Cosmology

EVN Future Visions meeting (Zaandam)

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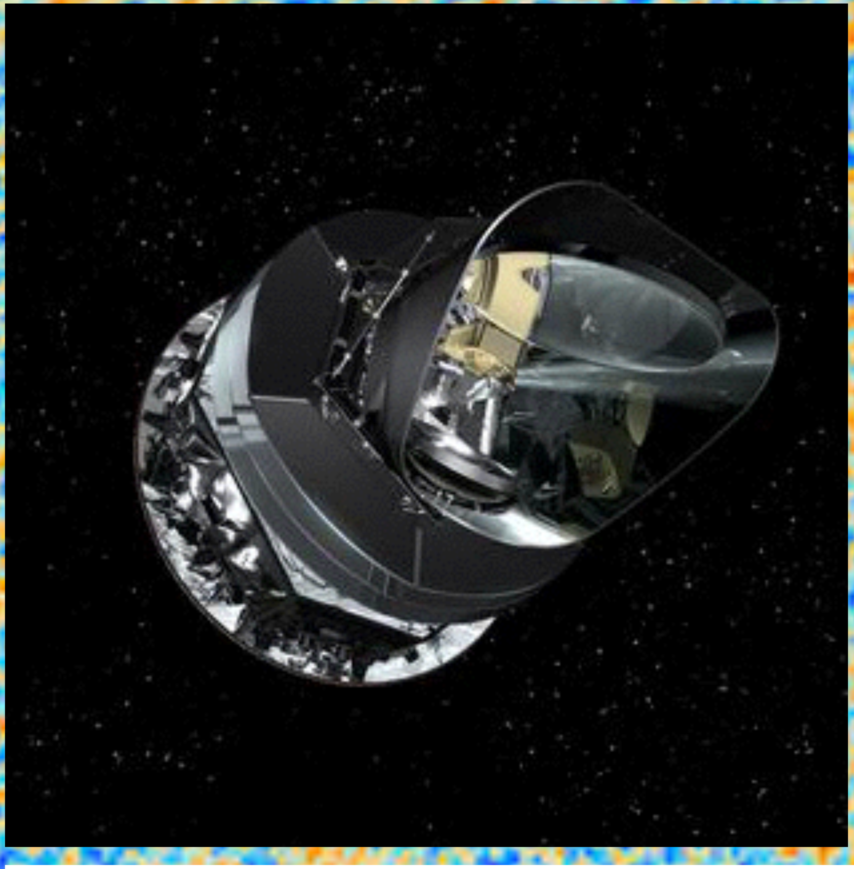
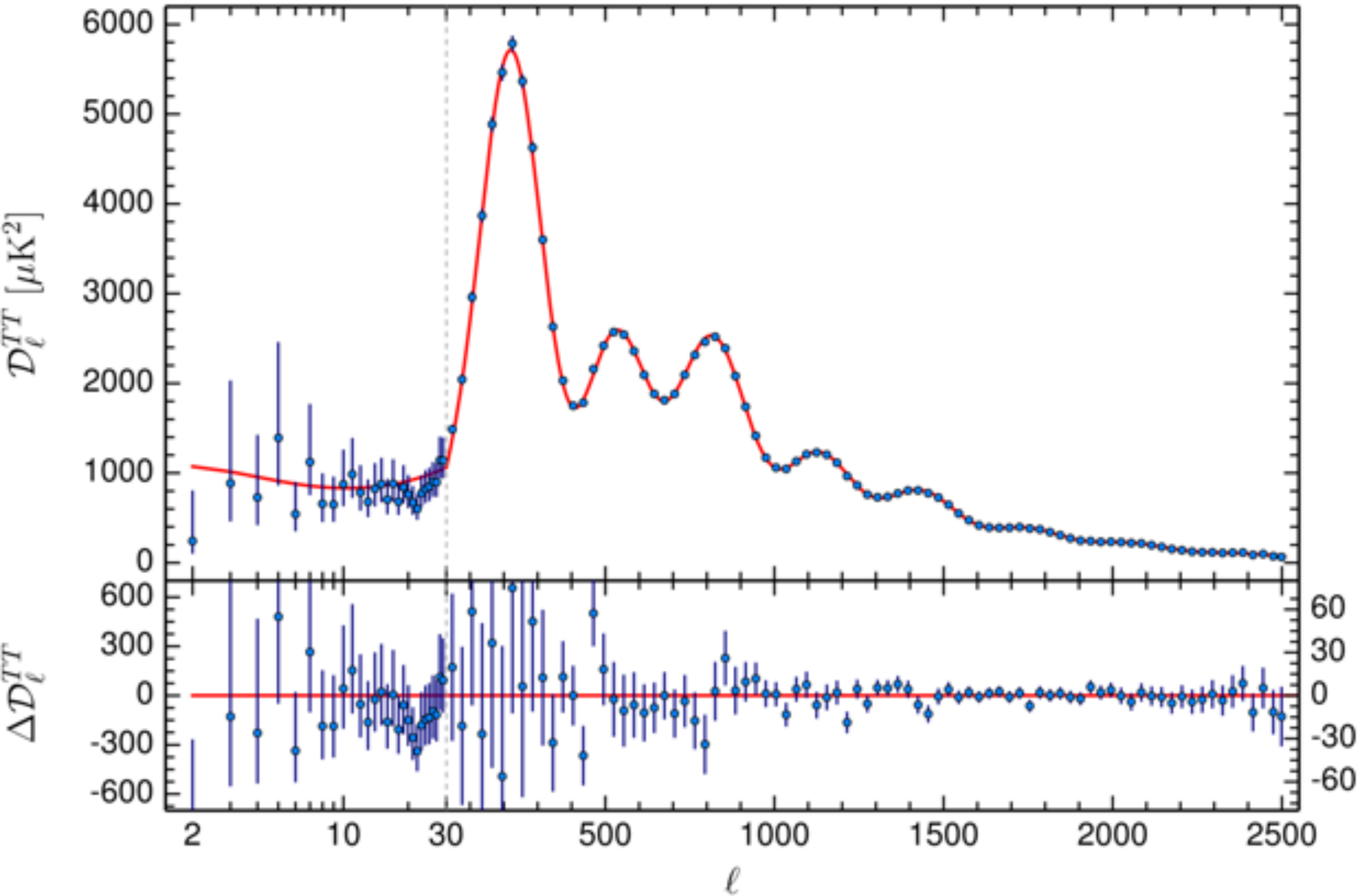




Parameter	TT+lowP 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10}A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_Λ	0.685 ± 0.013
Ω_m	0.315 ± 0.013
$\Omega_m h^2$	0.1426 ± 0.0020
$\Omega_m h^3$	0.09597 ± 0.00045
σ_8	0.829 ± 0.014
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013
z_{re}	$9.9^{+1.8}_{-1.6}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014
Age/Gyr	13.813 ± 0.038
z_*	1090.09 ± 0.42
r_*	144.61 ± 0.49
$100\theta_*$	1.04105 ± 0.00046
z_{drag}	1059.57 ± 0.46
r_{drag}	147.33 ± 0.49
k_D	0.14050 ± 0.00052
z_{eq}	3393 ± 49
k_{eq}	0.01035 ± 0.00015
$100\theta_{s,eq}$	0.4502 ± 0.0047
f_{2000}^{143}	29.9 ± 2.9
$f_{2000}^{143\times217}$	32.4 ± 2.1
f_{2000}^{217}	106.0 ± 2.0

Dark energy and dark matter

Key questions:

1) What is dark energy?
2) What is dark matter?

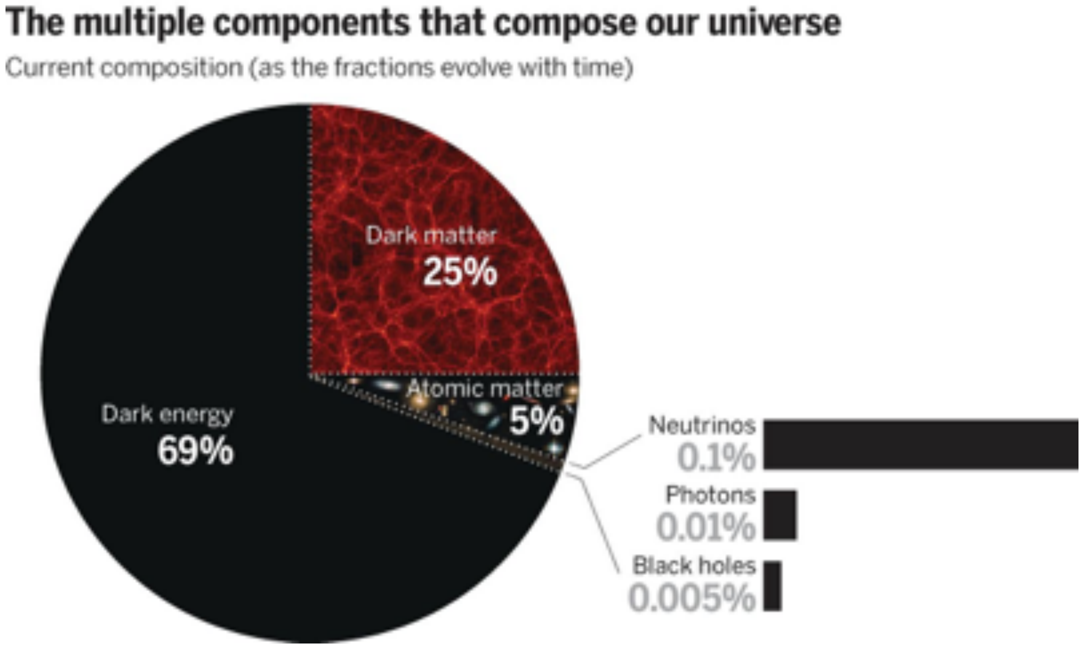
Large surveys aimed to answer these question (LSST, DES, *Euclid*).

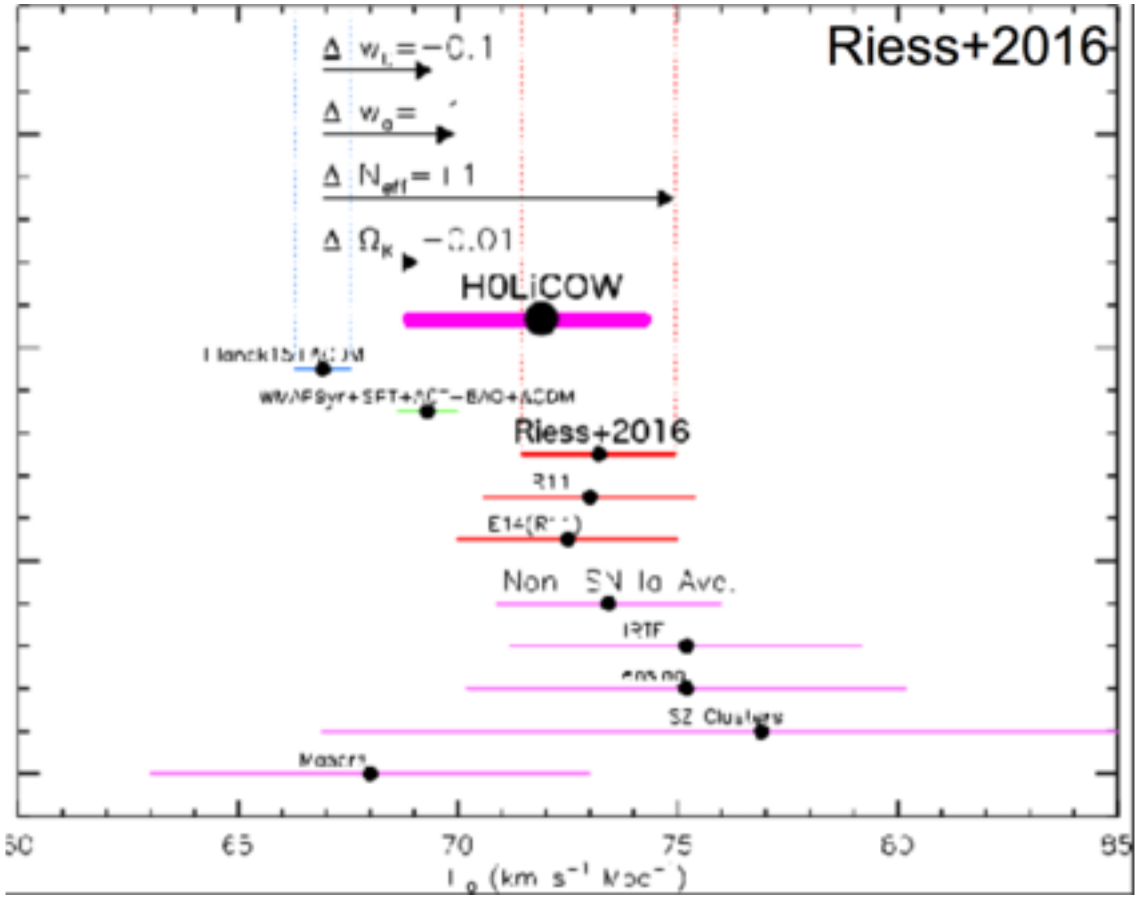
Can very long baseline interferometry answer these questions?

The key issue is being **competitive** (small error bars) and **independent** (different systematics).

Key observables:

1) Angular diameter distance (standard rulers, e.g. masers, lenses)
2) Luminosity distances (standard candels, SN1a, FRBs?, GW?)

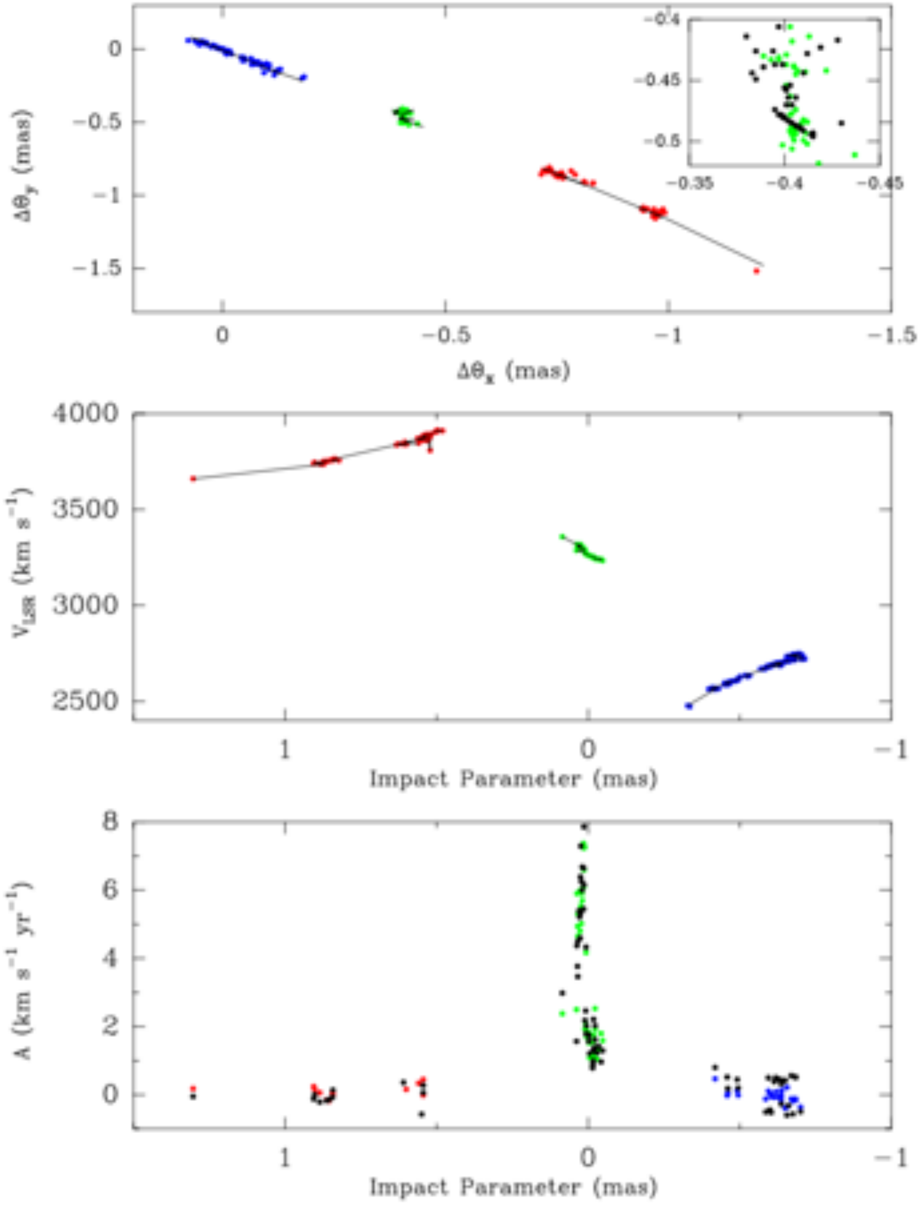


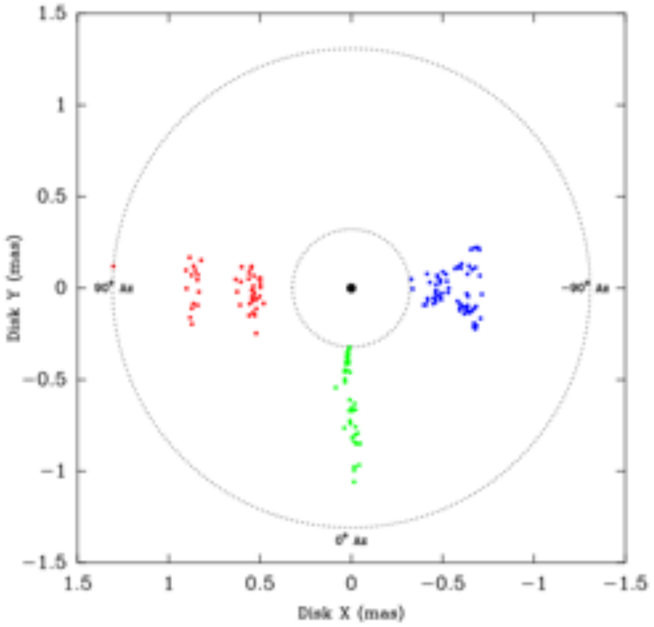


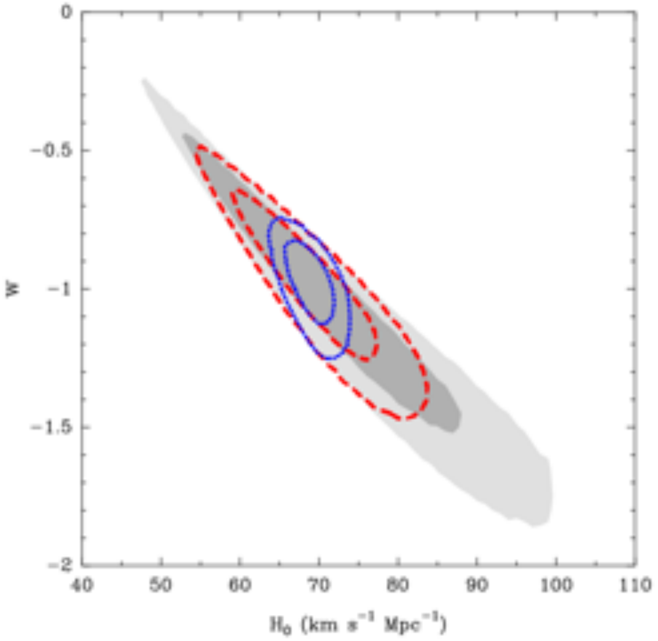
Dark energy: Probing cosmology **masers**

Proof of concept demonstrated by the NRAO key science programme: Megamaser Cosmology Project (MCP; PI Jim Braatz).

Targets 22.2 GHz water masers in disk galaxies with GBT and VLBA.



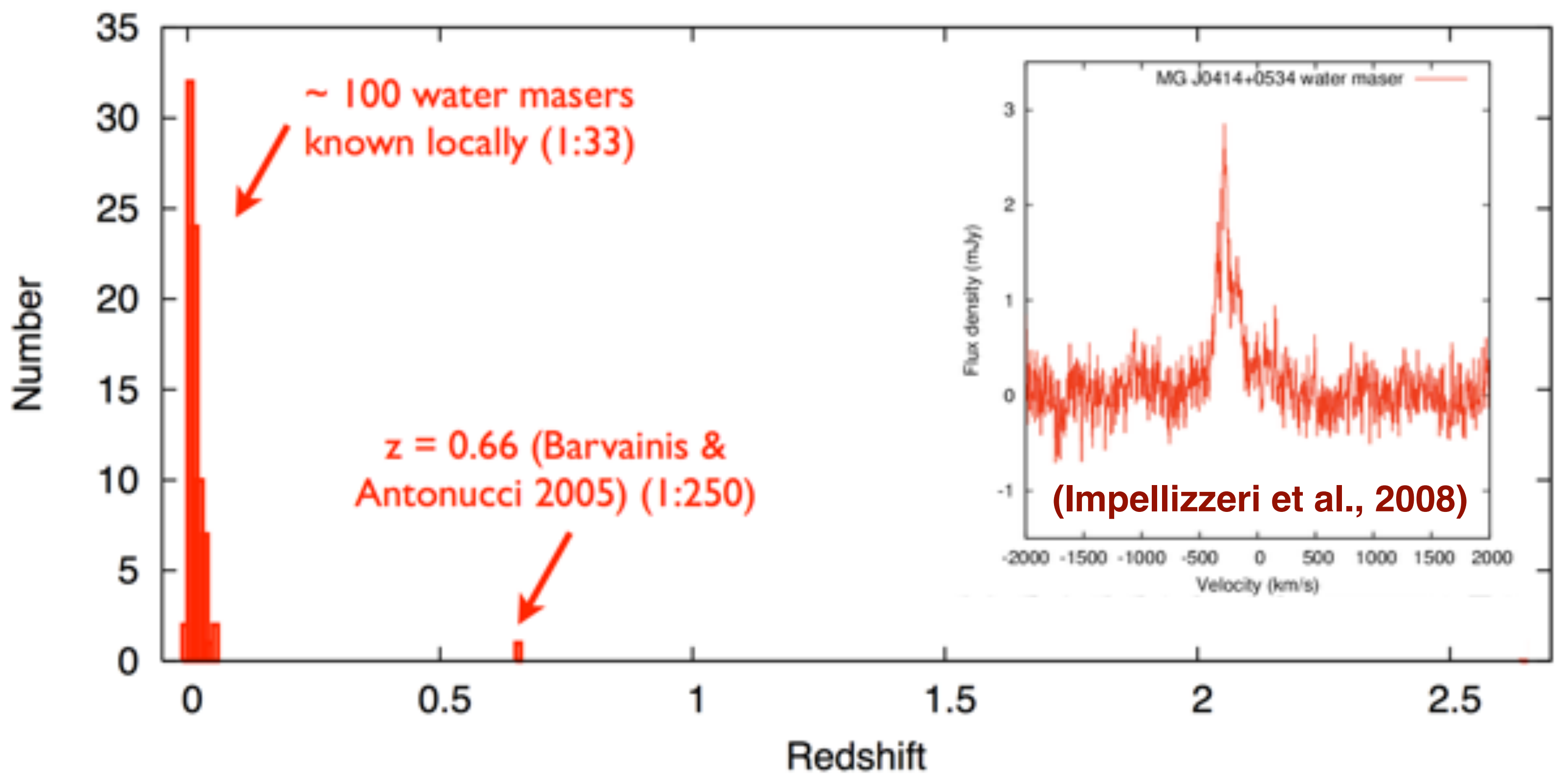




Only weakly constrains *w* (low redshifts) and may be limited systematics (e.g. BH proper motions, relative to the galaxy systemic velocity) at the few % level.

Dark energy: Probing cosmology **masers**

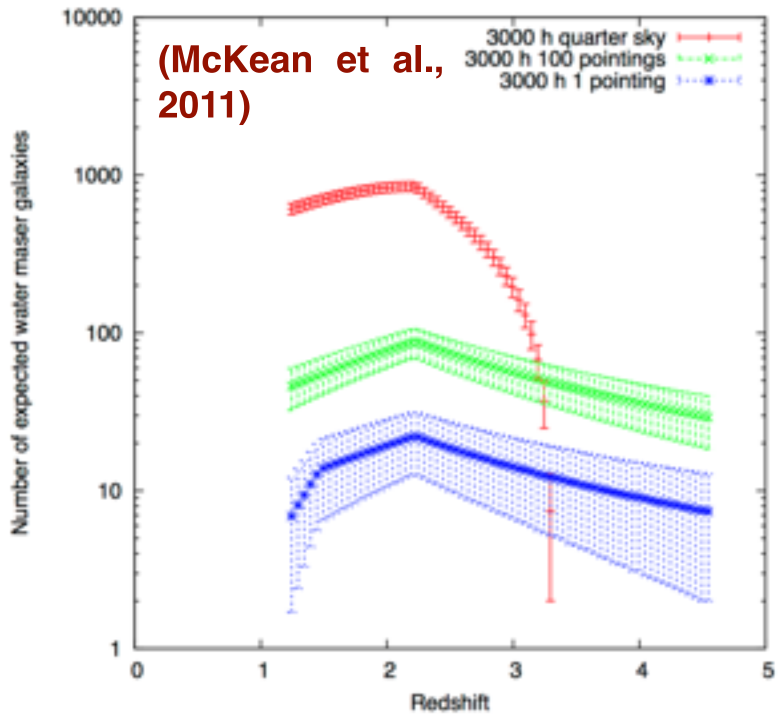
Need to find masers at higher redshift to constrain *w*.


~ 100 water masers known locally (1:33)

z = 0.66 (Barvainis & Antonucci 2005) (1:250)

(Impellizzeri et al., 2008)

SKA-Phase 2

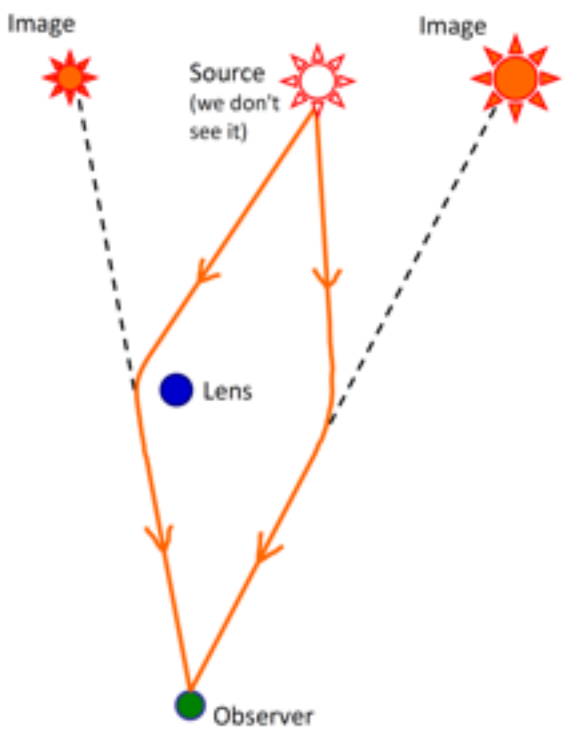

(McKean et al., 2011)

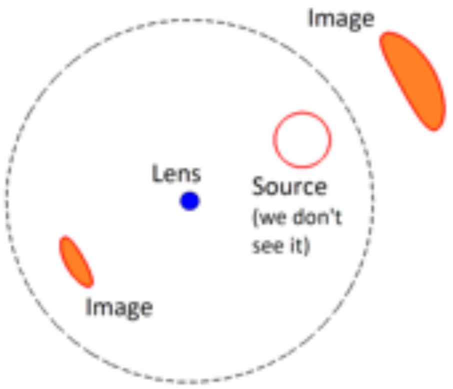
Key issues:

1. What is the detectability of water masers at $0.1 < z < 1$ with the SKA/MeerKAT? (sensitivity, frequency coverage, sky area).
2. What is the angular resolution needed? (at $z = 0.5$, 1 mas is 6 pc / at 15 GHz gVLBI has res. 0.2 mas)

Independent constraints on DE, but simulations needed to test feasibility

Dark energy: Probing cosmology **lensing**





Proof of concept demonstrated by the HOliCOW team, using quasar time-delays and sophisticated lens modelling.

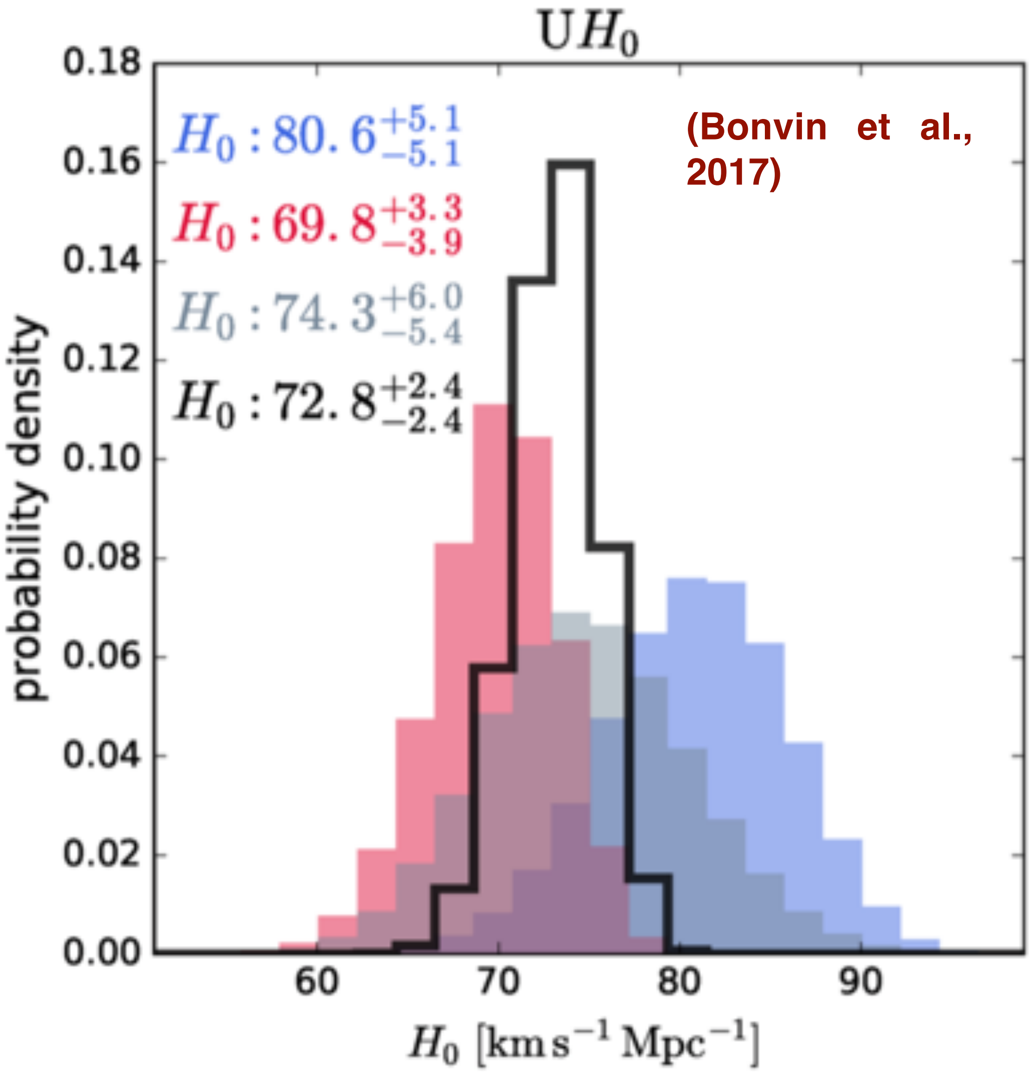
$$\tau = \frac{(1+z_d)}{c}\,\frac{D_d D_s}{D_{ls}}\left[\frac{1}{2}(\theta-\beta)^2 - \psi(\theta)\right]$$

First measurements with radio (monitoring VLA; mass models constraints MERLIN, VLBI).

Current best constraints from optical monitoring and HST/Keck-adaptive optics (65-100 mas).

Can we find more suitable lenses in the radio with e.g. SKA, wide-field VLBI?

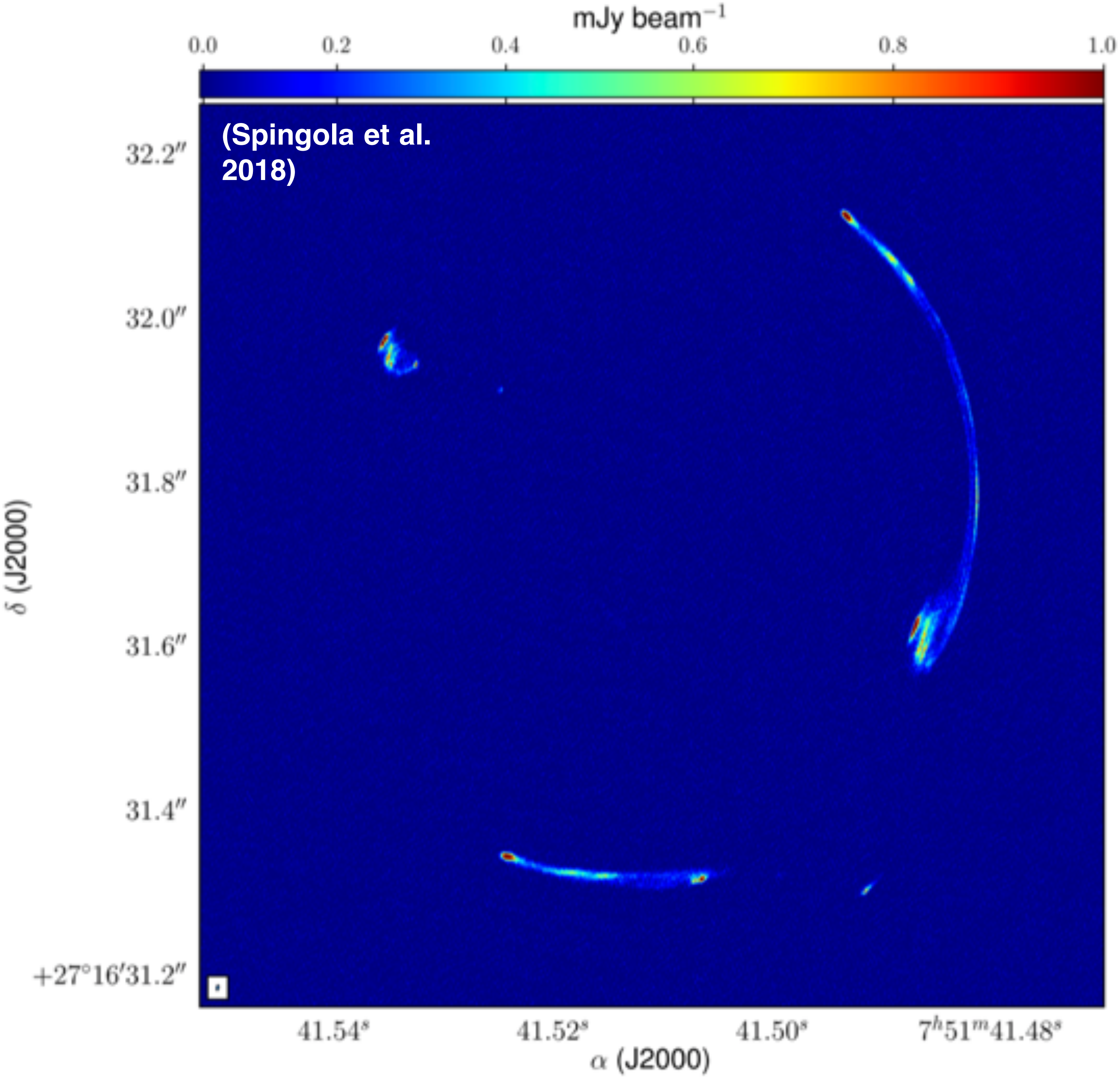
Can VLBI provide model constraints to be competitive/test for systematics?



(Bonvin et al., 2017)

Dark energy: Probing cosmology **lensing**

VLBI can detect extended structure on mas-scales providing detailed test of mass models.



To be interesting for a large number of (fainter) systems, sensitivities and image fidelity will need to improve by at least an order of magnitude.

Larger bandwidths, more telescopes (AVN; MeerKAT; SKA).

Dark energy and dark matter

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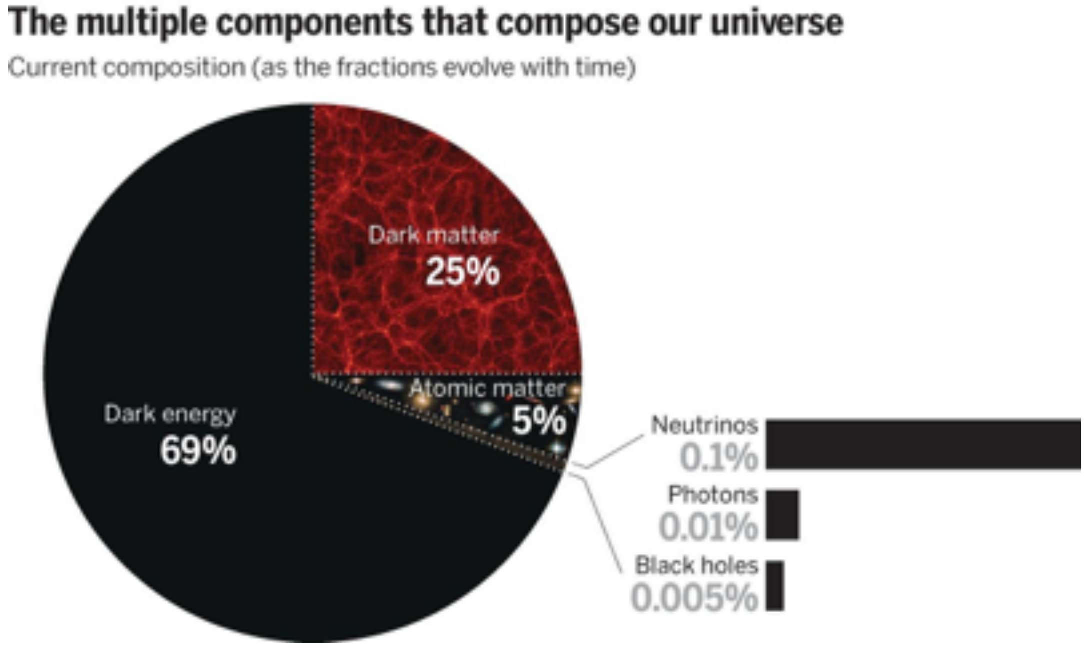
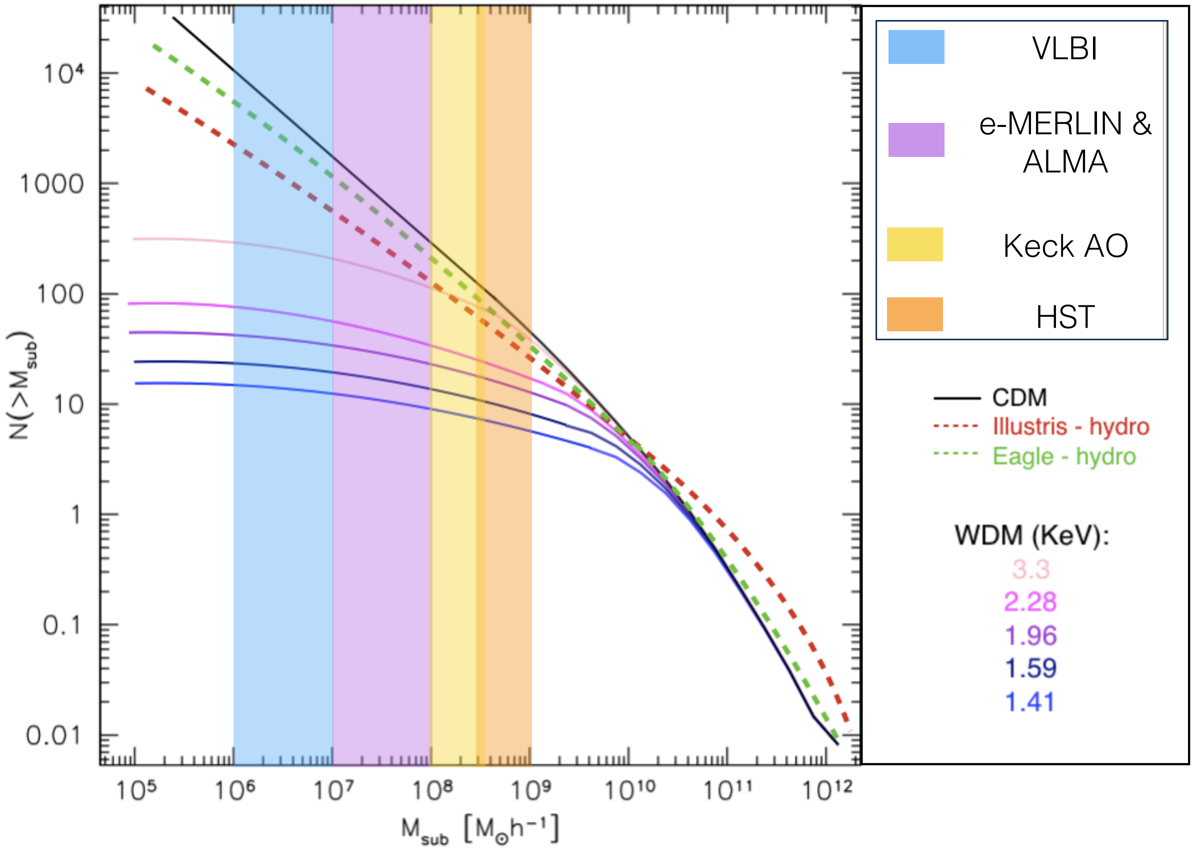
Key observables:

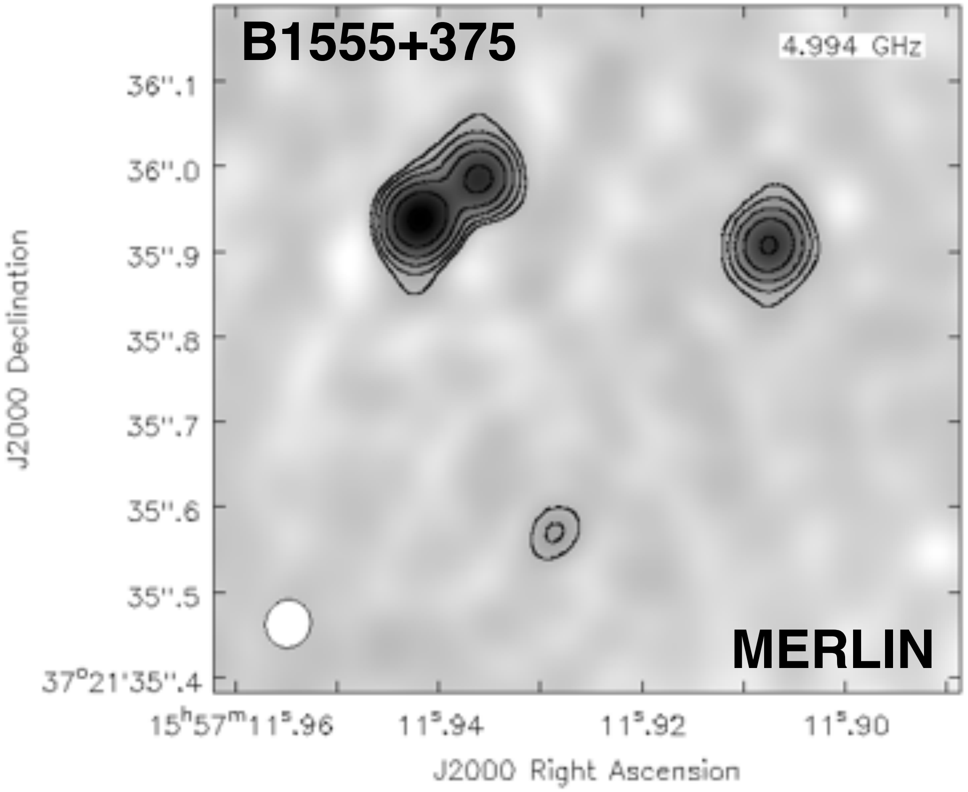
1) Mass function of sub-haloes to low mass levels $10^6\,M_{sun}$.

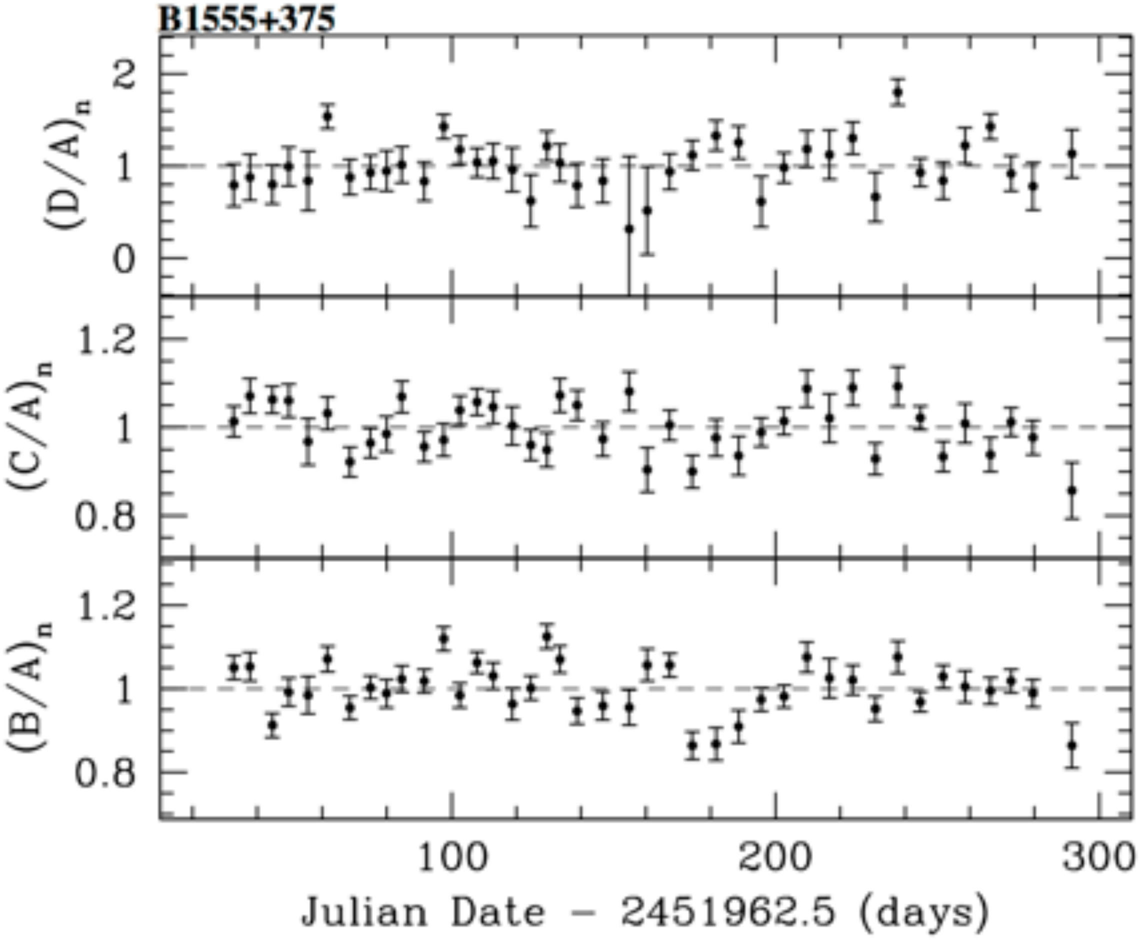
(Slope and normalization)





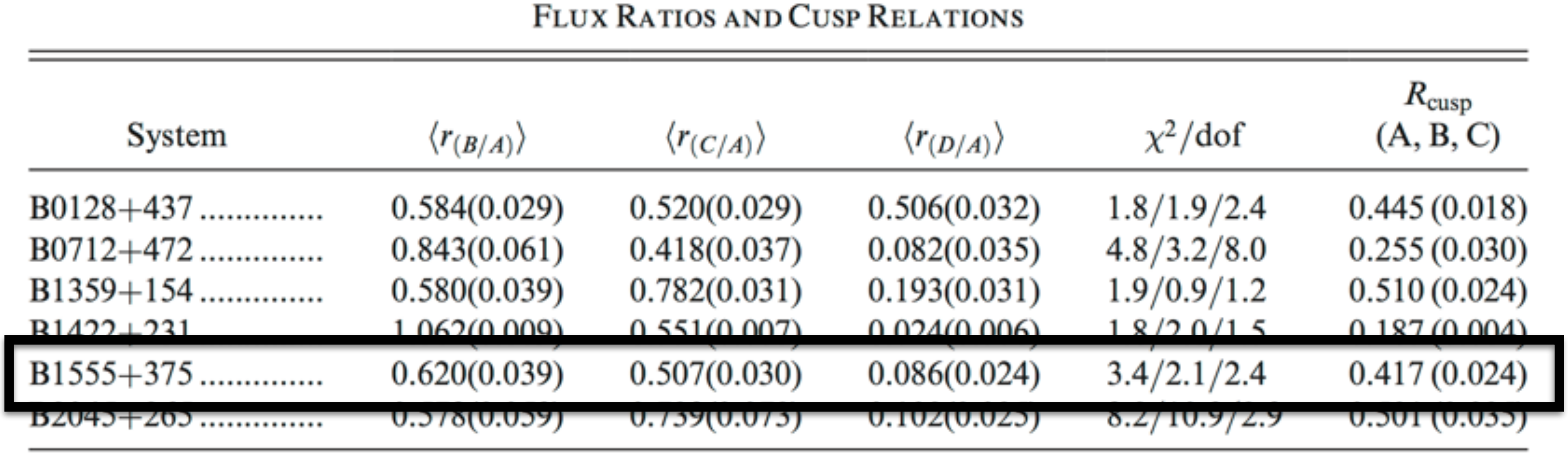
Dark matter: Probing cosmology **lensing**





$$R = \frac{F_B - F_A}{|F_B| + |F_A|} \rightarrow 0$$

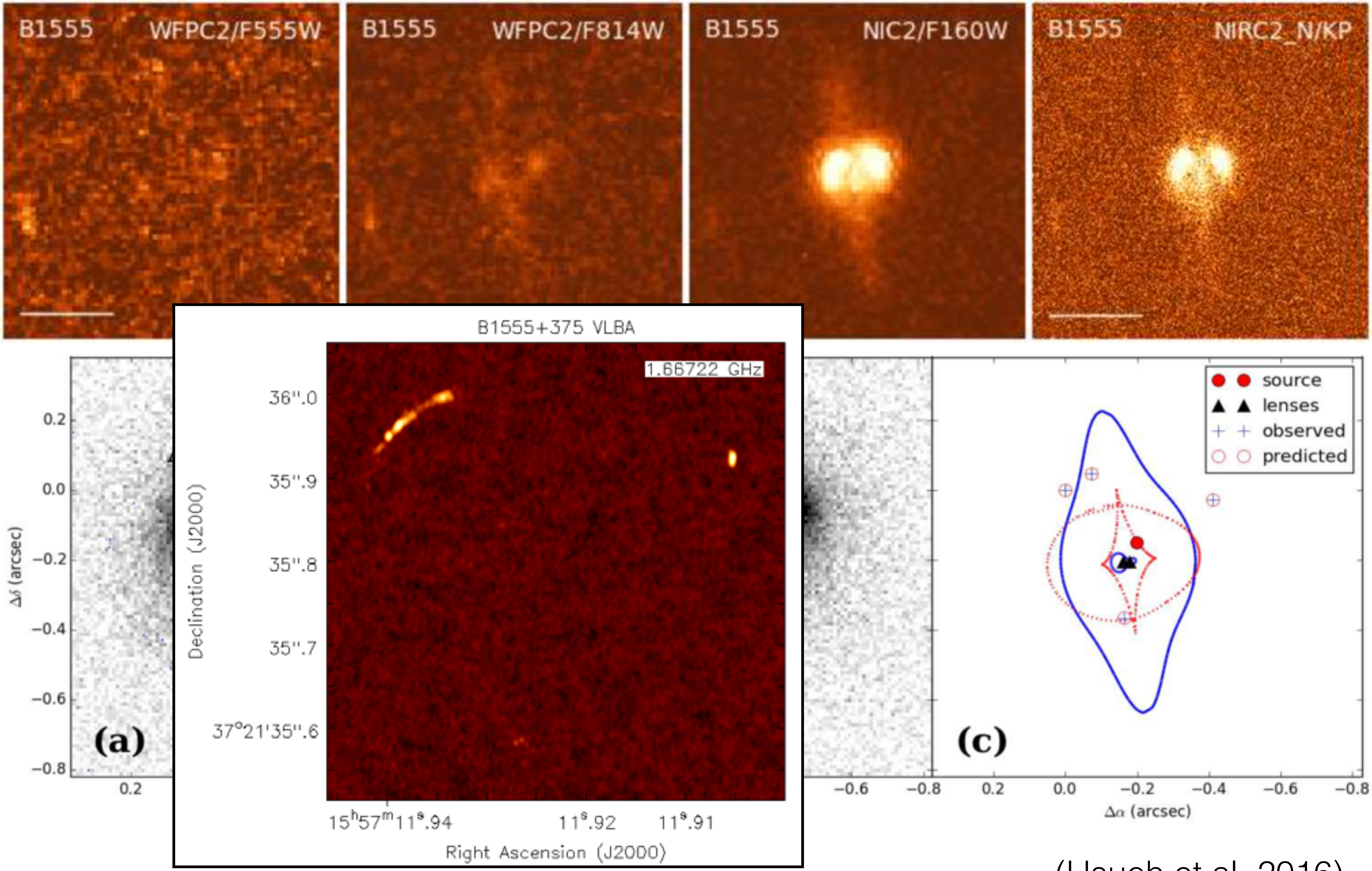
(Koopmans et al. 2003)



FLUX RATIOS AND CUSP RELATIONS

System	$\langle r_{(B/A)} \rangle$	$\langle r_{(C/A)} \rangle$	$\langle r_{(D/A)} \rangle$	χ^2/dof	$R_{\rm cusp}$ (A, B, C)
B0128+437	0.584(0.029)	0.520(0.029)	0.506(0.032)	1.8/1.9/2.4	0.445 (0.018)
B0712+472	0.843(0.061)	0.418(0.037)	0.082(0.035)	4.8/3.2/8.0	0.255 (0.030)
B1359+154	0.580(0.039)	0.782(0.031)	0.193(0.031)	1.9/0.9/1.2	0.510 (0.024)
B1422+231	1.062(0.009)	0.551(0.007)	0.024(0.006)	1.8/2.0/1.5	0.187 (0.004)
B1555+375	0.620(0.039)	0.507(0.030)	0.086(0.024)	3.4/2.1/2.4	0.417 (0.024)
B2045+265	0.578(0.059)	0.739(0.073)	0.102(0.025)	8.2/10.9/2.9	0.501 (0.035)

Dark matter: Probing cosmology **lensing**



(Hsueh et al. 2016)

Probing cosmology **requirements**

1. New lens searches — community;
2. Survey mode — technical;
3. Improved frequency range (1–16 GHz) — technical;
4. Improved sensitivity / image fidelity — technical;
5. Must demonstrate feasibility / relevance from simulations — community.

Lensing statistics using **SKADS**

How many gravitational lenses in the SKA sky?

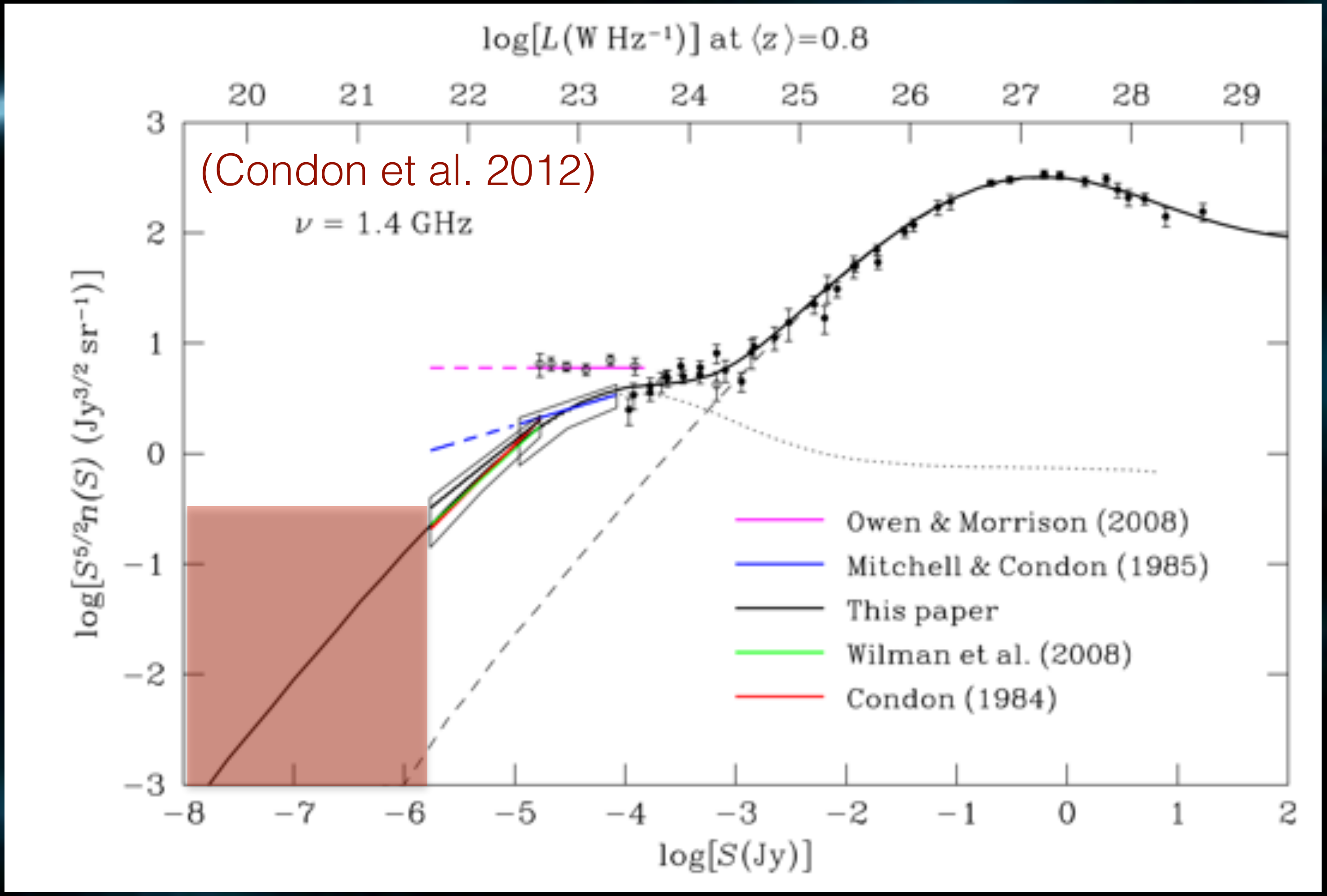
$$\tau(z_s) = \int_0^{z_s} n(z)\sigma_x \frac{cdt}{dz} dz = 10^{-3}$$

Gravitational lenses are rare, and the flat source number counts require shallow and wide-field surveys as opposed to deep and narrow-field (x 14 more efficient).

For 1 square degree,

360 with $S_{1.4\,\mathrm{GHz}}$ > 1 uJy (Deep)
50 with $S_{1.4\,\mathrm{GHz}}$ > 10 uJy
8 with $S_{1.4\,\mathrm{GHz}}$ > 50 uJy (Shallow)

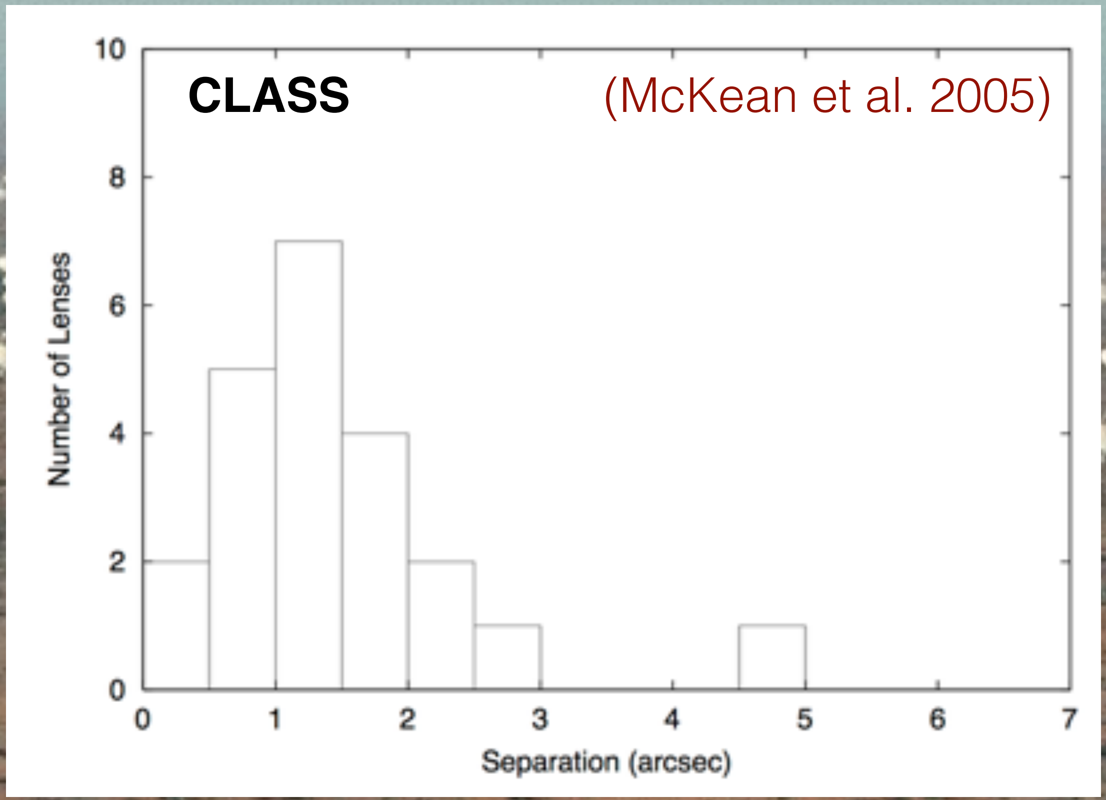
Statistics from a deep survey would directly constrain the SKA2 number counts.

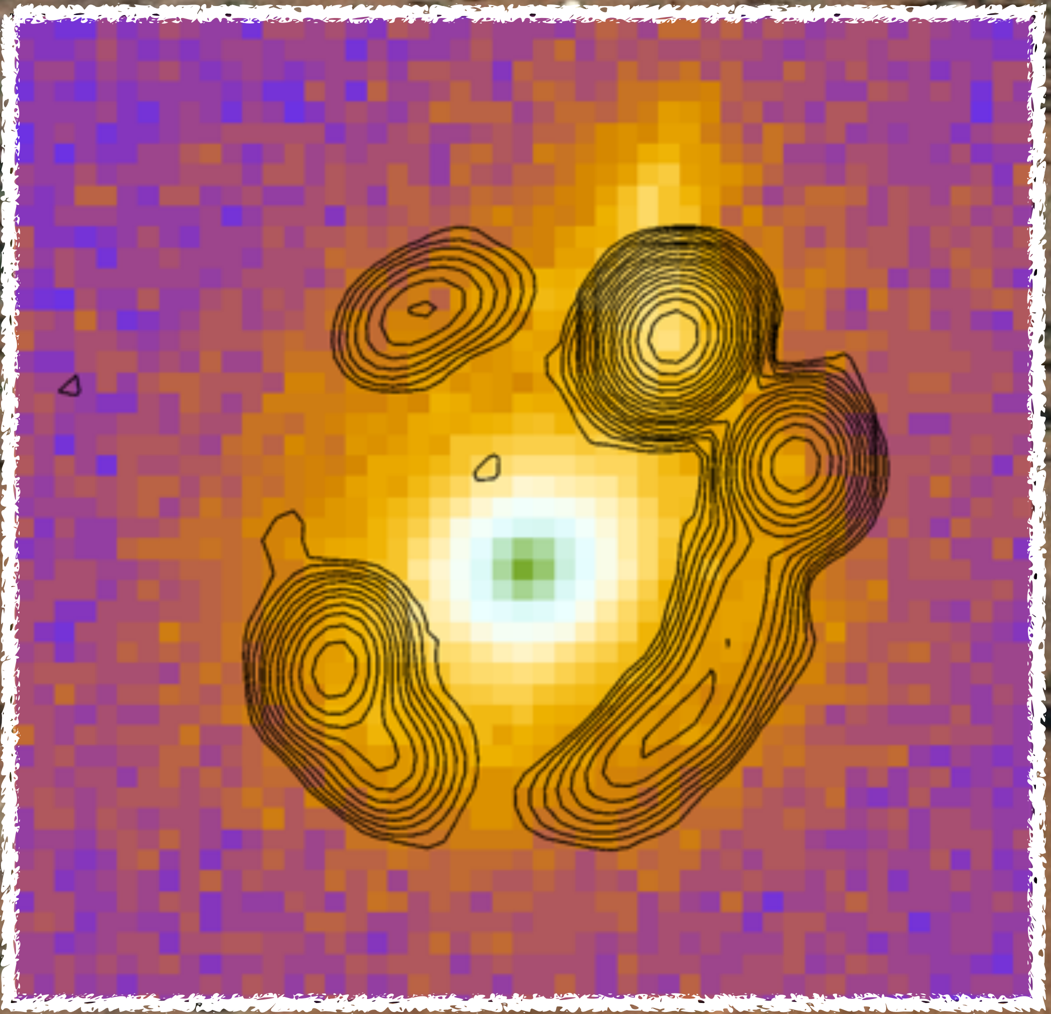

(Condon et al. 2012)

What do we need?

- Resolution (0.25-0.5 arcsec).
- Sensitivity (~3 uJy rms for 15 sigma at ~50 uJy).
- Band 2 (0.95-1.76 GHz) for **survey.**

- A matched sky area survey with ***Euclid*** should find 2000—8000 lenses with **SKA1-MID** (in just 3 months int. time).



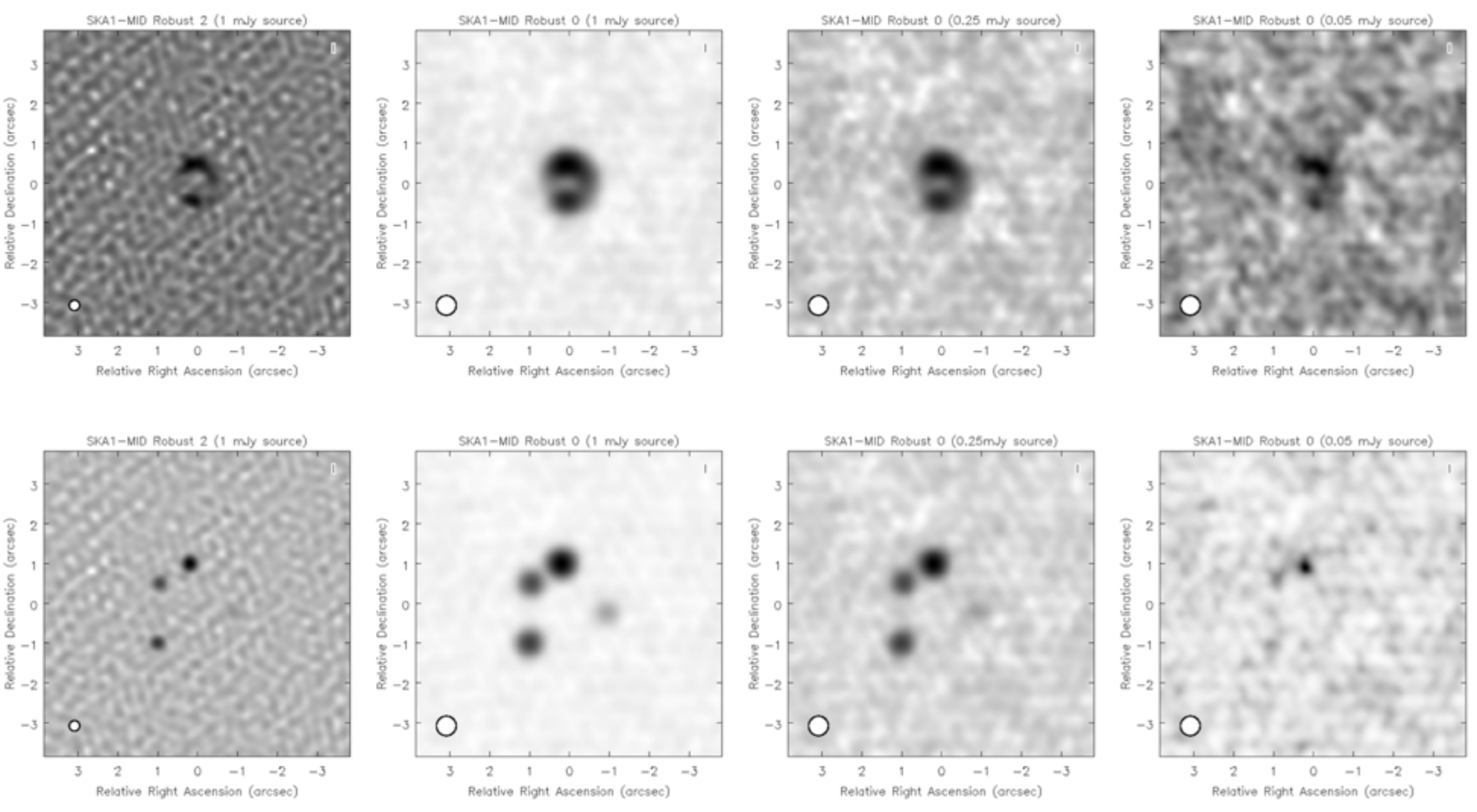


Challenges:

1. False positives
    A. Higher angular resolution imaging.
    B. Spectral information.
    C. Polarisation information.
2. Modelling large numbers of candidates.
3. Lens and source redshifts.

Euclid and **LSST** are vital.

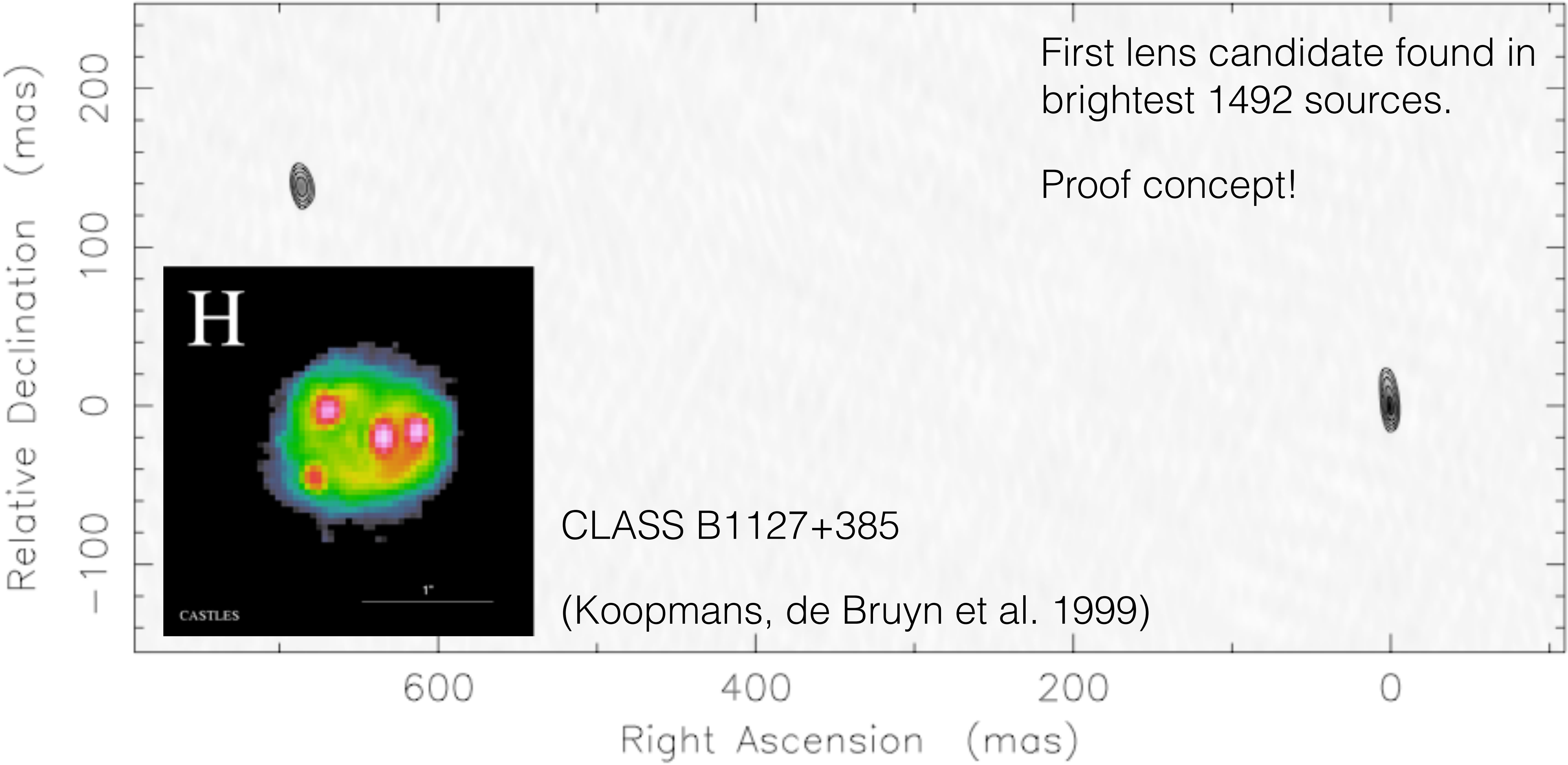
Simulations: SKA1-MID



(McKean et al. 2015)

Wide-field VLBI surveys

mJIVE-20: The mJy Imaging VLBI Exploration at 20 cm (Deller & Middelberg 2013).



First lens candidate found in brightest 1492 sources.

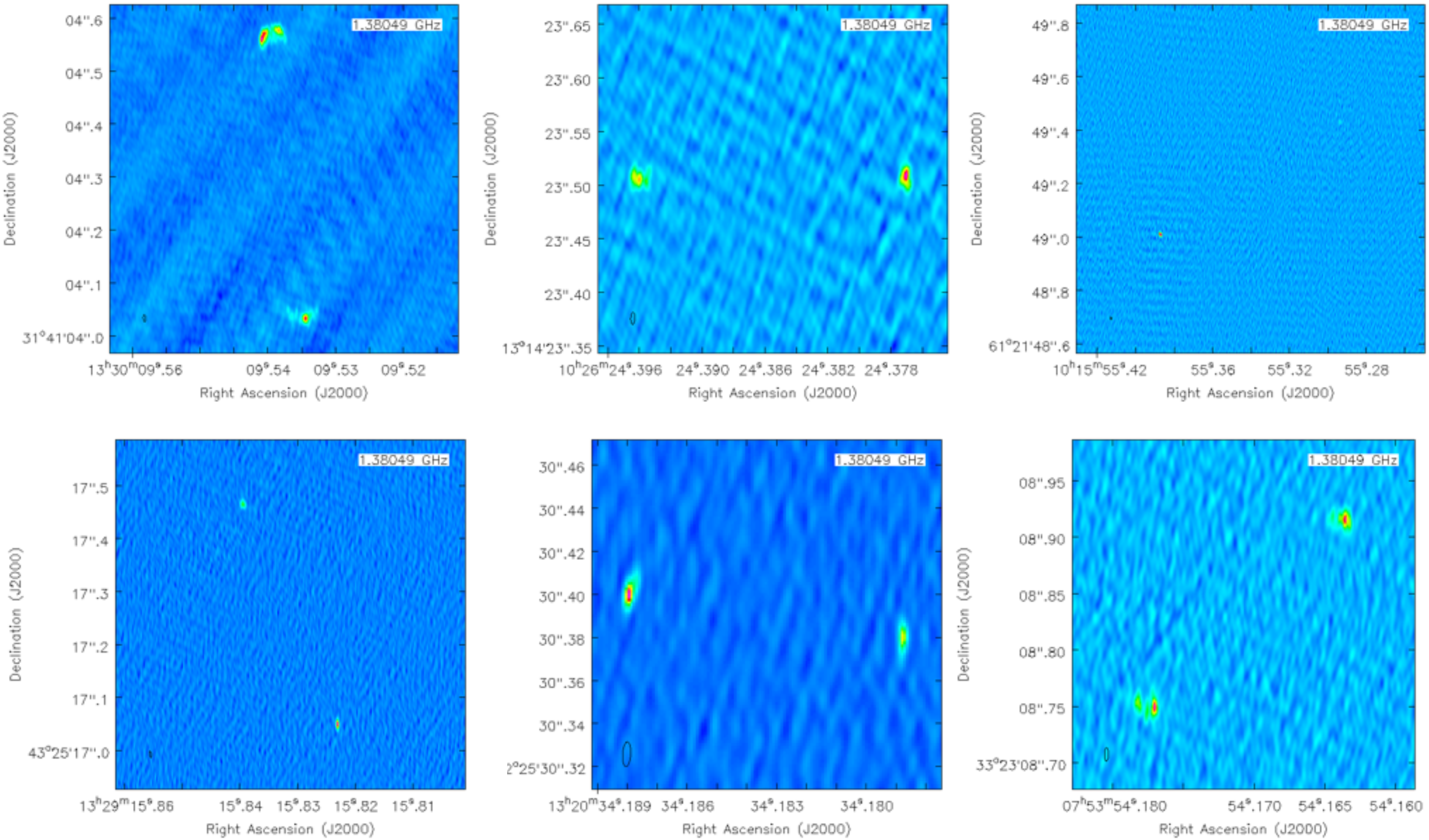
Proof concept!

CLASS B1127+385

(Koopmans, de Bruyn et al. 1999)

(See also HDF; Garrett and new work by Radcliffe et al. with the EVN)

(Spingola et al.,in prep.)

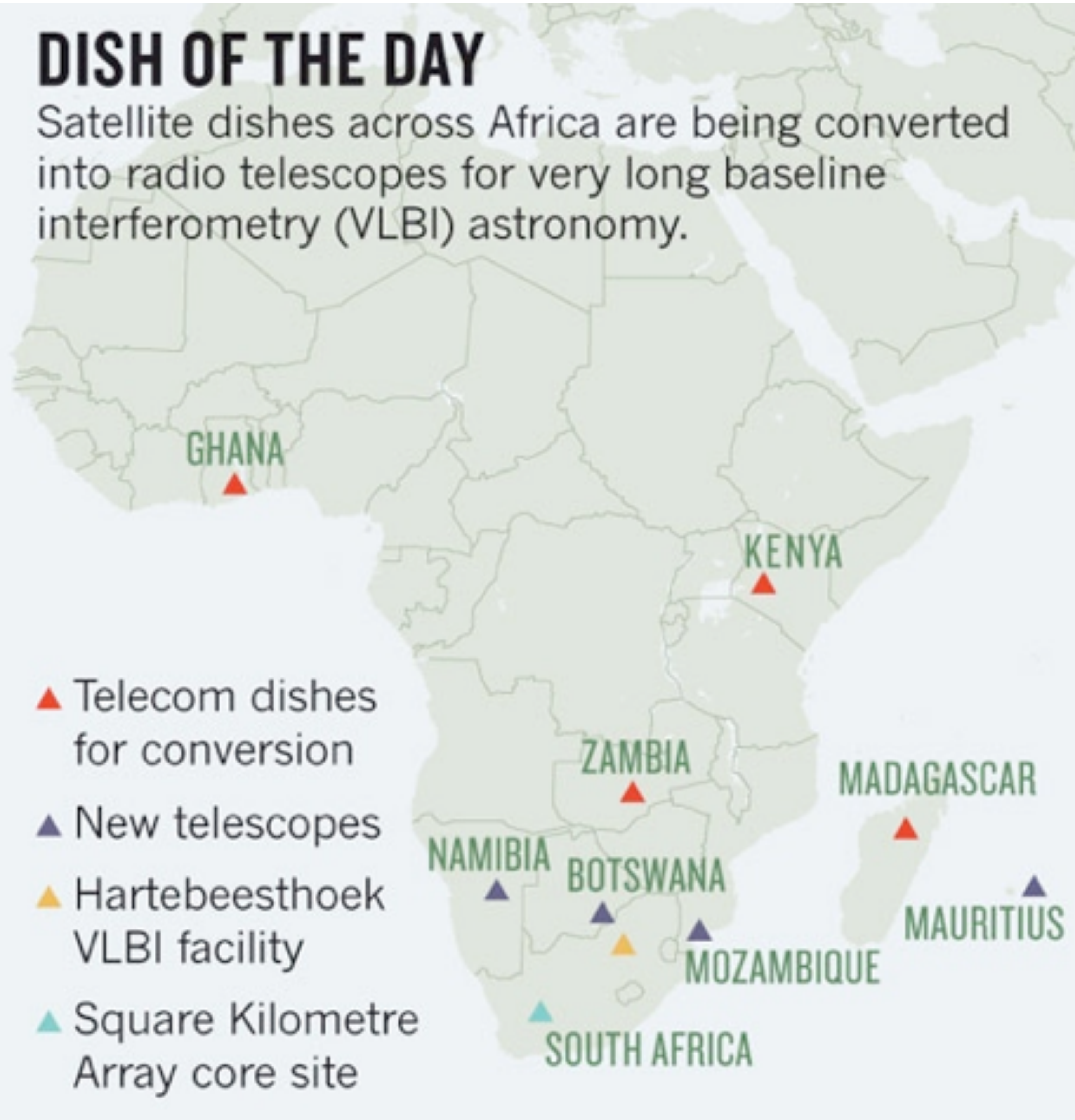


Multi-Frequency follow-up of 9 sources with the VLBA at 4 and 7 GHz.

Can wide-field VLBI become routine?

The importance of the AVN

Improved sensitivity and *uv*-coverage (new builds, phased-MeerKAT).



DISH OF THE DAY

Satellite dishes across Africa are being converted into radio telescopes for very long baseline interferometry (VLBI) astronomy.

Upgrading existing communication dishes for astronomy (e.g. Ghana)

Summary

1. Cosmological studies will play an important role in the scientific programmes of large optical programmes (LSST, DES, *Euclid*).
2. We need to engage with the astronomical community to show that VLBI is relevant for these studies.
3. VLBI can play an important role in testing the cosmological model, and in particular making independent measurements of Dark Energy and Dark Matter.
4. This will require

   Flexible frequency range (1–15 GHz).

   Improved sensitivity / image fidelity (more stations; e-MERLIN; MeerKAT; AVN; SKA).

   Survey mode

   Investment (incl. human capital) — must demonstrate feasibility relevance from simulations (time-frame?).