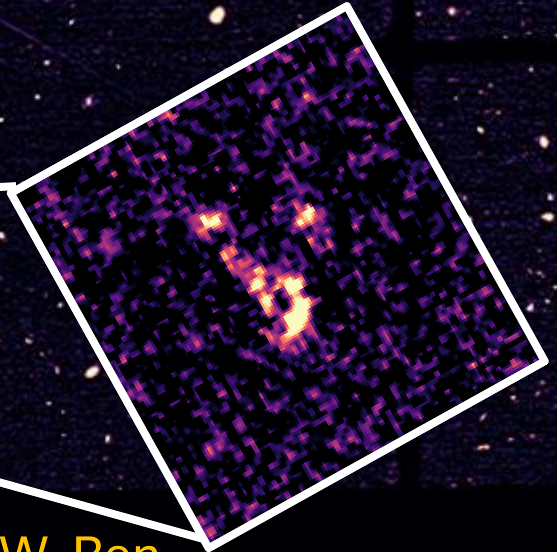
# The Physical Properties of Interstellar Medium in a Galaxy at z=6.81revealed by JWST and ALMA spectroscopy

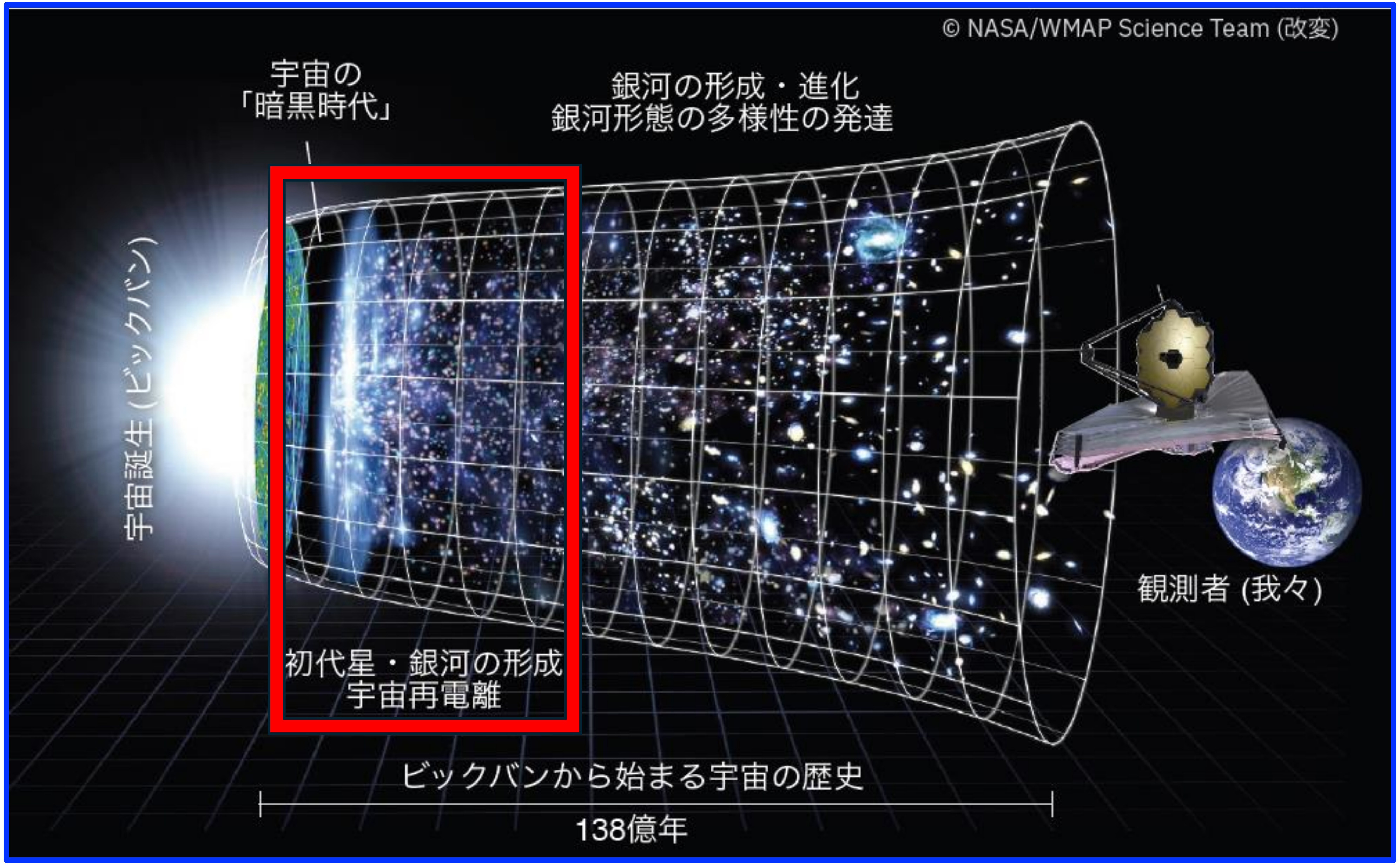


Date: December 16, 2024

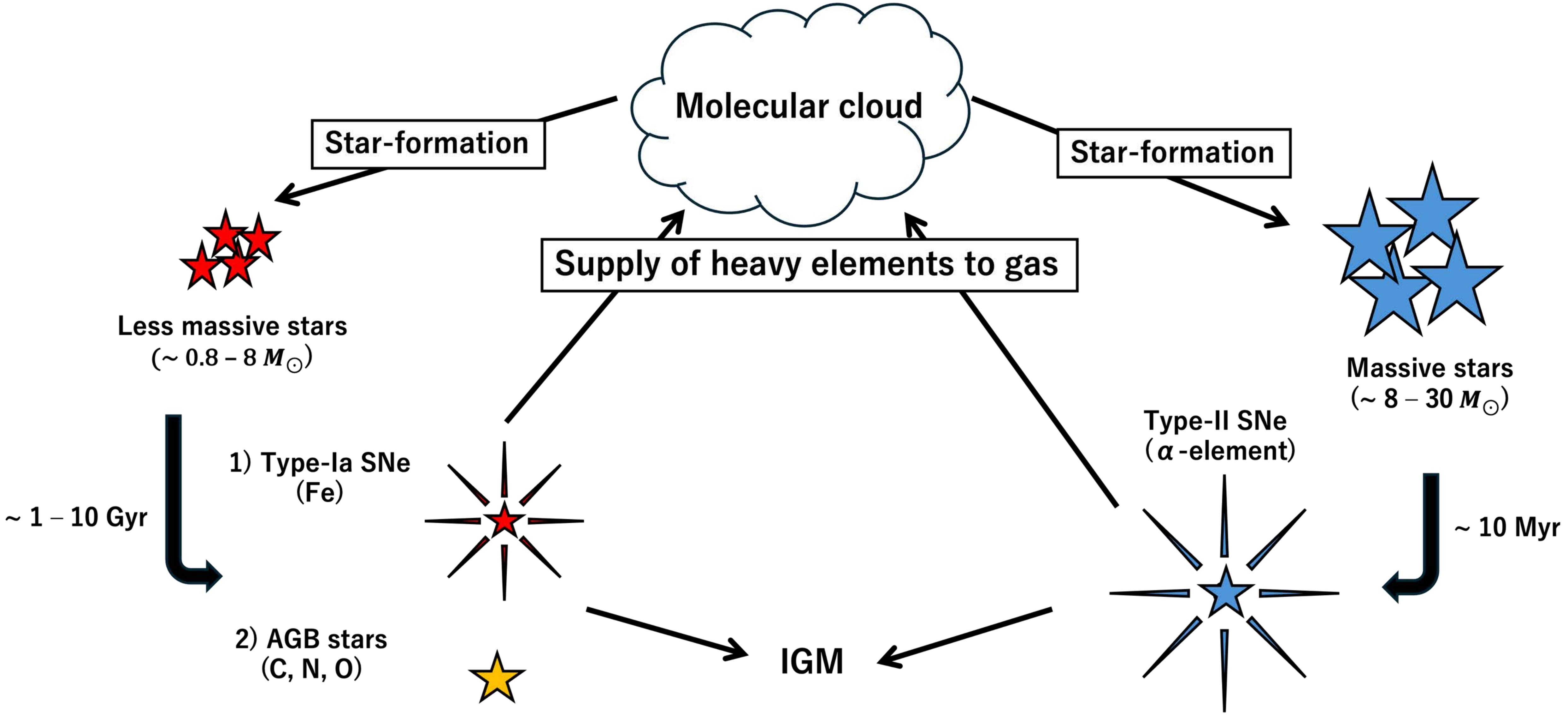
Presenter : **Mitsutaka Usui (宇宙観測研究室, M2)**

Collaborators: T. Hashimoto, W. Osone, A. K. Inoue, K. Mawatari, Y. Sugahara, Y. W. Ren, Y. Nakazato, N. Yoshida, Y. Fudamoto, M. Hagimoto, Y. Tamura, T. Hashigaya, H. Matsuo, T. J. L. C. Bakx, J. Álvalez-Márquez, A. Crespo Gómez, L. Colina, S. Arribas, M. Pereira-Santaella, L. Costantin, R. Marques-Chaves, D. Ceverino and C. Blanco-Prieto

# Galaxy Evolution and Formation in the Early Universe

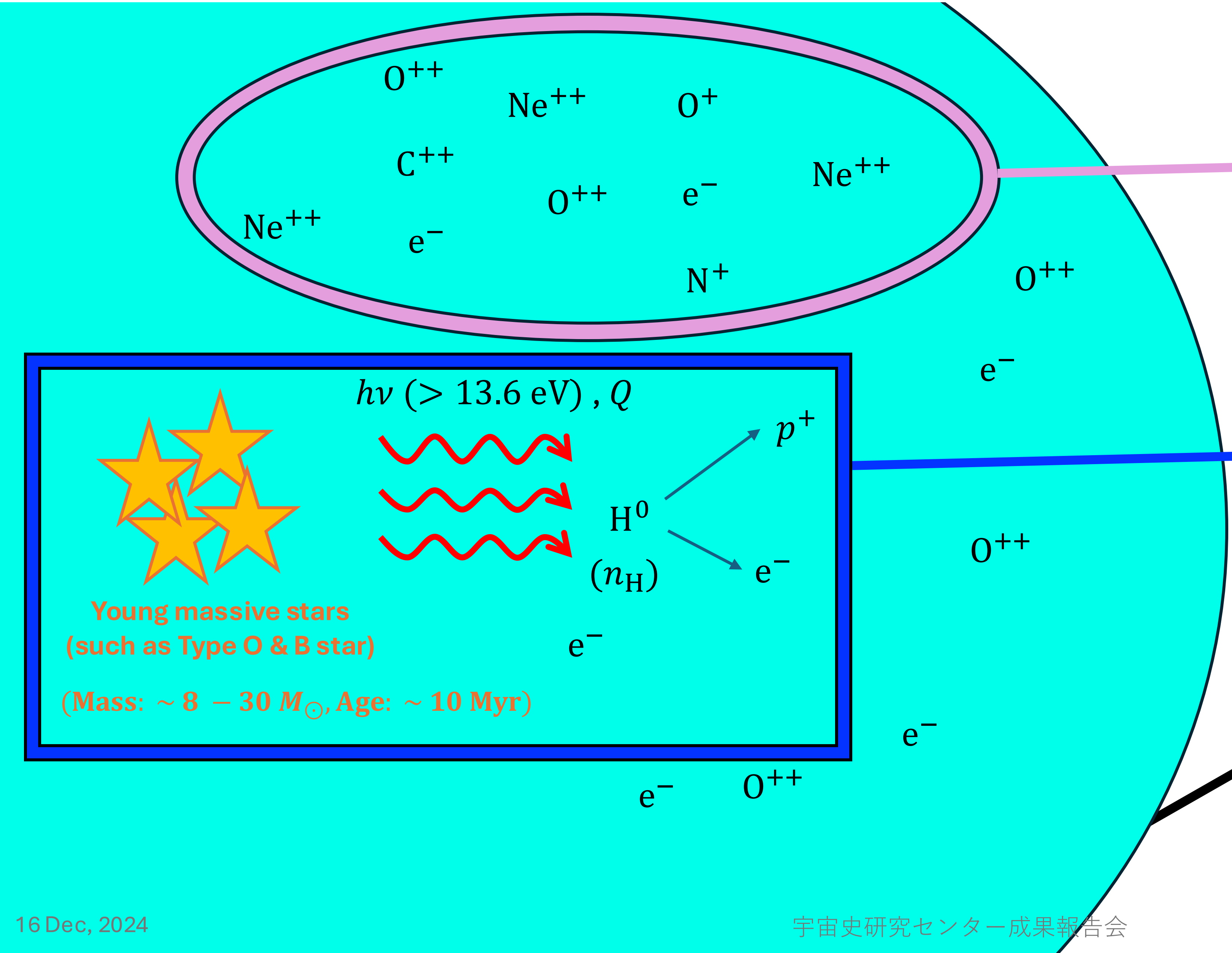


# Star Formation and Chemical Evolution



# HII region (ionized gas)

＊In astronomy, elements heavier than H and He are called “**Metal**”.




### Metallicity＊

- Trace the Star-Forming History (SFH)
- Trace the Chemical Evolution
- Express by 12+log(O/H)

### Ionizing Parameter

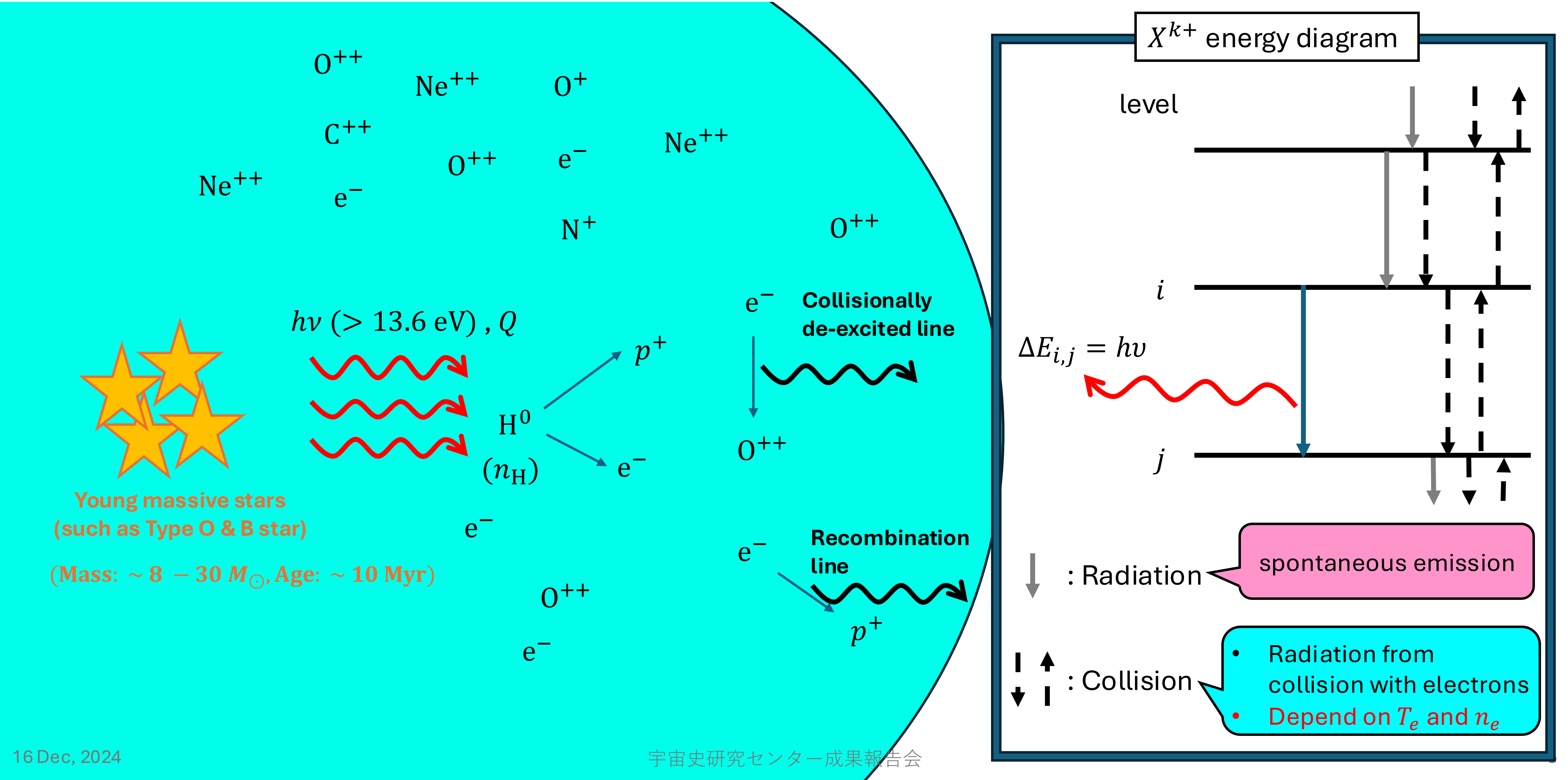
- Trace the excited state of the HII region

$$U_{\rm ion} = \frac{Q(r)}{4\pi r^2 n_H}$$

### Electron temperature, density

- The fundamental properties
- Necessary to measure metallicity and ionization parameter

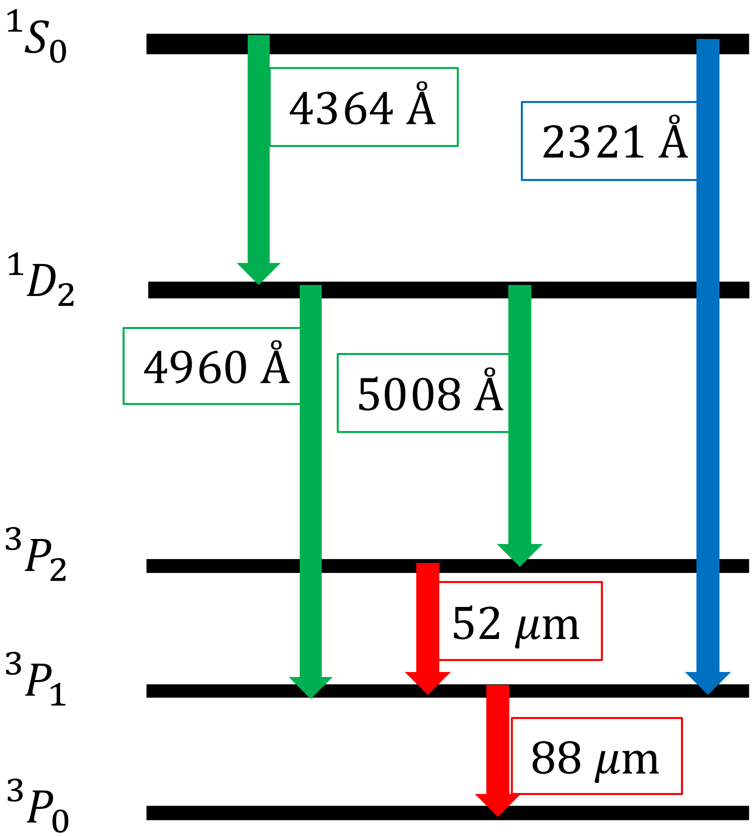
# Line Emission

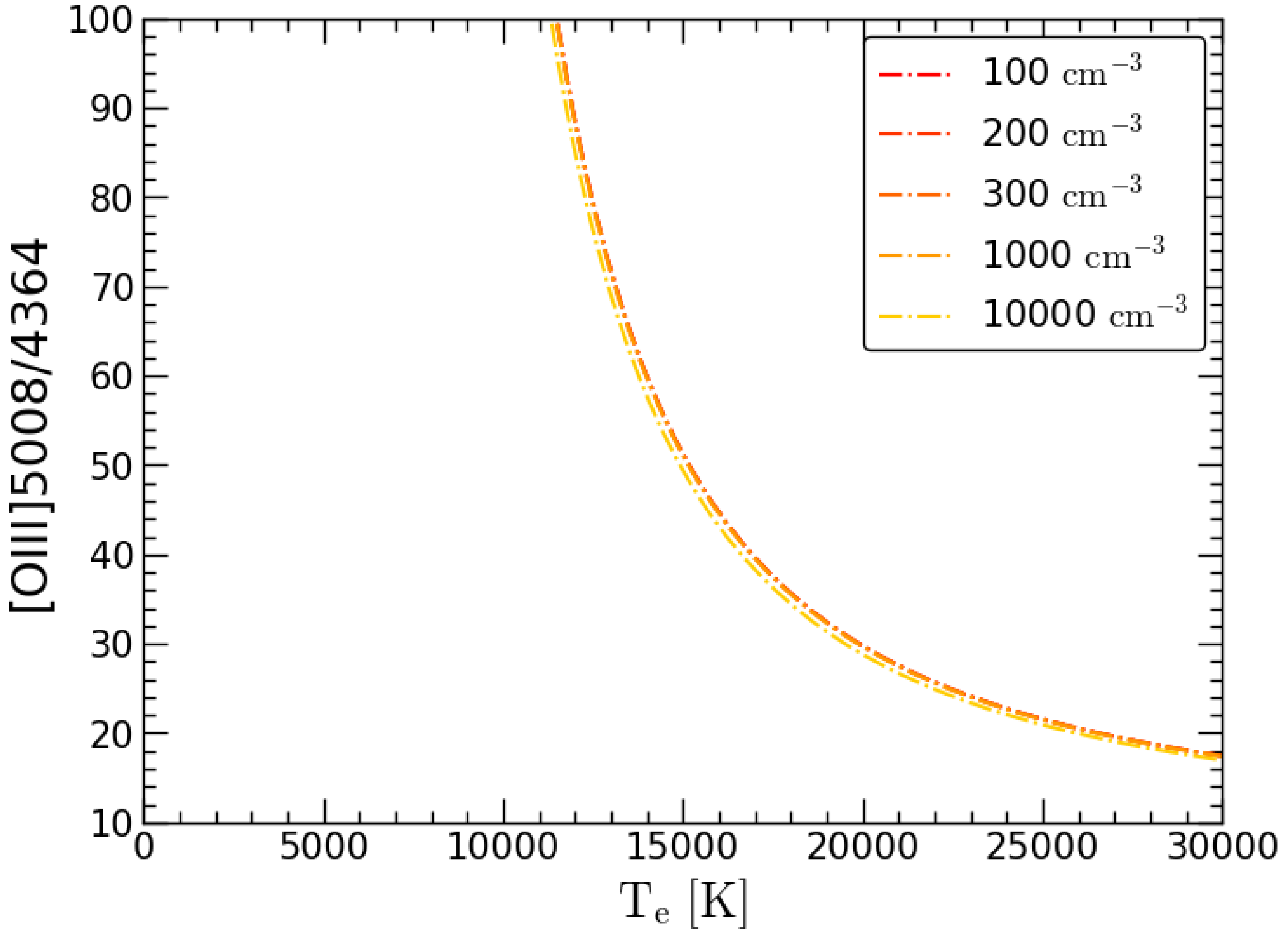


# Electron temperature Estimation

How do we estimate ISM physical properties? → **Emission Line Ratio**

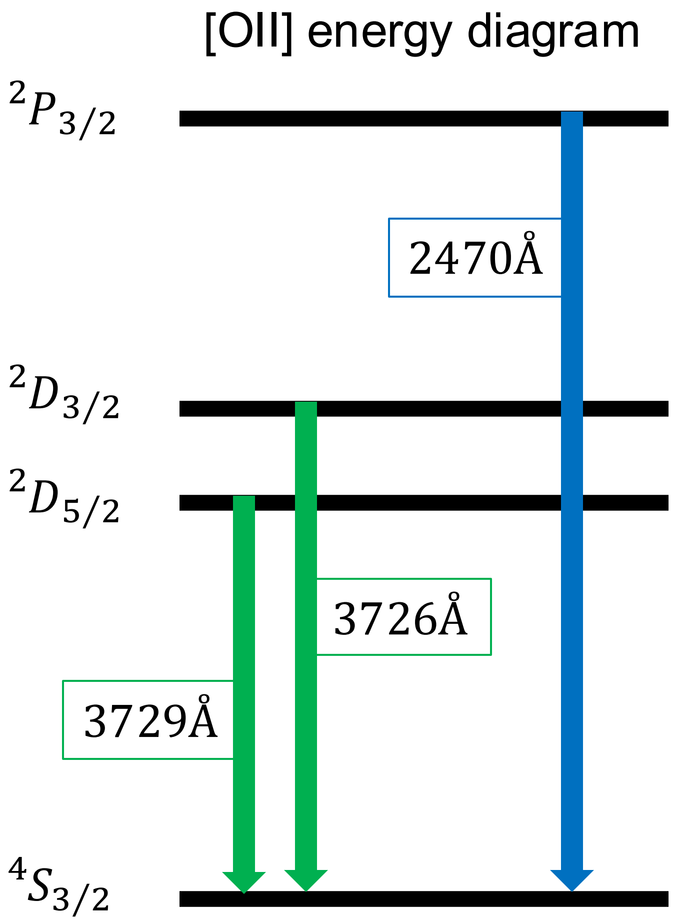
[OIII] energy diagram

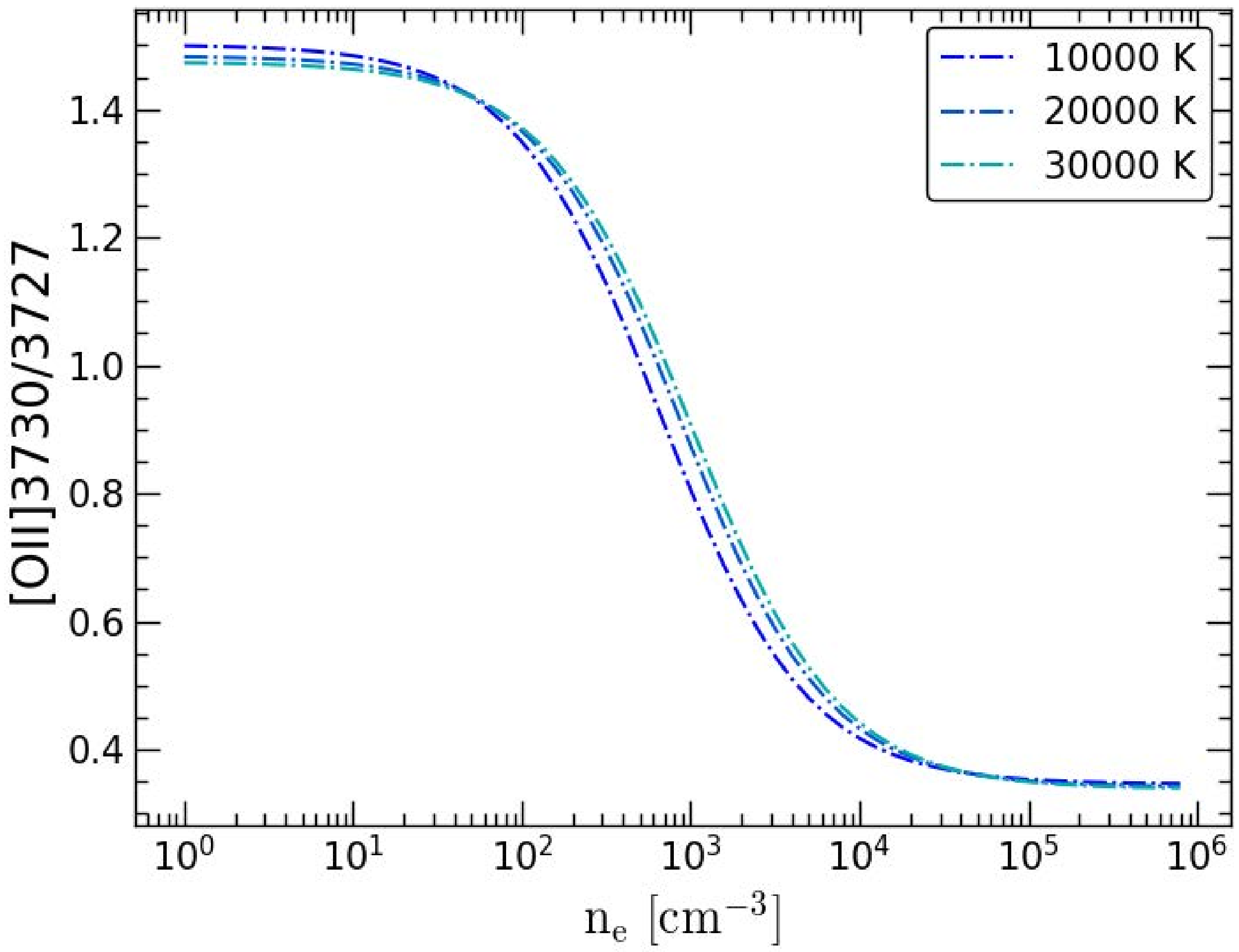


# Electron density Estimation

How do we estimate ISM physical properties? → **Emission Line Ratio**



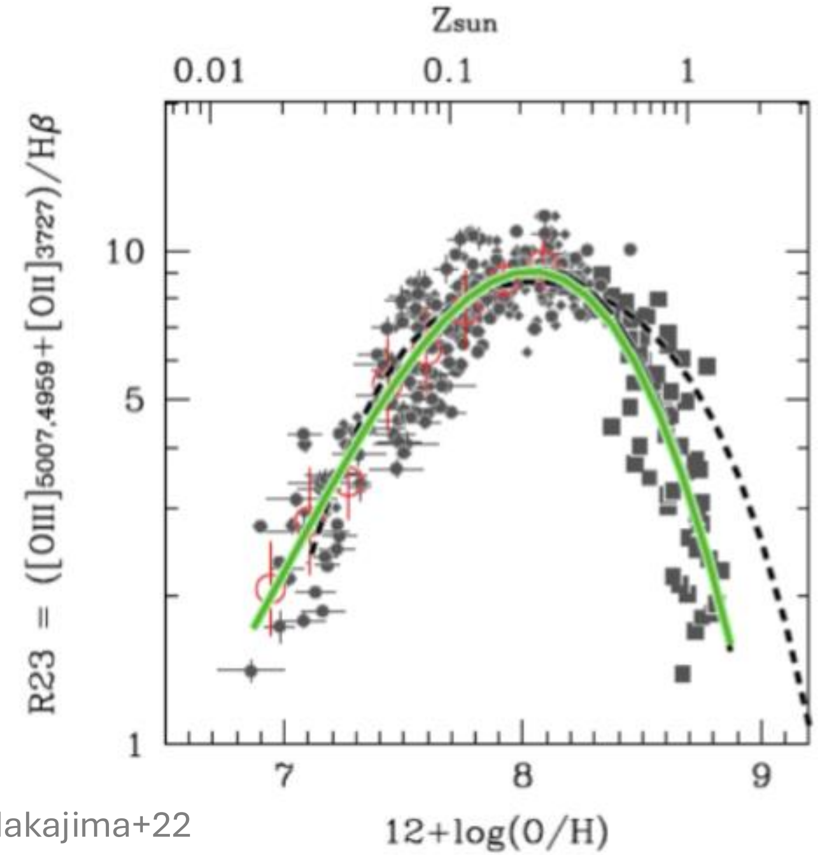



# Empirical Estimation

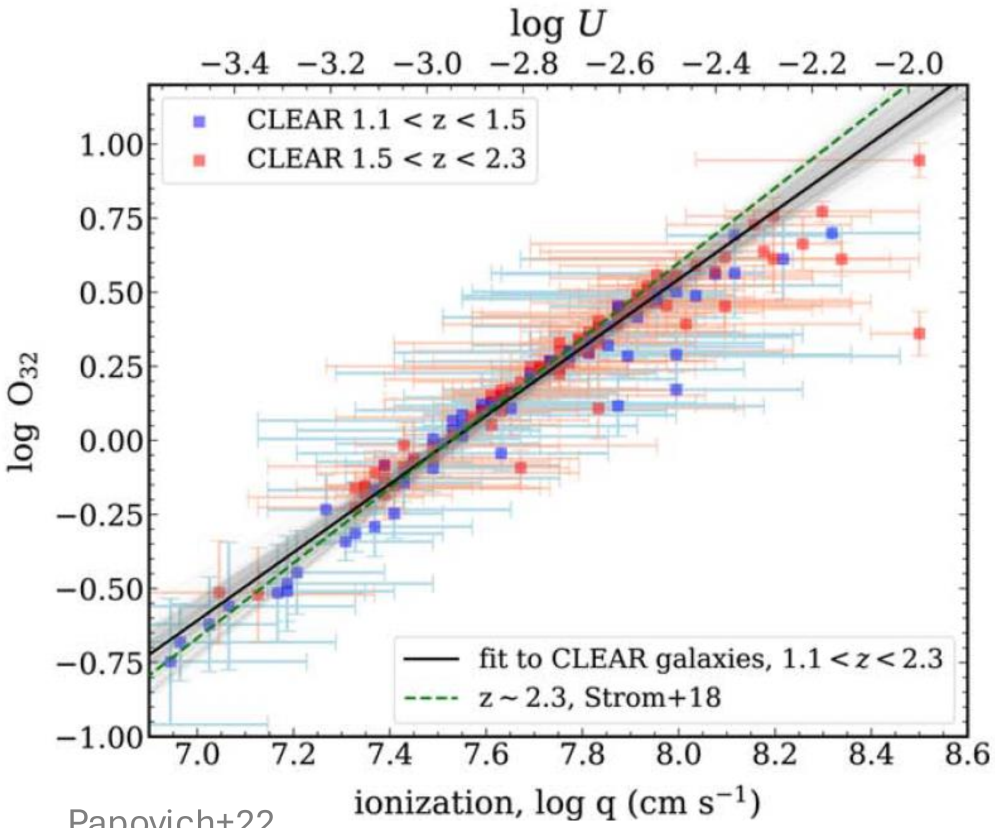
Difficult to estimate theoretically or lack of necessary information
→ Empirical estimation using emission line ratios

$$\mathrm{R23} = \log_{10}\left(\frac{[\mathrm{O\,II}]3727, 3730 + [\mathrm{O\,III}]4960, 5008}{\mathrm{H}\beta}\right)$$

$$\mathrm{O32} = \log_{10}\left(\frac{[\mathrm{O\,III}]5008}{[\mathrm{O\,II}]3727, 3730}\right)$$



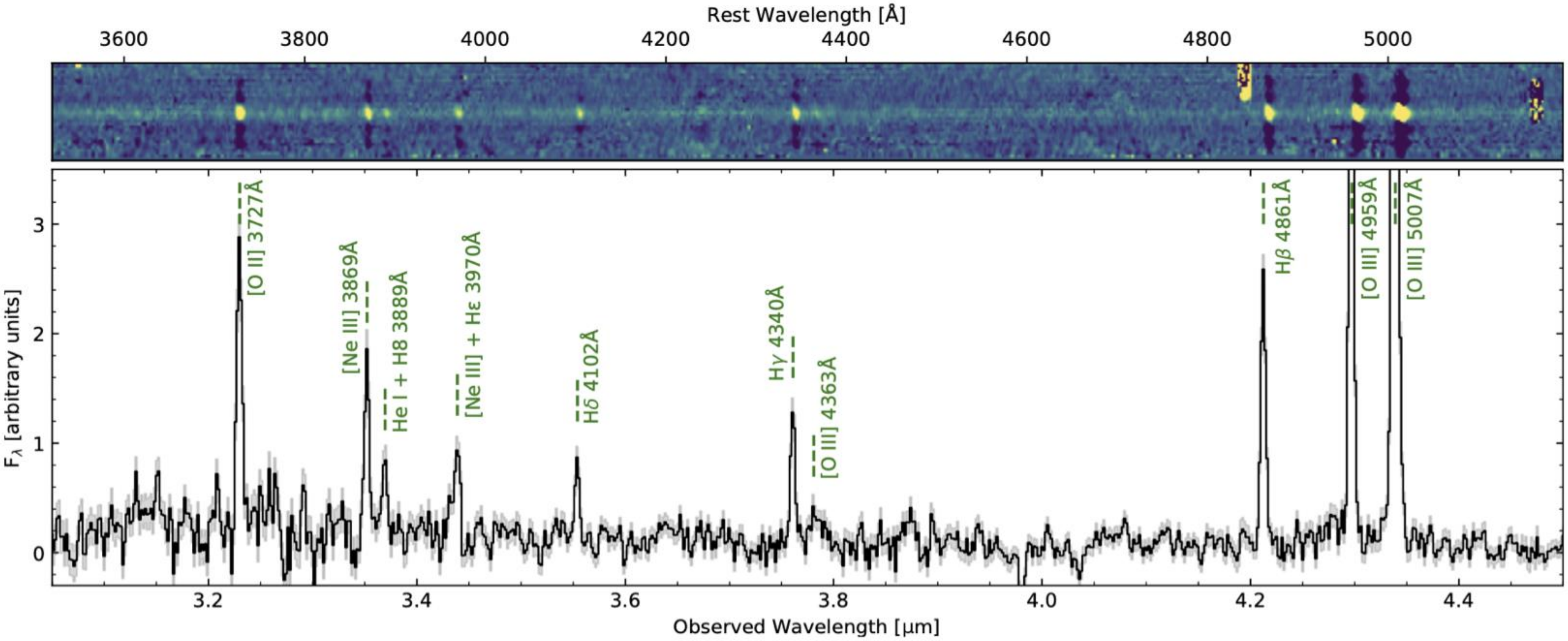

Nakajima+22




Papovich+22

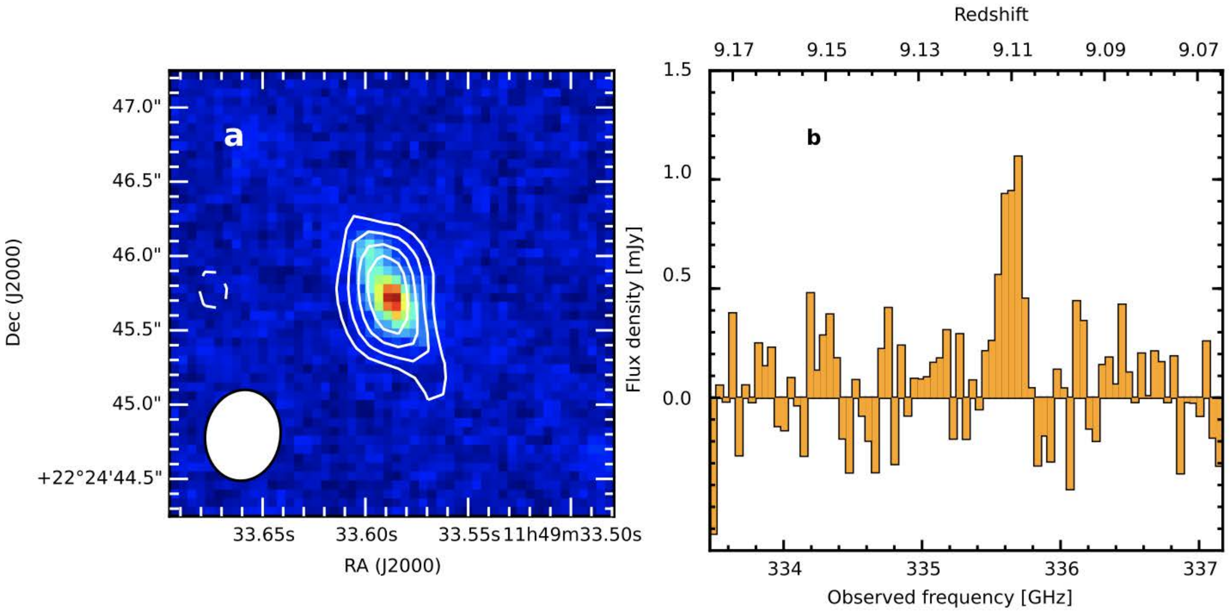
# Spectroscopic Observation

To measure the line intensity → Spectroscopic observation

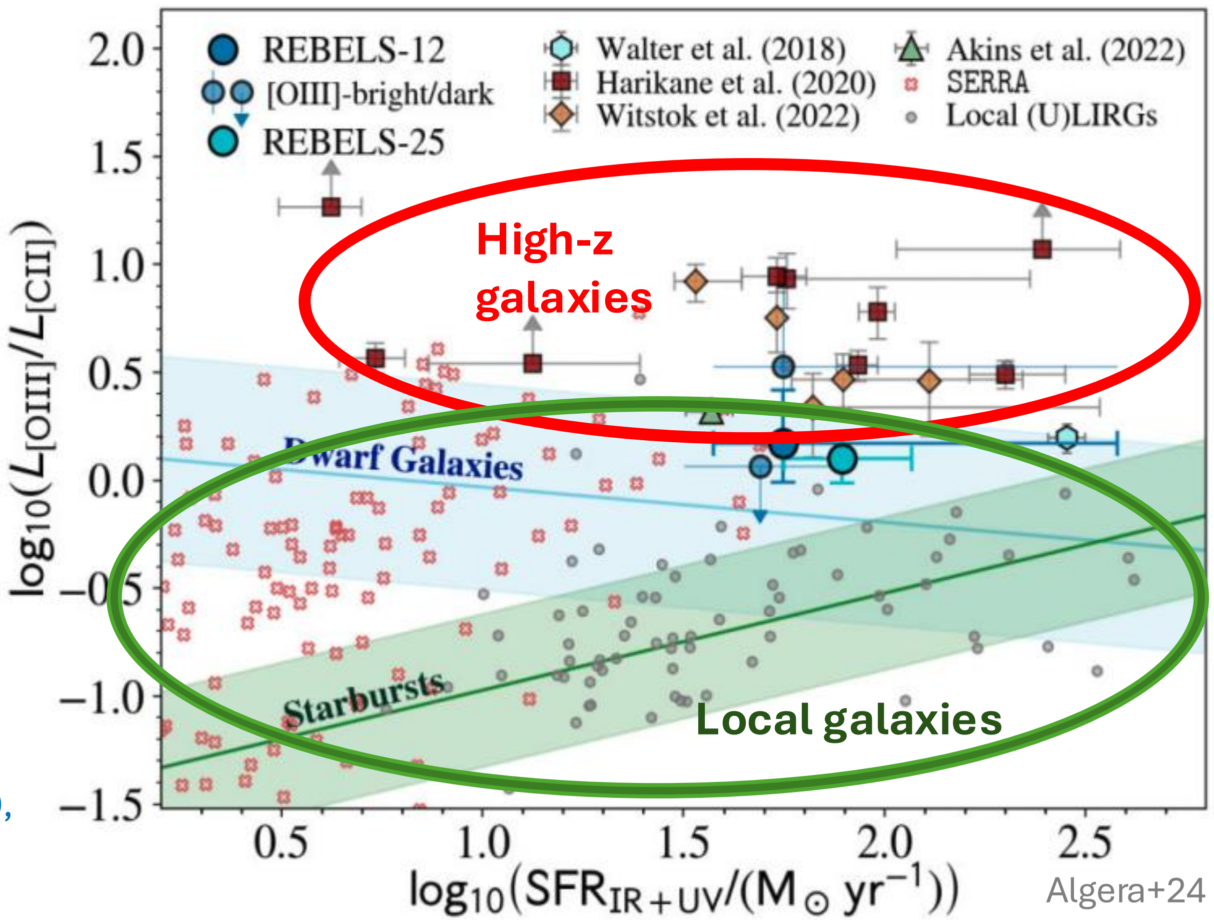



Schaerer+22

# ALMA Observations for High-z Galaxies




Hashimoto+18, Nature



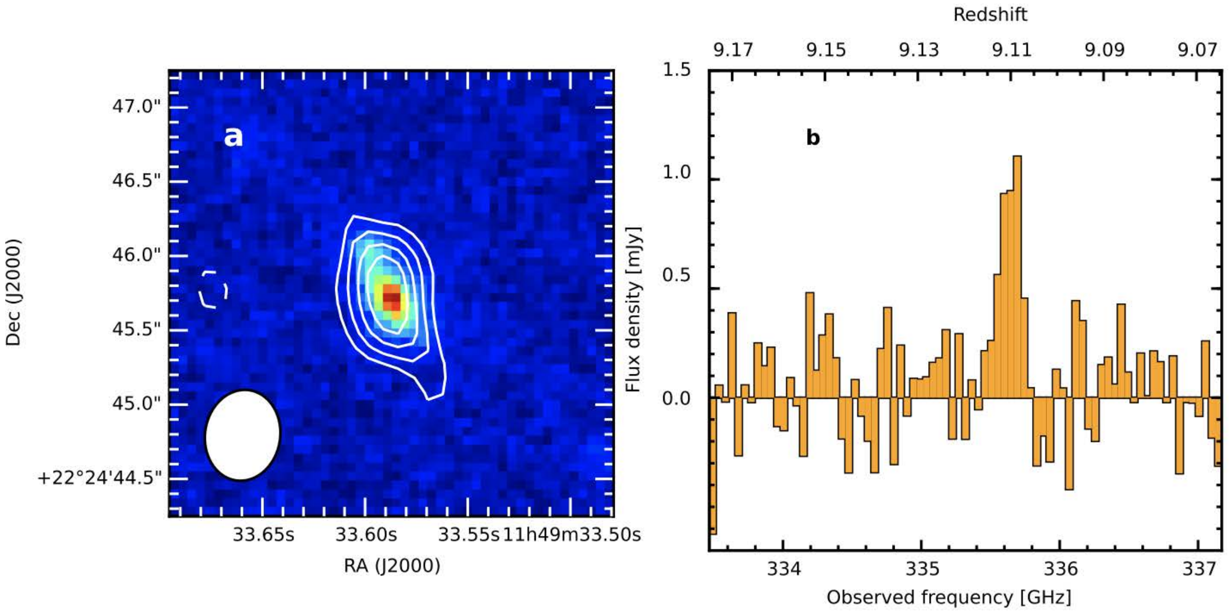

Algera+24

- ALMA observations for high-z galaxies（e.g., Inoue+16, Hashimoto+18, Tamura+19, Inami+22, Bouwens+22）
- High-[OIII]/[CII] ratio （e.g., Hashimoto+19, Harikane+20, Bakx+20, Sugahara+22, Algera+24）

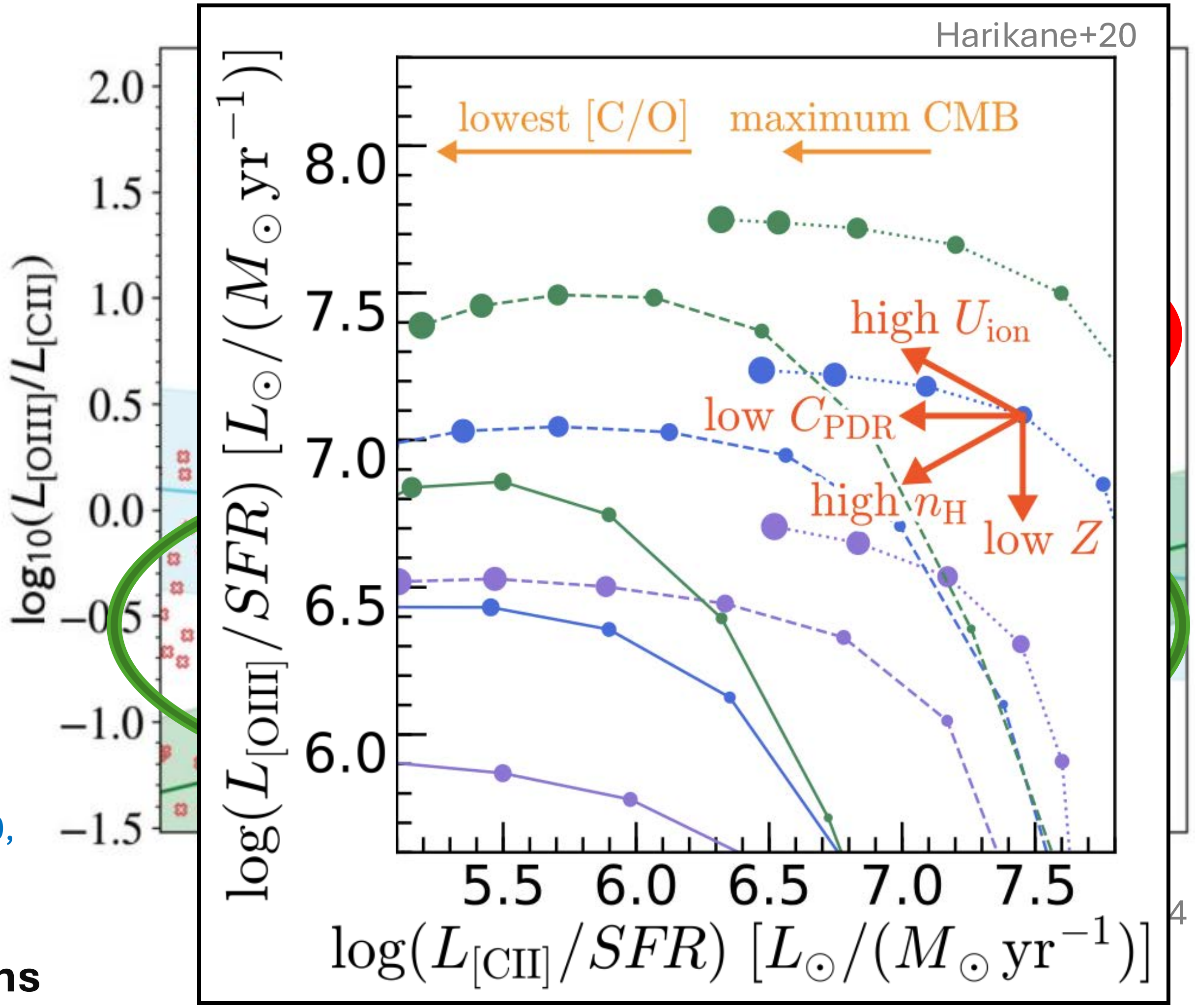
→ **Suggests that z~0 and z>6 have different ISM conditions**

- lower metallicity or higher ionization parameter?

# ALMA Observations for High-z Galaxies




Hashimoto+18, Nature

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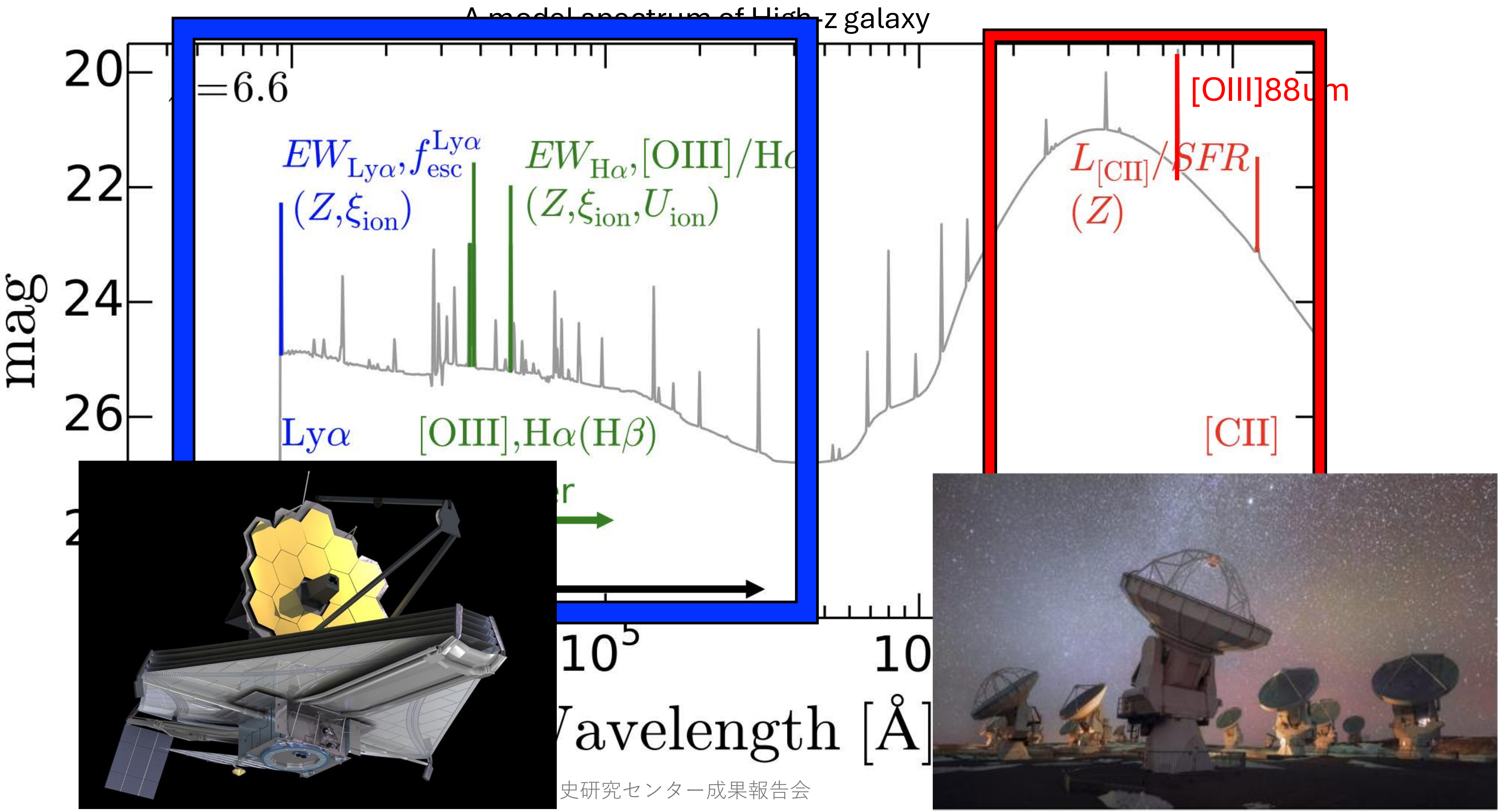
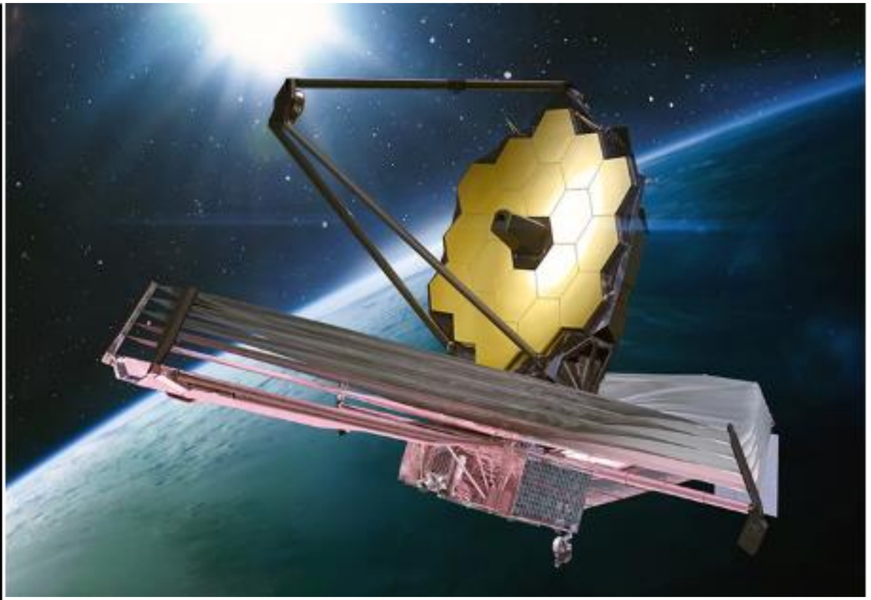
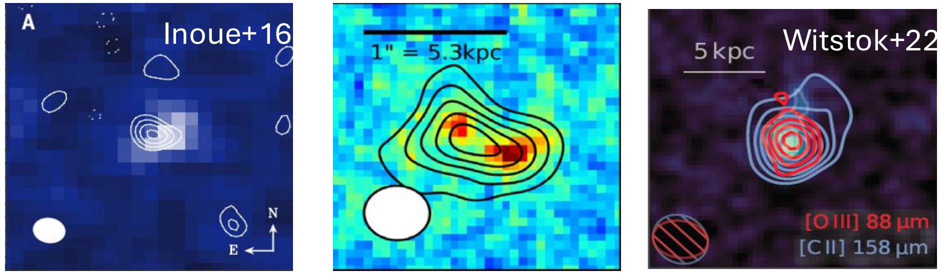
# Observations for Optical Lines in High-z Galaxies by JWST



# Rionization and the ISM/Stellar Origins with JWST and ALMA (RIOJA; JWST GO1 #1840)

- **PI & coPI**: J. Álvalez-Márquez & T. Hashimoto
- **Observation time** : 33.9 hrs
- **Target:** 12 ALMA [OIII] 88 um emitters @ z = 6 ~ 8



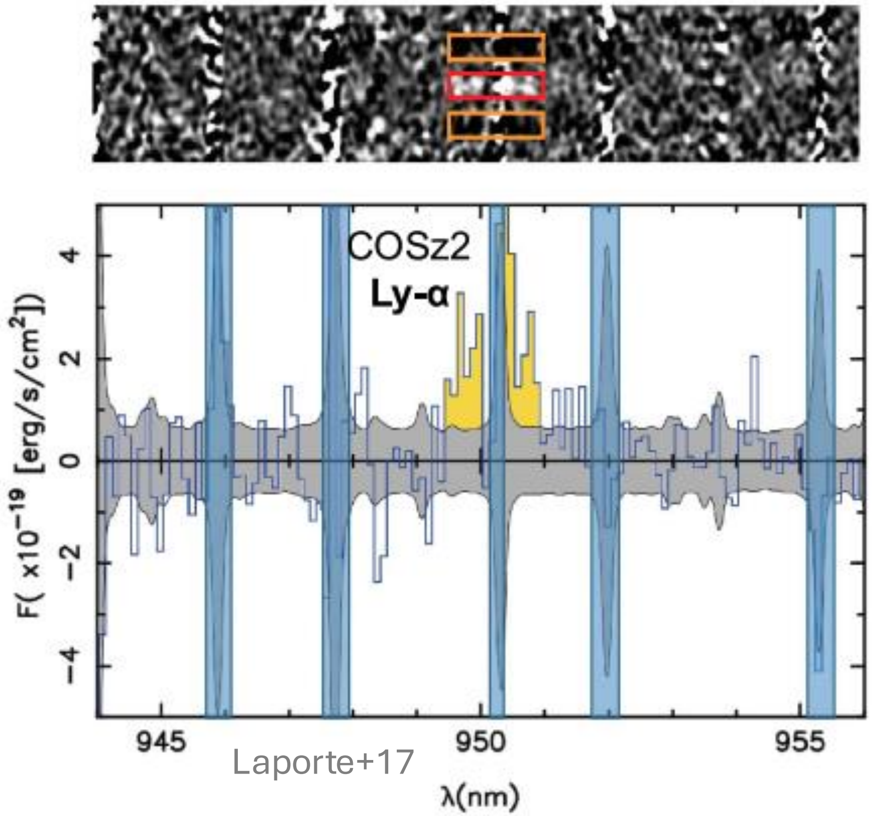

Hashimoto+18

- **Motivations:**

  Comprehensive understanding of stars, gas, and dust in galaxies @ z > 6
- **Instruments**
  - NIRCam Imaging (1 ~ 5 um)
  - NIRSpec IFS (3 ~ 5 um)
- **Analysis of NIRSpec and ALMA data for COS-2987**

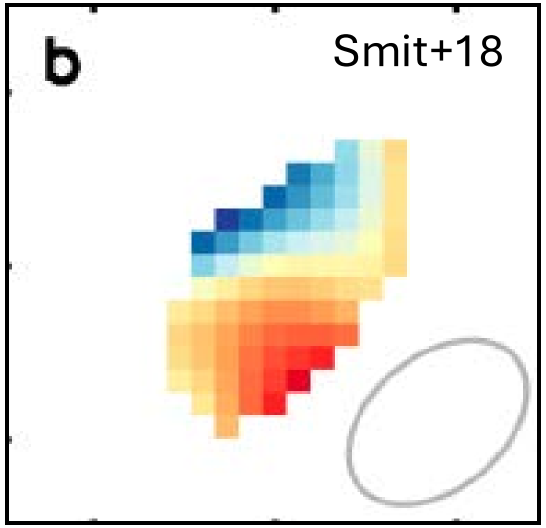
# Target : COS-2987

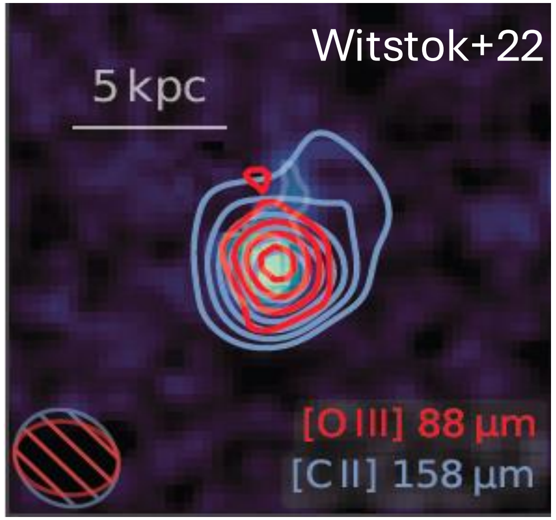
- A star-forming galaxy @ z=6.81
  (780 million years after the Big Bang)
- Spitzer/IRAC + HST →Lyman break galaxy (Smit+15)
- VLT/XSHOOTER → Lyα (Laporte+17)



Laporte+17

- ALMA observations
  - [CII] 158 um (Smit+18, Posses+22)
  - [OIII] 88 um (Witstok+22) → [OIII]/[CII]~6
  - Dust continuum → non-detection
    (Smit+18, Witstok+22)




This work : Examine the ISM properties using JWST and ALMA

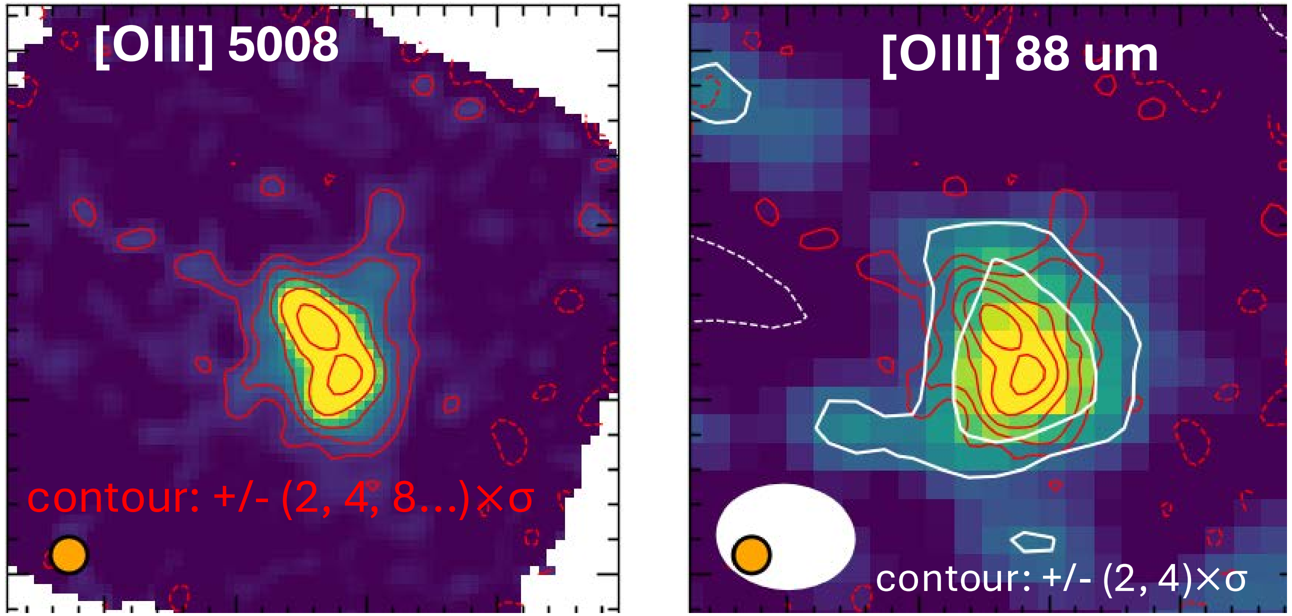
# NIRSpec/IFS and ALMA data

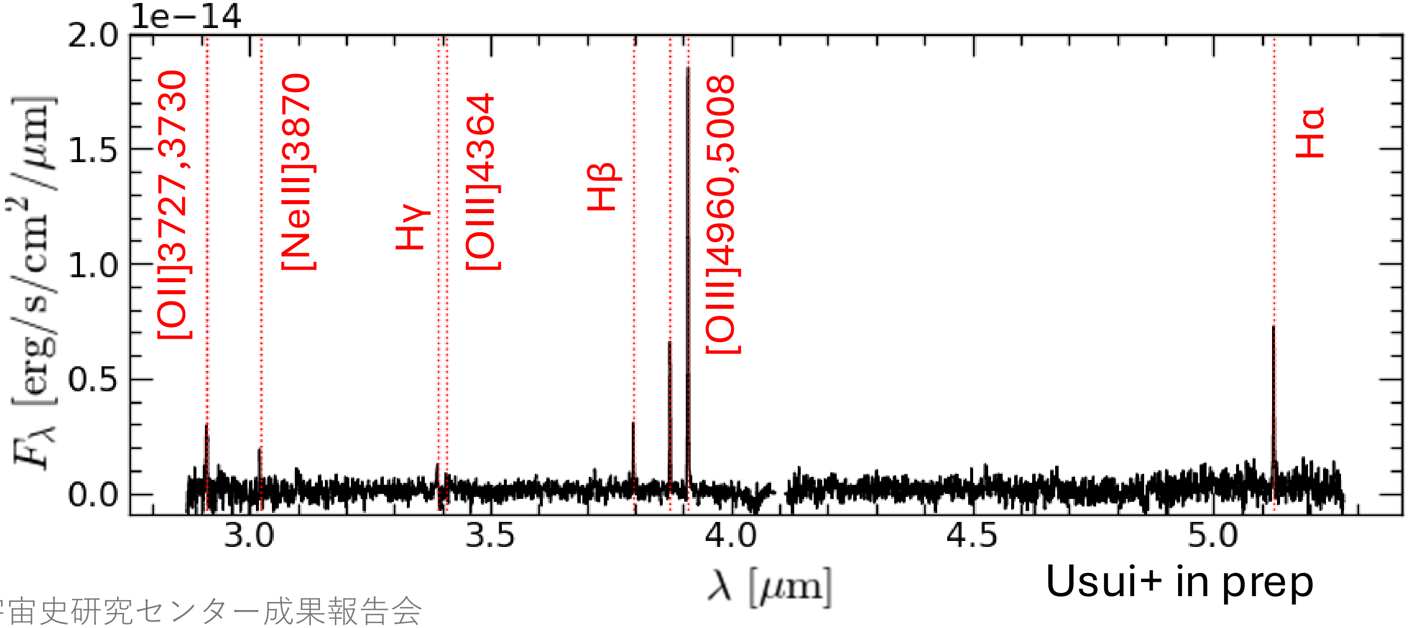
## NIRSpec/IFS data

- Cycle1 GO #1840
  (RIOJA: PIs; J. Alvarez-Marquez, T. Hashimoto)
- Grating/Filter：$G395H/F290LP$
  $\rightarrow$ $\boldsymbol{R \sim 2700}$, $\boldsymbol{\lambda \sim}$ **2.87 - 5.27 um**
- Extract the spectrum from 2σ region of the [OIII]5008 integrated intensity map
- Detection criteria：SNR ≥ 3
  （c.f., Laseter+24 , Morishita+24）

## ALMA archival data

- Band 8 data (reported in Witstok+22)
- We re-analyzed the [OIII] 88 um flux
  → Consistent with Witstok+22




Usui+ in prep

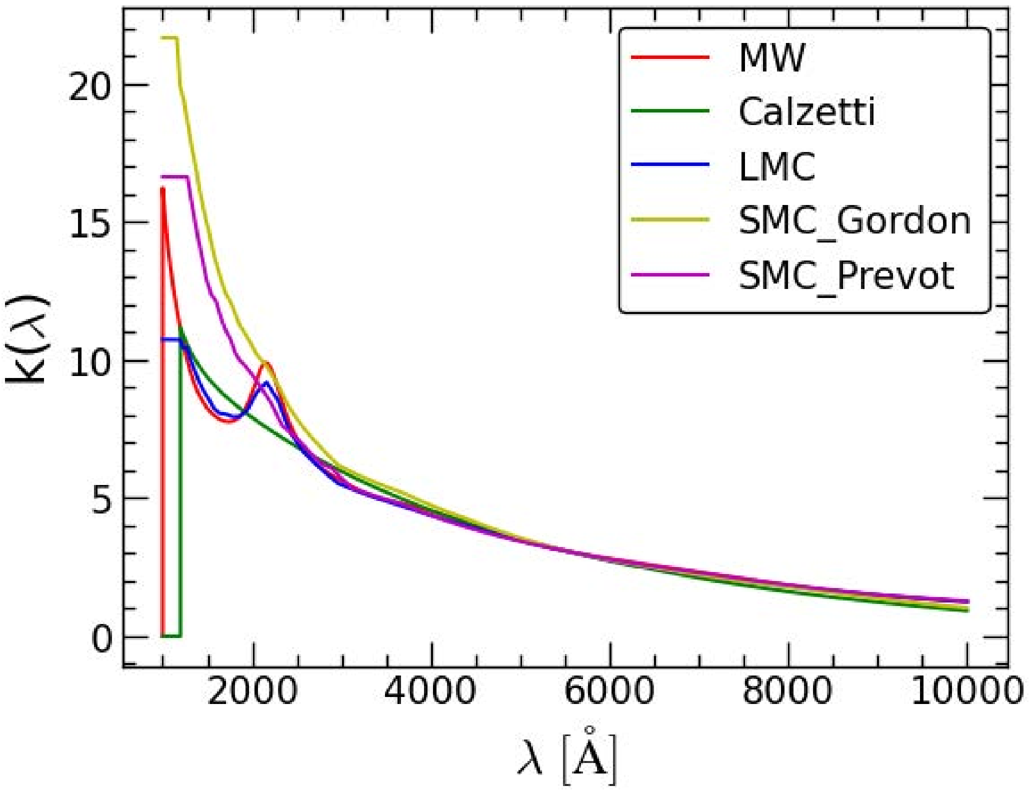
# Spatially-integrated properties from NIRSpec/IFS

## Extinction correction

- Hα/Hβ (Balmer decrement)

$$A_V = \frac{2.5 \times R_V}{k(\lambda_{\mathrm{H}\beta}) - k(\lambda_{\mathrm{H}\alpha})} \log_{10}\left\{ \frac{(\mathrm{H}\alpha/\mathrm{H}\beta)_{obs}}{(\mathrm{H}\alpha/\mathrm{H}\beta)_{theo}} \right\}$$

- Dust extinction curve $k(\lambda)$: SMC (Gordon+03, $R_V = 2.74$)
- $(\mathrm{H\alpha/H\beta})_{obs} = 2.93^{+0.29}_{-0.26}$
- $(\mathrm{H\alpha/H\beta})_{theo} = 2.74$ ($n_e = 500$ cm-3, $T_e = 20{,}000$ K )

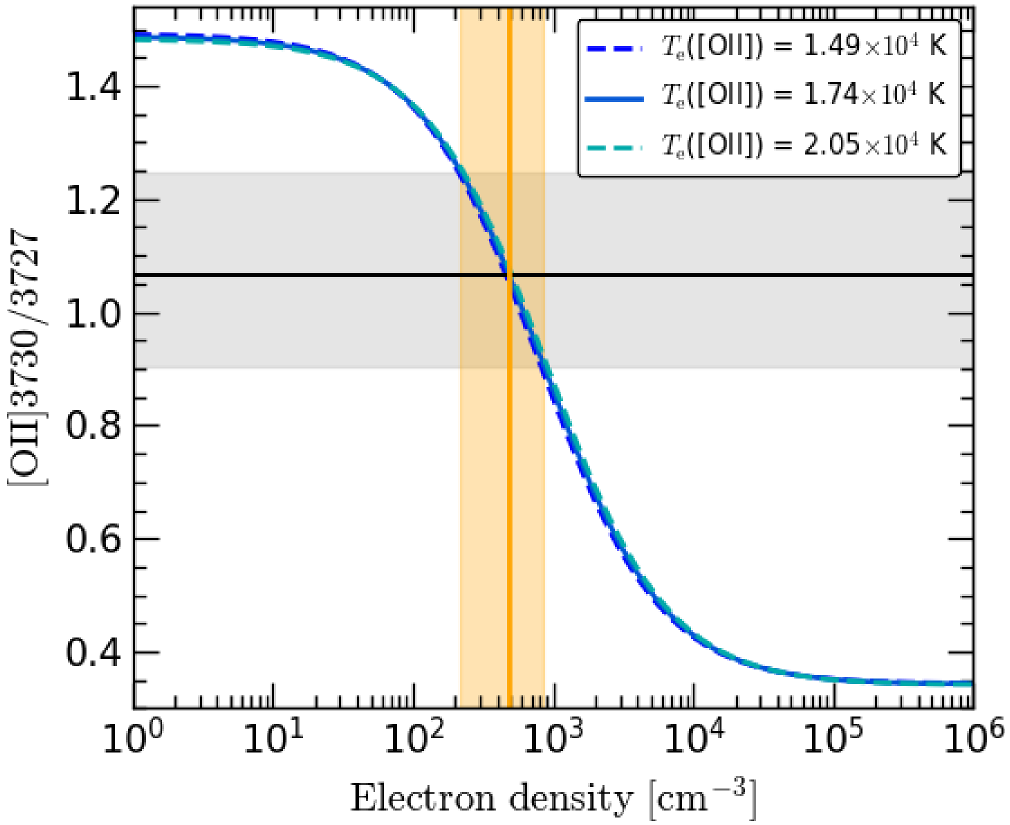


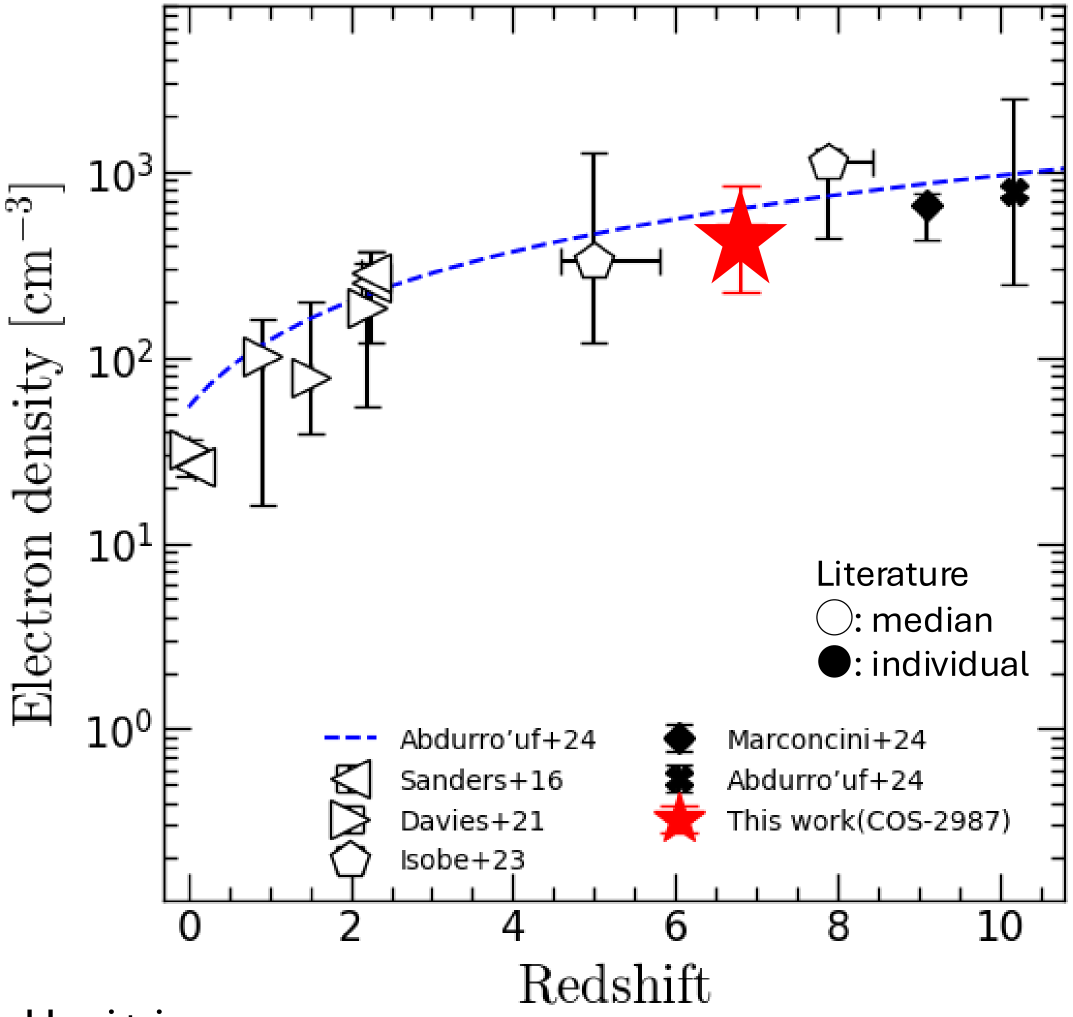

→ $A_V = 0.20^{+0.21}_{-0.20}$ mag

**Consistent with non-detection of ALMA dust continuum (Smit+18, Witstok+22)**

# Spatially-integrated properties from NIRSpec/IFS

- Electron density
  - [OII]3730/3727
  - $n_e = 480^{+630}_{-270}\ \mathrm{cm^{-3}}$



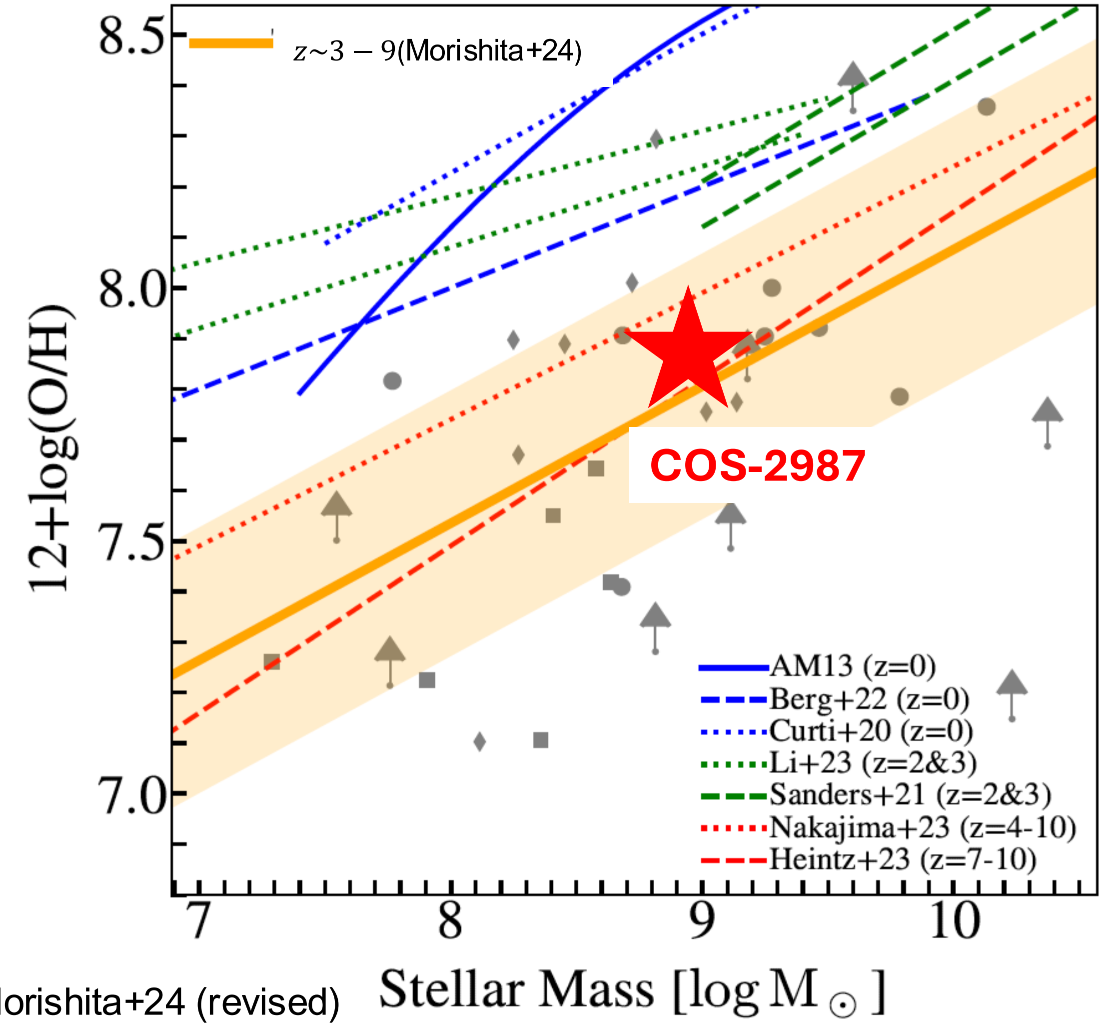




Usui+ in prep

# Spatially-integrated properties from NIRSpec/IFS

- Electron density
  - [OII]3730/3727
  - $n_e = 480^{+630}_{-270}\ \mathrm{cm}^{-3}$
- Gas-phase metallicity
  - Direct- $T_e$ method
  - [OIII]5008/4364 → $T_e = (2.1 \pm 0.4) \times 10^4$ K
  - $12 + \log_{10}(\mathrm{O/H}) = 7.7 \pm 0.2\ (\sim 0.1\ Z_\odot)$

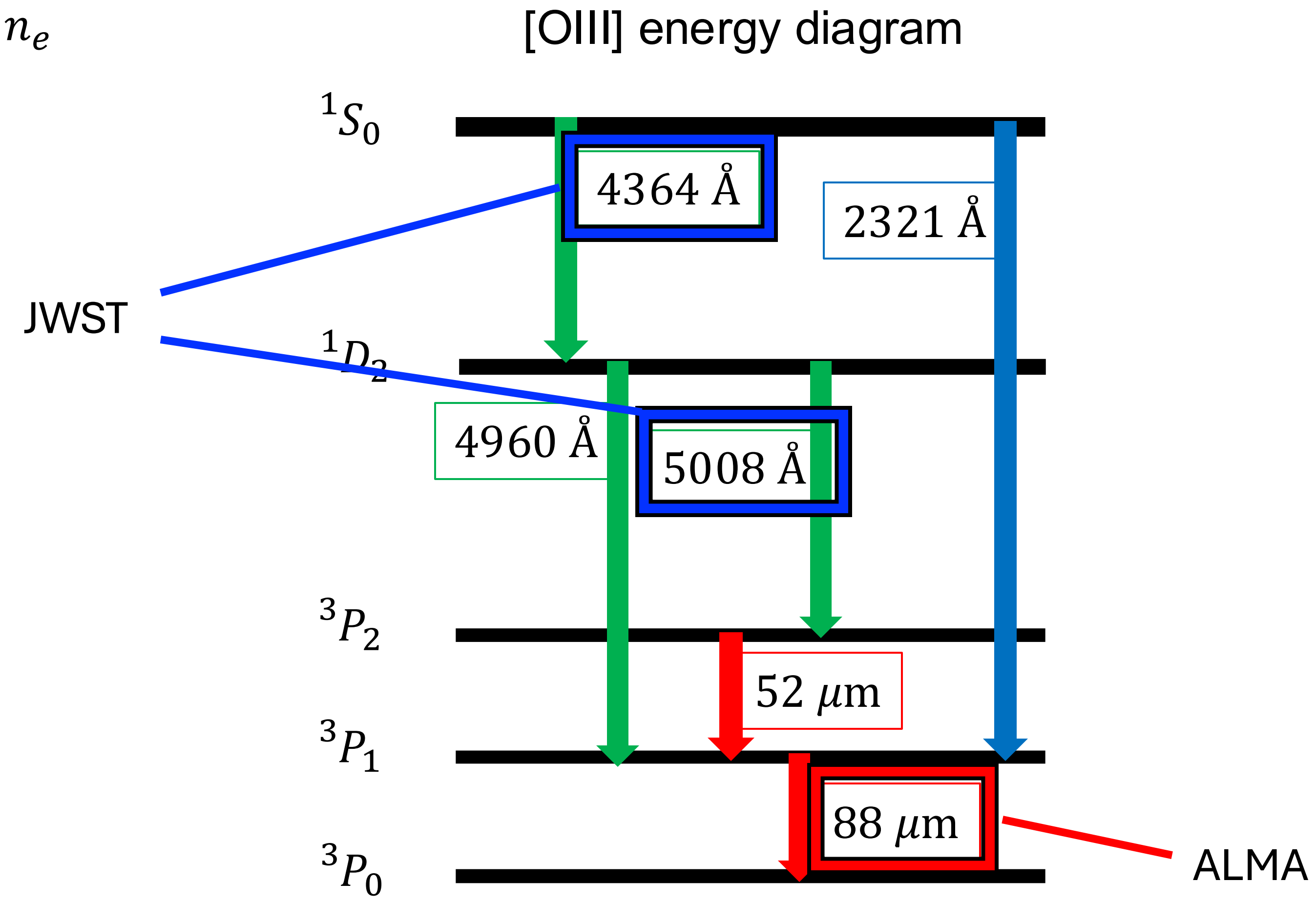
$* \log_{10} M_*/M_\odot \sim 8.7$ (Mawatari+ in prep)




Morishita+24 (revised)

# JWST + ALMA analysis - [OIII] line ratio diagnostics

- Three [OIII] lines allow us to constrain $T_e$ and $n_e$
  - [OIII]5008/4364 → sensitive to $T_e$
  - [OIII]88/5008 → sensitive to $T_e$ and $n_e$



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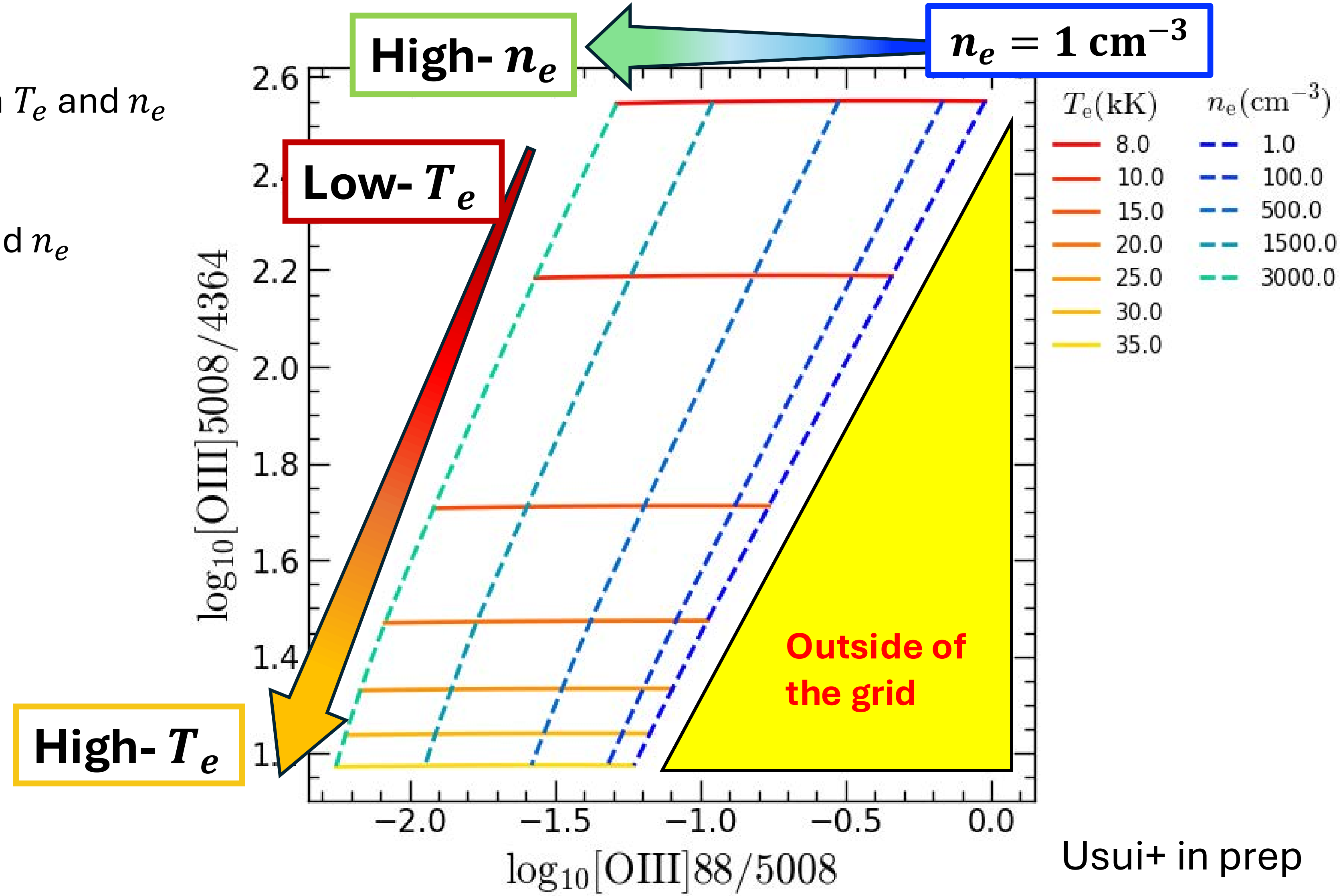


Usui+ in prep

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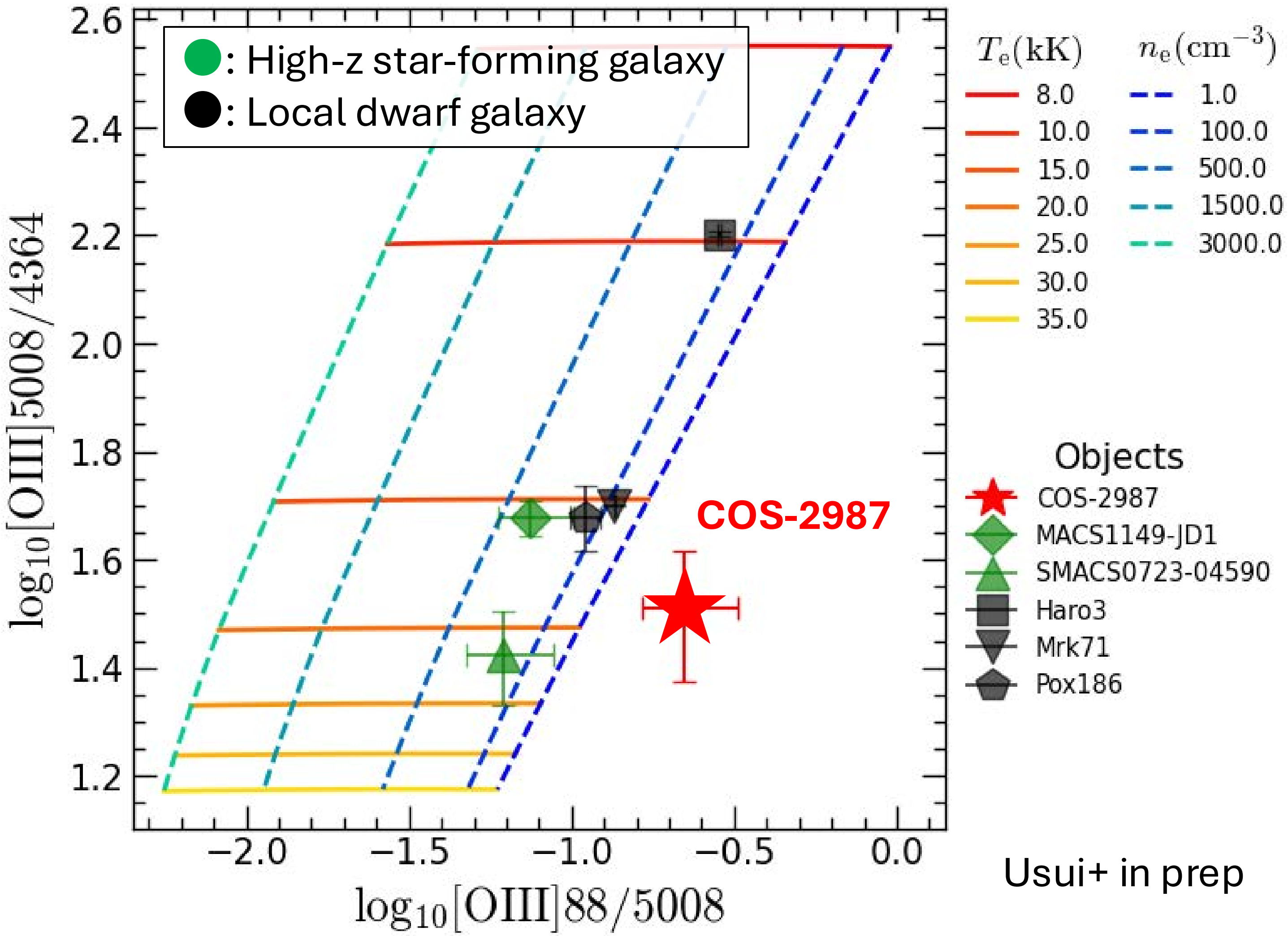
  - [OIII]5008/4364 → sensitive to $T_e$
  - [OIII]88/5008 → sensitive to $T_e$ and $n_e$
- **The [OIII] ratios of COS-2987 cannot be explained by homogeneous ionized gas with a constant $T_e$ and $n_e$.**
- Inconsistent with $n_e$ derived from [OII]
  ($n_e = 480^{+630}_{-270}\ \mathrm{cm^{-3}}$)
- Causes of this situation
  → we consider **"Two-phase ionized gas"**

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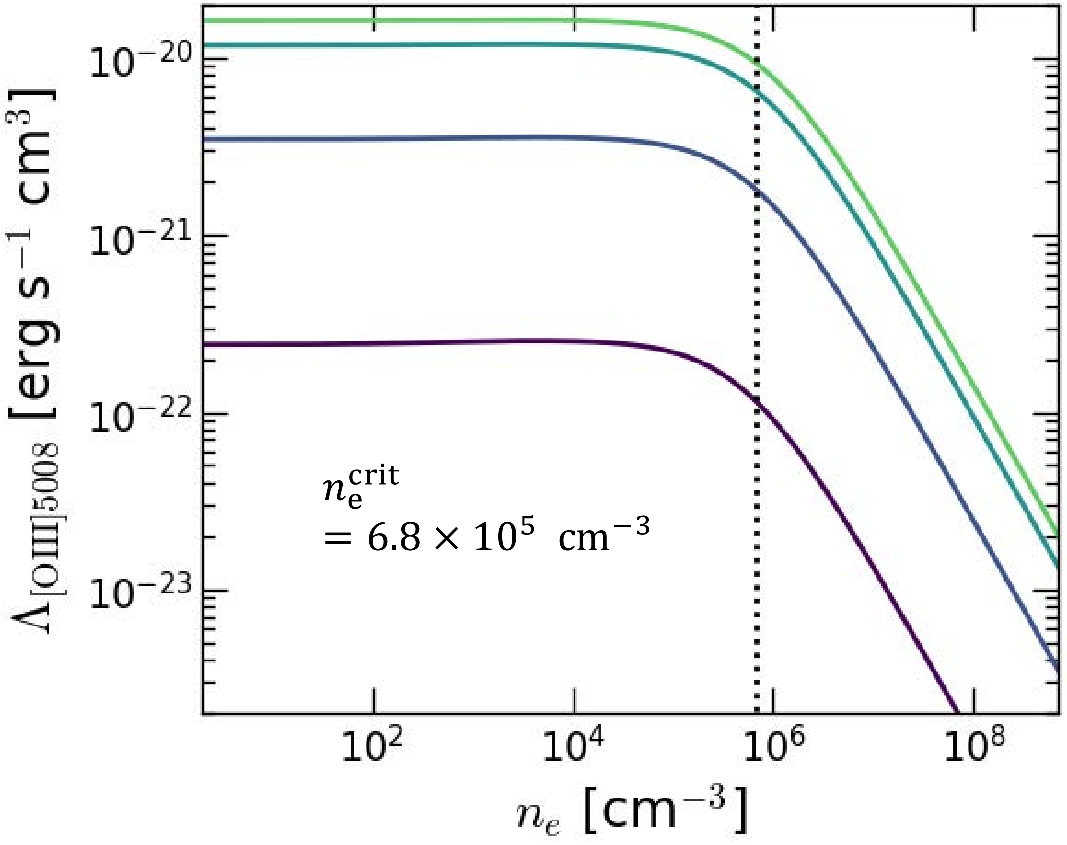
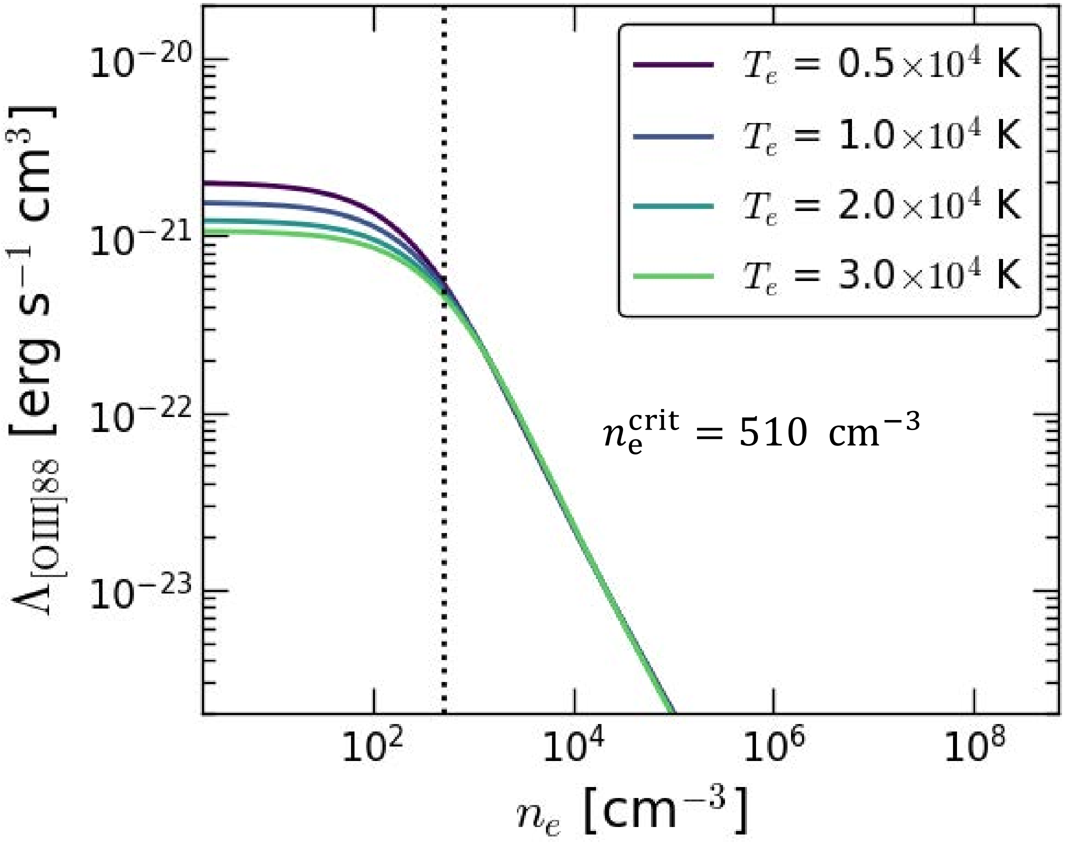
# Discussion – A toy model with two-phase ionized gas




[OIII] 5008 and 88 have

- ◆ different critical densities
- ◆ different temperature sensitivities

$\Rightarrow$ Assuming **“two-phase ionized gas”**

# Discussion – A toy model with two-phase ionized gas

- A luminosity ($L_{\rm line}$ ) can be written as follow;

$$\boldsymbol{L_{\rm line} = L_{\rm line,1} + L_{\rm line,2} = \epsilon_{\rm line,1} \times V_1 + \epsilon_{\rm line,2} \times V_2}$$

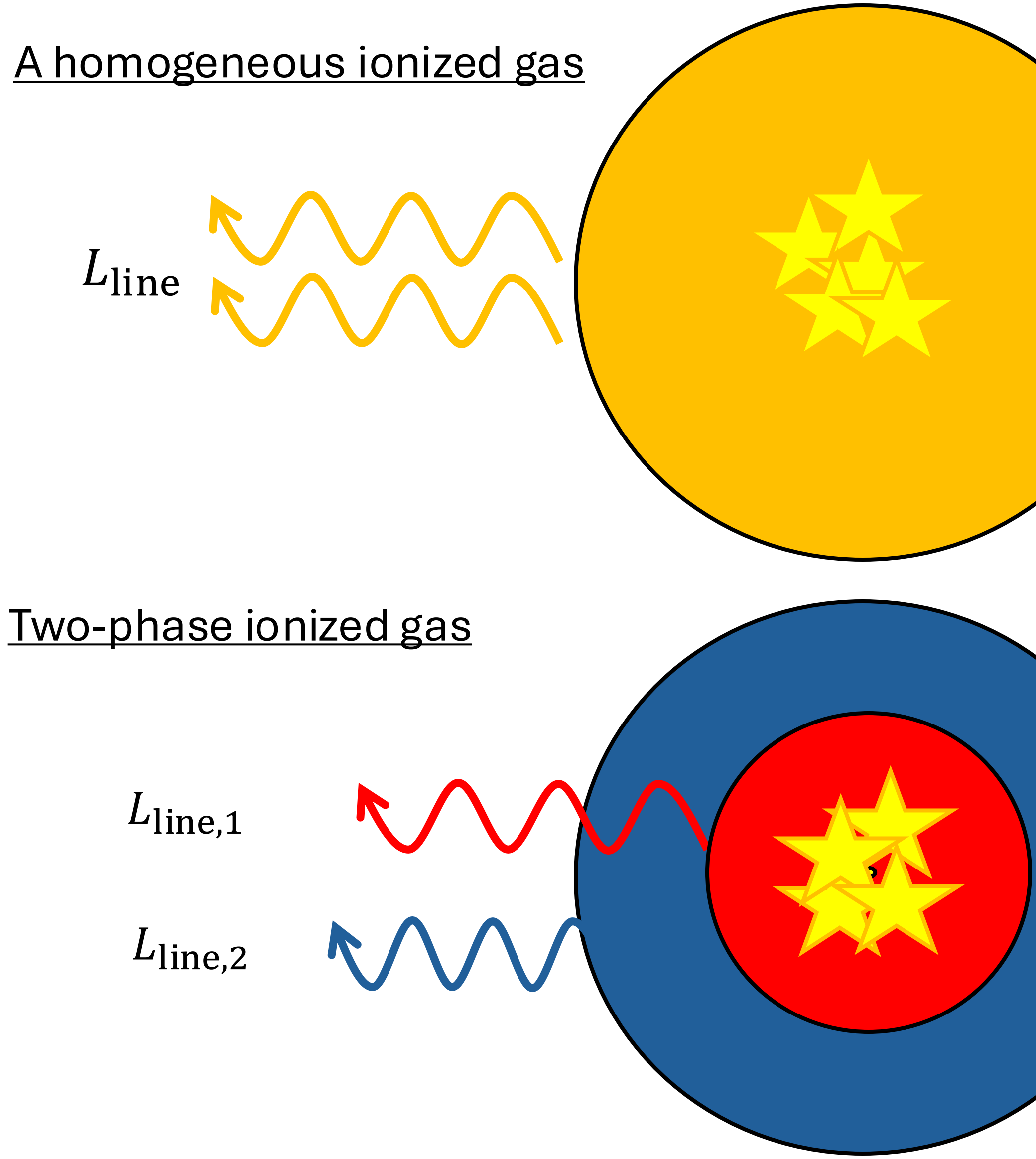
$\epsilon$ : emissivity [erg s$^{-1}$ cm$^{-3}$]

$V$ : volume [cm$^3$]

$\epsilon_{\rm line,i}$ : As a function of ($\boldsymbol{T_{e,i}}$,$\boldsymbol{n_{e,i}}$, $n_{\rm O^{2+}} = 10^{-4}$)

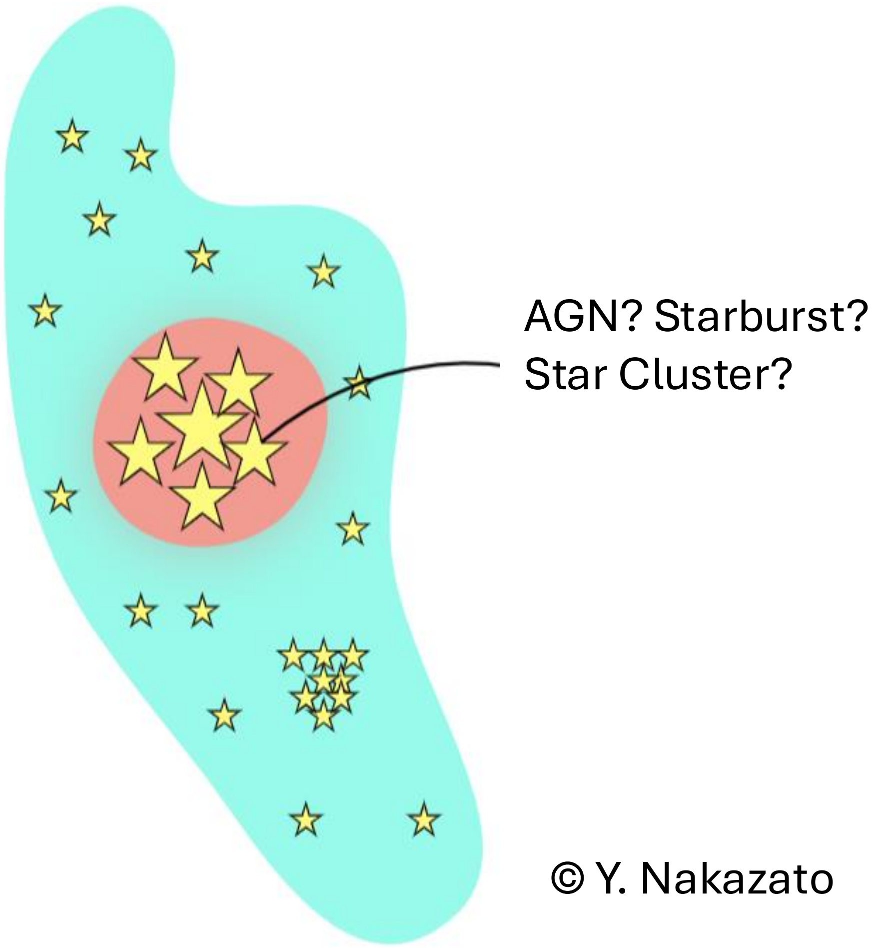
line: [OIII]5008 or 88

- We examine whether the observed line ratio can be reproduced under assumptions of $n_e$, $T_e$, and $n_{\rm O^{2+}}$ for each ionized gas.

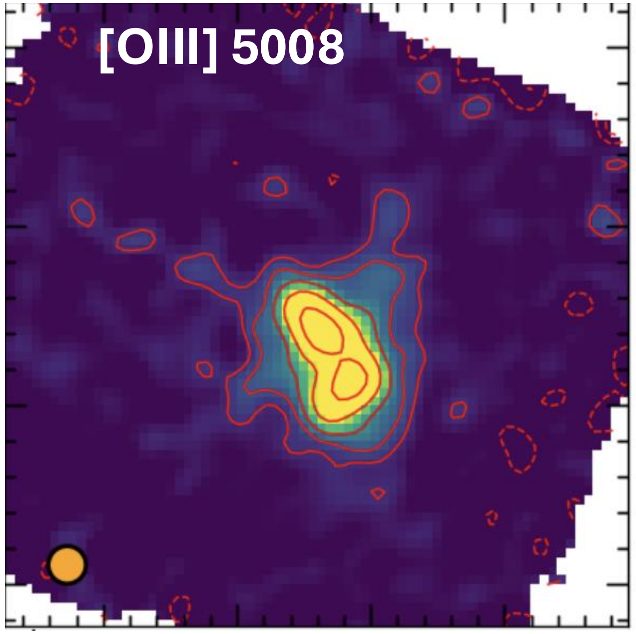


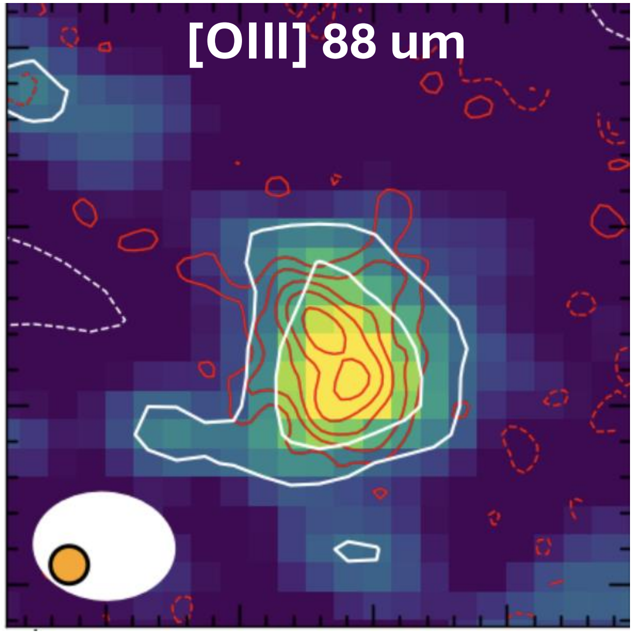
# Discussion – A toy model with two-phase ionized gas

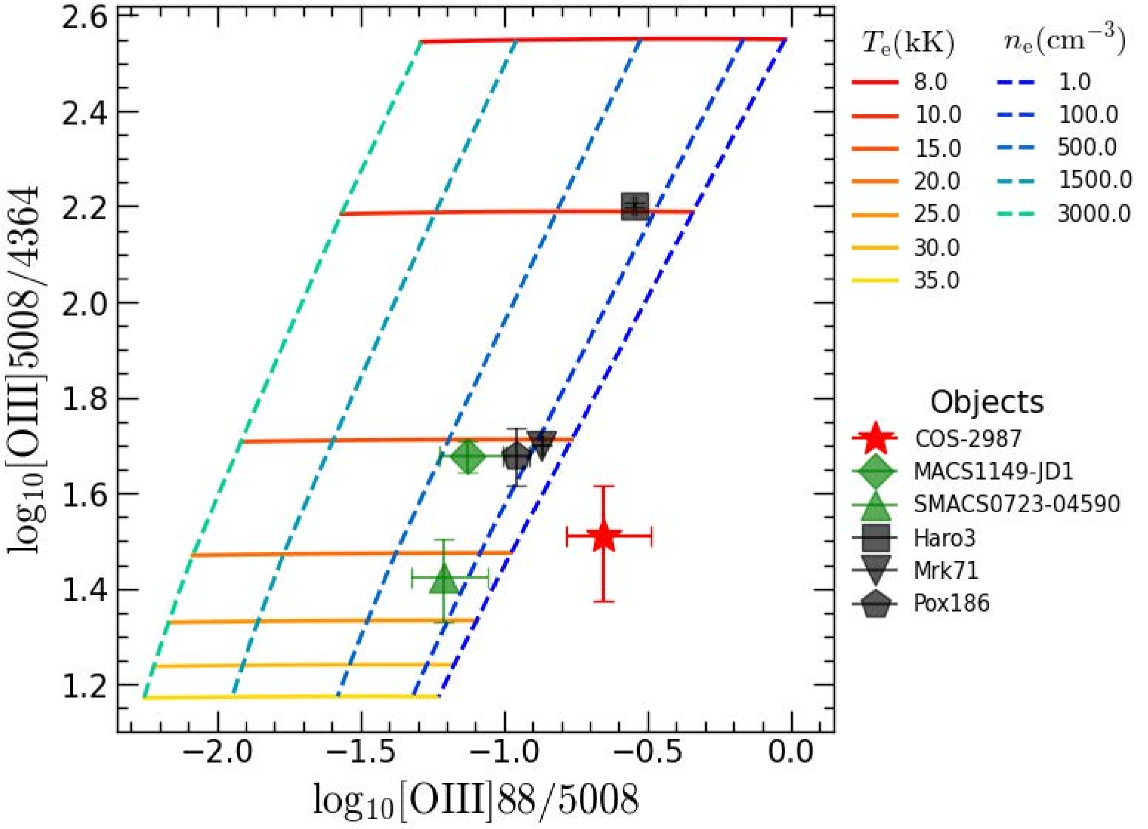
- **For example;**
  - Higher-Te, -ne ionized gas ($T_e$ = 20,000 K, $n_e$ = 600 $\mathrm{cm}^{-3}$)
  - Lower-Te, -ne ionized gas ($T_e$ = 10,000 K, $n_e$ = 100 $\mathrm{cm}^{-3}$)
  - ⇒ We can reproduce the [OIII]88/5008 ratio when $\boldsymbol{V_{\mathrm{hot}}} : \boldsymbol{V_{\mathrm{cold}}} = \mathbf{1:1000}$
- **To better constrain the situation in the future;**
  - Deeper JWST observations and Higher-resolution ALMA observations
    - → $T_e, n_e$ and the [OIII]88/5008 maps
  - UV lines (e.g., OIII]1666, CIII]1907,09)
    - → estimating $T_e$ and $n_e$ for the higher-ionization region
- **Important implications for ISM studies using JWST+ALMA**



# Summary




- A joint analysis of JWST and ALMA for COS-2987
- JWST measurements are consistent with other high-z galaxies
- The [OIII]88/5008 ratio of COS-2987 cannot be explained by homogeneous ionized gas with a constant $T_e$ and $n_e$.
- We reproduced the [OIII]5008 and 88 fluxes assuming a two-phase ionized gas
- **Important implications for ISM studies using JWST+ALMA**