Discovering the first stars and galaxies with JWST

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Space Telescope Science Institute

ESA/AURA Astronomer

JWST NIRSpec Instrument Scientist

Johns Hopkins University

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dancoe.space

Thank you Goddard!

Nov 2016

Oct 19, 2023

JWST Mission Control at the
Space Telescope Science Institute
(STScI) in Baltimore
James Webb Space Telescope
JWST
NASA • ESA • CSA
COMMAND CONTROLLER

JHU / GSFC students and postdocs

Tiger Hsiao
JHU

Keduse Worku
JHU

Tom Resseguier
JHU

Abdurro'uf
JHU

Brian Welch
GSFC

Taylor Hutchison
GSFC

How did we get here?

- How did stars and galaxies form?
- How did planets and life form?

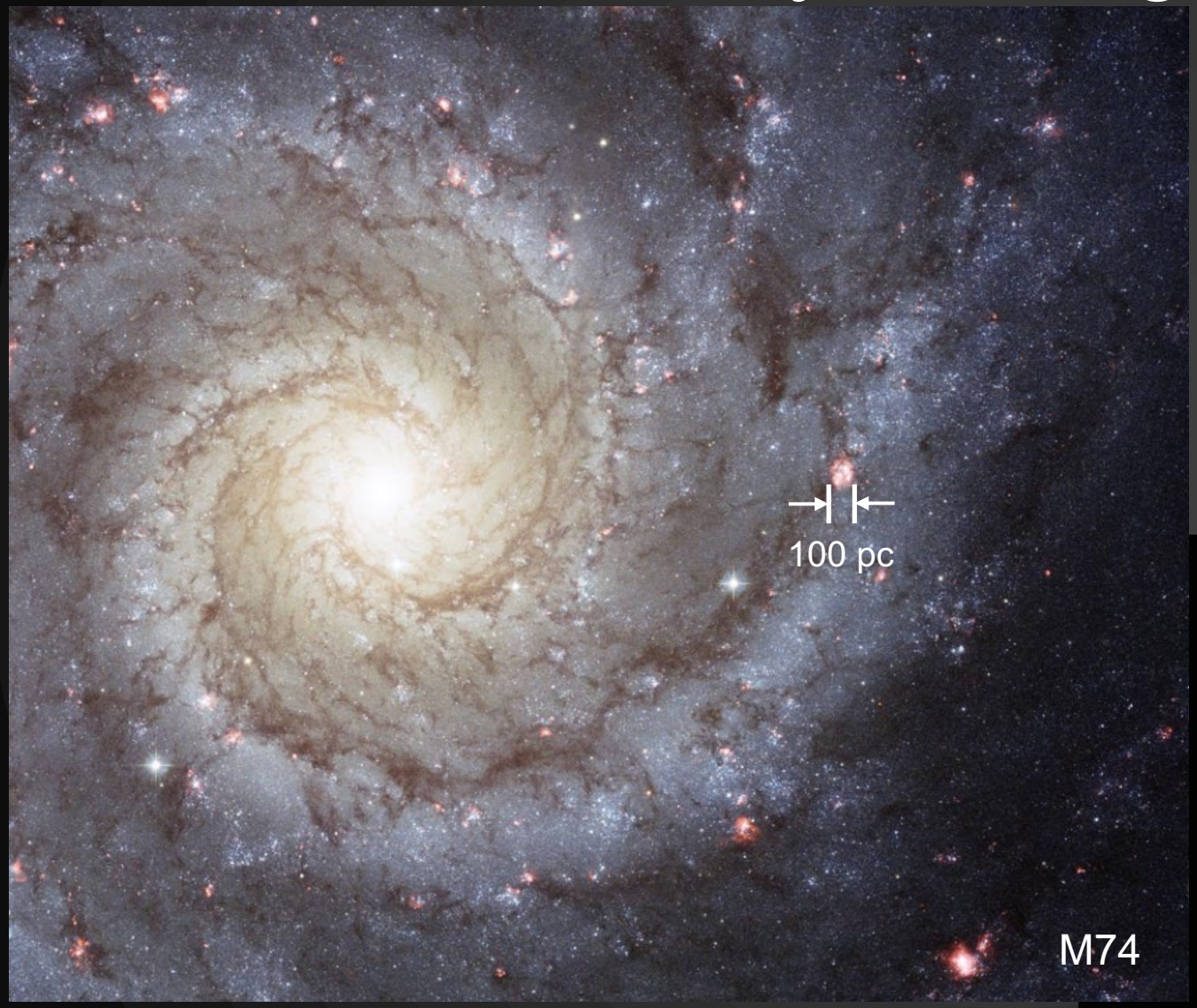
YOU ARE HERE

Milky Way
artist's rendition:
Nick Risinger

A 'Flip Book' of Galaxies Over Time

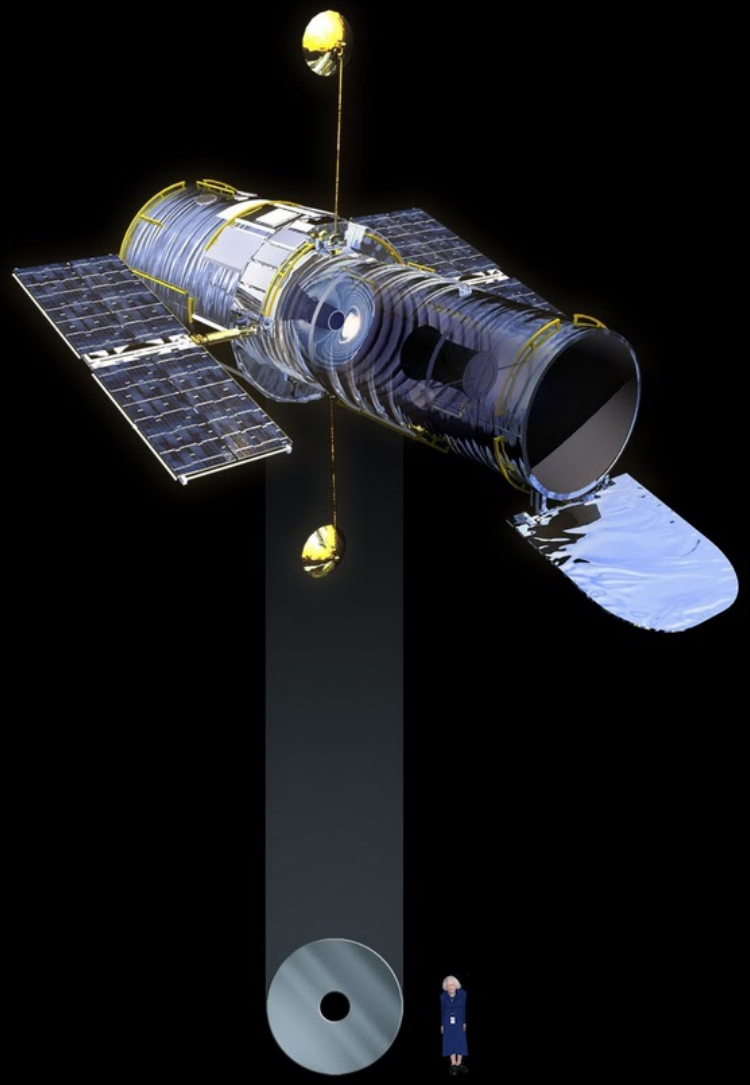
Slide credit: STScI OPO

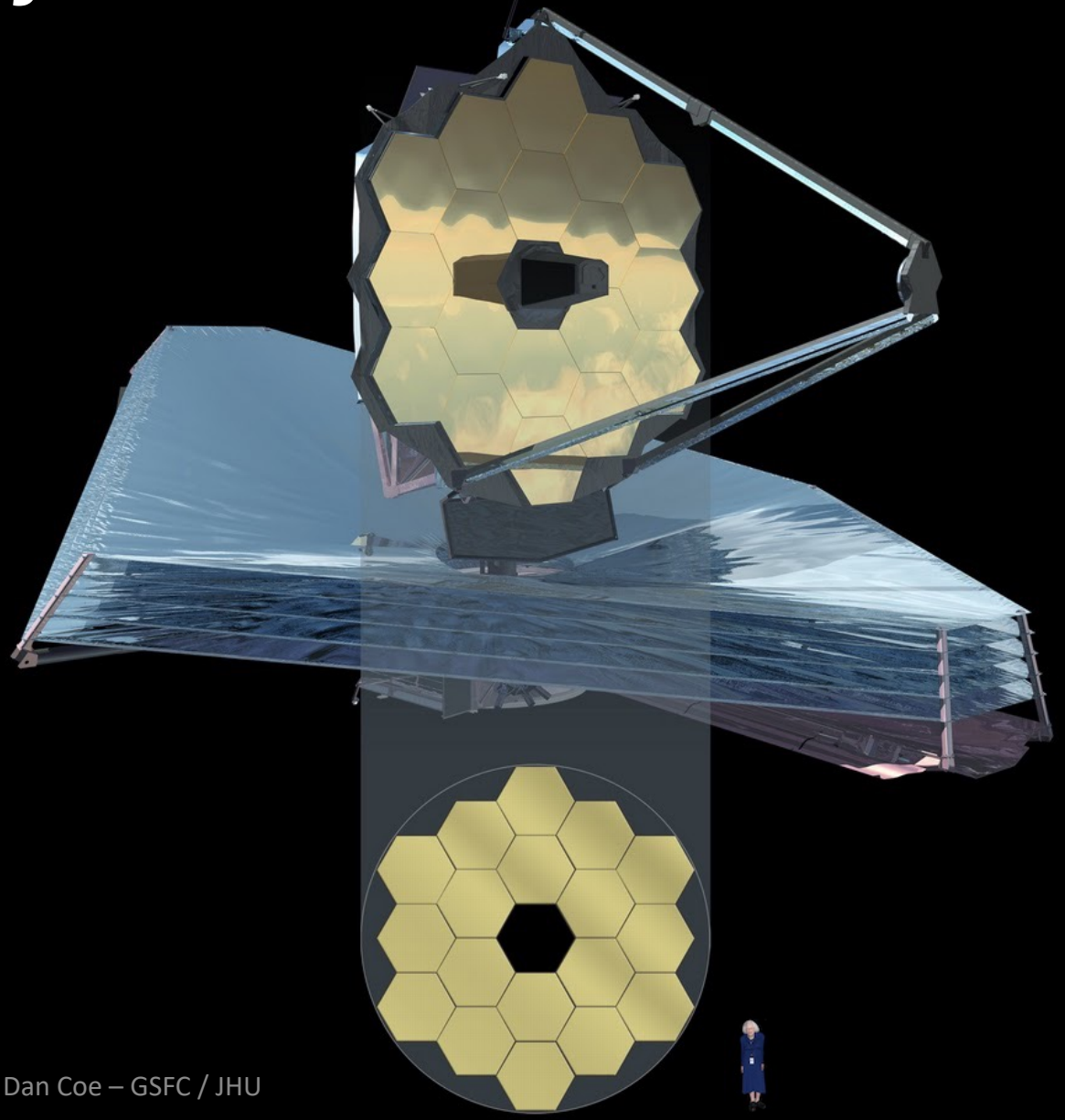
Galaxy building blocks



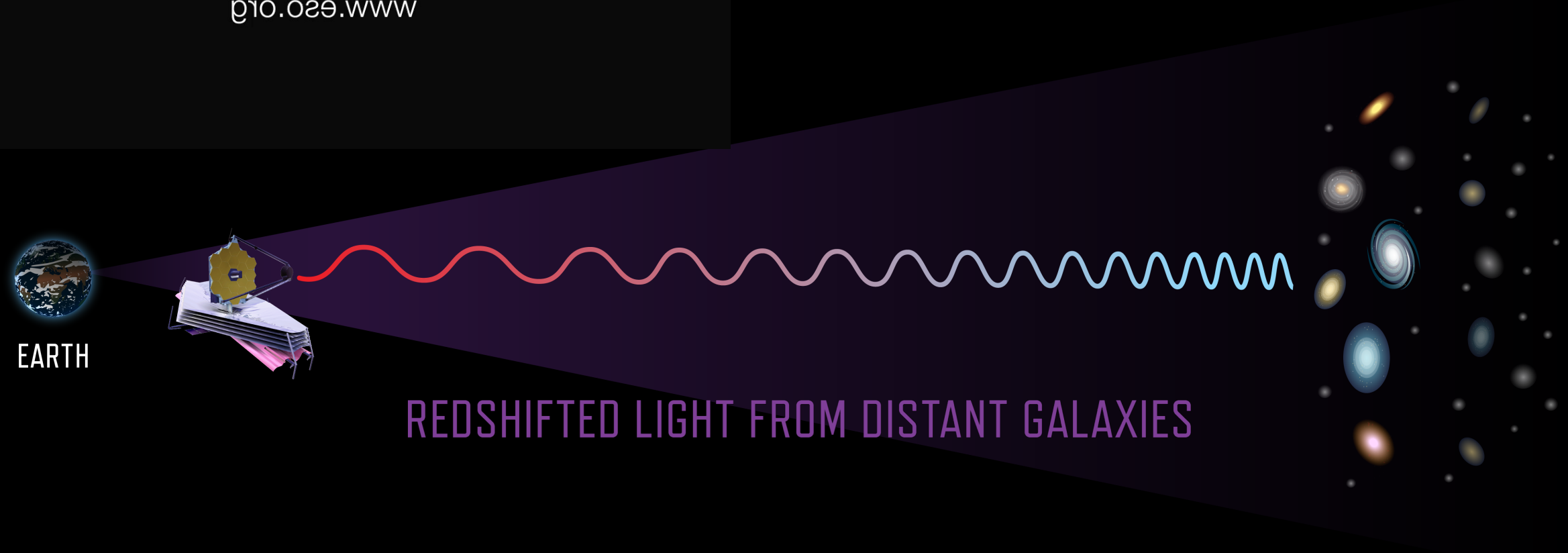
MACS0647-JD

Large ‘Honeycomb’ of Mirrors

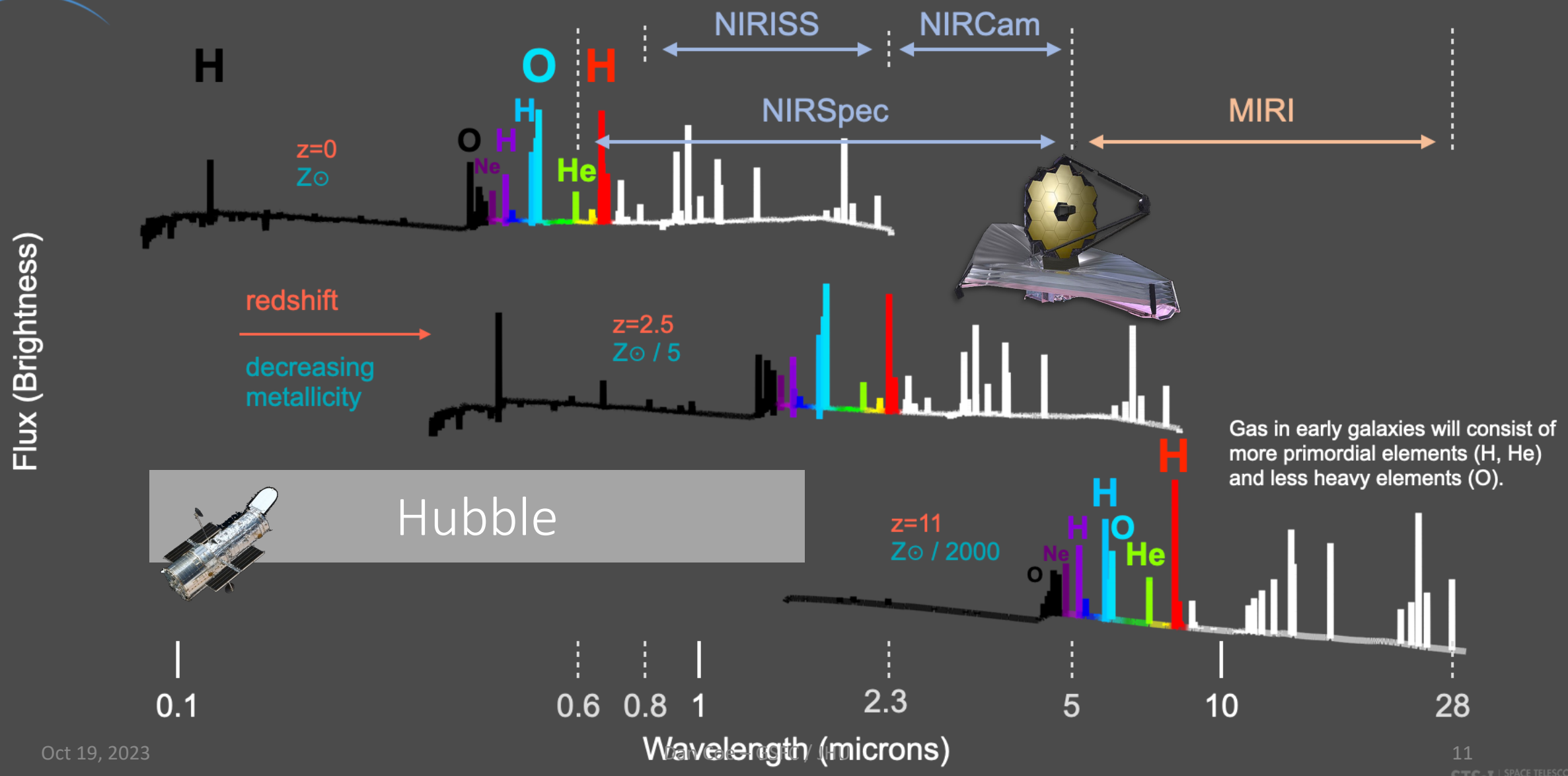




Expanding Universe Stretches Light to Infrared

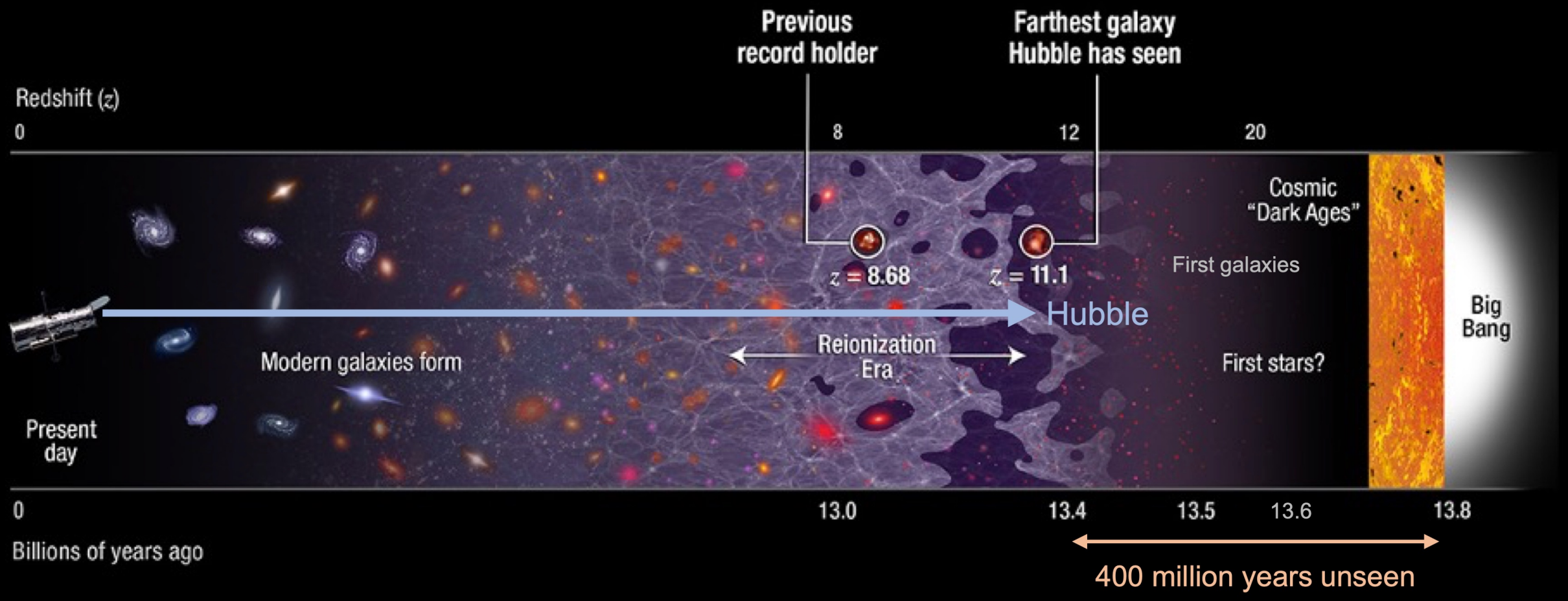


What were early galaxies made of?

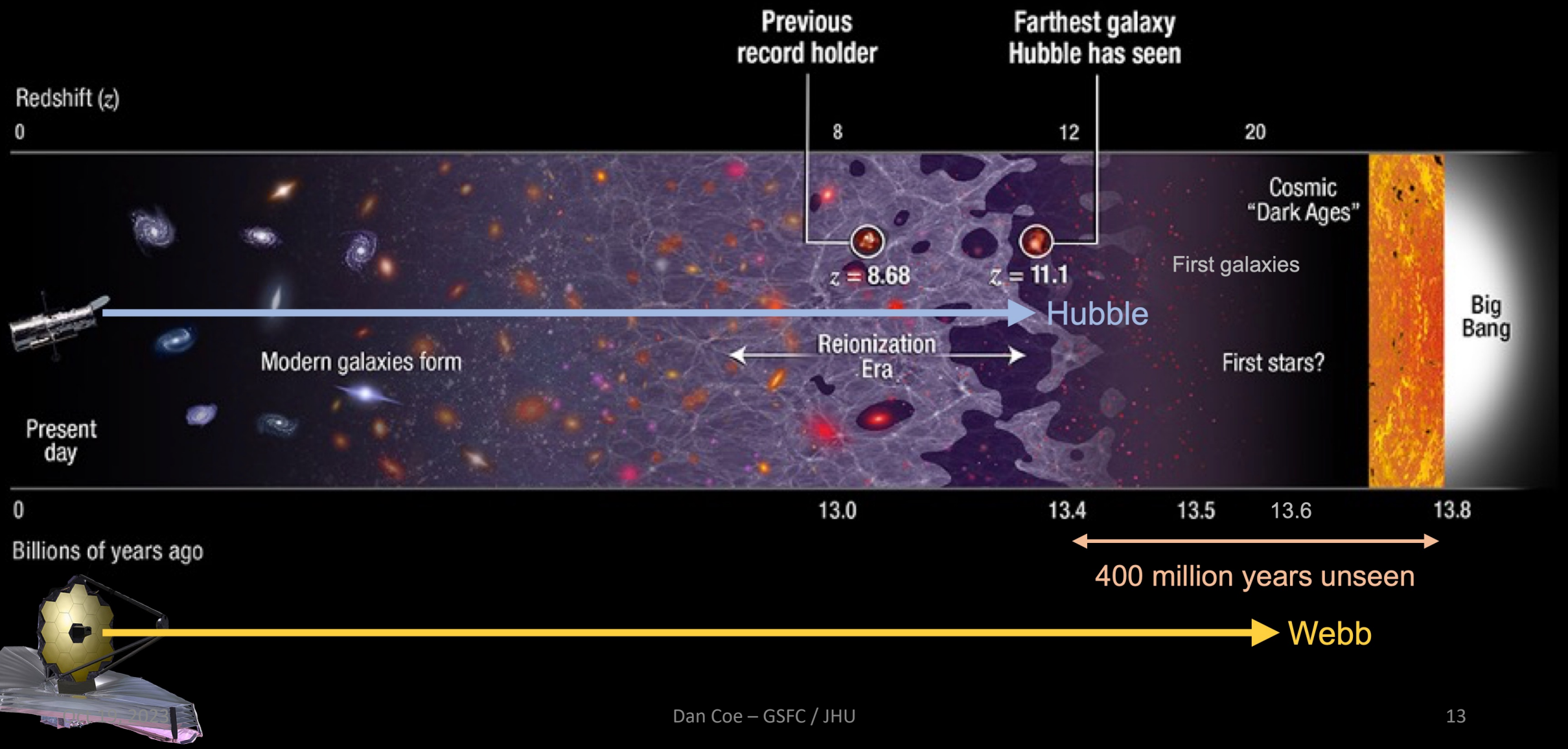


Gas in early galaxies will consist of more primordial elements (H, He) and less heavy elements (O).

Looking Back in Time



Looking Back in Time

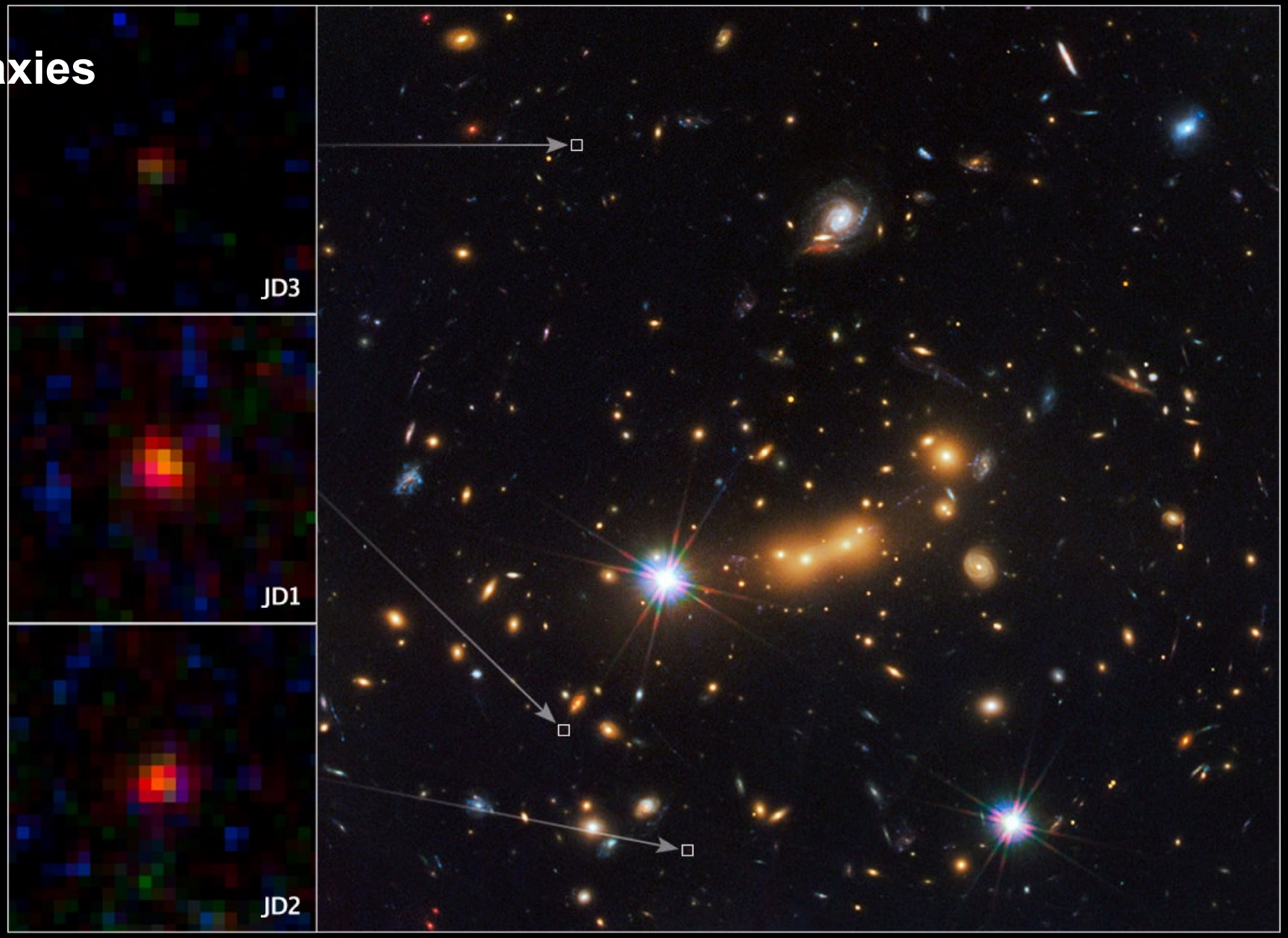


Hubble observed galaxies 97% of the way back to the Big Bang

13.3 billion years ago

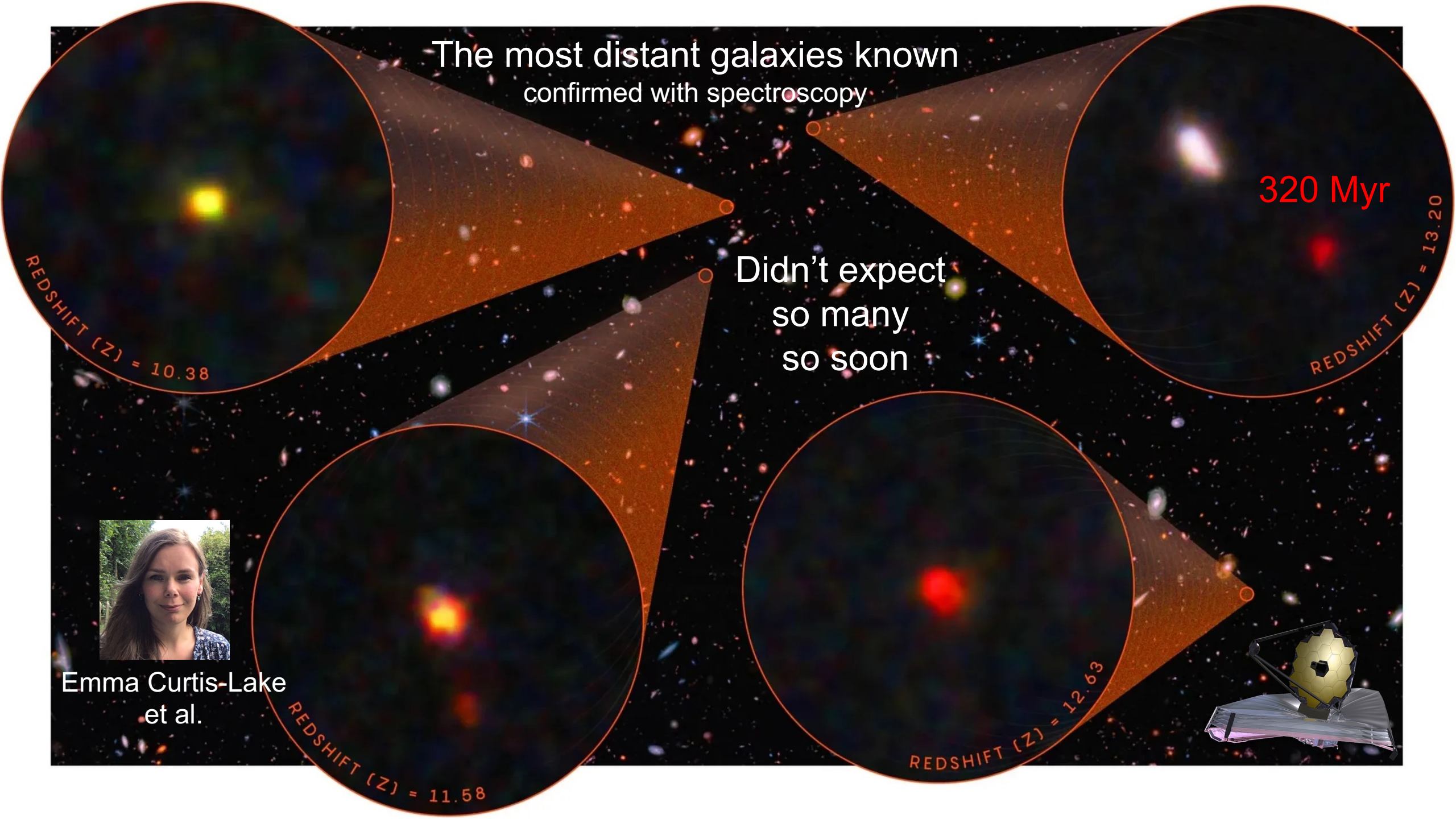
MACS0647-JD
Coe et al. 2013

460 Myr after the Big Bang
Hsiao et al. 2023



The most distant galaxies known

confirmed with spectroscopy



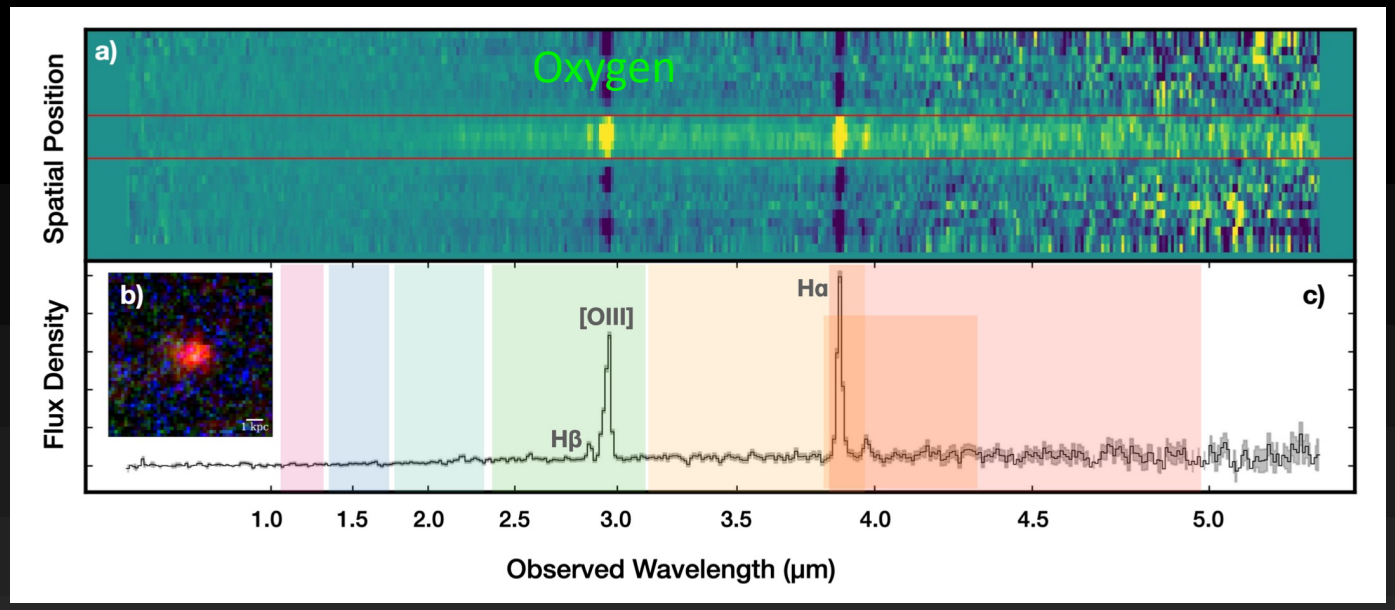
Didn’t expect
so many
so soon

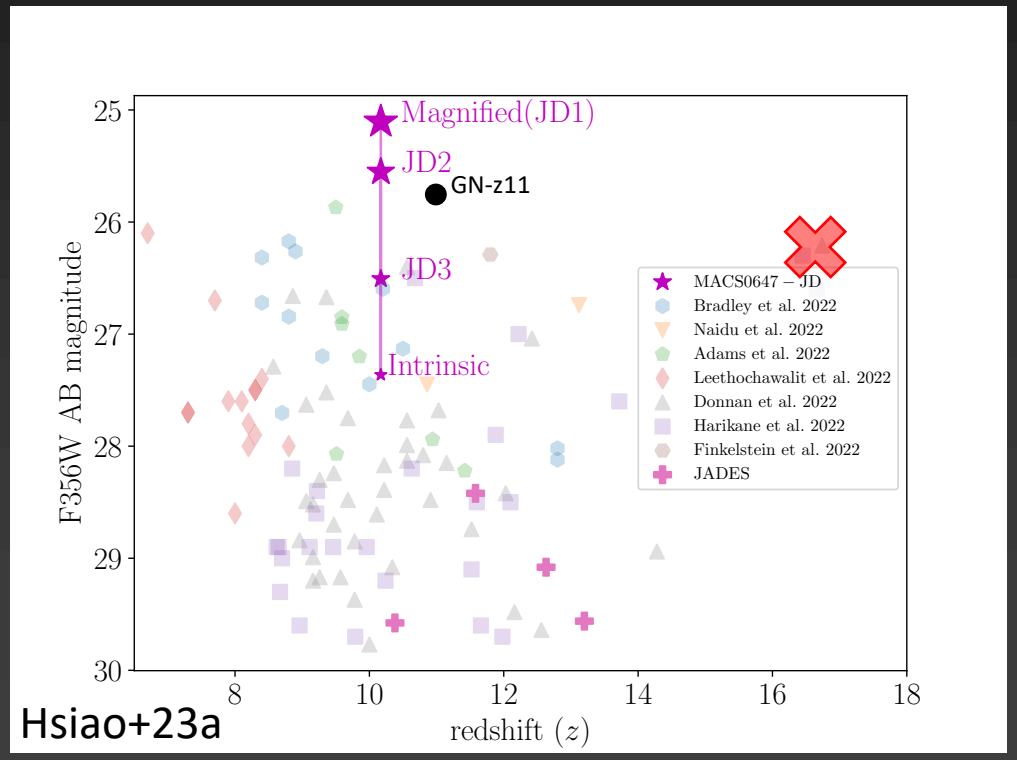
Emma Curtis-Lake
et al.

A strong z ~ 16 candidate shown instead to be at z = 4.9

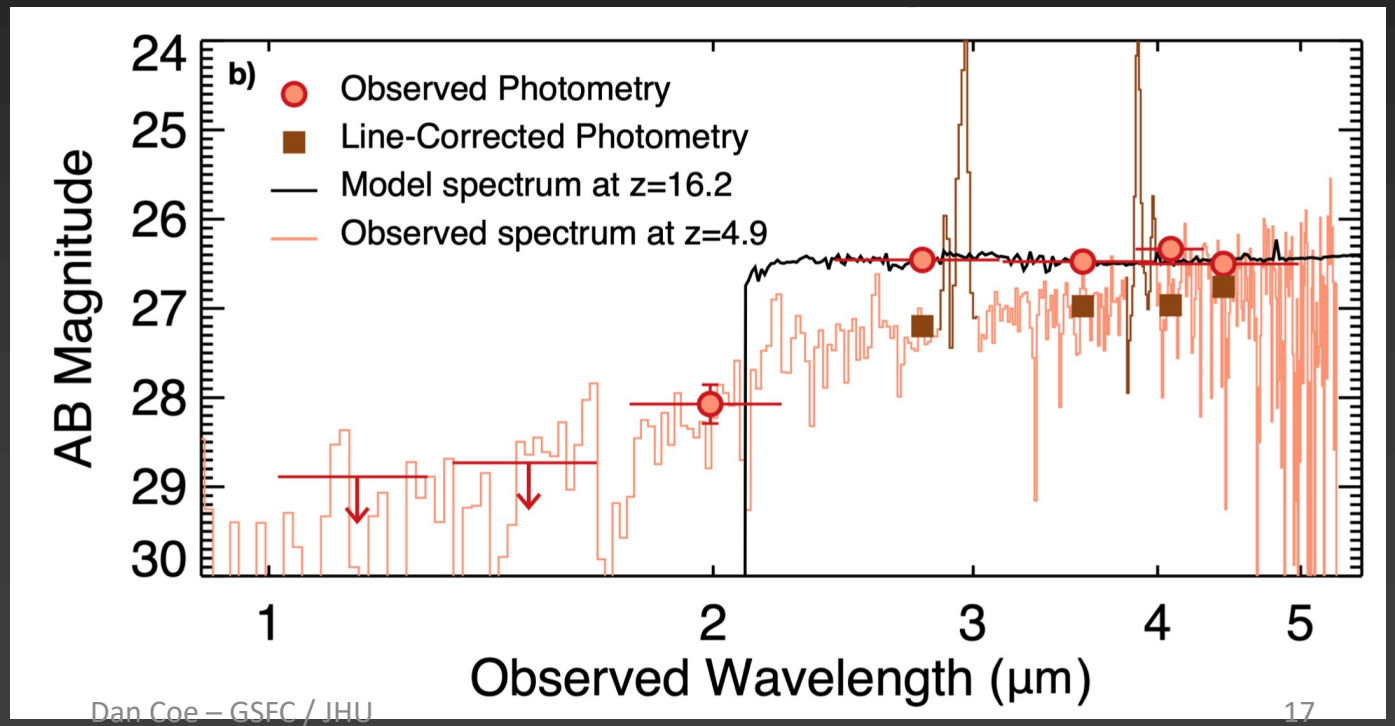
Pablo Arrabal Haro+23a

The universe isn't broken!



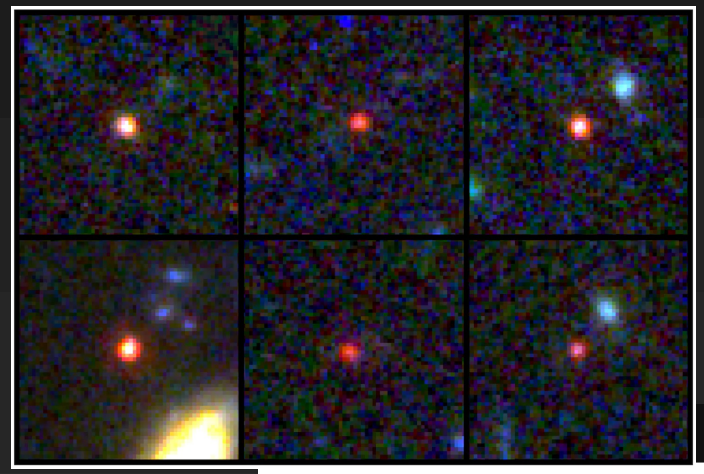


Hsiao+23a



Did JWST break the universe?

Were some galaxies too big too soon?



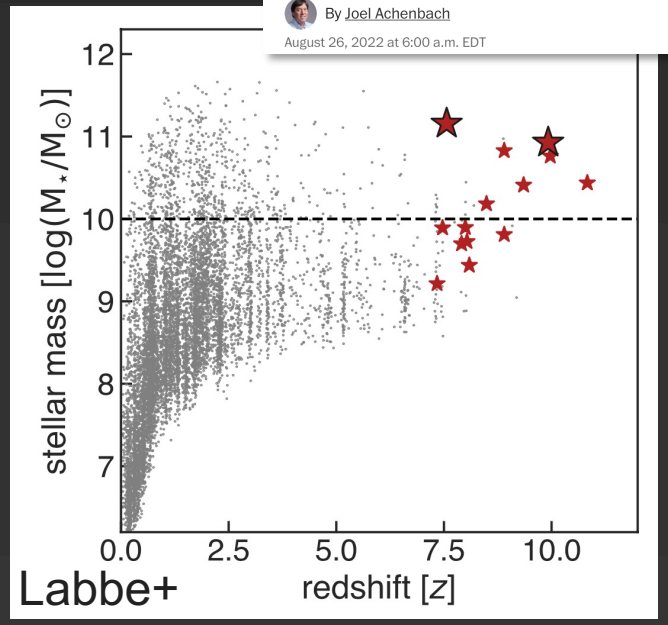
The Washington Post
Democracy Dies in Darkness

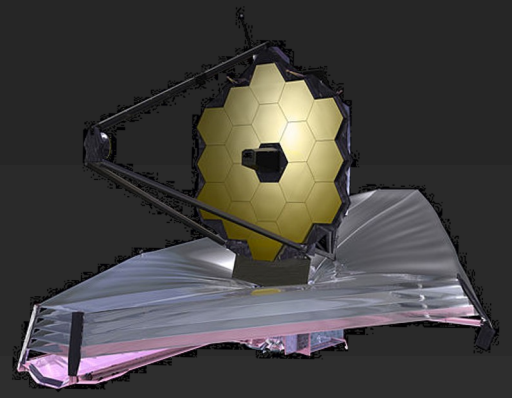
Webb telescope is already challenging what astronomers thought they knew

Surprisingly massive distant galaxies raise questions about early galaxy formation

By Joel Achenbach

August 26, 2022 at 6:00 a.m. EDT





arXiv:2207.12446
Ivo Labbe et al.
claimed $10^{10} – 10^{11}$ $M_\odot$
galaxies at z ~ 7 – 11

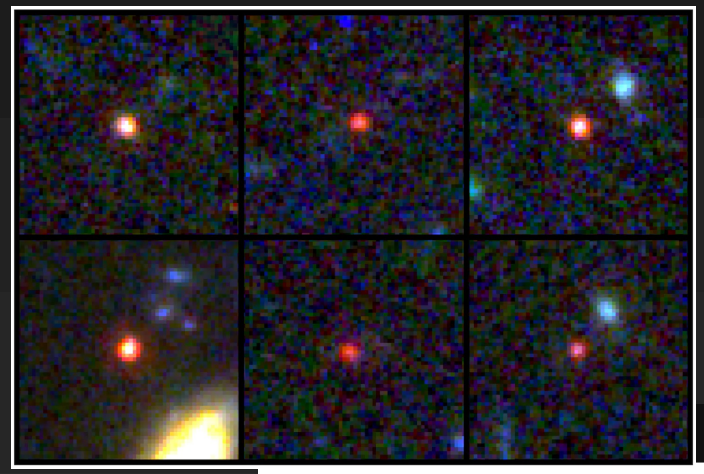
Michael Boylan-Kolchin
arXiv:2208.01611
claims tension with ΛCDM

also see Chris Lovell et al.
arXiv:2208.10479

Impossibly massive z ~ 10 galaxies?

solved by new spectral templates with hotter dust?

more recent surveys find no tension with ΛCDM



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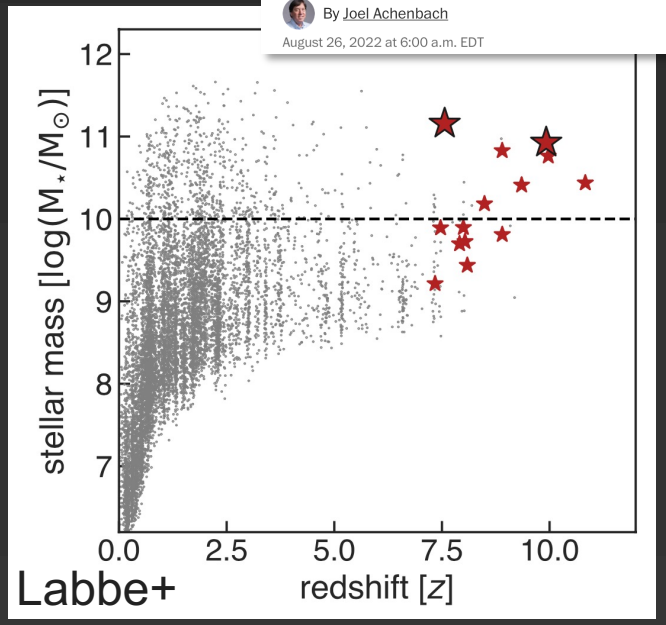

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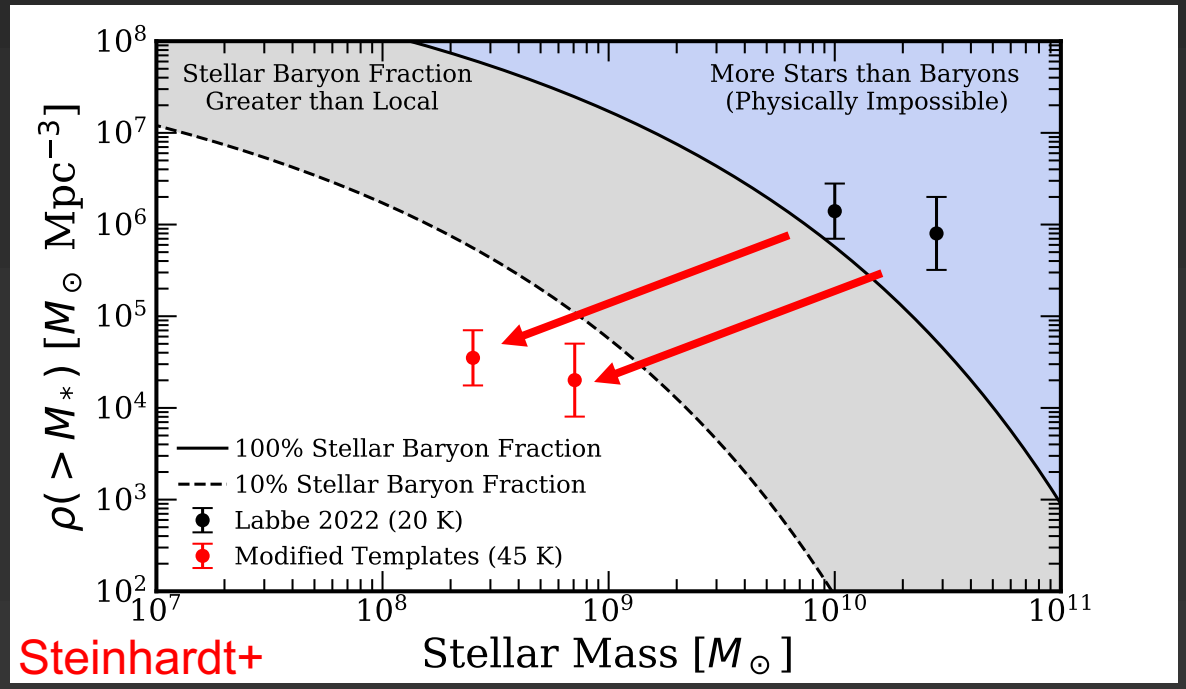
also see Chris Lovell et al.
arXiv:2208.10479

Ryan Endsley et al. arXiv:2208.14999
find solutions with lower mass or an AGN

Charles Steinhardt et al. arXiv:2208.07879
claim resolution with hotter dust



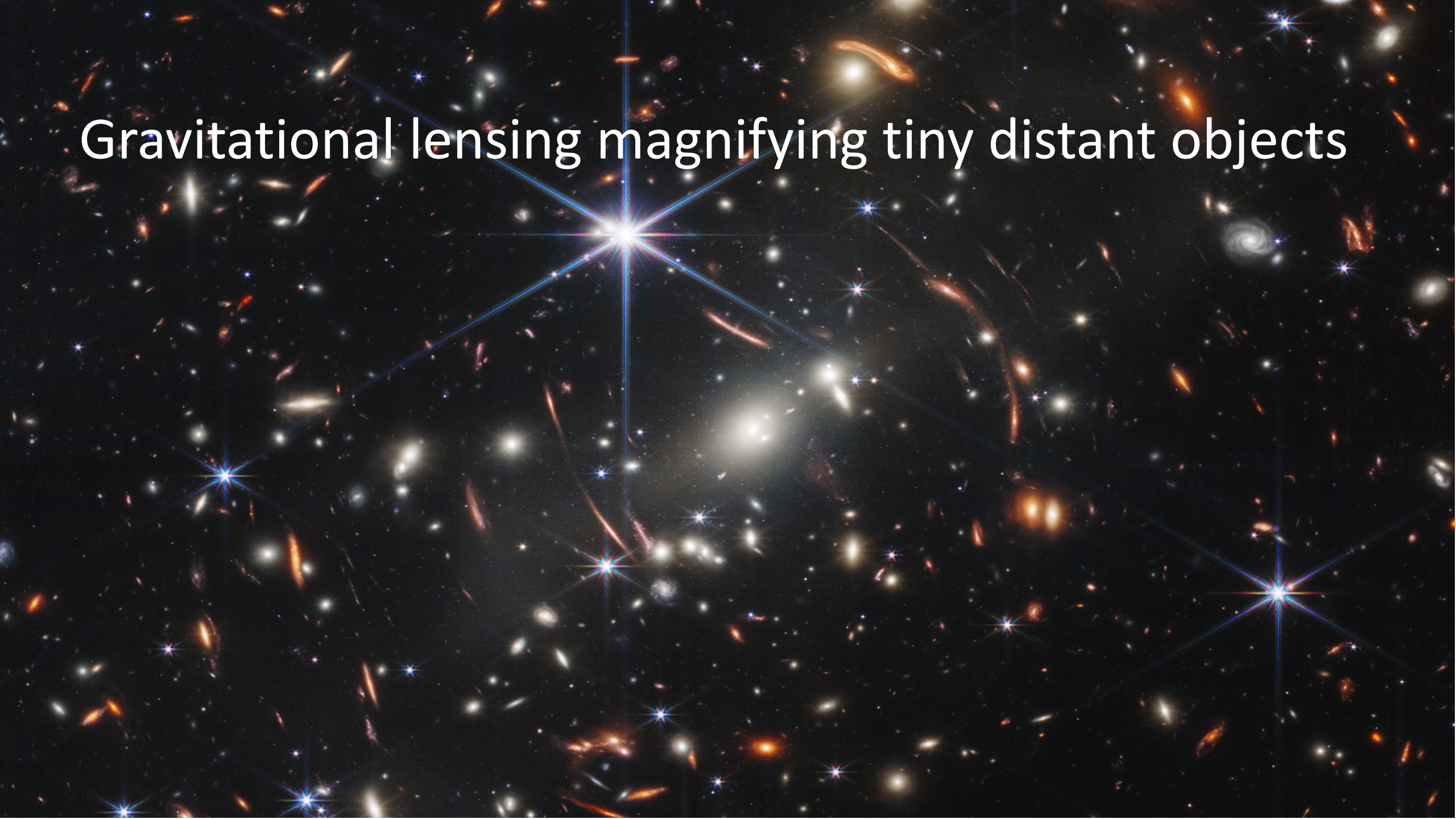
JWST is already revealing the first star clusters

RXJ2129 (PI Pat Kelly)
https://esawebb.org/images/potm2302a/

3 lensed images

Hayley Williams et al.

Gravitational lensing magnifying tiny distant objects

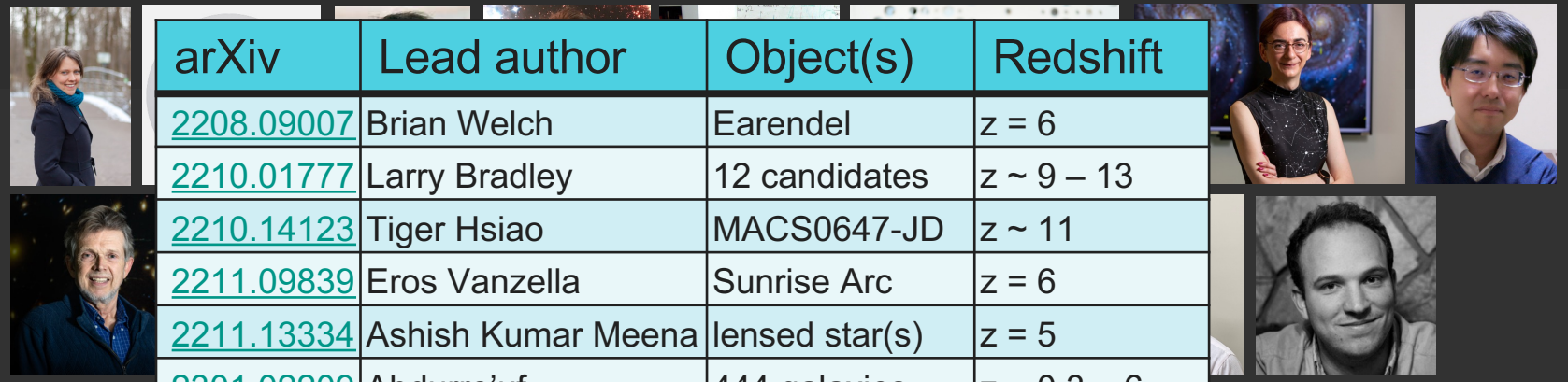


Cosmic Spring JWST

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 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



arXiv	Lead author	Object(s)	Redshift
2208.09007	Brian Welch	Earendel	z = 6
2210.01777	Larry Bradley	12 candidates	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(s)	z = 5
2301.02209	Abdurro'uf	444 galaxies	z = 0.3 – 6
2305.03042	Tiger Hsiao	MACS0647-JD	z = 10.17

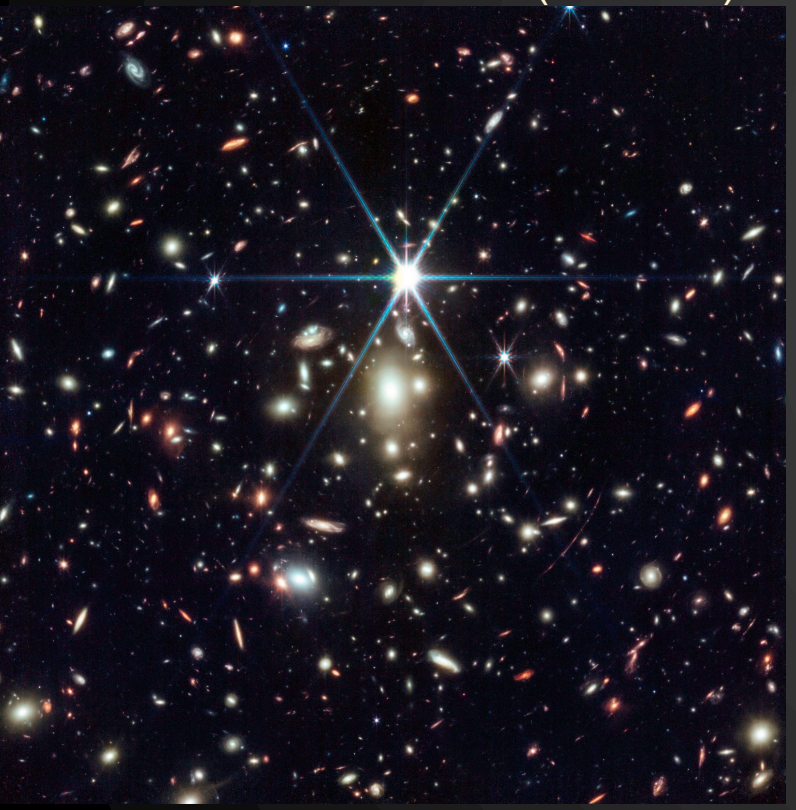
Larry Bradley
Eros Vanzella
Angela Adamo
Gabriel Brammer
Dan Coe
Jose Maria Diego
Rogier Windhorst
Adi Zitrin
Mario Nonino
Kirk Barrow
Marusa Bradac
Pratika Dayal
Megan Donahue
Selma E. de Mink
Erik Zackrisson
Jay Anderson
Stephan McCandliss
Steven Finkelstein
Swara Ravindranath
Brenda Frye
Patrick Kelly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

Cosmic Spring JWST

cosmic-spring.github.io

3 lensing clusters
NIRCam imaging
NIRSpec MSA
MIRI MRS (MACS0647-JD)

GO 2282 (PI Coe)
WHL0137-08 (RELICS)
Sunrise Arc + Earendel (z = 5.93)



GO 1433 (PI Coe)
GO 4246 (PI Abdurro'uf)
MACS0647+70 (CLASH)
MACS0647-JD (z = 10.17)

GO 4212 (PI Bradley)
SPT0615-57 (RELICS)
SPT0615-JD (z ~ 10)

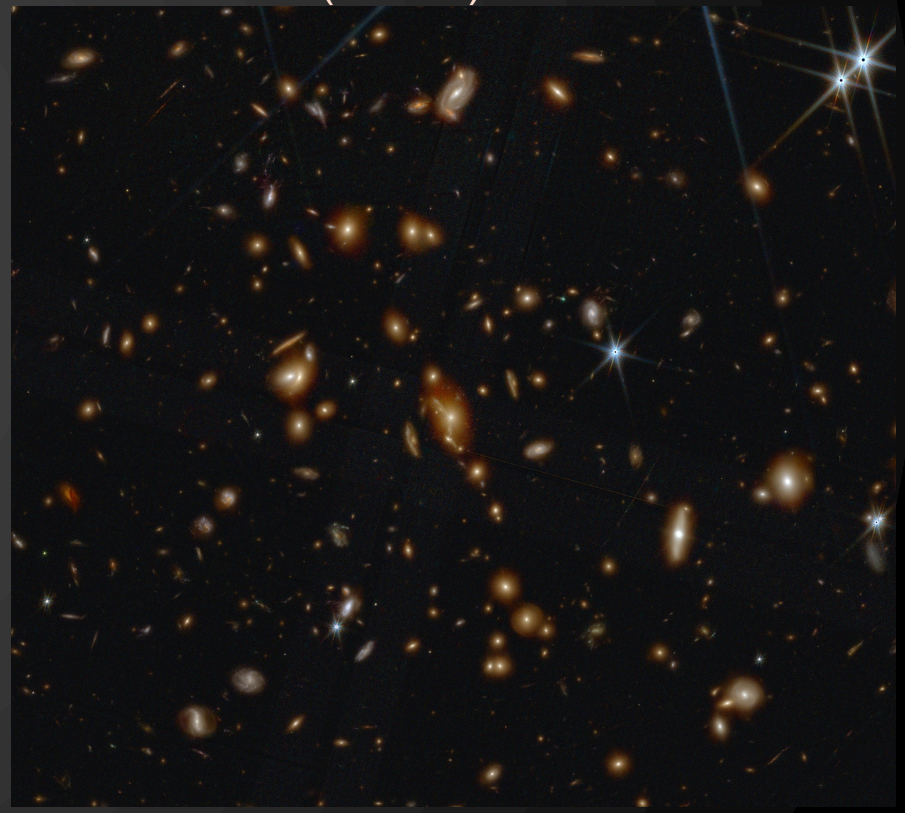
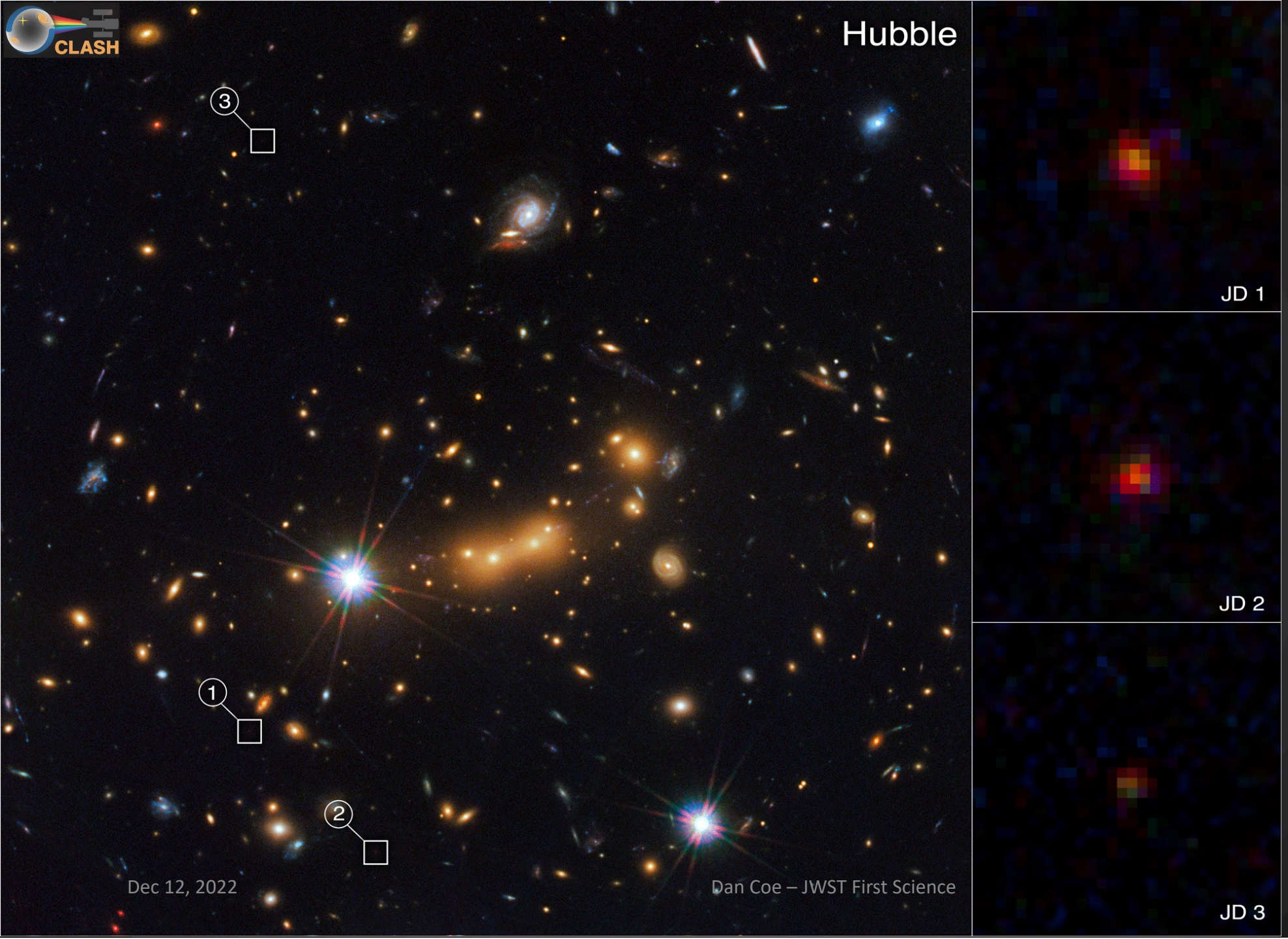


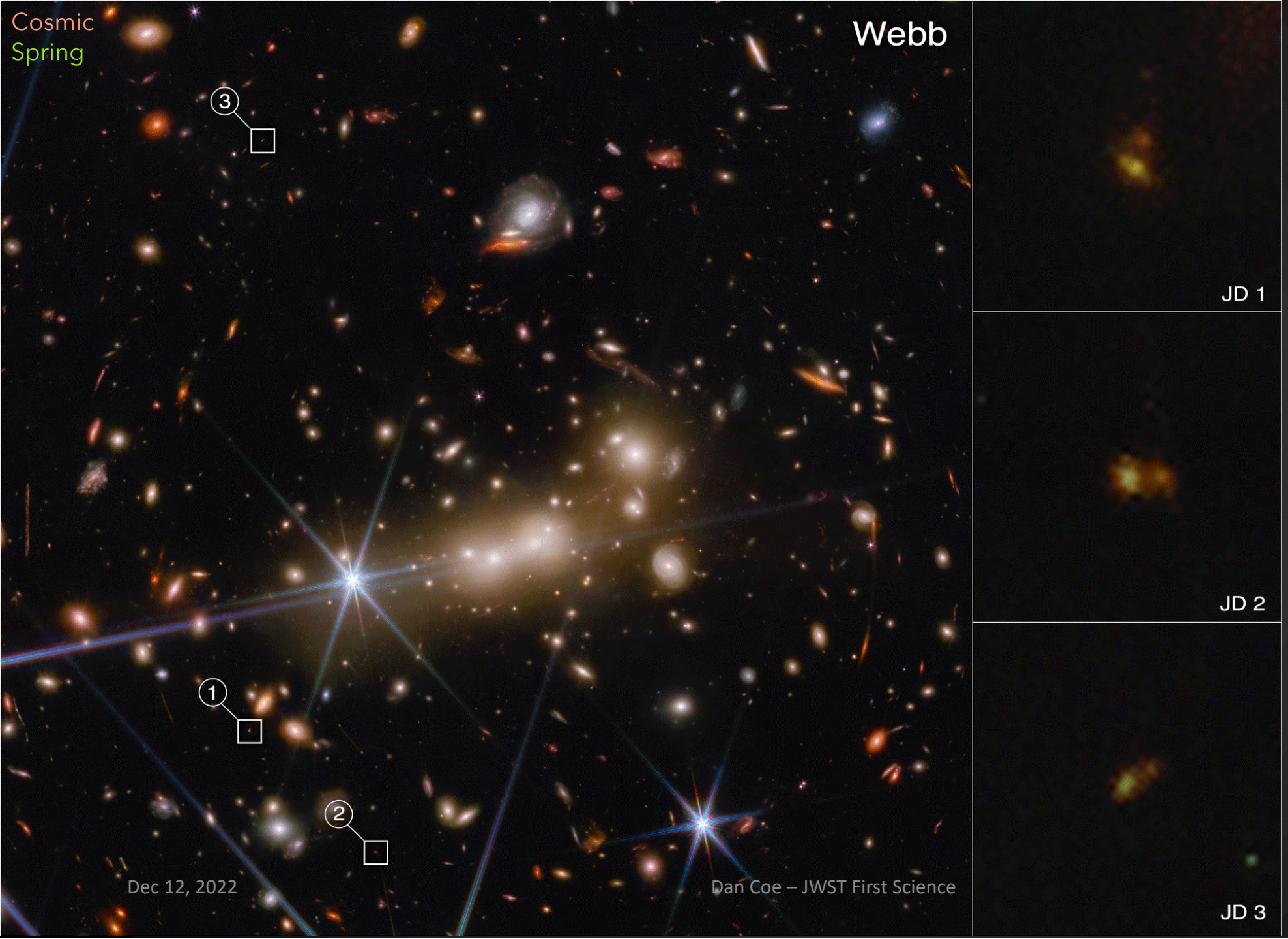
Image: Zolt Levay

Image: Alyssa Pagan

Look again at that dot

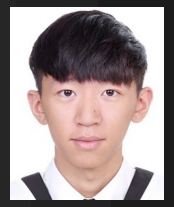


MACS0647-JD
z ~ 11 (400 Myr)
Coe et al. 2013

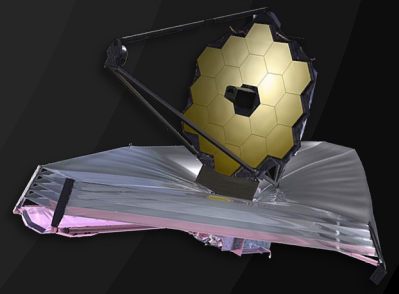


Look again at those dots

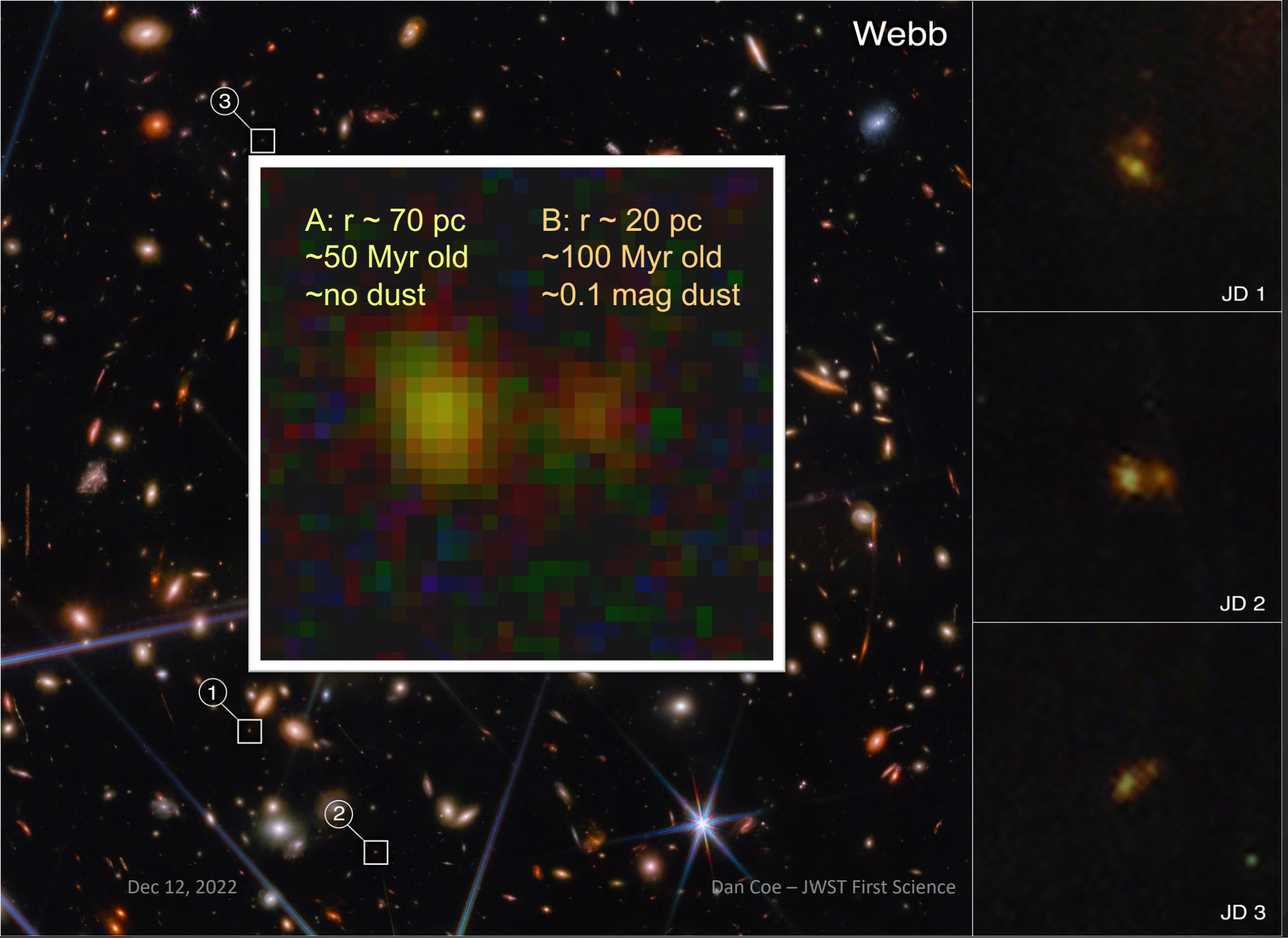
MACS0647-JD
z = 10.17 (460 Myr)



Tiger Hsiao et al.
arXiv:2210.14123
arXiv:2305.03042



Look again at those dots



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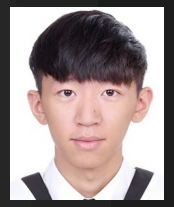

Tiger Hsiao et al.
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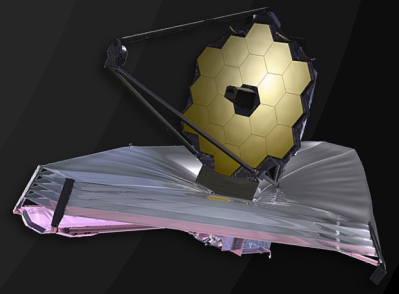
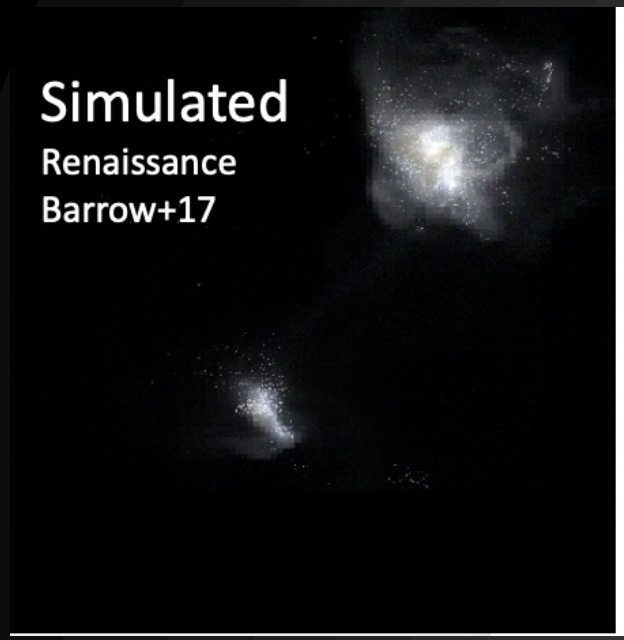
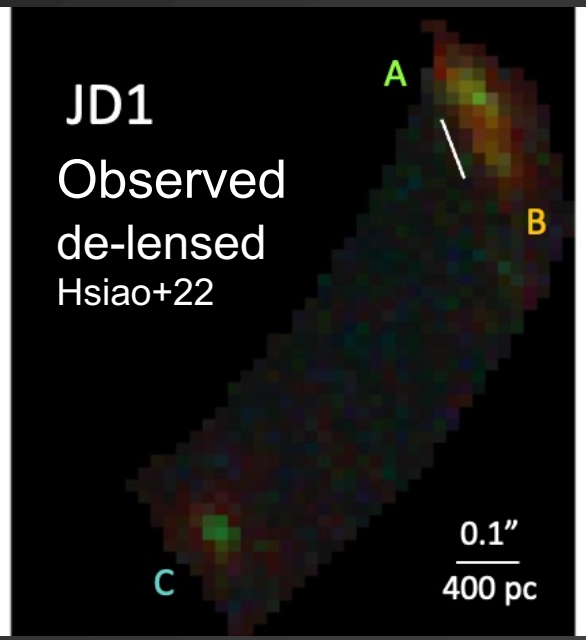
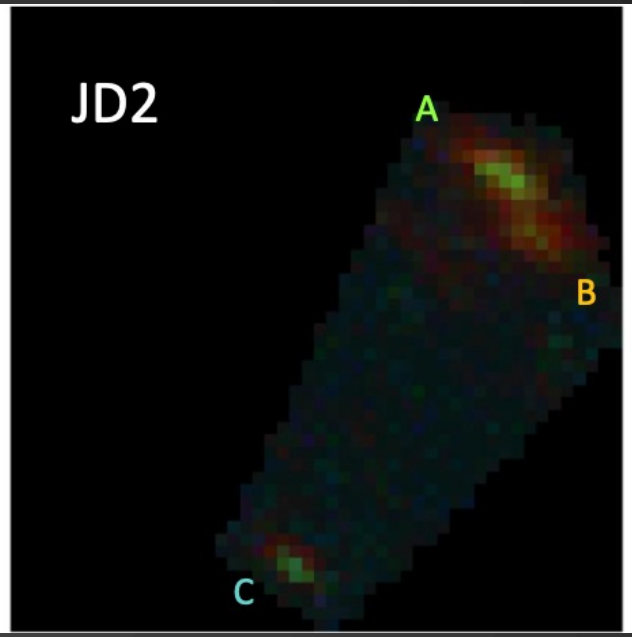
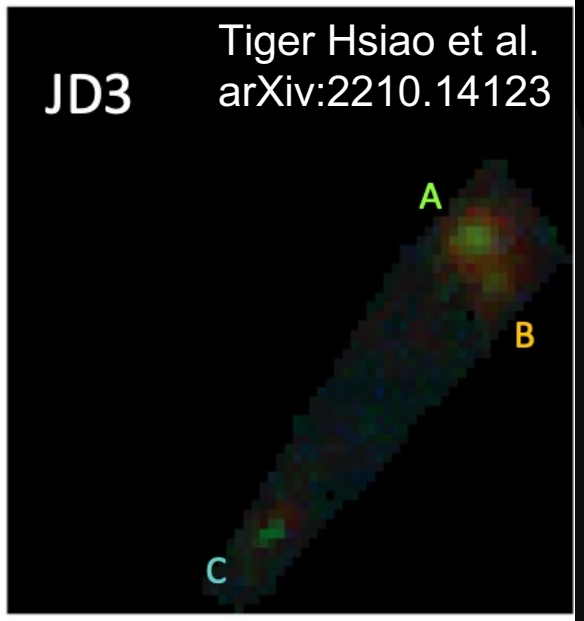


Galaxy merger 400 Myr after the Big Bang?

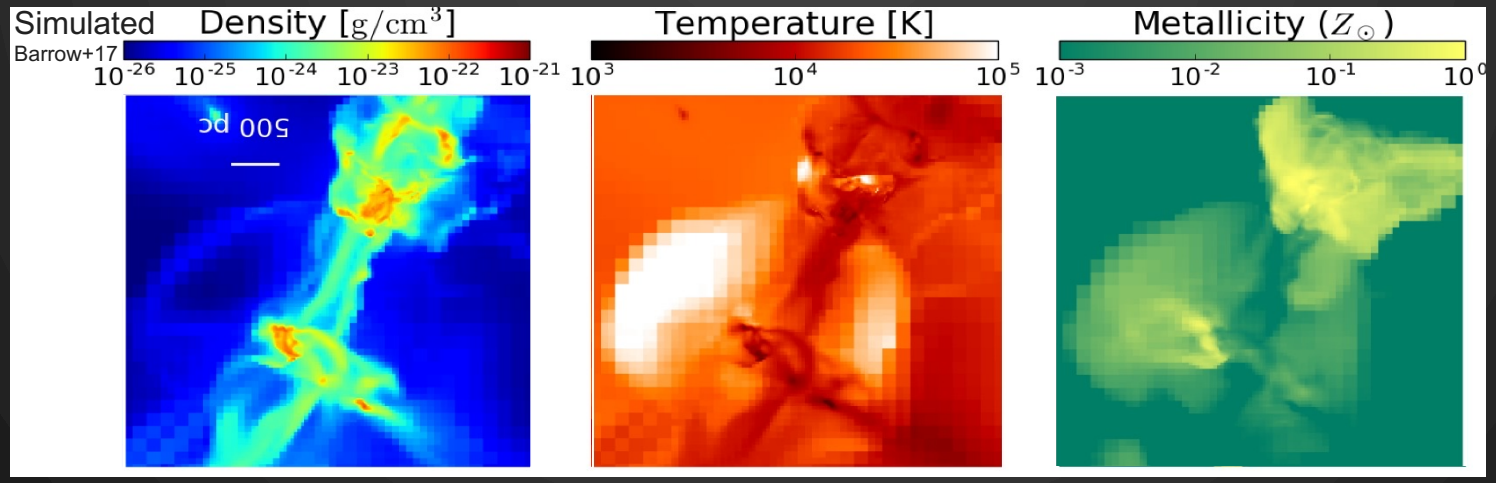






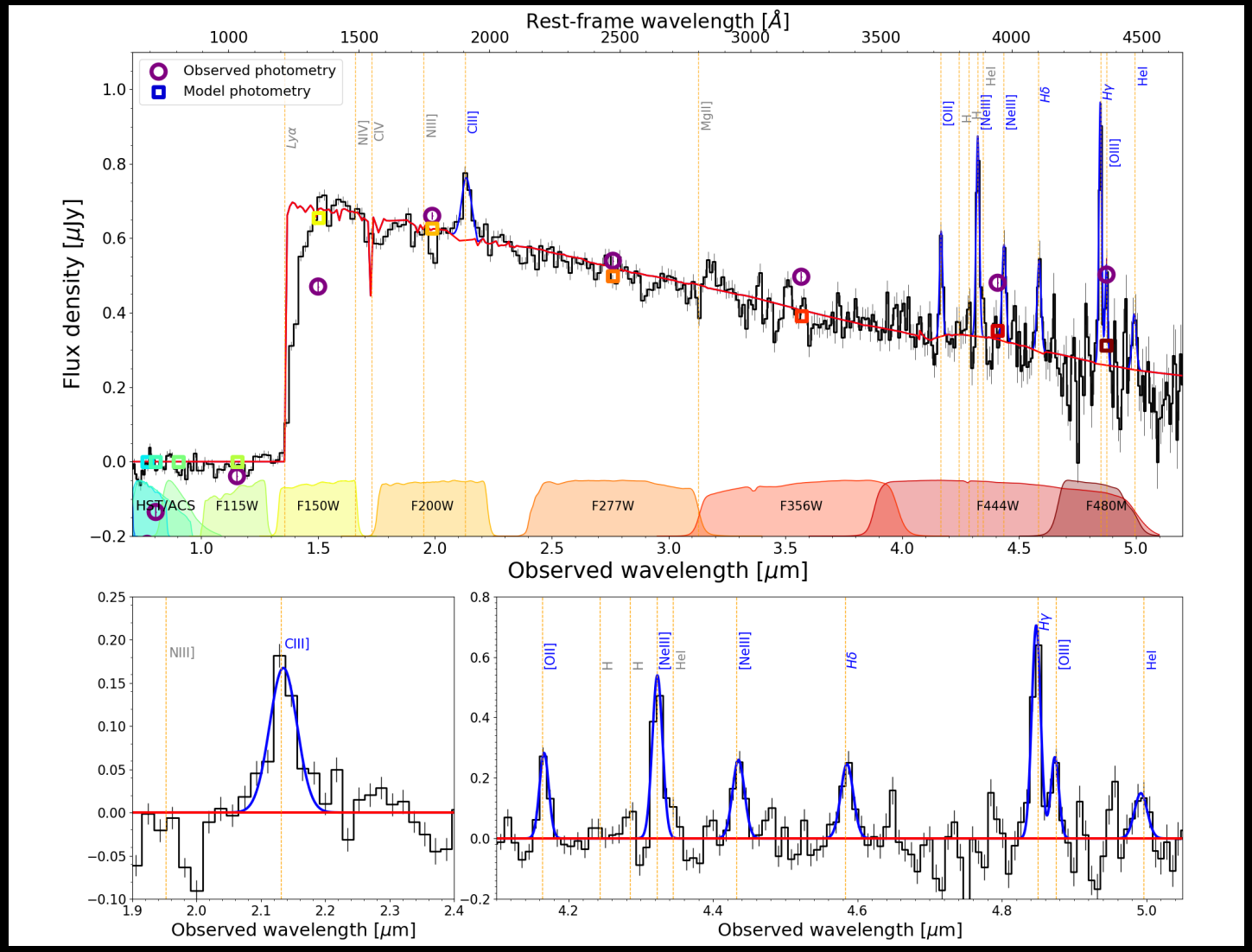


Kirk Barrow



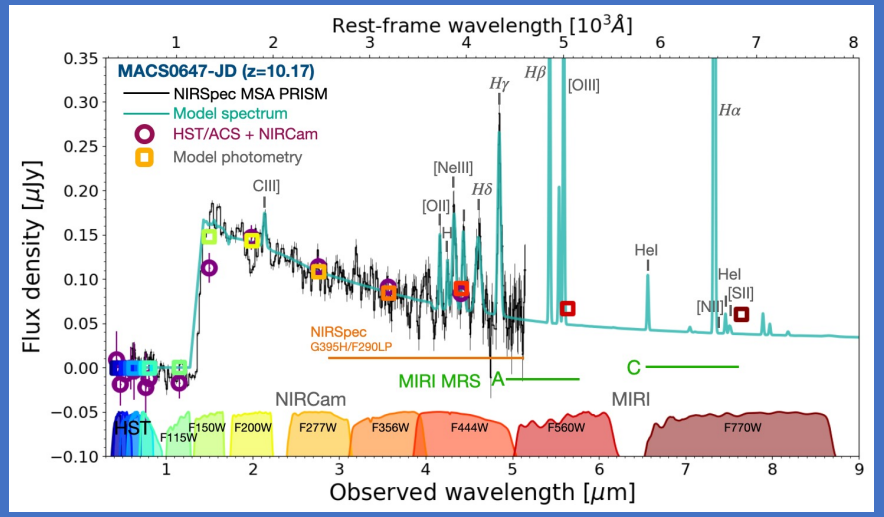
MACS0647-JD at z = 10.17 with 7 emission lines

CIII], [OII], [NeIII]x2, Hγ, Hδ, [OIII] 4363Å



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

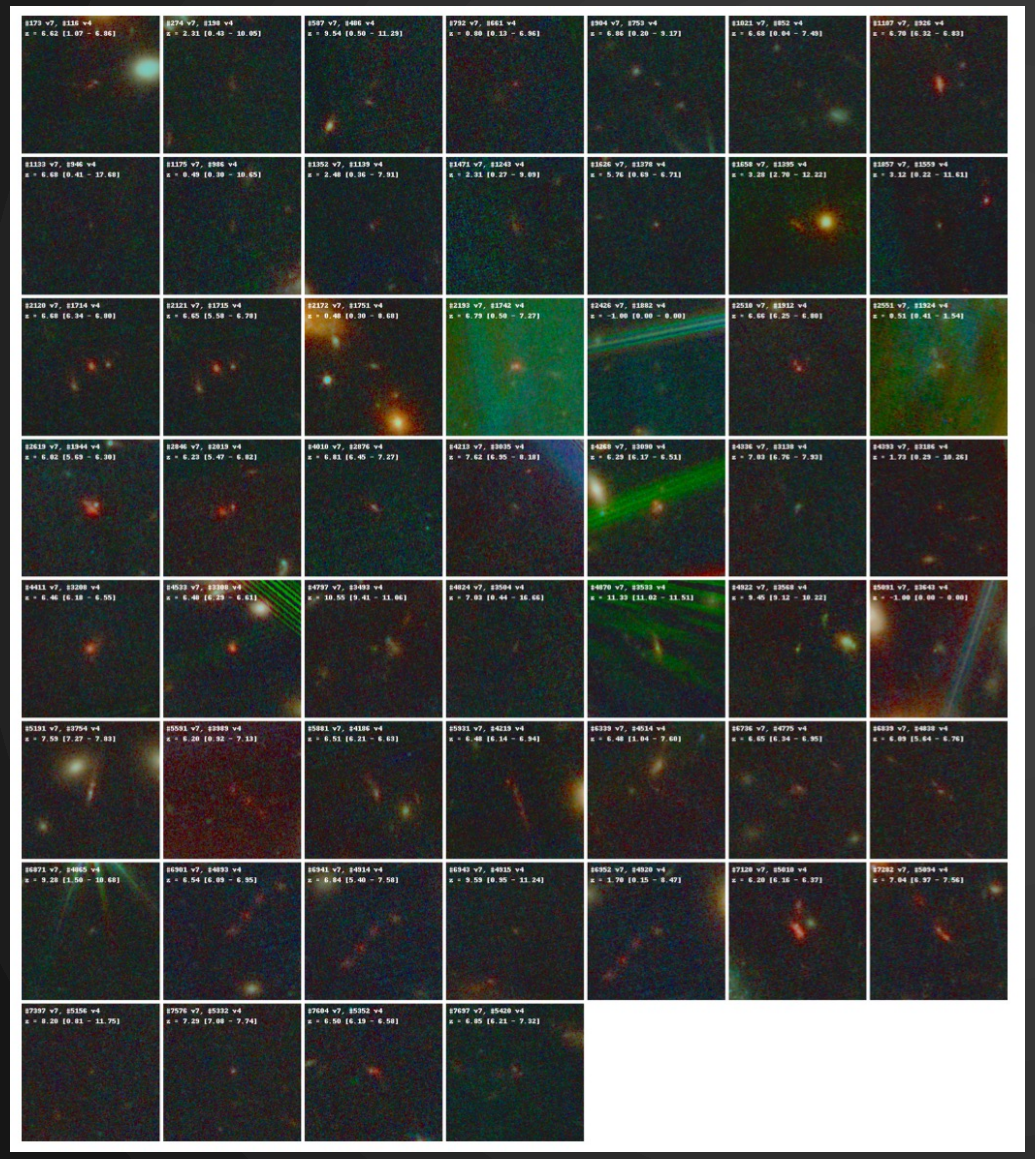
Cycle 2 program (PI Abdurro'uf) will add MIRI MRS for Hα & [OIII]+Hβ

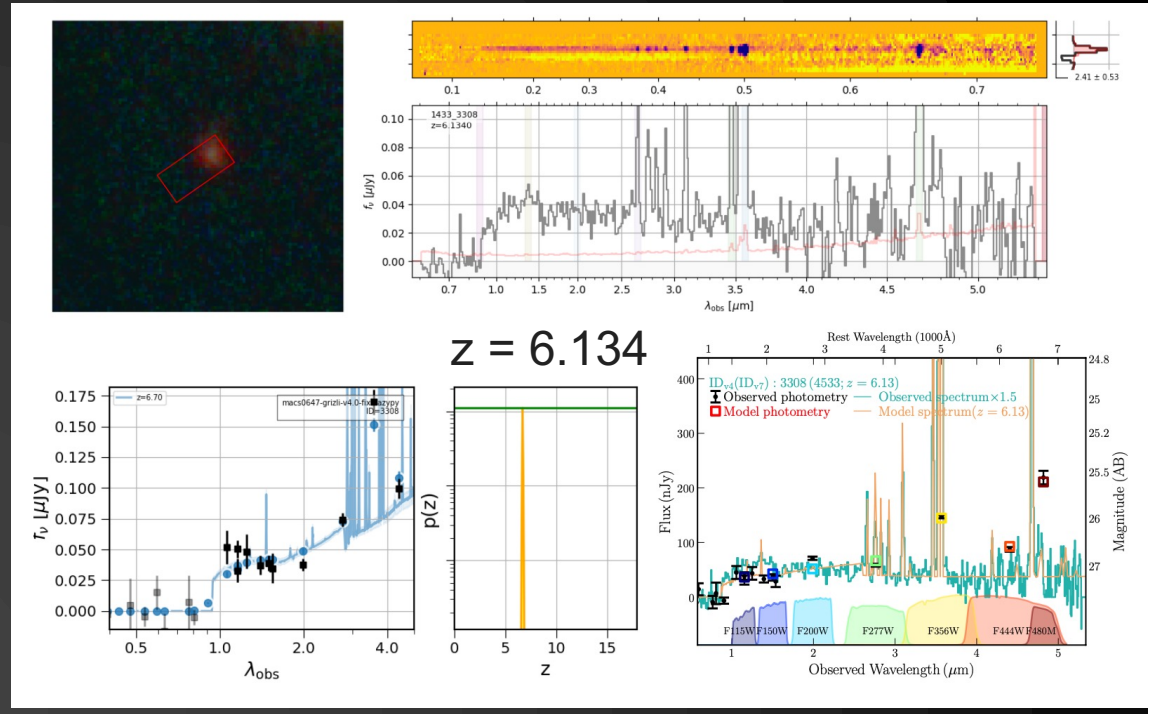


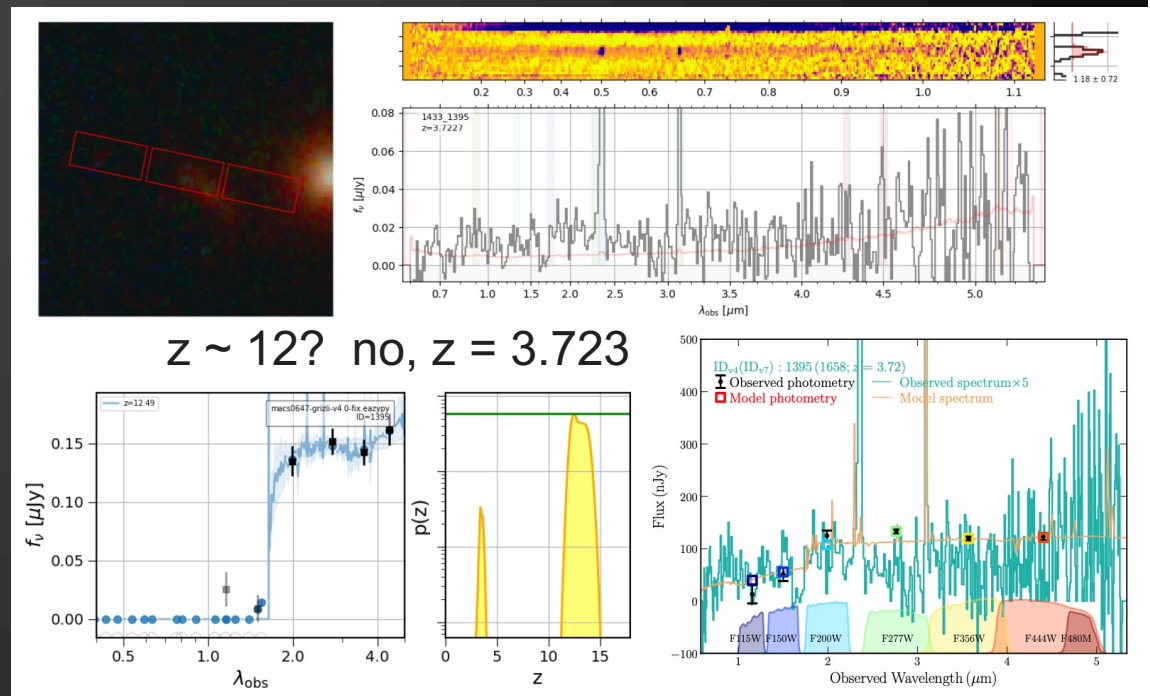
Distant galaxies lensed by MACS0647

observed in the universe's first billion years (z > 6)

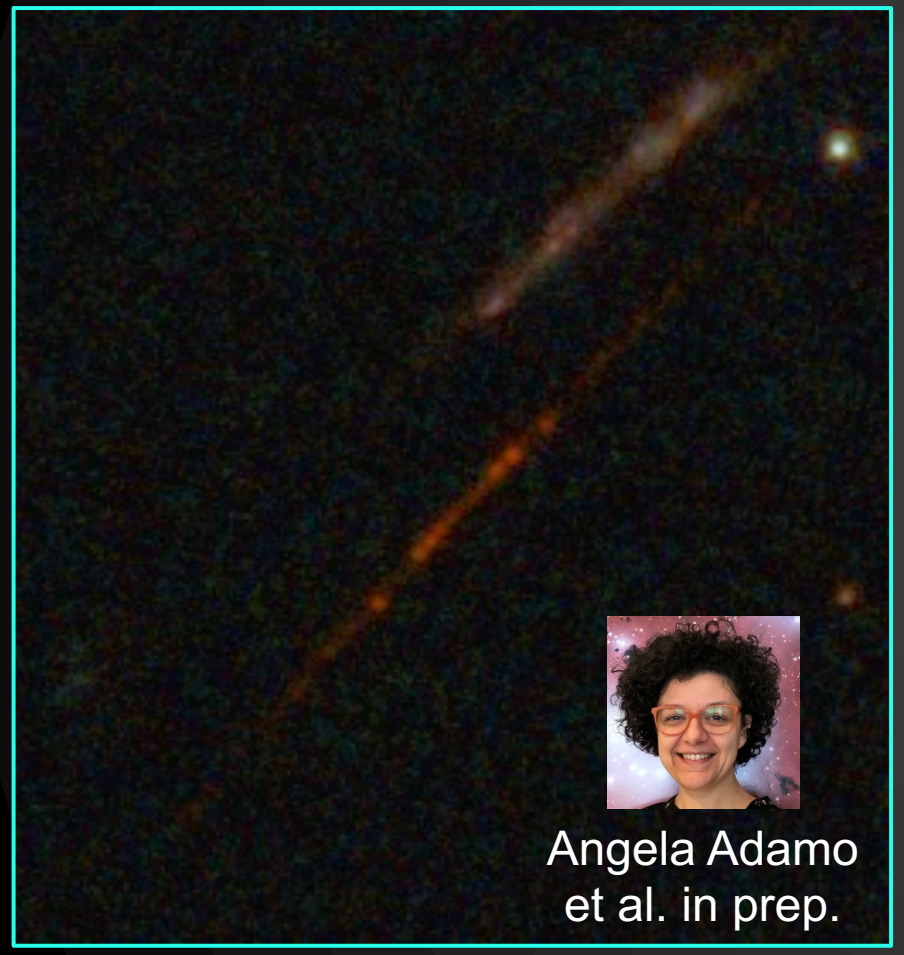
Keduse Worku



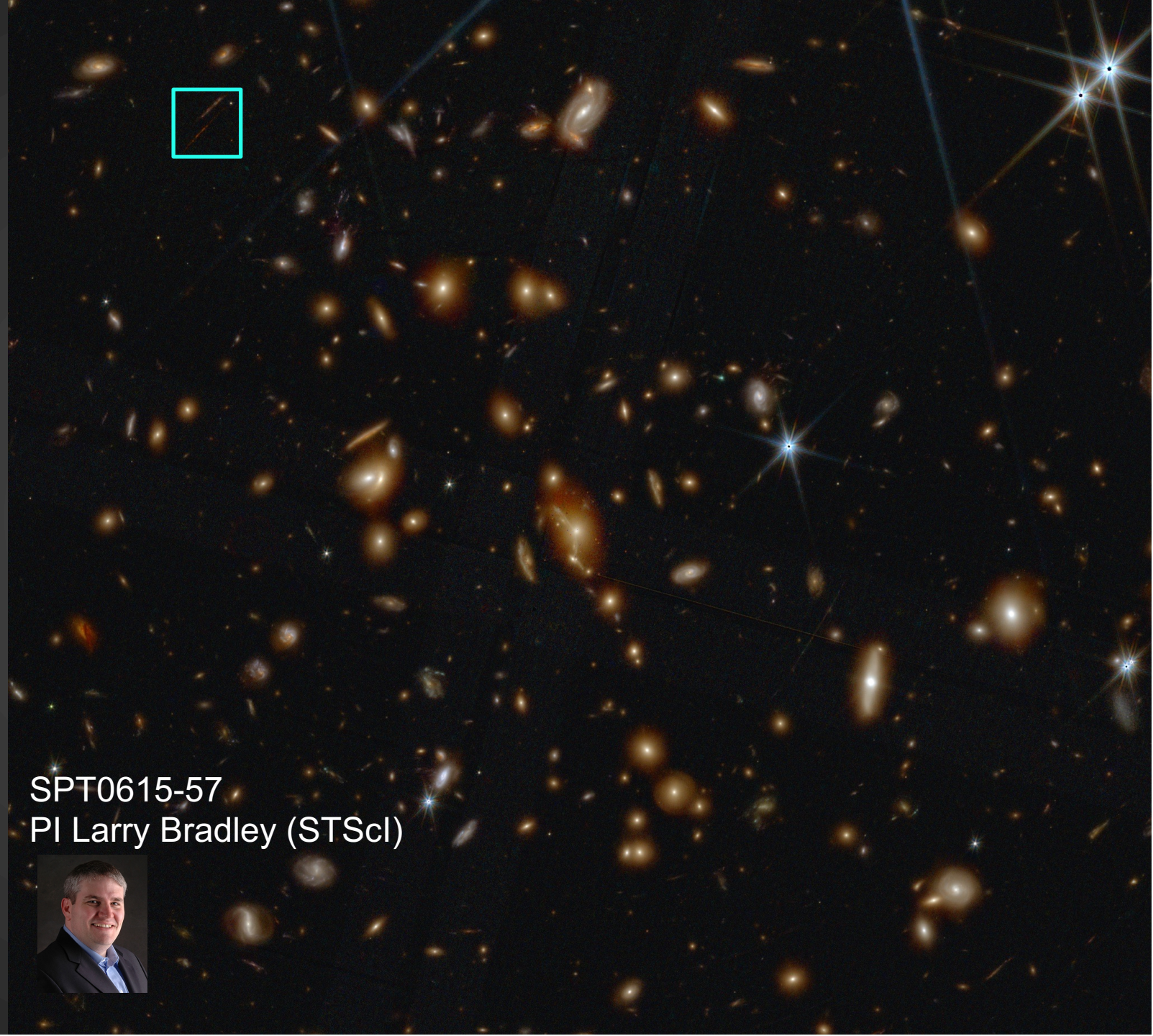




PRELIMINARY:
r ~ 1 pc star clusters at z ~ 10
observed 500 Myr after the Big Bang



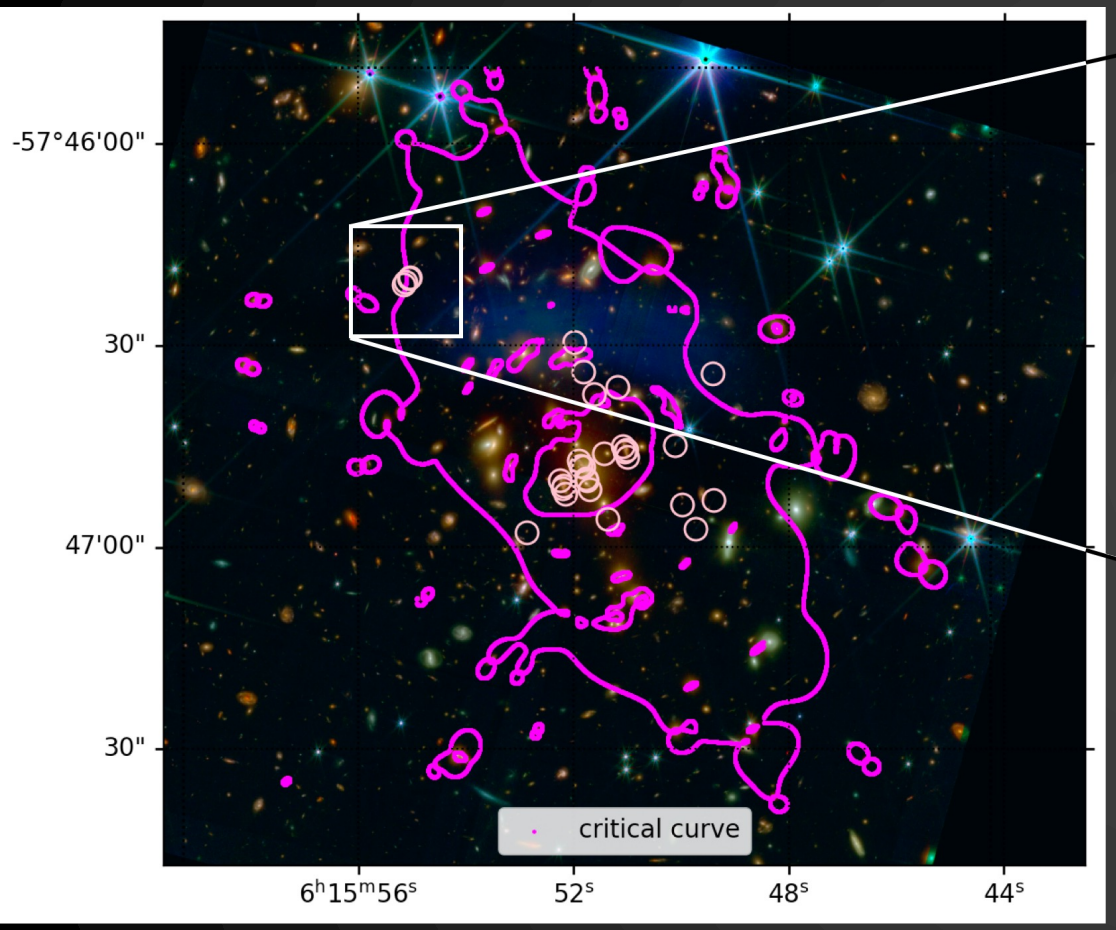
Angela Adamo
et al. in prep.



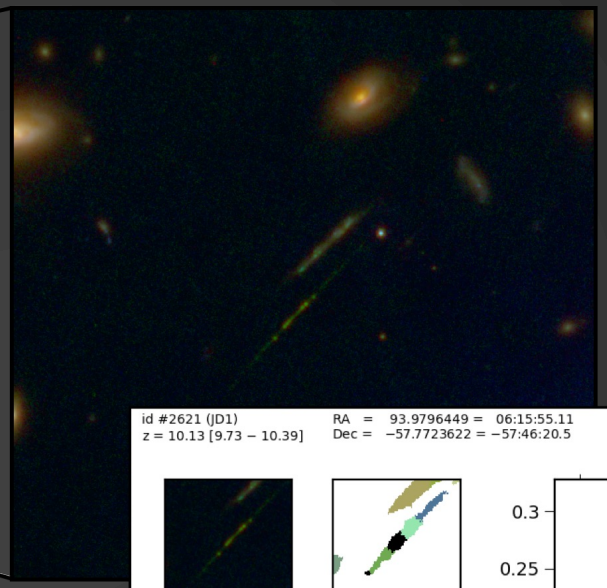
SPT0615-57
PI Larry Bradley (STScI)

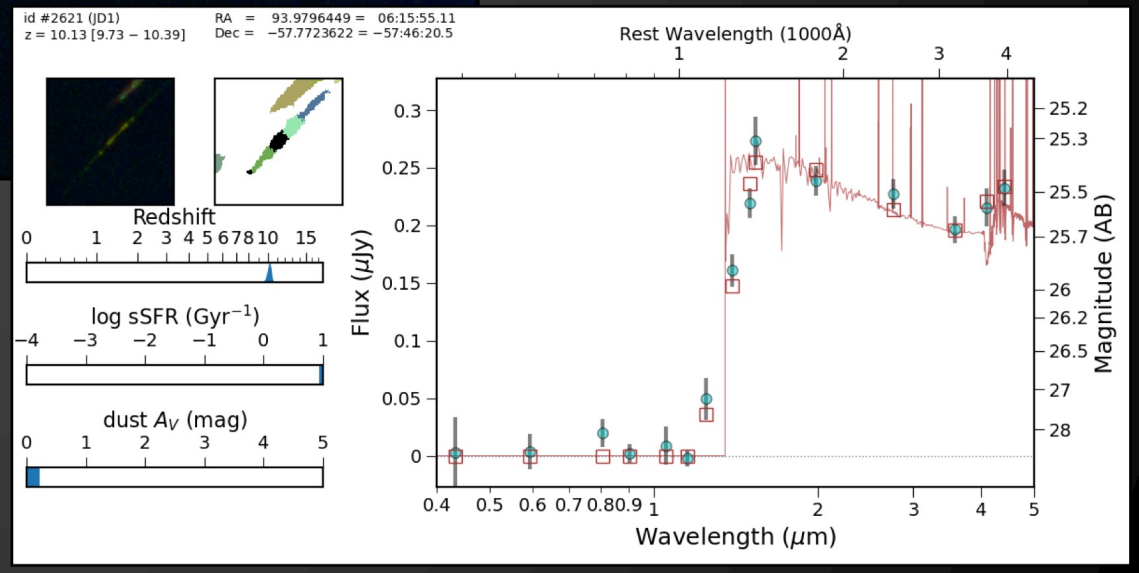
Lens modeling the z ~ 10 arc SPT0615-JD

Tom Resseguier



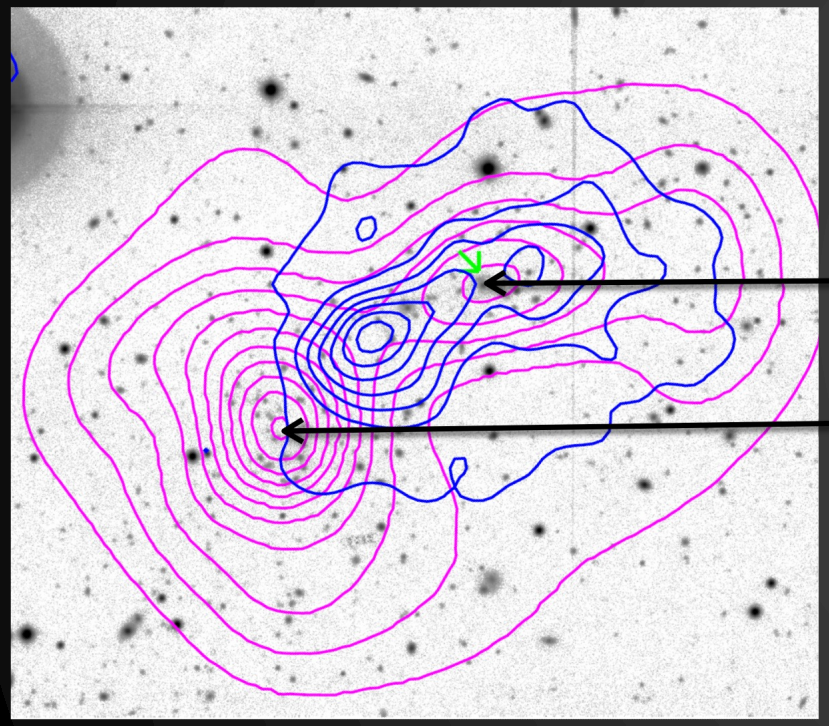
Critical curve from the lens model at z~10



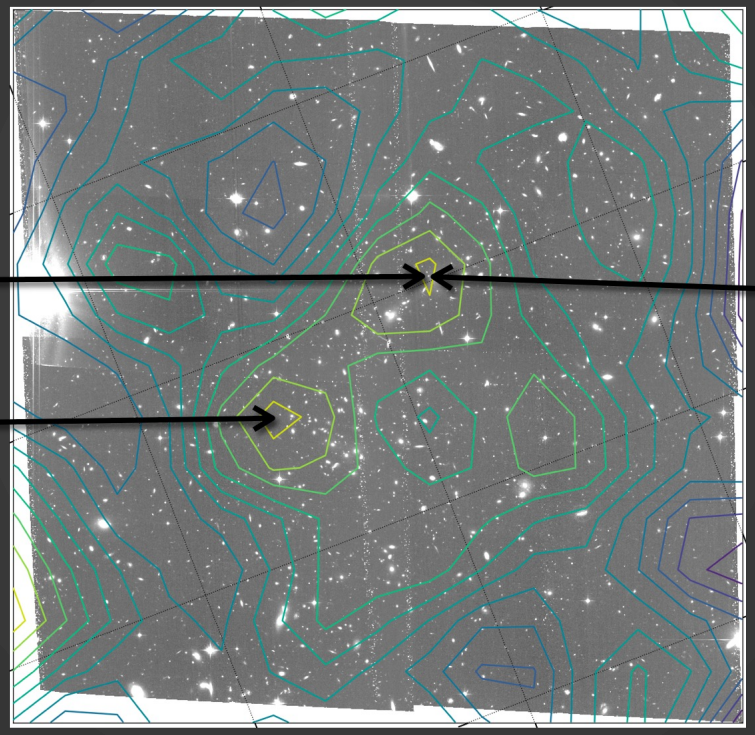


SED fitting of the z~10 arc from EAZY

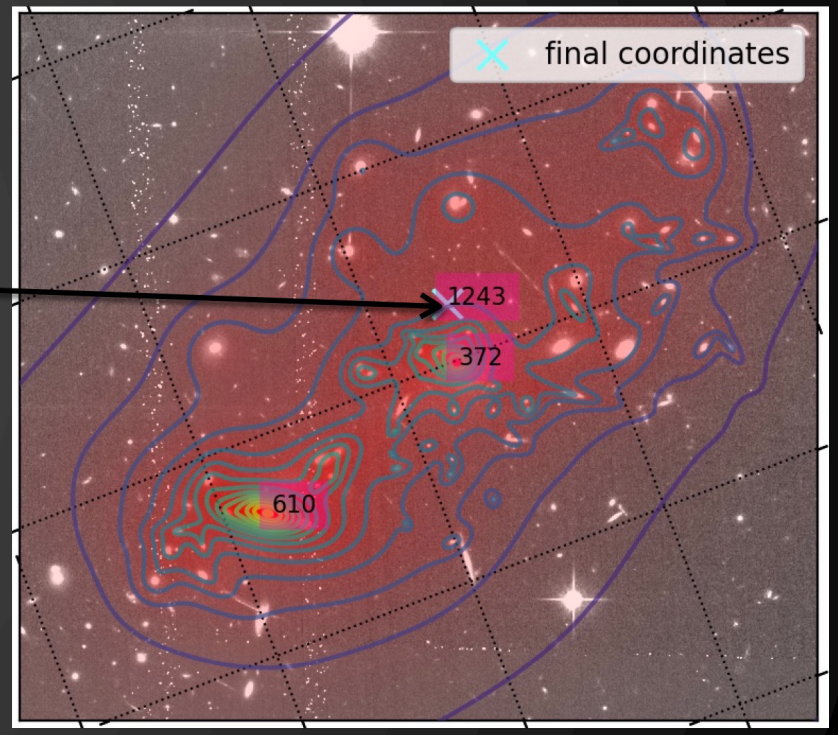
The Planck Bullet Cluster



Preliminary X-ray (blue) & galaxy number density (pink)



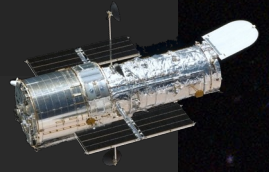
Weak lensing mass map



Strong lensing model

JWST was designed to study the first stars

We found one with Hubble to look at with JWST

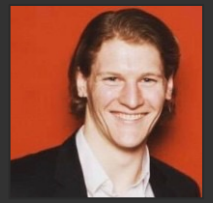


Earendel z = 6 star system

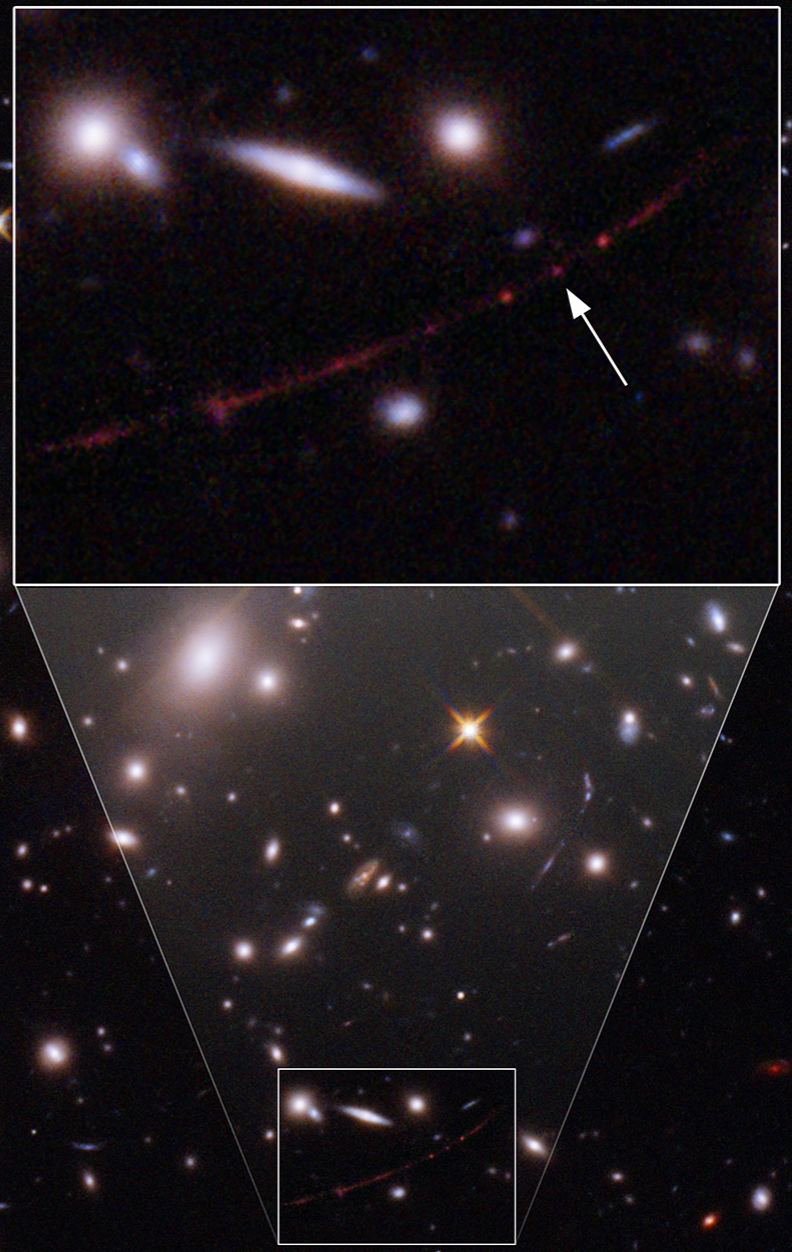
observed 1 Gyr after the Big Bang

magnified by thousands

Brian Welch et al.
2022 Nature



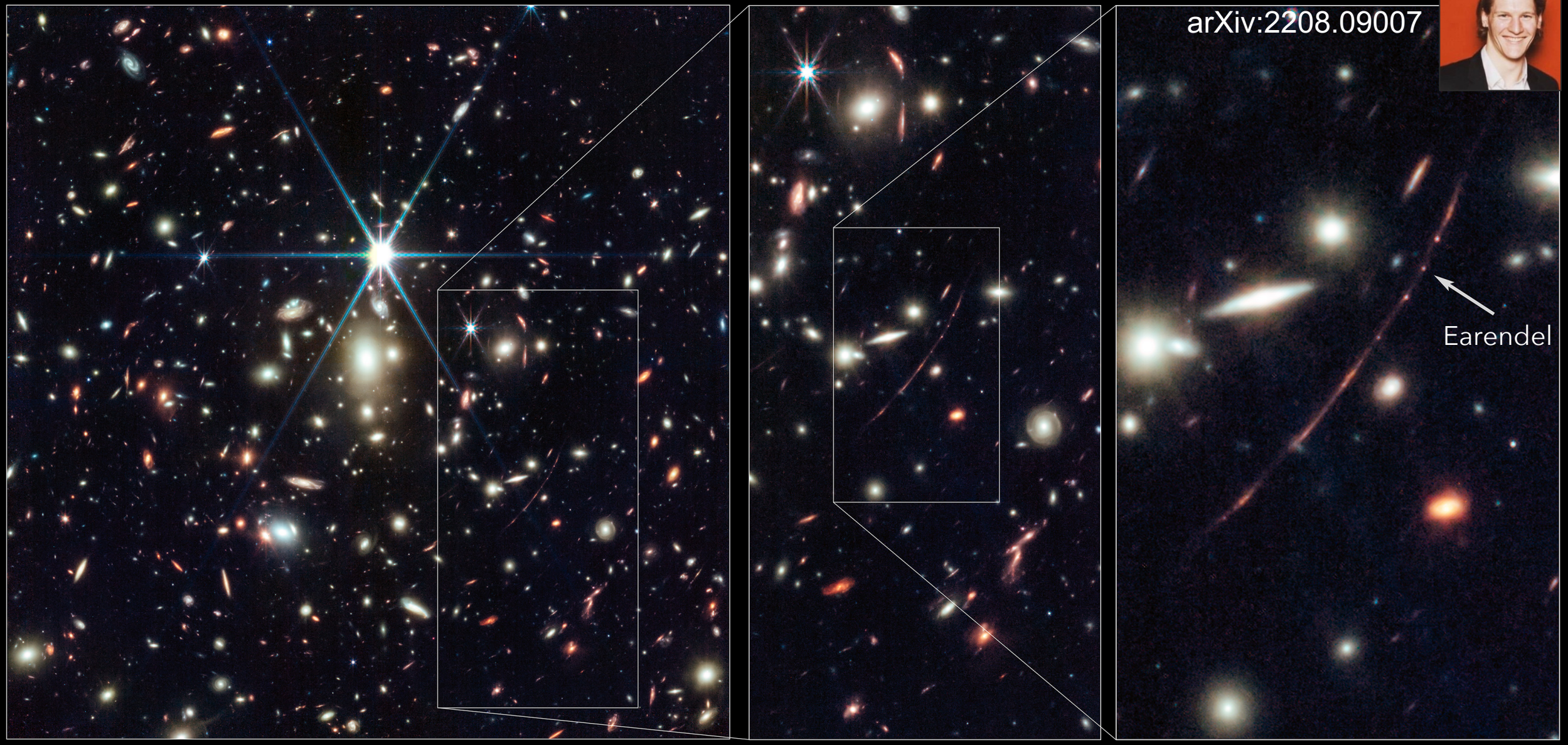
Earendel "morning light"



Dan Coe – GSFC / JHU

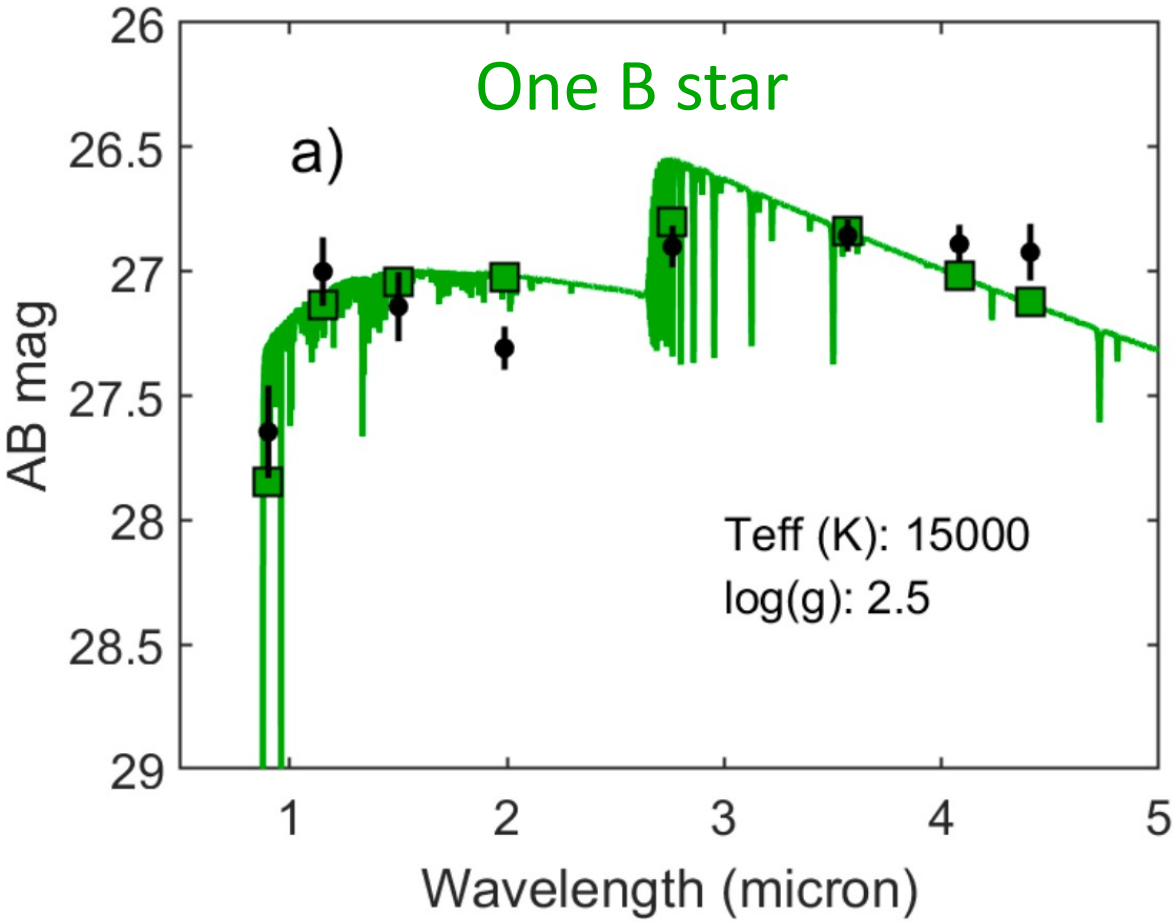
WHL0137/Earendel • JWST/NIRCAM

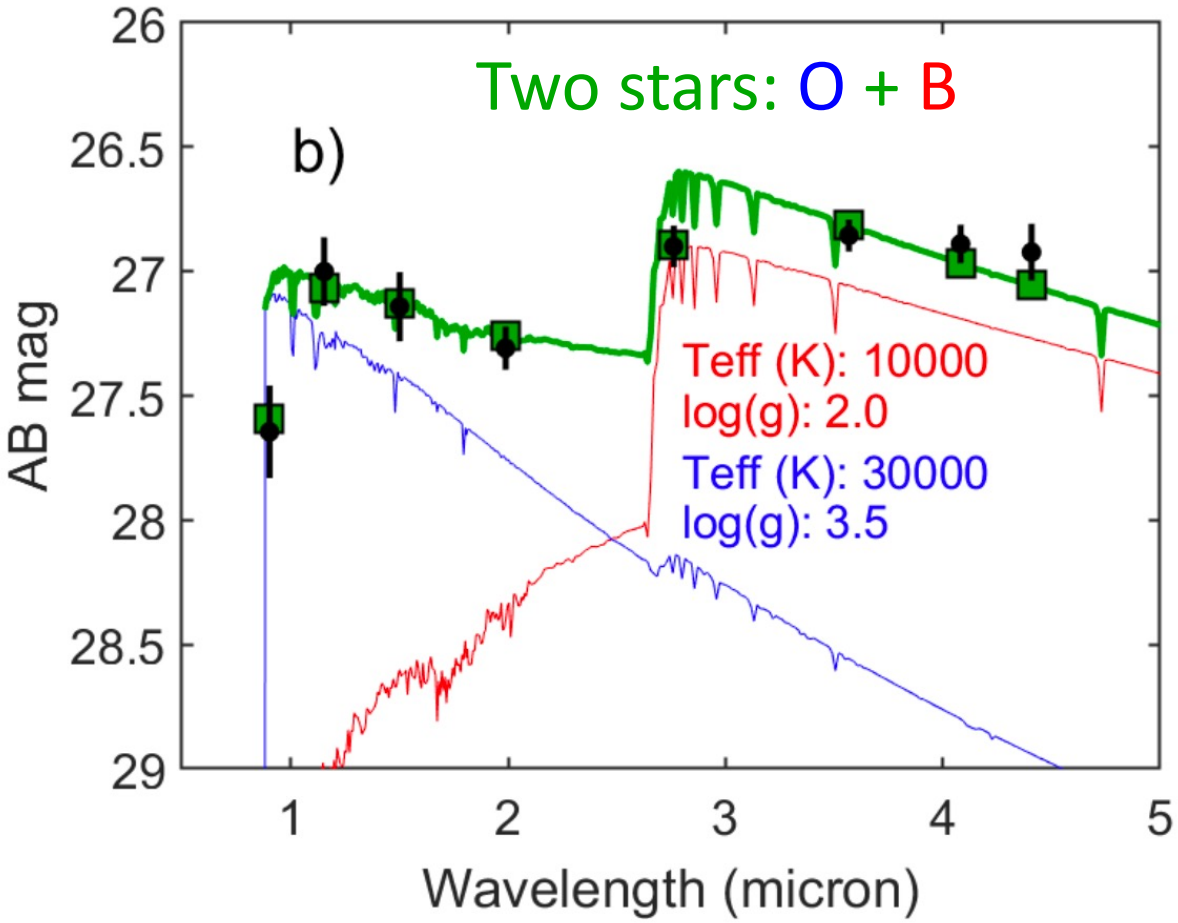
Brian Welch et al.
arXiv:2208.09007



Colors of Earendel measured by JWST NIRCam hinting at multiple star system

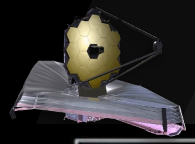
Brian Welch et al.
arXiv:2208.09007

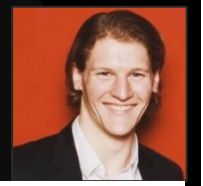


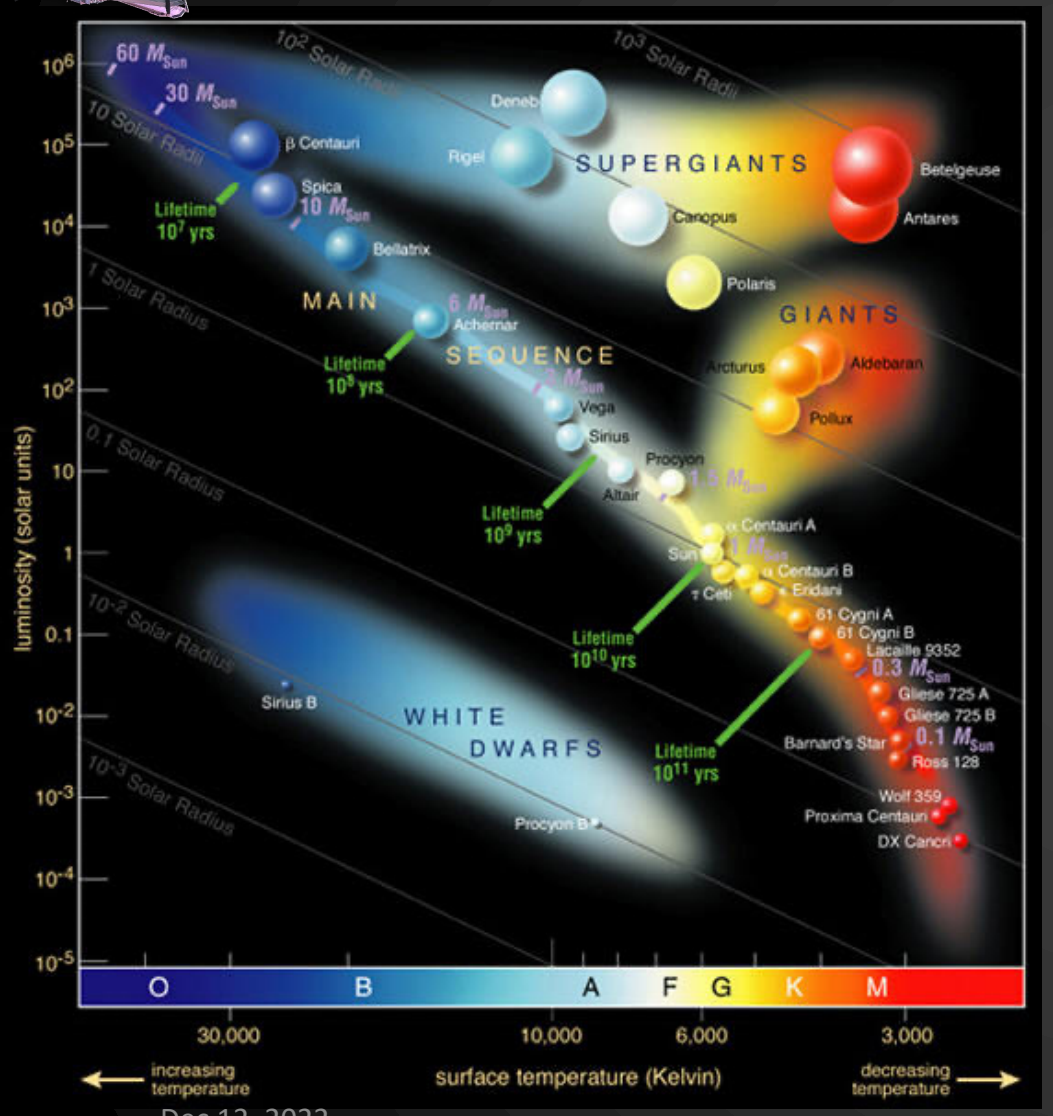


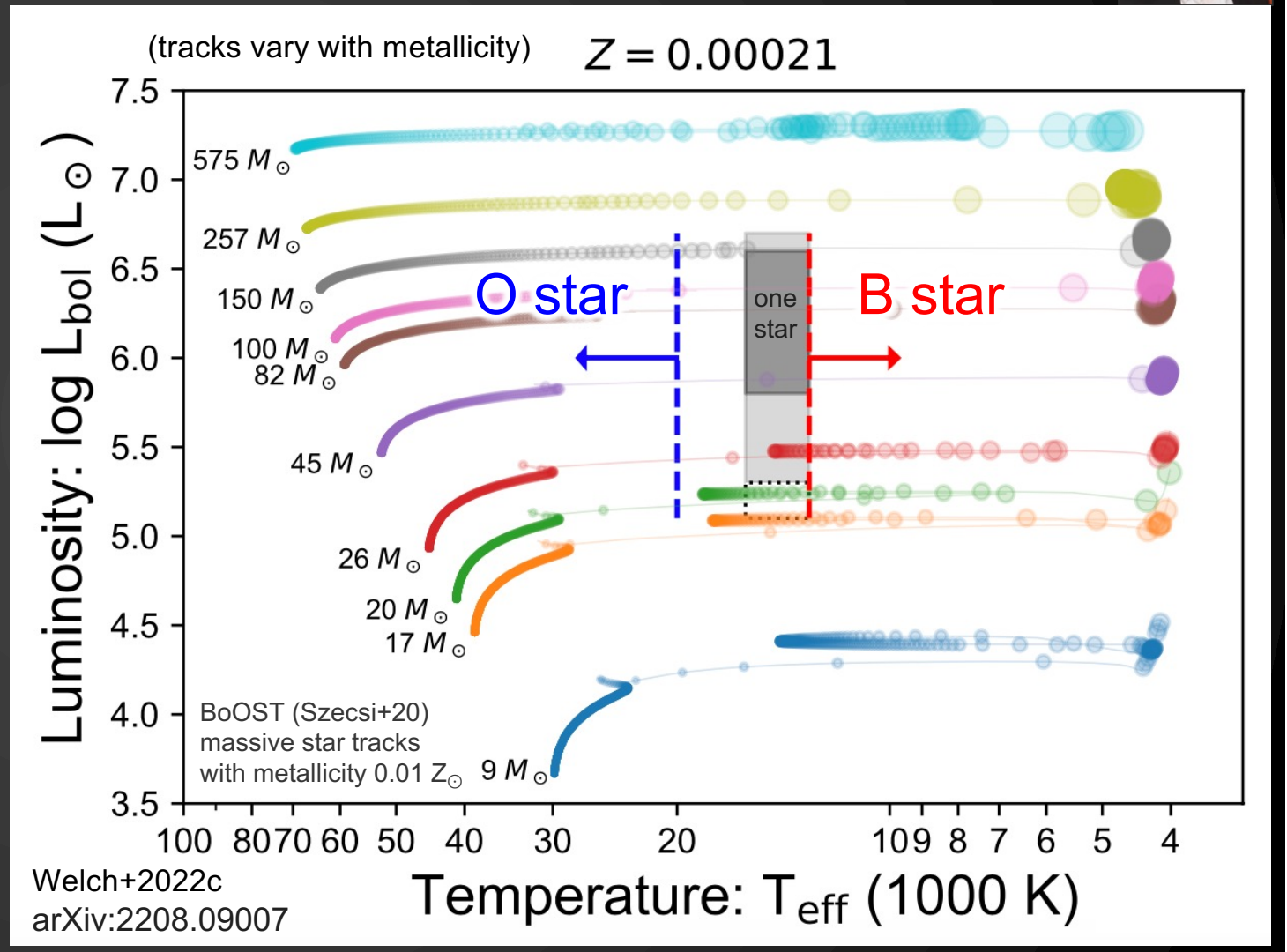
JWST: Earendel is 2 or more massive, luminous stars

We are placing them on the H-R diagram at z ~ 6









Welch+2022c
arXiv:2208.09007

Brian Welch
GSFC

Taylor Hutchison
GSFC

TEMPLATES

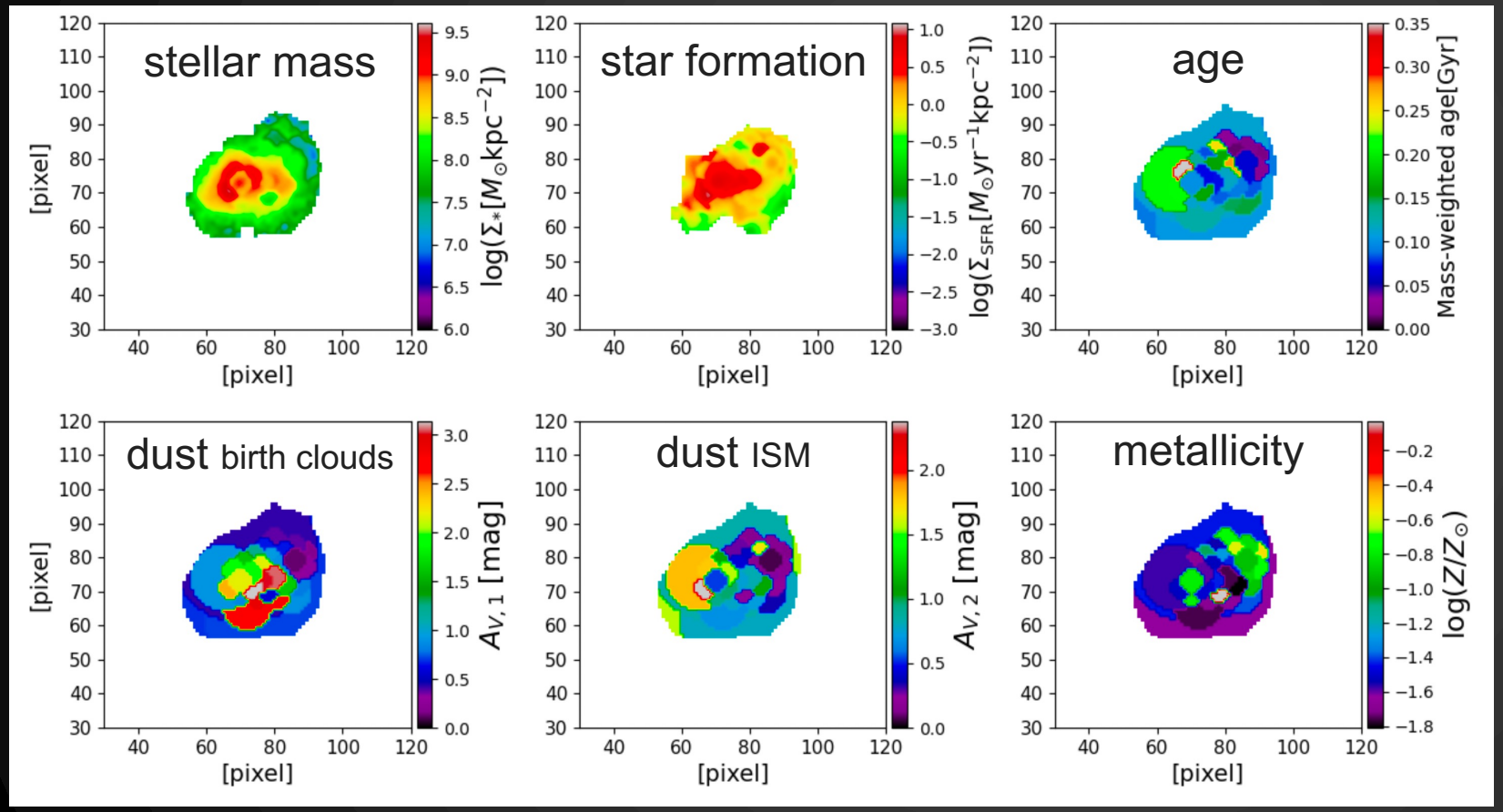
PI Jane Rigby

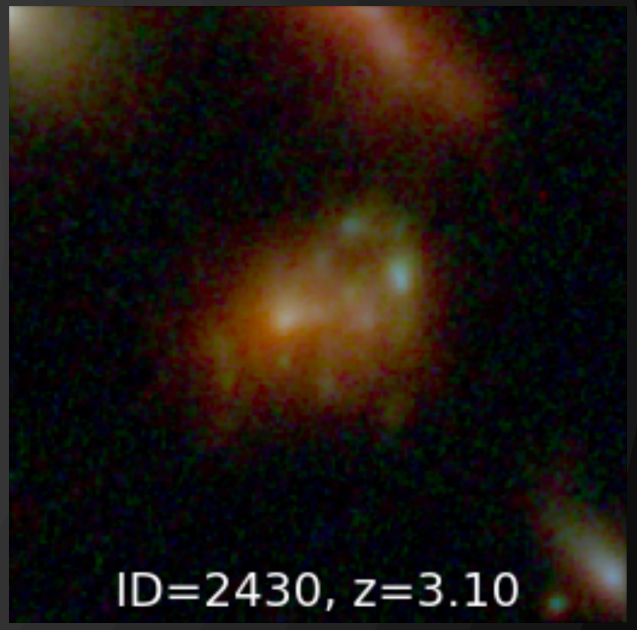
SDSS J1226+2149
https://esawebb.org/images/potm2303a/

How galaxies grow and quench over time

spatially resolved SED fitting and physical properties of 400+ galaxies at z = 0.3 – 6.0 with **piXedfit**

Abdurro'uf et al.
arXiv:2301.02209





JWST + gravitational lensing
is already revealing the first star clusters
on our way towards revealing the first stars

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Cosmic Spring
cosmic-spring.github.io