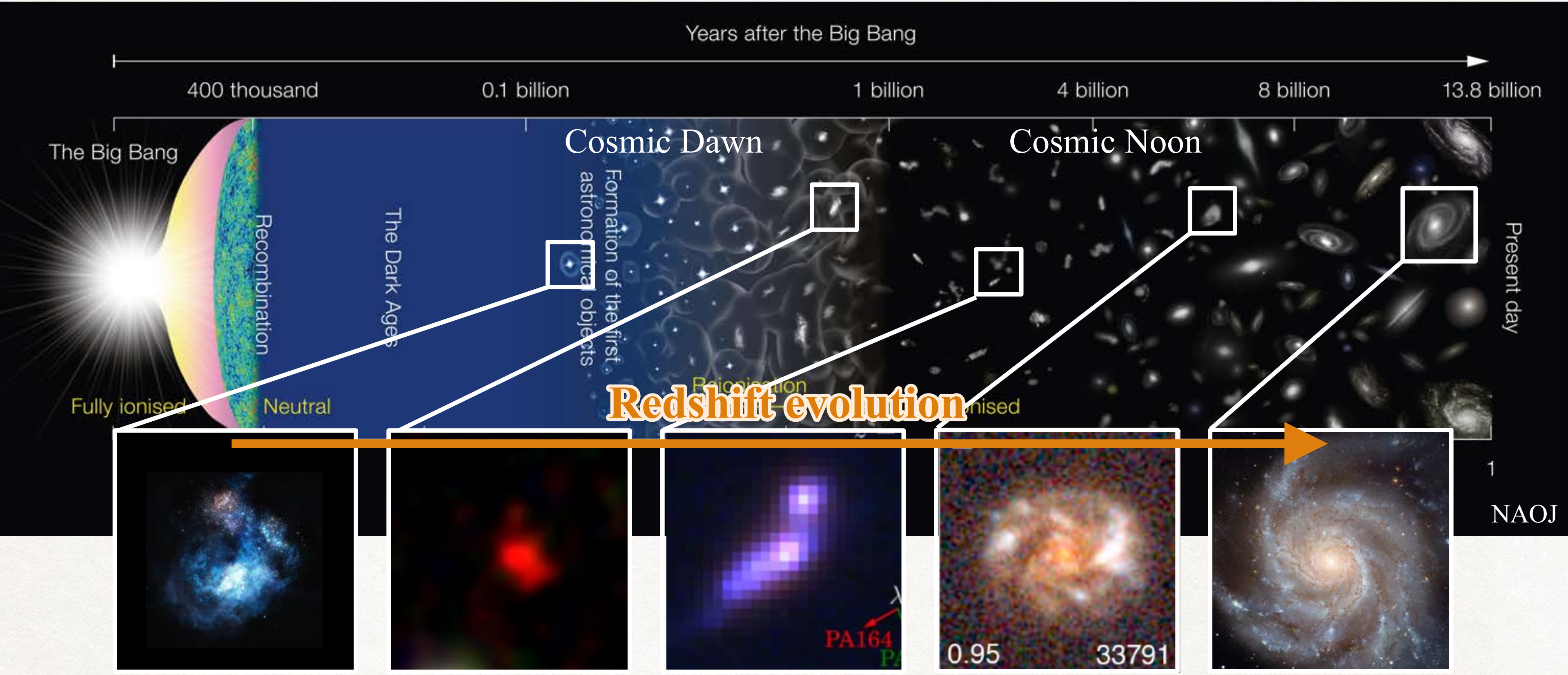
Emission Line Modeling of Galaxies at Cosmic Dawn

Yuma Sugahara

National Astronomical Observatory of Japan

Waseda University

History of Universe and Galaxies

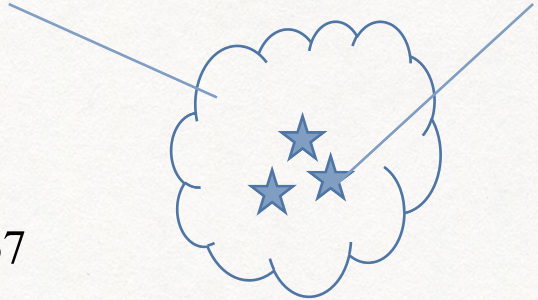


ESO/M. Kornmesser　Harikane, …, YS, et al. (2022)　Wang, et al. (2020)　Elmegreen, et al. (2009)　NASA, ESA, CXC, SSC, and STScI

Metallicity — Chemical Abundances

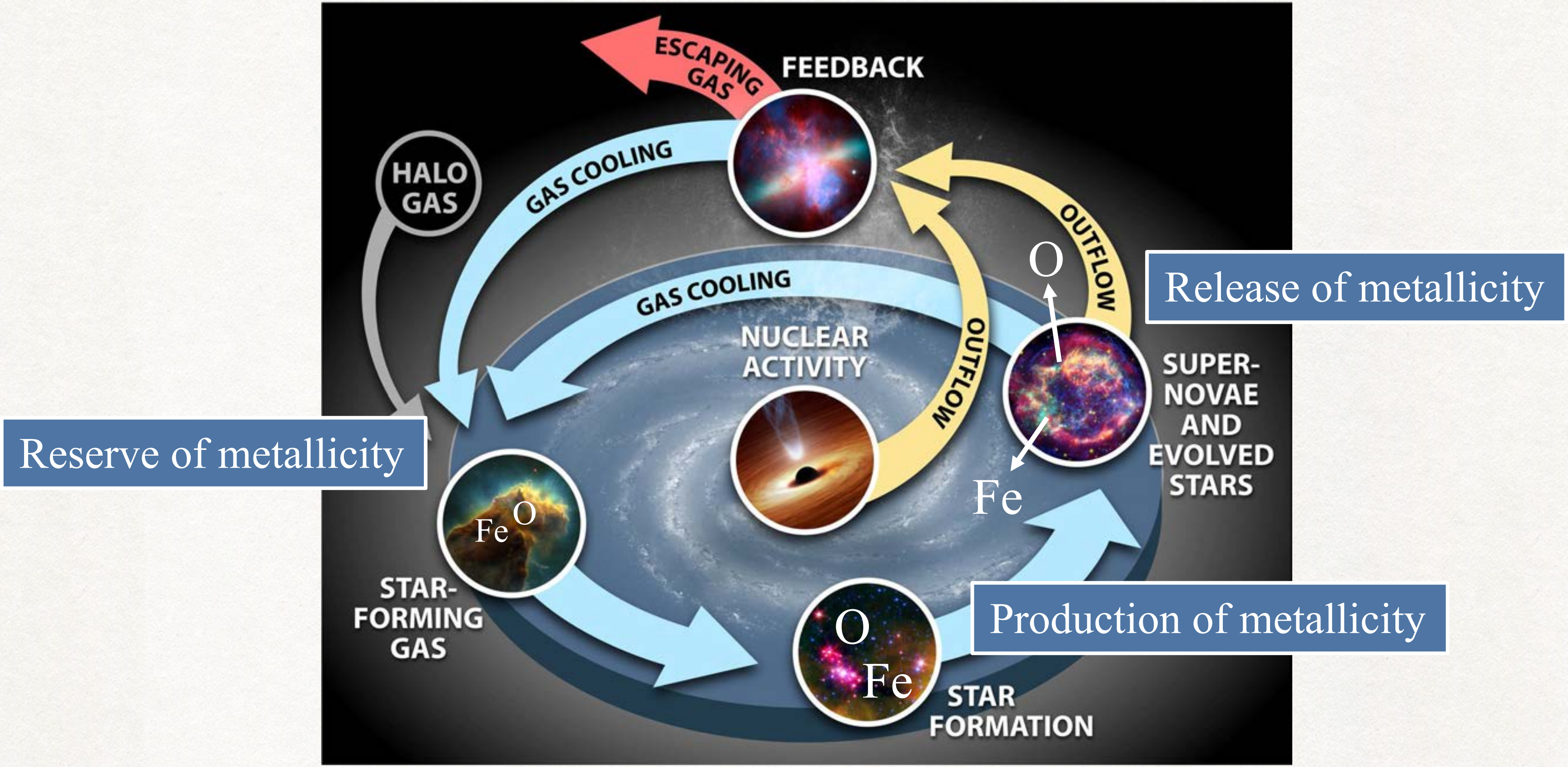
- Abundance of elements heavier than H and He.

- Gas-phase metallicity
  - Oxygen
  - Solar values
    - $12 + \log(O/H) = 8.67$
    - $Z_{gas} = 0.02 = 1Z_{\odot}$



- Stellar metallicity
  - Iron
  - Solar value:
    - $Z_{*} = 0.02 = 1Z_{\odot}$
    - $[Fe/H] = 1$

Cosmic and Galaxy Ecosystem



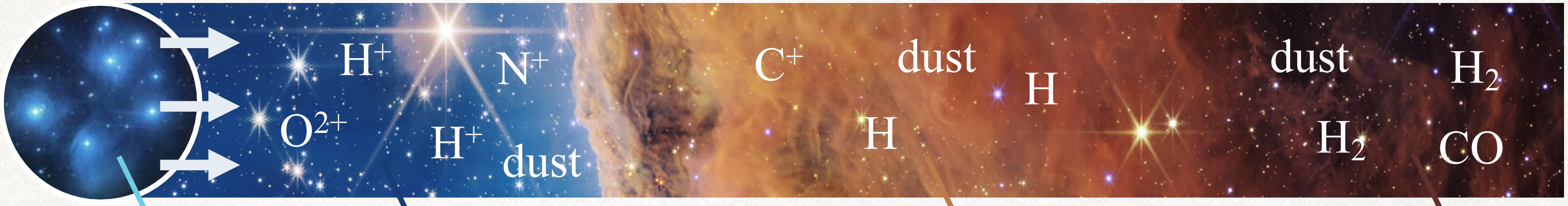
Meixner et al. 2021

How we observe the metallicity?

Ionized gas

Neutral gas

Molecular gas



[OIII], [NII], Ha

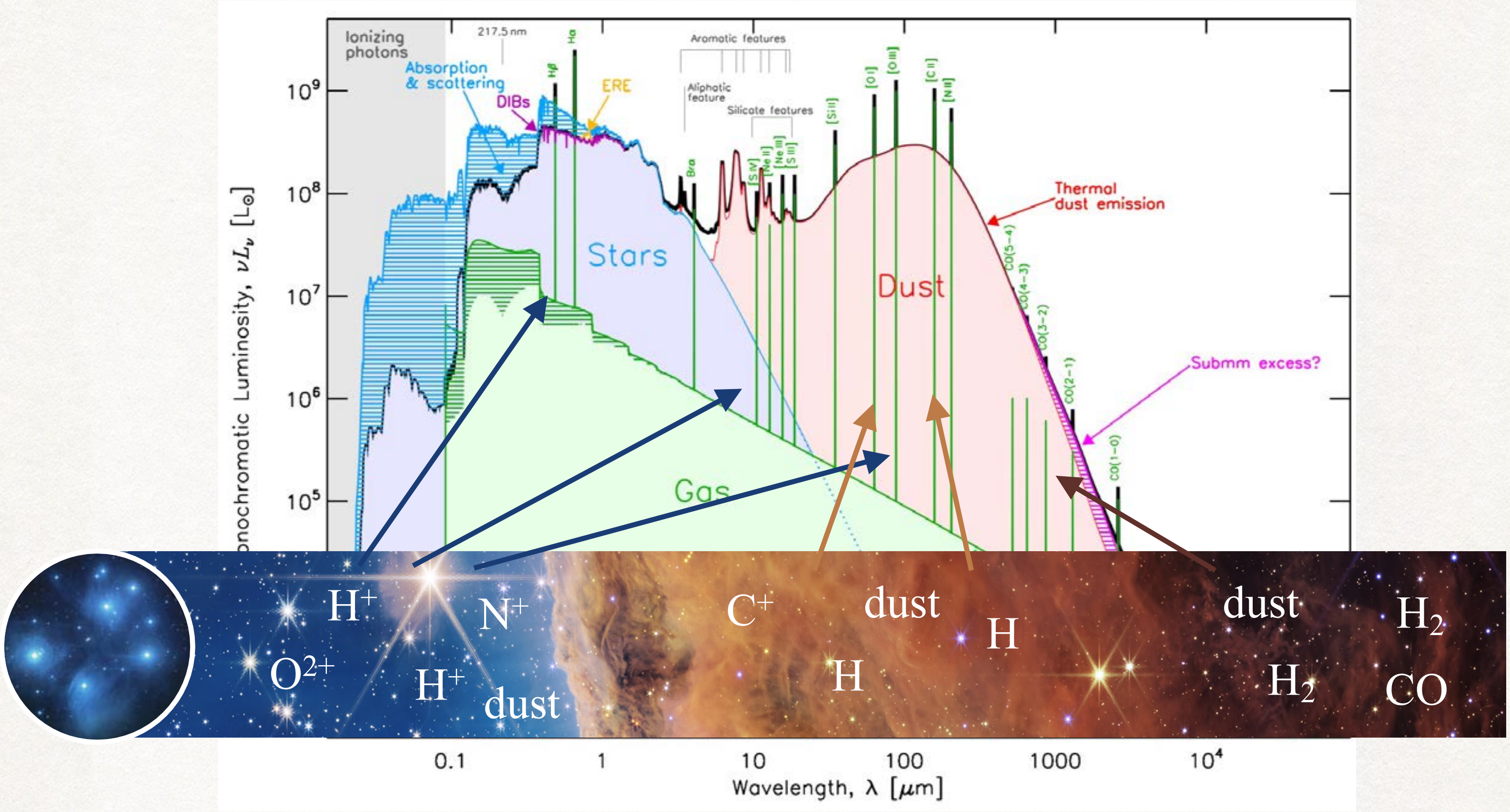
[CII] (, HI)

(CO, H_2)

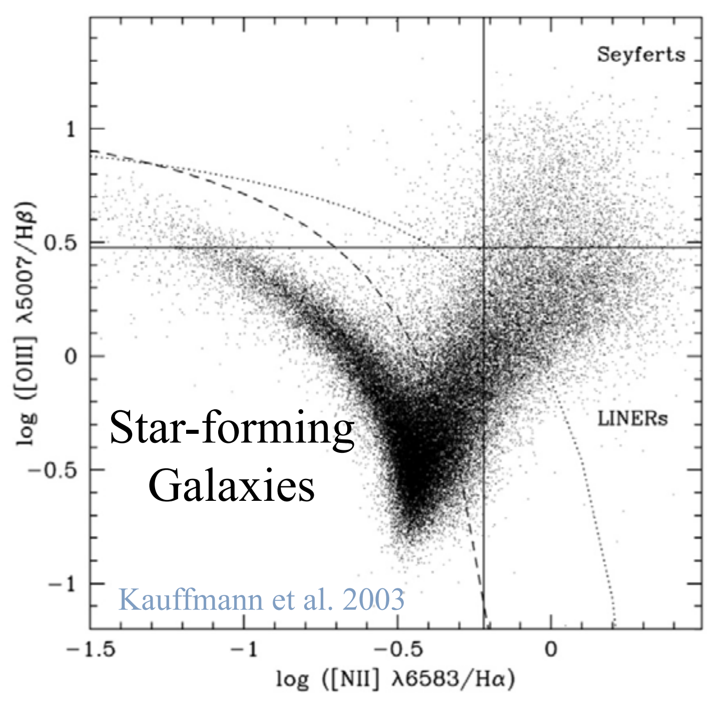
Stellar continuum

NASA, ESA, CSA, and STScI

Panchromatic Spectrum of Star-forming Galaxy



BPT diagram—Optical Emission-line Diagram



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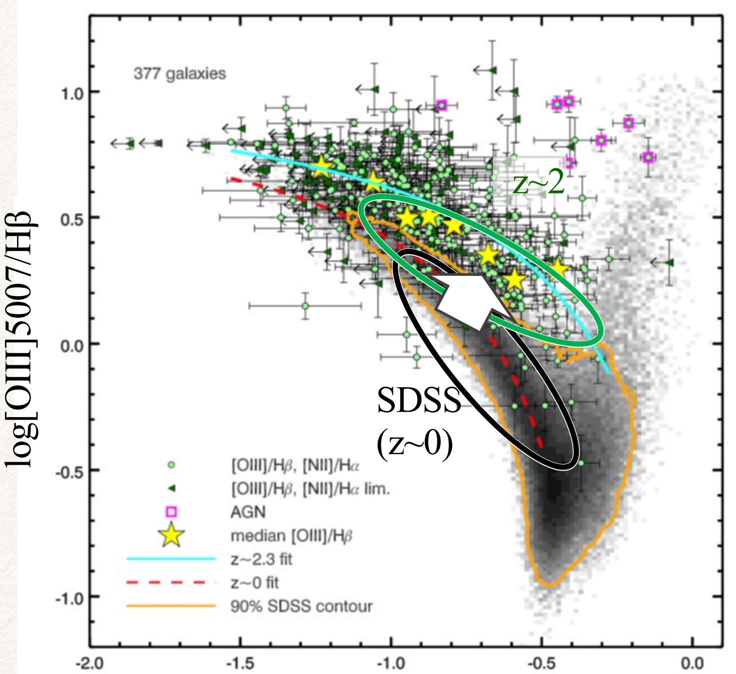
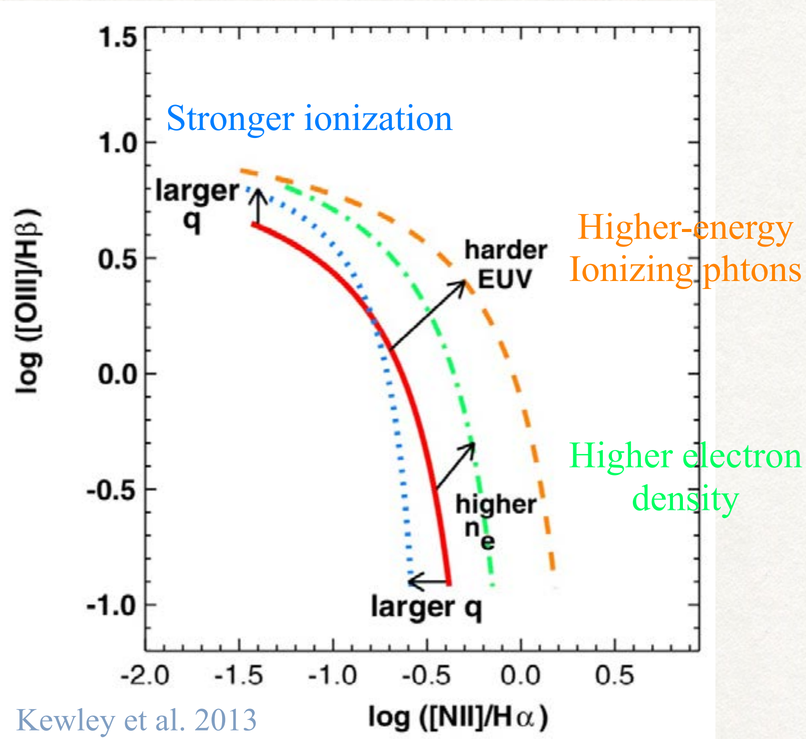


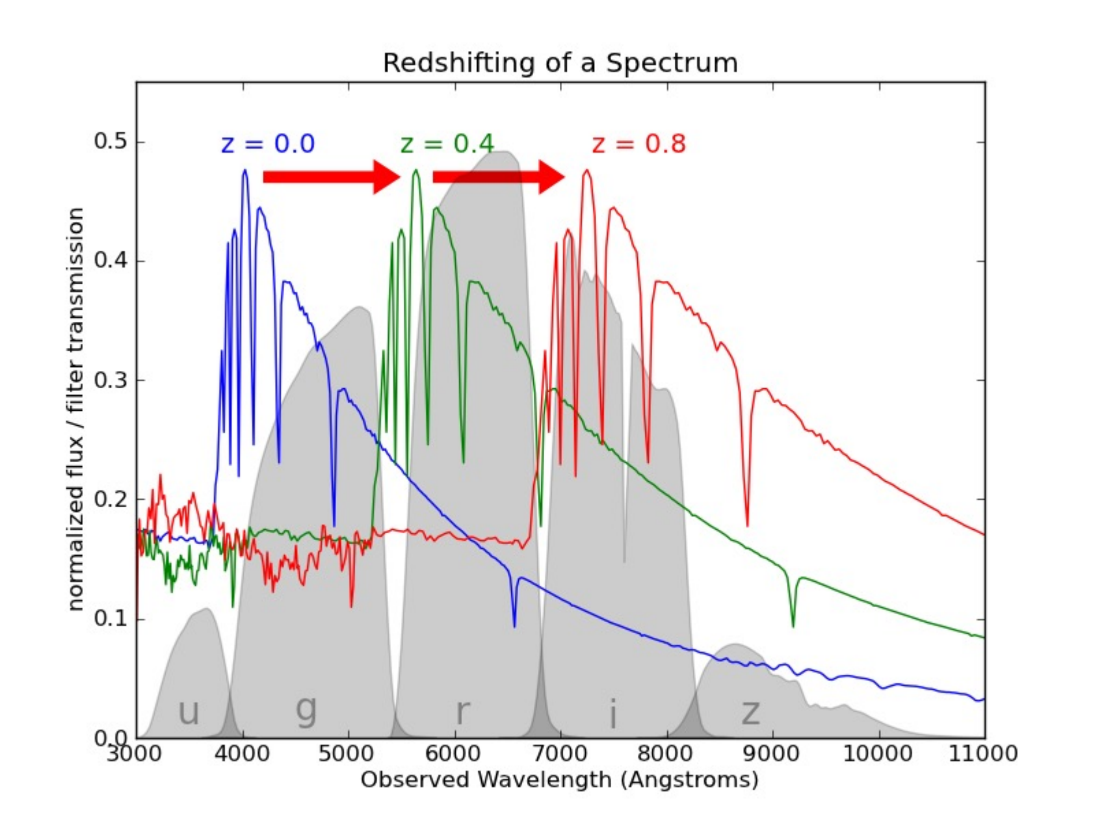
Strom+17



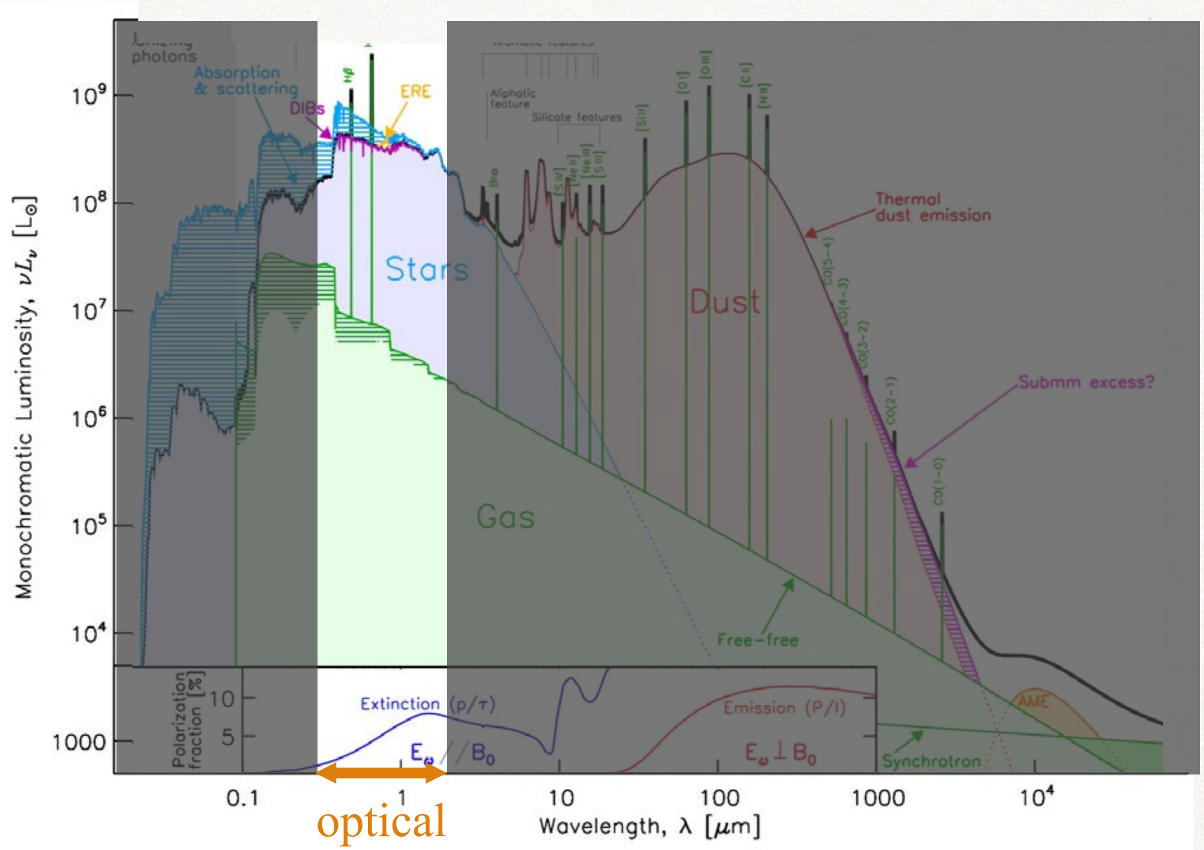
Kewley et al. 2013

○ z ~ 2 galaxies have higher [OIII]5007/Hb than local galaxies

Redshift of Galaxy Spectra caused by expansion of the universe



Redshift of Galaxy Spectra … requiring New Window

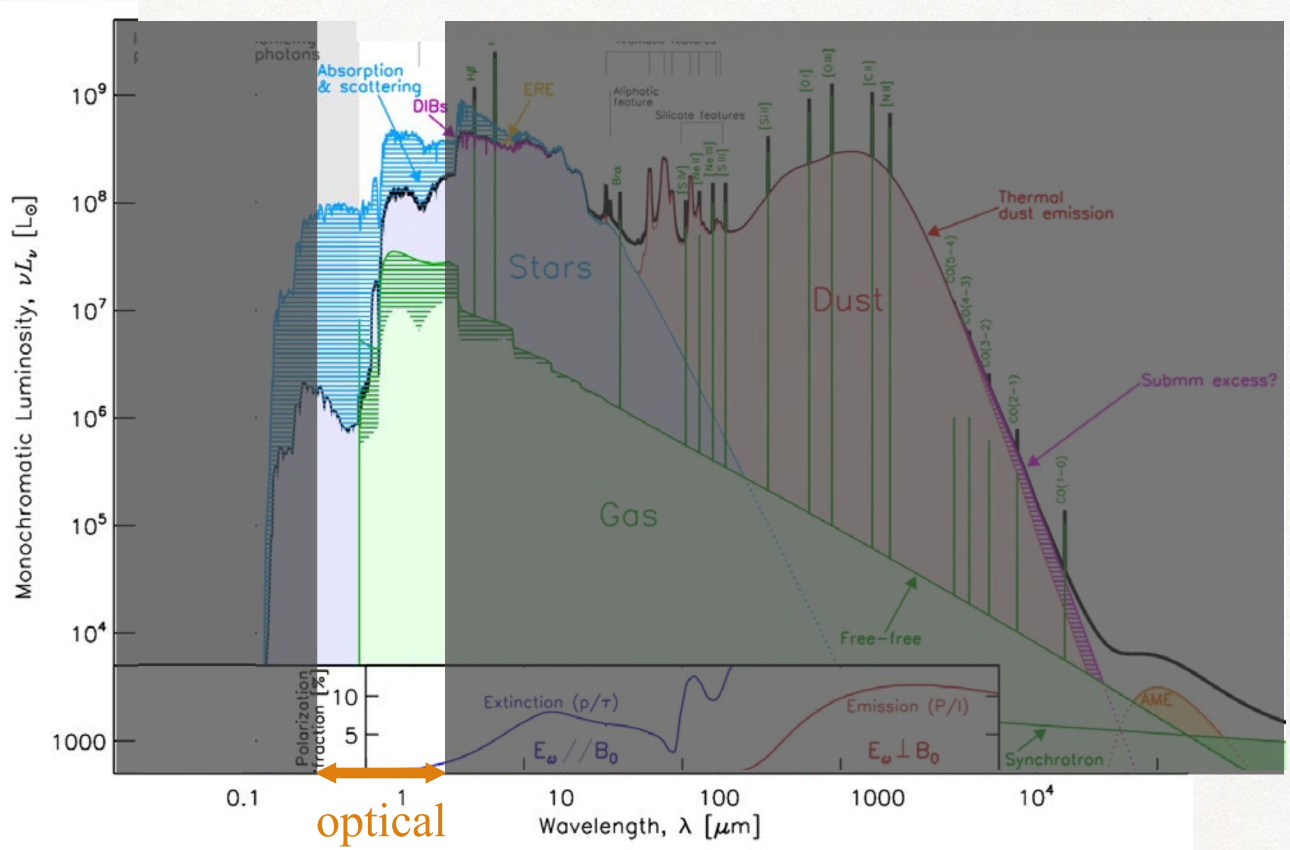


z ~ 0

At redshift z > 4,
it becomes difficult
to detect optical
emission lines.

Galliano, Galametz, and Jones 2018

Redshift of Galaxy Spectra … requiring New Window

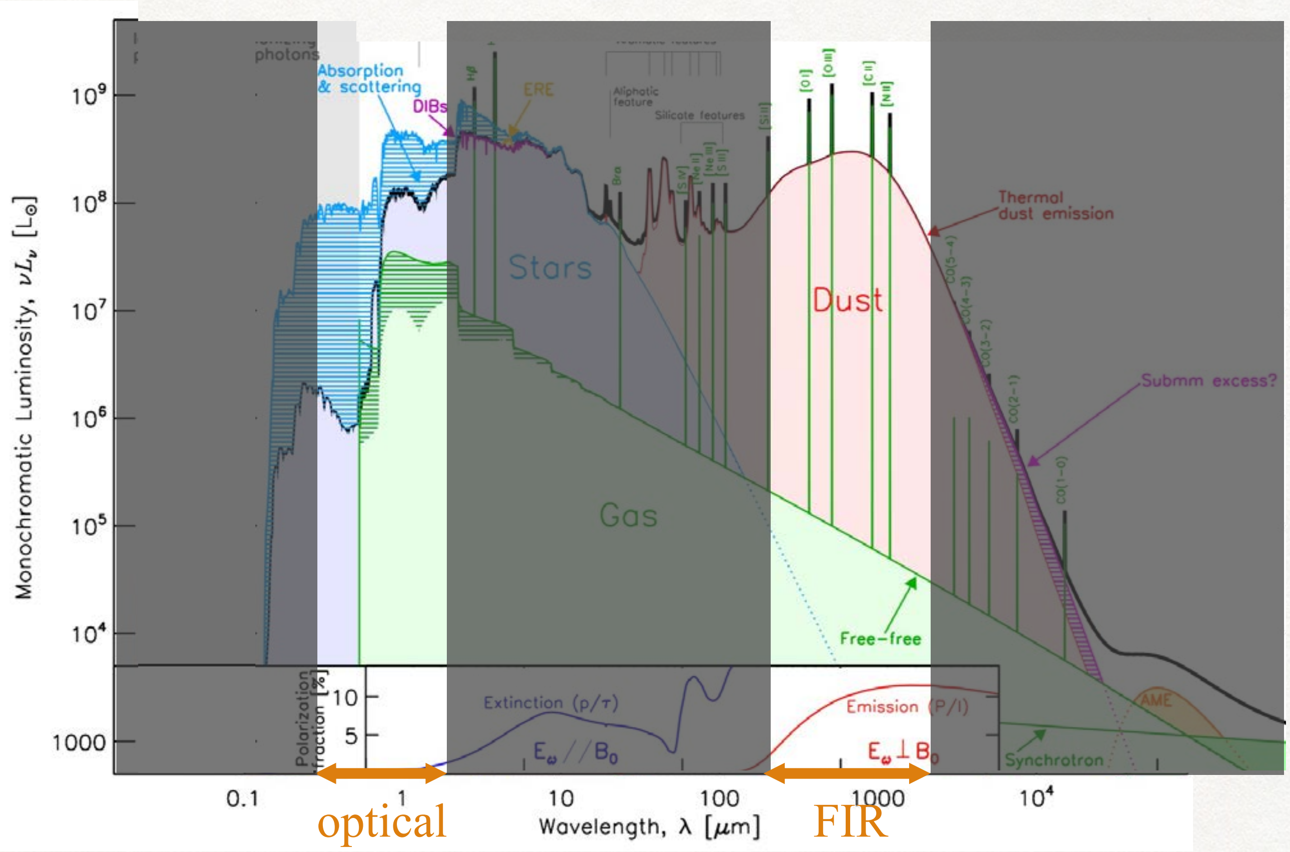


z ~ 4

At redshift z > 4, it becomes difficult to detect optical emission lines.

Galliano, Galametz, and Jones 2018

Redshift of Galaxy Spectra … requiring New Window

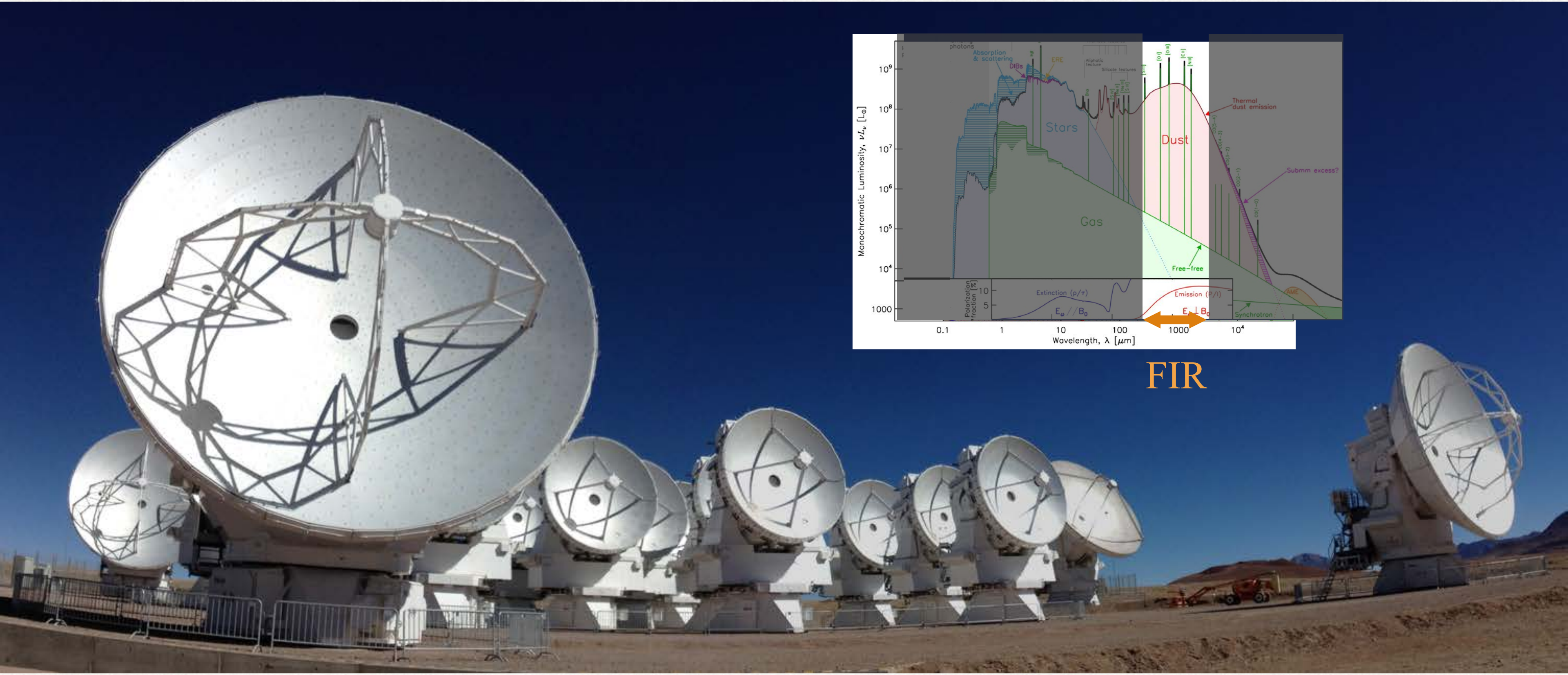


z ~ 4

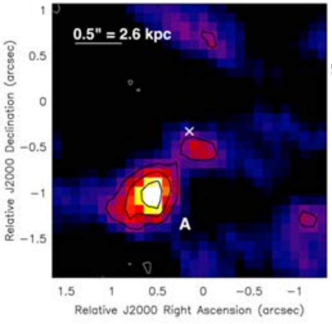
At redshift z > 4, we need another window to observe emission lines.

Galliano, Galametz, and Jones 2018

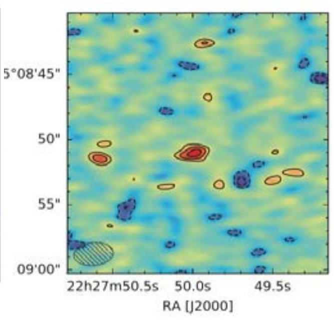
ALMA—Atacama Large Millimeter/submillimeter Array



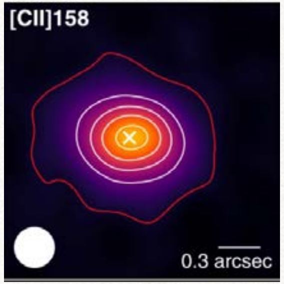
[CII] 158 μm emission lines



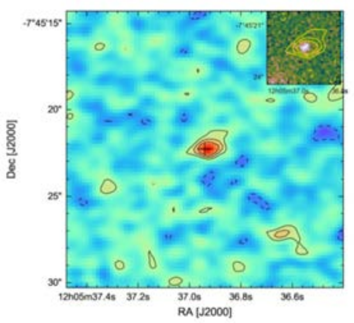
Maiolino et al. (2015)



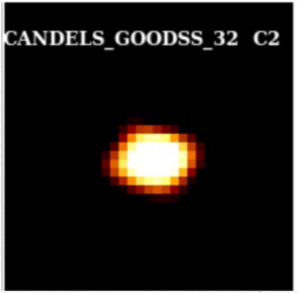
Carniani et al. (2018)



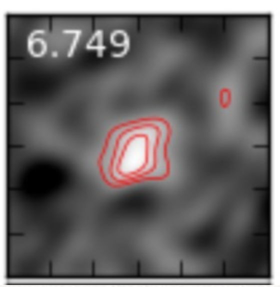
Tadaki et al. (2019)



Pentericci et al. (2016)



Le Fevre et al. (2020)
[ALPINE]

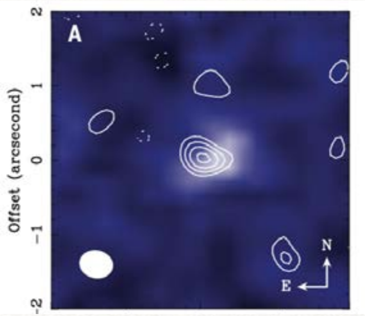


Bouwens et al. (2018)
[REBELS]

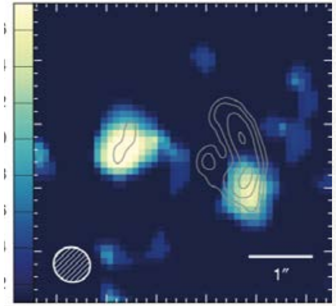
- C^+ Fine-structure emission line
  - Strongest at far-infrared
  - Important coolant in *neutral gas*
- Detected in many galaxies
  - ALMA large programs
    - ALPINE: 75 gals at 4<z<6
    - REBELS: >18 gals at 6.5<z

[OIII] 88 μm emission lines

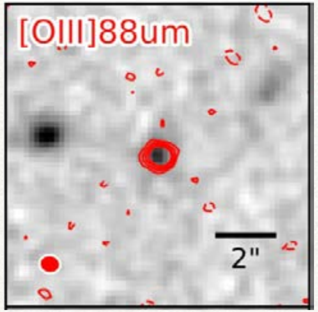
- ○ O^{2+} Fine-structure line
  - □ Coolant in *ionized gas*
- ○ Scientific Highlights
  - □ Prediction (Inoue+14)
  - □ Detection (Inoue+16)
  - □ Highest-z (Hashimoto+18)
  - □ [CII]&[OIII]&dust (Hashimoto+19)
  - □ Large dust mass (Tamura+19)



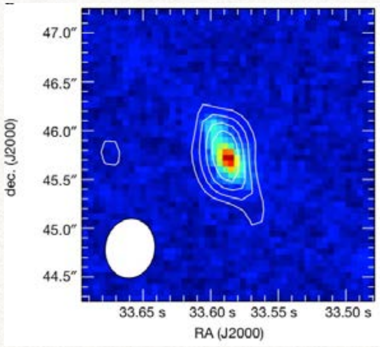
Inoue et al. (2016)
[First detection]



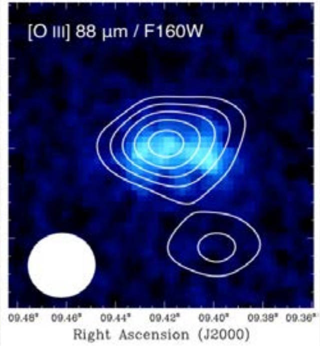
Marrone et al. (2018)



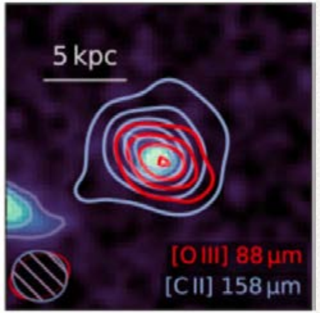
Harikane, …, YS, et al. (2020)



Hashimoto et al. (2018)
[z=9.1096, which was highest]

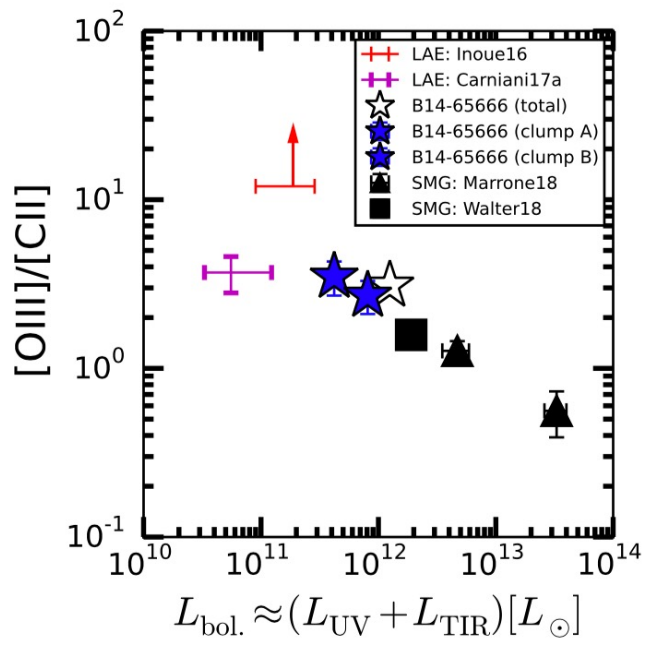


Tamura et al. (2019)

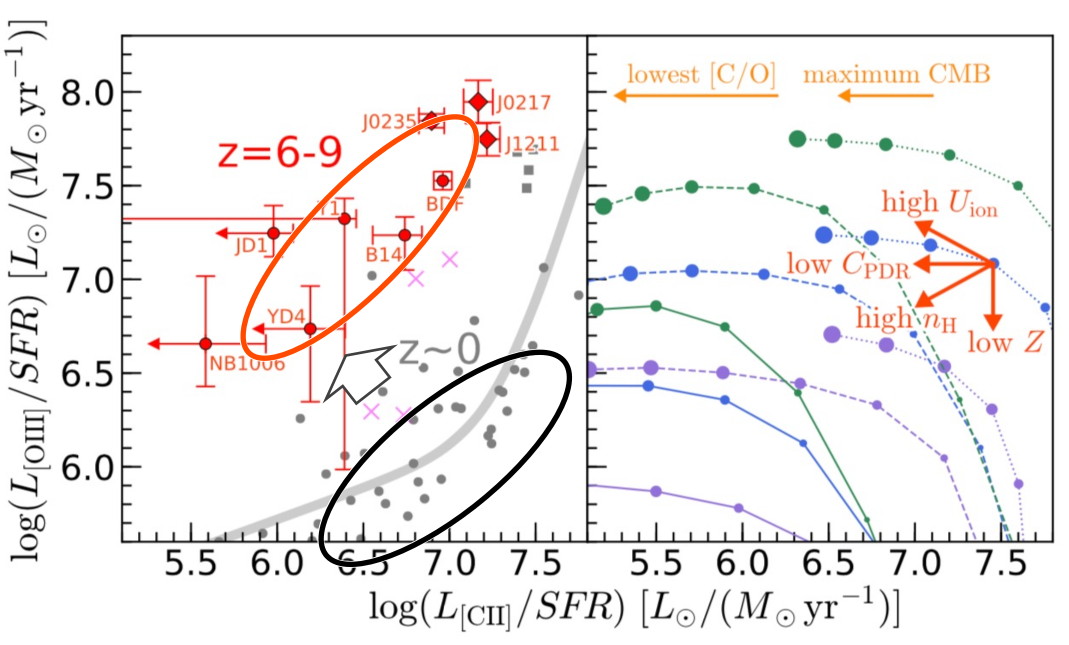


Witstok et al. (2022)

High [OIII]88/[CII]158 Ratios at z > 6



Hashimoto et al. (2019)

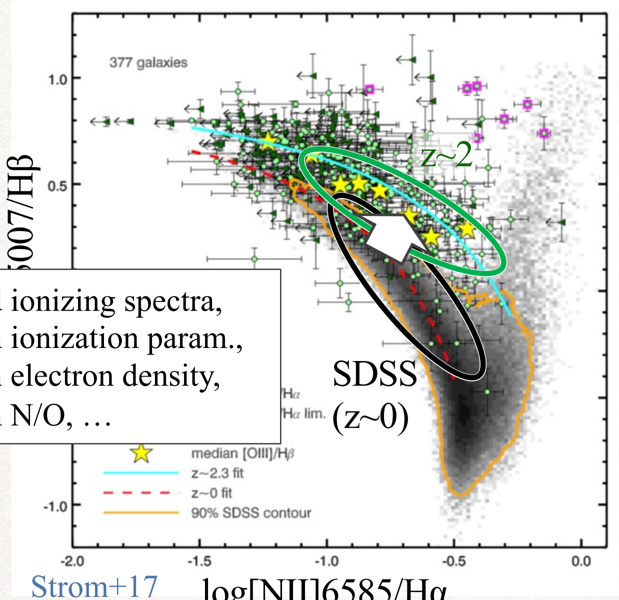


Harikane, …, YS et al. (2020)

○ Intense ionization at high redshift?

Short summary: To the next step

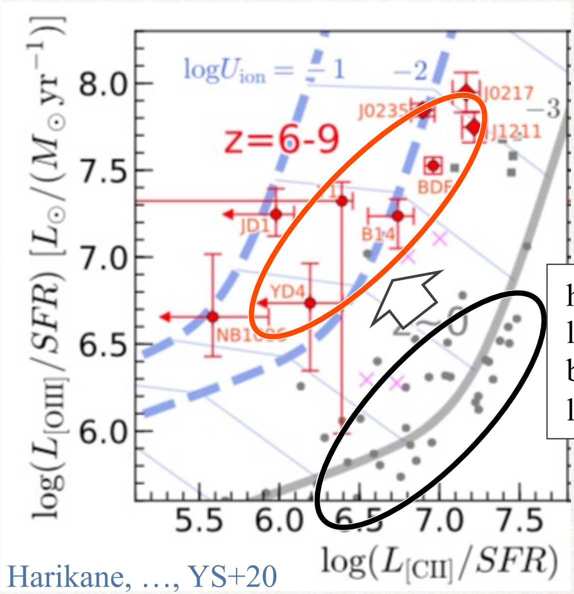
○ NIR obs. of rest-opt. lines at z~2



Strom+17

hard ionizing spectra,
high ionization param.,
high electron density,
high N/O, …

○ ALMA [OIII]88μm & [CII]158μm



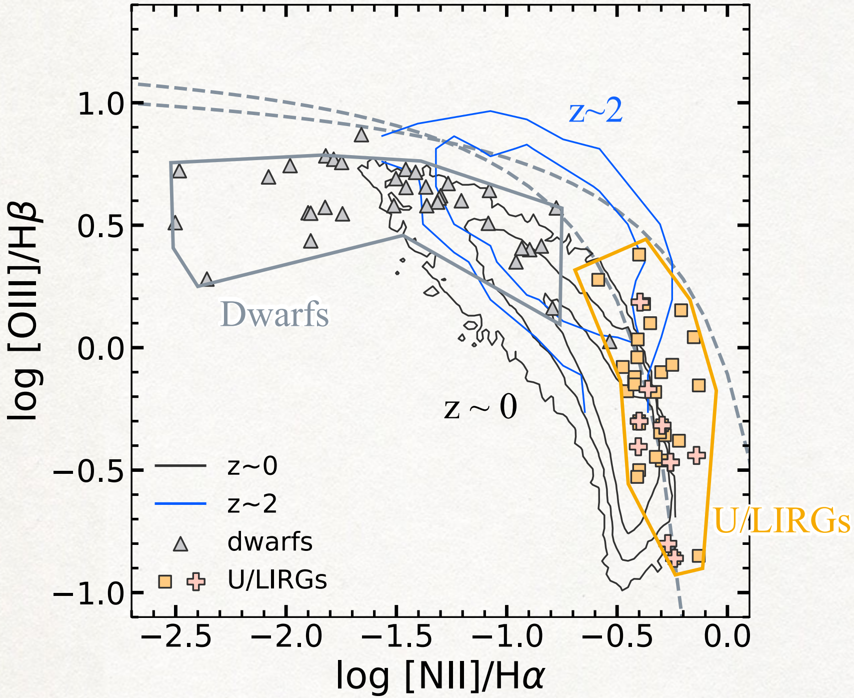
Harikane, …, YS+20

high ionization param.,
low PDR covering frac.,
bursty star-formation,
low C/O, …

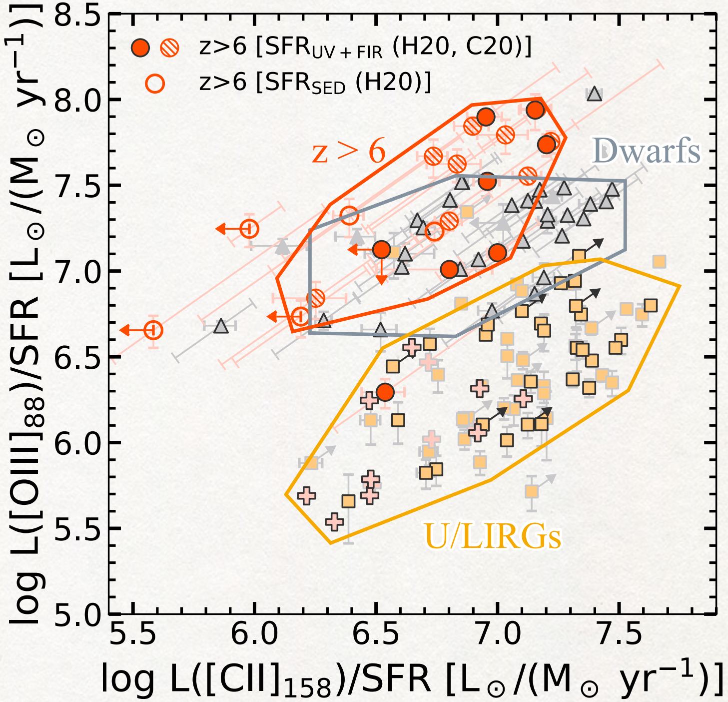
We would like to bridge optical and FIR diagrams from local to z > 6.

Observational Data

○ BPT diagram

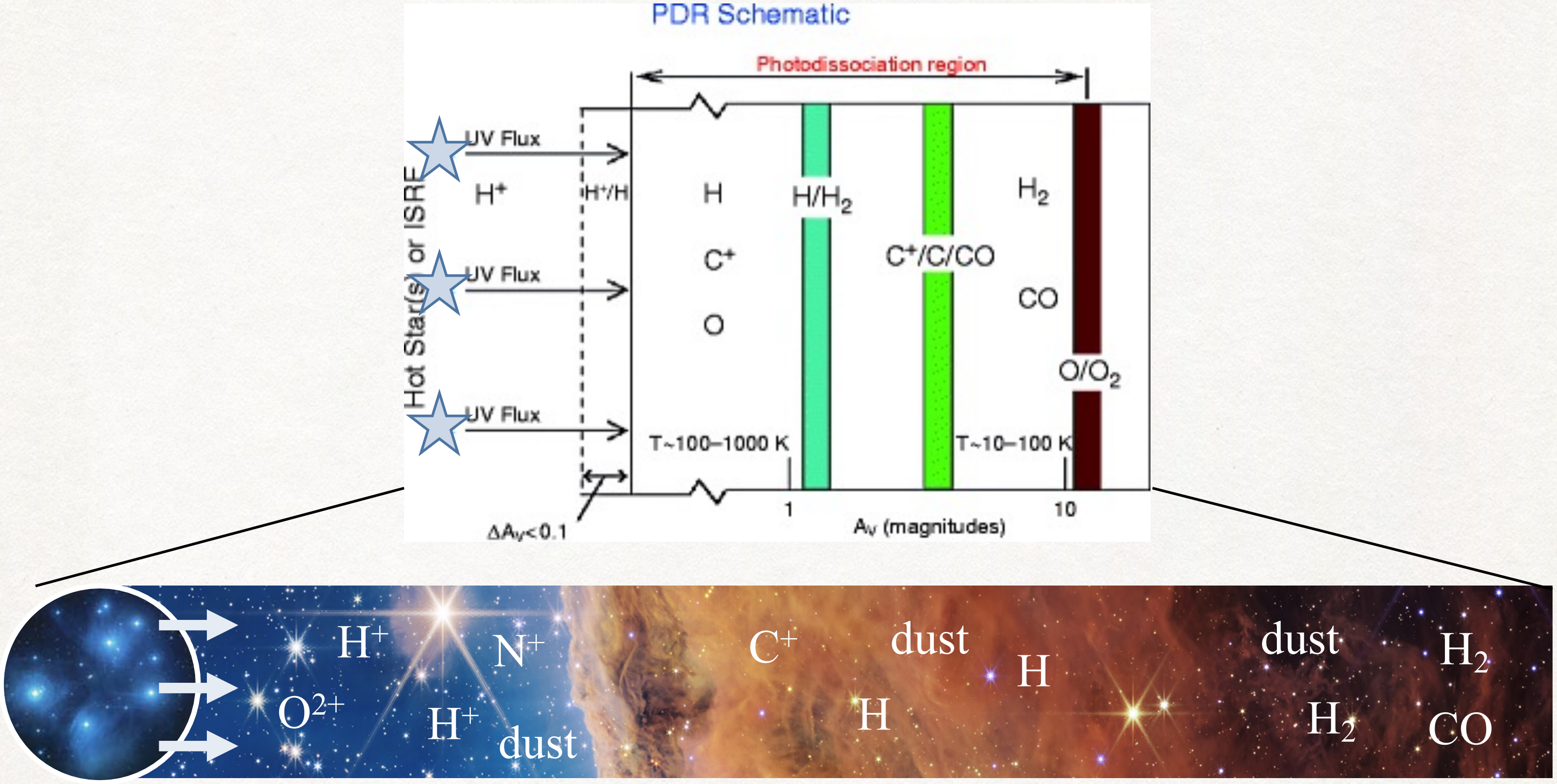


○ FIR diagram



dwarfs: Cormier+15; U/LIRGs: Diaz-Santos+17, Herrera-Camus+18; z~2: Strom+17, Shivaei+18; z > 6: Harikane+20, Carniani+20

Photoionization Models — CLOUDY v17.02



Ionized gas Neutral gas Molecular gas

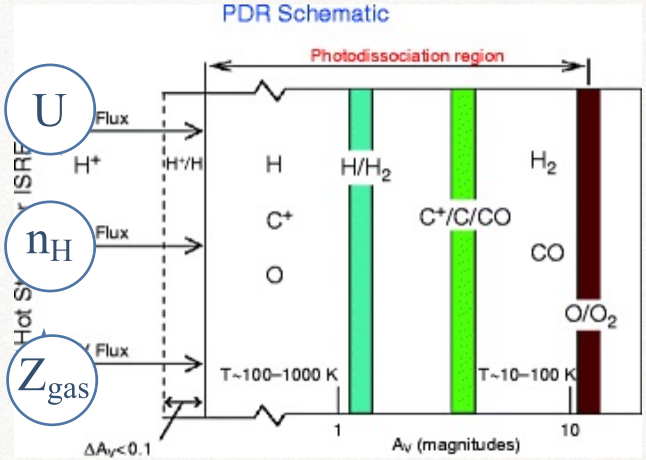
Encyclepedia of Astrobiology; Tielens and Hollenbach 85

Photoionization Models — CLOUDY v17.02

○ Fiducial models

<u>Input Ionizing Spectrum</u>

- □ ionizing spectra
  - SB99 300Myr for z ~ 0, U/LIRGs
  - BPASS 300 Myr, $Z_* = Z_{gas}$ for dwarfs
  - BPASS 300 Myr, $Z_* = 0.2Z_{gas}$ for z~2, >6
- □ output SFR ∝ L(Hβ, Z_*, age)



<u>Gas Structure</u>

- □ plane-parallel geometry
- □ constant pressure
- □ local N/O–Z abundance relation
- □ Solar C/O abundance ratio
- □ PDR covering fraction (C_{PDR}) = 1

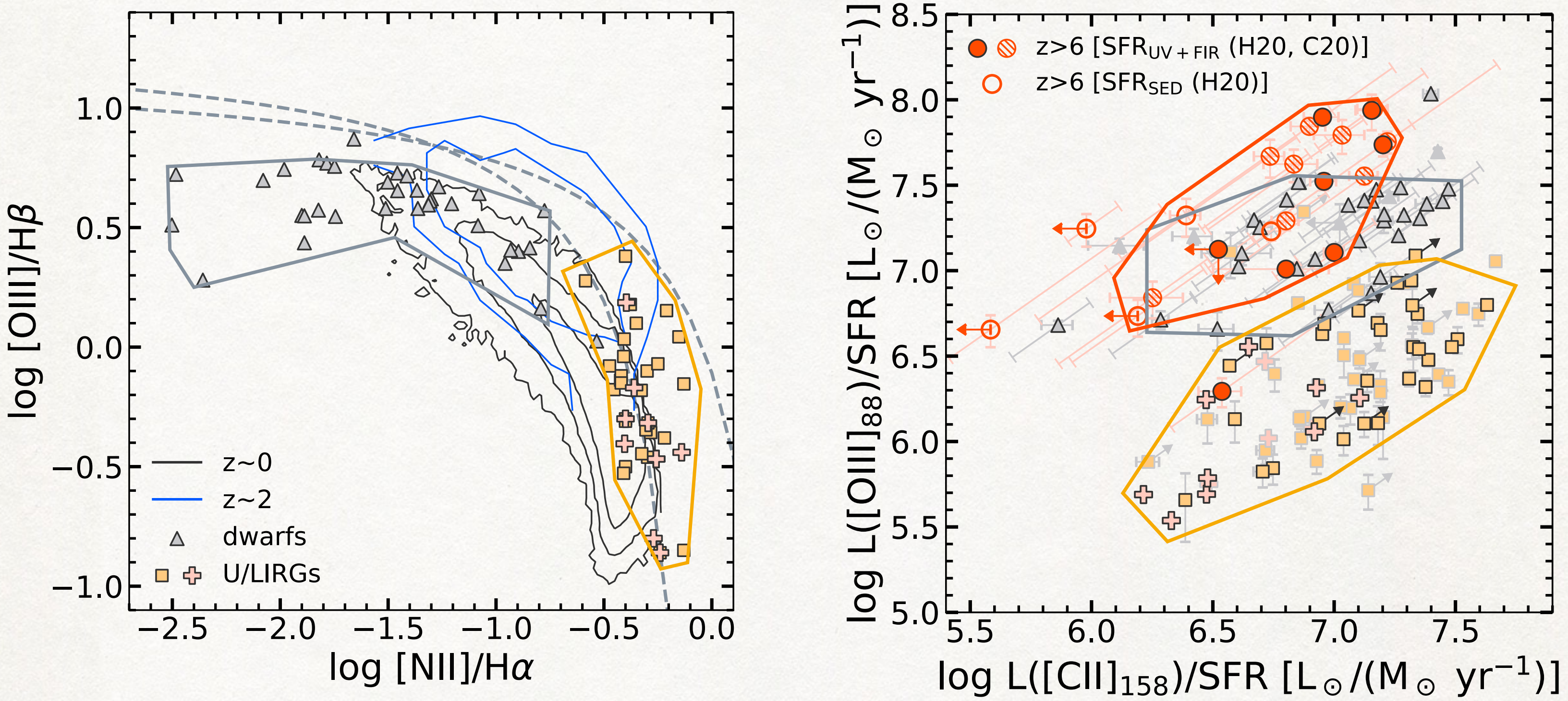
○ Free nebular parameters

- □ Ionization parameter U: $U = \frac{1}{c}\frac{\dot{n}_\gamma}{n_\mathrm{H}} = \frac{1}{c}\frac{\mathrm{ionizing\ photon\ number\ flux/cm^{-2}s^{-1}}}{\mathrm{hydrogen\ density/cm^{-3}}}$
- □ hydrogen density n_H
- □ gas metallicity Z_{gas}

Photoionization Model Grids

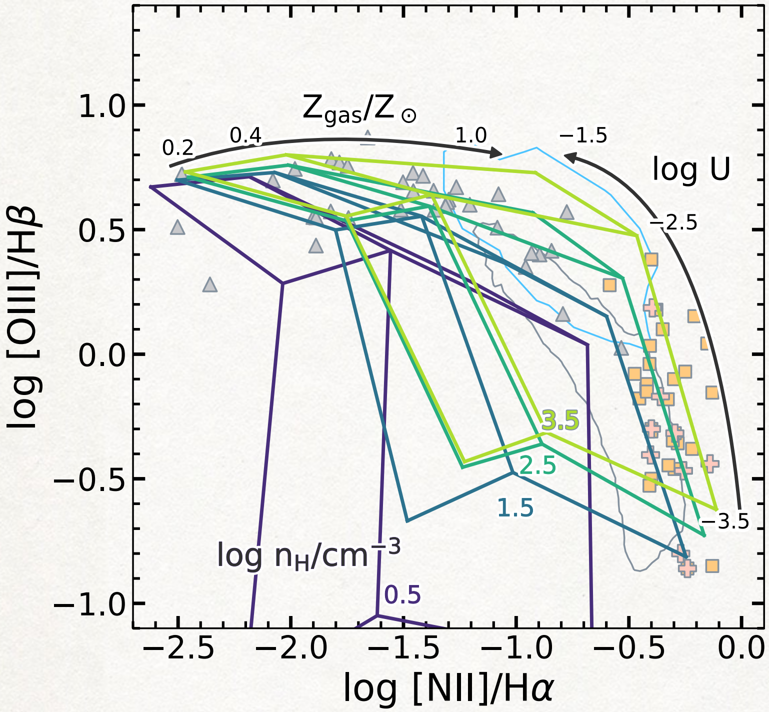
○ BPT diagram

○ FIR diagram

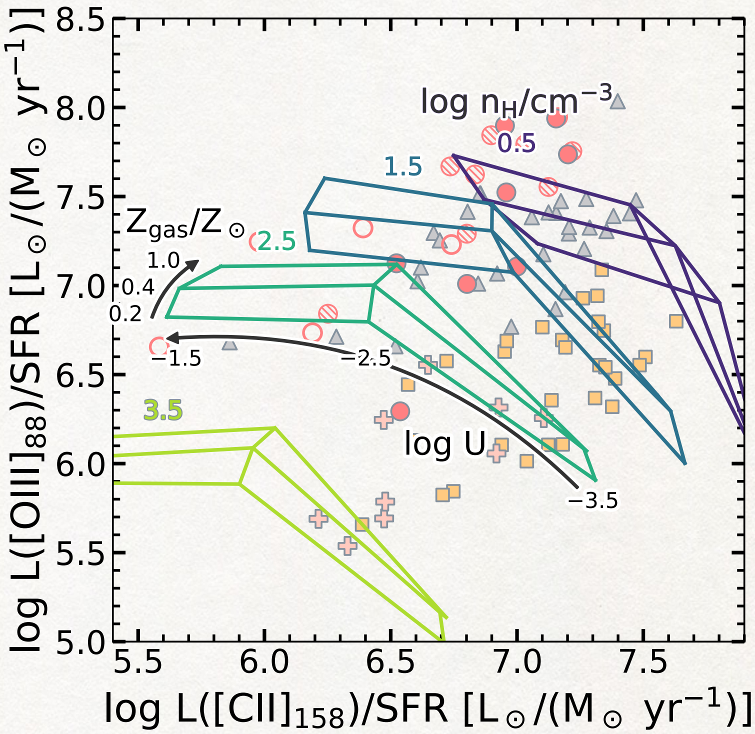


Photoionization Model Grids

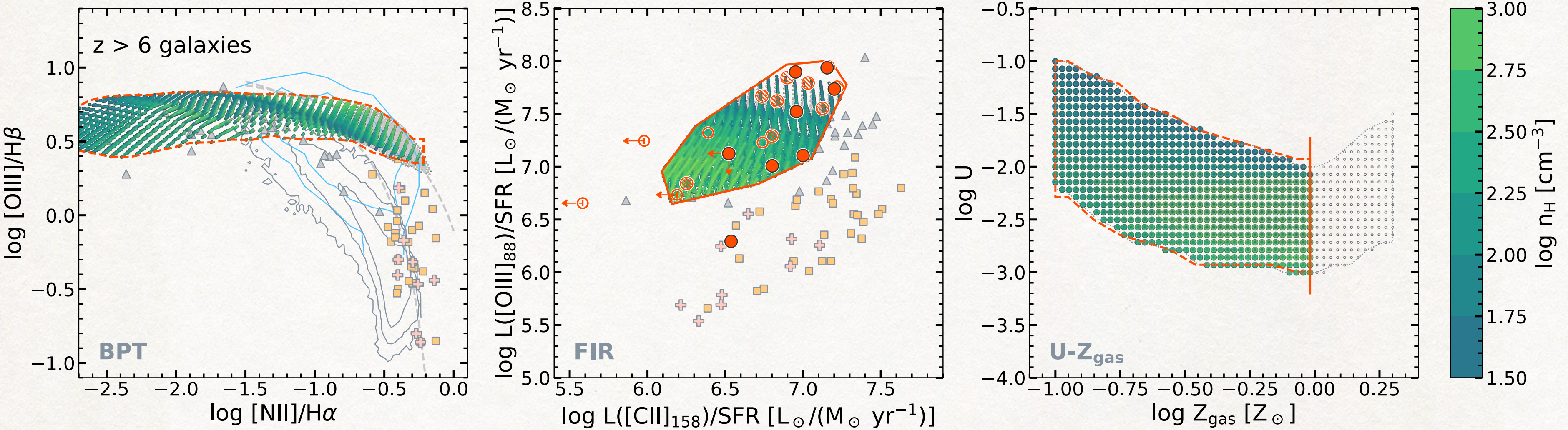
○ BPT diagram



○ FIR diagram



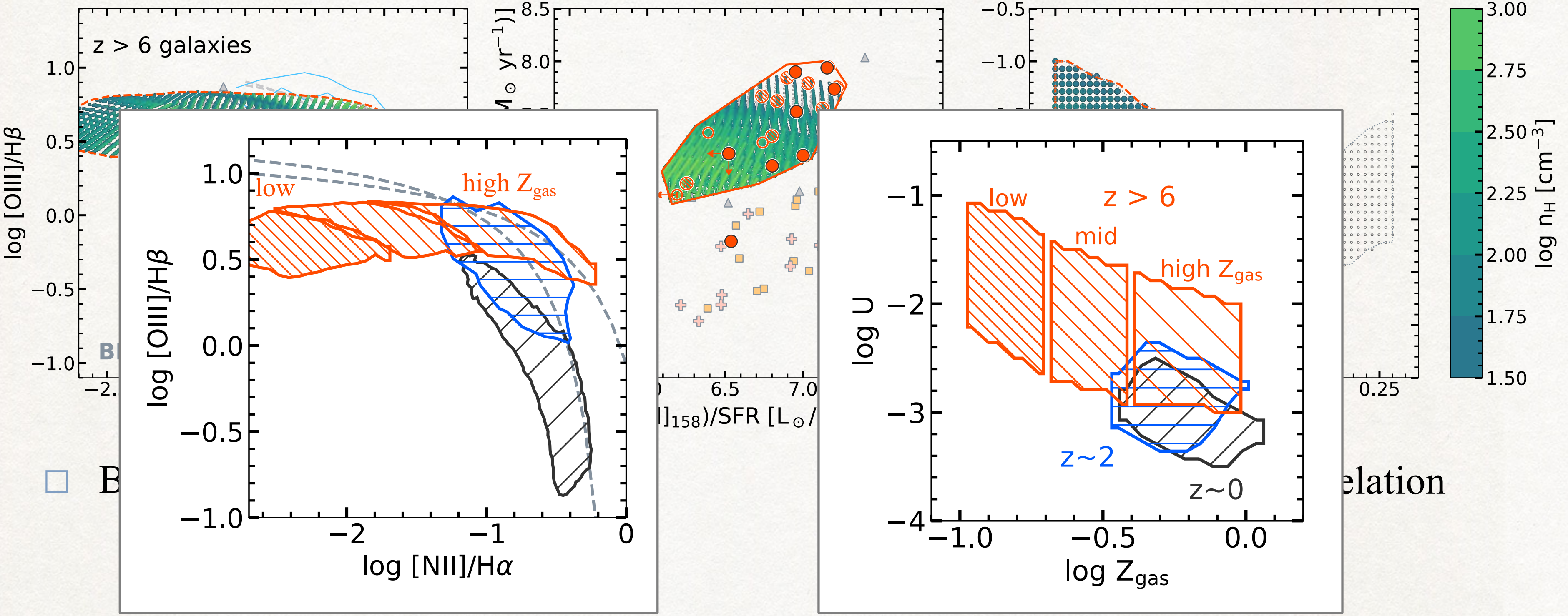
Modeling: z > 6 with FIR lines



- BPT: flat distribution

  (log[OIII]/Hβ=0.5–0.8)

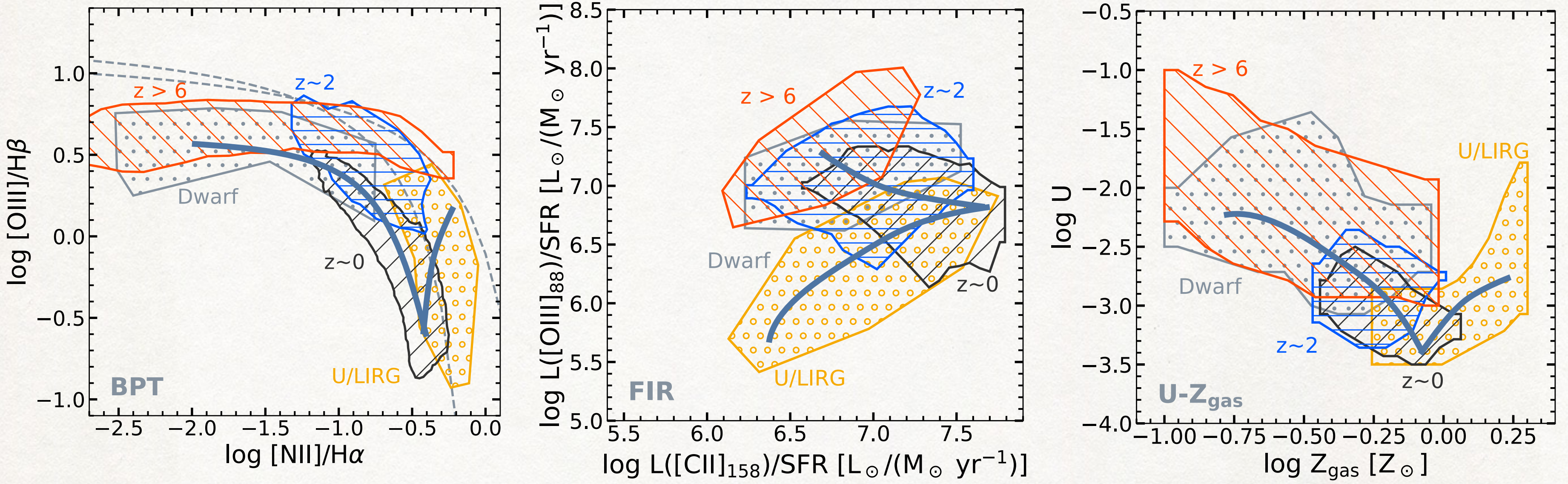
Modeling: z > 6 with FIR lines



- B … elation

Graphical Summary of Results

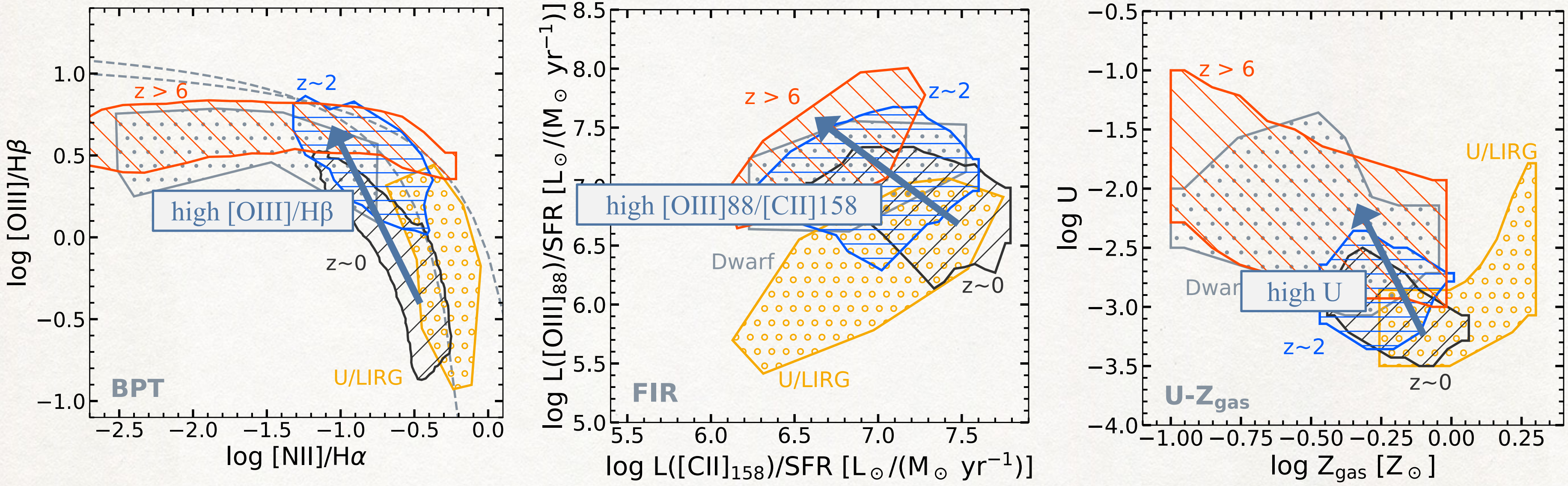
Sugahara+22



1. Continuous shifts at z~0: dwarfs → normal gals. → U/LIRGs

Graphical Summary of Results

Sugahara+22

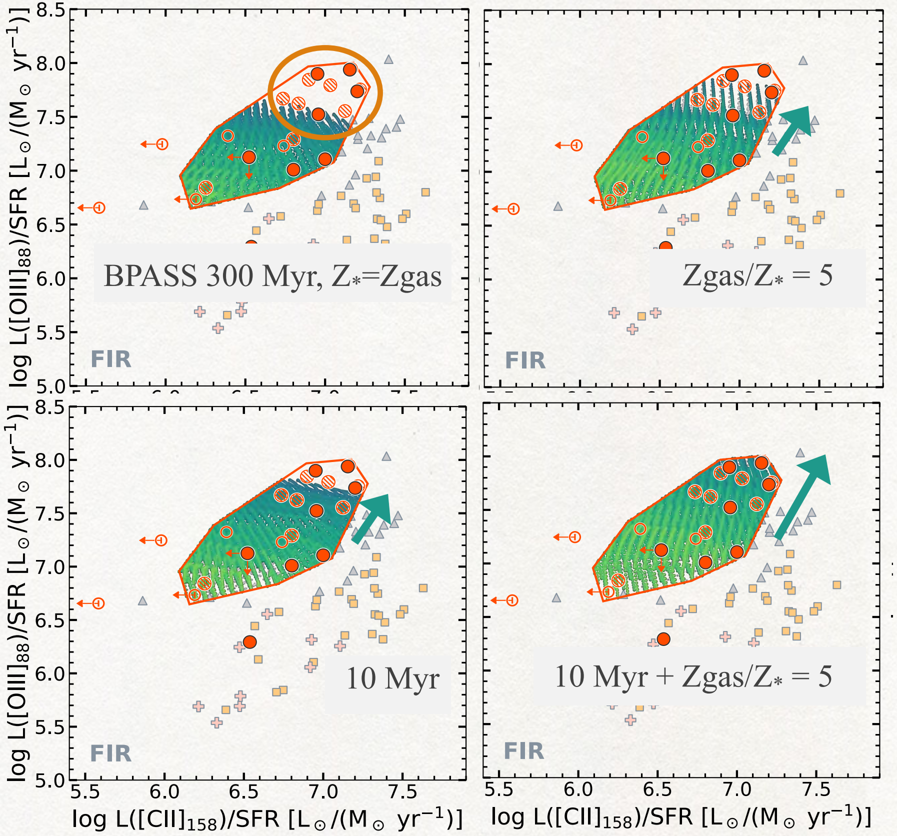


1. Continuous shifts at z~0: dwarfs → normal gals. → U/LIRGs
2. Continuous evolution from z ~ 0 to z > 6

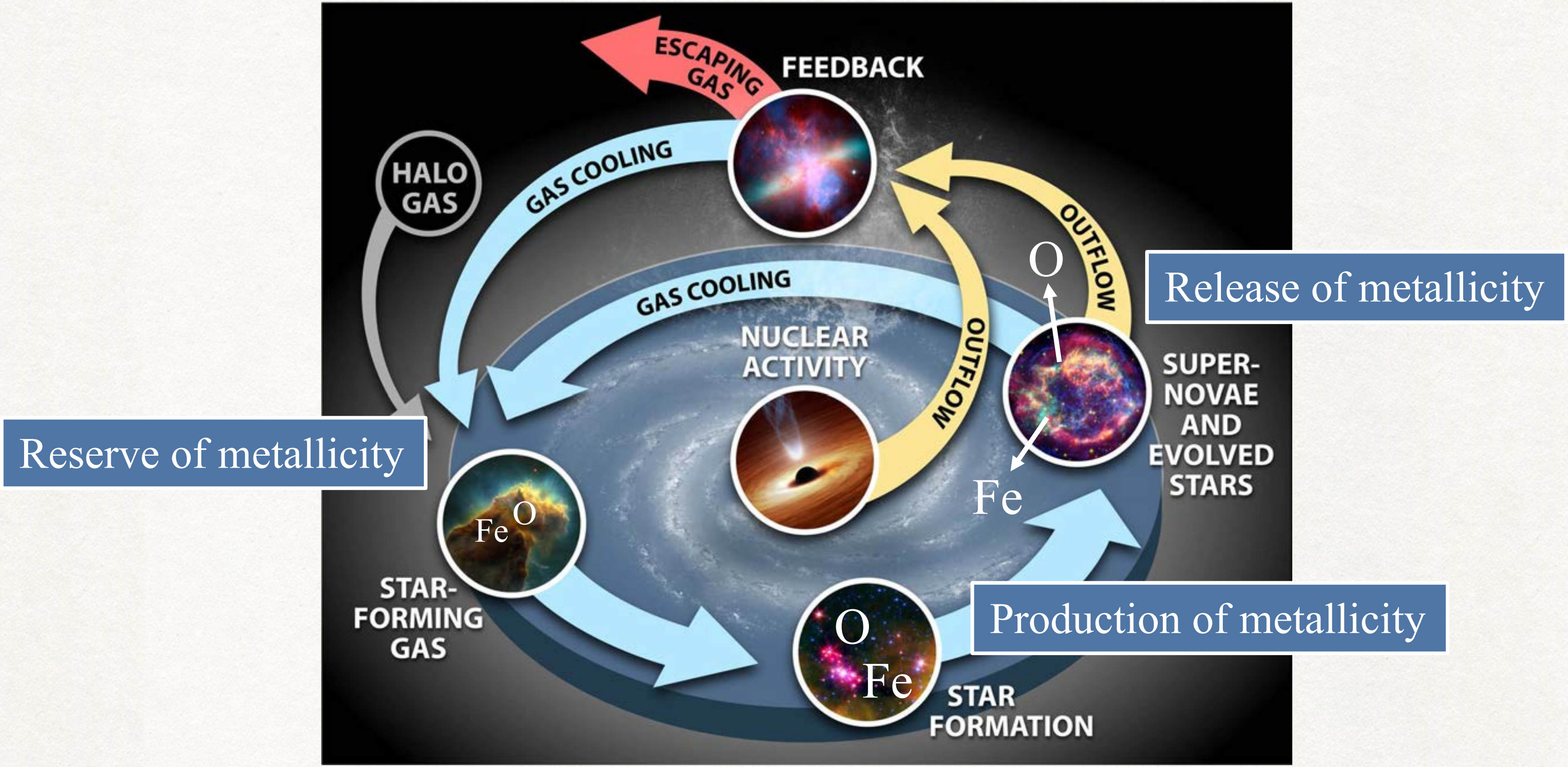
Ionizing spectra — high [OIII]88/SFR ratio at z > 6

- $[OIII]_{88}$/SFR > 7.5 $[L_\odot/(M_\odot yr^{-1})]$
  - cannot be explained by models w/ BPASS 300 Myr, Z_*=Zgas, 1.5 < log n_H

- Solutions
  1. high Z_{gas}/Z_* (i.e., α/Fe) (fiducial model)
     - supported by z ≧ 2 studies
       Steidel+16, Cullen+19; Day 2 talks
  2. bursty/increasing SFH
     - some galaxies ~5 Myr age from SED fitting
       Inoue+16, Hashimoto+18,19, Tamura+19



Cosmic and Galaxy Ecosystem



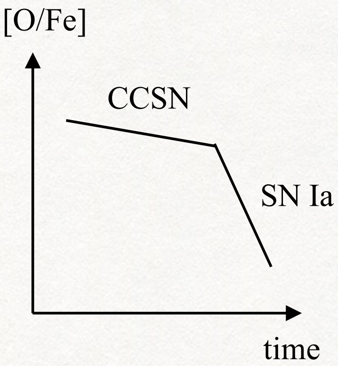
Meixner et al. 2021

Two types of Supernovae: abundance pattern

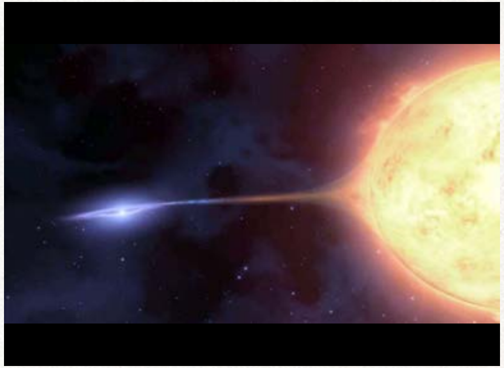
Release of metallicity

- Core-collapse supernovae

- High O/Fe (i.e., α/Fe)
- No time delay



- Type-Ia supernovae

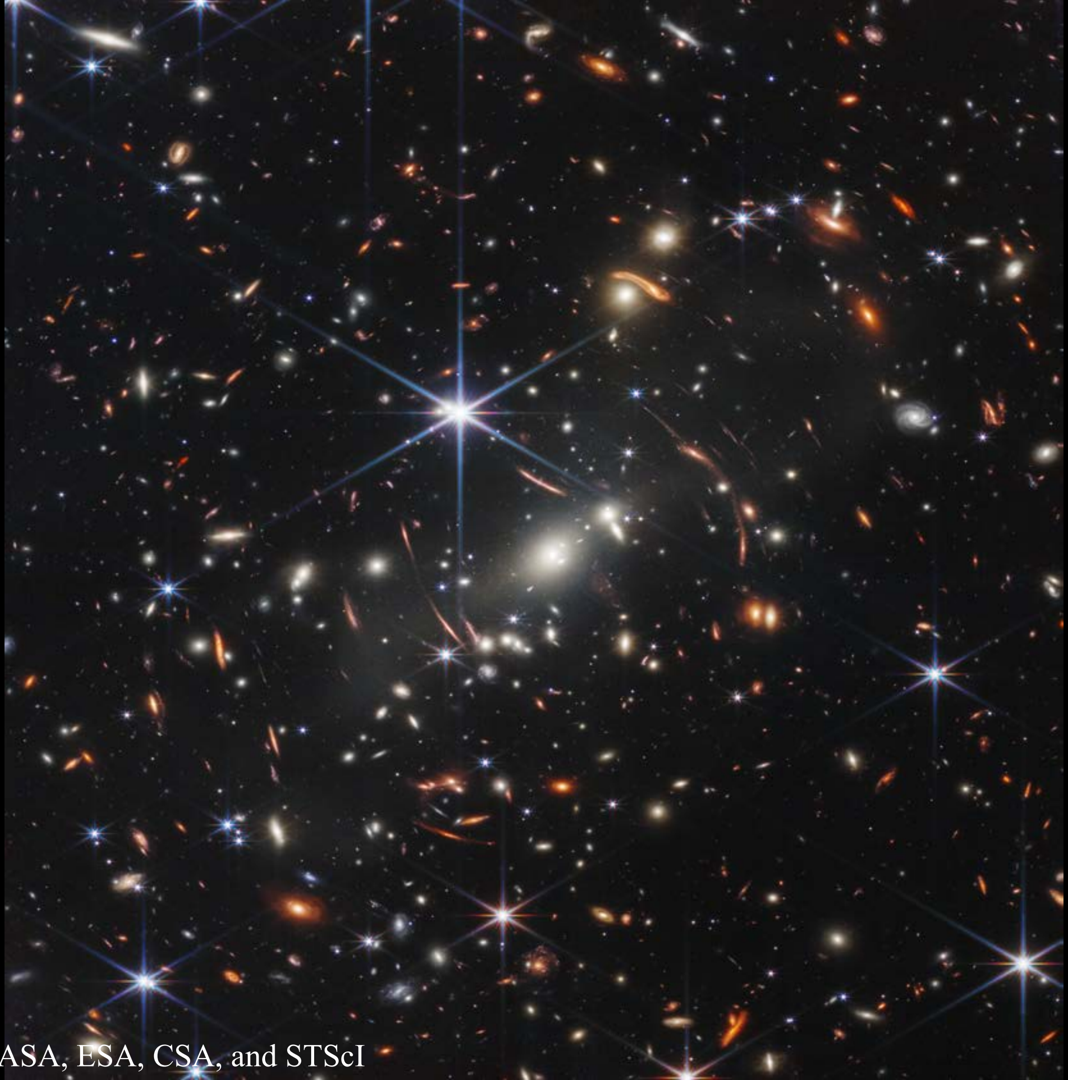


- High Fe
- Time delay of > 0.1-1 Gyr from SF
  → too late at early universe

High [OIII]88/SFR at $z > 6$ → high α/Fe caused by dominant CCSN

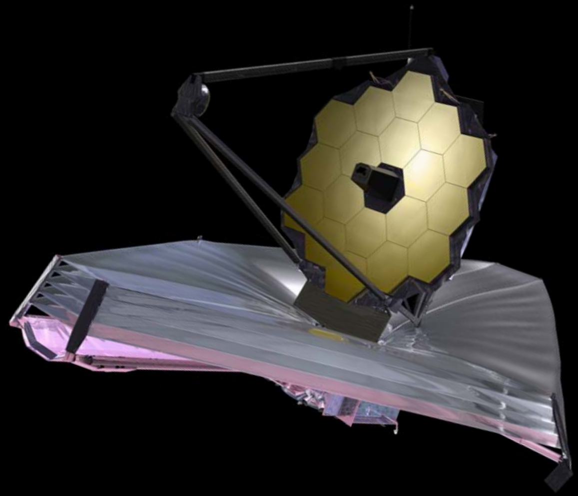
NASA/JPL-Caltech/STScI/CXC/SAO

ESO/M. Kornmesser



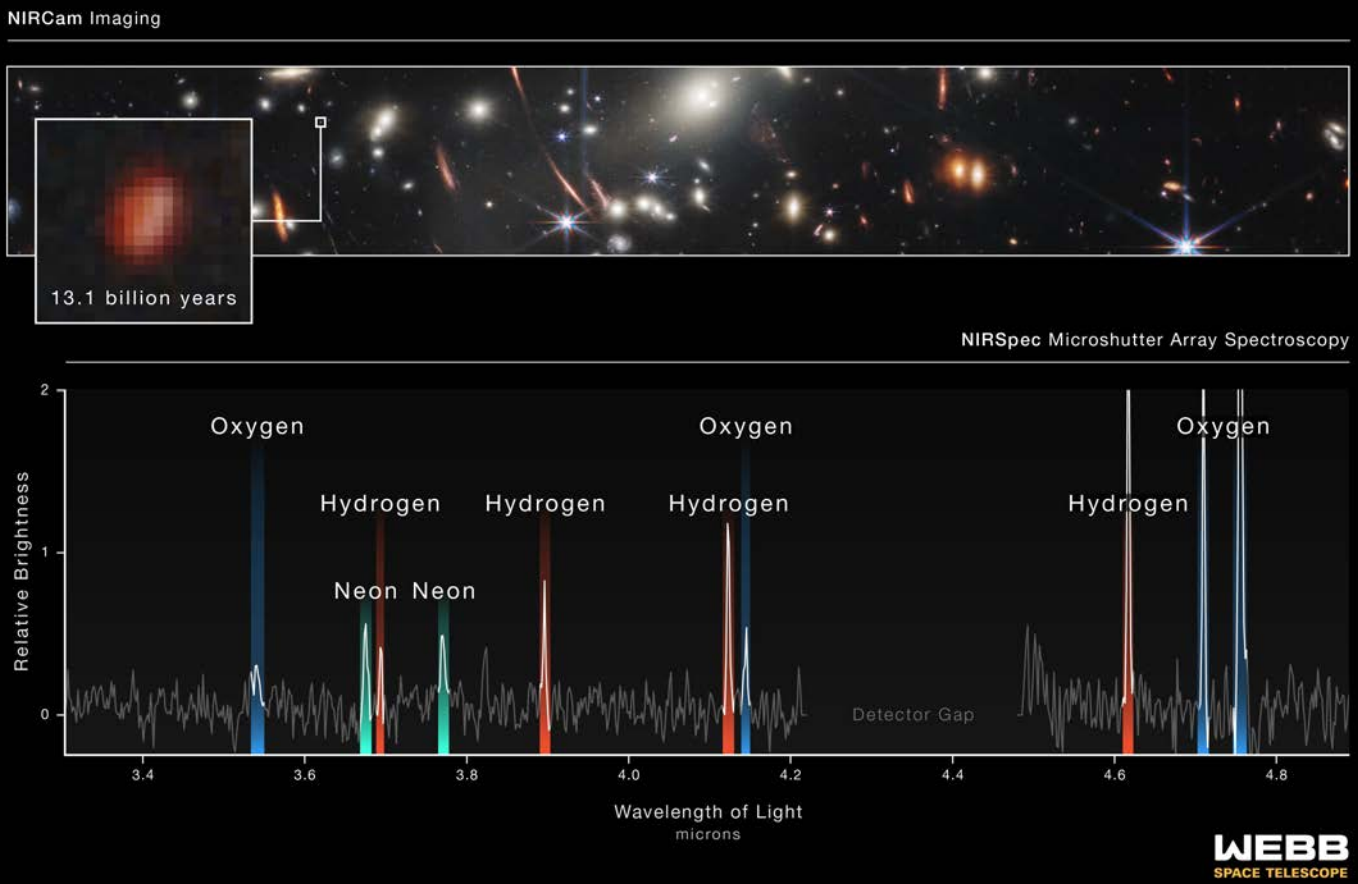
NASA, ESA, CSA, and STScI

JWST—*James Webb Space Telescope*



DISTANT GALAXY BEHIND SMACS 0723

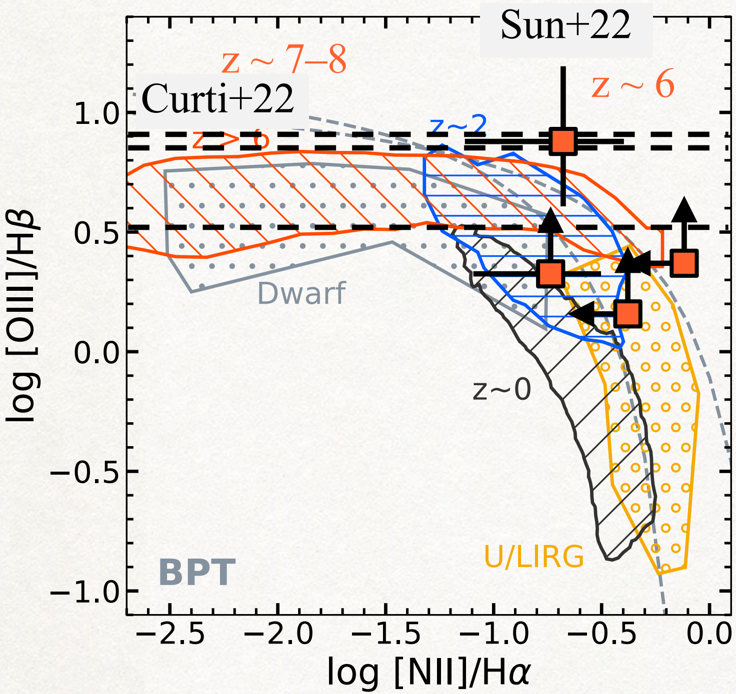
WEBB SPECTRUM SHOWCASES GALAXY'S COMPOSITION

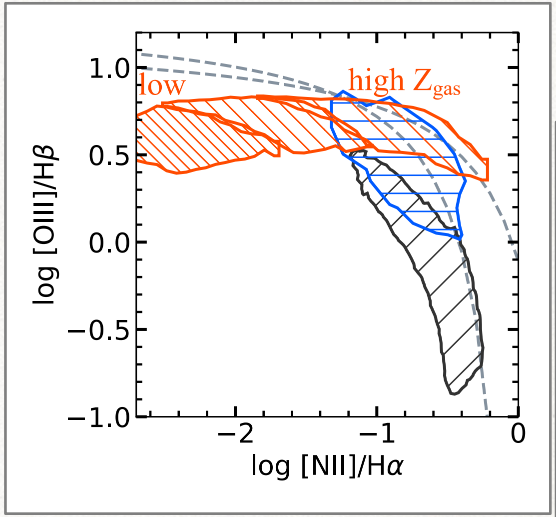


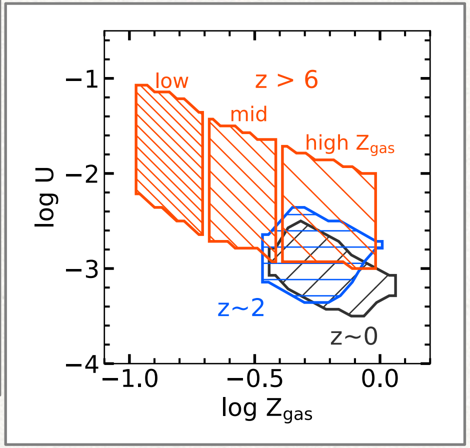
Comparison with JWST early measurements

Sugahara+22

+ JWST measurements



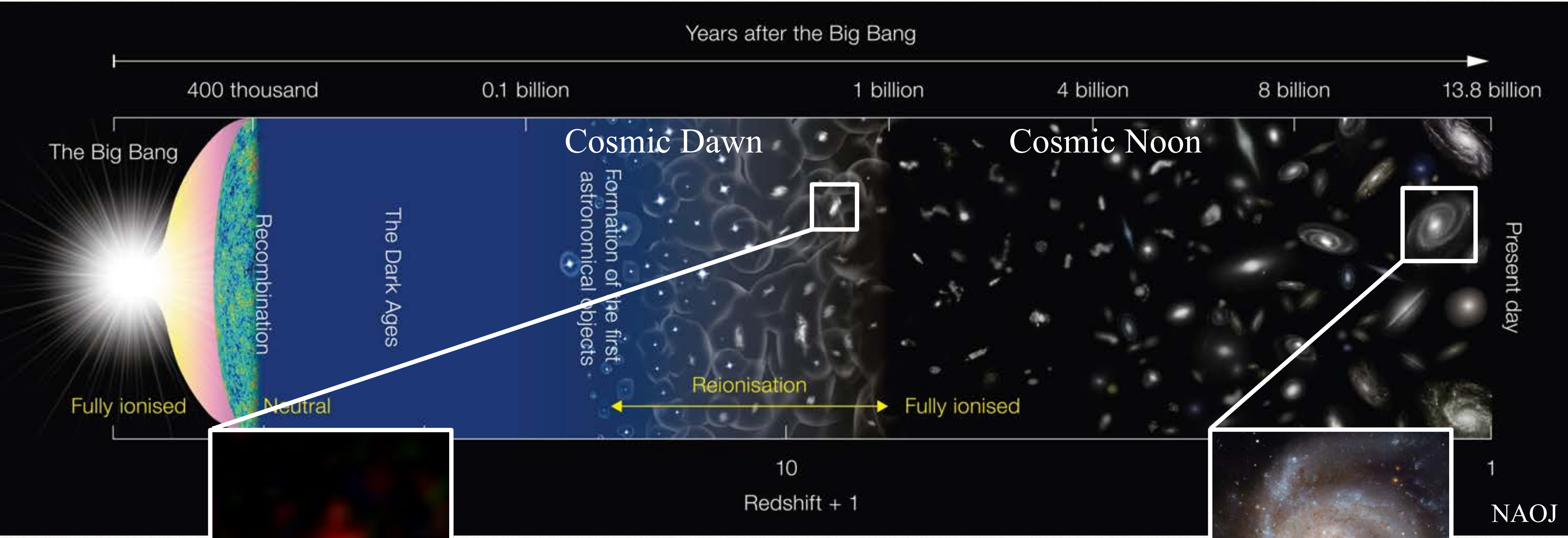




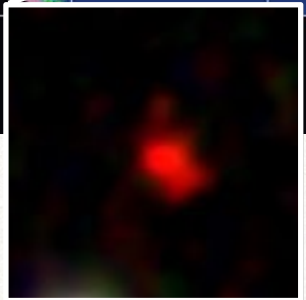
Bright galaxies at z>6:

Similar metallicity to solar

History of Universe and Galaxies



NAOJ



Similar metallicity

Quick enrichment in bright galaxies

Harikane, …, YS, et al. (2022)

NASA, ESA, CXC, SSC, and STScI

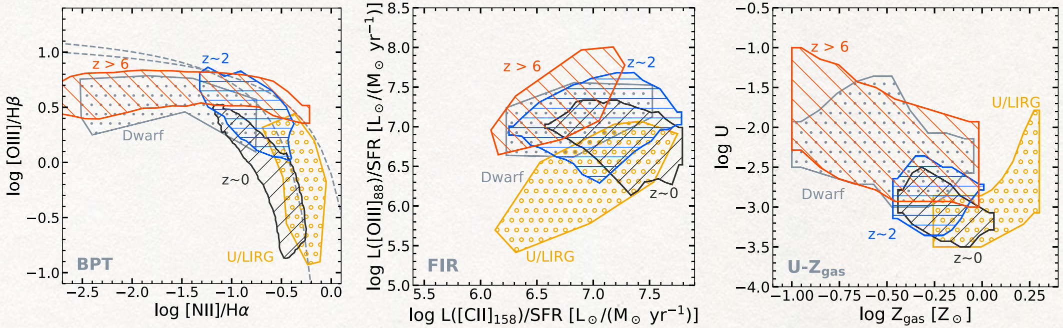
Summary

Sugahara et al., 2022, ApJ, 935, 2
Sugahara et al., 2021, ApJ, 923, 5

○ Continuous distributions on BPT, FIR, and U-Z diagrams predict:

- □ higher [OIII]/Hb
- □ higher [OIII]88/[CII]158
- □ Stronger ionization

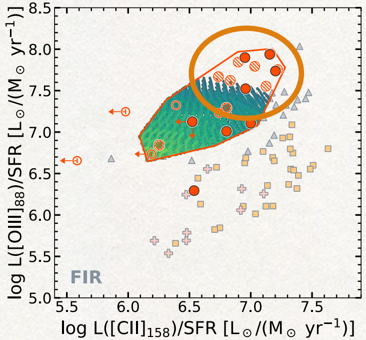
at higher redshift



○ High [OIII]88/SFR ratios at z > 6 support:

high gaseous-to-stellar metallicity ratio Zgas/Z*

→ Less contributions of SN Ia



○ Quick enrichment in bright high-z galaxies