Credit: NAOJ

How submillimeter facilities such as ALMA reveals early metal enrichment in the epoch of reionization

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SKA ワークショップ「銀河進化と遠方宇宙」

神奈川大学, 11-13 March 2019

Outline

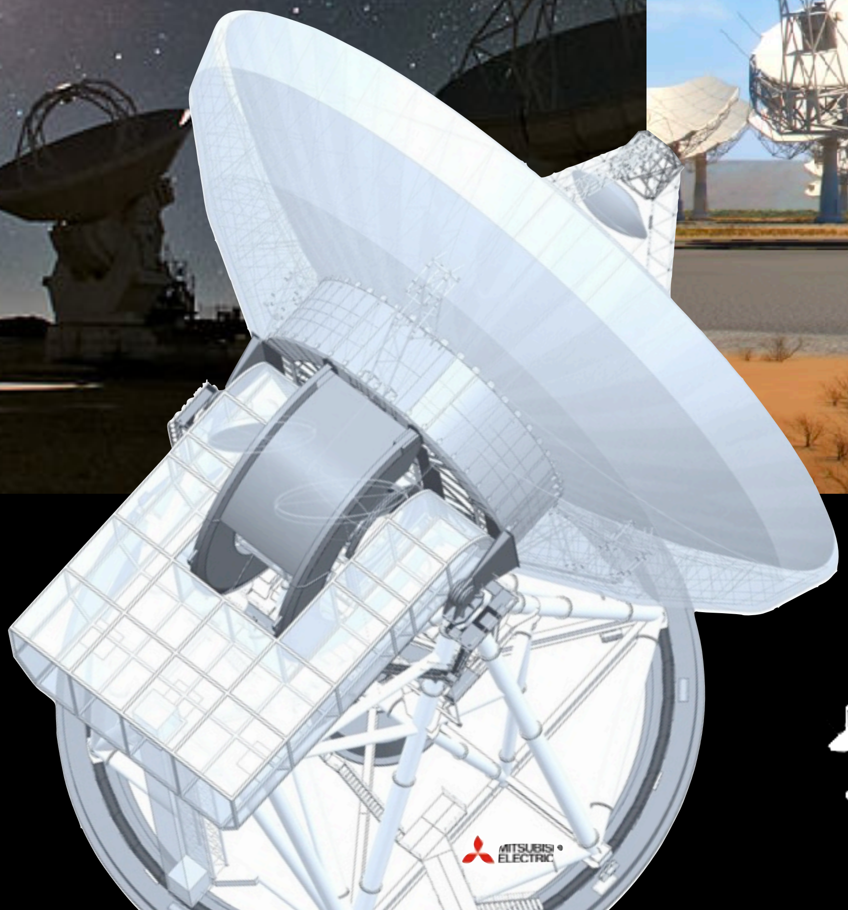
ALMA

- Exploring the `dirty' universe
- Well into the EoR
- Poor spatial dynamic range
- Poor instantaneous redshift coverage

www.almaobservatory.org

SKA

www.skatelescope.org



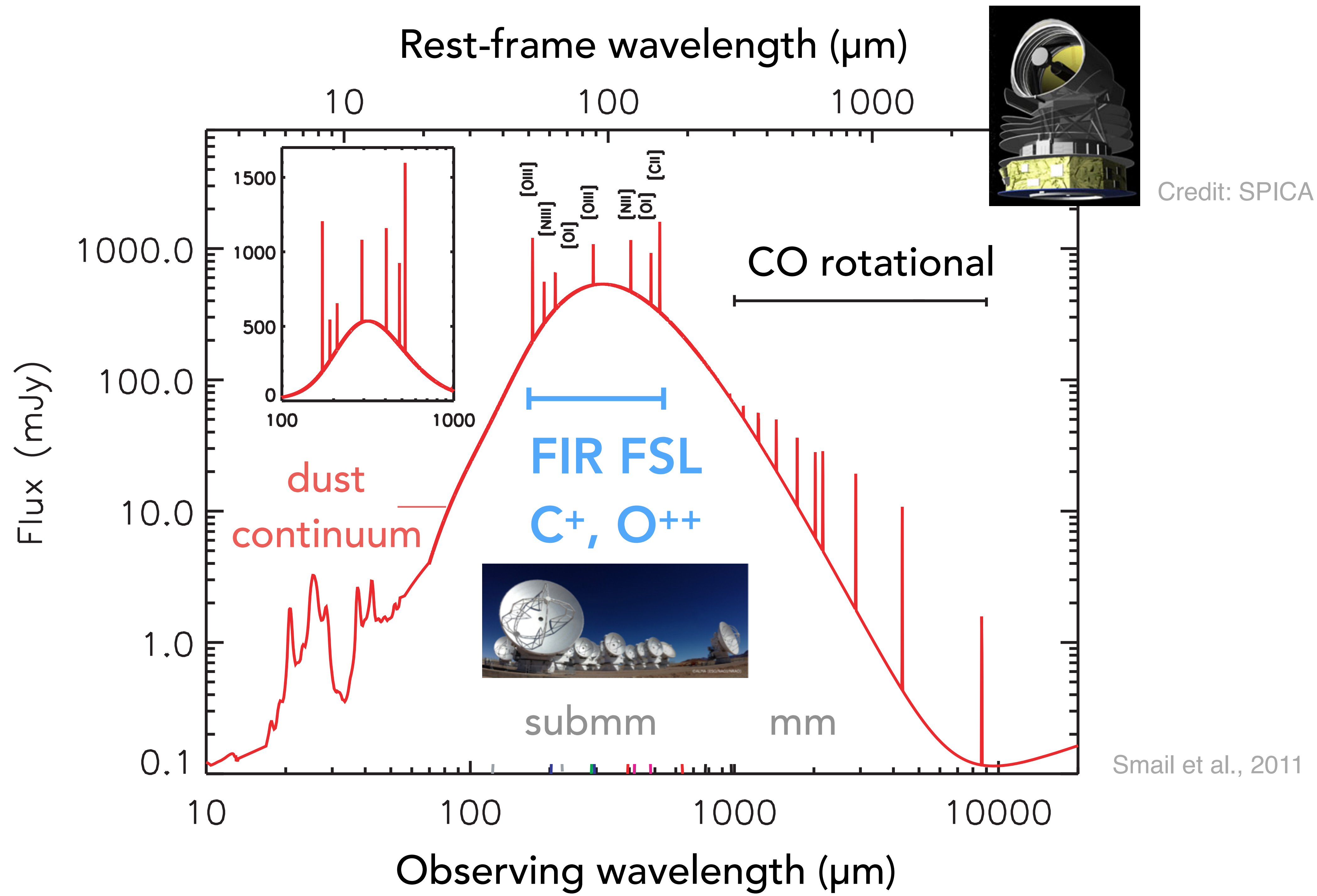
LST
Large Submillimeter Telescope

Outline

- Introduction
  - Submillimeter observations reveal "dirty" (!?) universe in the EoR
- Case study with ALMA (Tamura+)
  - Metal/dust enrichment in the EoR: [OIII] and dust in LBG at $z = 8.3$
- Future galaxy survey in the submillimeter
  - Simulation: Cross-correlation between 21cm vs. galaxies (Moriwaki+)
  - Technical challenge in submillimeter facilities
  - Large Submillimeter Telescope (LST) and synergy with SKA

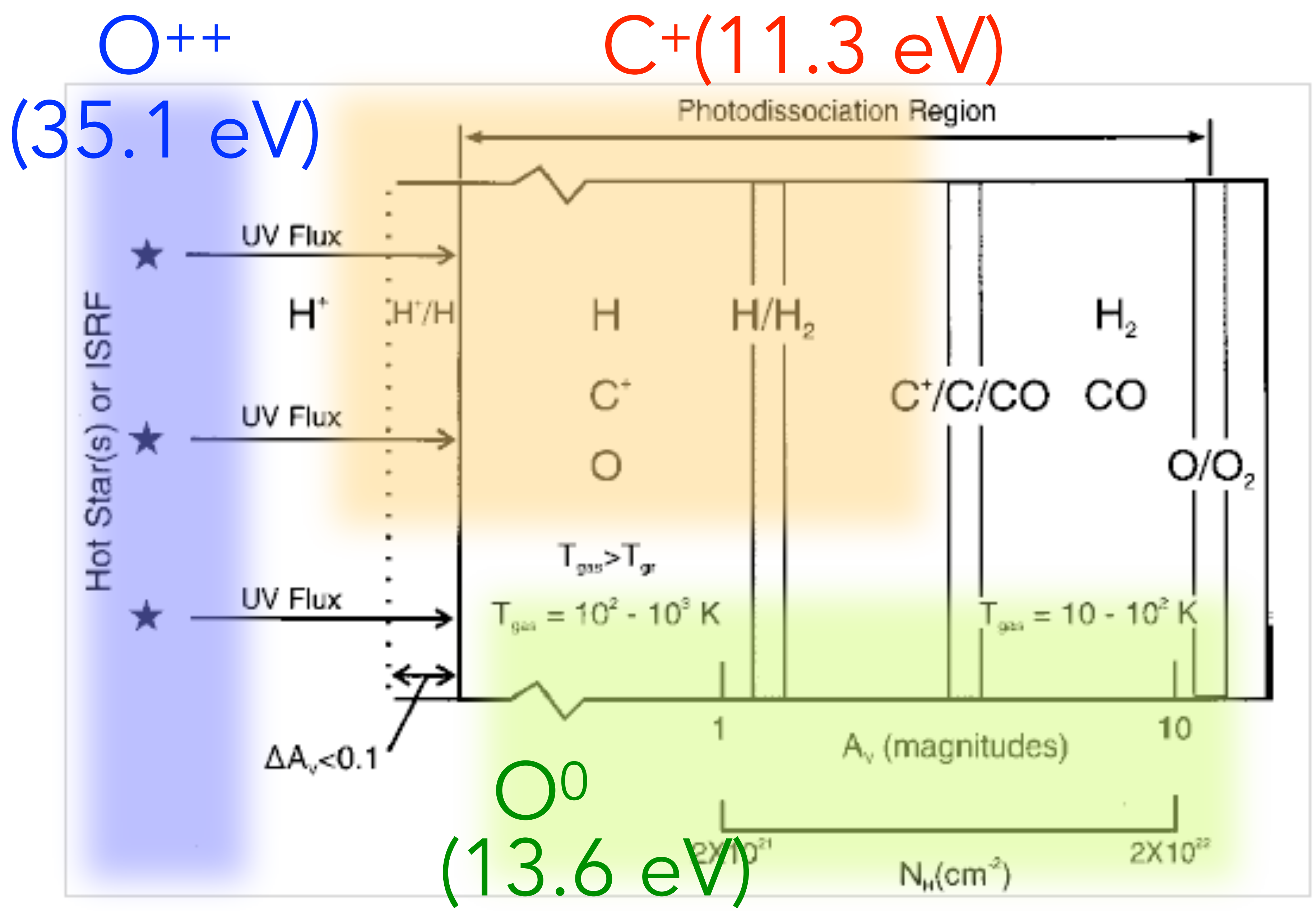
Introduction

Far-IR Emission as Important Coolant



Model spectrum of a lensed SMG at z = 2.5

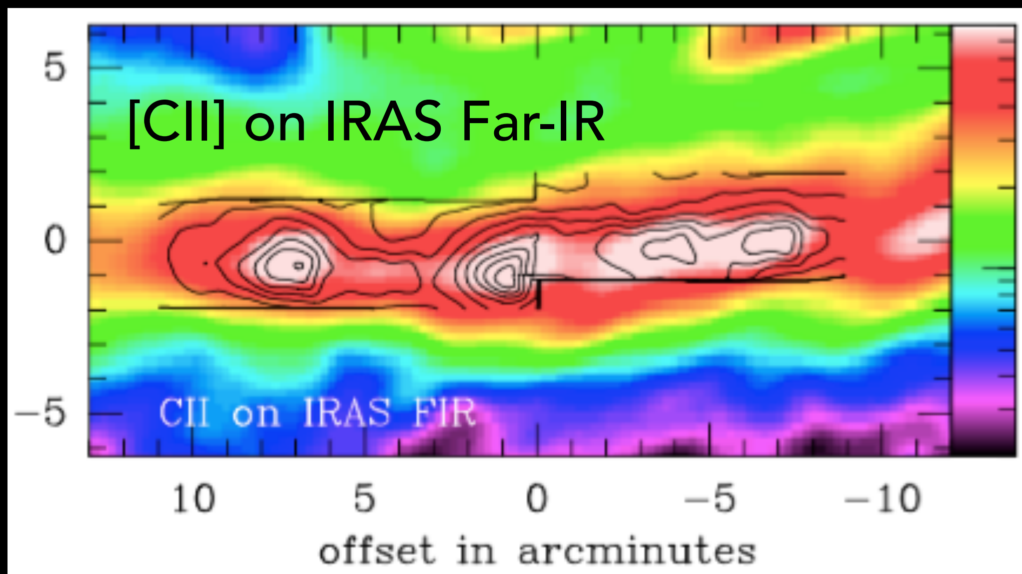
Properties of FIR Fine Structure Lines

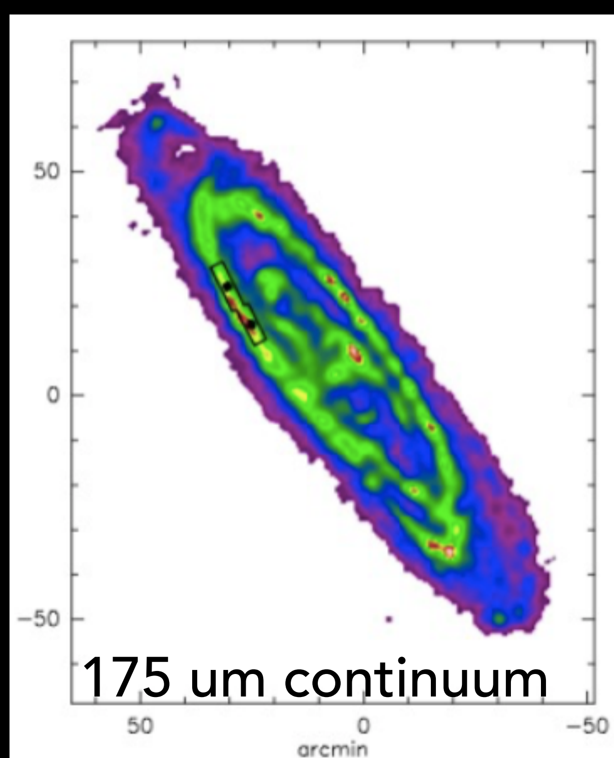


Tielens & Hollenbach 2005, Phys. Rev.

9

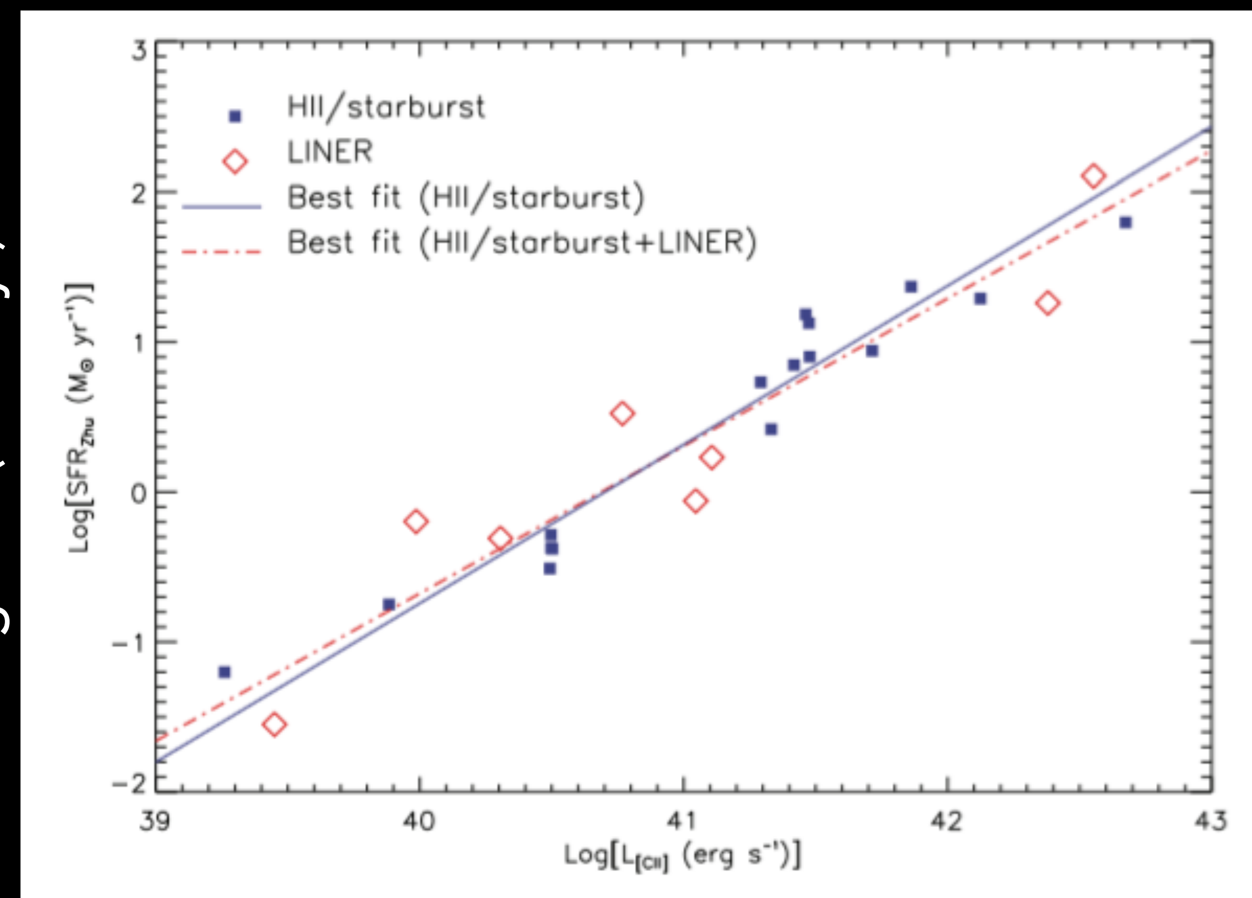
[C II] 158 μm: Star-formation indicator





ISO/LWS [CII] image of M31
(Rodriguez--Fernandez+2006)

log SFR (Msun/yr)

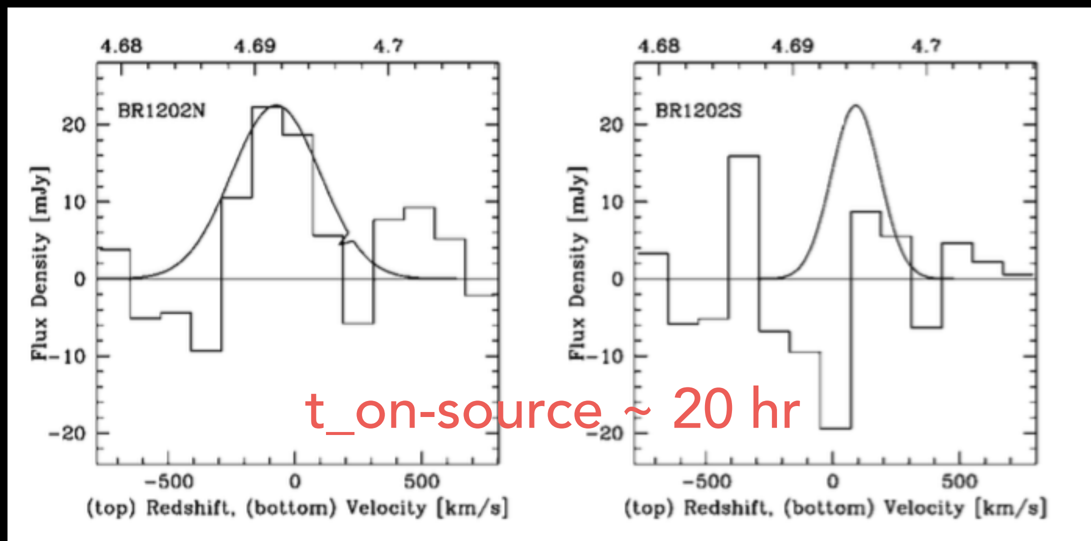


log L_[CII] (erg/s)

SFR — L_[CII] correlation (De Looze+2011)

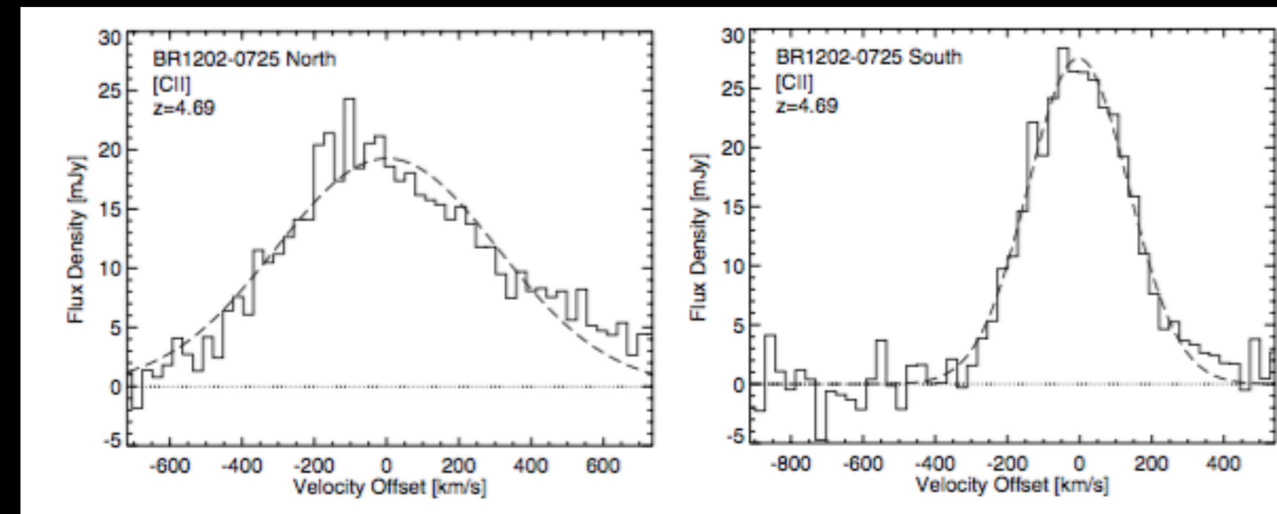
[C II] 158 μm: Important coolant

t_on-source ~ 25 min

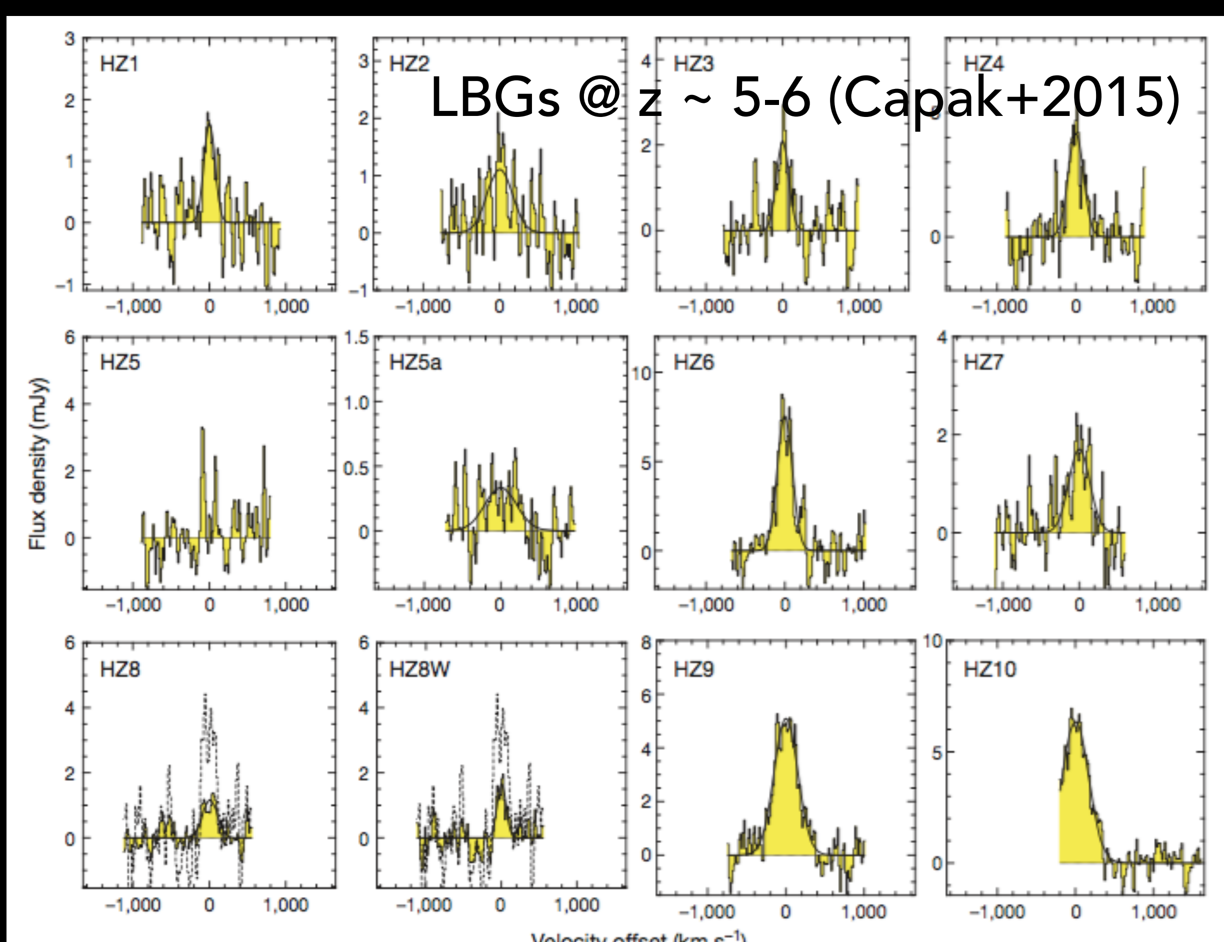


t_on-source ~ 20 hr

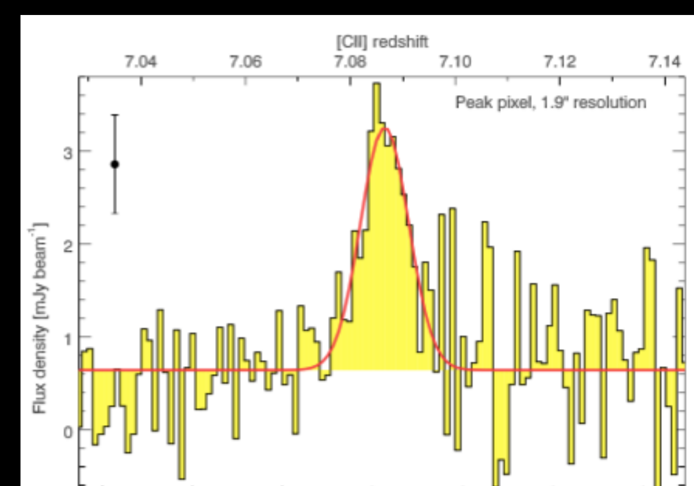
BR1202-0725 @ z = 4.7 (Iono+2006)



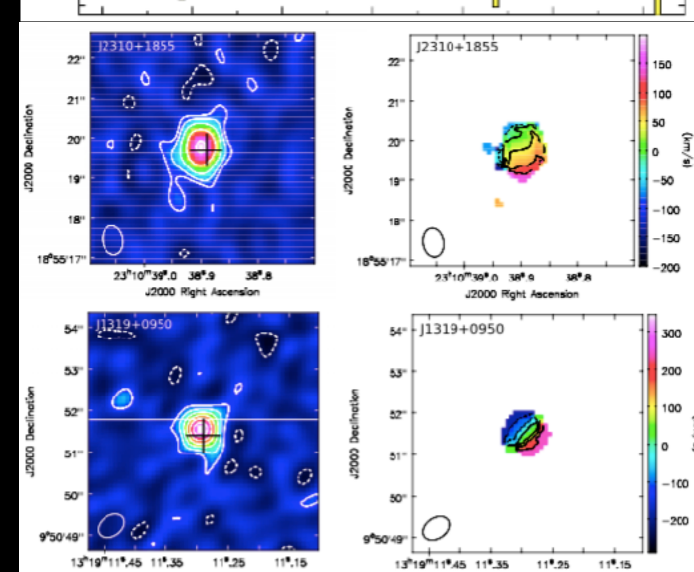
BR1202-0725 @ z = 4.7 (Wagg+2012)



LBGs @ z ~ 5-6 (Capak+2015)



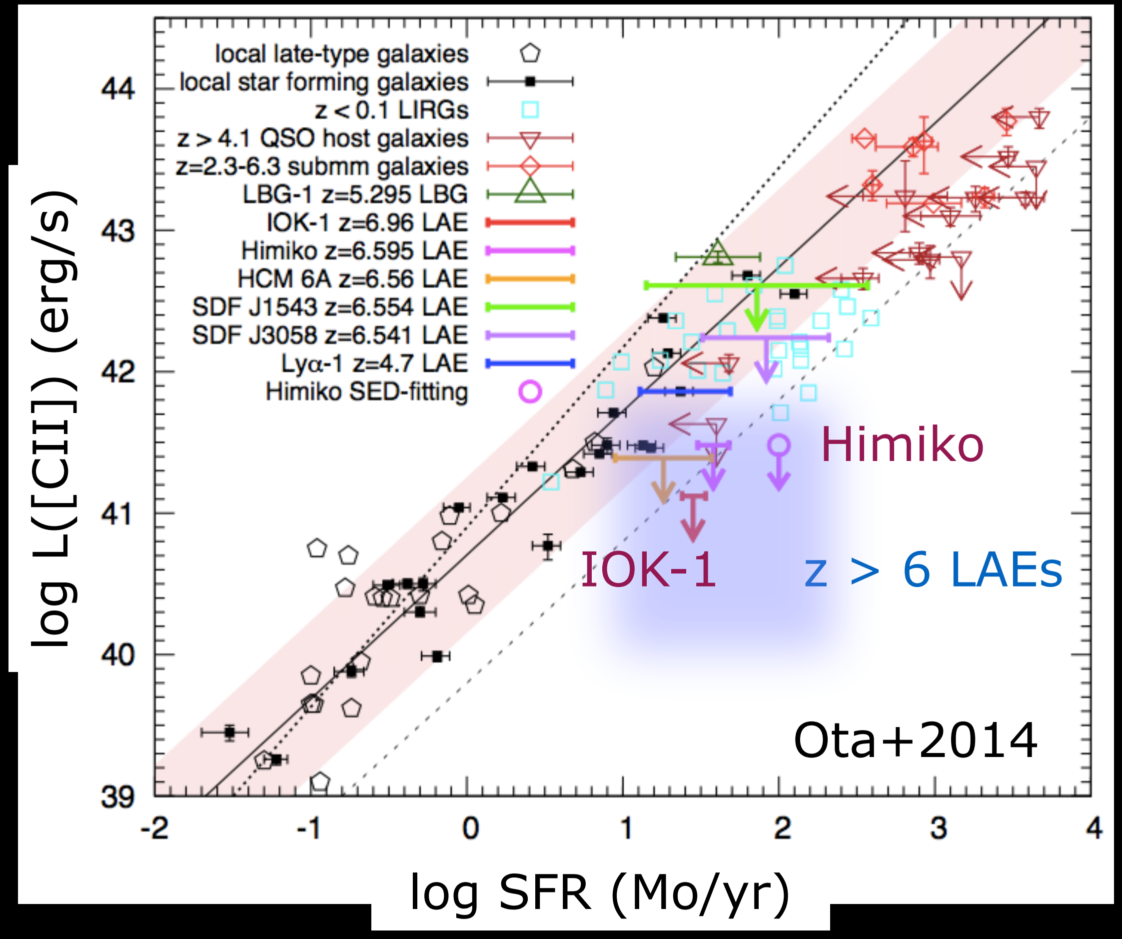
ULAS J1120 @ z = 7.1
(Venemans+2017)

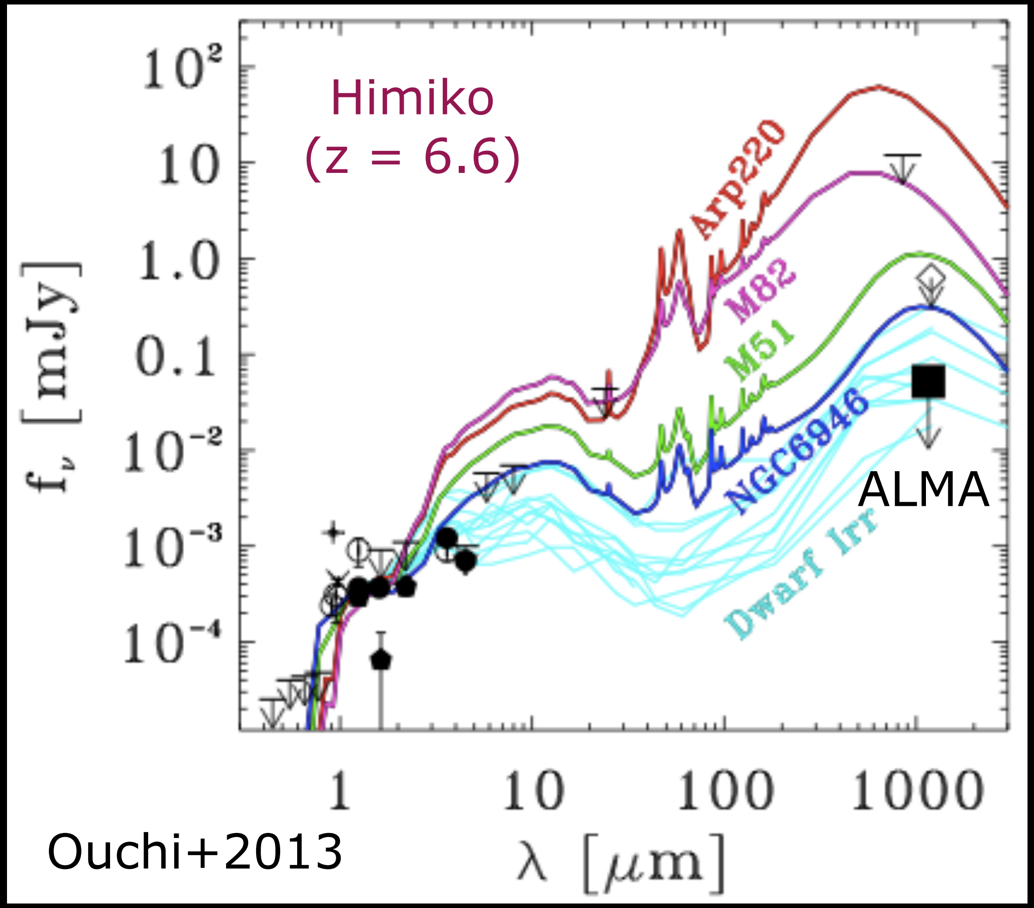


SDSS QSOs @ z ~ 6
(Wang+2013)

Suppressed C^+ and dust in young galaxies?

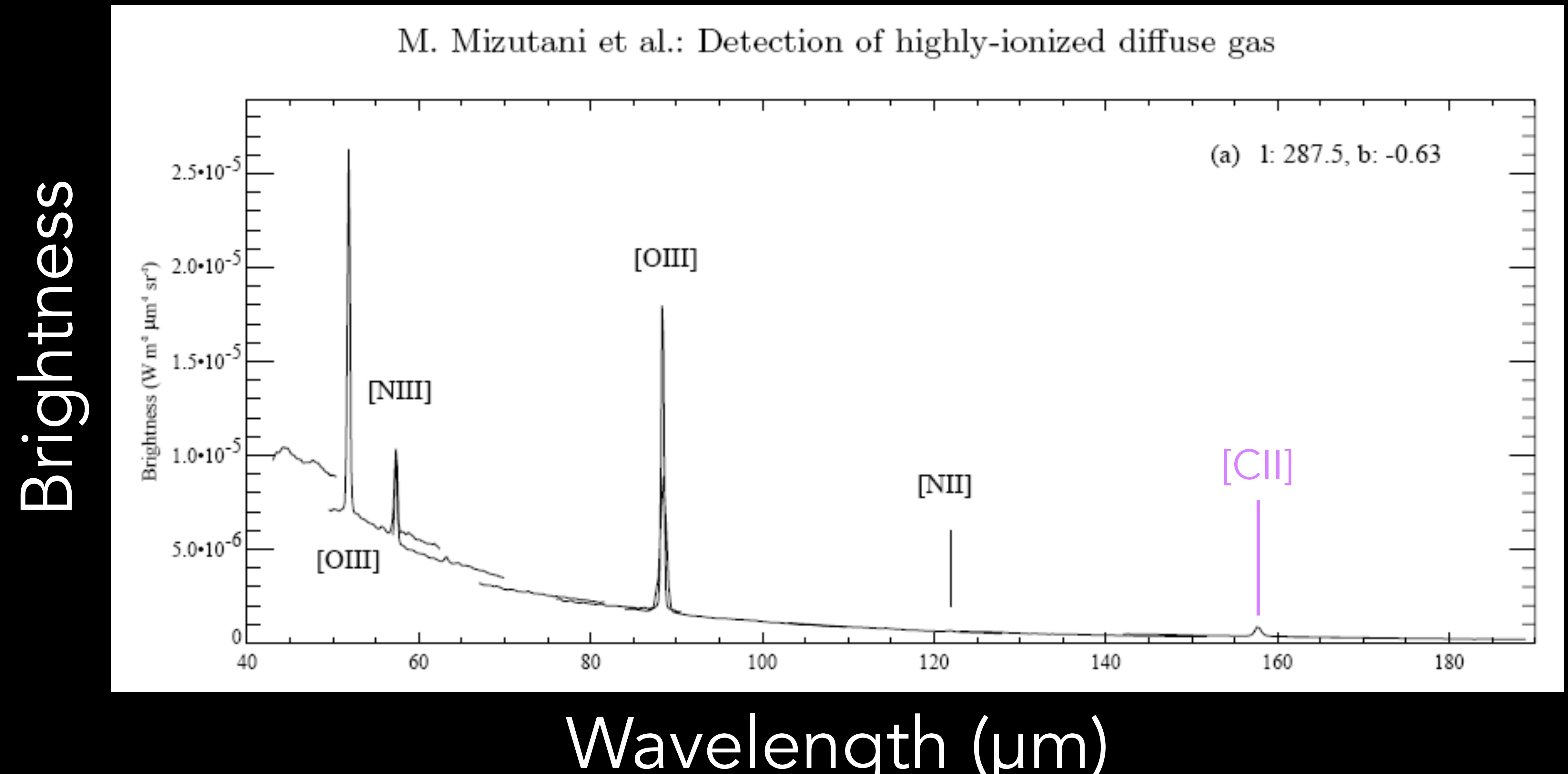
- Many ALMA non-detections of z > 6 LAEs/LBGs in [CII]158um and submm continuum have been reported.
  - Walter+2012, Kaneker+2012, Ouchi+2013, Ota+2014, Maiolino+2015, Inoue+2016
  - Something different from post EoR seems to happen…!





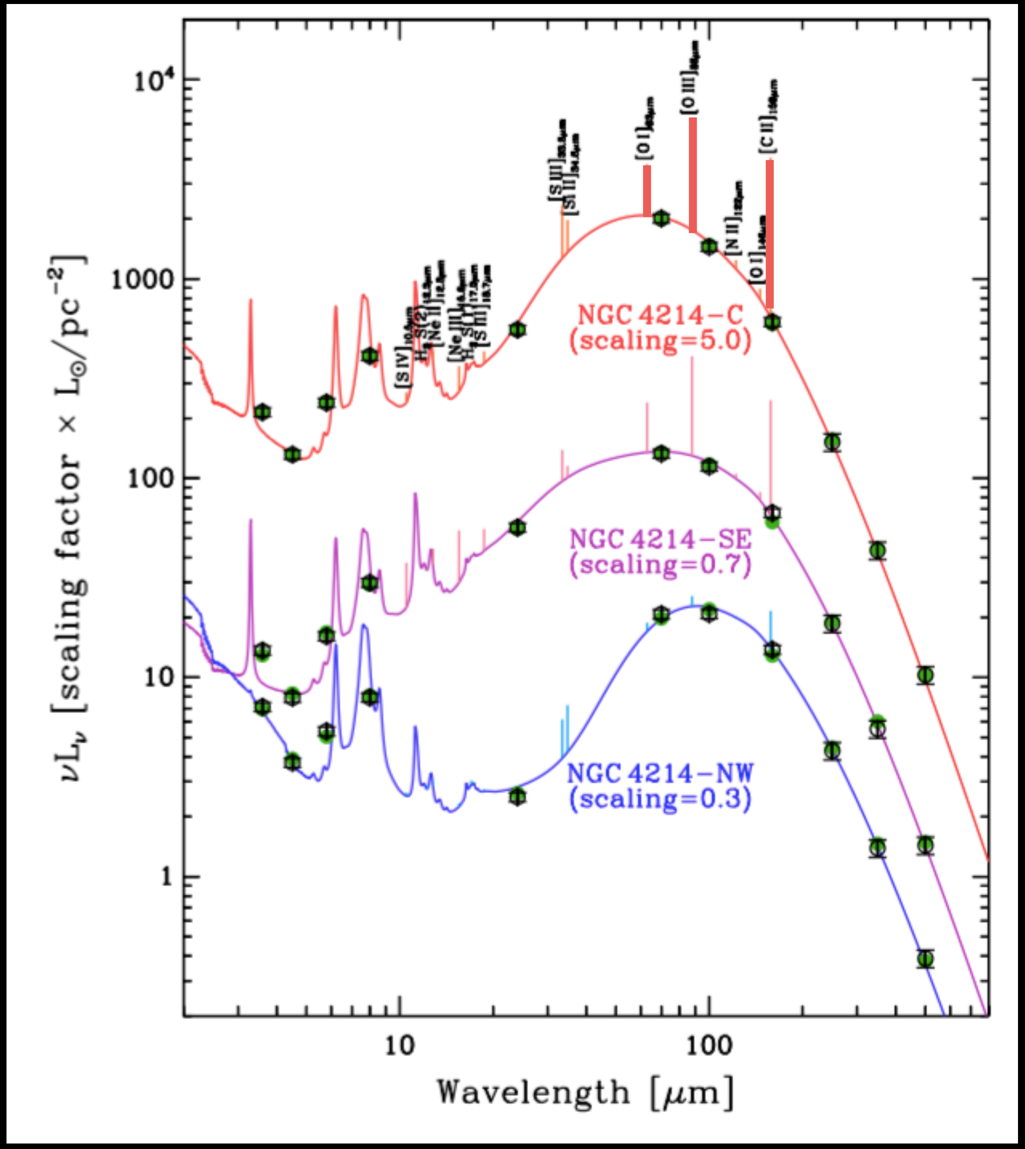
Strong [OIII] 88 um in a local HII region

- ISO LWS observations of eta Car (Mizutani, Onaka & Shibai 2002)

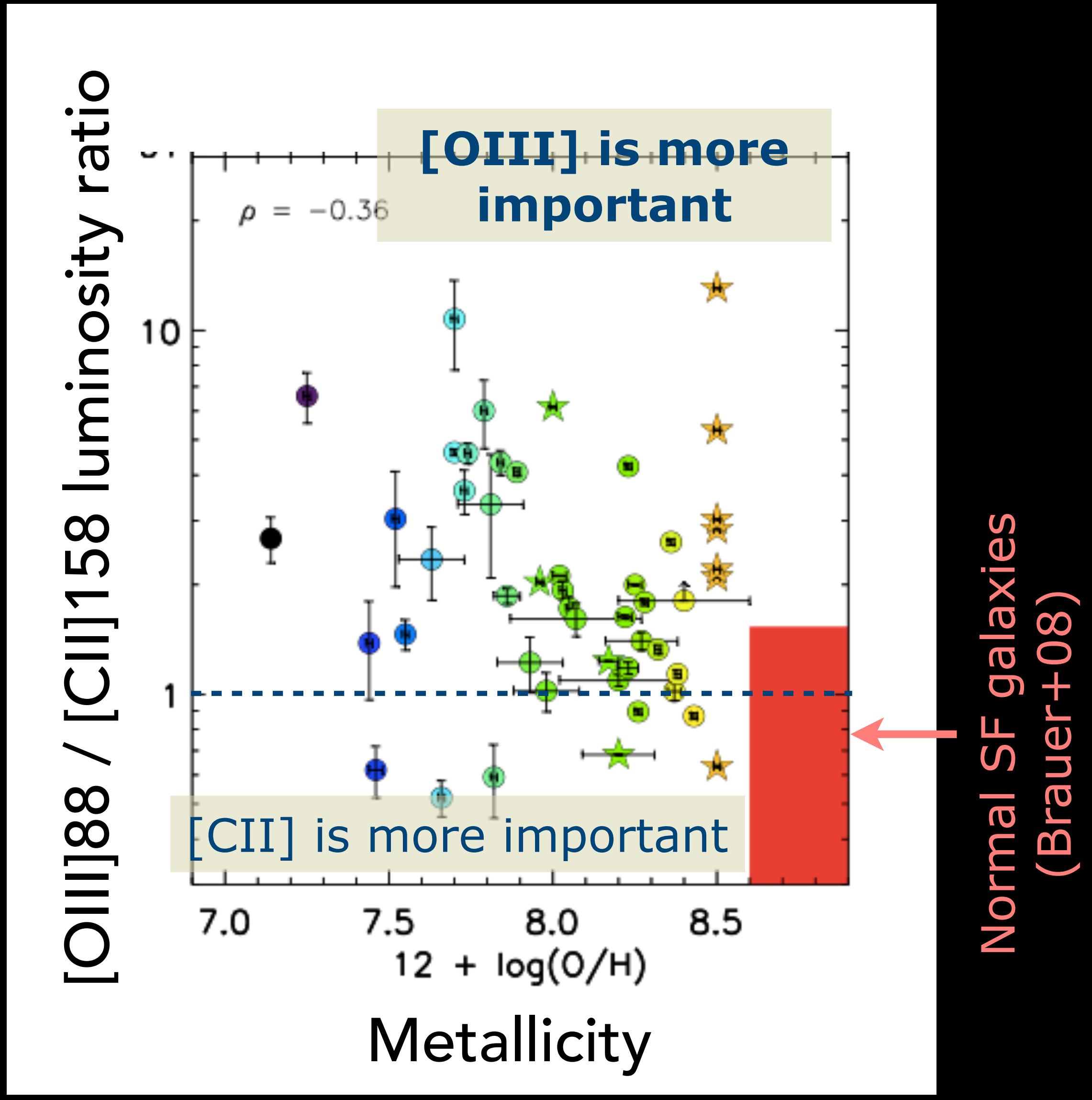


Herschel Dwarf Galaxy Survey (Madden+2013, Cormier+2015)

- Local dwarfs as low-z analogs of typical SF galaxies at high-z.
- [OIII]88 is the brightest
  - L_[OIII]88 / L_[CII]158 > 1 (up to ~10).



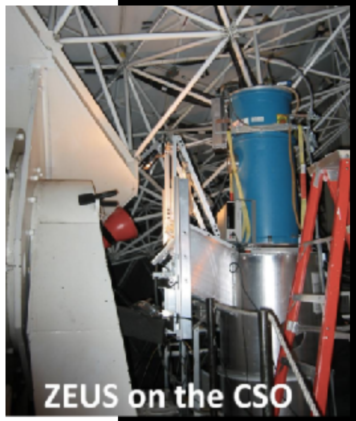
Madden+2013



Cormier+2015

High-z [OIII] 88um detections thus far

- Two ZEUS/CSO [OIII]88 detections (Ferkinhoff+2010)
  - detections in a z = 3.9 QSO and a z = 2.8 SMG
  - Only limited to lensed dusty sources



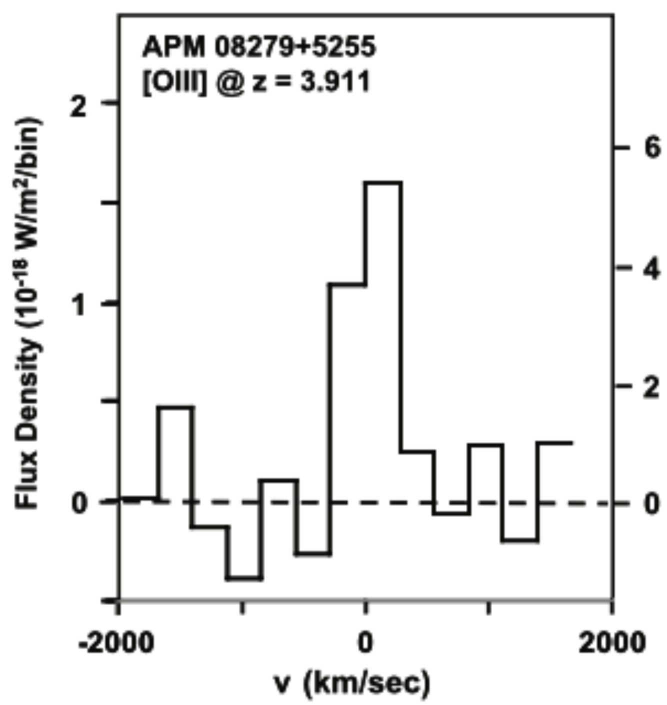


Figure 1. ZEUS/CSO detection of the [O III] 88 μm line from APM 08279+5255. Velocity is referenced to $z = 3.911$. The continuum emission has been subtracted off.

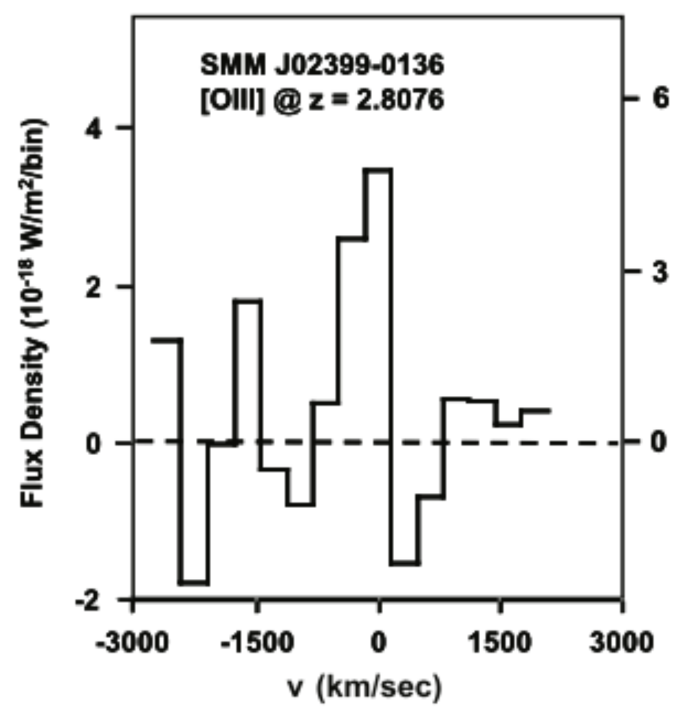


Figure 2. ZEUS/CSO detection of the [O III] 88 μm line from SMM J02399–0136. Velocity is referenced to $z = 2.8076$. The continuum emission has been subtracted off.

Ferkinhoff+2010

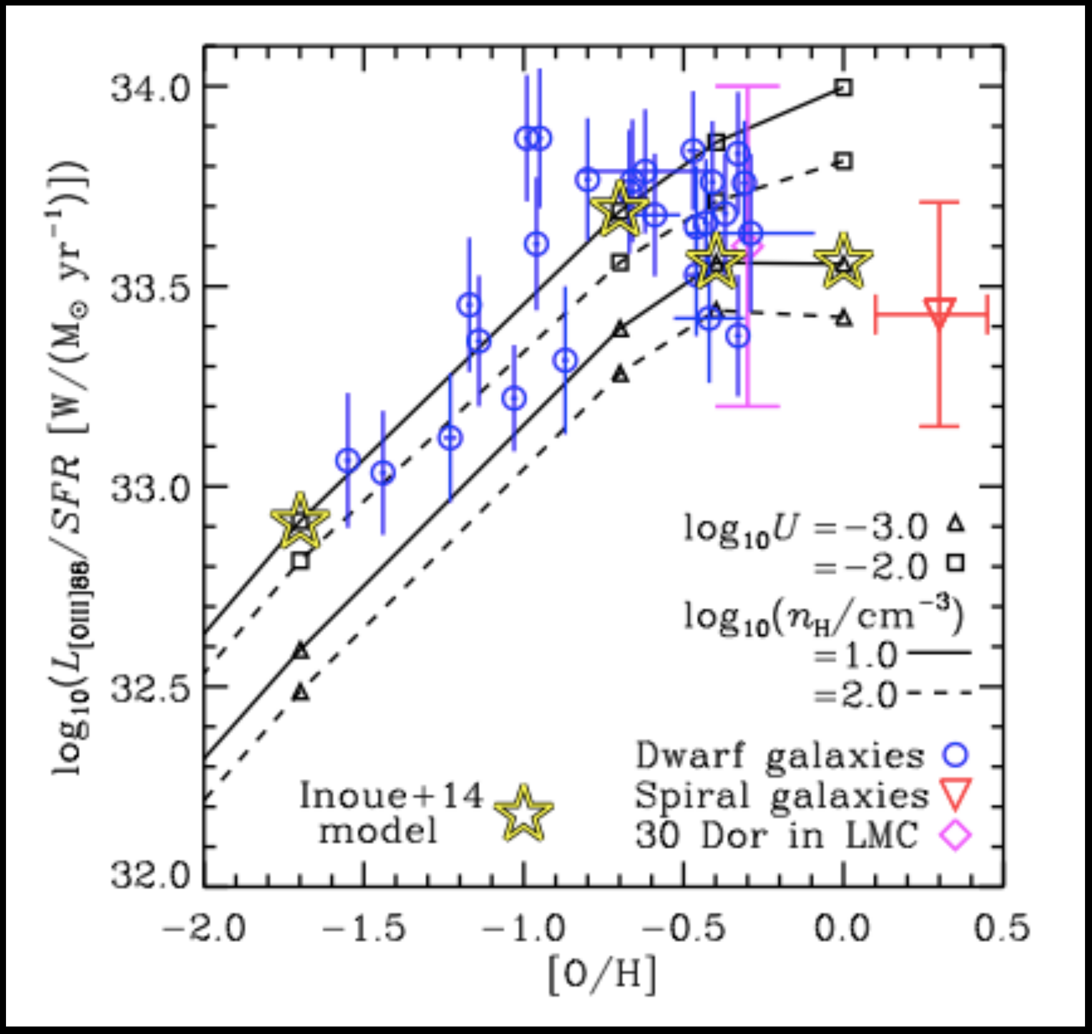
Is [OIII] 88um detection feasible?

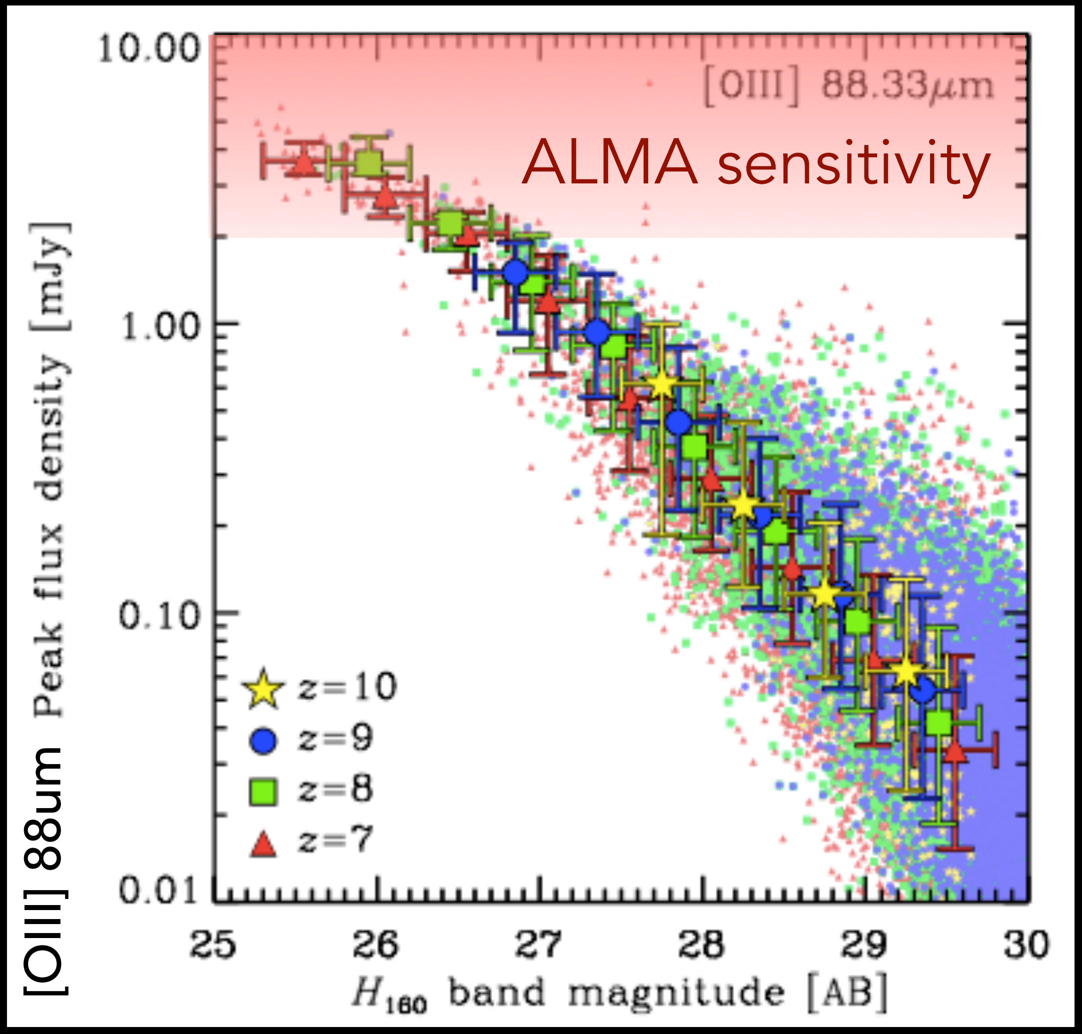
- Simulation where [OIII]88 luminosities are scaled by SFR.
- ALMA will detect [OIII]88 at z > 7!

[OIII] Emissivity

$$L_{[\mathrm{OIII}]\,88\mu\mathrm{m}} = \boxed{C_{[\mathrm{OIII}]\,88\mu\mathrm{m}}(Z,\,U,\,n_{\mathrm{H}})}\,\dot{M}_*$$

"[OIII] Emissivity"



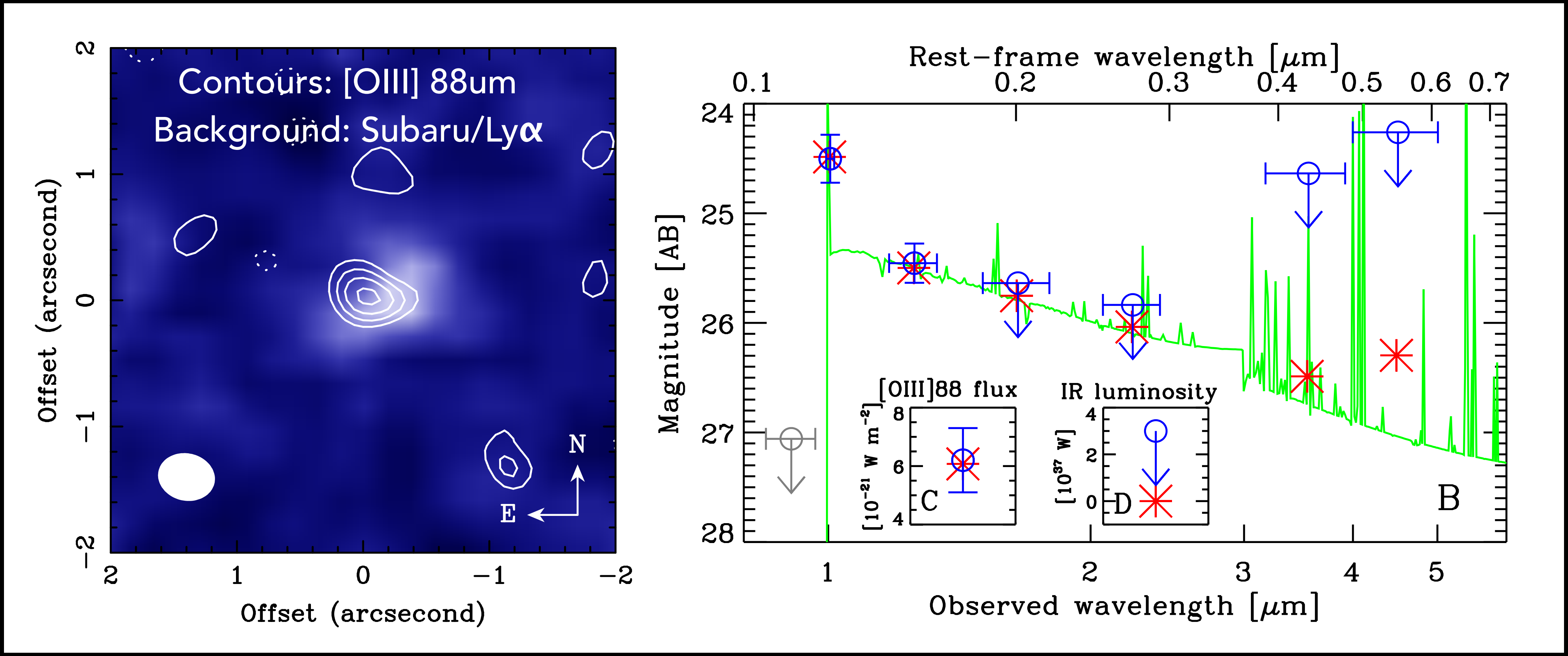


A. K. Inoue, I. Shimizu, YT+2014

First detection of [O III] in the reionization era

SXDF-NB1006-2 at z = 7.215

Inoue A. K, YT, et al. (2016) Science, 352, 1559

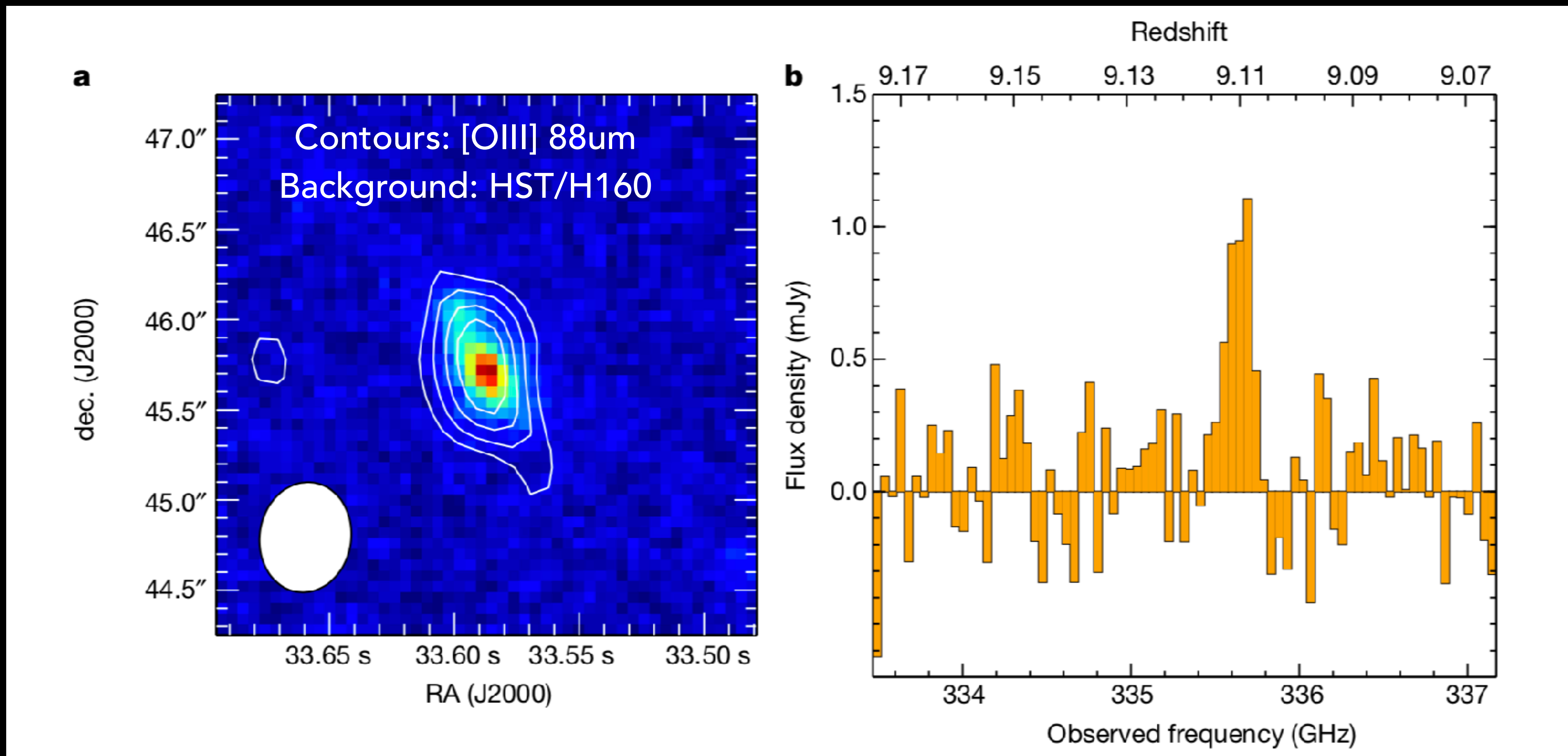


- Young star-forming metal-poor galaxy
  - Age < 30 Myr, SFR ~ 300 Mo/yr, Z = 0.05–1 Zo
- No dust and [C II] emission were found.

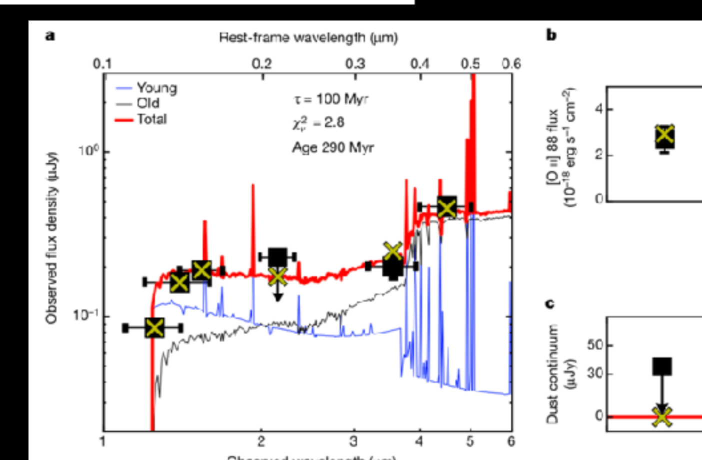
Furthest detection of [O III] at z = 9.1096

MACS1149-JD1

Hashimoto, incl. YT et al. (2018) Nature, 557, 392

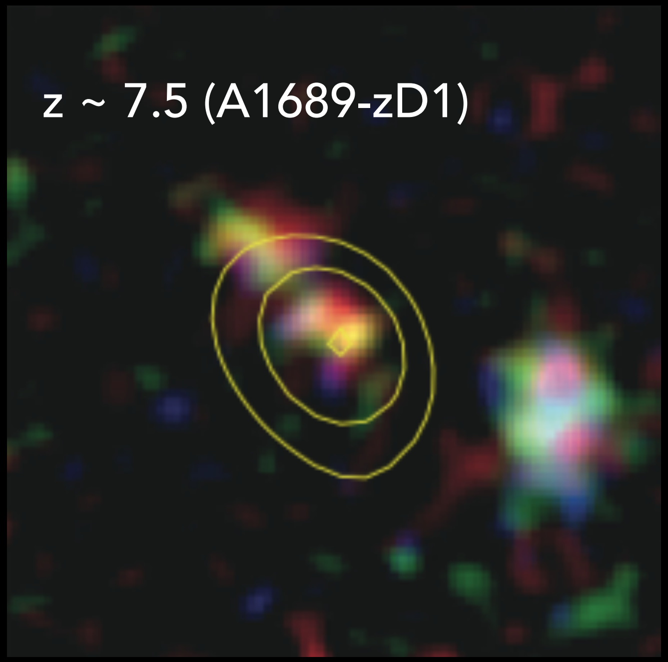


- Low-mass star-forming galaxy
  - Age = 290 Myr, SFR ~ 4 (μ_g/10)$^{-1}$ Mo/yr, Z = 0.05–1 Zo
  - No dust emission

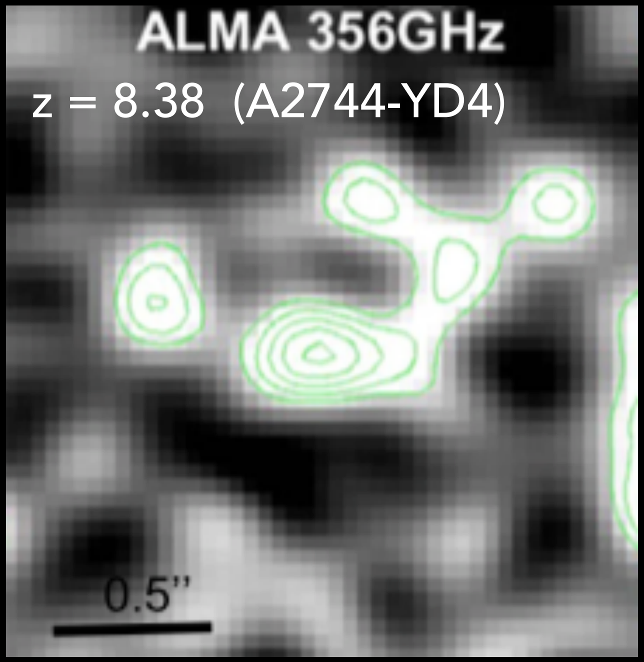


Early dust production

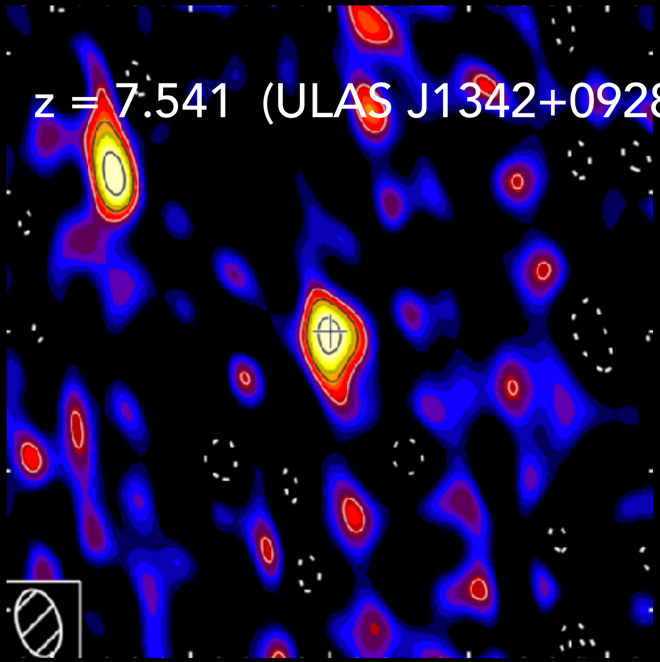
- Diversity in dust contents in EoR
  - Small dust mass in LAEs (e.g. Ouchi+13, Ota+14, Inoue+16,)
  - Large dust mass of ~10^7 M⊙ in LBGs (Watson+15, Laporte+17)
- **Dust budget crisis**: How galaxies got dust so quickly?
  - Type II SNe is the major contributors to dust mass at z > 8
  - Grain growth in dense ISM plays an important role?



Watson+2015, Nature



Laporte+2017



Venemans+2017

Redshift Record

#	Redshift	Object	References	Telescope/Line	Dust?
1	9.110	MACS J1149-JD	**Hashimoto+ (2018)**	**ALMA/[OIII]**	N
2	8.683	EGSY-2008532660	Zitrin+ (2015)	Keck/Lyα	n/a
3	8.38	A2744_YD4	Laporte+ (2017)	**ALMA/[OIII]**	**Y (4σ)**
4	8.312	MACS0416_Y1	**Tamura+ (2019)**	**ALMA/[OIII]**	**Y**
5	7.664	z7_GSD_3811	Song+ (2016)	Keck/Lyα	n/a
6	7.640	MACS1423-z7p64	Hoag+ (2017)	HST/Lyα & **ALMA/[CII]**	N
7	7.541	ULAS J1342+0928	Banados+(2017)	Magellan/Lyα & **ALMA/[CII]**	**Y**
8	7.508	z8-GND-5296	Finkelstein+ (2013)	Keck/Lyα	n/a
9	7.477	EGS-zs8-2	Stark+(2018)	Keck/Lyα, CIII]1909	n/a
10	7.452	GS2_1406	Larson+ (2018)	HST/Lyα	n/a
11	7.212	SXDF-NB1006-2	Shibuya+(2012) **Inoue, YT+ (2016)**	Subaru+Keck/Lya **ALMA/[OIII]**	N

Case Study with ALMA

Motivations

Key questions:

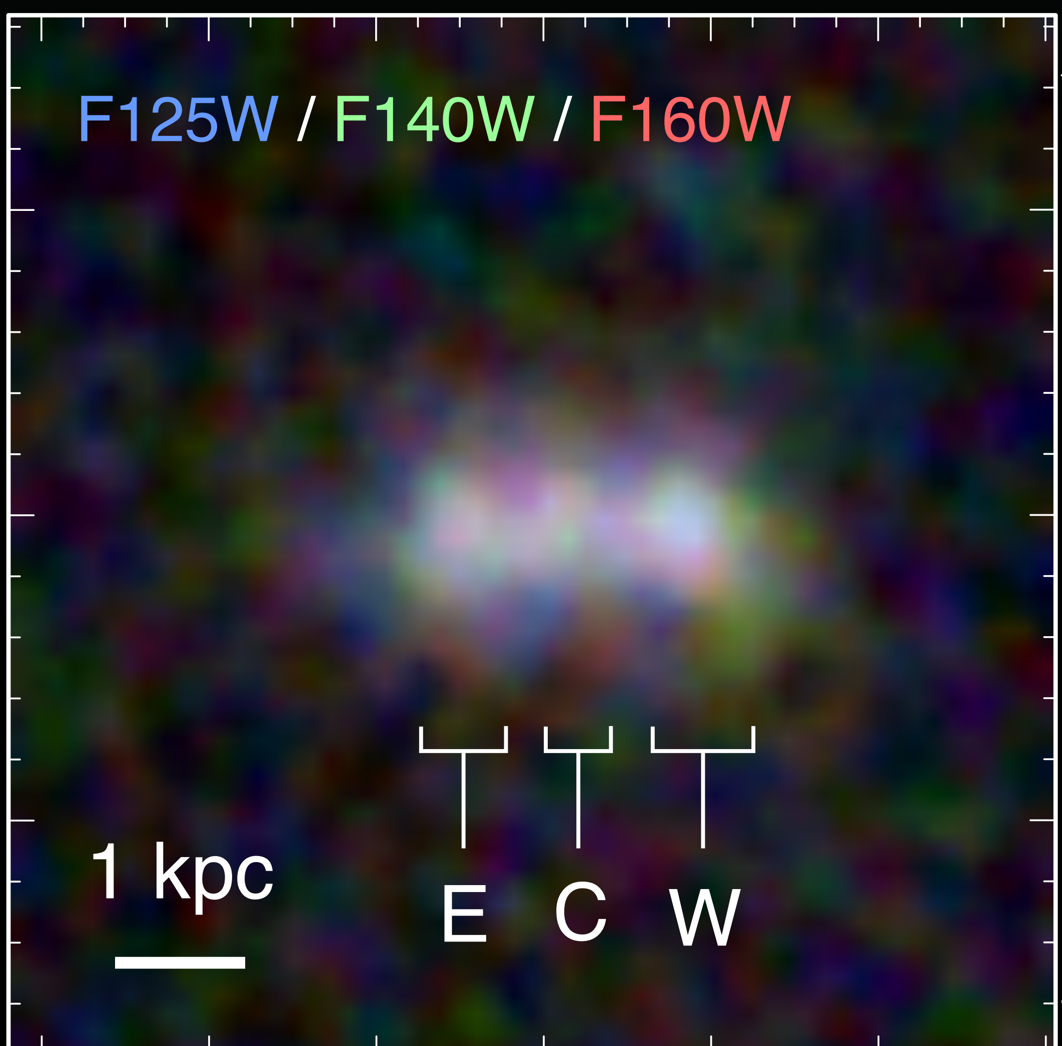
- *Can submillimeter telescopes serve as "z-machine" at $z > 8$?*
- *How and when metal enrichment happened?*
- *Why dust exists in the earliest universe?*

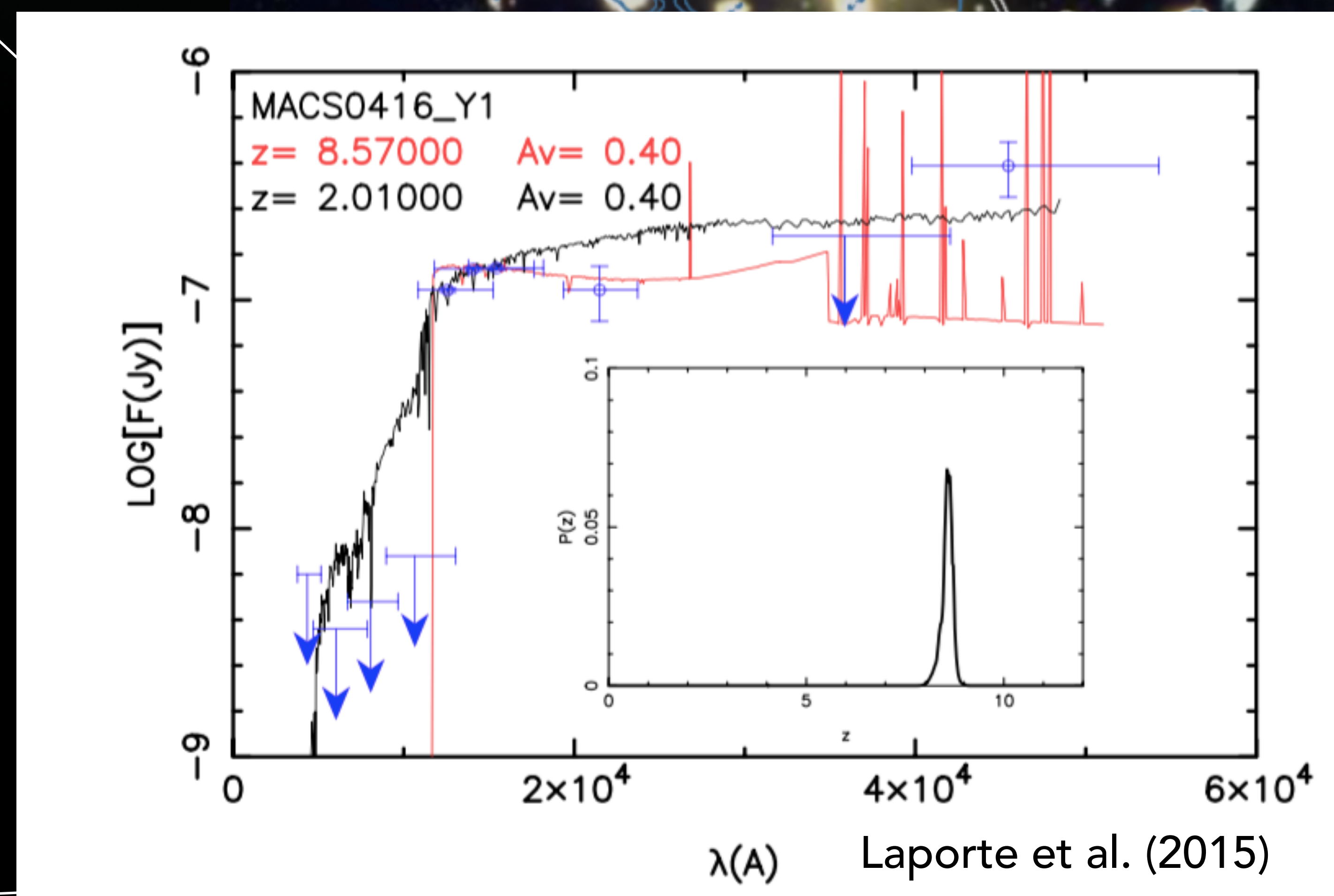
Purpose:

- *ALMA observations of a galaxy at EoR*
- *SED modeling with [OIII] + dust*
- *Dust mass evolution modeling*

Target: Frontier Field candidate LBG "MACS0416_Y1"

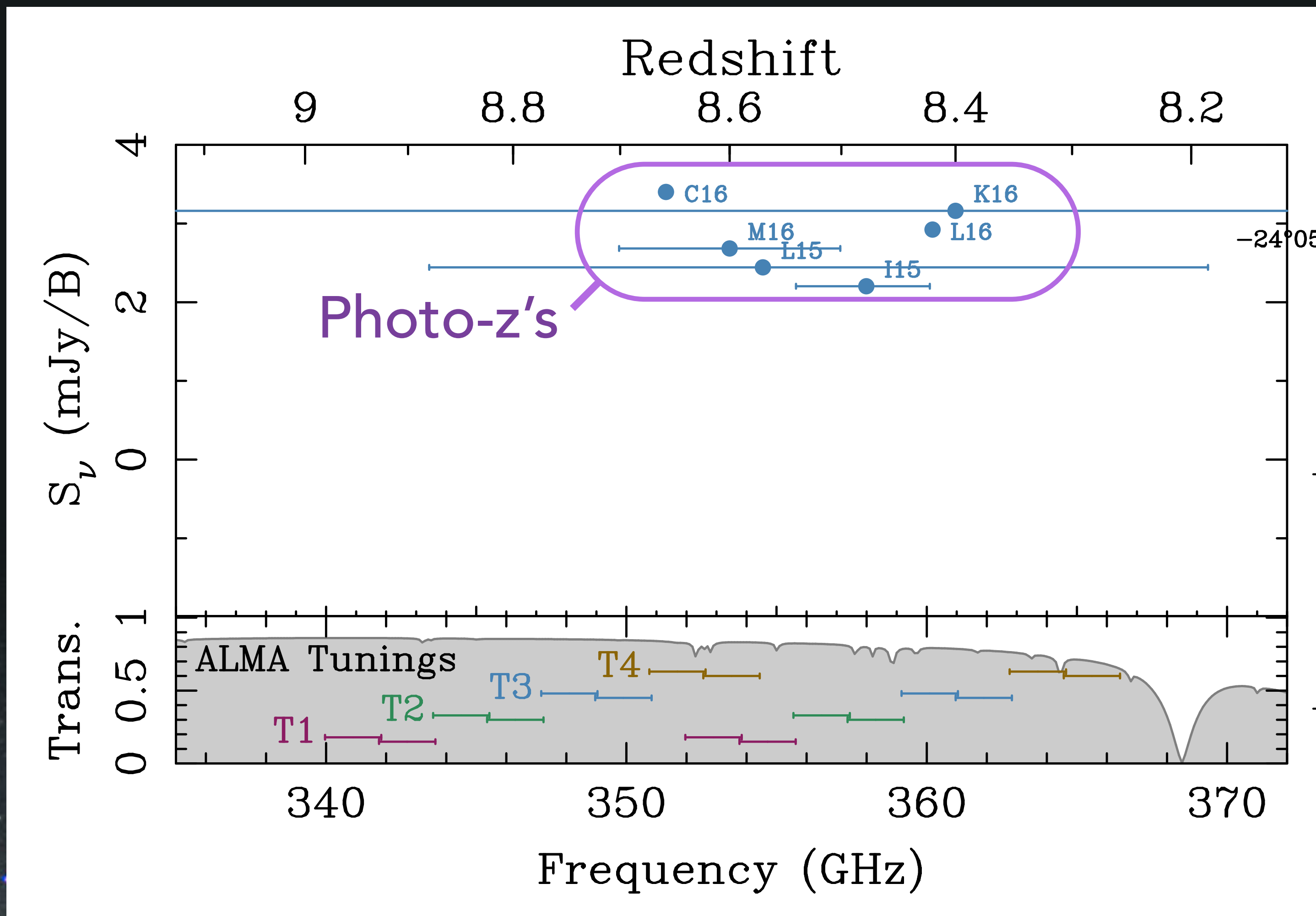
- The best among > 100 LBGs at z > 8
- Bright (H_{160} = 26.0 AB, μ_g = 1.4)
- Well-constrained redshift (z_ph ~ 8.3–8.7)
- Accessible from ALMA (Cycle 4)

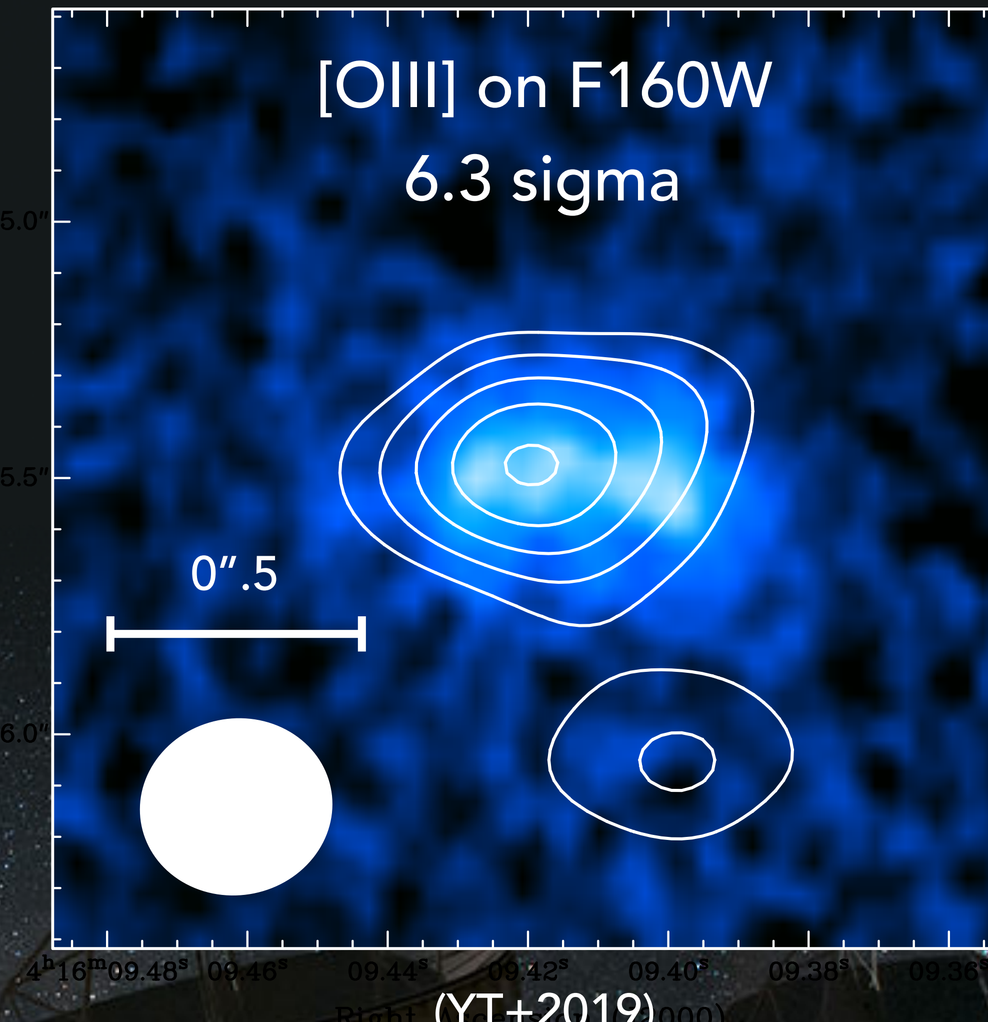




Laporte et al. (2015)

ALMA + [OIII] reveals a spectroscopic redshift

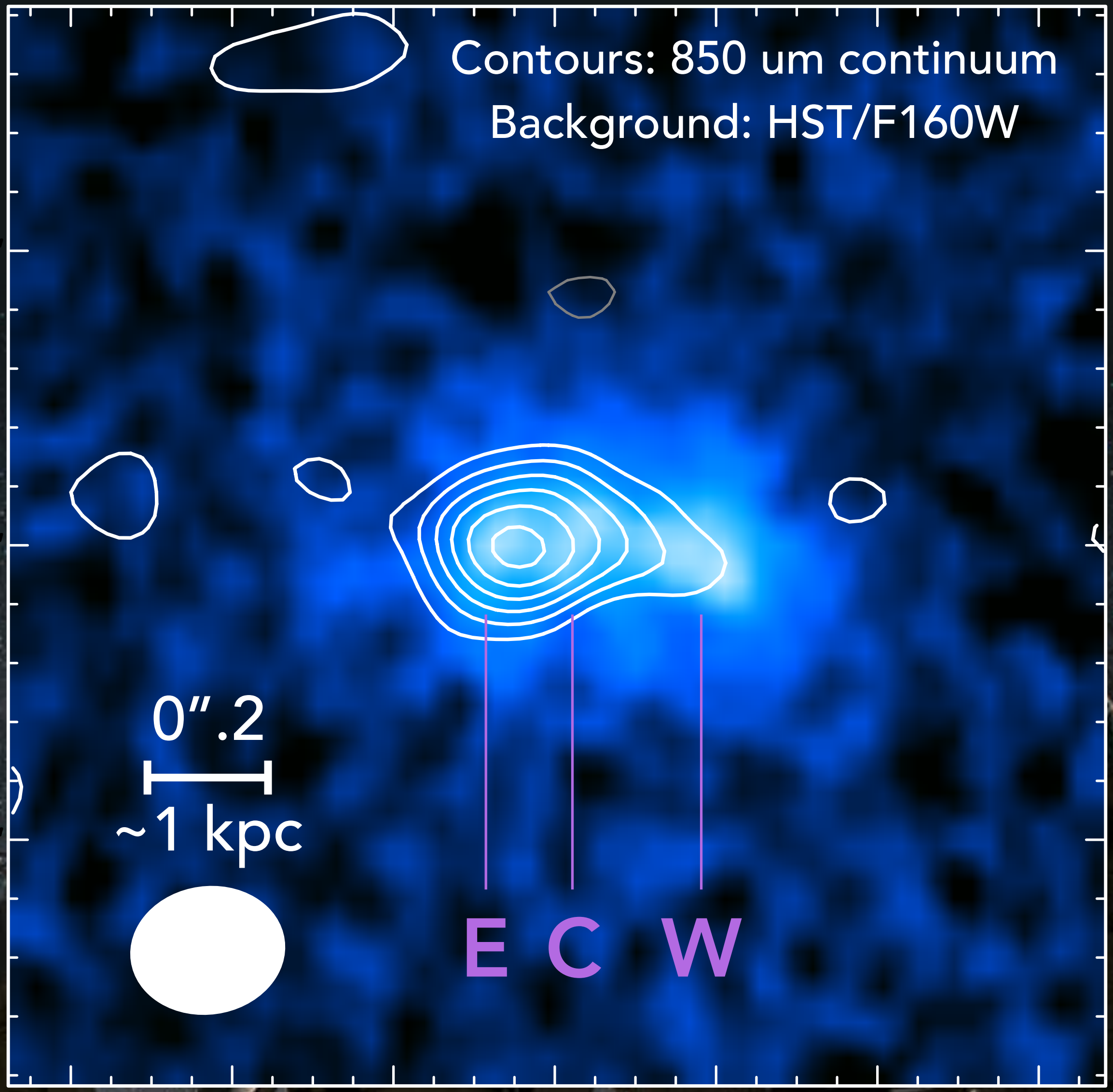




- Spectroscopic redshift ***z = 8.3118 ± 0.0003***

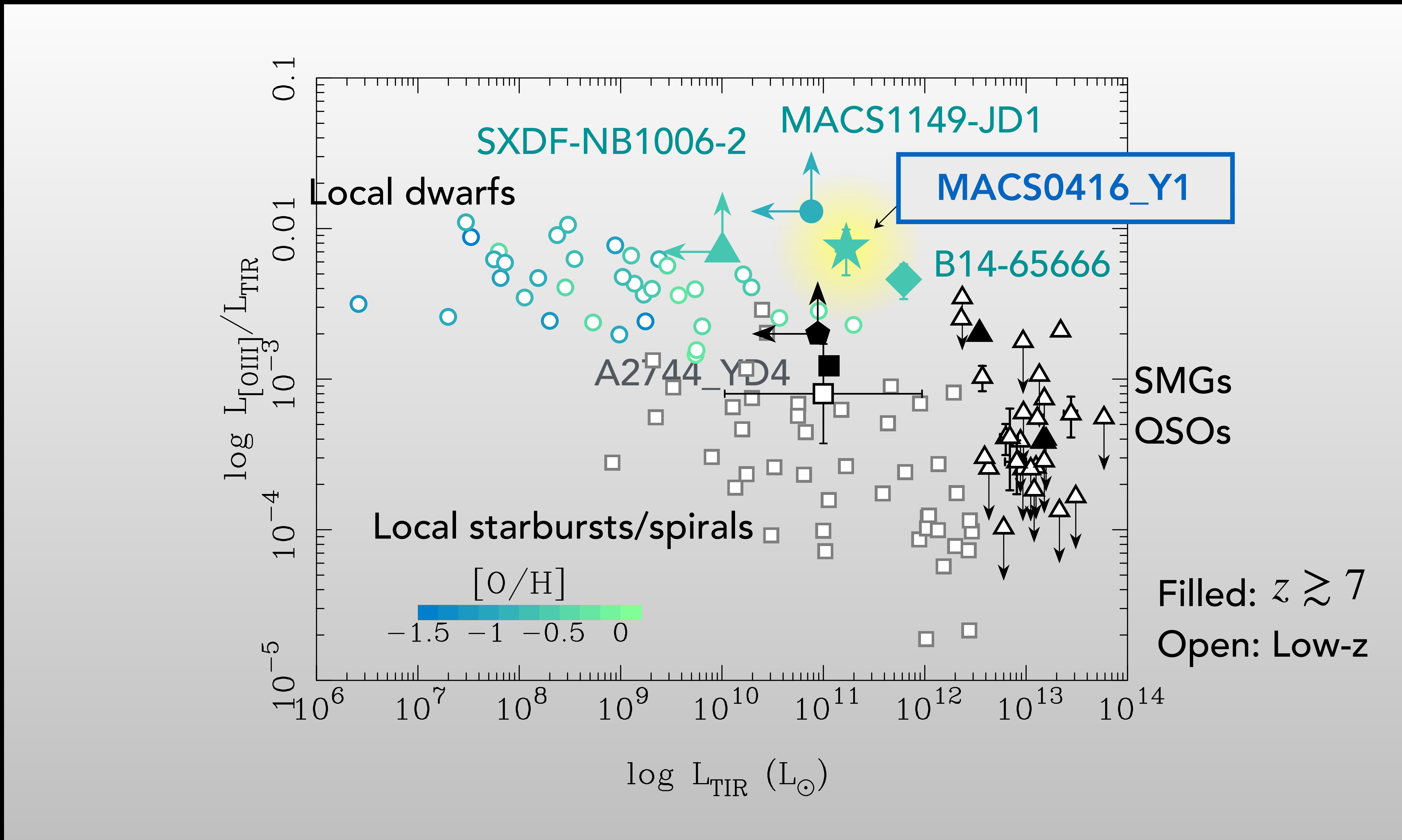
Dust detection at S/N = 7.6

- Second detection of dust at z > 8
  - S_850um = 137 ± 26 μJy
- Spatially resolved
  - Size: 0″.36 × 0″.10 = 1.7 × 0.5 kpc
  - Tracing UV emission
  - Peak at/between E-C clumps
- Large dust mass
  - assuming T_dust = 50 K, β = 1.5…
  - L_TIR = (1.7 ± 0.3) × 10^11 L⊙
  - M_dust = (0.4 ± 0.1) × 10^7 M⊙



YT+18, submitted

[O III]-to-IR Luminosity Ratio



- MACS0416_Y1 is a scale-up version of local dwarfs.

How does "dust" coexist with UV SED?

- PANHIT (Mawatari+2019, in prep.)
  - Stellar population synthesis analysis with Rest-frame UV-optical and FIR [OIII] + dust continuum

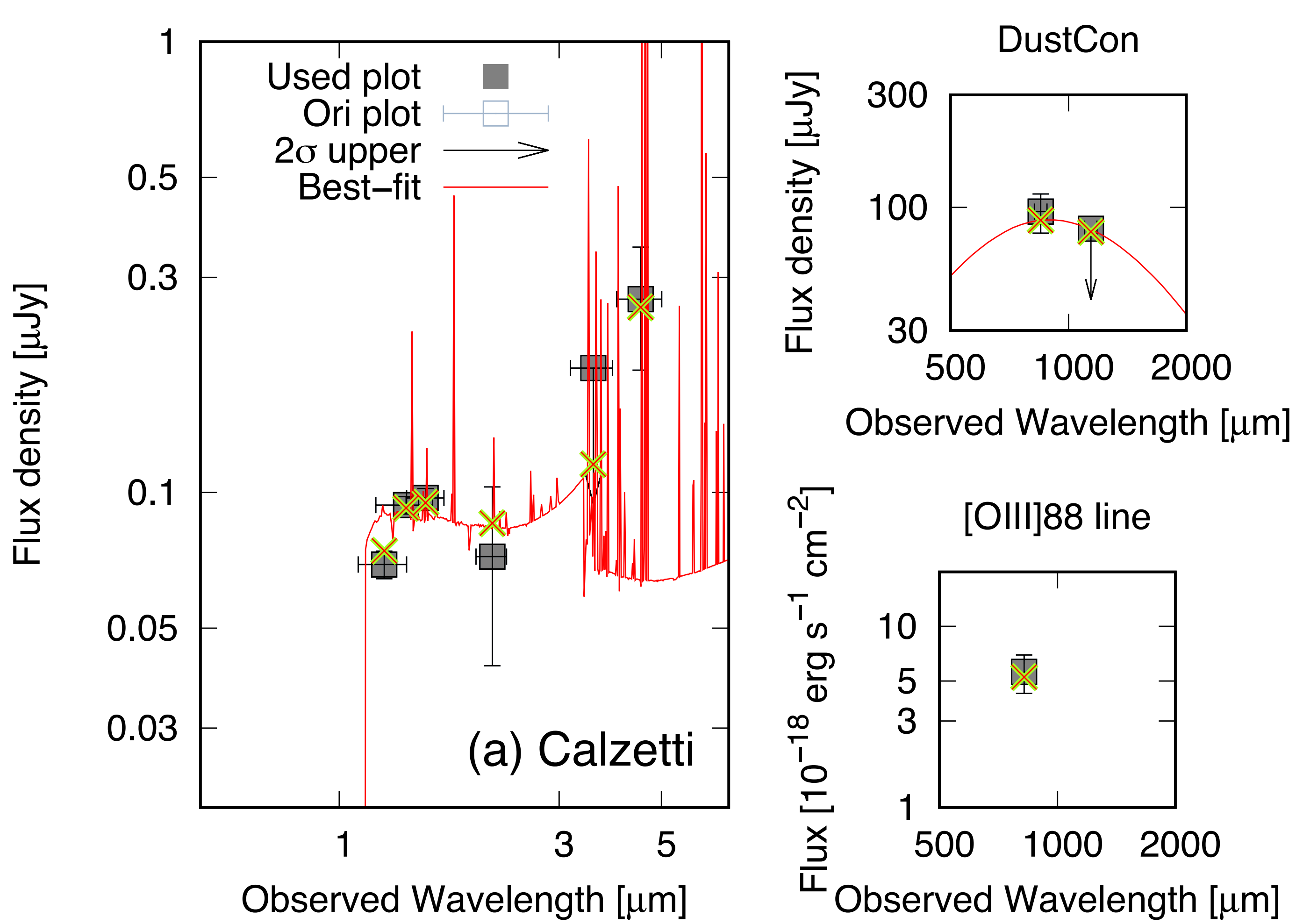
Fitting parameters

Dust attenuation A_V (mag)
Age $\tau_{\rm age}$ (Myr)
SFH $\tau_{\rm SFH}^{-1}$ ($\rm Gyr^{-1}$)$^{\sharp}$
Metallicity Z ($Z_\odot$)
LyC escape fraction $f_{\rm esc}$
Stellar mass $M_{\rm star}$ ($10^8 M_\odot$)
SFR ($M_\odot$ $\rm yr^{-1}$)†
$L_{\rm IR}$ ($10^{11} L_\odot$)†

- SED components
  - Stellar: Bruzual & Charlot 2003 (BC03)
  - Nebular: SFR -> N_ion -> Hβ -> Nebular (Inoue+11)
    SFR + Z -> [OIII]88 (Inoue+14)
  - Dust (FIR): Local LIRGs (Rieke+09)
- Three extinction curves are used
  - Calzetti, Milky Way (MW), Small Magellanic Cloud (SMC)
  - 2175 A bump (carbon) is evident in the MW law

SED Fits: Results

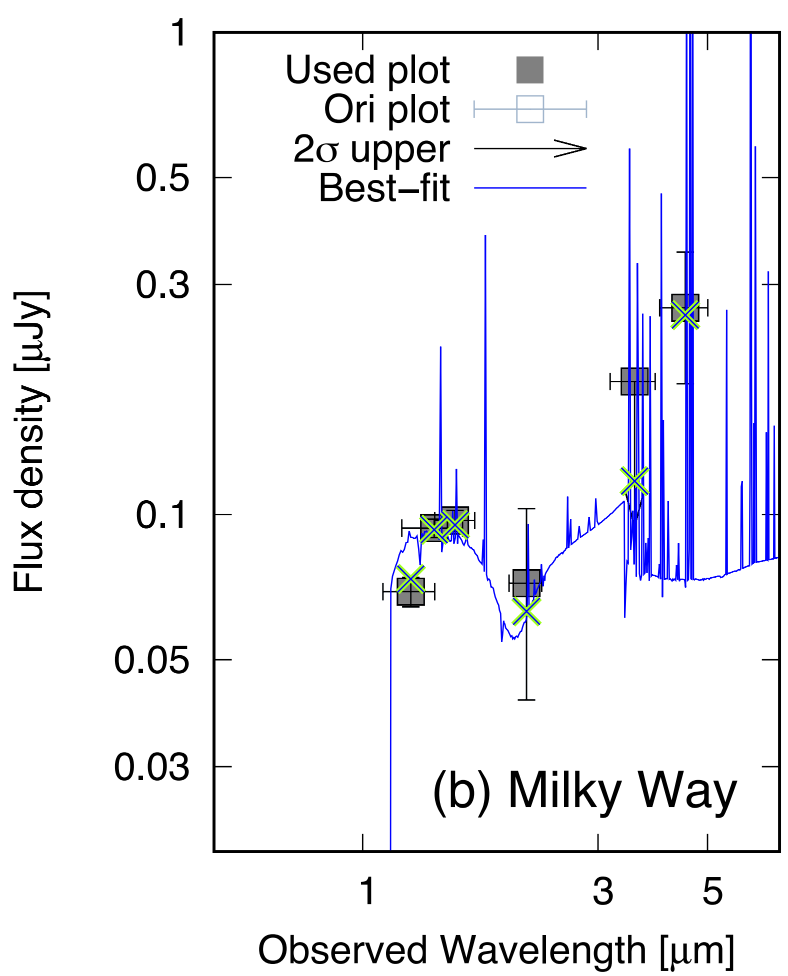
- UV-bright stellar component can co-exist with luminous dust component ***if the dust mass pre-exists***.
- Favors a young, but moderately metal-enriched solution
  - **Age ~ 4 Myr**, metallicity = 0.2 Z_Sun

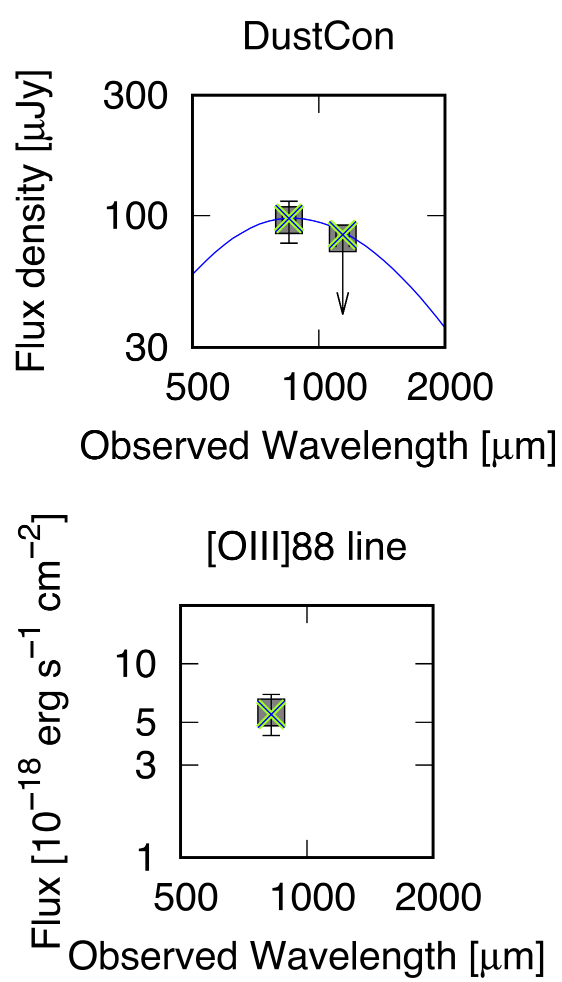


Items	Calzetti
χ^2	7.0
Degree Of Freedom	3
Dust attenuation A_V (mag)	$0.50^{+0.02}_{-0.04}$
Age $\tau_{\rm age}$ (Myr)	$3.5^{+3.5}_{-0.7}$
SFH $\tau_{\rm SFH}^{-1}$ (Gyr^{-1})$^\sharp$	100^{+0}_{-200}
Metallicity Z ($Z_\odot$)	$0.20^{+0.08}_{-0.17}$
LyC escape fraction $f_{\rm esc}$	$0.00^{+0.15}_{-0.00}$
Stellar mass $M_{\rm star}$ ($10^8 M_\odot$)†	$2.5^{+2.9}_{-0.6}$
SFR ($M_\odot$ yr^{-1})†	$59.8^{+2166.}_{-29.8}$
$L_{\rm IR}$ ($10^{11} L_\odot$)†	$1.56^{+0.60}_{-0.51}$

SED Fits: Results

- UV-bright stellar component can co-exist with luminous dust component ***if the dust mass pre-exists***.
- Favors a young, but moderately metal-enriched solution
  - **Age ~ 4 Myr**, metallicity = 0.2 Z_Sun

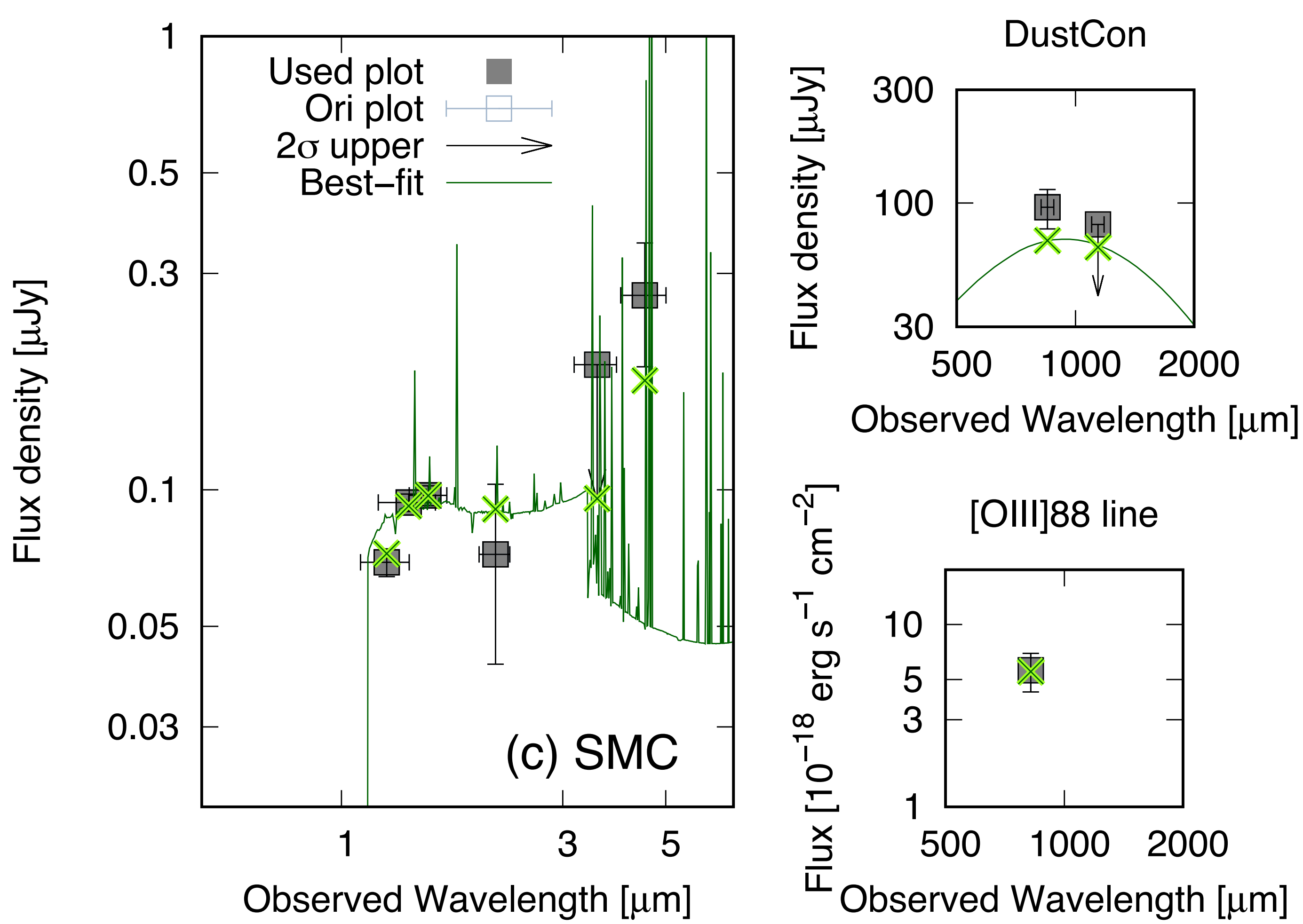




Items	Extinction law MW
χ^2	6.8
Degree Of Freedom	3
Dust attenuation A_V (mag)	$0.50^{+0.02}_{-0.06}$
Age $\tau_{\rm age}$ (Myr)	$4.2^{+5.2}_{-1.1}$
SFH $\tau_{\rm SFH}^{-1}$ (Gyr^{-1})$^\sharp$	-10^{+110}_{-90}
Metallicity Z ($Z_\odot$)	$0.20^{+0.10}_{-0.15}$
LyC escape fraction $f_{\rm esc}$	$0.00^{+0.12}_{-0.00}$
Stellar mass $M_{\rm star}$ ($10^8 M_\odot$)†	$2.5^{+2.9}_{-0.8}$
SFR ($M_\odot$ yr^{-1})†	$62.4^{+2235.3}_{-34.7}$
$L_{\rm IR}$ ($10^{11} L_\odot$)†	$1.68^{+0.53}_{-0.88}$

SED Fits: Results

- UV-bright stellar component can co-exist with luminous dust component ***if the dust mass pre-exists***.
- Favors a young, but moderately metal-enriched solution
  - **Age ~ 4 Myr**, metallicity = 0.2 Z_Sun

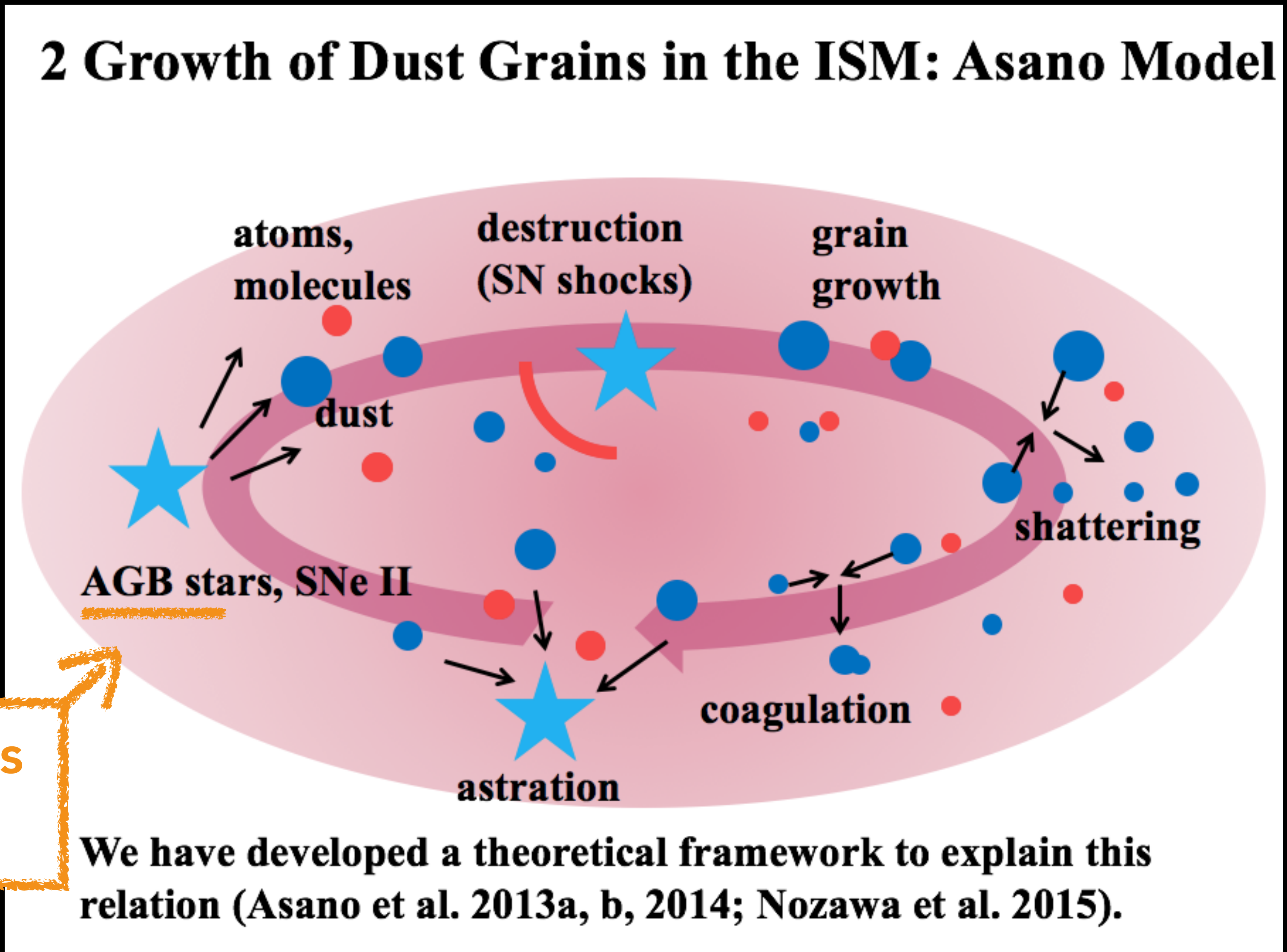


Items	SMC
χ^2	8.4
Degree Of Freedom	3
Dust attenuation A_V (mag)	$0.20^{+0.05}_{-0.01}$
Age $\tau_{\rm age}$ (Myr)	$2.0^{+1.0}_{-0.6}$
SFH $\tau_{\rm SFH}^{-1}$ (Gyr^{-1})$^\sharp$	100^{+0}_{-200}
Metallicity Z ($Z_\odot$)	$0.20^{+0.21}_{-0.15}$
LyC escape fraction $f_{\rm esc}$	$0.40^{+0.20}_{-0.23}$
Stellar mass $M_{\rm star}$ ($10^8 M_\odot$)†	$2.3^{+2.8}_{-0.6}$
SFR ($M_\odot$ yr^{-1})†	104^{+2091}_{-73}
$L_{\rm IR}$ ($10^{11} L_\odot$)†	$1.27^{+0.90}_{-0.38}$

Dust mass evolution model (Asano & Takeuchi+13)

- Dust budget crisis: How did a galaxy get dust so quickly?
  - Can our current understanding of dust evolution explain the observed M_dust?

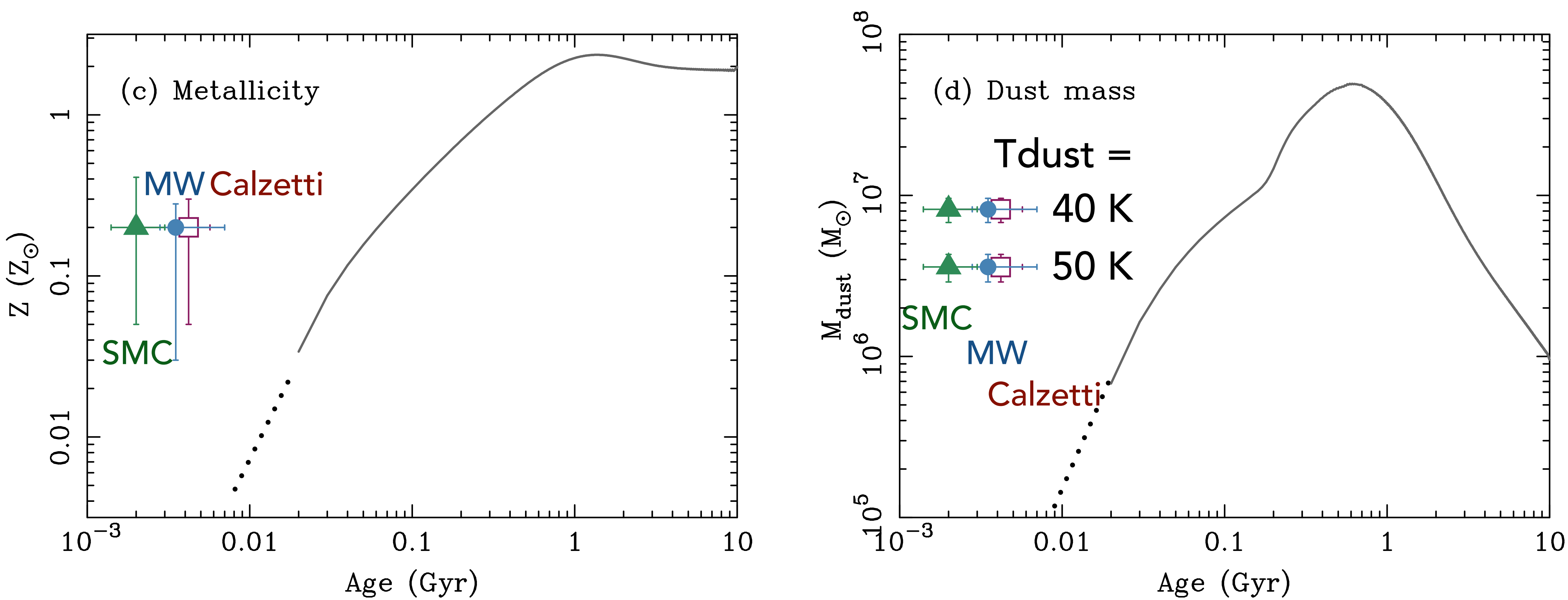
- Setup
- SF timescale tau_SF = 0.3 Gyr
- Roughly scaled so that predicted M_star and SFR match the observed ones



Few AGB stars at z ~ 8

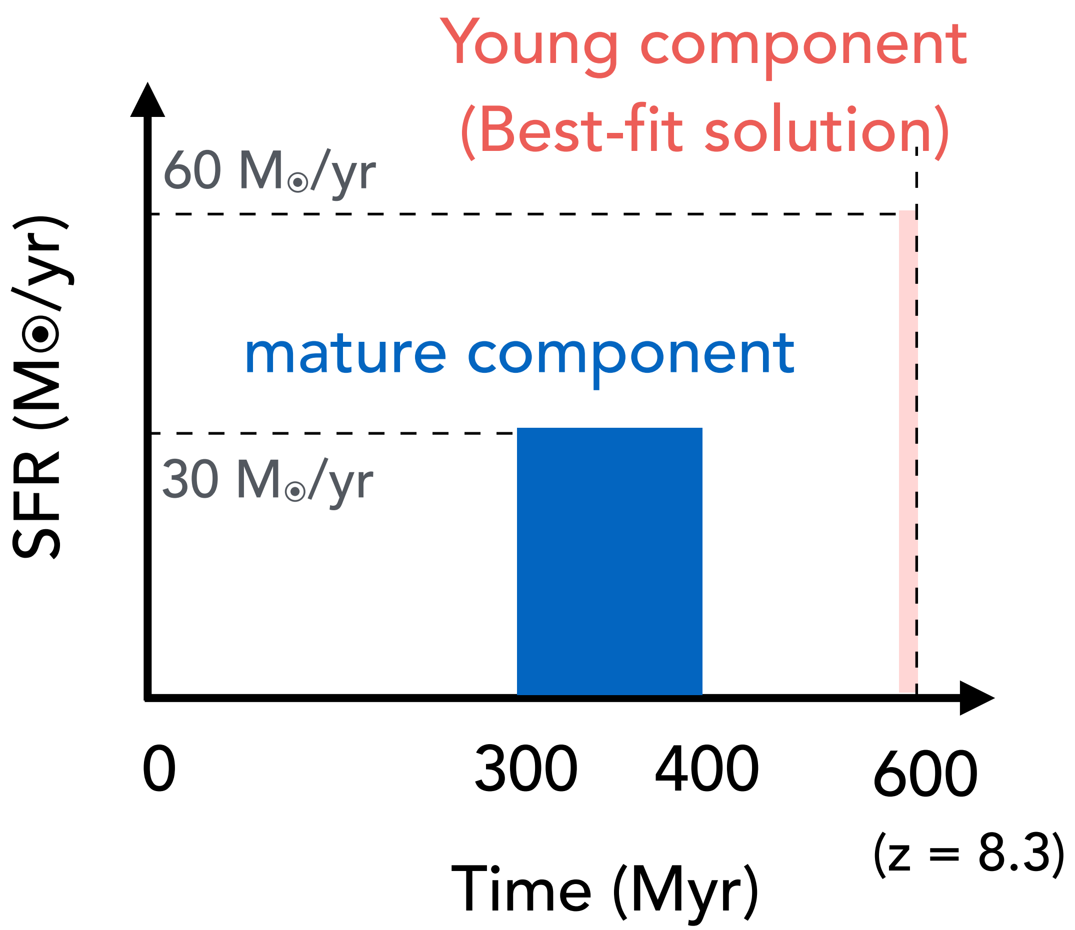
Credit: Tsutomu T. Takeuchi

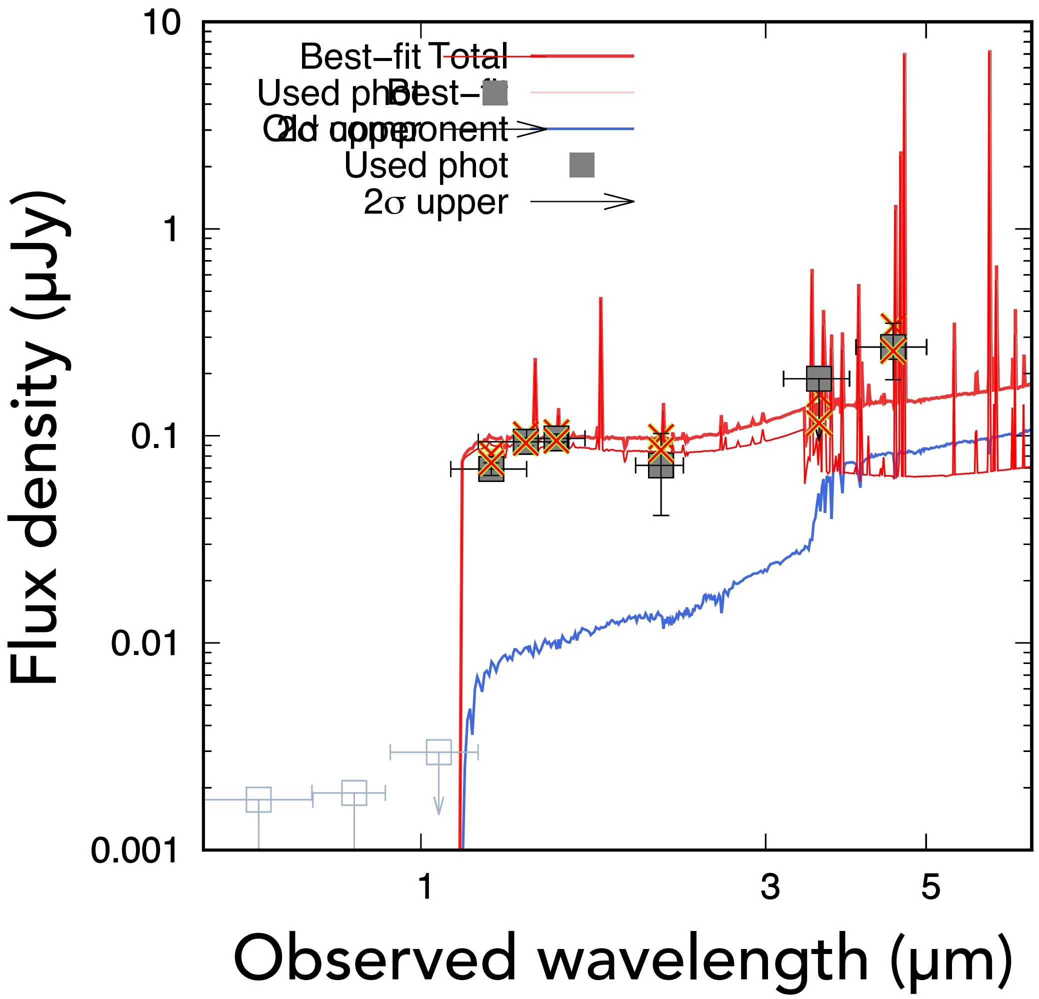
Dust and metallicity cannot be reproduced...!



- More massive (~1e9 M_Sun), mature (~0.1 Gyr) stellar component is required to reproduce $M_{\rm dust} \approx 4 \times 10^6 \, M_\odot$

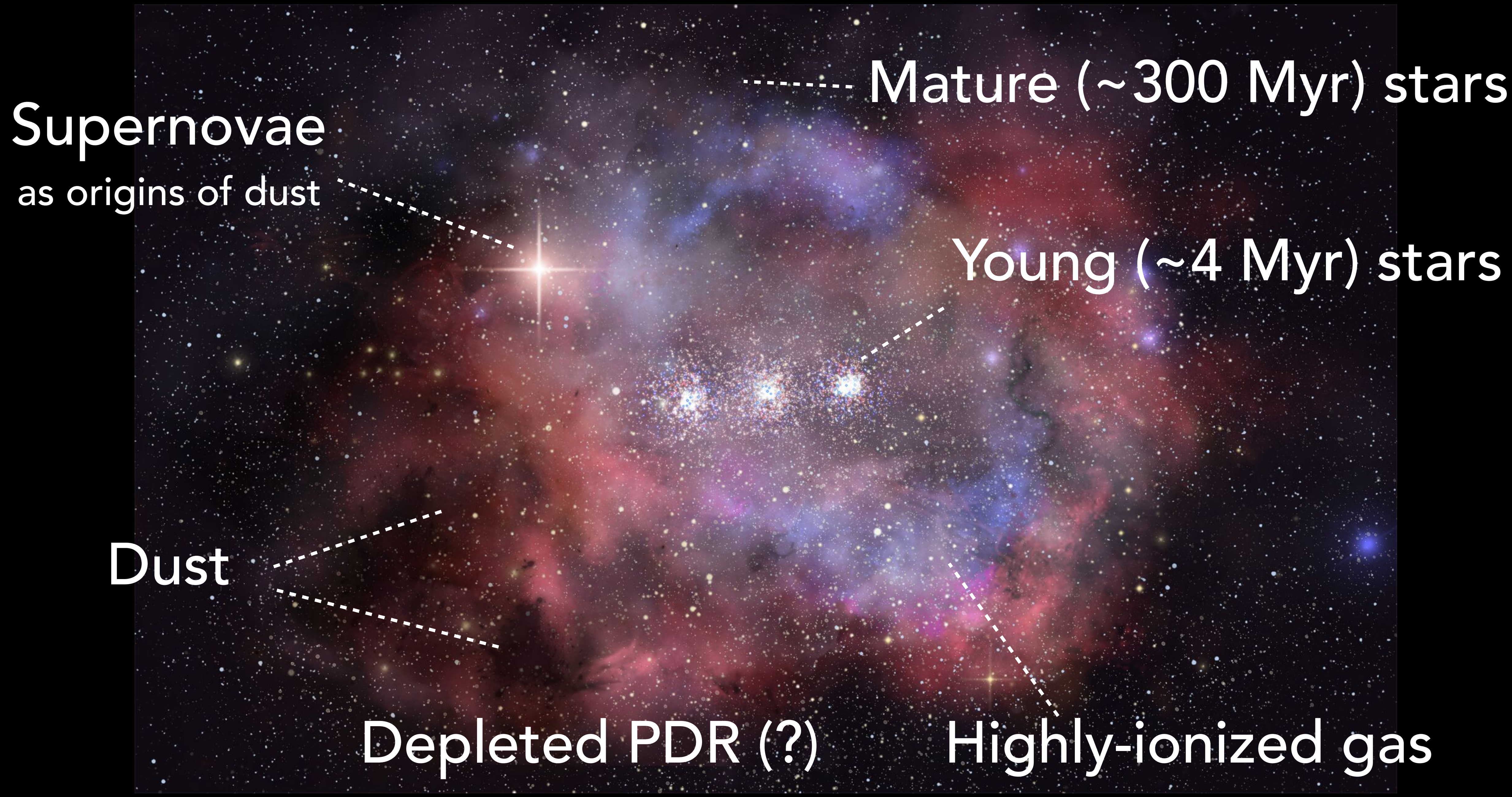
Underlying massive, mature stellar component





- A mature component ($3\times10^9\ M_\odot$, age = 0.1 Gyr) as the origin of dust can coexist with the young component.

What we learned from submm + NIR observations



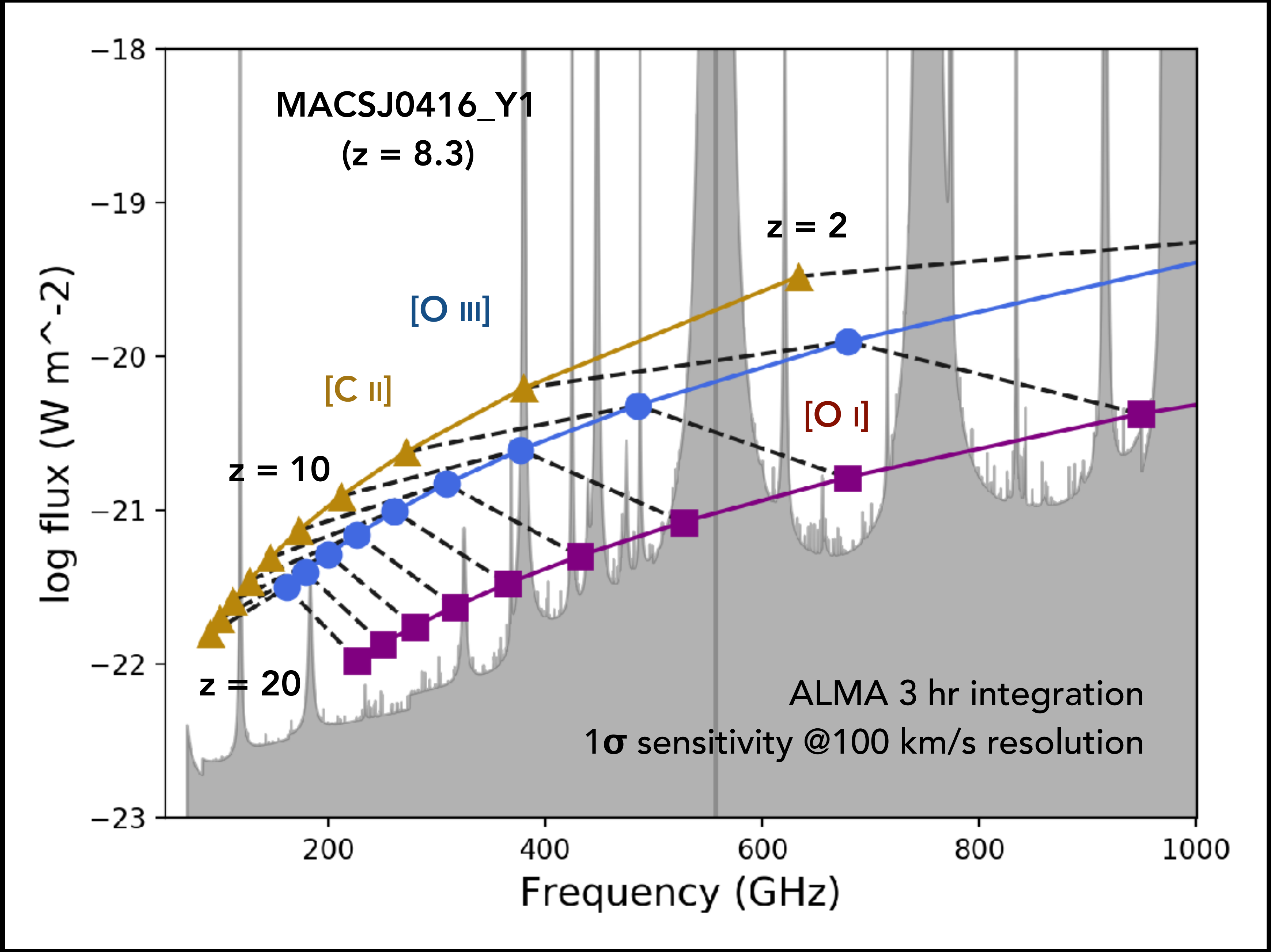
Artist's impression (Credit: NAOJ)

- Futre prospects
  - Sub-kpc ALMA imaging of multi-phase ISM in dust (MCs), [CII] (PDRs) and [OIII] (HII)
  - JWST/WFIRST search for "past star-formation" components

Future Galaxy Survey in the Submillimeter

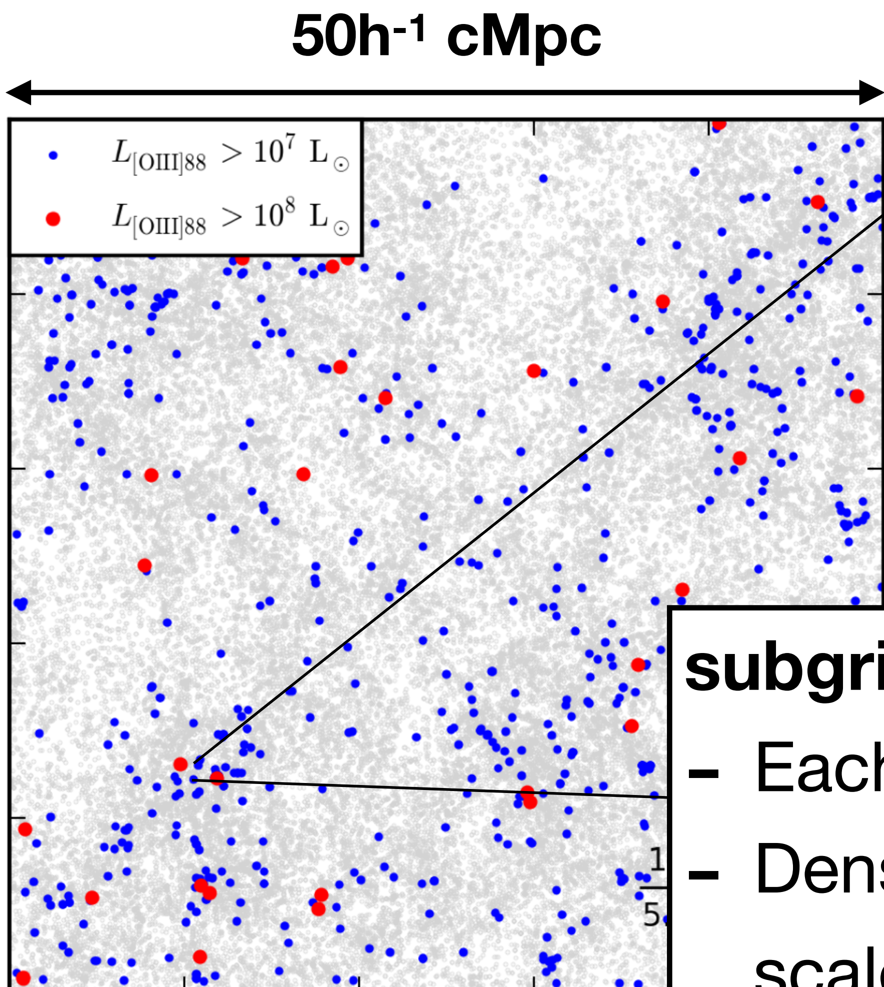
Far-Infrared Fine-Structure Lines

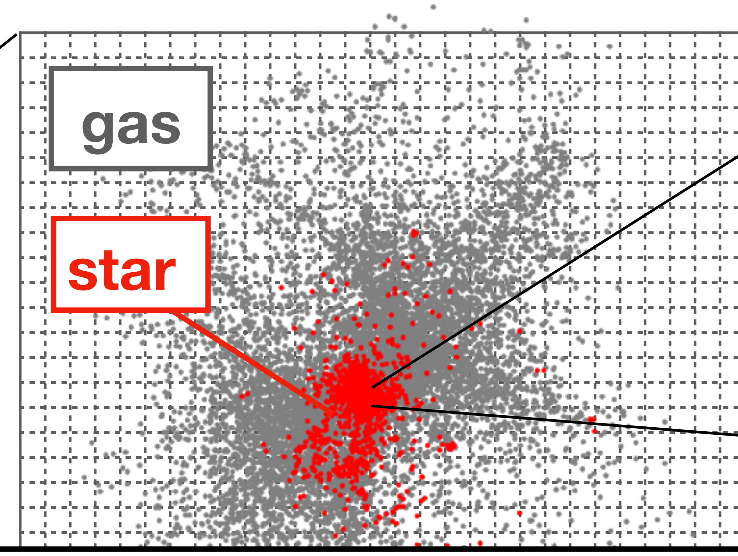
- Reach z = 20. Competitive with JWST/NIRSpec C III]1909A

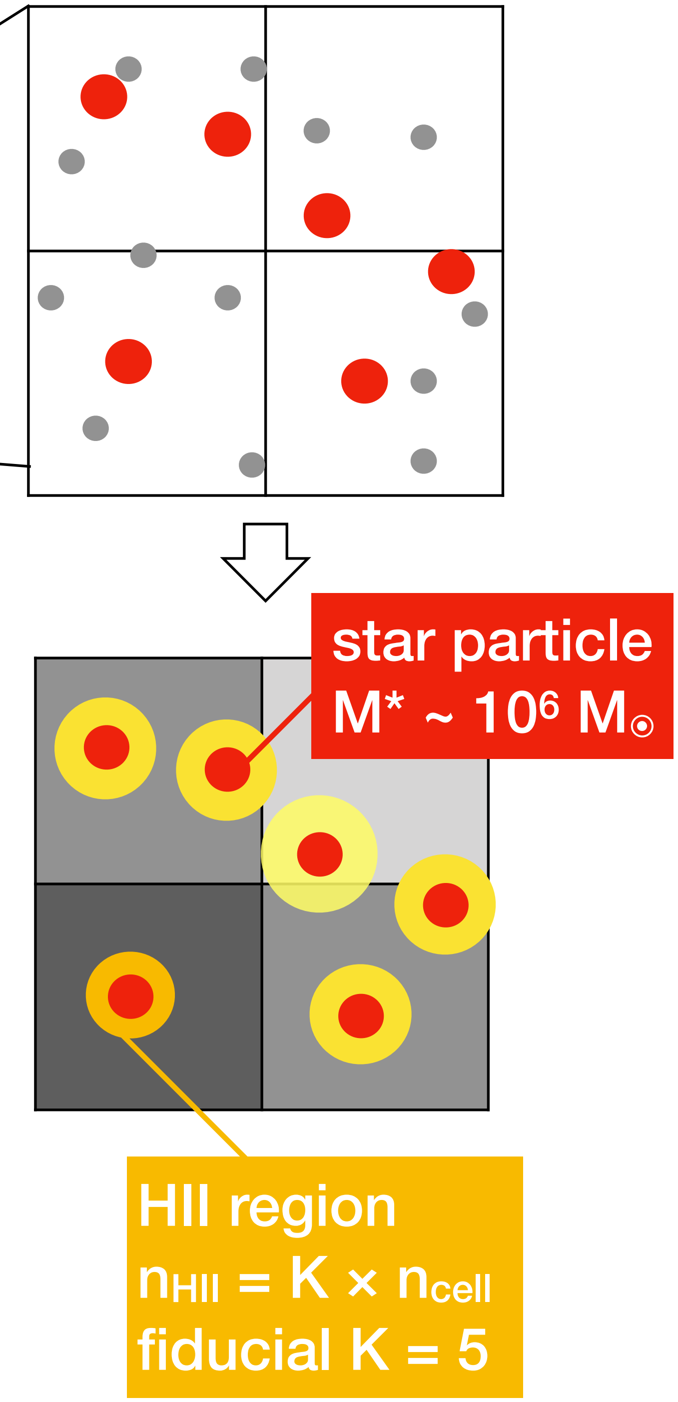


Line Emission from HII region

Kana Moriwaki-san (UTokyo)







subgrid model

- Each star particle forms a HII region.
- Density in HII region is constant and scales with surrounding gas density.

$$n_{\rm H} = K n_{\rm global}$$

$$\langle U \rangle = \frac{3\alpha_{\rm B}^{2/3}}{4c}\left(\frac{3Qn_{\rm H}}{4\pi}\right)^{1/3}$$

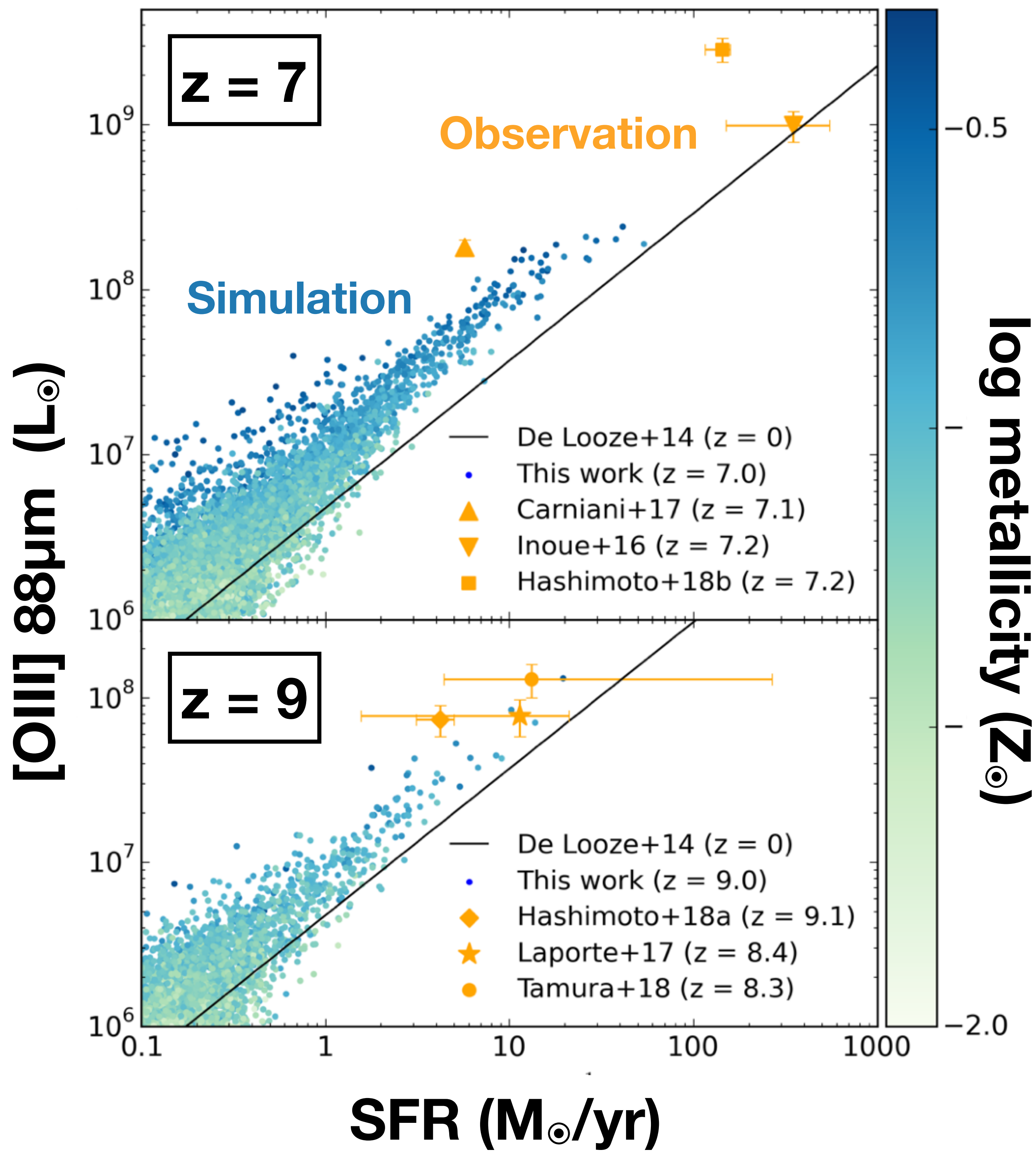
$$L_{\rm line} = C_{\rm line}(Z, n, U) \times L_{\rm H\beta}^{\rm caseB}$$

CLOUDY output

Moriwaki+ (incl. YT) 2018

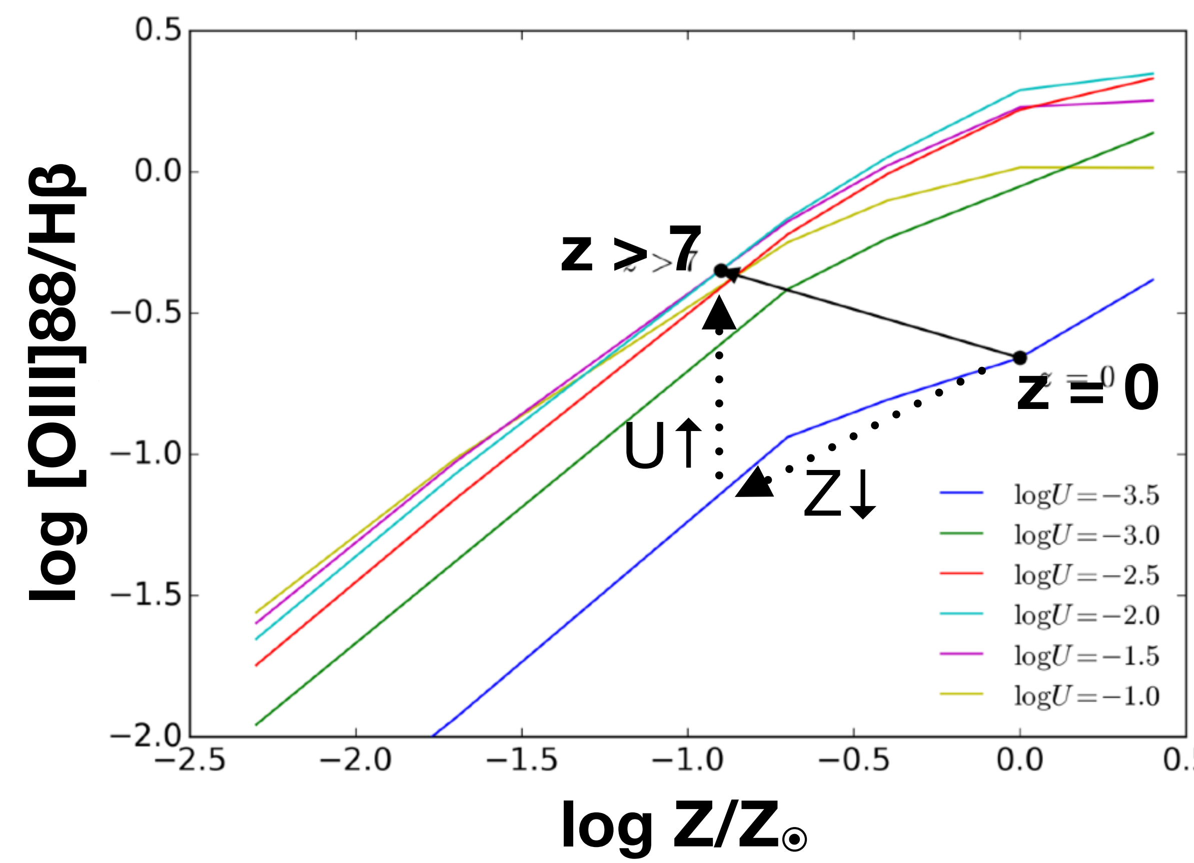
Kana Moriwaki-san (UTokyo)

Properties of high-z [OIII] emitters



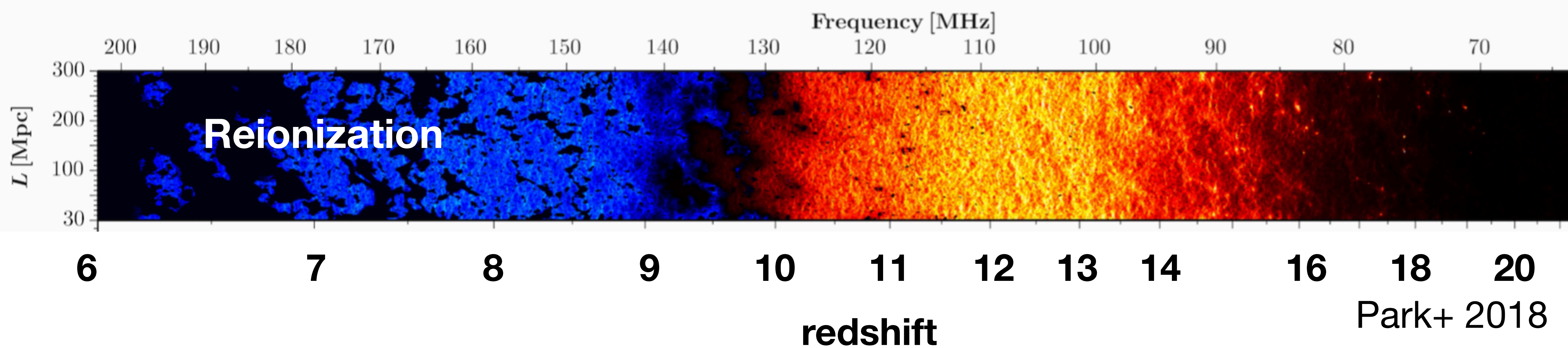
Moriwaki+ 2018

- **well-established star forming** galaxies are selectively observed
- L_{OIII88} is higher than expected from the local relation: **high ionization parameter & moderate metallicity**



Kana Moriwaki-san (UTokyo)

Cross-correlation: 21cm vs galaxies



Park+ 2018

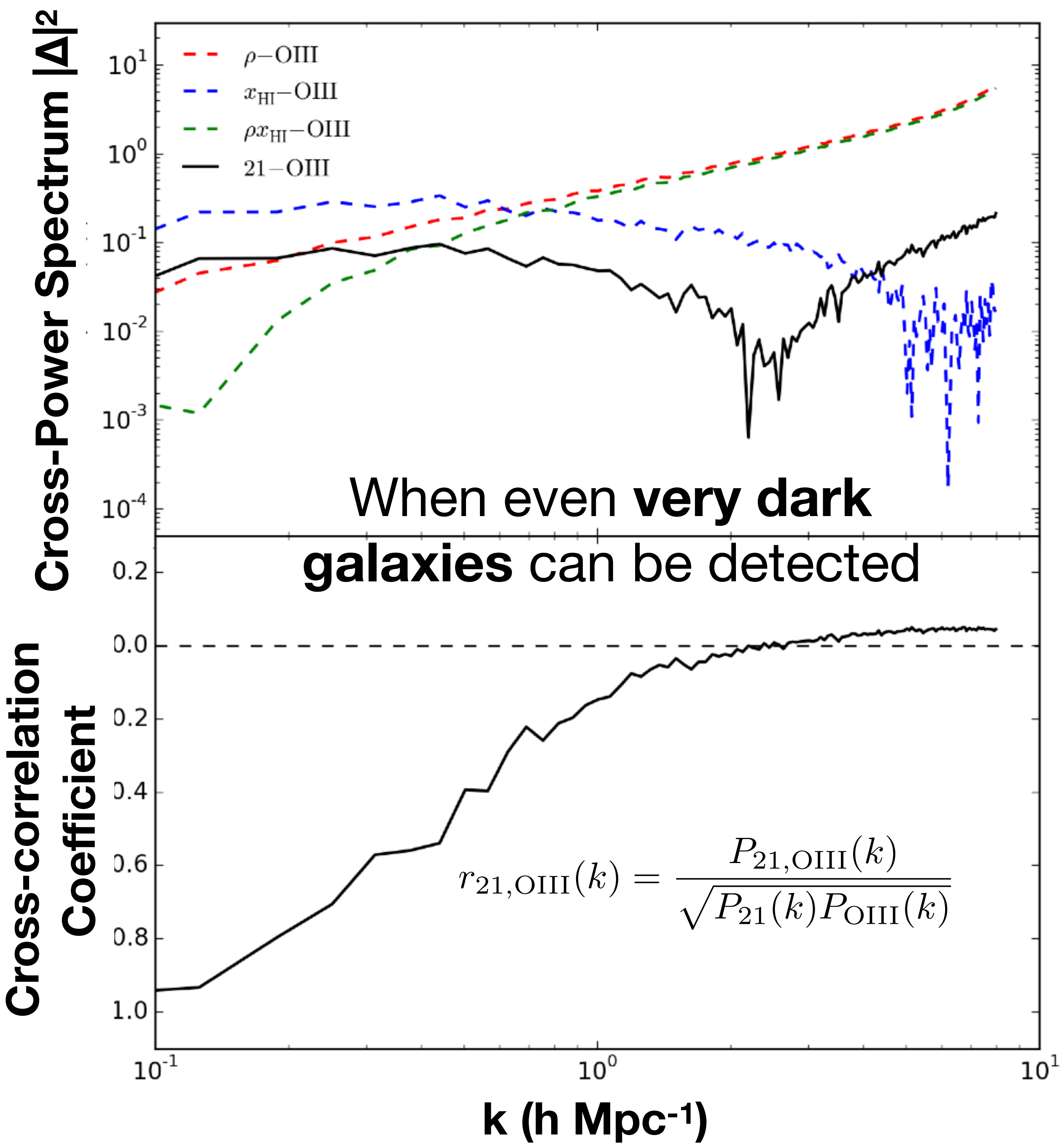
- **21-cm observation**:
  WFA, LOFAR, PAPER, HERA, SKA
  Only statistical information: power spectrum
  Foreground (synchrotron) should be excluded.

- **galaxy survey/intensity mapping**:
  LAE (HSC), [CII] (CONCERT, TIME), CO (COMAP), [OIII] (SPHEREx?)

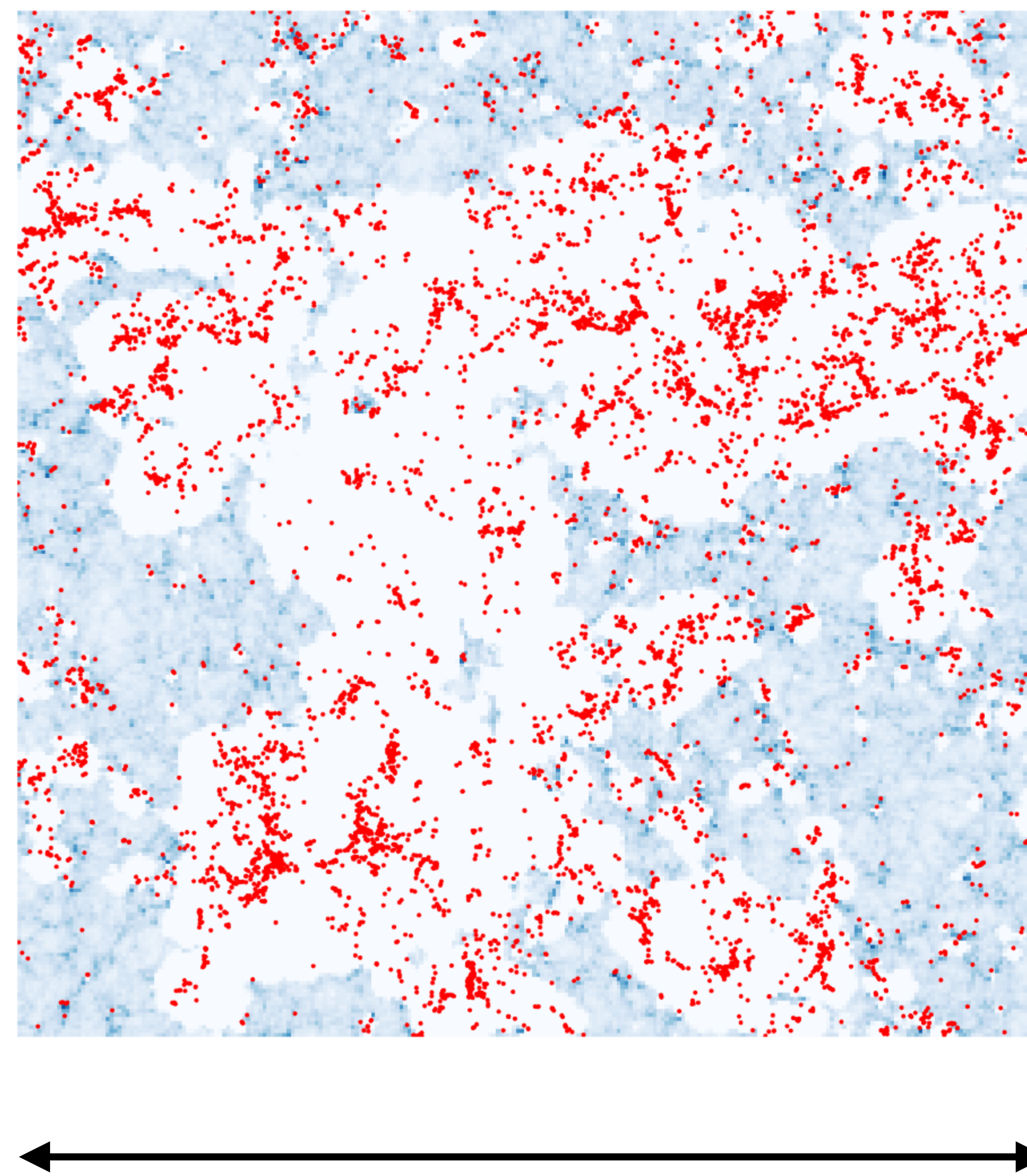
- Foreground contamination is excluded in **cross-correlation** signal

Kana Moriwaki-san (UTokyo)

Result: Ideal 3D Cross-Power Spectrum



z = 7.5, $\langle x_{\rm HI}\rangle$ = 0.46



100h⁻¹ cMpc

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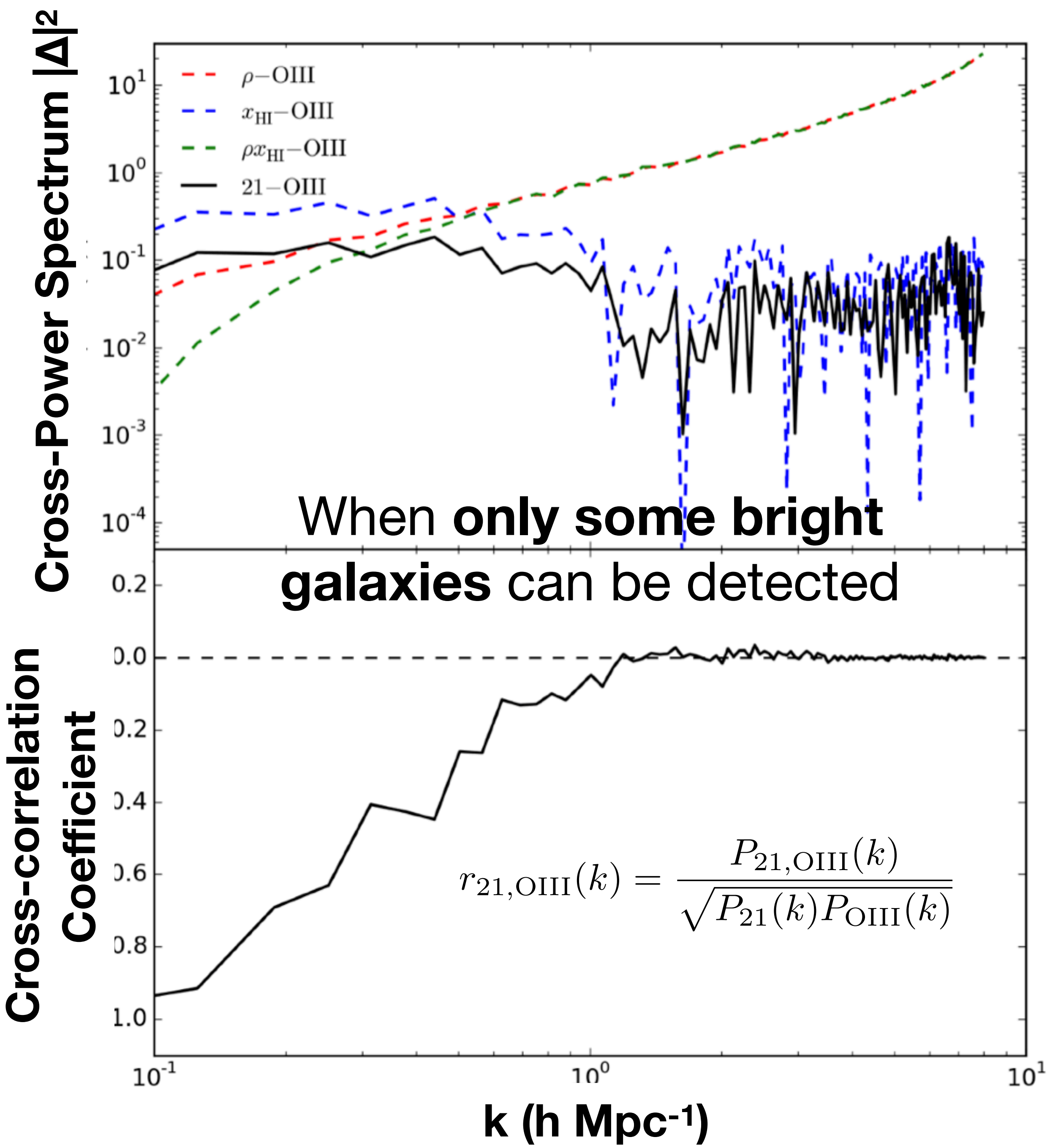
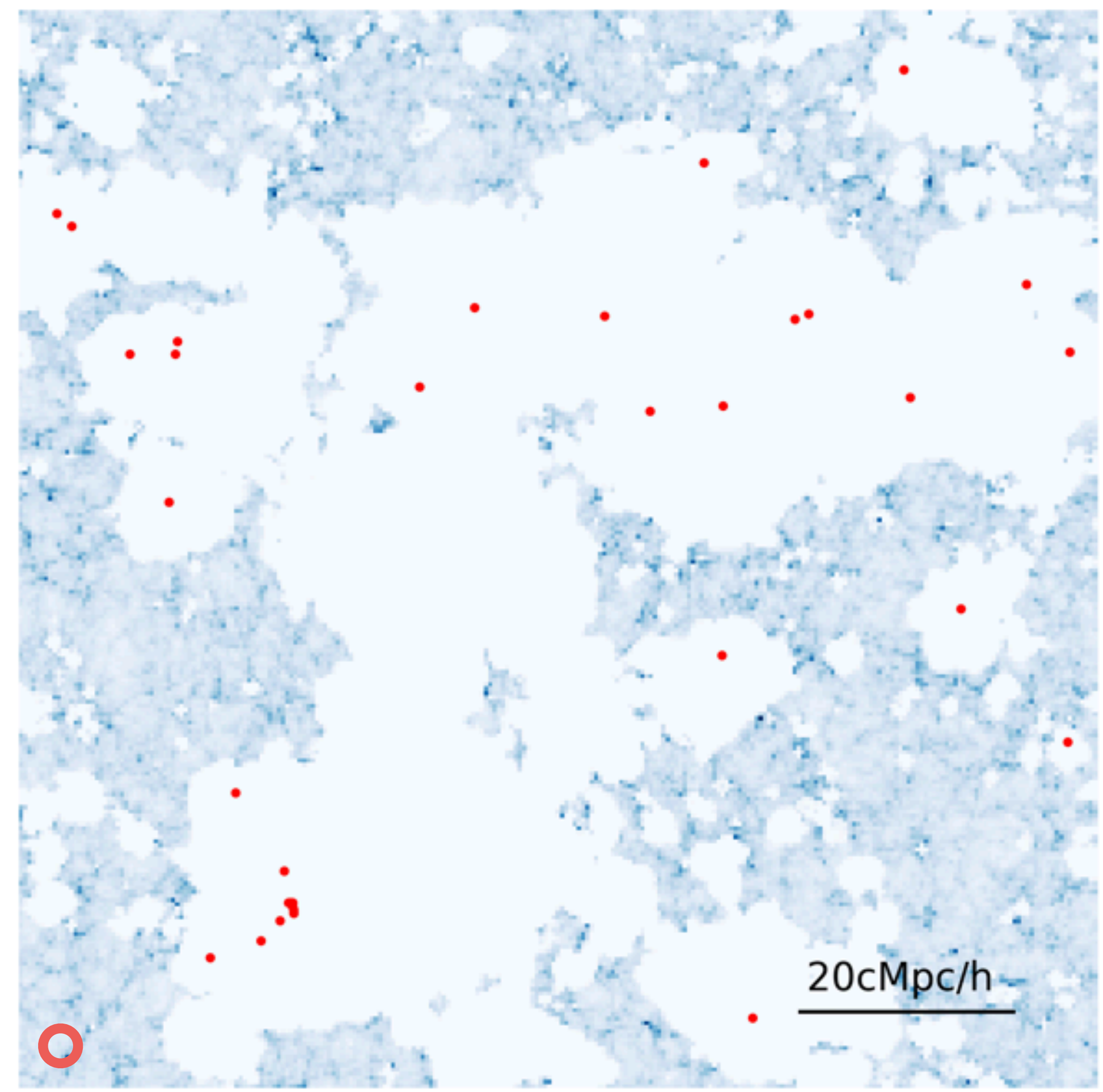
Result: Ideal 3D Cross-Power Spectrum

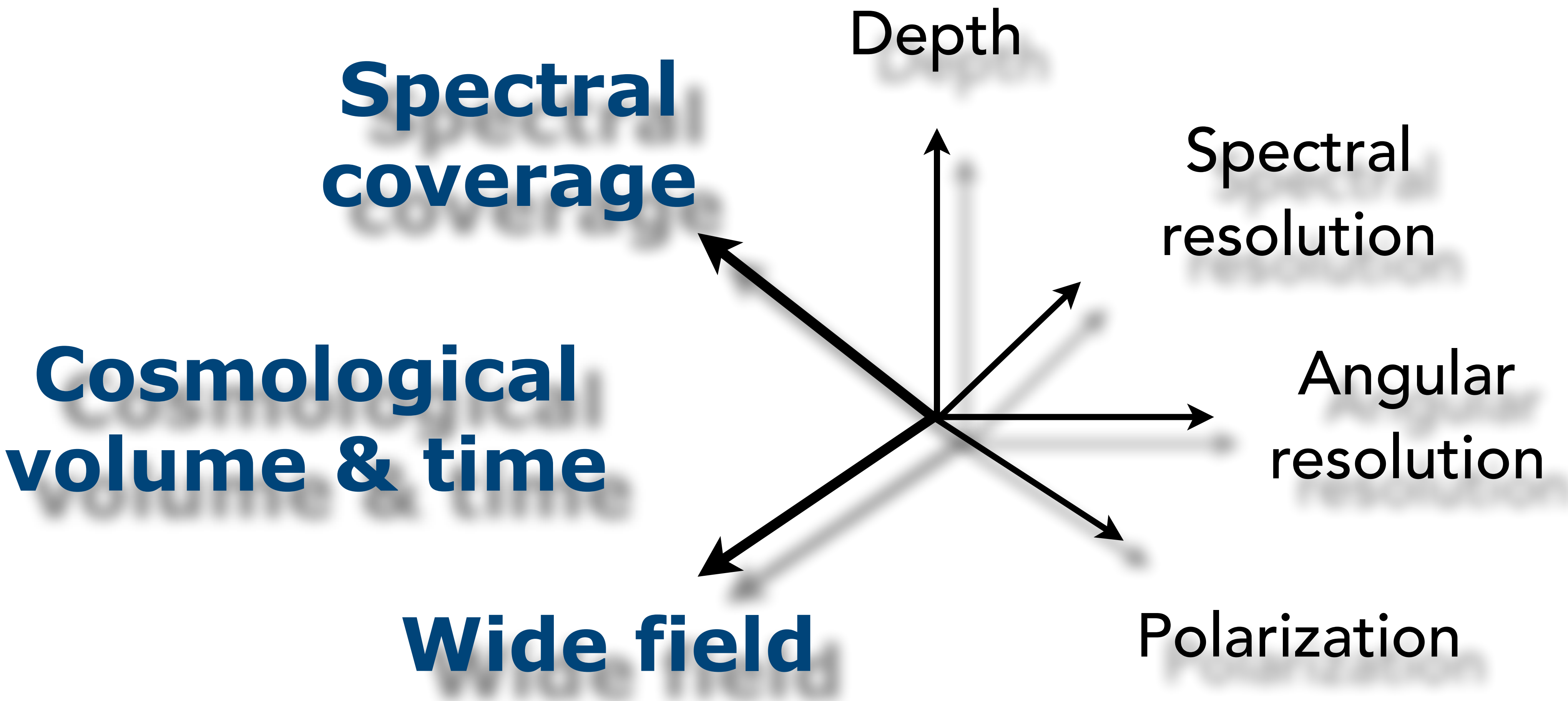


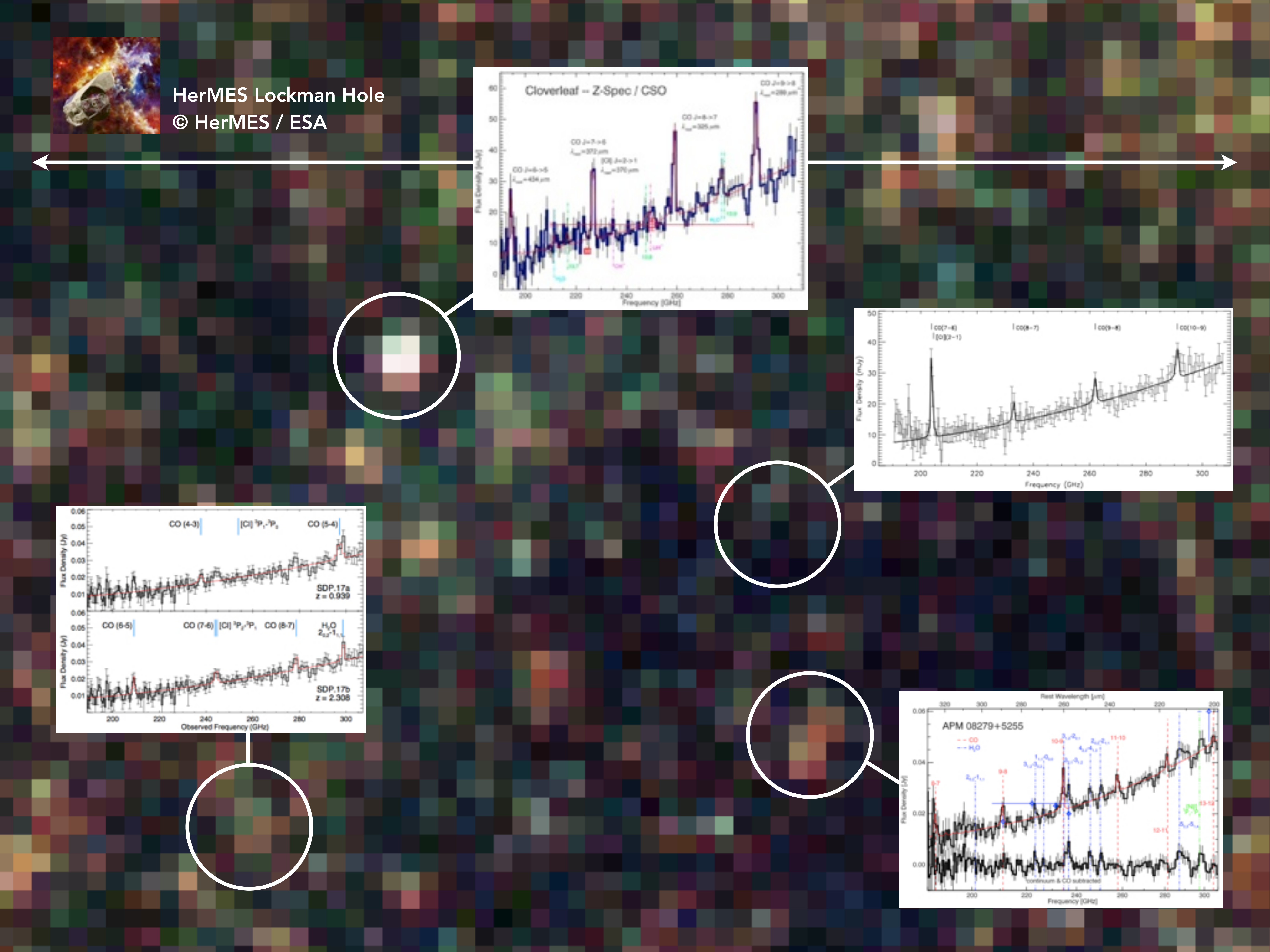


No turnover can be seen: observed galaxies reside in large HII bubble.

→ It is better to focus on large-scale power spectrum (at least for a while).

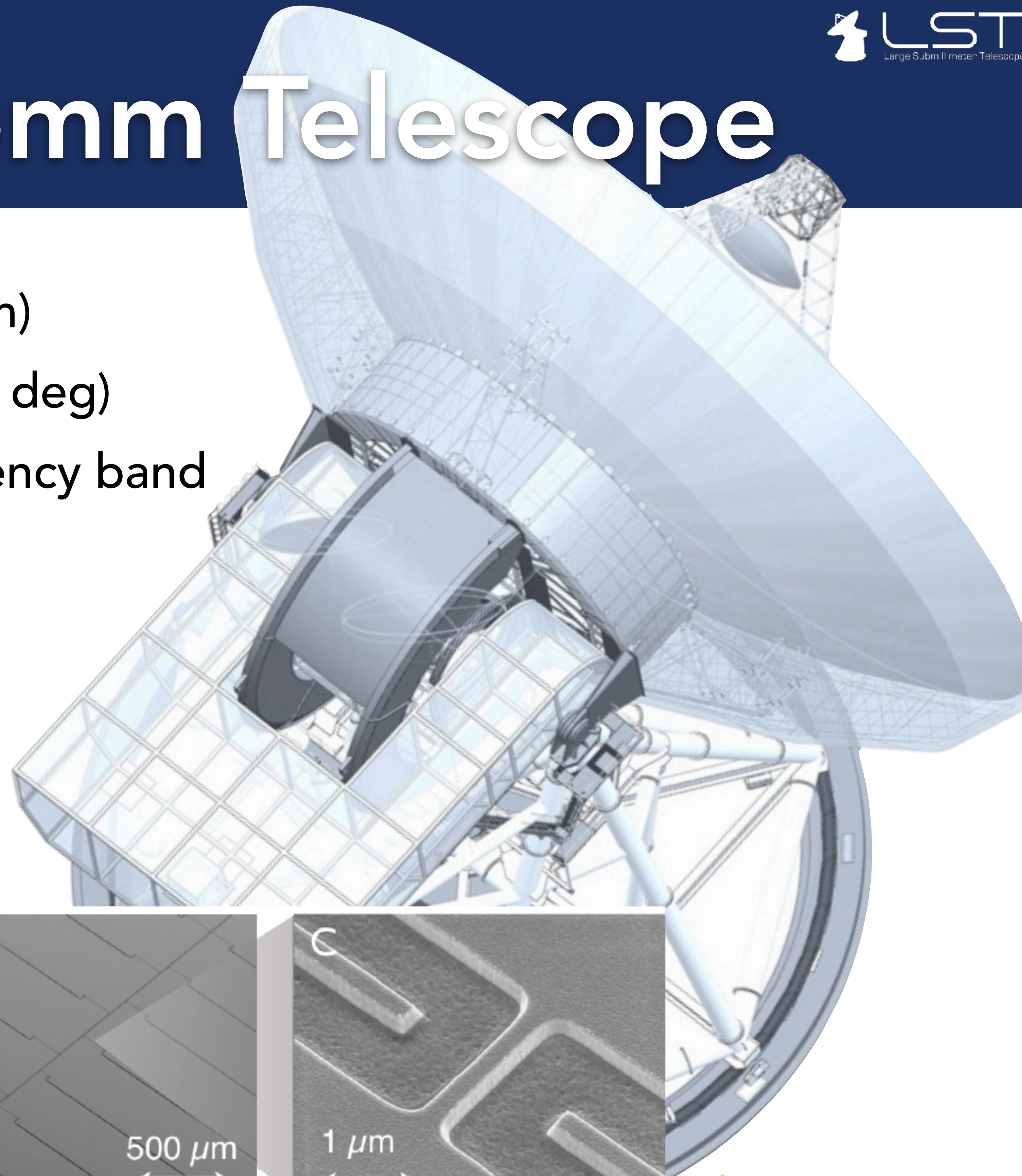
New discovery space?




HerMES Lockman Hole
© HerMES / ESA
Cloverleaf – Z-Spec / CSO
Flux Density [mJy]
Frequency [GHz]
Flux Density (mJy)
Frequency (GHz)
CO (4-3)
CO (5-4)
CO (6-5)
CO (7-6)
CO (8-7)
Flux Density (Jy)
SDP.17a
z = 0.939
SDP.17b
z = 2.308
Observed Frequency (GHz)
Rest Wavelength [μm]
APM 08279+5255
Frequency [GHz]

Large Submm Telescope

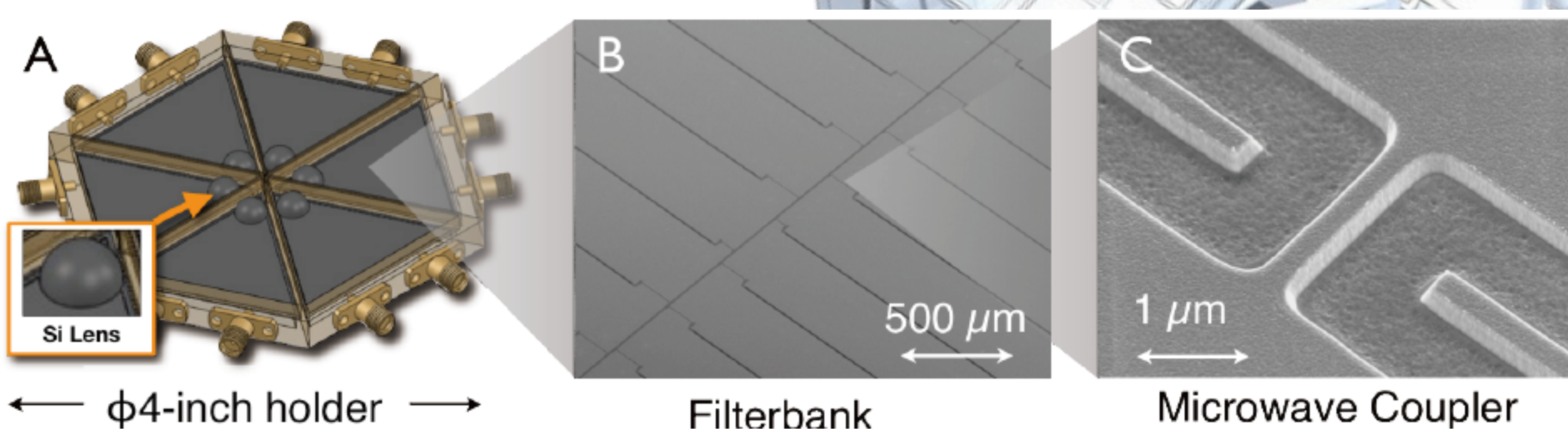
- Large aperture (D = 50 m)
- Wide field of view (> 0.5 deg)
- Long-submm/mm frequency band
- Survey-oriented



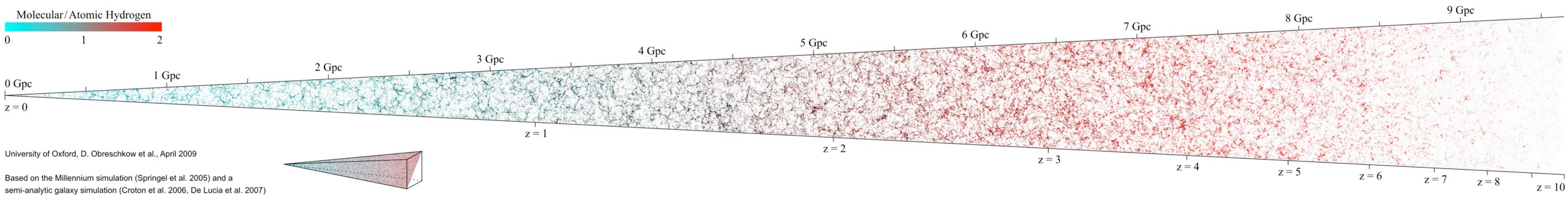
DESHIMA

Deep **Sp**ectroscopic **Hi**gh-z **Ma**pper

(Endo et al. 2011)

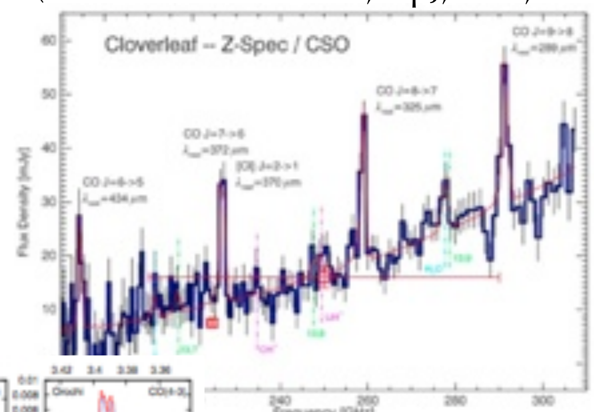


SKA Design Studies – Virtual Hydrogen Cone

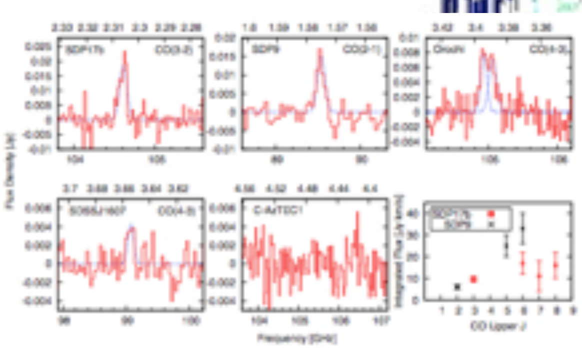


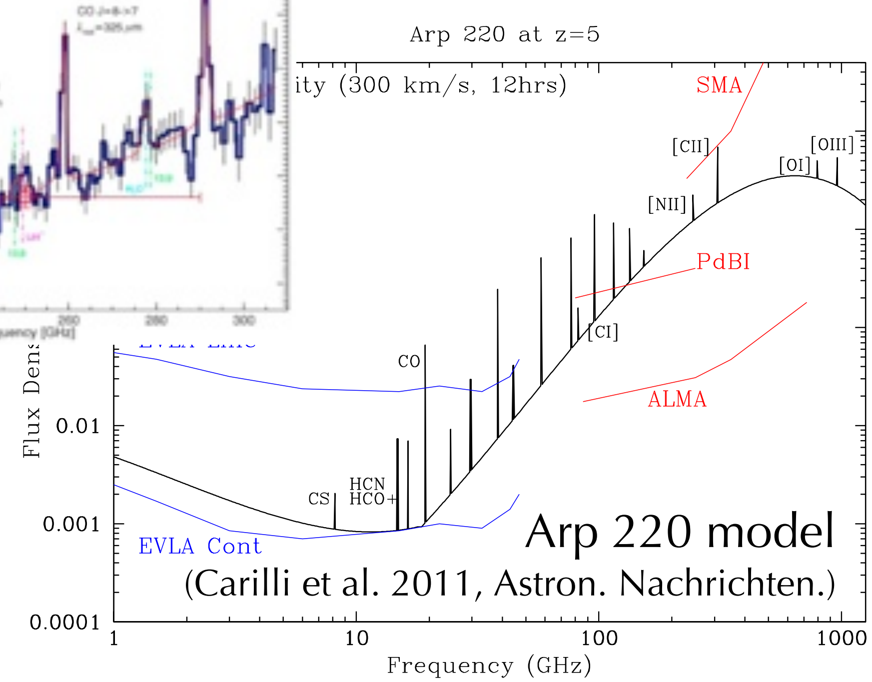
CO/[CII]/[OIII] Tomography

Cloverleaf QSO at z=2.6
(Bradford et al. 2009, ApJ, 705, 112.)

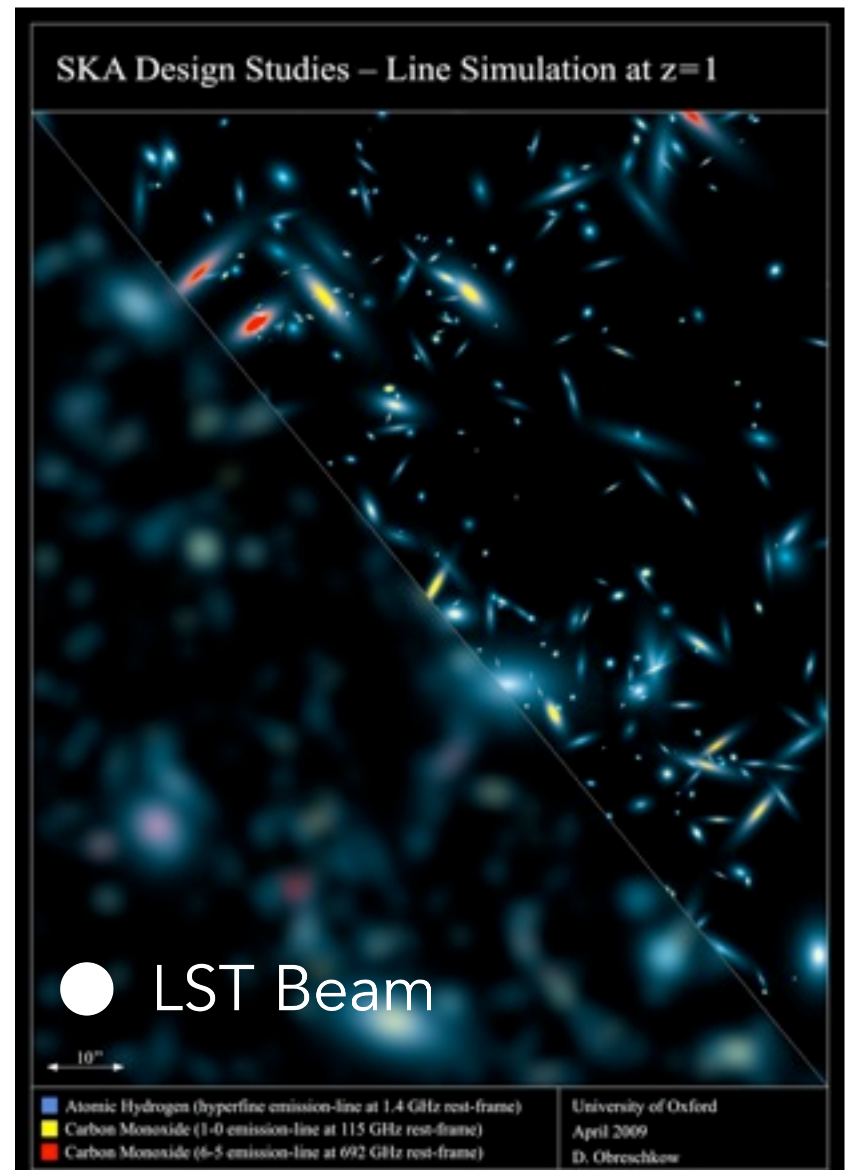


CO in SMGs w/ NRO45m
(Iono et al. 2012, PASJ)

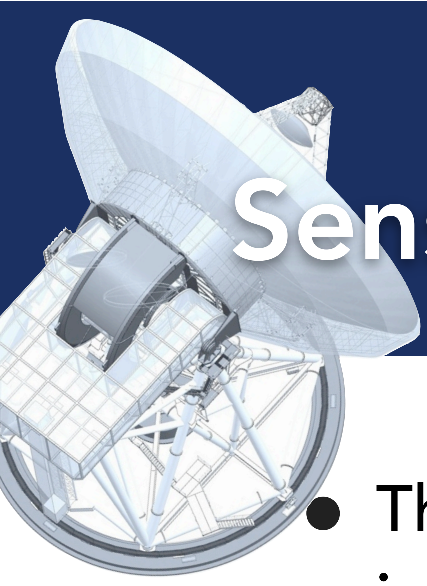




Arp 220 model
(Carilli et al. 2011, Astron. Nachrichten.)

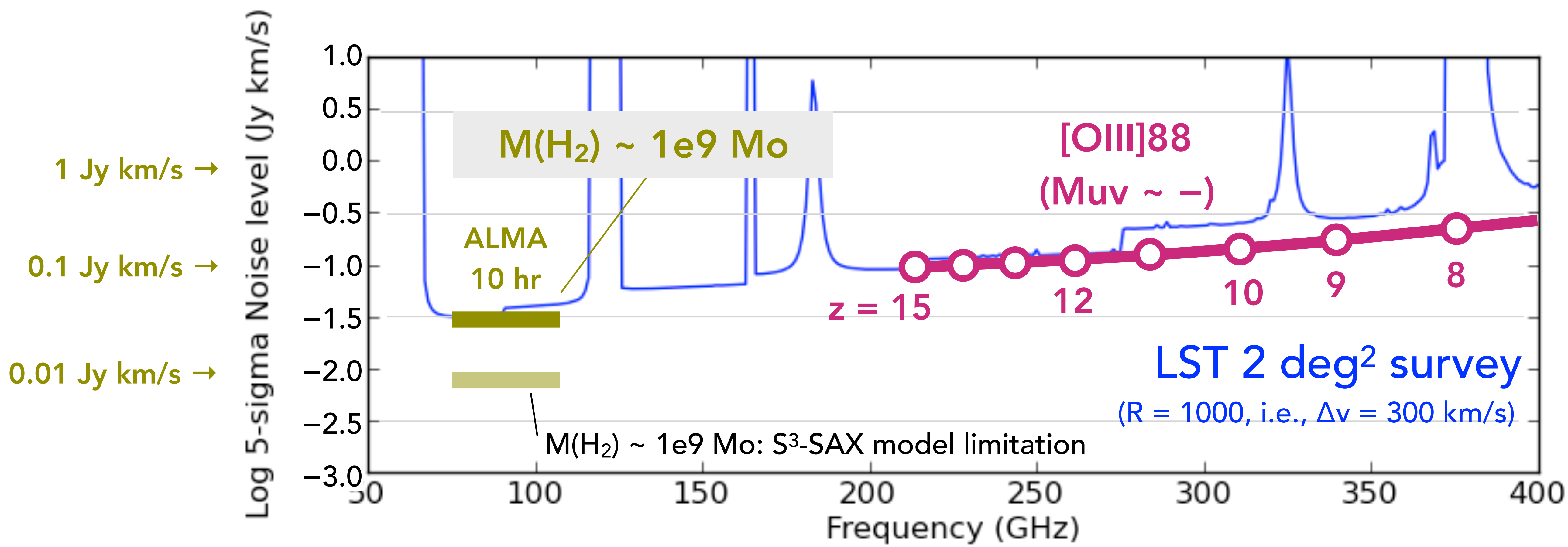


CO/[CII]: representative emission lines in mm-FIR.
Benefit from negative k-correction of CO ladder and FIR lines.
Overcome the confusion problems.

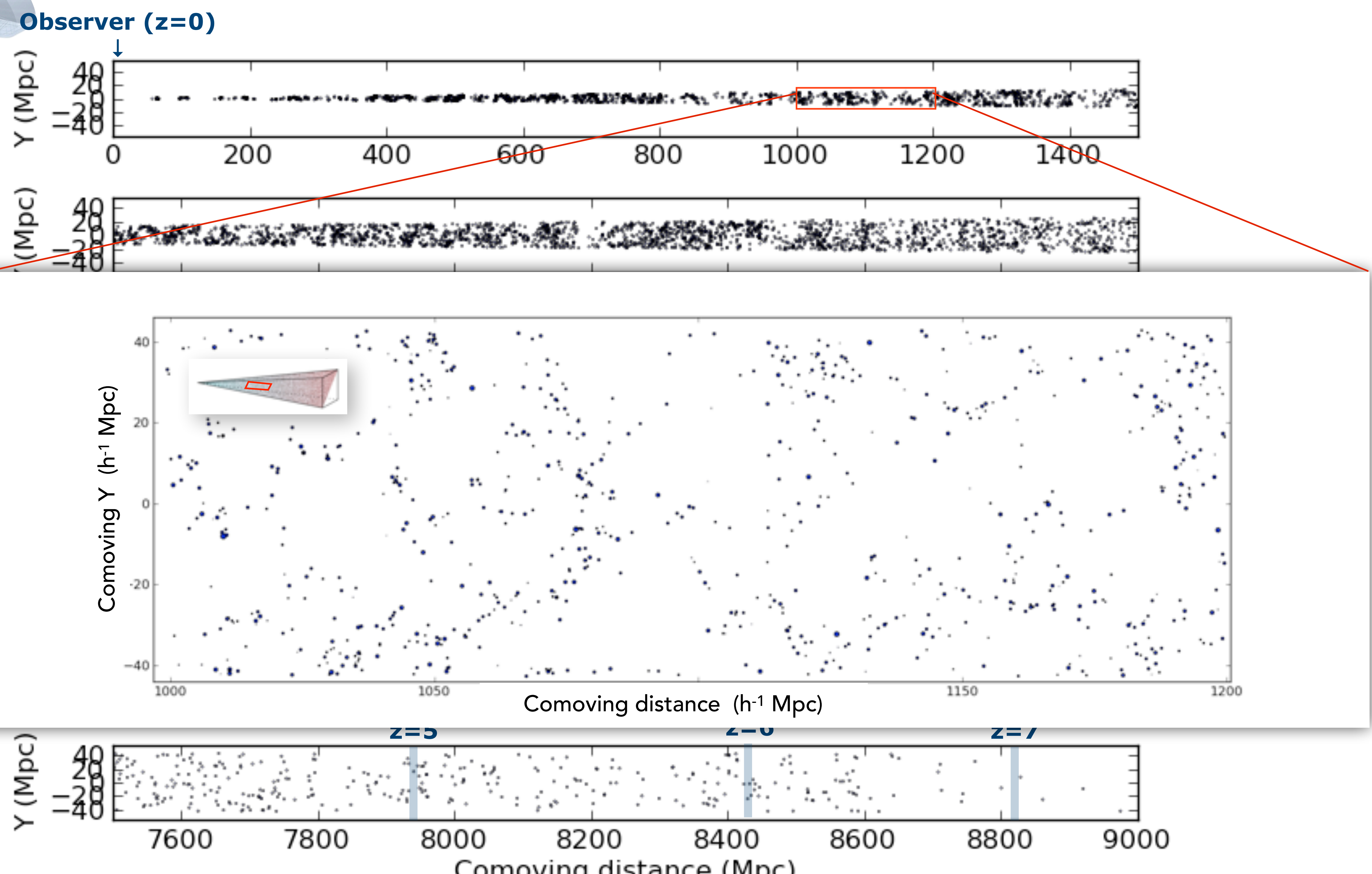


Sensitivity-Limited Survey with LST

- The depth achieved in the 2 deg^2 survey is comparable to that obtained in a 10-hr ALMA observation, but the survey area is ~13000 times larger than the ALMA FoV at 3 mm.
- The survey can detect the MW-like galaxies at z ~ 2.



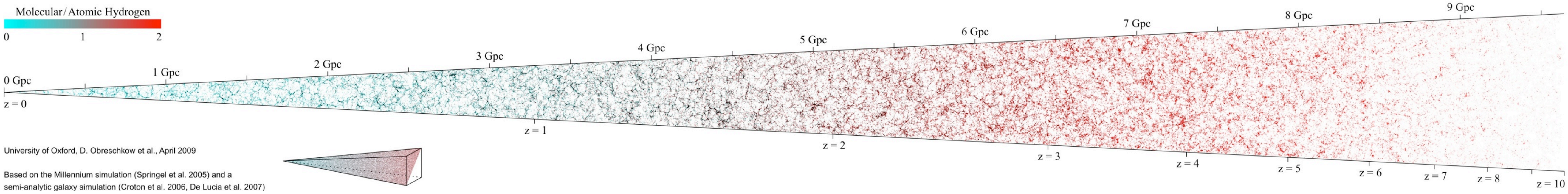
Light cone from the LST 2-deg² Survey



10^5 galaxies across the cosmic time

10^3 galaxies in the epoch of reionization

SKA Design Studies – Virtual Hydrogen Cone



CO/[CII]/[OIII] Tomography

RSD Redshift Space Distortion

Verify GR by estimating the growth rate of structure, dark energy problem

LSS Cosmic Large-Scale Structure

Investigate the correlation between dark and baryonic matters from clustering analysis, dark matter problem

CSFH Cosmic Star-formation History

Investigate mass/luminosity function of molecular gas as a function of redshift, "hidden" history of baryonic matter

EoR Epoch of Reionization

Search for earliest "hidden" galaxies, first generation galaxies

Evolution of Galaxies

Cosmic evolution of galaxies proved through properties of interstellar medium

... and serendipitous discoveries

Line emitters, transient and variables, ...

Summary

- サブミリ波によって、宇宙再電離期の銀河の ISM 物理状態・進化や星形成活動の変遷がわかってきた