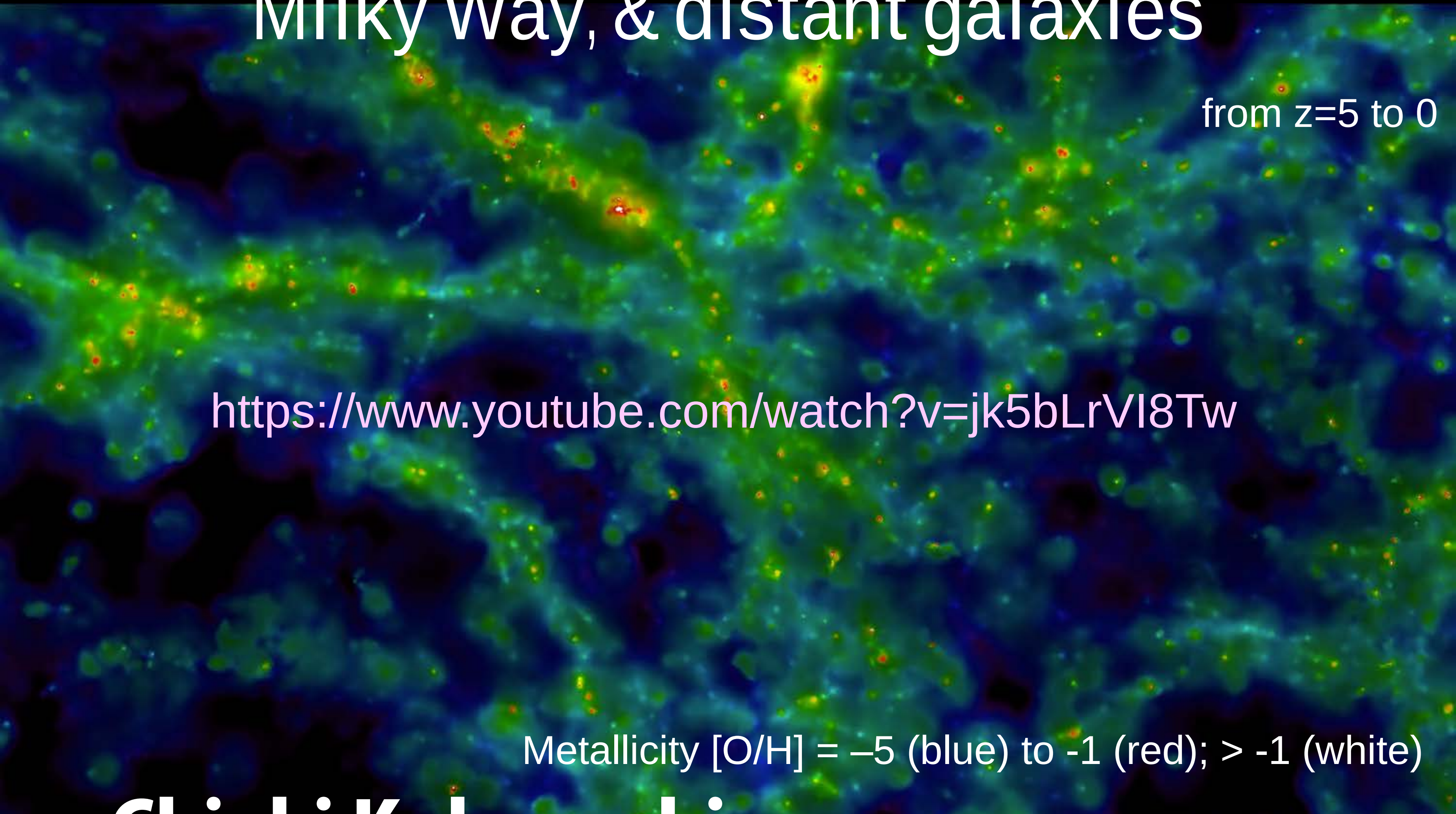
Nucleosynthesis: the origin of elements, Milky Way, & distant galaxies

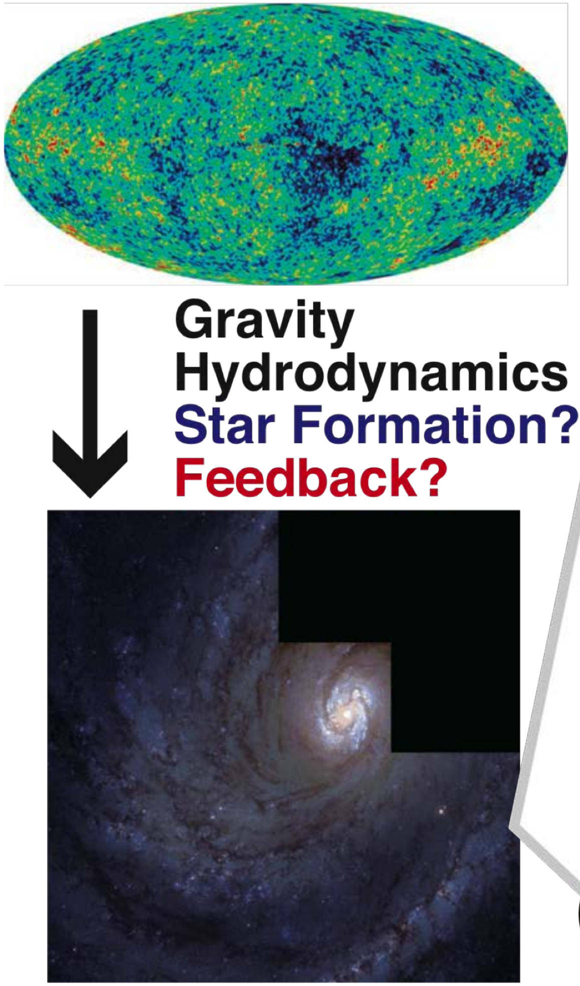


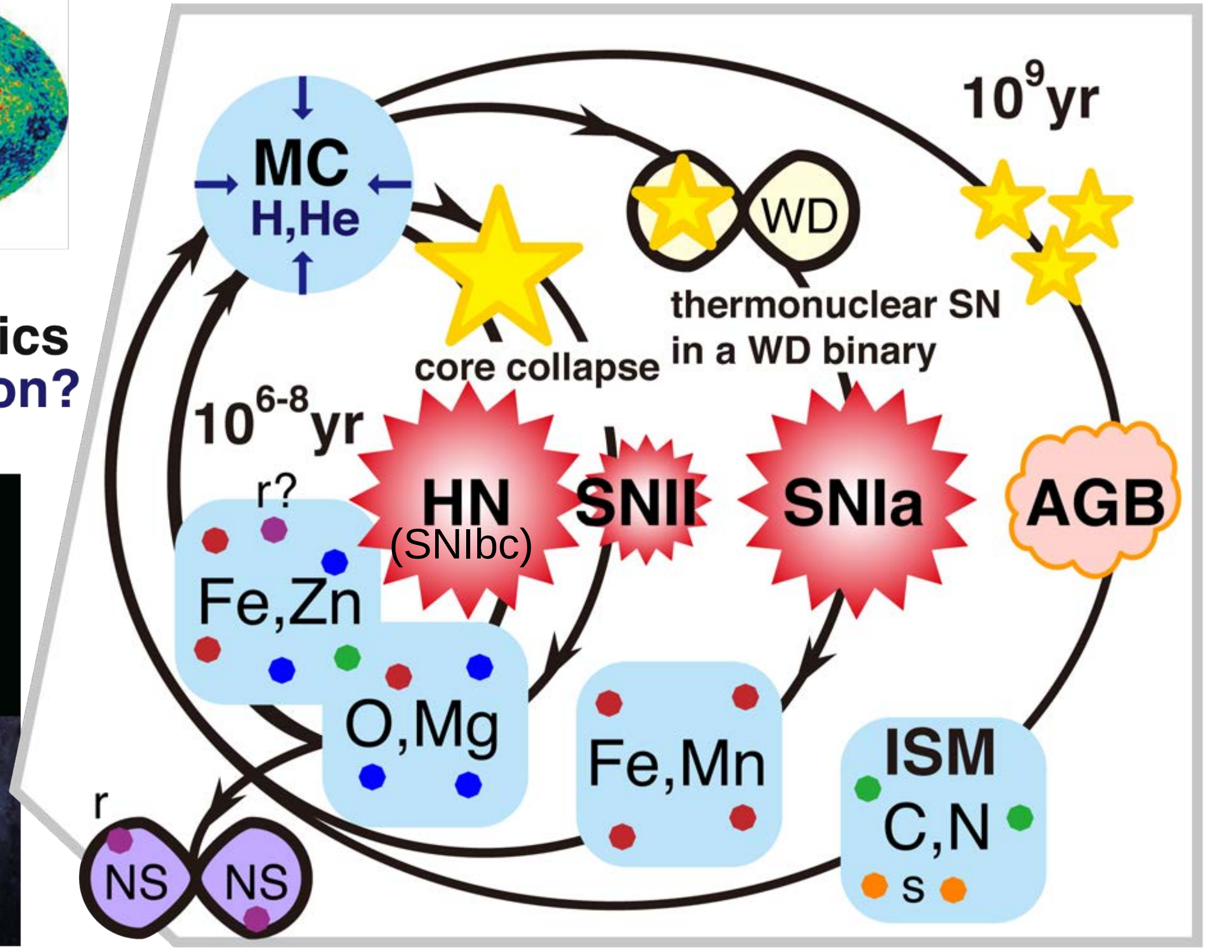
Chiaki Kobayashi
(Univ. of Hertfordshire, UK)

LEVERHULME TRUST

Galactic Archaeology

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**
- With IFU surveys/ALMA/JWST, **Extra-galactic Archaeology**

Galactic Chemical Evolution (GCE)

(1) One-zone model (instantaneous mixing): Tinsley 80, Timmes+95, Pagel 97, Matteucci 01, Prantzos+93, Ferrini+92 (Molla, Travaglio, Magrini), Chiappini+97, CK+ 00…, Vincenzo+14, Cote+16

$$\frac{d(Zf_g)}{dt} = \underbrace{E_{SW} + E_{SNcc} + E_{SNIa}}_{\text{Metal ejection rates}} - Z\psi + \underbrace{Z_{inflow}R_{inflow} - ZR_{outflow}}_{\text{given from hydrodynamics in}}$$

Inflow Outflow

decreased by star formation

Metal ejection rates

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

given from hydrodynamics in

(3) Chemodynamical simulation

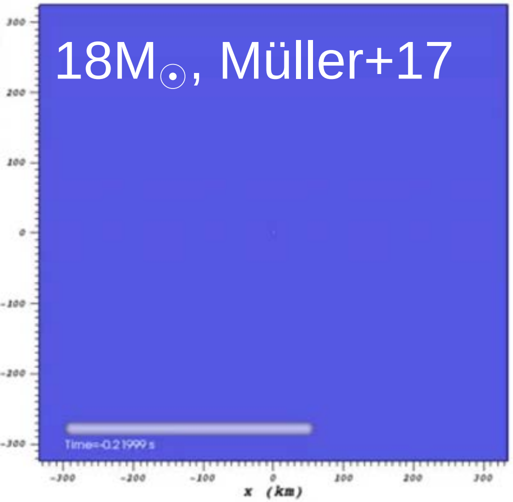
Burkert & Hensler 87, Katz 92, Steinmetz & Müller 94, Mihos & Hernquist 96, CK 04,…, FIRE, EAGLE, Horizon, Illustris

→ **inhomogeneous enrichment**

(2) Stochastic model

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

Core-collapse SNe



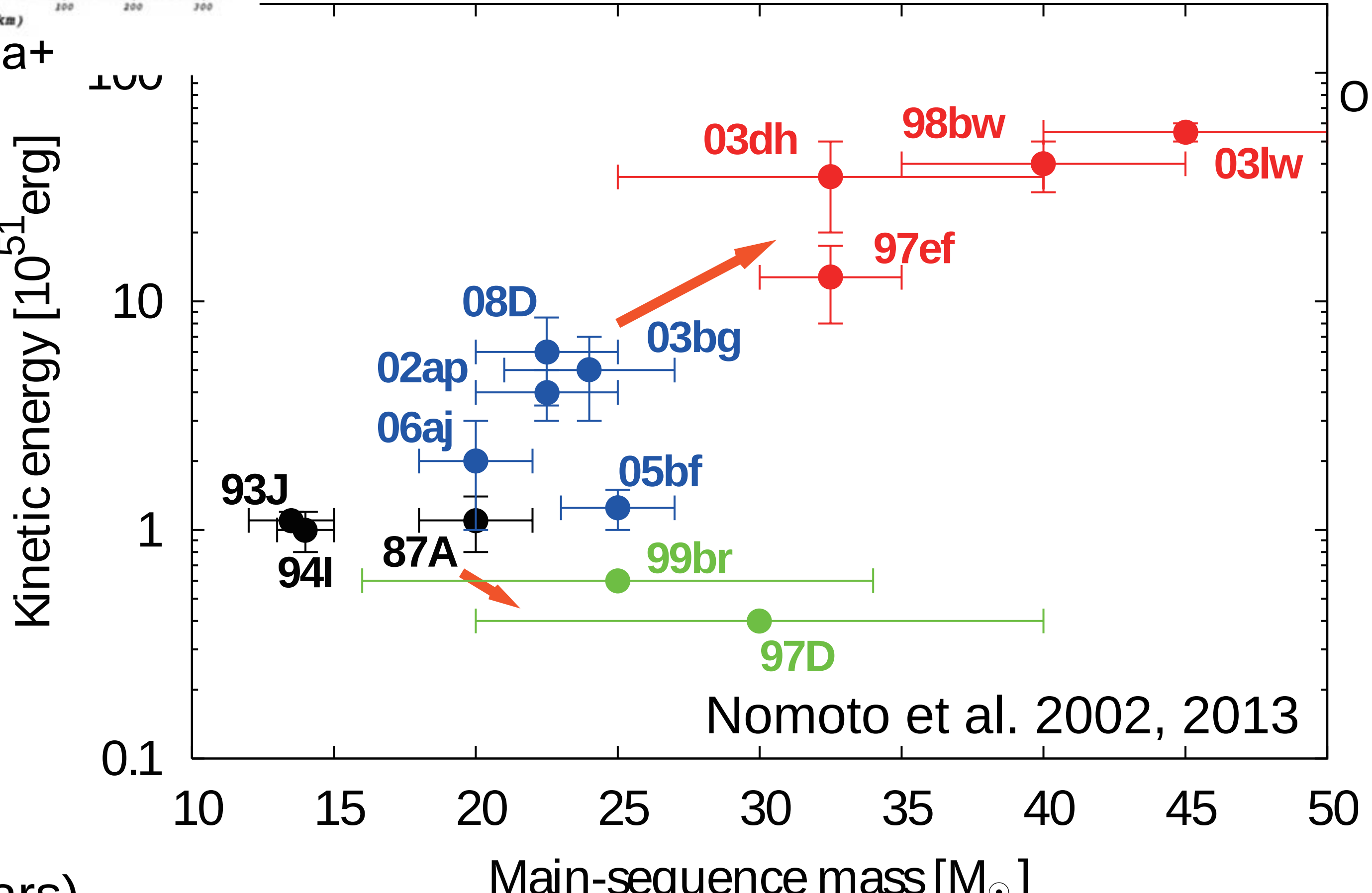
← ν-driven SNII & failed SN

Hypernovae (mechanism?) →

In GCE, 50-1% at $>20M_\odot$

Mezzacappa+
Burrows+
Kotake+

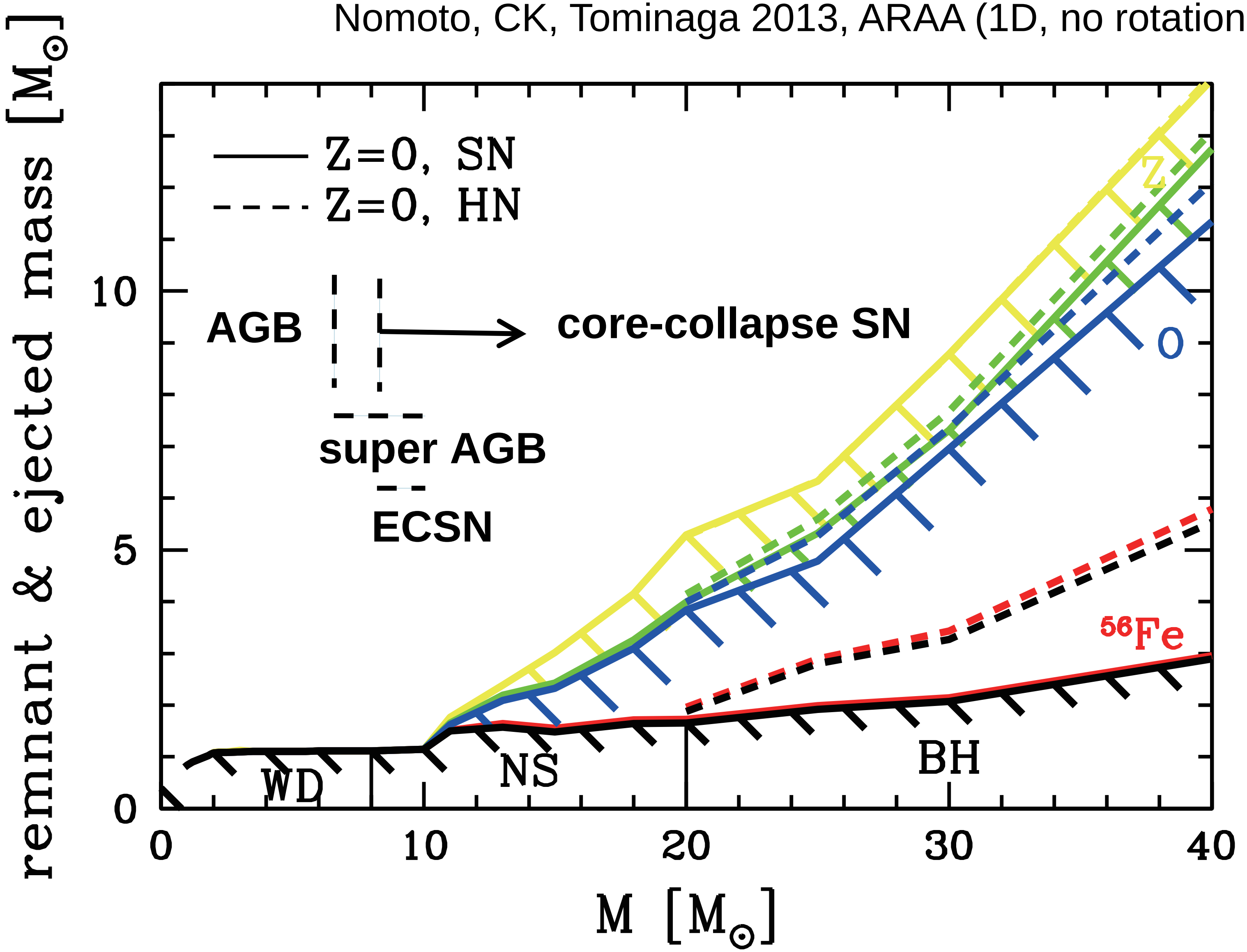
Takiwaki+
Obergaulinger
& Aloy



(single stars)

Nucleosynthesis Yields

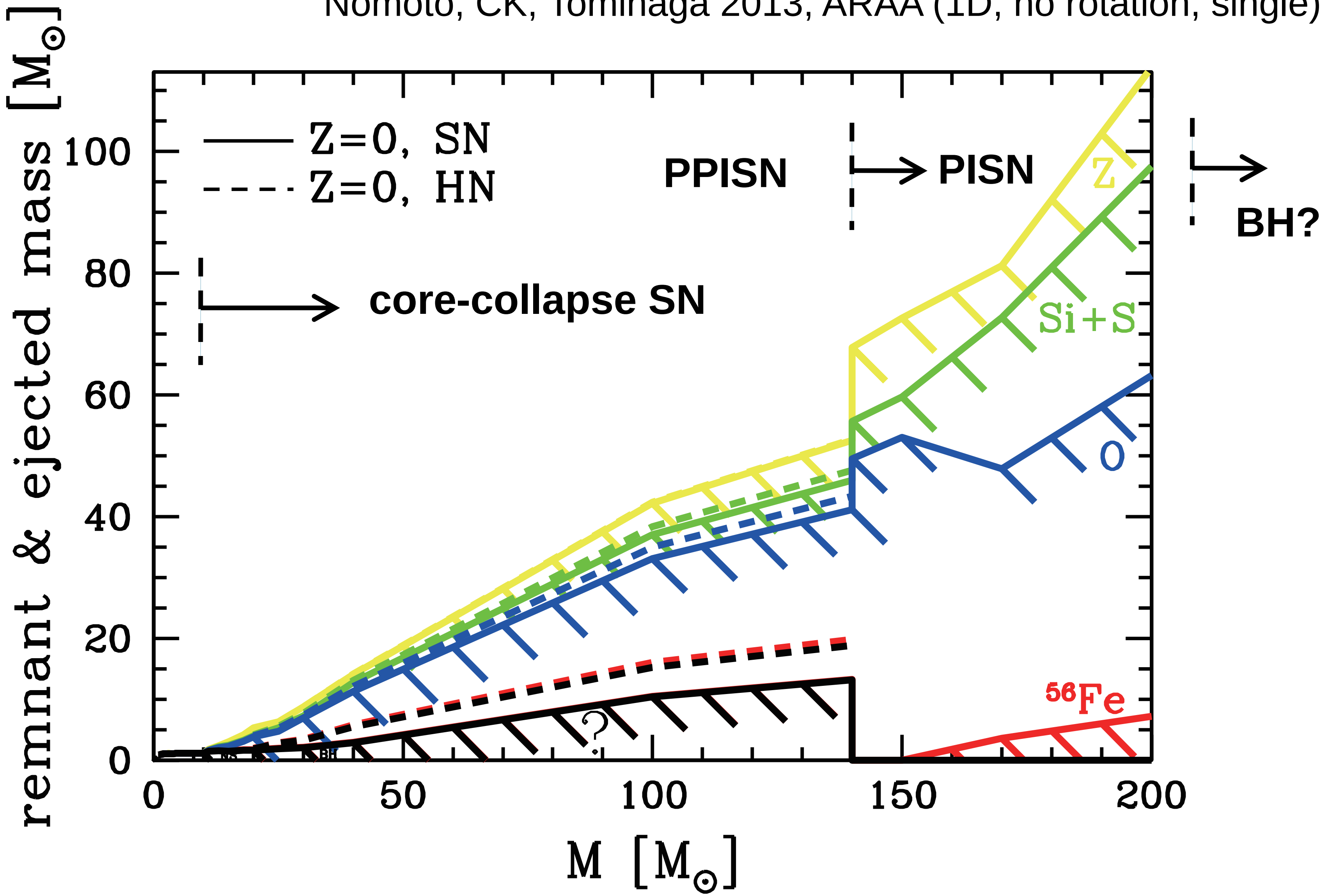
Nomoto, CK, Tominaga 2013, ARAA (1D, no rotation, single)



Also, Woosley & Heger; Limongi & Chieffi; NuGrid; PUSH

Nucleosynthesis Yields

Nomoto, CK, Tominaga 2013, ARAA (1D, no rotation, single)



Also, Woosley & Heger; Takahashi & Umeda

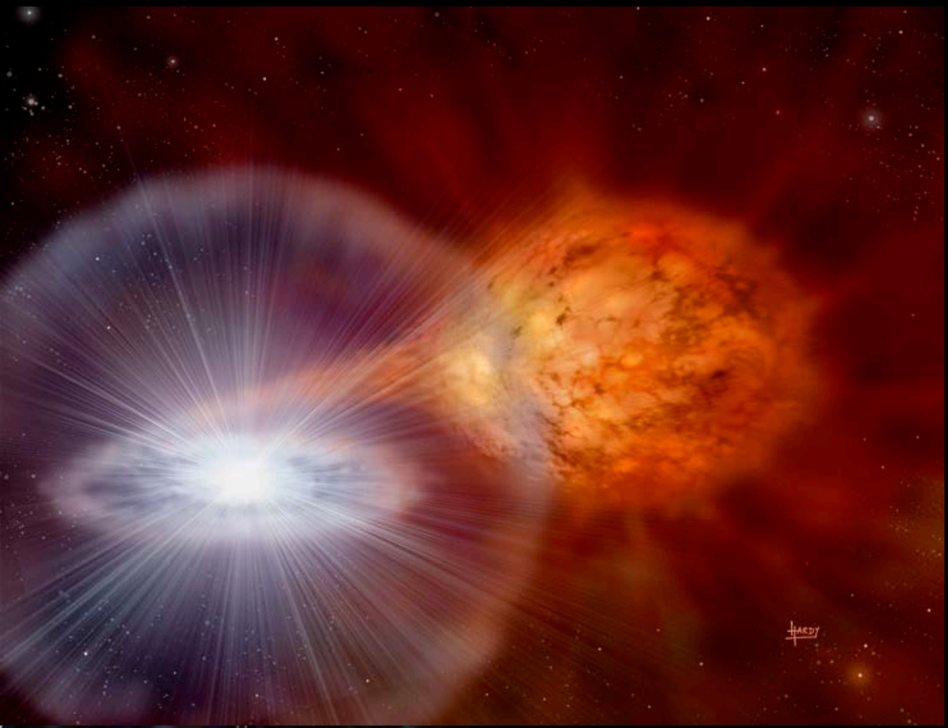
Thermonuclear (Type Ia) Supernovae

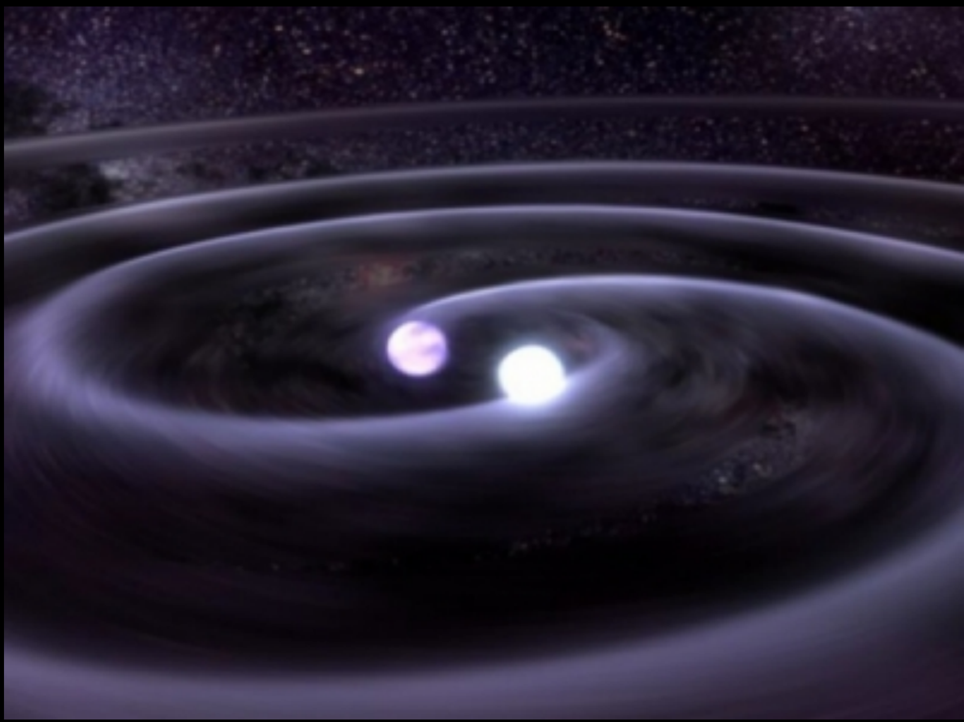
Thermonuclear explosion in a binary with C+O white dwarf

Chandrasekhar (Ch) mass explosion, expected in Single Degenerate (SD)

vs

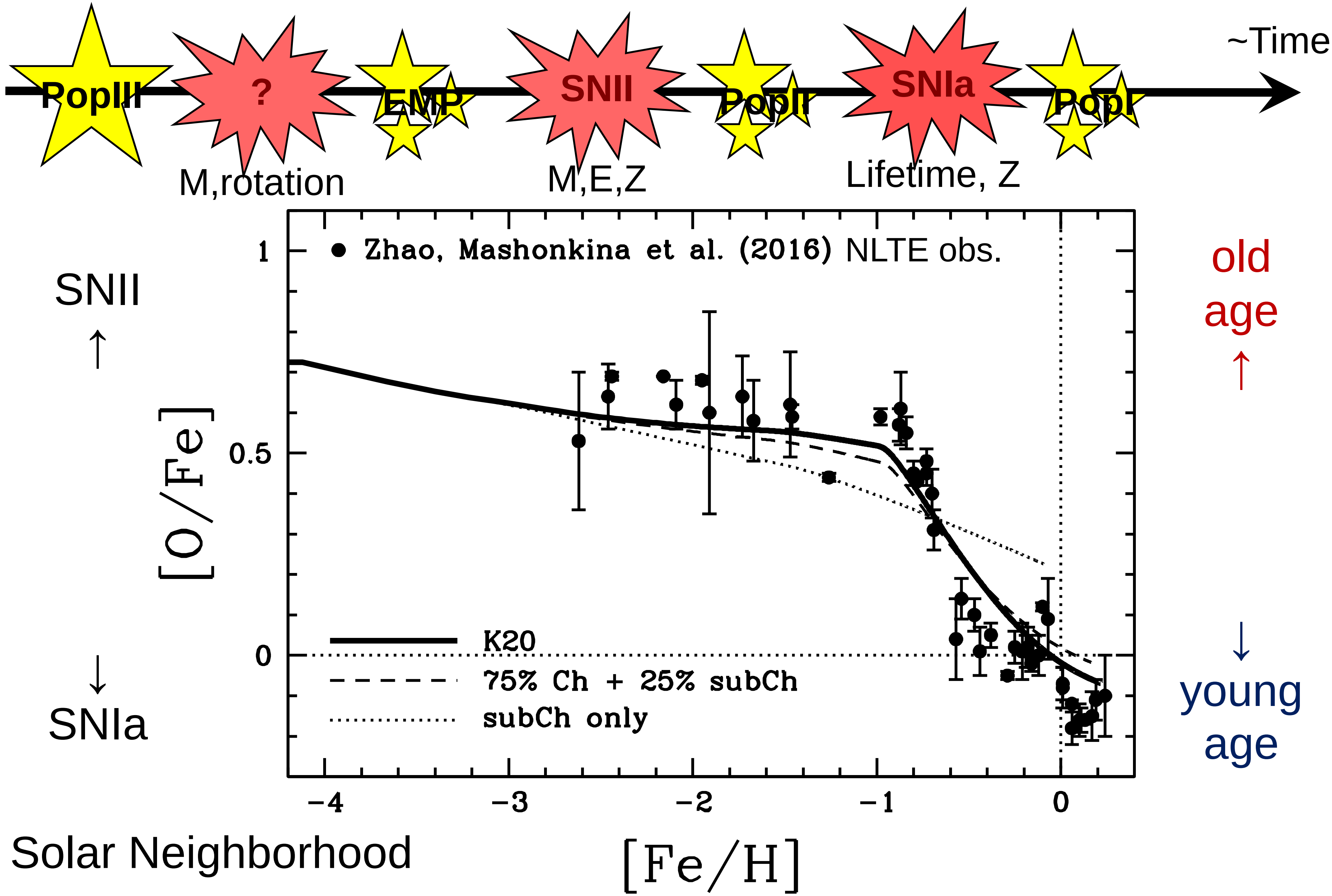
Sub-Ch mass explosion, showed in Double Degenerate (DD) simulations, also possible in SD





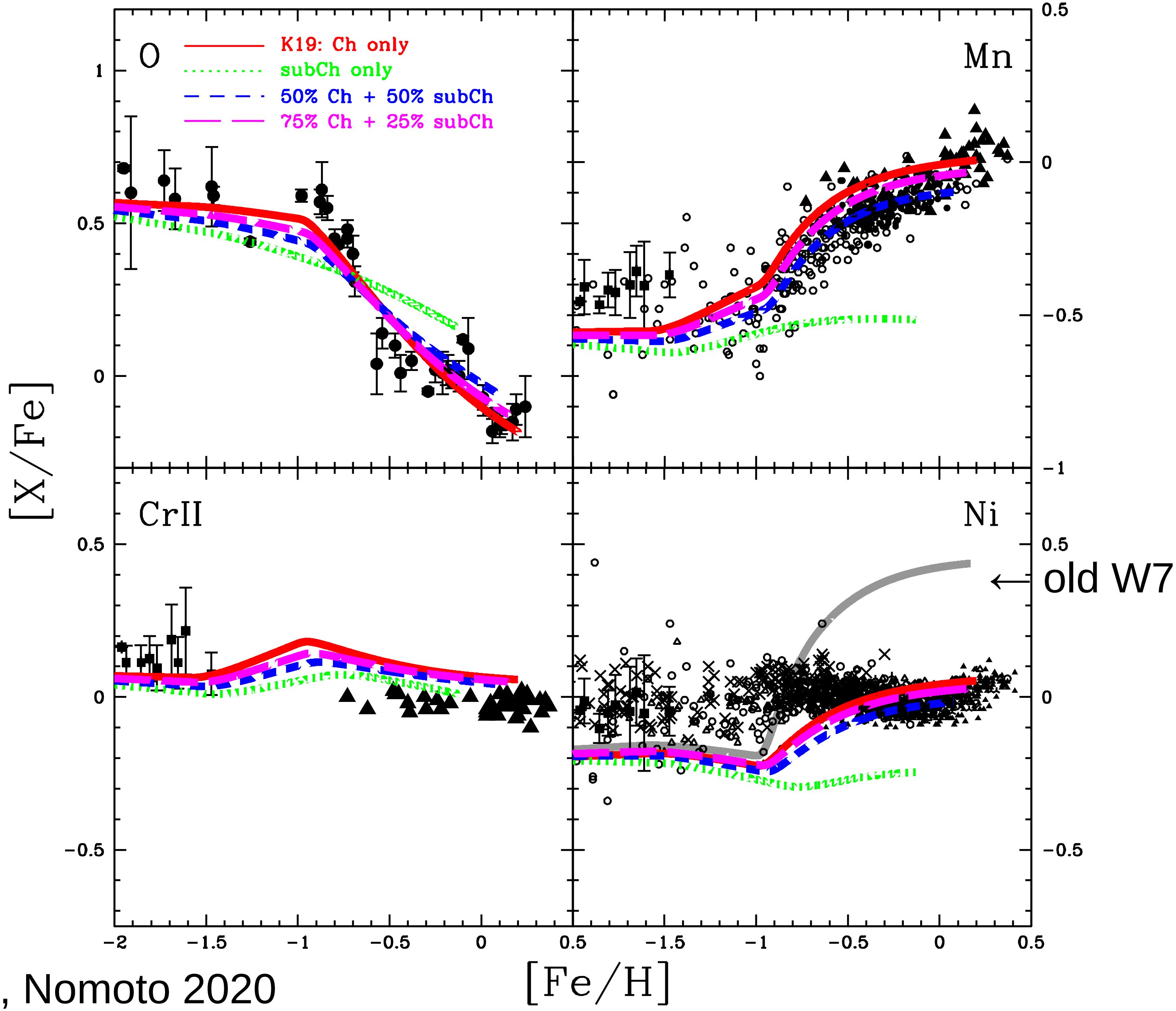
companion star observed! (McCully+14)

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



Solar Neighborhood

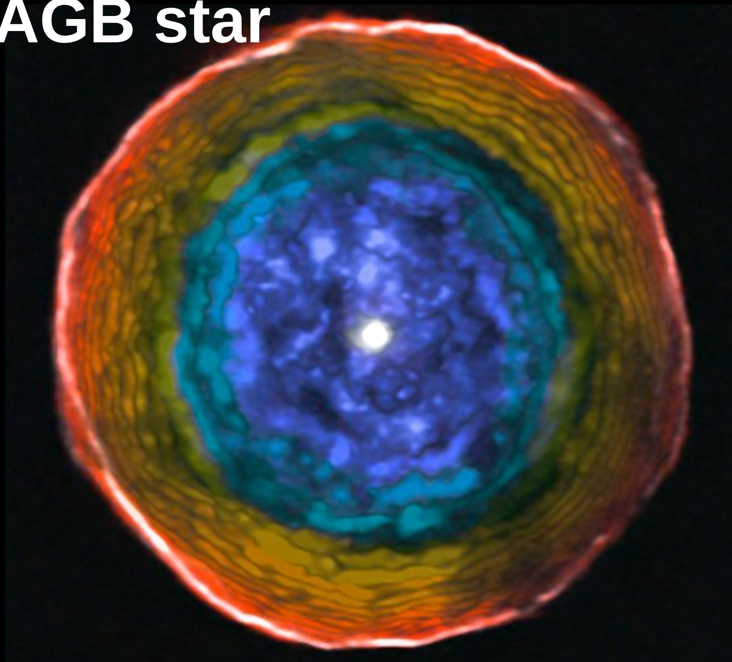
in MW, Ch dominant (WD+WD mergers <25%)



CK, Leung, Nomoto 2020

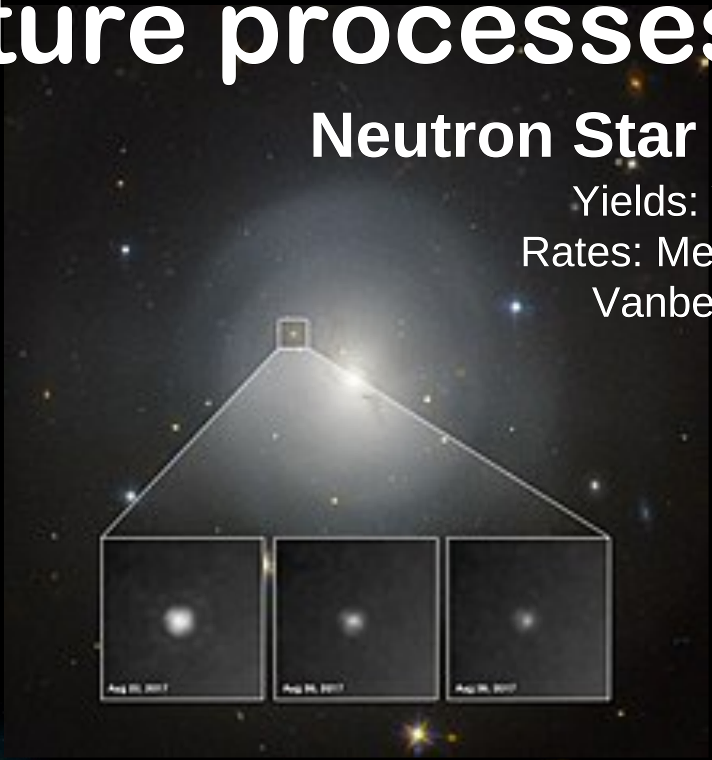
Neutron-capture processes

AGB star



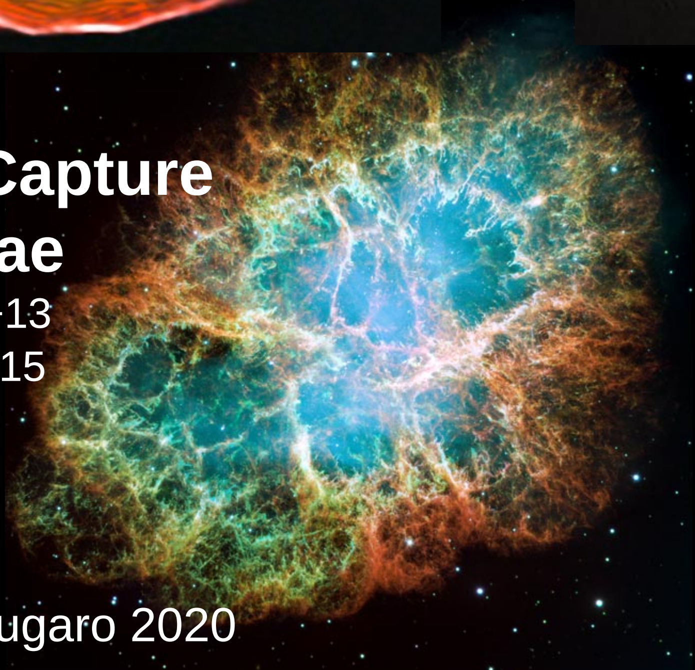
Neutron Star Merger

Yields: Wanajo+14
Rates: Mennekens & Vanbeveren 2014



Electron Capture Supernovae

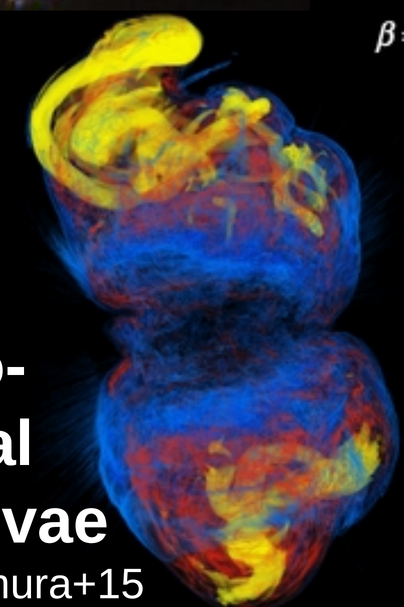
Yields: Wanajo+13
Mass: Doherty+15



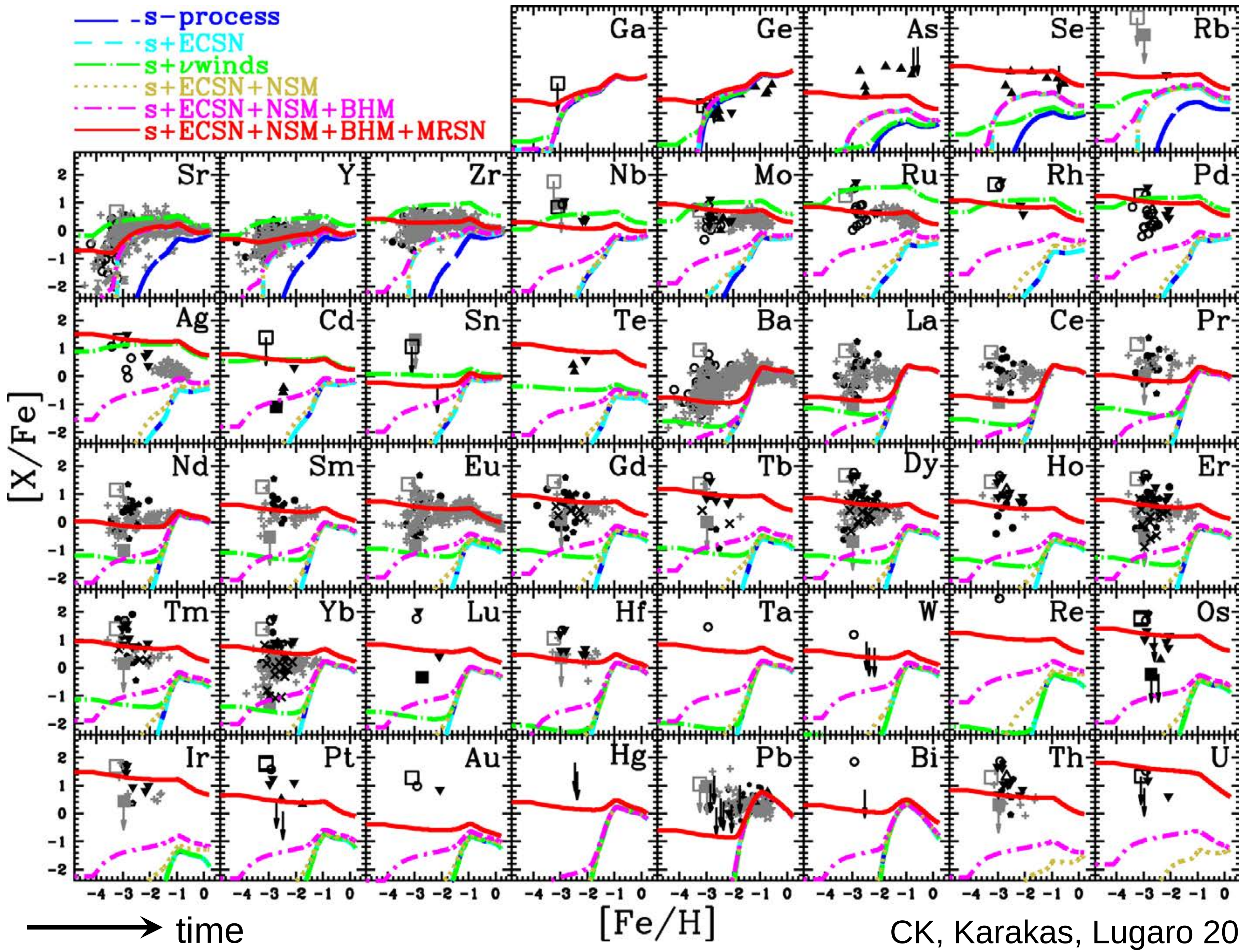
Magneto-rotational Supernovae

Yields: Nishimura+15

$$\beta = \frac{P_{gas}}{P_{mag}}$$



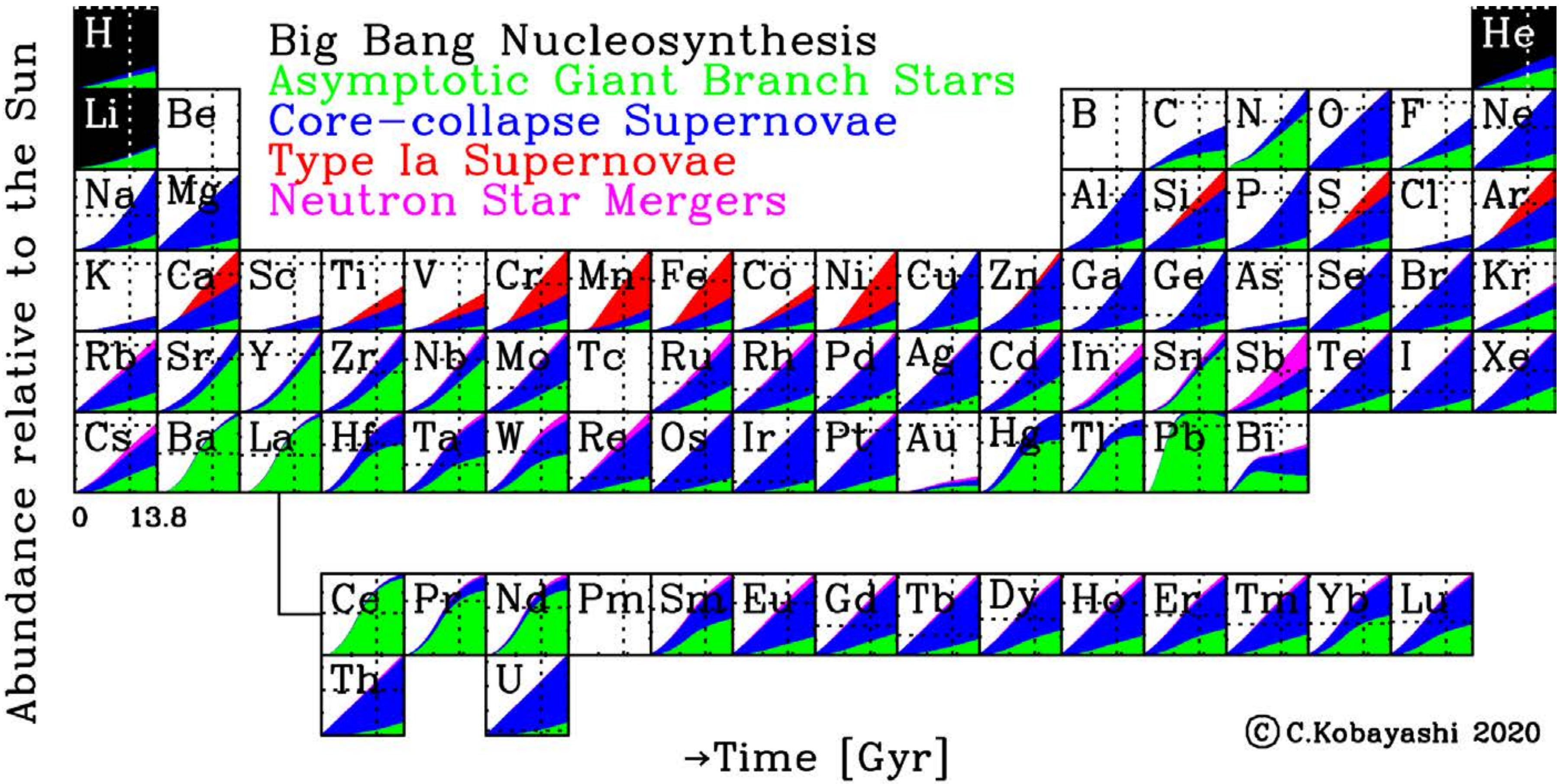
CK, Karakas, Lugaro 2020



CK, Karakas, Lugaro 2020

The Origin of Elements

CK, Karakas, Lugaro 2020, ApJ



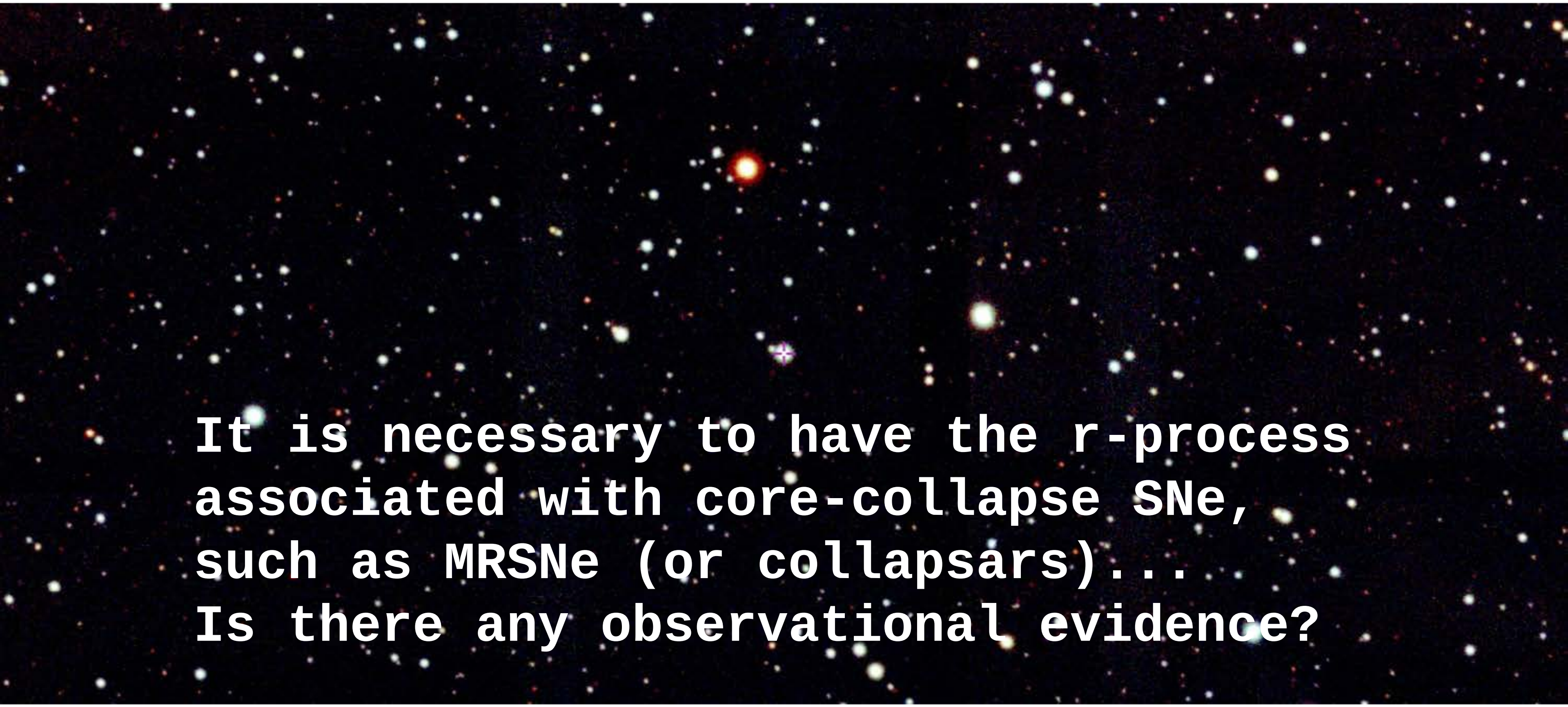
※Purely theoretical, no empirical equations.

dotted lines: solar values

Article | Nature | Vol 595 | 8 July 2021 | 223

r-Process elements from magnetorotational hypernovae

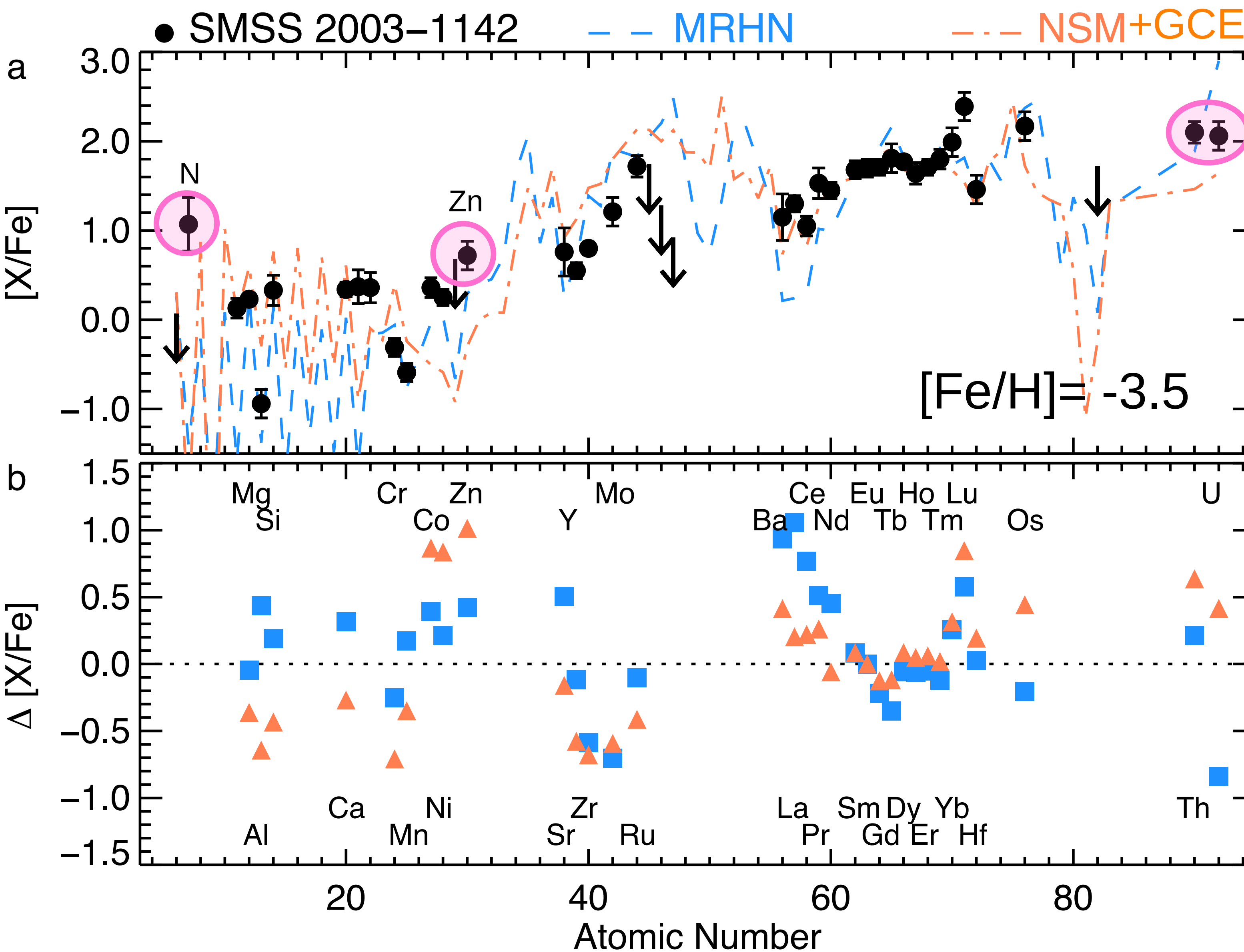
D. Yong[1,2]✉, C. Kobayashi[2,3], G. S. Da Costa[1,2], M. S. Bessell[1], A. Chiti[4], A. Frebel[4], K. Lind[5], A. D. Mackey[1,2], T. Nordlander[1,2], M. Asplund[6], A. R. Casey[2,7], A. F. Marino[8], S. J. Murphy[1,9] & B. P. Schmidt[1]



- 26000 SkyMapper photometric candidates
- 2618 EMP candidates with ANU 2.3m spectra (Da Costa+19)
- 479 stars in SkyMapper DR1.1 (Yong+21b) with Magellan/VLT/Kech
- SMSS J200322.54-114203.3, [Fe/H]= -3.5, 2.3kpc away, Halo orbit

Magneto-rotational Hypernova!

Yong, CK, Da Costa+ 21, Nature



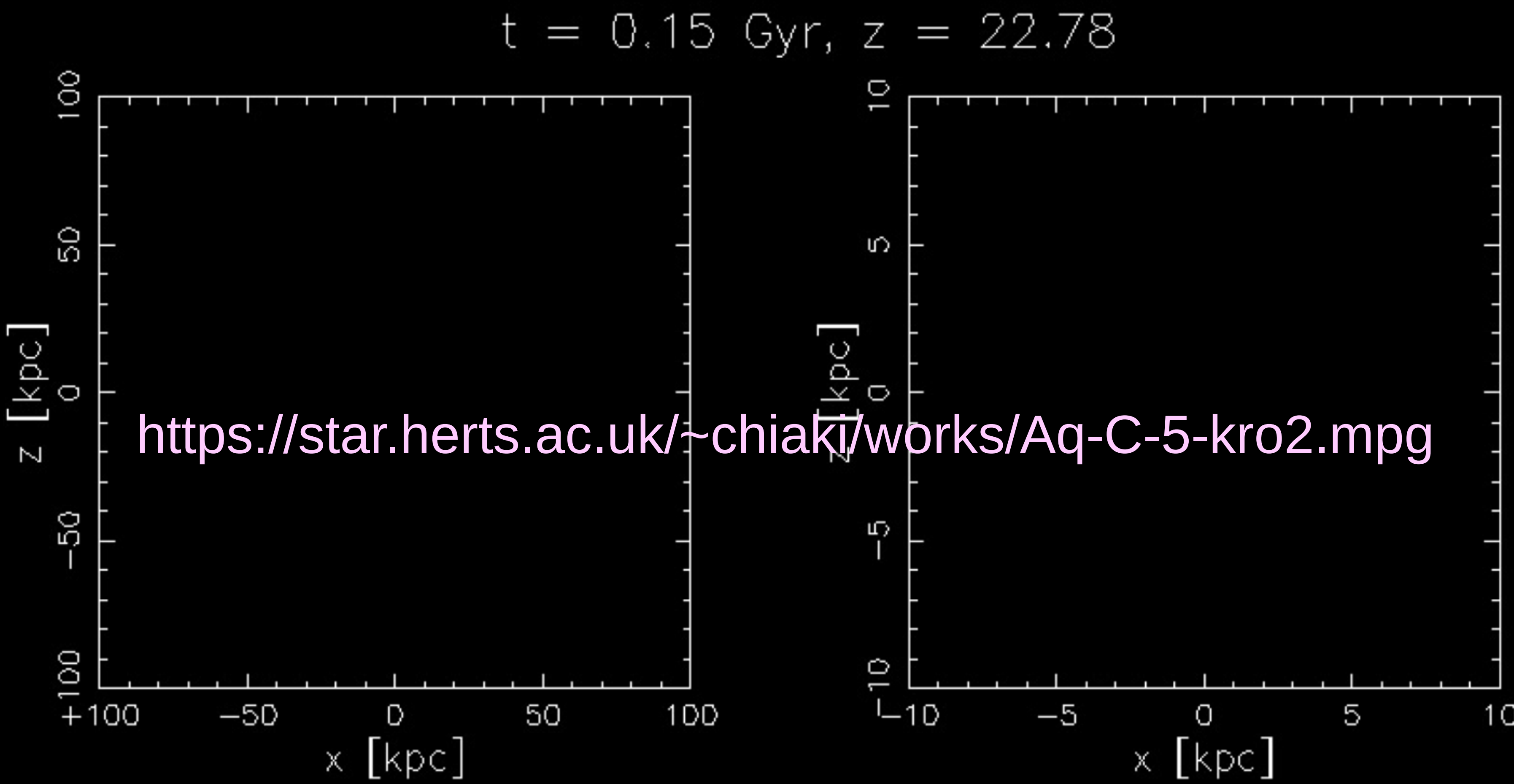
Galactic Archaeology surveys

of Milky Way and local dwarf galaxies

- Motions of one billion stars are measured with Gaia.
- Ages from asteroseismology COROT, Kepler, K2, TESS…
- Elemental Abundances (from Li to Eu) of one million 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)
- The origin of sub-structures? The merging history of MW?

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

MW-type galaxy zoom-in simulation

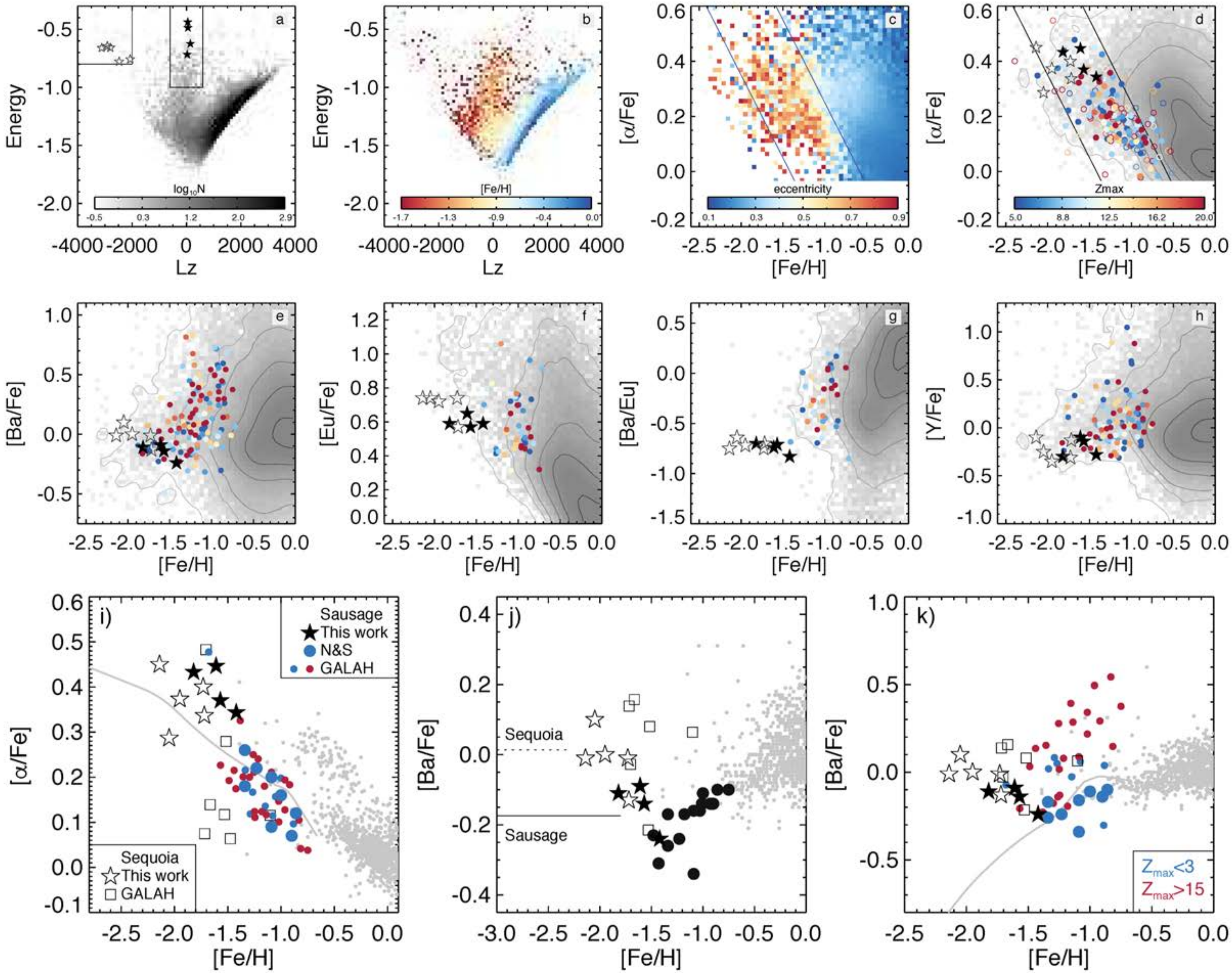


https://star.herts.ac.uk/~chiaki/works/Aq-C-5-kro2.mpg

Gadget3-based code (CK+ 2007)
Aquila Initial Condition (Scannapieco+12), $3\times10^5 M_\odot$, 0.5kpc
(CK 2015; Haynes & CK 2019; Vincenzo & CK 2020; CK 2022)

[X/Fe] in Gaia Satellites

Aguado, Belokurov, ..CK+ 2021



ASTROPHYSICS

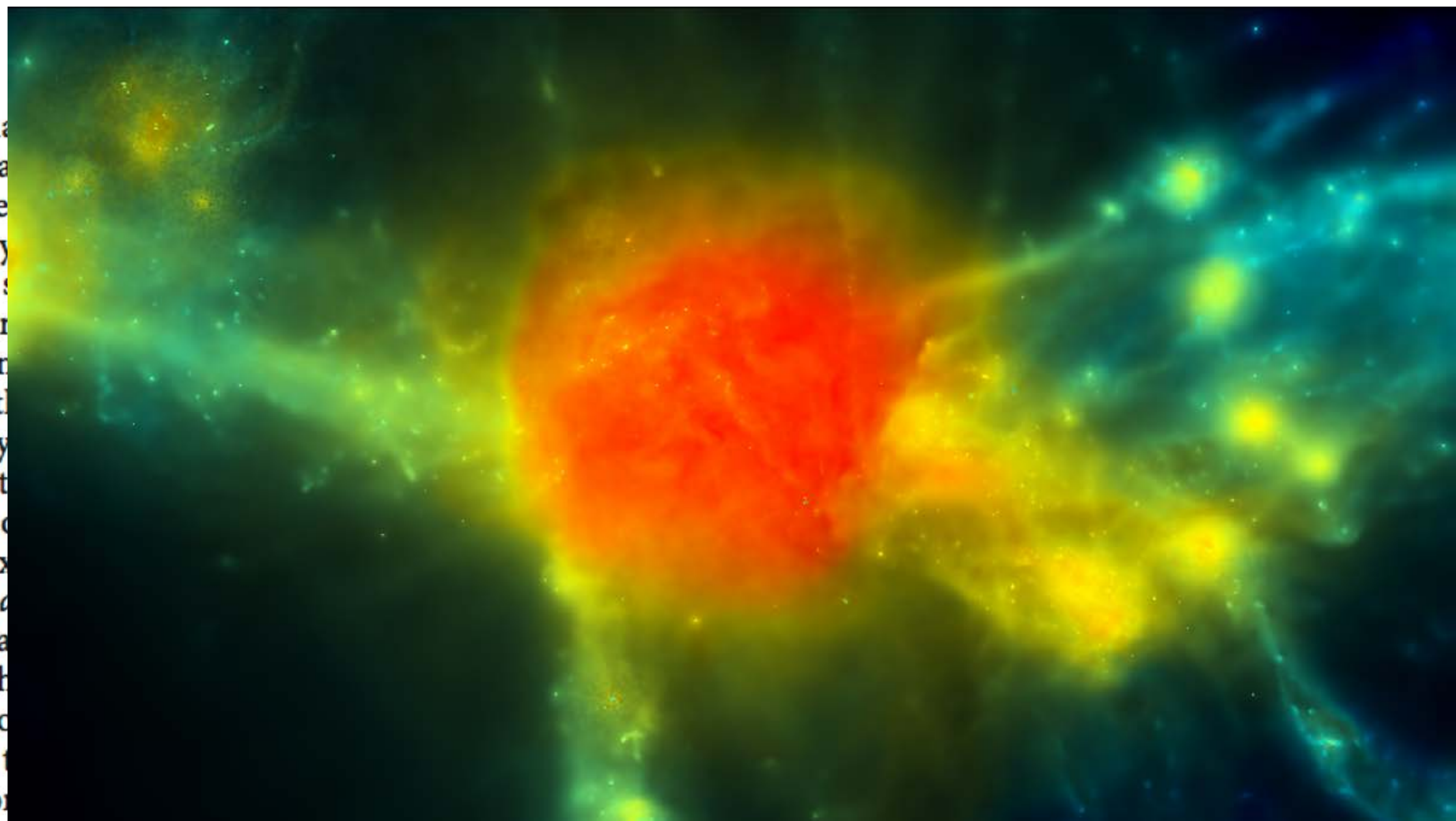
Elemental abundances across cosmic time

CK 2016, Nature News& Views

The chemical composition of a massive galaxy in the early Universe reveals an extremely short period of star formation. This result could challenge our ideas about the evolution of galaxies and of the Universe itself. SEE LETTER P.248

CHIAKI KOBAYASHI

Stars are fossils tha
of their host gala
their lives, they e
vae, producing heavy
distributed into the
stellar gas. New star
from this gas contain
were produced from t
tions of stars. By analy
patterns of the element
sible to determine h
kind of supernovae ex
On page 248, Kriek *et a*
tal abundances of a ma
11 billion years ago, wh
galaxy formed by a sho
of star formation and t
without producing mo



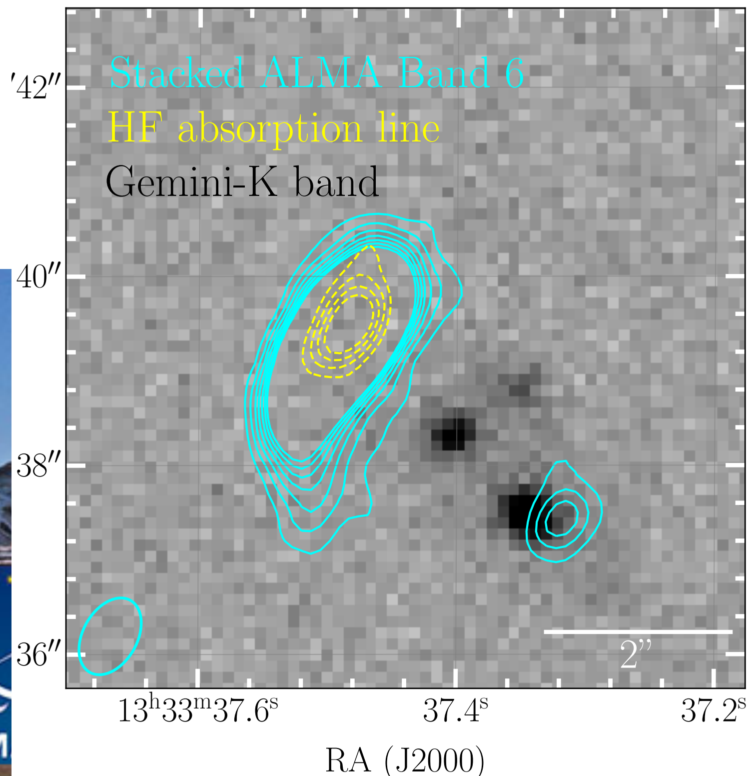
nature astronomy
4 Nov 2021
LETTERS
https://doi.org/10.1038/s41550-021-01515-9

The ramp-up of interstellar medium enrichment at $z > 4$

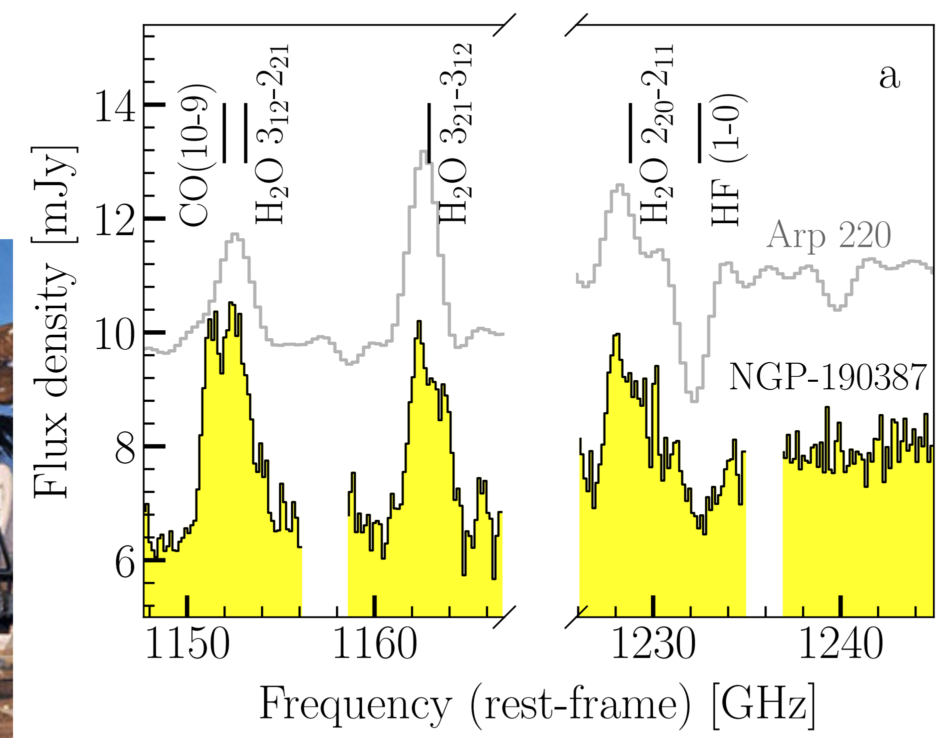
∧ Fluorine

M. Franco[1]✉, K. E. K. Coppin[1], J. E. Geach[1], C. Kobayashi[1], S. C. Chapman[2,3], C. Yang[4], E. González-Alfonso[5], J. S. Spilker[6], A. Cooray[7] and M. J. Michałowski[8]

- Lensed dusty star-forming galaxy **NGP-190387** at z = 4.420

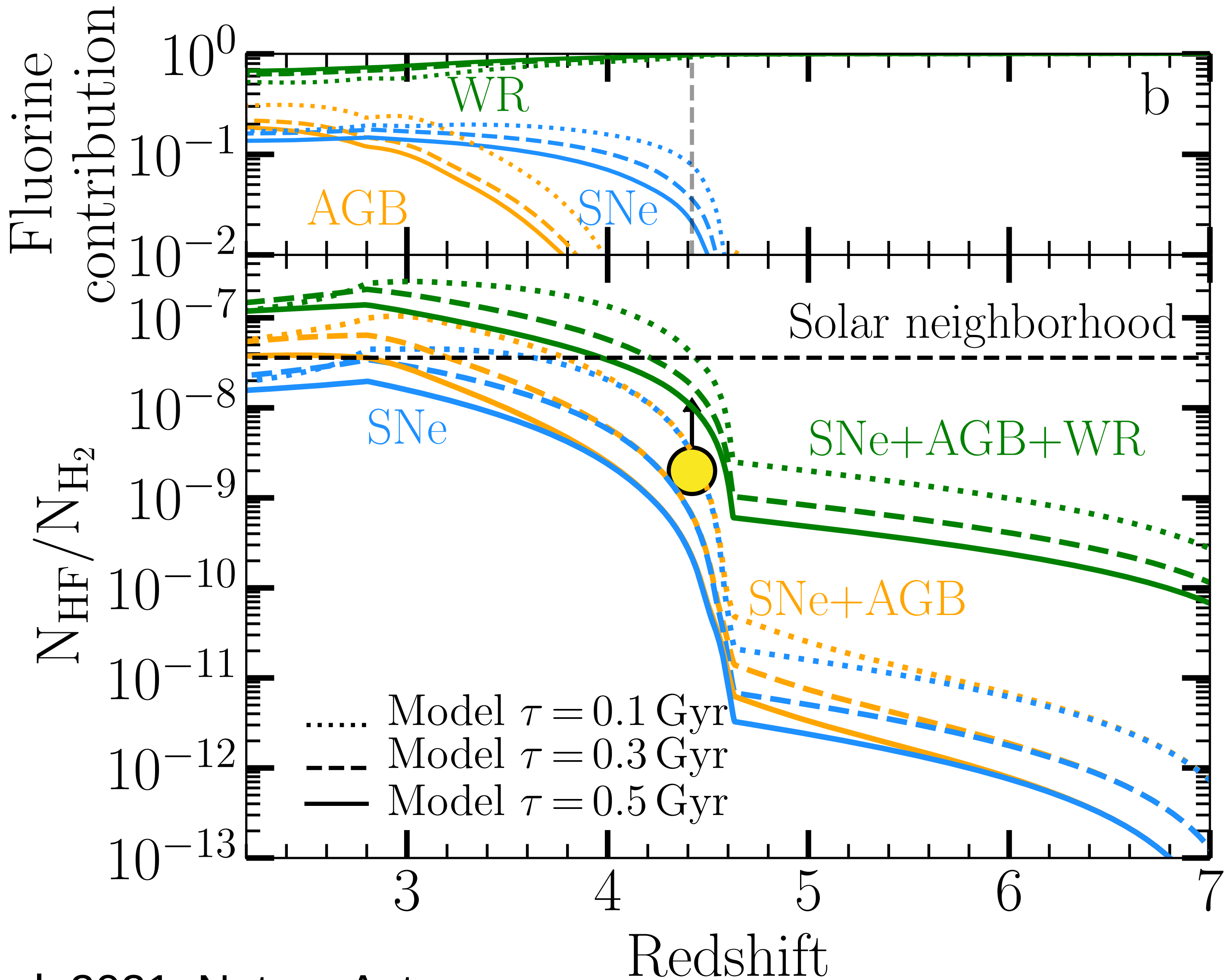


- $N(H_2)=2.1\pm0.4\ 10^{24}\ cm^2$ (from [C I])
- $H_2 + F \rightarrow H + HF$ (stable, dominant)



Wolf-Rayet stars!? (or ν-process)

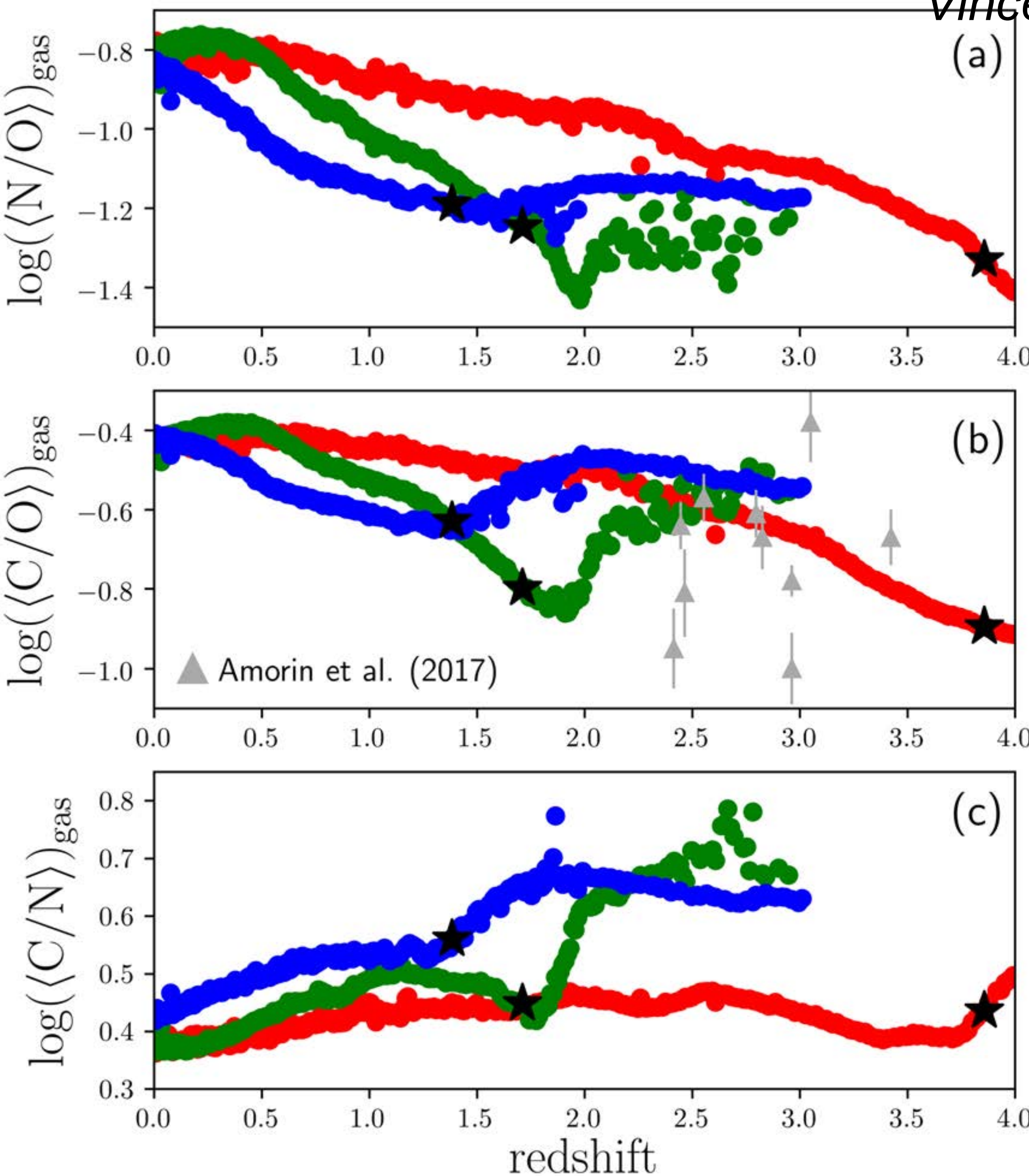
1.4 Gyrs after Big Bang, 0.7 Gyrs after re-ionization

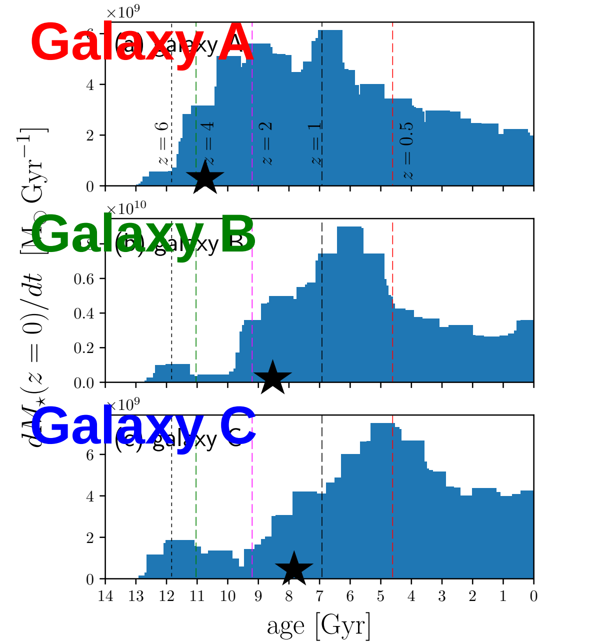


Franco et al. 2021, Nature Astronomy

Redshift evolution of CNO ratios

Vincenzo & CK 2018a, A&A, 610, 16





C: low-mass AGB, $<4M_\odot$

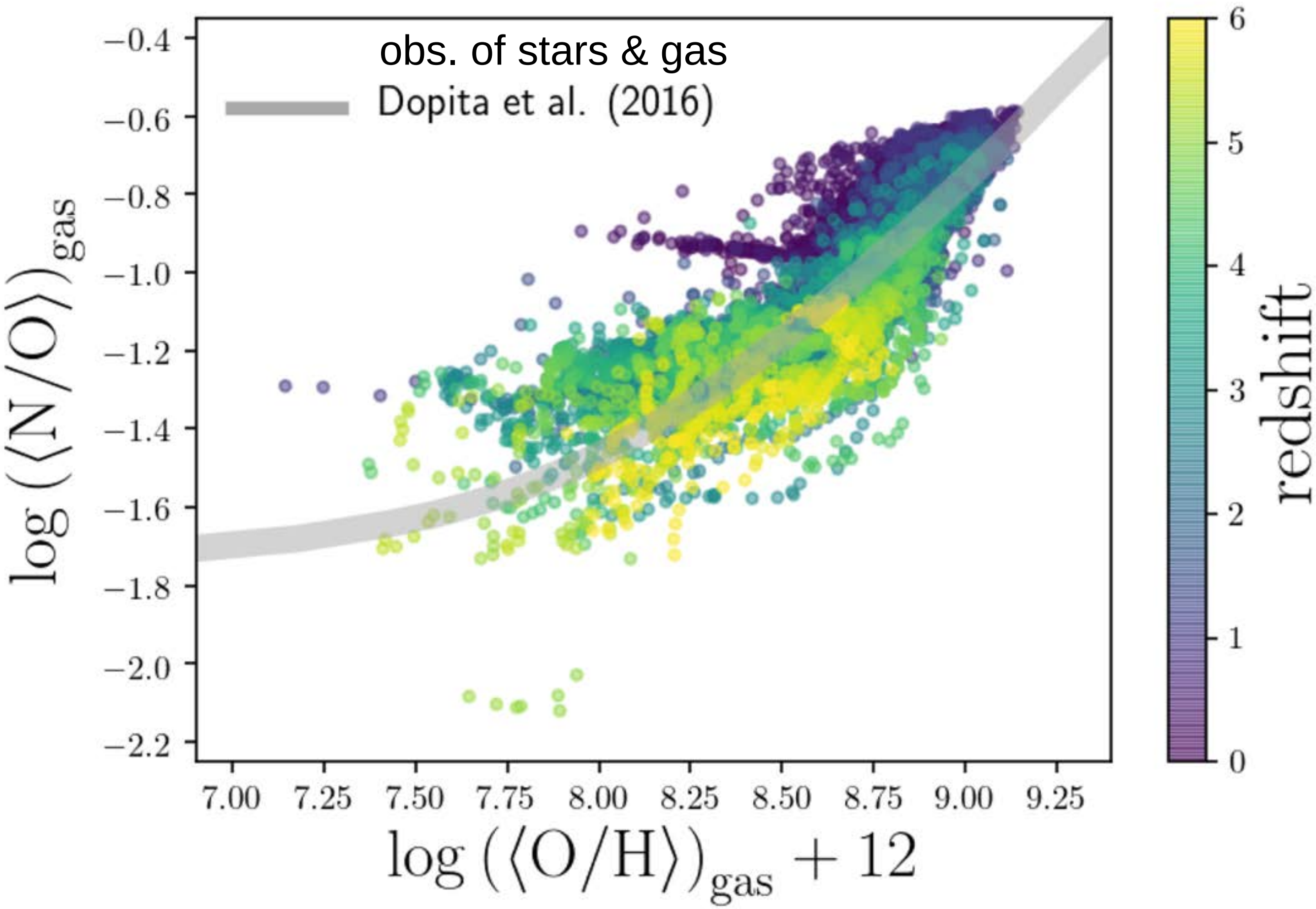
N: massive AGB, $>4M_\odot$

O: core-collapse SNe

Currently, N/O (z<2.5), C/O (z>2), but C/N with JWST/NIRSpec!

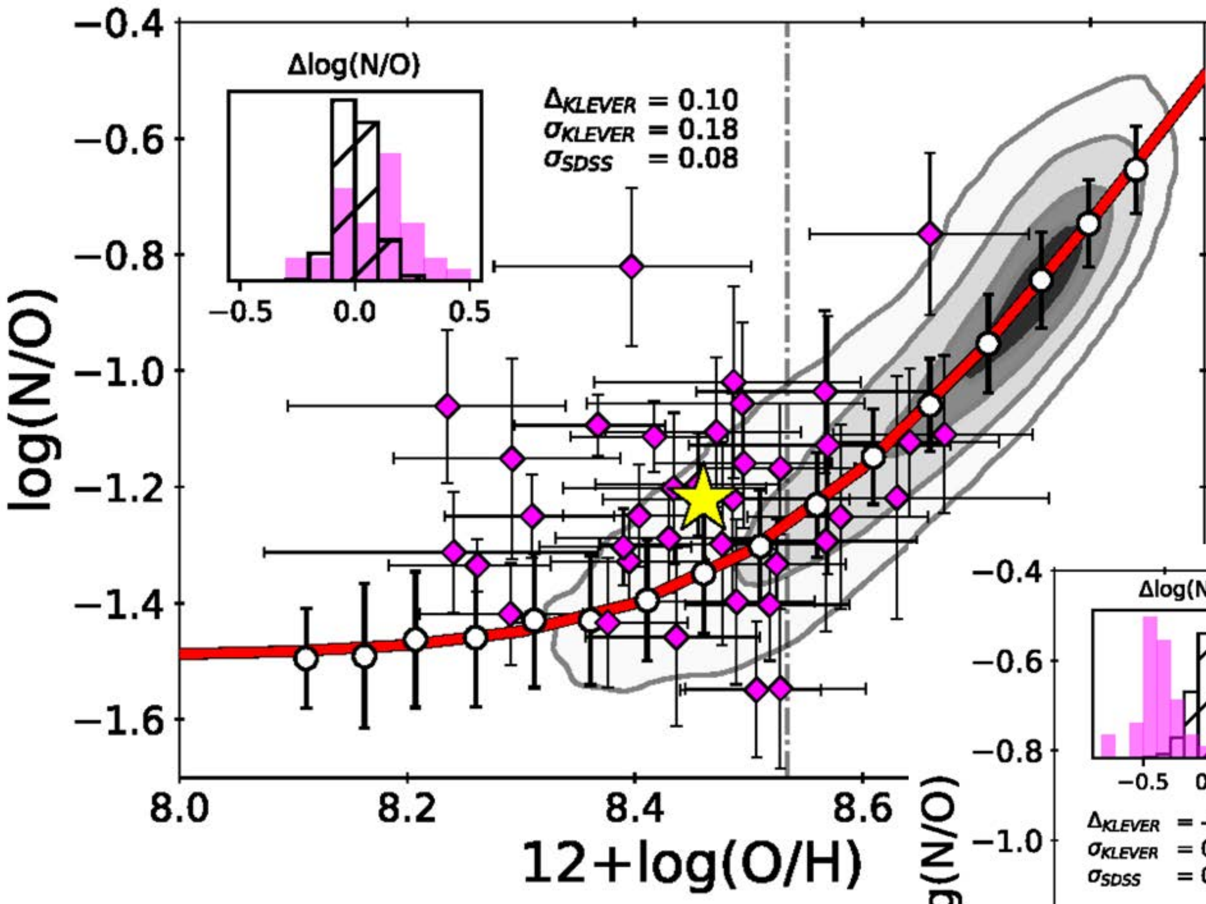
The N/O-O/H relation

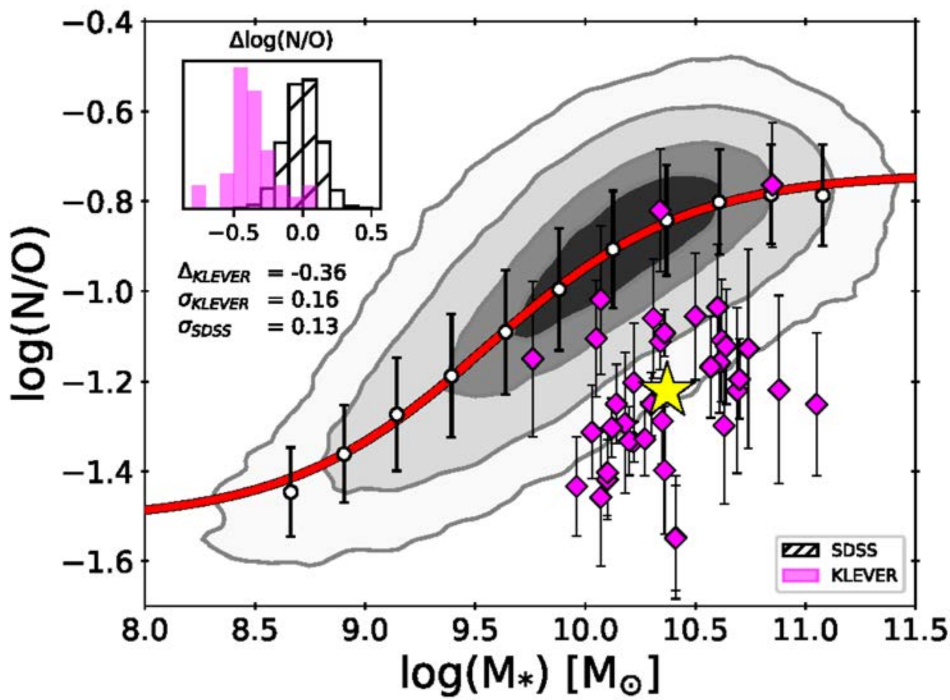
Vincenzo & CK 2018b, MNRAS, 478, 155



- ❖ *Local* relation reflects metallicity radial gradients.
- ❖ *Global* relation is caused by the mass-metallicity relation.
- ❖ for 33 star-forming galaxies in cosmological simulations

The N/O-O/H relation



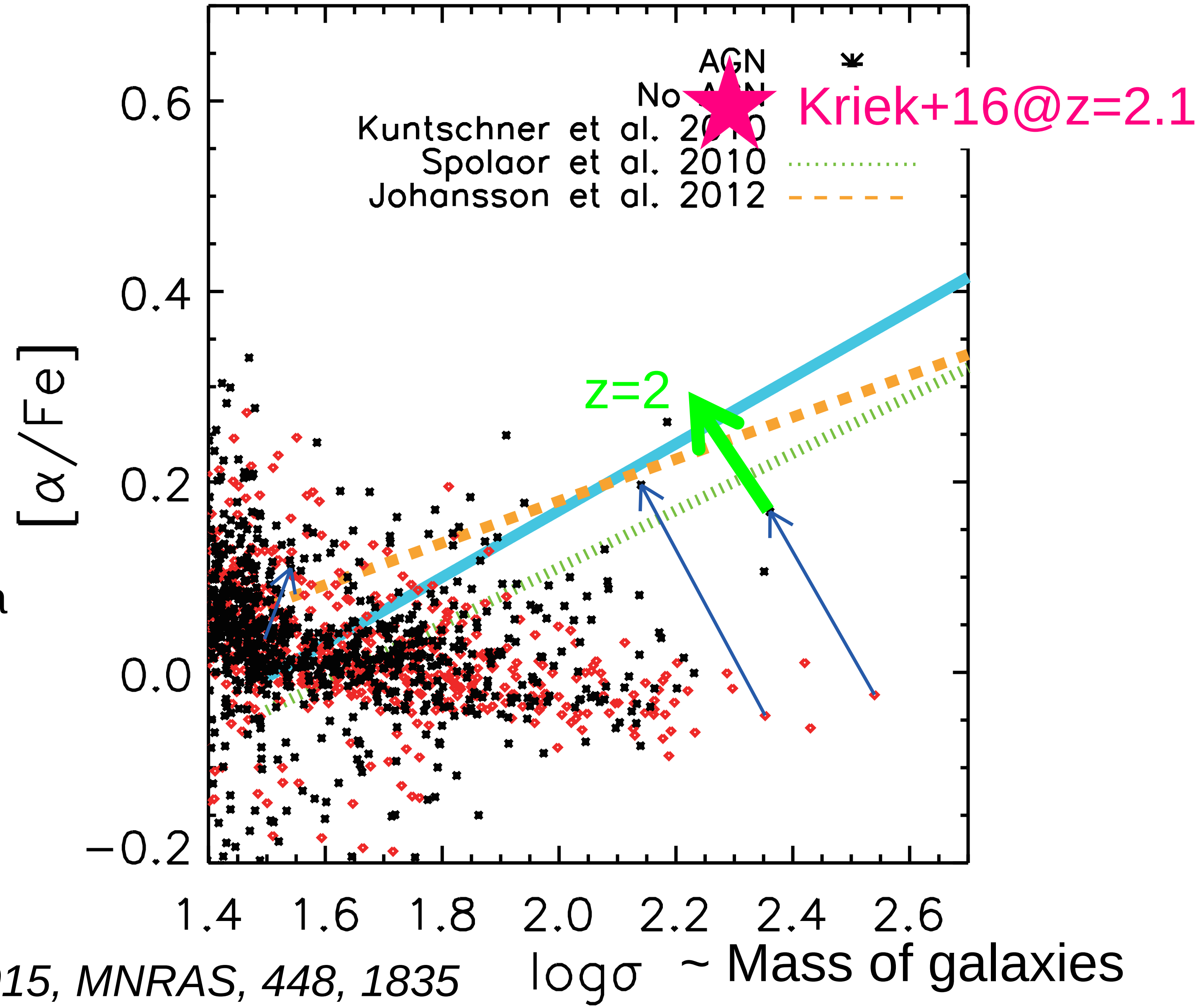


KLEVER survey:
Hayden-Pawson, Curti,
Maiolino ...CK+ 21, submitted

Stellar [α/Fe]-mass relation of ETGs

Not solved yet in any (proper) cosmological simulations...

longer SF
more SNe Ia

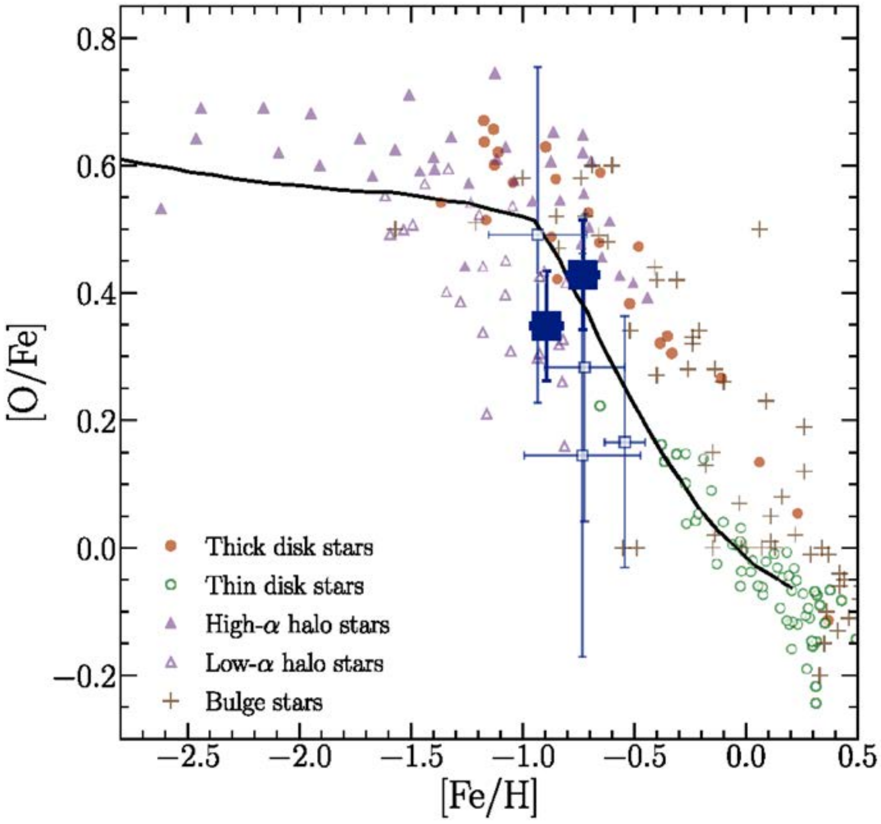


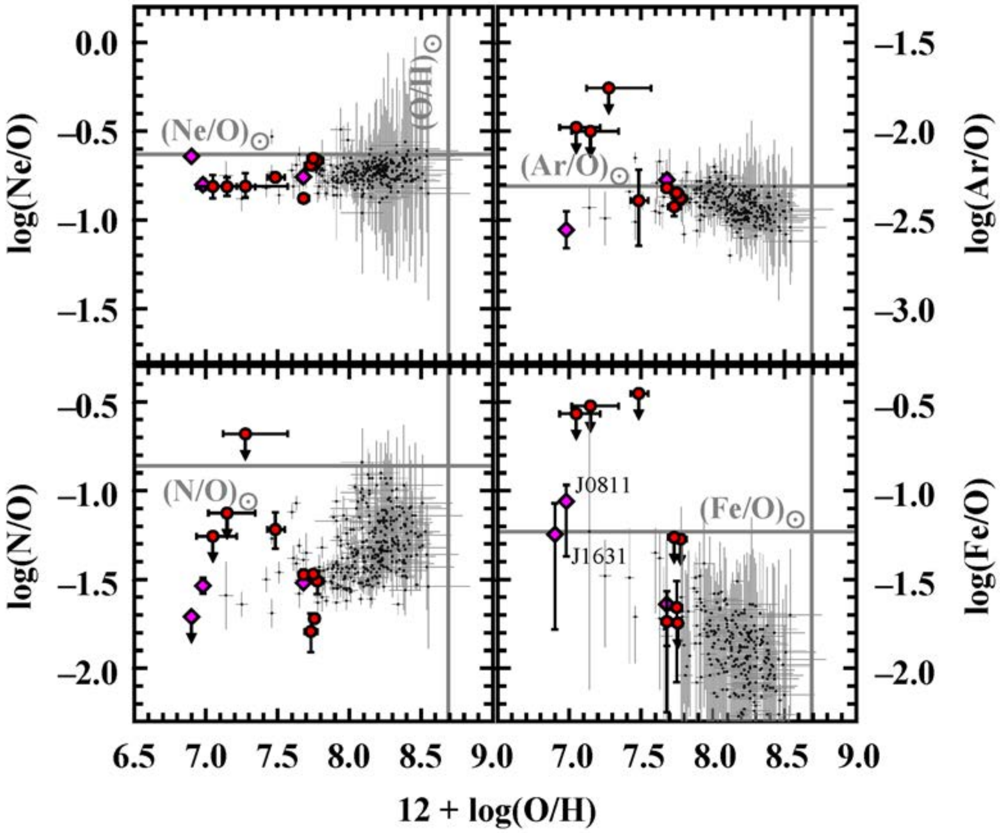
~ Mass of galaxies

Taylor & CK 2015, MNRAS, 448, 1835

More [α/Fe] observations

- NIRVANDELS survey on gas-phase O/H and stellar Fe/H of 33 star-forming galaxies 2.95 < z < 3.80 (Cullen+21)
- EMPRESS survey, local young low-mass galaxies (Kojima+20, Isobe+21)





#There was a long history until MW stars' [α/Fe] settle down...

Extra-galactic Archaeology

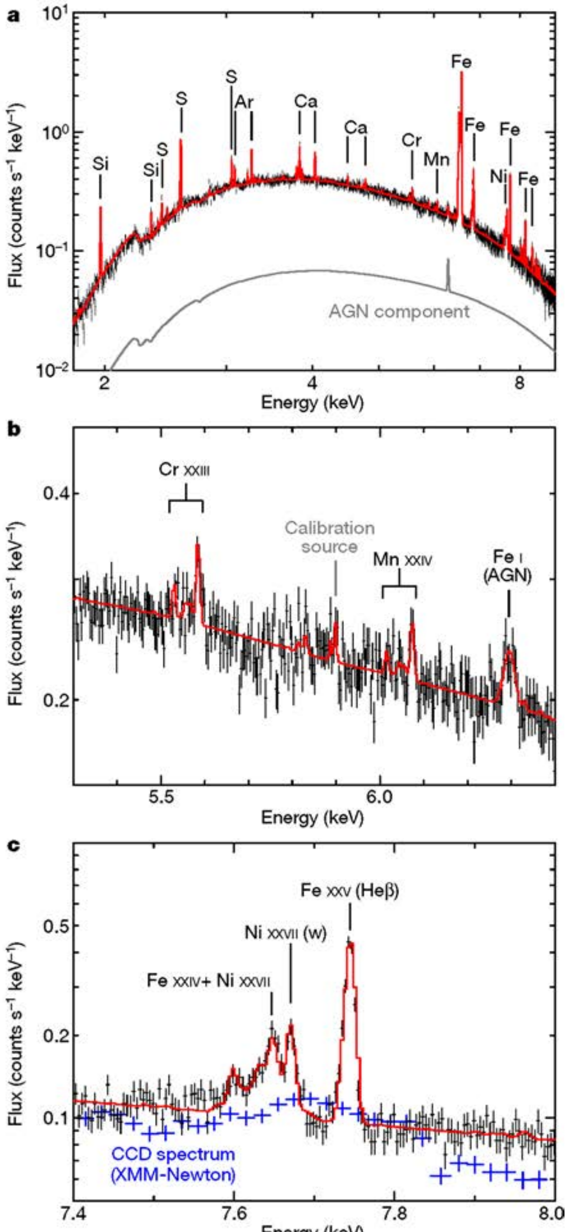
- Chemodynamical structures of galaxies, i.e., kinematics and 2D map of gas, stars, chemical abundances, are measured with Integral Field Units (SAURON, CALIFA, MaNGA, SAMI, KMOS, MUSE, Hector, NIRSpec/JWST…)

- Time evolution and scaling relations with larger sample (e.g., SDSS, MOSFIRE, VMOS, FMOS, MOONS, PFS)
- Evolution of mass-metallicity relations, metallicity gradients? Proof of galactic ecosystem?

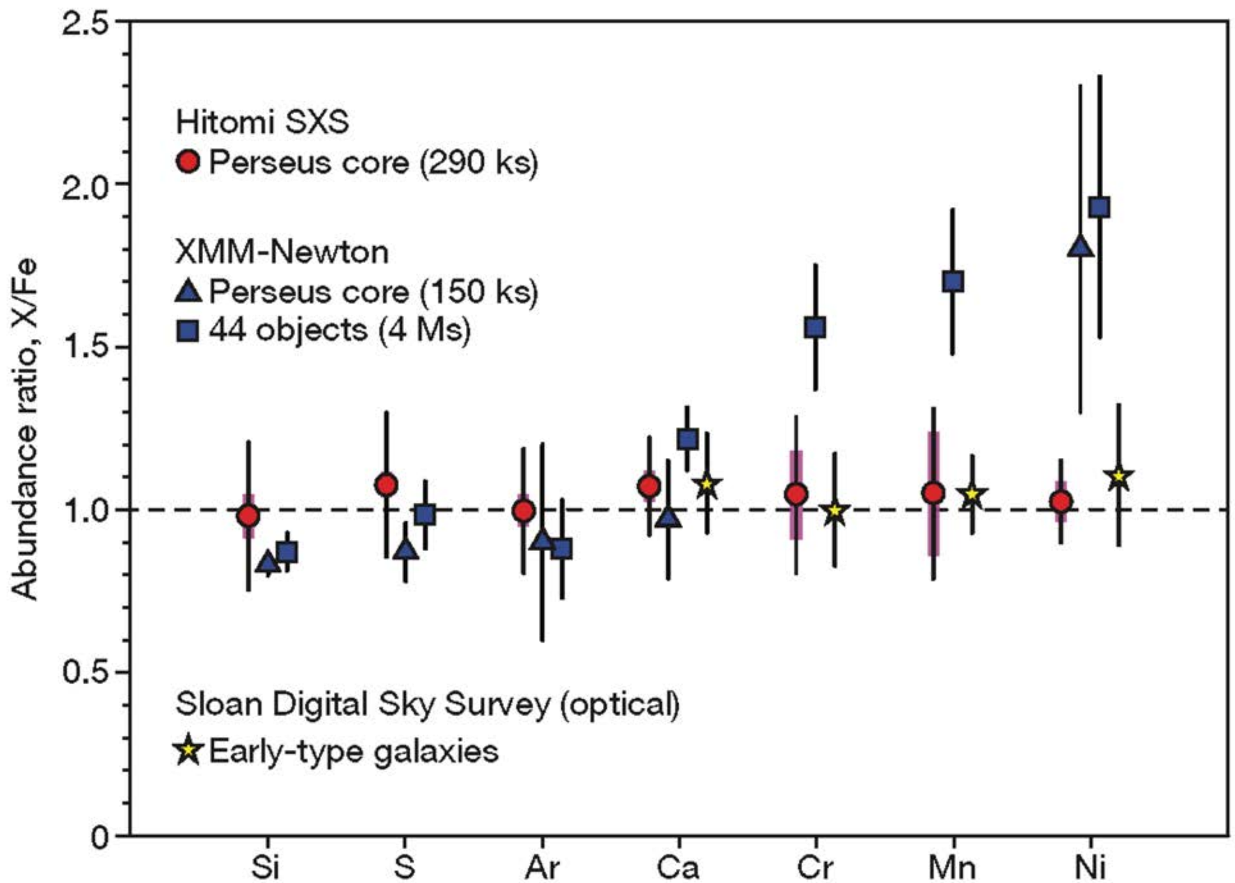
JWST http://www.jwst.nasa.gov

The topic not mentioned, but absolutely beautiful…

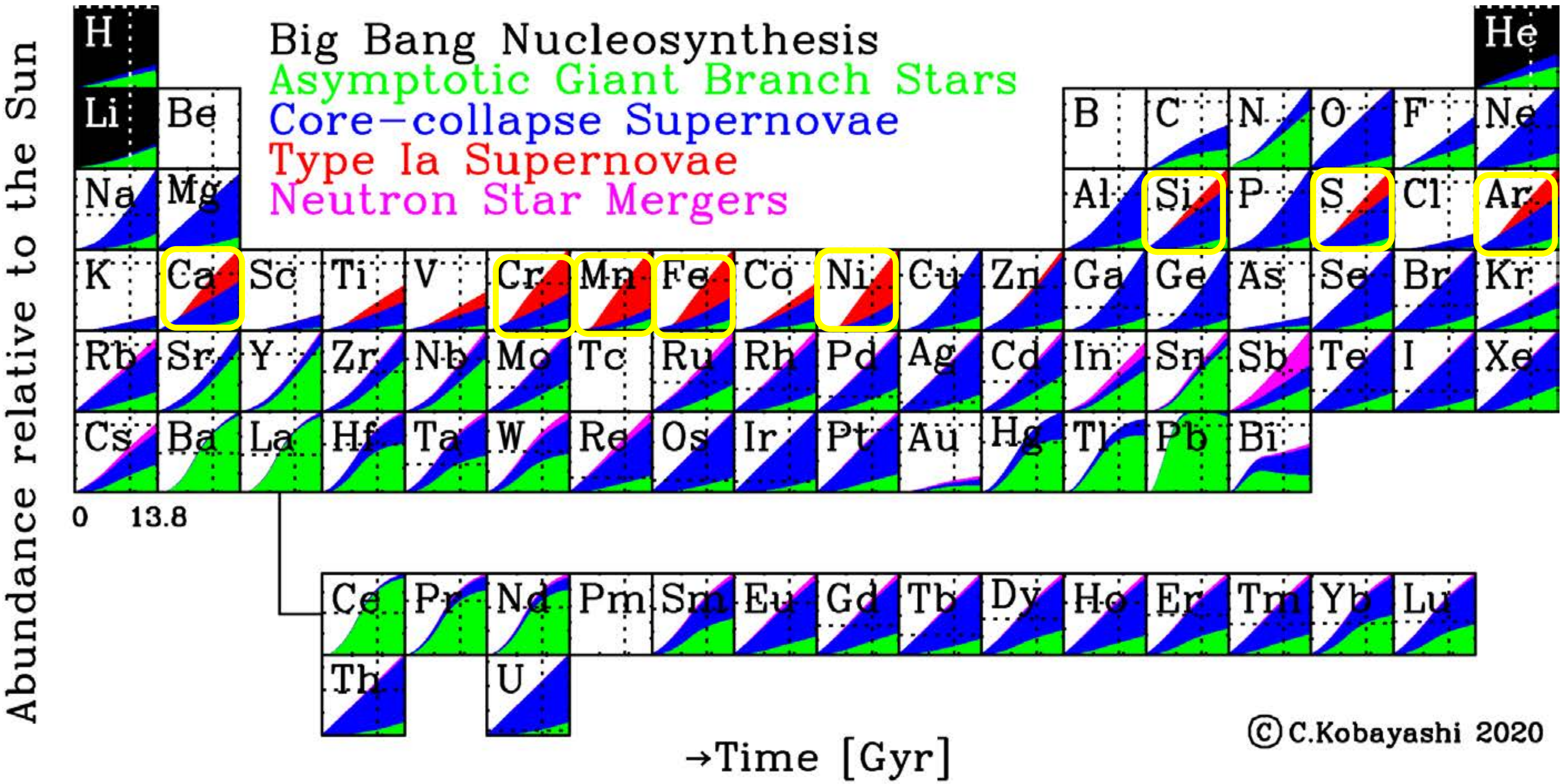
X-ray Intracluster medium (ICM)



Perseus cluster (Hitomi collaboration 2017)
Soft X-ray Spectrometer (SXS) on Hitomi
$\Delta E \approx 5$ eV in the 2–10 keV band



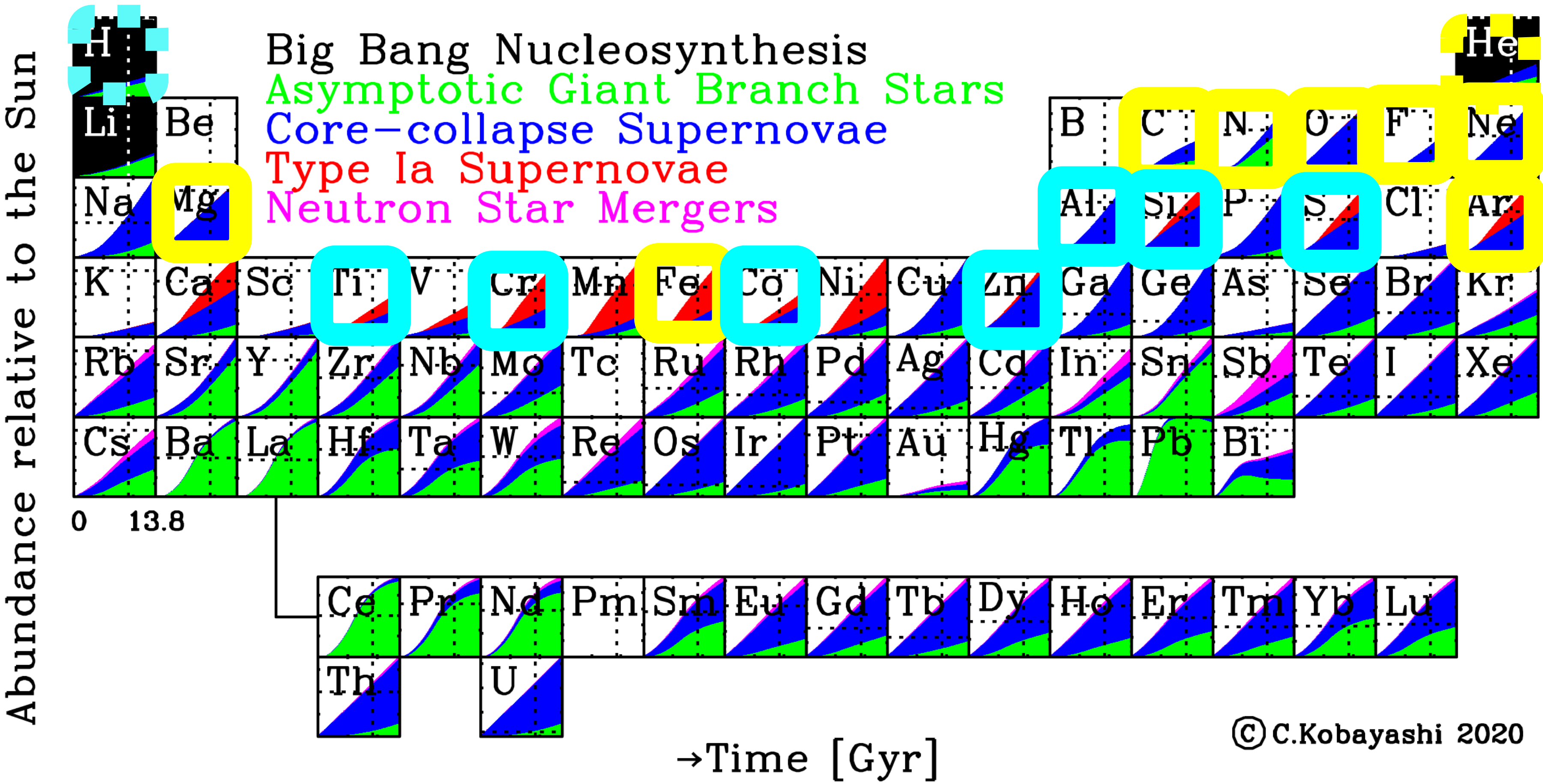
X-ray Intracluster medium (ICM)



How to translate line ratios into abundance ratios?

Distant galaxies, DLA, IGM

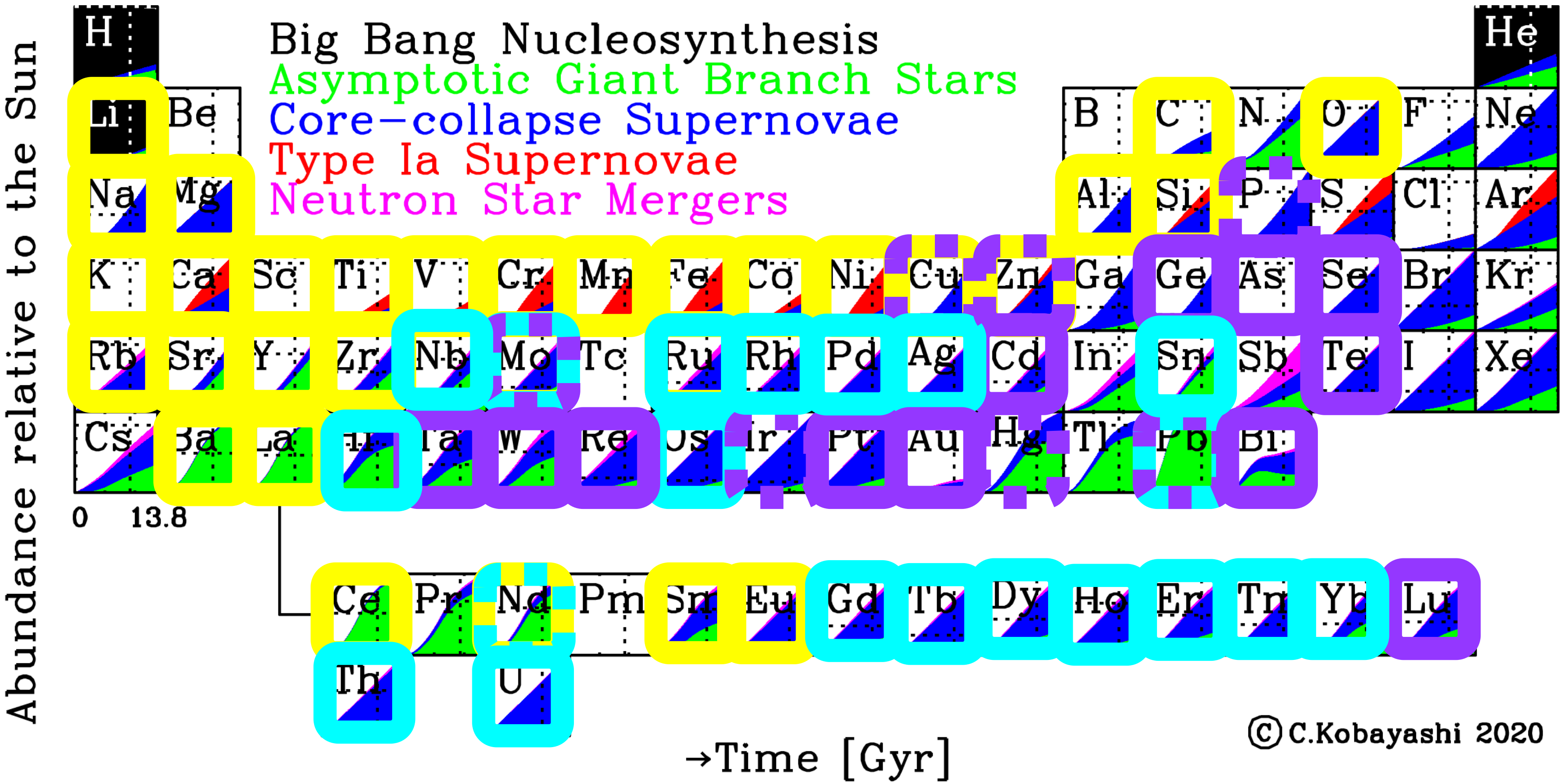
to witness time evolution



star-forming galaxies, DLA

How to translate line ratios into abundance ratios?

The need for UV spectra of stars

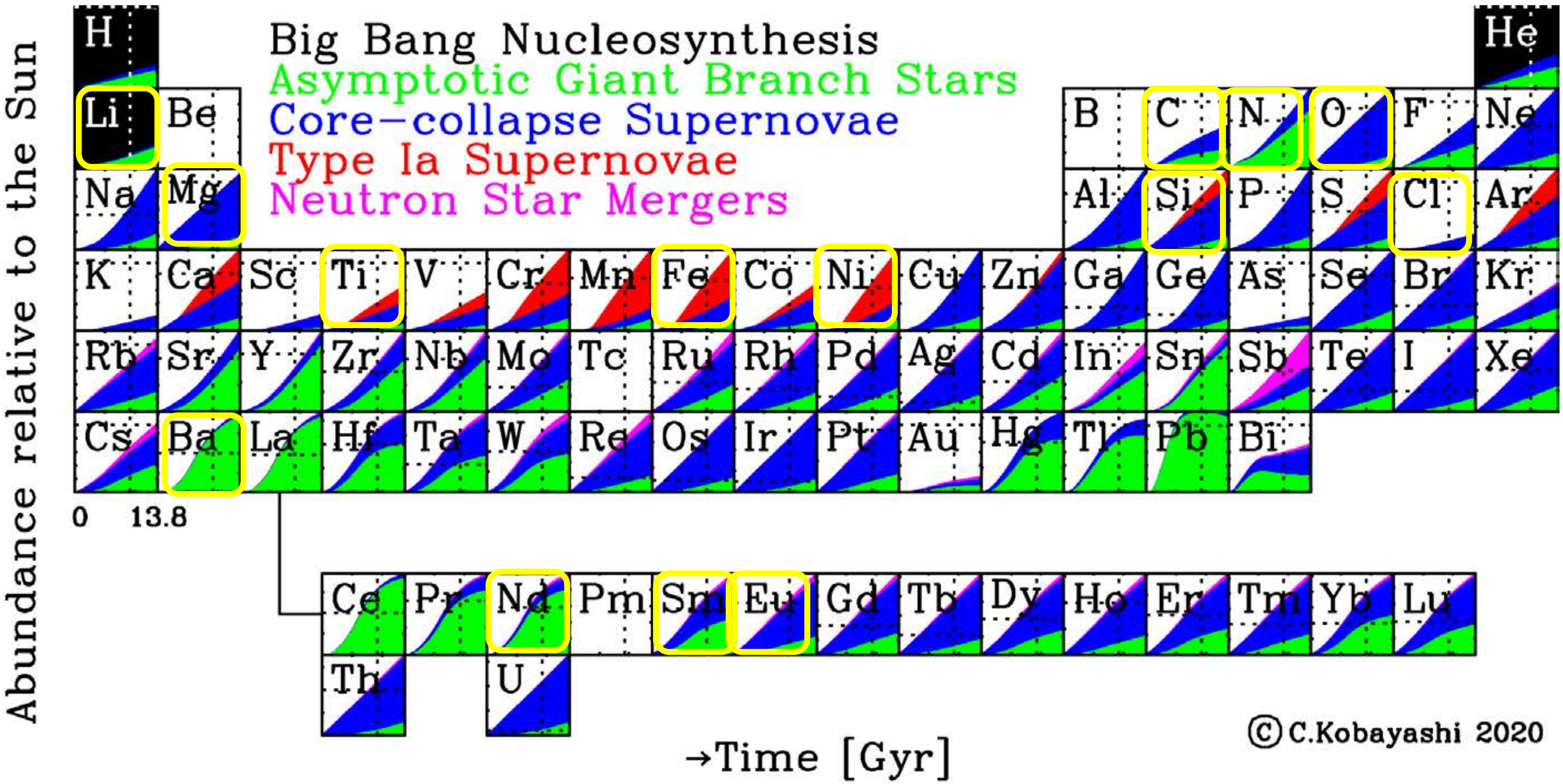


GALAH, CUBES, HST

The need for HRMOS: Isotopic ratios!

^

for accurate/true abundances & in stars



3D/NLTE analyses are essential.

Incomplete list (correct me, I will update the slide)

references

KAGRA	GW	NS/BH merger		-	
Super-K, Hyper-K	MeV ν, background	SN		-	
KamLAND	low E ν	SN, pp-chain		-	
IceCube-Gen2	high E ν	SN		2033	
XRISM	Xray high-res spec	SNR	Mn,Cr etc	2022	
FORCE	high E Xray 1-80keV	AGN	^{44}Ti	mid 2020s	Mori+
HiZ-GUNDAM	Xray 0.5-4keV	high-z GRB		late 2020s	Yonetoku+20
ATHENA	Xray IFU	ICM	C to Ni	2031	ESA
SuperDIOS	Xray	redshifted OVII, OVIII		2030s	Yamada+18
LAPYUTA, 60cm	UV 115-190nm	?	?	2029-31	Tsuchiya+
Subaru-HDS	optical	stars	Li to U	-	
Subaru-PFS	optical MOS (**HR/IFU**?)	stars, galaxies	Fe, α	2023	
TMT-HROS	optical	stars	Li to U	??	
ULTIMATE-Subaru	0.9-1.8μm (**IFU MOS**?)	galaxies		??	Akiyama+
JASMINE	1.1-1.6μm astrometry		dynamics	2022/30s	
GREX-PLUS, 1.2m	10-20μm, 30000A			2030s	Inoue+
ATT10@南極	300μm / 1THz	[OIII],[NII]	?	2032	Kuno+
ALMA	0.3mm-1cm / 31.3-950GHz		CNOF	-	
LST, merged to AtLAST	0.8-4mm / 70-420 GHz	[OIII]@z=7-9; some [CII],[NII]	?	2031?	Kohno+21
EAVN/VERA	10-100mm	AGB mass-loss		-	Imai+20
ngVLA@北米	0.3-20cm / 1.2-116 GHz			2030s	NRAO
SKA	3cm-4m /70MGz-10 GHz		H	2027-	