Lecture 2.
The Galactic Archaeology

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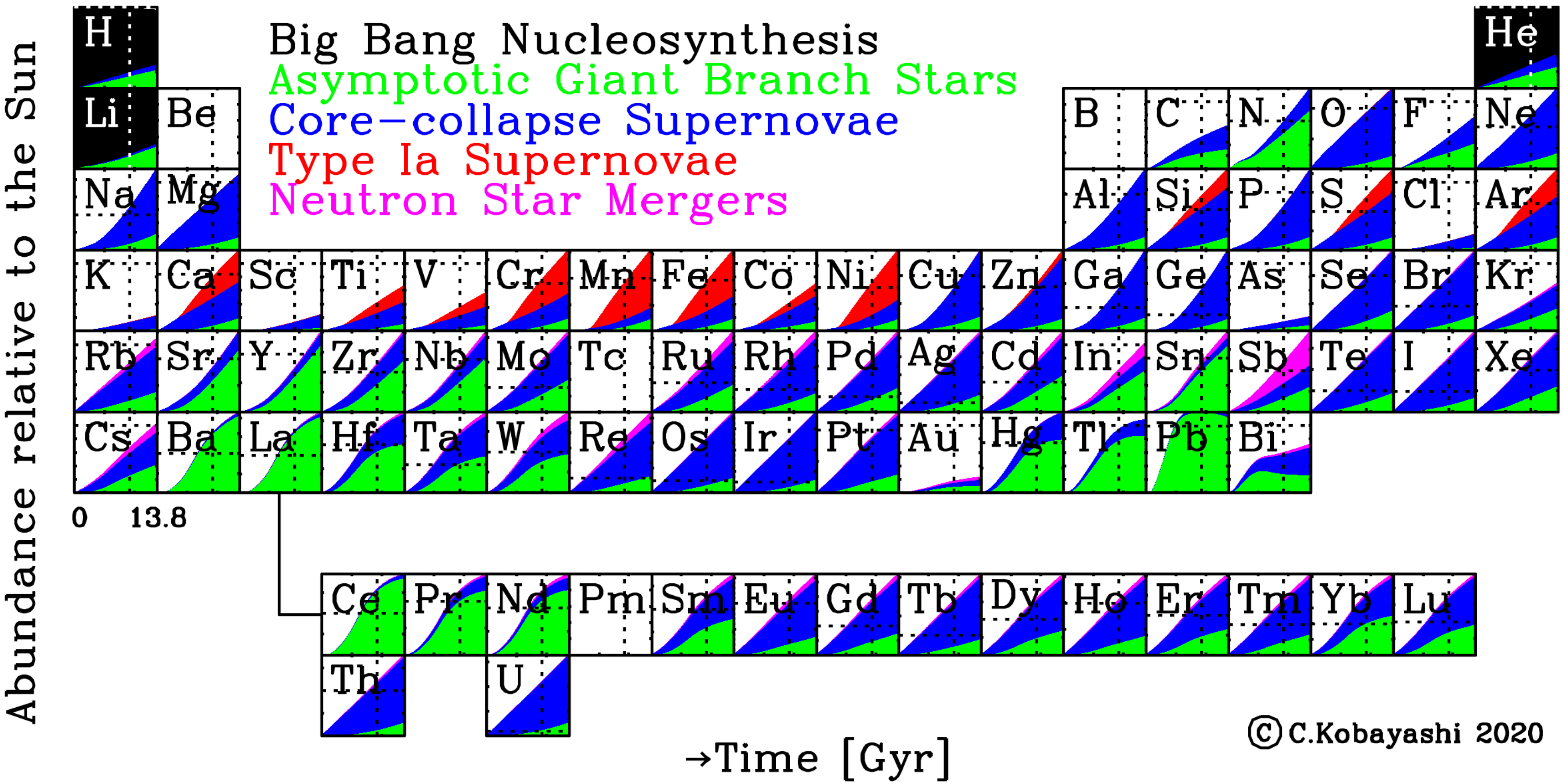
The Origin of Elements

CK, Karakas, Lugaro 2020, ApJ



※Purely theoretical, no empirical equations.

※Mass-loss is counted toward AGB or ccSN.

dotted lines: solar values

Galactic Chemical Evolution (GCE)

The amount of each element in the interstellar medium (ISM) at time *t*

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

decreased by star formation

Inflow Outflow

Metal ejection rates

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

Nuclear Astrophysics

Nuclei in the Cosmos XIII, Debrecen 2014

Galaxy Evolution

① One-zone models
(Tinsley 80, Pagel 97, Matteucci 01...)
- instantaneous mixing approximation

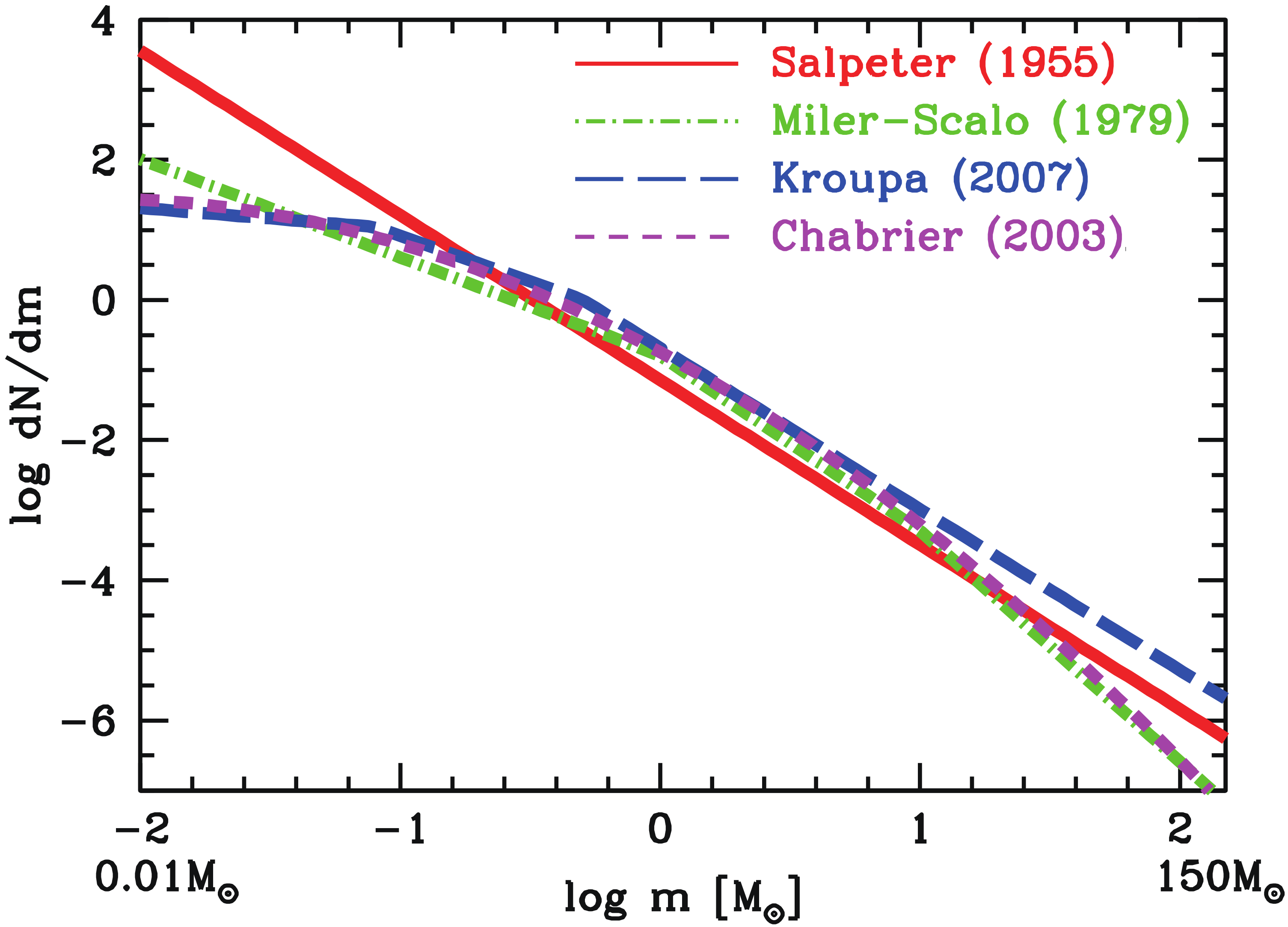
② Stochastic models
(Argast+04, Cescutti 08, Wehmeyer+15)
- inhomogeneous enrichment

③ Hydrodynamical simulations
- inhomogeneous enrichment
- internal structures
- metallicity gradients
- comparison to IFU!

Cosmological box, or “zoom-in” for MW

Initial Mass Function (IMF)

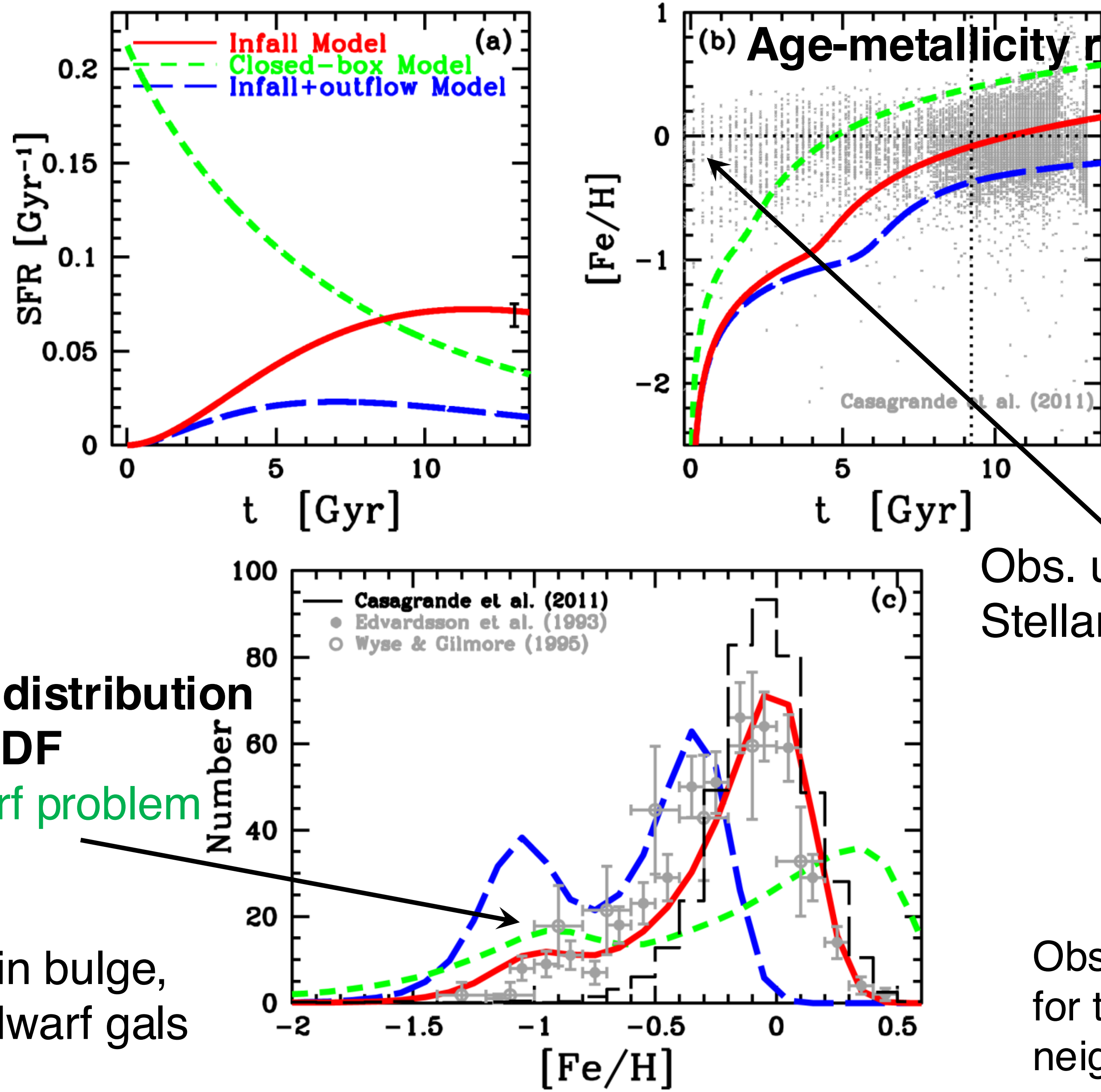
The number, or mass contribution, of stars formed at a given initial mass *m*



※ In GCE models, Salpeter IMF with a suitable m_ℓ can give similar results with Kroupa IMF.

Closed, infall, outflow models

$f_{g,0}$=1



Age-metallicity relation AMR

Obs. uncertain here
Stellar migration

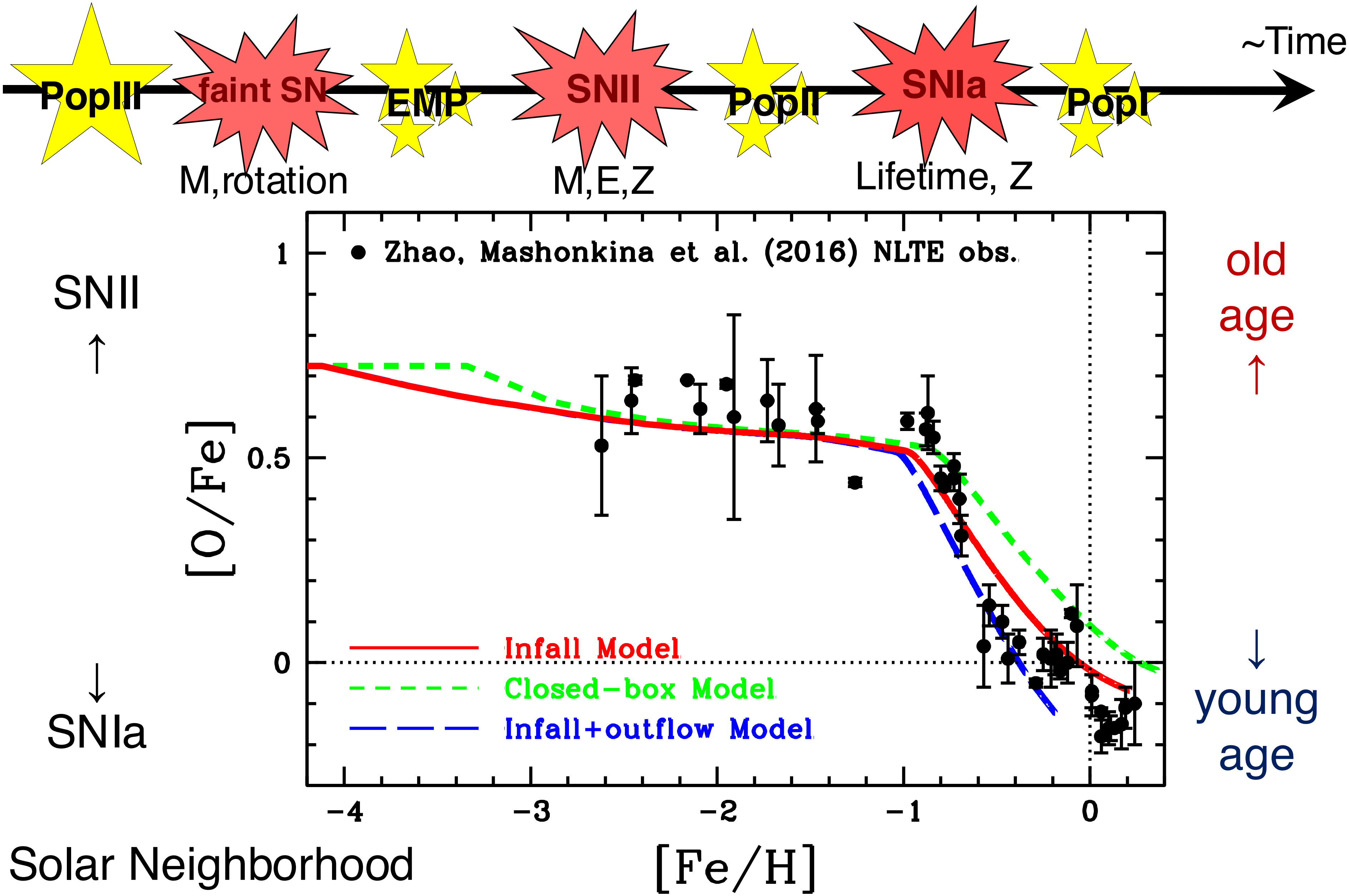
Metallicity distribution function MDF

The G-dwarf problem

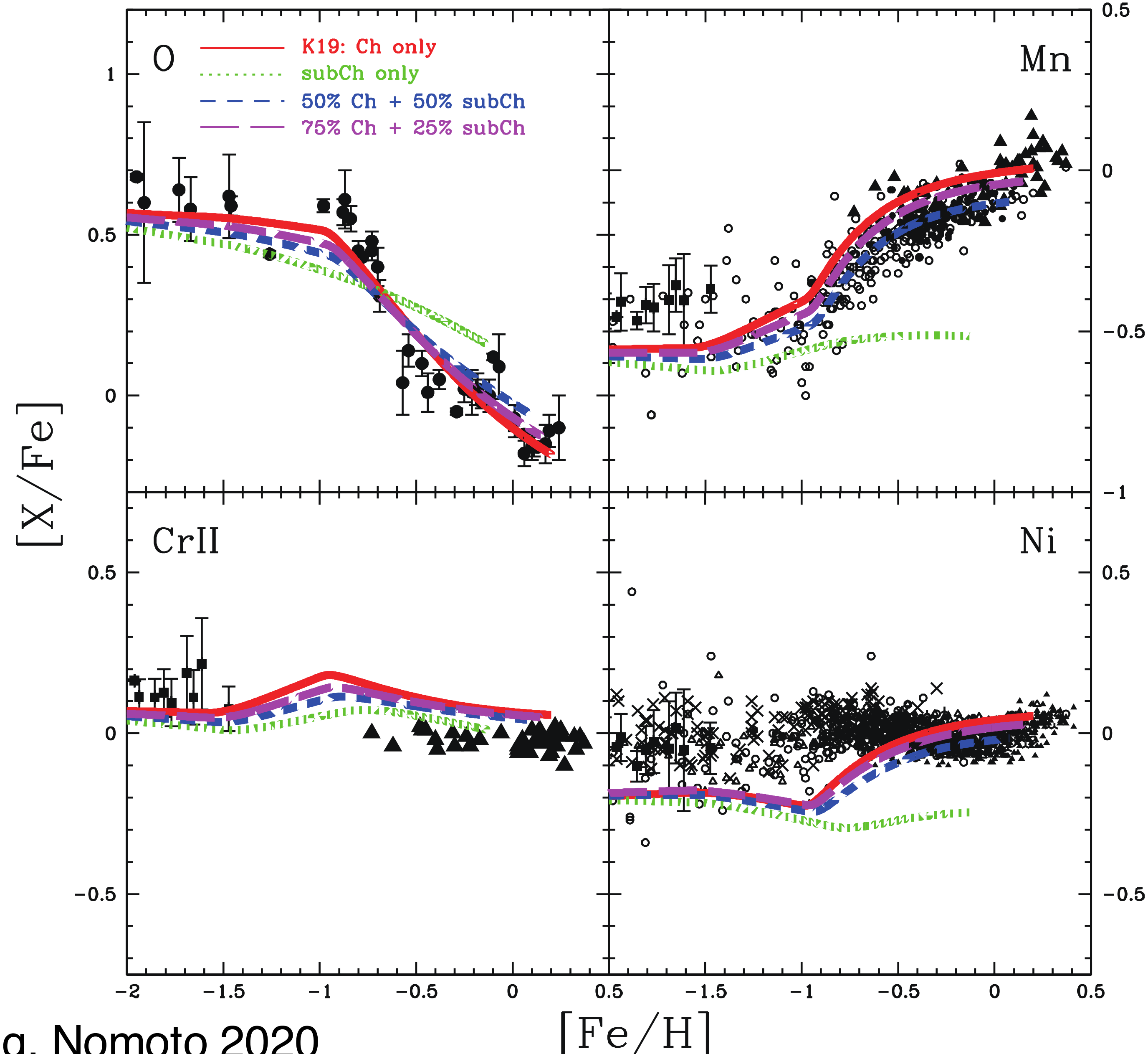
also exists in bulge, ellipticals, dwarf gals

Observations are for the solar neighbourhood.

The [α/Fe]-[Fe/H] relation



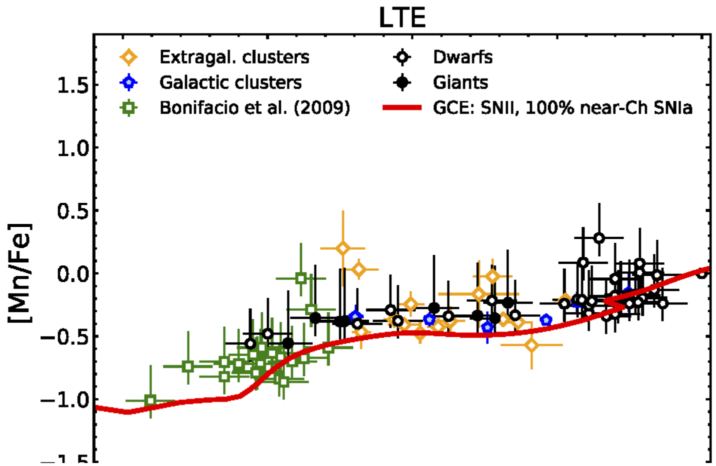
in MW, Ch is dominant (WD+WD mergers <25%)



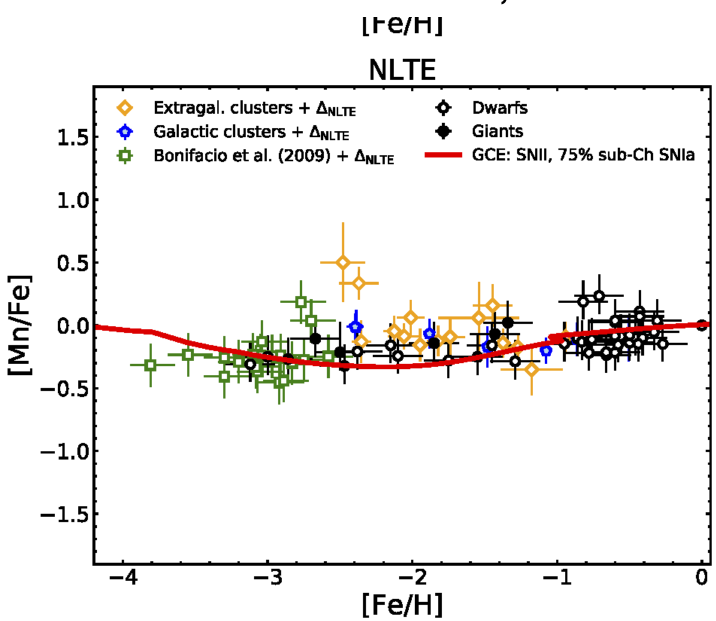
CK, Leung, Nomoto 2020

different GCE models/observations

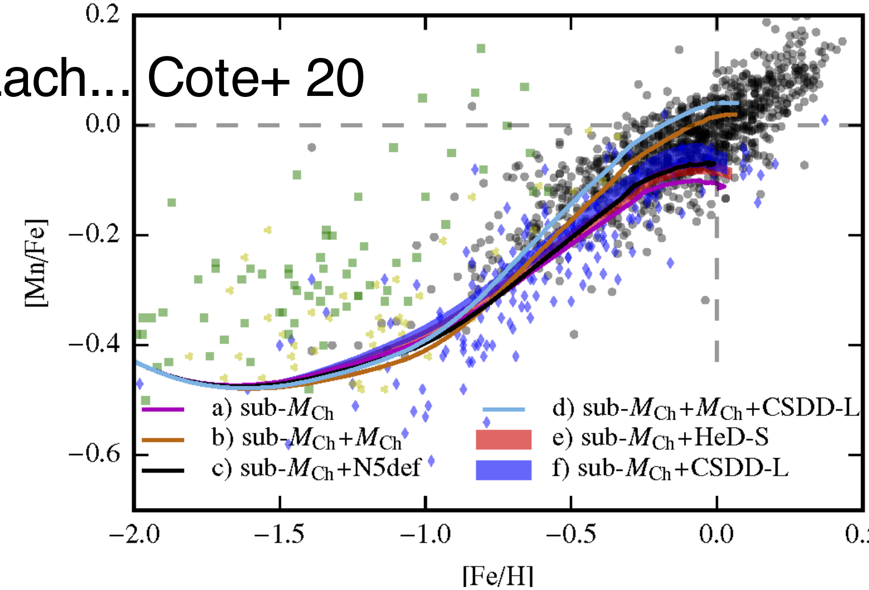
Seitenzahl, Cescutti+13, 50%



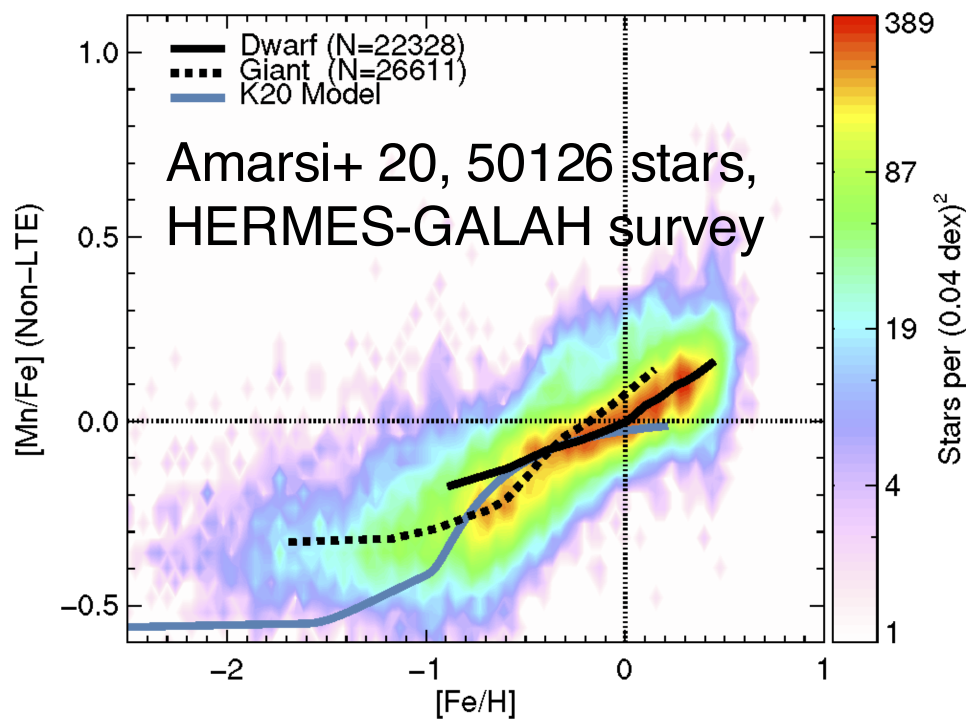
Eitner...Cescutti+ 20, 25% Ch

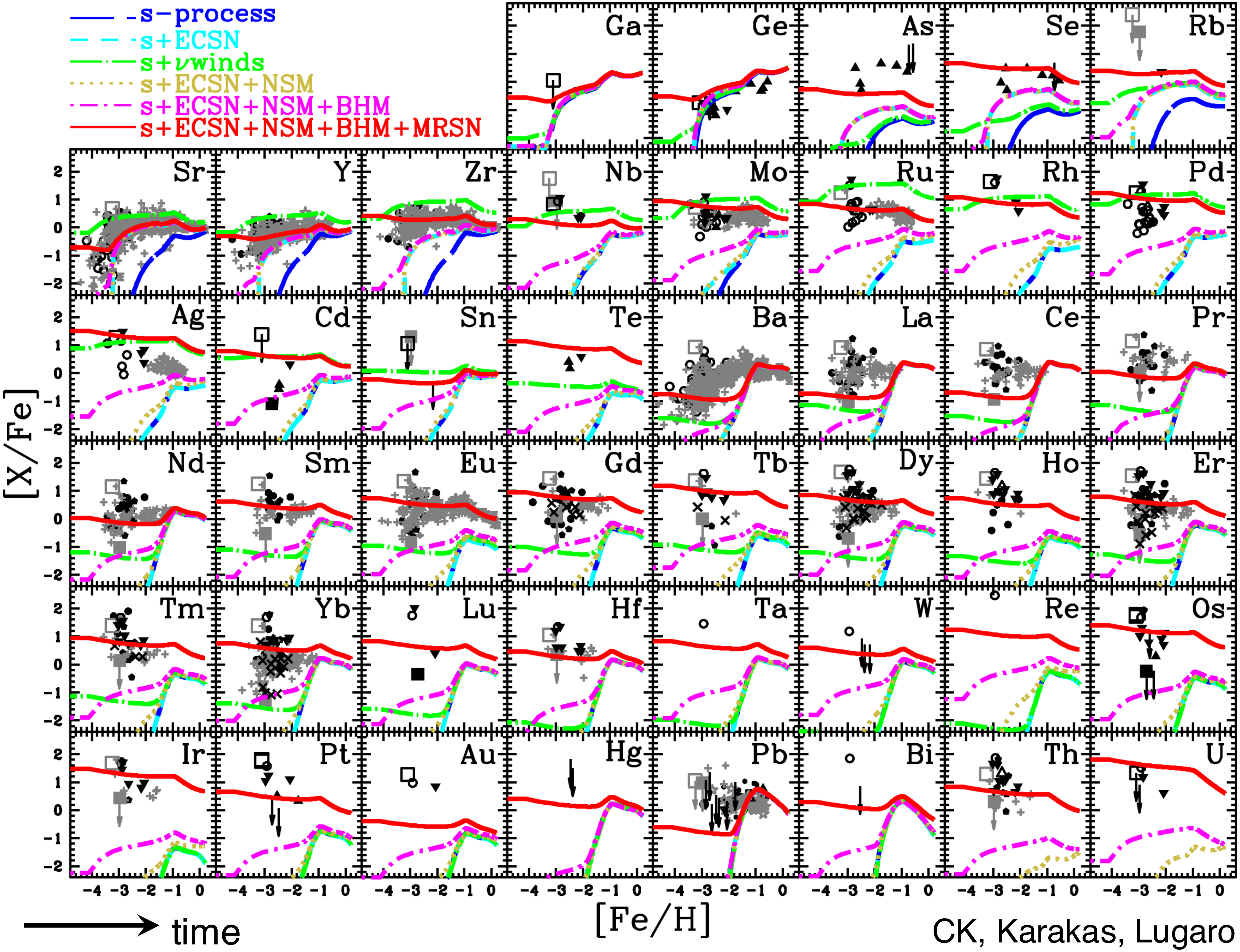


Lach... Cote+ 20



Amarsi+ 20, 50126 stars, HERMES-GALAH survey

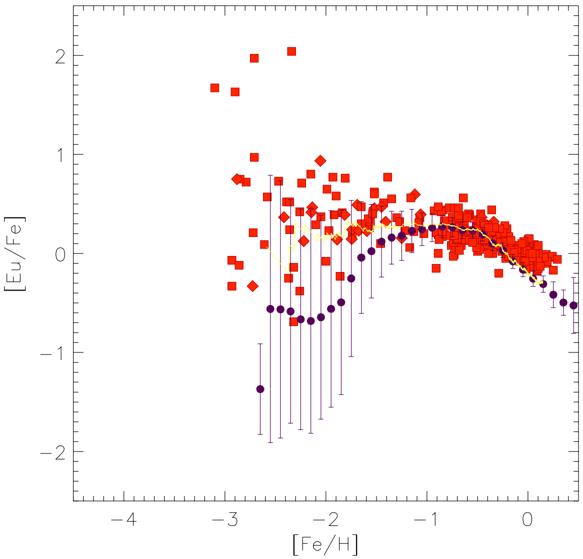




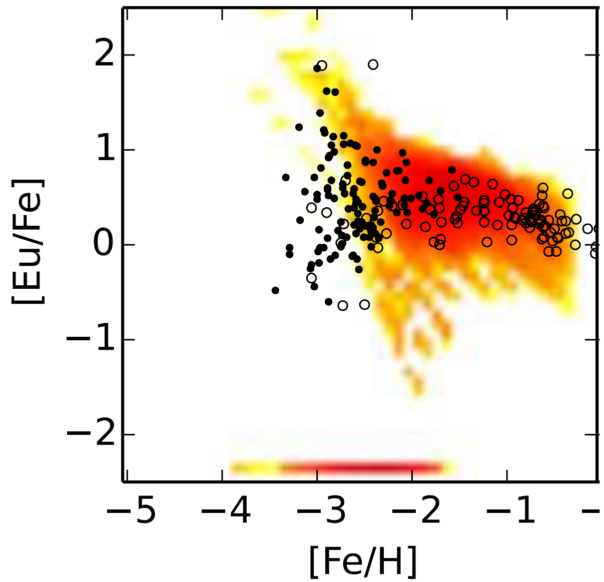
CK, Karakas, Lugaro 20

GCE models challenge NSMs

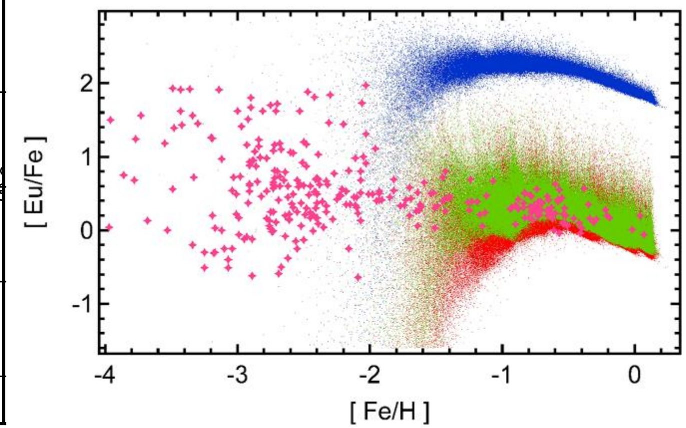
Argast+04



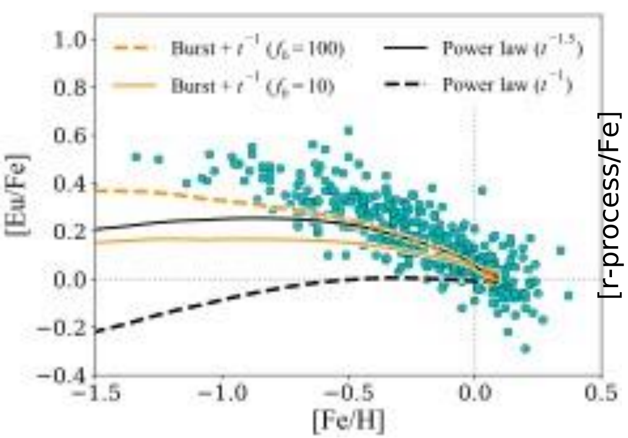
Cescutti+15



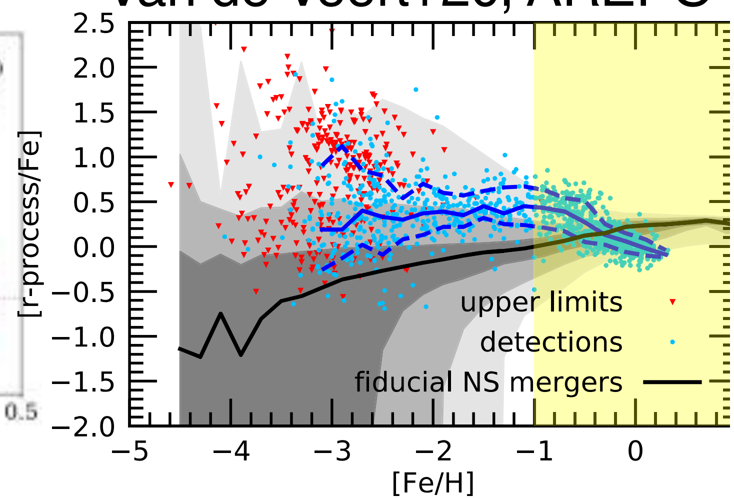
Wehmeyer+15



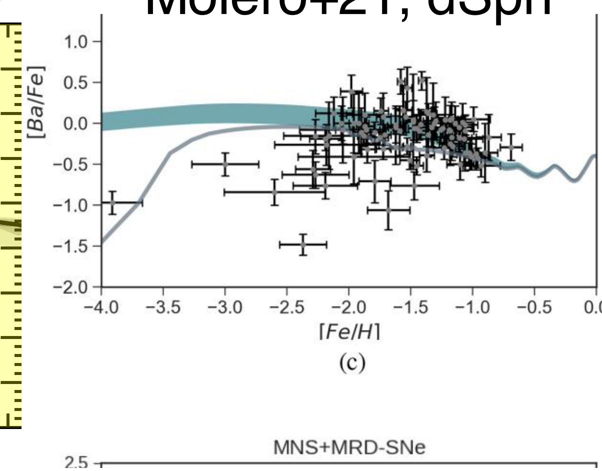
Cote+19



Van de Voort+20, AREPO

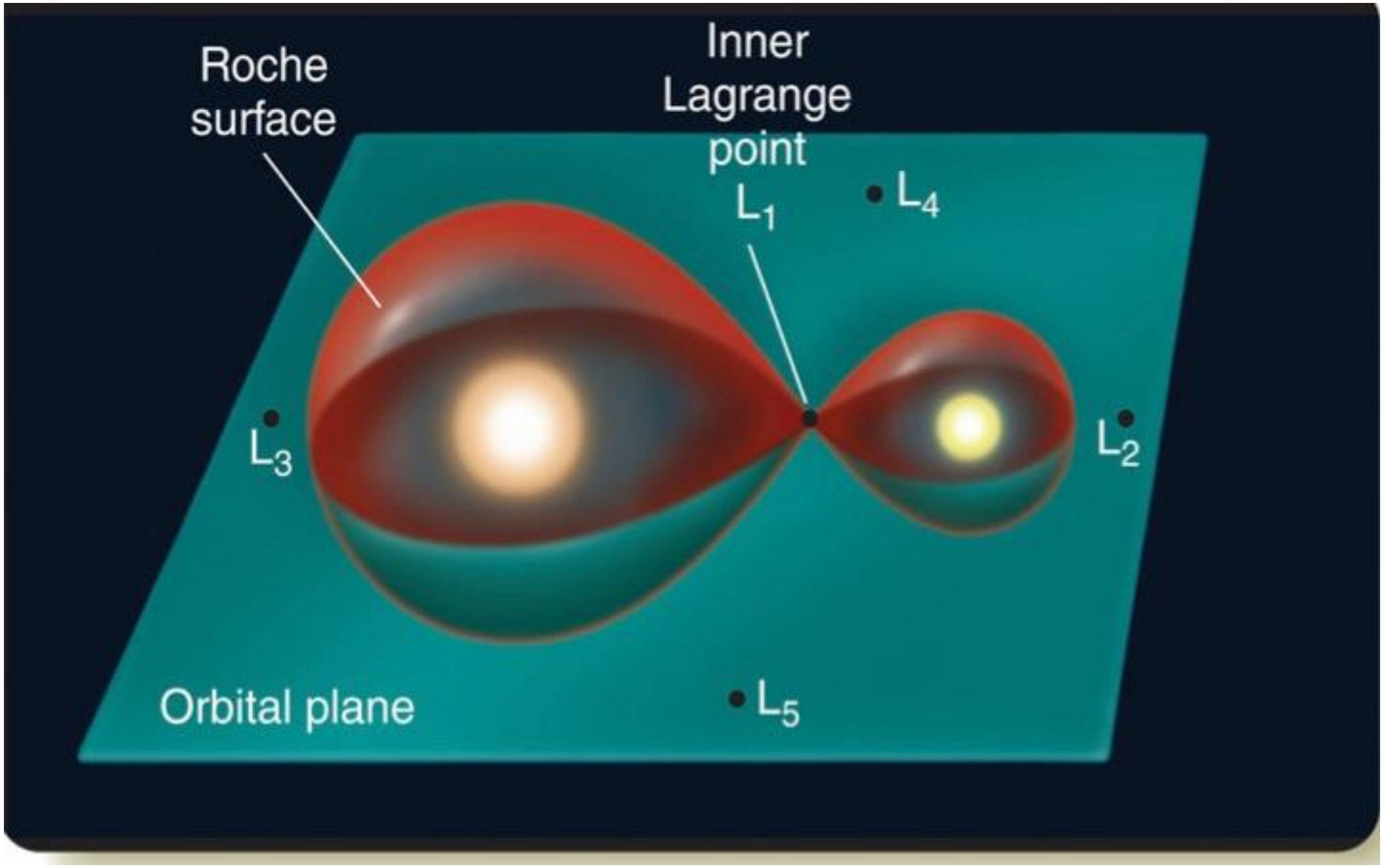


Molero+21, dSph

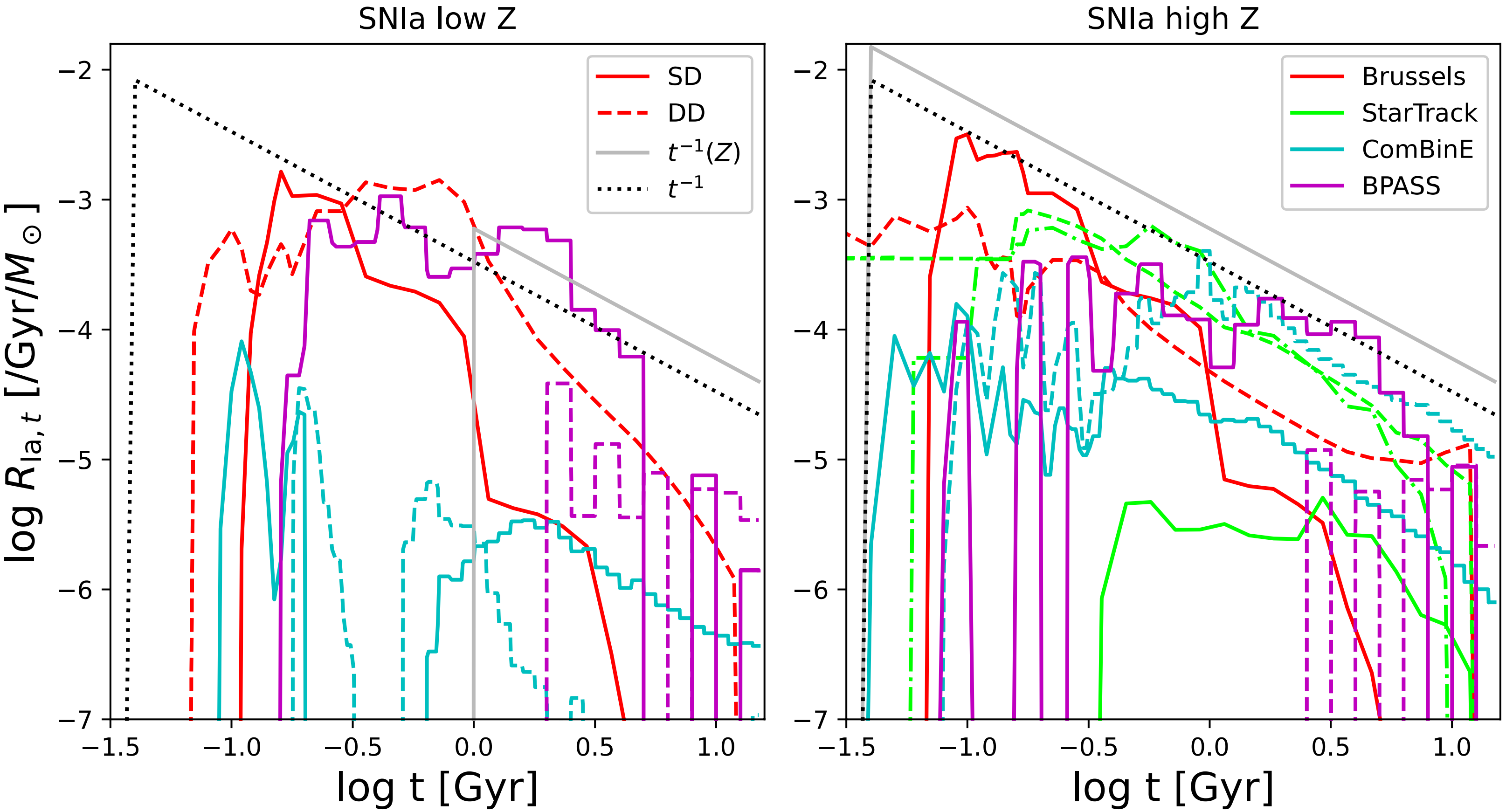


Binary population synthesis

- Stellar evoluiton of two stars in a binary system
  - Roche-lobe overflow
  - Common envelope
  - Merger



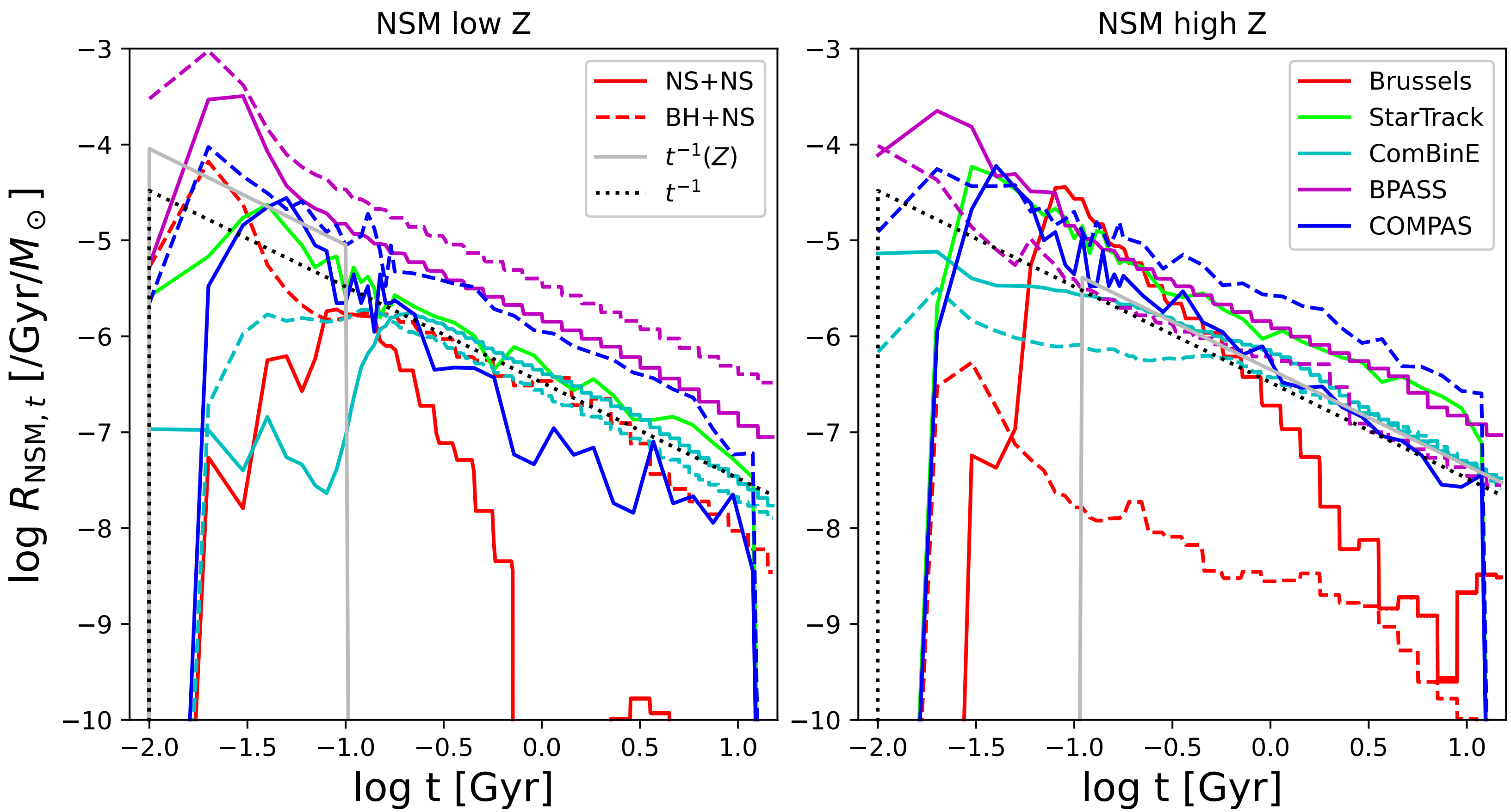
SNIa Delay-Time Distribution (DTD)



Brussels (Mennekens & Vanbeveren 10, 12; SD, DD), StarTrack (Ruiter+14; Sd, DD, He dd), ComBinE (Kruckow+18, DD only, Ch, sub-Ch), BPASS (Briel+22; SD, DD)

CK+23

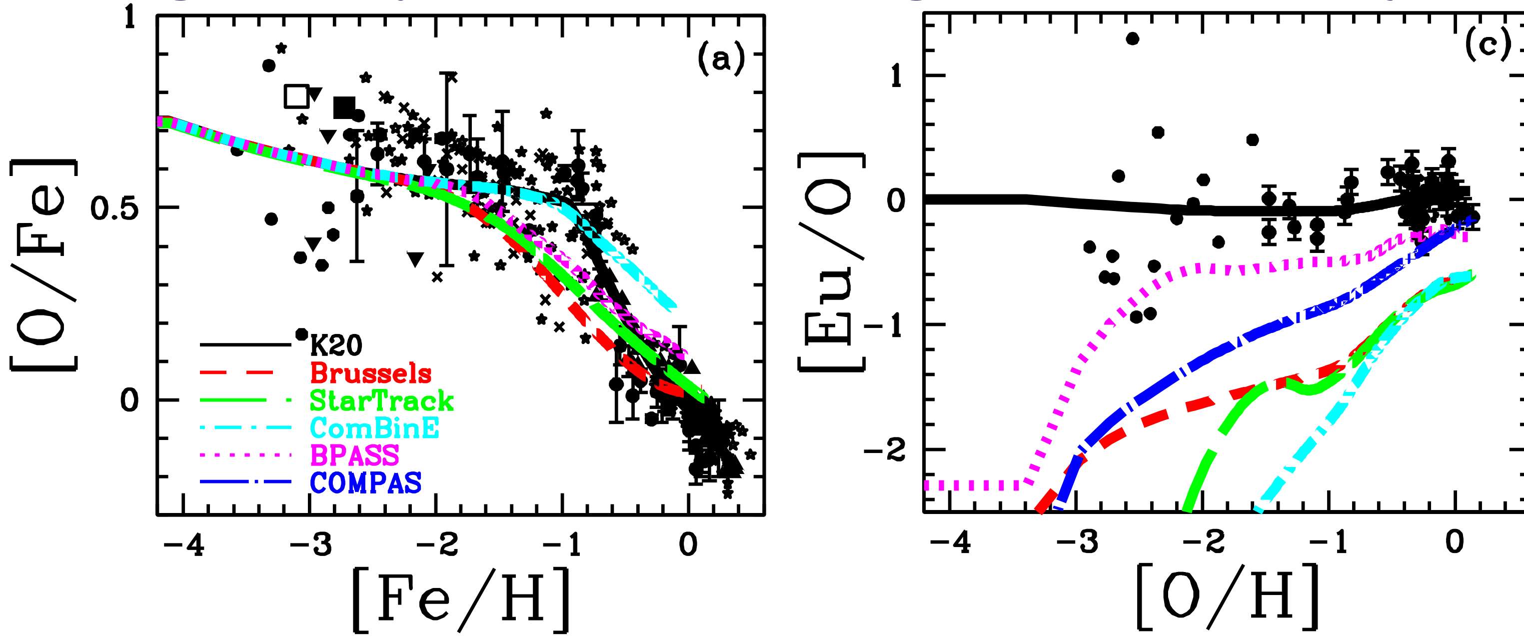
NSM Delay-Time Distribution (DTD)



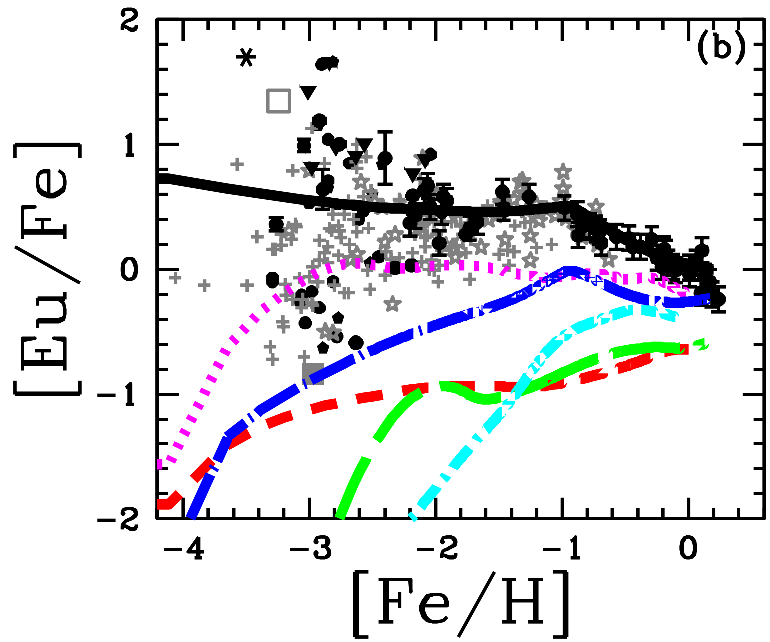
Brussels (Mennekens & Vanbeveren 14, 16), StarTrack (Belczynski+20; only NS plotted but BH included), ComBinE (Kruckow+18), COMPAS (Mandel+21), BPASS (Briel+22; only NS included)

CK+23

Binary Population Synthesis (BPS)



→ time



Points: observations of nearby stars

- DTDs are taken from BPS
- SNIa timescales too short
- NSM timescales too long
- 3D-GR yields: Wanajo+14
- K20 (black lines) include MRSNe as 3% of HNe.

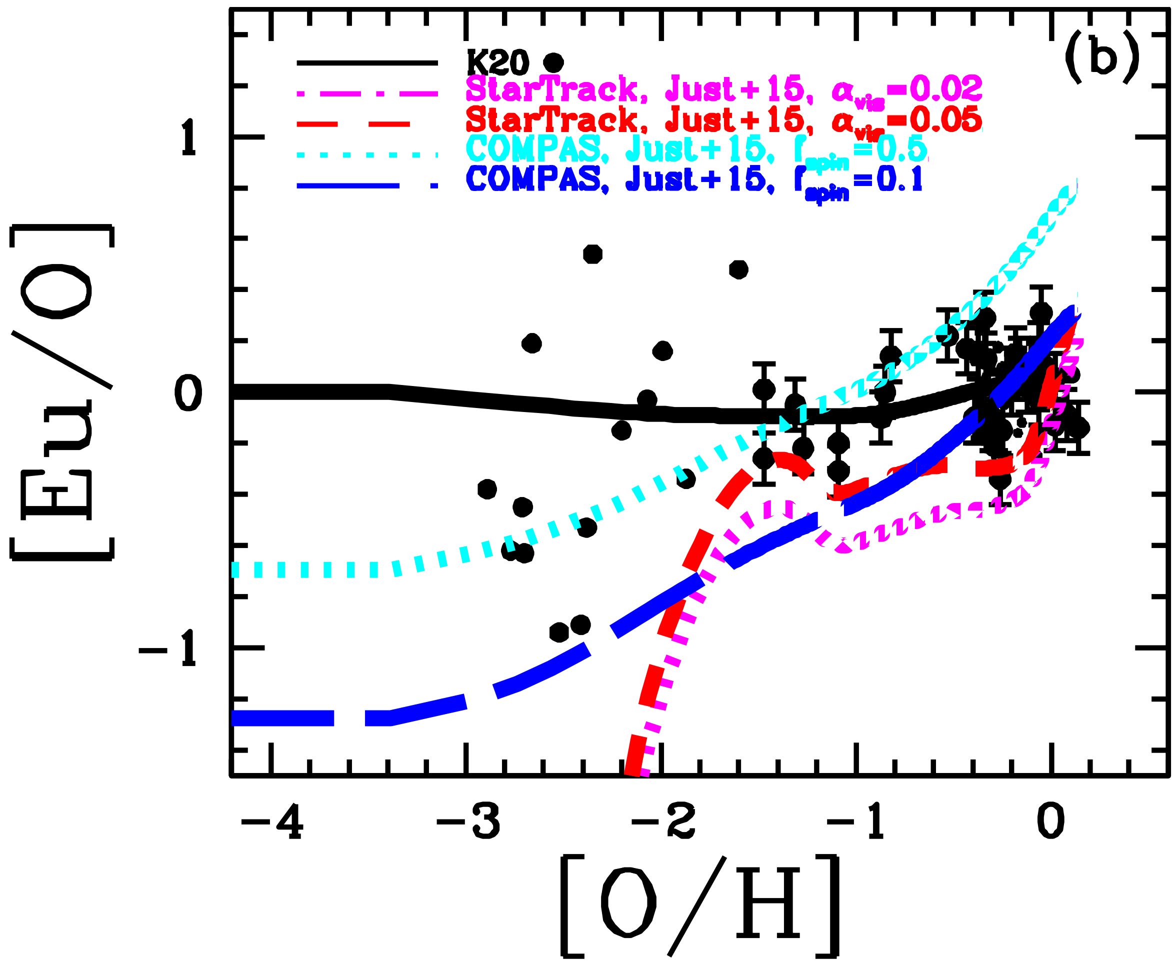
CK, Mandel, Belczynski+ 23, ApJL

The Astrophysical Journal Letters, 943:L12 (11pp), 2023 February 1 https://doi.org/10.3847/2041-8213/acad82

OPEN ACCESS

Can Neutron Star Mergers Alone Explain the r-process Enrichment of the Milky Way?

Chiaki Kobayashi[1], Ilya Mandel[2,3], Krzysztof Belczynski[4], Stephane Goriely[5], Thomas H. Janka[6], Oliver Just[7,8], Ashley J. Ruiter[9], Dany Vanbeveren[10], Matthias U. Kruckow[11], Max M. Briel[12], Jan J. Eldridge[12], and Elizabeth Stanway[13]

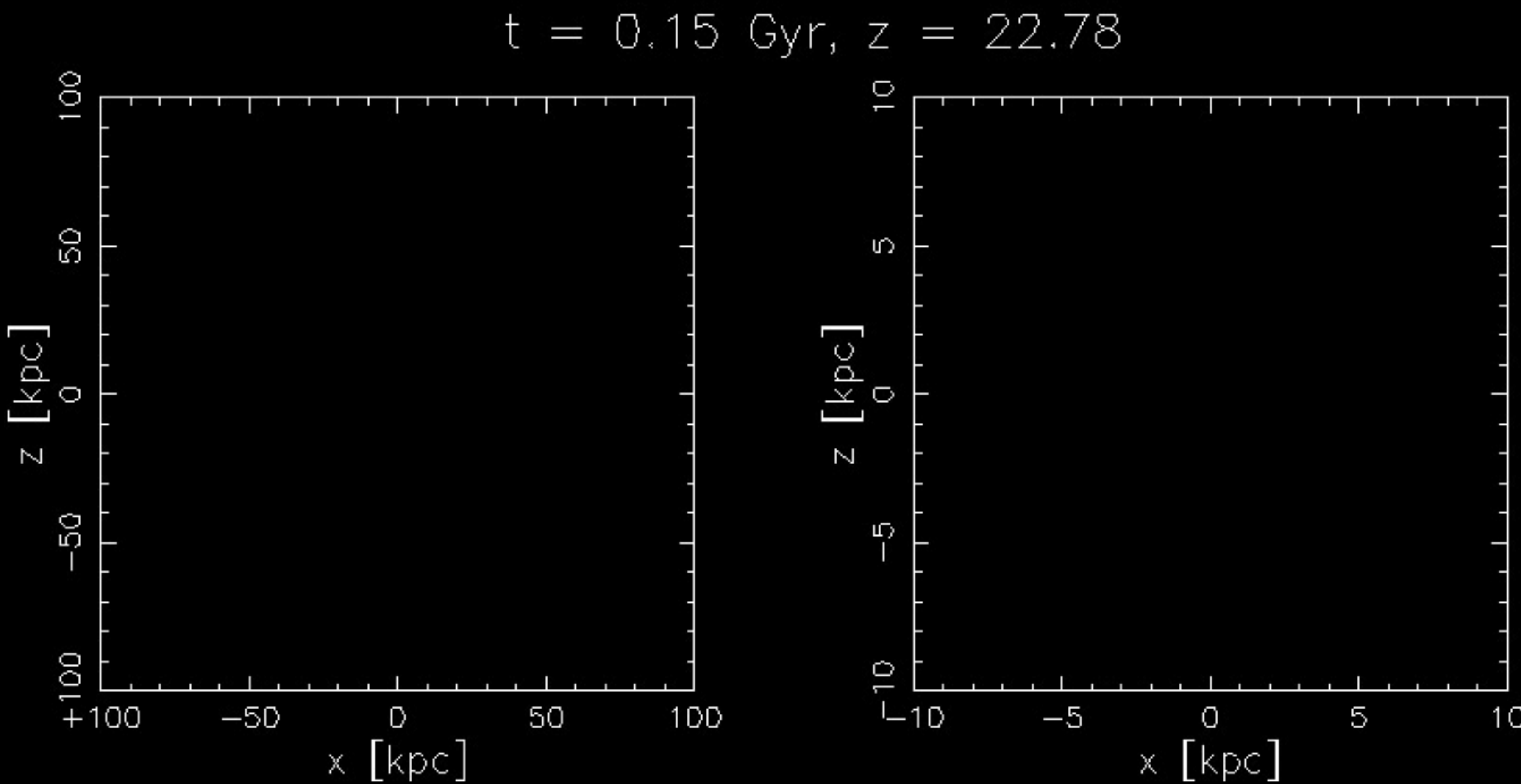


NS-BH mergers?

- **Larger yieds** including both dynamical ejecta (Ye<0.1) and ν-driven winds from torus (Ye~0.2).
- **Higher rates** depending on binary population synthesis.

Points: observations of nearby stars

Cosmological ‘zoom-in’ simulation

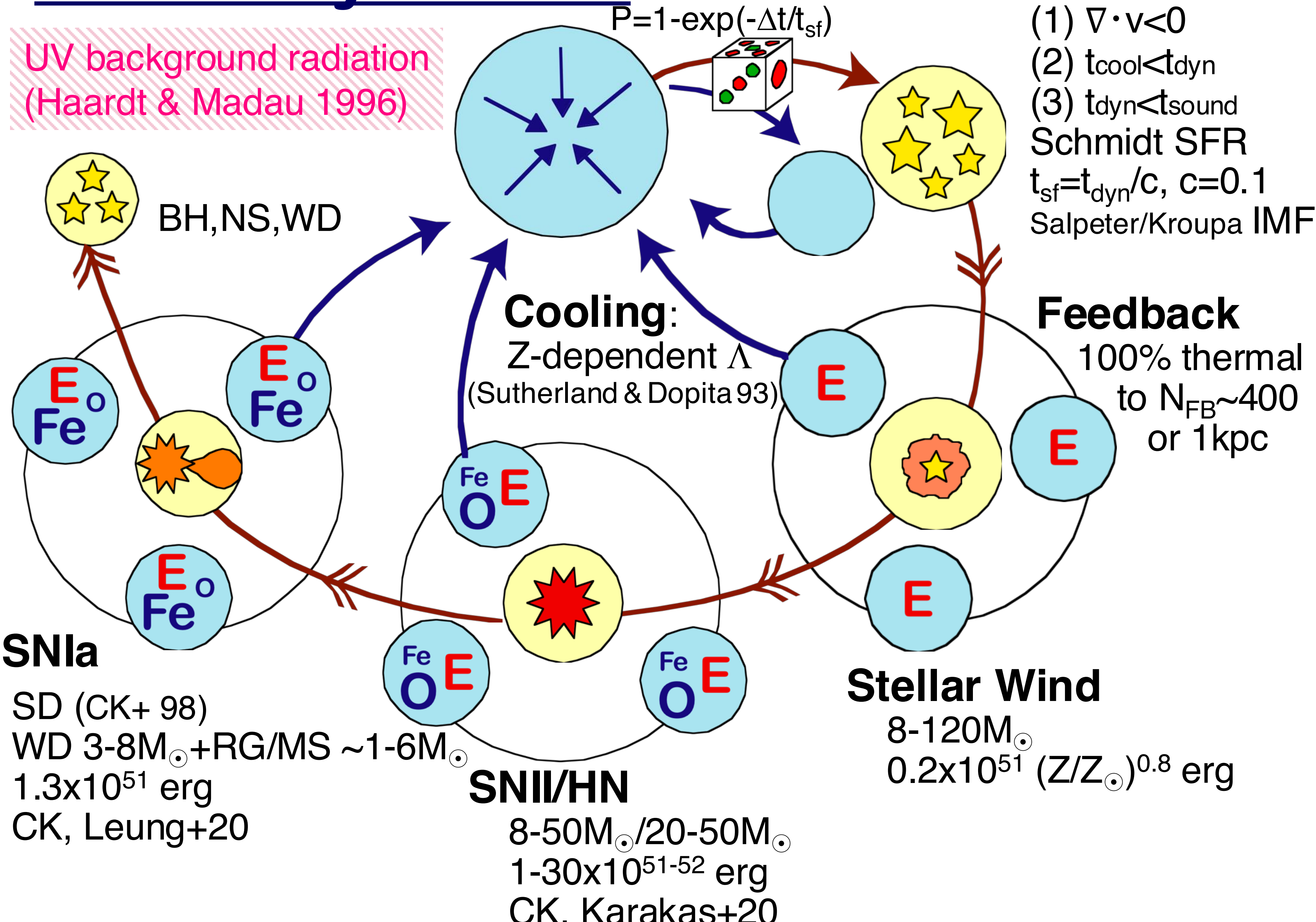


Gadget3-based code (CK+ 2007), Aquila IC (Scannapieco+12), $3x10^5 M_\odot$, 0.5kpc

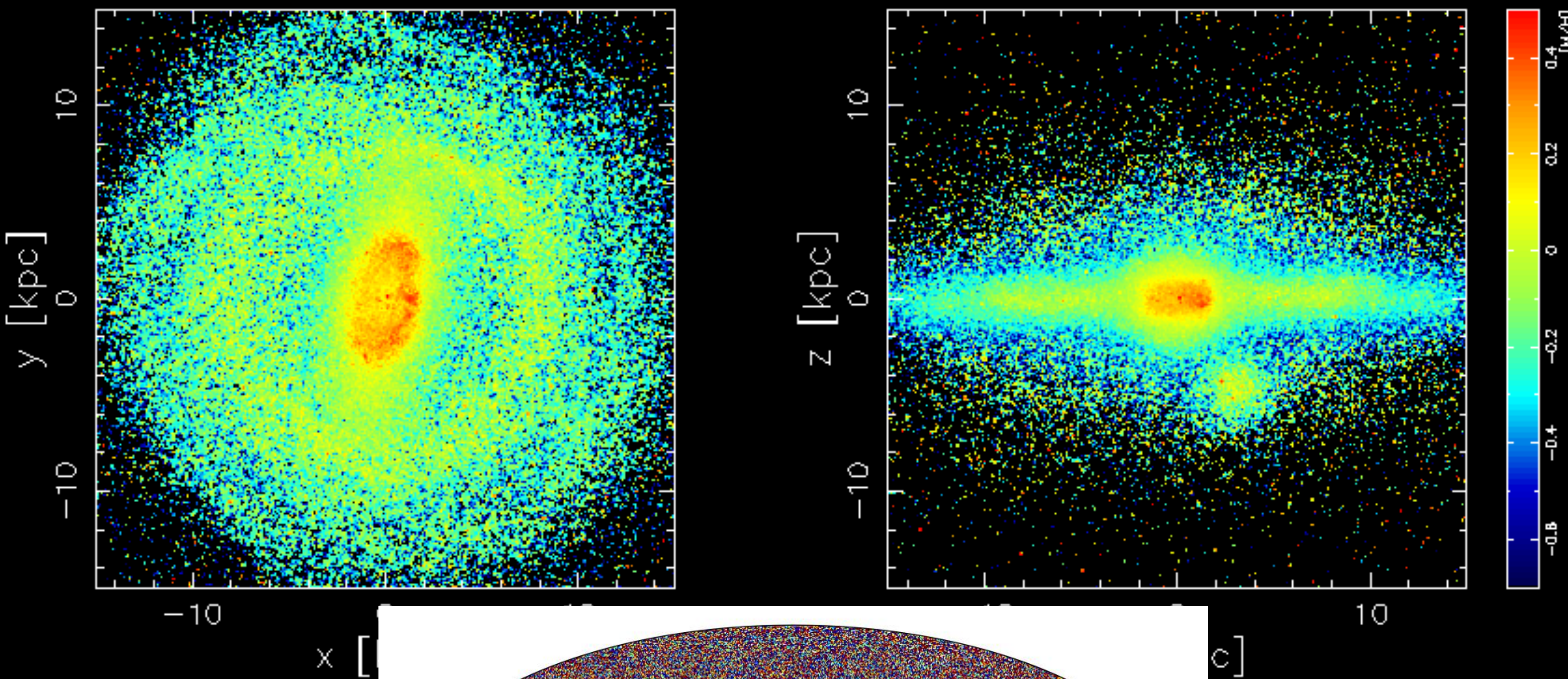
https://star.herts.ac.uk/~chiaki/works/Aq-C-5-kro2.mpg

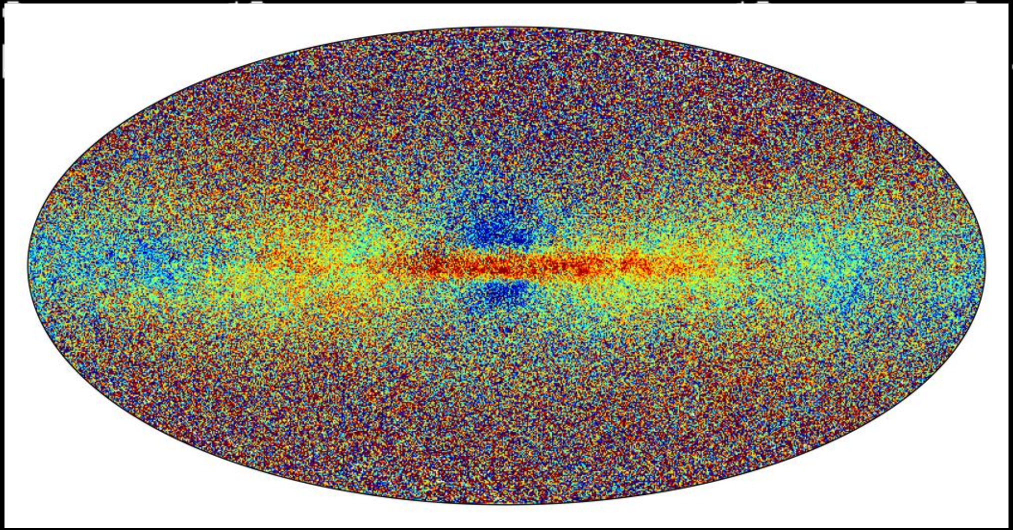
Basic features are the same in CK & Nakasato 11, Brook+12, Scannapieco+12, Auriga, FIRE-2, ARTEMIS, VINTERGATAN... but input stellar physics matters!

Chemodynamics

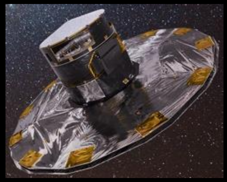


Metallicity Map

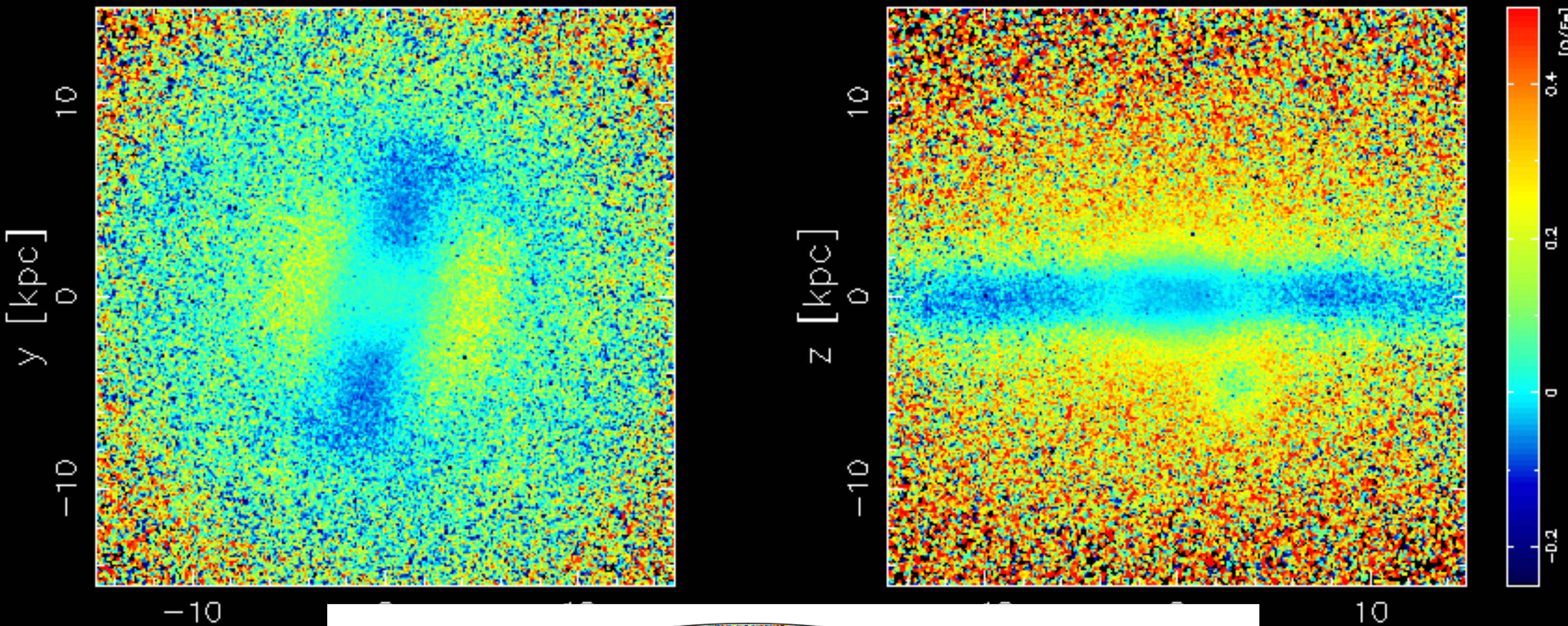


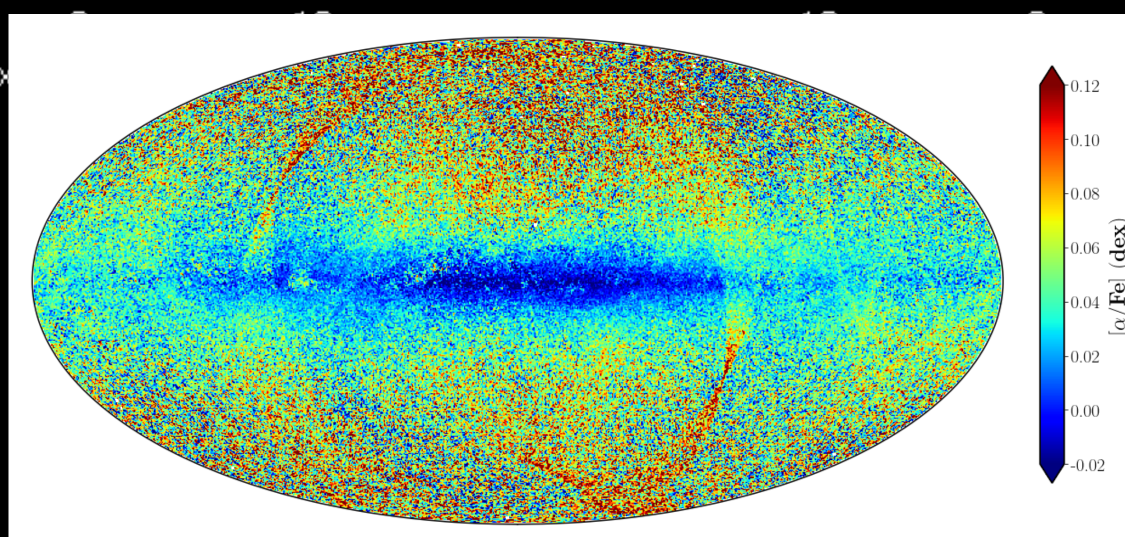


Metallicity
low to high
Gaia DR3



[O/Fe] Map

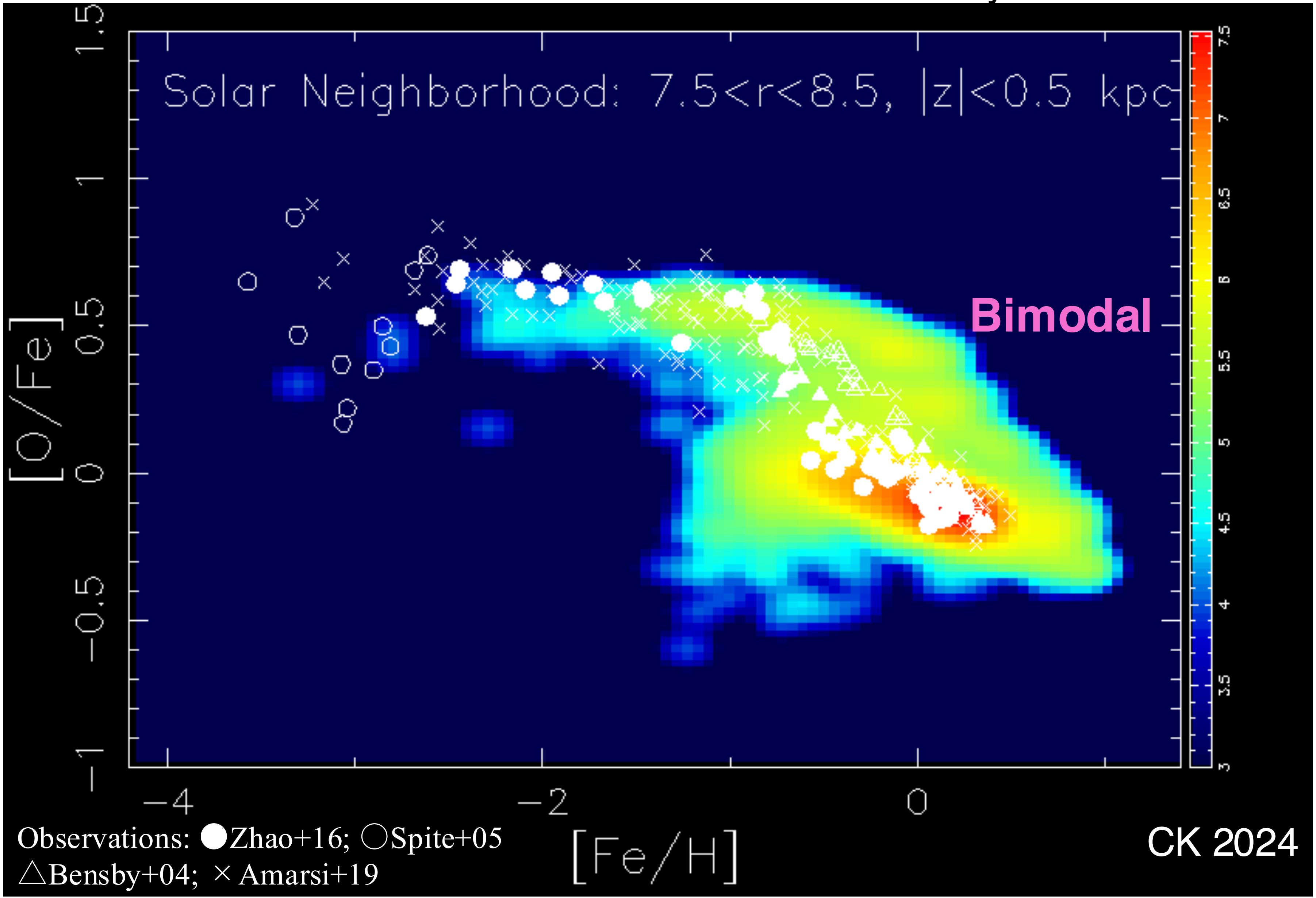




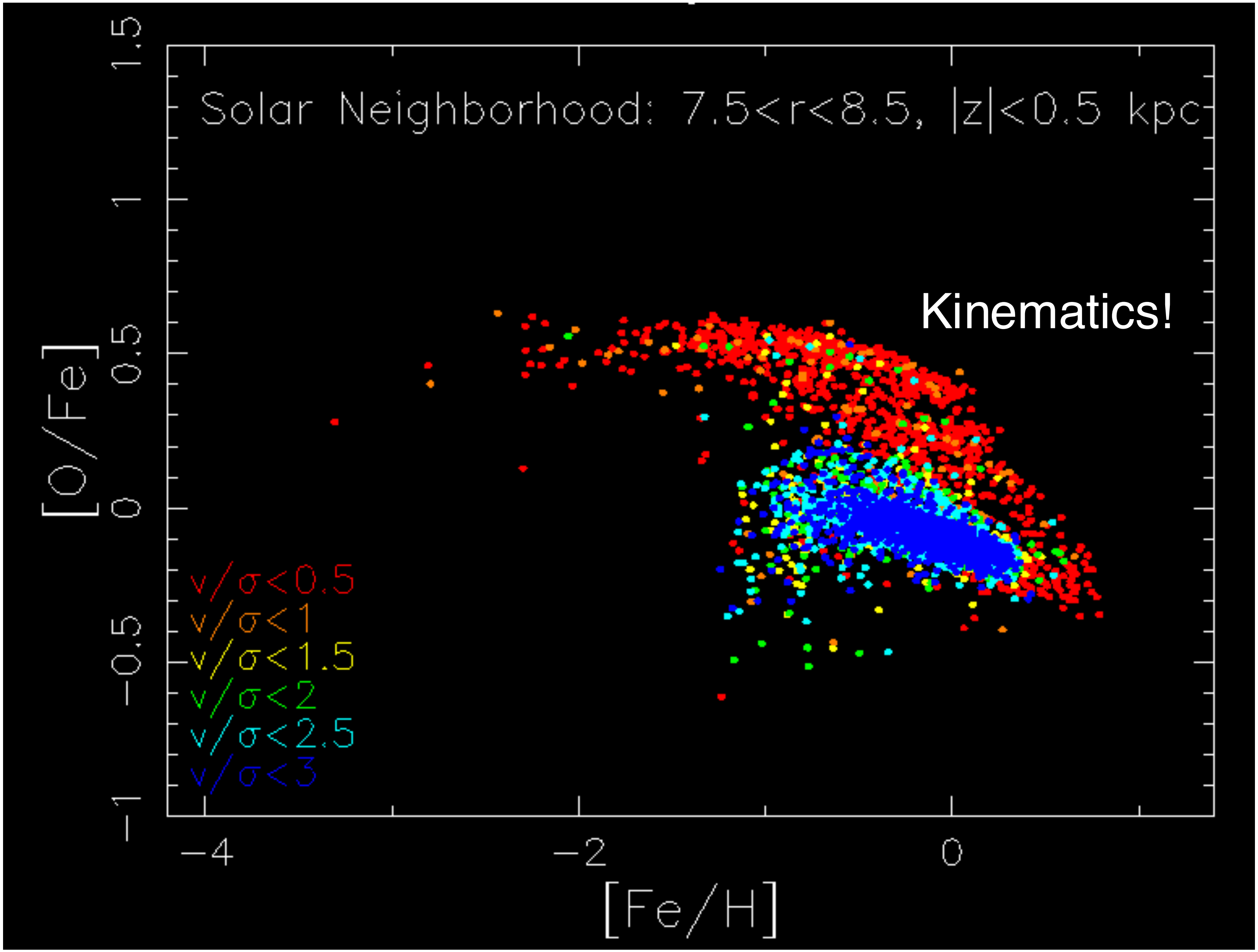
[α/Fe]
low to high
Gaia DR3

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

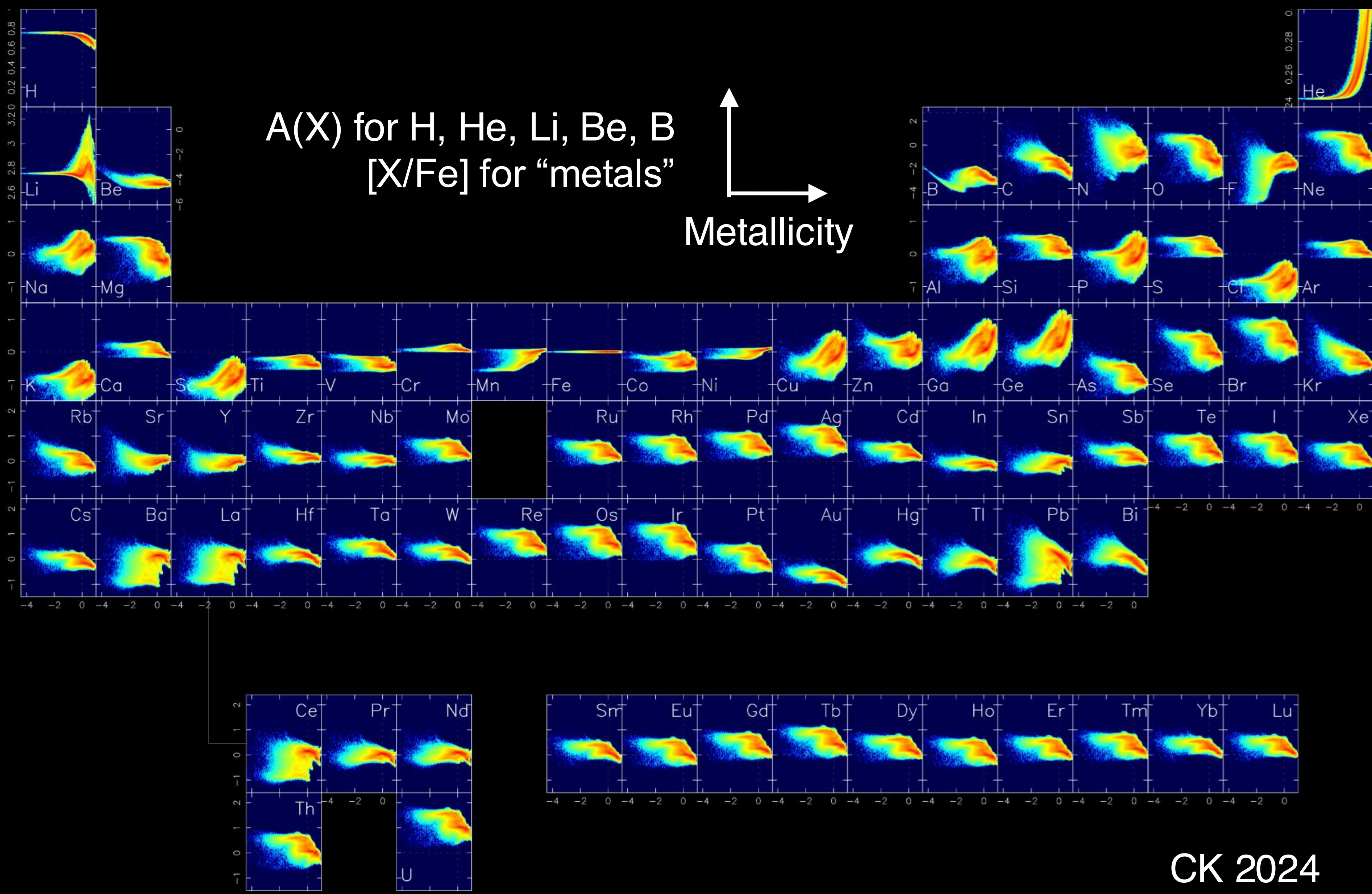
First shown in CK & Nakasato 2011 with chemodynamical simulations



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



[X/Fe]-[Fe/H] relations in MW



CK 2024