High-redshift radio galaxies with the International LOFAR Telescope (ILT)

Presenter:
Marco Bondi
Organization:
INAF - IRA

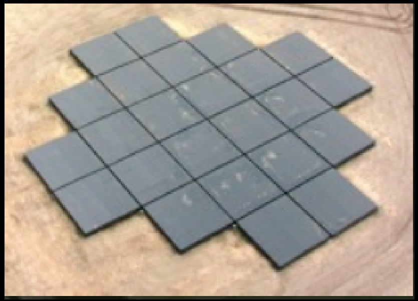
LOFAR.IT

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

BOLOGNA & FRIENDS
1-2 March 2023
INAF/IRA Bologna

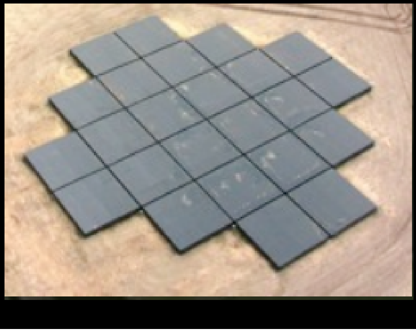
The Low Frequency Array (LOFAR)

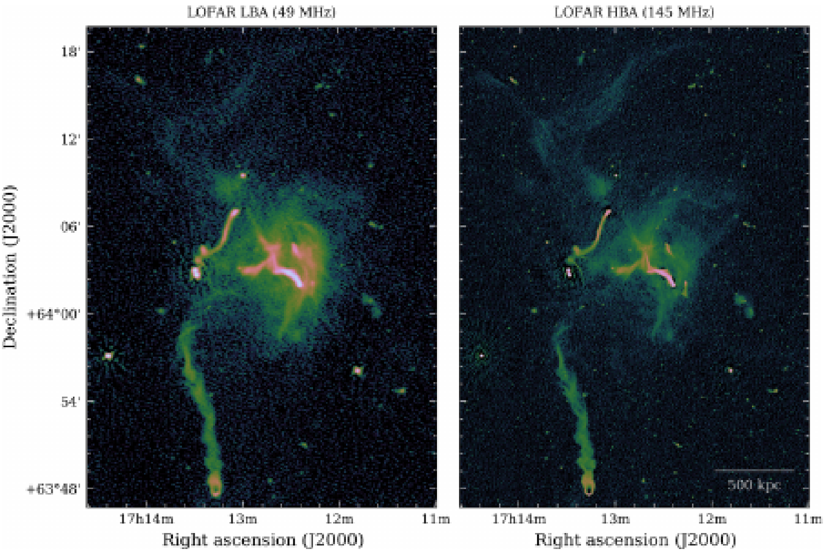
- Low Band Antenna (LBA; ~50 MHz)
- High Band Antenna (HBA; ~144 Mhz)
- Core stations (24, baseline 0.15-3 km)
- Remote stations (14, baseline 5-100 km)
- HBA: 6” resolution, rms ~80 µJy (8 hrs)



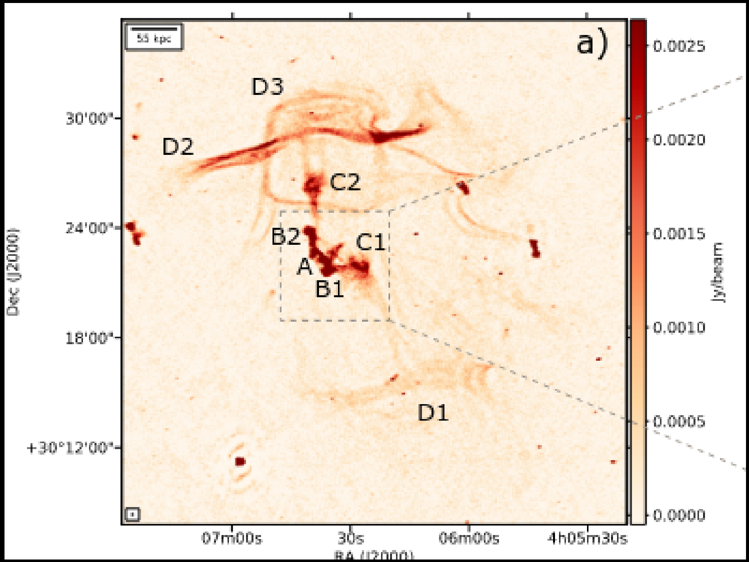
The Low Frequency Array (LOFAR)

- Low Band Antenna (LBA; ~50 MHz)
- High Band Antenna (HBA; ~145 Mhz)
- Core stations (24, baseline 0.15-3 km)
- Remote stations (14, baseline 5-100 km)
- HBA: 6” resolution, rms ~80 µJy (8 hrs)





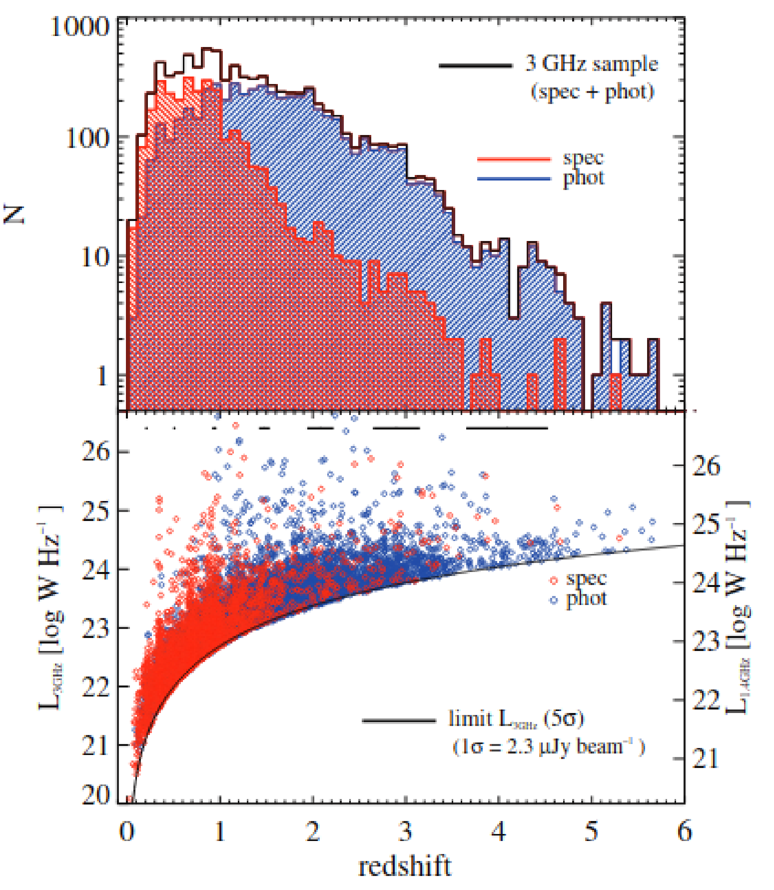
Botteon+2022, SciAdv



Brienza+2021, NatAst

International LOFAR Telescope (ILT)

Resolution from 6” to 0.3”
At z~1, from ~50 kpc to 2.5 Kpc

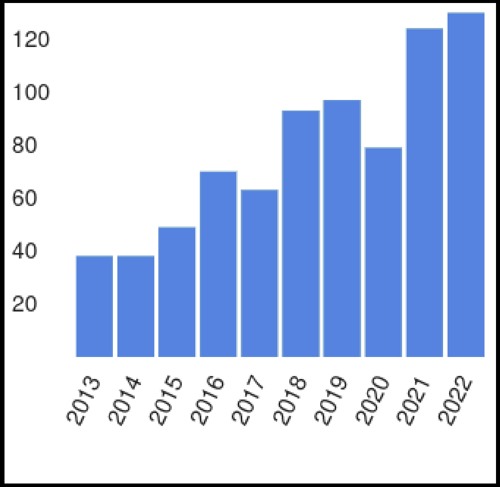


Delvecchio+2017

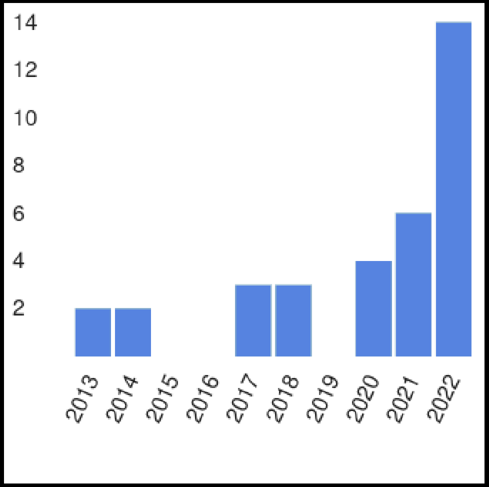
HBA: 144 MHz
38 Dutch stations
14 (+2) International stations: baselines up to ~ 2000 km

ILT Data Analysis: bottleneck

- Premises:
  - All LOFAR obs include the International Stations (IS)
  - Typically IS are NOT used



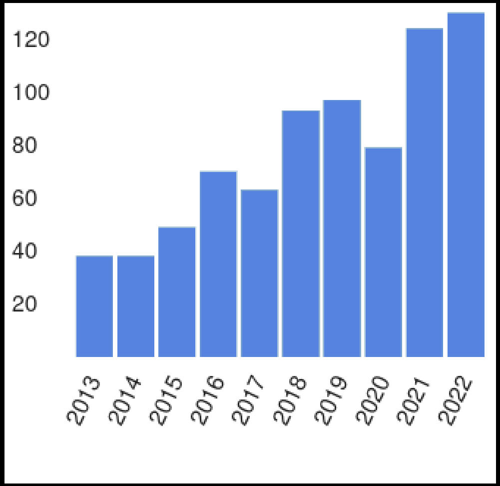
LOFAR papers 2013-2022



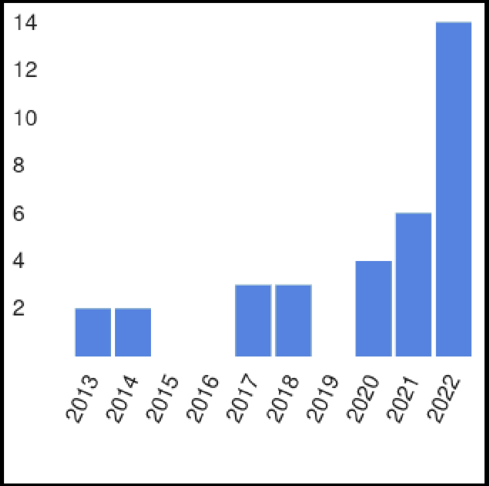
ILT papers 2013-2022

ILT Data Analysis: bottleneck

- Premises:
  - All LOFAR obs include the International Stations (IS)
  - Typically IS are NOT used



LOFAR papers 2013-2022



ILT papers 2013-2022

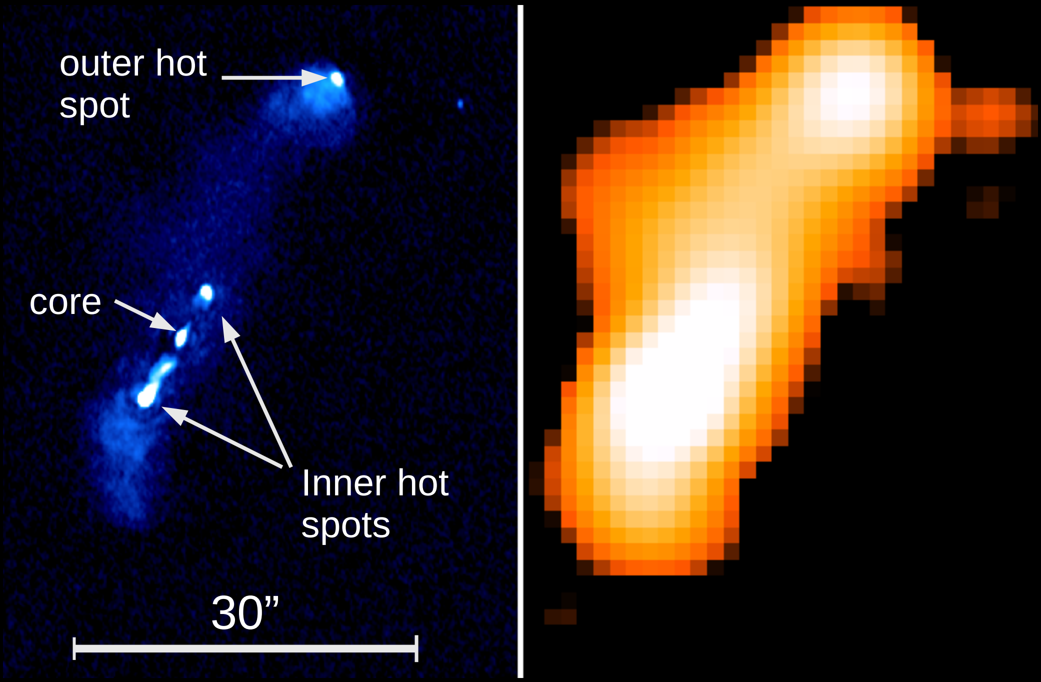
- Issues:
  - Time and computer resources demanding
  - A robust and reliable pipeline not available (until recently)

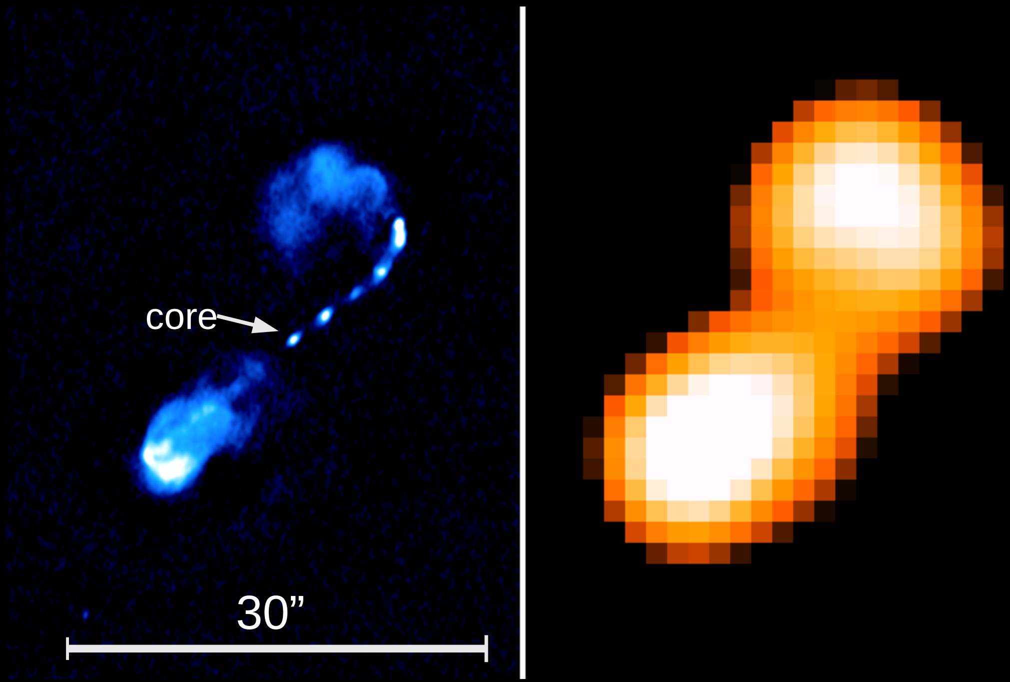
- Solution:
  - Long baseline pipeline (Morabito+2022)

https://github.com/lmorabit/lofar-vlbi/

ILT images: Radio Galaxies at z≥1 in the NEP Deep Field

(Bondi+ in prep.)

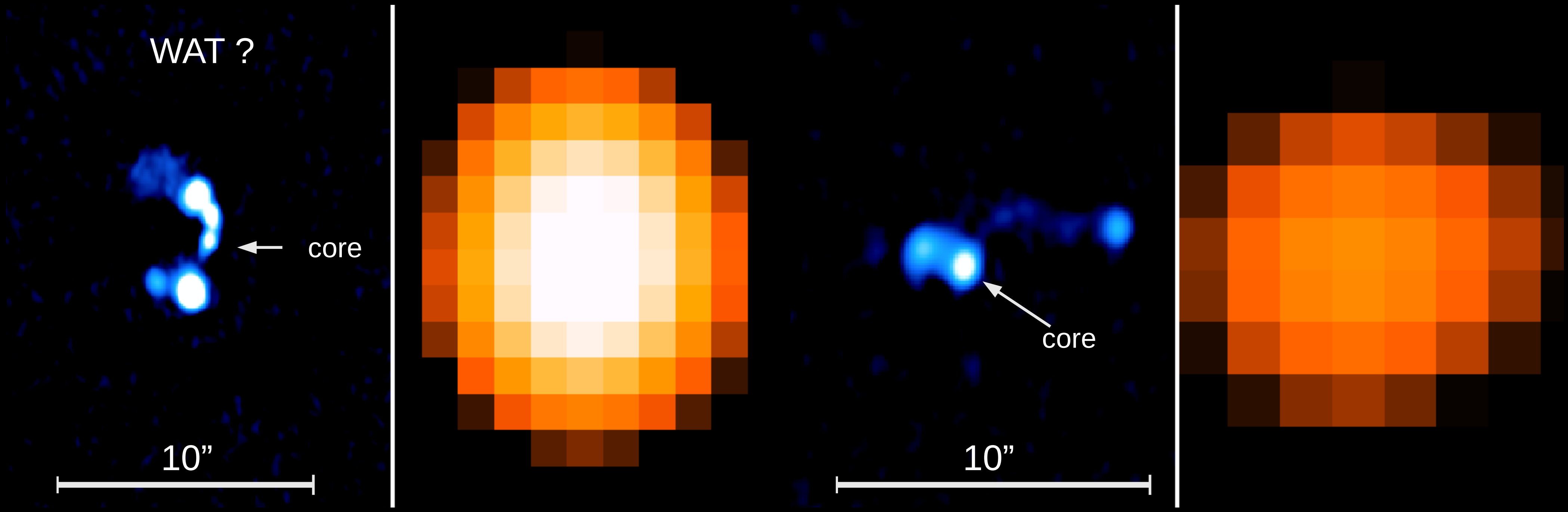




z=1.61 L_R = 6.7 x 10^{27} W/Hz

z=1.60 L_R = 4.7 x 10^{27} W/Hz

ILT (48 hrs)	LOFAR (72 hrs)	ILT (48 hrs)	LOFAR (72 hrs)
0”.45 x 0”.31	6”.0 x 6”.0	0”.46 x 0”.32	6”.0 x 6”.0
r.m.s ~ 18 µJy/beam	r.m.s = 41 µJy/beam	r.m.s ~ 20 µJy/beam	r.m.s = 42 µJy/beam
S_P = 40 mJy/beam	S_P = 150 mJy/beam	S_P = 4.8 mJy/beam	S_P = 106 mJy/beam



z=2.06 L$_R$= 2.5 x 10^{27} W/Hz

z=3.03 L$_R$= 8.5 x 10^{26} W/Hz

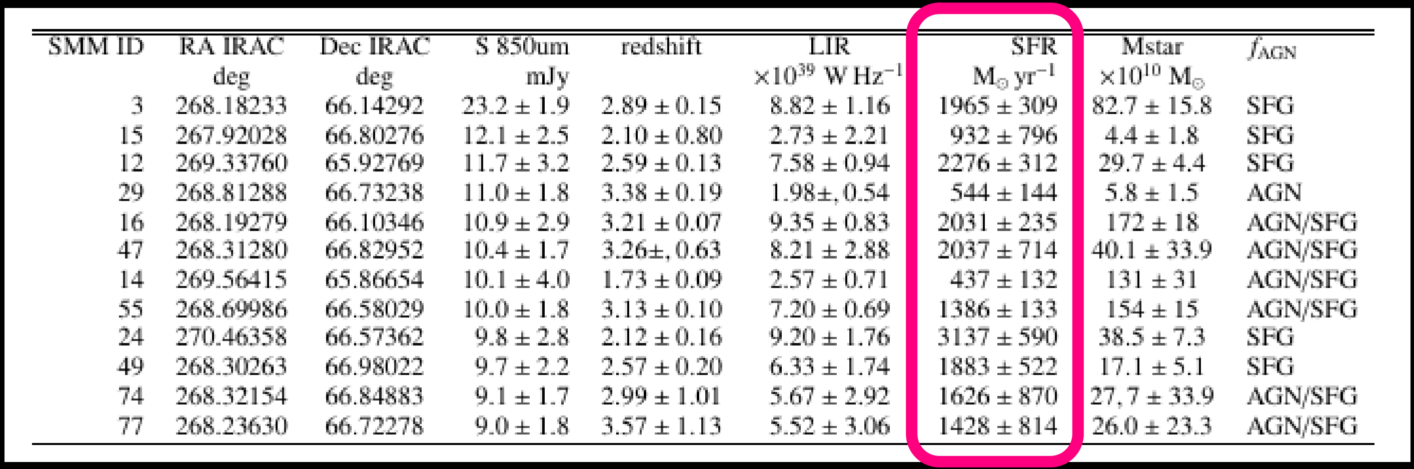
ILT (48 hrs)
0”.47 x 0”.33
r.m.s ~ 20 µJy/beam
S$_P$ = 17 mJy/beam

LOFAR (72 hrs)
6”.0 x 6”.0
r.m.s = 50 µJy/beam
S$_P$ = 73 mJy/beam

ILT (48 hrs)
0”.57 x 0”.42
r.m.s ~ 19 µJy/beam
S$_P$ = 6.0 mJy/beam

LOFAR (72 hrs)
6”.0 x 6”.0
r.m.s = 40 µJy/beam
S$_P$ = 12 mJy/beam

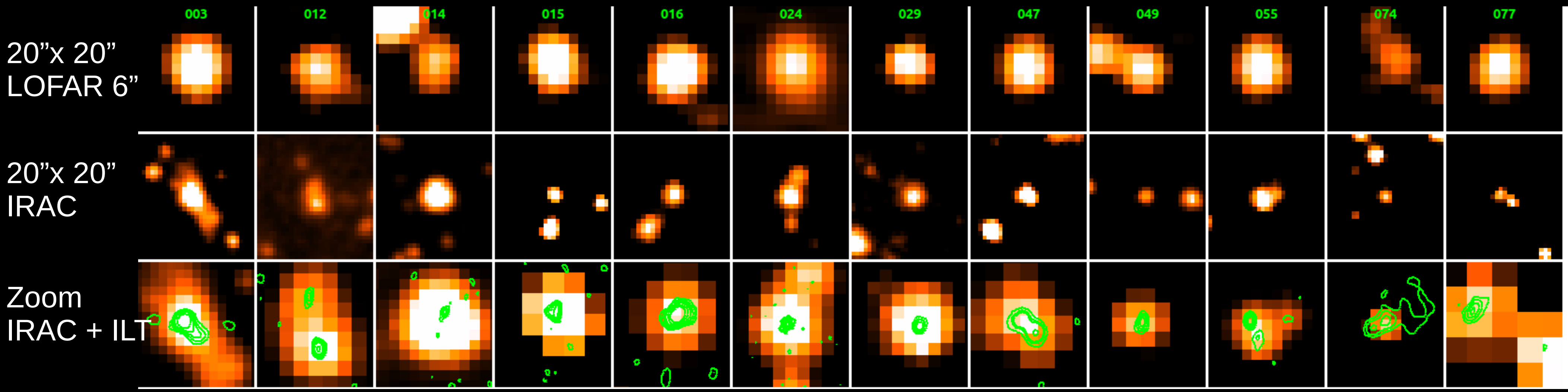
Exploiting Deep Fields observations with the ILT: bright sub-mm galaxies in the NEP field

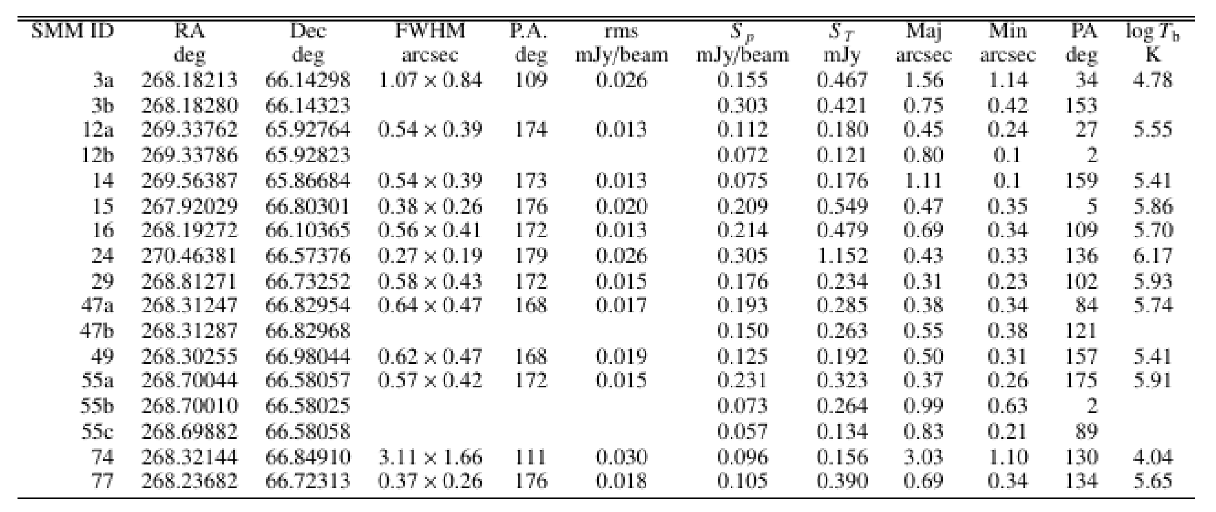


SMM ID	RA IRAC deg	Dec IRAC deg	S 850um mJy	redshift	LIR $\times10^{39}$ W Hz^{-1}	SFR $M_{\odot}$ yr^{-1}	Mstar $\times10^{10}$ $M_{\odot}$	f_{AGN}
3	268.18233	66.14292	23.2 ± 1.9	2.89 ± 0.15	8.82 ± 1.16	1965 ± 309	82.7 ± 15.8	SFG
15	267.92028	66.80276	12.1 ± 2.5	2.10 ± 0.80	2.73 ± 2.21	932 ± 796	4.4 ± 1.8	SFG
12	269.33760	65.92769	11.7 ± 3.2	2.59 ± 0.13	7.58 ± 0.94	2276 ± 312	29.7 ± 4.4	SFG
29	268.81288	66.73238	11.0 ± 1.8	3.38 ± 0.19	1.98±, 0.54	544 ± 144	5.8 ± 1.5	AGN
16	268.19279	66.10346	10.9 ± 2.9	3.21 ± 0.07	9.35 ± 0.83	2031 ± 235	172 ± 18	AGN/SFG
47	268.31280	66.82952	10.4 ± 1.7	3.26±, 0.63	8.21 ± 2.88	2037 ± 714	40.1 ± 33.9	AGN/SFG
14	269.56415	65.86654	10.1 ± 4.0	1.73 ± 0.09	2.57 ± 0.71	437 ± 132	131 ± 31	AGN/SFG
55	268.69986	66.58029	10.0 ± 1.8	3.13 ± 0.10	7.20 ± 0.69	1386 ± 133	154 ± 15	AGN/SFG
24	270.46358	66.57362	9.8 ± 2.8	2.12 ± 0.16	9.20 ± 1.76	3137 ± 590	38.5 ± 7.3	SFG
49	268.30263	66.98022	9.7 ± 2.2	2.57 ± 0.20	6.33 ± 1.74	1883 ± 522	17.1 ± 5.1	SFG
74	268.32154	66.84883	9.1 ± 1.7	2.99 ± 1.01	5.67 ± 2.92	1626 ± 870	27,7 ± 33.9	AGN/SFG
77	268.23630	66.72278	9.0 ± 1.8	3.57 ± 1.13	5.52 ± 3.06	1428 ± 814	26.0 ± 23.3	AGN/SFG

- Selected all SMGs with $S_{850\text{-}\mu m} \geq 9$ mJy, r<1.2 deg from field center, and robust SED fit from Shin+ 2022 catalog:
  - 12 objects: $1.7 < z < 3.5$, SFR > 1000 $M_{\odot}$/yr
  - 11/12 detected in LOFAR 6” image (72hrs) with SNR>5 (1/7 with 4<SNR<5):
    - 0.16 mJy/b < $S_{6''}$ < 1.6 mJy/b
    - ~8 x 10^{24} W/Hz < L_{144MHz} < 5 x 10^{25} W/Hz

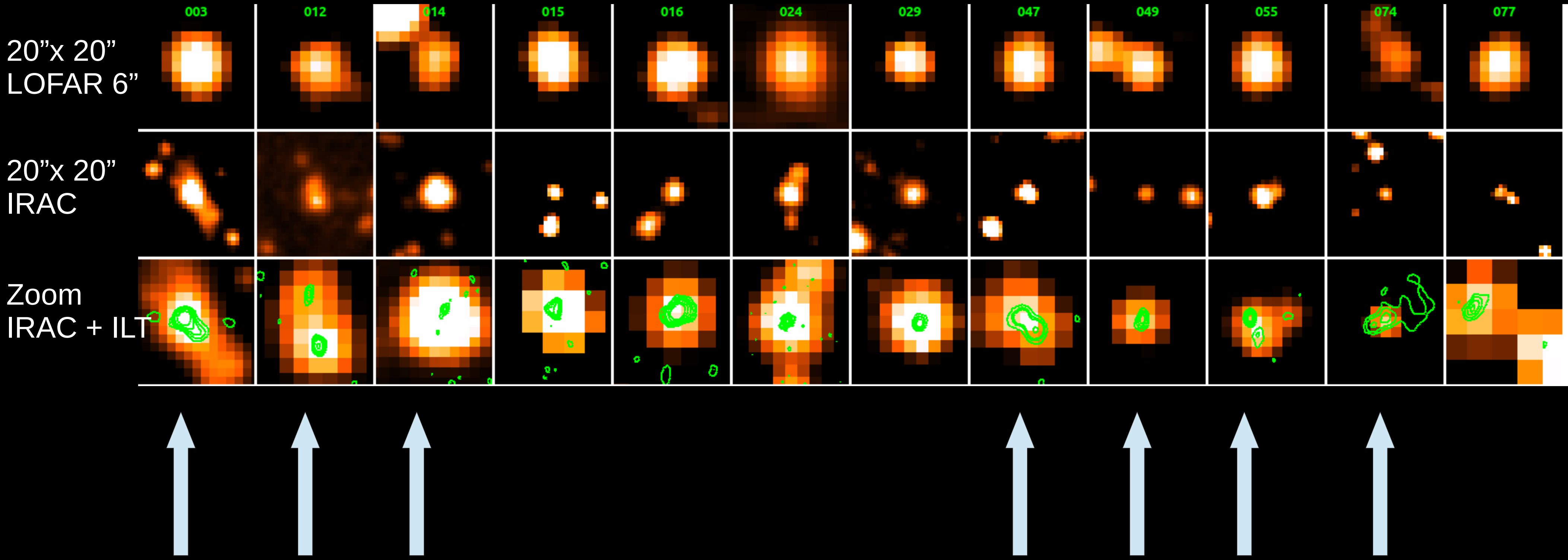
Bright SMGs in the NEP field: Multiplicity





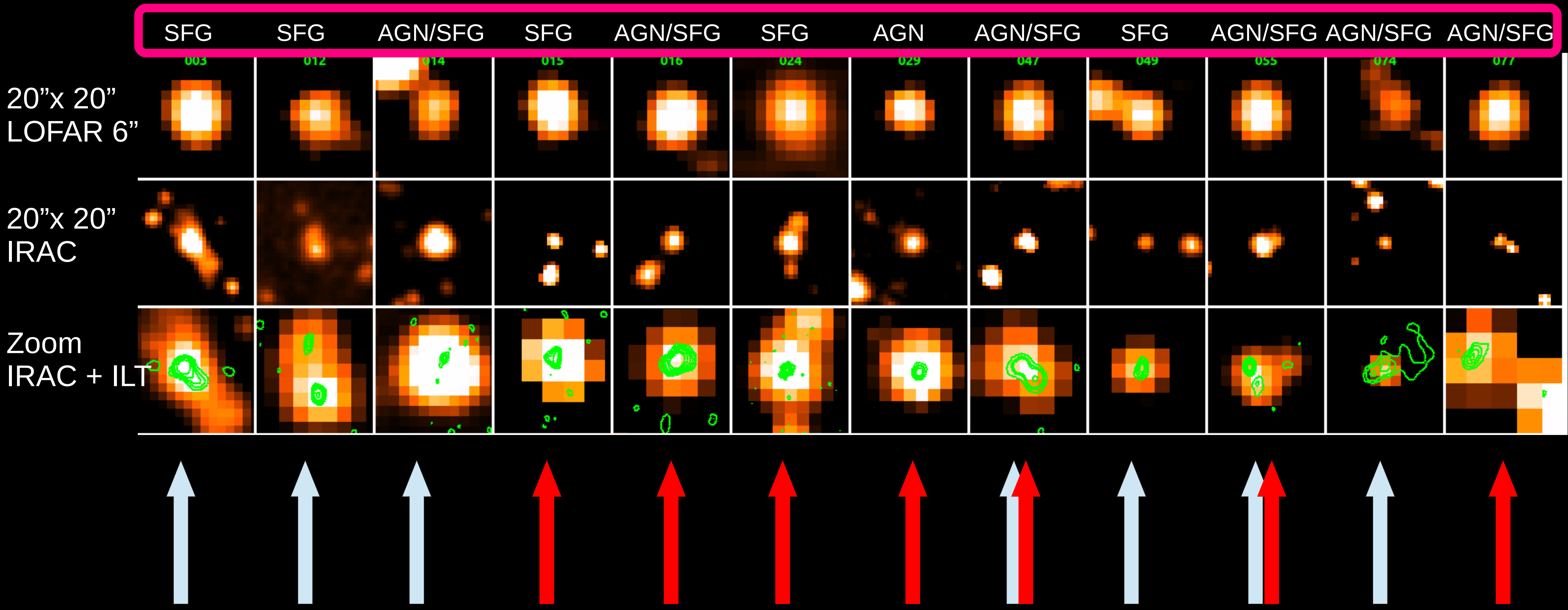
SMM ID	RA deg	Dec deg	FWHM arcsec	P.A. deg	rms mJy/beam	S_p mJy/beam	S_T mJy	Maj arcsec	Min arcsec	PA deg	log T_b K
3a	268.18213	66.14298	1.07 × 0.84	109	0.026	0.155	0.467	1.56	1.14	34	4.78
3b	268.18280	66.14323				0.303	0.421	0.75	0.42	153	
12a	269.33762	65.92764	0.54 × 0.39	174	0.013	0.112	0.180	0.45	0.24	27	5.55
12b	269.33786	65.92823				0.072	0.121	0.80	0.1	2	
14	269.56387	65.86684	0.54 × 0.39	173	0.013	0.075	0.176	1.11	0.1	159	5.41
15	267.92029	66.80301	0.38 × 0.26	176	0.020	0.209	0.549	0.47	0.35	5	5.86
16	268.19272	66.10365	0.56 × 0.41	172	0.013	0.214	0.479	0.69	0.34	109	5.70
24	270.46381	66.57376	0.27 × 0.19	179	0.026	0.305	1.152	0.43	0.33	136	6.17
29	268.81271	66.73252	0.58 × 0.43	172	0.015	0.176	0.234	0.31	0.23	102	5.93
47a	268.31247	66.82954	0.64 × 0.47	168	0.017	0.193	0.285	0.38	0.34	84	5.74
47b	268.31287	66.82968				0.150	0.263	0.55	0.38	121	
49	268.30255	66.98044	0.62 × 0.47	168	0.019	0.125	0.192	0.50	0.31	157	5.41
55a	268.70044	66.58057	0.57 × 0.42	172	0.015	0.231	0.323	0.37	0.26	175	5.91
55b	268.70010	66.58025				0.073	0.264	0.99	0.63	2	
55c	268.69882	66.58058				0.057	0.134	0.83	0.21	89	
74	268.32144	66.84910	3.11 × 1.66	111	0.030	0.096	0.156	3.03	1.10	130	4.04
77	268.23682	66.72313	0.37 × 0.26	176	0.018	0.105	0.390	0.69	0.34	134	5.65

Bright SMGs in the NEP field: Multiplicity



- Multiple components: 3 (arcsec scale) + 4 (sub-arcsec scale)

Bright SMGs in the EDFN: radio AGN



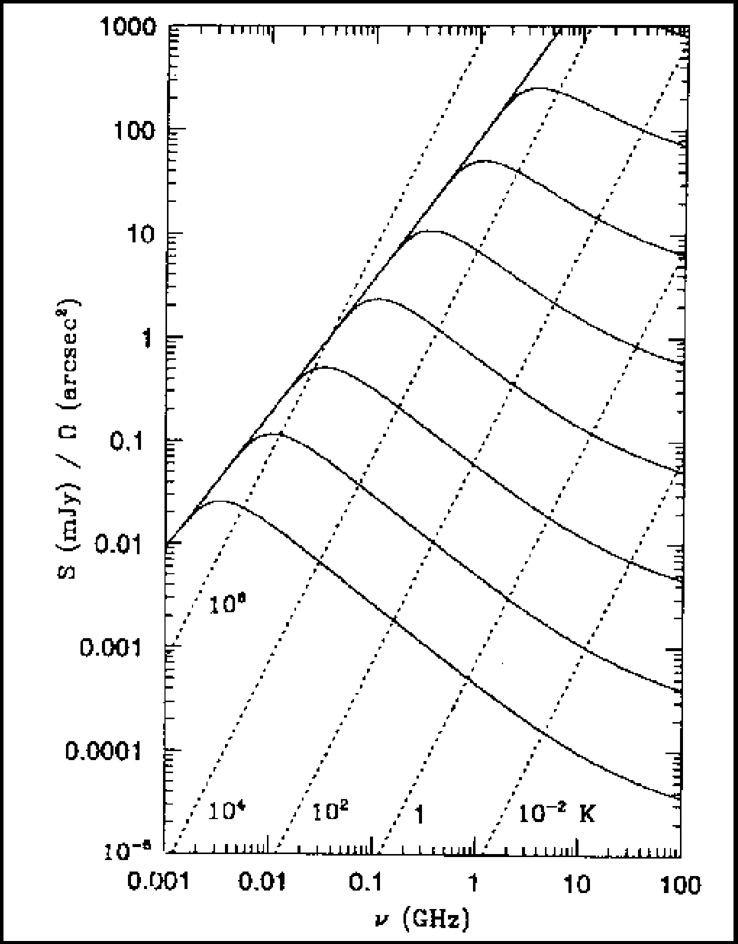
- Brightness Temperature exceeding the limit for star-formation (e.g. Condon 1991): 7 SMGs with log(T_b)>5.6

T_b as AGN proxy

- Maximum brightness temperature for a normal galaxy with thermal and non thermal emission (Condon 1991):

$$T_{\mathrm{b}} = T_{\mathrm{e}}\left(1 - e^{-\tau_{\mathrm{ff}}}\right)\left(1 + 10\left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{0.1+\alpha}\right)$$

- Normal galaxies have $T_b \leq 10^5$ for $\nu \geq 1$ GHz

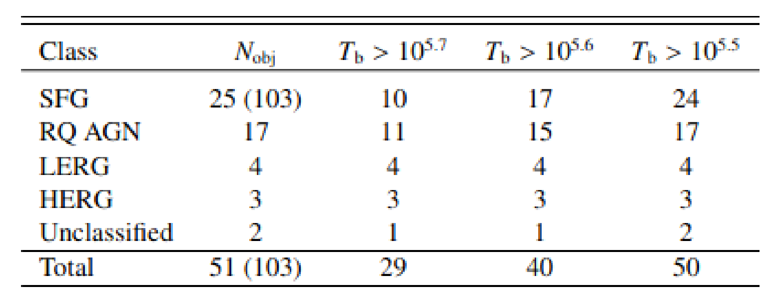


T_b as AGN proxy

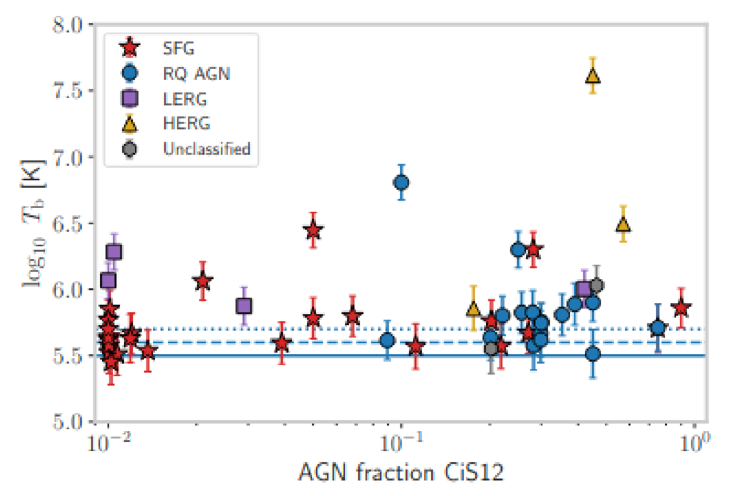
- Maximum brightness temperature for a normal galaxy with thermal and non thermal emission (Condon 1991):

$$T_{\rm b} = T_{\rm e}\left(1 - e^{-\tau_{\rm ff}}\right)\left(1 + 10\left(\frac{\nu}{1\ \rm GHz}\right)^{0.1+\alpha}\right)$$

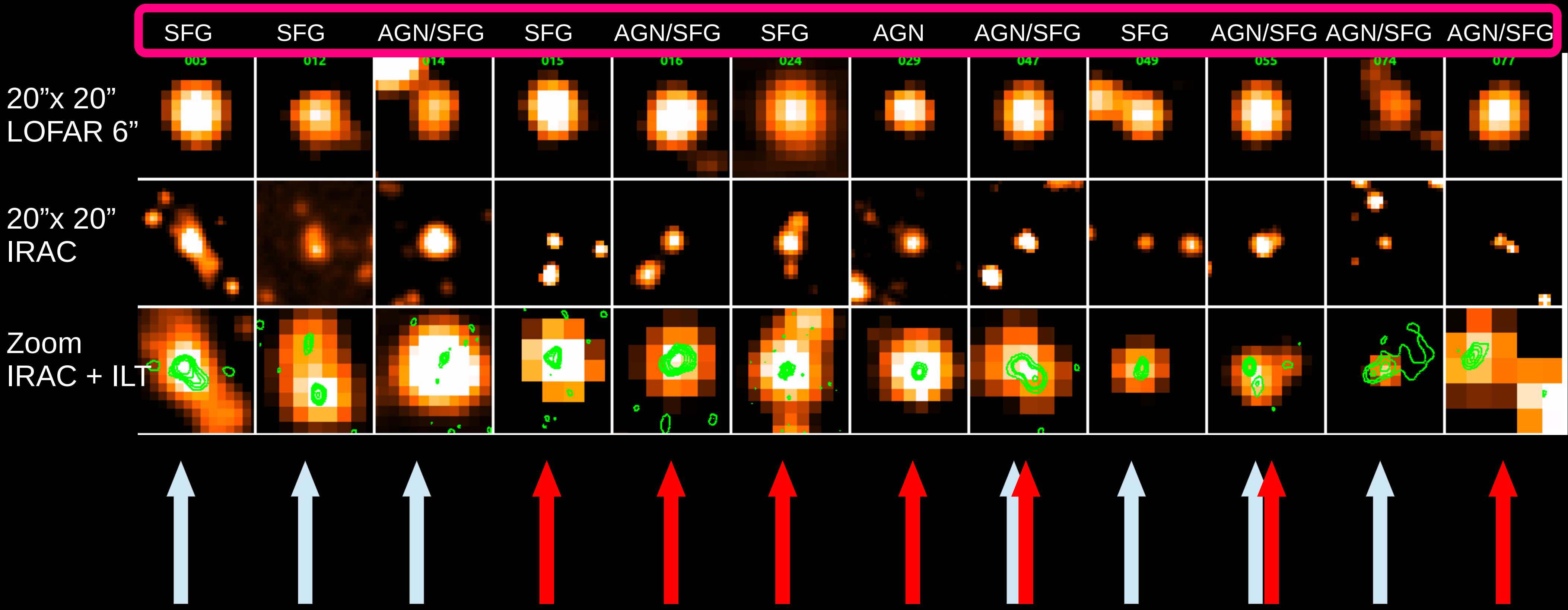
- Normal galaxies have $T_b \leq 10^5$ for $\nu \geq 1$ Ghz
- Sample of ~150 HLIRGs in the Lockman Hole (Sweijen+2023, in press), 33% detected with ILT



Class	$N_{\rm obj}$	$T_{\rm b} > 10^{5.7}$	$T_{\rm b} > 10^{5.6}$	$T_{\rm b} > 10^{5.5}$
SFG	25 (103)	10	17	24
RQ AGN	17	11	15	17
LERG	4	4	4	4
HERG	3	3	3	3
Unclassified	2	1	1	2
Total	51 (103)	29	40	50

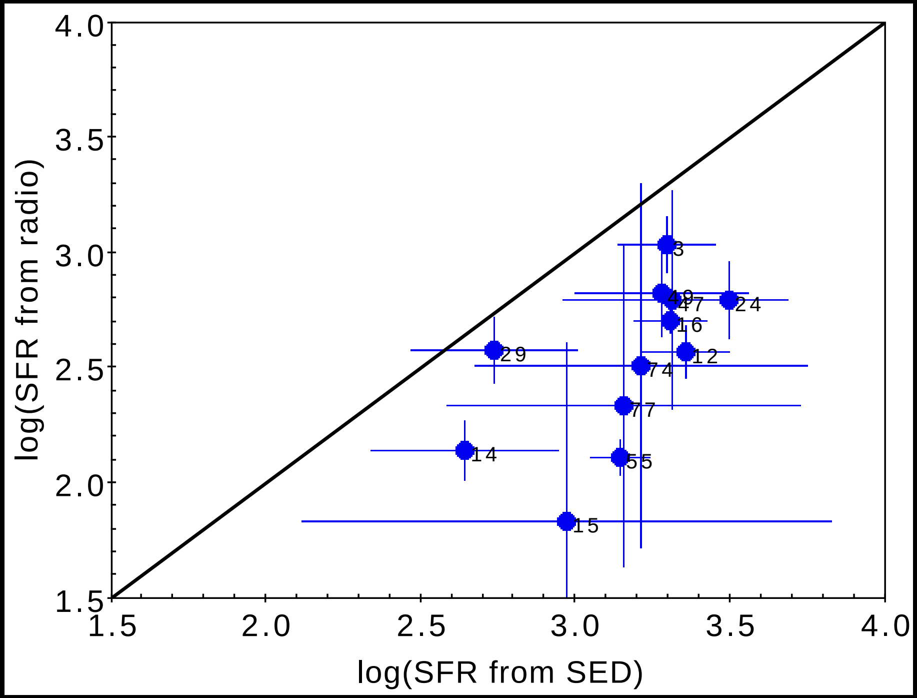


Bright SMGs in the EDFN: radio AGN



- Brightness Temperature exceeding the limit for star-formation (e.g. Condon 1991): 7 SMGs with log(T_b)>5.6

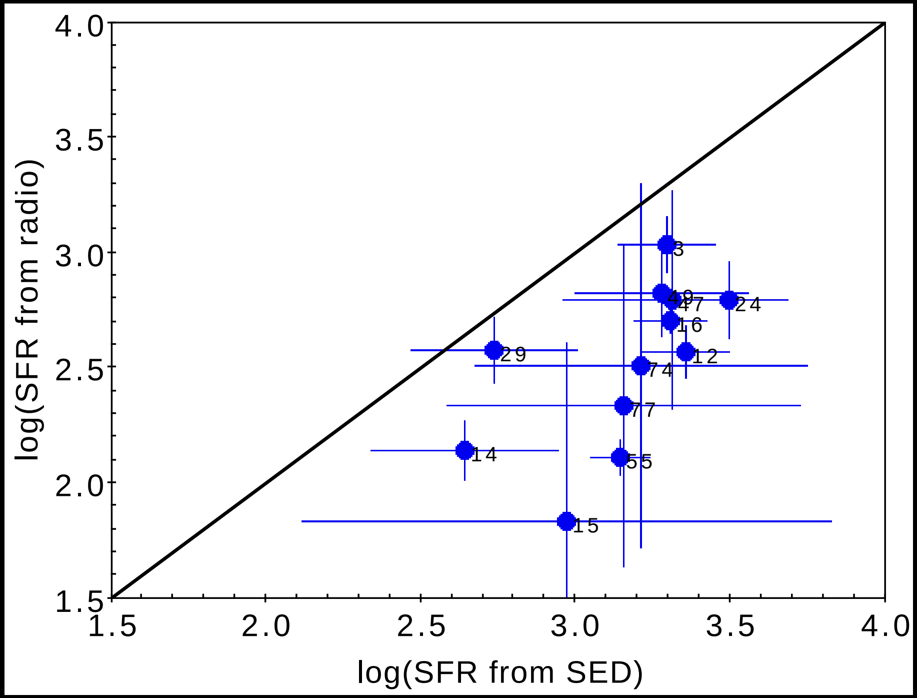
Radio vs SED SFRs & main sequence

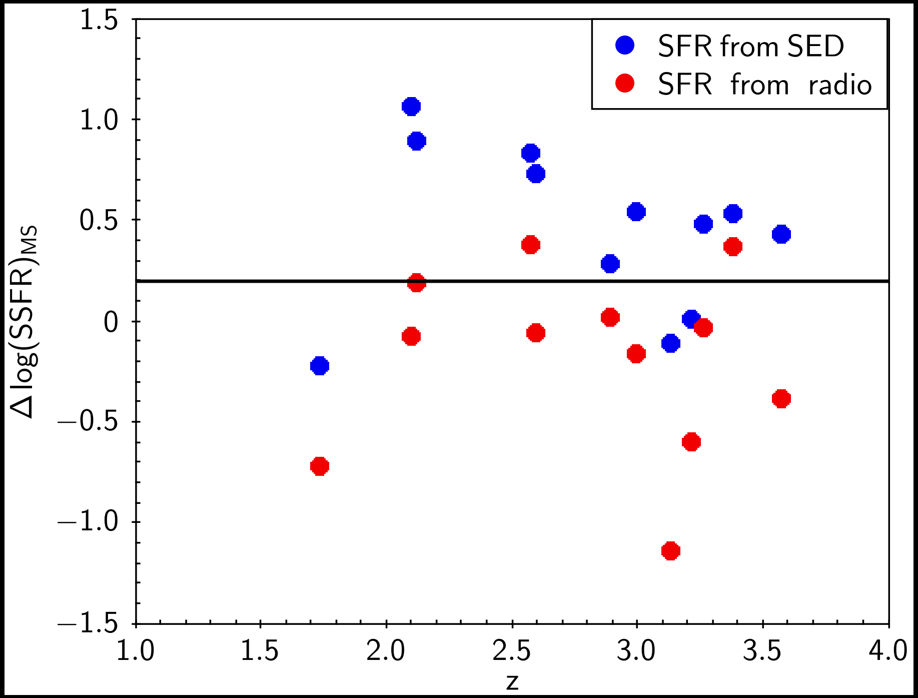


SFR from radio obtained from radio flux at 6” resolution after subraction of multiple comp and/or AGN comp: ~5 times lower than that from SED fitting

Radio vs SED SFRs & main sequence

$$\Delta\log(\mathrm{SSFR})_{\mathrm{MS}} = \log\left[\mathrm{SSFR}_{\mathrm{galaxy}}/\mathrm{SSFR}_{\mathrm{MS}}(M_{\mathrm{star}},\ z)\right]$$





SFR from radio obtained from radio flux at 6” resolution after subraction of multiple comp and/or AGN comp: ~5 times lower than that from SED fitting

Distance of a galaxy from the star-forming galaxy main sequence (MS) in the SFR-stellar mass plane, removing effects of different stellar mass and z evolution

Summary

- ILT allows imaging the radio sky at 144 Mhz with resolution down to ~0.3” with average 1σ sensitivity of ~50 μJy/beam for 8 hrs (~10-15 μJy/beam for Deep Fields).
  - Necessary for proper multi-λ identification
  - <10% of radio sources have sizes > 10”, ILT allows to study the details of the remaining 90% (widefield imaging necessary)
- To process a single target with the long-baseline pipeline:
  - e.g. 32-48 cores, Ram ~384 G, disk space >15 T
  - 4-8 days of processing, including selfcal and imaging
- A significant fraction of the sky (e.g. LoTSS) has already been observed with the ISs but not processed. Your favoutite source might be there !