International Conference on the Physics of the Two Infinities

ILANCE
International Laboratory for Astrophysics, Neutrino and Cosmology Experiments

Exploration of Particle Physics and Cosmology with Neutrinos

UTokyo Strategic Partnerships Project
Paris Grandes Écoles Team

27-30 March 2023
Kyoto University
Day 1, 09:50-10:15

Exploring “dark” side of galaxy formation in the early Universe

KOHNO, Kotaro 河野孝太郎

THE UNIVERSITY OF TOKYO

Astronomy/Astrophysics in UTokyo

SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO

Graduate School of Science

- Institute of Astronomy

@Mitaka campus

Next to NAOJ

- Department of Astronomy
- Department of Physics
- Department of Earth and Planetary Science
- Research Center for the Early Universe (RESCEU)

@Hongo campus

- Department of Earth Science & Astronomy, Graduate School of Arts & Science

@Komaba campus

- Kavli Institute for the Physics and Mathematics for the Universe (IPMU)
- Institute for Cosmic Ray Research (ICRR)

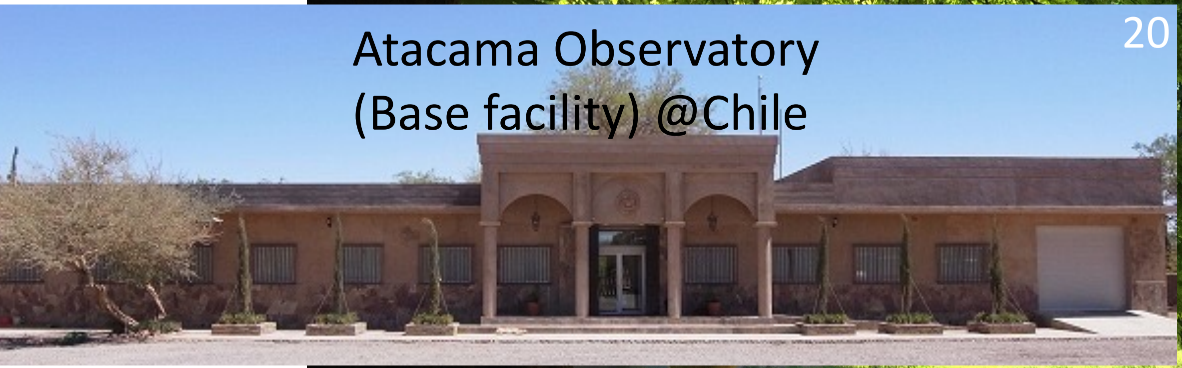
@Kashiwa campus

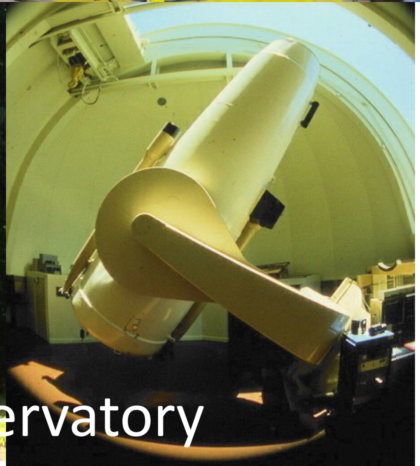
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Institute of Astronomy (IoA)

THE UNIVERSITY OF TOKYO
SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO

- Observational astronomy and astrophysics
- with emphasis on instrumentation for ground-based optical/infrared/mm-submm observations to explore new discovery space

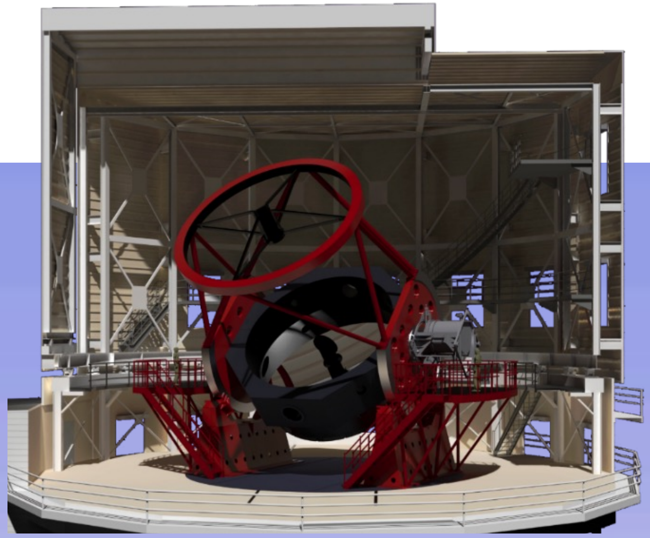




The University of Tokyo Atacama Observatory (TAO) 6.5m Telescope

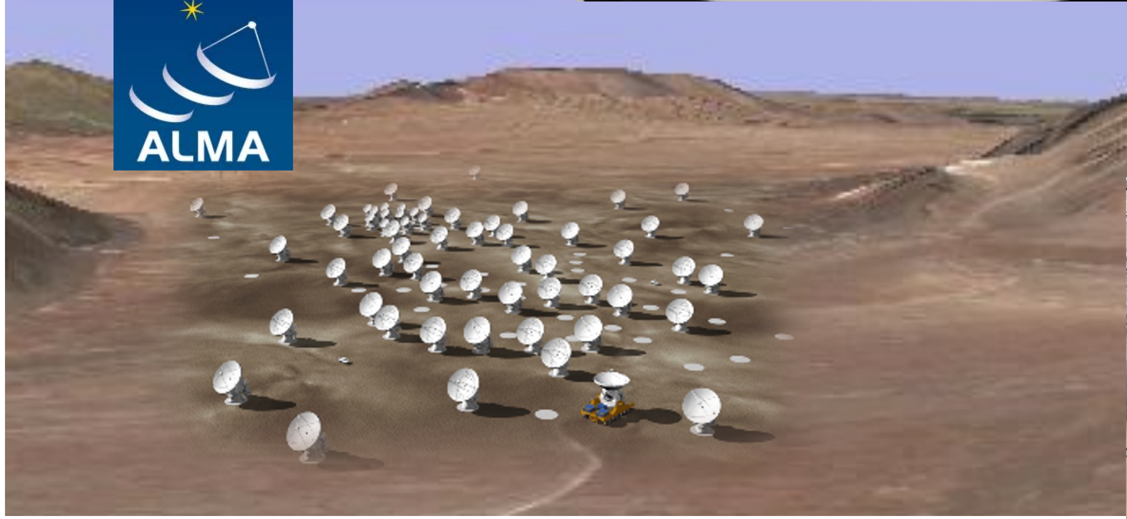
http://www.ioa.s.u-tokyo.ac.jp/TAO/en/

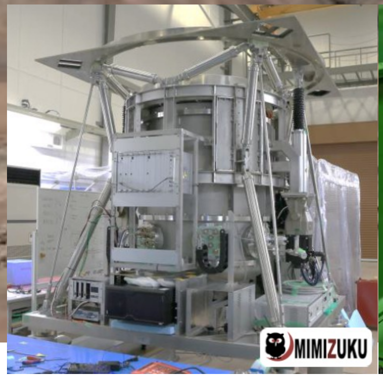
PI: Yoshii, Y. (U. Tokyo)

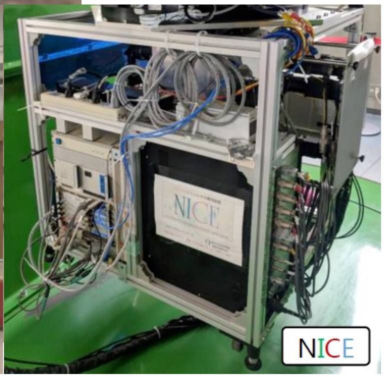


up to ~38 µm
from the ground!

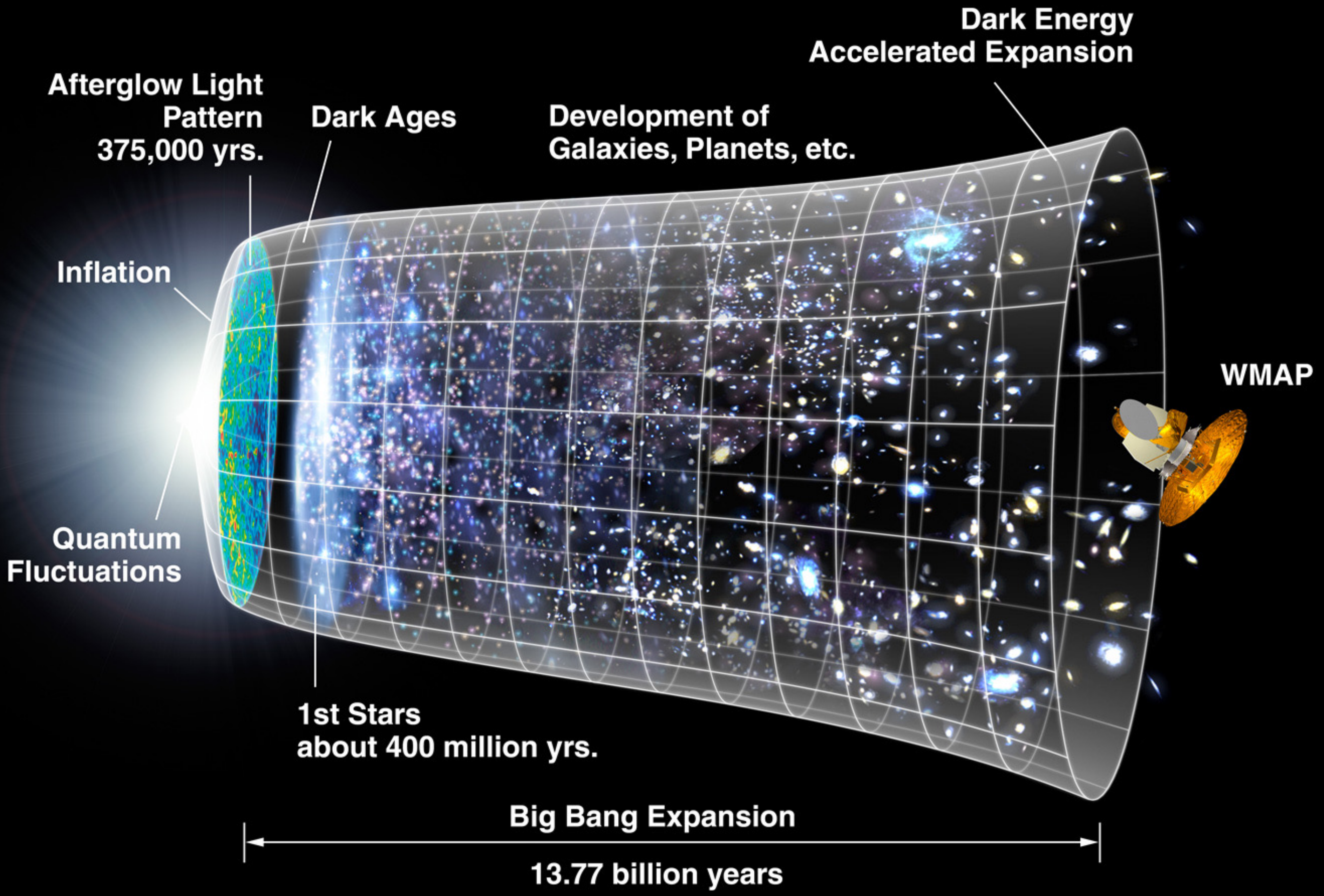
6.5-m optical-IR telescope
at 5640m elevation







The major milestones in the evolution of the Universe



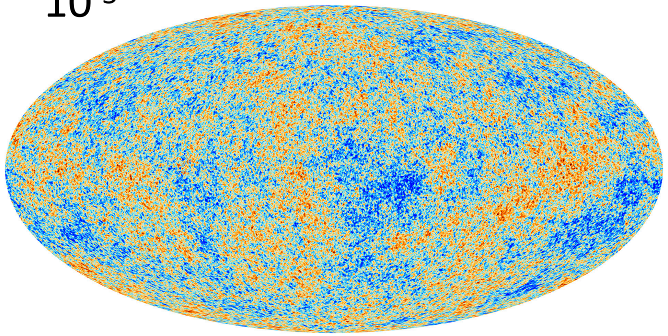
Our current understanding of galaxy formation and evolution

Inflation
➔ Tiny density fluctuation

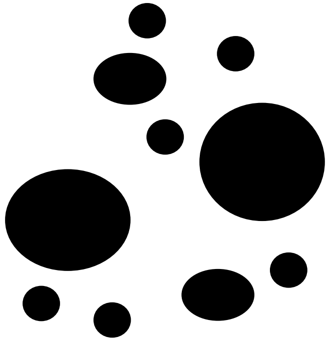
Growth of dark matter halos

Infall of baryons into dark matter halos ➔ formation & growth of galaxies

$\delta \sim 10^{-5}$



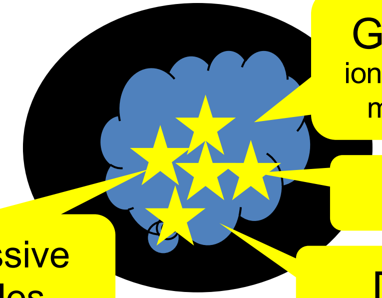
A temperature map of the cosmic microwave background (CMB) imaged using *Planck* @z~1100

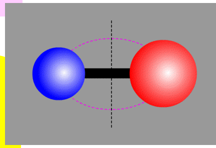


JWST+ALMA galaxy @z=16!? (but ..)

[OIII]88μm-detected galaxy @z=9.1

Most distant quasar (SMBH) @z=7.65



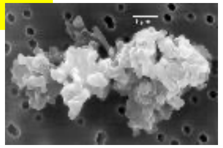


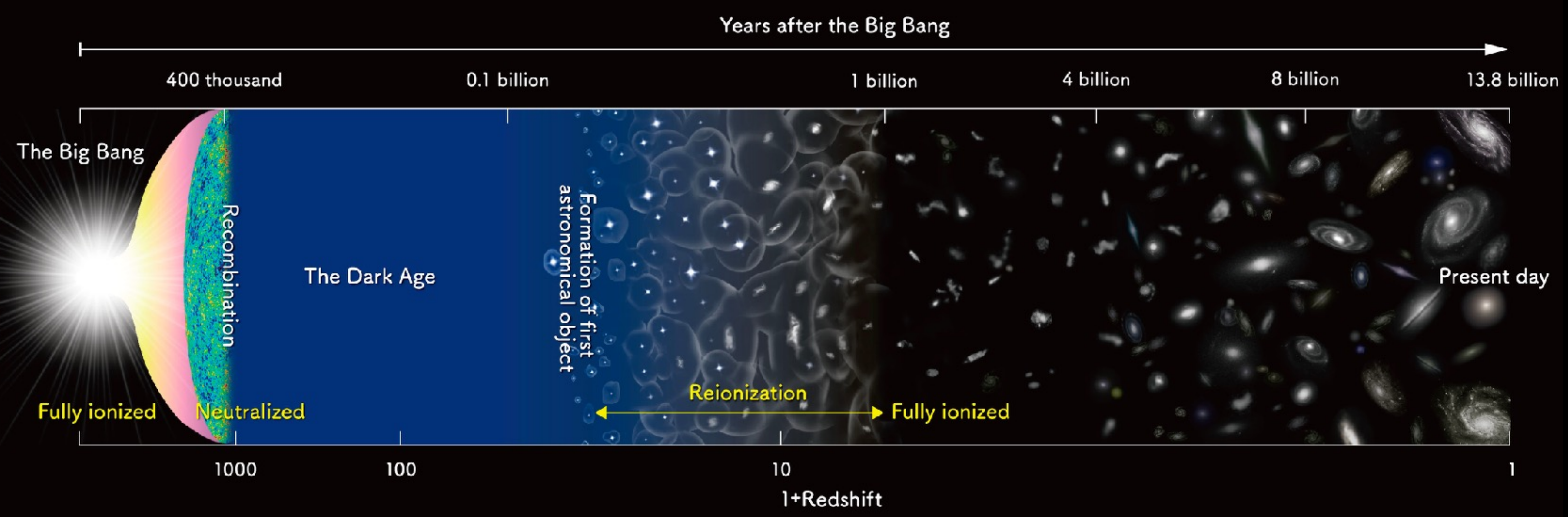
Gas plasma, ionized, neutral, molecular, ..

Stars

Supermassive black holes

Dust





Dark matter

Gas temperature

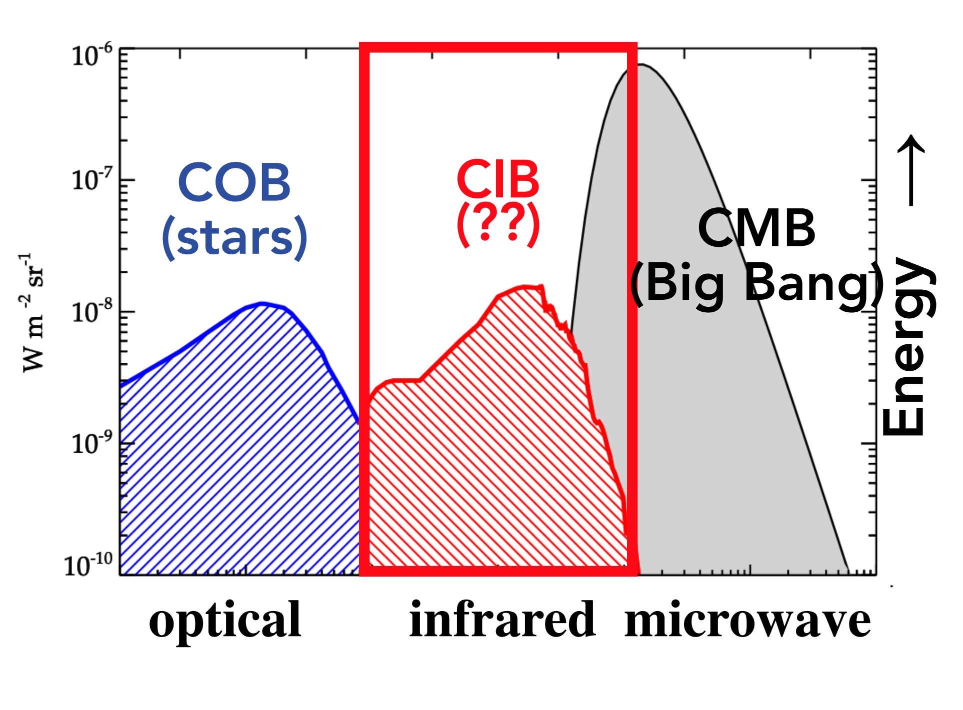
Outline of this talk

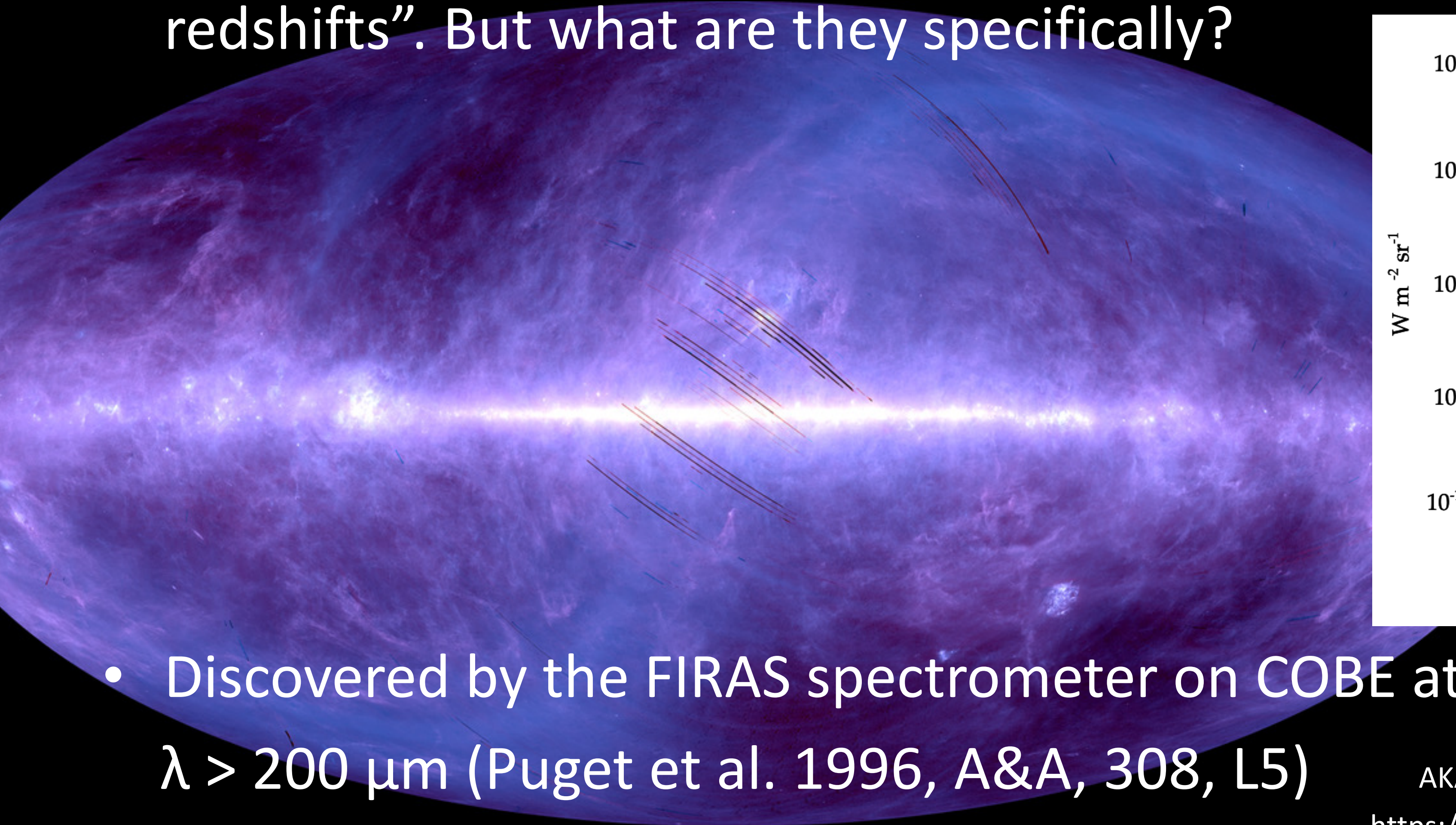
- Setting the stage: general introduction
- Topics 1: “Dark side” of galaxy evolution
  - near-infrared invisible galaxies selected by ALMA
  - The cosmic infrared extragalactic background light (CIB)
  - The ALMA Lensing Cluster Survey
- Topics 2: “Dark side” of supermassive blackhole (SMBH) growth
  - ALMA observations of Subaru/HSC-selected “faint” quasars during the epoch of reionization (EoR)
  - A buried growing SMBH within a dust-enshrouded starburst at EoR?
- Toward the future: Integrated Superconducting Spectrograph (ISS) technology

Topics 1:
“Dark side” of galaxy evolution

The cosmic infrared background (CIB)

- The infrared part of the isotropic extragalactic background, the radiation content of the Universe today, produced by "astronomical objects at all redshifts". But what are they specifically?





- Discovered by the FIRAS spectrometer on COBE at long wavelengths $\lambda > 200\ \mu m$ (Puget et al. 1996, A&A, 308, L5)

AKARI 90 µm & 140 µm two color composite image
https://www.u-tokyo.ac.jp/focus/ja/articles/a_00393.html

ALMA deep surveys of mm/submm continuum sources

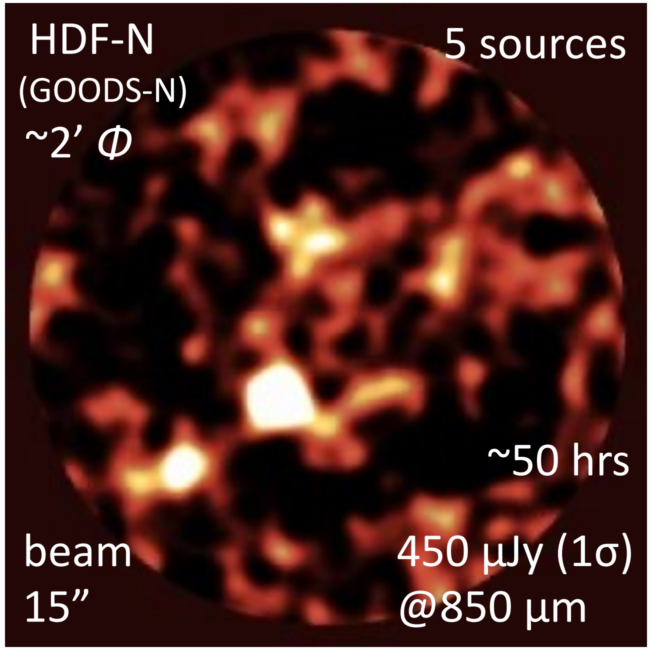
- One of the major breakthroughs by ALMA to beat the source confusion limit, which was fatal in the pre-ALMA single-dish telescopes equipped with bolometer arrays
- Now ALMA surveys, which are *perfectly confusion free*, can resolve the majority (> 50%) of the cosmic infrared background light (CIB) into discrete sources

Hatsukade et al. 2013, ApJ, 79, L27

- Next questions:
  - Can we fully resolve the CIB into discrete sources?
  - What is the nature of such faint (“sub-mJy”) dusty galaxies? Their faintness hampers further follow-ups...

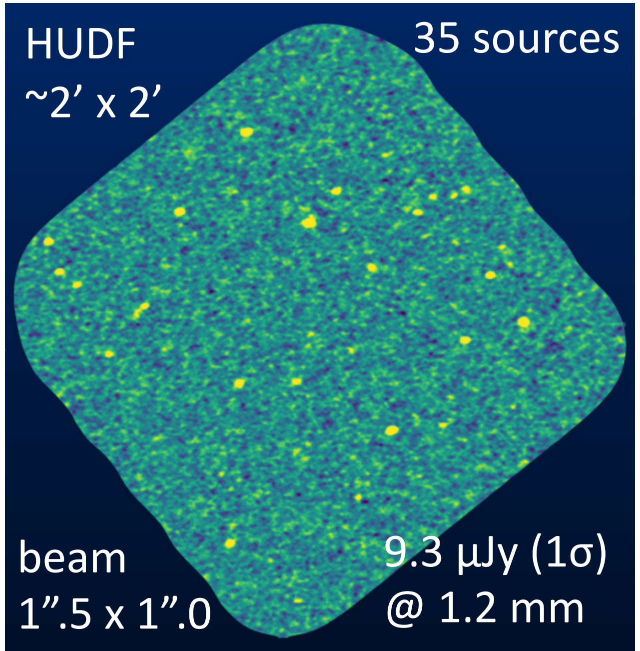
70 -- 100% resolved? Fujimoto, S. et al. 2016, ApJS, 222, 1; Munoz Arancibia, A. M., et al. 2019, A&A, 631, C2 ⟷ **only 40% resolved?** Gonzalez-Lopez, J. et al. 2020, ApJ, 897, 91

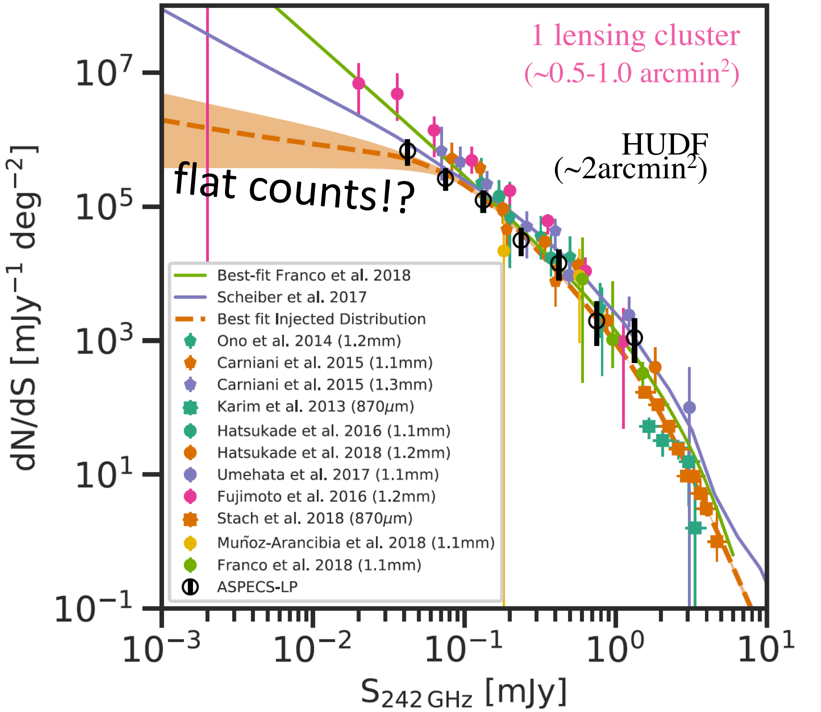
- Investigate such sources with a help of natural telescopes, i.e., gravitational lens ➔ **ALCS !!**



Hughes, D. H., et al. 1998 Nature, 394, 241

González-López, J., et al. 2020, ApJ, 897, 91





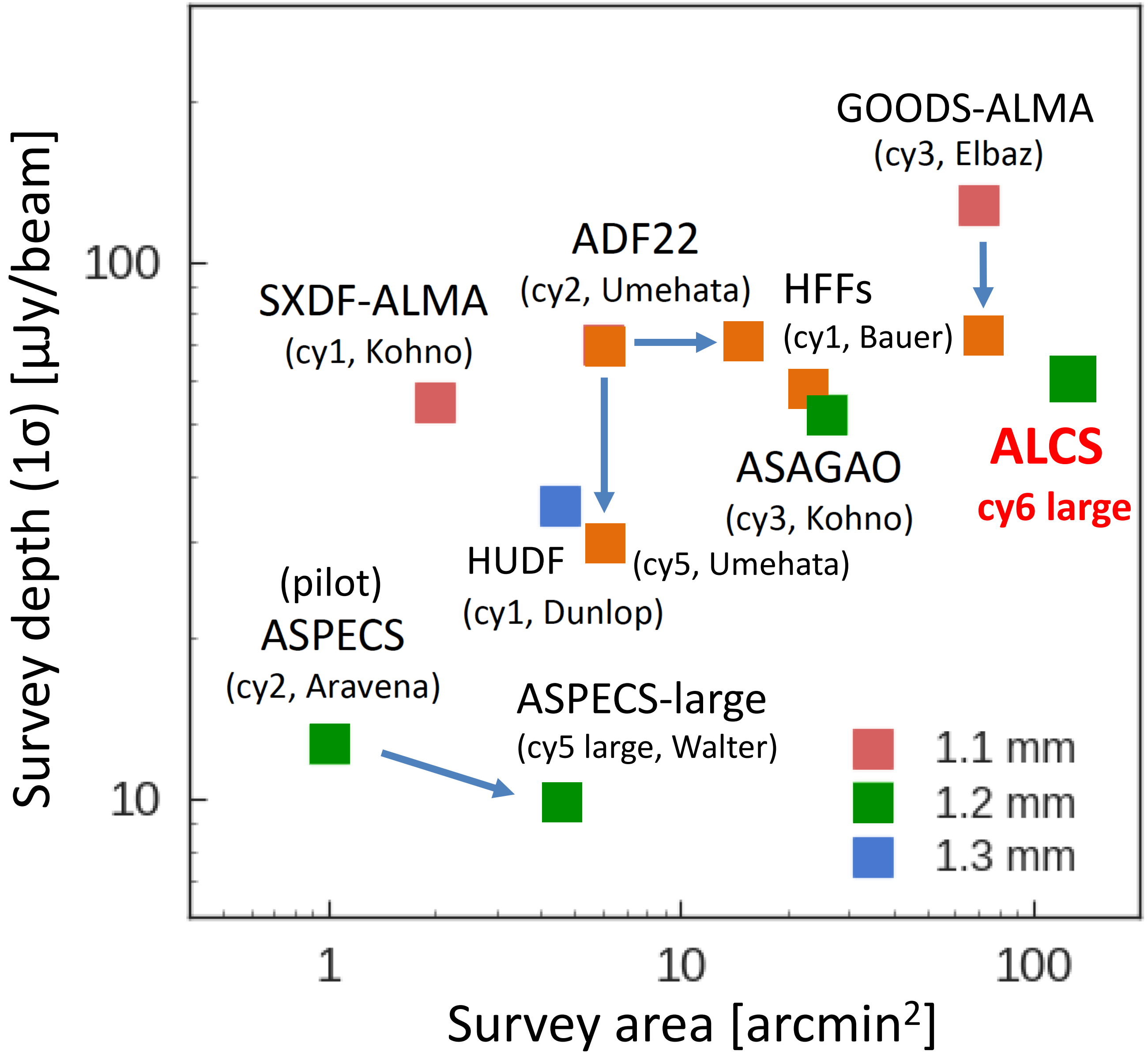

ALCS
ALMA Lensing Cluster Survey

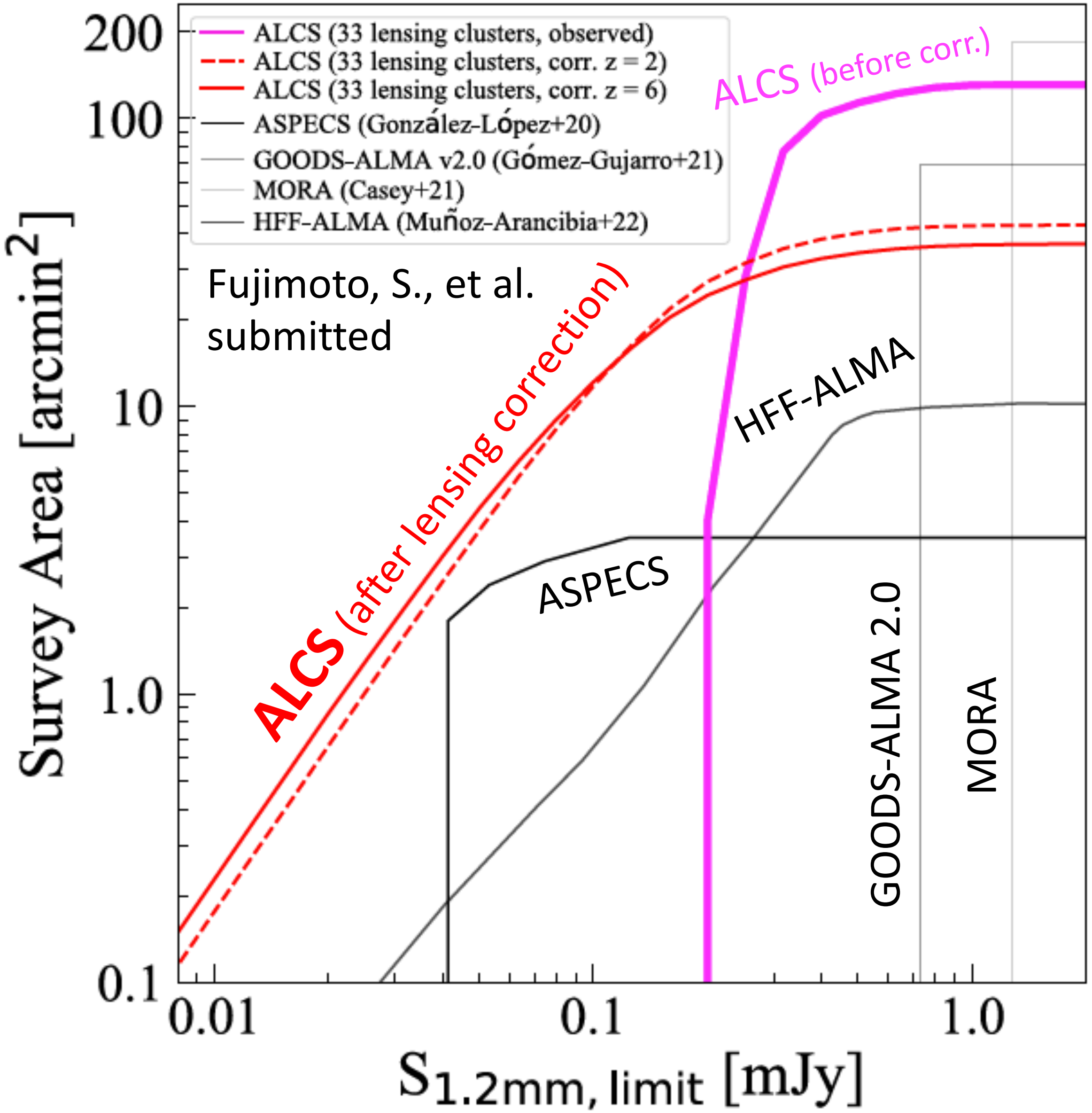
ALMA Lensing Cluster Survey

- A 96-hr ALMA large program in cycle 6 (PI: K. Kohno)
- To search for intrinsically faint continuum sources and line emitters with the assistance of massive galaxy clusters as “natural telescopes in space”
- 33 lensing clusters from HST treasury programs, i.e., CLASH, HFF & RELICS
- covering ~~88~~ 133 arcmin^2 (PB>0.3), with a depth of ~~80~~ ~60 μJy (1.2 mm, 1σ)
- 2 frequency tunings with a 15-GHz-wide spectral scan
- yielding 180 continuum source detections in total
  - Blind approach: 141 continuum detections with S/N ≧ 5.0 in the native resolution (~1”) images and S/N ≧ 4.5 in the tapered images (~2” resolution)
  - Prior-based approach: 39 continuum sources with S/N = 4 – 5 which have IRAC counterparts

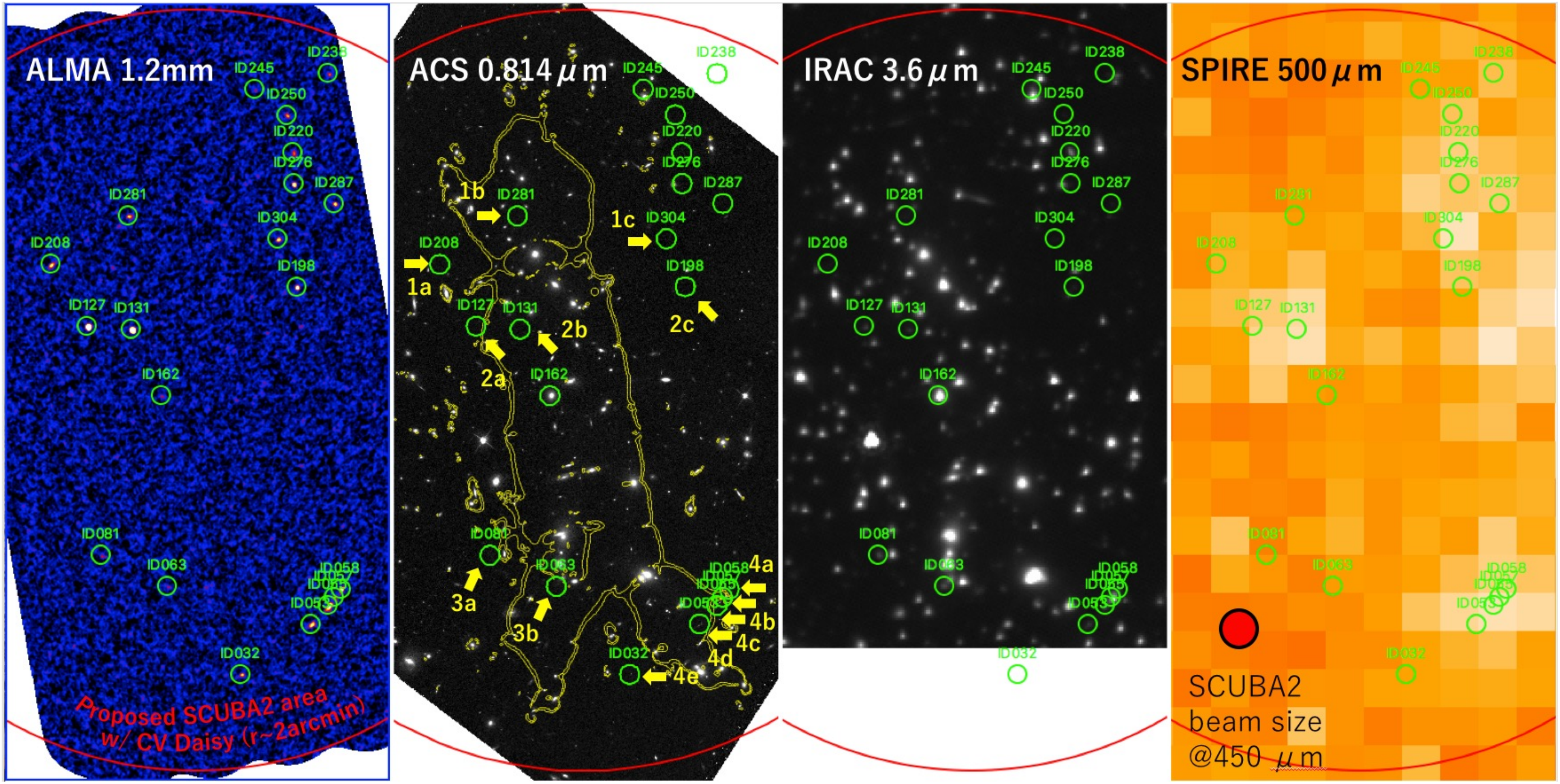
ALMA deep surveys @λ~1mm

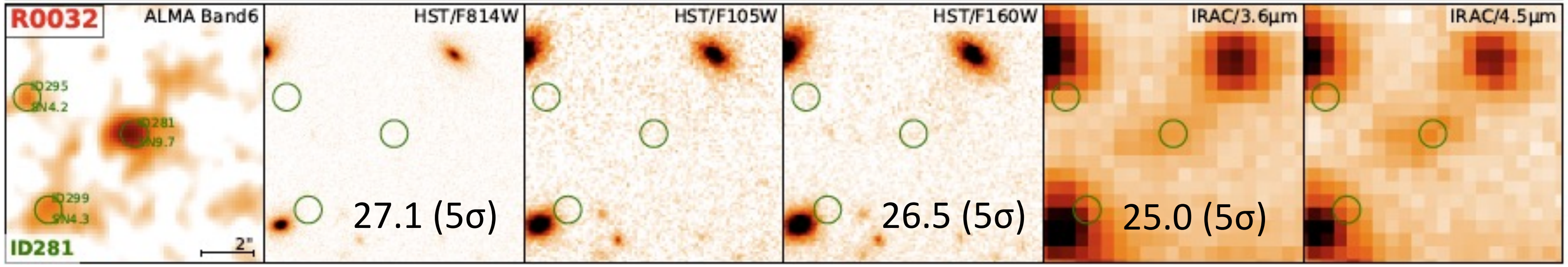
~60 μJy (1σ)@ λ1.2 mm
~133 arcmin² (PB>0.3)





Lensed H-dropout ALMA sources behind RXCJ0032.1+1808





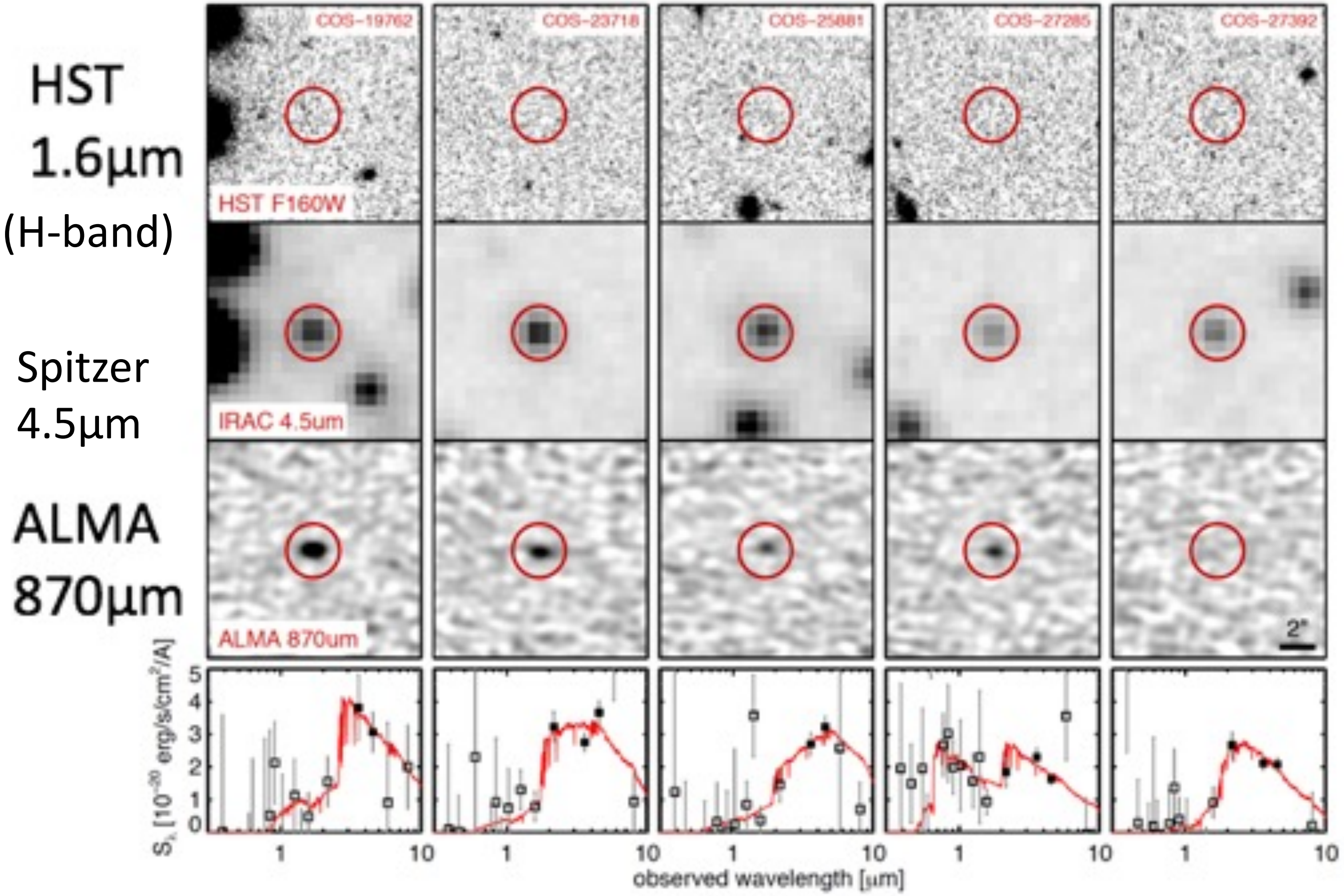
Sun, F., et al. 2022, ApJ, 973, 77

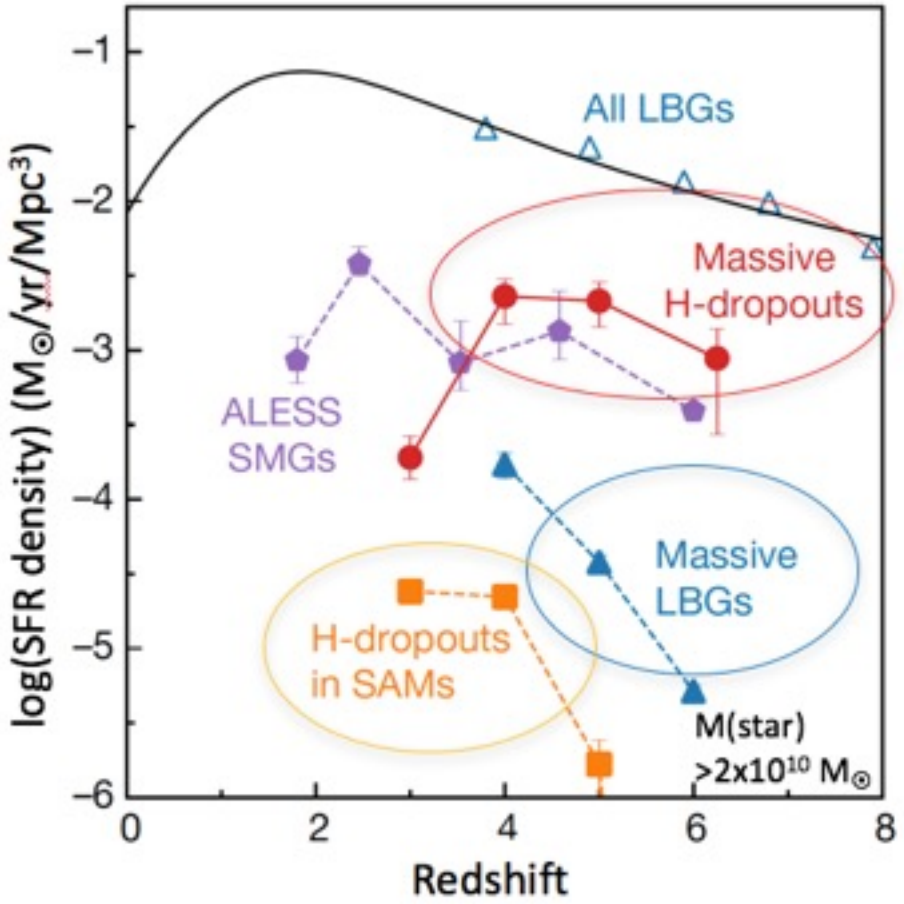
Fujimoto, S., et al. submitted

Follow-up observations including ALMA band-3/4 spectral scans (Tsujita et al., to be submitted)

Similar to H-band dropouts in COSMOS, GOODS-S, etc.
Franco et al. 2018, A&A, 620, A152
Wang, T., et al., 2019, Nature, 572, 211
Yamaguchi, Y., et al. 2019, ApJ, 878, 73
Gruppioni et al. 2020, A&A, 643, A8
and more ..

Why do we need to care "near-infrared-dark" or H-band dropout, faint ALMA sources?

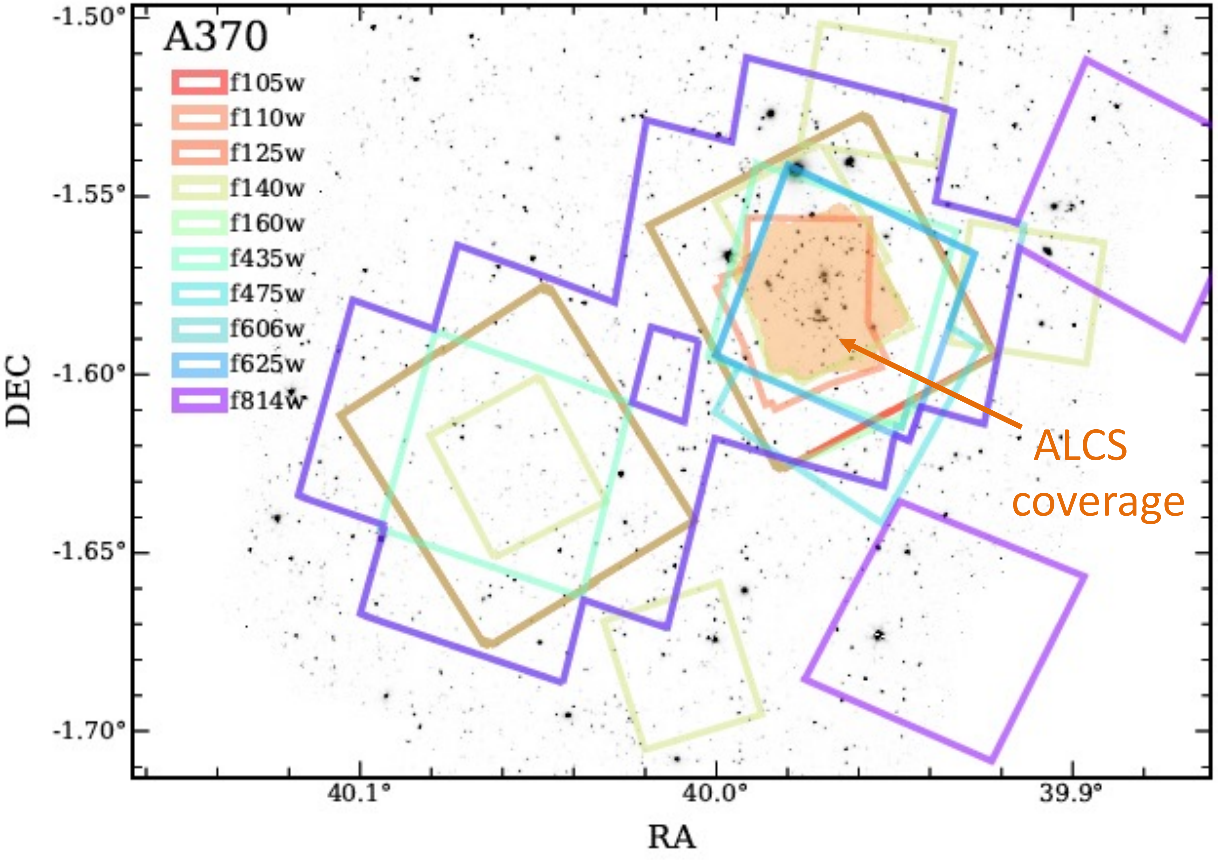


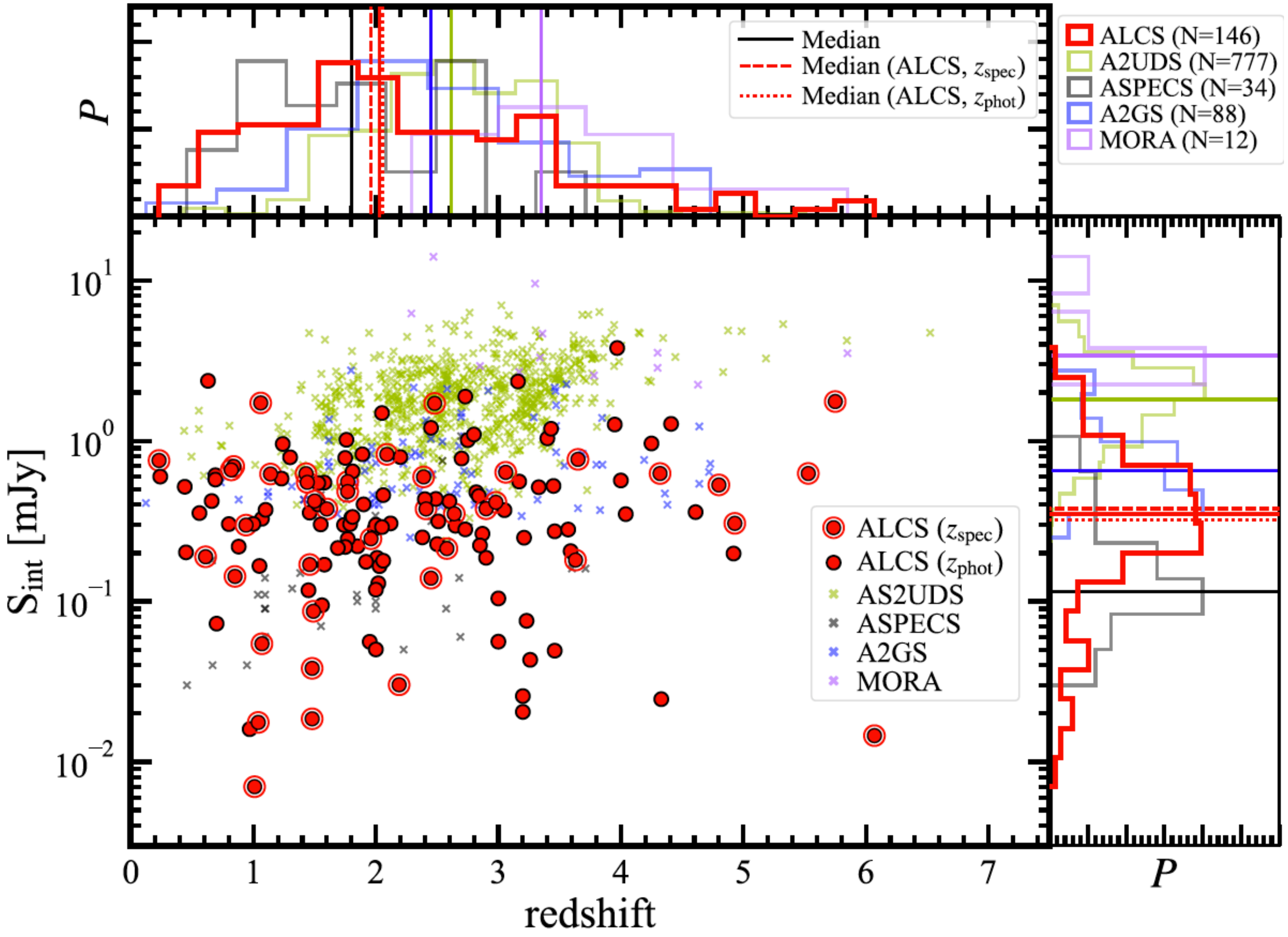


Current state-of-the-art galaxy formation models can't reproduce their (too) high abundance !
Existing HST/WFC3 near-infrared deep surveys may miss massive galaxies in their growing forming phase
But they are intrinsically faint..

Wang, T., Elbaz, D., KK, et al. 2019, Nature, 572, 211

ALMA + Multi-wavelength mosaics and photometric catalogs by reprocessing of archival data from Hubble & Spitzer Space Telescopes





- HST + Spitzer: 218,000 sources over 690 arcmin^2
- A robust internal alignment of HST and IRAC images using Gaia DR2 reference frame
- Consistent photometry across all 33 ALCS fields, SED fitting using EAZY

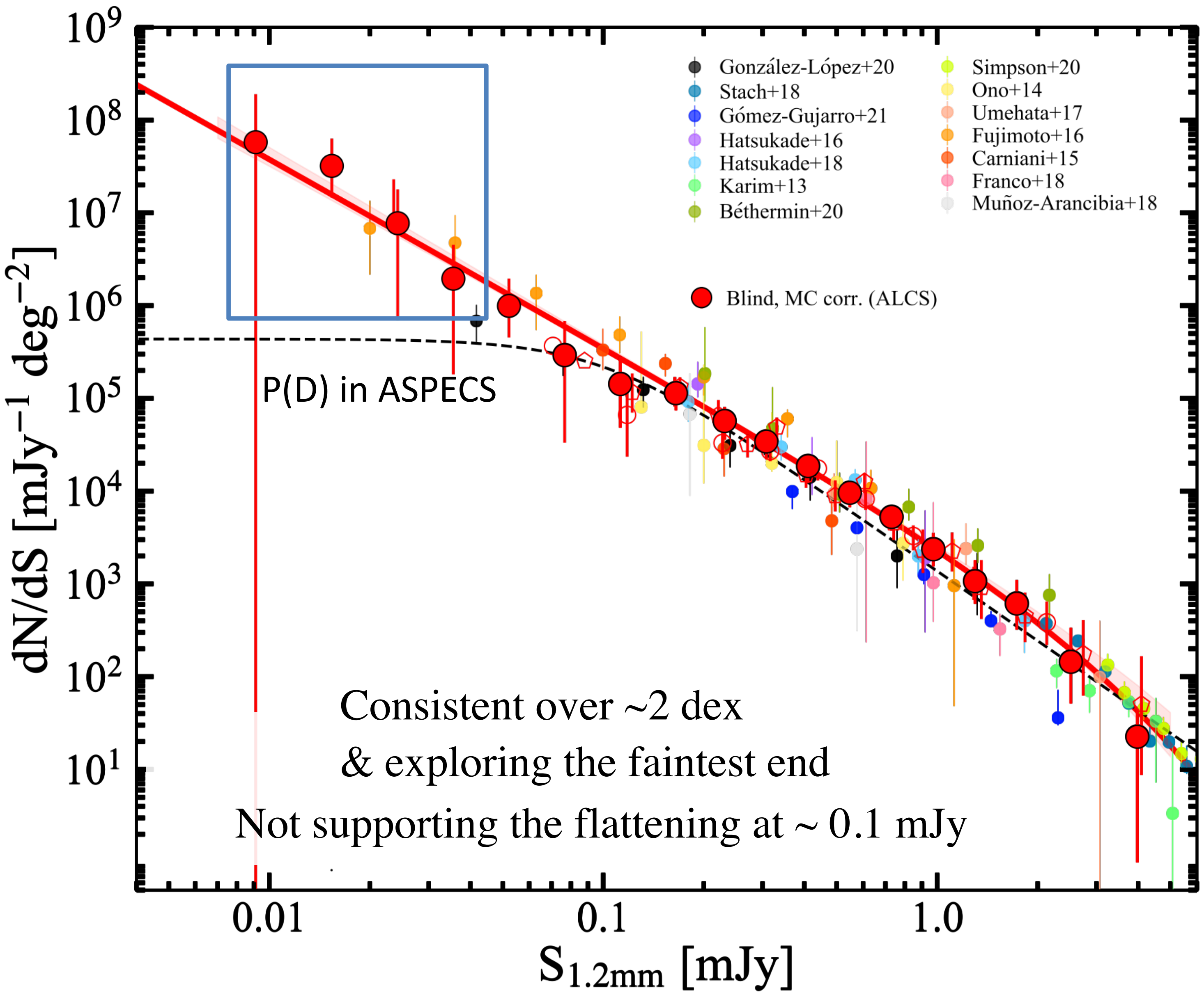
Fujimoto, S., et al. ApJS, Submitted

Kokorev, V., Brammer, G., et al. 2022, ApJS, 263, 38

Number counts at 1.2mm

Reliability of the faint-end counts

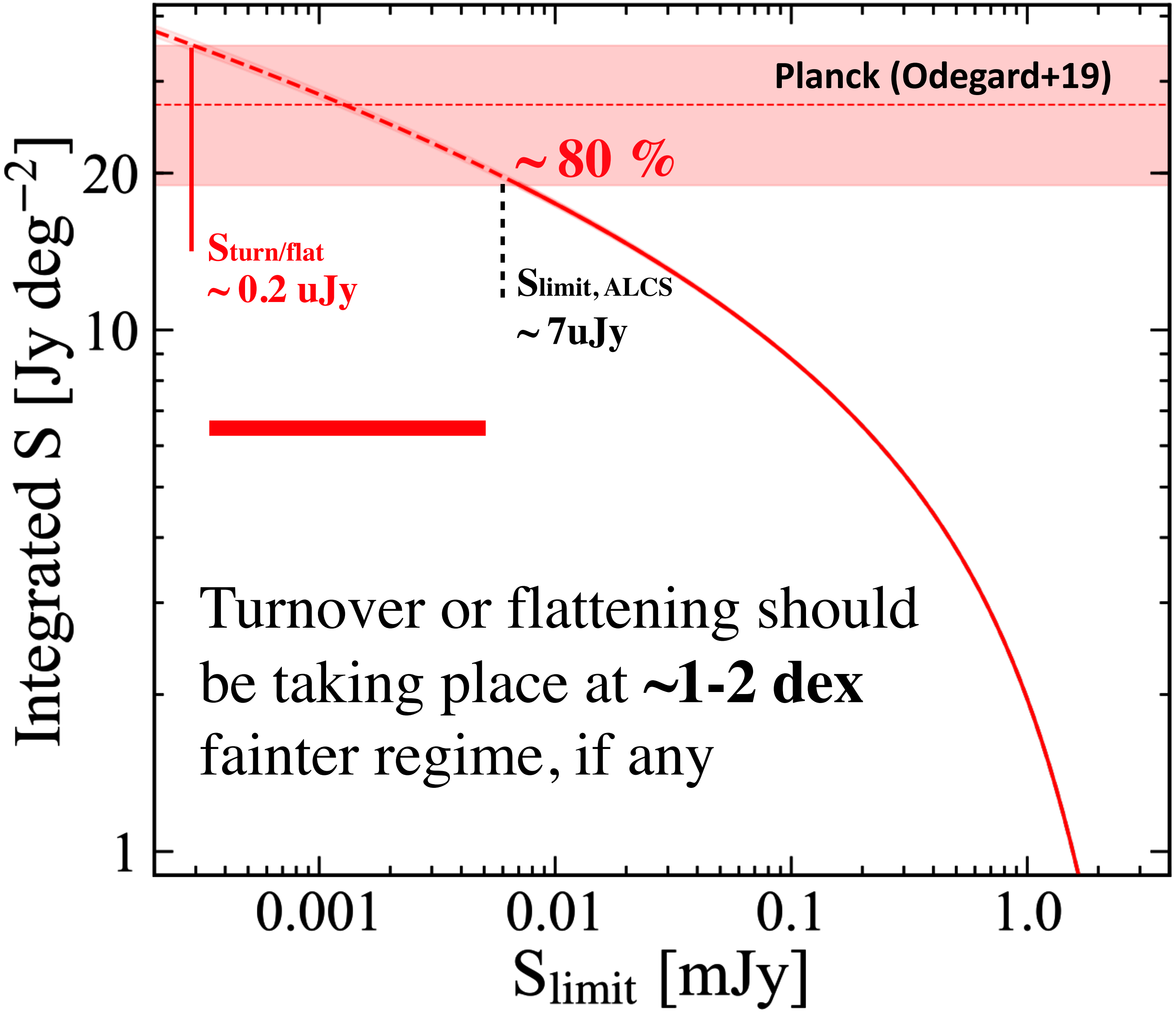
N = 5/8 are spectroscopically confirmed



Important implications for deeper ALMA surveys !

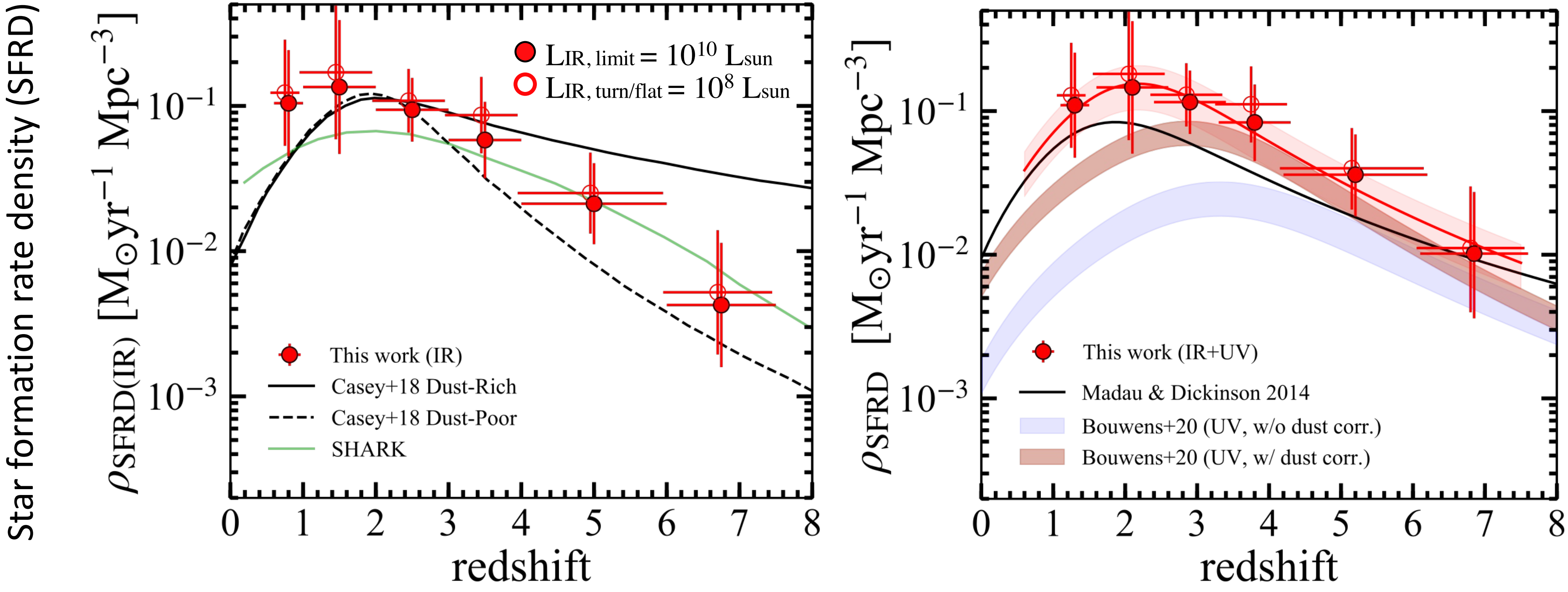
Fujimoto et al., submitted

ALCS resolves ~80% of the Cosmic Infrared Background Light



Fujimoto et al., submitted

Cosmic SFRD at z~1-8: Roles of dust-enshrouded star formation in galaxies

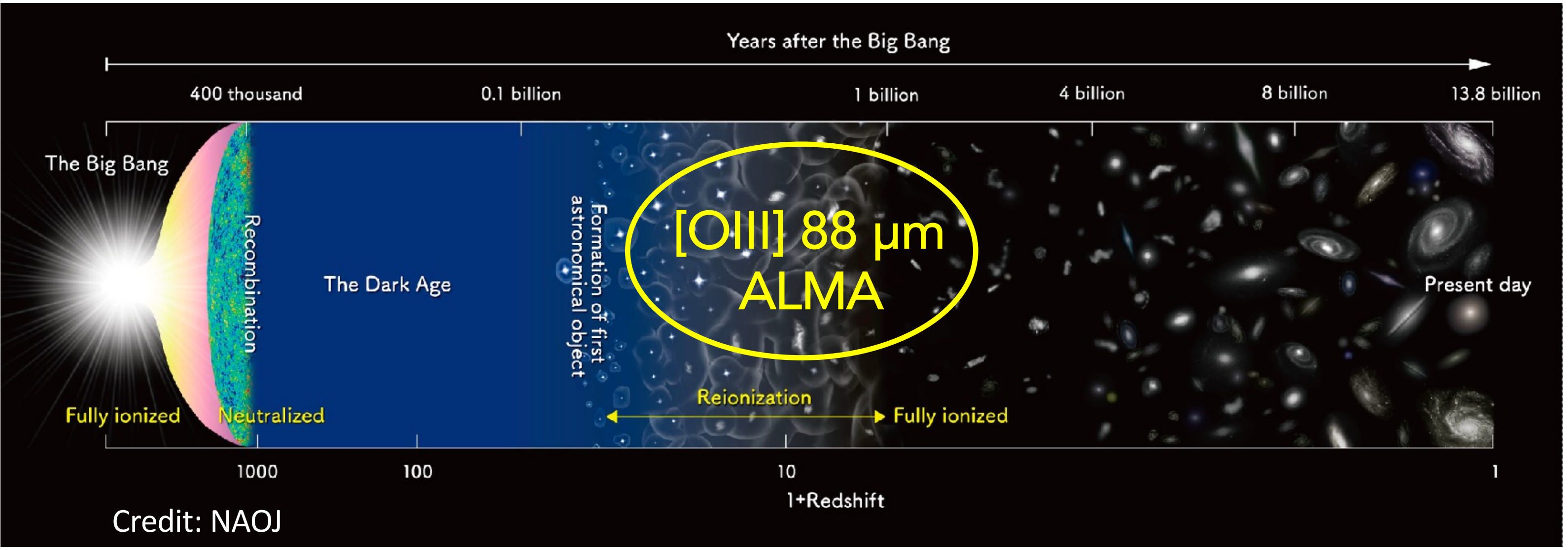


- Falling between Dust-rich & poor scenarios in Casey+18, consistent with SHARK
- Little difference with the integration range
- 140 ± 60% of previous measurements at z>4.
  Potential contributions (~40%) from NIR-dark objects at z > 4.

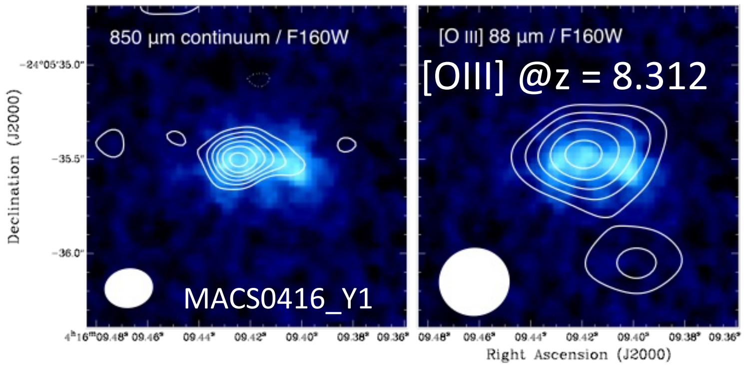
Fujimoto et al., submitted


”ultra-high-redshift galaxies”

ALMA already suggests significant star formation at z > 12 – 15?

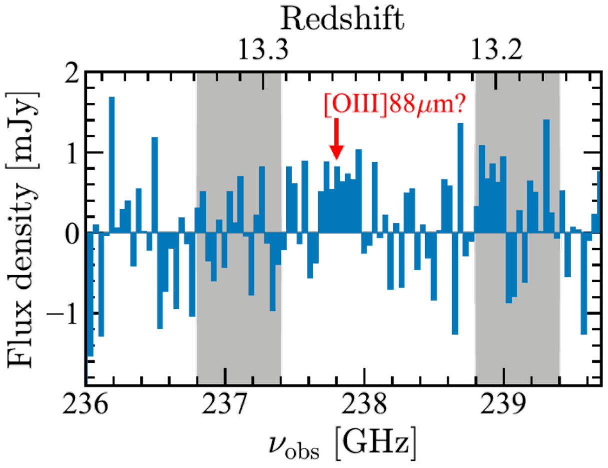


- Detection of candidate Balmer break galaxies at z~6 & absence of ALMA continuum detection ➔ Further evidence for the significant star formation at z > 14 !? (Mawatari, Inoue et al. 2020, ApJ, 889, 137)



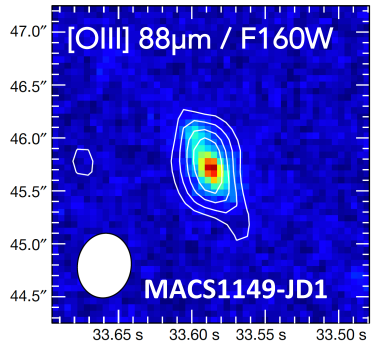
M(star) = 5 x 10^9 $M_\odot$
M(dust) = (4–8) x 10^6 $M_\odot$
$L_{[OIII]88}$ = 1.2 x 10^9 $L_\odot$

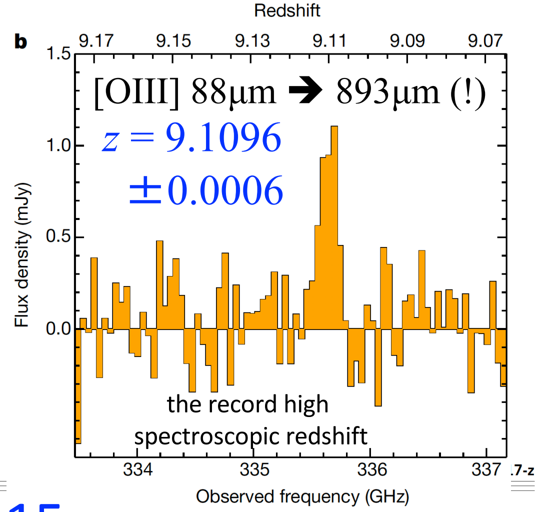
Tamura, Y., et al. 2019, ApJ, 874, 27
Bakx, T., et al. 2020, MNRAS, 493, 4294



H-dropout galaxy @ z =13.3 !?

Harikane et al. 2022, ApJ, 929, 1





LETTER

first star formation @z = 15 !?

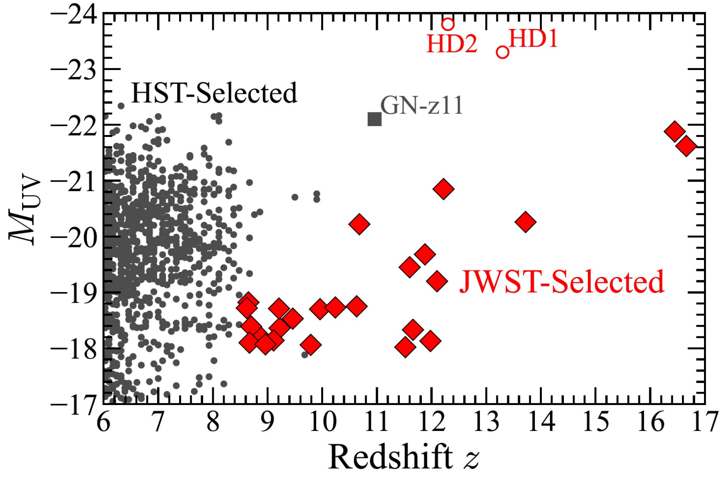
The onset of star formation 250 million years after the Big Bang

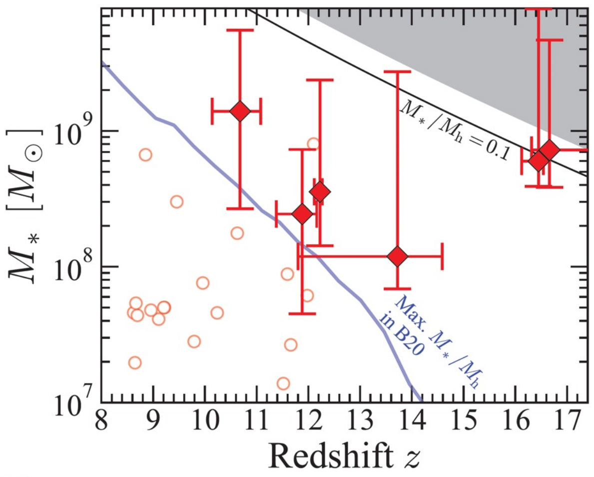
Takuya Hashimoto[1,2]*, Nicolas Laporte[3,4], Ken Mawatari[1], Richard S. Ellis[3], Akio K. Inoue[1], Erik Zackrisson[5], Guido Roberts-Borsani[3], Wei Zheng[6], Yoichi Tamura[7], Franz E. Bauer[8,9,10], Thomas Fletcher[3], Yuichi Harikane[11,12], Bunyo Hatsukade[13], Natsuki H. Hayatsu[12,14], Yuichi Matsuda[2,15], Hiroshi Matsuo[2,15], Takashi Okamoto[16], Masami Ouchi[11,17], Roser Pelló[4], Claes-Erik Rydberg[18], Ikkoh Shimizu[19], Yoshiaki Taniguchi[20], Hideki Umehata[13,20,21] & Naoki Yoshida[12,17]

Hashimoto, T., TY, et al. 2018, Nature, 557, 392

Candidate z~12-17 galaxies using JWST

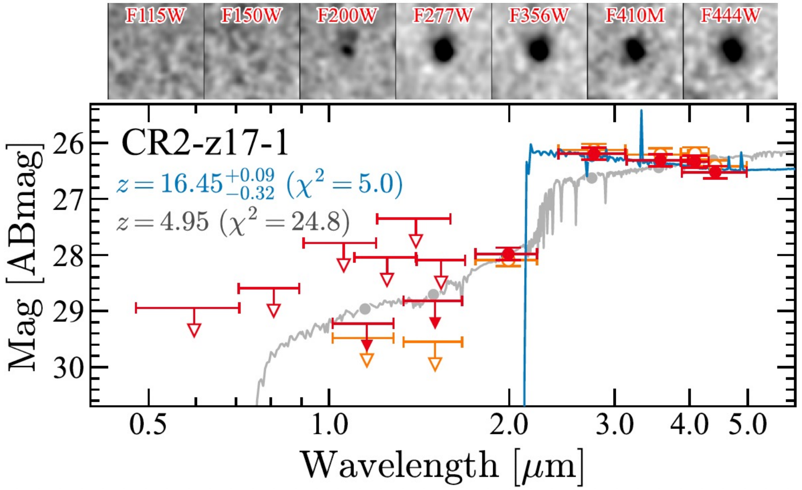
- a tension with the Λ-CDM !? (or inappropriate stellar mass estimates for z>10-ish galaxies?)

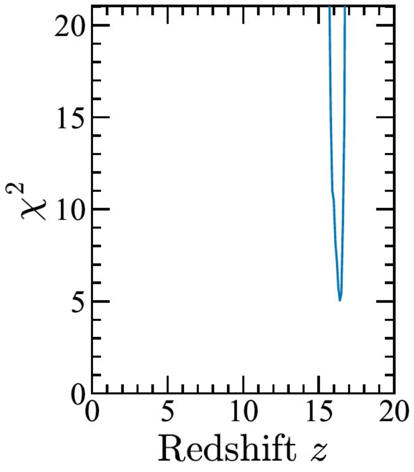




the maximum halo mass with M_{star}/M_{halo} = 0.1 and the maximum M_{star}/M_{halo} value at each redshift in Behroozi et al. (2020)

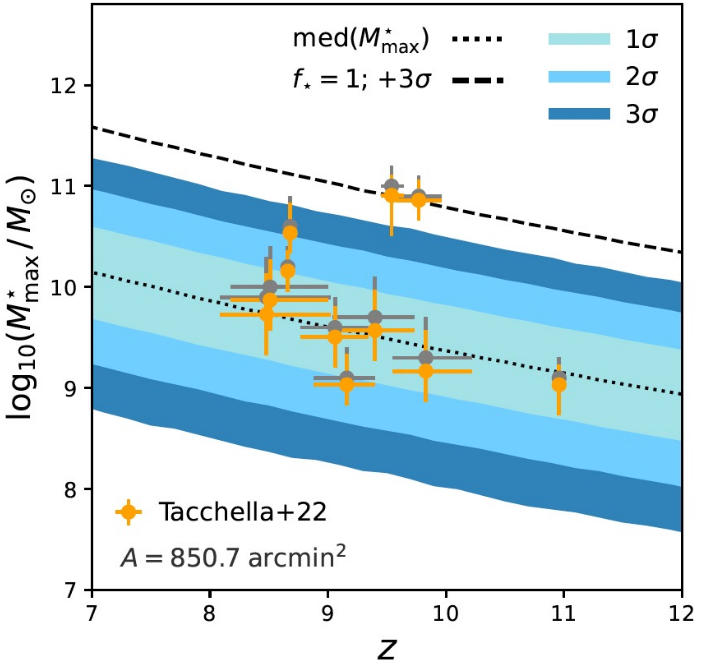
Harikane et al 2023, ApJS, 265, 5

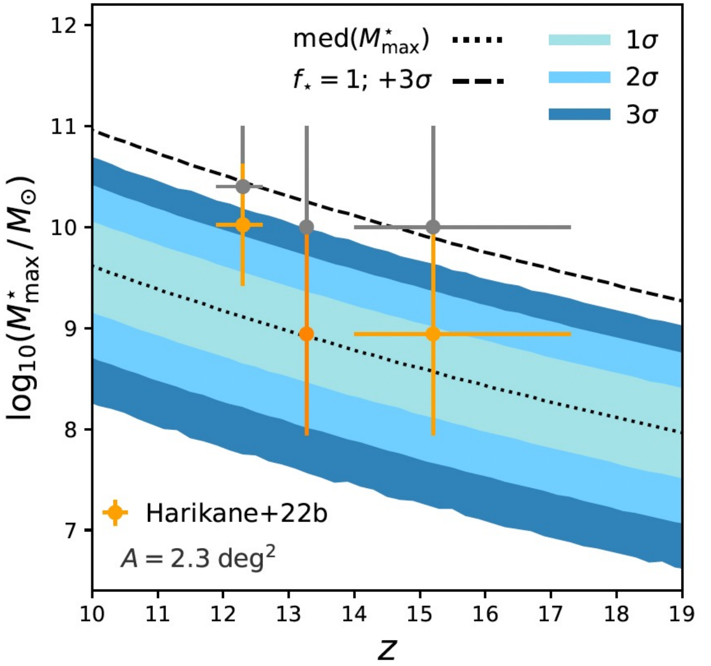




Extreme value statistics (EVS): a test of the underlying cosmology from the observation of *a single extreme* object !

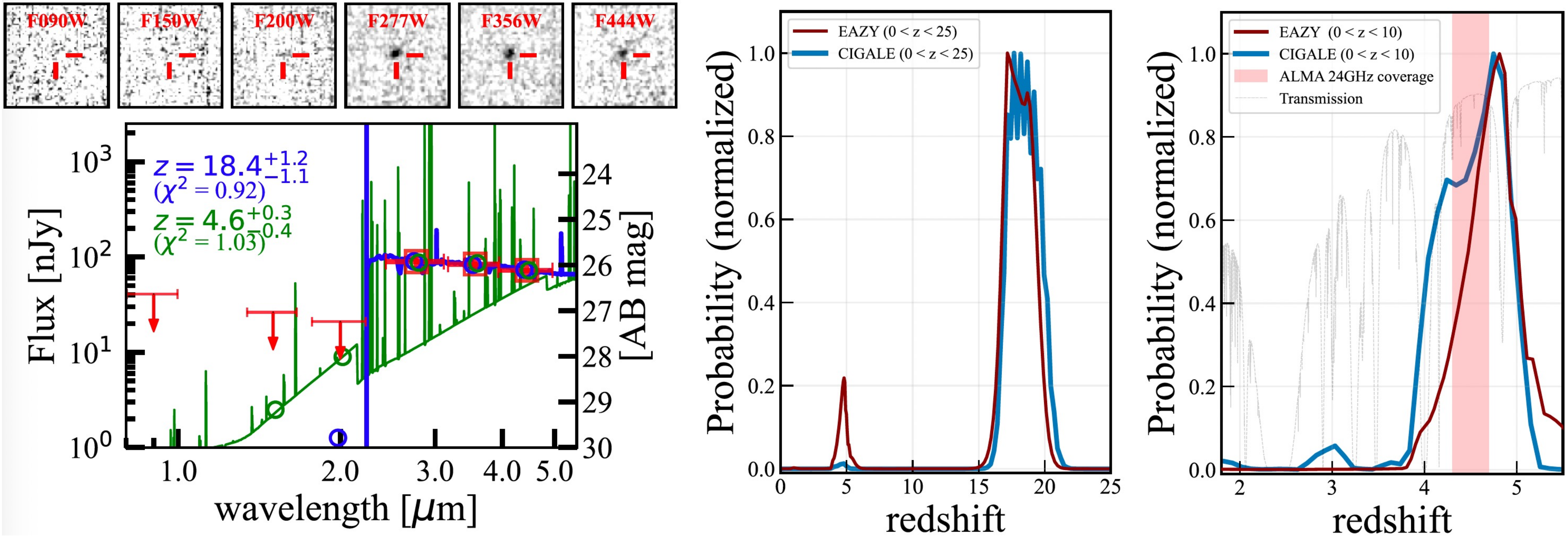
Lovell, C., et al., 2023, MNRAS, 518, 2511





NIRCam/F200W drop source: a z~18 candidate !

Fujimoto et al. (submitted) arXiv:2211.03896

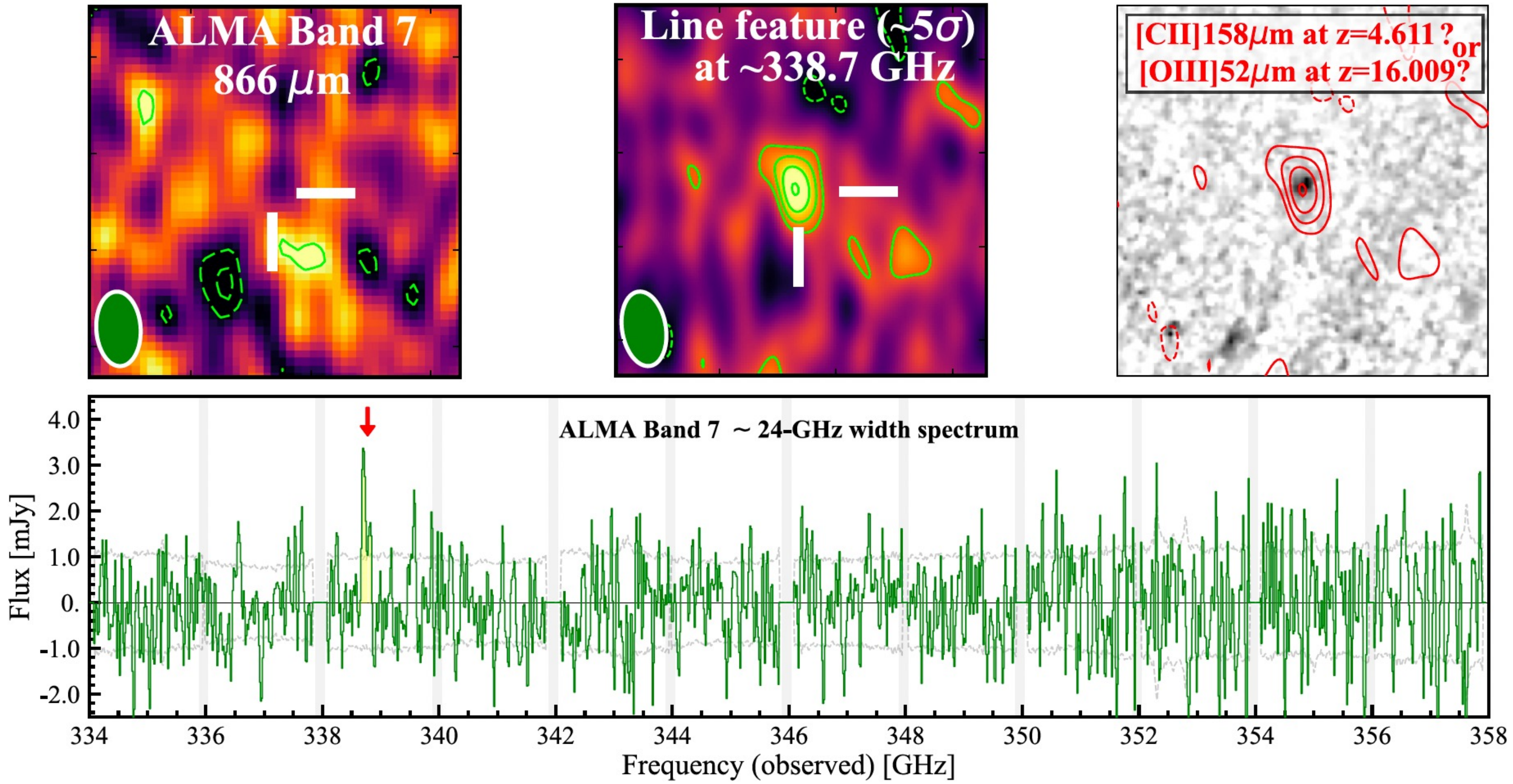


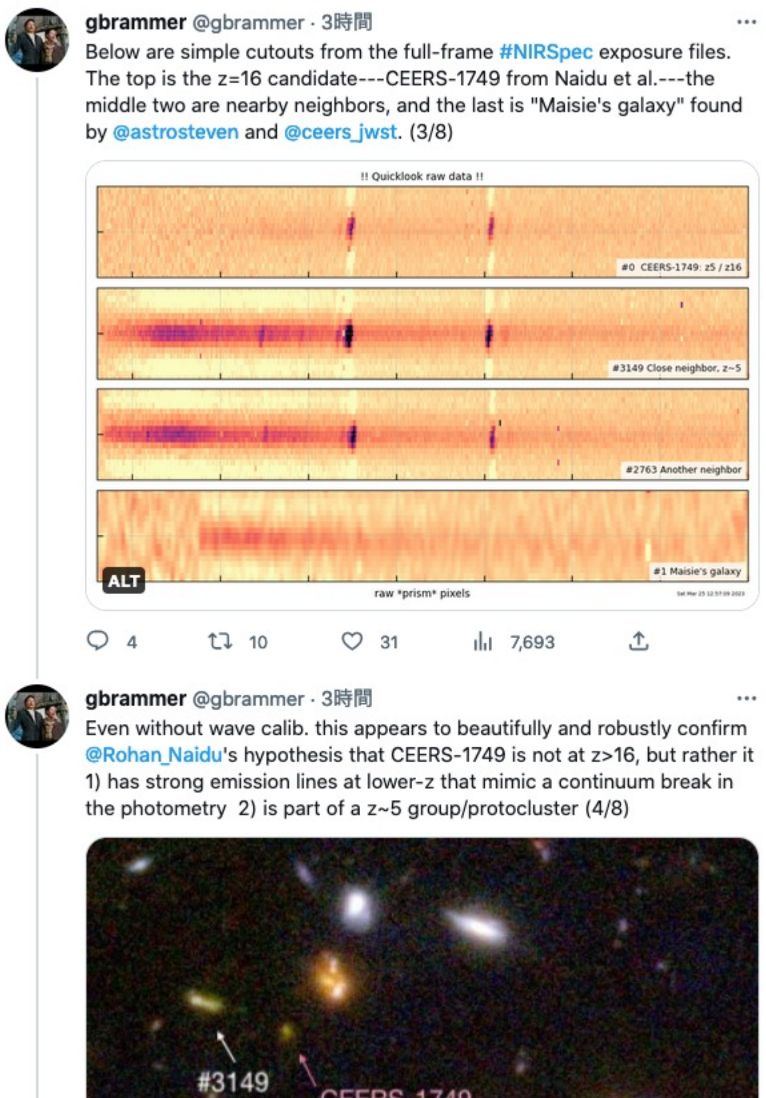
ALMA detects a line! Good, then ..?

Fujimoto et al. (submitted)
arXiv:2211.03896

- Likely [OIII] 52 μm @z = 16.009, but ..
- [CII] 158 μm @z = 4.611 solution still rem

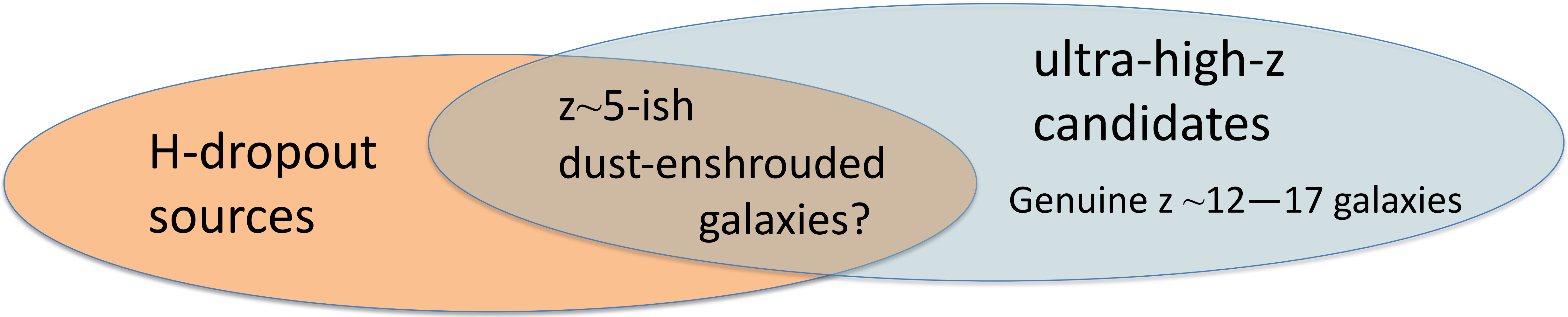
➔ See tweets by Gabe Brammer yesterday

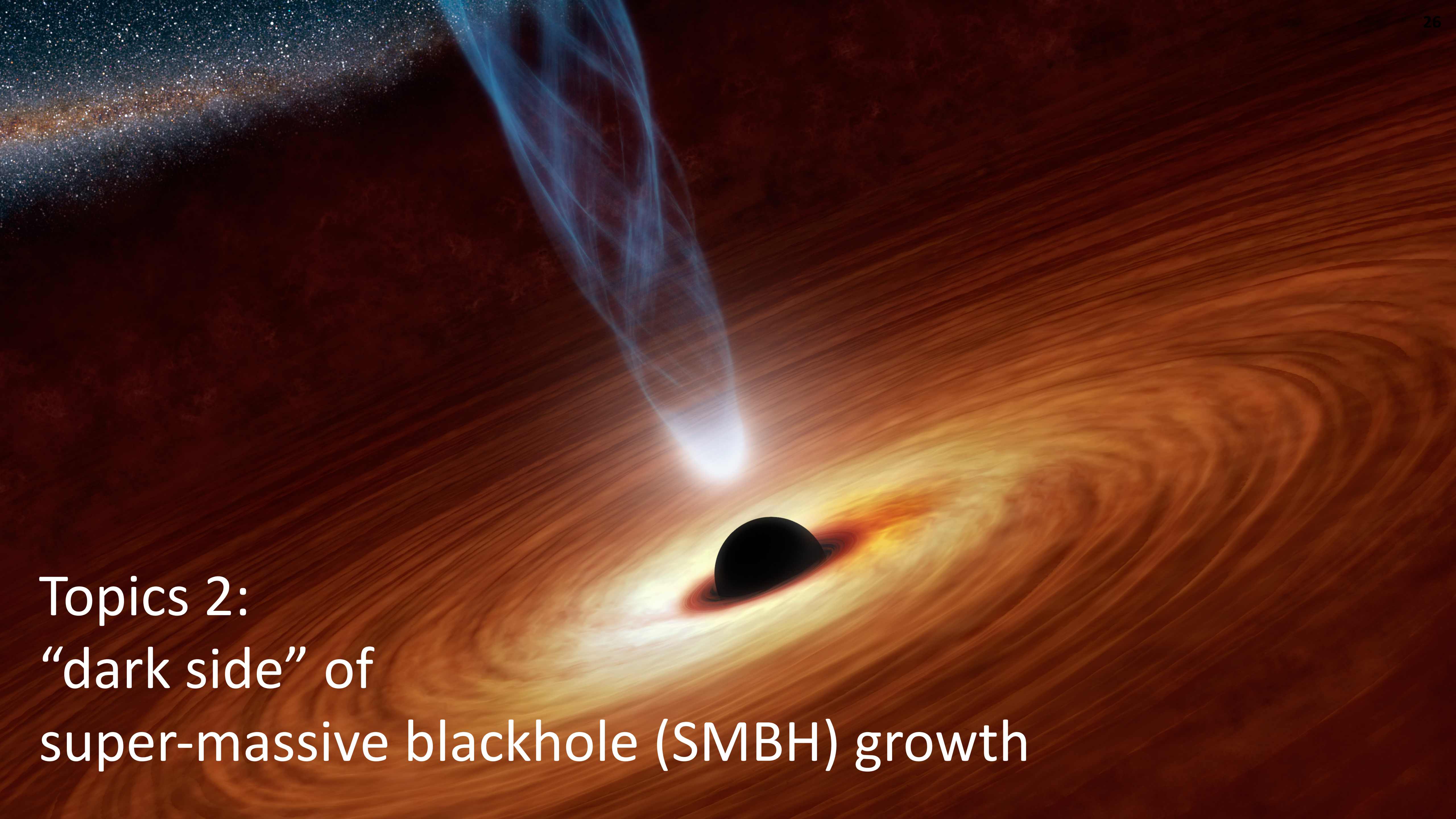




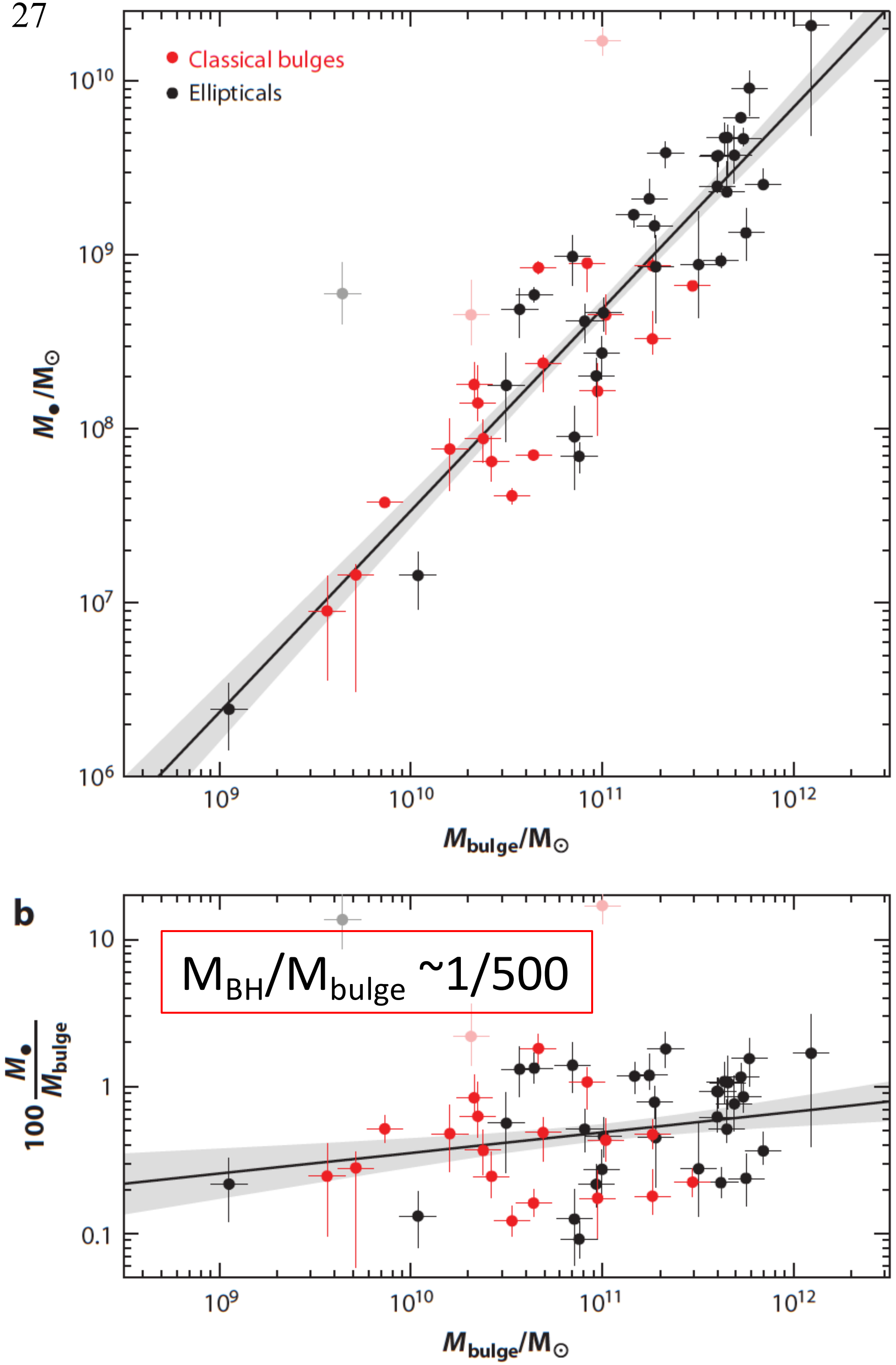
A part of "ultra-high-z candidates" = "H-dropout" !?

- "H-dropouts" (HST WFC3/F160W drop ALMA sources): dust-enshrouded forming massive galaxies at z ~3-6?
- "ultra-high-z candidates" (JWST NIRCAM/F200W drop mid-IR sources): two solutions remain: z ~12-17 less dusty galaxies or z ~5-ish dusty forming galaxies?





Topics 2:
“dark side” of
super-massive blackhole (SMBH) growth



Intimate connection between SMBHs and galaxies

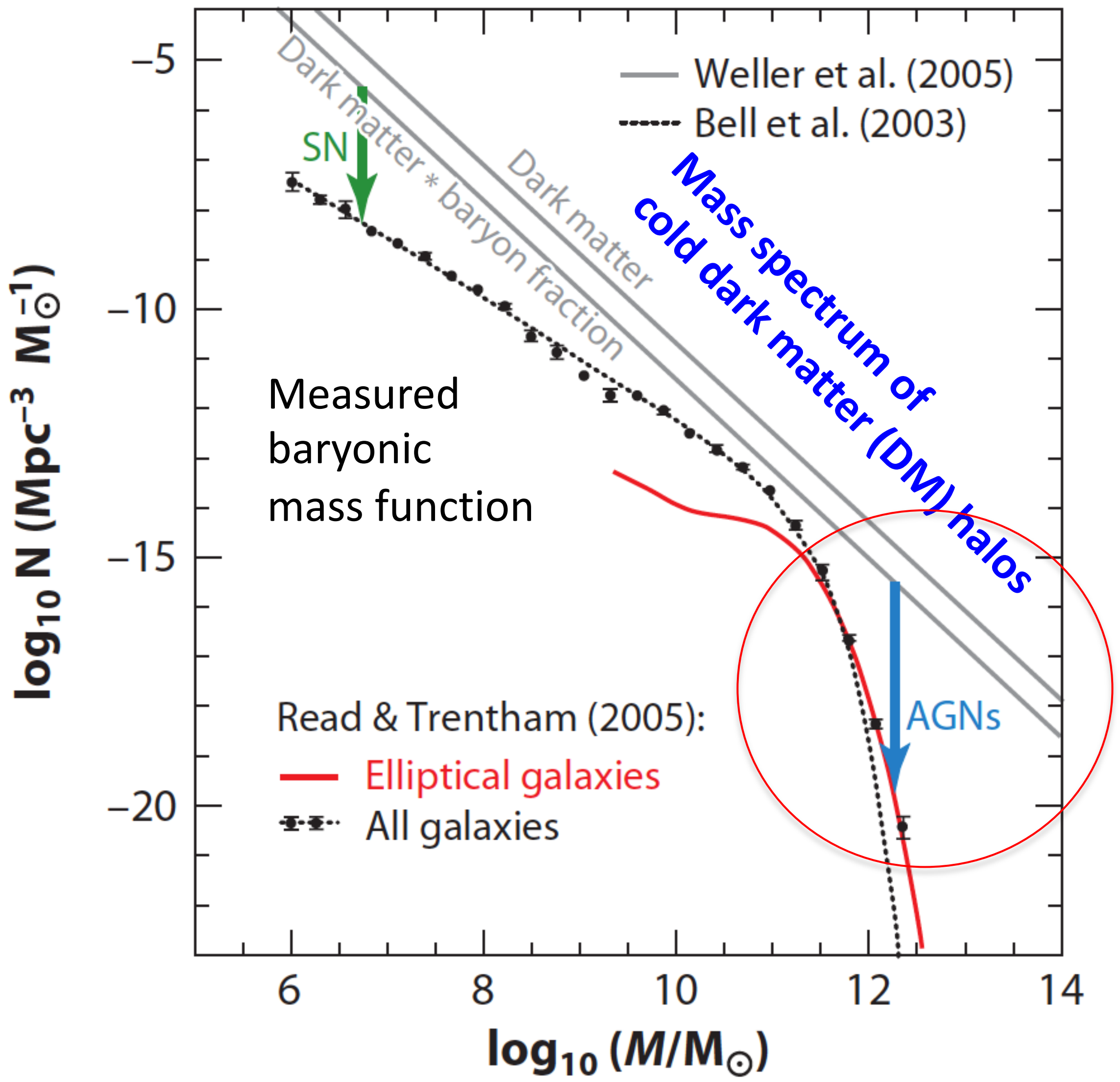
- More massive SMBHs reside in more massive host galaxies
- The mass ratio: typically 0.5%
- Ranging from 0.1% to 1.8%
- Exceptions up to 14% - 17% (NGC 4486B and NGC 1277, respectively)

$$\frac{M_\bullet}{10^9\,M_\odot} = (0.49^{+0.06}_{-0.05})\left(\frac{M_{bulge}}{10^{11}\,M_\odot}\right)^{1.17\pm0.08}$$

★ Why do they know each other despite ~10 orders of magnitude difference in spatial scale..?

Kormendy & Ho 2013, ARAA, 51, 511

Necessity of negative feedback from growing SMBHs



- Low-mass end: SN feedback makes SF efficiency smaller
- High-mass end: what makes high-mass cut-off of baryonic mass function?
- ➔ negative feedback from growing SMBHs (AGNs) !?

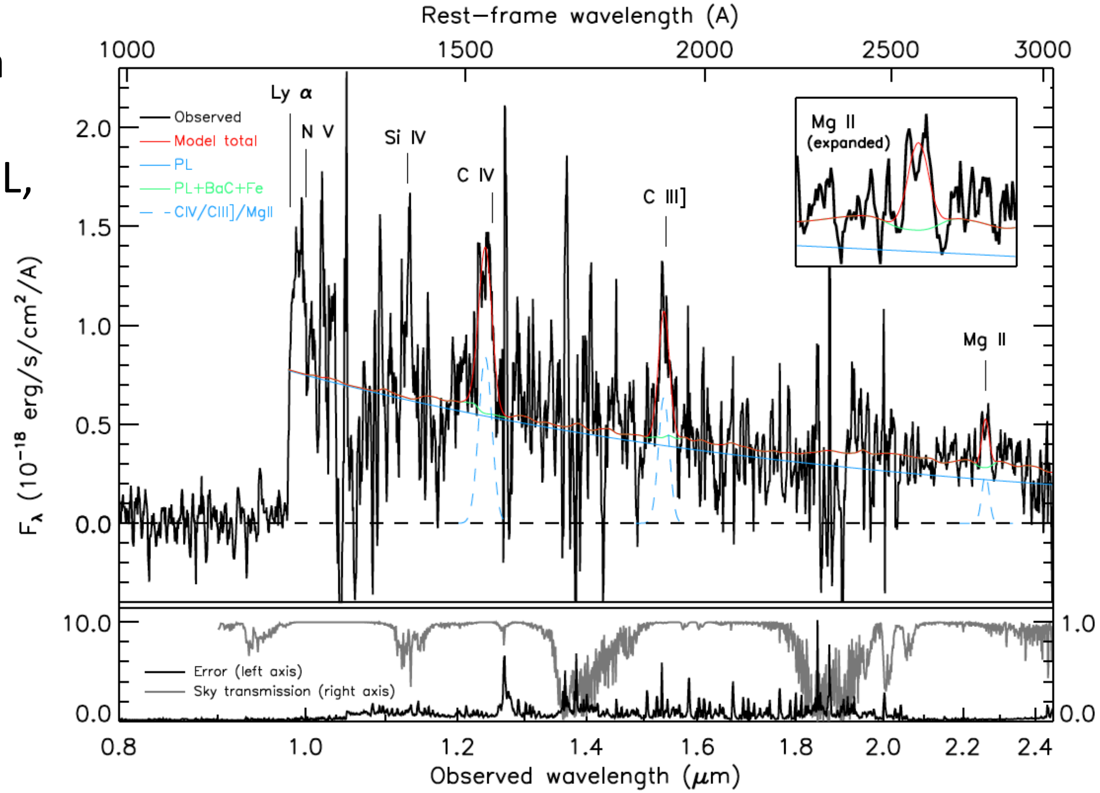
Sharp drop of stellar (baryonic) mass function at the high-mass end

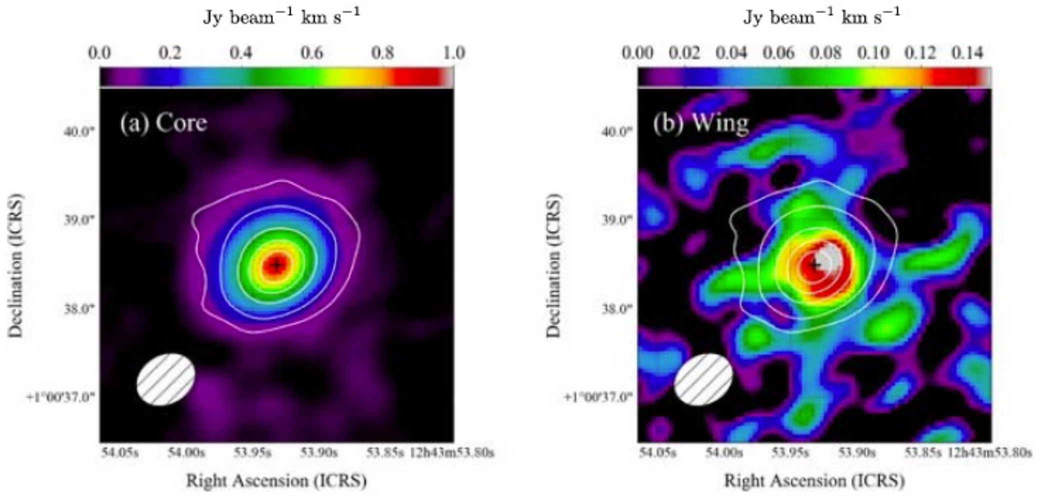
Read & Trentham 2005, Philisophical Transactions of The Royal Society A, 363, p. 2693

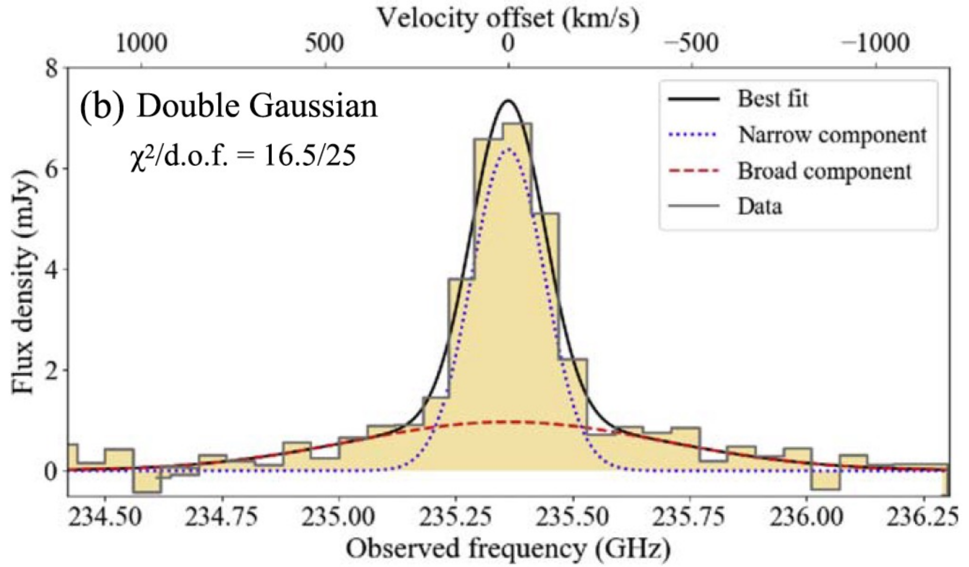
Kormendy & Ho, 2013, ARAA, 51, 511

Large-scale feedback seen as a [CII] 158 μm outflow in a low-luminosity quasar at z = 7.07 uncovered by Subaru/HSC (SHELLQs)

Matsuoka et al. 2019, ApJL, 872, L2



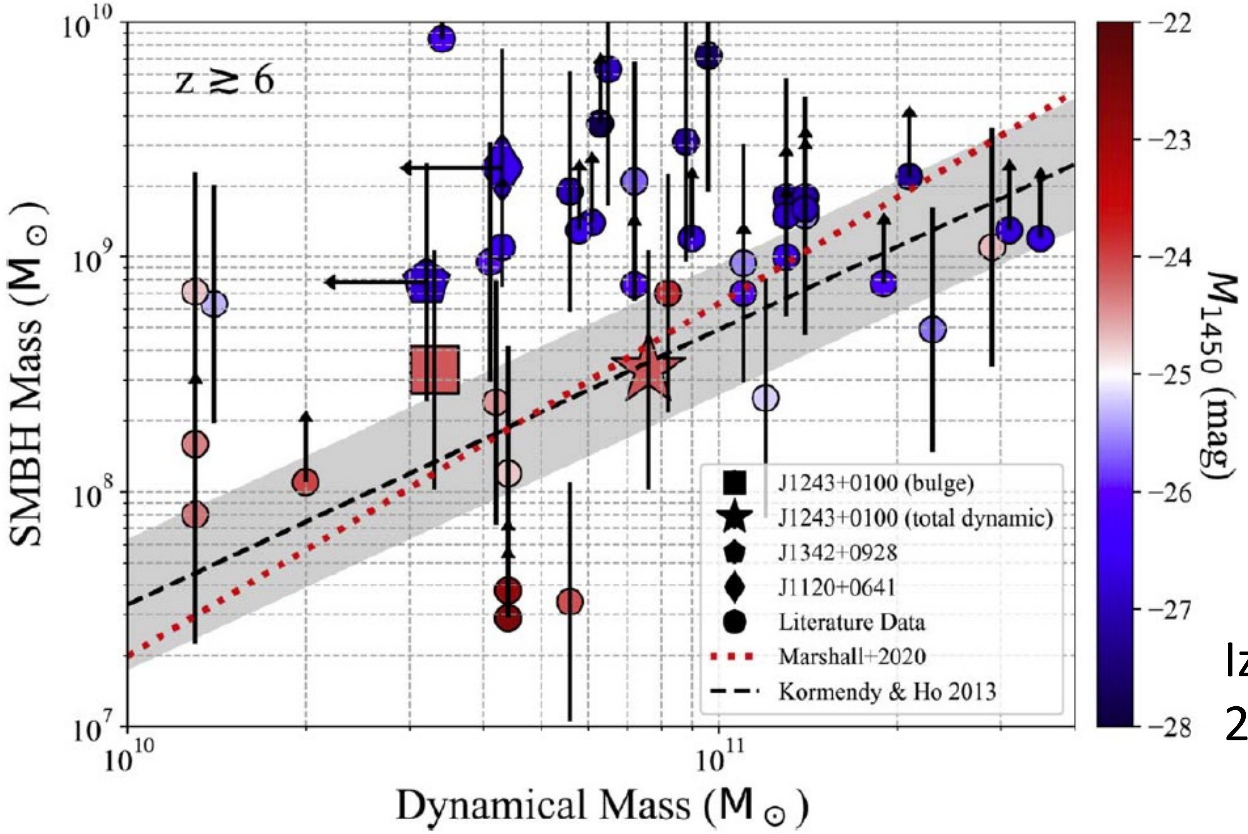




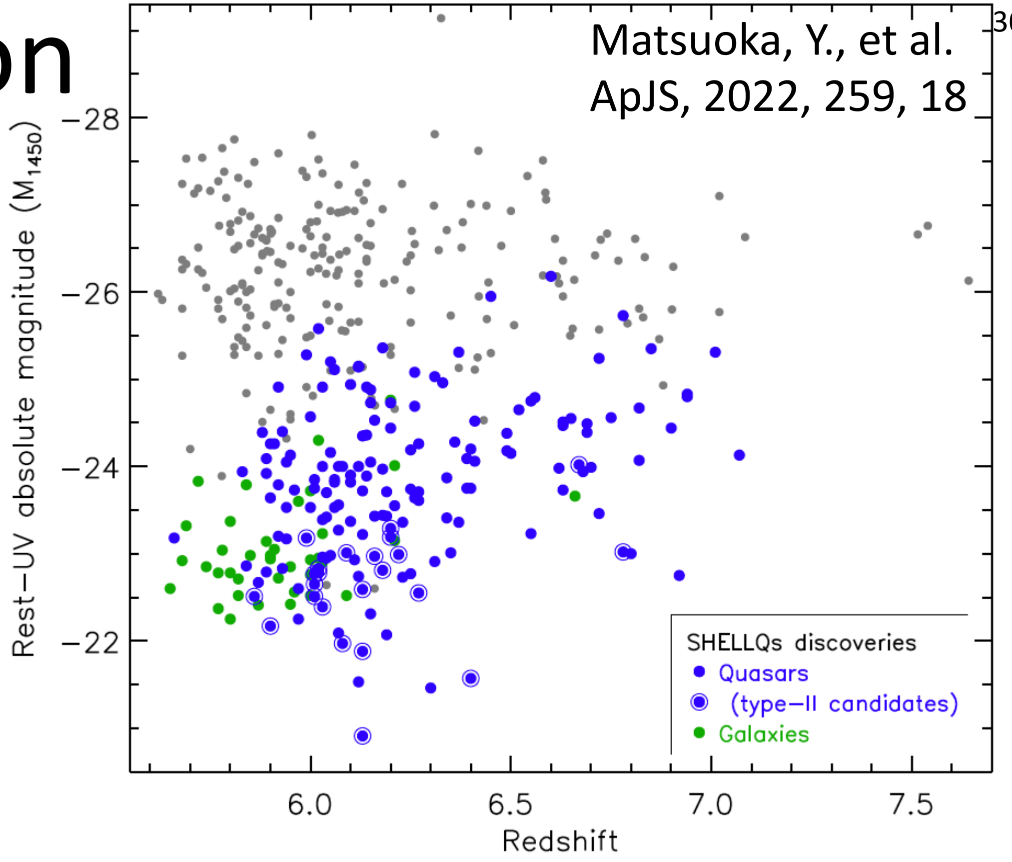
- Outflow velocity v_{out} = 500 ± 110 km/s
- Outflow extent R_{out} < 1.3 kpc
- Outflow timescale τ_{out} < (2.6 ± 0.6) x 10^6 yr
- Mass outflow rate dM/dt(atomic) > 450±140 $M_\odot$/yr
  ➔ dM/dt(total) > 1400 $M_\odot$/yr >> host SFR = 310 – 740 $M_\odot$/yr

Izumi, T., et al. 2021, ApJ, 914, 36

Does M(SMBH)-M(host) relation already exist at z > 6-7 ??



Izumi, T., et al. 2021, ApJ, 914, 36



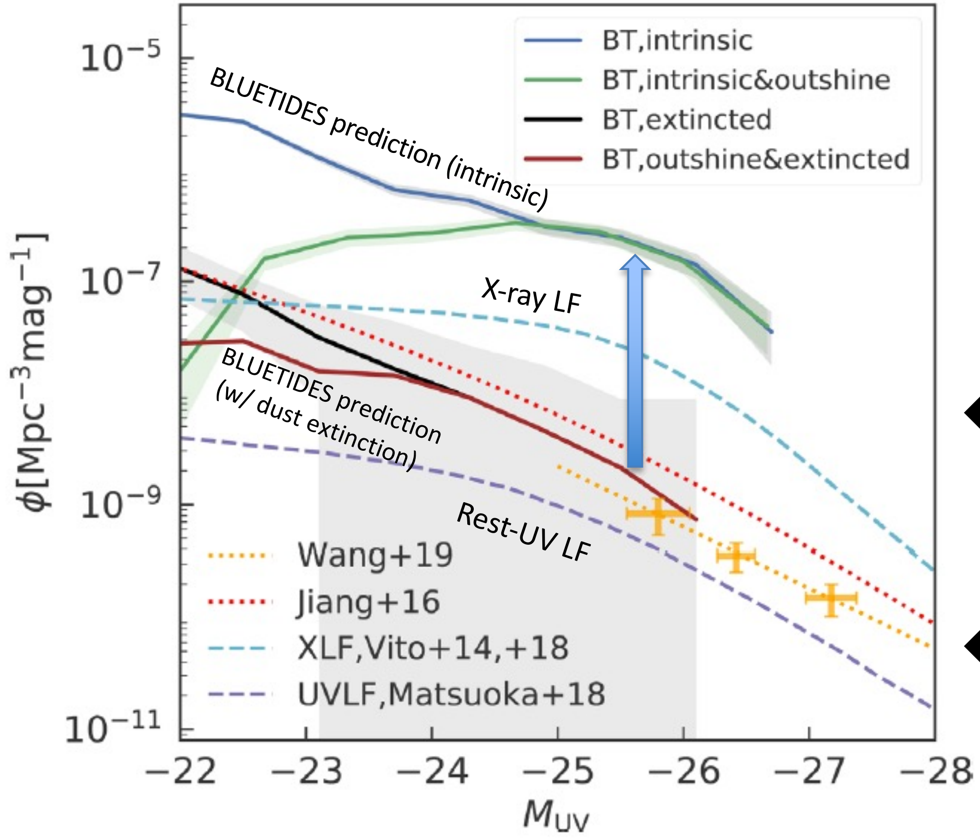
Matsuoka, Y., et al. ApJS, 2022, 259, 18

See also
Izumi, T., Onoue, M., et al. 2019, PASJ, 71, 111

- ALMA [CII]158um observations of low-luminosity quasars uncovered by Subaru/HSC surveys (SHELLQs) ➔ less biased view of the M(SMBH)-M(host) relation at z>6-7
- M(dyn) contains molecular gas mass, which can be M(gas) < 2.5 x 10^{10} Msun (from M(dust) by assuming Mgas/Mdust <100) → M(star) = M(dyn) – M(gas) ~ (5-7) x 10^{10} Msun ➔ M(bulge) = (3.3 ± 0.2) x 10^{10} Msun

What is the intrinsic "abundance" of quasars?

- Comparison of the predicted, intrinsic ultra-violet (UV)-band luminosity of quasars from the BLUETIDES simulations at z = 7.0 and observed luminosity functions (UV, hard X-ray)
- Dust-extincted UV luminosity function is about 1.5 dex lower than the intrinsic LF, implying that more than 99 % of the z = 7 AGNs are heavily dust extincted and therefore would be missed by the rest-ultra-violet band observations



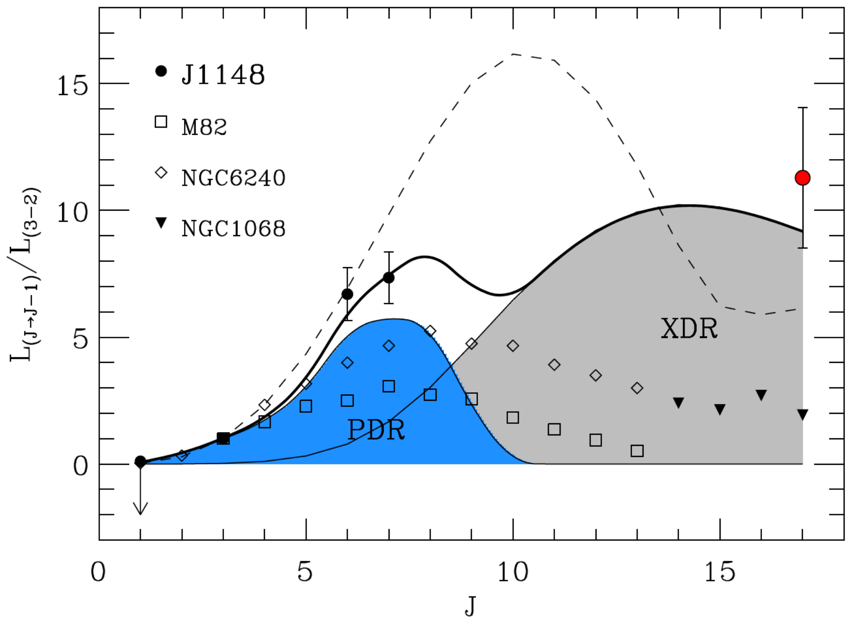
Gray shaded area: the range of realizations with respect to different lines of sight (along 972 different directions)

🡐 X-ray luminosity function at z = 7 extrapolated from z = 4 AGN population (Vito et al. 2018, MNRAS, 473, 2378)

🡐 Observed quasar luminosity functions including SHELLQs by Matsuoka et al.

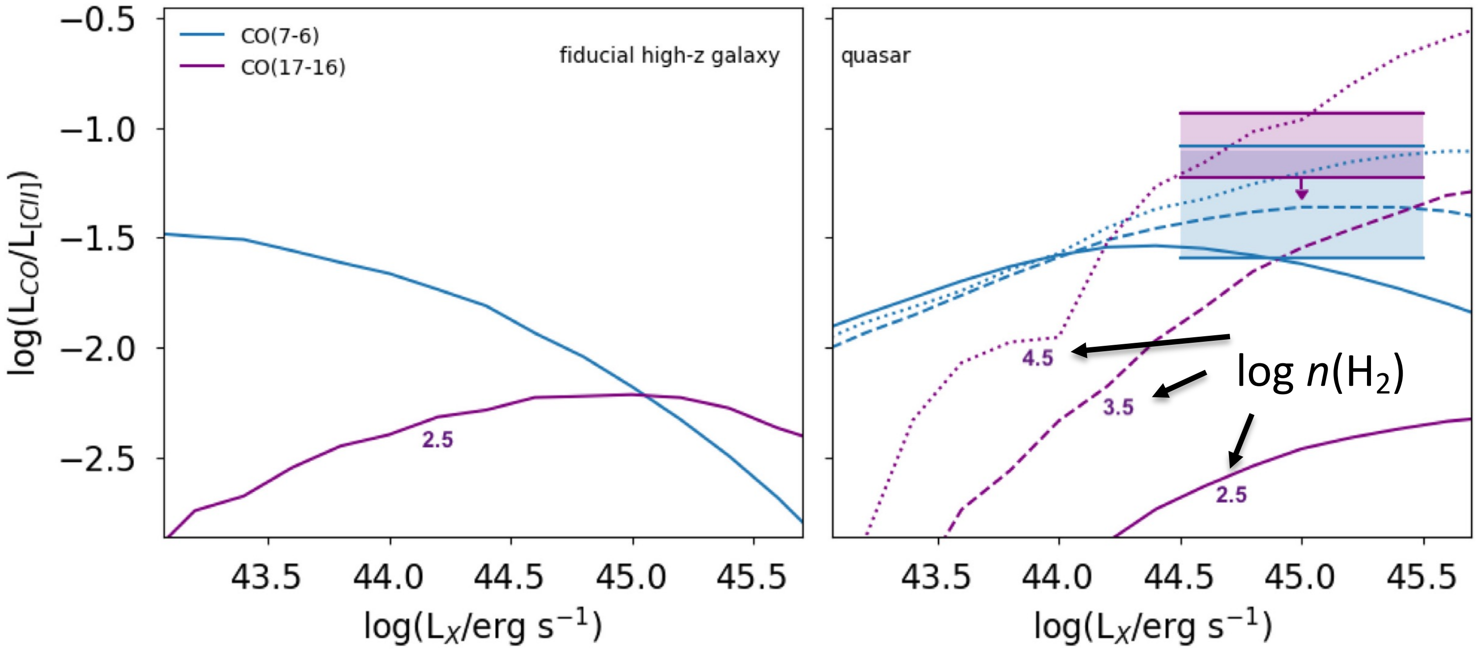
Ni et al. 2020, MNRAS, 495, 2135

Can we recognize dust-obscured, growing SMBHs?



High quantum number (J) CO lines (e.g., J=17→16) are expected to be drastically bright in X-ray dominated regions (XDRs)

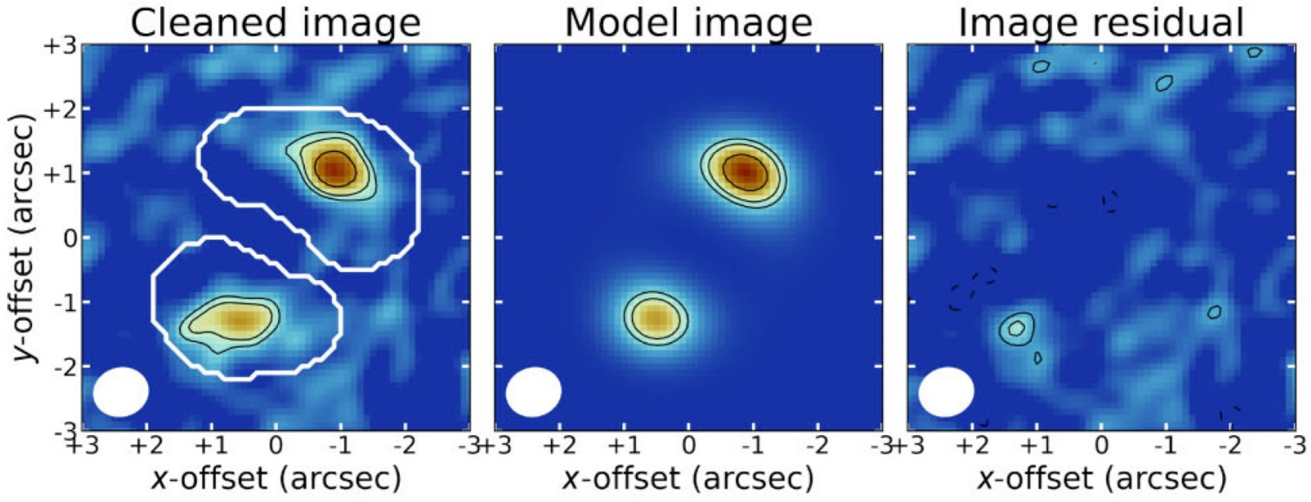
Gallerani et al. 2014, MNRAS, 445, 2848

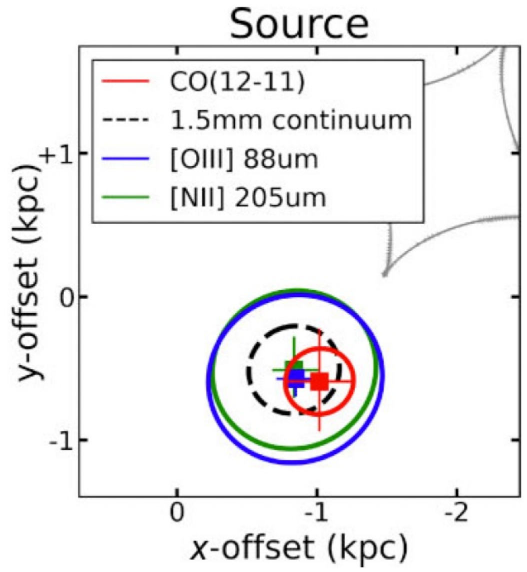


Observed ratios
CO(7-6)/[CII]158
CO(17-16)/[CII]158

Vallini et al. 2019, MNRAS, 490, 4502

A signature of an obscured, growing SMBH within dust-enshrouded starburst galaxy at the epoch of reionization

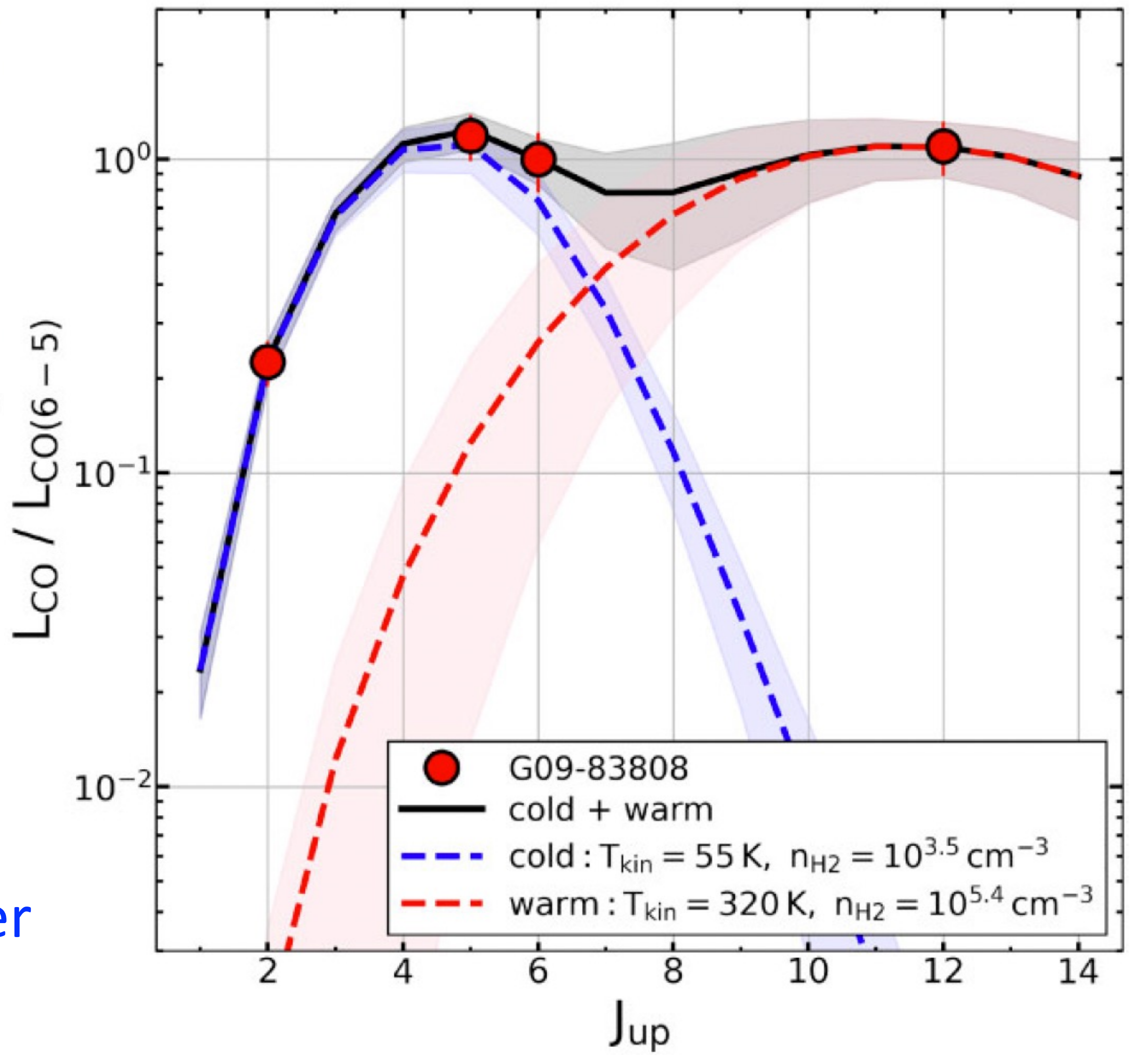




G09-83808 @z = 6.02
CO(J=12→11) velocity-integrated intensity image

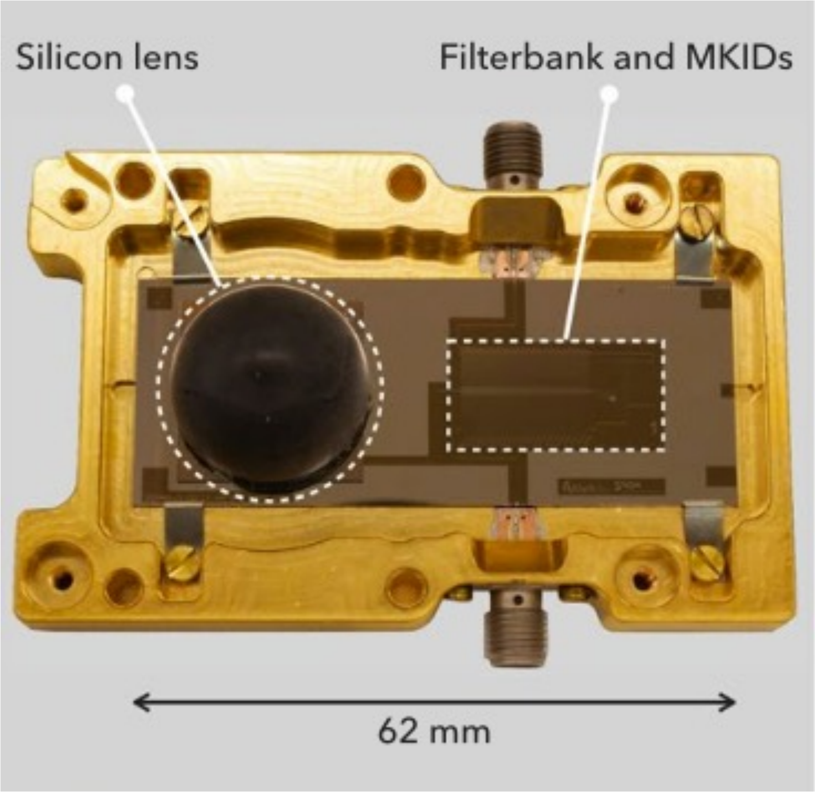
Very compact (compared with [OIII] 88 μm and [NII] 205 μm) & high excitation

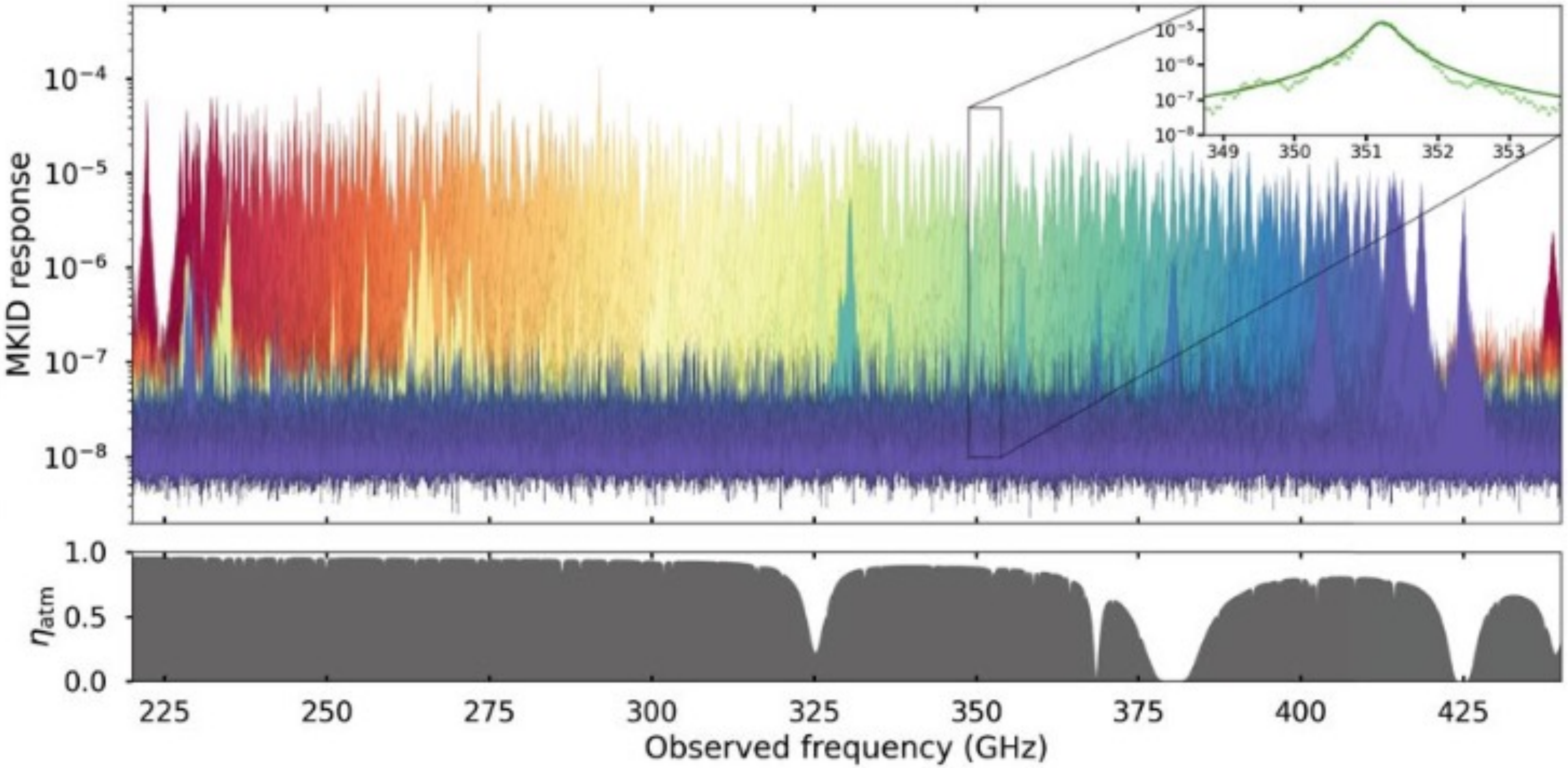
➔ Buried heating source other than star formation !?



We then need a redshift measurement machine: DESHIMA2.0 based on Integrated Superconducting Spectrometer (ISS) technology will be a game changer

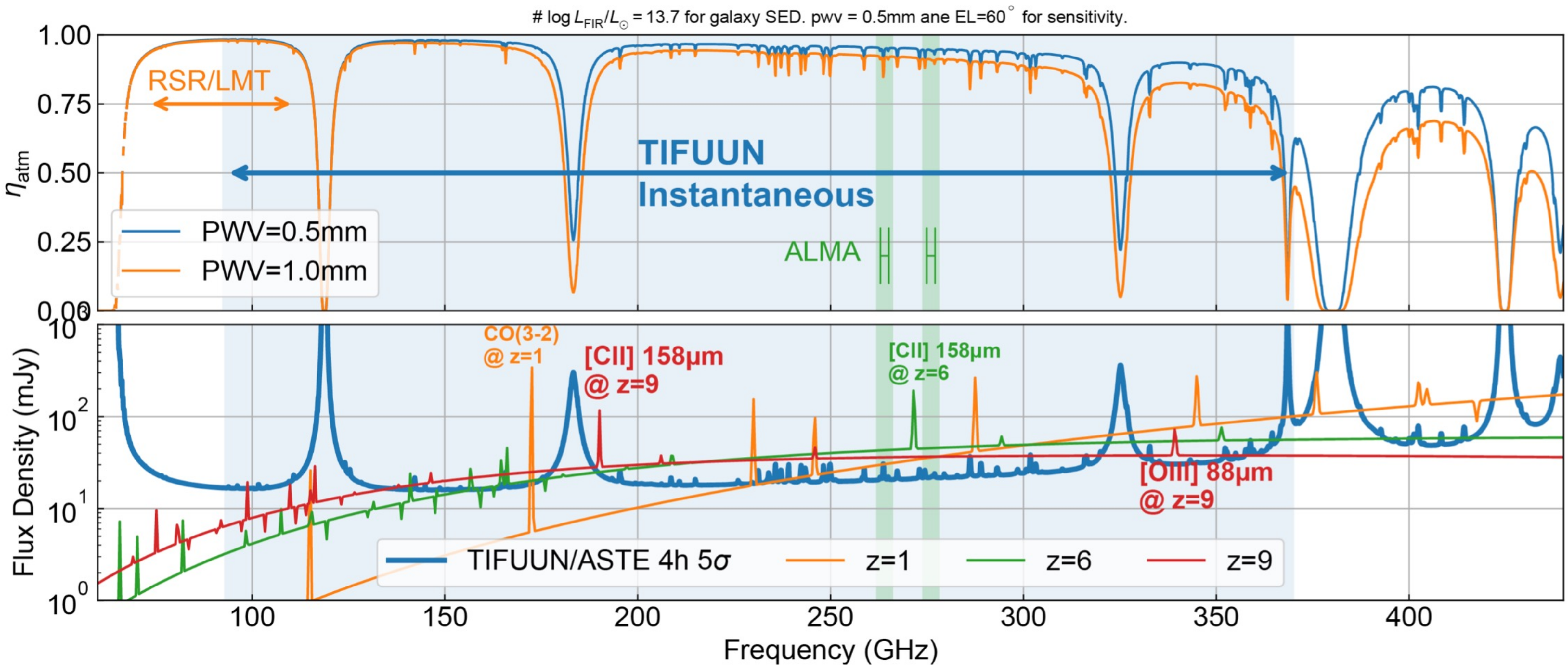
[CII] 158 μm redshift z = 3.3 - 7.6 in one-shot





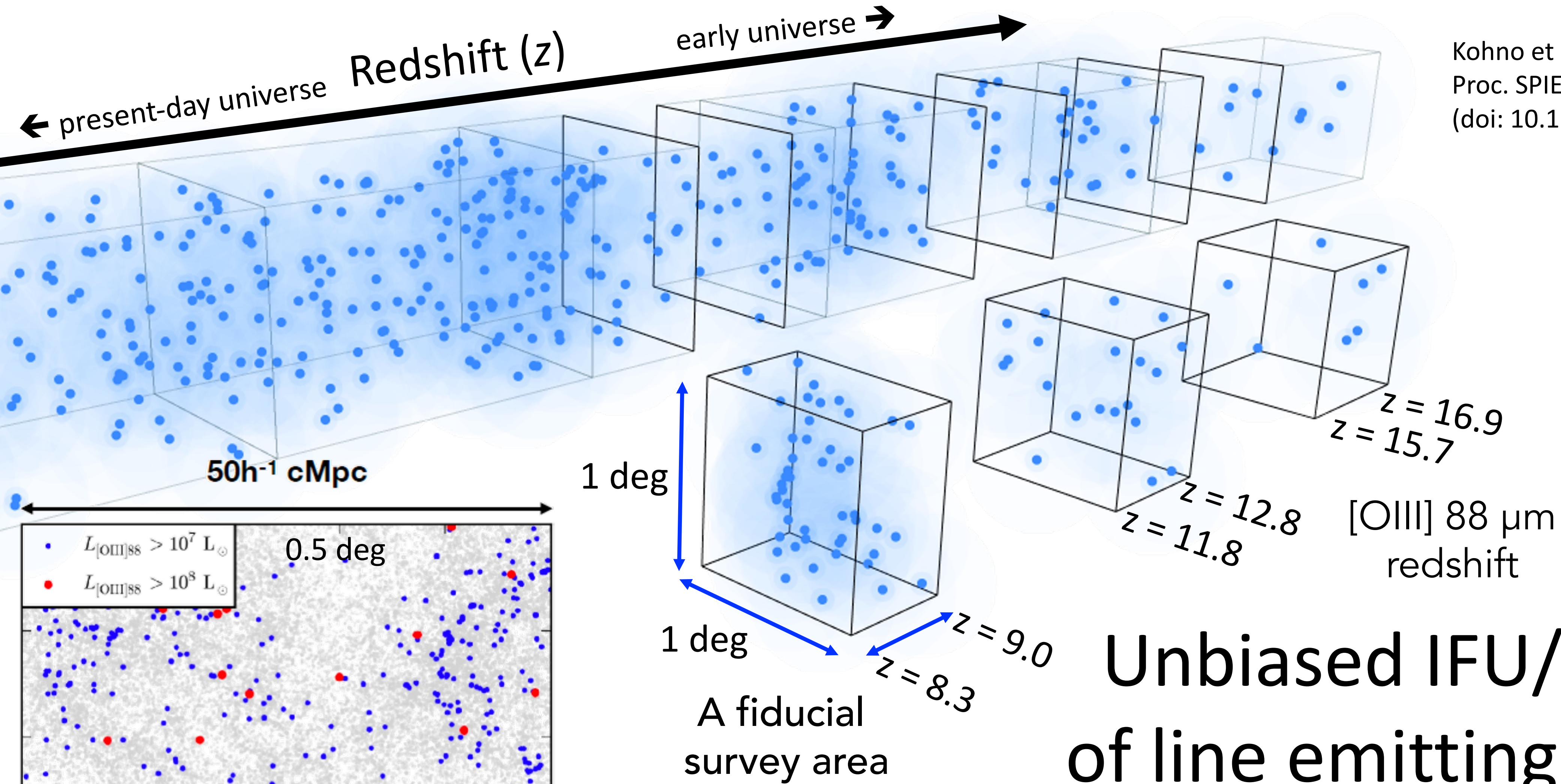
Taniguchi, A., et al. 2022, J. Low Temp. Phys., 209, pp. 278

Drastic growth of ISS technology: DESHIMA to TIFUUN

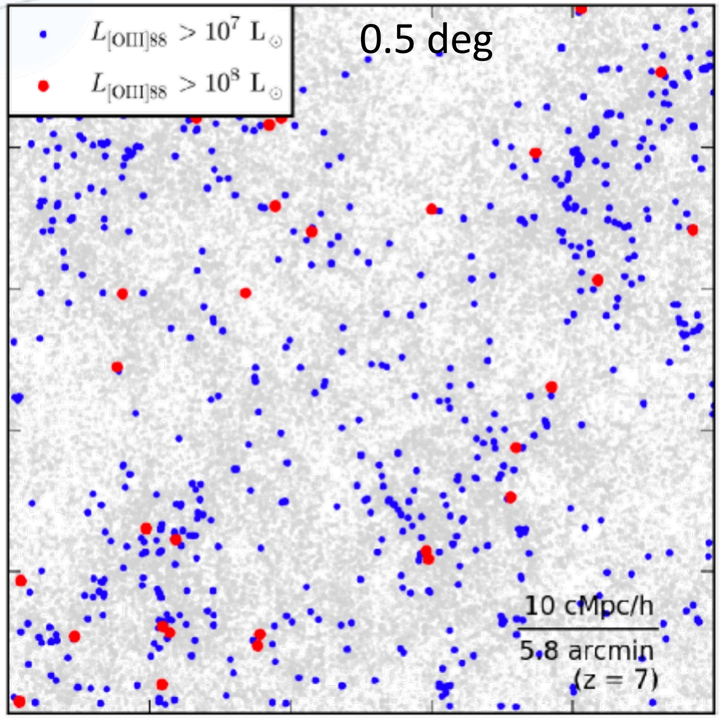


Simultaneous measurements of ionized carbon and oxygen [CII] 158um and [OIII] 88um lines @z=9

Kohno et al. 2020,
Proc. SPIE 11453
(doi: 10.1117/12.2561238)

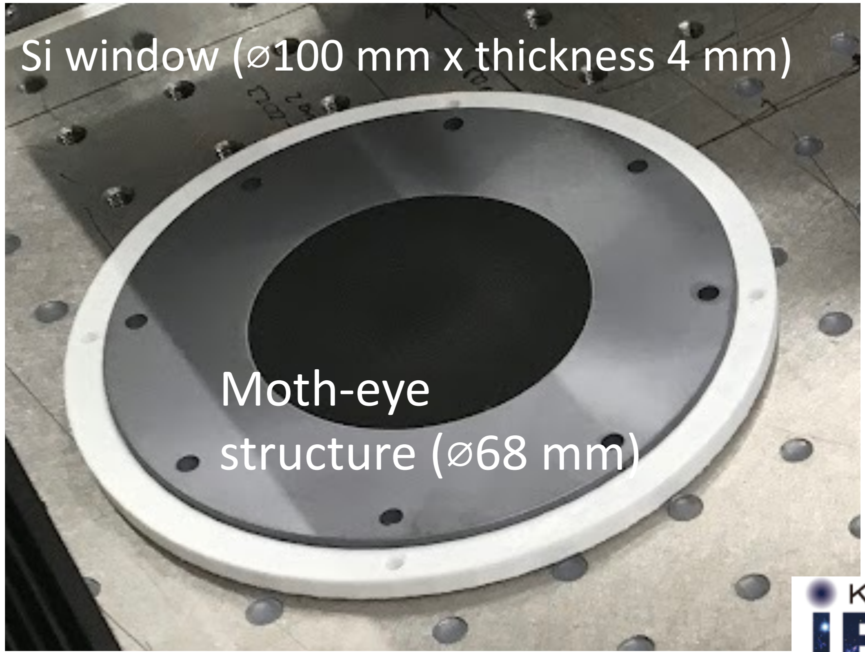


Unbiased IFU/3D survey of line emitting galaxies (LMT, LST/AtLAST + TIFUUN)



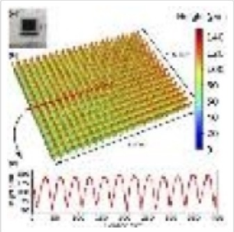
Simulated distribution of [OIII] 88 μm emitters @ z~7
Moriwaki et al. 2018, MNRAS, 481, L84

We are thankful for productive French & Japanese collaborations for the future!



Cryocoolers
with CONCERTO team
(NIKA2 technology)

OSA Continuum Vol. 2, Issue 9, pp. 2764-2772 (2019) • https://doi.org/10.1364/OSAC.2.0027



Terahertz broadband anti-reflection moth-eye structures fabricated by femtosecond laser processing

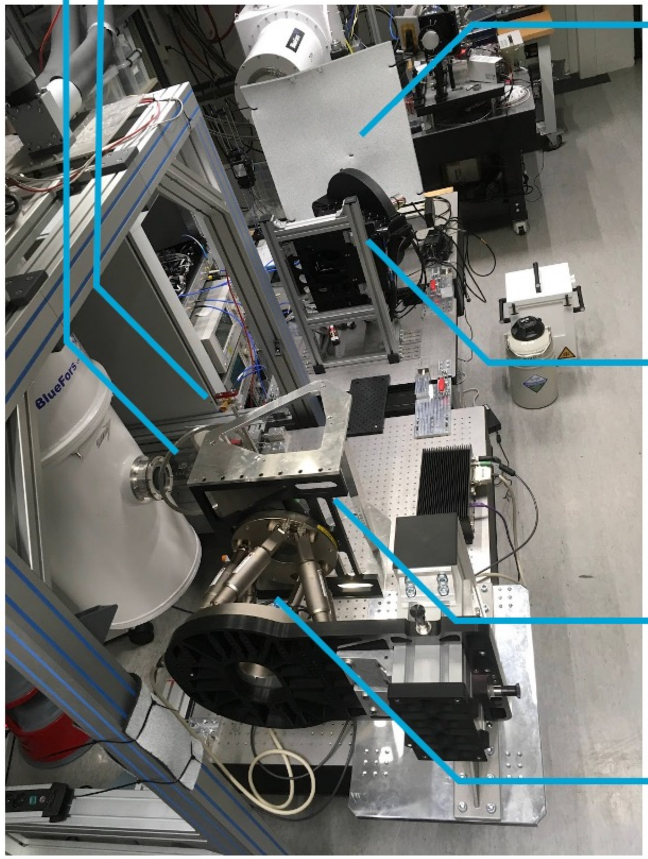
Haruyuki Sakurai, Natsuki Nemoto, Kuniaki Konishi, Ryota Takaku, Yuki Sakurai, Nobuhiko Katayama, Tomotake Matsumura, Junji Yumoto, and Makoto Kuwata-Gonokami

Author Information ▾ Find other works by these authors ▾

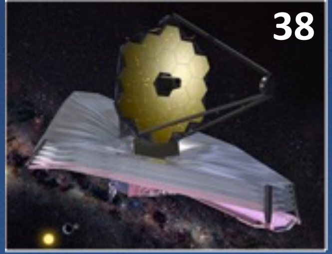
Open Access

Get PDF | Email | Share ▾ | Get Citation ▾ | Citation alert | Save article | Editors' Pick | Check for updates

DESHIMA2.0 Laboratory setup



Summary and outlook



- Dark-side of galaxy evolution
  - HST/Near-infrared dropout faint ALMA galaxies: A newly identified class of dusty galaxies, based on serendipitous ALMA detections
- ALMA Lensing Cluster Survey (ALCS)
  - Resolving ~80% of the cosmic infrared background (CIB) light into discrete sources
  - Steady increase of the number counts down to ~0.01 mJy (no flattening yet)
  - Near-infrared dark ALMA sources contribute ~40% of cosmic SFR density at $z > 4$
  - Near-infrared dark ALMA sources: potential overlap with the claimed "ultra-high-redshift galaxies" from JWST/NIRCam
- Dark-side of super-massive blackhole growth
  - Dust-enshrouded growth of SMBHs in the Epoch of Reionization (Subaru-selected, submm-selected)
  - Need a redshift machine (ultra-wide-band spectroscopy) ➔ Integrated Superconducting Spectrograph (ISS) technology will change the scene!