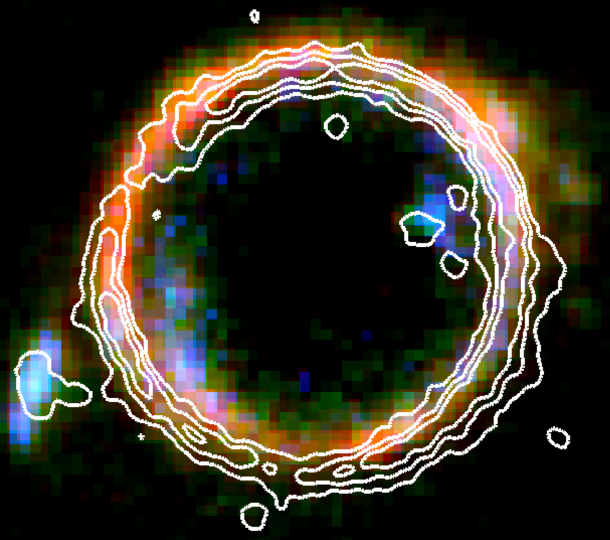
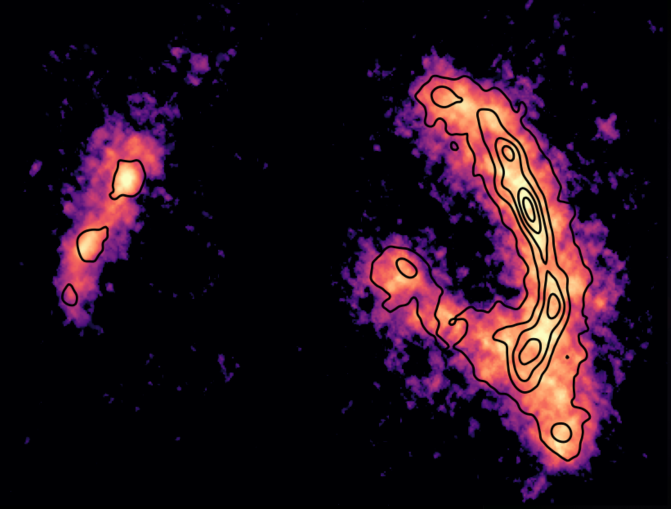
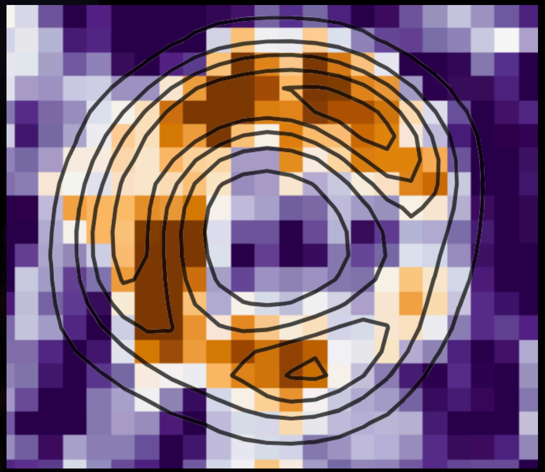
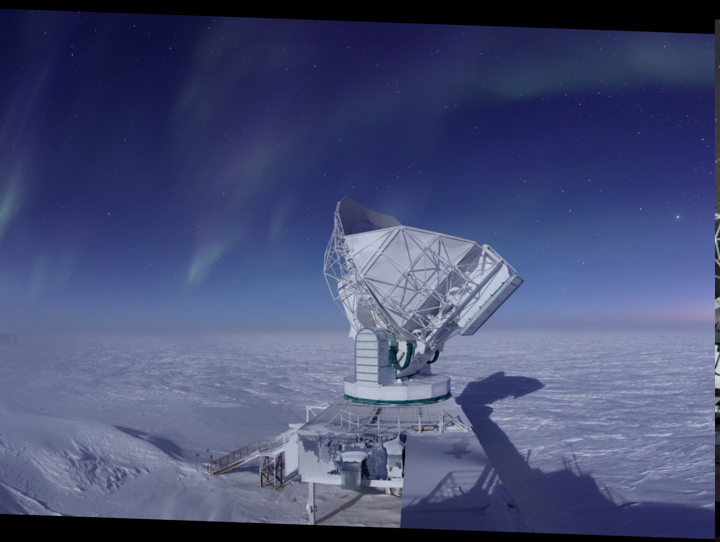
   

The Nature of mm-Selected Dusty Galaxies

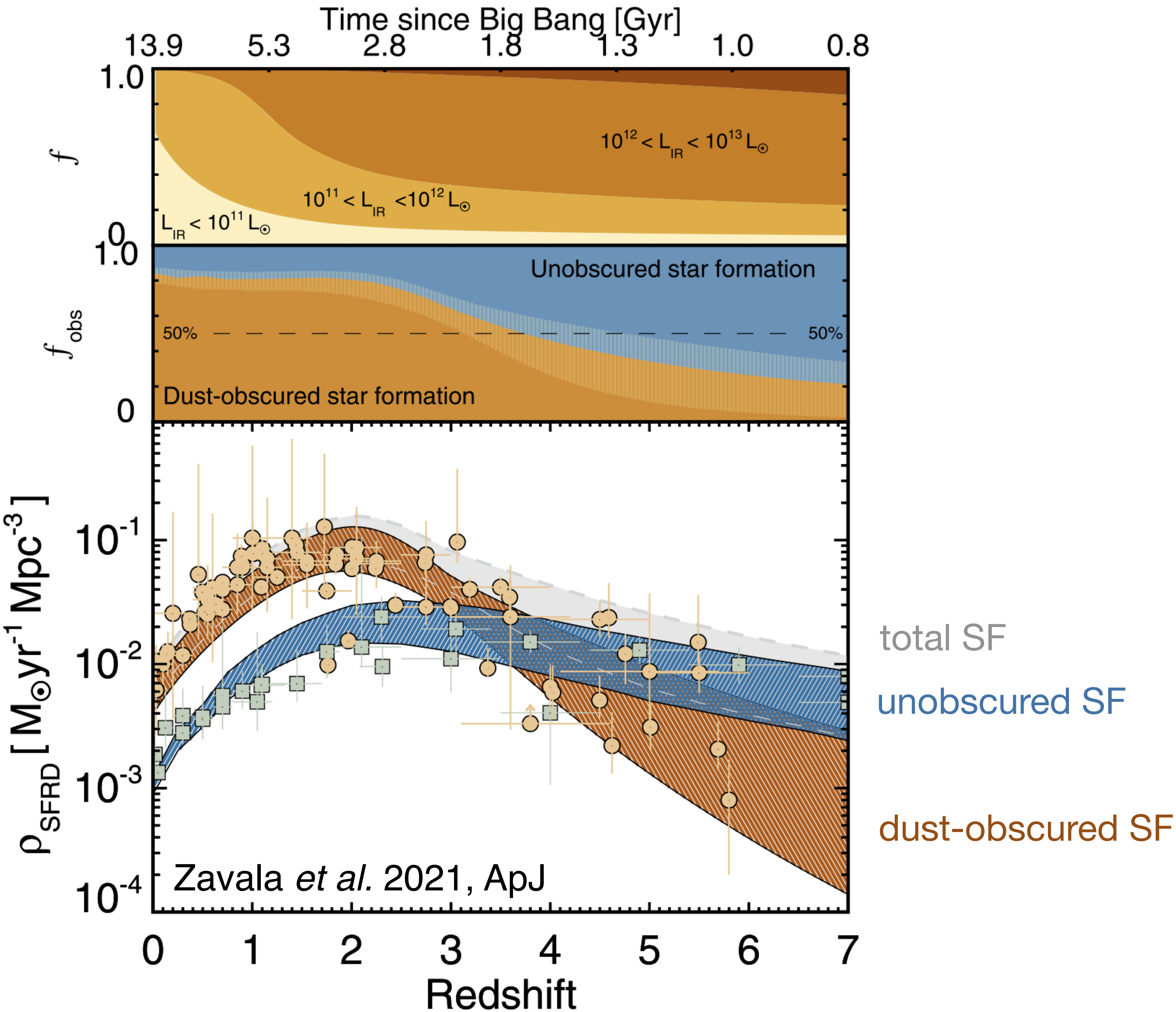
Joaquin Vieira ILLINOIS

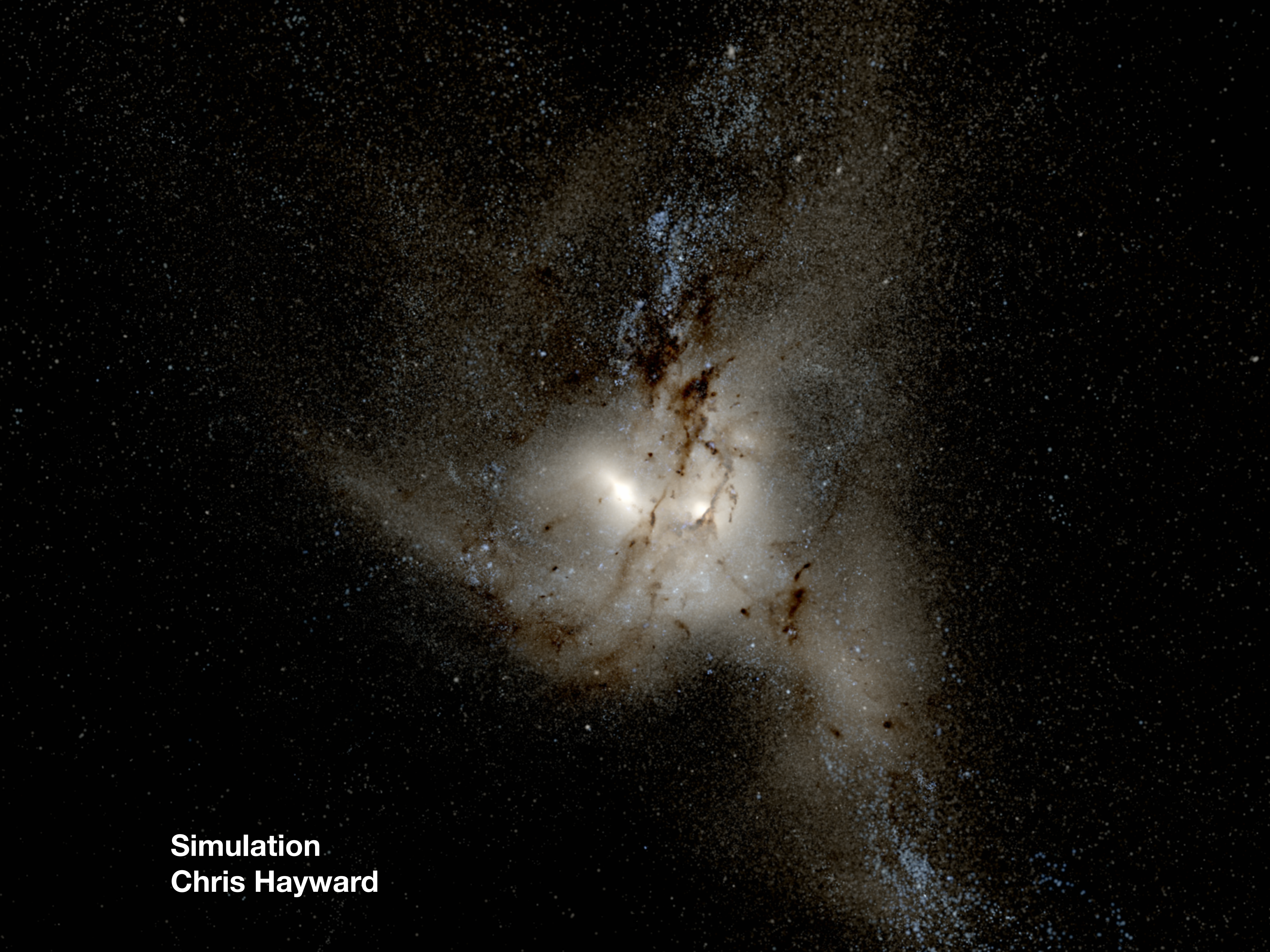
mm Universe / KICP

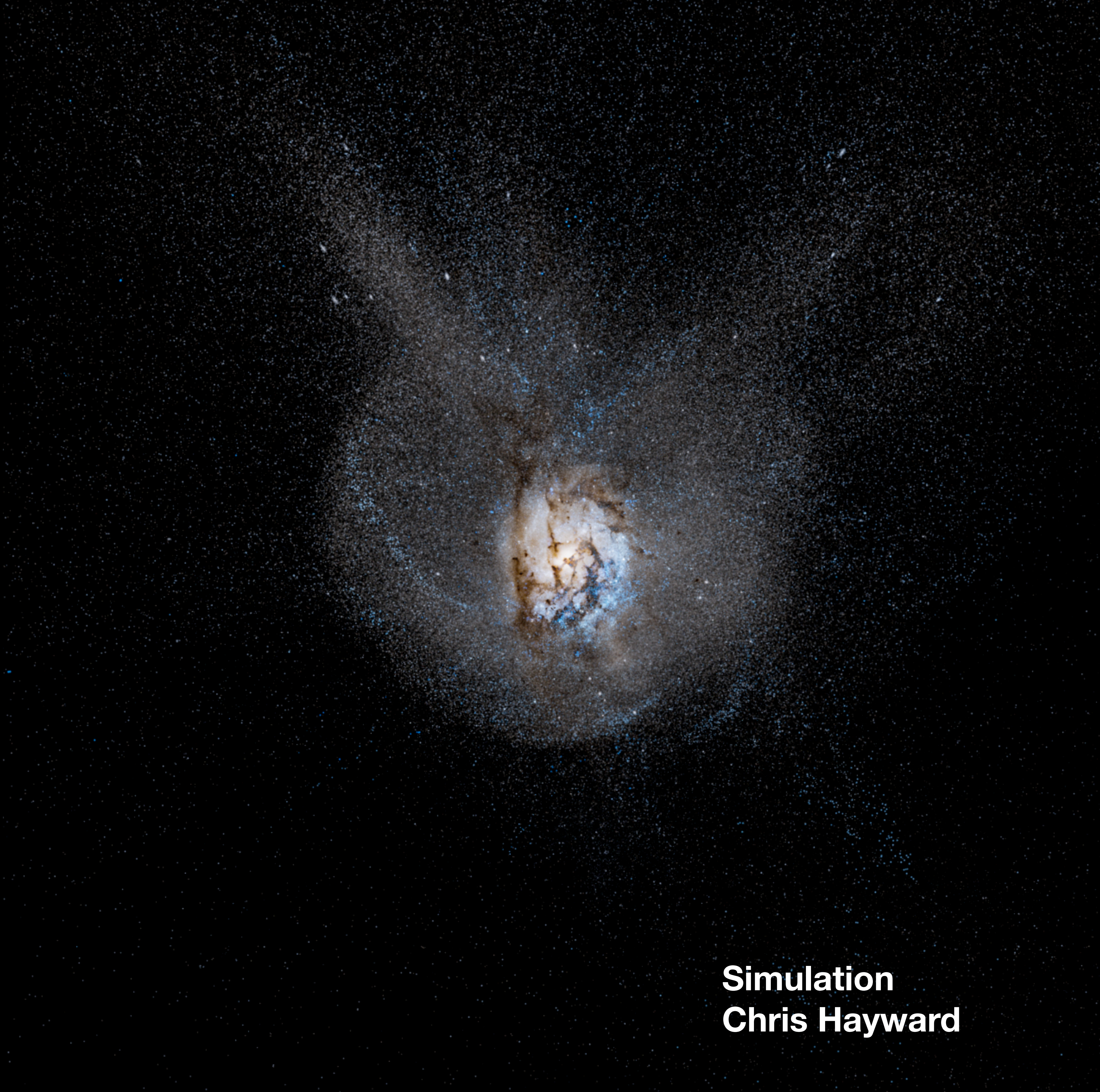
25 June 2025

The History of Cosmic Star Formation




Simulation
Chris Hayward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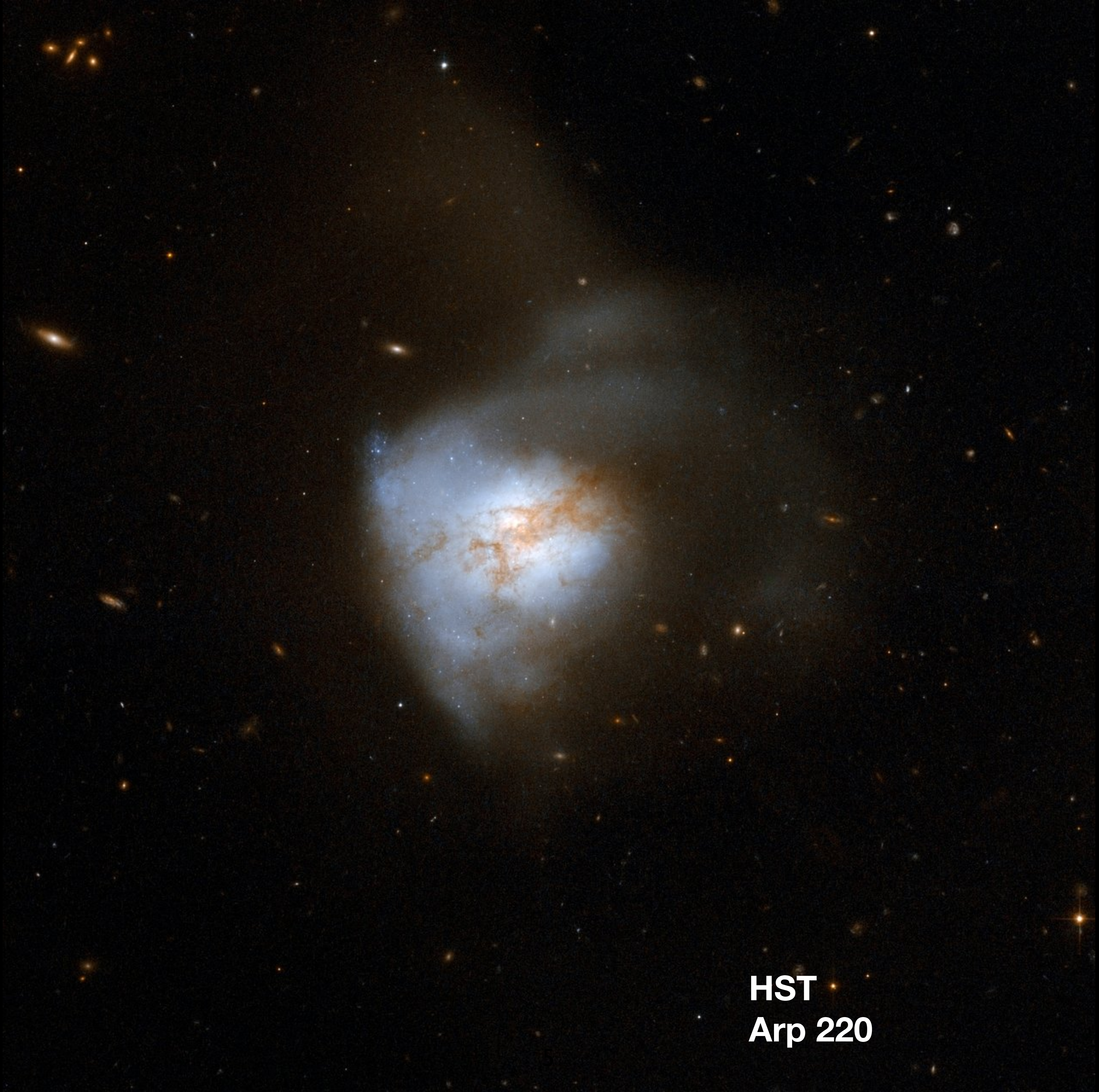
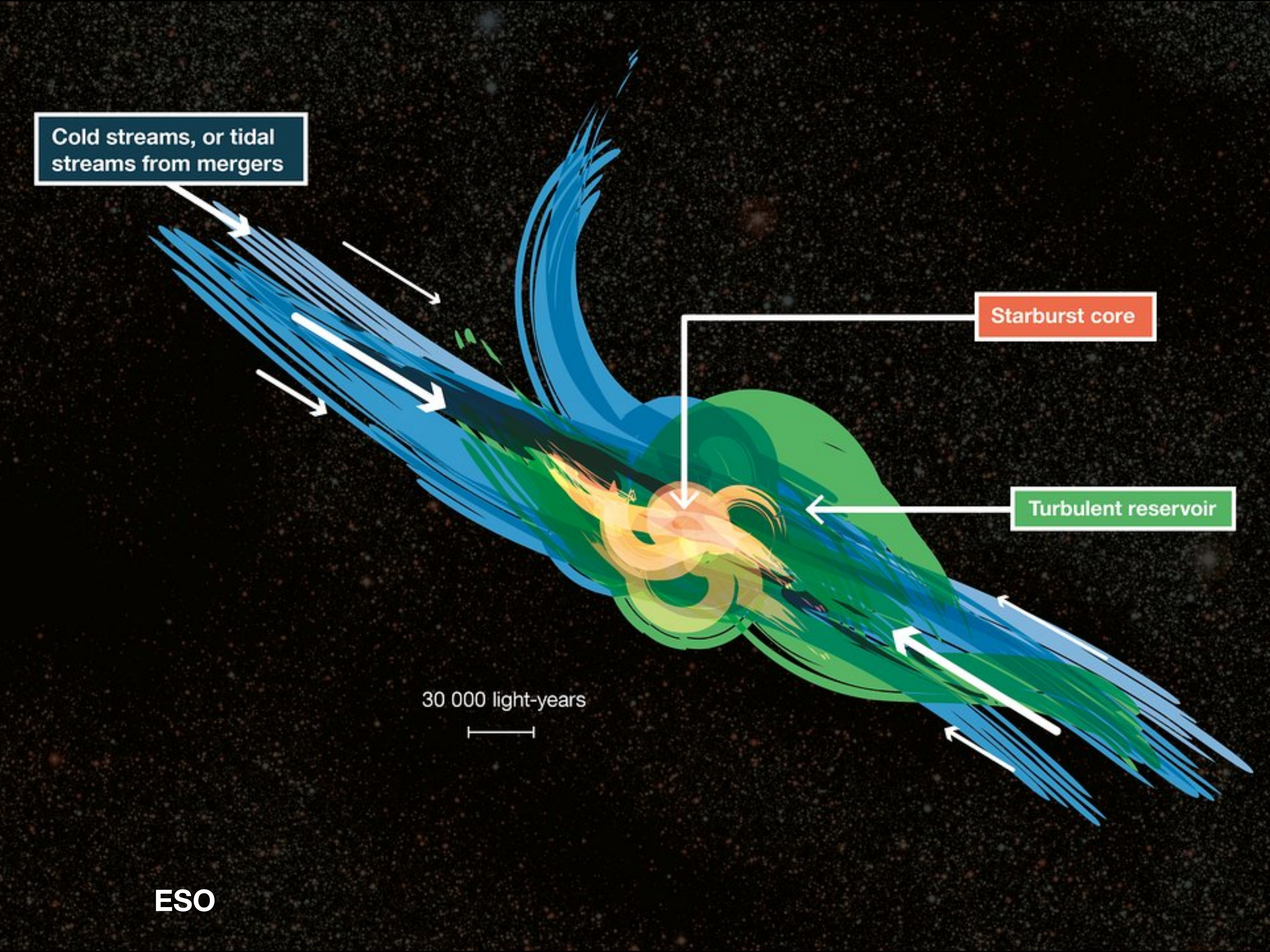
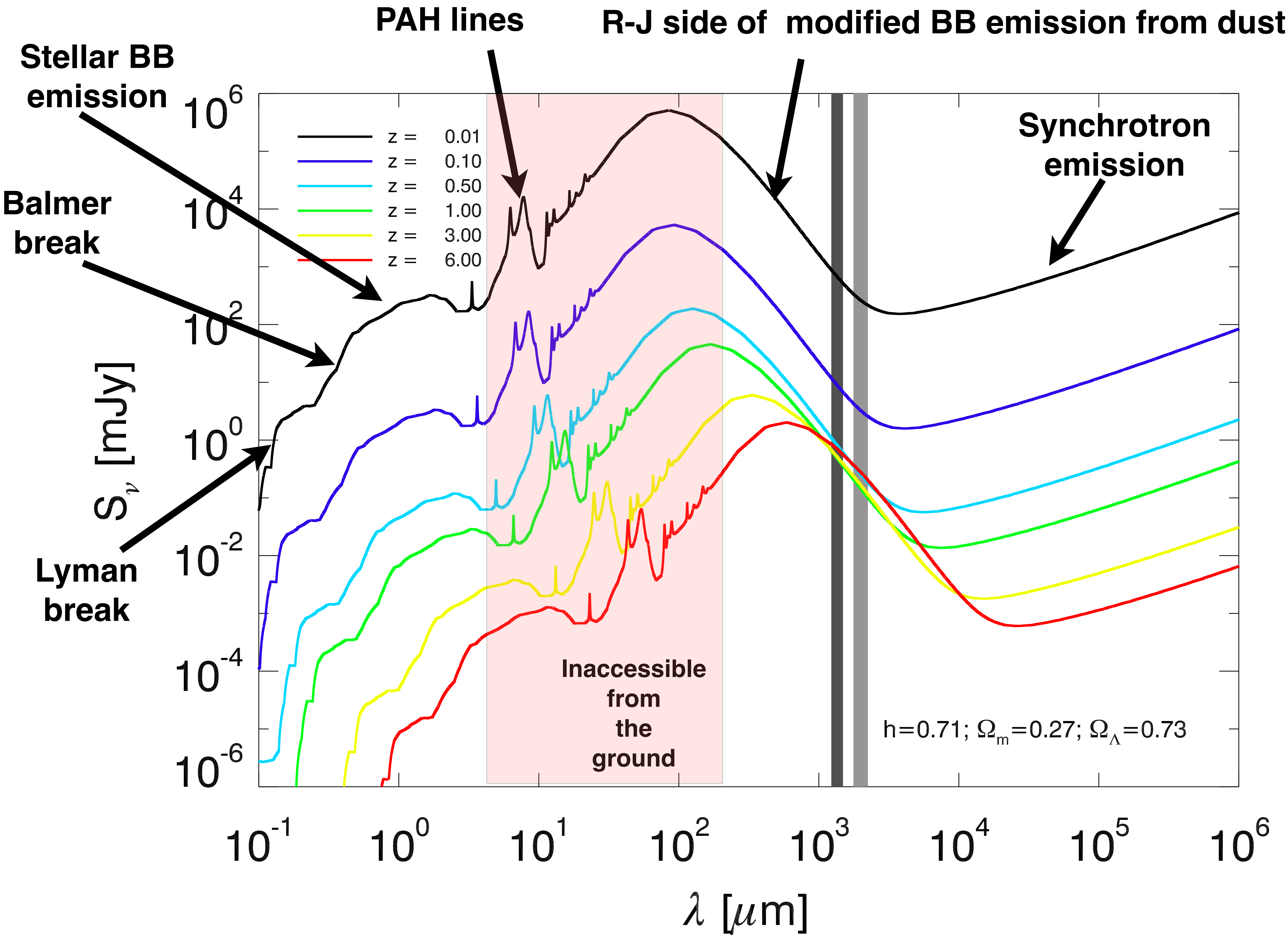
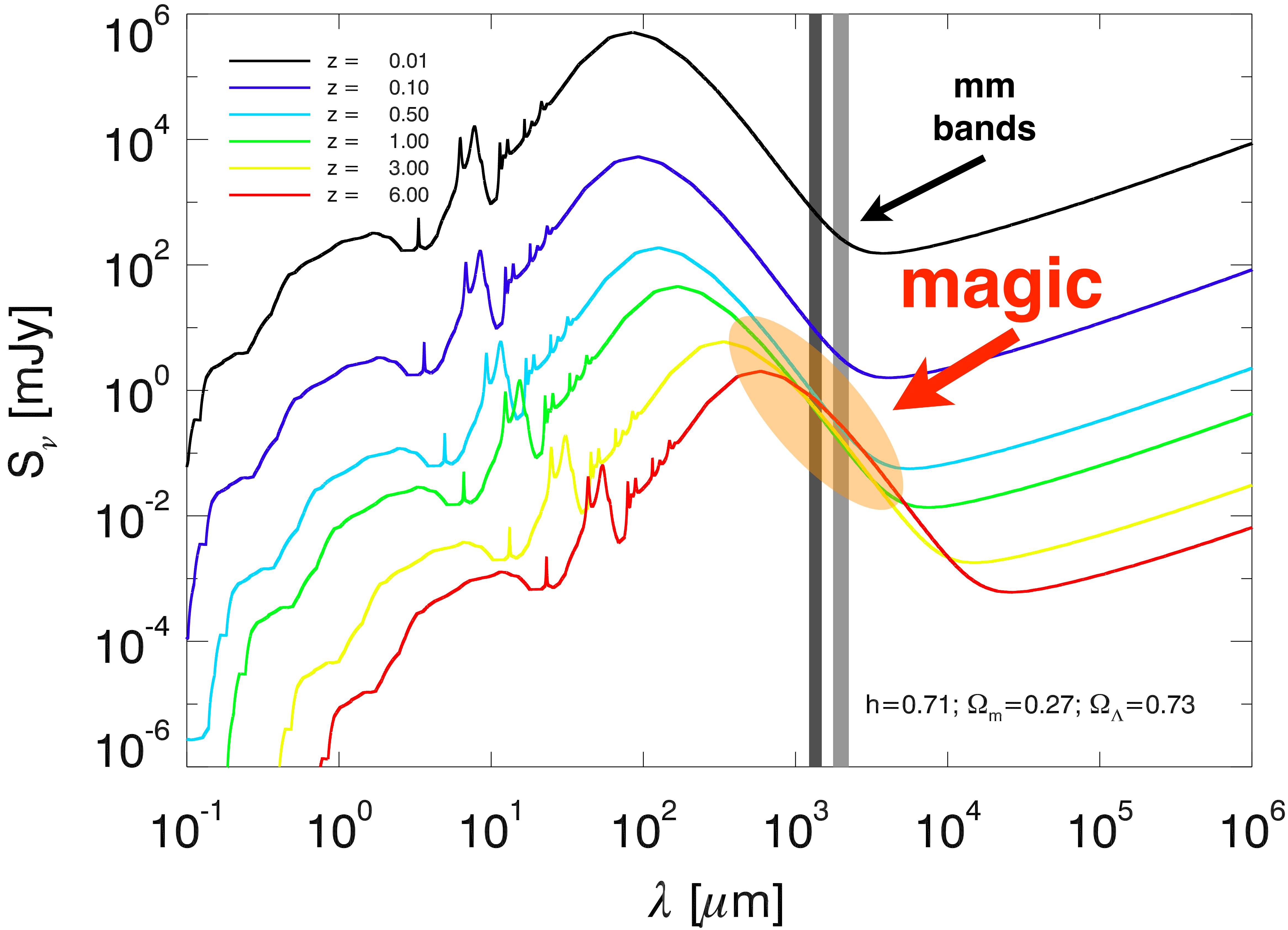
Chris Hayward


HST
Arp 220



Cold streams, or tidal streams from mergers
Starburst core
Turbulent reservoir
30 000 light-years
ESO

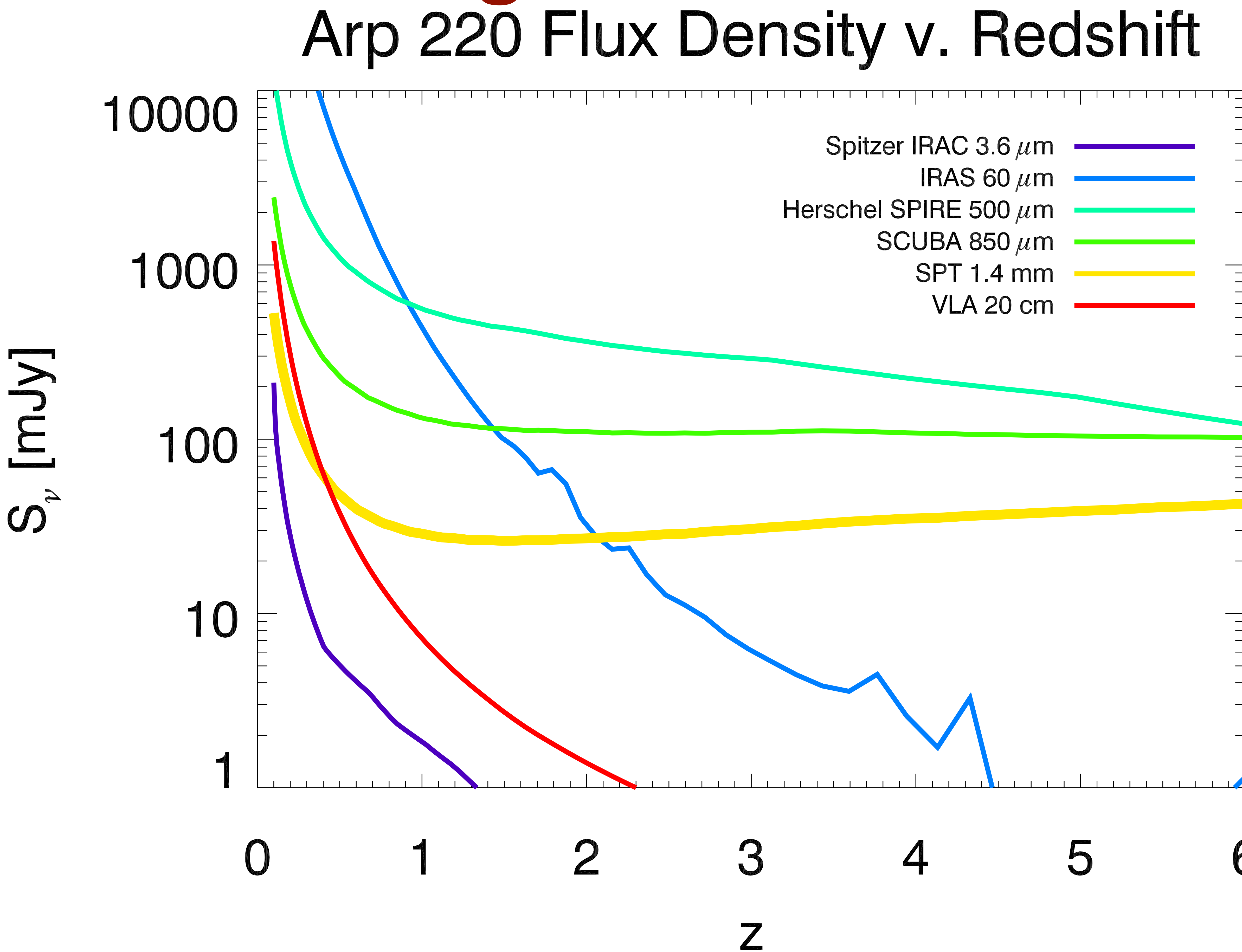

PAH lines
R-J side of modified BB emission from dust
Stellar BB emission
Synchrotron emission
Balmer break
Lyman break
z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
Inaccessible from the ground
h=0.71; Ω_m=0.27; Ω_Λ=0.73
S_ν [mJy]
λ [μm]



z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
mm
bands
magic
h=0.71; Ω_m=0.27; Ω_Λ=0.73
S_ν [mJy]
λ [μm]

Sub-mm magic

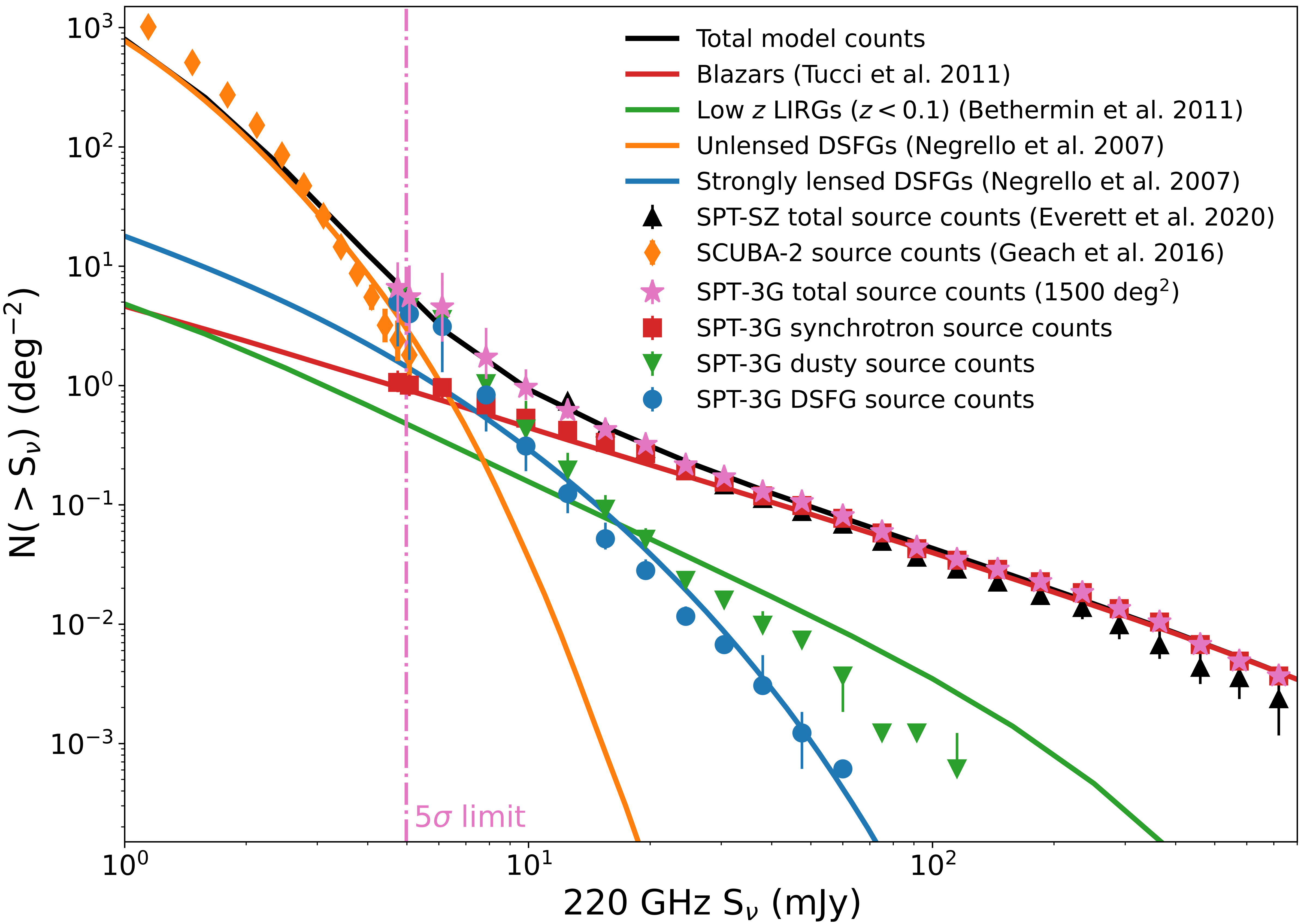
See Franceschini *et al.* 1991 and Blain & Longair 1993



mm-wave source counts

SPT-SZ Everett *et al.* 2020

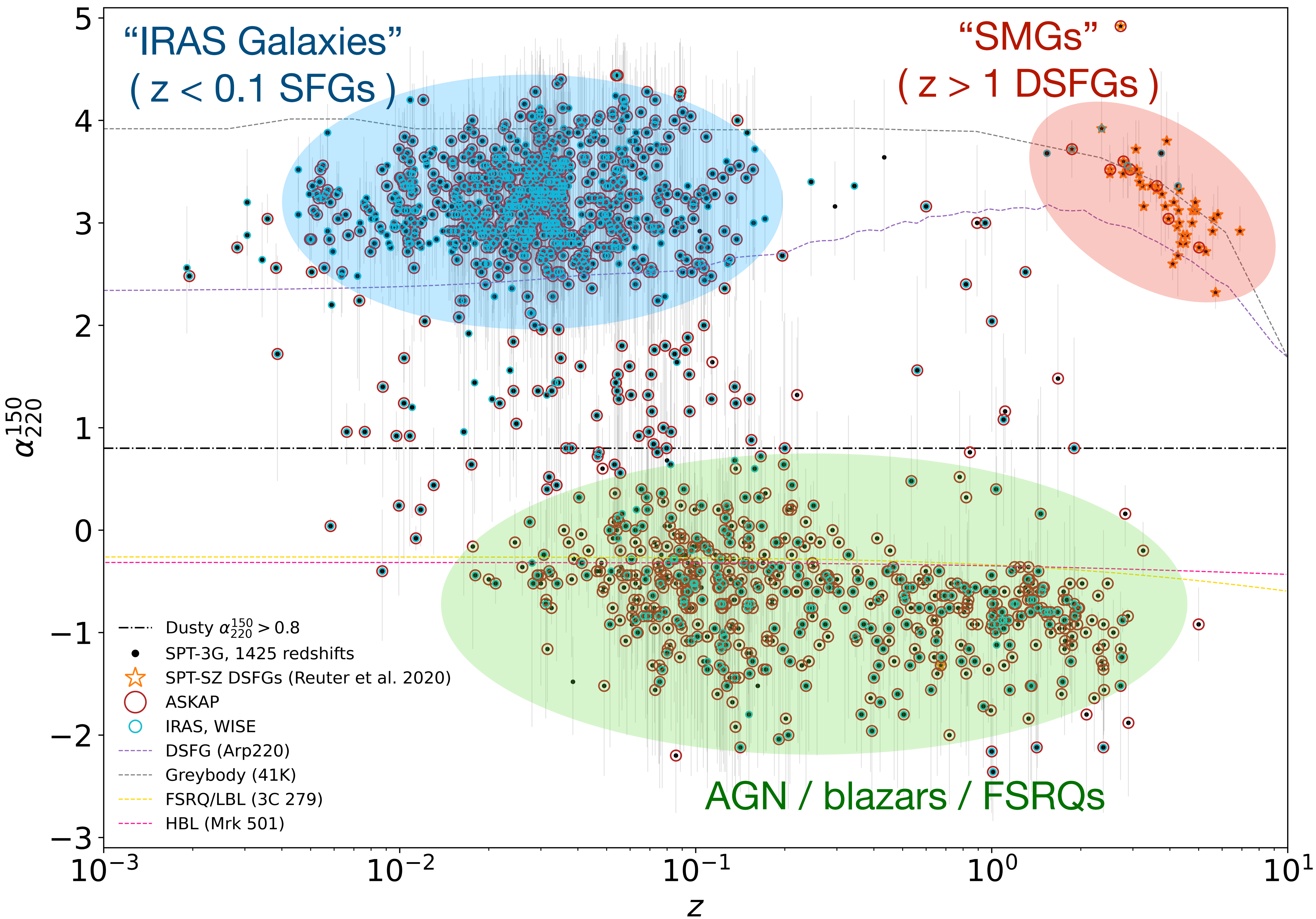
SPT-3G Archipley *et al. in prep*

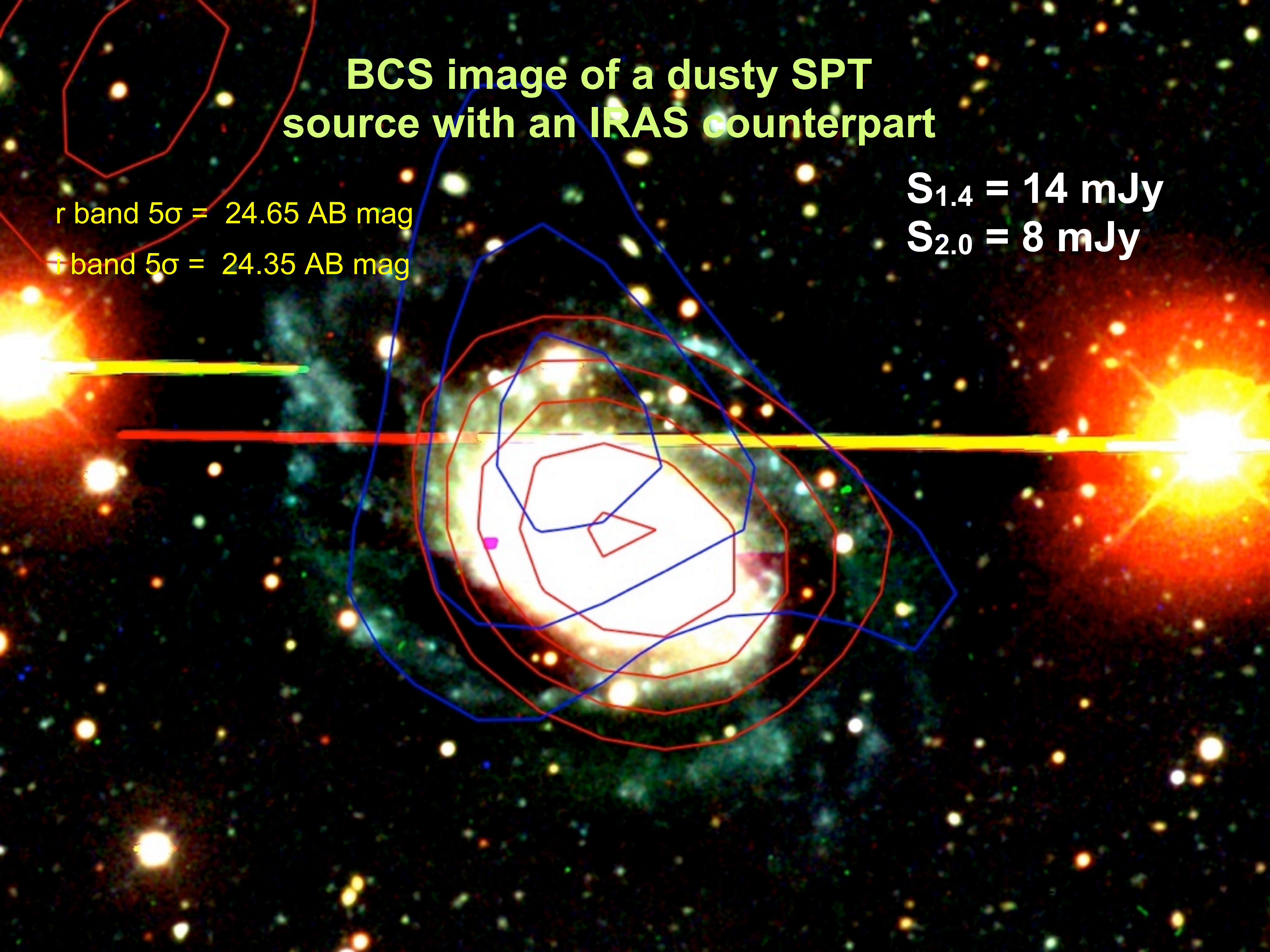


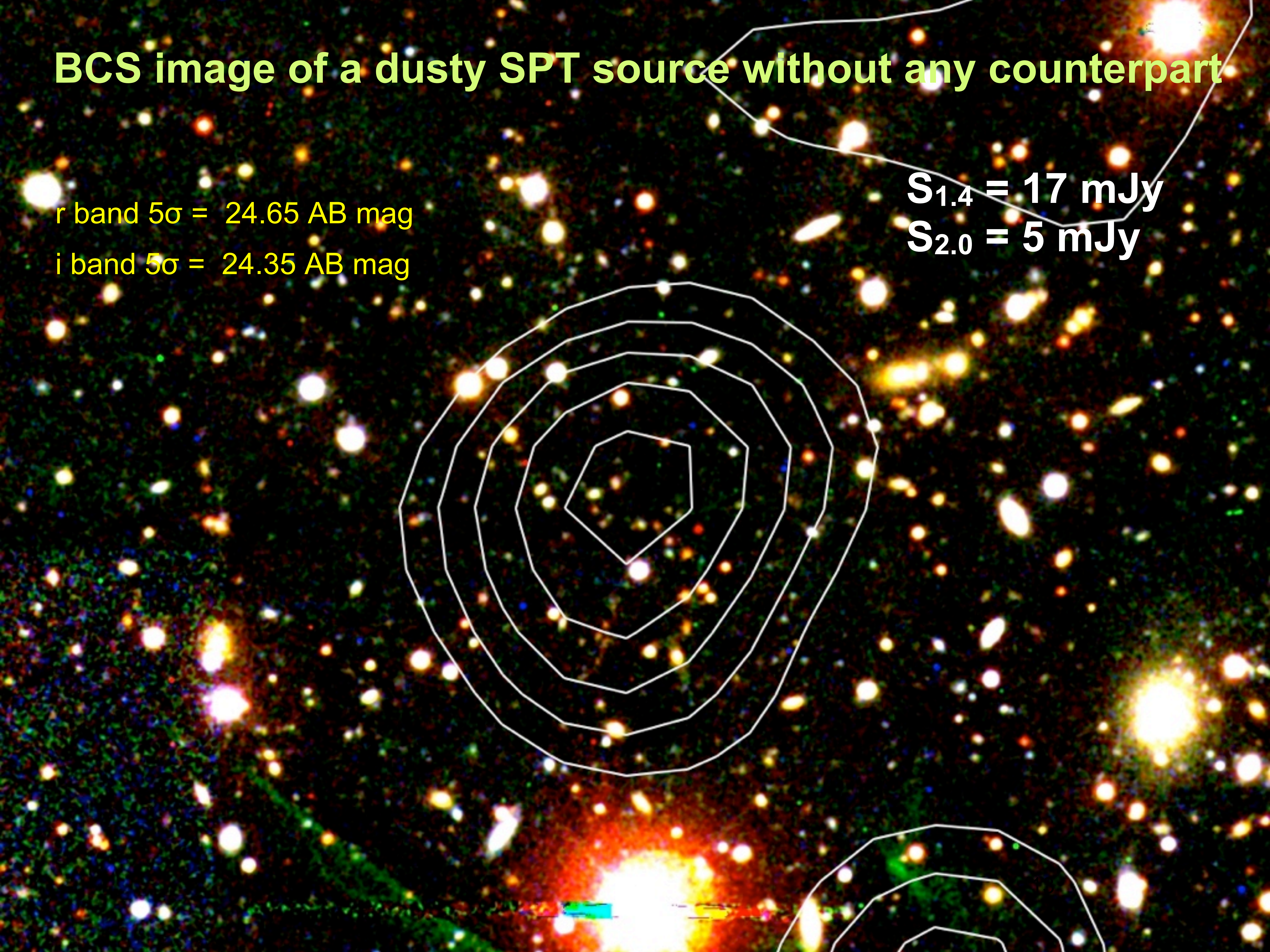
mm color (α) v. redshift

$$\frac{S_1}{S_2} = \left(\frac{\nu_1}{\nu_2}\right)^{\alpha} \qquad \frac{S_{150\mathrm{GHz}}}{S_{220\mathrm{GHz}}} = \left(\frac{150}{220}\right)^{\alpha}$$

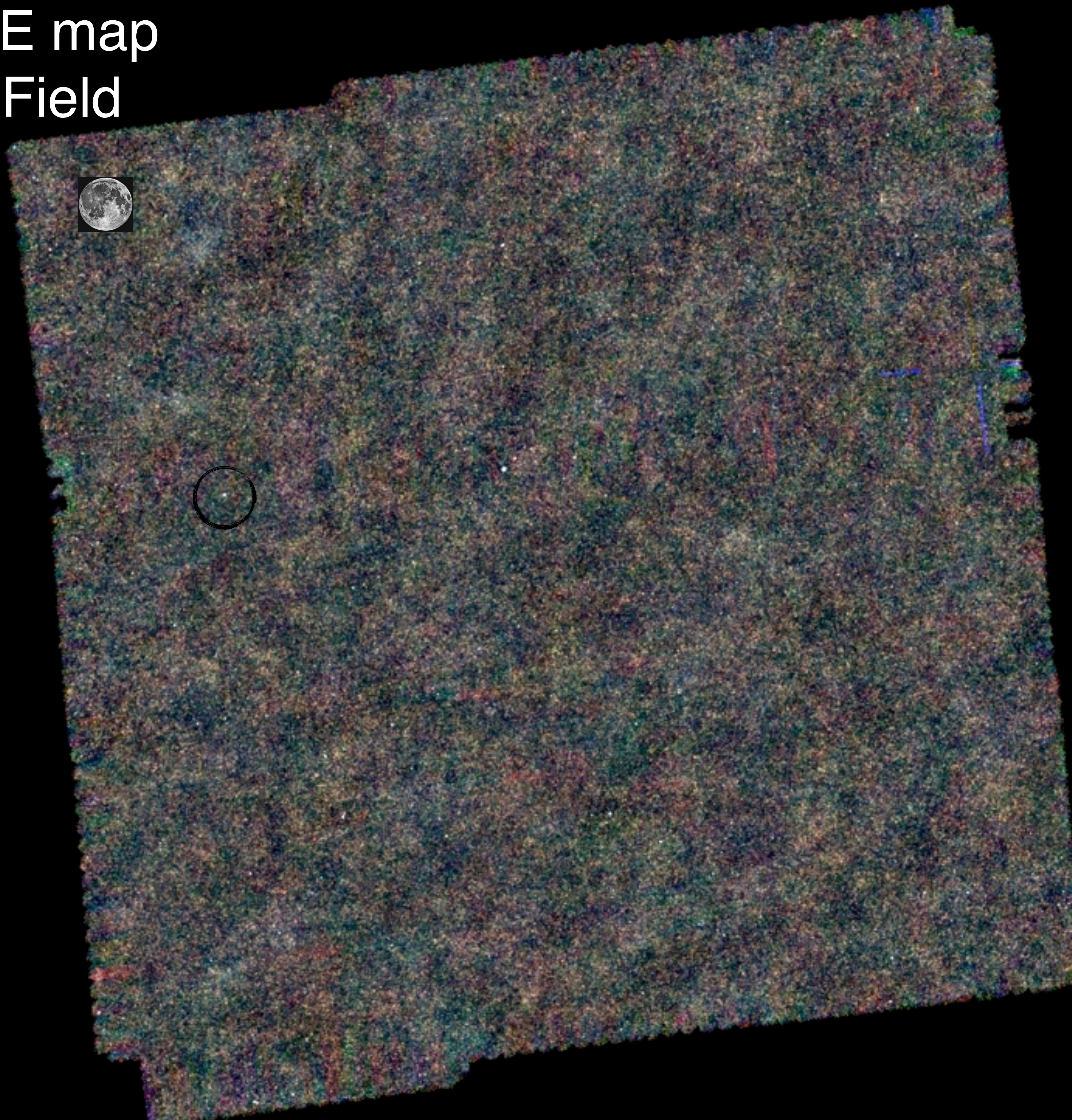
Everett *et al.* 2020 ApJ
Archipley *et al. in prep*




BCS image of a dusty SPT
source with an IRAS counterpart
r band 5σ = 24.65 AB mag
i band 5σ = 24.35 AB mag
$S_{1.4}$ = 14 mJy
$S_{2.0}$ = 8 mJy

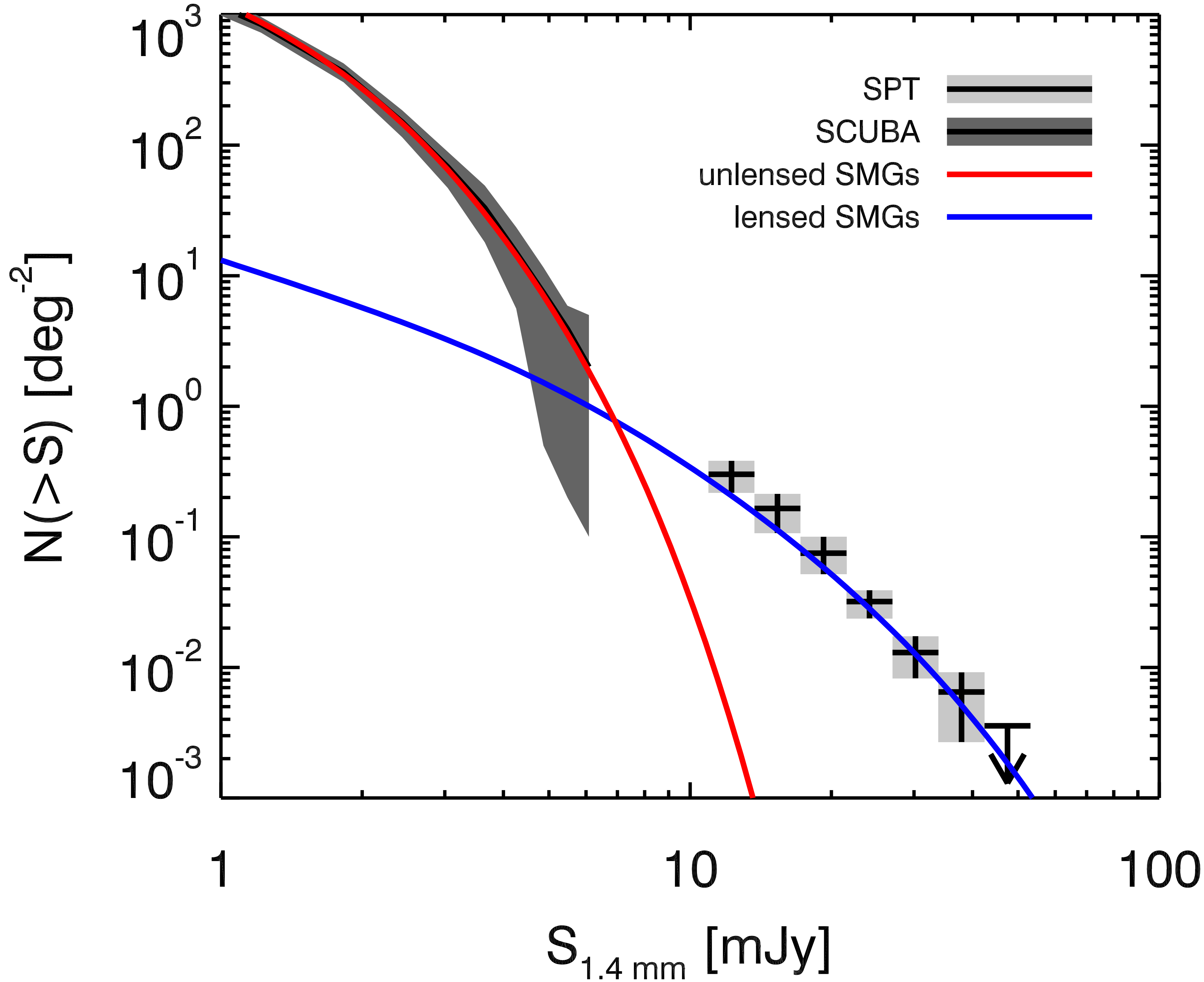

BCS image of a dusty SPT source without any counterpart
r band 5σ = 24.65 AB mag
i band 5σ = 24.35 AB mag
$S_{1.4}$ = 17 mJy
$S_{2.0}$ = 5 mJy

100 deg² SPIRE map of SPT Deep Field



Number counts of sub/mm galaxies

see e.g. :
Vieira *et al.* 2010
Everett *et al*. 2020



Number counts of sub/mm galaxies

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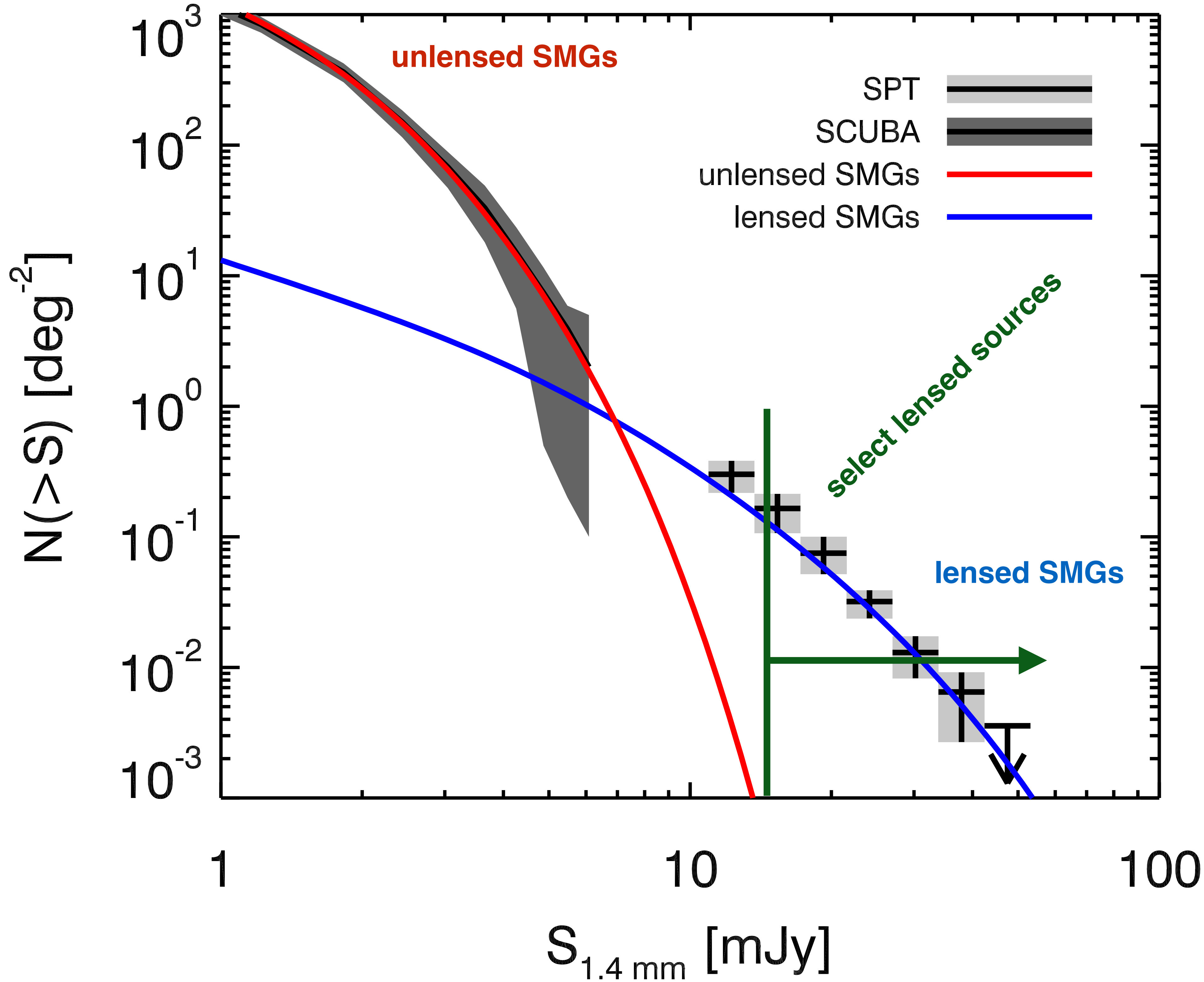
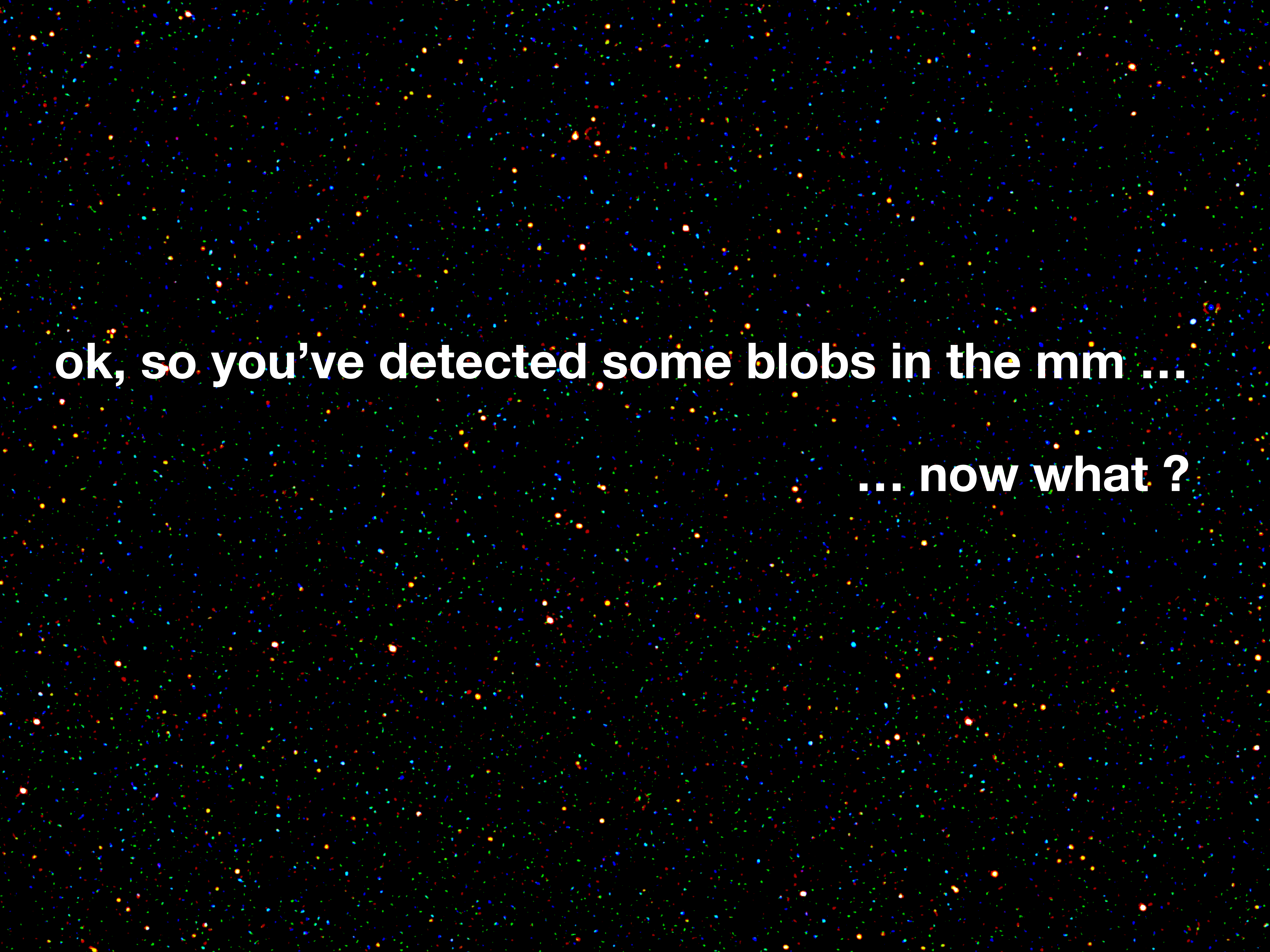
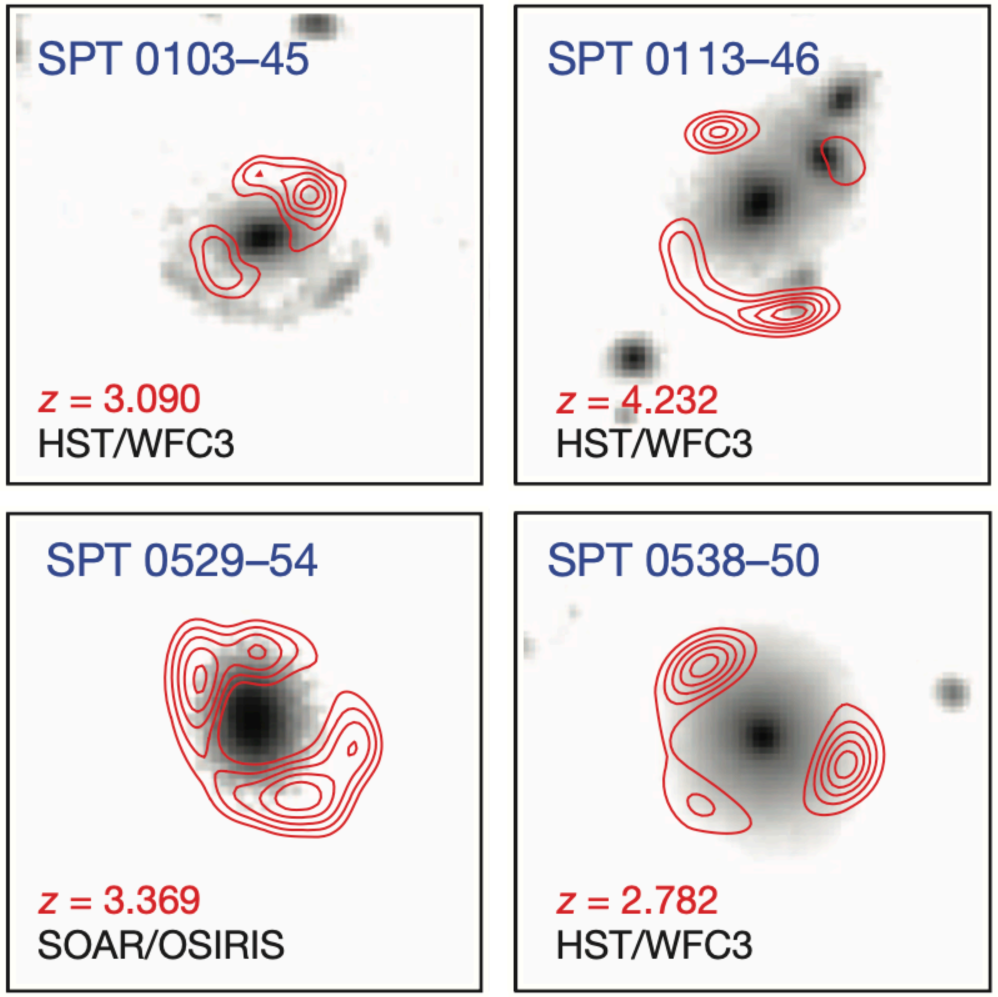



ok, so you’ve detected some blobs in the mm …
… now what ?

You need two things:

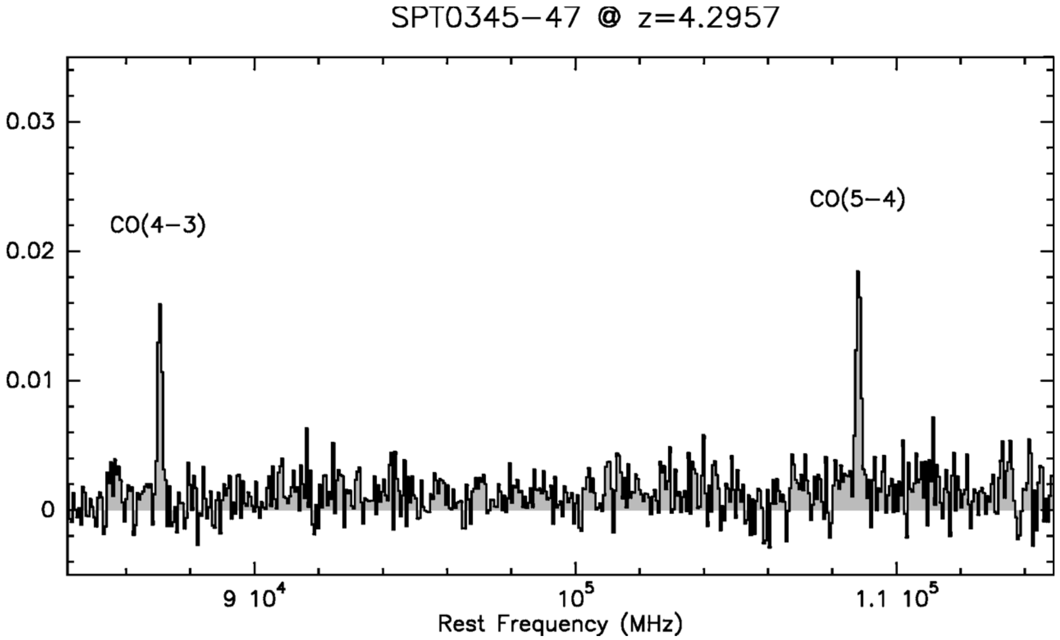
#1: High resolution (<arcsec) imaging

- need an accurate position to associate multiwavelength data.
- need to separate un-lensed, from lensed, and protoclusters.
- Facilities: e.g. ALMA, NOEMA, JWST

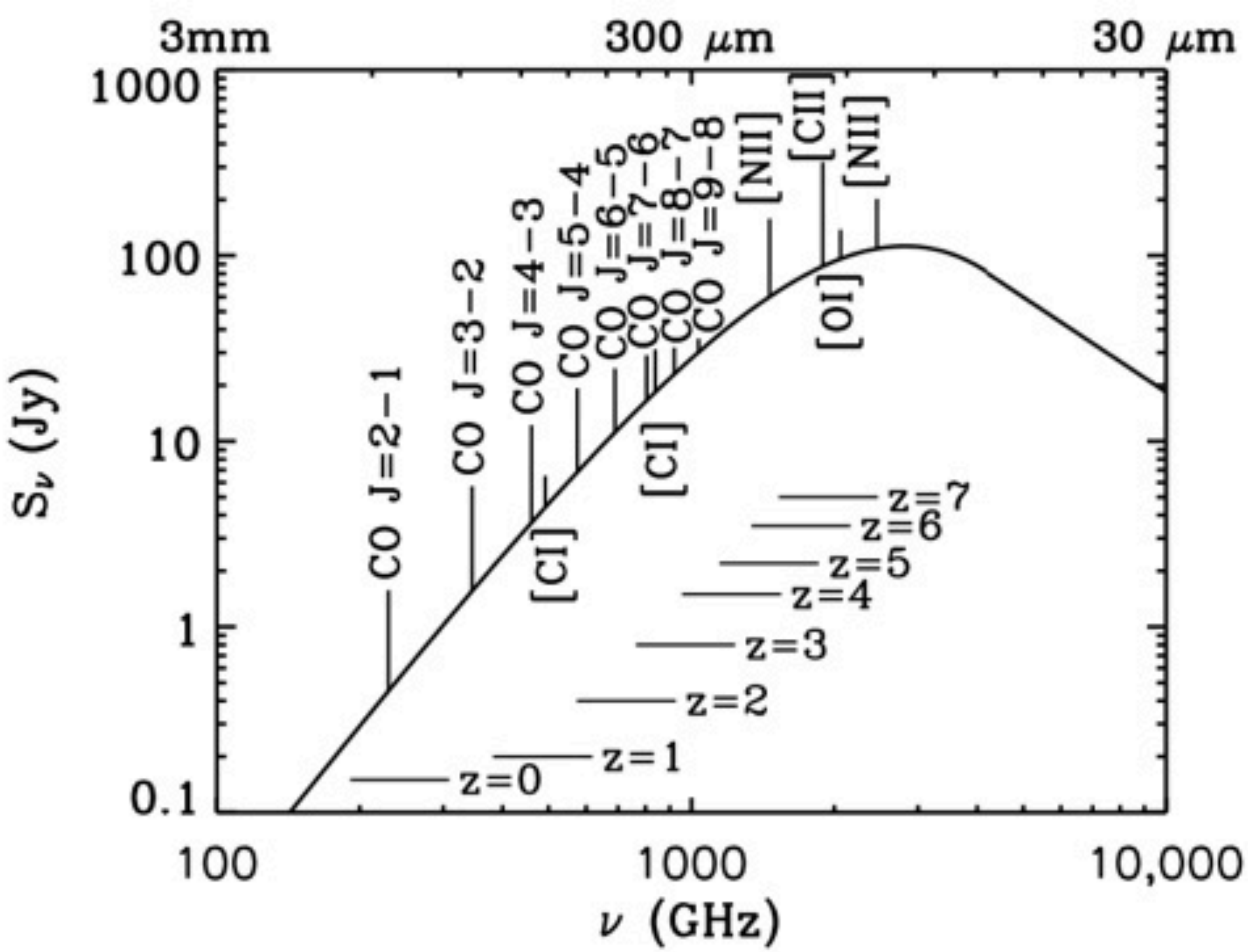


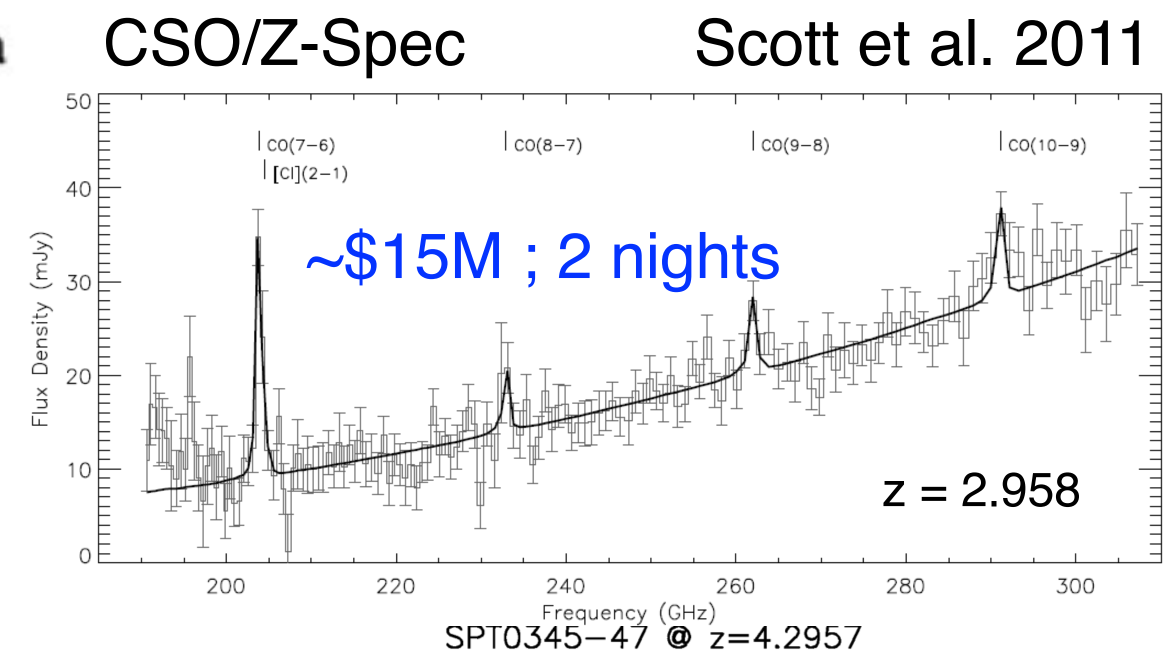
#2: Spectroscopy

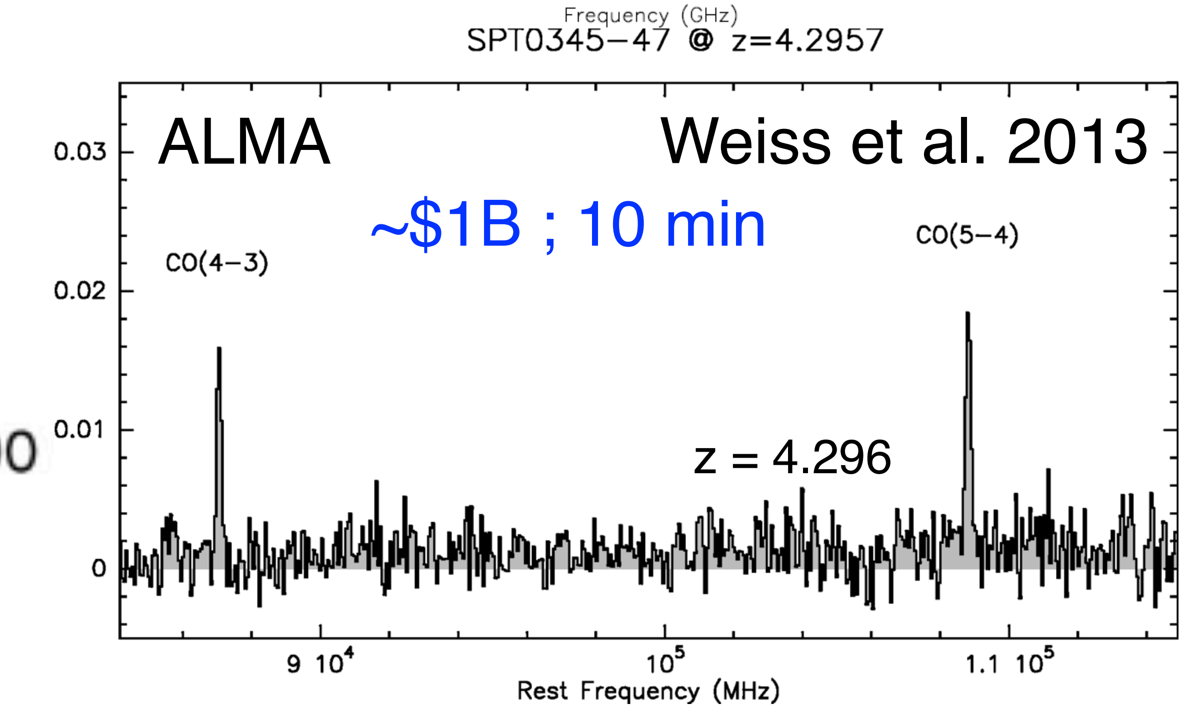
- You can't do anything without a redshift !
- Opens up: astrophysics, ISM diagnostics, dynamics, etc
- Facilities: e.g. ALMA, NOEMA, JWST



Spectroscopic Redshifts with Carbon Monoxide (CO)





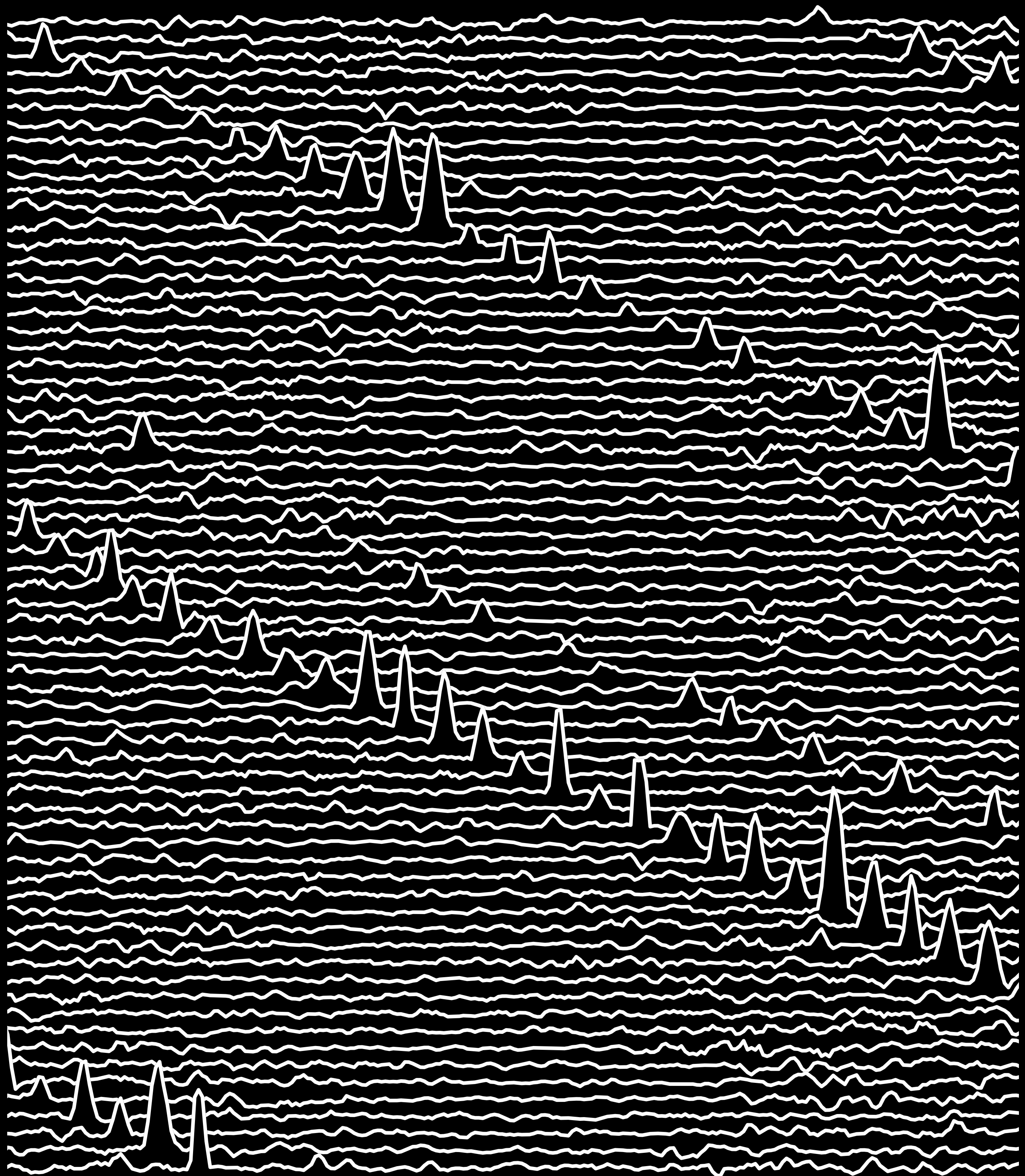


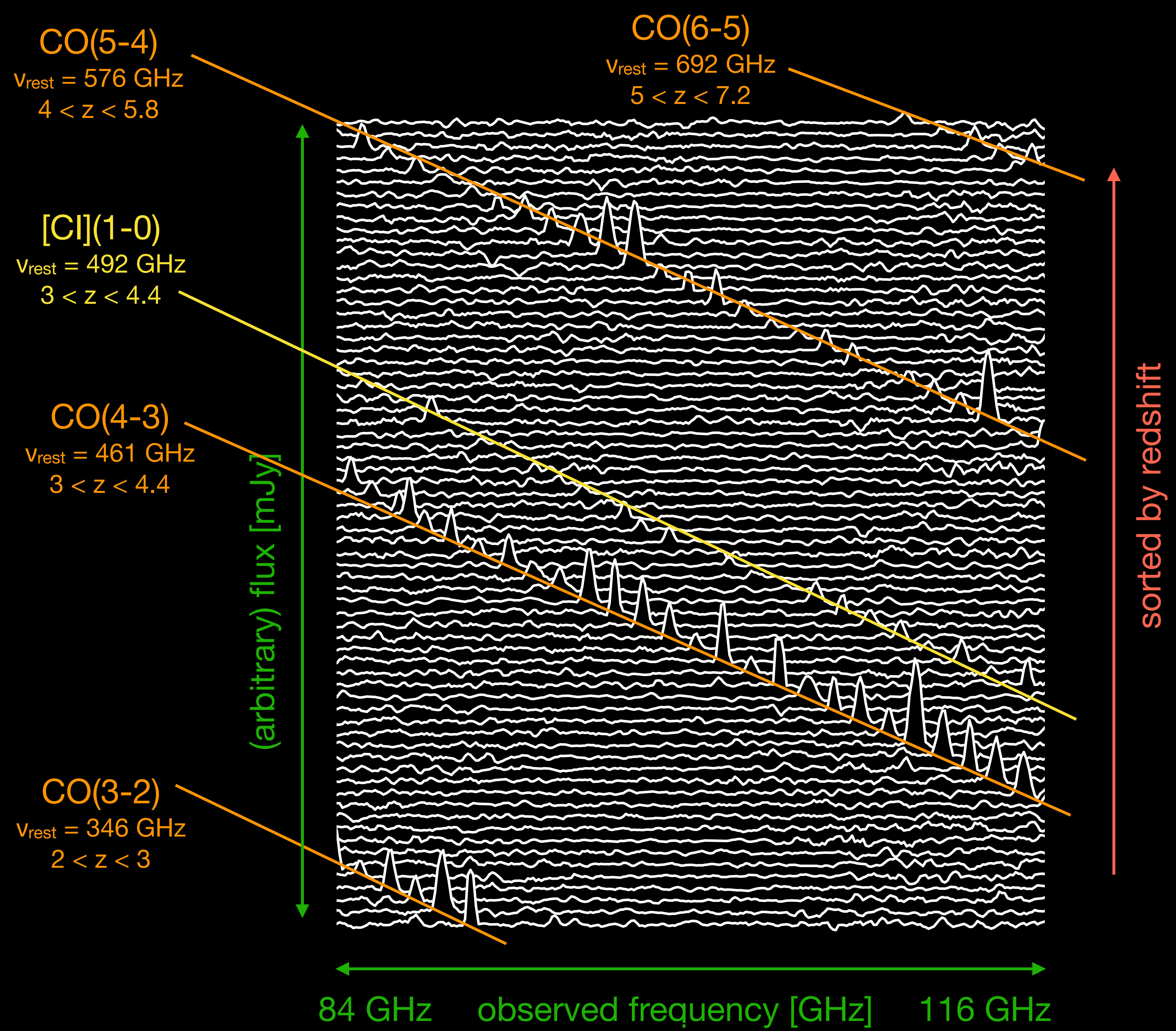
- CO is bright ! —> 2nd most abundant molecule in the universe
- CO ladder has 115 GHz spacing —> 2 lines gives a redshift
- L_{CO} traces molecular mass, line width gives dynamical mass, SLED constrains conditions of ISM

ALMA: The Atacama Large (sub) Millimeter Array

See:
Vieira *et al.* 2013, *Nature*

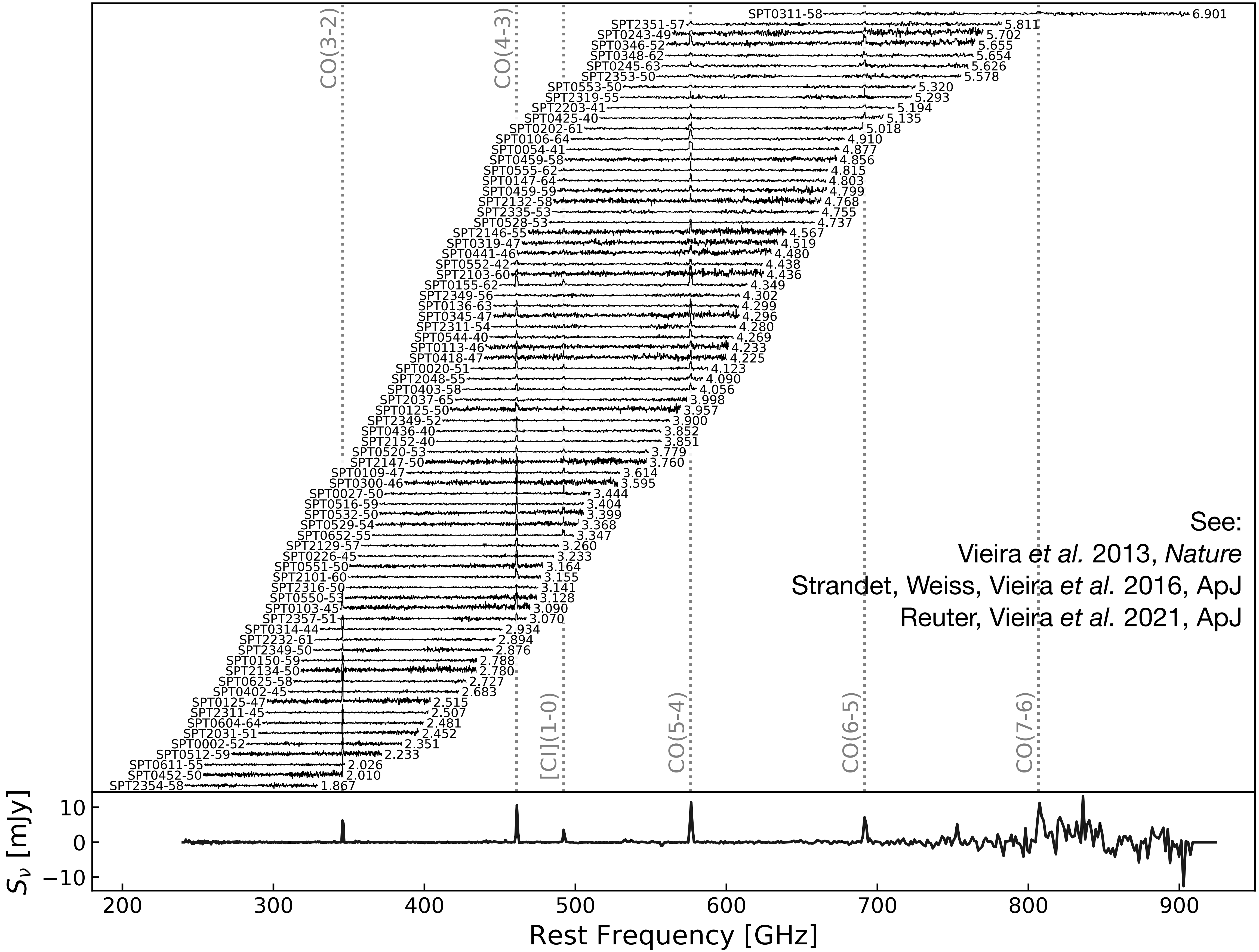
THE SPT+ALMA BLIND SPECTROSCOPIC
REDSHIFT SURVEY OF CARBON MONOXIDE





CO(5-4)
νrest = 576 GHz
4 < z < 5.8
CO(6-5)
νrest = 692 GHz
5 < z < 7.2
[CI](1-0)
νrest = 492 GHz
3 < z < 4.4
CO(4-3)
νrest = 461 GHz
3 < z < 4.4
CO(3-2)
νrest = 346 GHz
2 < z < 3
(arbitrary) flux [mJy]
sorted by redshift
84 GHz
observed frequency [GHz]
116 GHz

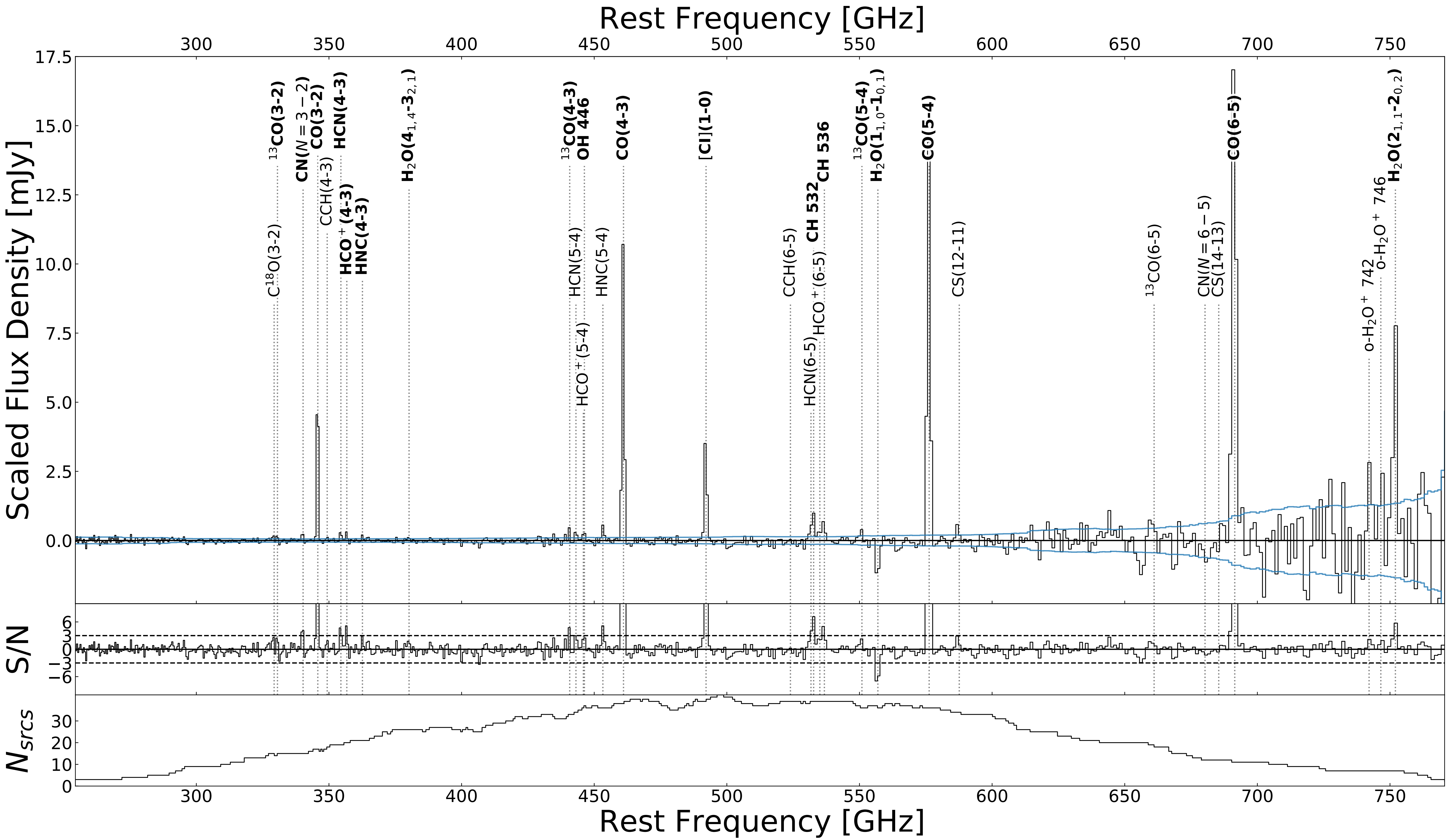
Spectroscopic redshift survey with ALMA



See:
Vieira *et al.* 2013, *Nature*
Strandet, Weiss, Vieira *et al.* 2016, ApJ
Reuter, Vieira *et al.* 2021, ApJ

Stacked mm spectrum

Reuter, Spilker, Vieira, Marrone, Weiss *et al.* 2023, ApJ



The Astrophysical Journal, 902:78 (35pp), 2020 October 10 https://doi.org/10.3847/1538-4357/abb599

CrossMark

The Complete Redshift Distribution of Dusty Star-forming Galaxies from the SPT-SZ Survey

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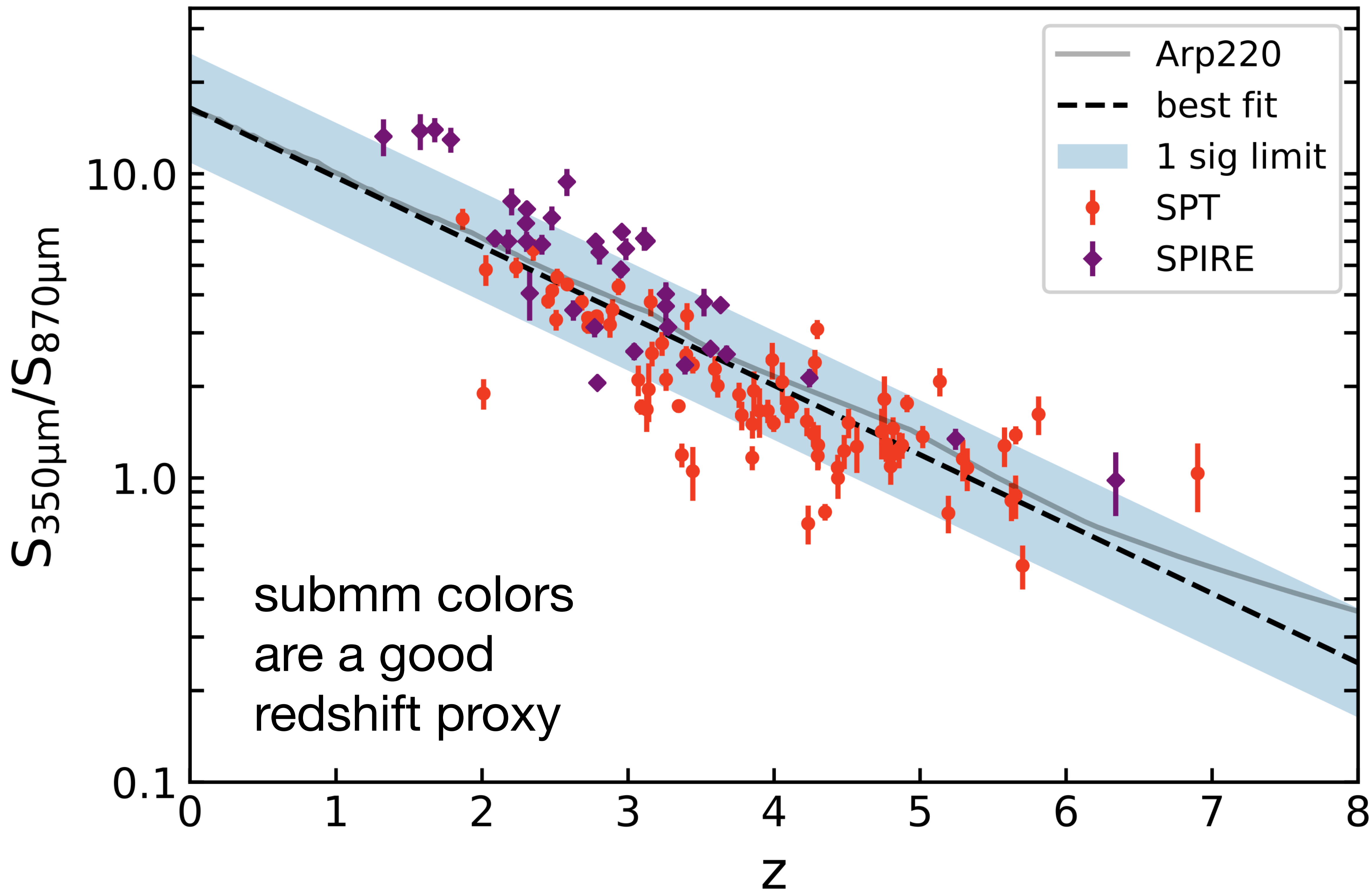

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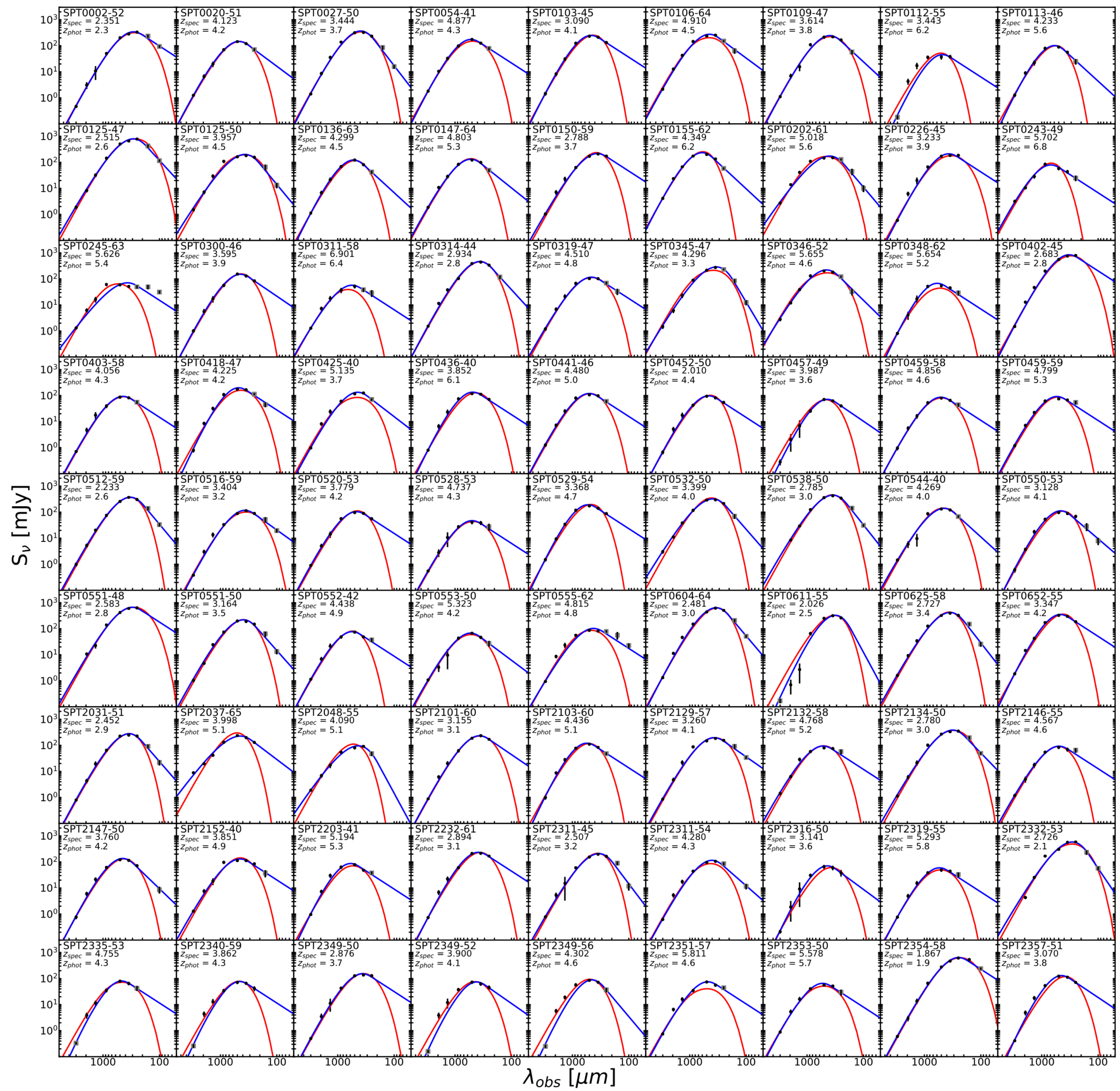
Complete FIR-mm SEDs of 81 SMGs



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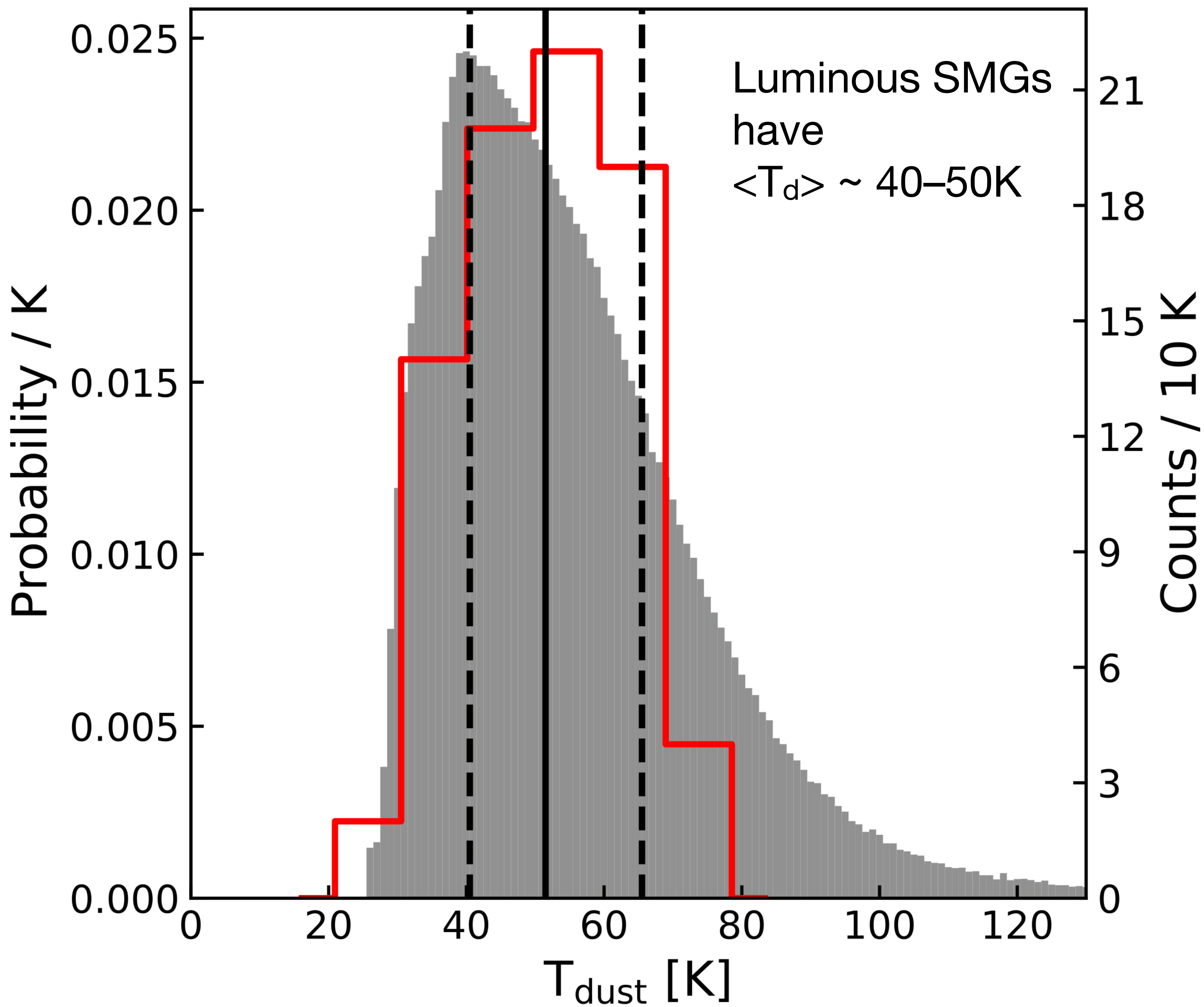

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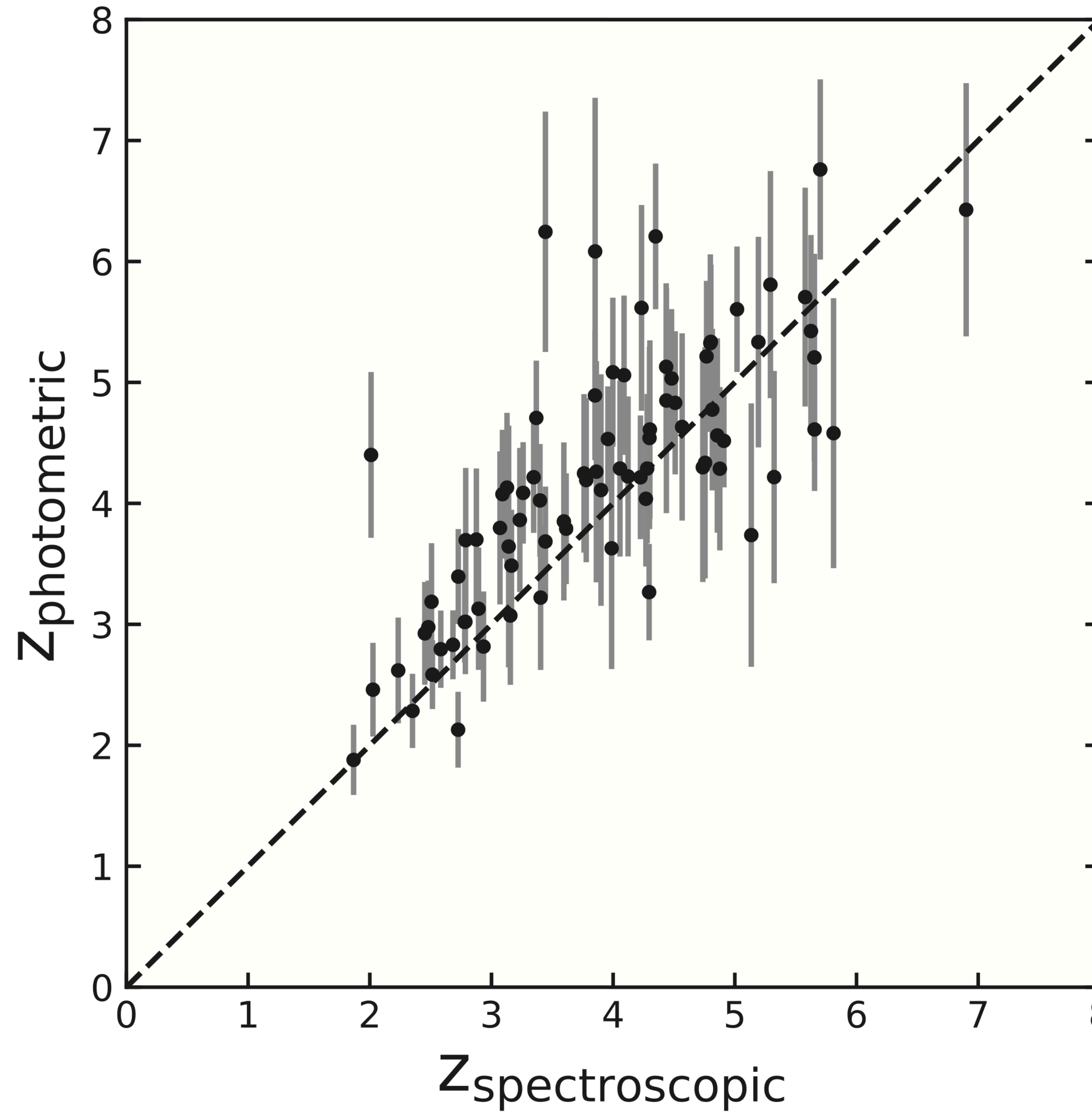
A well-sampled FIR SED can provide a photometric redshift to ~20% accuracy



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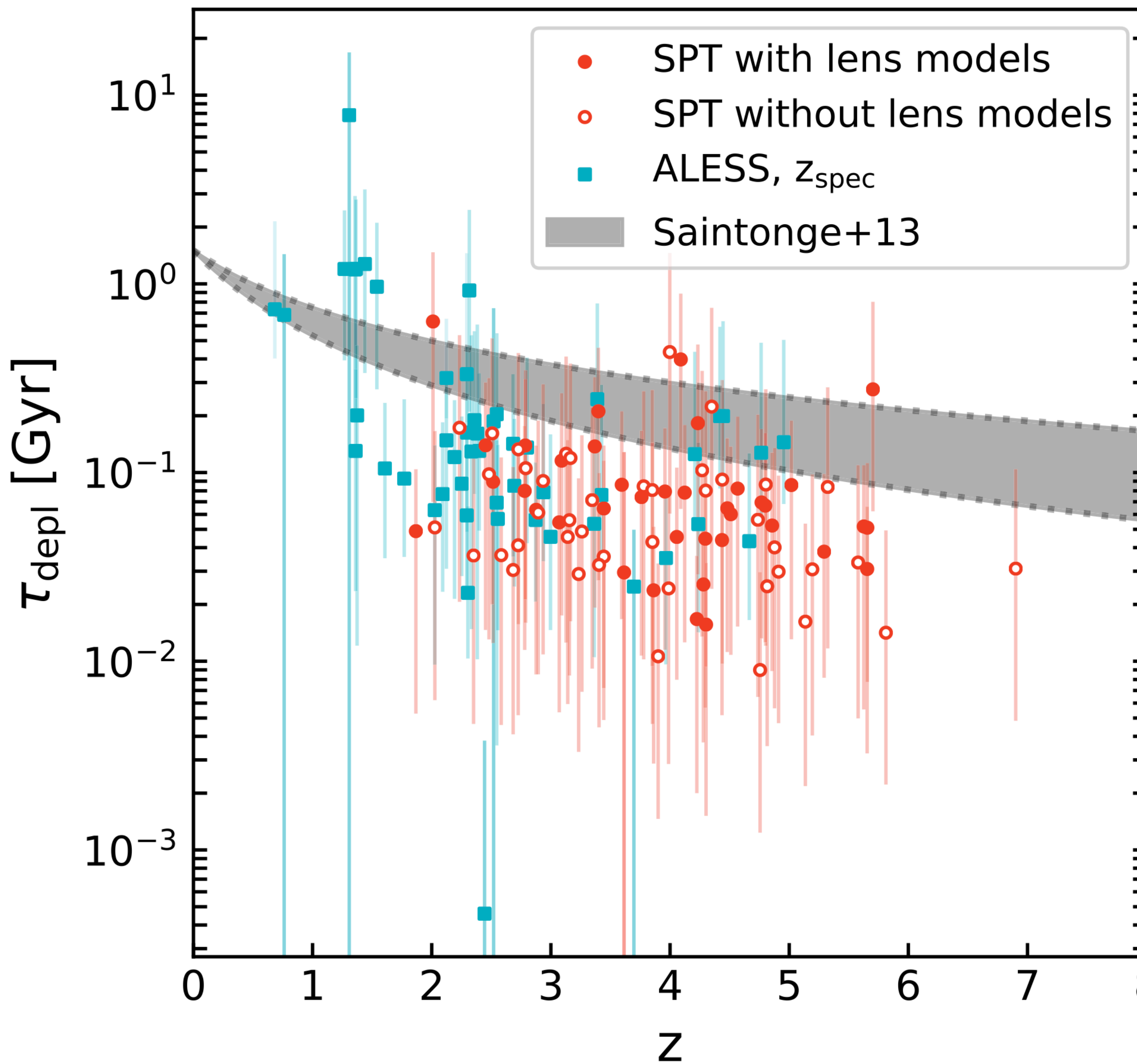
photometry and the shape of the SED can constrain the gas depletion time

$\tau_{\mathrm{depl}} = M_{\mathrm{gas}} / \mathrm{SFR}$

SMGs are burning their fuel faster than regular galaxies on the main sequence



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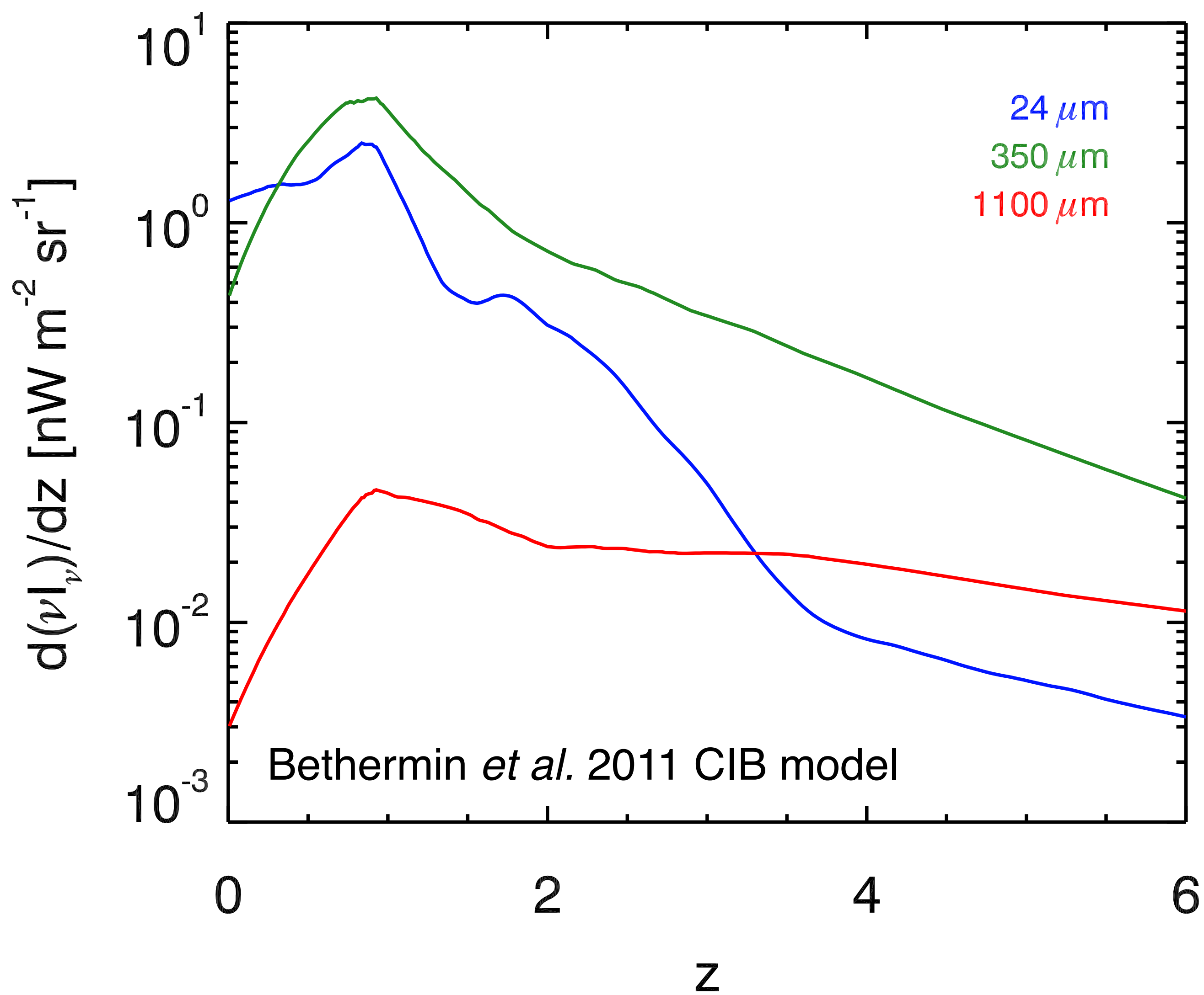
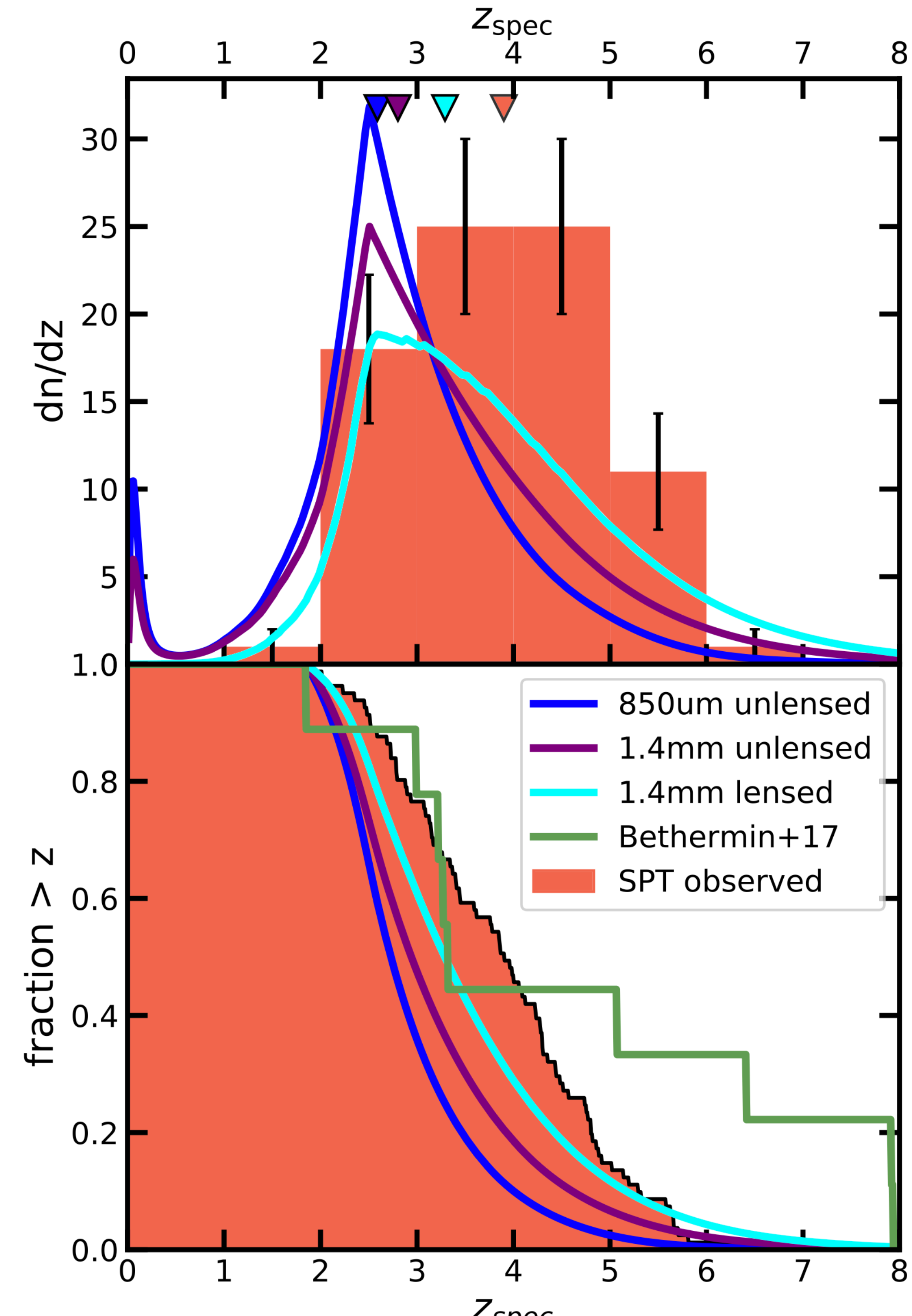
longer wavelength surveys select higher redshift sources

redshift distribution of the CIB





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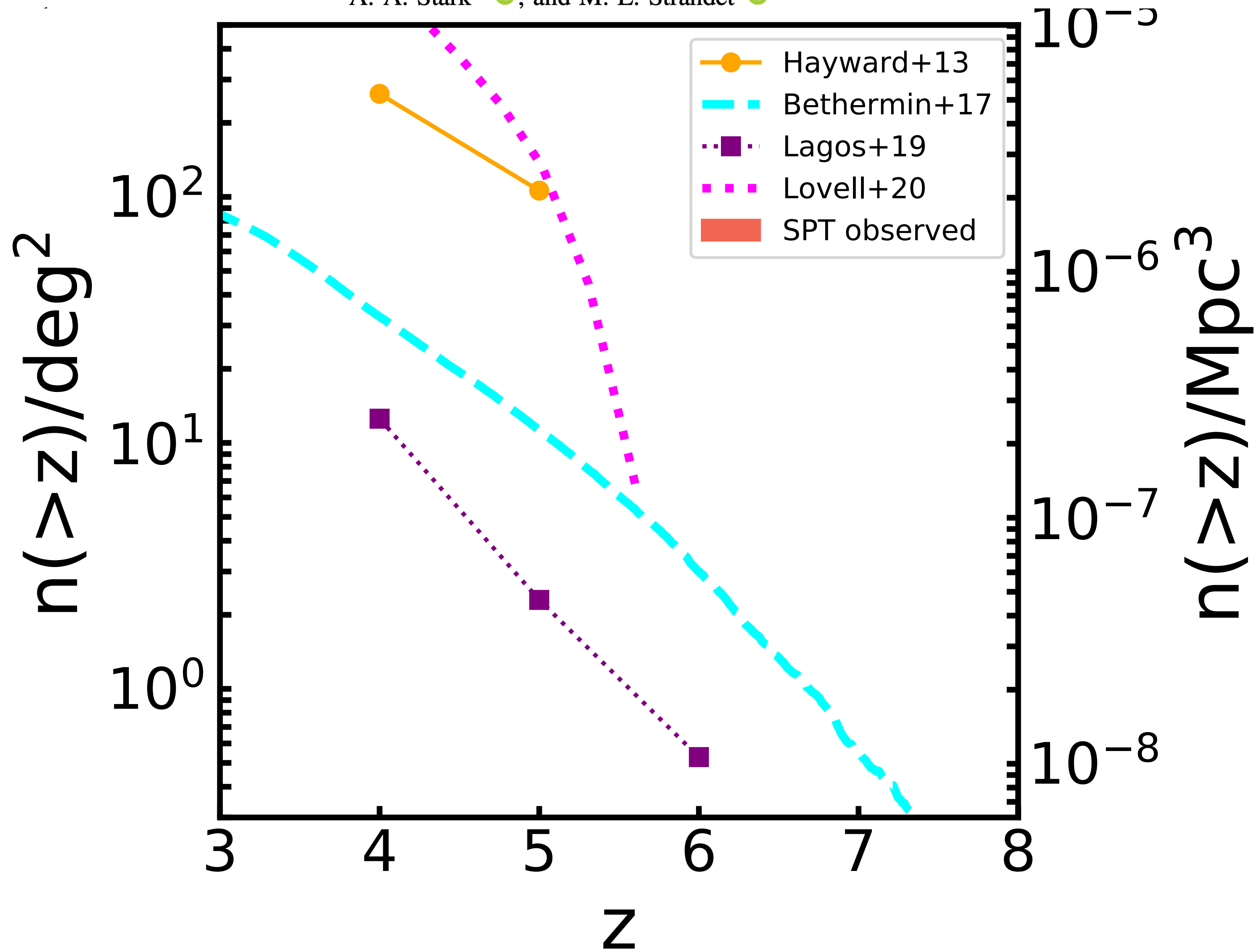
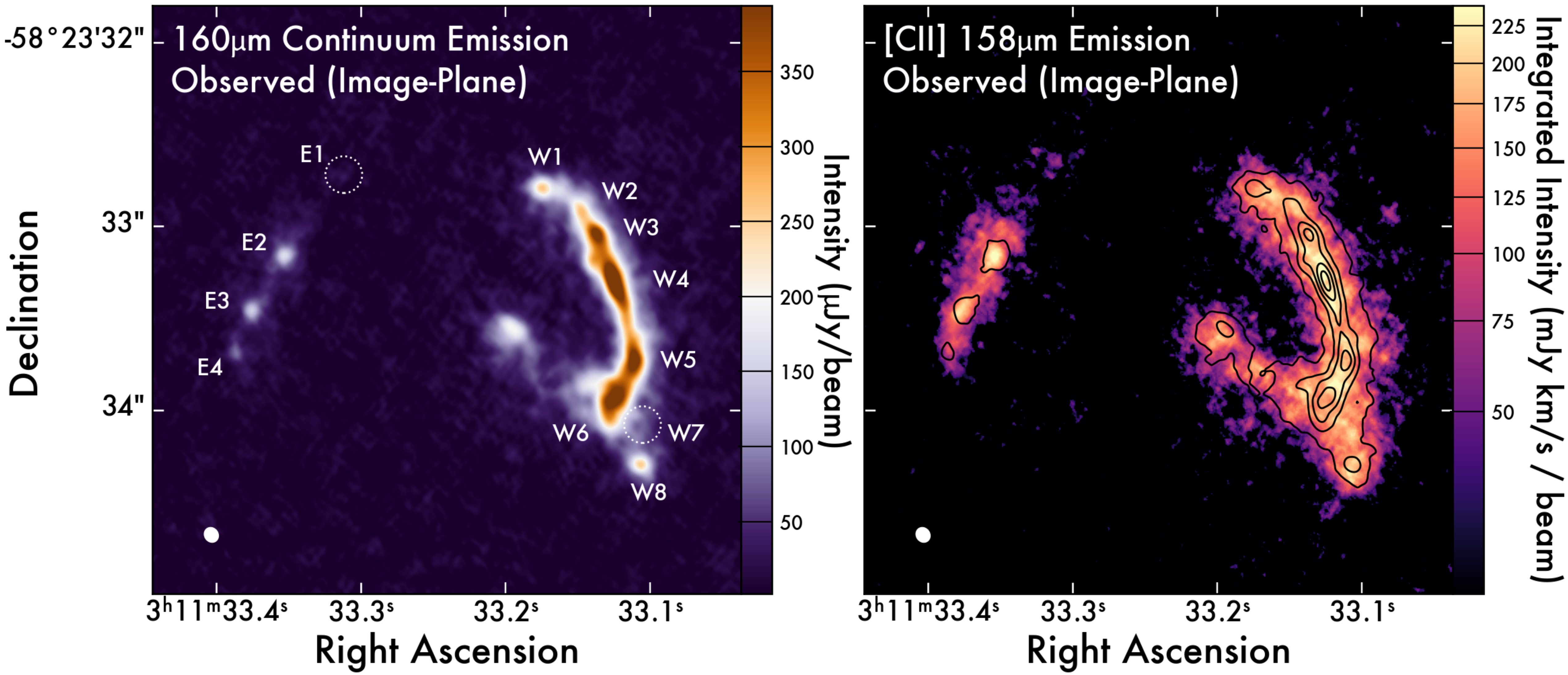


- With a complete spectroscopic survey, we can constrain the spatial density of high-redshift luminous galaxies.
- Because the selection is independent of redshift, we can empirically measure the onset of massive galaxy formation.

ALMA image of SPT0311-58 @ z=6.9



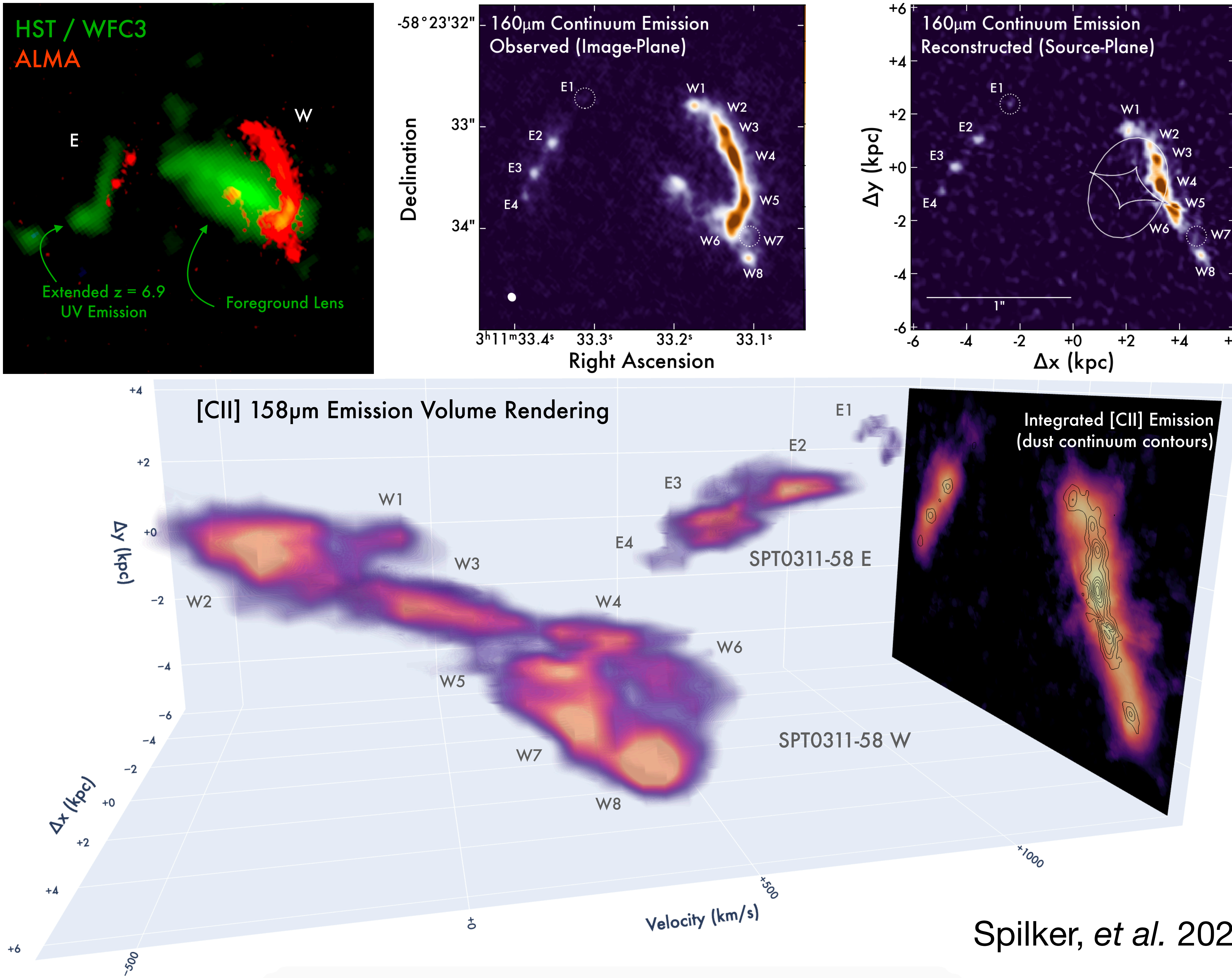
This is the most detailed look at the redshift ~7 Universe

Just 800M years after the Big Bang

This is what ALMA was MADE to do

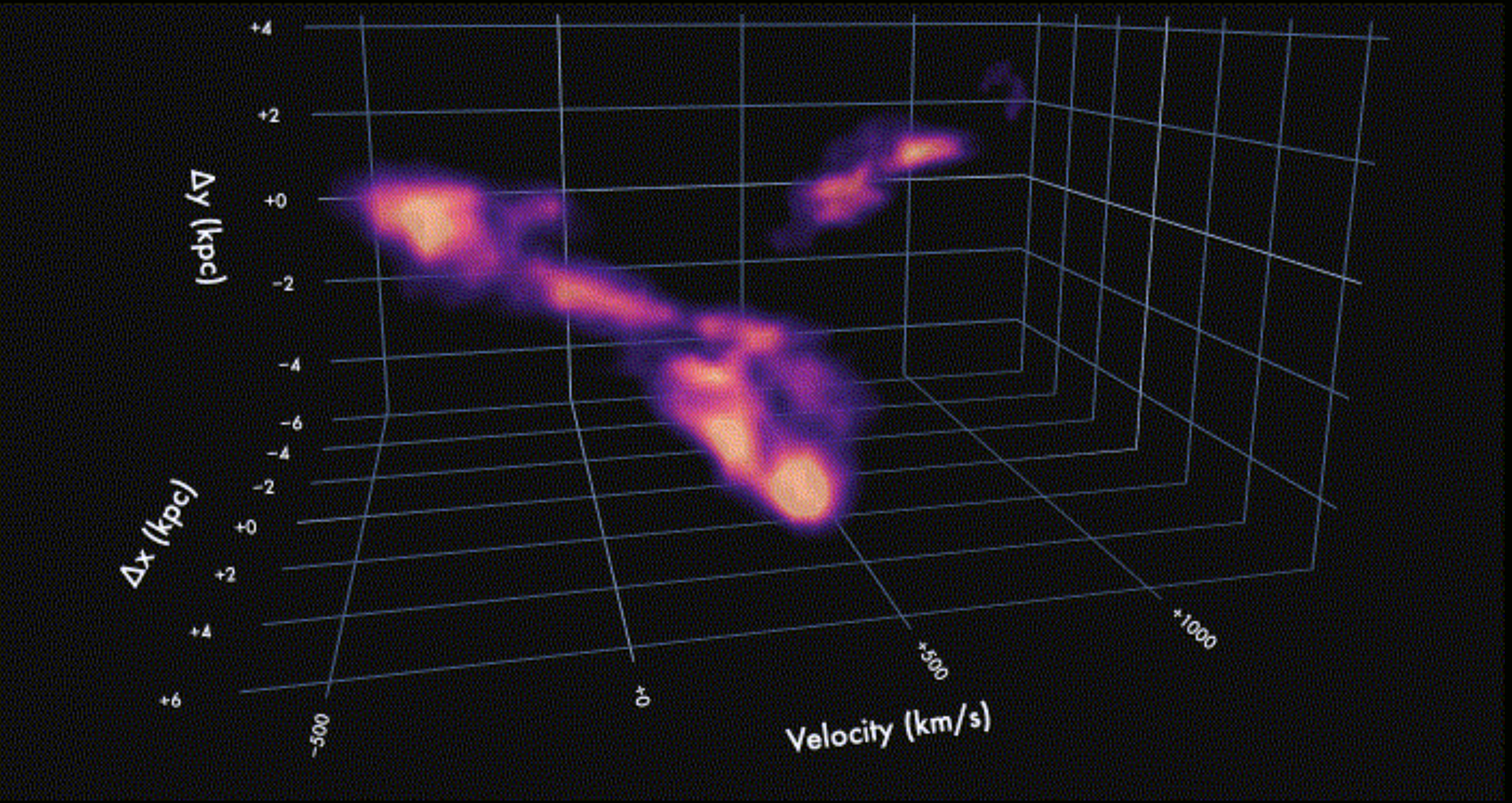
See also:
Strandet, *et al.* 2017, ApJ
Marrone, *et al.* 2018, Nature
Jarugula, *et al.* 2021, ApJ
Spilker, *et al.* 2022, ApJ

ALMA image of SPT0311-58 @ z=6.9



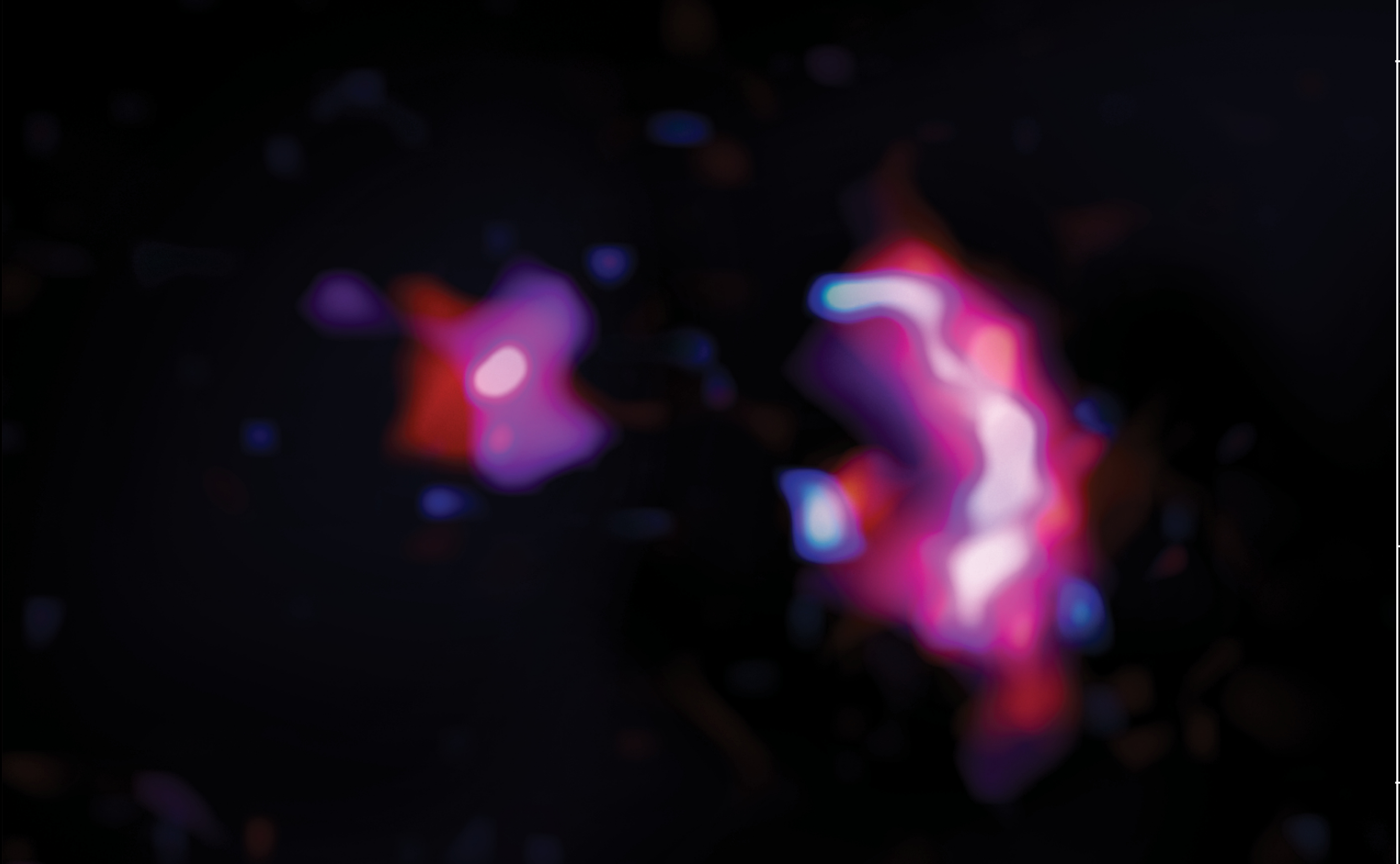
Spilker, *et al.* 2022, ApJL

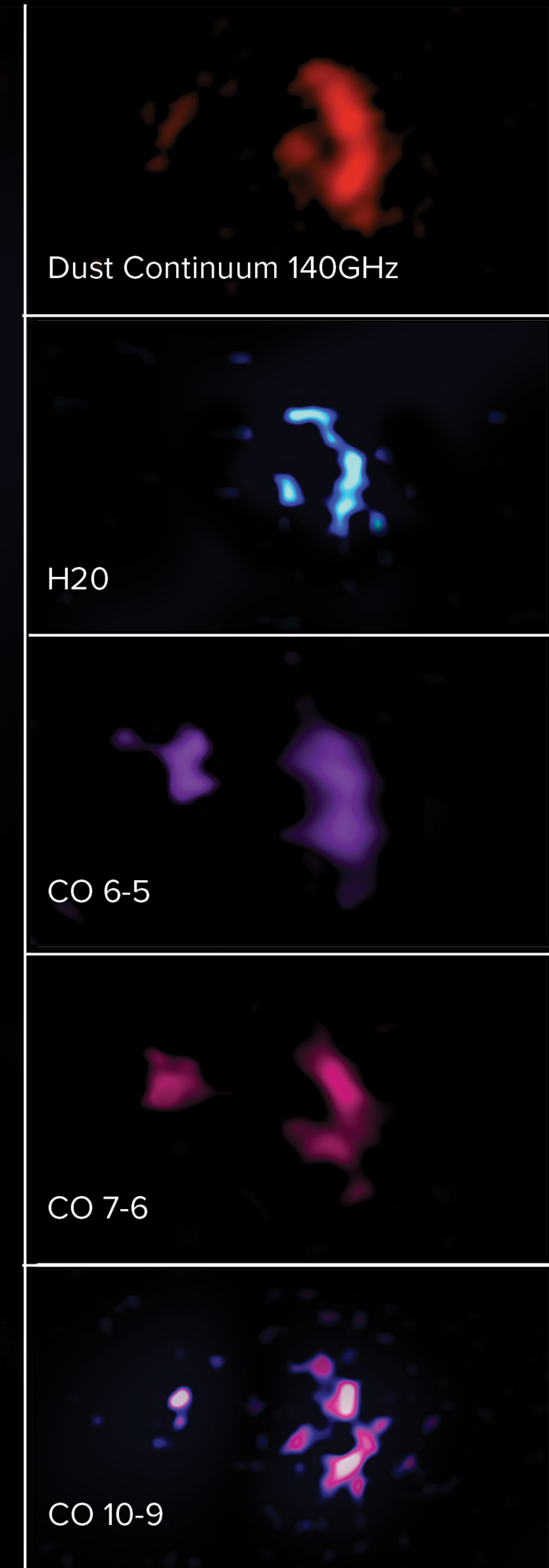
ALMA image of SPT0311-58 @ z=6.9



Spilker, *et al.* 2022, ApJL

ALMA image of SPT0311-58
in
MOLECULES





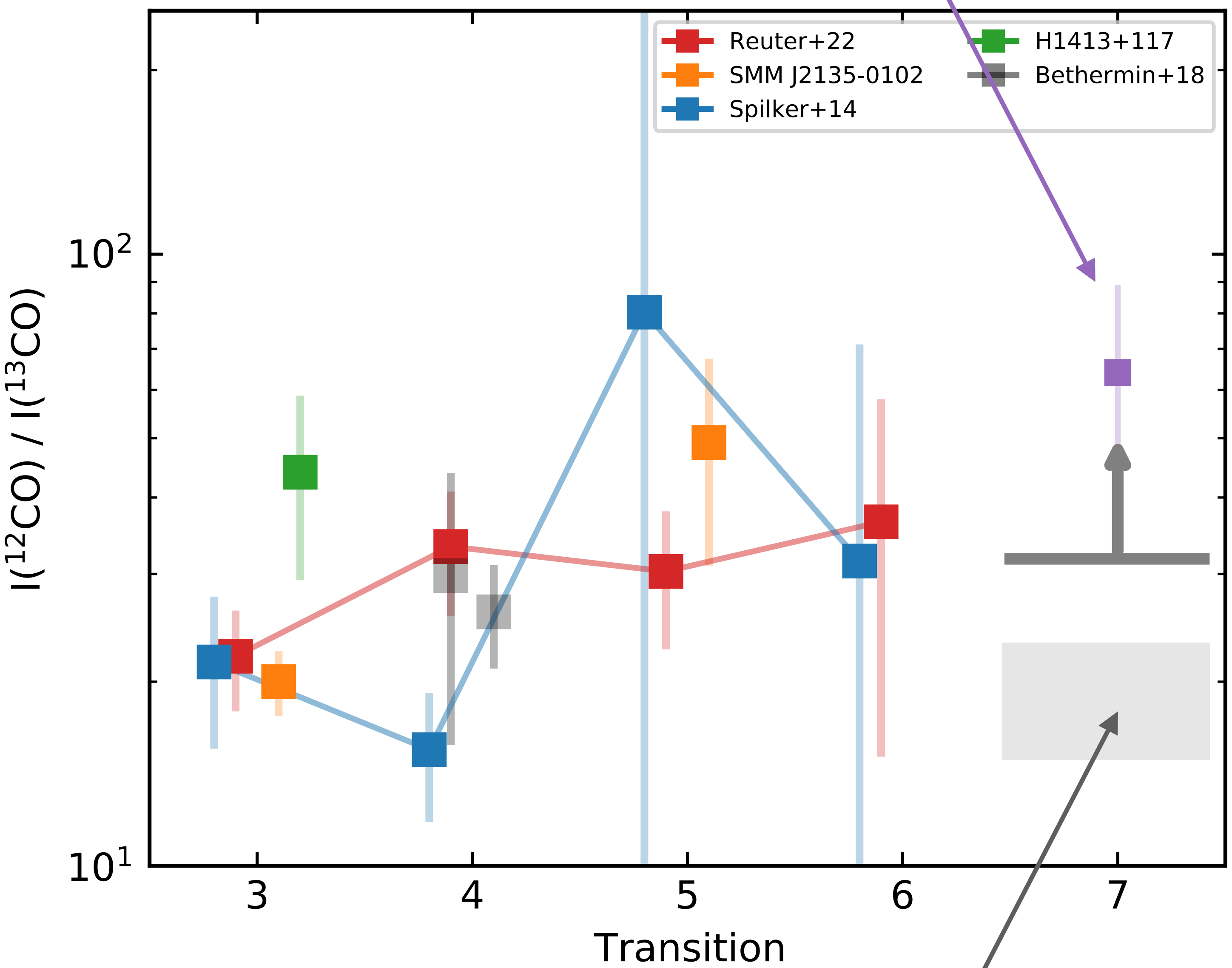
This is the most distant detection of water.

Jarugula, Vieira, Weiss, *et al*., 2021, ApJ

^{13}C in the Epoch of Reionization

- The history of nucleosynthesis leaves a "fossil record" on the atomic and molecular isotopes observed in the local and distant universe.
- Observations of isotopes in distant galaxies across cosmic time can provide powerful insights into the evolution of the universe, galaxy formation, and even the physics of stellar evolution.
- While ^{12}C nuclei are produced during "primary" He burning in high-mass stars on rapid timescales, ^{13}C nuclei are "secondary," formed in intermediate-mass stars undergoing CNO cycle burning (e.g. AGB stars), at ages of >1 Gyr.
- Thus, at z>6 there should be no ^{13}C.
- We designed an experiment with ALMA to spend 18.7 hours in B3 at z=6.9 to observe or set a limit on ^{13}CO.
- (Spoiler: we did *not* detect it, so stellar evolution works how we think.)

(preliminary) limit



range we would expect if $^{13}CO/^{12}CO$ were the same at z>6 and z<6

The Epoch of Reionization

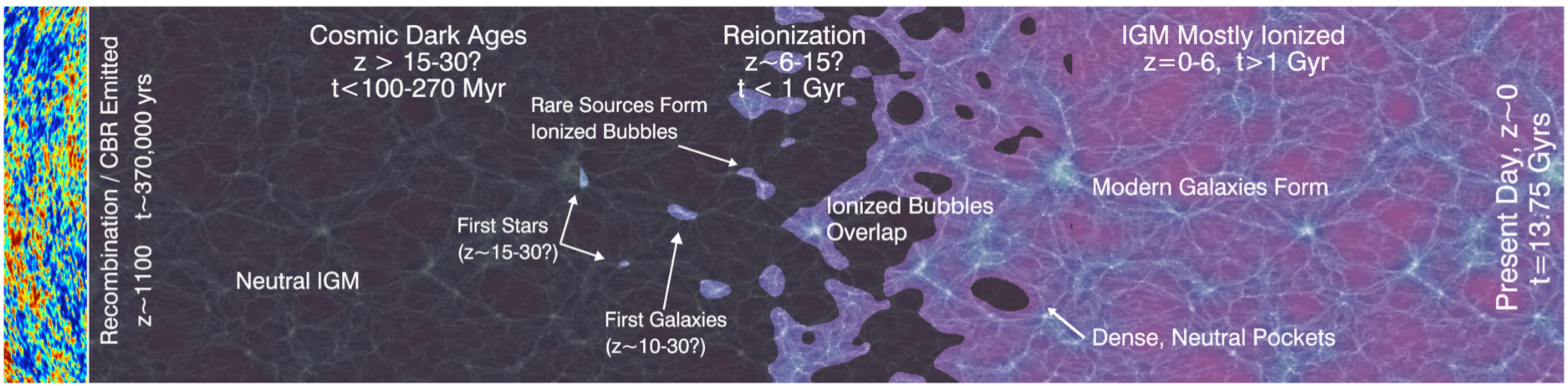
quark+gluon plasma

H+He forms

Universe becomes neutral

First stars and galaxies re-ionize the universe

Inflation / Big Bang



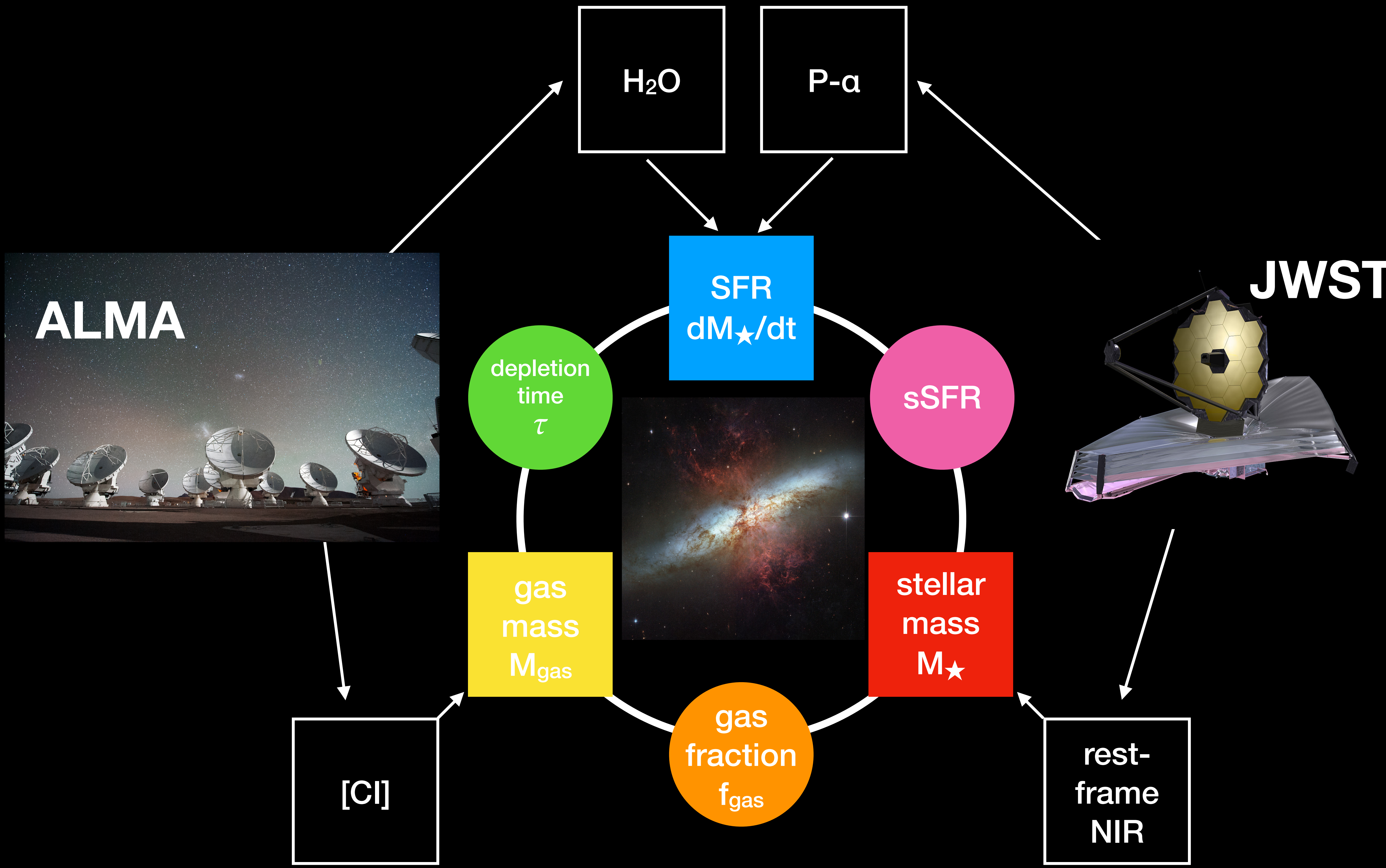
plasma **not a plasma** **plasma**

Beginning of the Universe

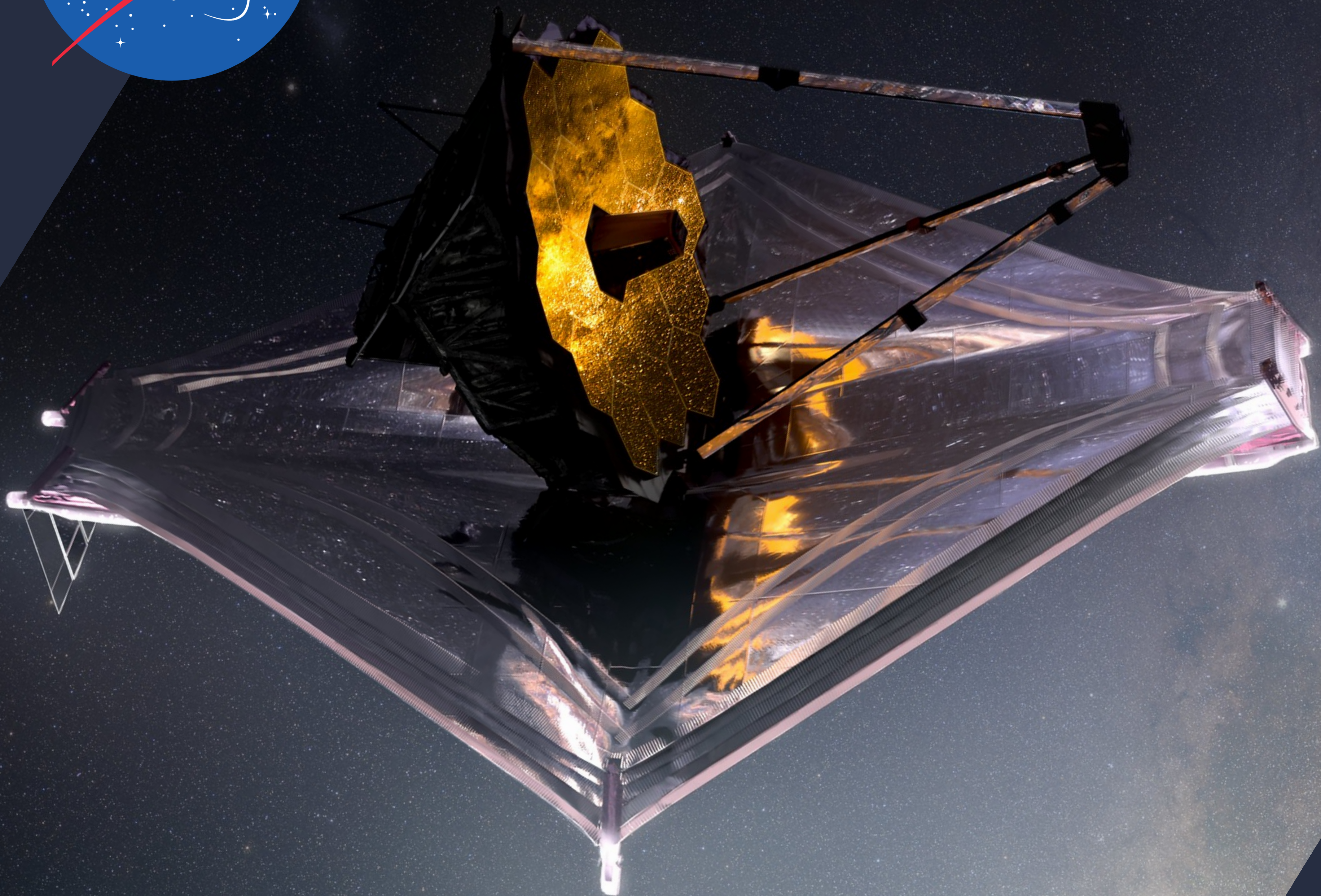
ALMA is now doing chemistry here

Today

the ingredients needed to understand galaxy evolution



James Webb Space Telescope



JWST Early Release Science (ERS) Program

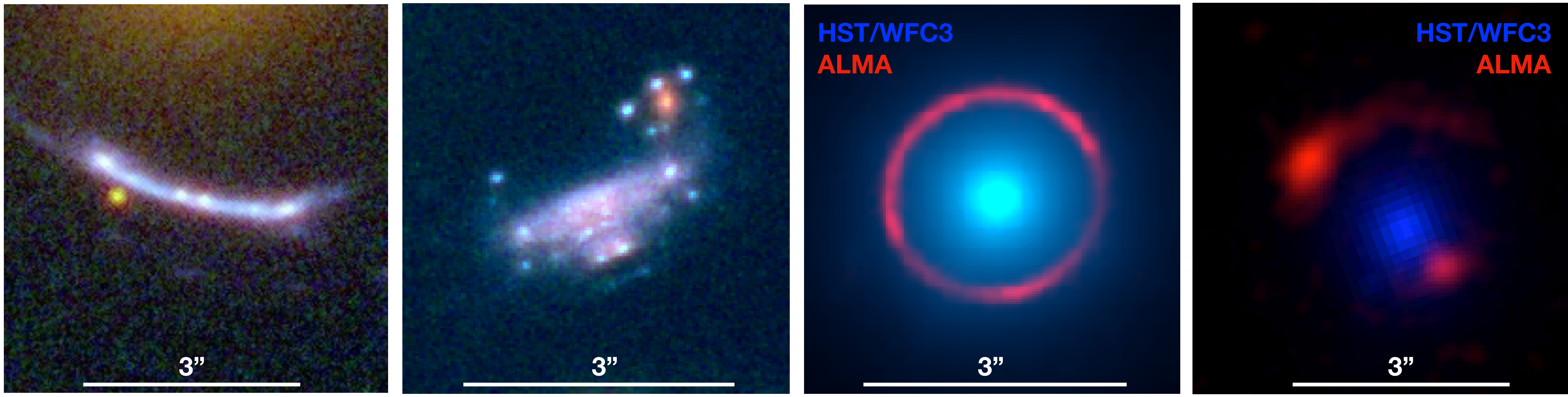
TEMPLATES: Targeting Extremely Magnified Panchromatic Lensed Arcs and Their Extended Star formation

PI: Jane Rigby (NASA Goddard) ; Co-PI: Joaquin Vieira (U. Illinois)

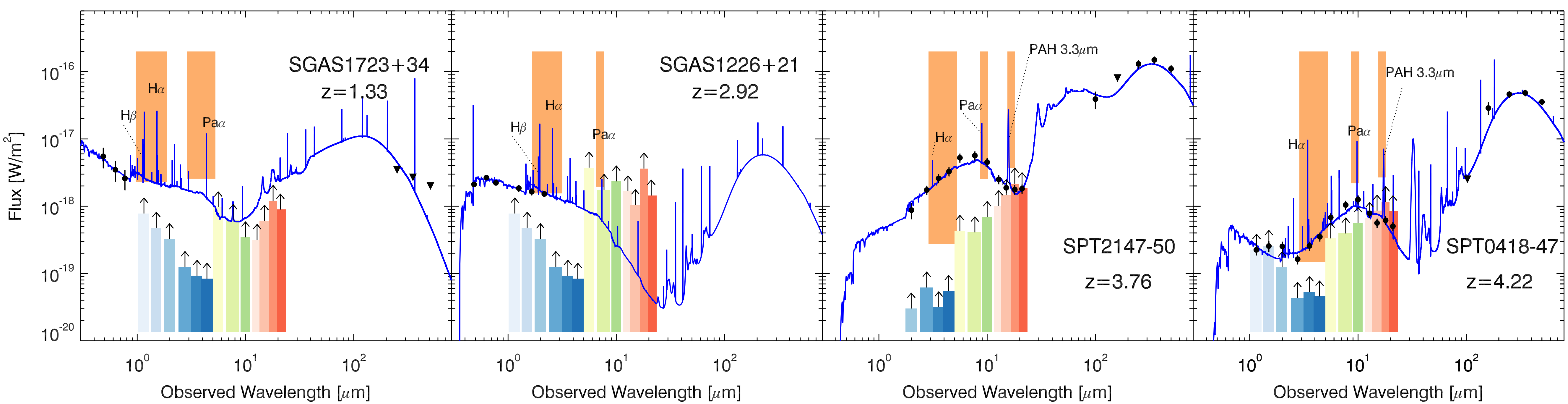
55 hours of Director's time

see Rigby, Vieira, Phadke *et al.* 2024 arXiv:2312.10465

JWST TEMPLATES Targets

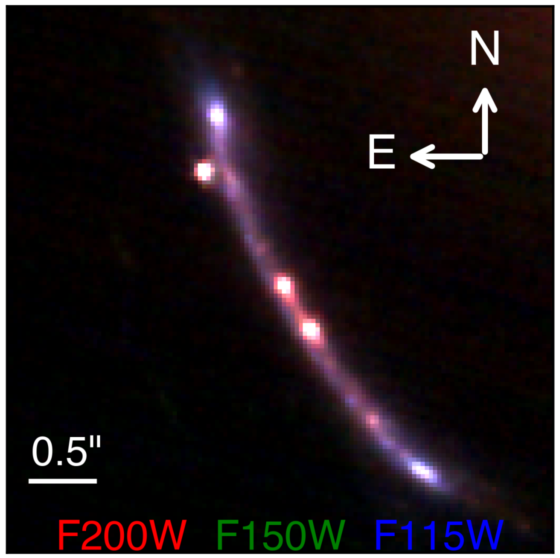


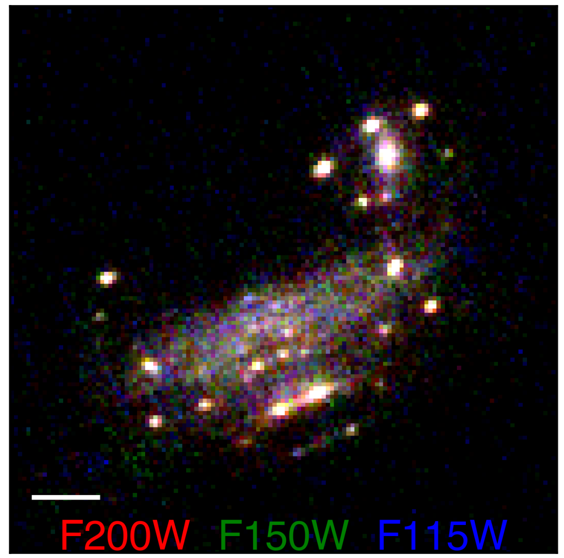
Source	SDSS1723+34	SDSS1226+21	SPT0418-47	SPT2147-50
redshift	1.32	2.92	4.22	3.76
magnification	20	40	32	6.6
r_E [arcsec]	4.7	9	1.2	1.2
$M_\star$ [$M_\odot$]	$<3\times10^{10}$	5×10^{9}	4.4×10^{10}	2.0×10^{10}
SFR [$M_\odot$/yr]	8	40	230	1290
sSFR [Gyr^{-1}]	>3	8	5.3	64
A_V	0.64—1.0	0.2—1	6	6

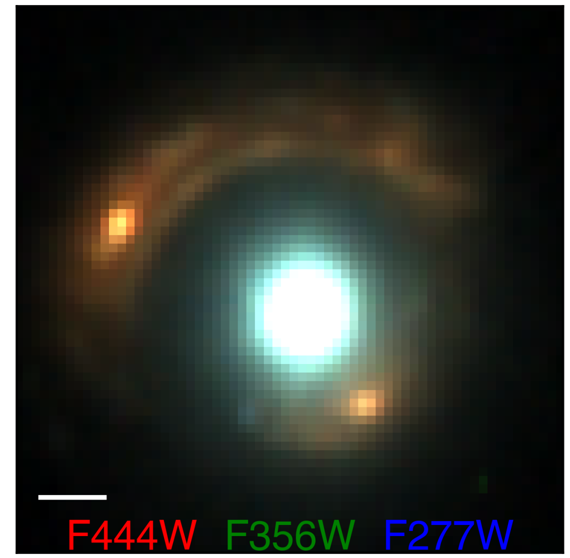


JWST TEMPLATES Targets

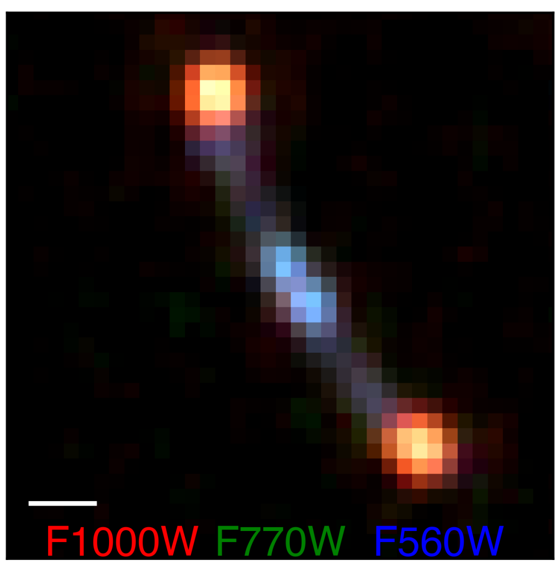
NIRCam imaging

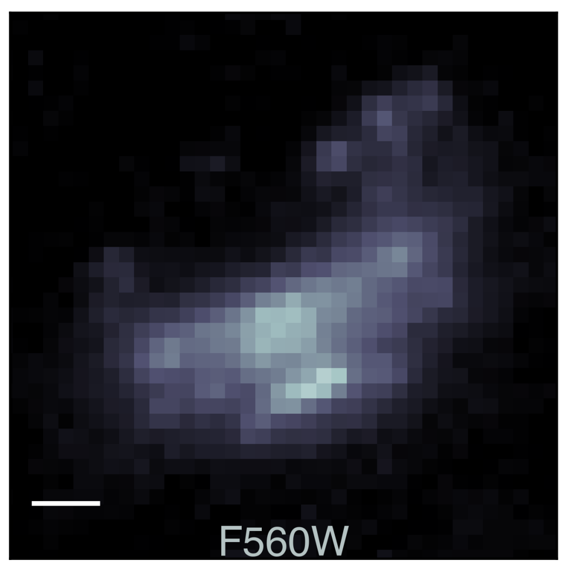


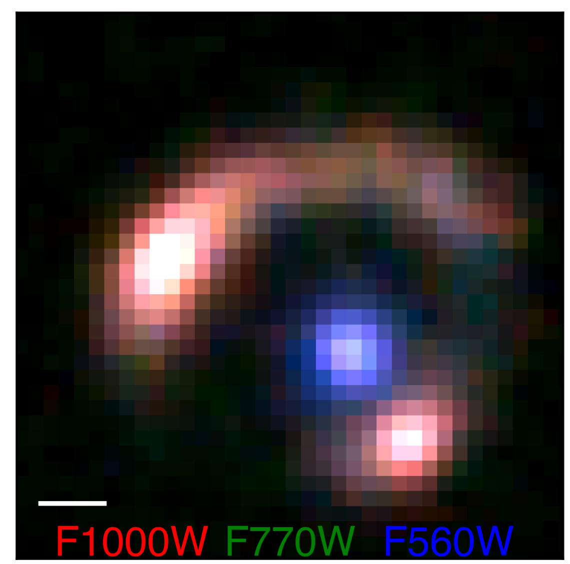


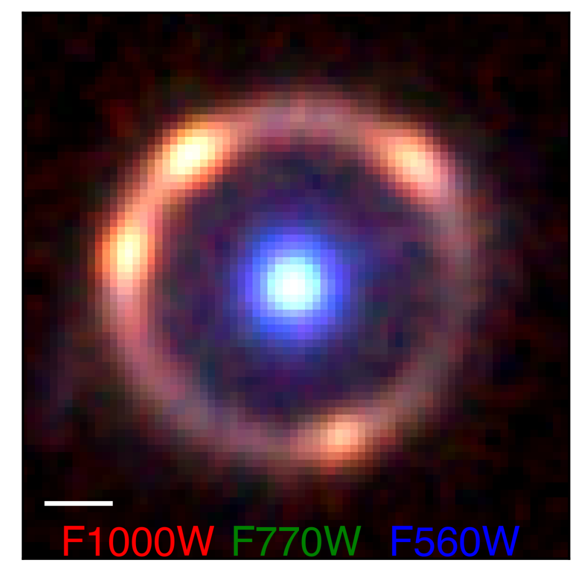


SGAS1723+34 SGAS1226+21 SPT2147-50 SPT0418-47





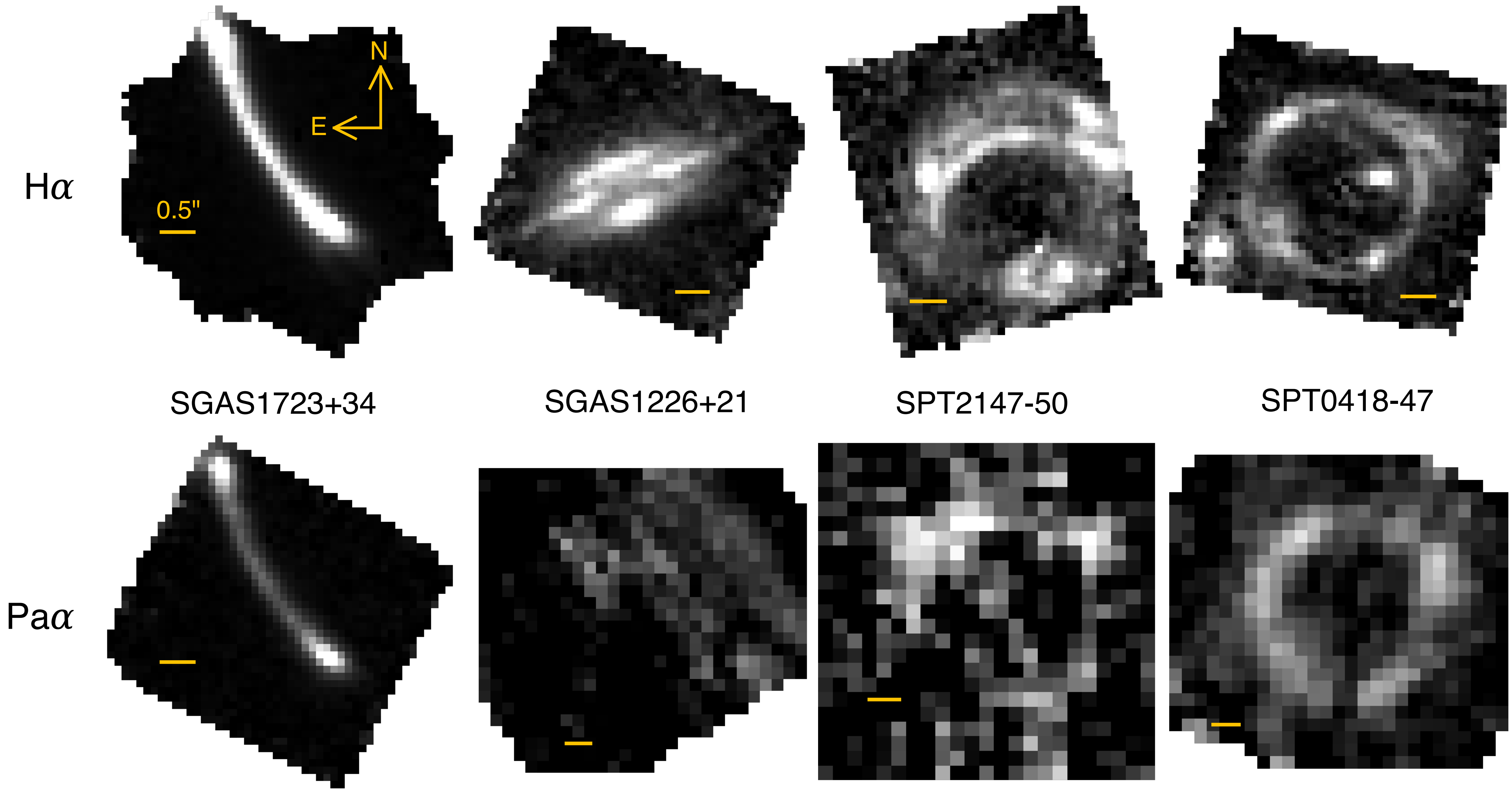




MIRI imaging

Rigby, Vieira, Phadke *et al.* 2025, ApJ

JWST TEMPLATES Targets



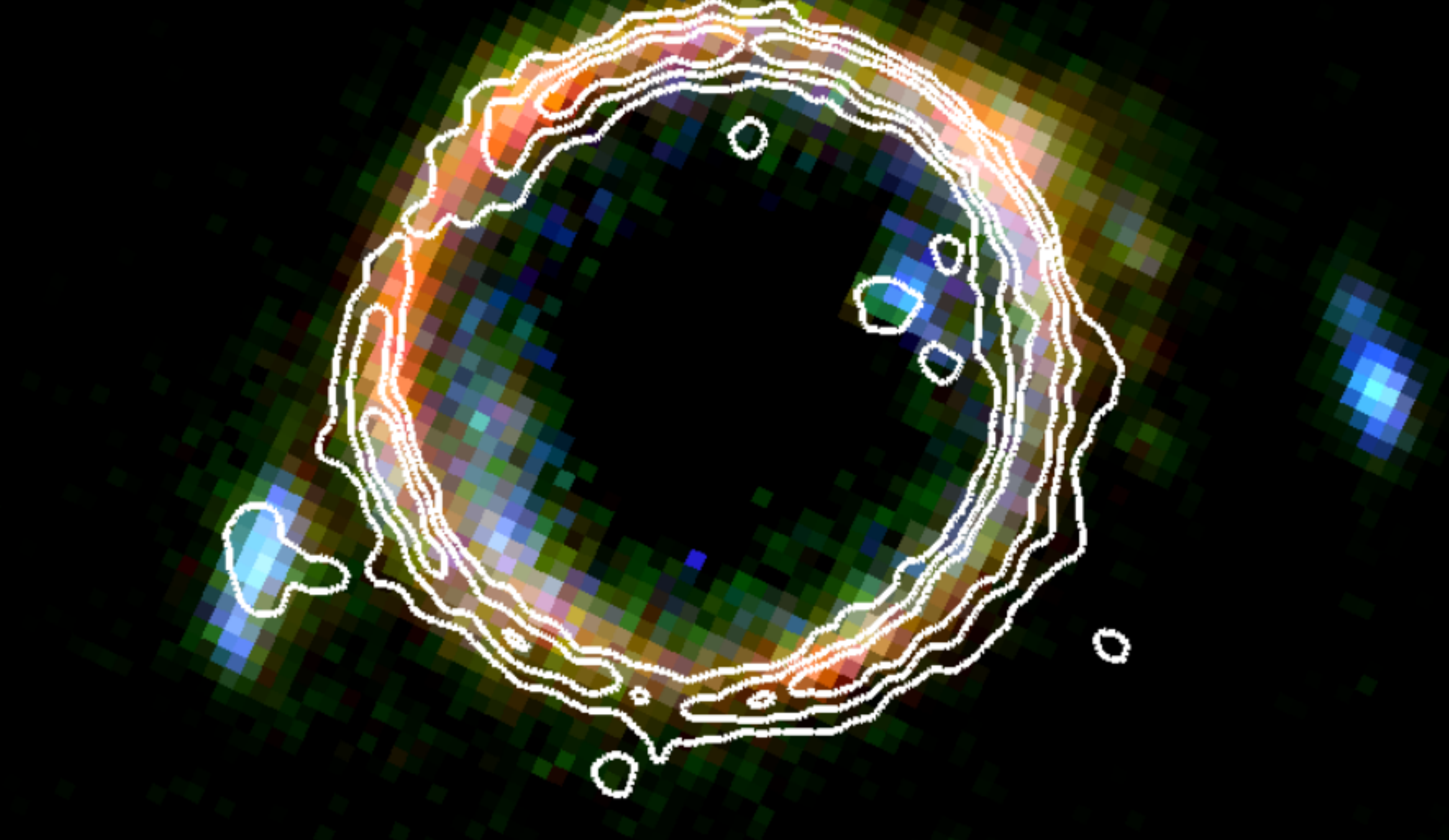
moment 0 maps

Rigby, Vieira, Phadke *et al.* 2025, ApJ

SPT0418-47 @ z = 4.2

JWST/NIRCam Observations

ALMA [CII] contours



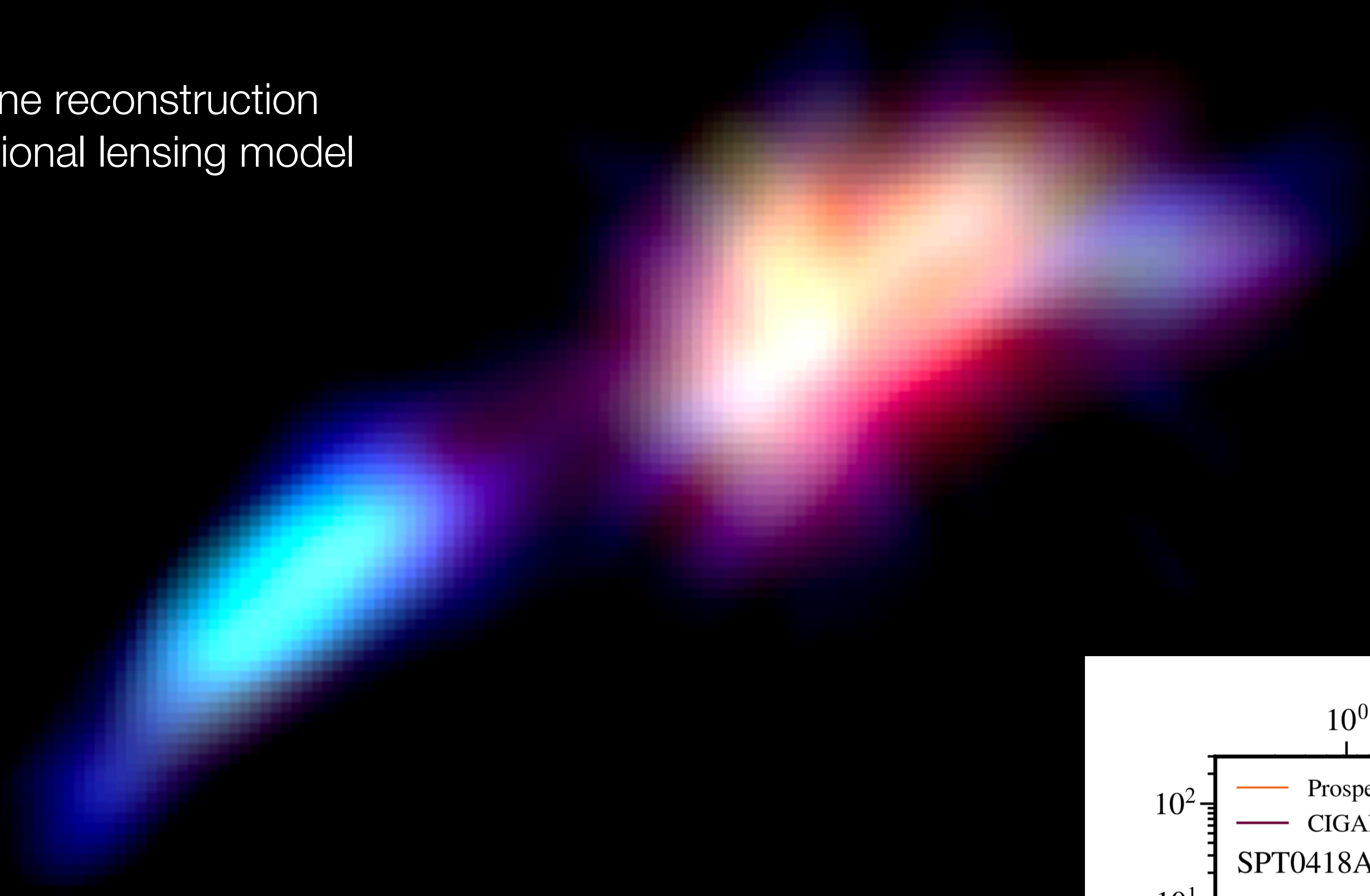
* The foreground lens has been subtracted and there is still a residual astrometry offset in the JWST image.

SPT0418-47 @ z = 4.2
JWST/NIRCam Observations

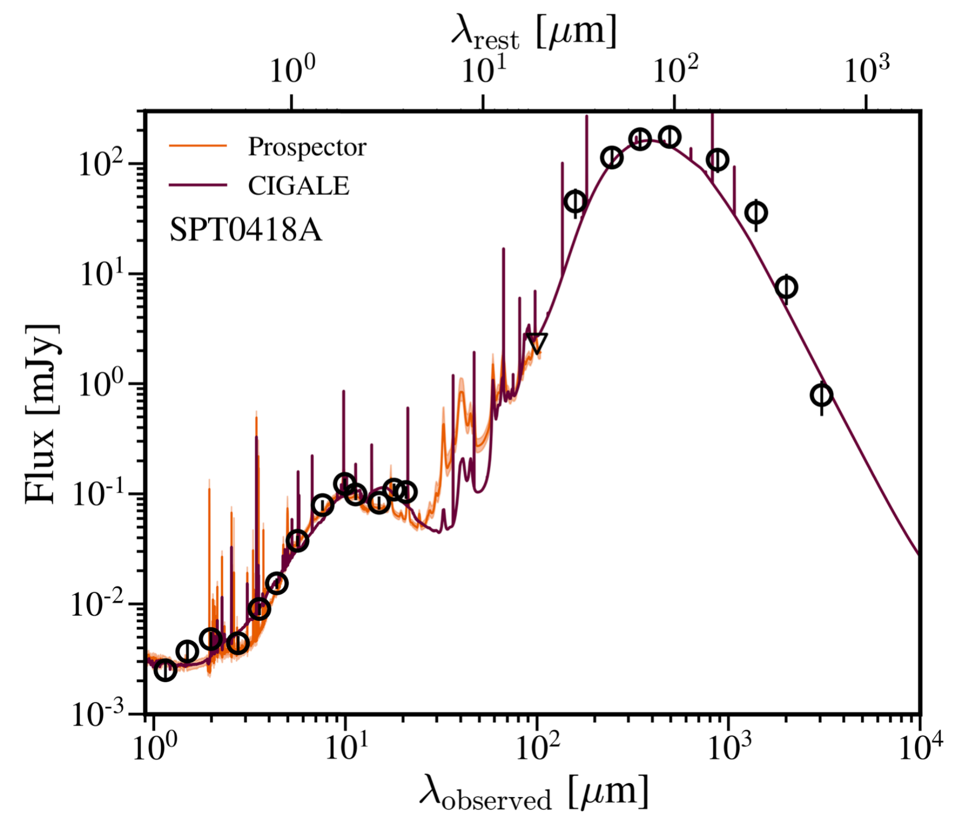
Cathey *et al. 2023*
arXiv:2307.10115

Work by U. Florida
grad student
Jared Cathey

source plane reconstruction
from gravitational lensing model



4.5 kpc



SPT0418-47 @ z = 4.2

JWST ERS IFU Observations

Hα 0.6563μm

Balmer series

Hydrogen 3–>2

JWST/NIRSpec

Although we are missing the H-β line, which means we haven't measured the traditional BPT diagnostics, we have a robust spatially resolved detection of the sulfur lines, which allows us to constrain temperature.

Pa-α 1.875μm

Paschen Series

Hydrogen 4–>3

JWST/MRS

This line is considered the "gold standard" for star formation rate indicators.

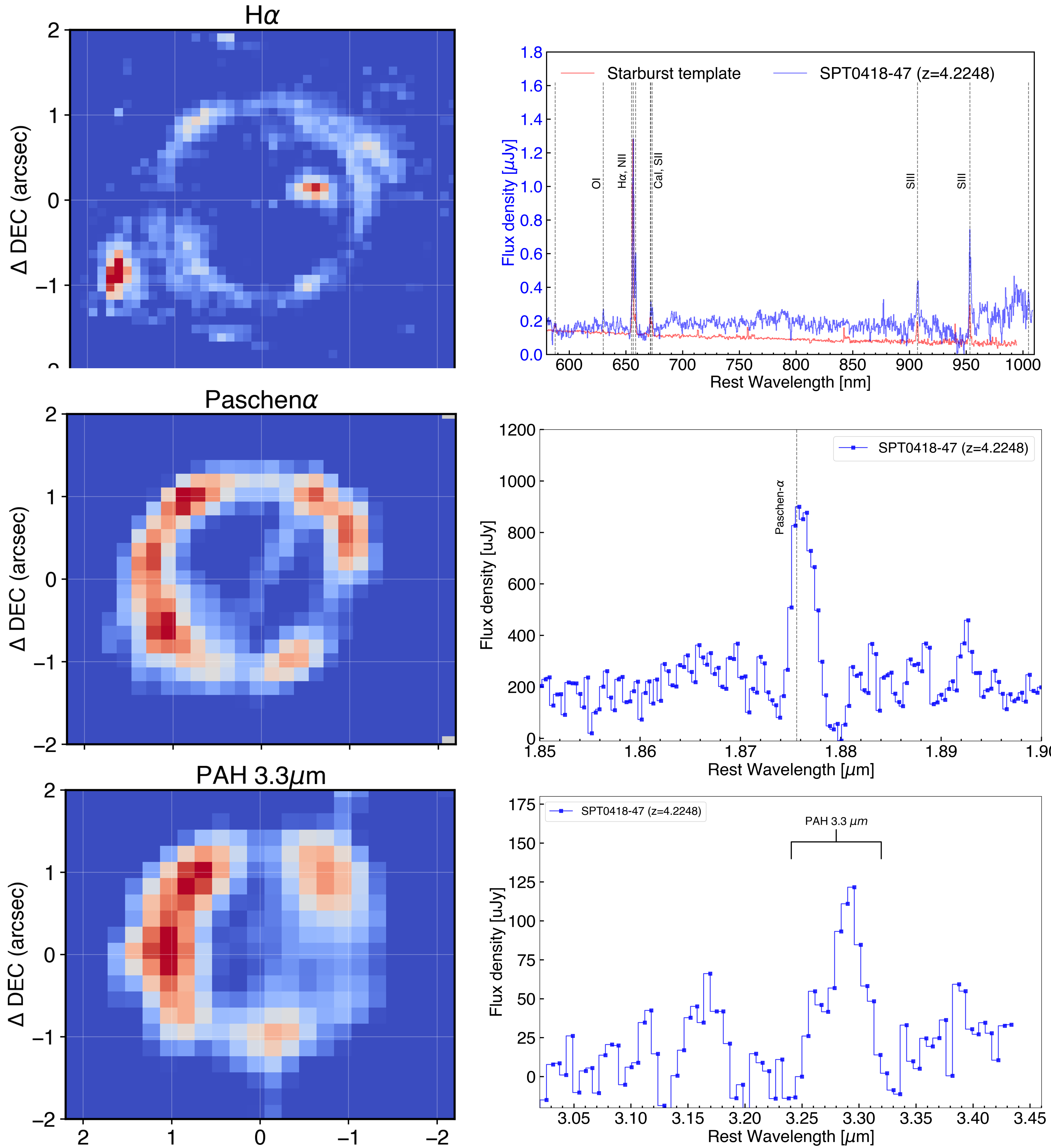
This is the highest redshift detection of Pa-α to-date (previous was at z=2.5 with *Spitzer*) and the first spatially resolved observations of this line outside of the nearby universe.

PAH 3.3μm

polycyclic aromatic hydrocarbon

JWST/MRS

This is the most distant detection of any PAH feature and the first time PAH emission has been spatially resolved outside the local universe.



Spatially resolved PAH 3.3 μm at z=4.2

Spilker *et al.* 2023, *Nature*

Article

Spatial variations in aromatic hydrocarbon emission in a dust-rich galaxy

https://doi.org/10.1038/s41586-023-05998-6

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Check for updates

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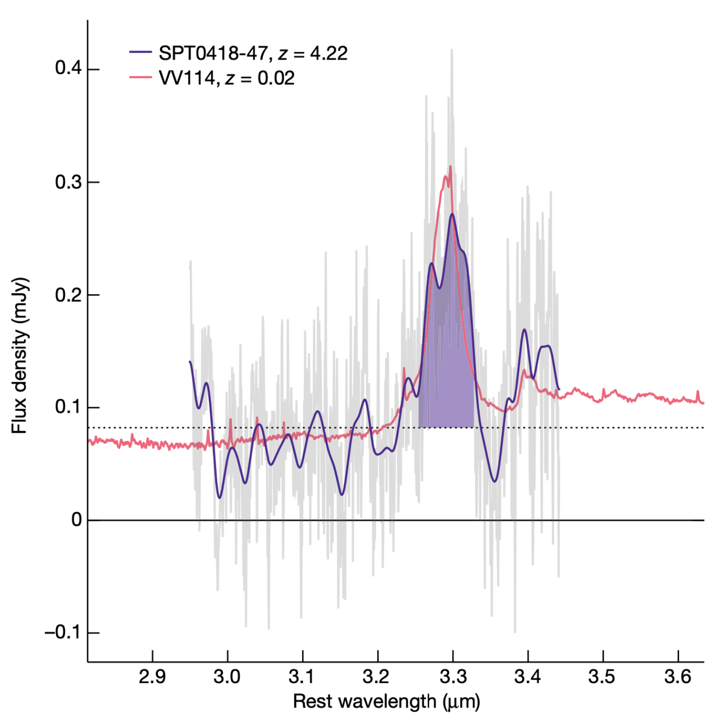
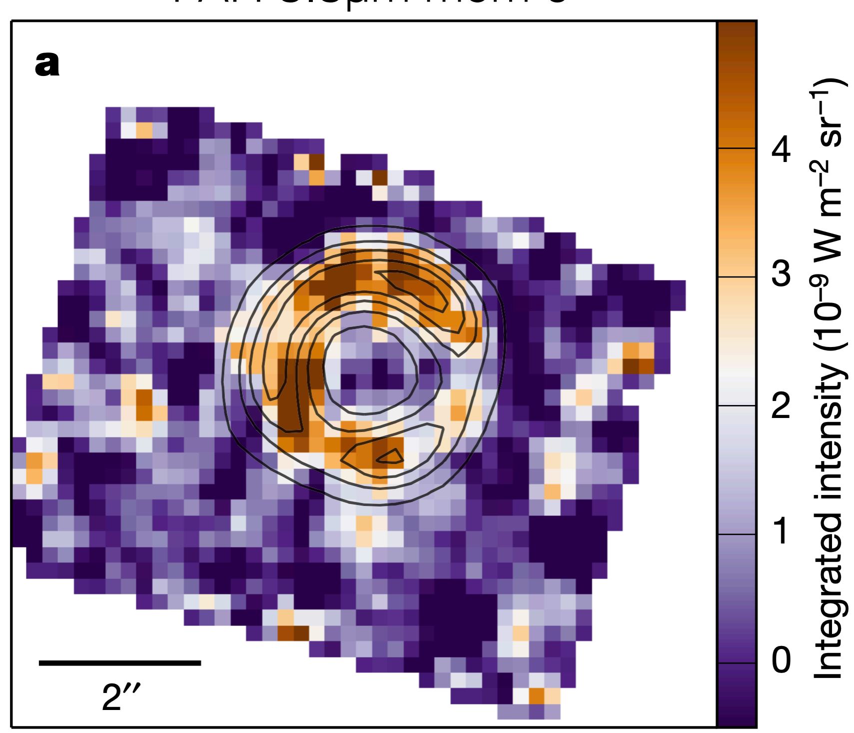
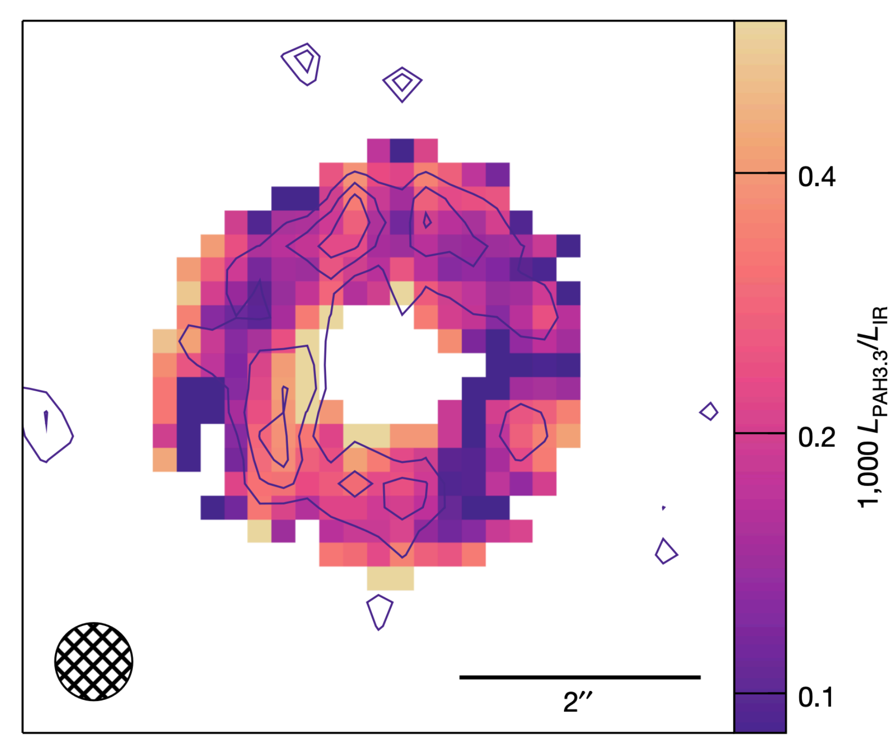
PAH 3.3μm integrated 1D spectrum

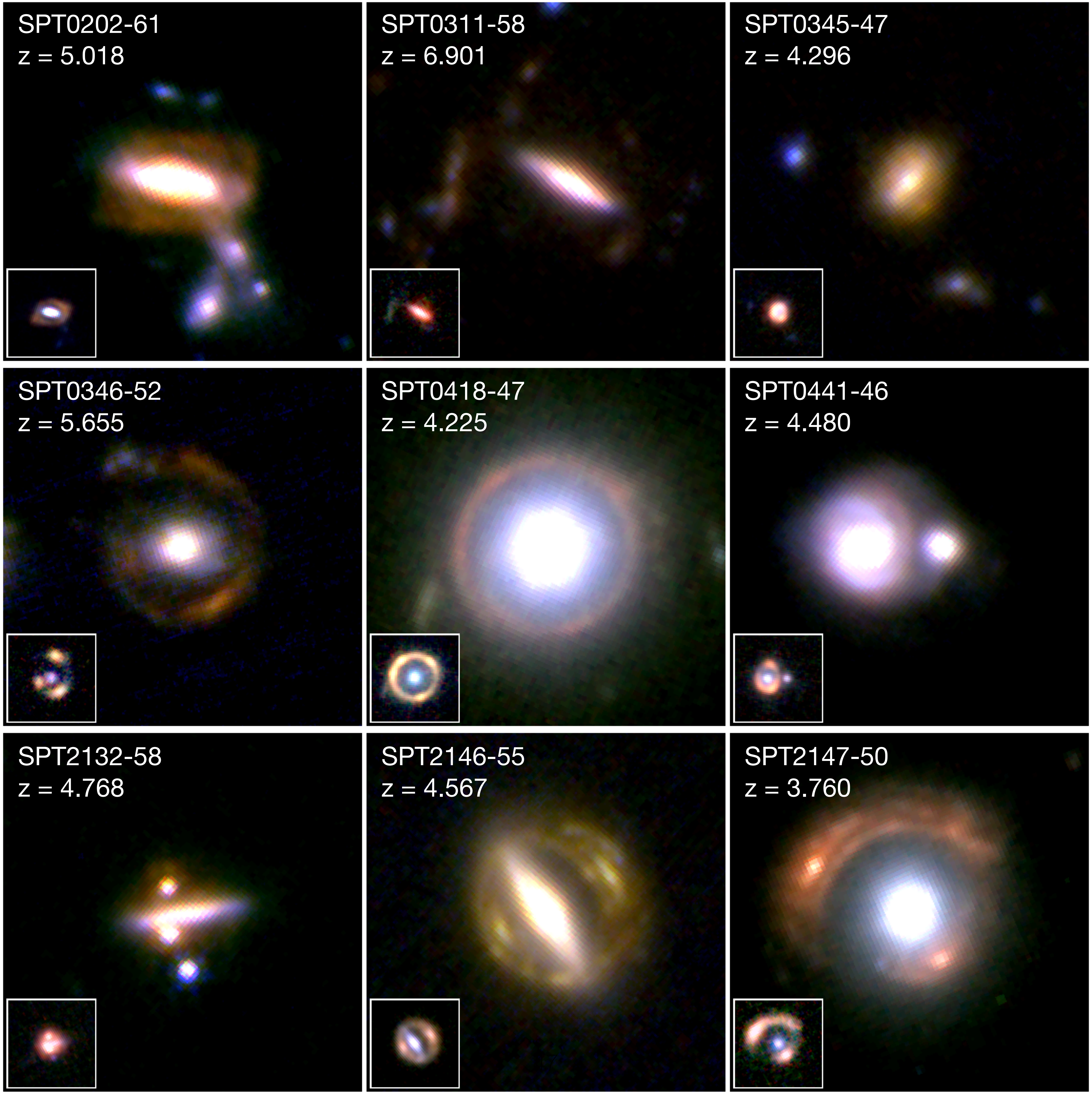


PAH 3.3μm mom 0

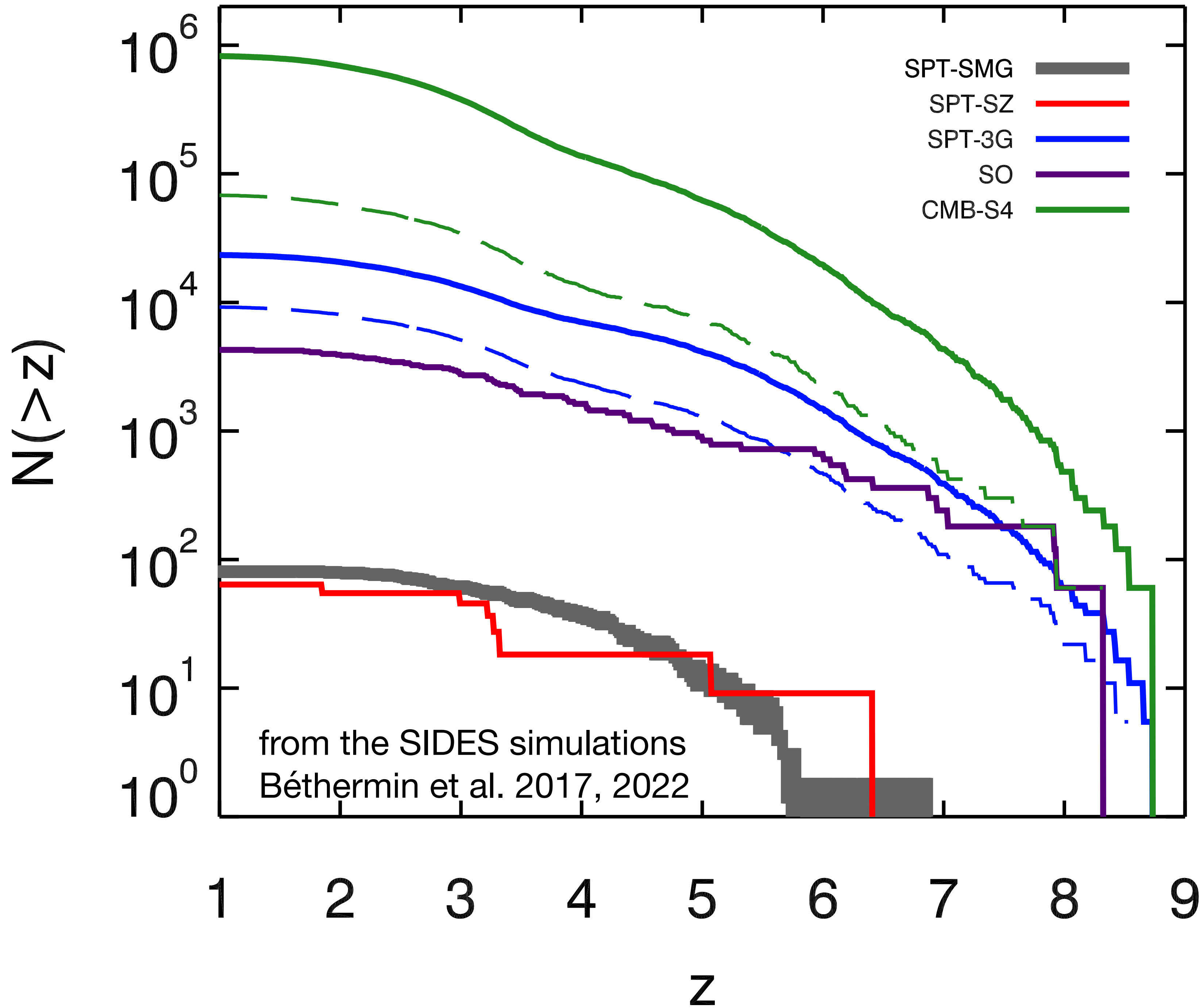


PAH 3.3μm / L_{IR} ratio




SPT0202-61
z = 5.018
SPT0311-58
z = 6.901
SPT0345-47
z = 4.296
SPT0346-52
z = 5.655
SPT0418-47
z = 4.225
SPT0441-46
z = 4.480
SPT2132-58
z = 4.768
SPT2146-55
z = 4.567
SPT2147-50
z = 3.760

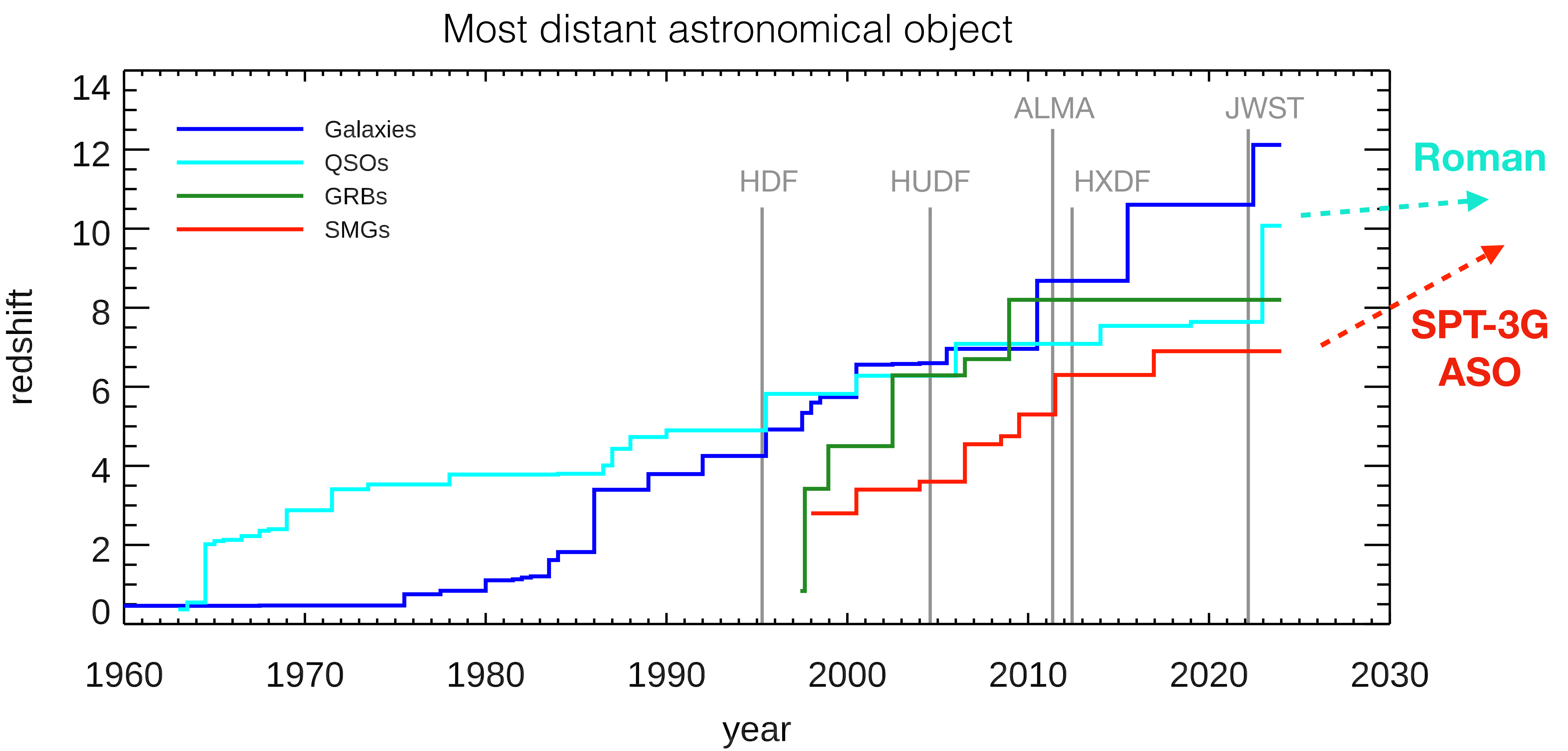
Expected high redshift source yield for future CMB surveys



mm-wave CMB surveys will detect:

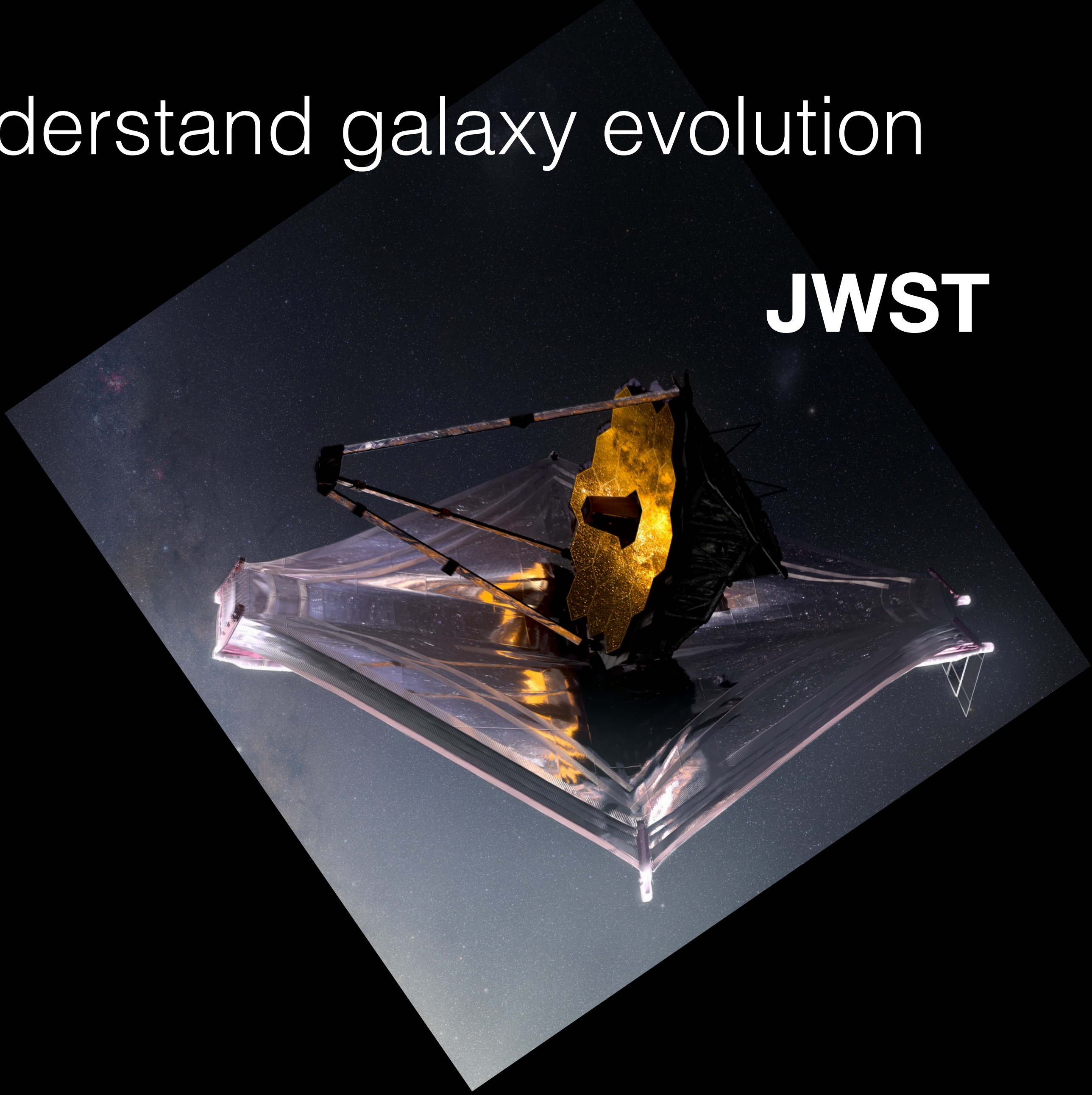
- 100s of dusty galaxies at z>7
- dusty galaxies out to z~9
- this is what is guaranteed … still lots of room for **DISCOVERY** !

where will the next haul of high redshift objects come from?



- New technologies, instruments, and surveys have traditionally opened the window to the high redshift universe.
- Deep, narrow surveys have led the redshift frontier for “normal” galaxies, while wide, shallower surveys have led the redshift frontier for extreme objects such as QSOs and GRBs.
- High redshift SMGs began in deep fields, but are now discovered in wide field sub/mm surveys, in particular, from ground-based mm-wave CMB surveys.
- Ground-based optical surveys have hit a wall at z=6 because of the Lyman break and the atmosphere. Ground based radio and mm-wave surveys should be able to extend to z>9 in the coming years.
- Space-based telescopes such as *JWST* can probe deep fields and provide crucial spectroscopic confirmations. Wide-field space-based telescopes such as *Euclid* and *Roman* should push beyond the current redshift horizon, but will require spectroscopic followup for confirmation.

the ingredients needed to understand galaxy evolution



These facilities are great for:

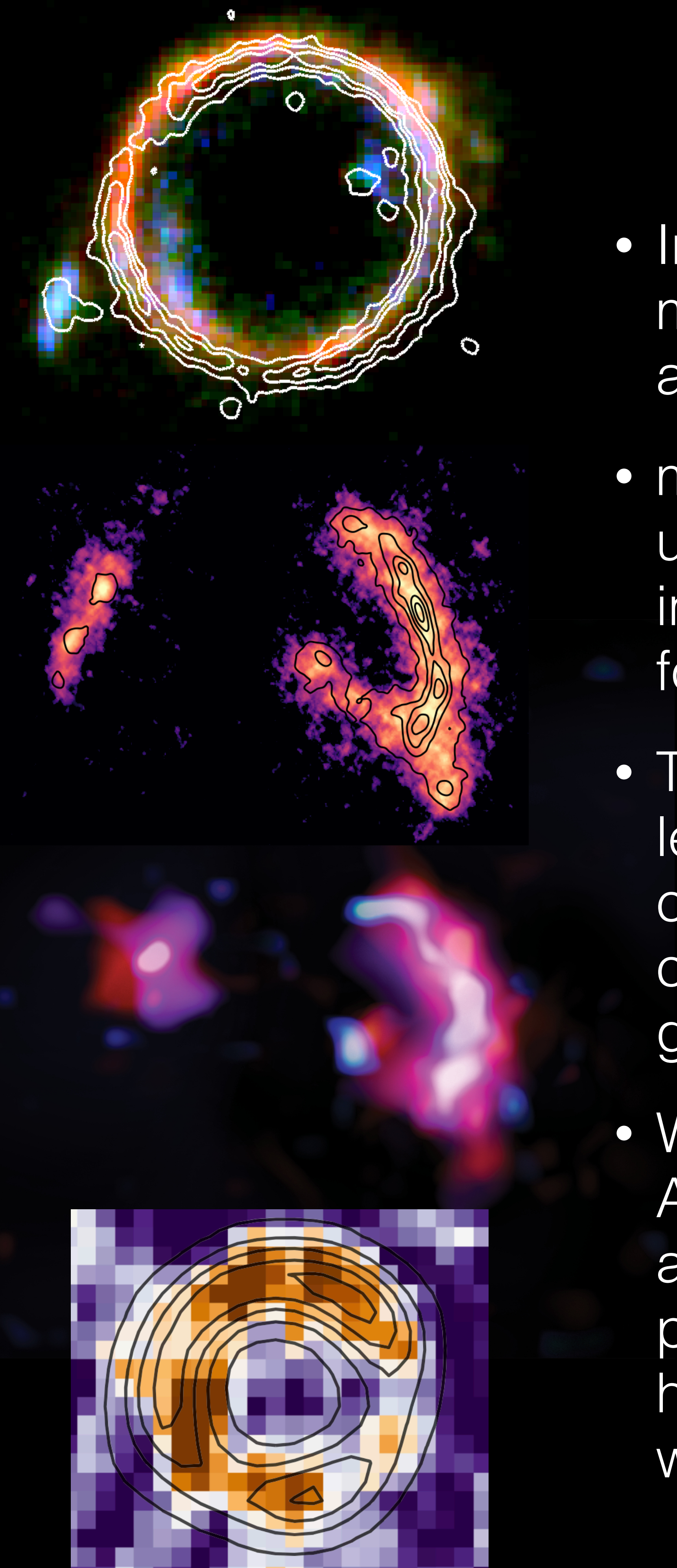
- deep blind surveys
- pointed spectroscopic observations

What about the missing discovery space?

- the spectroscopic coverage gap (ie using the same observables over cosmic time)
- wide field surveys (ie discovering new sources)


SPT-SMG Group May 2025 in Urbana

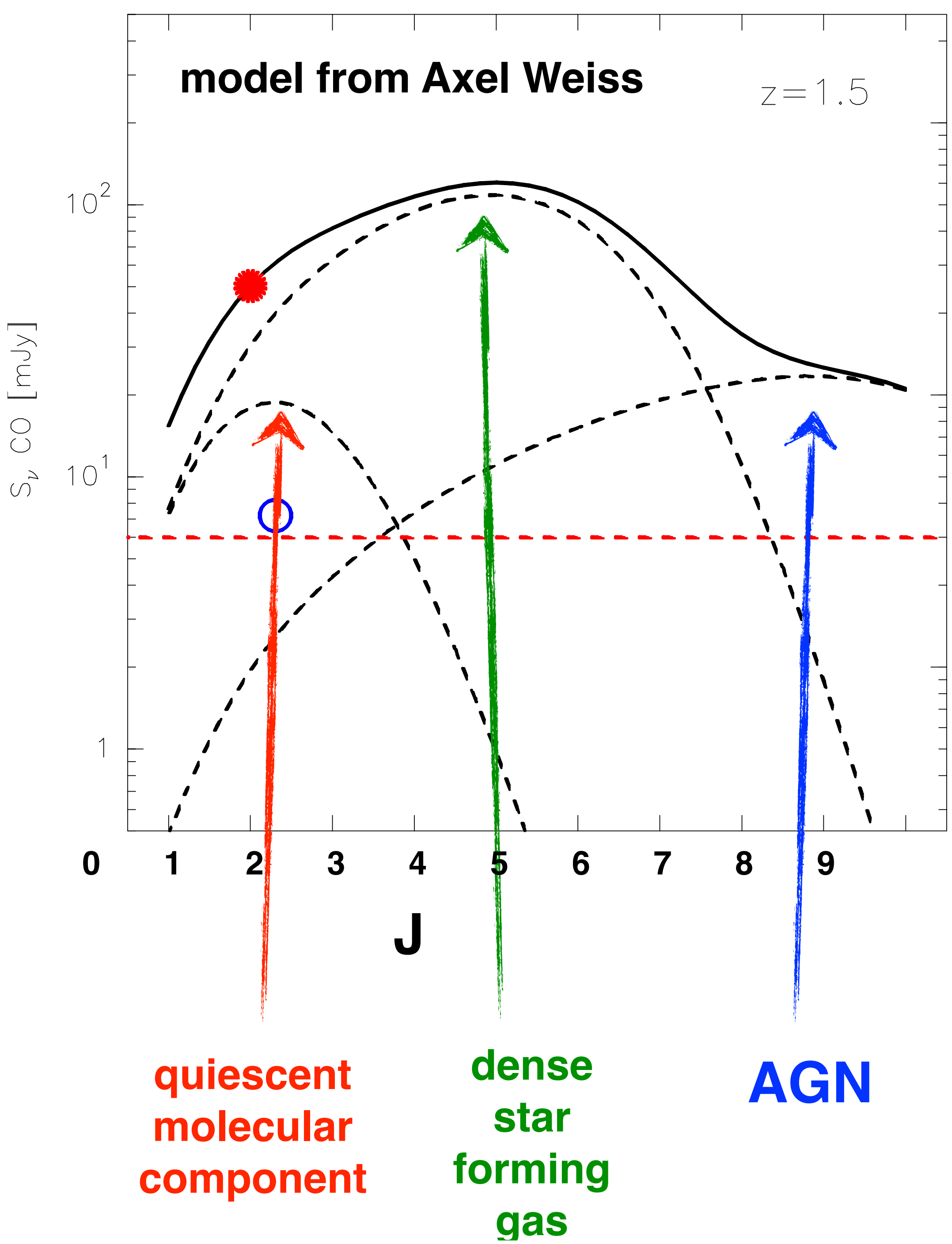
Conclusions

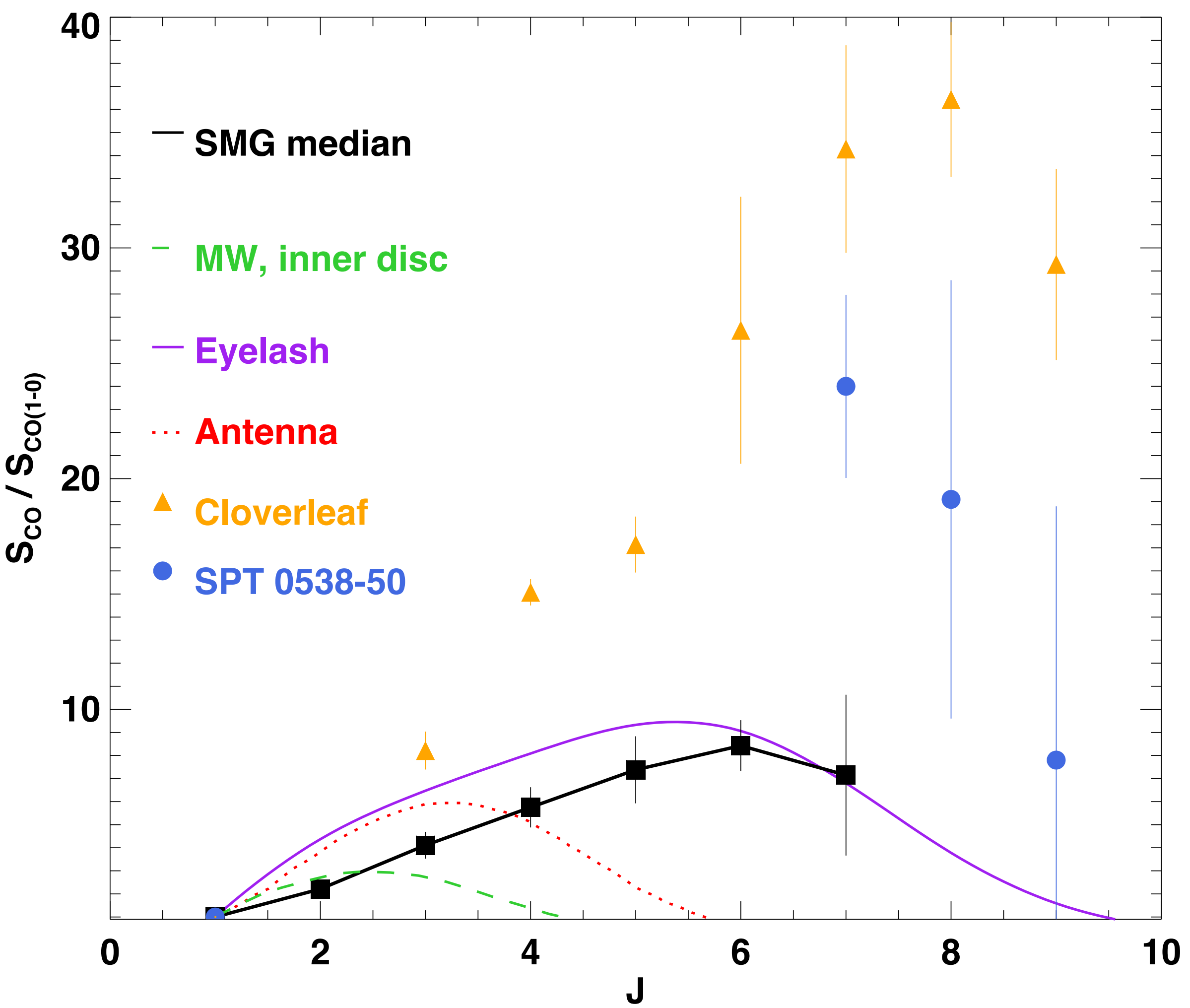


- In addition to cosmology, CMB surveys are making important contributions to astrophysics.
- mm wave selected sources are important for understanding galaxy evolution at all epochs, in particular the mechanism of massive galaxy formation at high redshift.
- The combination of wide surveys, gravitational lensing, ALMA, and JWST have allowed us to constrain the cosmic history, evolution, composition, and chemistry, of massive galaxies across cosmic time.
- We have another 5+ years of JWST, 20+ with ALMA, and even though things may look grim at the moment, it’s kind of a nice moment to pause and reflect on the amazing tools humans have built and we are allowed to play with today.

Funded by :

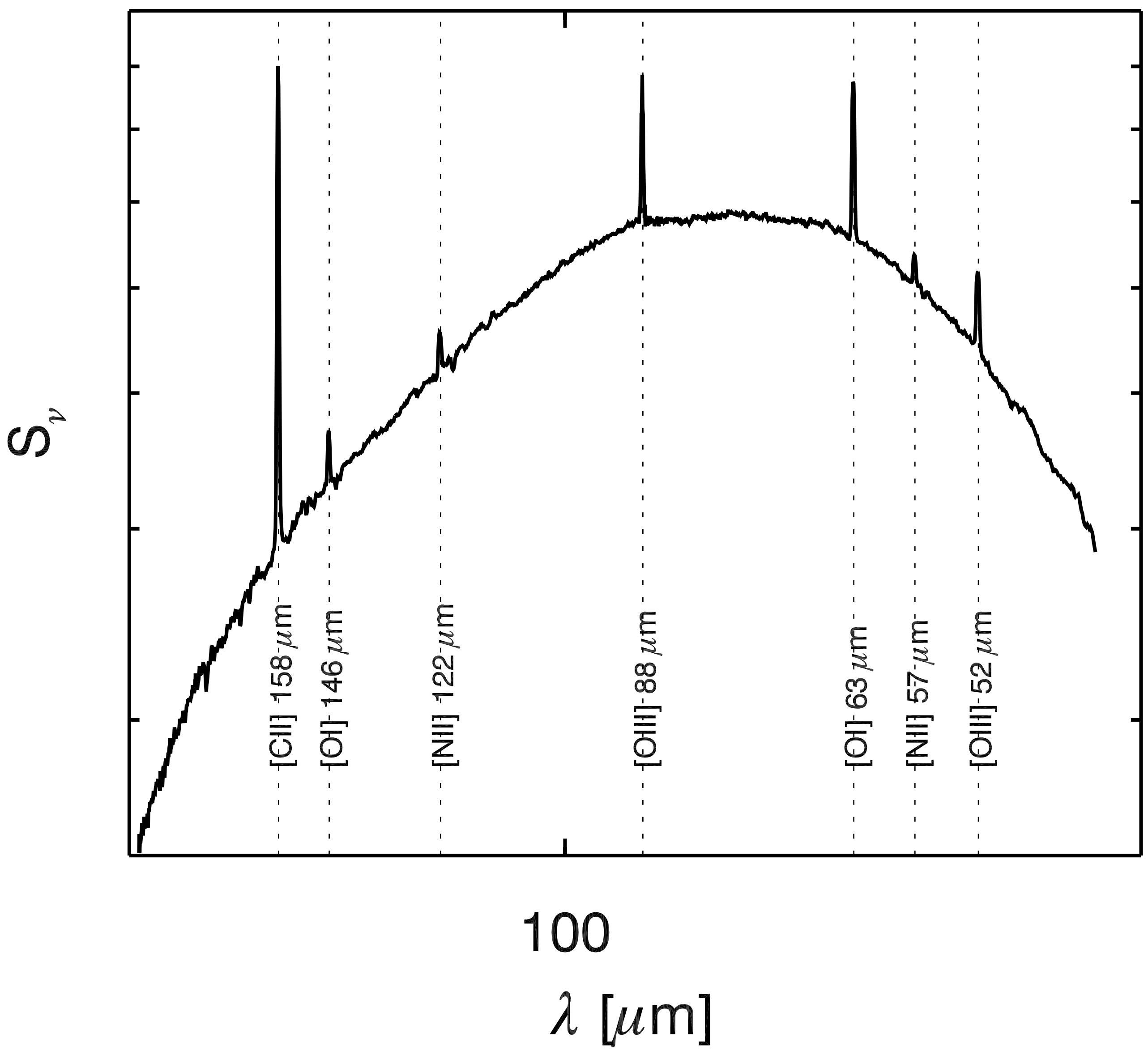
Carbon Monoxide excitation ladder:
constrains conditions of molecular gas and the radiation fields



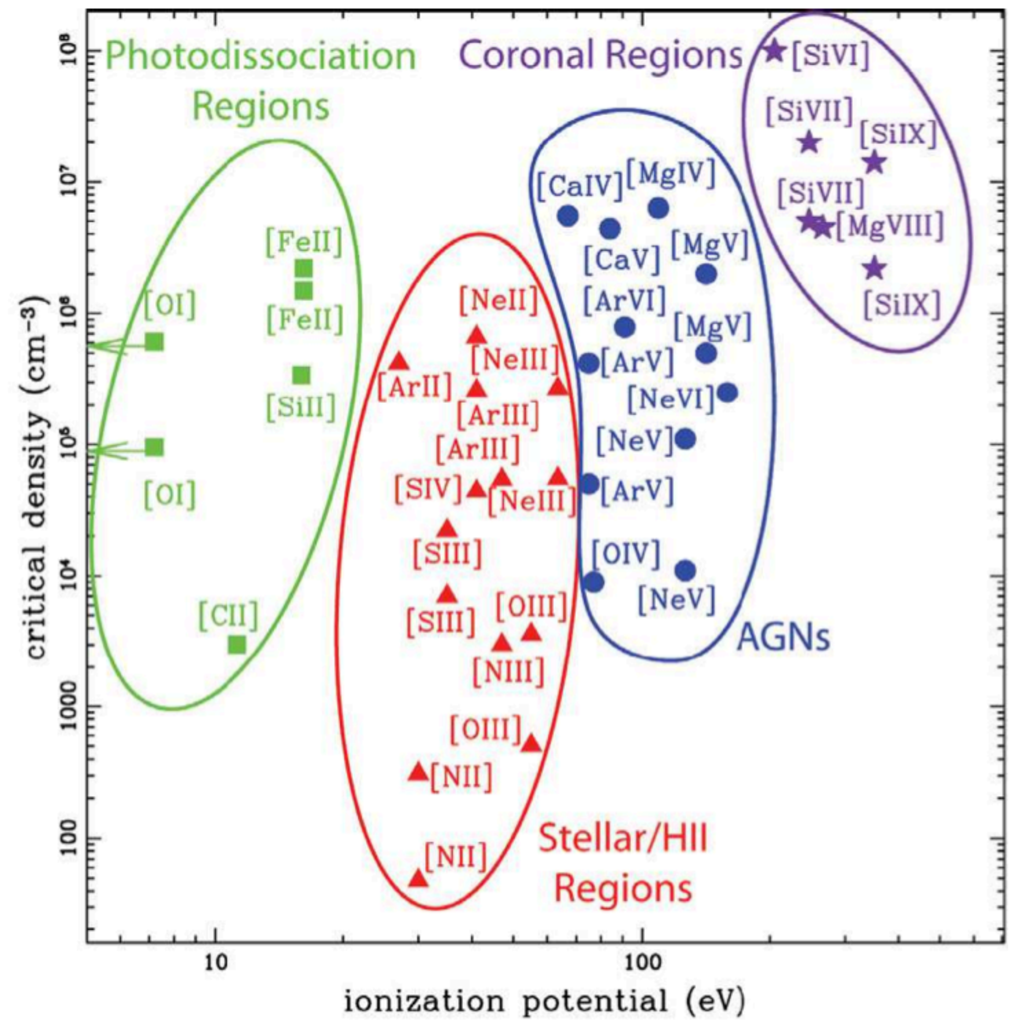


Fine structure lines

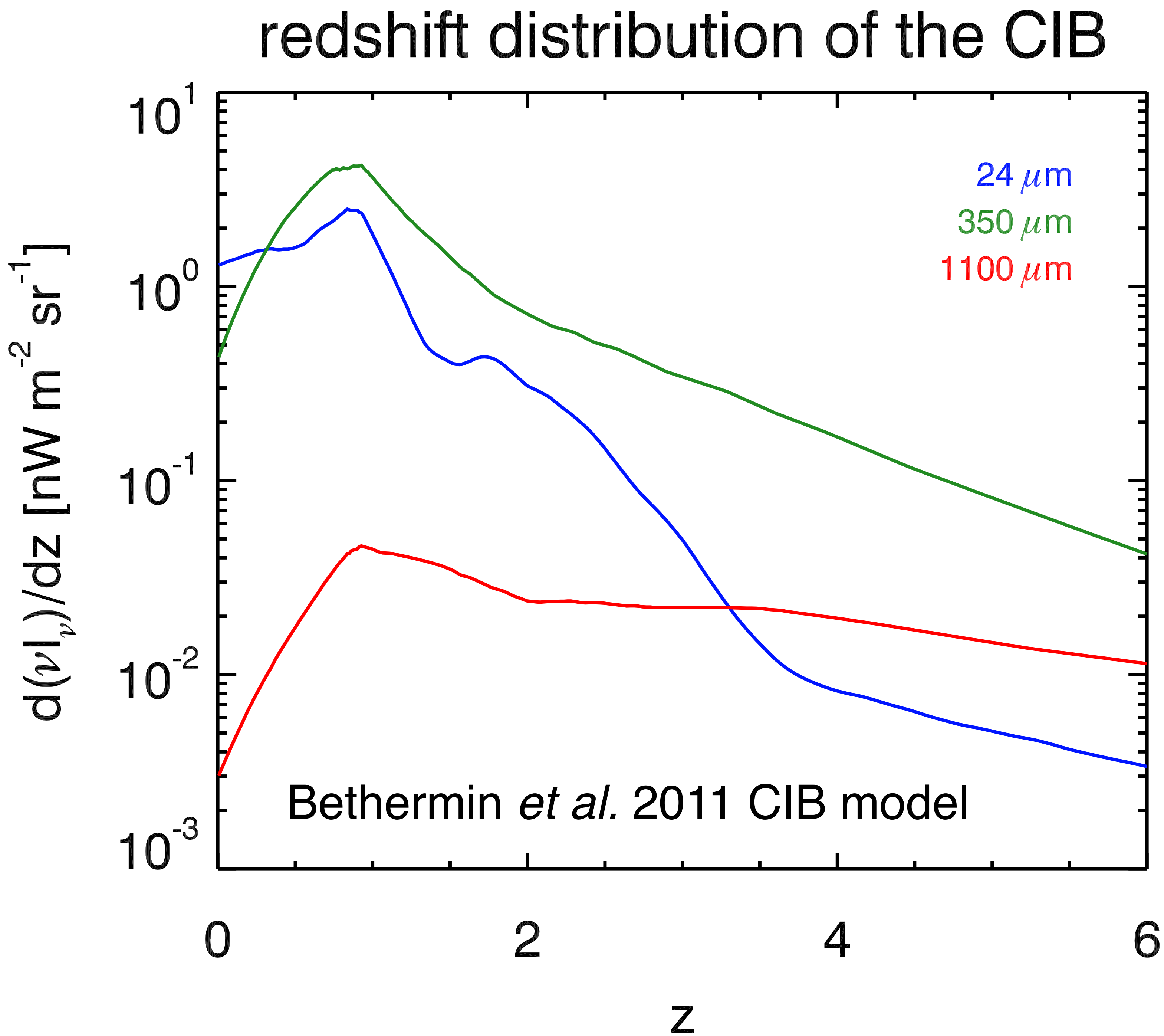
M82 ISO Spectrum



Spignolio 1992 and 2009



- Major coolants for ISM in DSFGs ⇒ C+ can be ~0.1% of total L_{FIR}
- extinction free probe of physical conditions of gas and radiation fields
- ratio of lines disentangles relative SF and AGN contribution
- ISO studied z~0, progress being made with *Herschel*, APEX, ALMA at high redshift



Longer wavelengths probe higher redshift components of the CIB

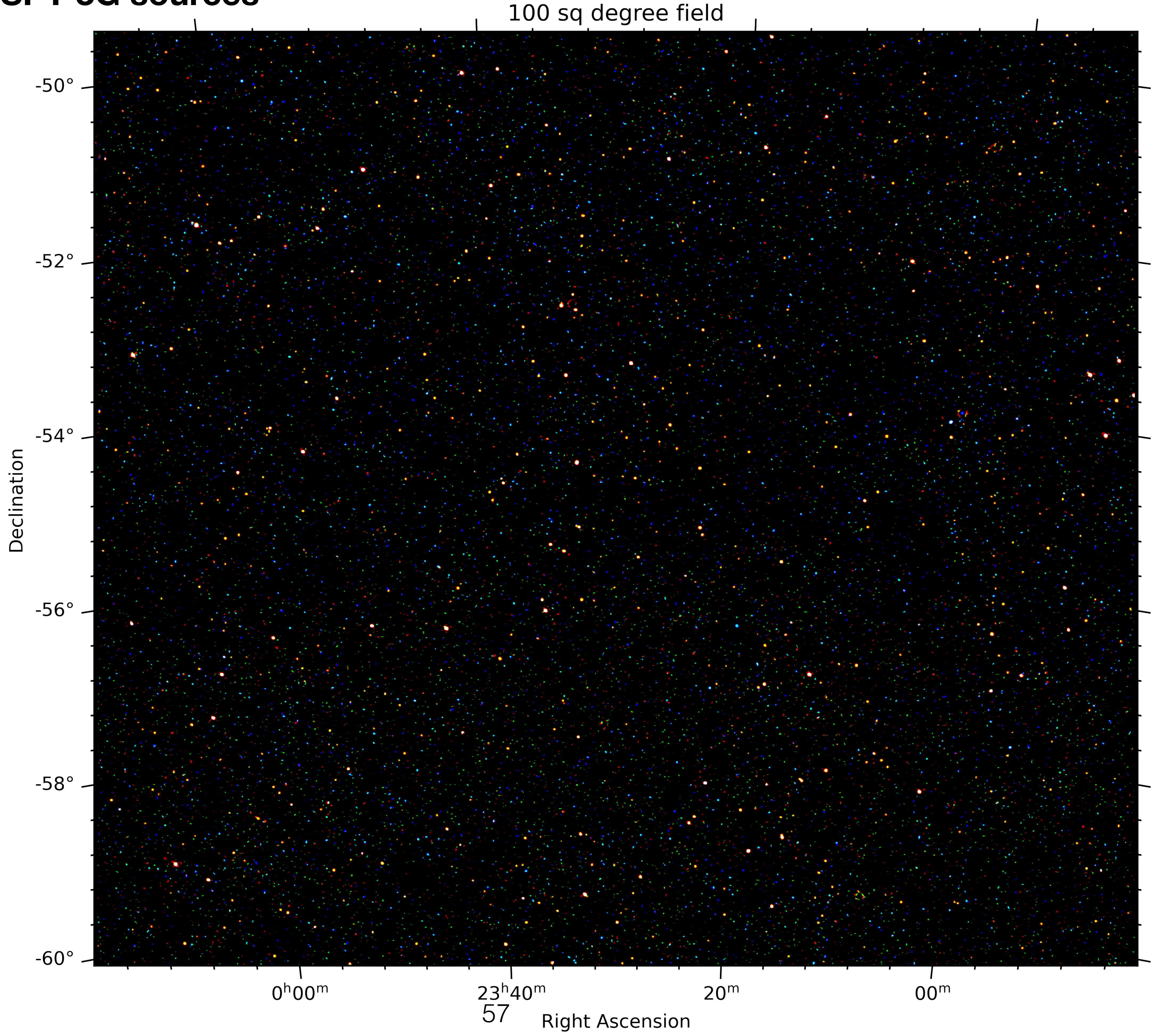
How to get redshifts?

Photo-z's are unreliable.

Coarse beam + faint, dust obscured objects at high redshift make optical spectroscopic redshifts very difficult.

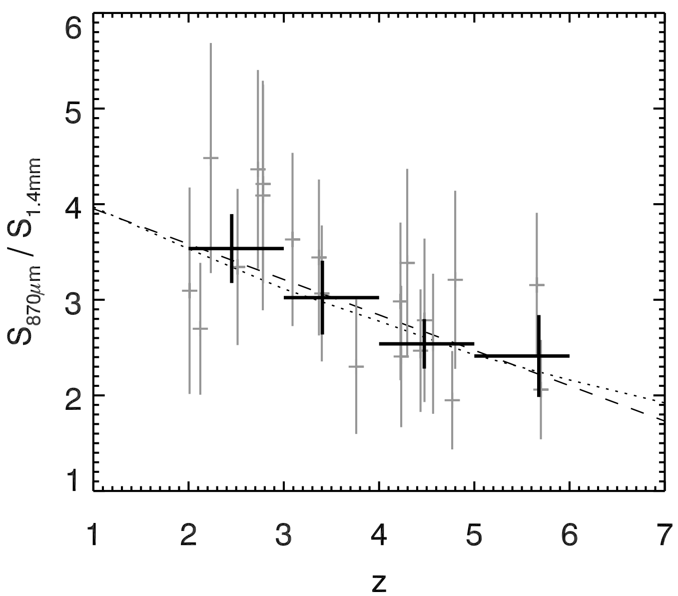
100 deg² of SPT-3G sources

95 GHz
150 GHz
220 GHz



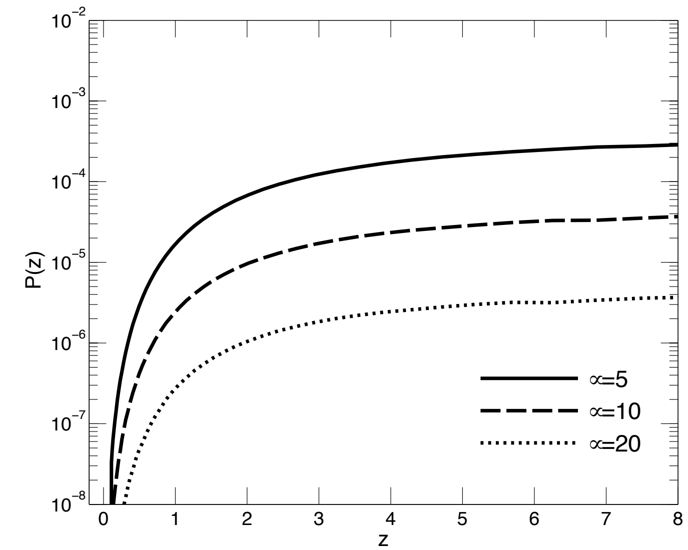
The SPT 1.4mm redshift distribution

long wavelength selection



strong lensing selection

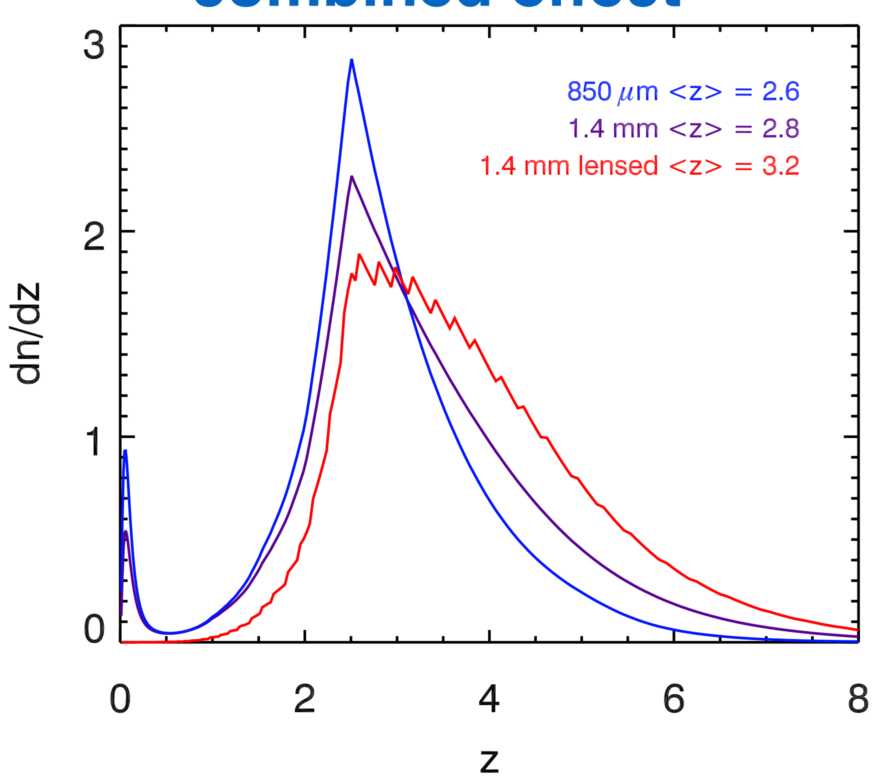
Hezaveh & Holder 2011 lens model



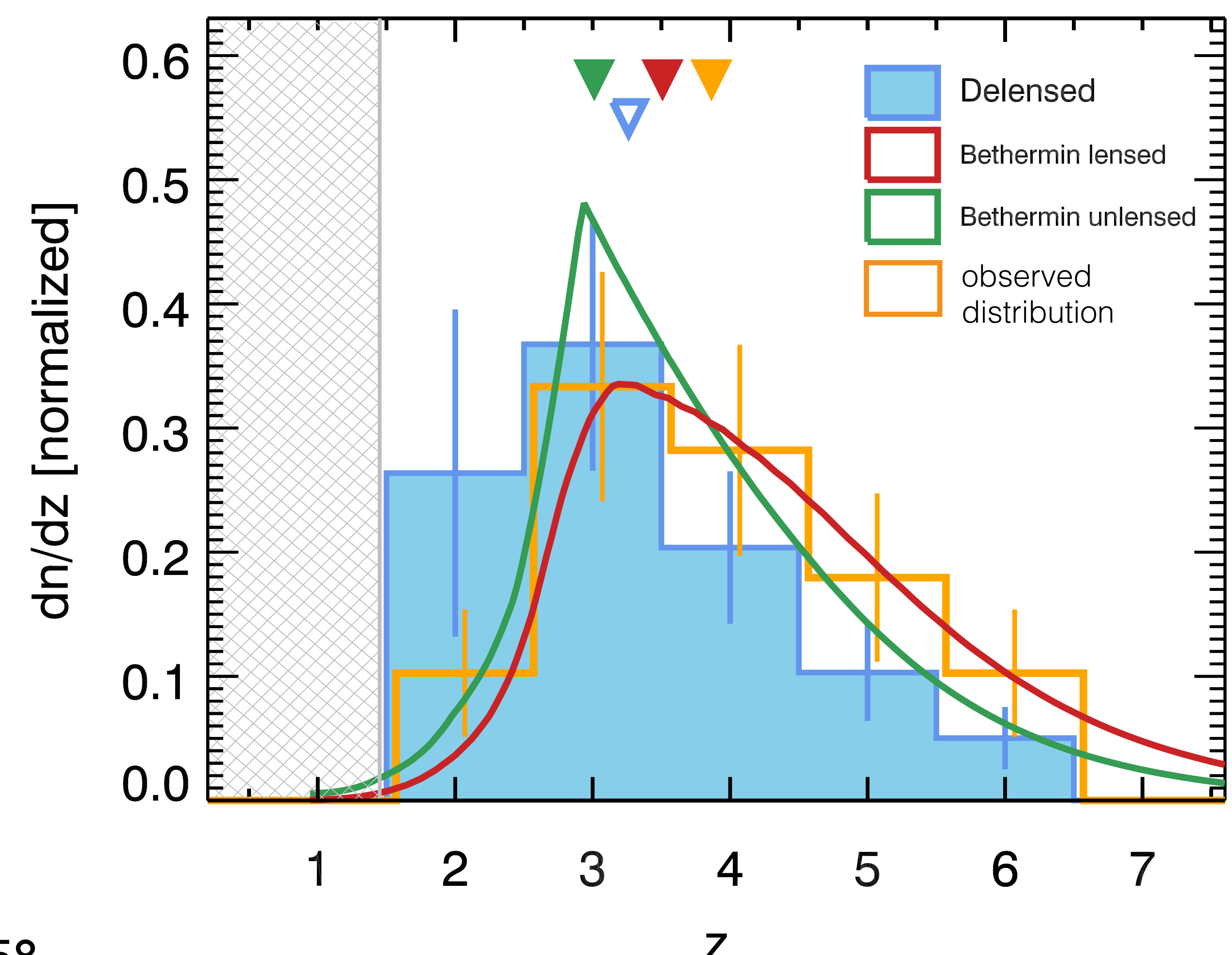
Strandet *et al.* 2016

Bethermin 2012 CIB model
+
Hezaveh lens model

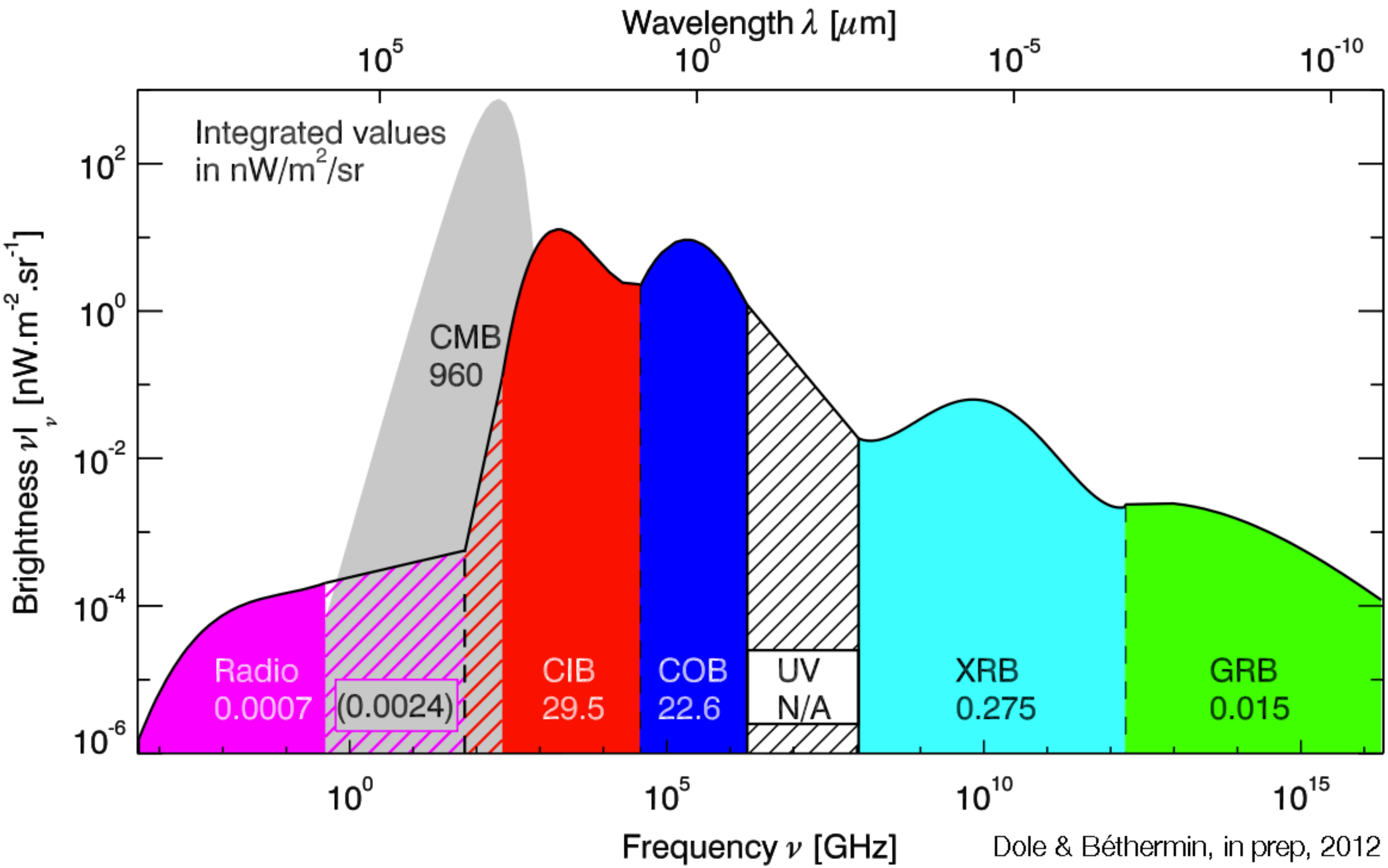
combined effect

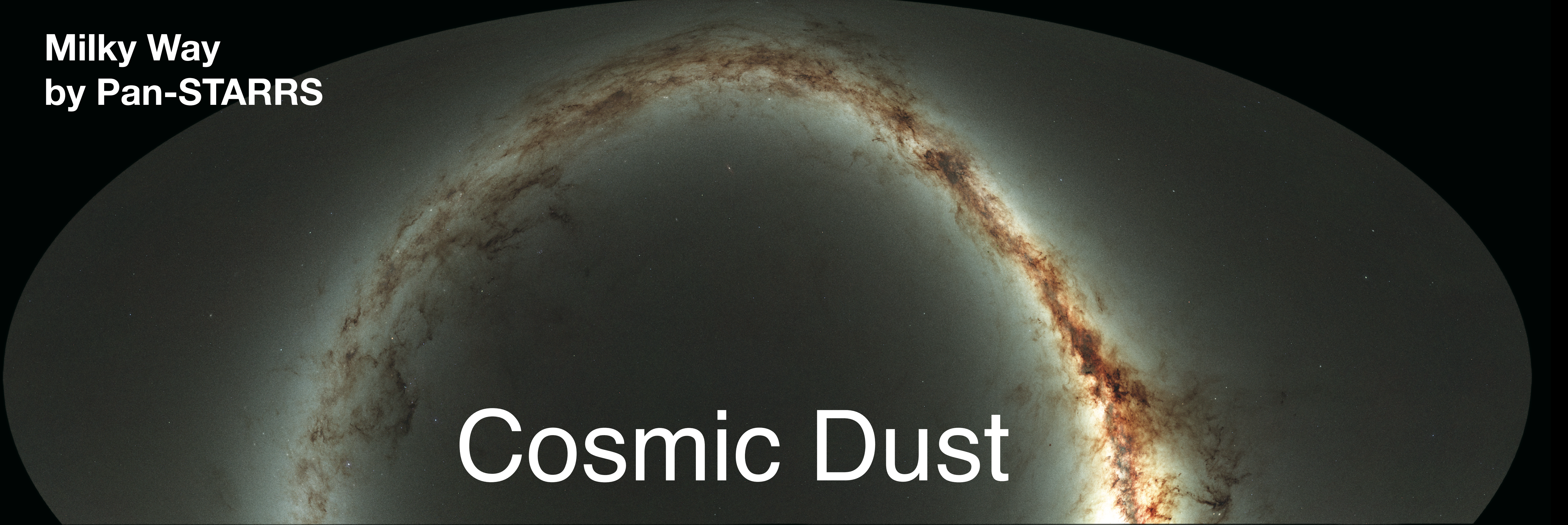


delensed 1.4mm redshift distribution

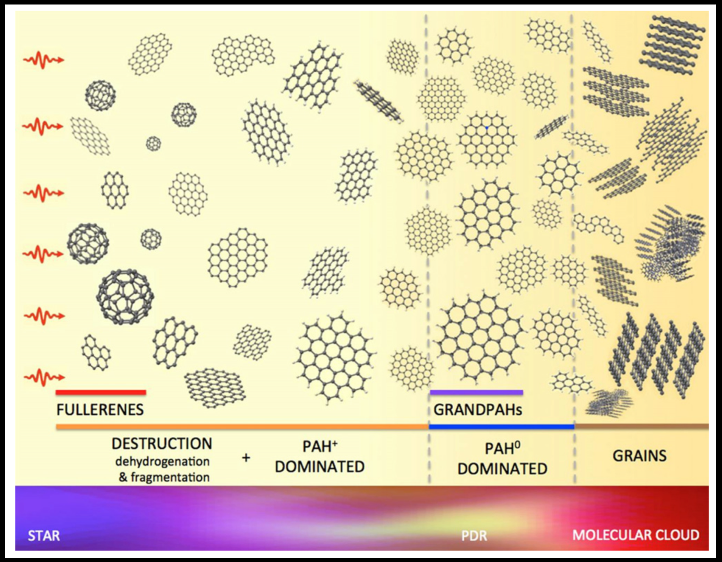


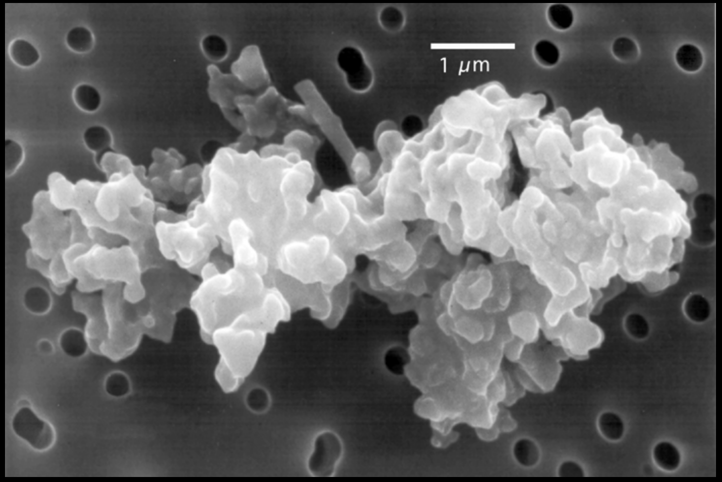
Spectrum of the Cosmic Background



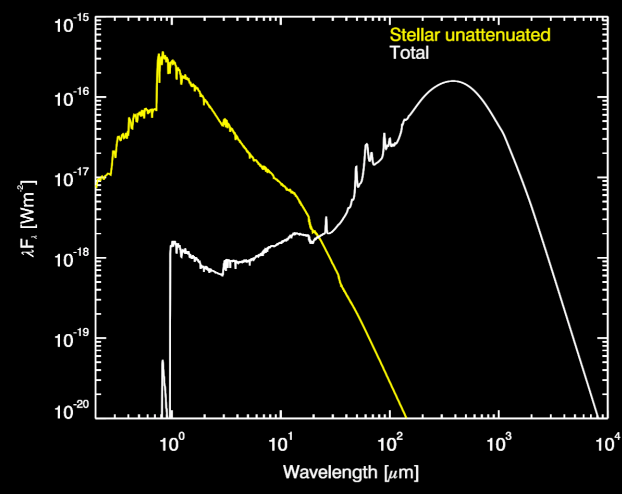


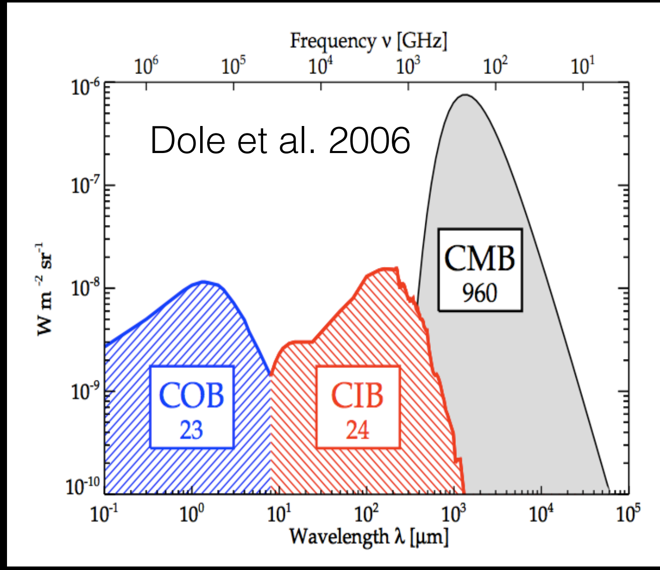
Cosmic Dust





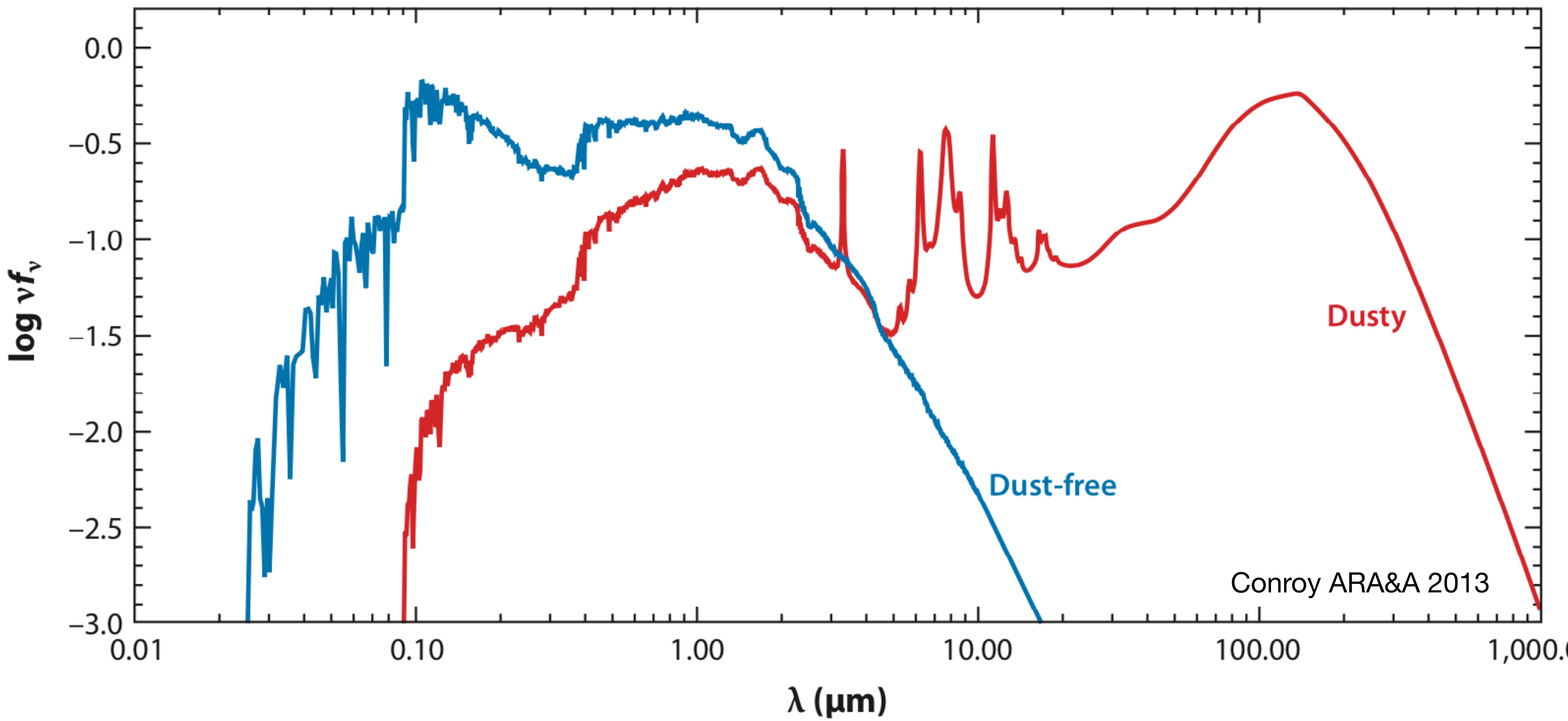
- Dust was first noticed a century ago by astronomers attempting to understand the structure the Milky Way
- The Infrared Astronomical Satellite (IRAS) satellite enabled the systematic study of dust in 1983.
- The Cosmic Background Explorer (COBE) satellite showed that half of the energy produced since the Big Bang has been absorbed and reemitted by dust.
- The majority of dust mass is produced by stars at the end of their lives, either by asymptotic giant branch (AGB) stars or super novae (SN) remnants.
- Star formation *always* occurs behind a dense shroud of dust.
- Dust is a crucial constituent in the formation and evolution of everything from planets to super massive black holes.
- Dust represents the rise of complex chemistry in the early universe and may even be a catalyst for the ingredients necessary for life





Why the Far-Infrared (FIR) ?

"God lives at 100 microns"
—Alan Sandage



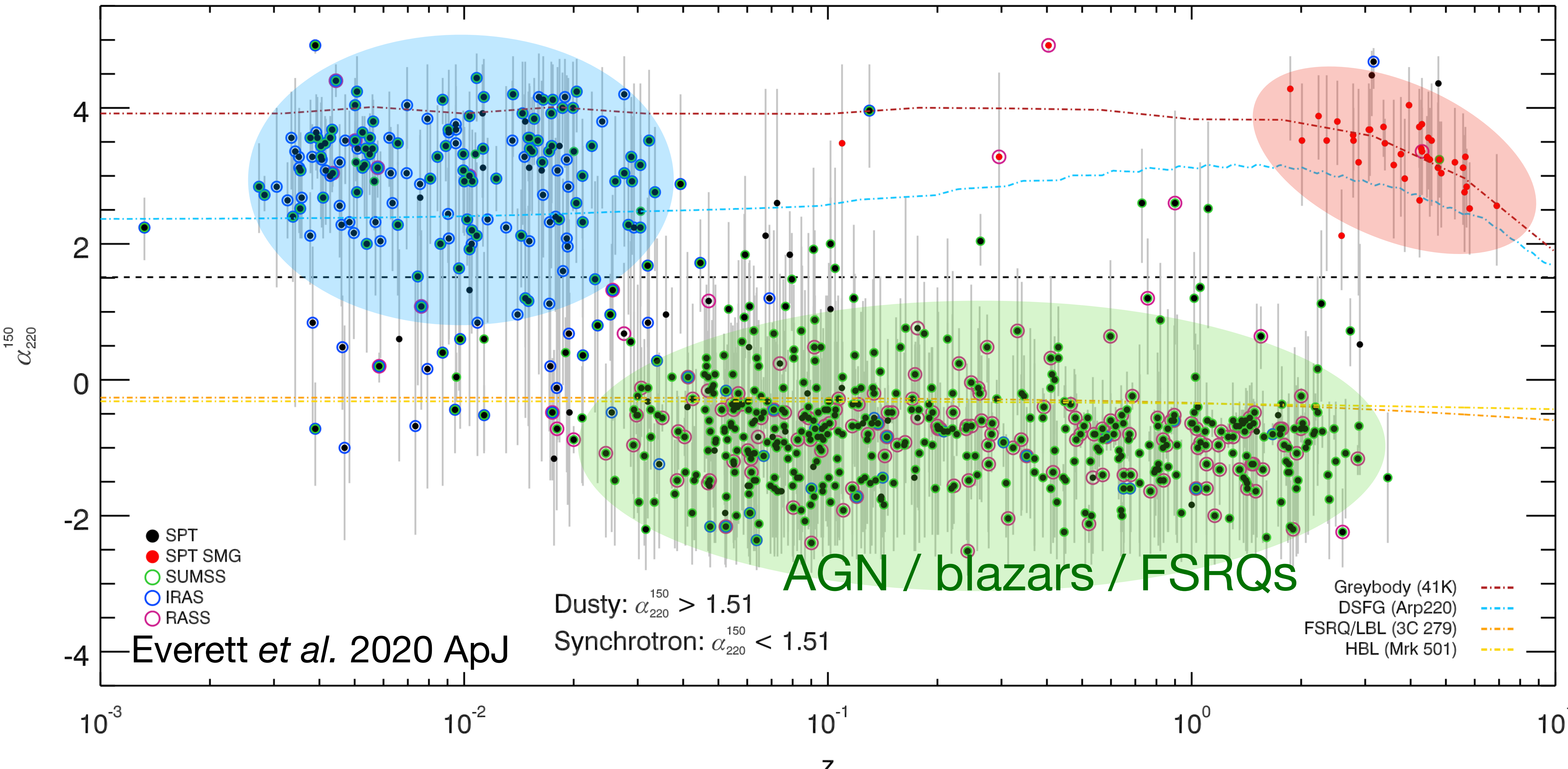
The majority of energy produced/released since the Big Bang has been absorbed and reprocessed by dust.

mm color verses redshift

$$\frac{S_1}{S_2} = \left(\frac{\nu_1}{\nu_2}\right)^{\alpha} \qquad \frac{S_{150\mathrm{GHz}}}{S_{220\mathrm{GHz}}} = \left(\frac{150}{220}\right)^{\alpha}$$

"IRAS Galaxies"
(z < 0.1 SFGs)

"SMGs"
(z > 1 DSFGs)



mm-wave source counts

SPT-3G Archipley *et al. in prep*

SPT-SZ Everett *et al.* 2020