

# Extremes revealed by lensing in the early universe

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[dancoe.space](http://dancoe.space)

auroral lines

6300Å O  $^1D \rightarrow ^3P$

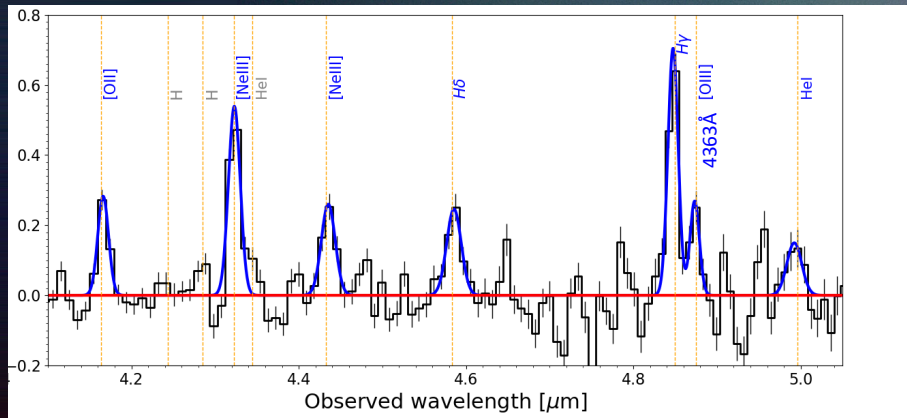
5577Å O  $^1S \rightarrow ^1D$

# Aurōra goddess of dawn

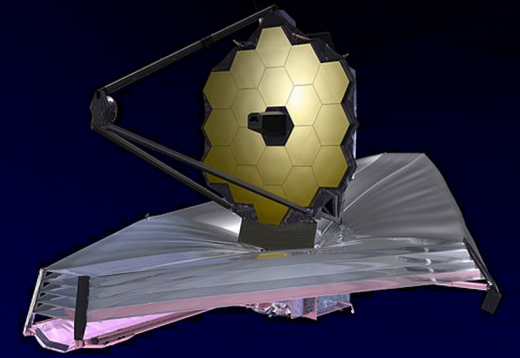
auroral line

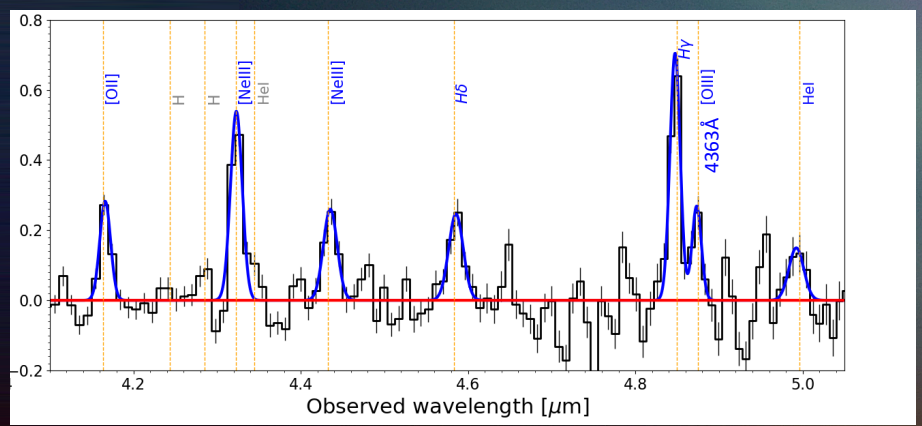
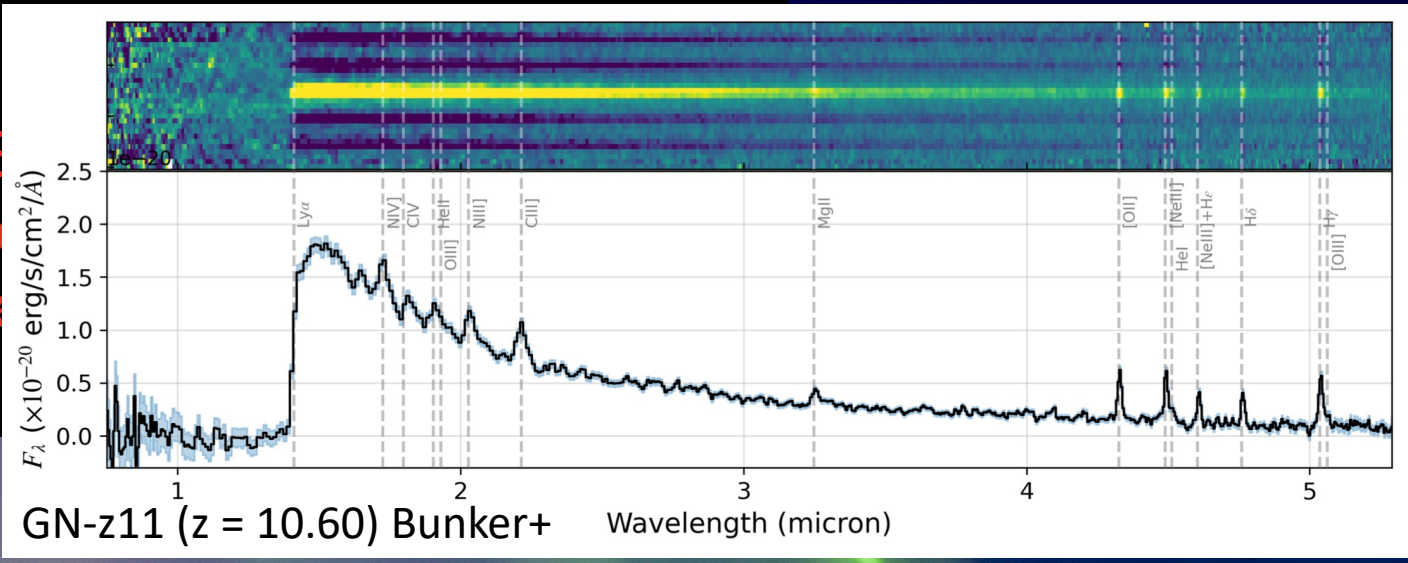
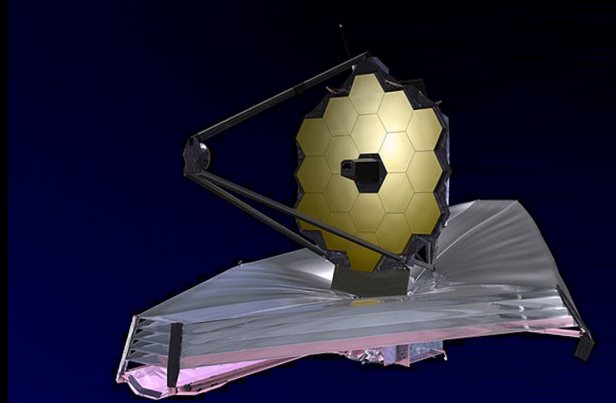
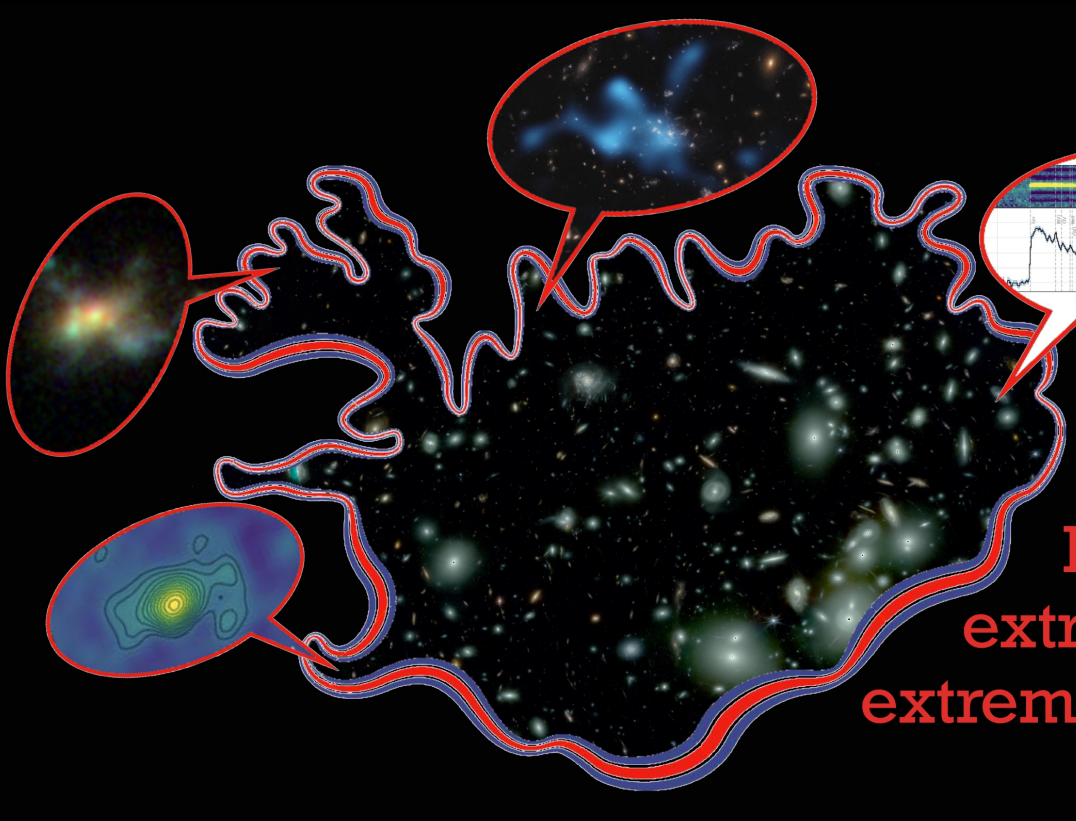
4363Å [OIII]  $^1S_0 \rightarrow ^3P_0$

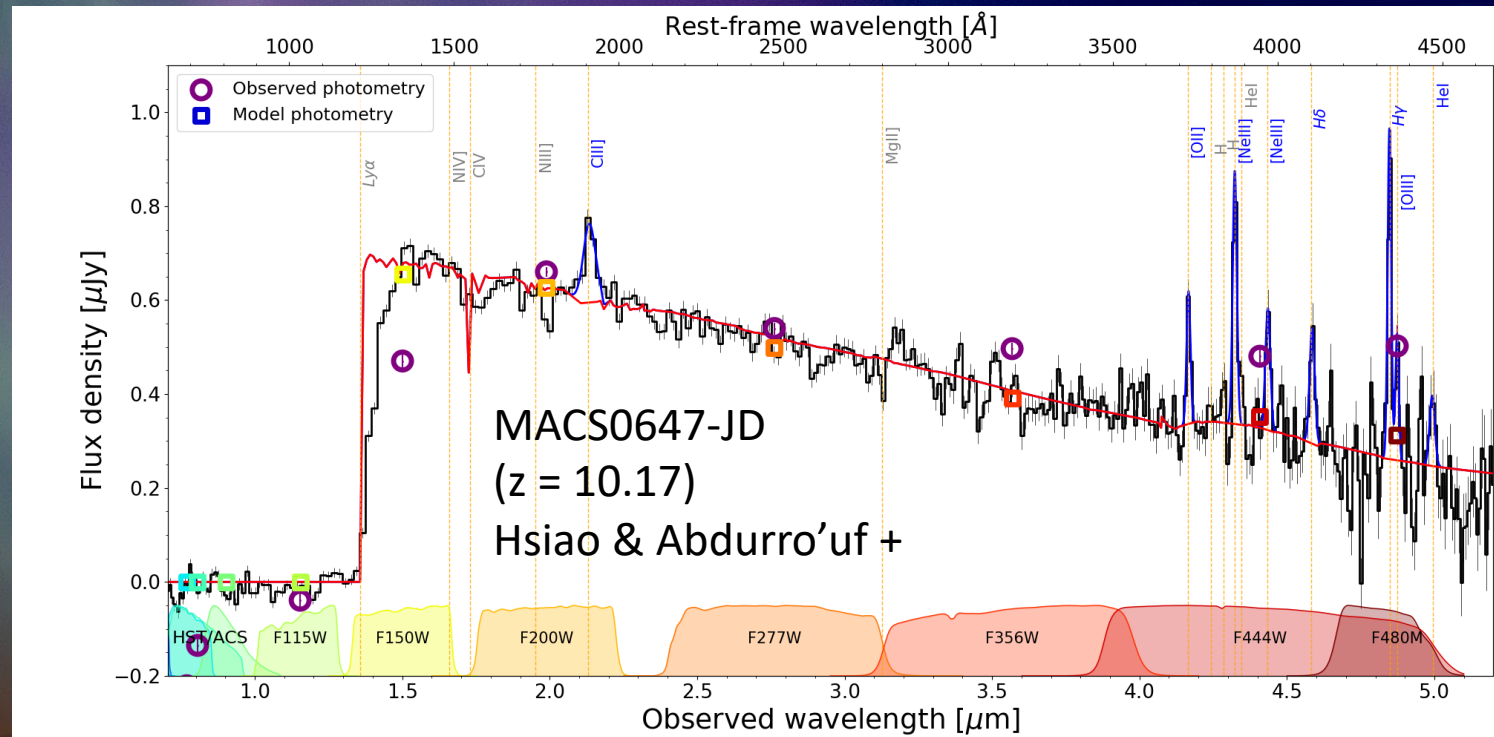
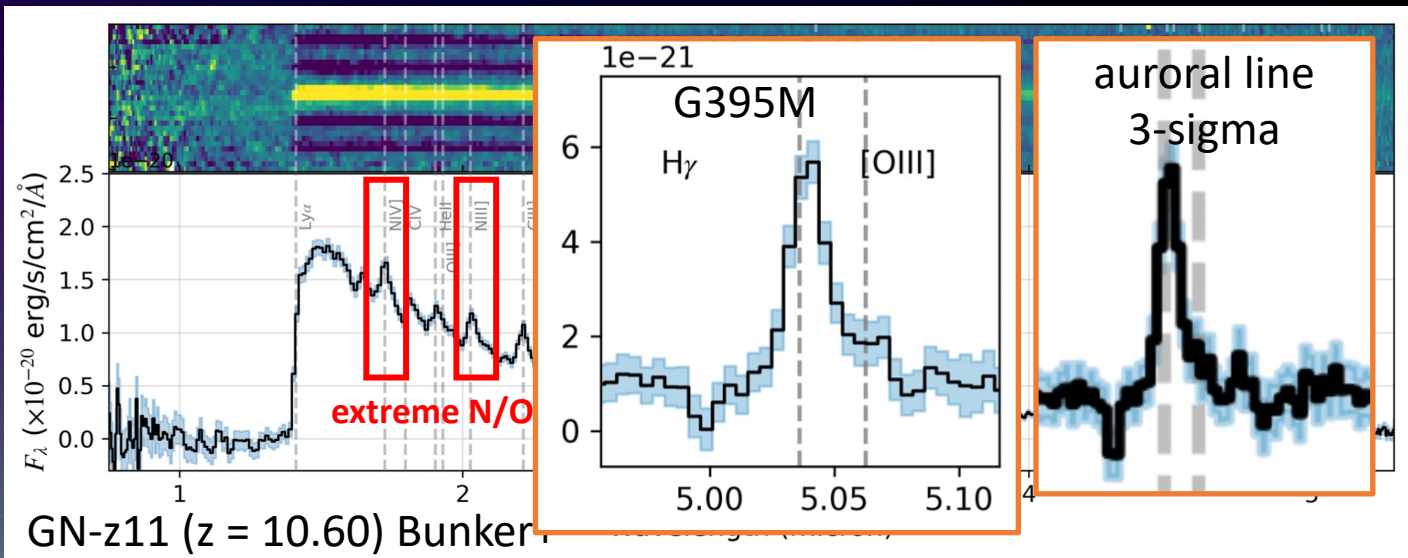
at cosmic dawn  $z = 10.17$  (460 Myr)



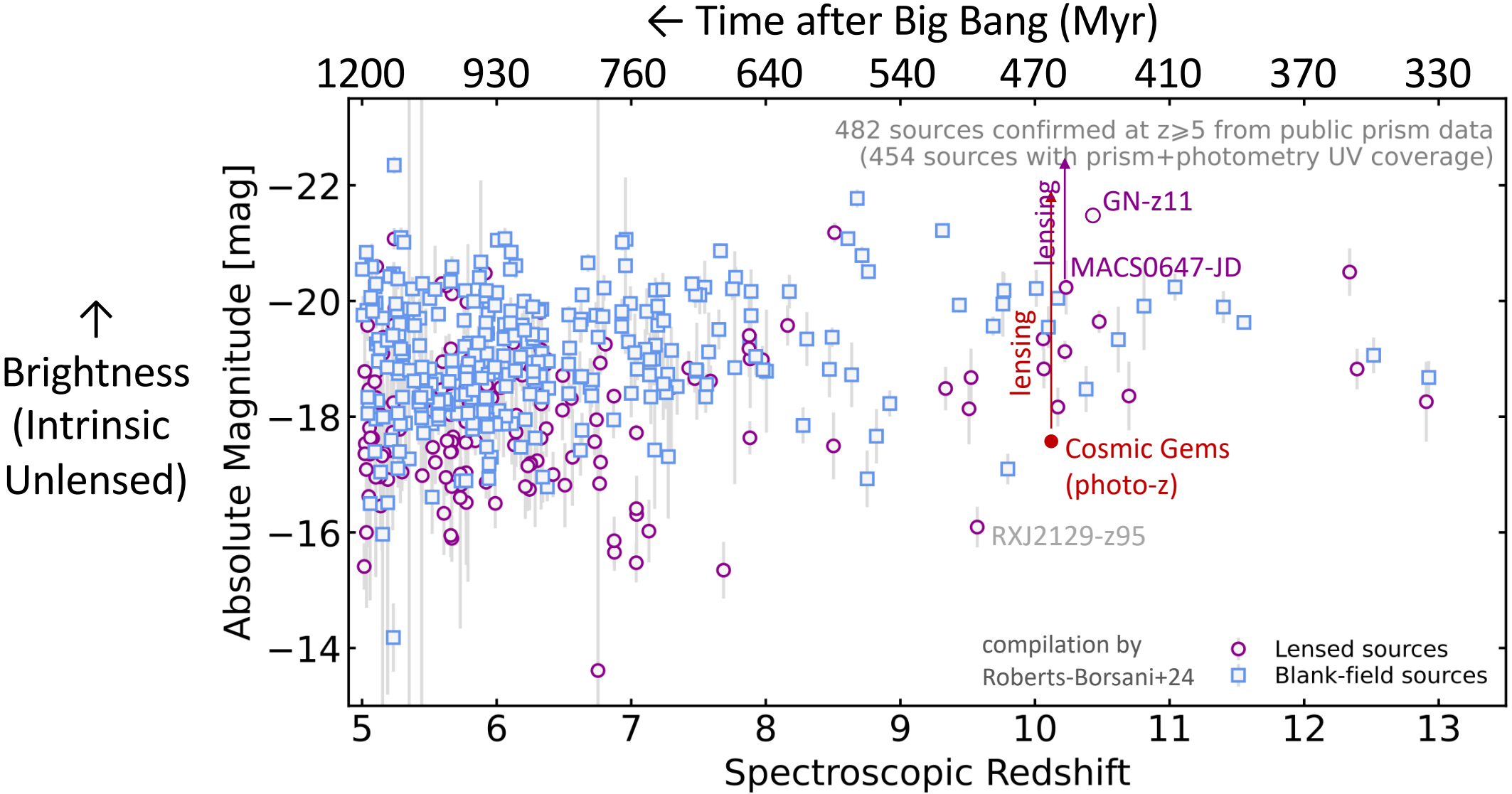
Tiger  
Hsiao Abdurro'uf







# Hundreds of galaxies confirmed in first billion years



# Cosmic Spring JWST

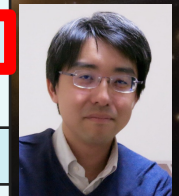
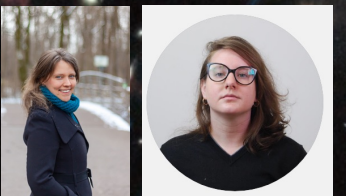
cosmic-spring.github.io  
public data, code, papers

join us if you're interested

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

Sinclair Manning  
Seiji Fujimoto  
Taylor Hutchison  
Lamiya Mowla  
Vasily Kokorev  
Namrata Roy  
Xinfeng Xu  
Victoria Strait  
Karthik 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

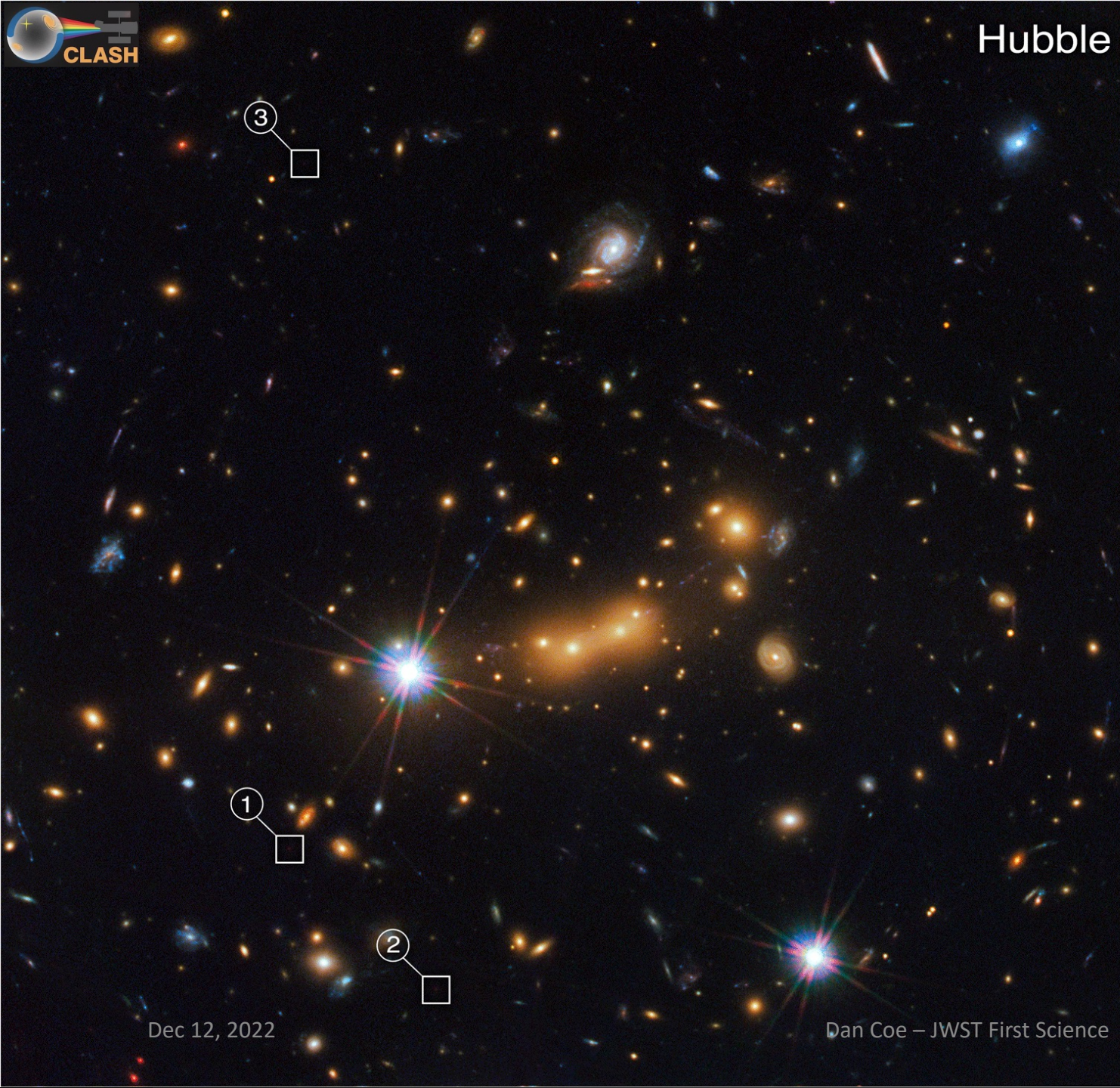
arXiv	Lead author	Object(s)	Redshift
<a href="#">2208.09007</a>	Brian Welch	Earendel star	$z \sim 6$
<a href="#">2210.01777</a>	Larry Bradley	12 galaxies	$z \sim 9 - 13$
<a href="#">2210.14123</a>	Tiger Hsiao	MACS0647-JD	$z \sim 11$
<a href="#">2211.09839</a>	Eros Vanzella	Sunrise Arc	$z \sim 6$
<a href="#">2211.13334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



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

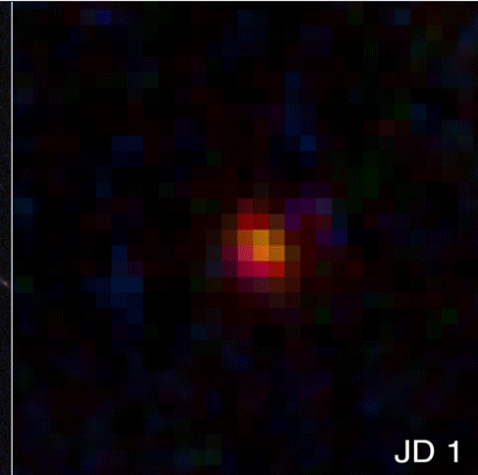
Jane Rigby  
Lou Strolger  
Francesco Valentino  
Ana Acebron  
Gabriel B. Caminha  
Christian Binggeli  
Michael Florian  
Masami Ouchi  
Roberto Avila  
Susan Kassin  
Nor Pirzkal  
Russell Ryan  
David Law  
Felipe Andrade-Santos  
Takahiro Morishita  
Matthew Bayliss  
Sune Toft  
Tod Lauer  
Michele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



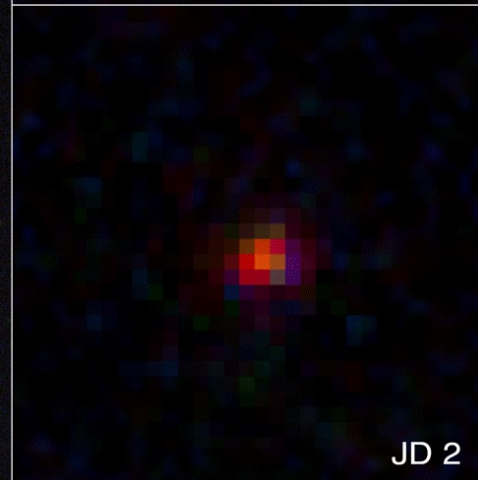
Dec 12, 2022

Dan Coe – JWST First Science

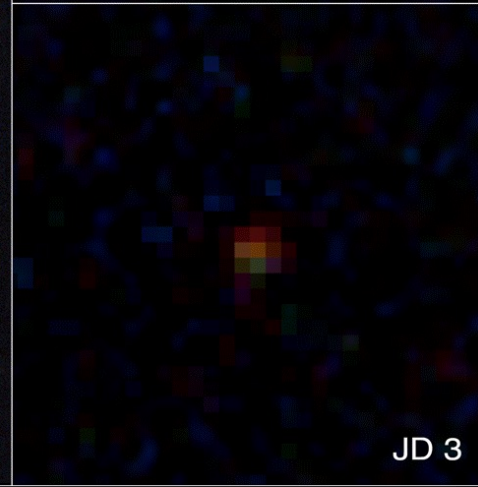
JD 1



JD 2



JD 3



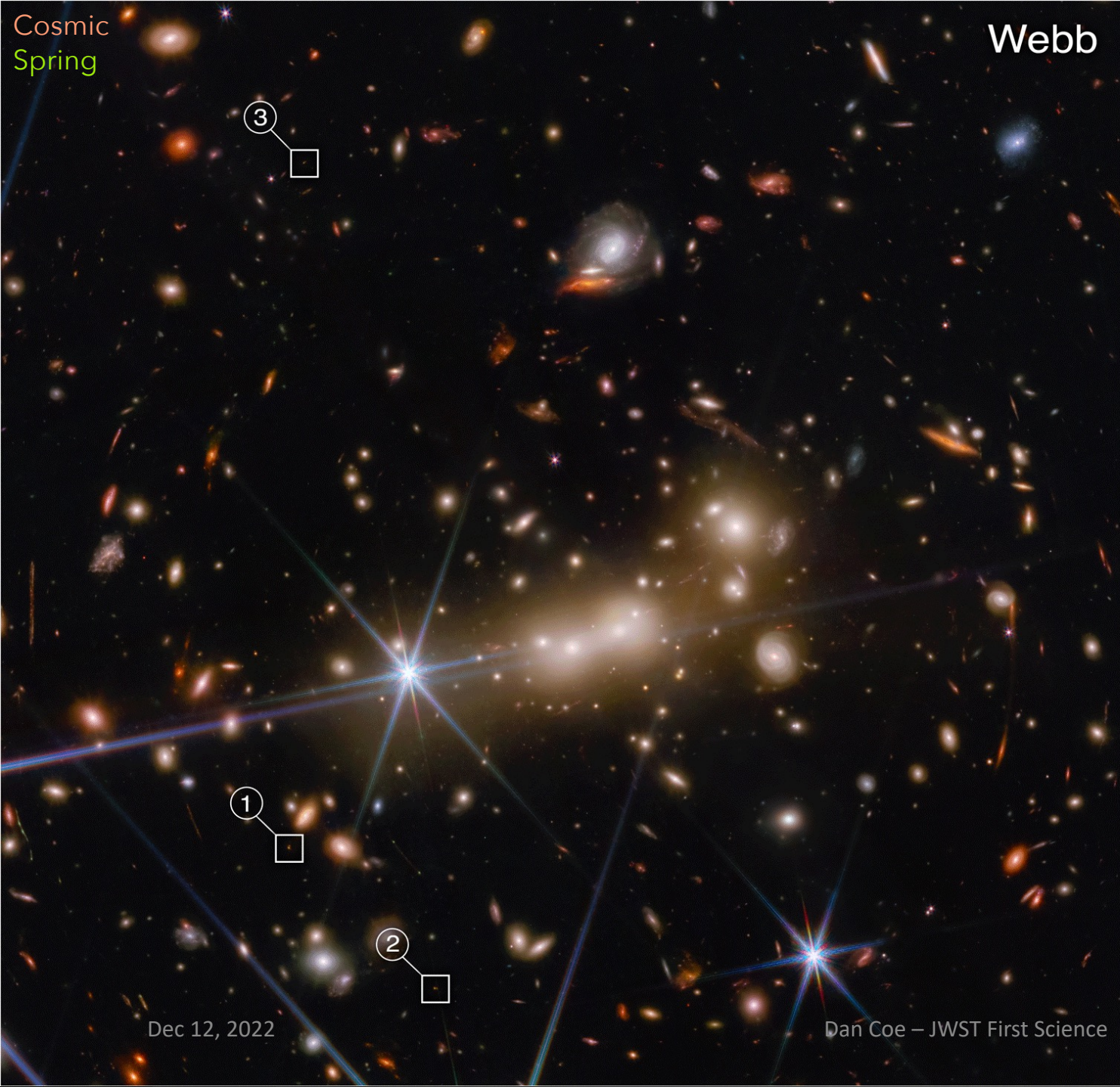
# Look again at that dot

MACS0647-JD  
 $z \sim 11$  (400 Myr)  
Coe et al. 2013



Cosmic  
Spring

Webb



Dec 12, 2022

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F200W AB mag 25.0  
magnification ~ 8x

JD 1

F200W AB mag 25.4  
magnification ~ 5x

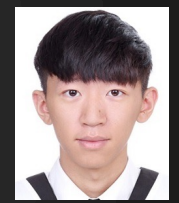
JD 2

F200W AB mag 26.2  
magnification ~ 2x

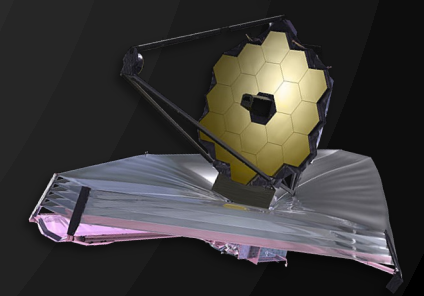
JD 3

# Look again at those dots

MACS0647-JD  
 $z = 10.17$  (460 Myr)



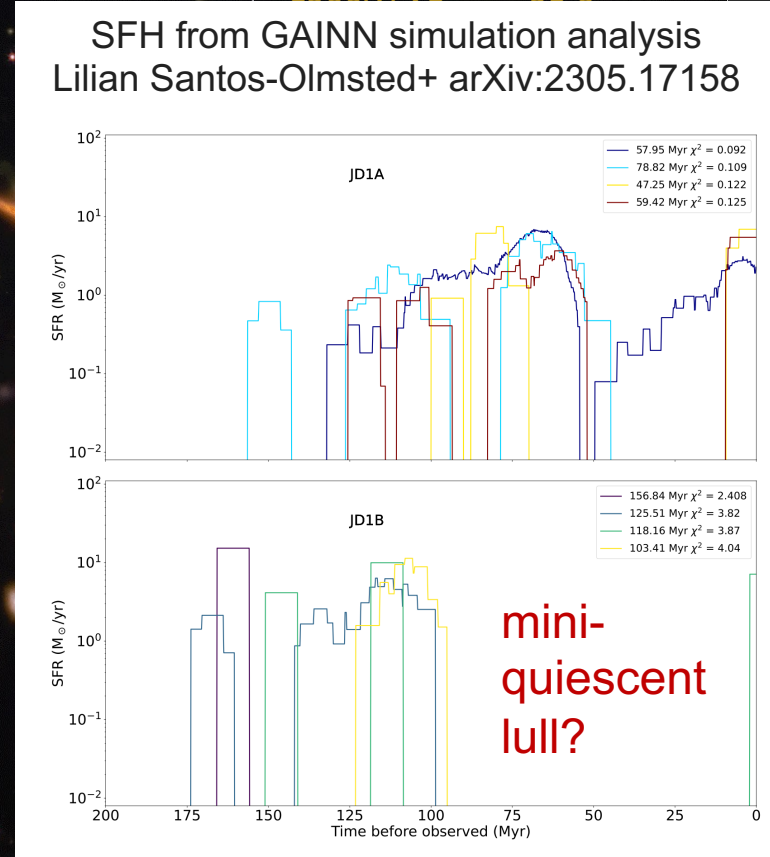
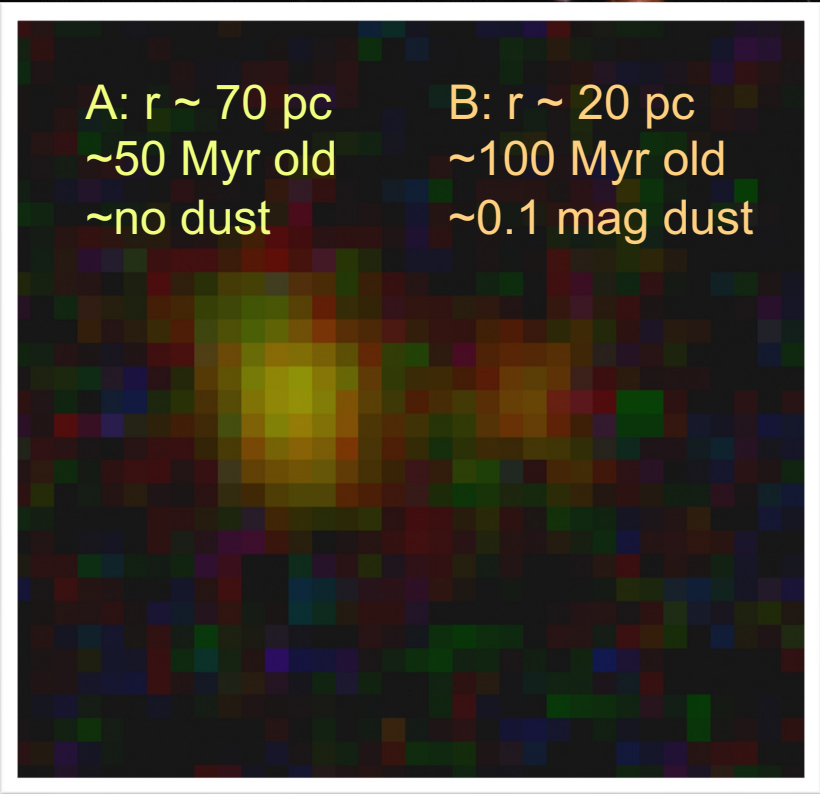
Tiger Hsiao et al.  
arXiv:2210.14123  
arXiv:2305.03042



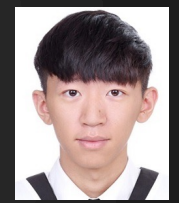
Webb

# Look again at those dots

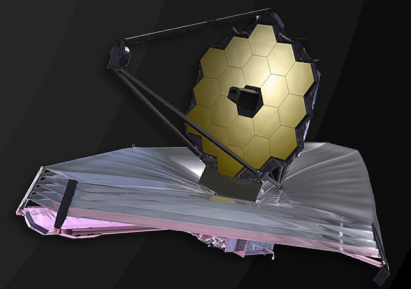
3



MACS0647-JD  
 $z = 10.17$  (460 Myr)



Tiger Hsiao et al.  
arXiv:2210.14123  
arXiv:2305.03042



1

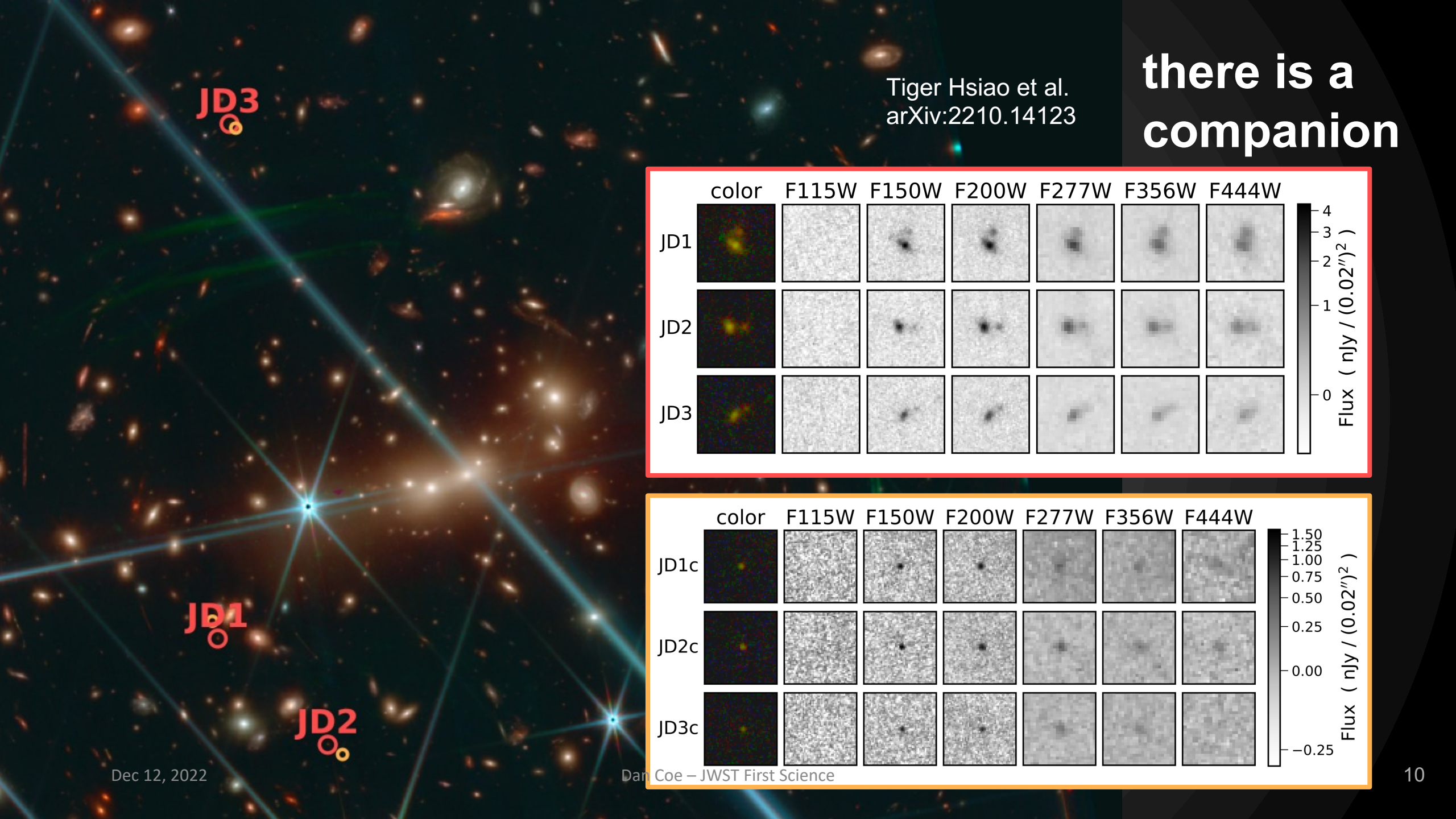
2

Dec 12, 2022

Dan Coe – JWST First Science

F200W AB mag 26.2  
magnification  $\sim 2x$

JD 3



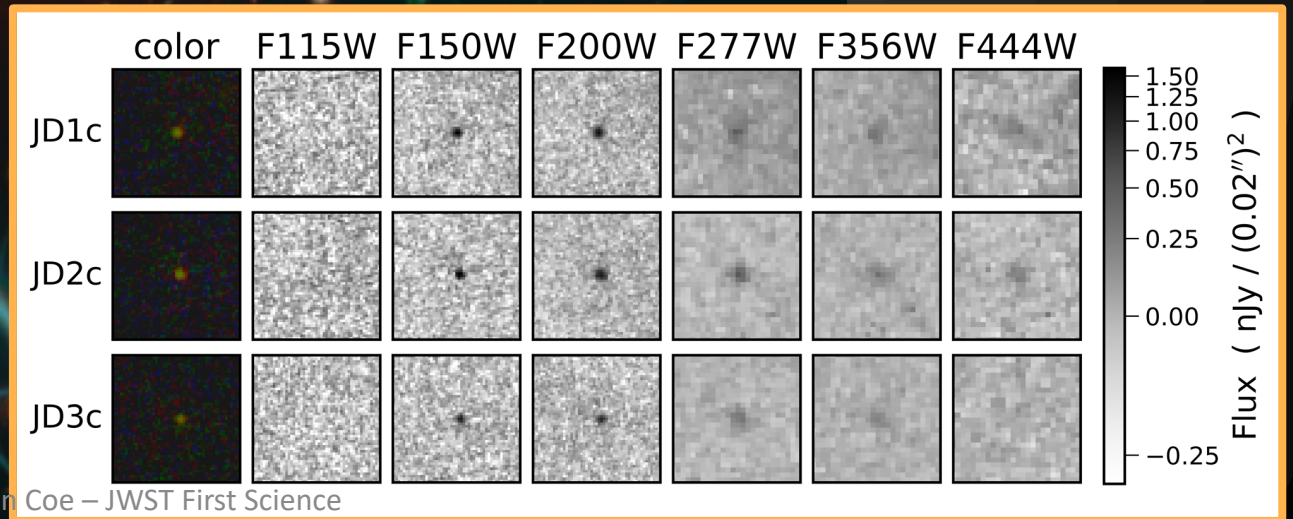
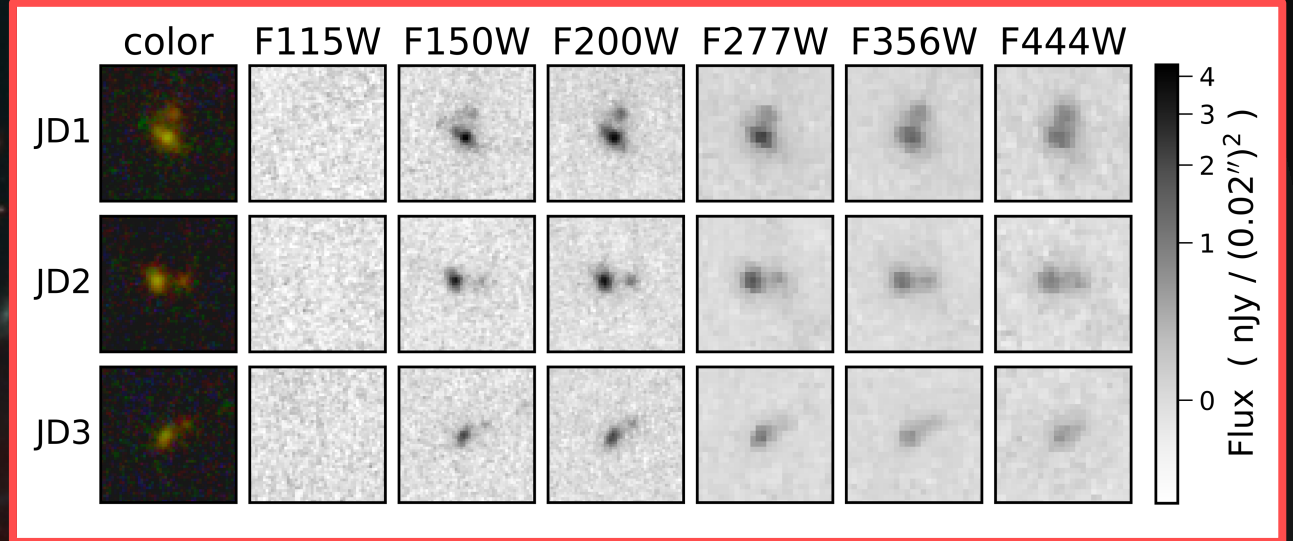
JD3

JD1

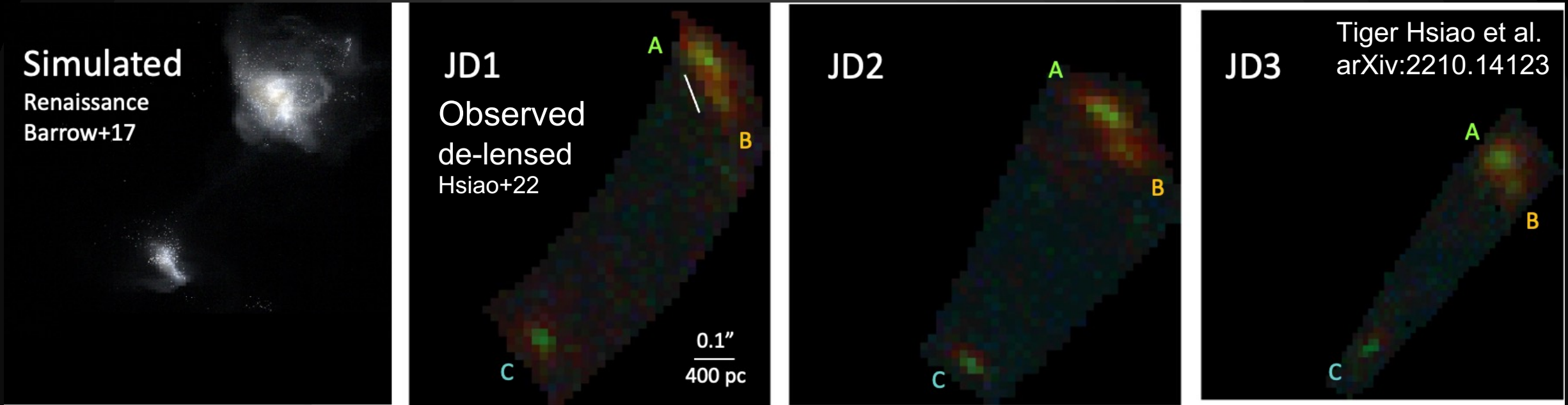
JD2

Tiger Hsiao et al.  
arXiv:2210.14123

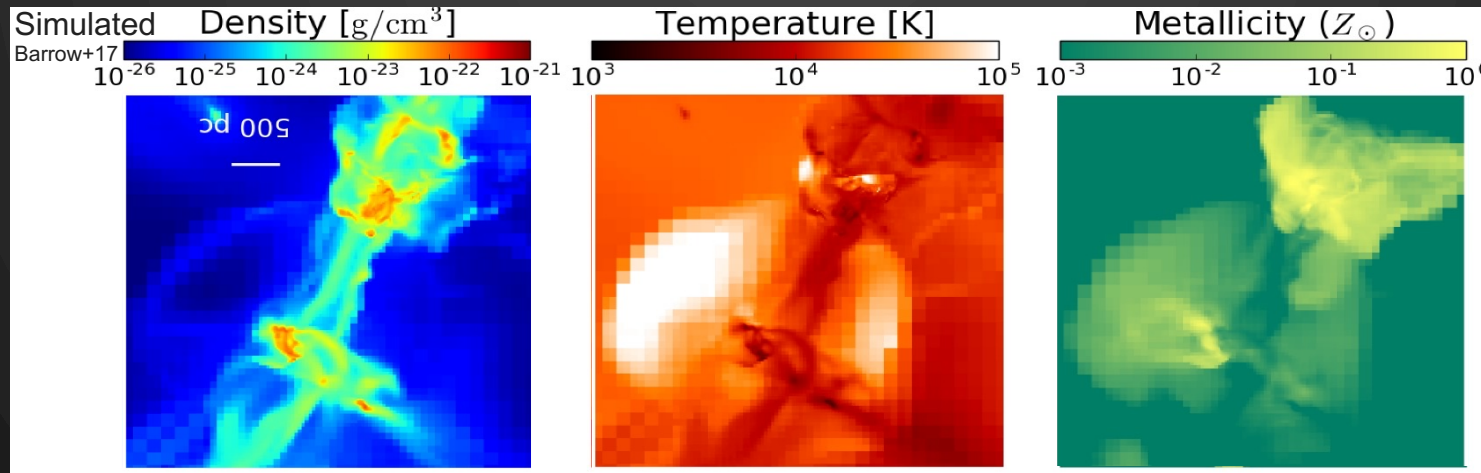
there is a  
companion



# Galaxy merger 400 Myr after the Big Bang?



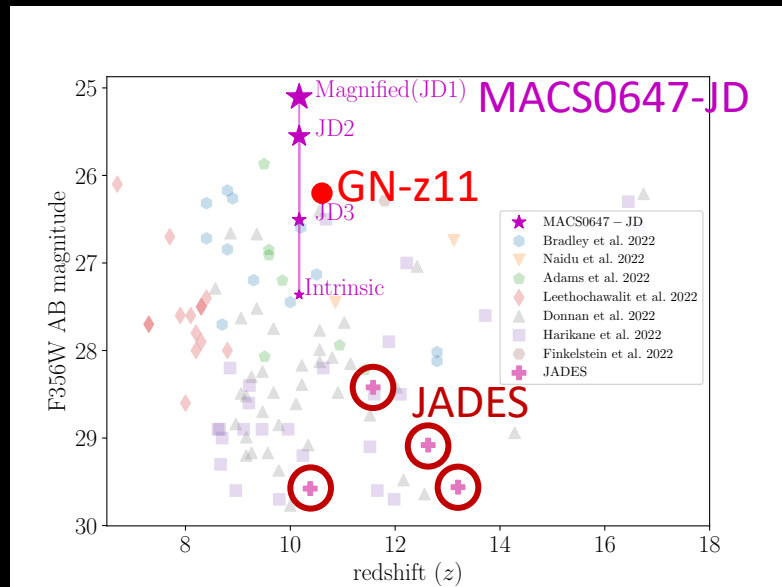
Kirk Barrow



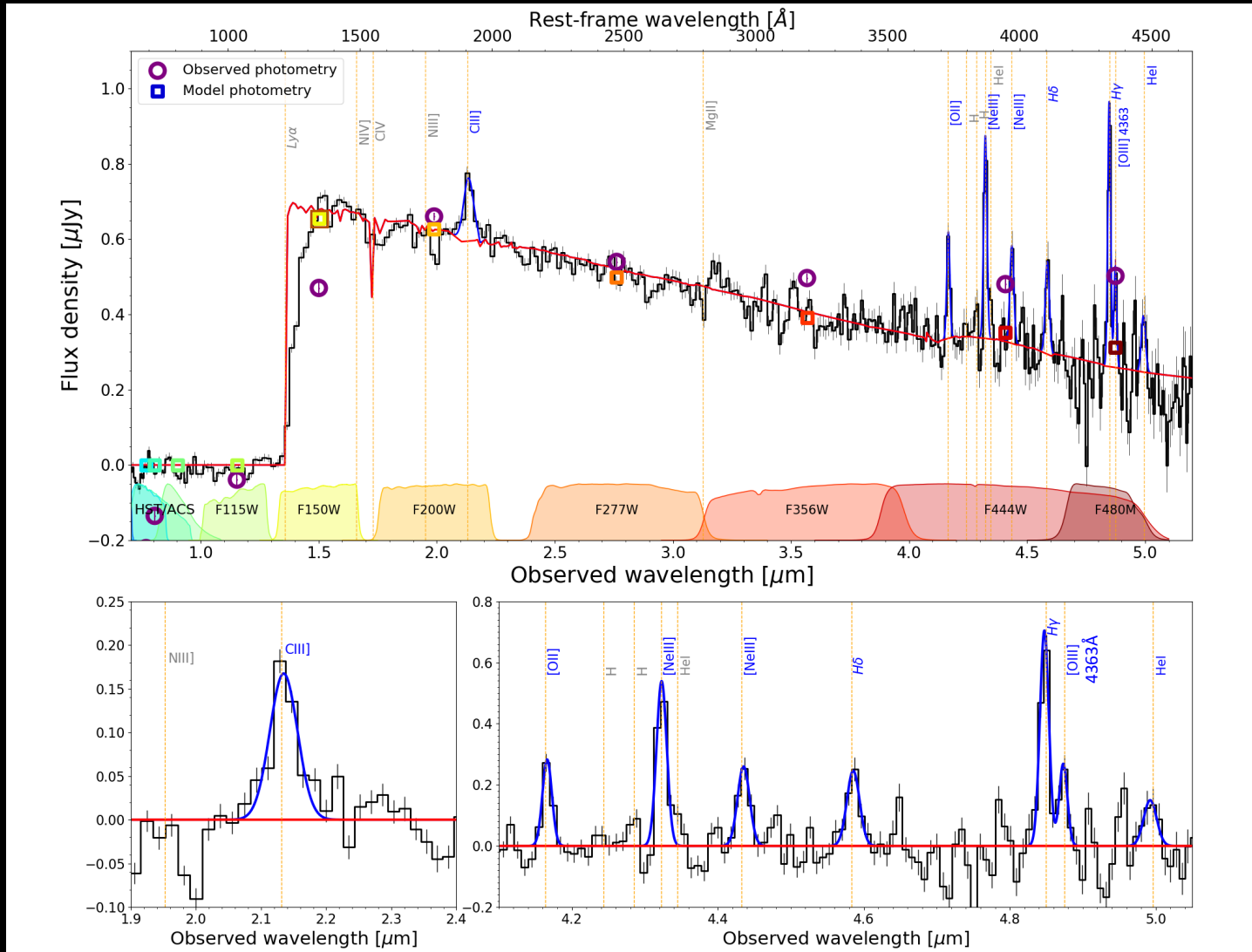
# MACS0647-JD at $z = 10.17$ with 7 emission lines:

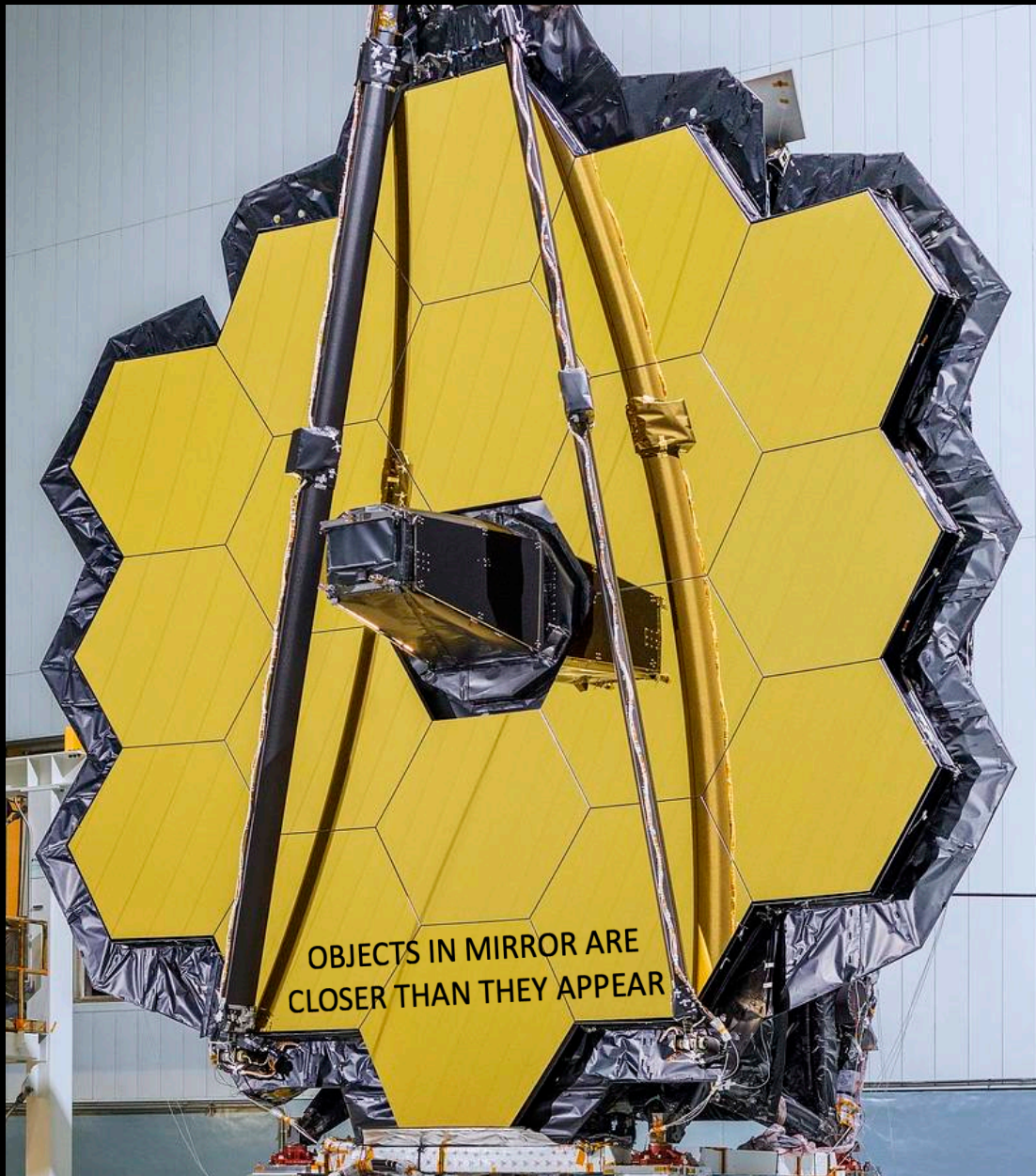
CIII], [OII], [NeIII]x2, H $\gamma$ , H $\delta$ , [OIII] 4363Å

Bright  $z > 10$  galaxies yield emission lines



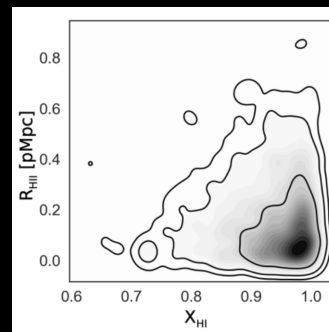
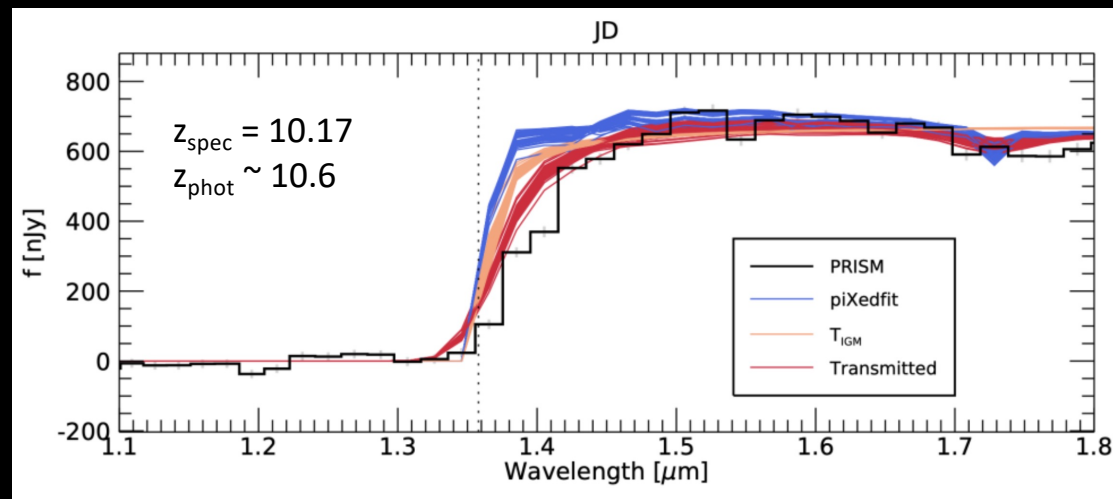
Tiger Hsiao & Abdurro'uf et al.  
(co-lead authors)  
arXiv:2305.03042





# Photo-z's slightly underestimated

- Ly $\alpha$  damping wing due to neutral IGM (Heintz+)
- or low-metallicity top-heavy IMF (Cameron, Katz+)

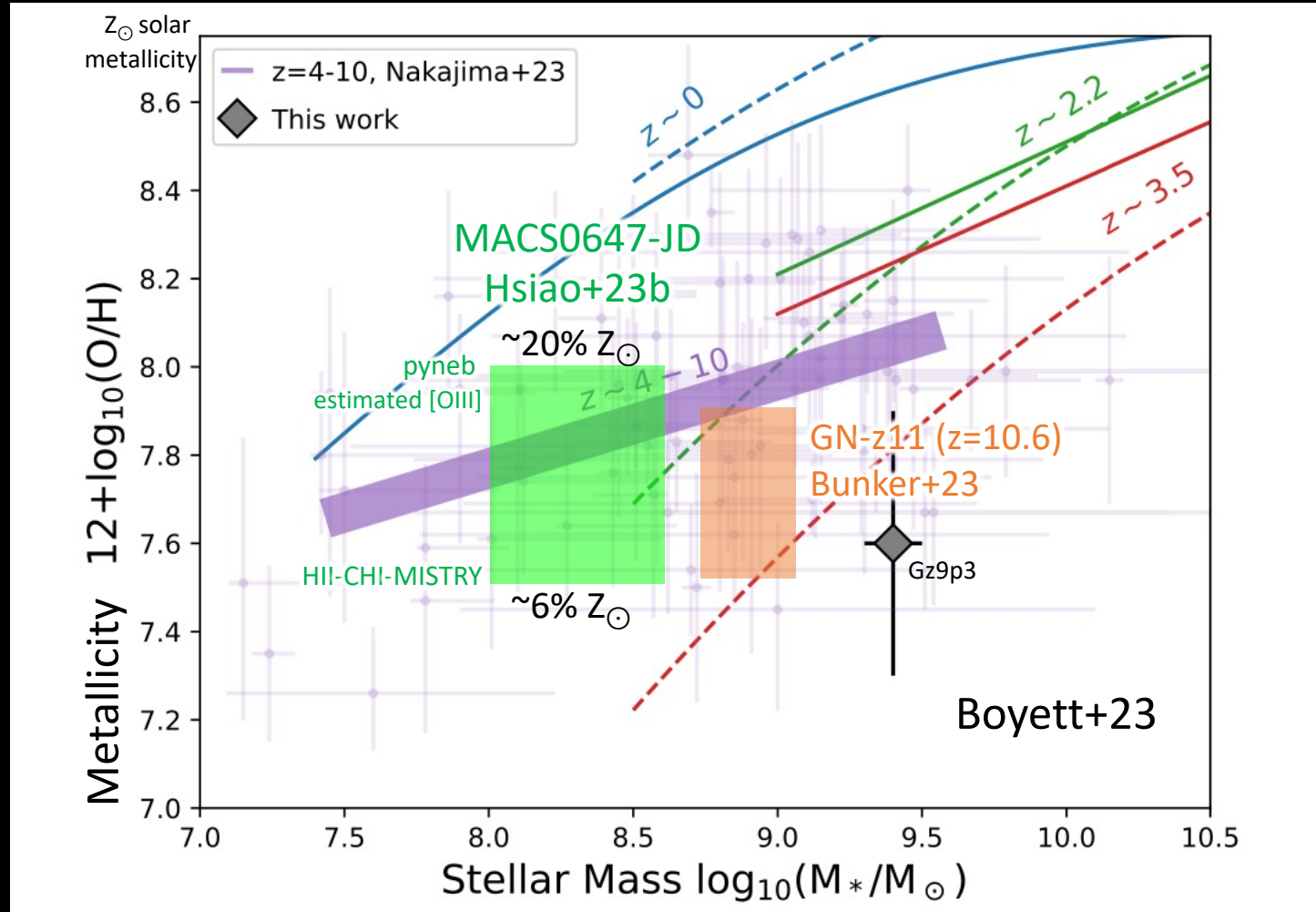


analysis by Intae Jung  
in Hsiao & Abdurro'uf et al.  
arXiv:2305.03042



see also Heintz+23, Umeda+23, Cameron+23

# MACS0647-JD metallicity consistent with other $z \sim 4 - 11$ measurements





# JWST Cycle 2 GO 4246 PI Abdurro'uf

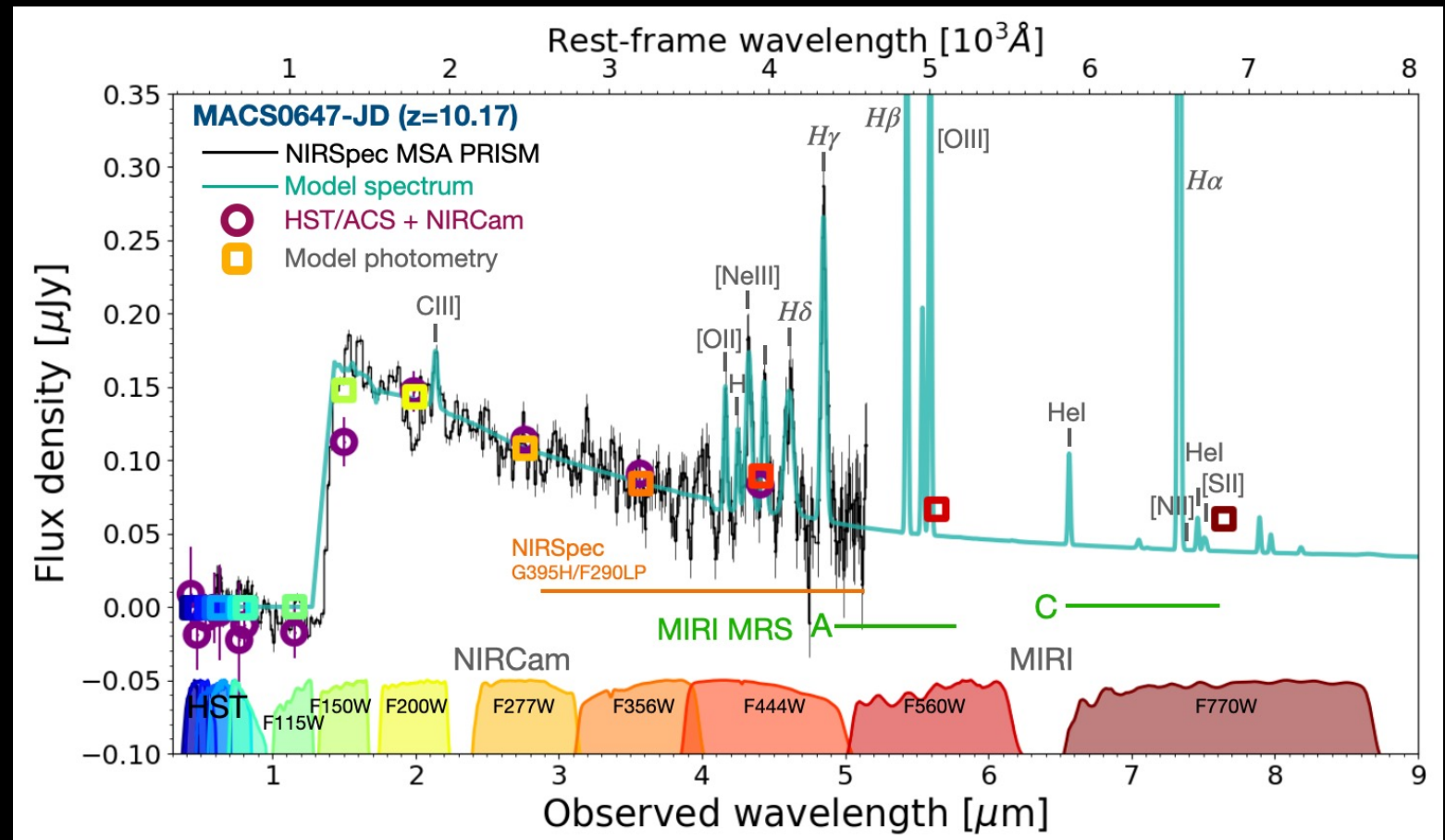
## MACS0647-JD NIRSpec G395H; MIRI imaging + spectroscopy

“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  $f_{\text{esc}}$ ?

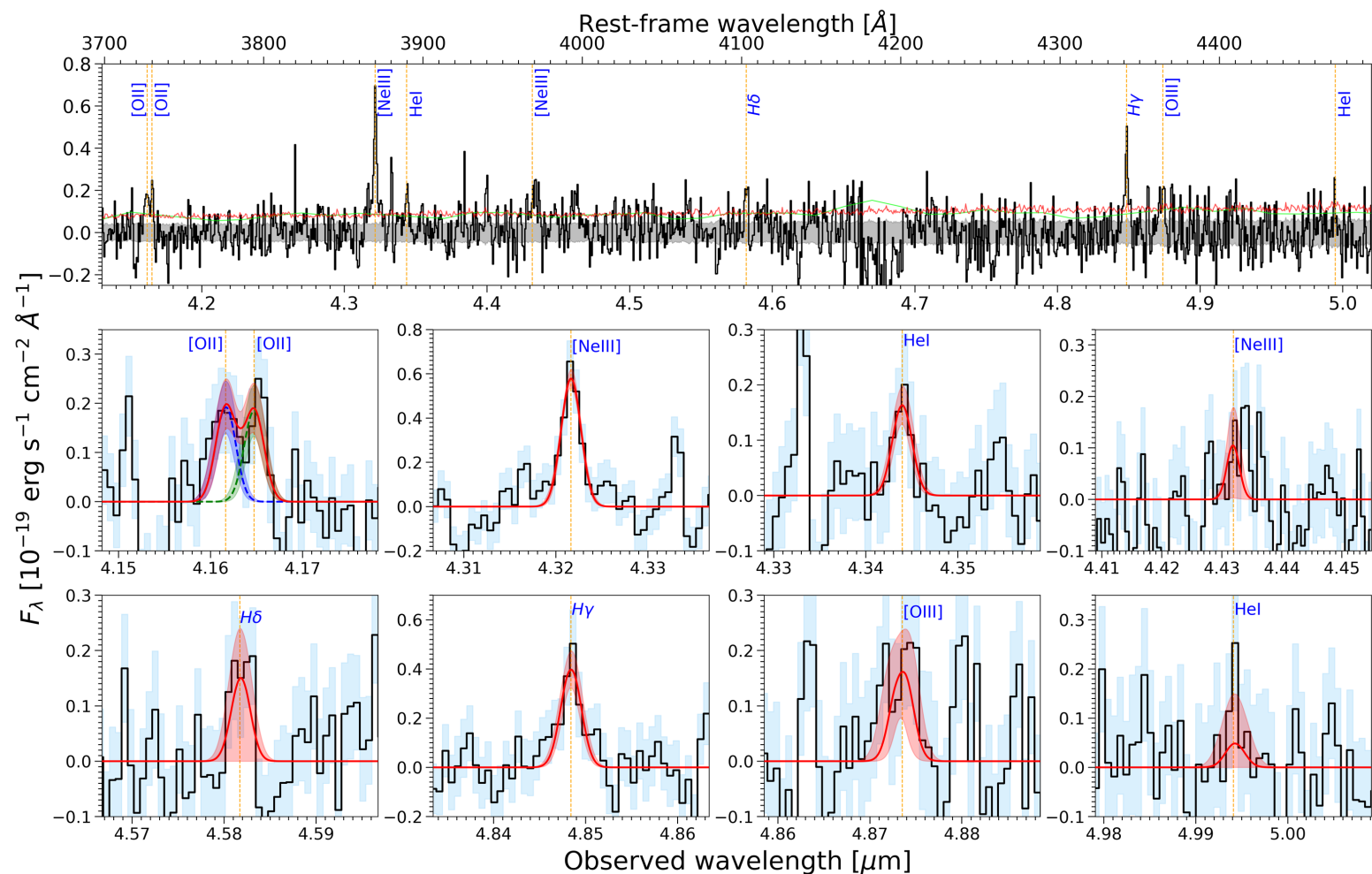


# No strong outflows / AGN



Abdurro'uf et al. 2024

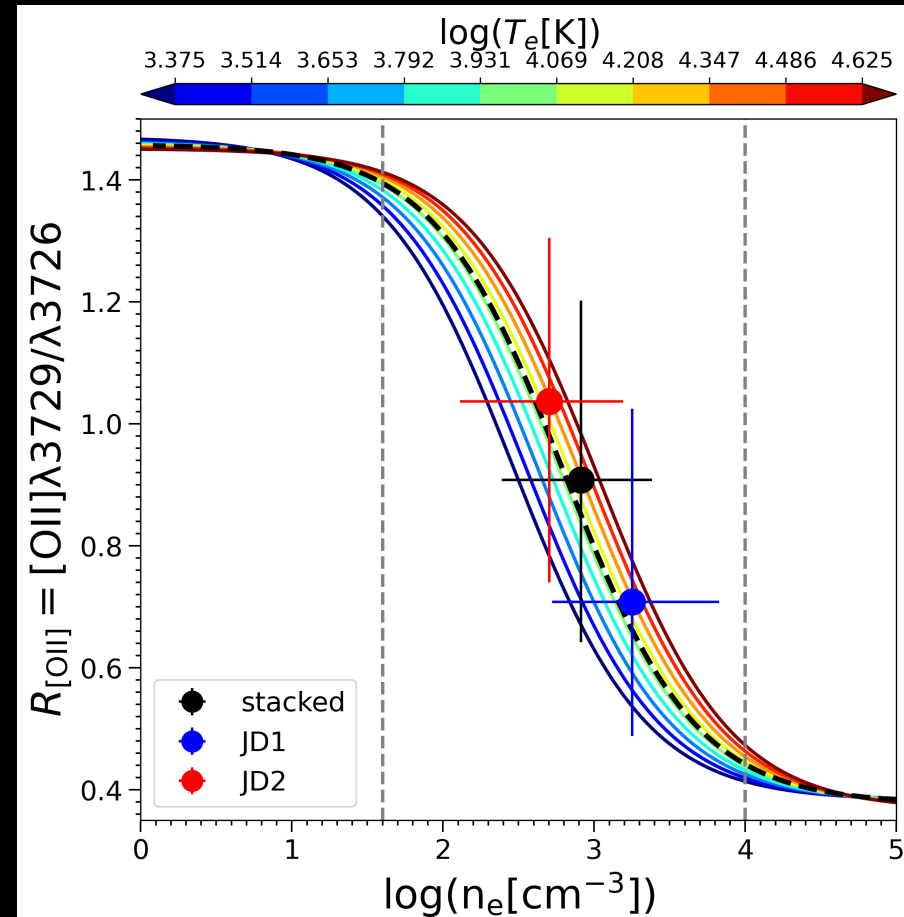
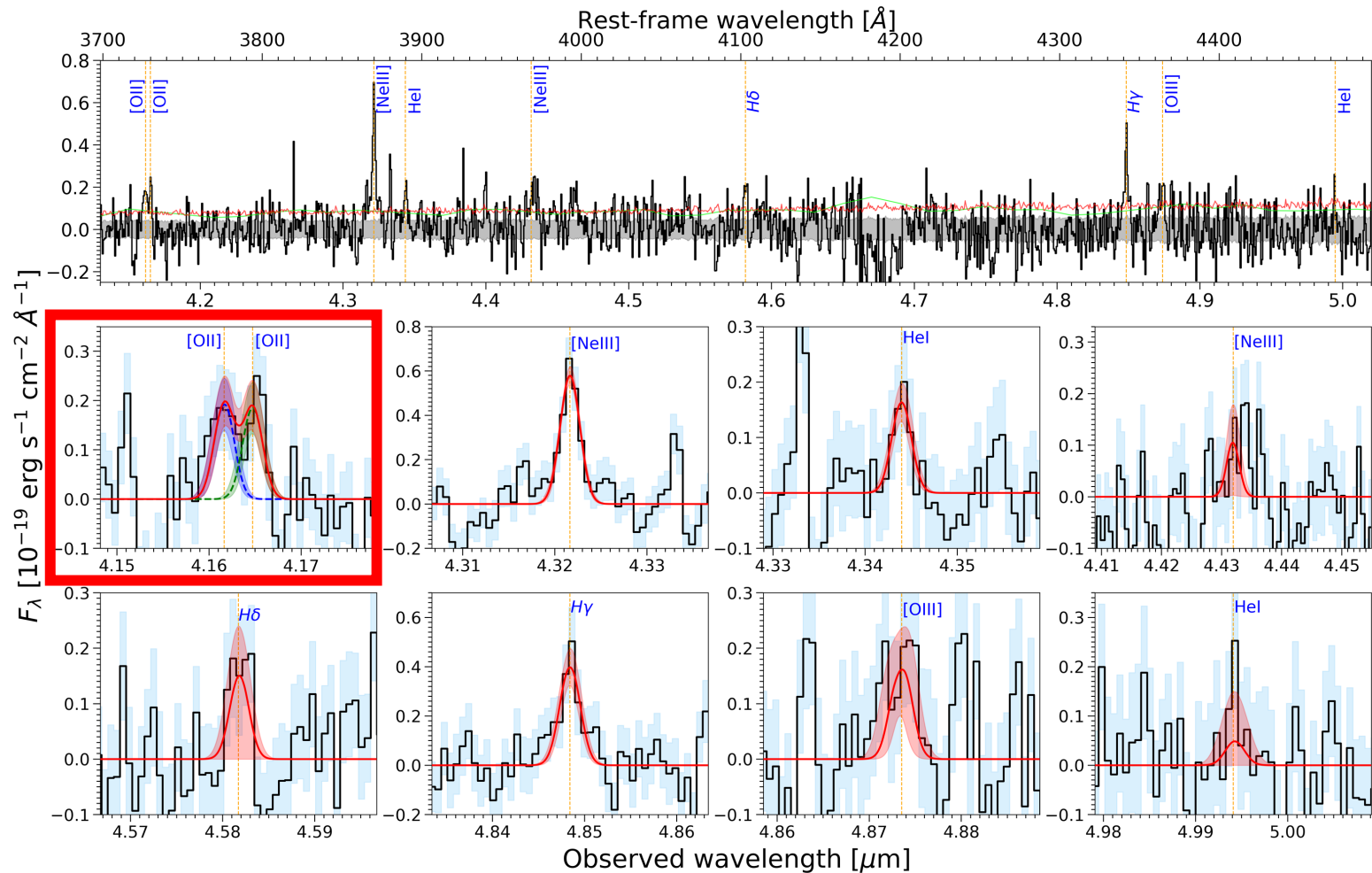
High resolution NIRSpect G395H  
Line widths  $\sim 150$  km/s  
after correcting for broadening

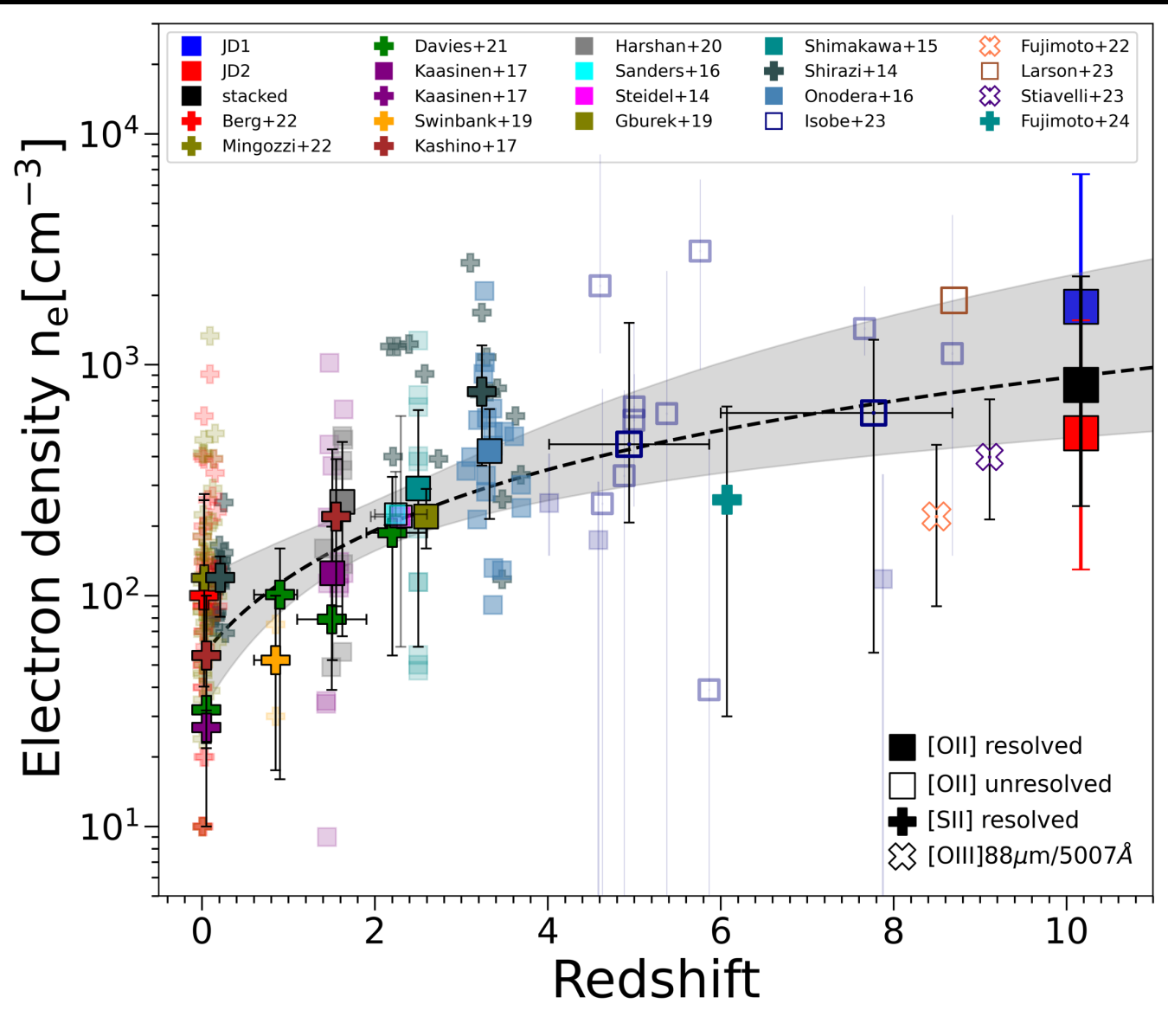


# Resolved [OII] doublet: density $n_e \sim 1000 / \text{cm}^3$



Abdurro'uf et al. 2024



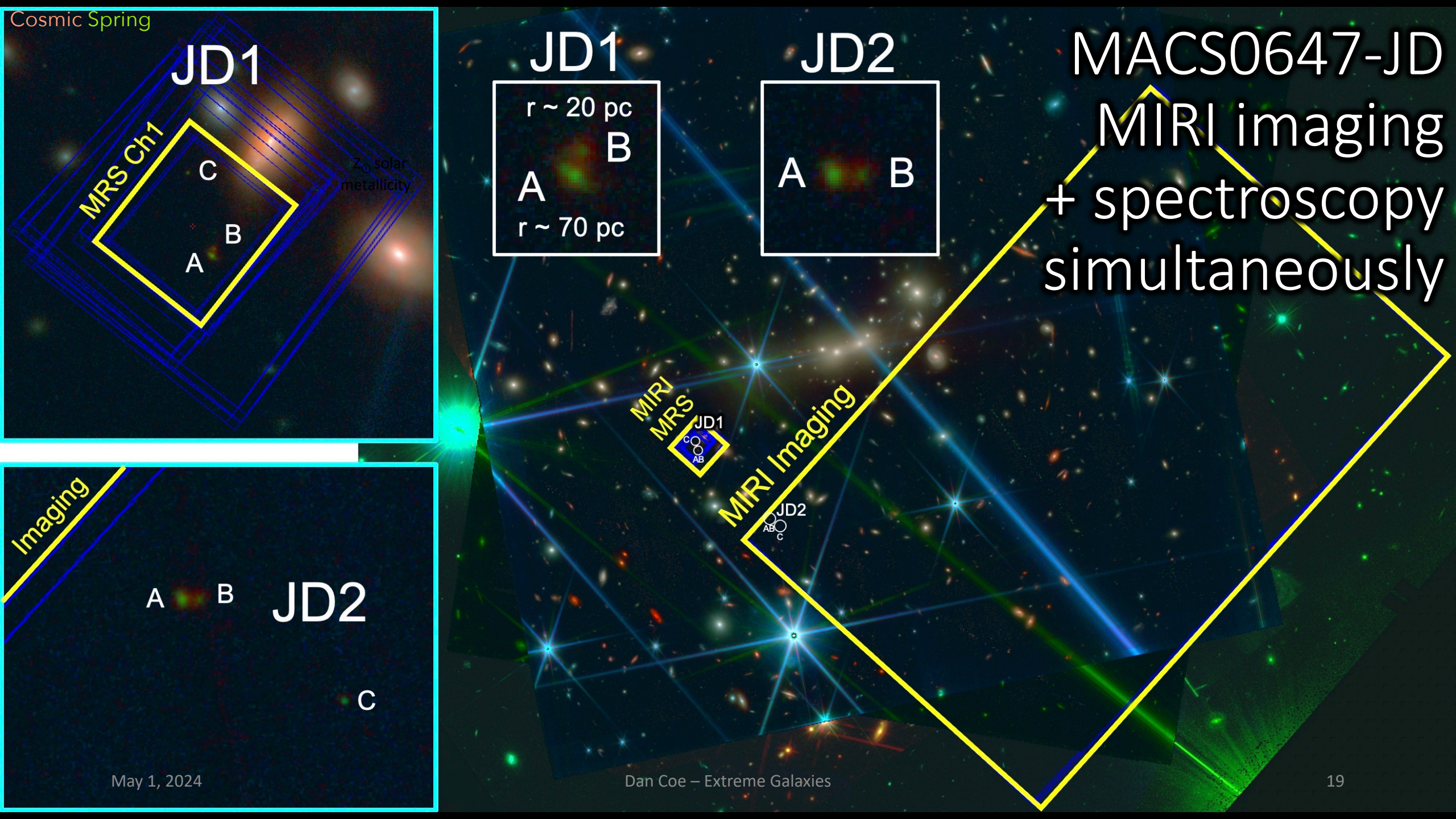


# Electron density evolution with redshift

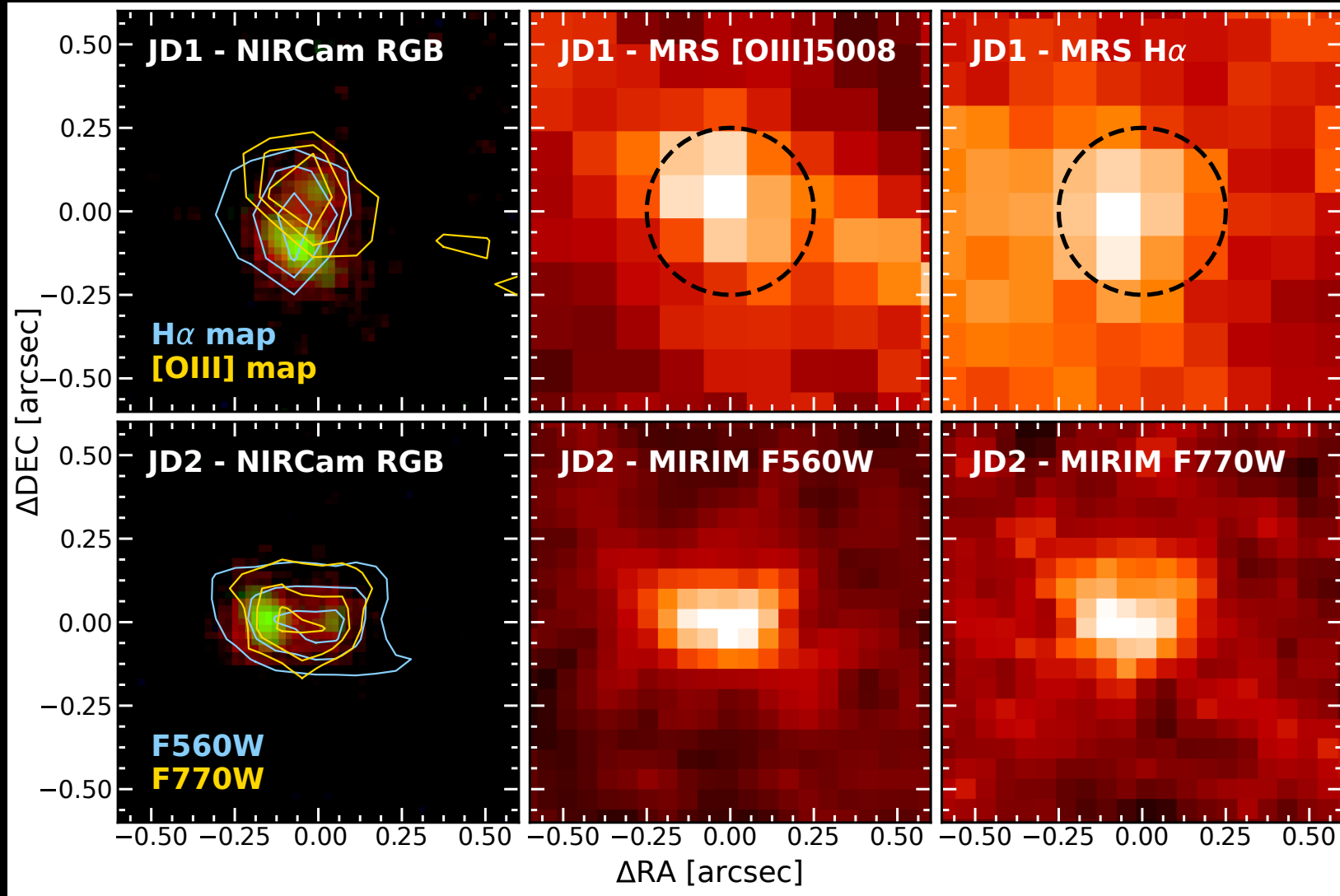
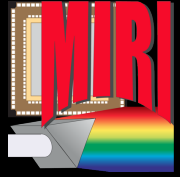
First resolved [OII] doublet at  $z > 8$



Abdurro'uf et al. 2024



# MIRI detects MACS0647-JD ( $z=10.17$ )



MIRI MRS IFU reductions:  
Javier Álvarez-Márquez



MIRI image reductions:  
Alex Crespo Gómez

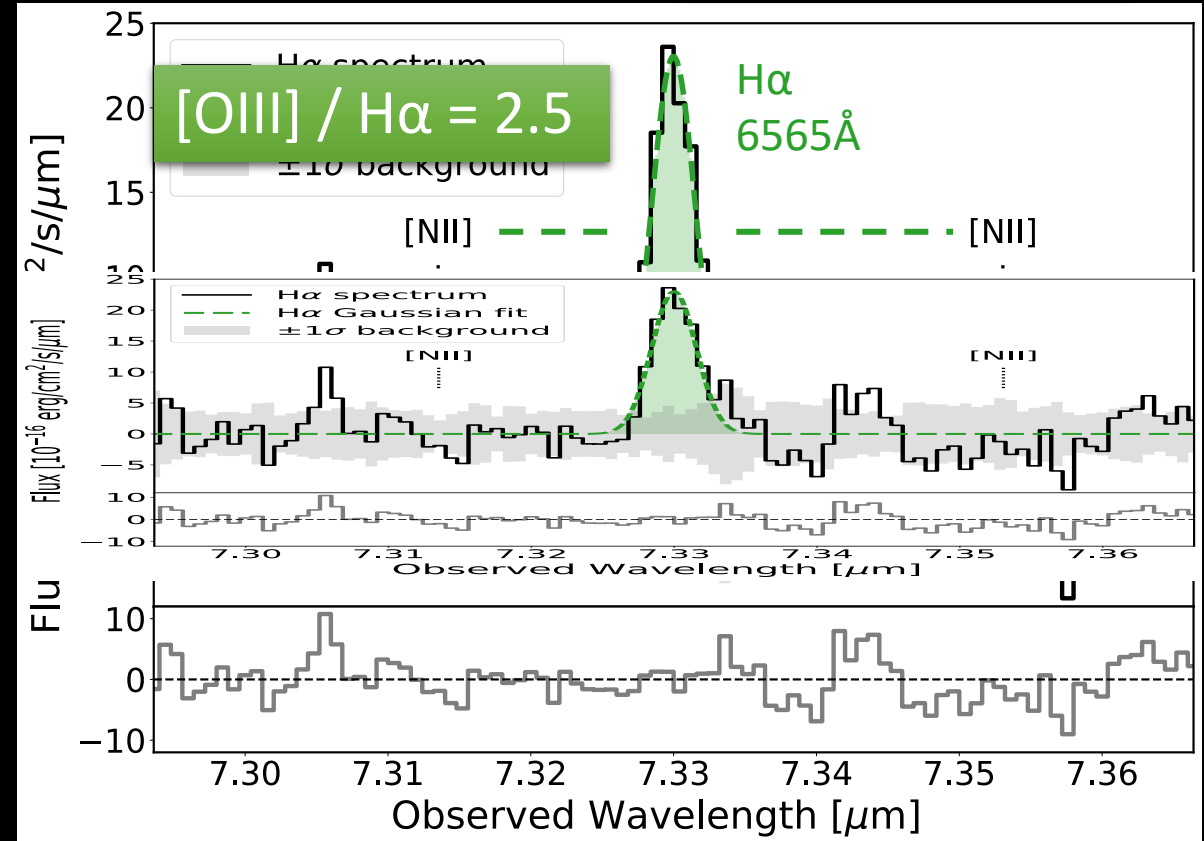
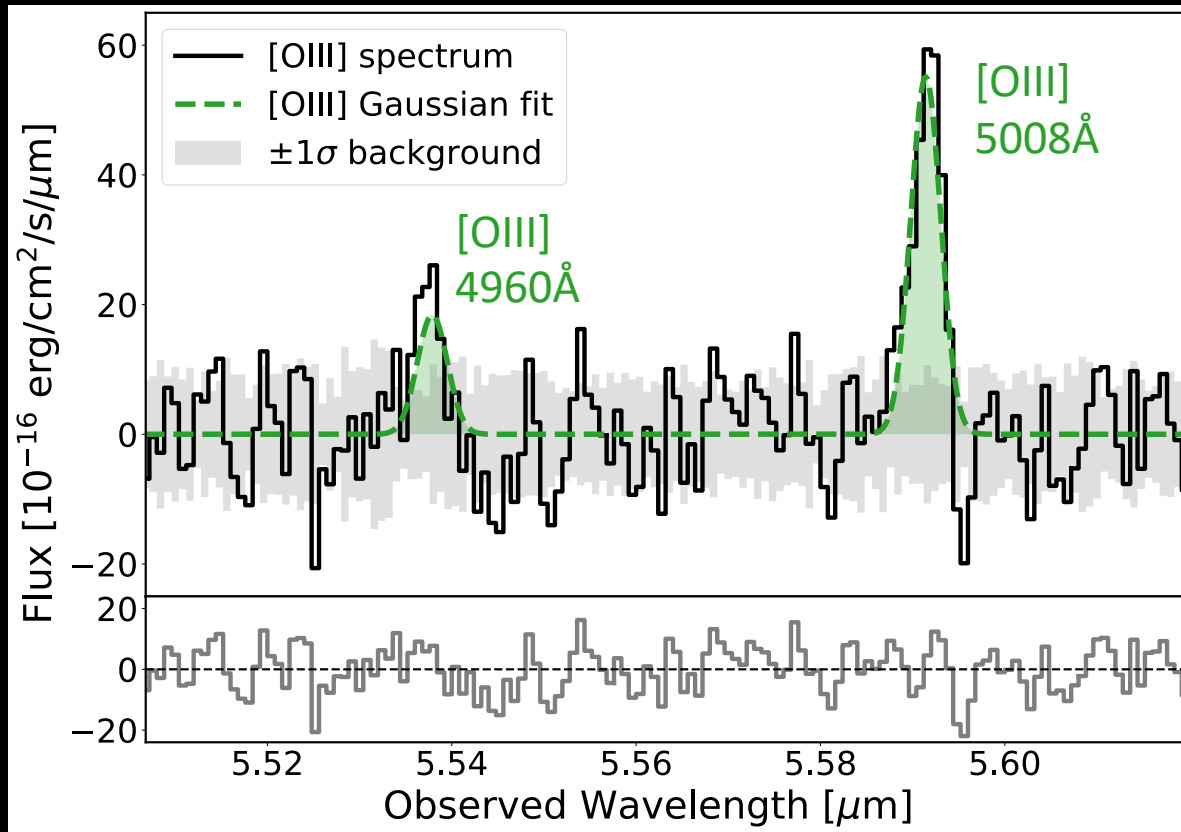
paper:  
Hsiao & Álvarez et al. 2024

# MIRI MRS: [OIII], H $\alpha$ in MACS0647-JD (z=10.17)

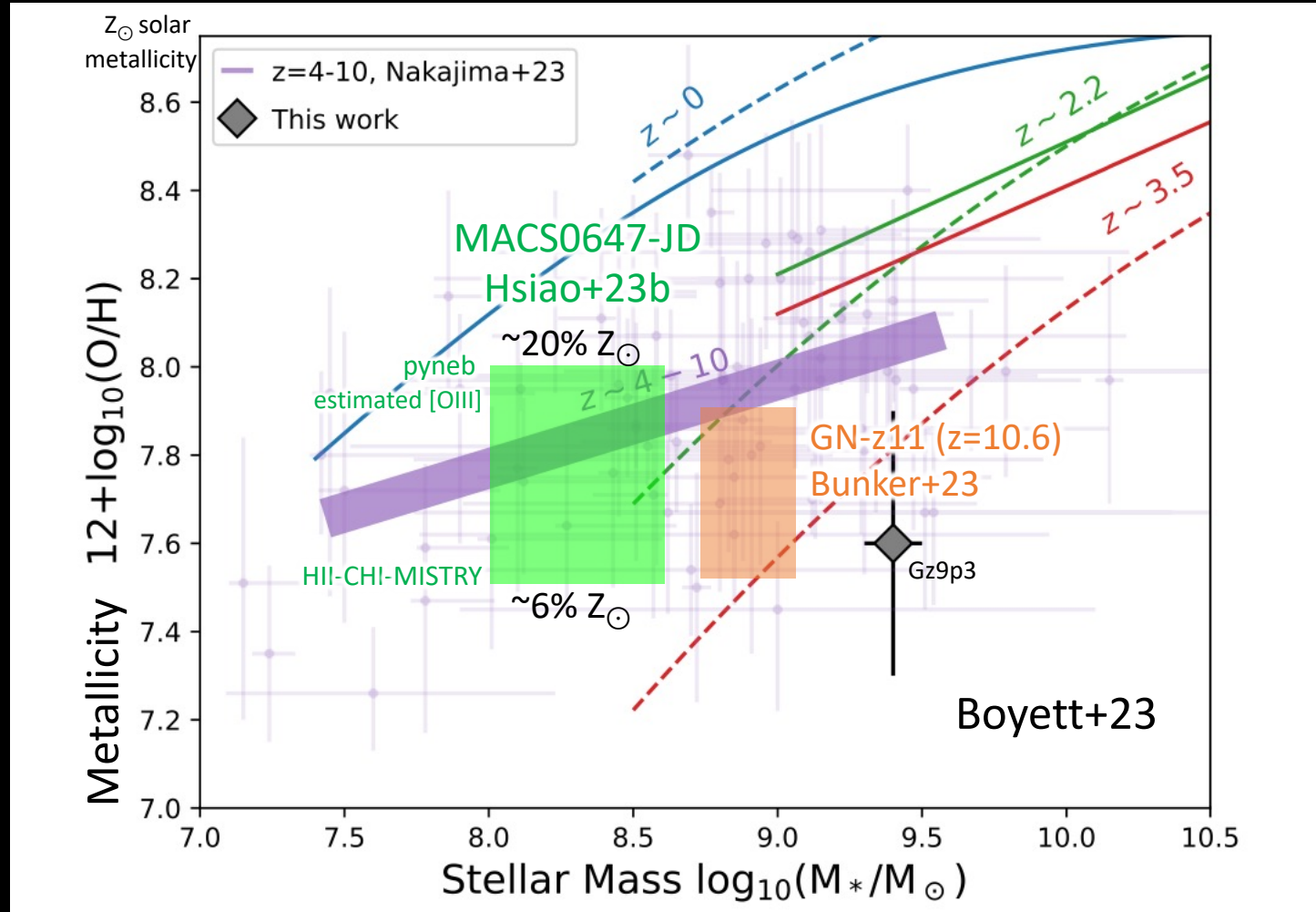


MIRI MRS reductions and analysis: Javier Álvarez  
paper: Tiger Hsiao & Javier Álvarez et al. 2024

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

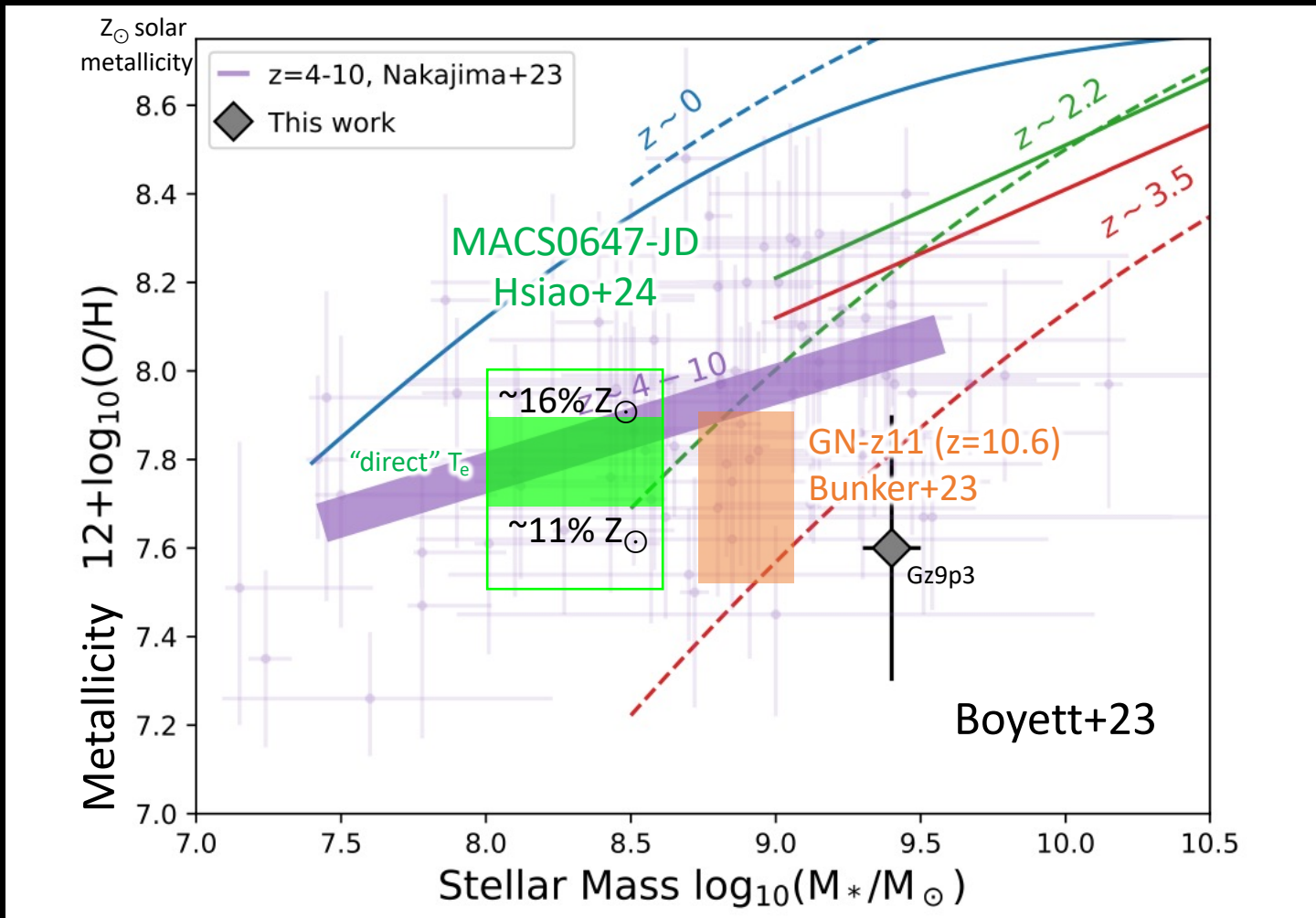


# MACS0647-JD metallicity consistent with other $z \sim 4 - 11$ measurements



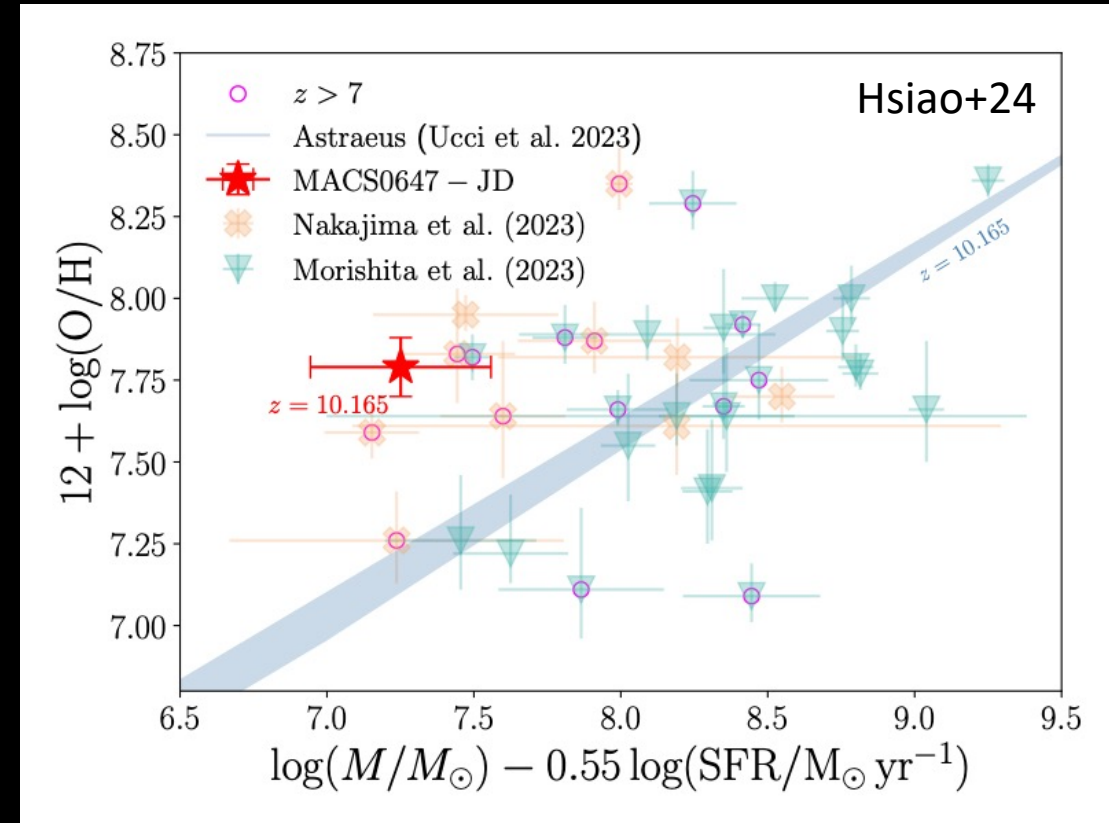
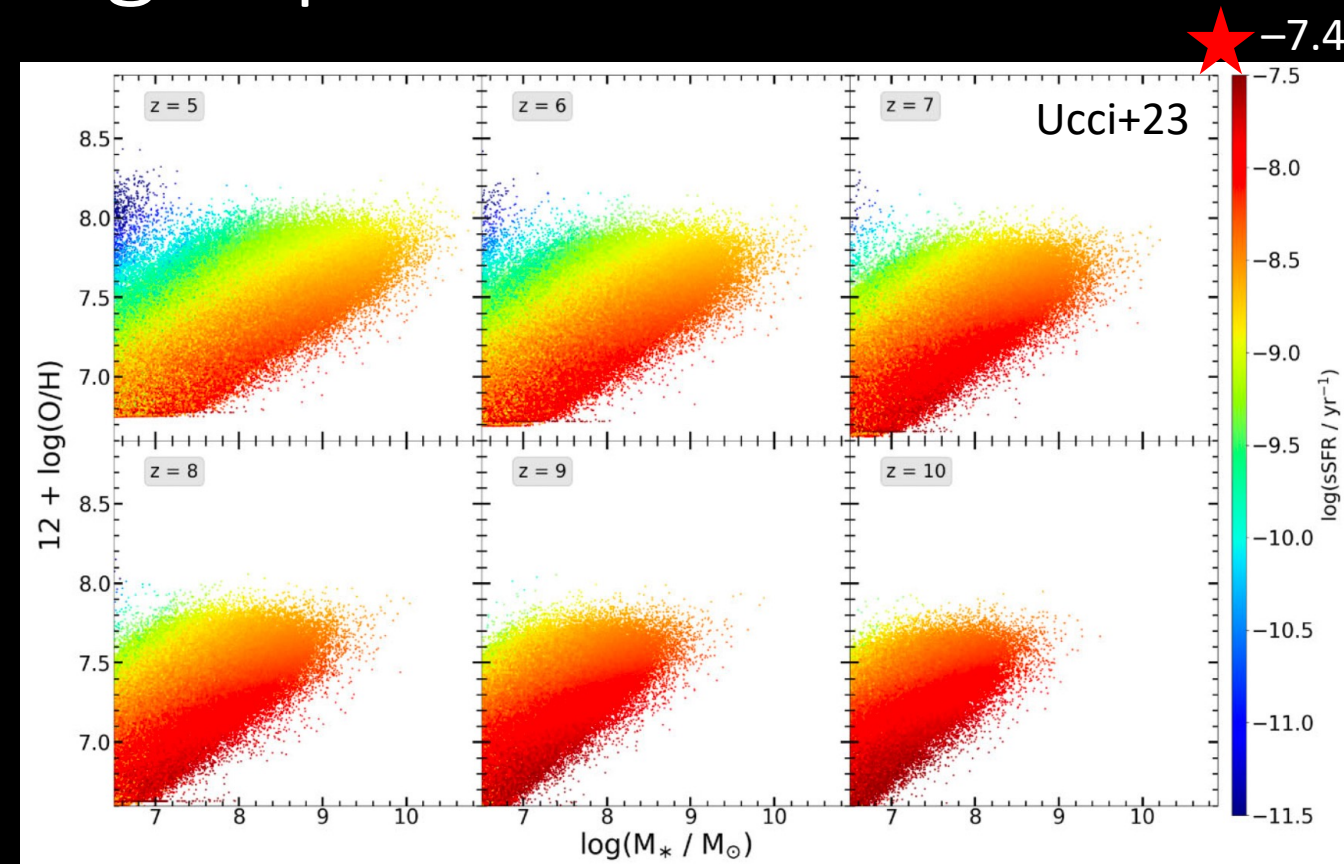
# MACS0647-JD direct metallicity consistent with other $z \sim 4 - 11$ measurements

[OIII] 5007 / 4363 =  $40 \pm 5$   
 $T_e$  [OIII] =  $17000 \pm 2000$  K



# Expect lower metallicity given high specific star formation rate

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

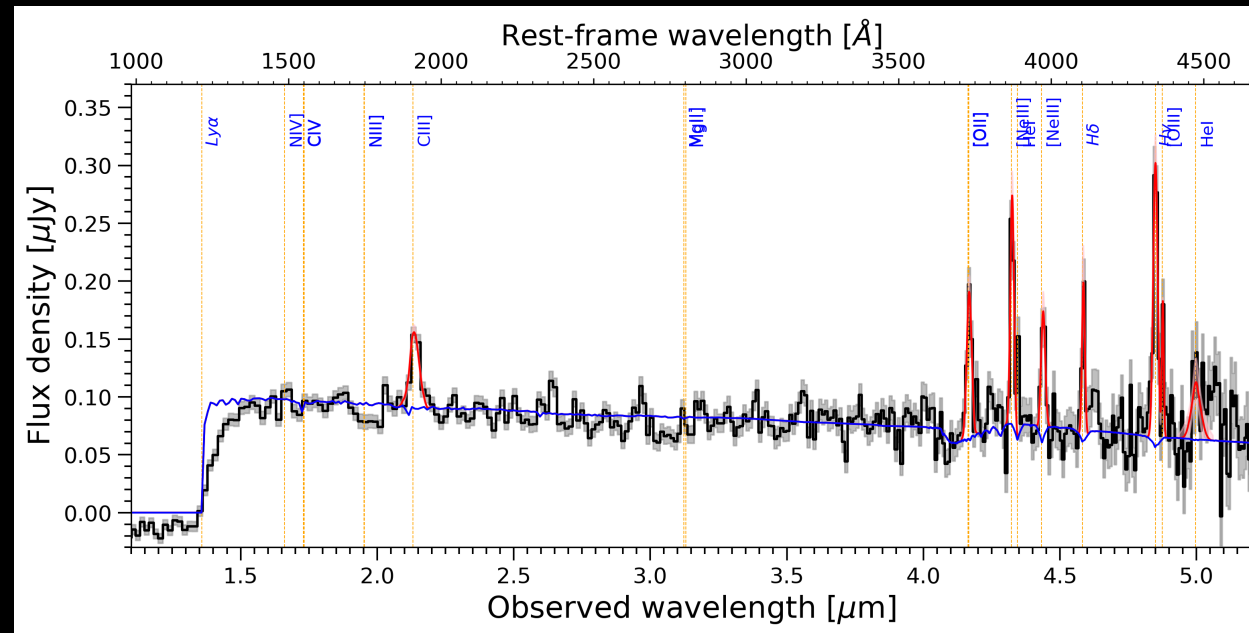
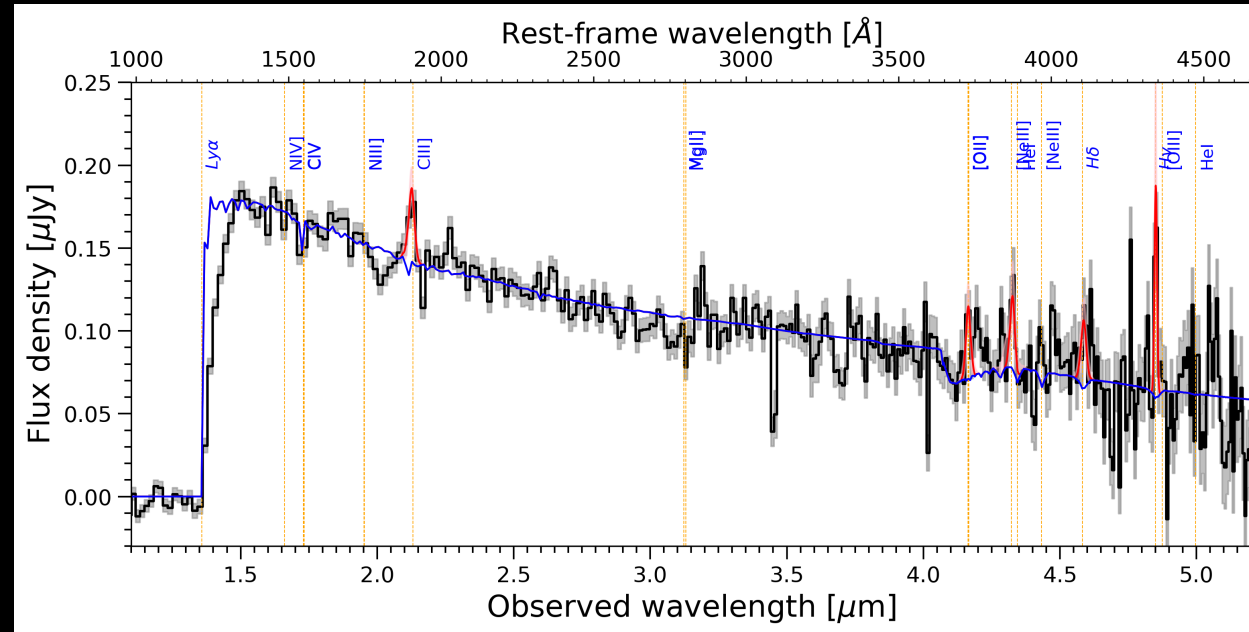
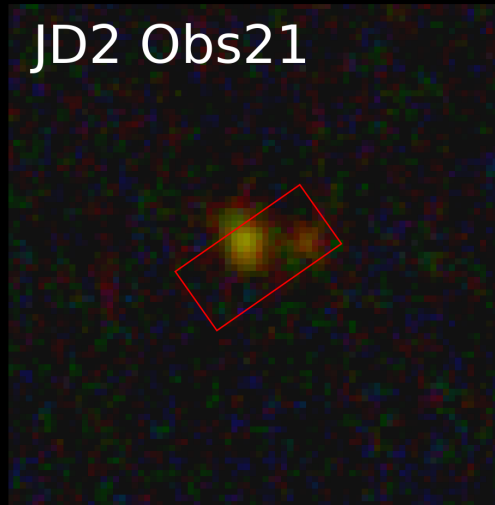
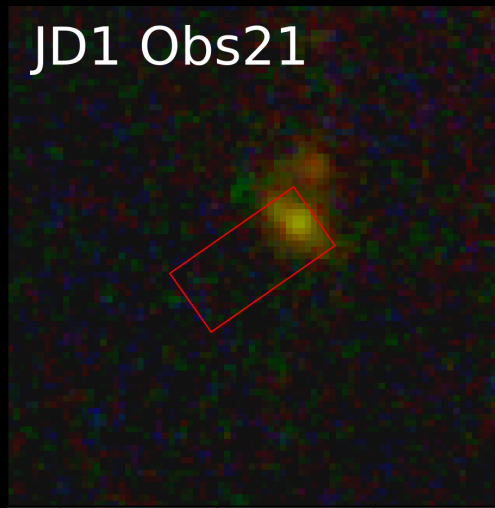


Cycle 1 (GO 1433)

# Individual clump properties?

Where is the emission coming from?

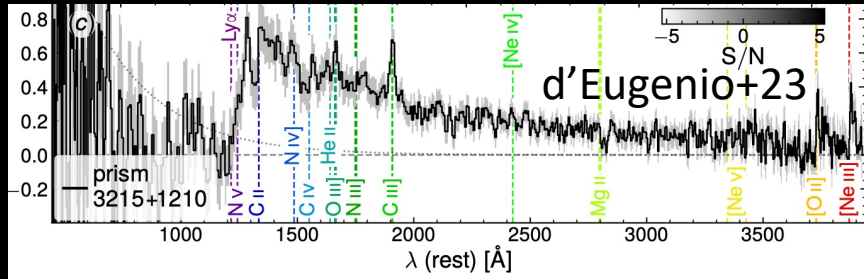
upcoming JWST Cycle 3  
NIRSpec IFU G395M  
GTO 4528 (PI Isaak)  
+13 targets incl.  
MACS0647-JD



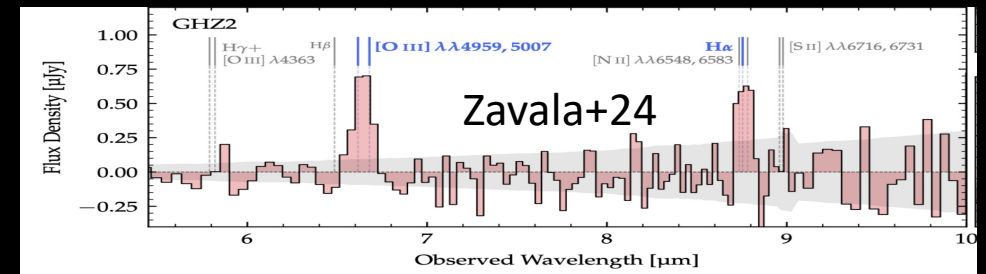
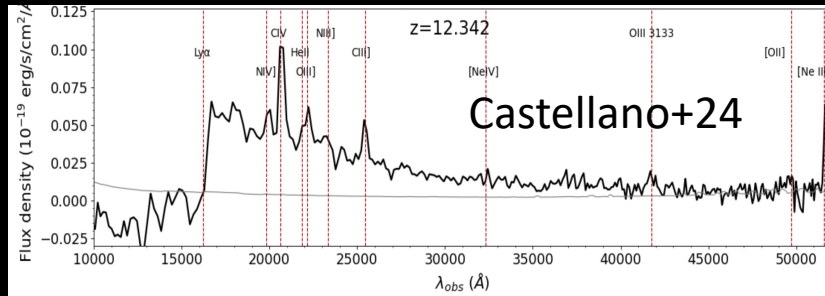
# Are all $z > 10$ galaxies “extreme”?

unexpected,  
requiring  
explanation

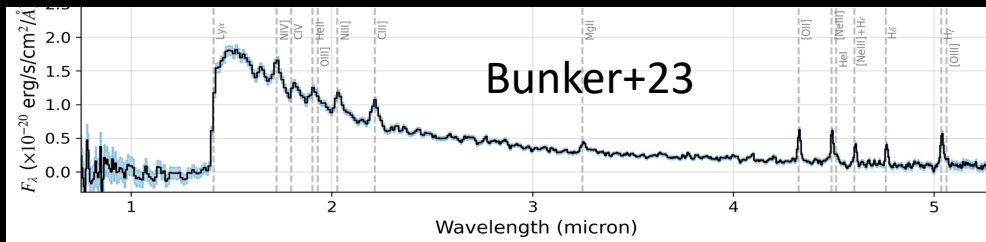
GS-z12  
 $z = 12.48$  (350 Myr)  
 $M_{UV} = -18.2$   
 AB mag 29.0  
**extreme C/O**



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

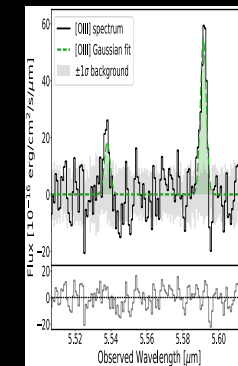
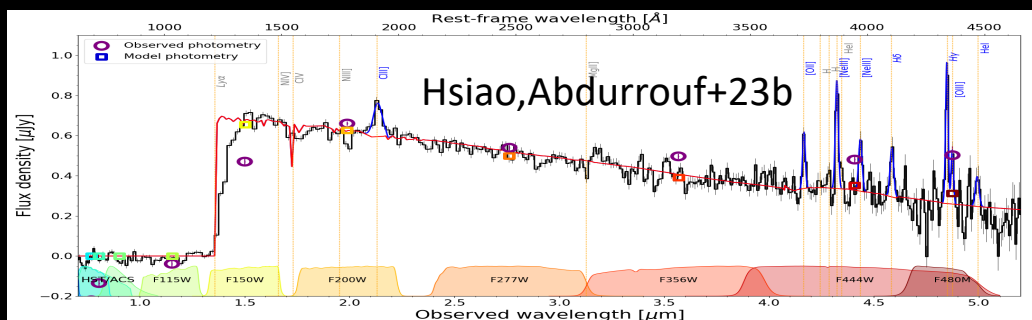


GN-z11  
 $z = 10.60$  (430 Myr)  
 $M_{UV} = -21.5$   
 AB mag 26.0  
**extreme N/O, AGN**

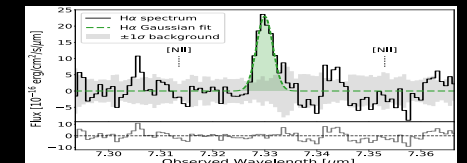


MIRI in prep. (PI Colina)

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

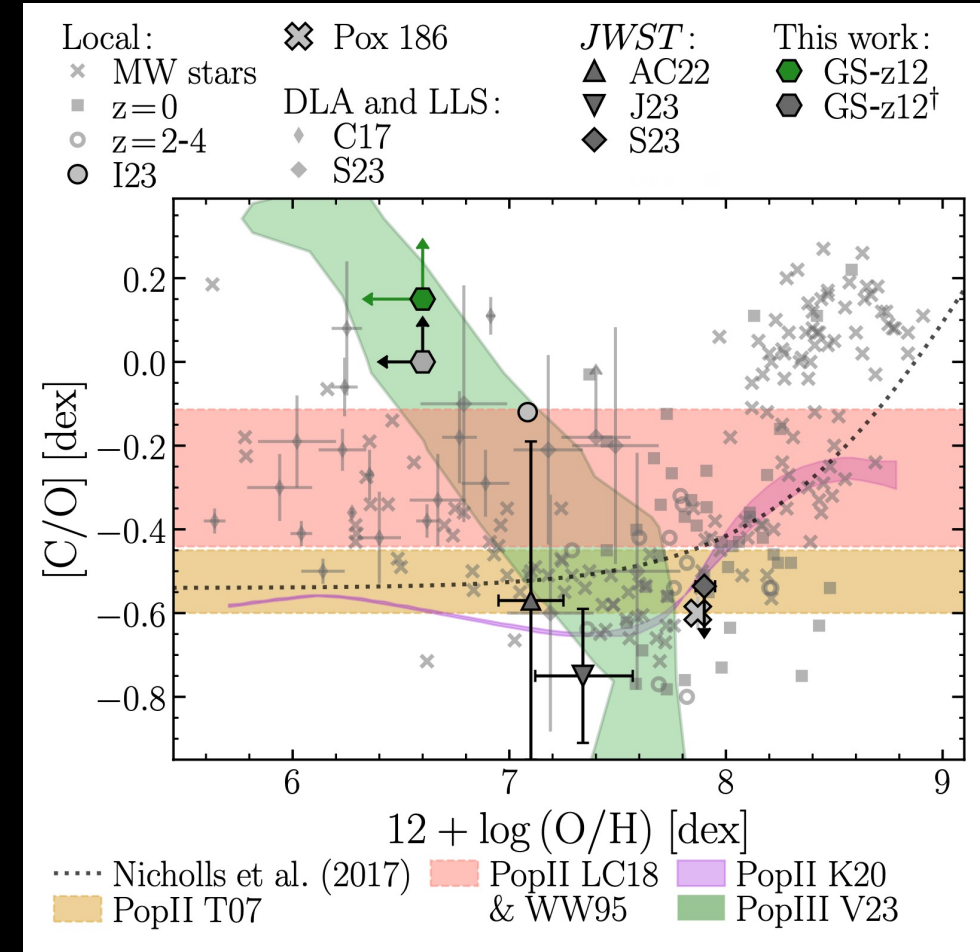
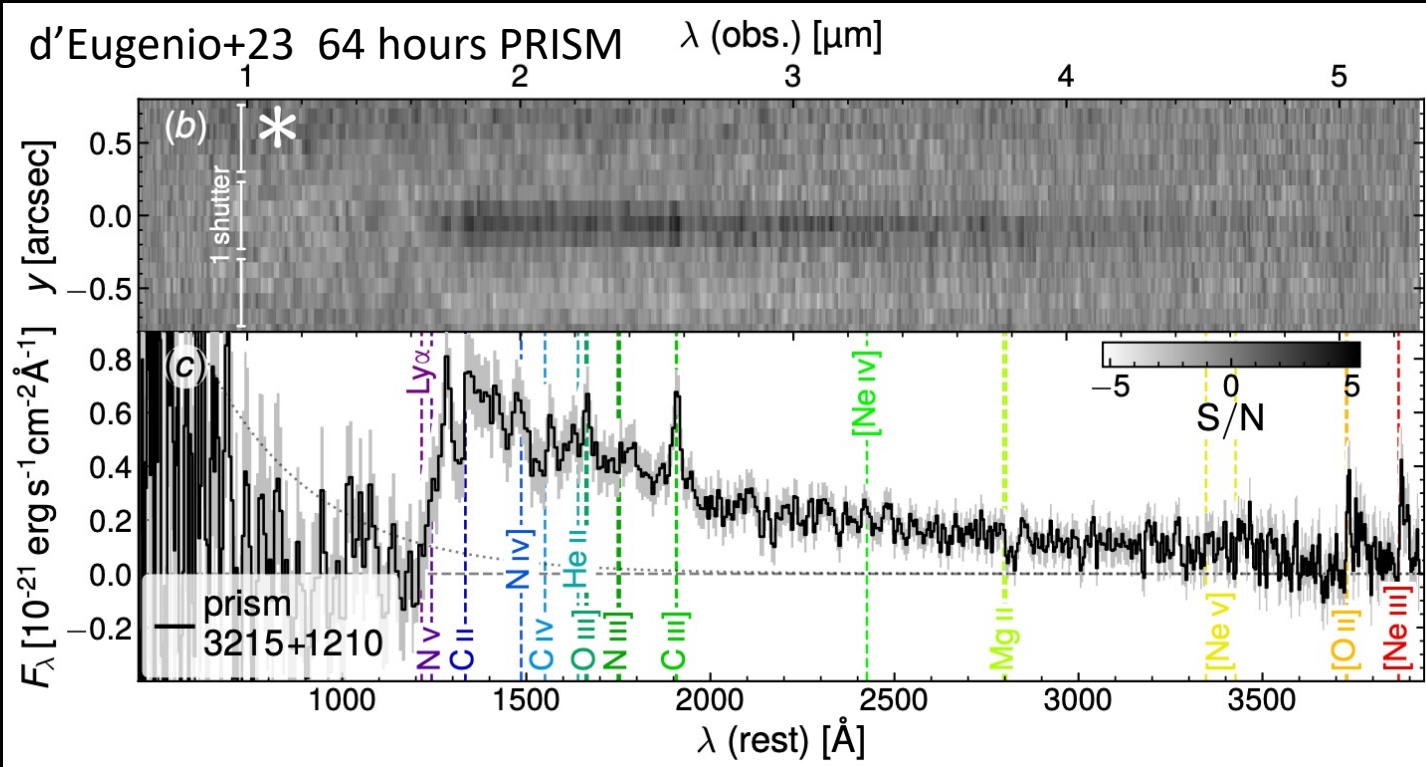


Hsiao & Álvarez+ 24



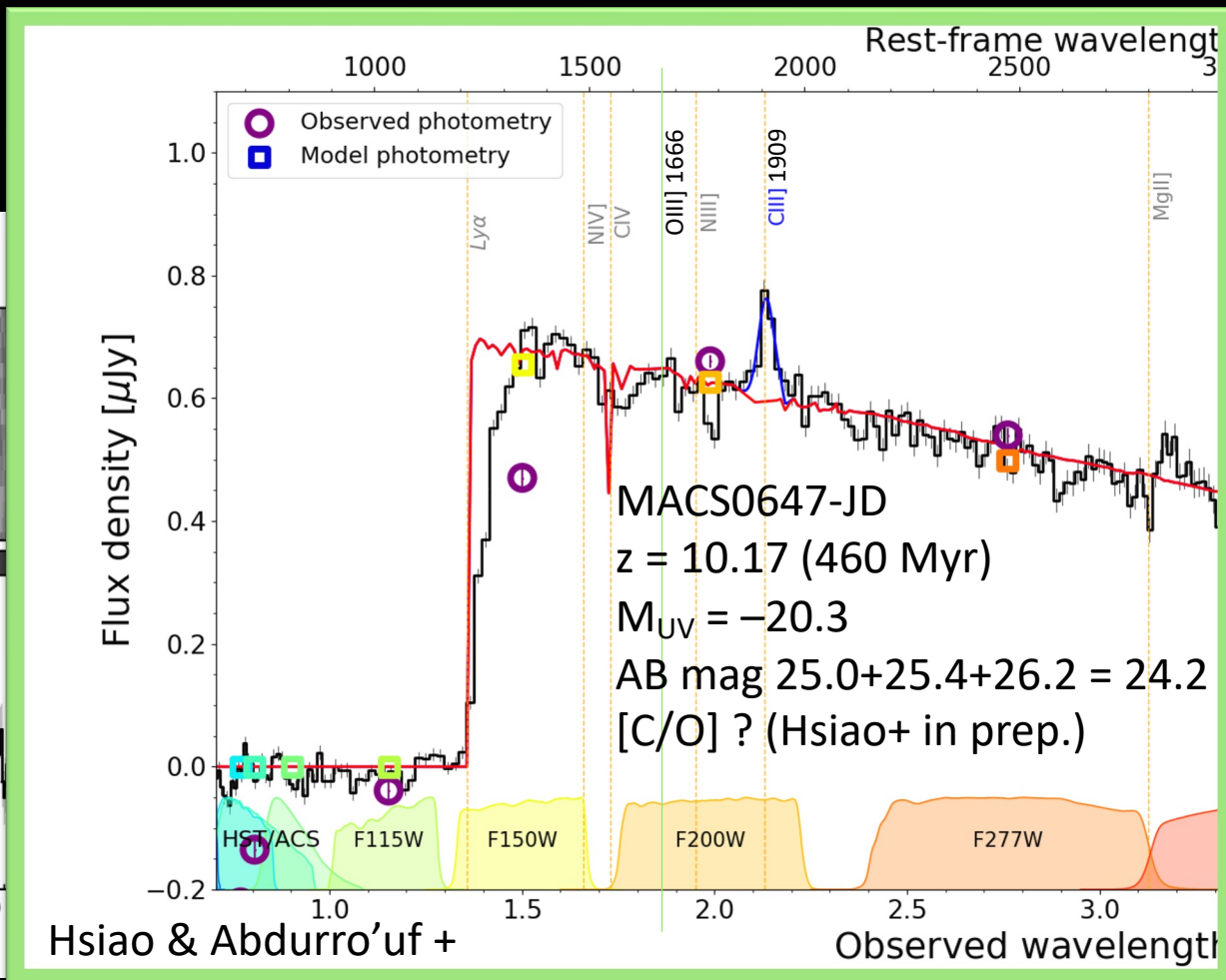
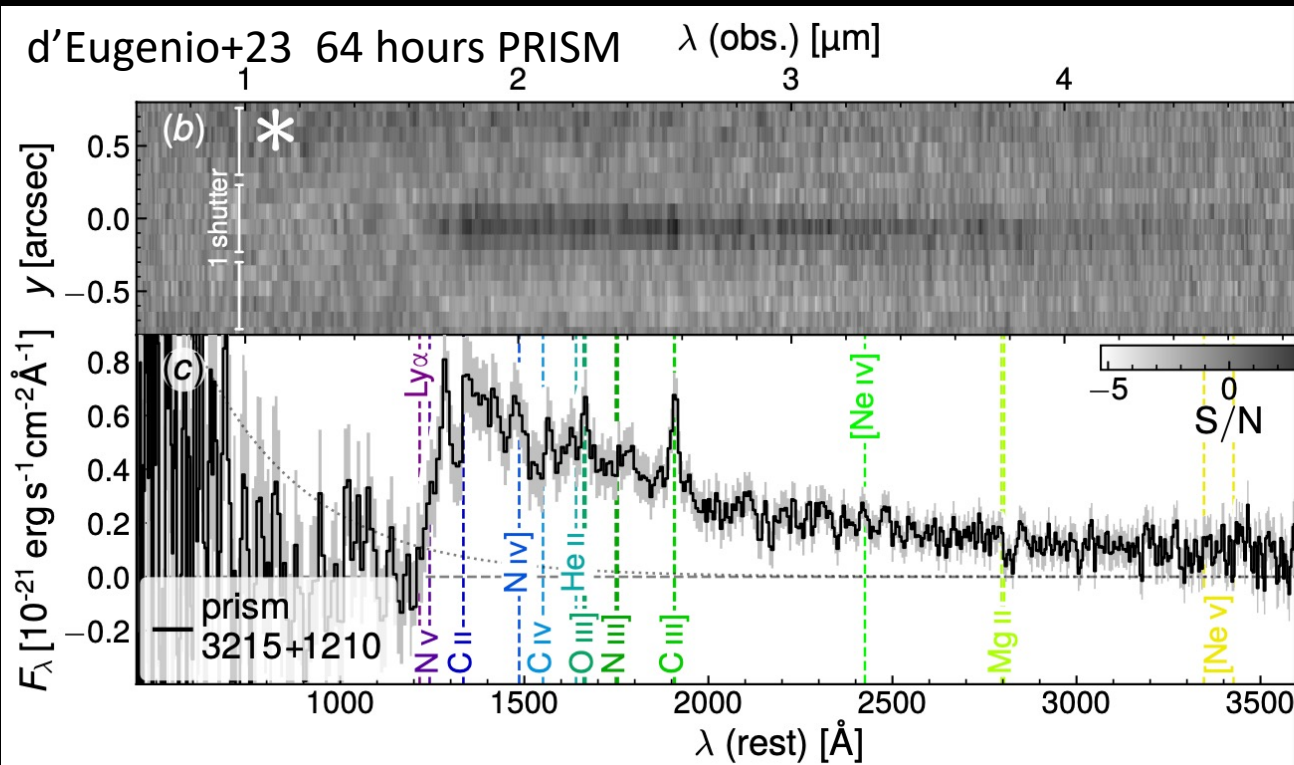
GS-z12  
 $z = 12.48$   
 $MUV = -18.2$   
 AB mag 29.0  
 $[C/O] > 0.15$

# Super solar C/O



GS-z12  
 $z = 12.48$   
 $M_{UV} = -18.2$   
 AB mag 29.0  
 $[C/O] > 0.15$

# Super solar C/O?



# Globular cluster progenitors over time

Cosmic Gems arc  
 $z \sim 10$   
 (500 Myr)

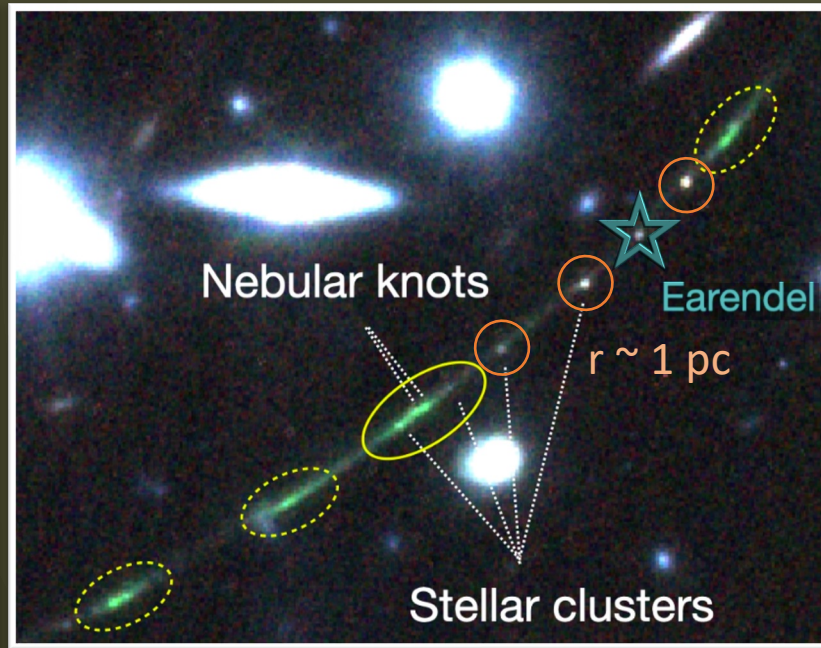
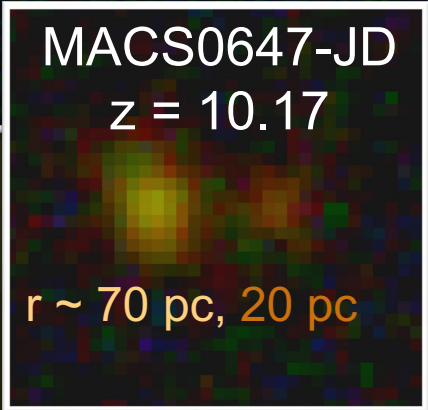
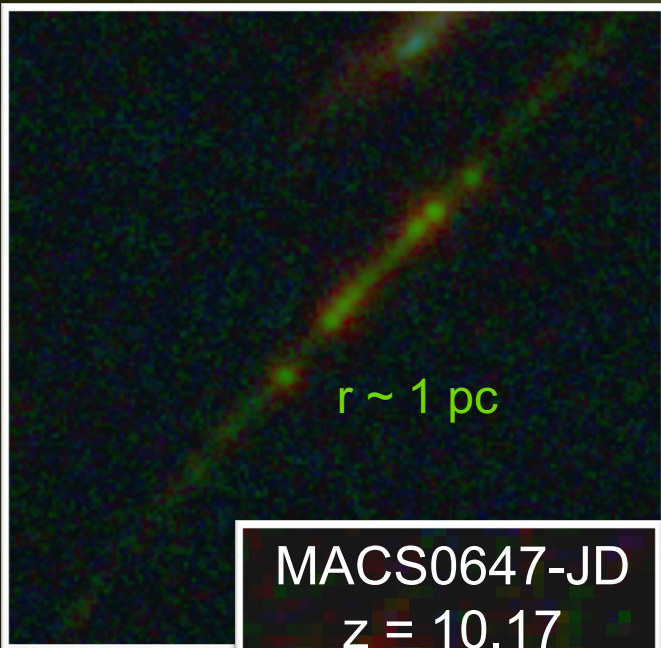
Cosmic  
 Spring

Sunrise Arc  
 $z \sim 6$   
 (1 Gyr)

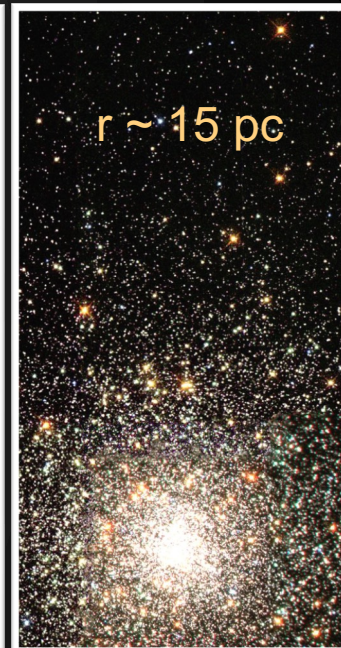
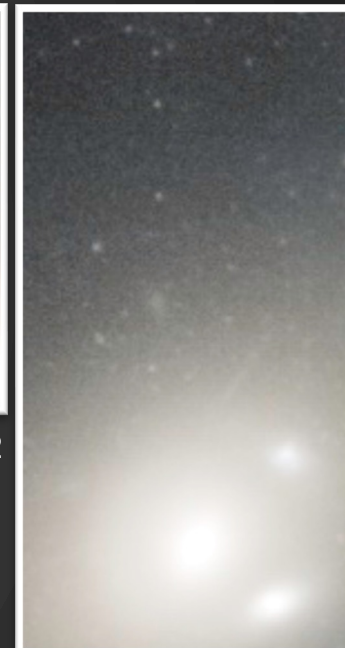
Sparkler  
 $z = 1.38$   
 (4.5 Gyr)

SMACS0723  
 $z = 0.390$   
 (9.4 Gyr)

Messier 80  
 $z = 0$   
 (13.8 Gyr)



Mowla, Iyer, et al. 2022  
 Claeysens et al. 2022  
 Adamo et al. 2023



Adamo+  
 Bradley+

Welch+  
 Vanzella+

Hsiao+  
 Hsiao & Abdurrouf+  
 Abdurrouf+  
 Hsiao & Álvarez+

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

$z \sim 10$  (500 Myr)

featuring papers led by:



Brett Salmon  
Hubble



Victoria Strait  
Spitzer



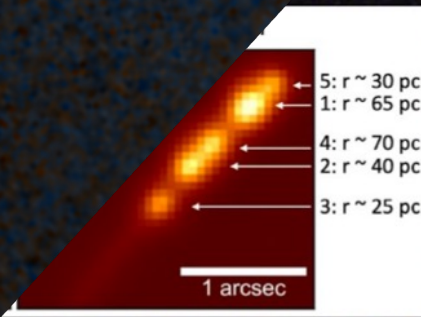
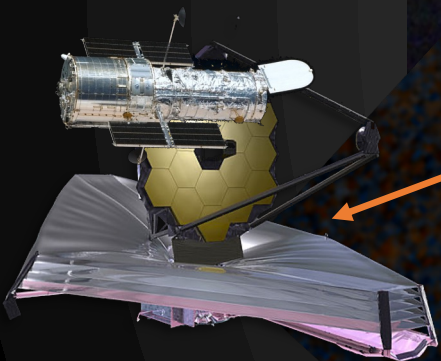
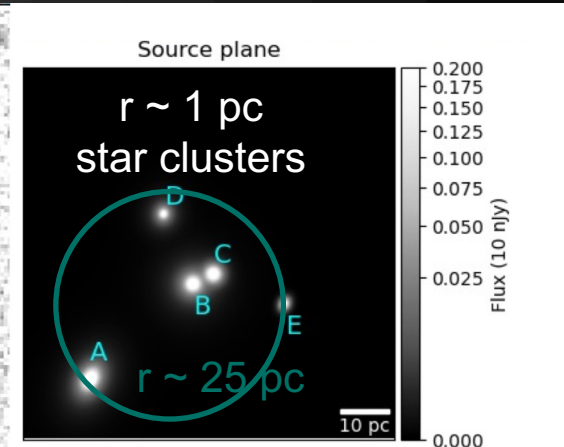
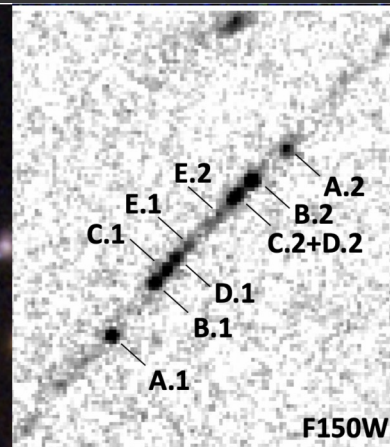
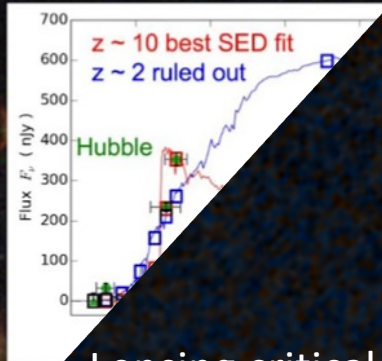
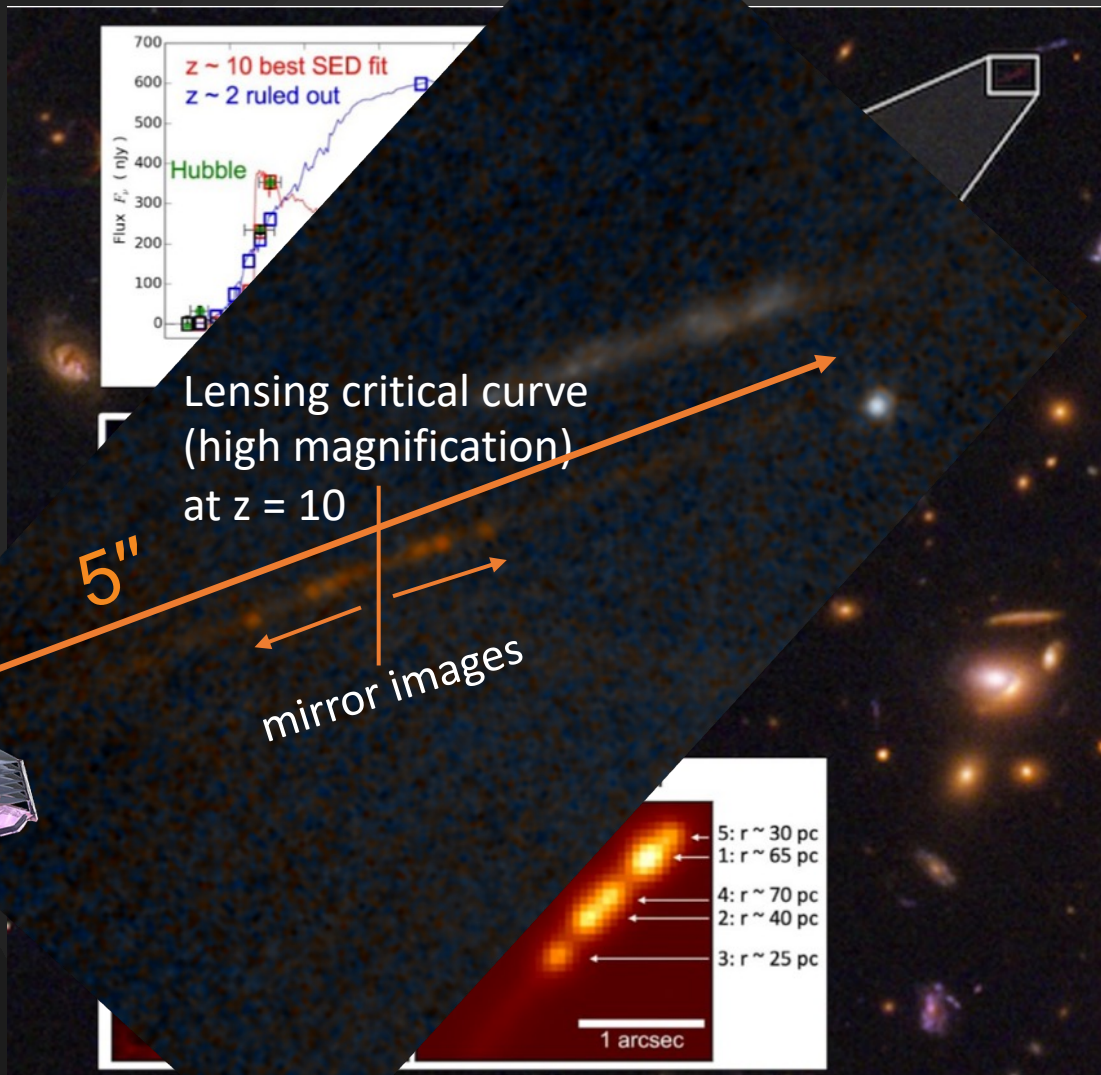
Rachel Paterno-Mahler  
lens modeling



# JWST: the smudge comes into focus

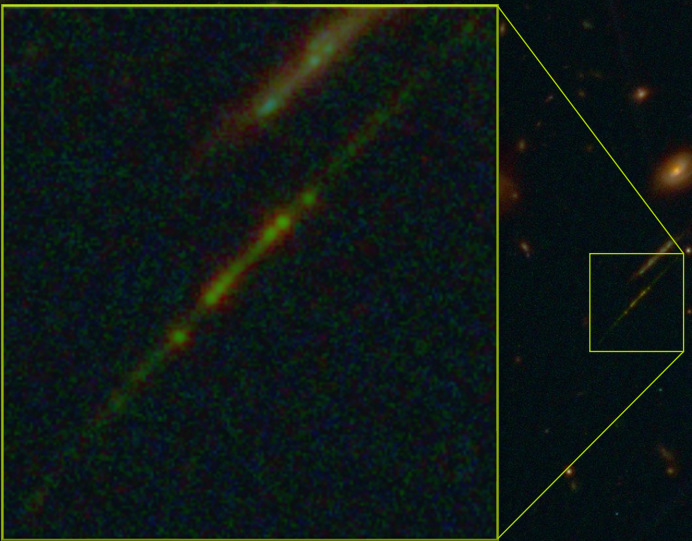


Larry Bradley  
JWST Cycle 2  
PI GO 4246



Adamo et al. 2024

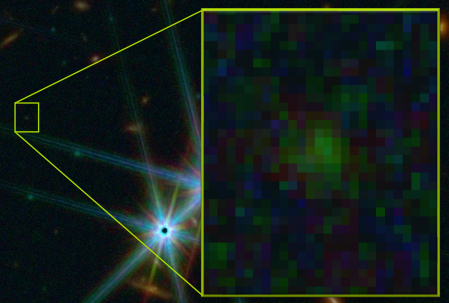
# Cosmic Gems arc



high magnification  
 $\mu \sim 60$   
x 2 images

F200W  
AB mag 25.3  
x 2 =  
AB mag 24.5

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

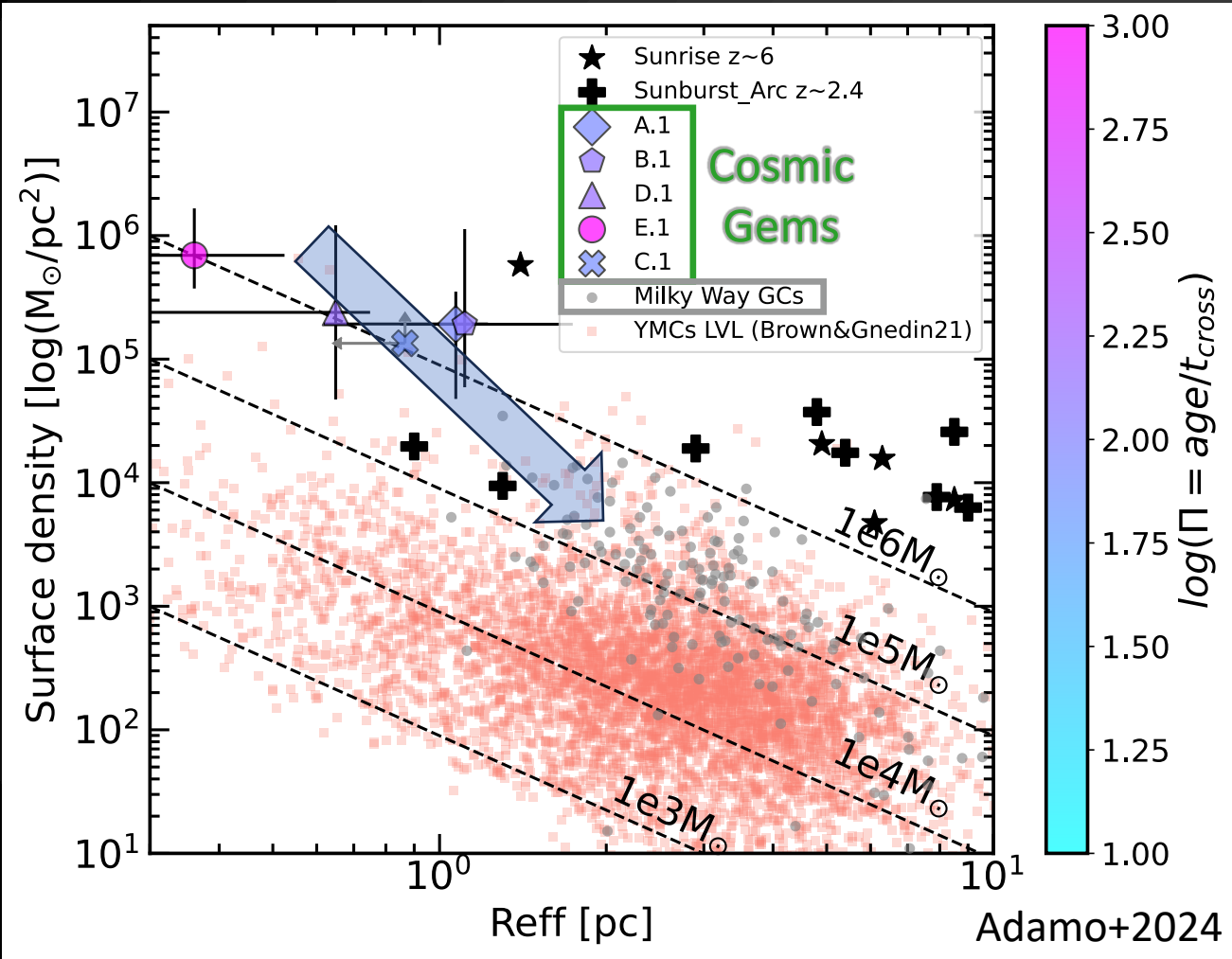


low magnification  
 $\mu \sim 2$   
AB mag 28.4  
full galaxy



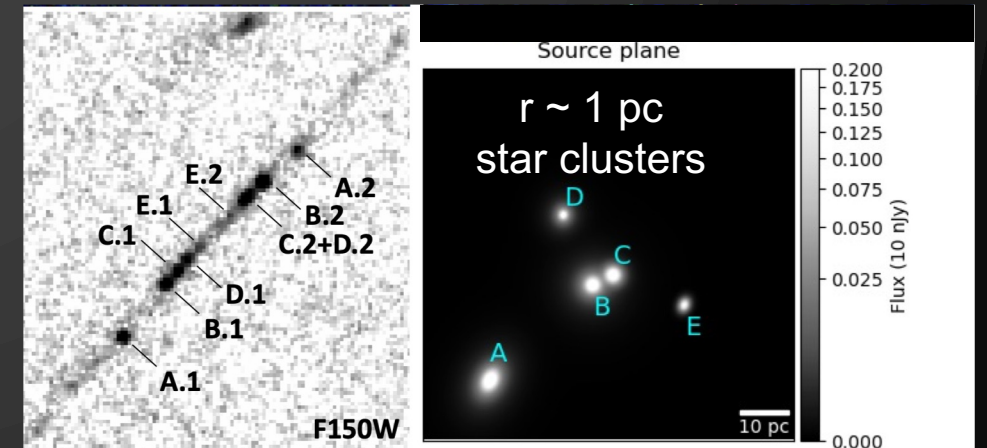
Adamo et al. 2024  
Bradley et al. 2024

# Cosmic Gems: most distant bound star clusters known



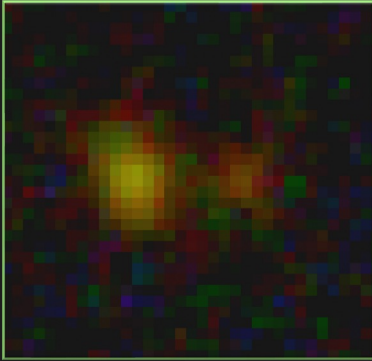
very small and dense clumps  $\sim 2e6 M_{\odot}$   
 gravitationally bound ( $\text{age} > 10 \sqrt{r^3/GM}$ )

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

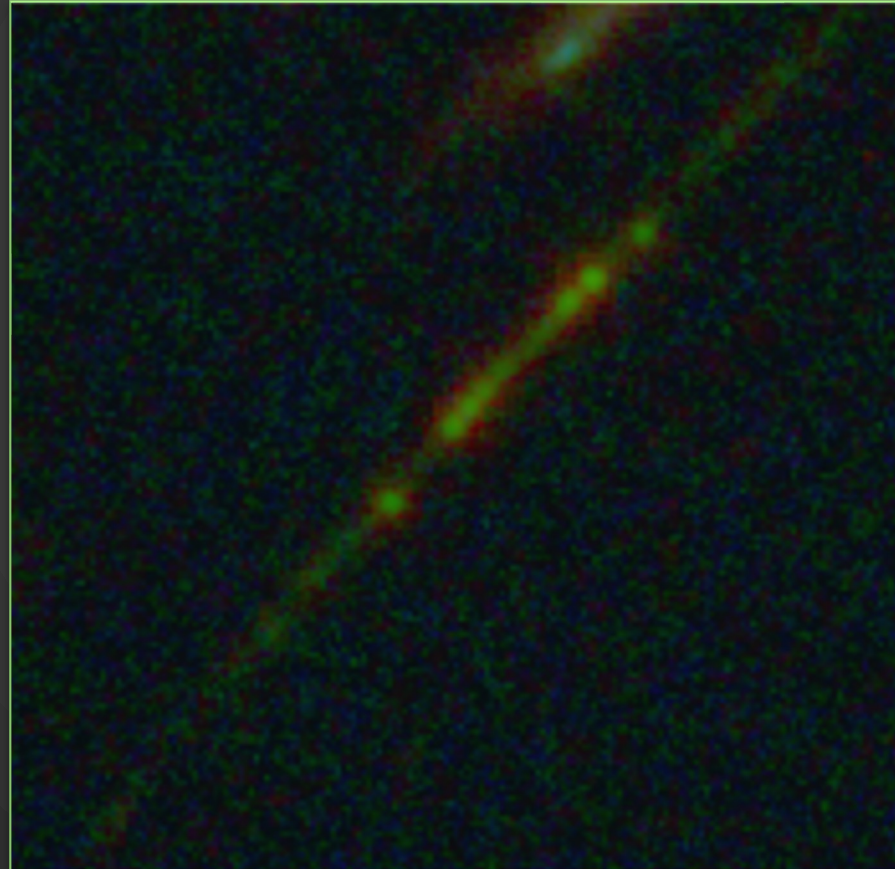


Extremely

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



extreme C/O?



extreme? or common?

Cycle 3 GO 5917

PI Eros Vanzella

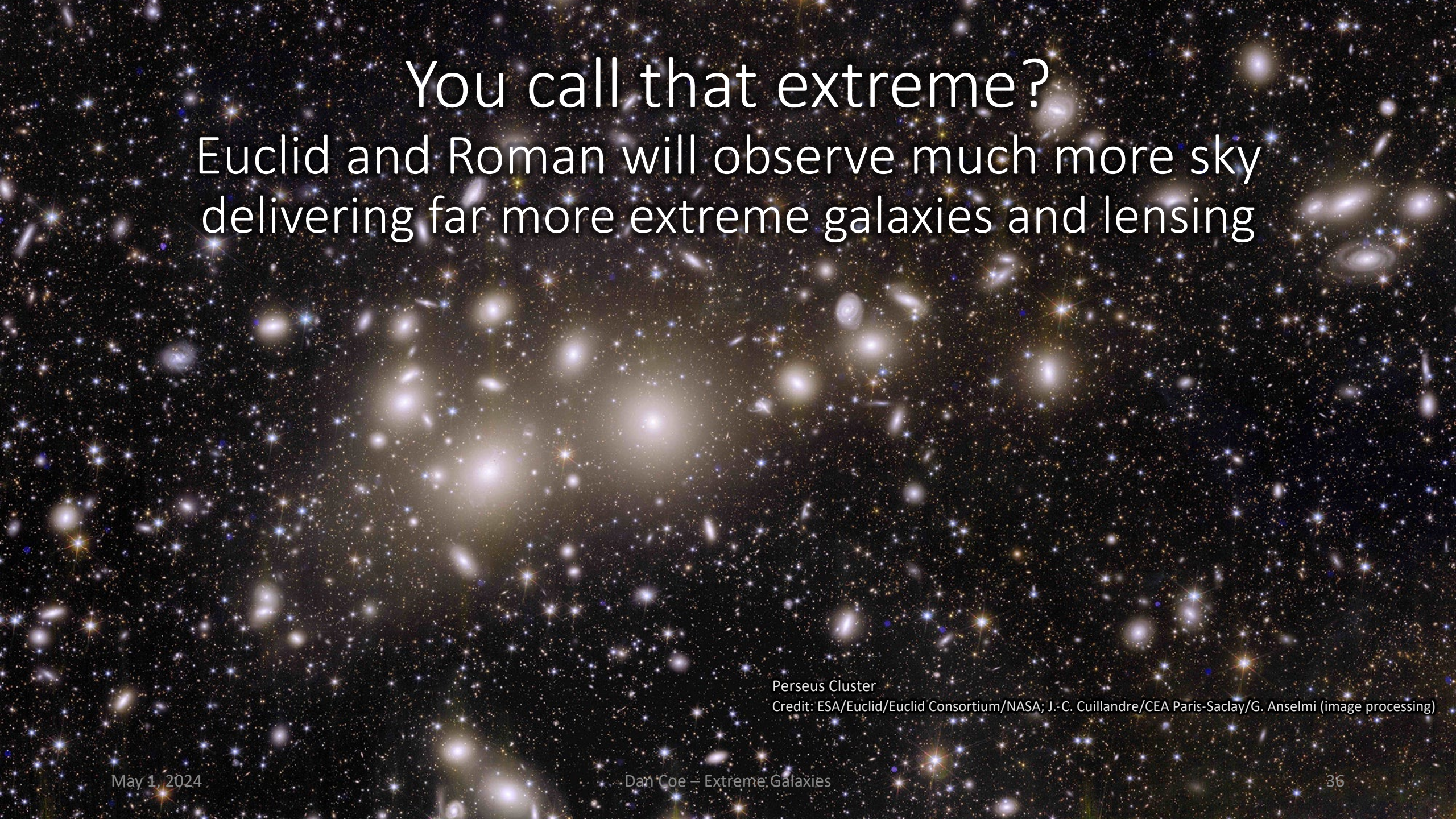
NIRSpec IFU prism

MIRI MRS long

“I have been a child playing on the seashore,  
diverting myself now and then finding a smoother pebble or a prettier shell,  
while the great ocean of truth lay all undiscovered before me.”

- Newton

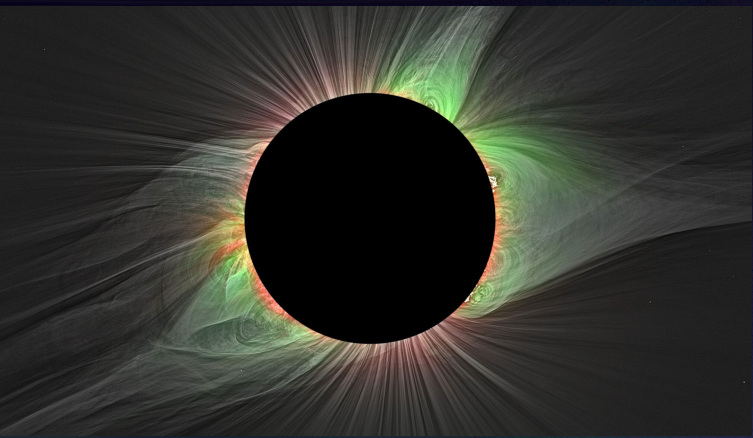




You call that extreme?  
Euclid and Roman will observe much more sky  
delivering far more extreme galaxies and lensing

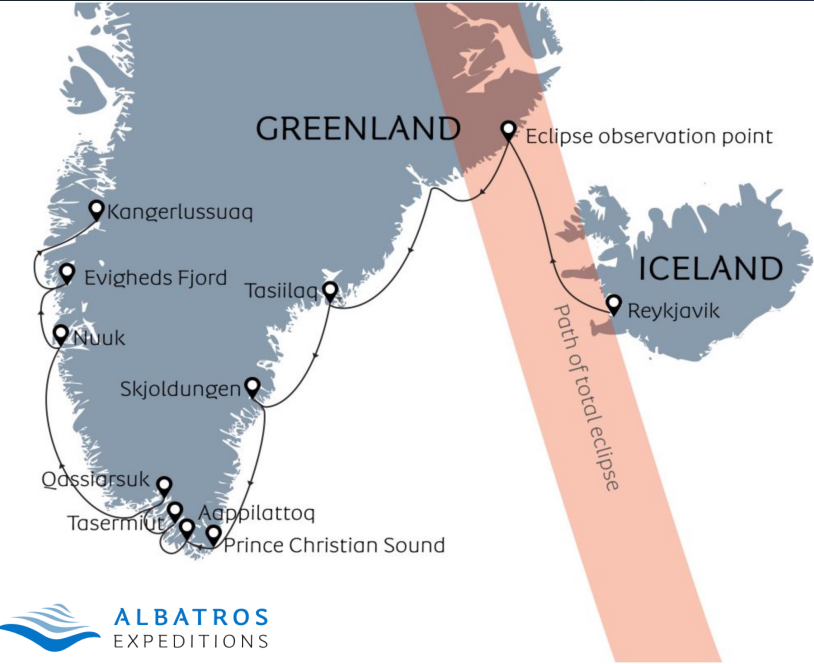
Perseus Cluster

Credit: ESA/Euclid/Euclid Consortium/NASA; J. C. Cuillandre/CEA Paris-Saclay/G. Anselmi (image processing)



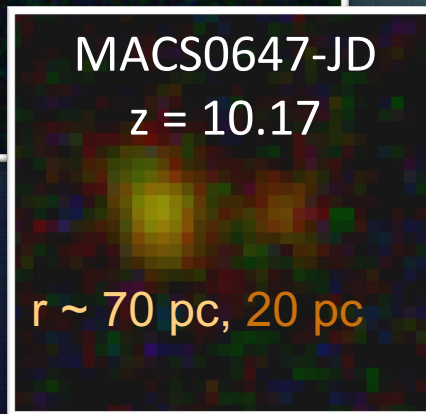
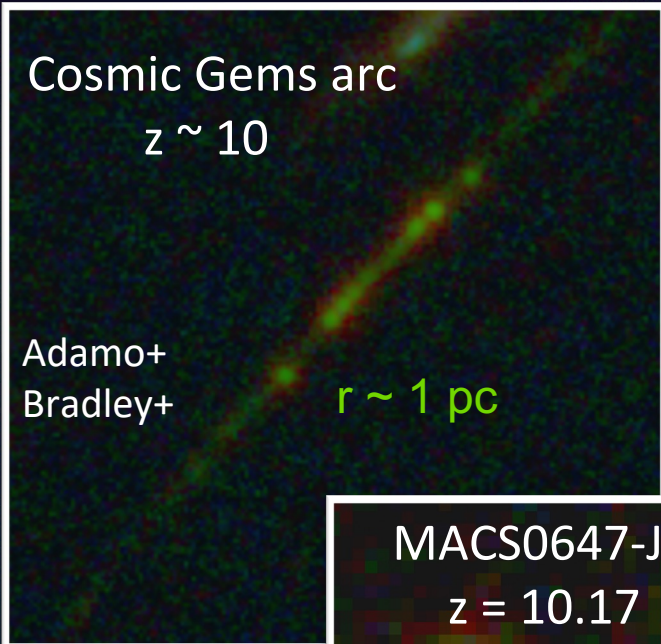
# See you at Extreme Galaxies 2026 for the eclipse Aug 12!

if we plan it



# JWST is observing the first star clusters

and they are extreme!



Hsiao+  
Hsiao & Abdurrouf+  
Abdurrouf+  
Hsiao & Alvarez+

Tiger  
Hsiao    Abdurro'uf



Cosmic Spring  
[cosmic-spring.github.io](https://cosmic-spring.github.io)  
public data, code, papers



talk to me about  
NIRSpec MOS!

