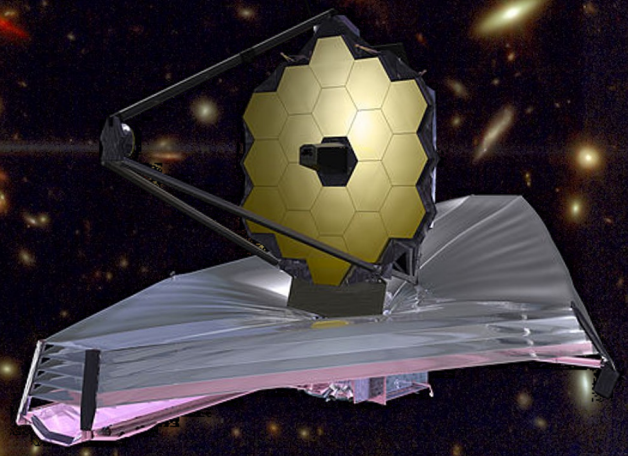
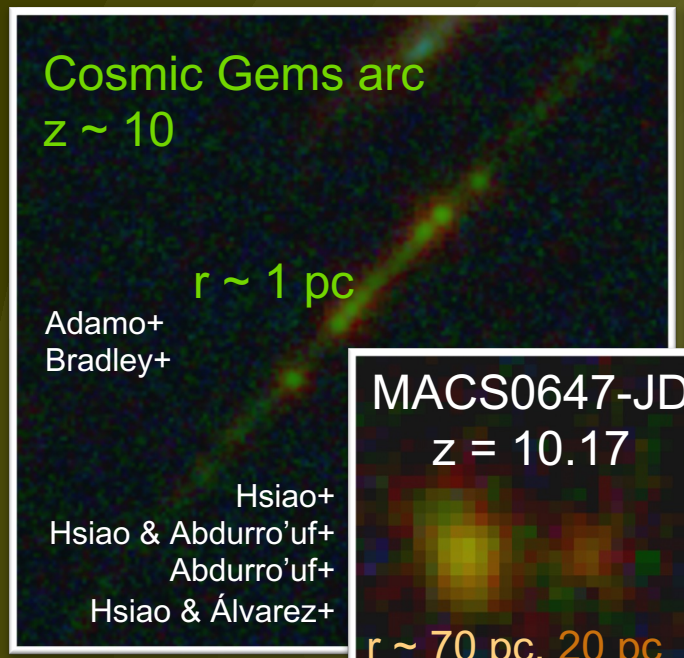


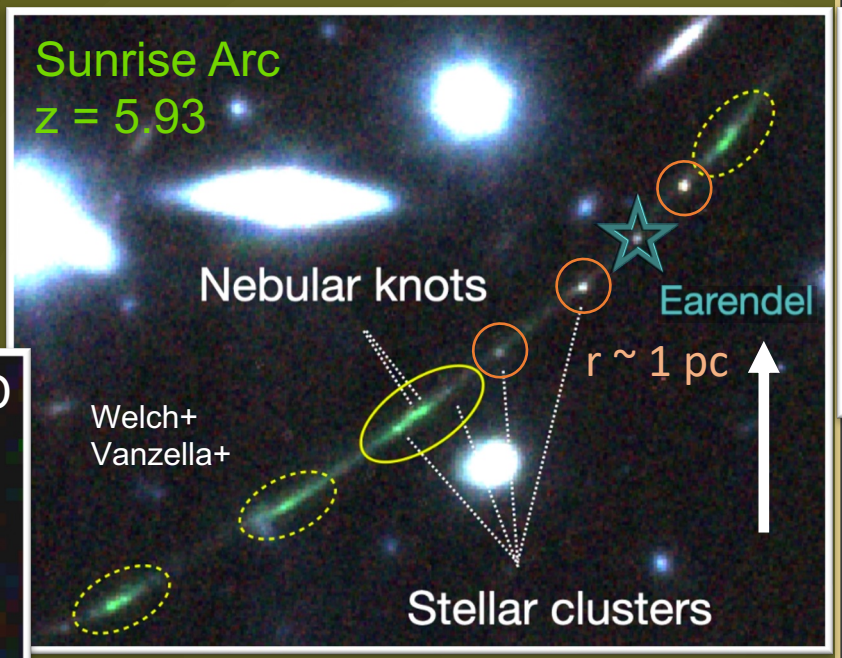
What was I made for?

JWST reaching for the First Stars

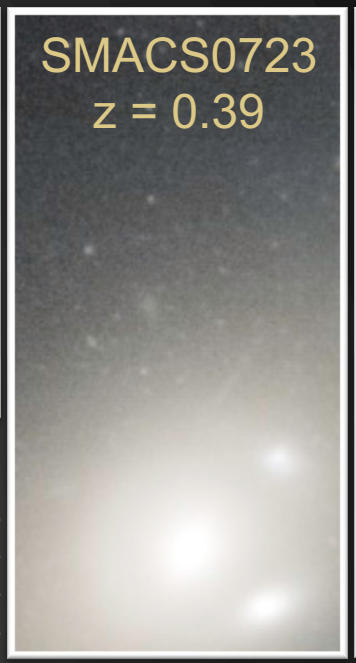
Dan Coe
Space Telescope Science Institute
Johns Hopkins University
ESA/AURA Astronomer
JWST NIRSpec Instrument Scientist
dancoe.space

Cosmic Spring Globular cluster progenitors over time

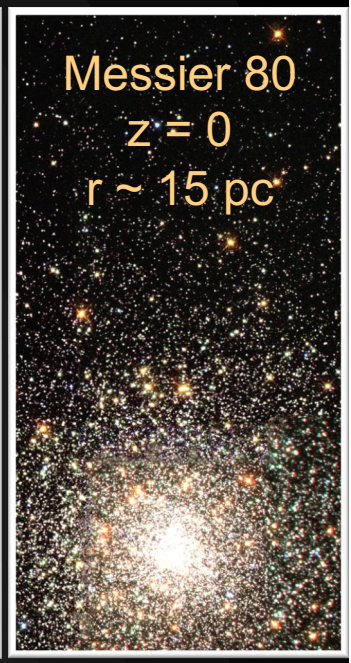


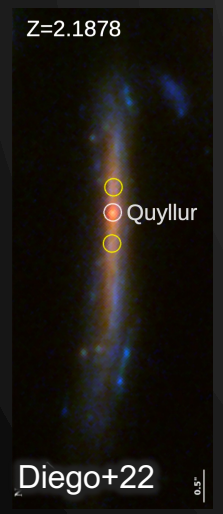


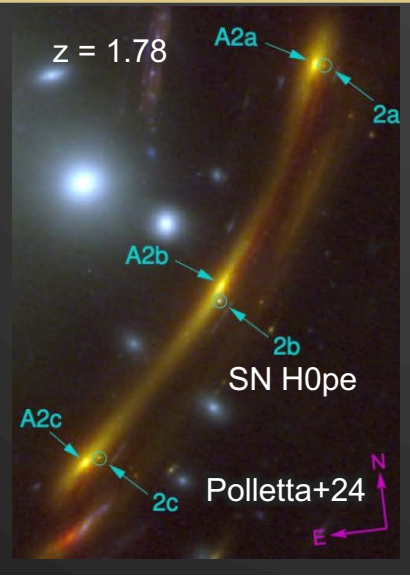
Mowla & Iyer+
Claeyssens+
Adamo+



Faisst+
Lee+
Harris+
Martis+







Individual stars

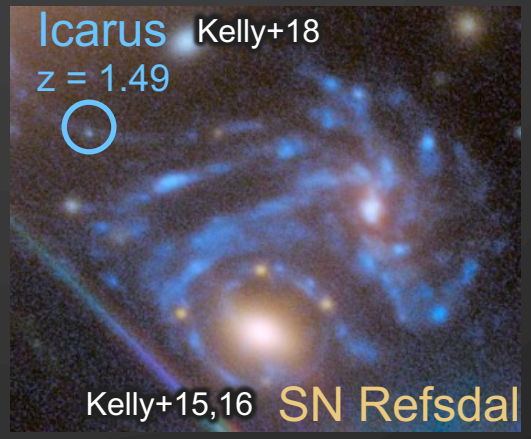


Image: Zolt Levay

Image: Alyssa Pagan

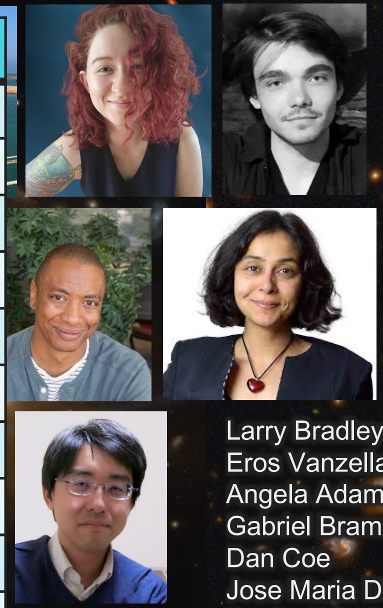
Image: Dan Coe (Trilogy)

Cosmic Spring

cosmic-spring.github.io
public data, code, papers

join us if you're interested

arXiv	Lead author	Object(s)	Redshift
2208.09007	Brian Welch	Earendel star	z ~ 6
2210.01777	Larry Bradley	12 galaxies	z ~ 9 – 13
2210.14123	Tiger Hsiao	MACS0647-JD	z ~ 11
2211.09839	Eros Vanzella	Sunrise Arc	z ~ 6
2211.13334	Ashish Kumar Meena	lensed star	z ~ 5
2301.02209	Abdurro'uf	444 galaxies	z = 0.3 – 6
2305.03042	Tiger Hsiao	MACS0647-JD	z = 10.17
2308.00042	Lukas Furtak	lensed star	z = 4.76
2309.02504	Anton Vikaeus	Balmer breaks	z ~ 6 – 11
2312.03065	Meghana Killi	AGN	z = 4.53
2401.03224	Angela Adamo	Cosmic Gems	z ~ 10
2404.10770	Larry Bradley	Cosmic Gems	z ~ 10
2404.16201	Abdurro'uf	MACS0647-JD	z = 10.17
2404.16200	Tiger Hsiao	MACS0647-JD	z = 10.17



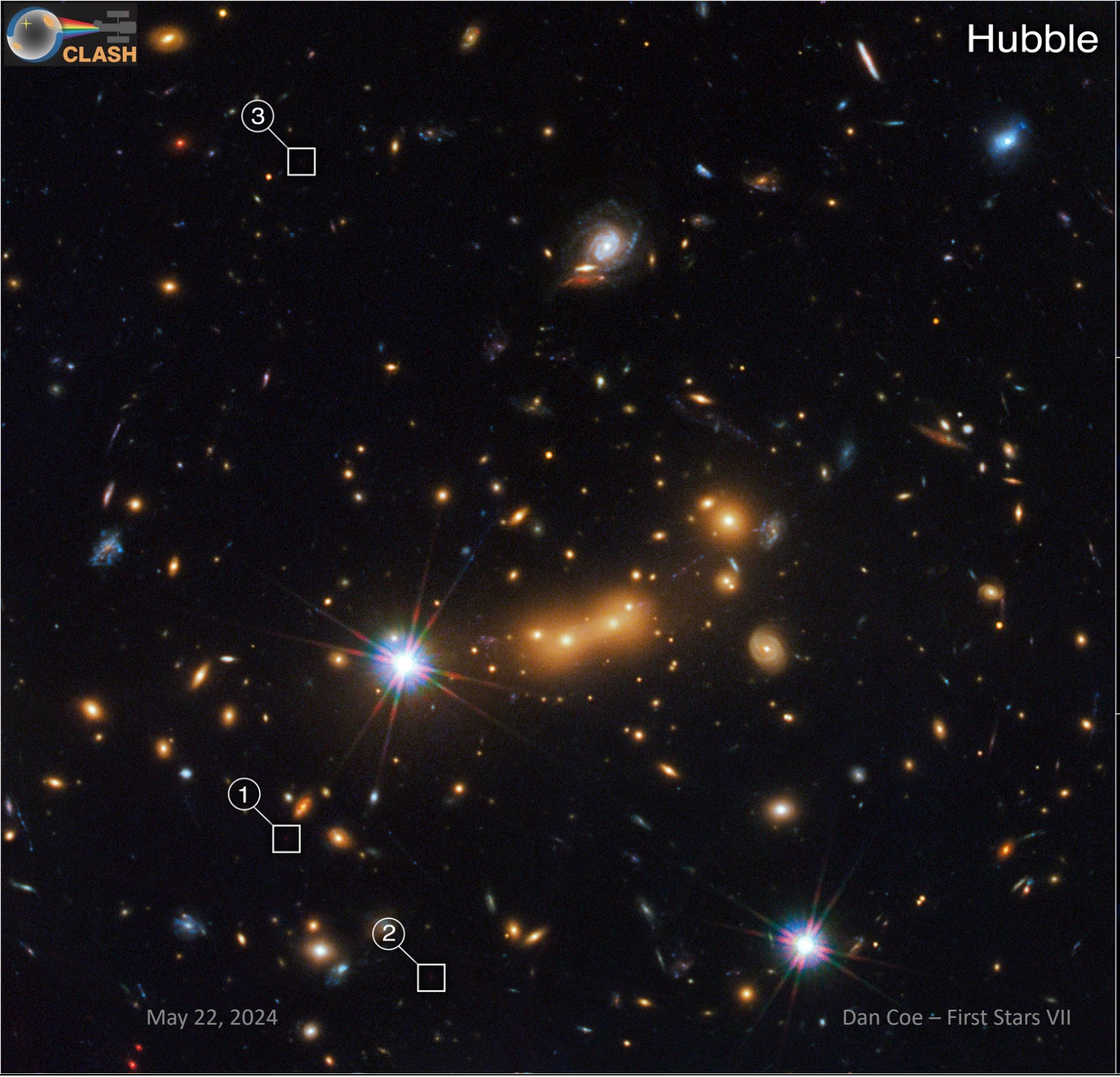
Abdurro'uf
Tiger Hsiao
Keduse Worku
Brian Welch
Gourav Khullar
Guillaume Mahler
Ashish Kumar Meena
Lukas Furtak
Yolanda Jiménez-Teja
Rosa Newshore
Alex Benitez
Paola Dimauro
Intae Jung
Rebecca Larson
Lily Whitler
Adélaïde Claeyssens
Adam Carnall
Jacqueline Antwi-Danso
Ebraheem Farag
Rachana Bhatawdekar
Meridith Joyce
Wenlei Chen

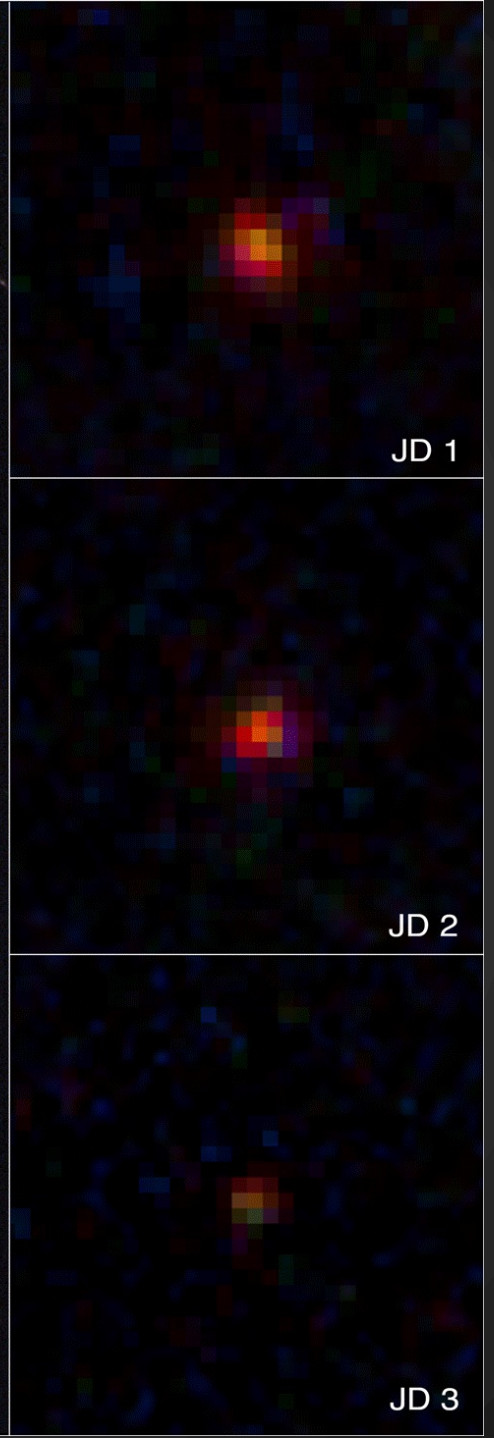
Sinclaire Manning
Seiji Fujimoto
Taylor Hutchison
Lamiya Mowla
Vasily Kokorev
Namrata Roy
Xinfeng Xu
Victoria Strait
Kartheik Iyer
Ramesh Mainali
Adam Casselman
Lillian Santos-Olmsted
Anton Vikaeus
Patricia Bolan
David Nicholls
Peter Senchyna
Ikko Shimizu
Mengtao Tang
Tom Resseguier
Janvi Madhani
Celia Mulcahey
Kyle O'Connor

Larry Bradley
Eros Vanzella
Angela Adamo
Gabriel Brammer
Dan Coe
Jose Maria Diego
Rogier Windhorst
Adi Zitrin
Mario Nonino
Kirk Barrow
Marusa Bradac
Pratika Dayal
Megan Donahue
Selma E. de Mink
Erik Zackrisson
Jay Anderson
Stephan McCandliss
Steven Finkelstein

Swara Ravindranath
Brenda Frye
Patrick Kelly
Nir Mandelker
Masamune Oguri
Keren Sharon
Christopher Conselice
Frank Timmes
Jan Eldridge
Colin Norman
Dan Stark
Jinmi Yoon
Lisa Kewley
Pascal Oesch
Marc Postman
Tom Broadhurst
Alaina Henry
Bethan James

Jane Rigby
Lou Strolger
Francesco Valentino
Ana Acebron
Gabriel B. Caminha
Christian Binggeli
Michael Florian
Masami Ouchi
Roberto Avila
Susan Kassin
Nor Pirzkal
Russell Ryan
David Law
Felipe Andrade-Santos
Takahiro Morishita
Matthew Bayliss
Sune Toft
Tod Lauer
Michele Trenti



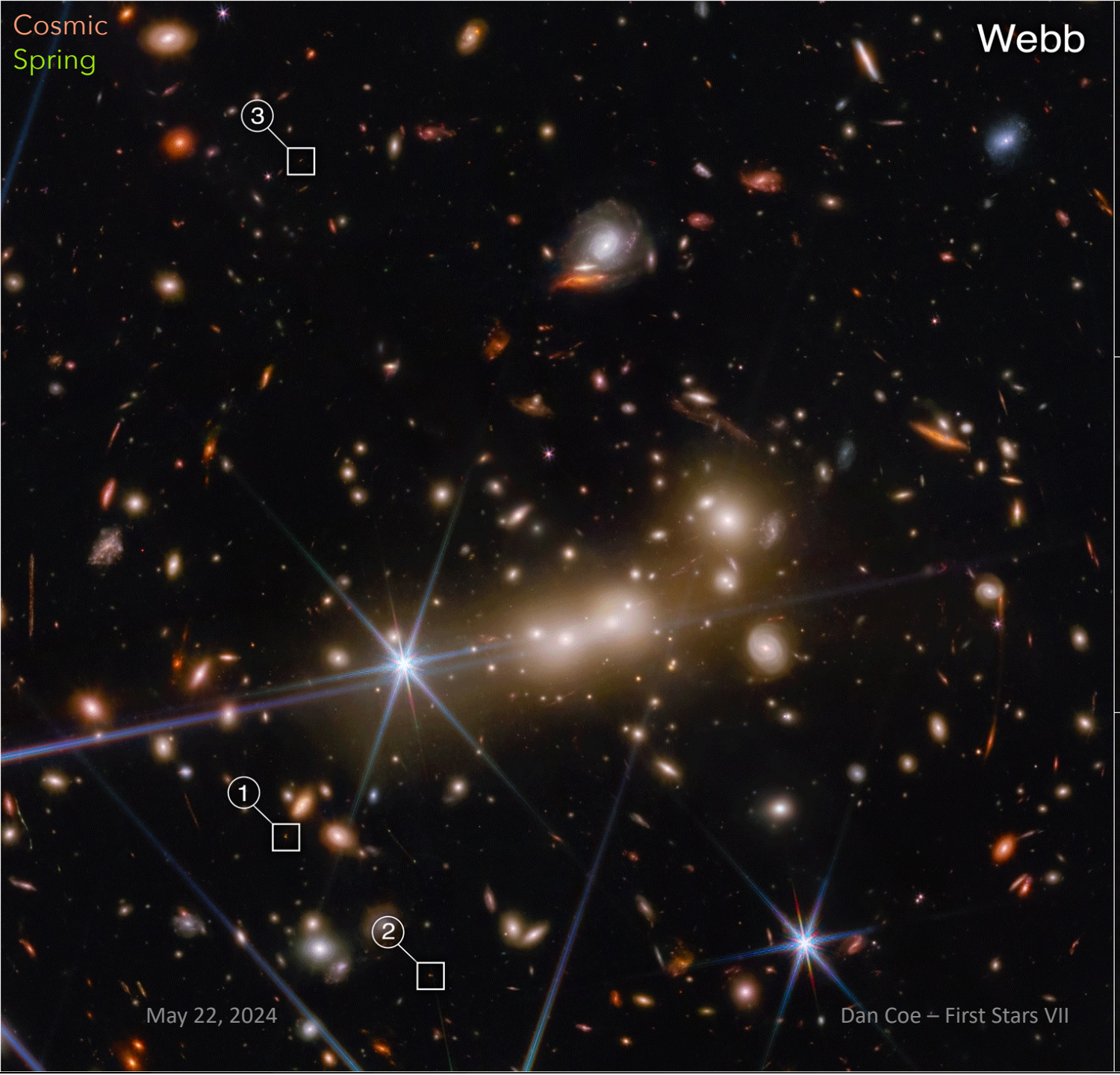


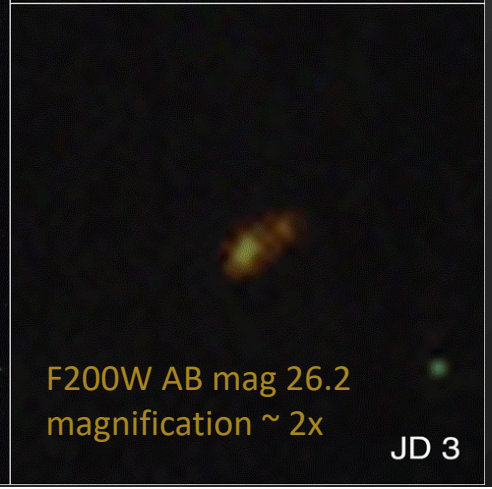
Look again at that dot

MACS0647-JD
z ~ 11 (400 Myr)
Coe et al. 2013

Cosmic Spring

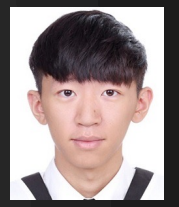
Webb



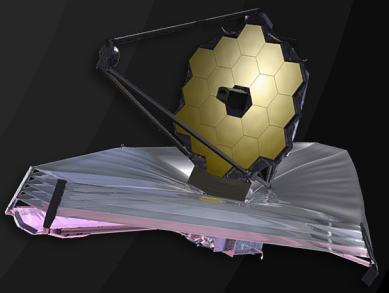


Look again at those dots

MACS0647-JD
z = 10.17 (460 Myr)



Tiger Hsiao et al.
arXiv:2210.14123
arXiv:2305.03042



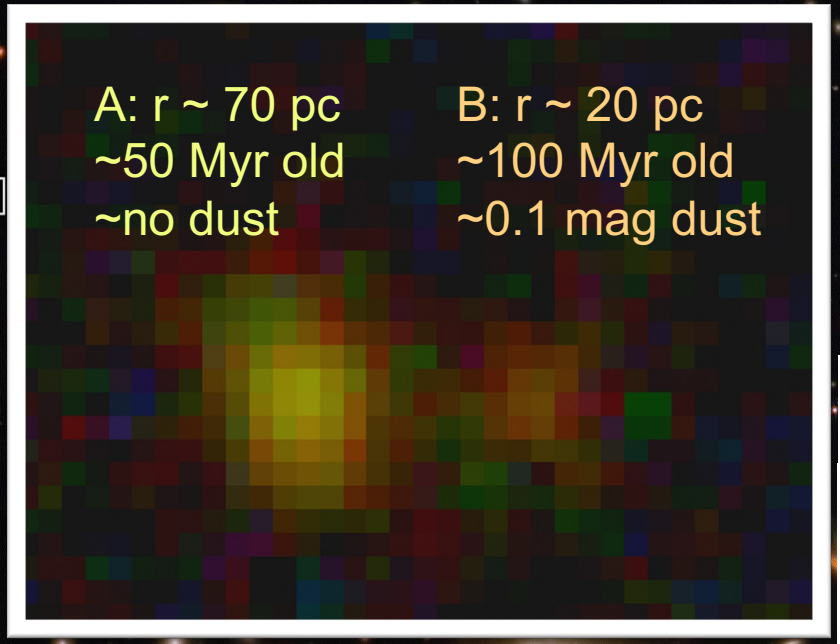
May 22, 2024

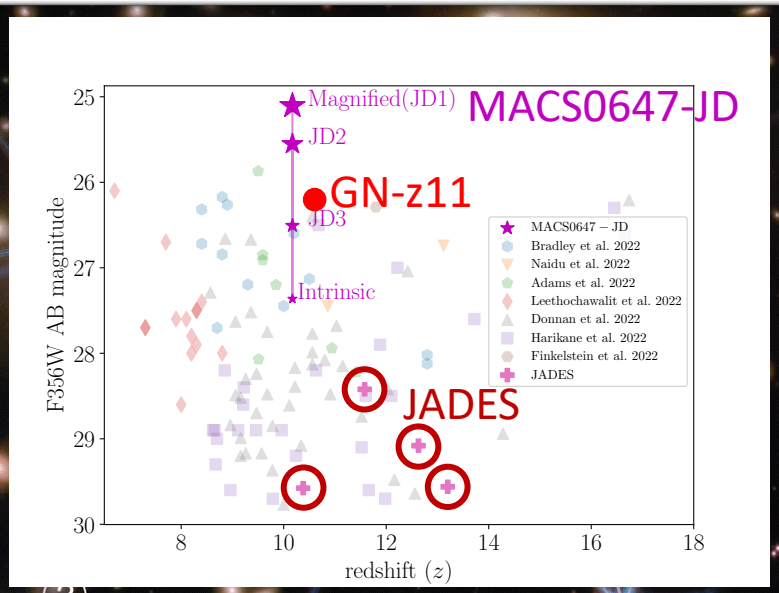
Dan Coe – First Stars VII

Cosmic Spring

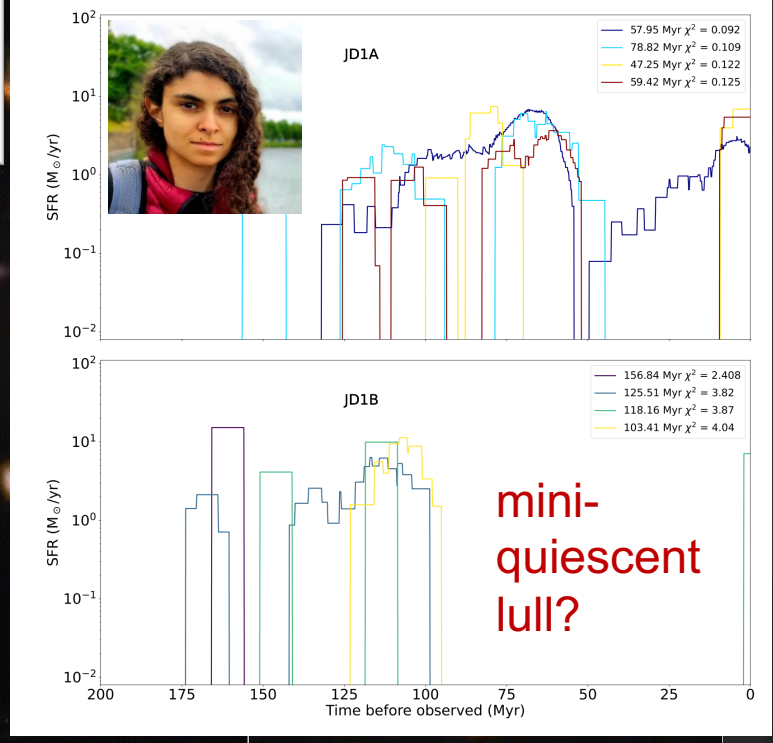
Webb

Look again at those dots

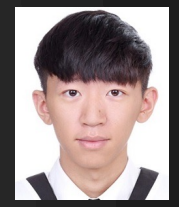




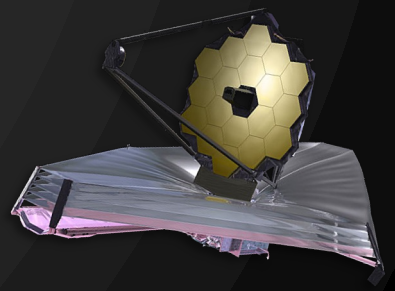
SFH from GAINN simulation analysis
Lillian Santos-Olmsted+ arXiv:2305.17158



MACS0647-JD
z = 10.17 (460 Myr)



Tiger Hsiao et al.
arXiv:2210.14123
arXiv:2305.03042



F200W AB mag 26.2
magnification ~ 2x

JD 3

Cosmic Spring

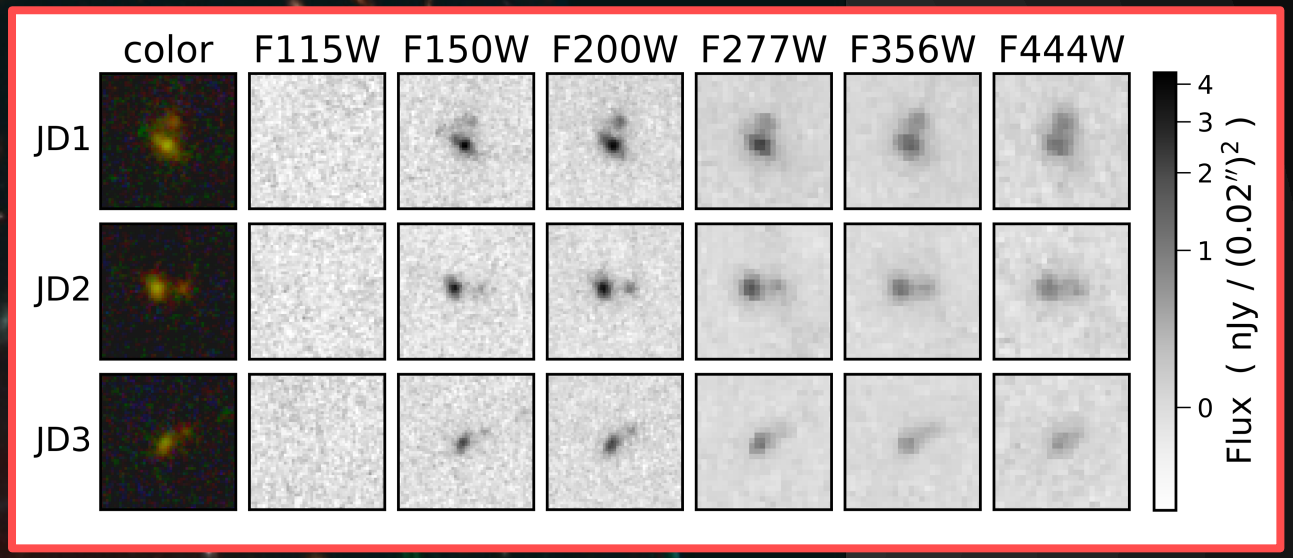
JD3

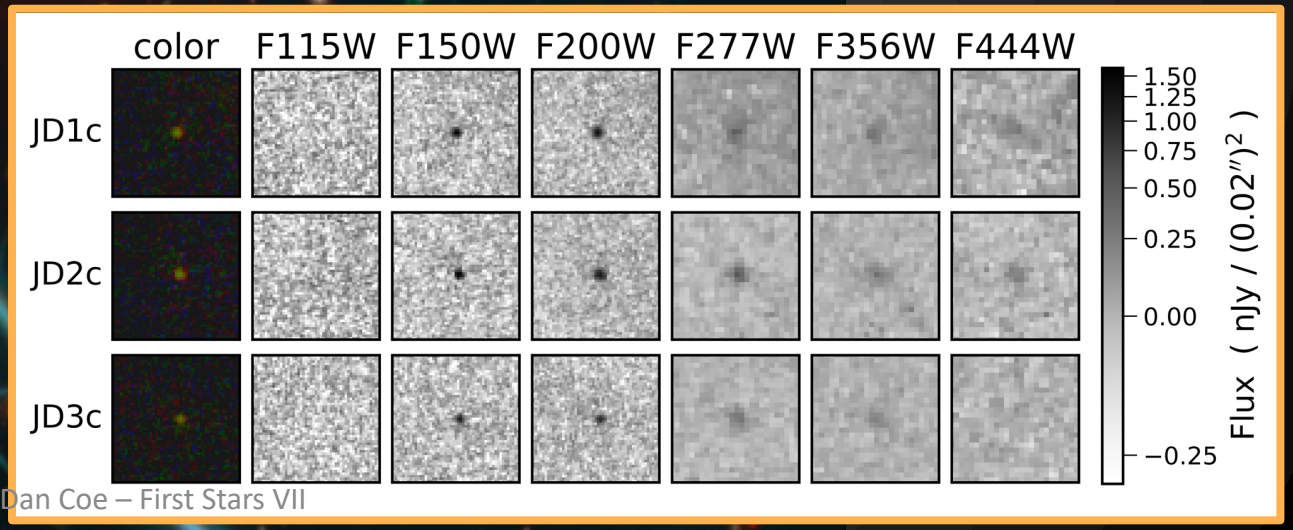
JD1

JD2

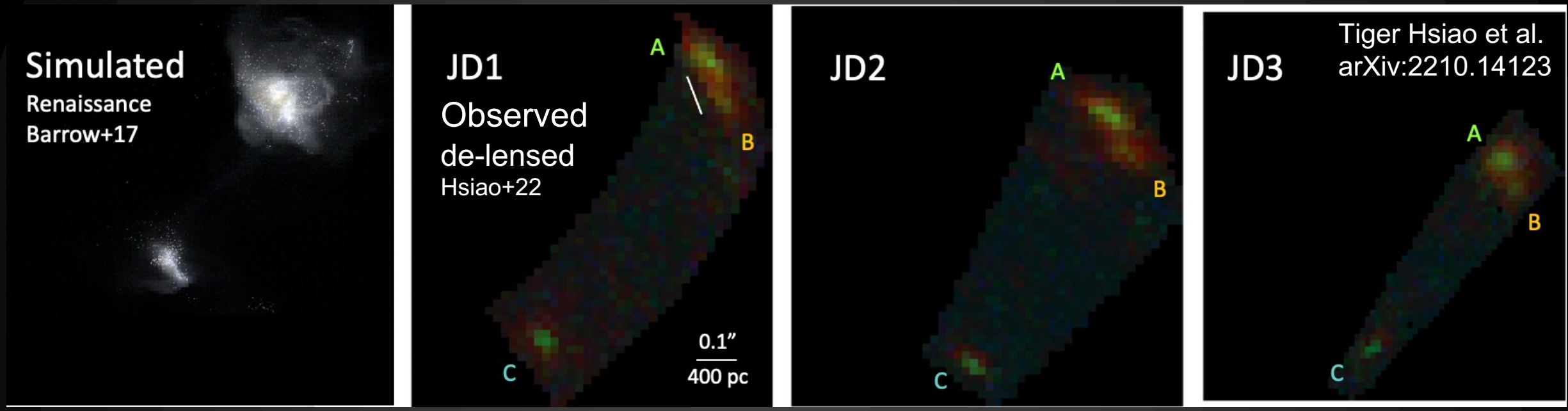
Tiger Hsiao et al.
arXiv:2210.14123

there is a companion

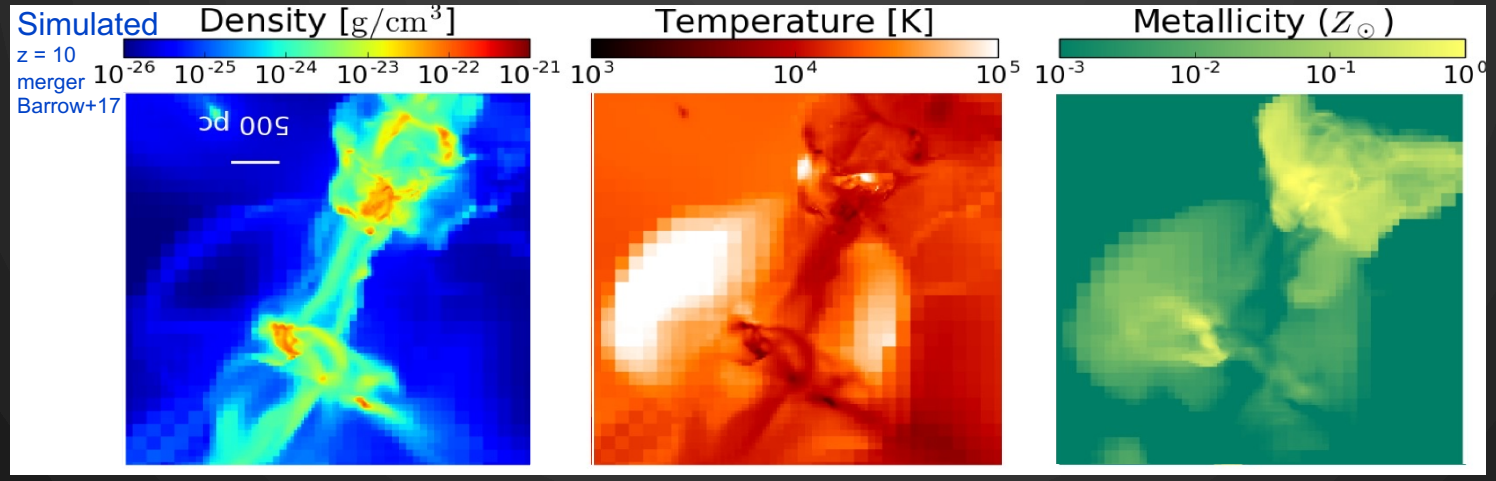




Galaxy merger 400 Myr after the Big Bang?



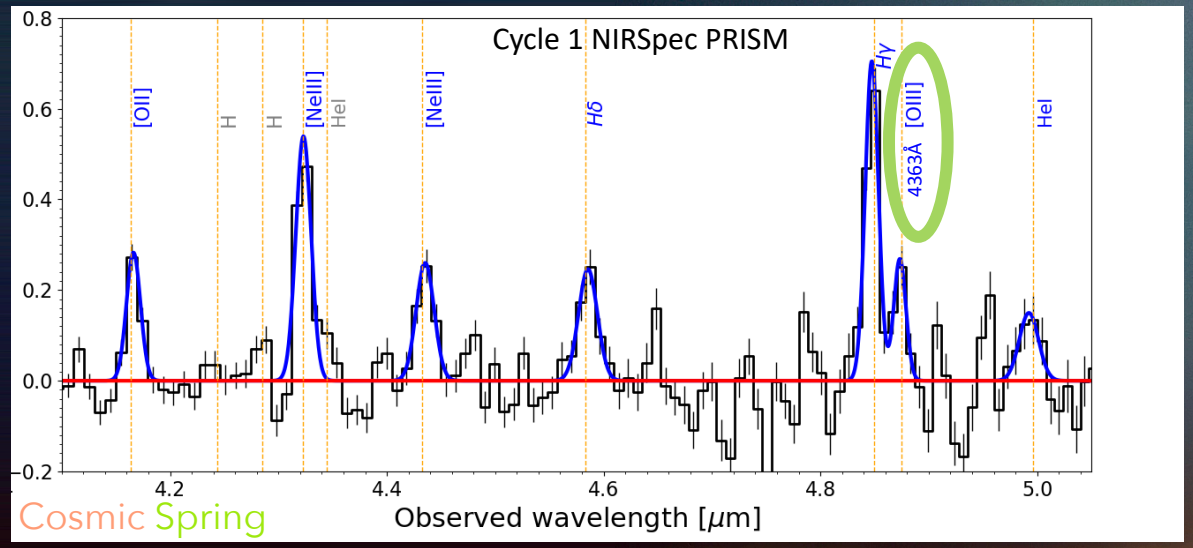
Kirk Barrow



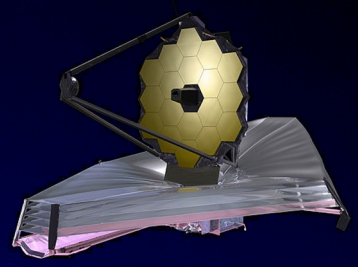

Tiger Hsiao & Abdurro'uf et al.
(co-lead authors)
arXiv:2305.03042

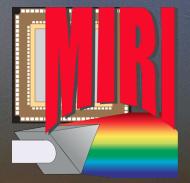
MACS0647-JD at z = 10.17 with 7 emission lines

CIII], [OII], [NeIII]x2, Hγ, Hδ,
and the auroral line [OIII] 4363Å
for direct metallicity measurement



[OIII] 5008Å



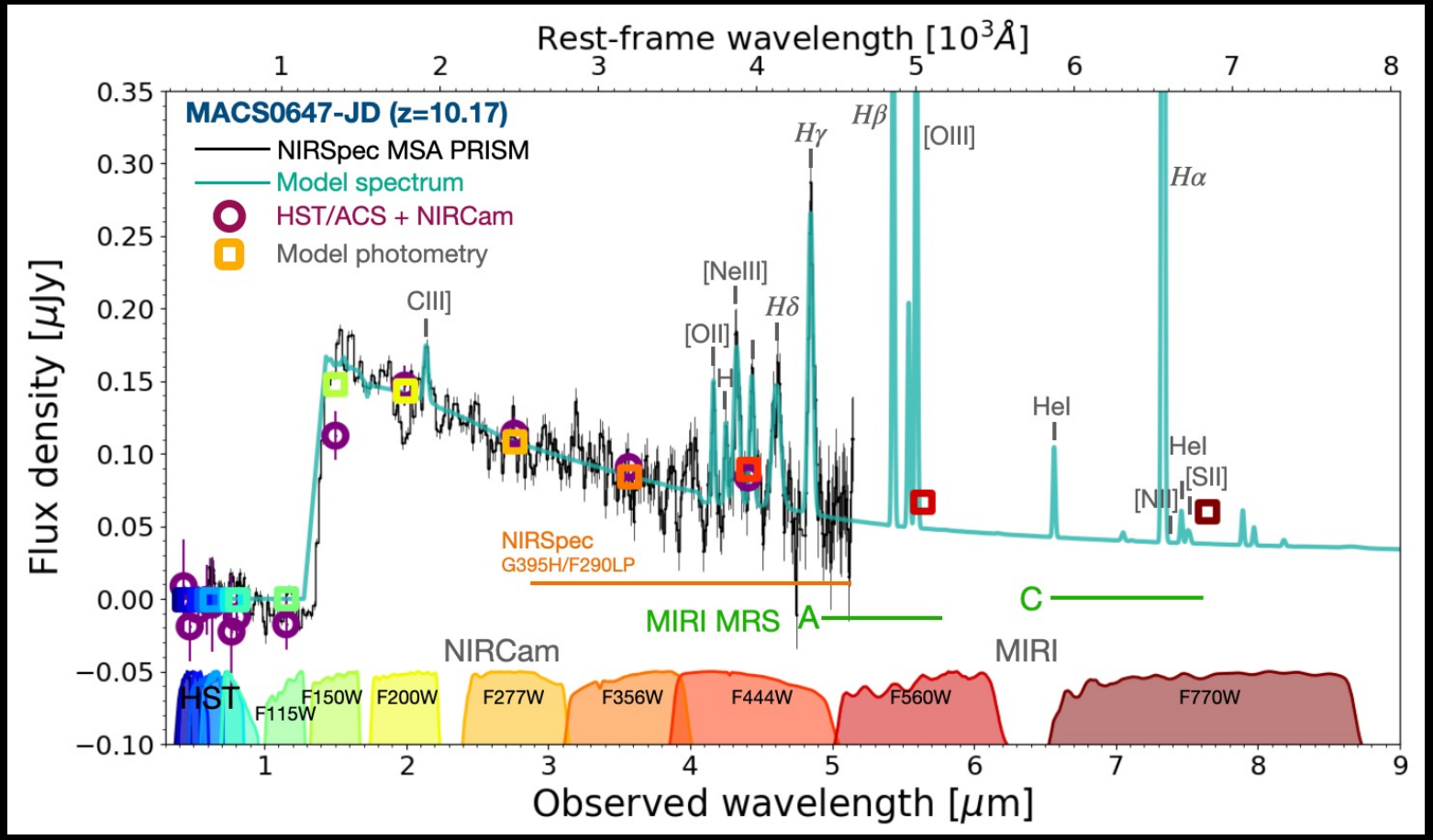


JWST Cycle 2 GO 4246 PI Abdurro'uf

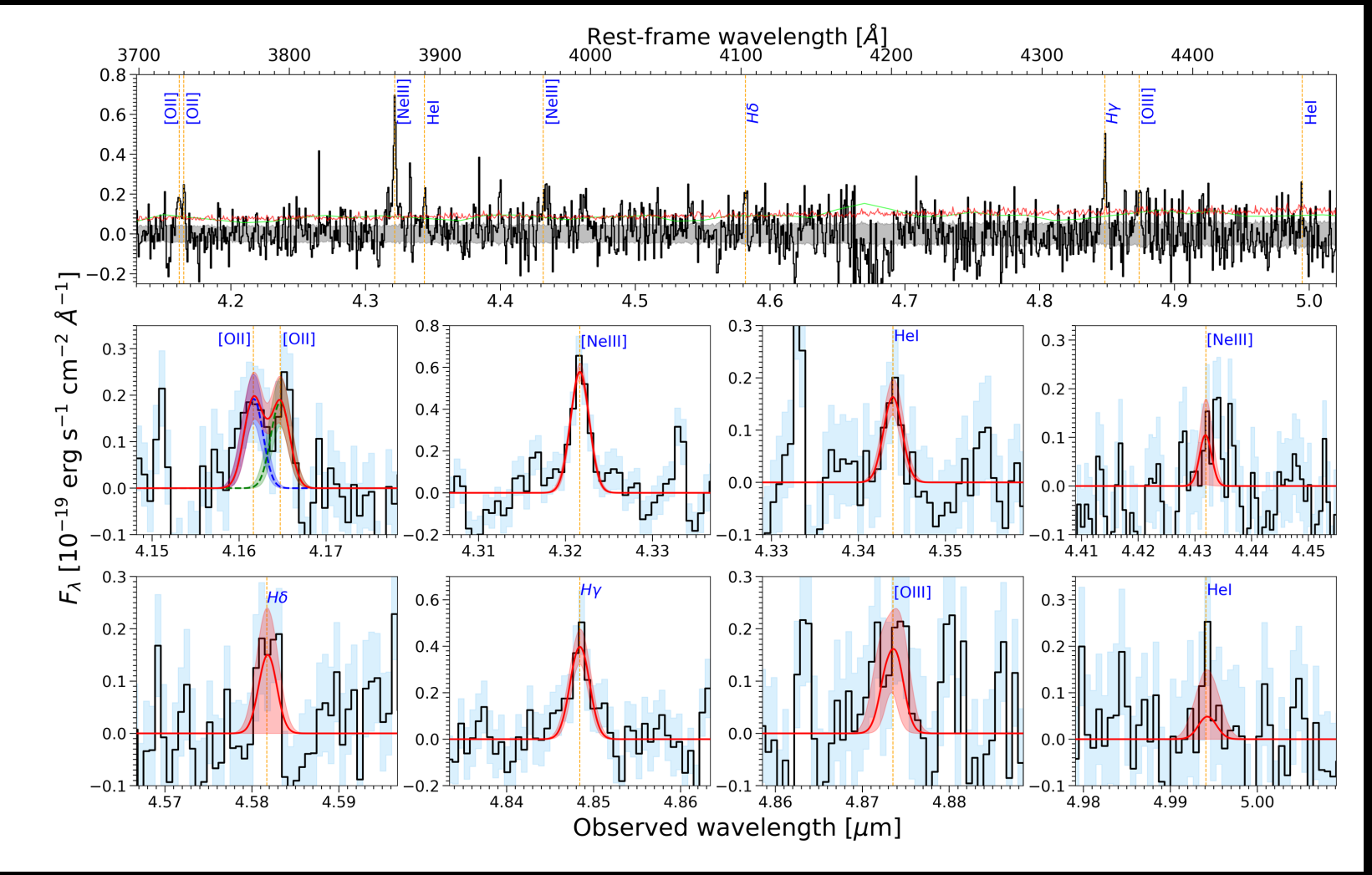
MACS0647-JD NIRSpec G395H; MIRI imaging + spectroscopy

"direct" metallicity
- [OIII] 4363Å – Cycle 1 NIRSpec PRISM
- [OIII] 5007Å – Cycle 2 MIRI MRS

[OII] doublet – resolved w/ G395H:
- gas density
- line widths
- outflows allow f_{esc}?



No strong outflows / AGN



Abdurro'uf, Larson et al. 2024

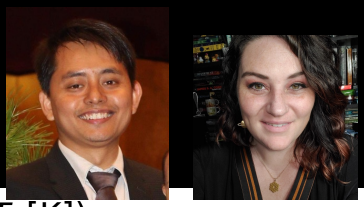
High resolution NIRSpec G395H

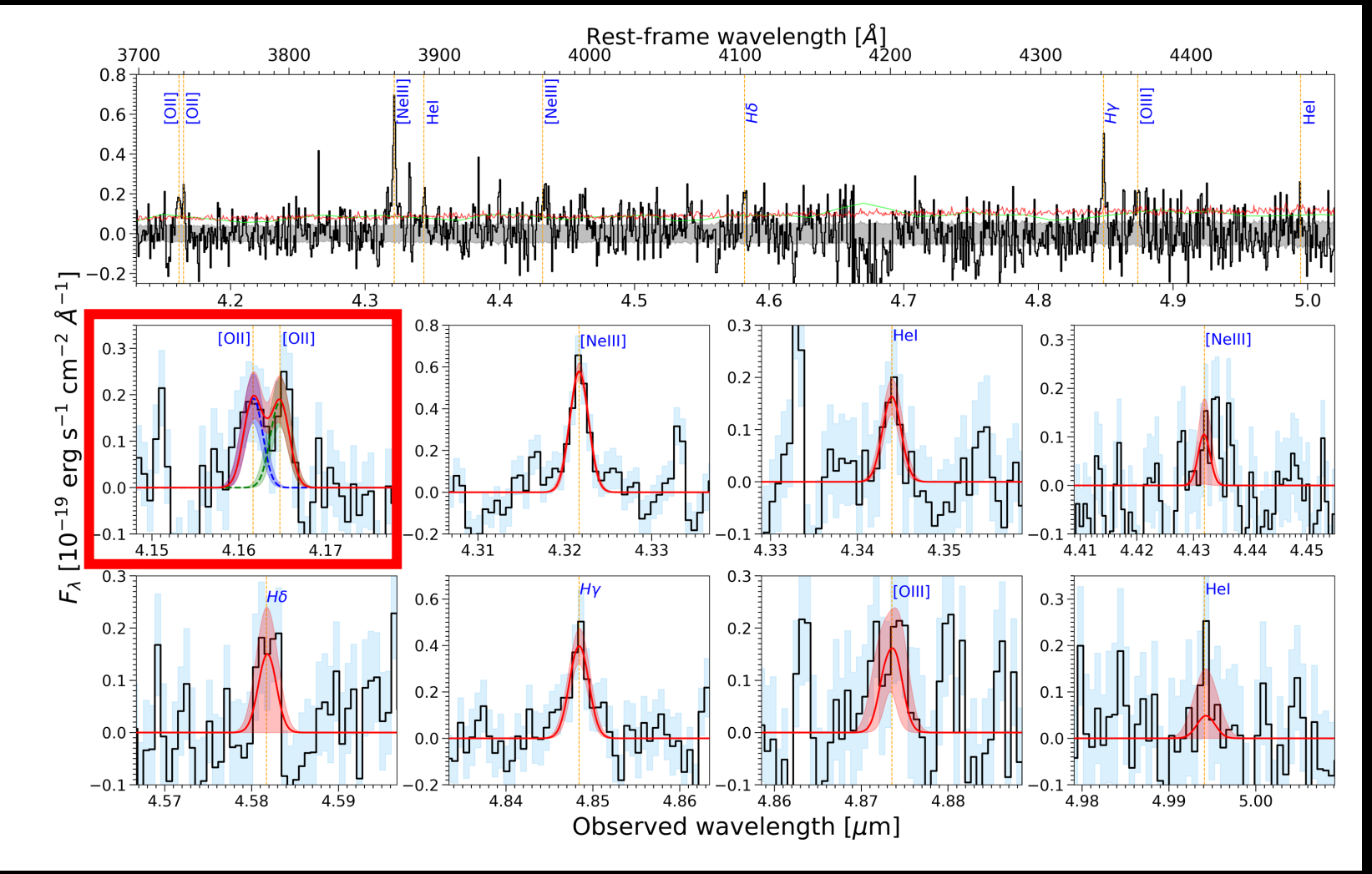
Line widths ~ 150 km/s

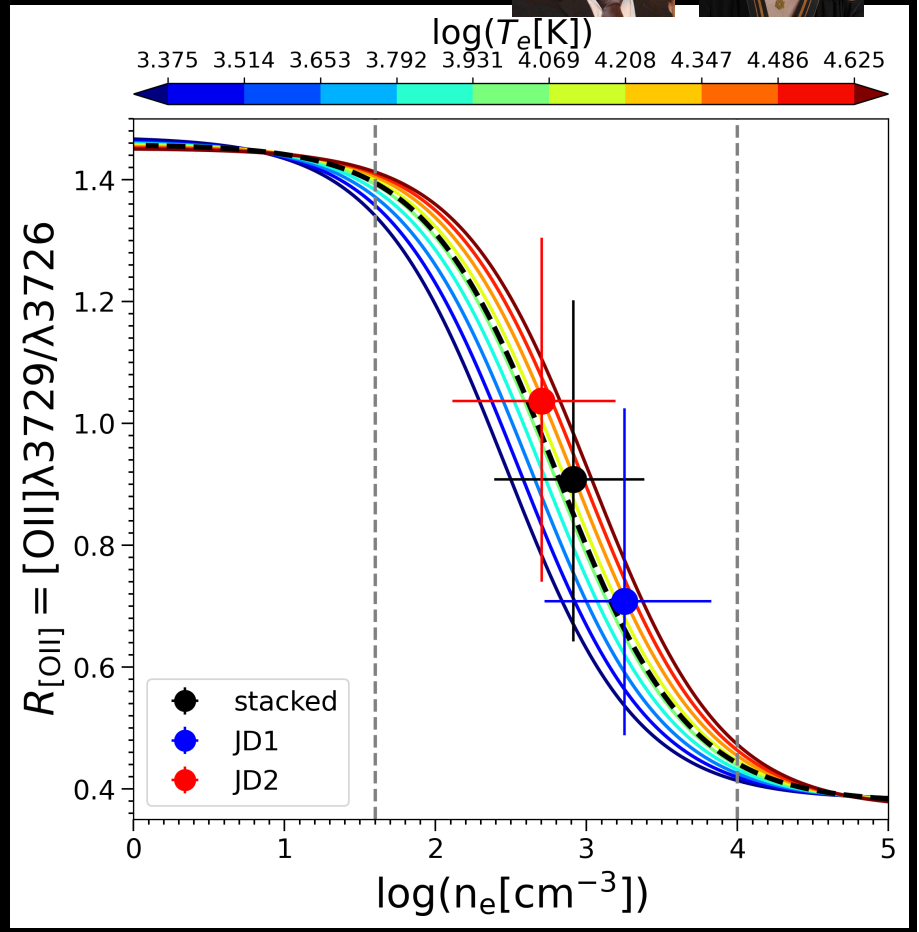
after correcting for broadening

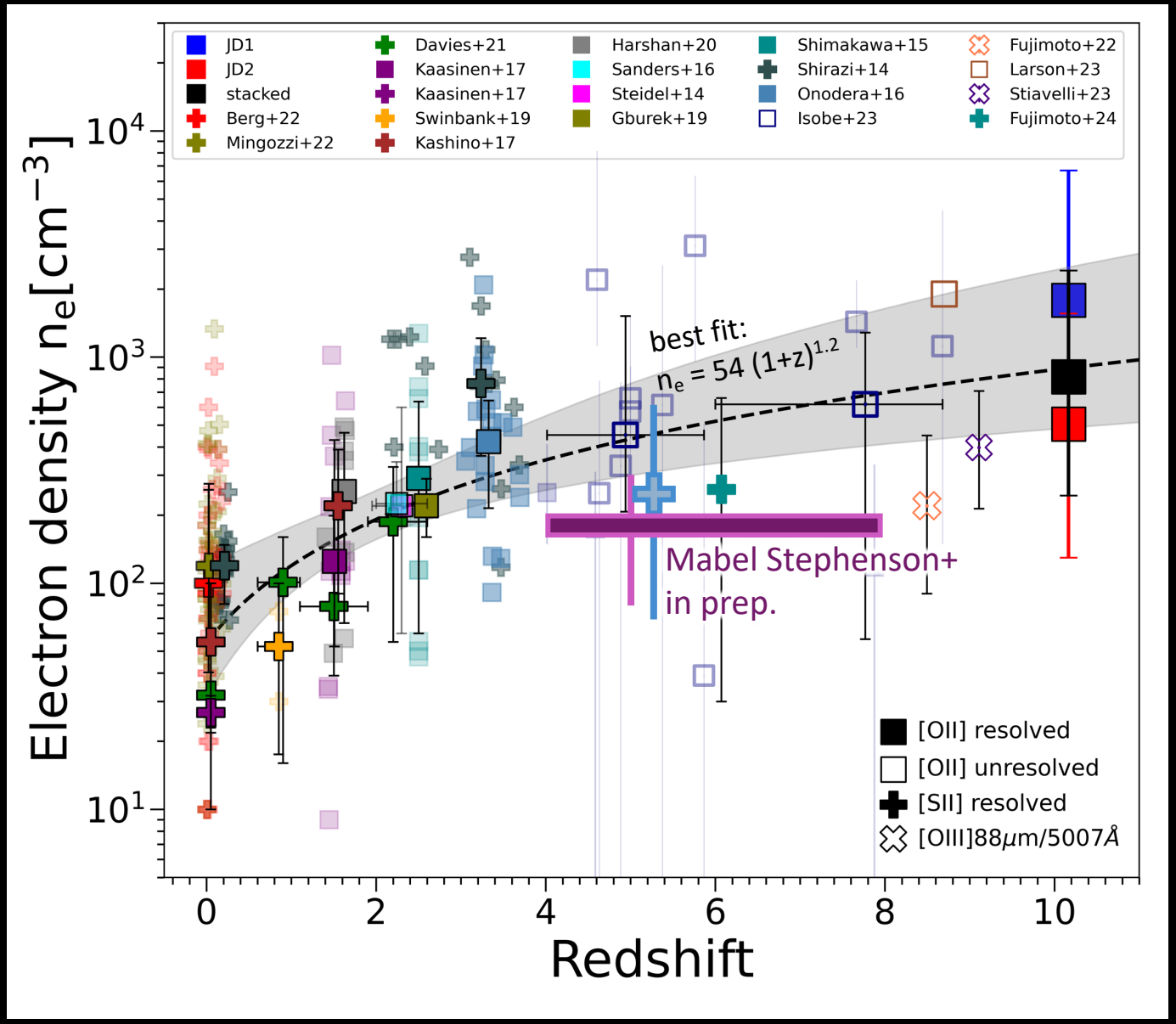
Resolved [OII] doublet: density $n_e \sim 1000$ / cm^3

Abdurro'uf, Larson et al. 2024







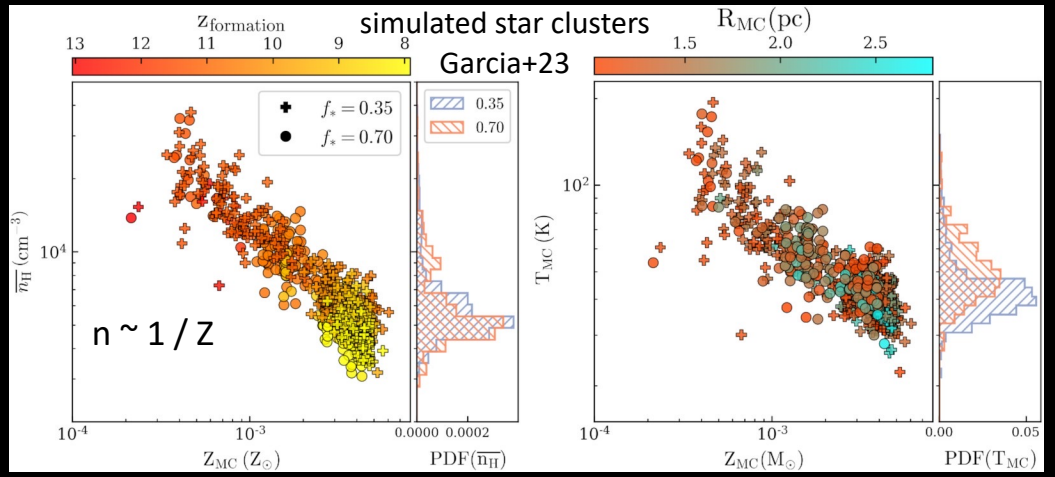


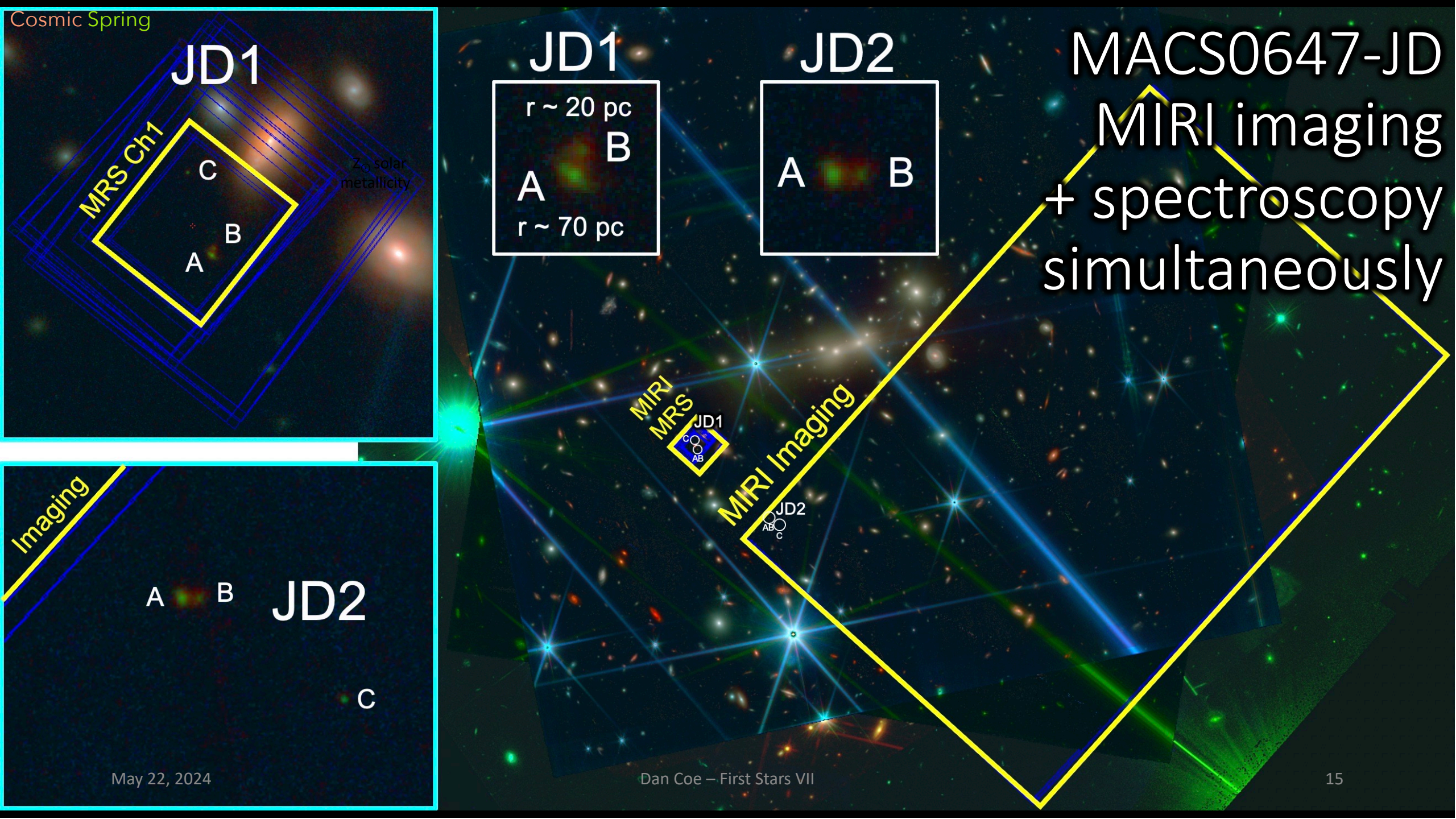
First resolved [OII] doublet at z > 8

Abdurro'uf, Larson et al. 2024

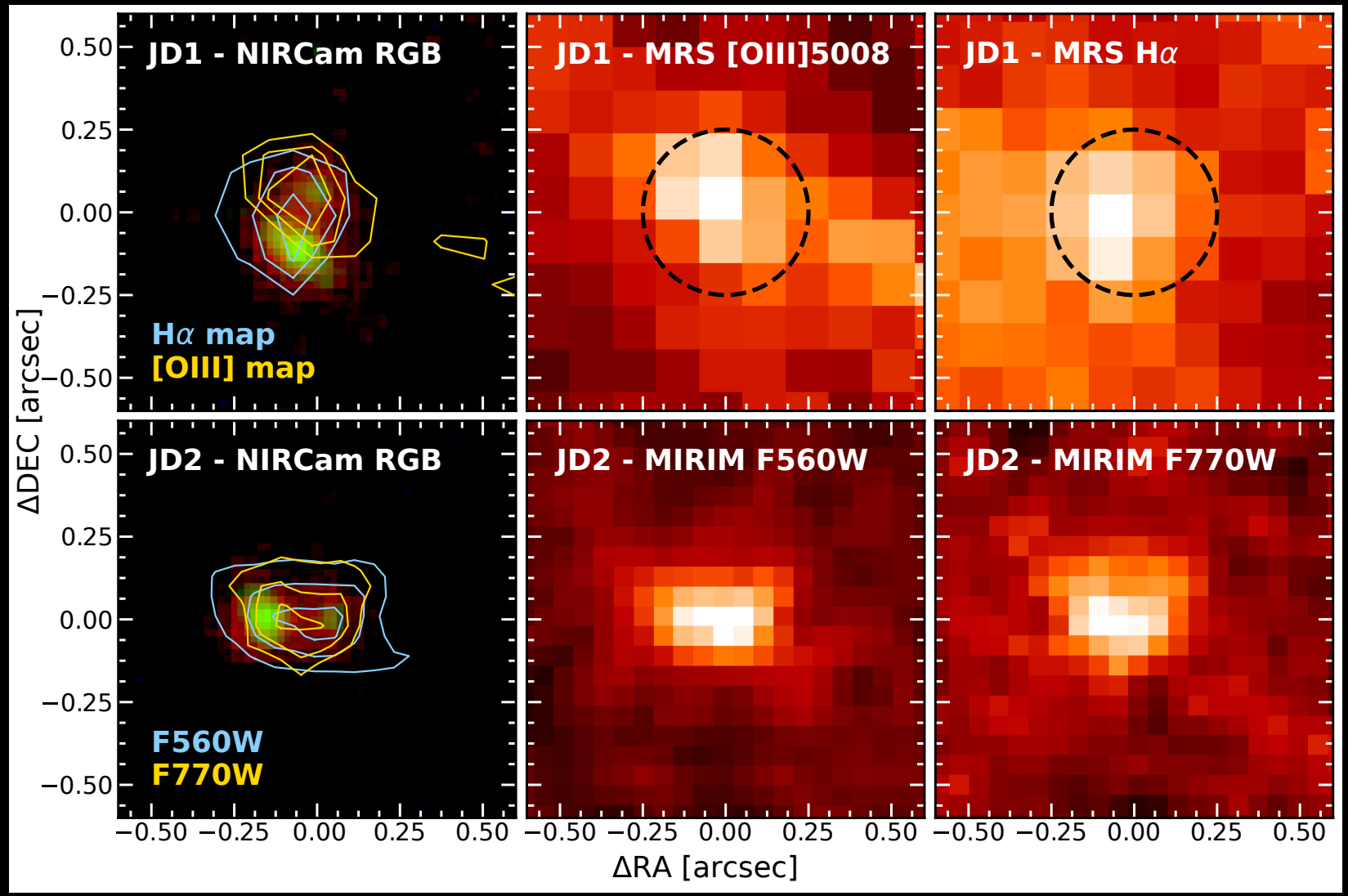
Electron density evolution with redshift

$n_e \sim 1 / Z \sim (1 + z)^p$ with p ~ 1, not 2




Cosmic Spring
JD1
MRS Ch1
C
B
A
$Z_\odot$ solar metallicity
Imaging
A
B
JD2
C
JD1
r ~ 20 pc
B
A
r ~ 70 pc
JD2
A
B
MACS0647-JD
MIRI imaging
+ spectroscopy
simultaneously
MIRI MRS
JD1
C
AB
MIRI Imaging
JD2
AB
C

MIRI detects MACS0647-JD (z=10.17)

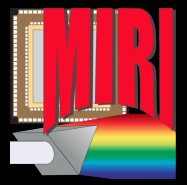


MIRI MRS IFU reductions:
Javier Álvarez-Márquez

MIRI image reductions:
Alex Crespo Gómez

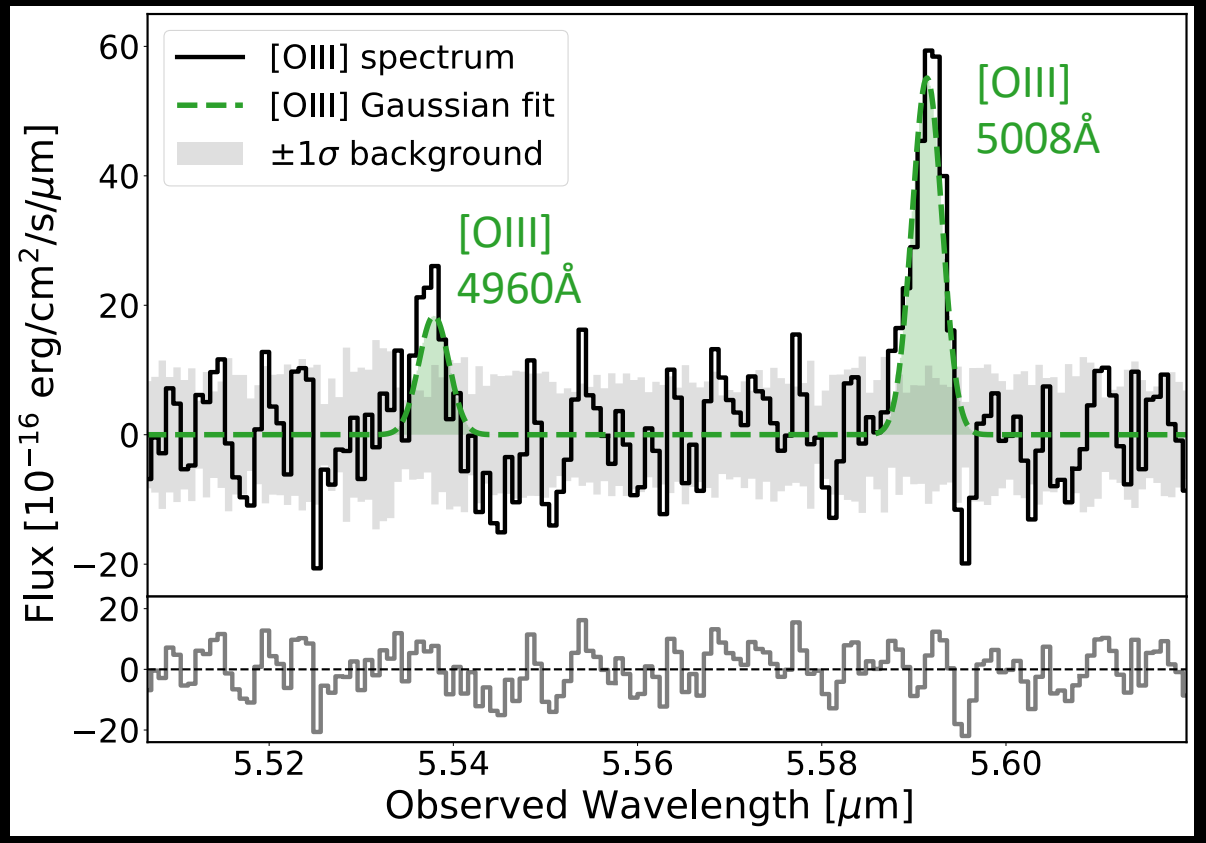
paper:
Hsiao & Álvarez et al. 2024

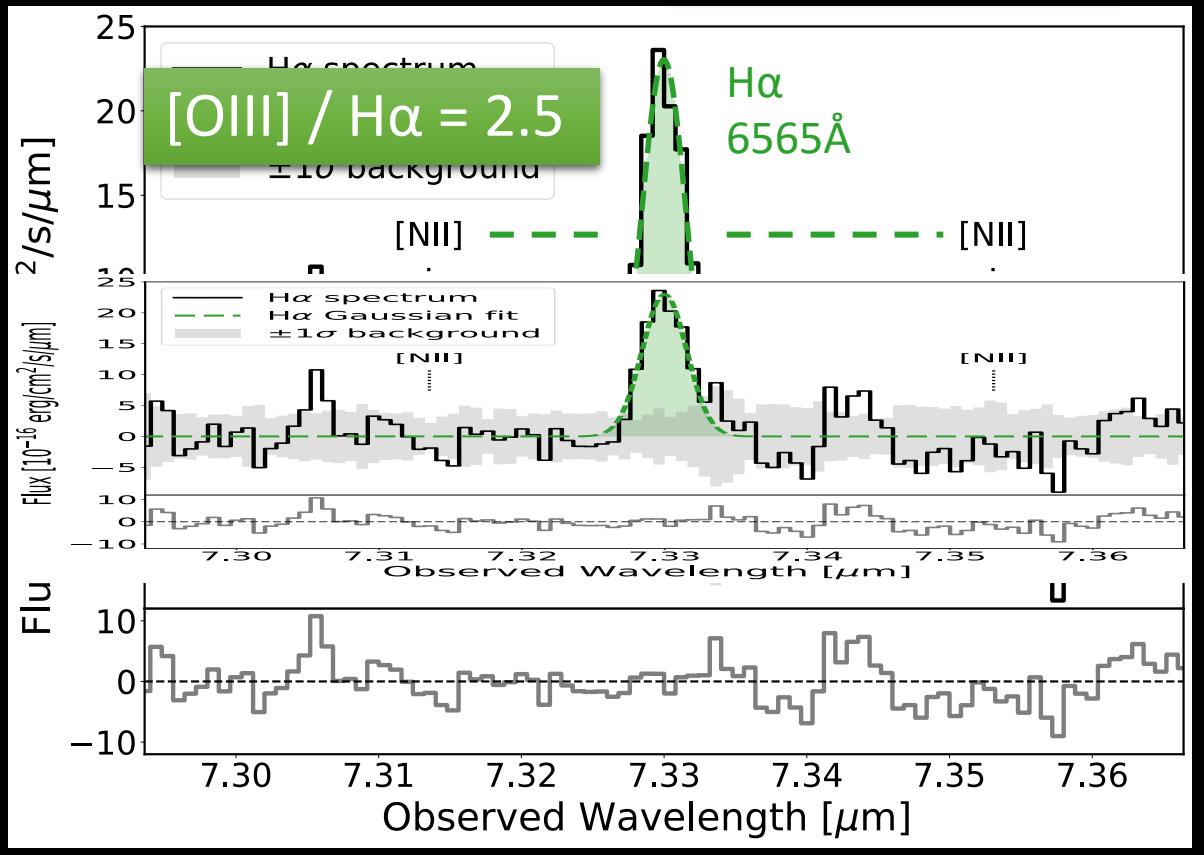
MIRI MRS: [OIII], Hα in MACS0647-JD (z=10.17)



MIRI MRS reductions and analysis: Javier Álvarez
paper: Tiger Hsiao & Javier Álvarez et al. 2024

SFR = 5.0 ± 0.6 $M_\odot$ / yr
$\log(\xi_{ion})$ = 25.3 ± 0.1
log(U) = –1.9 ± 0.1





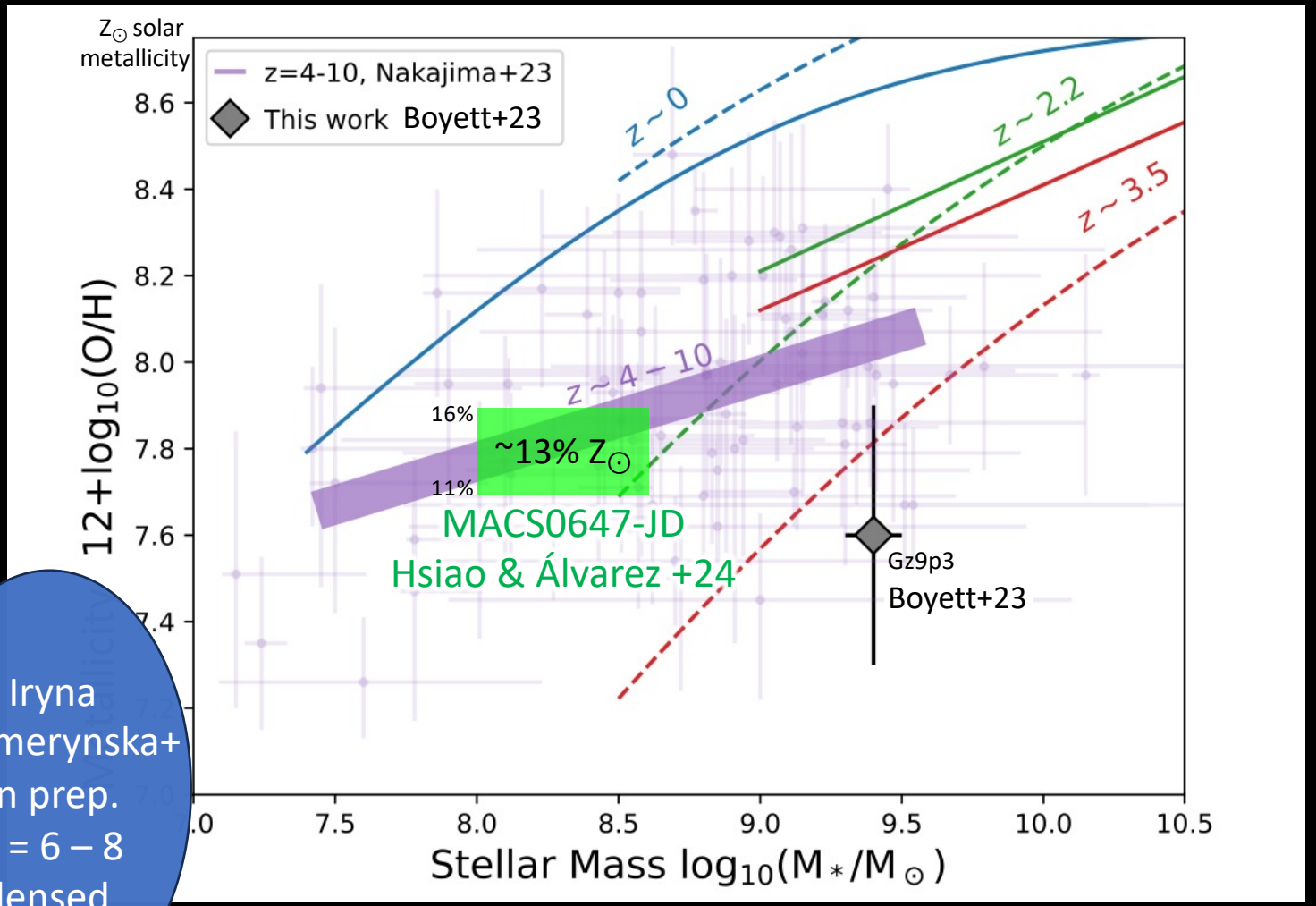
MACS0647-JD direct metallicity consistent with other z ~ 4 – 10 measurements

[OIII] 5007 / 4363 = 40 ± 5

T_e [OIII] = 17000 ± 2000 K

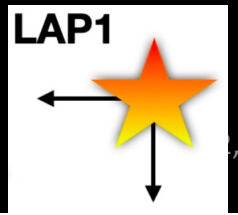
12+log(O/H) = 7.8±0.1

~13% $Z_\odot$ (11 – 16%)



Iryna Chemerynska+ in prep. z = 6 – 8 lensed

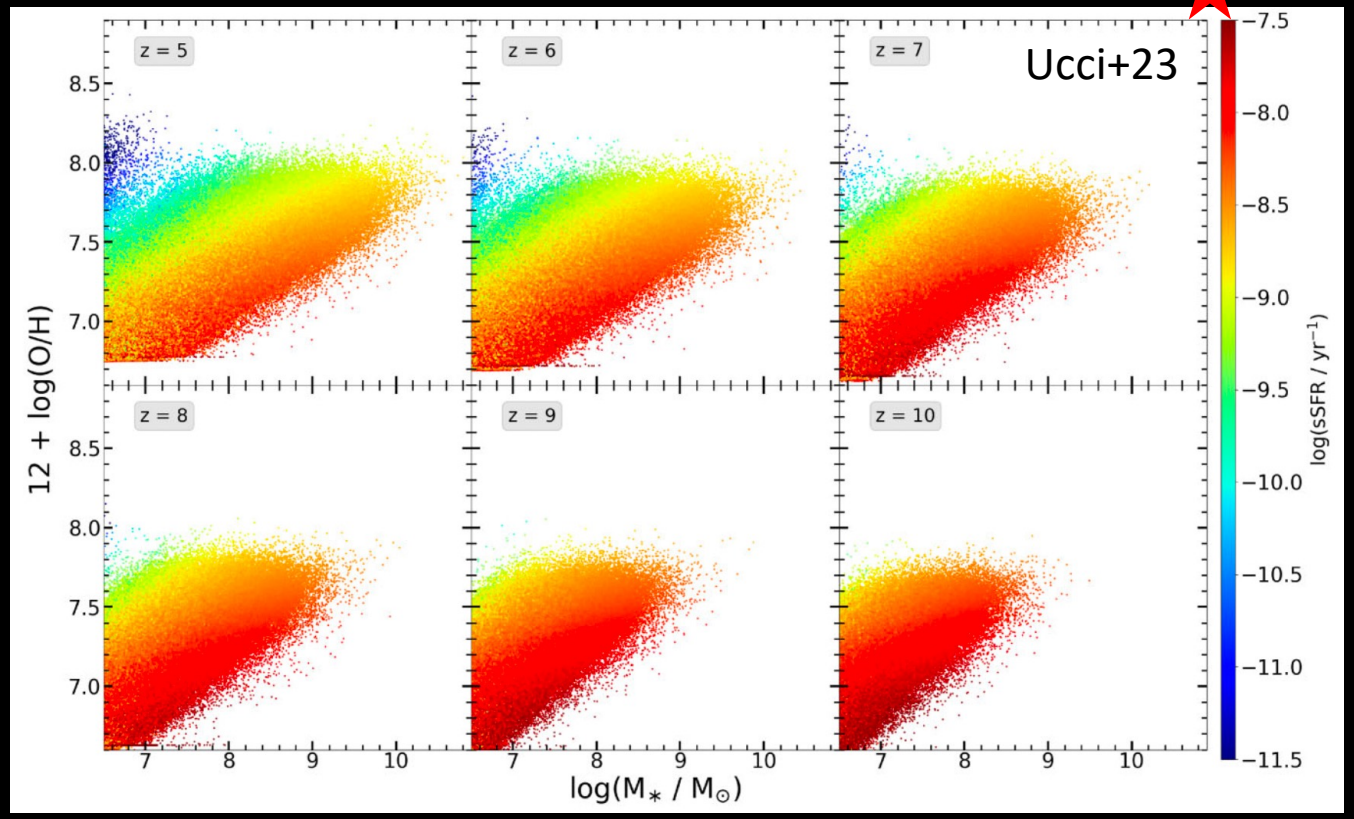
Eros Vanzella+ arXiv:2305.14413 z = 6.64 lensed



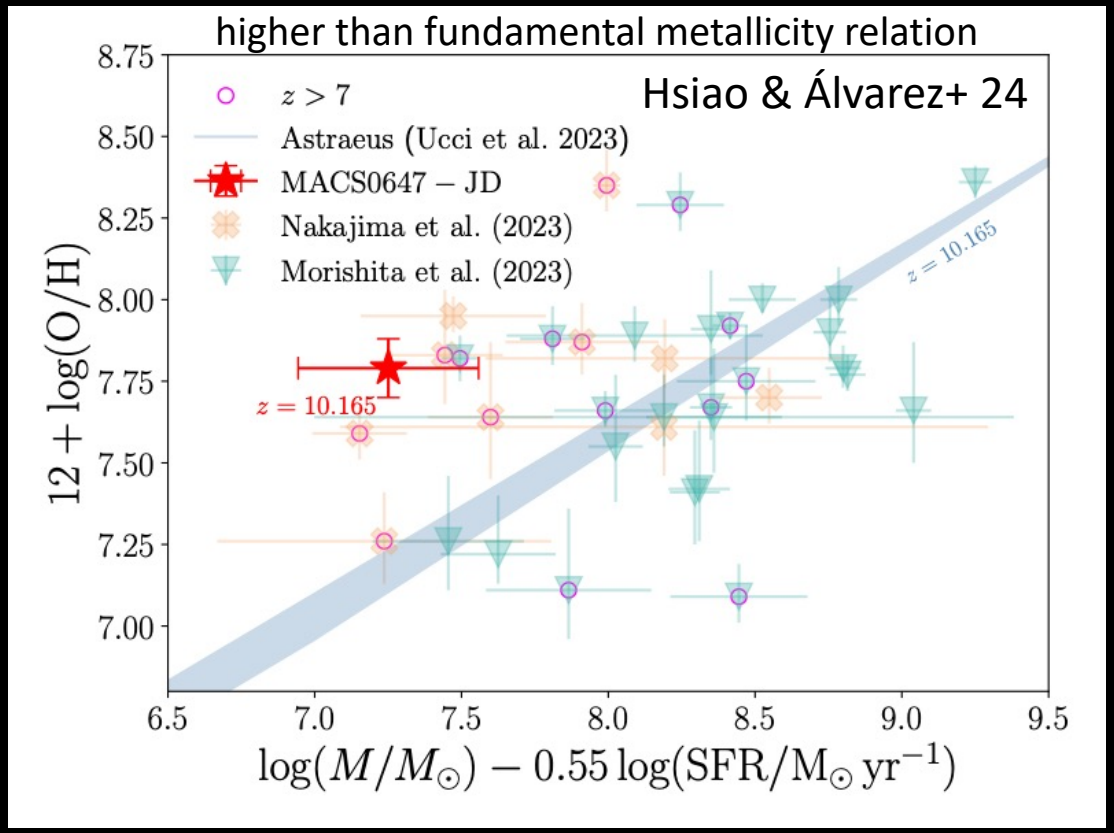
Expect lower metallicity given high specific star formation rate

MACS0647-JD ★
SFR: star formation rate = 5 $M_\odot$ / yr
M*: stellar mass = 10 ^ 8.1 $M_\odot$
sSFR: specific SFR = SFR / M*
sSFR = 10 ^ –7.4 / yr

★ –7.4



higher than fundamental metallicity relation

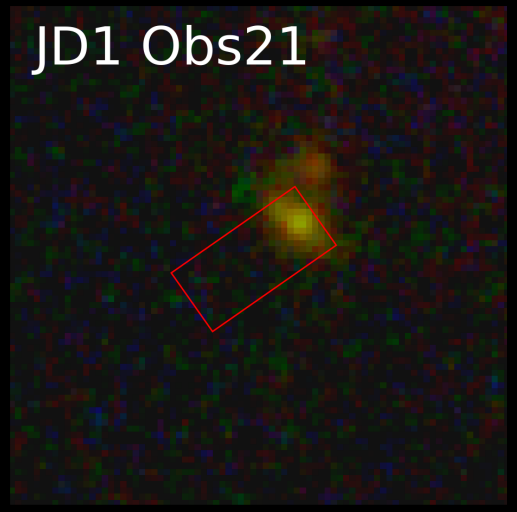


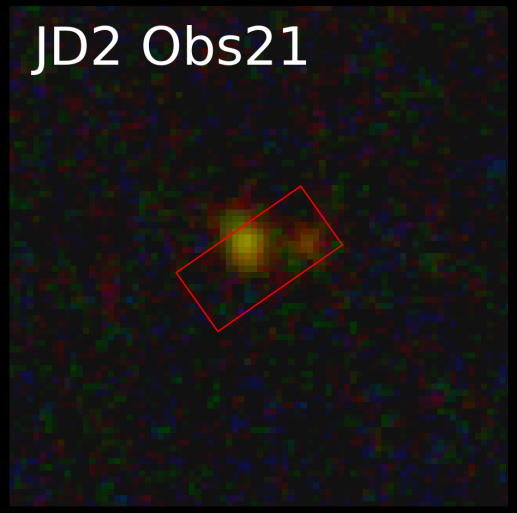
Cycle 1 (GO 1433)

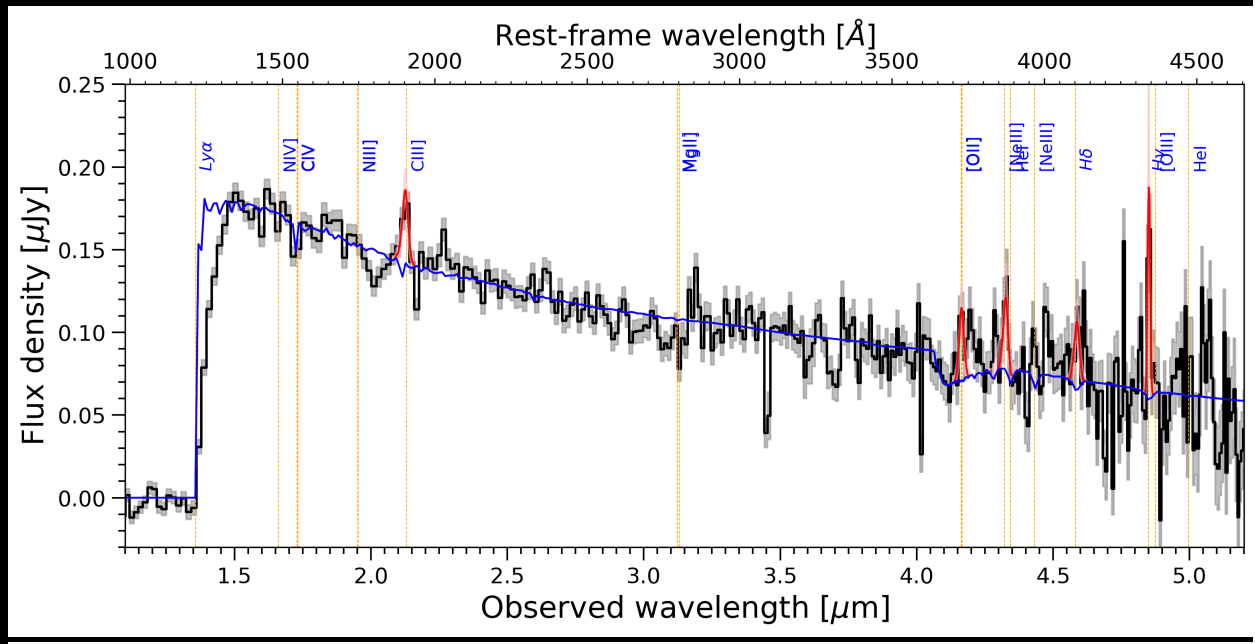
Metallicity of each clump?

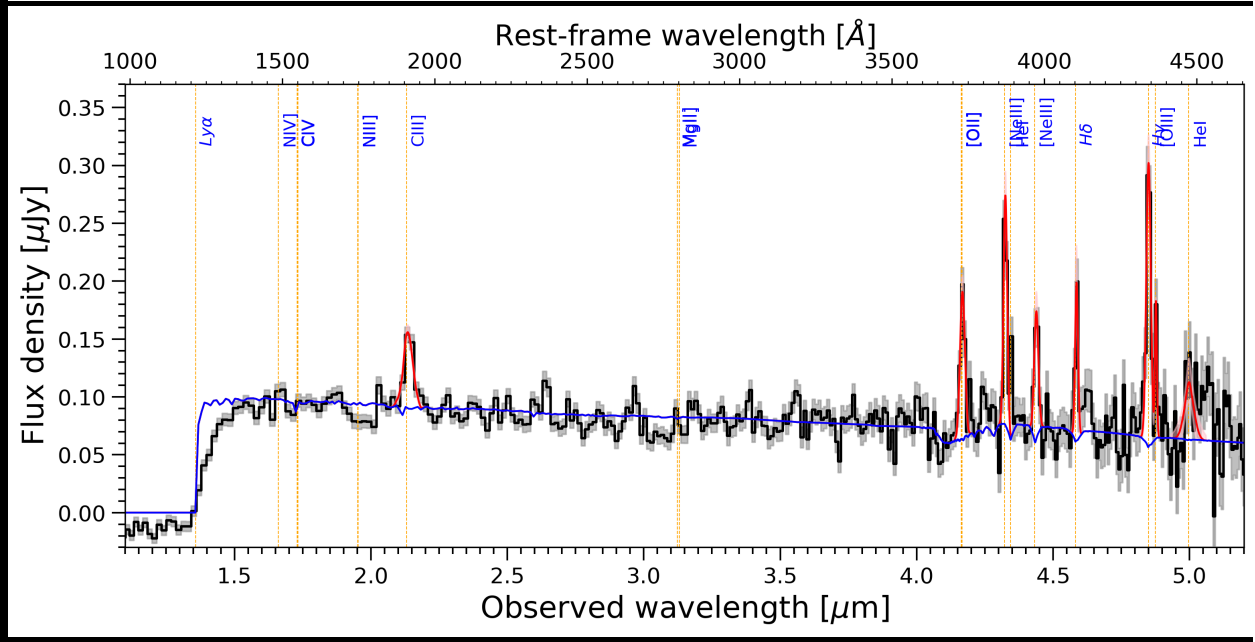
Where is the emission coming from?

upcoming JWST Cycle 3
NIRSpec IFU G395M
GTO 4528 (PI Isaak)
+13 targets incl.
MACS0647-JD





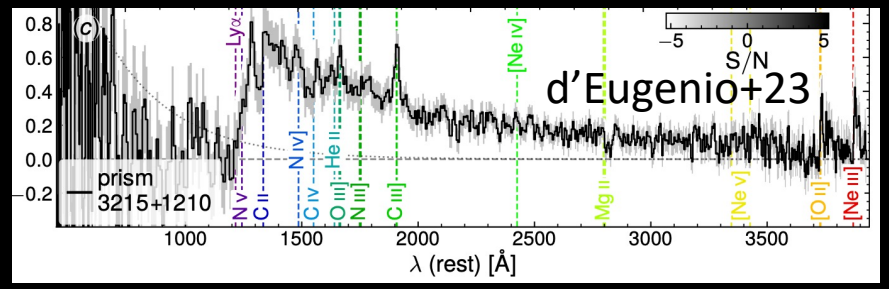


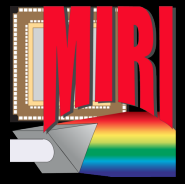


z > 10 galaxies have “extreme” spectra

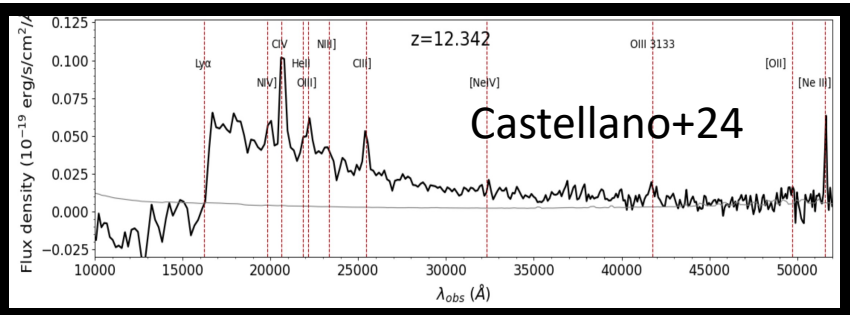
unexpected, requiring explanation

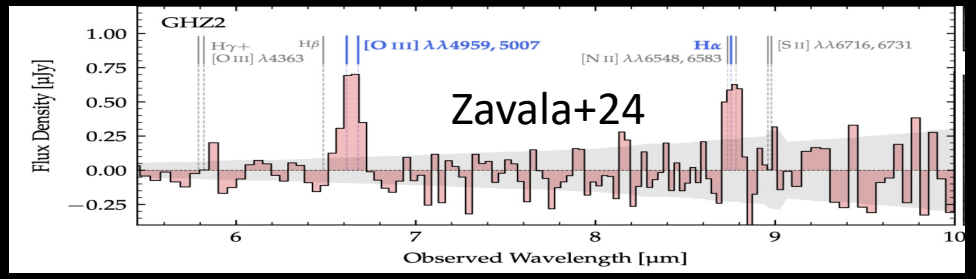
GS-z12
z = 12.48 (350 Myr)
M_{UV} = –18.2
AB mag 29.0
extreme C/O



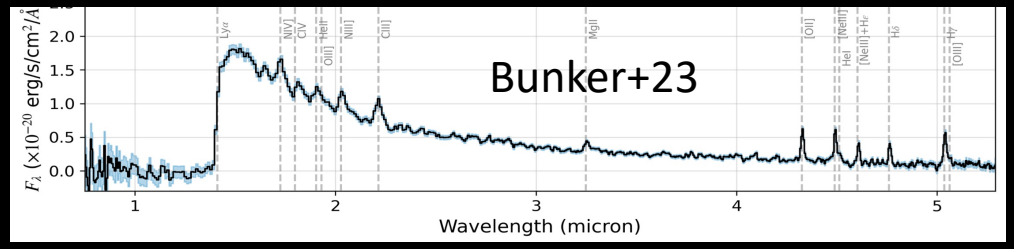


GHZ2/GLASS-z12
z = 12.34 (360 Myr)
M_{UV} = –20.5
AB mag 27
extreme N/O, CIV



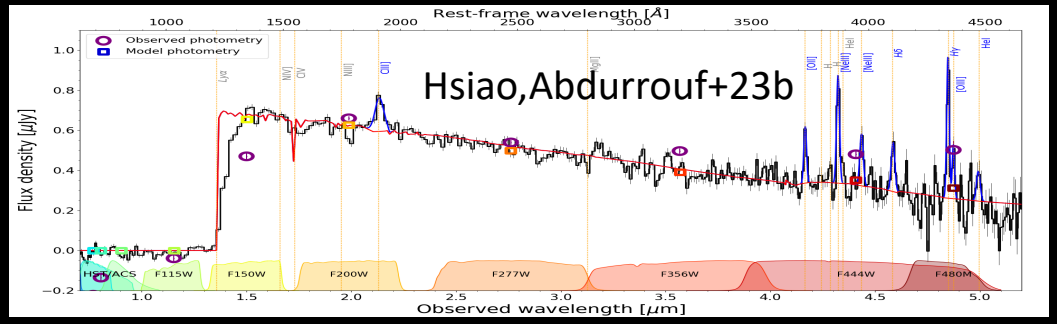


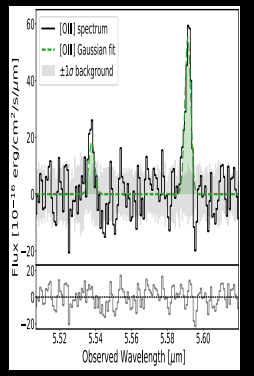
GN-z11
z = 10.60 (430 Myr)
M_{UV} = –21.5
AB mag 26.0
extreme N/O, AGN



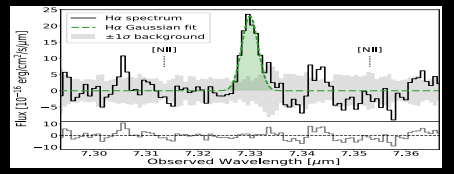
MIRI in prep. (PI Colina)

MACS0647-JD
z = 10.17 (460 Myr)
M_{UV} = –20.3
25.0+25.4+26.2=24.2
extreme…?



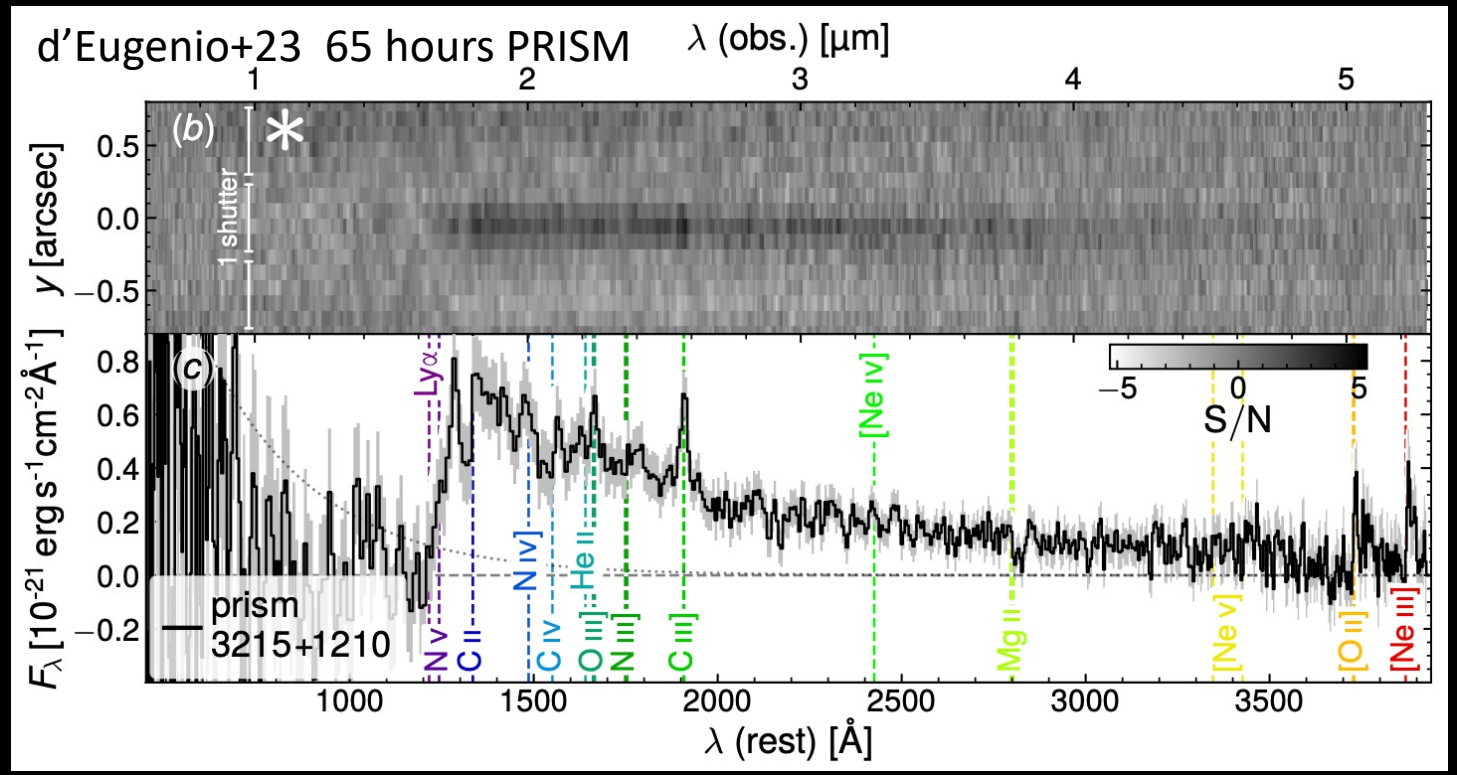


Hsiao & Álvarez+ 24

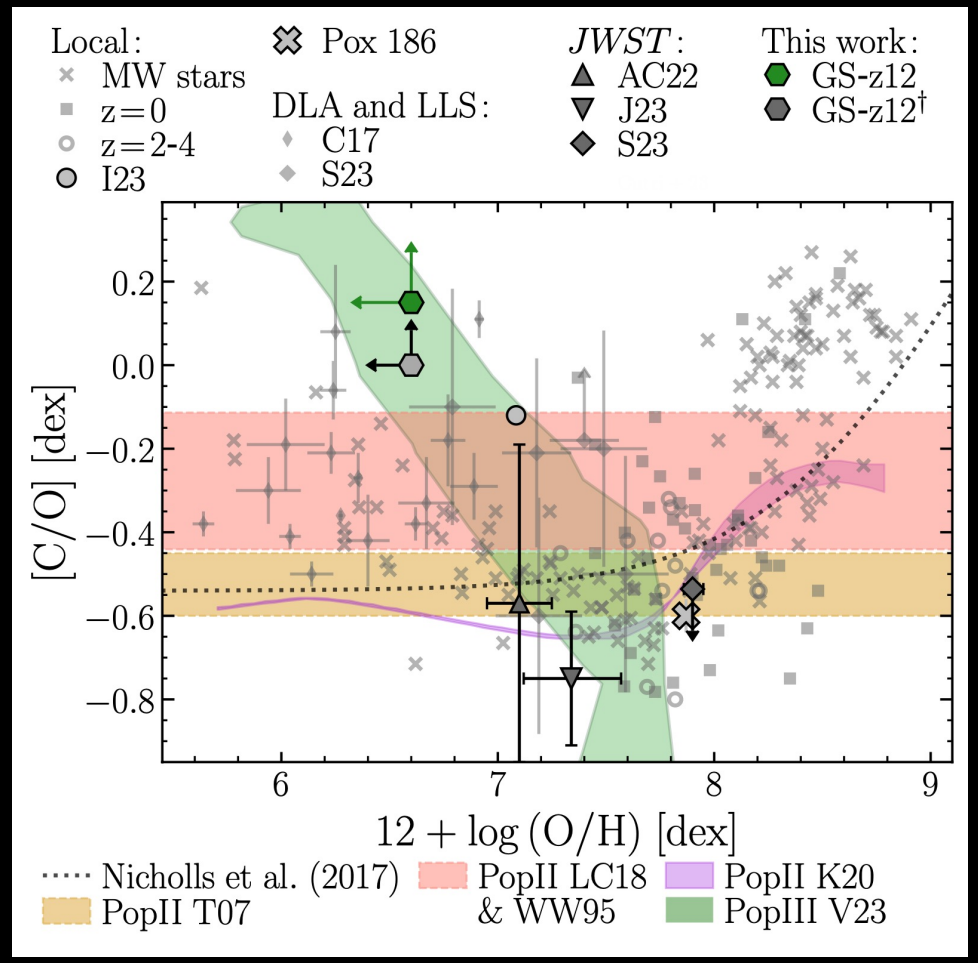


GS-z12
z = 12.48
MUV = –18.2
AB mag 29.0
[C/O] > 0.15

Super solar C/O

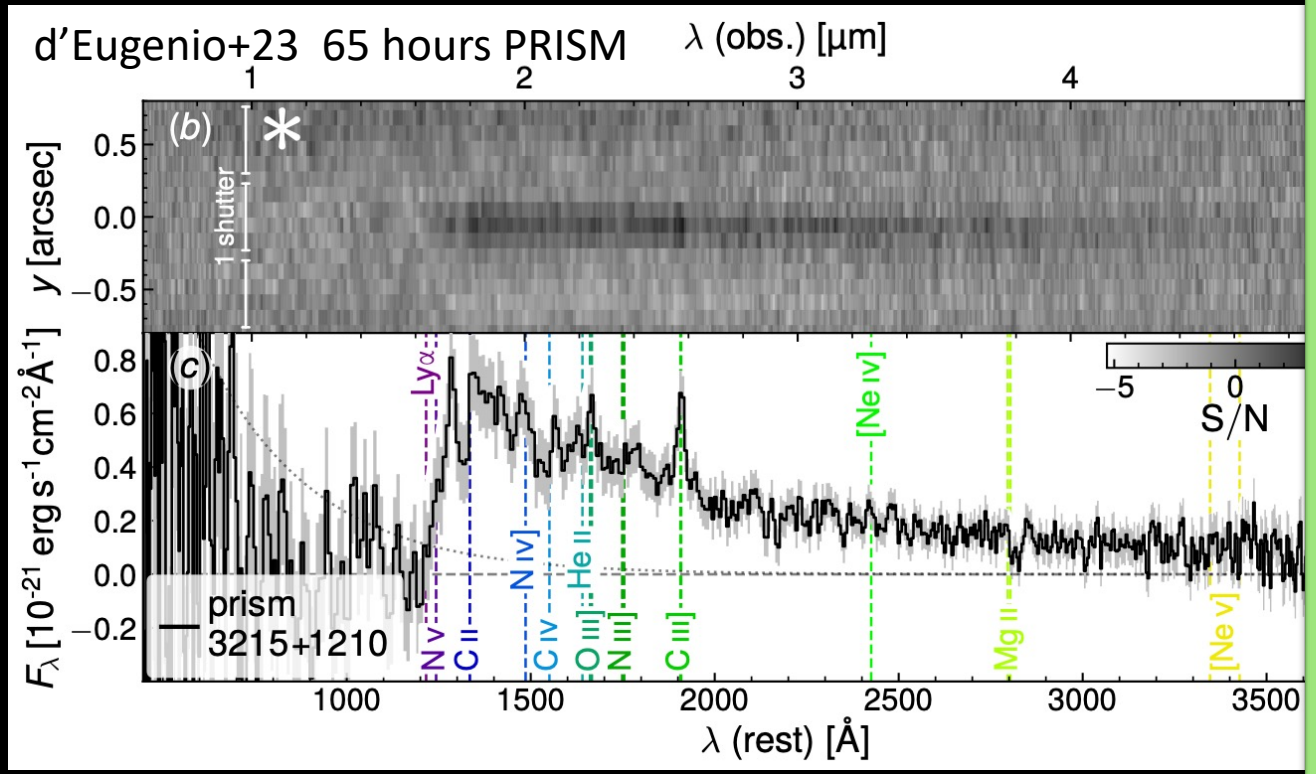


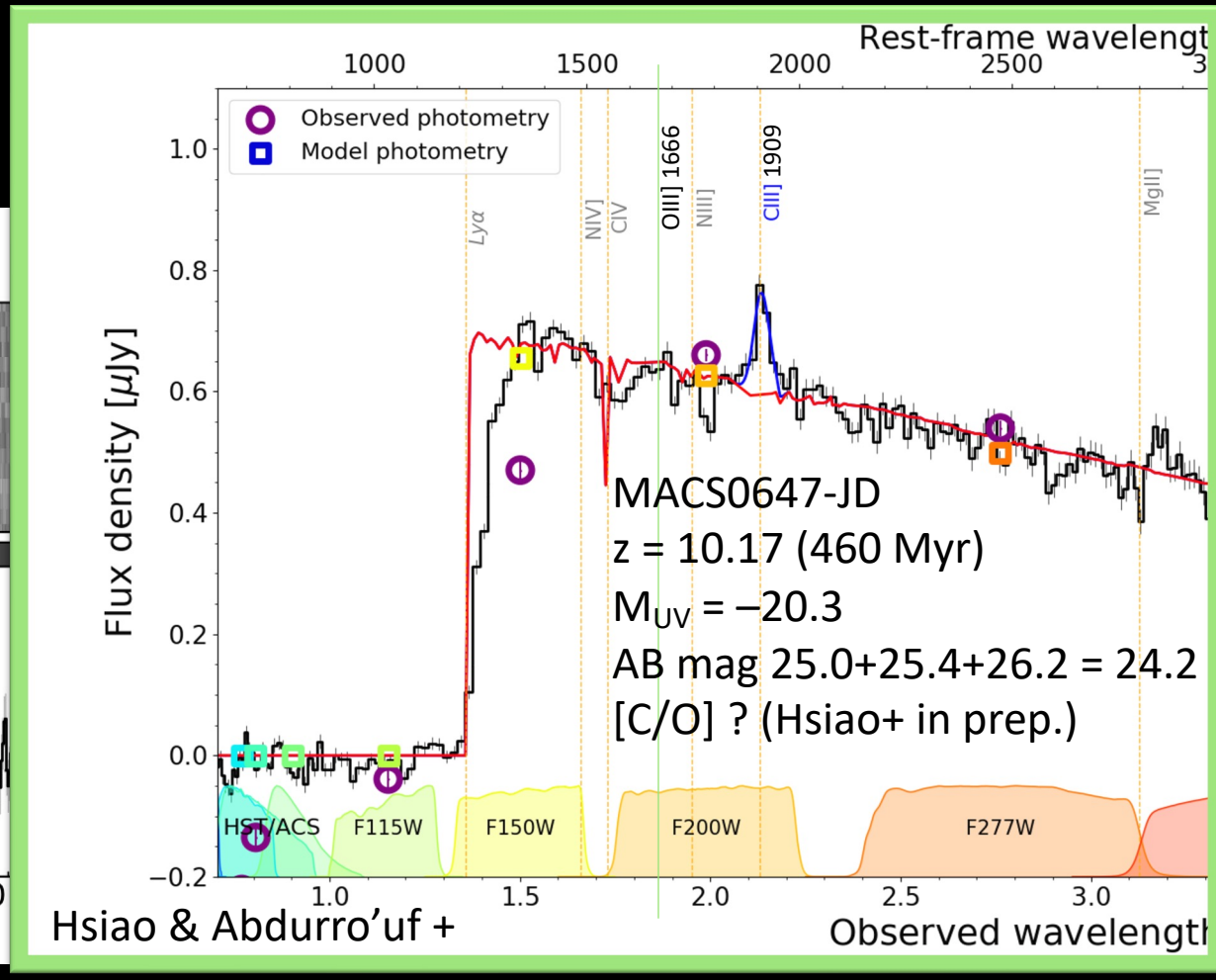
Pop III supernova enriched?



GS-z12
z = 12.48
MUV = –18.2
AB mag 29.0
[C/O] > 0.15

Super solar C/O?

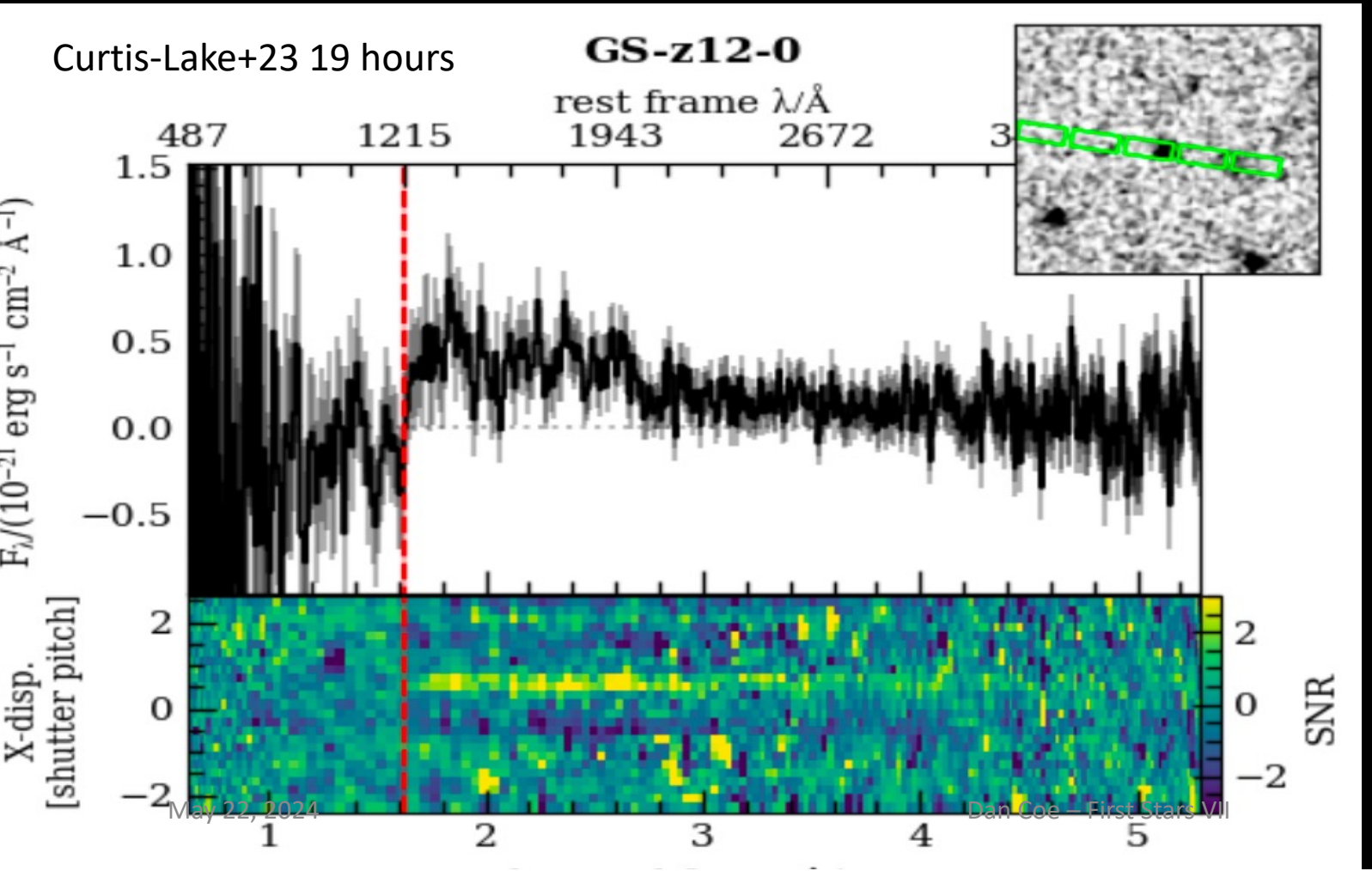




GS-z12
z = 12.48
MUV = –18.2
AB mag 29.0

Required super deep spectrum
65 hours >> 19 hours

Curtis-Lake+23 19 hours



d'Eugenio+23

This detection of the most distant metal transition, which has provided such precious information about the earliest phases of the chemical enrichment, has required a very long exposure (65 h, although mostly as a parallel observation). This is due to the extreme faintness of such distant galaxies. However, in the future, large-area surveys and gravitational lenses may help identify more high-redshift galaxies that are sufficiently bright for deep spectroscopic follow up with shorter exposures.

RELICS
Reionization Lensing Cluster Survey

SPT0615-JD: the most distant lensed arc “the smudge”

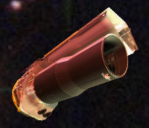
z ~ 10 (500 Myr)

featuring papers led by:

Brett Salmon
Hubble

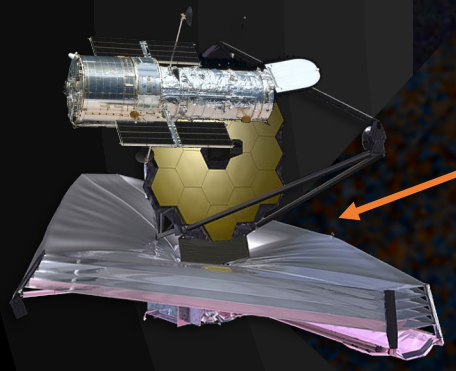
Victoria Strait
Spitzer

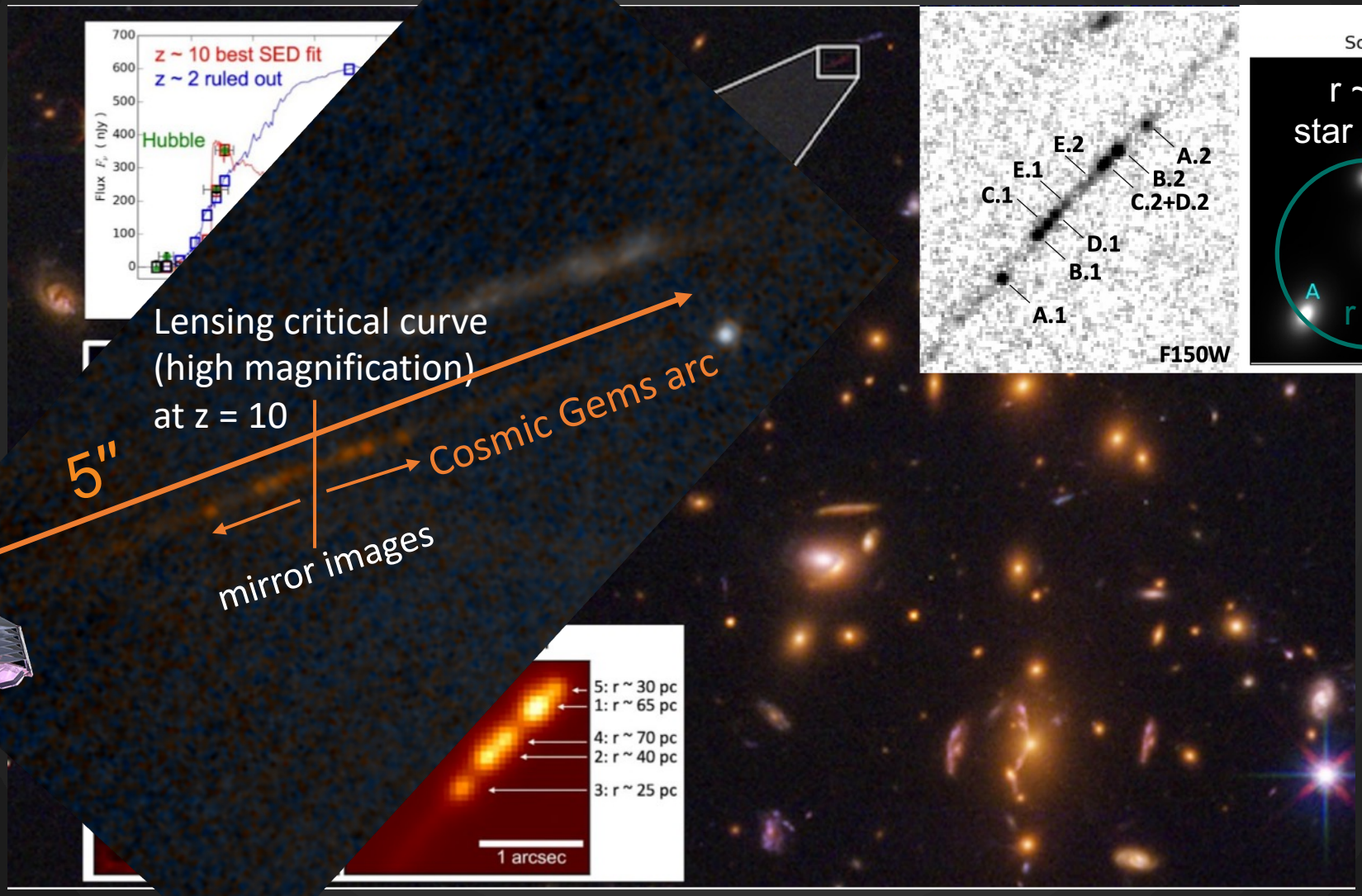
Rachel Paterno-Mahler
lens modeling

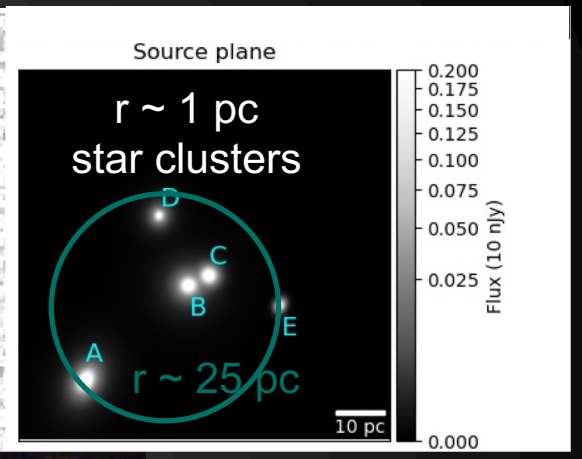


JWST: the smudge comes into focus

Larry Bradley
JWST Cycle 2
PI GO 4246

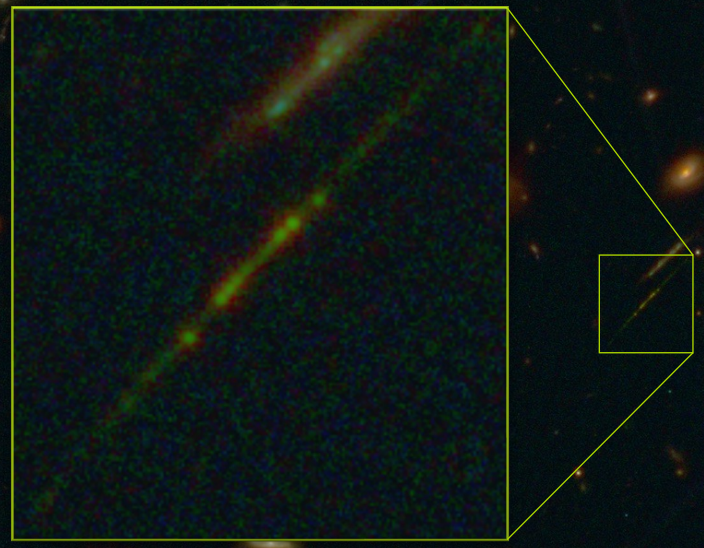






Angela Adamo
et al. 2024

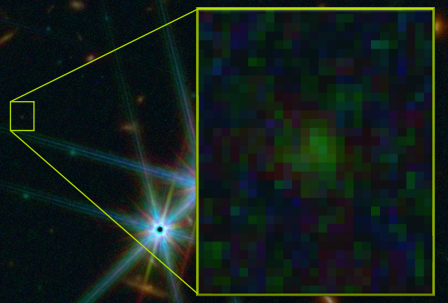
Cosmic Gems arc



high magnification
μ ~ 60
x 2 images

F200W
AB mag 25.3
x 2 =
AB mag 24.5

delensed
AB mag 29.7
M_{UV} = –17.8
M_* ~ 4e7 $M_\odot$

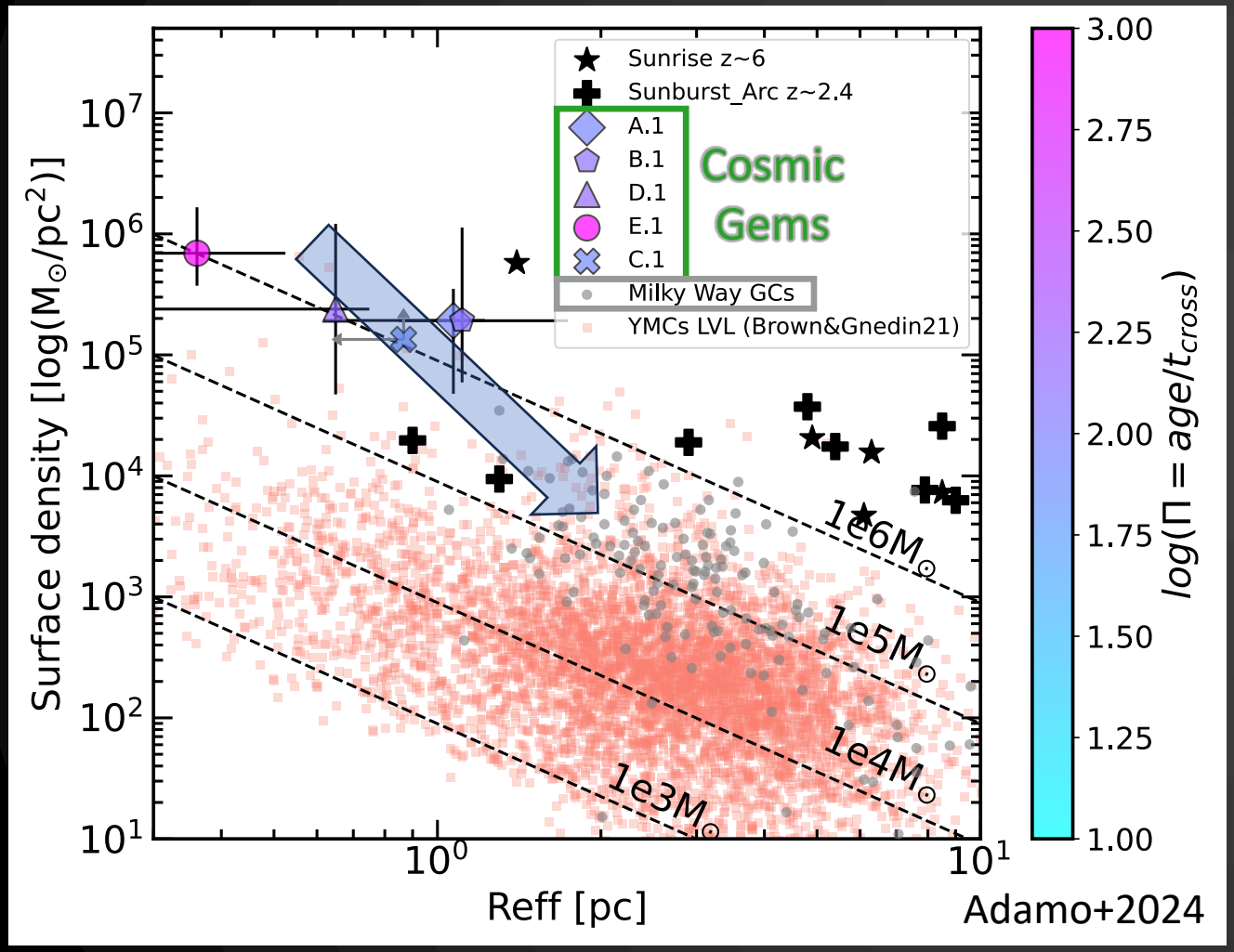


low magnification
μ ~ 2
AB mag 28.4
full galaxy

Adamo et al. 2024
Bradley et al. 2024

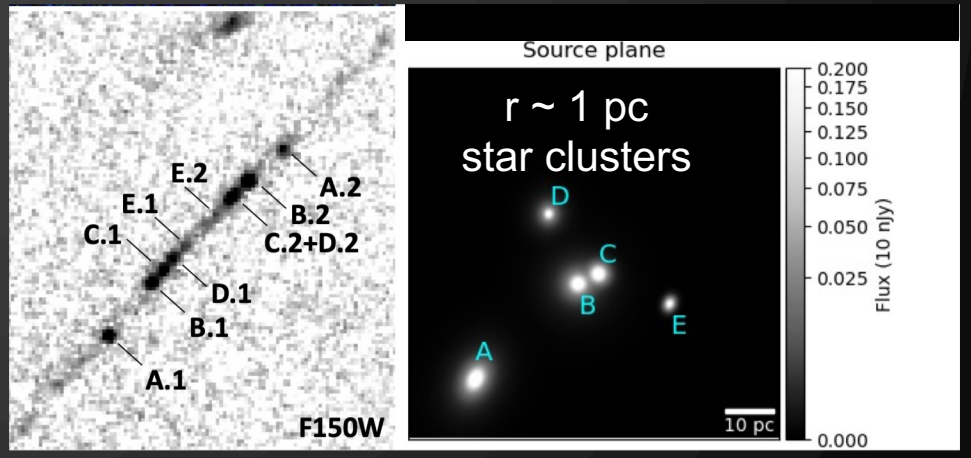
Cosmic Spring

Cosmic Gems: most distant bound star clusters known

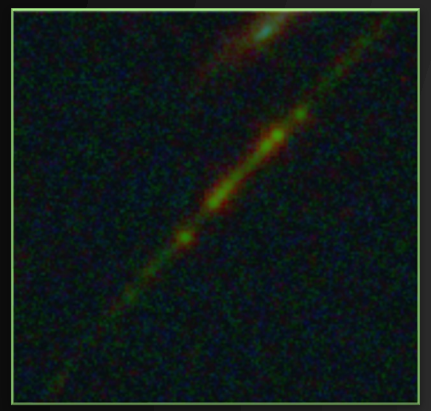


very small and dense clumps ~2e6 $M_\odot$
gravitationally bound (age > 10 $\sqrt{R^3/GM}$)

Expected to evolve, relax, and expand
to resemble globular clusters
in our own galaxy

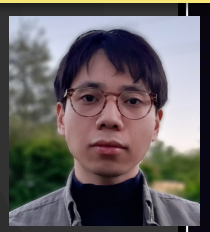


Dense star clusters and mergers may drive starbursts helping to explain abundance of “bright” early galaxies



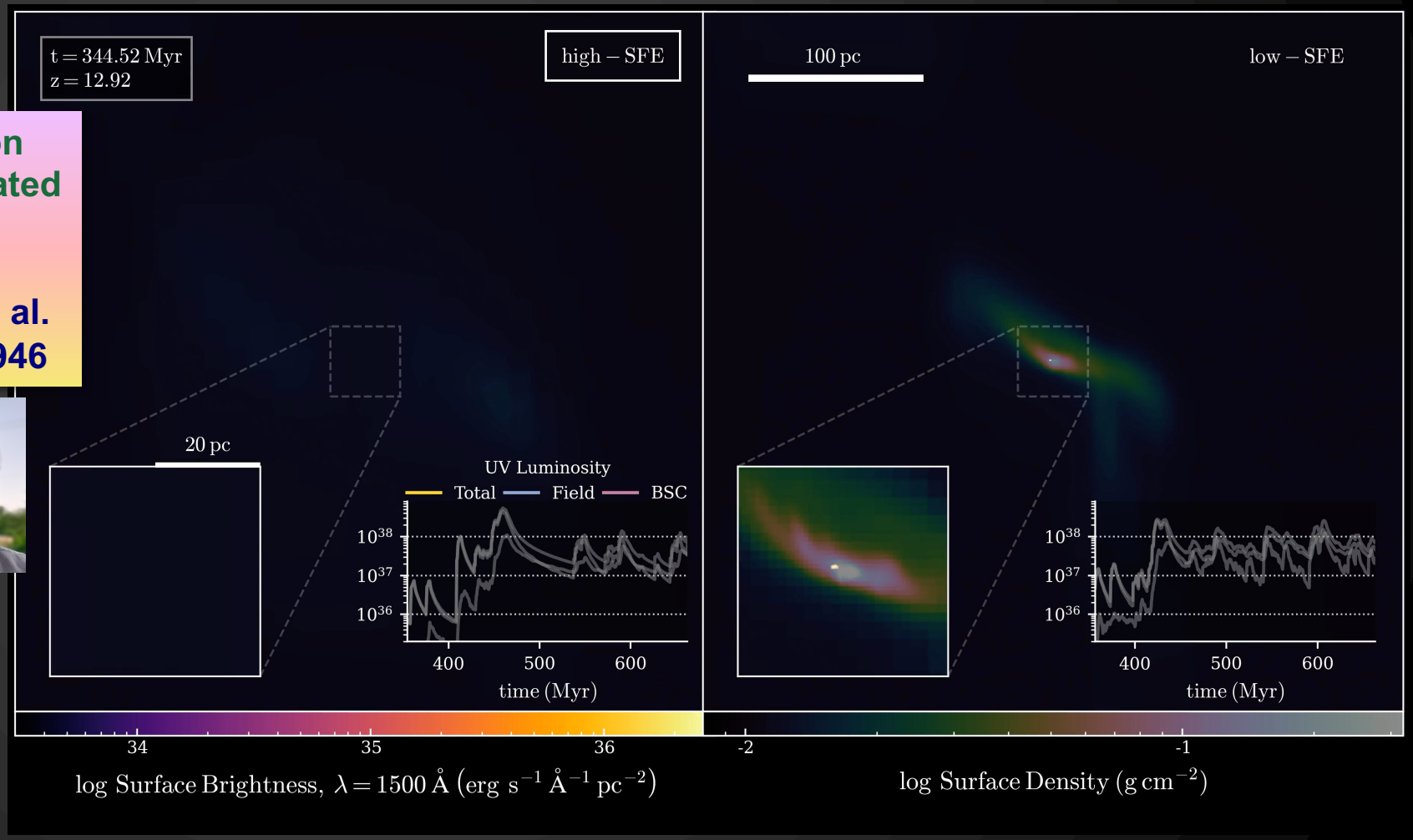
High-resolution (0.1 pc) simulated high-z galaxy

Fred Garcia et al. arXiv:2212.13946



upcoming
Cycle 3 GO 5917
PI Eros Vanzella
NIRSpec IFU prism
MIRI MRS long

Observed star clusters suggest high star formation efficiency



Globular cluster progenitors over time

Cosmic Gems arc
z ~ 10
r ~ 1 pc
Adamo+
Bradley+

MACS0647-JD
z = 10.17
r ~ 70 pc, 20 pc
Hsiao+
Hsiao & Abdurro'uf+
Abdurro'uf+
Hsiao & Álvarez+

Sunrise Arc
z = 5.93
Nebular knots
Earendel
r ~ 1 pc
Welch+
Vanzella+
Stellar clusters

Sparkler
z = 1.38
Mowla & Iyer+
Claeyssens+
Adamo+

SMACS0723
z = 0.39
Faisst+
Lee+
Harris+
Martis+

Messier 80
z = 0
r ~ 15 pc

Individual stars

z = 4.76
Meena+23
Furtak+24

Z=2.1878
Quyllur
Diego+22

Z=2.09
MOTHRA
Diego+23

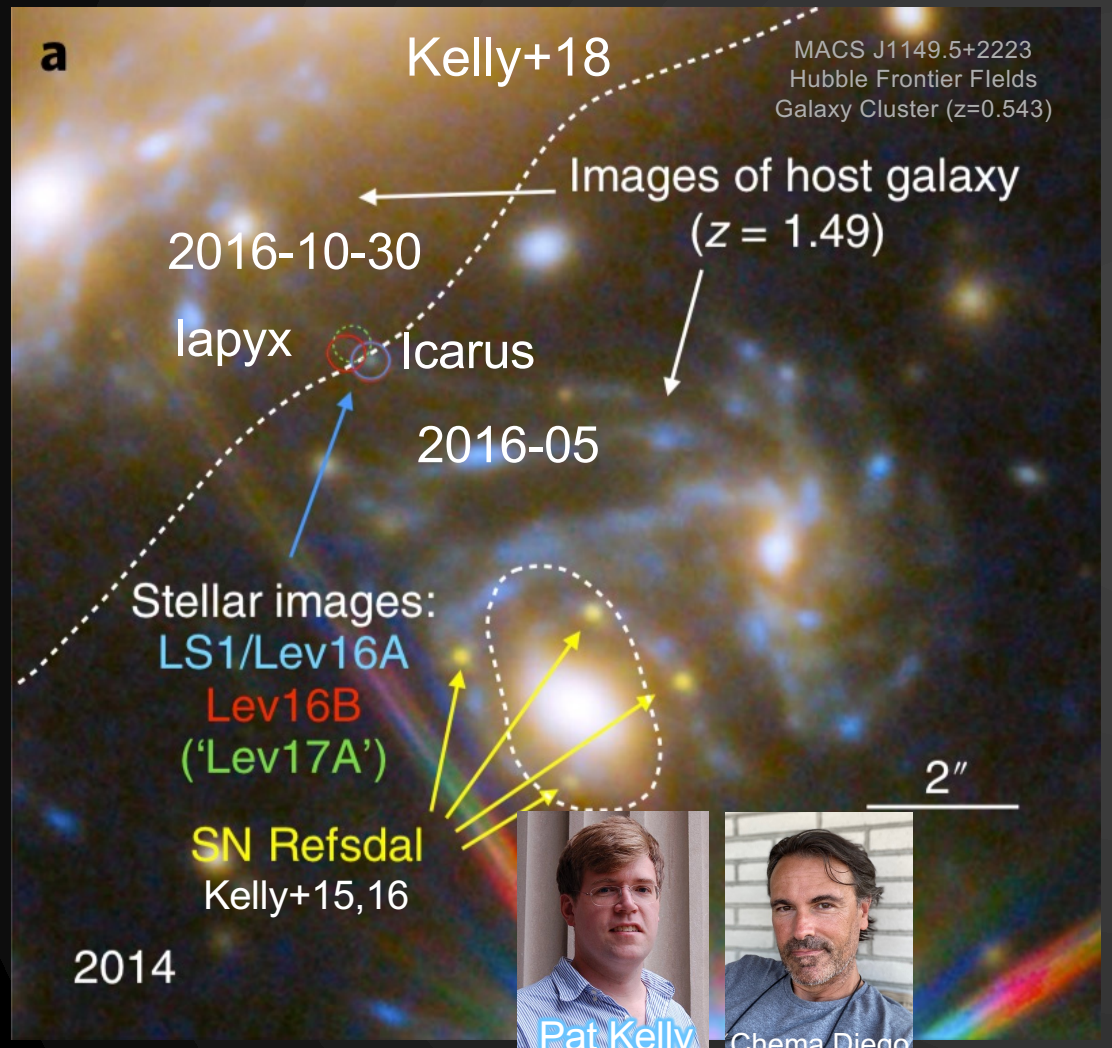
z = 1.78
A2a
2a
A2b
2b
SN H0pe
A2c
2c
Polletta+24

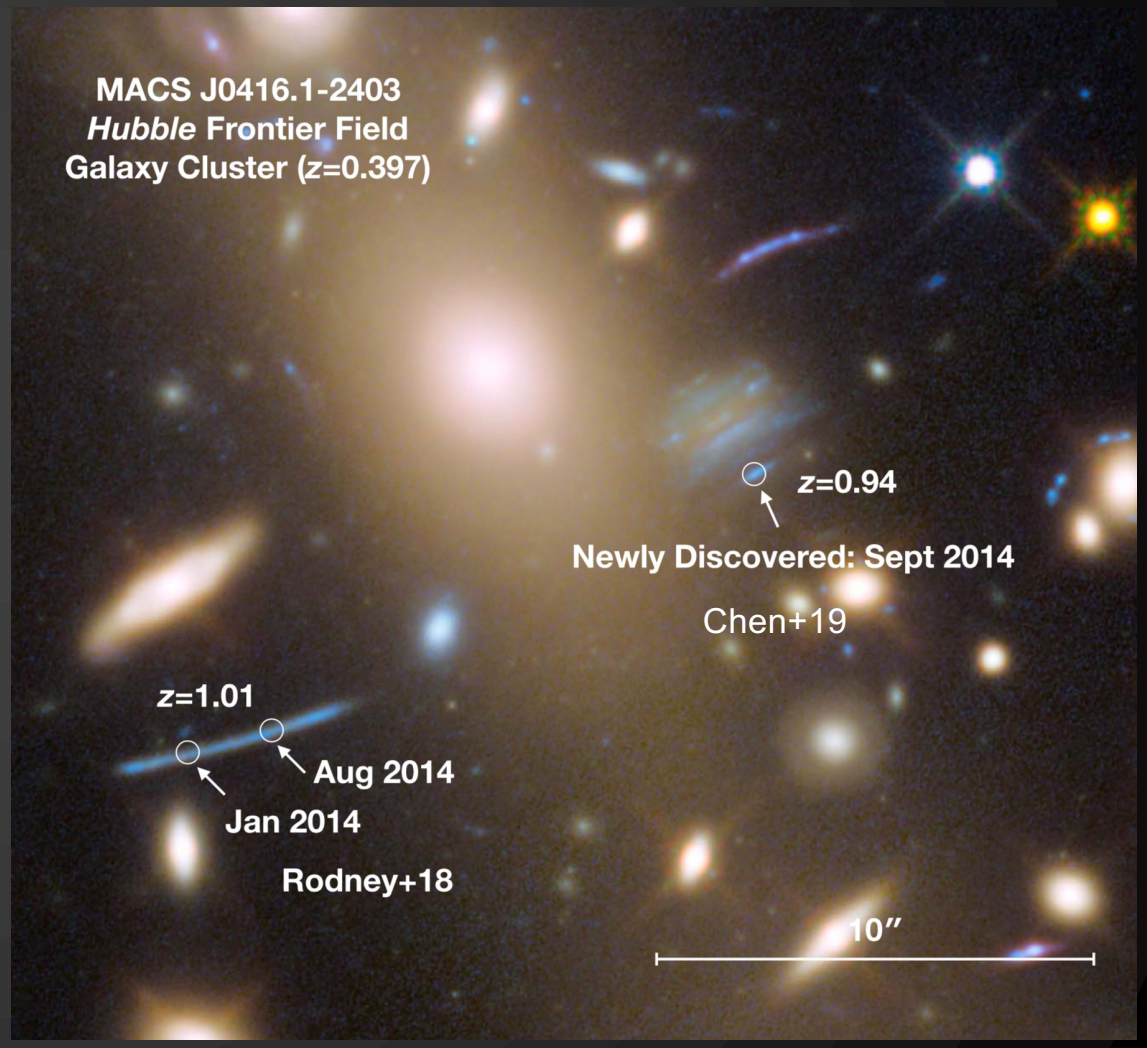
Icarus
Kelly+18
z = 1.49
Kelly+15,16
SN Refsdal

z = 2.37 Sunburst Arc + Godzilla
Choe+24

z = 0.73 Cosmic Dragon: 40 transient stars
Fudamoto+24

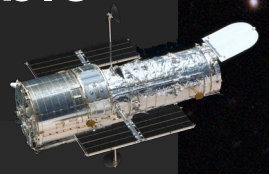
Lensed stars: first discoveries at z ~ 1 – 1.5





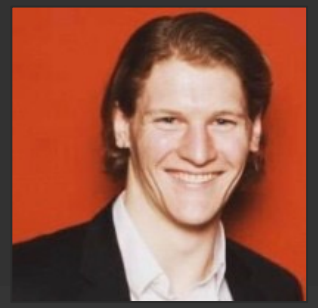
JWST was designed to study the first stars

We found one with Hubble to look at with JWST



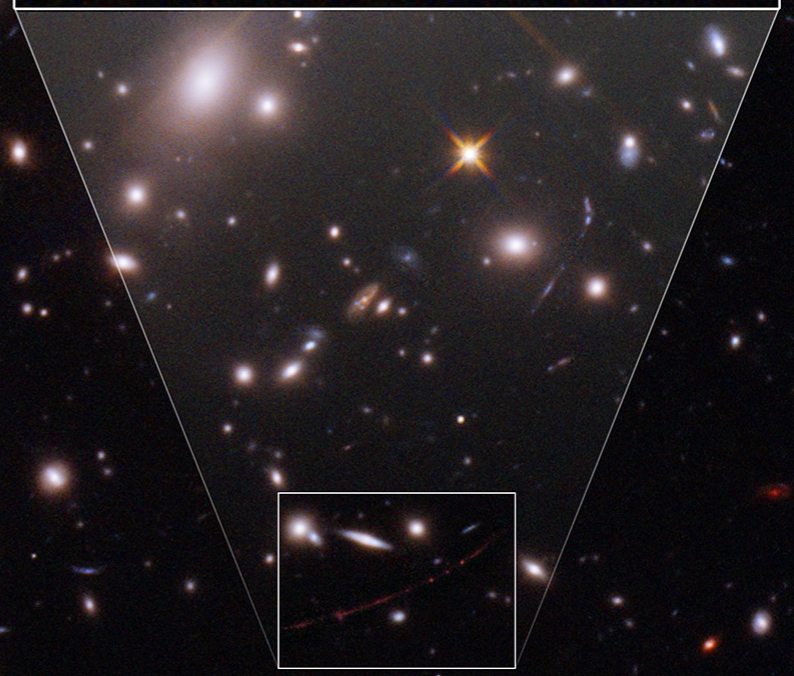
Earendel z = 6 star system
observed 1 Gyr after the Big Bang
magnified by thousands

Brian Welch et al.
2022 Nature

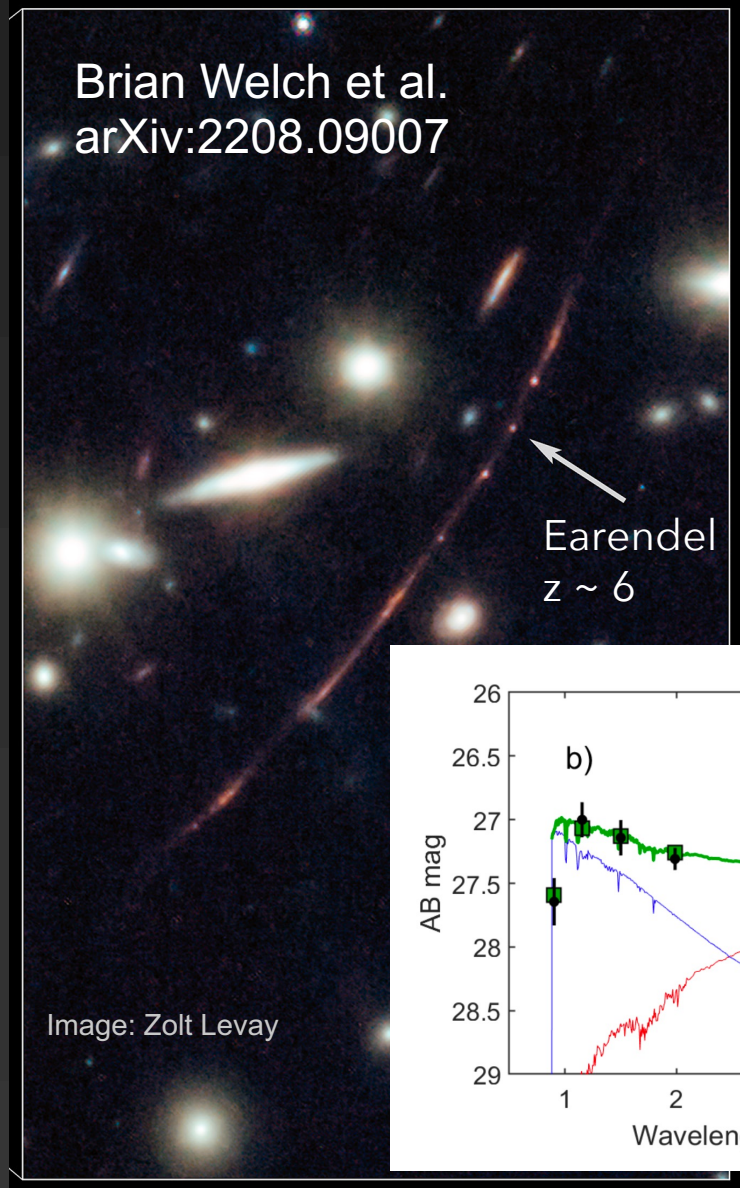


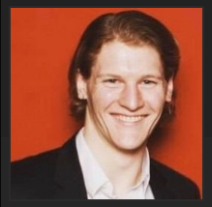
RELICS
Reionization Lensing Cluster Survey

Earendel "morning light"
Eärendil



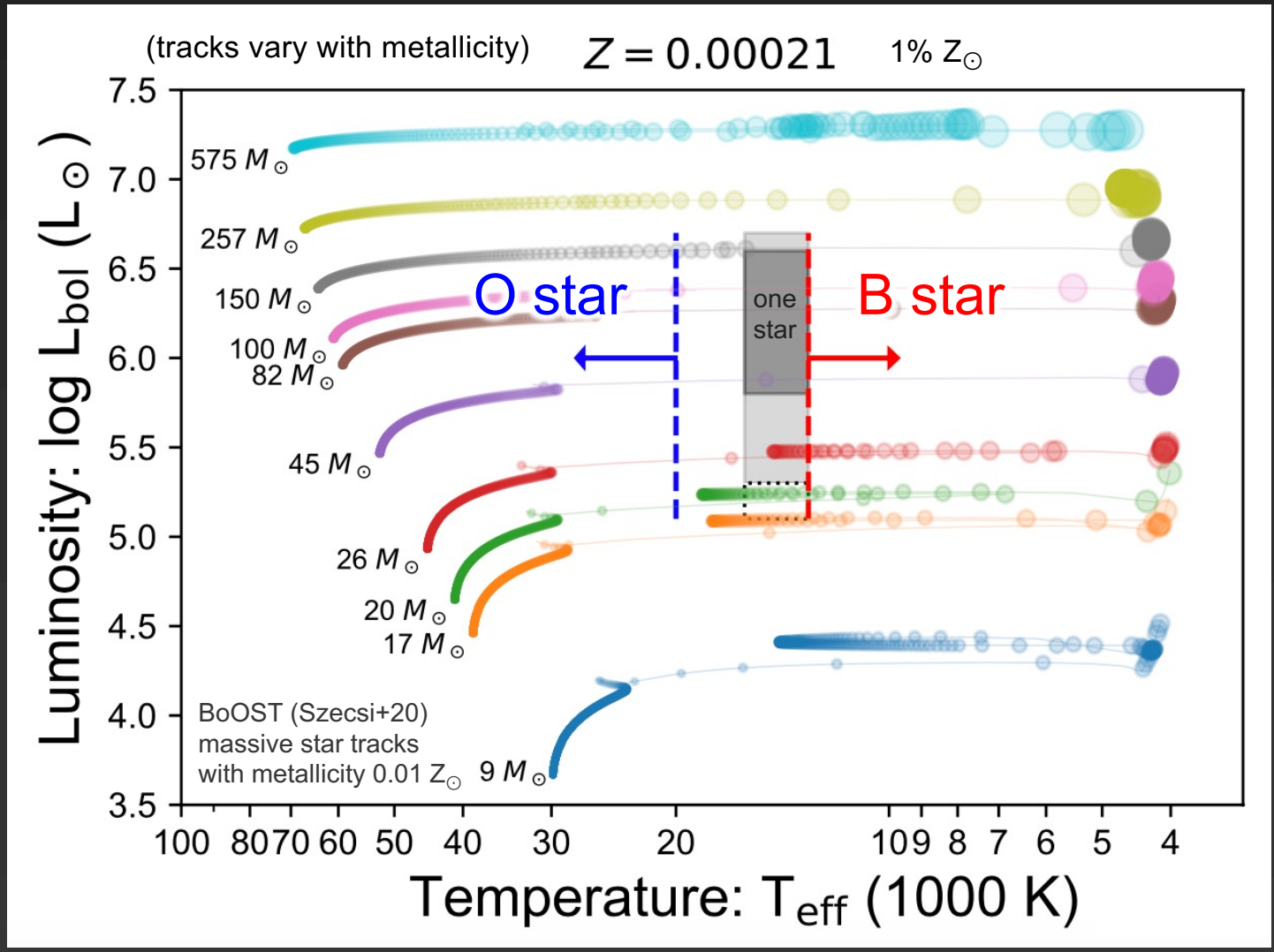
JWST reveals the colors of Earendel



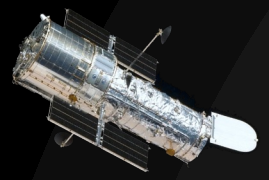


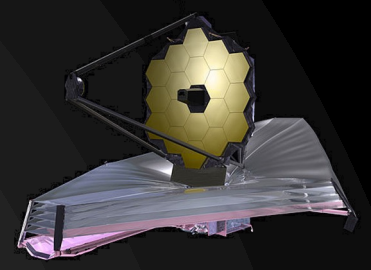
magnification
μ > 4000

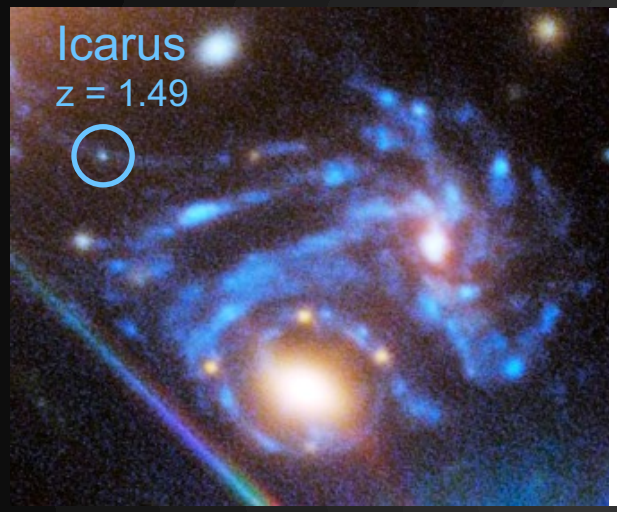
z = 6 star on the H-R diagram

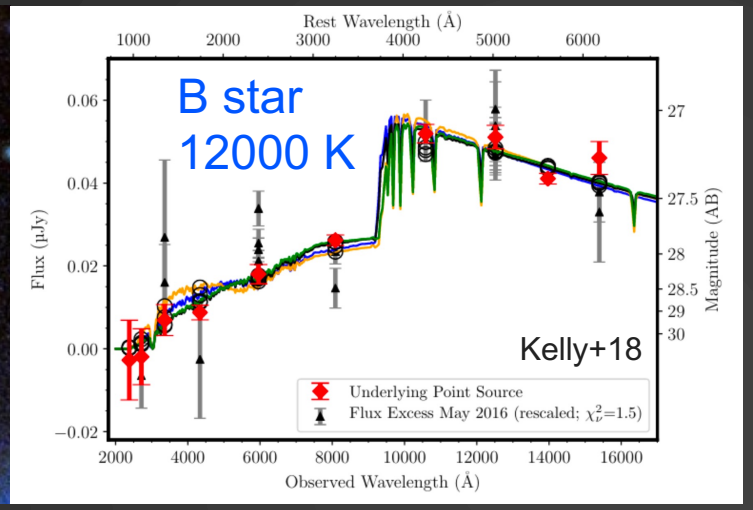


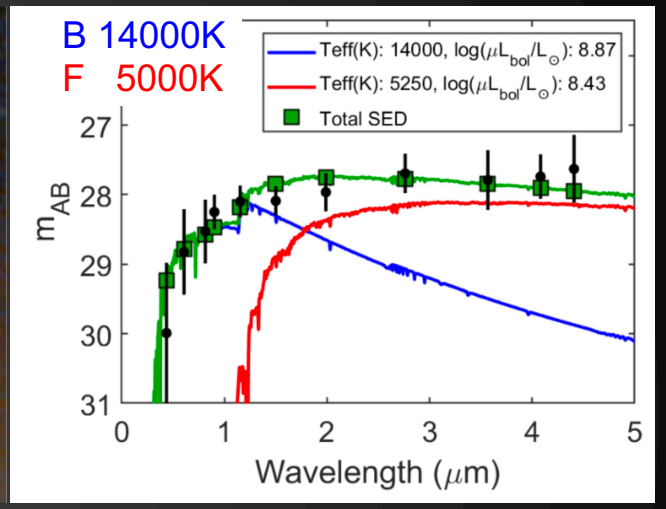
Star SEDs at z = 1 – 6
temperatures and luminosities

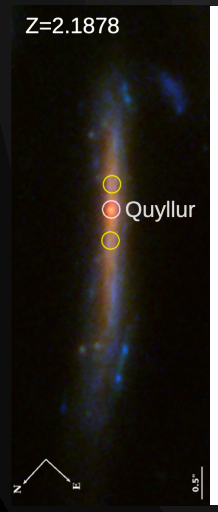


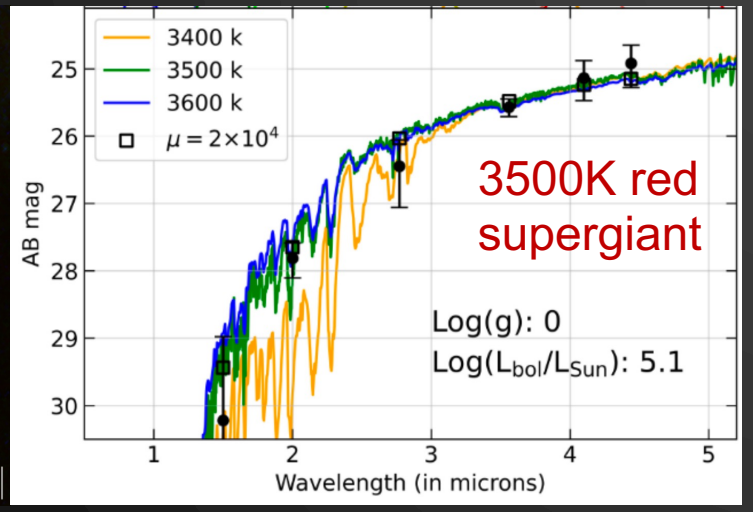


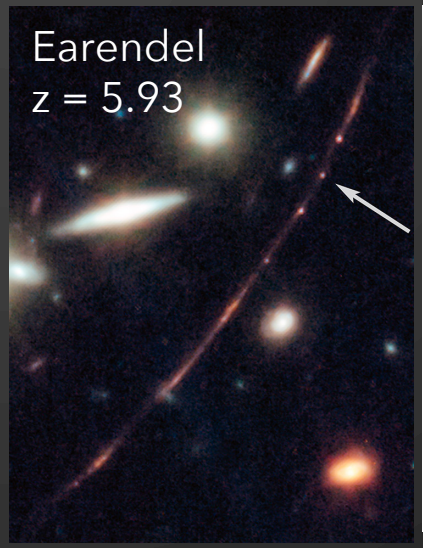


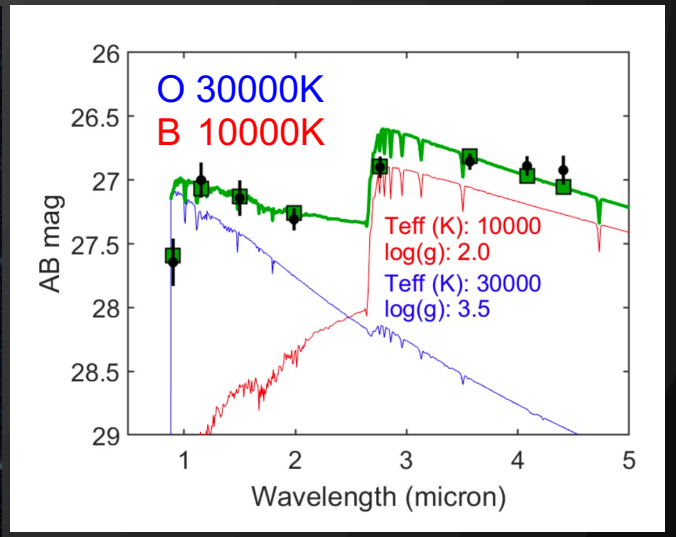




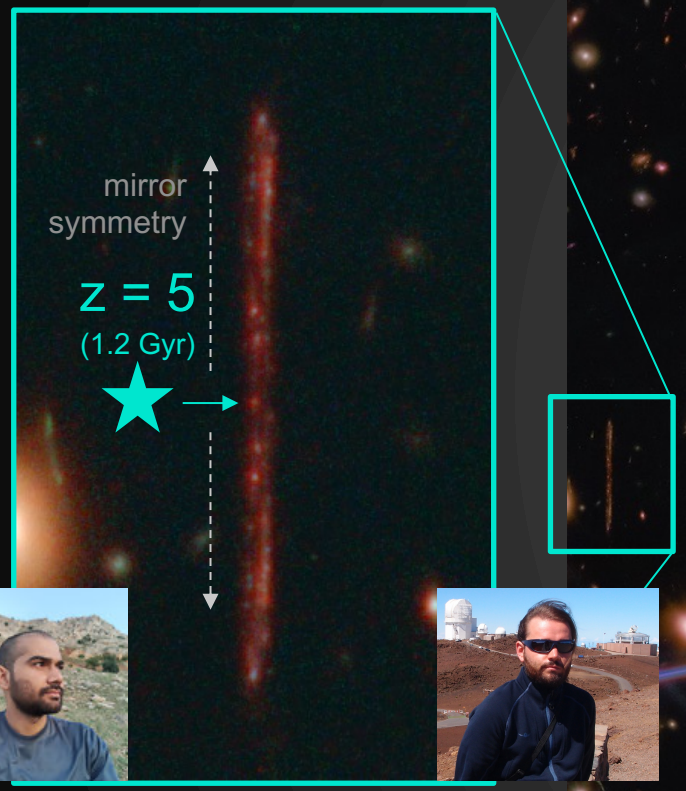






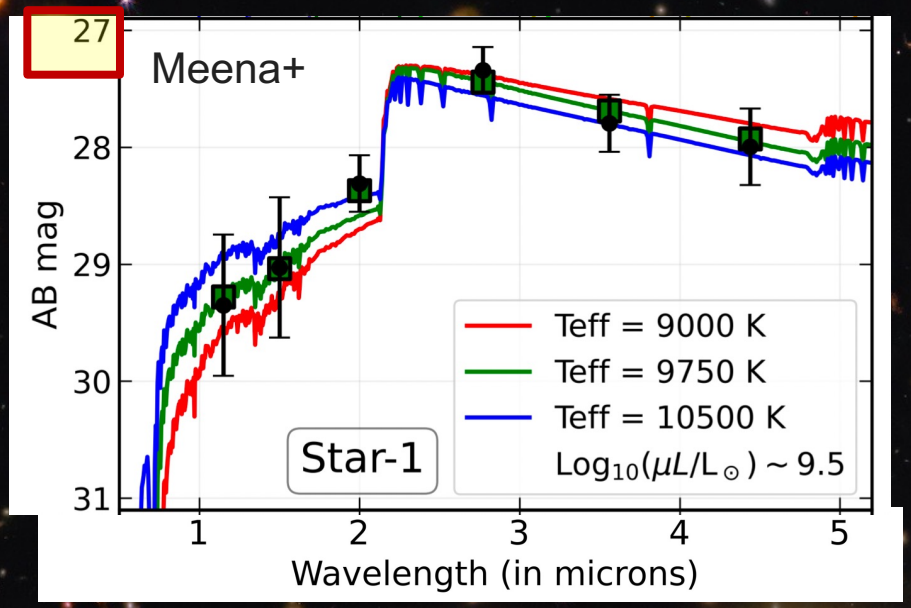


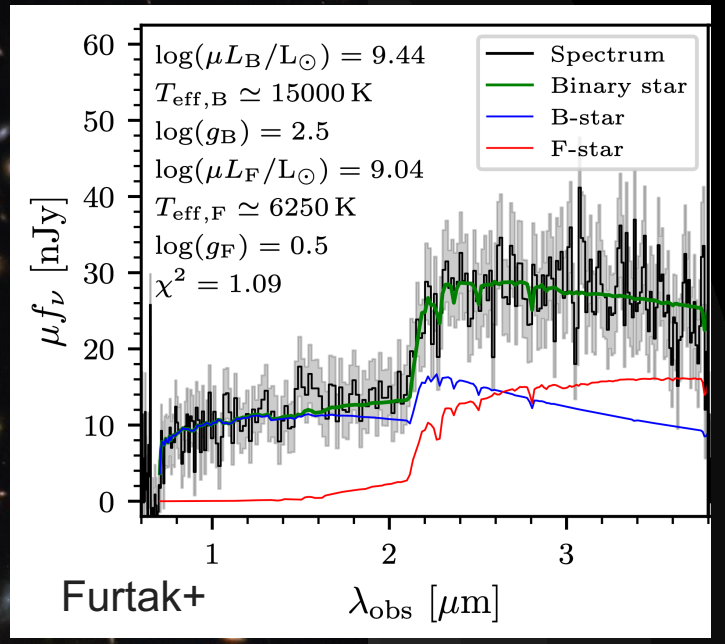
z = 5 star SED and spectrum

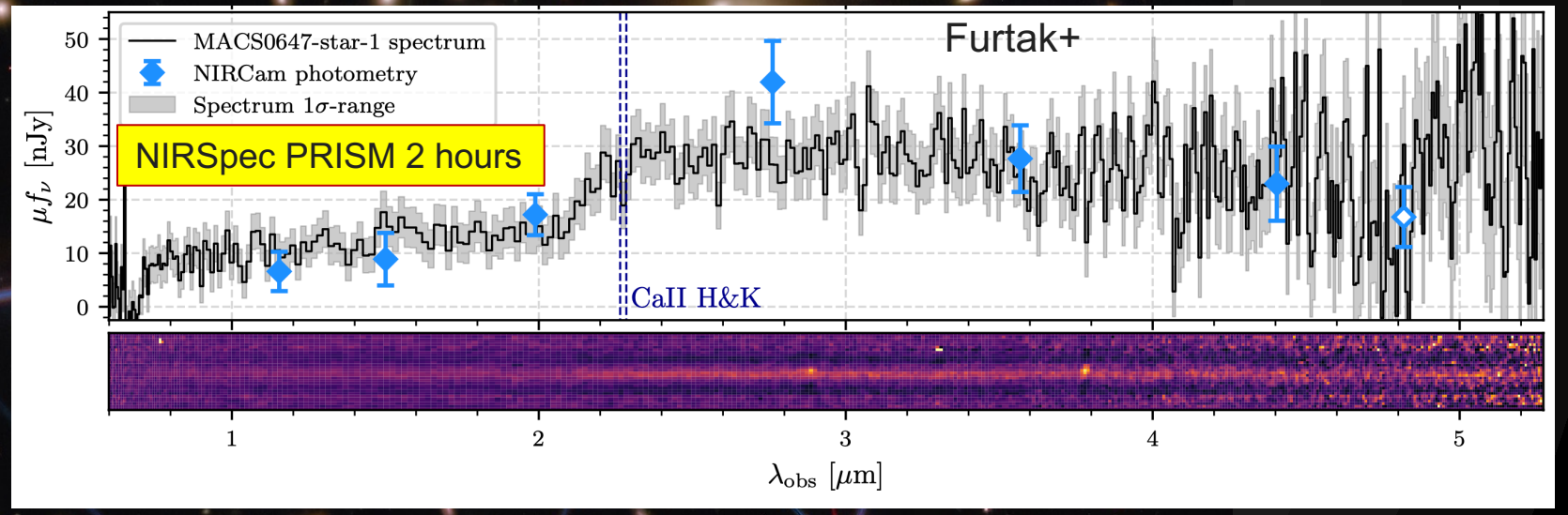


Ashish Meena et al.
arXiv:2211.13334

Lukas Furtak et al.
arXiv:2308.00042







MACS 0647+70
Image: Alyssa Pagan

Predicted JWST NIRSpec spectra of stars

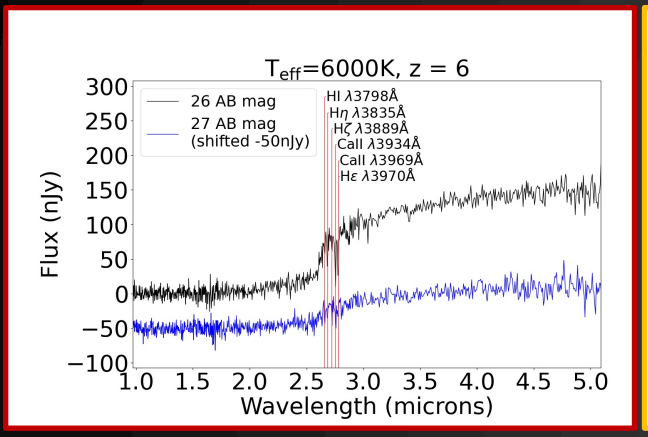
stellar temperature from continuum, Balmer absorption lines

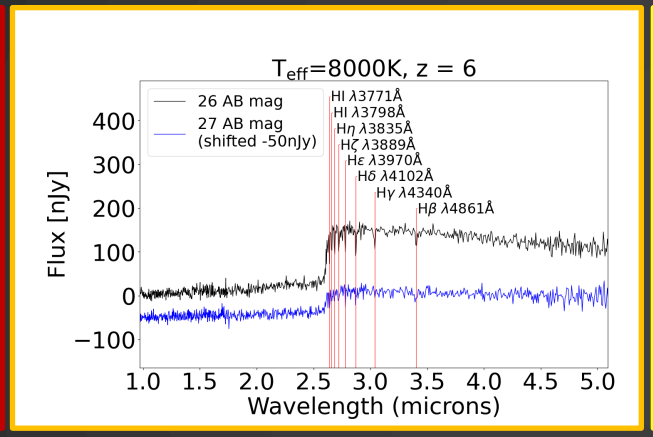
Emma Lundqvist

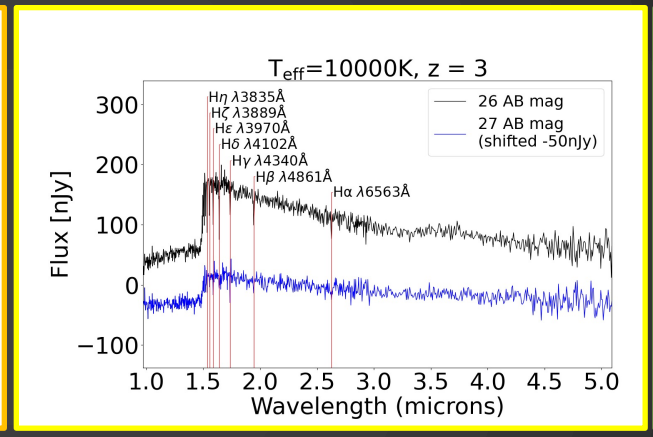
50 hours in each medium grating: G140M, G235M, G395M

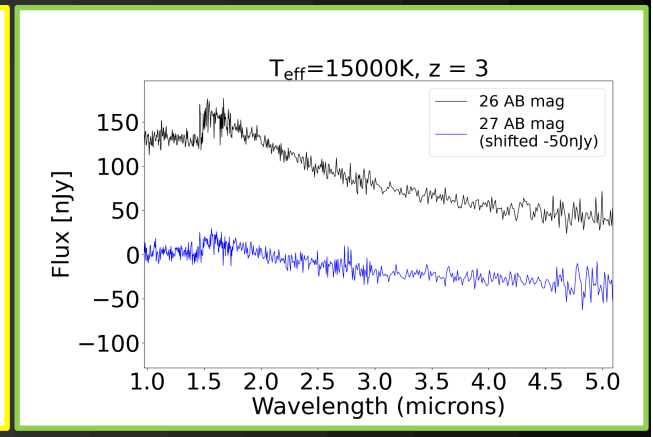
arXiv:2404.10817

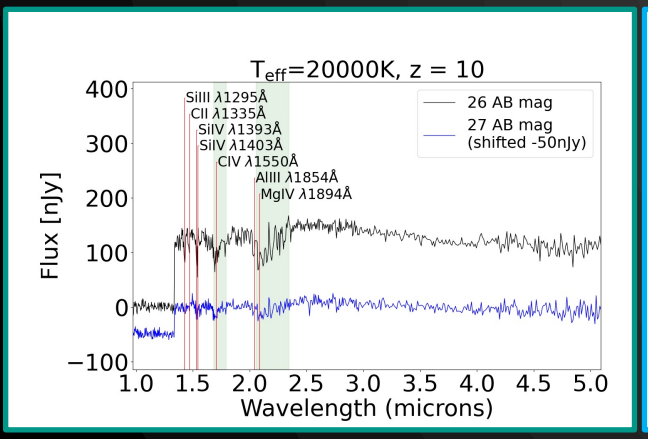
Erik Zackrisson

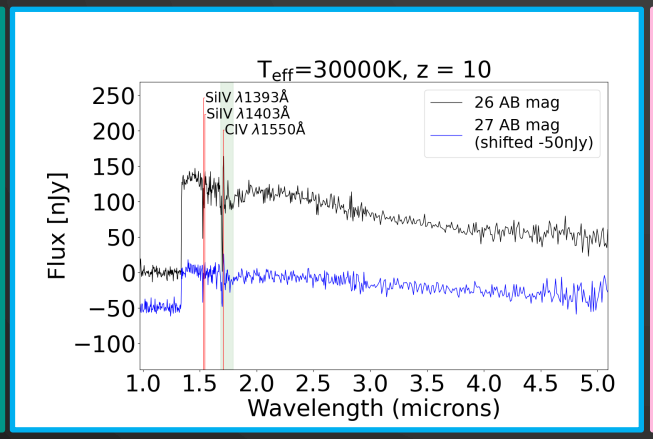


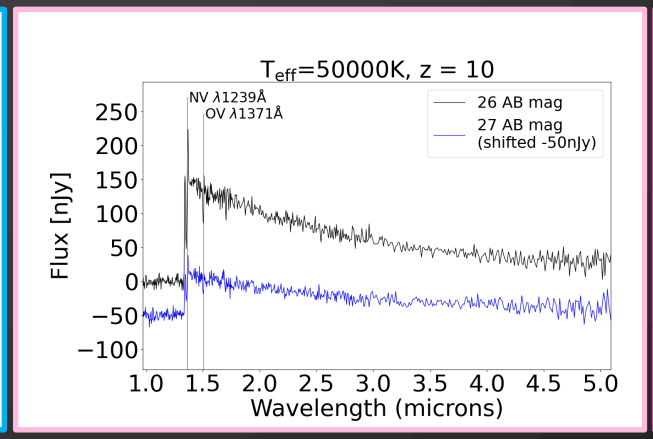


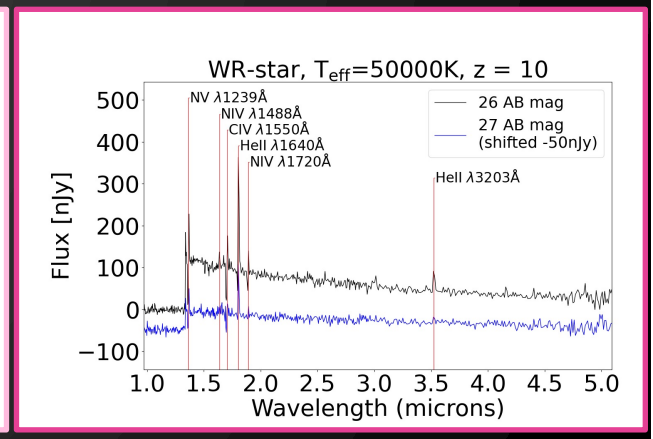












predicted spectral line features

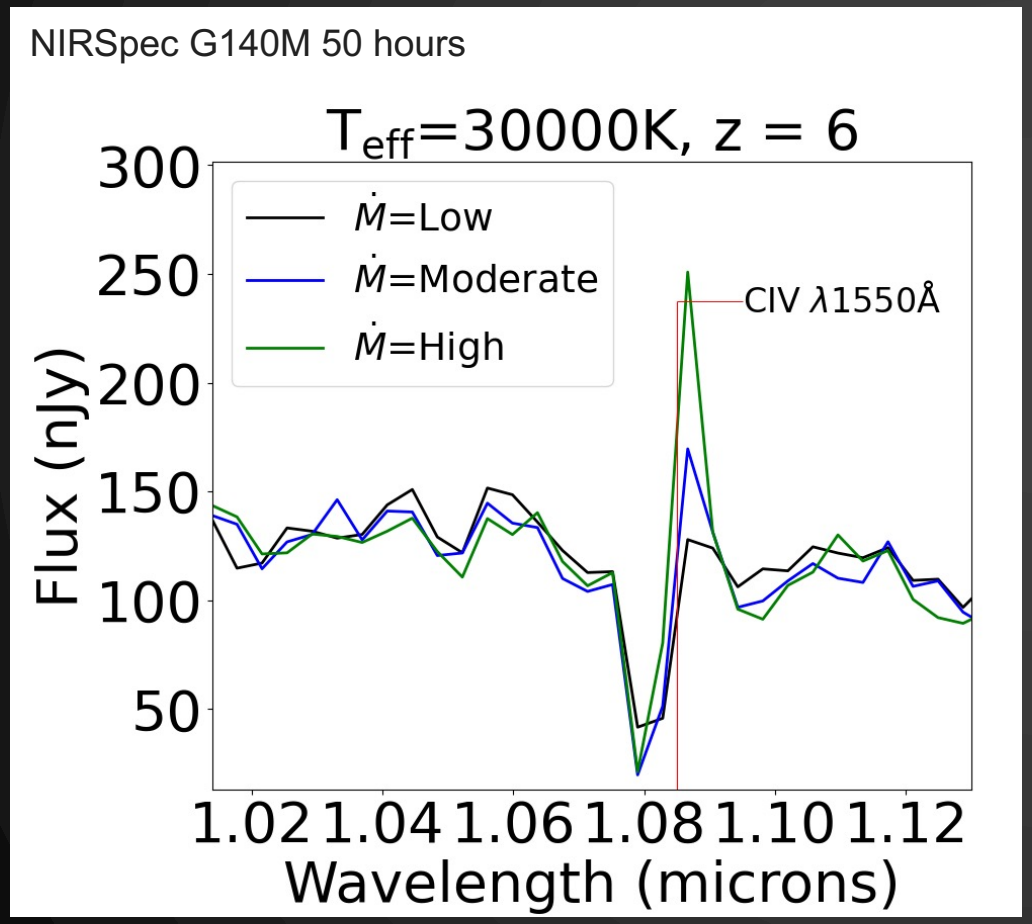
Emma Lundqvist

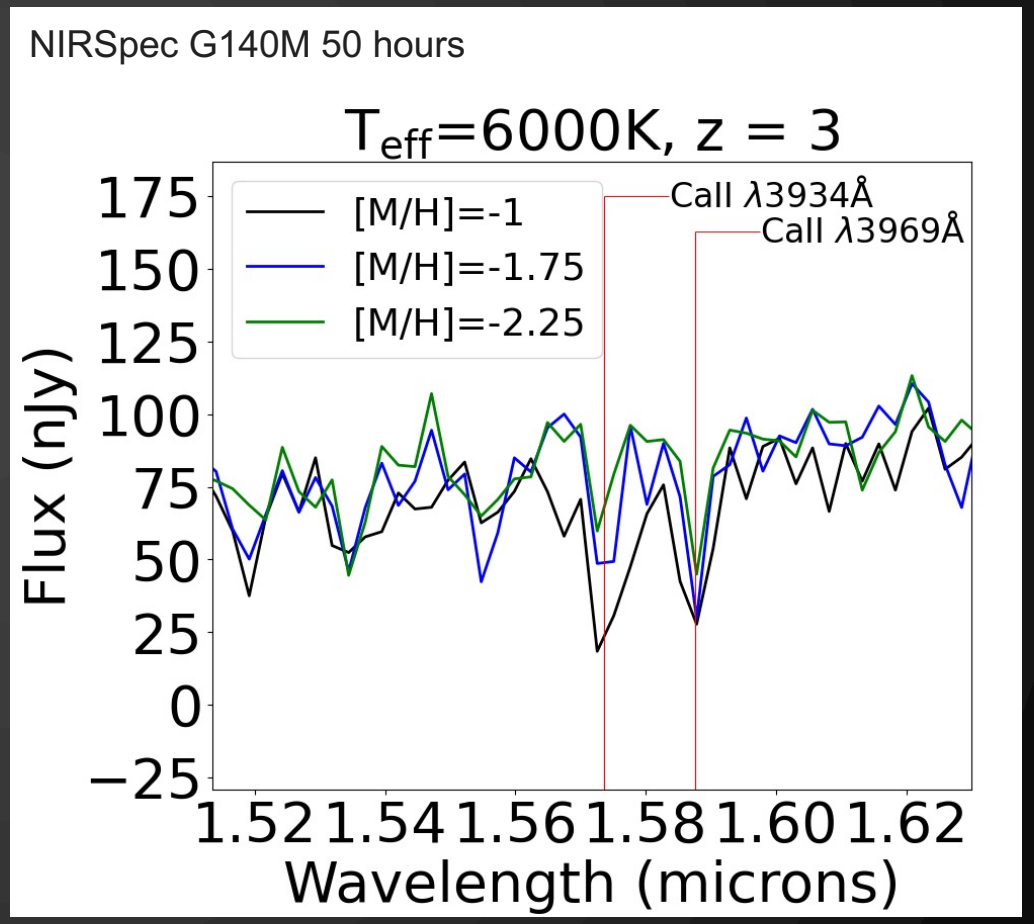
CIV: outflow wind strength (T > 15000K)

arXiv:2404.10817

CaII: metallicity? (T ~ 6000K)

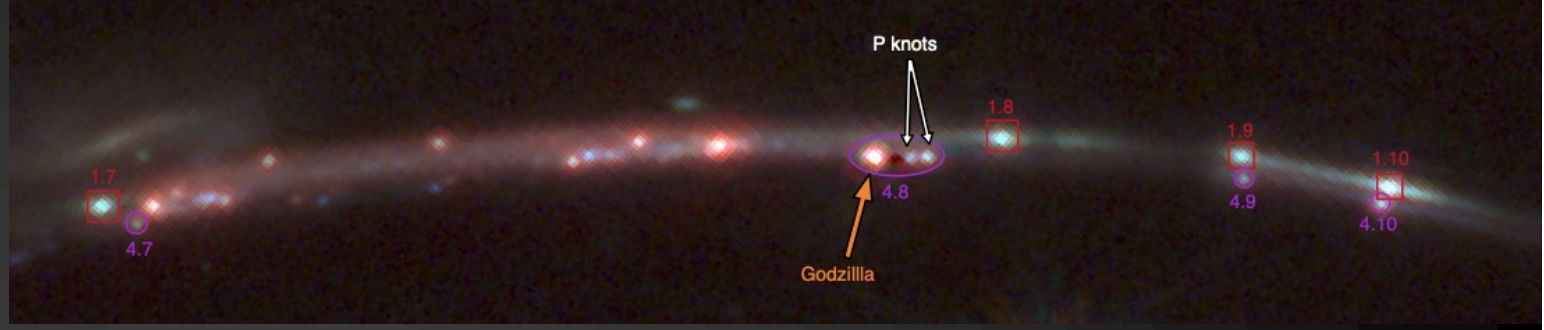
Erik Zackrisson

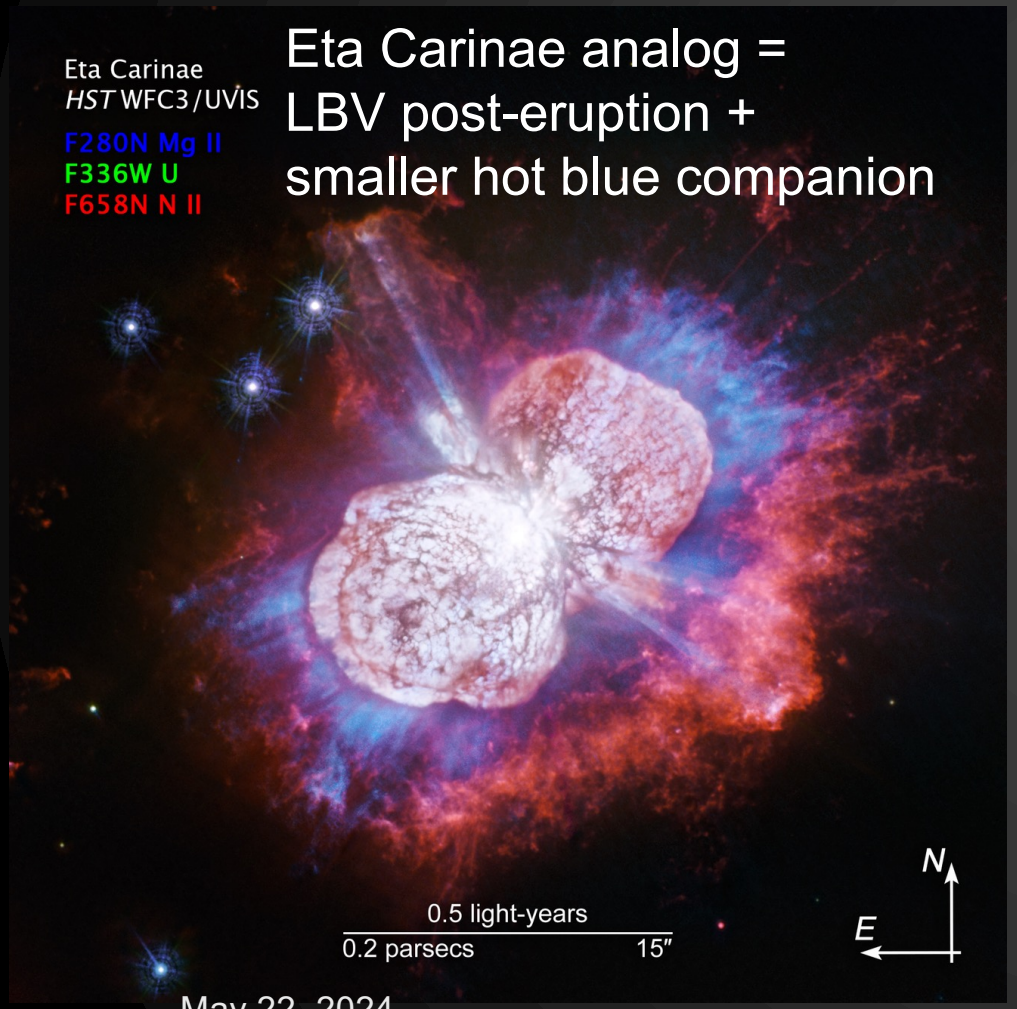




z = 2.37 star spectrum

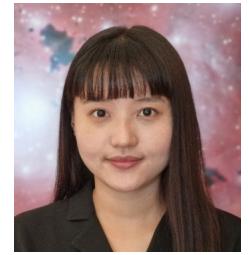
"Godzilla" AB mag 22
magnified by ~7000x
in the Sunburst Arc





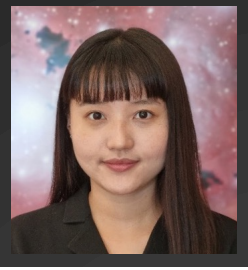
Eta Carinae analog =
LBV post-eruption +
smaller hot blue companion

Suhyeon Choe



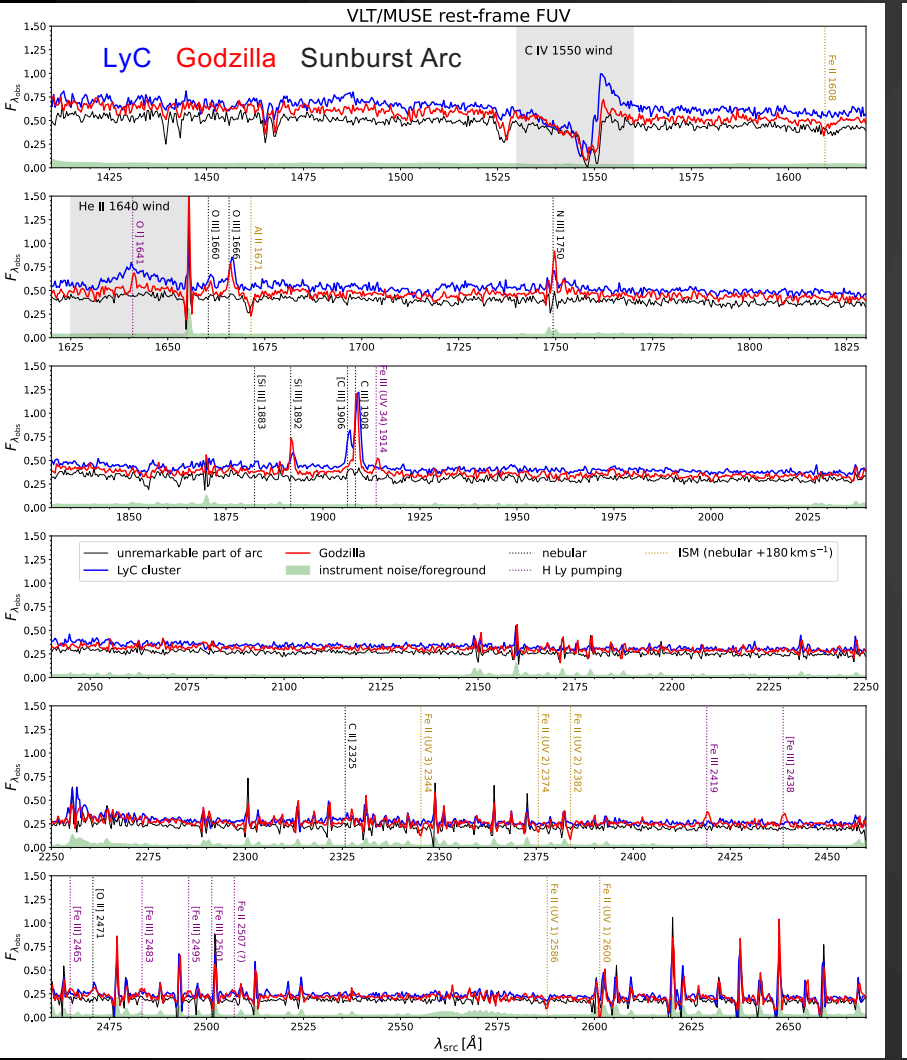
arXiv:2405.06953

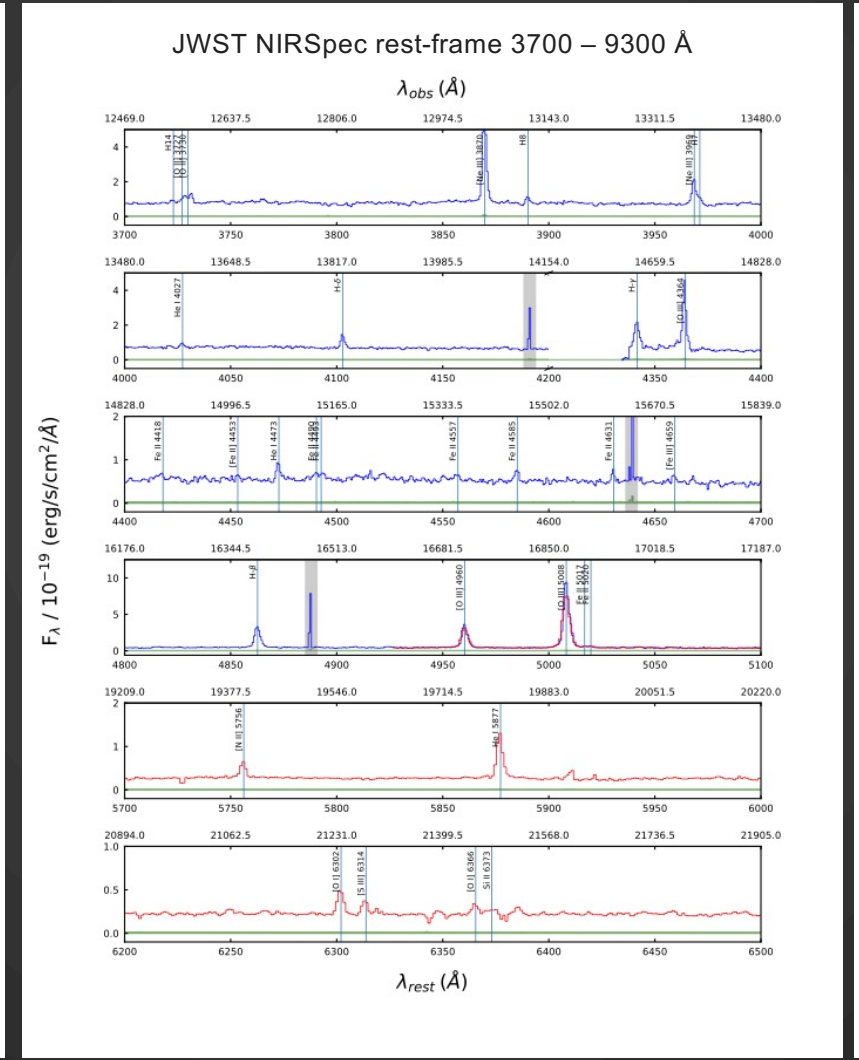
Massimo Pascale
VLT MUSE
PIs Vanzella; Aghanim

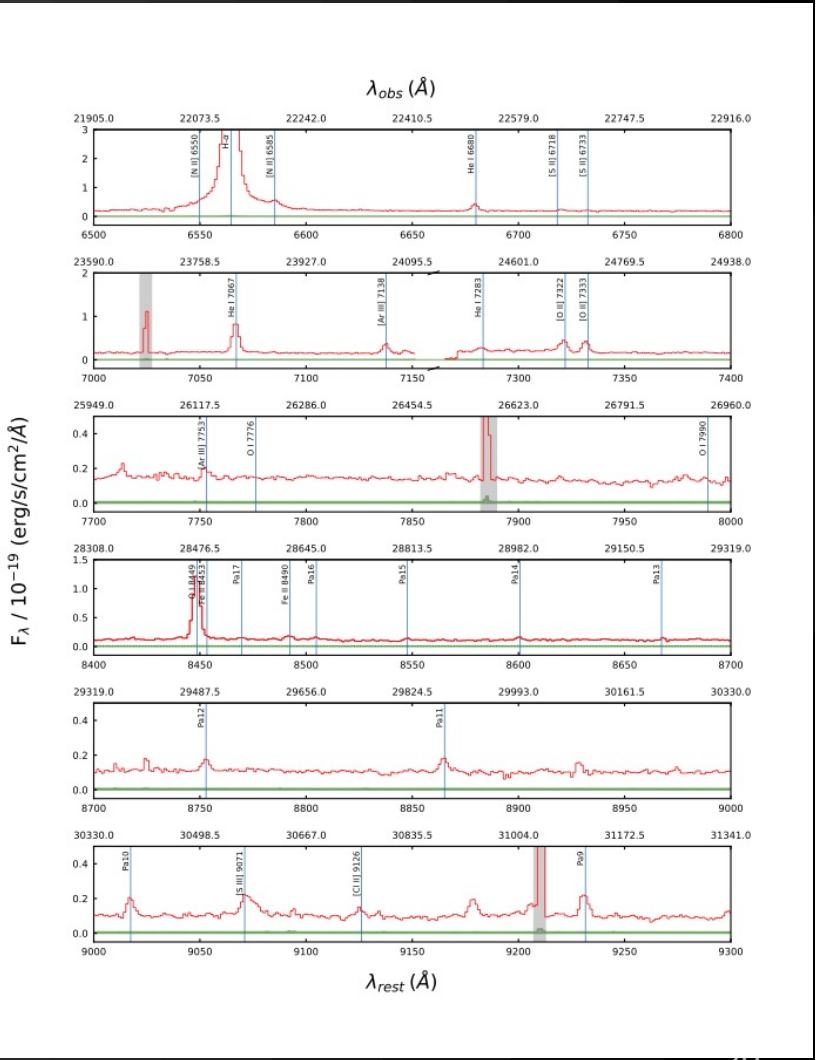


Suhyeon Choe
JWST NIRSpec
PI Rivera-Thorsen

z = 2.37 star “Godzilla” detailed spectrum





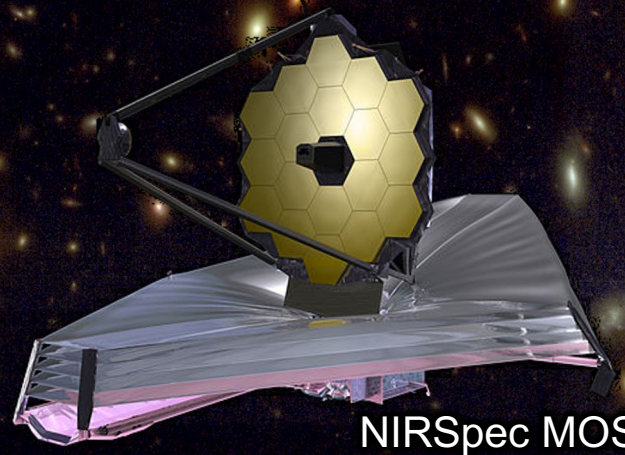


What was First Stars made for?

JWST Cycle 4 deadline Wed Oct. 16

- deep spectra of stars
- more lensing clusters = more stars
- monitoring = microlensed stars, supernovae

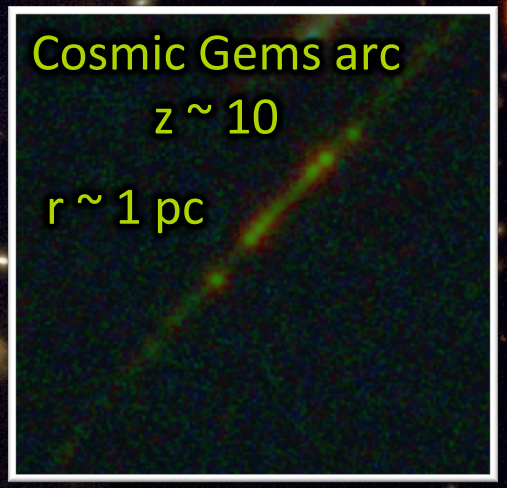
Help us learn what we're made from

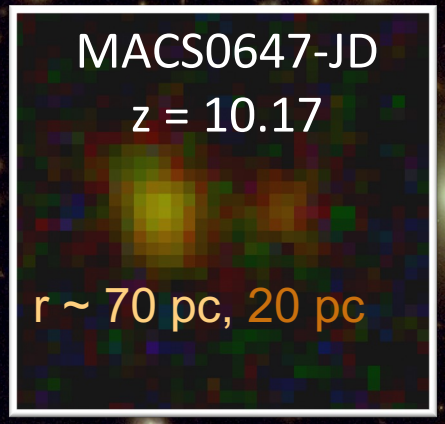


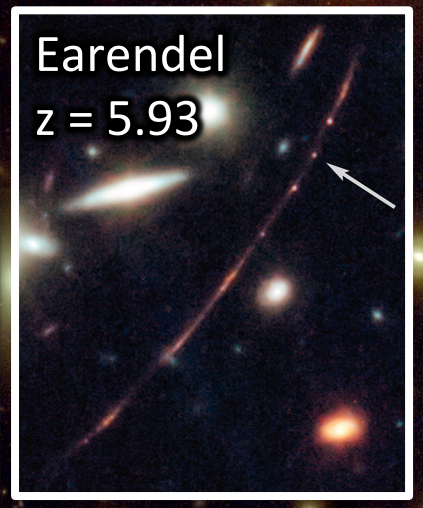
NIRSpec MOS
JWebbinar
June 27

Cosmic Spring
cosmic-spring.github.io
public data, code, papers

STScI
JWST pipeline







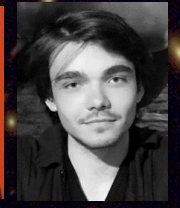
Tiger Hsiao

Abdurro'uf

Rebecca Larson

Brian Welch

Vasily Kokorev



DAWN JWST archive