DiRAC Day 2024

Simulating the chemical enrichment of the Galaxy and in the Universe (since 2013)

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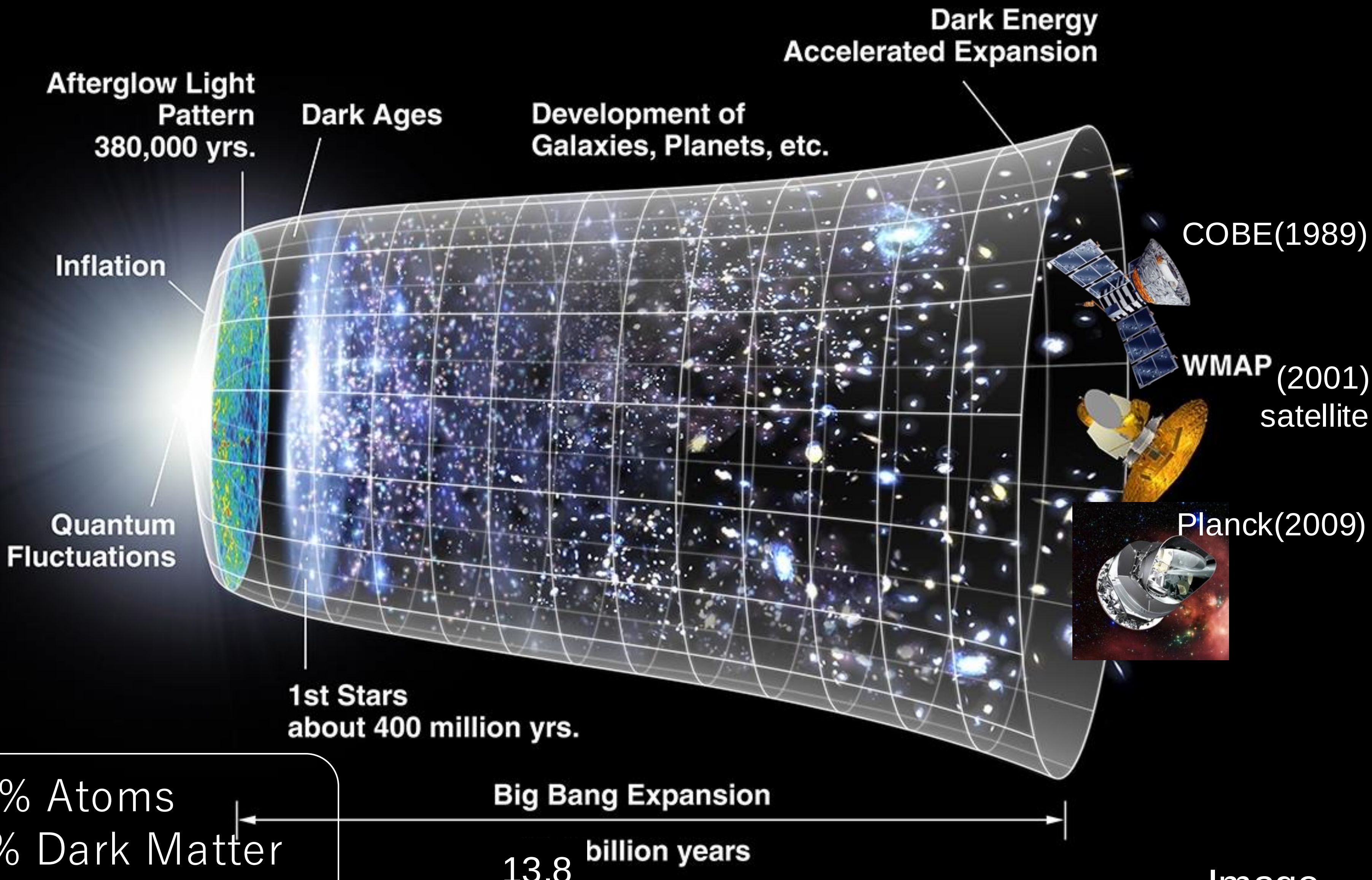
2024 George Darwin Lecturer, Royal Astronomical Society

History of the Universe

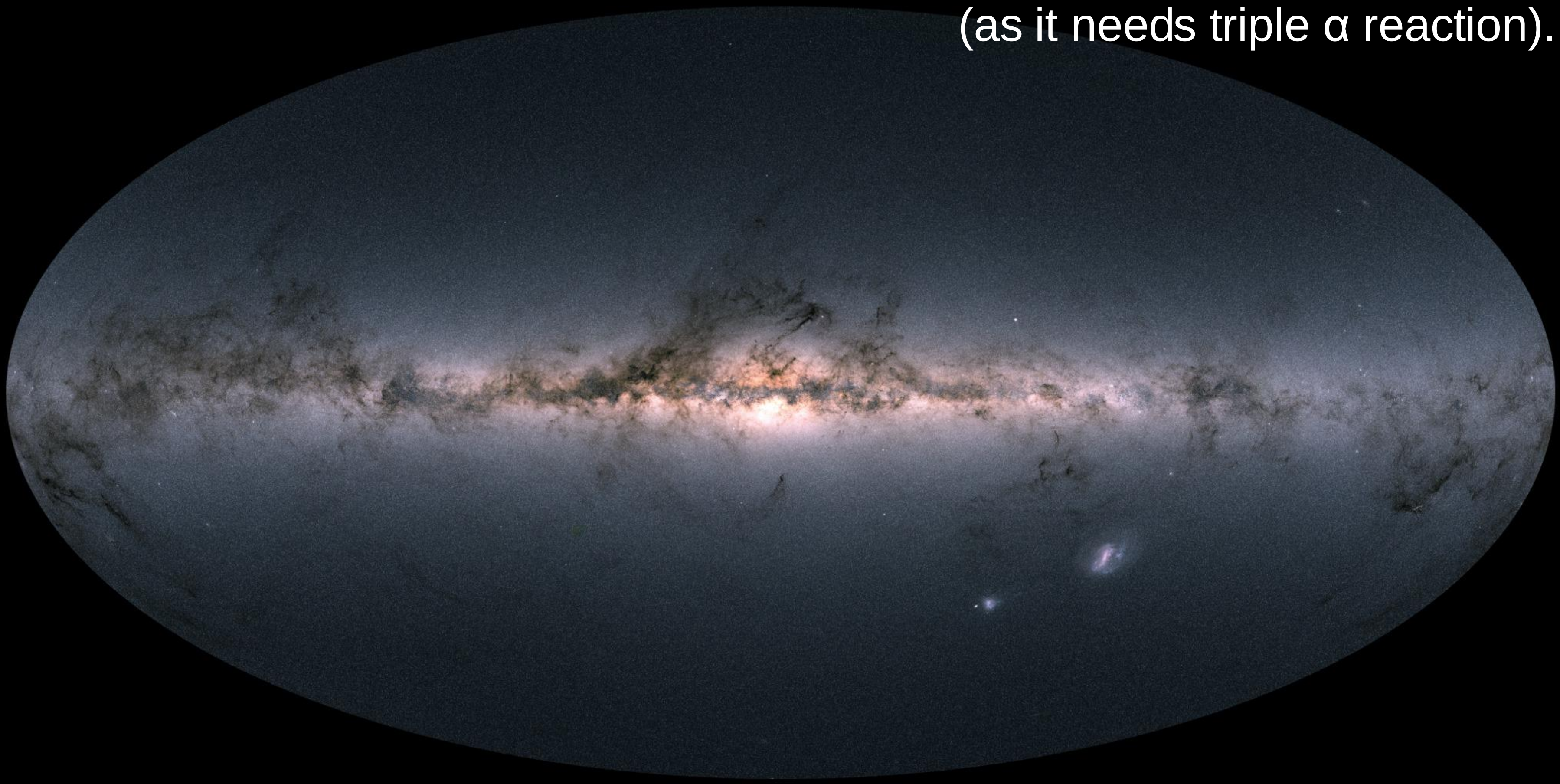


4.9% Atoms
26% Dark Matter
69% Dark Energy

Image

Our Milky Way Galaxy

Carbon and heavier elements ("metals") are produced in stars
(as it needs triple α reaction).



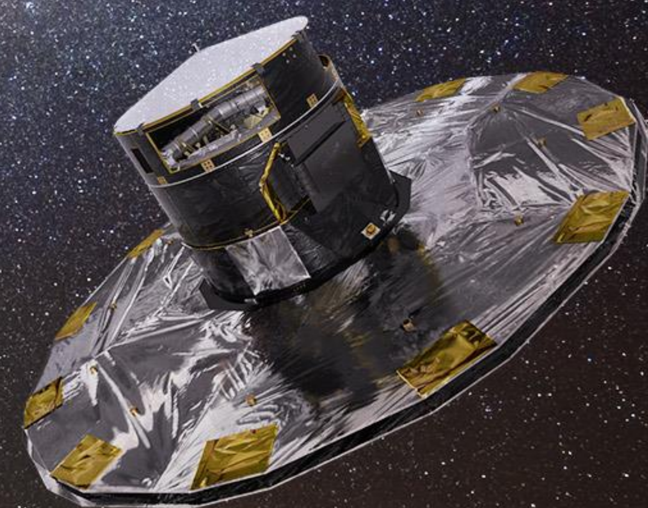
Bulge, thin/thick disks, halo, satellites, streams
– How were these sub-structures formed?

Gaia spacecraft (DR2) http://sci.esa.int/gaia/

Galactic Archaeology observations

of Milky Way and local dwarf galaxies

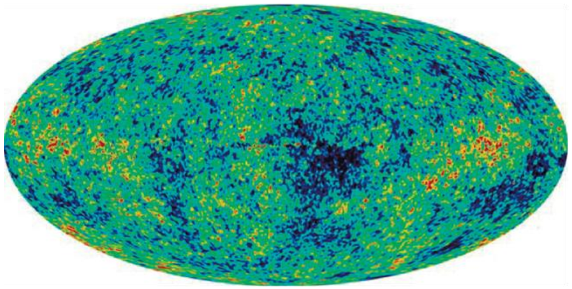
- ❖ Motions of 1.5 billion stars are measured with Gaia (2013-25).
- ❖ Ages from asteroseismology COROT, Kepler, K2, TESS…
- ❖ Elemental Abundances (from Li to Eu) of one million stars are measured with multi-object spectrographs:
  - ◆ **SEGUE** (Resolution~1800) on SDSS
  - ◆ **RAVE** (R~7500) on 1.2m UKST
  - ◆ **APOGEE** (R~20000, IR) on SDSS
  - ◆ **HERMES** on AAT (R~28000/50000)
  - ◆ **GAIA-ESO** with VLT (R~20000/40000)
  - ◆ ~~WFMOS on Subaru~~
  - ◆ **LAMOST** (R~500-1500)
  - ◆ **DESI** on Mayall (R~2000-5000)
  - ◆ **WEAVE** on WHT (R~5000/20000)
  - ◆ **4MOST** on VISTA (R~4000/21000)
  - ◆ **MOONS** on VLT (R~4000-6000/20000)
  - ◆ **PFS** on Subaru (R~2300-5000)
  - ◆ **MRMOS** (R~80000) on VLT
  - ◆ **MSE** (R~5000/40000)
  - ◆ **WST** (R~40000)
- ❖ For Au, U etc, target survey of EMP stars w higher res./ UV



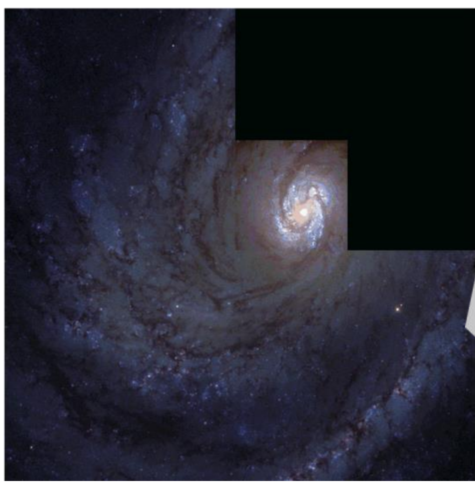
Gaia spacecraft http://sci.esa.int/gaia/

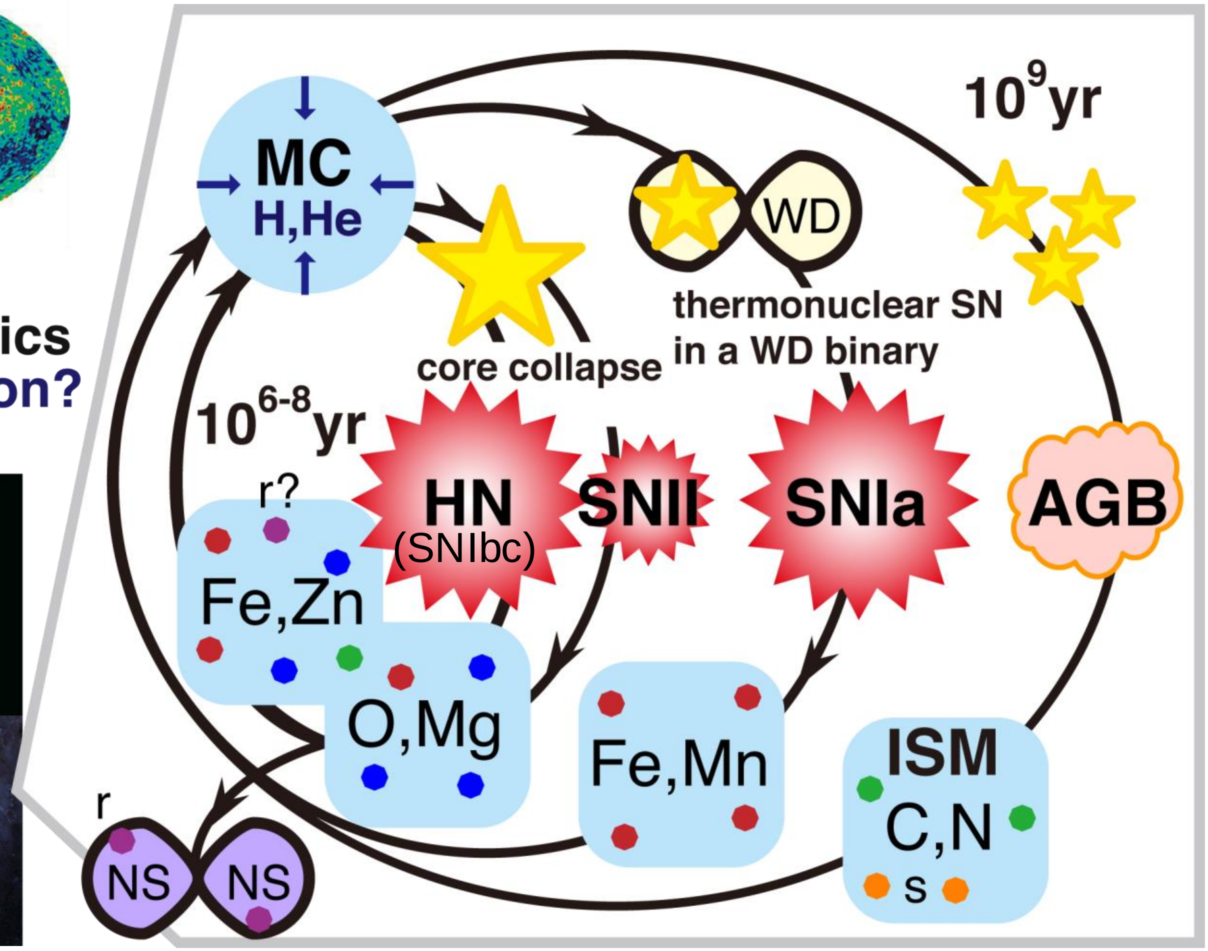
Chemical Enrichment

Nomoto, CK, Tominaga 2013 ARAA



Gravity
Hydrodynamics
Star Formation?
Feedback?



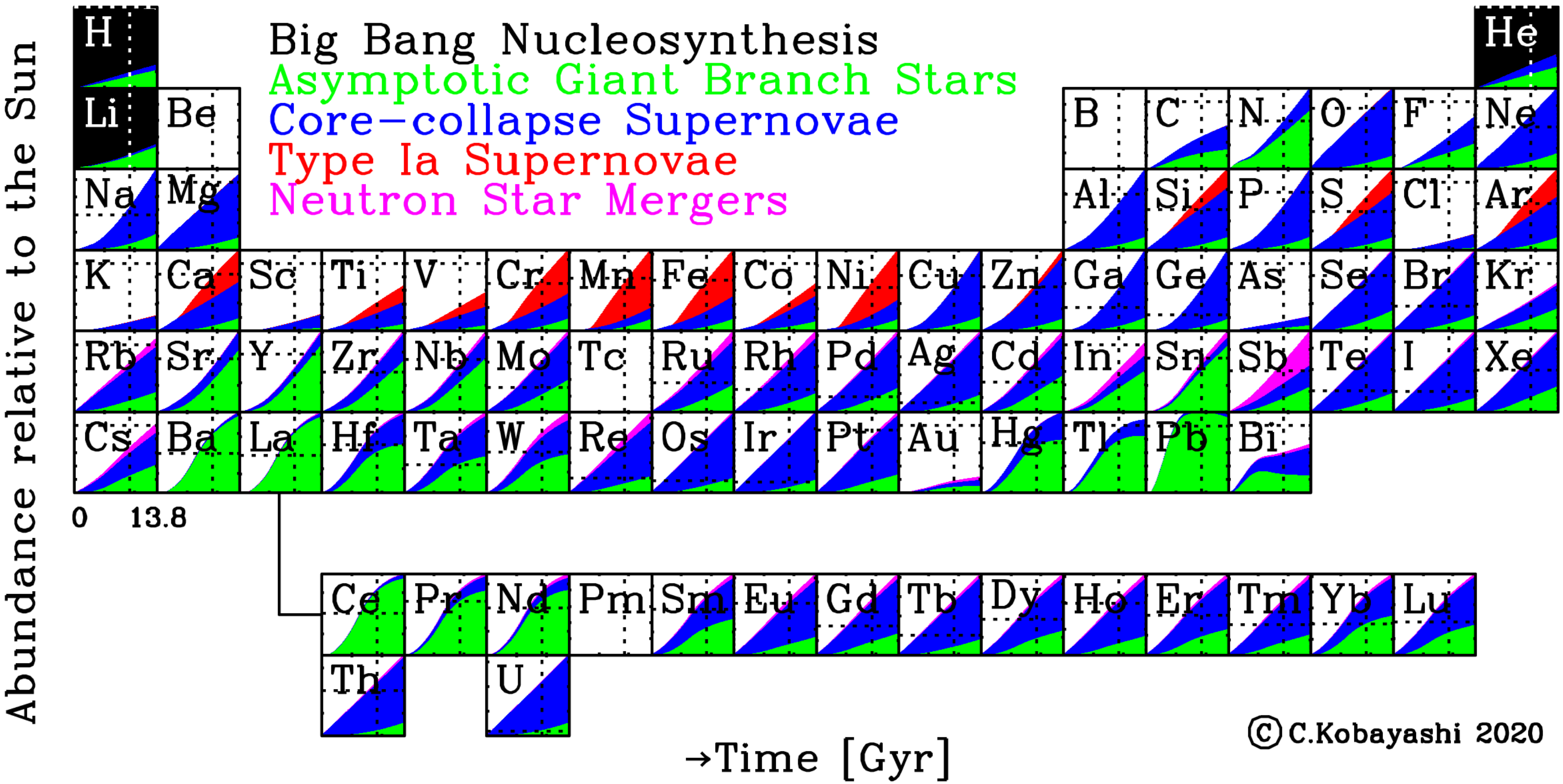


- [Fe/H] and [X/Fe] evolve in a galaxy: fossils that retain the evolution history of the galaxy → **Galactic Archaeology**

$[X/Y]=\log(X/Y)-\log(X/Y)_\odot$

The Origin of Elements

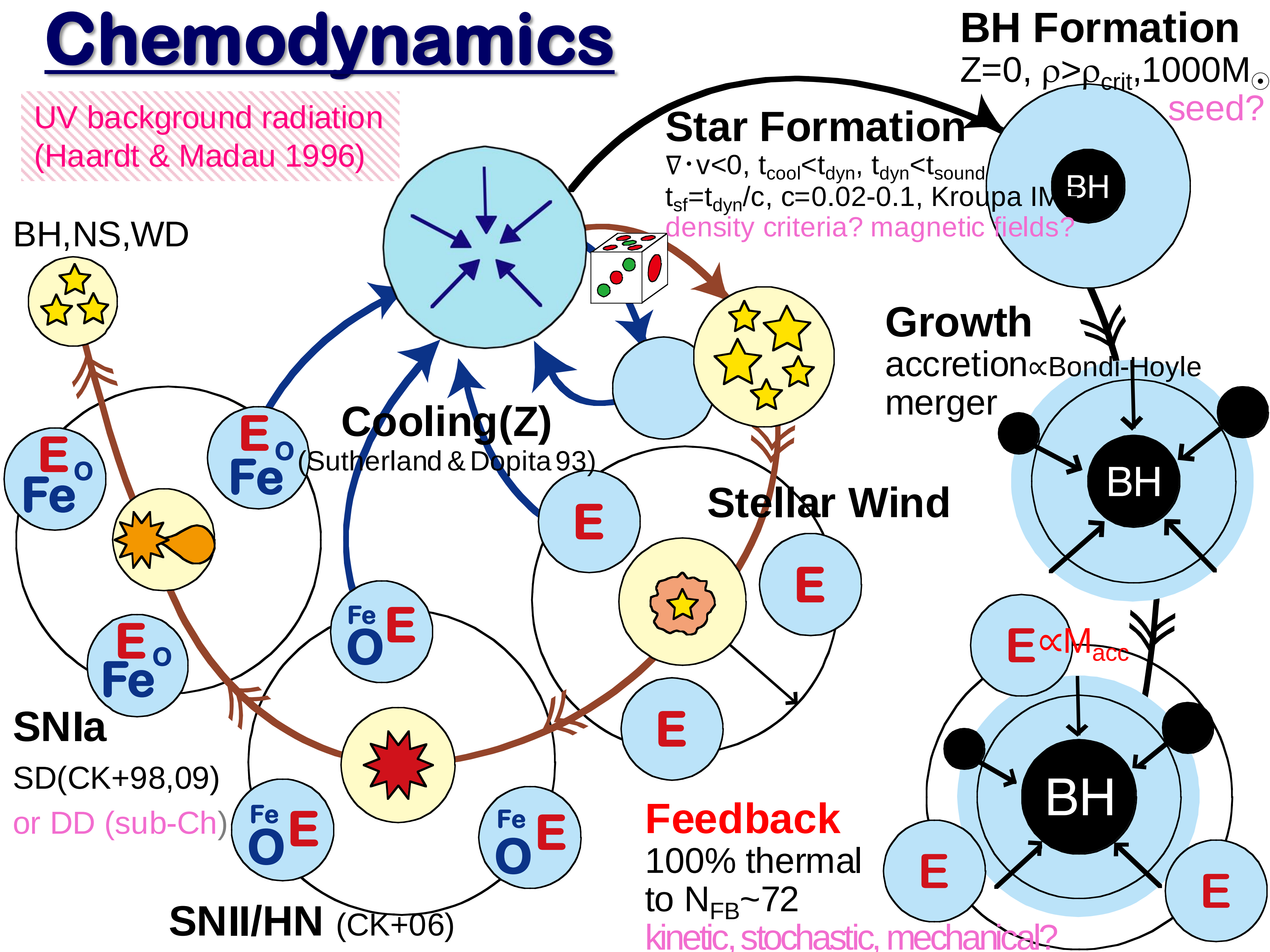
CK, Karakas, Lugaro 2020, ApJ



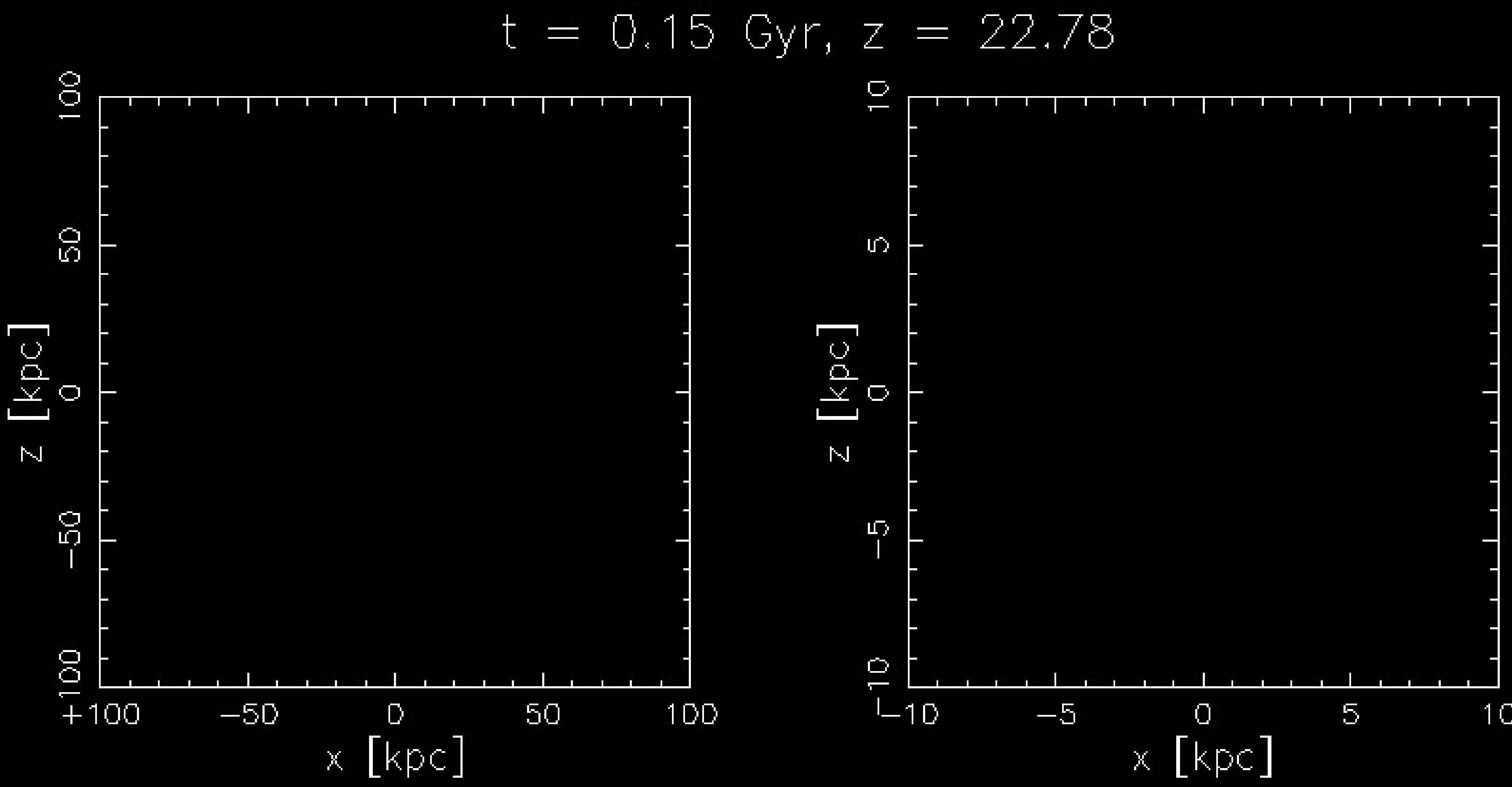
※Purely theoretical, no empirical equations.

※Mass-loss is counted toward AGB or ccSN.

dotted lines: solar values

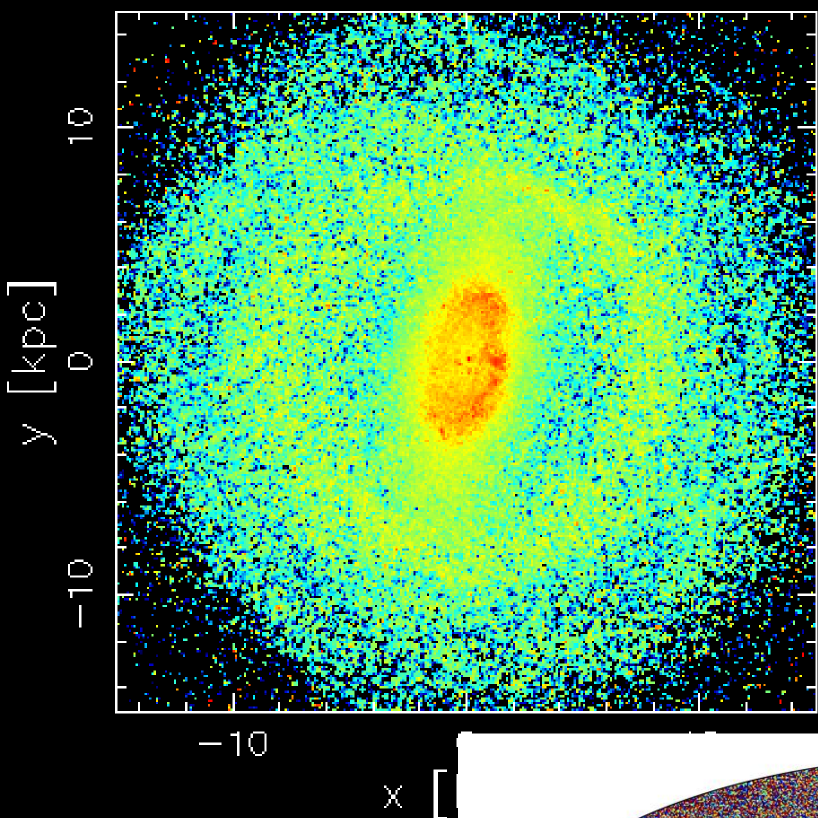

Chemodynamics
UV background radiation
(Haardt & Madau 1996)
BH Formation
Z=0, ρ>ρ$_{crit}$,1000M$_{\odot}$
seed?
Star Formation
∇·v<0, t_{cool}<t_{dyn}, t_{dyn}<t_{sound}
t_{sf}=t_{dyn}/c, c=0.02-0.1, Kroupa IMF
density criteria? magnetic fields?
BH
BH,NS,WD
Growth
accretion∝Bondi-Hoyle
merger
BH
Cooling(Z)
(Sutherland & Dopita 93)
Stellar Wind
E
E
E
E$_o$ Fe
E$_o$ Fe
E$_o$ Fe
Fe O E
Fe O E
Fe O E
E∝M$_{acc}$
BH
E
E
SNIa
SD(CK+98,09)
or DD (sub-Ch)
SNII/HN (CK+06)
Feedback
100% thermal
to N_{FB}~72
kinetic, stochastic, mechanical?

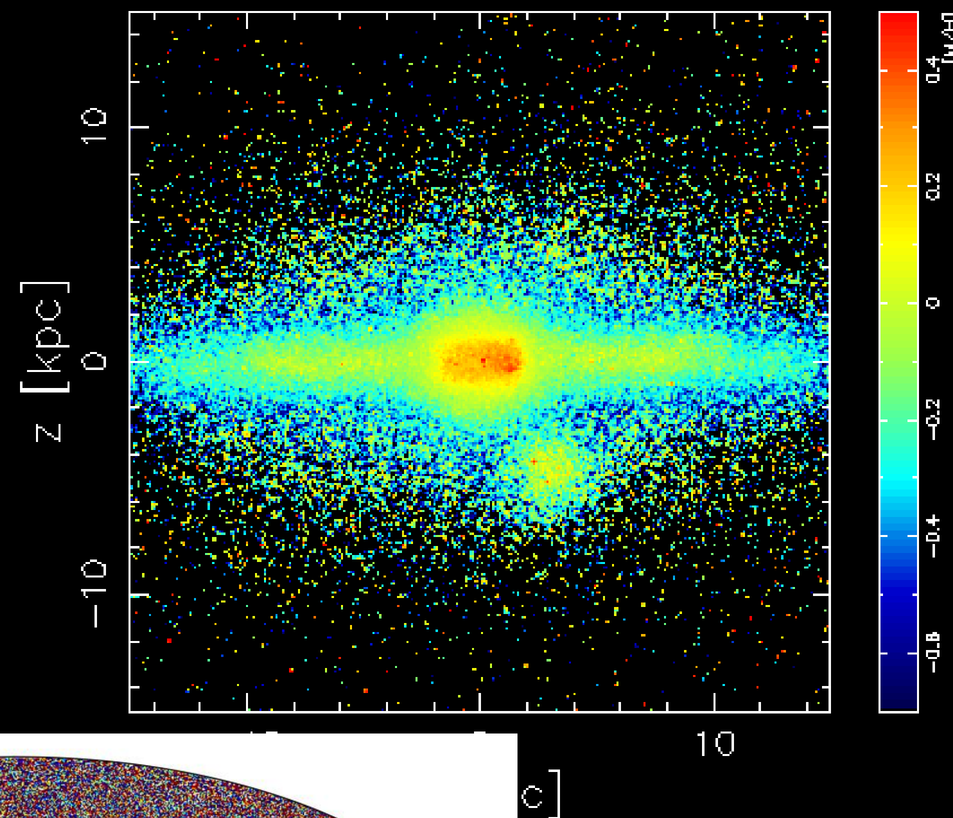
Cosmological zoom-in simulation

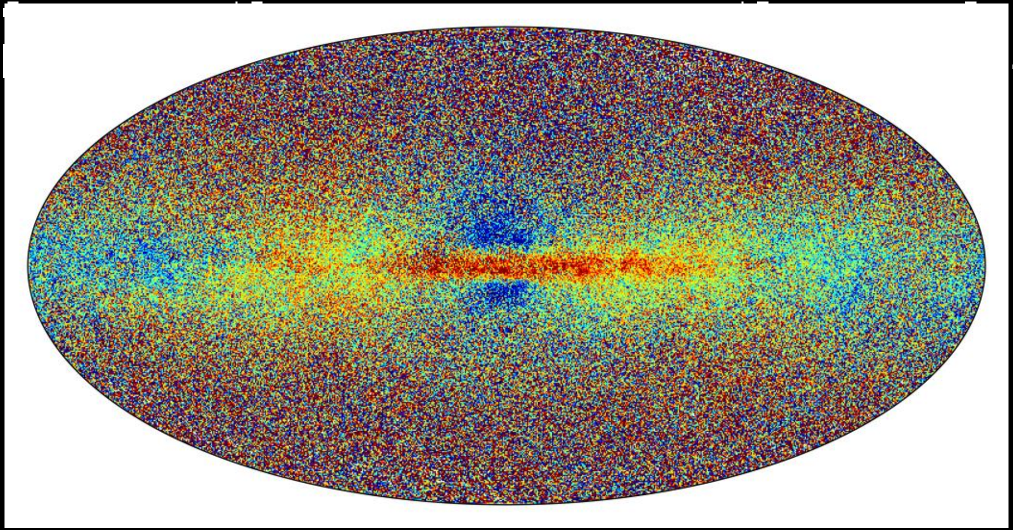


Chemical enrichment routine (CK04) + Gadget3-based code (CK+07)
Aquila Initial Condition (Scannapieco+12), $3x10^5M_\odot$, 0.5kpc
https://star.herts.ac.uk/~chiaki/works/Aq-C-5-kro2.mpg

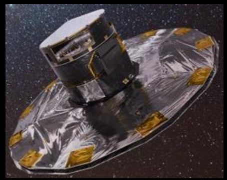
Metallicity Map



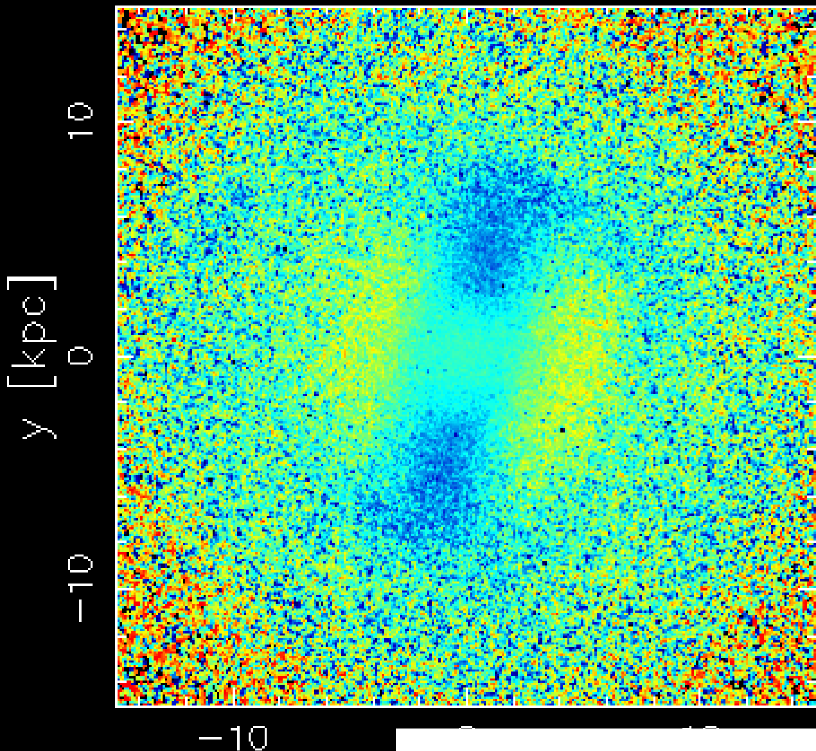


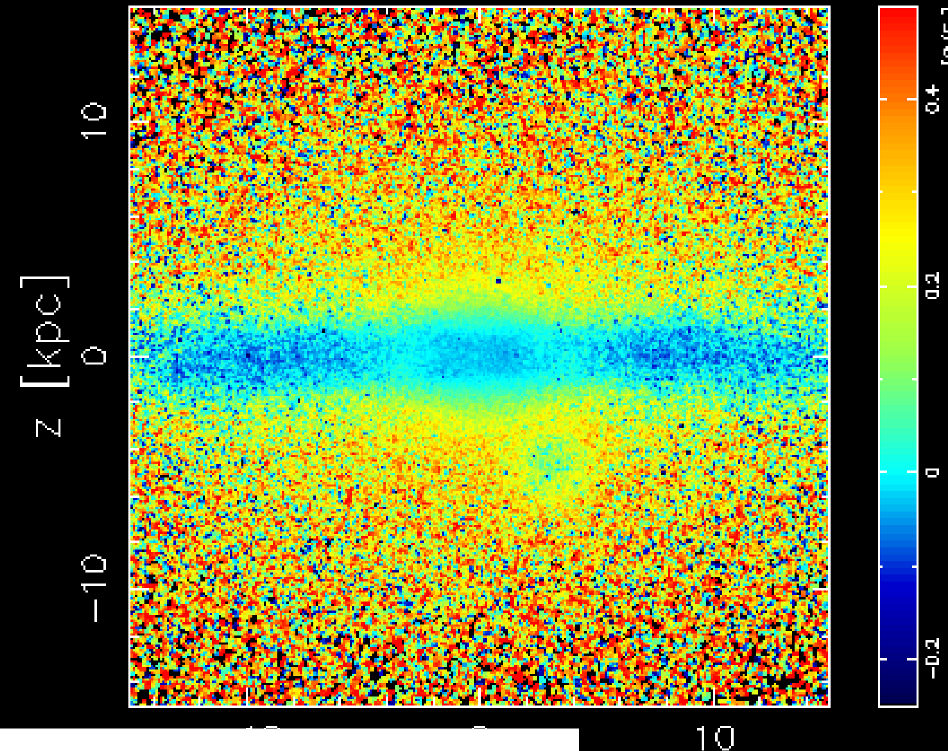


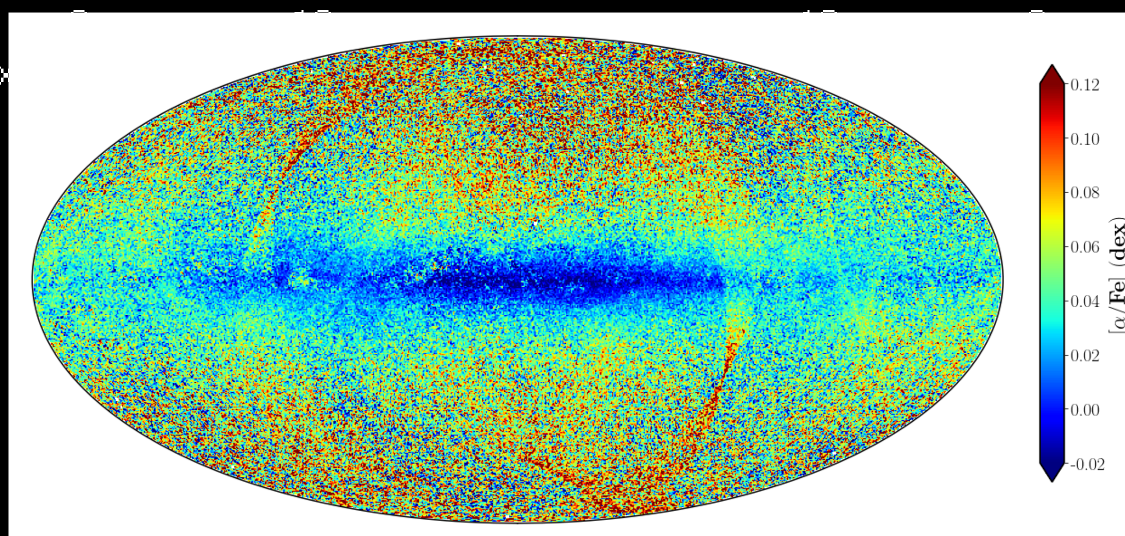
Metallicity
low to high
Gaia DR3



[O/Fe] Map



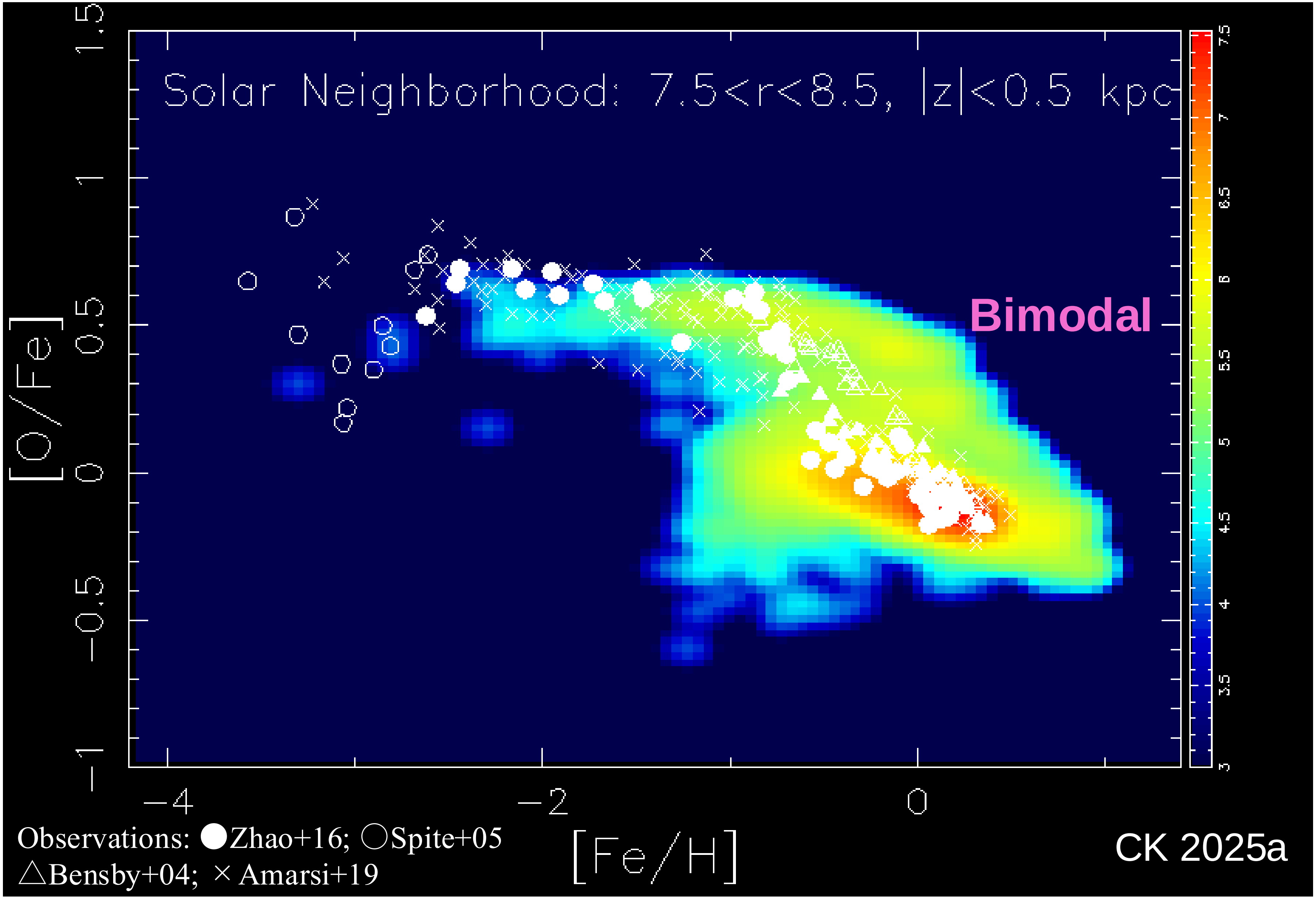




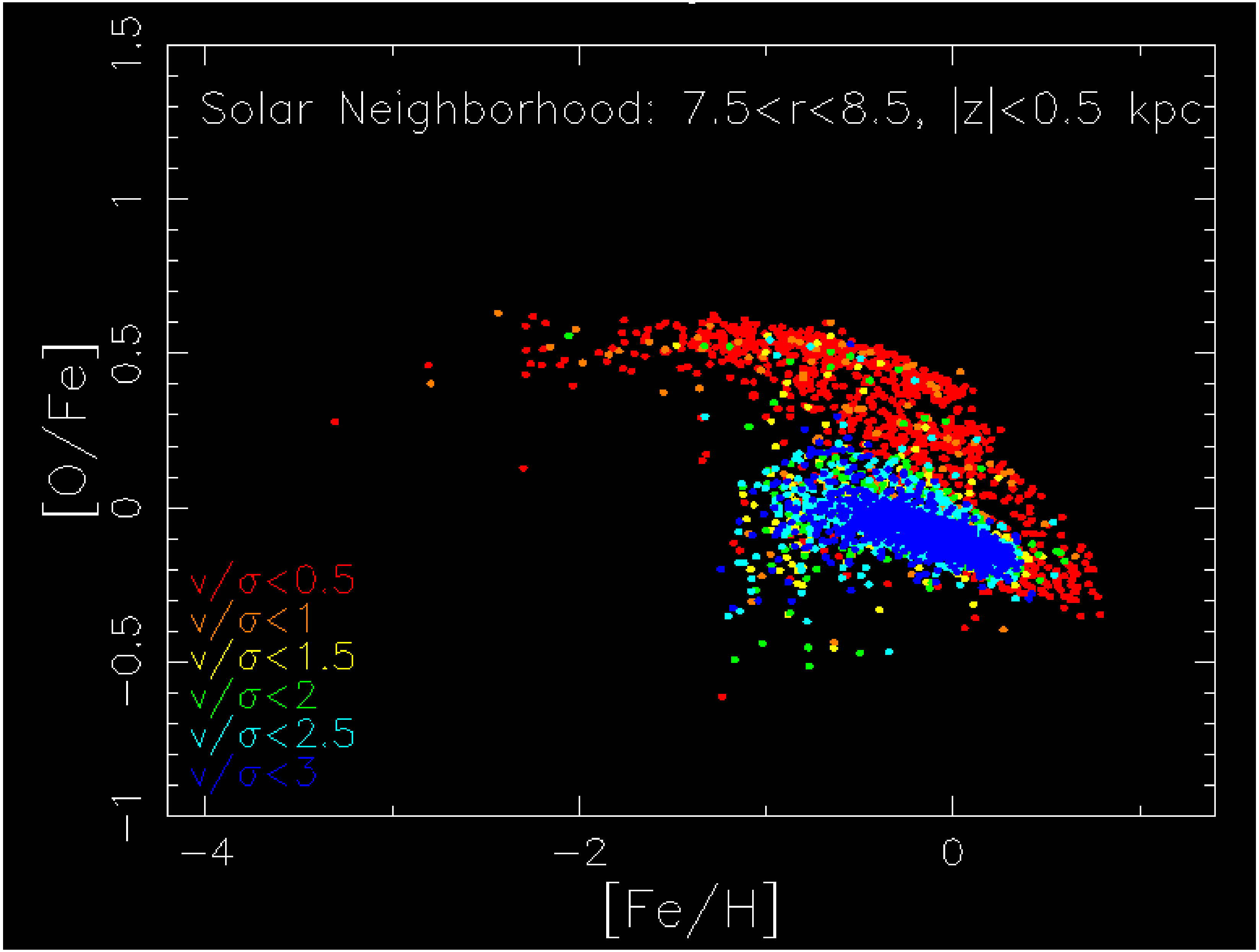
[α/Fe]
low to high
Gaia DR3

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

First shown in CK & Nakasato 2011, *chemodynamical simulations*



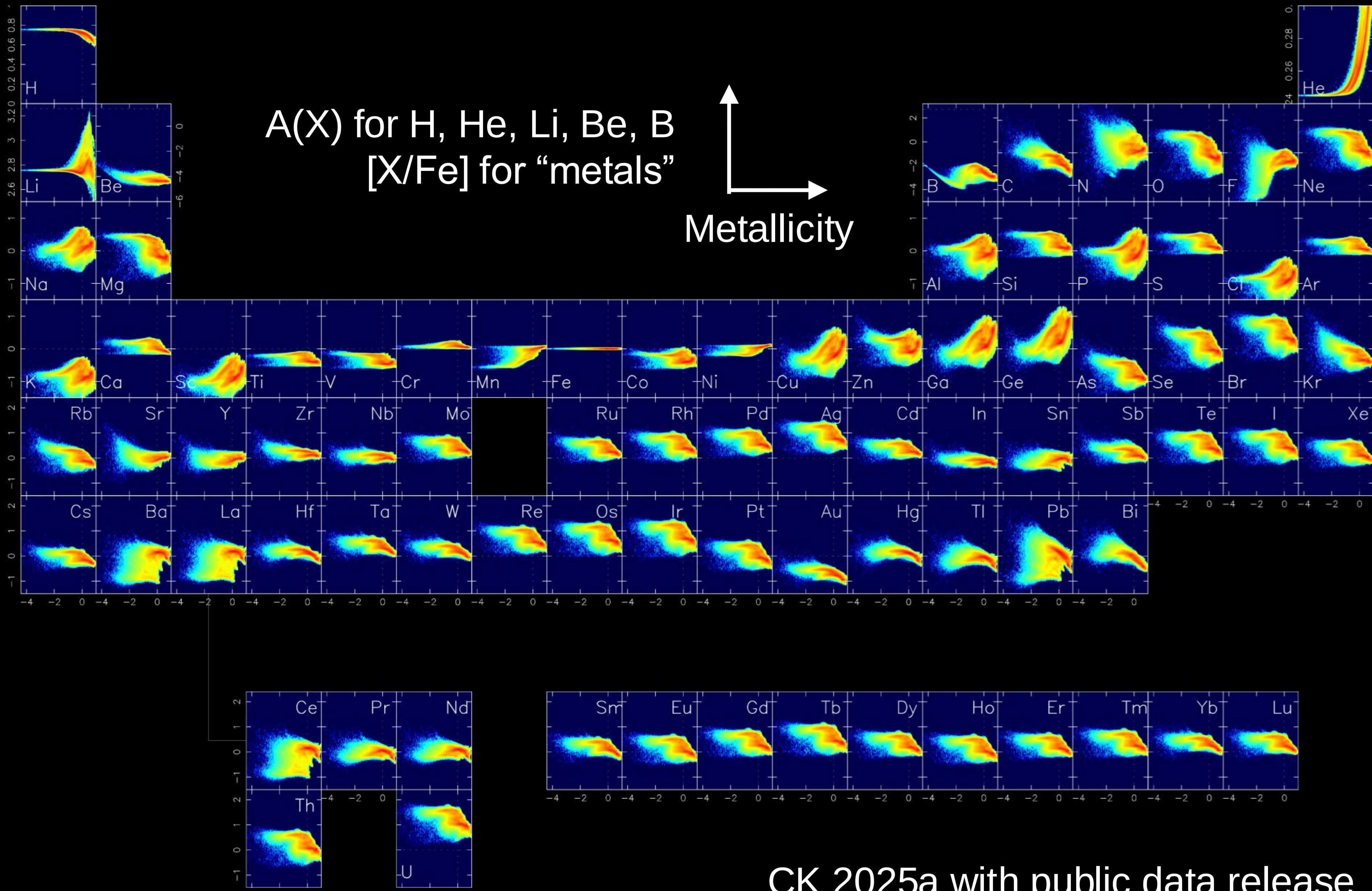
The [O/Fe]-[Fe/H] relation



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

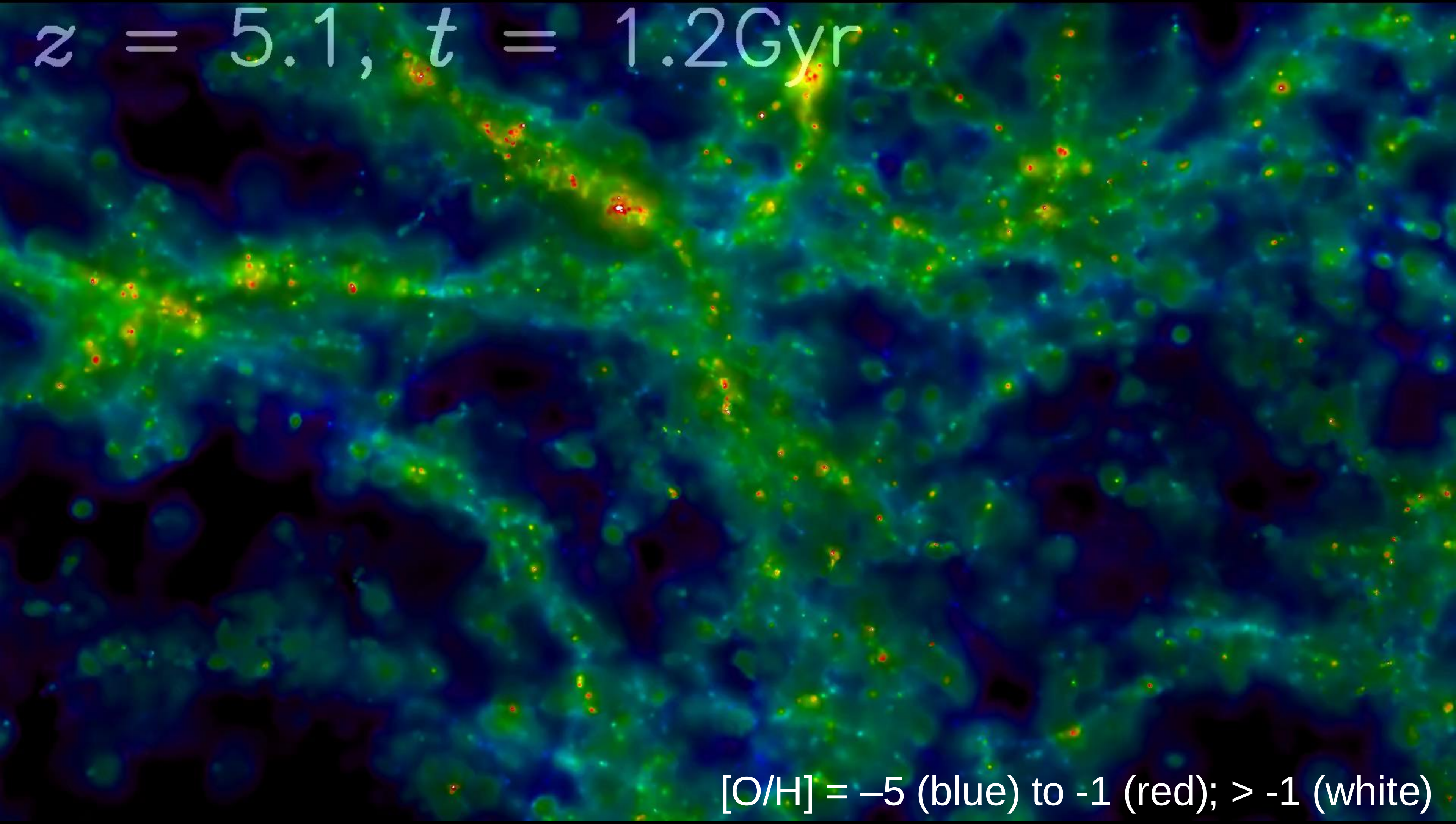
A(X) for H, He, Li, Be, B
[X/Fe] for "metals"

Metallicity



CK 2025a with public data release

Cosmological box simulation

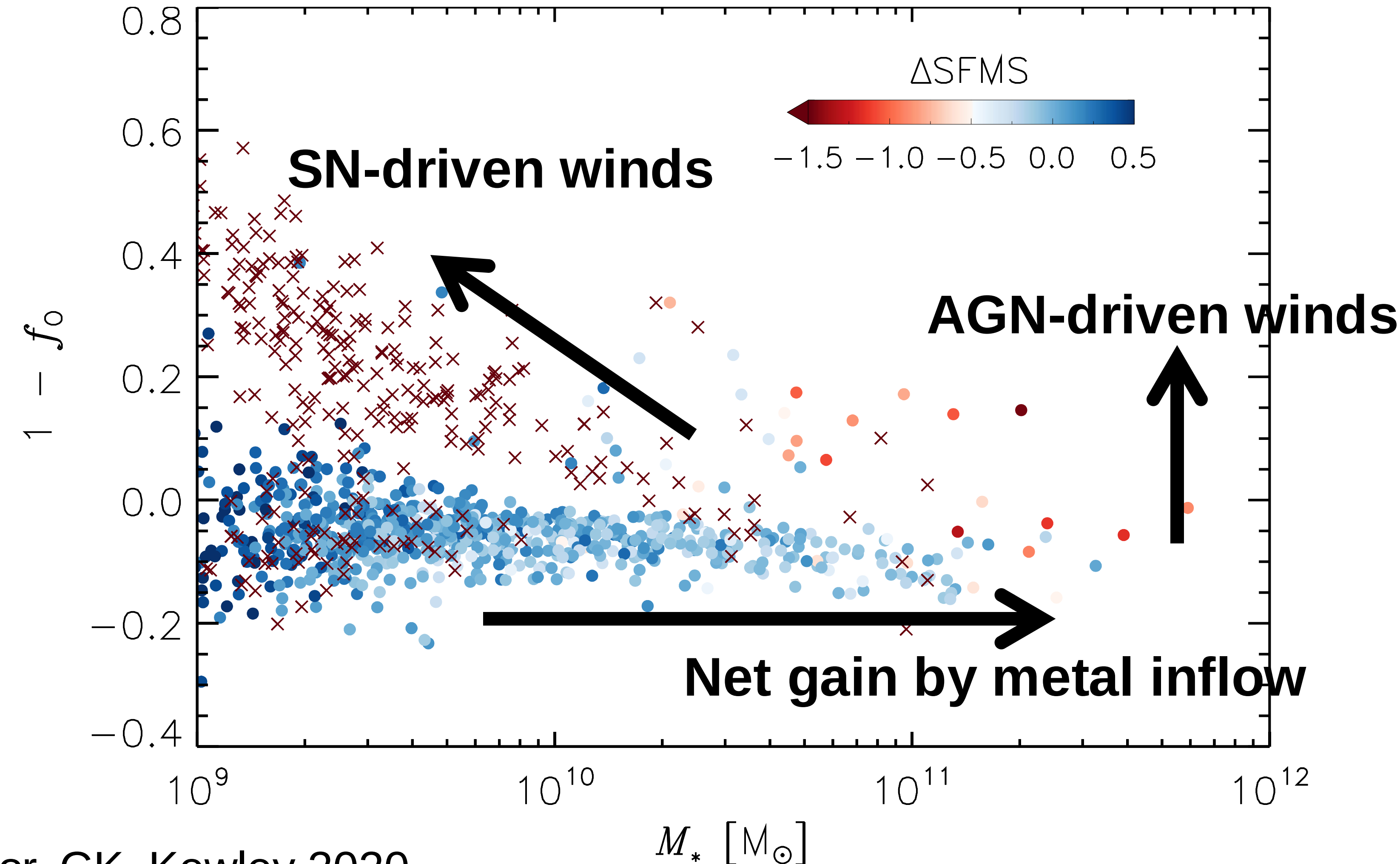


25Mpc, $1.4x10^{7}M_{\odot}$, 1.6kpc resolution, SMBHs grow along M-σ from “light” seeds
Philip Taylor (ANU), https://www.youtube.com/watch?v=jk5bLrVI8Tw

Metal Flow Main Sequence (ZFMS)

Fraction of oxygen lost from the galaxy

$$1 - f_O = \frac{\sum y(A, Z_*) M_{*,\mathrm{init}} - (\sum M_{*,O} + \sum M_{g,O})}{\sum y(A, Z_*) M_{*,\mathrm{init}}}$$

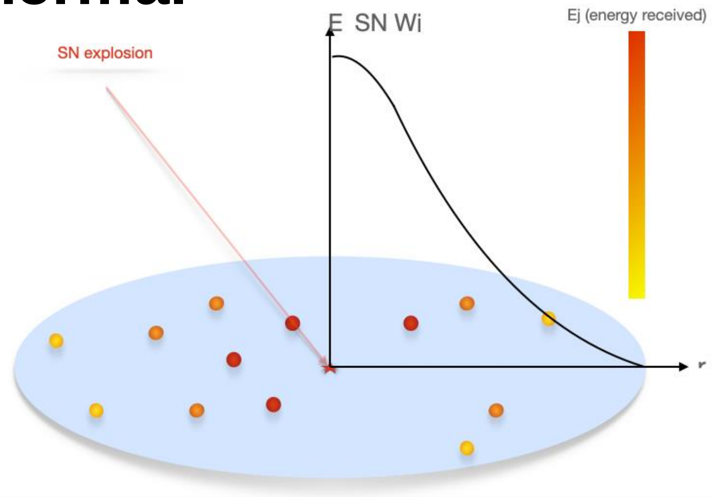


Taylor, CK, Kewley 2020

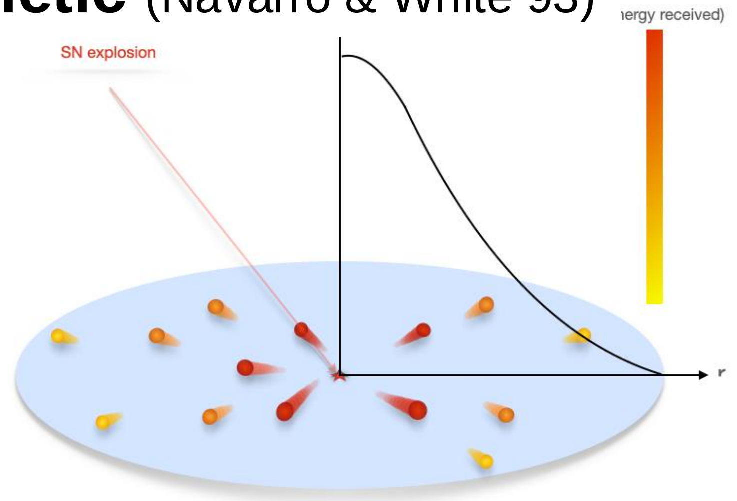
Feedback Modelling

Dyna Ibrahim's PhD thesis (with DiRAC)

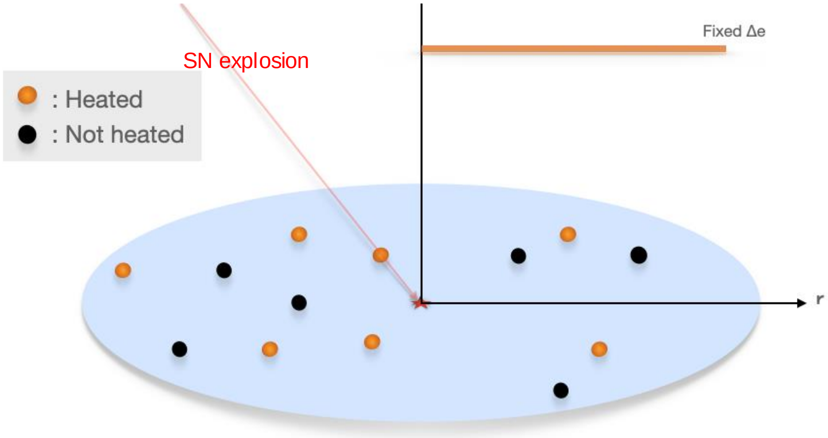
Thermal



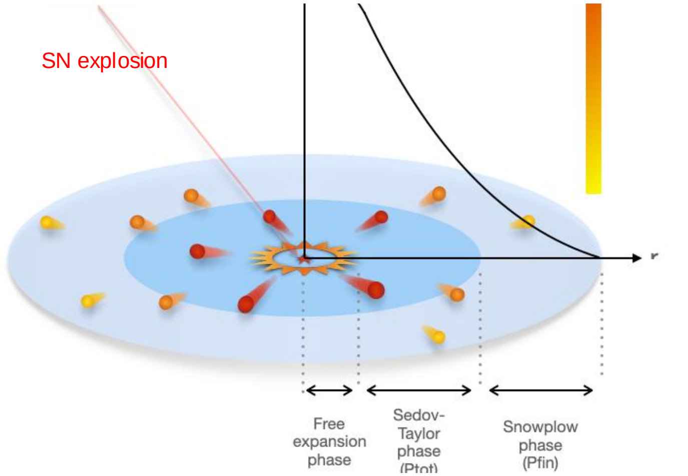
Kinetic (Navarro & White 93)



Stochastic (Dalla Vecchia & Schaye 12)



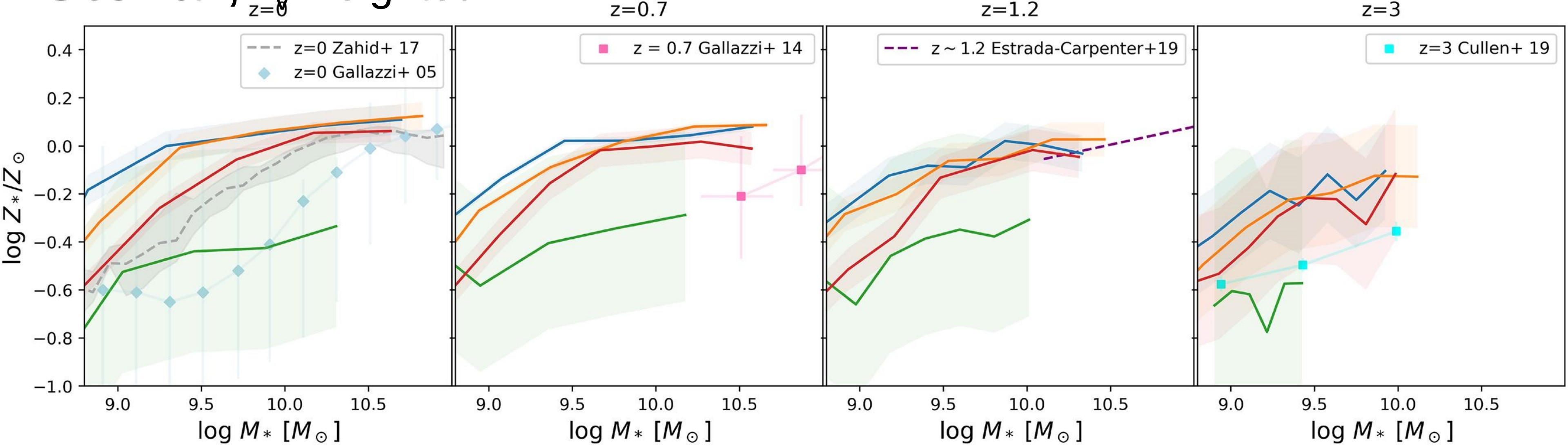
Mechanical (Hopkins+18, Smith+18)



Mass-Metallicity relations (MZR)

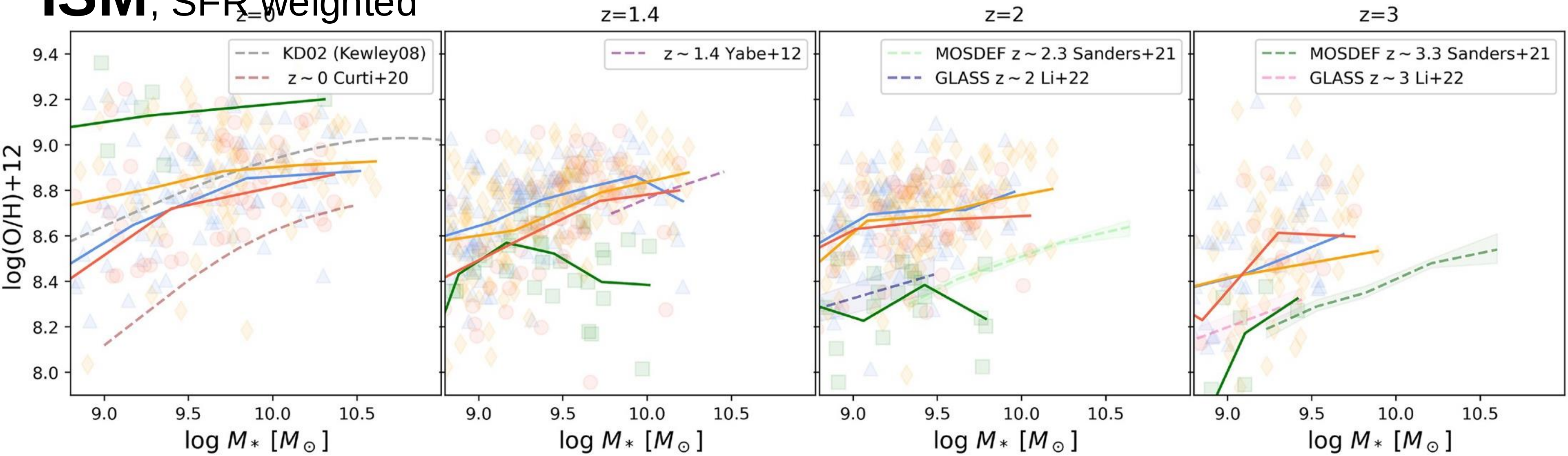
Stellar, L_V weighted

Dyna Ibrahim & CK 2024, MNRAS, 527, 3276



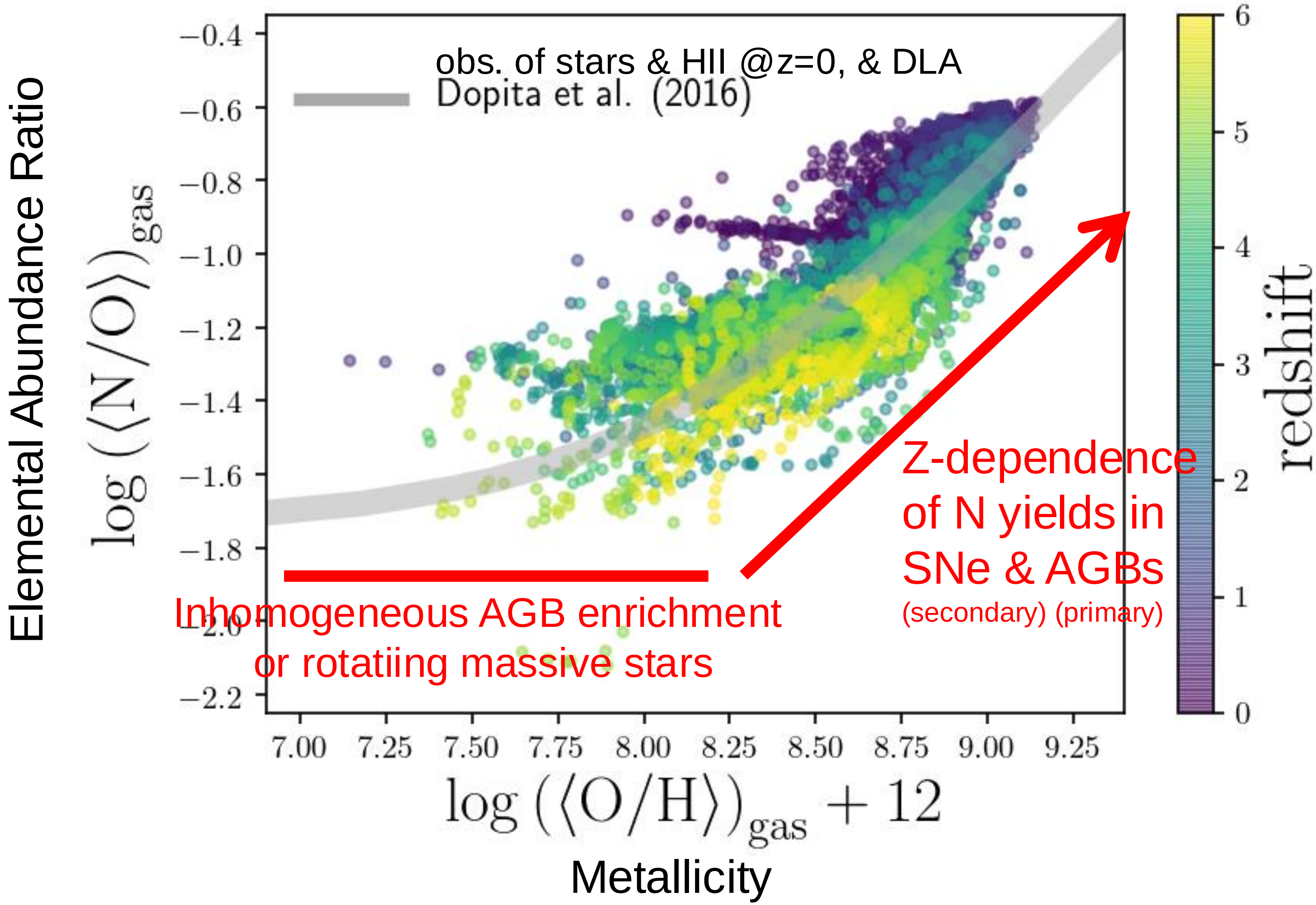
thermal, kinetic, stochastic, mechanical feedback

ISM, SFR weighted

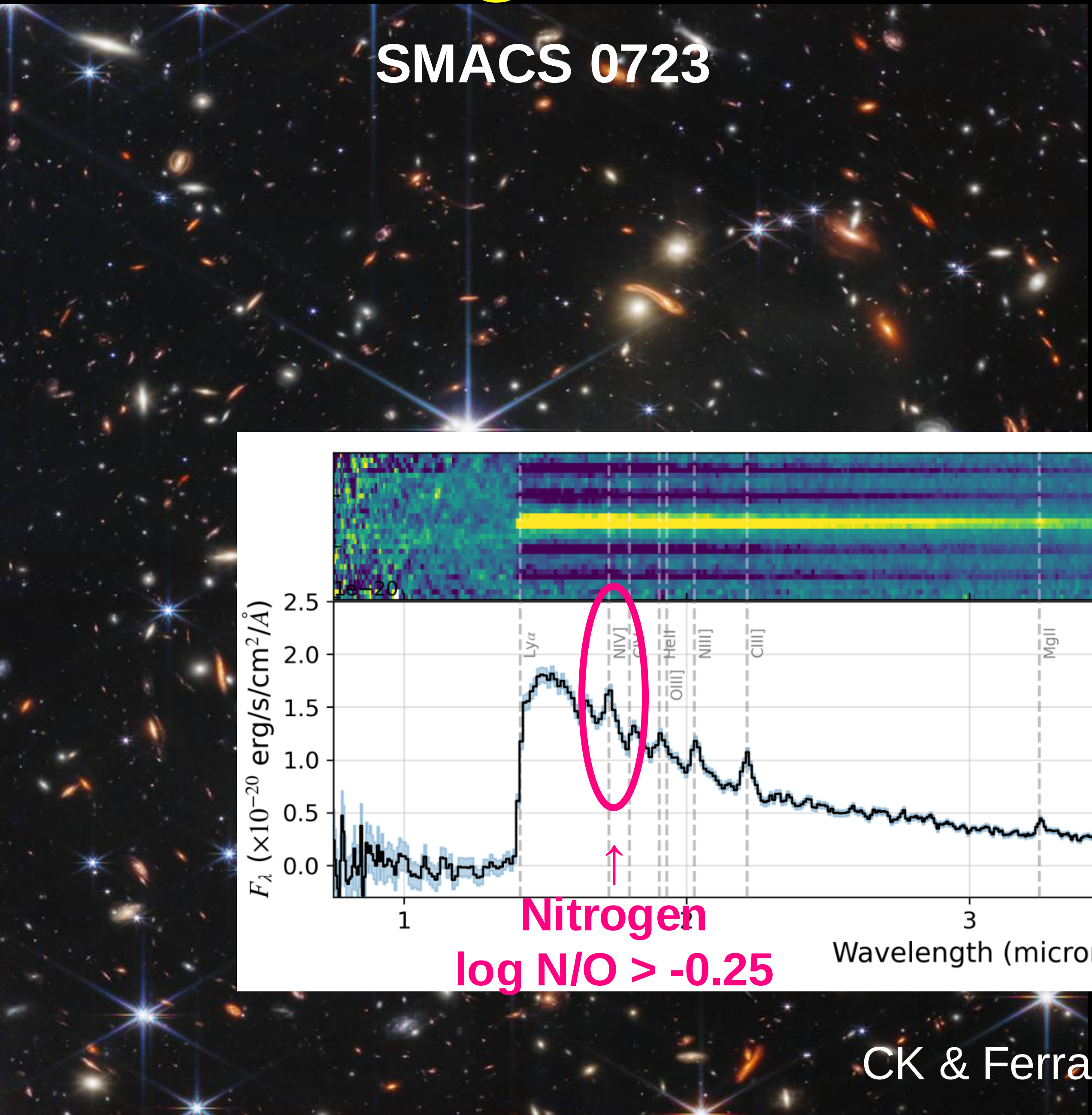


The N/O-O/H relation

Fiorenzo Vincenzo & CK 2018b
Colour: 33 star-forming galaxies in cosmological simulation



Extra-galactic Archaeology!



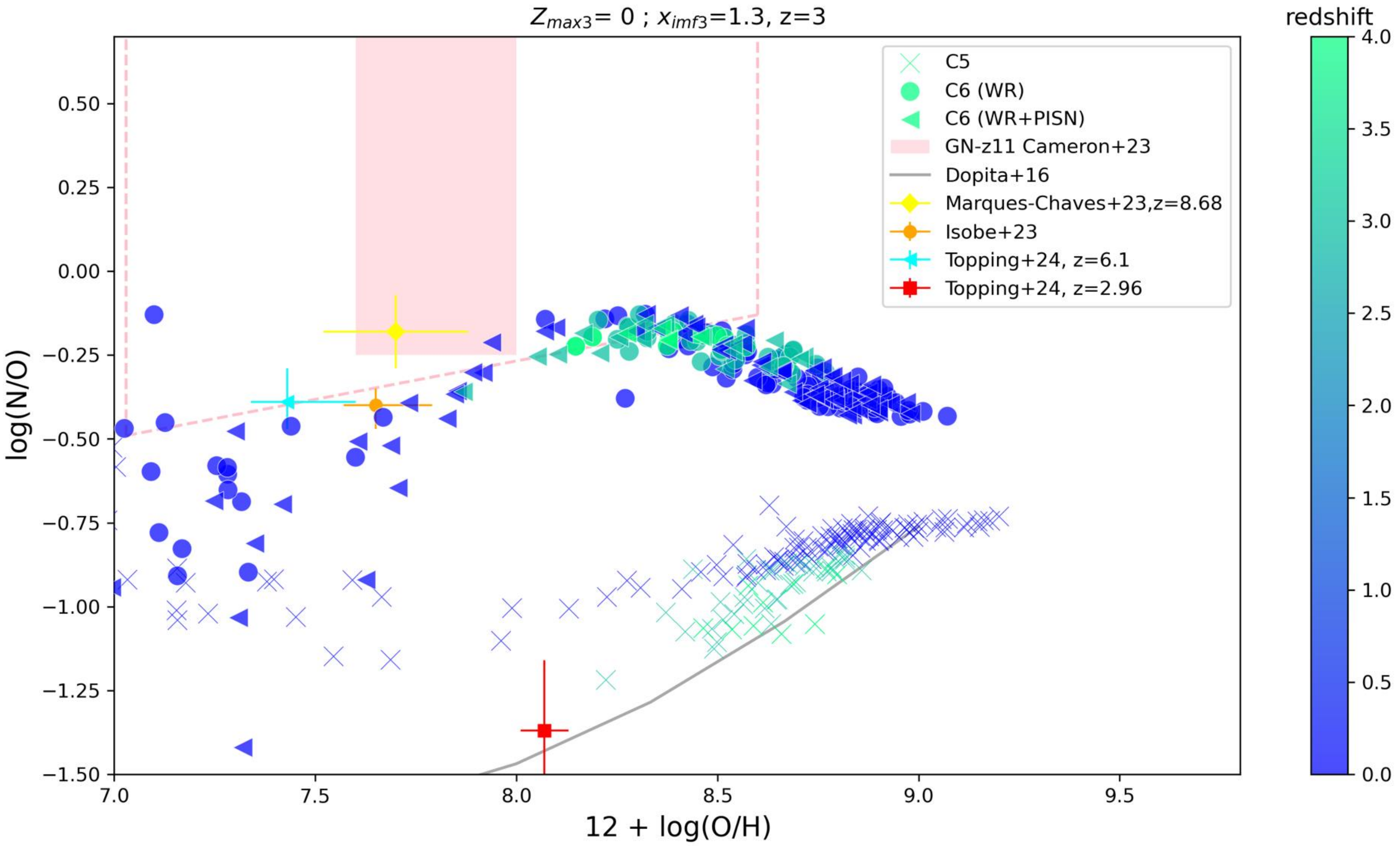
25 Dec 2021 launch
11 July 2022

NIRSpec/JWST
R = 100 (MOS)
R = 1000 (MOS + fixed Slits)
R = 2700 (fixed Slits + IFU)
CNO, Ne, Ar, S, Fe

CK & Ferrara 2024 for a GCE model

The N/O-O/H relation

Dyna Ibrahim & CK 2025b, **preliminary**



For future obseravtional projects

- **Larger** telescopes to measure more elements (with weak lines of S, Ar; and with absorption lines) in external galaxies
- **Higher** resolution multi-object spectrographs to more accurately measure elements and isotopic ratios in the Local Group
- and covering **UV** (<300nm) in space to detect more neutron-capture elements e.g. Au, Pt
  - **CUBES** (Cassegrain U-Band Efficient Spectrograph; 300-400nm, R~20/7k) on VLT – 2028/29 commissioning
  - **HRMOS** (High-Resolution Multi-Object Spectrograph) on VLT– 2030s
  - **WST** (wide-field spectroscopic telescope; R~4k) on a 12m telescope – 2040?
  - **MSE** (MaunaKea Spectroscopic Explorer) 11.25m in Hawaii – 2029?
  - **HWO** (Habitable Worlds Observatory) – 2040s
- Theoretical simulations (on DiRAC) will help £££ projects for funding, and for the support at the sites through public outreach (better visualization needed).

Summary

- ❖ We have good understanding on **the origin of elements** in the universe, which can be included in large-scale chemodynamical simulations of galaxies.

- ❖ **Zoom-in simulations** – Spatial distribution of elements (from Li to Eu) in a Milky Way-type galaxies are in good agreement with observations, and detailed analysis will unveil the merging history of our Milky Way Galaxy (**Galactic archaeology**).

- ❖ **Cosmological box simulations** – Average metallicities (and their radial gradients) are in good agreement with observations at present. The mismatches at higher redshifts requires modification of the modelling of baryon physics, e.g. supernova feedback. Elemental abundances from JWST can constrain the stellar populations across Cosmic time (**Extra-galactic archaeology)**.