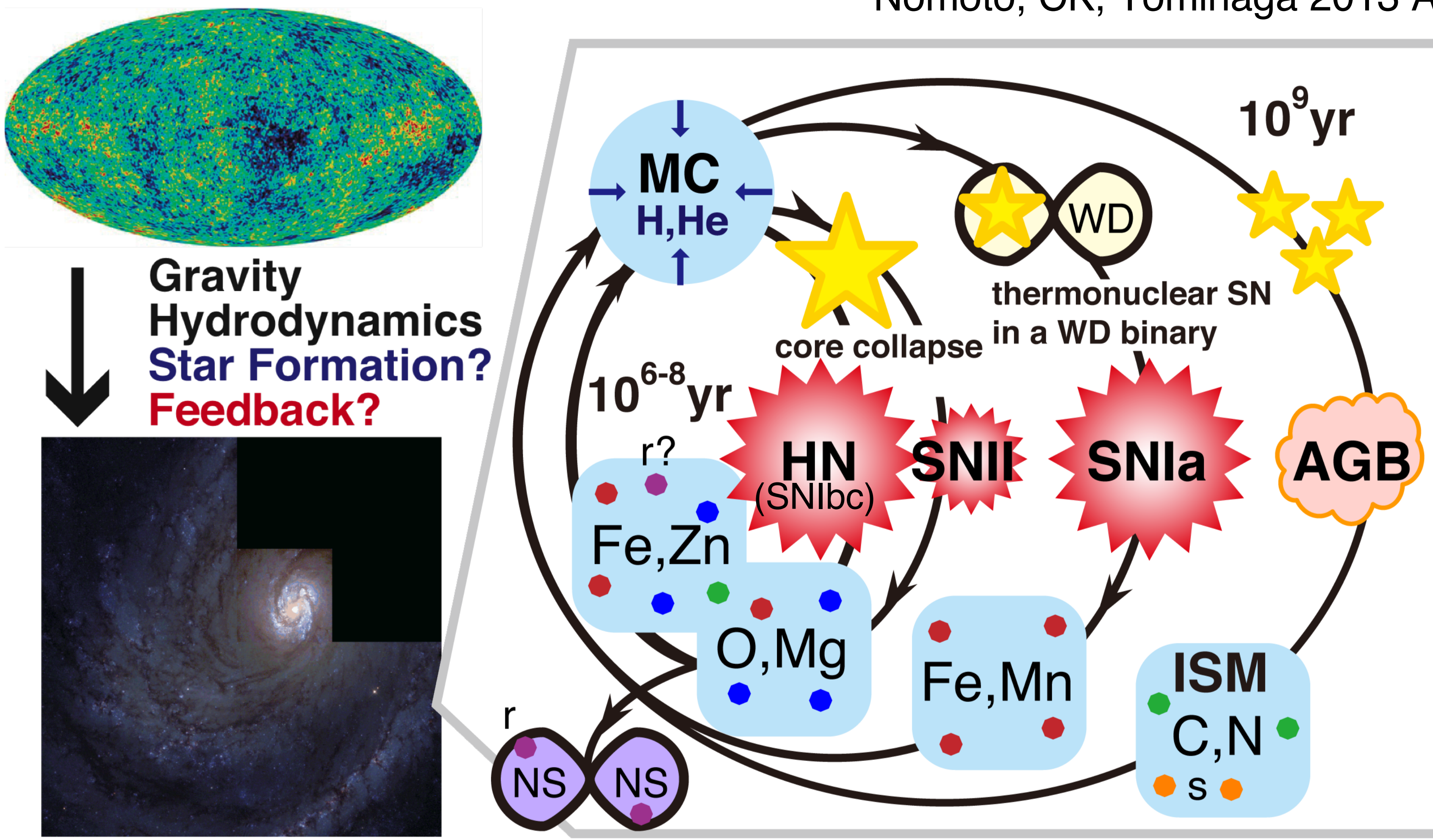
小林千晶 (Univ. of Hertfordshire, UK)

Cosmic evolution from z=5 to 0, [O/H] = –5 (blue) to -1 (red); > -1 (white)

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

Chemical Enrichment

Nomoto, CK, Tominaga 2013 ARAA

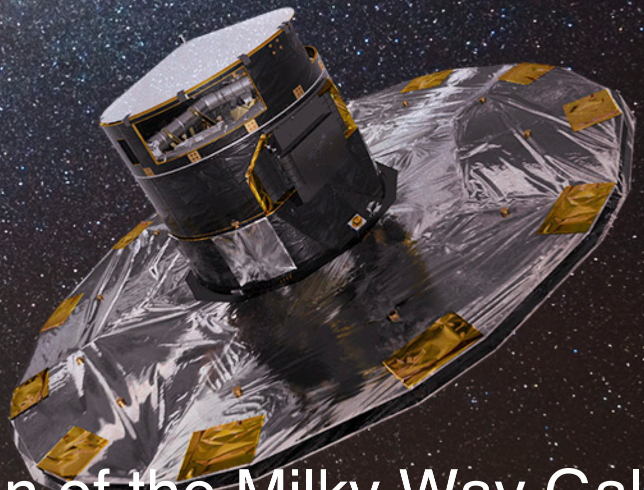


- [Fe/H] and [X/Fe] evolve in a galaxy: fossils that retain the evolution history of the galaxy → **Galactic Archaeology**

Galactic Archaeology

of Milky Way and local dwarf galaxies

- Motions of <u>one billion</u> stars are measured with GAIA.
- Ages from asteoseismology COROT, Kepter, 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
  - **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)
  - **PFS** on Subaru (R~2300-5000)
  - **MSE** (R~2000/6500/20000)
- Chemical and dynamical evolution of the Milky Way Galaxy are being revealed!



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

Galactic Chemical Evolution (GCE)

No instantaneous approximation

(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

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

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**

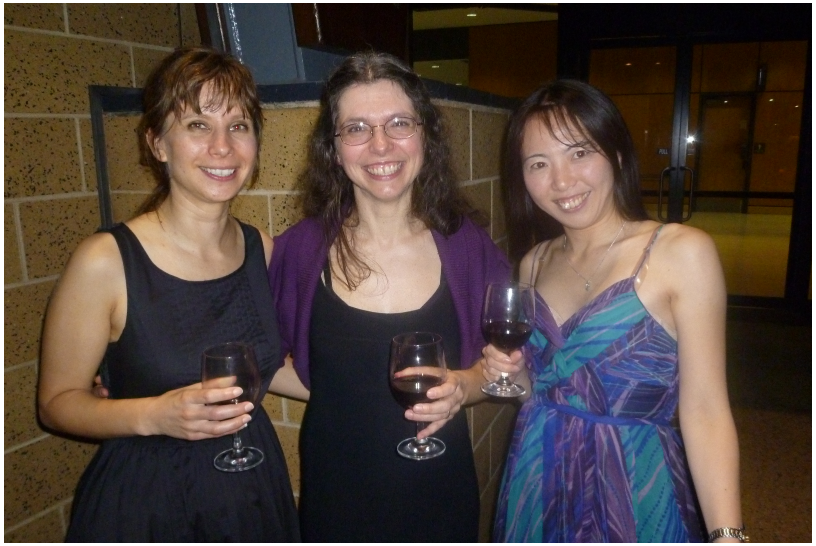
(2) Stochastic model

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

New GCE model

CK, Karakas, Lugaro 2020, ApJ, press release tomorrow!

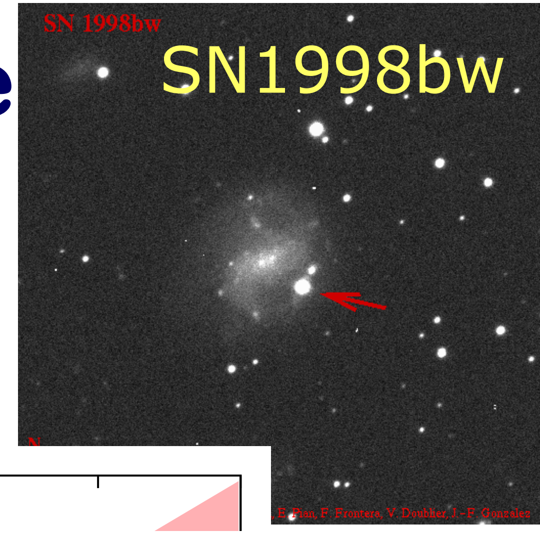
- New solar abundances
- New initial (BBN) abundances
- New SNIa yields (CK, Leung, Nomoto 2020, ApJ, 895, 138)
- With super-AGB stars (~8-10$M_\odot$)
- With failed SNe at >30$M_\odot$, keeping Hypernovae >=20$M_\odot$
- Elements up to U with s and r-processes

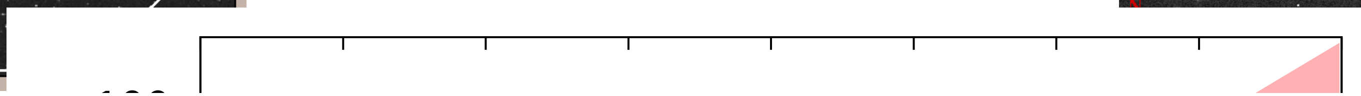


Nuclei in the Cosmos XII, *Cairns 2012 &* XIII, *Debrecen 2014*

Core-collapse SNe

- Explosion mechanism??
- SN light curves & spectra fitting → M, E_{kin}, M(Fe)





THE ASTROPHYSICAL JOURNAL, 900:179 (33pp), 2020 September 10

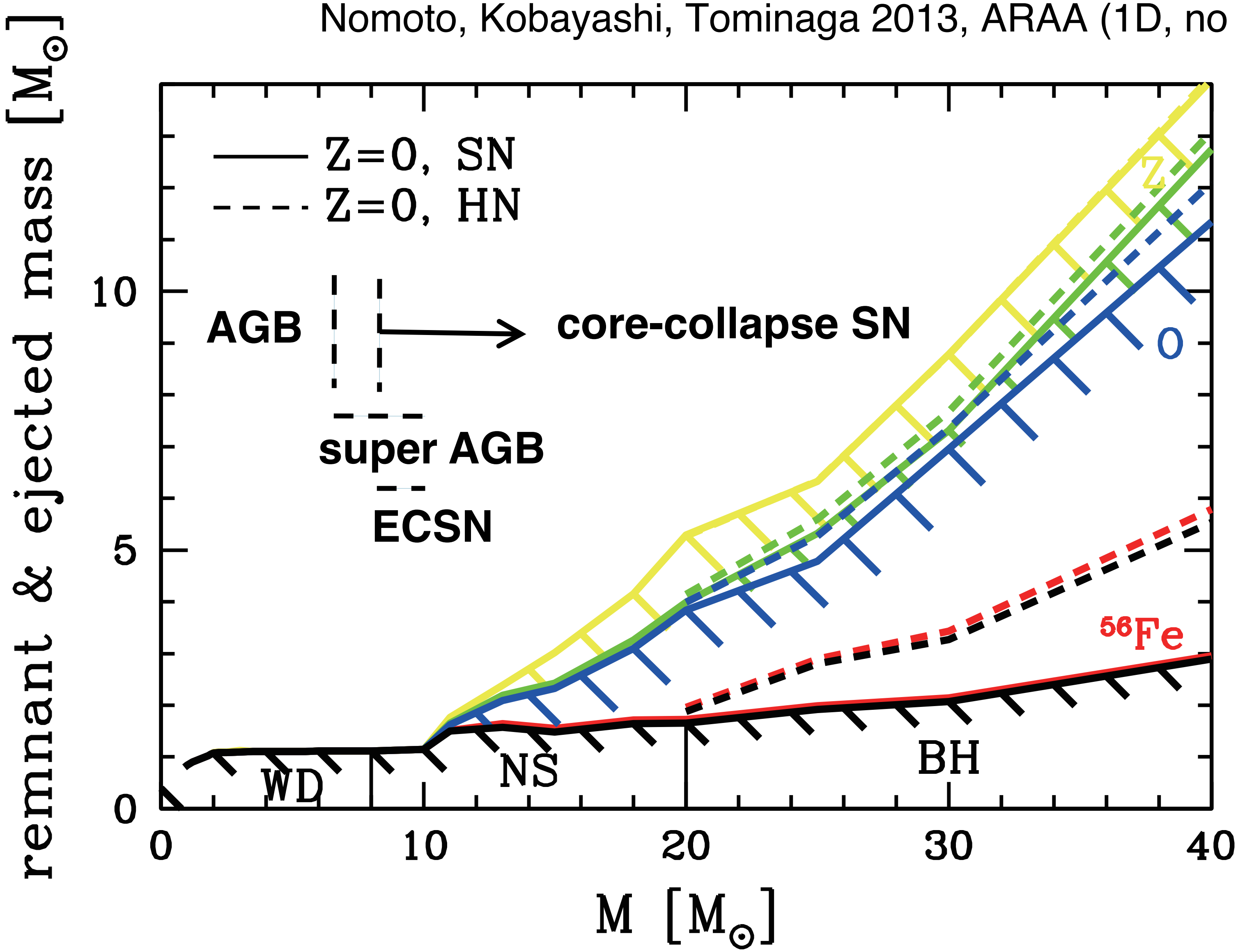
Table 2

Mass Ranges of Core-collapse Supernovae Used in Our Fiducial GCE Model, and Necessary Conditions for the Explosions

	Stellar mass ($M_\odot$)	Rotation	Magnetic field
ECSN	∼8.8–9	no	no
SNII/Ibc	10–30	no	no
failed SN	30–50	no	no
HN	20–50	yes	weak?
MRSN	25–50	yes	strong

Nucleosynthesis Yields

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



Also, Woosley & Heger; Limongi & Chieffi

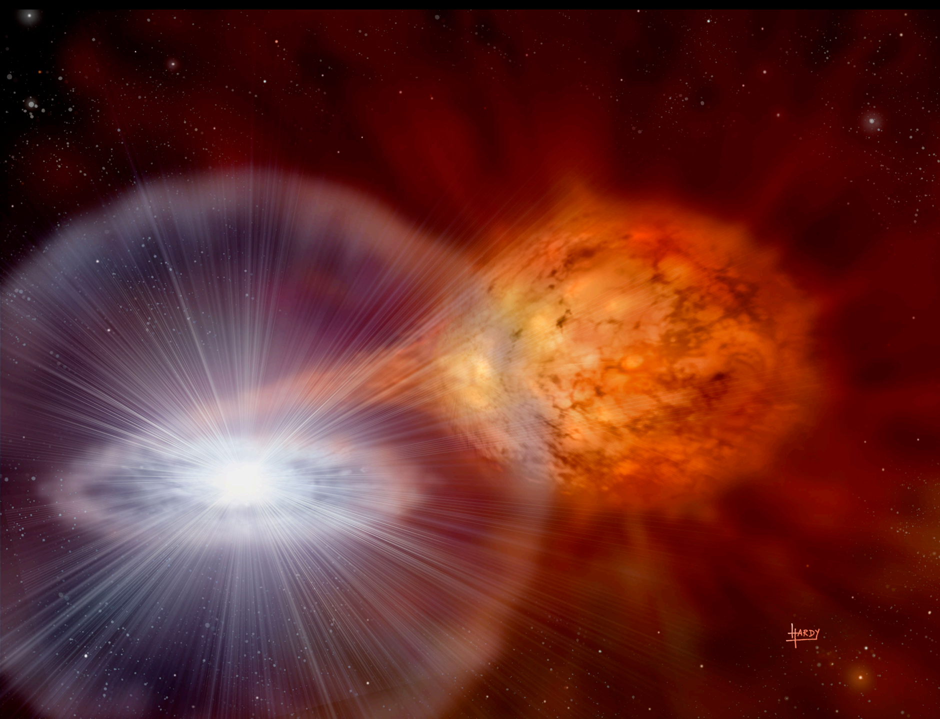
Thermonuclear (Type Ia) Supernovae

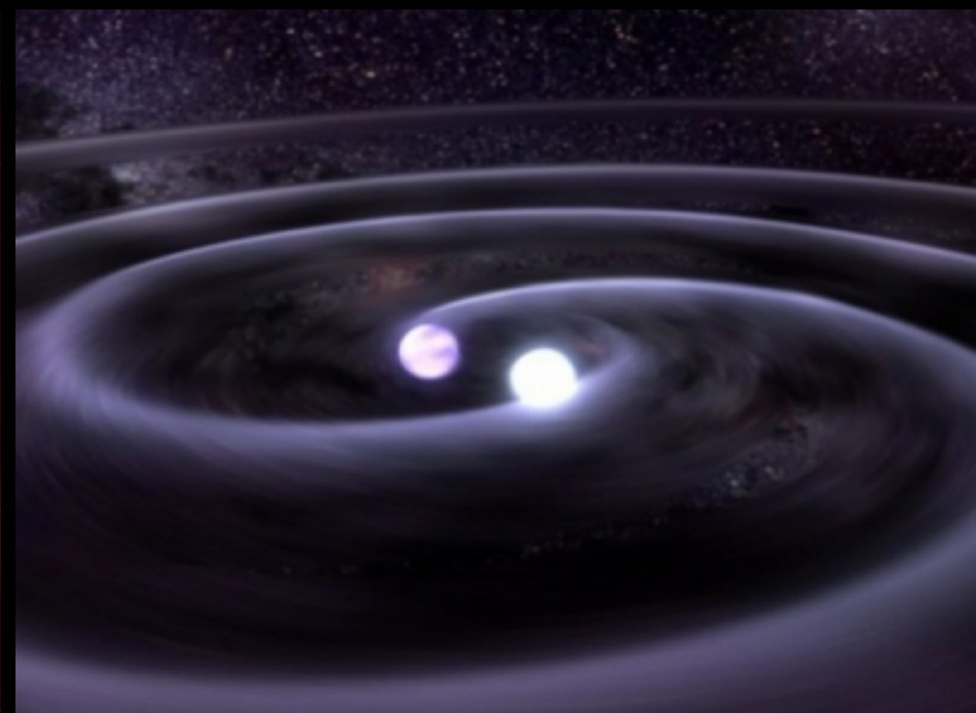
Thermonuclear explosion in a binary with C+O white dwarf

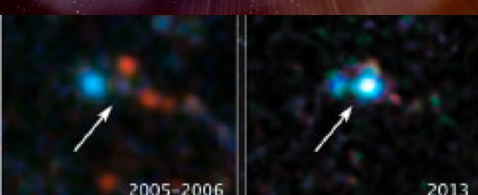
Ch-mass explosion
(deflagration or delayed detonation) possibly in SD

vs

sub-Ch mass explosion
(double detonation) in DD and SD





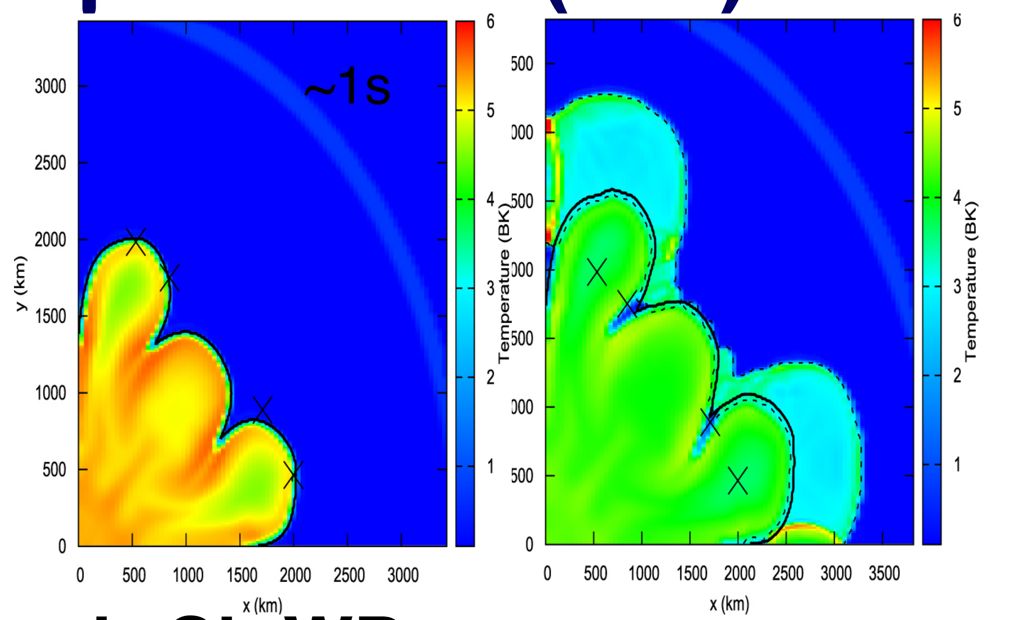


companion star observed (McCully+14)

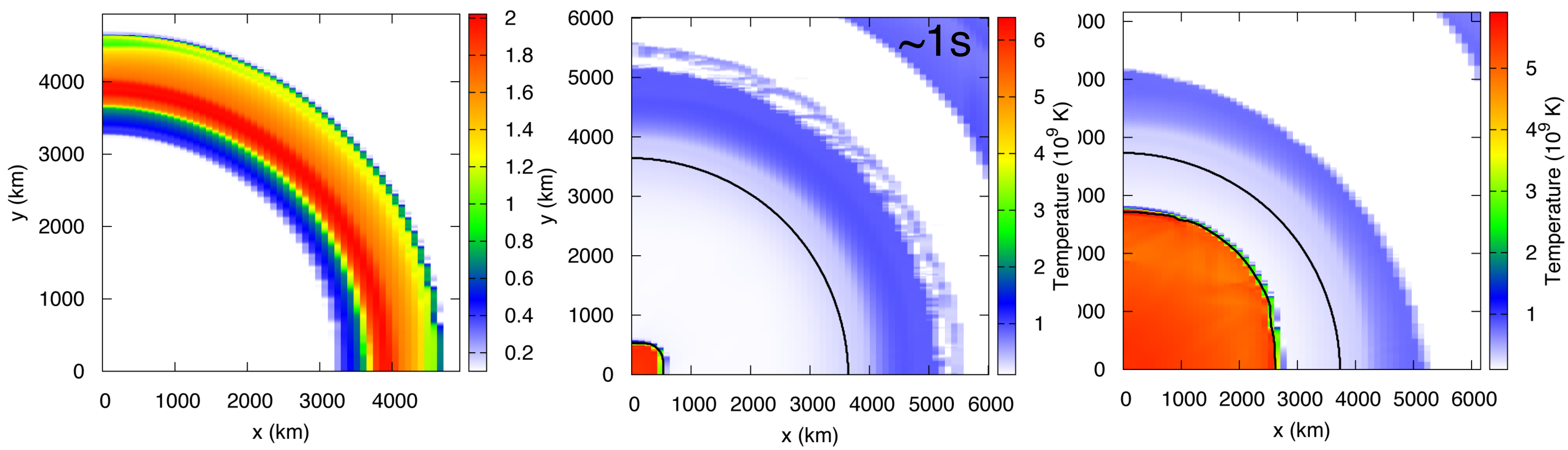
CK, Leung, Nomoto 2020 for 2D hydrodynamical explosions, nucleosynthesis, & CCE

Type Ia SN explosions (2D)

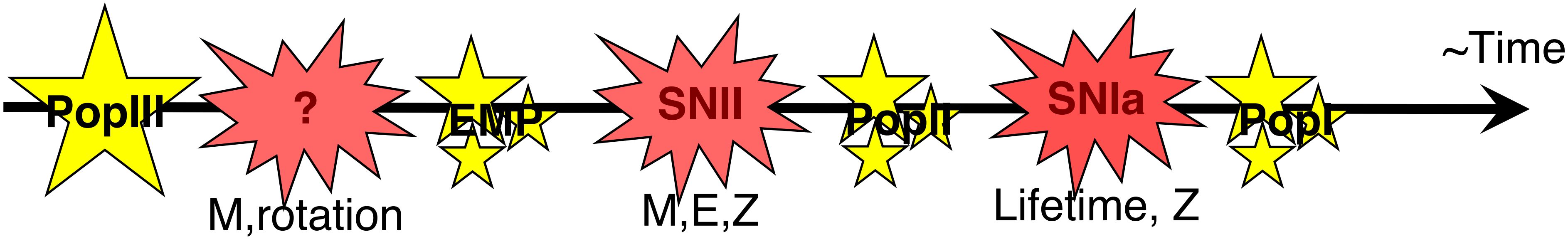
- **Delayed detonation of Ch WD:** $1.38M_\odot$ C+O WD, X(C)=X(O)=(1-Z)/2, solar composition Z, $\rho_c = 3 \times 10^9 g/cm^3$, 10^8K

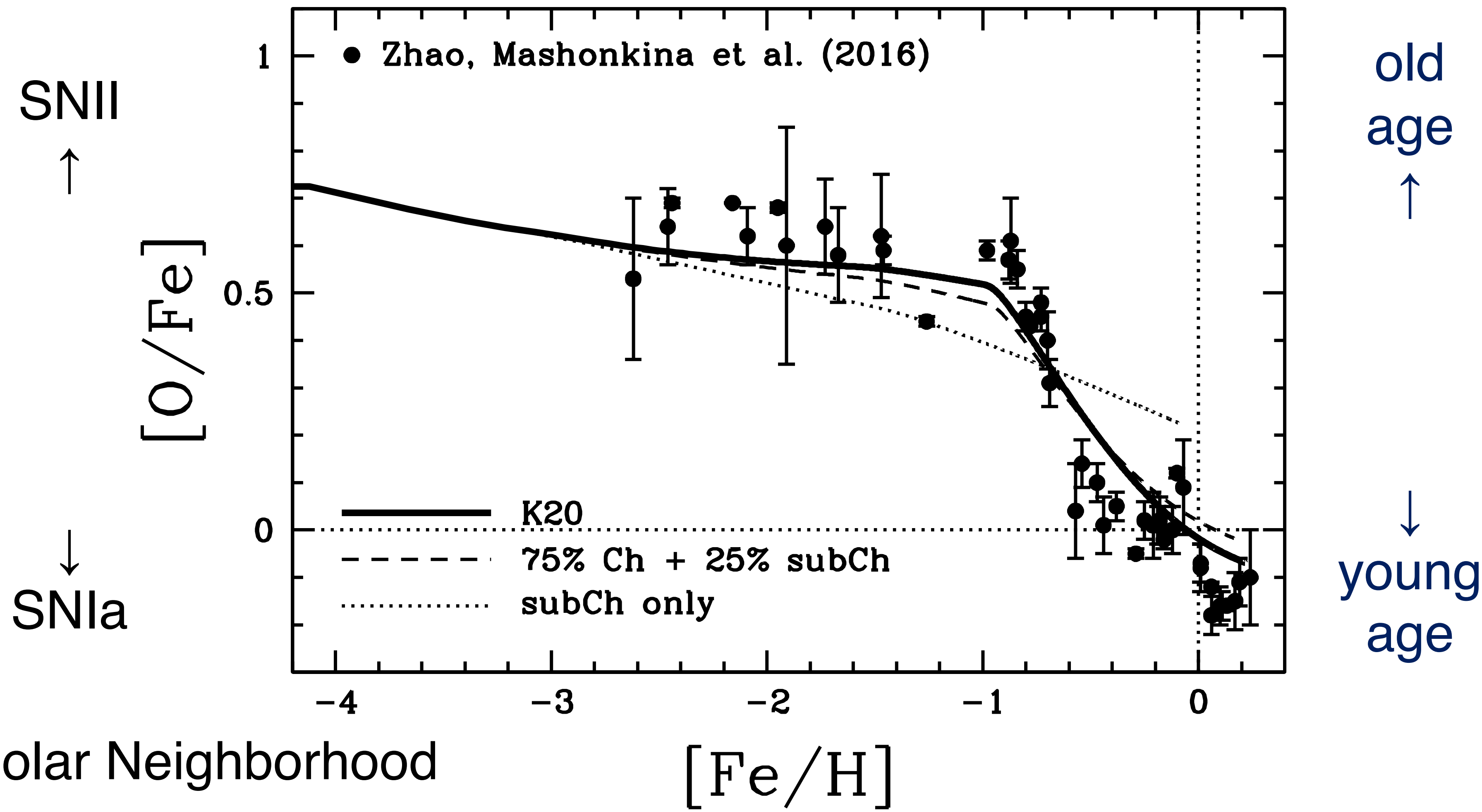


- **Double detonation of sub-Ch WD:** $1M_\odot$ C+O WD including $0.05M_\odot$ He envelope, $\rho_c = 3.2 \times 10^7 g/cm^3$, 10^8K



The [α/Fe]-[Fe/H] relation

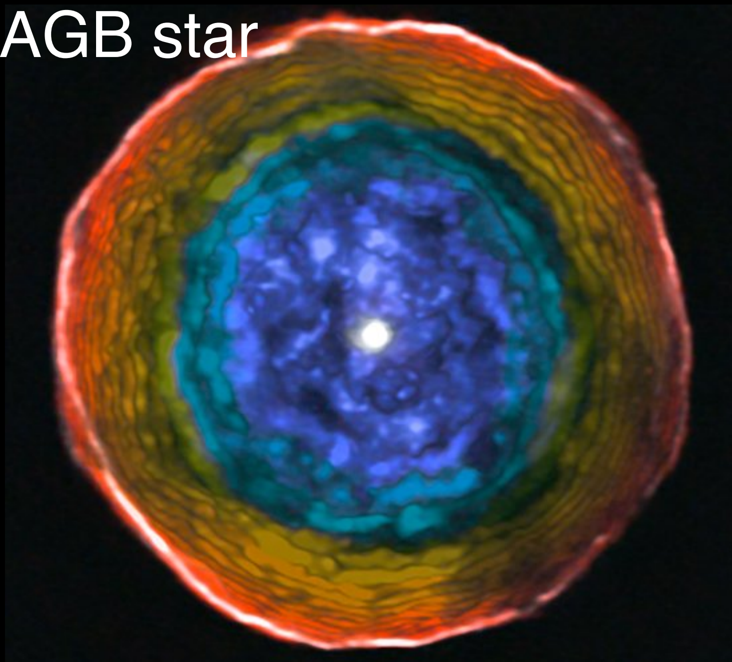




Solar Neighborhood

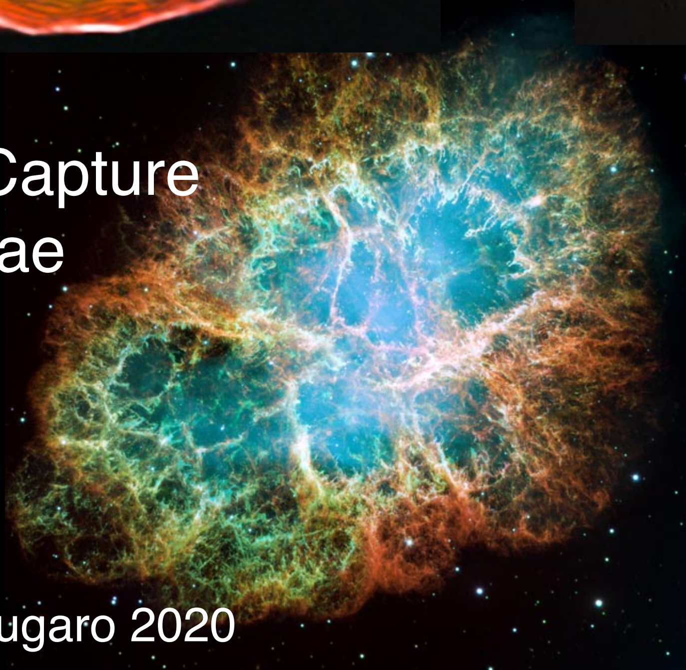
Neutron-capture processes

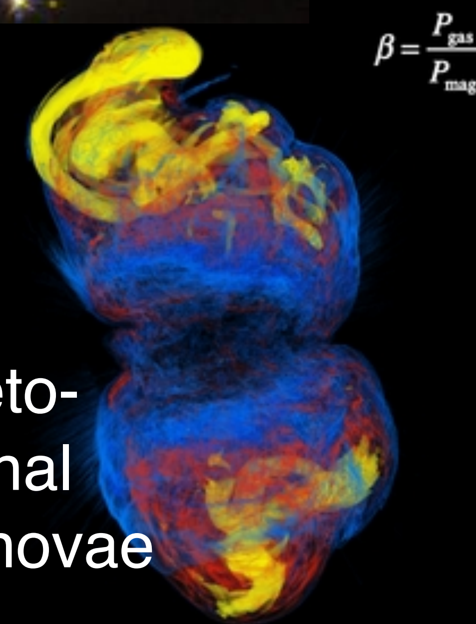
AGB star



Neutron Star Merger

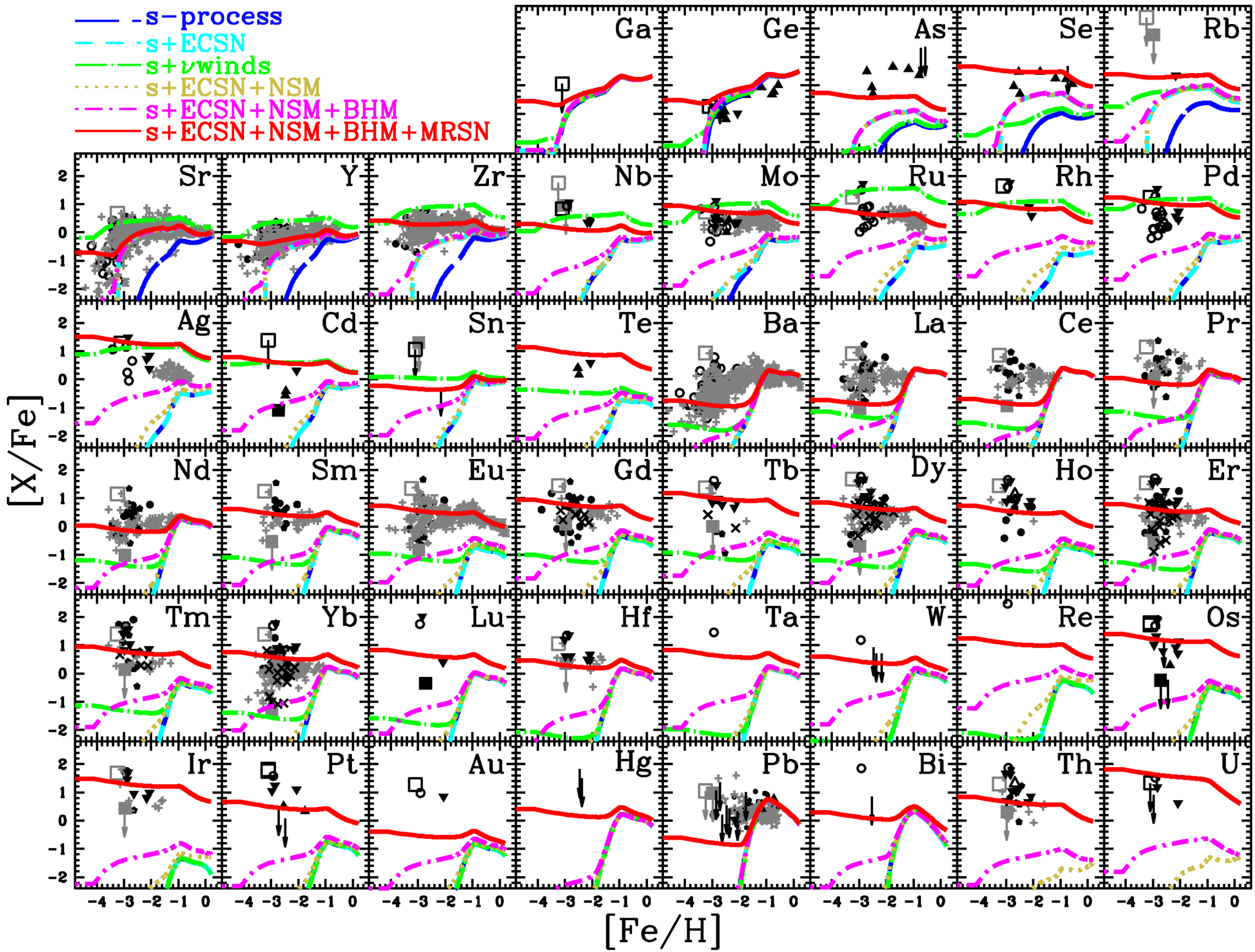
Electron Capture Supernovae





Magneto-rotational Supernovae

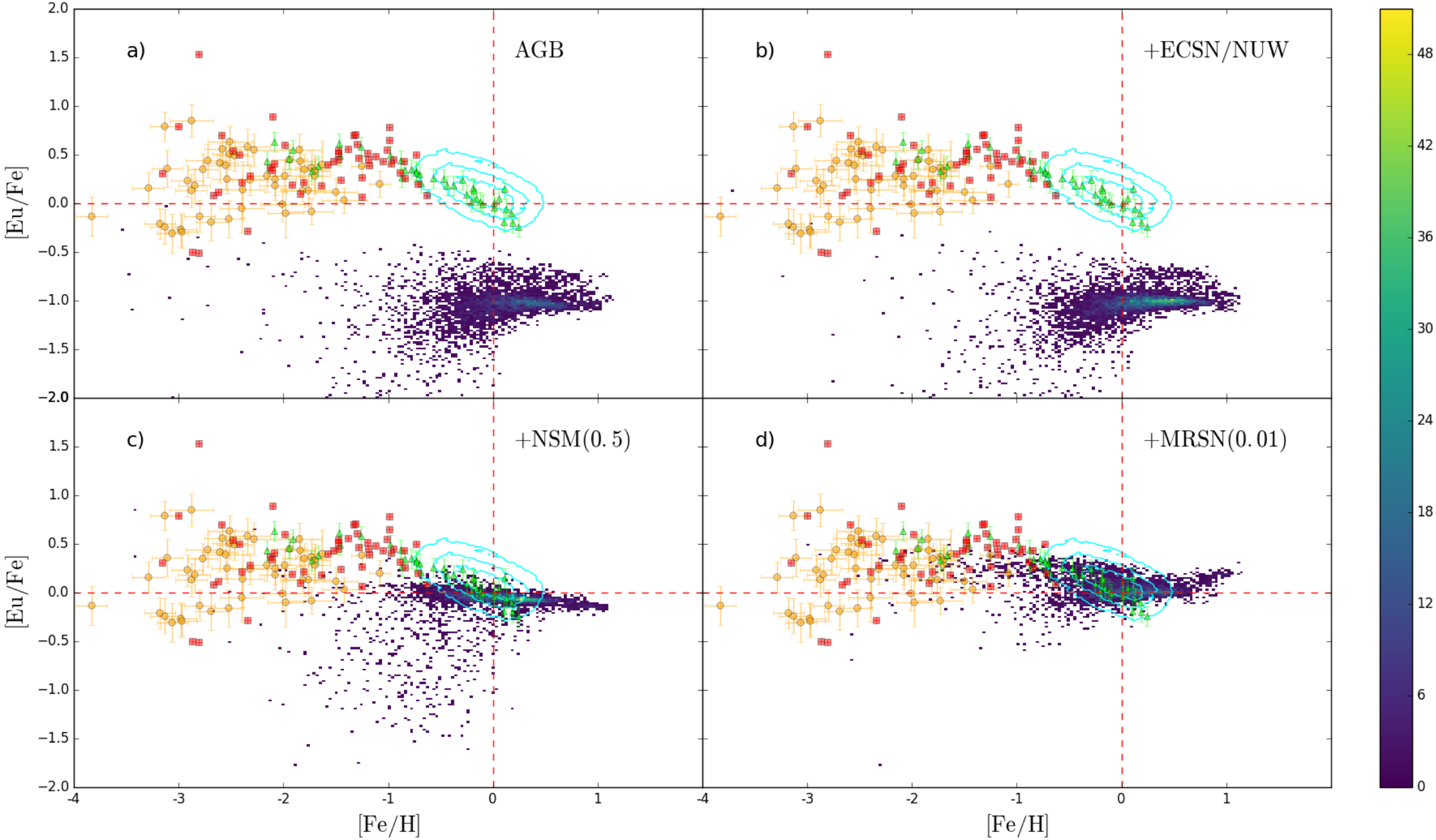
CK, Karakas, Lugaro 2020



s−process
s+ECSN
s+νwinds
s+ECSN+NSM
s+ECSN+NSM+BHM
s+ECSN+NSM+BHM+MRSN
Ga
Ge
As
Se
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
Sn
Te
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Pb
Bi
Th
U
[X/Fe]
[Fe/H]

[Eu/Fe]-[Fe/H]

Chemo-hydrodynamical Simulation
Chris Haynes & CK 2019

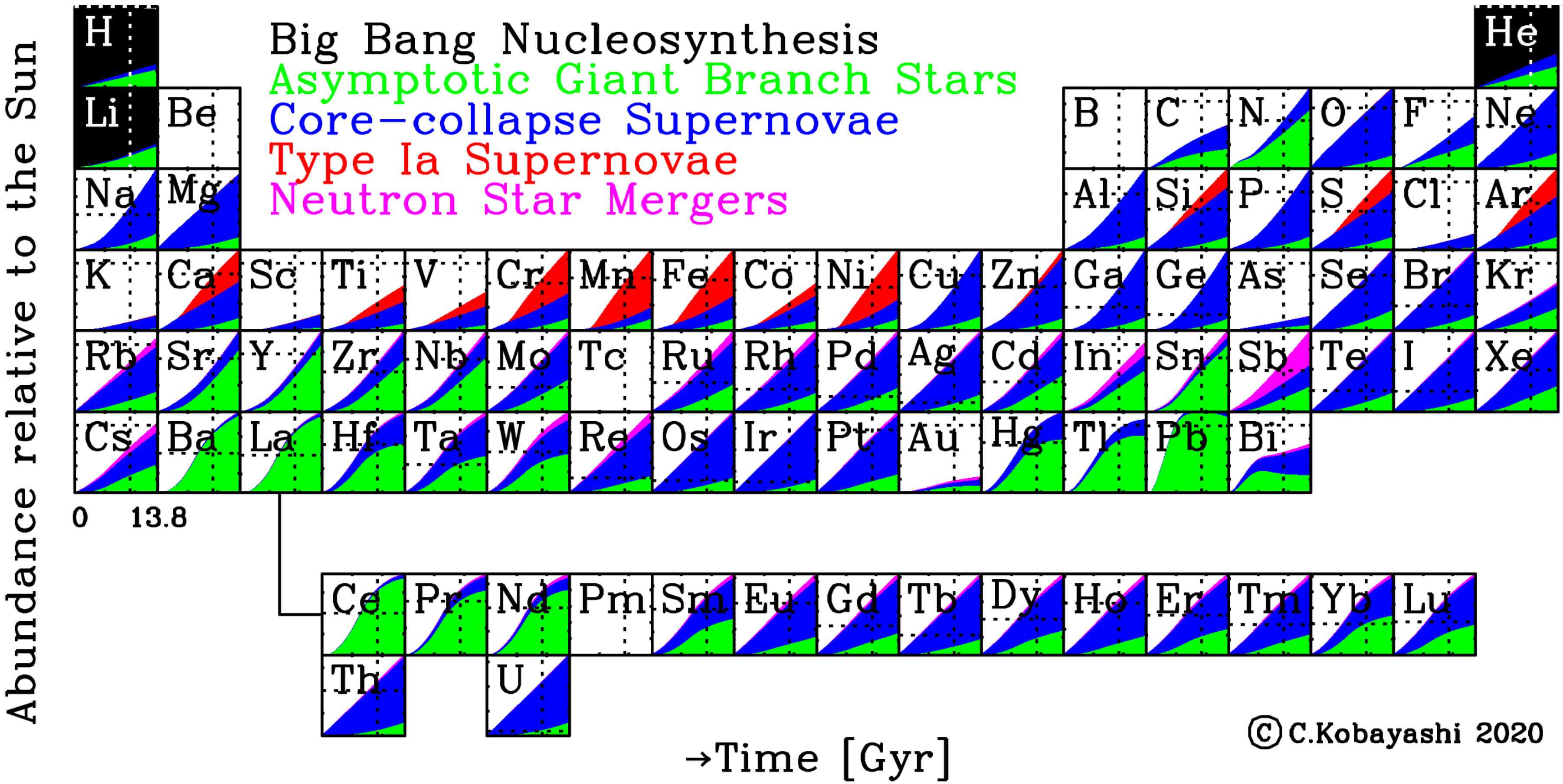


Neutron star mergers alone cannot reproduce the observations.

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

The Origin of Elements

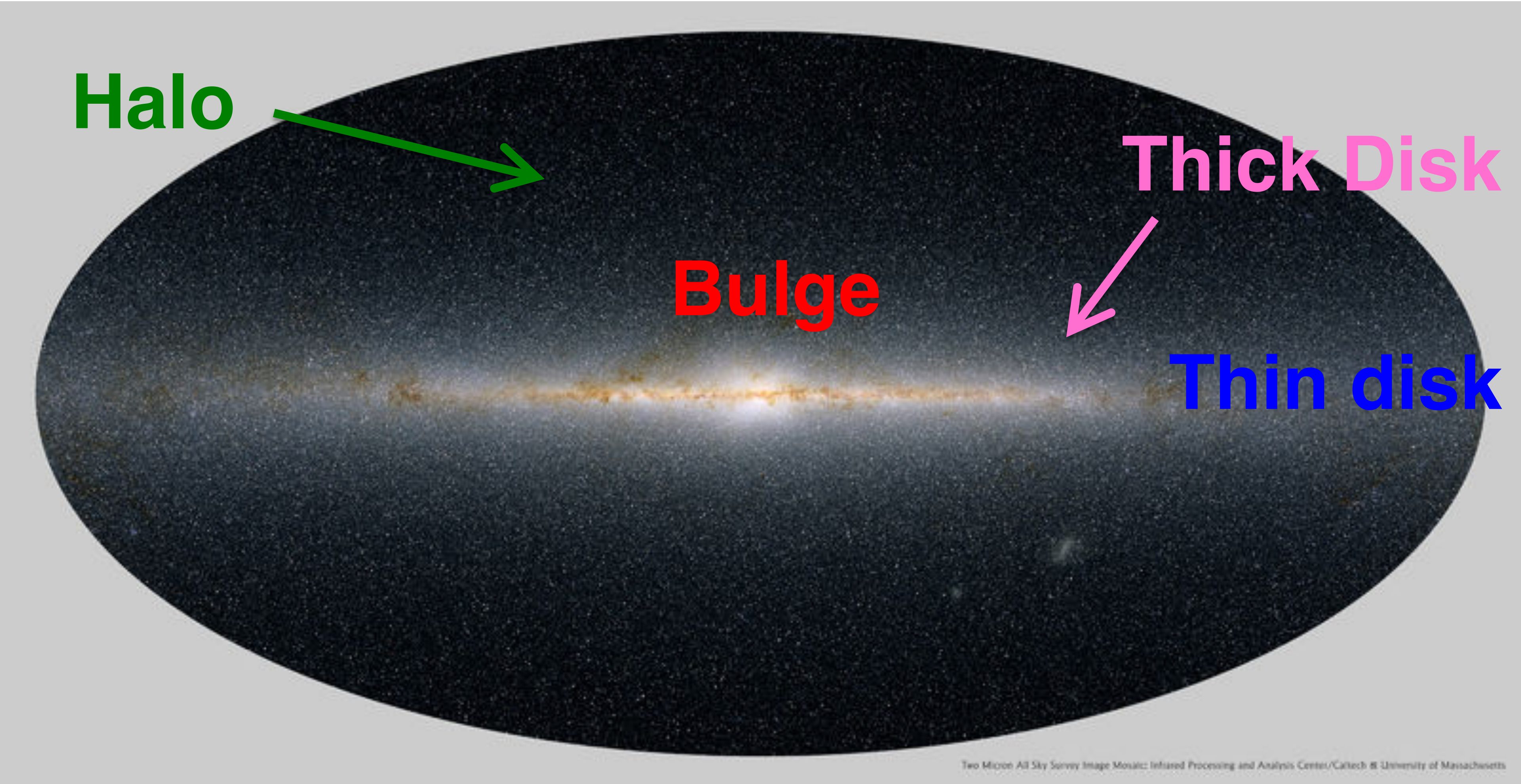
CK, Karakas, Lugaro 2020, ApJ



※Purely theoretical, no empirical equations.

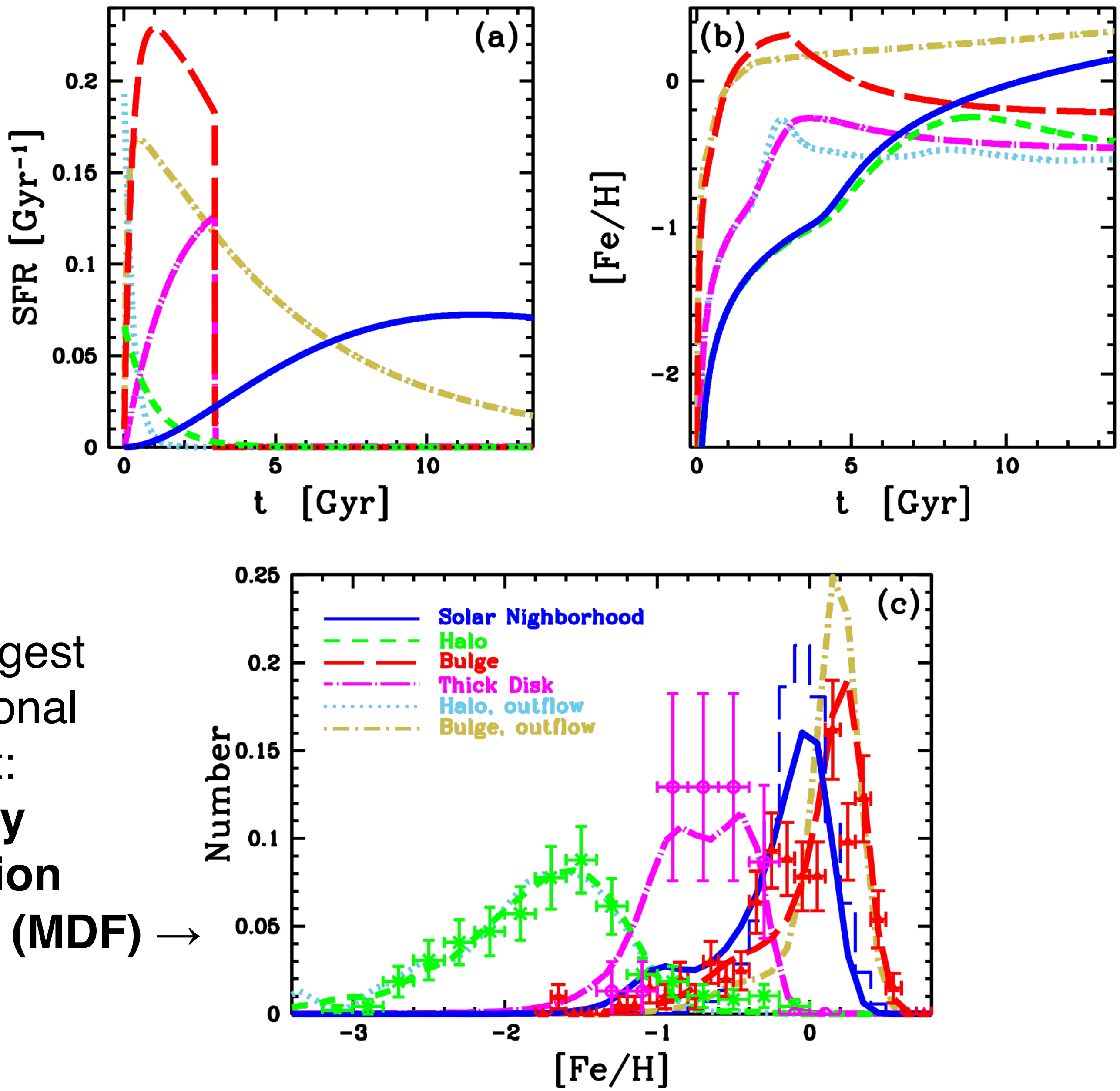
dotted lines: solar values

The Milky Way (MW) Galaxy



What was the main physical process of each component?

MW bulge, thin disk, thick disk, halo



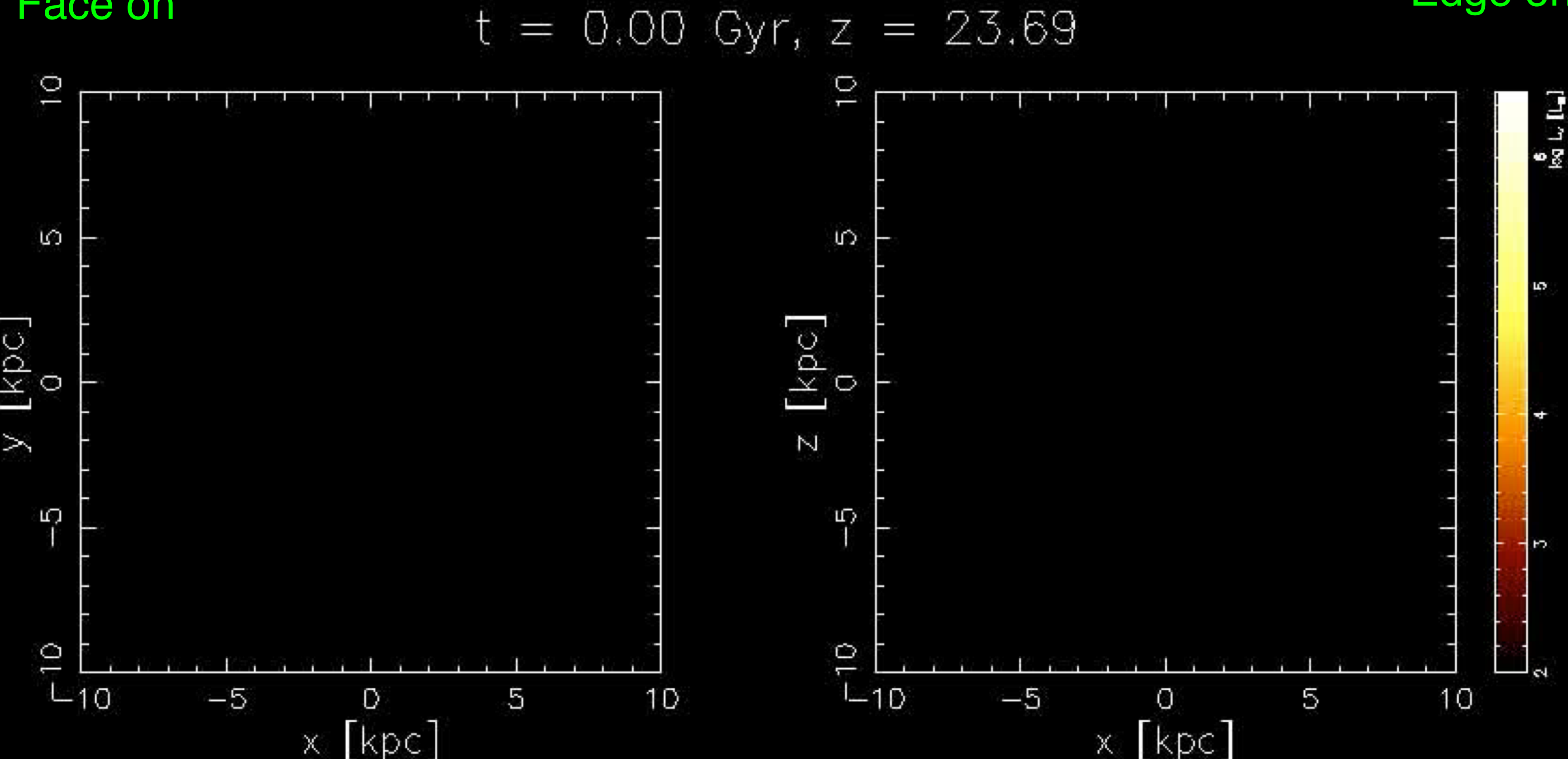
The strongest observational constraint: **Metallicity Distribution Function (MDF)** →

Milky Way-type galaxy

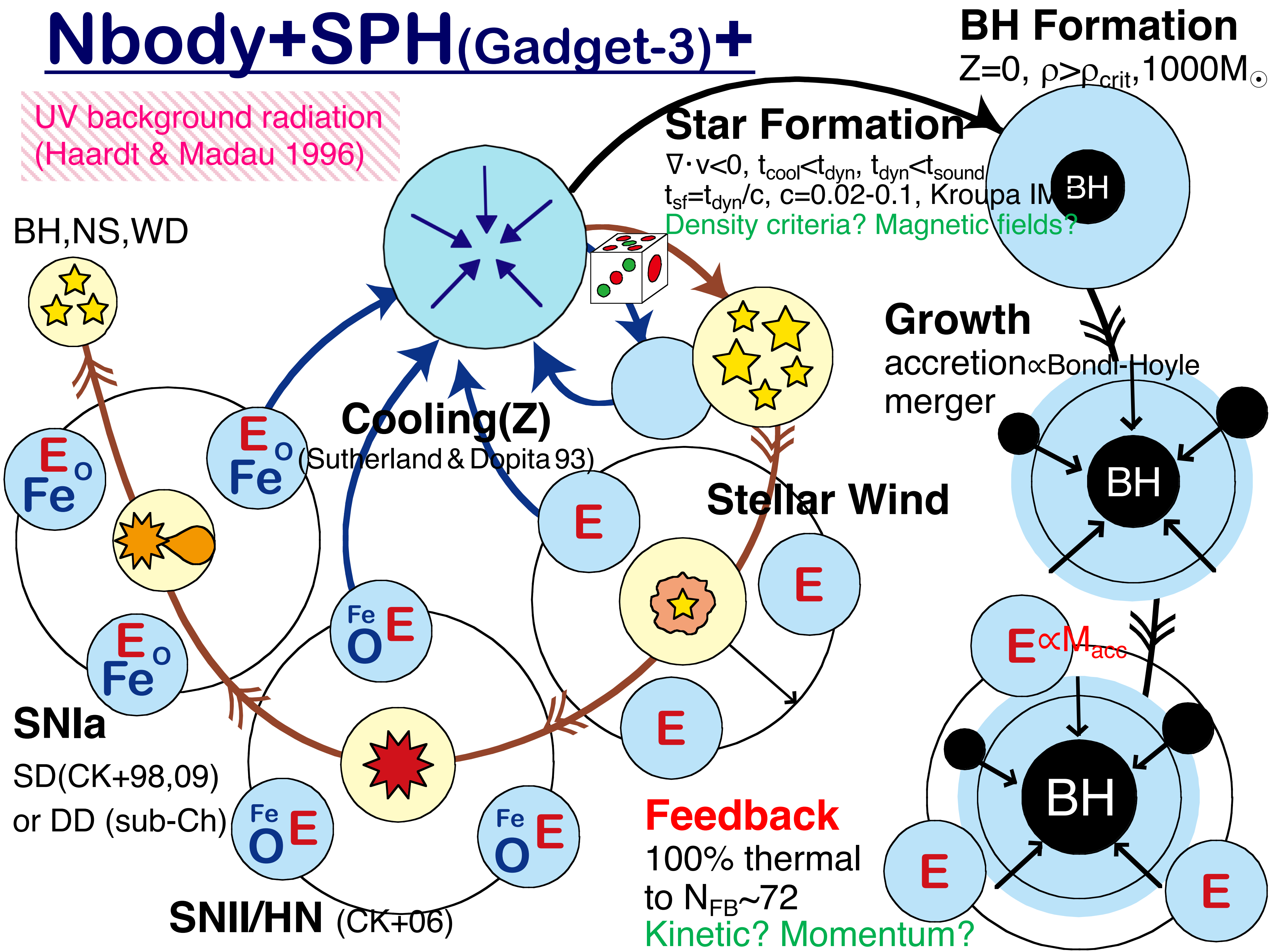
Initial Condition: λCDM fluctuated sphere with λ~0.1, r~3Mpc,
M_{tot}~10^{12} $M_{\odot}$, N_{tot}~120.000, M_{gas}~10^{6} $M_{\odot}$, M_{DM}~10^{7} $M_{\odot}$
(CK & Nakasato 2011, ApJ, 729, 16)

Face on

Edge on

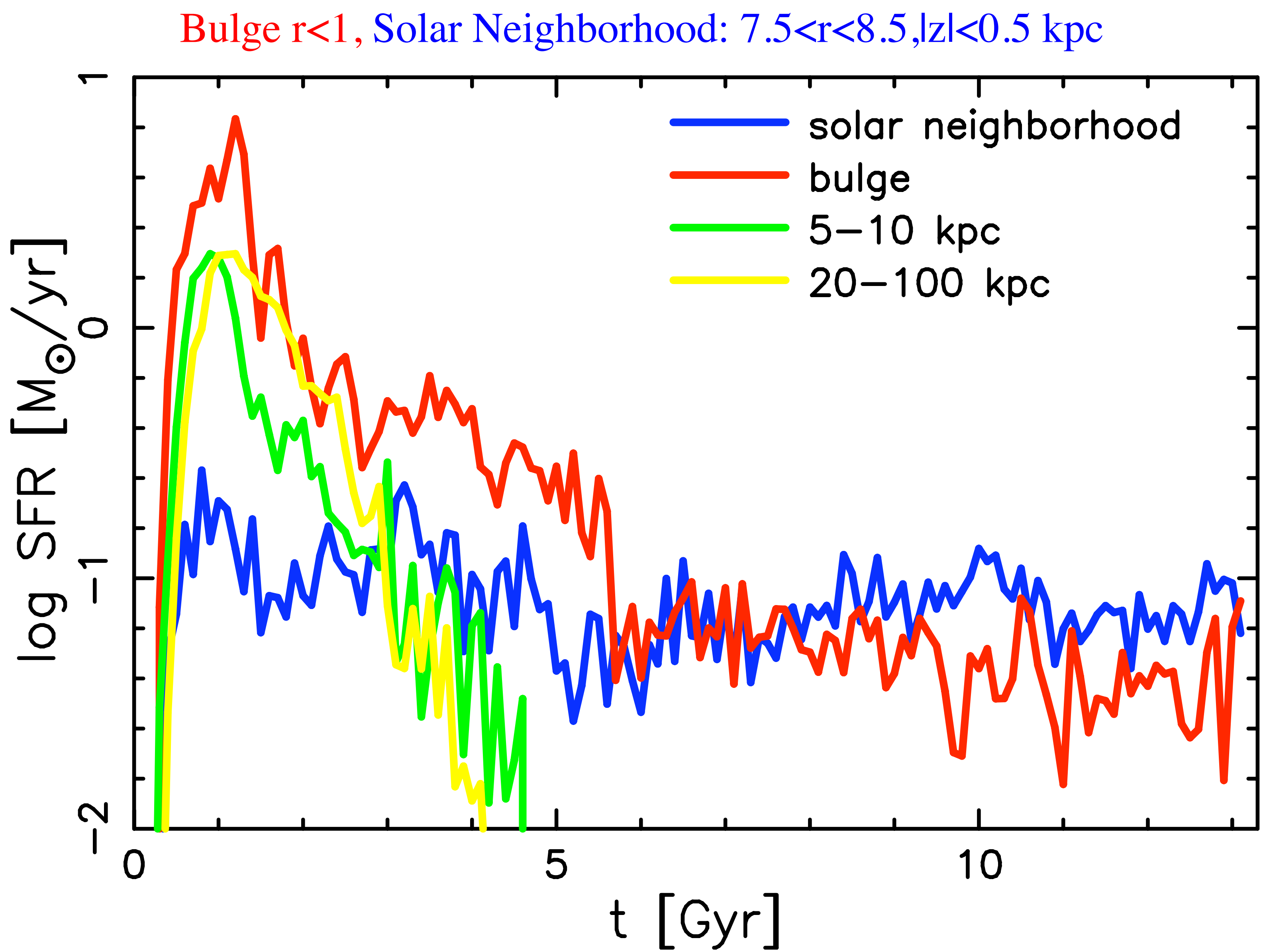


Similar results obtained also with Aquarius Initial Condition (CK 2015).



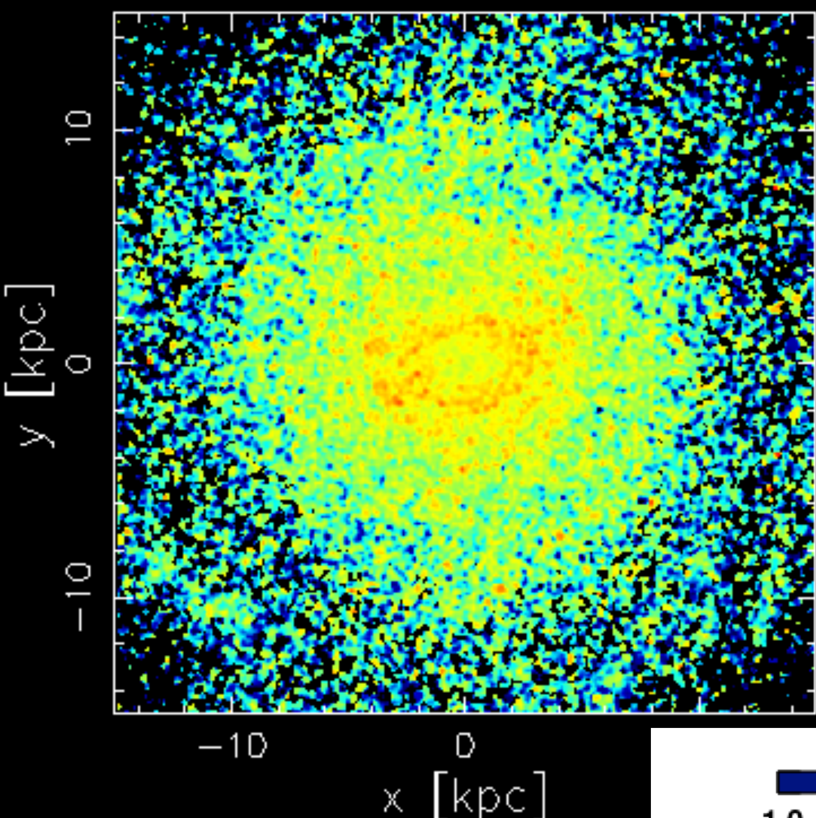
Nbody+SPH(Gadget-3)+
UV background radiation
(Haardt & Madau 1996)
BH Formation
Z=0, ρ>ρcrit, 1000M⊙
BH
Star Formation
∇·v<0, tcool<tdyn, tdyn<tsound
tsf=tdyn/c, c=0.02-0.1, Kroupa IMF
Density criteria? Magnetic fields?
BH,NS,WD
Growth
accretion∝Bondi-Hoyle
merger
BH
Cooling(Z)
(Sutherland & Dopita 93)
E
O
Fe
Stellar Wind
E
E
E
E
Fe
O
E∝Macc
SNIa
SD(CK+98,09)
or DD (sub-Ch)
BH
Feedback
100% thermal
to NFB~72
Kinetic? Momentum?
SNII/HN (CK+06)

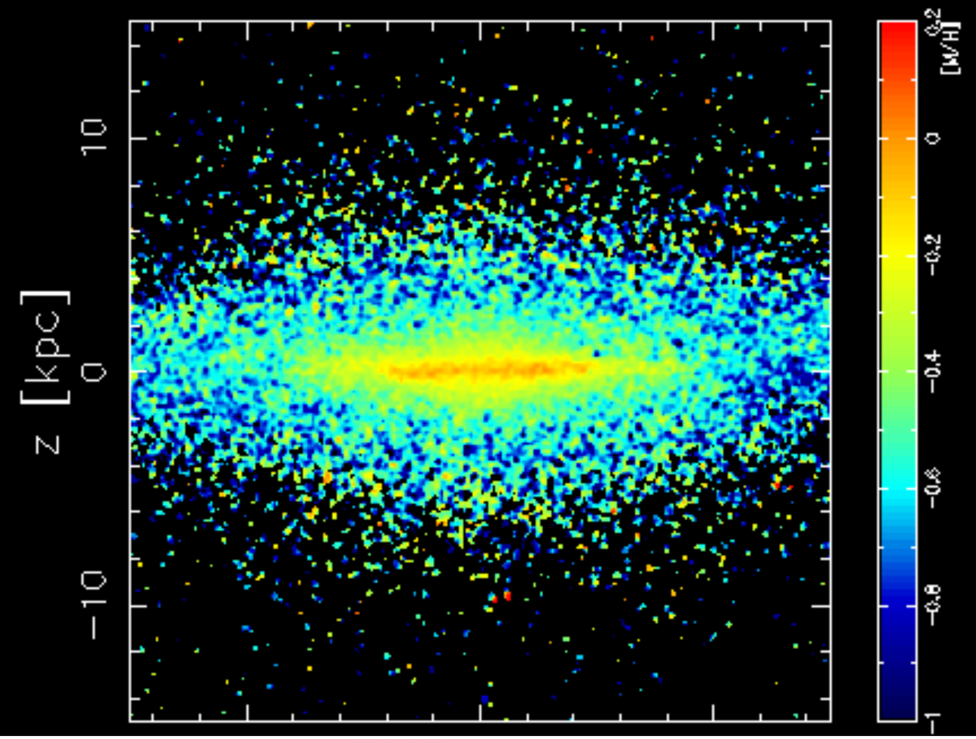
Star Formation History depends on environment



CK & Nakasato 2011

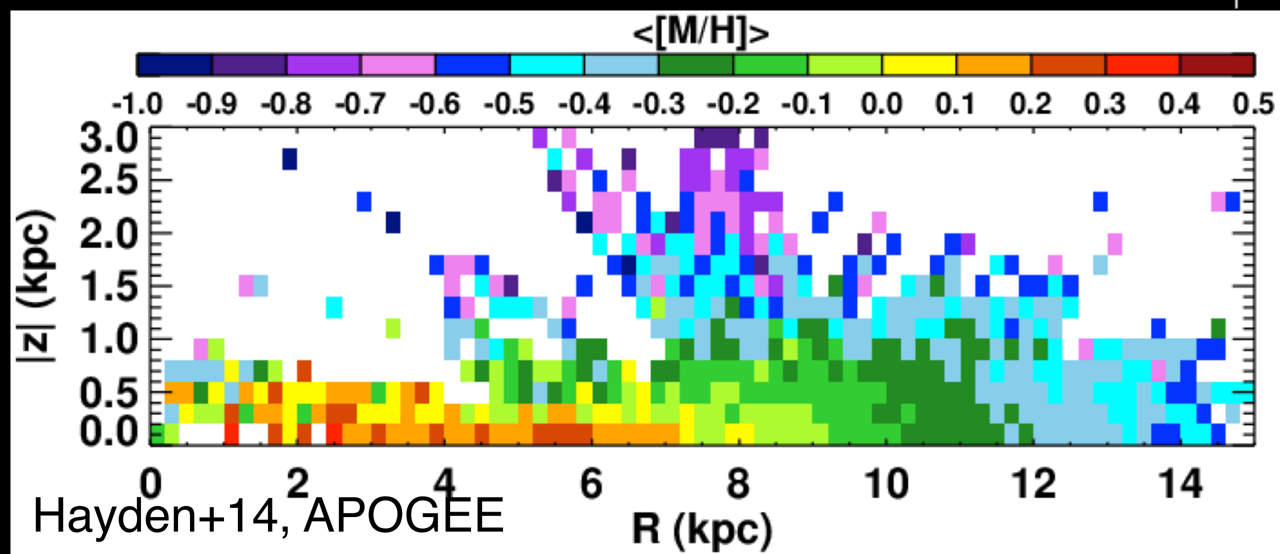
Metallicity Map





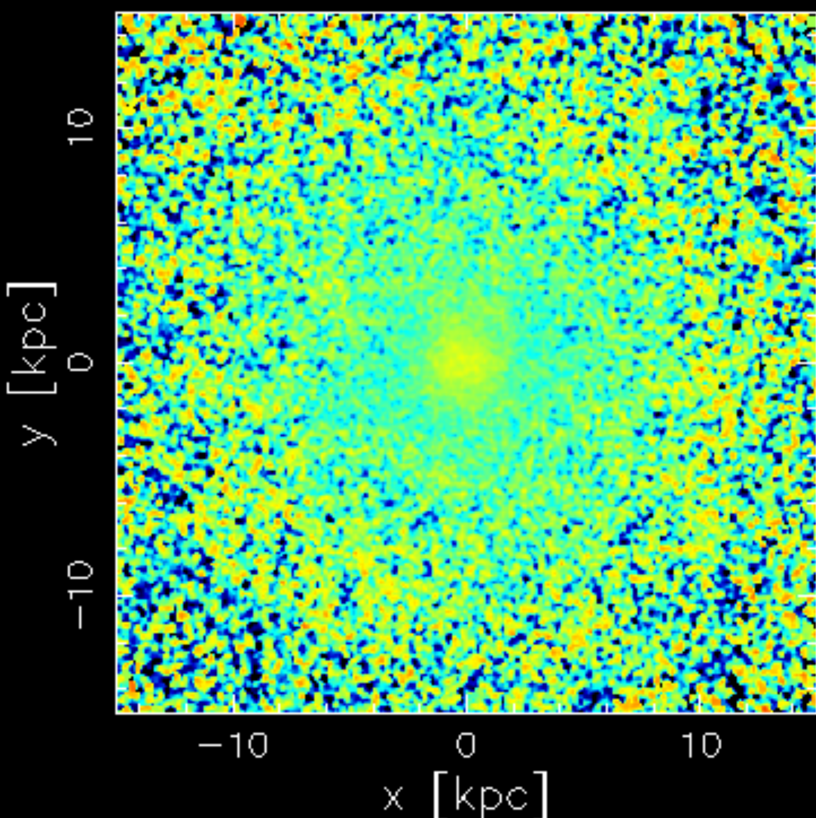
- ✓ Radial gradient
- ✓ Vertical gradient

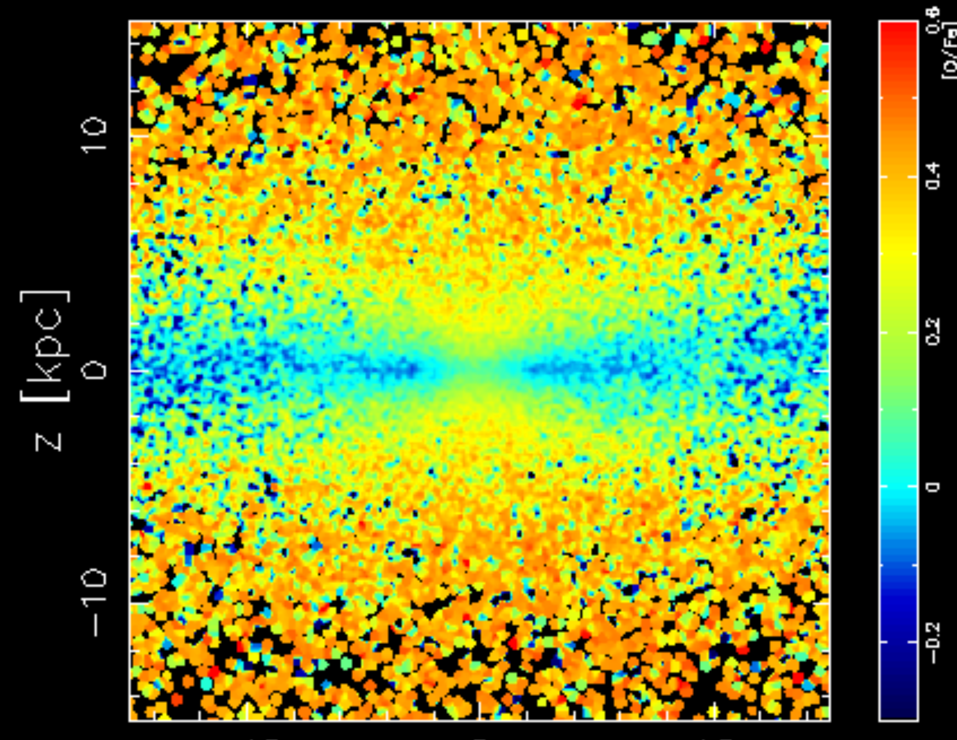
low-mass stellar mass weighted, projected

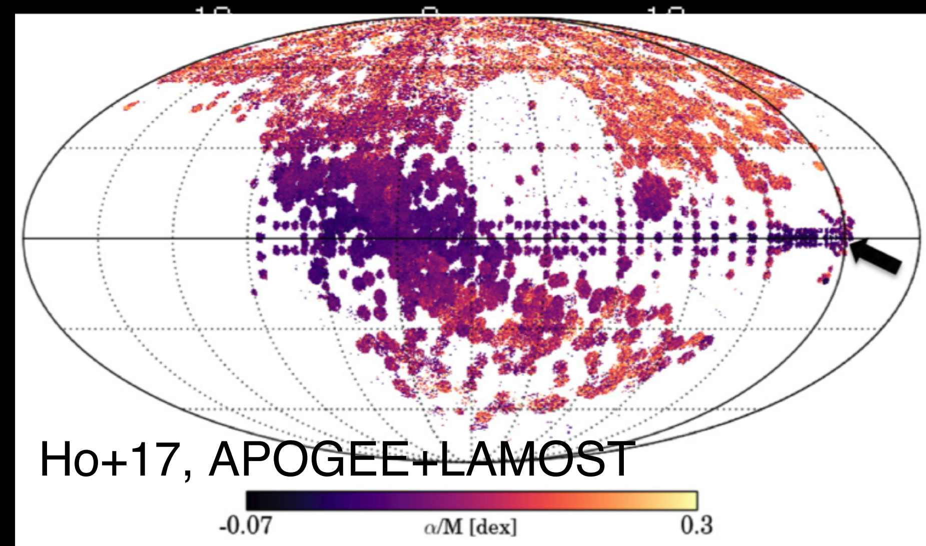


Hayden+14, APOGEE

[O/Fe] Map





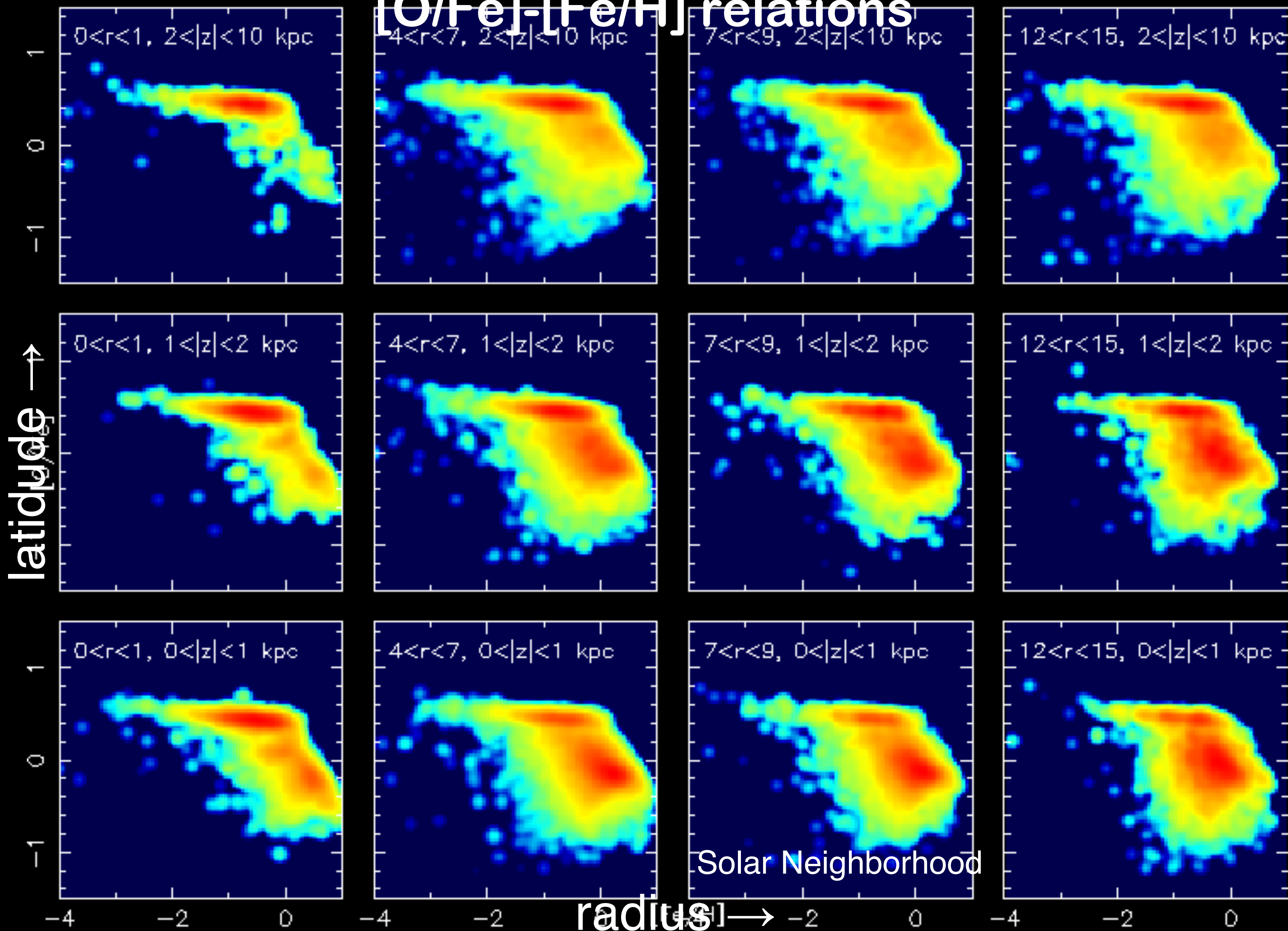


✗ Radial gradient

✓ Vertical gradient

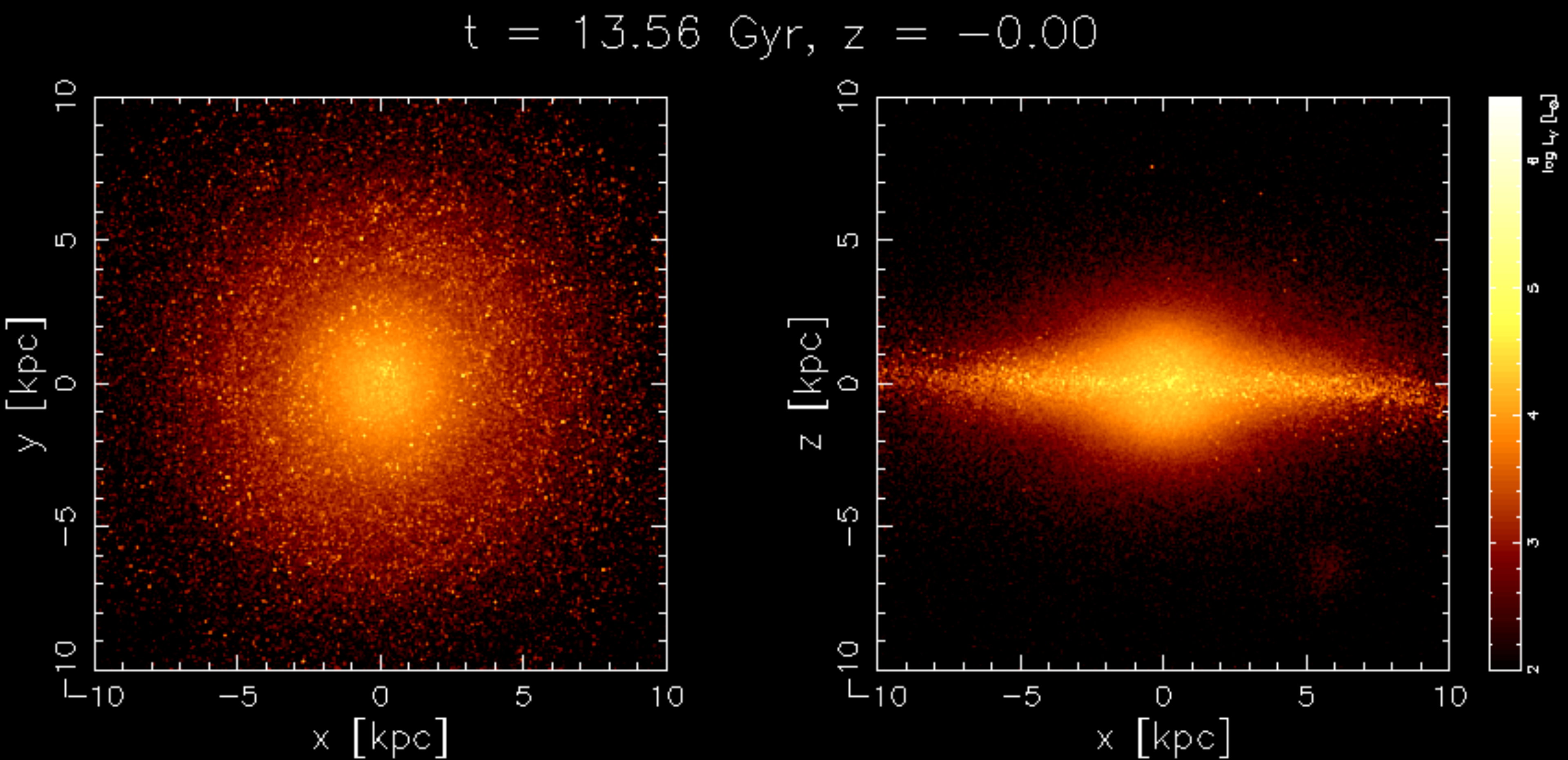
low-mass stellar mass weighted, projected

[O/Fe]-[Fe/H] relations



New Milky Way-type galaxy

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



CK 2015; Haynes & CK 2019; Vincenzo & CK 2020; CK 2021

Q1/3
What is “inside-out” formation of galaxies?

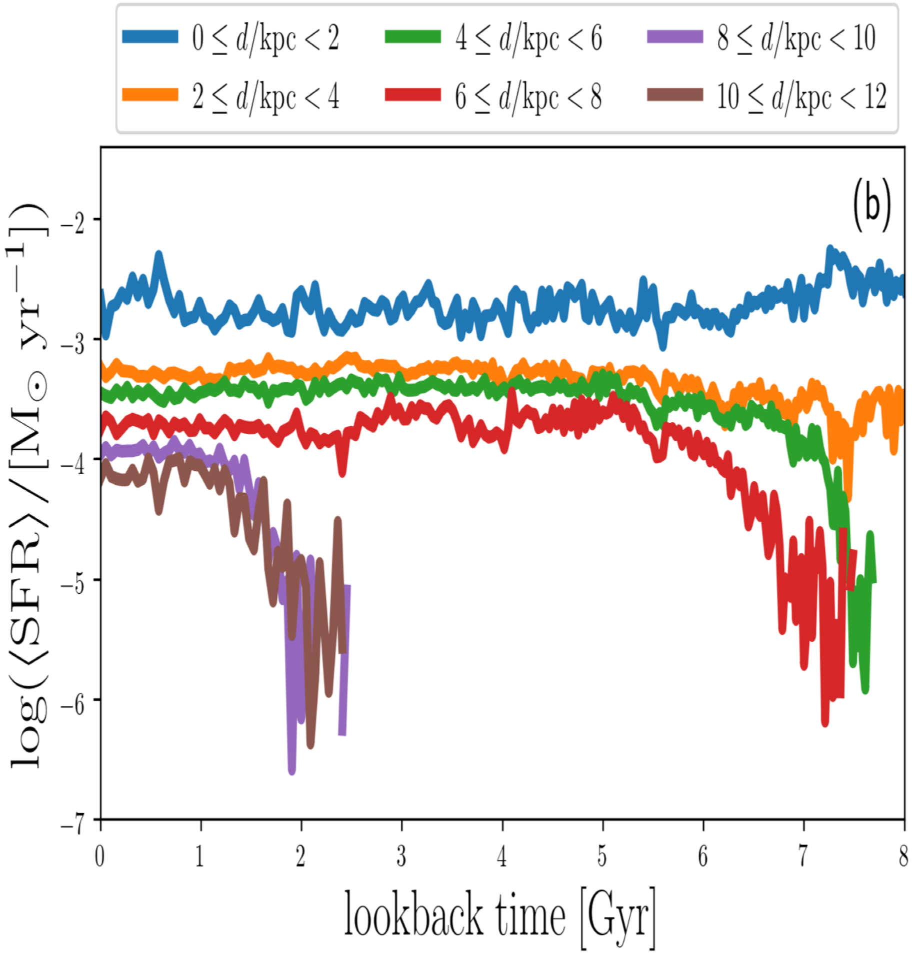
- Hydrodynamical simulations allow us to look back the galaxy disc and measure the properties as a function of radius.
- Since Galaxy radius itself grow, we normalize them by the half-mass radius at each time:

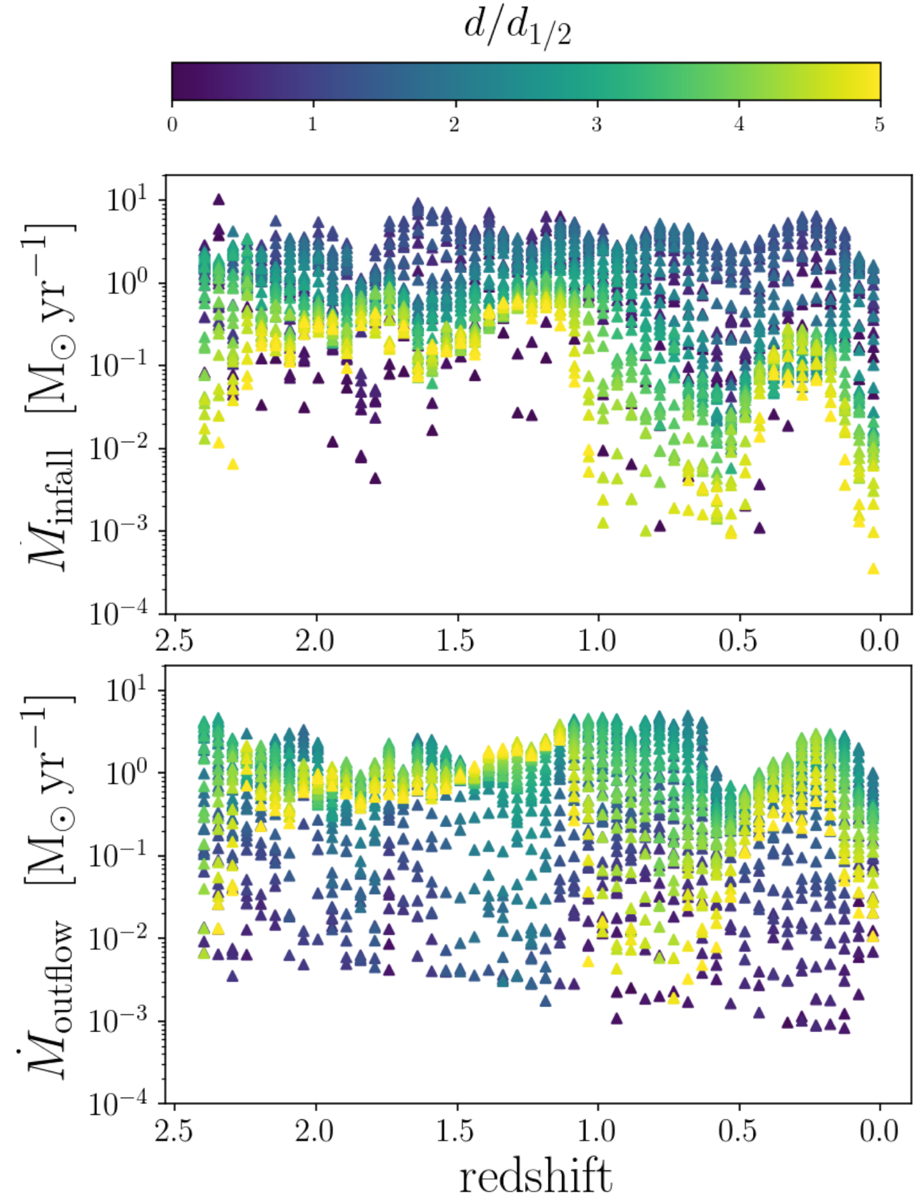
$$d/d_{1/2}$$

Vincenzo & CK 2020, MNRAS, 496, 80

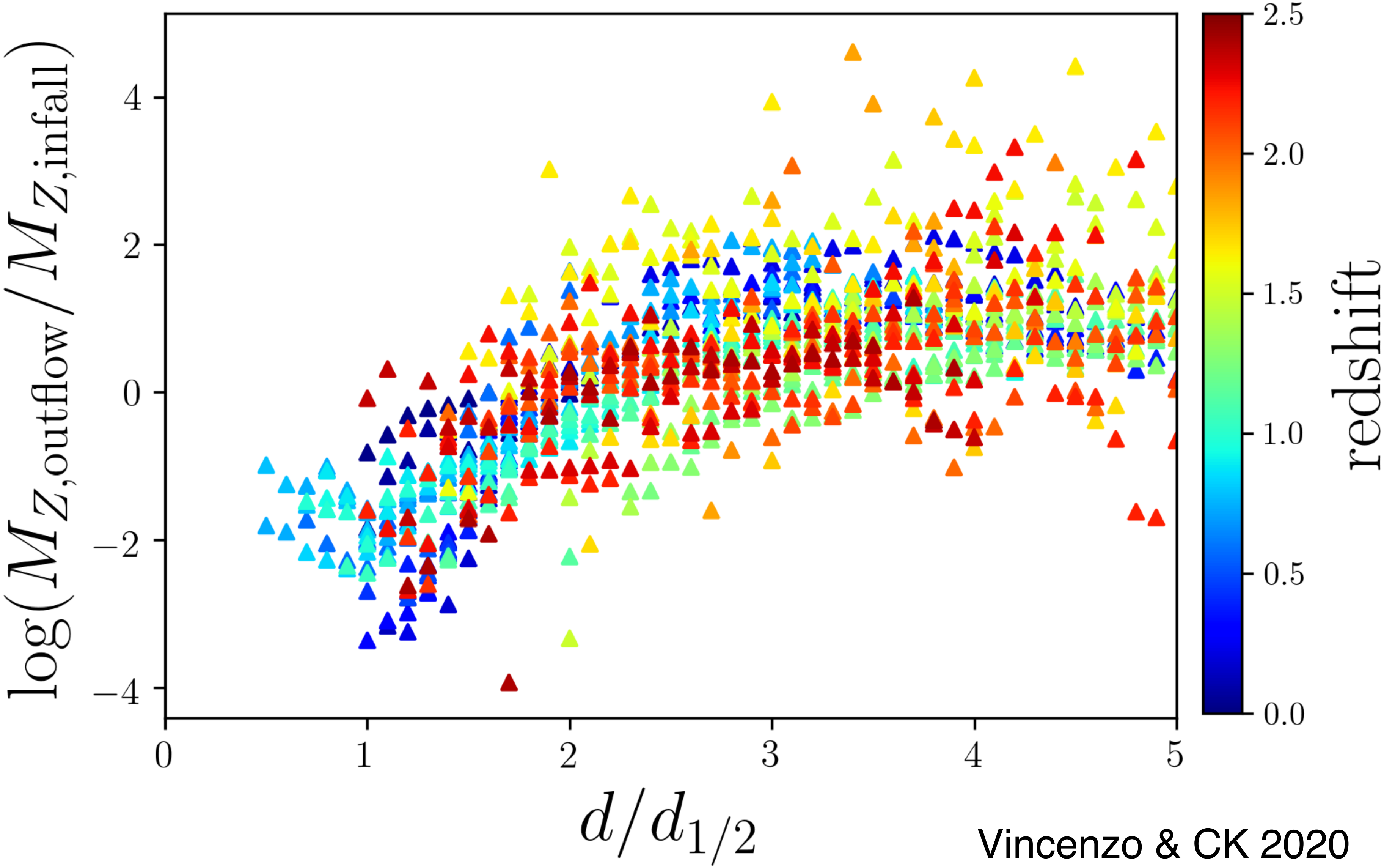
Radial dependence of SF,infall,outflow

- ❖ Inside-out infall
- ❖ Inside-out star formation
- ❖ Outside-in outflow





Universal outflow/infall profile



Vincenzo & CK 2020

Q2/3
What is the role of gas flows in disc formation?

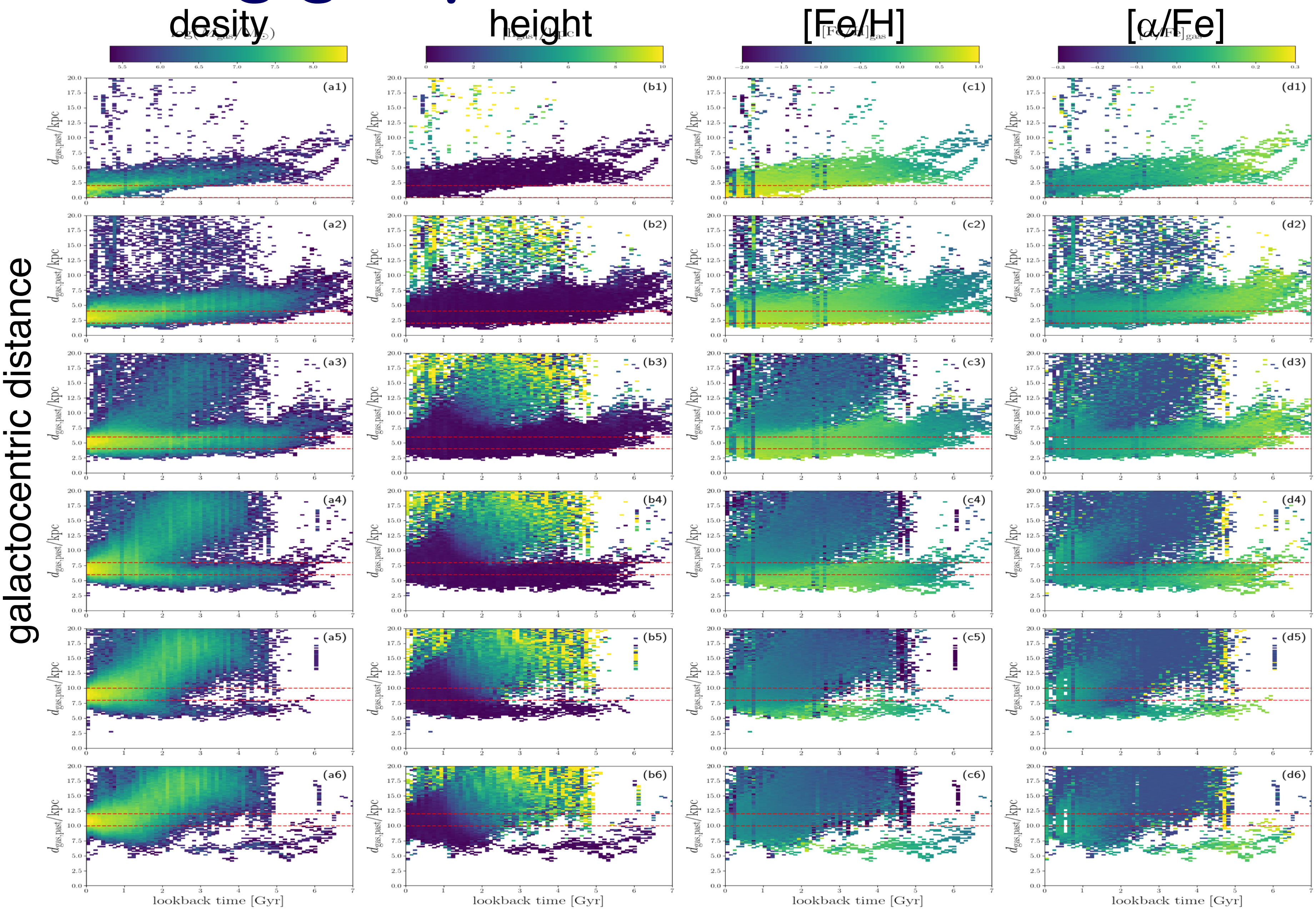
We traced the orbits of gas particles in present-day disc and identified:

infall ($d_{present} < d_{past}$ & $h_{present} < h_{past}$)
radial flow ($d_{present} < d_{past}$ & $h_{present} \sim h_{past}$)

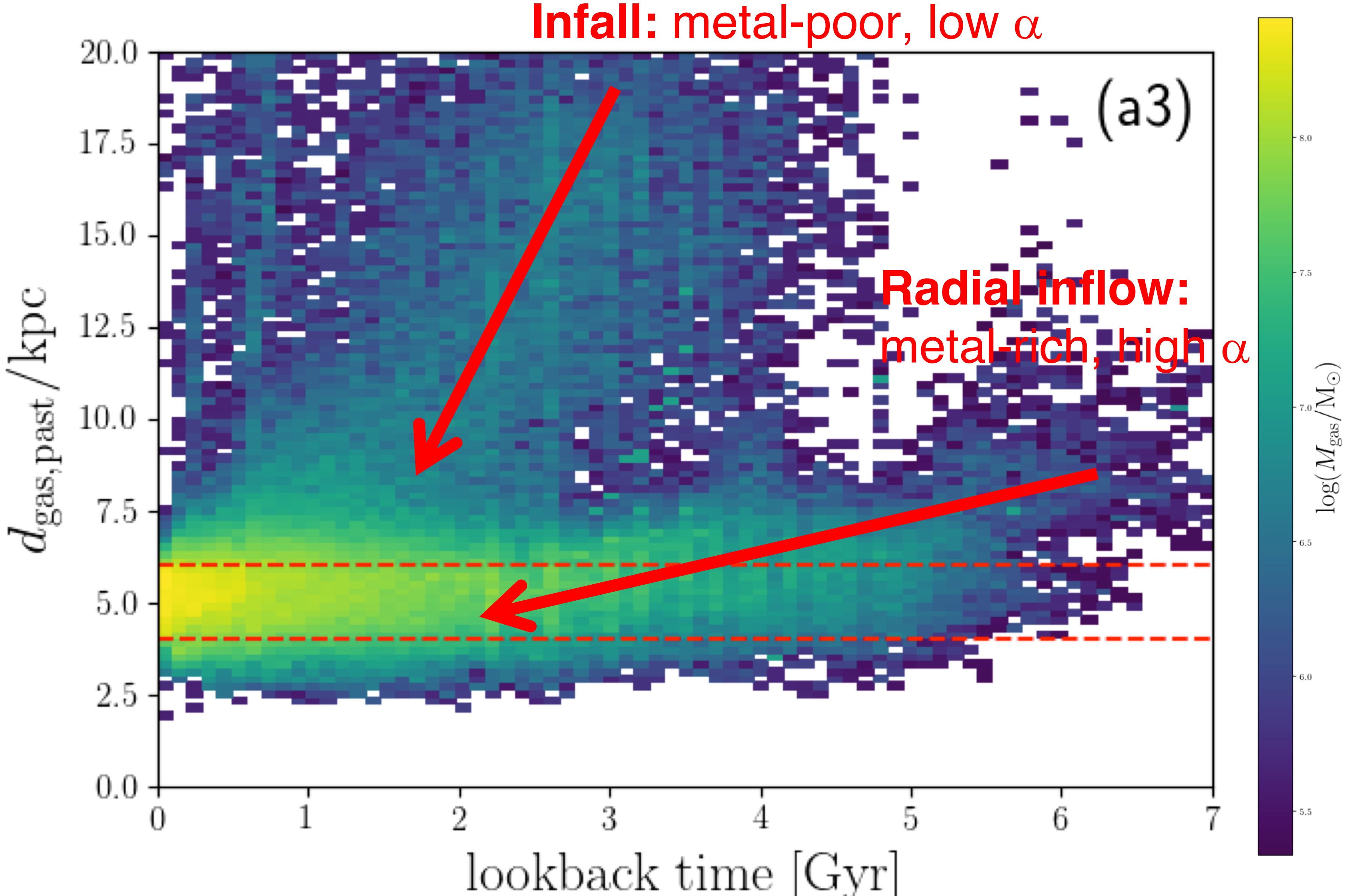
d: galactosentric distance, h: height from the disc plane

Vincenzo & CK 2020, MNRAS, 496, 80

Tracing gas particles at each radius…

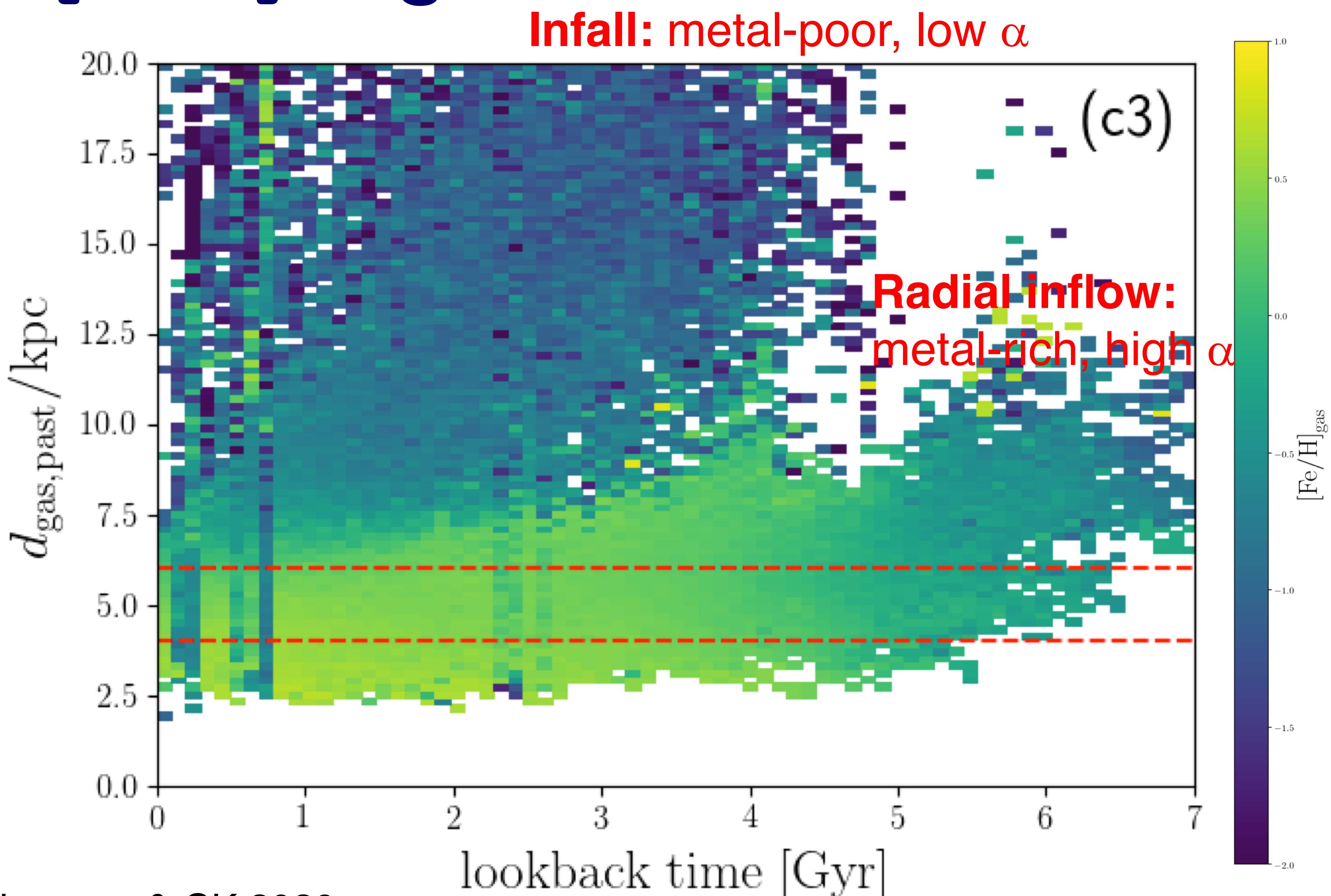


Gas flows – tracing gas particles



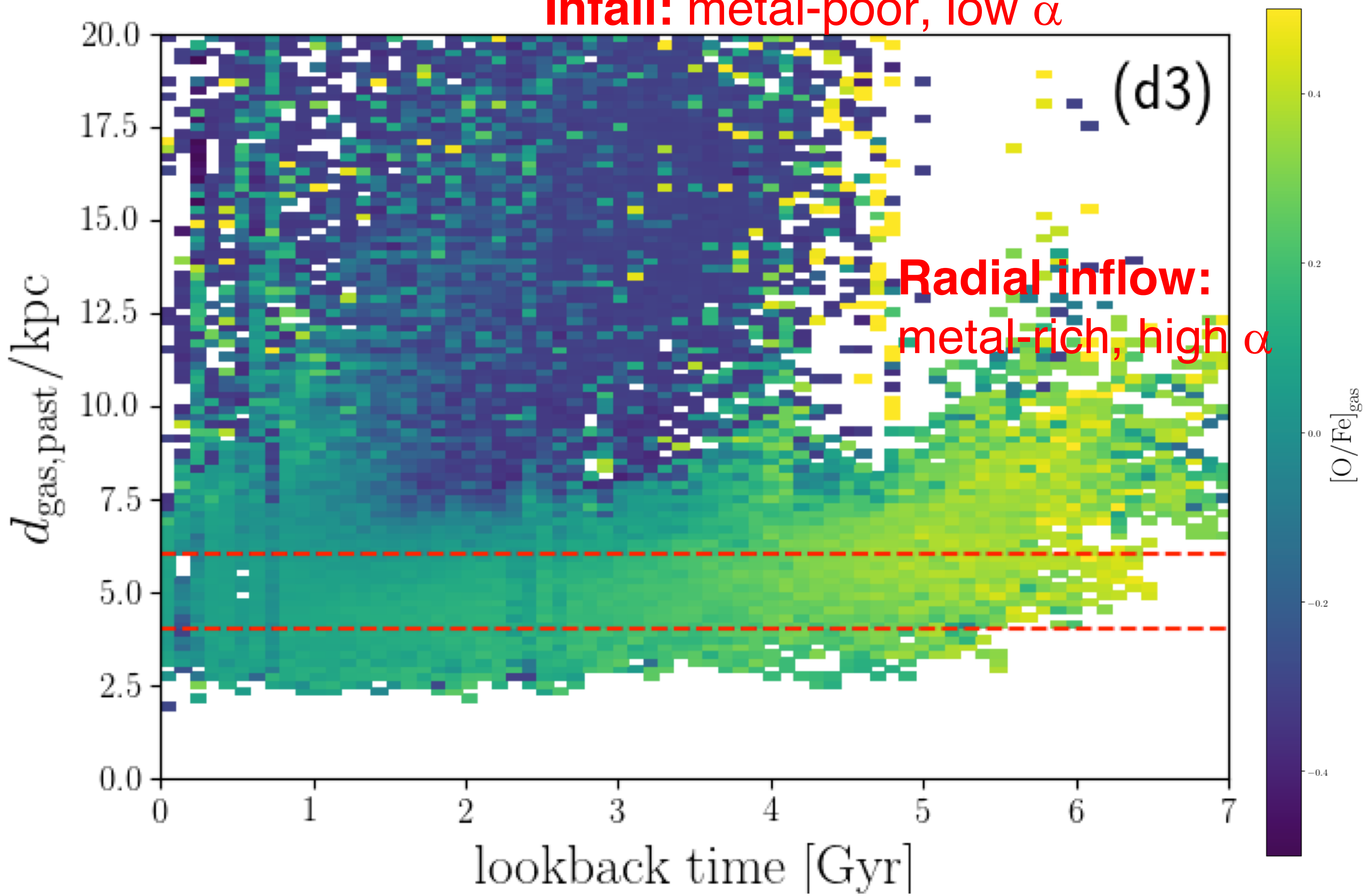
Vincenzo & CK 2020

[Fe/H] of gas infall & radial flow



Vincenzo & CK 2020

[O/Fe] of gas infall & radial flow



Vincenzo & CK 2020

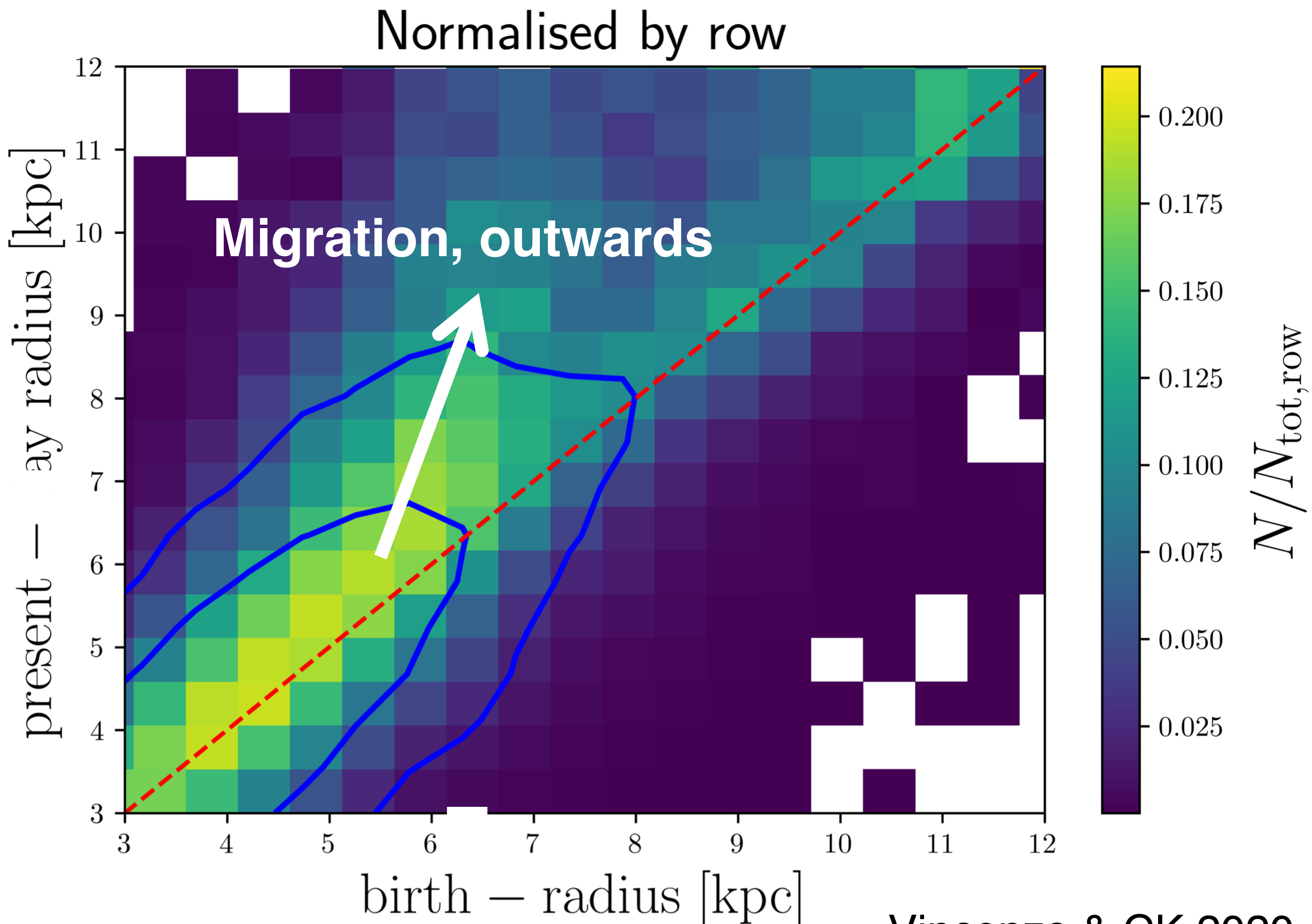
Q3/3
What is the role of stellar migration in disc evolution?

We traced the birth places of the star particles in present-day thin-disc back and identified:

migration ($r_{present}$!= r_{birth})

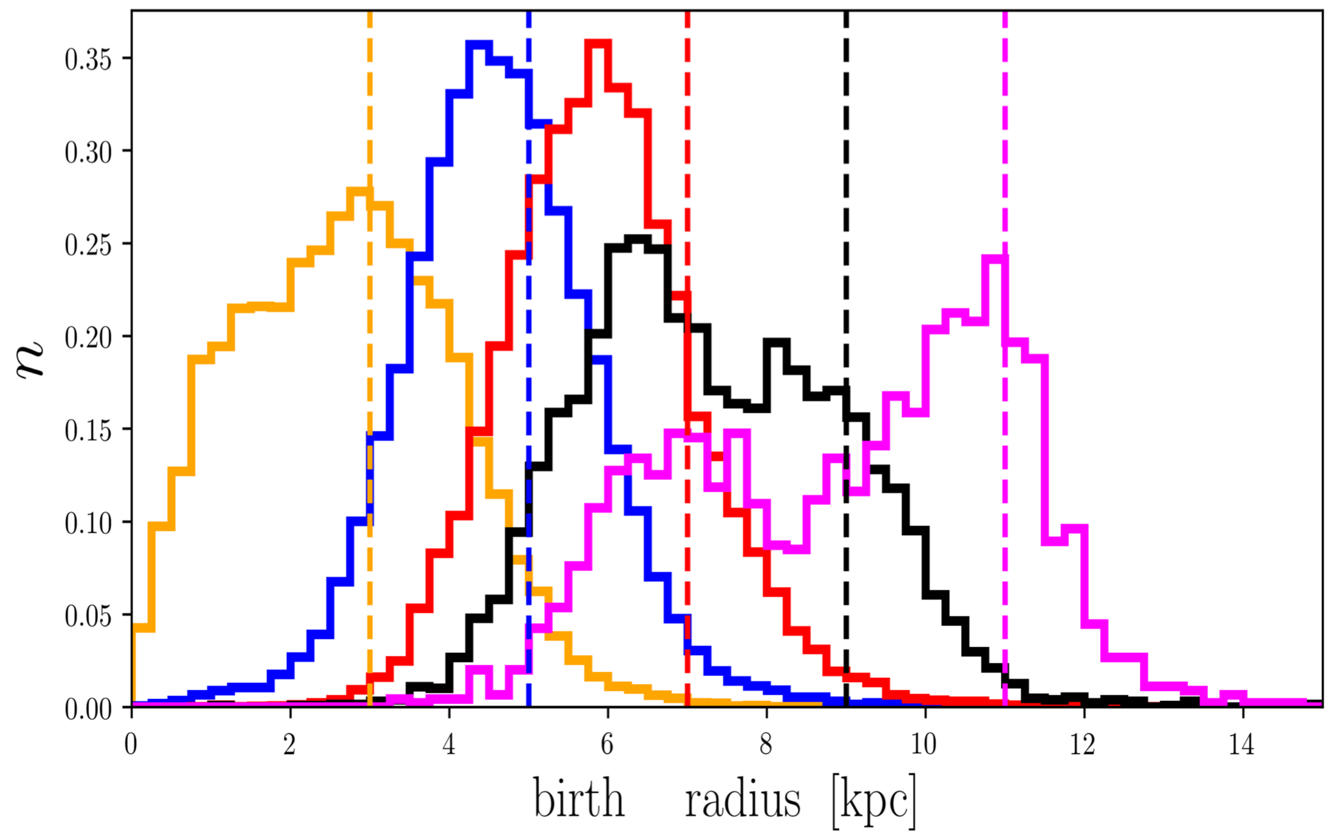
Vincenzo & CK 2020, MNRAS, 496, 80

Migration – tracing the stellar birth place



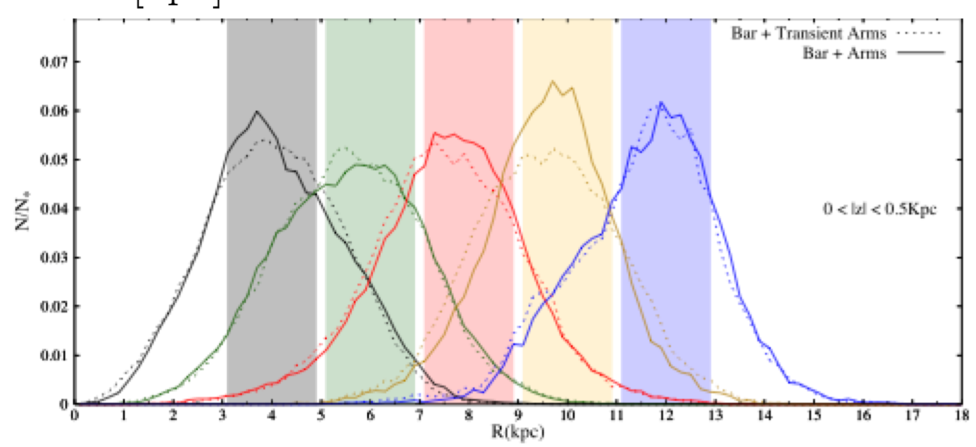
Vincenzo & CK 2020

Migration – outwards!

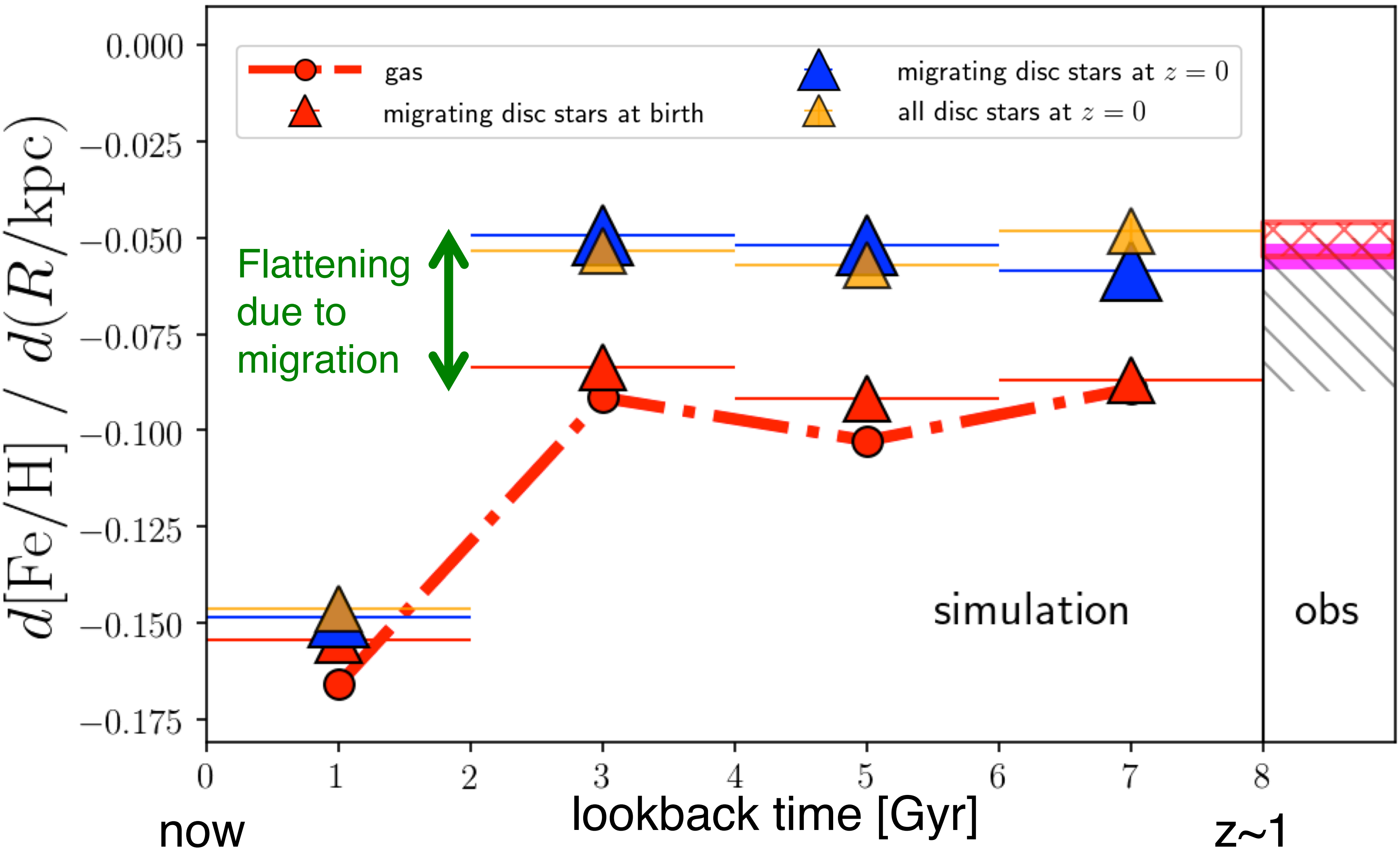


Vincenzo & CK 2020

N-body simulations →
(Martinez-Medina+16)



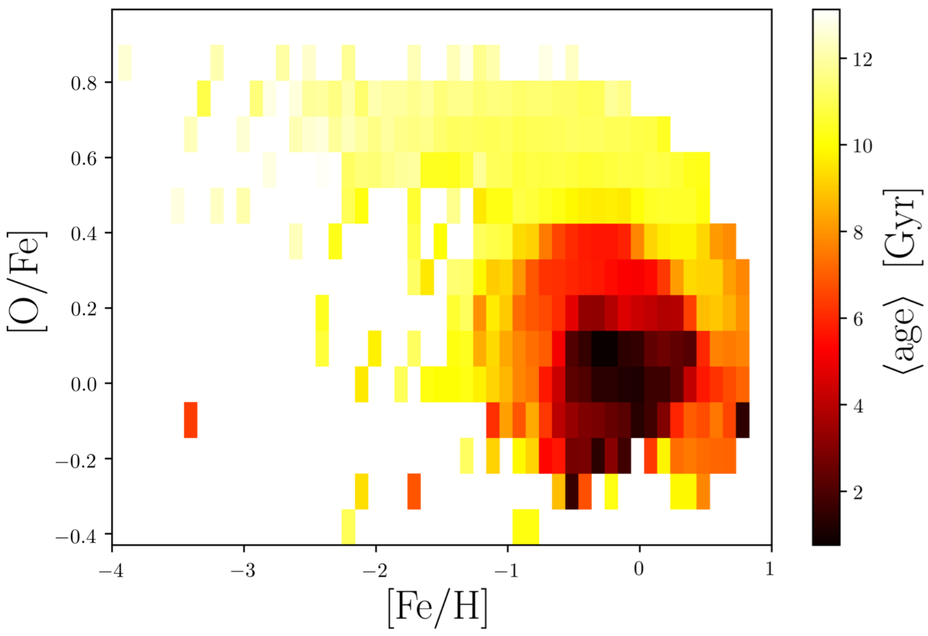
Metallicity radial gradient

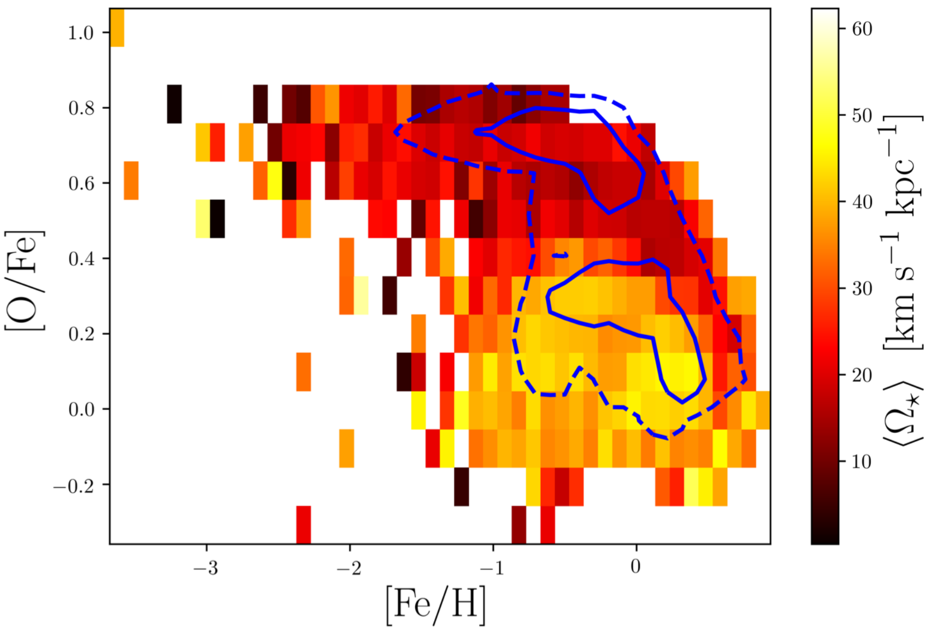


Vincenzo & CK 2020

Origin of high-α population (thick disk)?

- ❖ If disk heating, age difference is not expected
- ❖ If migration, rotation difference is not expected





→Satellite accretion

Vincenzo & CK 2020

Chemical Evolution (CE) of MW

- **Classical bulge** formed by gas-rich mergers/assembly in a short-timescale (z>1.5). Short CE timescale & high CE efficiency result in old, metal-rich, and high α/Fe stars.
- **Stellar halo** built up by mergers/stellar accretion of globular clusters (rather than dSph galaxies) to form Gaia-Enceladus and Sequoia streams. Short CE timescale but low CE efficiency result in old, metal-poor ([Fe/H] ~ -1.6), and high α/Fe stars. Many CEMP.
- **Thick disk** formed by stellar accretion (old age & no rotation), disk heating, or in-situ (dual or parallel flows)?
- **Thin disk** formed **inside-out** gas accretion and star formation, which create a metallicity radial gradient. Outflow occurs **outside-in**, following the universal outflow/infall profile. Radial inflow (~0.7km/s) steepens the metallicity gradient, while **outward stellar migration** (timescale ~5Gyr) flattens the gradient by 0.05 dex. Young, metal-rich, and low α/Fe stars.
- **Pseudo bulge** probably formed by secular evolution.
- Topics not covered: The first stars? (Ishigaki et al. 2018), Satellite dwarf galaxies? (Hayashi et al.)