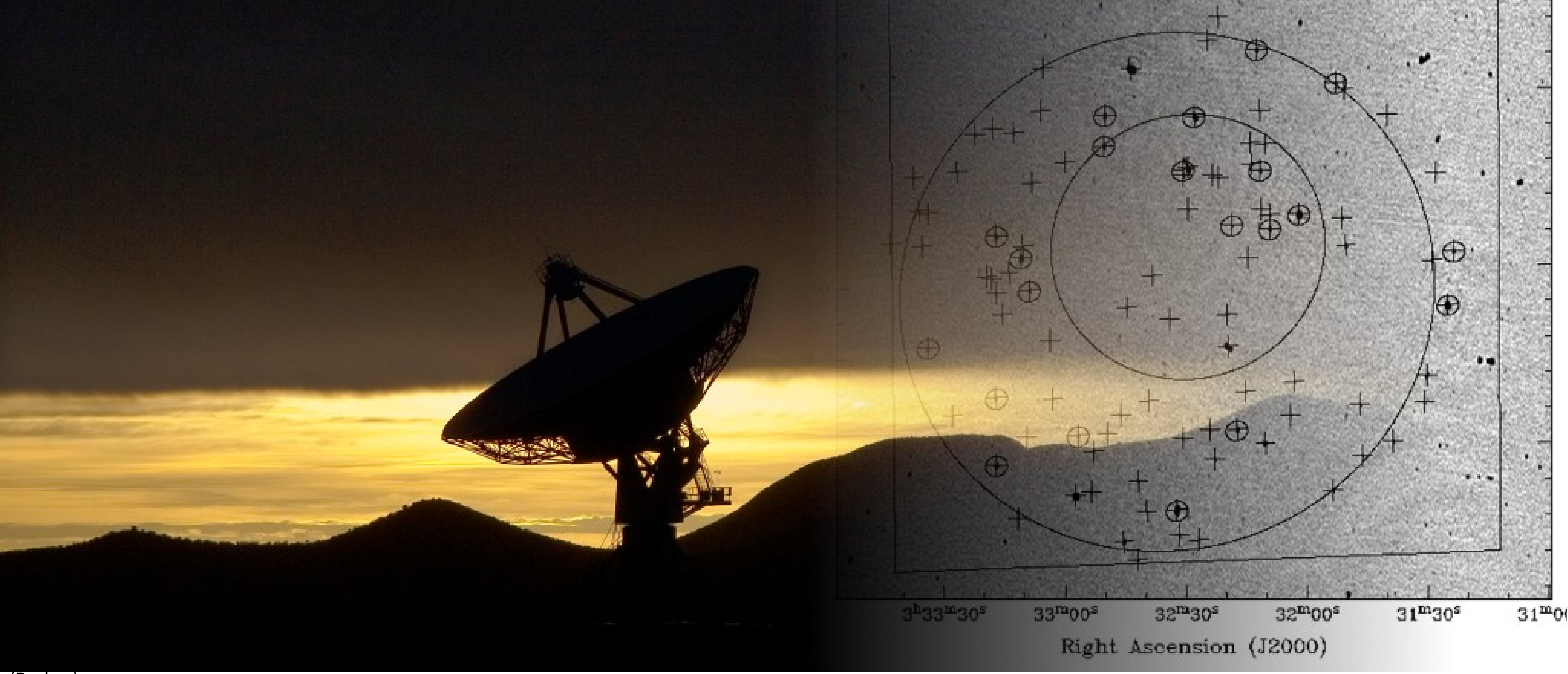

(Parker)

Hunting for AGN with VLBI wide-field observations

13 July 2012

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Astronomisches Institut der Ruhr-Universität Bochum

RUB

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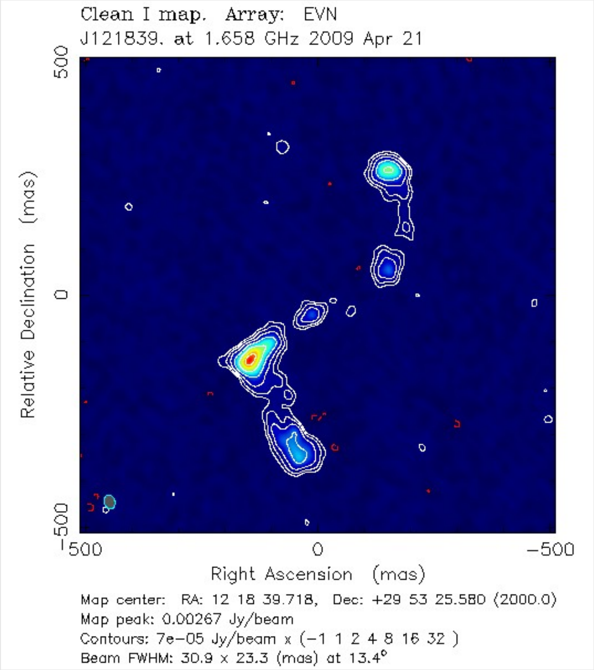
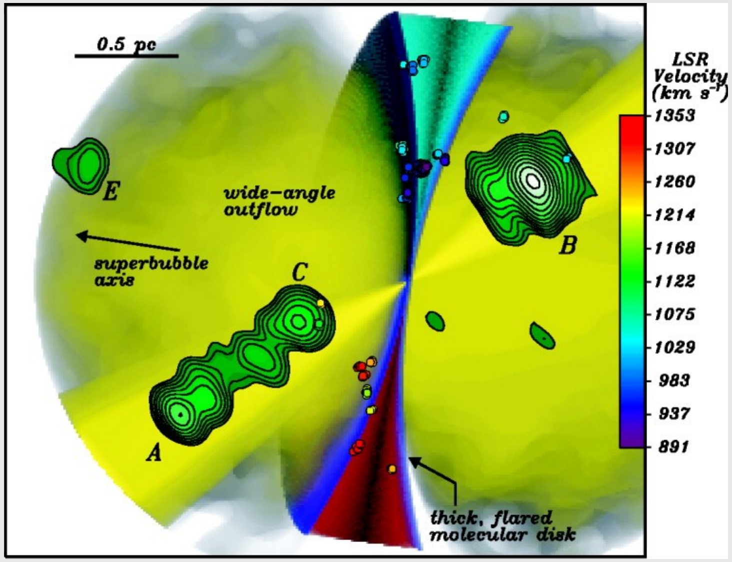
VLBI: typical applications

Radio jets in AGN/μAGN



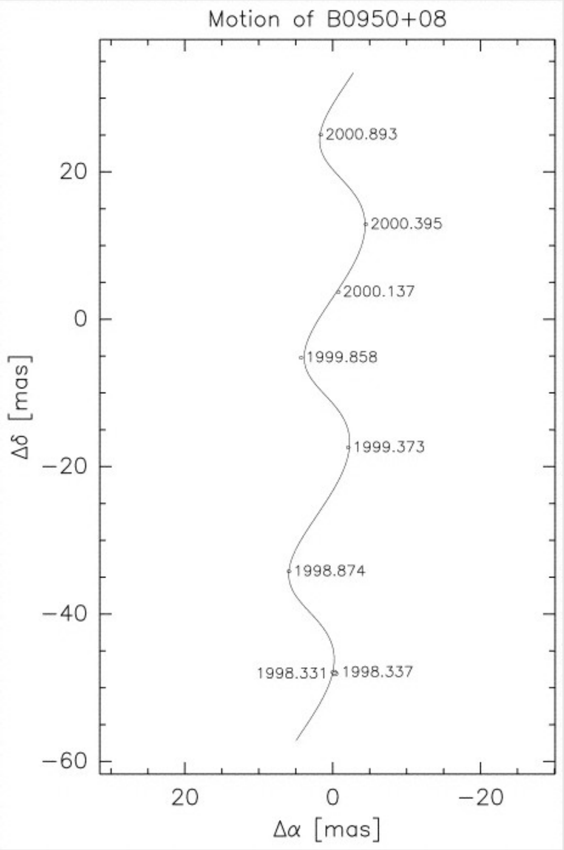
Frey+ (2010)

(Extra-) Galactic masers



Kondratko+ (2005)

Astrometry



Brisken+ (2002)

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VLBI: why wide-field observations?

- Survey science has a golden future: LSST, VST, ASKAP, Pan-STARRS, Lofar, SKA, ...
- Observe sub-mJy radio sky with pc-scale resolution
- Investigate faint, normal AGN and their evolution
- Expect the unexpected

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VLBI: limitations

Fact:

- Field of view: limited by processing power: arcsec vs deg!
- Object types: limited by T_B requirement (=sensitivity)
- Sensitivity: limited by recording media / network bandwidth
- Large array extend requires self-calibration

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VLBI: limitations

Fact:	Consequence:
▪ Field of view: limited by processing power: arcsec vs deg!	▪ Well-selected, isolated objects are observed, no „survey“ science
▪ Object types: limited by T_B requirement (=sensitivity)	▪ Observations limited to non-thermal sources
▪ Sensitivity: limited by recording media / network bandwidth	▪ Sensitivity mostly lower than with VLA et al, but improving
▪ Large array extend requires self-calibration	▪ Observations of faint sources have limited dynamic range

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VLBI: limitations

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Quick reminder: how ~~VLBI~~ radio interferometry works

- „An interferometer is a device for measuring the spatial coherence function“ (Clark 1999)
- Spatial coherence of electric field corresponds to Fourier transform of the sky brightness distribution

- Coherence function:

$$V_\nu(\vec{r}_1, \vec{r}_2) = \langle E_\nu(\vec{r}_1) E_\nu^*(\vec{r}_2) \rangle$$

- Electric field at one antenna:

$$E_\nu(\vec{r}) = \int \mathcal{E}_\nu(\vec{R}) \frac{e^{2\pi i \nu |\vec{R}-\vec{r}|/c}}{|\vec{R}-\vec{r}|} dS$$

- Insert:

$$V(\vec{r}_1, \vec{r}_2) = \left\langle \iint \mathcal{E}_\nu(\vec{R}_1) \mathcal{E}_\nu^*(\vec{R}_2) \frac{e^{2\pi i \nu |\vec{R}_1-\vec{r}_1|/c}}{|\vec{R}_1-\vec{r}_1|} \frac{e^{-2\pi i \nu |\vec{R}_2-\vec{r}_2|/c}}{|\vec{R}_2-\vec{r}_2|} dS_1 dS_2 \right\rangle$$

- Make a few assumptions:

$$V_\nu(u, v) = \iint I_\nu(l, m) e^{-2\pi i (ul+vm)} dl\, dm$$

This is the “visibility function” one wishes to measure.

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Quick reminder: how ~~VLBI~~ radio interferometry works

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$V_\nu(\vec{r}_1, \vec{r}_2) = \langle E_\nu(\vec{r}_1) E^*_\nu(\vec{r}_2) \rangle$

- Ele [redacted]

$E_\nu(\vec{r}$ [redacted]

- Ins [redacted]

$V(\vec{r}_1$ [redacted] $-\vec{r}_2|/c$ $dS_1 dS_2 \rangle$ $\vec{r}_2 \,|$

CENSORED

- Ma [redacted]

$V_\nu(u,v) = \iint I_\nu(l,m) e$ [redacted] $dl\, dm$

This is the “visibility function” one wishes to measure.

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Quick reminder: how ~~VLBI~~ radio interferometry works

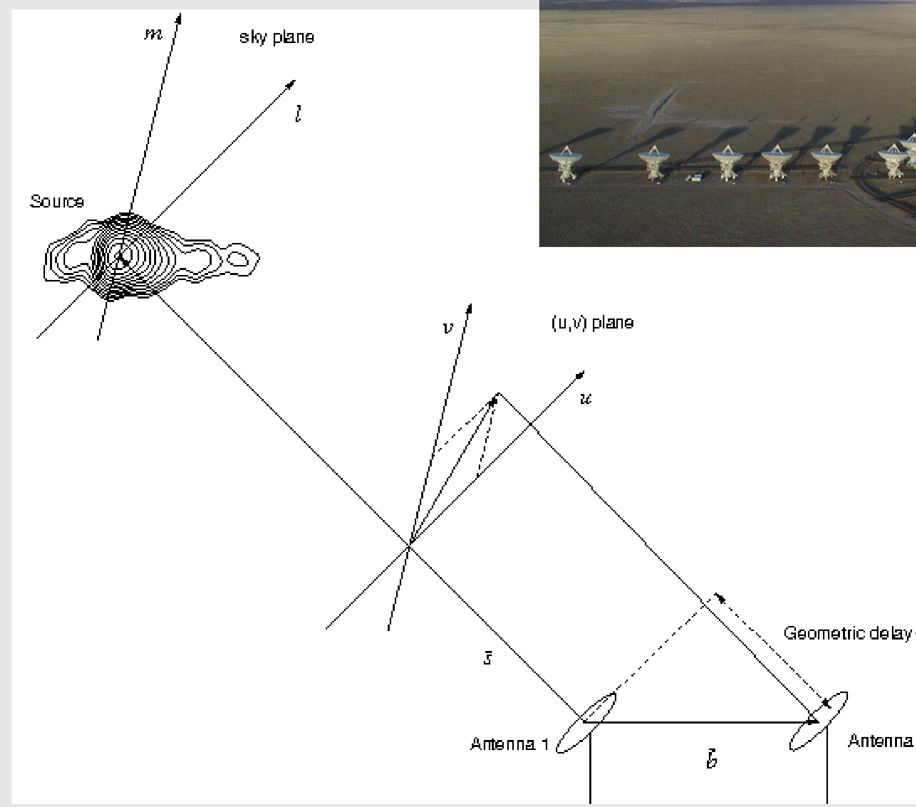
- Interferometer array is an array of two-element interferometers

- Each baseline measures the spatial coherence function in „uv plane”
  → aperture synthesis as earth rotates

- Spatial coherence of electric field corresponds to Fourier transform of the sky brightness distribution

- Gridding all measurements onto an image and FFT^{-1}'ing returns the sky brightness distribution

NRAO



Middelberg & Bach 2008

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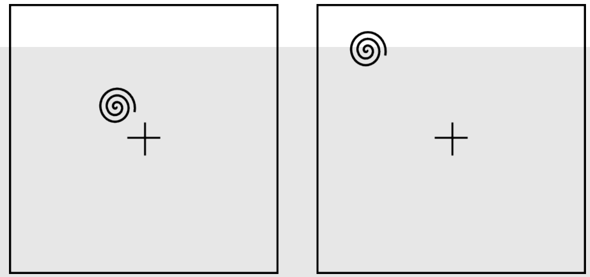
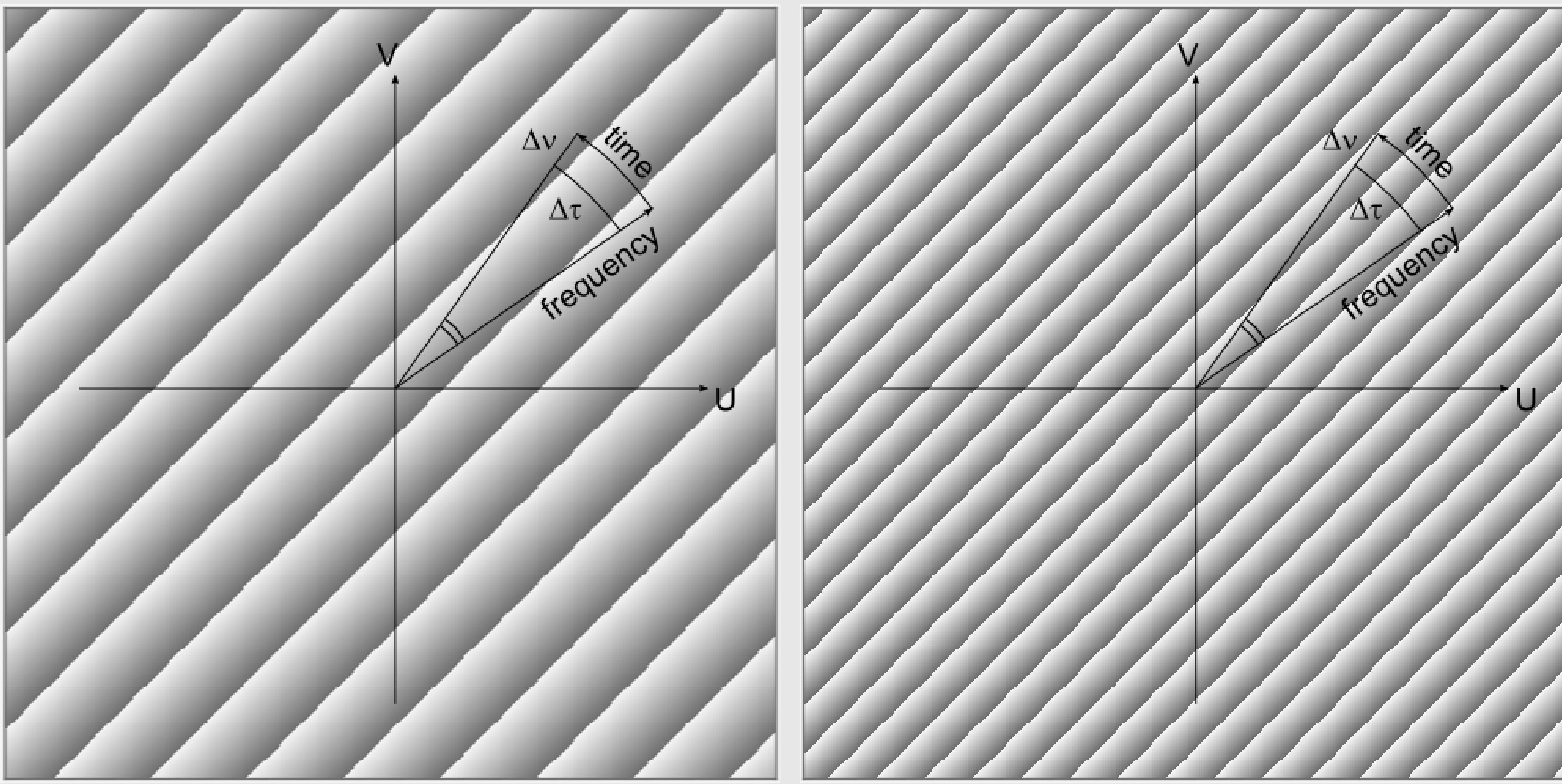
Why small FOV?





Measurement phase of point source with small/large distance to phase centre

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Wide-field VLBI with conven

- Extending FOV to antenna's FOV requires 50ms integrations and 4kHz channels
- Results in a TB-sized data set
- Post-processing a pain
- Data contain much more information than required (in my case): ~10^{12} image pixels for ~100 sources

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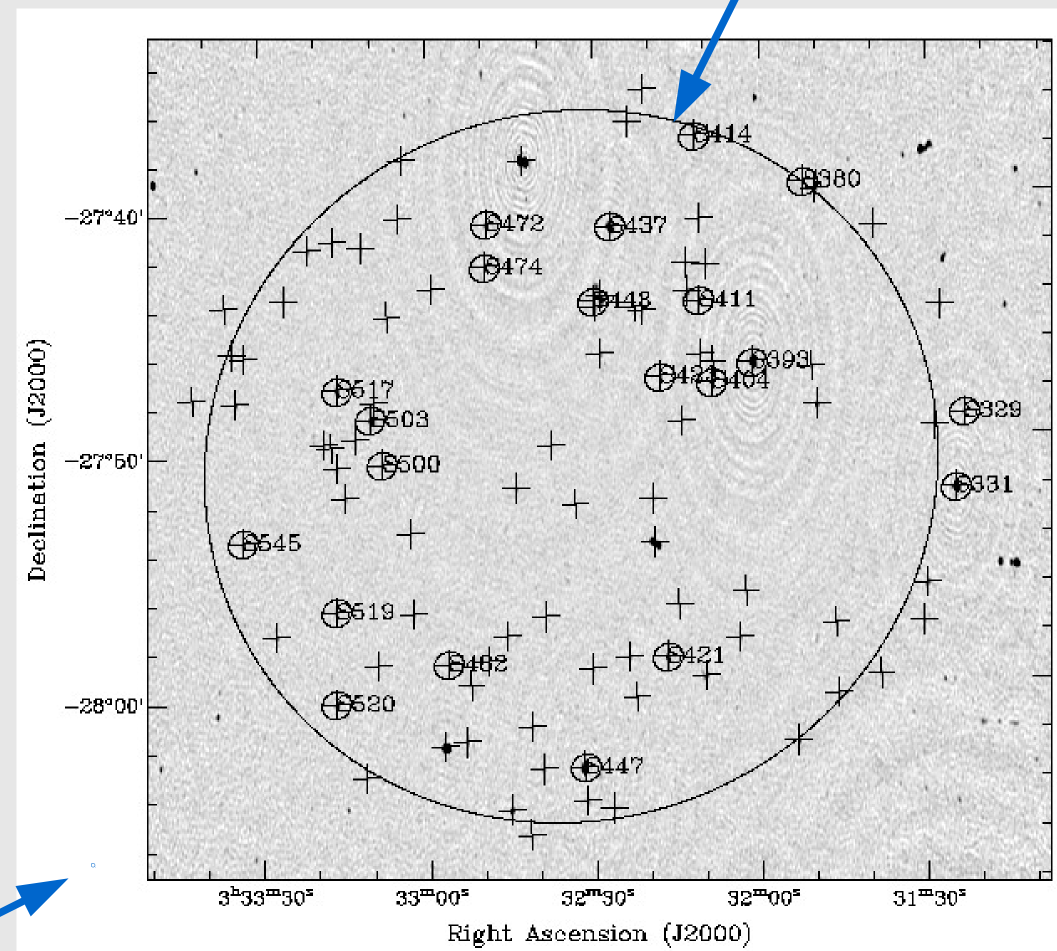
The new approach for wide-field VLBI

- Correlation of data with multiple phase centres using the DiFX correlator (Deller+ 2007/2011)
- Each phase centre positioned on a known radio source
- Result: a “normal” VLBI data set for each radio source
- Calibration: deal with one, copy to others

Interferometer elements' instantaneous field of view: 30 arcmin



VLBI array's field of view: 10 arcsec

1.4 GHz image of CDFS, crosses mark target positions (Middelberg+ 2011)

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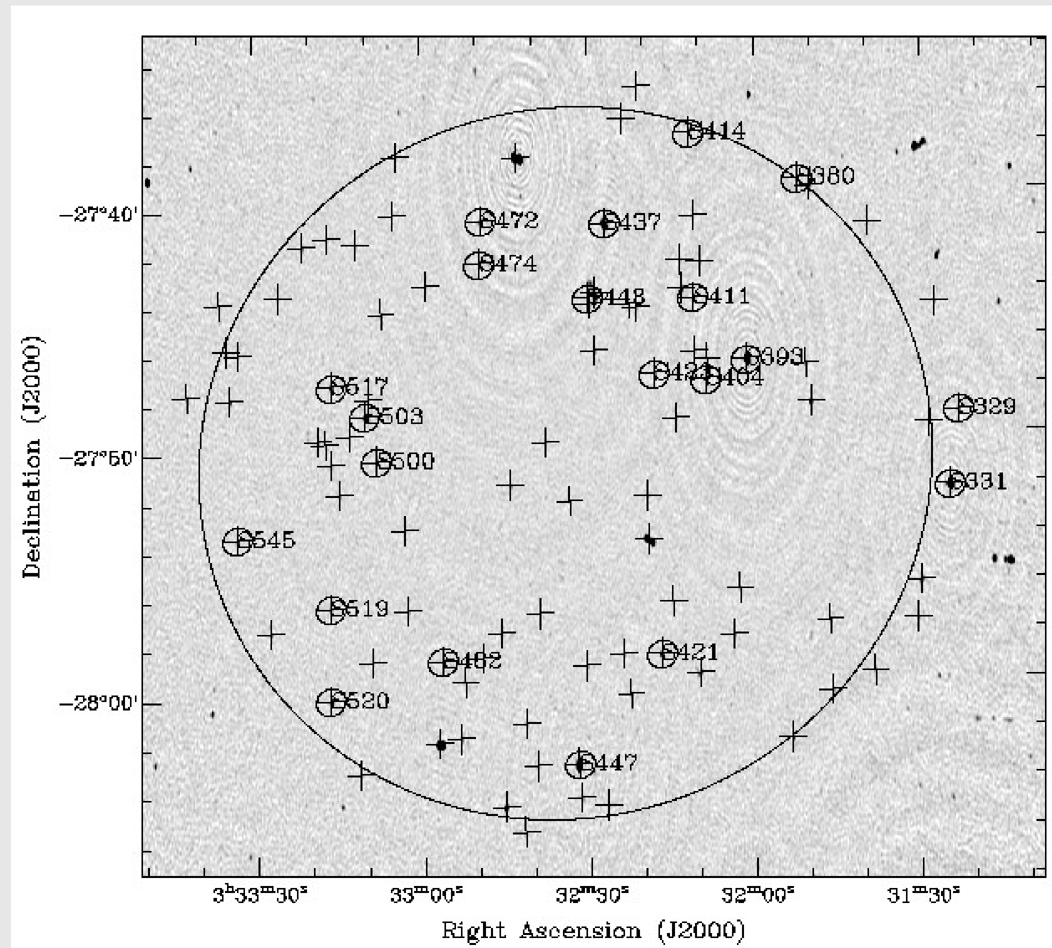
Pilot project I
Chandra Deep Field South

- CDFS one of the best-studied areas in the sky (optical/IR/X-ray/spec-z)
- Observed CDFS with VLBA for 9h; nominal sensitivity 50µJy to 100µJy
- 96 sources known with S>150µJy
- One source bright enough for calibration (but 40% data loss!)
- Calibration copied to other data and imaged



1.4 GHz image of CDFS, crosses mark target positions (Middelberg+ 2011)

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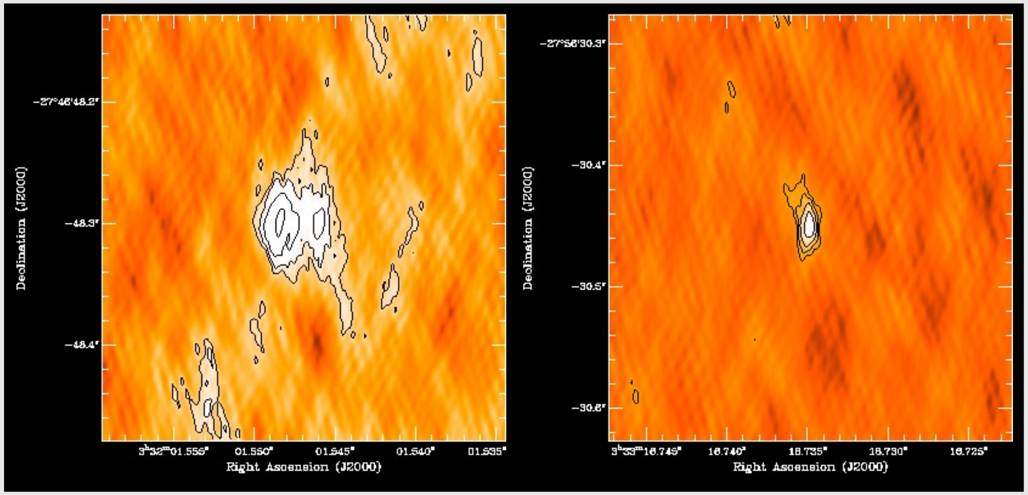
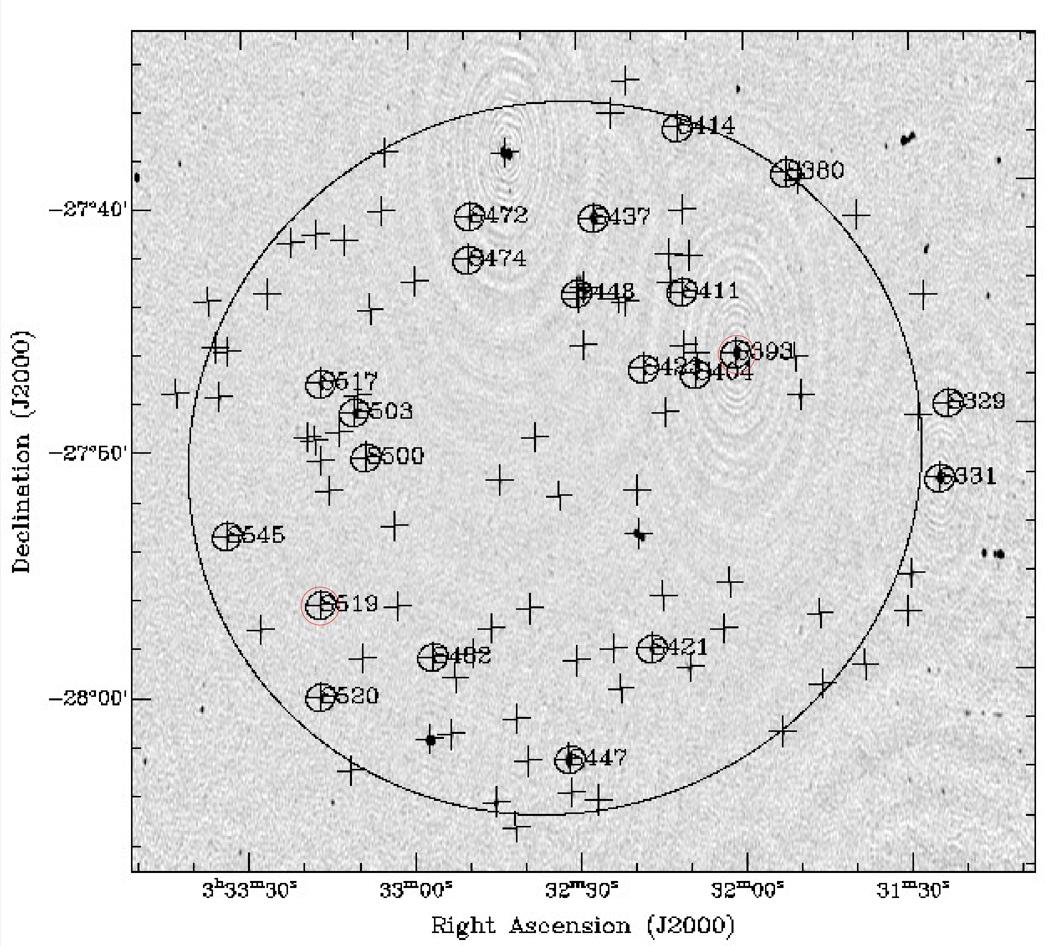
Pilot project I: Chandra Deep Field South

Results (Middelberg+ 2011)



Target S393: z=1.07, S_{ATCA}=49.1mJy, S_{VLBI}=2.5mJy

Target S519: z=0.69, S_{ATCA}=0.9mJy, S_{VLBI}=1.1mJy



1.4 GHz image of CDFS, crosses mark target positions (Middelberg+ 2011)

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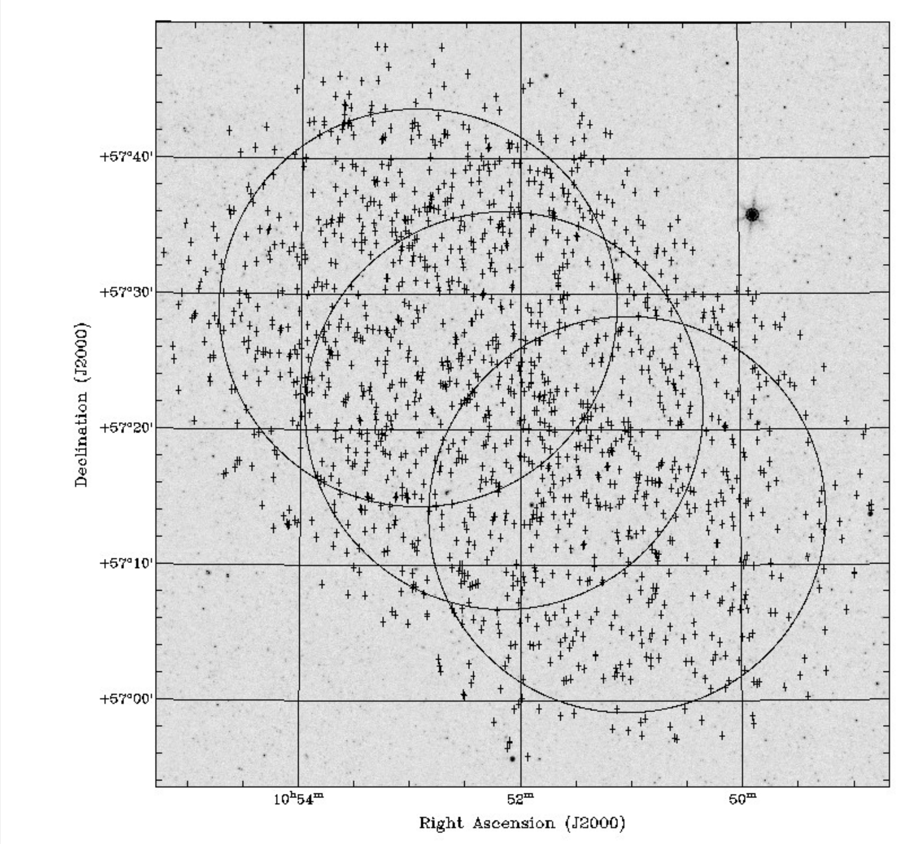
Pilot project II: Lockman Hole/East
Overview

- 496 sources with S>100μJy, 1500 sources total
- 3x12h required to reach ~25μJy/beam, observed in July/September 2010
- Adding data from pointings increases sensitivity – first VLBI mosaicing ever
- Lack of strong sources requires multi-source calibration strategy



Greyscale: 3.6μm; crosses: source positions; circles: antenna FWHM

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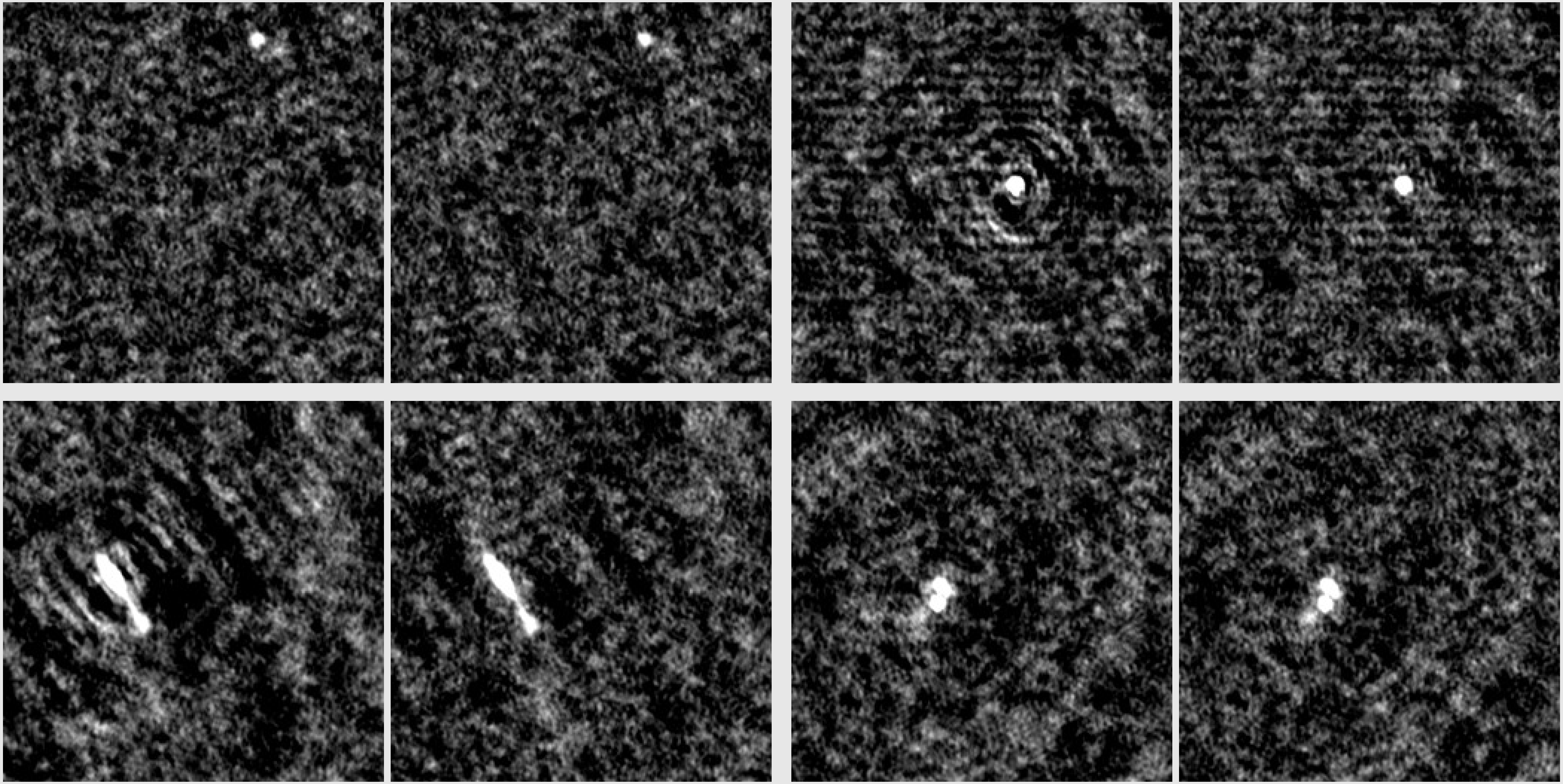
Pilot project II: Lockman Hole/East
Multi-source selfcal



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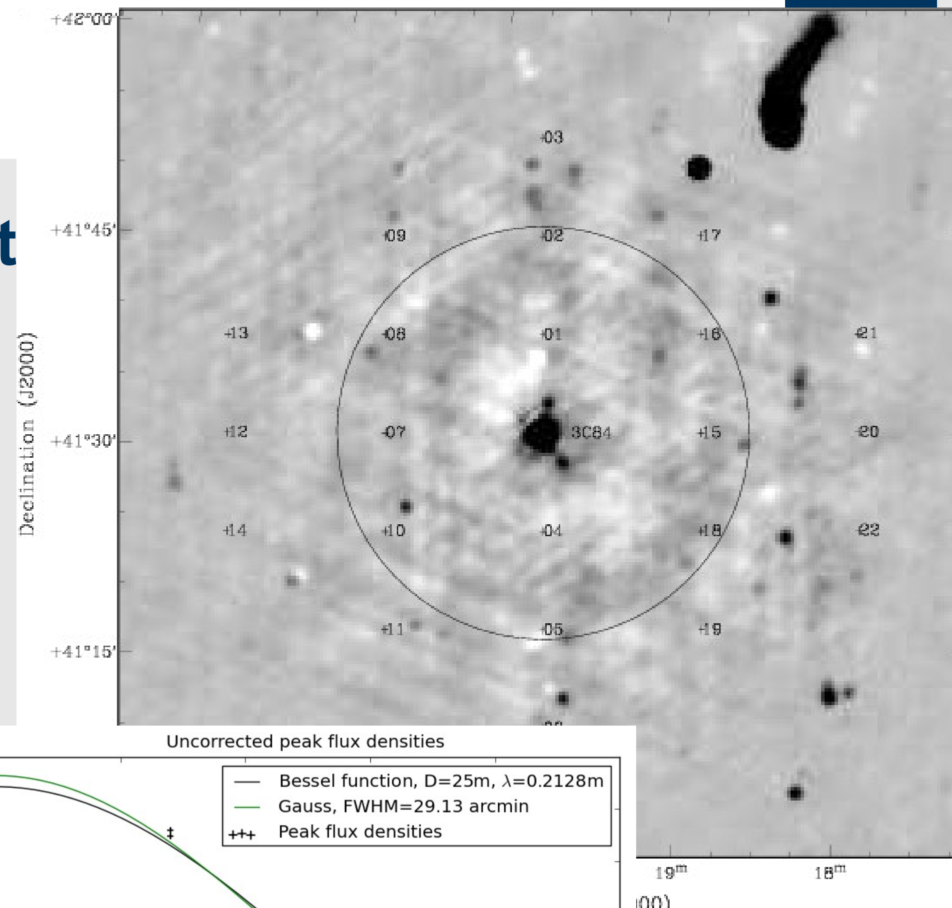
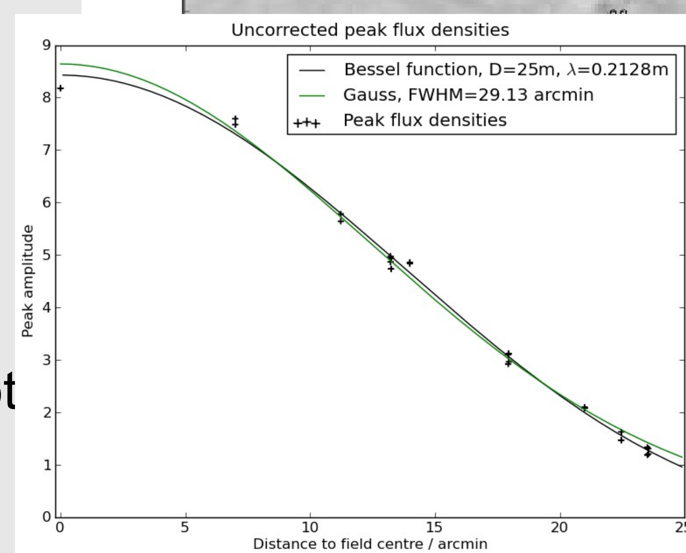
Pilot project II: Lockman Hole/East

Primary beam corrections

- VLBA primary beam response not well known
- Needed for accurate flux density measurements, source counts
- Observations went beyond FWHM circle
- Tests at 1.6/1.4 GHz: use Airy disk, not Gaussian; residuals <5%





Primary beam measurements at 1.4 GHz vs best-fit Gaussian/Airy disk model

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Pilot project II: Lockman Hole/East

Primary beam corrections

- VLBA primary beam response not well known
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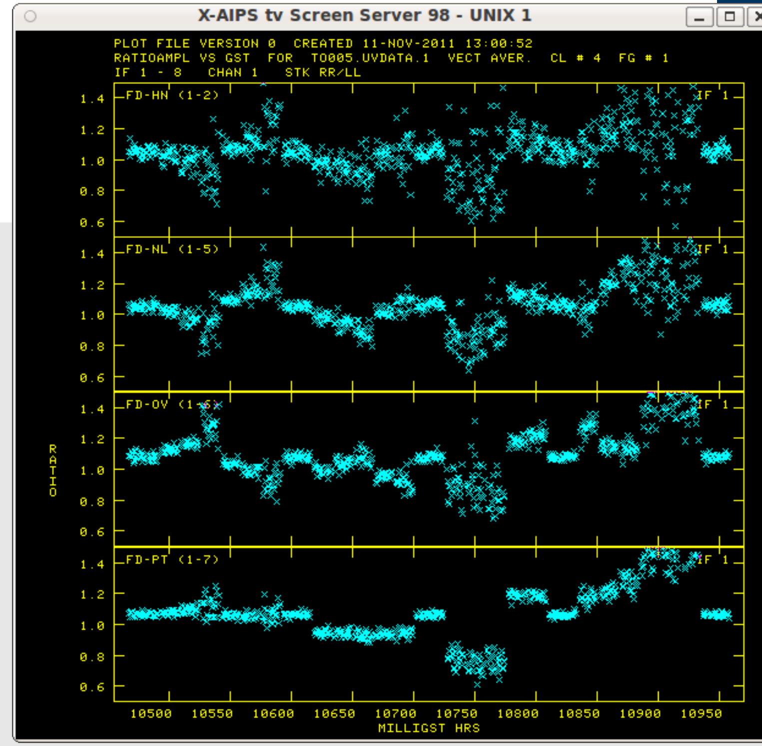
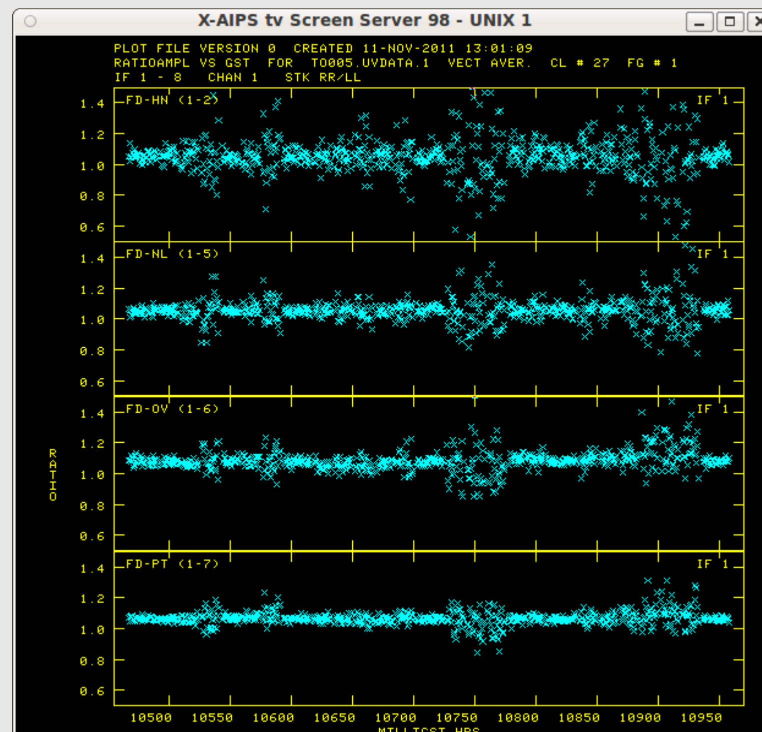
- Observations went beyond FWHM circle
- Tests at 1.6/1.4 GHz: use Airy disk, not Gaussian; residuals <5%
- Squint also taken care of





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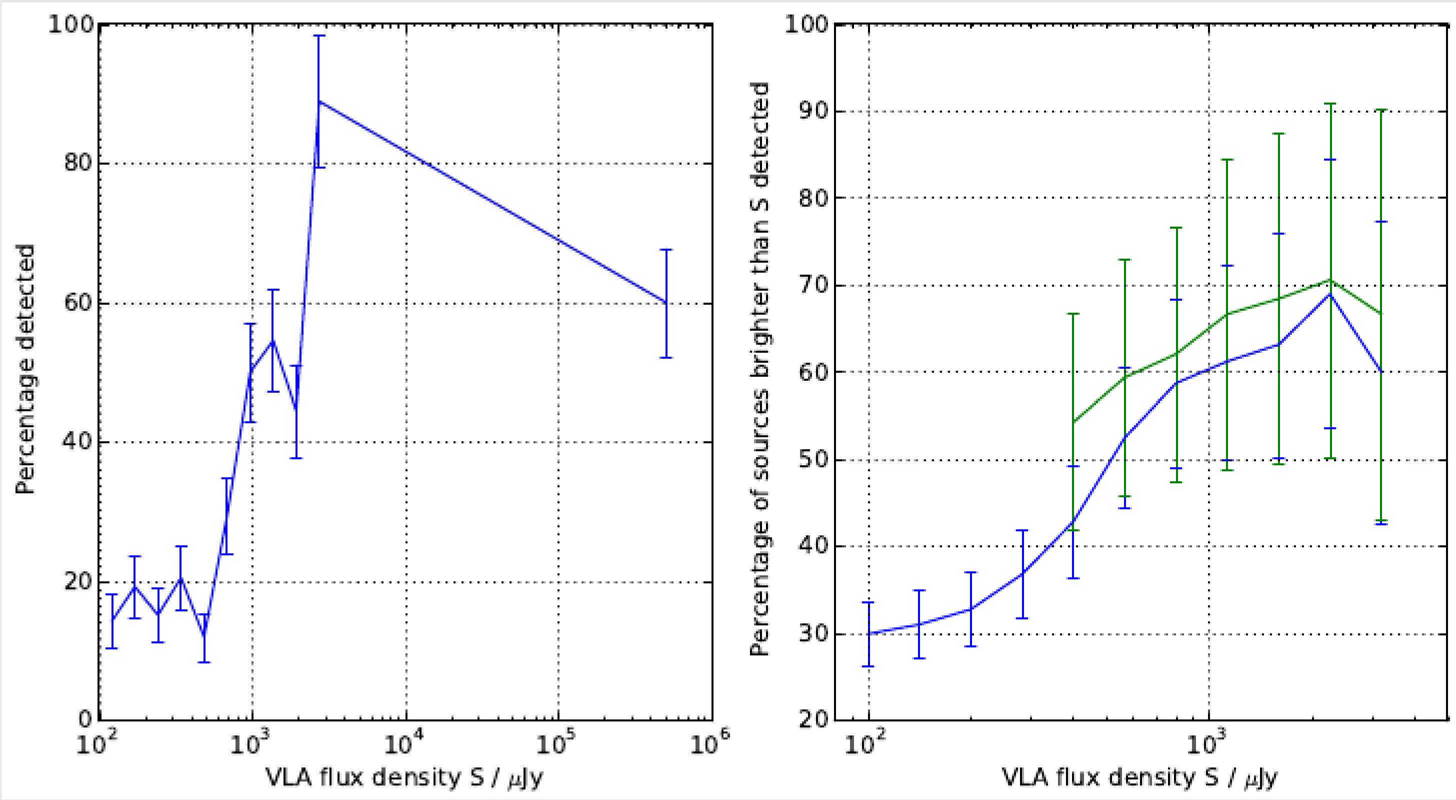
Pilot project II: Lockman Hole/East
Results

- Surprisingly large number of detected sources: 65 out of 217 (not 496)



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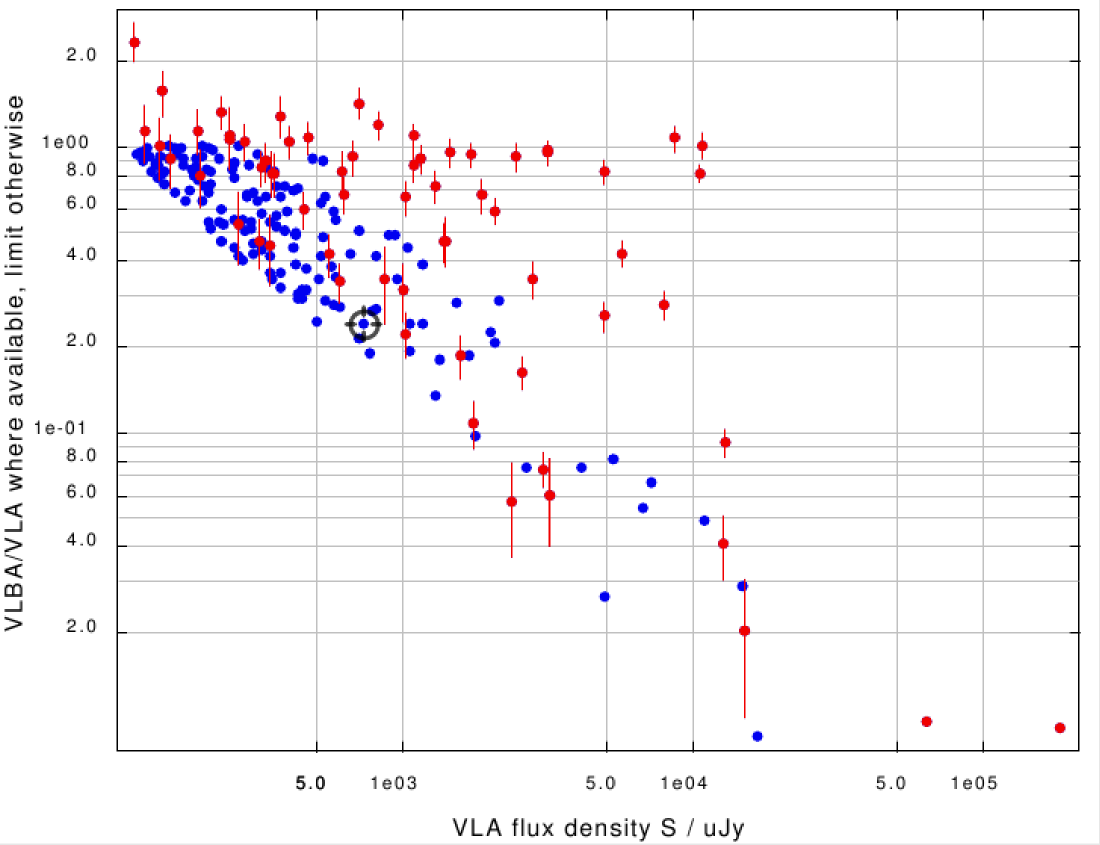
Pilot project II: Lockman Hole/East
Results

- Resolution bias: at low flux density levels, only the most compact objects are detected
- Some sources are variable



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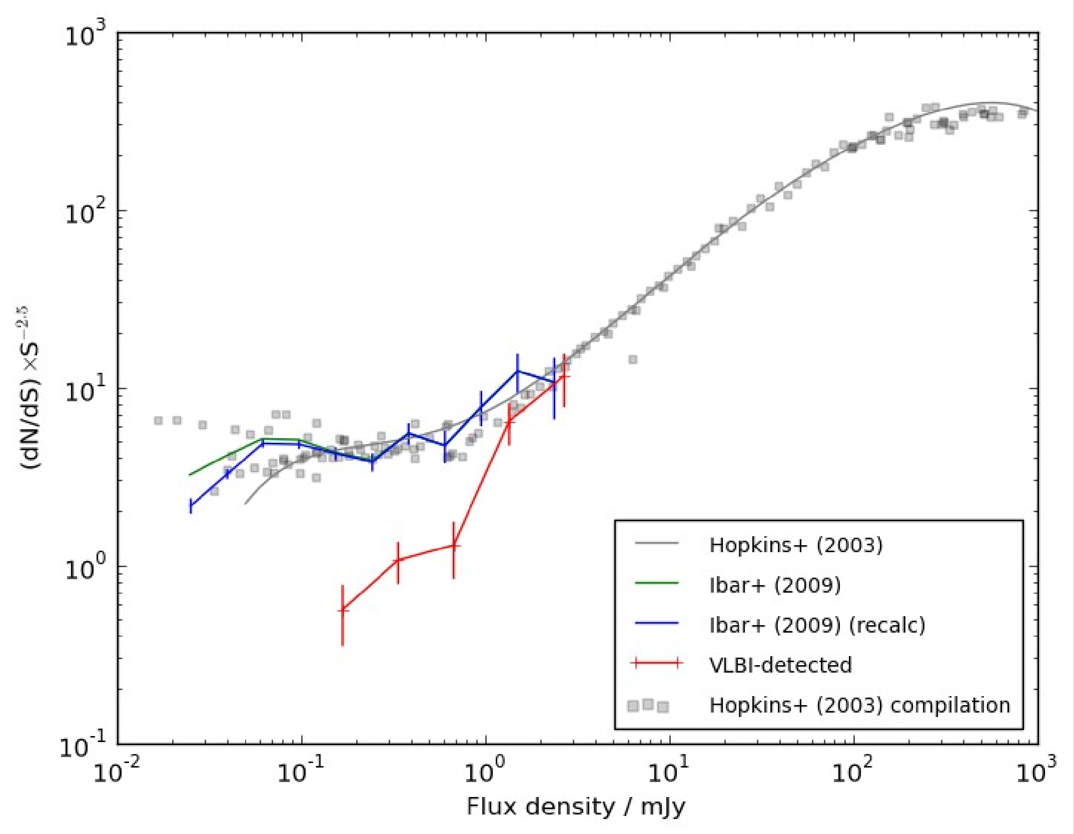
Pilot project II: Lockman Hole/East
Results

- Source counts – lower limit on the number of AGN
- Sub-mJy radio source population has a large fraction of AGN
- Faint end subject to resolution bias – but how much?



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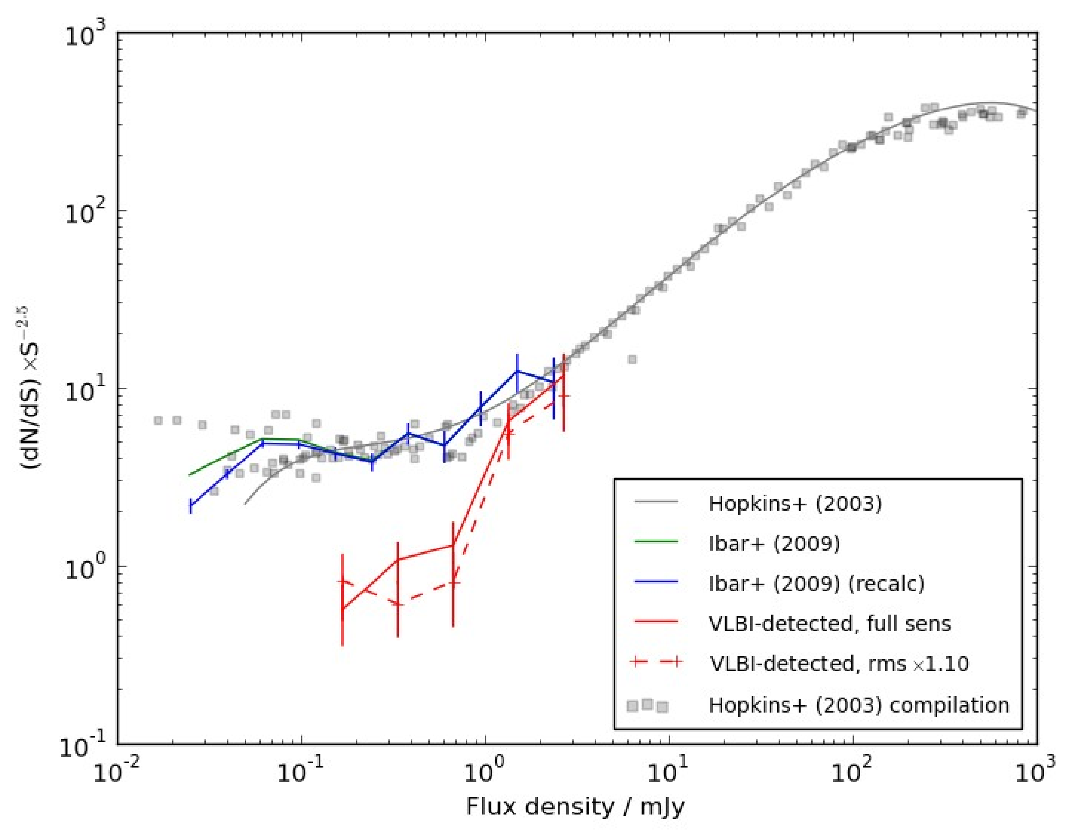
Pilot project II: Lockman Hole/East
Results

- Noise increased by 1.1



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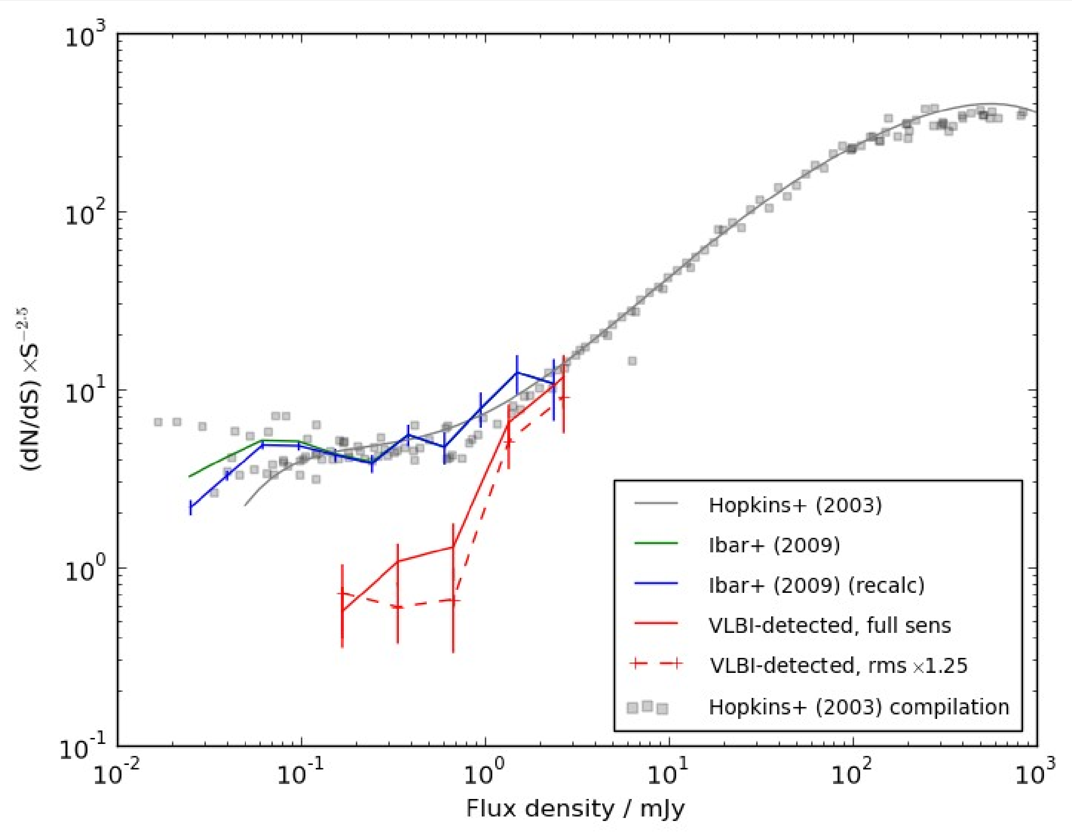
Pilot project II: Lockman Hole/East
Results

- Noise increased by 1.25



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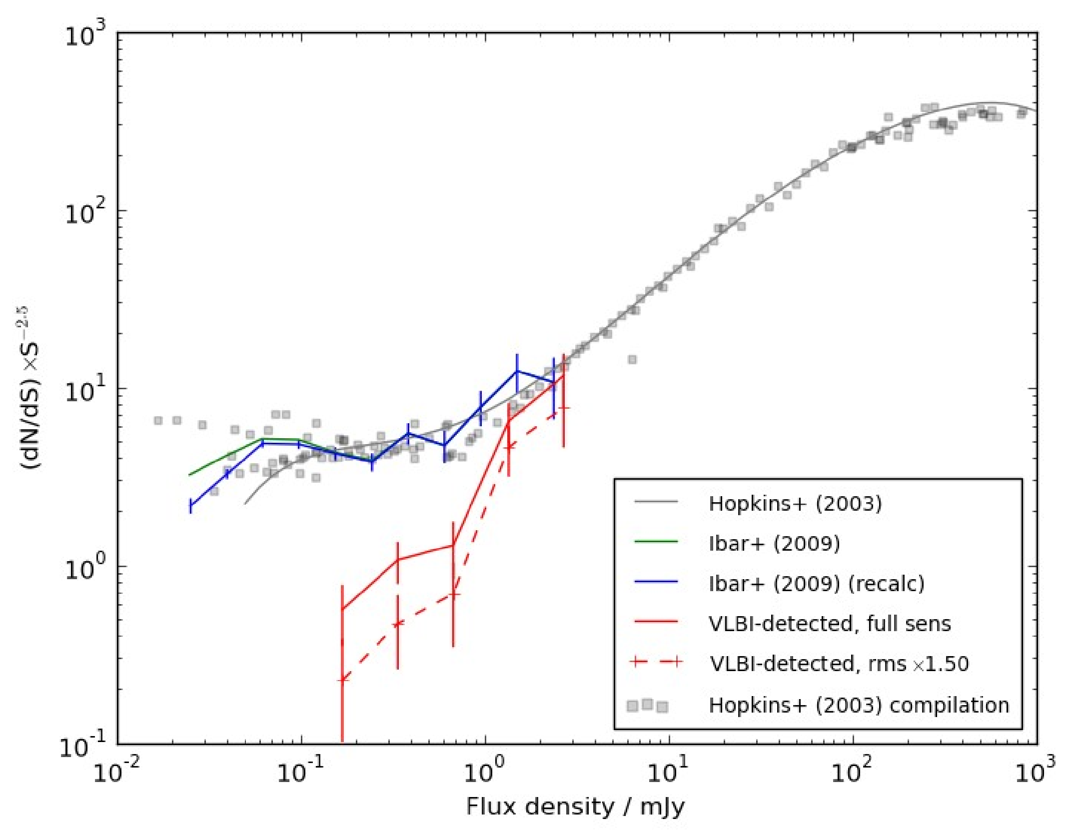
Pilot project II: Lockman Hole/East
Results

- Noise increased by 1.5



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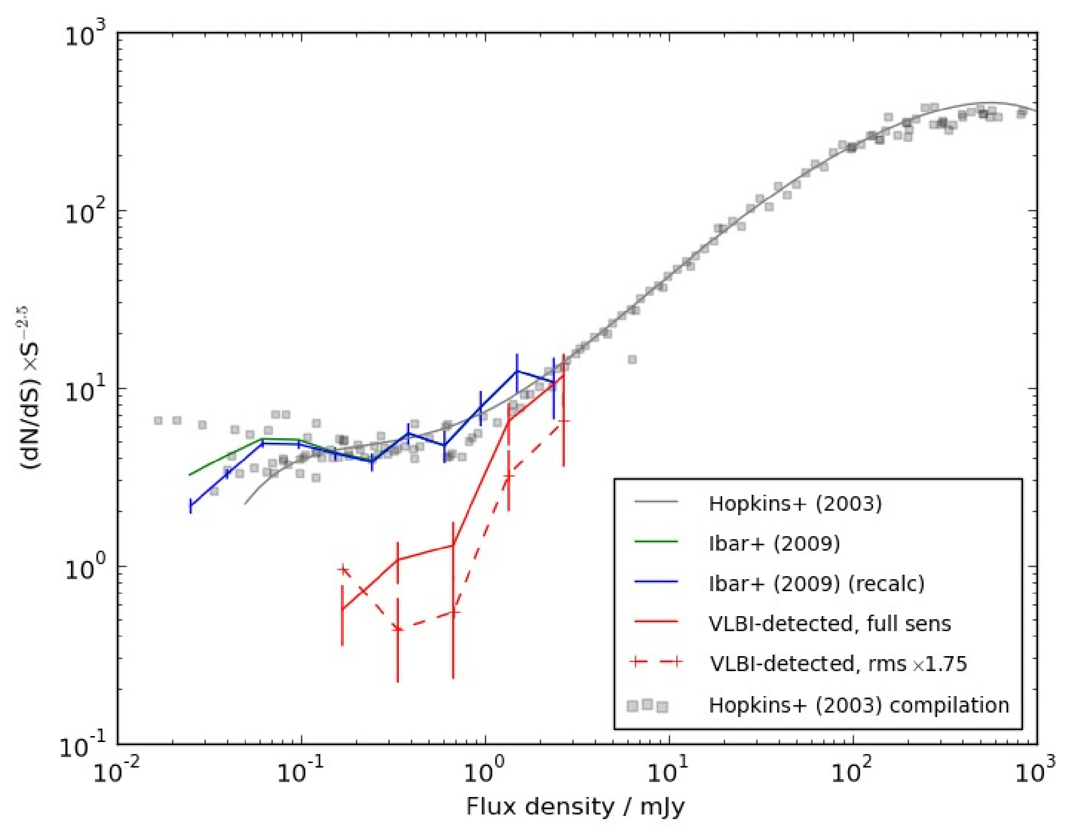
Pilot project II: Lockman Hole/East
Results

- Noise increased by 1.75



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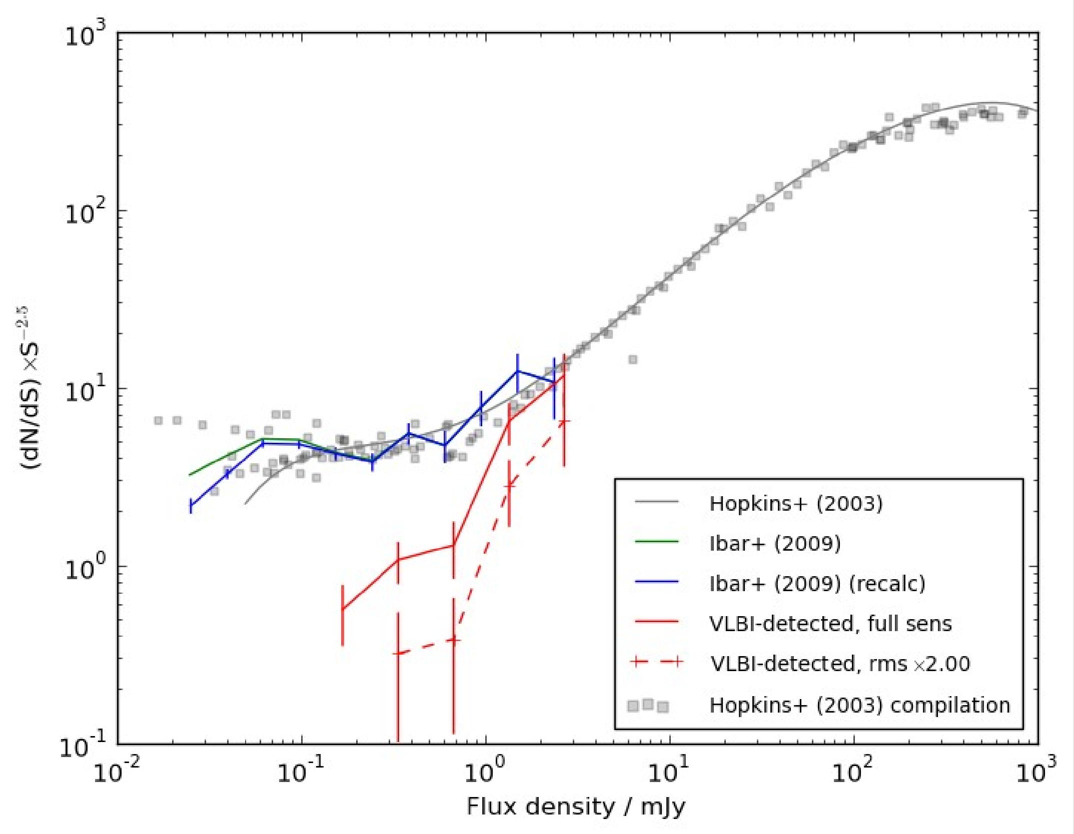
Pilot project II: Lockman Hole/East
Results

- Noise increased by 2.0



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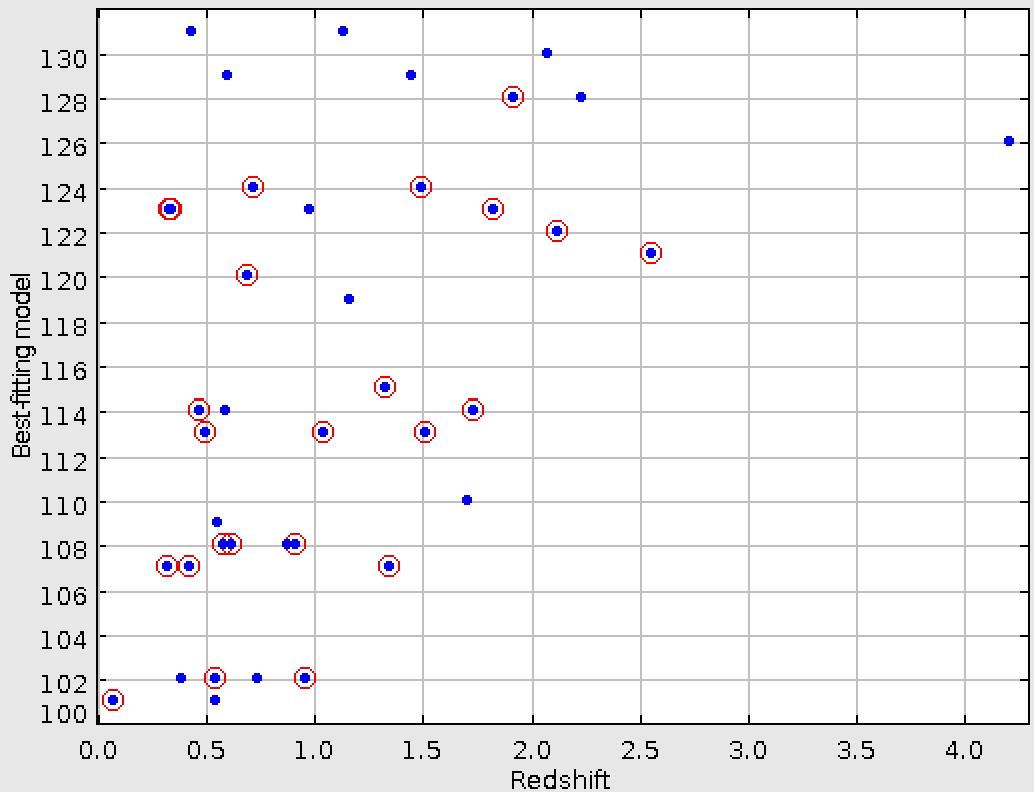
Pilot project II: Lockman Hole/East
Results

- Photo-z's and host types from Fotopoulou+ (2012)
  (this is still experimental and being worked on)

120-131: starbursts

108-119: spirals

101-107: ellipticals



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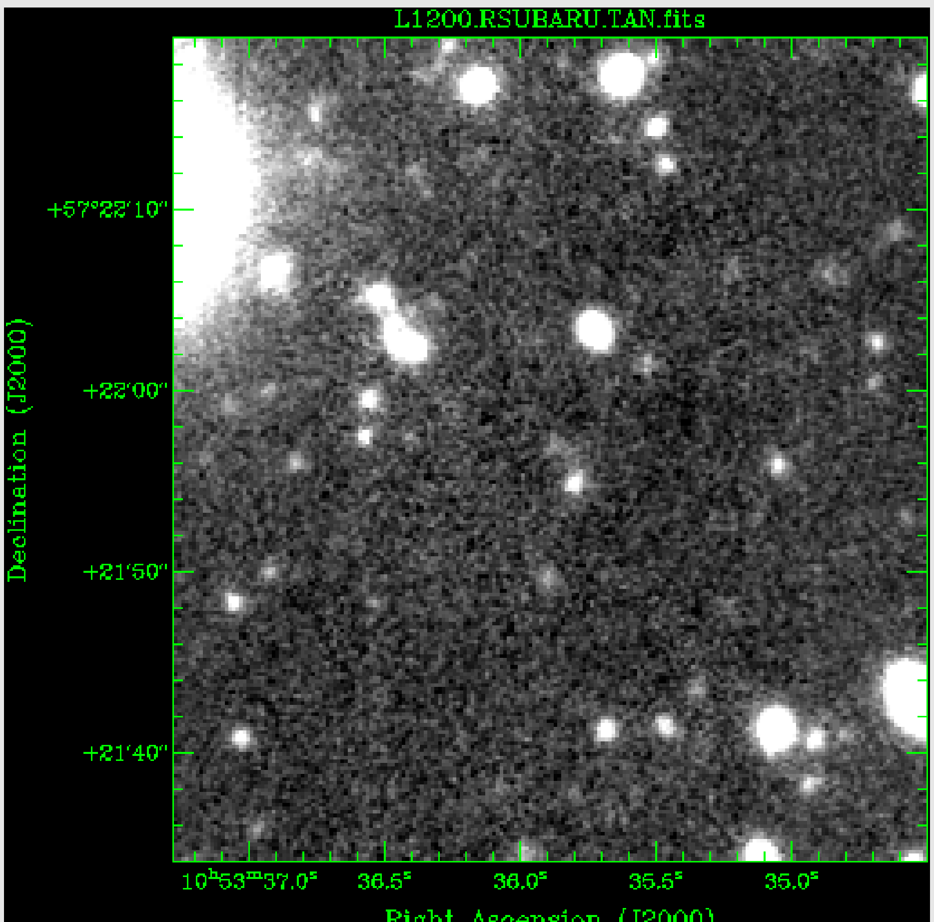
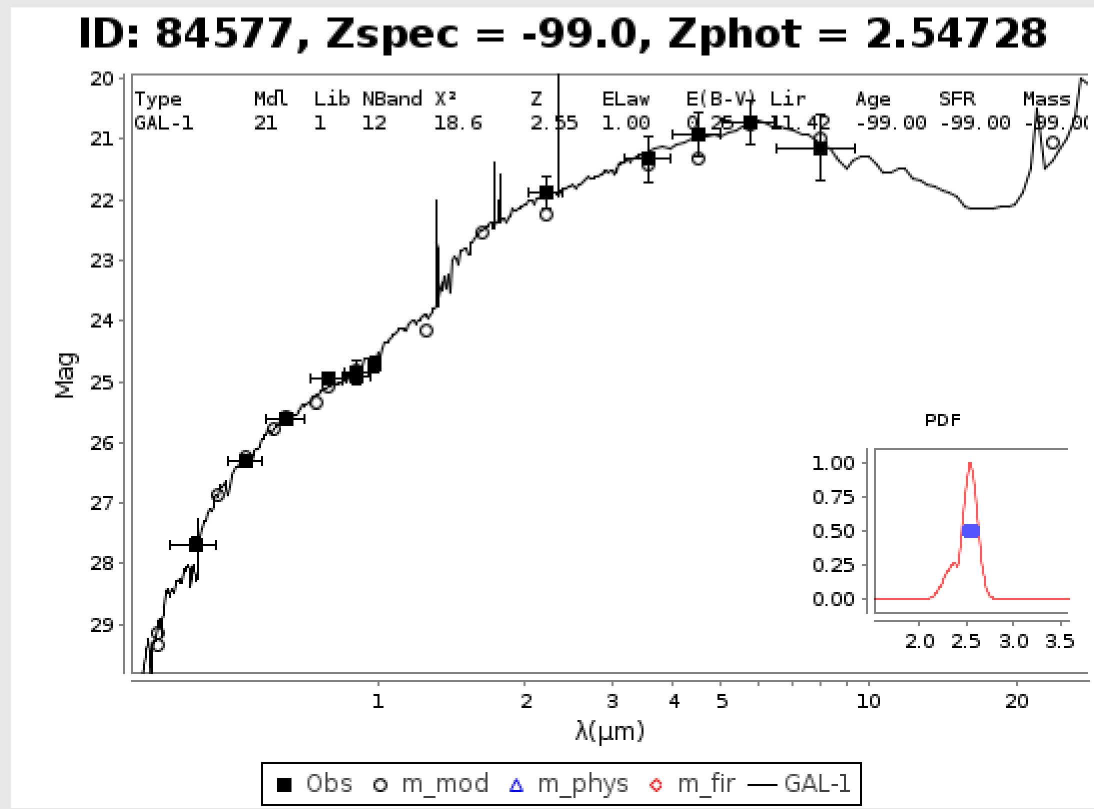
Pilot project II: Lockman Hole/East
Results

- Two nice examples: L1200 – faint, but clearly a starburst





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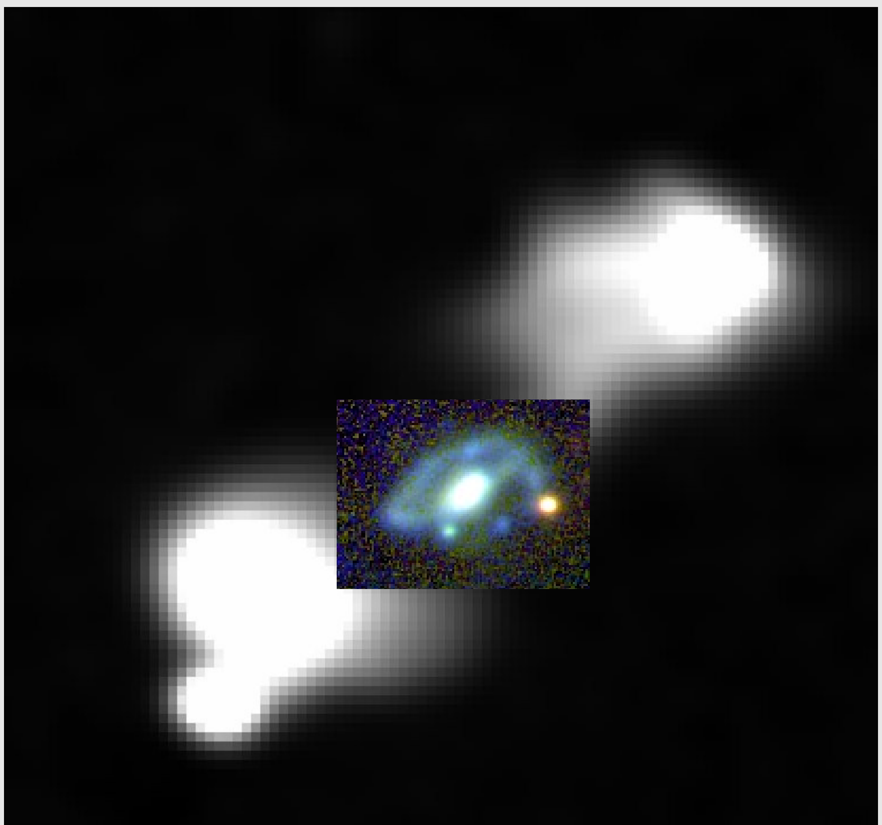
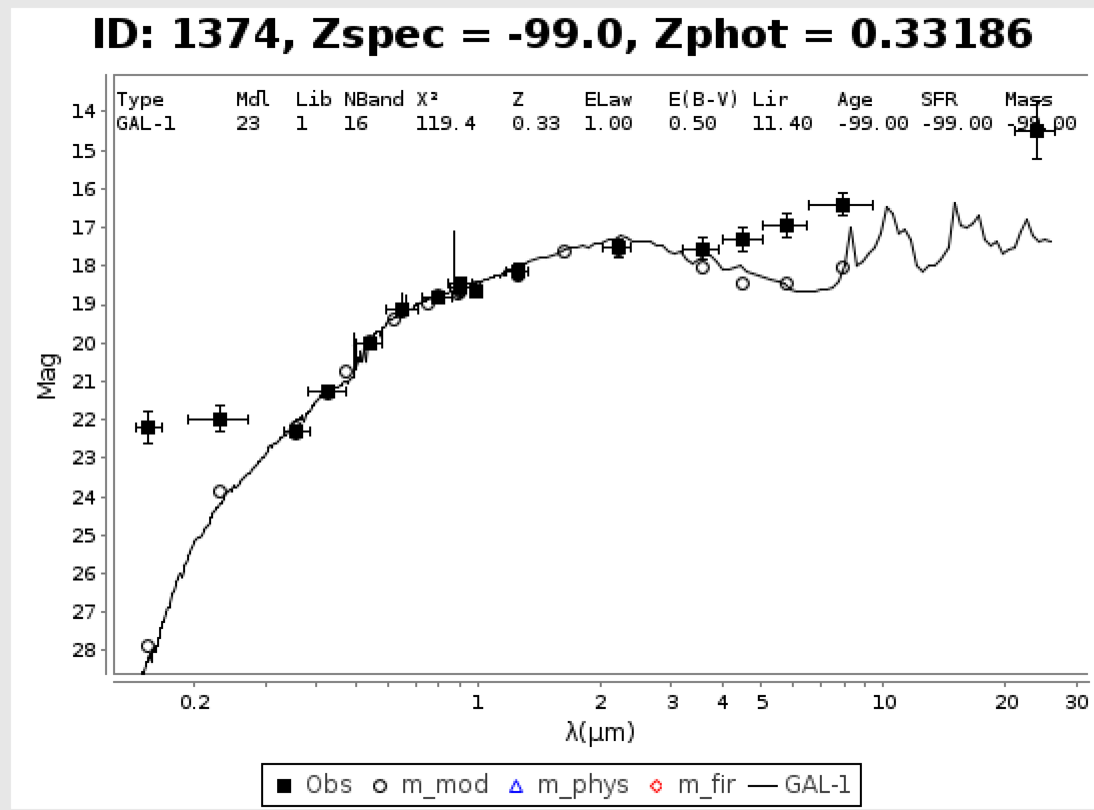
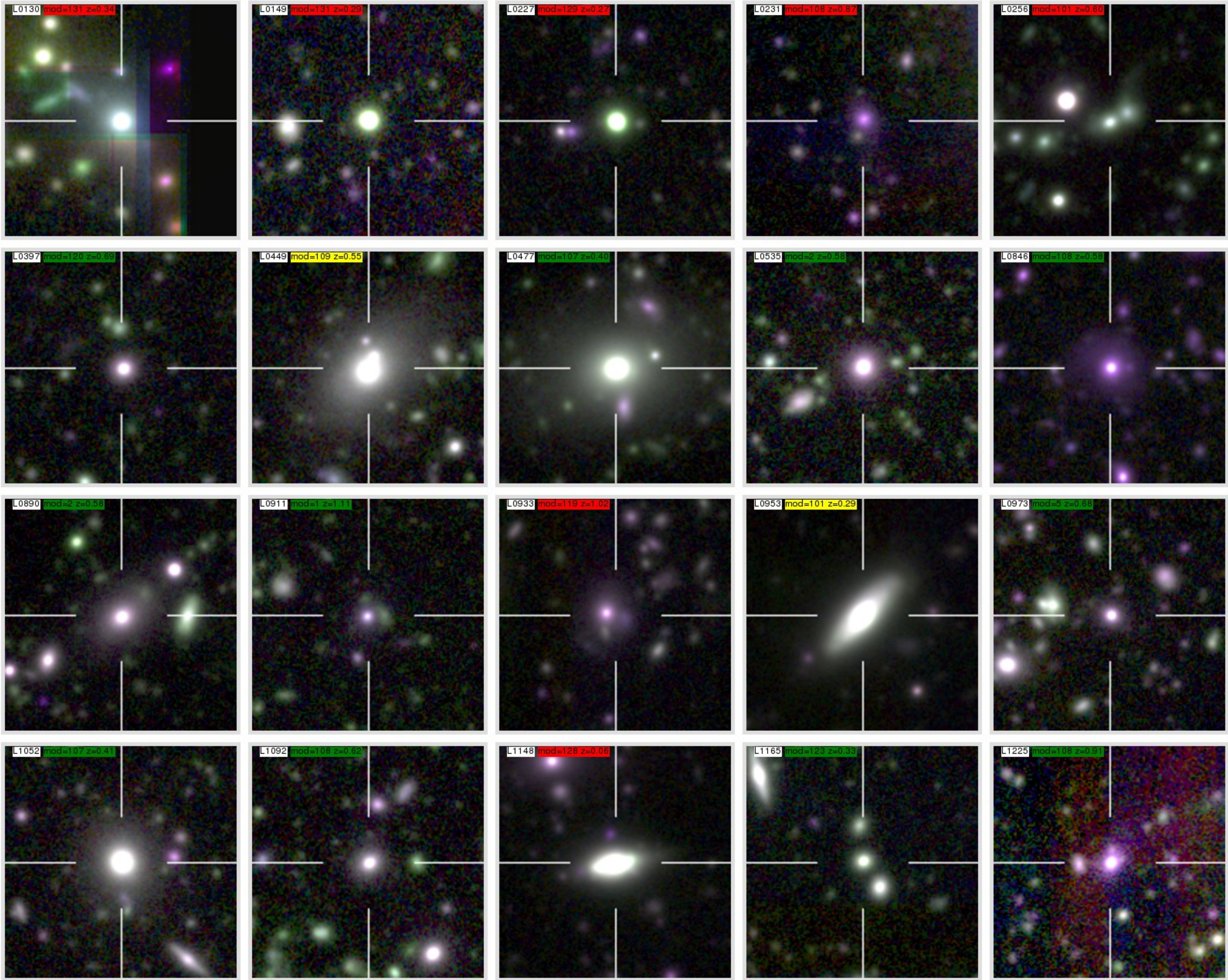
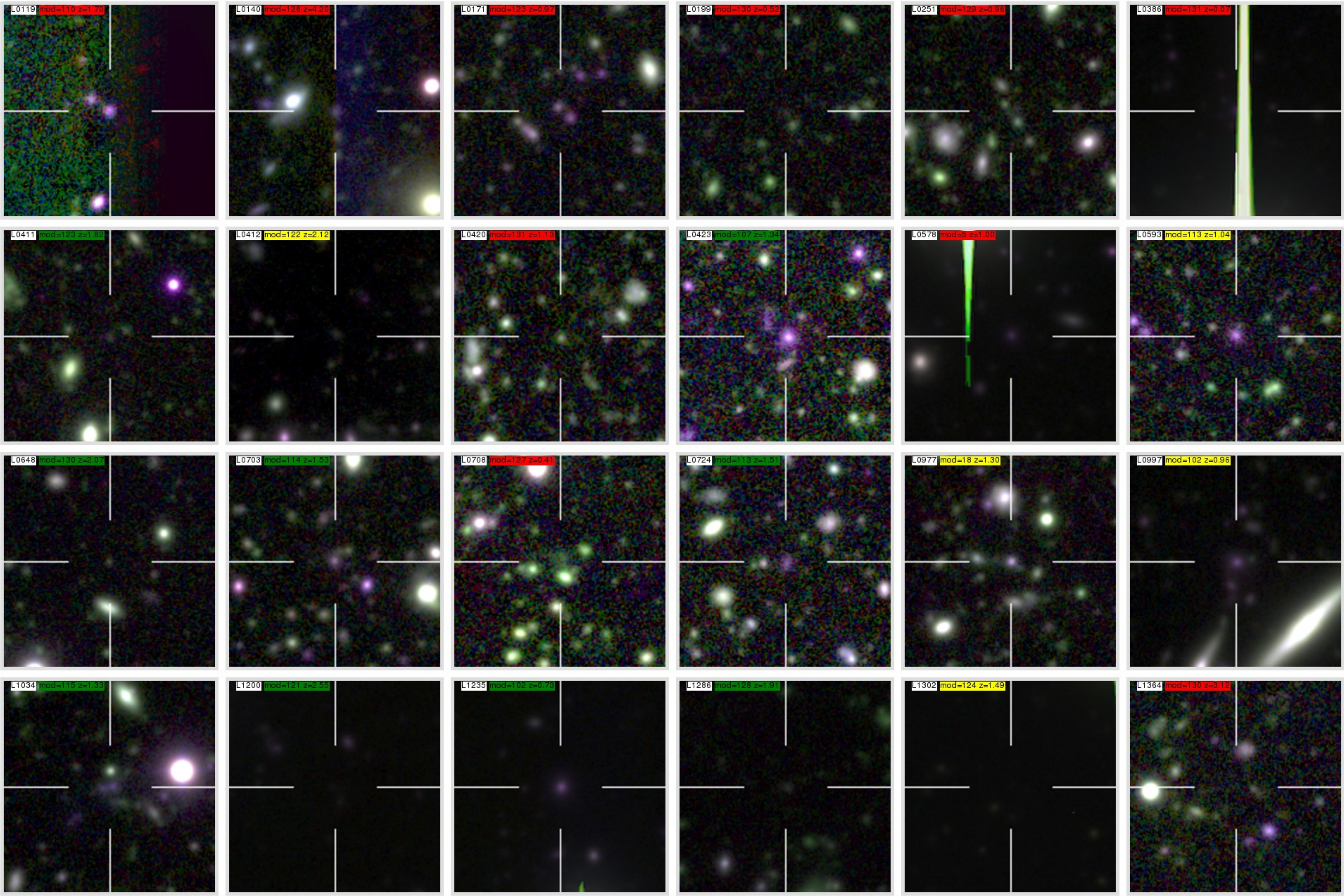
Pilot project II: Lockman Hole/East
Results

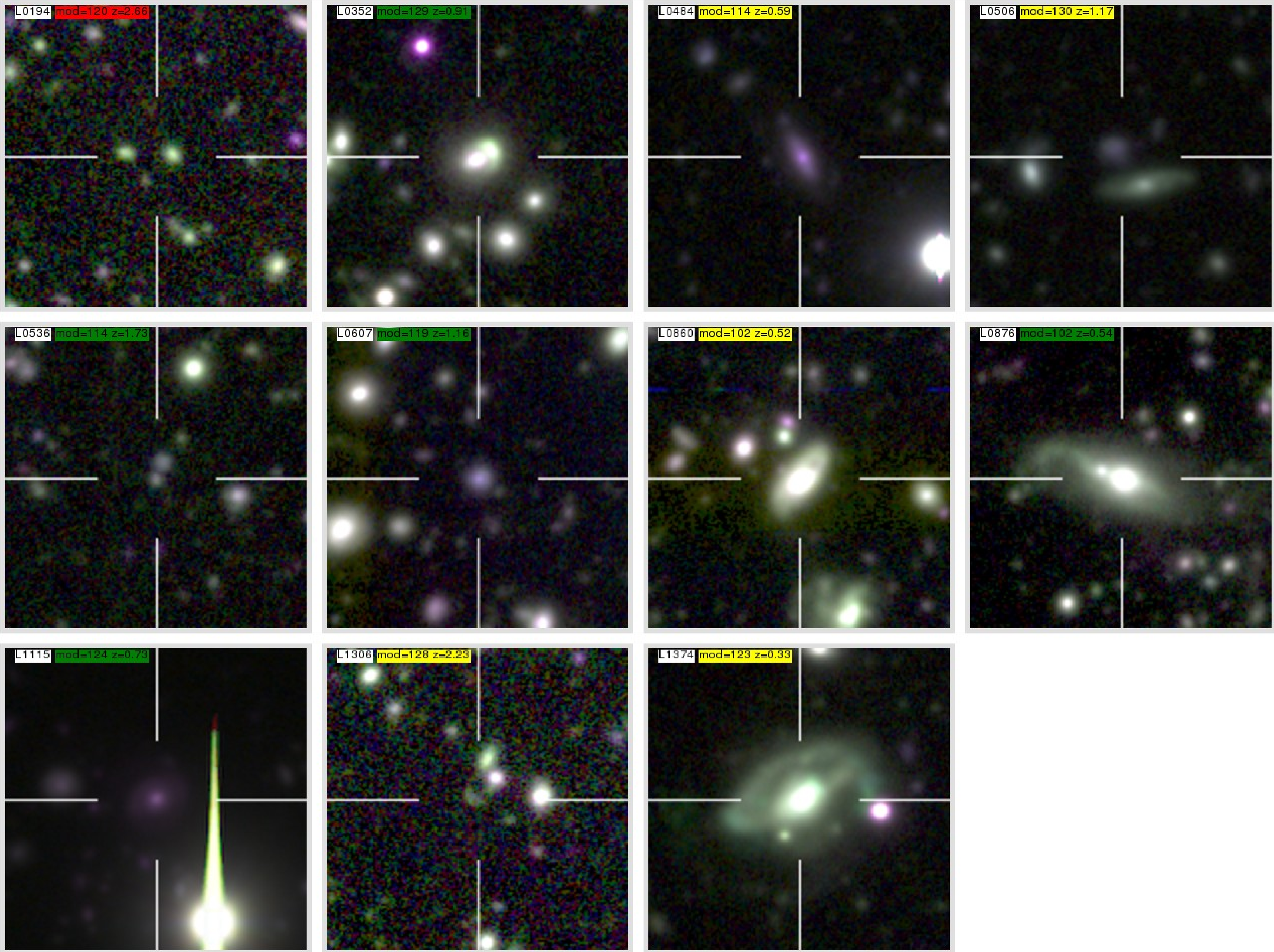
- Two nice examples: L1374 – double-lobed radio, complex optical, unclear spectral type






L0130 mod=131 z=0.34
L0149 mod=131 z=0.29
L0227 mod=129 z=0.27
L0231 mod=108 z=0.87
L0256 mod=101 z=0.80
L0397 mod=120 z=0.89
L0449 mod=109 z=0.55
L0477 mod=107 z=0.40
L0535 mod=2 z=0.58
L0846 mod=108 z=0.58
L0890 mod=2 z=0.58
L0911 mod=1 z=1.11
L0933 mod=119 z=1.02
L0953 mod=101 z=0.29
L0973 mod=5 z=0.68
L1052 mod=107 z=0.41
L1092 mod=108 z=0.62
L1148 mod=128 z=0.06
L1165 mod=123 z=0.33
L1225 mod=108 z=0.91


L0119 mod=110 z=1.70
L0140 mod=126 z=4.20
L0171 mod=123 z=0.97
L0199 mod=130 z=0.52
L0251 mod=129 z=0.96
L0386 mod=131 z=0.07
L0411 mod=123 z=1.82
L0412 mod=122 z=2.12
L0420 mod=131 z=1.13
L0423 mod=107 z=1.34
L0578 mod=5 z=1.00
L0593 mod=113 z=1.04
L0648 mod=130 z=2.07
L0703 mod=114 z=1.53
L0708 mod=127 z=0.41
L0724 mod=113 z=1.51
L0977 mod=18 z=1.30
L0997 mod=102 z=0.96
L1034 mod=115 z=1.33
L1200 mod=121 z=2.55
L1235 mod=102 z=0.73
L1286 mod=128 z=1.91
L1302 mod=124 z=1.49
L1364 mod=130 z=3.12


L0194 mod=120 z=2.66
L0352 mod=129 z=0.91
L0484 mod=114 z=0.59
L0506 mod=130 z=1.17
L0536 mod=114 z=1.73
L0607 mod=119 z=1.16
L0860 mod=102 z=0.52
L0876 mod=102 z=0.54
L1115 mod=124 z=0.73
L1306 mod=128 z=2.23
L1374 mod=123 z=0.33

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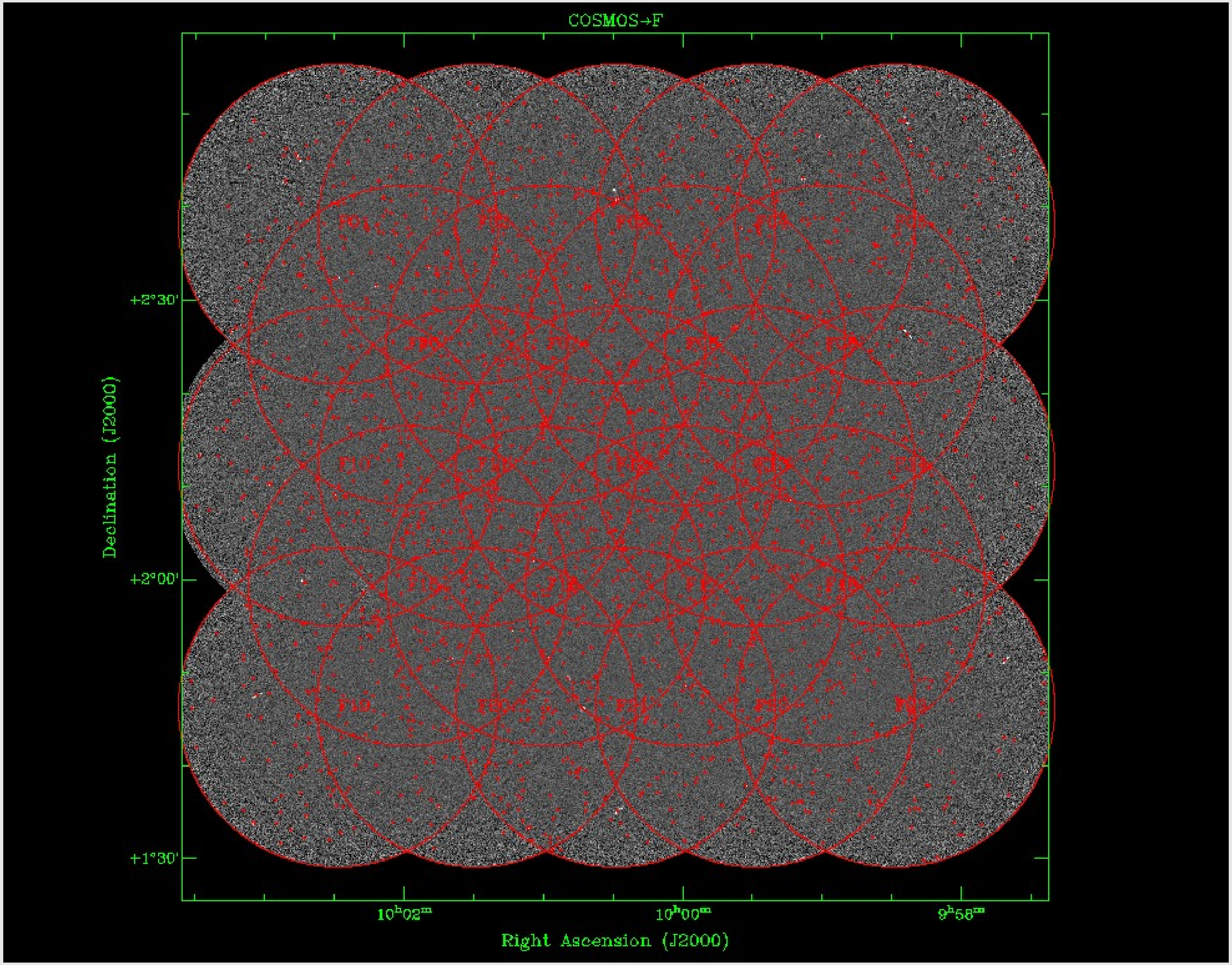
The real thing: ~2900 sources in the COSMOS field @10uJy rms



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Conclusions

- Wide-field VLBI now practical and relatively painless (you can do it!)
- Multi-source selfcal opens up *entire* sky for VLBI imaging
- Primary beam corrections ok, improvements to come
- Complementing large radio surveys (FIRST, COSMOS, SKA pathfinder surveys) is feasible

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Conclusions

- Wide-field VLBI now practical and relatively painless (you can do it!)
- Multi-source selfcal opens up *entire* sky for VLBI imaging
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- Complementing large radio surveys (FIRST, COSMOS, SKA pathfinder surveys) is feasible

- Everything indicates that there are a *lot* more AGN than we thought
- Fraction could be as high as 30% at 50uJy...1mJy (or higher?)
- A substantial fraction of which is *not* in „ellipticals"
- Using wide-field VLBI one discovers new AGN even in the best-studied areas of the sky