An estimate of ISM “porosity” in a Lyman Break Galaxy at z=8.312 based on the luminosities of [OIII] 88μm, [CII] 158μm, and dust continuum

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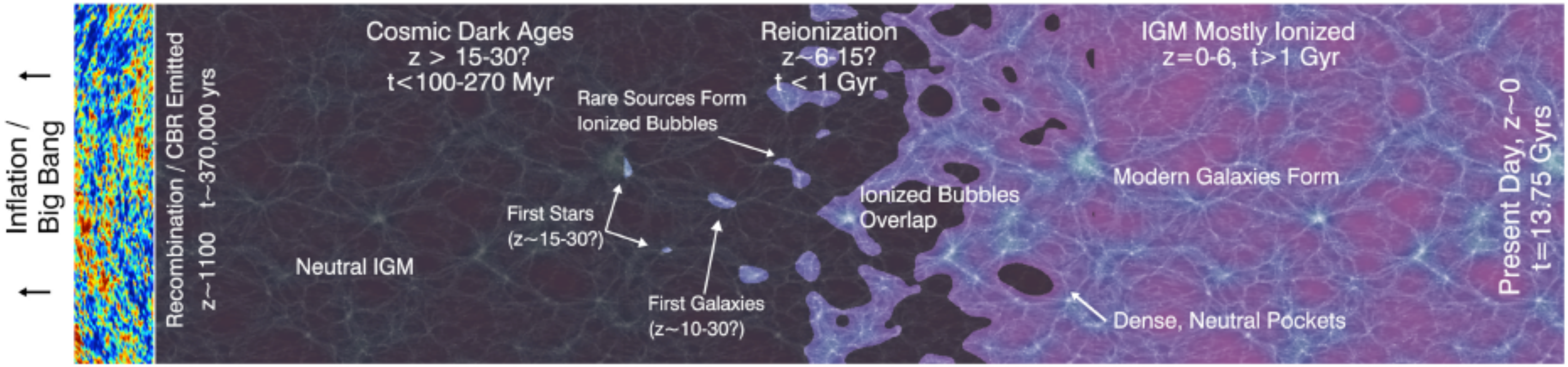
Outline

1. Introduction
   - What is the Epoch of Reionization (EoR)?
   - Far-infrared emission lines in the galaxies of EoR
   - Previous studies
   - The goal of this work
2. Target / Method
3. Result
4. Discussion
5. Future works / Summary

Introduction: What is the Epoch of Reionization?



Robertson +2010

- Epoch of Reionization
  - The era when the universe was re-ionized by UV radiation of some objects (e.g.; galaxies, QSOs) after the birth of first stars
  - Metal and dust enrichment for the first time in the cosmic-history
    - Before this time there are only hydrogen and helium in the universe
- How does the ISM structure affect on the escape fraction of ionizing photons?
- What physical conditions did the galaxies at EoR have?

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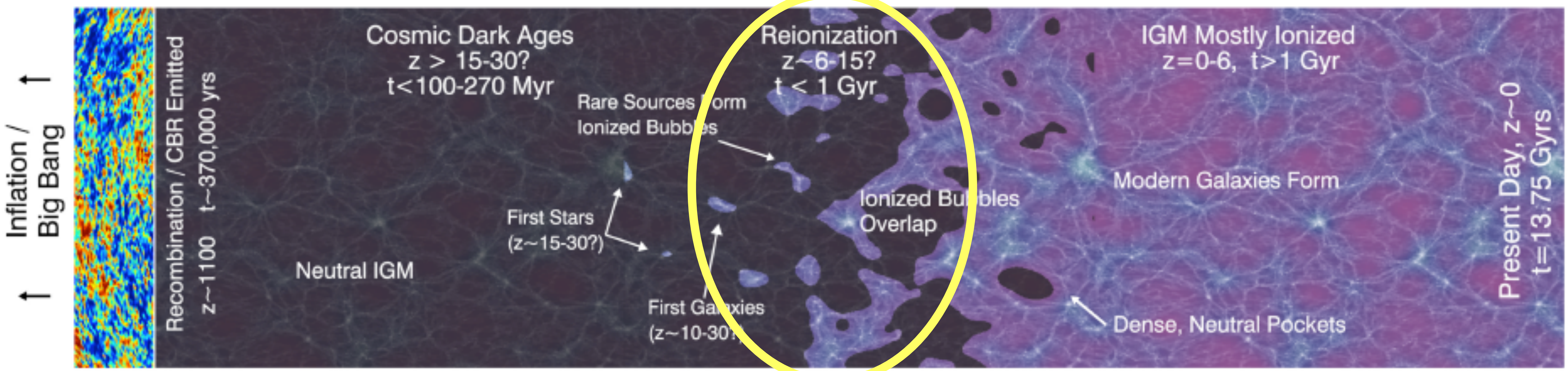

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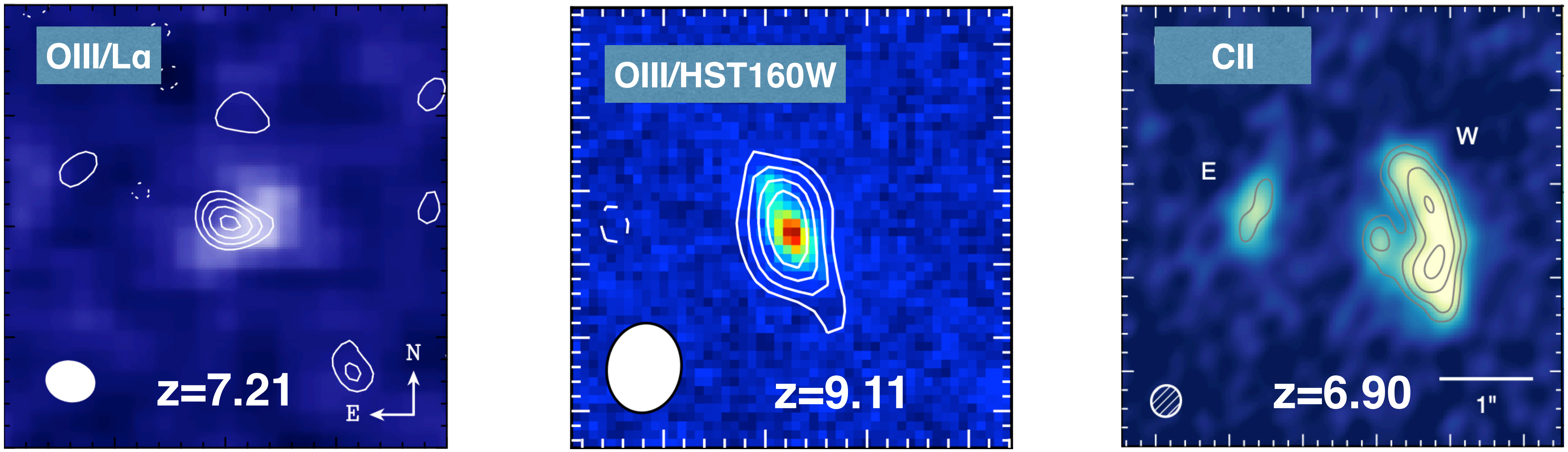
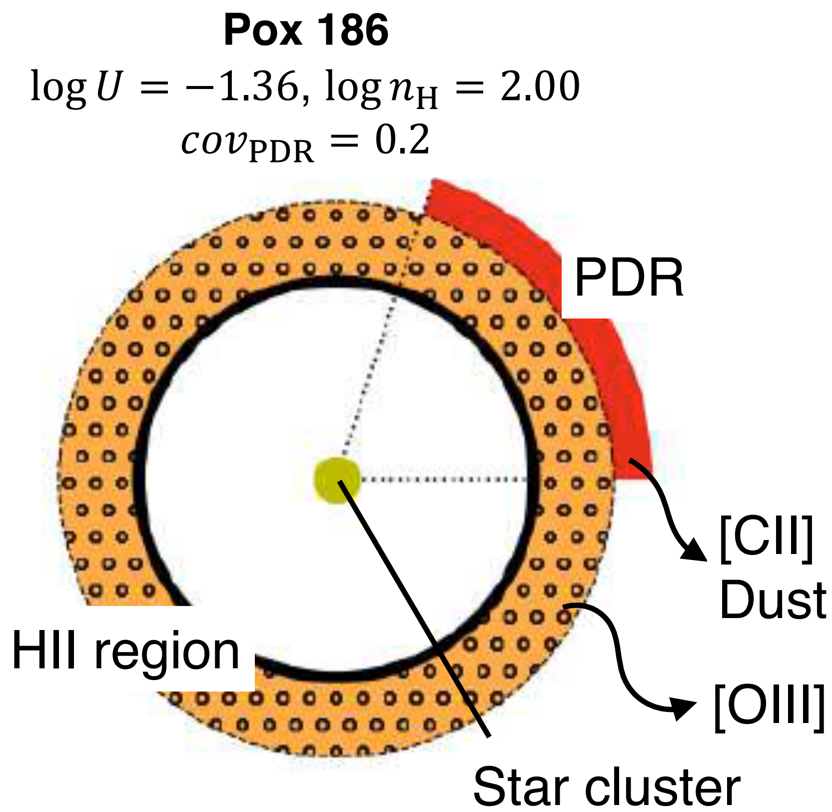
Introduction: Far-Infrared line emissions at EoR

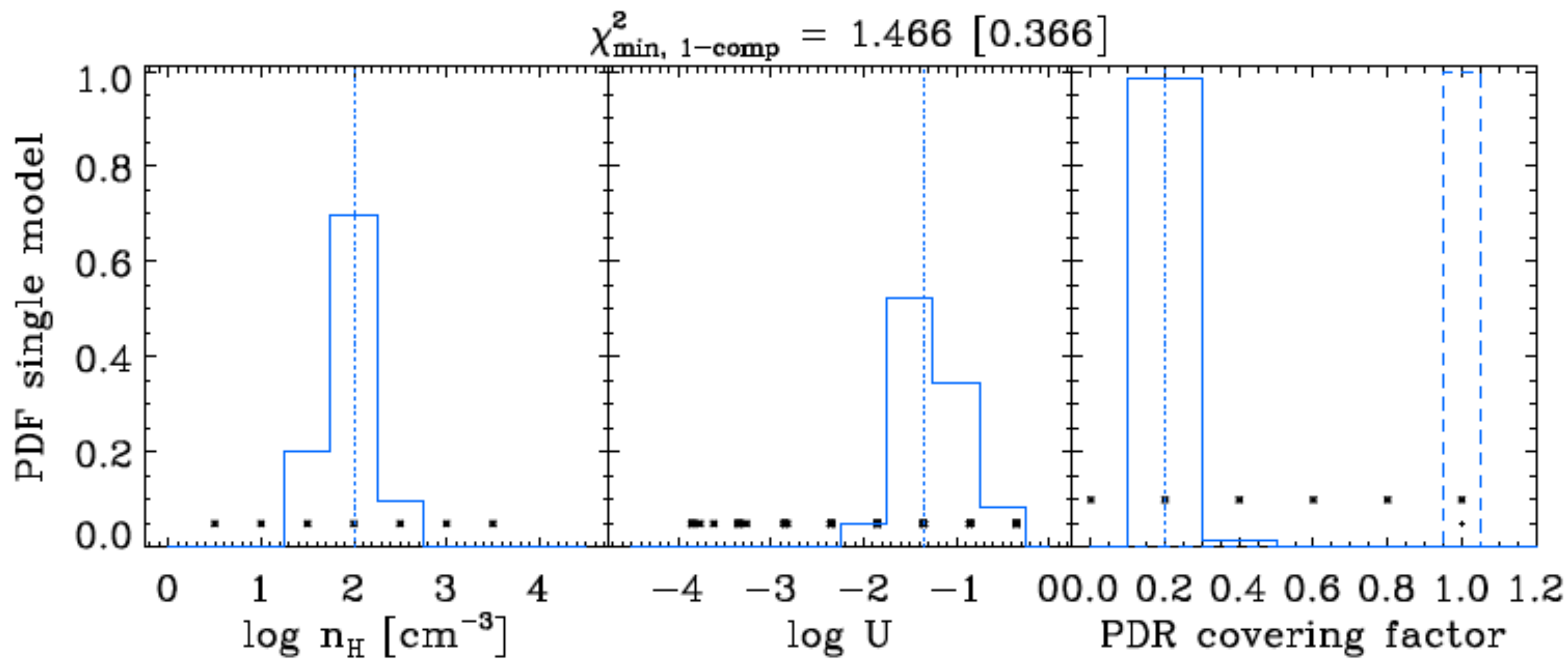


Inoue +2016 Hashimoto +2018 Marrone +2018

- Far-Infrared fine structure lines
    - Observable by ALMA at z > 6 (EoR) (e.g. : Inoue +2014)
    - The number of detections has been increasing
- Useful to understand the multi-phase structure of ISM
    - Various ionization potentials
      (O++: 35.1eV → HII region, C+: 11.3eV → PDR)

Introduction: multi-phase modeling in dwarf galaxies





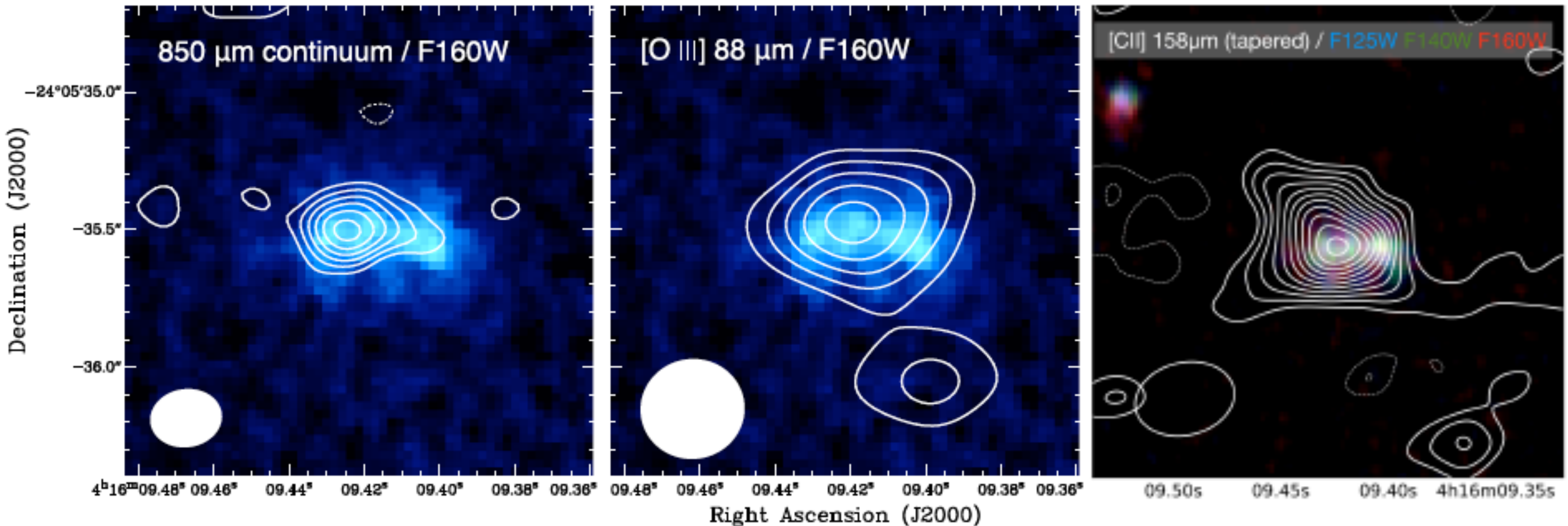
Cormier +2019 : the result of modeling in Pox186

- Cormier +2019: multi-phase modeling based on FIR lines and dust continuum using the spectral synthesis code, CLOUDY (Ferland +2017)
  - target: Herschel Dwarf Galaxy Survey (DGS) samples (Madden +2013)
    - $Z \sim 0.1 Z_\odot$, SFR $\sim 0.1\ \mathrm{M_\odot\ yr^{-1}}$
  - Free parameters:
    covering fraction($\mathrm{cov_{PDR}}$), ionization parameter (U), hydrogen density ($\mathrm{n_H\ [cm^{-3}]}$)
    ↪ the fraction of PDR covering HII region: indicator of “porosity”

Introduction: The goal of this work

- Problem
  - What is the ISM structure affected on the escape fraction of ionizing photons?
  - What are similarities and differences between the galaxies at EoR and nearby galaxies?
- Goal: to estimate the physical properties, especially “porosity” of the neutral gas, in the galaxy at EoR from FIR emission lines and dust continuum
  - Method: modified Cormier’s method
  - Target object: MACS0416_Y1
    - Observed [OIII] 88µm, [CII] 158µm, and dust continuum at 90µm in the rest-frame

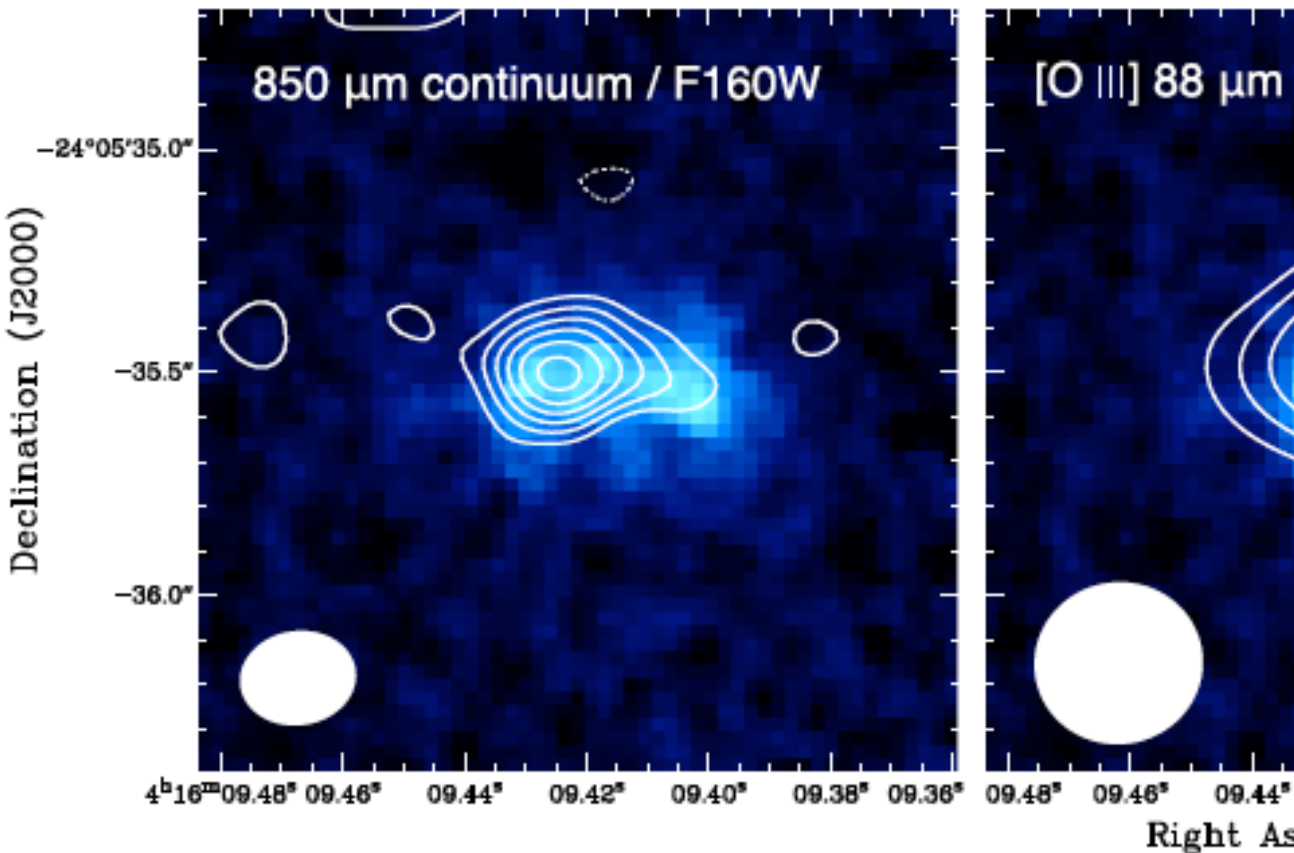
Target: MACS0416_Y1 at z=8.312



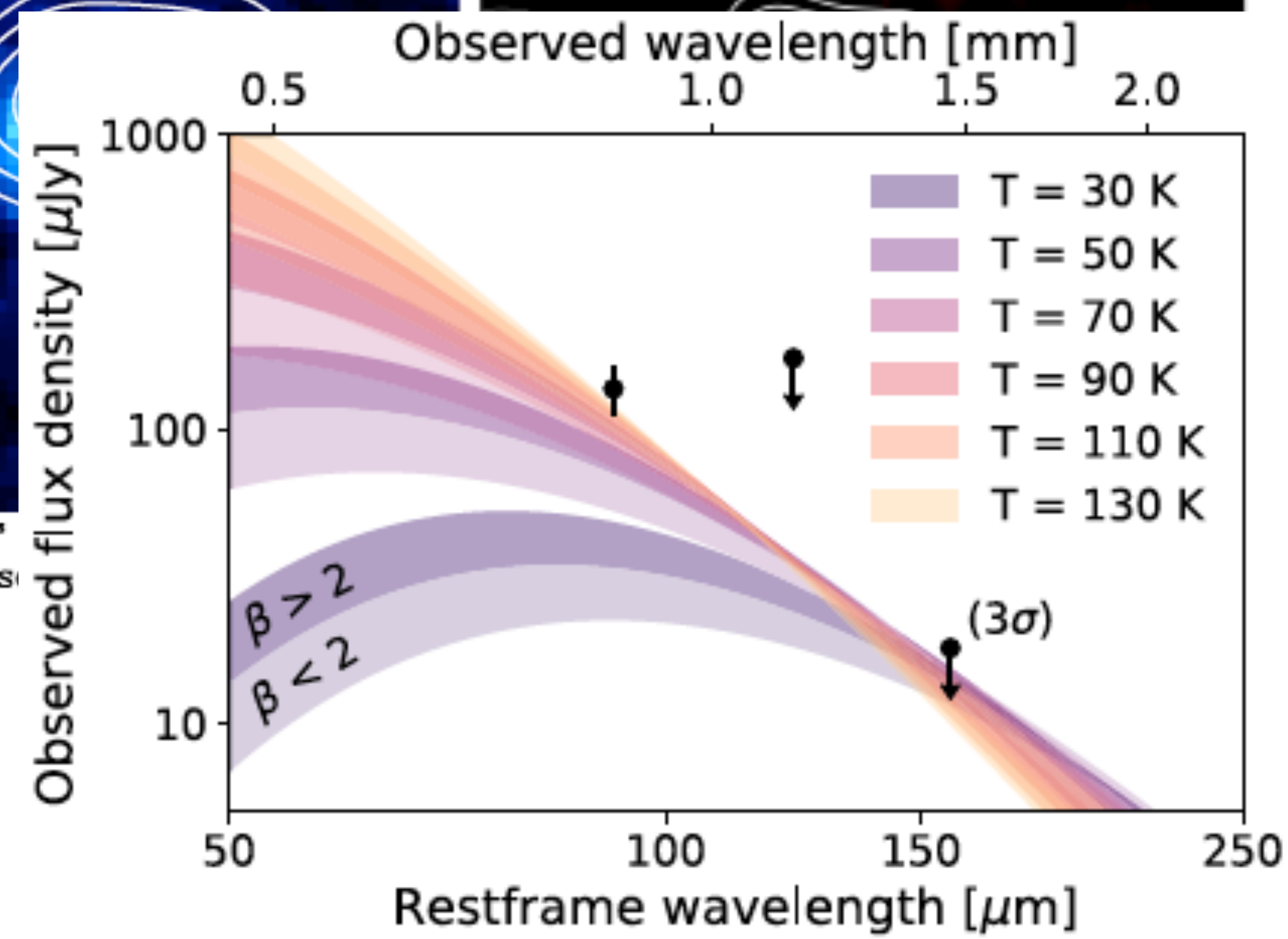
Tamura +2019 Bakx +2020

- ALMA observation result
  - [OIII] 88µm: $(1.2 \pm 0.3) \times 10^{9}\ \mathrm{L}_{\odot}$
  - [CII] 158µm: $(1.40 \pm 0.22) \times 10^{8}\ \mathrm{L}_{\odot}$
  - Dust continuum: $(11.1 \pm 2.0) \times 10^{11}\ \mathrm{L}_{\odot}\ \ (\mathrm{T}_{\mathrm{dust}} = 80\ \mathrm{K},\ \beta = 2.0)$
    - Only detected at 850µm → calculate a luminosity assuming a modified black body

Target: MACS0416_Y1 at z=8.312



Tamura +2019



Bakx +2020

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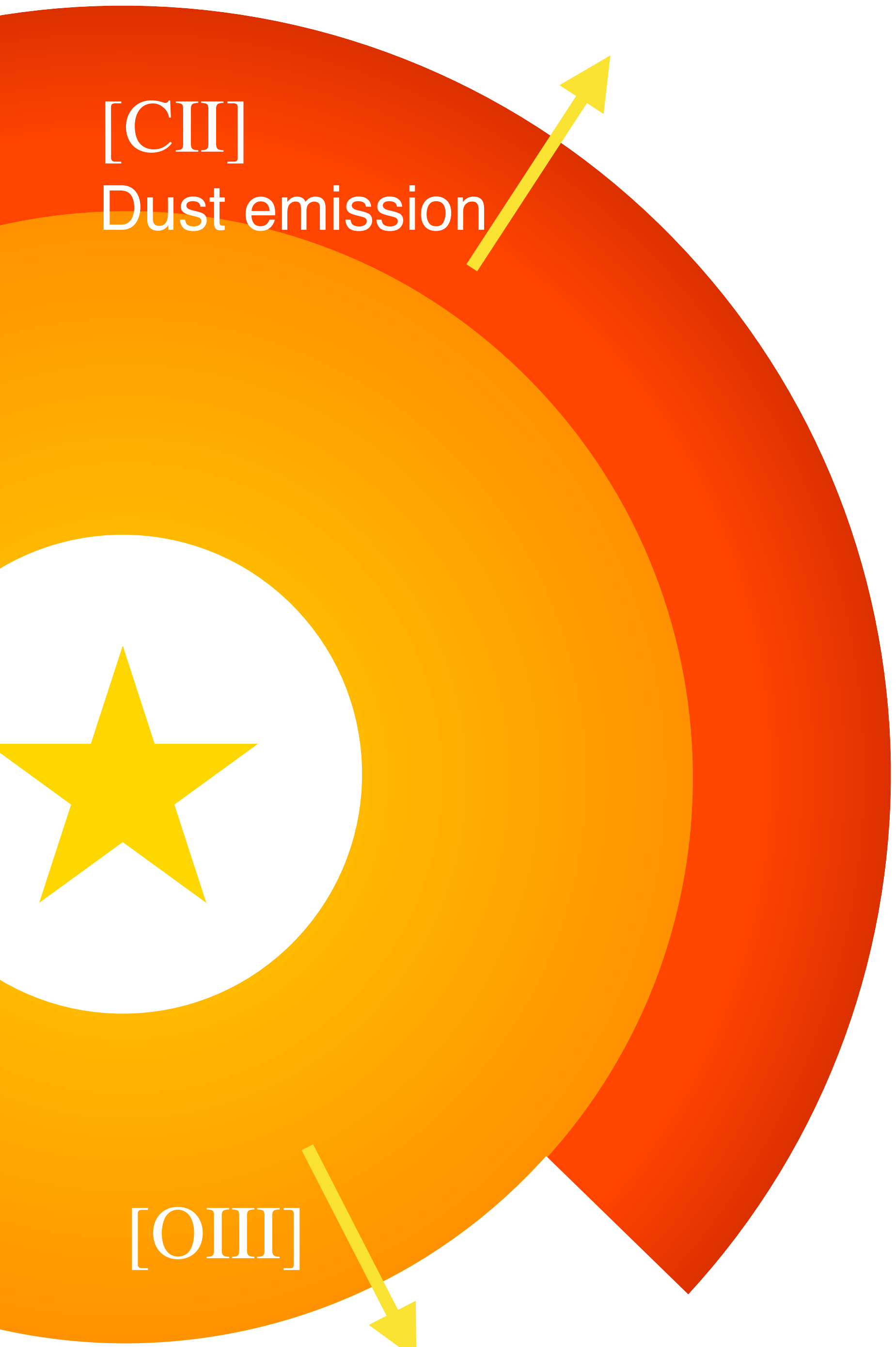
Method: geometry and model parameters



ISM structure assumed in this research

Fixed Parameters	
dominant radiation field	BPASS ver 2.1 (1) binary, age of star= $4\ \mathrm{Myr}$, $Z_{*} = 0.2Z_{\odot}$ (2)
Background radiation field	CMB radiation at z=8.312 (2) cosmic ray background (3)
Gas metallicity	$Z_{\mathrm{gas}} = 0.2Z_{\odot}$ (2)
Density transition law	$n_{\mathrm{H,PDR}} = n_{\mathrm{H,HII}} \times (1 + N(\mathrm{H})/10^{21}[\mathrm{cm}^{-2}])$ (4)
Stopping criterion of calculation	$\mathrm{H}^{+}/\mathrm{H}_{\mathrm{tot}} = 10^{-2}$ for HII region (5) $\mathrm{A_V} = 5\ \mathrm{mag}$ for PDR (4)

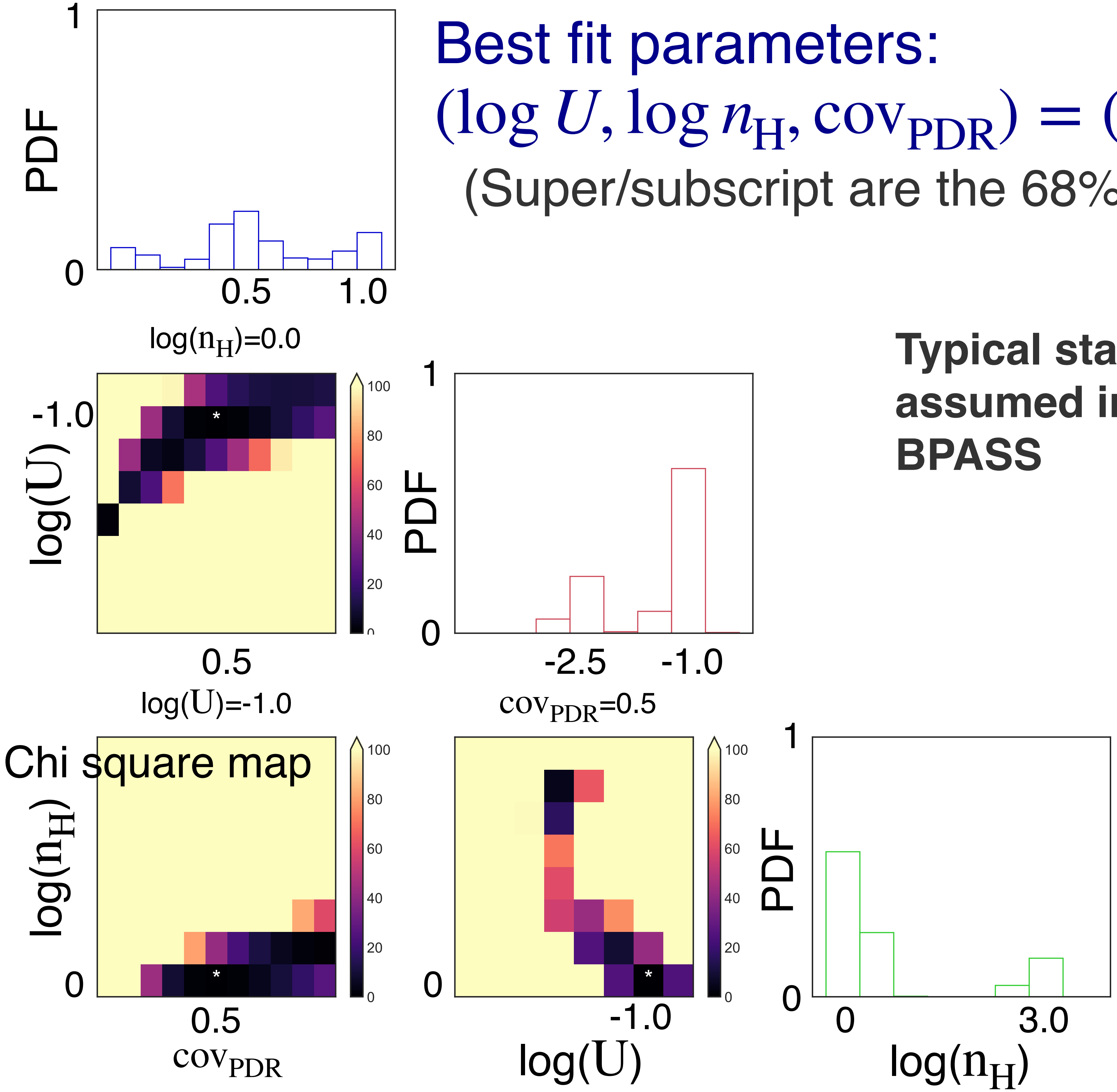
(1): Eldridge +2017, (2): Tamura +2019,
(3): Peebles +1971, Mather +1999, Wilkinson +1987
(4): Cormier +2019, (5): Abel +2005

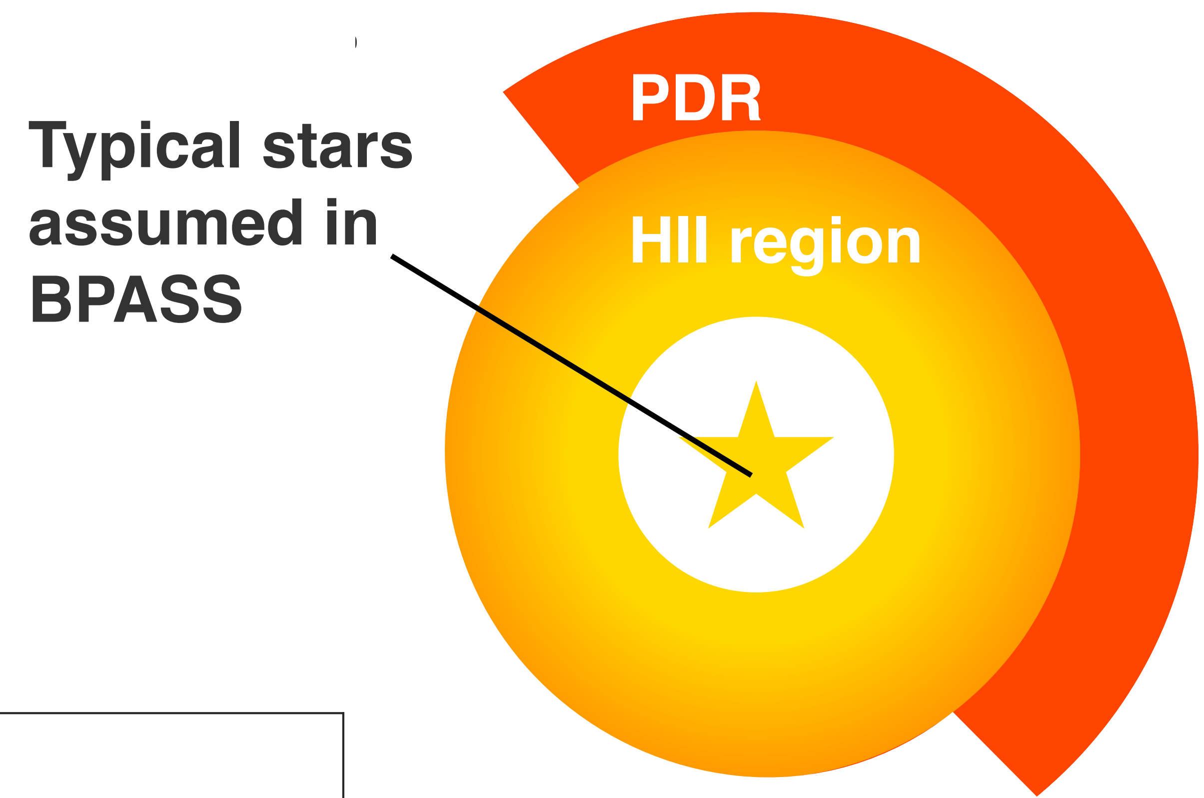
result: construction of multi-phase model

Best fit parameters:

$$(\log U, \log n_{\mathrm{H}}, \mathrm{cov_{PDR}}) = (-1.0^{-1.0}_{-2.5}, 0.0^{2.5}_{0.0}, 0.5^{0.9}_{0.3})$$

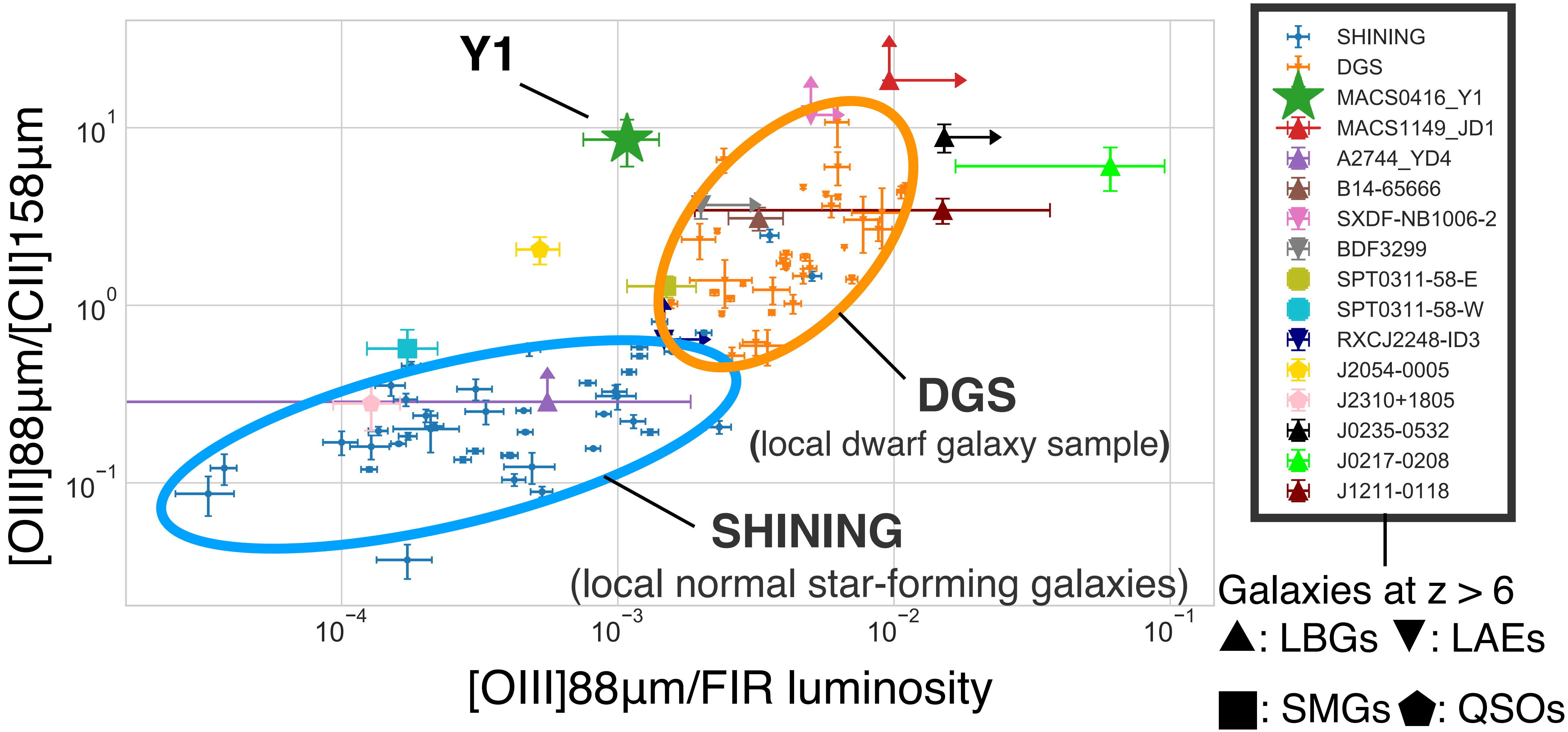
(Super/subscript are the 68% confidence interval)





U: high
Covering fraction: low
→ similar to dwarf galaxy samples?

discussion: compare with nearby galaxies



- Trend: positive correlation → [CII] luminosity ∝ FIR luminosity
- **Y1 is similar to Dwarf galaxies than normal star-forming galaxies**

Future works

- To further restrict the model parameters
  - Observe additional lines or dust continuum at various wavelengths
  - Compare to the latest hydrodynamic simulations
    - Limiting the range of possible parameters

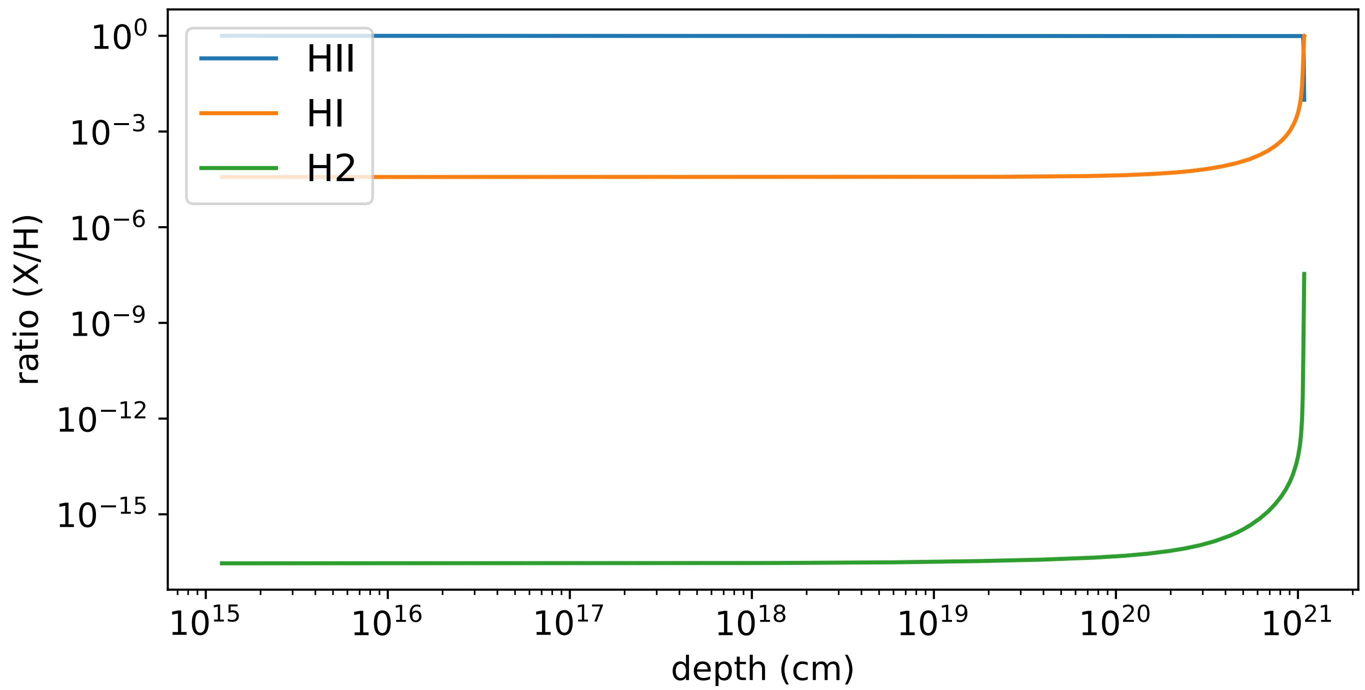
- Construct the multi-phase models for other high-z galaxies or local analogs
  - Do I find any trends among them ?

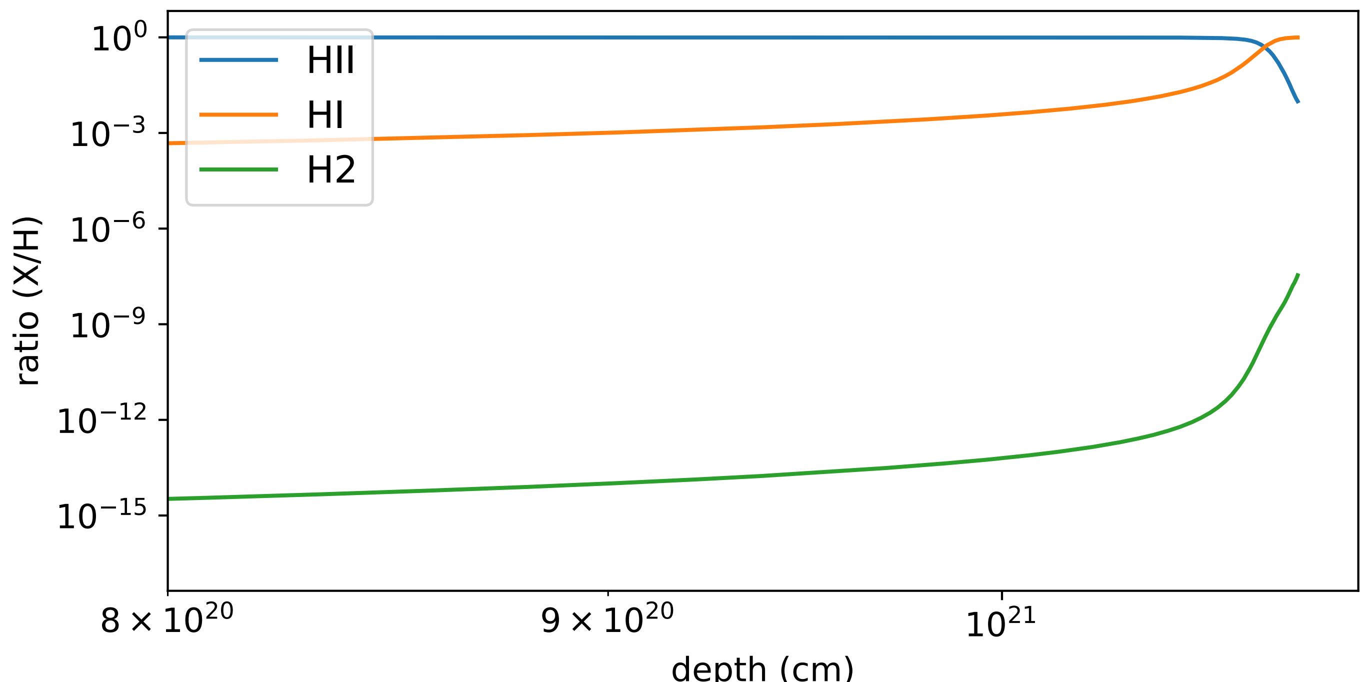
Summary

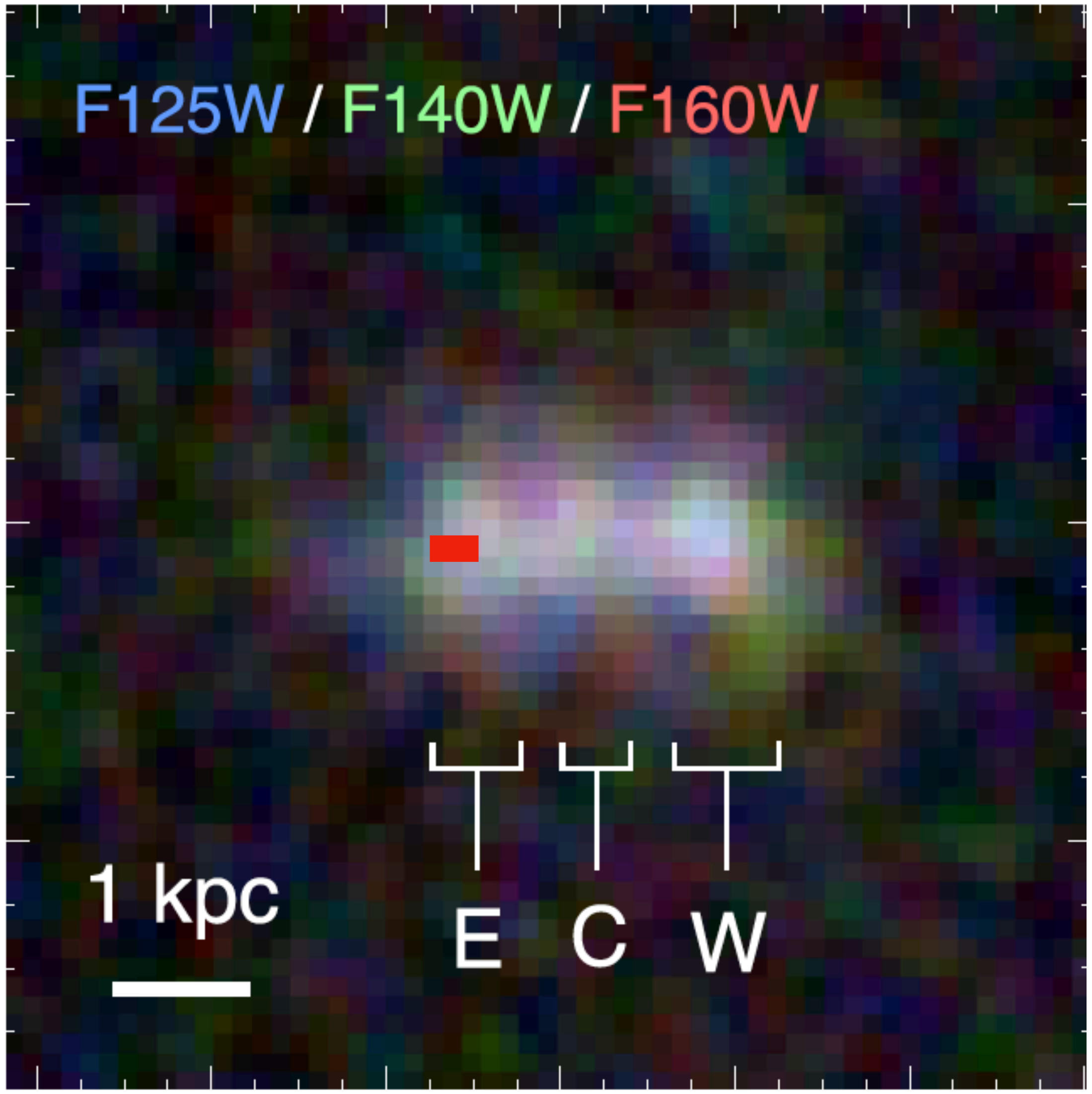
- I construct the multi phase model of ISM in a Lyman break galaxy at z=8.312 on the basis of [OIII] 88μm, [CII] 158μm, and dust continuum emissions using CLOUDY
  - Best fit parameters:
    $(\log U, \log n_{\mathrm{H}}, \mathrm{cov}_{\mathrm{PDR}}) = (-1.0^{-1.0}_{-2.5},\ 0.0^{2.5}_{0.0},\ 0.5^{0.9}_{0.3})$
  - This galaxy has strong ionization parameter and small covering fraction, i.e. big "porosity"
  - Perhaps, ionizing photons could escape into IGM easily
- I compare this galaxy to local dwarf galaxies and star-forming galaxies by plotting [OIII] / [CII] vs. [OIII] / FIR luminosity ratios
  - This galaxy is similar to local dwarfs especially which have high ionization parameter and big "porosity"

Appendix

Calculate range



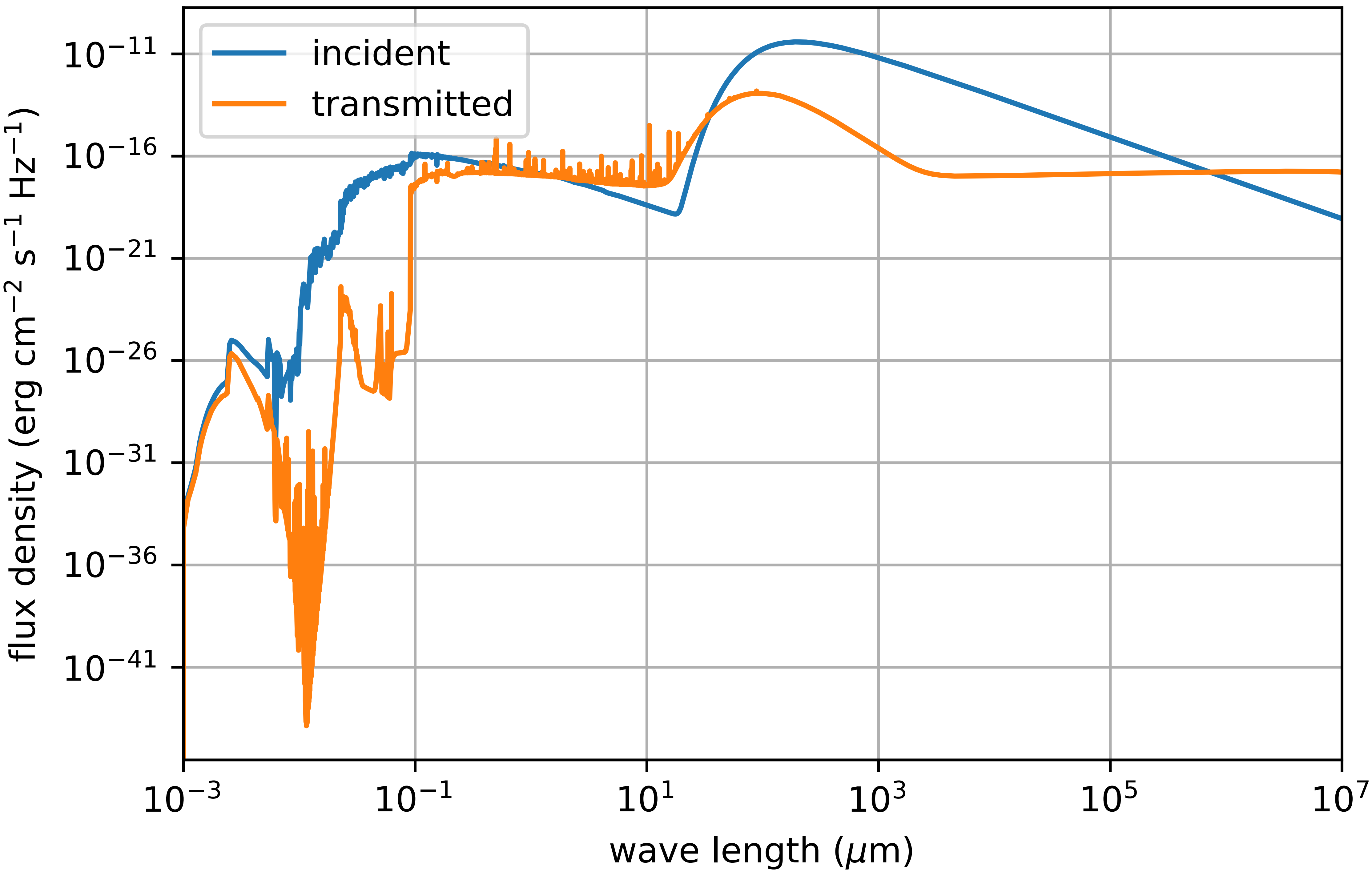




Tamura +2019

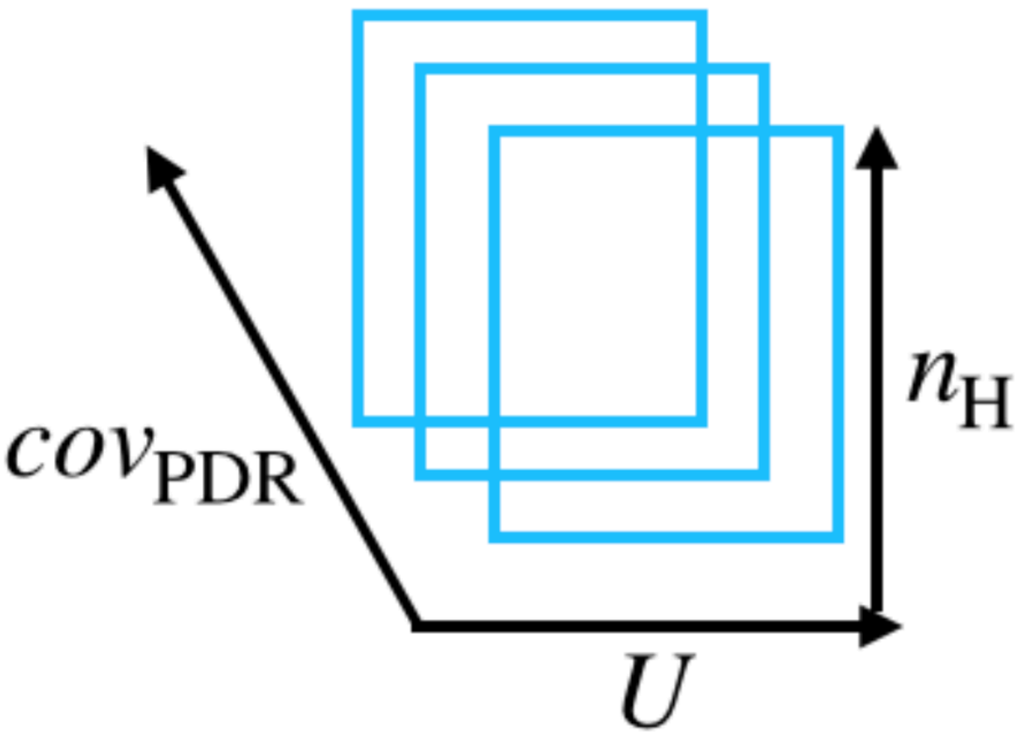
- 1.08×10^{21} cm → 300pc : red line in right figure

Total SED



incident
transmitted
flux density (erg cm^{-2} s^{-1} Hz^{-1})
10^{-11}
10^{-16}
10^{-21}
10^{-26}
10^{-31}
10^{-36}
10^{-41}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
wave length (μm)

Schematic view of parameter space



- Ionization parameter：

  $\log U = \{-4.0, -3.5, -3.0, -2.5, -2.0, -1.5, -1.0, -0.5\}$

- Hydrogen density：

  $\log \mathrm{n_H} = \{0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5\}$ $[\mathrm{cm}^{-3}]$

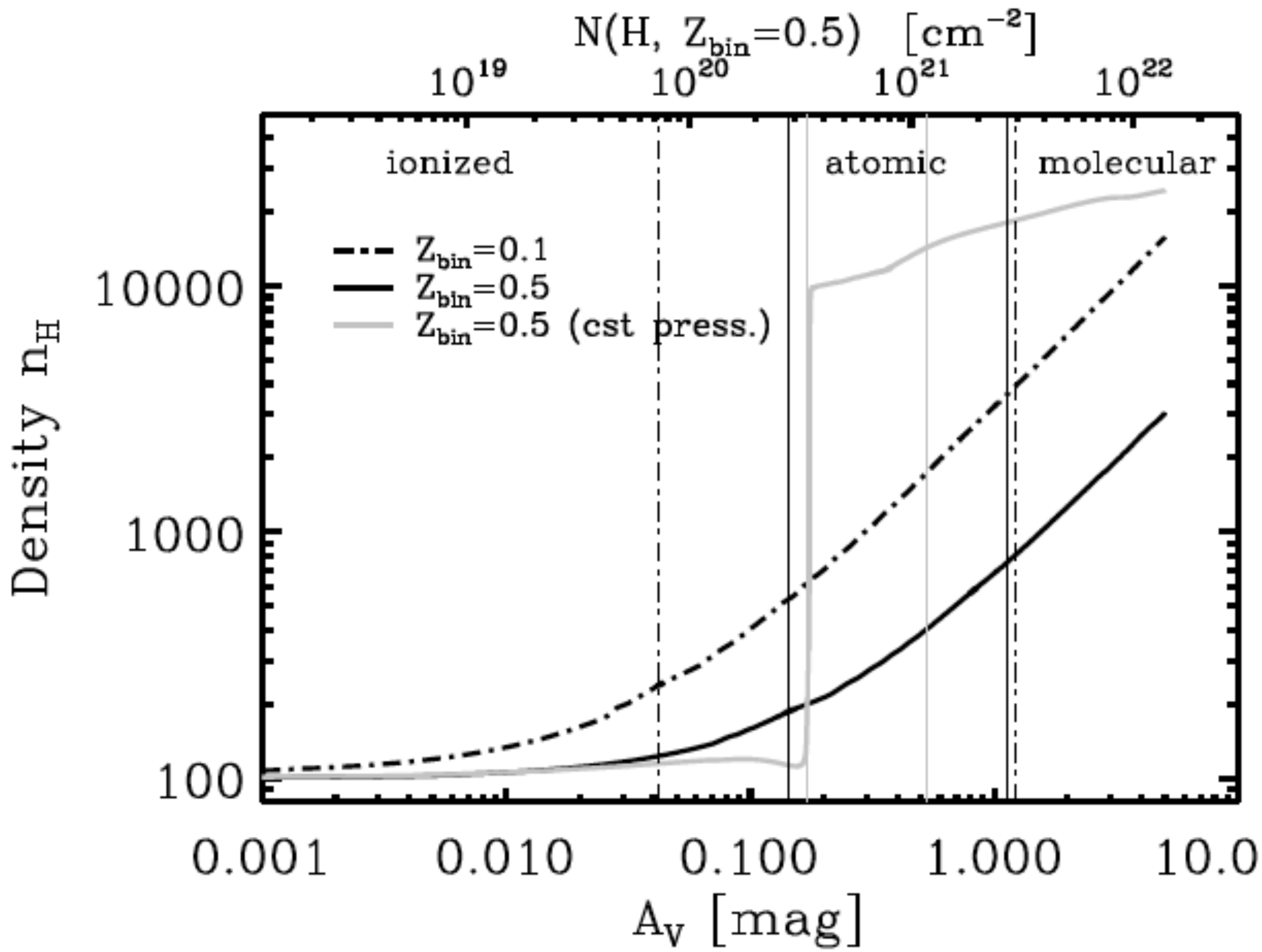
- Covering factor：

  $\mathrm{cov_{PDR}} = \{0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0\}$

The calculation of FIR luminosity

Object	Dust temperature	Emissivity Index β	FIR luminosity $L_{\odot}$	Reference
MACS1149_JD1	40 K	1.5	$< 0.77 \times 10^{10}$	Hashimoto +2018
A2744_YD4	50 K	2.0	$(12.6 \pm 5.5) \times 10^{10}$	Laporte +2017, 2019
B14-65666	54 K	1.75	$(10.5 \pm 2.0) \times 10^{11}$	Hashimoto +2019
SXDF-NB10006-2	50 K	1.5	$< 1.96 \times 10^{11}$	Inoue +2016, Bakx +2020
BDF-3299	50 K	1.5	$< 0.9 \times 10^{11}$	Carniani +2017, Bakx +2020
SPT0311-058E	50 K	1.5	$(4.6 \pm 1.2) \times 10^{12}$	Marrone +2017
SPT0311-058W	50 K	1.5	$(3.3 \pm 0.7) \times 10^{13}$	Marrone +2017
RXCJ2248-ID3	50 K	1.5	$< 6.1 \times 10^{11}$	Tamura& sunaga + in prep, Bakx +2020
J2054-0005	50 K	1.8	$(1.3 \pm 0.2) \times 10^{13}$	Hashimoto +2019
J2310+1805	37 K	2.2	$1.9^{+0.2}_{-0.1} \times 10^{13}$	Hashimoto +2019
J0235-0532	50 K	1.5	$< 2.5 \times 10^{11}$	Harikane +2020
J0217-0208	25 K	1.5	$1.4^{+2.5}_{-0.3} \times 10^{11}$	Harikane +2020
J1211-0118	38 K	1.5	$3.2^{+18.7}_{-1.7} \times 10^{11}$	Harikane +2020

Density transition law

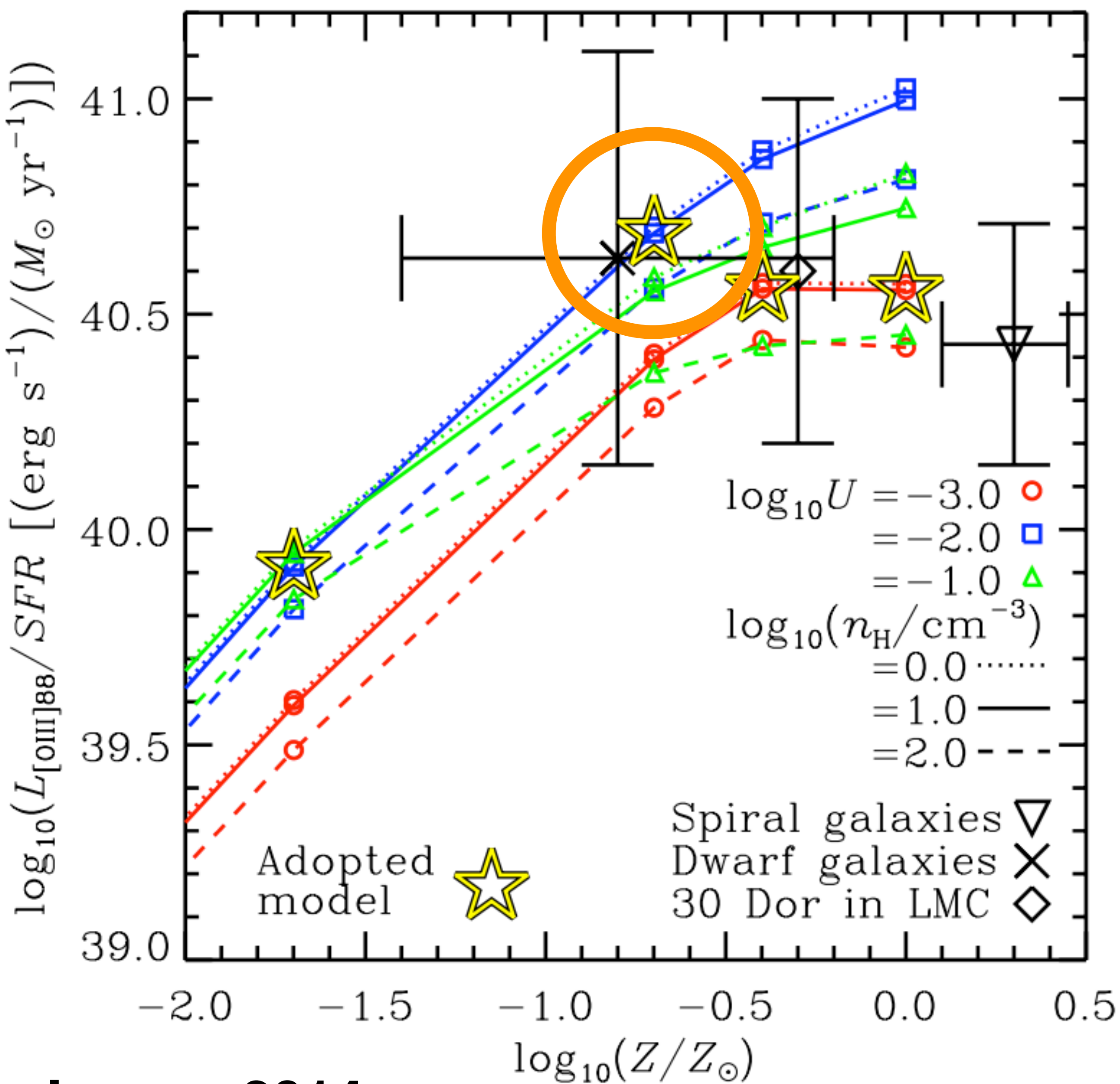


- The result of Cormier +2019 : assumed $n_H = 10^2\ [cm^{-3}]$

The definition of ionization parameter

- $$U = \frac{Q(\mathrm{H})}{4\pi r_o^2 n(\mathrm{H})\mathrm{c}} = \frac{\Phi(\mathrm{H})}{n(\mathrm{H})\mathrm{c}}$$
  - r_o : the distance from ionizing source to illuminated face (cm)
  - n(H) : hydrogen density(cm^{-3})
  - Q(H) : the number of ionizing photons radiated from source
  - $\Phi(H)$: the luminosity of ionization photon
- The value normalizing SED

The validity of the gas metallicity



Inoue +2014

- The star marked by circle :
  metallicity $= 0.2\ Z_\odot$
  → the similar to local dwarfs
- In this work,
  $Z_* = 0.2\ Z_\odot$
  → the star was born in the surrounding gas
  $\Rightarrow Z_{\mathrm{gas}} = 0.2\ Z_\odot$

Fixed and varied parameters in Cormier +2019

Fixed parameters	
Radiation field	Starburst99 continuous SF of 10 Myr,
	… Geneva stellar track, scaled to Z,
	… Kroupa IMF,
	… $\log(L/L_\odot) = 9$
	Blackbody $T = 5 \times 10^6$ K (X-ray),
	… $\log(L/L_\odot) = 5.2$
	Cosmic rays background 0.5 log
	CMB
	Table ISM
v_{turb}	$1.5\ \mathrm{km\,s^{-1}}$
D/G mass ratio	$(5 \times 10^{-3}) \times Z$
Metal, PAH abund.	Set to values below
Density law	$n_{H,\,PDR} = n_{H,\,HII} \times (1 + N(H)/[10^{21}\ \mathrm{cm^{-2}}])$
Stopping criterion	$A_V = 5$ mag

Varied parameters and grid values	
$\log n_H$	[0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5] $\mathrm{cm^{-3}}$
$\log U$	[−4, −3.5, −3, −2.5, −2, −1.5, −1, −0.5]
$\mathrm{cov_{PDR}}$	[0, 0.2, 0.4, 0.6, 0.8, 1]
Z_{bin}	[0.05, 0.10, 0.25, 0.50, 1.00]
… log O/H	[−4.80, −4.50, −4.10, −3.80, −3.50]
… log C/O	[−0.99, −0.87, −0.69, −0.56, −0.44]
… log N/O	[−1.60, −1.60, −1.60, −1.30, −1.00]
… log Ne/O	[−0.82, −0.79, −0.75, −0.73, −0.70]
… log S/O	[−1.70, −1.71, −1.72, −1.73, −1.74]
… log Si/O	[−2.00, −2.00, −2.00, −2.00, −2.00]
… log Ar/O	[−2.43, −2.42, −2.41, −2.39, −2.38]
… log Fe/O	[−1.37, −1.55, −1.79, −1.98, −2.16]
… log Cl/O	[−3.50, −3.47, −3.42, −3.38, −3.35]
… log PAH/H	[−9.51, −8.82, −7.90, −7.22, −6.52]

Chi square calculation

- $$\chi^2 = \sum_{i=1}^{n_{\rm lines}} \frac{(M_i - O_i)^2}{(\min\{M_i;\ O_i\} \times \sigma_i)^2}$$
    - M_i : modeled intensity
    - O_i : observed intensity
    - σ_i : fractional error on the observed flux (uncertainly / flux)
    - For non-detection with a 1σ upper limit : $\sigma_{\rm ul}$
        - $M_i \leq 3\sigma_{\rm ul} \rightarrow O_i$ set to M_i $(\chi^2 = 0)$
        - $M_i > 3\sigma_{\rm ul} \rightarrow O_i$ set to $3\sigma_{\rm ul}$ and σ_i set to 1

Typical values of DGS sample

- $-2.9 \leq \log U \leq -0.3$ → median value : $\log U = -2.4$
- $0.2 \leq \mathrm{cov}_{\mathrm{PDR}} \leq 1.0$ → median value : $\mathrm{cov}_{\mathrm{PDR}} = 0.4$
- $0.5 \leq \log \mathrm{n_H} \leq 3.0\ [\mathrm{cm^{-3}}]$ → median value : $\log \mathrm{n_H} = 2.0\ [\mathrm{cm^{-3}}]$
    - Medians are very close to the values found in Cormier +2015