More than ~~Towards~~ one thousand Giant Radio Galaxies

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What are "Giant Radio Galaxies" (GRG) ?

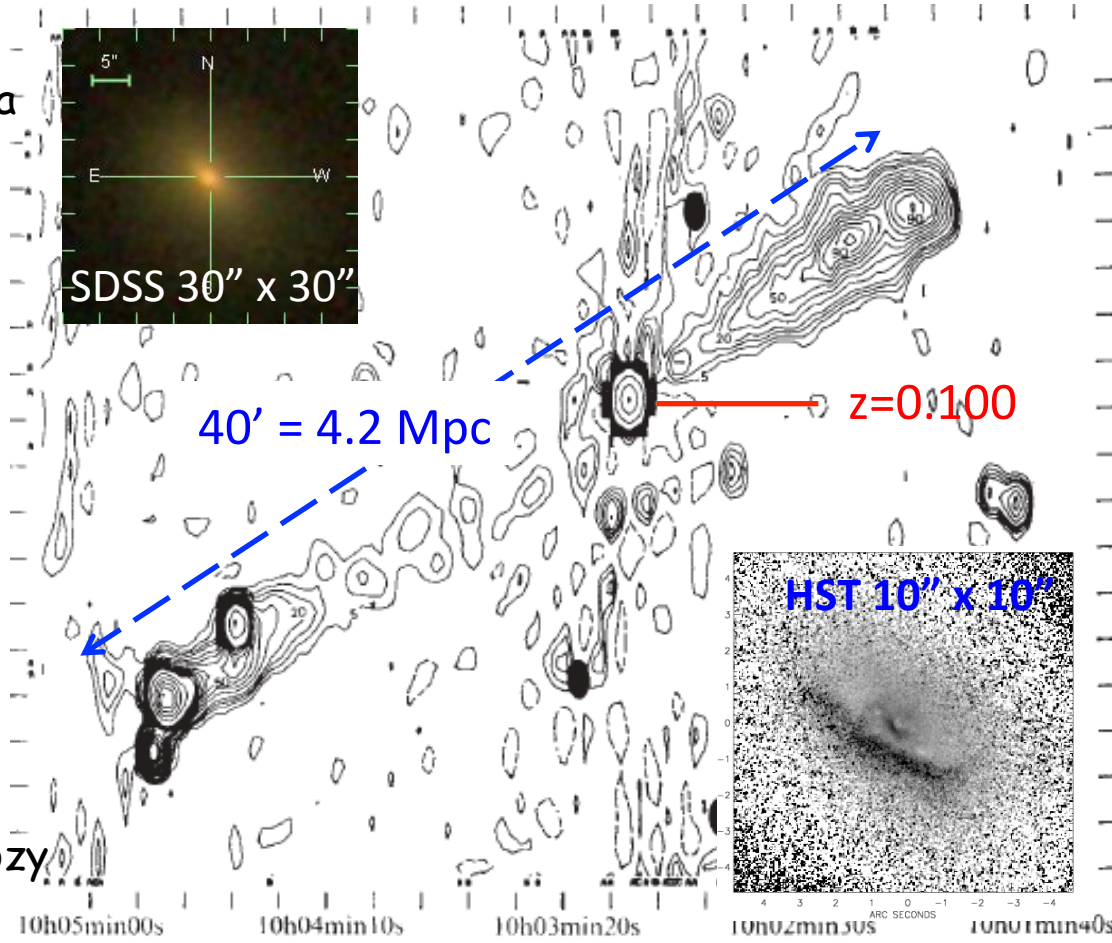
Usually whenever "largest linear size" (LLS) exceeds ~ 1 Mpc (in projection)
First GRG discovered by Willis et al. **1974**: LLS = 5.7 /h_{50} Mpc → 4.2 /h_{75} Mpc
Here: H_0 = 75 km/s/Mpc (but: for some authors LLS ≥ 0.75 Mpc is a GRG)

Only partial lists of GRGs exist:

1996MNRAS.279..257Subrahmanyan
1999MNRAS.309..100Ishwara-Chandra
2001A&A...370..409Lara+
2001A&A...374..861Schoenmakers+
2005AJ....130..896Saripalli
2009AcA....59..431Kuligowska
2012ApJS..199...27Saripalli
2009ARep...53.1086Komberg+

~85% are galaxies, but
~15% are quasars (**GRQs**) :

2004MNRAS.347L..79Singal
2010A&A...523A...9Hocuk & Barthel
2011AcA....61...71Kuzmicz+
2012MNRAS.426..851Kuzmicz & Jamrozy



Of all radio galaxies, GRGs are NOT the most radio luminous sources, but
* they have the lowest minimum energy densities (down to ~ 10^{-15} J m^{-3})
in particles and magnetic field (U_{min}), and due to their huge volume,
* they have the highest energy content
(a bit forgotten today, as only energy densities are quoted)

How are GRGs found ?

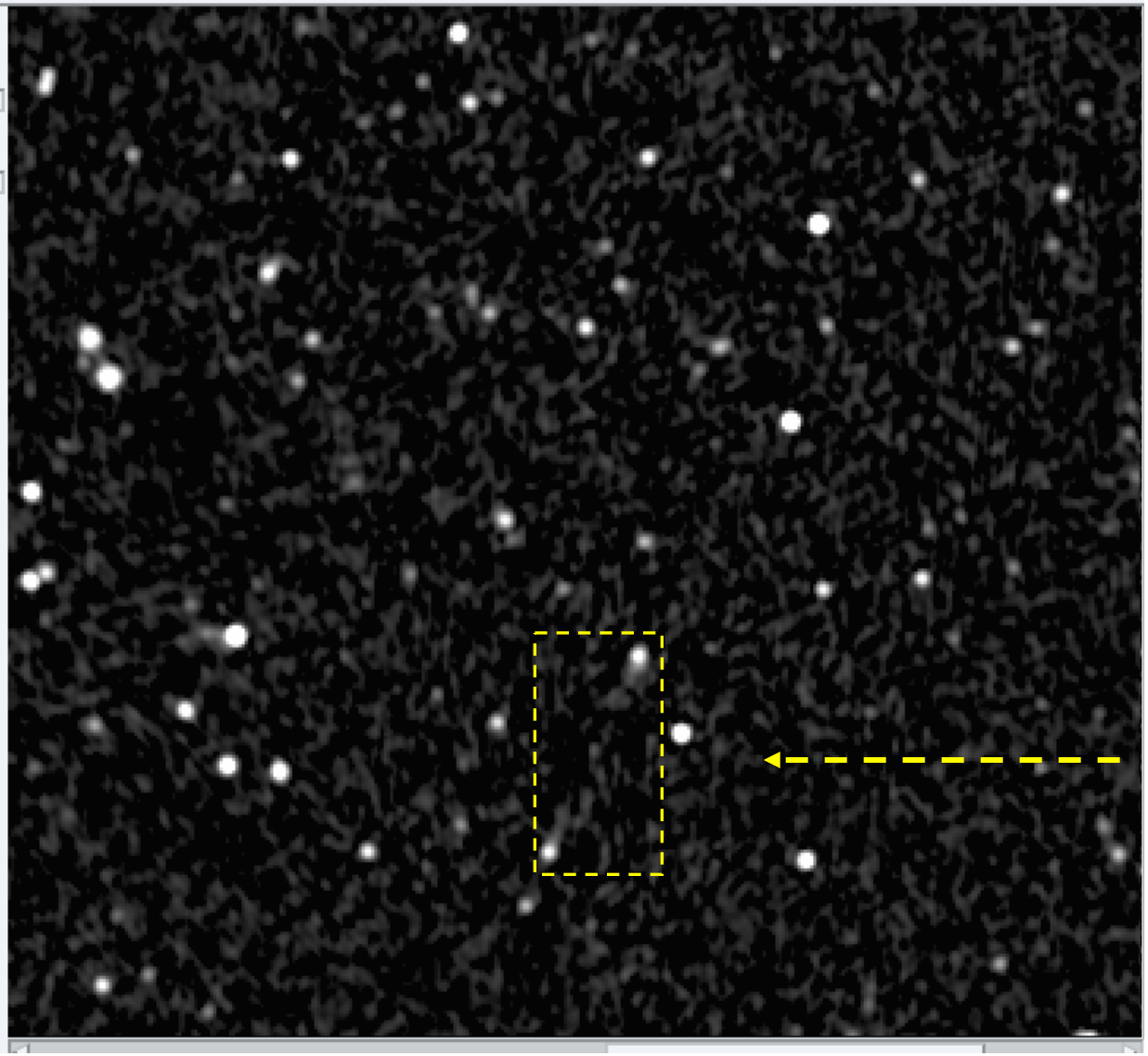
- sometimes accidentally: looking for an optical ID of an "extended" radio source → if at high z and LAS >~ 2 arcmin ➔ LLS > 1 Mpc

- once we "know" their radio morphology we can do a systematic search in radio surveys covering large parts of the sky

Example:
2001A&A...374..861Schoenmakers+ inspected the 325-MHz WENSS
→ found 105 candidate GRGs (now: 57 confirmed)

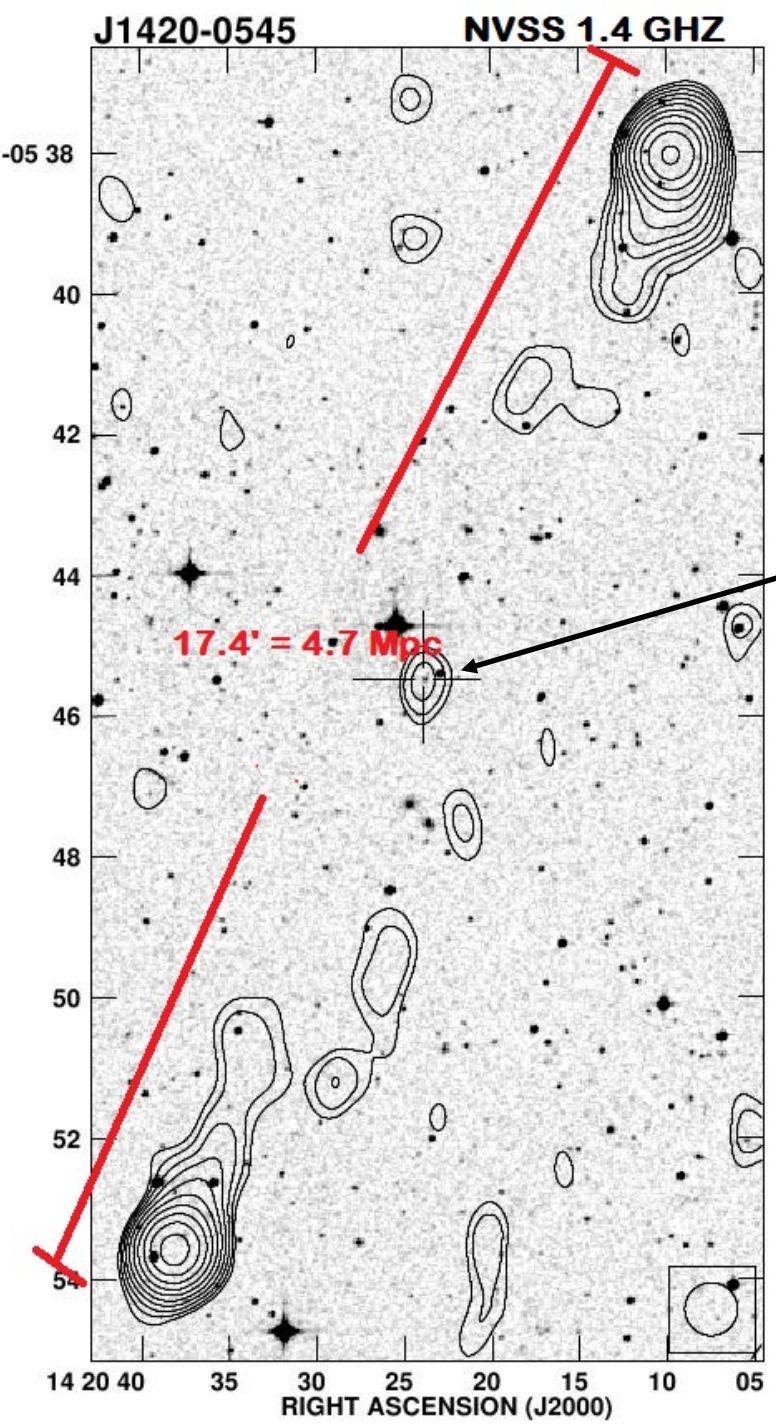
advantages of WENSS:
* sensitive to spatial components up to ~1°
* radio lobes dominate at lower frequencies
* radio cores (host galaxies) dominate at higher frequencies

Since 1998: a more complete and sensitive survey:
NVSS (NRAO VLA Sky Survey, Condon et al. 1998)
- covers 82 % of the sky (Dec > -40°) at 1.4 GHz (λ = 21 cm)
- angular resolution 45"
- minim. flux ~2 mJy
- catalogue of 1,800,000 sources
- atlas of 2300 images of 4° x 4°



The currently largest GRG, is J1420-0545 (cf. Machalski et al. 2008ApJ...679..149M)

discovered on NVSS atlas image by eye inspection



How does one know it is a GRG?

* The nucleus must coincide with a galaxy or QSO, which may be very faint
* the supposed lobes must NOT coincide with a galaxy (except for projection)
* the radio structure should show certain symmetry (by experience from other GRGs)

host galaxy (R=19.7, z=0.31)

total angular size = LAS ~ 17.4',
→ LLS = 4.7 Mpc (H_0 = 75 km/s/Mpc (Machalski et al., 2008)

This is only the **projected size** :
with an inclination with respect to the plane of the sky it may well be larger !

In 2012: only ~100 GRGs known, and NOBODY HAD INSPECTED the full image atlas of the NVSS . . . (available since 1998 !)

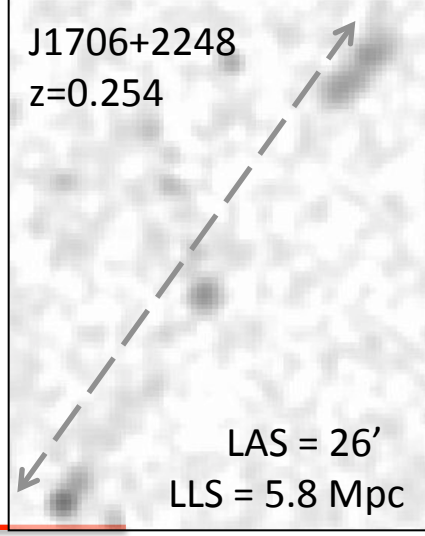
Raúl F. Maldonado S.

Finding Giant Radio Galaxies (GRGs) in Imaging Radio Surveys

Heinz Andernach & three summer students
Universidad de Guanajuato, Mexico 2012

poster at adsabs.harvard.edu/abs/2012sngi.confE..33A

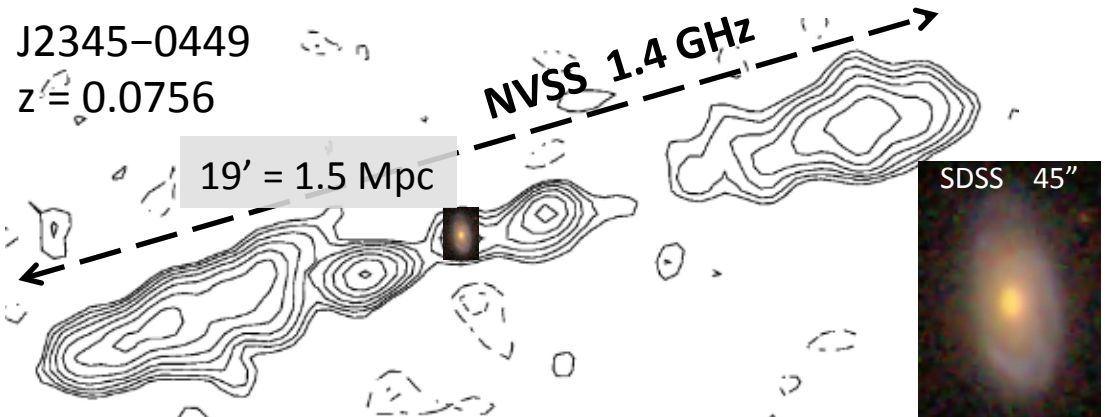
Known in 2012: ~100 GRGs with LLS > 1 Mpc /h_{75}
all have LLS <3 Mpc; except 2 with 4.2 and **4.4 Mpc**
(only small fraction from visual inspection of radio atlases)



Method: inspect **all 3050 images** (4° x 4°) of NVSS and SUMSS covering **all sky** at ~45" resolution
look for : extended or triple sources with LAS >~ 4' (after "training" with known GRGs in NVSS)
* check NED for optical ID with known z, near radio core or symmetry center → derive LLS (Mpc)
* classify the optical ID: (a) already known as GRG, (b) known RG, (c) yet unknown as radio source

Results Aug. 2012: we find the largest yet known GRG with LAS = 26', z = 0.254 → LLS = **5.8 Mpc**;
* we **duplicate** the number of GRGs to ~200, and **quadruple** N_{GRG} with LLS > 3 Mpc (from 2 to 8)
* we add 4 new GRQs at z > 1, and find the first GRG identified with an **optical spiral**

Eric F. Jimenez A.



Ingrid R. Vázquez B.

- Three summer students logged the positions of **~17,000 potential GRGs** in NVSS, WENSS & SUMSS
- Most promising ones followed up by H. A. since 2012
- Additional sources of GRG candidates: e.g.

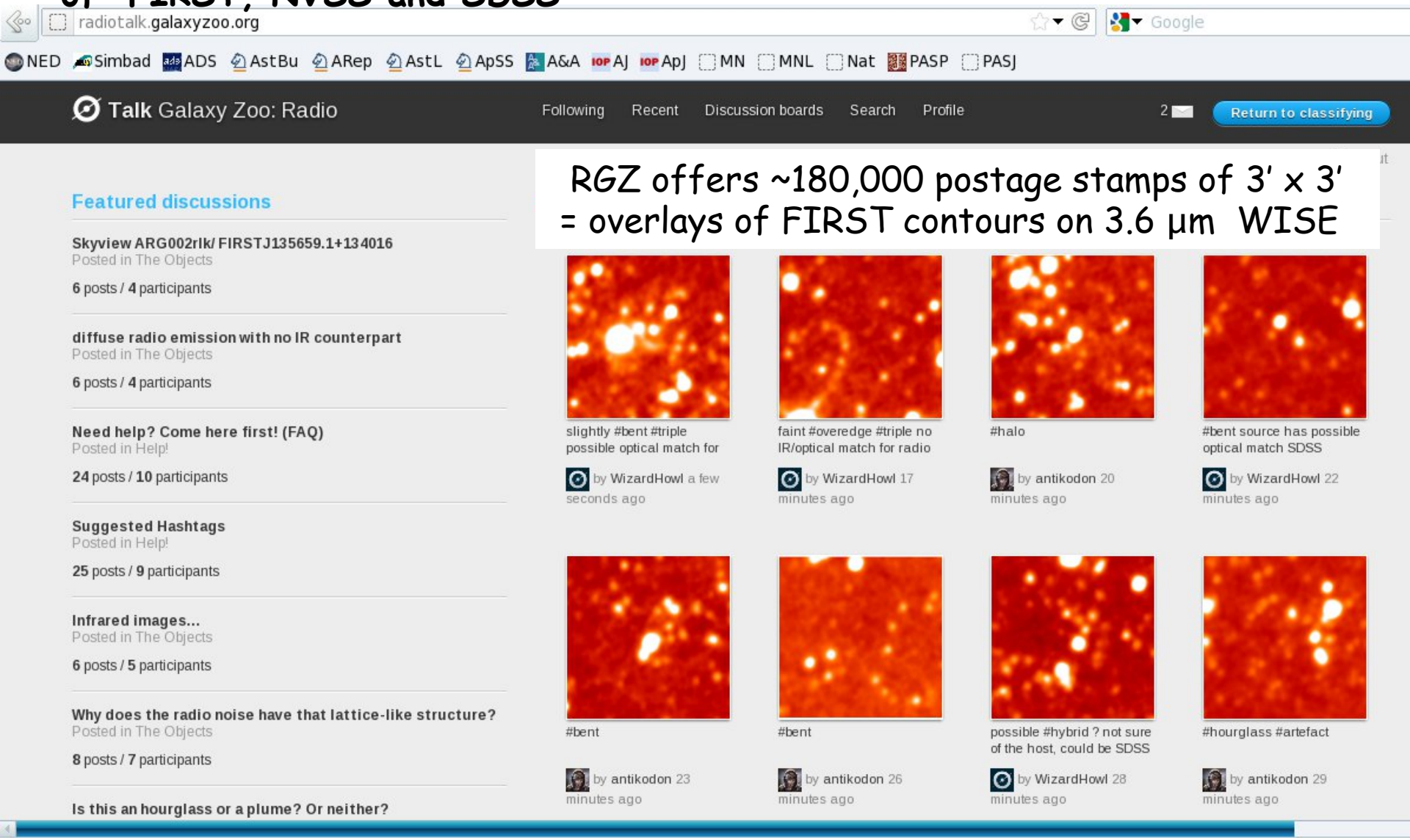
- 2011ApJS..194...31**Proctor** D.D.: Morphological Annotations for Groups in the FIRST Database (most with LAS < 1', but also very few GRGs)
- 2016ApJS..224...18**Proctor** D.D.: Selection of Giant Radio Sources from NVSS (no optical IDs, ~1/3 of her 1620 candidates were already in my compilation; LAS up to ~20', already 20 new GRGs found, perhaps another 20 expected)
- 2016PASA...33...52**Flesch** E.:The Million Optical Radio/X-ray Associations (MORX) catalogue (includes optical objects with double lobes with LAS < 4')
- 2016MNRAS.460.2385Williams W.L.+ LOFAR 150-MHz obs. of Bootes

. . .

Until now: I checked ~300 references with promising samples for the presence of GRGs (200 other ref's to go ...)

➔ "outsourcing" seems necessary . . .
in Dec. 2013: **Radio Galaxy Zoo** was launched

Example of a discussion page: each icon allows to open larger images of FIRST, NVSS and SDSS



➔ requires follow-up by science team ➔ diverse results

Will Giant Radio Galaxies (GRG) be found in RGZ ?

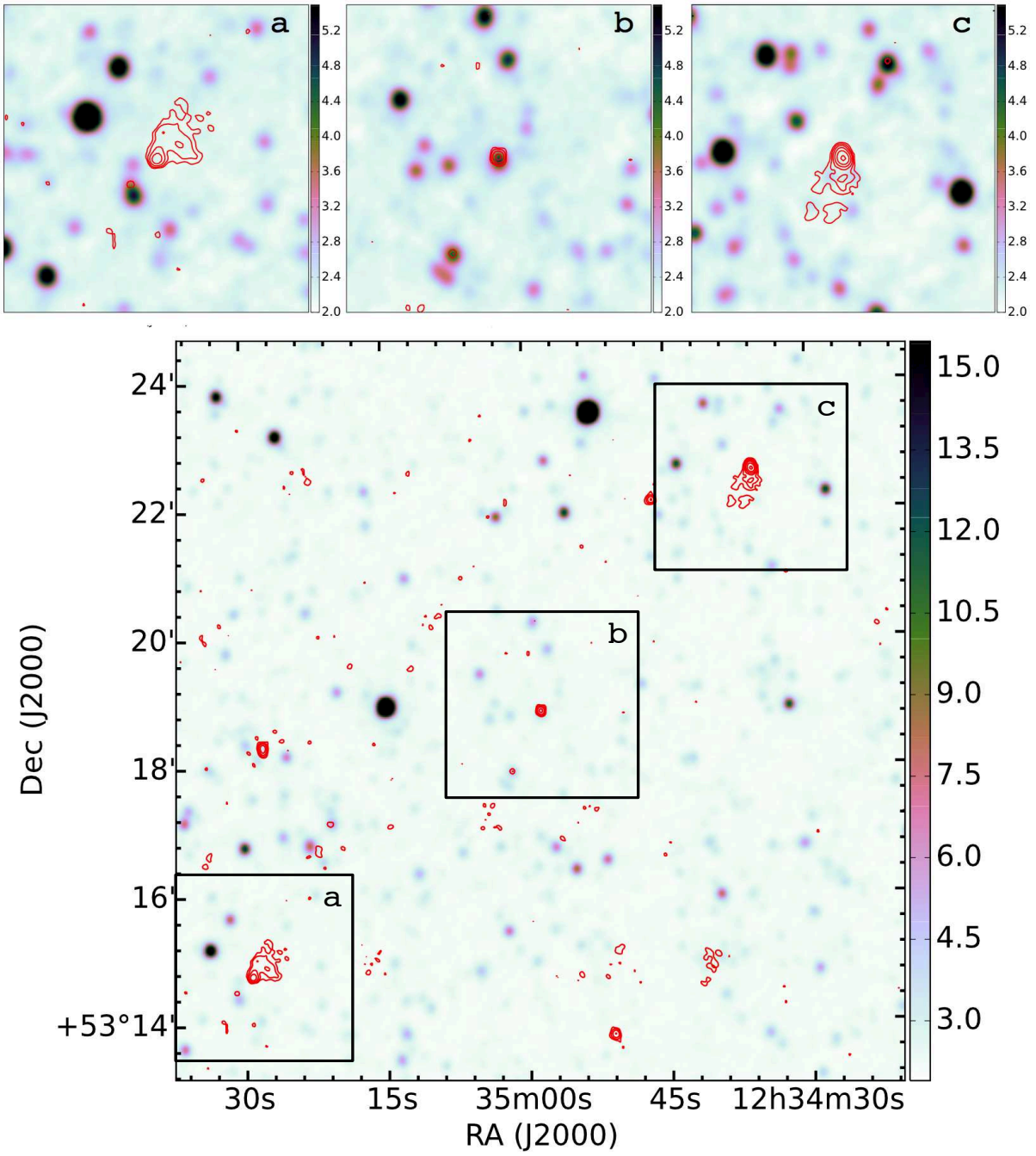
FIRST: angular resolution 5.4", largest component detectable ~2'
➔ unlikely to reveal new GRGs (needs LAS≳2 arcmin at z ~ 1.0–1.5)

From Dec 2013 through September 2016:

RGZ users found / refound / pointed me at
- 313 giant RGs (> 1 Mpc); 201 of them newly found in RGZ;
of these 201, **120** have no doubt about optical ID or GRG nature;
6 are larger than 2 Mpc; another 16 larger than 1.5 Mpc (LAS=4.0' ...9.7')
155 (~78%) were found by 2 specific "super"users;

Comparison of published GRGs and those newly found in RGZ

	231 published	201 new RGZ GRGs
median z	**0.26**	**0.57** ←
fraction of QSOs	38 (16%)	34 (17%)
median r'mag	18.2	20.8
median LAS (')	6.2	3.35
median LLS (Mpc)	1.3	1.18
N (LLS > 2 Mpc)	29	6



J1234+5318 was rediscovered in Radio Galaxy Zoo 6 days after its start!

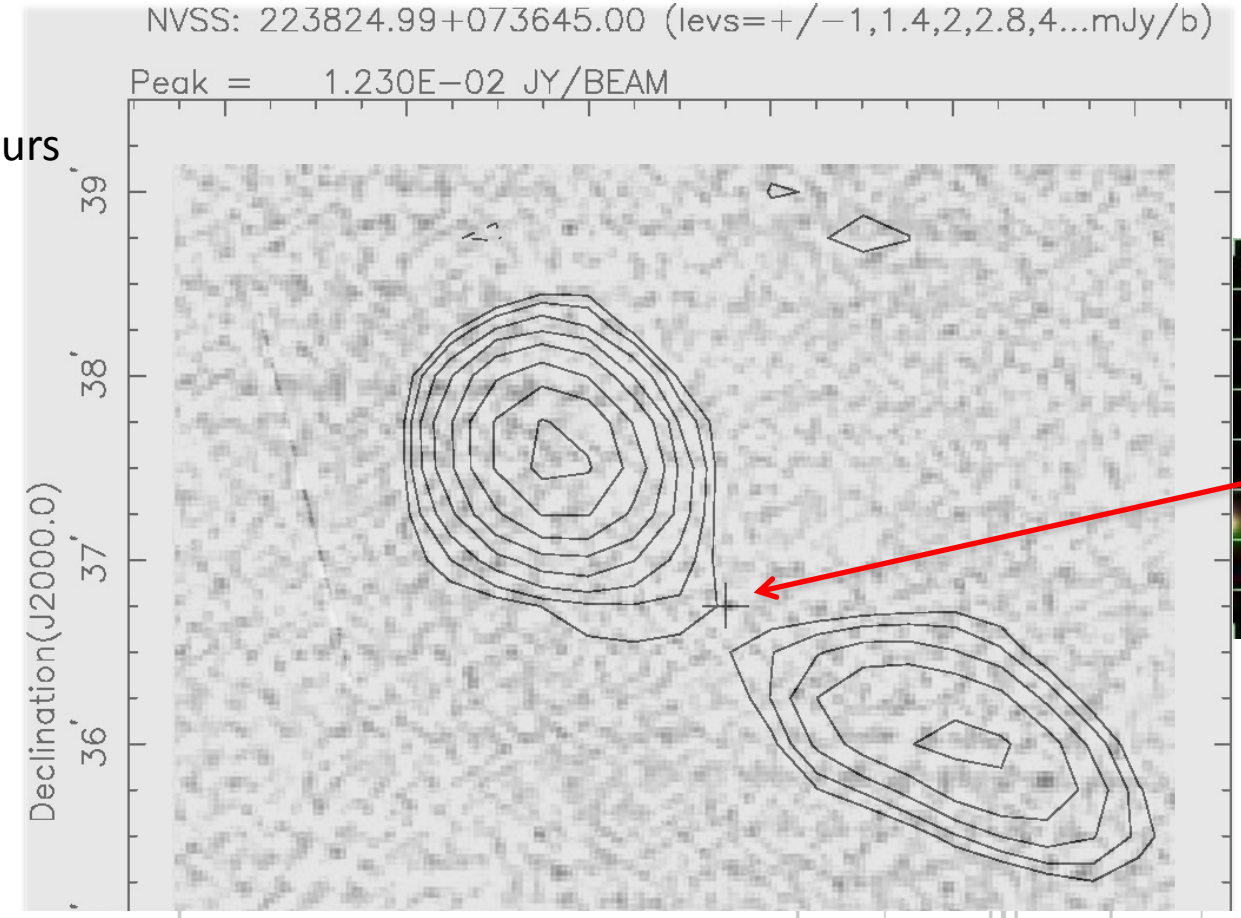
Looking at only one lobe (with no opt. ID) 2 volunteers noted its huge size of 11.2′
z_{phot} = 0.6 → **4.2 Mpc**

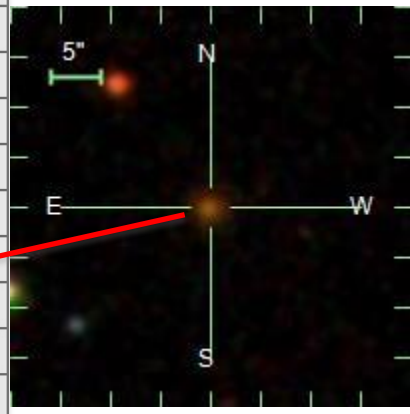
Image from the RGZ "definition paper" 2015MNRAS.453.2326B

→ our optical spectroscopy confirmed z_{phot} to within ~4%,

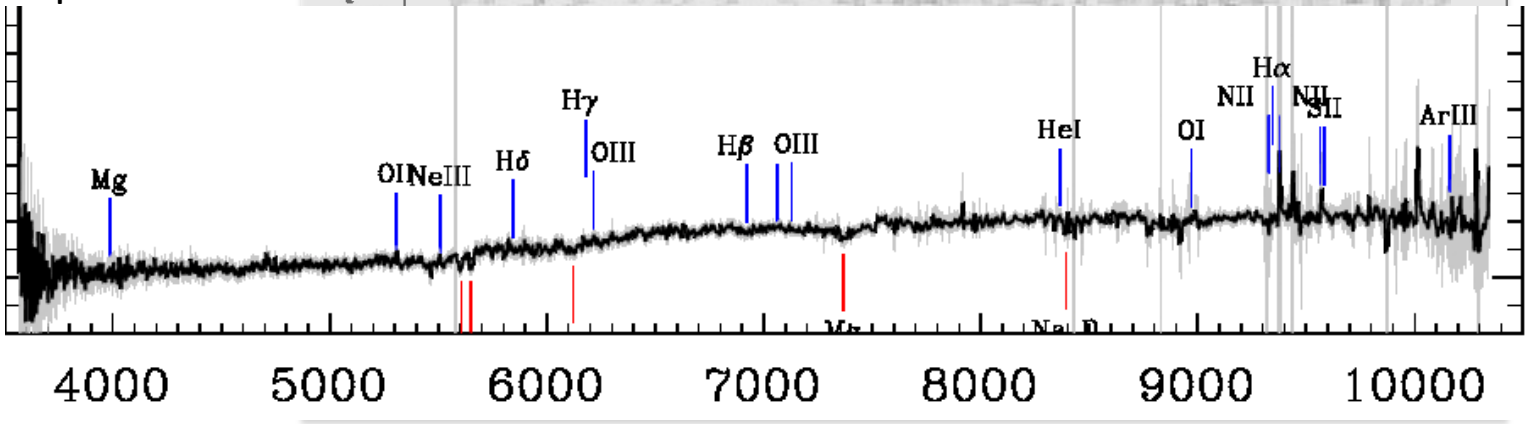
we also confirmed z_{phot} for two QSOs at z=1.3 and 1.8 to within 5% of z_{phot}

NVSS contours over FIRST grayscale





SDSS optical spectrum



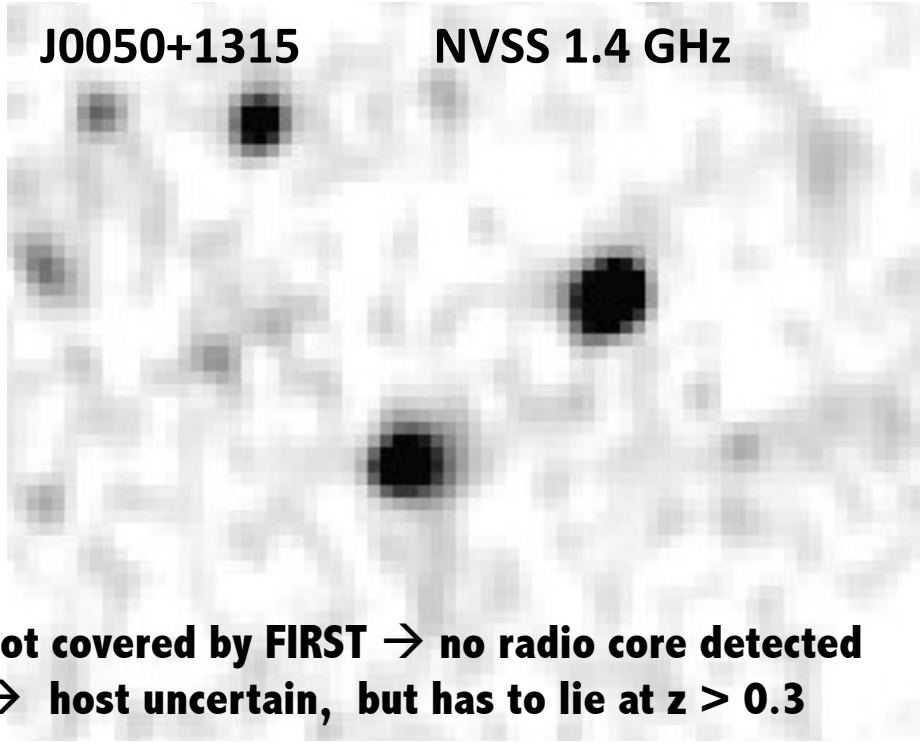
z=0.4234
LAS=3.4’
LLS=1.1 Mpc

More recent large-scale surveys: TGSS-ADR1 (GMRT)

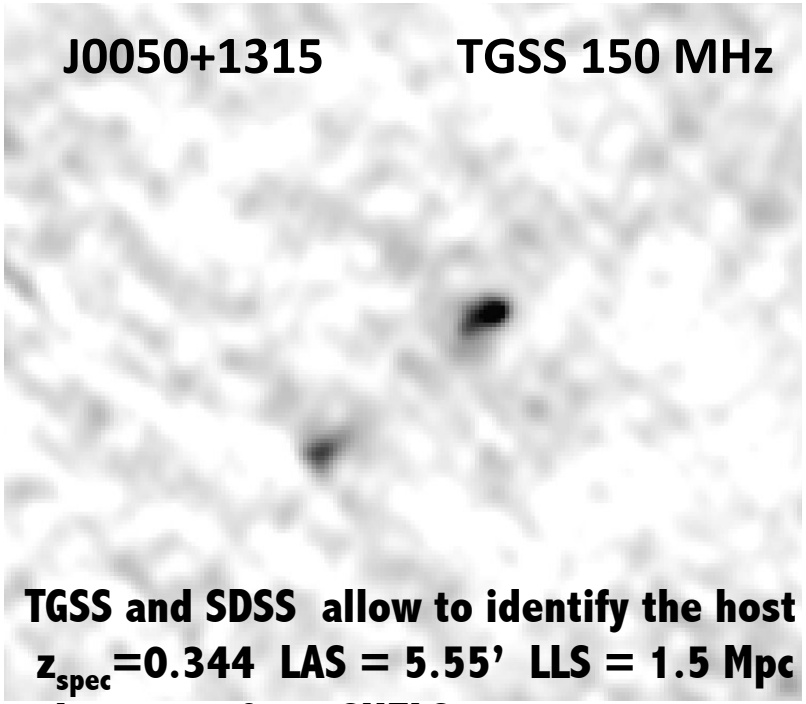
Intema et al. 2016, submitted (arXiv:1603.04368)

- covers 91% of sky at 150 MHz with 25" resolution
- not as sensitive as NVSS :
  → it does not "see" the lowest-surface brightness NVSS emission
  but it has better resolution !

Many sources are easier to recognize in TGSS



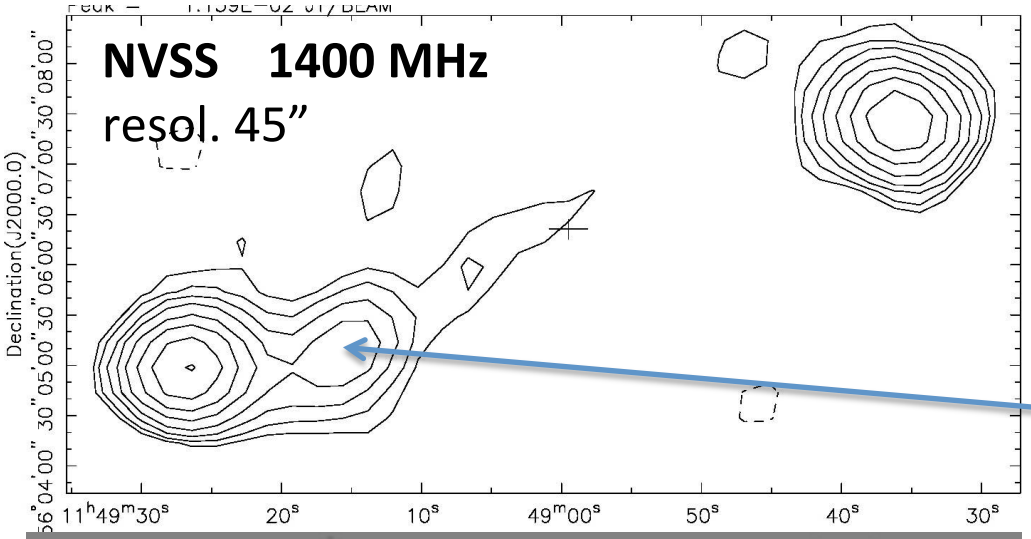
not covered by FIRST → no radio core detected
→ host uncertain, but has to lie at z > 0.3

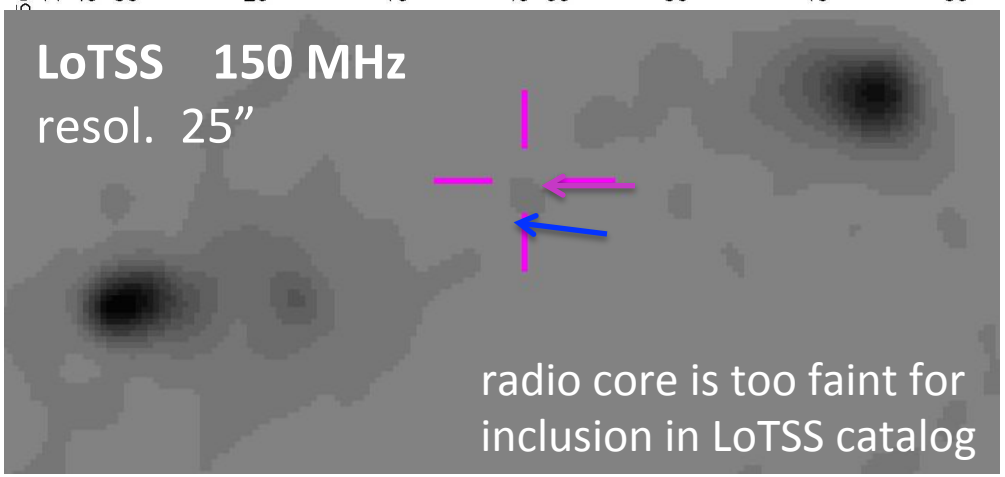


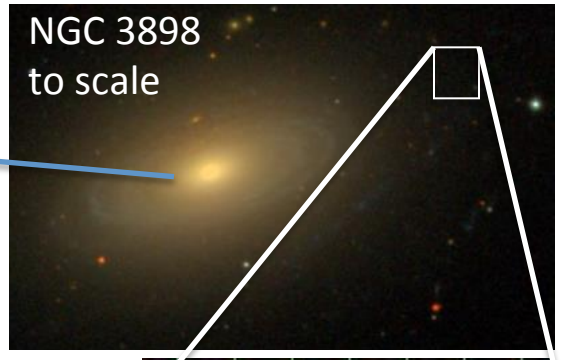
TGSS and SDSS allow to identify the host
z_{spec}=0.344 LAS = 5.55' LLS = 1.5 Mpc
where z_{spec} from SHELS (2016ApJS..224...11G)

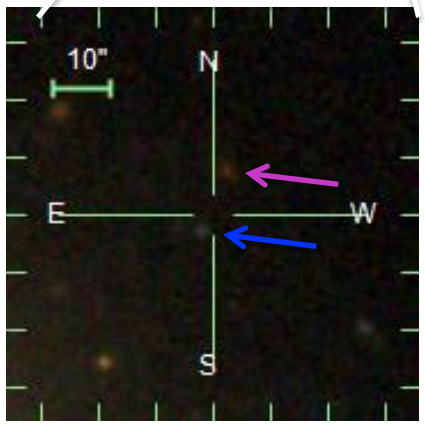
Candidate GRG (from students in 2012): too faint for TGSS-ADR1, but

it is covered by LoTSS @ 150 MHz
(Shimwell+2016, arXiv:1611.02700)
LOFAR Two-metre Sky Survey,
25" resolution









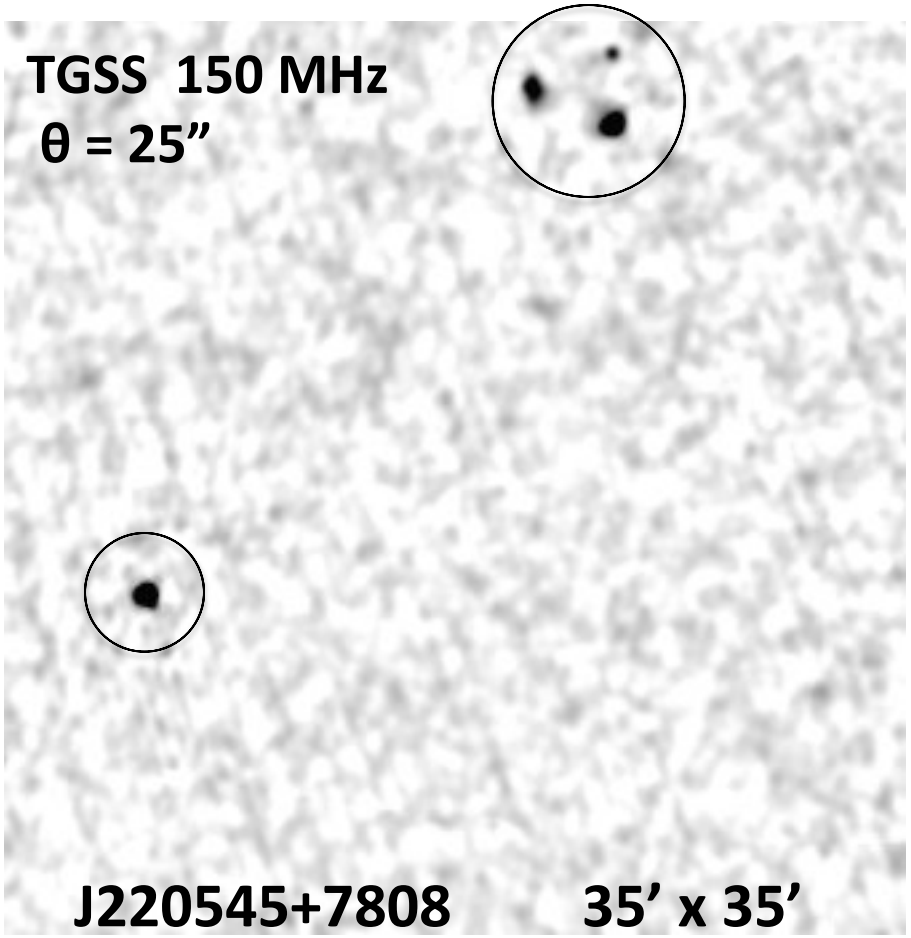
LoTSS-core at J114859.77+560613.3: 2 hosts within 8" and 5":
SDSS J114859.50+560621.2, r'=21.28, z_{phot}=0.4244, or
SDSS J114900.02+560610.6, r'=21.38, z_{phot}=0.422;
in SDSS DR7, but not in later DRs (due to halo of NGC 3898 ?)
FIRST: only shows SE hotspot, but resolves out the NW lobe

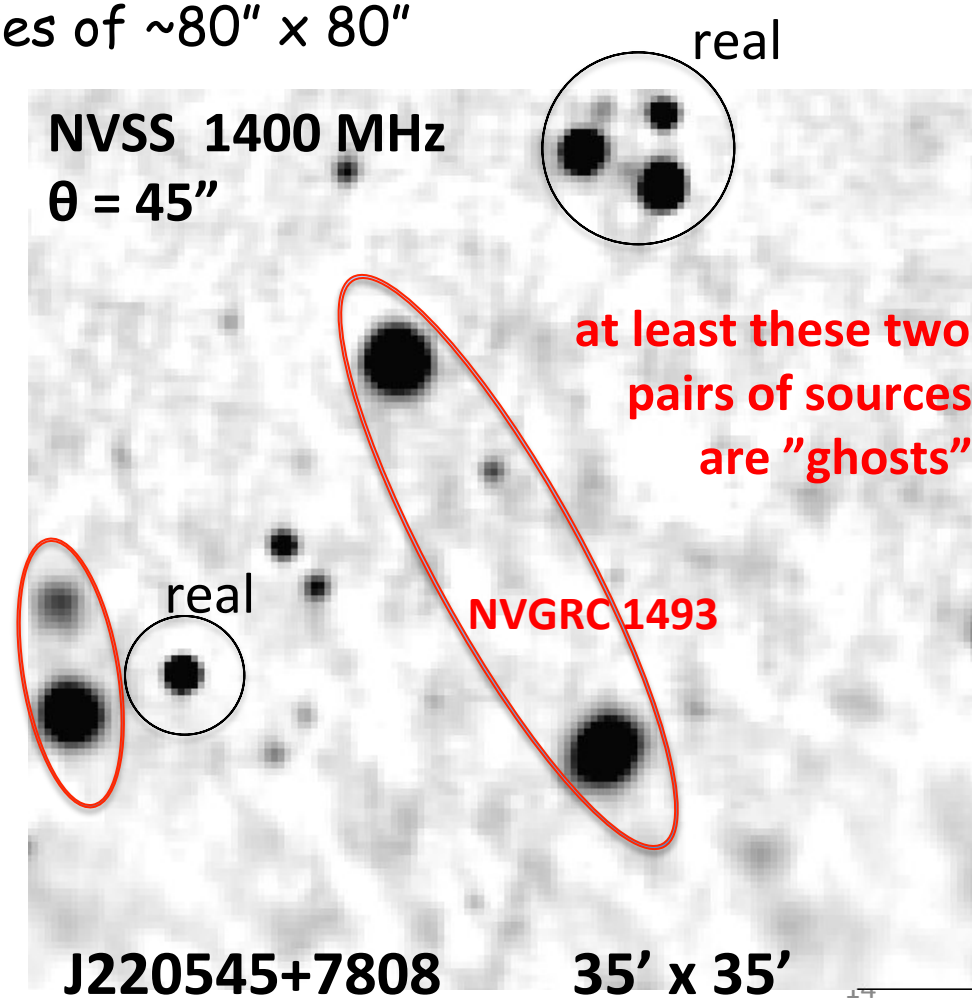
➔ **with LAS = 7.7'**
➔ **LLS = 2.3 Mpc**

Some bad news: NVSS has regions with "ghost" (artificial) sources

Proctor (2016) classifies her candididate NVGRC 1493 like this:
"d? points, both fuzzy, also at least two other similar nearby"

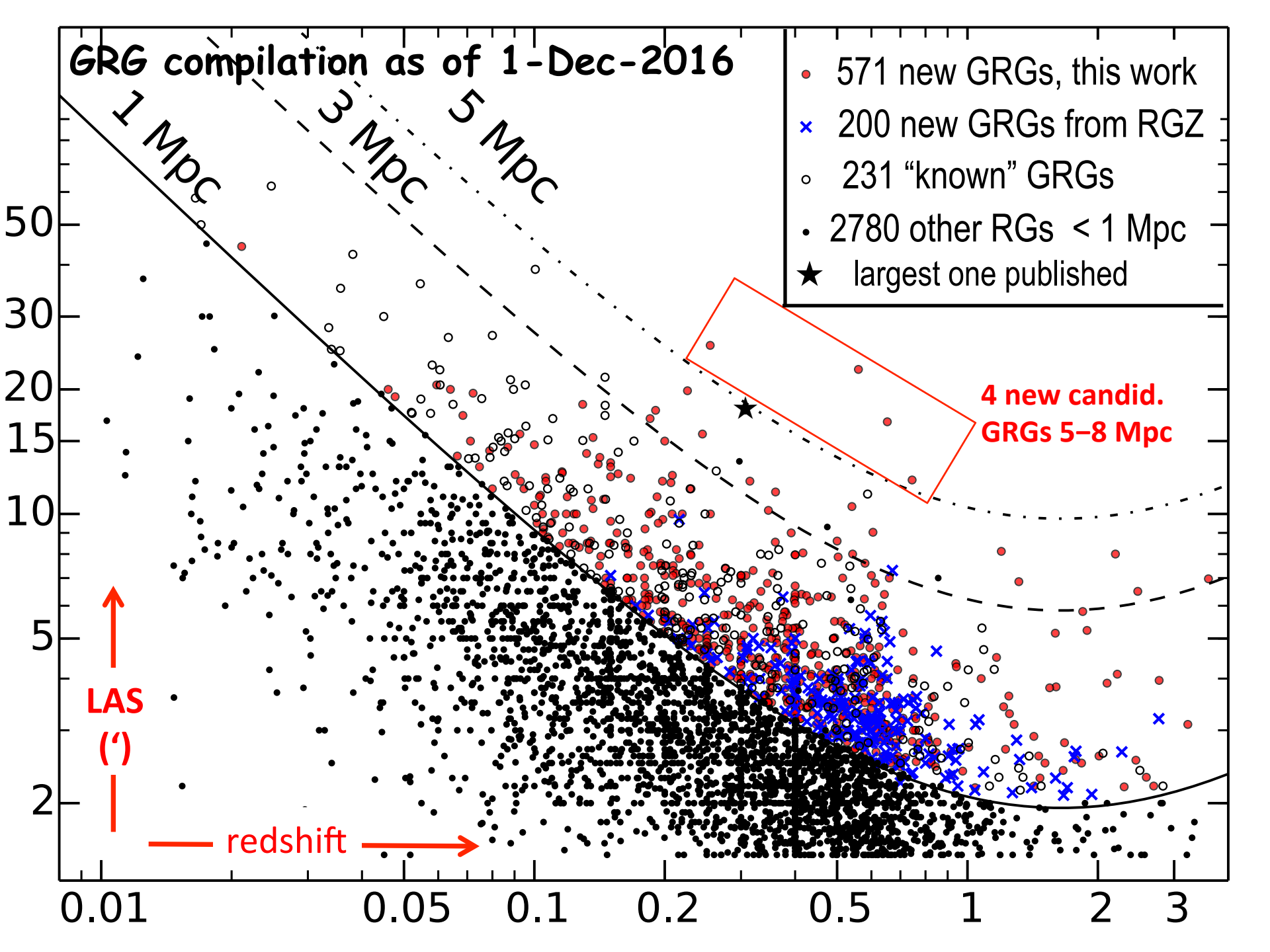
From a few other examples I found → NVSS "ghosts" all have circular shapes with deconvolved sizes of ~80" x 80"





Very essential for this work: combination of **FIRST+SDSS**, but also the huge amount of **photometric redshifts** now available:

2004ApJS..155..257Richards+	SDSS DR1 QSOs	100,563
2004MNRAS.351.1290Rowan-Rob.	ELAIS field	3,523
2007MNRAS.380.1608Lopes P.A.A.	LRGs in SDSS-DR5	1,459,536
2007MNRAS.375...68Collister+	SDSS DR4 LRGs	1,214,117
2009ApJS..180...67Richards+	SDSS DR6 QSOs	1,015,082
2010ApJ...714.1305Strazzuolo+	Deep SWIRE AGNs	1,580
2011MNRAS.416..857Smith+	Herschel-ATLAS	6,876
2011ApJ...729..141Bovy J.+	SDSS DR8	4,009,058
2011ApJ...736...21Szabo+	SDSS clusters	69,173
2012ApJ...757...83Desai+	Blanco Cosm. Survey	1,955,400
cesam.lam.fr/cfhtls-zphots	SDSS stripe82	13,621,717
2013MNRAS.428.1958Rowan-Rob.	SWIRE, Lockman	1,009,607
2014ApJS..210....9Bilicki+	2MASS 2MPZ	928,352
2014A&A...568A.126Brescia+	SDSS-DR9	143,500,000
2015ApJS..219...12Alam+	SDSS DR12	208,474,076
2015PASA...32...10Flesch	Half Million Quasars	510,764
2015MNRAS.452.3124DiPompeo+	SDSS QSOcands	5,537,436
2015ApJS..219...39Richards+	SDSS-III/BOSS	2,490,080
2016ApJS..225....5Bilicki +	SCOSxWISE	78,000,000
	Total:	**464,000,000**


GRG compilation as of 1-Dec-2016
1 Mpc
3 Mpc
5 Mpc
571 new GRGs, this work
200 new GRGs from RGZ
231 "known" GRGs
2780 other RGs < 1 Mpc
largest one published
4 new candid.
GRGs 5–8 Mpc
LAS
(')
redshift
50
30
20
15
10
5
2
0.01
0.05
0.1
0.2
0.5
1
2
3

The GRG compilation as of 01-Dec-2016

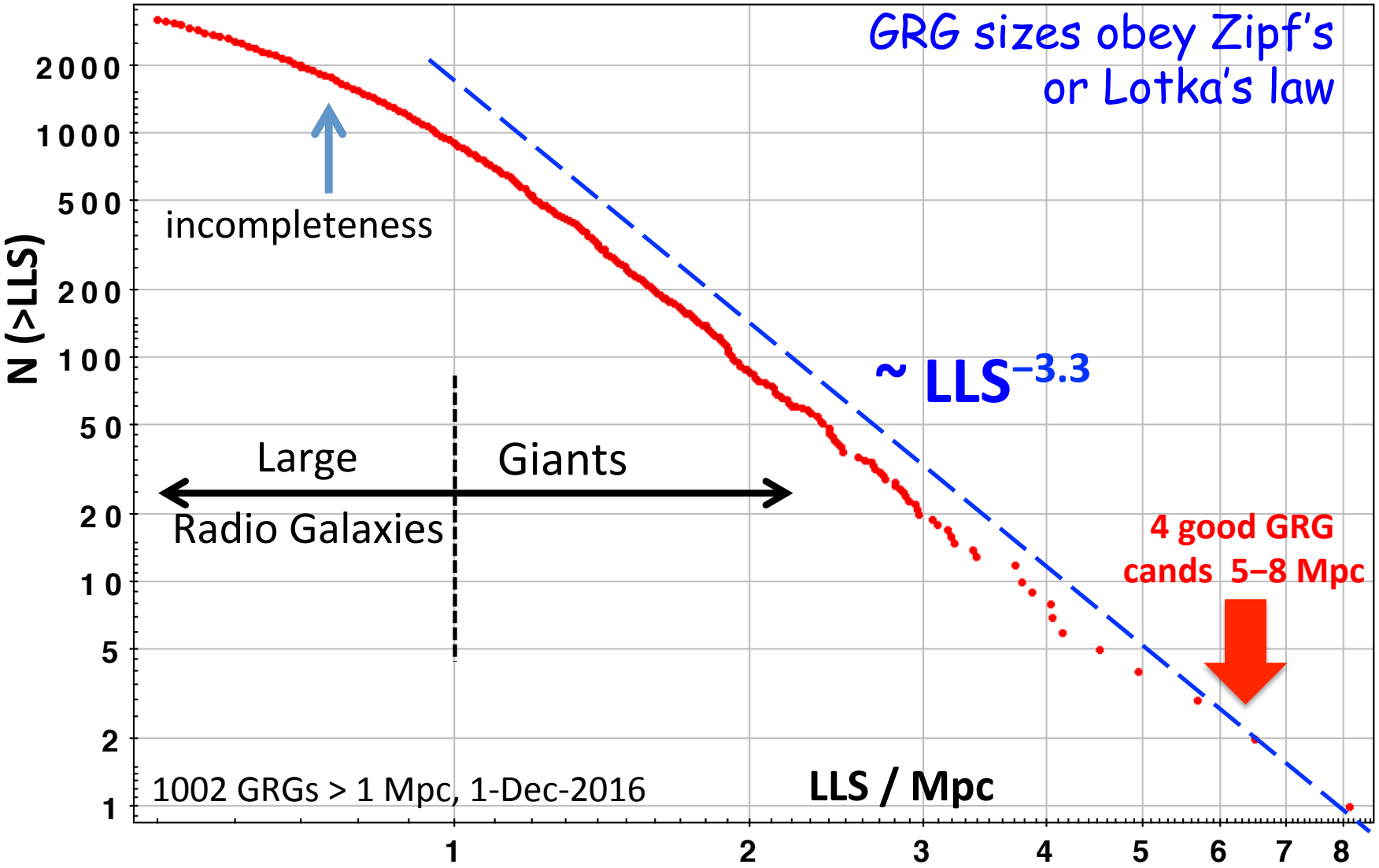
* Total of **1003 GRGs** > 1 Mpc/h_{75} (~310 have minor doubts)
  only 200+ are reported as GRGs, spread over dozens of papers
* difficult to tag as "published": NED has only 55 GRGs:
  36 have LLS > 1 Mpc; 18 have LLS < 1 Mpc; 1 is wrong ID (4C vs. 4CT)
* vast majority of **FR II** morphologies, but often one or both
  lobes are resolved out (very diffuse) in FIRST
* **52% have z_{spec}**; 37% have good z_{phot}, ~10% are "best guesses"
* 83% galaxies, 16% quasars, ~1.5% unknown (e.g. WISE-only)
* median z is 0.4: 0.364 for galaxies and 0.83 for QSOs
* 57 GRGs lie at z > 1, and a few **up to z~3** !

Additional objects collected "in passing" ...

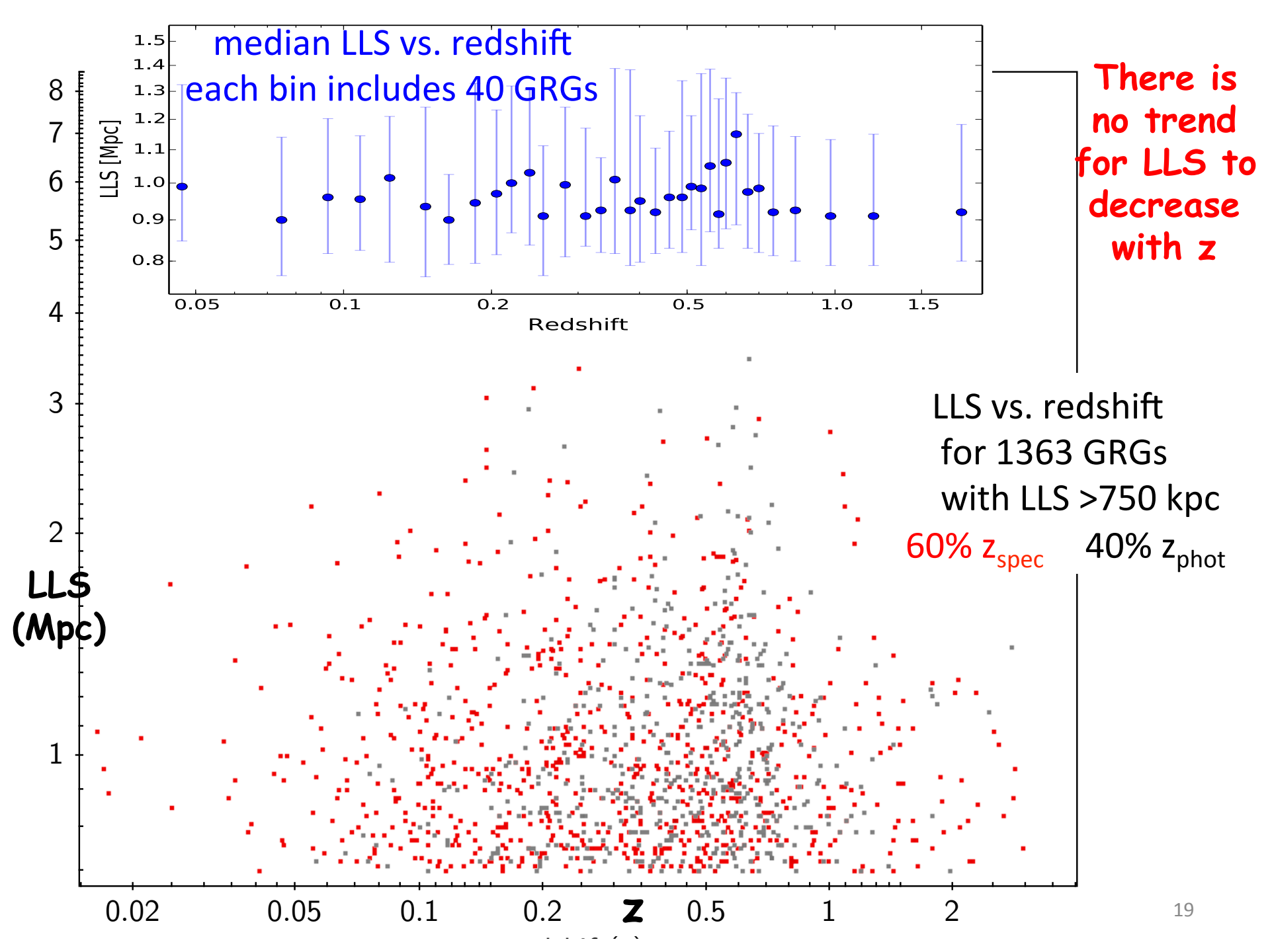
- 3500 sources of LAS =10 kpc ... 1 Mpc (INCOMPLETE)
- of these, ~750 are larger than 750 kpc (called GRGs by some)
- this is the largest-ever compilation of linear source size

How fast does the number of GRGs decrease with their size ?

The Log(N) – log(Size) distribution of GRGs



If statistics works: we need **twice as many** GRGs to find **one** with LLS~**10 Mpc**


median LLS vs. redshift
each bin includes 40 GRGs
LLS [Mpc]
Redshift
There is no trend for LLS to decrease with z
LLS vs. redshift
for 1363 GRGs
with LLS >750 kpc
60% z_spec
40% z_phot
LLS (Mpc)
z

Some challenging trends . . .

- **slope of log(N) – log(size)** seems to vary with redshift :

  500 "nearby" GRGs ($z < 0.4$) = 3.47 ± 0.02

  501 "distant" GRGs ($z > 0.4$) = 3.28 ± 0.04

  5σ difference

  ➔ are we missing some nearby GRGs (for having an LLS >> 1°
  or too low a surface brightness ?)

- **mean density of Universe** grows as ~ $(1+z)^3$

  So, how can GRGs grow to these sizes even at $z > 1$?

- **CMB photon density** grows as ~$(1+z)^4$

  ➔ synchrotron-emitting electrons suffer severe "inverse Compton" losses

  ➔ diffuse sources at high redshift should "disappear" more rapidly than nearby ones (at $z \sim 0$)

- Cosmology predicts a **surface brightness dimming** ~$(1+z)^4$

  ➔ diffuse sources should become undetectable at high z

We classified SDSS spectra for ~200 GRGs ➔ their hosts are of **any optical activity type** (QSO, Sy1, Sy2, LINER, dwAGN, NoEm), and

at $z < 0.4$ low-luminosity AGN (dwAGN) dominate, while
at $z > 0.4$ high-luminosity AGN (QSO/Sy1/Sy2) dominate

Are there trends in radio symmetry for GRGs ?

For ~240 GRGs (with SDSS optical spectra) we used NVSS & FIRST images to measure for both lobes (arms) : total flux, length, width, and orientation and we find :

- armlength ratio (ALR) = $\frac{\text{length of the stronger lobe}}{\text{length of the weaker lobe}}$

  ➔ ALR varies from 0.3 to ~3.5, with a median of ~0.9

  ➔ any trend for the stronger lobe to be the shorter one is weak

- the median bending angle between lobes is ~5°
- the larger sources are not significantly straighter
- quasars do not differ from galaxies in radio symmetry nor in their linear size distribution

Lessons learnt

- the simultaneous coverage of low-res (NVSS), high-res (FIRST). and deep optical surveys (SDSS) with good photometric redshifts has been crucial for this work
  ➔ will there be such optical surveys in the south when EMU starts ?

- contributions of citizen scientists will be essential for future surveys

- The radio morphology of (not only giant) sources is surprisingly varied (just like the optical morphologies of galaxies)
  ➔ after Hubble's and deVaucouleurs' Atlas of Galaxy Morphology it is time for an Atlas of Radio Morphology (with a highly multidimensional parameter space)

- The side-to-side asymmetries of GRGs clearly suggest that they are tracers of the large-scale structure on Mpc scales
  → requires deep redshift surveys within ~10 Mpc around GRGs (see **2013MNRAS.432..200Malarecki** and **2015MNRAS.449..955Malarecki**)