Gravitational lensing reveals extreme dust-obscured star formation in quasar host galaxies

Hannah Stacey

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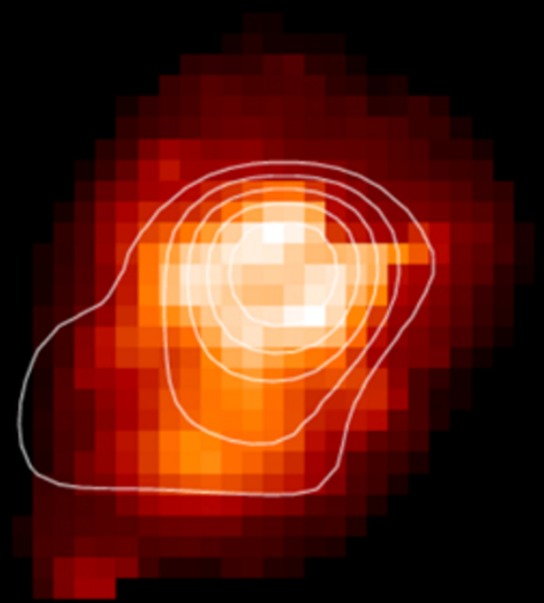
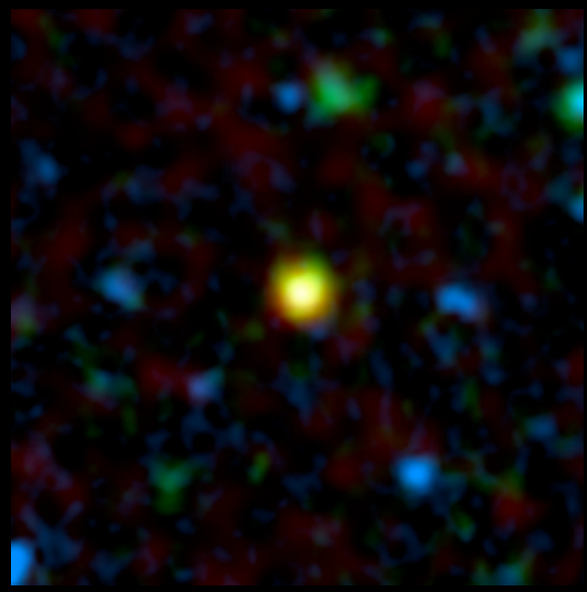
ASTRON
Netherlands Institute for Radio Astronomy

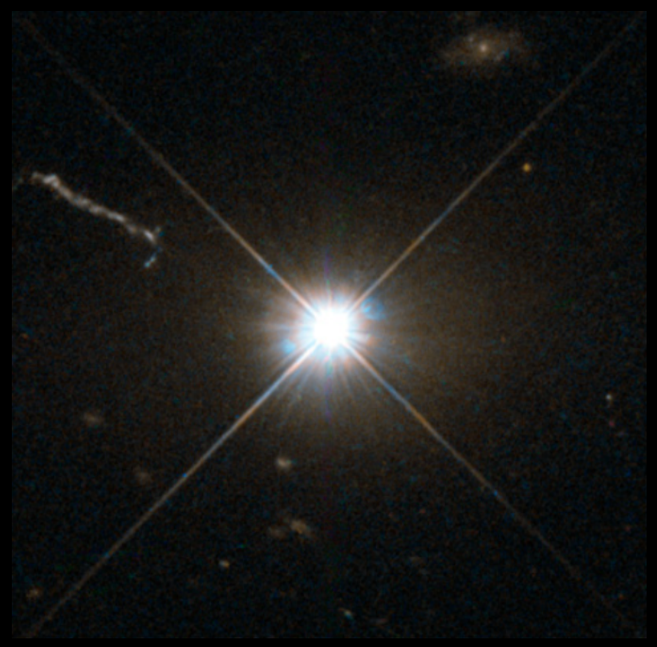
dusty star forming galaxy



dust-obscured quasar



unobscured quasar

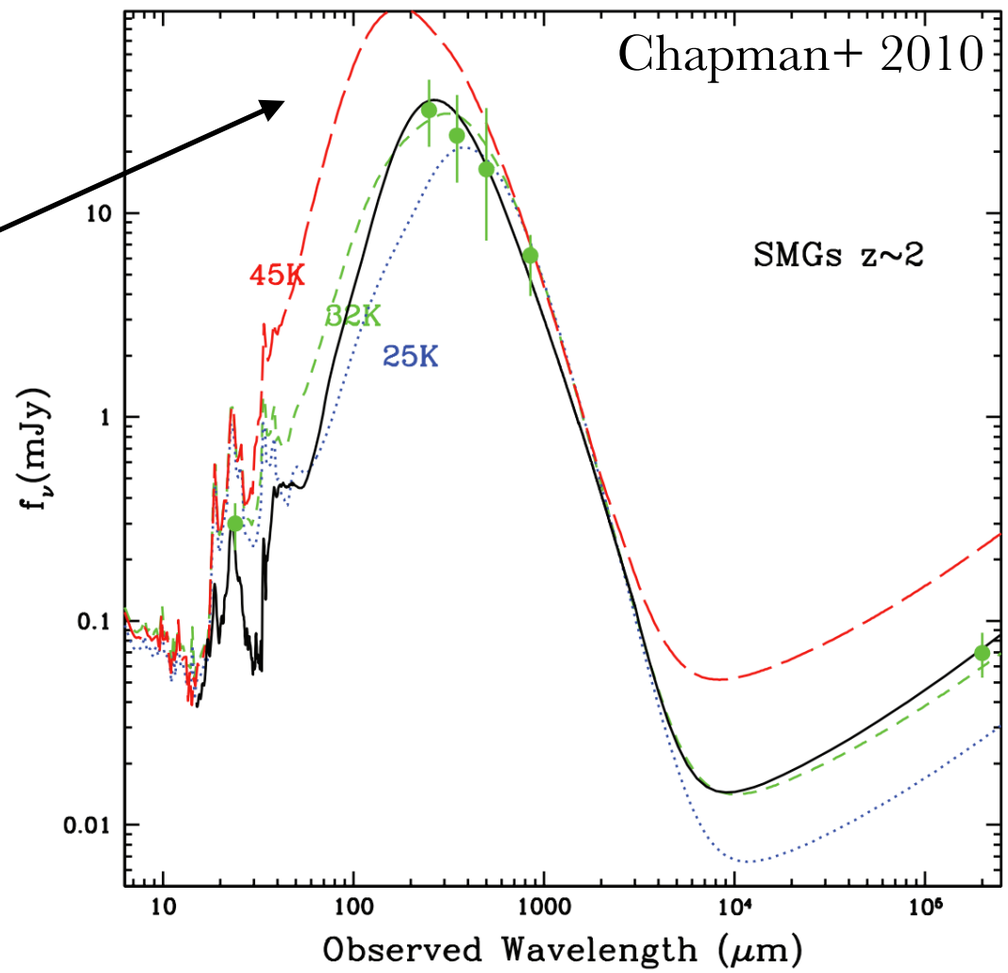


passive spheroidal

SMG vs obscured QSO

dust bump

$$S_\nu = \frac{2h}{c^2}\frac{\nu^{3+\beta}}{e^{\frac{h\nu}{kT}}-1}\Delta\Omega$$



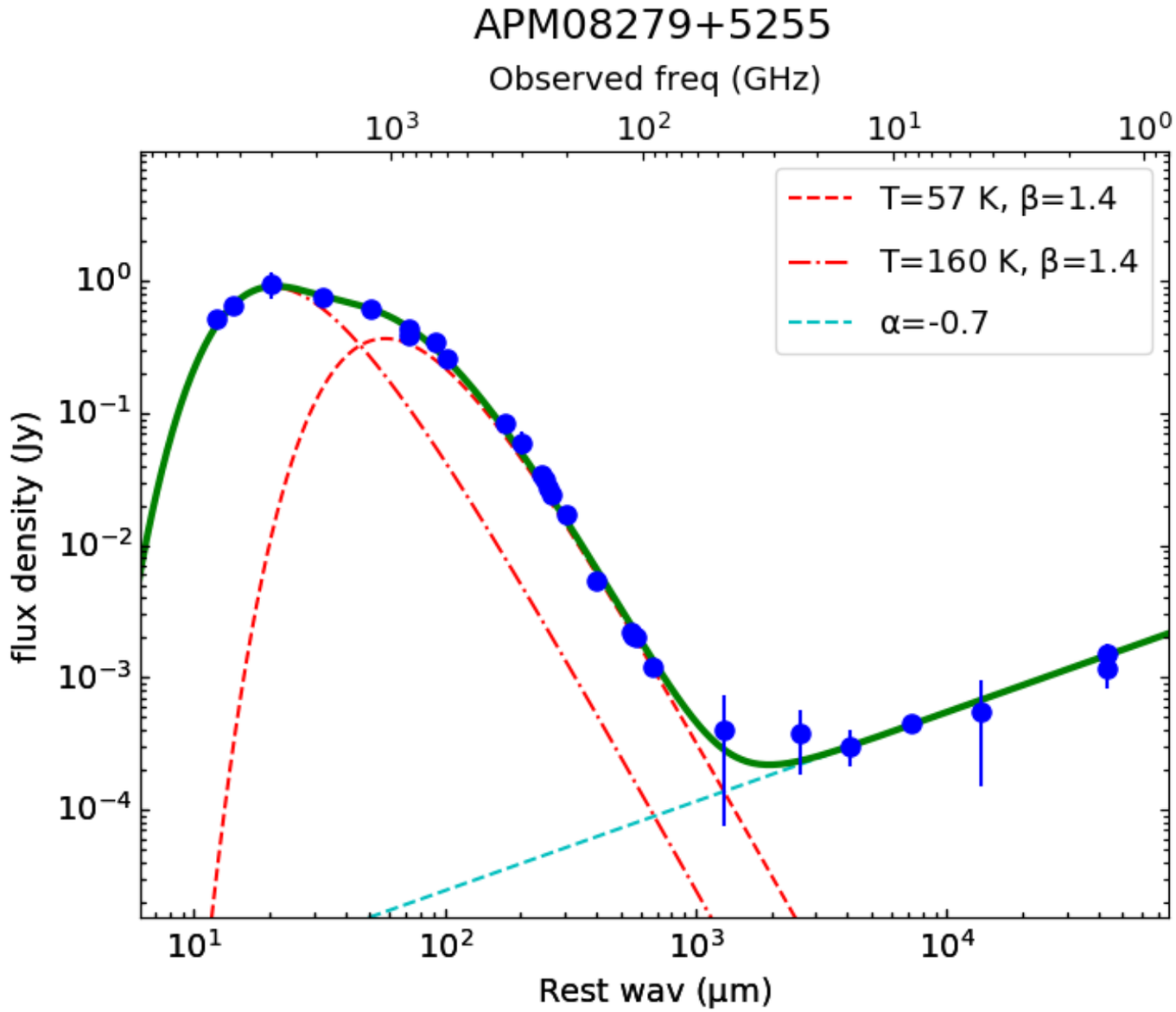
synchrotron

$$S_\nu \propto \nu^\alpha$$

- SMG multiple components of molecular gas, 5-25 kpc (Ivison et al. 2010, 2011)
- QSO single compact component, higher excitation temps, 0.5-2 kpc (Riechers et al. 2006, 2011)

Motivation

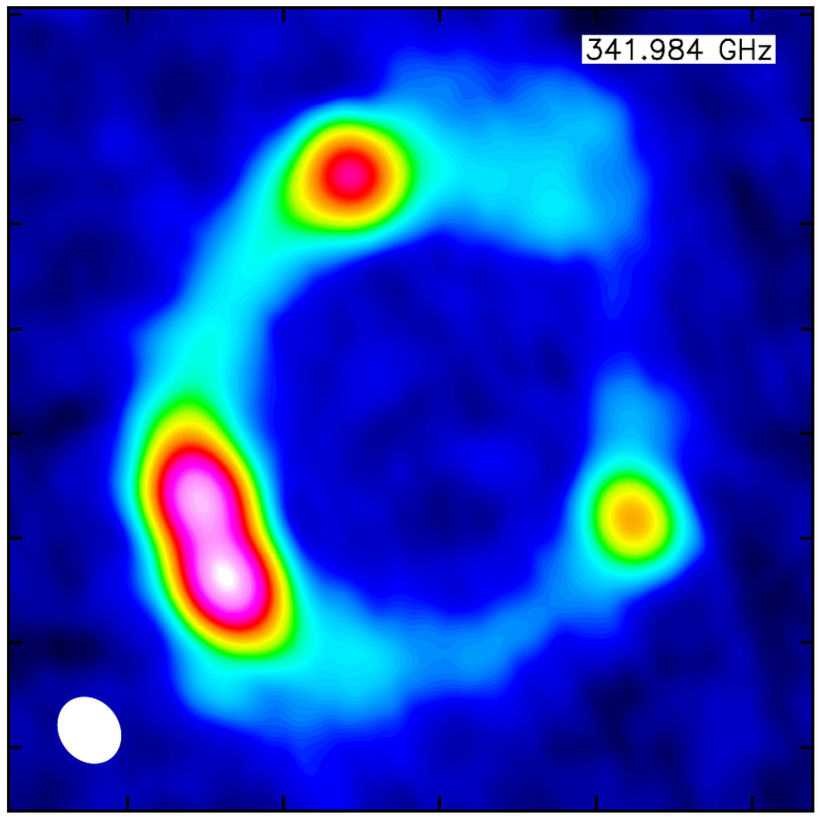
- How many quasars have FIR emission?
- How much SF?
- Where is it?
- What contribution from AGN or SF?



- Barvainis & Ivison (2002) 23/40 quasars at 850μm SCUBA

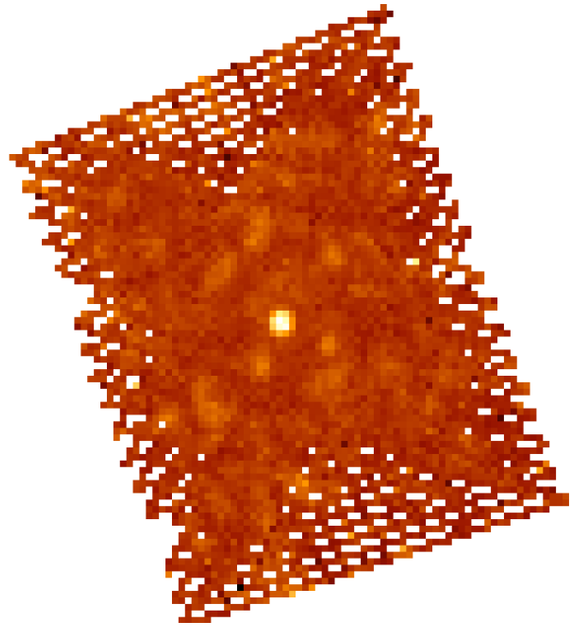
Why gravitationally lensed quasars?

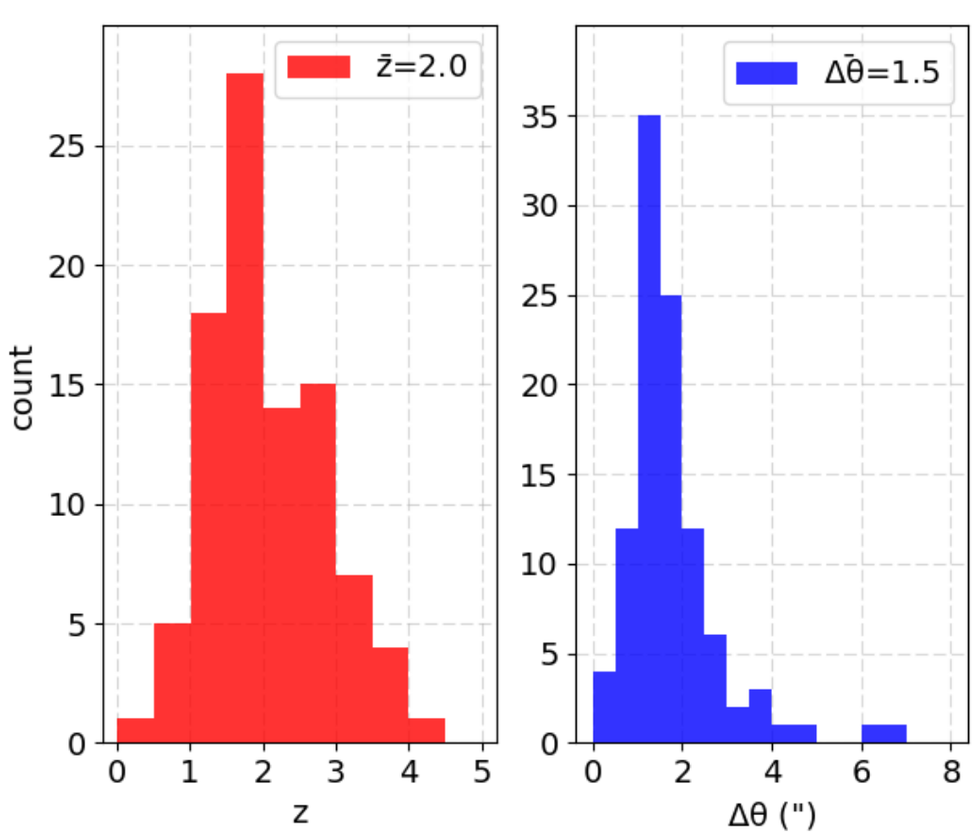
- Intrinsically faint sources
- Different selection effects
- High resolution follow-up
- BUT! Need good lens modelling



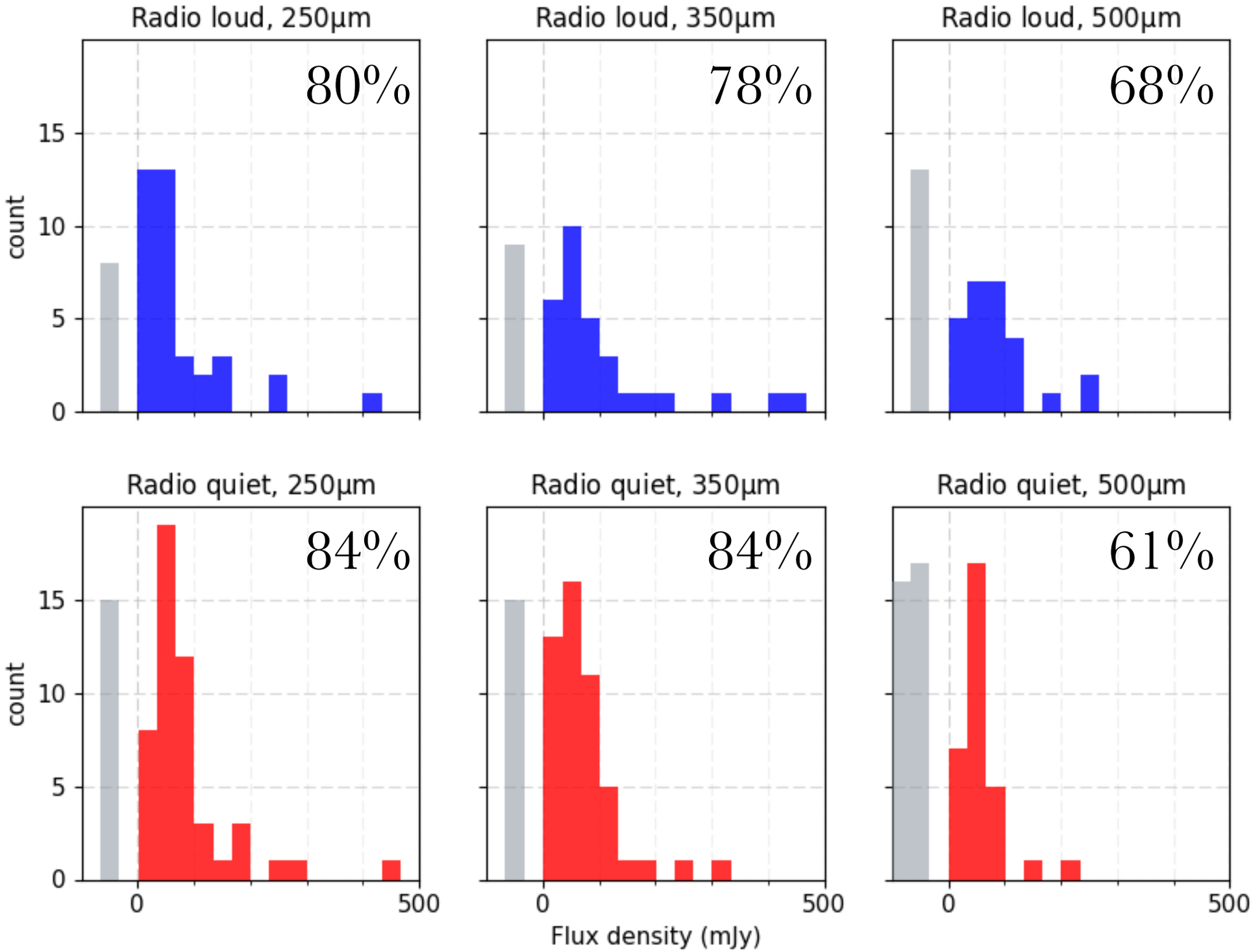
The Herschel sample

- **104** lensed quasars
- 40 radio-loud, 84 radio-quiet
- CLASS, SQLS, HST etc
- 250, 350, 500μm
- Resolution 18-35”



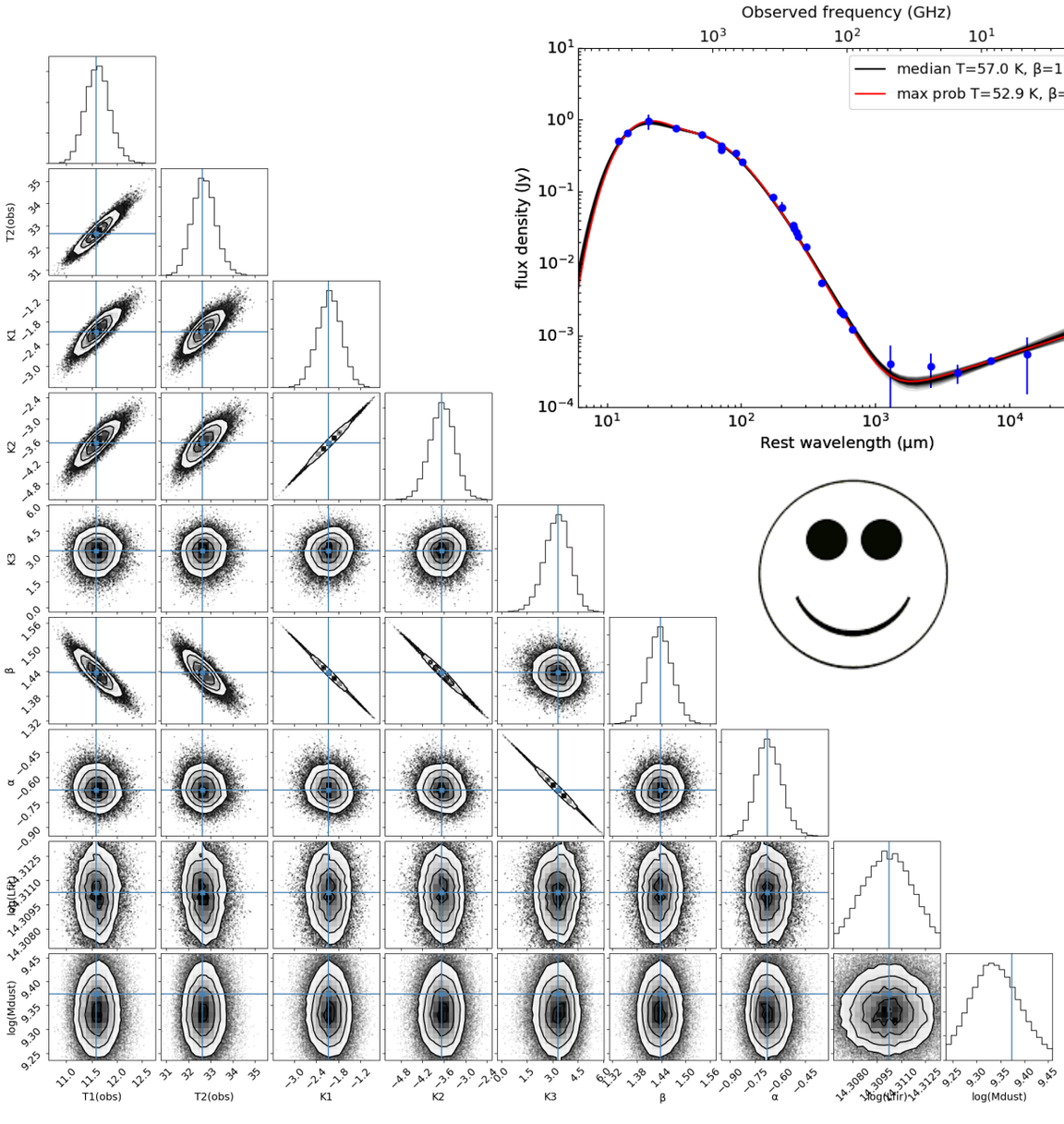


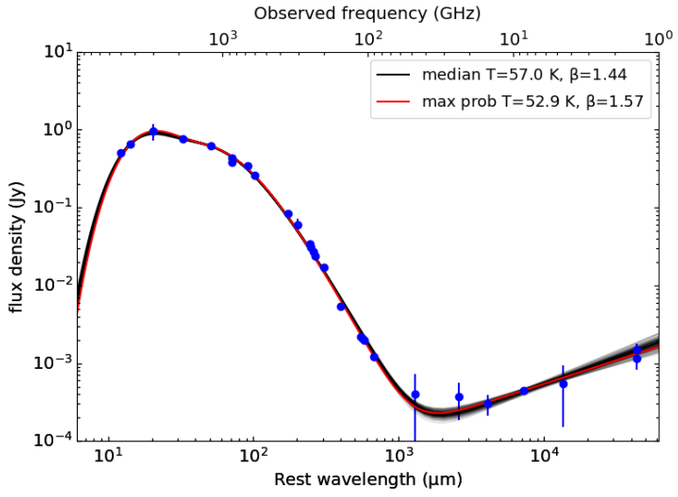
Detection rate in SPIRE bands

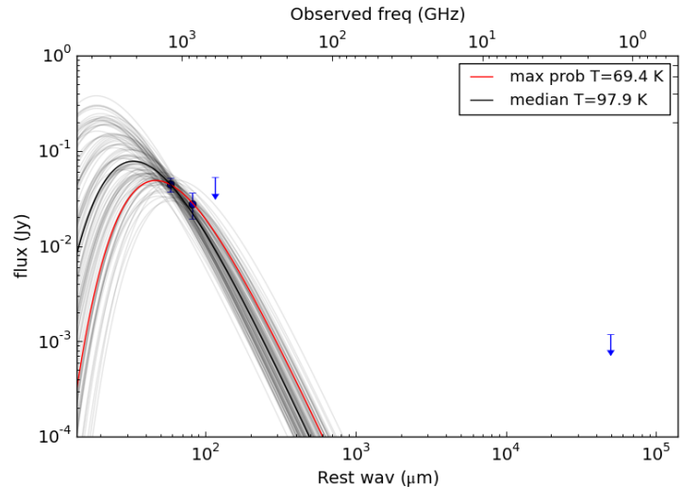


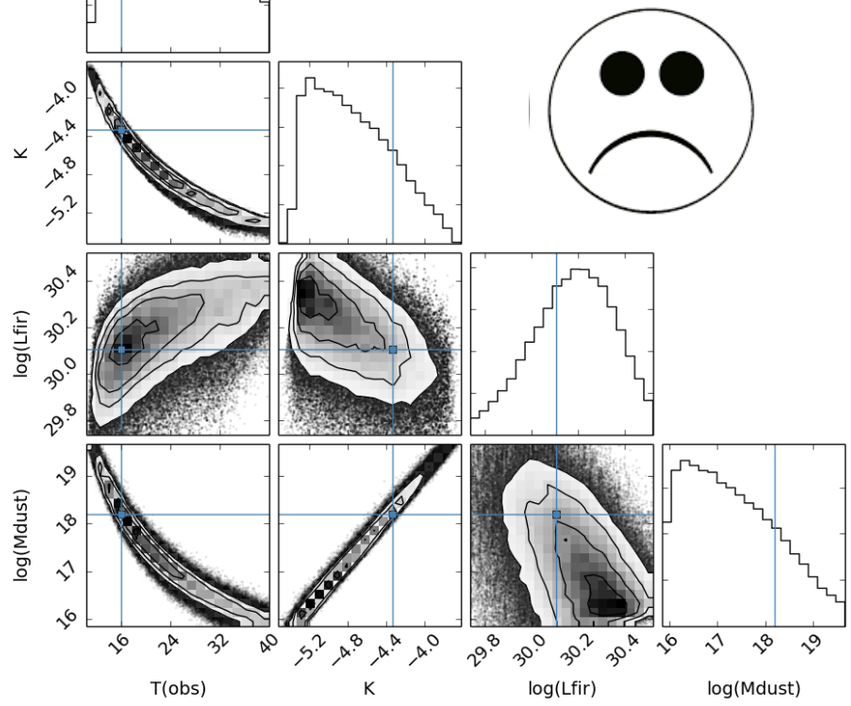
SED fitting

- Fitting 1-7 parameters with MCMC analysis
- Account for correlation in error determination







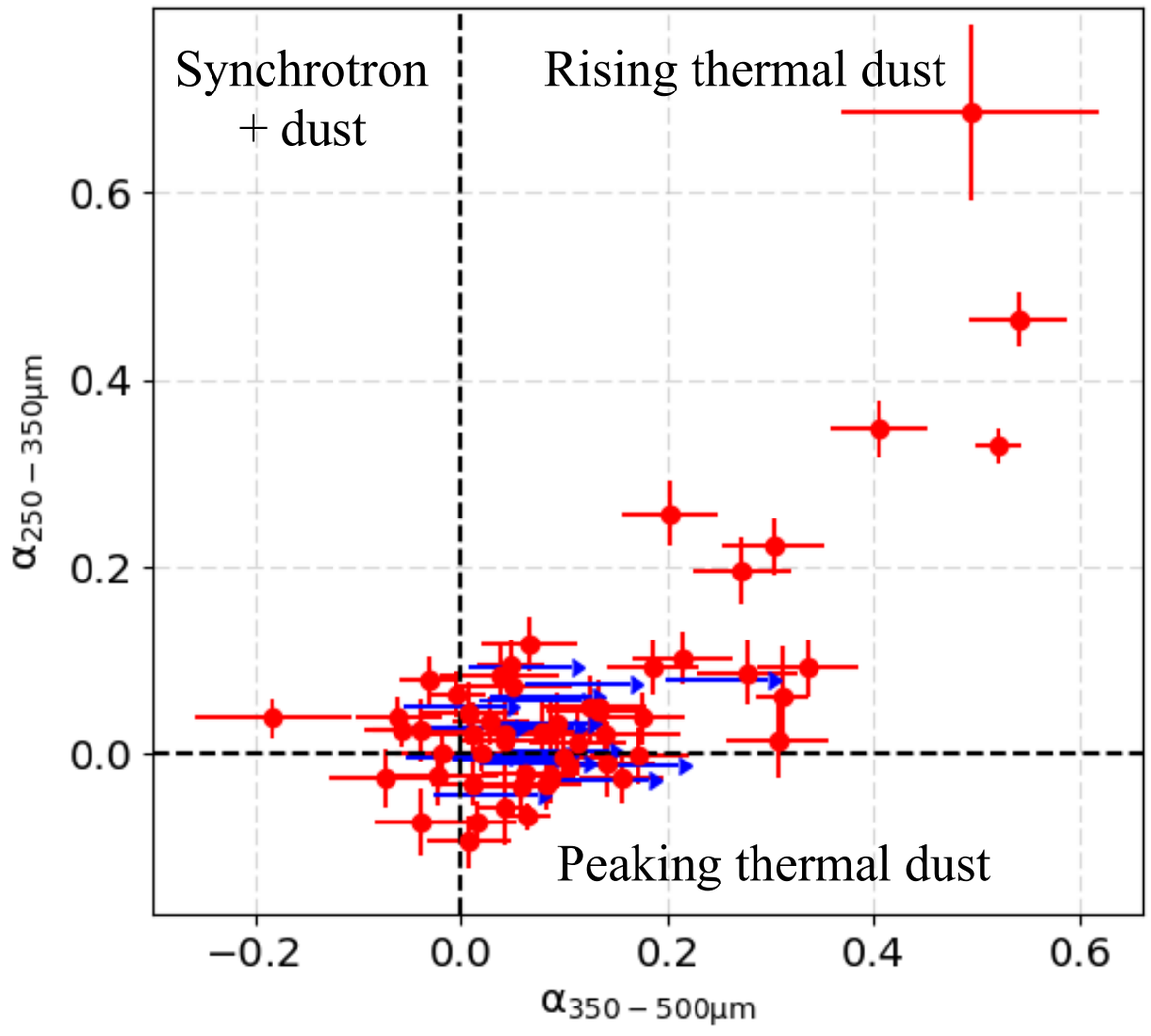


Results of SED fitting

- 82 (79%) strong evidence of dust emission

- 72 (69%) dust temperatures <50 K typical of star formation

- Comparison with DSFGs in Magnelli+ 2012



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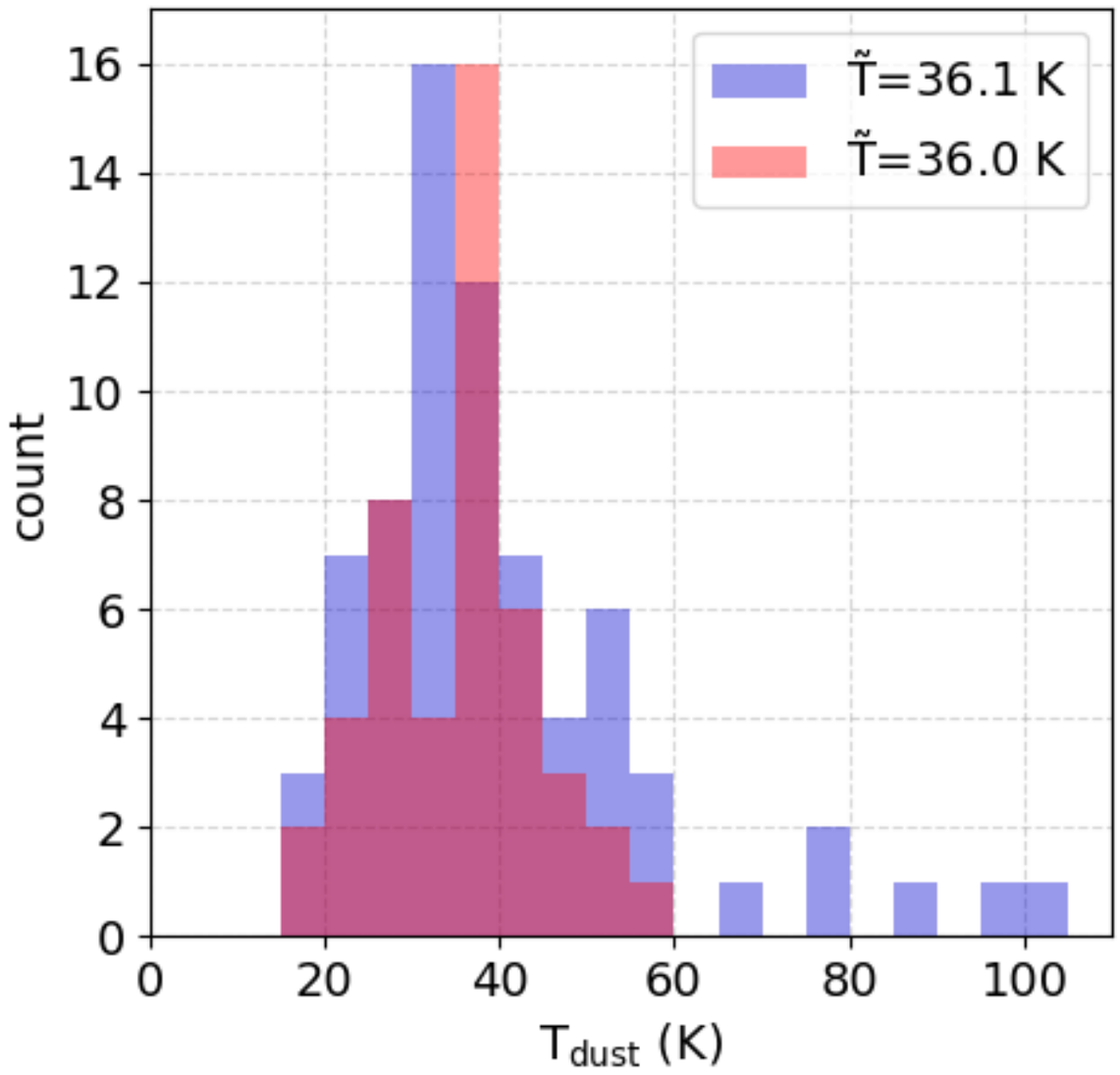
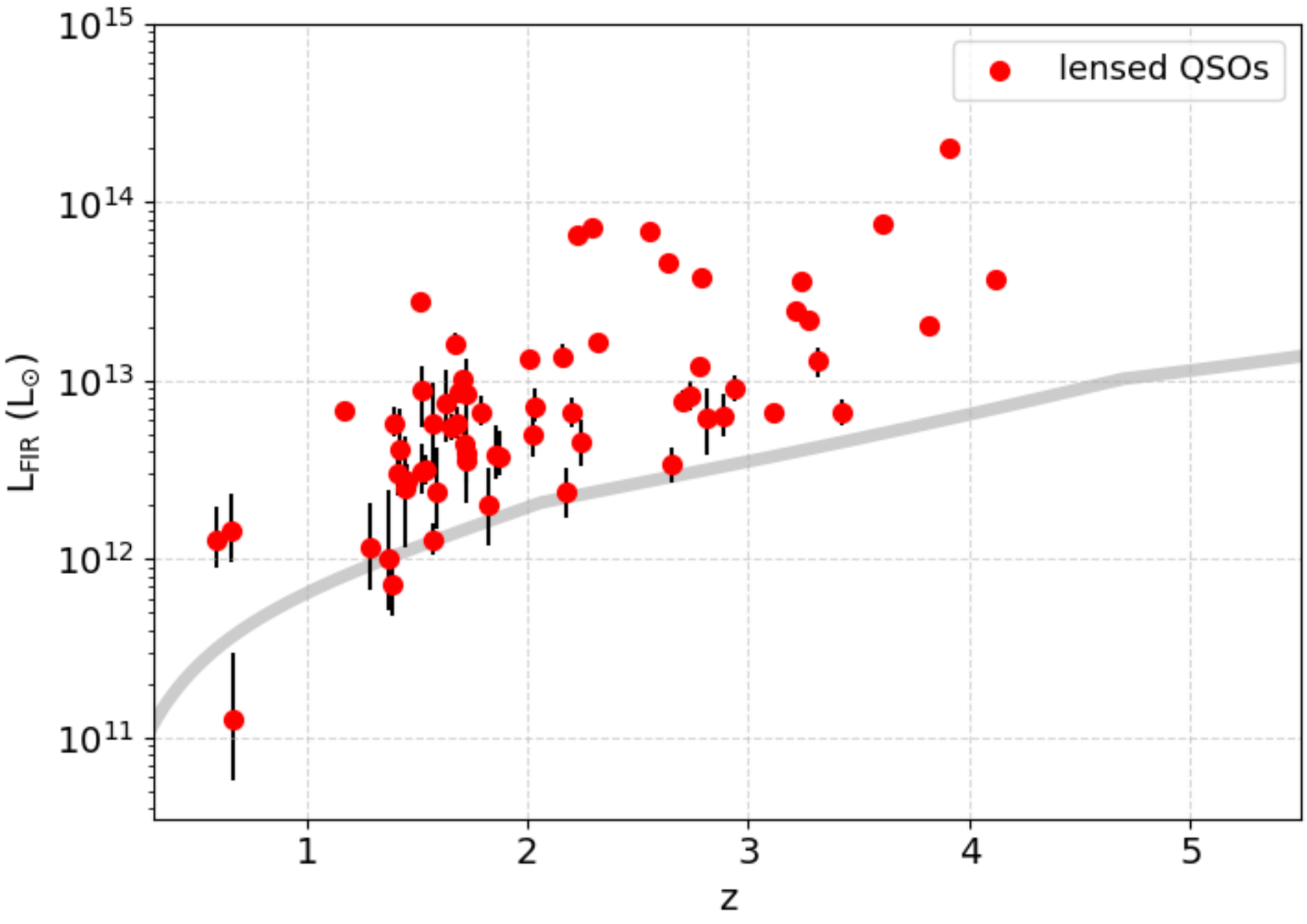


Intrinsic luminosities of quasar sample



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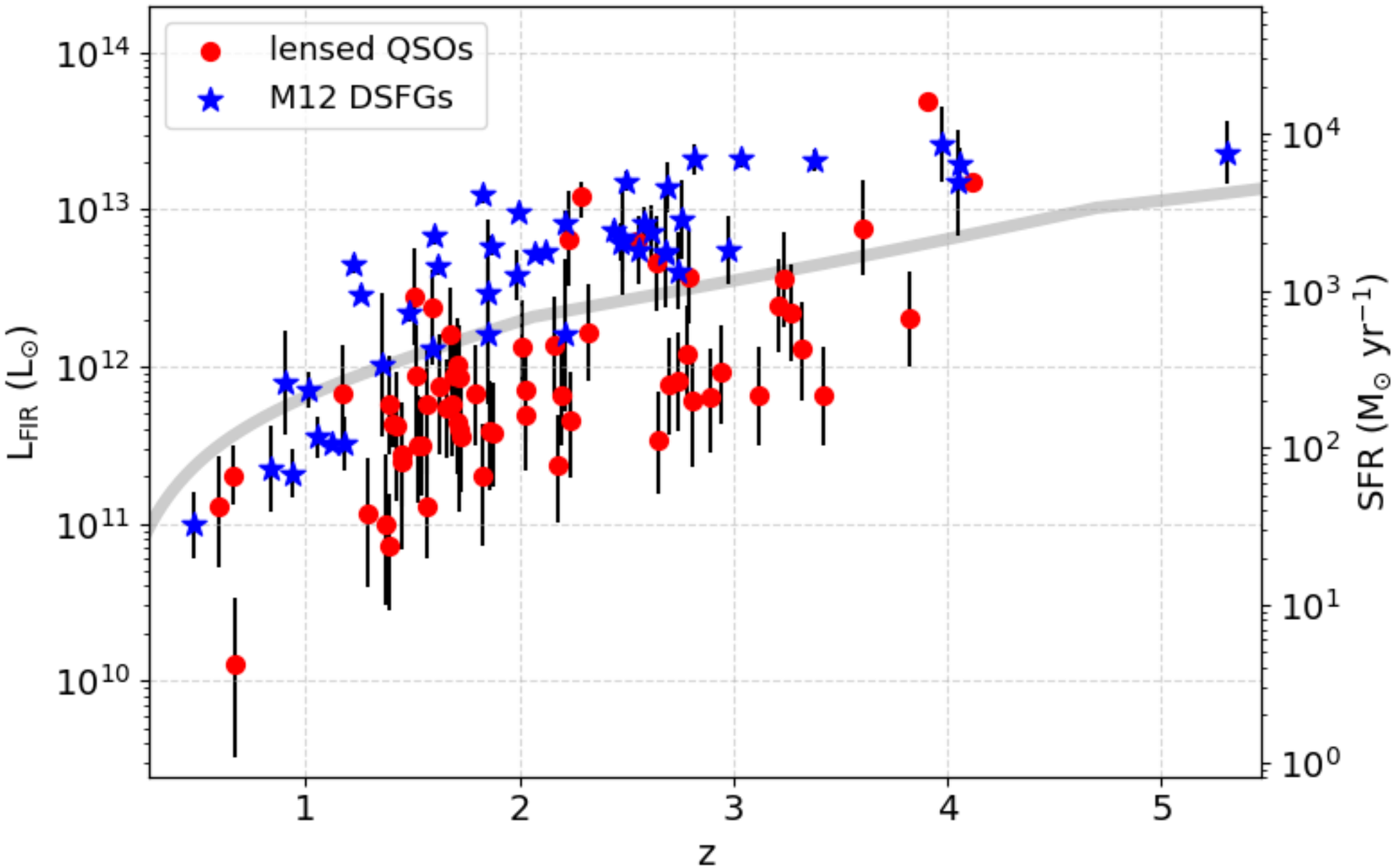
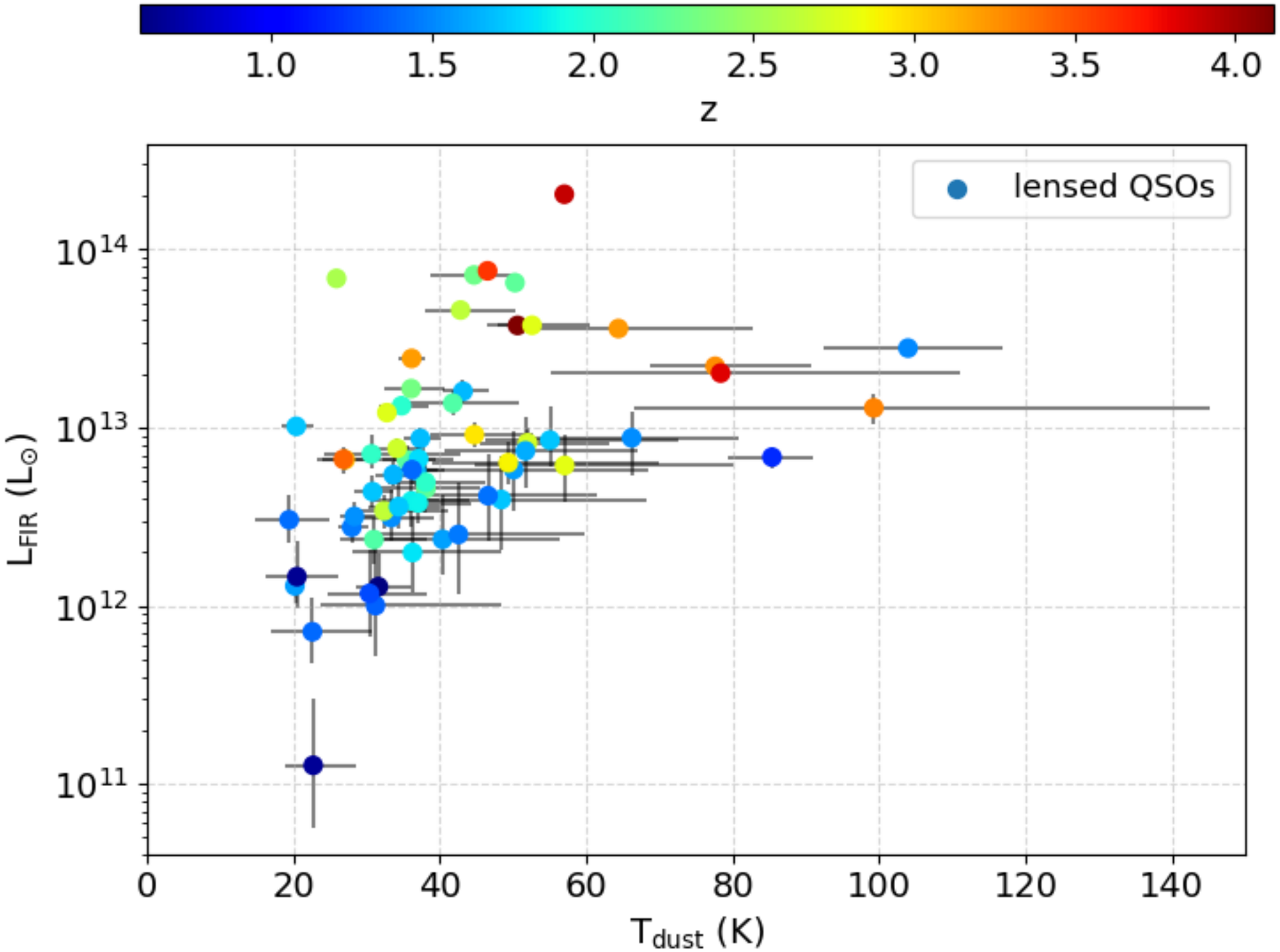


Luminosity-temperature of quasar sample



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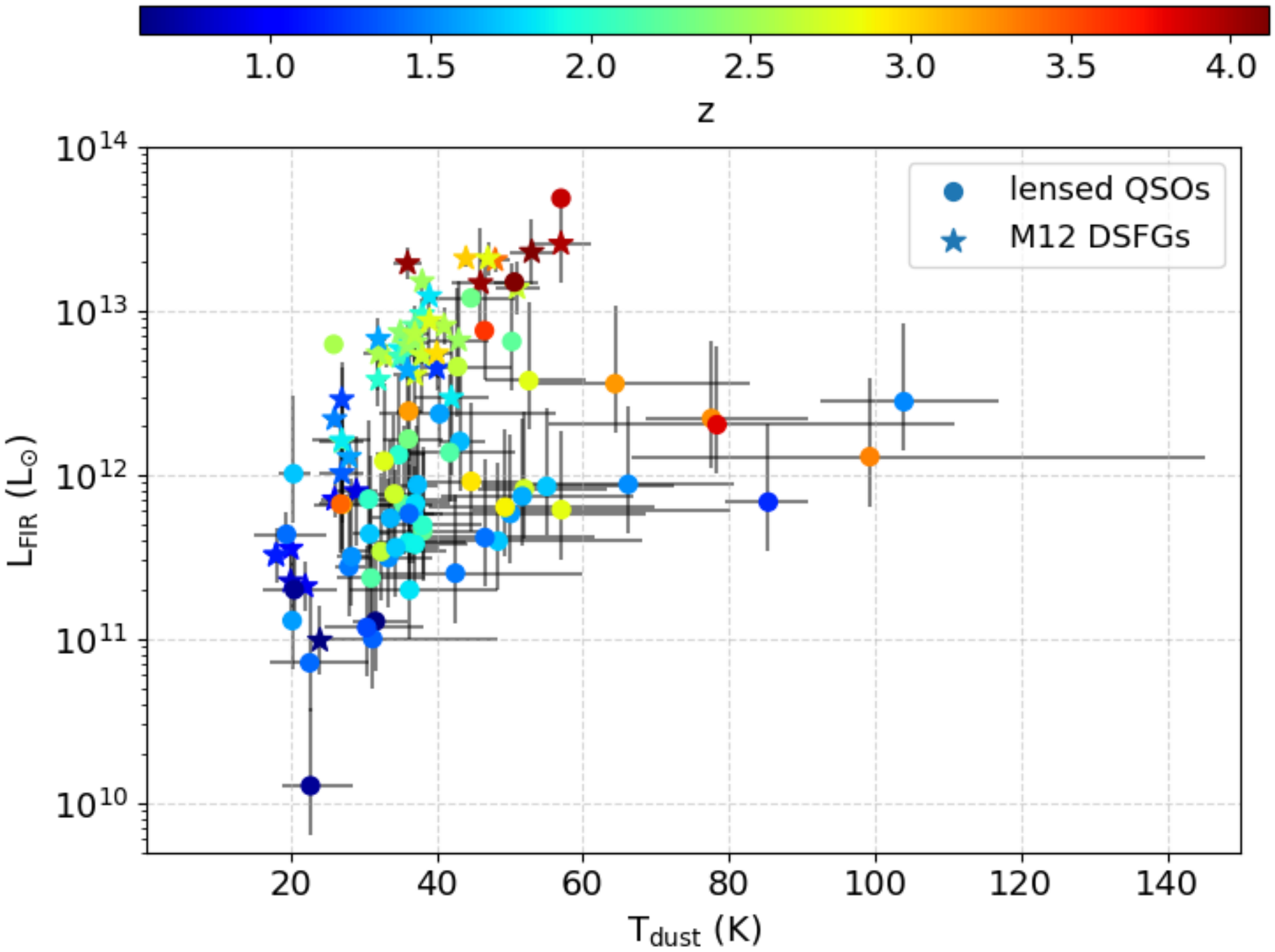
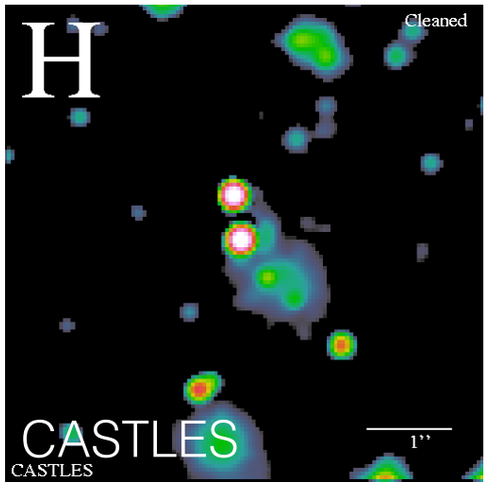
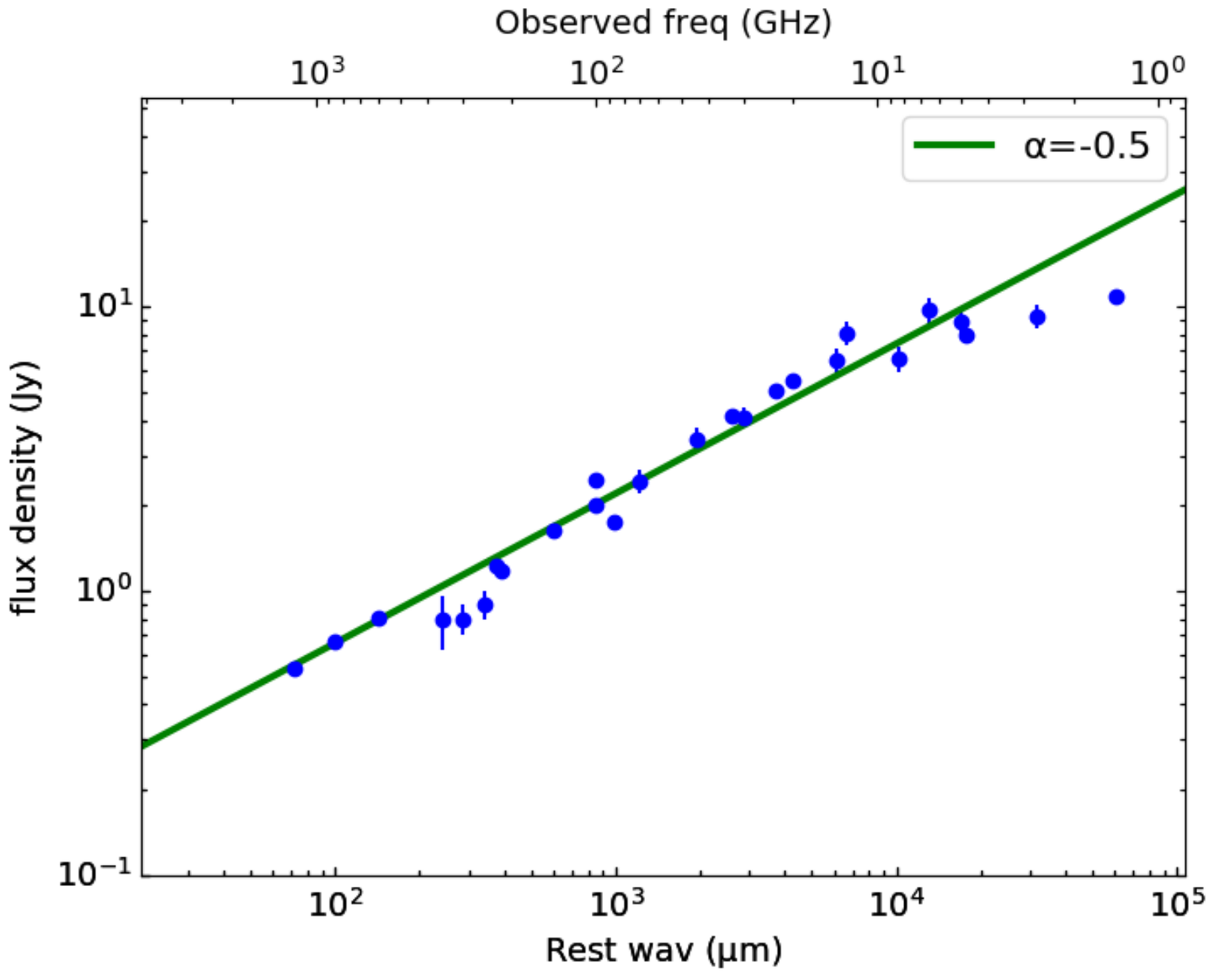
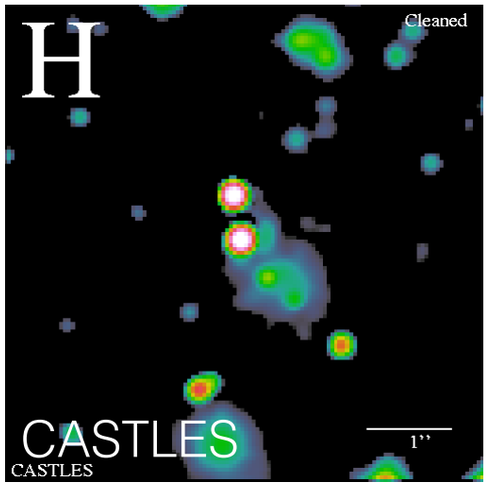




PKS1830-211 (z=2.51)

- Radio loud, blazar
- synchrotron dominated SED
- SFR <1000 $M_\odot$/yr





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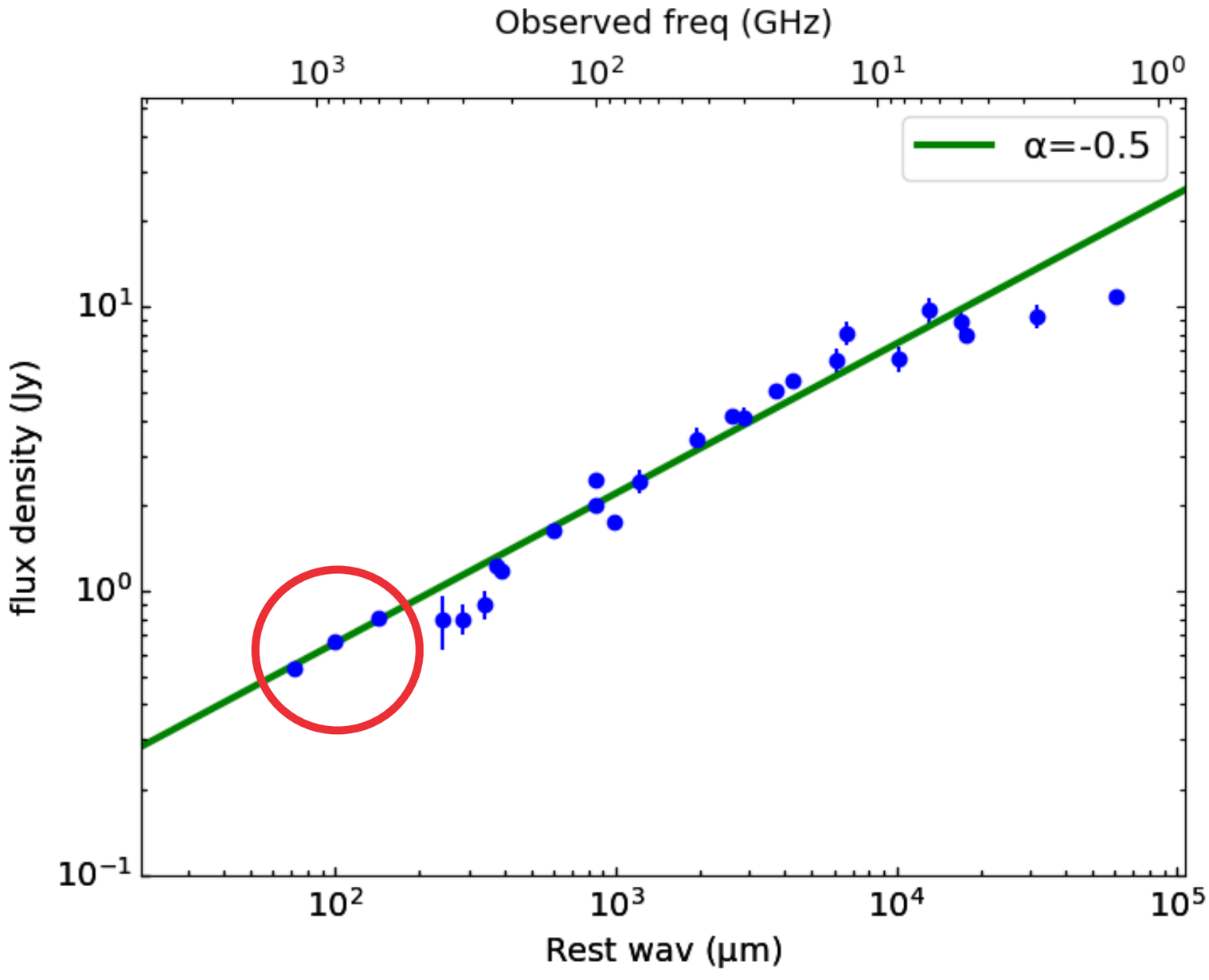
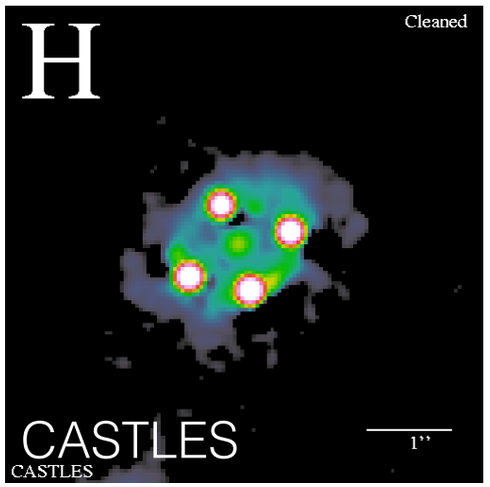
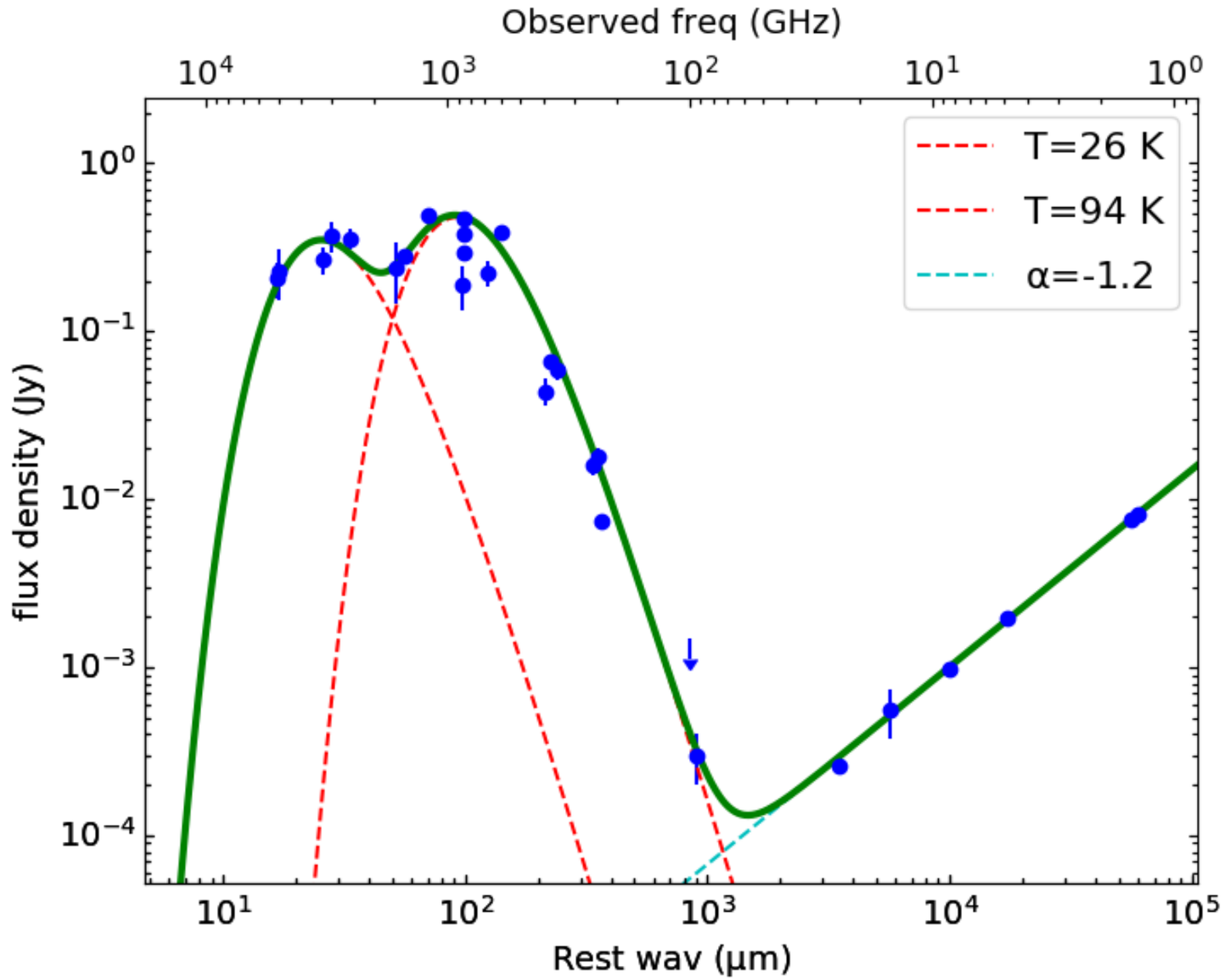
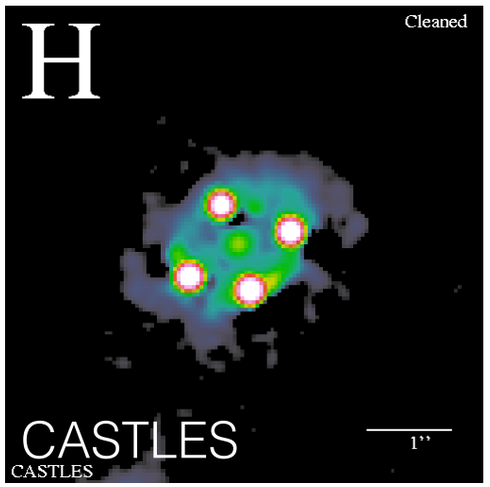




Cloverleaf (z=2.56)

- Double peak
- SFR~ 4000 (μ/11) $M_\odot$/yr





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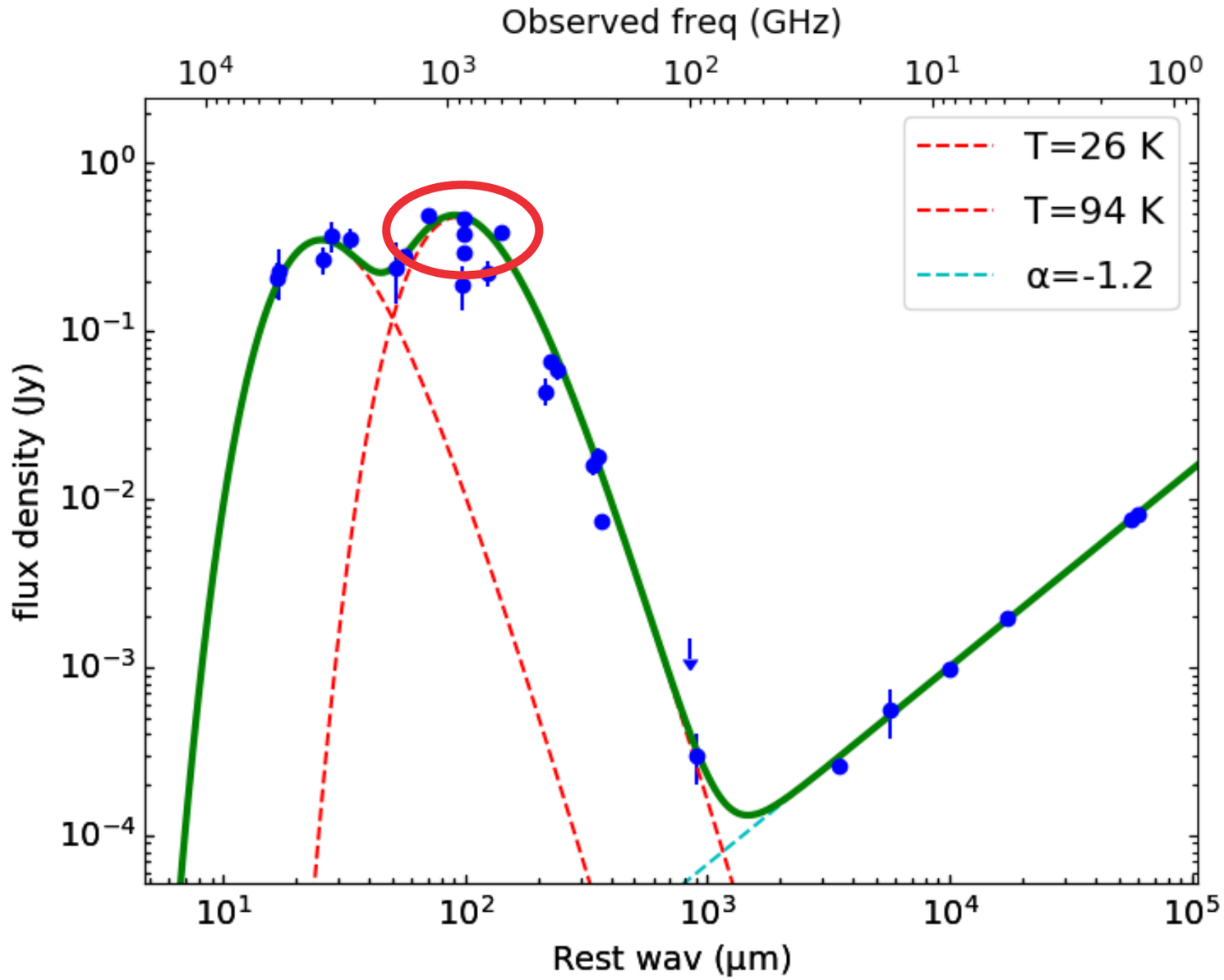
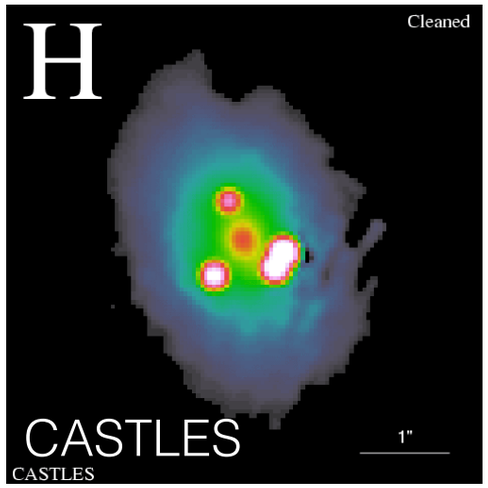
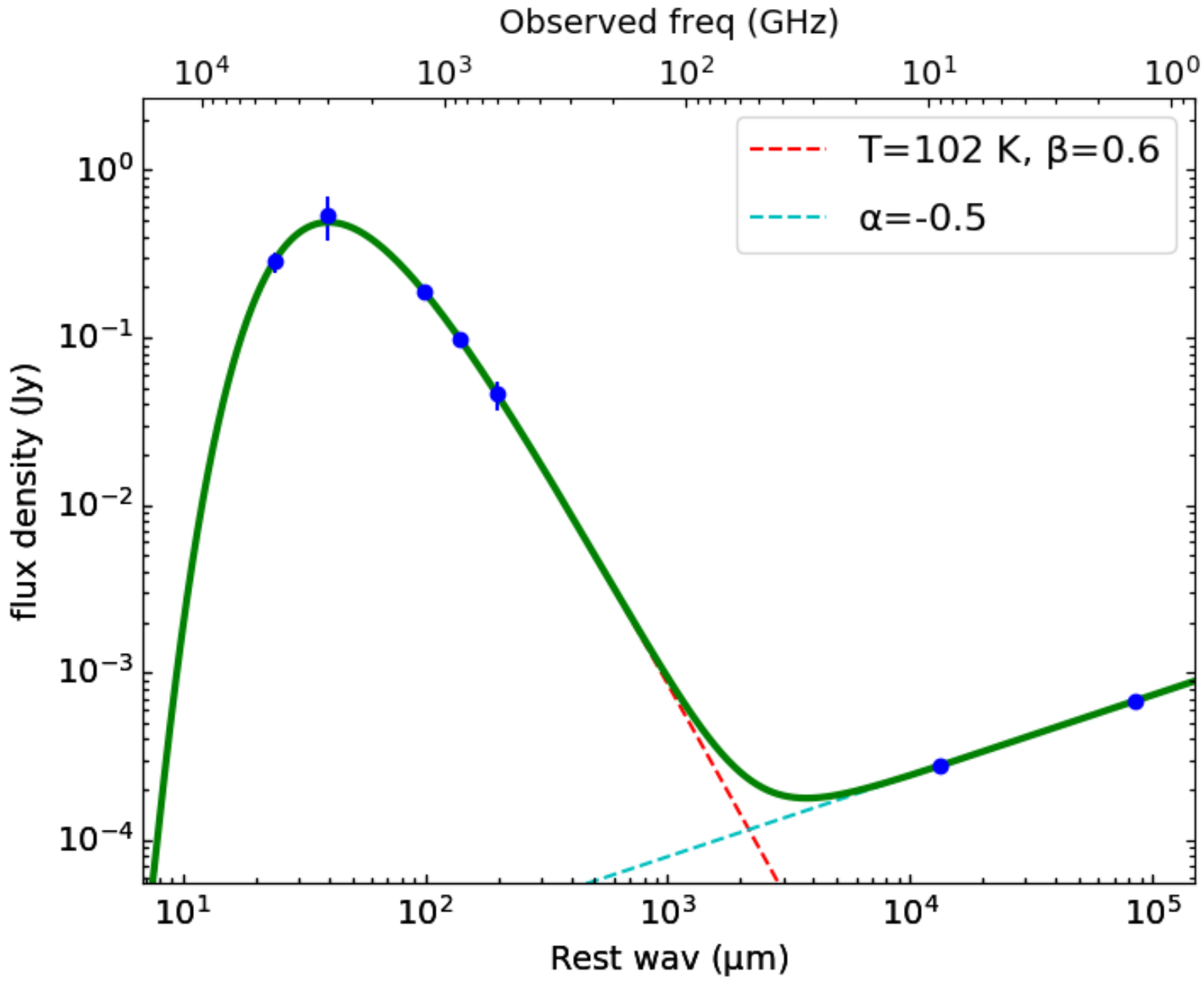
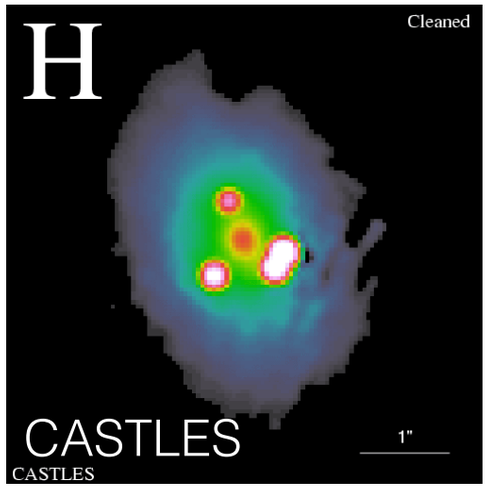




HS0810+2554 (z=1.51)

- Radio quiet
- High dust temp, T=102 K?
- Compact radio component (Jackson+2015)





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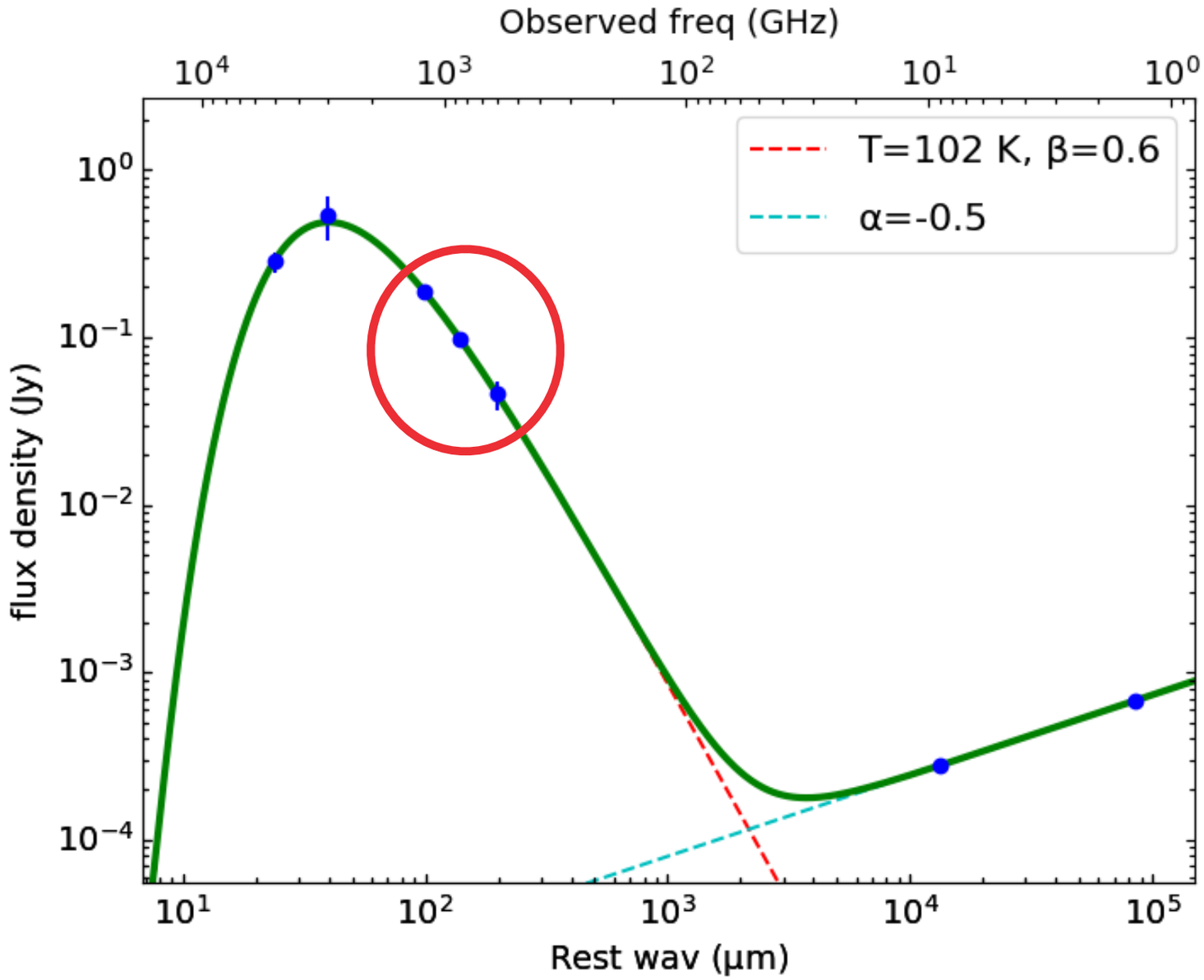

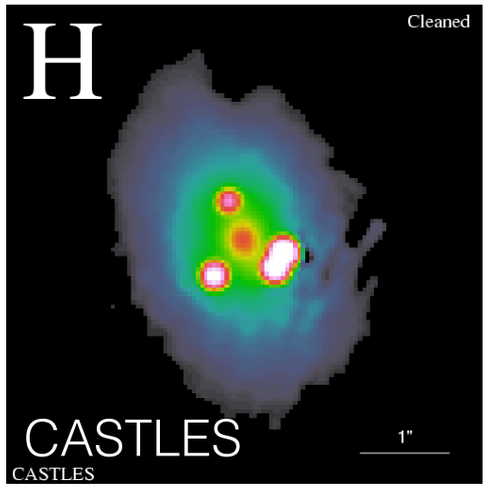

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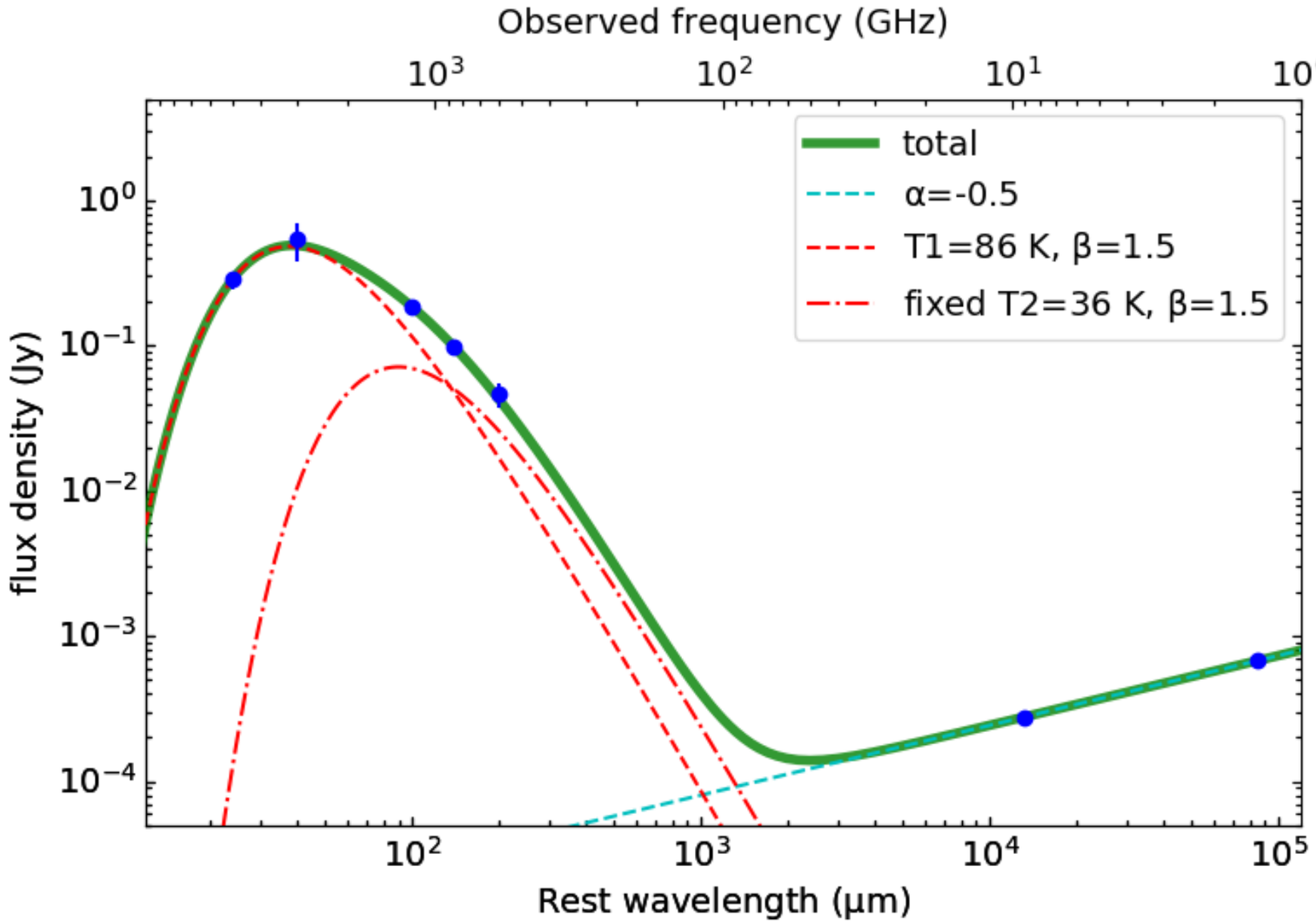
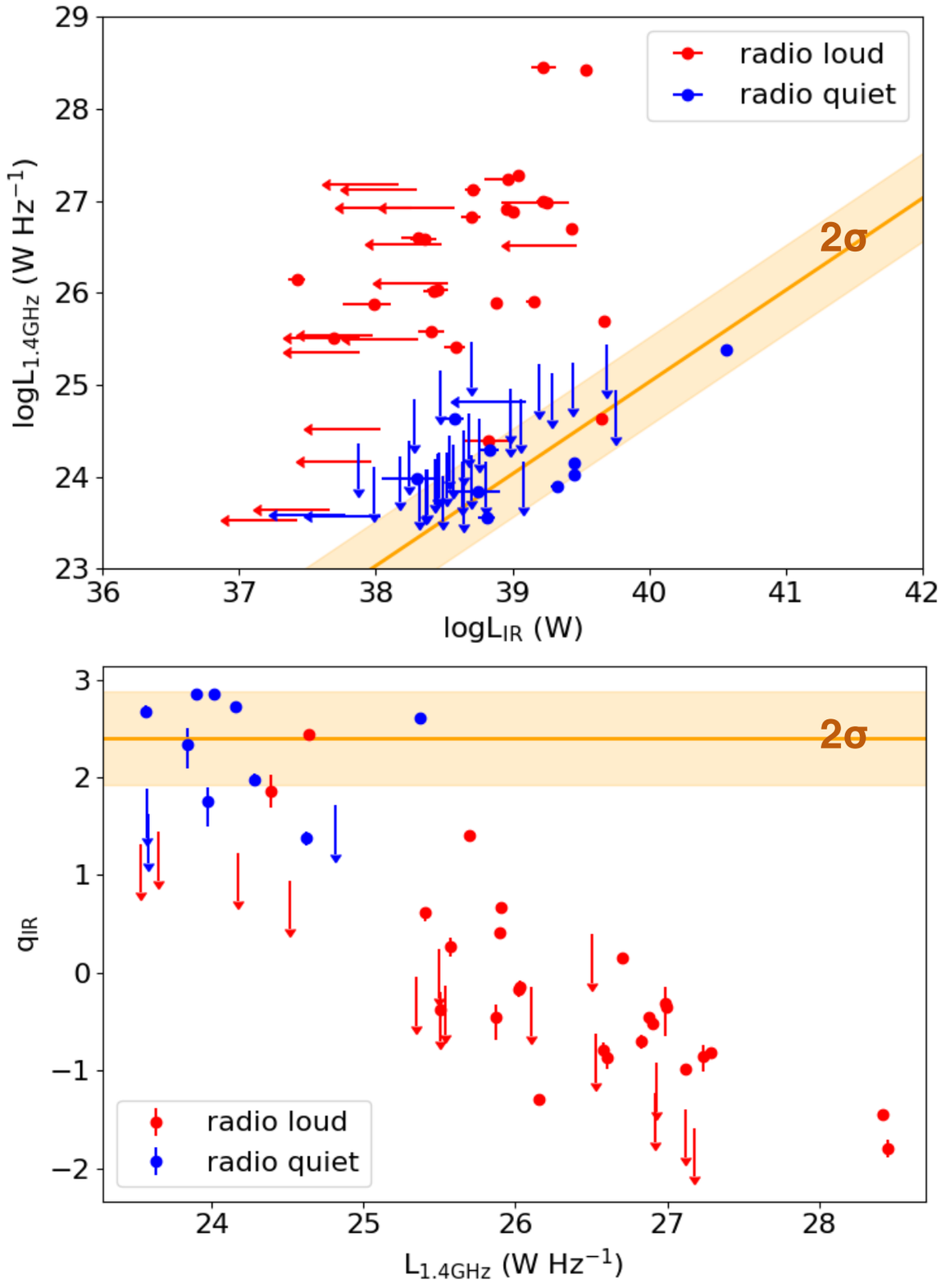


Radio-FIR correlation

$$q_{IR} = log_{10}\left(\frac{L_{IR}}{3.75 \times 10^{12}\ L_{1.4GHz}}\right)$$

- Radio excess in radio-loud sources
- Some radio-quiet sources show excess IR relative to SF galaxies (Ivison+ 2010) due to AGN contribution
- No significant difference between FIR properties of subsamples



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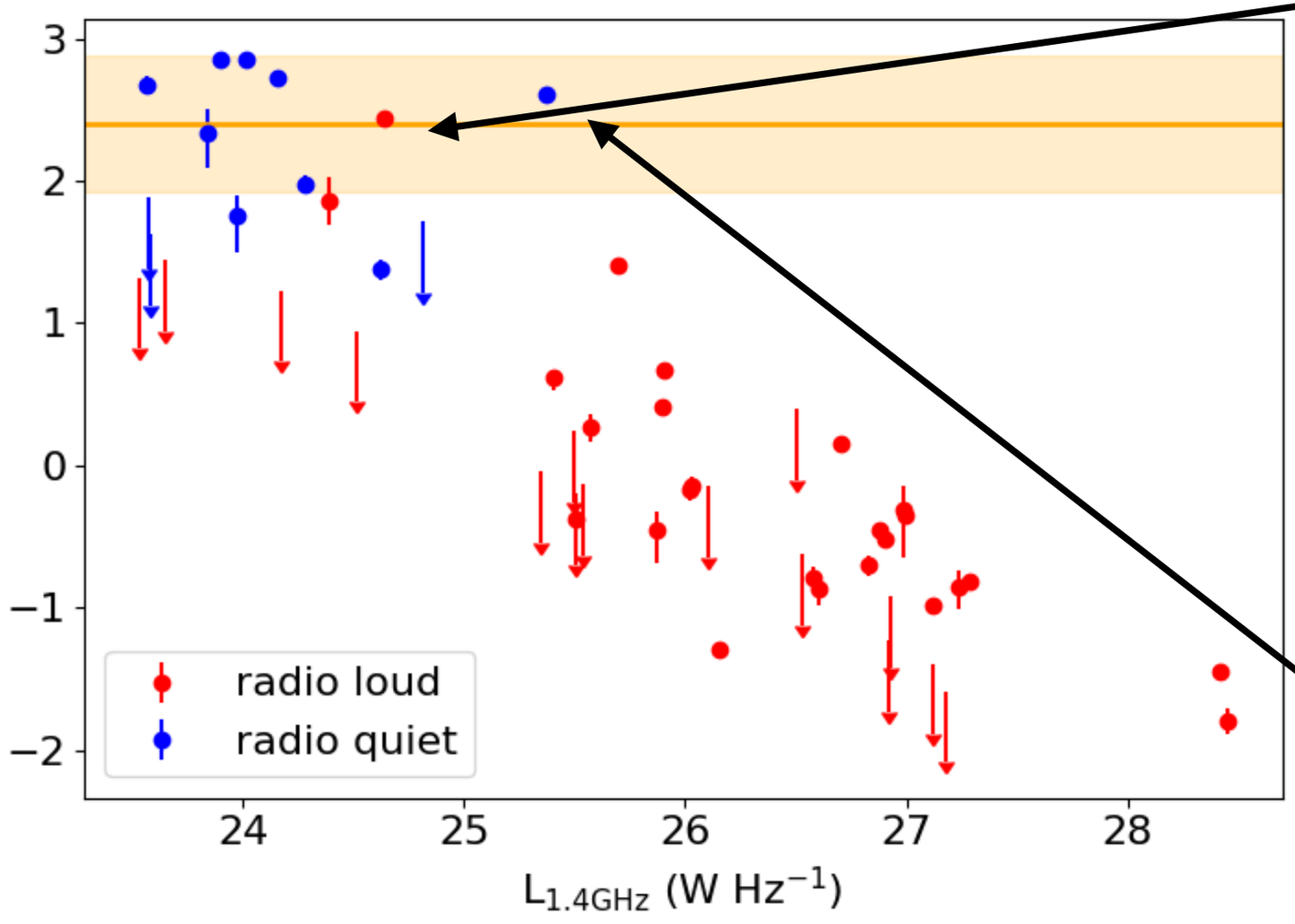
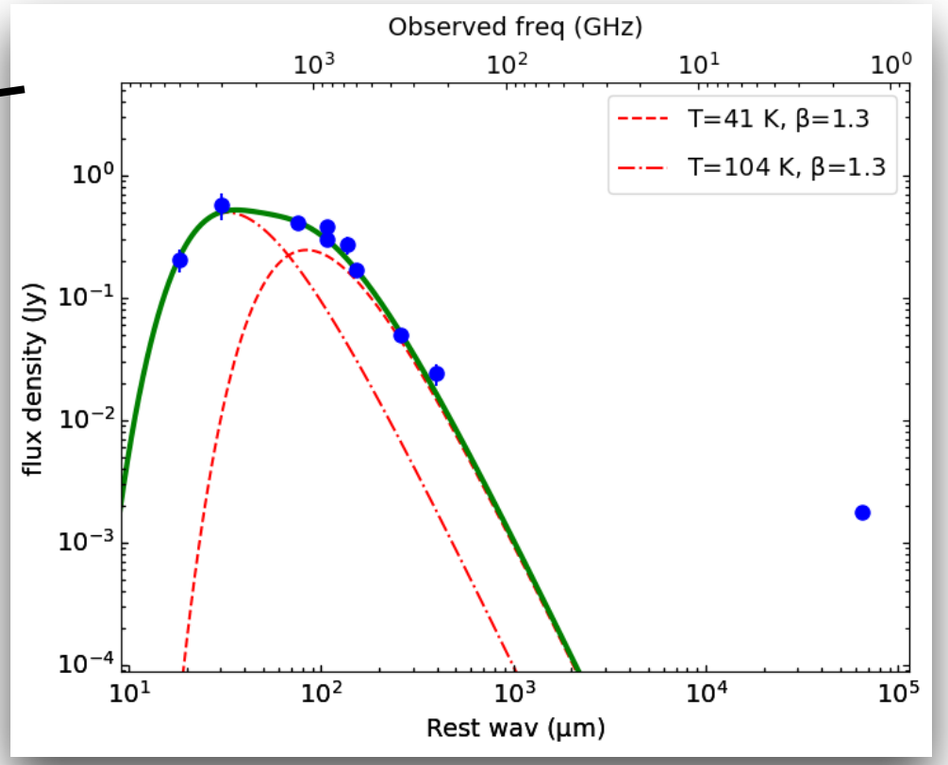
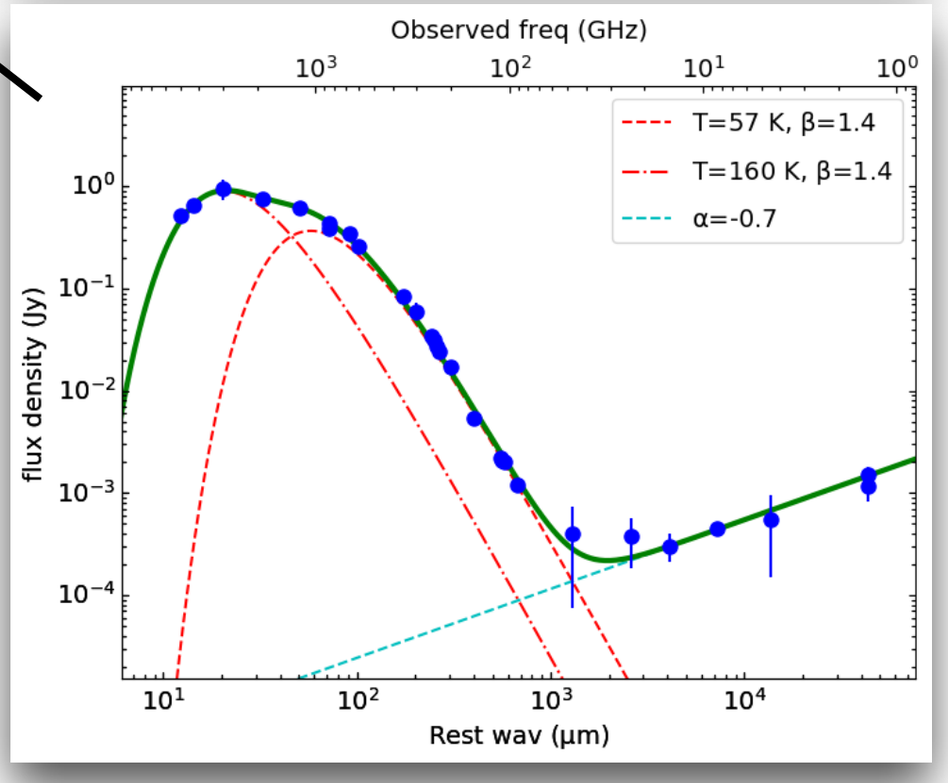


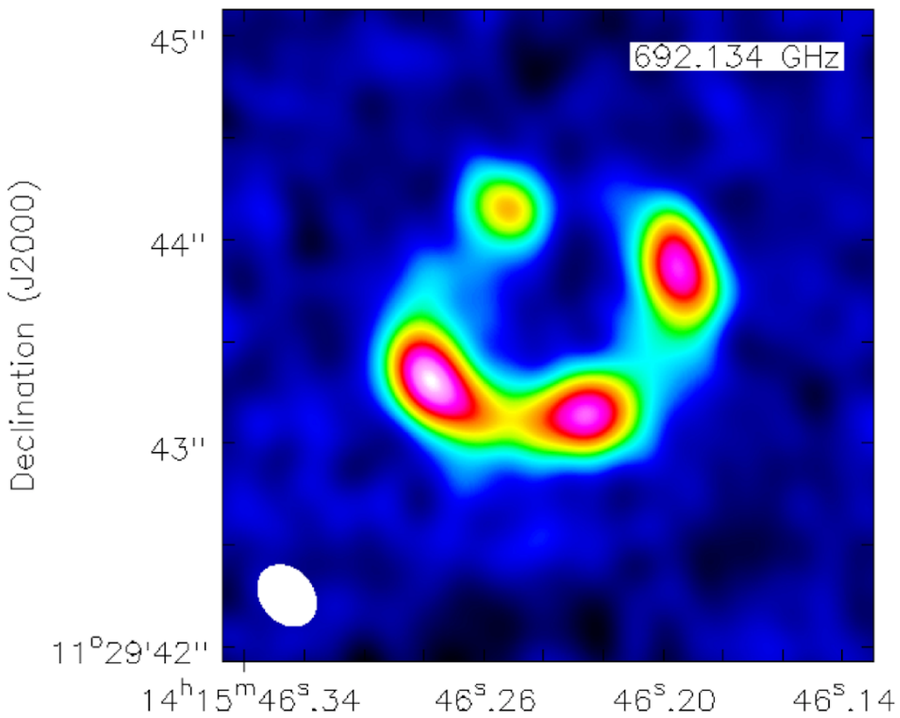




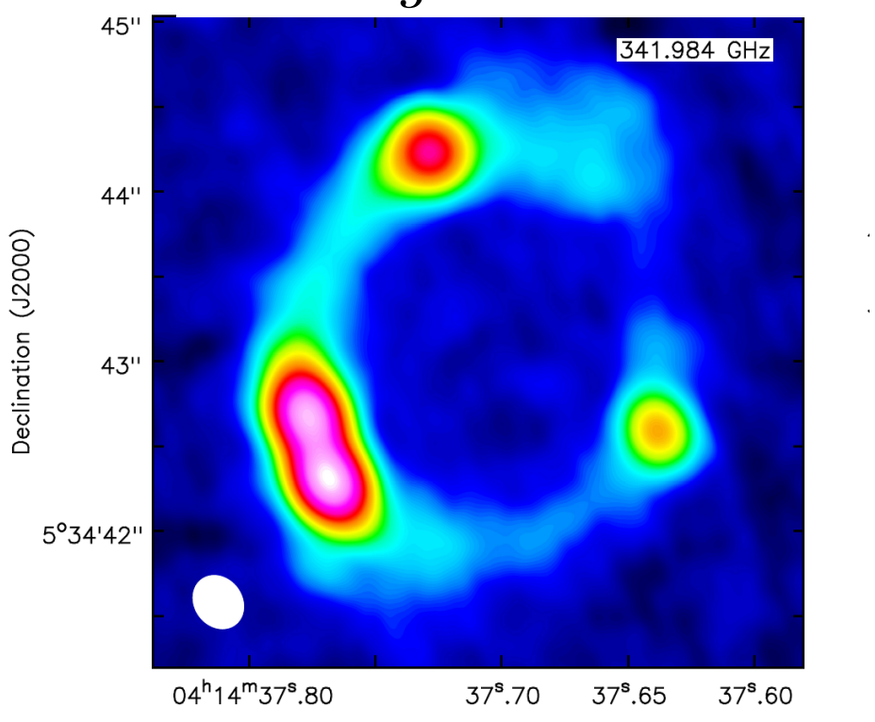
- APM08279 and IRAS10214 fall on q_{IR} relation
- Can fully account for SF/AGN with enough data

Resolving dust and gas with ALMA

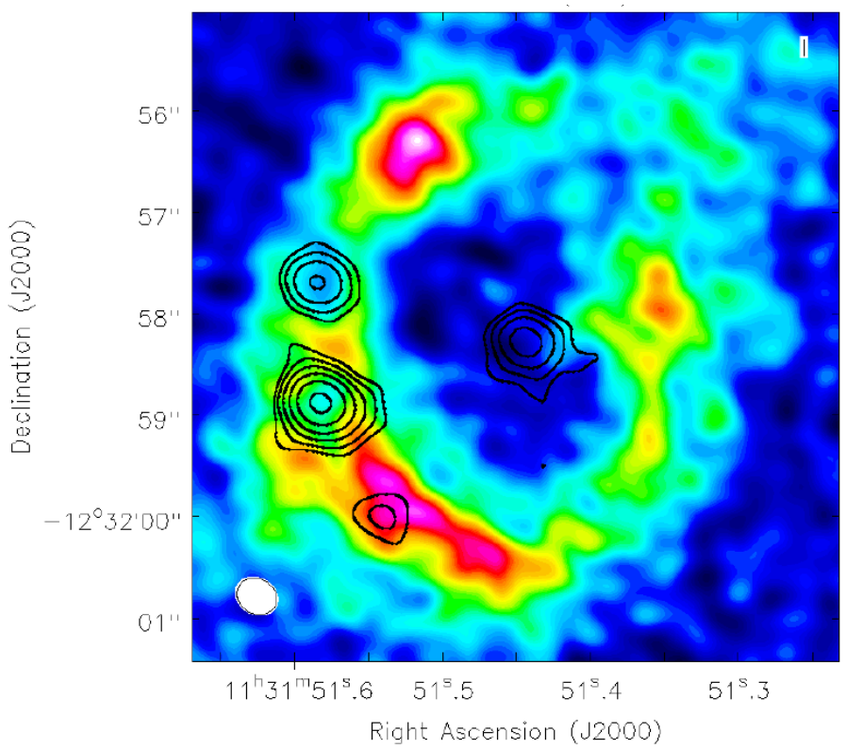
Cloverleaf



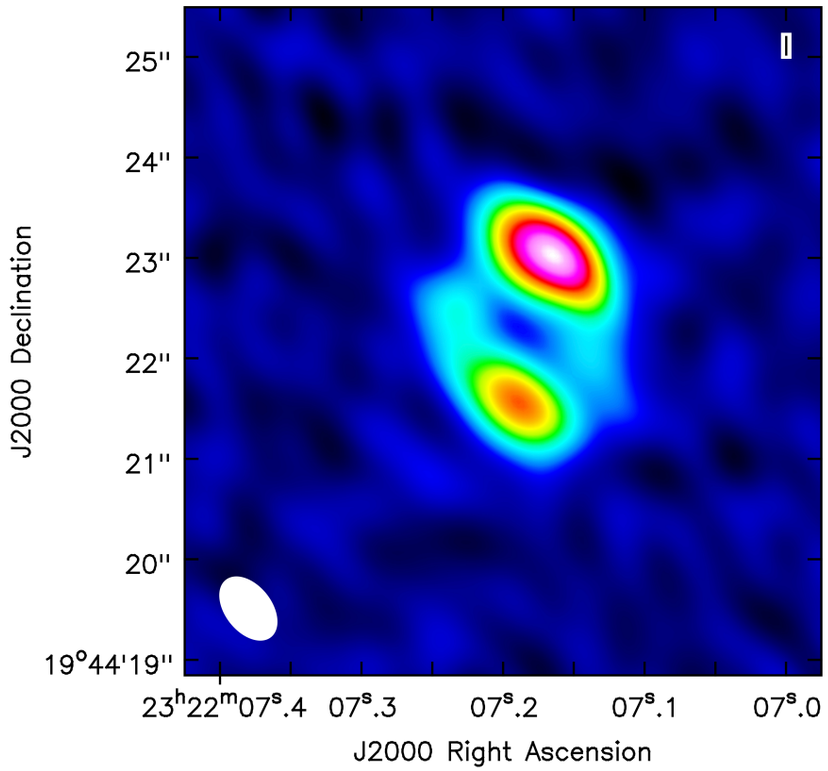
MGJ0414+0534



RXJ1131-1231 (CO 2-1)



PSSJ2322+1944



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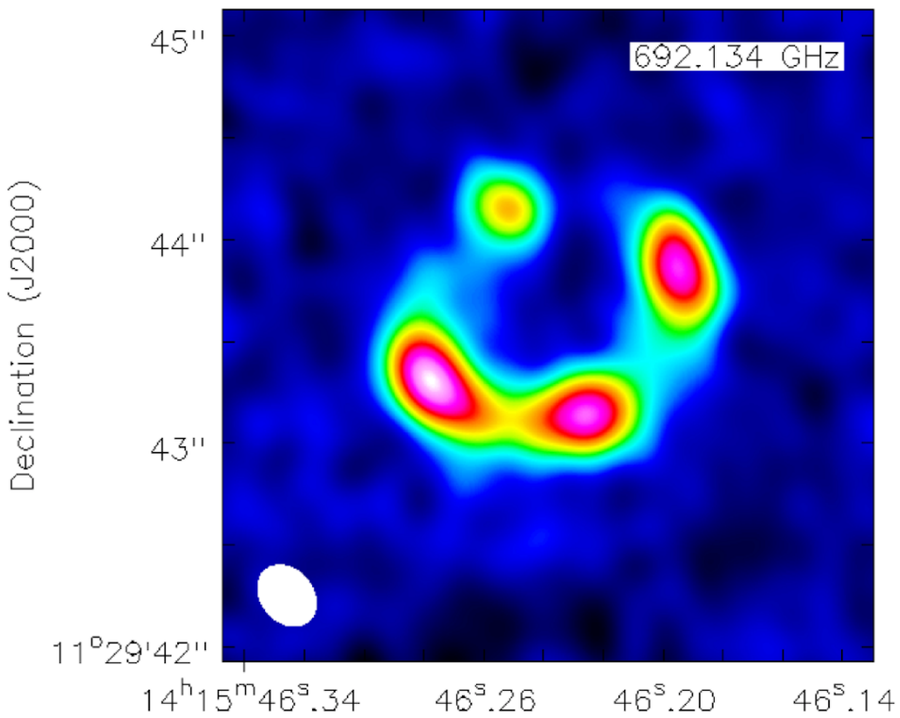

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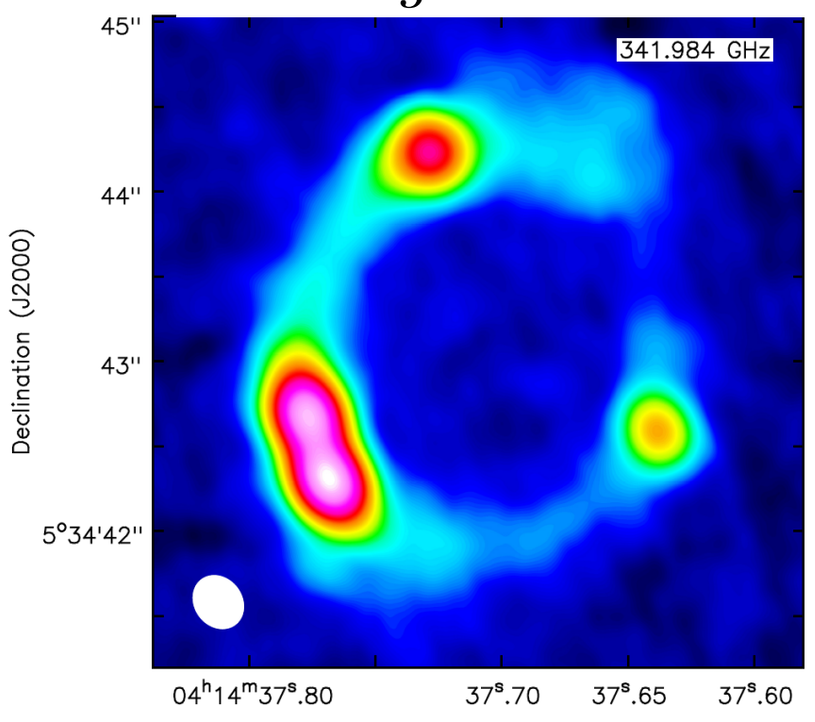
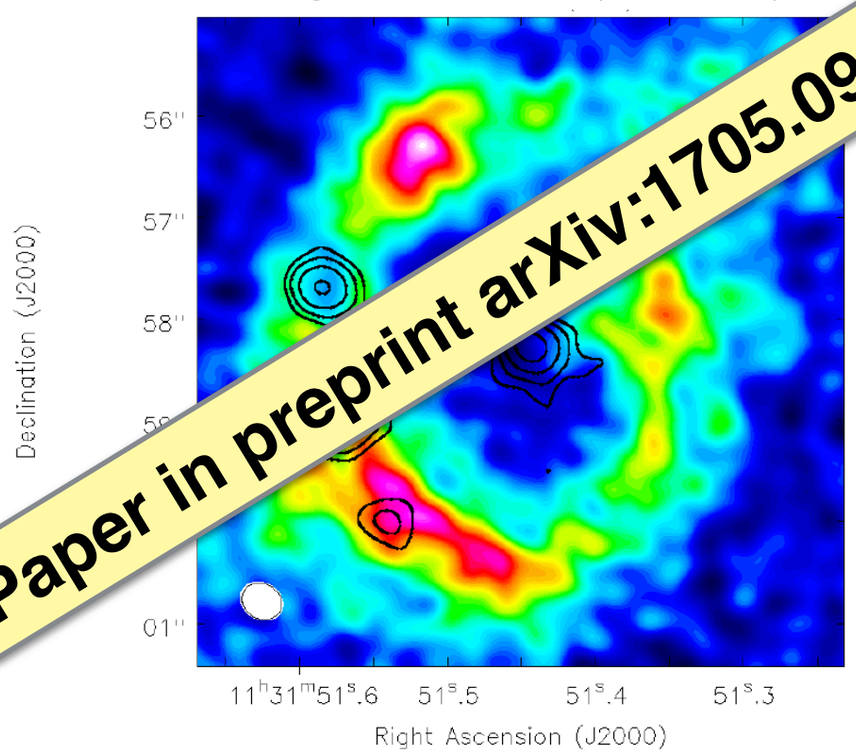
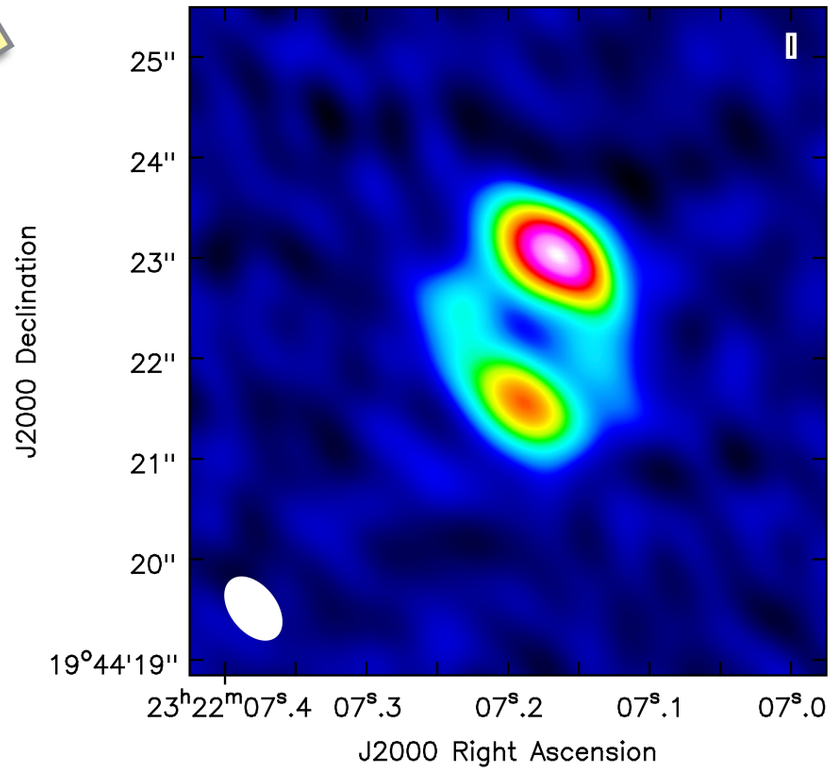


RXJ1131-1231 (CO 2-1)



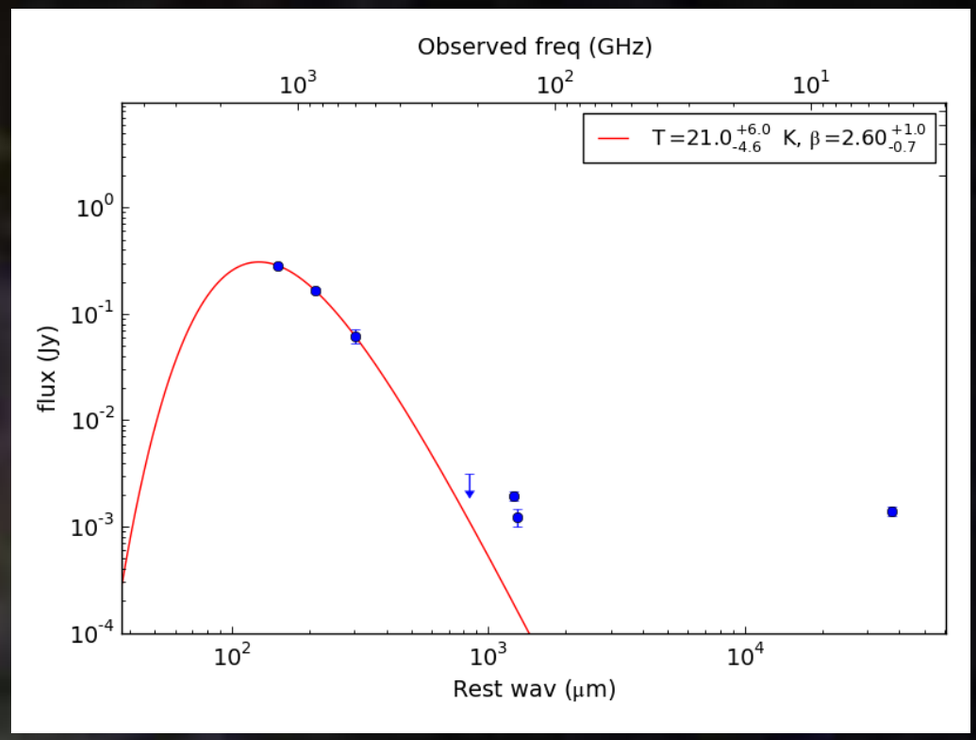
Paper in preprint arXiv:1705.09931

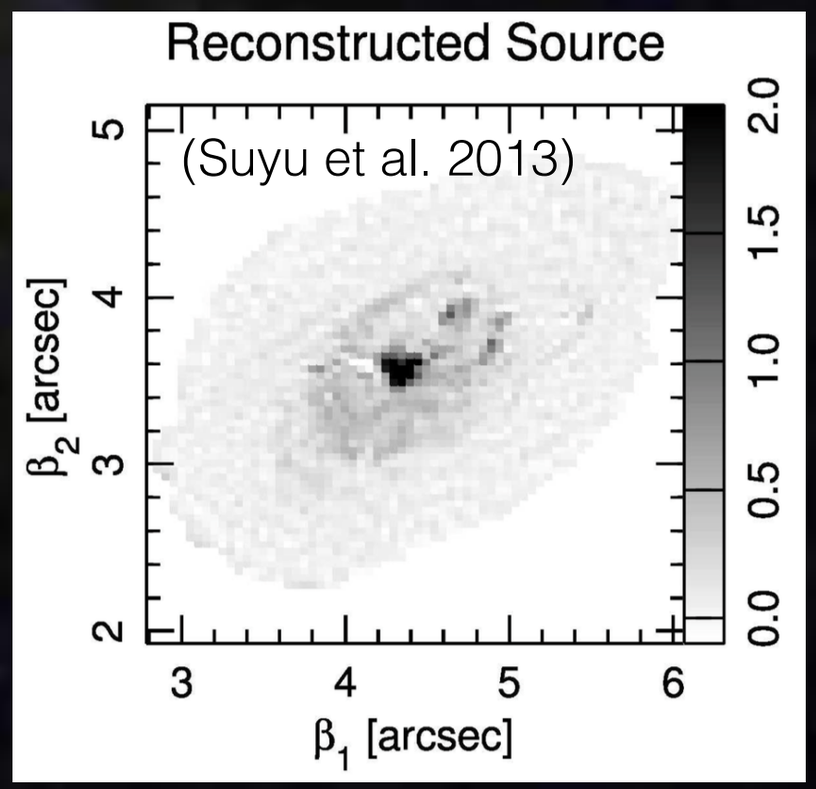
PSSJ2322+1944



High redshift **dusty quasars**

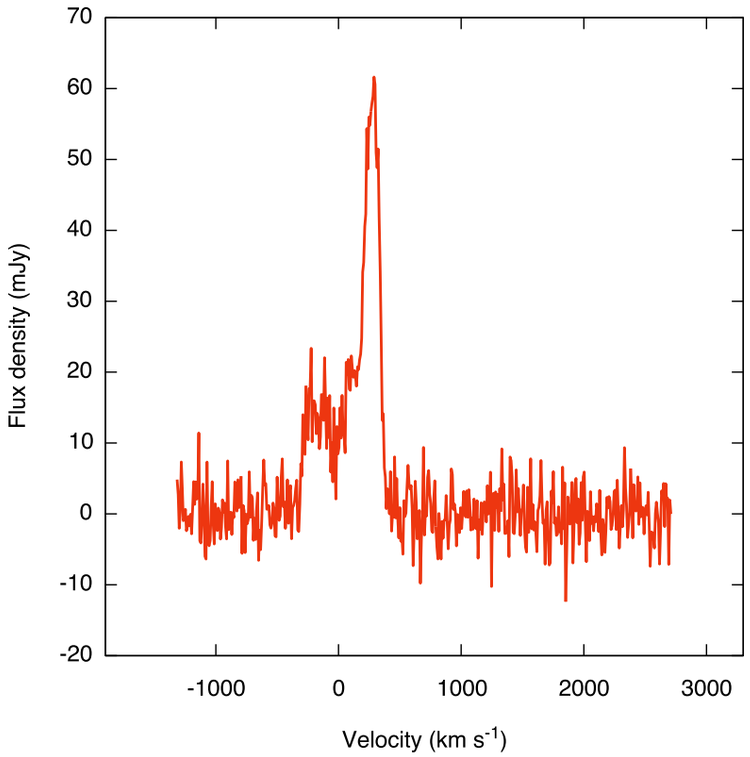
- **RXJ1131-1231 (**z = 0.645**)**

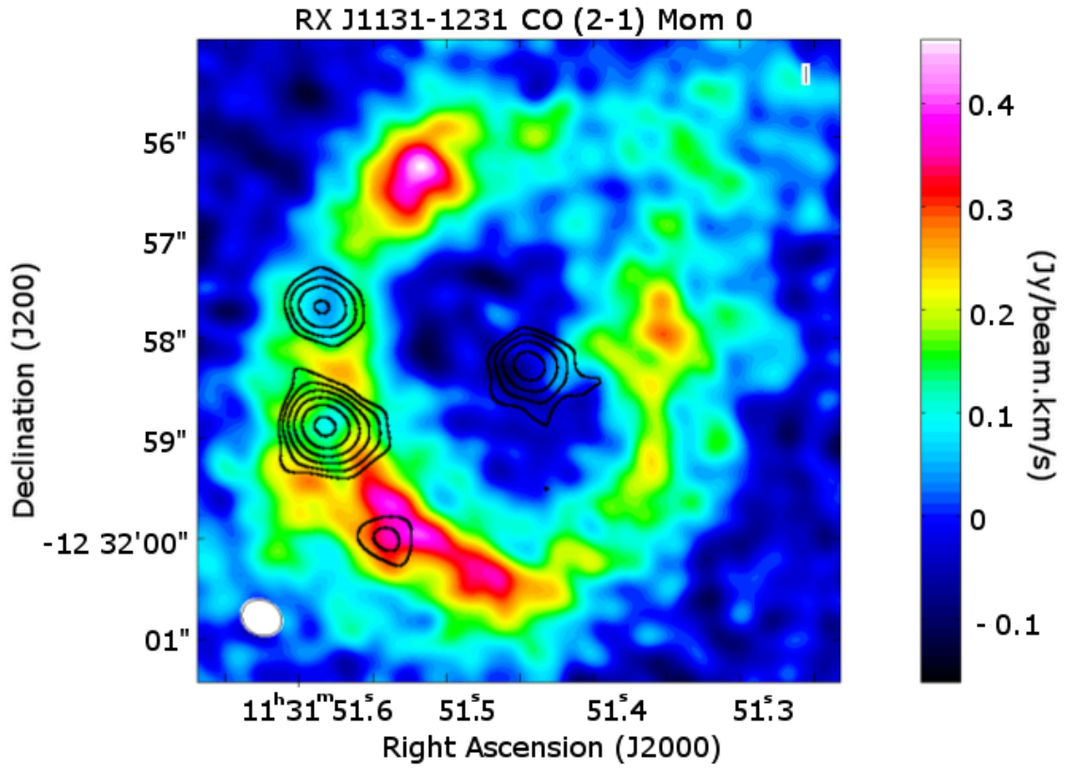


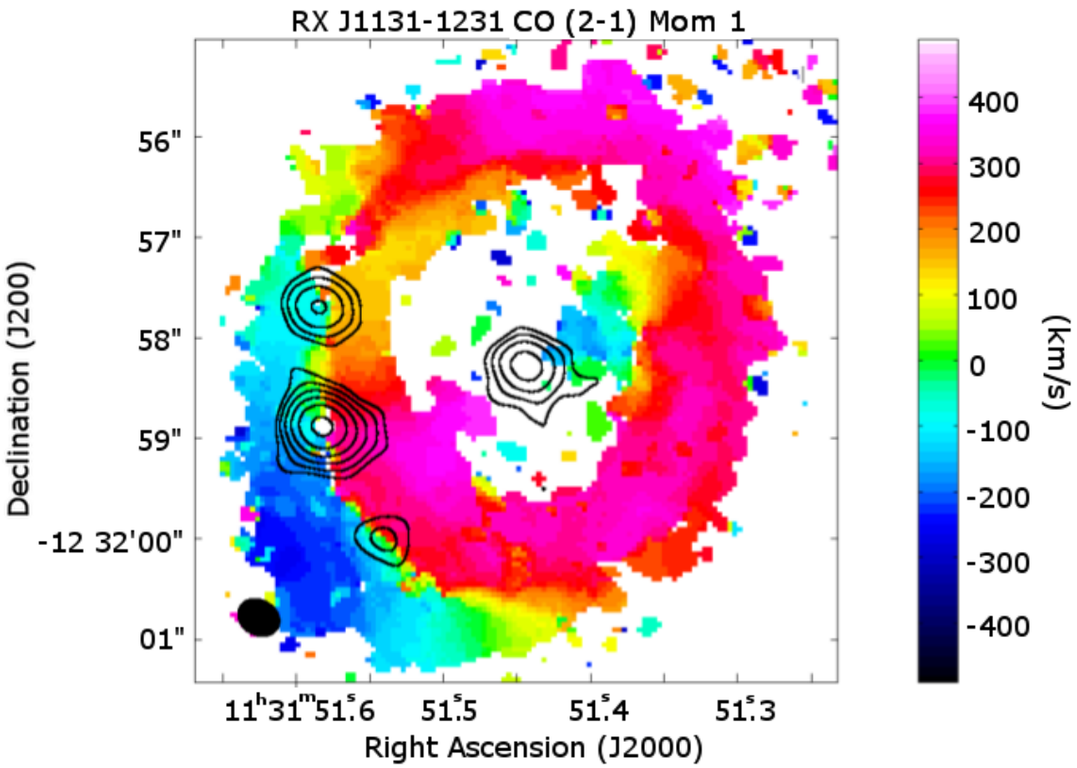


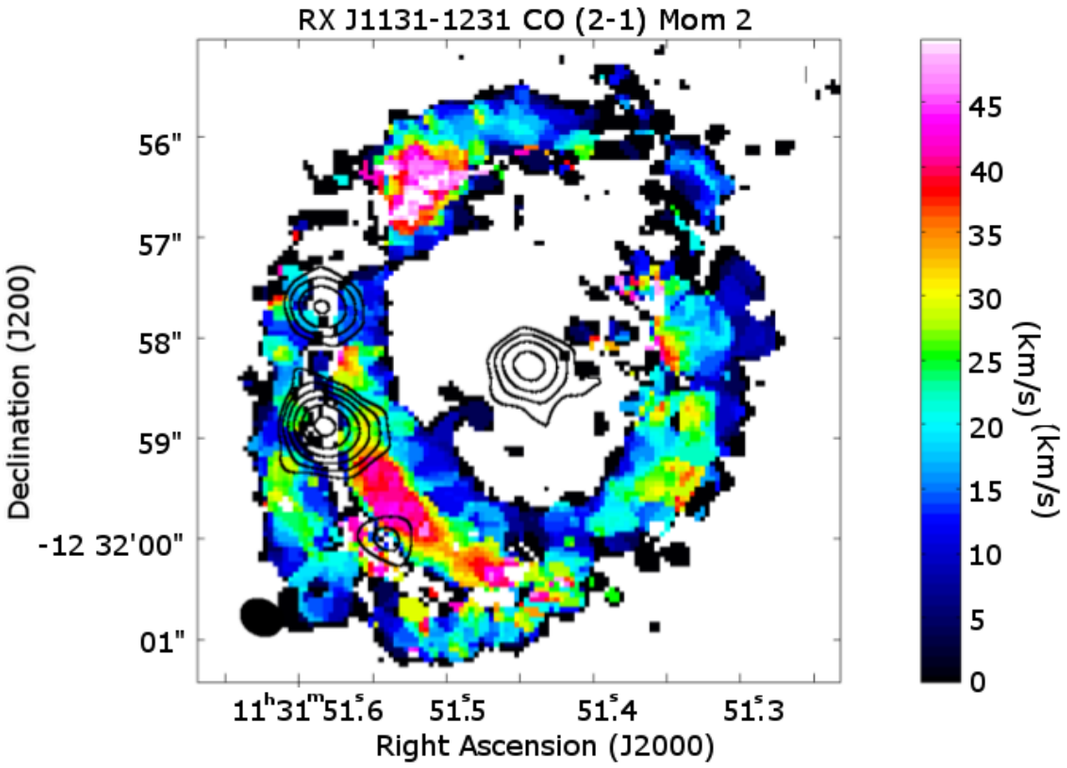
- **Aim:** Improve the lensing mass model using extended molecular gas emission.

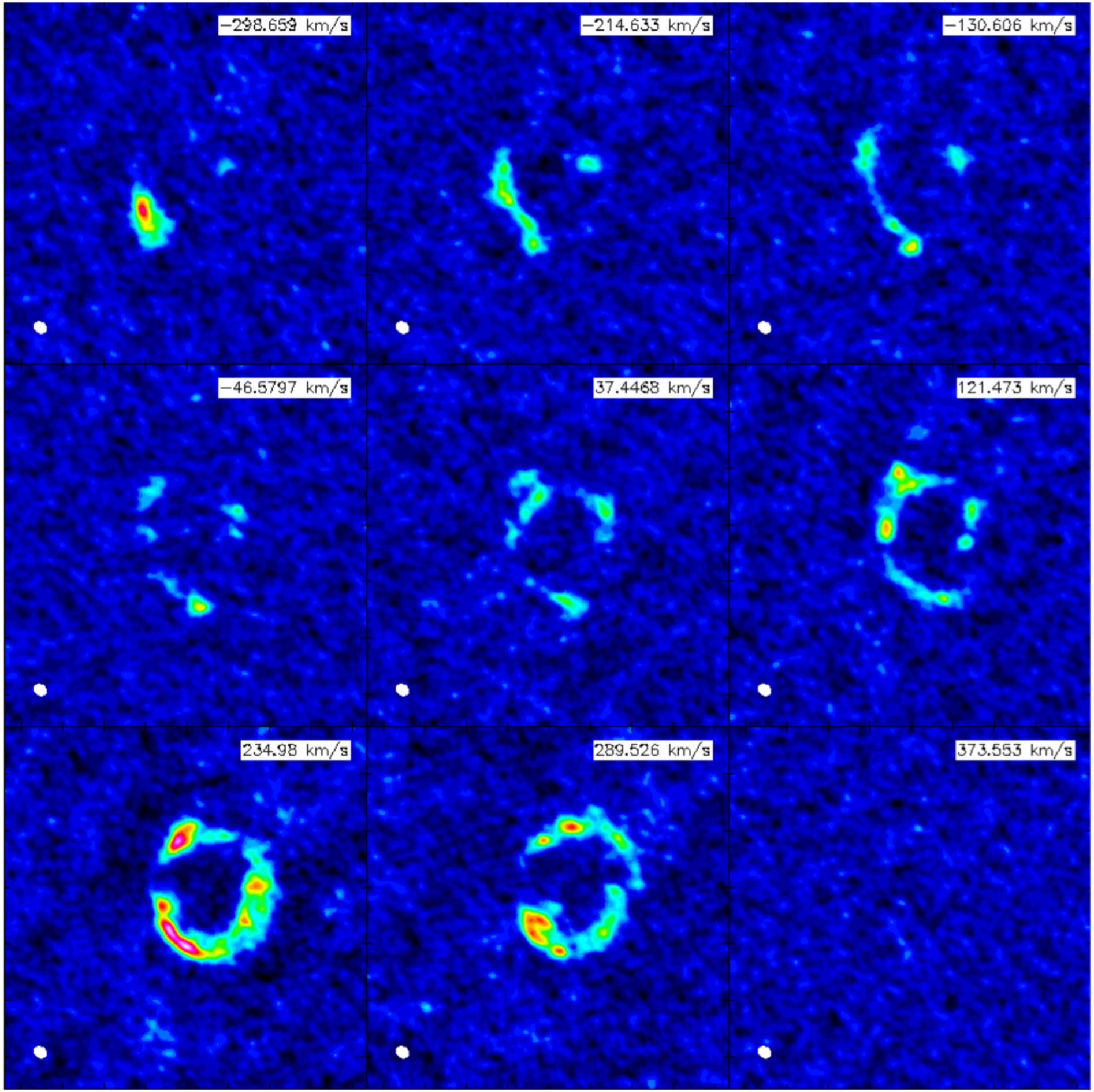
ALMA CO (2-1)

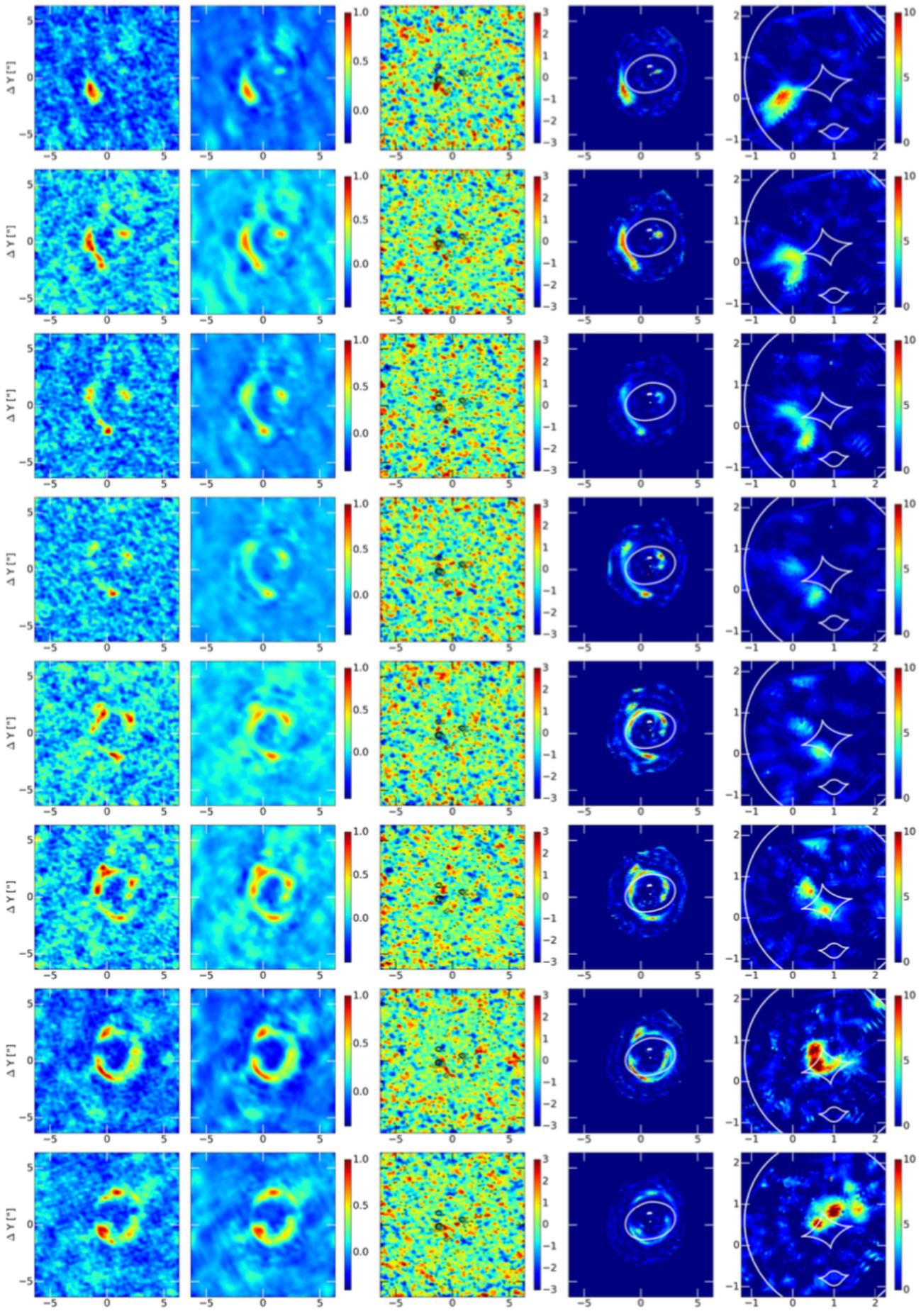

Flux density (mJy)
70
60
50
40
30
20
10
0
-10
-20
-1000
0
1000
2000
3000
Velocity (km s-1)


RX J1131-1231 CO (2-1) Mom 0
Declination (J200)
56"
57"
58"
59"
-12 32'00"
01"
11h31m51.6
51.5
51.4
51.3
Right Ascension (J2000)
0.4
0.3
0.2
0.1
0
- 0.1
(Jy/beam.km/s)


RX J1131-1231 CO (2-1) Mom 1
Declination (J200)
56"
57"
58"
59"
-12 32'00"
01"
11h31m51.6
51.5
51.4
51.3
Right Ascension (J2000)
400
300
200
100
0
-100
-200
-300
-400
(km/s)


RX J1131-1231 CO (2-1) Mom 2
Declination (J200)
56"
57"
58"
59"
-12 32'00"
01"
11h31m51.6
51.5
51.4
51.3
Right Ascension (J2000)
45
40
35
30
25
20
15
10
5
0
(km/s) (km/s)


−298.659 km/s
−214.633 km/s
−130.606 km/s
−46.5797 km/s
37.4468 km/s
121.473 km/s
234.98 km/s
289.526 km/s
373.553 km/s

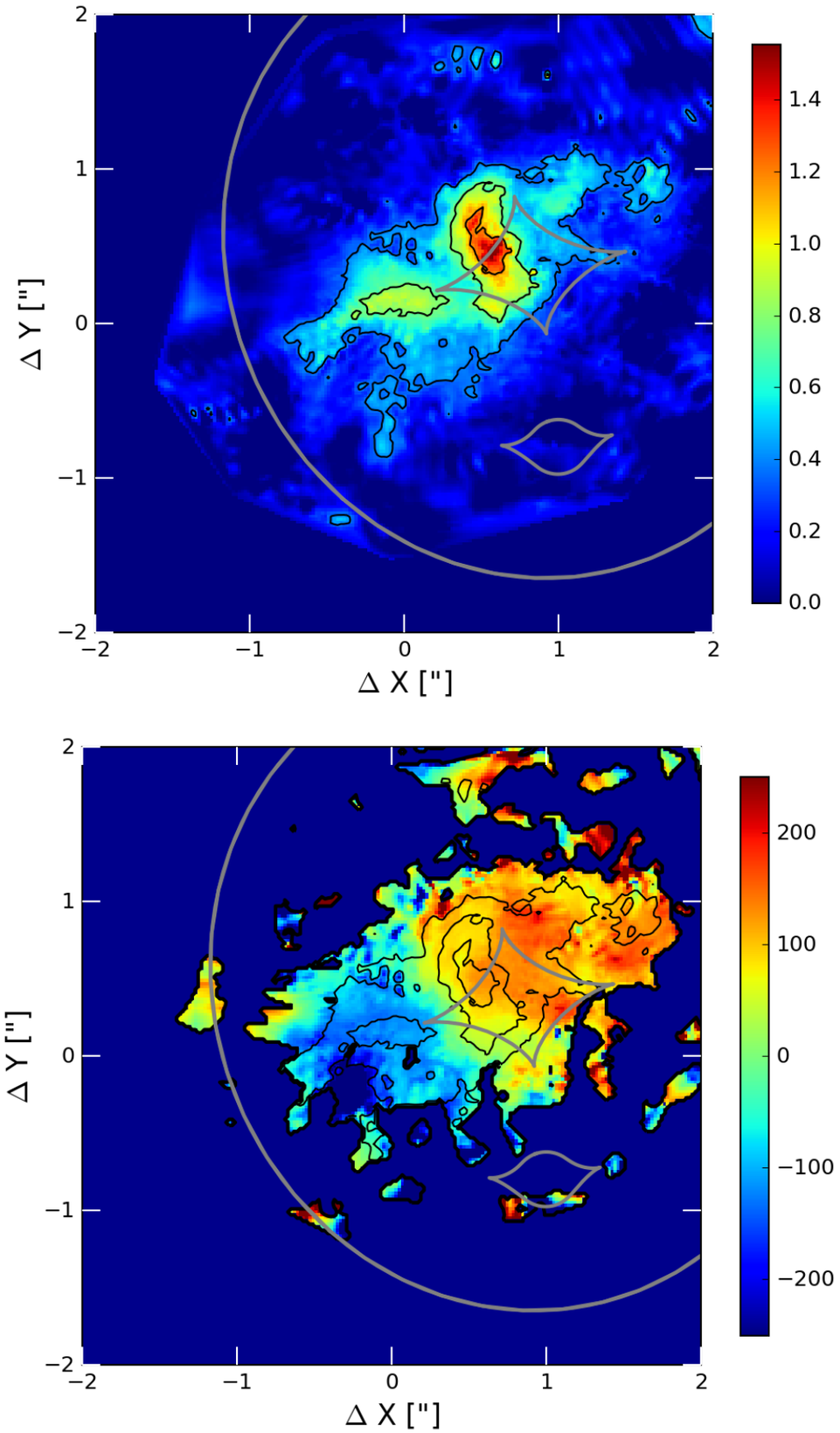


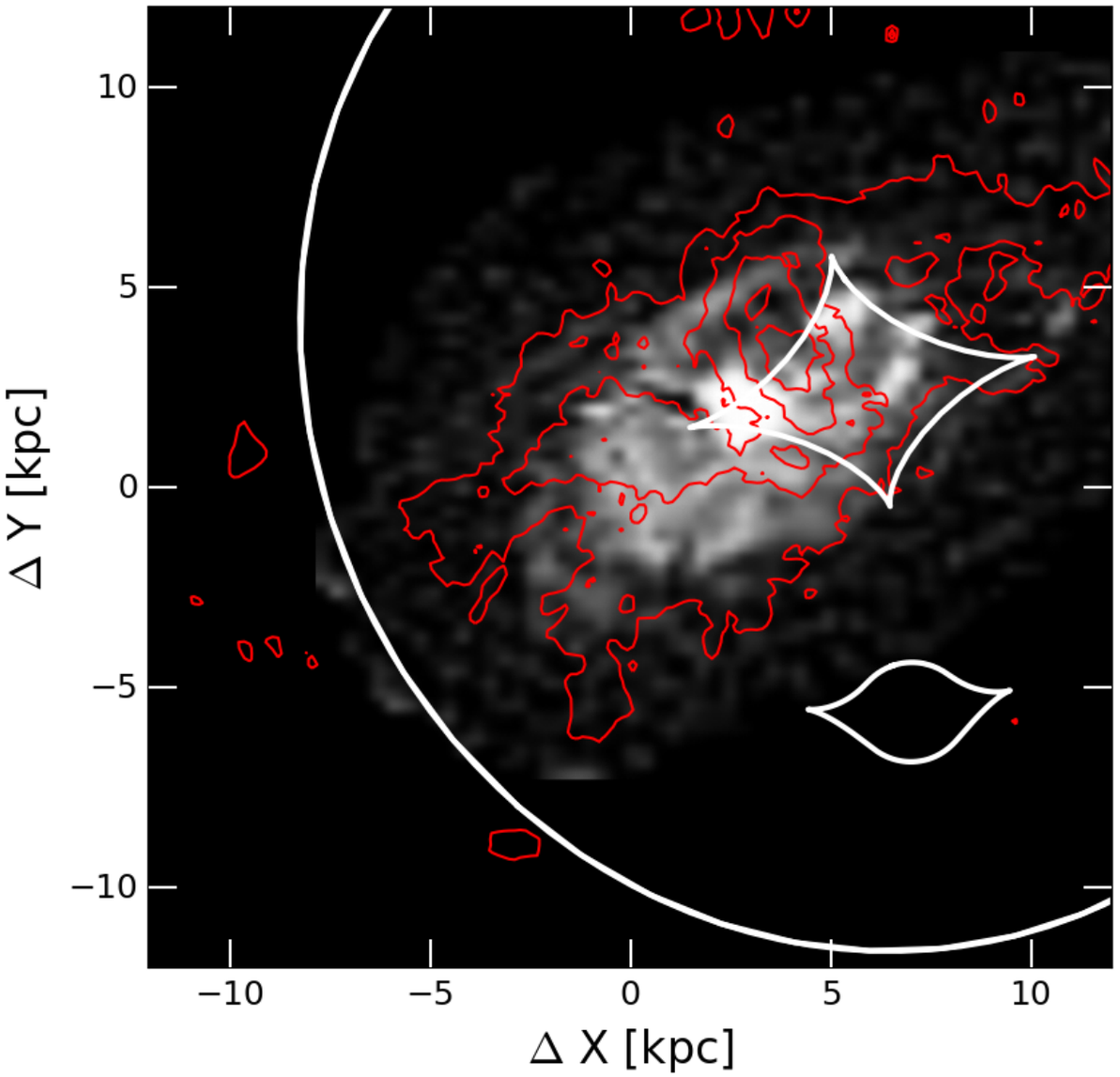
Important not to use the image data (unlike for optical/ IR observations)

- The visibilities (and errors) are the data
- The noise in the image plane is correlated
- Image plane data dependent on
  - Gridding
  - Weighting of the visibilities (natural / uniform)
  - Tapering
  - Deconvolution (clean, MS-Clean, MEM, CS,…)
  - Human factor

$$\mathbf{S} \times \mathbf{F} \times \mathbf{L} \times \boldsymbol{source} + \boldsymbol{noise} = \boldsymbol{V}^{obs}(u, v)$$

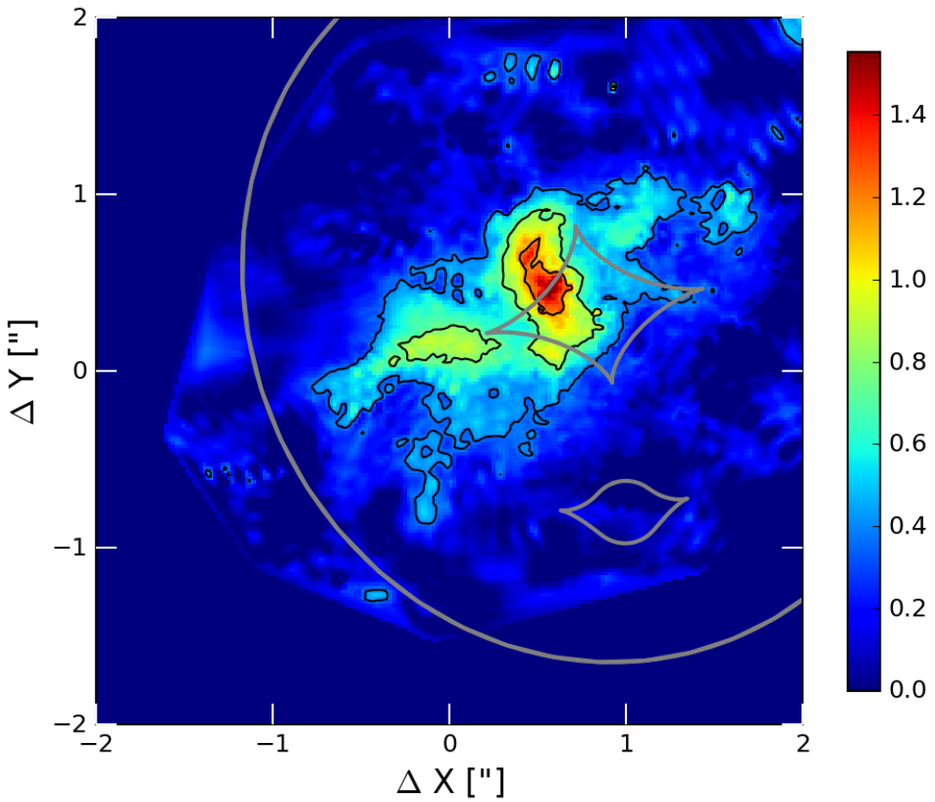
Intrinsic source properties

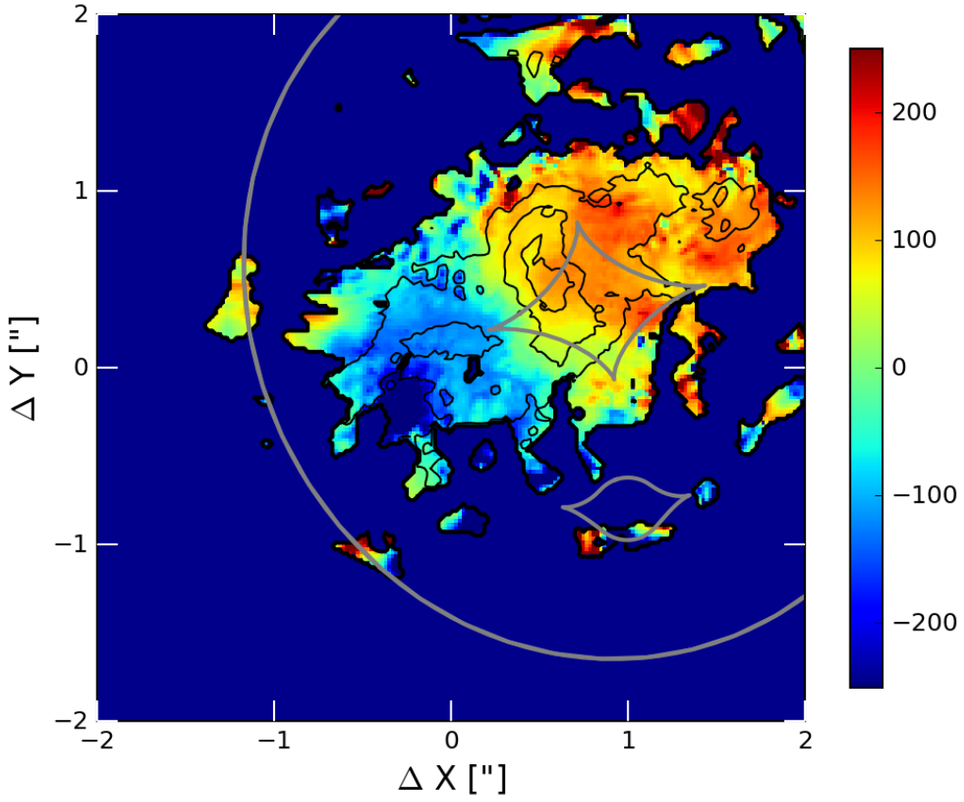


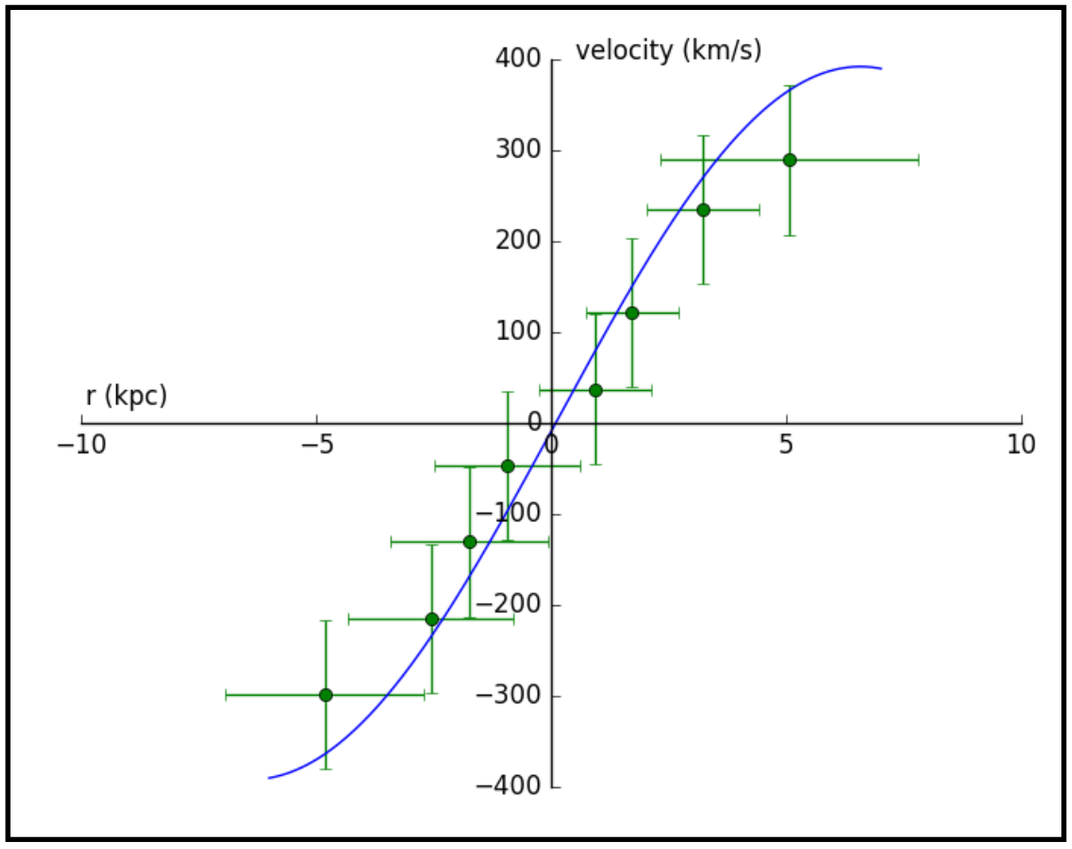


- Extended molecular gas disk (15 kpc) — size-redshift evolution?
- Molecular gas peak not coincident with the AGN.

Intrinsic source properties

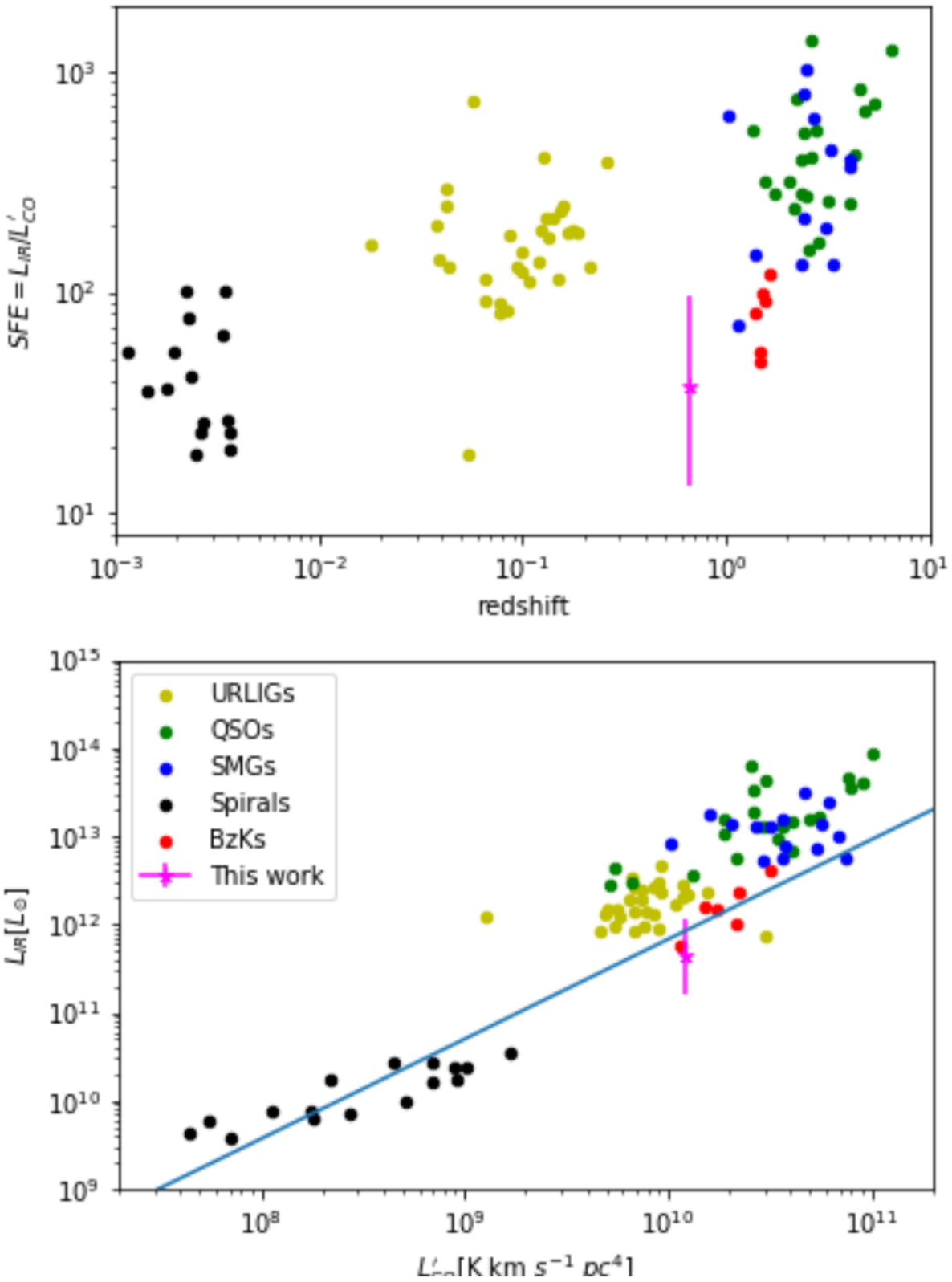






- Toomre parameter, Q = 1.1 (stable rotating disk).
- Dyn. mass: M(< 5 kpc) = (1.5 ± 0.3) x 10^{11} $M_\odot$.
- Stellar mass: M^* = (3.0 ± 1.0) x 10^{10} $M_\odot$.
- Gas mass: M_{gas} = 8.3 ± 3.0 x 10^{10} $M_\odot$.
- CO-H_2 conversion: 5.5 ± 2.0 (K kms^{-1} pc^2)$^{-1}$ [Milky Way-like = 4.6 (K kms^{-1} pc^2)$^{-1}$]

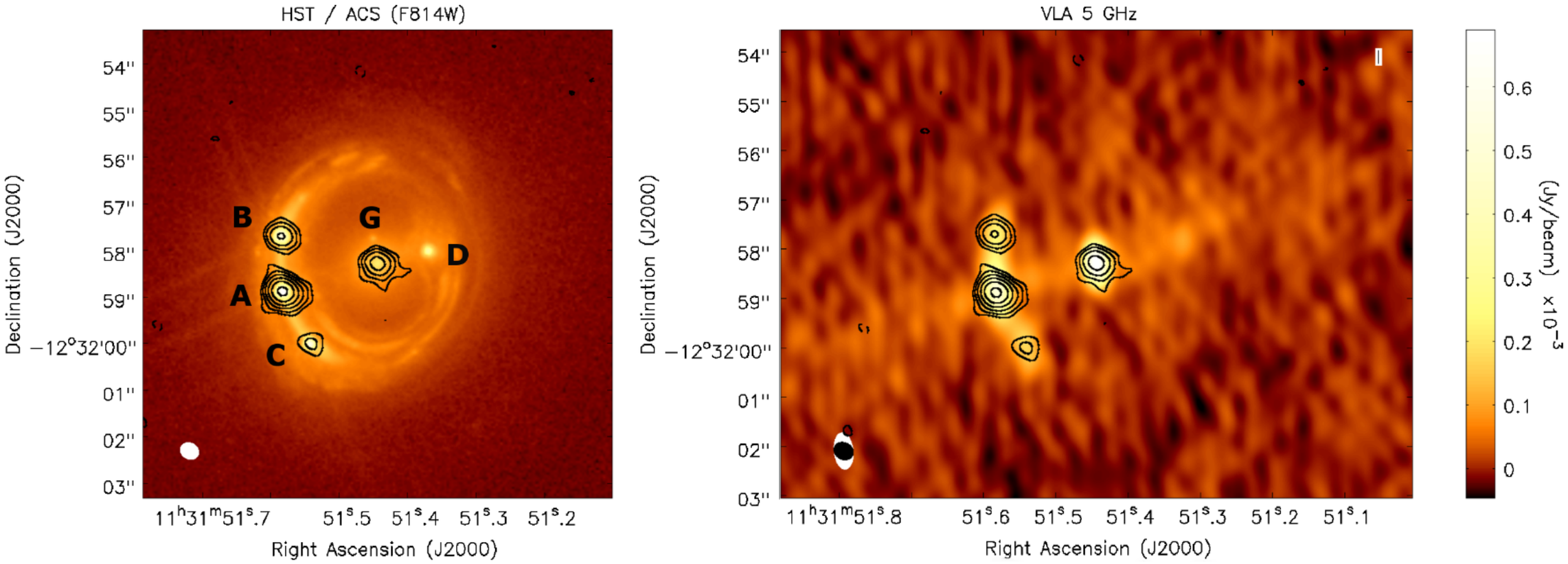
Comparison with other galaxies

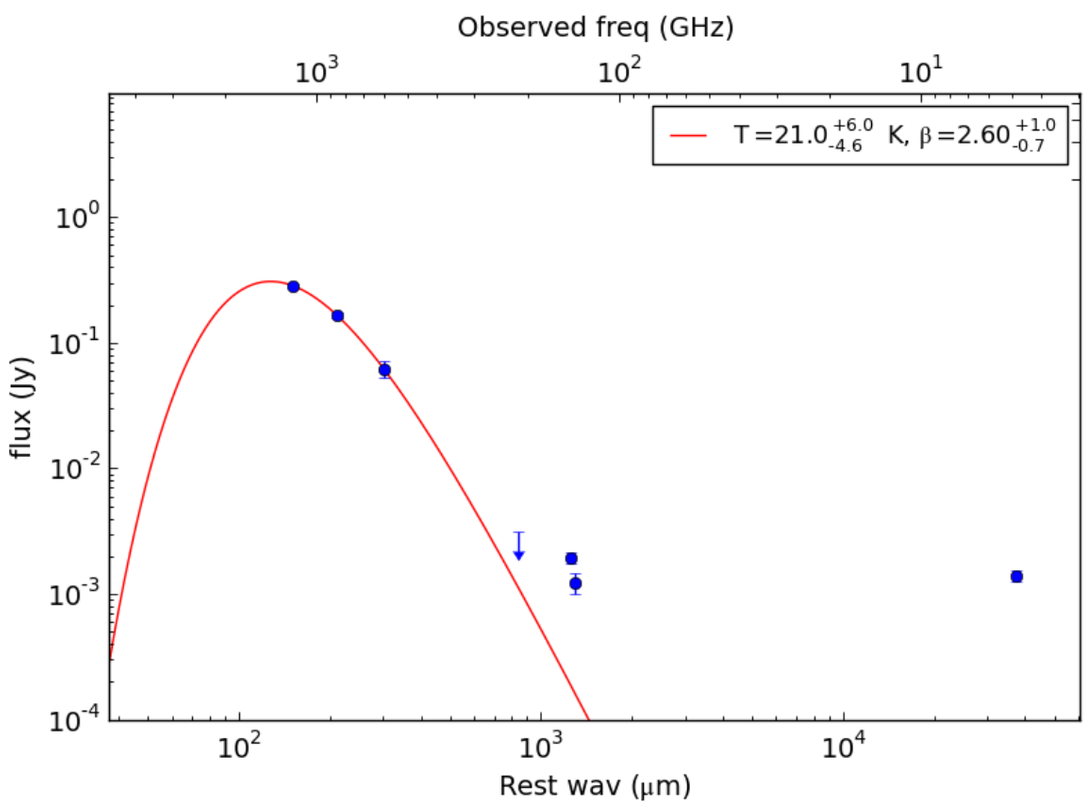


- Evidence for a lower Star-formation efficiency, **feedback from the Black Hole?**

- Evidence for a Milky Way / disk galaxy like CO-H_2 conversion, **dependent on host galaxy not state of the AGN?**

ALMA 2 mm continuum





- Compact 2 mm emission.
- Not consistent with heated dust emission — AGN interpretation.
- Flux-ratios inconsistent with the macro-modelling
- Micro-lensing by stars in the lensing galaxy suggest an intrinsic size of 10^{-3} to 10^{-4} pc.

Results & Conclusions

- **84%** detections in FIR, **69%** characteristic SF: strong coexistence of SF and AGN in most quasars
  - Mean dust temp 36 K similar to DSFGs
  - L_{FIR} ~10^{11}-10^{13} $L_\odot$ (median 6.7 x 10^{11} $L_\odot$)
  - SFR ~100-1000 $M_\odot\,yr^{-1}$ (median 220 $M_\odot\,yr^{-1}$)
- No difference in FIR luminosity distribution between RL and RQ

Stacey et al. in preprint arXiv:1705.10530

Paraficz et al. (RXJ1131-1231) in preprint arXiv:1705.09931