ALMA reveals the early dust enrichment in a galaxy in the heart of the reionization era

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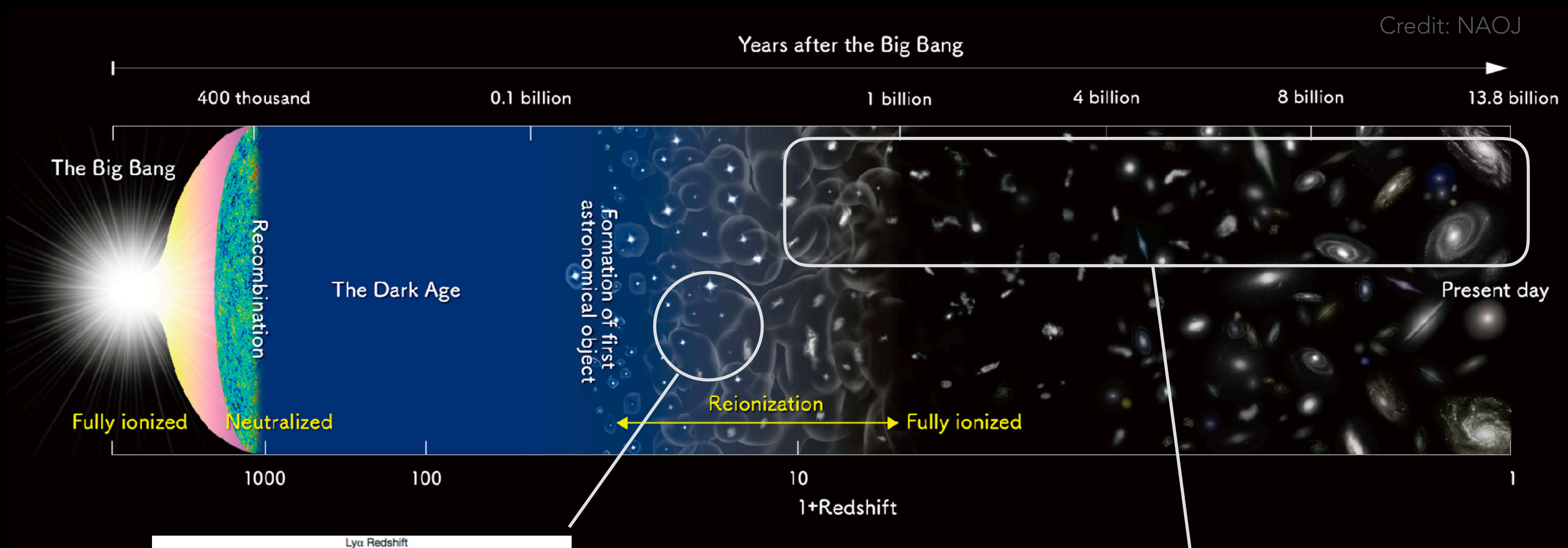
Chile/Latin America - Japan Academic Forum 2018
Nikko, 25 Sep 2018

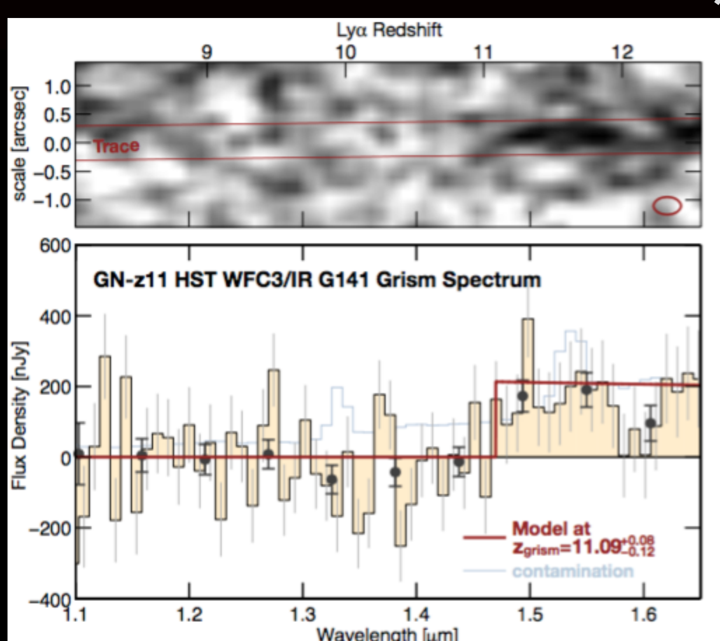
Radio Astronomy Group (A-Lab) at Nagoya U

- Astrophysics lab (A-lab; radio astronomy)
  - 4 faculty members, 8 PDs, 18 graduate students
- Nanten2 submillimeter telescope: Galactic molecular clouds
- "Experimental" galaxy research group (since 2017)
  - High-z studies with ALMA
  - Instrumentation for ASTE 10m (**DESHIMA**), LMT 50m (**MOSAIC**), Millimetric AO for LST/AtLAST 50m

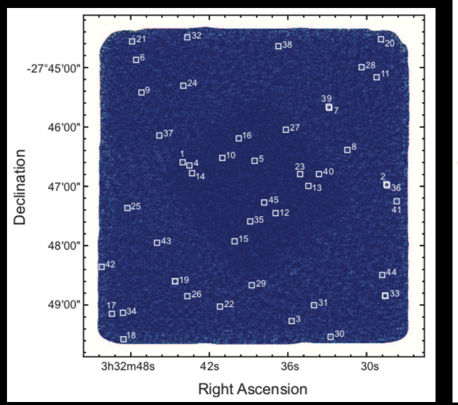



Frontiers in extragalactic astronomy

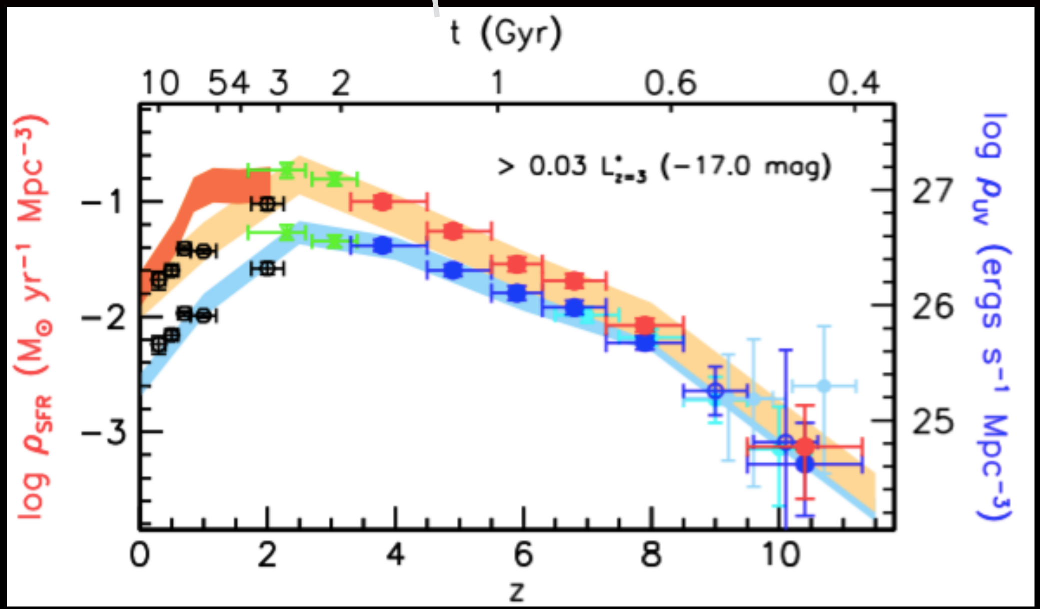




z ~ 11.1 galaxy! (Oesch et al. 2016)



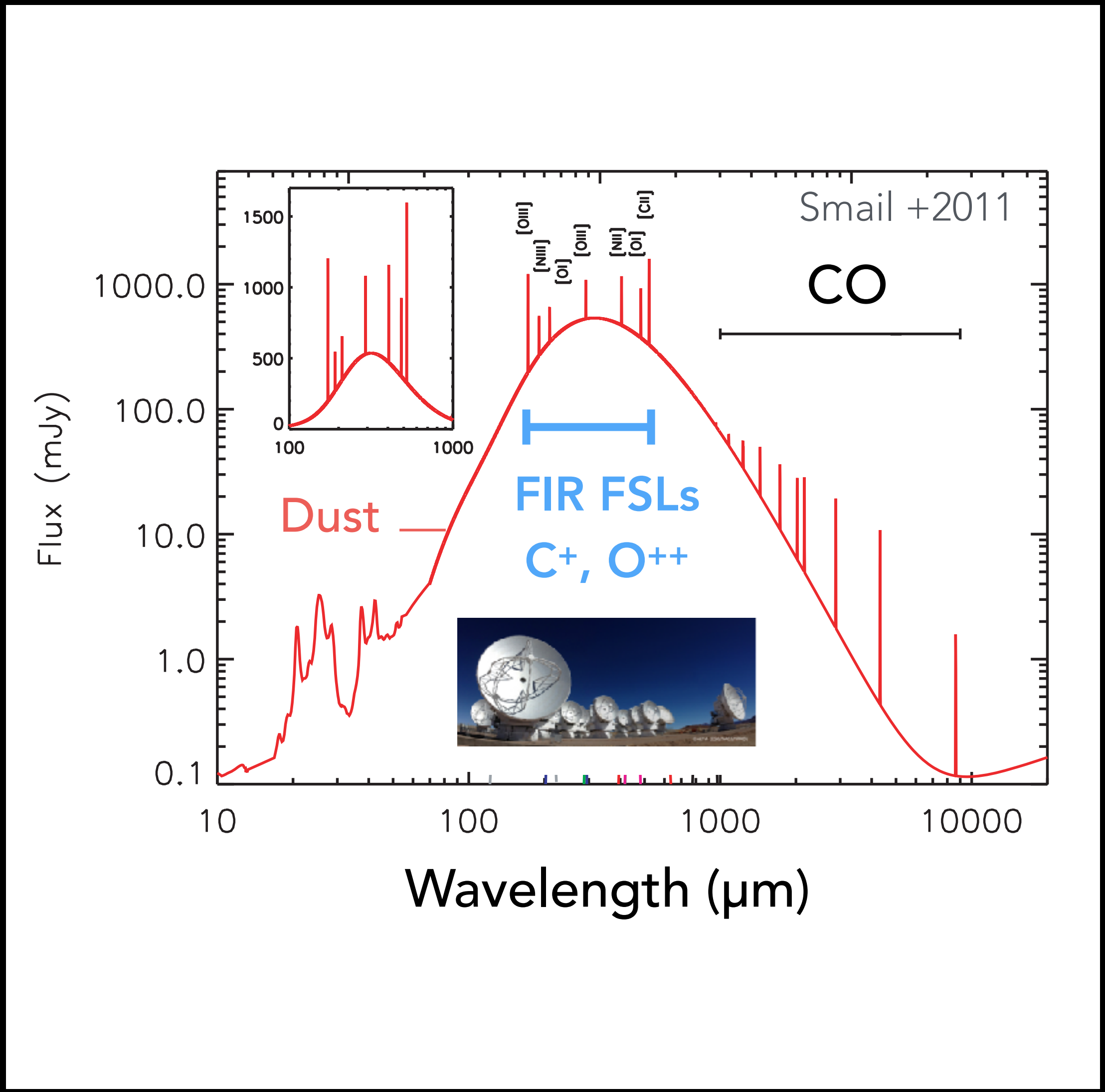
ALMA Deep Survey
(Hatsukade+)

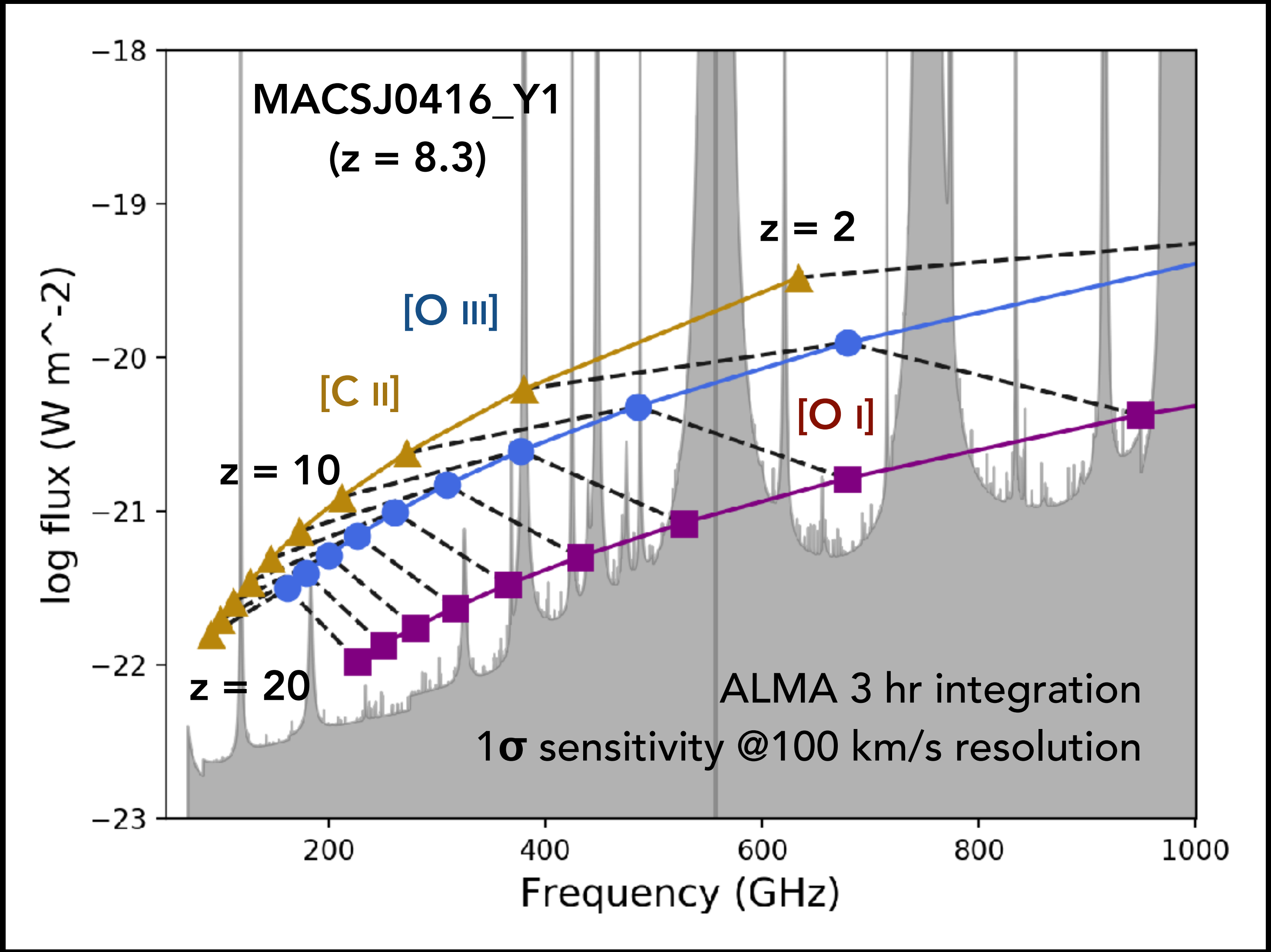


Cosmic SFRD (Bouwens et al. 2015)

Far-Infrared Fine-Structure Lines

- Brightest lines in the FIR: [C II] 158um, [O III] 88um, [O I] 63um
- Probe physical properties of ISM (ionization state, metallicity)
- Reach z = 20. Competitive with JWST/NIRSpec C III]1909A

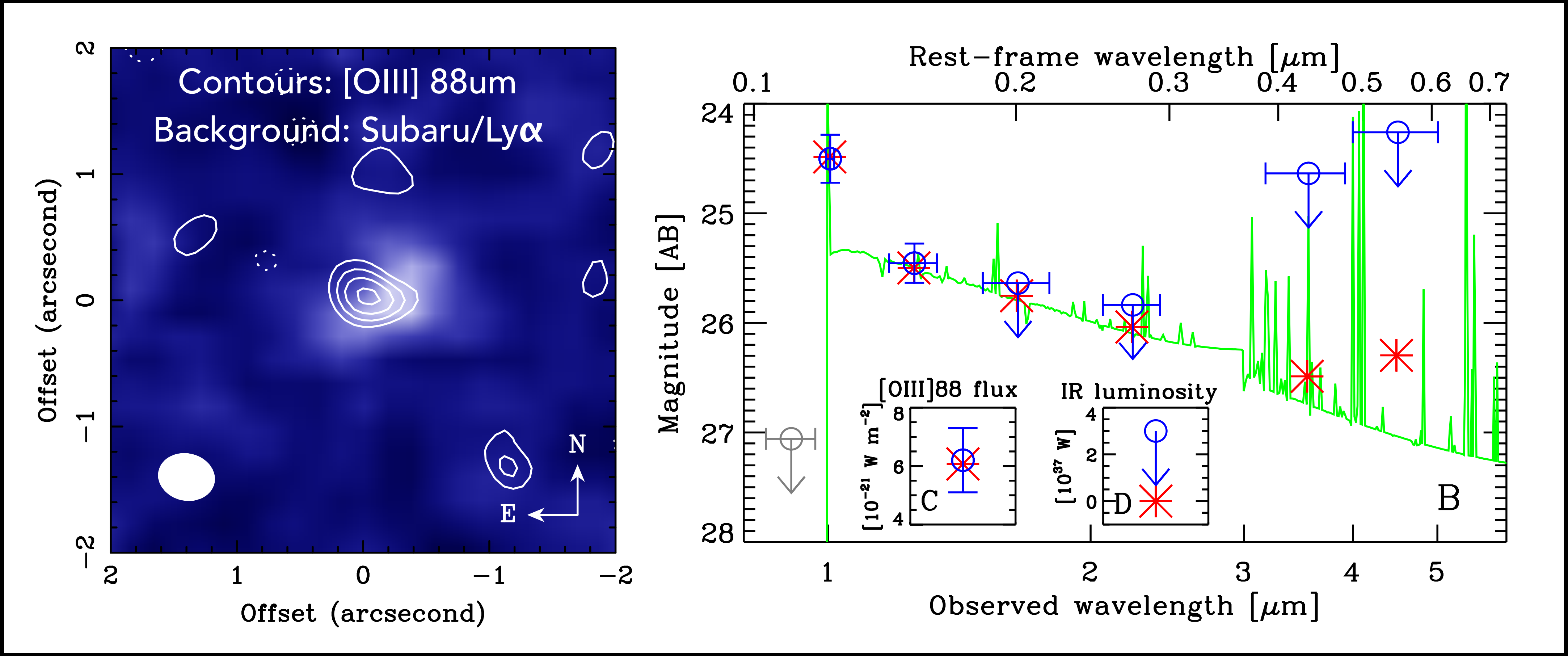




First detections of [O III] in the reionization era

SXDF-NB1006-2 at z = 7.215

Inoue, YT+16, Science, 352, 1559

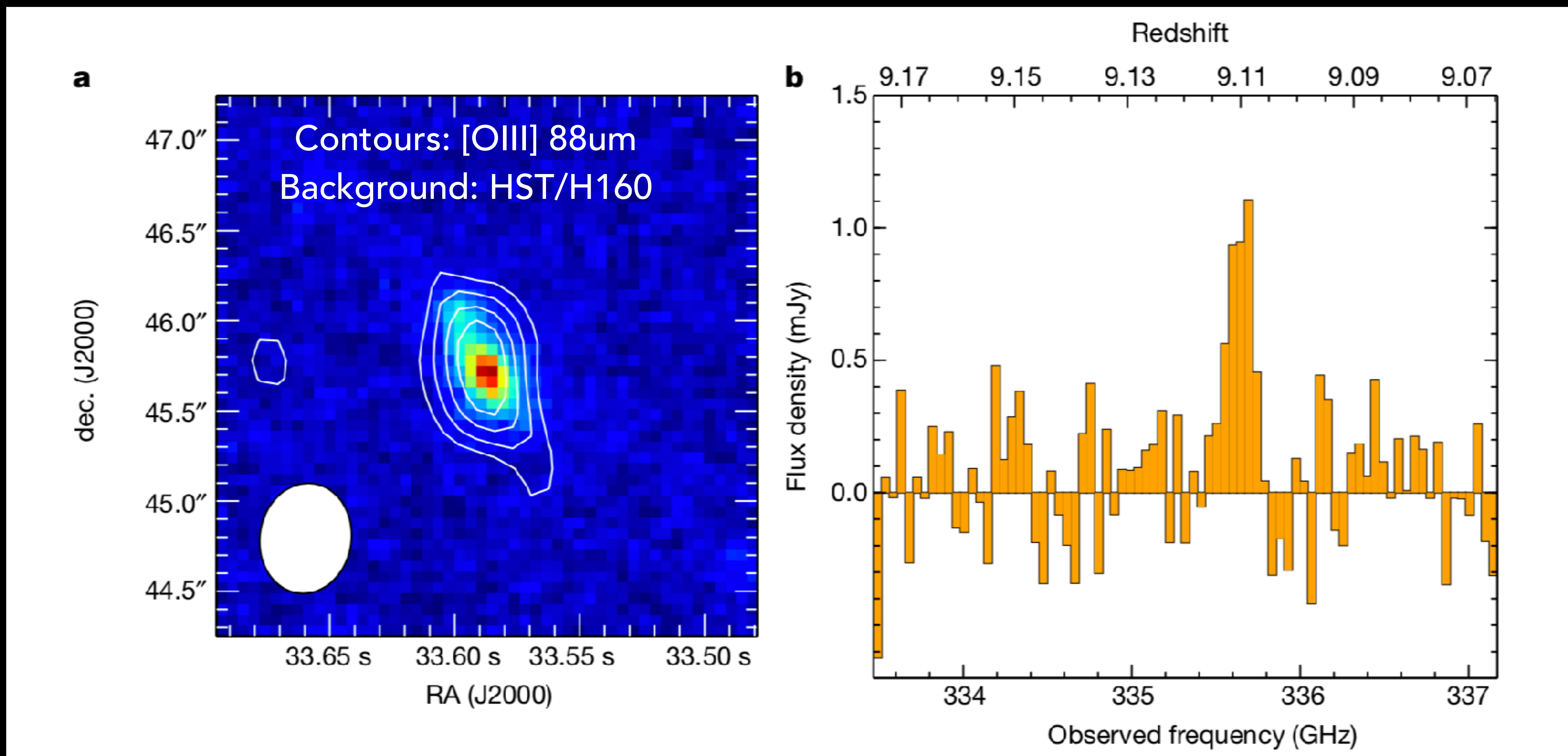


- Young star-forming metal-poor galaxy
  - Age < 30 Myr, SFR ~ 300 Mo/yr, Z = 0.05–1 Zo
- No [C II] and dust emission were found.

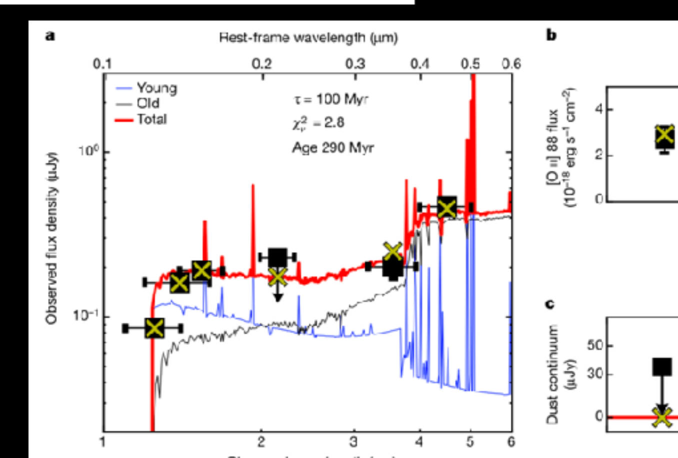
Furthest detection of [O III] at z = 9.1096

MACS1149-JD1

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

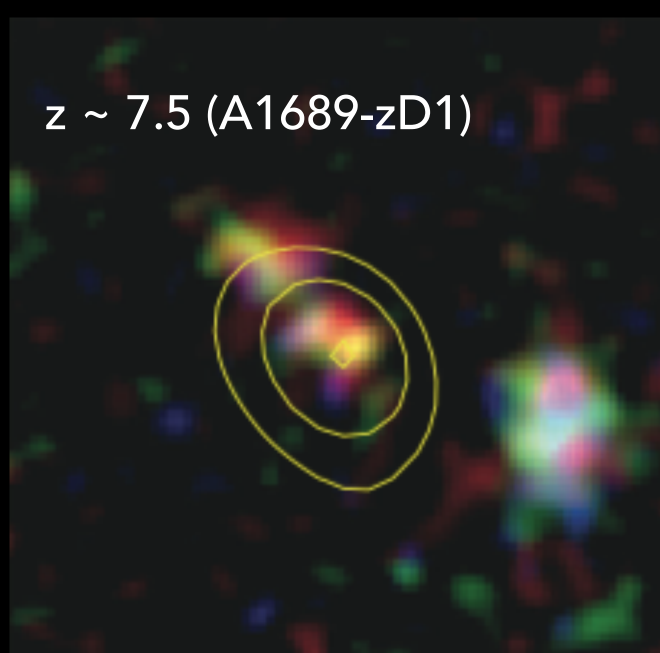


- Low-mass star-forming galaxy
  - Age = 290 Myr, SFR ~ 4 (μ_g/10)$^{-1}$ Mo/yr, Z = 0.05–1 Zo
  - No dust emission

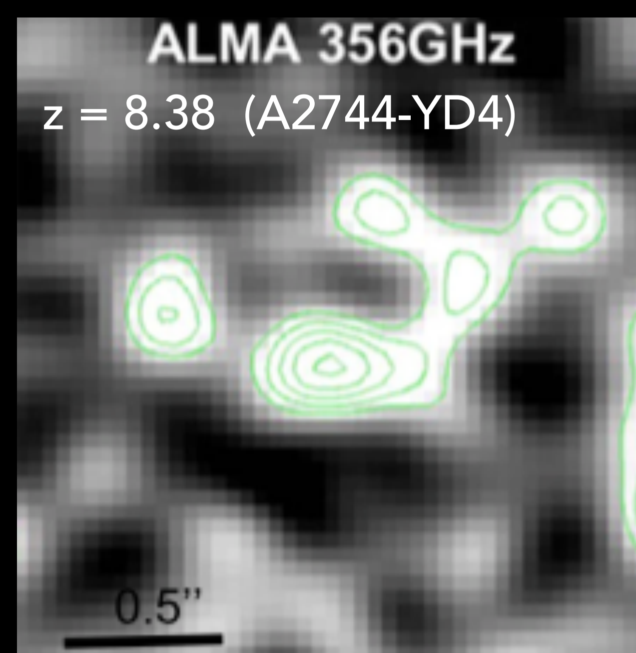


Early dust production

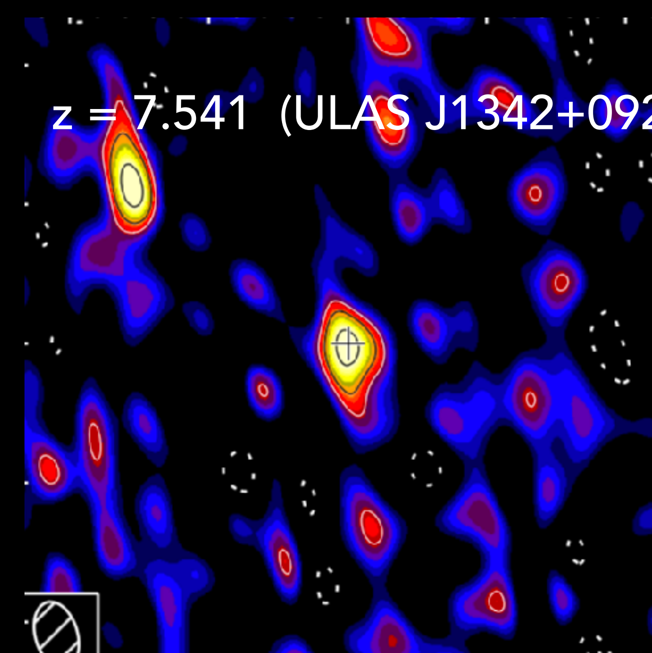
- Diversity in dust contents in EoR
  - Small dust mass in LAEs (e.g. Ouchi+13, Ota+14, Inoue & YT+16)
  - Large dust mass of ~10^7 $M_\odot$ in LBGs (Watson+15, Laporte+17)
- **Dust budget crisis**: How galaxies got dust so quickly?
  - Type II SNe is the major contributors to dust mass at z > 8
  -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



Watson+2015, Nature



Laporte+2017



Venemans+2017

Motivations

Key questions:

Can ALMA really serve as “z-machine” at $z > 8$?

How and when metal enrichment happened?

Why dust exists in the earliest universe?

↓

Purpose:

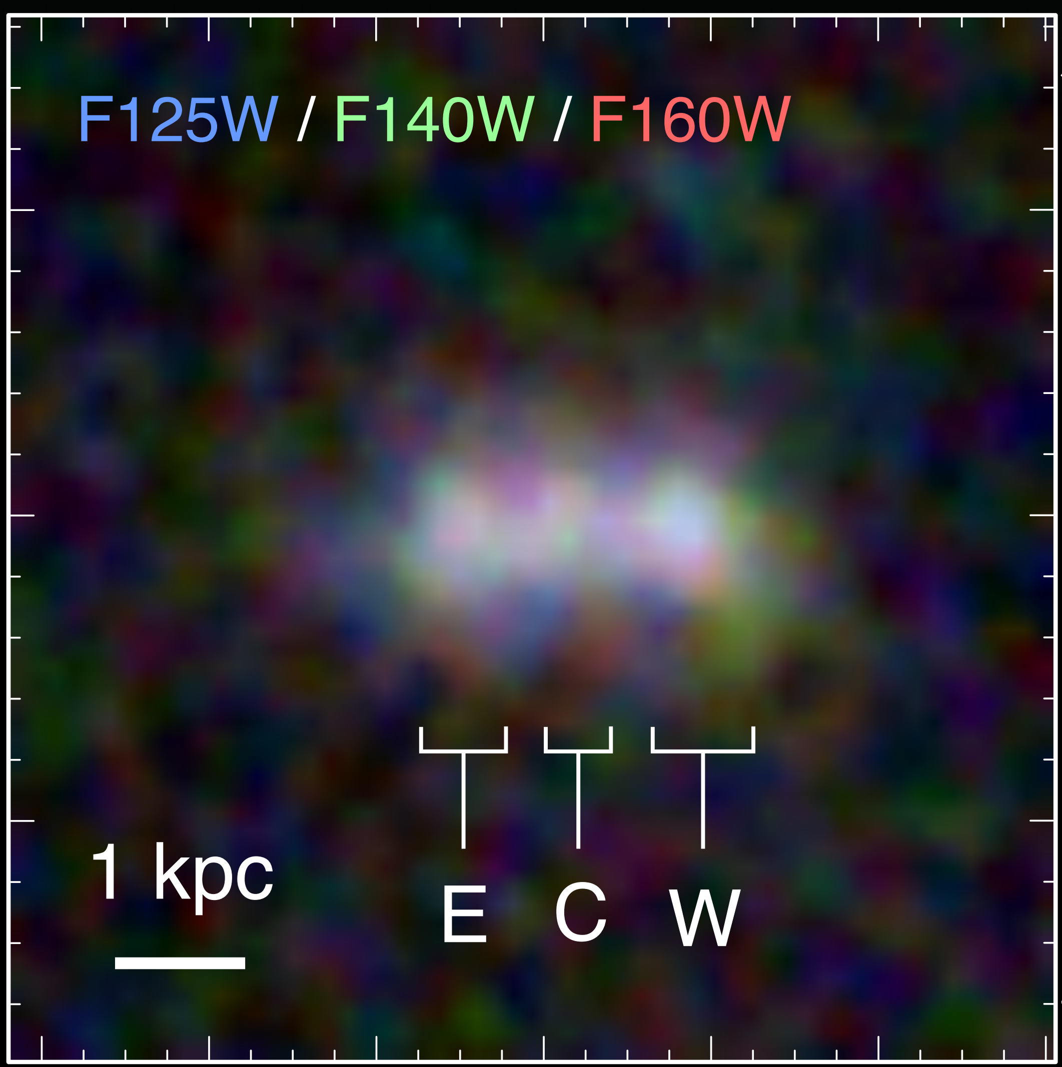
ALMA observations of a galaxy at EoR

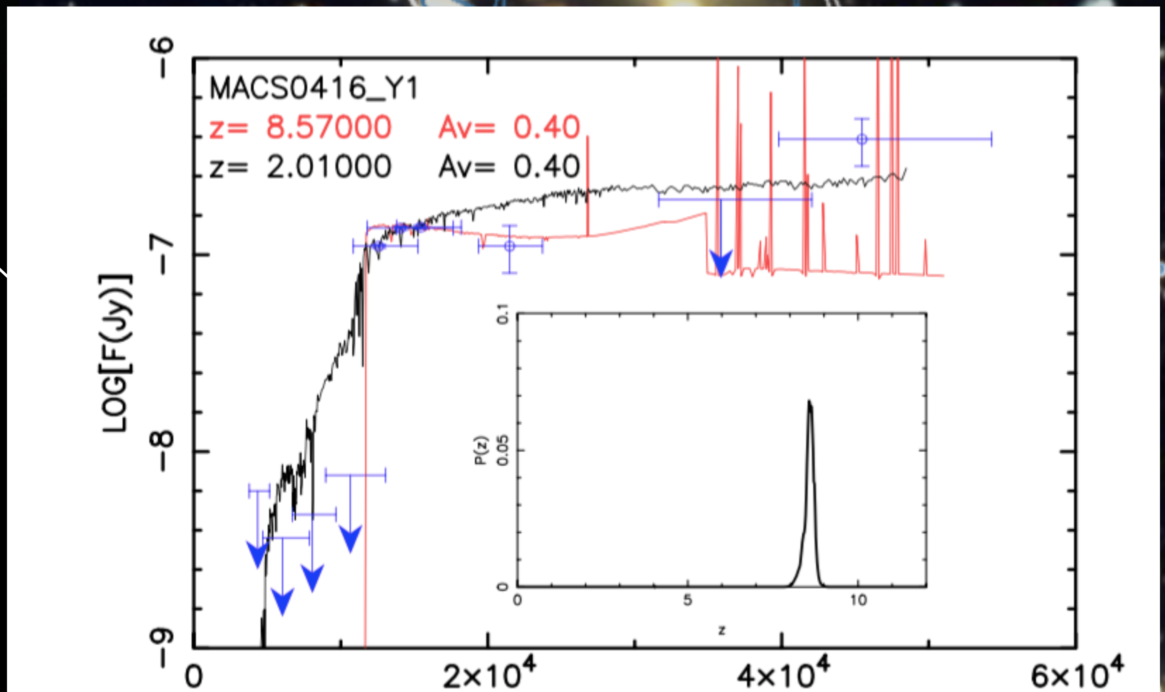
SED modeling with [OIII] + dust

Dust formation / destruction modeling

Target: Frontier Field 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)

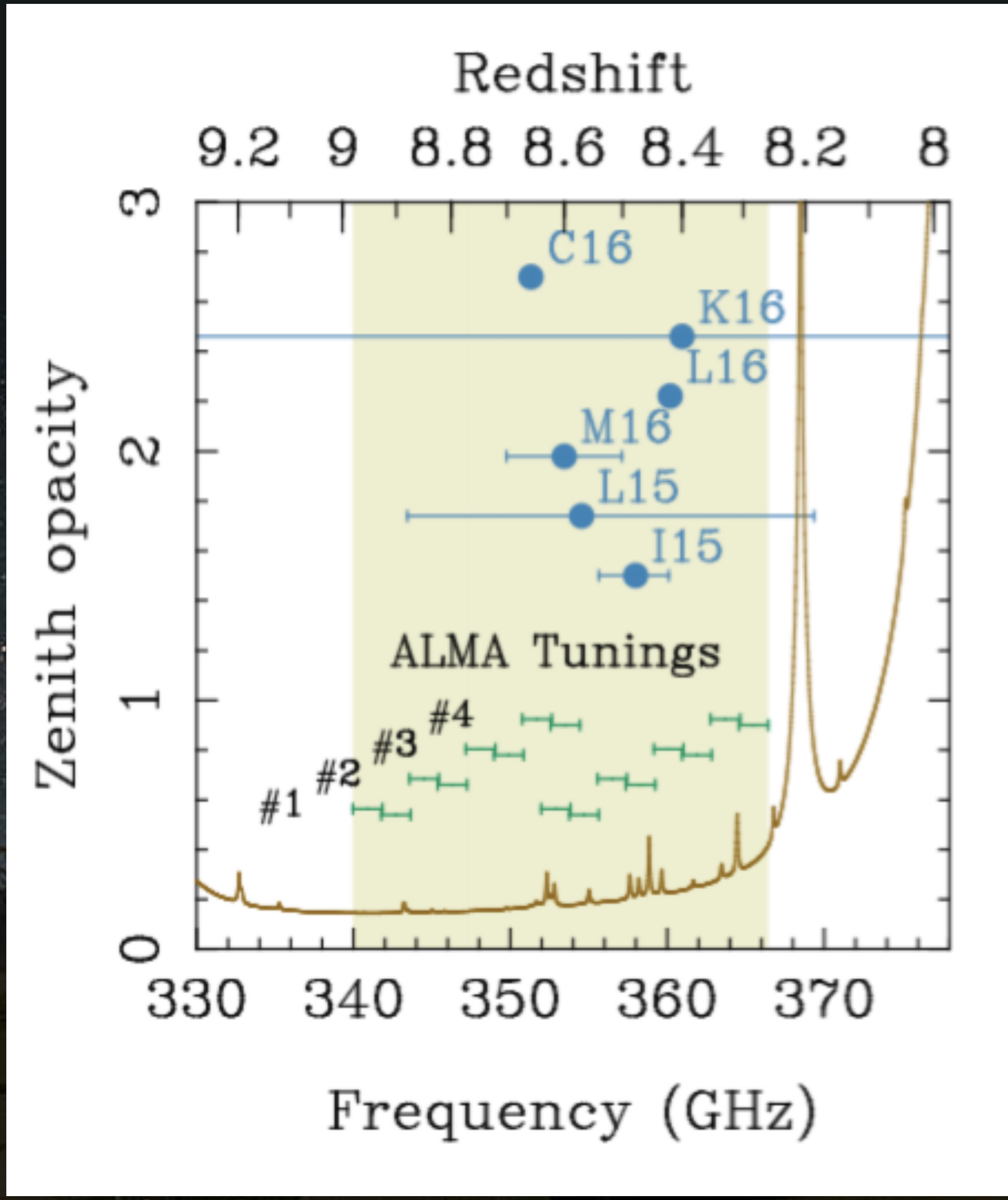




Laporte et al. (2015)

ALMA Observations (Cycle 4)

- 2016-Oct … 2017-Jul
- Band 7 (340–366 GHz, 850 um)
- **4 tunings (Δz = 0.72)**
- Beam size ~ 0.1–0.2 arcsec
- t_integ ~ 2 hr/tuning
- Imaging
  - CASA (v.4.7)
  - 0".1 tapered
  - 1σ = 10.9 uJy/B (continuum)
  - 1σ = 0.5 mJy/B (line)

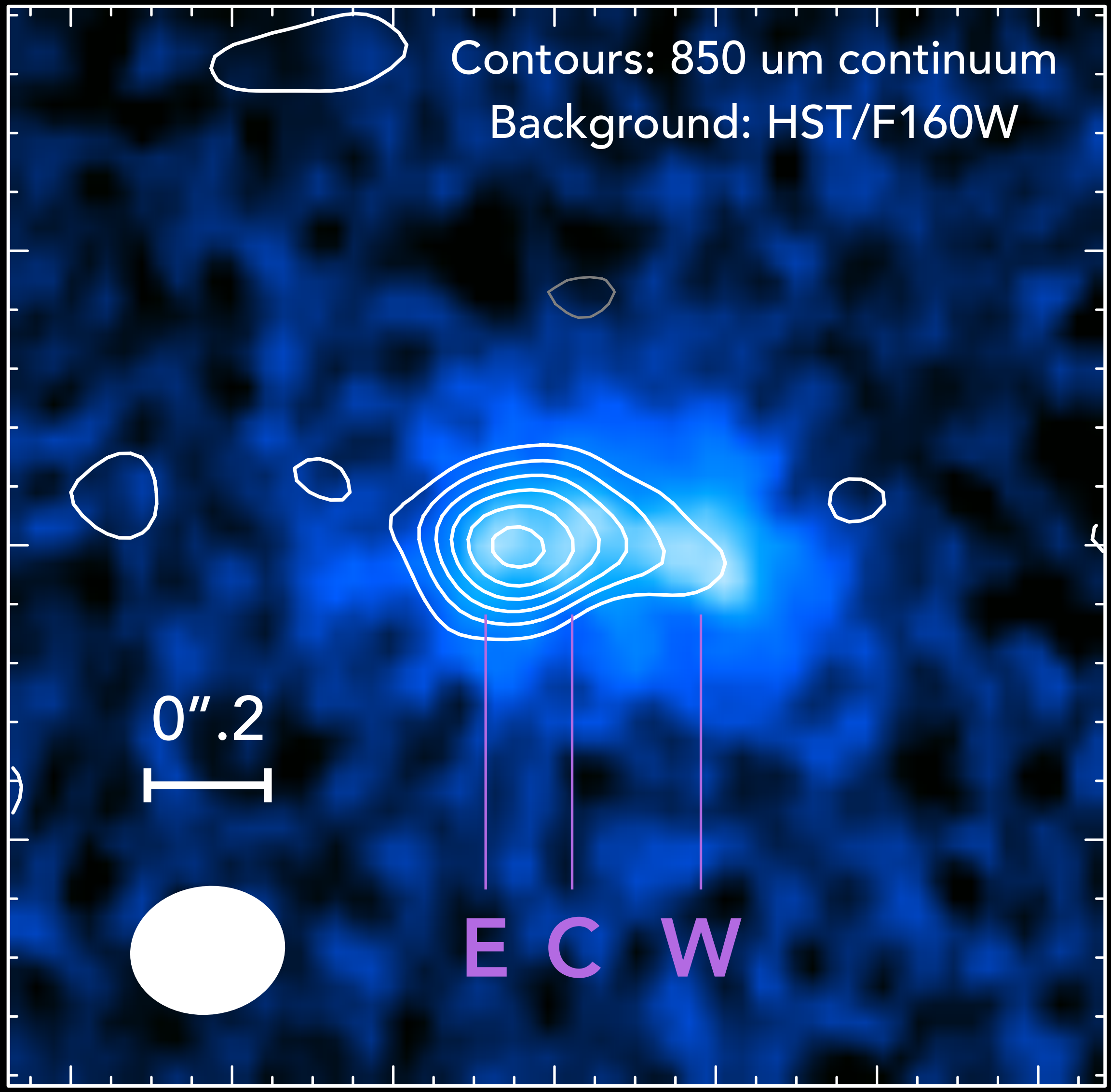


ALMA proposal (YT+)

Credit: ALMA/ESO/NAOJ/NRAO

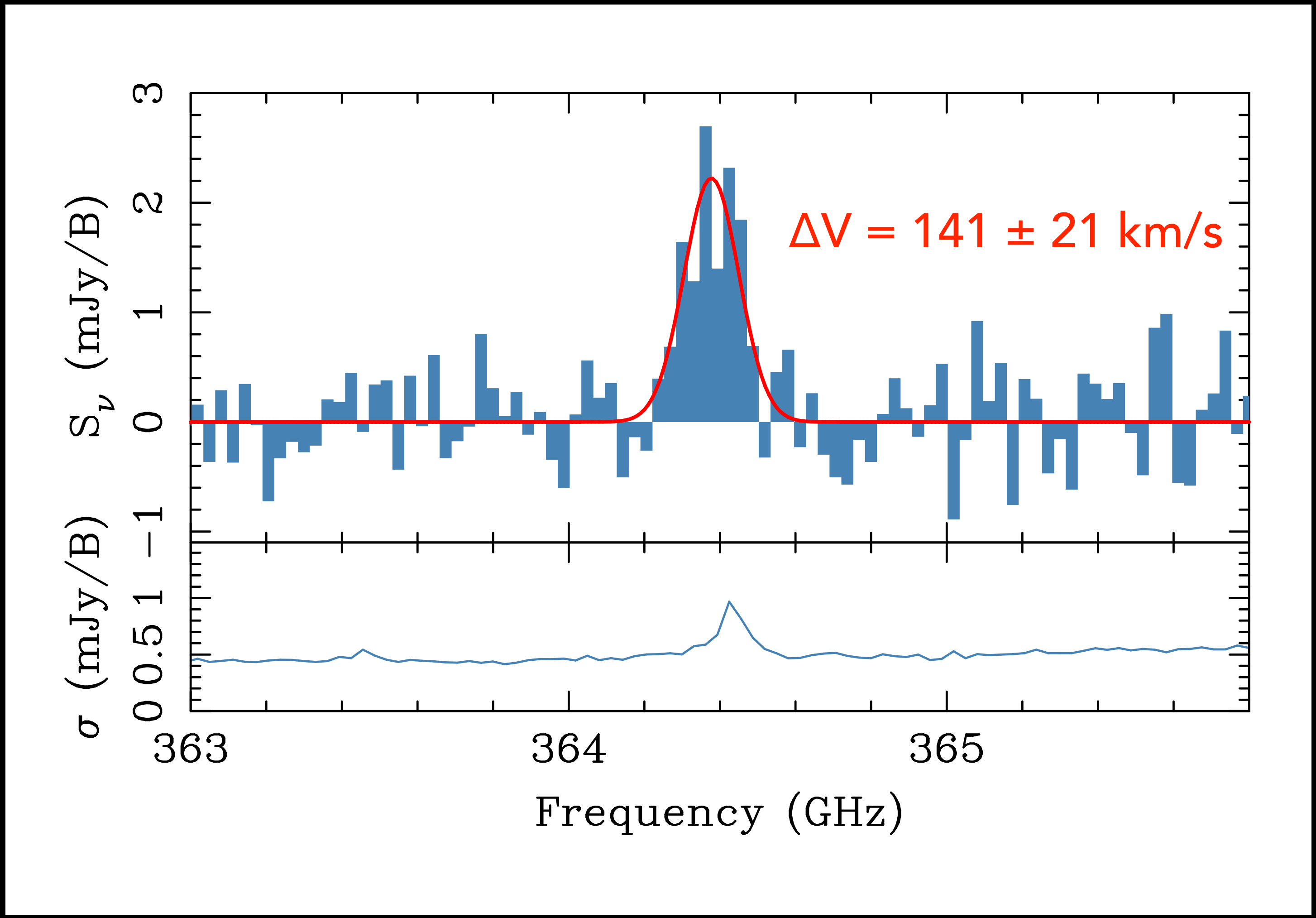
Results: Dust detection at S/N = 7.6

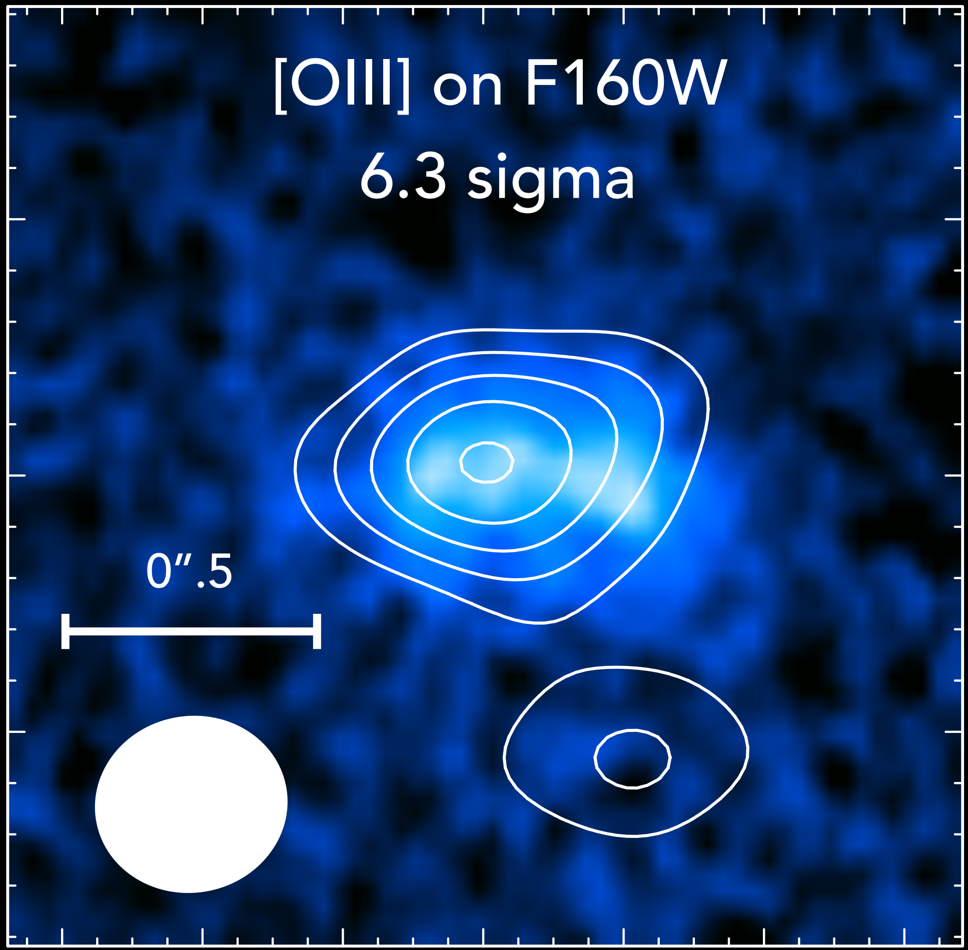
- Second detection of dust at z > 8
  - S_850um = 137 ± 26 μJy
- Spatially resolved
  - Size: 0″.36 × 0″.10 = 1.7 × 0.5 kpc
  - Tracing UV emission
  - Peak at/between E-C clumps
- Large dust mass
  - assuming T_dust = 50 K, β = 1.5…
  - L_TIR = (2.4 ± 0.5) × 10^11 L⊙
  - M_dust = (0.5 ± 0.1) × 10^7 M⊙



YT+18, submitted

Yes, [OIII] can identify a spectroscopic redshift!





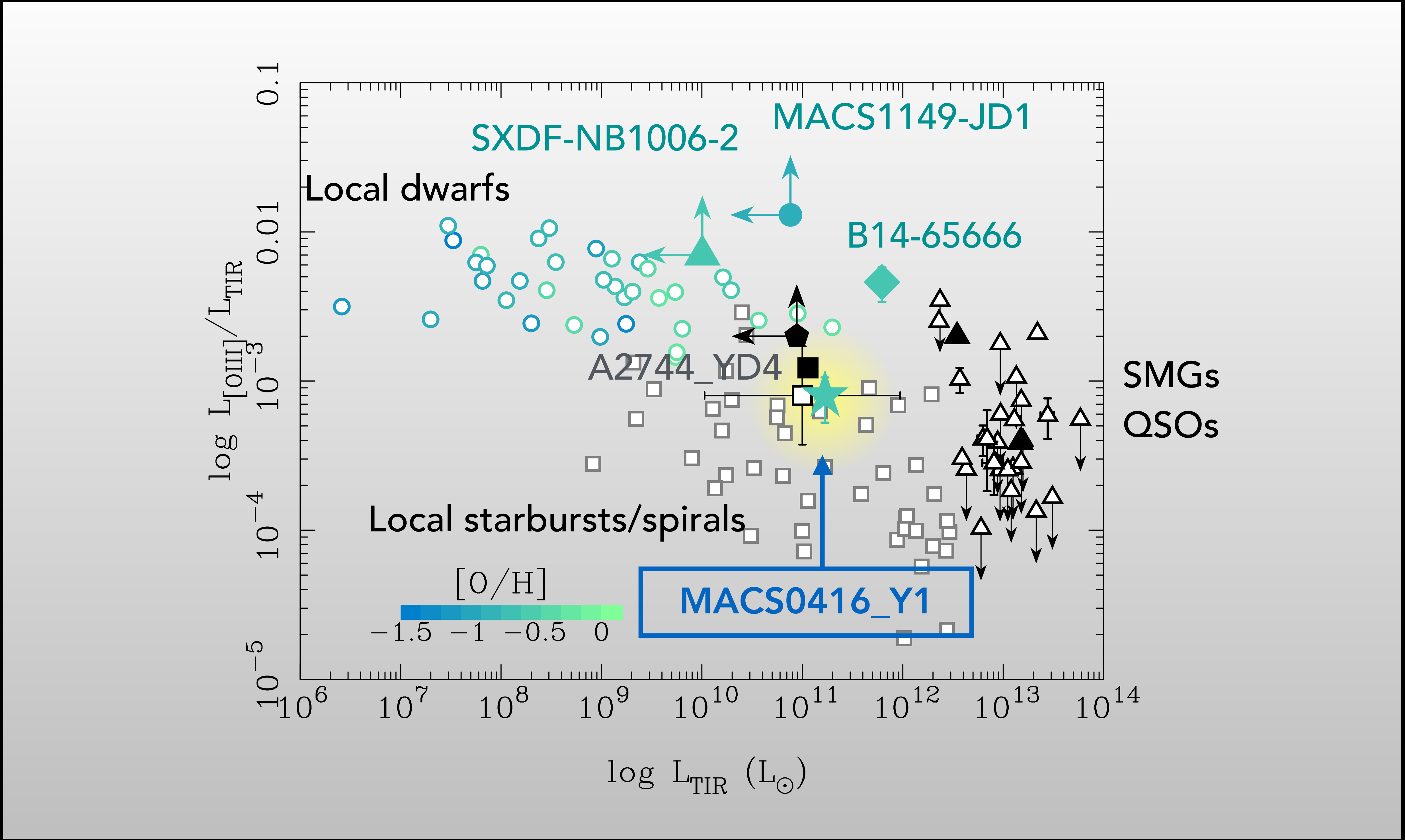
YT+18, submitted

- Spectroscopic redshift ***z = 8.3118 ± 0.0003***
- One of the furthest galaxies identified spectroscopically
  - z = 9.1096 (Hashimoto, YT et al. 2018, Nature)
  - z = 8.38 with S/N = 4.0 and ΔV ~ 40 km/s (Laprote+17)

Redshift Record

#	Redshift	Object	References	Telescope/Line	Dust?
1	9.110	MACS J1149-JD	**Hashimoto, YT+ (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+ (2018)**	**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	7.452	GS2_1406	Larson+ (2017)	HST/Lyα	n/a
10	7.212	SXDF-NB1006-2	Shibuya+(2012) **Inoue, YT+ (2016)**	Subaru+Keck/Lya **ALMA/[OIII]**	N

[O III]-to-IR Luminosity Ratio



- MACS0416_Y1 is (surprisingly!) similar to dusty starbursts.

Questions arise...

- **SED modeling**: How does "dust" coexist with UV SED?
  - Can dust emission and blue UV slope be explained self-consistently?
  - TIR + [OIII]88 should be a key (A.K. Inoue+16; Mawatari+, in prep.)

- **Dust budget crisis**: How did a galaxy get 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?

Purpose:

How and when metal enrichment happened?

Why dust exists in the earliest universe?

Stellar Population Synthesis Analysis

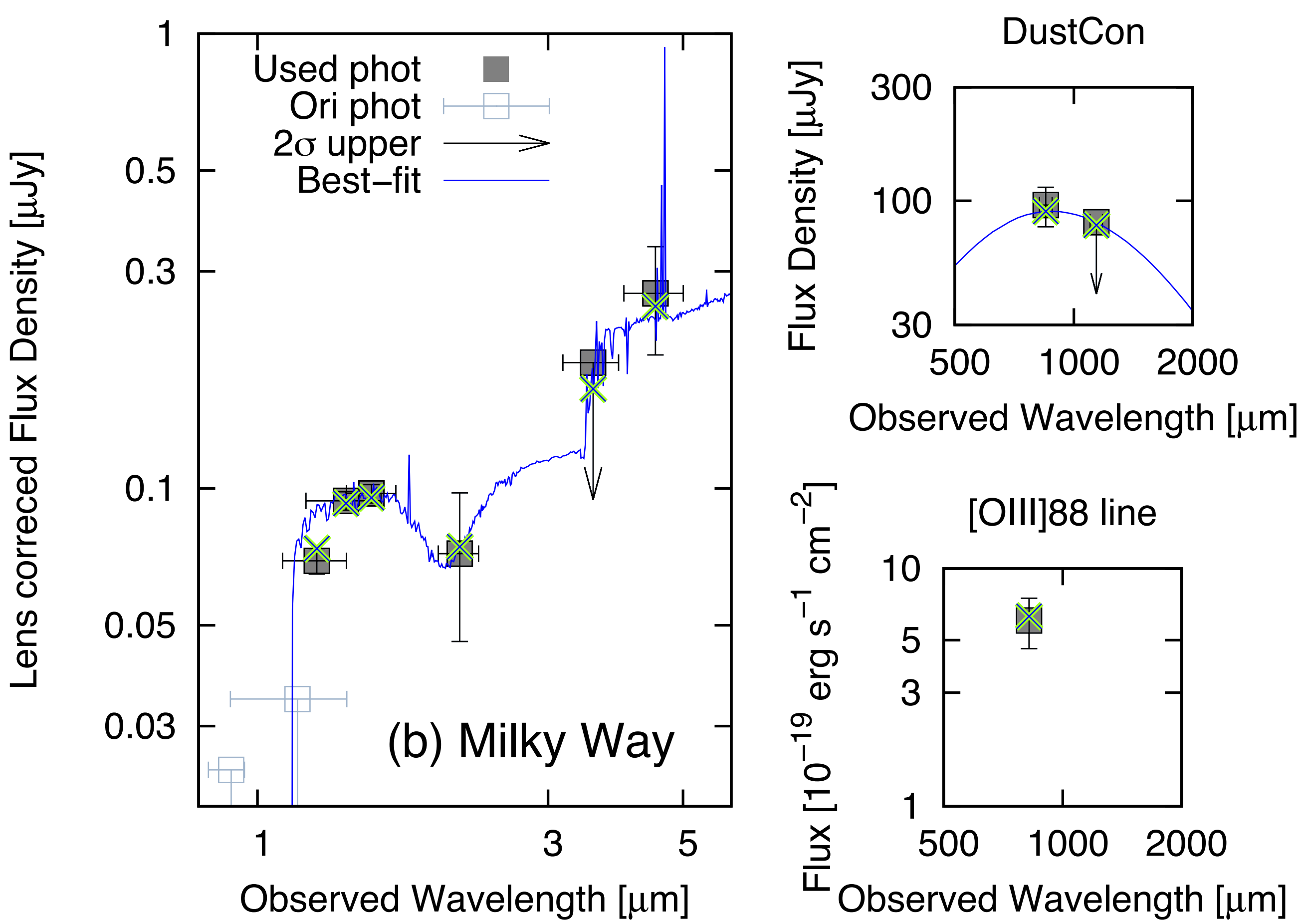
- Rest-frame UV-optical and FIR [OIII] + dust continuum
- Based on Mawatari+2016, 2019 (in prep)
  - Stellar: Bruzual Charlot 2003 (BC03)
  - Dust (FIR): Local LIRGs (Rieke+09)
  - Nebular: SFR -> N_ion -> Hβ -> [OIII] (Inoue+11)
- Three extinction curves are used
  - Calzetti, Milky Way (MW), Small Magellanic Cloud (SMC)
  - 2175 A bump (carbon) is evident in the MW law

Fitting parameters

Dust attenuation A_V (mag)
Age $\tau_{\rm age}$ (Gyr)
SFH $\tau_{\rm SFH}$ (Gyr)
Metallicity Z
LyC escape fraction $f_{\rm esc}$
Stellar mass $M_{\rm star}$ $(10^9 M_\odot)^\dagger$
SFR $(M_\odot\ {\rm yr}^{-1})^\dagger$
$L_{\rm IR}$ $(10^{11} L_\odot)^\dagger$

SED Fits: Results

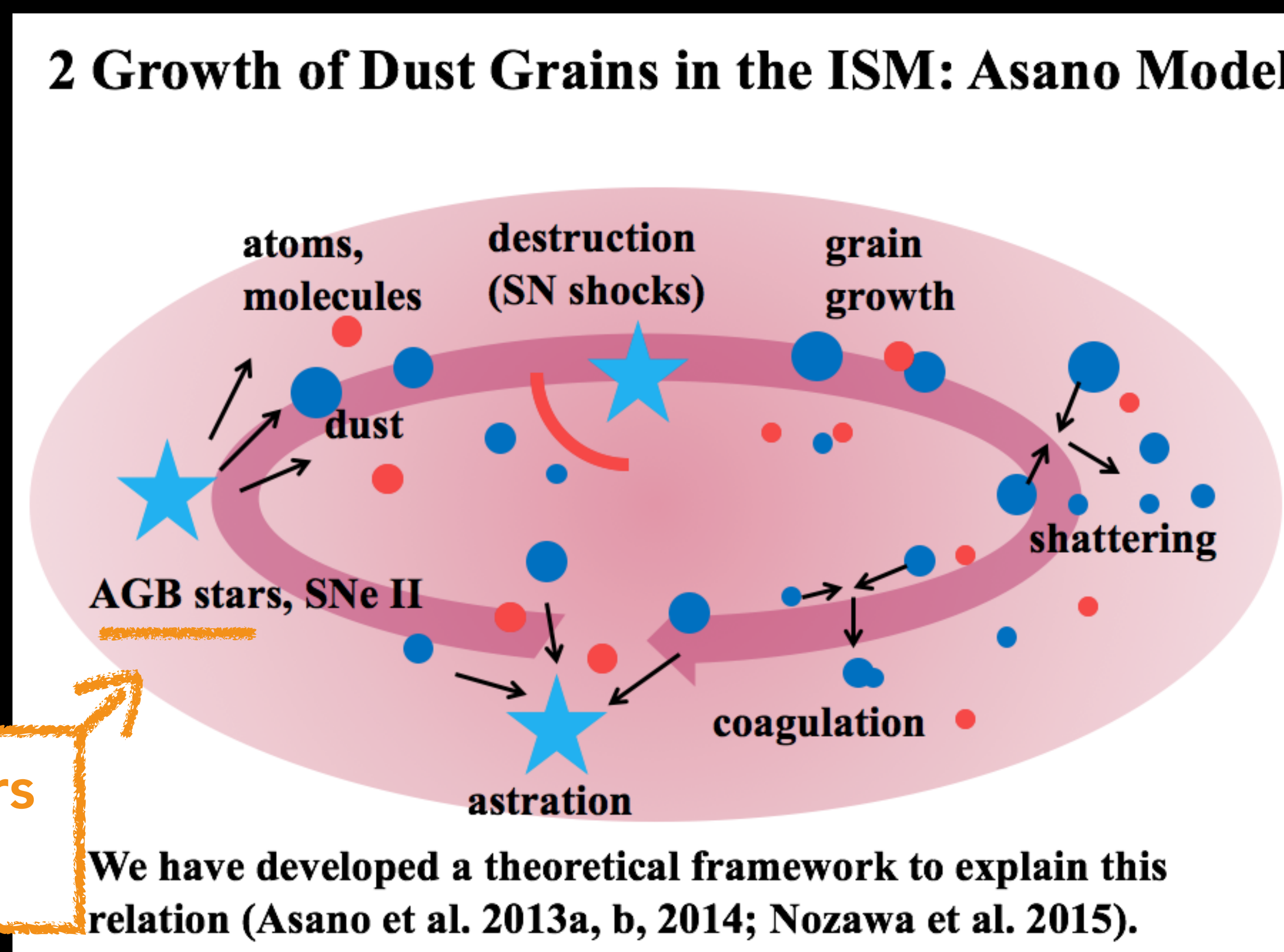
- UV-bright stellar component can co-exist with luminous dust component ***if the dust mass pre-exists***.
- Formation epoch dates back to z ~ 11
  - Age of ~0.18 Gyr indicates the onset of star-formation happened at z ~ 11



Items	MW
χ^2	8.0
DOF	3
Dust attenuation A_V (mag)	$0.50^{+0.04}_{-0.05}$
Age $\tau_{\rm age}$ (Gyr)	$0.18^{+0.07}_{-0.05}$
SFH $\tau^{-1}_{\rm SFH}$ (Gyr^{-1})$^\sharp$	$10.0^{+43.7}_{-11.6}$
Metallicity Z	$0.0040^{+0.0160}_{-0.0024}$
LyC escape fraction $f_{\rm esc}$	$0.50^{+0.15}_{-0.27}$
Stellar mass $M_{\rm star}$ $(10^9 M_\odot)^\dagger$	$5.1^{+7.1}_{-4.9}$
SFR $(M_\odot\ {\rm yr}^{-1})^\dagger$	$13.7^{+225.6}_{-10.1}$
$L_{\rm IR}$ $(10^{11} L_\odot)^\dagger$	$1.50^{+0.55}_{-0.52}$

Dust mass evolution model (Asano & Takeuchi+13)

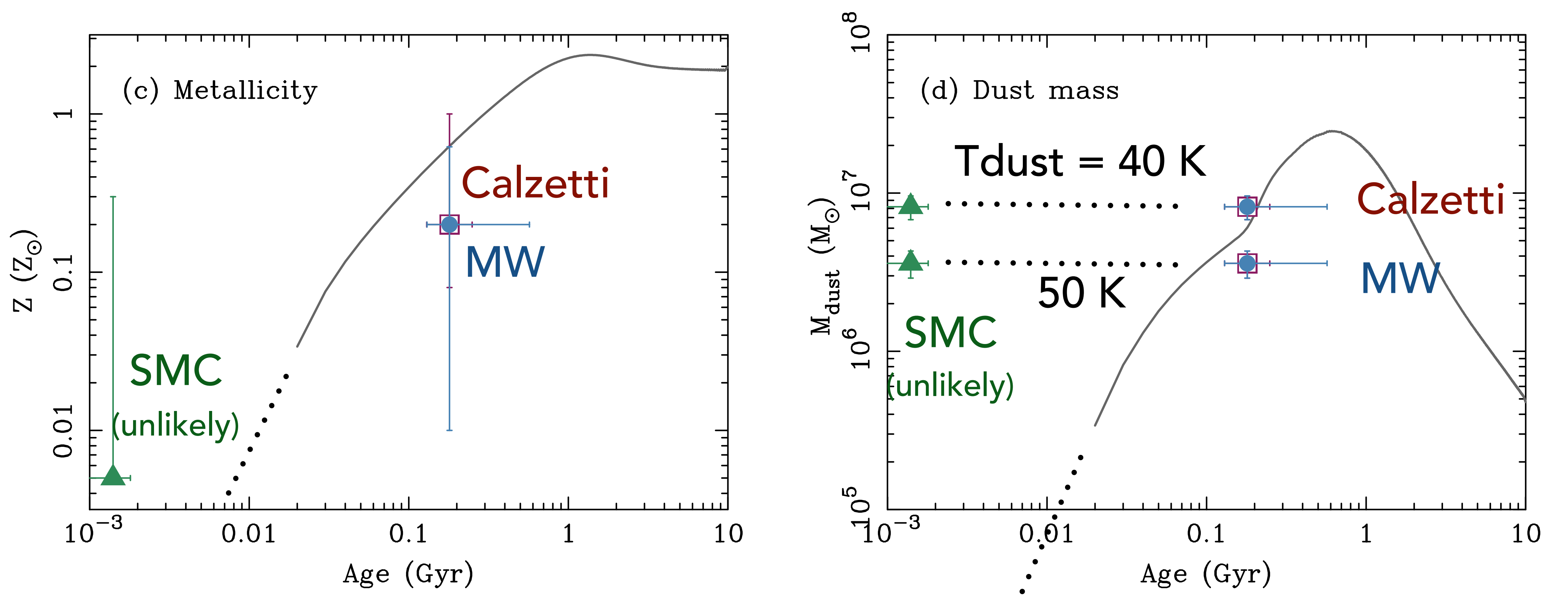
- Current understanding of dust evolution reproduces observed dust mass?
- Dust mass evolution in MACS0416_Y1
  - SF timescale tau_SF = 0.3 Gyr
  - Roughly scaled so that predicted M_star and SFR match the observed ones



Few AGB stars at z ~ 8

Dust mass evolution model: Results

- Dust enrichment can naturally be explained by the dust evolution model in which grain growth and destruction are reasonably considered.



Summary

- ALMA reveals early dust enrichment in a z > 8 galaxy
    - UV-to-FIR SED modeling reveals (surprisingly) relatively-mature stellar component with enriched ISM (gas and dust).
    - Formation epoch dates back to z = 11.
    - Dust enrichment can naturally be explained by a dust evolution model in which grain growth and destruction are reasonably considered.
- Future prospects with ALMA
    - Cycle 5: [C II] measurements with band 5 + deep [OIII] imaging
    - Cycle 6: 500-pc imaging of multi-phase ISM in dust (GMCs) and [OIII] (HII regions)
    - Cycle 6: Further [OIII] search