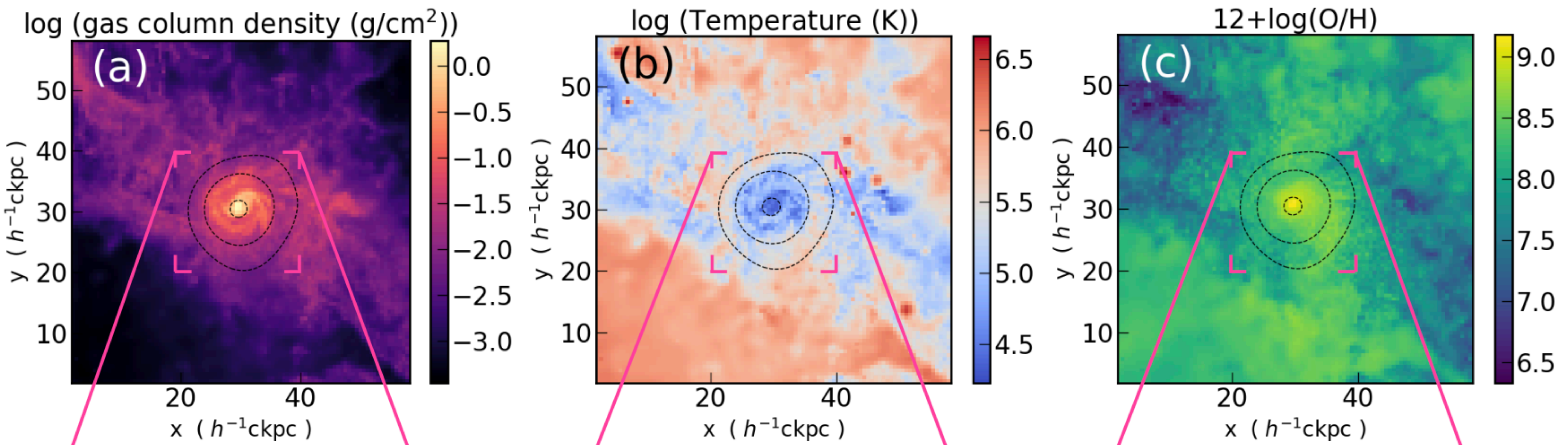
First Galaxies, Anomalous abundance ratios & Top-heavy IMF

— contrasting high-z & local dwarf gals



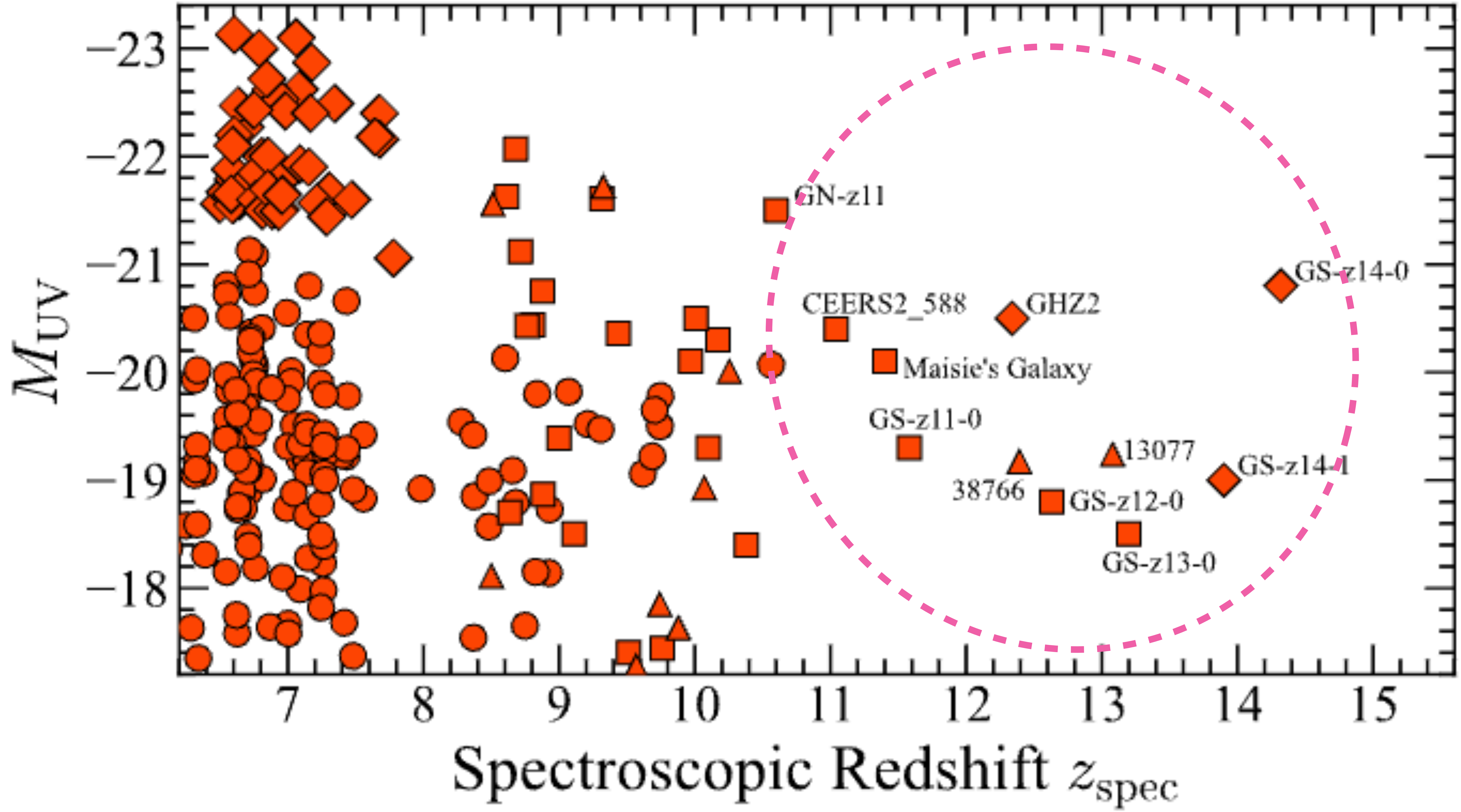
Ken Nagamine (Osaka / K-IPMU / UNLV)

Collaborators: **Keita Fukushima**, **Yuri Oku, Kazuki Tomaru, …**
Matsumoto, Isobe, Yanagisawa, Ouchi, & EMPRESS team

Redshift frontier is moving up!

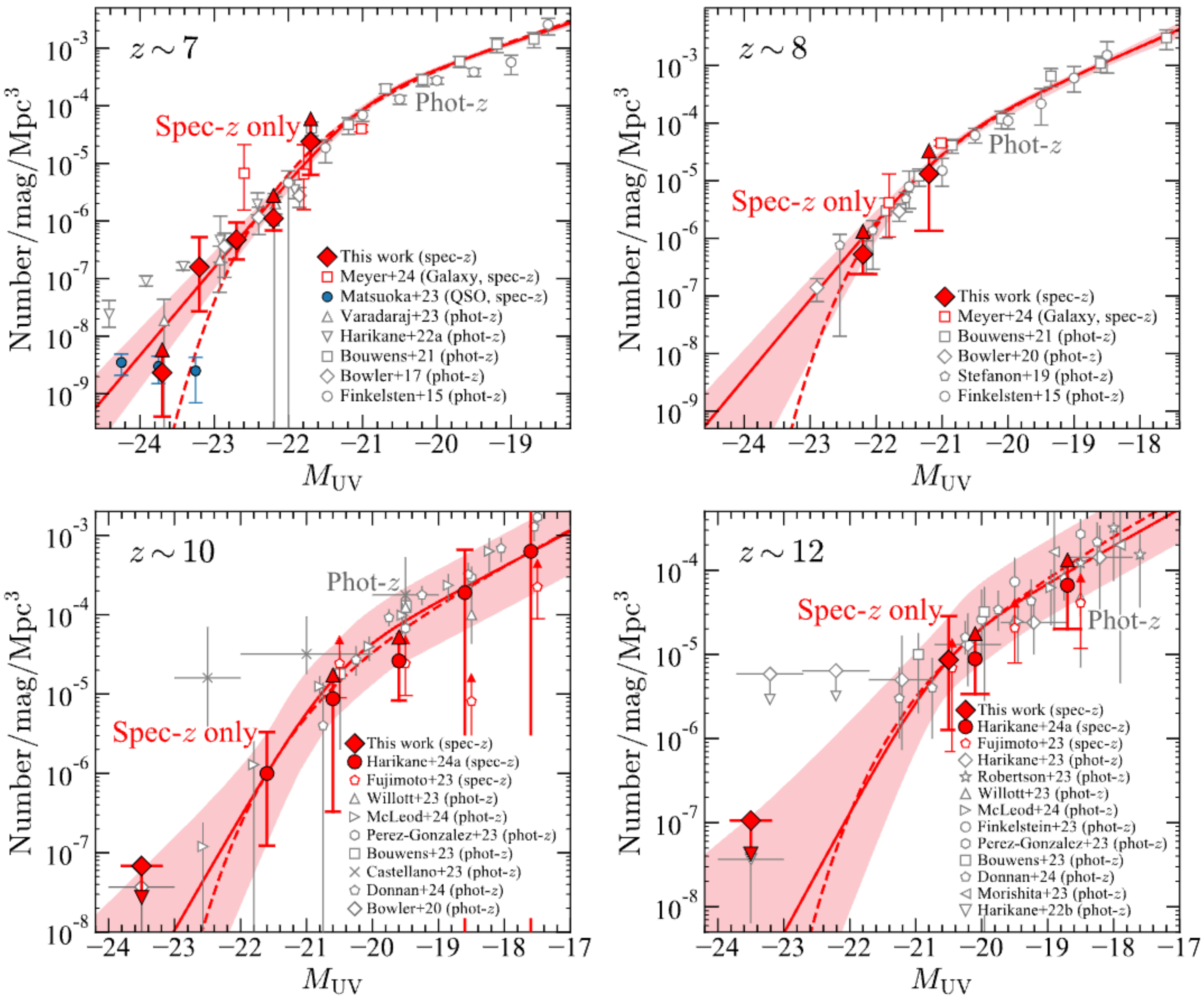
Ever Earlier Galaxy Formation Epoch

— `first' galaxy formation @ z>12

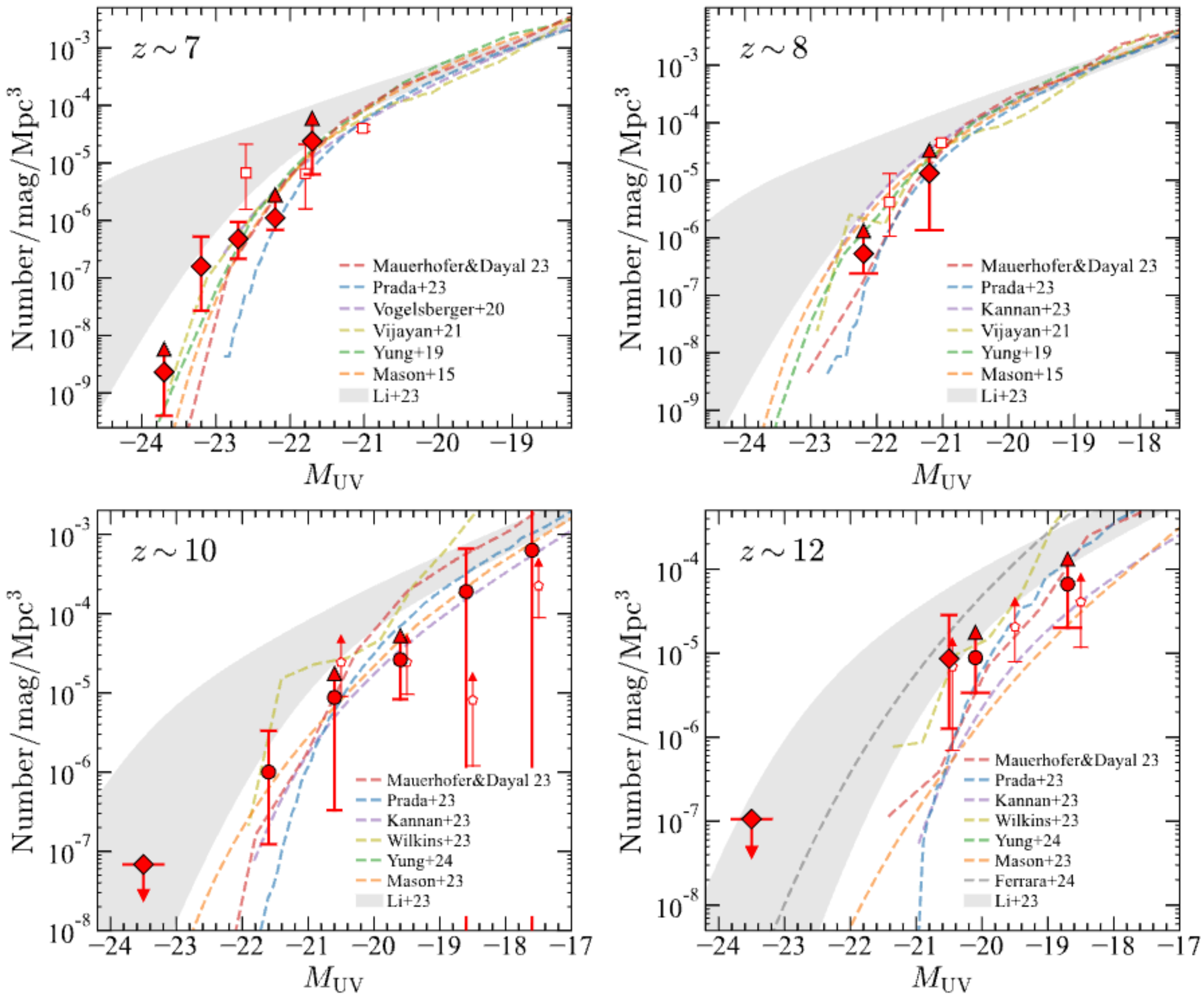


Harikane+'24

Spec-z UV LF



Harikane+24

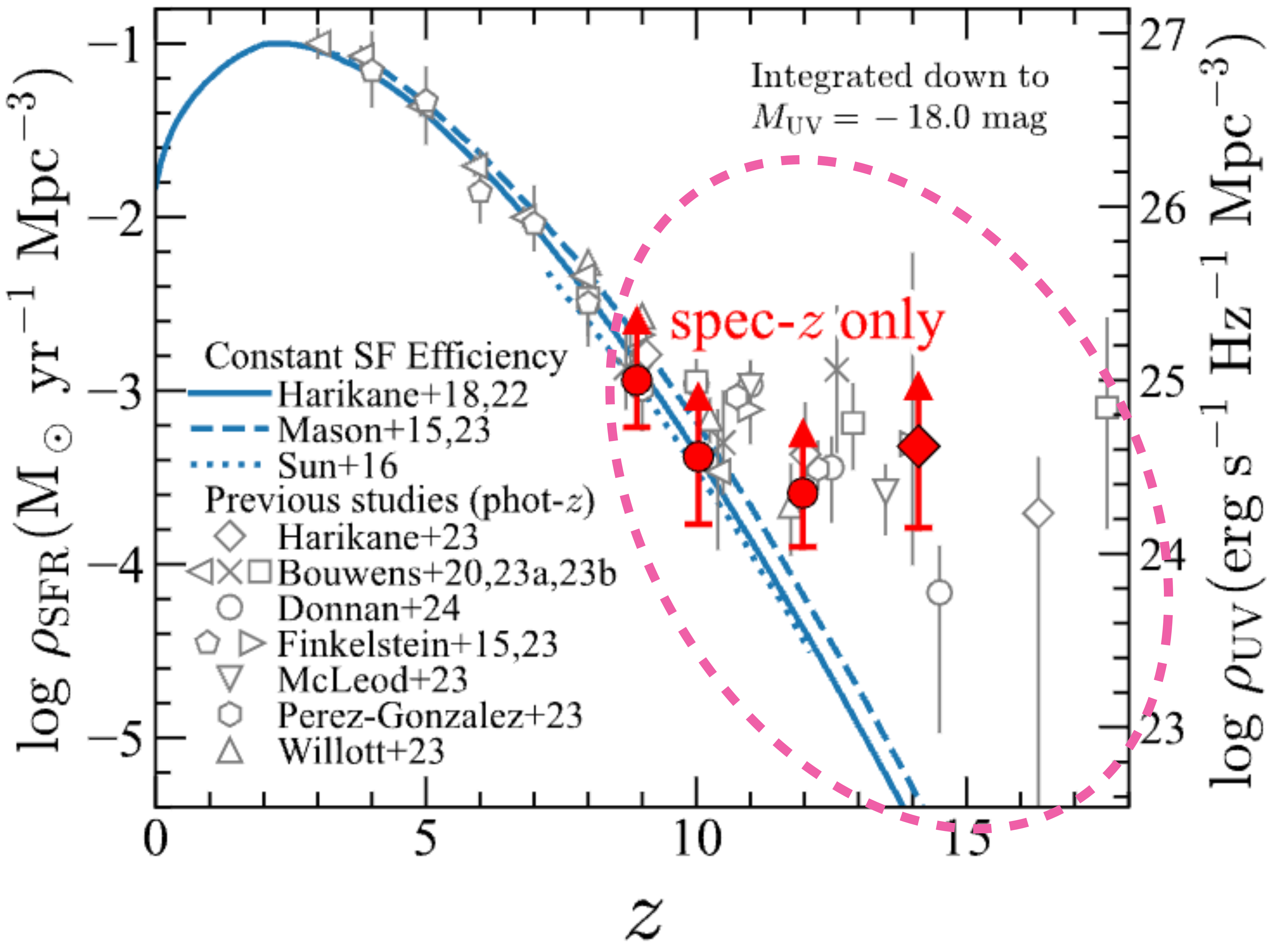


z ~ 7
Number/mag/Mpc^3
M_UV
Mauerhofer&Dayal 23
Prada+23
Vogelsberger+20
Vijayan+21
Yung+19
Mason+15
Li+23
z ~ 8
Mauerhofer&Dayal 23
Prada+23
Kannan+23
Vijayan+21
Yung+19
Mason+15
Li+23
z ~ 10
Mauerhofer&Dayal 23
Prada+23
Kannan+23
Wilkins+23
Yung+24
Mason+23
Li+23
z ~ 12
Mauerhofer&Dayal 23
Prada+23
Kannan+23
Wilkins+23
Yung+24
Mason+23
Ferrara+24
Li+23

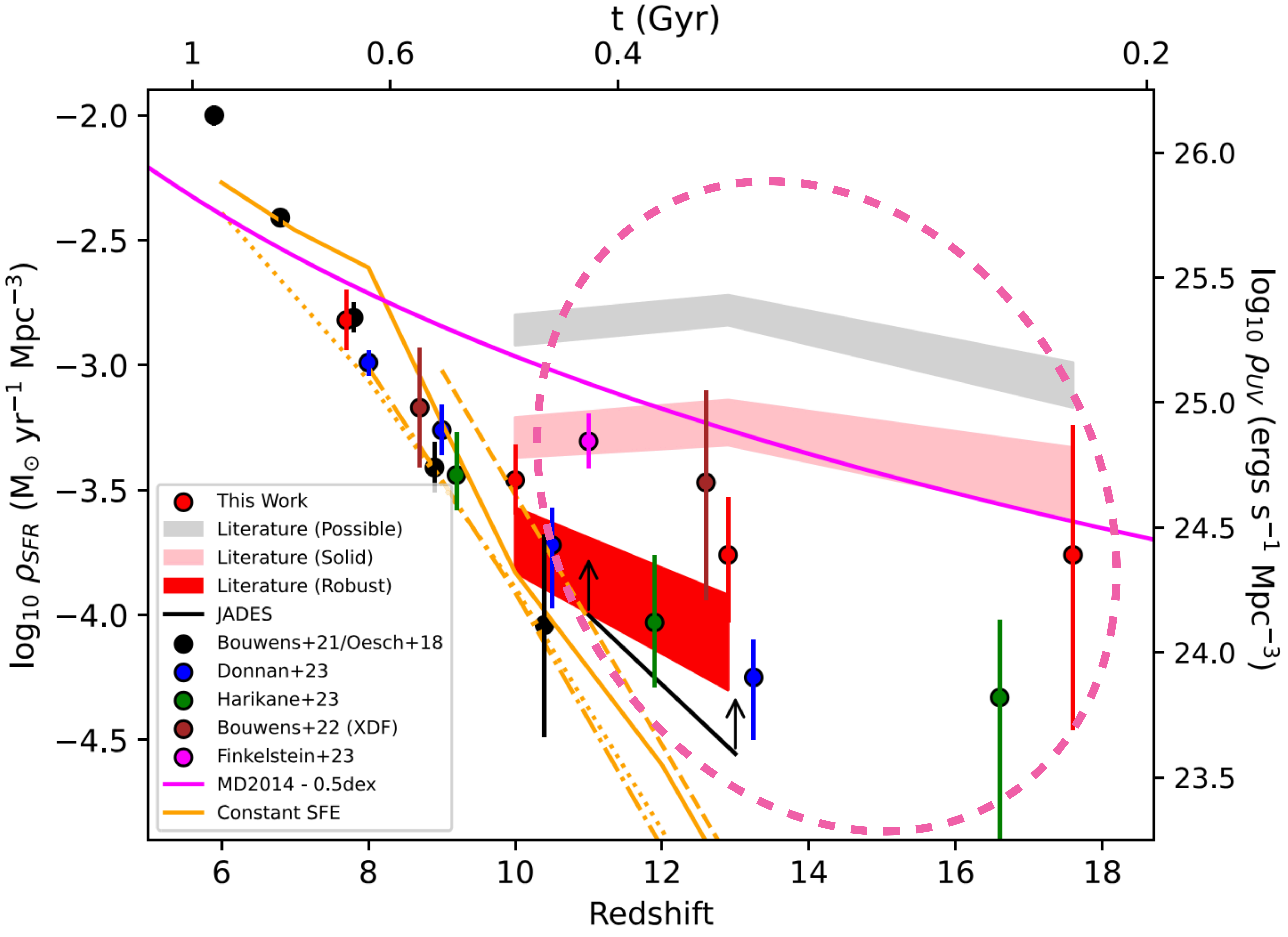
Harikane+24

Ever Earlier Galaxy Formation Epoch

– `first' galaxy formation @ z>12

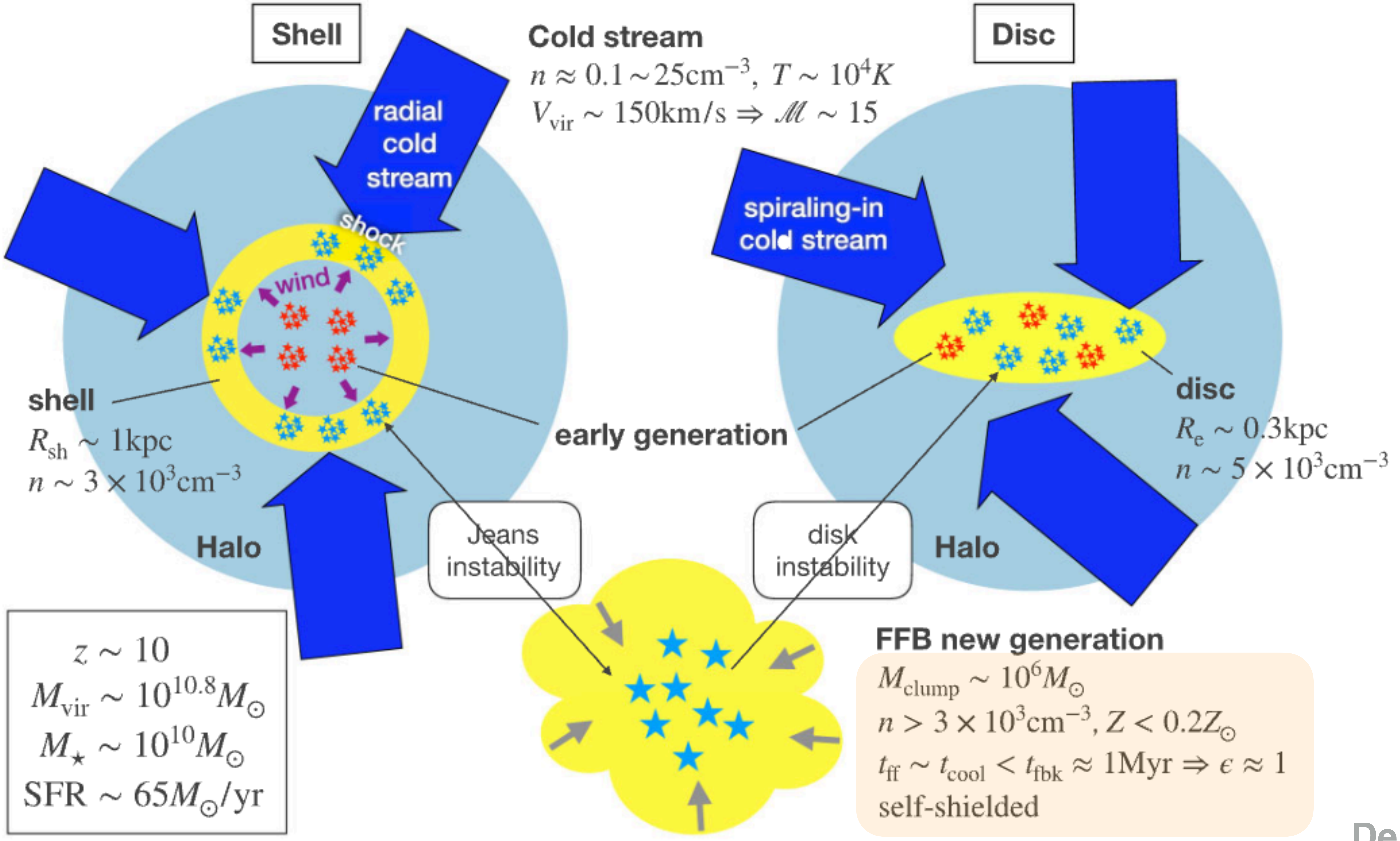


Harikane+'24



Bouwens+'23

Feedback-Free Starbursts (FFB)



Dekel+ '23

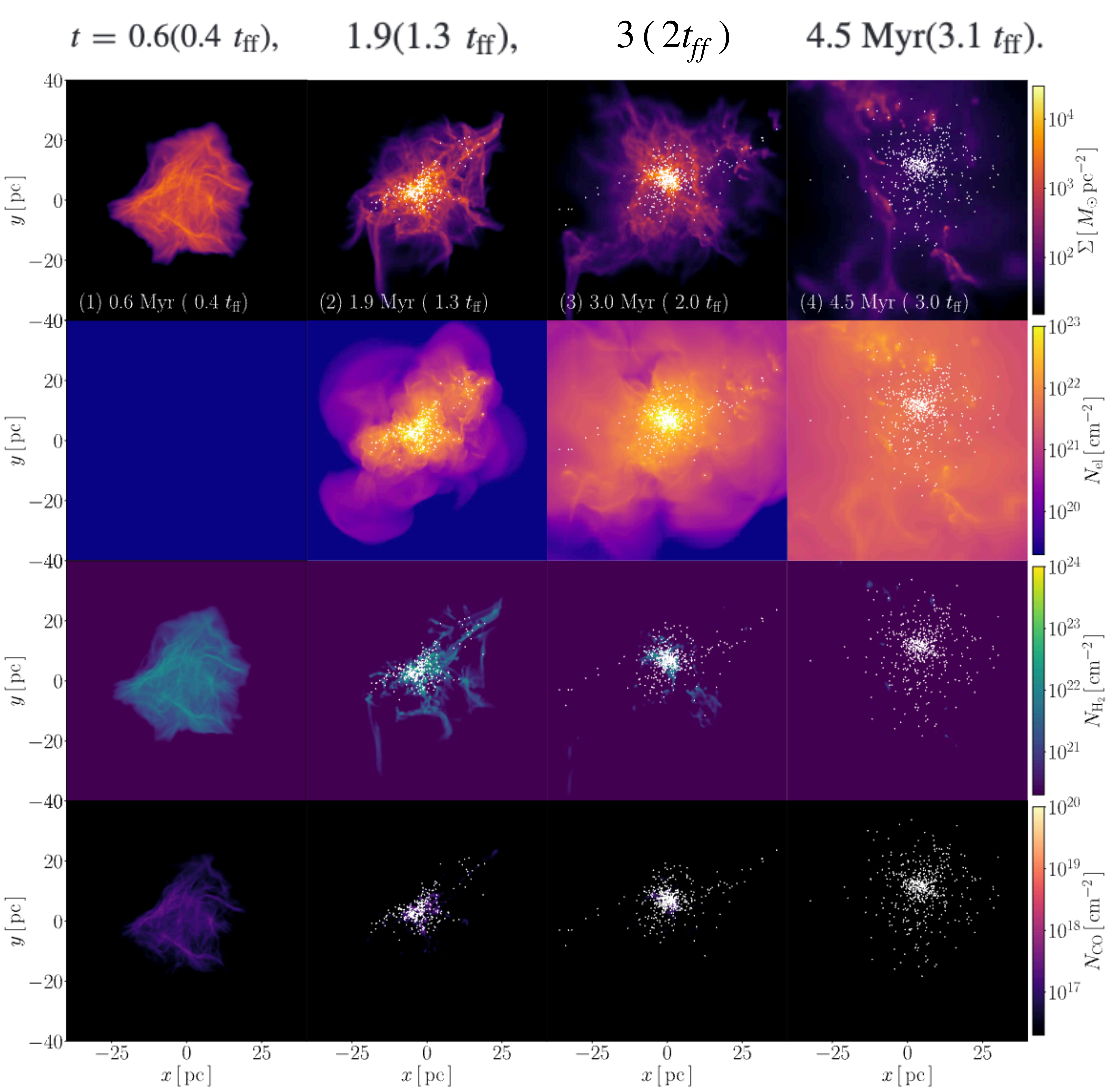
3D Rad hydro sim by SFUMATO

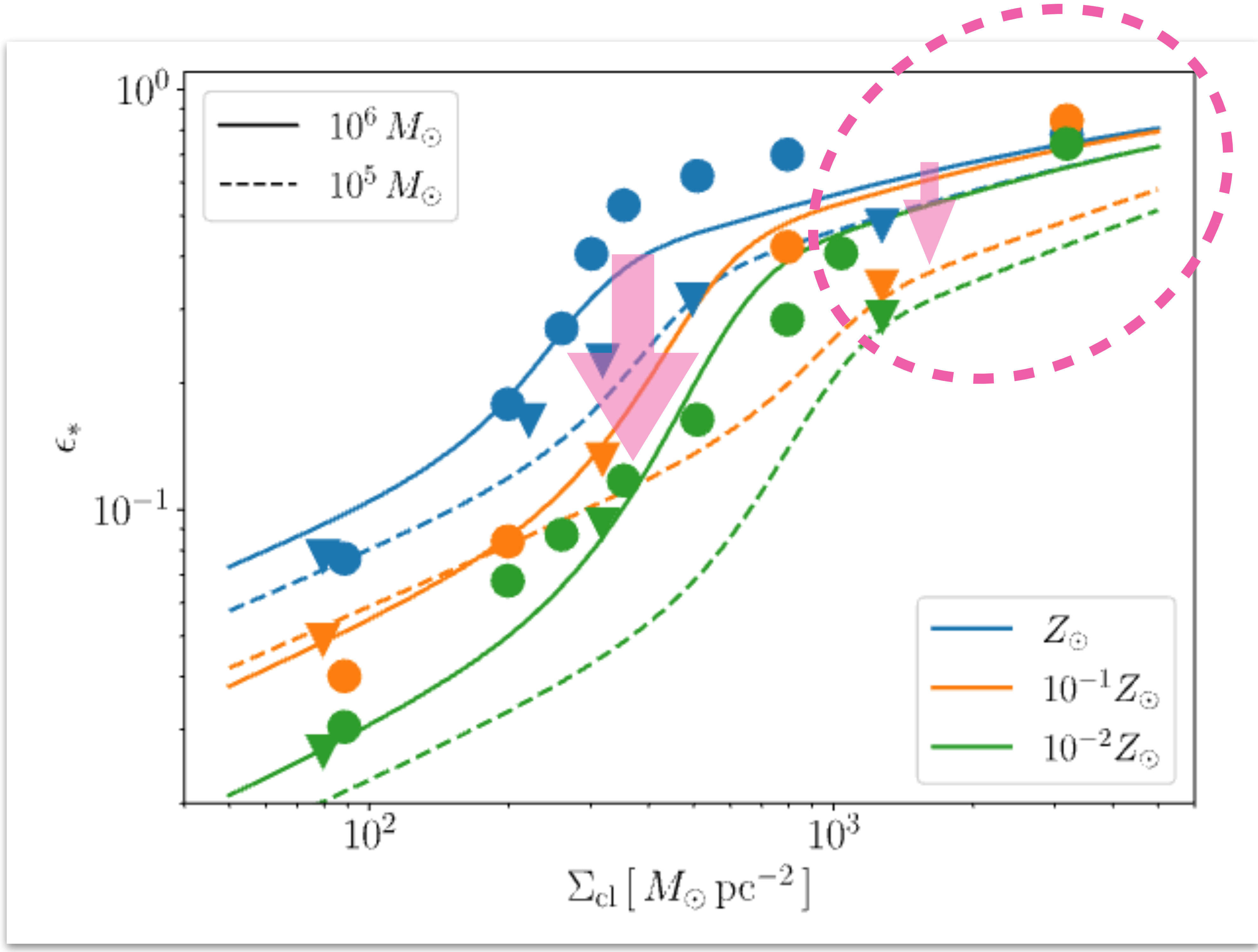
$(M_{\rm cl}, R_{\rm cl}, Z) = (10^6\ {\rm M_\odot}, 20\ {\rm pc}, 10^{-2}\ {\rm Z_\odot})$.

lower Z → $T_{\rm ioniz}$ high

→ ineffective dust shielding of UV

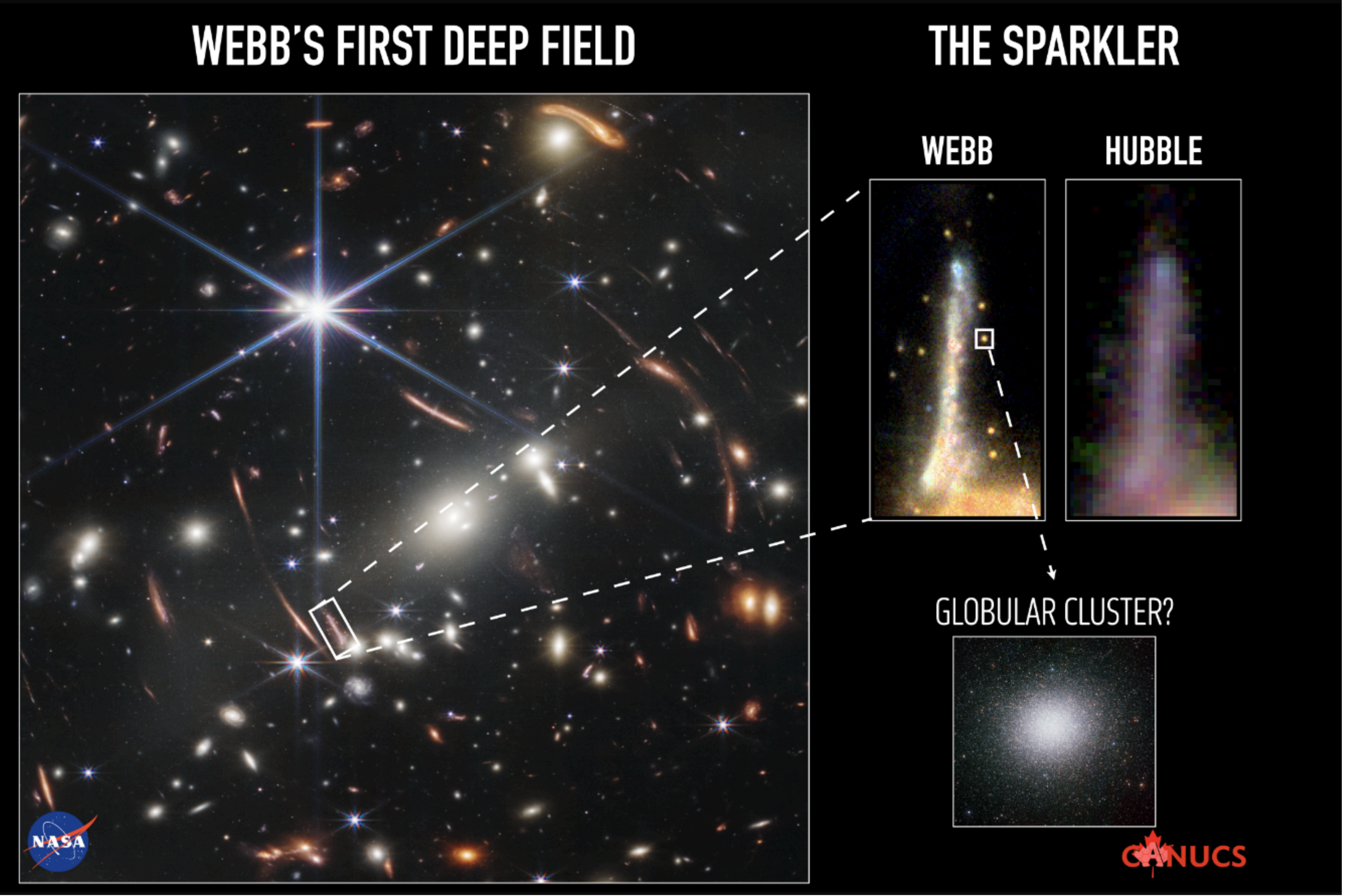
→ lower SFE





Fukushima & Yajima+ '21

cf. Grudic+18; Kim+18; Menon+23;



z = 0.39 gal cluster
SMACS J0723.3-7327

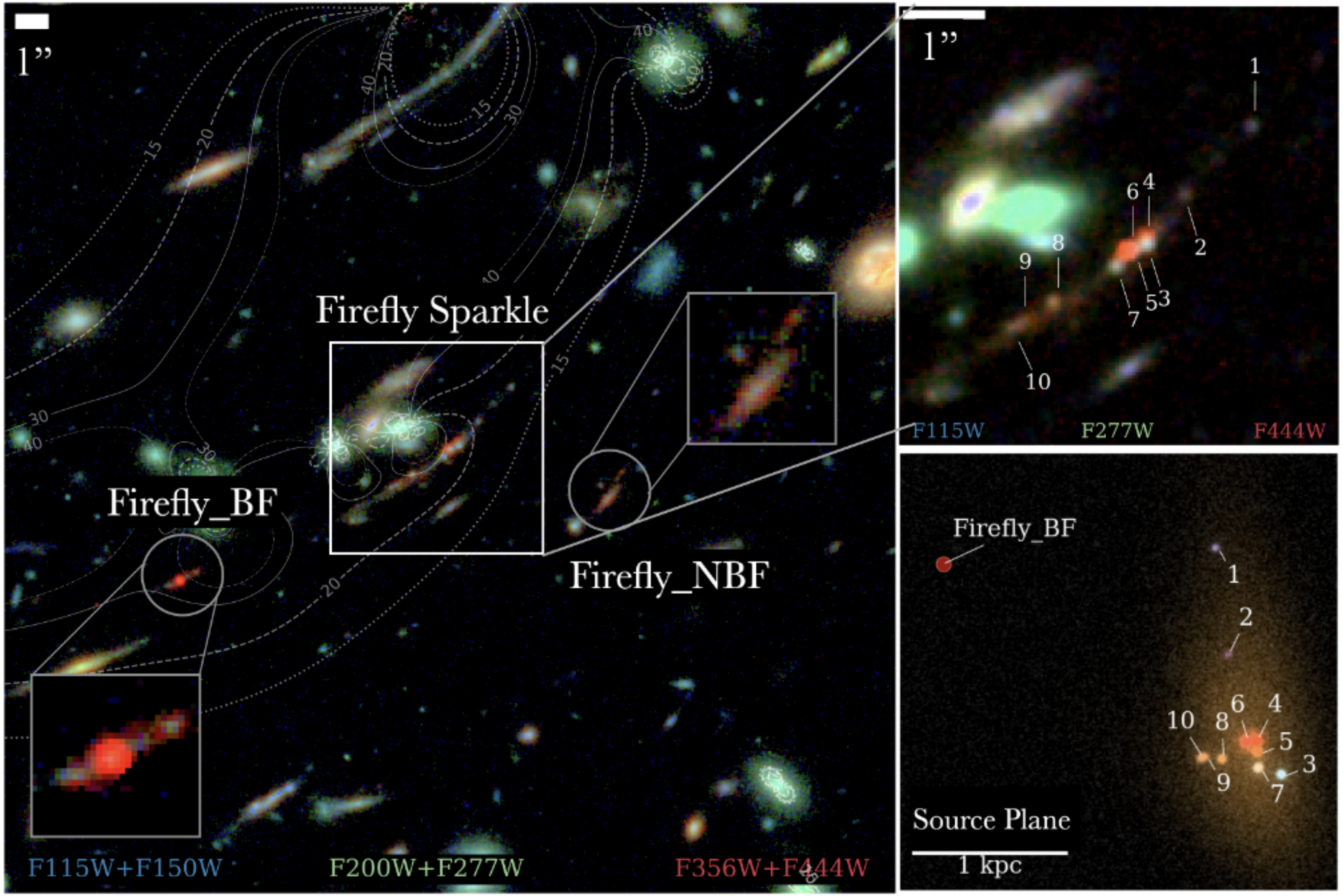
z_{spec} ~ 1.4 gal
(the 'Sparkler)

Evolved globular
cluster?

z_{form} ~ 7–11

red, quenched, old
stellar system

Mowla+'22



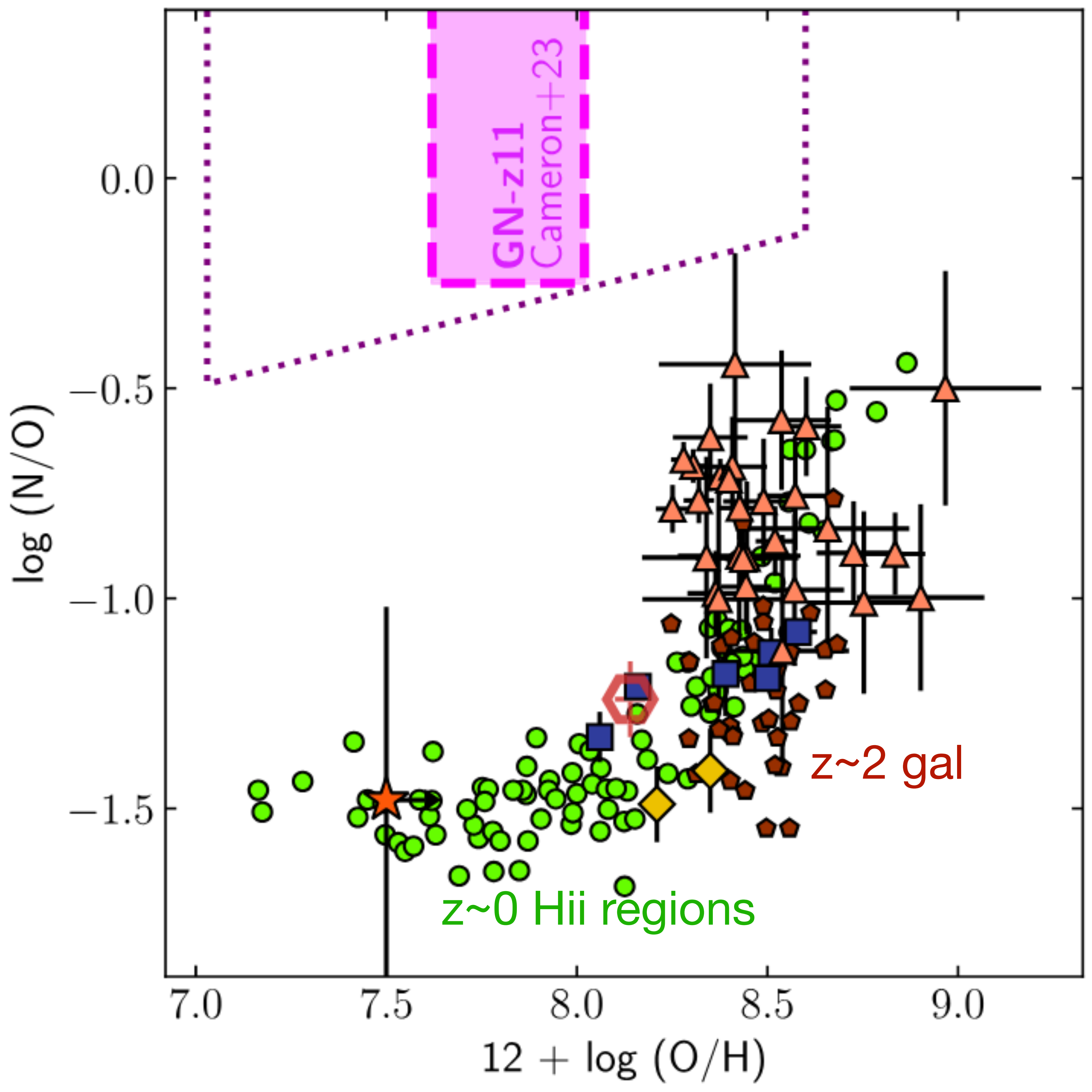
Grav. lensed gal in MACS J1423:

$z_{\rm spec} \sim 8.3$

- **[Oiii] detection**
- **10 star clusters**
- $M_\star \sim 10^5 - 10^6\, M_\odot$
- **nebular dominated spectra —> high** $T_e \sim 4 \times 10^4\, K$
- **top-heavy IMF ?**

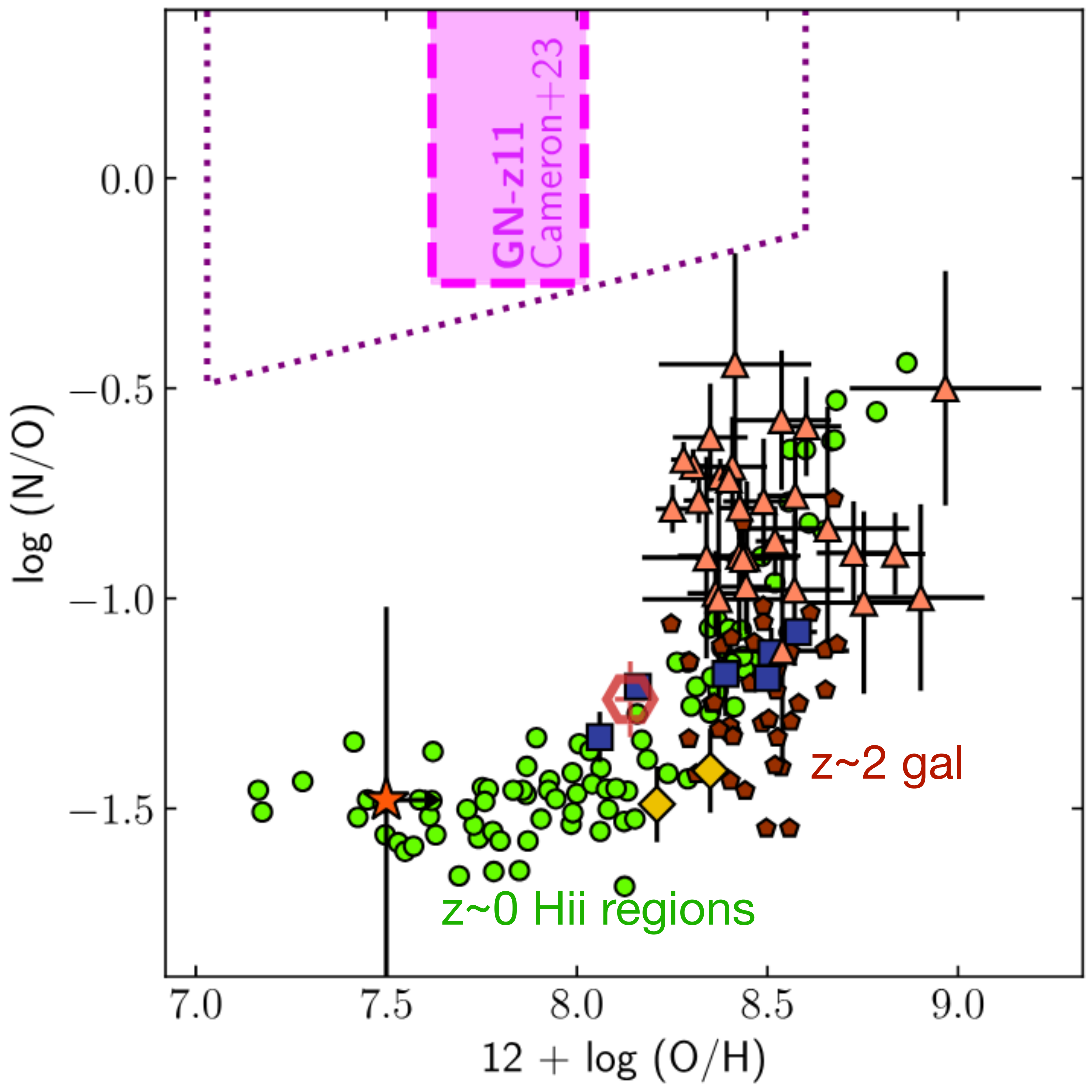
Mowla+’24

Anomalous abundance ratios — top-heavy IMF?

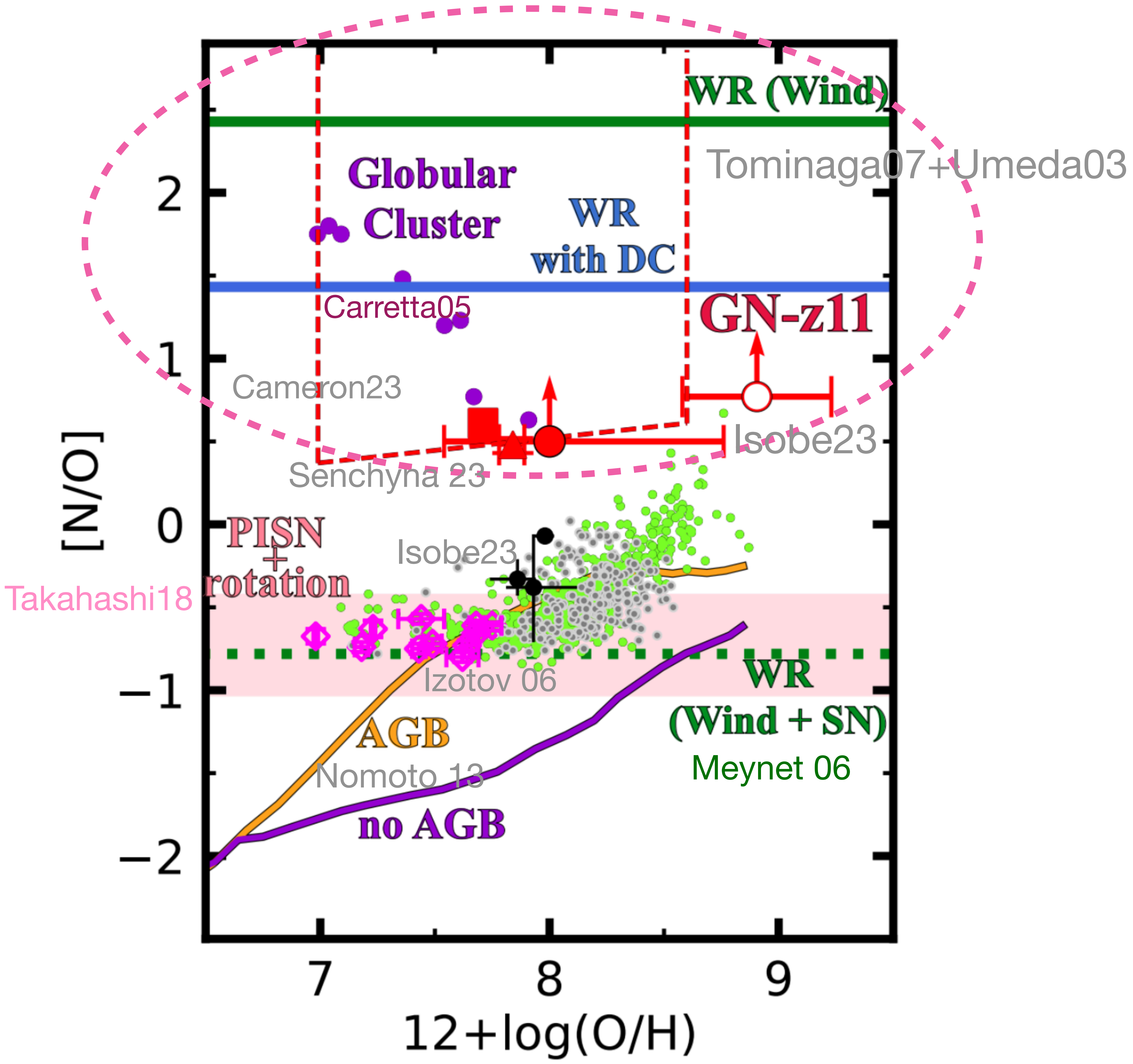


Cameron+'23a

Anomalous abundance ratios — top-heavy IMF?



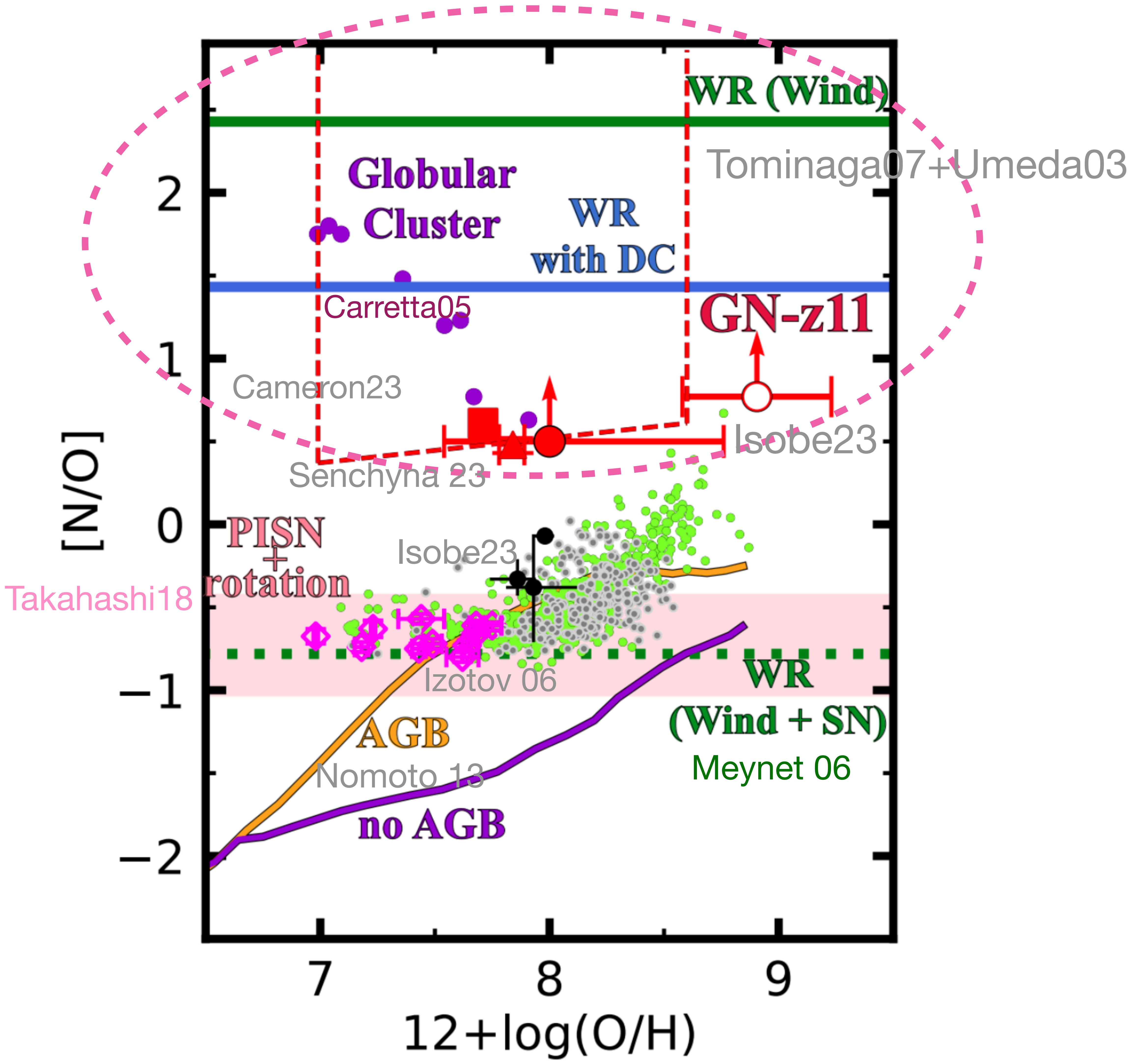
Cameron+'23a



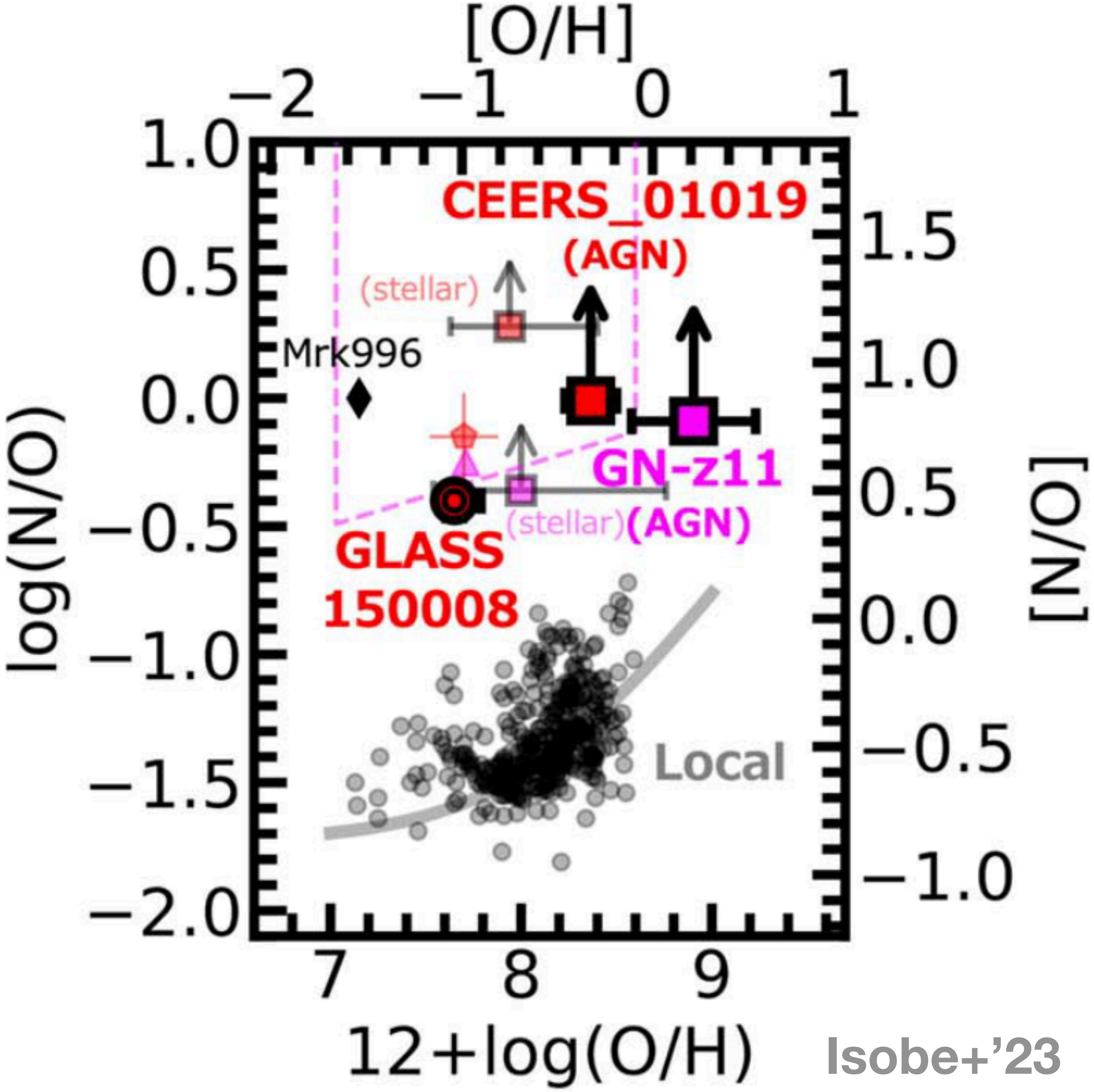
Watanabe+'23

cf. Carretta+05, Izotov+06, Piyugin+12, Berg+20, Cameron+23a, Senchyna+23, …

Anomalous abundance ratios — top-heavy IMF?



Watanabe+’23



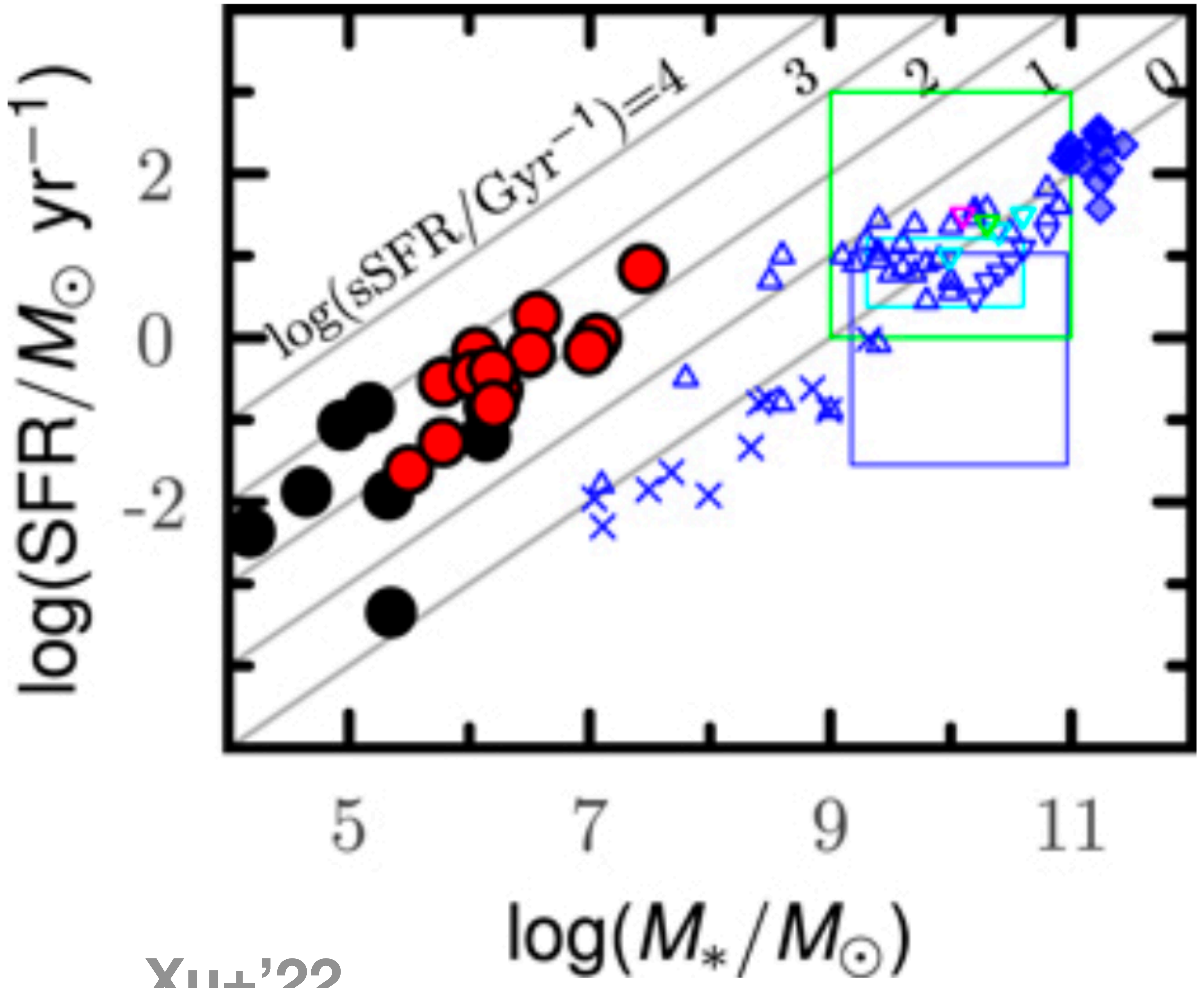
Isobe+’23

cf. Carretta+05, Izotov+06, Piyugin+12, Berg+20, Cameron+23a, Senchyna+23

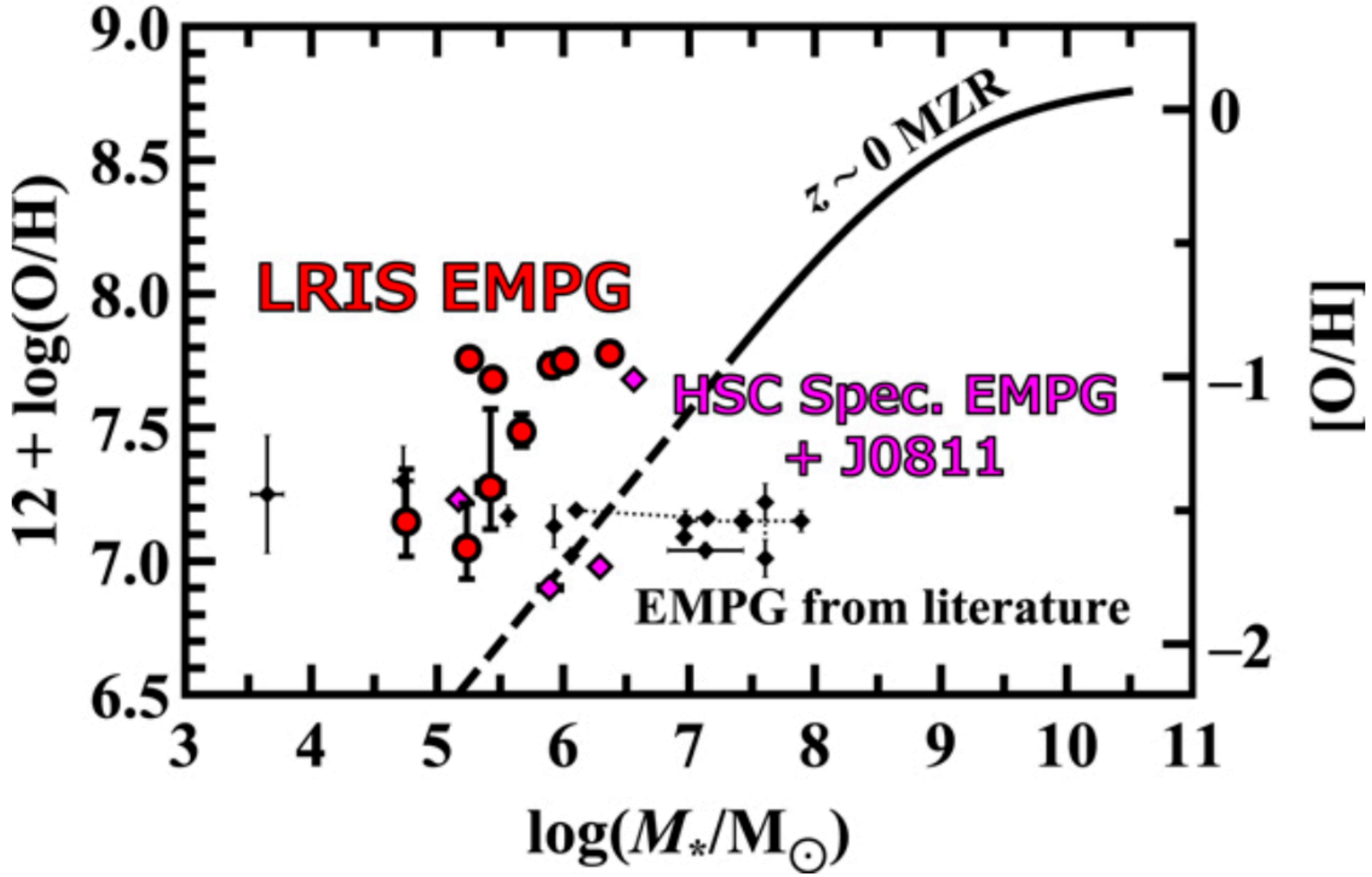
Extremely Metal-poor Galaxies (EMPGs)

as analogues of primordial gals; the **EMPRESS** project

low $M_\star$ ($< 10^7 M_\odot$), high sSFR, low-Z ($< 0.1 Z_\odot$) gals



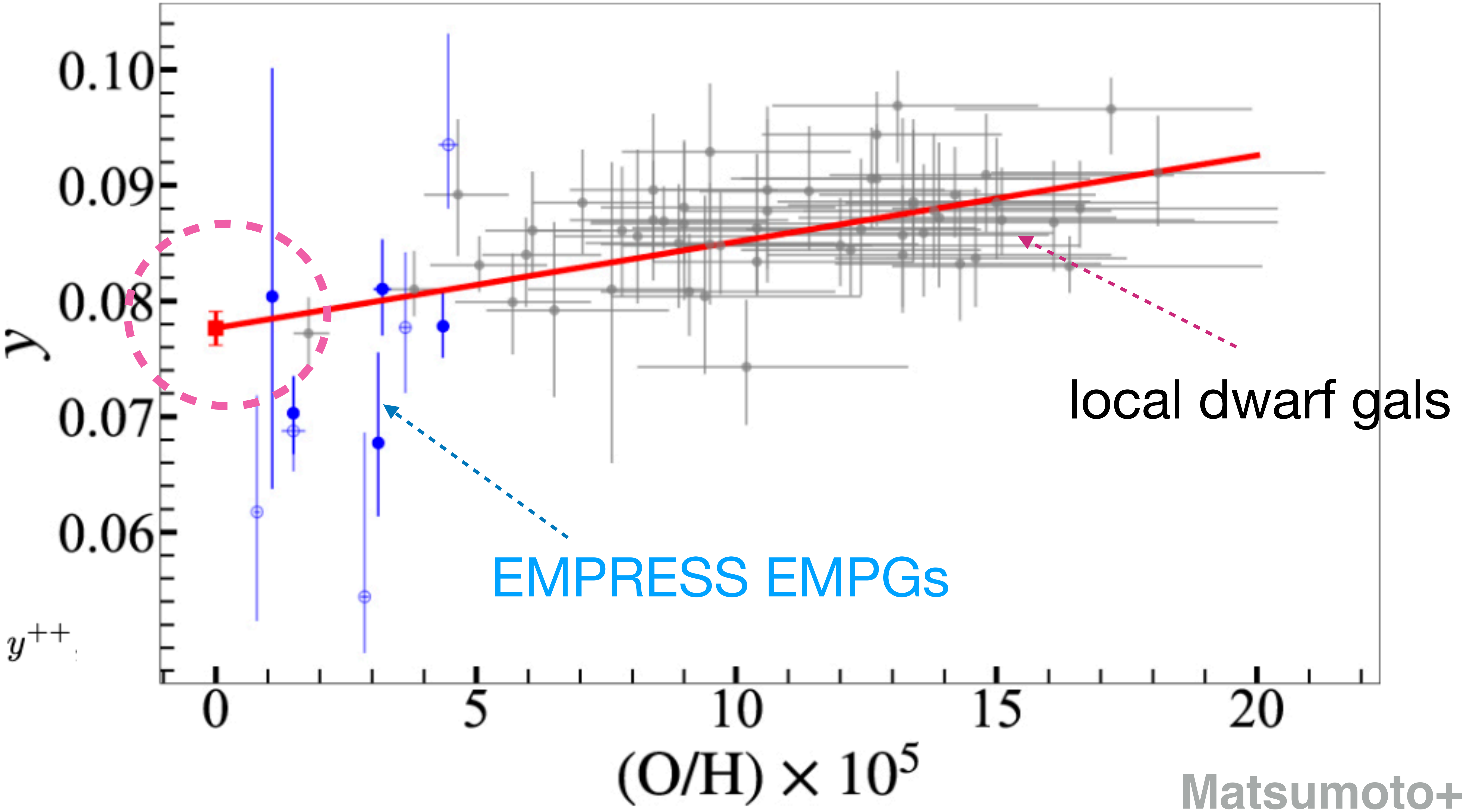
Xu+'22



Isobe+'22

Primordial He abundance from local EMPGs

$$y \equiv \frac{He}{H}$$

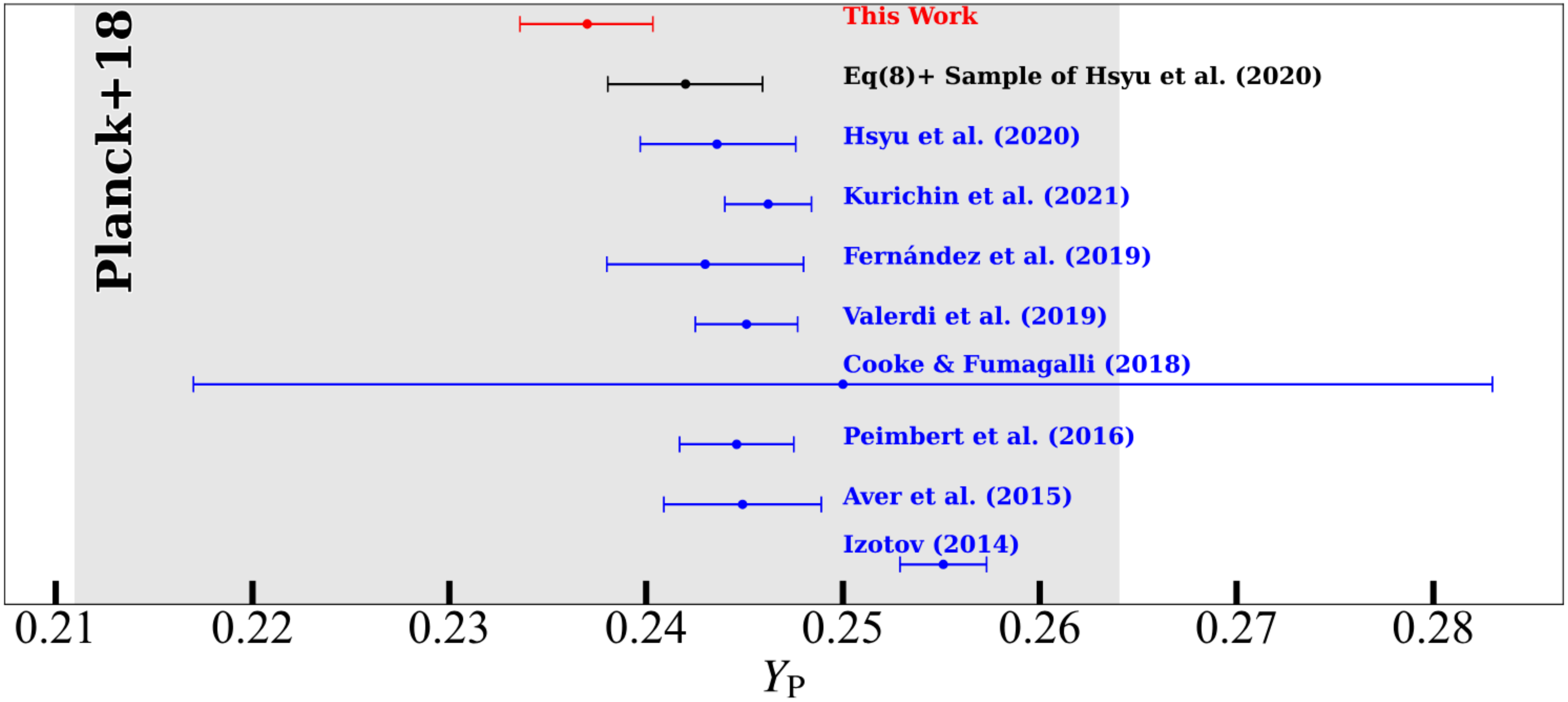


$$y = \frac{\mathrm{He}^+}{\mathrm{H}^+} + \frac{\mathrm{He}^{++}}{\mathrm{H}^+} = y^+ + y^{++},$$

Matsumoto+'23

Primordial He abundance from local EMPGs

as analogues of first galaxies…



Matsumoto+'23

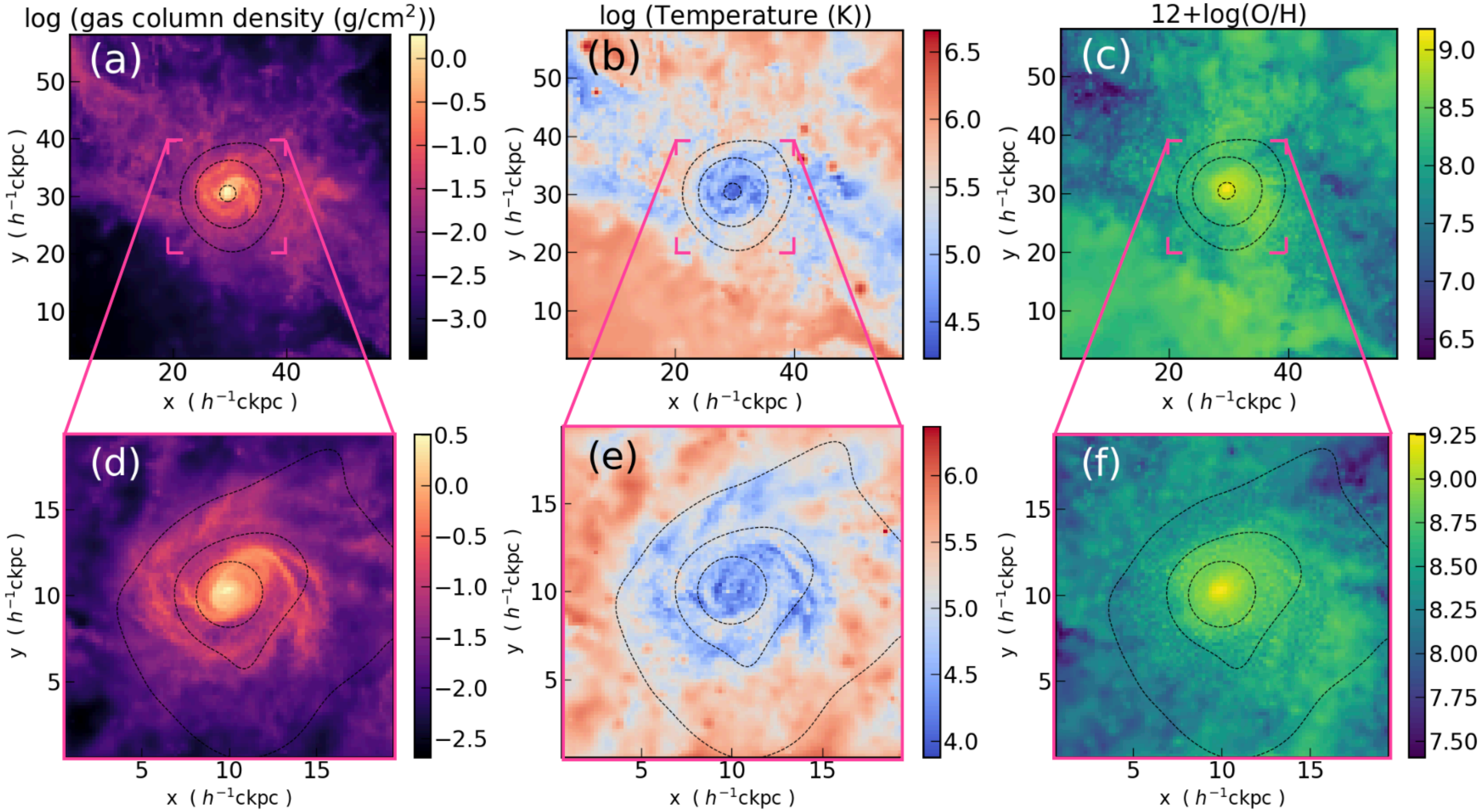
Draft version December 29, 2023
Typeset using LaTeX **twocolumn** style in AASTeX631

arxiv: 2401.06450

Probing Chemical Enrichment in Extremely Metal-Poor Galaxies and First Galaxies

Keita Fukushima,[1] Kentaro Nagamine,[1,2,3] Akinori Matsumoto,[4,5] Yuki Isobe,[4,5] Masami Ouchi,[6,4,7] Takayuki R. Saitoh,[8] and Yutaka Hirai[9,10]

zoom-in cosmo sim: z~10



$m_{DM} = 1.6 \times 10^4 h^{-1} M_\odot$ $m_{gas} = 3.2 \times 10^3 h^{-1} M_\odot$ $\epsilon_{grav,phy} \sim 20 h^{-1}\mathrm{pc}$ @ $z \sim 10$

GADGET3-Osaka code

Shimizu+19; KN+21

- SF+SN feedback
- CELib chemical ev. lib. (12 species)
- GRACKLE cooling
- updated SPH
- HM12 UVB, etc.

Tested in the **AGORA** project

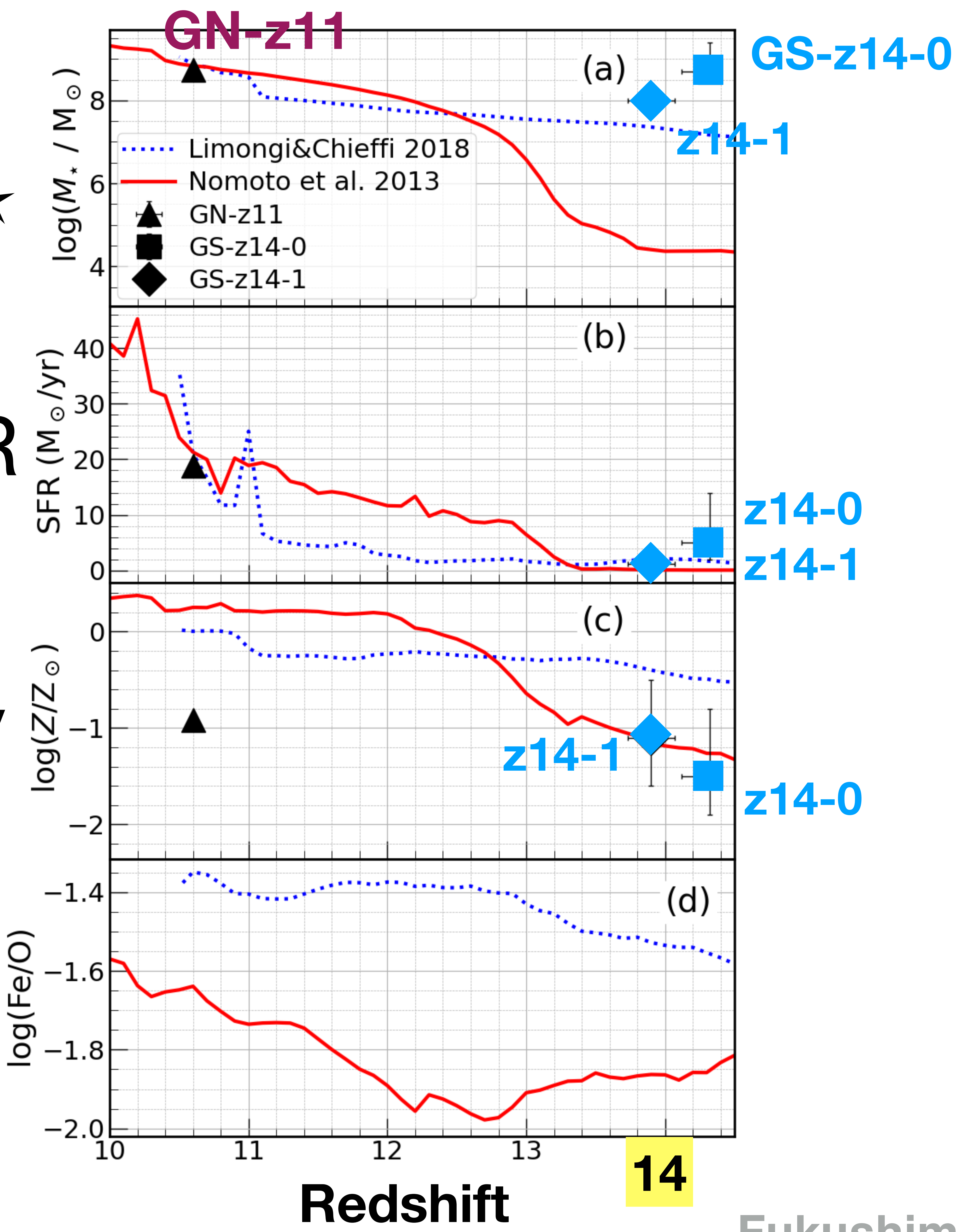
w/ Nomoto+13 yields

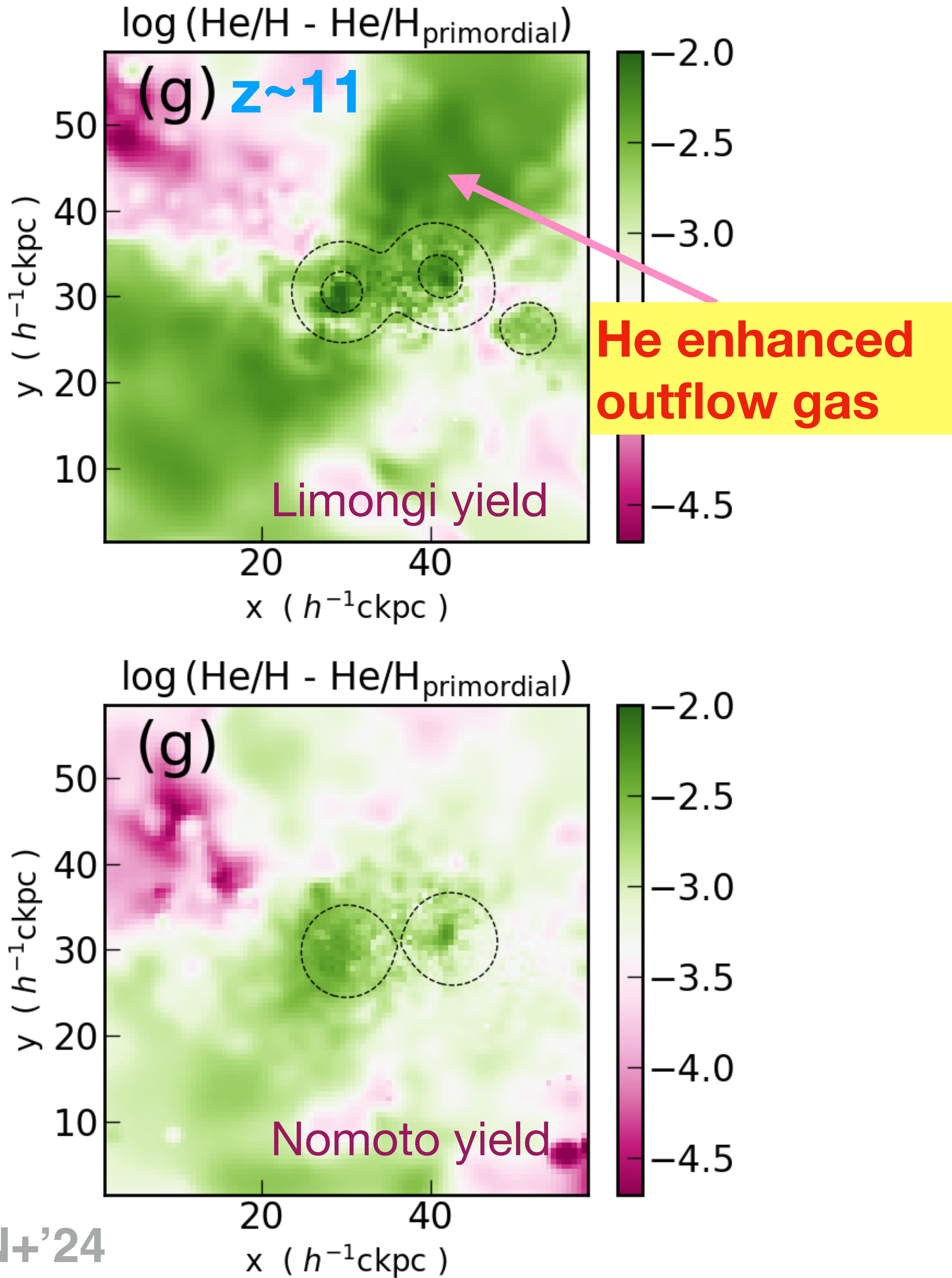
$M_\star$

SFR

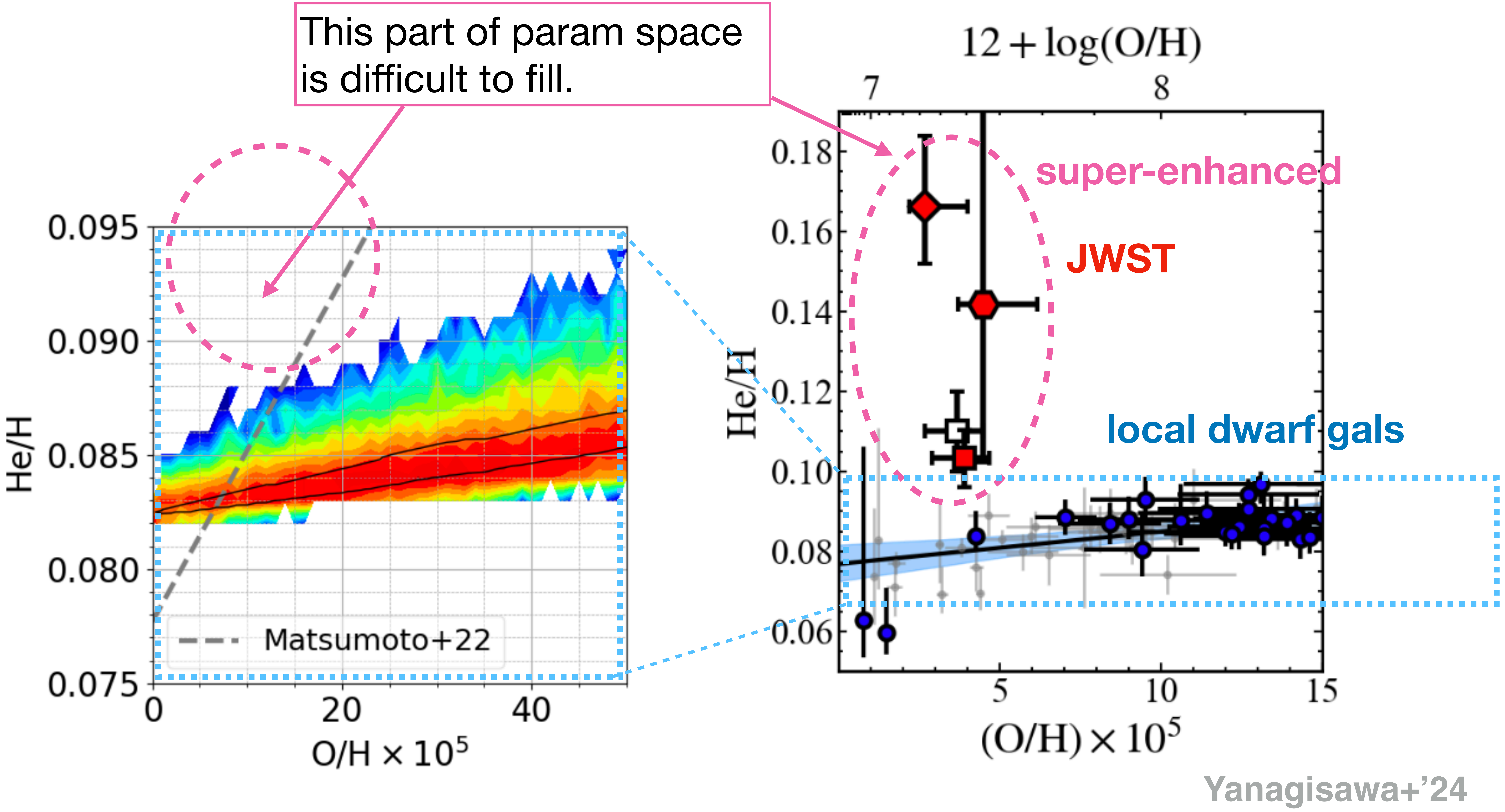
Metallicity

Fe/O





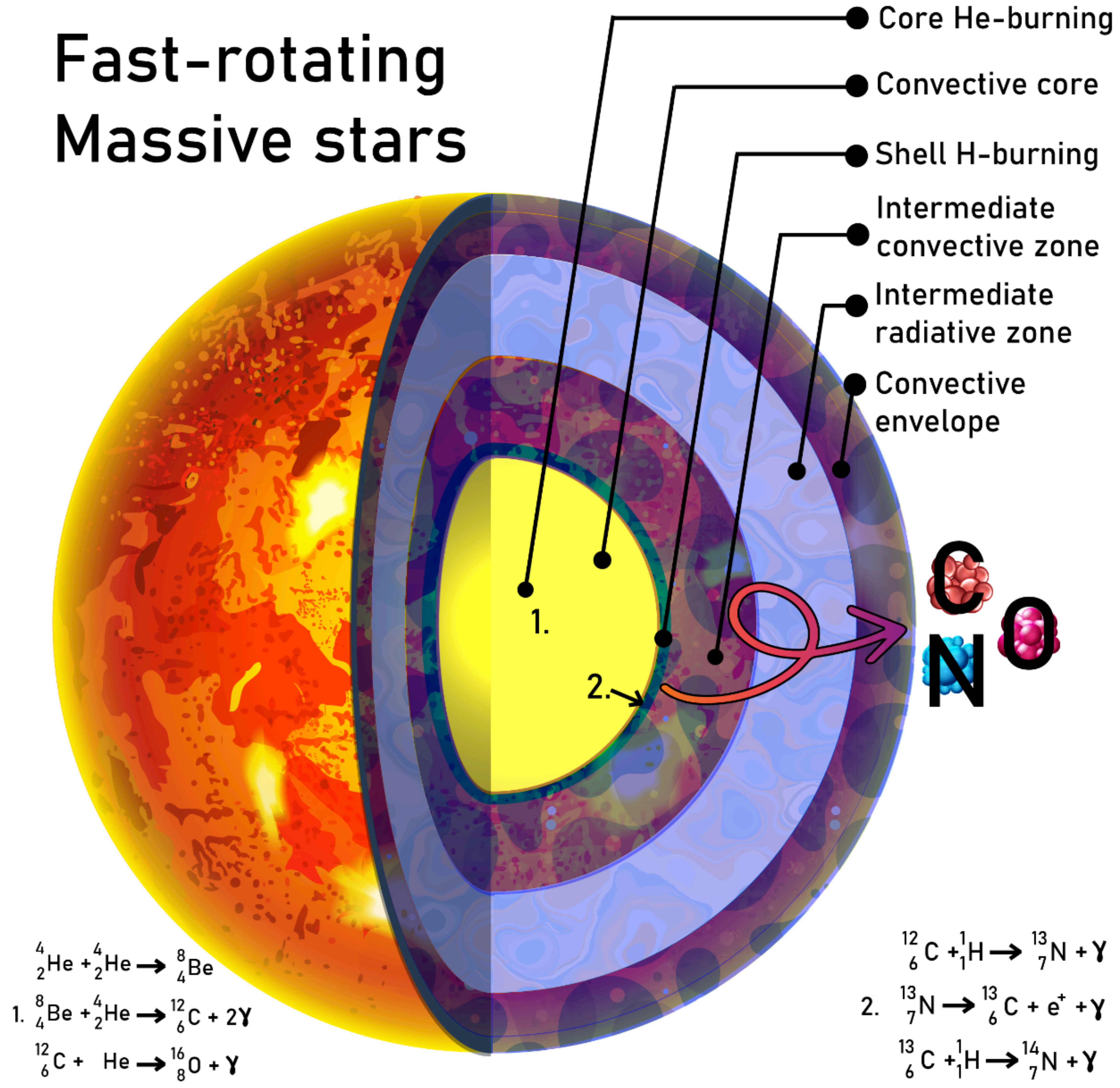
Fukushima, KN+'24


This part of param space
is difficult to fill.
0.095
0.090
0.085
0.080
0.075
He/H
0
20
40
O/H × 10^5
Matsumoto+22
12 + log(O/H)
7
8
0.18
0.16
0.14
0.12
0.10
0.08
0.06
He/H
5
10
15
(O/H) × 10^5
super-enhanced
JWST
local dwarf gals
Yanagisawa+'24

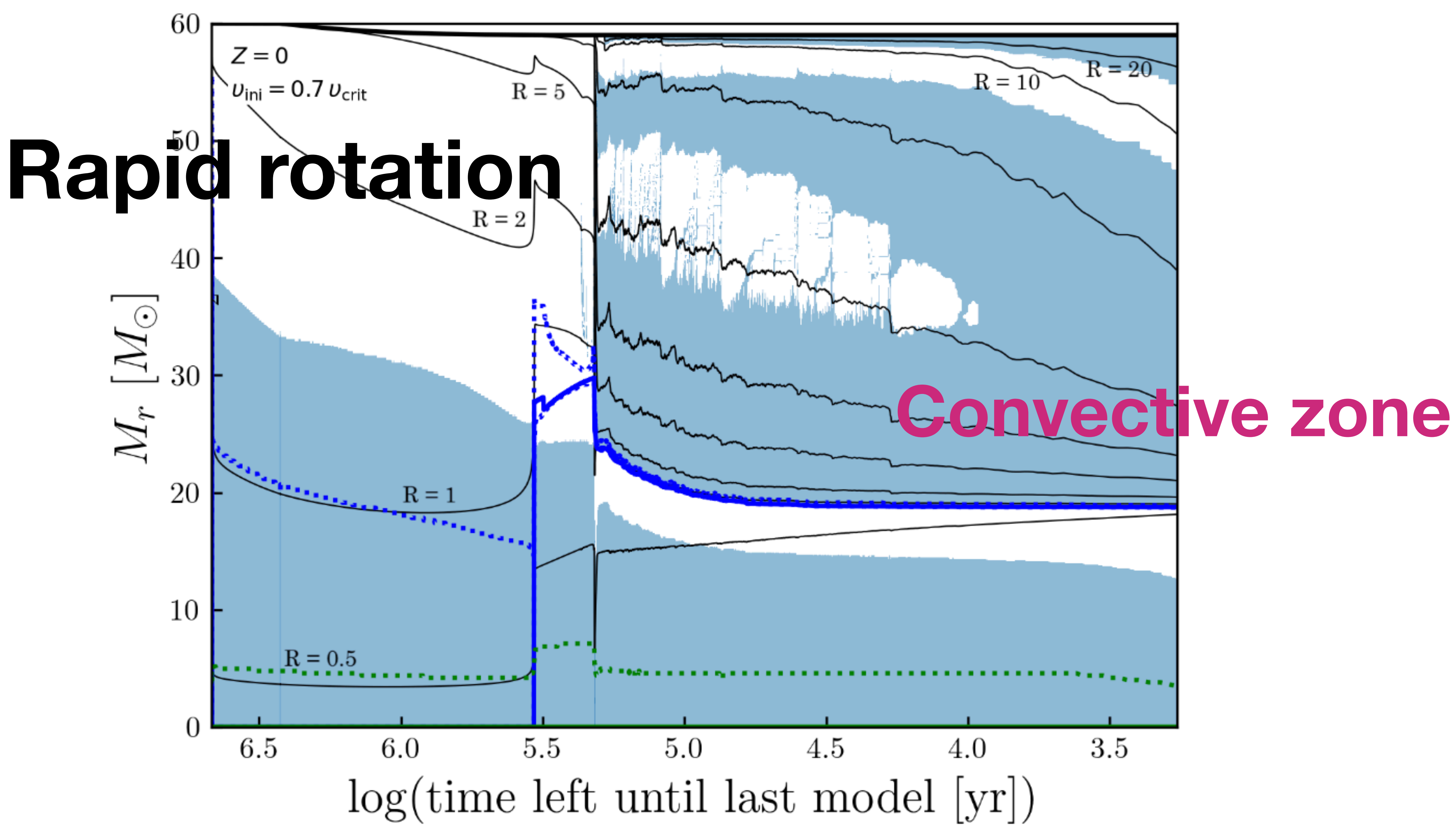
12 + log(O/H)
7
8
0.18
0.16
0.14
0.12
0.10
0.08
0.06
He/H
JWST
local
5
10
(O/H) × 10^5
Obs : Isobe+23, Topping+24,
Yanagisawa+24, Ji+24
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
[N/O]
super-enhanced
High-z gal
low-z dwarf
Limongi
Nomoto
Limongi&Chieffi 2018
Nomoto et al. 2013
High-z gal.
Dwarf gal.
Izotov+06
7.5
8.0
8.5
9.0
(O/H)+12
[C/O]
−1
0
1
2
1
0
−1
−2
log(N/O)
SMS
TDE
WR
−2
−1
0
log(C/O)

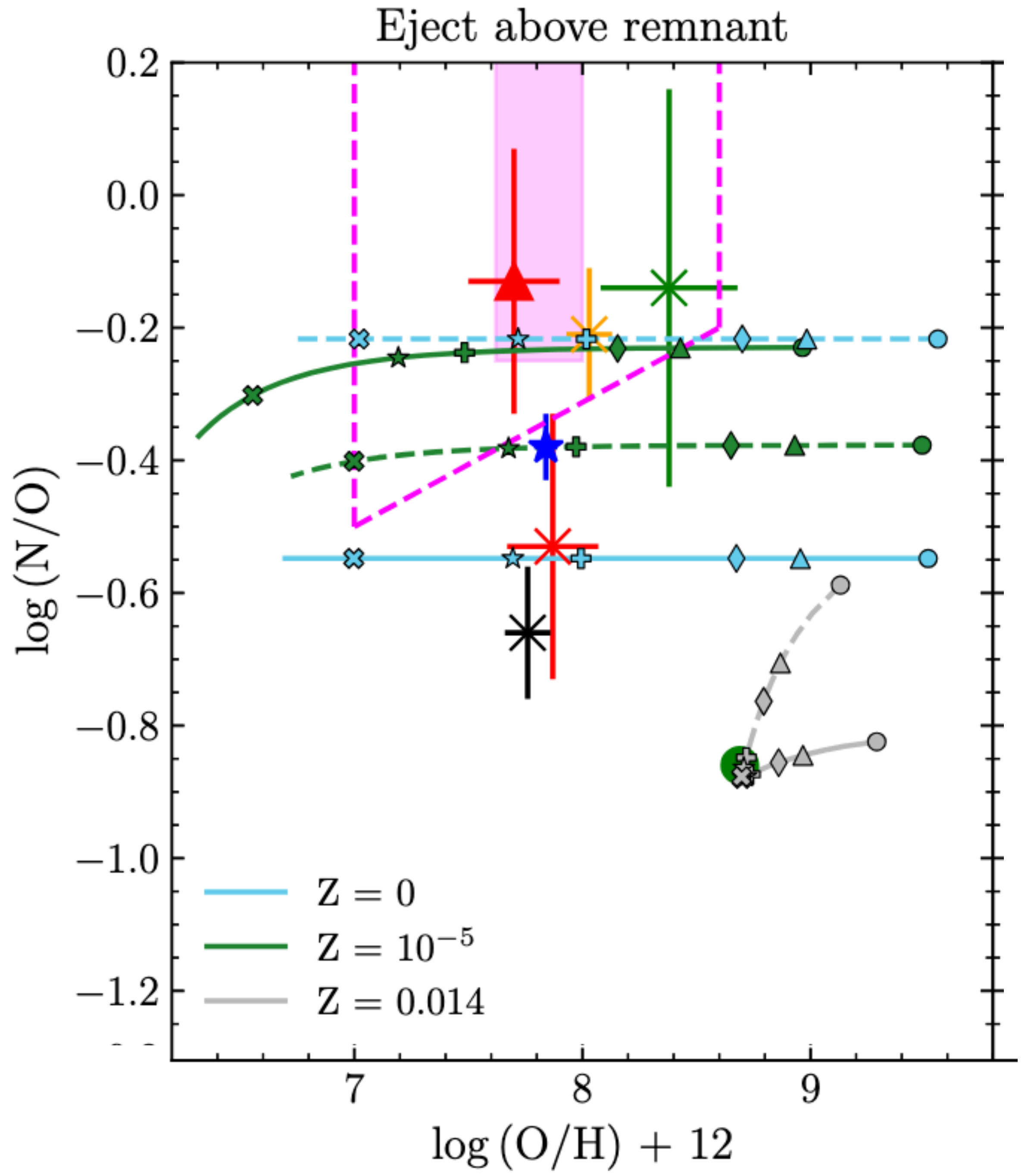
Isobe+'23

Fast-rotating Massive stars



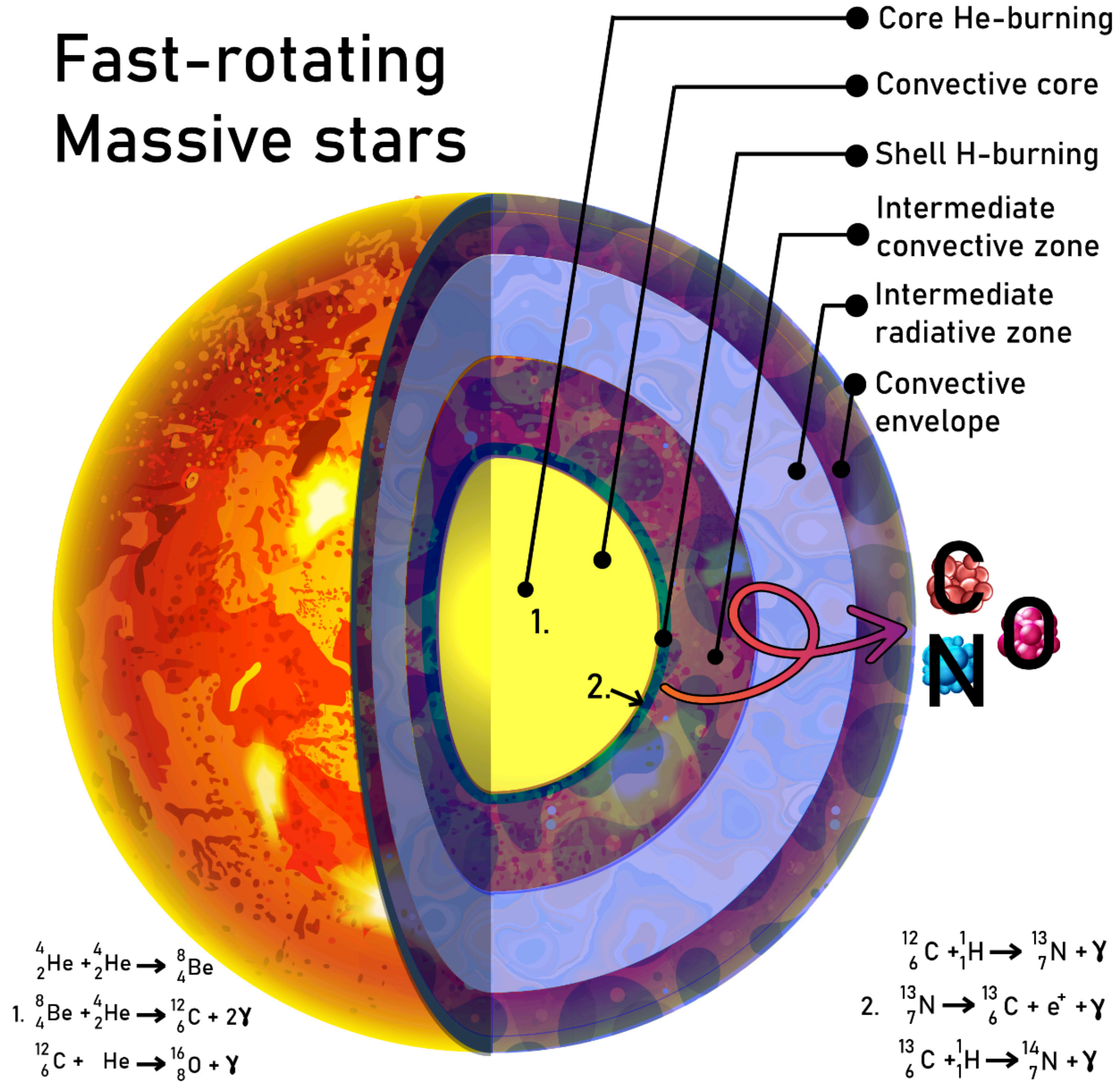
$60 M_\odot$ model



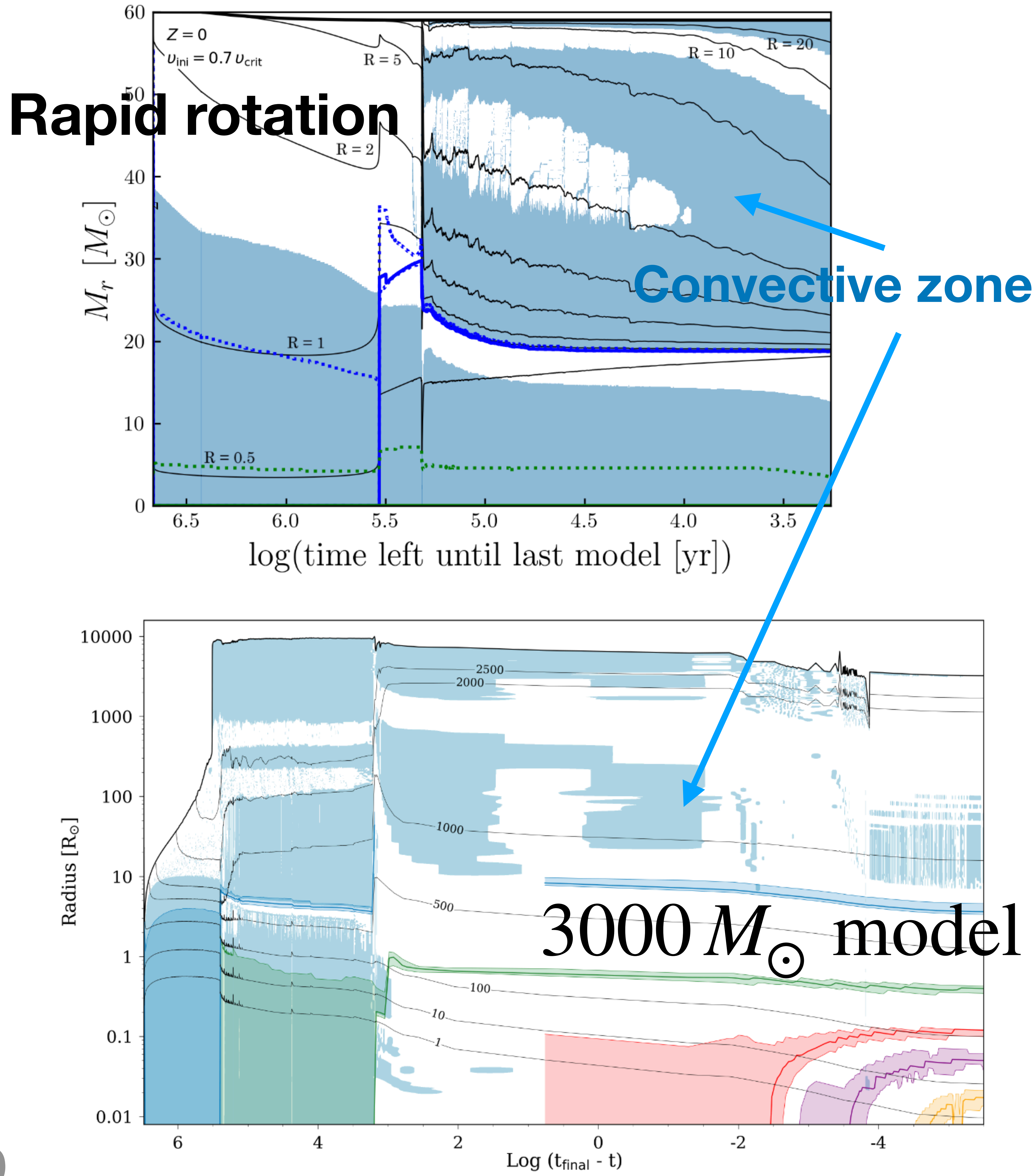


Nandal+23, 24 cf. Ohkubo+'09

Fast-rotating Massive stars



$60M_{\odot}$ model

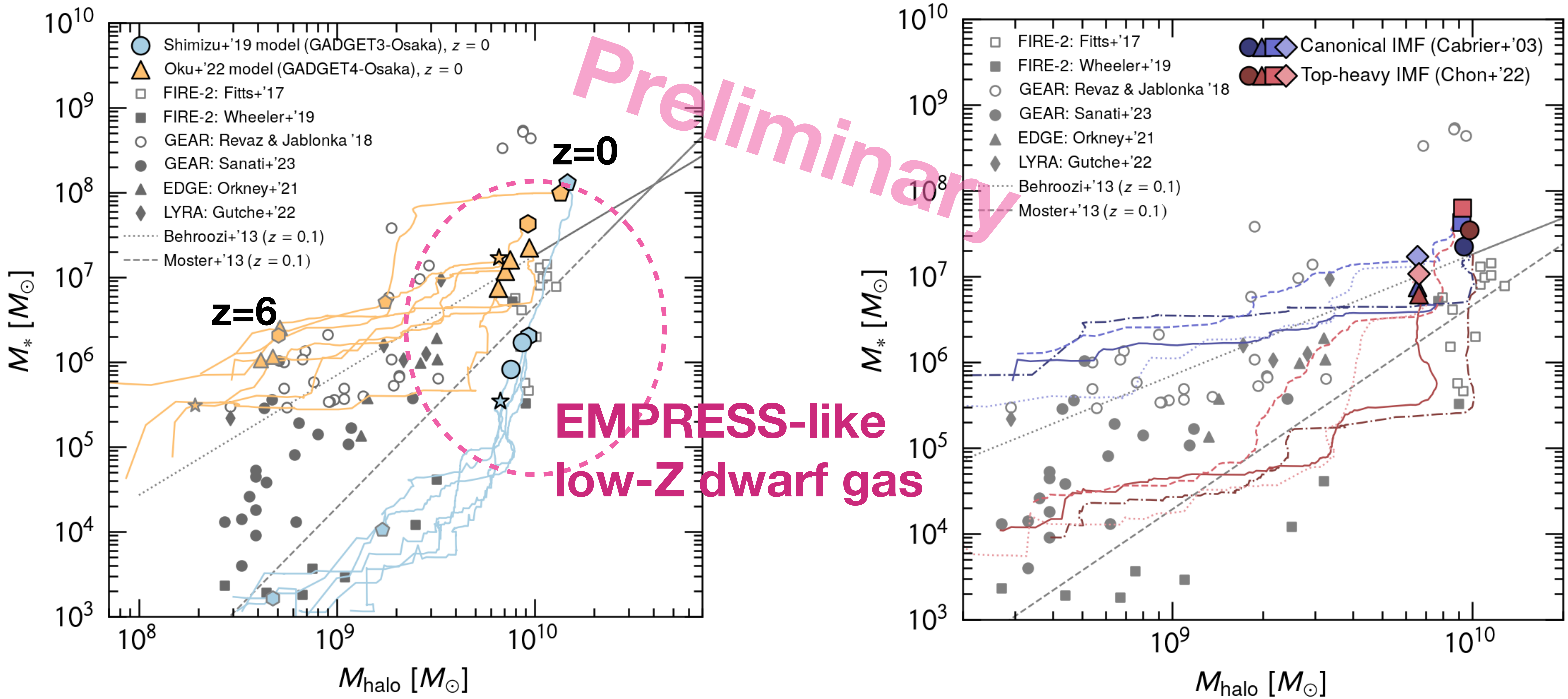


Nandal+23, 24 cf. Ohkubo+'09

GADGET4-Osaka Cosmo. Zoom-in Hydro Sims.

— dwarf gals in isolated regions

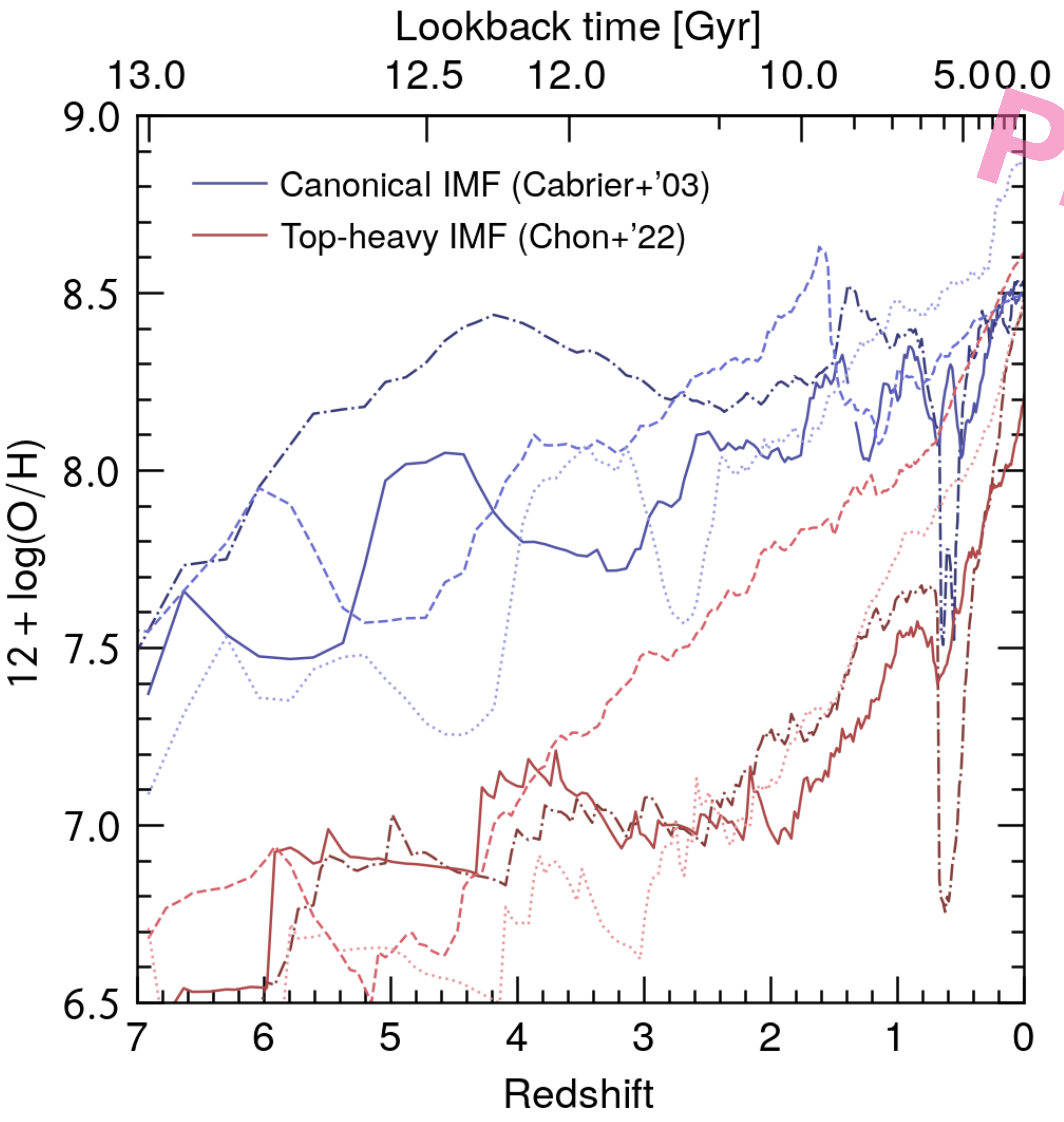
Tomaru+'24, in prep.

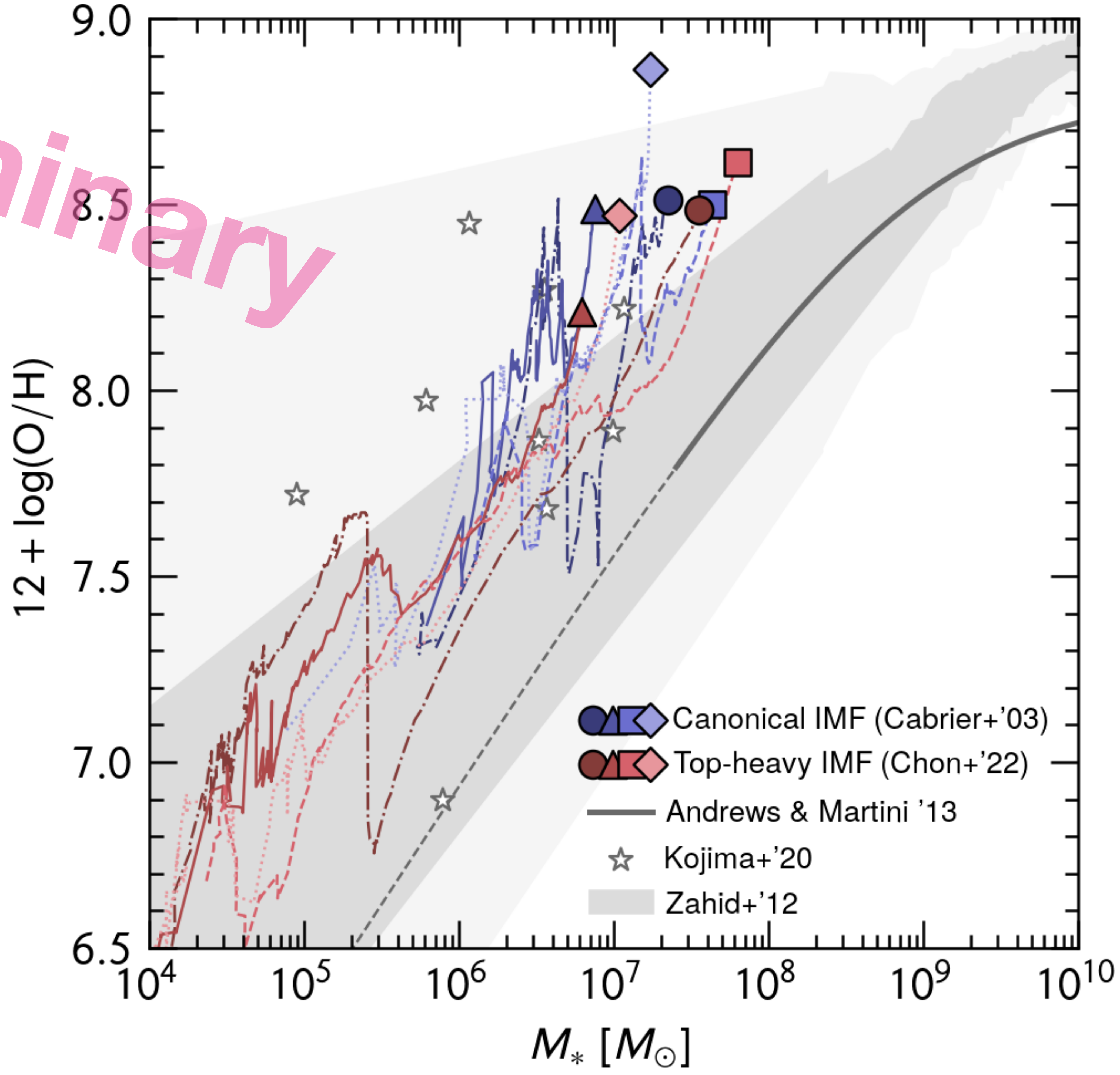


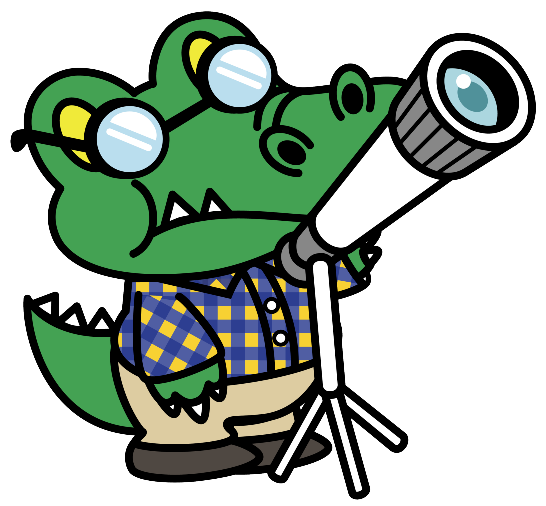
GADGET4-Osaka Cosmo. Zoom-in Hydro Sims.

— dwarf gals in isolated regions

Tomaru+'24, in prep.







CROCODILE simulation

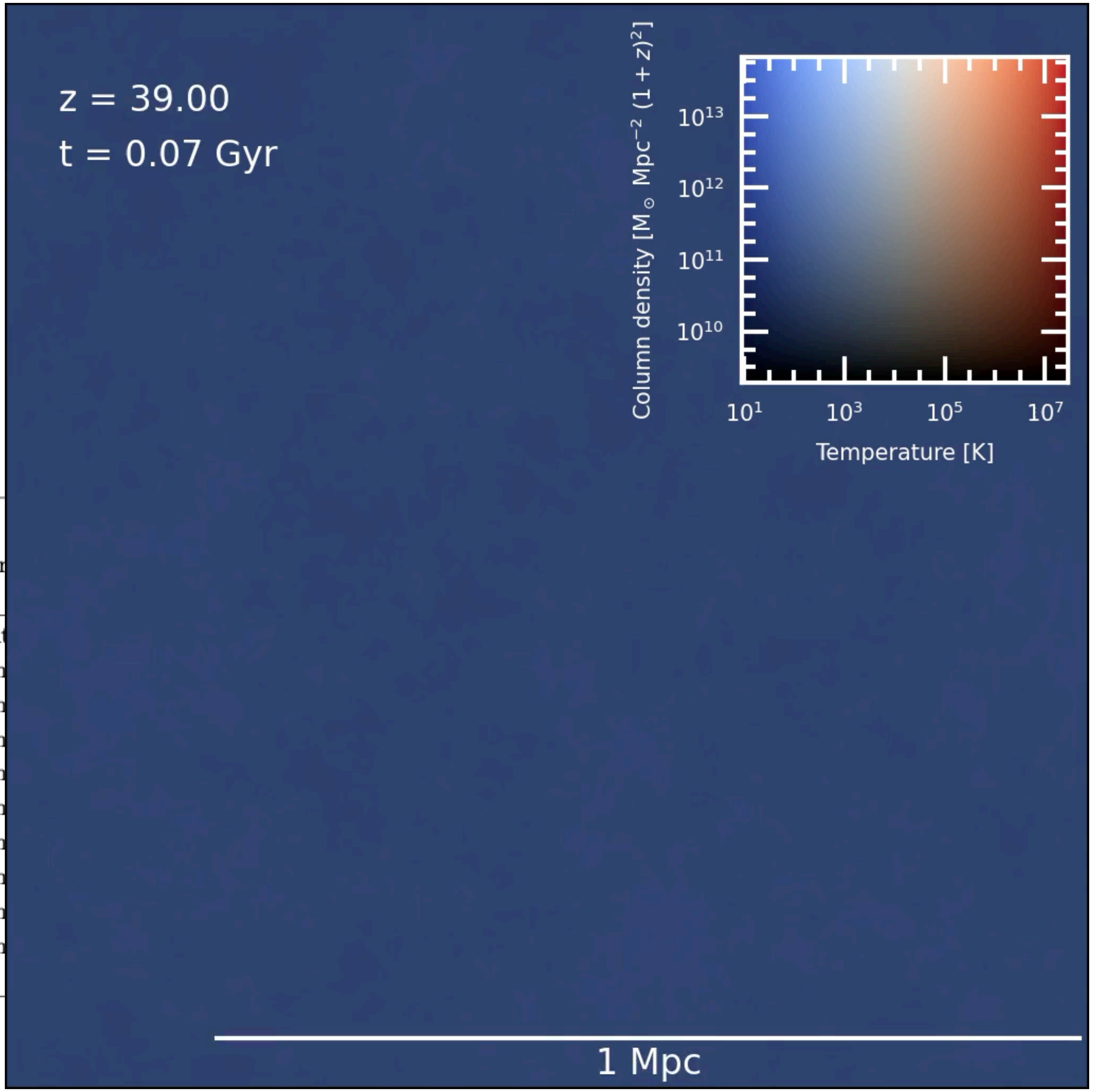
Oku & KN '24

arXiv:2401.06324

- **Cosmological SPH GADGET4-Osaka code**
- Star formation, SN / AGN feedback, HM12/FG09 UVB
- **Top-heavy IMF at low-metallicities** Oku+'22 / TIGRESS models
- 13 species chemistry & cooling module — CELib (Saitoh '17)
- variety of feedback model combinations in 25, 50 Mpc/h

Name	$L_{\rm box}$	$N_{\rm particle}$	$C_{\rm visc}$	$m_{\rm seed}$	Feedback Type: SN Mechanical	SN GalWind	AGN	Stellar IMF	HN fraction
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Fiducial	50	2×512^3	200π	1×10^5	✓	✓	✓	variable[a]	Z-dependent
NoSNGalWind	50	2×512^3	200π	1×10^5	✓		✓	variable	Z-dependen
AGNonly	50	2×512^3	200π	1×10^5			✓	variable	Z-dependen
SNonly	50	2×512^3	200π	1×10^5	✓	✓		variable	Z-dependen
NoFB	50	2×512^3	200π	1×10^5				variable	Z-dependen
LowCvisc	50	2×512^3	2π	1×10^5	✓	✓	✓	variable	Z-dependen
LowCviscLowMseed	50	2×512^3	2π	1×10^4	✓	✓	✓	variable	Z-dependen
L25N512	25	2×512^3	200π	1×10^5	✓	✓	✓	variable	Z-dependen
L25N256	25	2×256^3	200π	1×10^5	✓	✓	✓	variable	Z-dependen
L25N128	25	2×128^3	200π	1×10^5	✓	✓	✓	variable	Z-dependen
L25N256NoZdepSN	25	2×256^3	200π	1×10^5	✓	✓	✓	Chabrier	0.01

Also contributing to ***CAMELS*** project



CROCODILE

Cosmological hyd**RO**dynamical simulation of stru**C**ture f**O**rmation and fee**D**back phys**I**cs in ga**L**axy **E**volution

Dr. Wani
ワニ博士

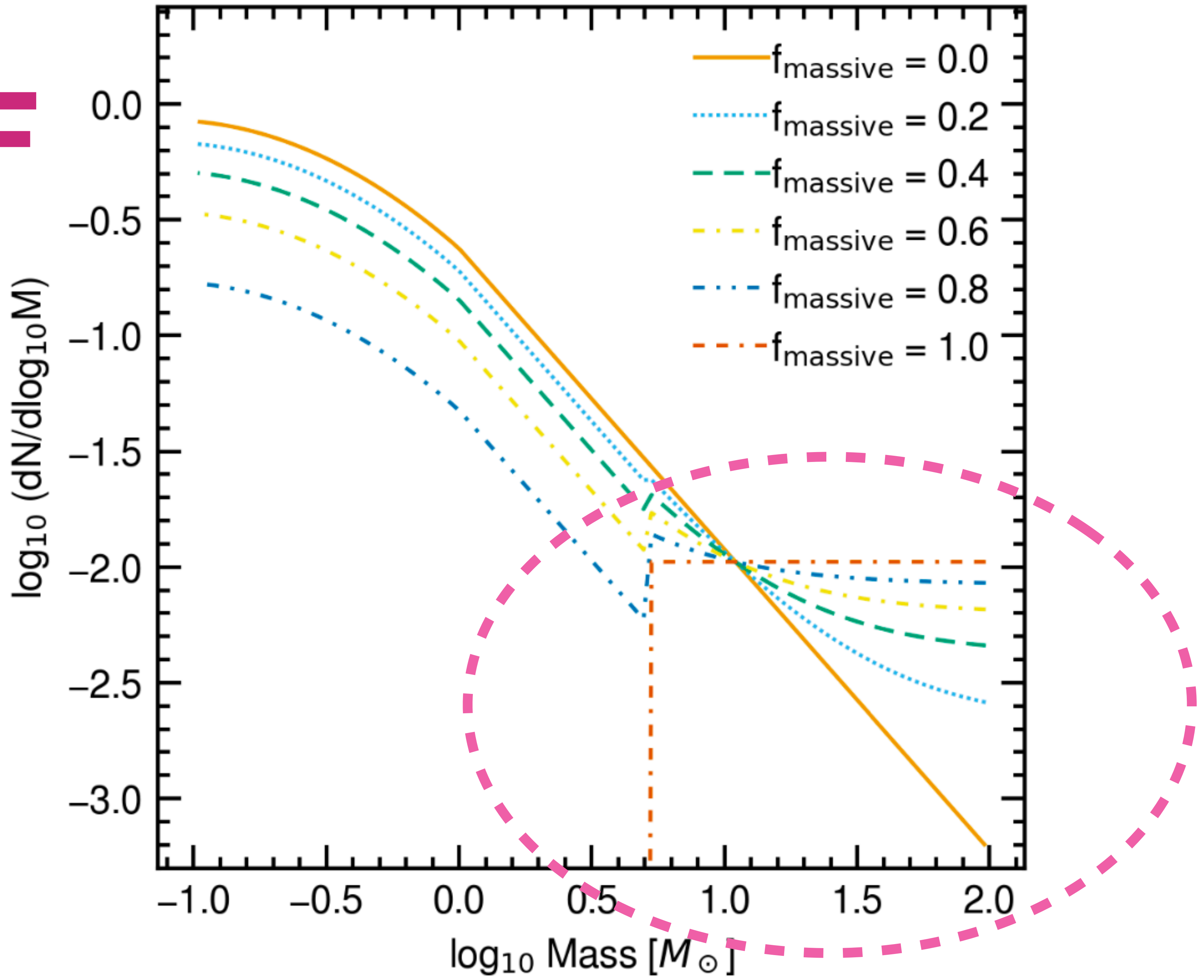
— official mascot of OU and Toyonaka city


理学部校舎建設現場での発掘風景

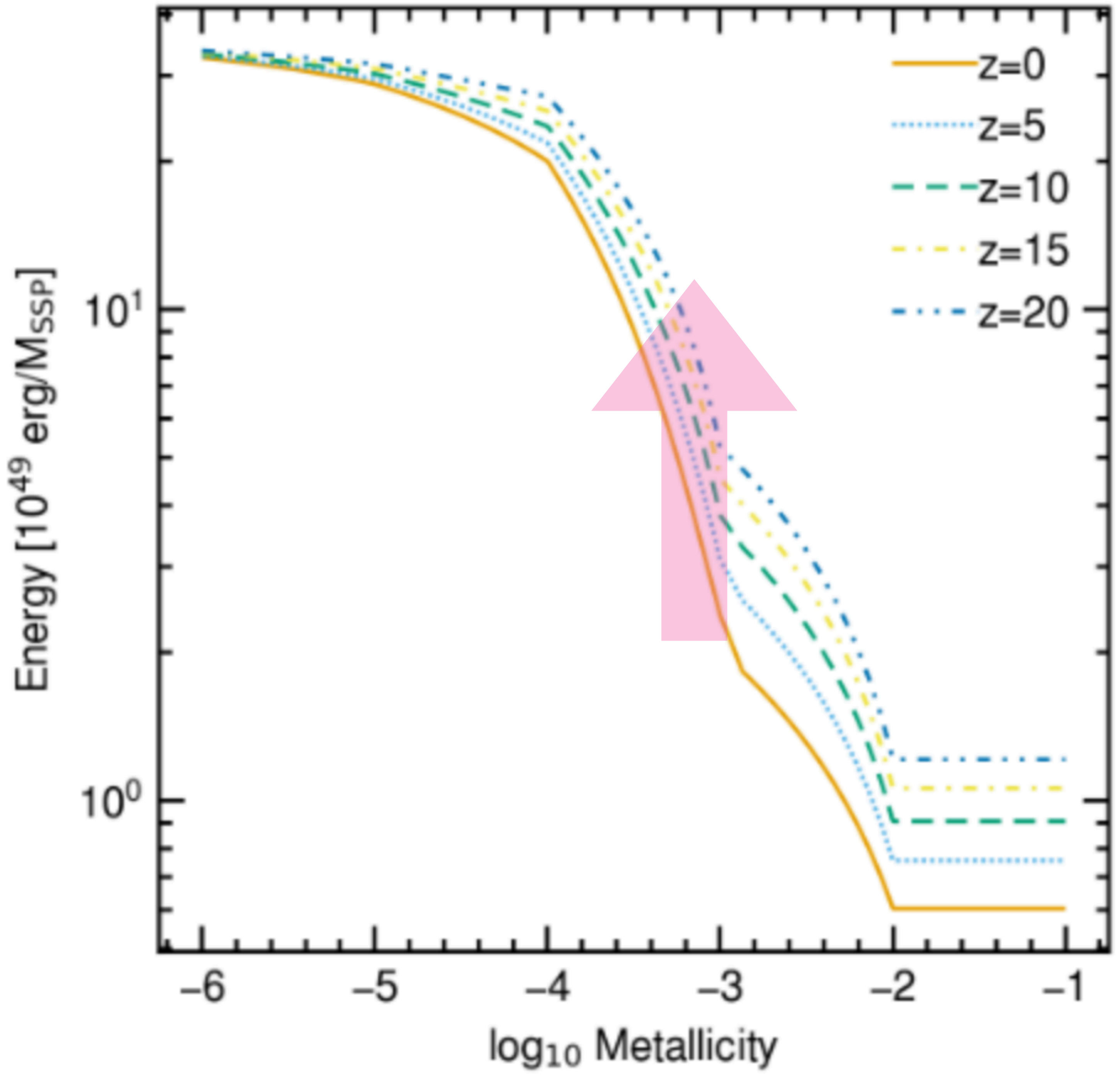

発掘されたマチカネワニの頭骨（上方から）


Machikanensis

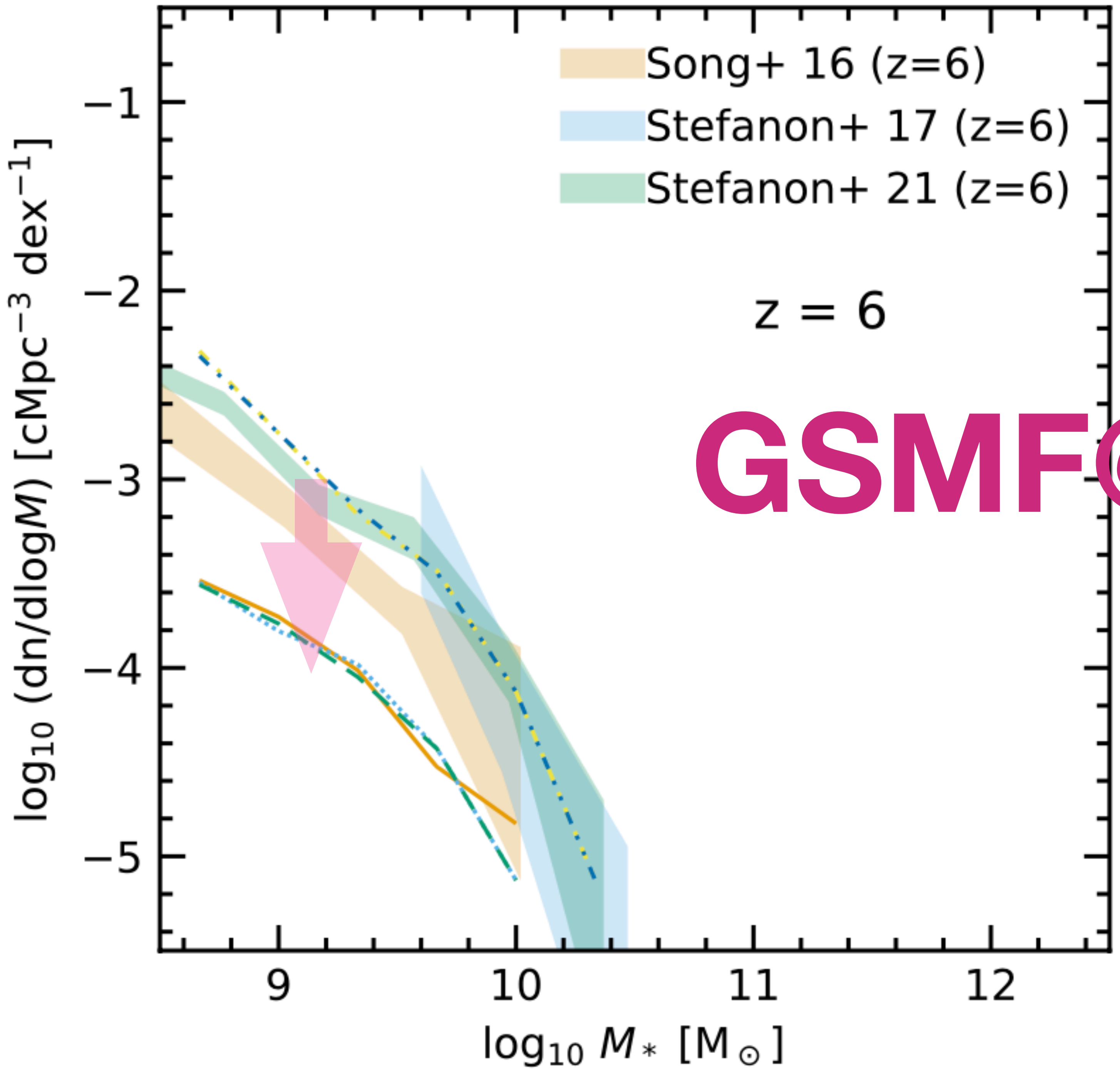
IMF



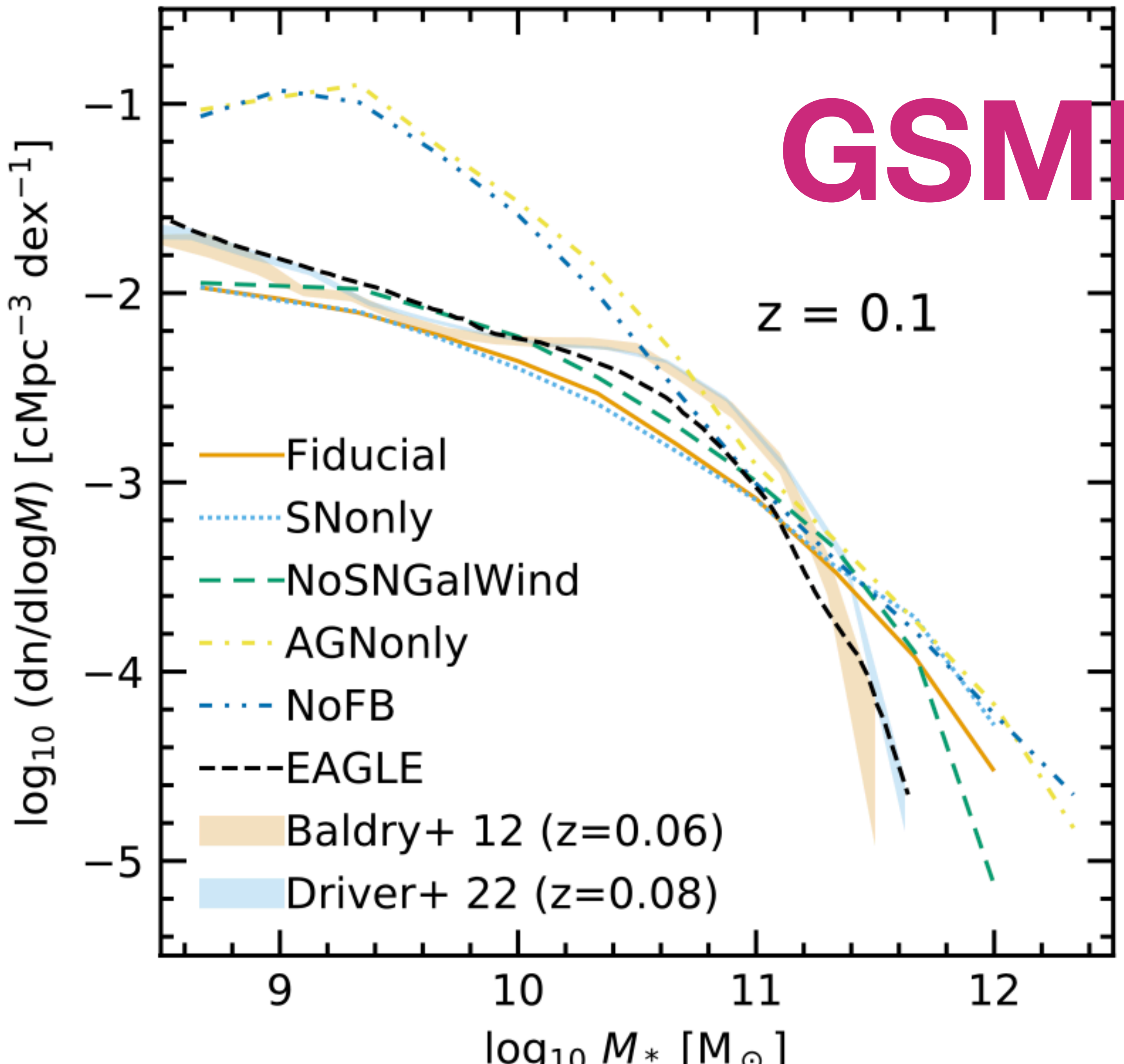
Top-heavy IMF model (Chon+'22)



specific E_{SN} injection



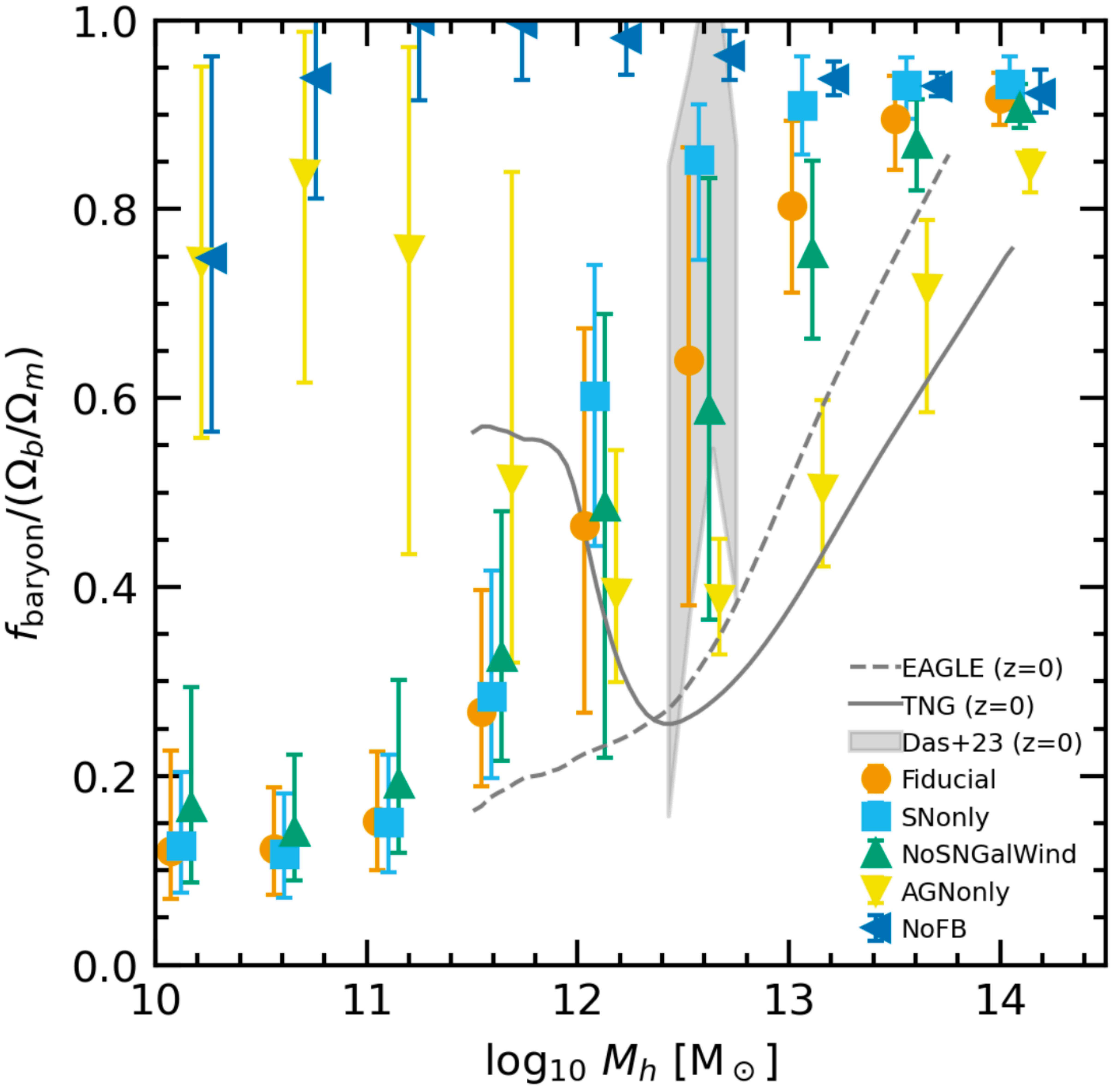
GSMF@z=6



GSMF@z=0.1

Oku & KN '24

Baryon fraction



cf. Davies+'20

Oku+ '24, in prep.

https://sites.google.com/view/crocodilesimulation/home

List of CROCODILE simulations

							Feedback Type				
Name	**L_{box} [h^{-1} Mpc]**	**$N_{particles}$**	**m_{DM} [h^{-1} M_{sun}]**	**m_{gas} [h^{-1} M_{sun}]**	**C_{visc}**	**m_{seed} [h^{-1} M_{sun}]**	**SN Mechanical**	**SN GalWind**	**AGN**	**Stellar IMF**	**HN fraction**
L200N1024_Fiducial	200	2×1024^3	5.39×10^8	1.01×10^8	200π	1×10^5	✔	✔	✔	variable[1]	Z-dependent[2]
L100N1024_Fiducial	100	2×1024^3	6.74×10^7	1.26×10^7	200π	1×10^5	✔	✔	✔	variable	Z-dependent
L100N1024_NoBH	100	2×1024^3	6.74×10^7	1.26×10^7	-	-	✔	✔		variable	Z-dependent
L50N512_Fiducial	50	2×512^3	6.74×10^7	1.26×10^7	200π	1×10^5	✔	✔	✔	variable	Z-dependent
L50N512_NoSNGalWind	50	2×512^3	6.74×10^7	1.26×10^7	200π	1×10^5	✔		✔	variable	Z-dependent
L50N512_AGNonly	50	2×512^3	6.74×10^7	1.26×10^7	200π	1×10^5			✔	variable	Z-dependent
L50N512_SNonly	50	2×512^3	6.74×10^7	1.26×10^7	200π	1×10^5	✔	✔		variable	Z-dependent
L50N512_NoZdepSN	50	2×512^3	6.74×10^7	1.26×10^7	200π	1×10^5	✔	✔	✔	Chabrier	0.01
L50N512_NoBH	50	2×512^3	6.74×10^7	1.26×10^7	-	-	✔	✔		variable	Z-dependent
L50N512_NoFB	50	2×512^3	6.74×10^7	1.26×10^7	200π	1×10^5				variable	Z-dependent
L50N512_NoFBNoBH	50	2×512^3	6.74×10^7	1.26×10^7	-	-				variable	Z-dependent
L50N512_LowCvisc	50	2×512^3	6.74×10^7	1.26×10^7	2π	1×10^5	✔	✔	✔	variable	Z-dependent
L50N512_LowCviscLowMseed	50	2×512^3	6.74×10^7	1.26×10^7	2π	1×10^4	✔	✔	✔	variable	Z-dependent
L25N512_Fiducial	25	2×512^3	8.43×10^6	1.58×10^6	200π	1×10^5	✔	✔	✔	variable	Z-dependent
L25N256_Fiducial	25	2×256^3	6.74×10^7	1.26×10^7	200π	1×10^5	✔	✔	✔	variable	Z-dependent
L25N128_Fiducial	25	2×128^3	5.39×10^8	1.01×10^8	200π	1×10^5	✔	✔	✔	variable	Z-dependent

L25, L50, L100, L200


CROCODILE simulation
Oku & KN '24
Column density [M☉ Mpc⁻² (1 + z)²]
10¹³
10¹²
10¹¹
10¹⁰
10¹
10³
10⁵
10⁷
Temperature [K]
z = 20
z = 10
z = 5
z = 2
z = 1
z = 0.5
z = 0.1
10 cMpc

The *AGORA* High-resolution Galaxy Simulations Comparison Project. V: Satellite Galaxy Populations In A Cosmological Zoom-in Simulation of A Milky Way-mass Halo

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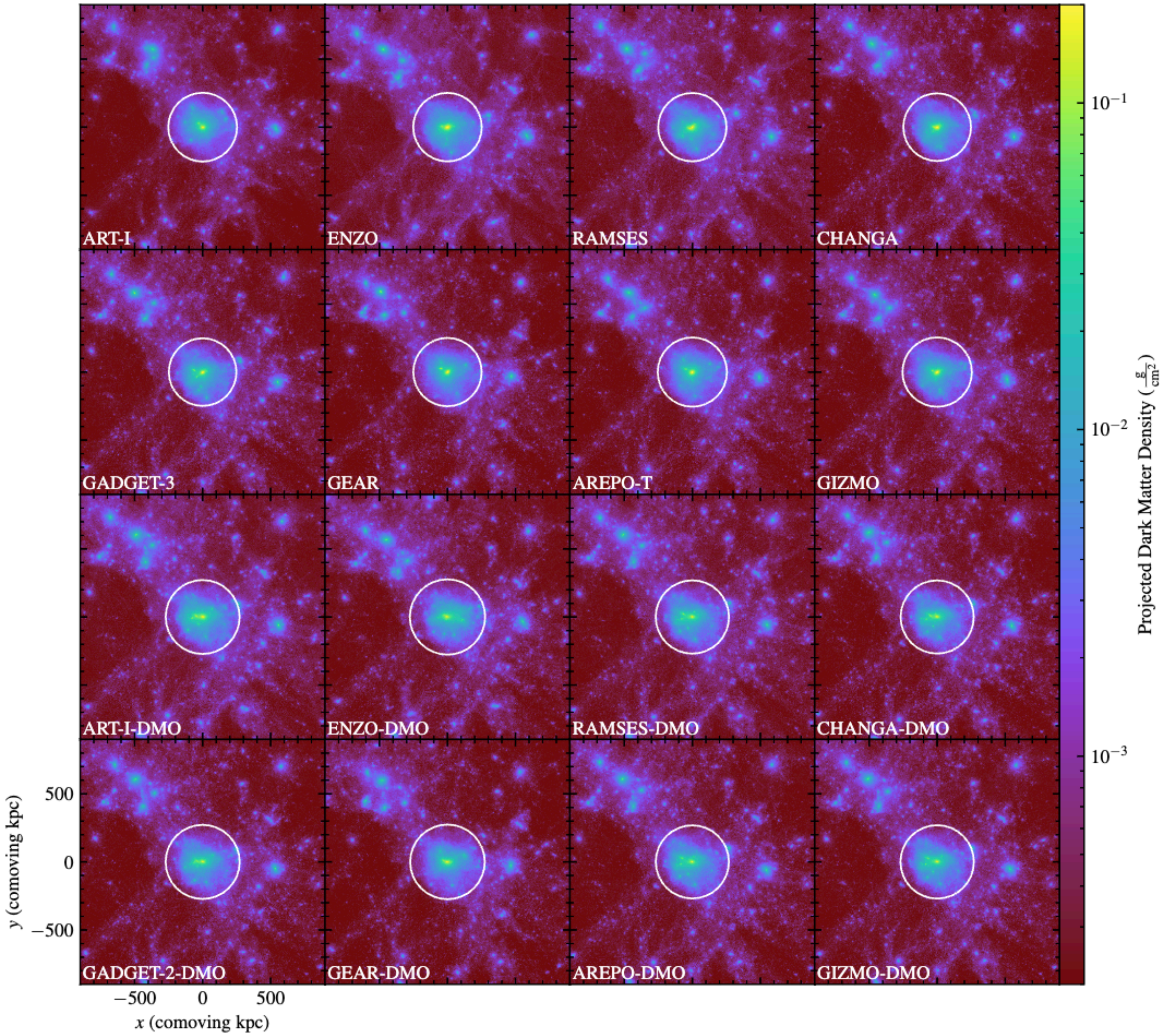


- 8 Cosmological Hydrodynamic Codes

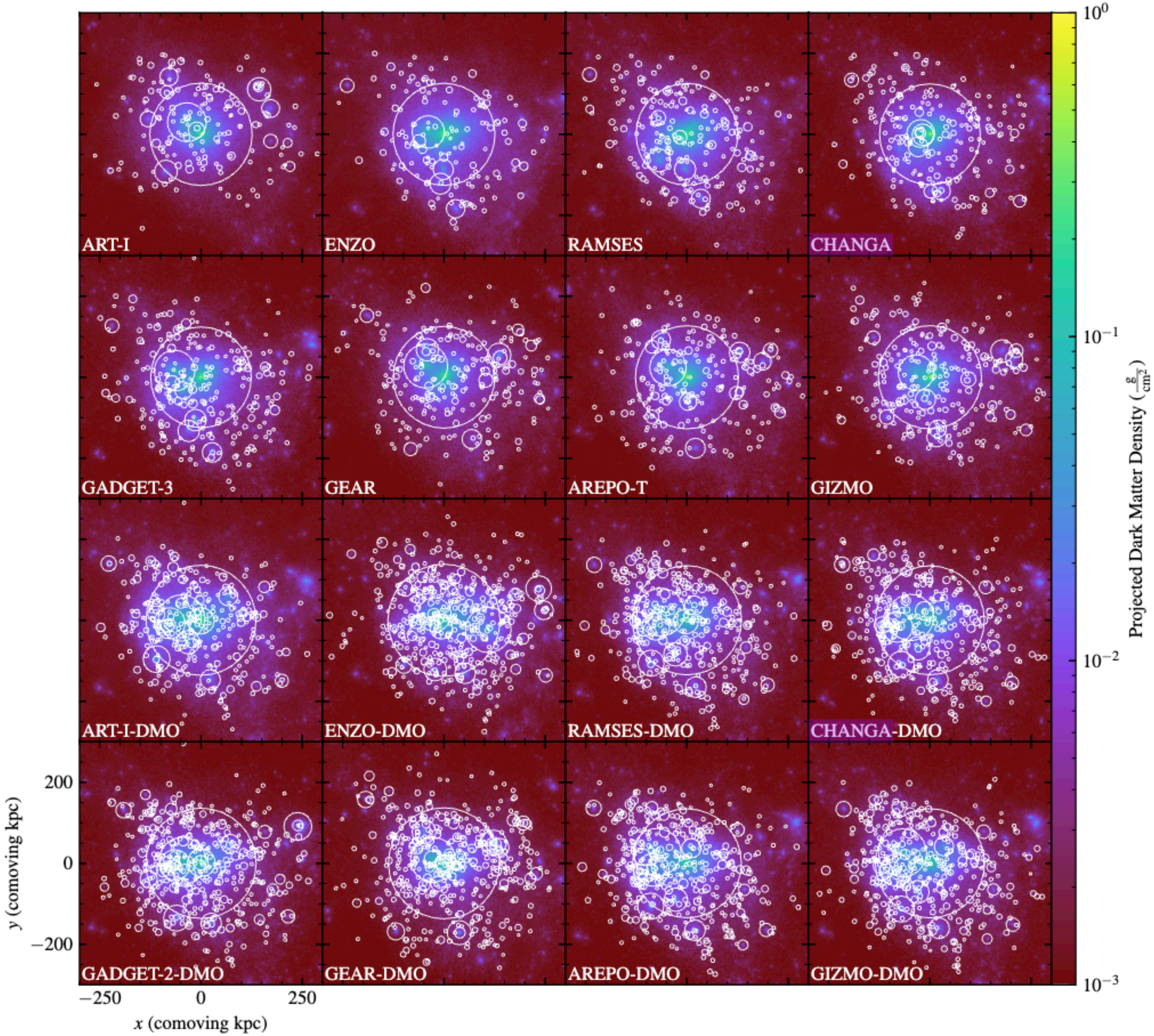
mesh: ART, Enzo, RAMSES

Lagr. —Eurlerian: AREPO, Gizmo

SPH: CHANGA, GADGET-3, GEAR

- Detailed examination of satellites down to z~2 & z~0

- Compared hydro & DM-only runs



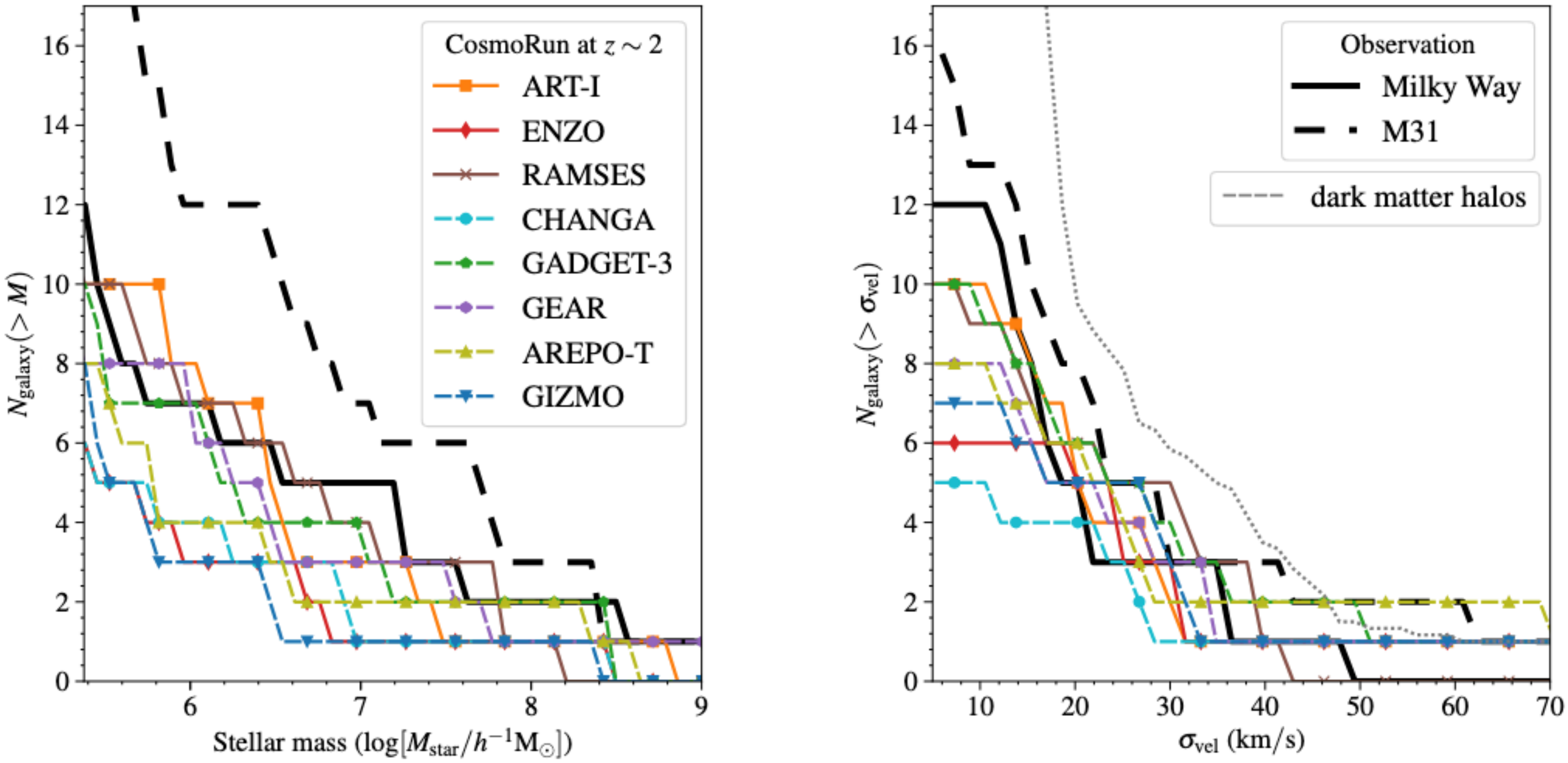
white circles: halos w. $M_h \geq 10^7 M_\odot$

up to 0.5 R_{vir}

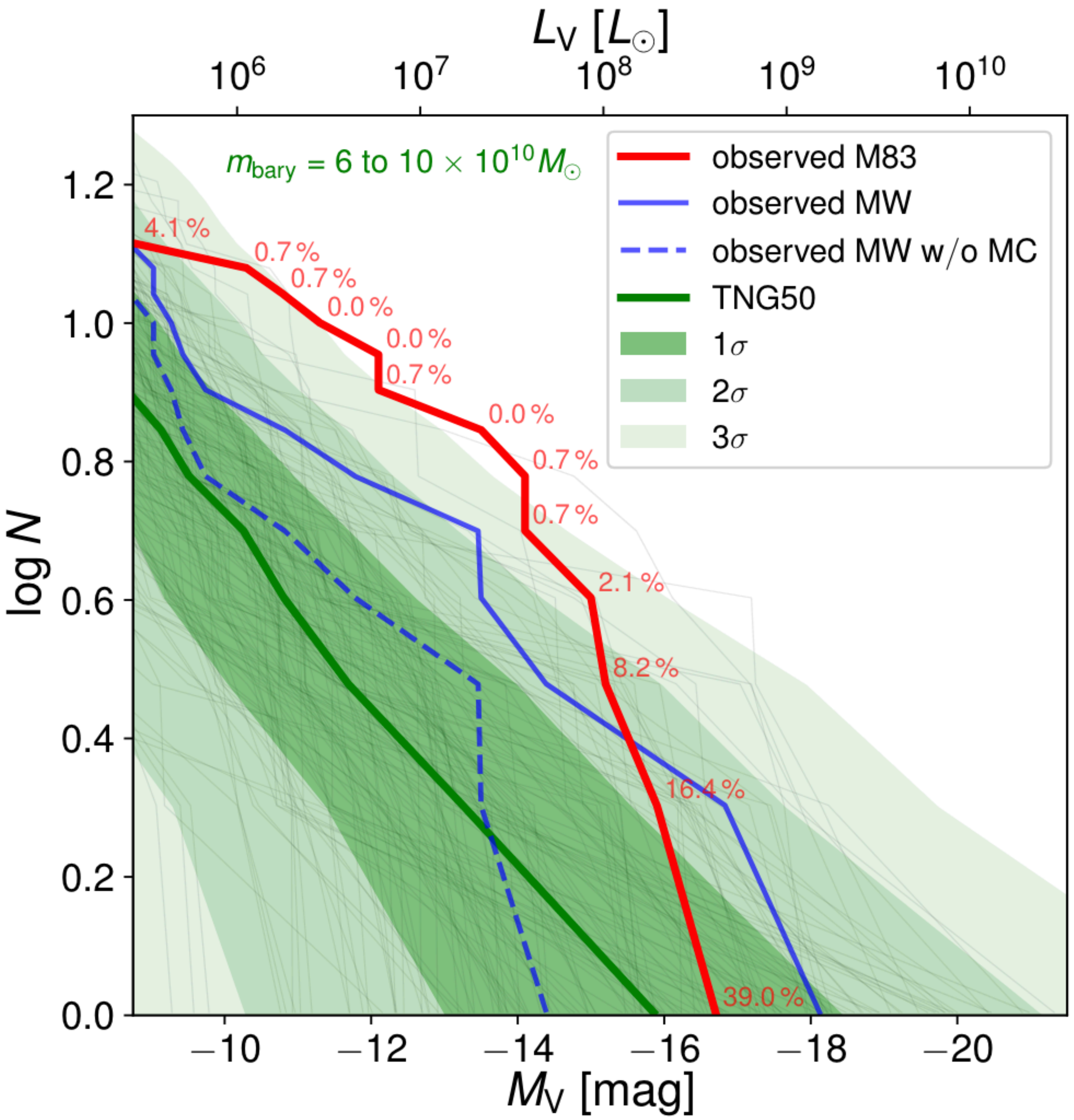
Jung+ '24

No more "Missing Satellites Problem"

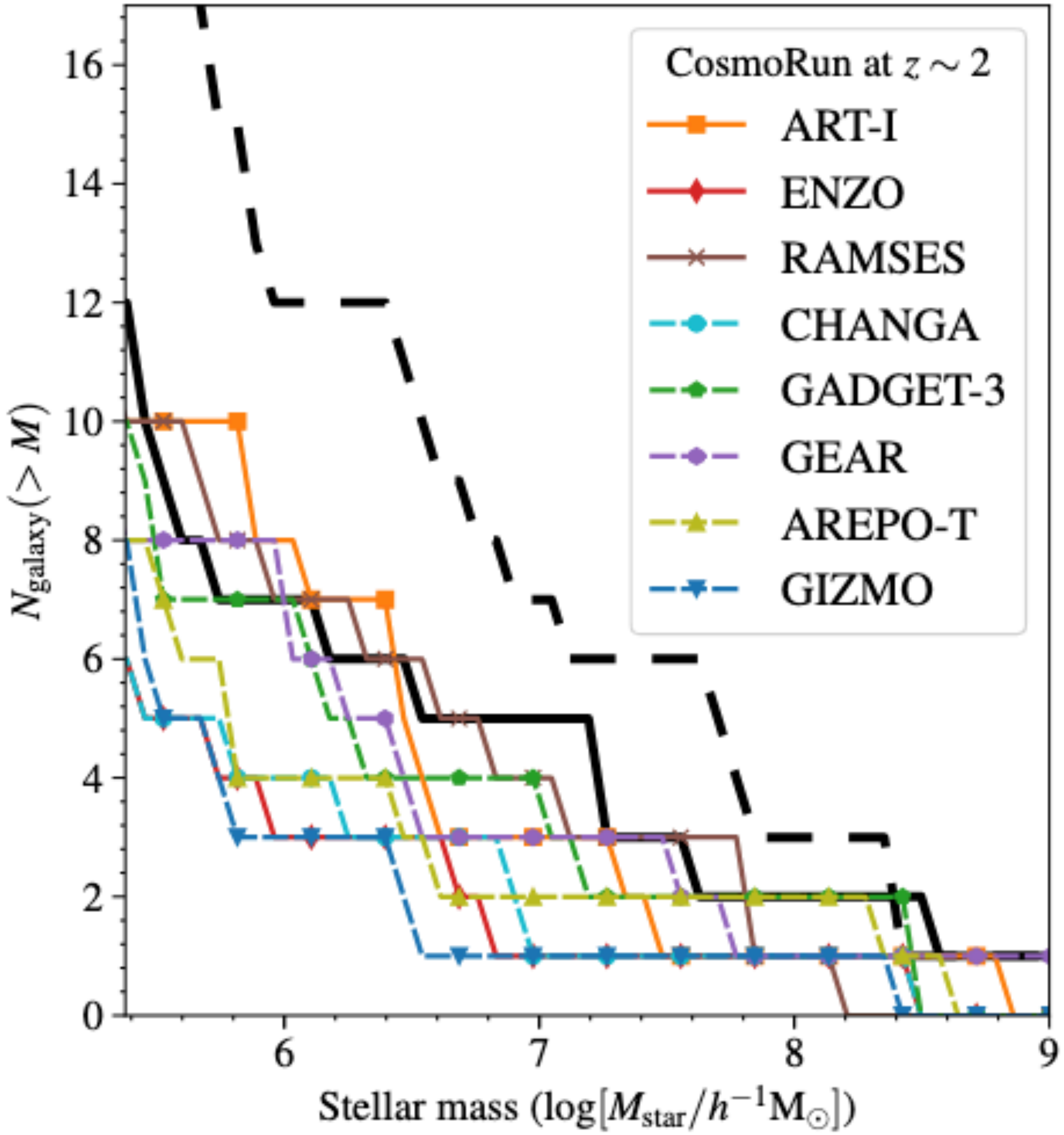
AGORA collab. — Jung+ '24



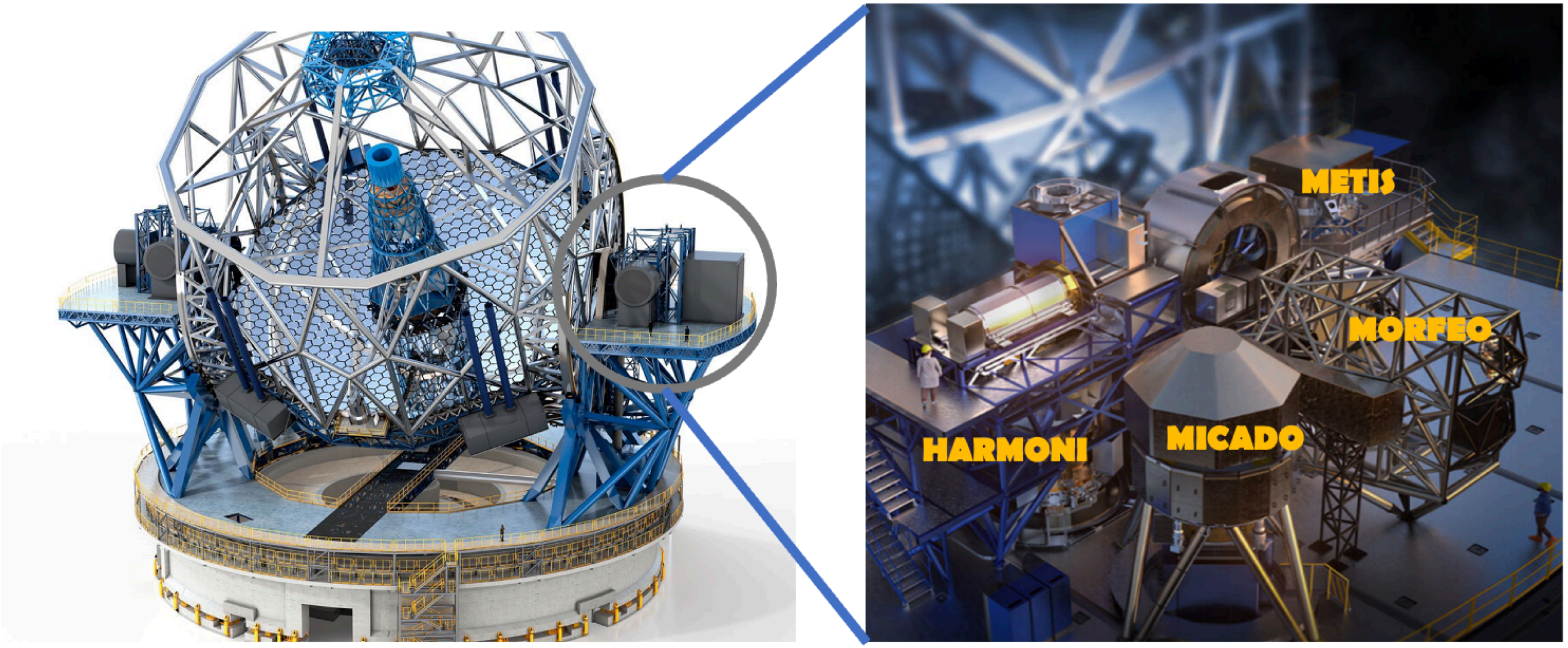
Reionization, UV backgrnd, ram-pressure/tidal stripping, SN feedback


L_V [$L_\odot$]
10^6 10^7 10^8 10^9 10^{10}
m_{bary} = 6 to 10 × $10^{10} M_\odot$
observed M83
observed MW
observed MW w/o MC
TNG50
1σ
2σ
3σ
4.1 %
0.7 %
0.7 %
0.0 %
0.0 %
0.7 %
0.0 %
0.7 %
0.7 %
2.1 %
8.2 %
16.4 %
39.0 %
log N
1.2 1.0 0.8 0.6 0.4 0.2 0.0
−10 −12 −14 −16 −18 −20
M_V [mag]

Muller+'24


CosmoRun at z ∼ 2
ART-I
ENZO
RAMSES
CHANGA
GADGET-3
GEAR
AREPO-T
GIZMO
$N_{galaxy}(>M)$
16 14 12 10 8 6 4 2 0
6 7 8 9
Stellar mass ($\log[M_{star}/h^{-1}M_\odot]$)

FIRST GENERATION INSTRUMENTS



MICADO

Diffraction Limited Imaging

HARMONI

Visible and near infrared (0.7 to 2.45 micron) integral field spectrograph

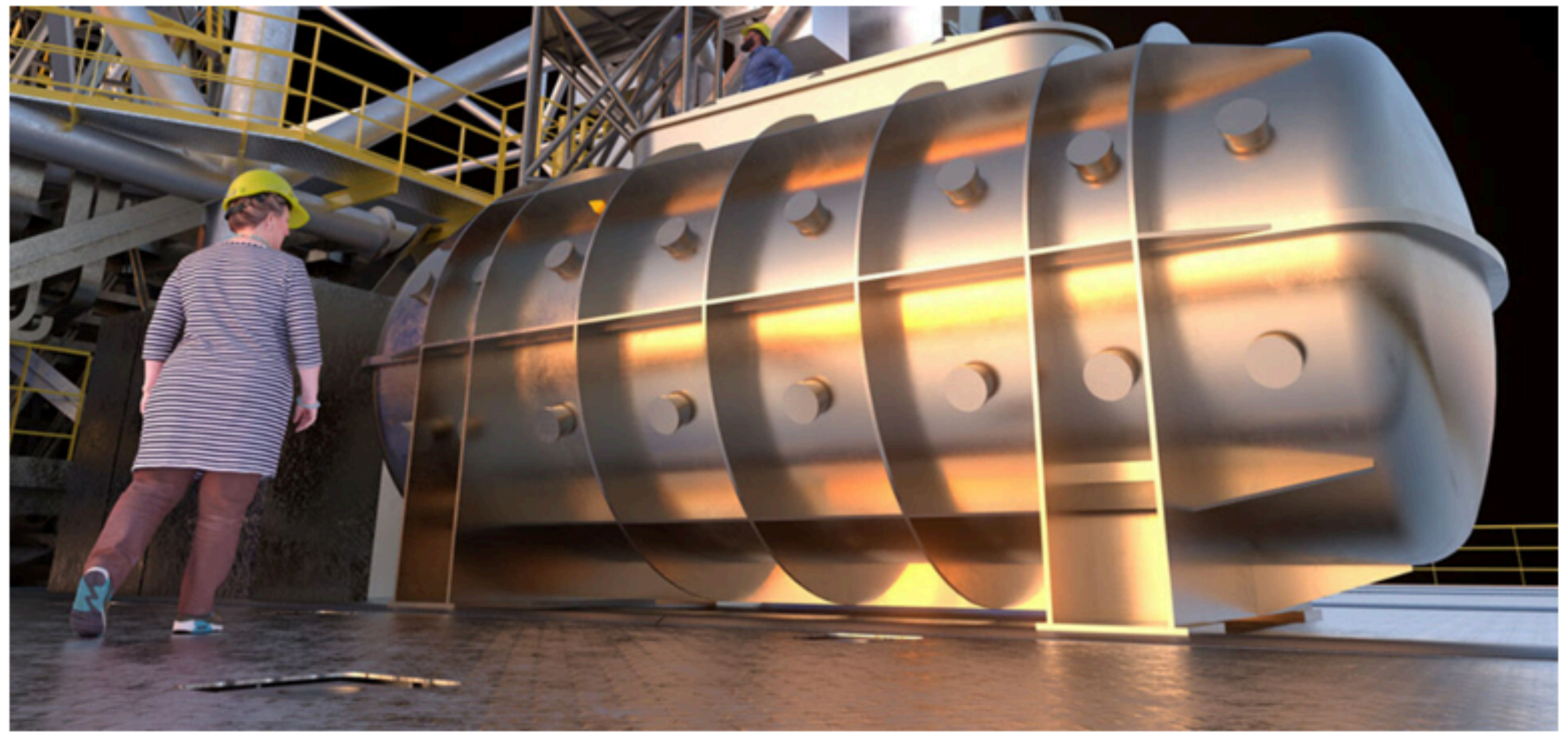
METIS

Mid Infrared Imager and Spectrograph (3-20 microns)

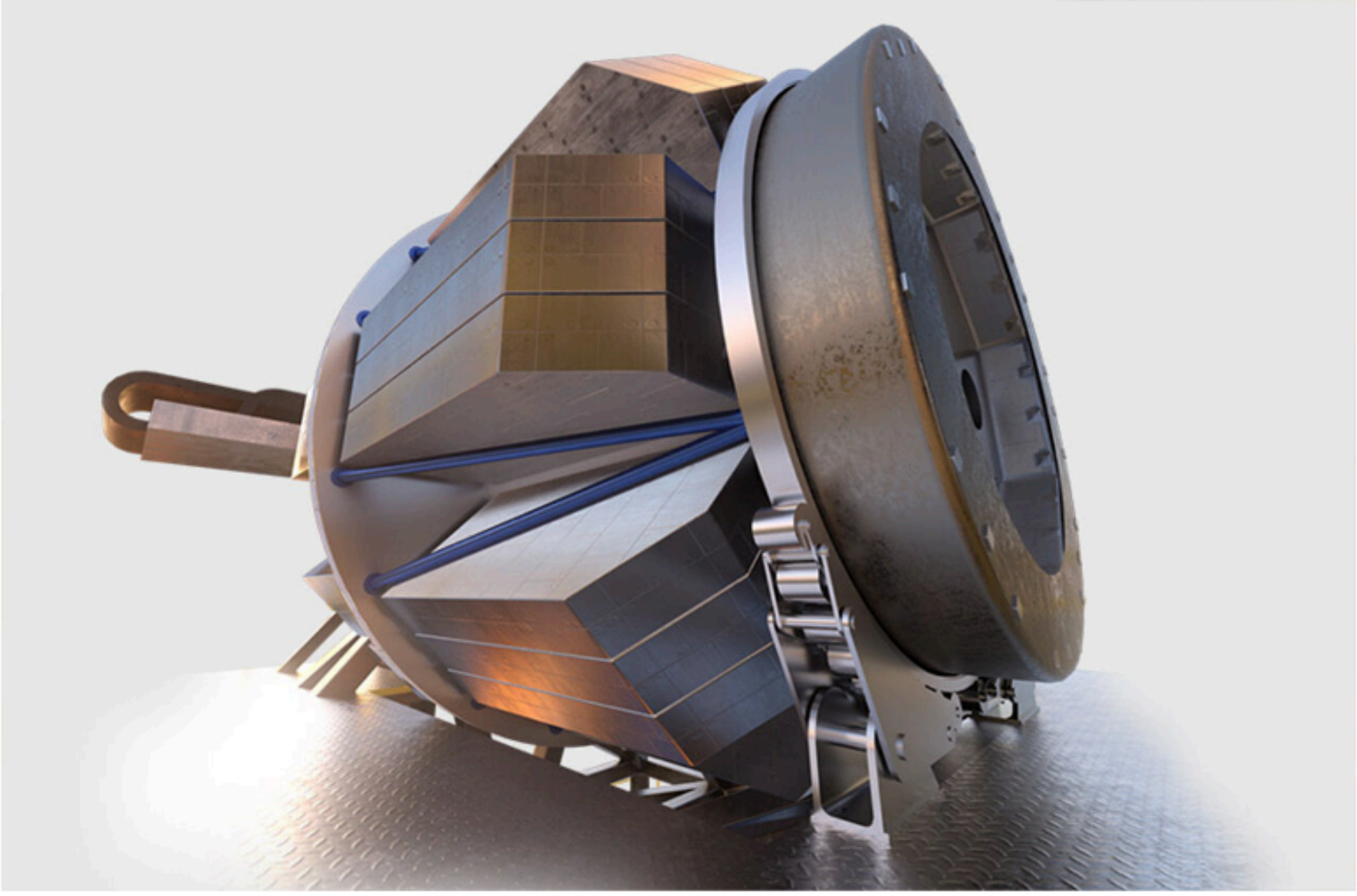
MORFEO

Adaptive Optics Module

SECOND GENERATION INSTRUMENTS



ANDES ArmazoNes high Dispersion Echelle Spectrograph



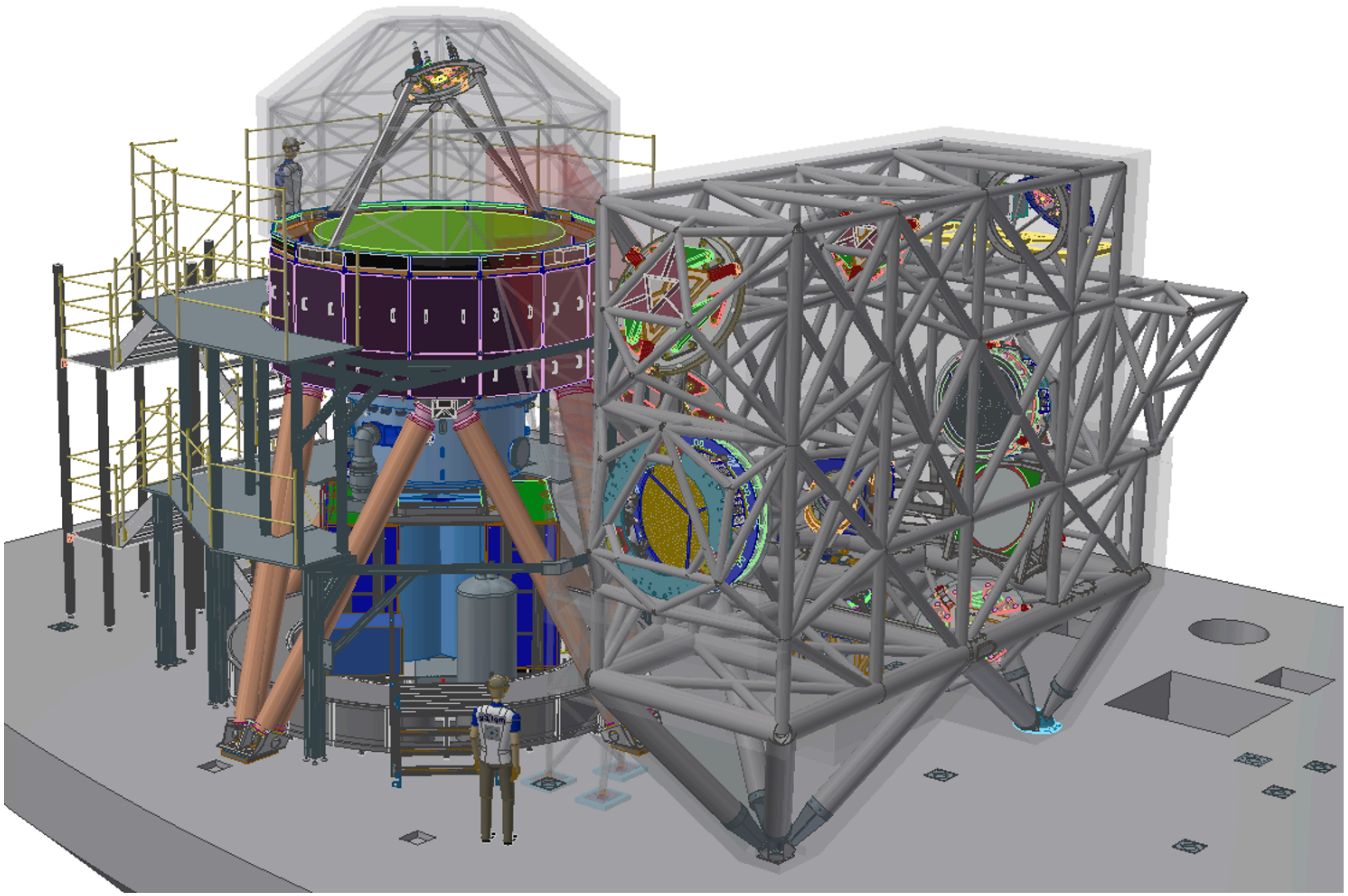
MOSAIC: Multi-Object Spectrograph
Three Observation mode :

1) **High multiplex mode in the visible (HMM-VIS)**: Simultaneous integrated-light observations of almost 200 objects
2) **High multiplex mode in the near-infrared (HMM-NIR)**: Simultaneous integrated-light observations of 80 objects
3) **High-definition mode (HDM)**: Simultaneous observations of eight integral field units (IFUs) (goal: 10 IFUs) deployed within a ~40 arcmin patrol field

CONSORTIUM

- **Canada:** National Research Council of CANADA (NRC), Herzberg Astronomy and Astrophysics Research Victoria
- **France:** LAGRANGE Nice, IPAG Grenoble, Institut de Physique des deux Infinis de Lyon LMA, LUPM Montpellier
- Italy: INAF Istituto Nazionale di AstroFisica (Lead, with about 90% of total FTE) (Arcetri, Bologna, Brera, Padova, Napoli, Teramo)
- **Ireland:** the National University of Ireland, Galway (University of Galway),
- **Japan: Formalization with NAOJ in progress for «in kind» contribution of two mirrors**

MORFEO OVERVIEW



As a first-generation ELT instrument, MORFEO (formerly known as MAORY), will help compensate for the distortion of light caused by turbulence in the Earth's atmosphere which makes astronomical images blurry.

MORFEO will not make observations itself; rather, it will enable other instruments, such as MICADO in the first instance, to take exceptional images.

MORFEO will use nine guide stars (three real stars and six artificial laser stars), state-of-the-art wavefront sensors, and up to three deformable mirrors to measure and correct for turbulence at three different heights in the atmosphere.

Key Capabilities

MORFEO and MICADO will be used to provide:

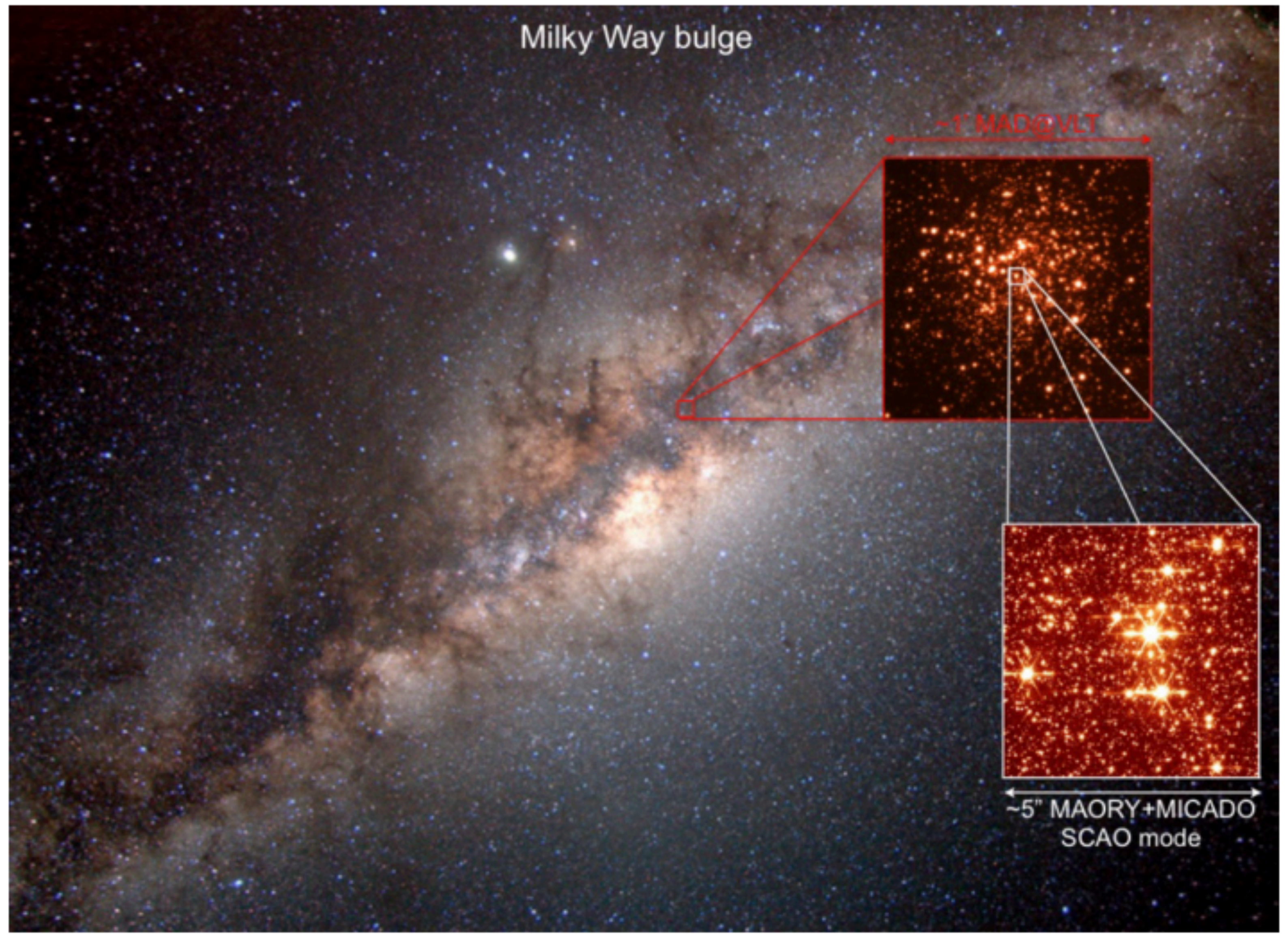
- ❑ Imaging
  - 0.8-2.4μm with 30 broad/narrow filters
  - 1.5 & 4mas pixels for 19” & 51” FoV at 6-12mas
  - Similar sensitivity to JWST, and 6× better resolution
- ❑ Astrometric imaging
  - 10-50μas precision anywhere in the field
  - 10μas/yr = 5km/s at 100 kpc after only a few years
- ❑ High Contrast imaging
  - focal & pupil plane coronagraphs
  - angular differential imaging
  - small inner working angle
- ❑ Spectroscopy
  - for compact sources
  - fixed configuration for 0.84-1.48μm & 1.48-2.46μm
  - R ~ 20000 for point sources (R ~ 10000 across slit)

MORFEO MICADO SCIENCE THEMES

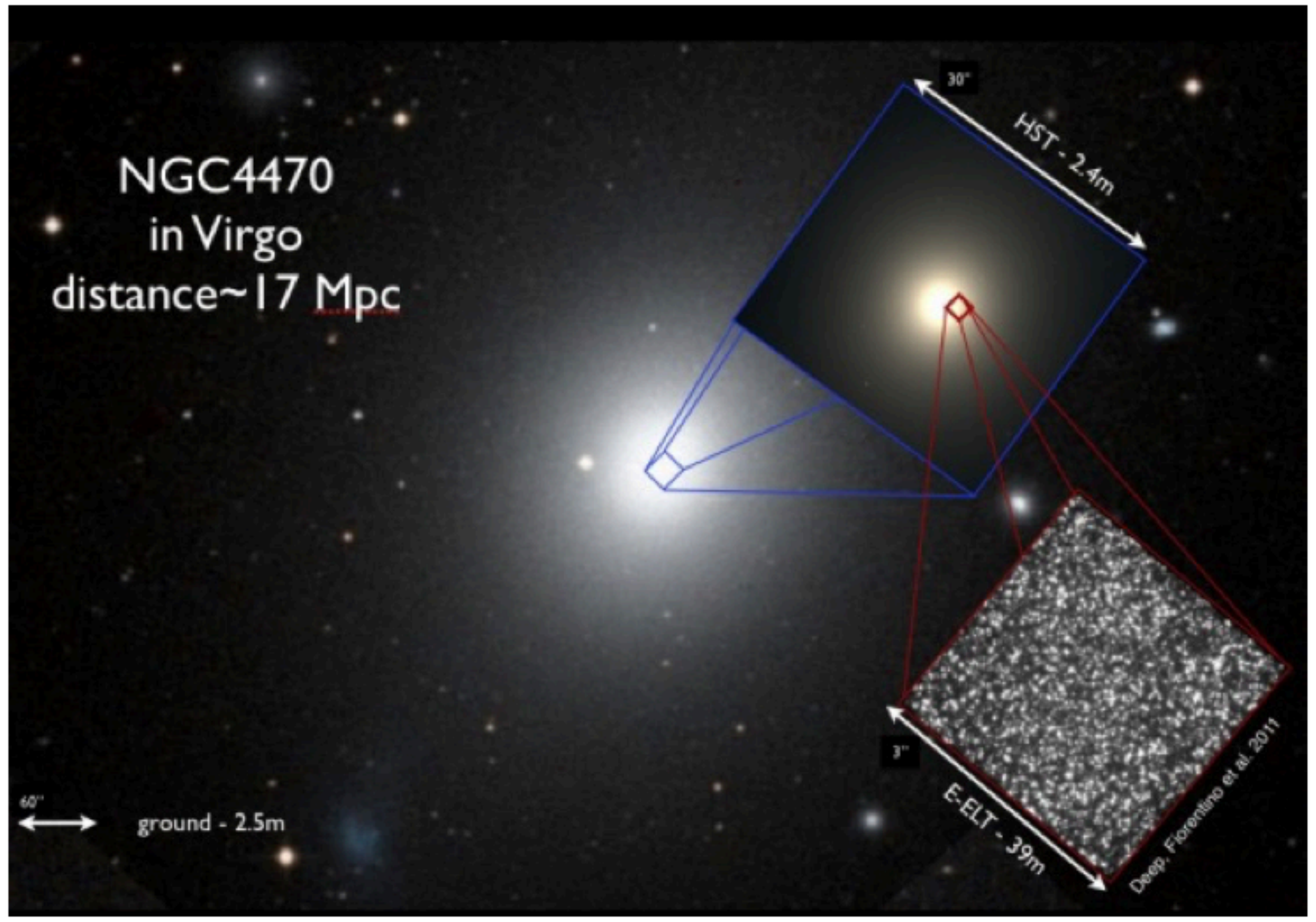
- Potential to address a large number of science topics

- Dynamics of dense stellar systems,
- Black holes in galaxies and the centre of the Milky Way,
- Formation and evolution of galaxies in the early universe,
- Star formation history of galaxies through resolved stellar populations,
- Planets and planet formation,
- The solar system.

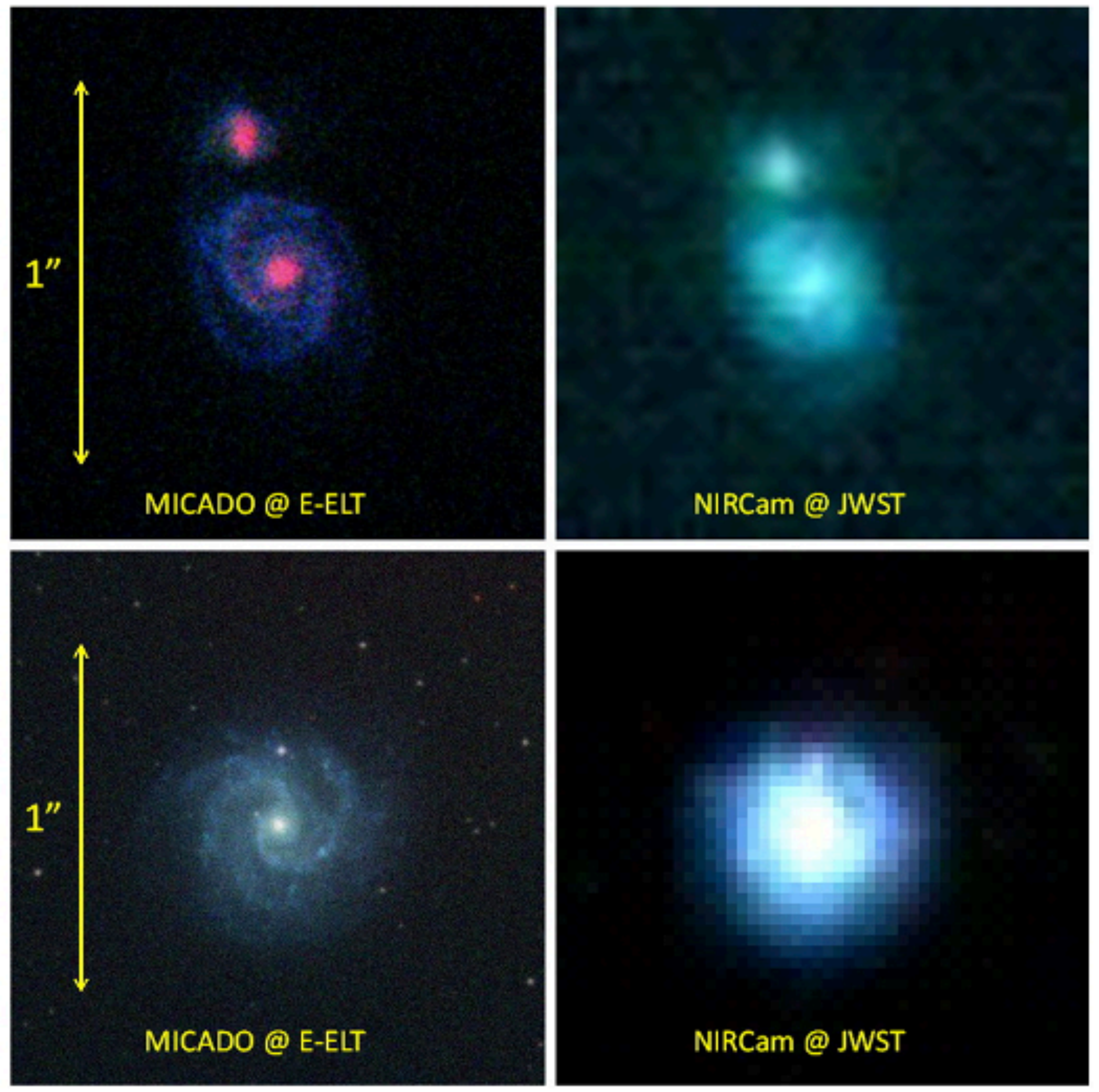
Nearby Stellar System



Local Universe



High Redshift Universe



ILR-WS 2024 Home Program Venue & A

ILR workshop @ Osaka 2024

From Galaxy Formation to Supermassive Black Holes

Sep. 25-27, 2024

Department of Earth and Space Science, Osaka University, Japan

Workshop Rationale

Understanding the intricate processes behind galaxy formation and the role of massive black holes is crucial for advancing our knowledge of the universe. This workshop aims to bring together leading experts and young researchers to explore the dynamic interplay between these cosmic structures with a stronger emphasis on theoretical studies but will not exclude observational talks. With the recent advent of JWST high-redshift discoveries and LIGO observations of merging black holes, we are in a watershed moment in cosmological studies. Through a series of talks and discussions, participants will delve into cutting-edge theories and observational evidence, shedding light on how supermassive black holes influence star formation and the evolution of galactic structures. By fostering a collaborative environment, this workshop seeks to stimulate innovative approaches and facilitate the development of new frameworks for interpreting the complex mechanisms that drive galaxy formation and coevolution with massive black holes. This workshop is supported by **the International Leading Research (ILR) grant**, which aims to promote international research collaborations between young Japanese researchers and distinguished researchers who are invited to this workshop. We encourage participation of early-career researchers (postdocs and graduate students) who are eager to establish fruitful research collaborations with the invited foreign speakers. The primary goals are to strengthen international ties, foster a new generation of researchers, and advance our understanding of the universe through collaborative efforts.

Invited Speakers

- Monica Colpi (Milano-Bicocca)
- Sebastiano Cantalupo (Milano-Bicocca)
- Claudio Dalla Vecchia (IAC)
- Andrea Ferrara (SNS, Pisa)
- Michele Fumagalli (Milano-Bicocca)
- Stefania Salvadori (Firenze)
- Hidenobu Yajima (University of Tsukuba)

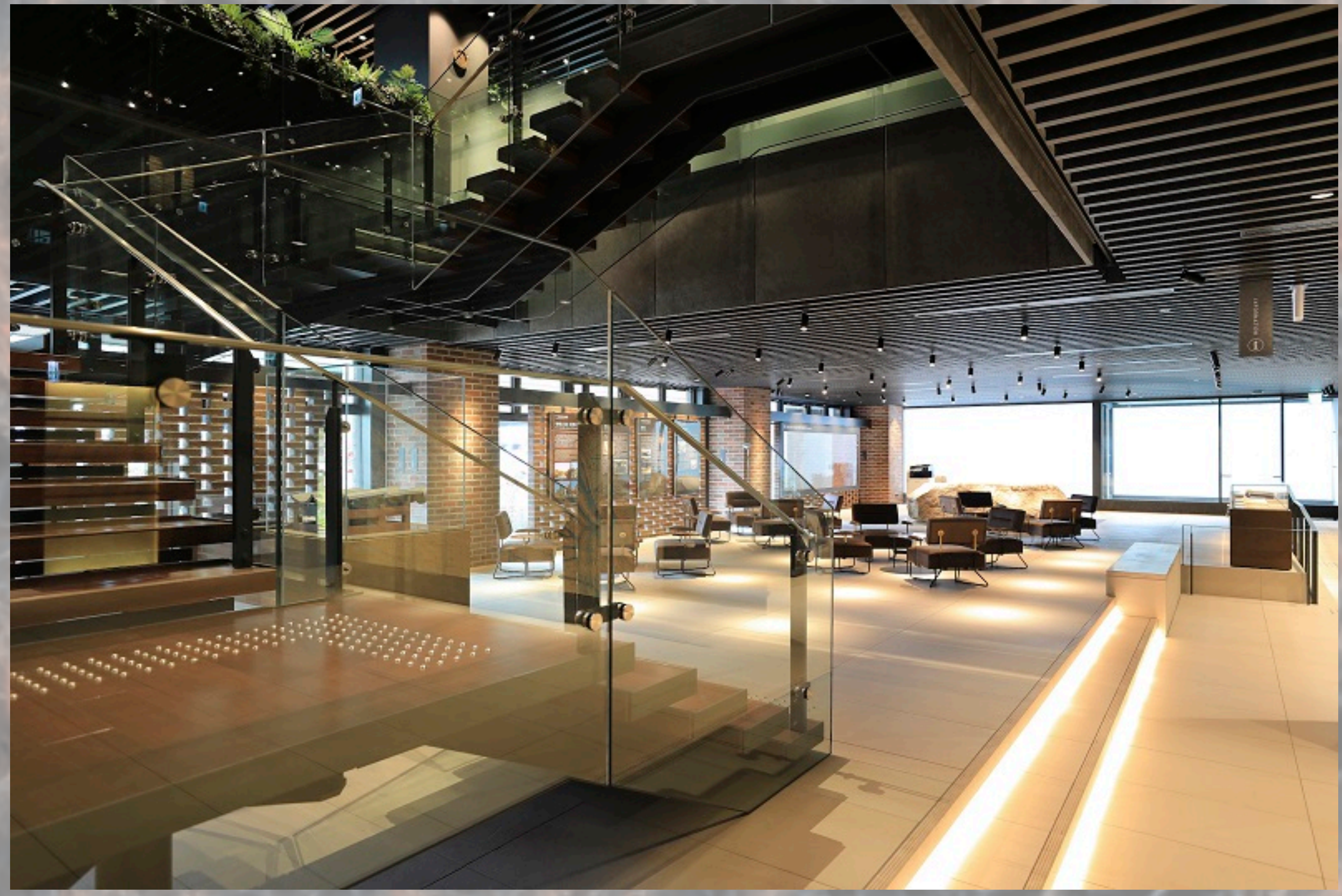
https://sites.google.com/view/ilr-ws-2024/home

Galaxy Workshop + AGORA in Asia ?

May 2025

2nd or 4th week: which is good for you?

5/12-16 **5/26-30**



https://forms.gle/ph8YcRMmczaHKaJTA

Summary

- ***Overmassive*** gals & MBHs at high-z
- **Enhanced He/H & N/O** at both **high-z** and **local EMPGs**.
- **Cosmo hydro sim** shows **enhanced He** for selective regions in **the earliest unpolluted ejecta** (by rapidly rotating massive stars), but ***yet higher He/H or N/O @ low O/H is still difficult to explain.*** **Fukushima, KN+'24**
- **Nomoto+13 yield** cannot account for the super-enhanced N/O; **Limongi & Chieffi+18** does better — **but some obs data are even higher (e.g. Isobe+23, Yanagisawa+24)**
- Contribution from ***rotating massive stars*** & yields for He, N super-enhancement **cf. Ohkubo+09, Nandal+23, 24**
- **CROCODILE** sim set & **dwarf zoom-in** to come. **Oku & KN '24; Tomaru+**