ALMA reveals the early dust enrichment in a z = 8.3 galaxy (YT+, submitted; arXiv:1806.04132v1)

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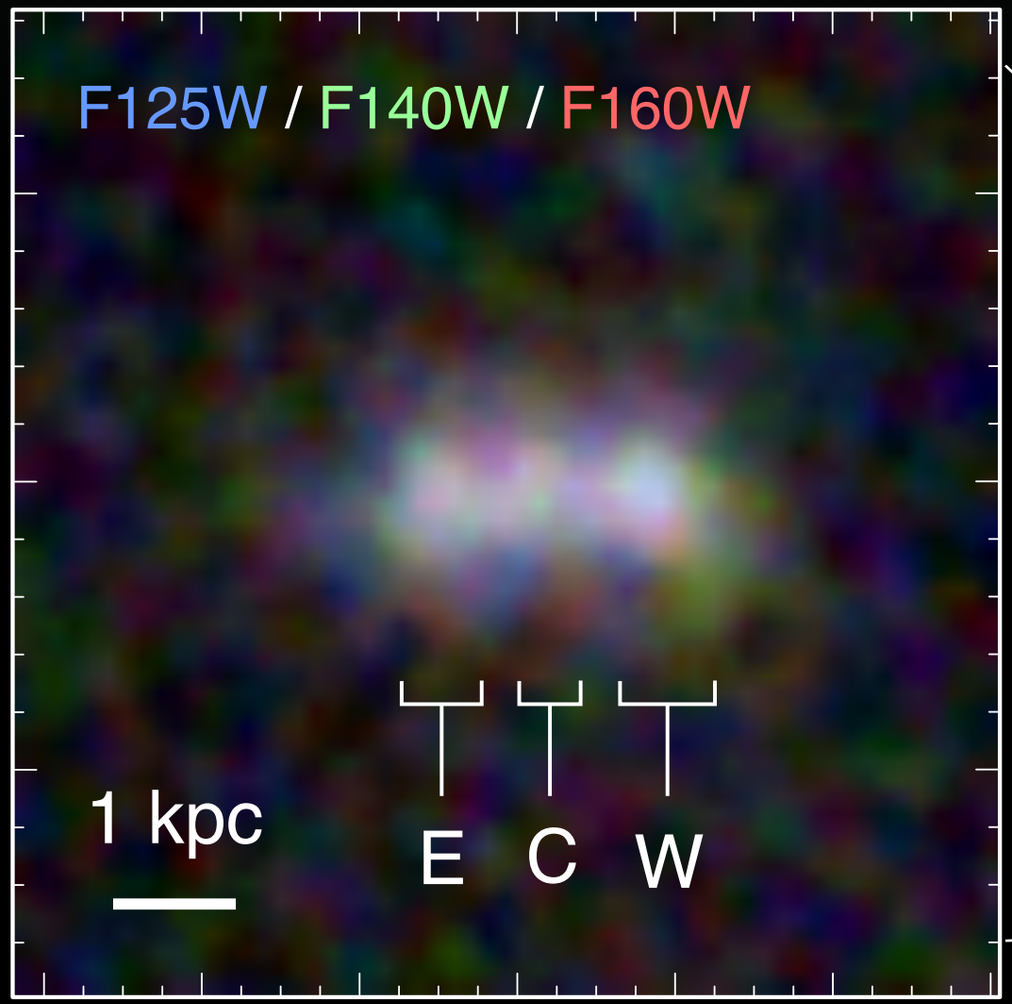
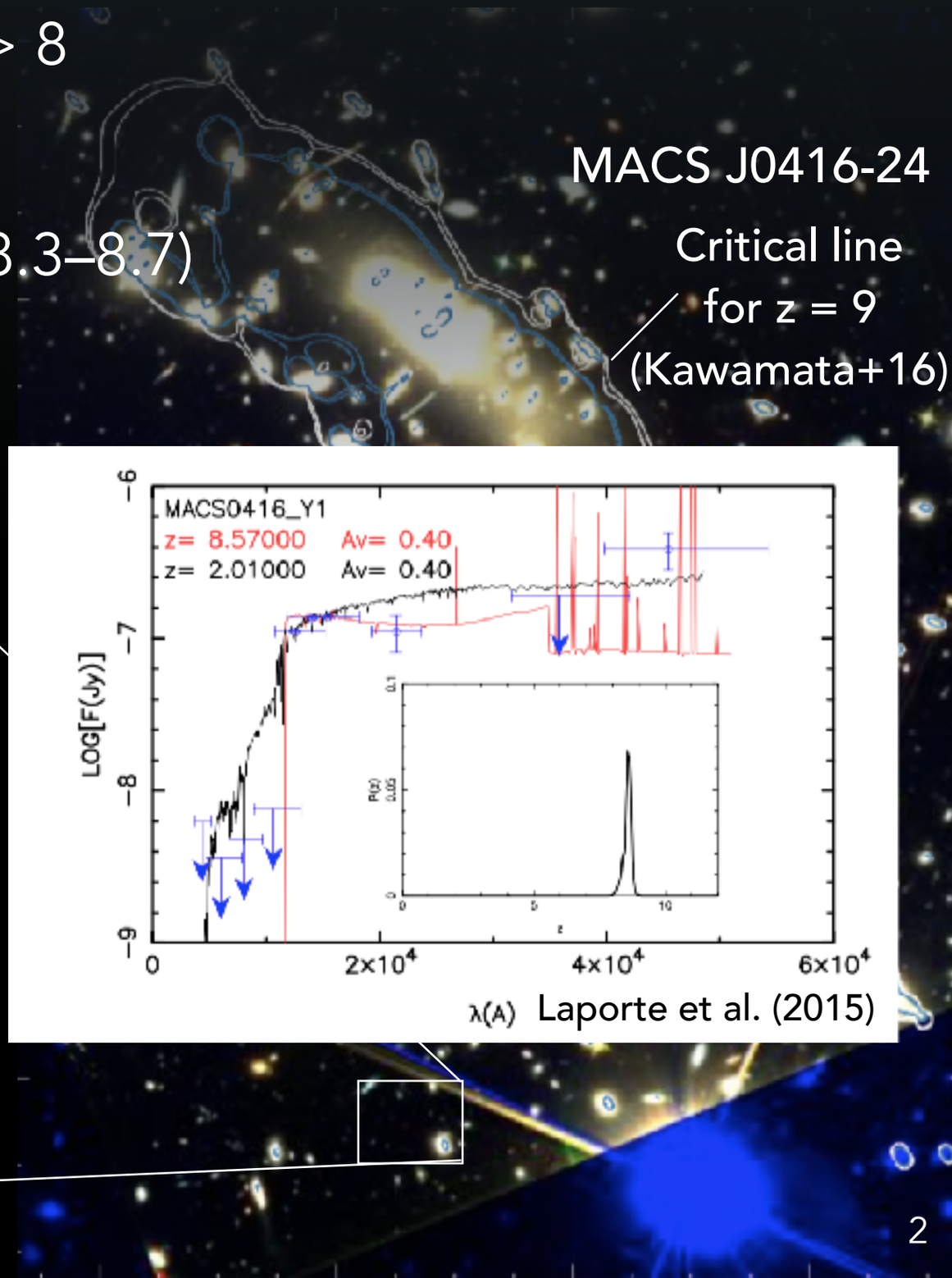
Credit: ESO/M. Kornmesser

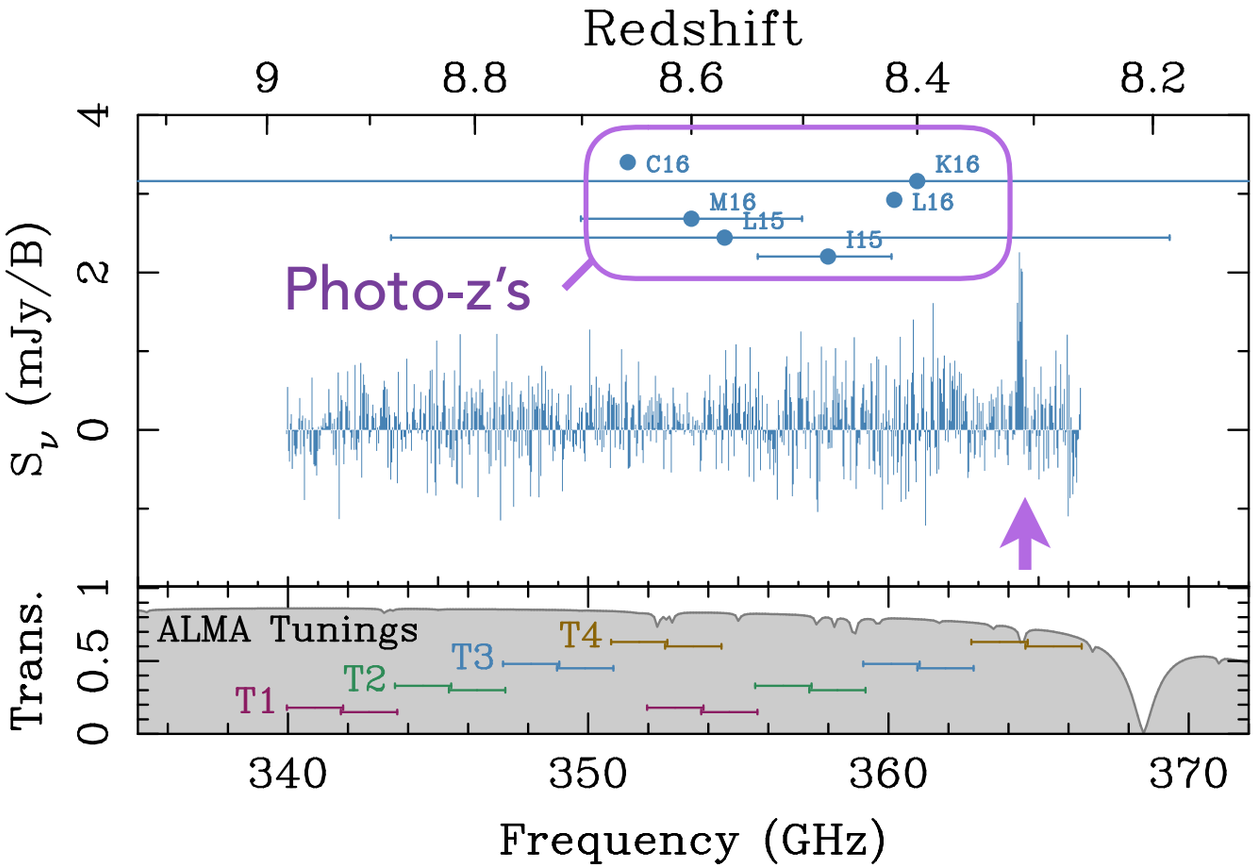
Target: Frontier Field LBG “MACS0416_Y1”

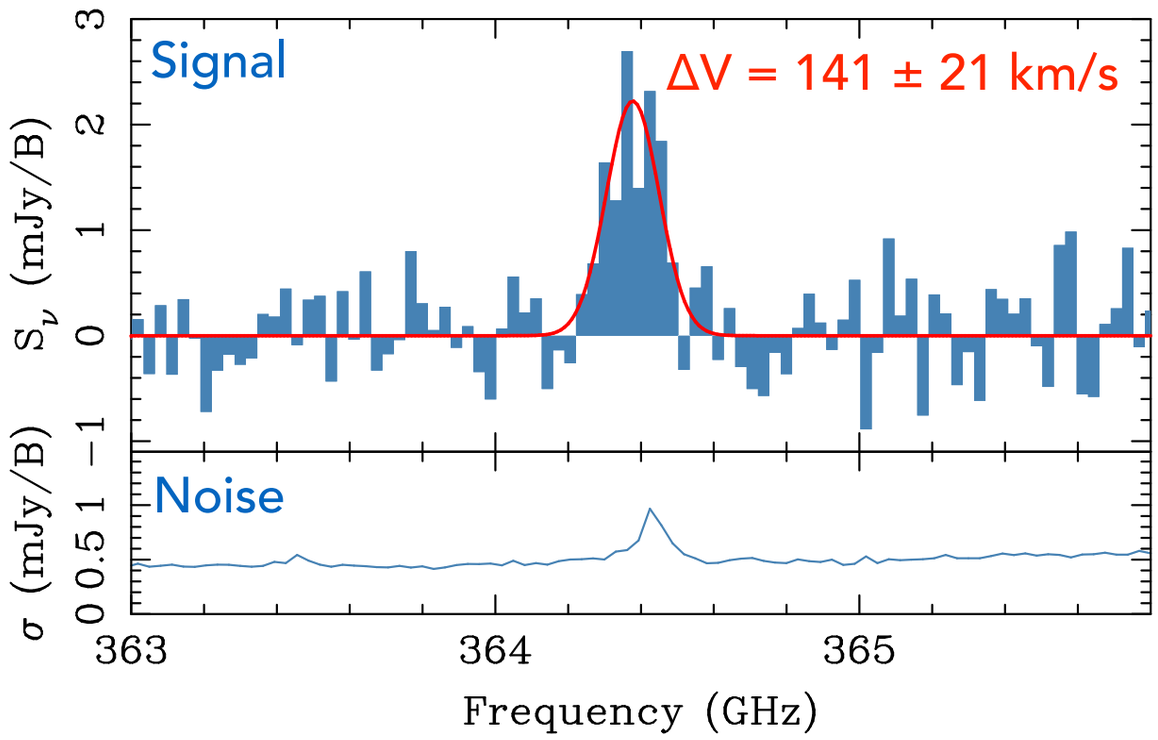
- The best among > 100 LBGs at z > 8
- Bright (H_{160} = 26.0 AB, μ_g = 1.4)
- Well-constrained redshift (z_ph ~ 8.3–8.7)
- Accessible from ALMA (Cycle 4)





Results: "Blind" Redshift Identification with [OIII]

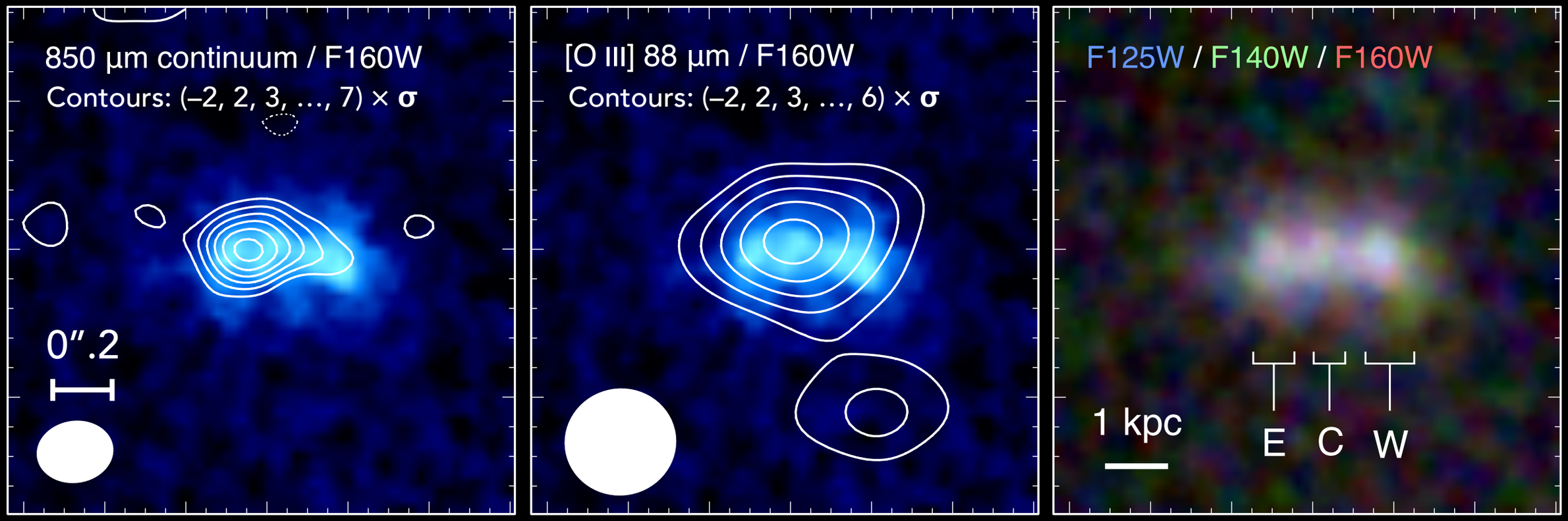




- Spectroscopic redshift ***z = 8.3118 ± 0.0003***
- ***Blind*** detection with submillimeter spectroscopy
  - Failed to detect Lya and other bright UV lines with X-Shooter/VLT

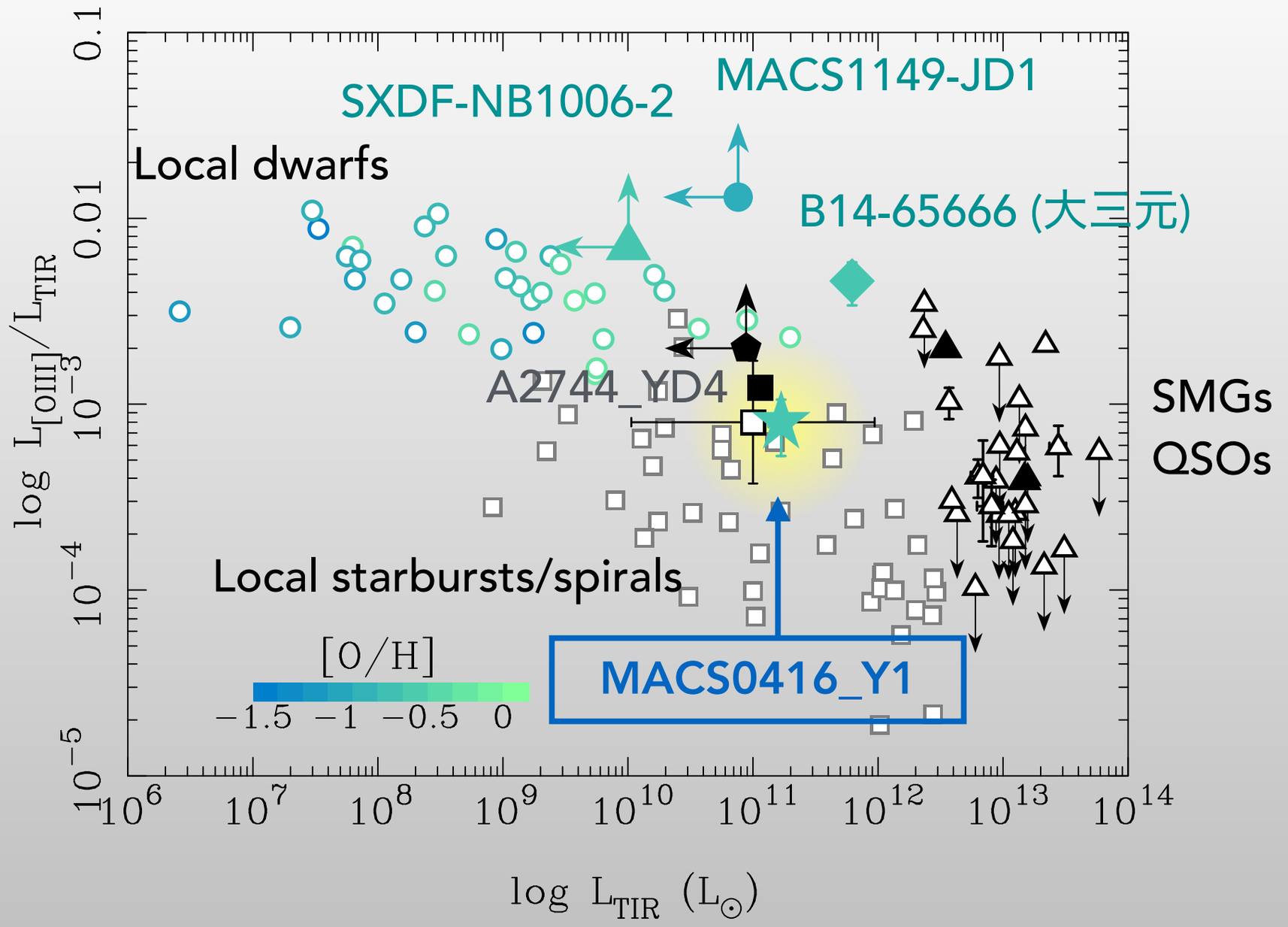
Results: Detections of Dust and [OIII] 88 um

YT+18, submitted



- Second detection of dust at z > 8
- Spatially resolved, tracing UV emission
  - Size: 0″.36 × 0″.10 = 1.7 × 0.5 kpc
- Large dust mass
  - **M_dust_t = (3.6 ± 0.7) × 10^6 $M_\odot$** (T_{dust} = 50 K, β = 1.5)

[O III]-FIR Luminosity Ratio



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

Motivations

- **SED modeling**: How does "dust" coexist with UV SED?
  - How can the red [3.6] – [4.5] color be explained?
  - TIR + [OIII]88 should be a key (A.K. Inoue+16; Mawatari+18, 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?

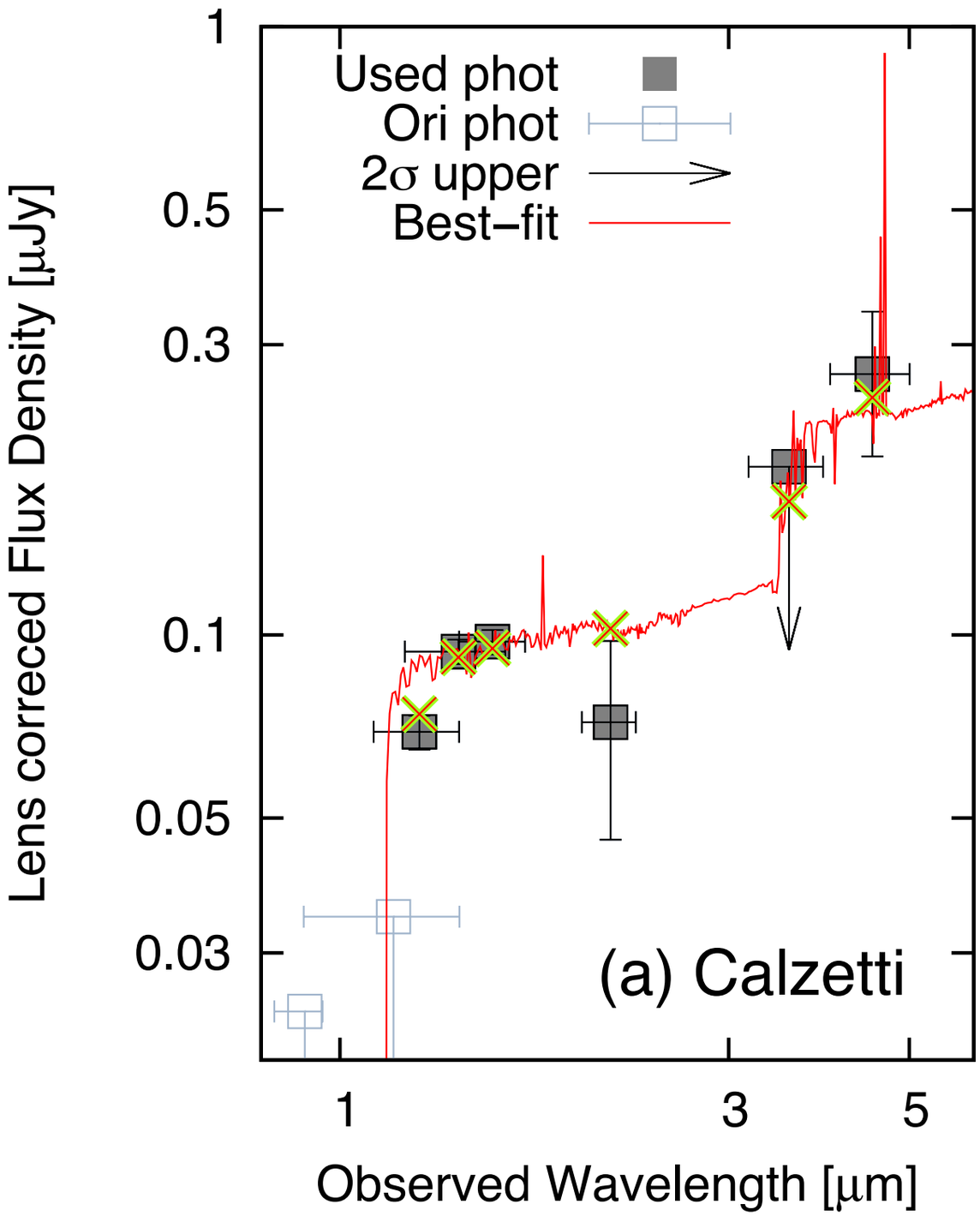
Stellar Population Synthesis Analysis

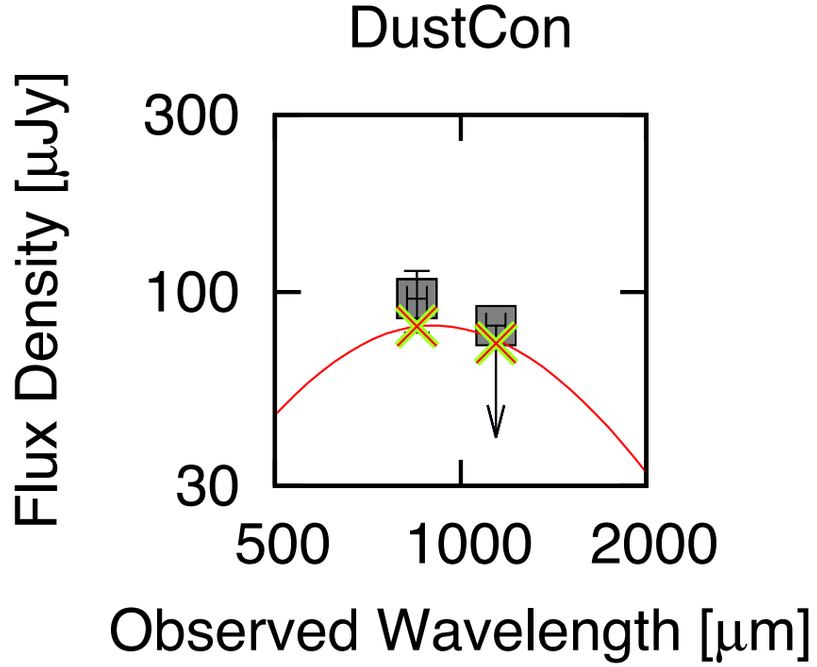
- Rest-frame UV-optical and FIR [OIII] + dust continuum
- Based on Mawatari+2016
  - Stellar: Bruzual Charlot 2003 (BC03)
  - Dust (FIR): Local LIRGs (Rieke+09)
  - Nebular: SFR -> N_ion -> Hβ -> [OIII] (Inoue+11)
- Three extinction curves are used
  - Calzetti, Milky Way (MW), Small Magellanic Cloud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

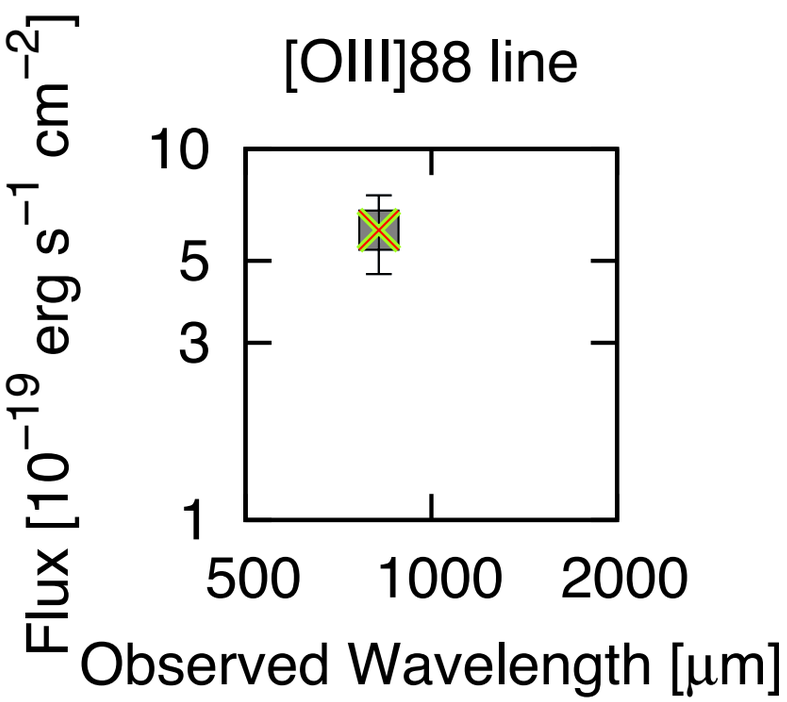
Fitting parameters

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 $(M_\odot\ {\rm yr}^{-1})^\dagger$
$L_{\rm IR}$ $(10^{11} L_\odot)^\dagger$

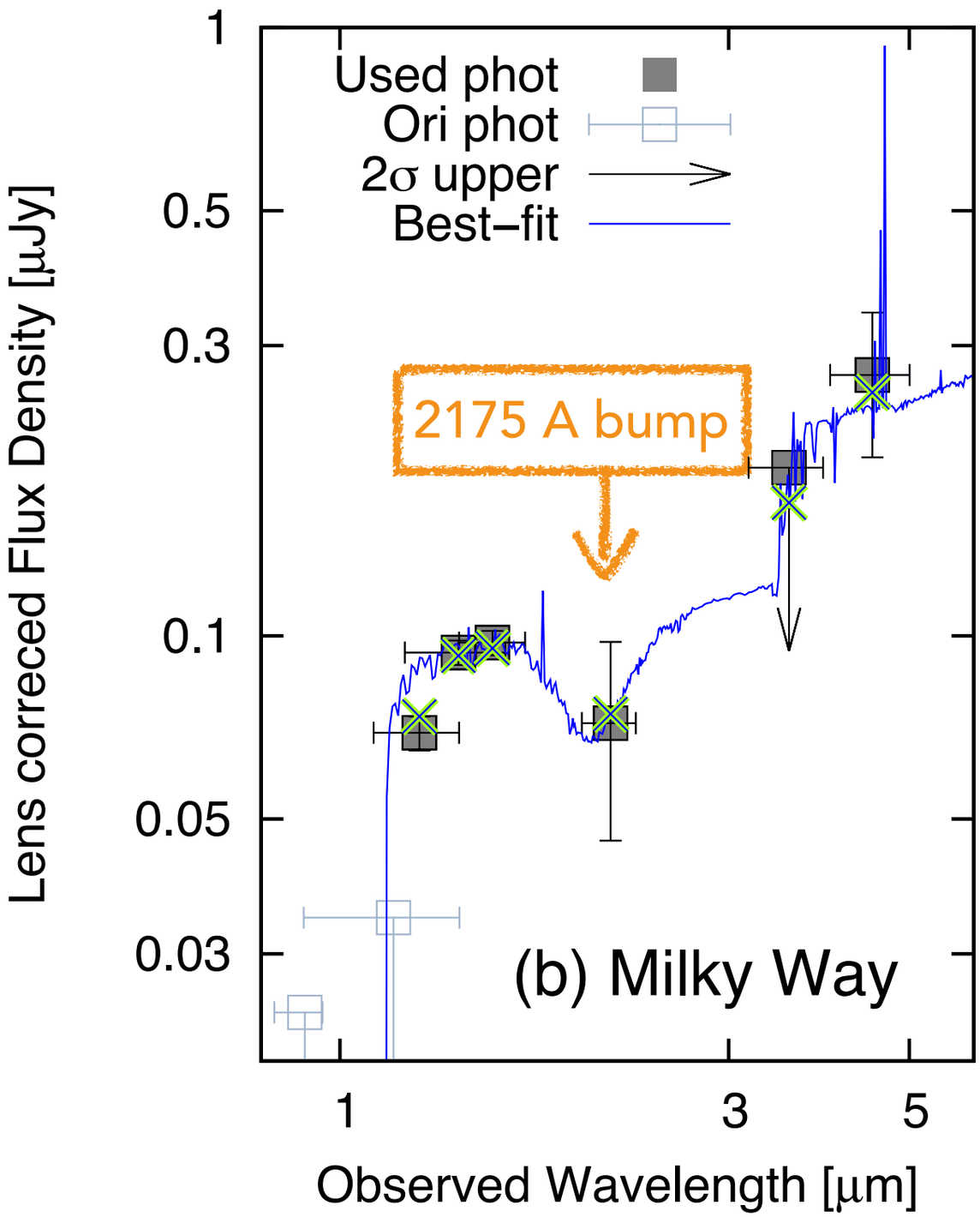
SED Fits: Calzetti Extinction Law

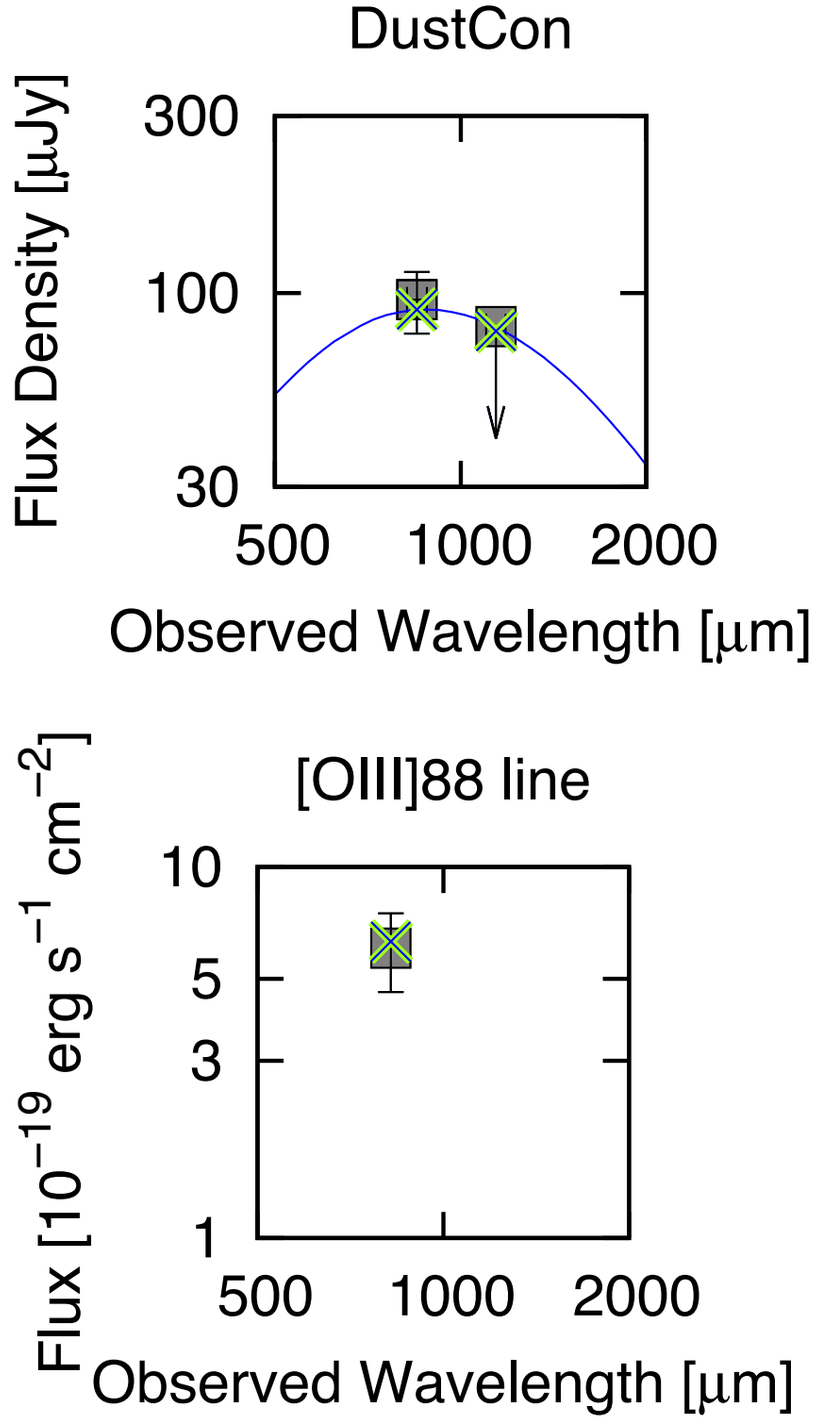




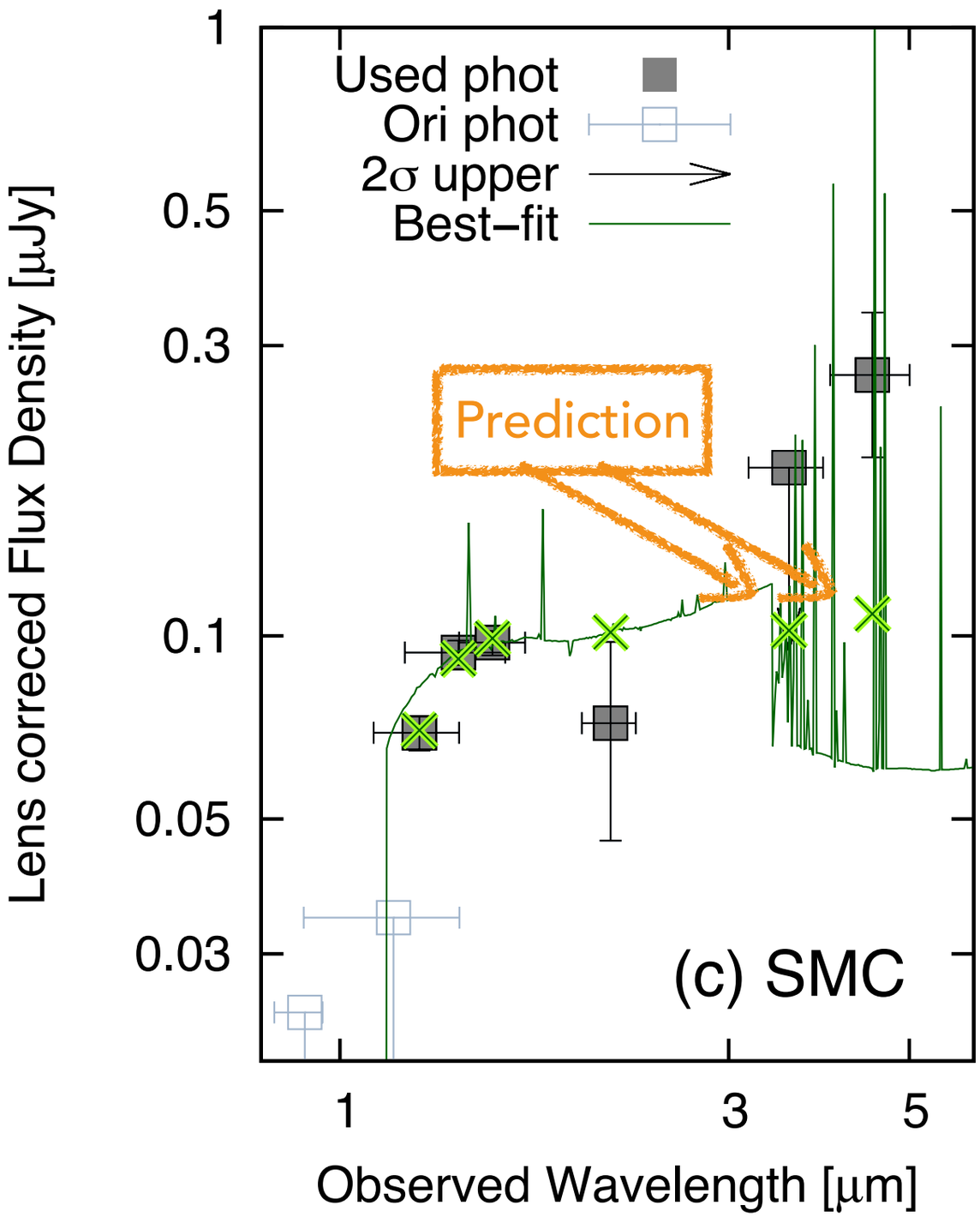


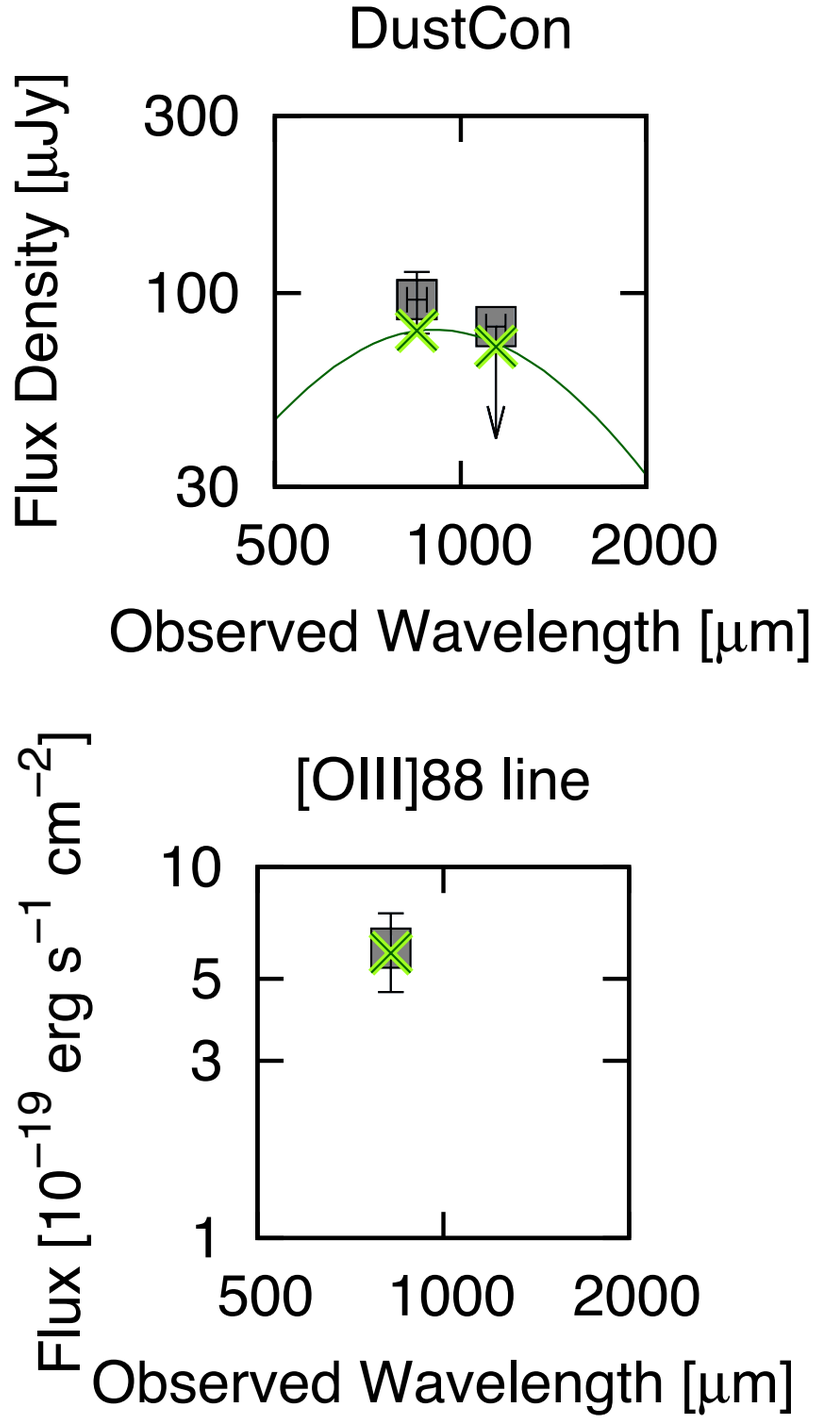
SED Fits: Milky-Way Extinction Law





SED Fits: SMC Extinction Law





SED Fits: Results

Table 5. The best-fitting parameters of the rest-frame ultraviolet to far-infrared spectral energy distribution of MACS0416_Y1.

Items	Extinction law		
	Calzetti	SMC	MW
χ^2	10.1	12.2	8.0
DOF	3	3	3
Dust attenuation A_V (mag)	$0.50^{+0.07}_{-0.06}$	$0.20^{+0.10}_{-0.01}$	$0.50^{+0.04}_{-0.05}$
Age $\tau_{\rm age}$ (Gyr)	$0.18^{+0.39}_{-0.05}$	$0.0014^{+0.0004}_{-0.0005}$	$0.18^{+0.07}_{-0.05}$
SFH $\tau_{\rm SFH}^{-1}$ (Gyr^{-1})$^\sharp$	$10.0^{+90.0}_{-17.2}$	-100^{+200}_{-0}	$10.0^{+43.7}_{-11.6}$
Metallicity Z	$0.0040^{+0.0084}_{-0.0037}$	$0.0001^{+0.0059}_{-0.0000}$	$0.0040^{+0.0160}_{-0.0024}$
LyC escape fraction $f_{\rm esc}$	$0.50^{+0.20}_{-0.24}$	$0.30^{+0.41}_{-0.19}$	$0.50^{+0.15}_{-0.27}$
Stellar mass $M_{\rm star}$ ($10^9 M_\odot$)†	$4.8^{+6.8}_{-4.7}$	$0.26^{+7.01}_{-0.09}$	$5.1^{+7.1}_{-4.9}$
SFR ($M_\odot$ yr^{-1})†	$13.2^{+255.2}_{-8.8}$	199^{+355}_{-194}	$13.7^{+225.6}_{-10.1}$
$L_{\rm IR}$ ($10^{11} L_\odot$)†	$1.37^{+0.68}_{-0.48}$	$1.35^{+0.67}_{-0.63}$	$1.50^{+0.55}_{-0.52}$

SED Fits: Results

- UV-bright stellar component with luminous dust component
  - Can be explained consistently in terms of energy budget ***if the dust mass pre-exists***.
- The SMC extinction law is not likely
  - Extremely young populations of stars with bright nebular emission
    - ***Seems to be difficult to explain the dust mass.***
- Formation epoch dates back to z ~ 11
  - Age of ~180 Myr indicates the onset of star-formation happened at z ~ 11

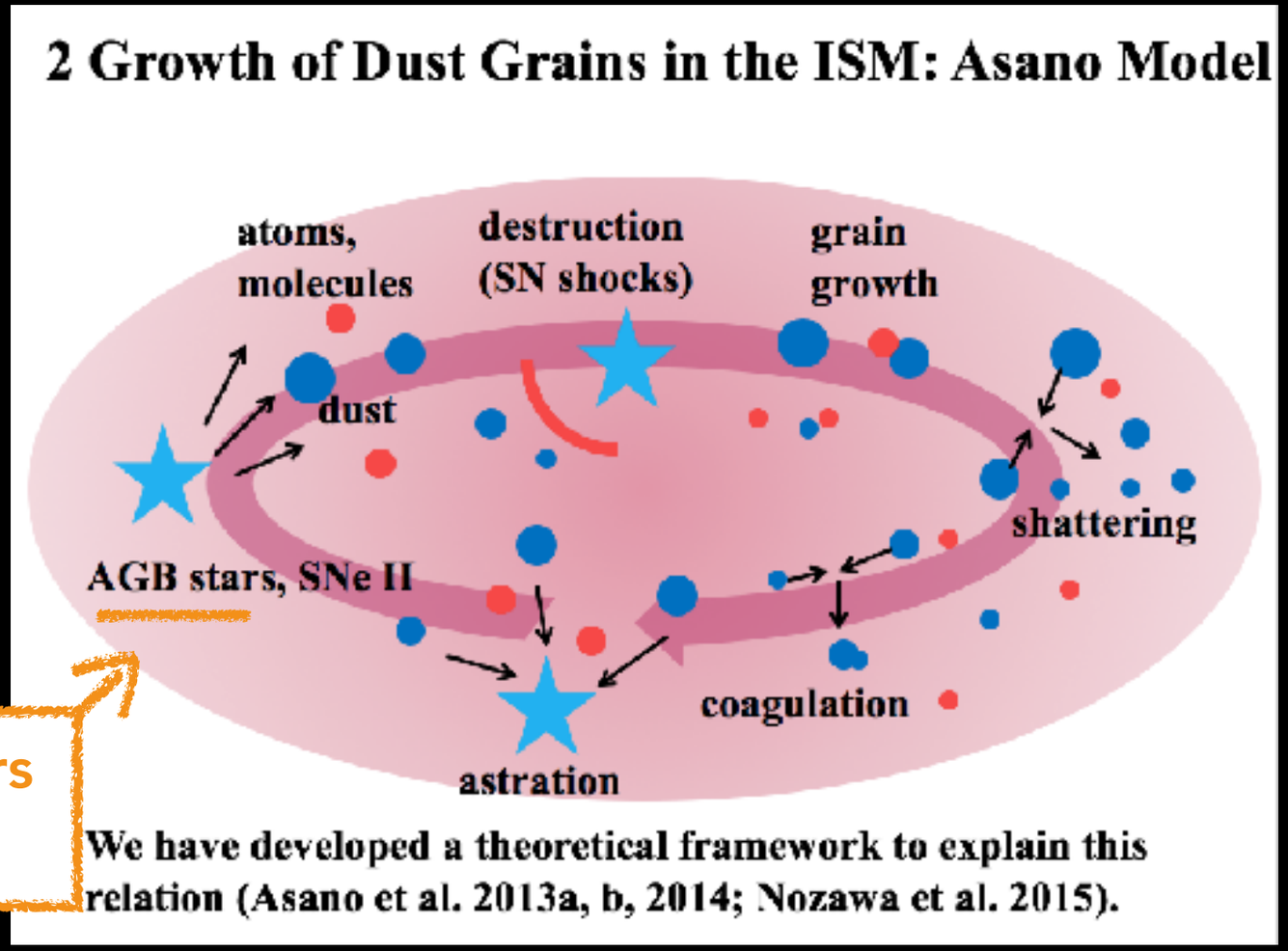
Purpose:

How and when metal enrichment happened?

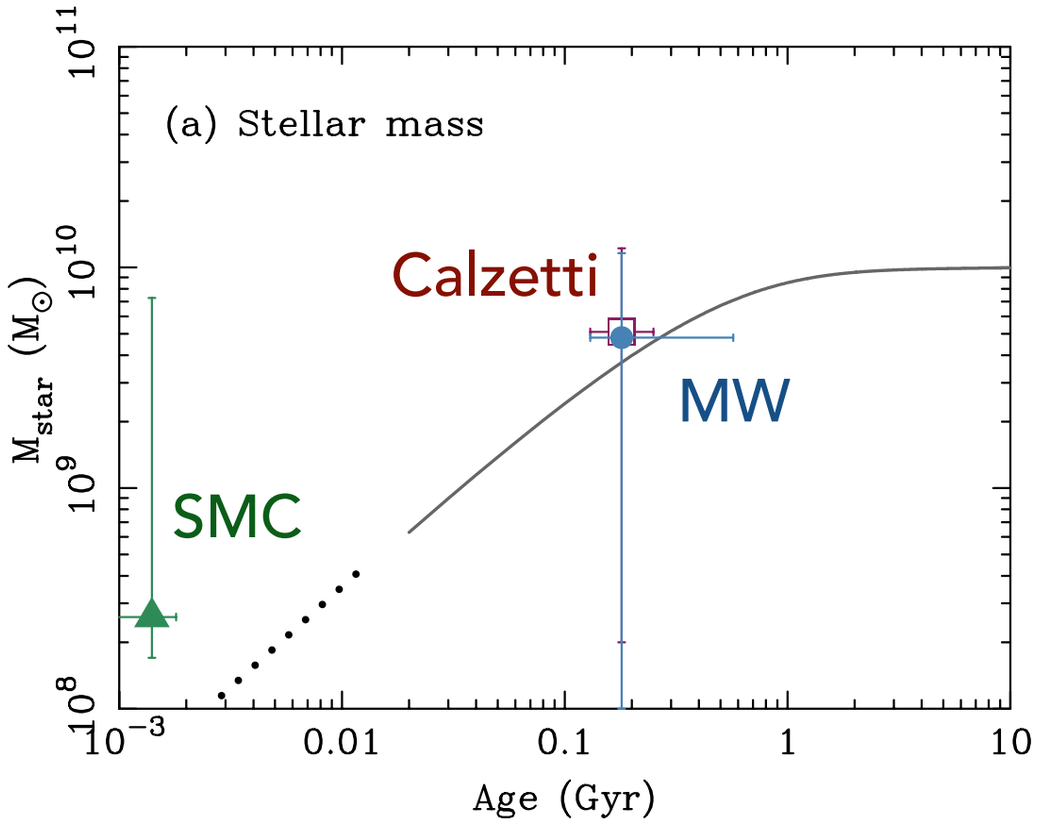
Why dust exists in the earliest universe?

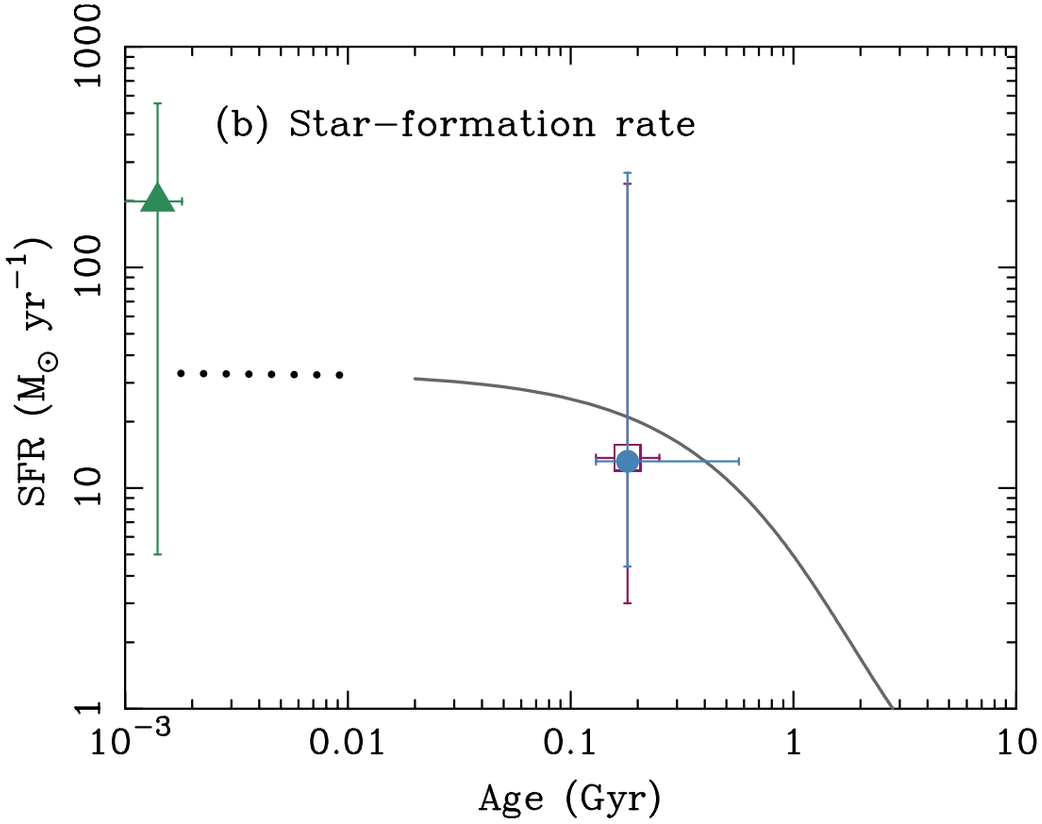
Interstellar grain growth divides the populations?

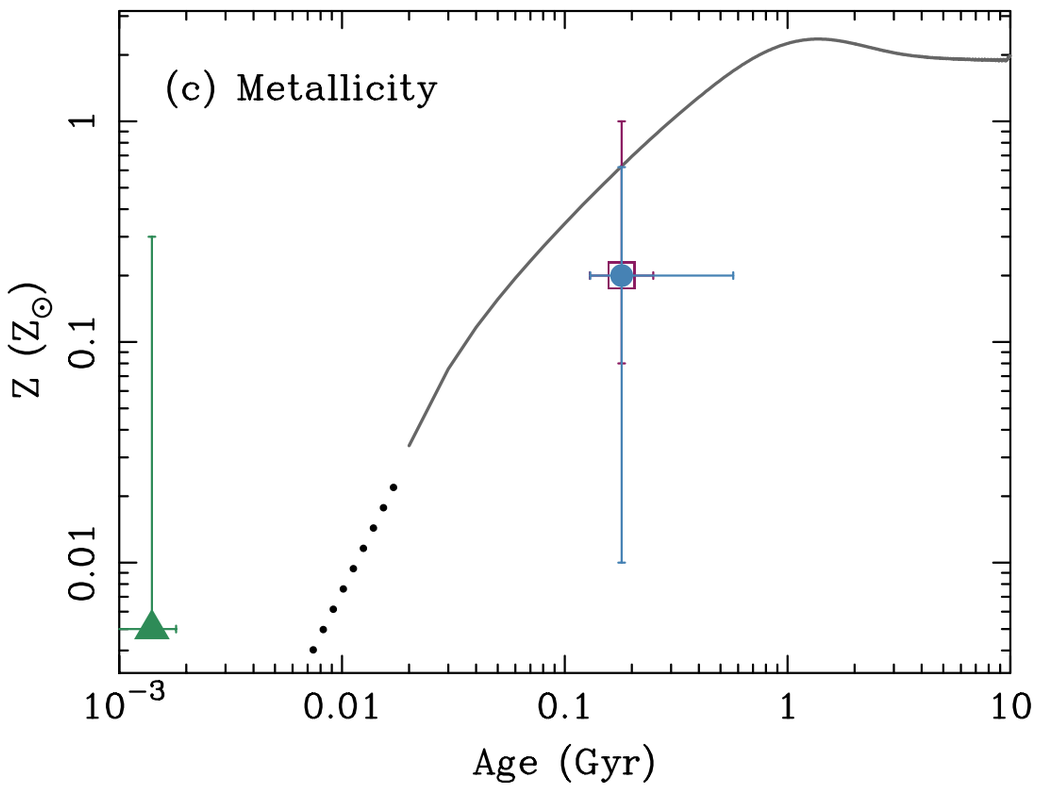
- Asano-Takeuchi model (Asano & Takeuchi+13)
- Dust mass evolution in MACS0416_Y1
  - SF timescale tau_SF = 0.3 Gyr
  - Roughly scaled so that predicted M_star and SFR match the observed ones

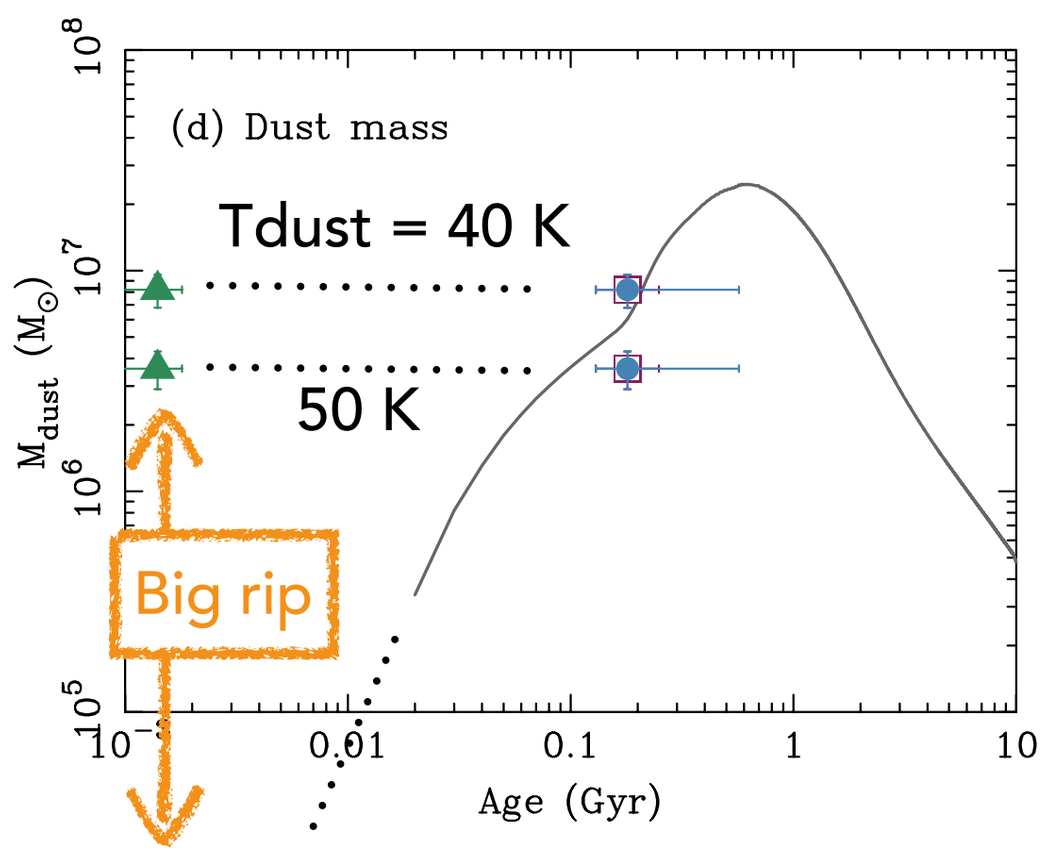


Few AGB stars at z ~ 8


(a) Stellar mass
Calzetti
MW
SMC
M_{star} ($M_\odot$)
10^{11}
10^{10}
10^{9}
10^{8}
10^{-3}
0.01
0.1
1
10
Age (Gyr)

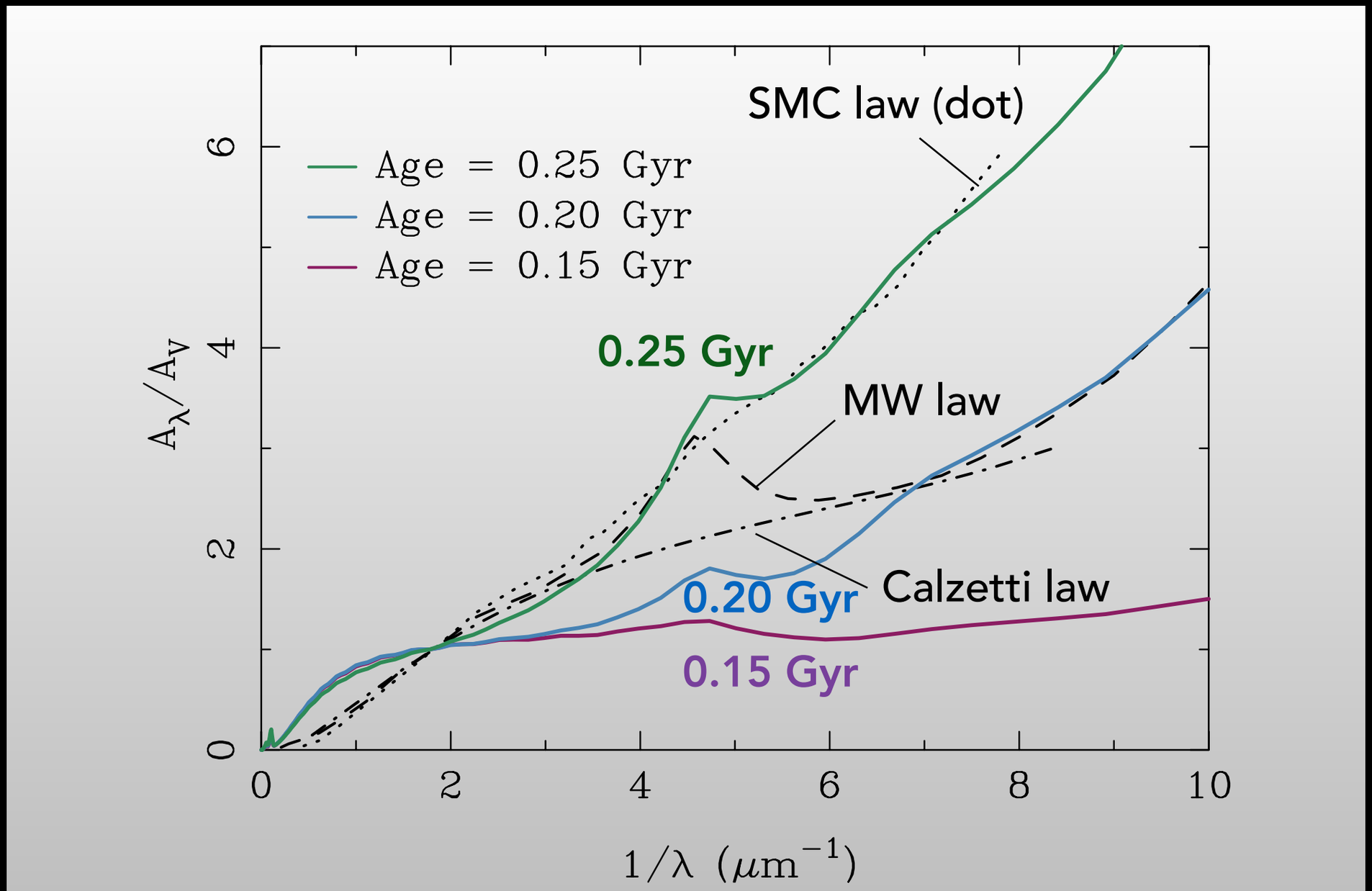

(b) Star−formation rate
SFR ($M_\odot$ yr^{-1})
1000
100
10
1
10^{-3}
0.01
0.1
1
10
Age (Gyr)


(c) Metallicity
Z ($Z_\odot$)
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
Age (Gyr)


(d) Dust mass
Tdust = 40 K
50 K
Big rip
M_{dust} ($M_\odot$)
10^{8}
10^{7}
10^{6}
10^{5}
10^{-3}
0.01
0.1
1
10
Age (Gyr)

Predicted extinction curve has the 2175A bump

- Extinction curve established in galaxy age = $0.18^{+0.07}_{-0.05}$ Gyr
- Roughly consistent with MW/Calzetti law



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