Lessons learnt from observing a z~13 candidate with ALMA

Melanie Kaasinen (ESO)

To see or not to see a z~13 galaxy, that is the question

Targeting the [C II] 158 μm emission line of HD1 with ALMA

M. Kaasinen, J. van Marrewijk, G. Popping, M. Ginolfi, L. Di Mascolo, T. Mroczkowski, A. Concas, C. Di Cesare, M. Killi, I. Langan (A&A, 671, 29)

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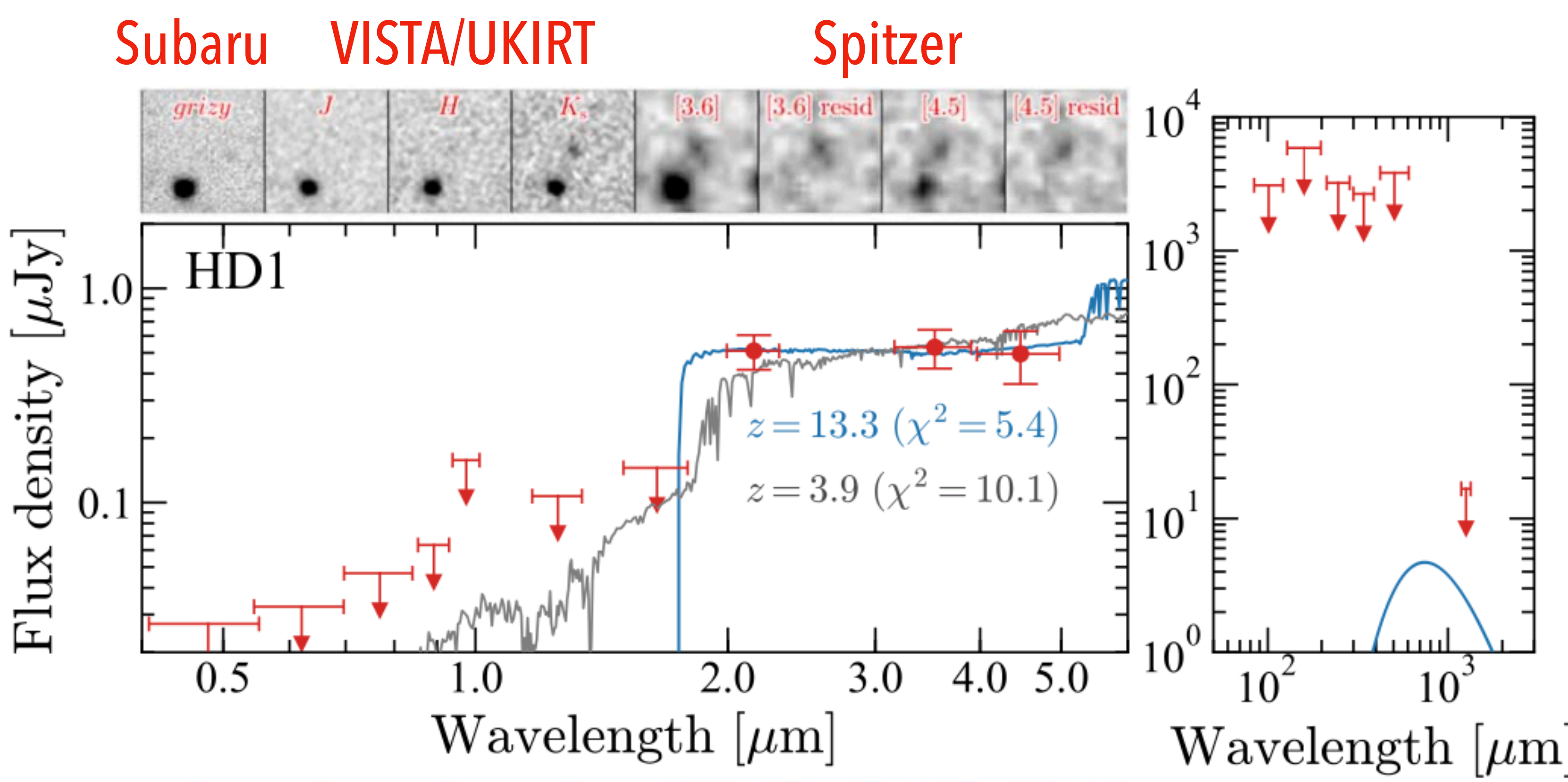
And so it begins… “Who’s there?”

THE ASTROPHYSICAL JOURNAL, 929:1 (15pp), 2022 April 10 on arxiv: Dec 2021
https://doi.org/10.3847/1538-4357/ac53a9

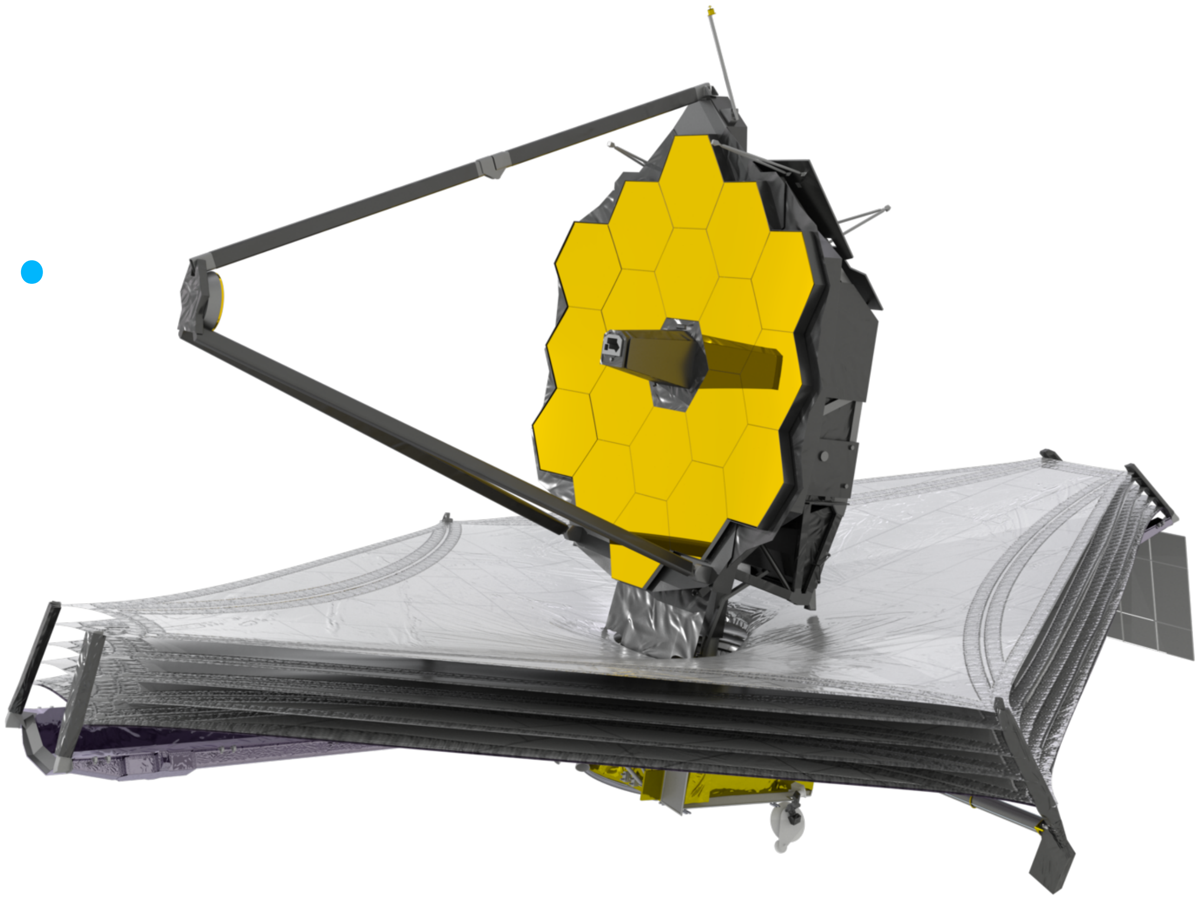
CrossMark

A Search for *H*-Dropout Lyman Break Galaxies at $z \sim 12$–16

Yuichi Harikane[1,2], Akio K. Inoue[3,4], Ken Mawatari[5], Takuya Hashimoto[6], Satoshi Yamanaka[4,7,8], Yoshinobu Fudamoto[4,5], Hiroshi Matsuo[5,9], Yoichi Tamura[10], Pratika Dayal[11], L. Y. Aaron Yung[12], Anne Hutter[11], Fabio Pacucci[13,14], Yuma Sugahara[4,5], and Anton M. Koekemoer[15]

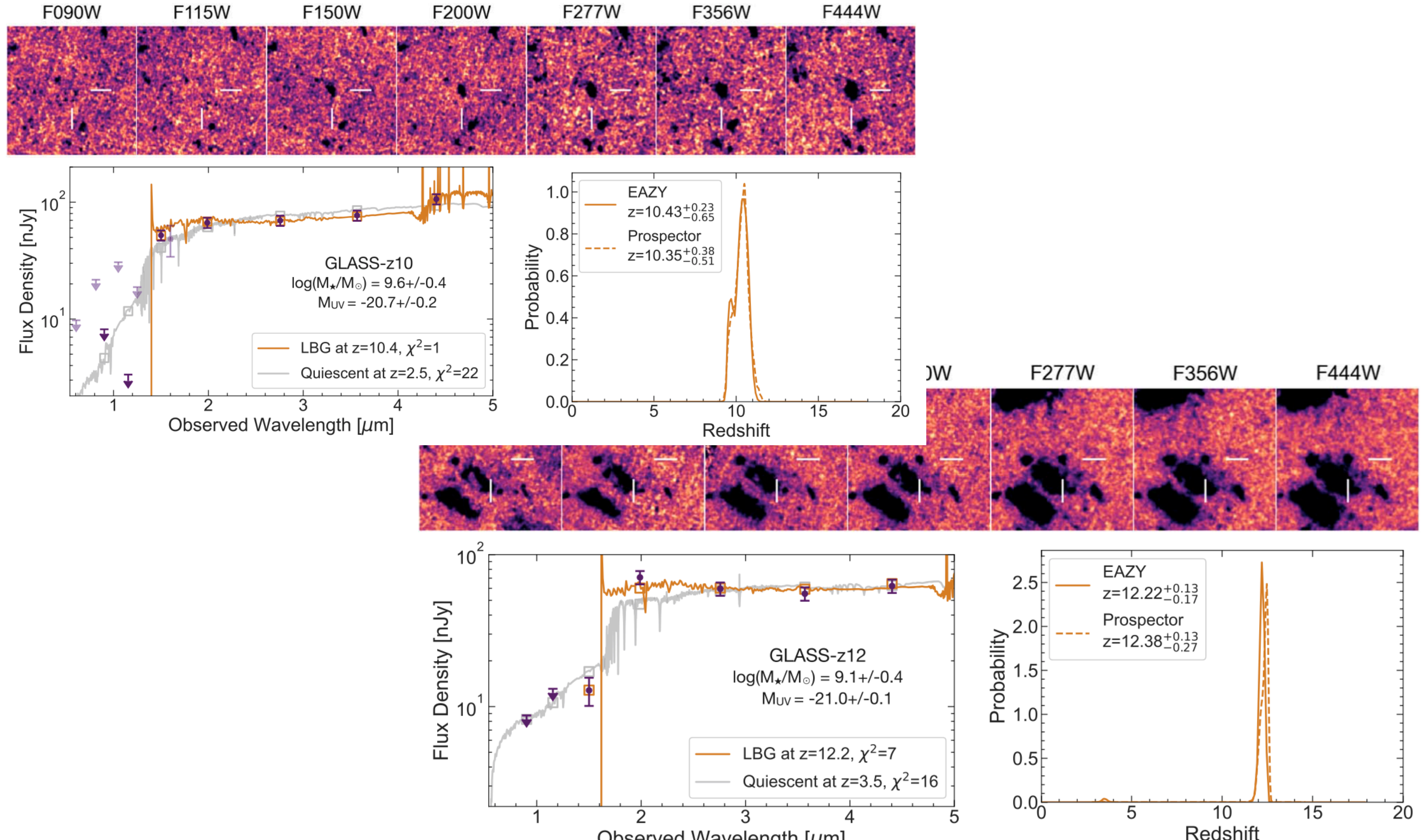


In the meantime…



Two Remarkably Luminous Galaxy Candidates at $z \approx 11 - 13$ Revealed by *JWST*

Rohan P. Naidu,[1] Pascal A. Oesch,[2,3] Pieter van Dokkum,[4] Erica J. Nelson,[5] Katherine A. Suess,[6,7] Katherine E. Whitaker,[8,9] Natalie Allen,[3] Rachel Bezanson,[10] Rychard Bouwens,[11] Gabriel Brammer,[3] Charlie Conroy,[1] Garth Illingworth,[12] Ivo Labbe,[13] Joel Leja,[14,15,16] Ecaterina Leonova,[17] Jorryt Matthee,[18] Sedona H. Price,[19] David J. Setton,[10] Victoria Strait,[3] Mauro Stefanon,[20,21] Sandro Tacchella,[22,23] Sune Toft,[3] John R. Weaver,[8] and Andrea Weibel[2]

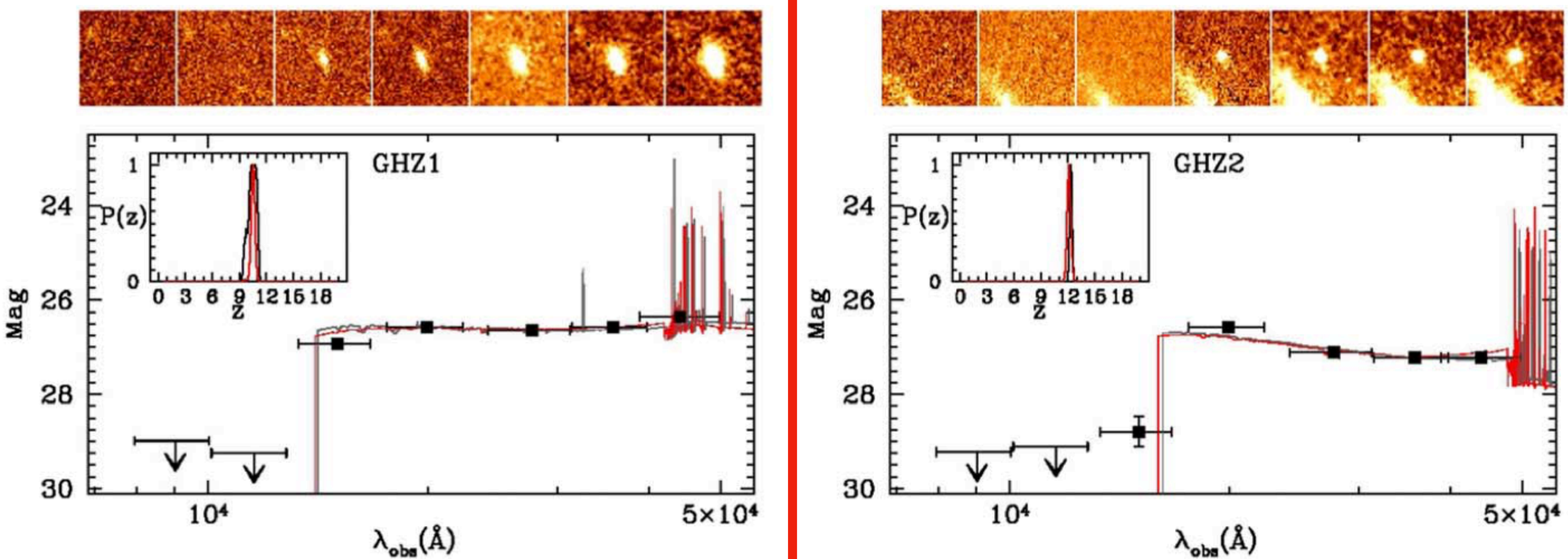


The Astrophysical Journal Letters, 938:L15 (9pp), 2022 October 20 https://doi.org/10.3847/2041-8213/ac94d0

OPEN ACCESS

Early Results from GLASS-JWST. III. Galaxy Candidates at $z \sim 9$–15*

Marco Castellano[1], Adriano Fontana[1], Tommaso Treu[2], Paola Santini[1], Emiliano Merlin[1], Nicha Leethochawalit[3,4,5], Michele Trenti[3,4], Eros Vanzella[6], Uros Mestric[6], Andrea Bonchi[7], Davide Belfiori[1], Mario Nonino[8], Diego Paris[1], Gianluca Polenta[7], Guido Roberts-Borsani[2], Kristan Boyett[3,4], Maruša Bradač[9,10], Antonello Calabrò[1], Karl Glazebrook[11], Claudio Grillo[12,13], Sara Mascia[1], Charlotte Mason[14,15], Amata Mercurio[16], Takahiro Morishita[17], Themiya Nanayakkara[11], Laura Pentericci[1], Piero Rosati[18,19], Benedetta Vulcani[20], Xin Wang[21], and Lilan Yang[22]



GLASS-z10

Revealing Galaxy Candidates out to $z \sim 16$ with JWST Observations of the Lensing Cluster SMACS0723

Hakim Atek[1★], Marko Shuntov[1], Lukas J. Furtak[2], Johan Richard[3], Jean-Paul Kneib[4], Guillaume Mahler[5] Adi Zitrin[2], Henry Joy McCracken[1] Clotilde Laigle[1] Stéphane Charlot[1]
[1]Institut d'Astrophysique de Paris, CNRS, Sorbonne Université, 98bis Boulevard Arago, 75014, Paris, France
[2]Physics Department, Ben-Gurion University of the Negev, P.O. Box 653, Be'er-Sheva 84105, Israel
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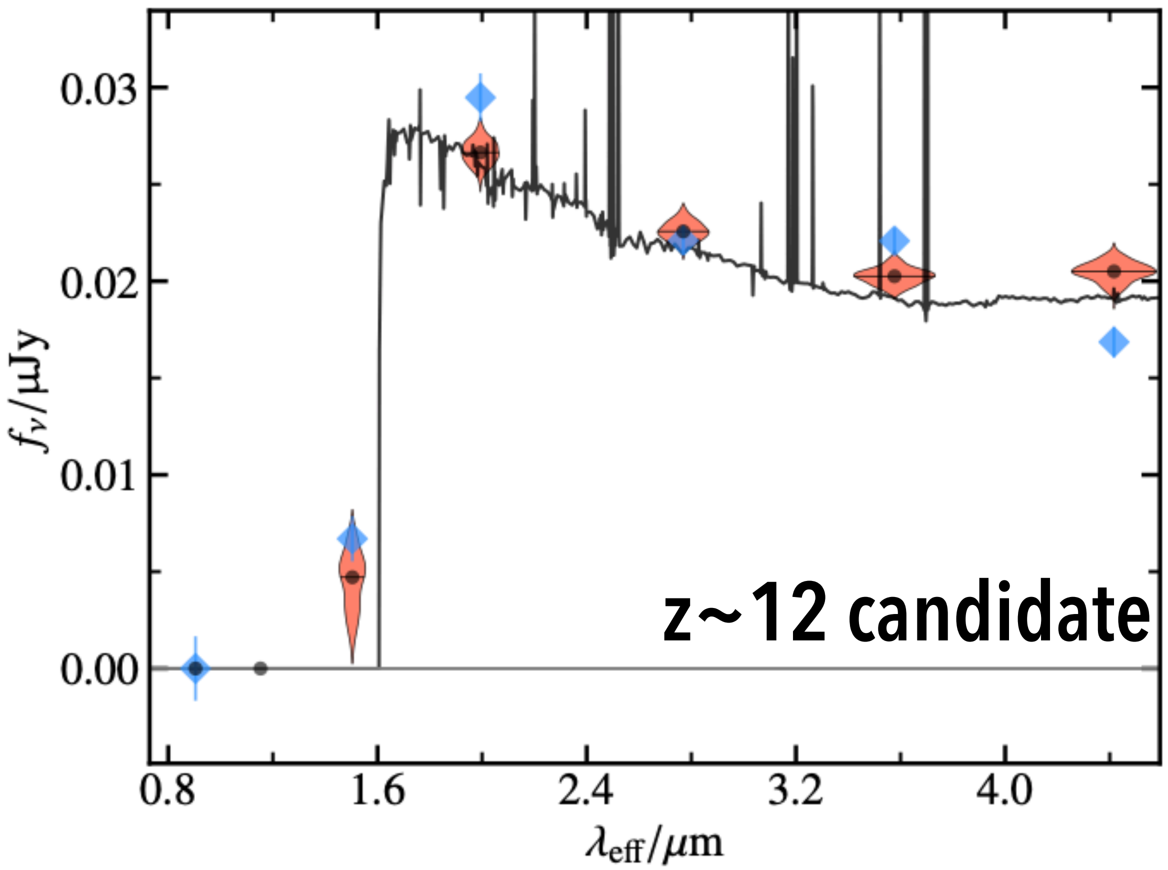
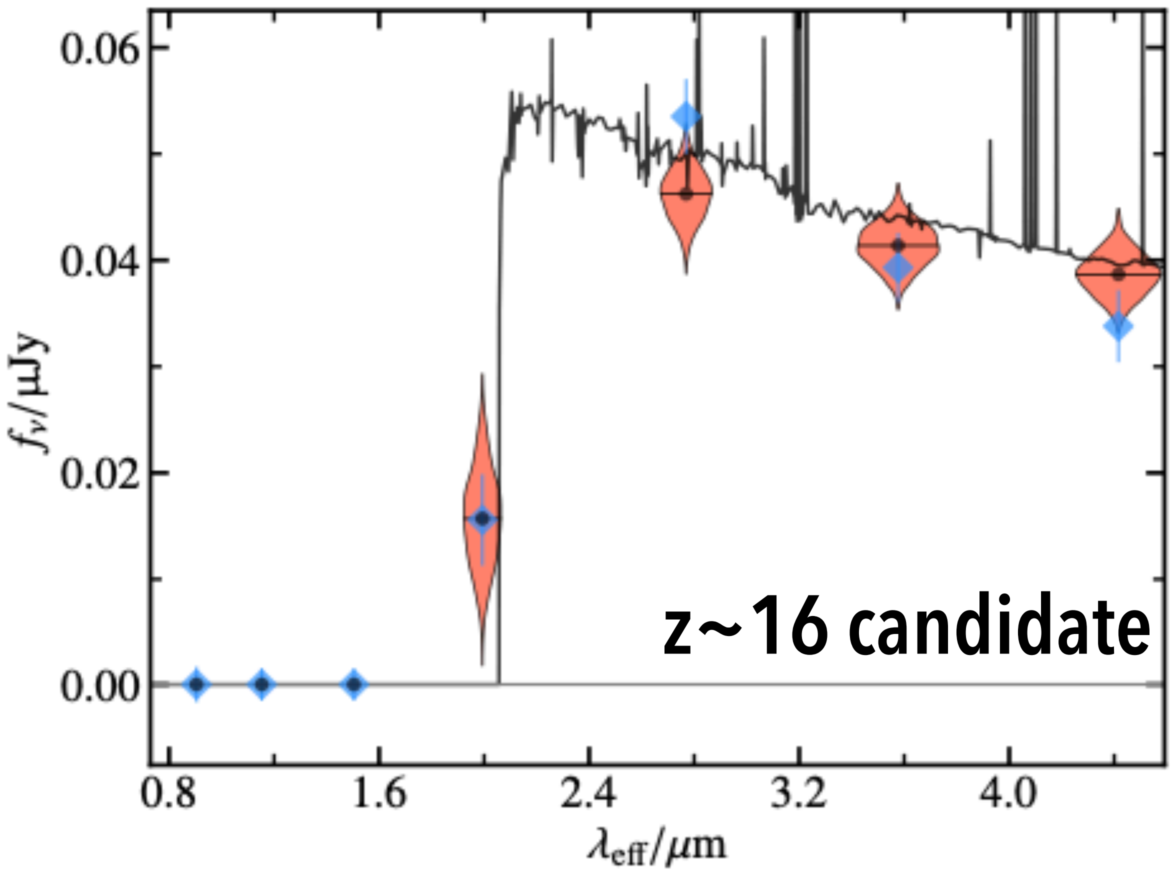
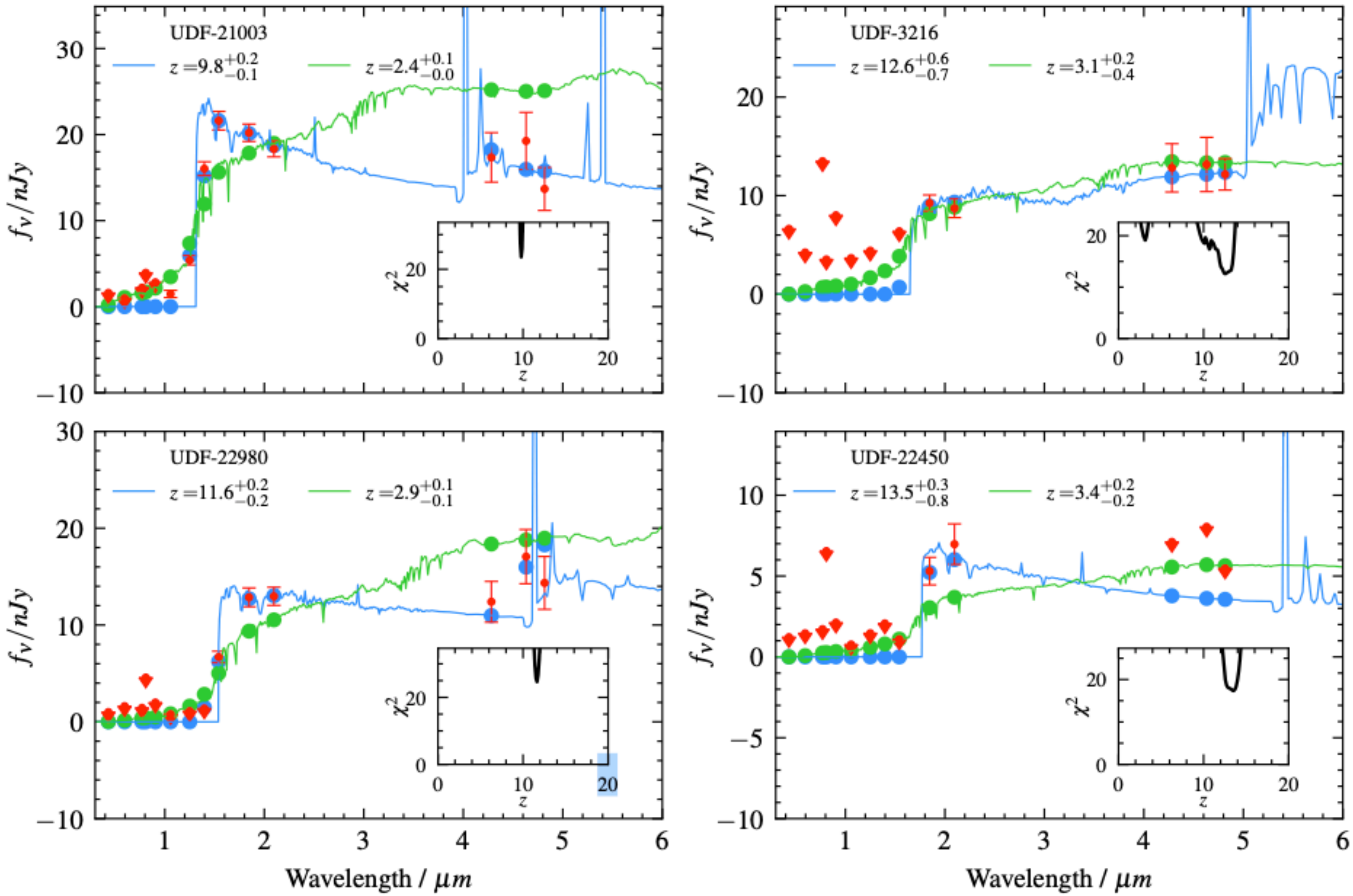
[4]Laboratoire d'Astrophysique, Ecole Polytechnique Fédérale de Lausanne, Observatoire de Sauverny, CH-1290 Versoix, Switzerland
[5]Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK





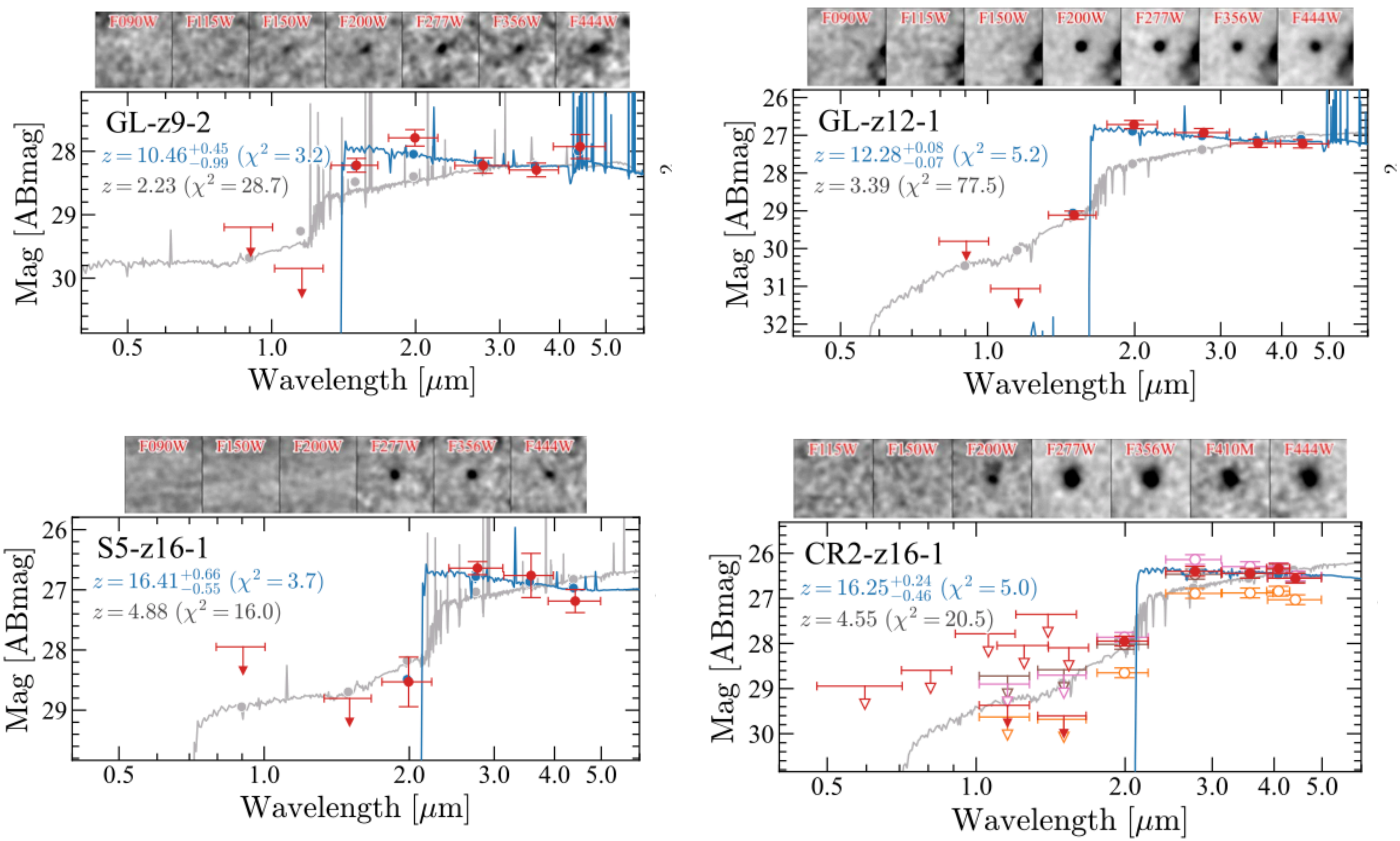
The evolution of the galaxy UV luminosity function at redshifts $z \simeq 8-15$ from deep JWST and ground-based near-infrared imaging

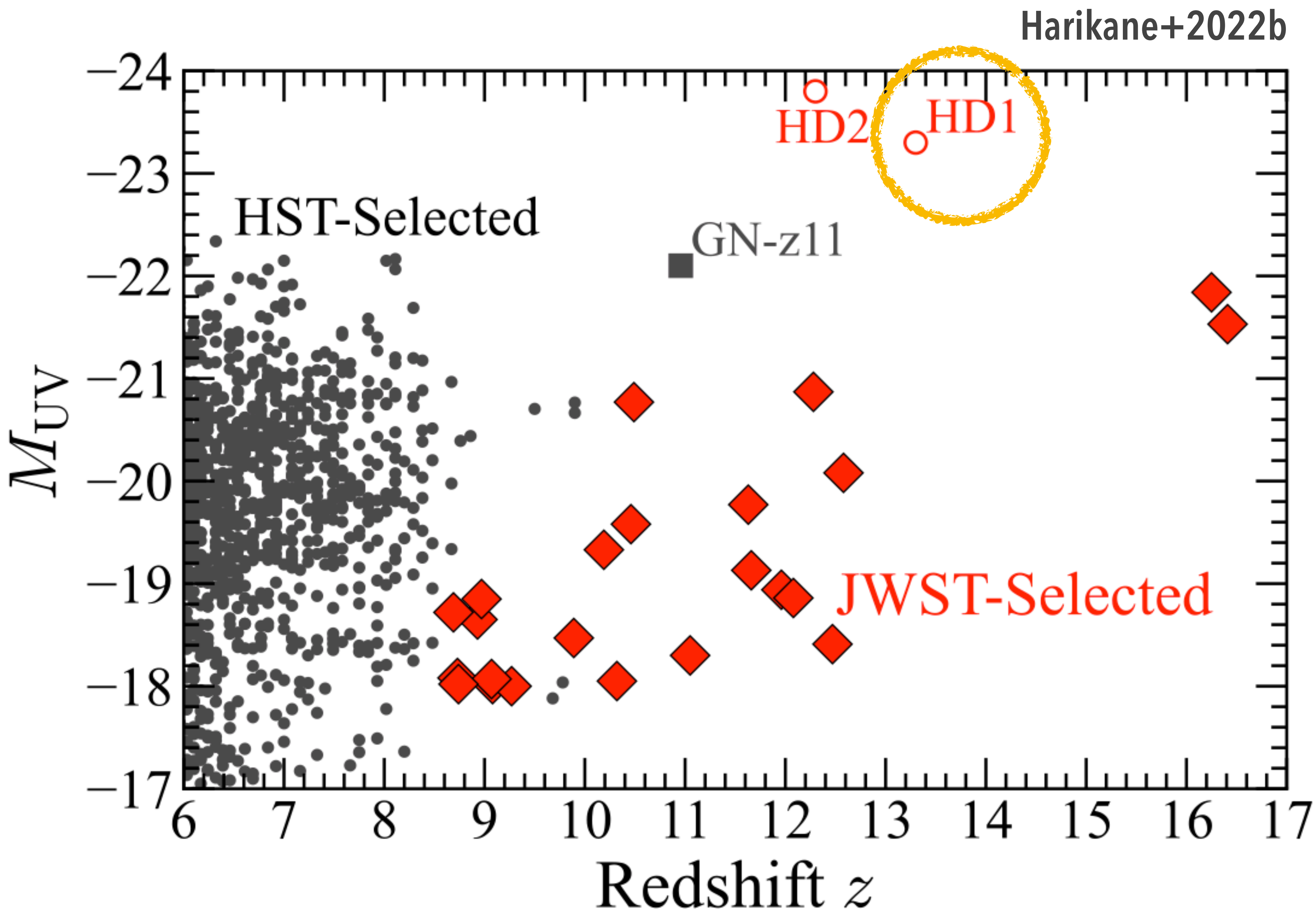
C. T. Donnan[1]★, D. J. McLeod[1], J. S. Dunlop[1], R. J. McLure[1], A. C. Carnall[1], R. Begley[1], F. Cullen[1]
M. L. Hamadouche[1], R. A. A. Bowler[2], D. Magee[3], H. J. McCracken[4], B. Milvang-Jensen[5,6]
A. Moneti[4] & T. Targett[7]



A Comprehensive Study on Galaxies at $z \sim 9 - 17$ Found in the Early JWST Data: UV Luminosity Functions and Cosmic Star-Formation History at the Pre-Reionization Epoch

Yuichi Harikane,[1] Masami Ouchi,[2,1,3] Masamune Oguri,[4,5] Yoshiaki Ono,[1] Kimihiko Nakajima,[2] Yuki Isobe,[1,6] Hiroya Umeda,[1,6] Ken Mawatari,[2] and Yechi Zhang[1,7]



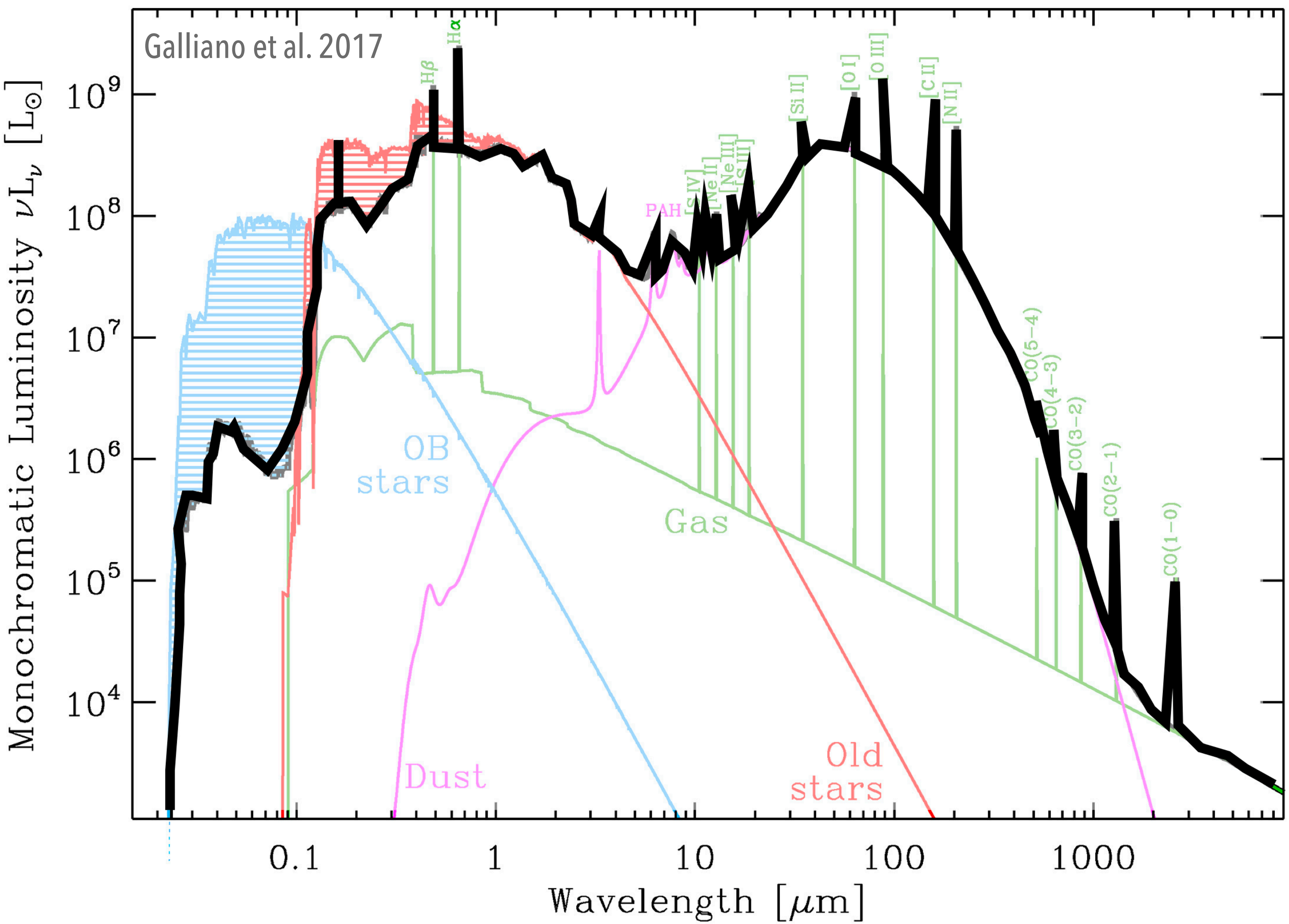

Harikane+2022b
HD2
HD1
HST-Selected
GN-z11
JWST-Selected
M_{UV}
−24
−23
−22
−21
−20
−19
−18
−17
6
7
8
9
10
11
12
13
14
15
16
17
Redshift z

Yet, these be only candidates

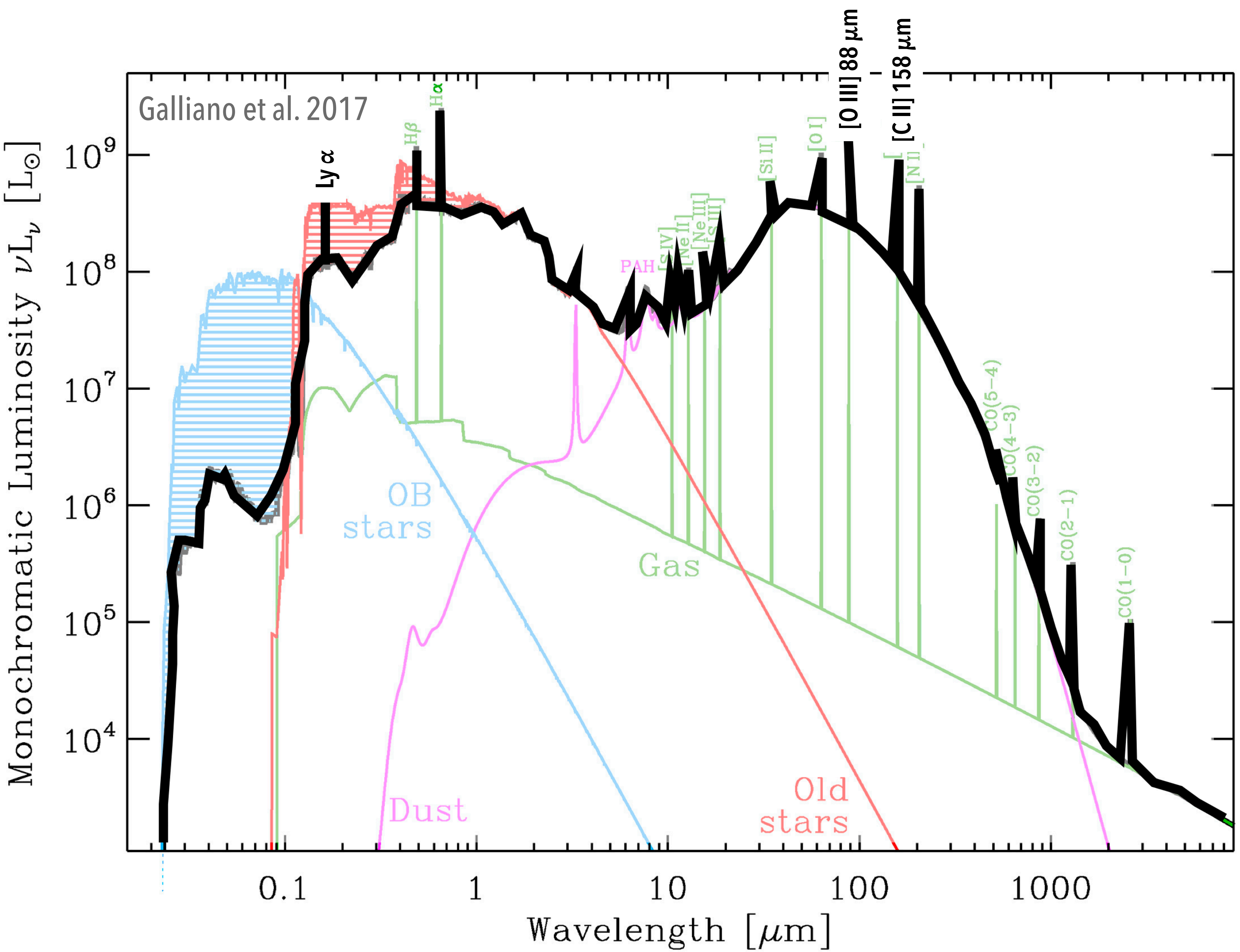
how to spectroscopically confirm them?


ALMA

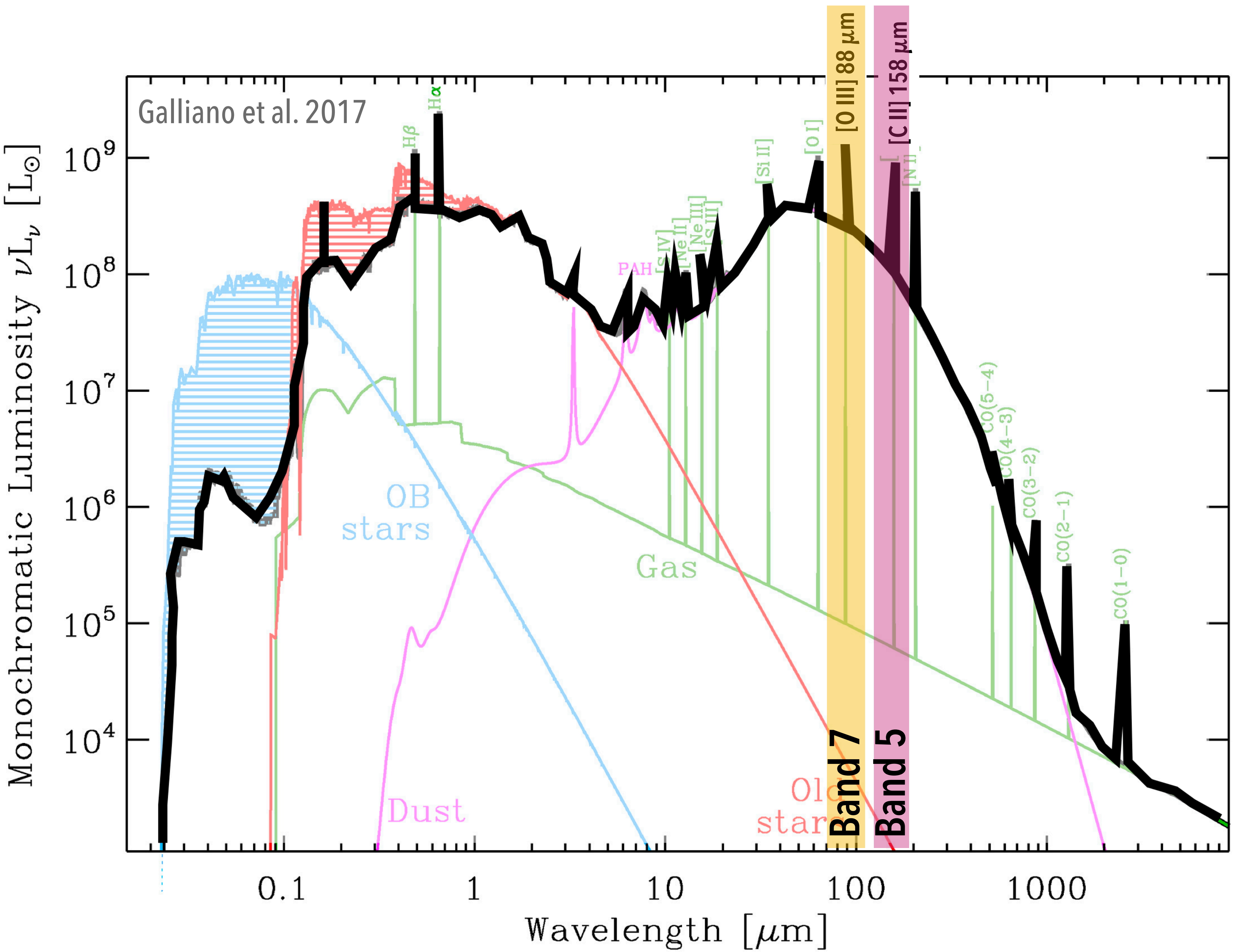
Spectroscopic confirmation



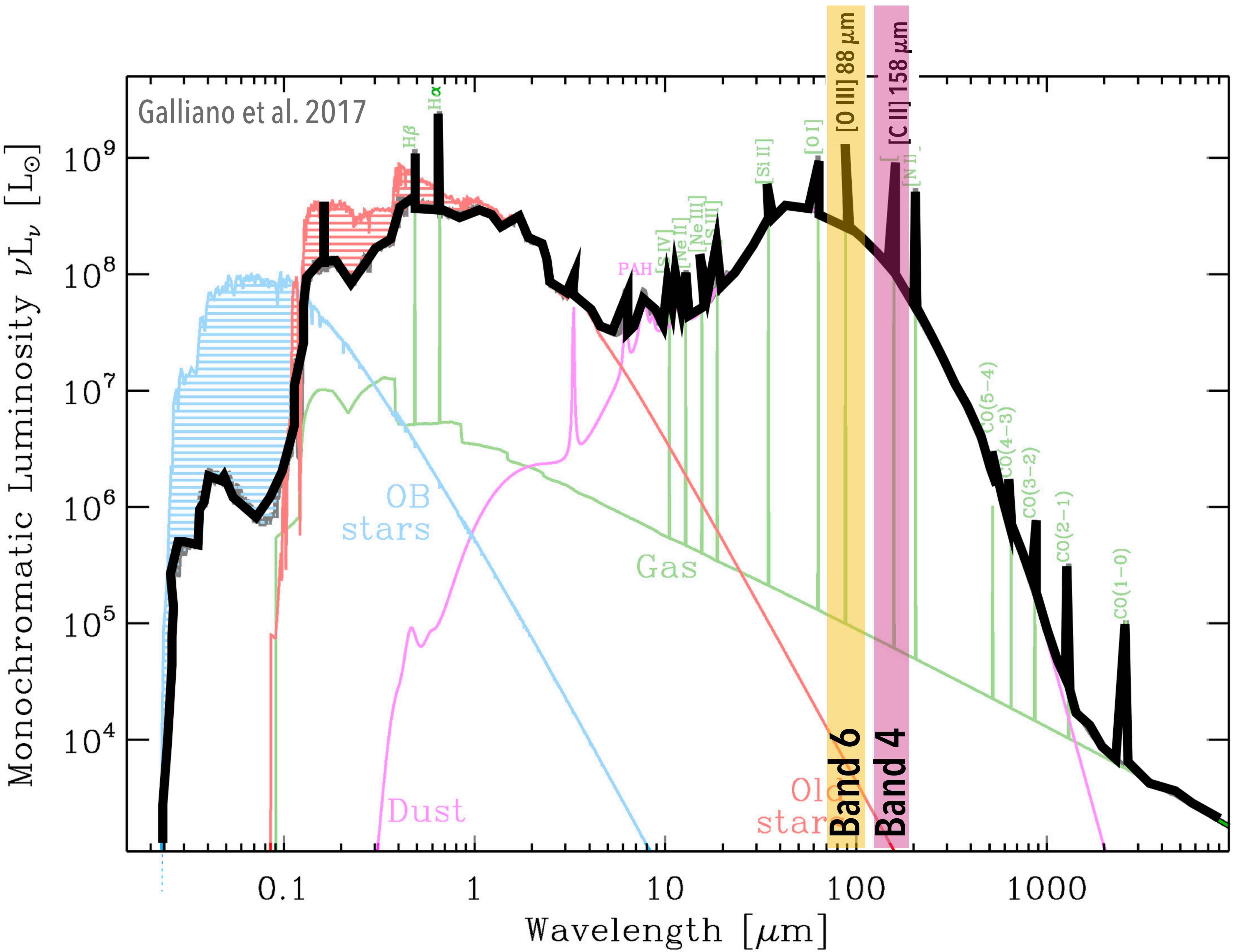
Spectroscopic confirmation



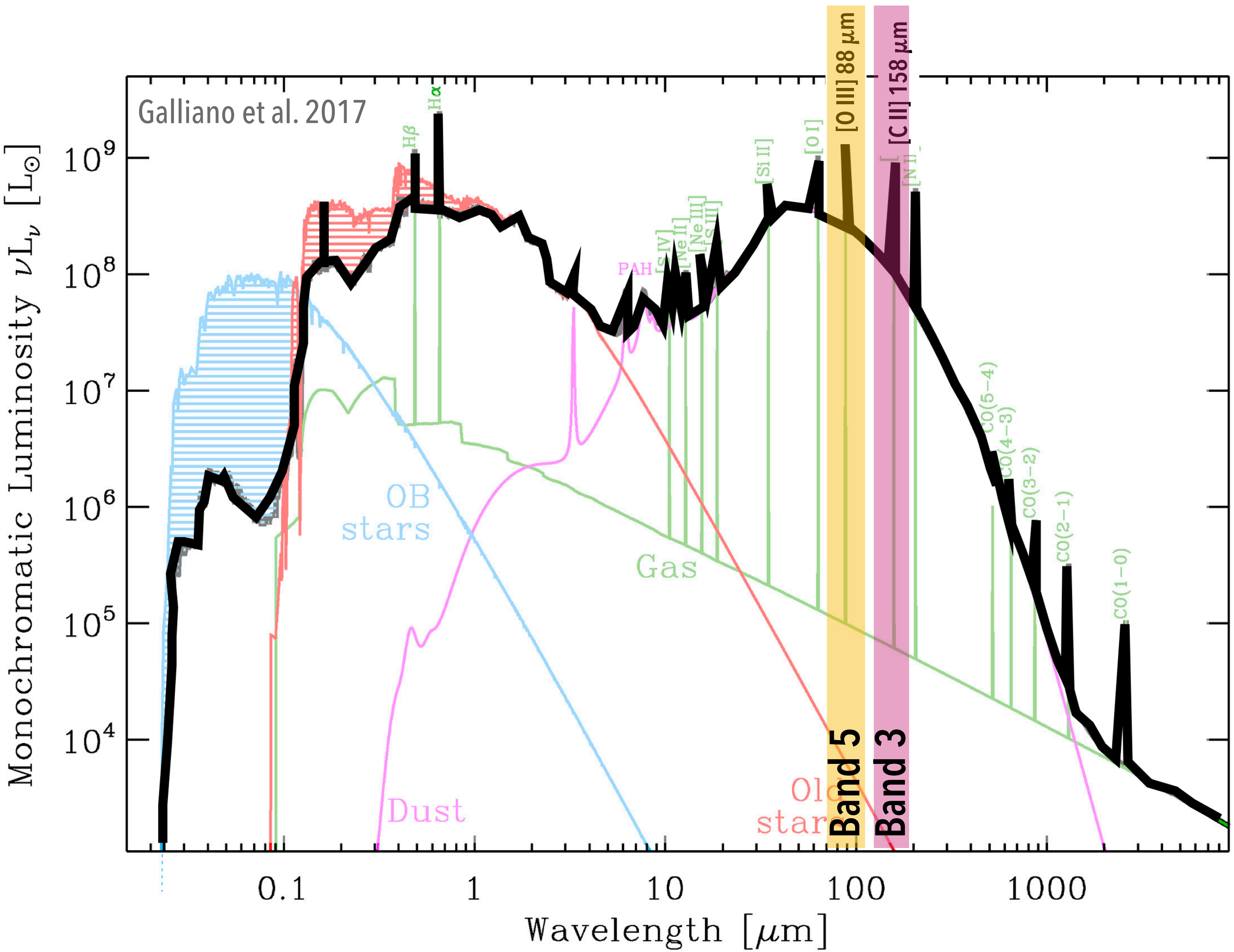
Spectroscopic confirmation with ALMA at z~9



Spectroscopic confirmation with ALMA at z~13

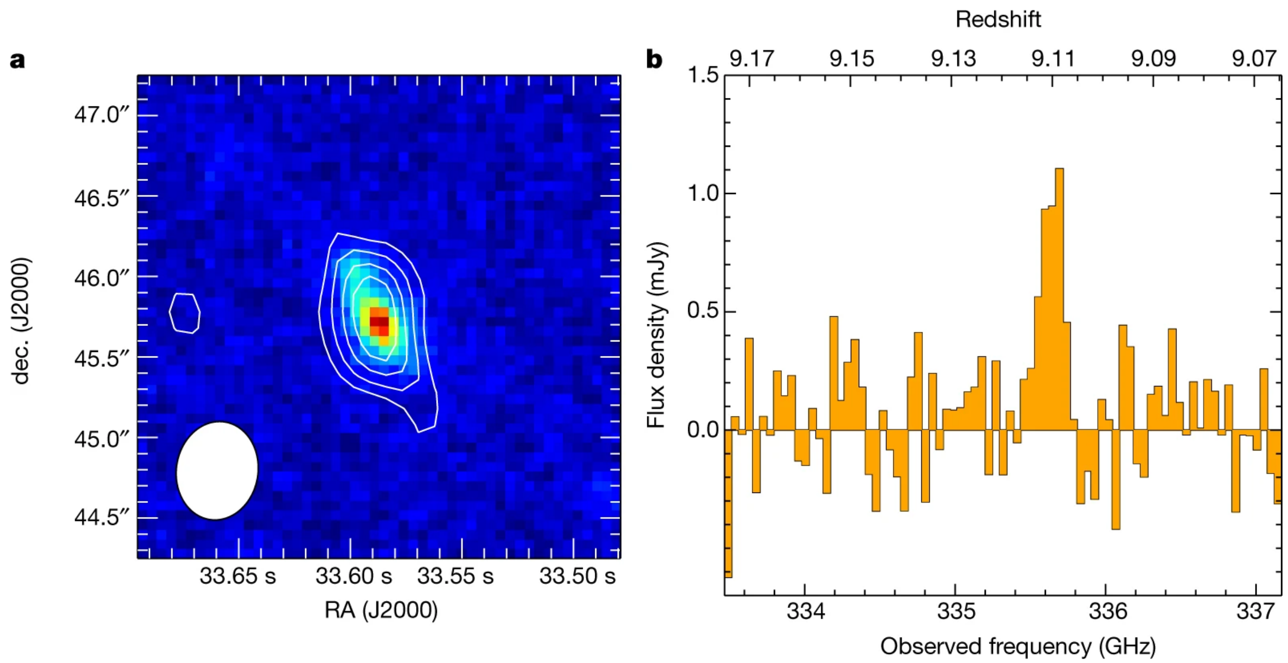


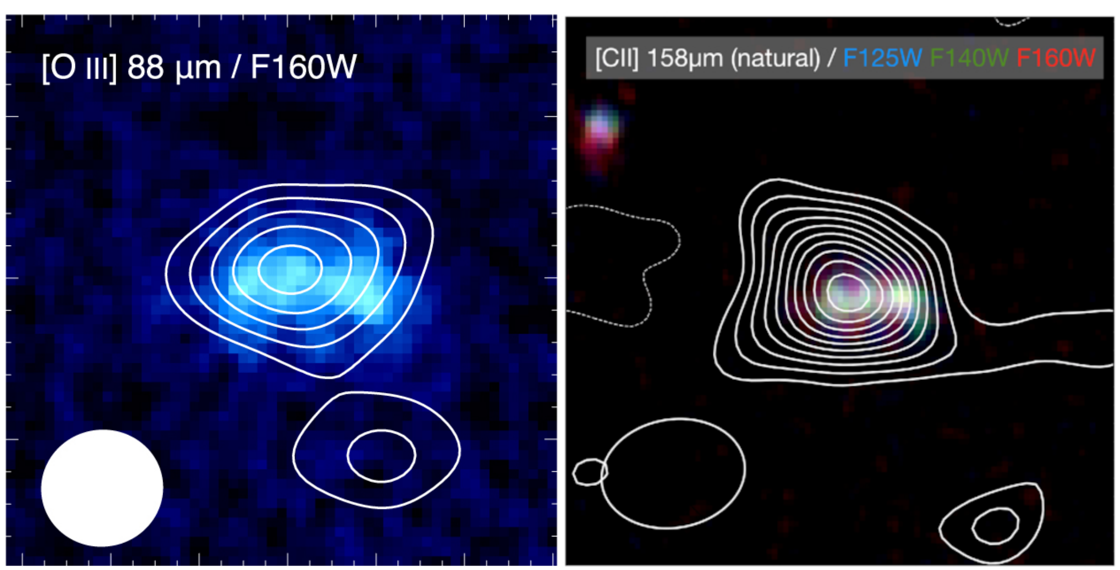
Spectroscopic confirmation with ALMA at z~16



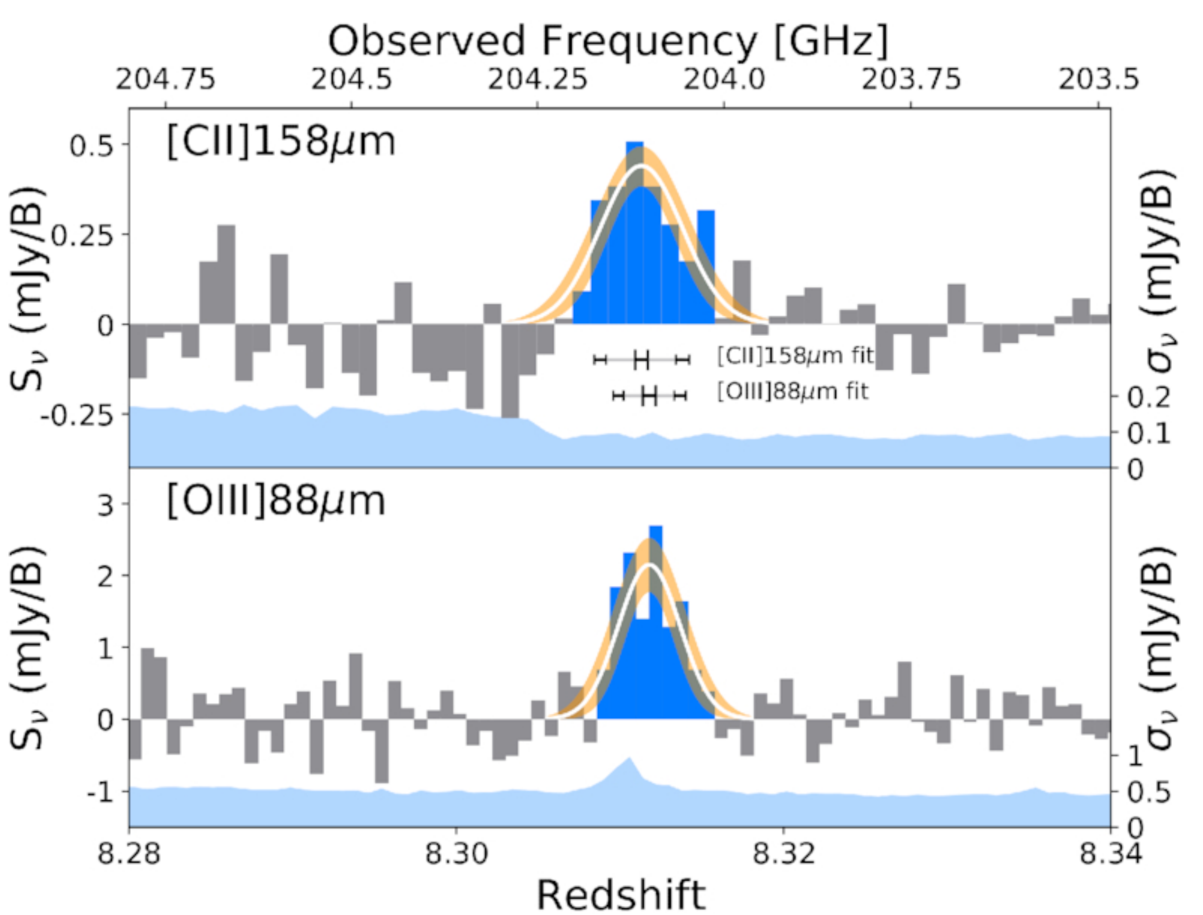
Previous spectroscopic confirmation with ALMA

[O III] 88 μm emission of MACS1149-JD1 at z=9.1 (Hashimoto+2018)



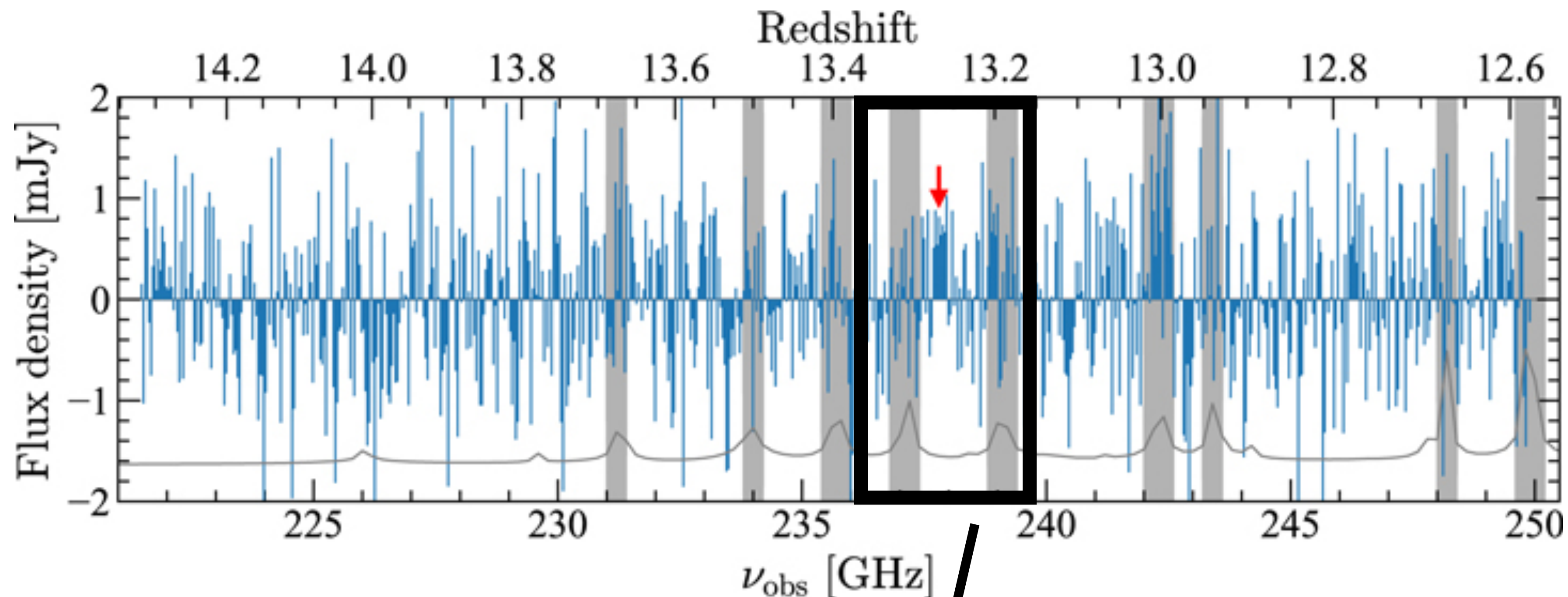


[O III] 88 μm and [C II] 158 μm emission of MACS0416_Y1 at *z* = 8.3 (Tamura+2019, Bakx+2020)



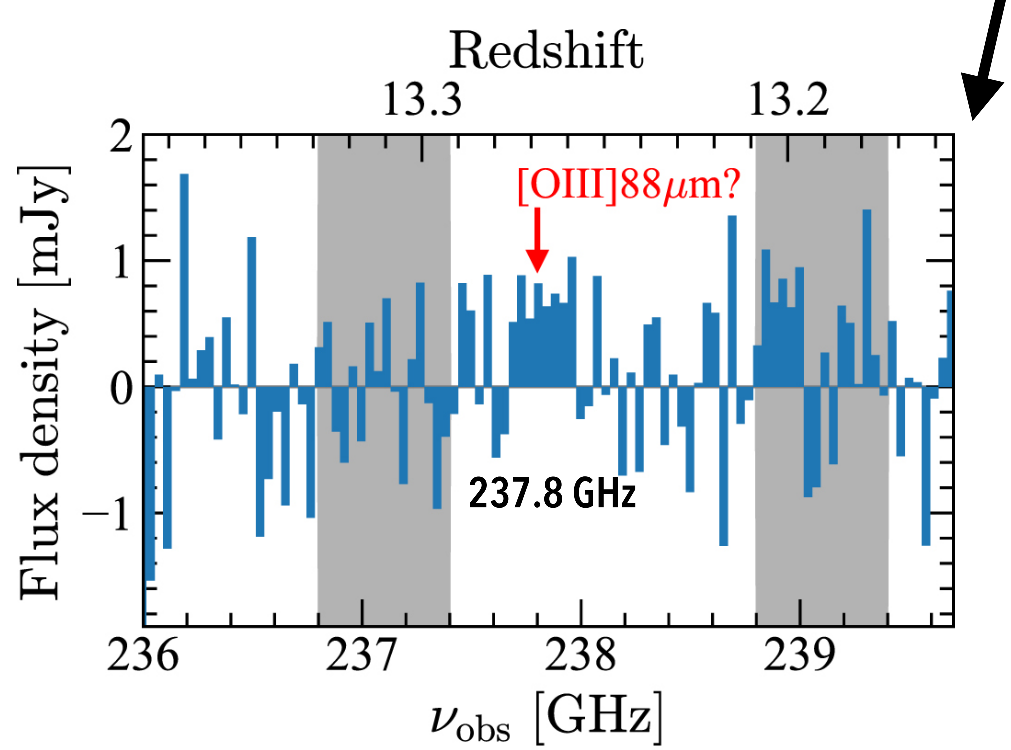
ALMA Band 6 observations of HD1

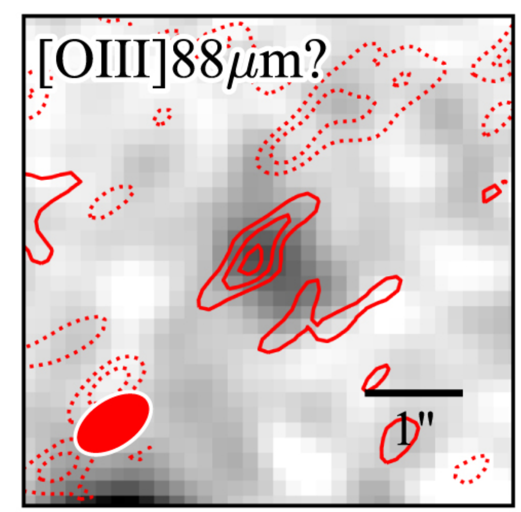
Harikane et al. (2022)



spectrum within 1″ circular aperture (equivalent to ~3.5 kpc at z=13.27)

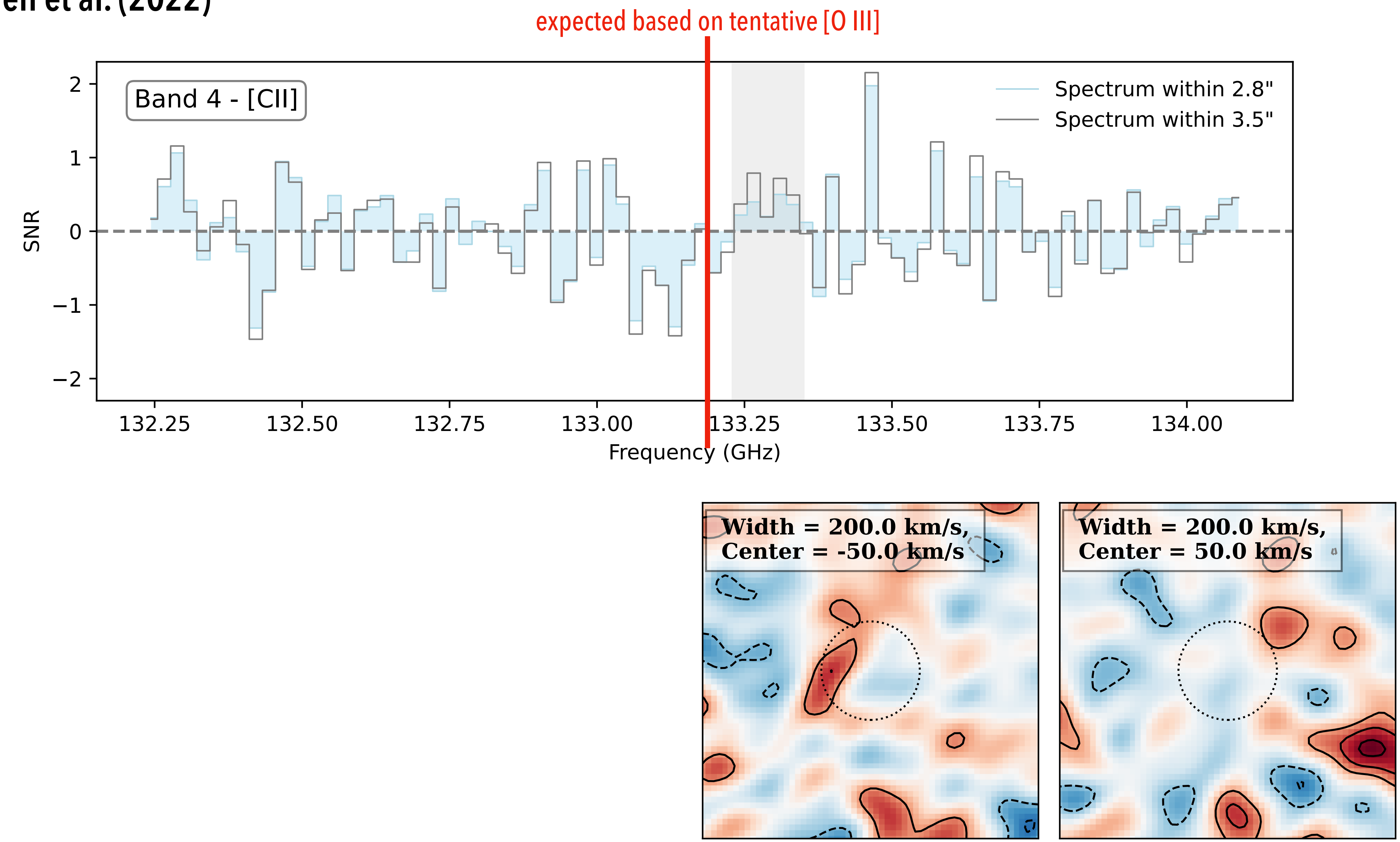
beam size: 0.51″ x 0.87″





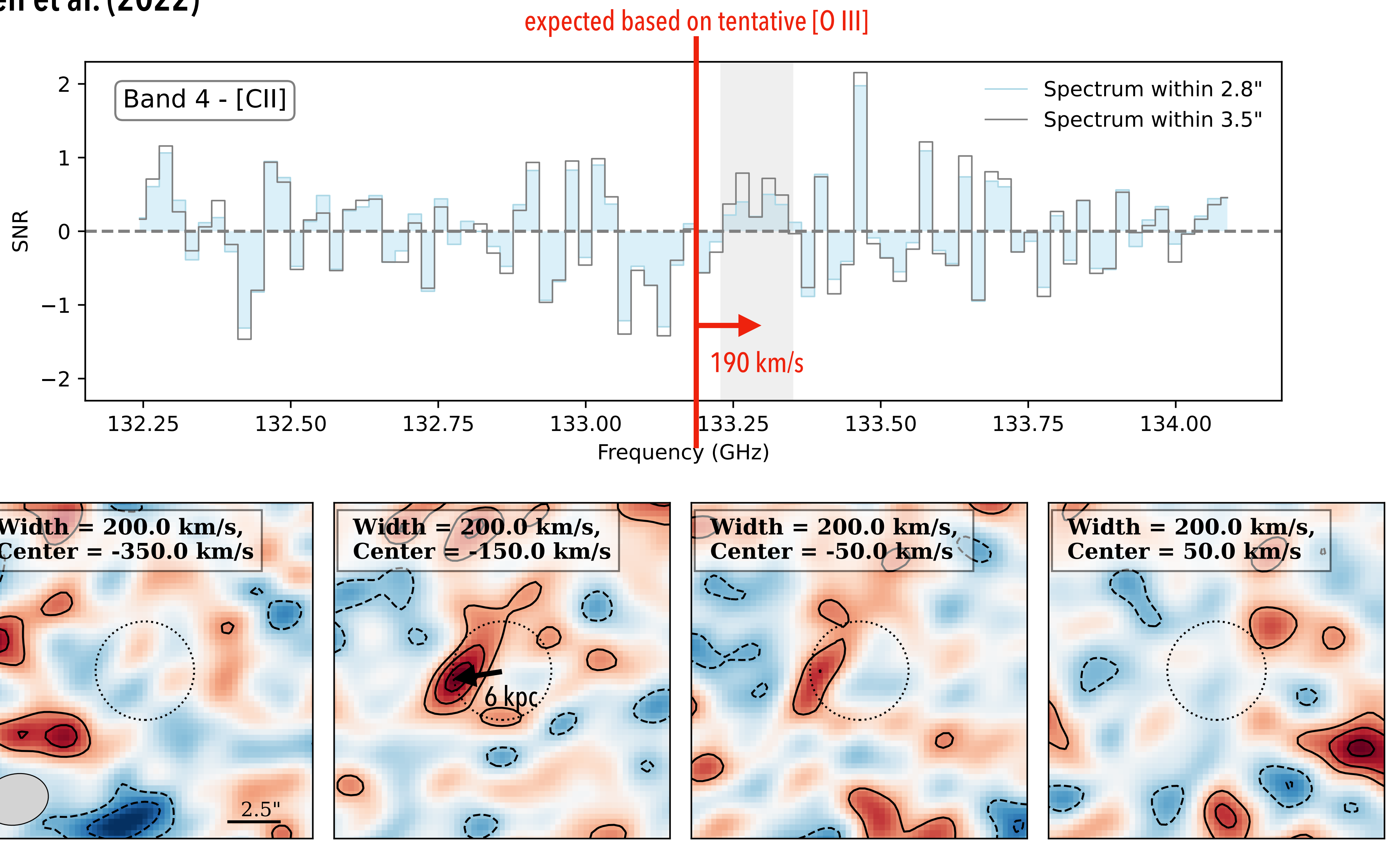
New ALMA Band 4 (DDT) observations of HD1

Kaasinen et al. (2022)



New ALMA Band 4 (DDT) observations of HD1

Kaasinen et al. (2022)

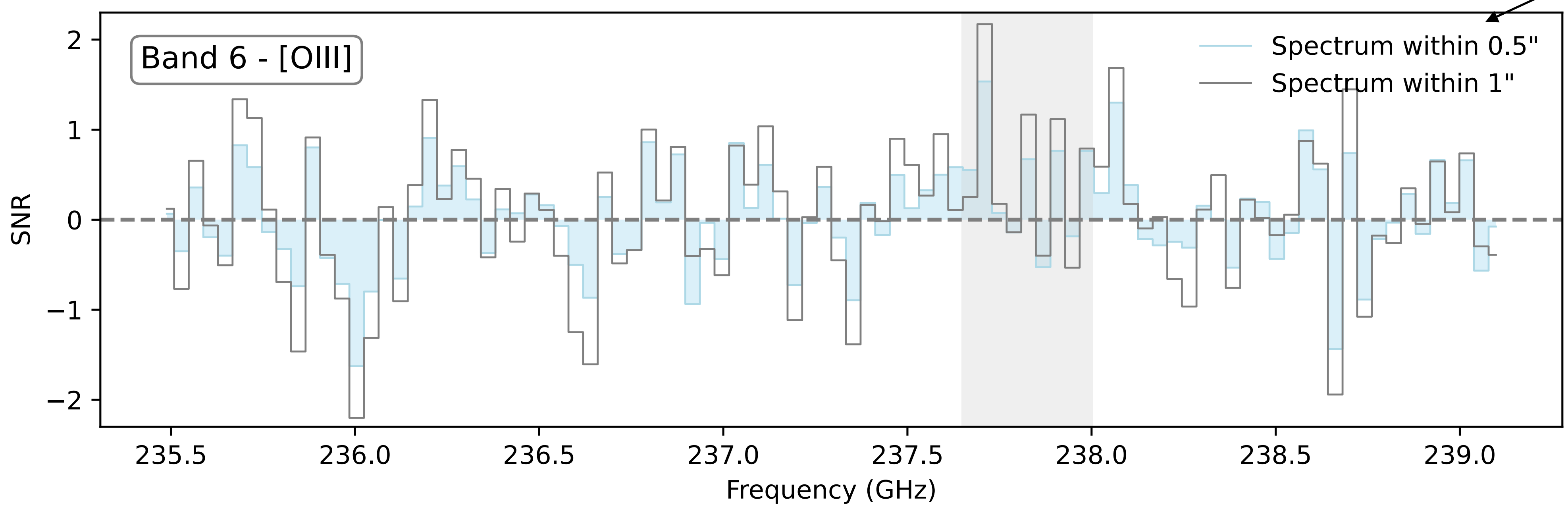


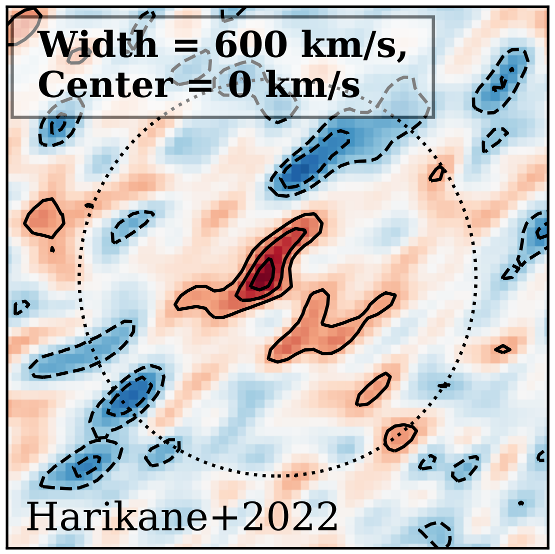
A potential [C II] 158 μm line, both spatially and spectrally offset?

ALMA Band 6 observations of HD1

Kaasinen et al. (2022)

equivalent to ~3.5 kpc
beam size: 0.51″ x 0.87″

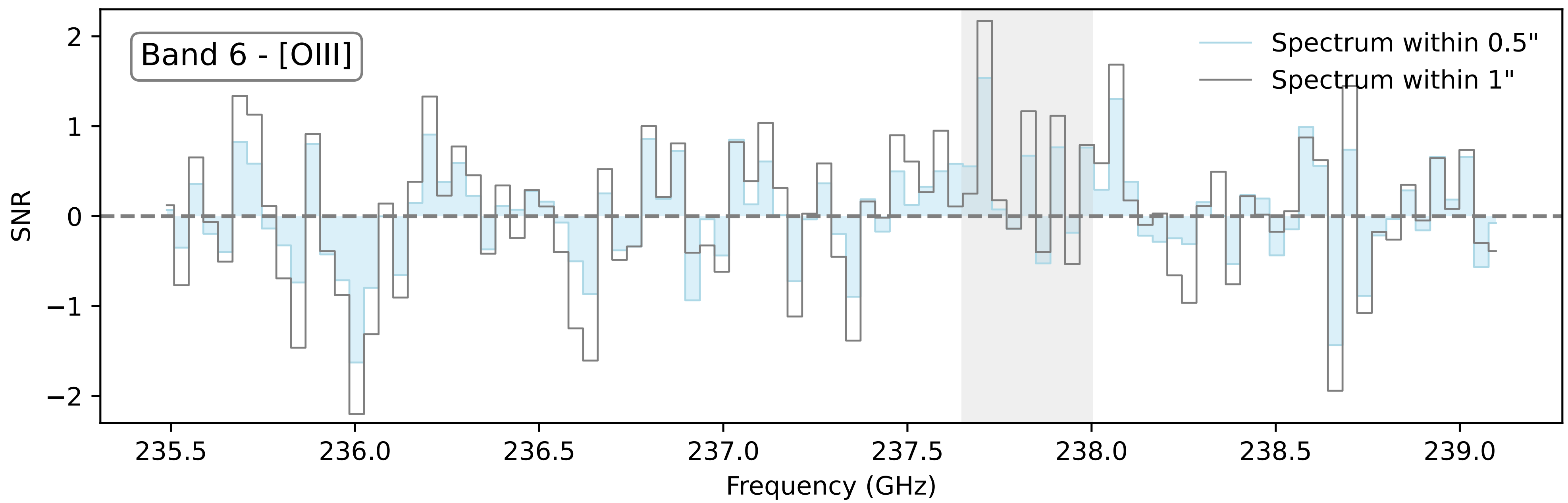


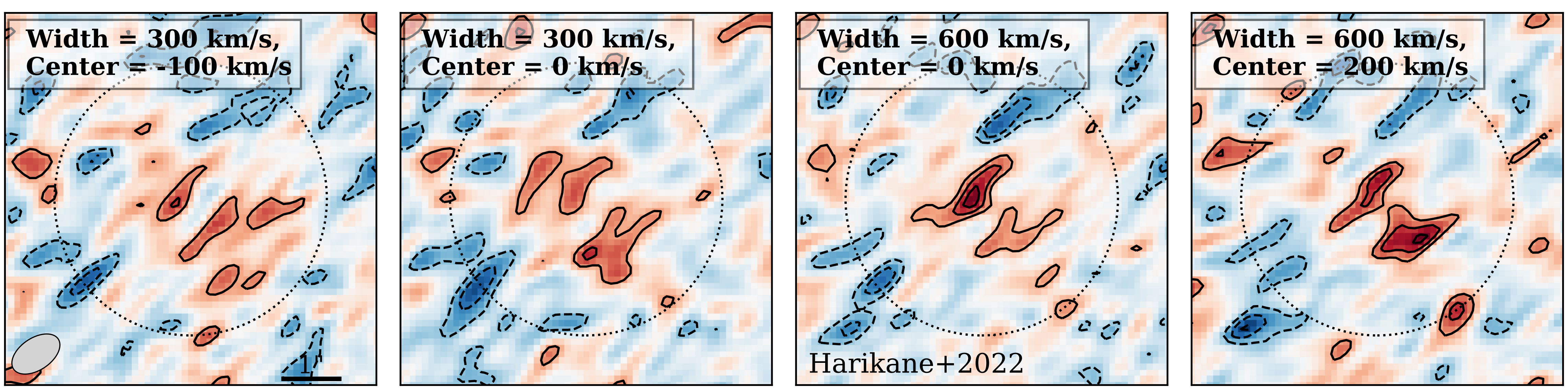


We recover the same tentative 3.8σ [O III] 88 μm as Harikane+2022, although the spectrum extracted from ~beam size is not convincing

ALMA Band 6 observations of HD1

Kaasinen et al. (2022)





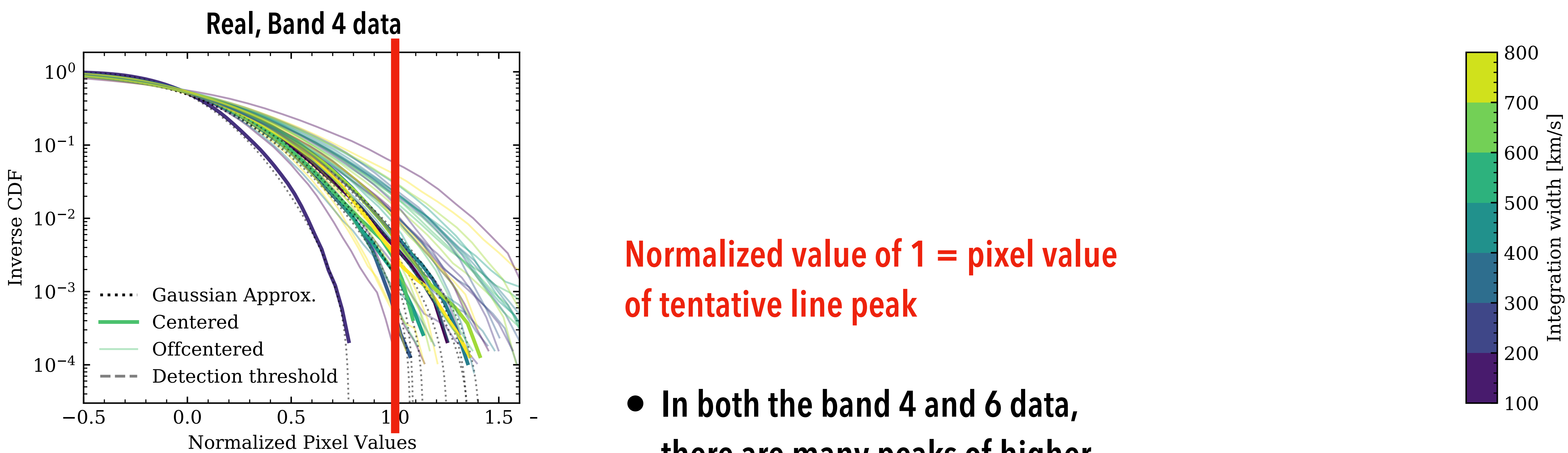
The tentative 3.8σ [O III] 88 μm feature is highly sensitive to the line width and aperture size, any narrower and it's not a line, any smaller aperture and it's not a line

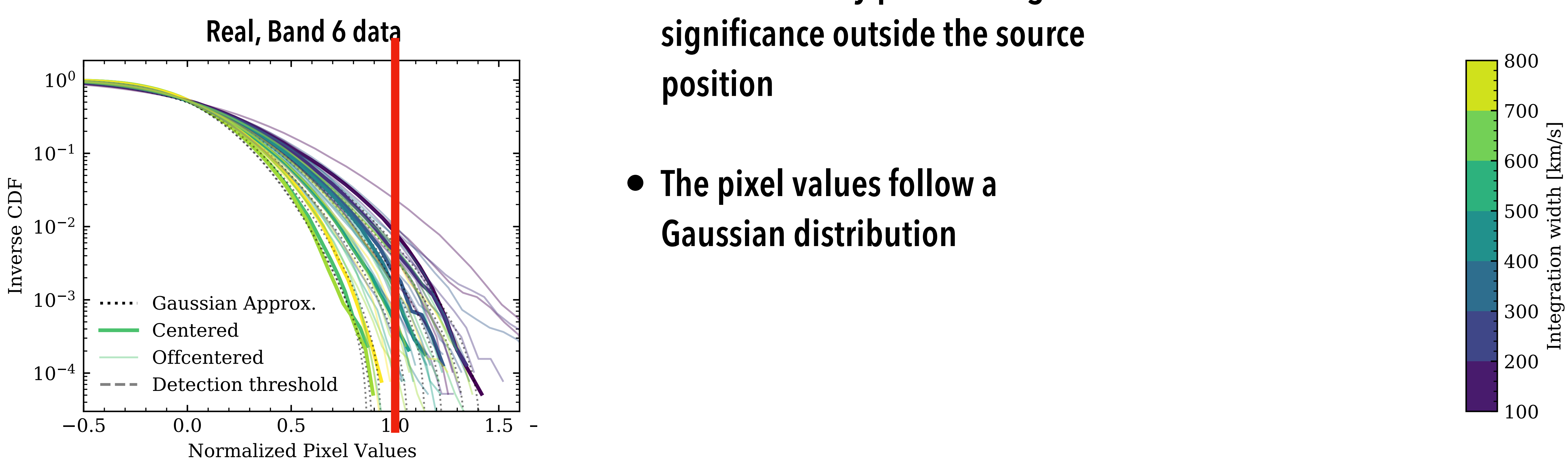
Though this be madness, yet there be method in't

***Hamlet*, Shakespeare**

ALMA noise properties - pixels outside source

Joshiwa van Marrewijk (Kaasinen+2022)





Normalized value of 1 = pixel value of tentative line peak

- In both the band 4 and 6 data, there are many peaks of higher significance outside the source position

- The pixel values follow a Gaussian distribution

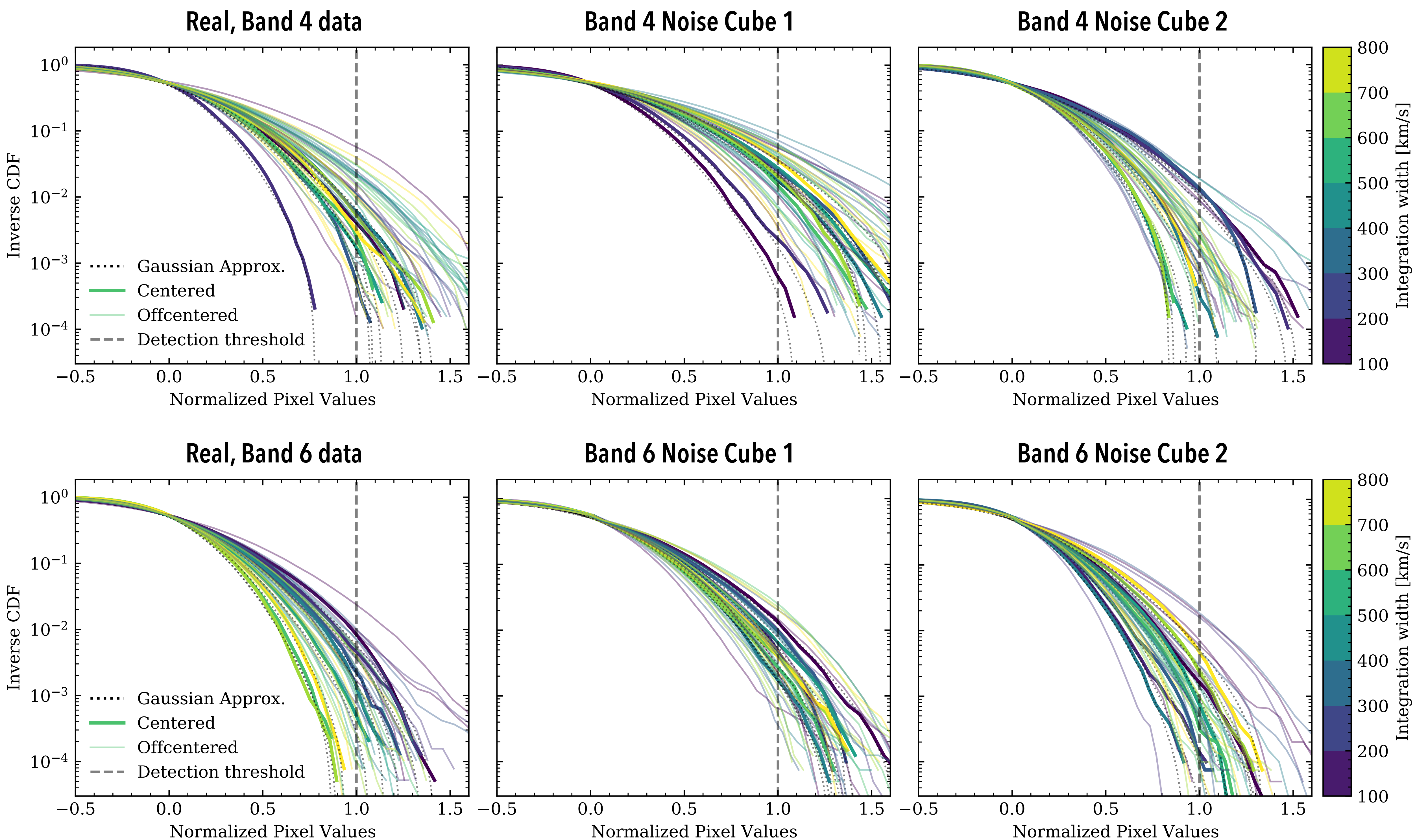
ALMA noise properties - pixels outside source

Joshiwa van Marrewijk (Kaasinen+2022)

Created 10 pure noise cubes each by jack-knifing -
i.e. randomly inverting sign of data in *uv* space and re-imaging
– make moment-0 maps over different integration widths

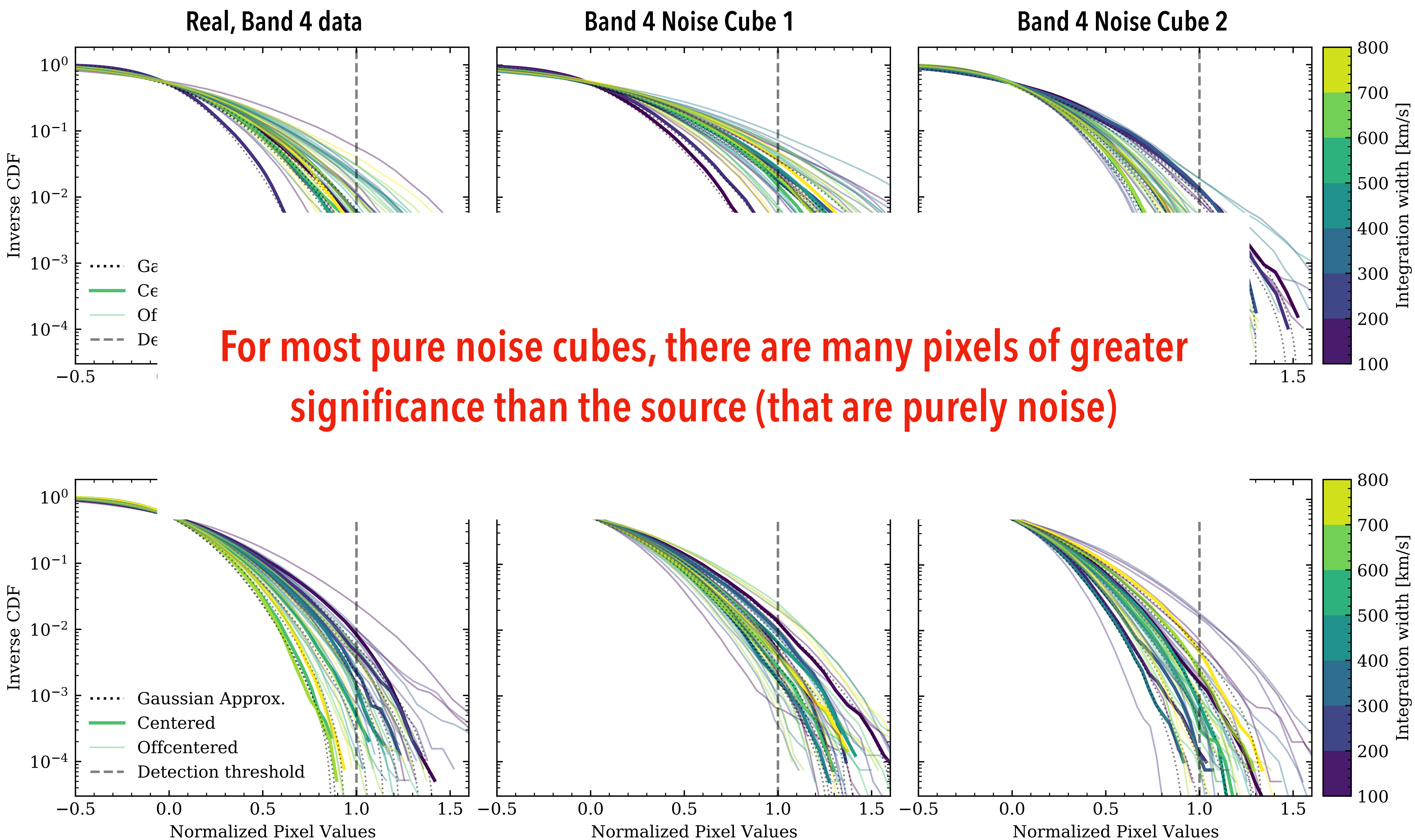
ALMA noise properties - pixels outside source

Joshiwa van Marrewijk (Kaasinen+2022)

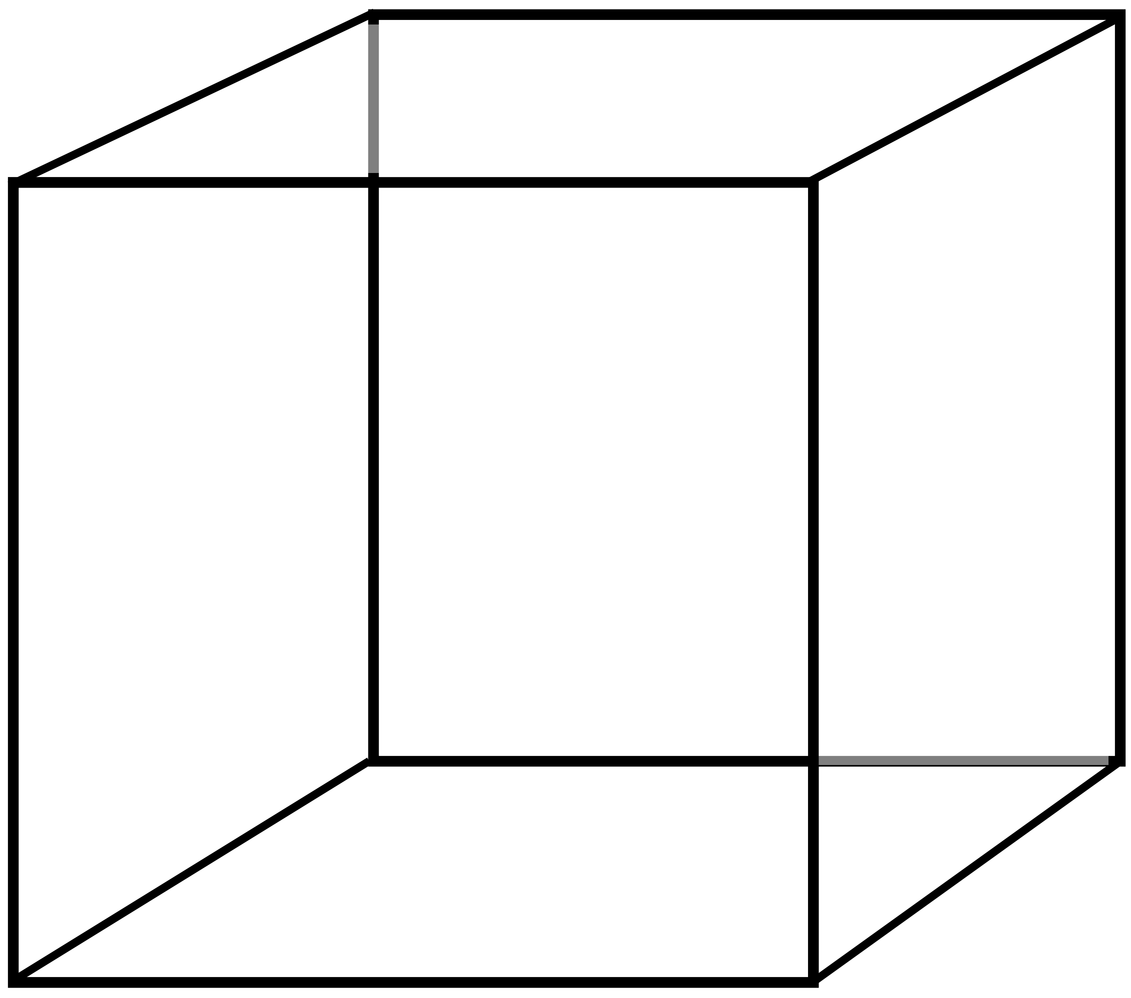


ALMA noise properties - pixels outside source

Joshiwa van Marrewijk (Kaasinen+2022)



Line finding

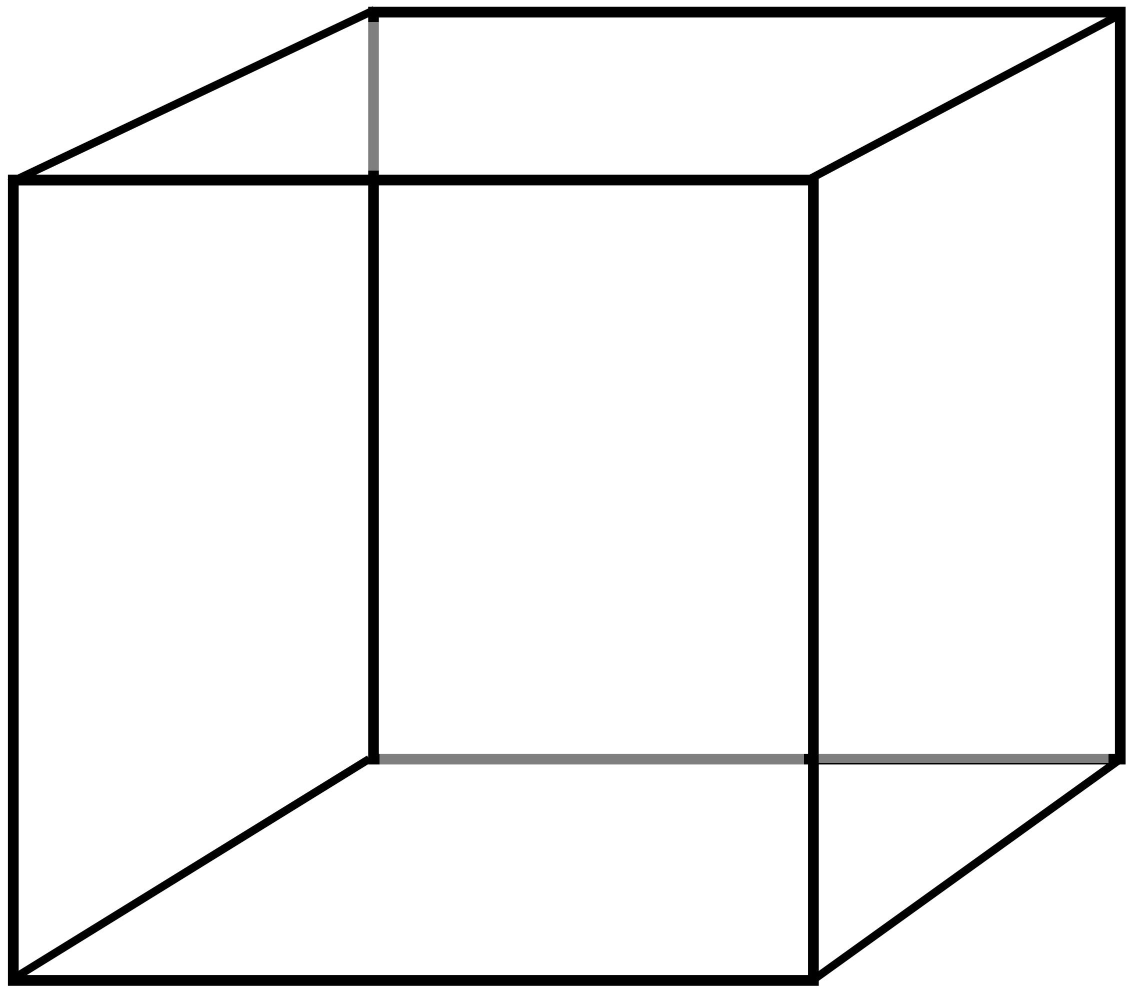


**Line-finding code from Béthermin et al. (2020) and Ginolfi et al. (2022) + FindClump (Walter+2016)

For real and mock noise cubes,

find lines of ≥ potential [O III] 88 μm feature S/N

Line finding



**Line-finding code from Béthermin et al. (2020) and Ginolfi et al. (2022) + FindClump (Walter+2016)

For real and mock noise cubes,

find lines of ≥ potential [O III] 88 μm feature S/N

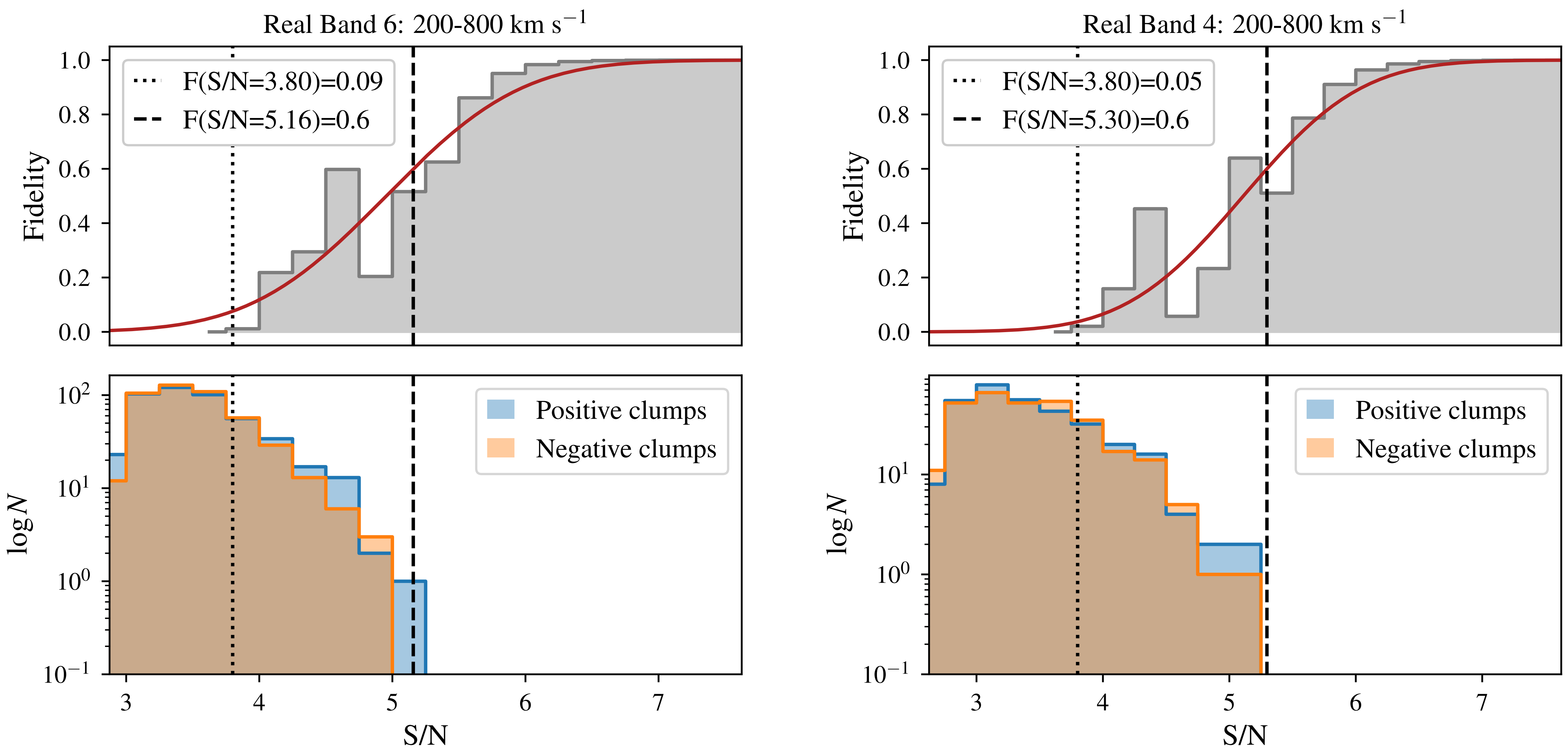
- loop over line widths of 200-800 km/s
- collapse over this width and search for peaks in moment 0 map
- extract spectrum at moment-0 peak position and determine the spectral S/N
- keep feature if also over spectral S/N threshold
- remove any duplicates

Line finding

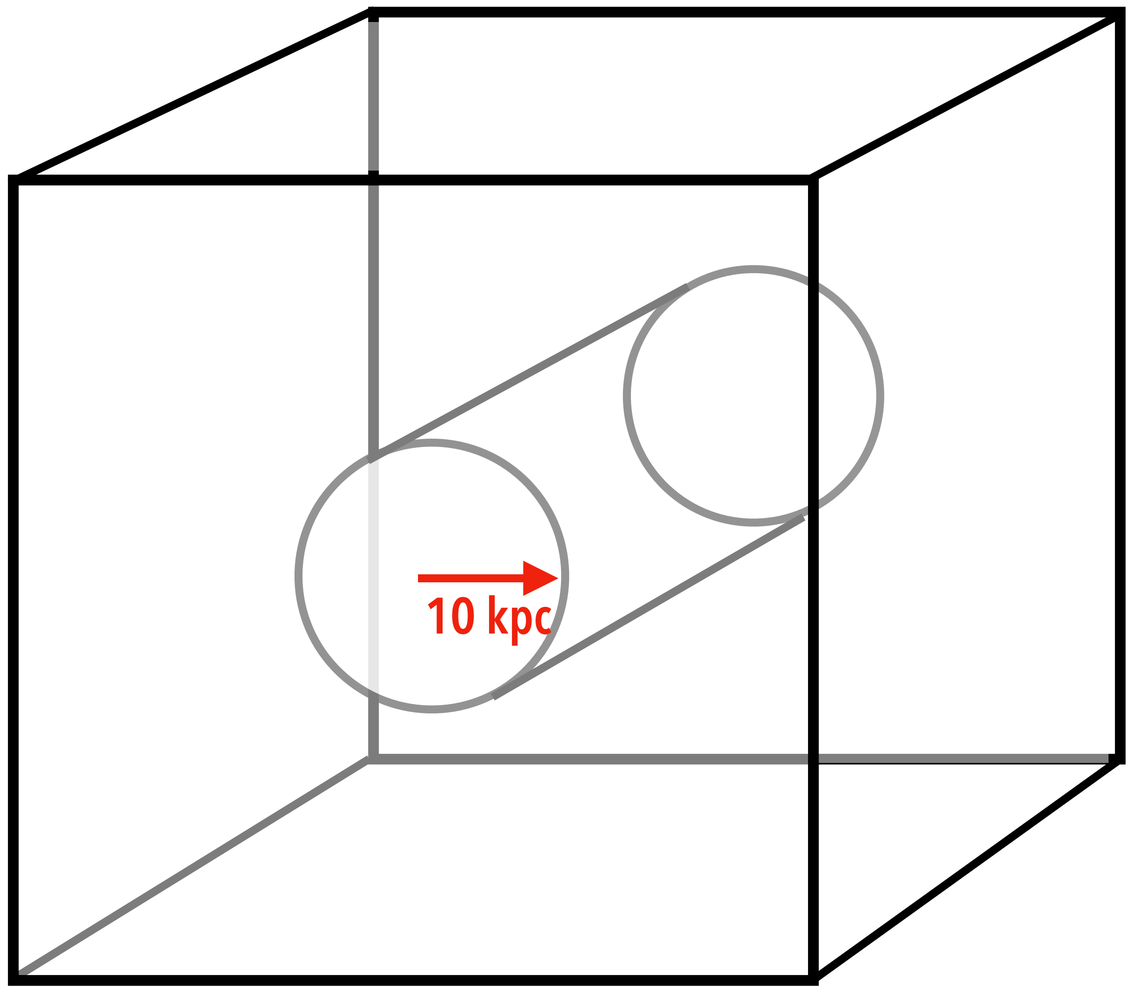
$$\text{fidelity}(S/N) = 1 - \frac{N_{neg}(S/N)}{N_{pos}(S/N)}$$

Line finding

$$\text{fidelity}(S/N) = 1 - \frac{N_{neg}(S/N)}{N_{pos}(S/N)}$$



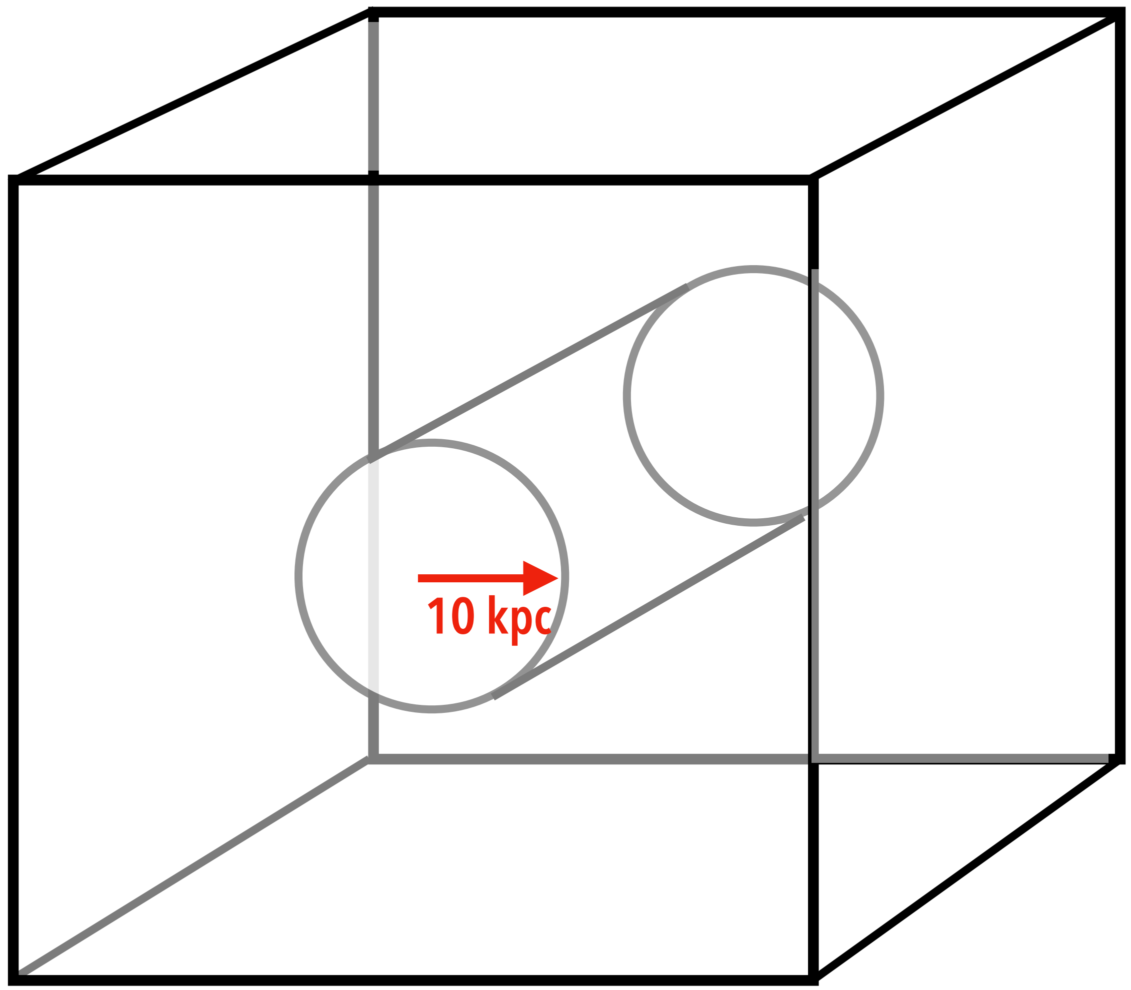
Line finding within 10 kpc of expected source



For real and mock noise cubes,

find lines of ≥ potential [O III] 88 μm feature S/N

Line finding



Band 4 noise cubes:

- 5/10 cubes have ≥1 positive ≥3.8 σ feature
- 3/10 cubes have ≥1 negative ≥3.8 σ feature

[CII] line 50% consistent with being noise

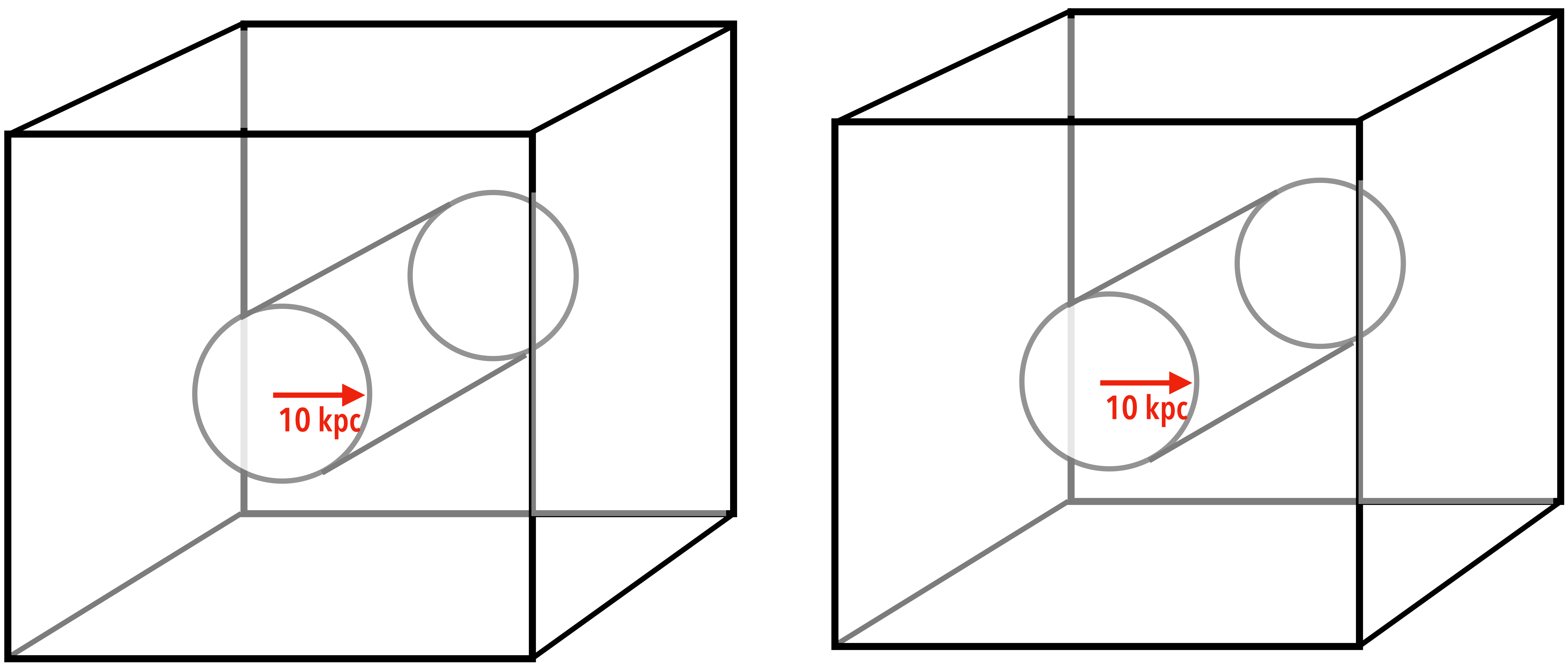
Band 6 noise cubes:

- all cubes have ≥1 positive ≥3.8 σ feature, mean of 6 features per cube
- all cubes have ≥1 negative ≥3.8 σ feature, with a mean of 7 such features

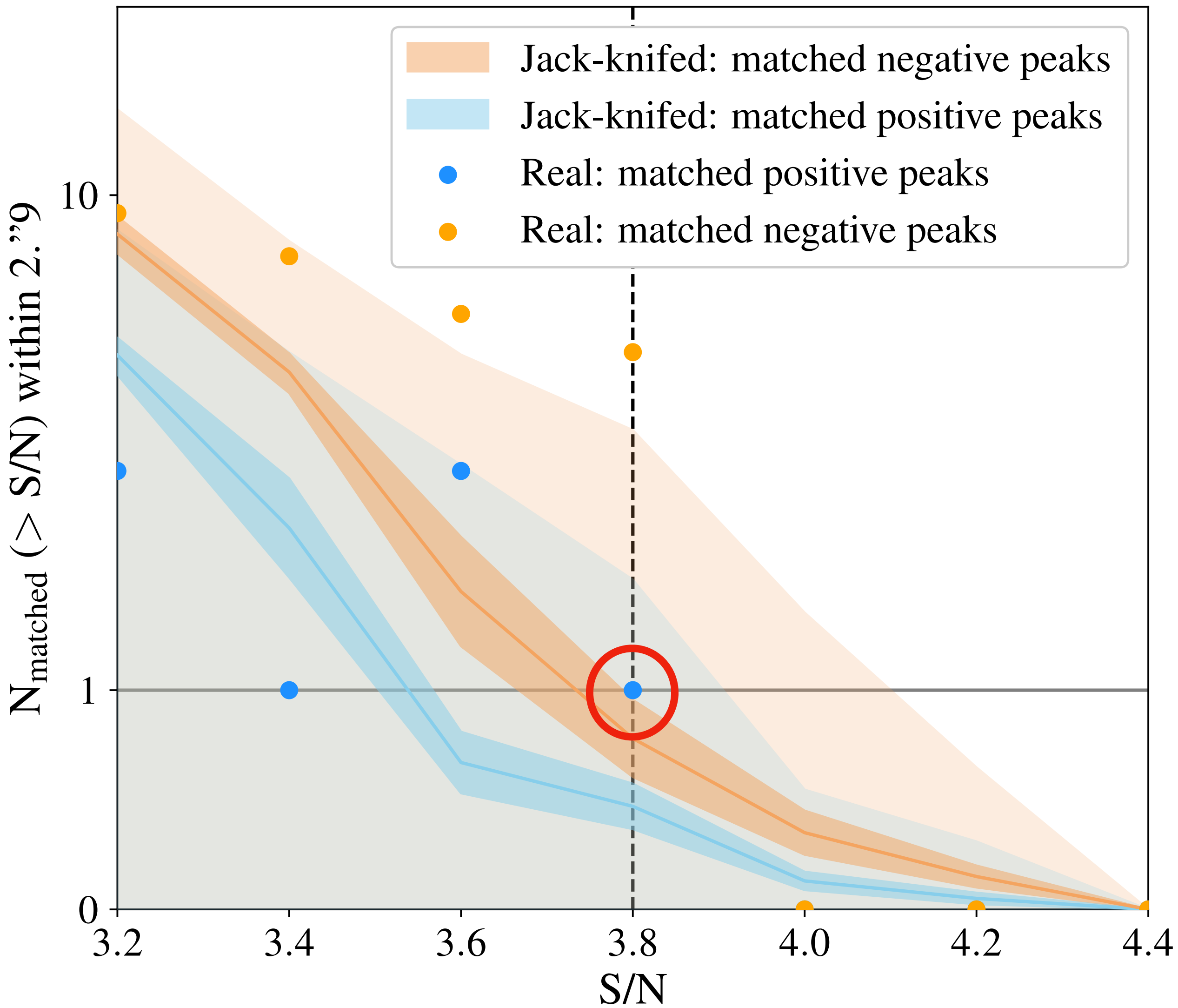
[O III] line is fully consistent with being noise

Matching peaks: <1000 km/s, <10 kpc

Real data: 1 matched positive peak (the two tentative lines)

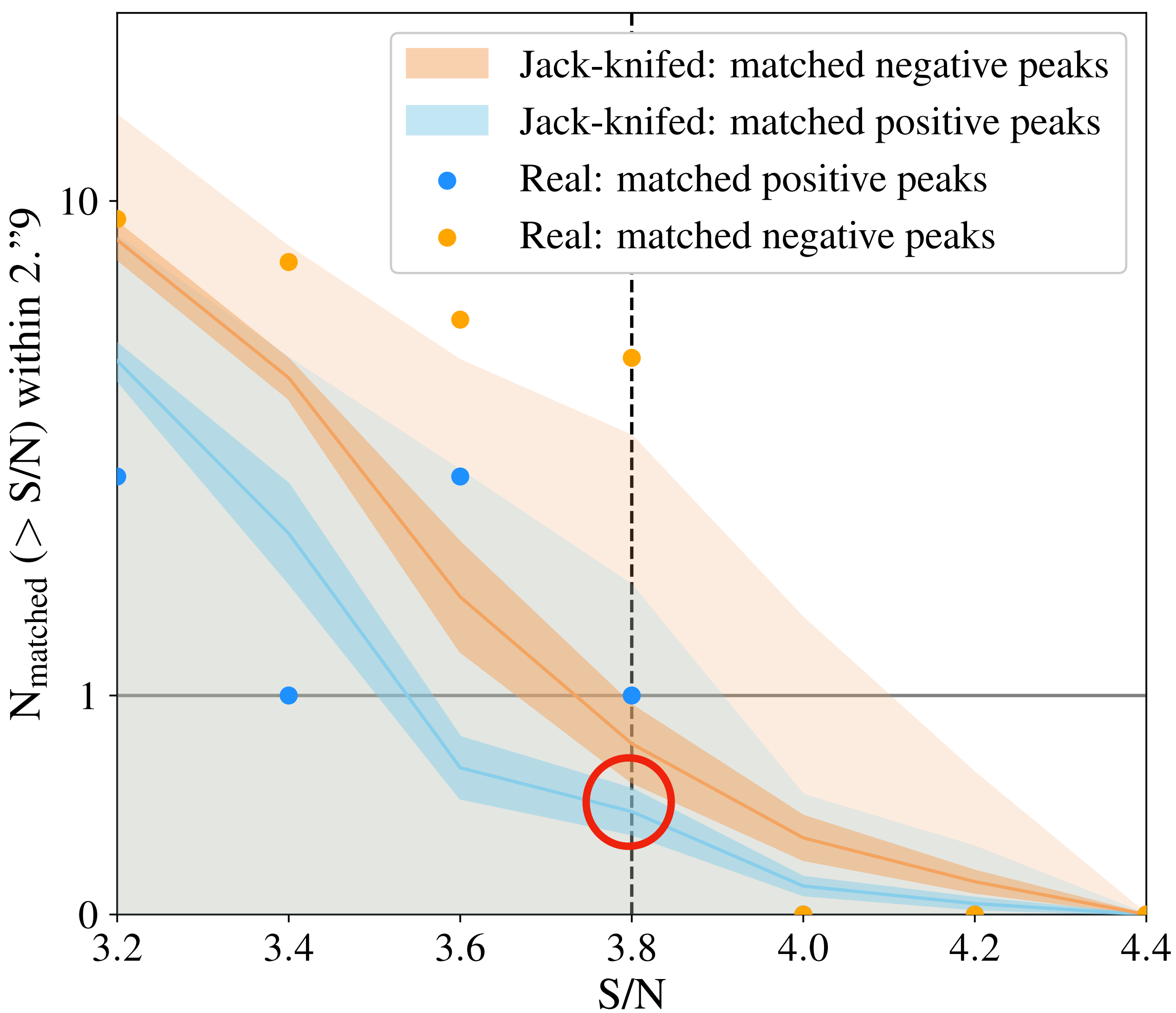


Matched “peaks”: <1000 km/s, <10 kpc



1 matched, positive > 3.8 σ feature in data

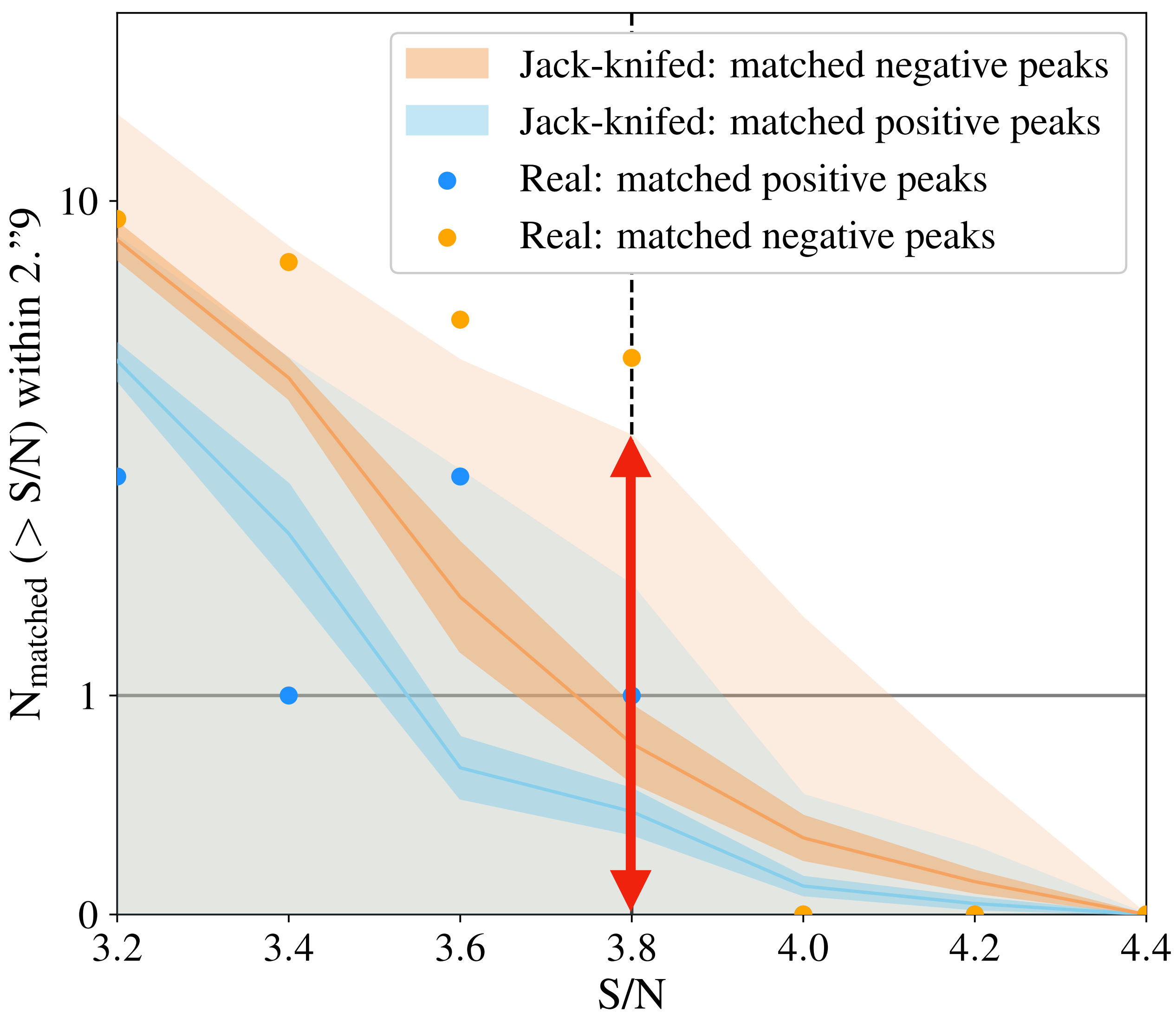
Matched "peaks": <1000 km/s, <10 kpc



1 matched, positive > 3.8 σ feature in data

mean of 0.5 positive > 3.8 σ features in noise cubes

Matched "peaks": <1000 km/s, <10 kpc

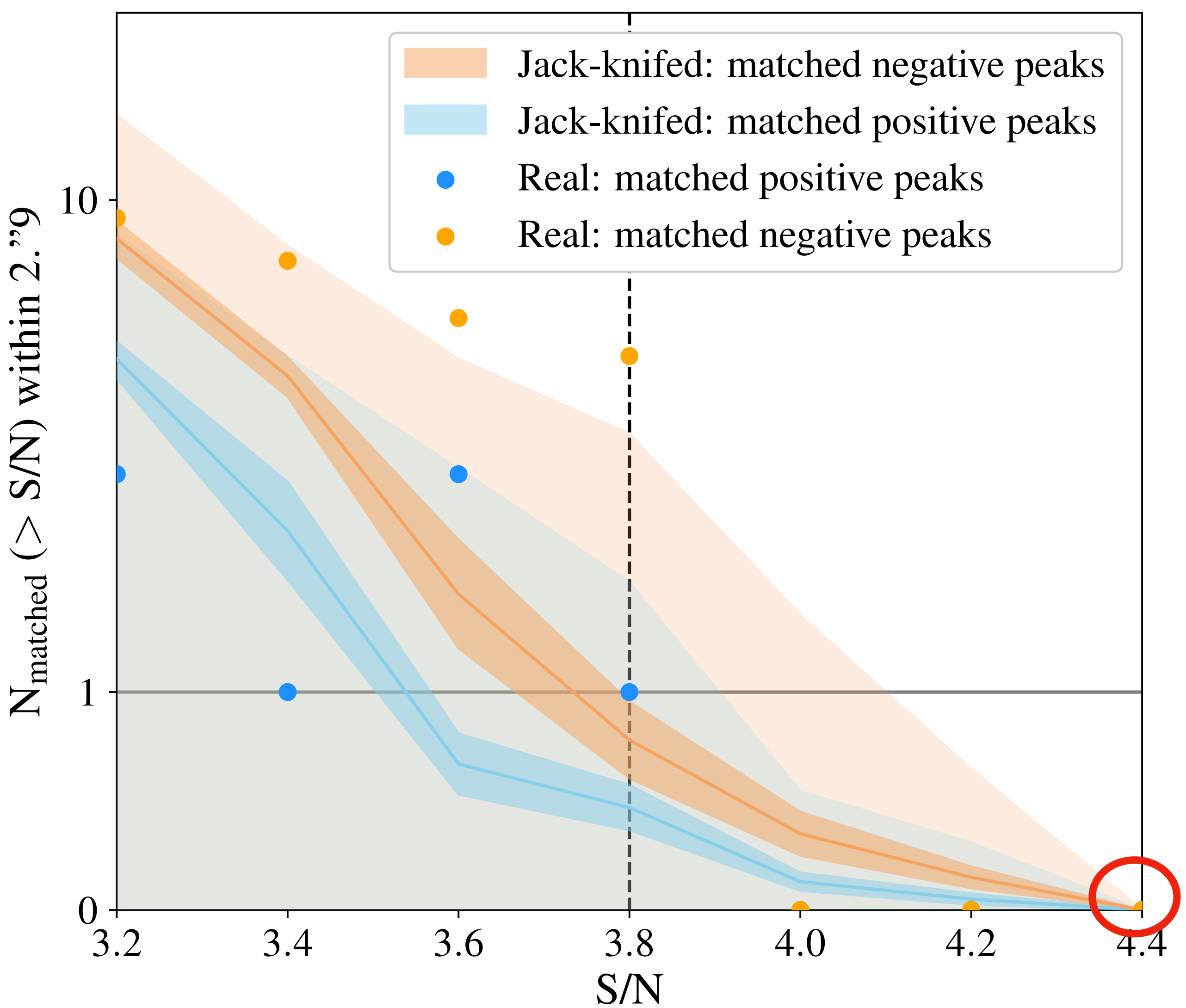


1 matched, positive > 3.8 σ feature in data

mean of 0.5 positive > 3.8 σ features in noise cubes

many matched cubes with >1 pair of >3.8 σ features

Matched "peaks": <1000 km/s, <10 kpc



1 matched, positive > 3.8 σ feature in data

mean of 0.5 positive > 3.8 σ features in noise cubes

many matched cubes with >1 pair of >3.8 σ features

$N_{matched}$ only drops to 0 at S/N=4.4

What is the likelihood of picking up two, $\geq 3.8\sigma$ features, neither of which are real line emission?

at least 50%

3 redshift solutions

z~0.3

- HCN(2-1), CO(3-2), potentially covered
- lines too faint for a dust-rich but barely star-forming dwarf
- lack of line and continuum detections consistent

3 redshift solutions

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z~4

- CO(6-5) or CO(10-9) could be covered
- lines too faint for a low-Av, low-SFR galaxy
- lack of line and continuum detections consistent

3 redshift solutions

Kohandel+2022

z~0.3

- HCN(2-1), CO(3-2), potentially covered
- lines too faint for a dust-rich but barely star-forming dwarf
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z~4

- CO(6-5) or CO(10-9) could be covered
- lines too faint for a low-Av, low-SFR galaxy
- lack of line and continuum detections consistent

z~13

- no [O III] or [C II] detected
- low metallicity, low ionisation parameter and/or high gas density
- lack of line and continuum detections consistent

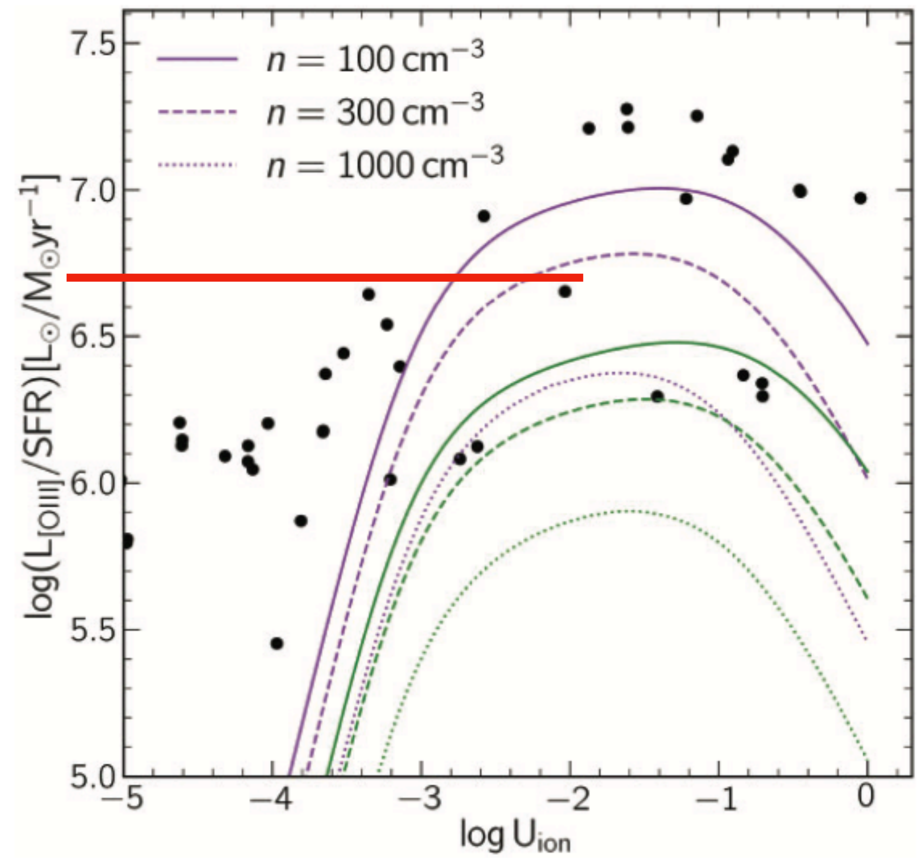


Figure 2. $L_{[O\,III]}$/SFR ratio as a function of U_{ion} for SERRA galaxies ($z = 11$–14, black circles) along with the results from single-zone CLOUDY models (lines) for different gas density, n, as shown in the legend. The purple (green) lines correspond to $Z = 0.2\,Z_\odot$ ($Z = 0.05\,Z_\odot$).

3 redshift solutions

Kohandel+2022

z~0.3

- HCN(2-1), CO(3-2), potentially covered
- lines too faint for a dust-rich but barely star-forming dwarf
- lack of line and continuum detections consistent

z~4

- CO(6-5) or CO(10-9) could be covered
- lines too faint for a low-Av, low-SFR galaxy
- lack of line and continuum detections consistent

z~13

- no [O III] or [C II] detected
- low metallicity, low ionisation parameter and/or high gas density
- lack of line and continuum detections consistent
- could also simply be at z>14.3 in which case [O III] and [C II] not covered

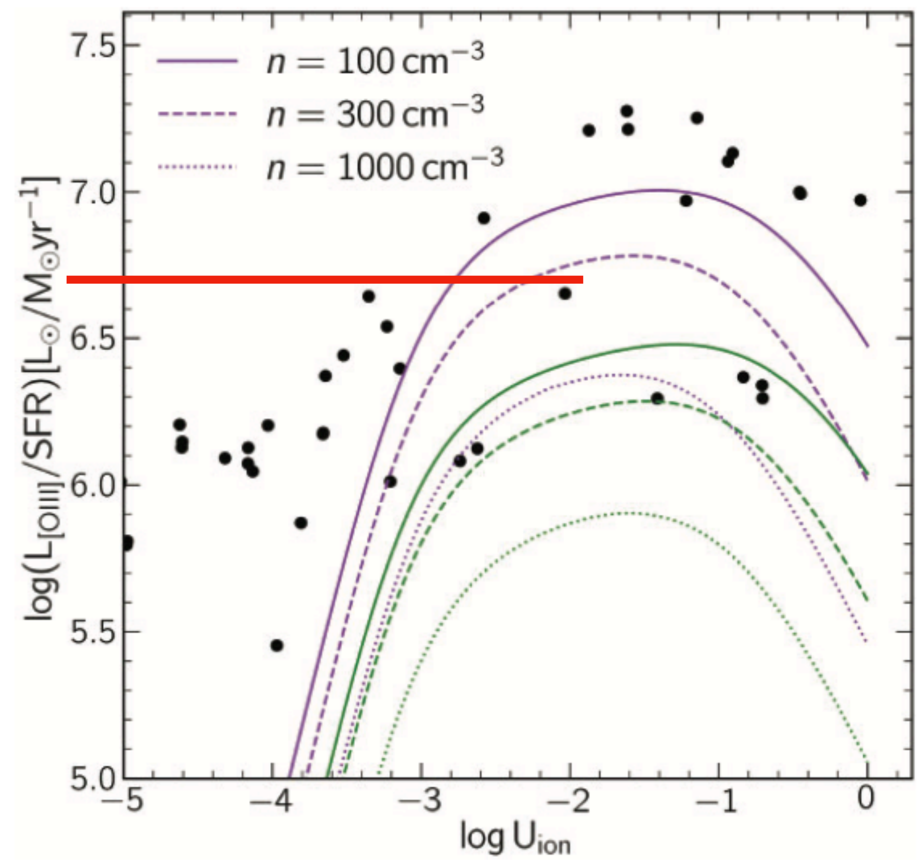


Figure 2. $L_{[\mathrm{O\,III}]}/\mathrm{SFR}$ ratio as a function of $U_{\rm ion}$ for SERRA galaxies ($z = 11$–14, black circles) along with the results from single-zone CLOUDY models (lines) for different gas density, n, as shown in the legend. The purple (green) lines correspond to $Z = 0.2\,\mathrm{Z}_\odot$ ($Z = 0.05\,\mathrm{Z}_\odot$).

Line upper limits provide no more constraining power!

Take-away

1) We cannot rule out that HD1 is a $z\sim13$ galaxy, but the current data do not confirm it.
In this there is nothing either good or bad, but thinking makes it so (Shakespeare)

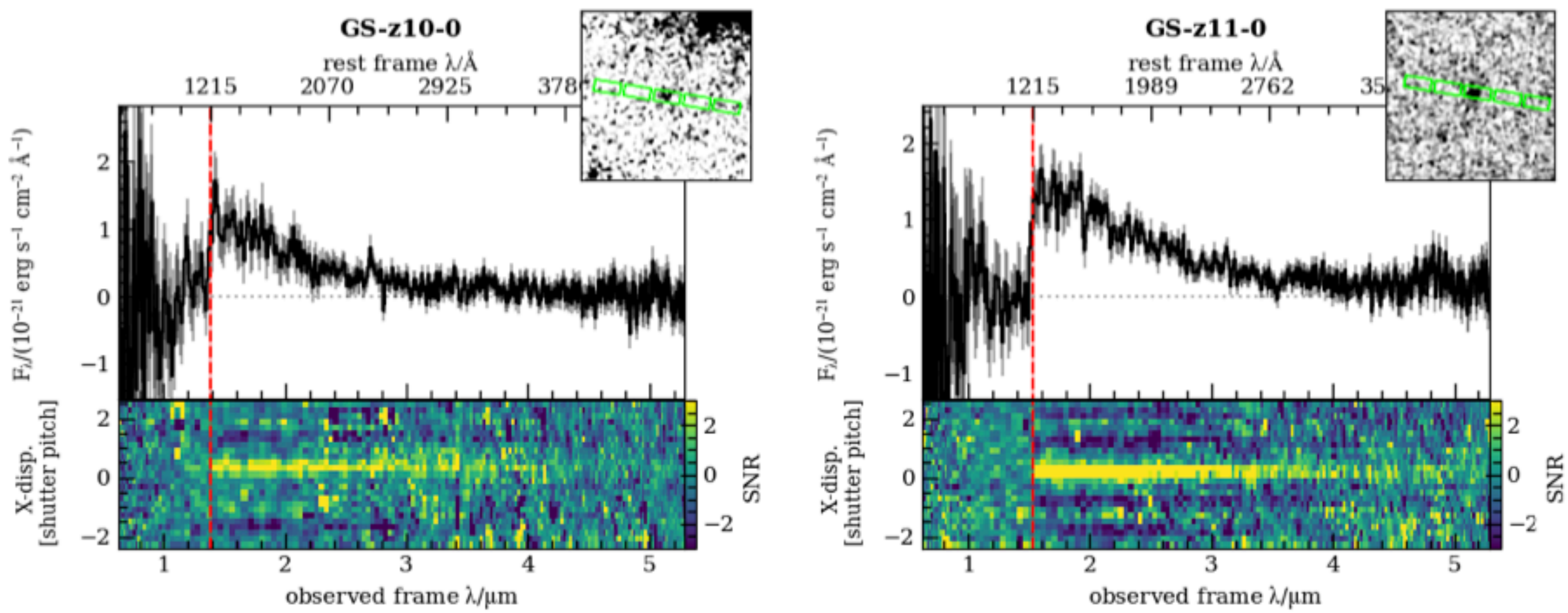
Take-away

1) We cannot rule out that HD1 is a z~13 galaxy, but the current data do not confirm it.

   In this there is nothing either good or bad, but thinking makes it so (Shakespeare)

2) To discover *where* and *exactly what* type of galaxy HD1 is will require deeper spectroscopy, most likely with NIRSpec

Curtis-Lake+2022



Lessons

1) Know thy data!
   All too often, we are willing to trust a 3 – 4σ peak at the position where we expect to find it. But without testing how likely this is to be a noise fluctuation, we may be sorely mistaken.

2) ALMA is not a redshift machine. With only 1-2 h on source, there are no convincing detections of z>10 candidates yet

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Stay tuned

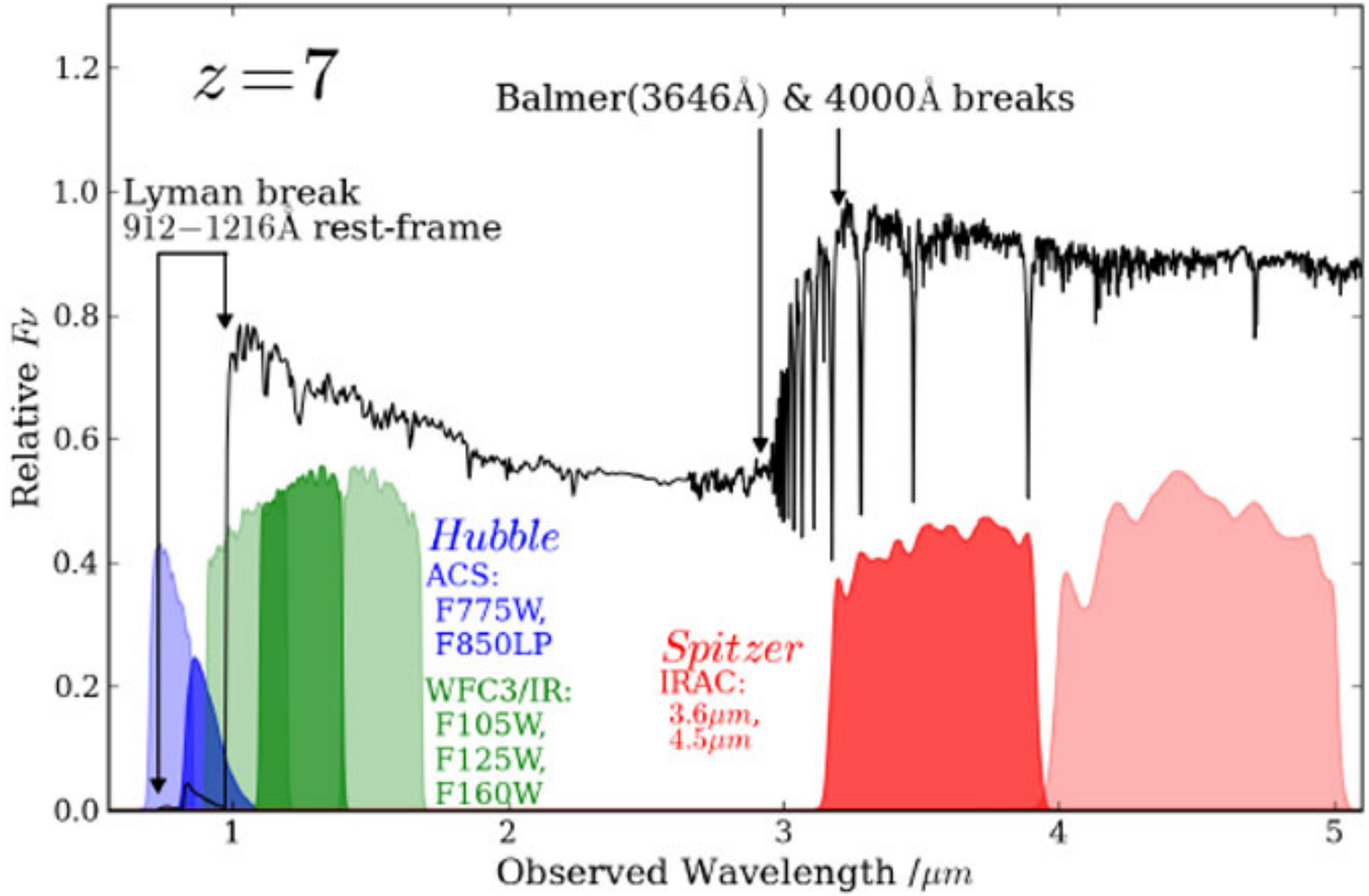
We – van Marrewijk, J.; Kaasinen, M; et al. (in prep) – are developing tool for the community

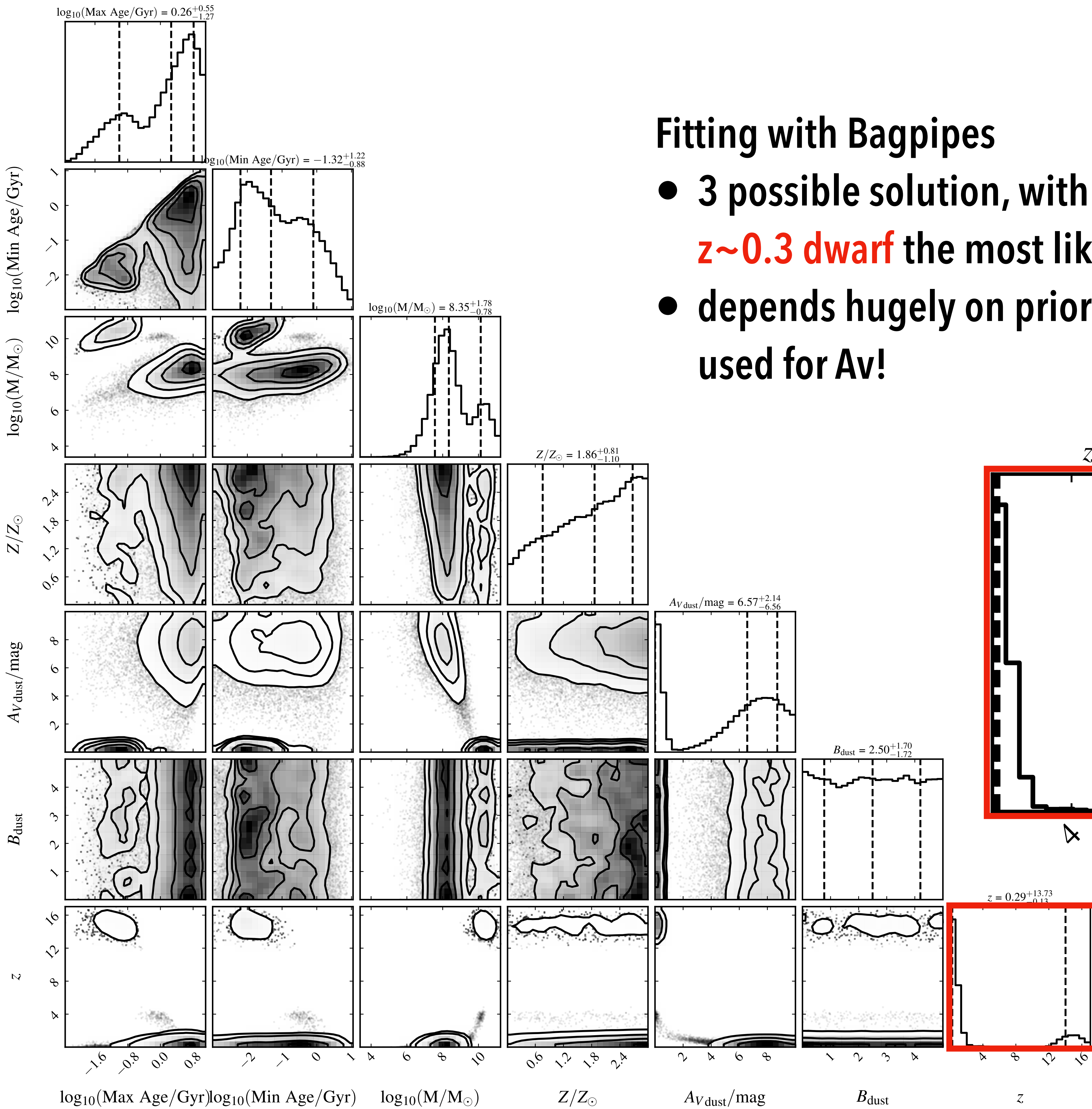
→ testing underway for z>10 candidates with ALMA DDT observations

ID	HD1	GLASS-z12	GLASS-z10	S5-z17-1
Paper reporting tentative detection	Harikane+2022	Bakx+2022	Yoon+2022	Fujimoto+2022
Paper reporting tentative detection	Kaasinen+2022	Popping+2022		
S/N of tentative [O III]	3.8	5.8	4.4	5.1
z proposed	13.27	12.12	10.38	16.01
Spatial offset		0.″5 (1.9 kpc)	0.″17 (0.7 kpc)	

Finding high-z candidates via the Lyman Break

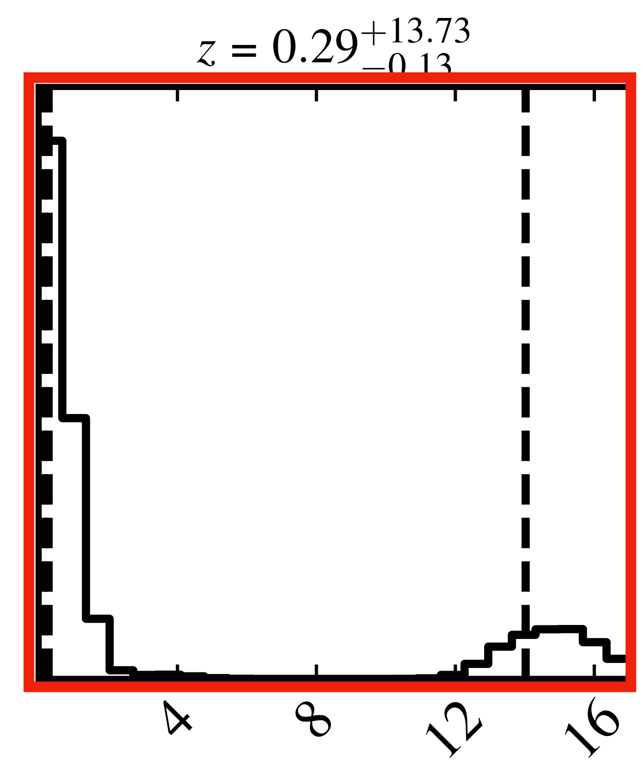
Credit: S Dunlop

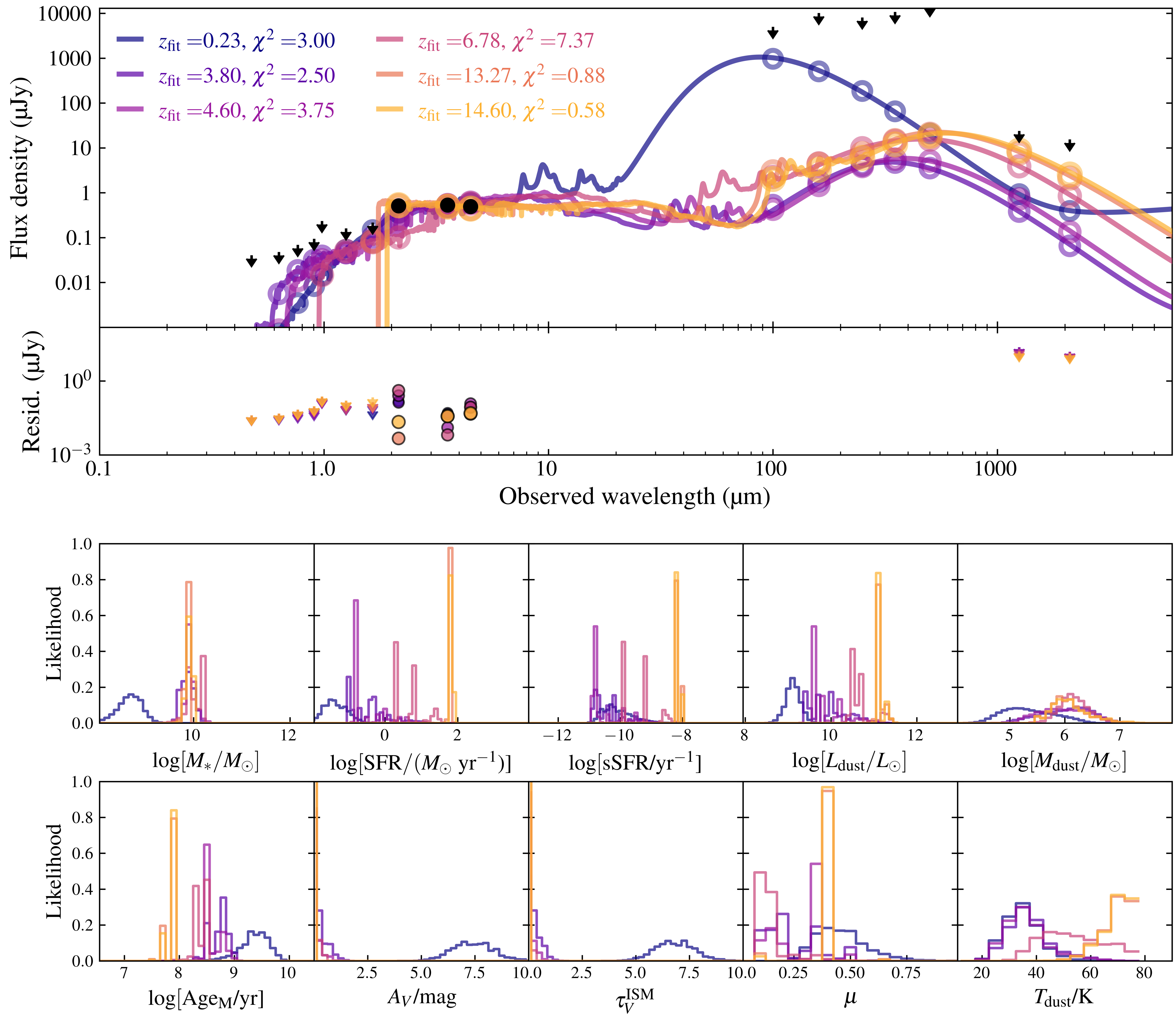




Fitting with Bagpipes

- 3 possible solution, with z~0.3 dwarf the most likely
- depends hugely on prior used for Av!



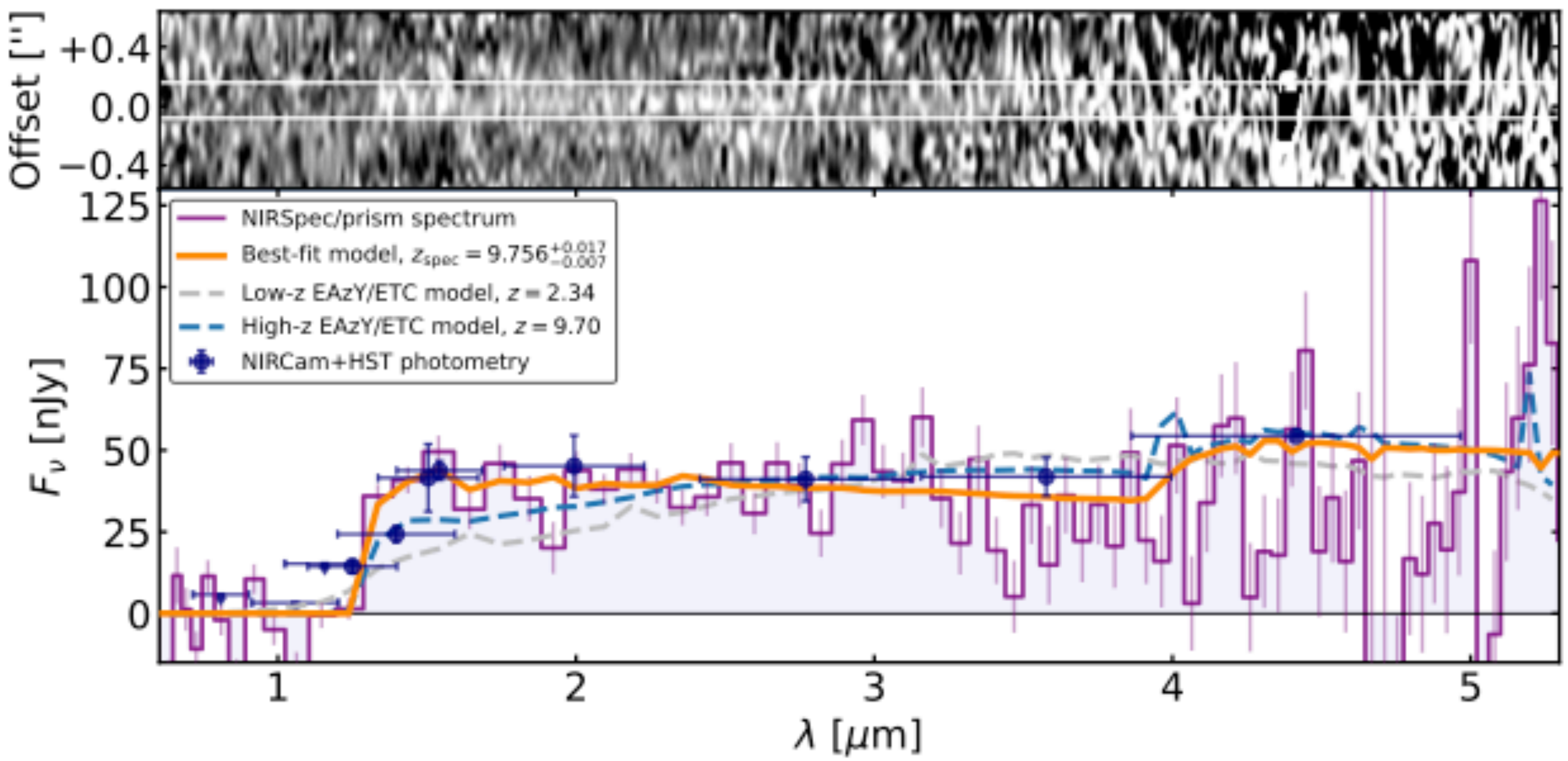


$z_{\rm fit}$ =0.23, χ^2 =3.00
$z_{\rm fit}$ =3.80, χ^2 =2.50
$z_{\rm fit}$ =4.60, χ^2 =3.75
$z_{\rm fit}$ =6.78, χ^2 =7.37
$z_{\rm fit}$ =13.27, χ^2 =0.88
$z_{\rm fit}$ =14.60, χ^2 =0.58
Flux density (μJy)
Resid. (μJy)
Observed wavelength (μm)
Likelihood
$\log[M_*/M_\odot]$
$\log[\mathrm{SFR}/(M_\odot\ \mathrm{yr}^{-1})]$
$\log[\mathrm{sSFR/yr}^{-1}]$
$\log[L_{\rm dust}/L_\odot]$
$\log[M_{\rm dust}/M_\odot]$
$\log[\mathrm{Age_M/yr}]$
A_V/mag
$\tau_V^{\rm ISM}$
μ
$T_{\rm dust}$/K

First spectroscopic confirmation with JWST

z=9.76 galaxy

Roberts-Borsani+, Oct 2022



More recently, 4 galaxies at z>10

Curtis-Lake+,
Dec 2022