Gravitational lensing with the next generation of VLBI arrays

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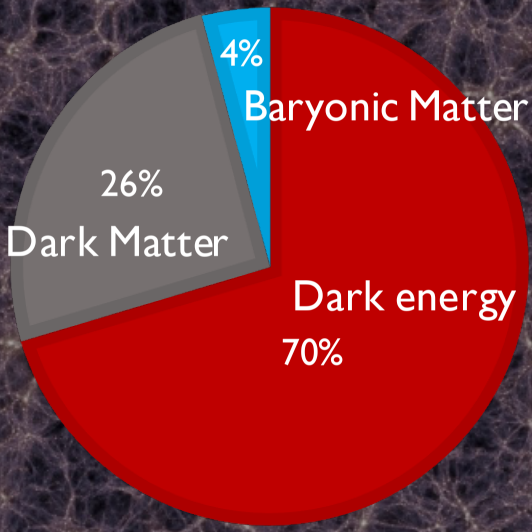
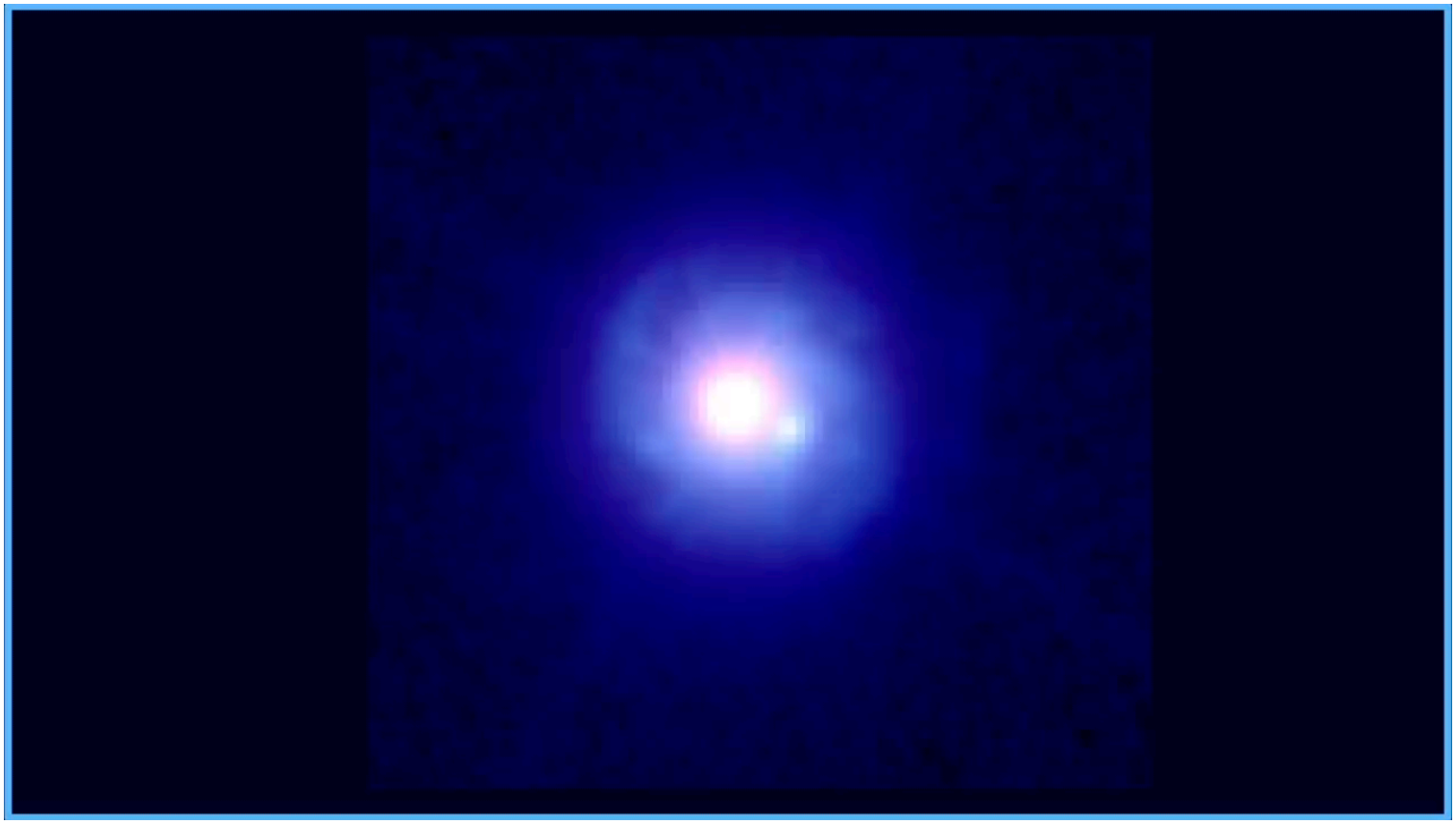
Can VLBI answer these questions?

- What is dark energy? (can we constrain the equation of state?)
- What is dark matter? (can we constrain the dark matter particle?)



What is gravitational lensing?



[Gravitational lens B0218+357, Credits: NASA]

Matter (baryonic + dark) curves spacetime.
As a result, the path of a light ray is deflected.

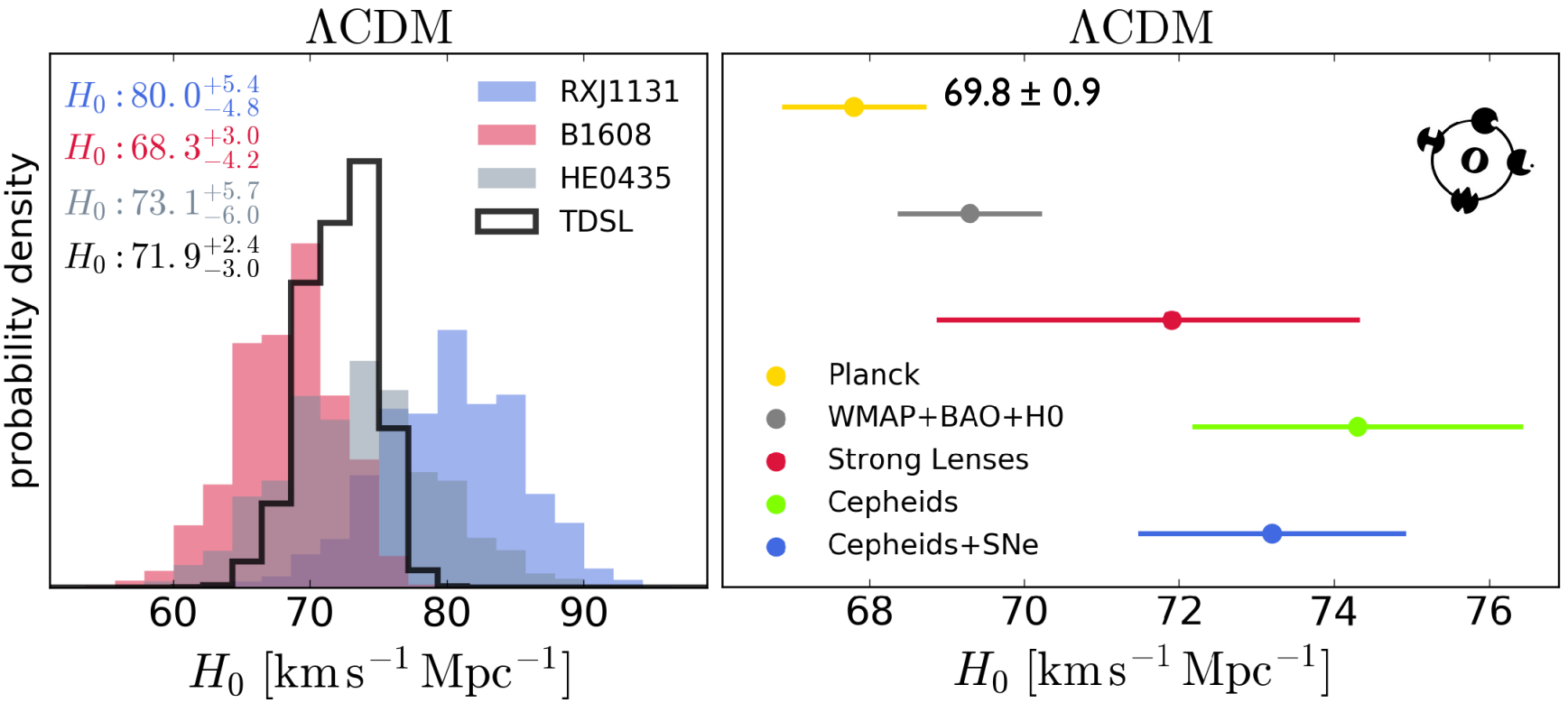
The source is lensed in multiple images.

Variability in the lensed images at different times because of the different path length.

Gravitational lensing time delays are probes of dark energy [Refsdal 1964]

$\Delta t \propto 1/H_0$

Probing cosmology: Dark Energy

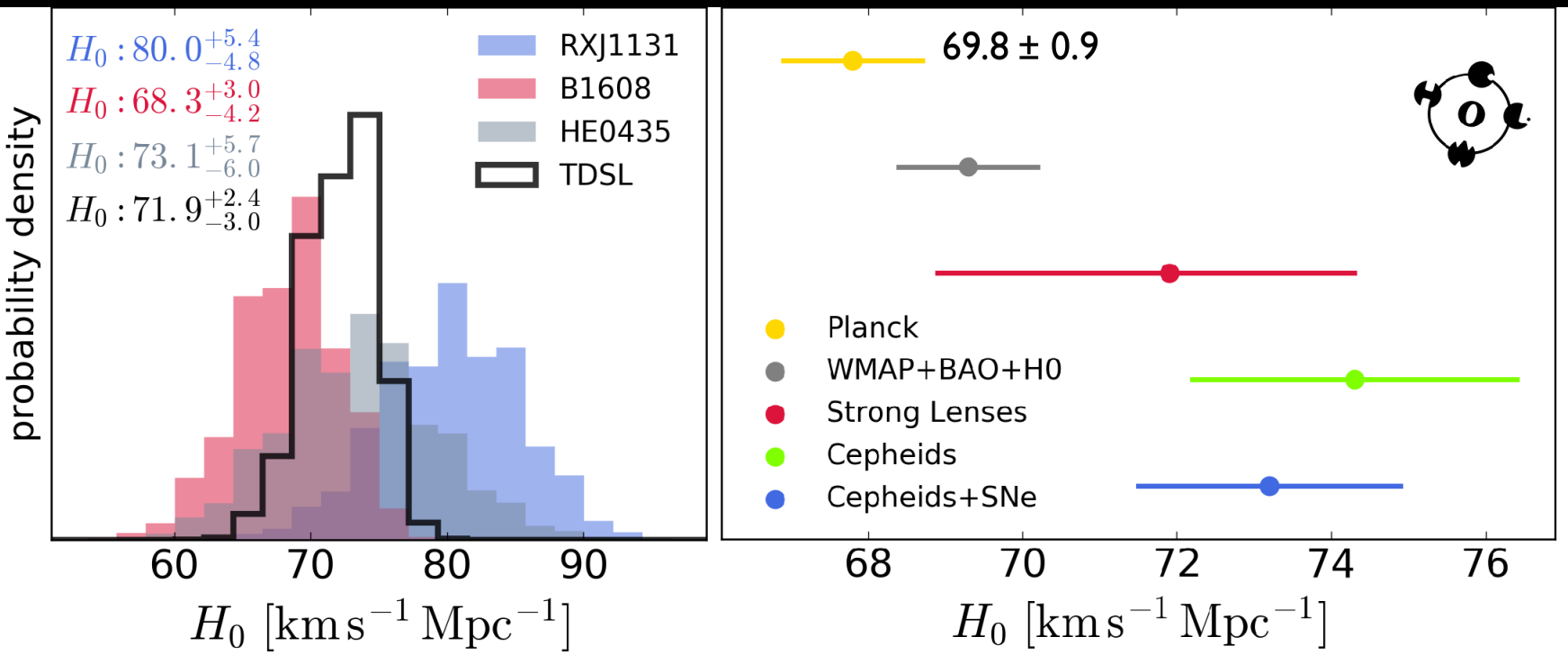


Gravitational lensing time delays are probes of dark energy

[H0liCOW collaboration; Suyu+2017, Bonvin+ 2017]

Probing cosmology: Dark Energy

Are there systematics or is there a physical reason?
We need VLBI imaging at high angular resolution for detailed lens models



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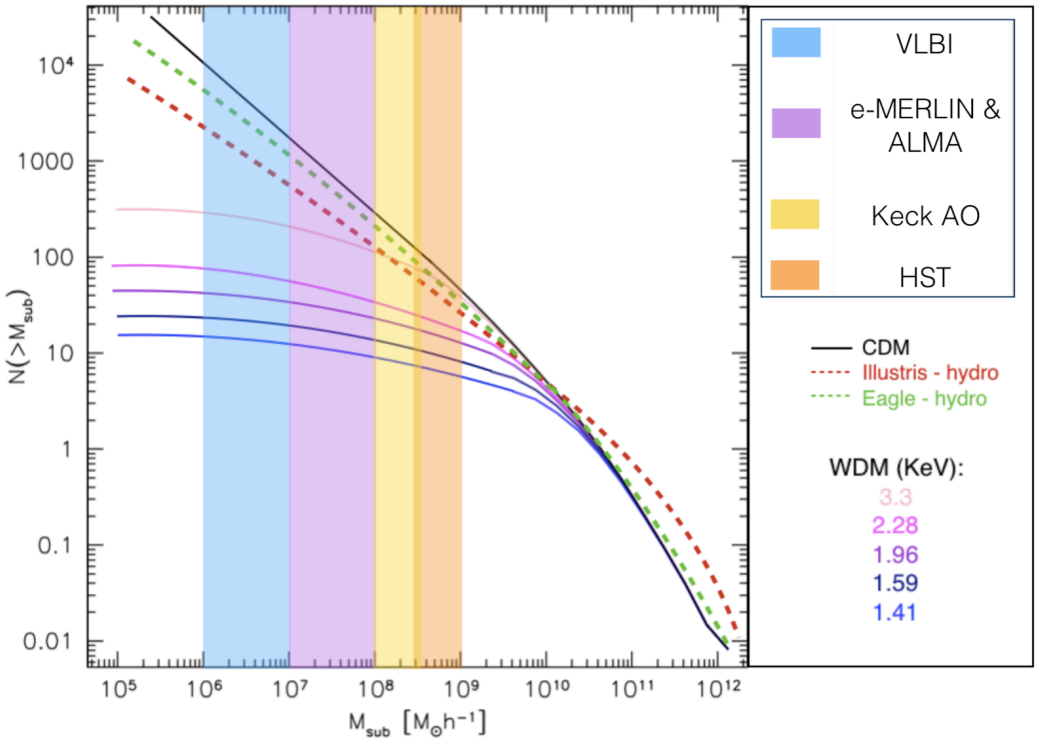
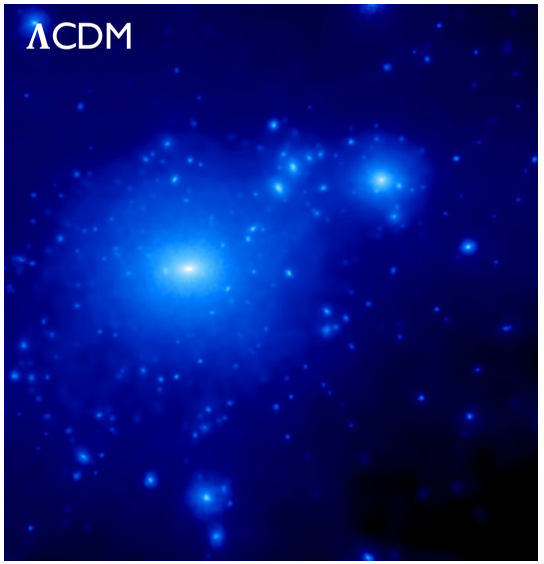


[Credits: S. Vegetti on behalf of SHARP collaboration]



[Credits: Durham University]

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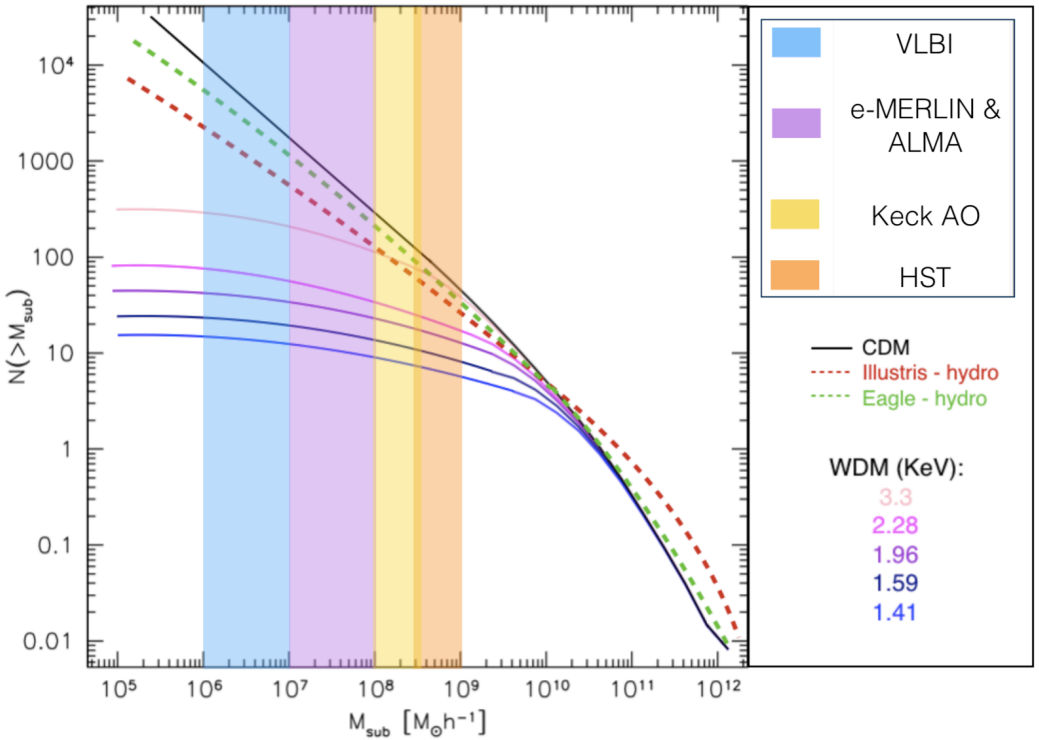

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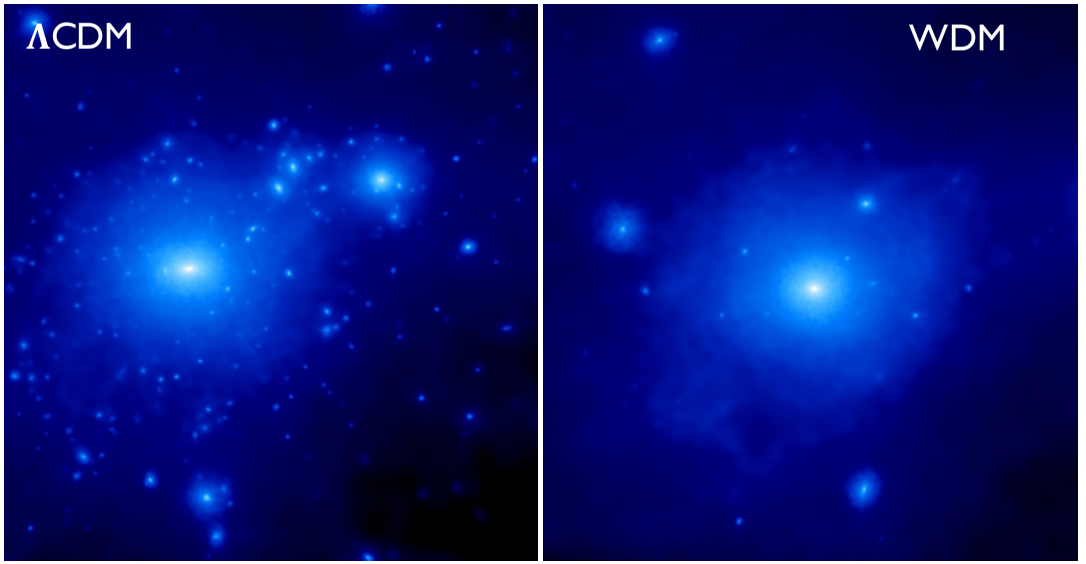

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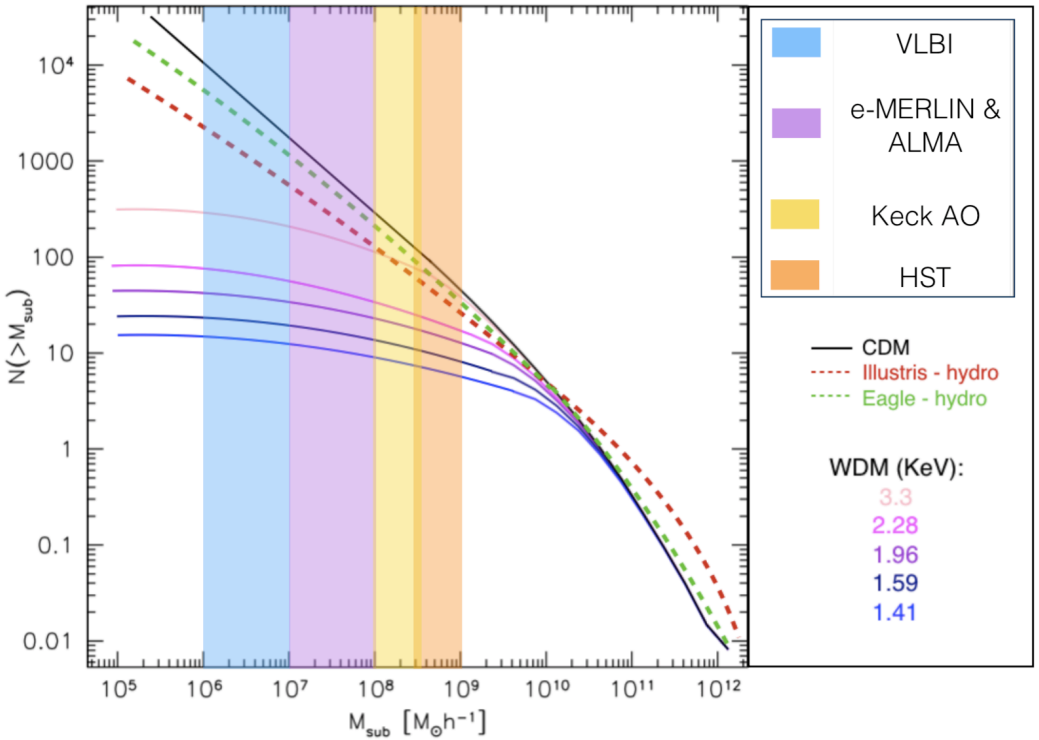

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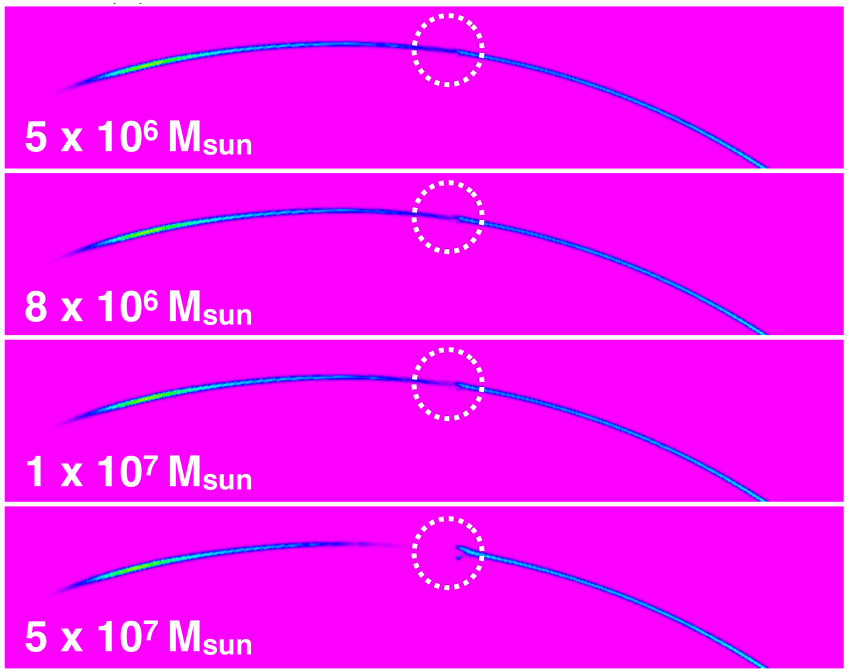
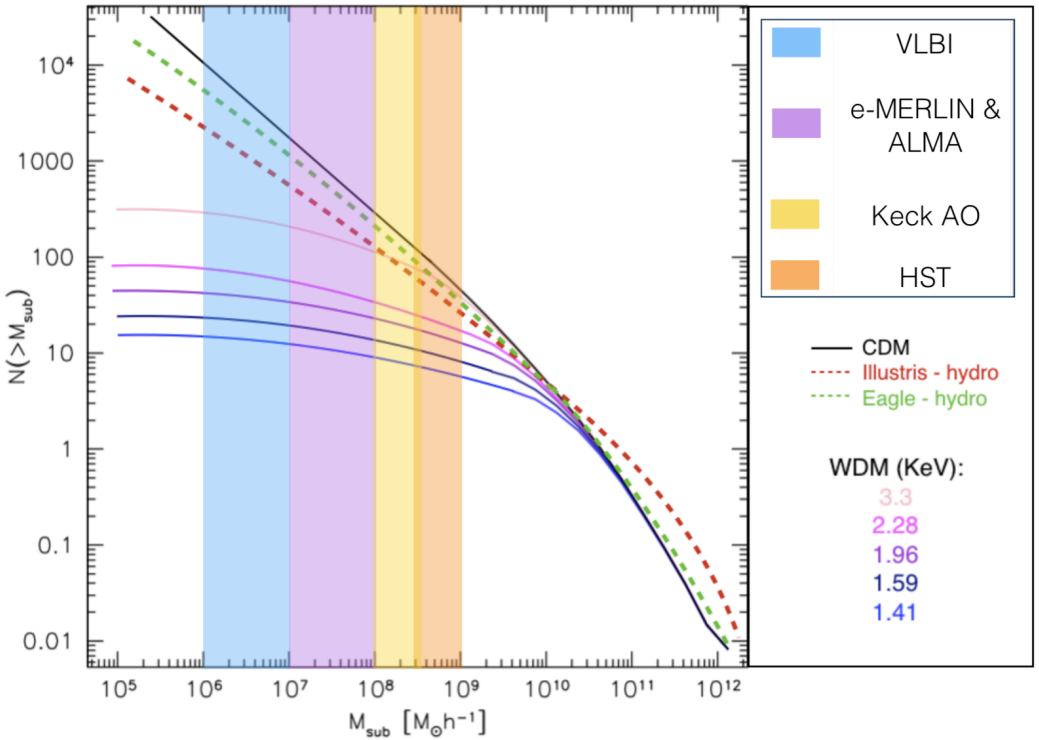


[Courtesy of G. Despali]

10^6 Msun corresponds to 3 mas Einstein Radius → it's possible to image this only with VLBI observations

Probing cosmology: Dark Matter



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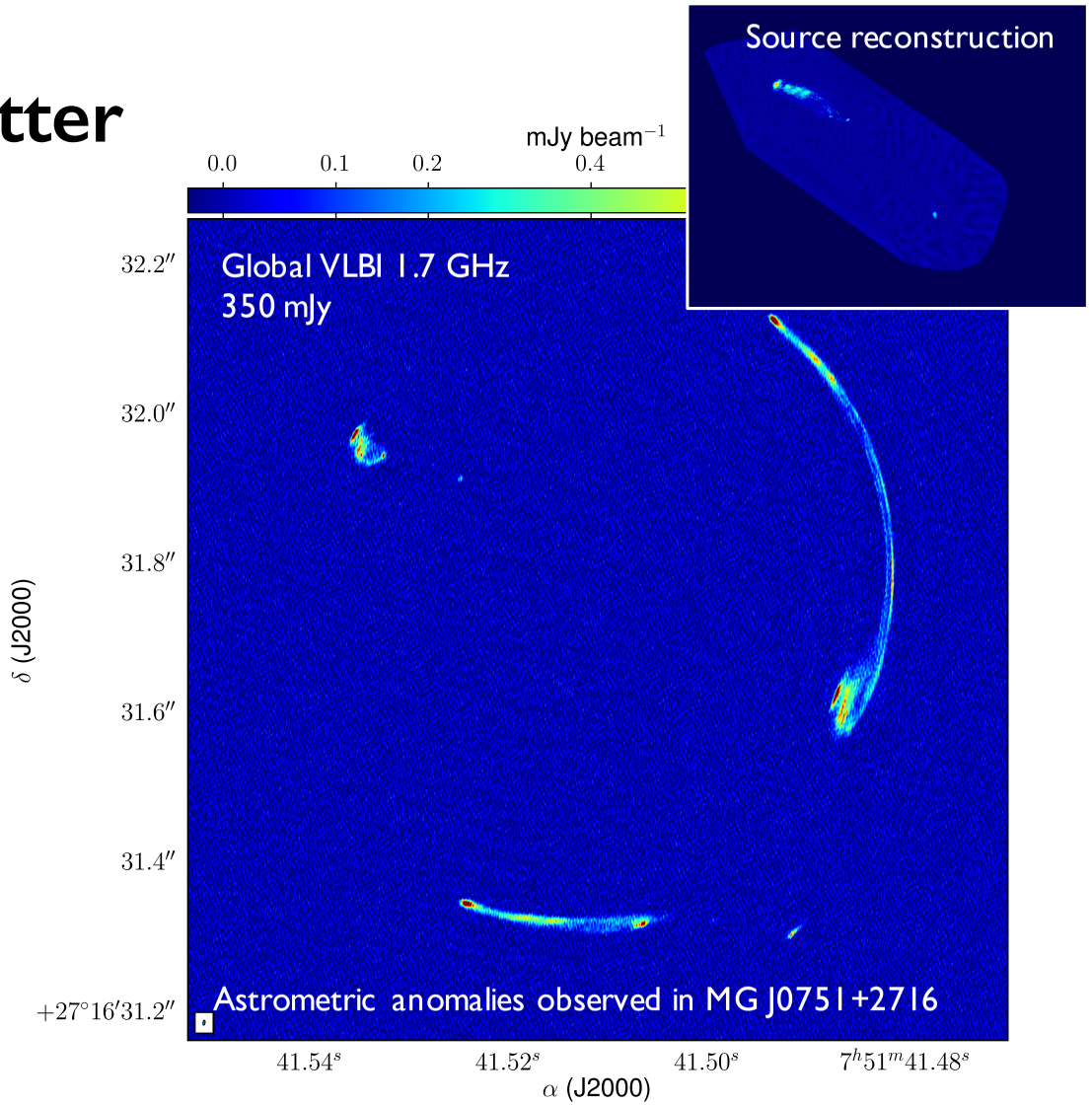

[Spingola+ submitted, SHARP collaboration]

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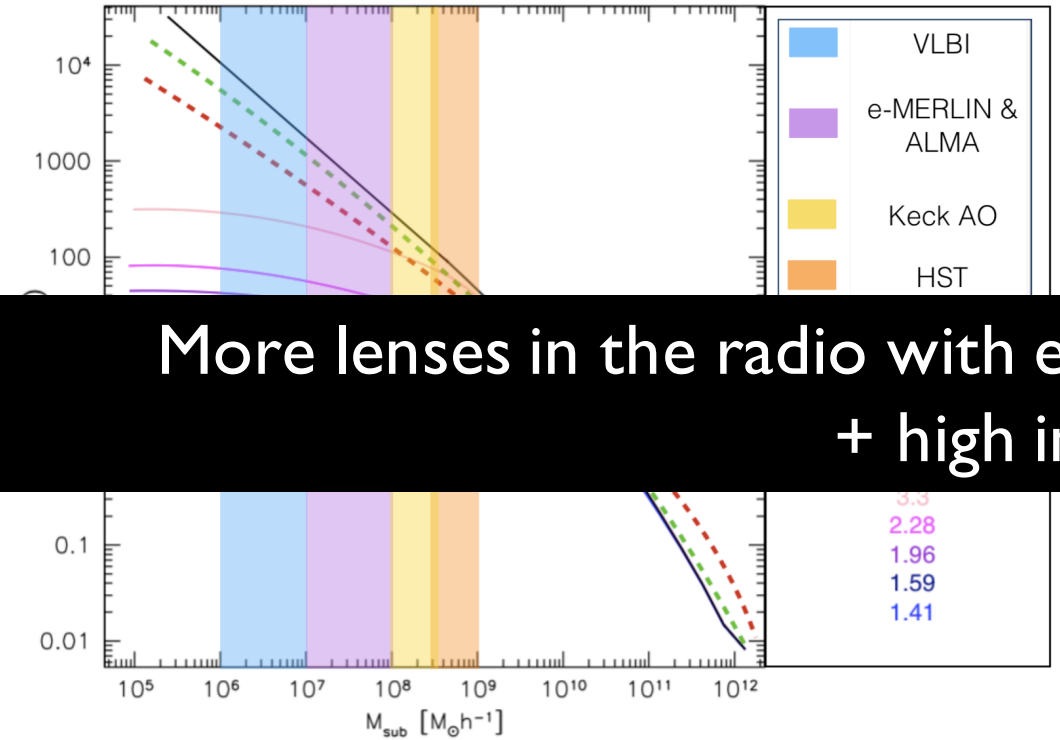

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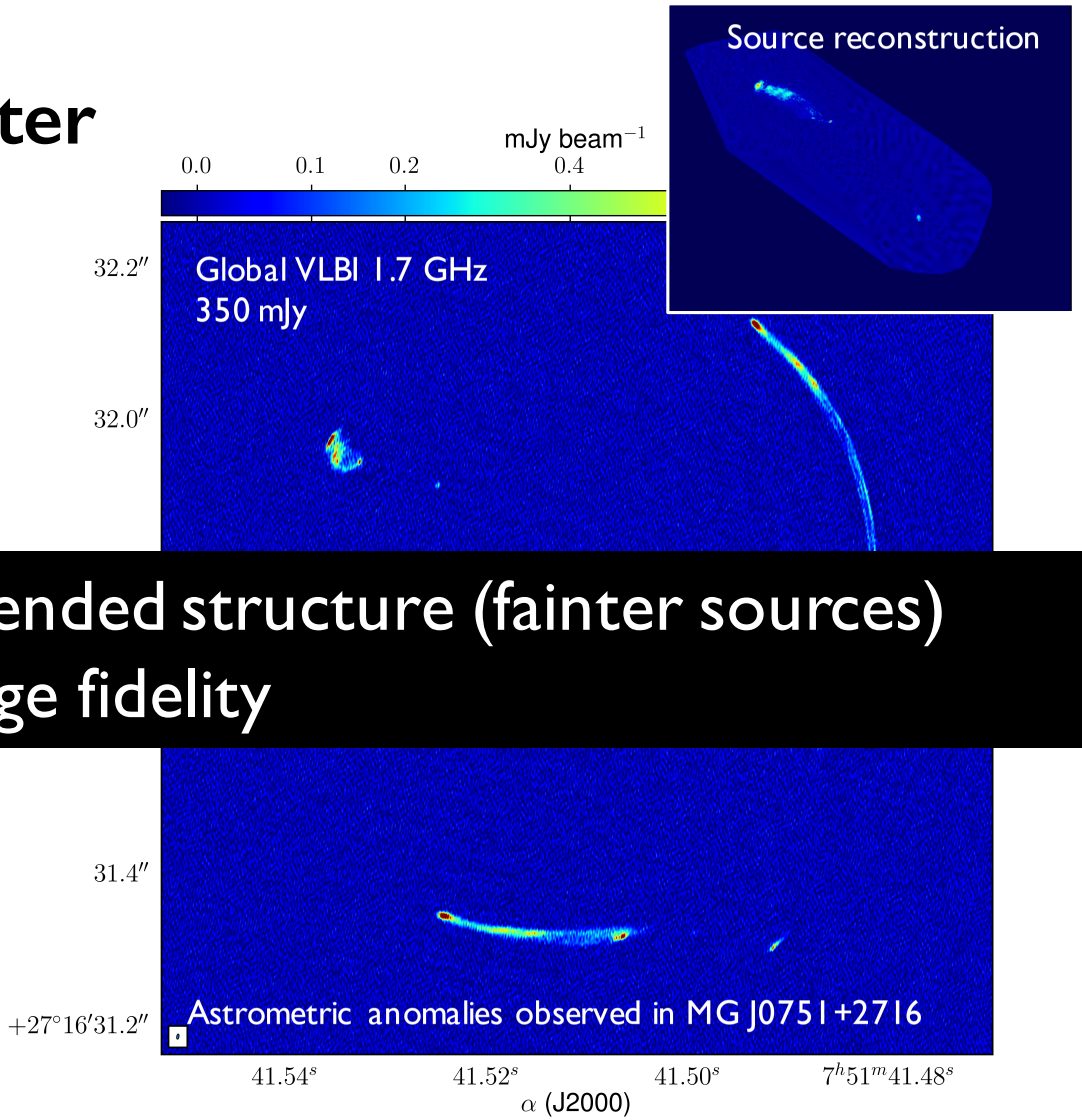
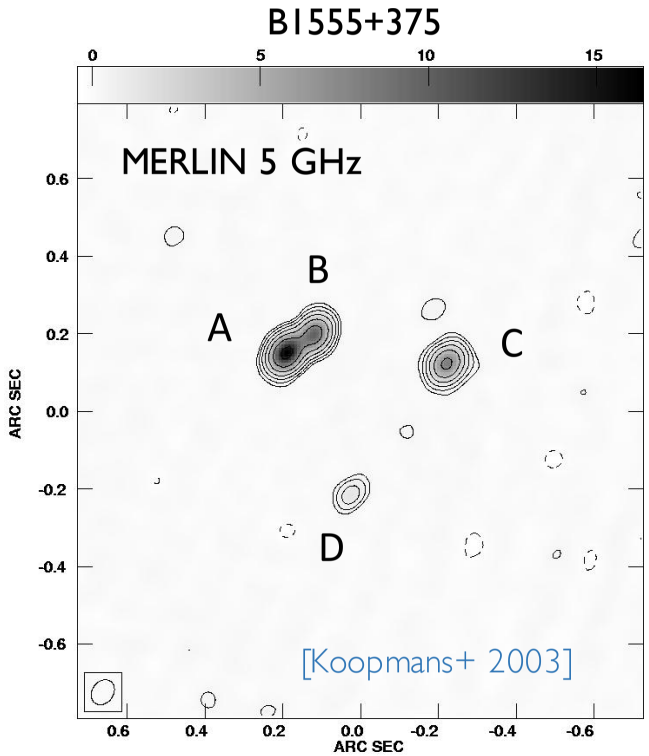


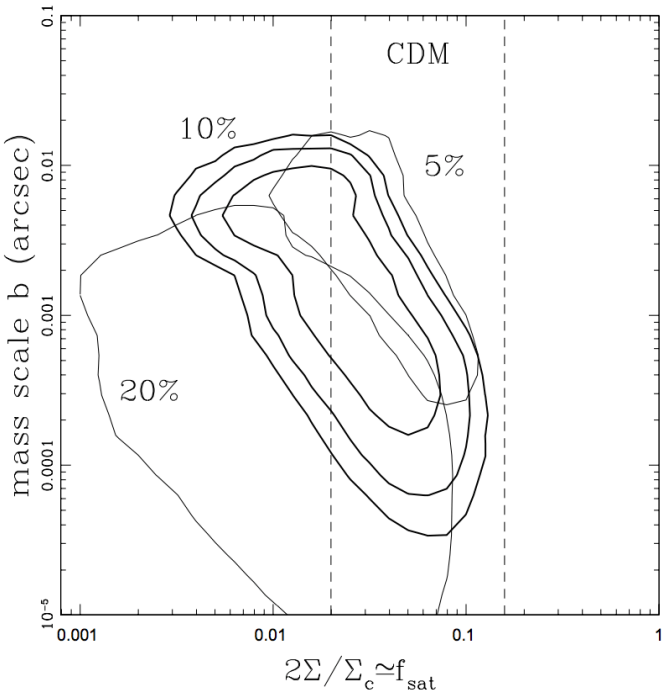
[Spingola+ submitted, SHARP collaboration]

More lenses in the radio with extended structure (fainter sources) + high image fidelity

Probing cosmology: Dark Matter



Flux ratio anomaly
A and B should have same flux density
[Mao & Schneider1998]



[Dalal & Kochanek 2002]
Using 7 radio loud lenses with flux ratio anomaly
~2% of the projected mass at the Einstein Radius is in substructure

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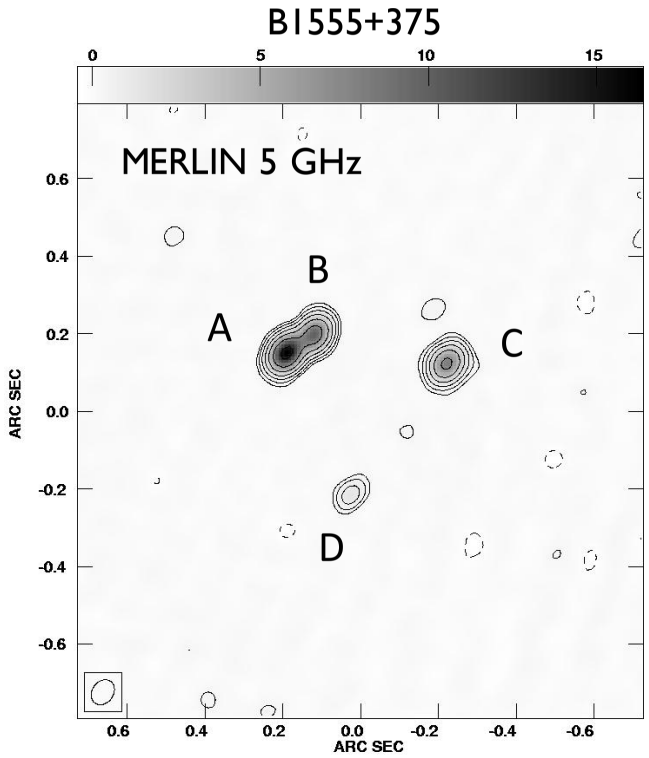

[Koopmans+ 2003]

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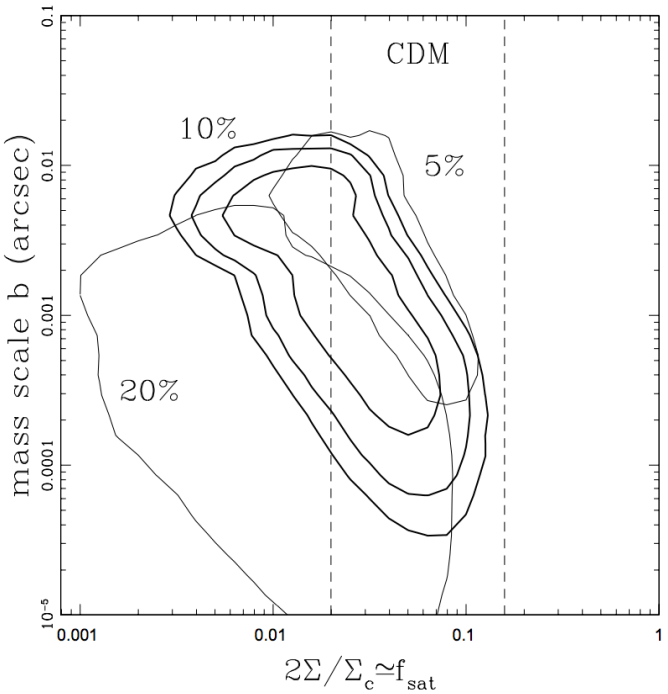

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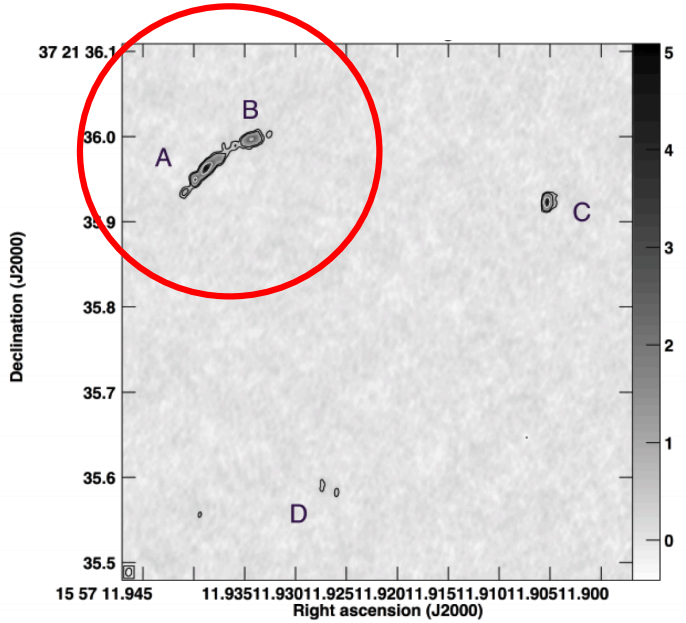

[Adapted from Hsueh+ 2016]

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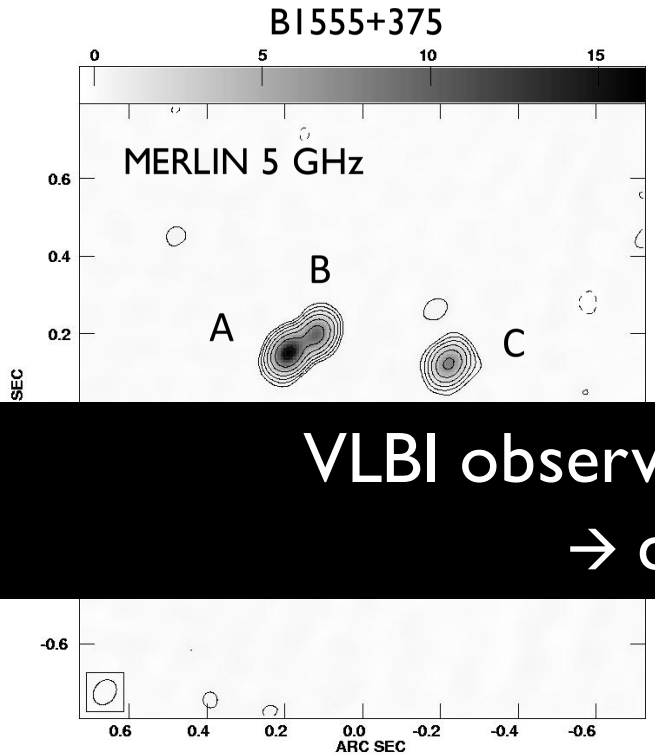

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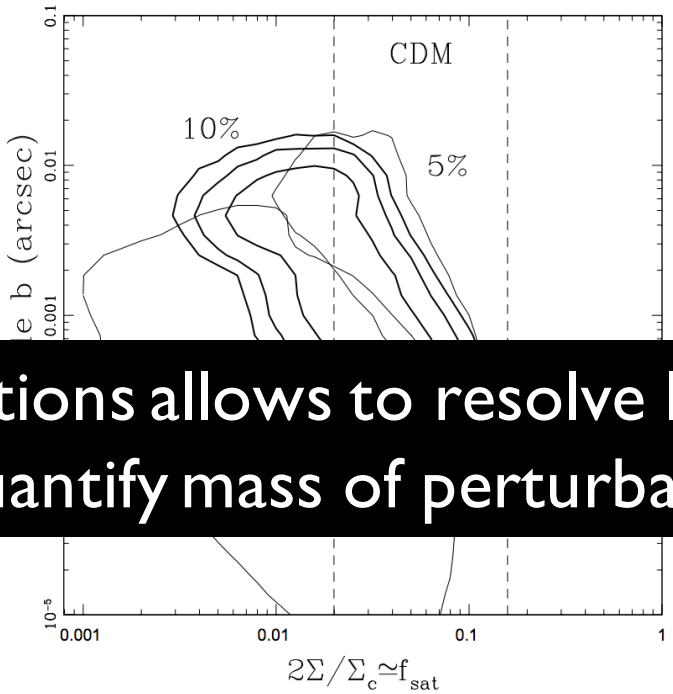

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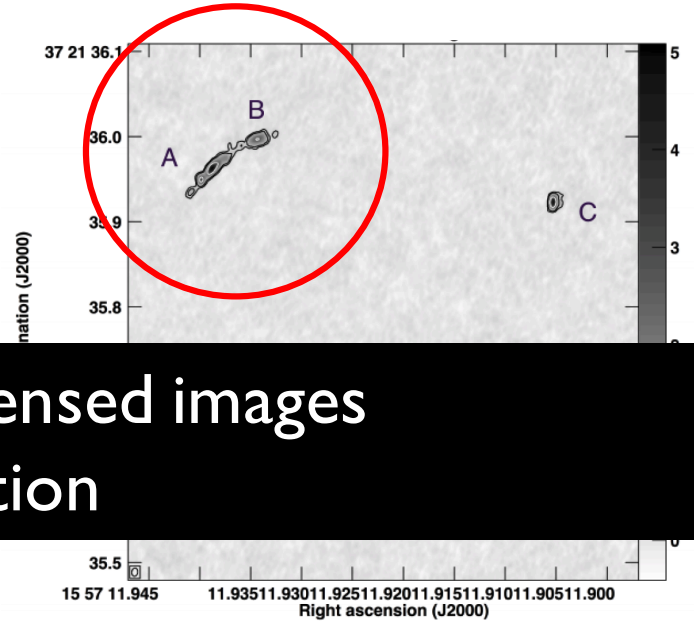

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VLBI observations allows to resolve lensed images
→ quantify mass of perturbation

Future

What is Dark Energy?

Constraining the parameter space of the equation of state

- More lenses with variability
- Lensing systems also optically bright

What is Dark Matter?

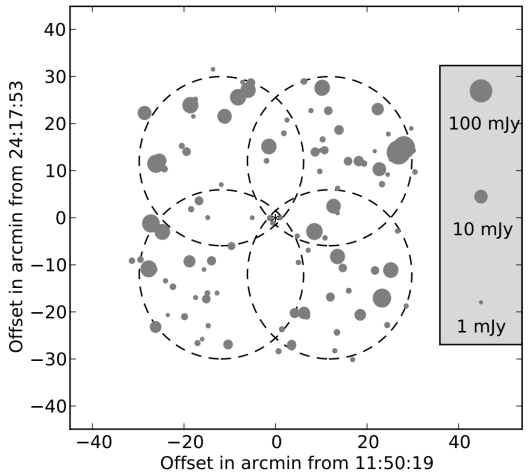
Constraining the parameter space of DM particle

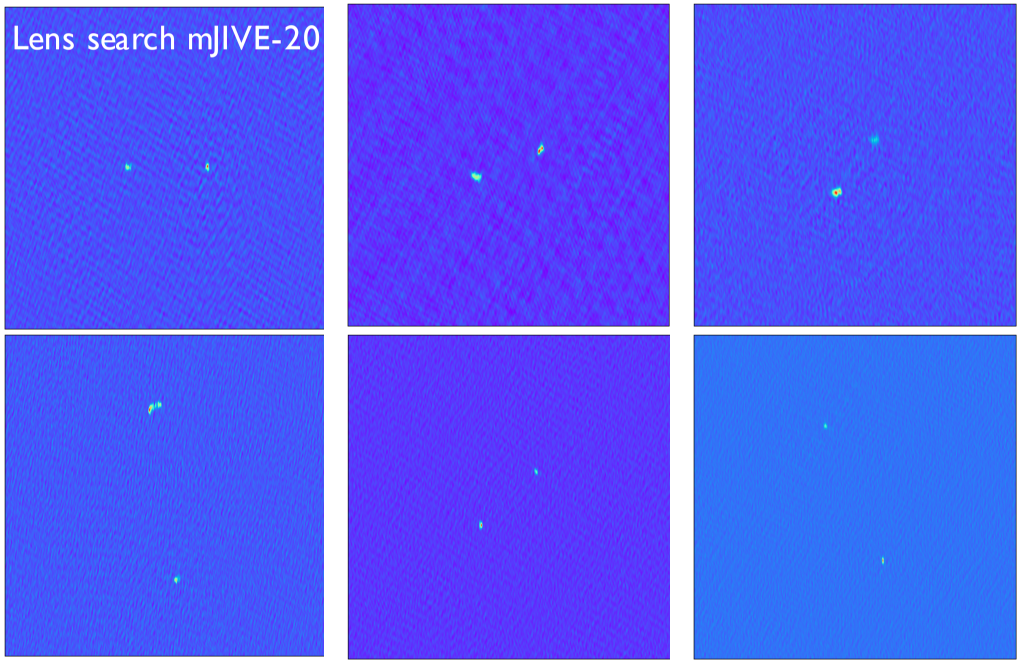
- More lenses with extended structure
- More quadruply imaged lenses

What do we need?

Improved sensitivity
Wide-field VLBI surveys
Flexibility in observing frequency

Future





[Spingola et al. in prep]

Example: **mJIVE-20 survey** (mJy imaging VLBI exploration at 20 cm)
[Deller & Middleberg 2014, but also Radcliffe et al. 2016]

Area = 200 deg^2 / Resolution = 5 mas

~17000 sources FIRST → ~4000 at VLBI scales → 14 lens candidates (2 known lenses + 1 new)

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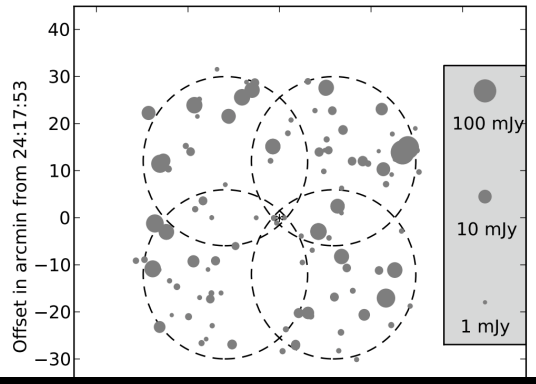

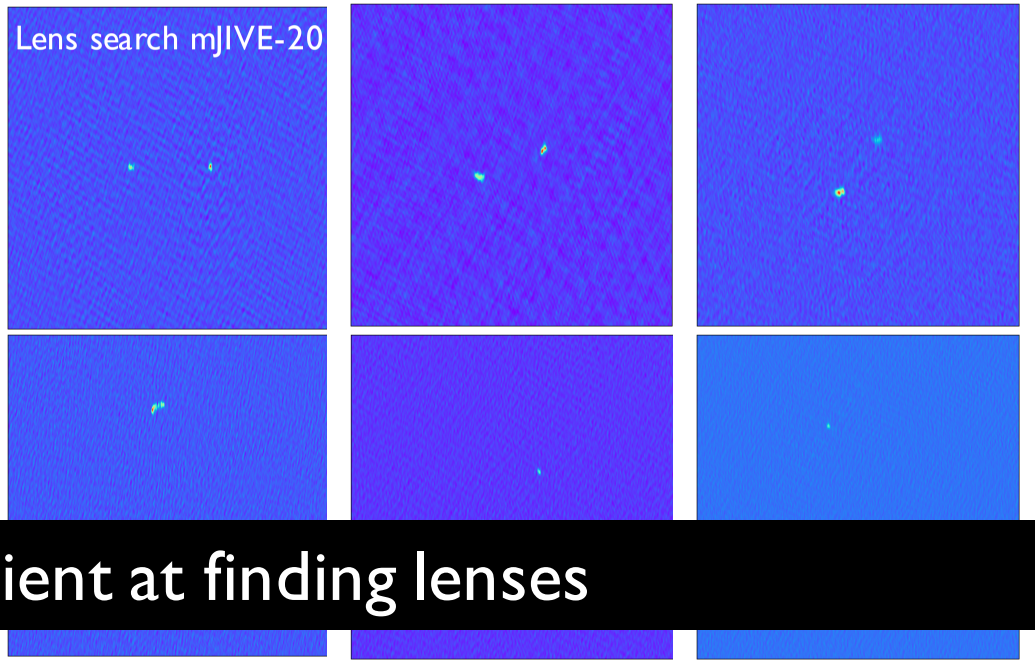

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VLBI surveys can be efficient at finding lenses

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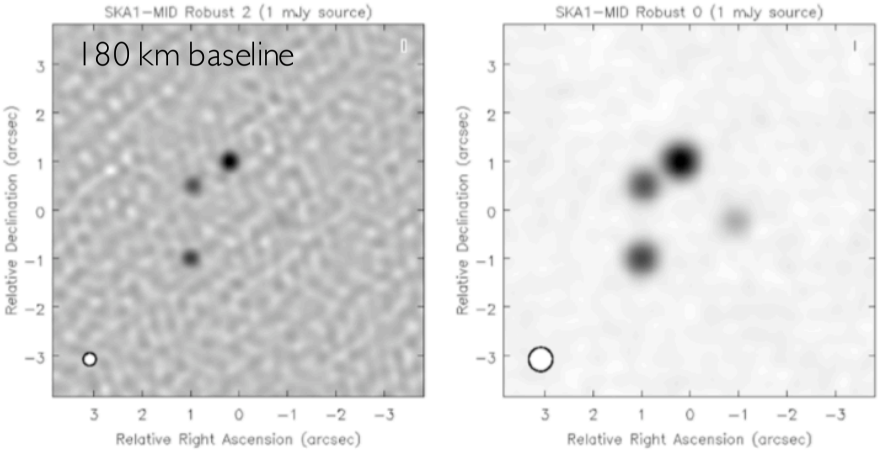
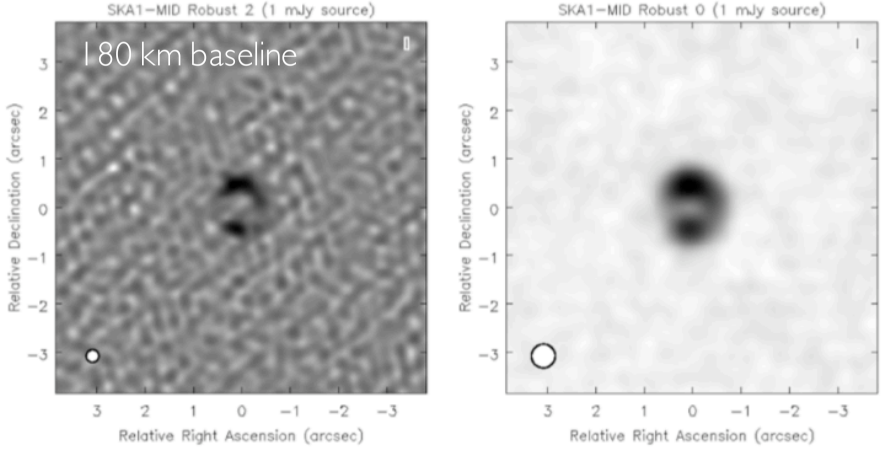
SKA1-MID can find $>10^5$ lenses with image separation > 300 mas

[Koopmans et al. 2004, McKean et al. 2015]

Source = AGN



Source = extended galaxy



[Simulation of a snapshot observation with SKA1-MID, McKean et al. 2015]

Future

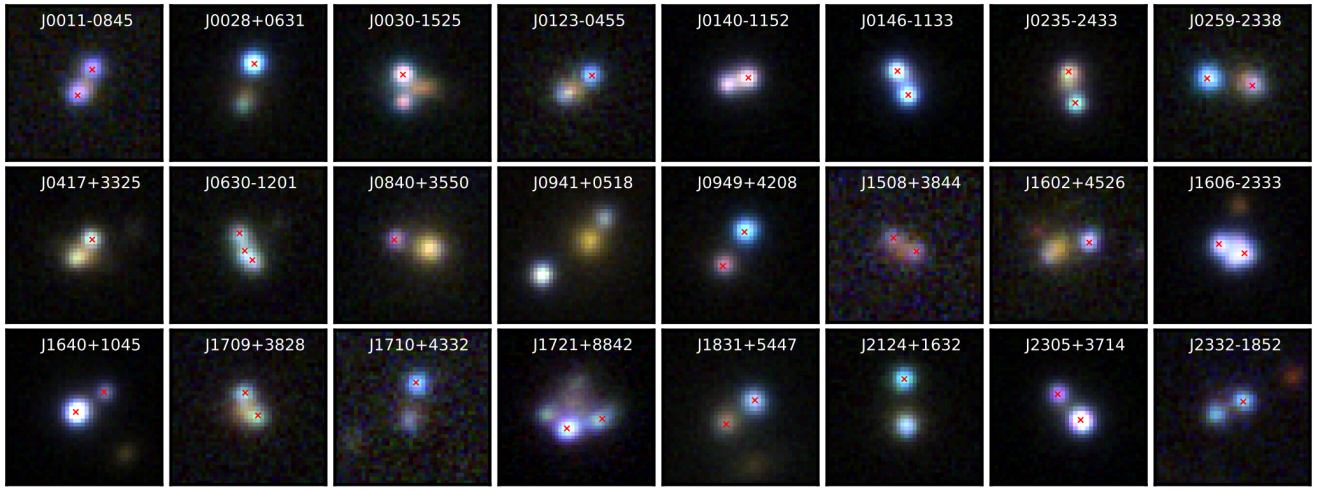
SKA1-MID can find >10^5 lenses with image separation > 300 mas

[Koopmans et al. 2004, McKean et al. 2015]

We need
multi-wavelength observations

recognize true gravitational lenses
false positives
detailed lens models
lens and source redshift

Matched sky areas with LSST, Euclid …



[new 24 lensed quasars found in Pan-STARSS (RGB) + GAIA (red crosses), Lemon et al. 2018]

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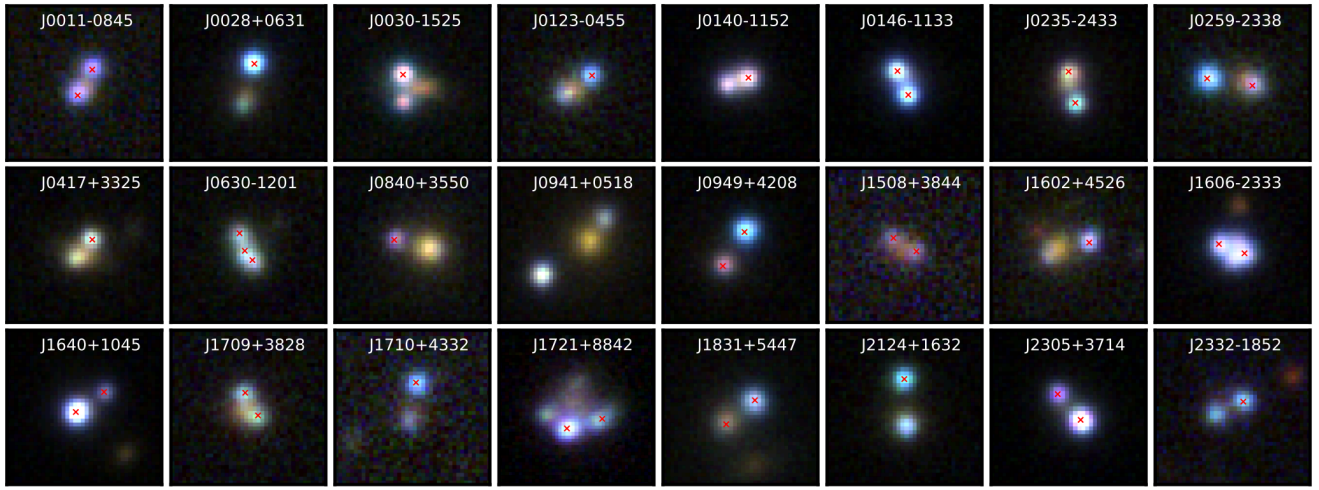

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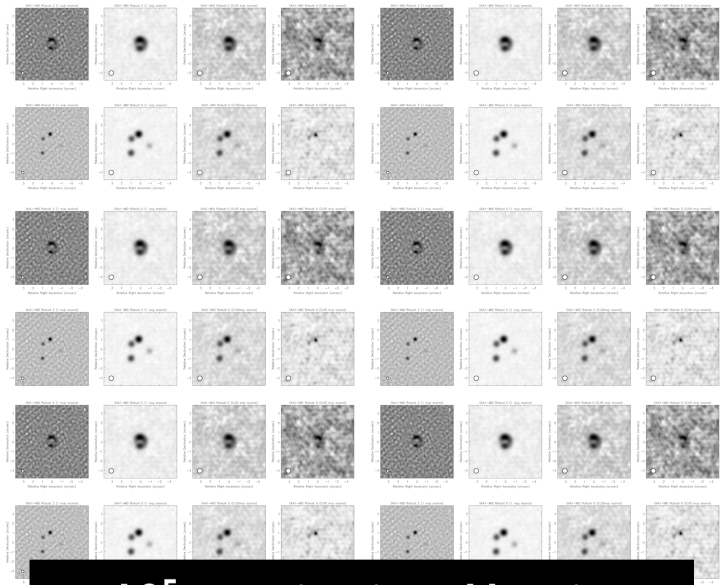
VLBI capability of SKA is fundamental

Future

What we need

Improved sensitivity (larger bandwidths + uv-coverage + larger recording rates)
Wide-field surveys + matched sky areas with optical surveys
Flexibility in observing frequency
VLBI mode for SKA



~10^5 gravitational lensing systems

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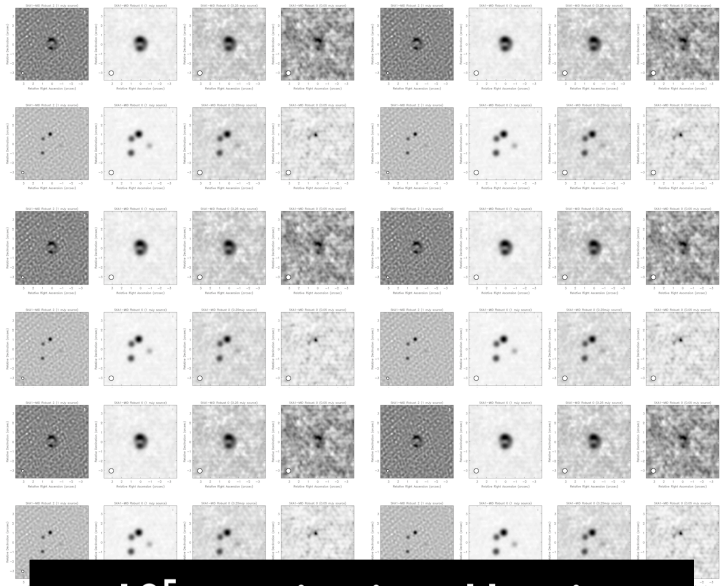

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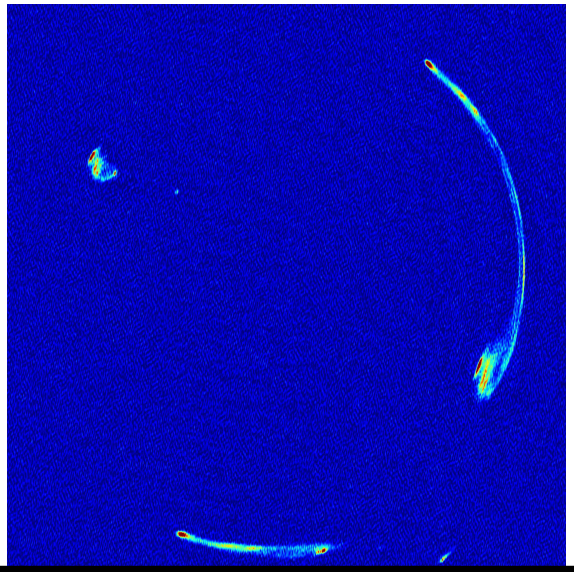

Lensing systems with variability and arcs

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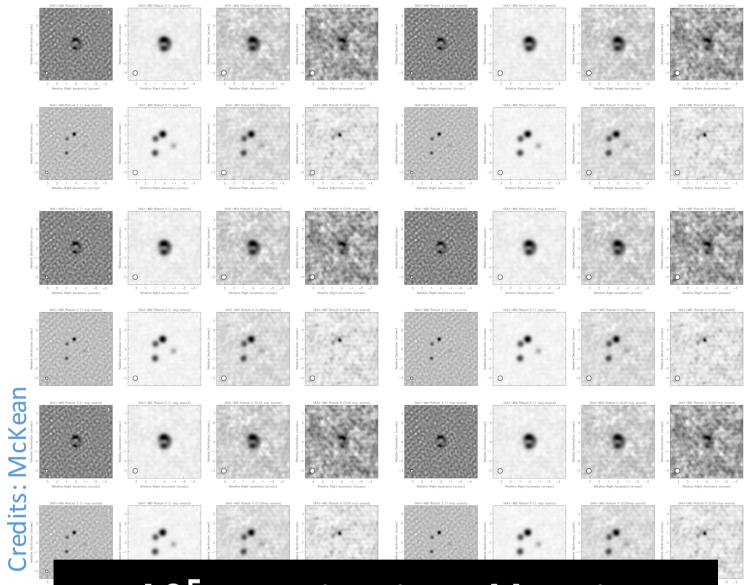
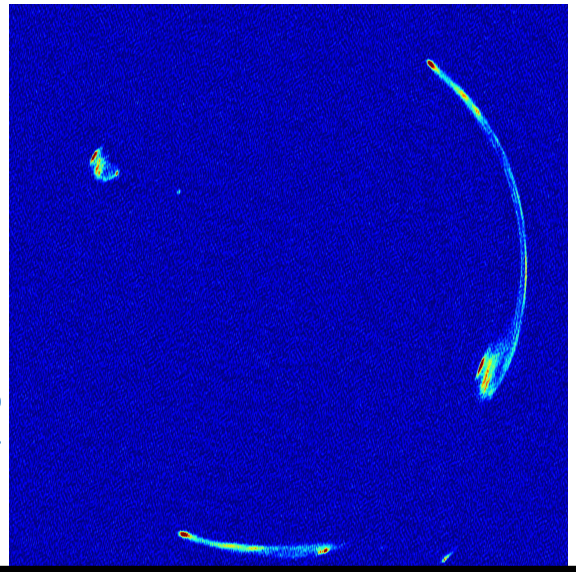


Credits: McKean

~10^5 gravitational lensing systems



Credits: Spingola

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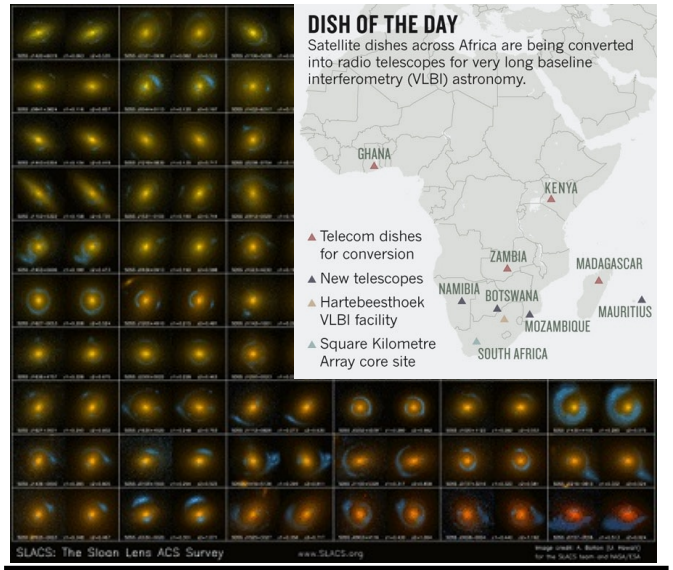
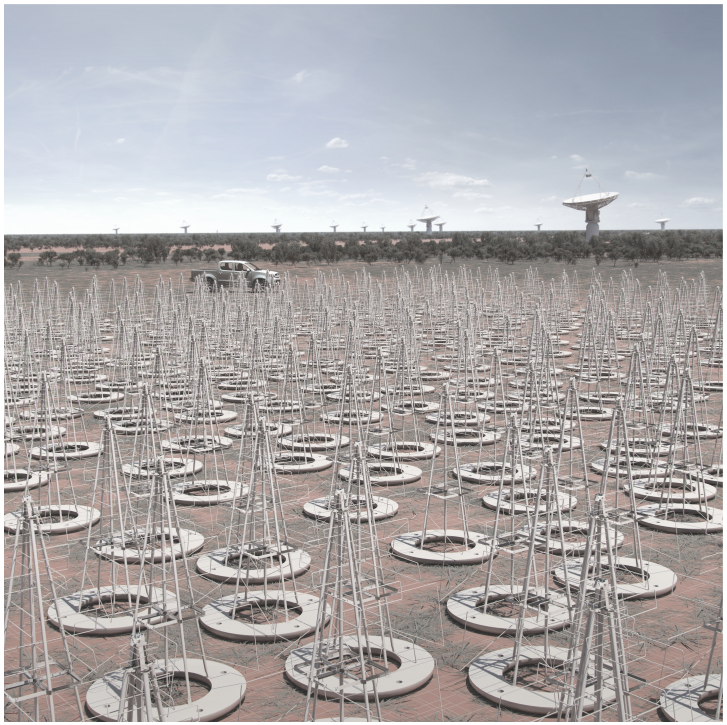


Credits: Bolton

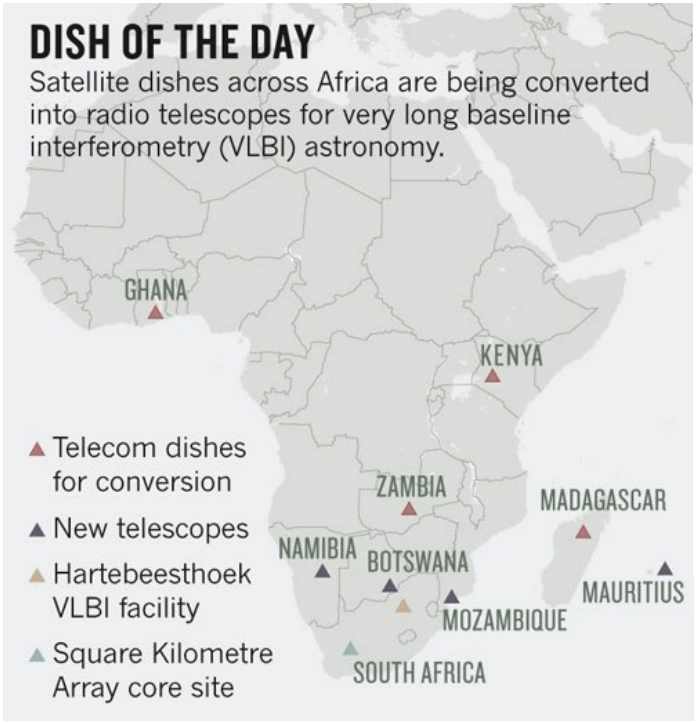
Sensitivity & Synergy with Euclid and LSST

Future

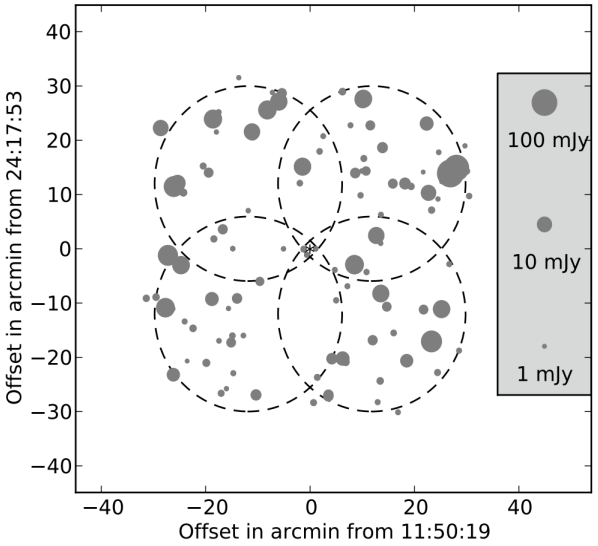
Improved sensitivity
Wide-field survey mode



SKA-MID low frequency antennas



Africa VLBI Network



Example of Wide-Field pointings
[Deller & Middleberg 2014]