The Giant Radio Galaxy Content of LoTSS DR2

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Definition and previous Giant Radio Galaxy (GRG) discoveries

The "largest linear size" (LLS) of a RG is based on its angular size (LAS), its redshift, and "standard" cosmological parameters

Willis+1974 found 3C 236 & DA 240 (of 5.7 and 2 Mpc projected size) when H_0 = 50 km/s/Mpc was in use; GRG := LLS > 1 Mpc

3C 236 remained the record holder for 34 years until 2008

Ishwara-Chandra & Saikia 2000 compiled 53 GRGs > 1 Mpc (5 are QSOs)

Since ~2000 we use H_0 = 70 km/s/Mpc ➔ GRG := **LLS > 0.7 Mpc**

however: there is as yet no physical reason for any threshold value

Kuzmicz & Jamrozy 2018 compiled from lit. 349 GRGs >0.7 Mpc (39% < 1 Mpc)

→ **proves that GRGs < 0.7 Mpc have been neglected in literature**

Dabhade+2020a found 239 GRGs >0.7 Mpc from LoTSS DR1 (63% < 1 Mpc)

Dabhade+2020b found 162 GRGs >0.7 Mpc in NVSS (40% < 1 Mpc)

Kuzmicz & Jamrozy 2021 found 174 new GRQs (QSO hosts) (60% < 1 Mpc)

Andernach + students since 2012 search for + compile GRGs in public surveys → ~6 times more than in literature until 2022; unpubl. except for:

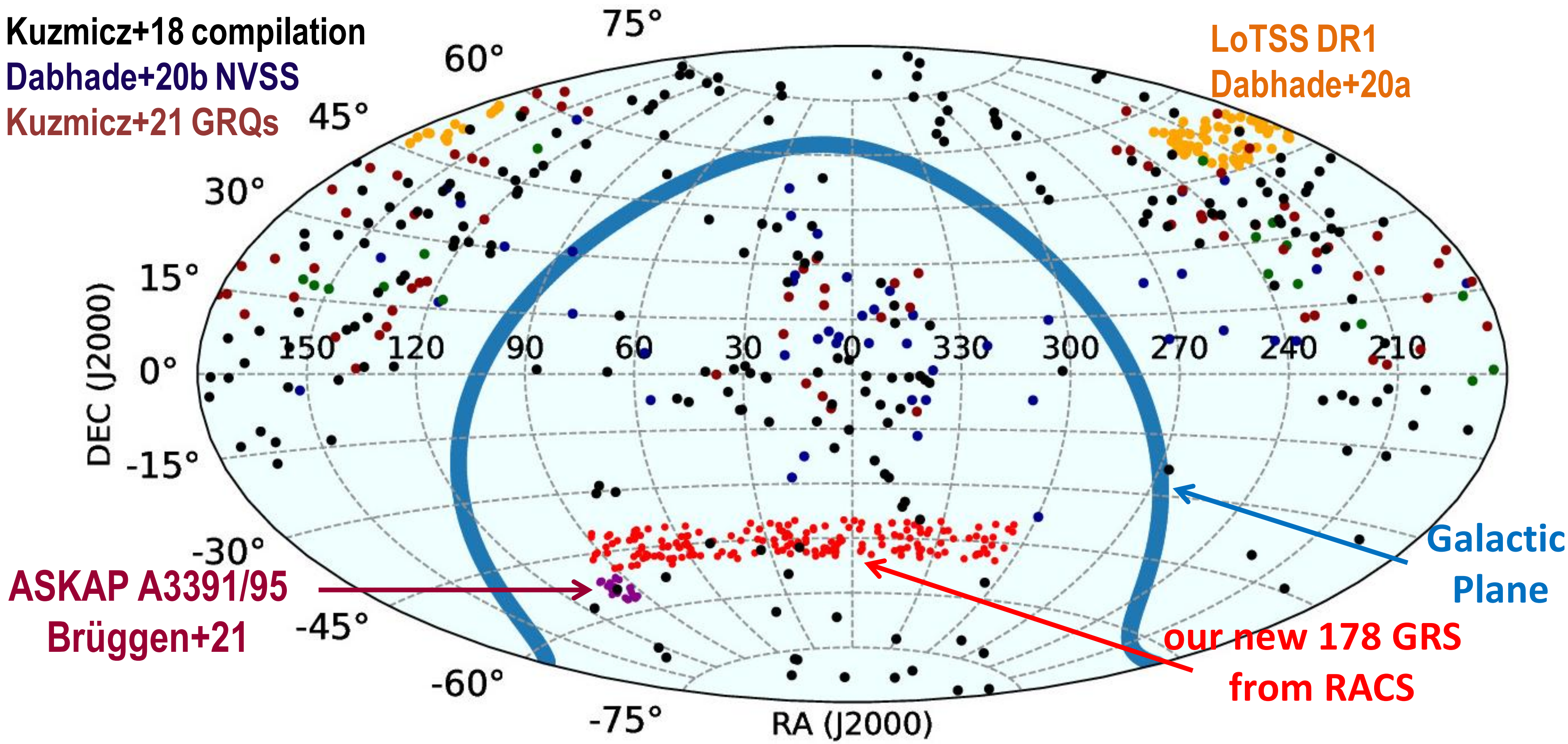
Brűggen+2021 derived a surface density of 1.7 deg^{-2} in deep ASKAP image

Simonte+2021+22 found 143 GRGs >0.7 Mpc in 2 LoTSS Deep Fields

Andernach+2021 found 178 new GRGs >1 Mpc in 1059 deg^2 of RACS

Inspection of 1059 deg² of RACS: all-sky map of published GRS >1 Mpc in late 2021 (2021Galax...9…99Andernach H., E.F. Jiménez-Andrade & A.G. Willis)

Our **178 new GRS** increased the previously known ones by 39% to (then) **636**



This paper held the record of the largest number of new GRGs >1 Mpc in a single paper, but only for one year . . . until October 2022 . . .

. . . when Oei et al. beat our previous record by a factor of >8 !

arXiv > astro-ph > arXiv:2210.10234 **2059 new GRGs !**

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[Submitted on 19 Oct 2022] **published in May 2023 : A&A 672A, 163**

Measuring the giant radio galaxy length distribution with the LoTSS DR2

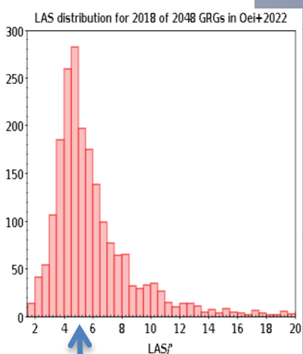
Martijn S. S. L. Oei, Reinout J. van Weeren, Aivin R. D. J. G. I. B. Gast, Andrea Botteon, Martin J. Hardcastle, Pratik Dabhade, Tim W. Shimwell, Huub J. A. Röttgering, Alexander Drabent

Radio galaxies are luminous structures created by the jets of supermassive black holes, and consist of atomic nuclei, relativistic electrons, and magnetic fields. In exceptional cases, radio galaxies attain cosmological, megaparsec extents - and thus turn into giants. Giants embody the most extreme known mechanism through which galaxies can impact the Cosmic Web around them. The triggers of giant growth remain a mystery. Excitingly, new sensitive low-frequency sky surveys hold promise to change this situation. In this work, we perform a precision measurement of the distribution of giant growth's central dynamical quantity: total length. We first construct a statistical geometric framework for radio galaxies that is both rigorous and practical. We then search the LOFAR Two-metre Sky Survey DR2 for giants, discovering 2050 previously unknown specimina: more than have been found in all preceding literature combined. Spectacular discoveries include the longest giant hosted by an elliptical galaxy, the longest giant hosted by a spiral galaxy, and 13 giants with an angular length larger than that of the full Moon. By combining theory and observations - and carefully forward modelling selection effects - we infer that giant radio galaxy lengths are well described by a Pareto distribution with tail index -3.5 ± 0.5. This finding is a new observational constraint for models and simulations of radio galaxy growth. In addition, for the first time, we determine the comoving number density of giants, $5 \pm 2\ (100\ \mathrm{Mpc})^{-3}$, and the volume-filling fraction of giant radio galaxy lobes in clusters and filaments, $5^{+8}_{-2} \cdot 10^{-6}$. We conclude that giants are truly rare - not only from an observational perspective, but also from a cosmological one. At any moment in time, most clusters and filaments - the building blocks of the modern Cosmic Web - do not harbour giants.

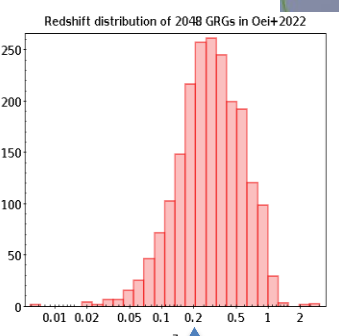
Goal: find "all" GRGs within a redshift of z < 0.2 (dist. < 850 Mpc) based on LoTSS DR2: use images at 6" and 20" resolution (public), but also at 60" and 90" (not public) with point sources removed → high sensitivity for diffuse emission + visually outstanding!

One quarter (23%) of Oei et al's GRGs lie outside the published LoTSS DR2 footprint
→ currently no way to control their findings (needs access to unreleased tiles, not in HiPS)

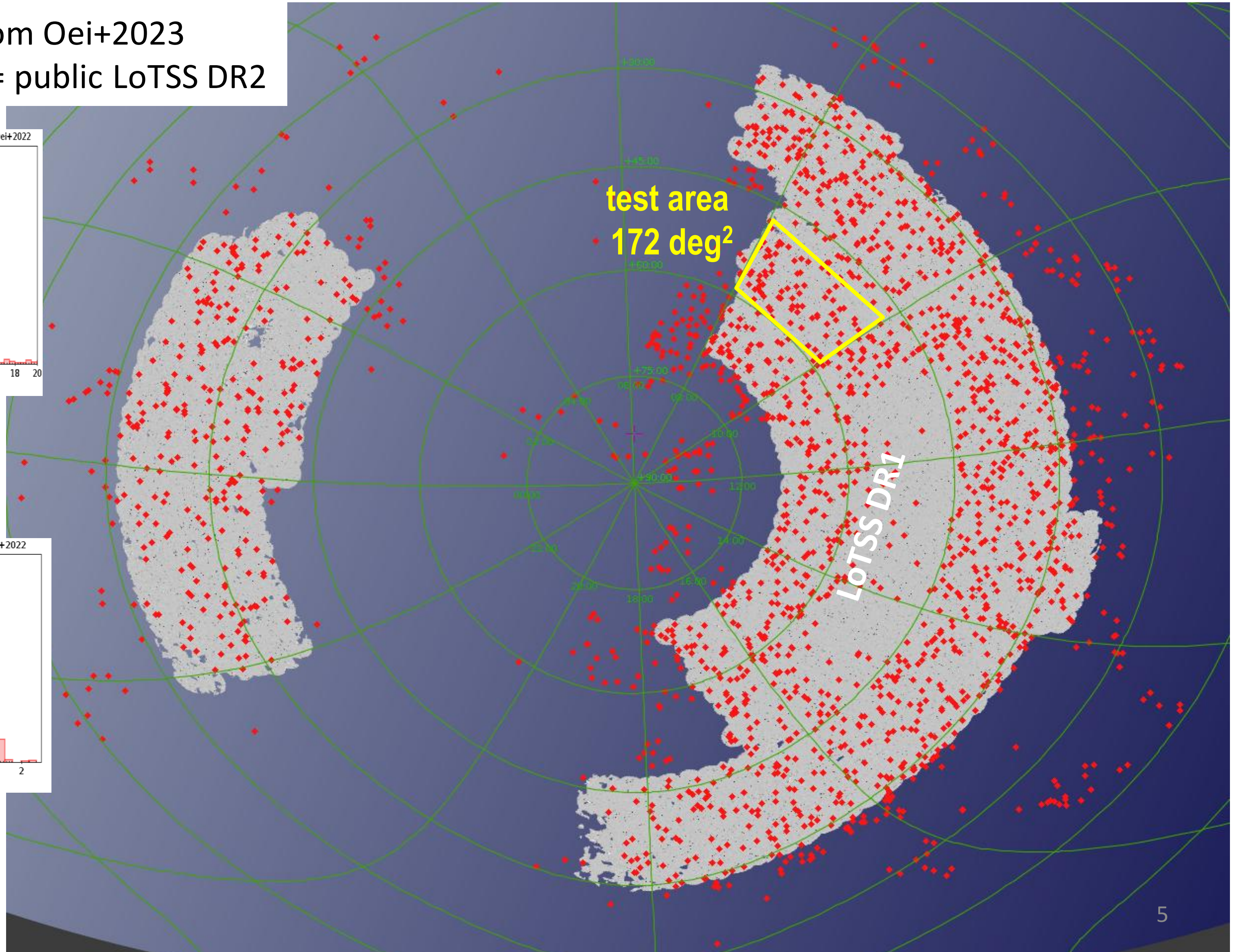
● GRGs from Oei+2023
grey area = public LoTSS DR2



half of their GRGs have LAS < 5'



over half of their GRGs have z >0.2

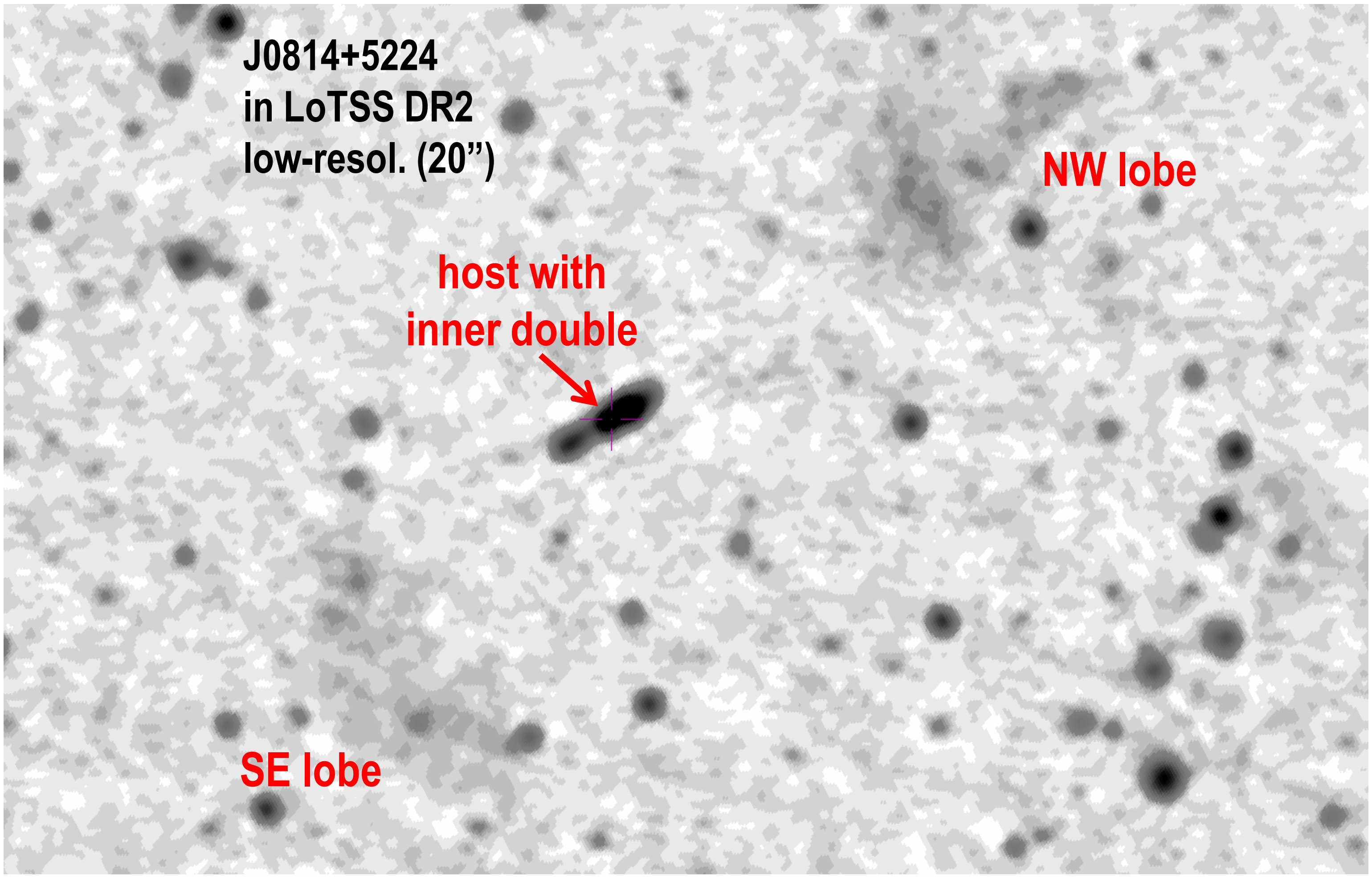


Oei+2023, A&A 660, A2 **claim the largest GRG found as yet: "Alcyoneus" of 5.0 Mpc**

The discovery of a radio galaxy of at least 5 Mpc

Martijn S. S. L. Oei[1], Reinout J. van Weeren[1], Martin J. Hardcastle[2], Andrea Botteon[1], Tim W. Shimwell[1], Pratik Dabhade[3], Aivin R. D. J. G. I. B. Gast[4], Huub J. A. Röttgering[1], Marcus Brüggen[5], Cyril Tasse[6,7], Wendy L. Williams[1], and Aleksandar Shulevski[1]

However, using standard measures for LAS, and H_0=70, Ω_m=0.3, Ω_Λ=0.7 I find for J0814+5224 :



LAS=20.4' ,
z_{spec}=0.2467
LLS = 4.74 Mpc

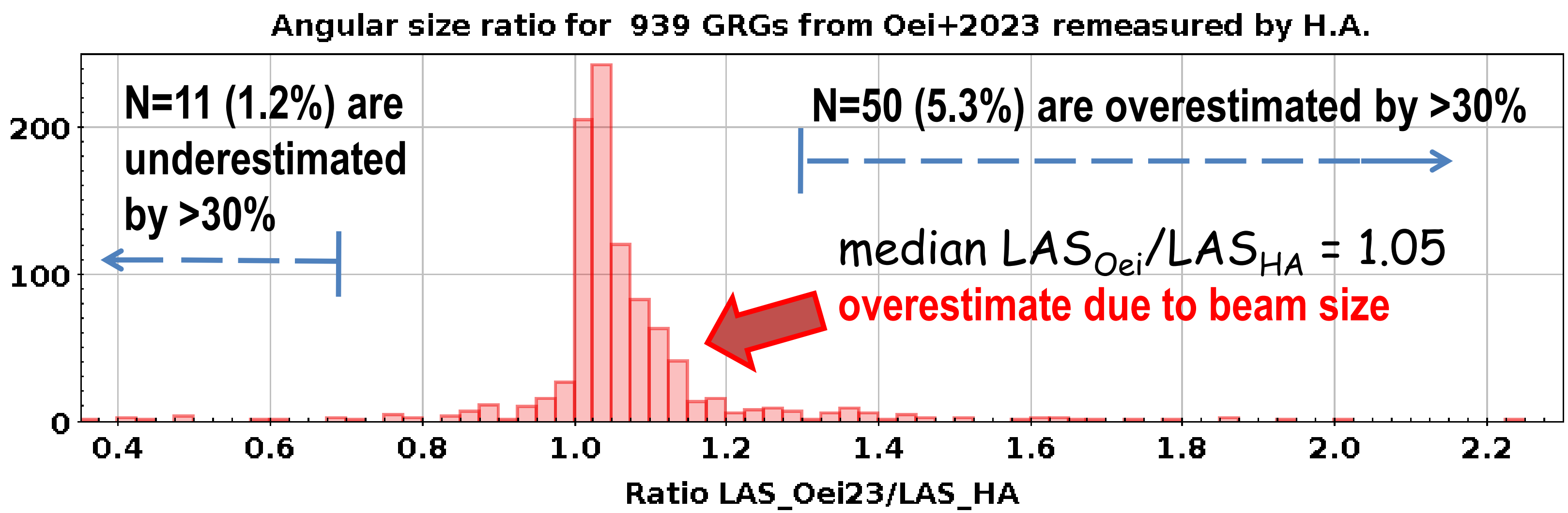
= same as previously largest one J1420−0545 (Machalski+08)

The list of 2059 new GRGs published by Oei et al. (2023):

Rank	Host name SDSS DR12	Host coordinates J2000 (°)	Redshift (1)	Redshift type	Angular length (′)	Projected proper length (Mpc)	Host stellar mass ($10^{11} M_\odot$)	Host SMBH mass ($10^9 M_\odot$)	Host quasar
1	J081956.41+323537.6	124.9851, 32.5938	0.749 ± 0.073	*p*	11.2	5.07 ± 0.20	...	...	...
2	J081421.68+522410.0	123.5904, 52.4028	$0.2467 \pm 6 \times 10^{-5}$	*s*	20.8	4.99 ± 0.04	2.4 ± 0.4	0.4 ± 0.2	*n*
3	J142910.70+311245.0	217.2946, 31.2125	0.5921 ± 0.0001	*s*	11.7	4.80 ± 0.06	...	2.3 ± 2.0	*n*
4	J131823.42+262622.8	199.5976, 26.4397	$0.6230 \pm 5 \times 10^{-5}$	*s*	11.0	4.62 ± 0.06	...	...	*y*
5	J152634.77+262003.2	231.6449, 26.3342	$0.1507 \pm 2 \times 10^{-5}$	*s*	28.0	4.56 ± 0.03	3.7 ± 0.6	1.4 ± 0.3	*n*
6	J121815.66+382407.5	184.5653, 38.4021	0.634 ± 0.064	*p*	10.6	4.49 ± 0.21	...	...	...
7	J175735.88+405154.2	269.3995, 40.8651	0.585 ± 0.036	*p*	10.5	4.29 ± 0.14	...	...	...
8	J161622.52+111135.7	244.0939, 11.1933	$0.3574 \pm 7 \times 10^{-5}$	*s*	13.4	4.15 ± 0.05	9.5 ± 1.8	5.7 ± 3.1	*n*
9	J154709.22+353846.1	236.7884, 35.6462	$0.0794 \pm 1 \times 10^{-5}$	*s*	43.8	4.08 ± 0.01	4.6 ± 0.1	3.9 ± 0.9	*n*

neither a classification of radio morphology (FR I, II, WAT, NAT, …) nor optical magnitudes of the hosts are given !

While merging Oei's new GRGs (in LoTSS DR2 footprint) with my GRG list, I
a) checked host, **b)** classfied radio morphology, **c)** included z_{phot} from ~10 refs.,
d) remeasured the LAS for **939 GRGs** either new in Oei+23 or found earlier by us on previous surveys (mainly NVSS) with large discrepancy wrt. Oei+23

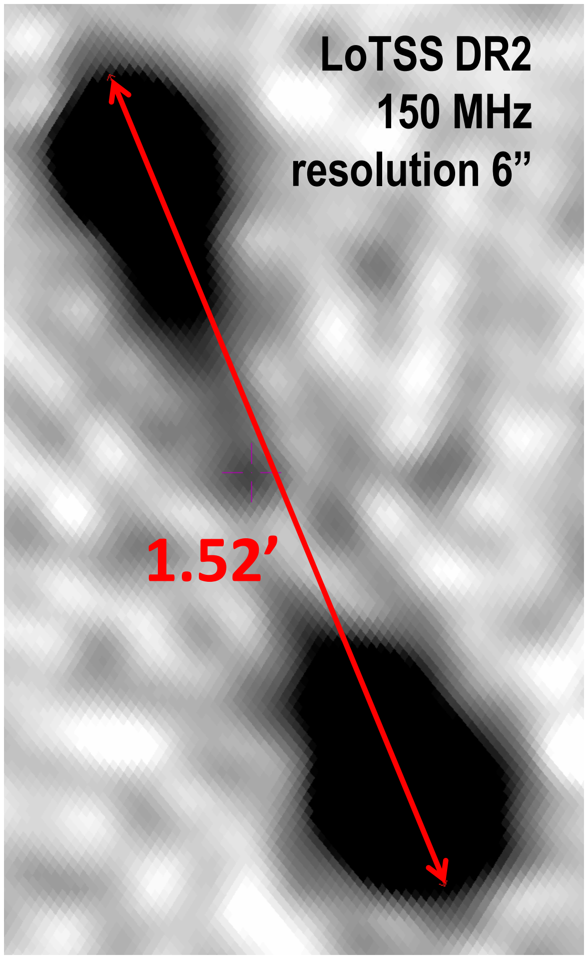


4 outliers of ratio > 3 not shown

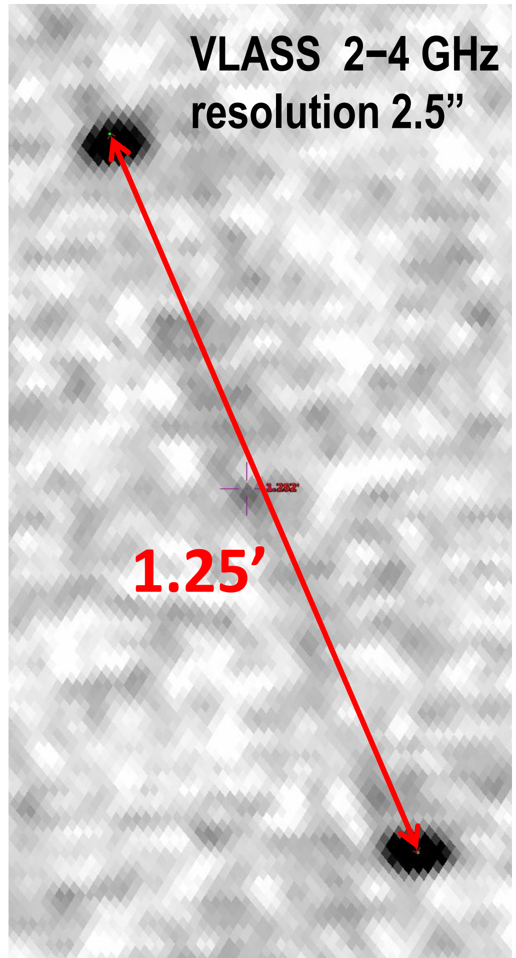
Example of angular size overestimate for a classical FR II

J0926+5521 = DESI J141.5976+55.3640 : z_{phot}~1.4, r = 23.1 mag

measured down to **3 σ :**
LAS = 1.52’, 0.77 Mpc



between peaks of terminal hotspots:
LAS = 1.25’, 0.63 Mpc (or ~20% smaller!)

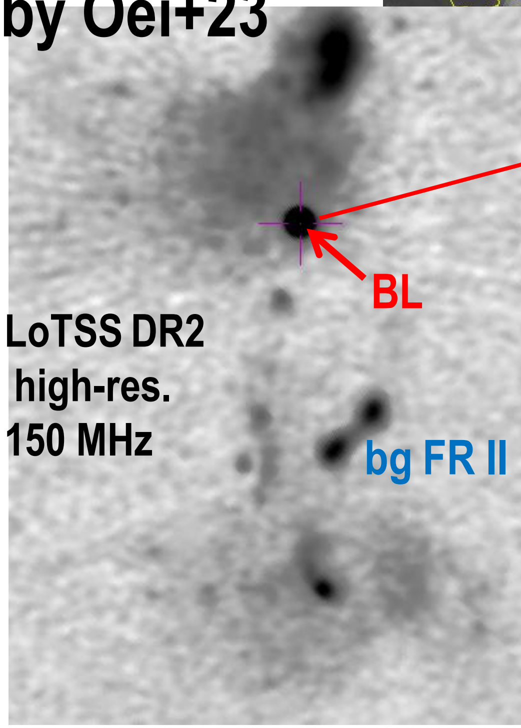


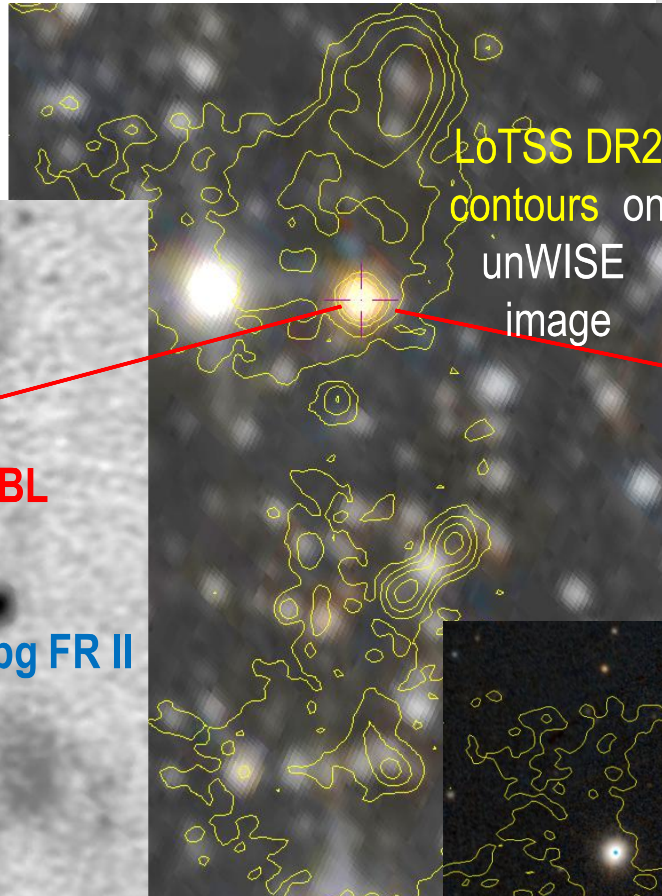
abs. overestimate is larger for brighter hotspots; relative overestimate increases with decreasing source angular size

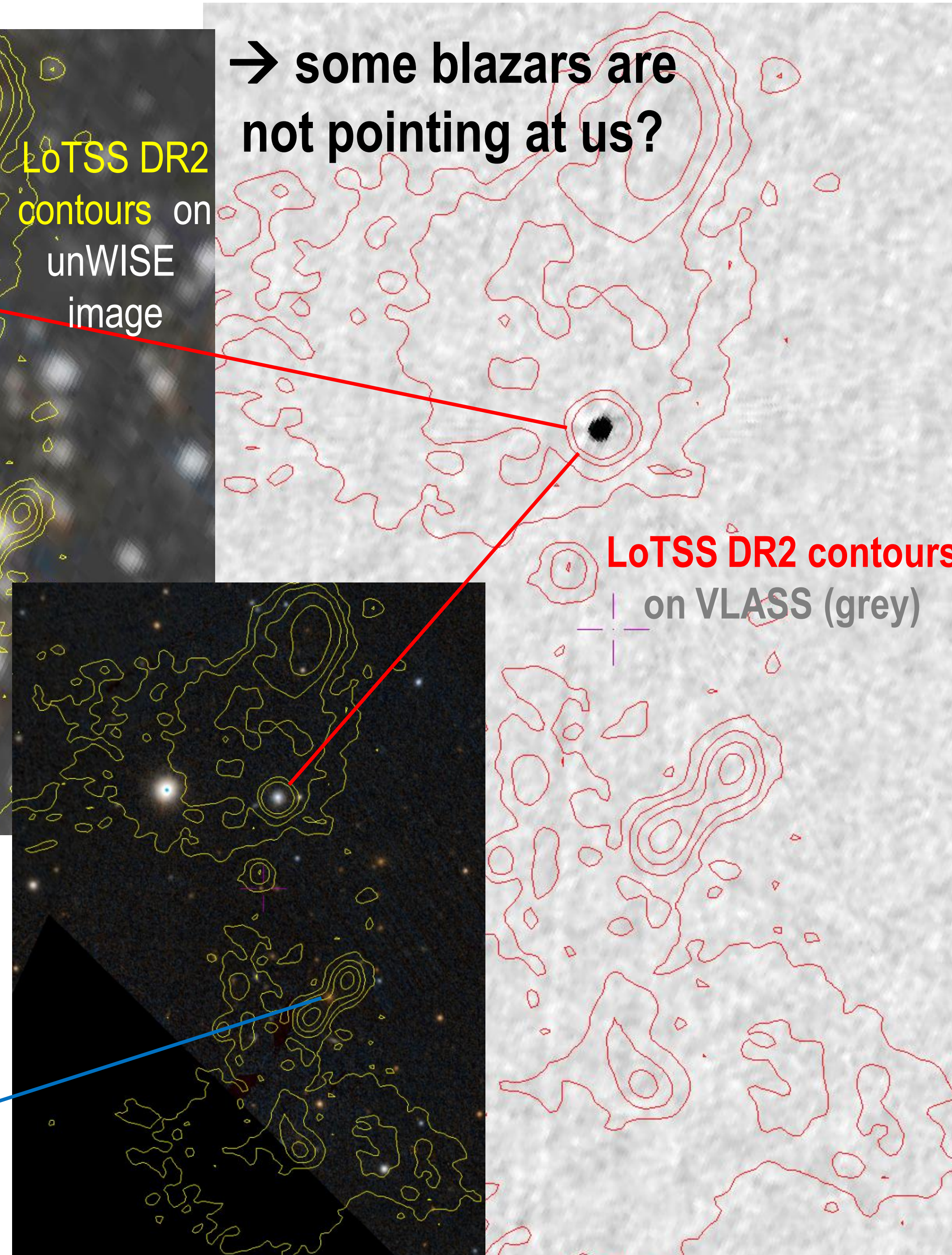
Occasionally there is LSB emission beyond hotspots

For FR I’s (WATs, NATs, etc) there is no problem with measuring LAS down to 3 sigma (or even lower)

correctly identified by Oei+23







A **giant radio blazar** 5BZU J1608+6018,
2MASX J16082057+6018281, r=16.8 mag
LAS = 5.2′, z_{spec}=0.178 **LLS = 0.94 Mpc**

S lobe has **small backgr. FR II superposed**
SDSS J160817.27+601653.6, r = 18.7 mag,
LAS = 0.55′, z_{spec} = 0.410, LLS = 180 kpc

While checking these 939 GRGs I found some erroneous IDs + problems

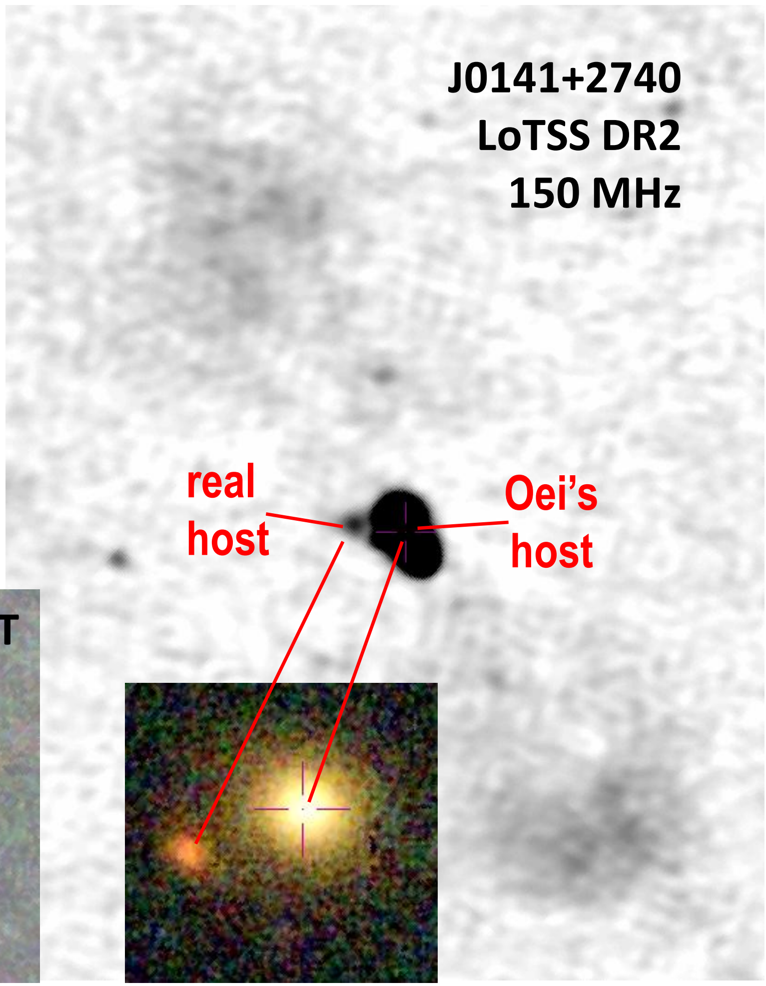
* for ~25 GRGs I corrected the host, e.g. closer to major source axis, closer to the stronger lobe, more AGN-like WISE colors, or detected VLASS core, e.g.

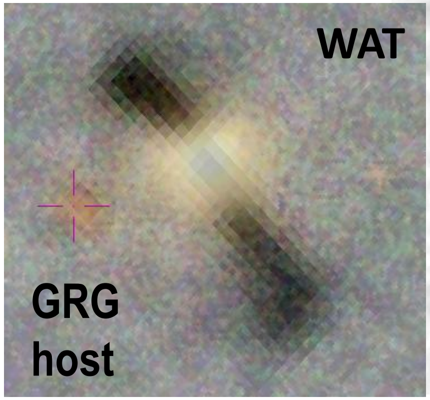
- **J0949+7314** is the well-known 4C+73.08 = VII Zw 292, published long ago; and
- **J1111+2657** is hosted by NGC 3563B 21″ENE, Abell 1185 (2002IAUS..199..171Owen+)

* another ~20 GRGs have a more likely host and 7 were discarded altogether

* an error by NED and other authors : many z_{spec} are in fact z_{phot} , e.g. 2014ApJS..210....9Bilicki+ in NED) and WHL BrClG's are tagged as z_{spec} if **any** cluster member has a z_{spec} value

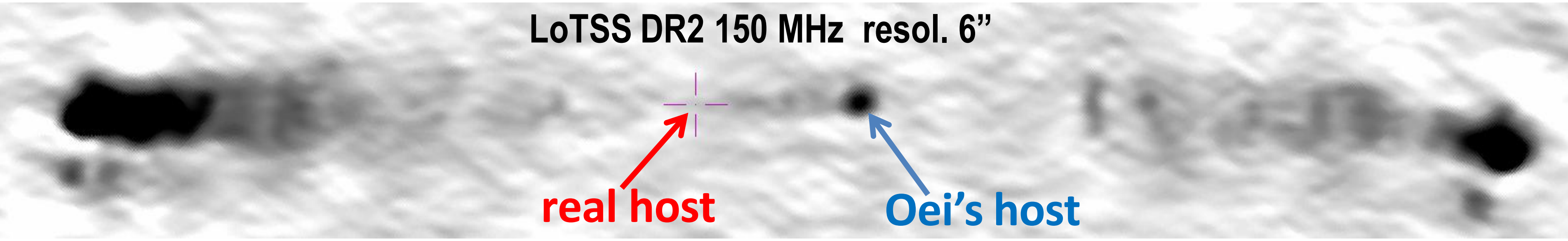
* **J0141+2740** is unlikely a DDRG, but has a more distant host, while Oei's host is a fg WAT → **LLS=2.25 Mpc (not 1.44)**



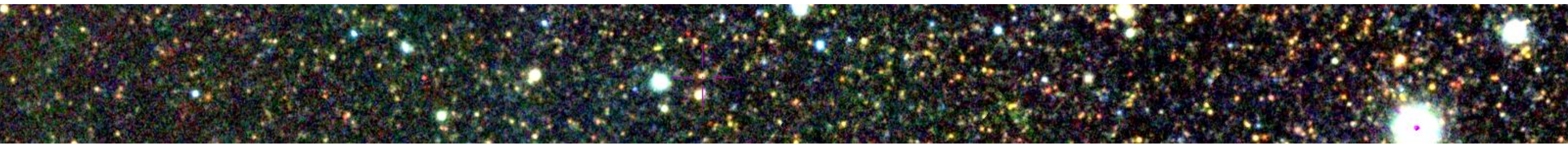


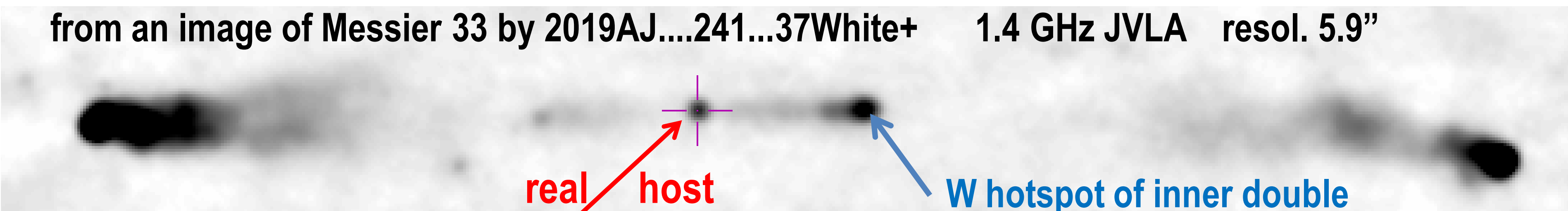
VLASS (grey) over Pan-STARRS g,r,i shows "inner double" to be a separate WAT

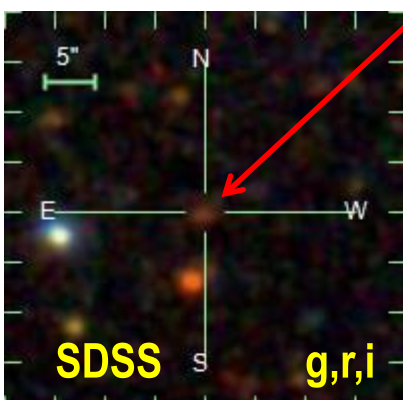
An example where LoTSS suggests the wrong host



the area is terribly confused by S outskirts of Messier 33: here a cutout of Pan-STARRS g,r,i







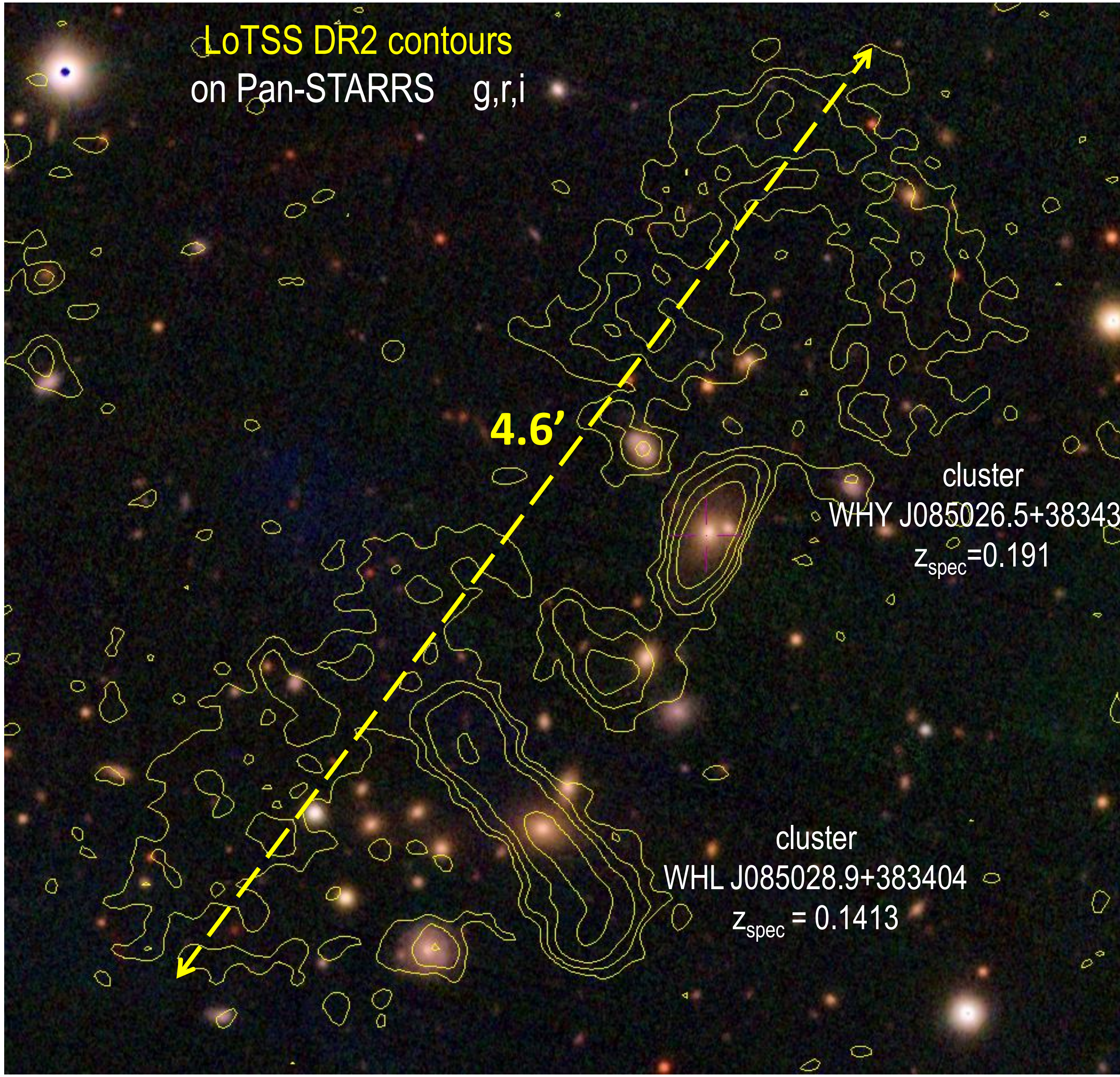
The true host is SDSS J013410.63+301537.7, z_{phot} ~0.5, with LAS = 8.1’ → LLS = 3.1 Mpc

while Oei’s “host” suggested LLS ~ 4.1 Mpc

A source in Oei's list with significant overestimate in angular size

J0850+3835
Oei+2023: LAS=4.6'
→ LLS ~0.7 Mpc

but actually there are two WATs of ~2.5' each in two different clusters at z_{sp} =0.191 and z_{sp} =0.141



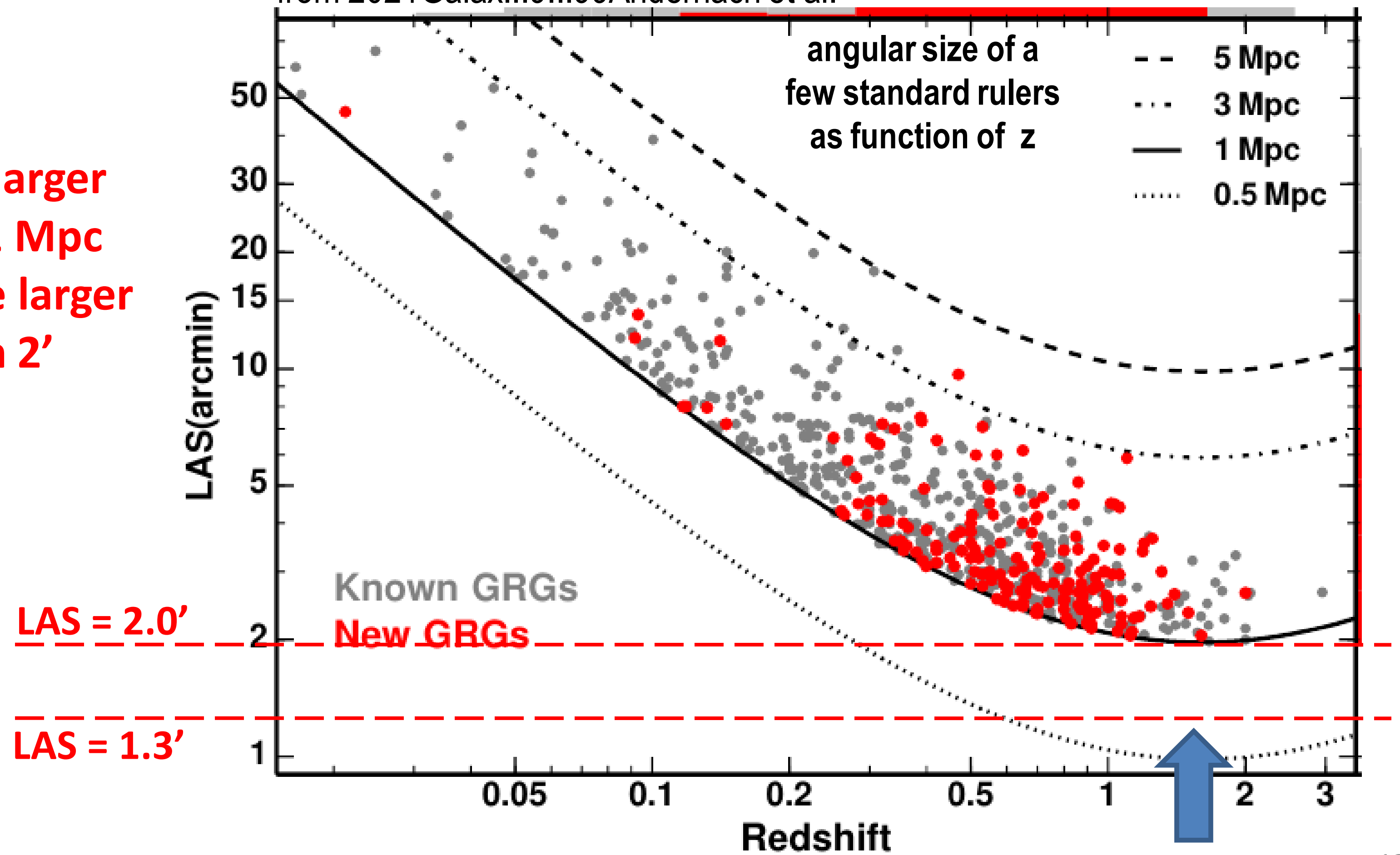
So how many GRGs are there really in LoTSS DR2 . . . ?

To find all GRGs > 0.7 Mpc one needs to inspect all sources > 1.3 arcmin
→ if the host falls between z=1.4 and 1.8 → LLS ~ 0.7 Mpc

→ ~5 such sources need to be inspected such that one is a GRG > 1 Mpc!

from 2021Galax...9...99Andernach et al.

GRGs larger than 1 Mpc must be larger than 2'



Results of my visual search for GRGs in 3% of LoTSS DR2 area

I chose **172 deg²** of good sensitivity LoTSS DR2 (RA=8^h – 10^h, DEC = +50° … +60°)
I inspected **~800 full screens** of ~25' x 30' → took 16 h to log all **1200+ candidates**, and then spent **4 x more time** to find their hosts, magnitudes, and redshifts
→ **using Oei's search criteria** (z<0.4 and LAS>3') they found N = 51 GRGs with LLS > 0.7 Mpc, I found **25 more** (~50%) GRGs (compilation by 2018ApJS..238....9Kuzmicz+ has only **2**)

➔ **total surface number density** of GRGs is **~5 times larger.** Results of inspecting 172 deg^2:

	N>1 + N>0.7 Mpc	LAS_{med}	z_{med}	$\%z_{spec}$	$rmag_{med}$	%QSO
Oei+2023	44 + 25 = 69	4.9'	**0.28**	64%	18.2	> 6 %
+HA vis.insp.	134 +194 = 328	2.3'	**0.73**	27%	21.8	> 12 %

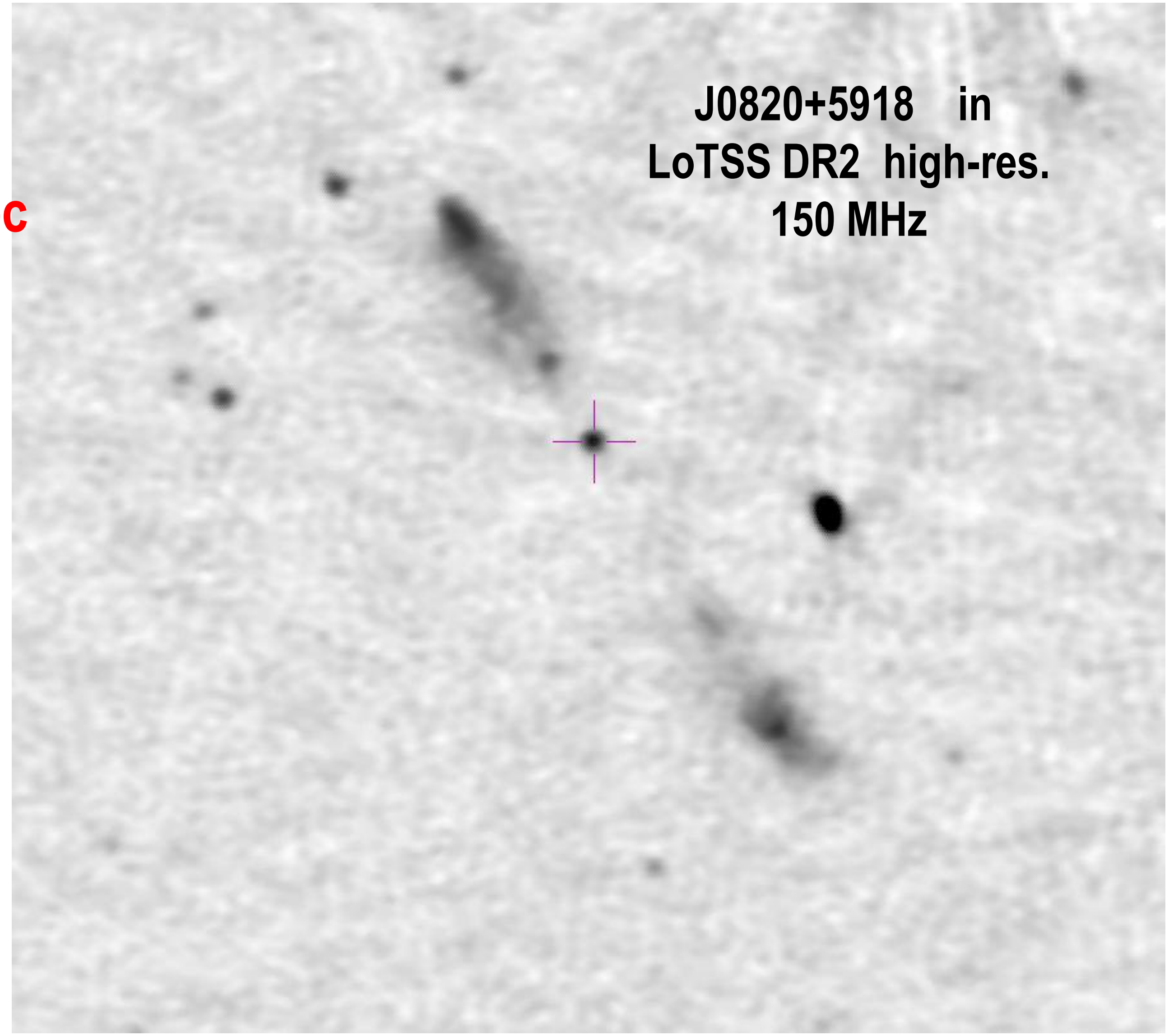
→ In total **~1.0 GRGs/deg² >1 Mpc , plus ~1.3/deg²** w/0.7−1.0 Mpc → **total 2.3/deg²**
This is **5.8 times** the (corrected) density of **Dabhade+2020 in LoTSS DR1** and 35% more than in ASKAP field A3391/95 by Brűggen+2021
→ requires ~2200 h for entire LoTSS DR2 ! Variety of objects (also smaller ones):

* Wide-angle tails (WATs) with projected size > 2 Mpc (10 / 12 known are from LoTSS)
* amorphous, roundish, diffuse sources, apparently RGs seen "end-on"
* QSOs of Fanaroff-Riley type I or with remnant-type diffuse lobes (no hotspots)
* cluster haloes and relics (which I do not generally compile . . .)

Following slides: a taste of the varied radio morphology of GRGs

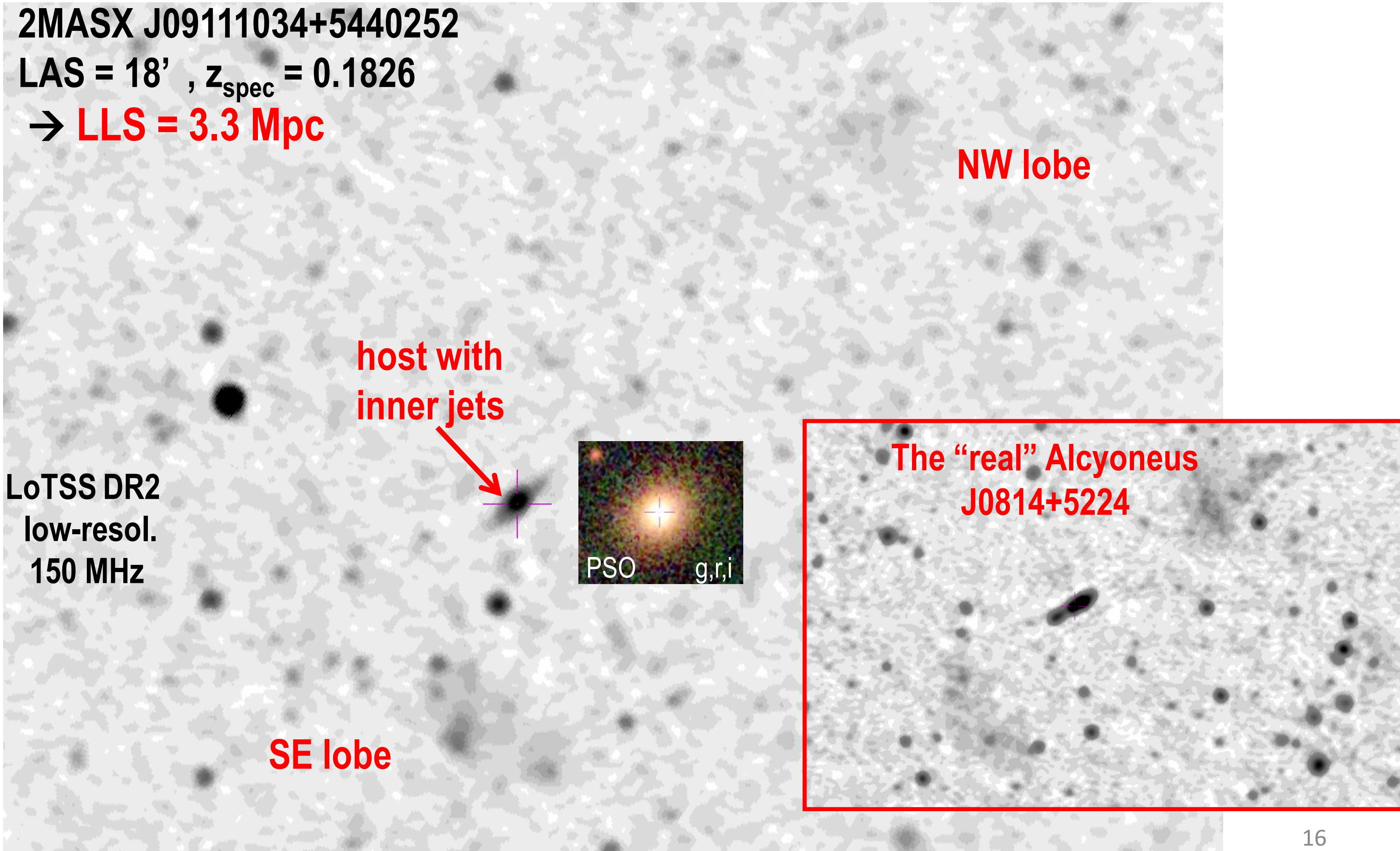
Example of a large, straight FRII (not in Oei+23 for too high z ?)

SDSS J082030.34+591843.9
r'=21.15 mag
LAS = 4.36' ,
z_{phot} ~0.74
→ LLS = 1.9 Mpc



A smaller twin of the 4.8-Mpc Alcyoneus ?

8.7° NE of Alcyoneus I found J0911+5440



Alcyoneus is not the largest . . .

SDSS J083801.77+532714.4

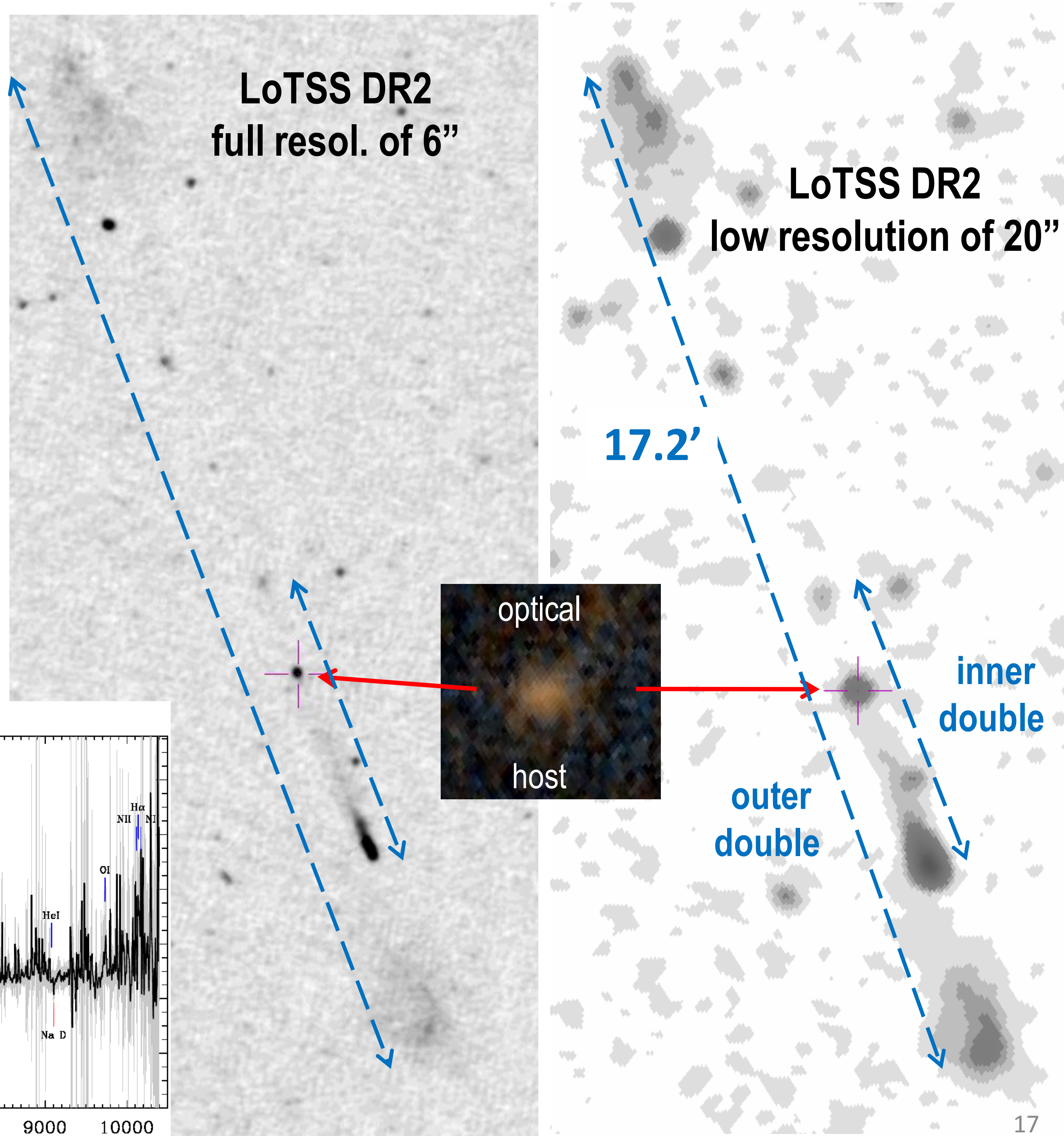
r’ = 20.7 mag

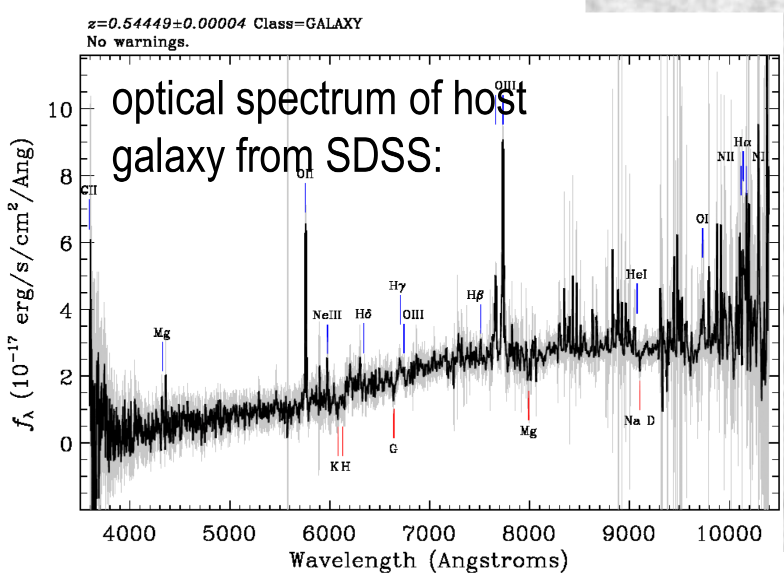
LAS = 17.2’, z_{spec} = 0.5445

→ LLS = **6.6 Mpc**

→ A DDRG that exceeds published record by ~33 %.

Was it excluded by Oei+23 for its z > 0.4 ??



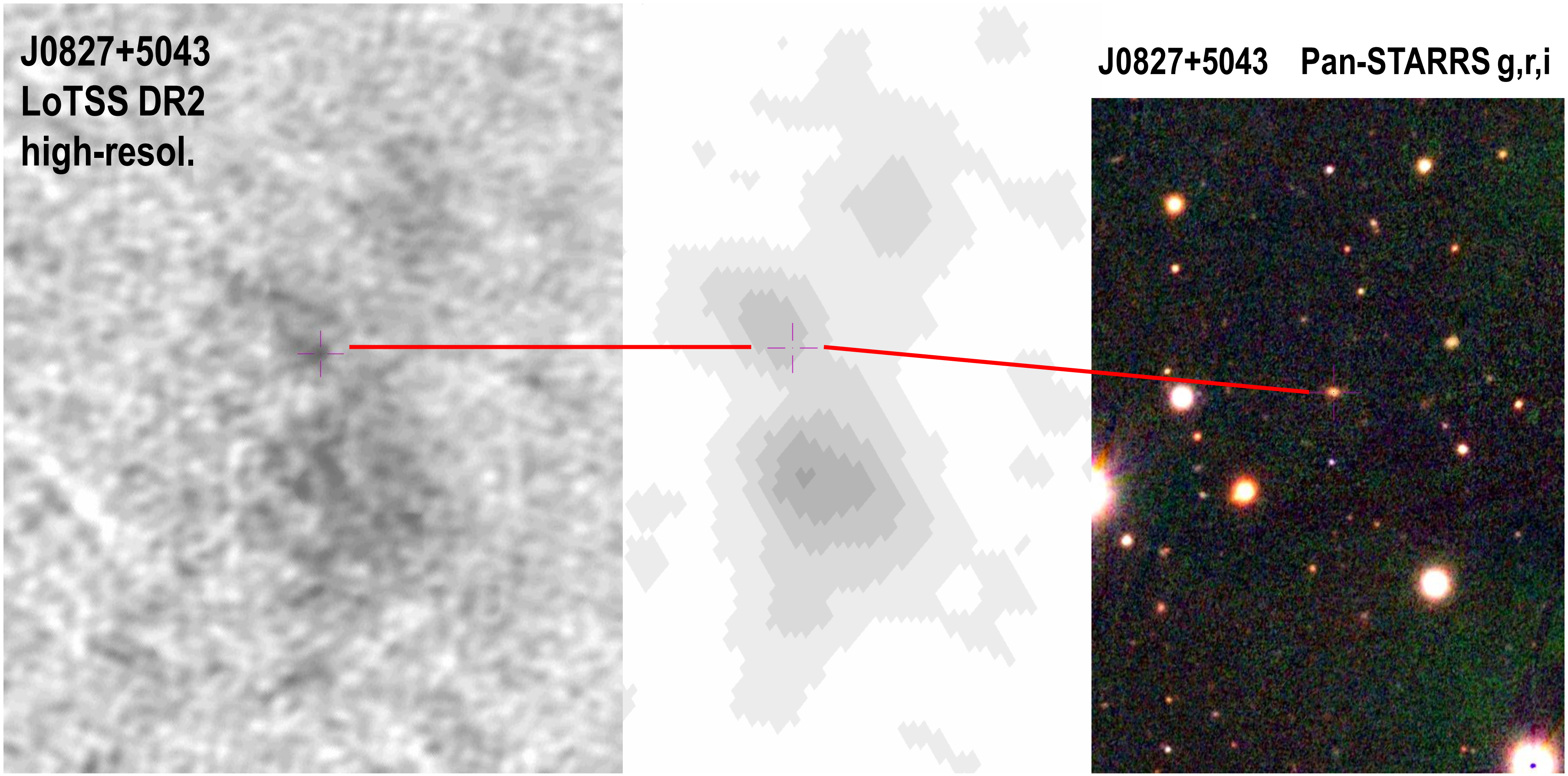


Amorphous sources: the RGs seen "end-on" or "down the barrel" ?

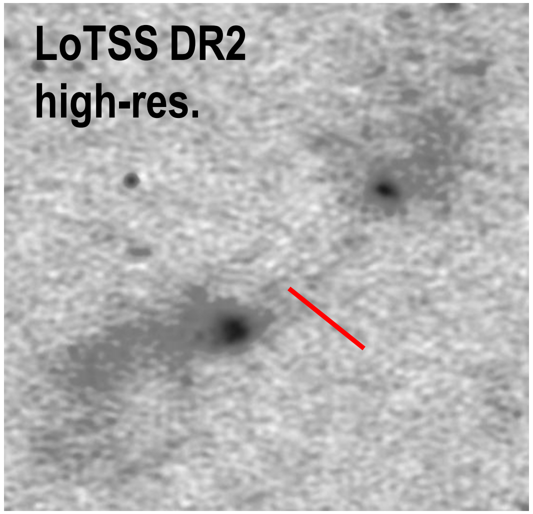
likely to be overlooked as GRGs in visual searches

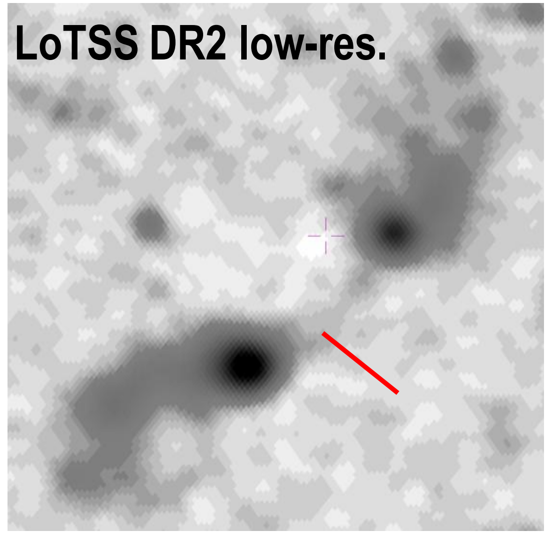
likely host is SDSS J082705.16+504307.9

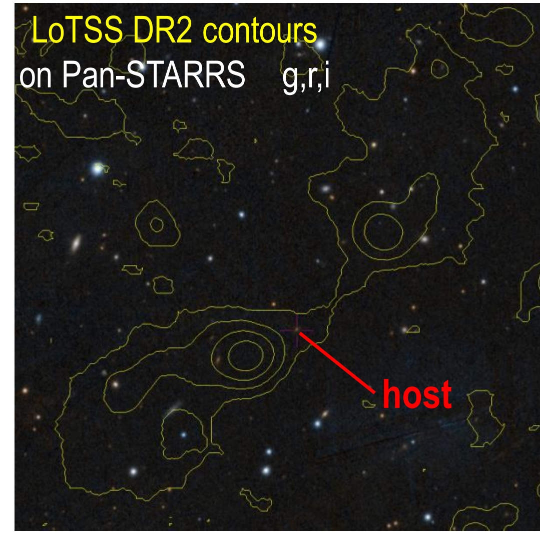
R'=19.5 mag, LAS > 3.6' z_{phot} ~ 0.42 → LLS > 1.2 Mpc



Another very large wide-angle tailed radio galaxy (WAT)

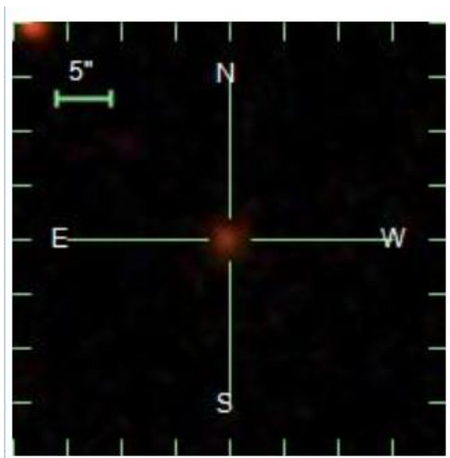




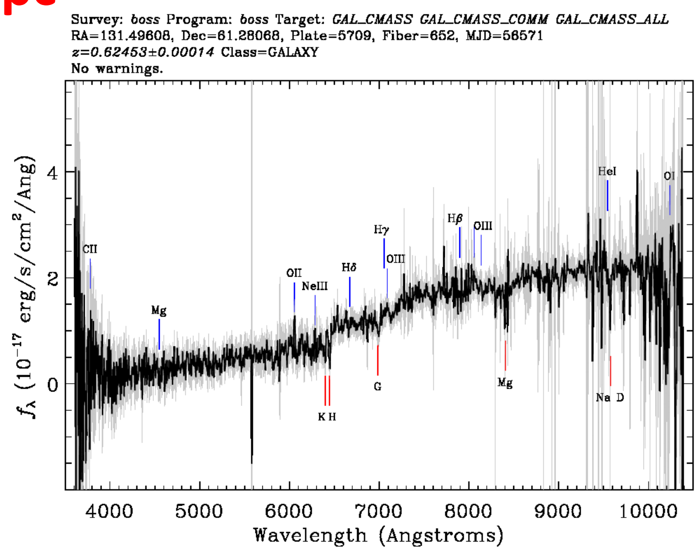


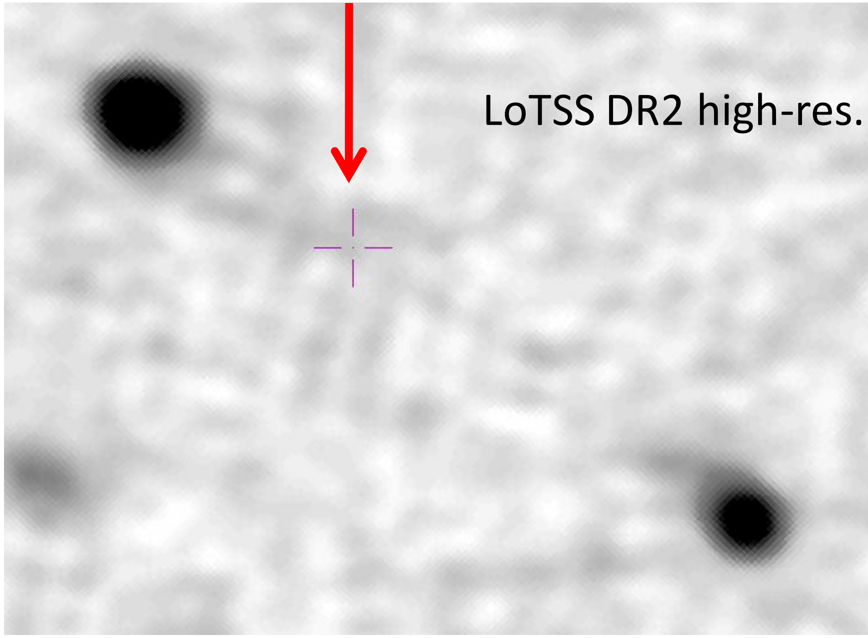
SDSS J084559.05+611650.1, r'=20.4 mag

LAS = 7.1', z_{spec} = 0.6245 ➔ **LLS = 2.90 Mpc**



Magnitudes		
u	g	r
23.79	21.84	20.43
Magnitude uncertain		
err_u	err_g	err_r
1.64	0.14	0.07

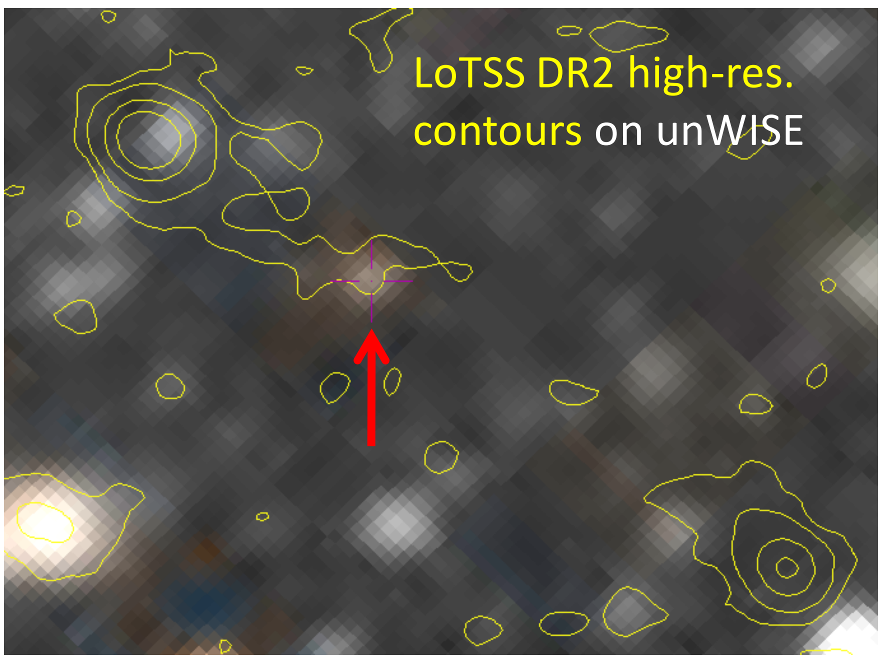


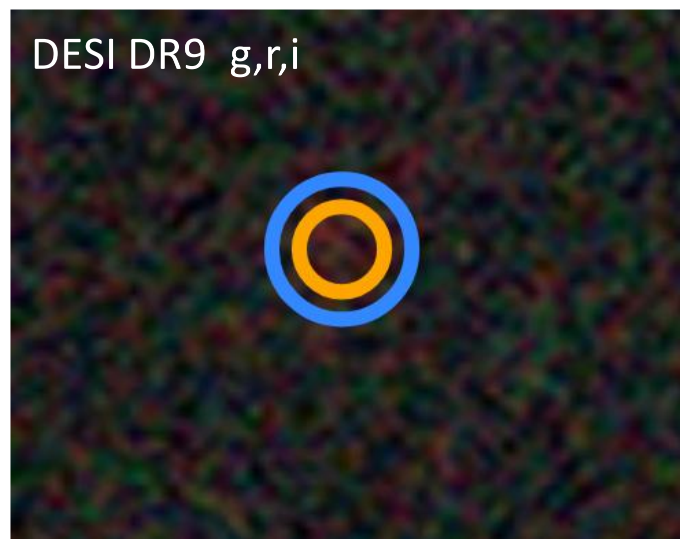


There are a few so-called "**naked FR IIs**", i.e. pure hotspots without tails towards the host, with or without a radio core

Here: J0032+2011 = DESI J008.0453+20.1861
r=26.2 mag, z_{phot}=1.2 → LLS = 1.0 Mpc, extremely faint in optical, but clearly detected in WISE

Very difficult to recognize : how many we may have missed ?





Summary and conclusions

* LoTSS DR2 promises to reveal >2 deg^{-2} GRGs > 0.7 Mpc or ~10,000 in total albeit in ~2000 (wo)man-hours → ML is desirable, but . . .

* visual control of each GRG by (more than one) humans is essential

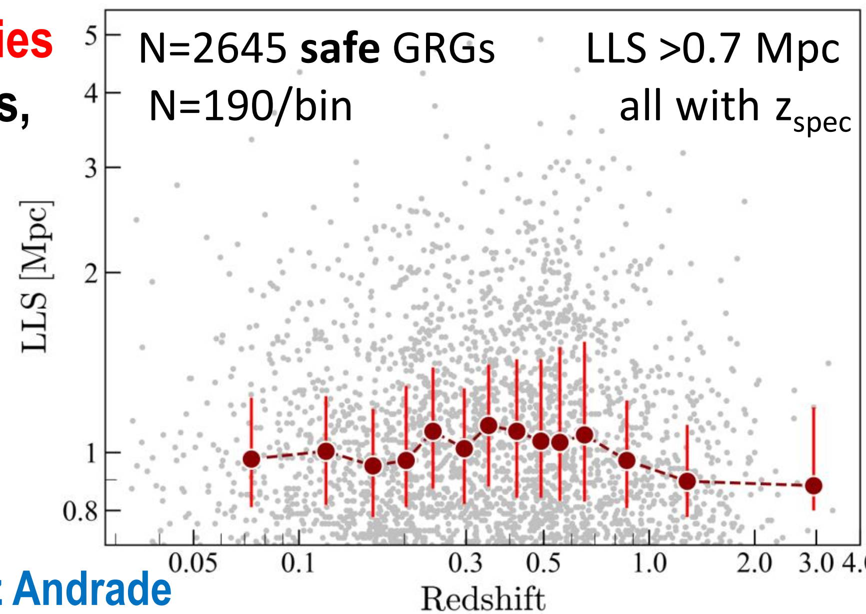
* photometric redshifts are available from a dozen different references

* LoTSS reveals a larger fraction of GRGs that are FR Is (incl. WATs) and remnant RGs than any previous surveys

* high-resolution radio surveys (e.g. VLASS) and WISE help to identify the host

* avoid bias against unusual radio morphologies like: amorphous (end-on?) RGs, WATs, NATs, "naked" FR II's, FR Is with QSO host, . . .

* among all >8500 GRGs (>0.7 Mpc) there is no trend for LLS to decrease with redshift (as we'd expect for a denser early Universe)



plot ctsy. E.F. Jiménez Andrade

Thank you !

With special thanks to:

* the LoTSS + VLASS teams
* CDS for maintaining VizieR
* optical survey teams (SDSS, Pan-STARRS, DESI, …)

My extended RG (ERG) compilation as of 05-Jun-2023

* Host positions, mag, redshift, radio size, … for ~22,000 extended RGs
* Total of **4300 GRGs** > 1 Mpc/h_{70} (~500 have minor doubts) which is **>2 times more** than published in literature (incl. Oei et al. 2023)
* another **4300** smaller GRGs (0.7 … 1.0 Mpc) or **4 x more** than in literature
* of all 8600 GRGs >0.7 Mpc : **~33% have z_{spec}**; ~60% z_{phot}, ~8% "best guesses"
* 80% galaxies, 17% QSO(cand's), ~3% unknown (e.g. WISE-only)

median z of all is ~0.55: 0.48 for galaxies and 0.9 for QSOs

z_{med} ~ 0.38 for published ones, z_{med} ~0.62 for unpublished ones

~1000 GRG/GRQs lie at z > 1 (265 with z_{spec}), and 5 with **$3 < z_{spec} < 4$** !

Additional 11,400+ **"Large RGs" (**LLS = 200–700 kpc) collected "in passing" … :

➔ this is the largest-ever compilation of linear source sizes and the largest for optical IDs of extended sources

Radio morphology distribution of GRGs >0.7 Mpc in 172 deg^2 of LoTSS DR2:

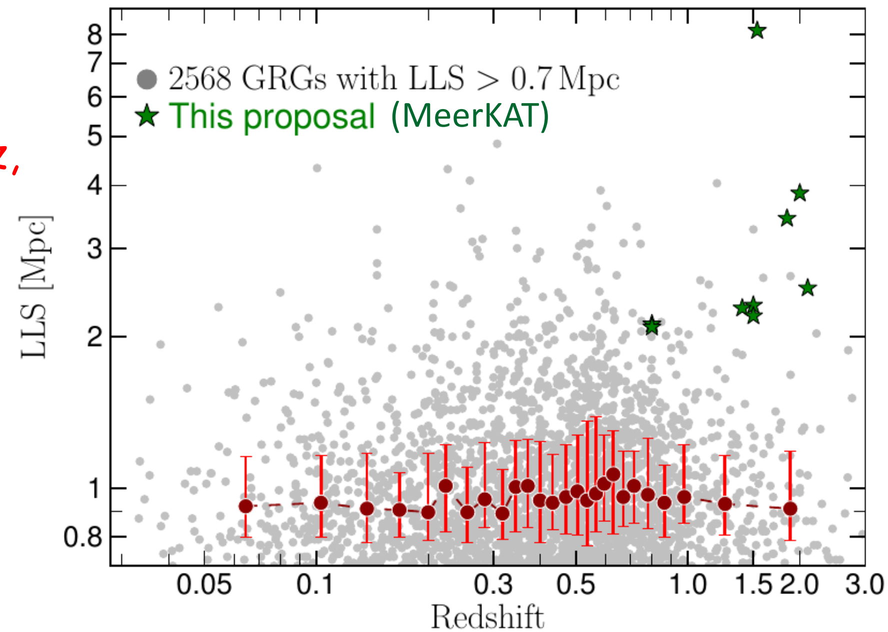
Percentage of types:	FR I	remn	amorph	WAT	DDRG
Oei+2023 (N=64)	28	30	—	28	1
HA-inspect (N=328)	11	32	3	10	1

A puzzling conflict with cosmology

The median LLS of GRS does not decrease with z, while standard cosmology predicts

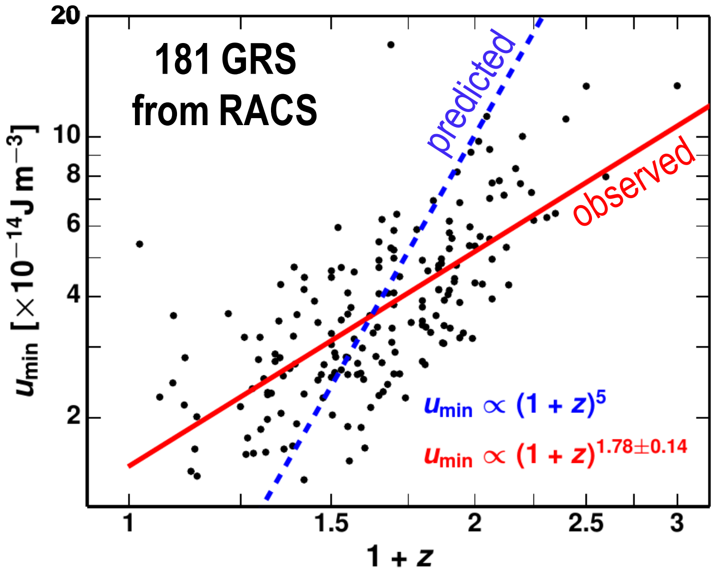
$\rho_{matter} \propto (1+z)^3$, $\rho_{CMB} \propto (1+z)^4$ which should not let RGs grow as large at higher z,

plus: surface brightness dimming $SB \propto (1+z)^{-4}$ should make them unobservable . . .



More puzzling results from equipartition parameter estimates:

total energy density u_{min} rises much slower than the expected pressure of IGM



the mean radio surface brightness does not seem to change with redshift