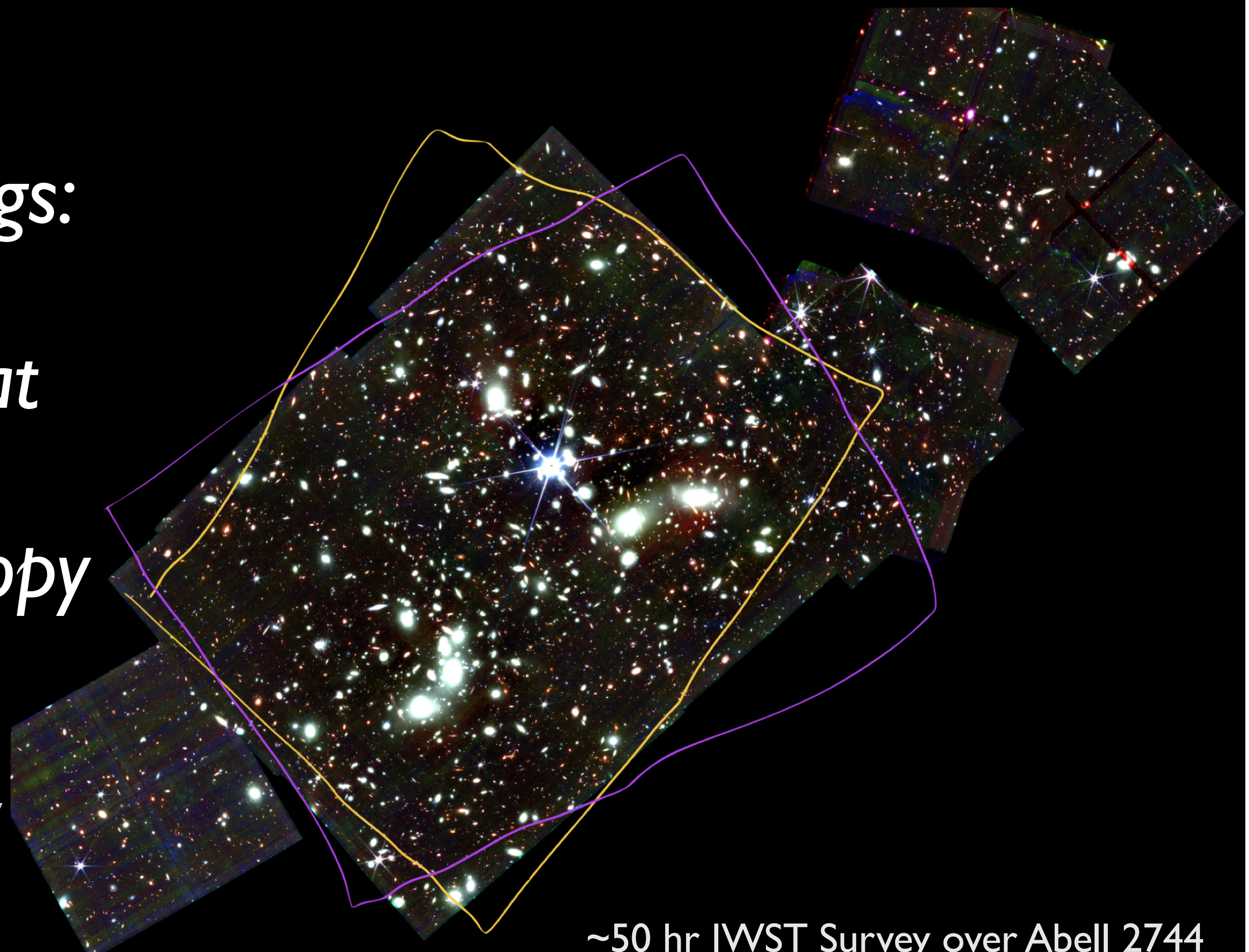
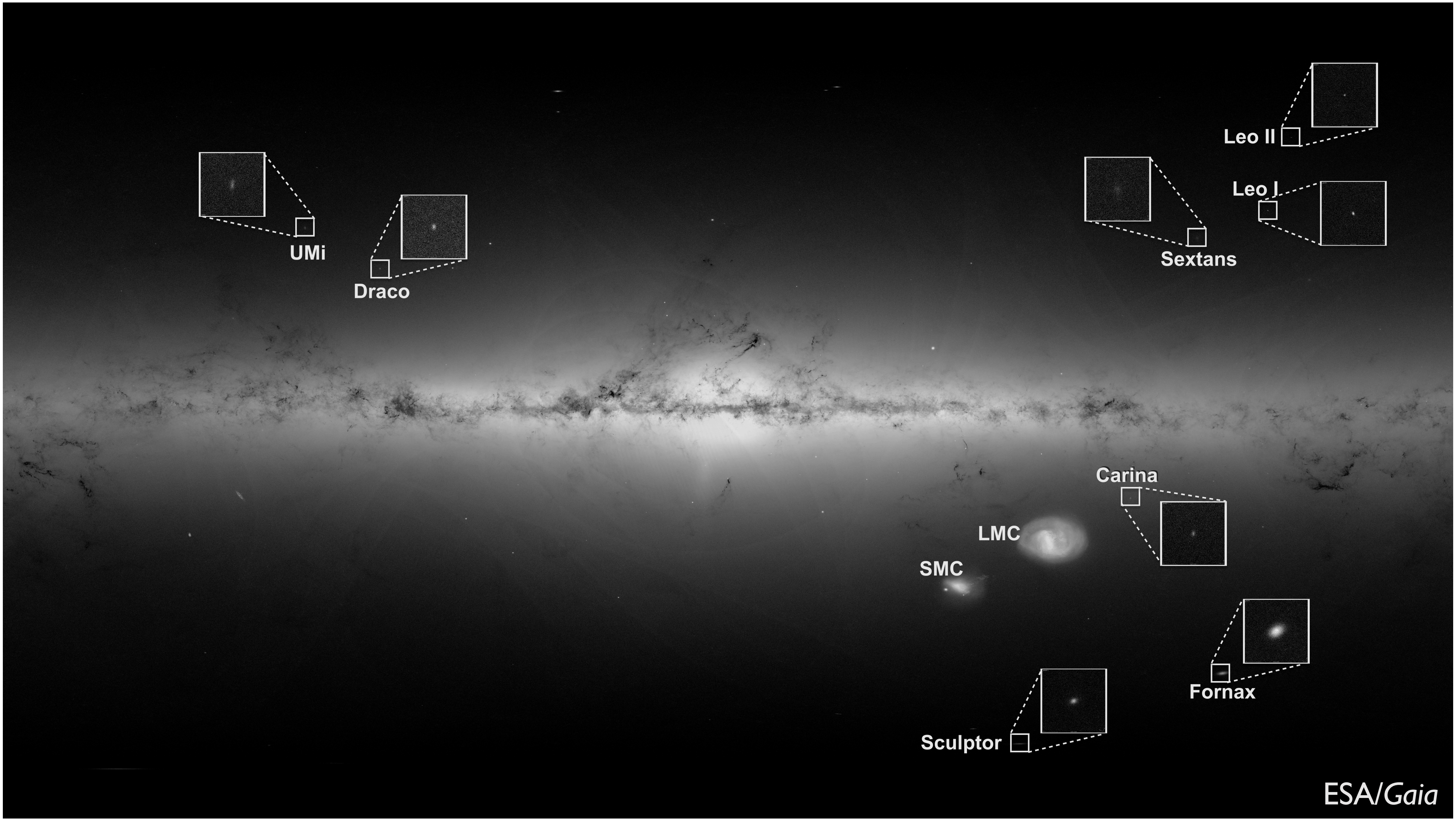
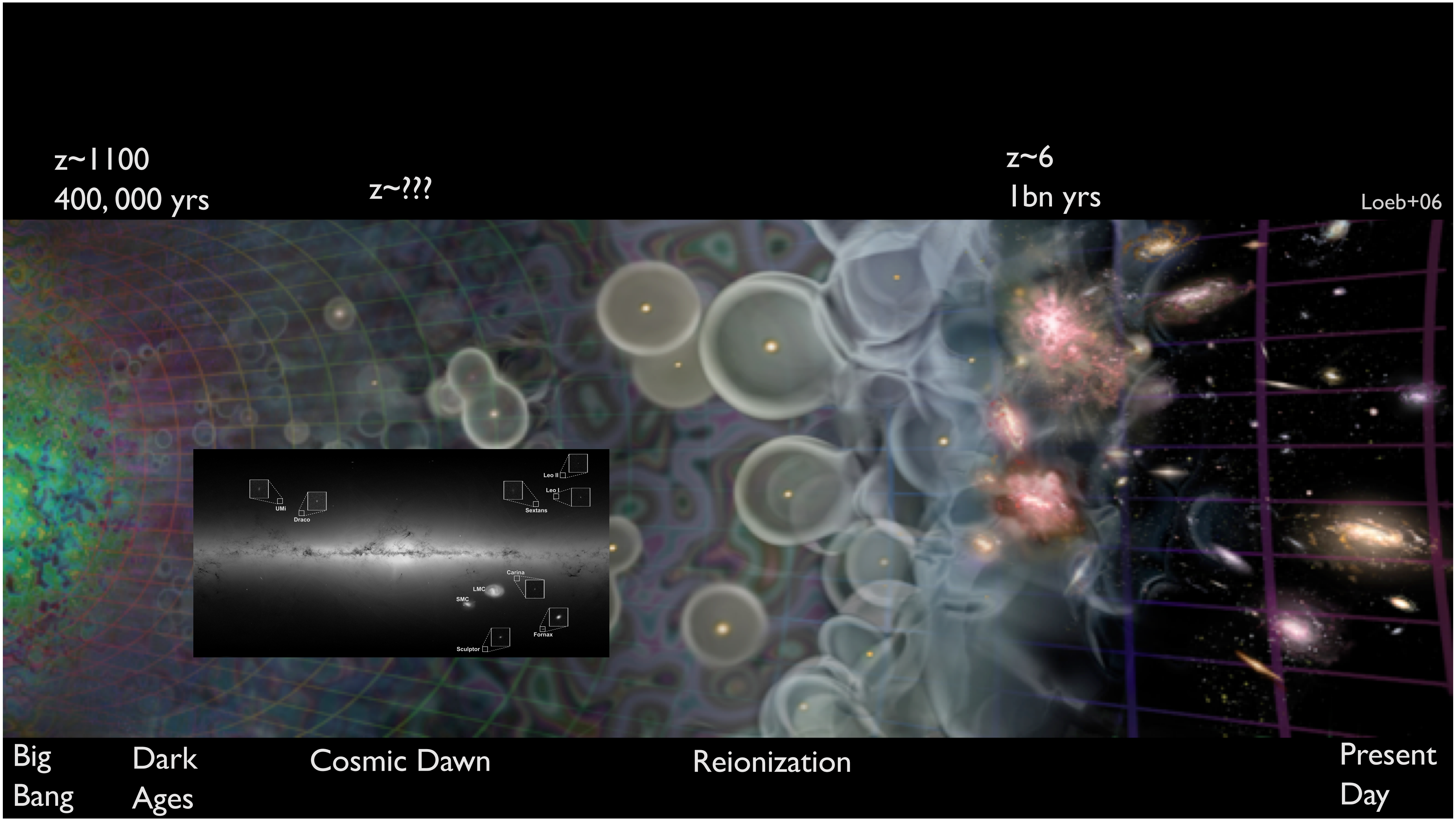
All the Little Things: >1000 Lensed Dwarf Galaxies at z=0-9 via JWST Grism Spectroscopy

Rohan Naidu
NASA Hubble Fellow
MIT Kavli Institute



~50 hr JWST Survey over Abell 2744
PIs: R.P. Naidu & J. Matthee


Leo II
Leo I
UMi
Draco
Sextans
Carina
LMC
SMC
Fornax
Sculptor
ESA/Gaia

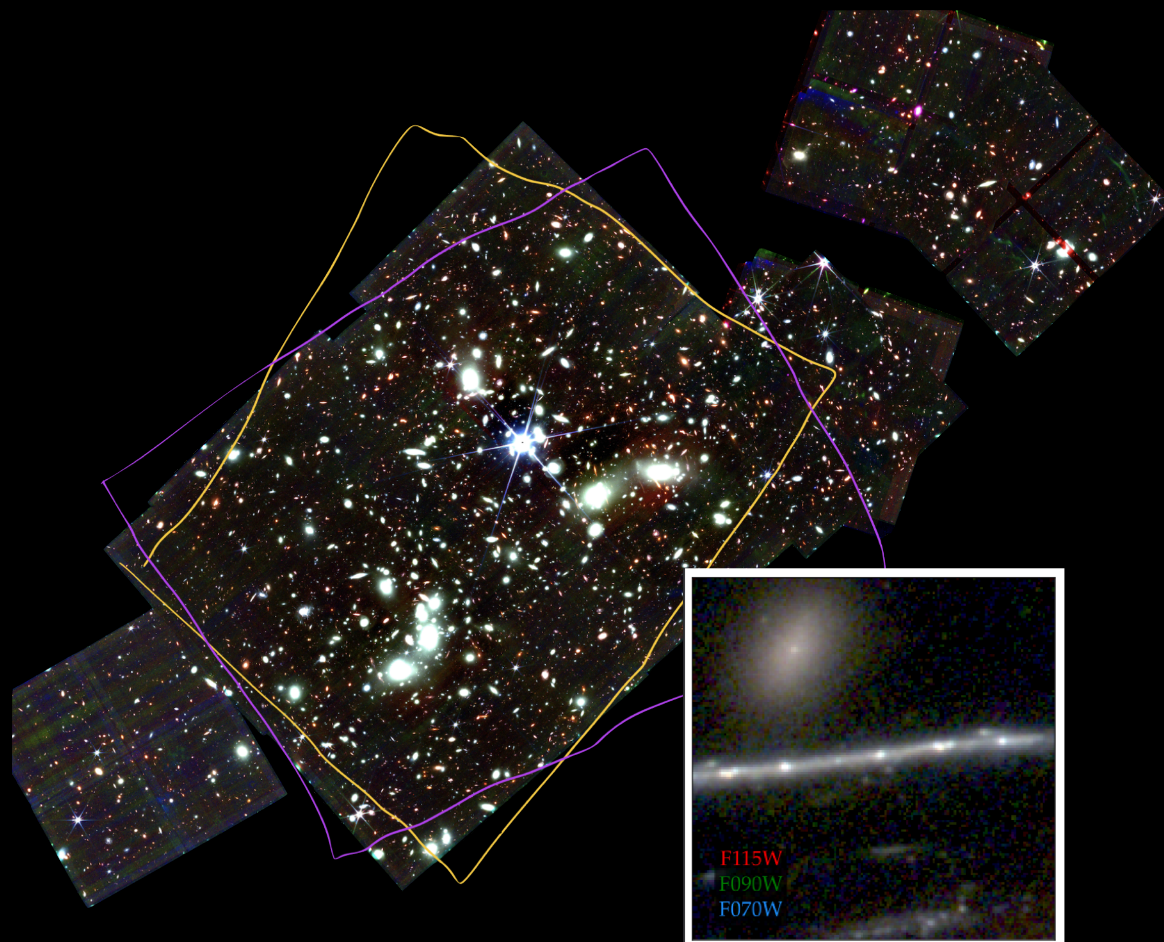

z~1100
400, 000 yrs
z~???
z~6
1bn yrs
Loeb+06
UMi
Draco
Leo II
Leo I
Sextans
Carina
LMC
SMC
Fornax
Sculptor
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day

All the Little Things

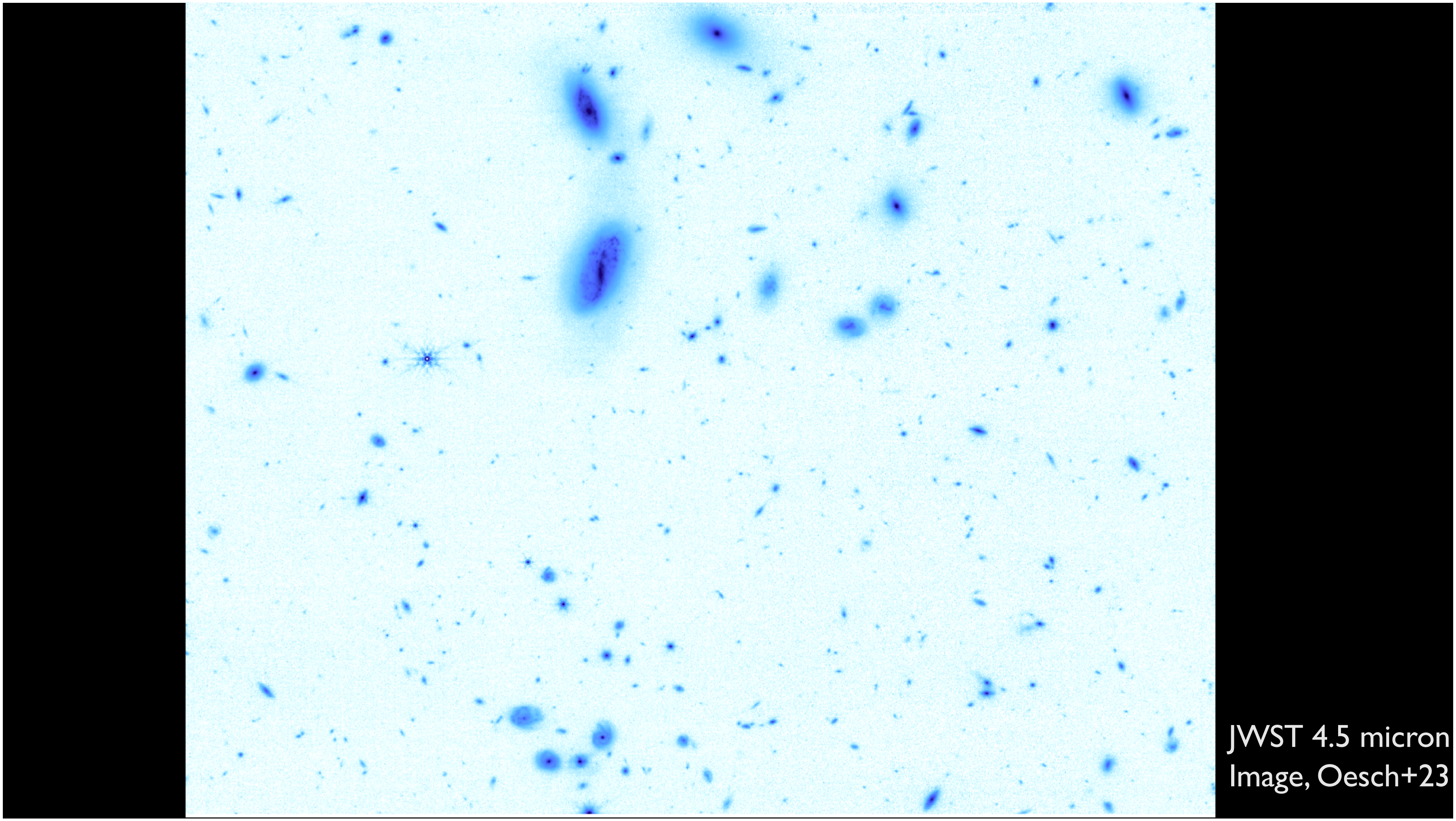
PIs: Naidu & Matthee
34 team-members from 23 institutions US/Europe

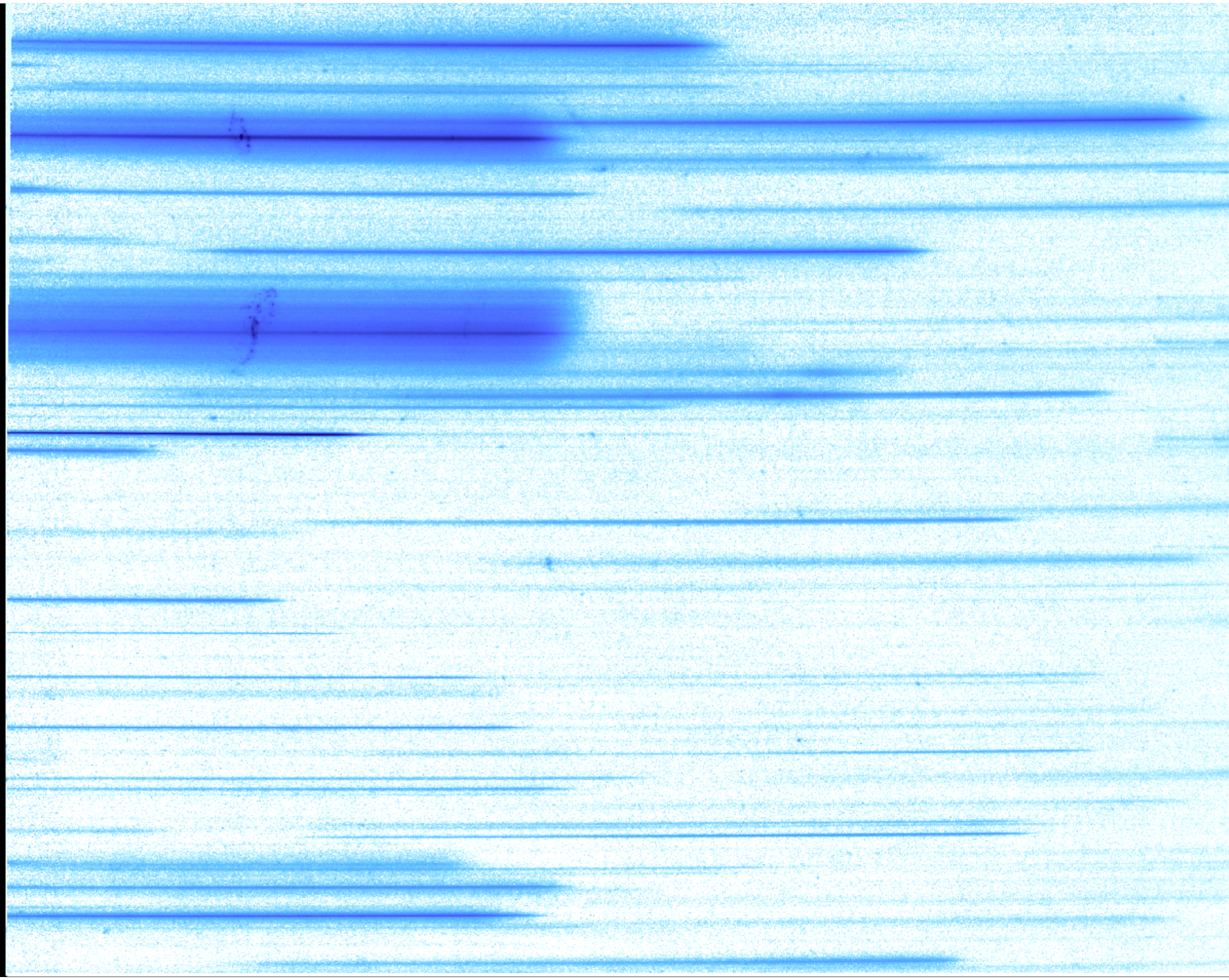
~50 hr JWST spectra + imaging over Abell 2744

Deepest grism spectra till date (27hrs!)



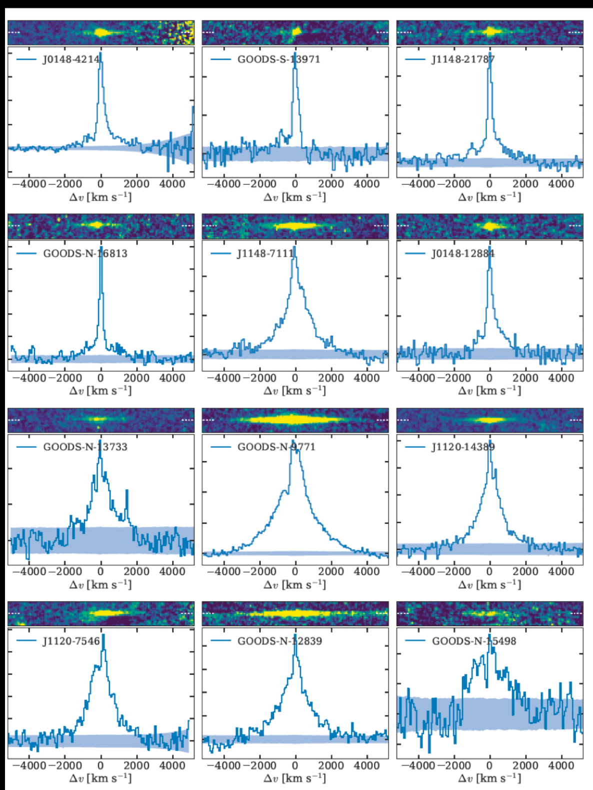
z~4 galaxy magnified 50x

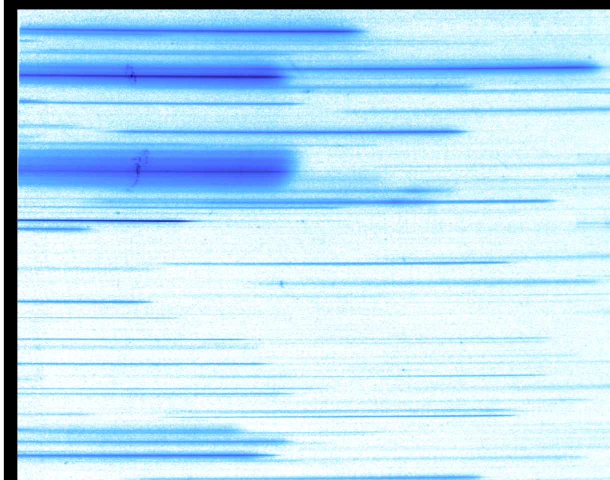

JWST 4.5 micron
Image, Oesch+23

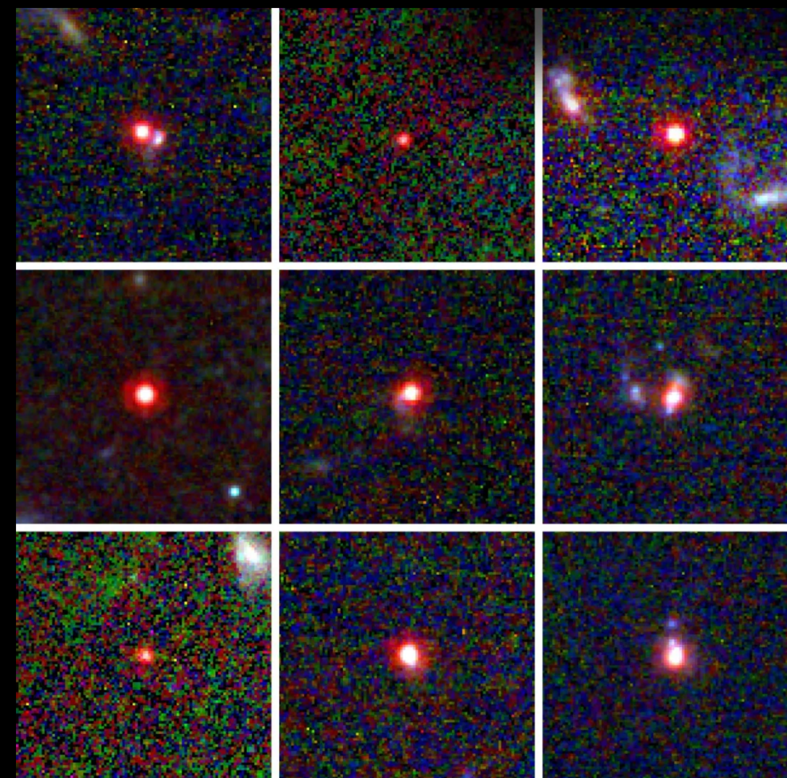


JWST 4.5 micron
grism spectra

Little Red Dots found with NIRCam/grism





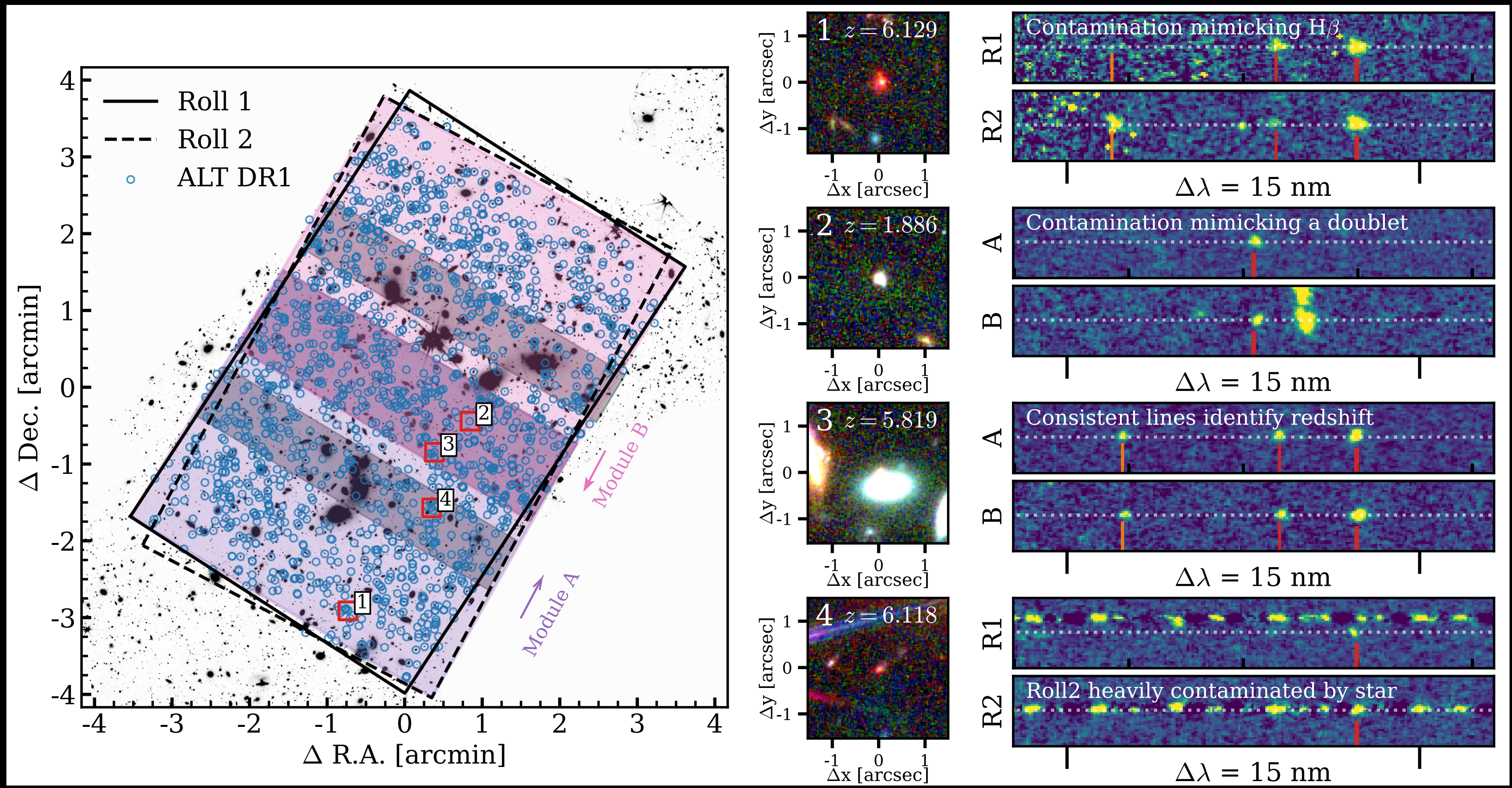


Matthee, Naidu+24

Quanta Magazine's "The Biggest Discoveries in Physics, 2023"

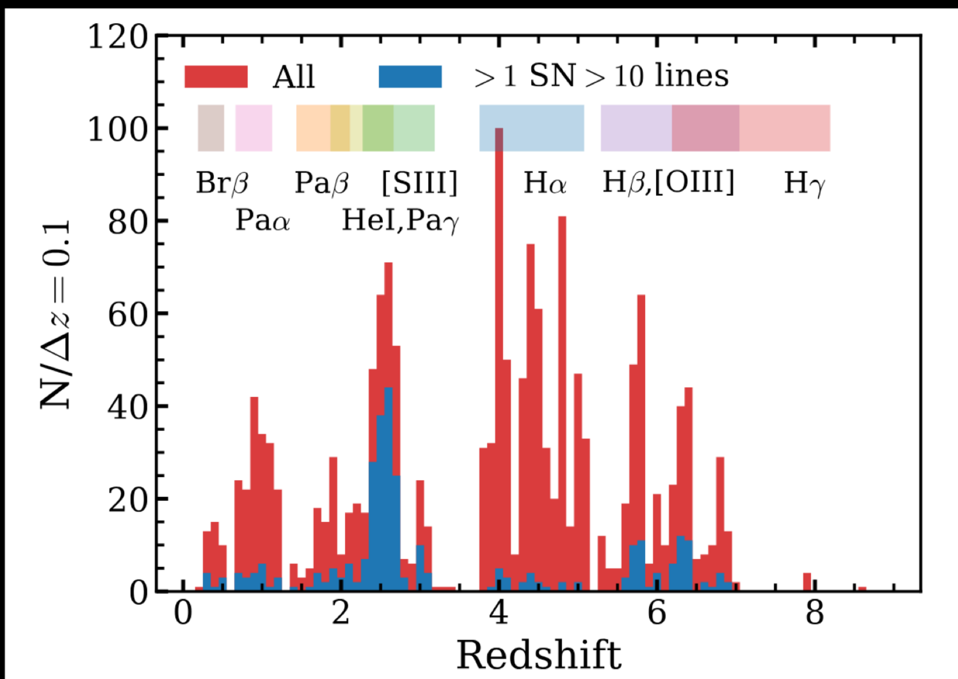
All the Little Things: Survey Design

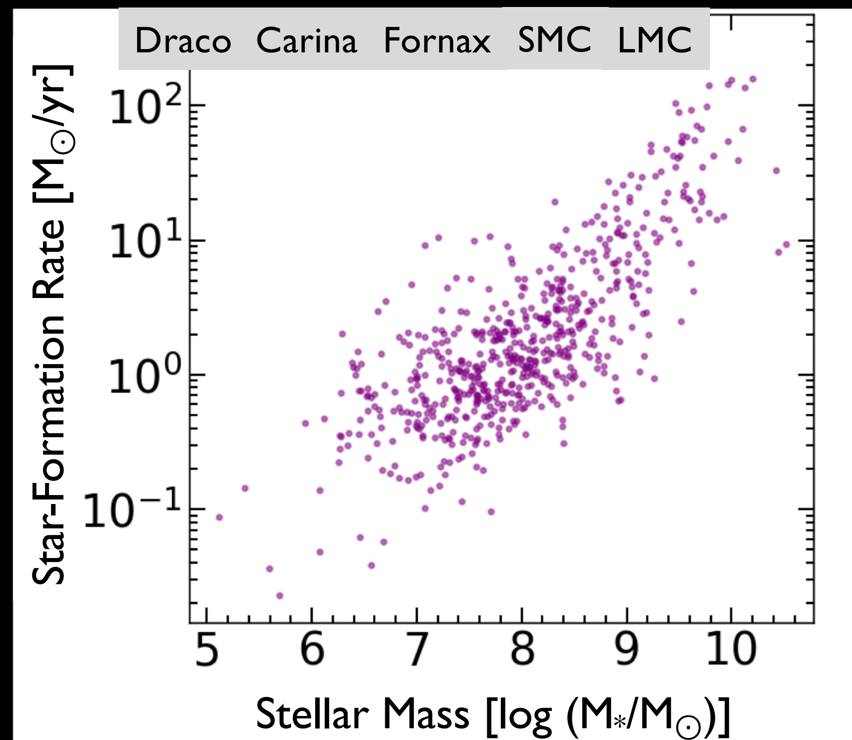
- Deepest grism survey till date
- Required several technical innovations such as the "butterfly mosaic"



Yield

>500 ultra-faint (~0.1-10% L*) galaxies in the EoR





~1000 <SMC-mass galaxies in sample, tripling the JW archive

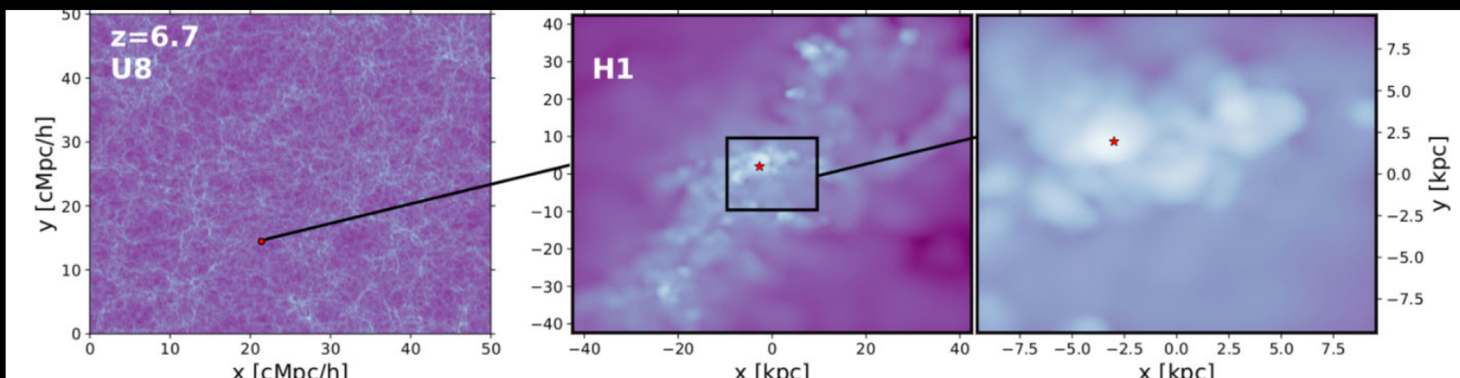
Metal-poor (perhaps metal-free?) stars

- Very first Pop-III stars at z>15 need 100m telescope on the moon (mag~40) e.g., Schauer+20

Ryan MacDonald

Metal-poor (perhaps metal-free?) stars

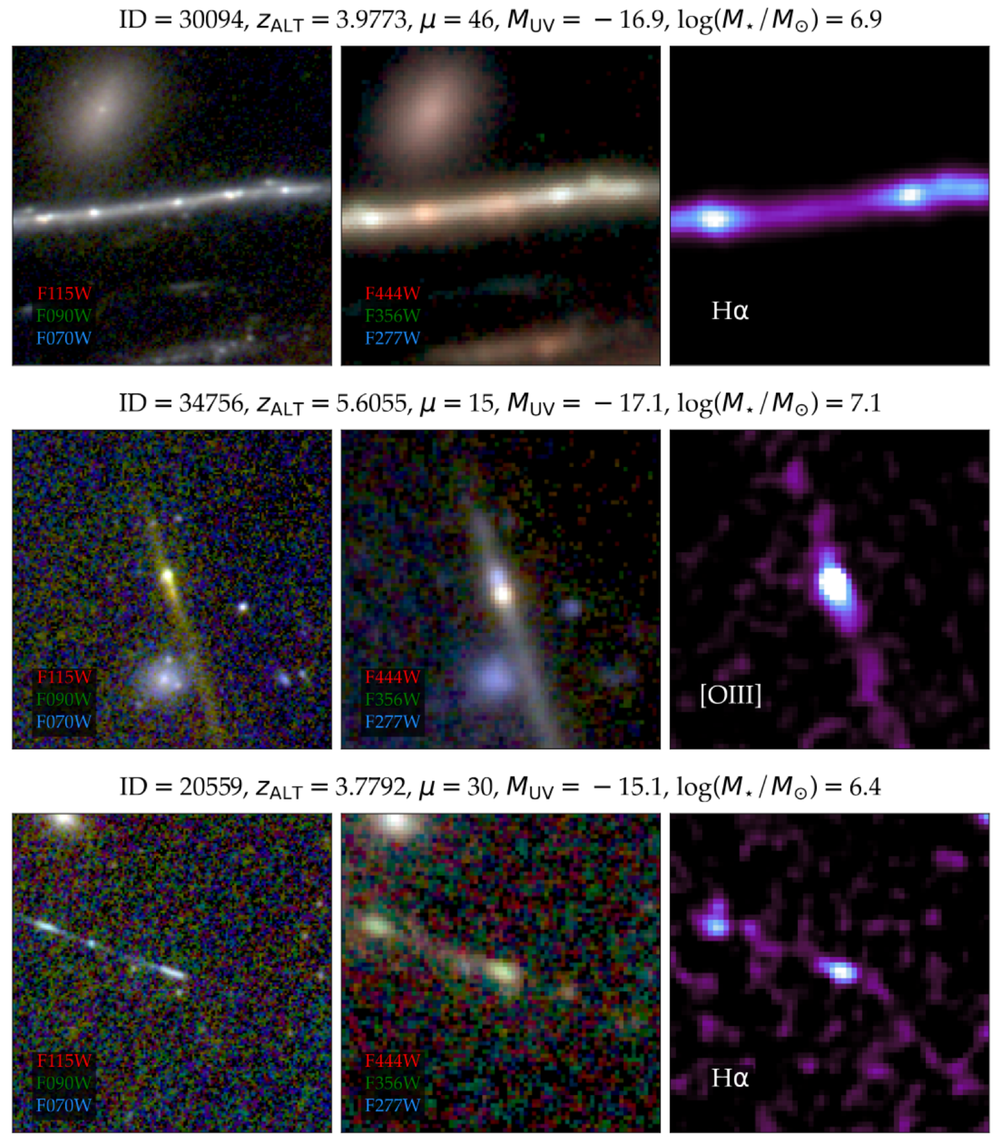
- Very first Pop-III stars at z>15 need 100m telescope on the moon (mag~40) e.g., Schauer+20
- But…in cutting-edge simulations, Pop-III star-formation possible out to z~6-7 e.g., Venditti+23,+24, Katz+23



Venditti+23

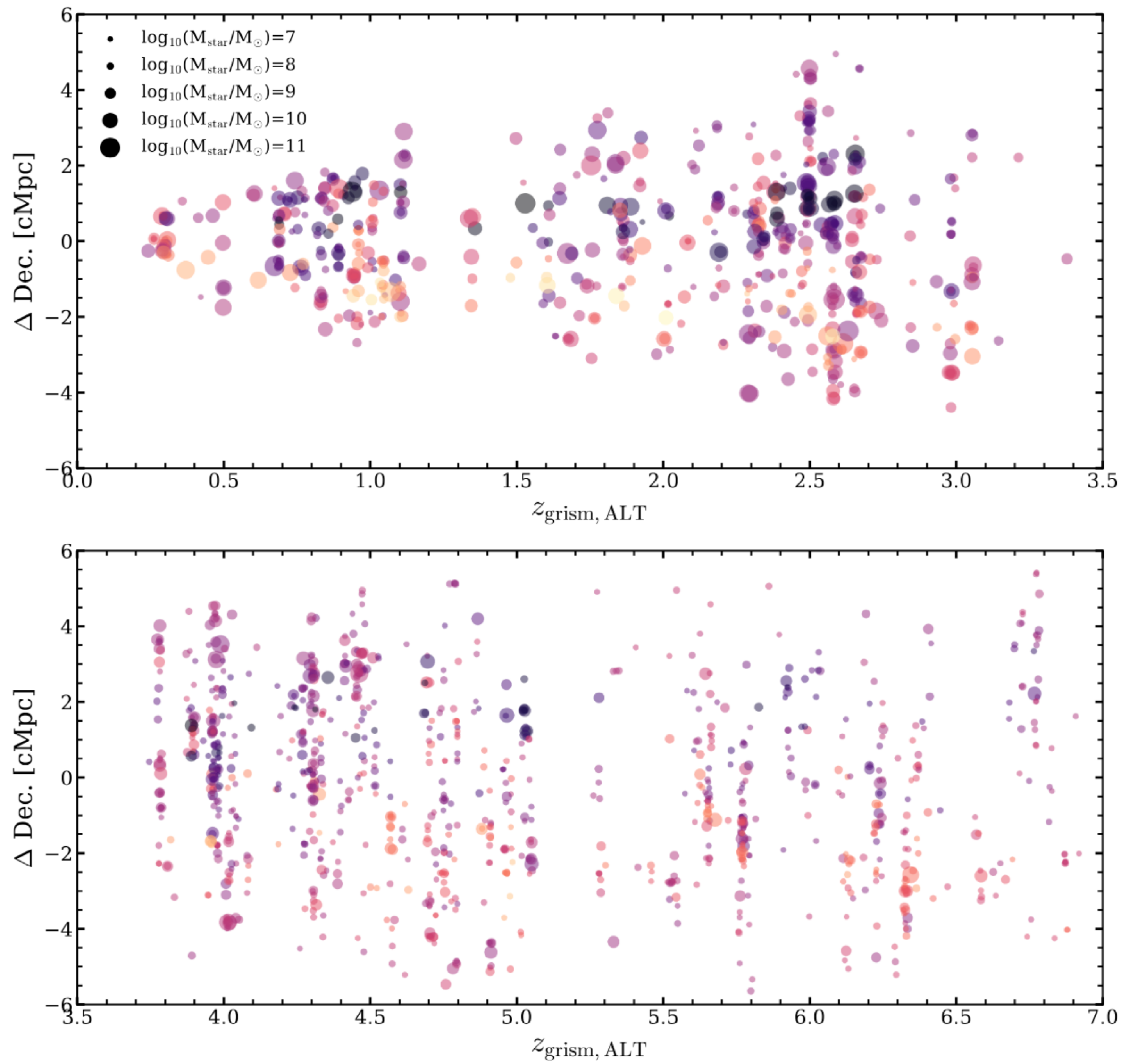
ALT's lensed arcs

- Spatially resolved spectroscopy of extremely magnified objects
- Search for metal-poor clumps
- Inventory ionizing photons



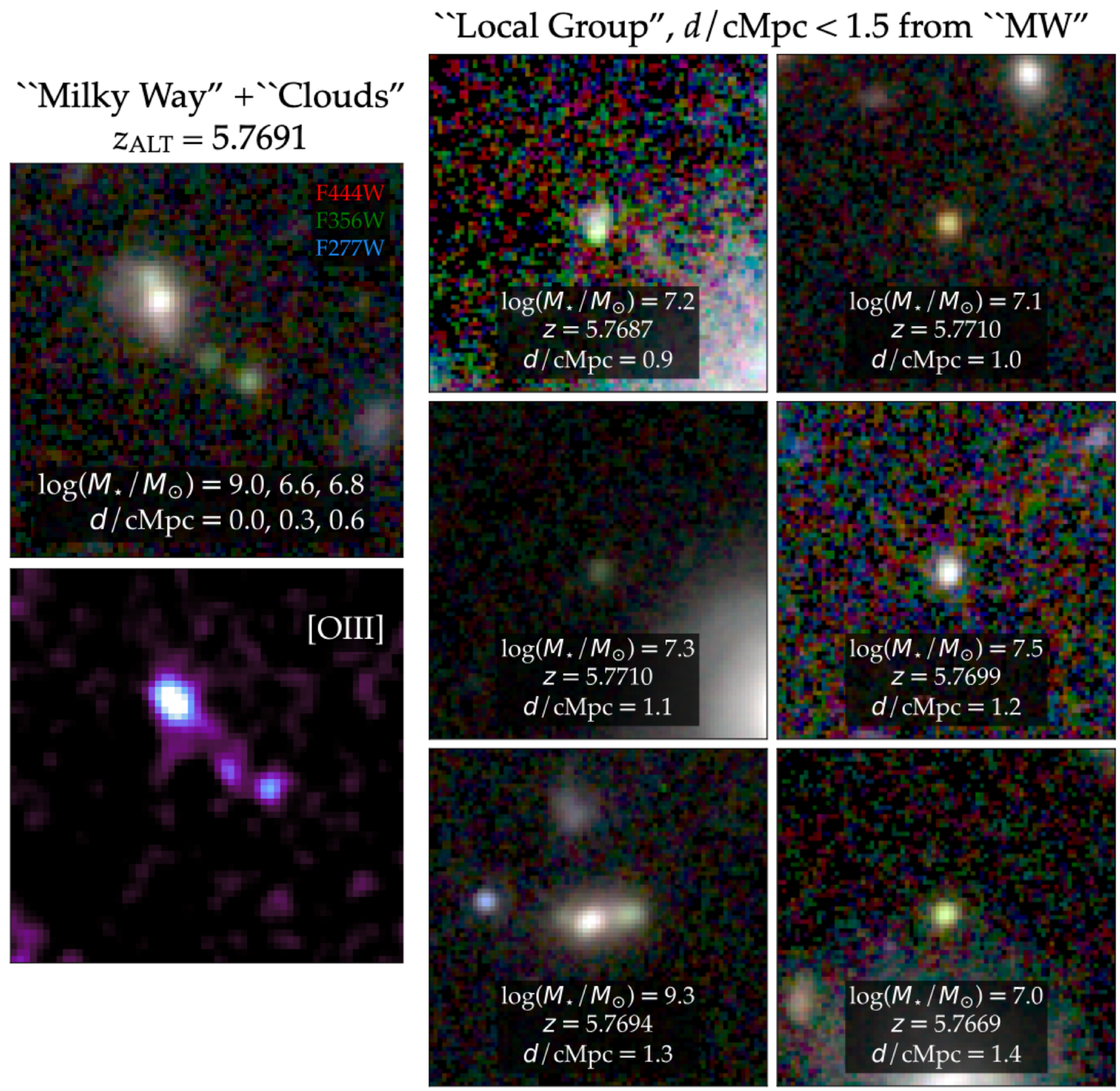
Large-scale environment

- Protoclusters
- Local/global overdensities

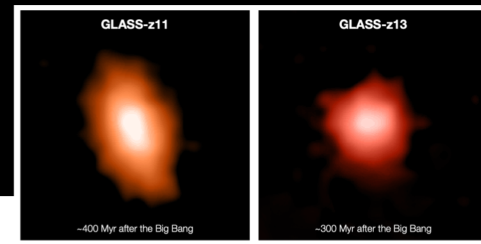


Small-scale environment

- Full inventory of satellite systems…but at high-z!



Luminous galaxies at z>10

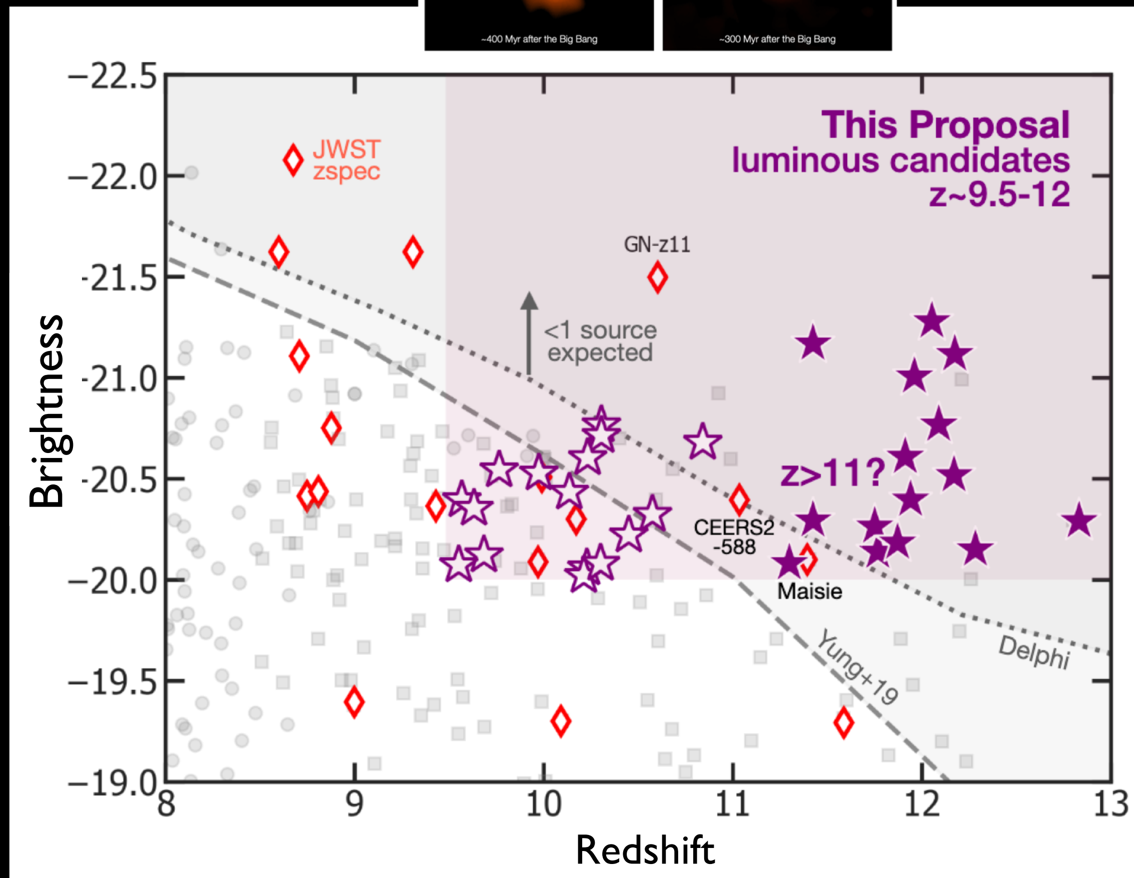


Naidu+22

- *Mirage or Miracle? Spectroscopic Confirmation of Remarkably Luminous Galaxies at z>10* (PIs: Naidu & Oesch)

If these candidates are confirmed spectroscopically, and indeed two $z \approx 10$–12 candidates lie awaiting discovery in every ~ 50 arcmin^2 extragalactic field, it is clear that JWST will prove highly successful in pushing the cosmic frontier all the way to the brink of the Big Bang.

Naidu+22



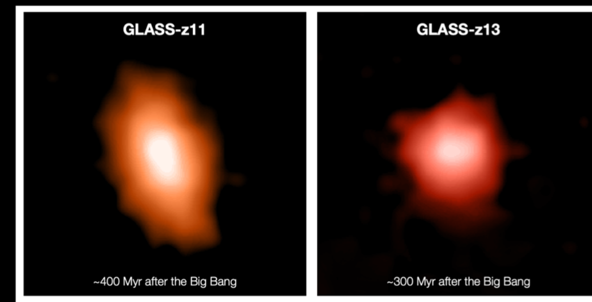
Primary Targets: ~15 extremely bright galaxies at z>11

1920: do other galaxies exist?
2020s: a final expansion of the cosmic frontier to the brink of the Big Bang

Loeb+06

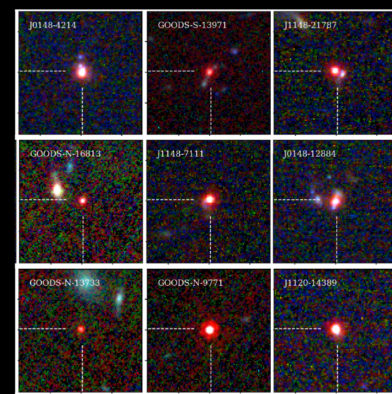
Big Bang | Dark Ages | Cosmic Dawn | Reionization | Present Day

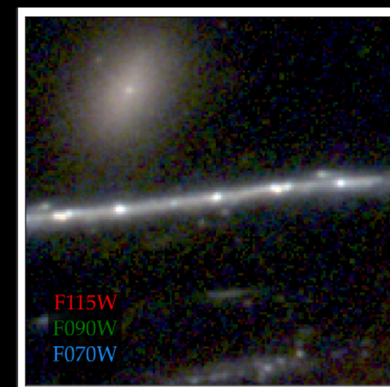
Summary

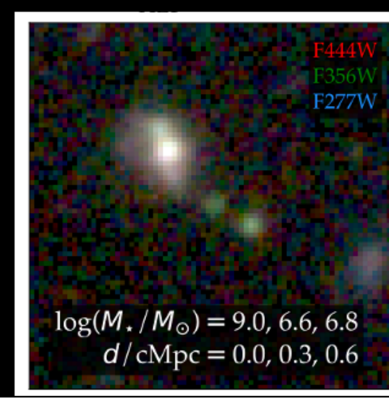


- *JWST* is revealing epochs of the Universe we've never seen before.
  - Remarkably luminous z>10 galaxies
  - An abundance of supermassive black holes
  - Extremely metal-poor (metal-free?) galaxies
  - The sources of cosmic reionization
  - Dwarf galaxies at cosmological distances

- A golden era for early universe astronomy beckons!







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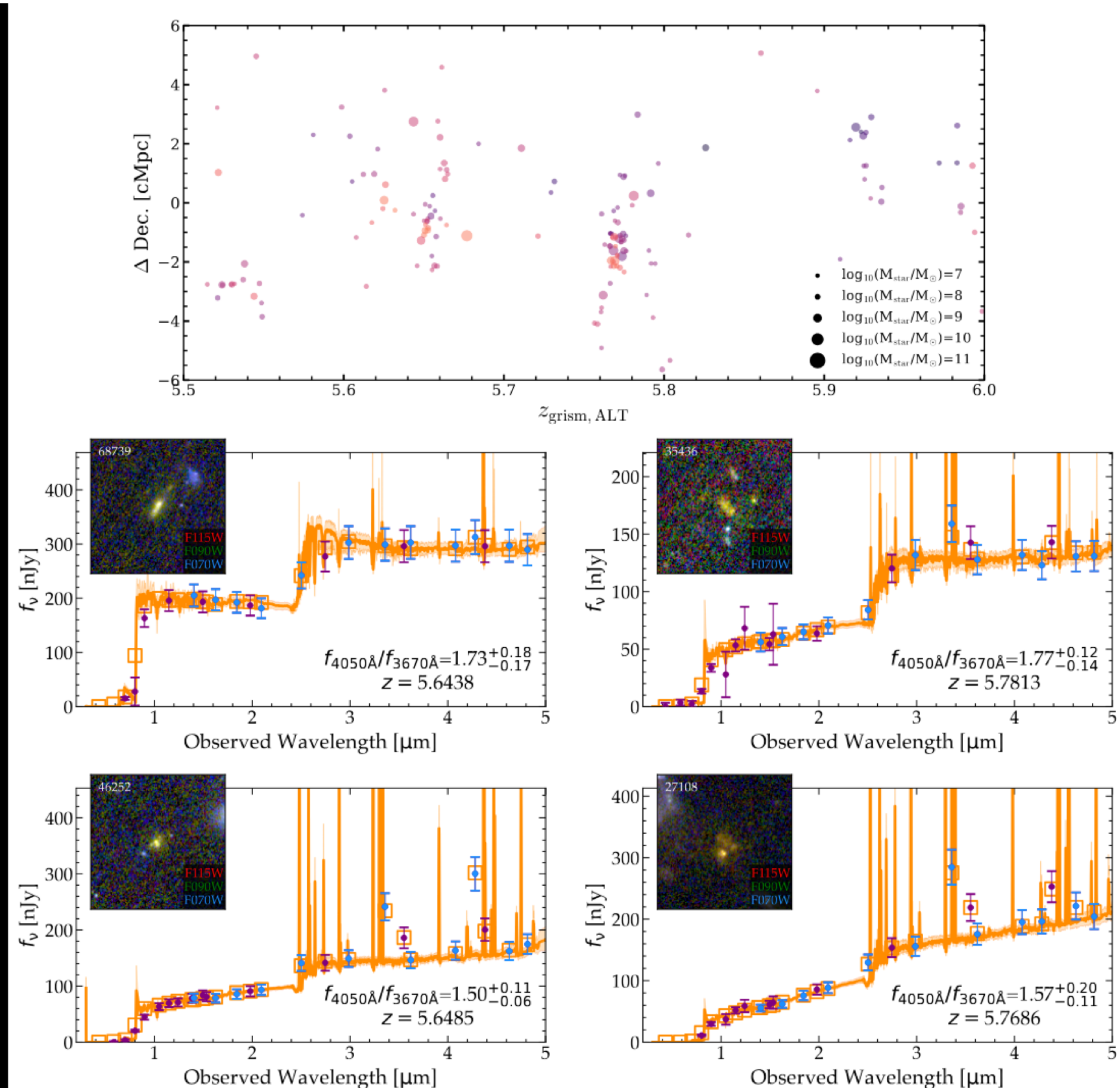
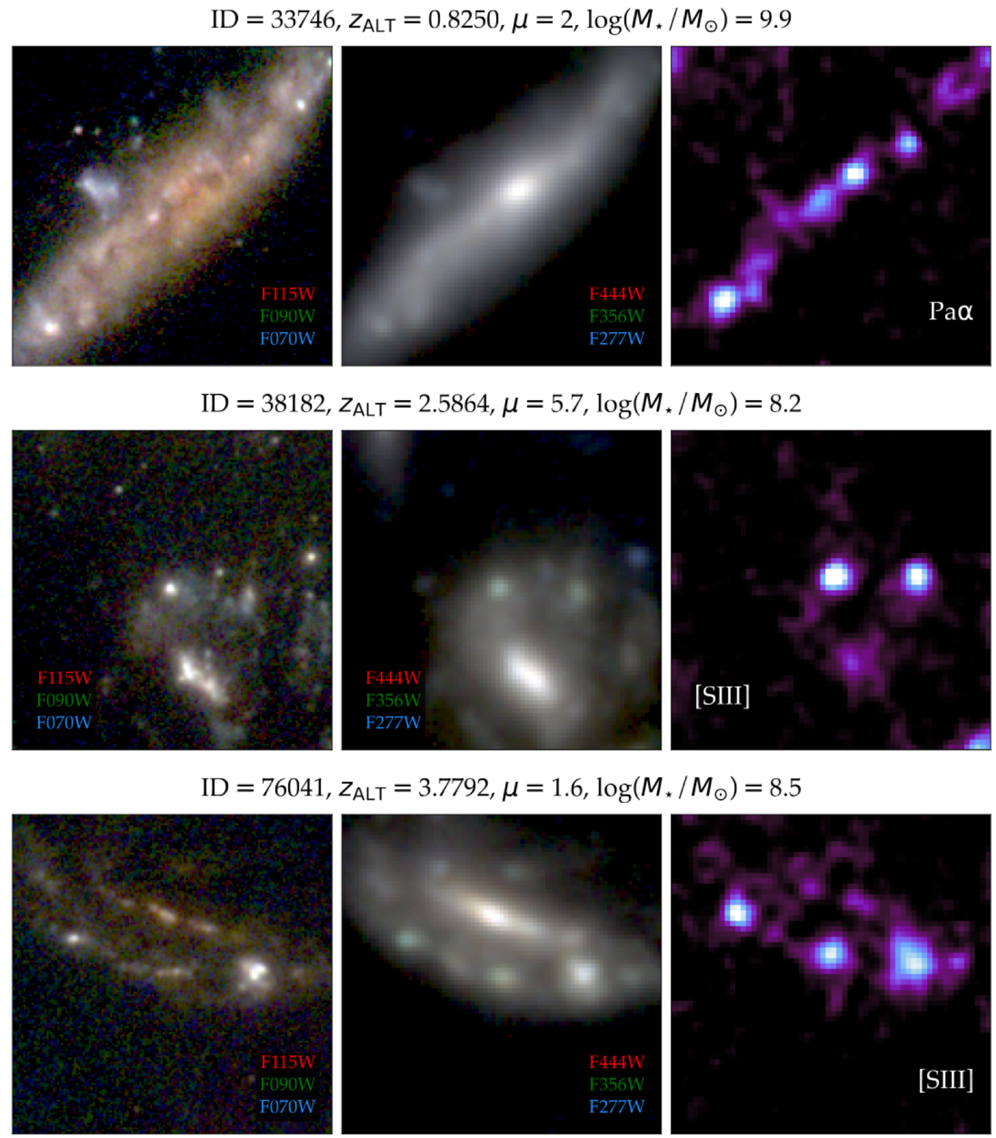
Galaxy-Environment Connection



Star-formation maps



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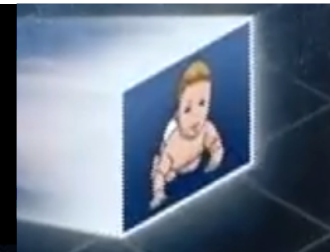
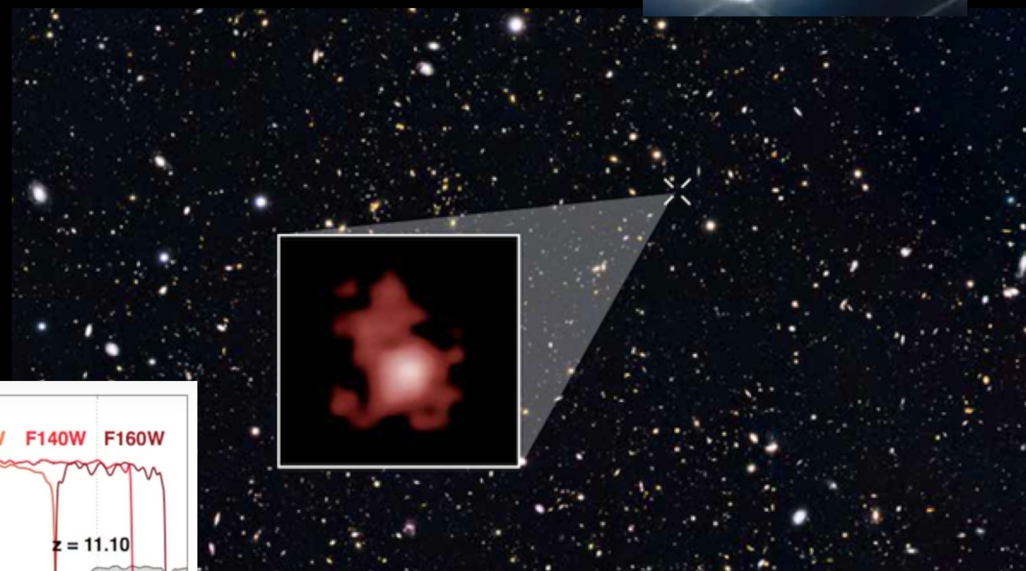
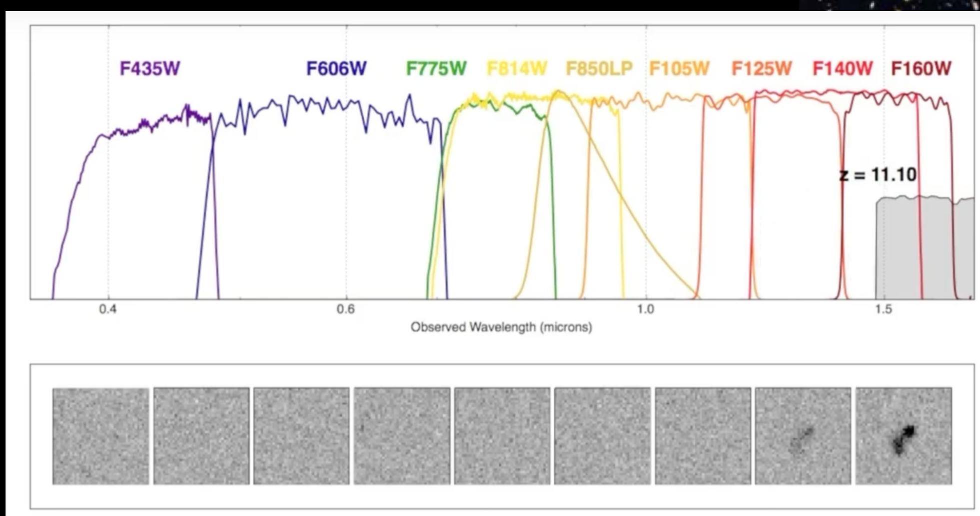
The search for the first galaxies



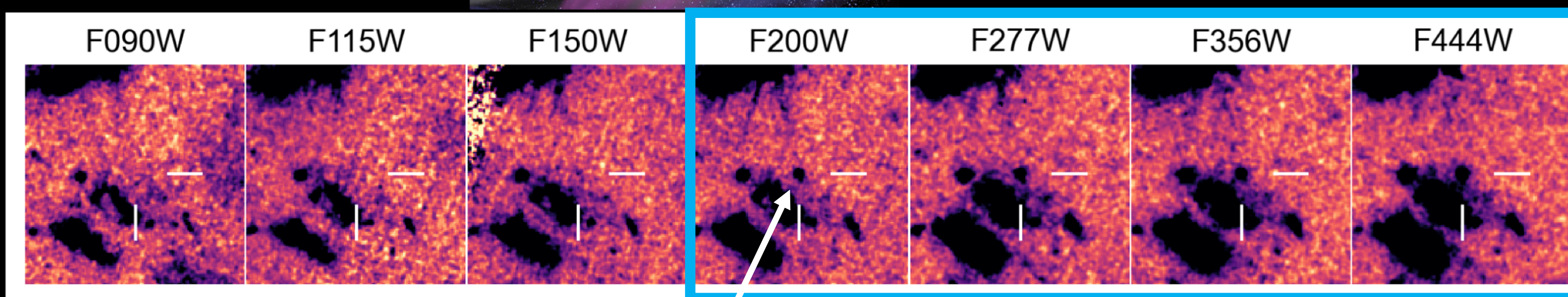
- HST record-holder: z~11 (~400 mn years after the Big Bang, ~billion solar masses, Oesch+16)



GNz11 discovered with the *Hubble Space Telescope*



Enter *JWST*…



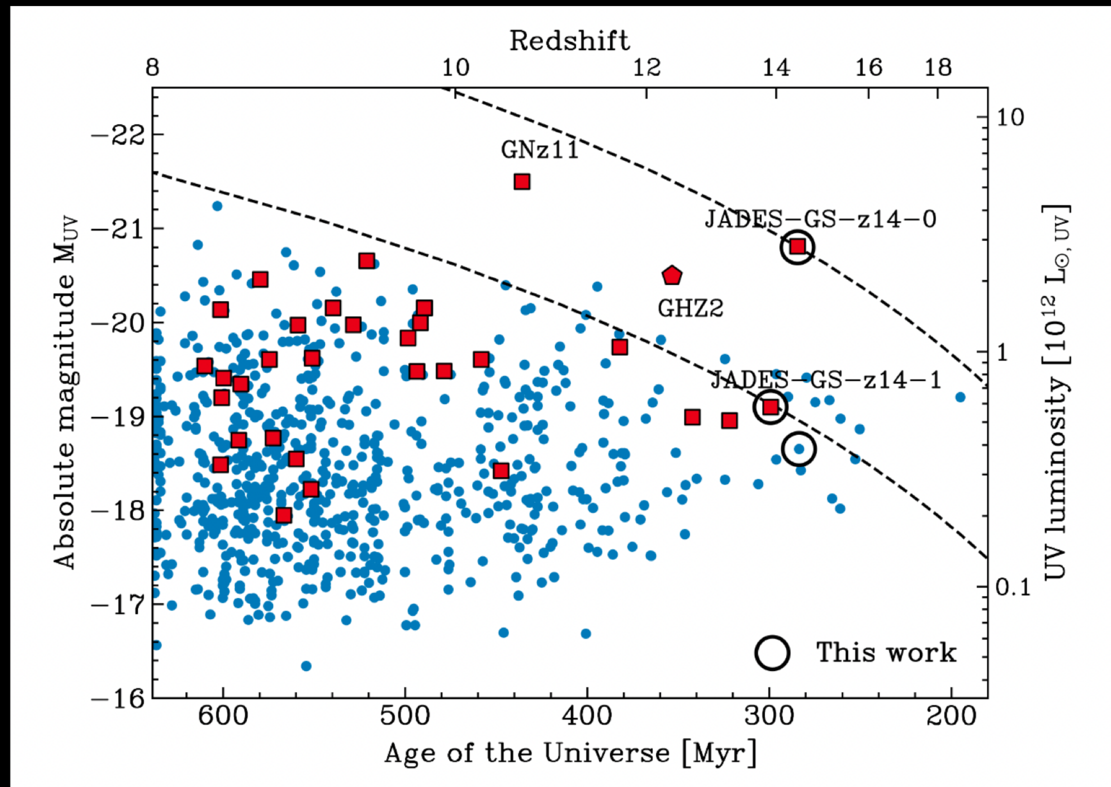
z~12.5 galaxy

Completely invisible to any prior facility

Naidu+22a

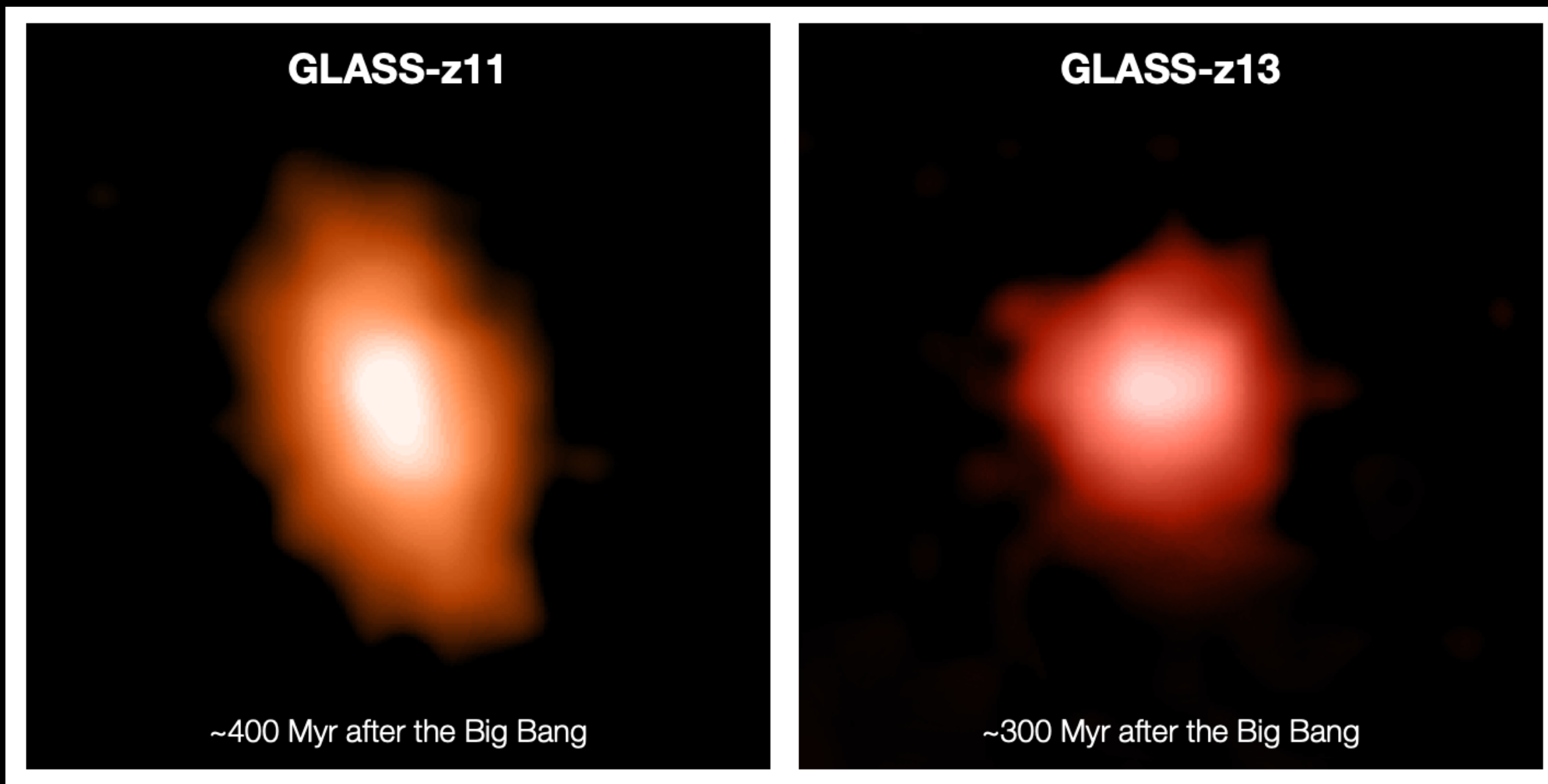
State of the (z>10) Union

- ~100s of robust z>10 photometric candidates
  Naidu+22a,b, Bouwens+23, Finkelstein+23, Casey+23, Hainline+24, Donnan+24, …
- ~10 galaxies confirmed spectroscopically
  Castellano+24, Zavala+24, Fujimoto+23, Wang+23, Curtis-Lake+23, Bunker+23, …



Carniani+24; JADES

Remarkably Luminous Galaxies at z>10



Naidu+22a, Castellano+22

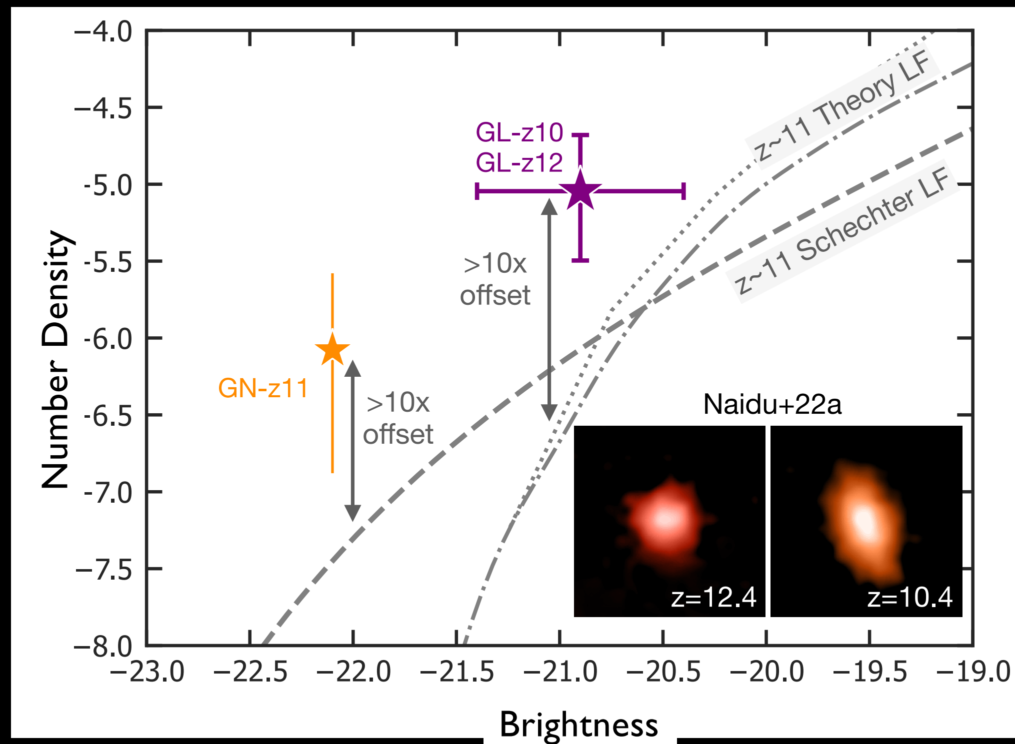
Too many bright galaxies at very early times?

- Expectation

- Reality

Too many bright galaxies at very early times?

- Predicted N=0 galaxies at z>10 from combined area of JWST surveys Mason+15, Williams+18, Tacchella+18
- A "too bright to be" problem? Naidu+22b



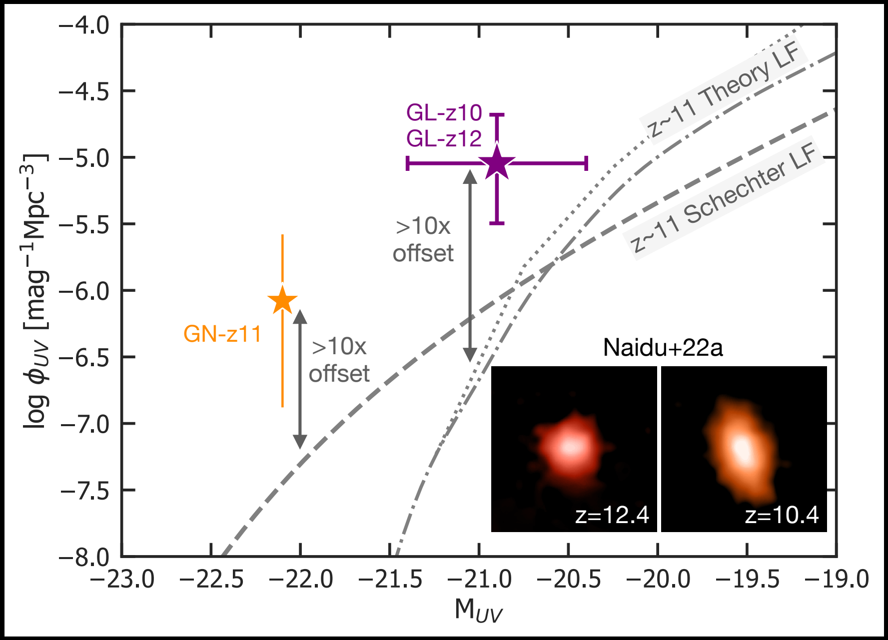
Bouwens+23, Casey+23, Castellano+23, Donnan+24, Finkelstein+23,+24, Fujimoto+23, Harikane+23, Wang+24, …

Too many bright galaxies at very early times?

- Modifies the simple coupling between dark matter and baryons.

$$SFR(M_{halo}, z) = \varepsilon(M_{halo}) \quad x \quad dM_{halo}/dt$$

Redshift-Independent
Star-Formation Efficiency
e.g., Tacchella+13,18, Naidu+20, Mason+15, 23, Shen+23, Sun+23



Solutions for “too bright/big to be”

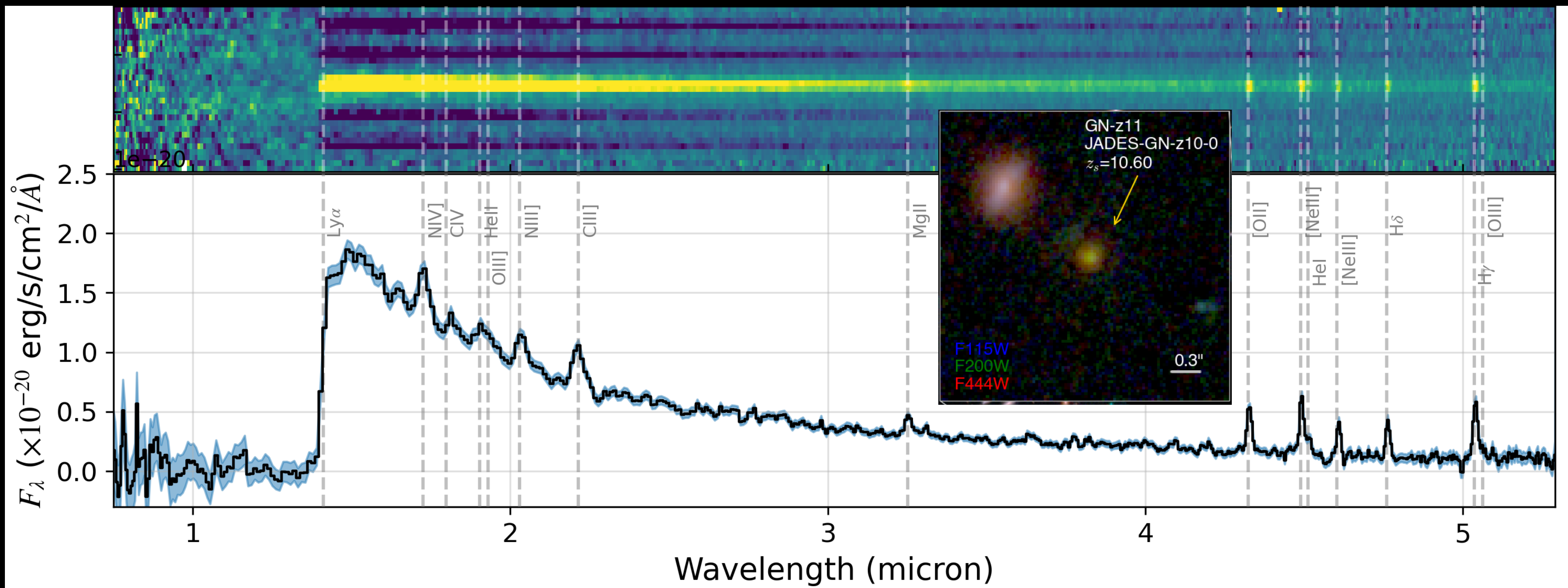
- *Boost brightness with baryons*
  - Early black holes (i.e., accretion disks)
  - Stochastic star-formation (burstiness, dust-clearing cycles, …)
  - Feedback-free starbursts
  - IMFs

- *Tweak cosmology/dark matter*
  - Early dark energy
  - Primordial black holes
  - …

e.g.,
Riaz+22
Ziparo+22
Ferrara+22
Steinhardt+22
Boylan-Kolchin 22
Lovell+22
Mirocha+22
Mason+23
Shen+23
Pacucci+23
Menci+23
Sun+23
Dekel+23
Boyuan & Bromm 23
Sun+24
Adler+24
Feldmann+24
Shen+24
…

Pieces of the z>10 puzzle: GN-z11

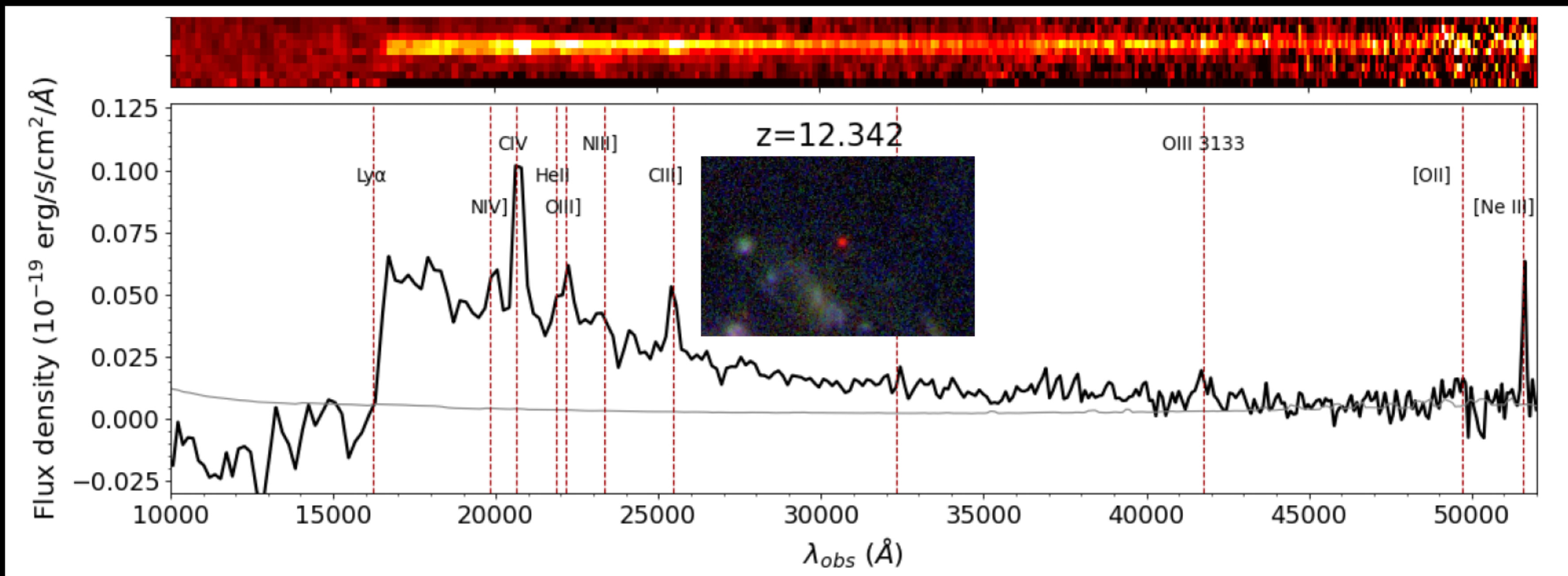
Oesch+16
Tacchella+23
Bunker+23



- First luminous galaxy with spectrum showed spectacular features (e.g., super-solar Nitrogen abundance? extreme gas density?)
- Starburst? Black Hole? Globular Cluster Formation? Tidal Disruption Event?...

Bunker+23, Maiolino+23, Senchyna+23, Belokurov & Kravstov 23, Charbonnel+23, Cameron+23, …

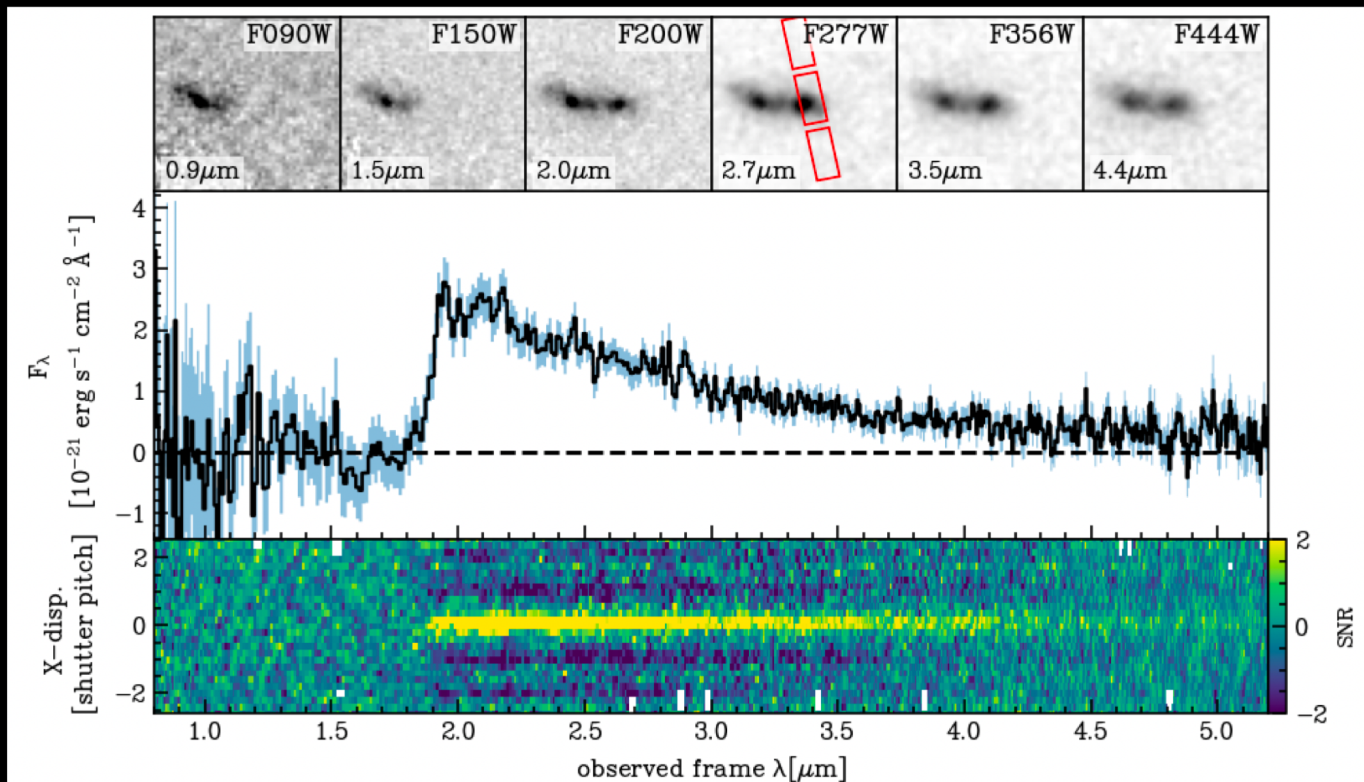
Pieces of the z>10 puzzle: GLASS-z12/GHz2



- Second spectrum also shows spectacular features (strong Nitrogen, exceptionally strong ionization field) Naidu+22, Castellano+22, 24, Zavala+24
- Starburst? Black Hole? Globular Cluster? Tidal Disruption Event?...

Bunker+23, Maiolino+23, Senchyna+23, Belokurov & Kravstov 23, Charbonnel+23, Cameron+23

Pieces of the z>10 puzzle:GS-z14-0

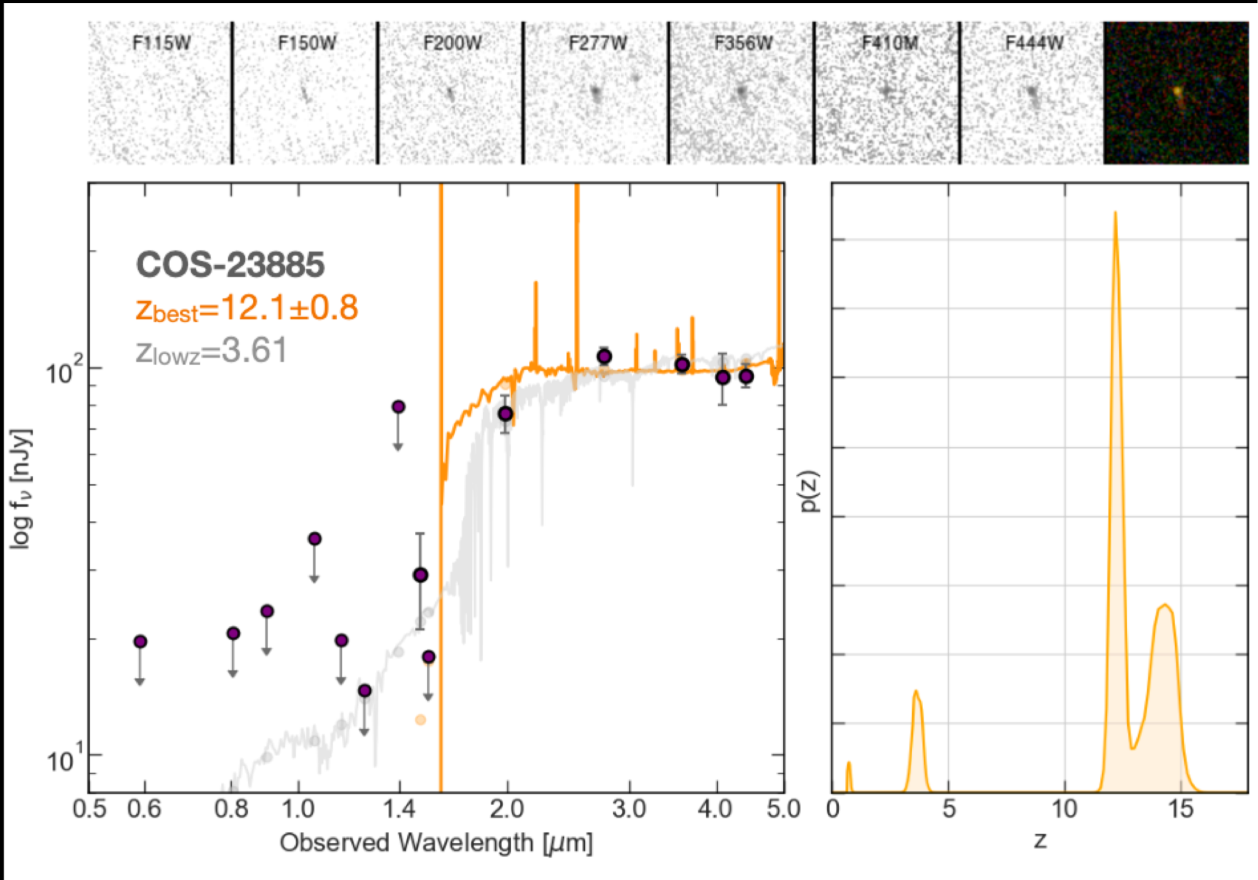


Robertson+24
Carniani+24
Helton+24

- Puzzling lack of strong UV emission lines (resolution?) + rest-optical emission?
- High escape fraction? Super-Eddington “blue monster”?... Ferrara+24, Carniani+24

Pieces of the puzzle: from 0 → 1 → 10

- Upcoming JWST program: *Mirage or Miracle? Spectroscopic Confirmation of Remarkably Luminous Galaxies at z>10* (PIs: Naidu & Oesch)



Primary Targets: ~15 extremely bright galaxies like these at z>11

Pieces of the puzzle: from 0 → 1 → 10

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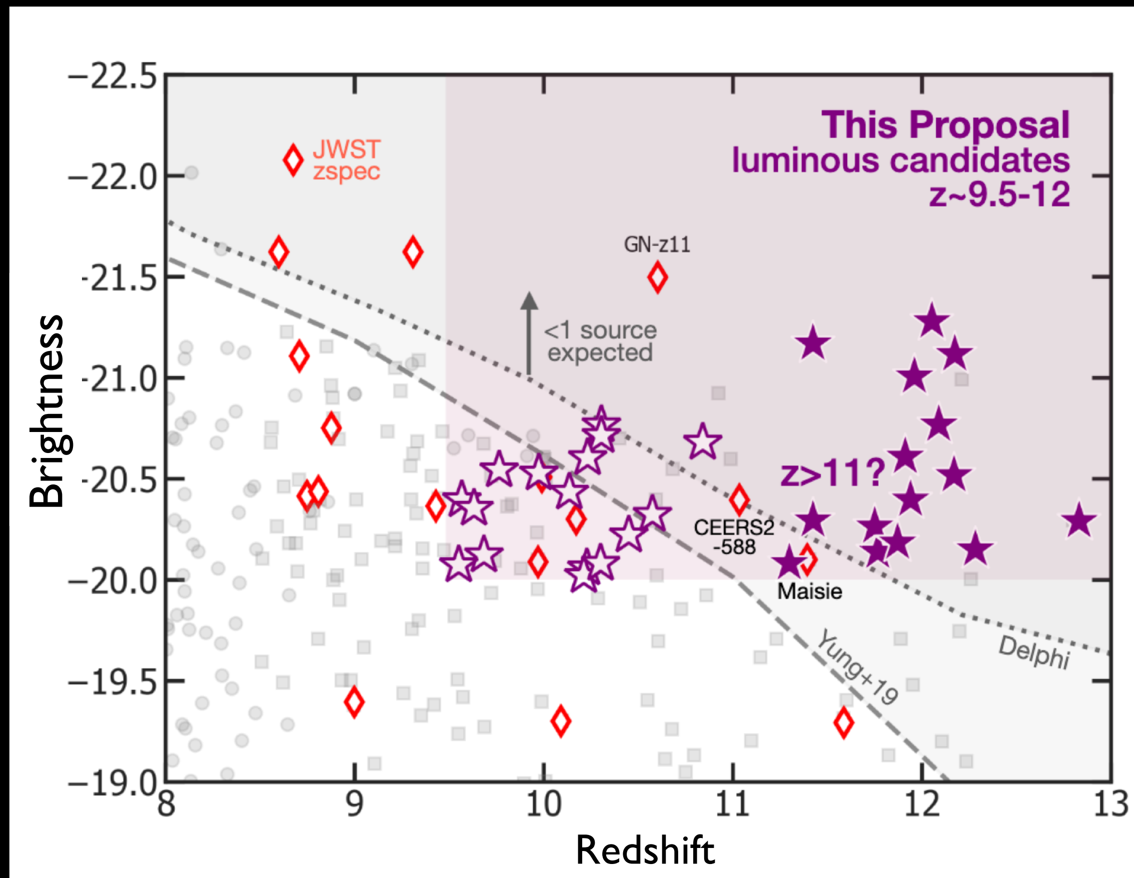

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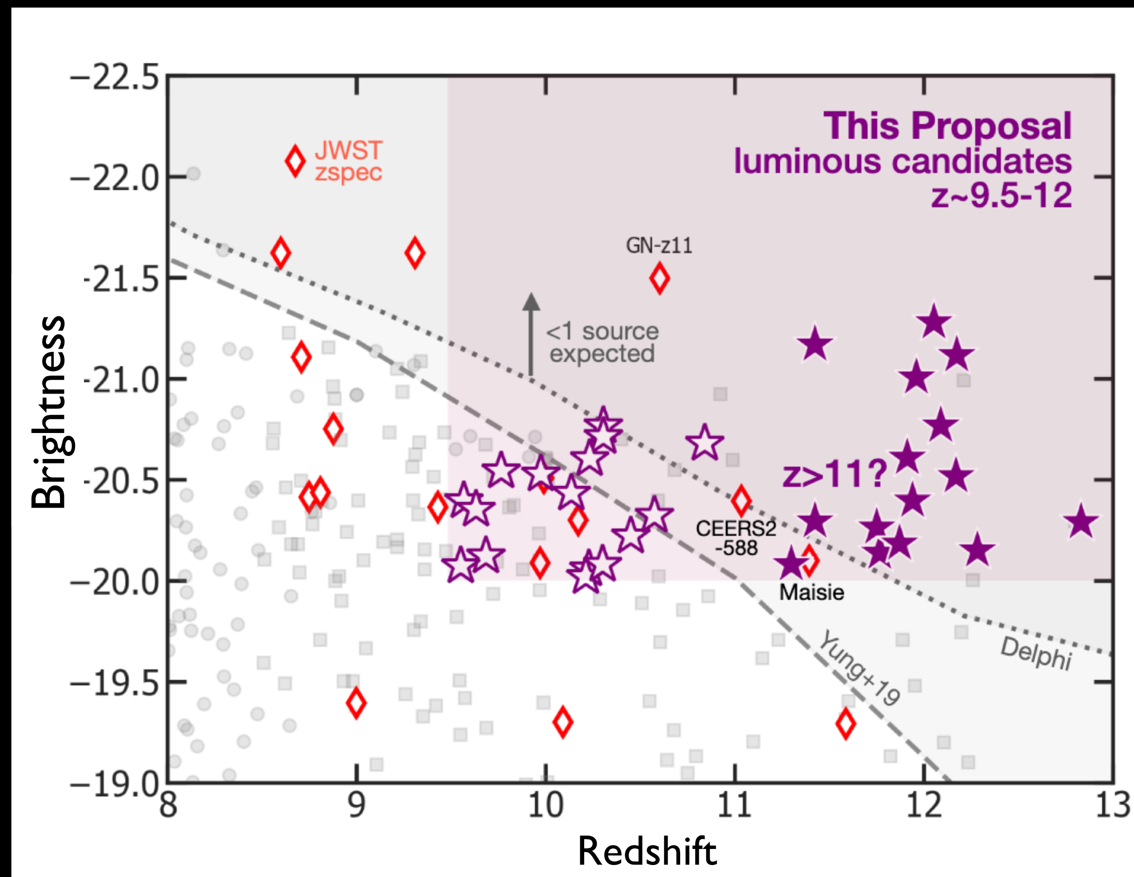
Pieces of the puzzle: from 0 → 1 → 10

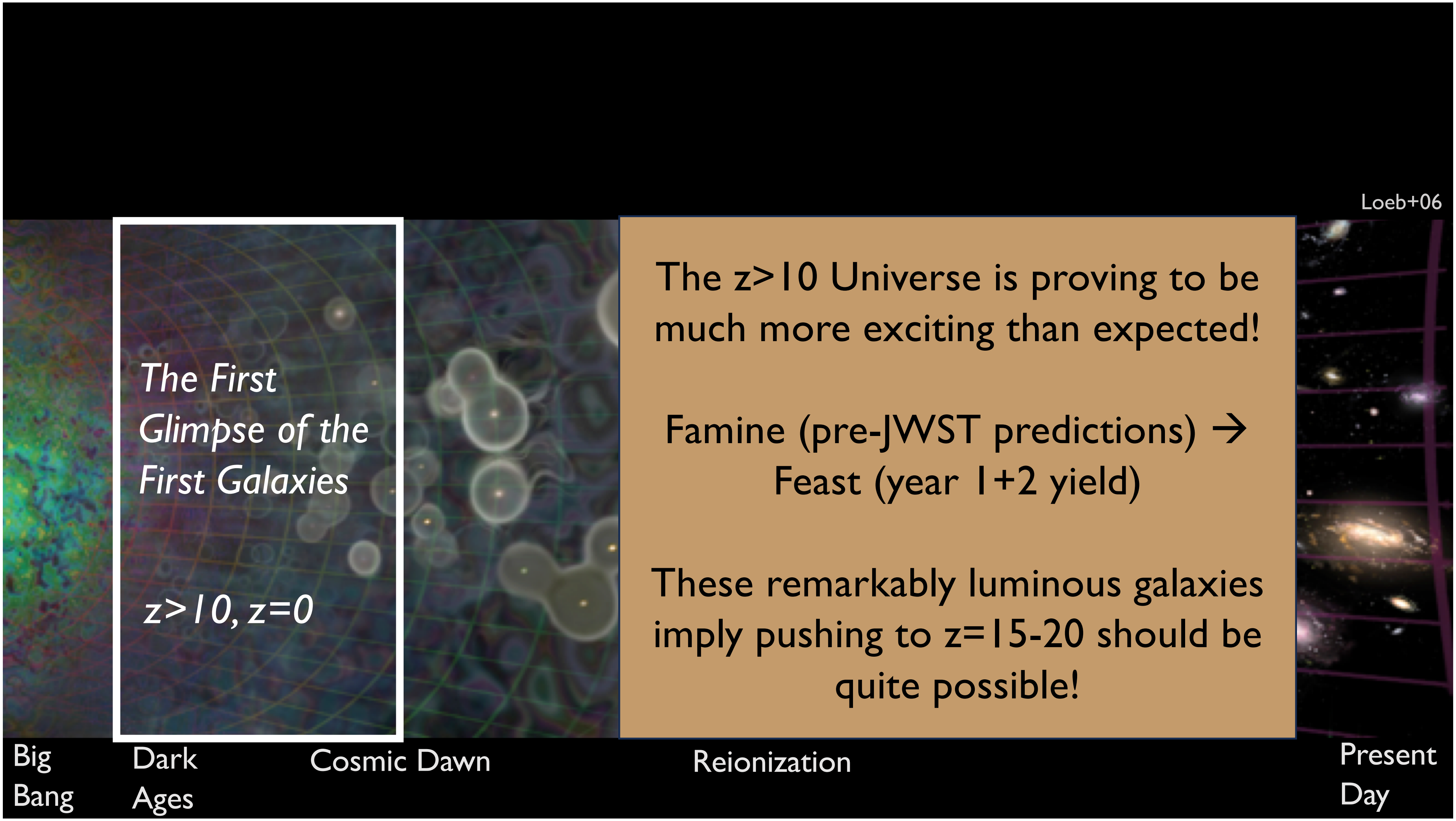
- Upcoming JWST program: *Mirage or Miracle? Spectroscopic Confirmation of Remarkably Luminous Galaxies at z>10* (PIs: Naidu & Oesch)

> If these candidates are confirmed spectroscopically, and indeed two $z \approx 10$–12 candidates lie awaiting discovery in every ~ 50 arcmin^2 extragalactic field, it is clear that JWST will prove highly successful in pushing the cosmic frontier all the way to the brink of the Big Bang.

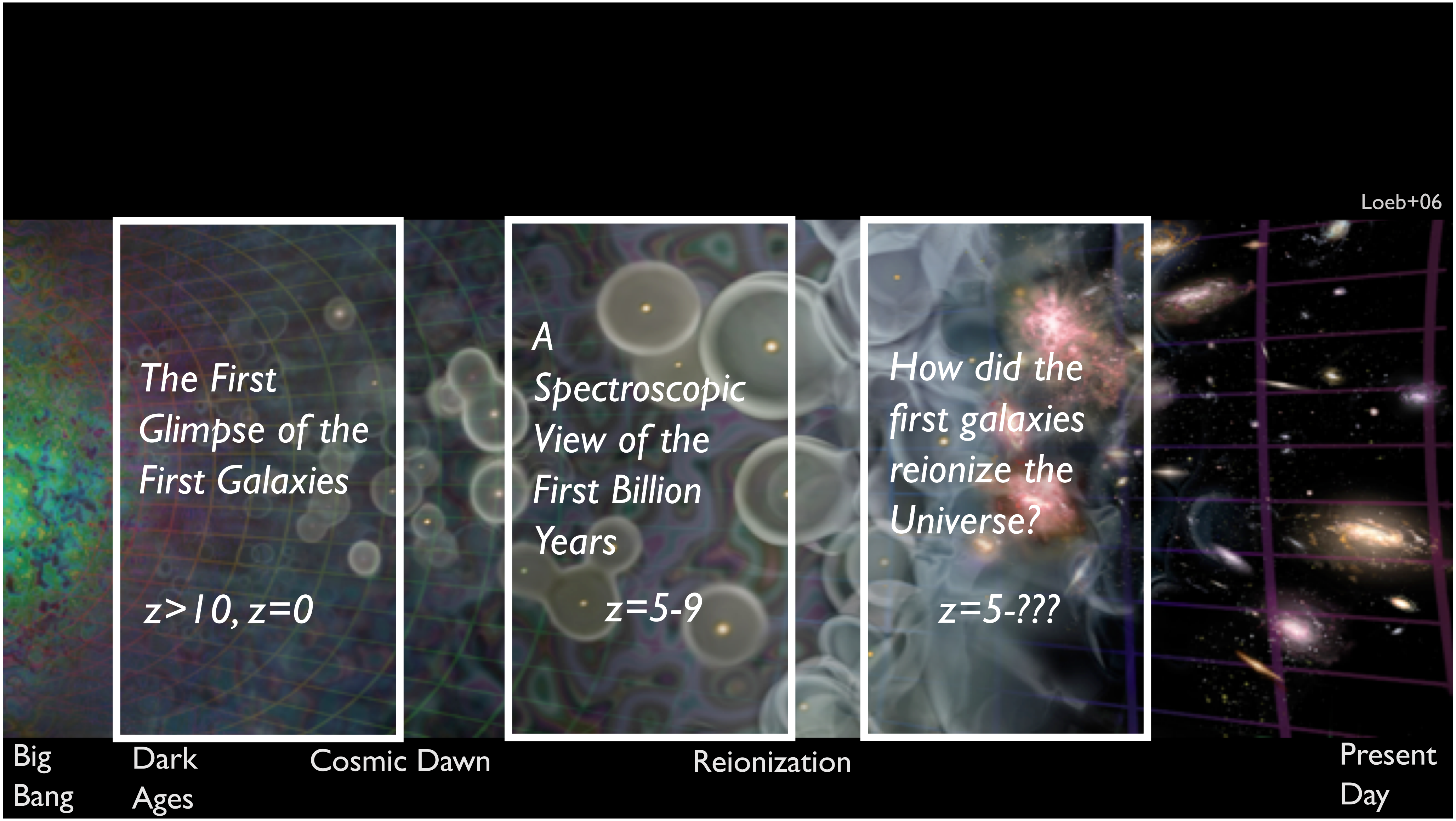
Naidu+22



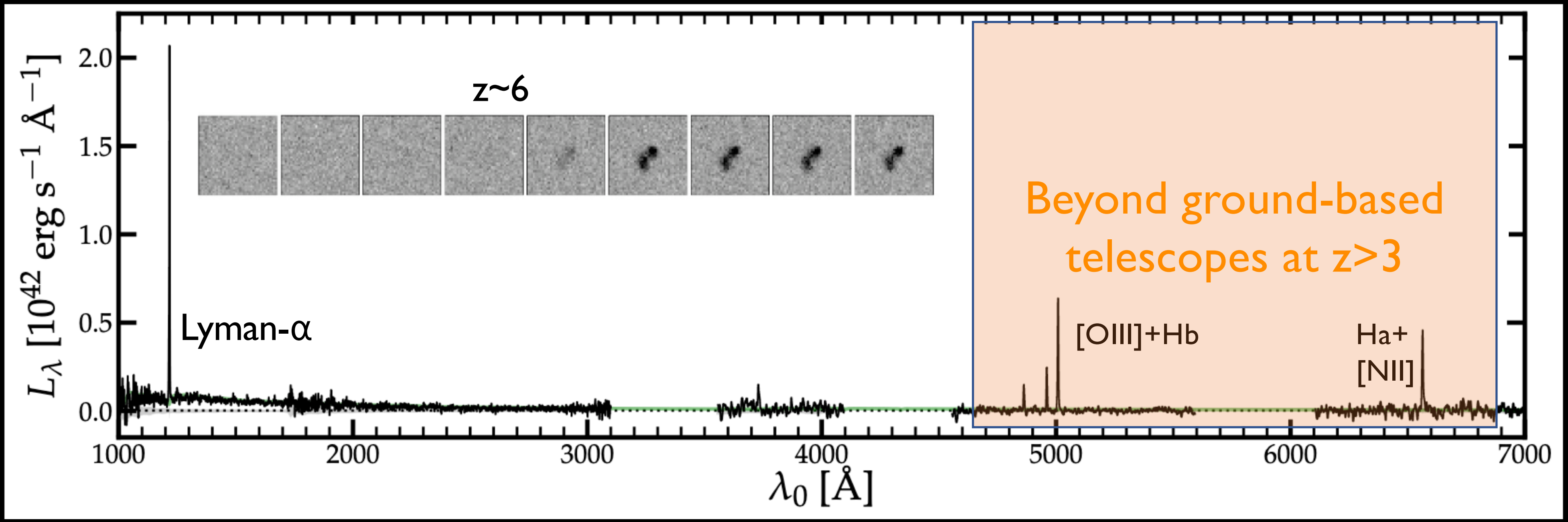
Primary Targets: ~15 extremely bright galaxies at z>11



Loeb+06
The First
Glimpse of the
First Galaxies
z>10, z=0
The z>10 Universe is proving to be much more exciting than expected!
Famine (pre-JWST predictions) → Feast (year 1+2 yield)
These remarkably luminous galaxies imply pushing to z=15-20 should be quite possible!
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day

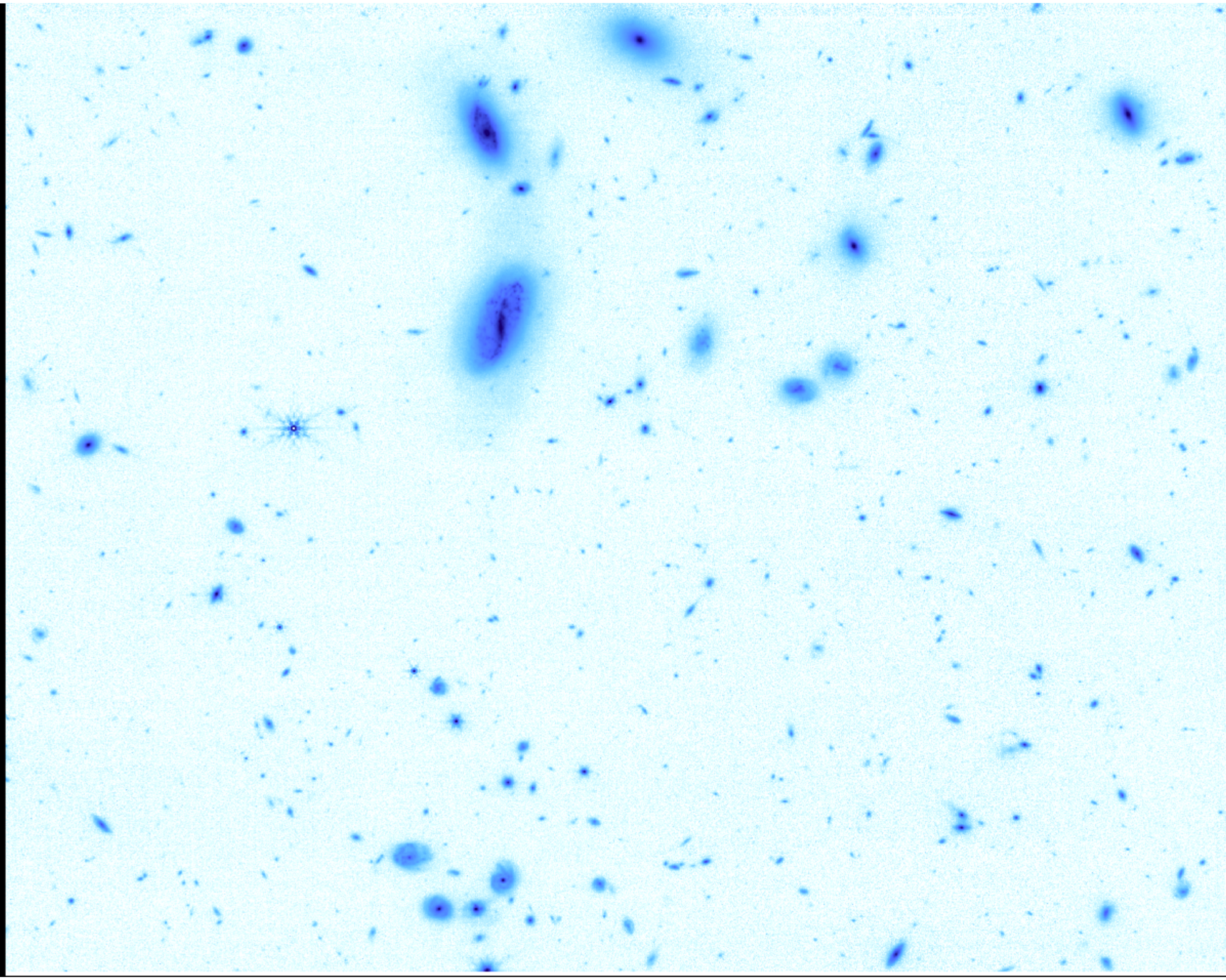

Loeb+06
The First Glimpse of the First Galaxies
z>10, z=0
A Spectroscopic View of the First Billion Years
z=5-9
How did the first galaxies reionize the Universe?
z=5-???
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day

Pre-JWST <0.1% of photometrically selected galaxies at z>6 had spectra

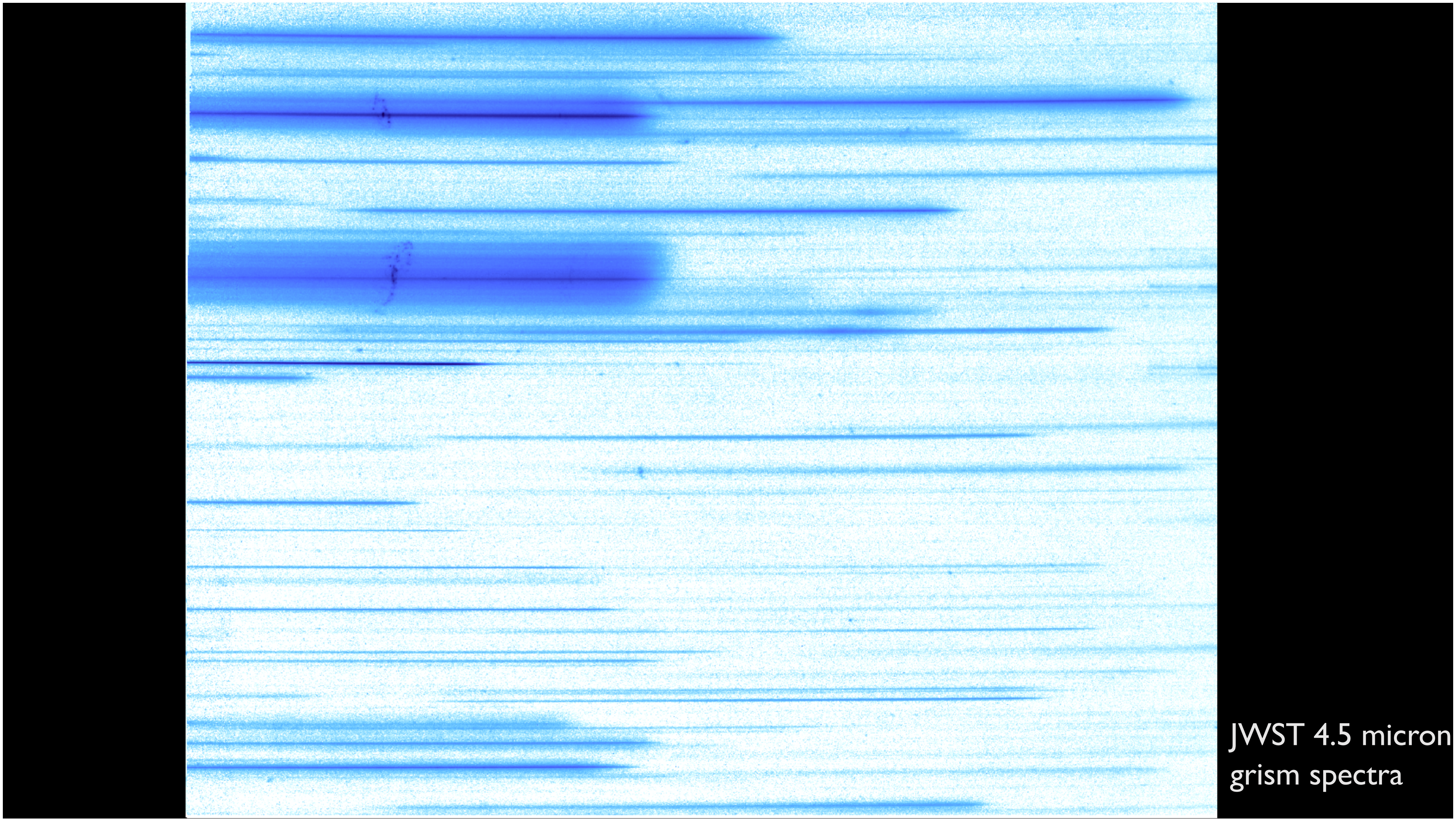


Most fundamental quantities like stellar masses uncertain

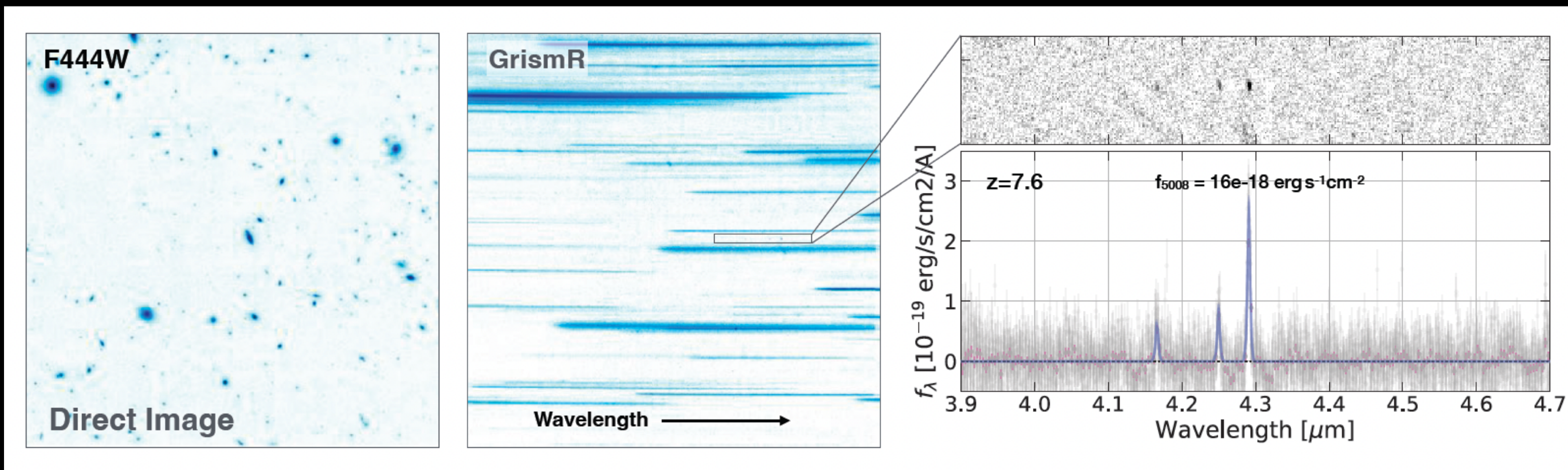
Stack from XLSz2 Survey
Matthee+21, Naidu+22c



JWST 4.5 micron image


JWST 4.5 micron
grism spectra

The power of NIRCam/grism spectroscopy



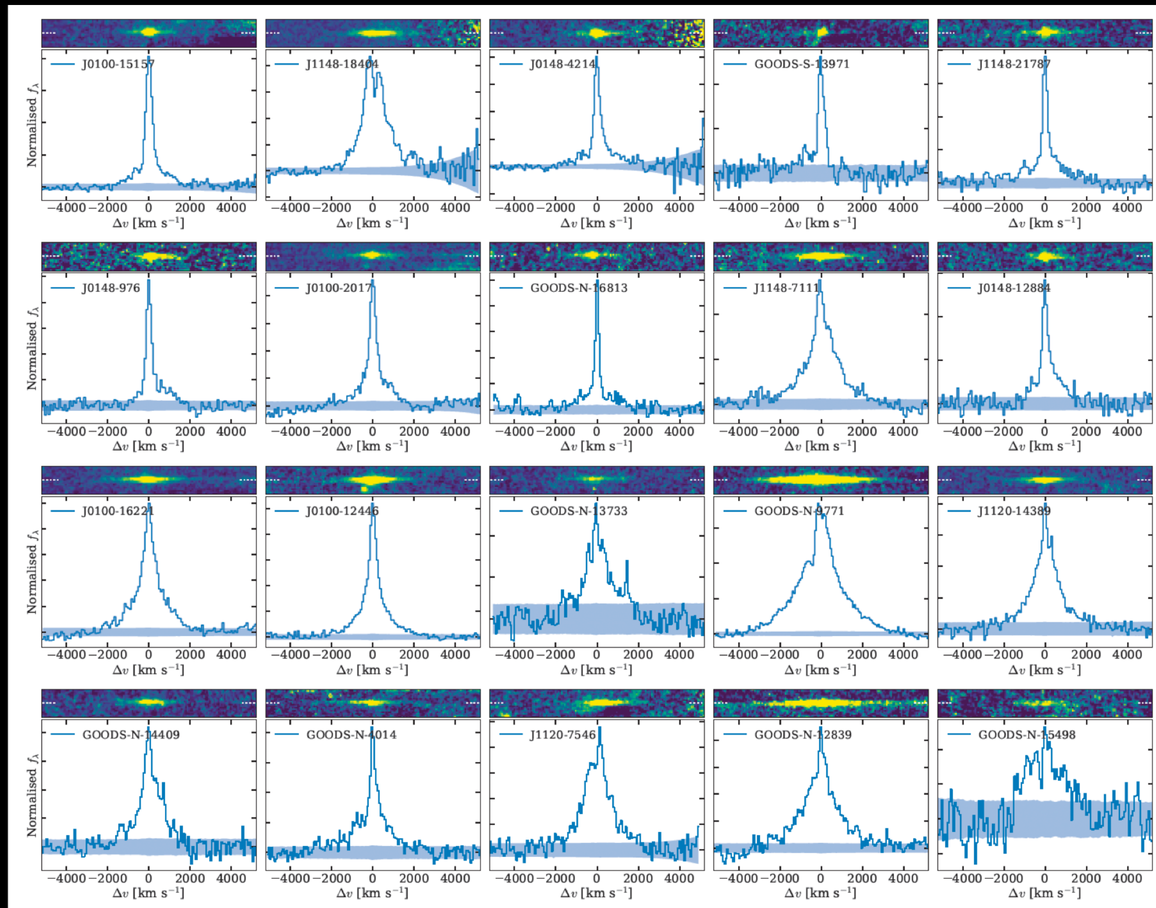
Oesch, Brammer, Naidu+23

- <10% of JWST spectroscopic time, but >70% (~3500) of public z>5 spectra!

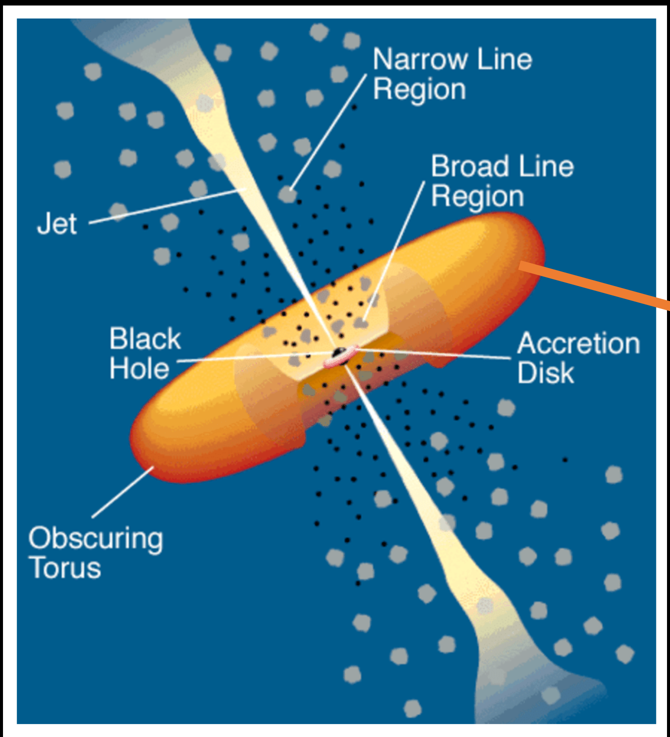
An abundance of broad-line sources

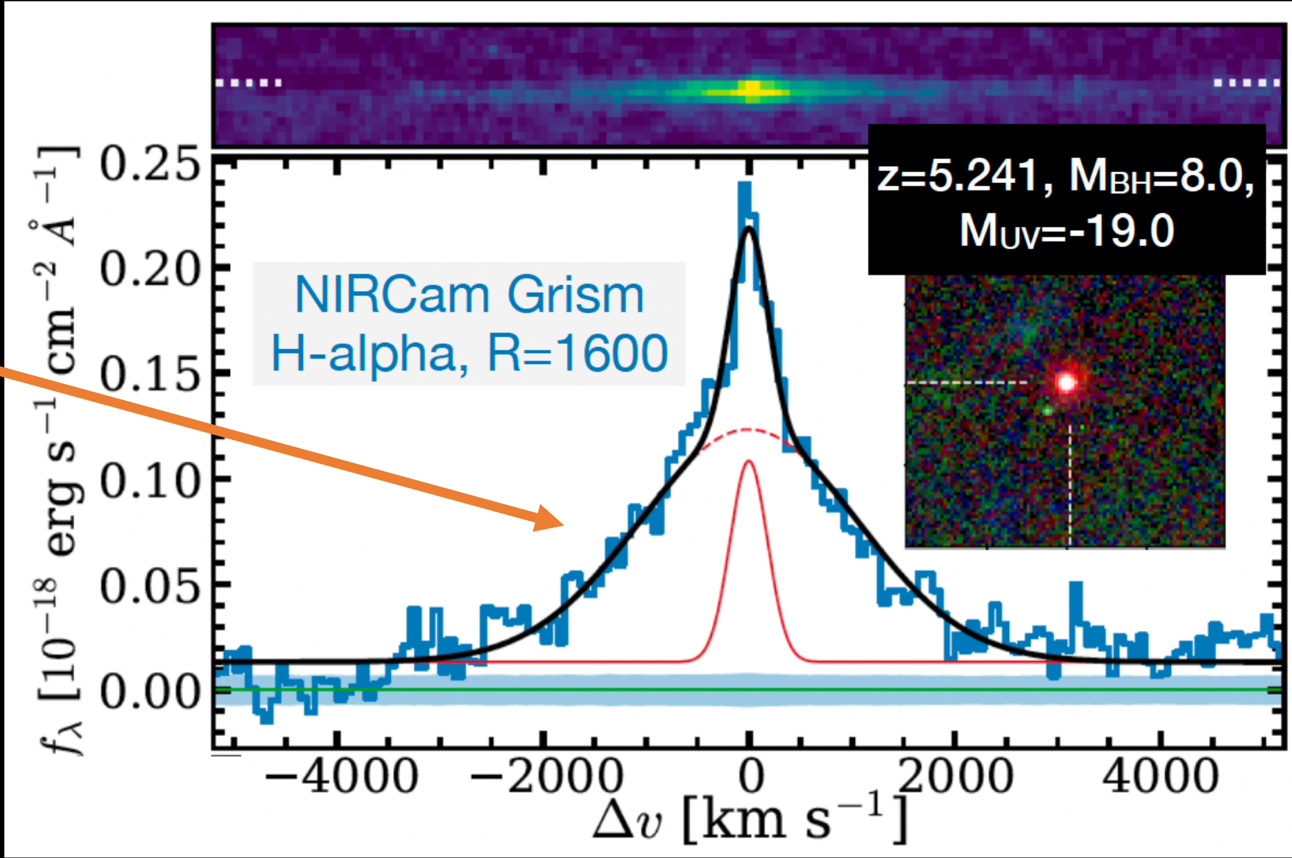
- Roughly ~1 such source per 10 arcmin^2
- FWHM>2000 km/s

Matthee, Naidu+24



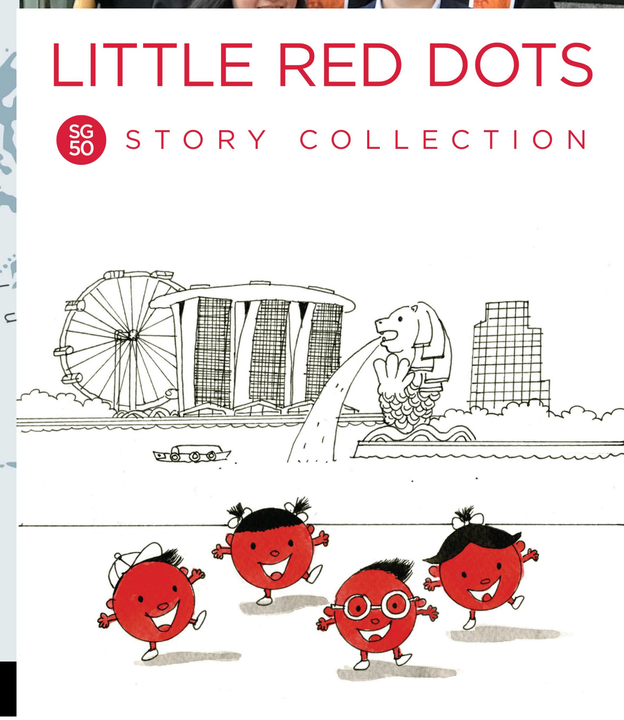
Little Red Dots appear to be broad-line AGN





Kocevski+23, Ubler+23, Kokorev+24, Furtak+24, Maiolino+23, 24, Harikane+24, Greene+24, Labbe+24, …

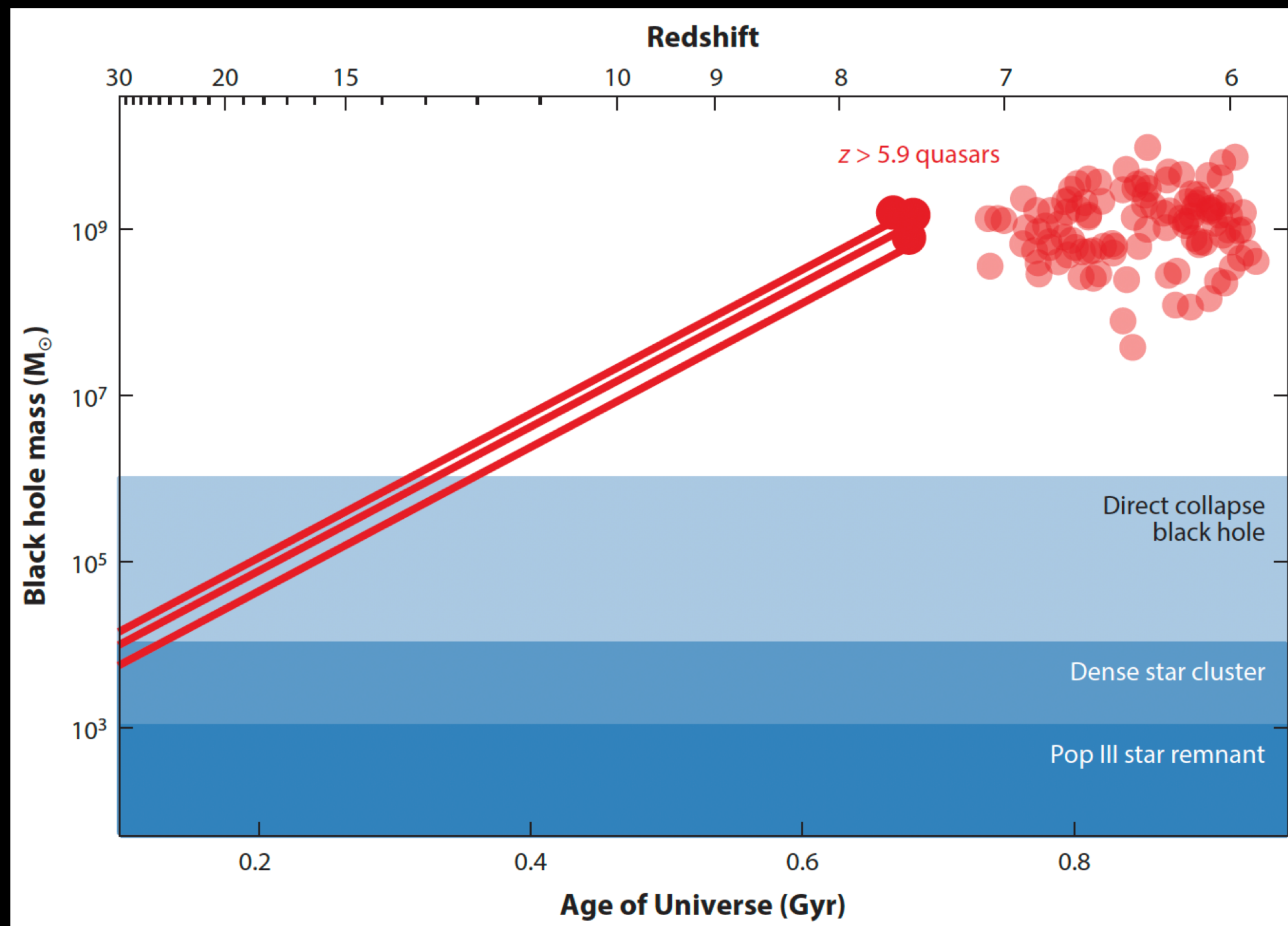
On "little red dots"



On “little red dots”

Little Red Dots in context

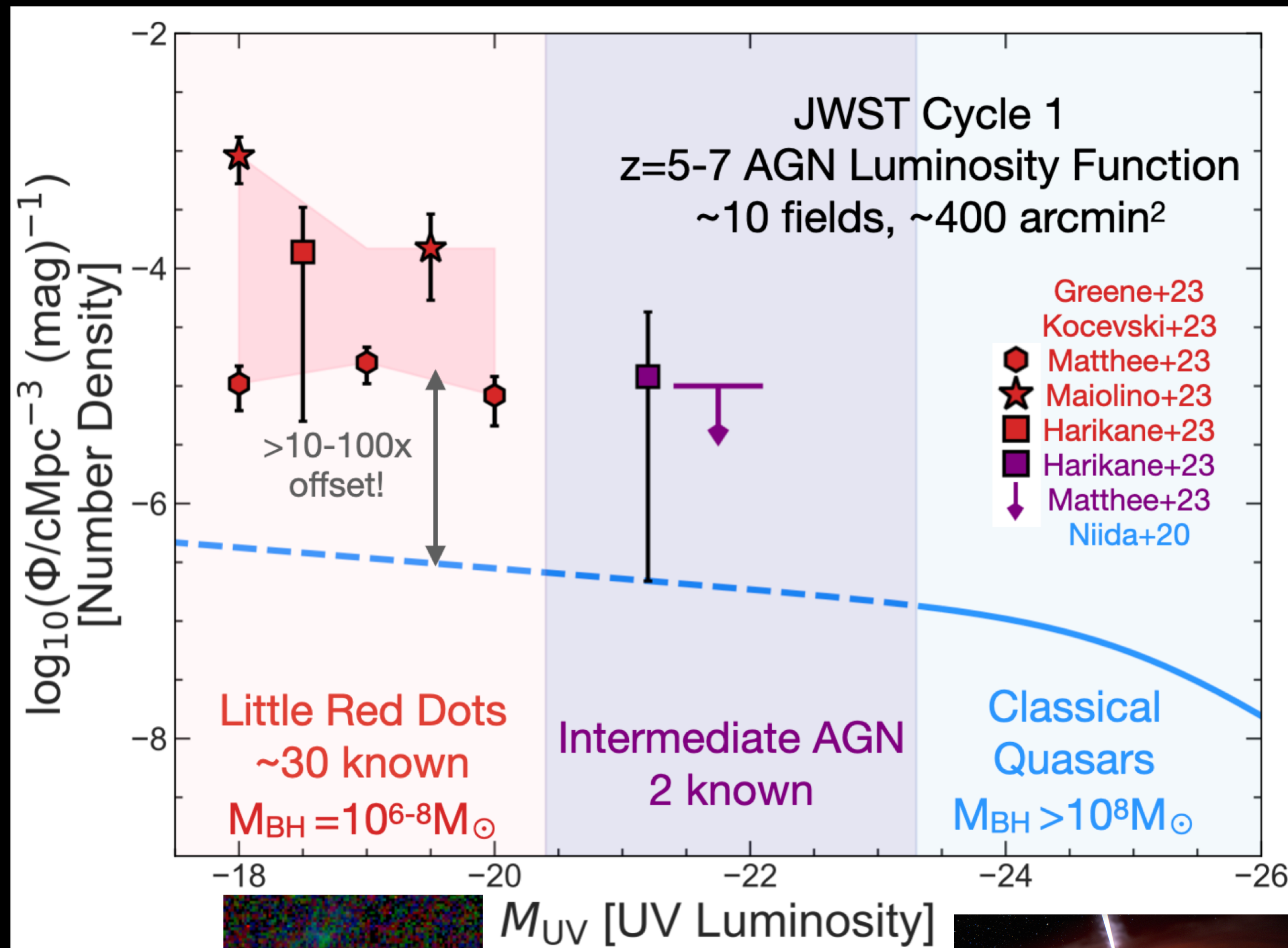
- Behemoth black holes in the first billion years have been known for decades.

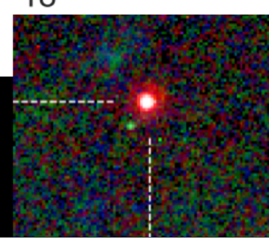


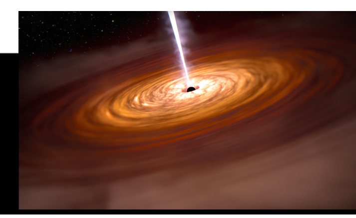
Fan, Banados, Simcoe 2023

Little Red Dots in context

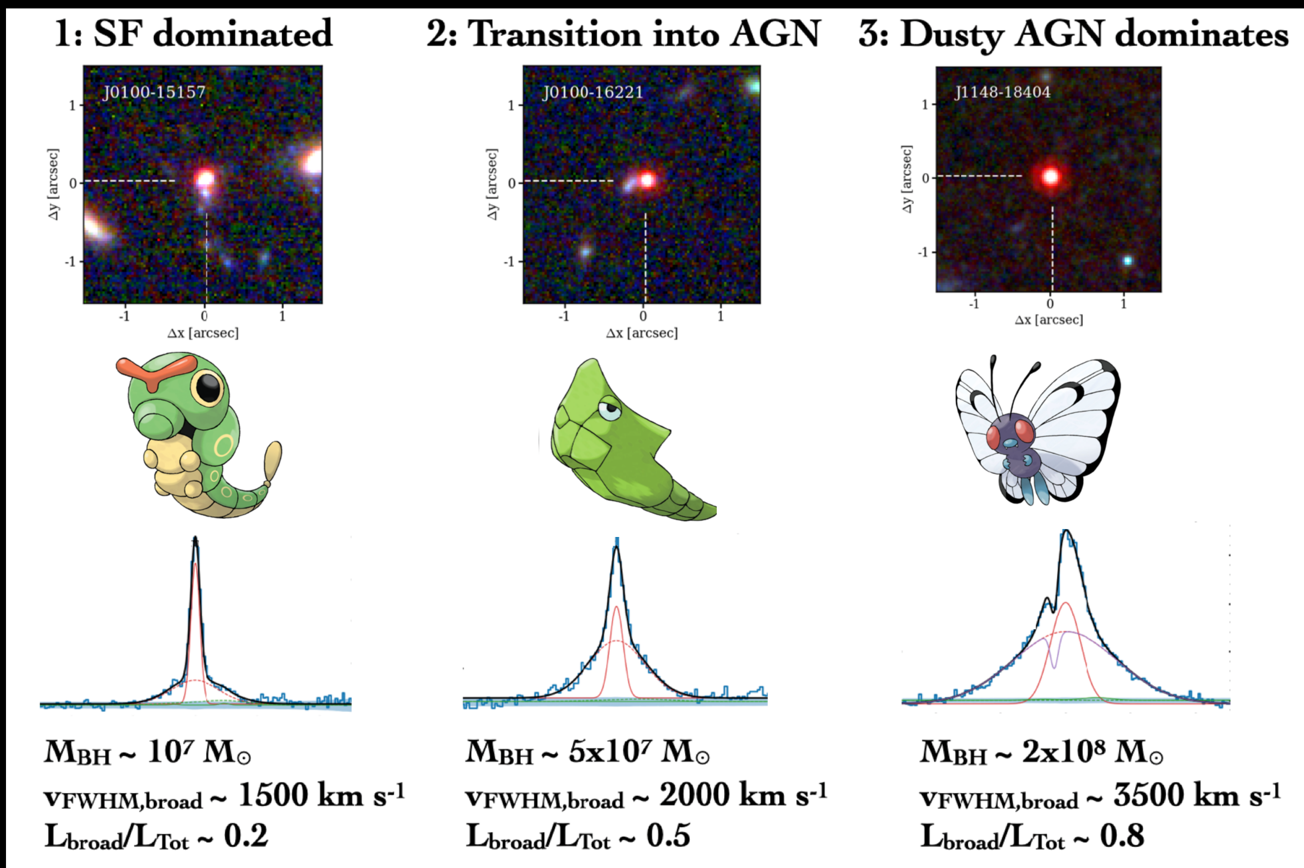
- Extremely faint in the UV, beyond the reach of previous telescopes.

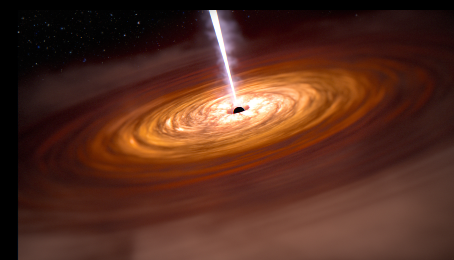






Hidden chapters of black hole growth?

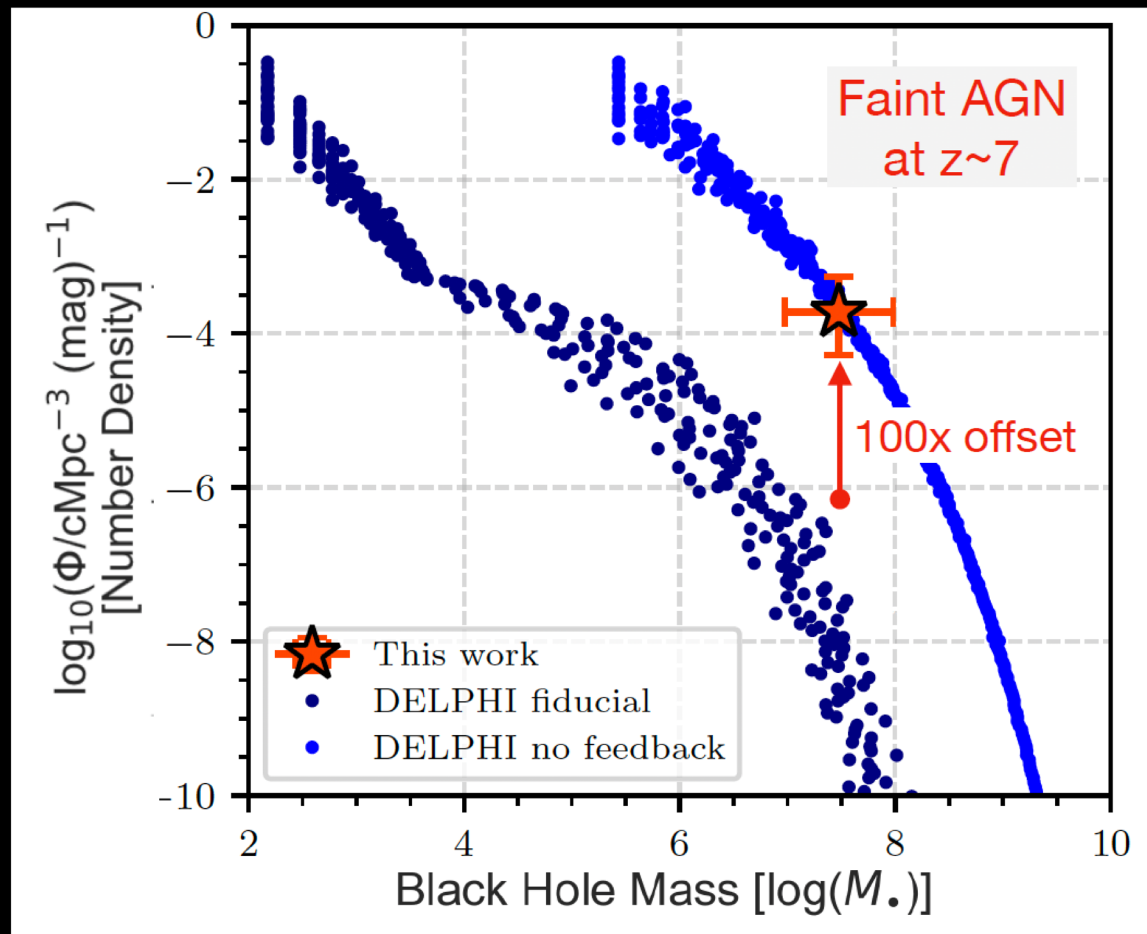




Ultra-luminous $>10^9 M_\odot$ quasar at $z>6$

Puzzles: black holes everywhere!?

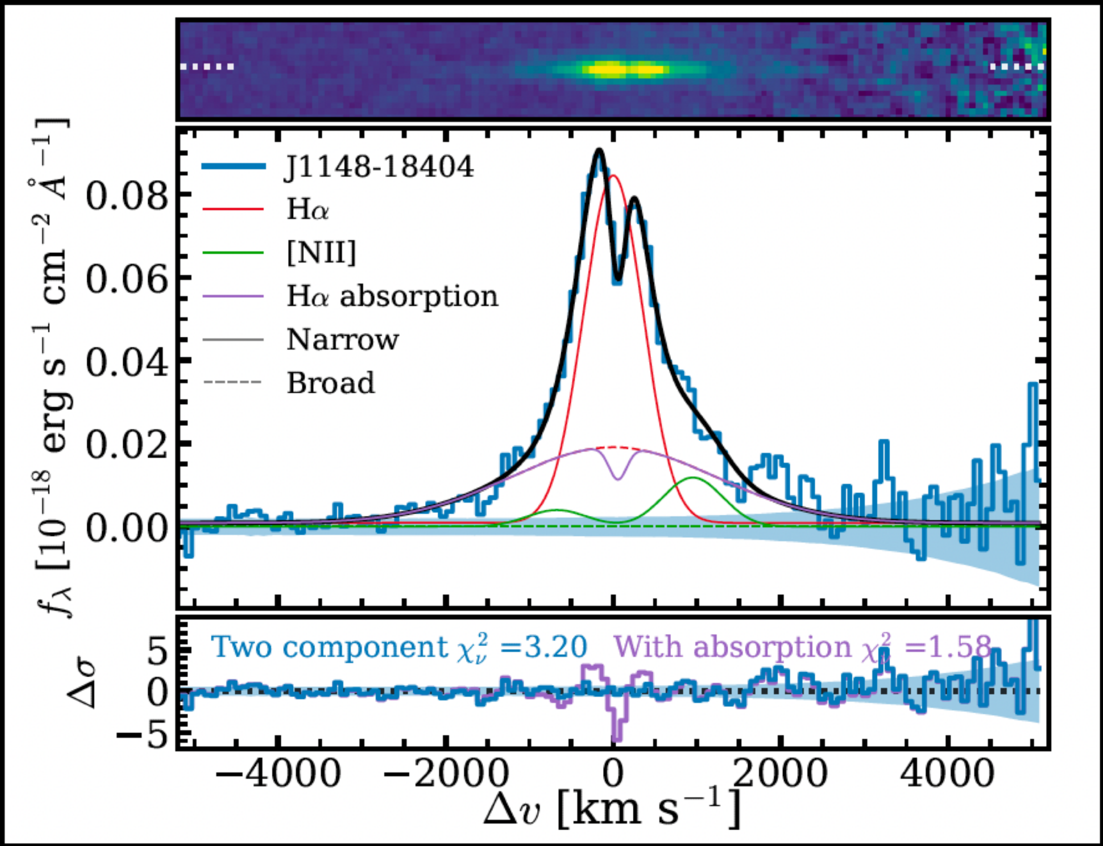
- More than 10-100x common compared to expectations.
- Need to invoke spectacular physics (e.g., feedback-free growth) to match numbers.



Kokorev+23, Dayal+24

Puzzles: peculiar properties

- Extreme column densities are common (~10-20%), producing Balmer absorption (!?)



Matthee, Naidu+24

Puzzles: peculiar properties

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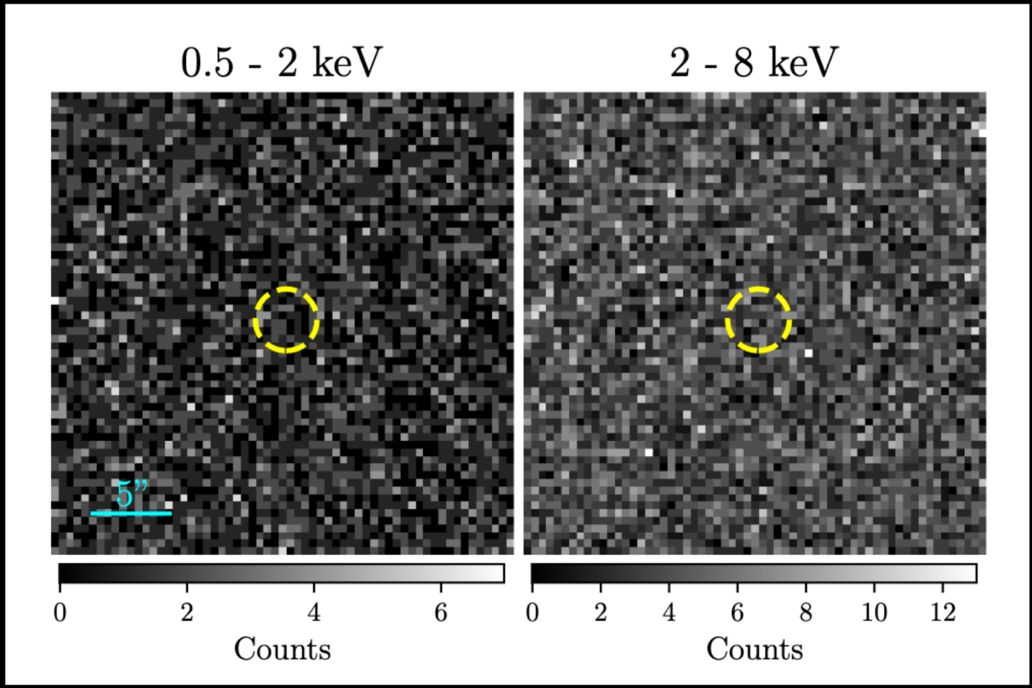
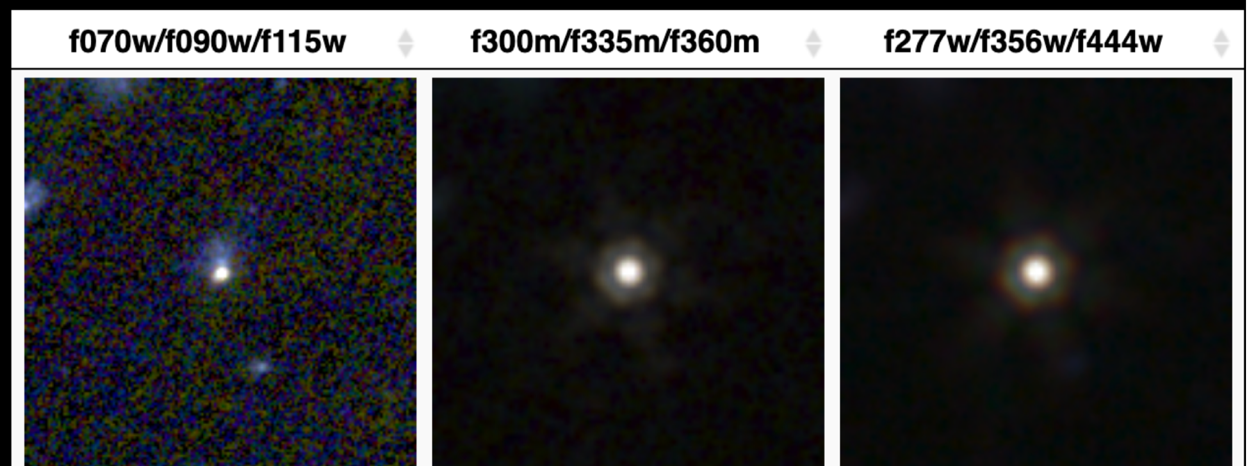
- Non-detections in x-rays



Yue+24
also Matthee+24, Maiolino+24, Judozbalis+24, Wang+24, …

Puzzles: peculiar properties

- Extreme column densities are common (~10-20%), producing Balmer absorption (!?)
- Non-detections in x-rays
- V-shaped SED (consistent with star-light in the UV, AGN in the optical, but Balmer breaks???)



Labbe, Greene+ in prep., "Monster"
UNCOVER + All the Little Things

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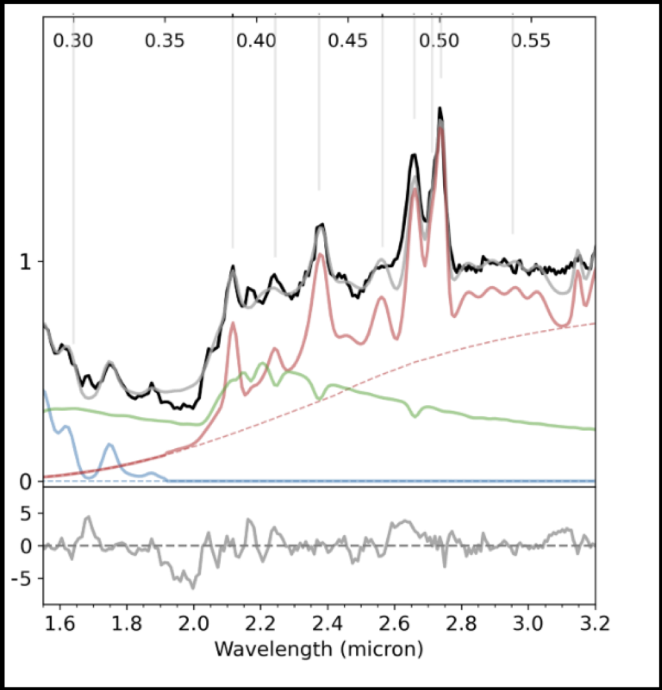
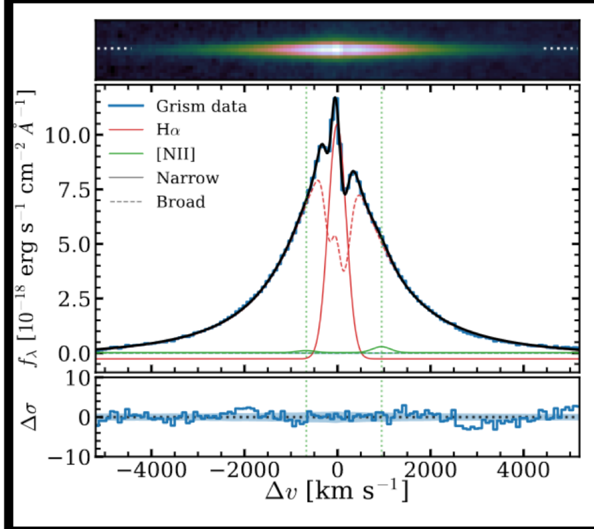


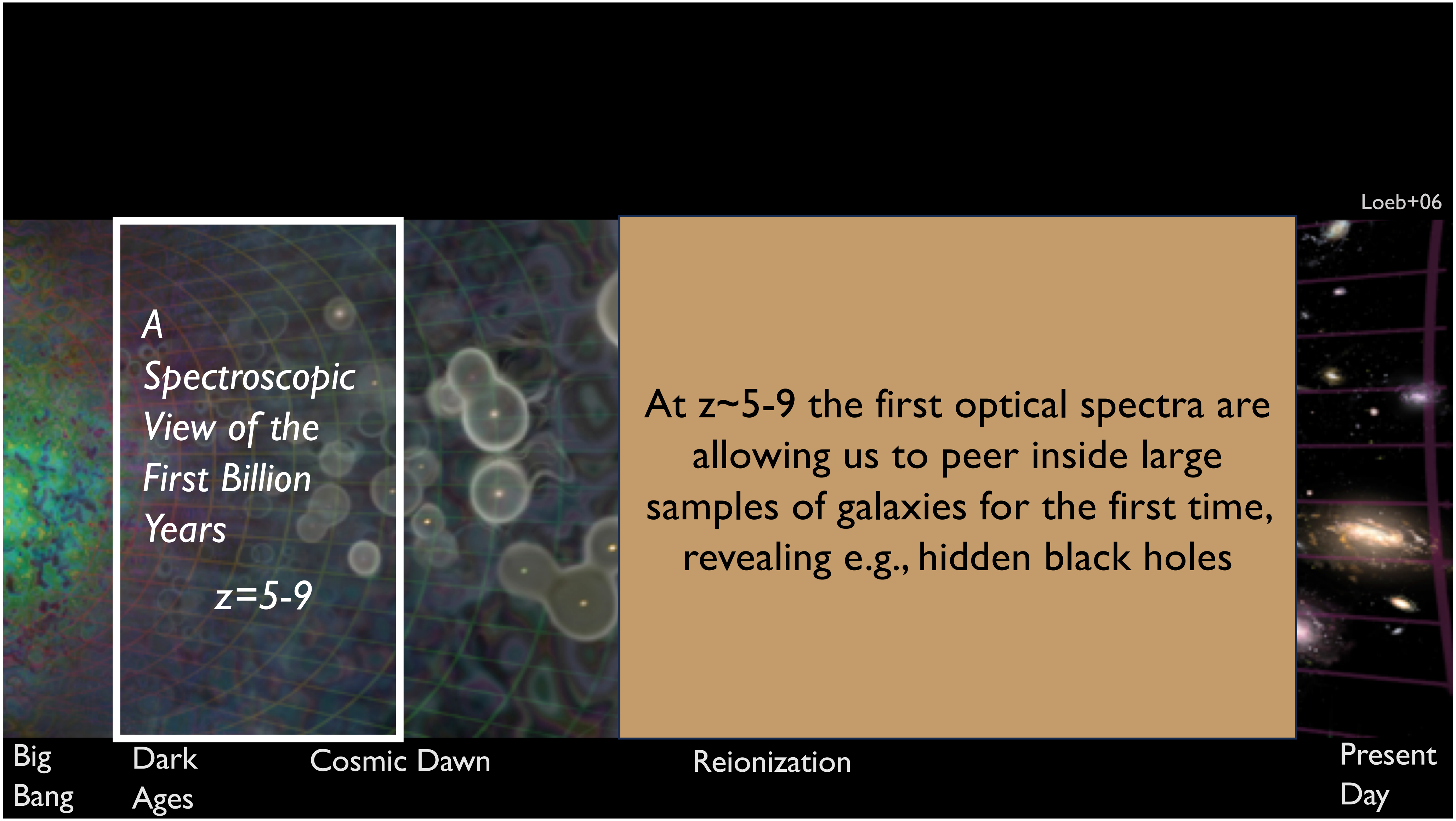
Balmer Break?

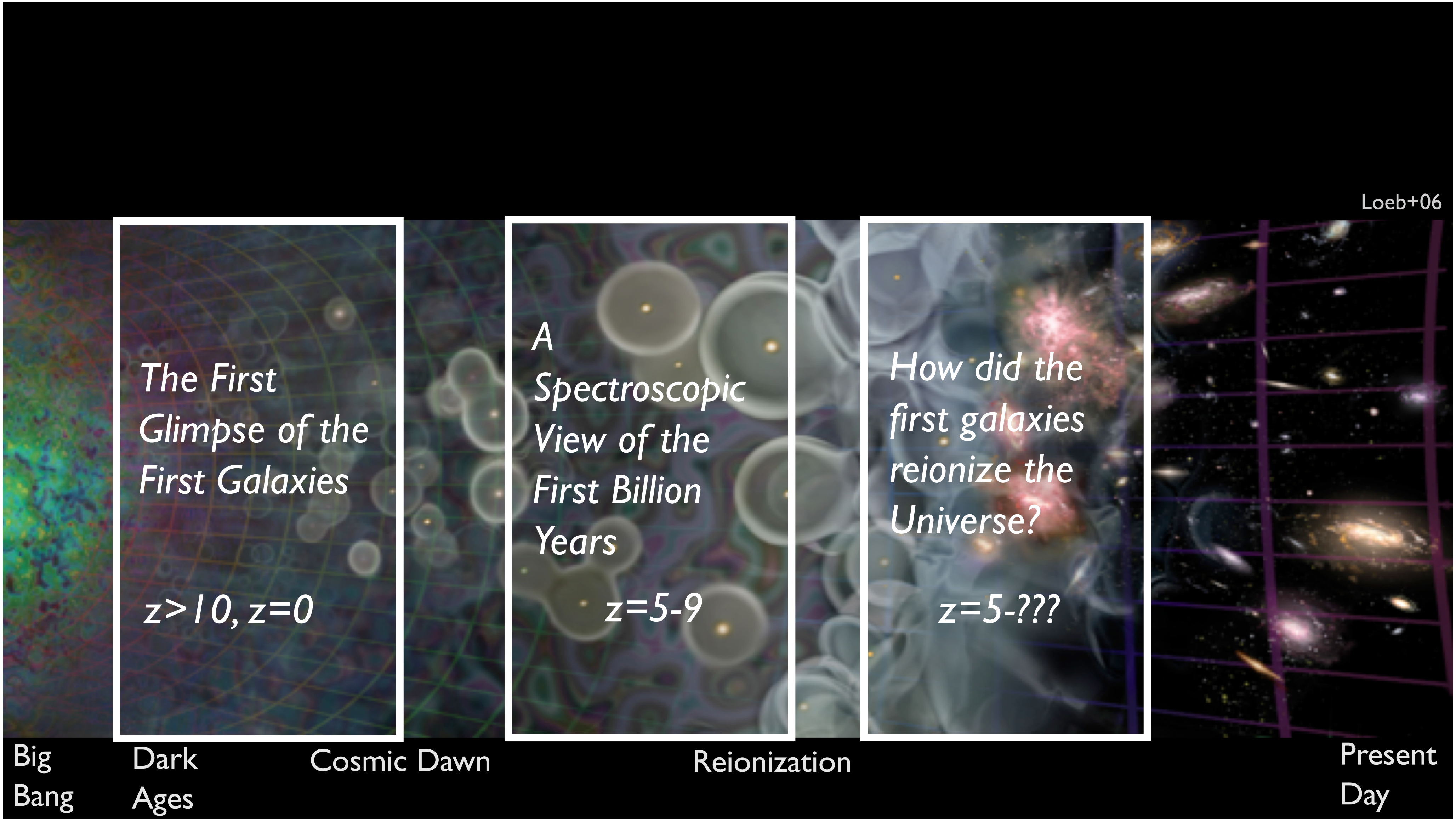
see also Wang+24



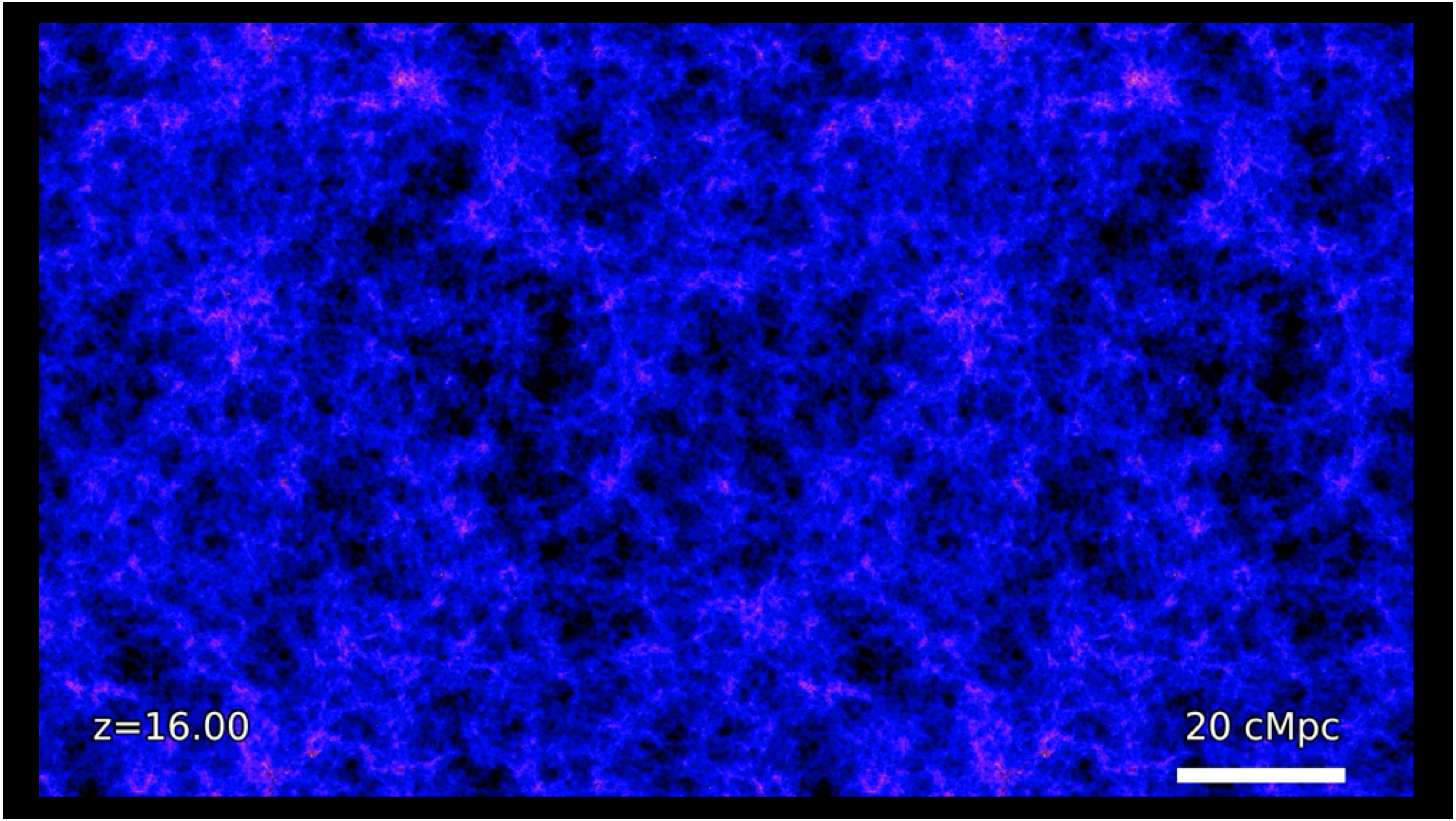
H-alpha

Labbe, Greene+ in prep., "Monster"
UNCOVER + All the Little Things

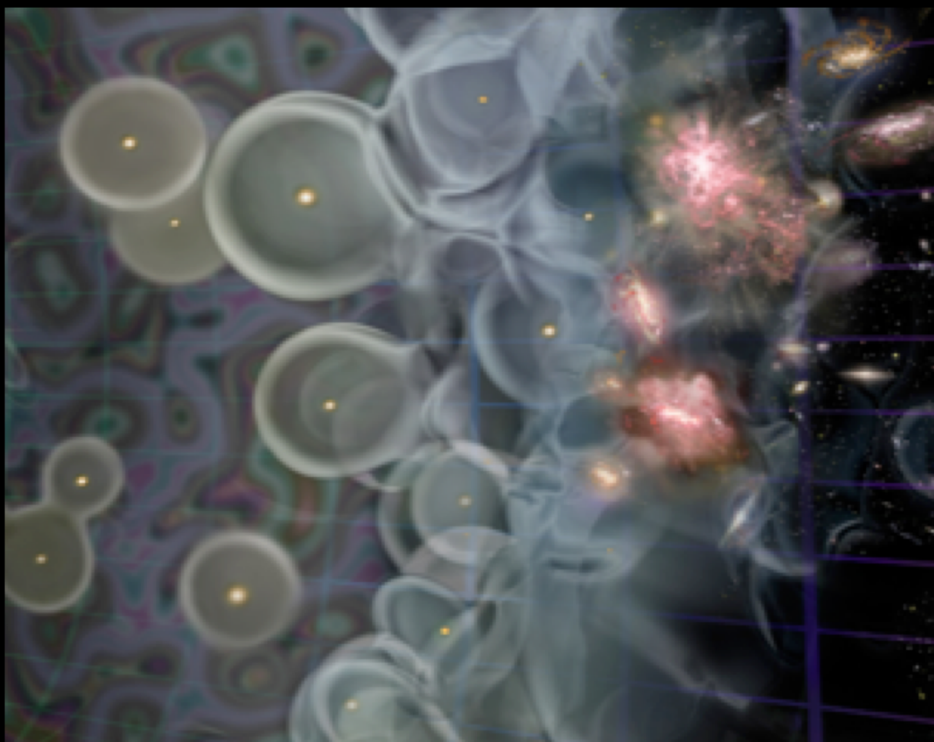

Loeb+06
A Spectroscopic View of the First Billion Years
z=5-9
At z~5-9 the first optical spectra are allowing us to peer inside large samples of galaxies for the first time, revealing e.g., hidden black holes
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day



Loeb+06
The First Glimpse of the First Galaxies
z>10, z=0
A Spectroscopic View of the First Billion Years
z=5-9
How did the first galaxies reionize the Universe?
z=5-???
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day


z=16.00
20 cMpc

Reionization: where did the photons come from?

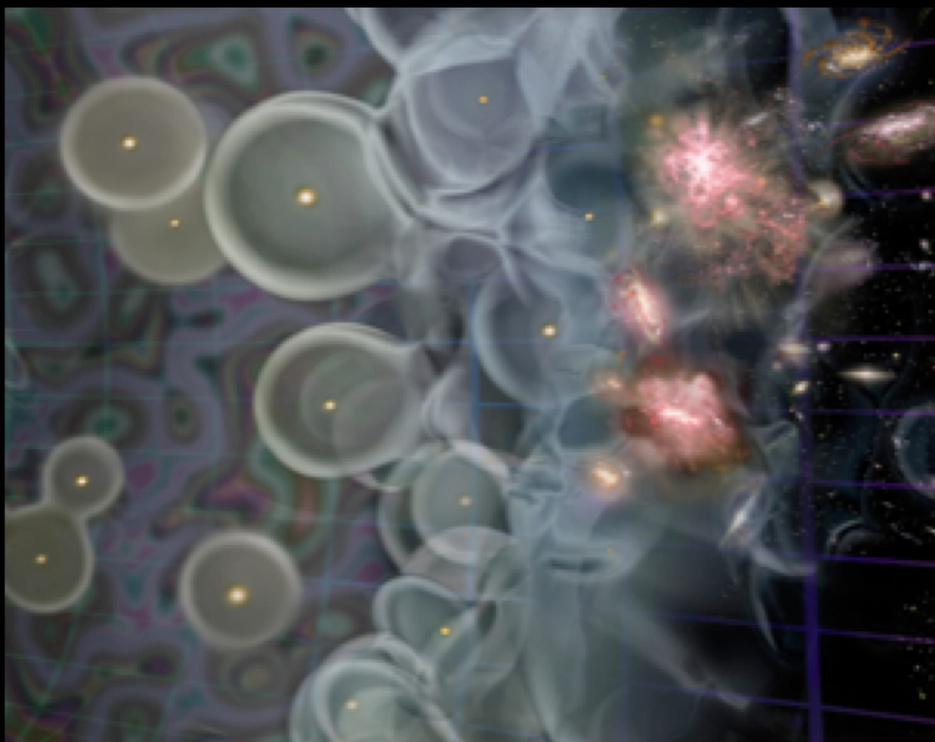


- Numerous, tiny, faint galaxies?
"Democratic Reionization"
Wise+14, Finkelstein+19, Chisholm+22

- Rare, bright, massive galaxies?
"Reionization by the Oligarchs"
Naidu+20, Naidu & Matthee+22, Matthee & Naidu+22

- Faint AGN/Little Red Dots? Madau+15,+24, Giallongo+15, Finkelstein+19

Reionization: where did the photons come from?



Reionization Budget = Number of galaxies

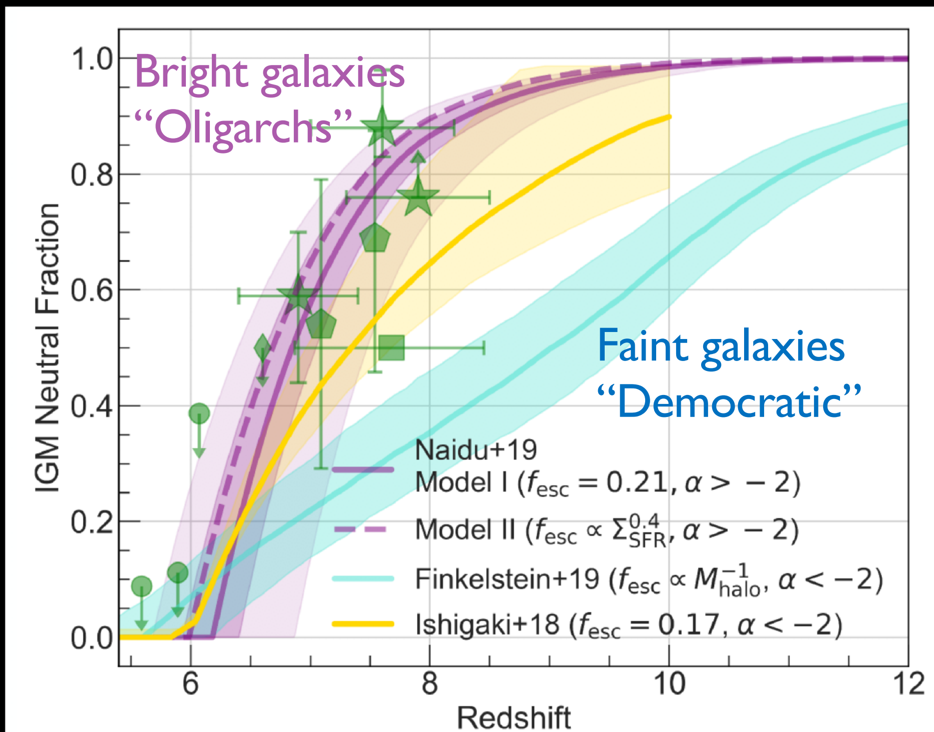
x Ionizing photons/galaxy

x Fraction that evade dust+HI

= $\rho_{UV}\, \xi_{ion}\, f_{esc}$

Reionization: where did the photons come from?

Timeline

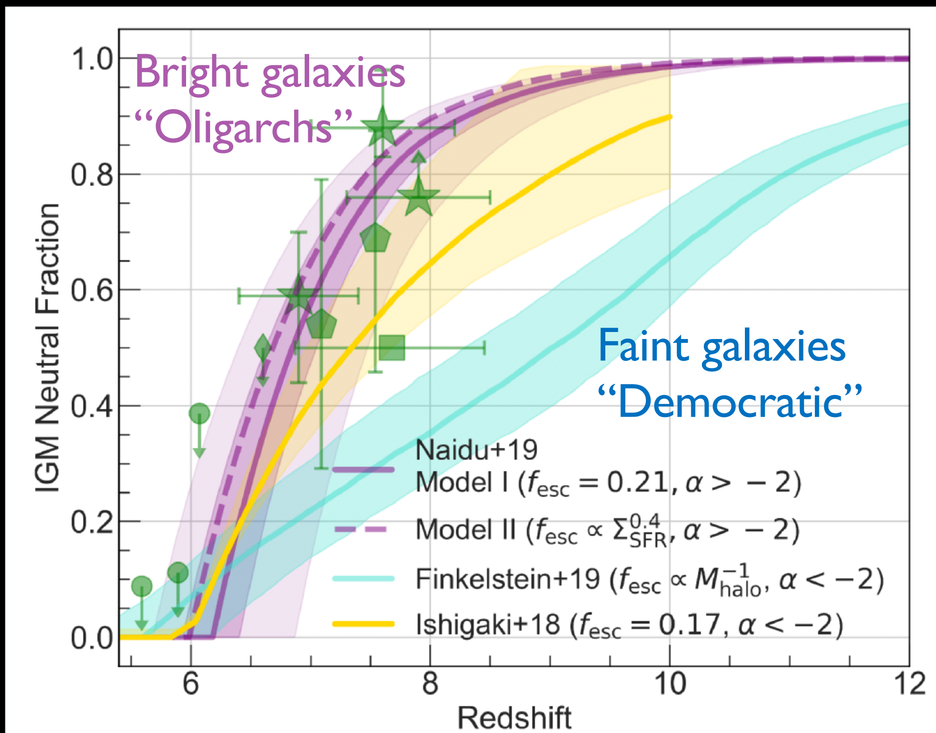


Naidu+20, Tacchella+18

- Radically different pictures of reionization.

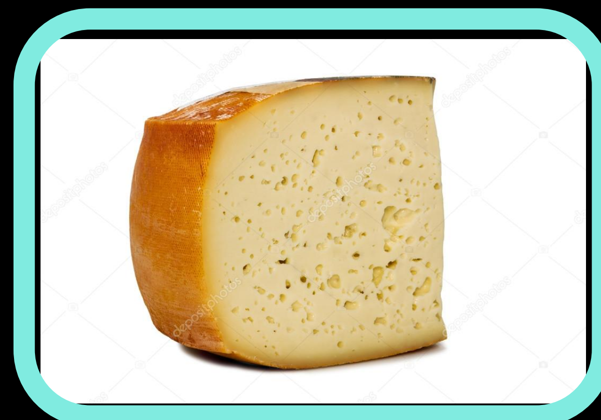
Reionization: where did the photons come from?

Timeline



Naidu+20, Tacchella+18

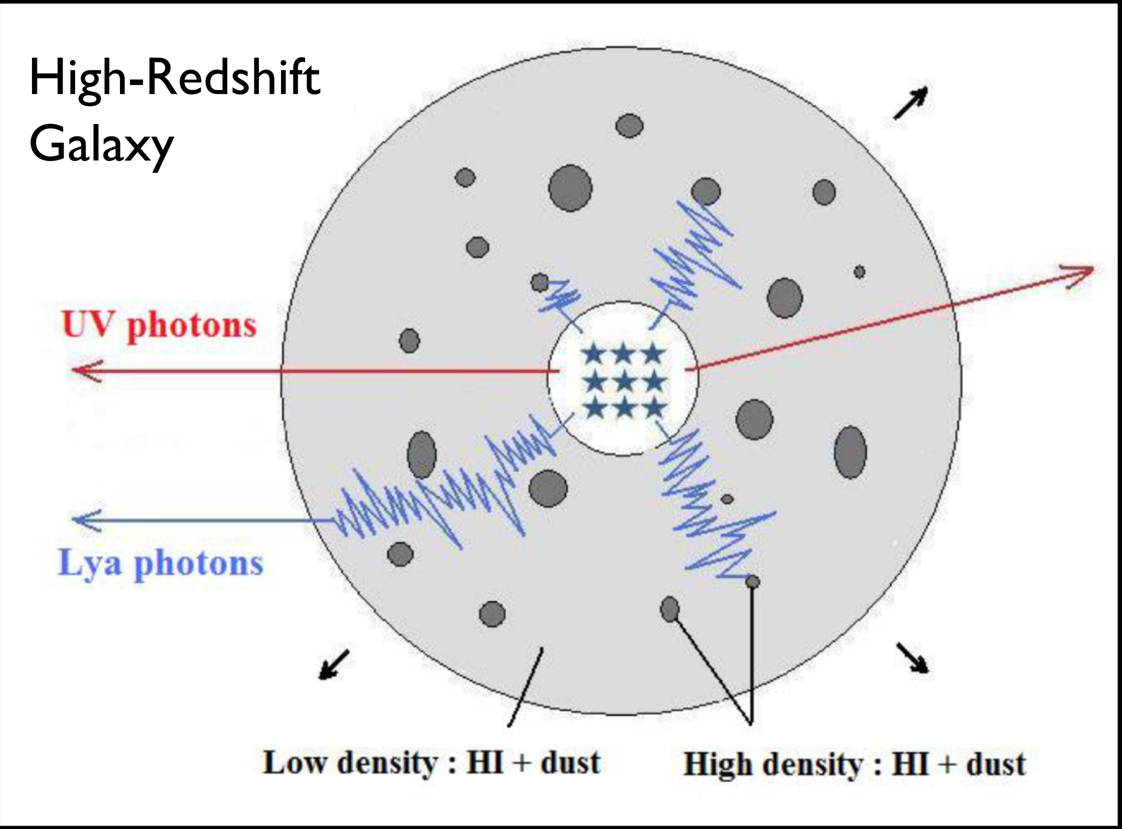
Topology



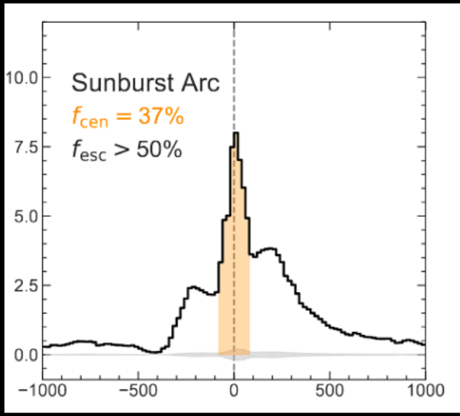
- Radically different pictures of reionization.
- Set the course of galaxy evolution across cosmic time (e.g., Milky Way satellite counts)

High-resolution Lyman-α: a key probe for reionization

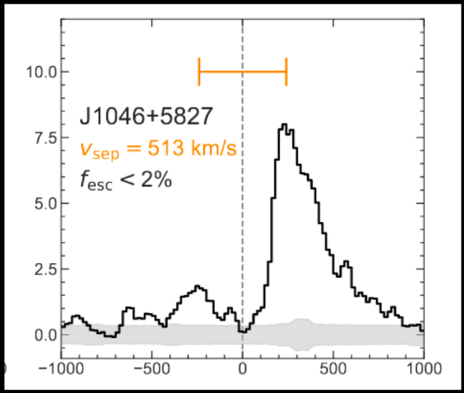
Naidu & Matthee+22; Matthee & Naidu+22
c.f. Izotov+18, Flury+22, Verhamme+18, Gronke+18, Giovinazzo+24, Pahl+24



Duval+14



Highly Ionizing



Poorly Ionizing

High-resolution Lyman-α: a key probe for reionization

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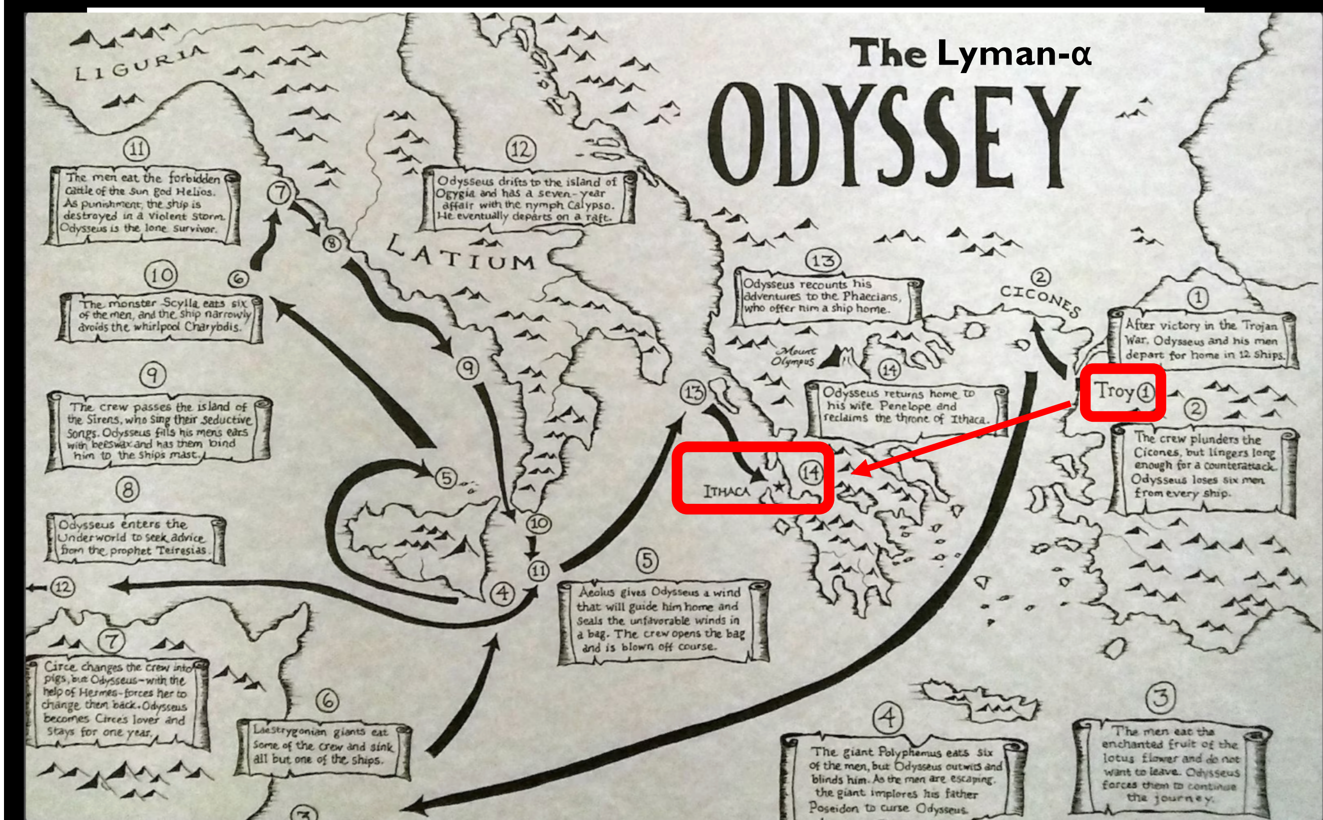
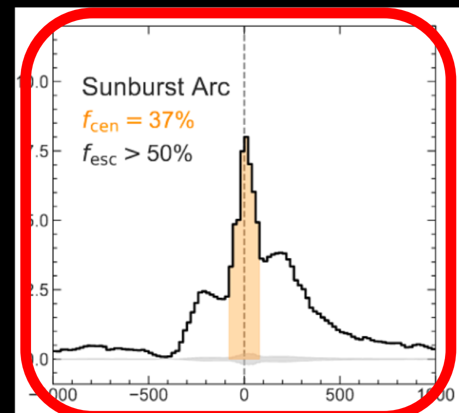
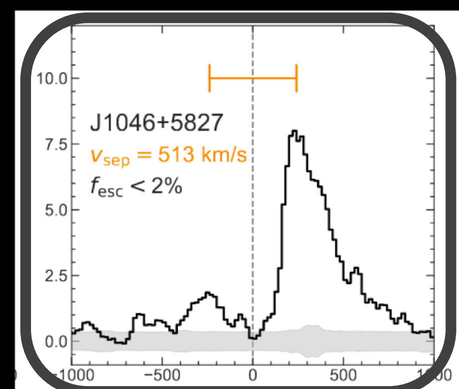


Duval+14

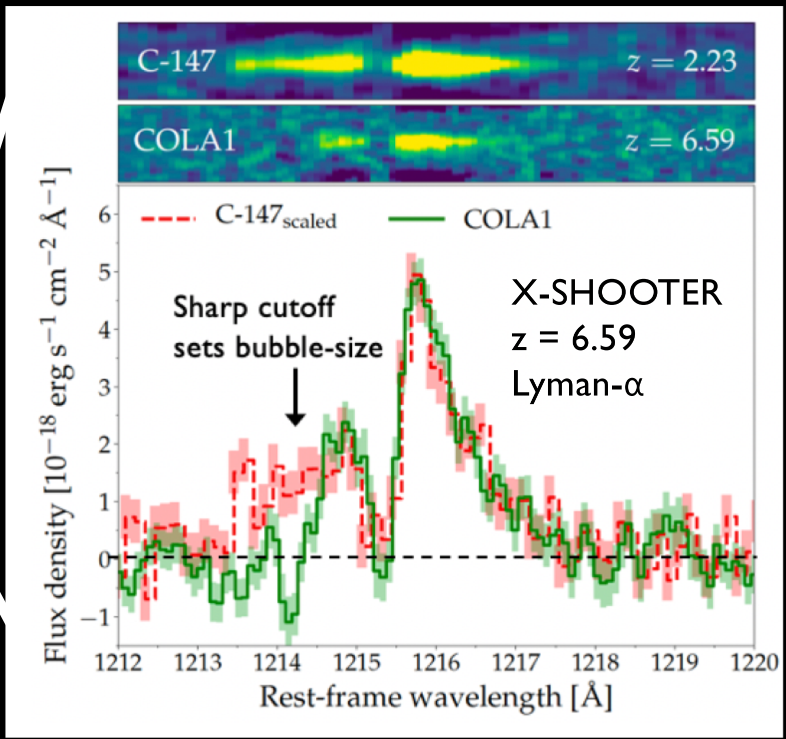


Highly Ionizing



Poorly Ionizing

Which galaxies reionized the Universe?
JWST bubble program PIs: Naidu & Matthee



z~7 bubble with strongly constrained size Hu+16, Matthee+18, Mason & Gronke 2020

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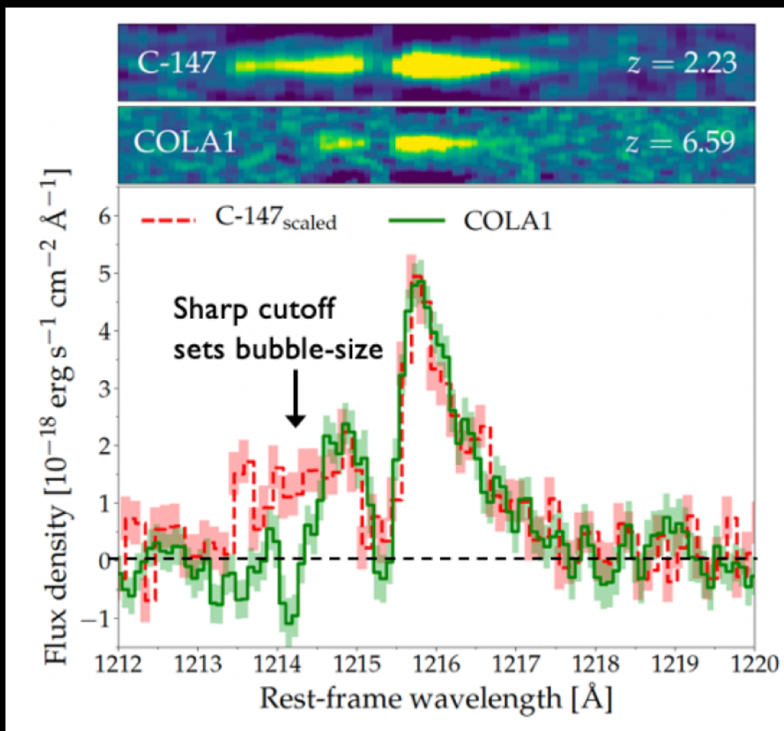
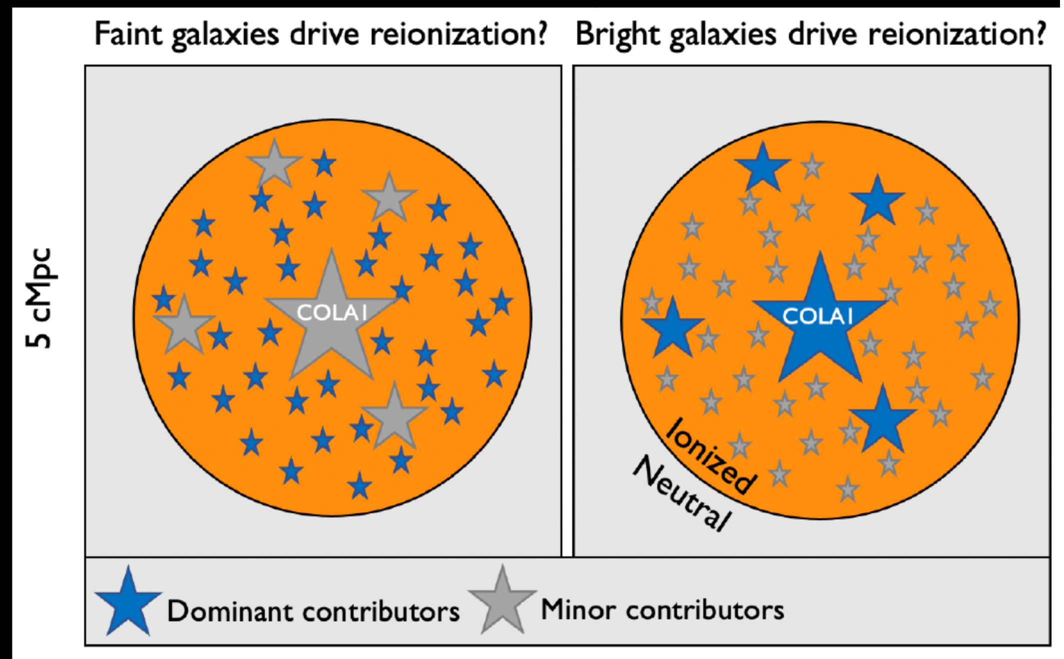


z~7 bubble with strongly constrained size

Matthee+18, Mason & Gronke 2020



Total ionizing photon budget known (since size is known ~ Stromgren sphere)

JWST grism survey: can bright galaxies do it all?

Which galaxies reionized the Universe?
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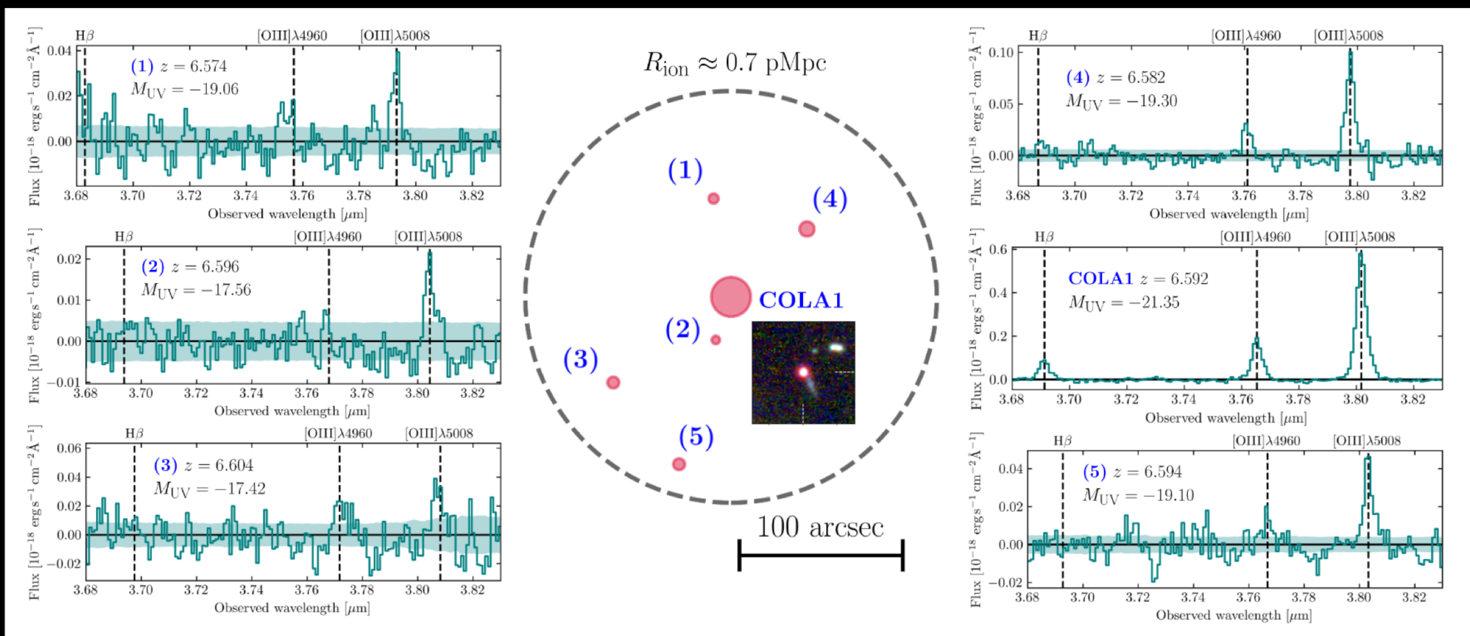
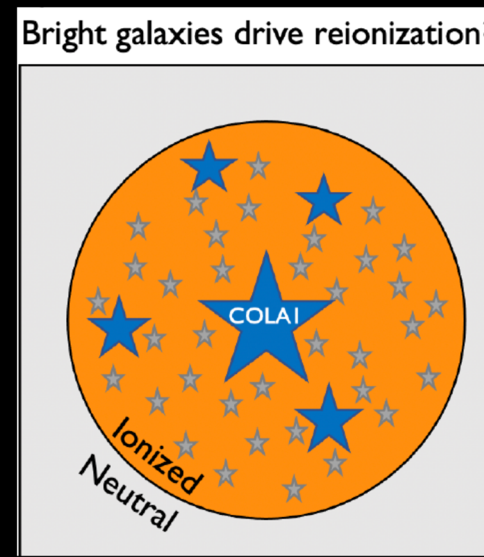
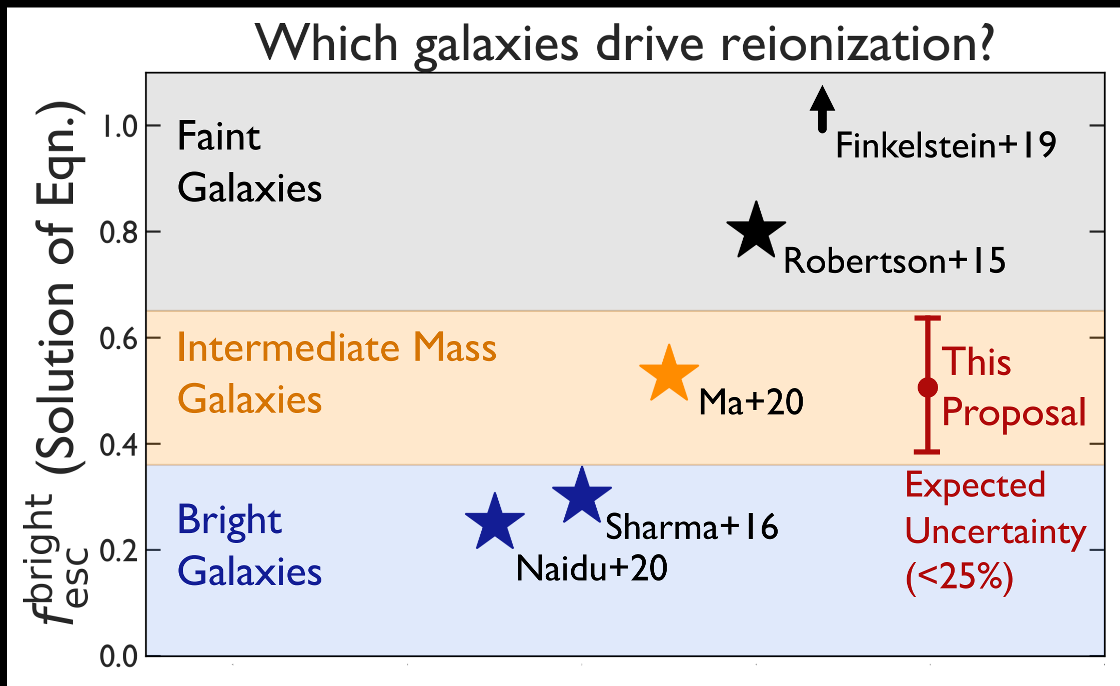


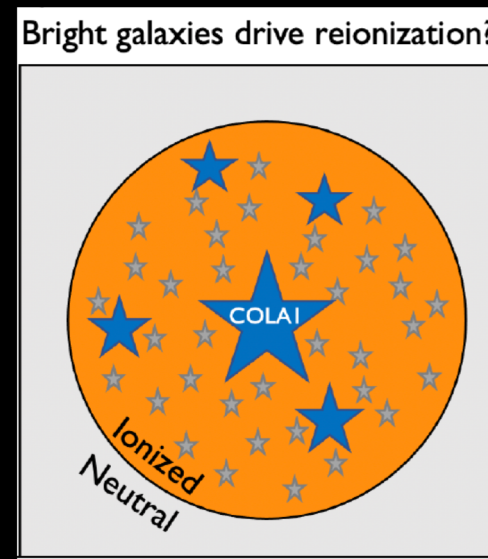


- COLA1+ 5 luminous friends can account for the majority of budget with modest escape fractions of <20% Torralba-Torregrosa+24

Which galaxies reionized the Universe?

JWST bubble program PIs: Naidu & Matthee





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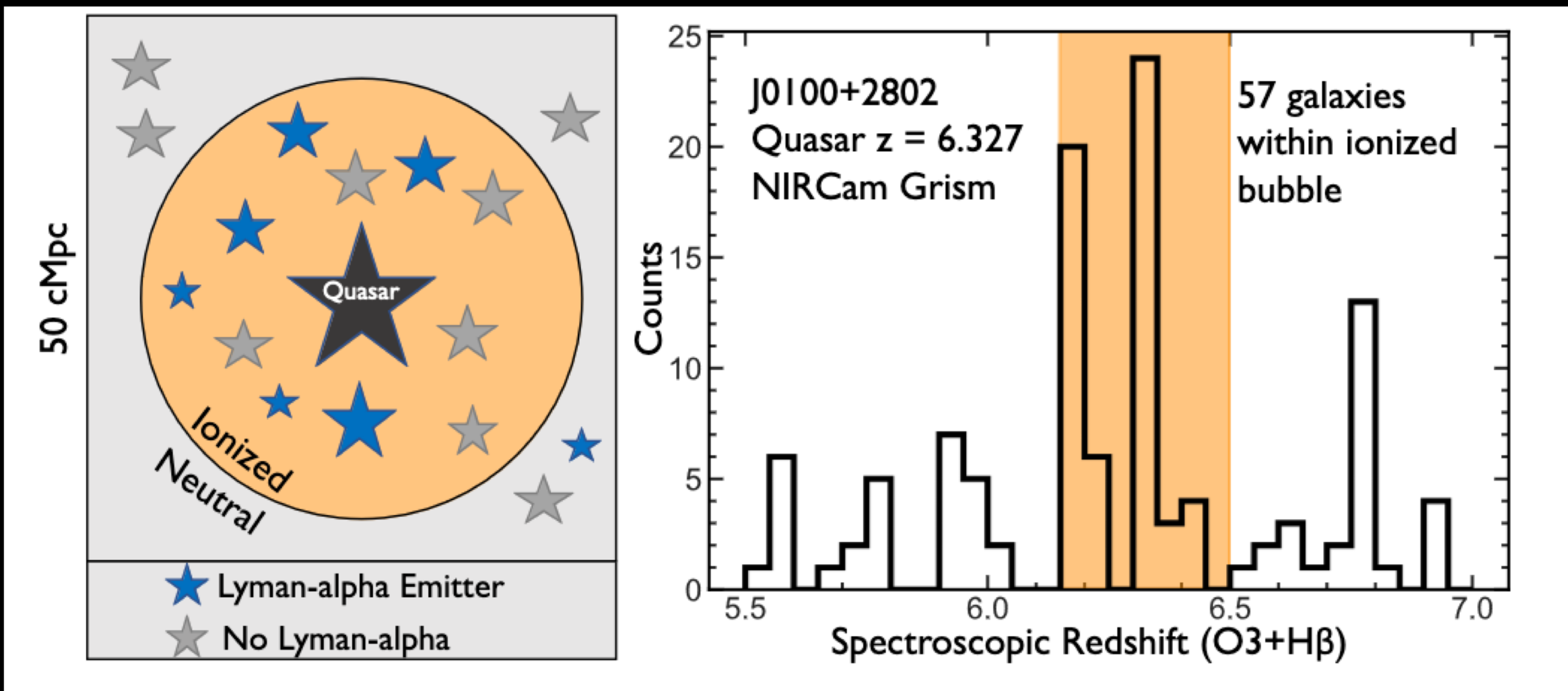
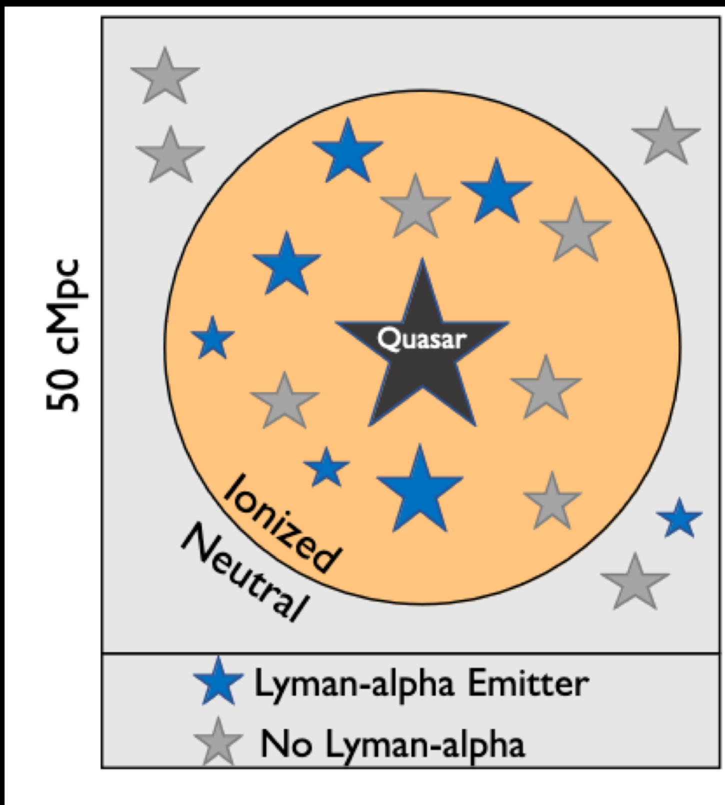
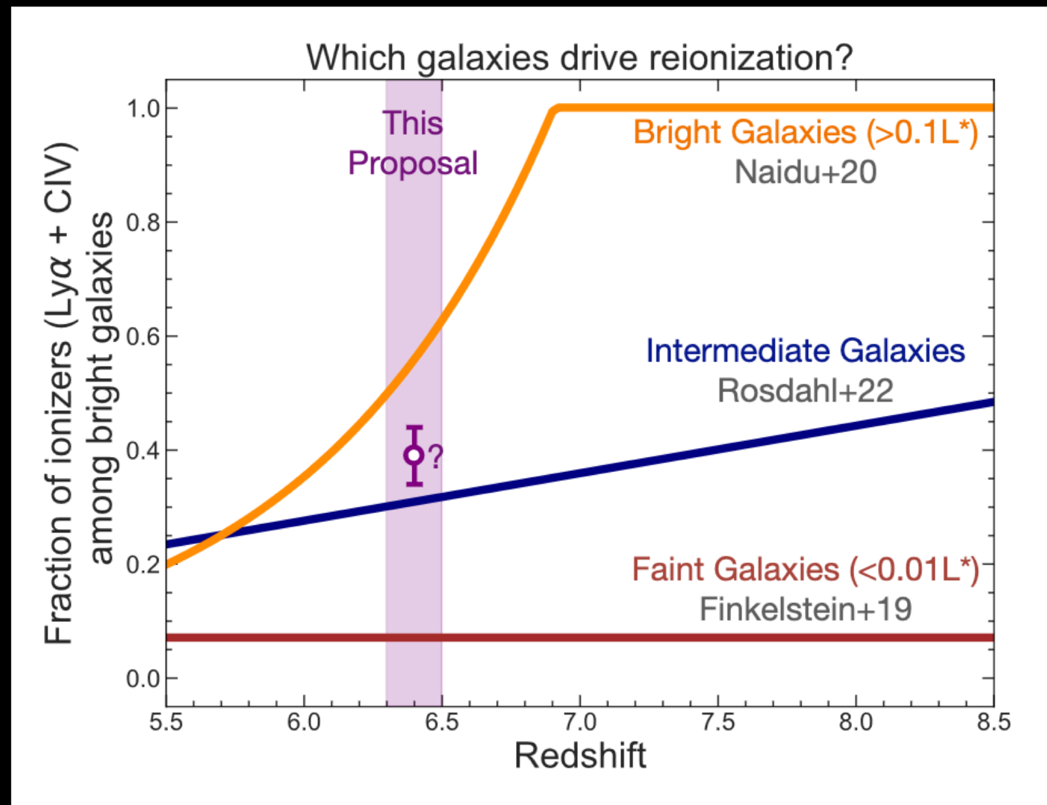
Bubble experiments around quasars



Kashino+23, EIGER Survey

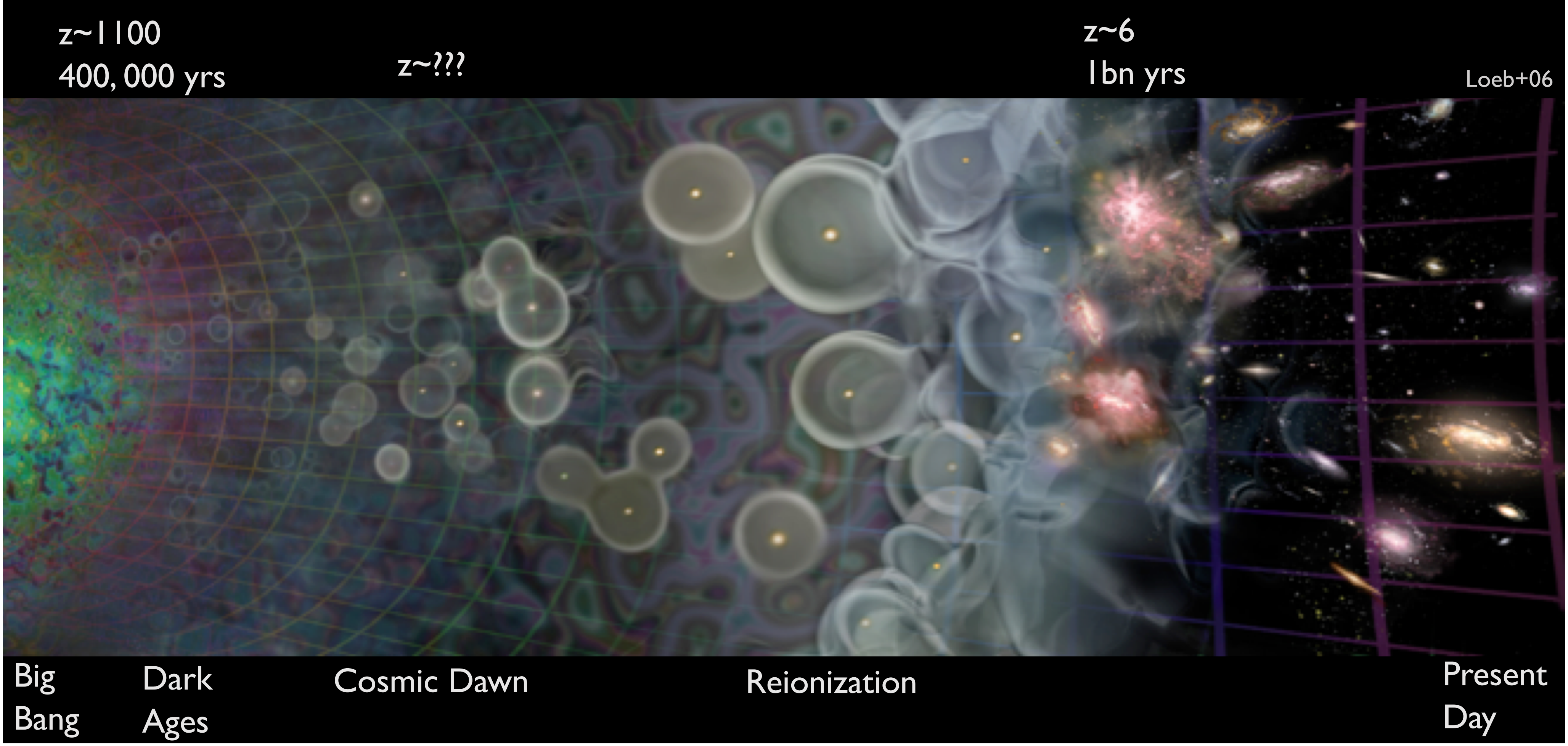
Bubble experiments around quasars



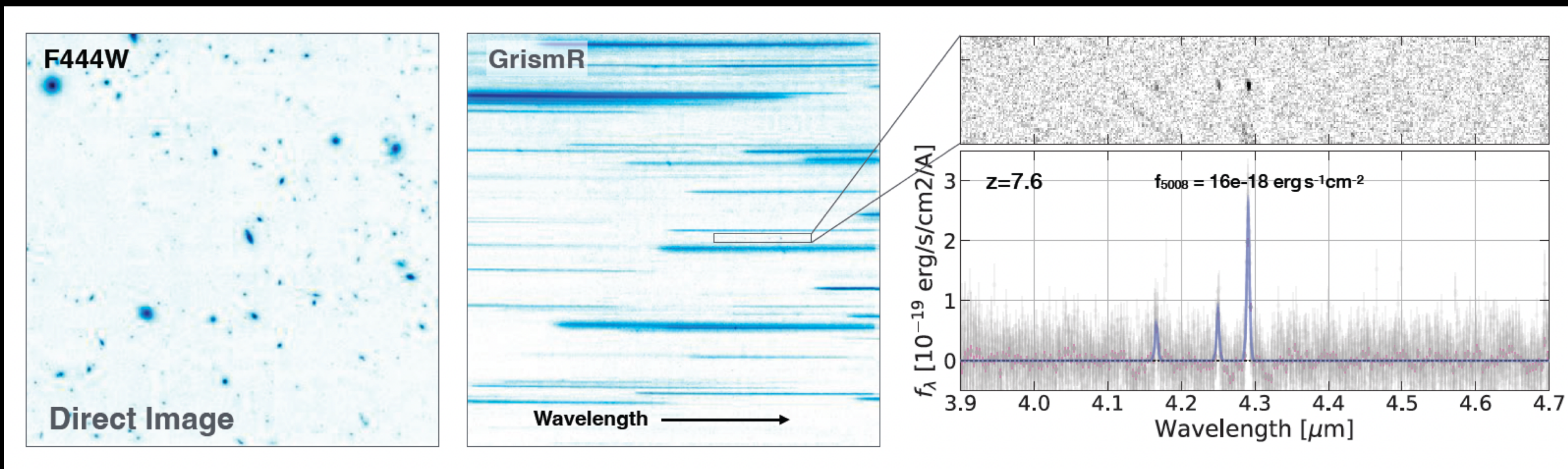


Approved JWST NIRSpec MSA in Cycles 2 and 3, PIs: Eilers, Davies, Naidu, Matthee

Statistical Surveys of Ionizing Photons



The power of NIRCam/grism spectroscopy



Oesch, Brammer, Naidu+23

- <10% of JWST spectroscopic time, but >70% (~3500) of public z>5 spectra!

Emission-line galaxies drive reionization

$$\dot{n}_{\rm ion,LBG}(z) = \rho_{\rm UV}(z)\,\xi_{\rm ion}\,f_{\rm esc}^{\rm LyC} \longrightarrow \dot{n}_{\rm ion,LAE}(z) = \rho_{\rm Ly\alpha}(z)\,\xi_{\rm ion}^{\rm Ly\alpha}\,f_{\rm esc}^{\rm LyC}$$

Madau+99, Robertson+13

Matthee & Naidu+21

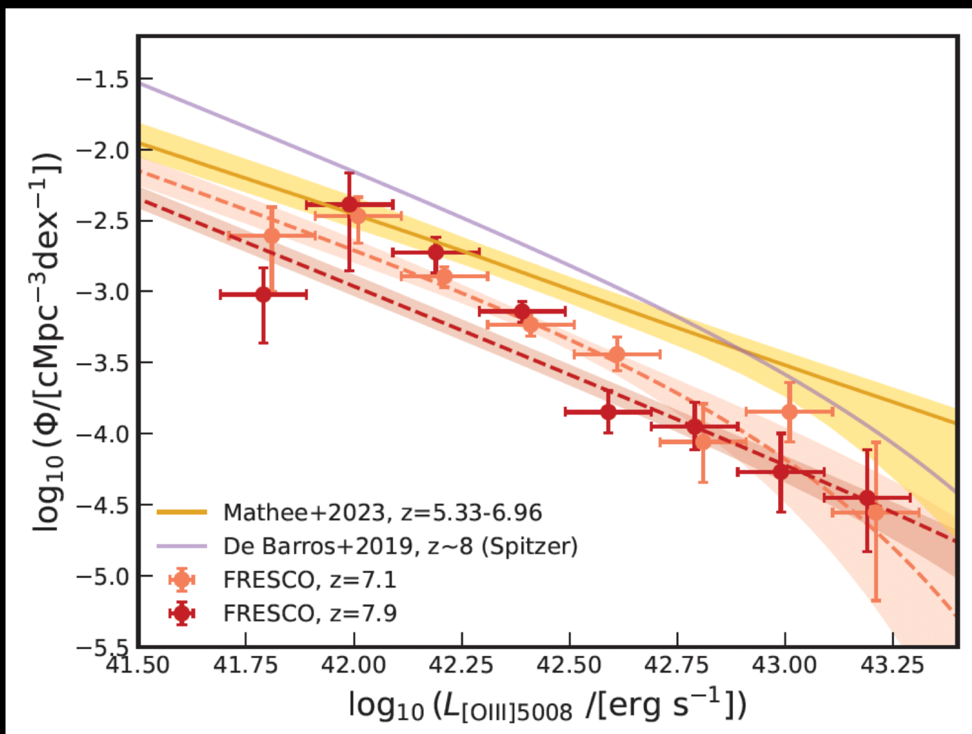
Reionization Budget = Number of galaxies

x Ionizing photons/galaxy

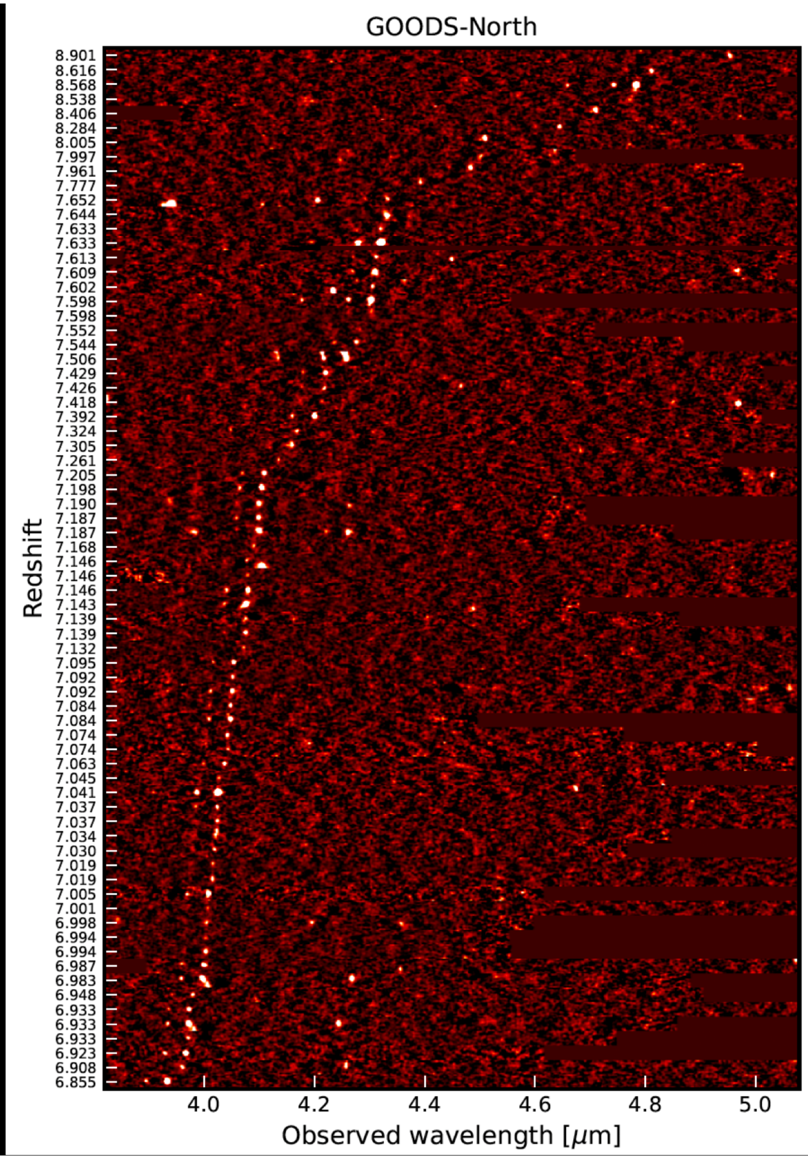
x Fraction that evade dust+HI

= $\rho_{UV}\ \xi_{ion}\ f_{esc}$

Emission-line galaxies drive reionization



Meyer+24, FRESCO, ~50% L*

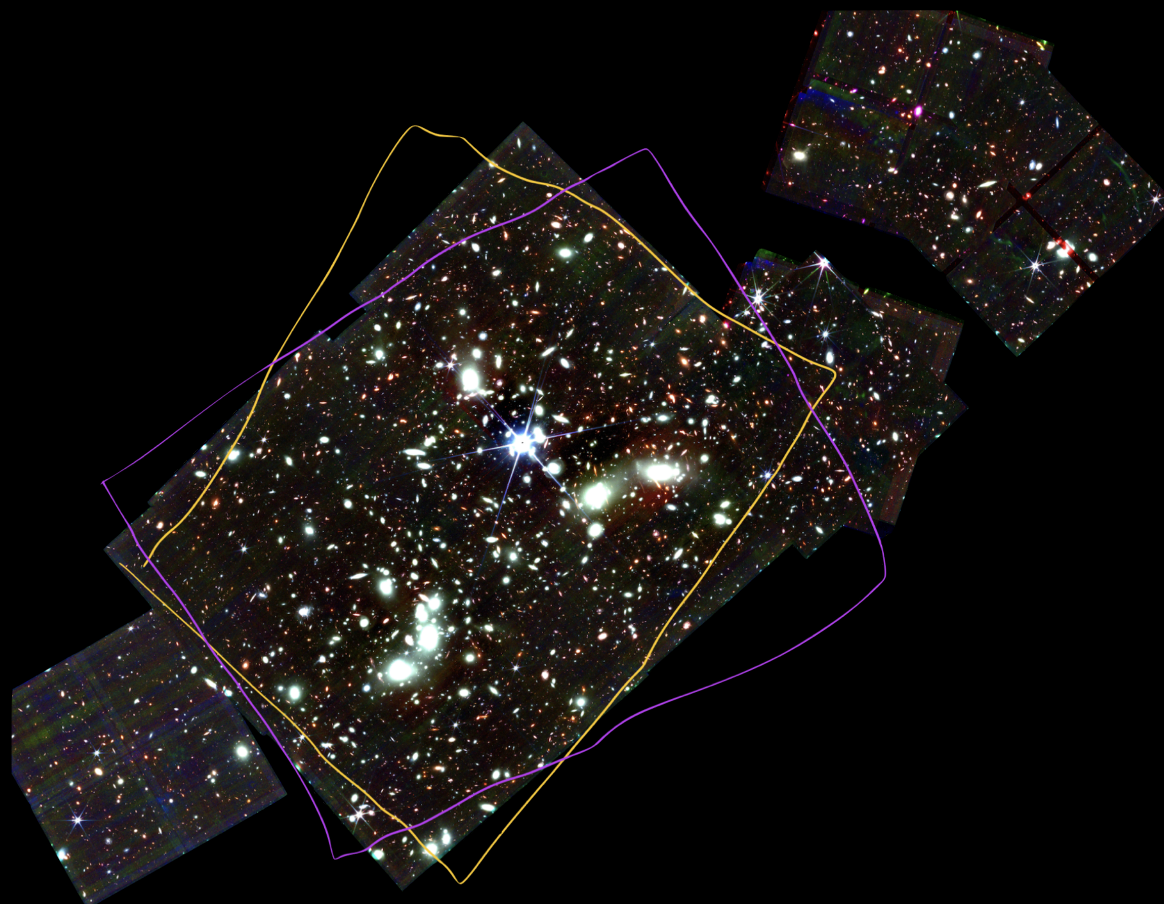


All the Little Things

PIs: Naidu & Matthee

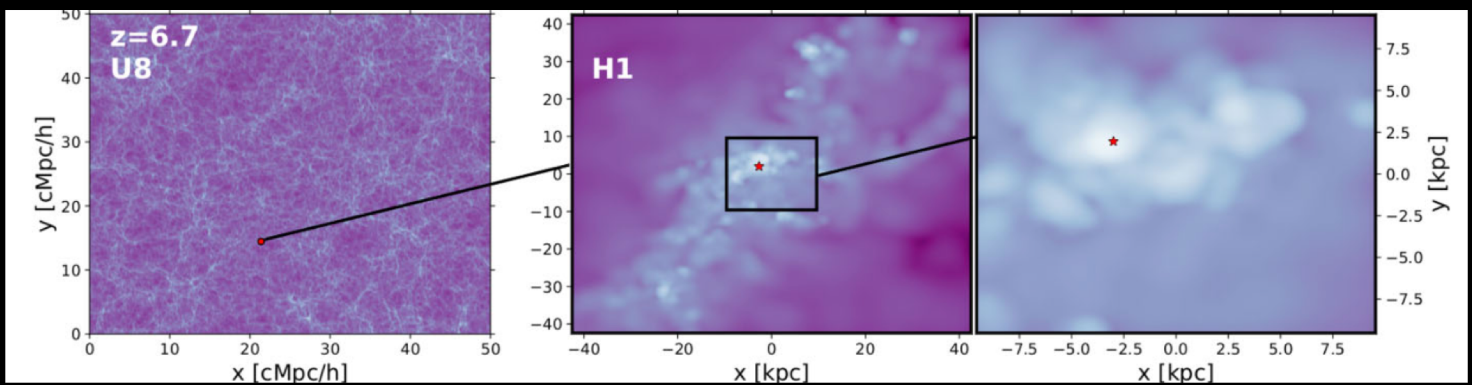
~50 hr NIRCam grism + imaging over Abell 2744

Deepest grism spectra till date (7-27hrs!)



Metal-poor (perhaps metal-free?) stars

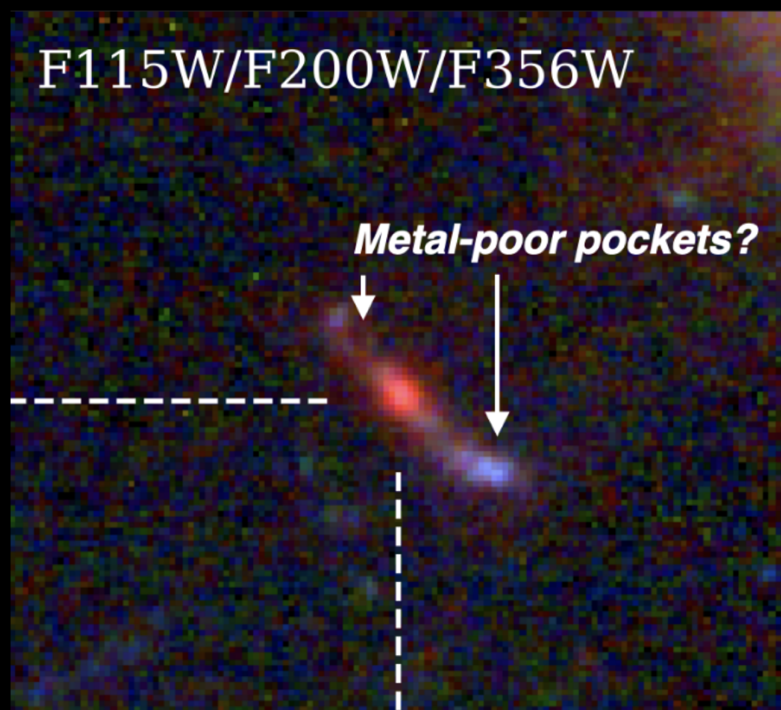
- Very first Pop-III stars at z>15 need 100m telescope on the moon (mag~40) e.g., Schauer+20
- But…in cutting-edge simulations, Pop-III star-formation possible out to z~6-7 e.g., Venditti+23,+24, Katz+23



Venditti+23

Metal-poor (perhaps metal-free?) stars

- Metal-poor regions, some with very low O3/Hb<2 observed.



EIGER
Survey

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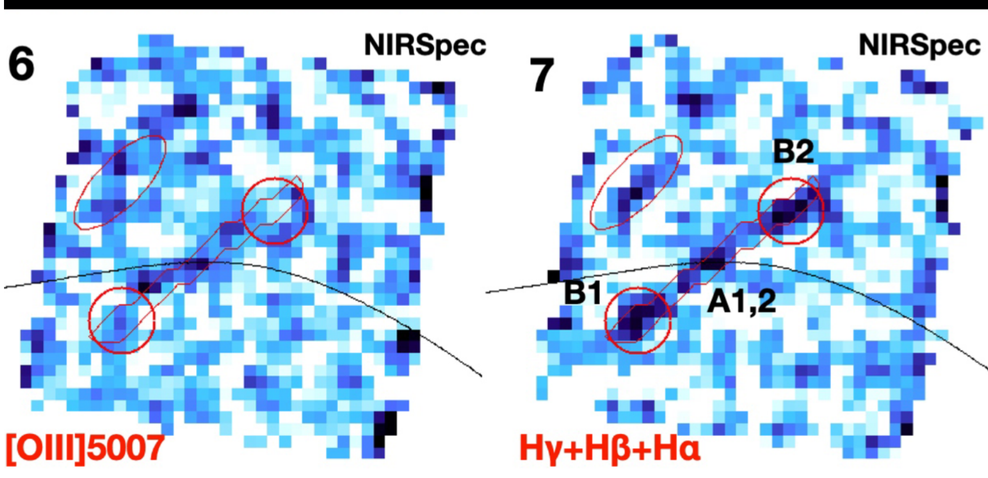

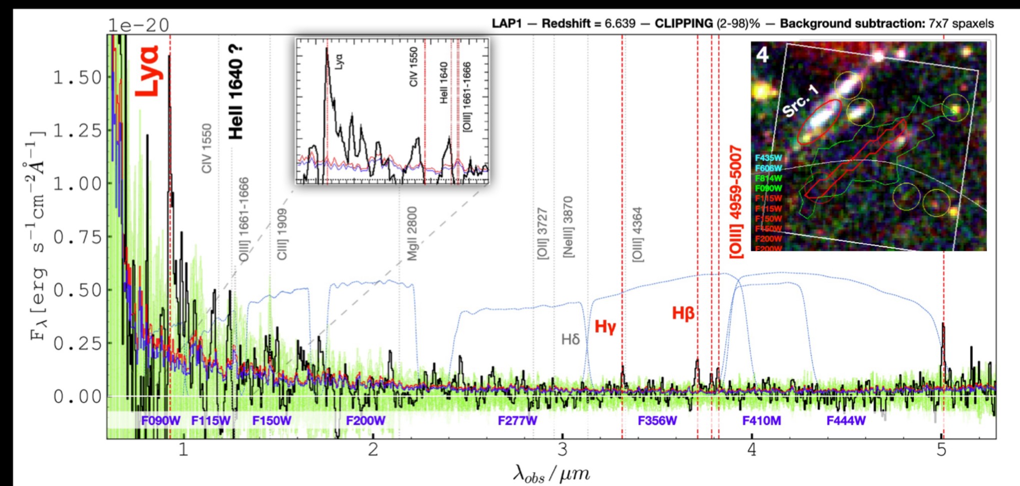

Vanzella+23, LAP1 at z=6.63, O3<Hb
Cycle 3 -- PI: Nakajima, ~70 h

All the Little Things

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~50 hr NIRCam grism + imaging over Abell 2744

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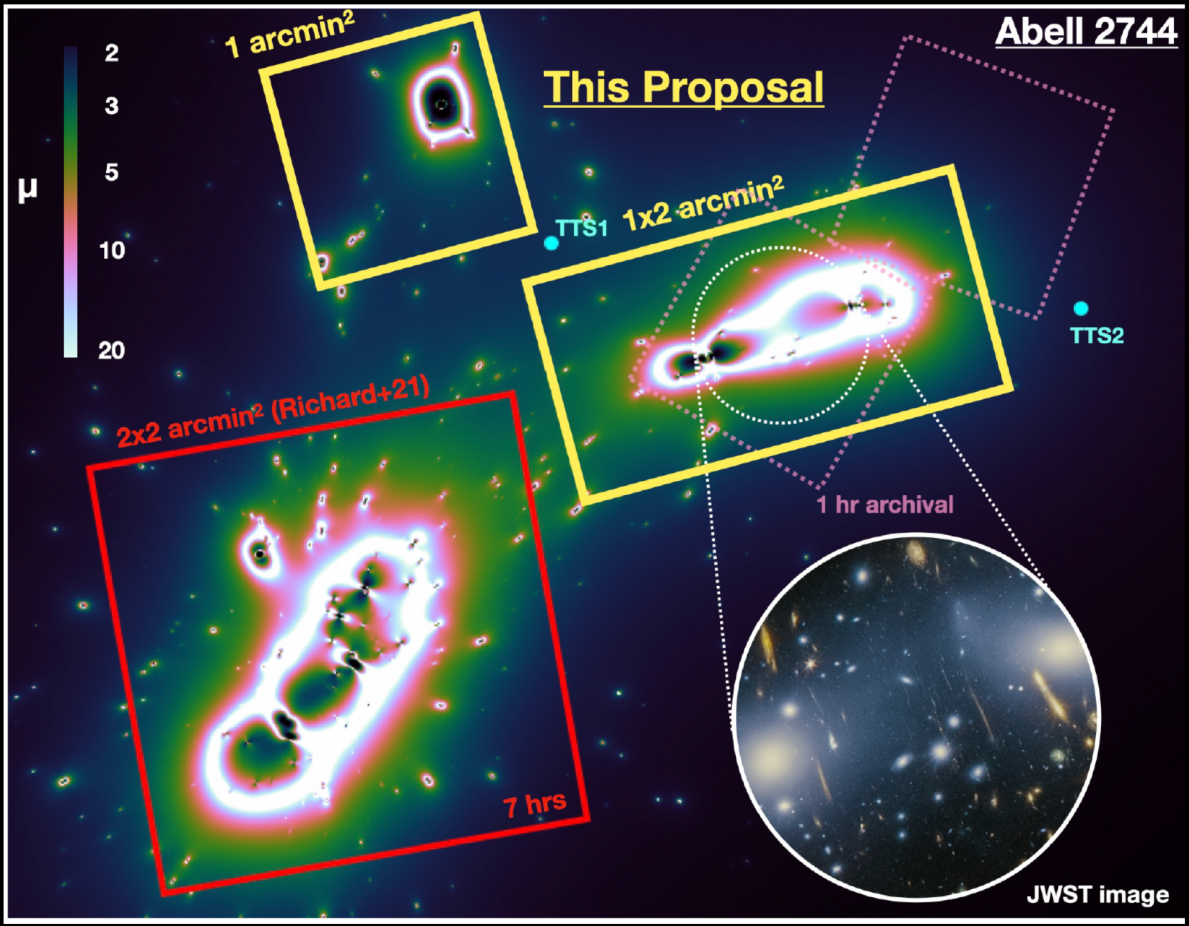
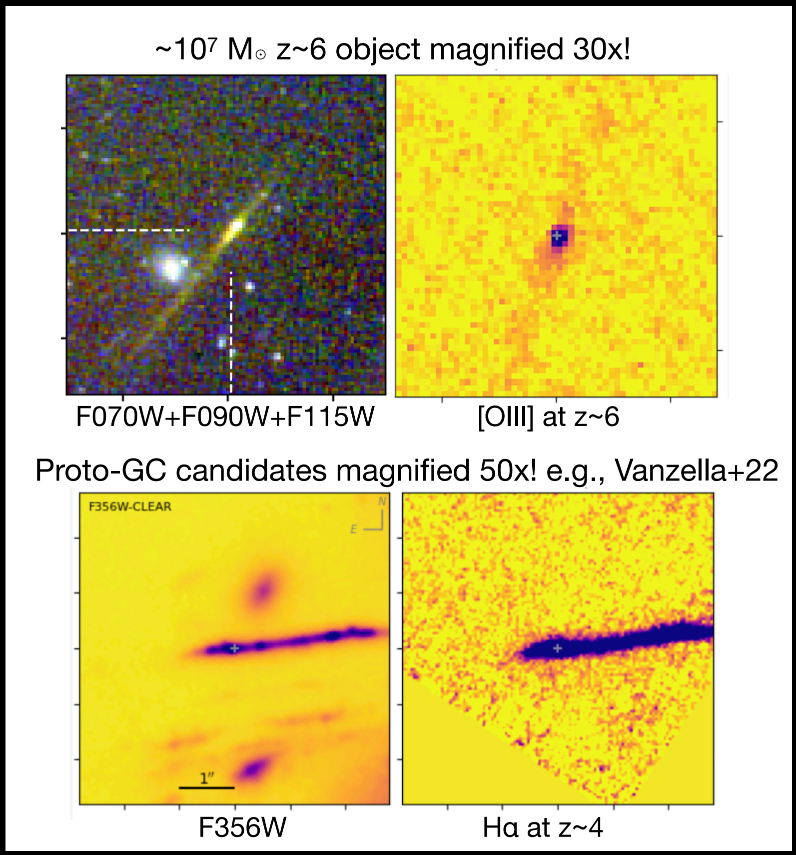


All the Little Things

>500 ultra-faint (~0.1-10% L*) galaxies in the EoR



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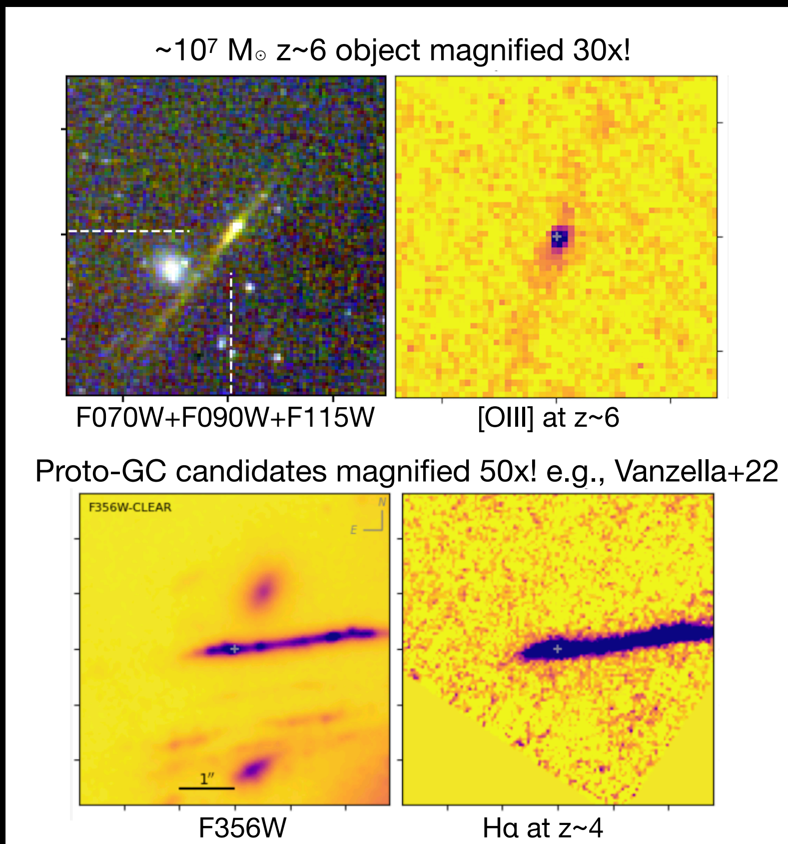
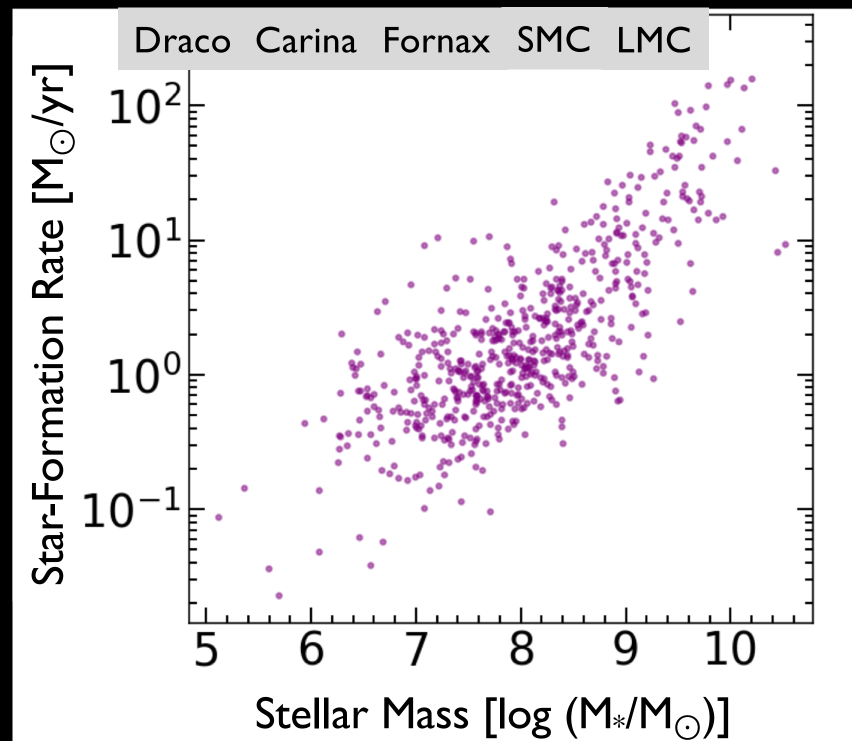
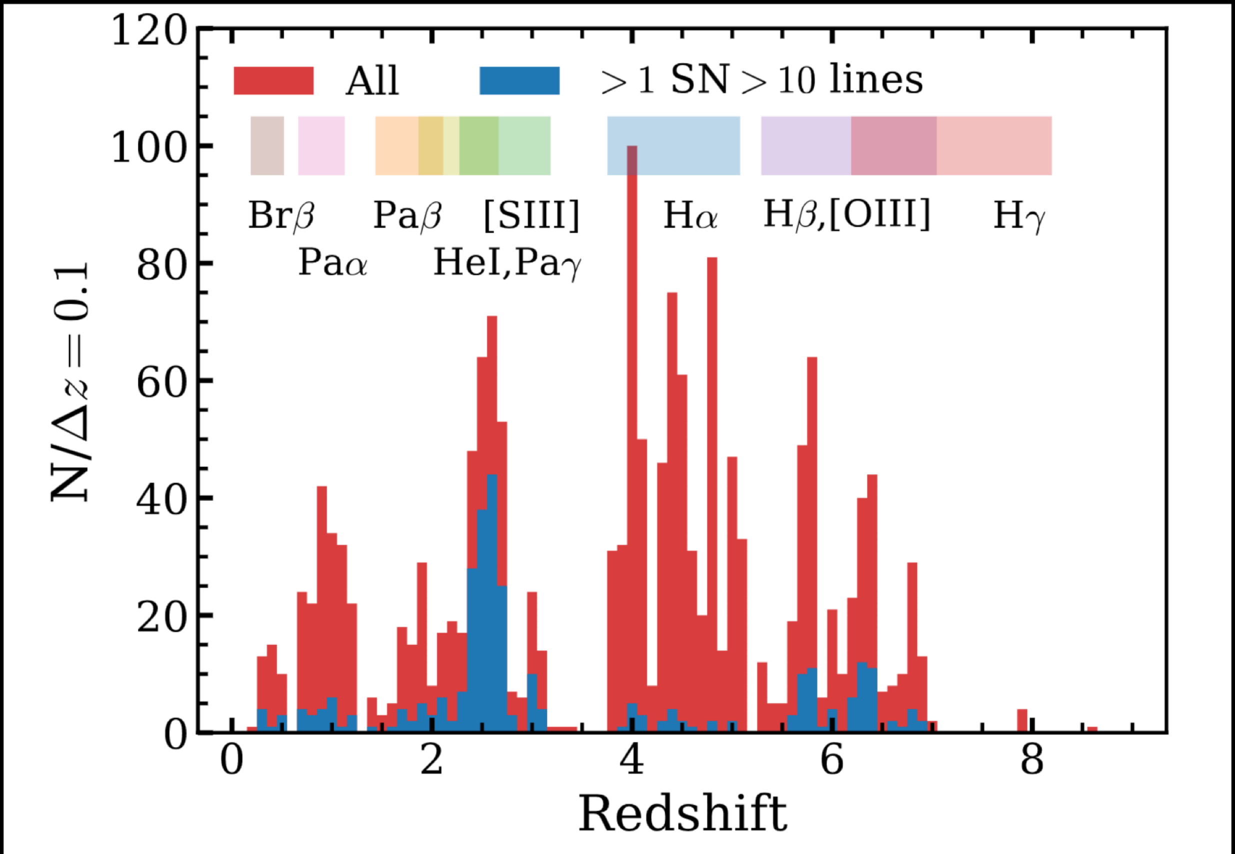




~1000 <SMC-mass galaxies in sample, tripling the JW archive

All the Little Things Propaganda

- Pan-redshift coverage!



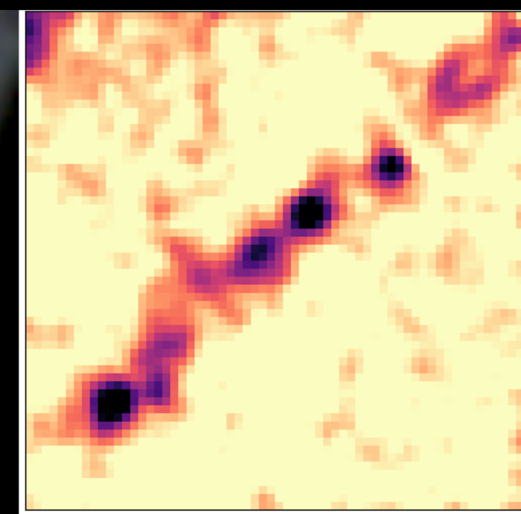
All the Little Things Propaganda

- Line-maps!

NIRCam SW

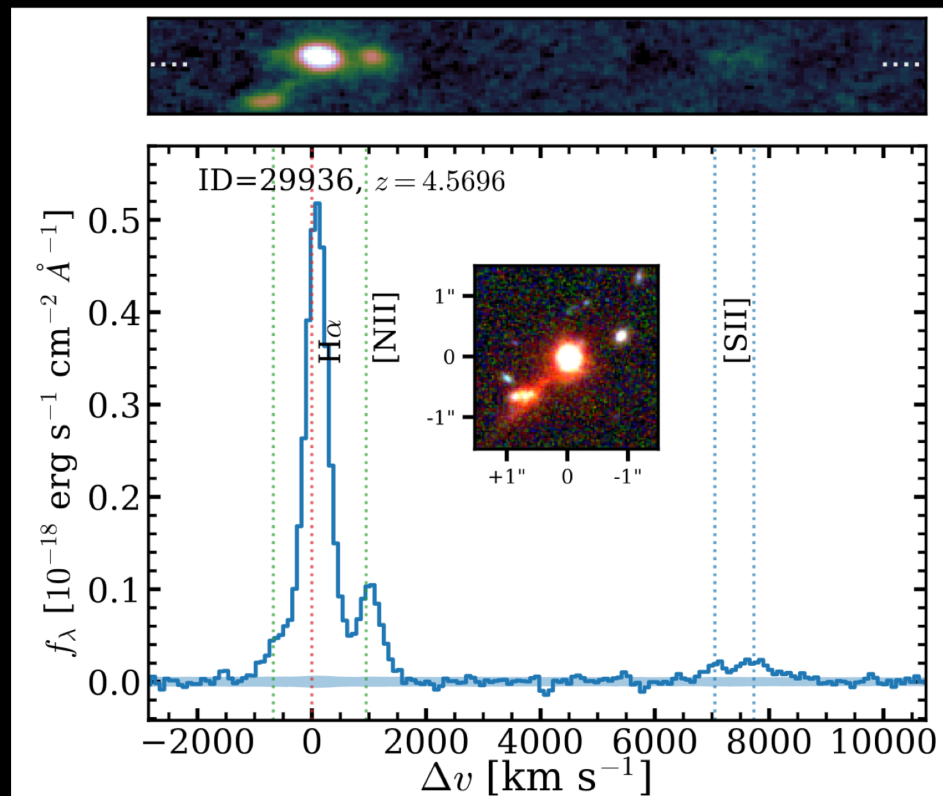
NIRCam LW

Paschen-α, z=0.8



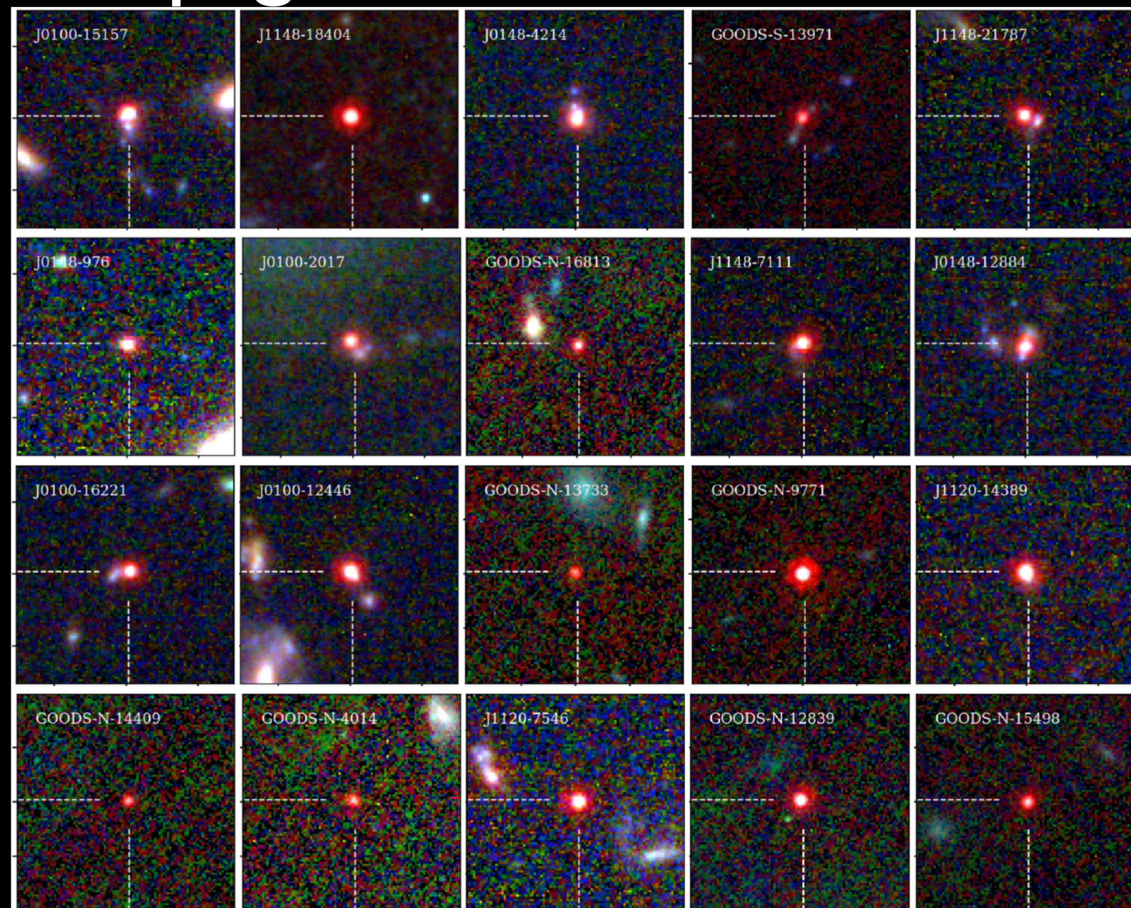
All the Little Things Propaganda

- Resolution (R~1600)!



All the Little Things Propaganda

- Rare objects (e.g., ultra-massive galaxies, Little Red Dots, …)



Matthee, Naidu+24

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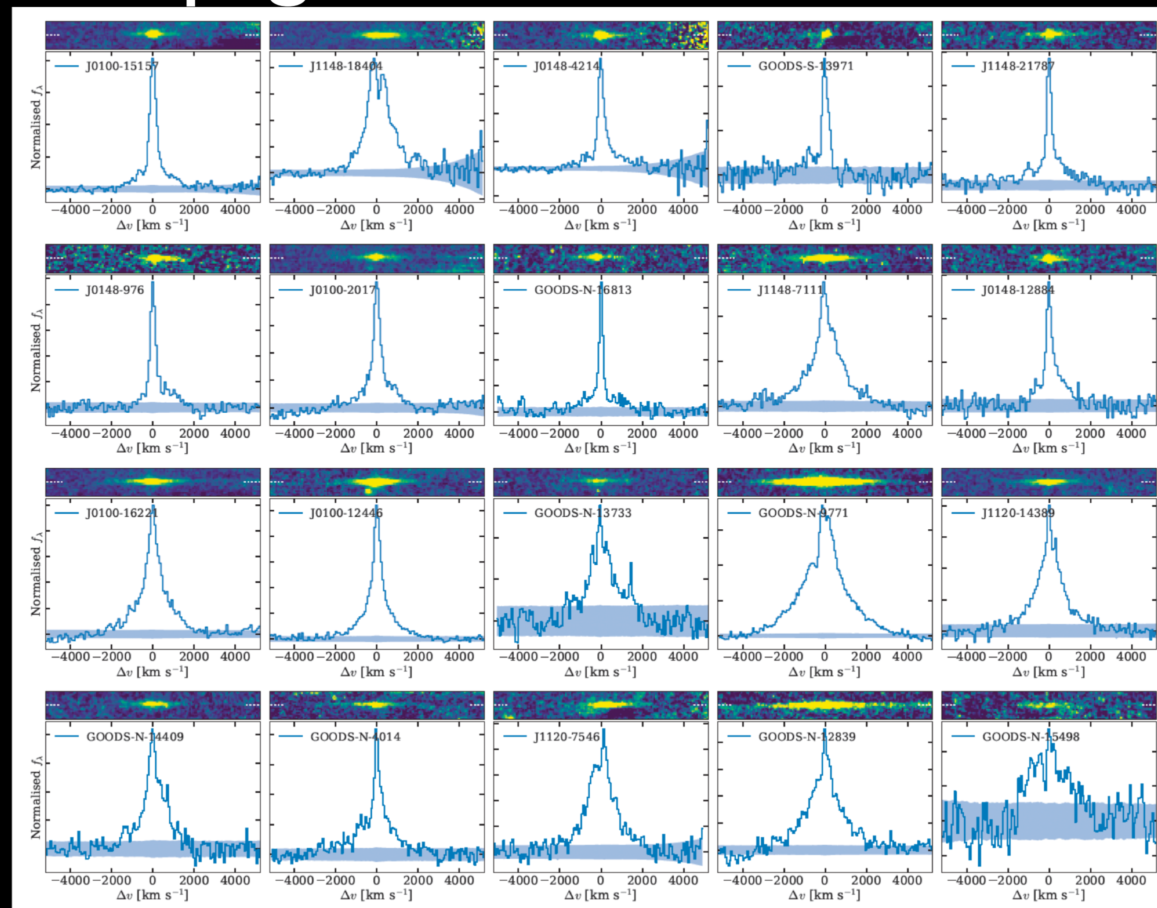

Matthee, Naidu+24

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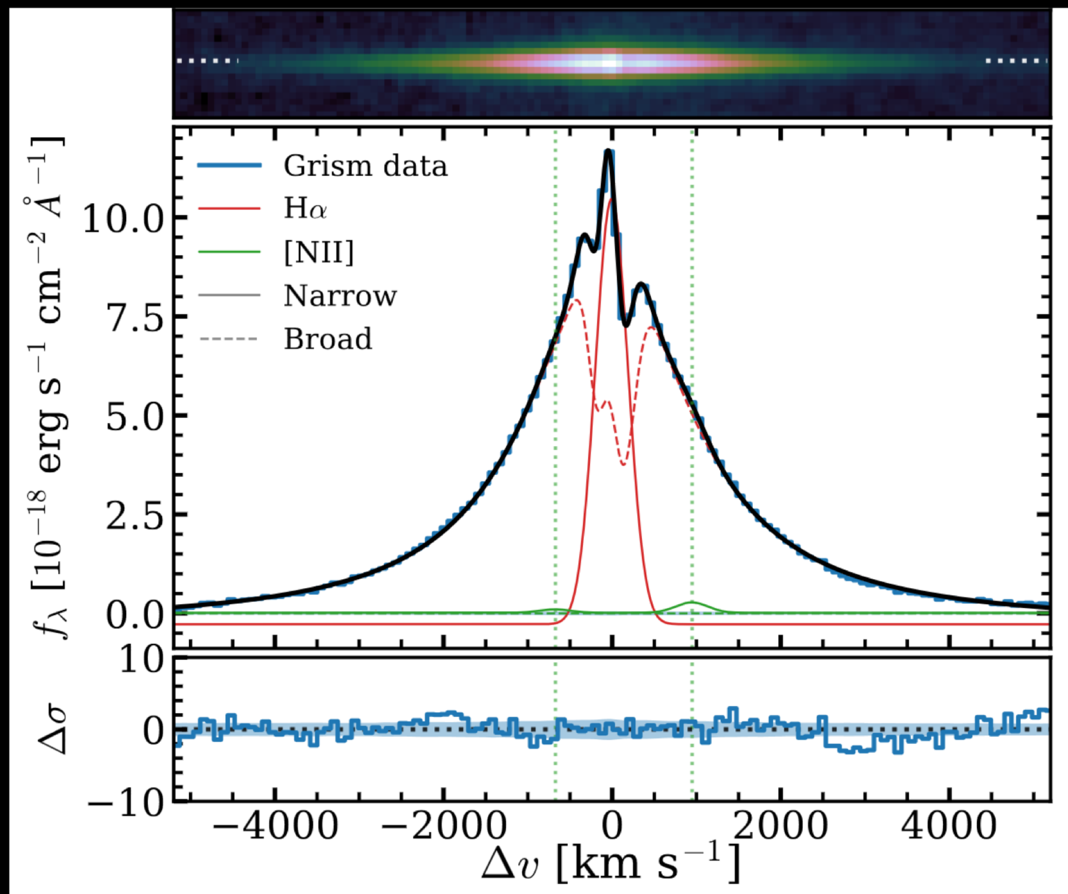
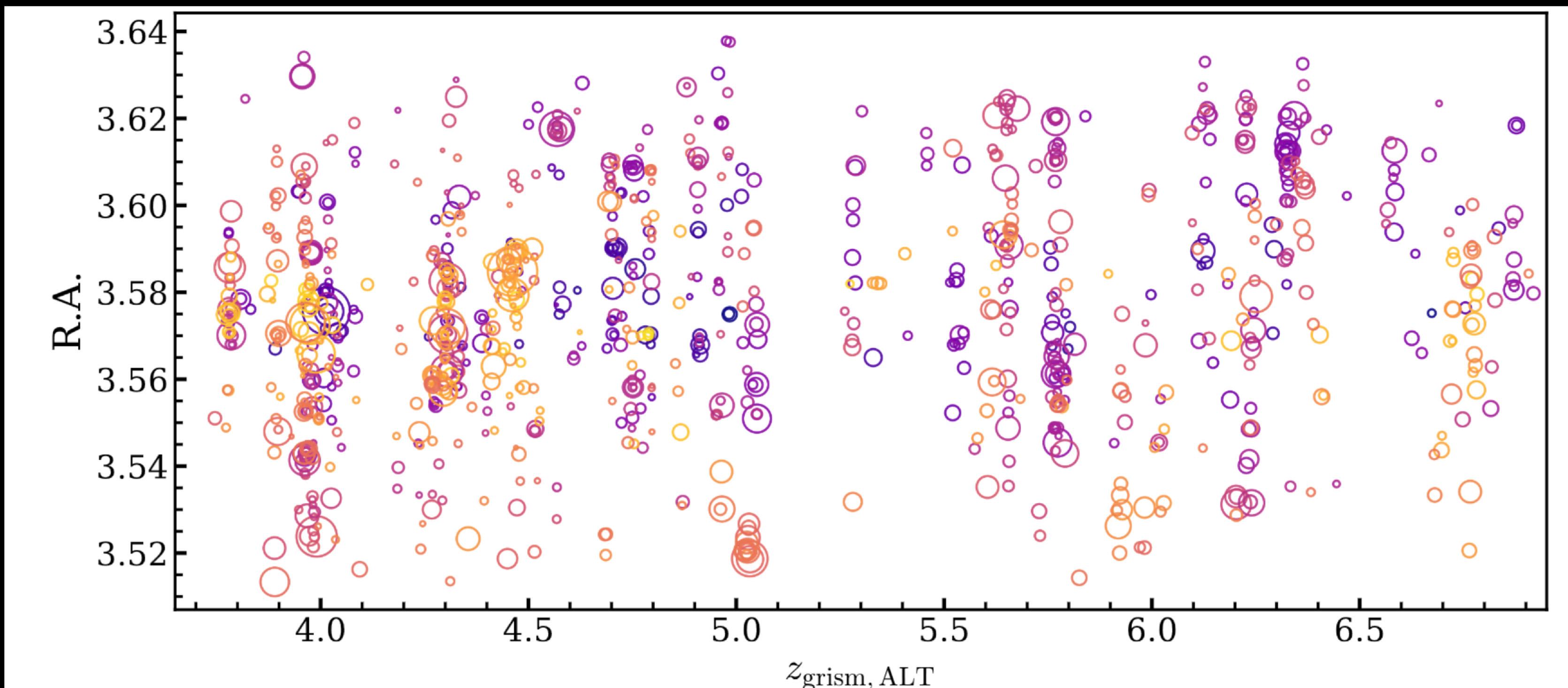


Labbe, Greene+ in prep.

All the Little Things Propaganda

- Clustering/environments



All the Little Things Propaganda

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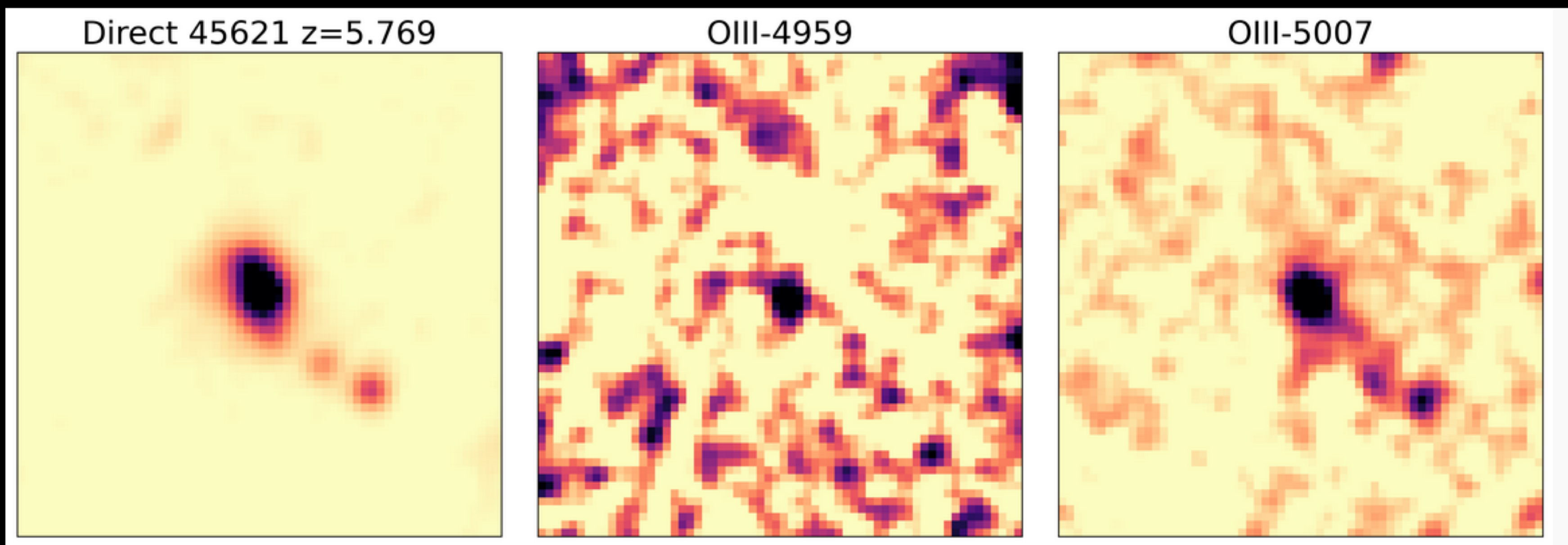
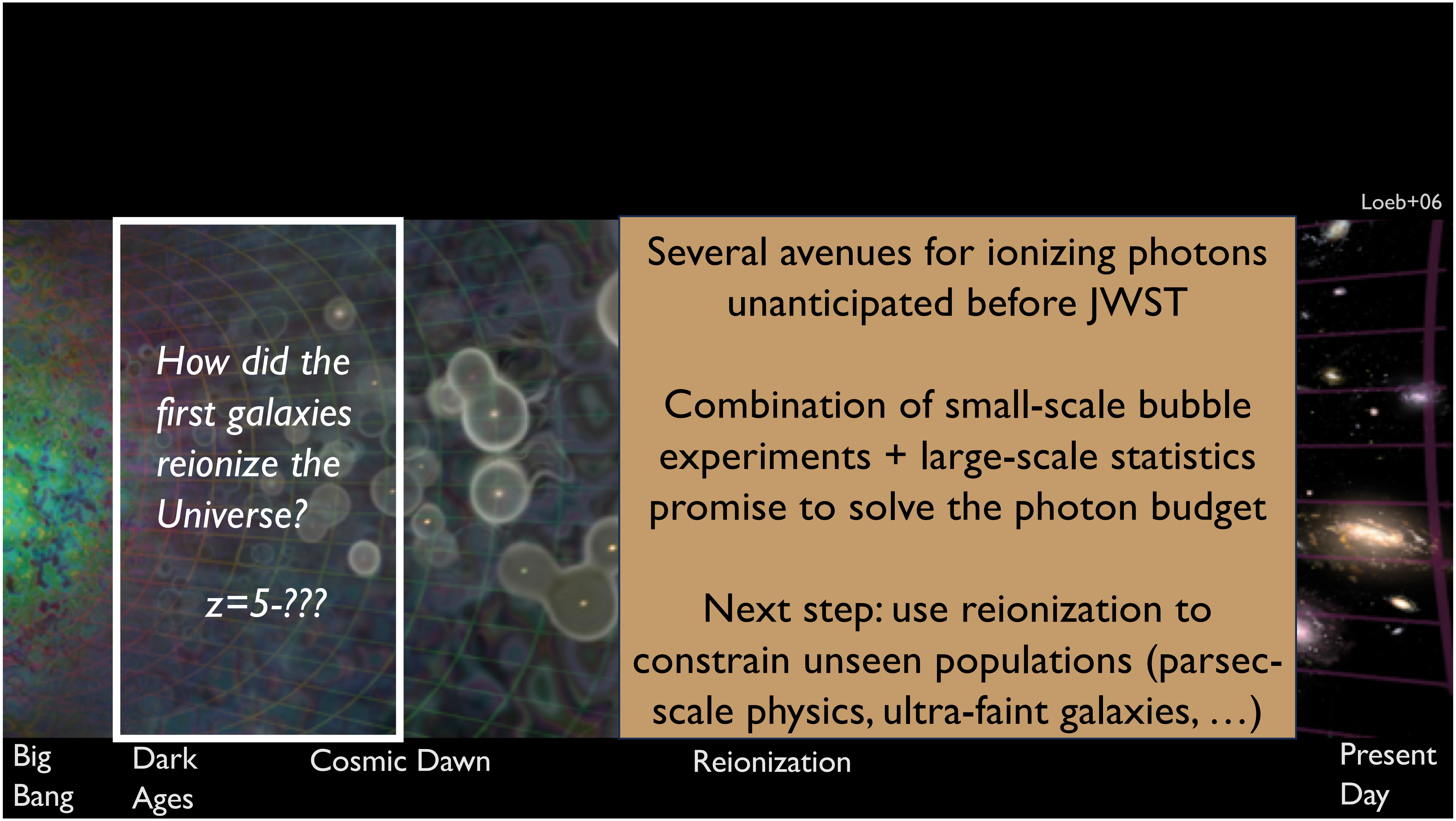


Milky Way + LMC + SMC analog by mass-ratio


Loeb+06
How did the first galaxies reionize the Universe?
z=5-???
Several avenues for ionizing photons unanticipated before JWST
Combination of small-scale bubble experiments + large-scale statistics promise to solve the photon budget
Next step: use reionization to constrain unseen populations (parsec-scale physics, ultra-faint galaxies, …)
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day

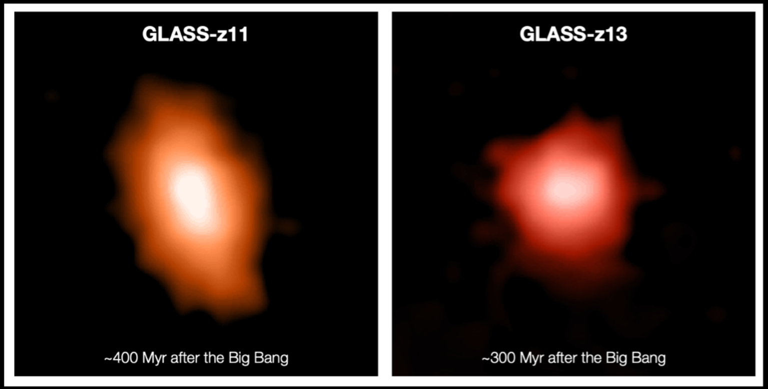
1920: do other galaxies exist?
2020s: a final expansion of the cosmic frontier to the brink of the Big Bang

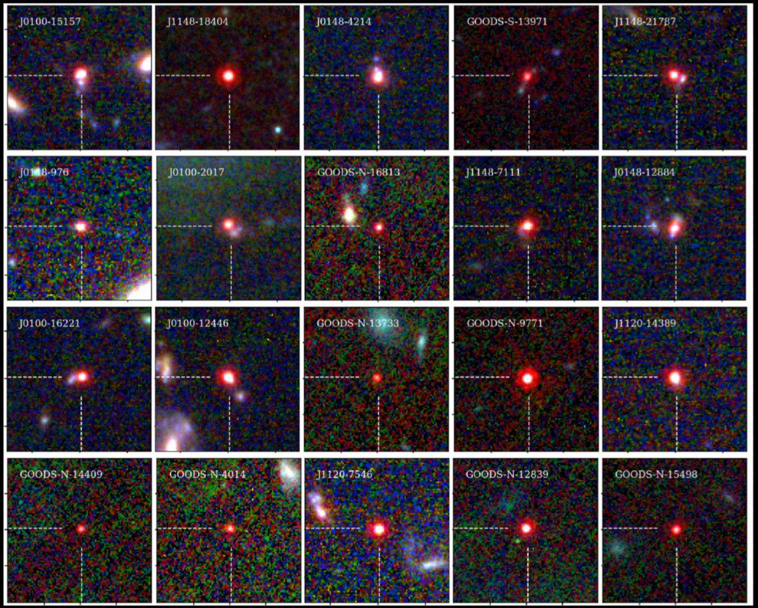
Loeb+06

Big Bang | Dark Ages | Cosmic Dawn | Reionization | Present Day

Summary

- *JWST* is revealing epochs of the Universe we've never seen before.
  - Remarkably luminous z>10 galaxies
  - An abundance of supermassive black holes
  - Extremely metal-poor galaxies
  - The sources of cosmic reionization?
- A golden era for early universe astronomy beckons!





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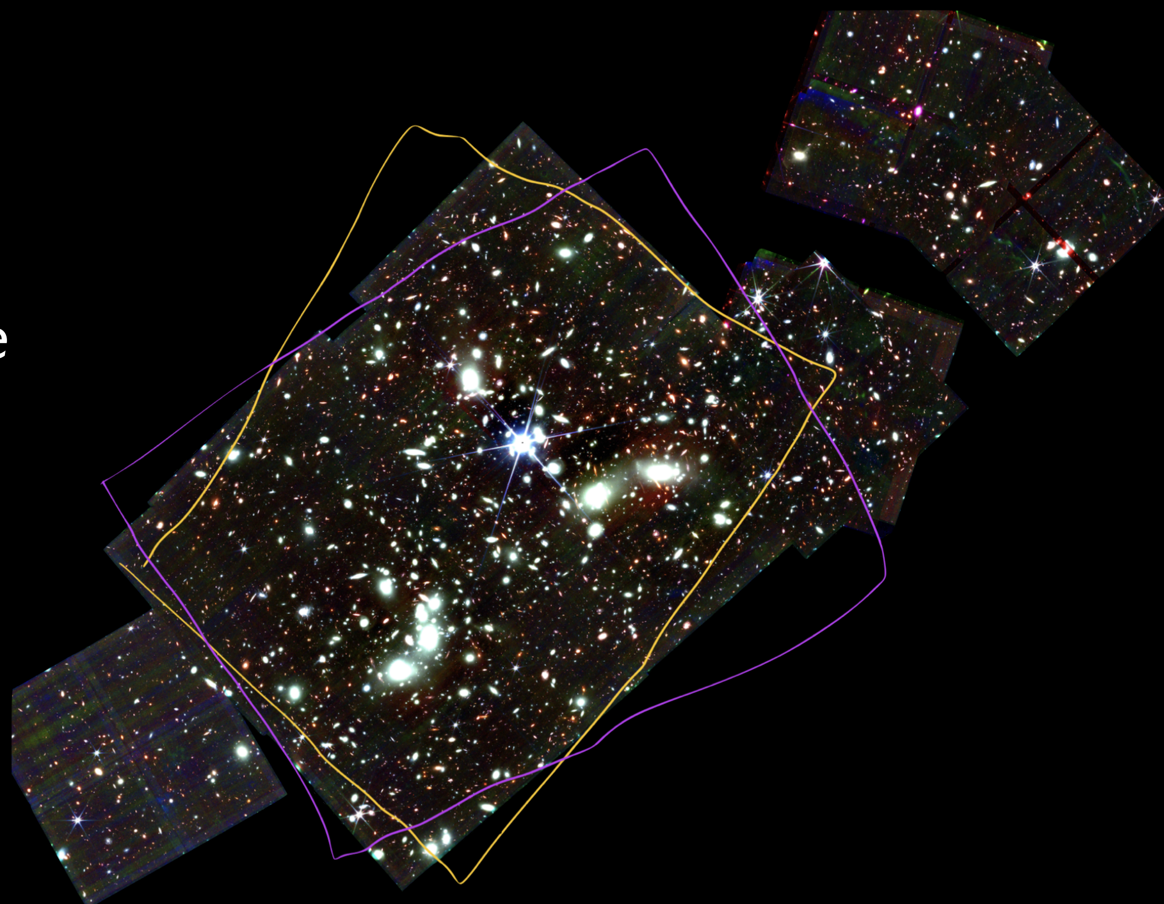
All the Little Things:

Pop III Signatures & the Ionizing Photon Budget of Dwarf Galaxies in the Epoch of Reionization

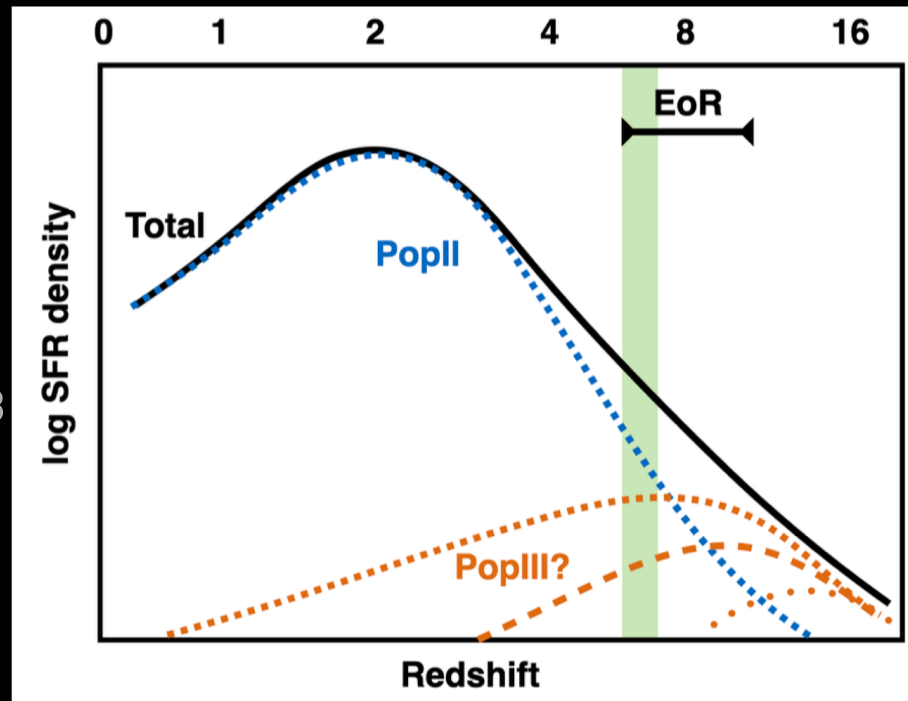
PIs: Naidu & Matthee

~50 hr NIRCam grism + imaging program over Abell 2744



Metal-poor (perhaps metal-free?) stars

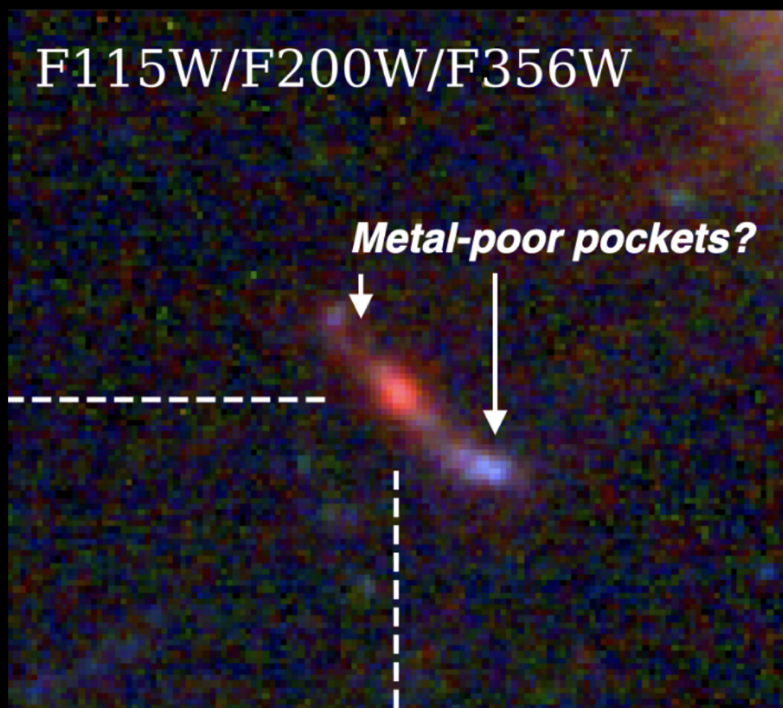
- Very first Pop-III stars at z>15 need 100m telescope on the moon (mag~40) e.g., Schauer+20
- But…late Pop-III star-formation possible out to z~6-7 e.g., Venditti+23



Based on Venditti+23

Metal-poor (perhaps metal-free?) stars

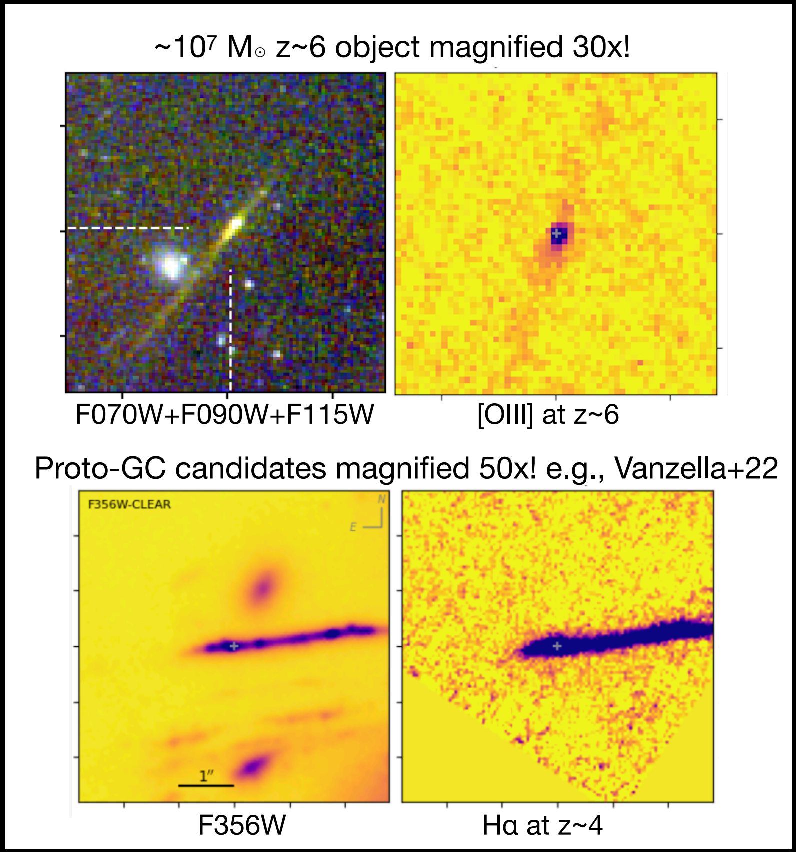
- Metal-poor pockets, some with very low O3/Hb<2 observed.



EIGER Survey

All the Little Things

>500 ultra-faint (0.1-10% L*) galaxies at z=5-7



All the Little Things

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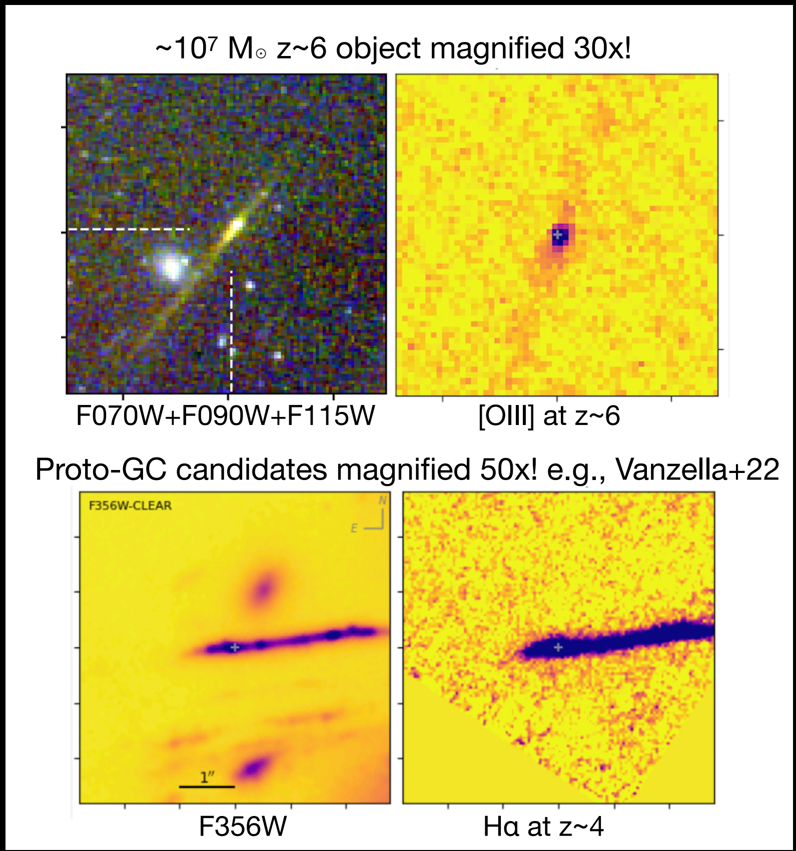
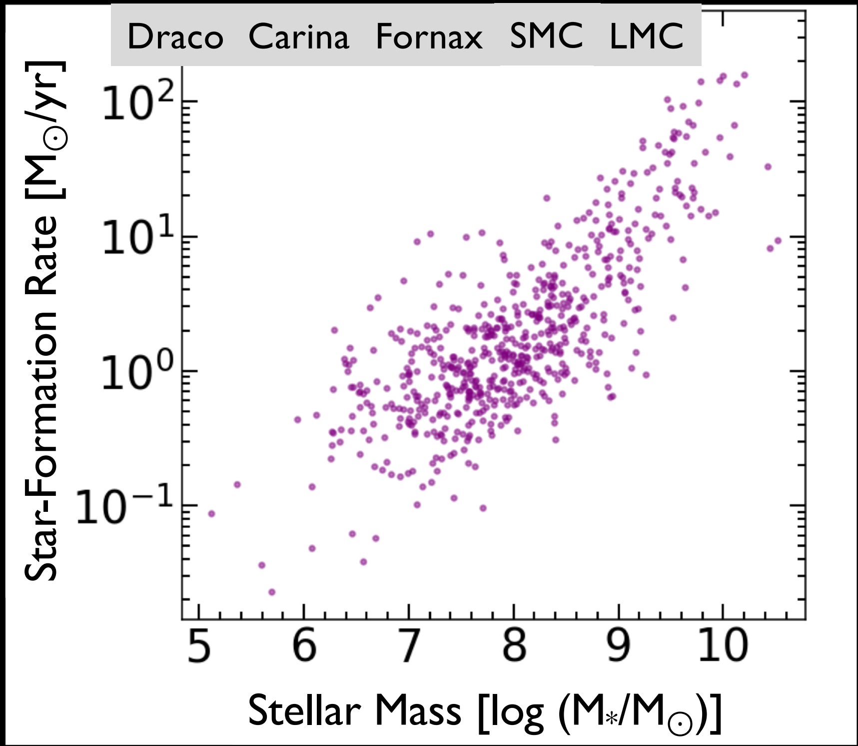
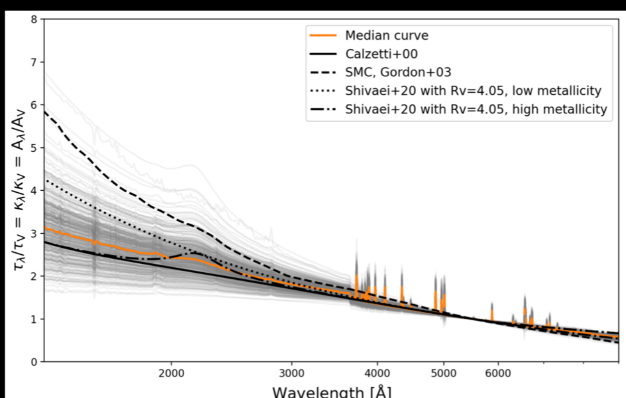


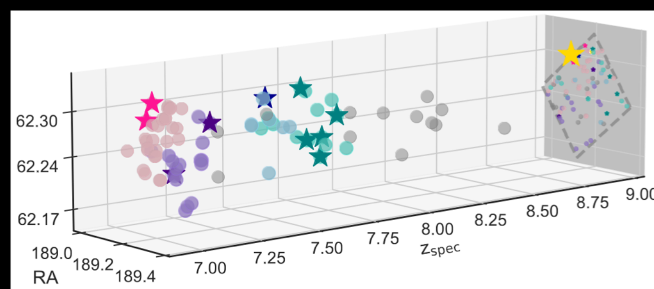


The sheer numbers/completeness enable diverse science

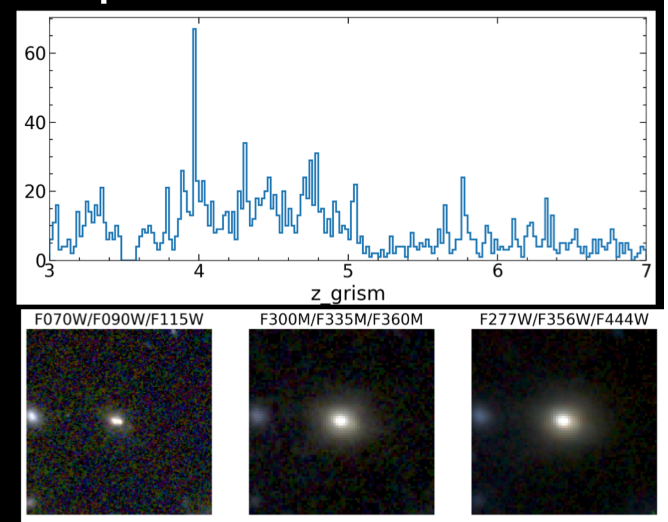
- A new dust law for z>6 galaxies Irene Shivaei, Naidu+ in prep.

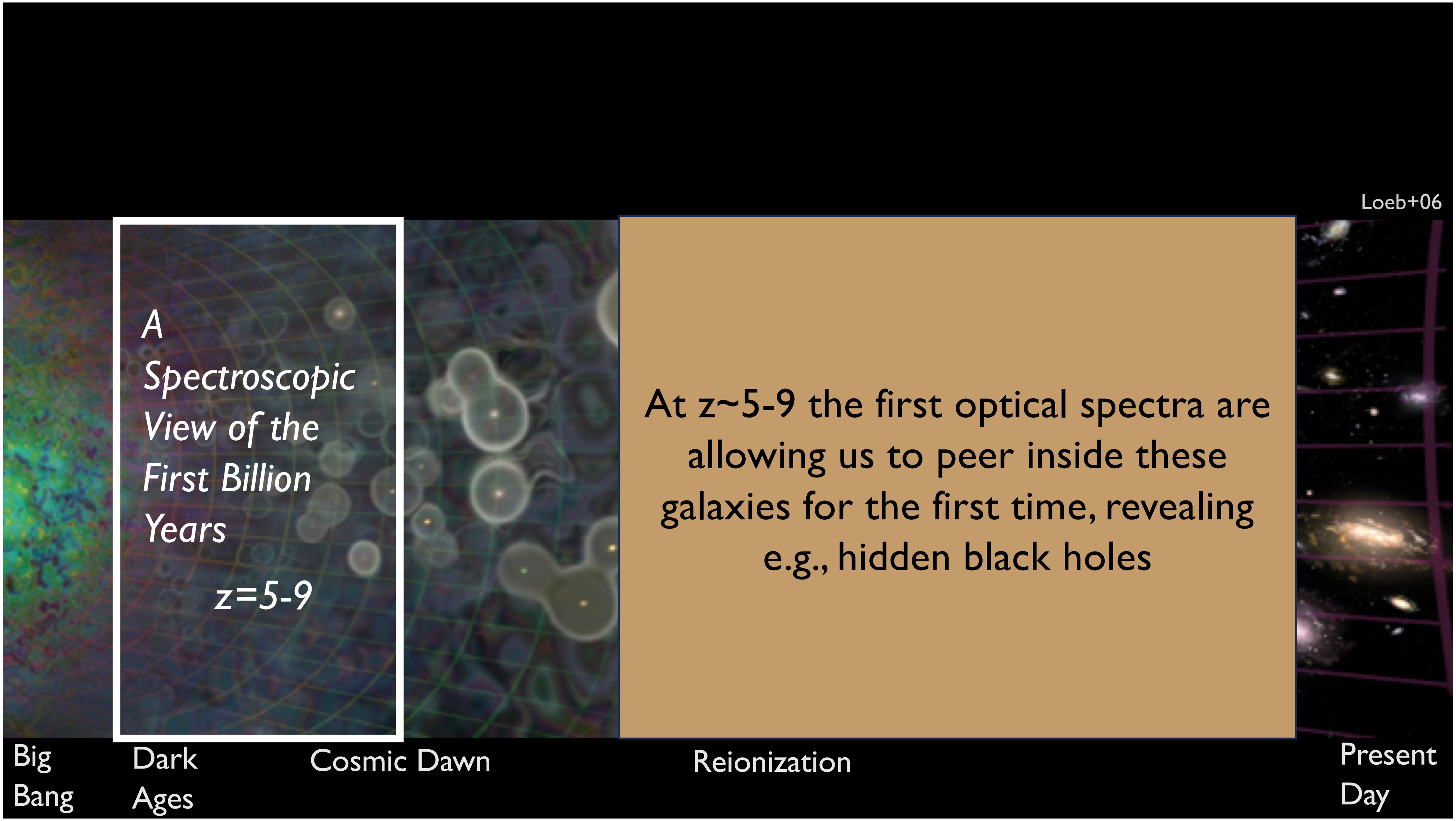


- Ionization field in the Epoch of Reionization Kate Leonova, Naidu+ in prep.

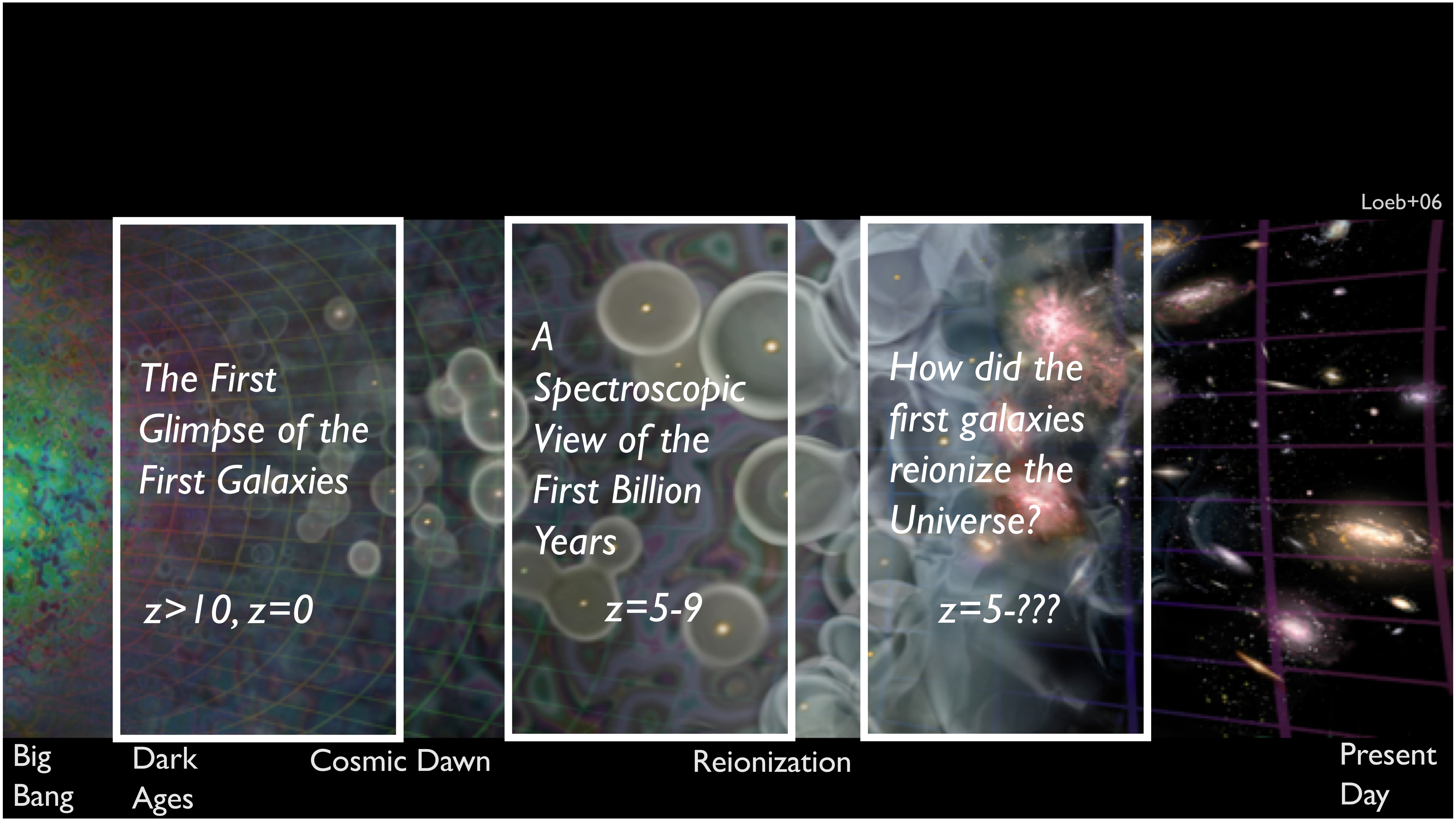


- Ultra-massive galaxies in density spikes

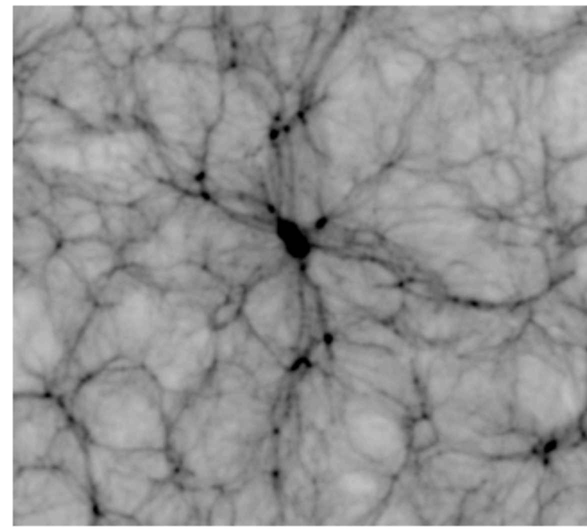




Loeb+06
A Spectroscopic View of the First Billion Years
z=5-9
At z~5-9 the first optical spectra are allowing us to peer inside these galaxies for the first time, revealing e.g., hidden black holes
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day

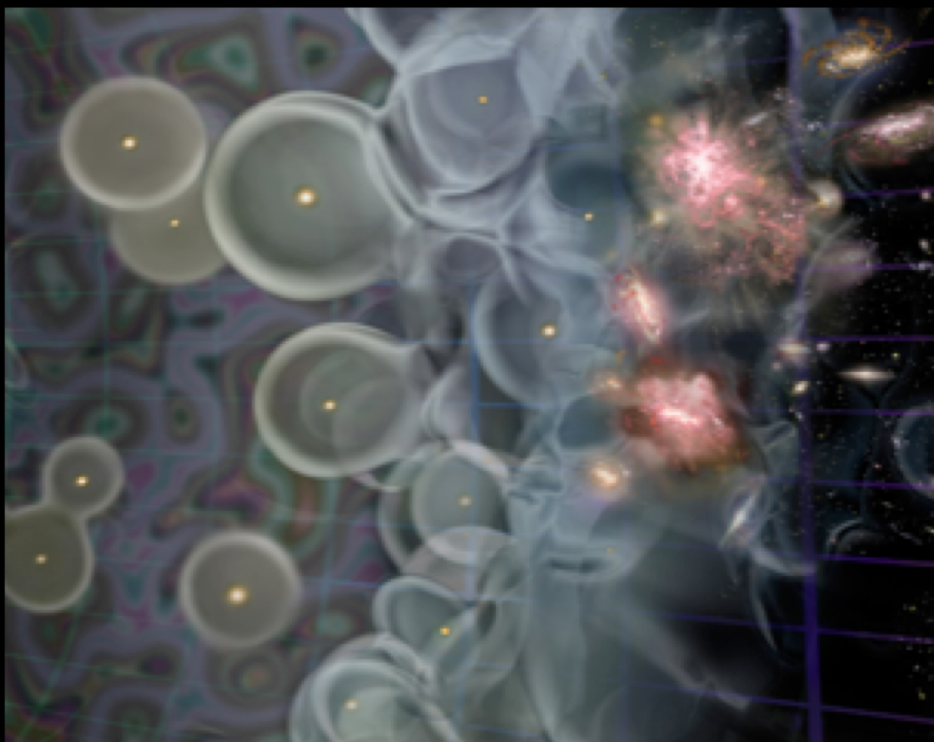

Loeb+06
The First Glimpse of the First Galaxies
z>10, z=0
A Spectroscopic View of the First Billion Years
z=5-9
How did the first galaxies reionize the Universe?
z=5-???
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day

Reionization: a focal point for all early universe physics



- Production of ionizing photons (metal-poor stars, binaries, accretion disks)
- Journey through interstellar medium (dust, gas, feedback)
- Contact with intergalactic medium (large-scale structure, gas physics)

Reionization: where did the photons come from?



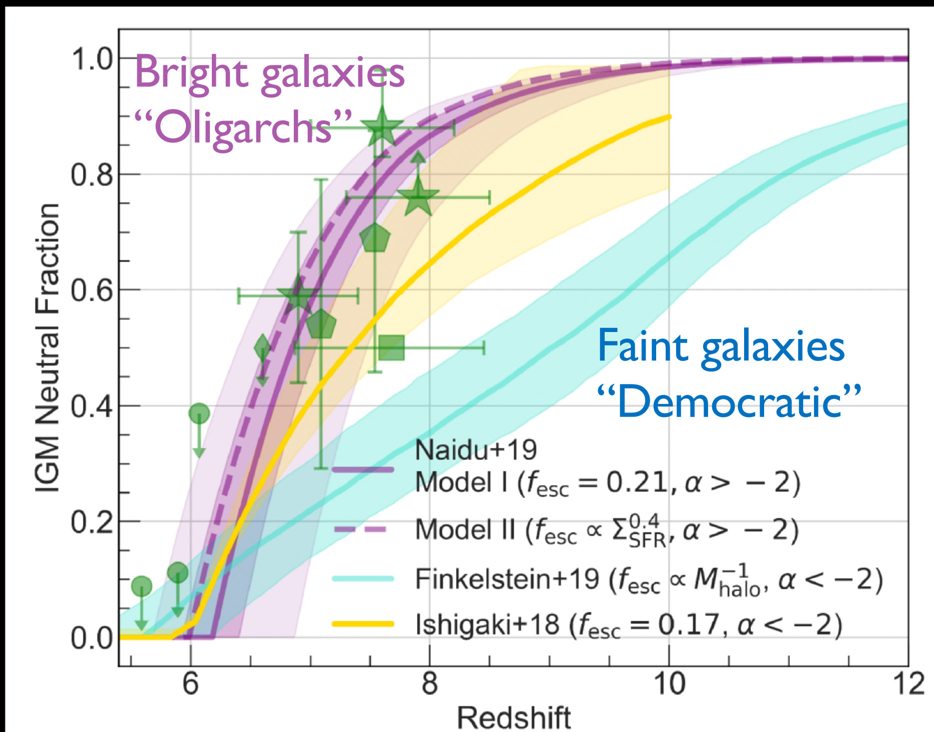
- Numerous, tiny, faint galaxies?
  “Democratic Reionization”
  Wise+14, Finkelstein+19, Chisholm+22

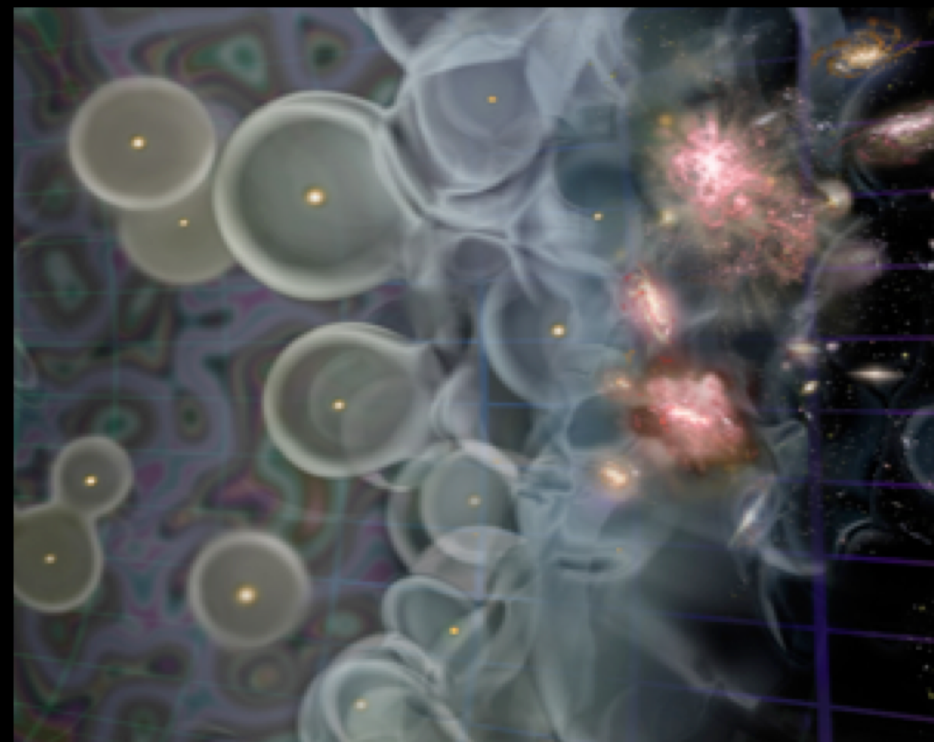
- Rare, bright, massive galaxies?
  “Reionization by the Oligarchs”
  Naidu+20, Naidu & Matthee+22, Matthee & Naidu+22

- Little Red Dots? Madau+15, Giallongo+15, Finkelstein+19

Reionization: where did the photons come from?

Timeline



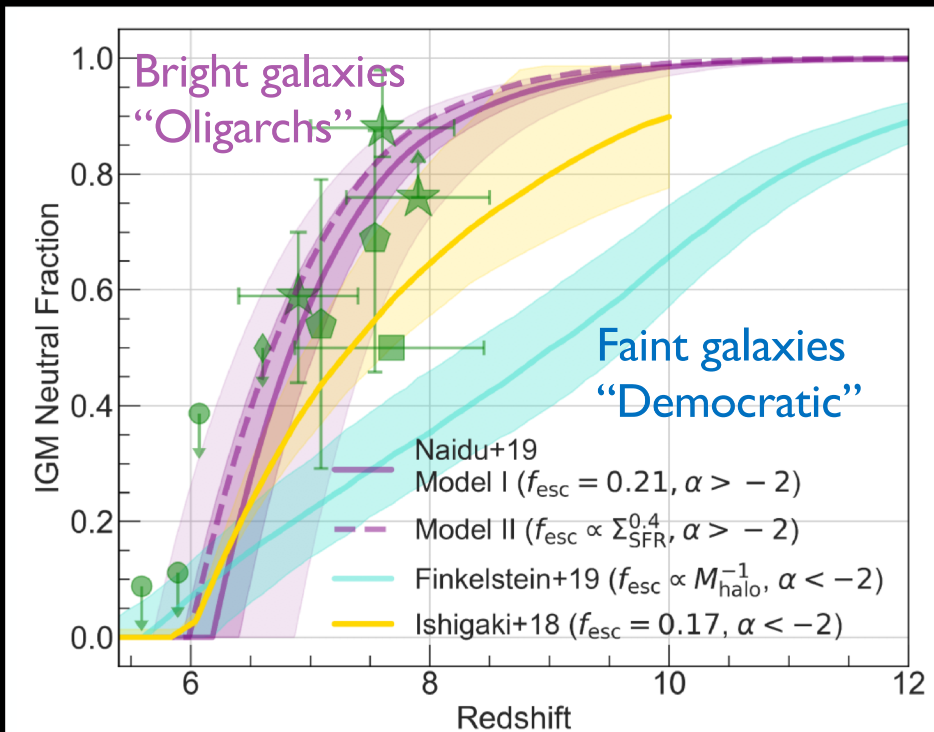


Naidu+20, Tacchella+18

- Radically different pictures of reionization.

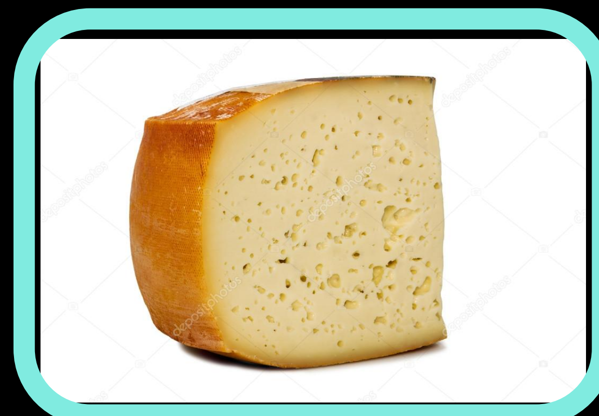
Reionization: where did the photons come from?

Timeline



Naidu+20, Tacchella+18

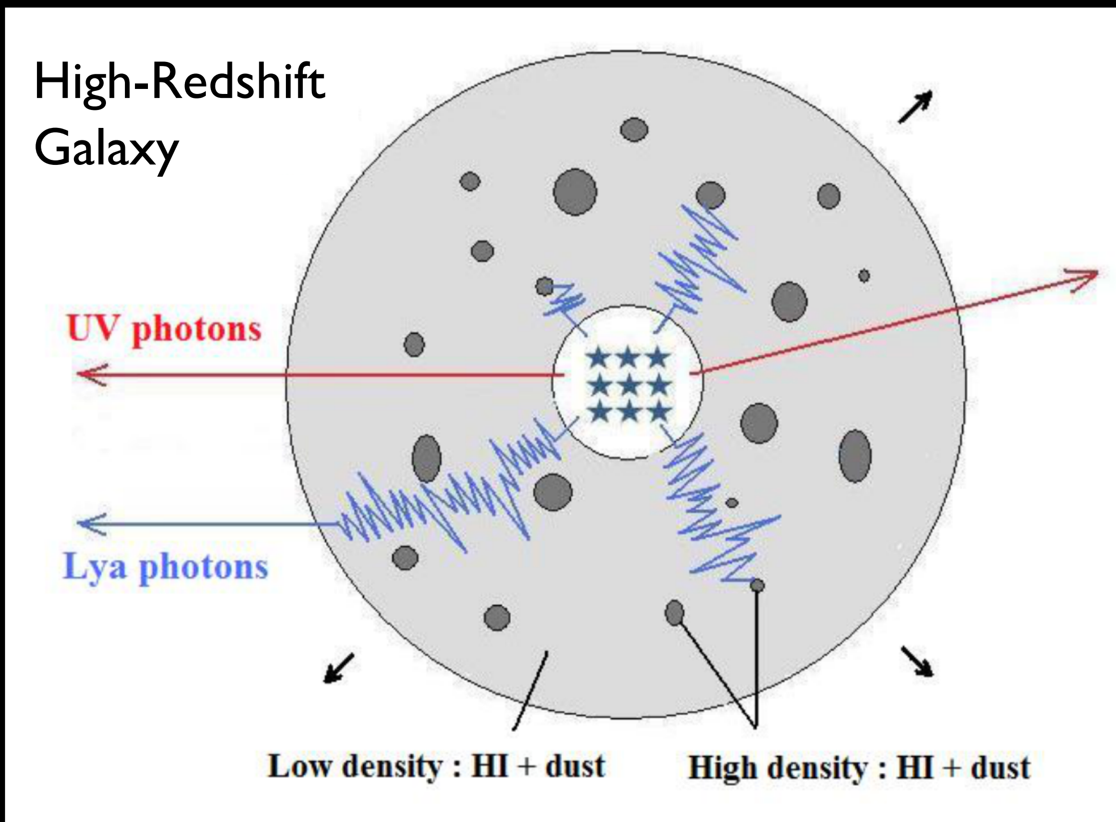
Topology



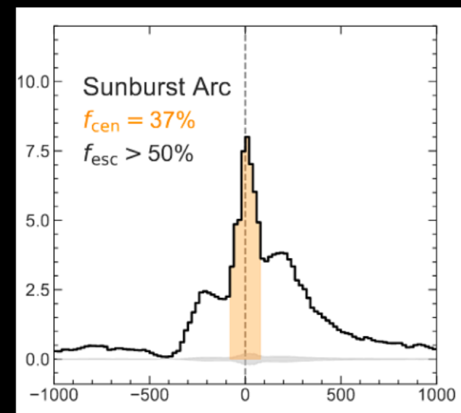
- Radically different pictures of reionization.
- Set the course of galaxy evolution across cosmic time (e.g., Milky Way satellite counts)

High-resolution Lyman-α: a key probe for reionization

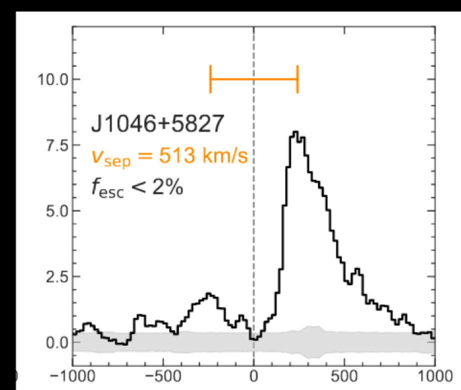
Naidu & Matthee+22; Matthee & Naidu+22
c.f. Izotov+18, Flury+22, Verhamme+18,
Gronke+18, Giovinazzo+24, Pahl+24



Duval+14



Highly Ionizing



Poorly Ionizing

High-resolution Lyman-α: a key probe for reionization

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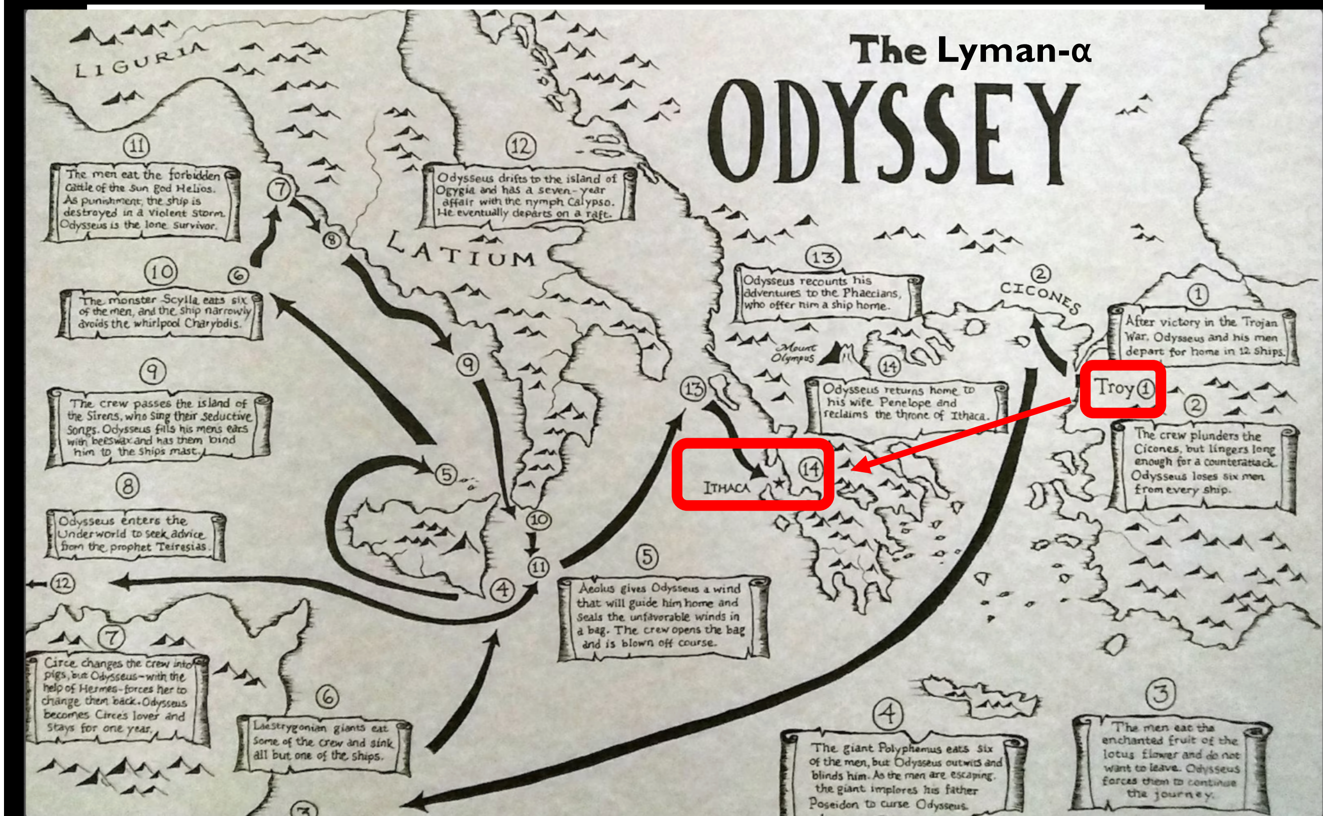
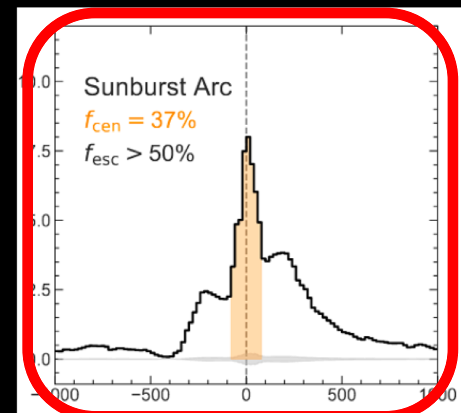
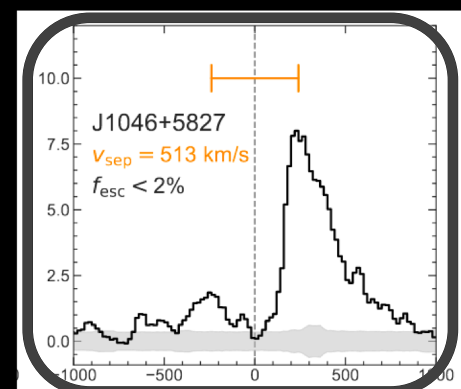


Duval+14

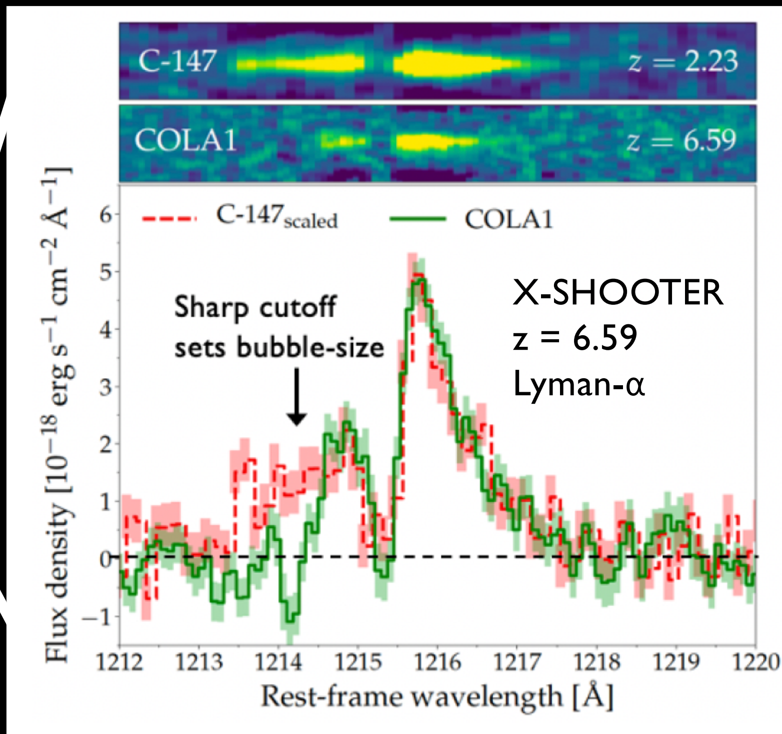


Highly Ionizing



Poorly Ionizing

Which galaxies reionized the Universe?
JWST bubble program PI: Naidu & Matthee



z~7 bubble with strongly constrained size Hu+16, Matthee+18, Mason & Gronke 2020

Which galaxies reionized the Universe?
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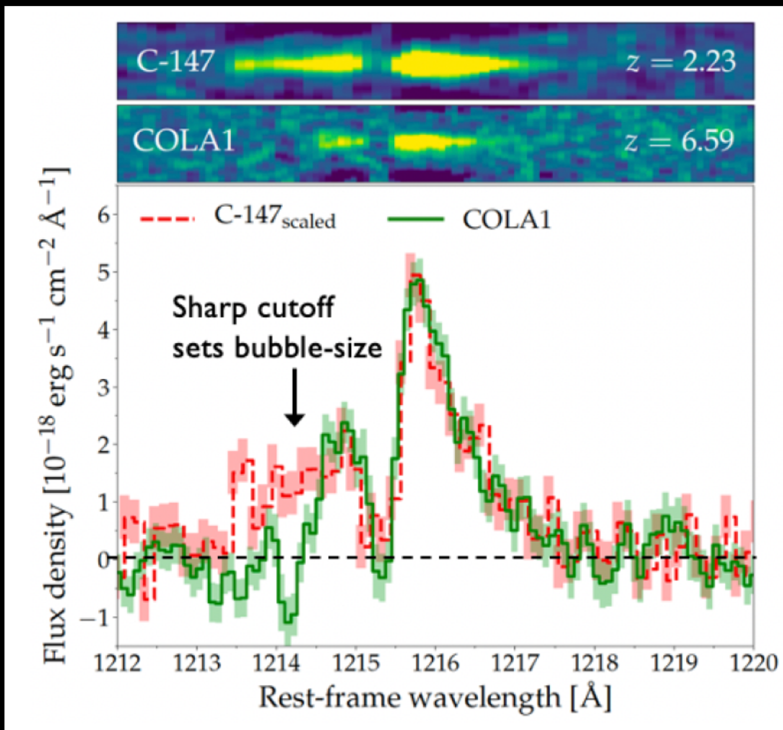
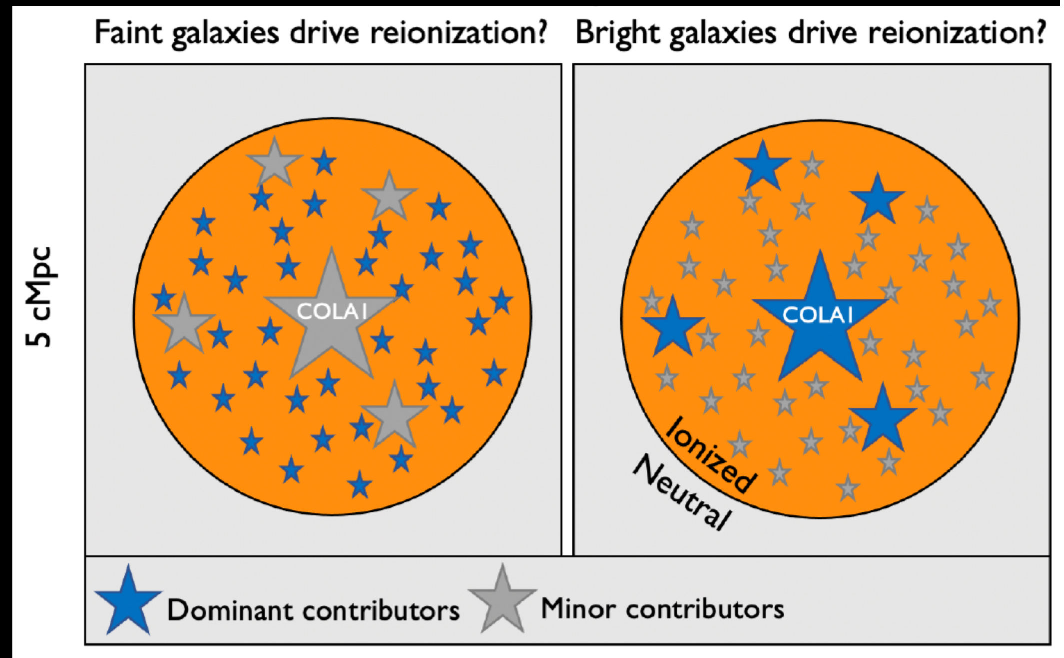


z~7 bubble with strongly constrained size
Matthee+18, Mason & Gronke 2020



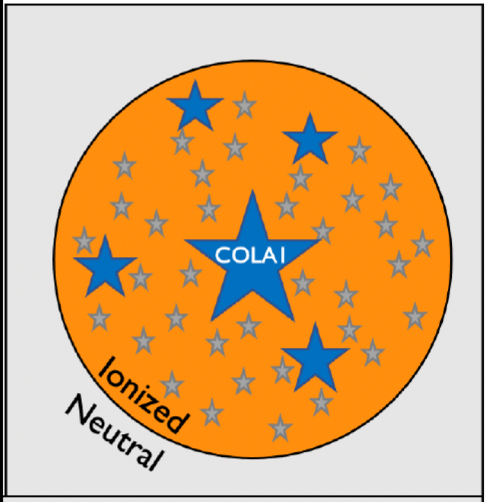
Total ionizing photon budget known (since size is known ~ Stromgren sphere)

JWST grism survey: can bright galaxies do it all?

Which galaxies reionized the Universe?

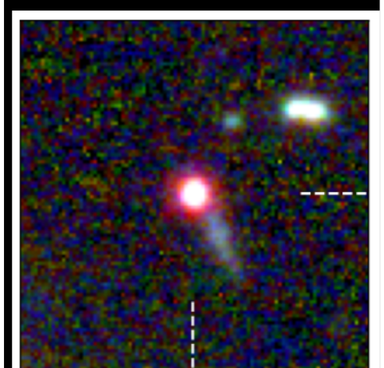
JWST bubble program PI: Naidu & Matthee

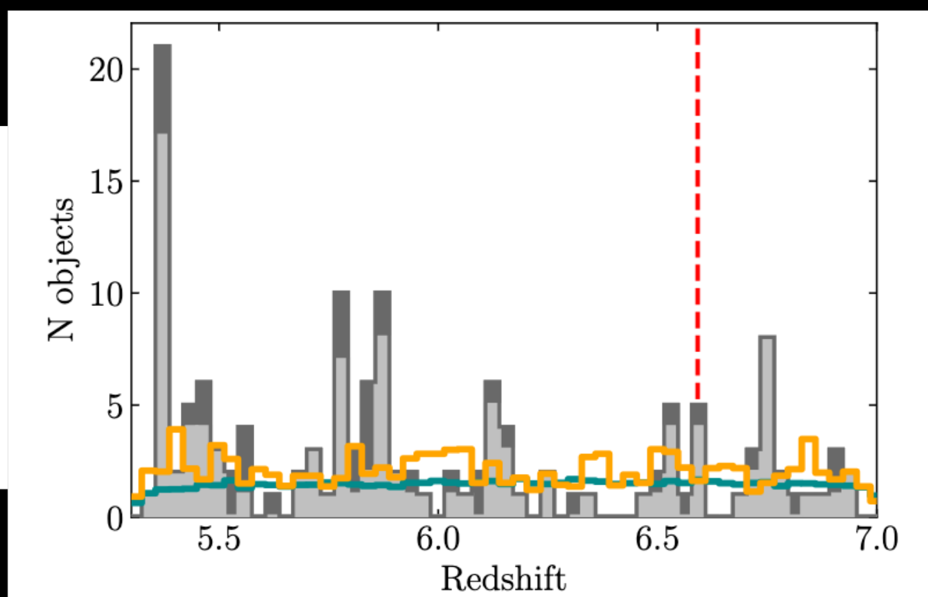
Bright galaxies drive reionization?

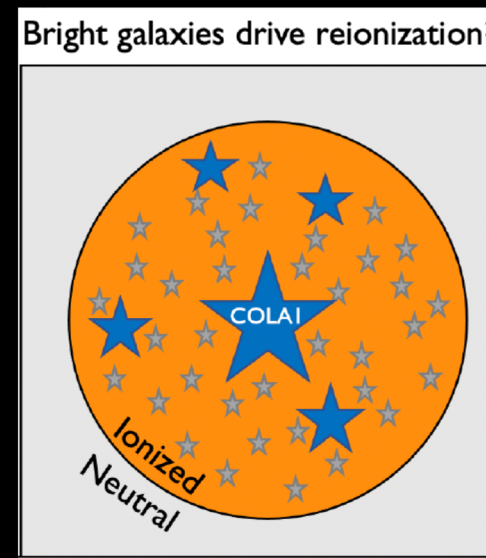


Which galaxies reionized the Universe?
JWST bubble program PI: Naidu & Matthee

- COLA1+ 3 luminous friends in the bubble can account for majority of budget!







Torralba Torregrosa+ in prep.

Which galaxies reionized the Universe?
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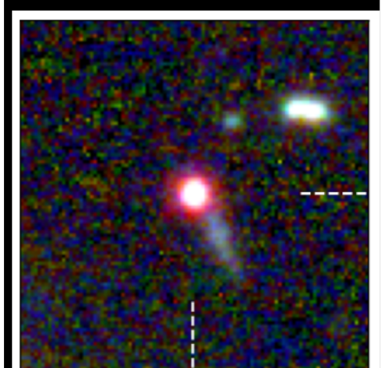
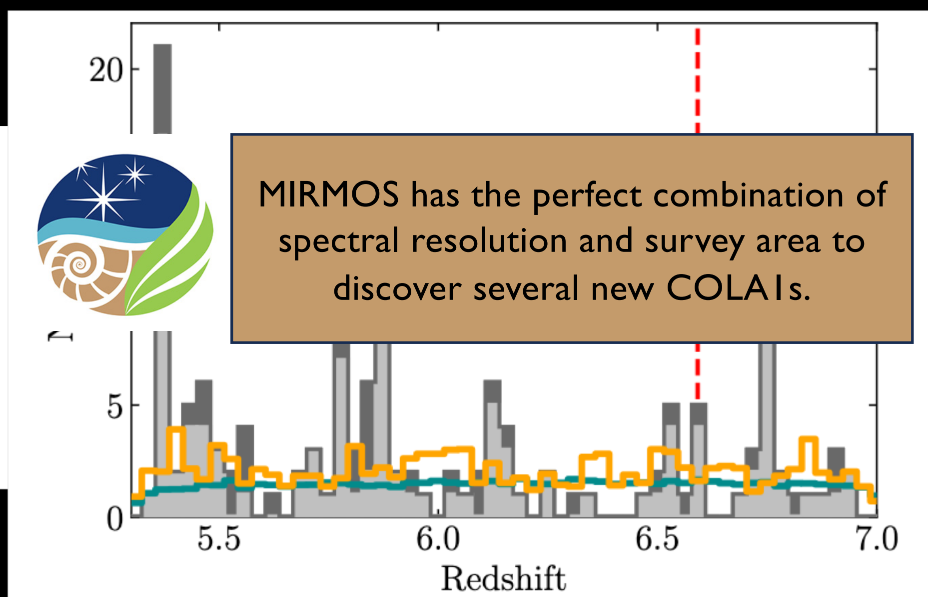
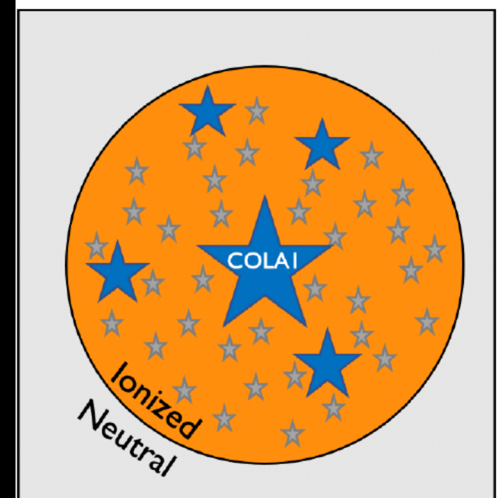




MIRMOS has the perfect combination of spectral resolution and survey area to discover several new COLA1s.

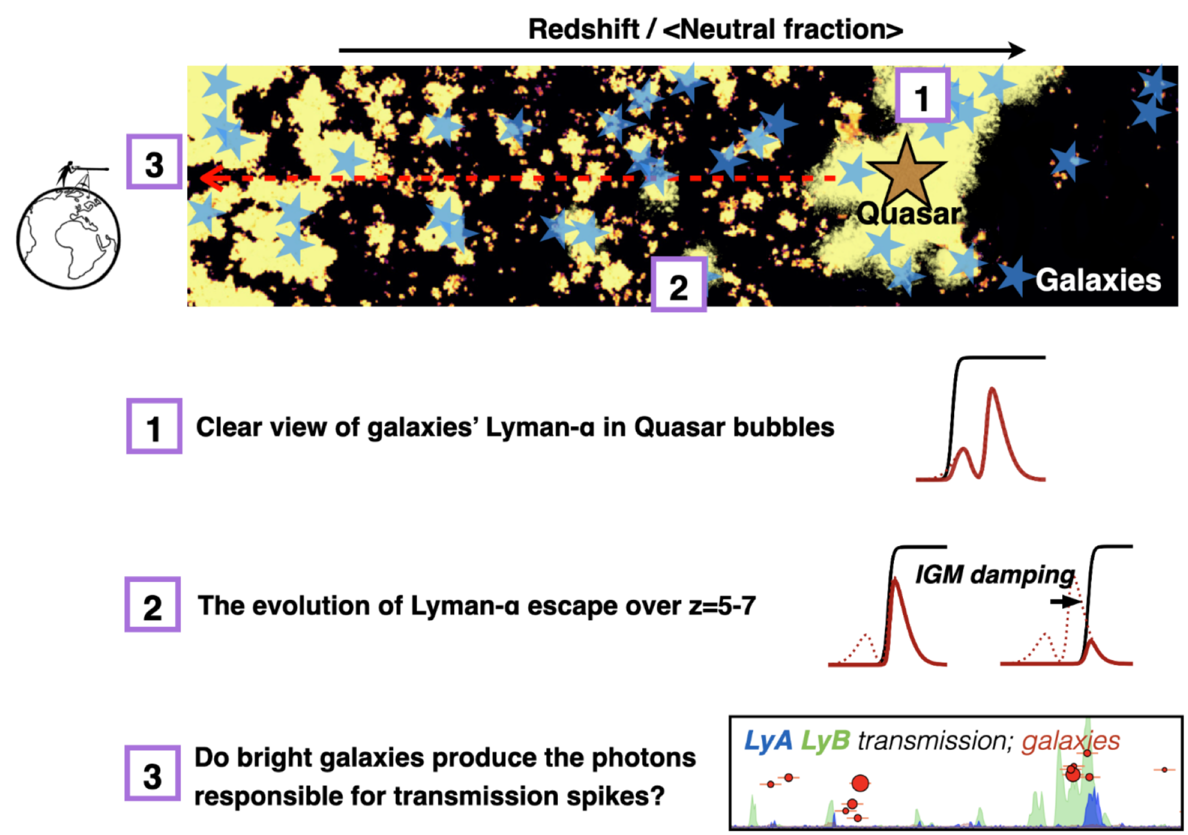
Bright galaxies drive reionization?

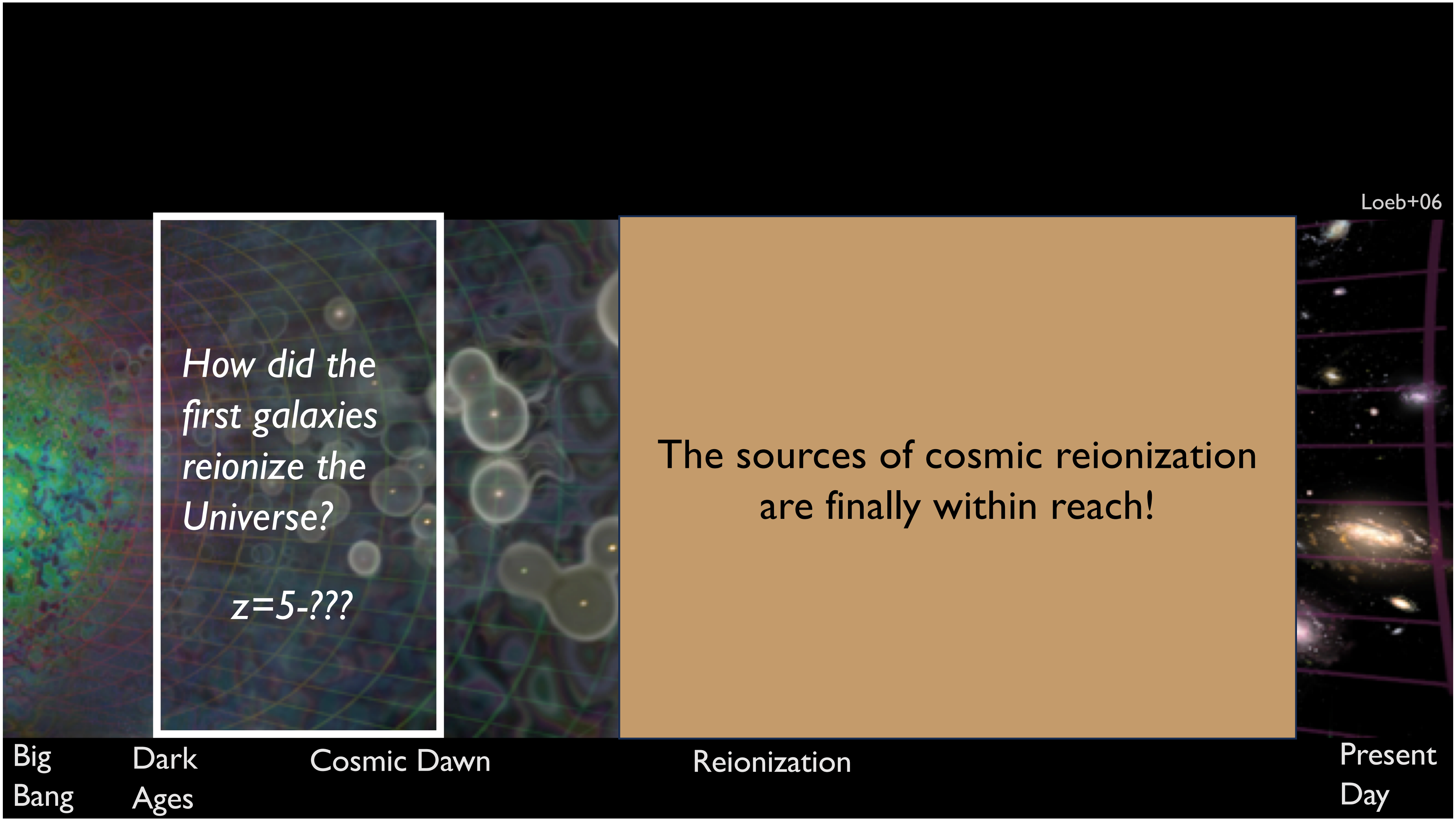


Torralba Torregrosa+ in prep.

Which galaxies reionized the Universe?
Quasar bubble program PI: Eilers, Davies, Naidu, Matthee

- Controlled environment for LyA experiments.
- ~40 hours of deep UV spectroscopy at z~6-7




Loeb+06
How did the first galaxies reionize the Universe?
z=5-???
The sources of cosmic reionization are finally within reach!
Big Bang
Dark Ages
Cosmic Dawn
Reionization
Present Day

1920: do other galaxies exist?
2020s: a final expansion of the cosmic frontier to the brink of the Big Bang

Loeb+06

Big Bang

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Summary

- *JWST* is revealing epochs of the Universe we've never seen before.
  - Remarkably luminous z>10 galaxies
  - An abundance of supermassive black holes
  - Extremely metal-poor galaxies
  - The sources of cosmic reionization?
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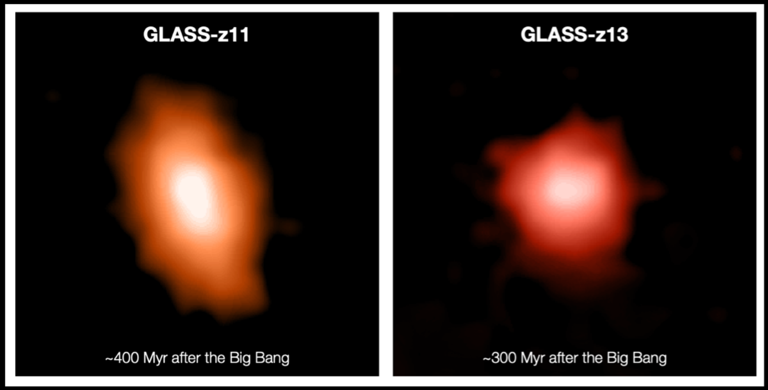

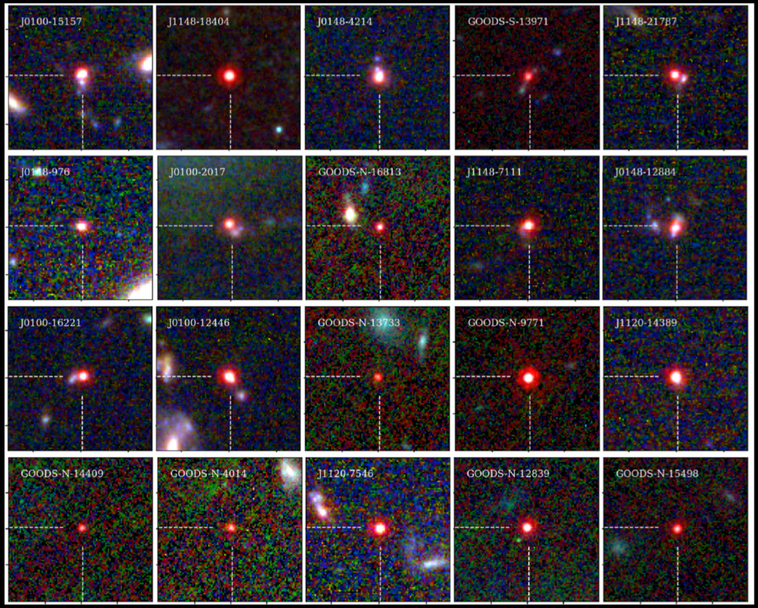

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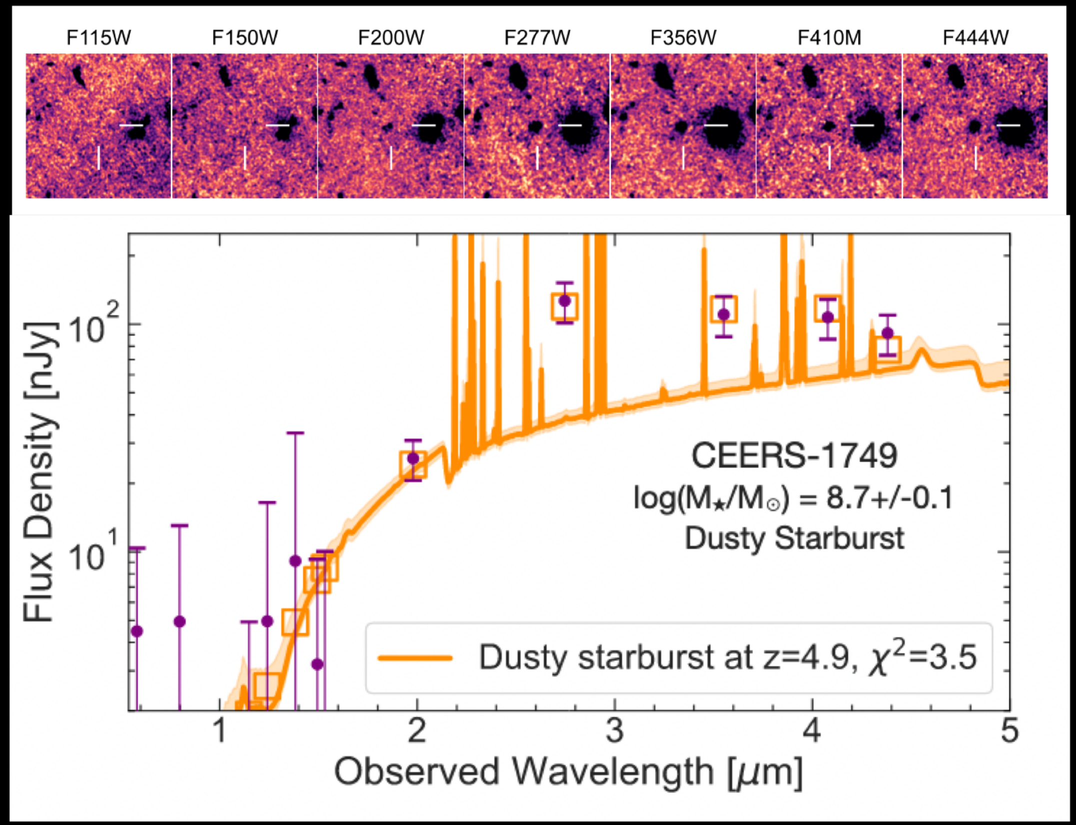
Pieces of the puzzle: Bad Redshifts?

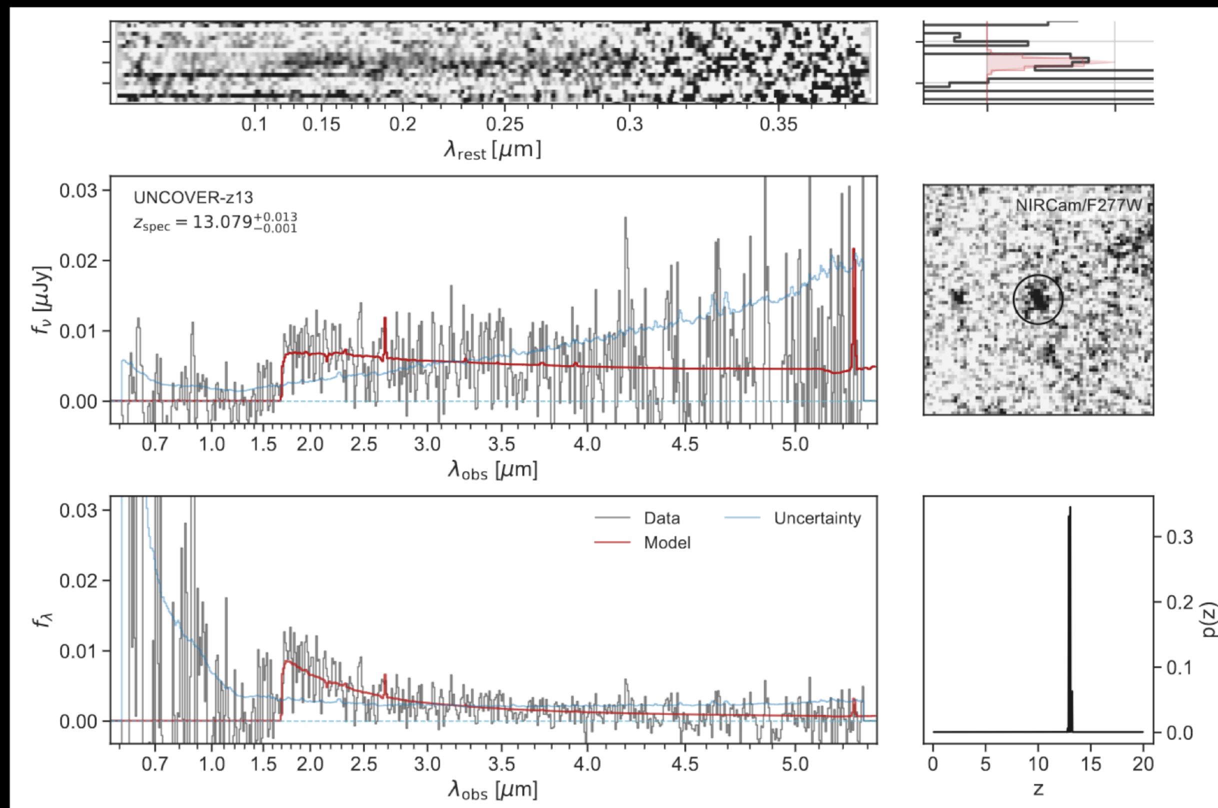
- Spectroscopic follow-up largely successful, only one key failure.



"Schrodinger's Galaxy: z=17 or z=5?", Naidu+22b

Pieces of the puzzle: Bad Redshifts?

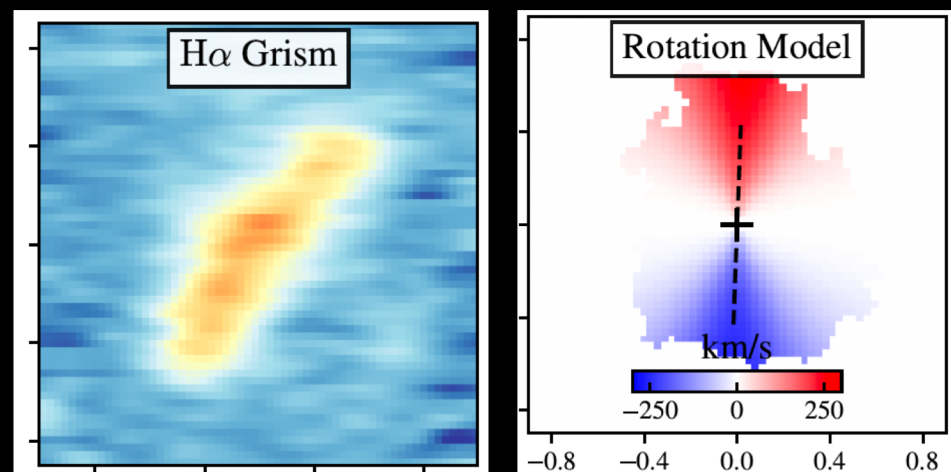
- Spectroscopic follow-up largely successful, only one key failure.
- ~15 (faint) galaxies now confirmed at z>10 Curtis-Lake+22, Arrabal-Haro+23, Harikane+23, Fujimoto+23, Wang+23



Wang+23, UNCOVER Survey

Pieces of the puzzle:
Disk-formation earlier than expected?

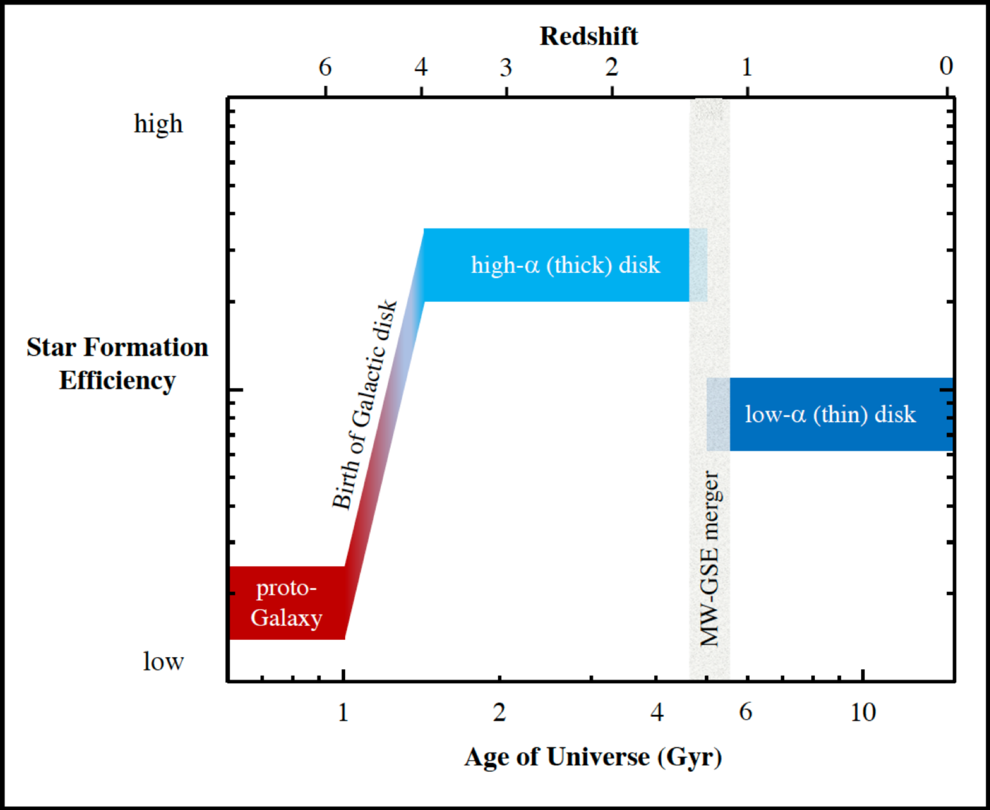
Disk-like extended profile at z~11?
Analysis led by Erica Nelson & Wren Suess
Robertson+22, Ferreira+22, Kartaltepe+23



Rotating disk in a massive galaxy at z~6!
Li+23, Nelson…Naidu+23

Pieces of the puzzle: Disk-formation earlier than expected?

- The Milky Way's ancient disk appears to be in place already by z~5!
- Not common in simulations. Belokurov & Kravstov 22, Semenov+23a,b, Hopkins+23

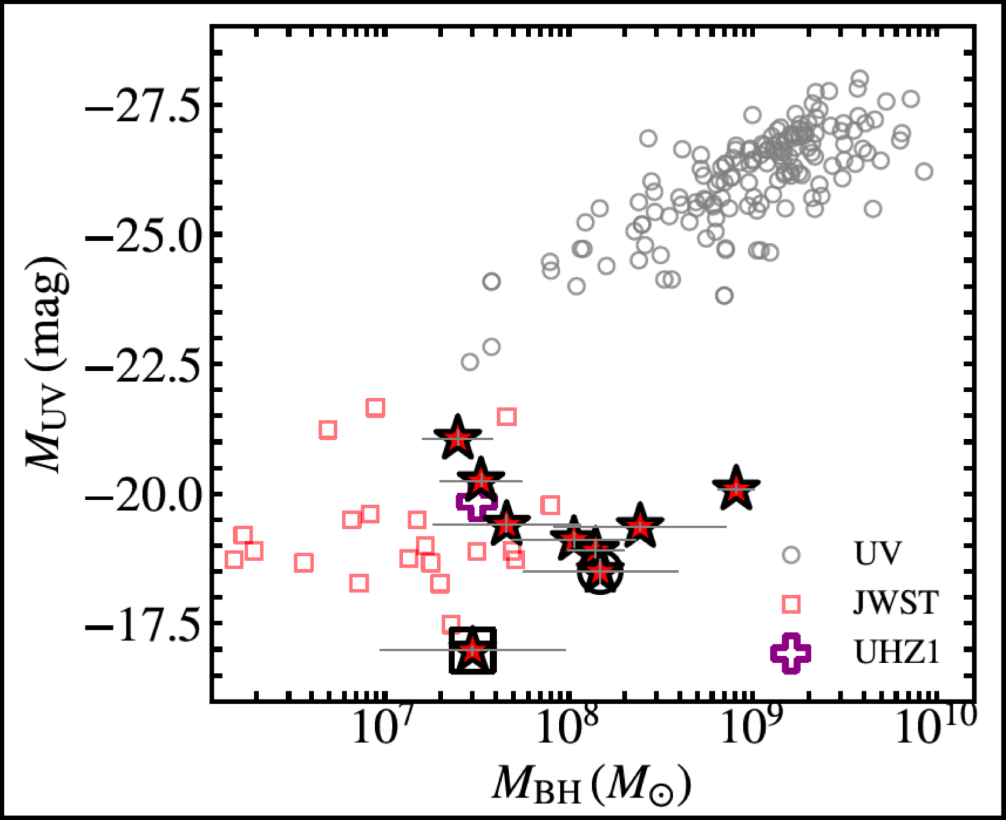


Milky Way

Conroy, Weinberg, Naidu+22

Hidden chapters of black hole growth

- Some of these objects are simply red versions of the behemoth quasars.



Greene+23

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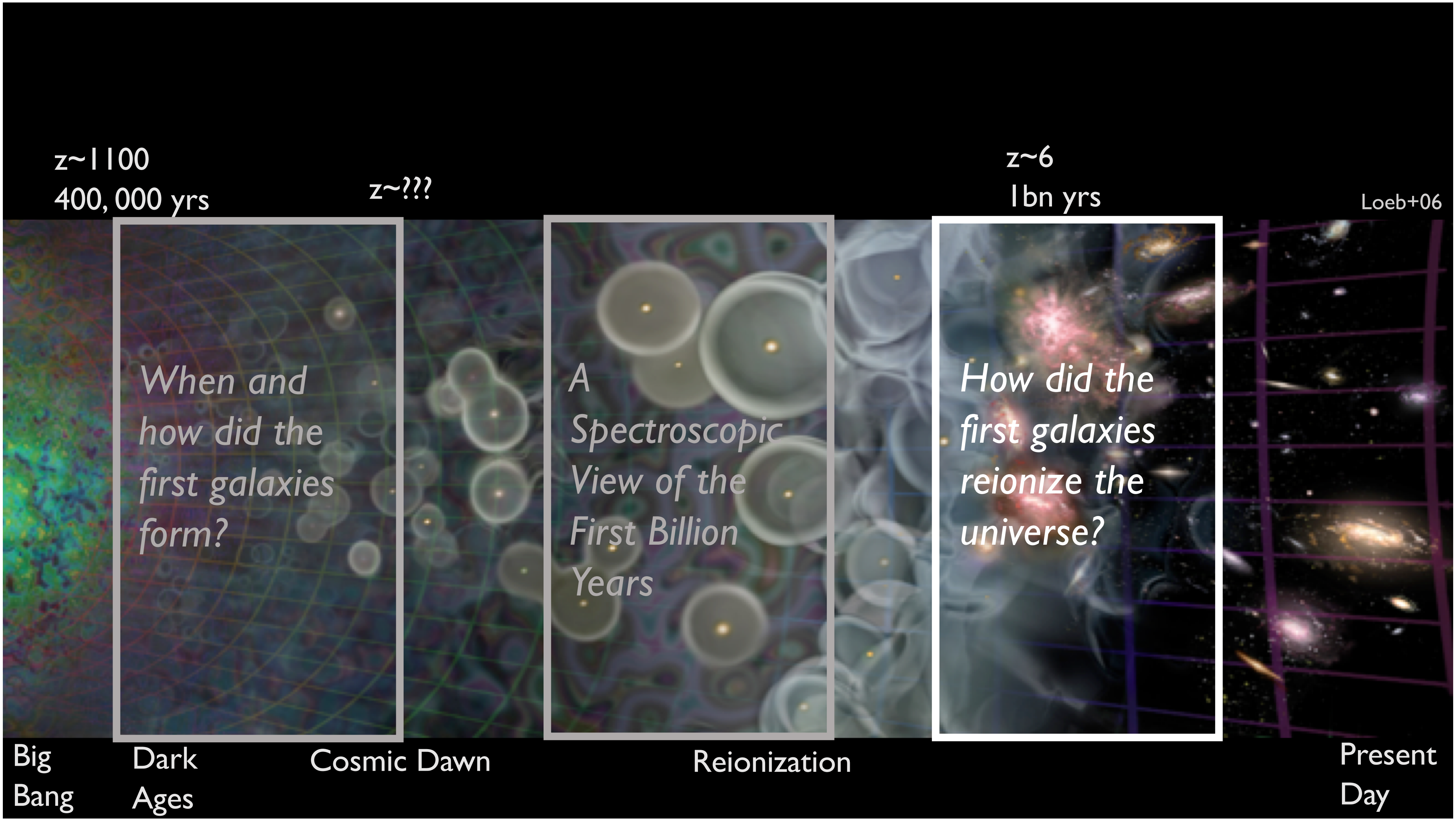
z~1100
400, 000 yrs
z~???
z~6
1bn yrs
Loeb+06
When and how did the first galaxies form?
A Spectroscopic View of the First Billion Years
How did the first galaxies reionize the universe?
Big Bang
Dark Ages
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Reionization
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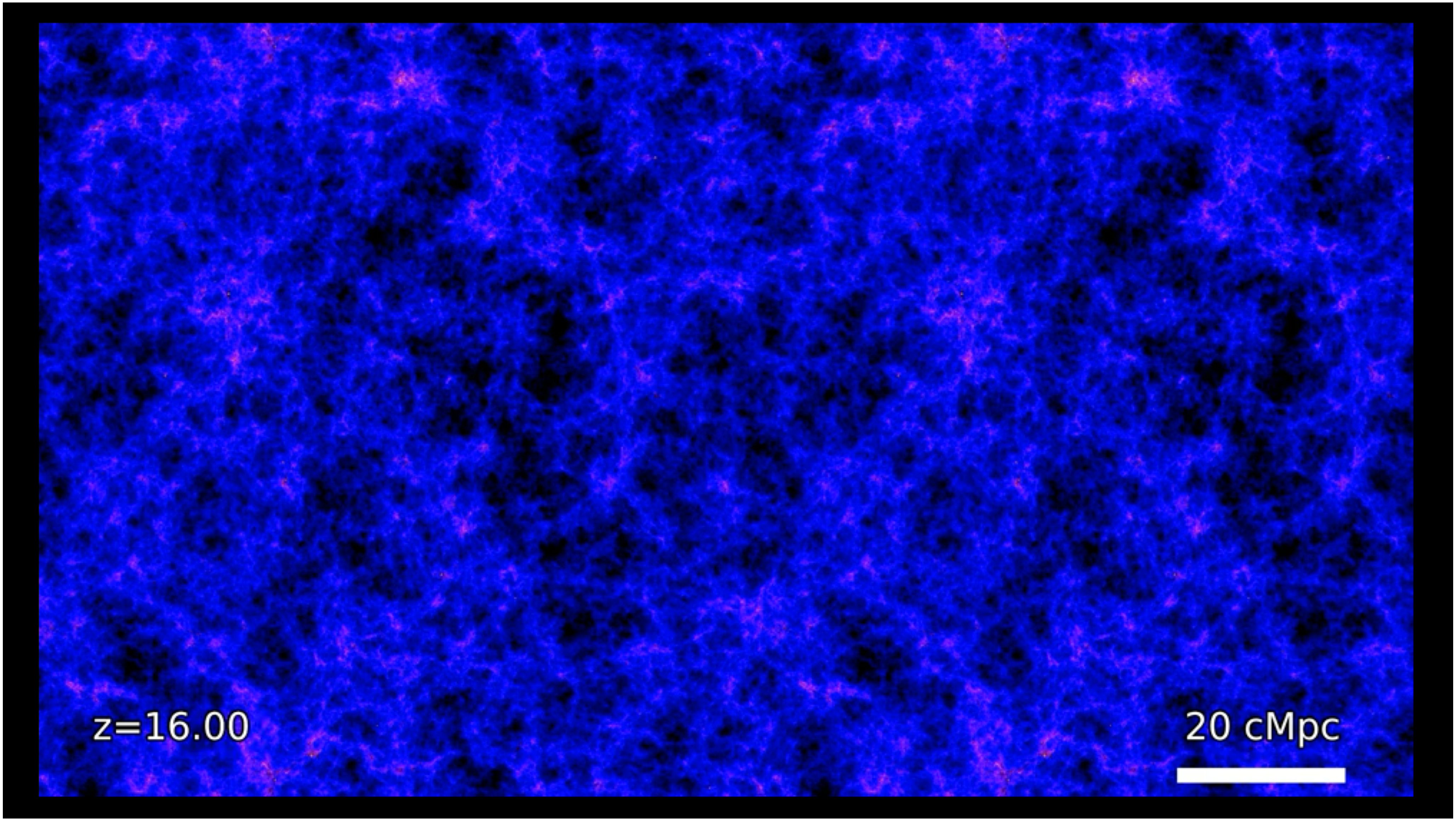
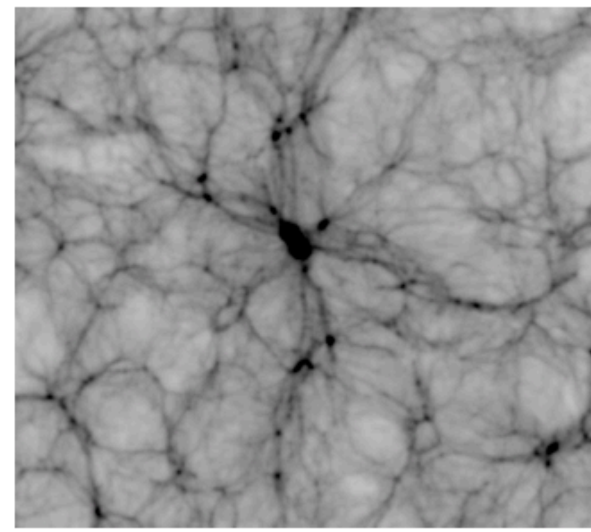
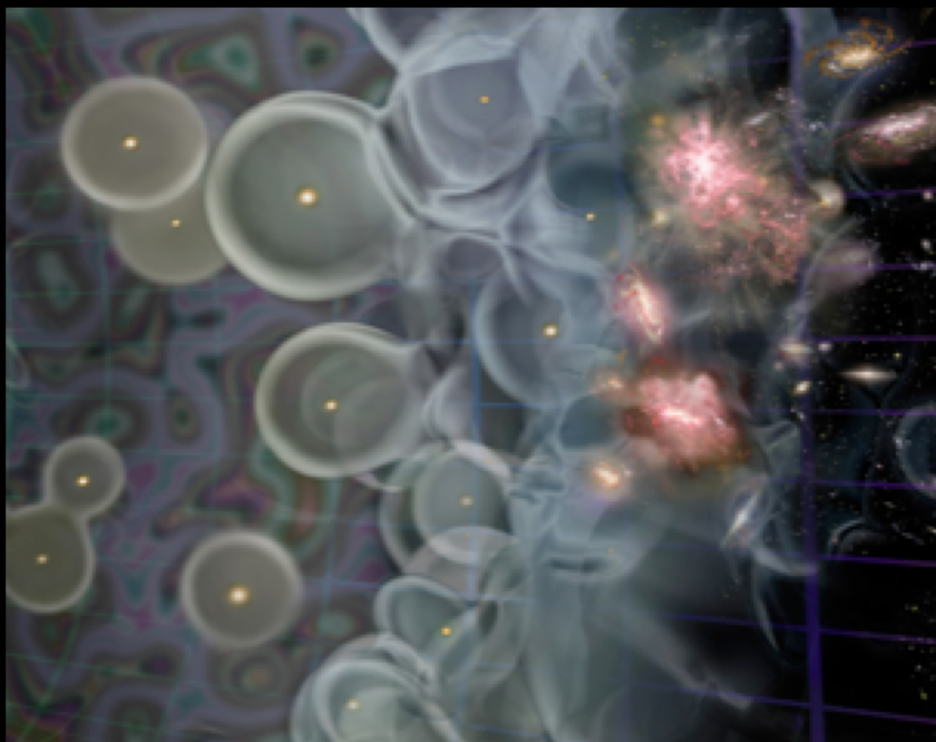

z=16.00
20 cMpc

Reionization: a focal point for all early universe physics



- Production of ionizing photons (metal-poor stars, binaries, accretion disks)
- Journey through interstellar medium (dust, gas, feedback)
- Contact with intergalactic medium (large-scale structure, gas physics)

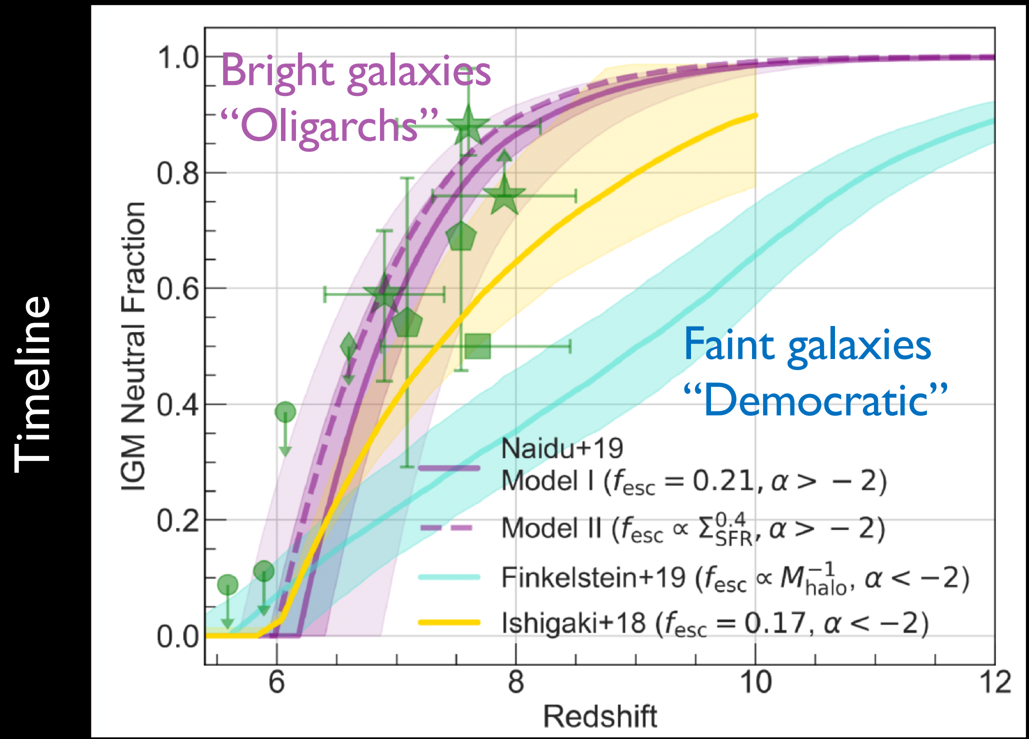
Reionization: where did the photons come from?



- Numerous, tiny, faint galaxies? "Democratic Reionization"
  Wise+14, Finkelstein+19, Chisholm+22

- Rare, bright, massive galaxies? "Reionization by the Oligarchs"
  Naidu+20, Naidu & Matthee+22, Matthee & Naidu+22

Reionization: where did the photons come from?

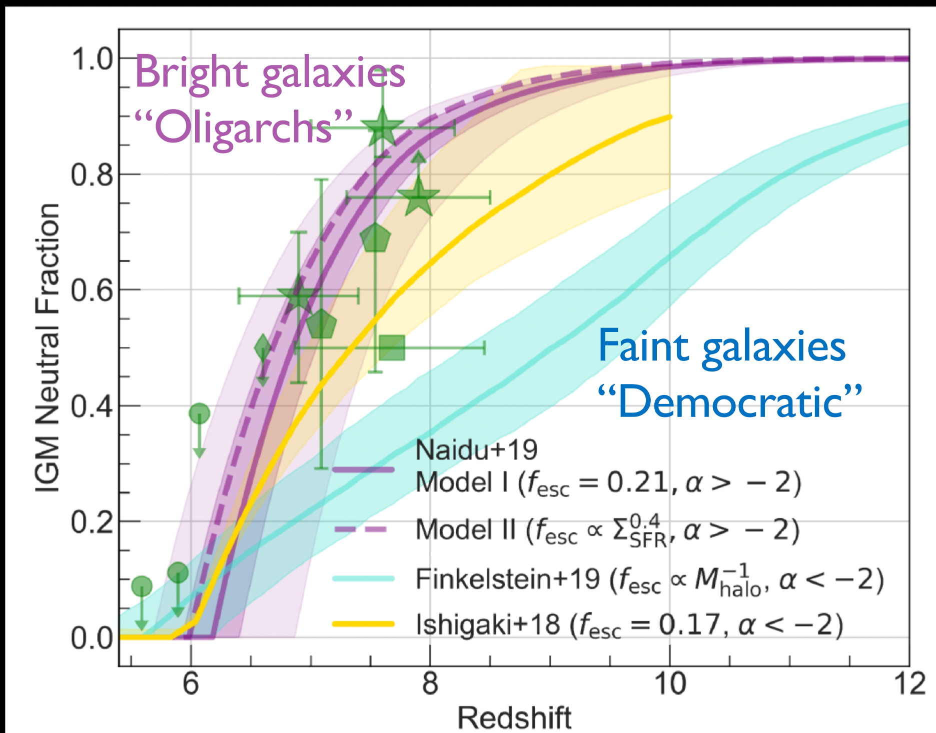


Naidu+20, Tacchella+18

- Radically different pictures of reionization.

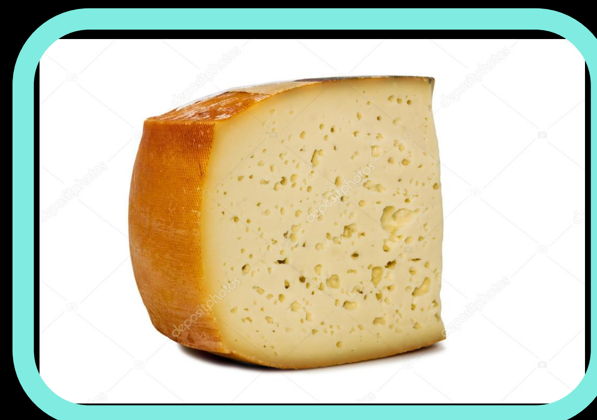
Reionization: where did the photons come from?

Timeline



Naidu+20, Tacchella+18

Topology

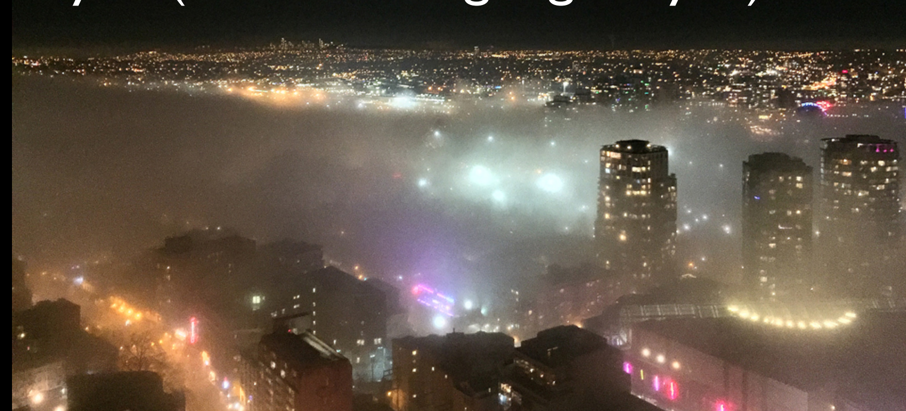


- Radically different pictures of reionization.
- Set the course of galaxy evolution across cosmic time (e.g., Milky Way satellite counts)

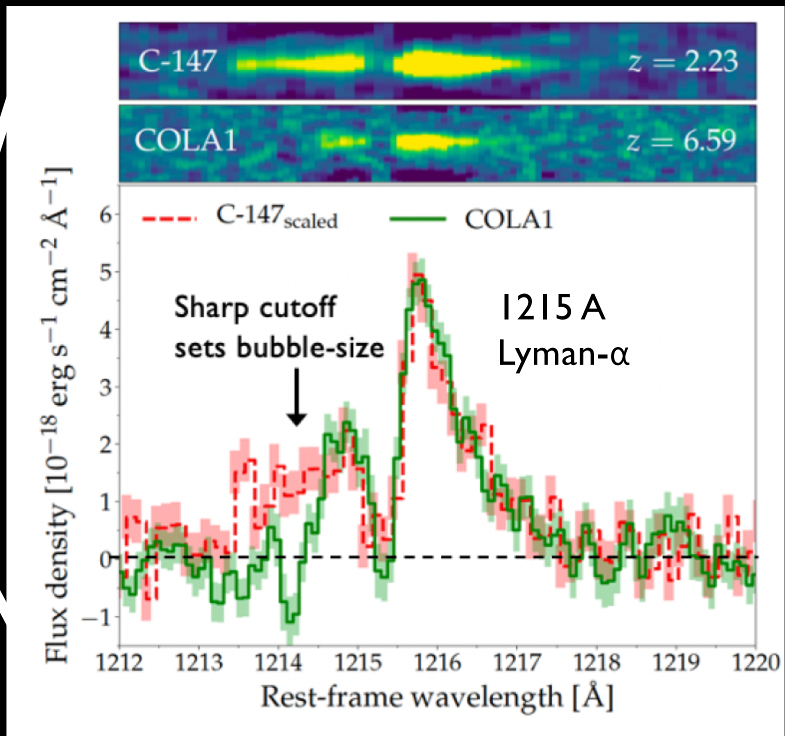
State of the (reionization) Union

- Fundamental impasse: can’t tell which galaxies are leaking ionizing photons
- Beyond z~4, the intervening IGM soaks up all photons

Fog (IGM) → can’t tell how bright the city is (how ionizing a galaxy is)



Which galaxies reionized the Universe? *JWST* bubble program PI: Naidu & Matthee

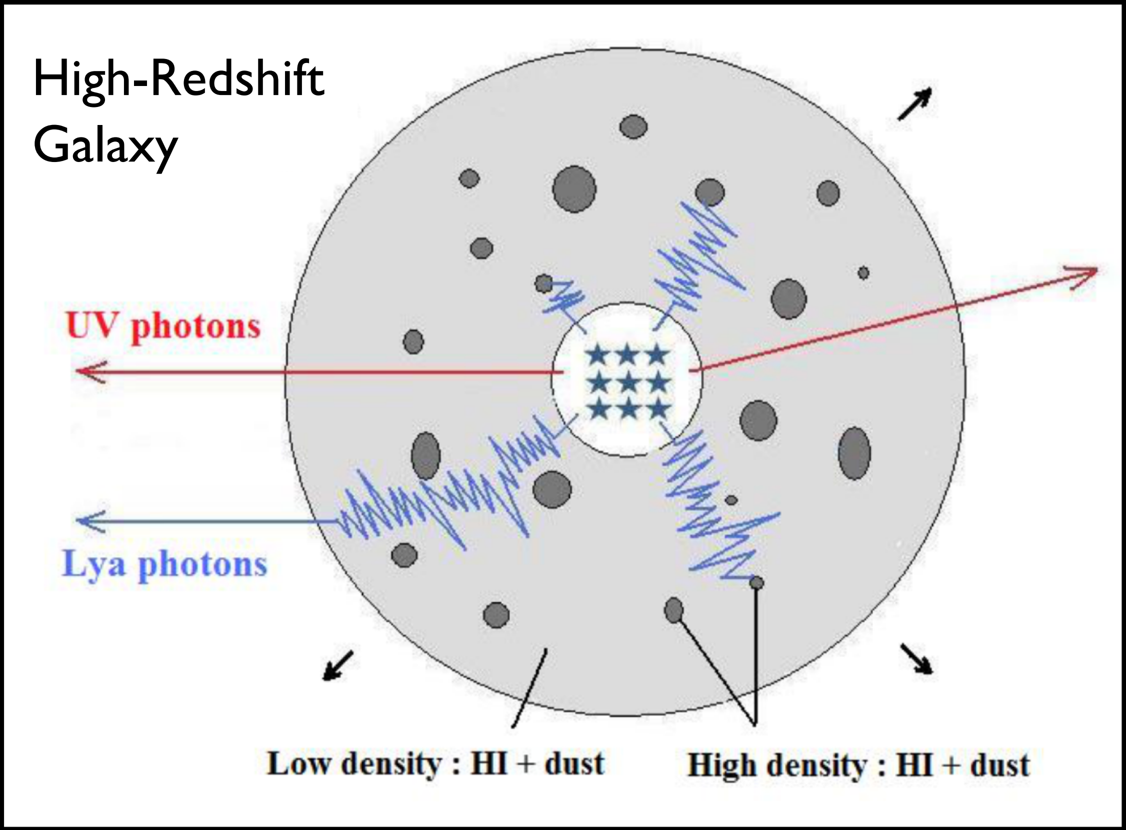


Only z~7 bubble with strongly constrained size

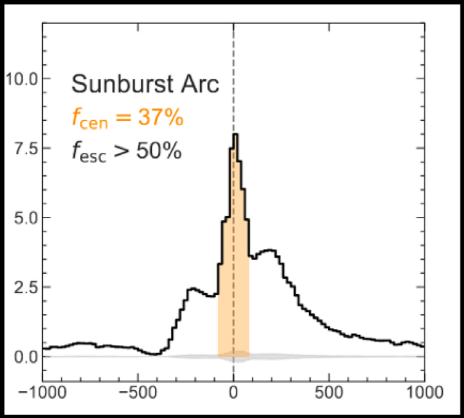
Matthee+18, Mason & Gronke 2020

High-resolution Lyman-α holds the key

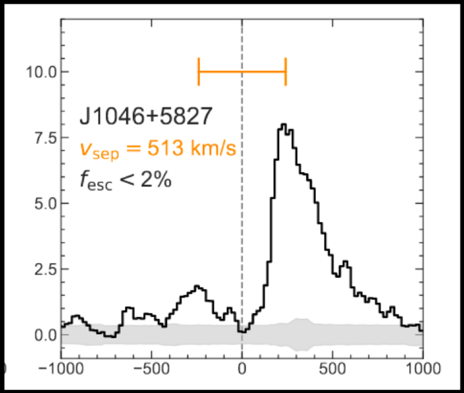
Naidu & Matthee+22
Matthee & Naidu+22



Duval+14



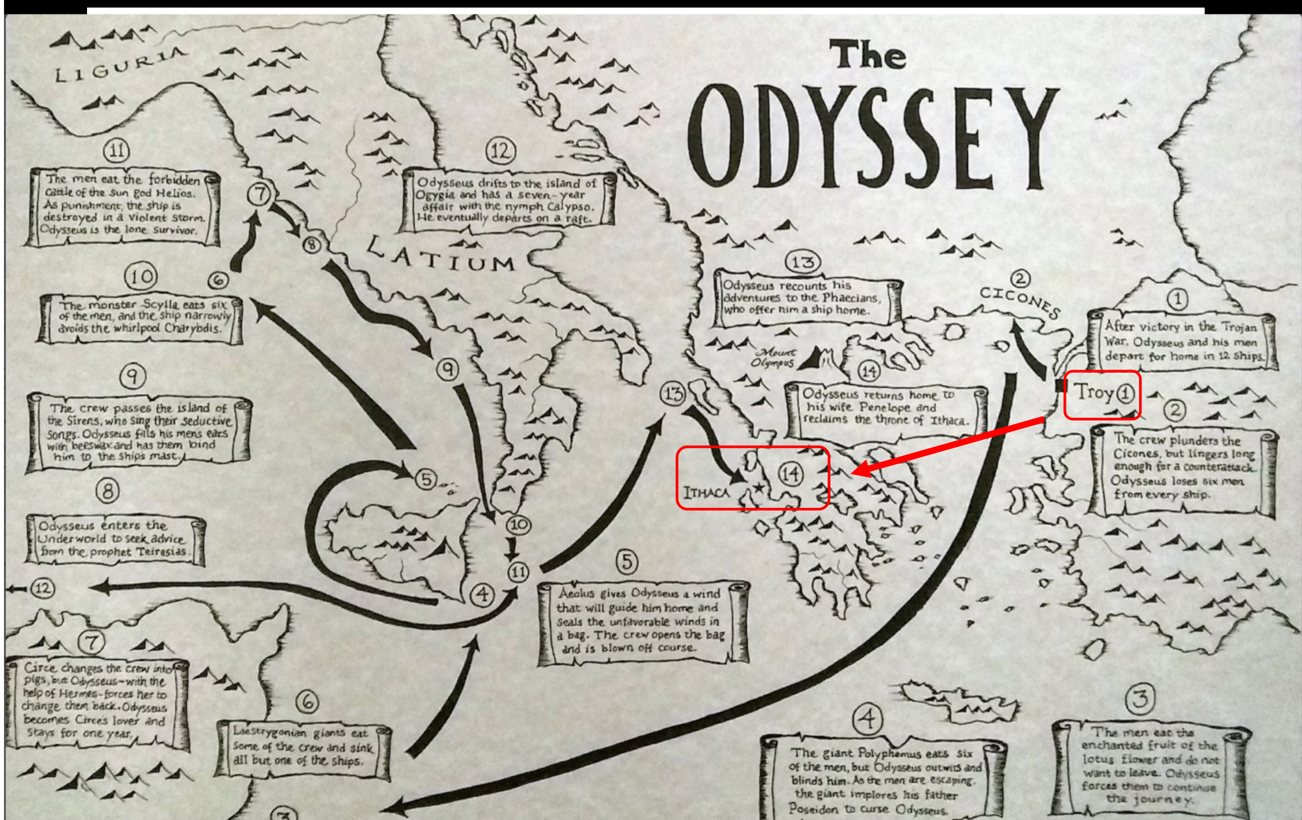
Highly Ionizing



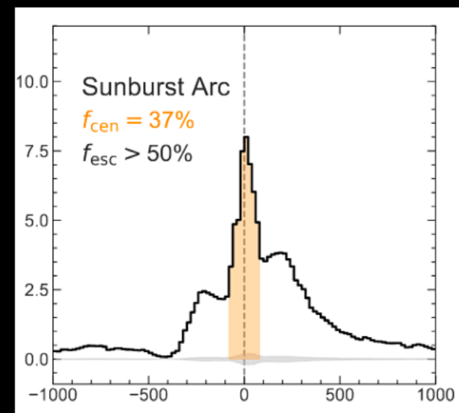
Poorly Ionizing

High-resolution Lyman-α holds the key

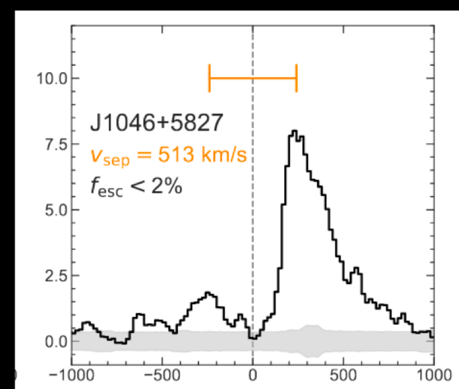
Naidu & Matthee+22
Matthee & Naidu+22



Duval+14

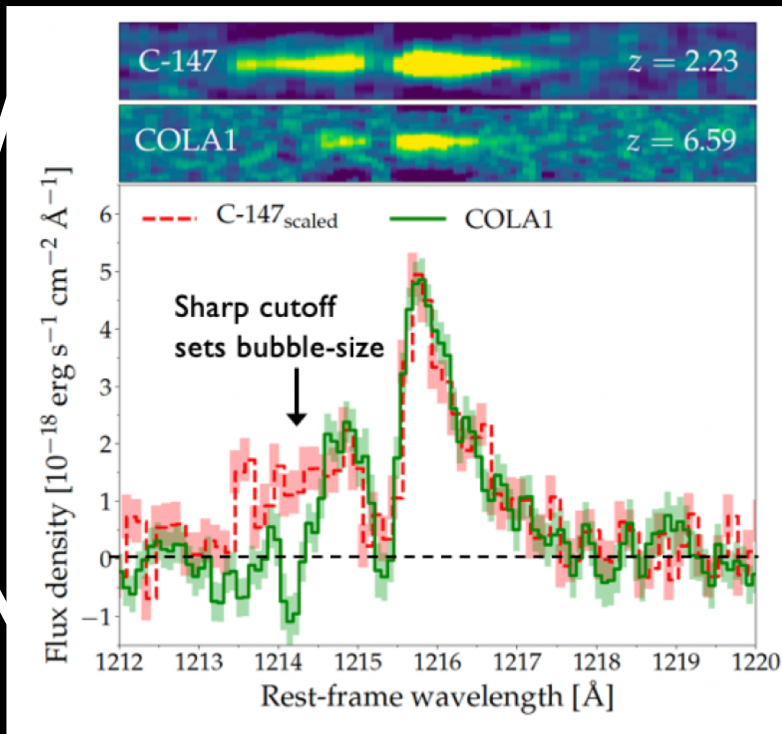


Highly Ionizing



Poorly Ionizing

Which galaxies reionized the Universe?
JWST bubble program PI: Naidu & Matthee



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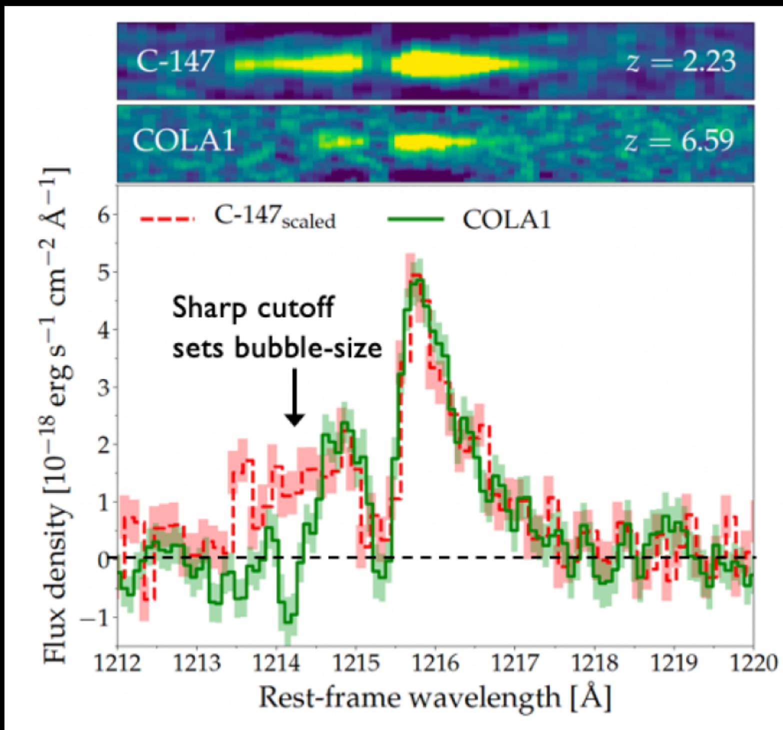
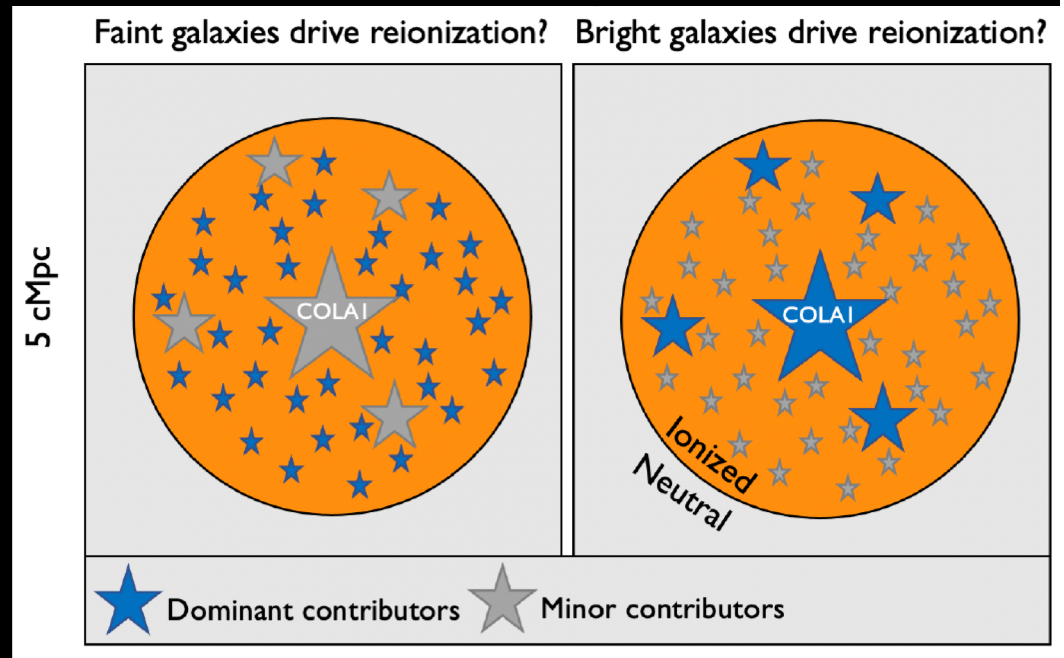


Only z~7 bubble with strongly constrained size Matthee+18, Mason & Gronke 2020



Total ionizing photon budget known (since size is known ~ Stromgren sphere)

JWST survey: can bright galaxies do it all?

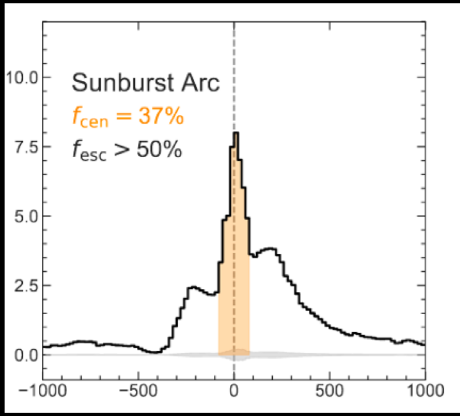
High-resolution Lyman-α Experiments

- 100+ hrs on VLT in 2023/24

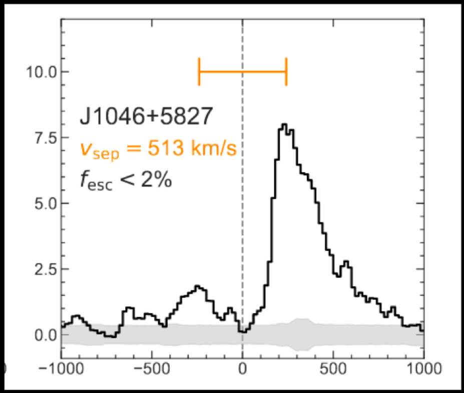
i) first direct constraints on ultra-faint galaxies in lensed fields

ii) survey *within* z~6-7 quasar bubbles

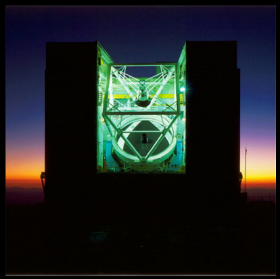
- MMT/Binospec is the perfect instrument -- combination of resolution + throughput + field of view



Highly Ionizing



Poorly Ionizing

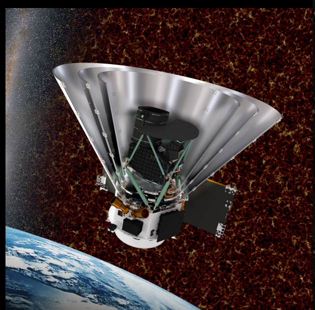


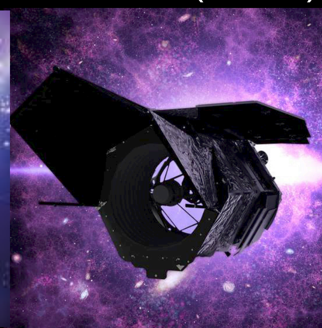
A golden era for early universe science

JWST

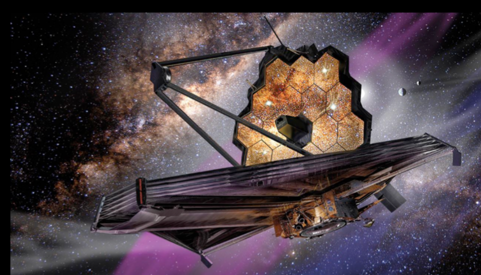
A golden era for early universe science

SPHEREx (2025) Euclid (2023) Roman (2027)





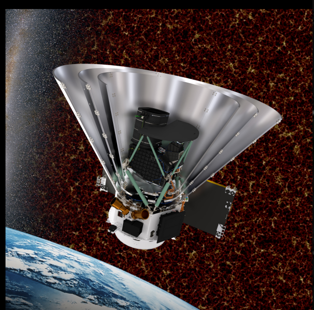
- All-sky surveys will find >1000 luminous z>10 galaxies, rare overdensities



JWST

A golden era for early

SPHEREx (2025) Euclid (2023) Roman (2027)



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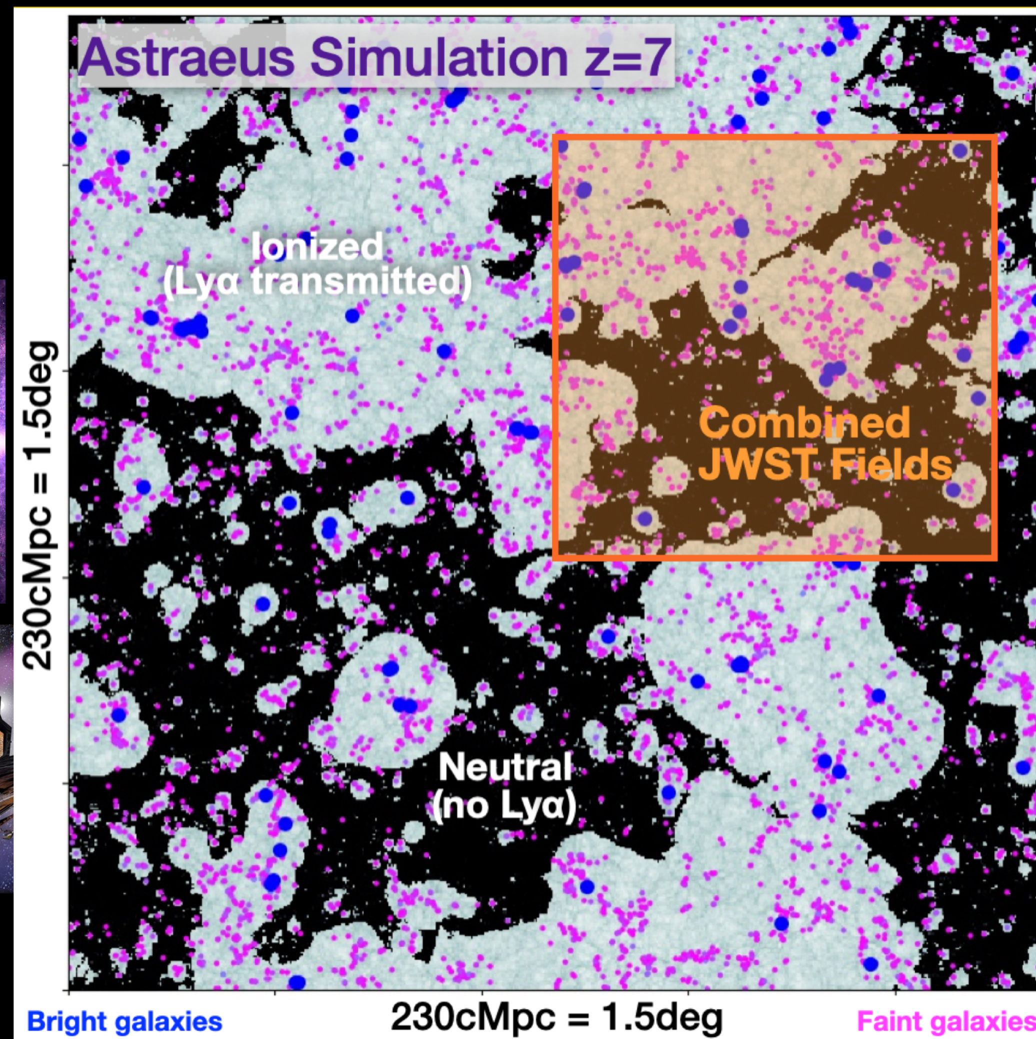
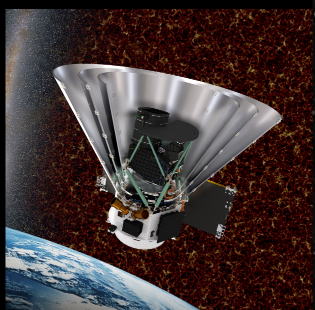
JWST

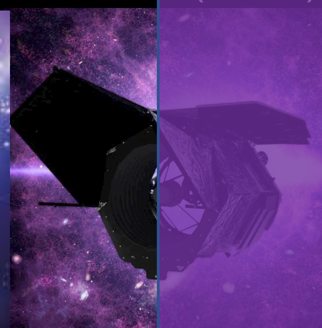


e.g., Hutter+20

A golden era for early universe science

SPHEREx (2025) Euclid (2023) Roman (2027)





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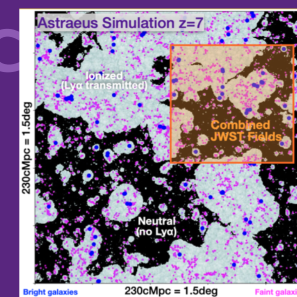
JWST



Euclid Deep Survey (40 deg^2)

e.g., Hutter+20

A golden era for early universe science

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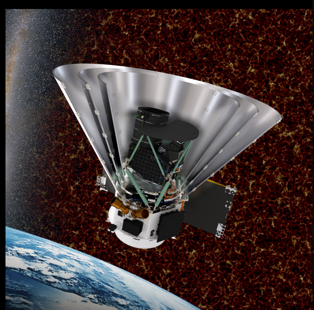

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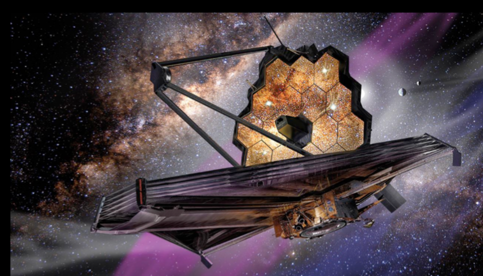
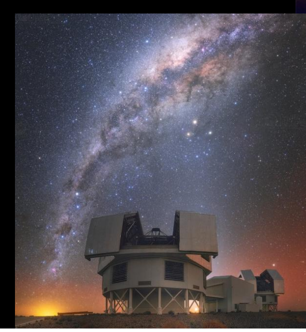
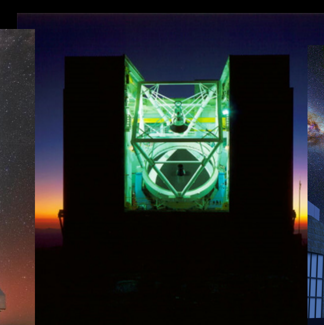


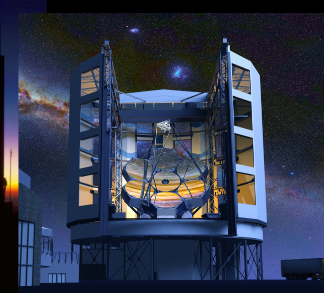
JWST

- Rest-UV spectroscopy at z>6 – e.g., LyA (reionization), HeII (Pop III), CIV (AGN)

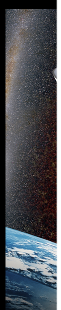
Magellan MMT GMT

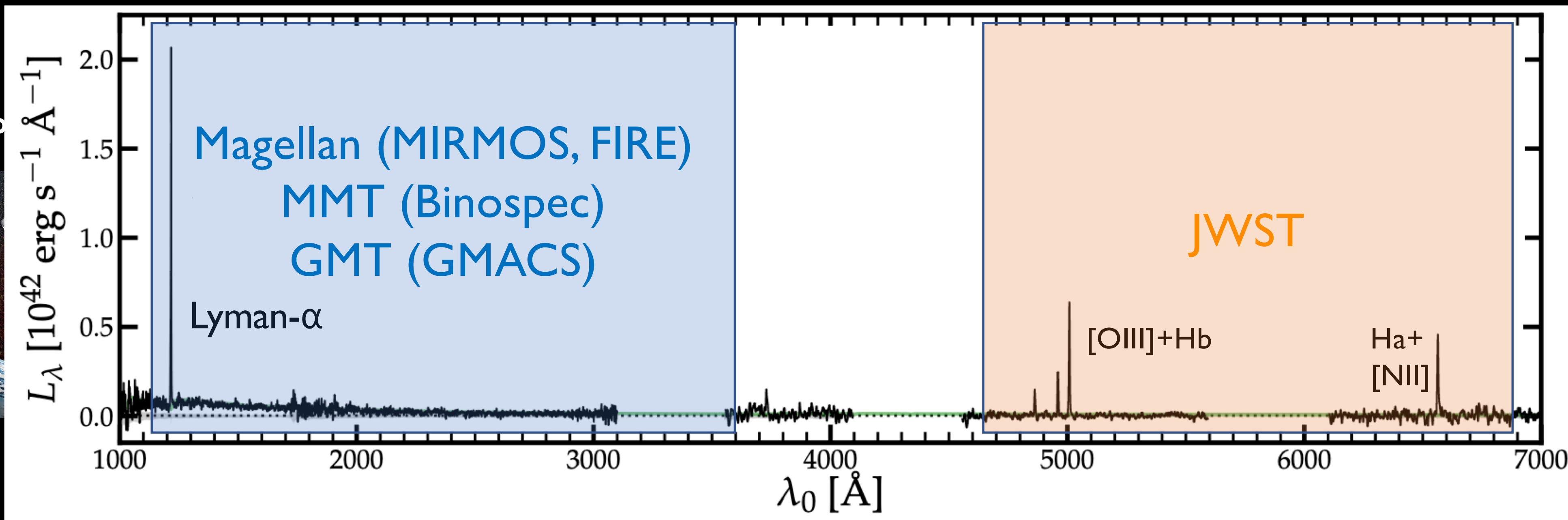






SP





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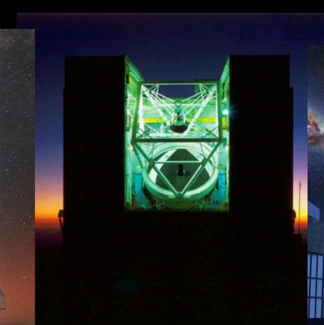
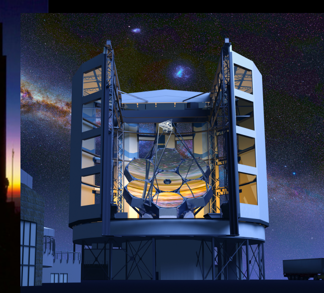
JWST

Magellan

MMT



GMT



A golden era for early universe science

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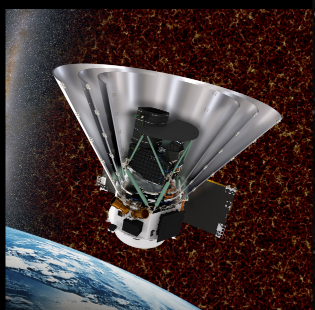

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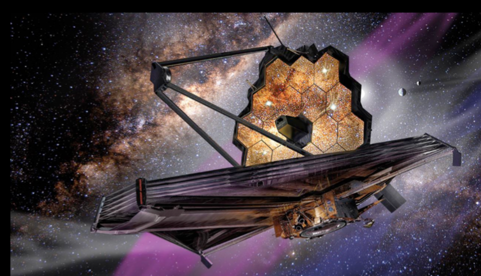
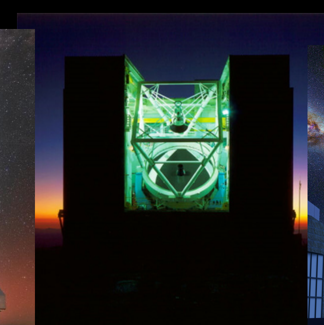


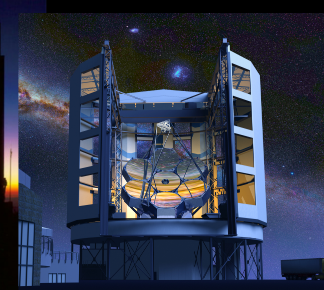
JWST

Magellan

MMT

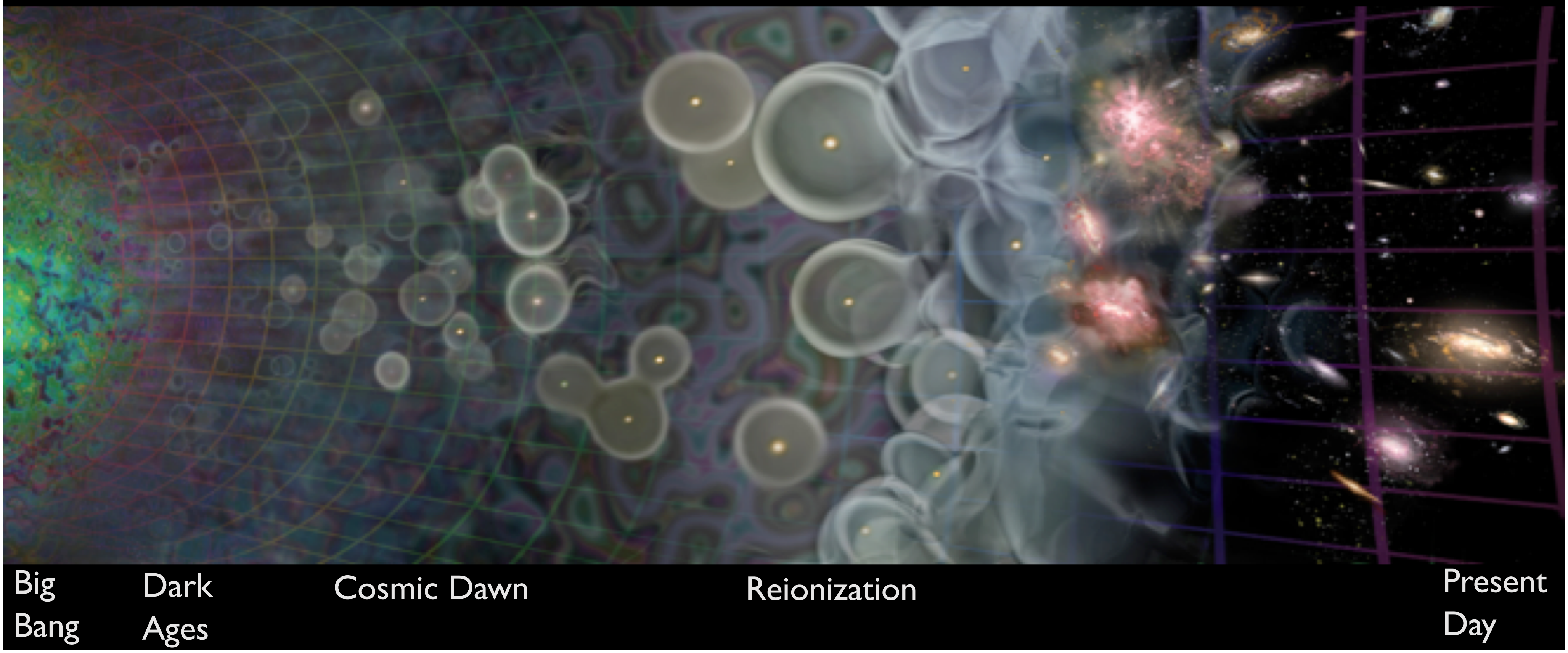


GMT



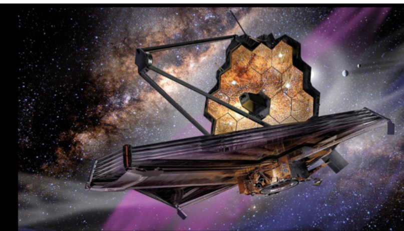
1920: do other galaxies exist?
2020s: a final expansion of the cosmic frontier to the brink of the Big Bang

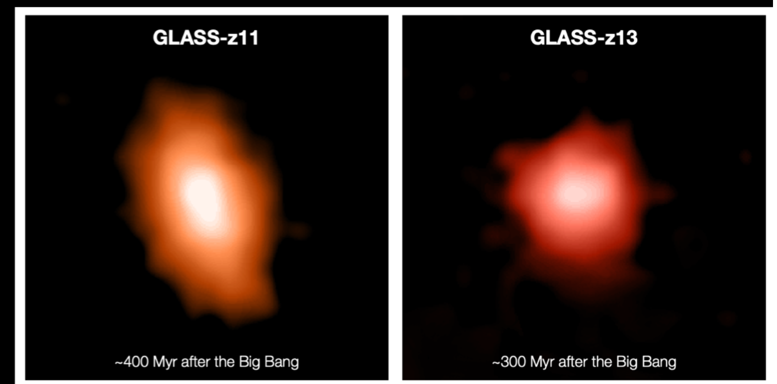
Loeb+06

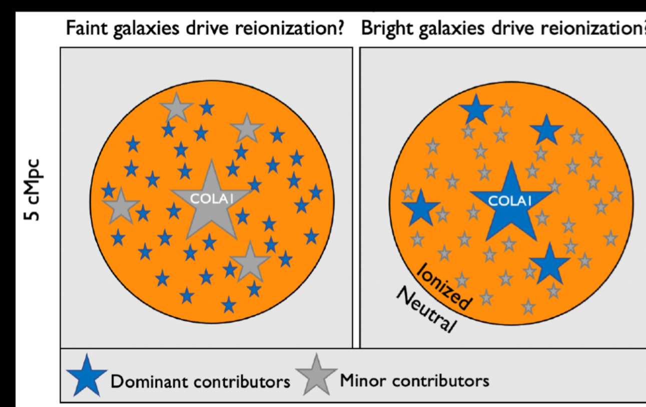


Summary

- The first generations of stars and galaxies are finally within reach thanks to JWST.
- The early universe has already shown us several surprises – e.g., luminous z>10 galaxies, abundant AGN.
- The elusive protagonists of cosmic reionization will be revealed through high-resolution LyA and bubble experiments.
- Upcoming space and ground-based missions promise to complete our census of cosmic history in the next few years.







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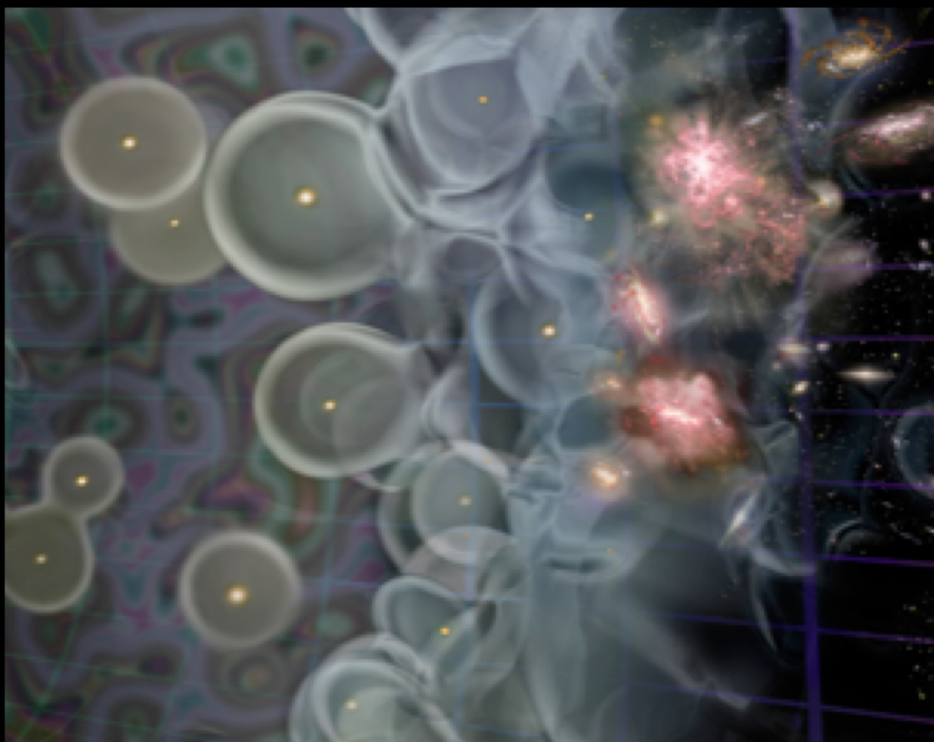
Cosmic Reionization: ionizing photon budget



Loeb+06

Reionization Budget = Number of galaxies

x Ionizing photons/galaxy

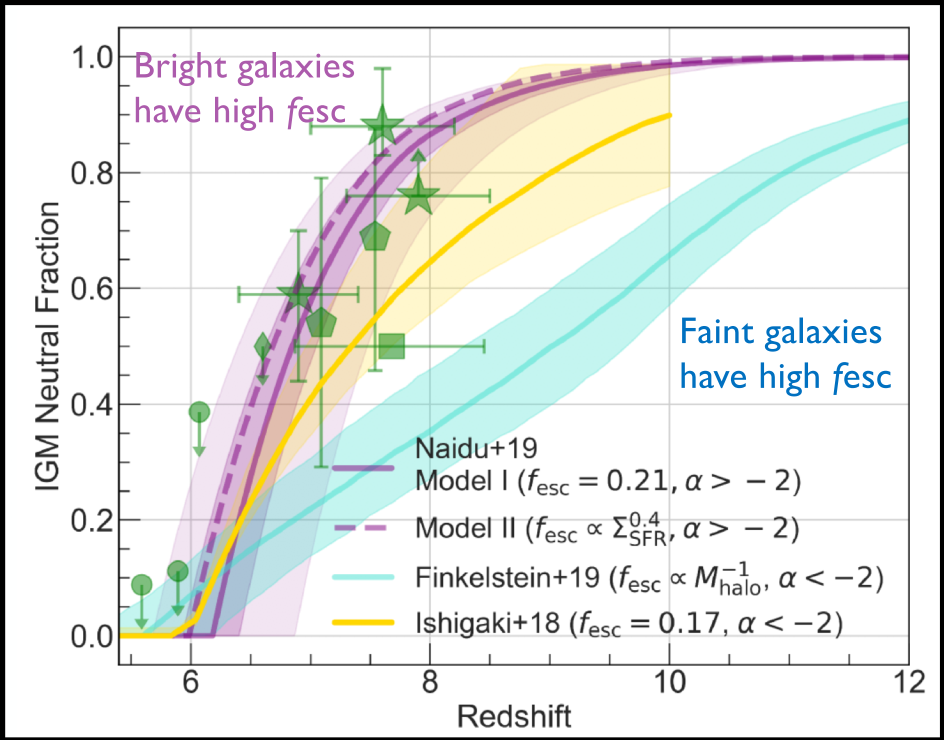
x Fraction that evade dust+HI

= $\rho_{SFR}\ \xi_{ion}\ f_{esc}$

- Clear path to ρ_{SFR} and ξ_{ion}(?) with *JWST.*
- Direct measurements of escape fractions (f_{esc}) impossible at z>4 due to IGM opacity.

Cosmic Reionization: everything hinges on LyC f_{esc}

Timeline

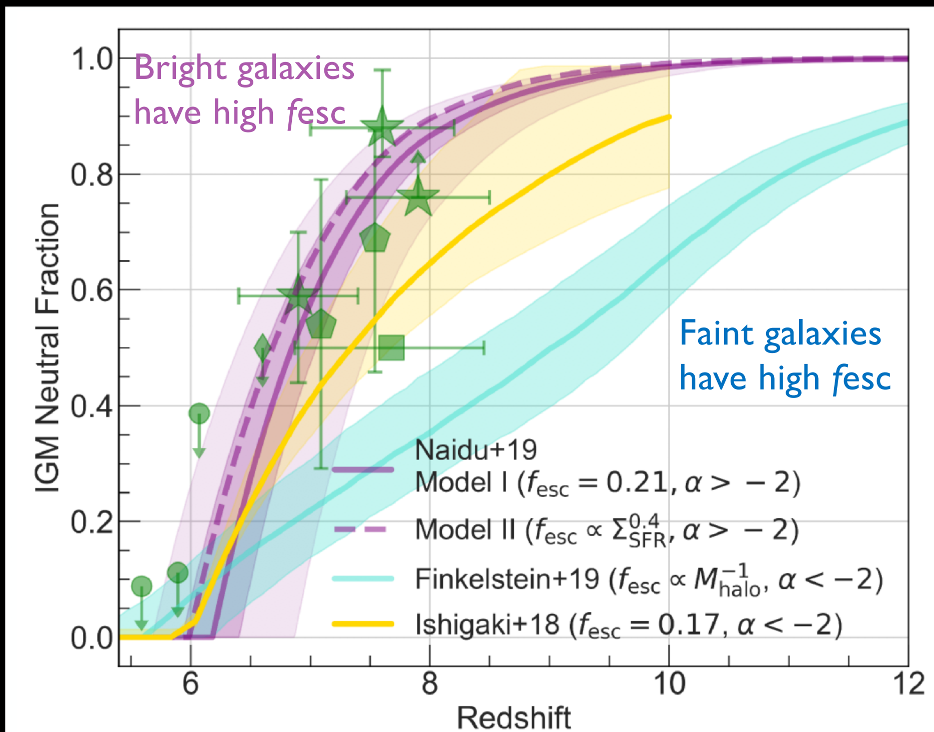


Naidu+20, Tacchella+18

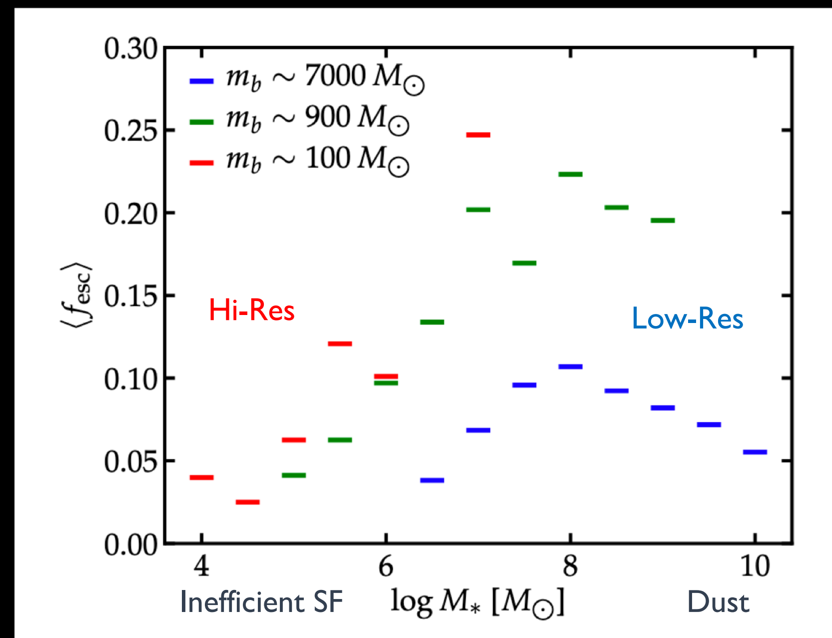
- Radically different pictures of reionization depending on *fesc* distribution.

Cosmic Reionization: everything hinges on LyC f_{esc}

Timeline



Naidu+20, Tacchella+18



Ma+20, FIRE-2 Simulations
See also Ma+15,16

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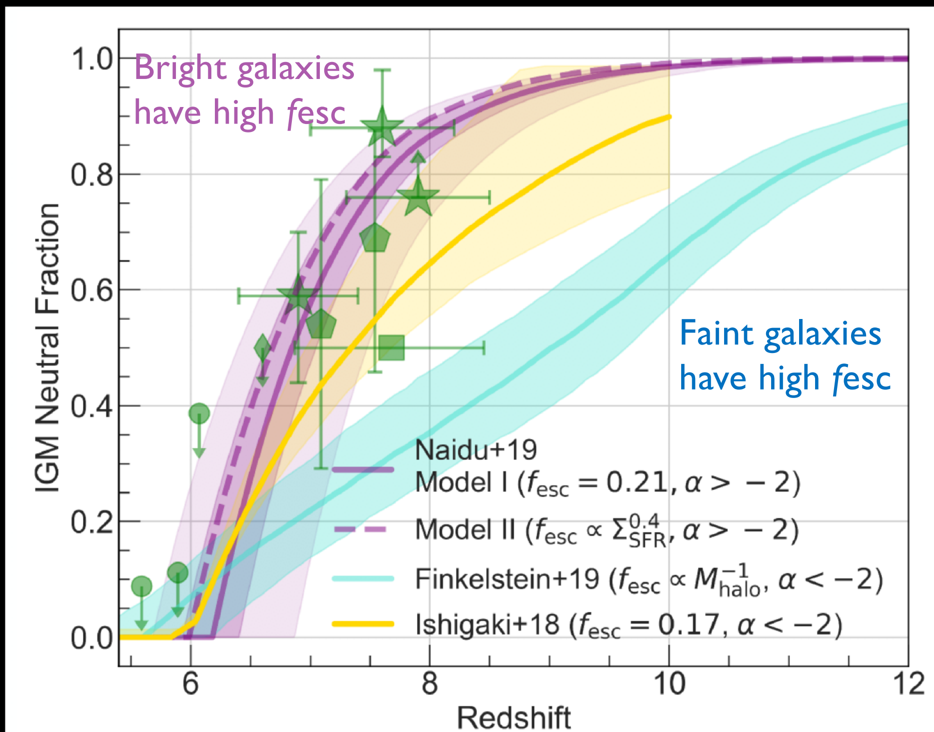
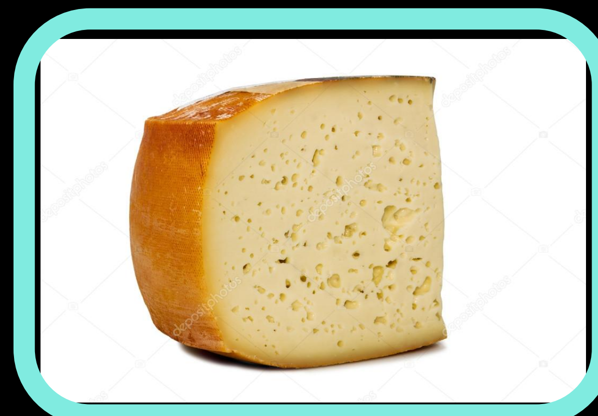


Naidu+20, Tacchella+18

Topology



- Radically different pictures of reionization depending on *fesc* distribution.

State of the (LyC *f*esc) Union

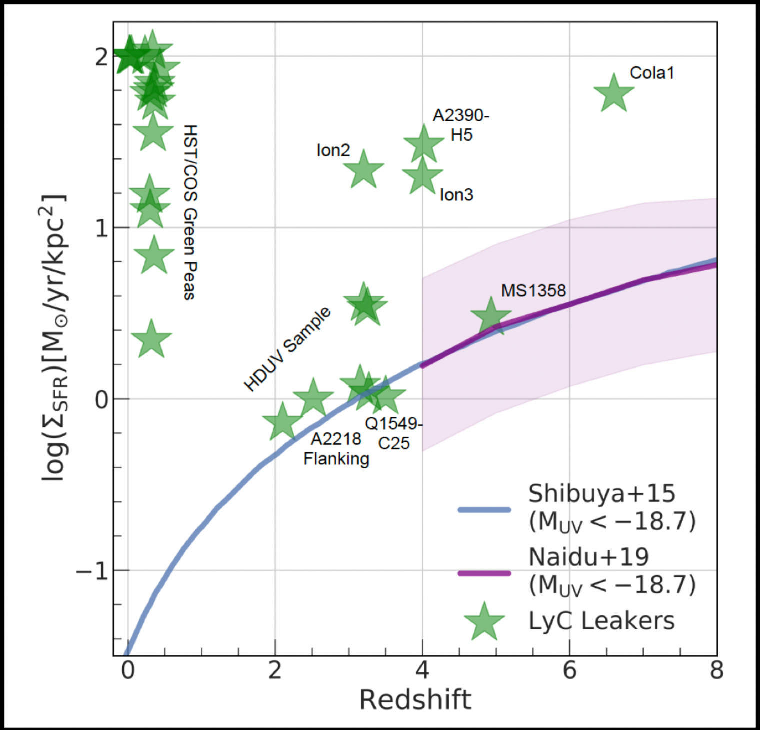
- Difficult to perform a simple test at significant redshift: what are the properties of high *f*esc vs. low *f*esc galaxies?

Fog (IGM/viewing angle effects) = can’t tell how bright the city (*f*esc) is

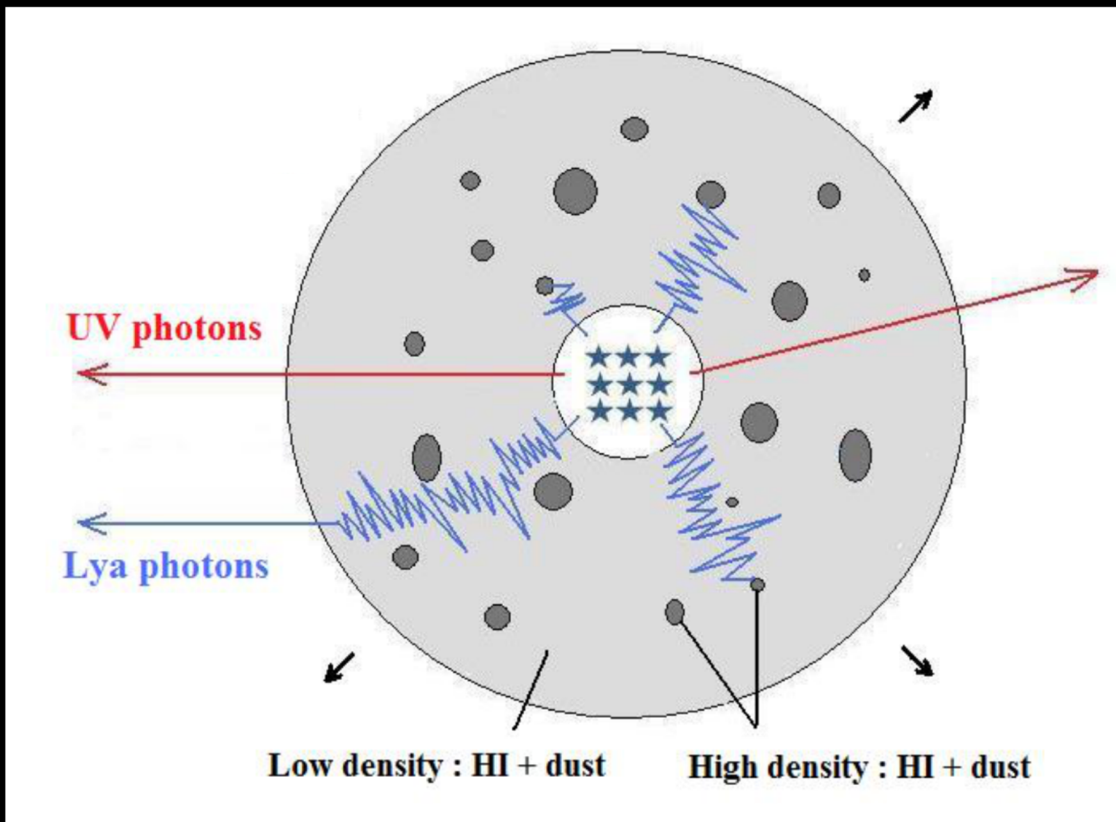
State of the (LyC *fesc*) Union

- Difficult to perform a simple test at significant redshift: what are the properties of high *fesc* vs. low *fesc* galaxies?

- What is the connection between results at lower redshifts and the Epoch of Reionization?



Naidu+20



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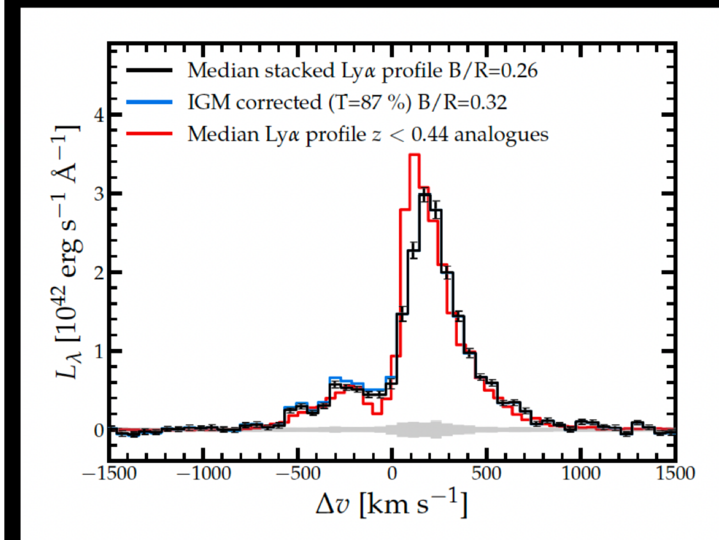
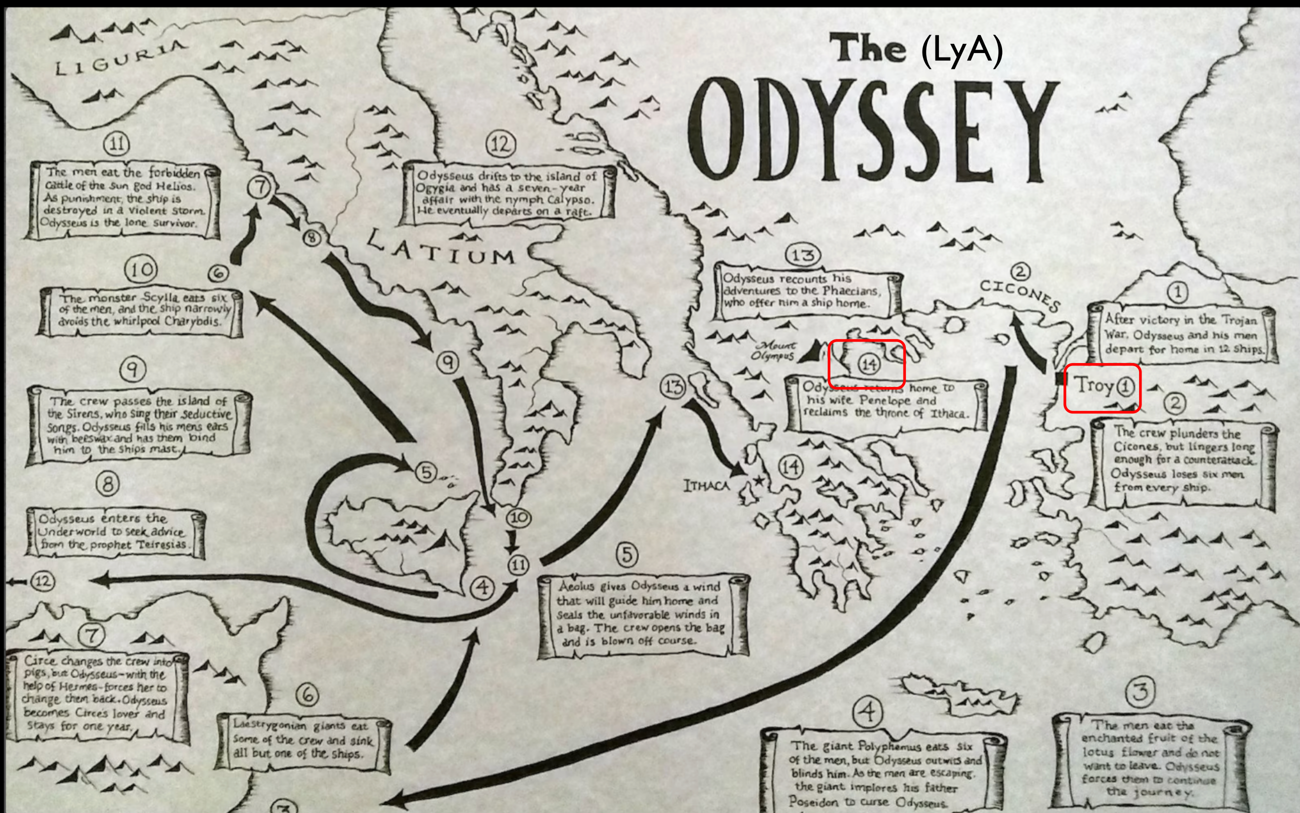
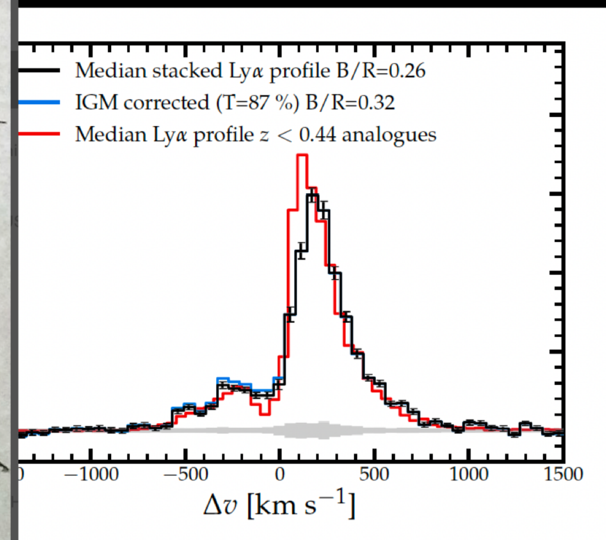


Duval+14

Resolved Lyman-α
is the panacea

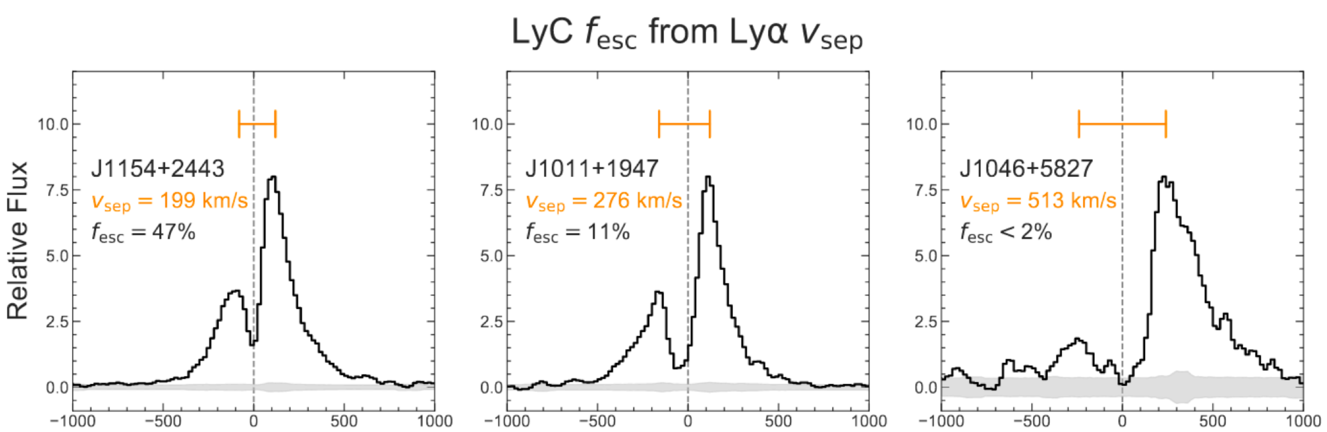




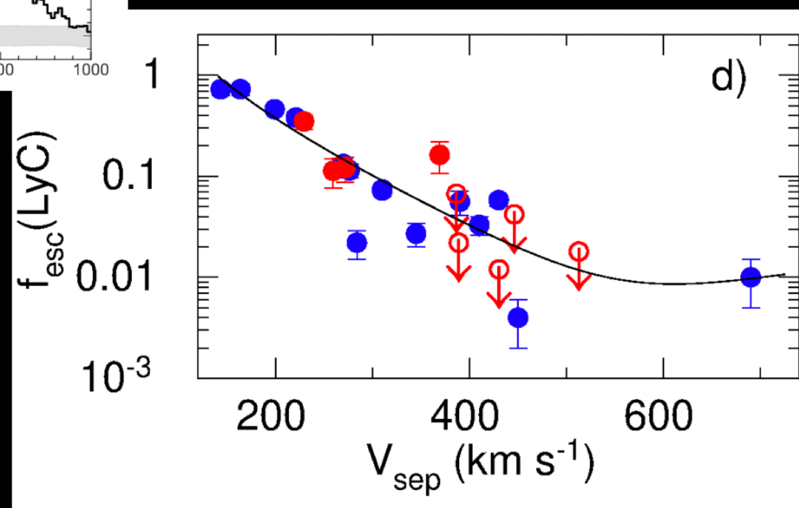
Resolved Lyman-α
is the panacea

Duval+14

Lyα profiles are excellent tracers of LyC *f*esc: peak separation (*V*sep)



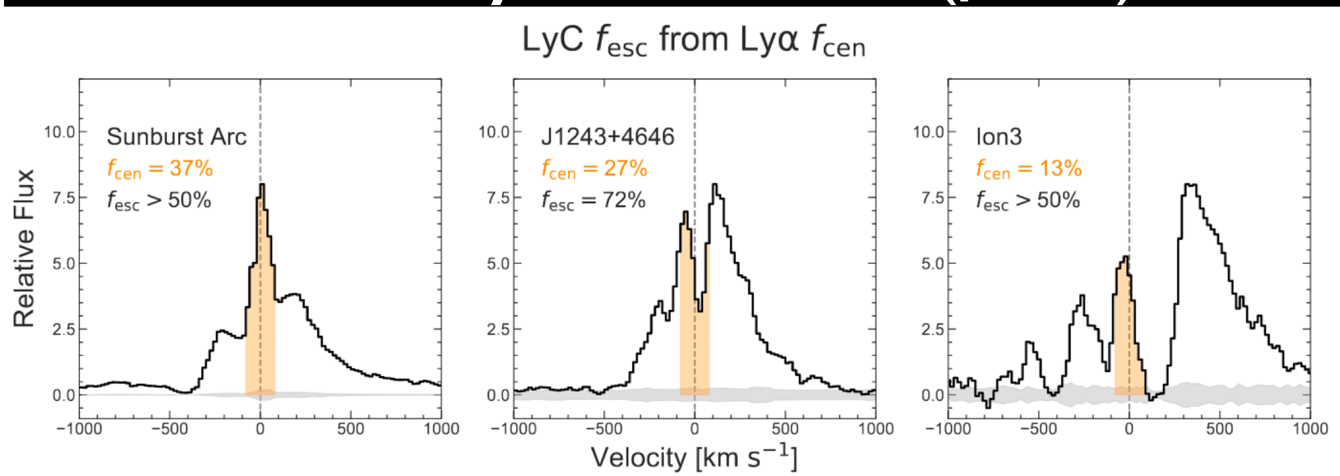
z~0.3

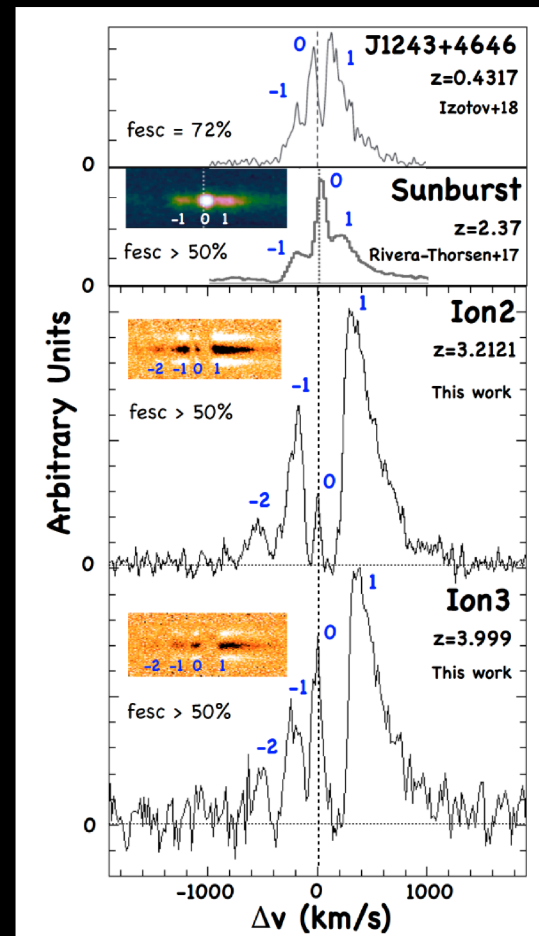


Low V*sep* = High fesc

Izotov+21

Lyα profiles are excellent tracers of LyC *fesc*: central Lyα fraction (*fcen*)



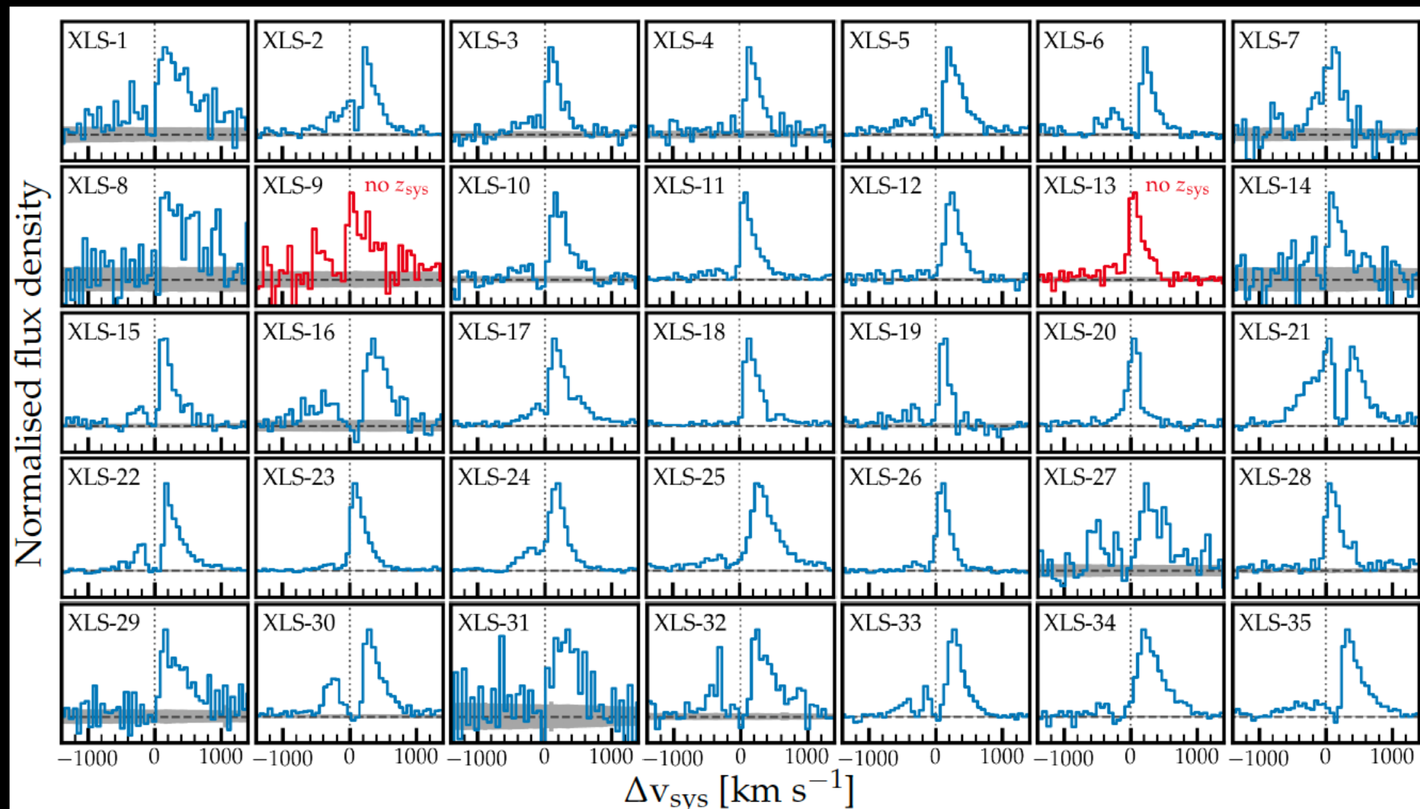


High *fcen*= High *fesc*

Systemic Lyα traces ionized channels

Vanzella+18

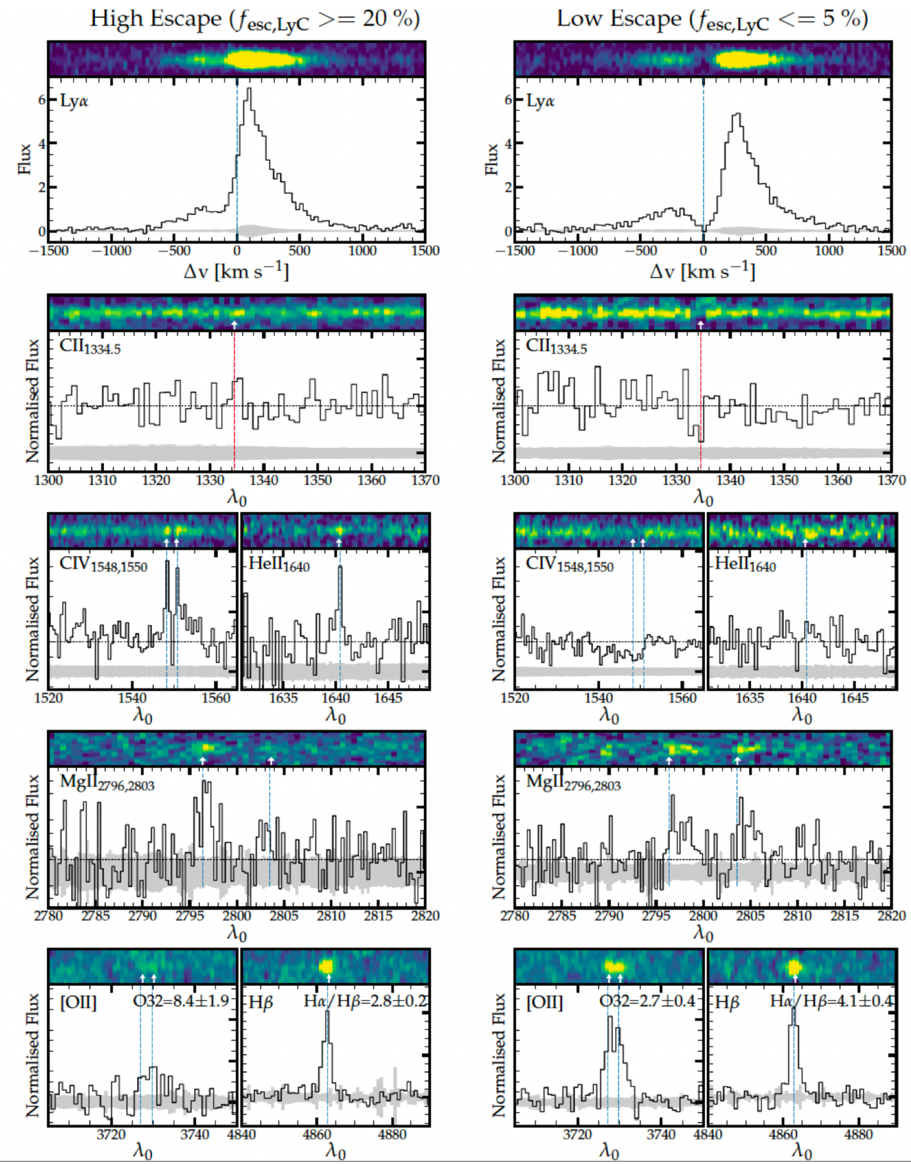
XLSz2: X-SHOOTER Lyα Survey at z~2



- R>4000 Lyα profiles, <10 km/s systemic zs
- N=35, well-defined, flux-limited sample (Lyα L>0.2 Lyα L*)
- Coverage from Lyα to Hα

Matthee+21, MNRAS, 1292M

Stacks comparable log(M*)~9, Muv~-20, β~-2, 12 + log(O/H)~8

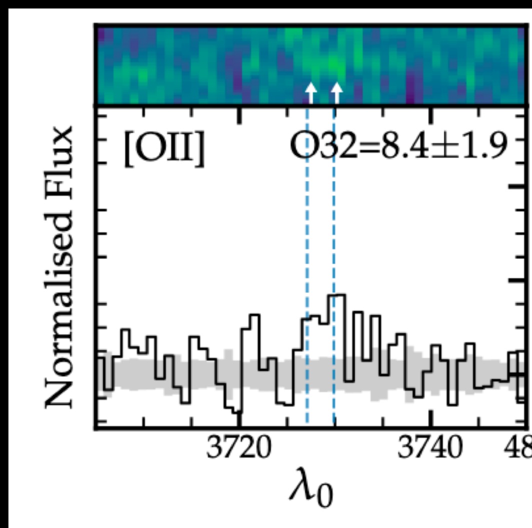


Naidu & Matthee 2022

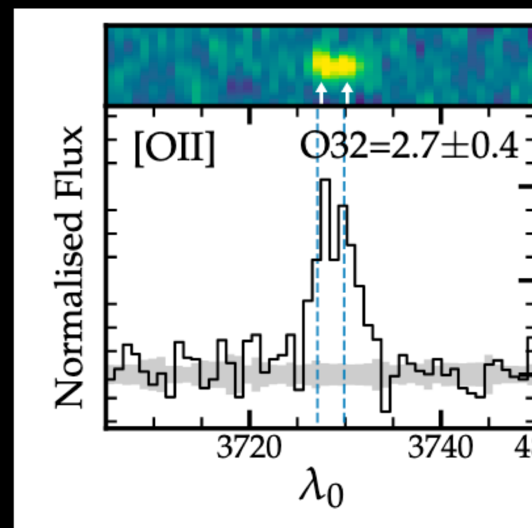
High Escape occurs in an extreme ionization state ISM

High Escape (>20%)

O32=8.4



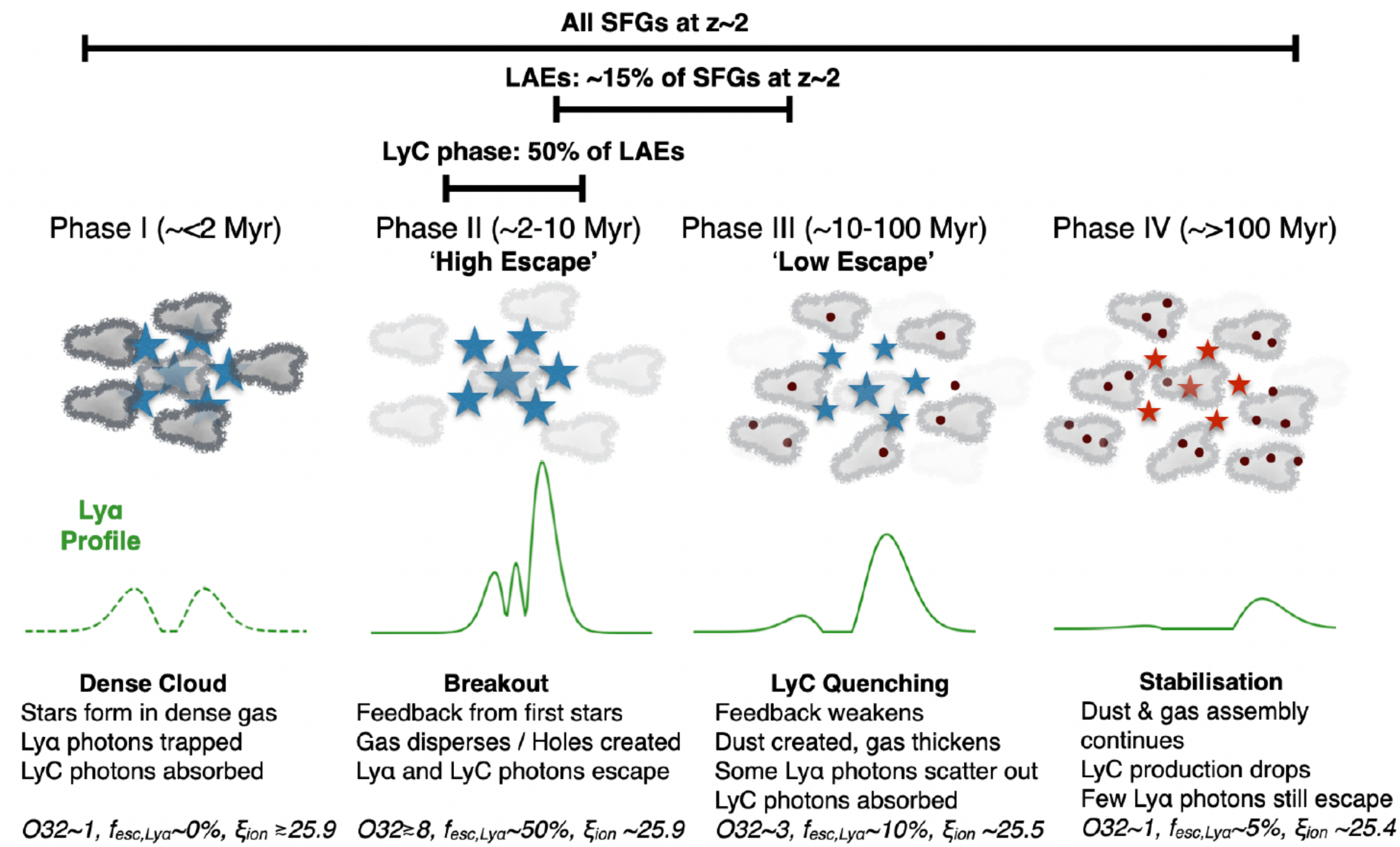
Low Escape (<5%)



O32=2.7

- O32 = [OIII]5007A/[OII]3727A.
- Extreme [OIII] emission (EW >800 A) can be used to select agents of reionization.

Evolutionary sequence for LyA and LyC



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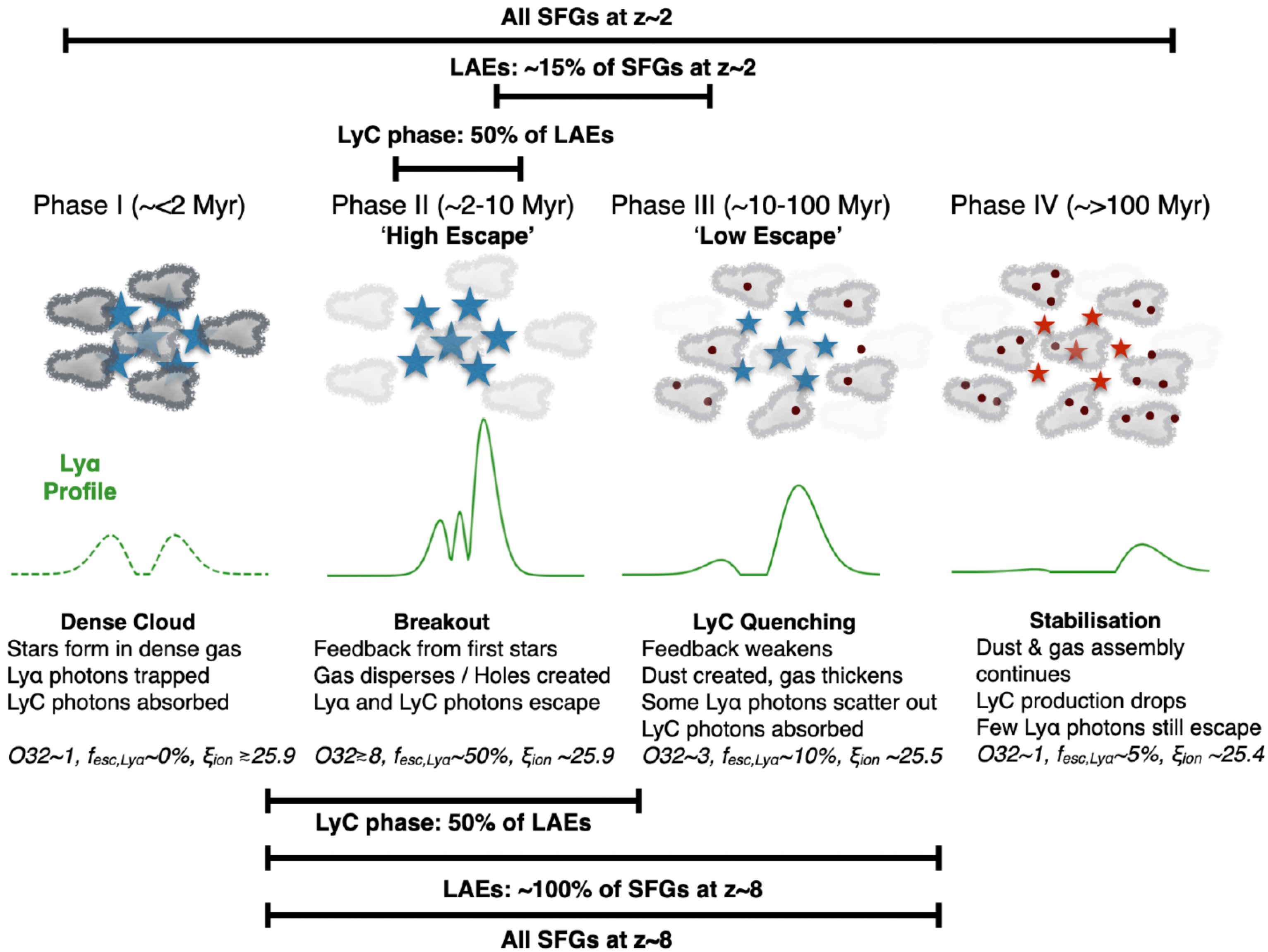
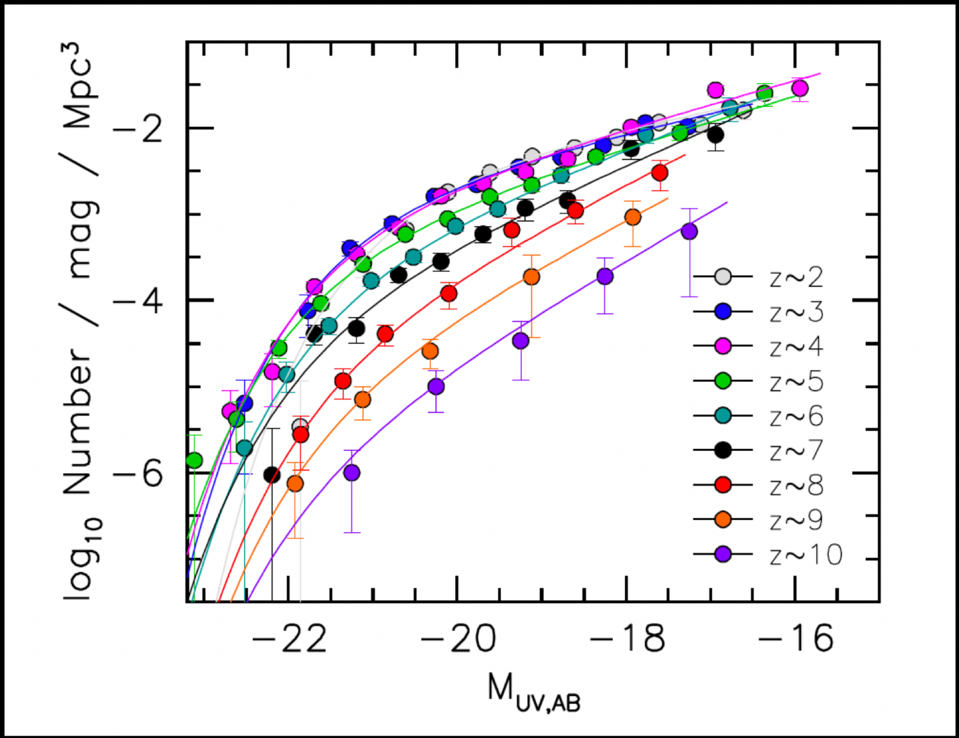


UV Luminosity Functions are the classical standard for reionization calculations



Bouwens+21

Total photons = Number of galaxies

x Ionizing photons/galaxy

x Fraction that evade dust+HI

$= \rho_{SFR}\, \xi_{ion}\, f_{esc}$

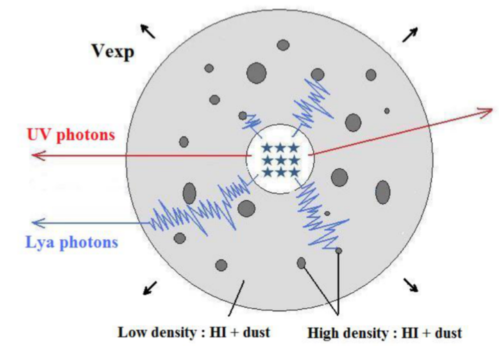
LyA luminosity functions are a more intuitive choice

- If there is no LyA escape, there is no ionizing photon escape
- UV luminosity functions sum photons from all galaxies

  LyA luminosity functions focus on "productive" galaxies

$$\dot{n}_{\mathrm{ion,LBG}}(z) = \rho_{\mathrm{UV}}(z)\, \xi_{\mathrm{ion}}\, f_{\mathrm{esc}}^{\mathrm{LyC}} \longrightarrow \dot{n}_{\mathrm{ion,LAE}}(z) = \frac{\rho_{\mathrm{Ly}\alpha}(z)\, f_{\mathrm{esc}}^{\mathrm{LyC}}}{8.7 f_{\mathrm{esc}}^{\mathrm{Ly}\alpha} \left(1 - f_{\mathrm{esc}}^{\mathrm{LyC}}\right) c_{\mathrm{H}\alpha}}$$

Madau+99, Robertson+13

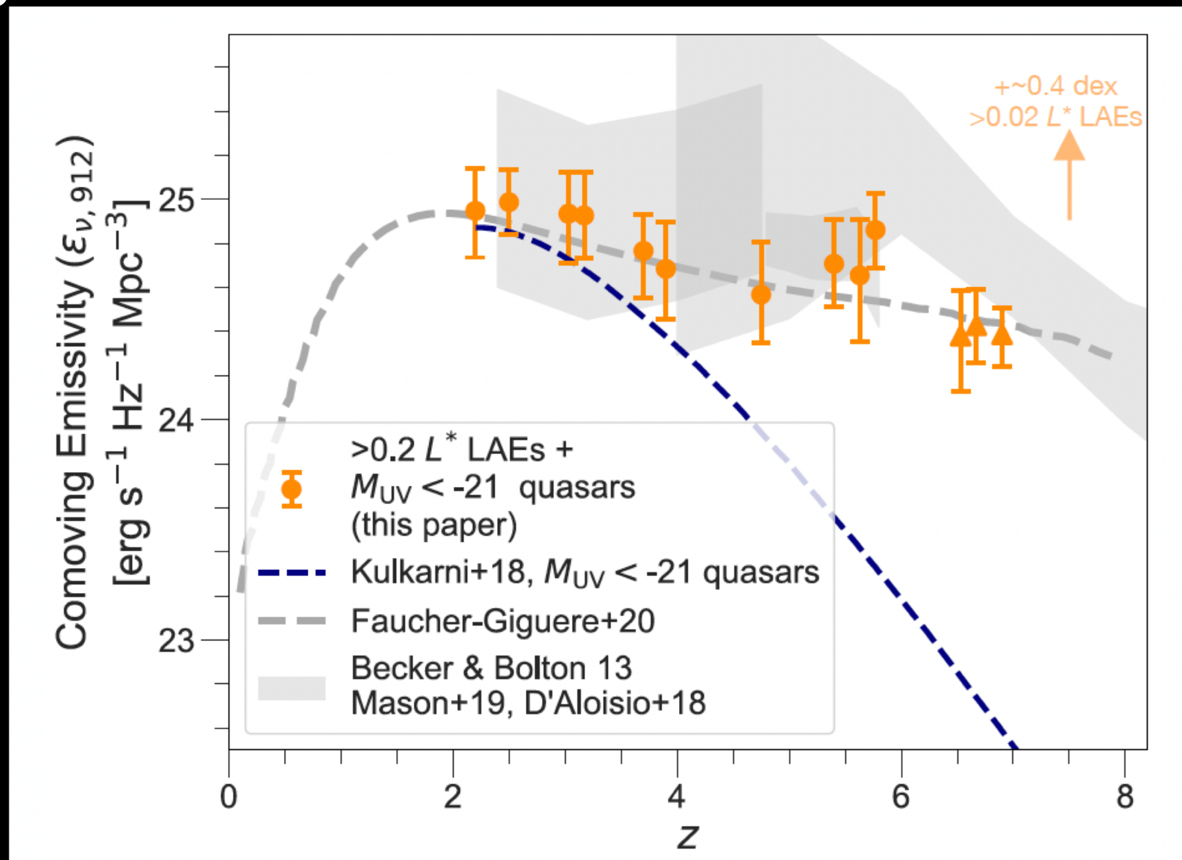


Duval+14

Matthee & Naidu+21

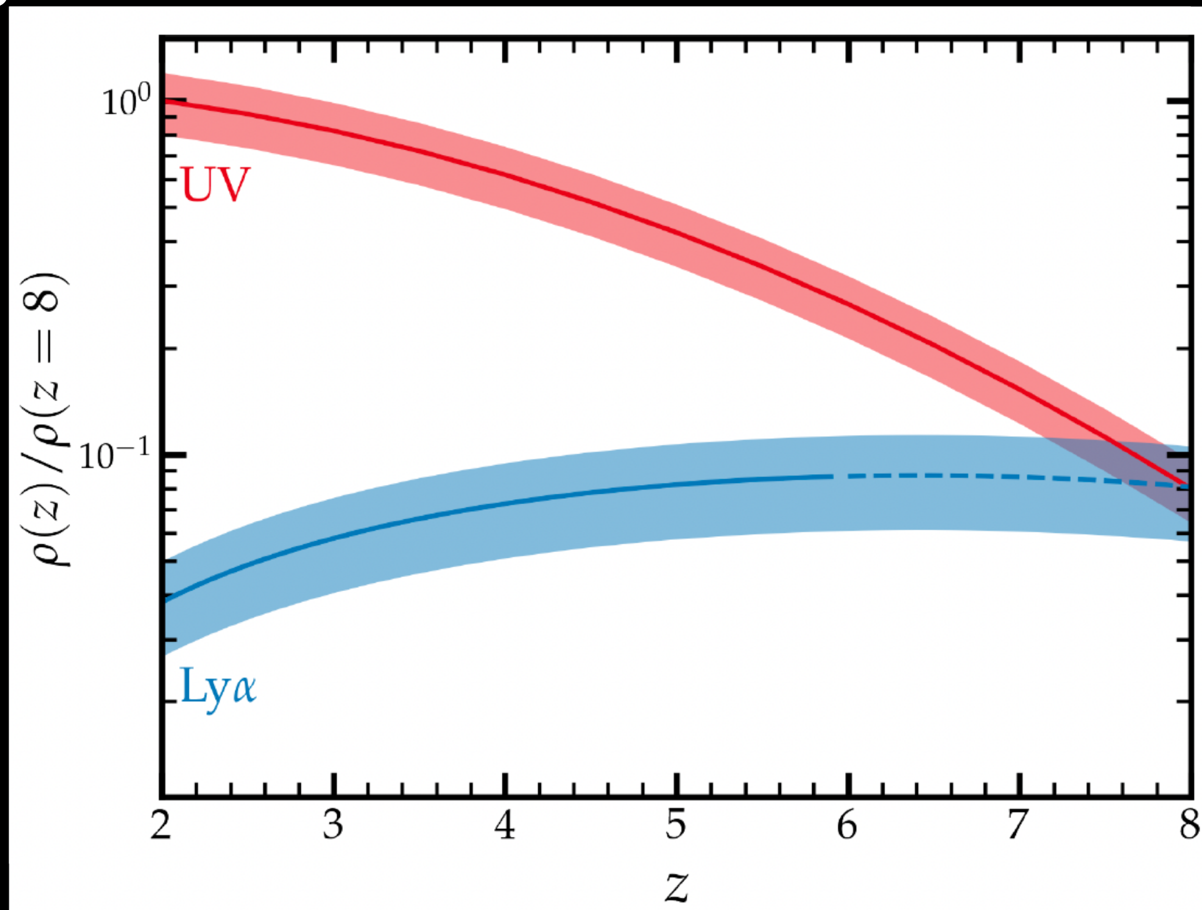
The Ionizing background at z~2-8 is due to bright Lyman-alpha emitters

- Excellent match to the shape of the emissivity

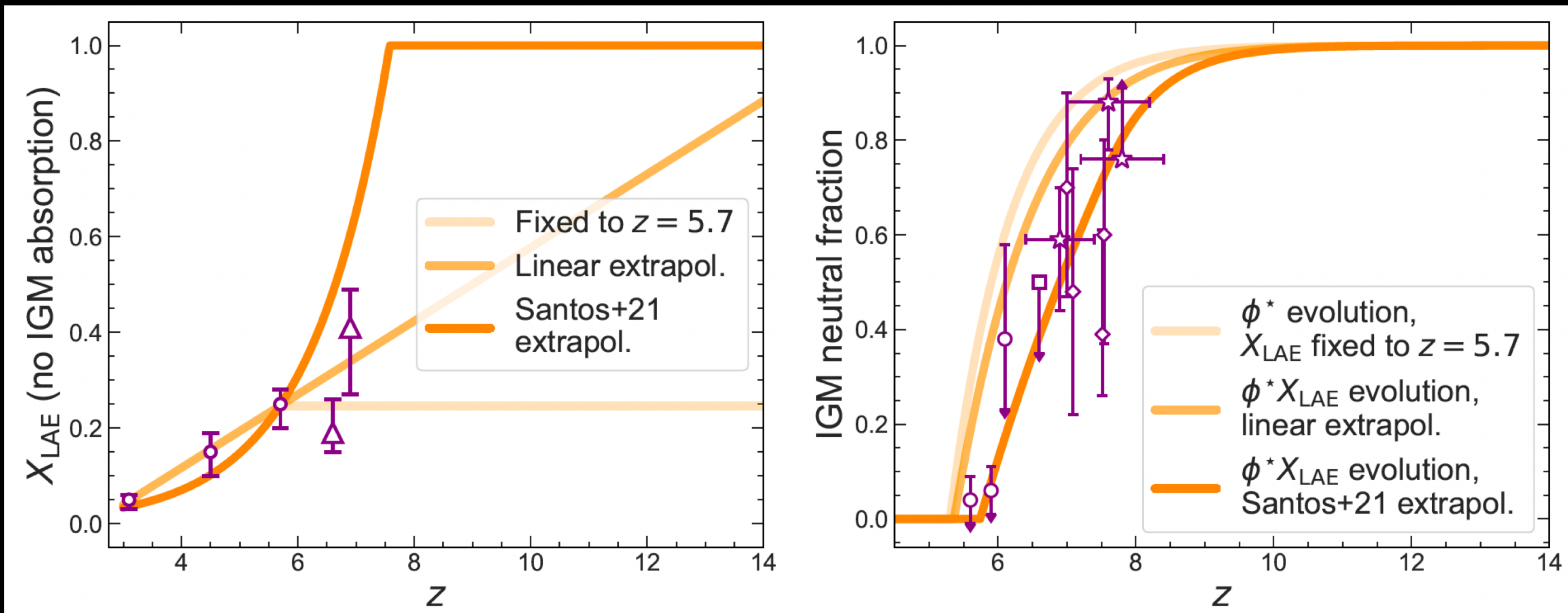


The Ionizing background at z~2-8 is due to bright Lyman-alpha emitters

- Excellent match to the shape of the emissivity
- The falling star-formation density is balanced by the rising LAE fraction

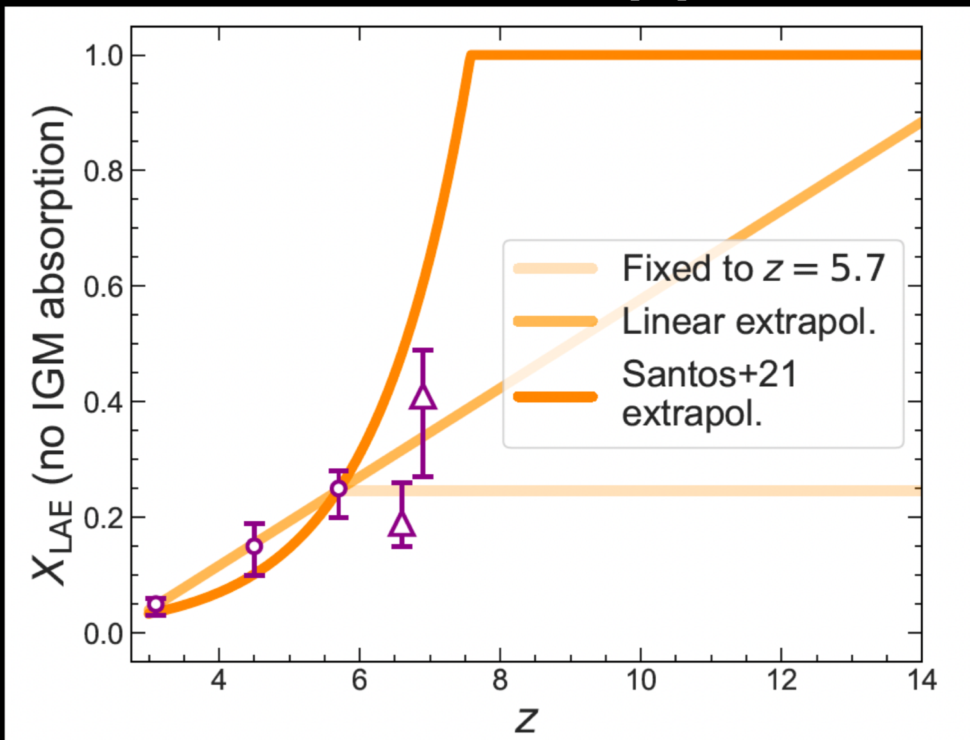


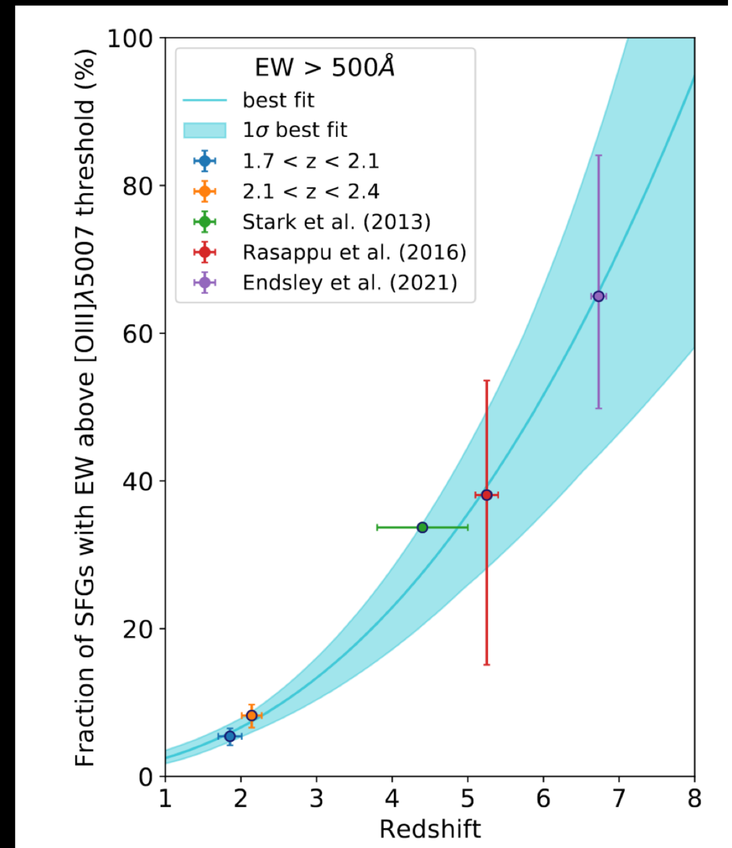
Rapid Reionization by bright Lyman-alpha Emitters



- Only free parameter is the fraction of galaxies that are Lyman-alpha emitters.

But LAEs disappear at z>6?



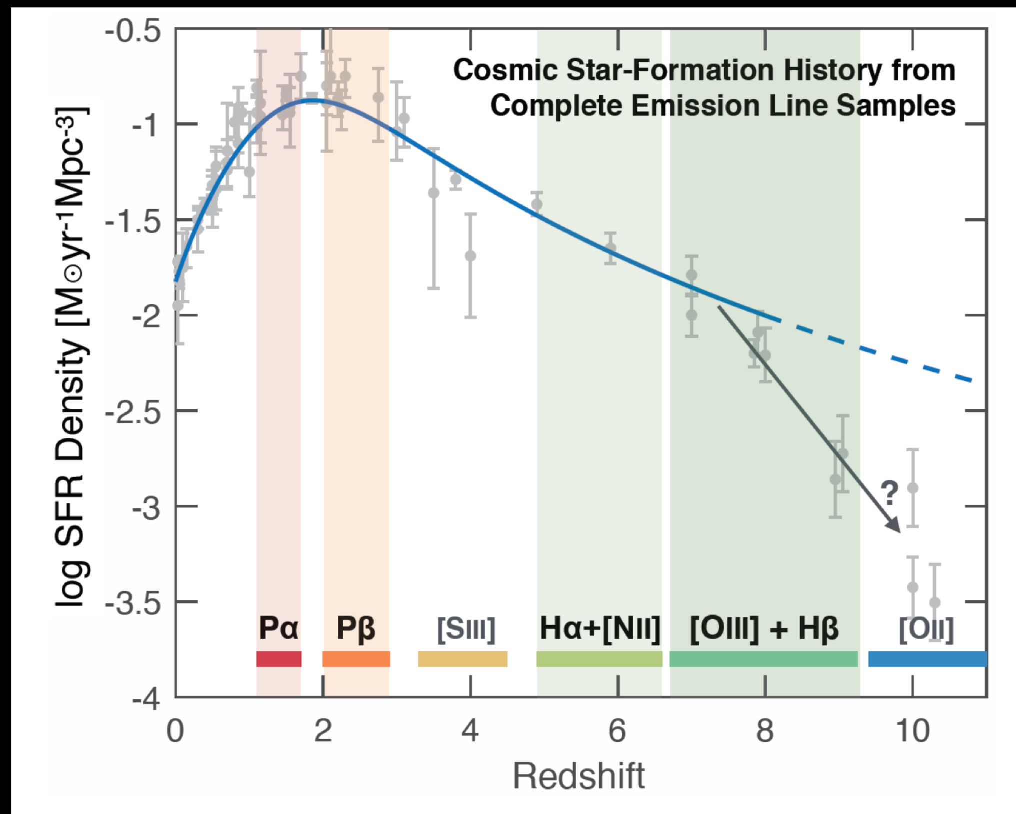


- Map LyA fraction to extreme [OIII] emitter fraction
- Integrate Hb luminosity function

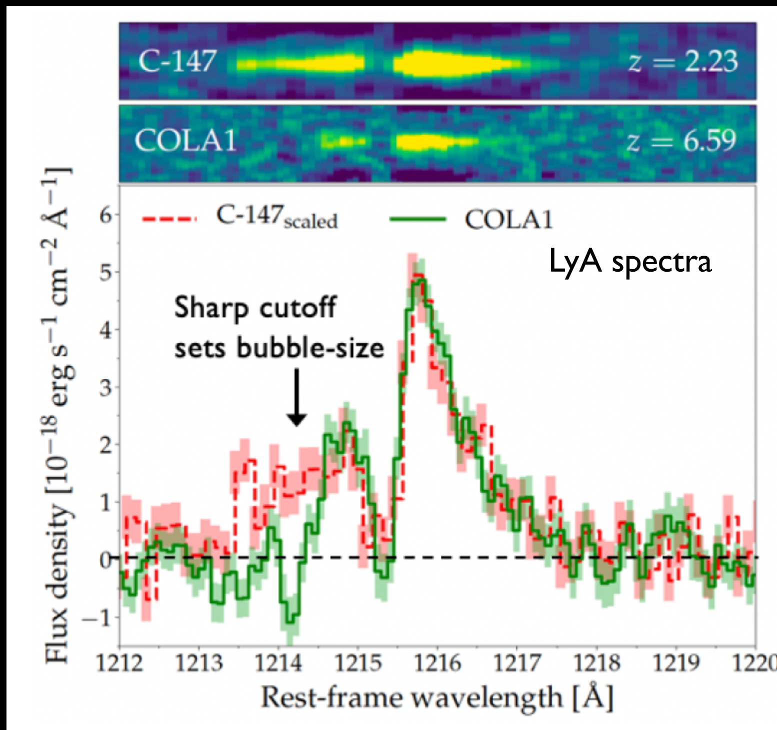
Boyett+21
de Barros+19
Stefanon+22

FRESCO: First Reionization Epoch Survey that is COmplete PI: Pascal Oesch

- *JWST*/NIRCam F444W grism survey.
- Spectra for *every* galaxy in the field of view: 60 arcmin^2 each in GOODS-S (covering HUDF) and GOODS-N.
- First *complete* line luminosity functions out to z~9



Which galaxies reionized the Universe?
JWST bubble program PI: Matthee & Naidu



Only z~7 bubble with strongly constrained size

Matthee+18, Mason & Gronke 2020

Which galaxies reionized the Universe?
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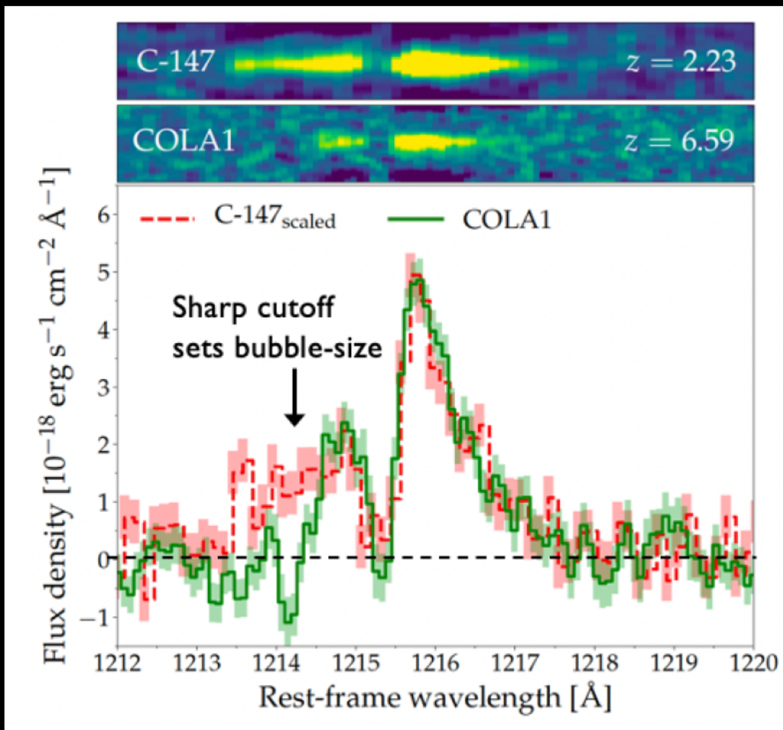
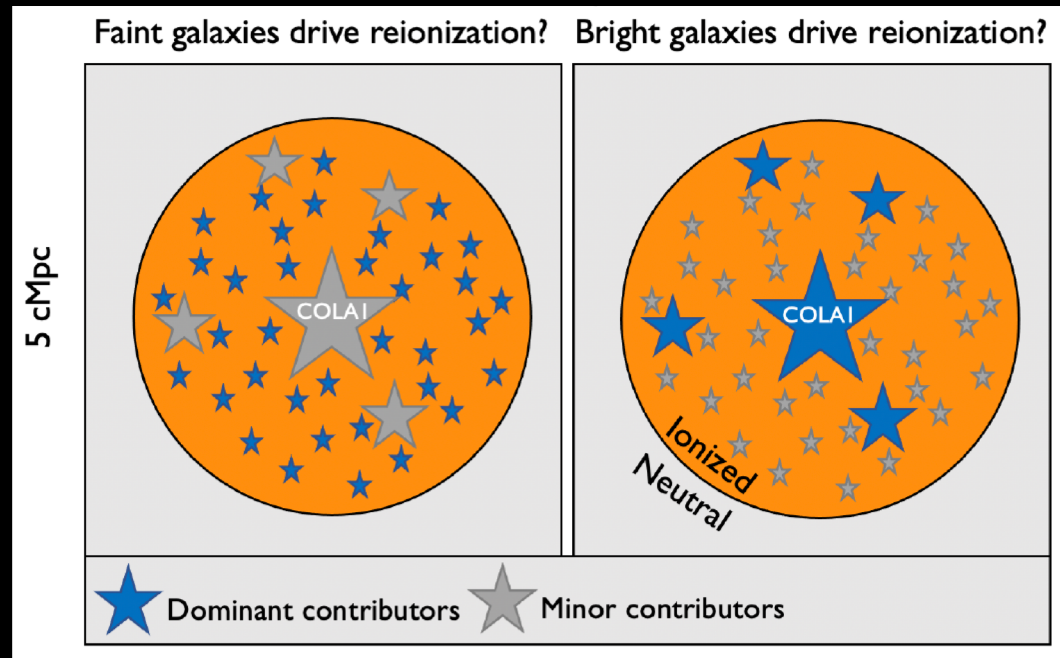


Only z~7 bubble with strongly constrained size Matthee+18, Mason & Gronke 2020



Total ionizing photon budget known (since size is known ~ Stromgren sphere)

Grism spectroscopy: can bright galaxies do it all?