Max-Planck-Institut für Astrophysik

Lens modelling with synthesis imaging data

Strong lensing meets interferometry

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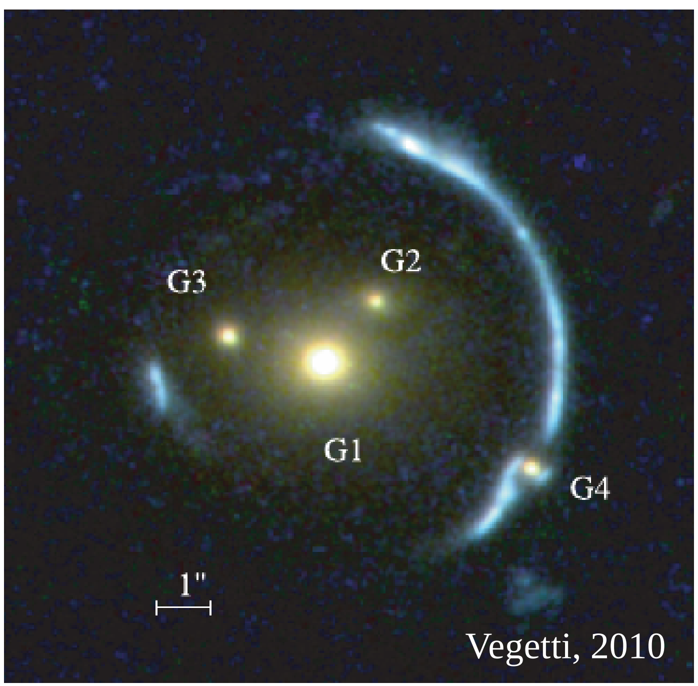
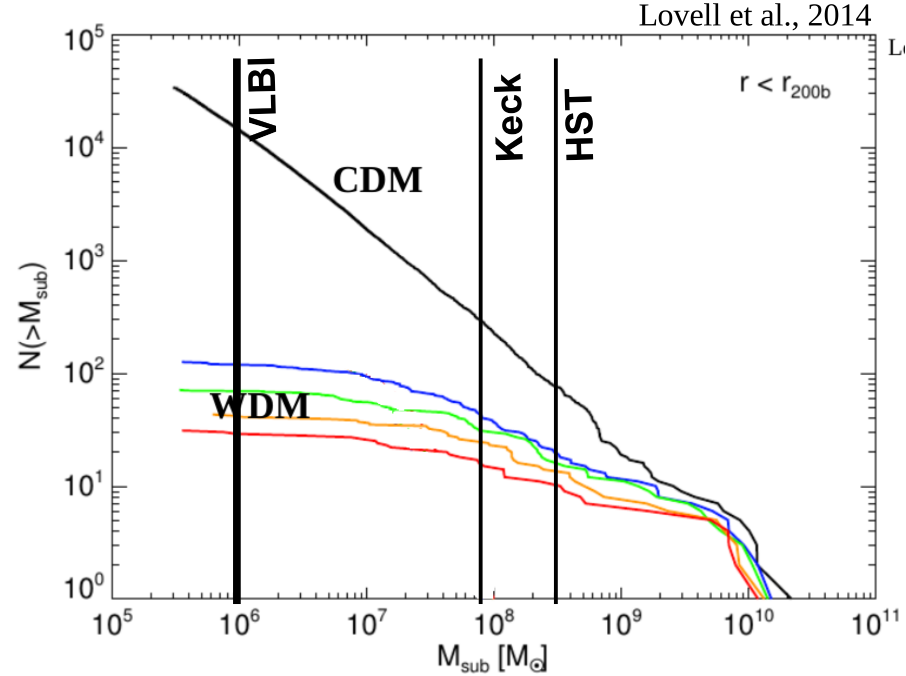
Kavli IPMU, 18/11/2014

Why interferometry?

- Detection limit: $\boldsymbol{r_E \sim \Delta\theta}$
- Long baselines – high resolution! $\boldsymbol{\Delta\theta = \lambda/D}$
- Radio: extinction & microlensing negligible
- HST: ~ 50 mas, Keck (AO): ~40 mas
- Full ALMA: ~10 mas @ 680 GHz, Global VLBI: sub-mas!

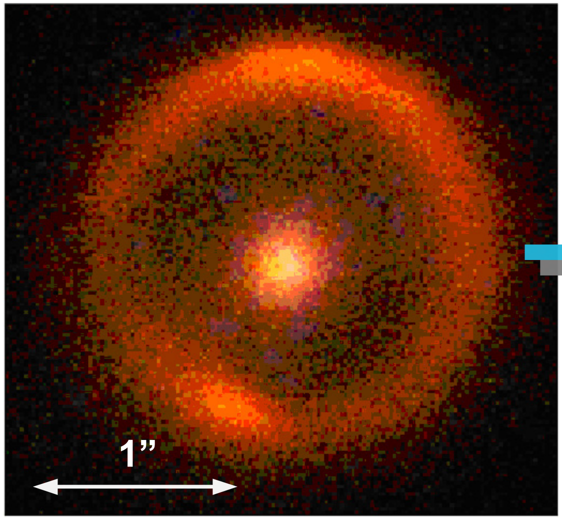


Lovell et al., 2014

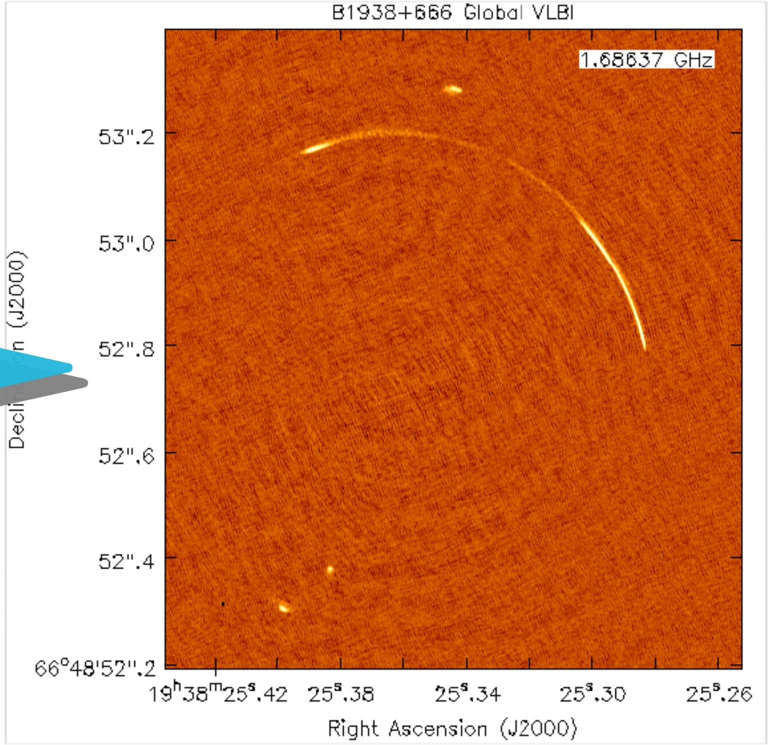


B1938+666: Keck vs. Global VLBI

Keck, K-Band



Lagatutta et al., 2012



Courtesy of John McKean

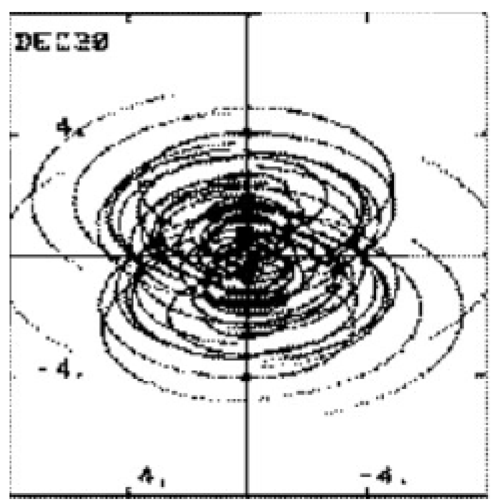
Visibility space

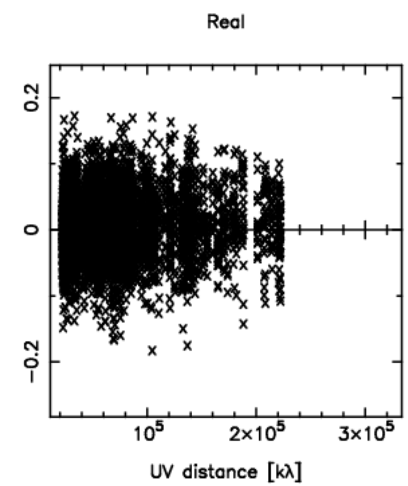
- Interferometers measure the ***visibility function V(u,v)***:

$$V(u,v) = \iint I(l,m) e^{-2\pi i[ul+vm]} dl dm$$

- 2D Fourier transform of the sky brightness distribution $I(l,m)$
- *UV* plane coverage: we measure *V(u,v)* only where the baselines are

+





Plan of attack

Visibility fitting

+

Parametric lens model

(r_E, axis ratio, orientation, lens position, density profile & shear)

+

Pixellated source

+

Substructure

(just not yet)

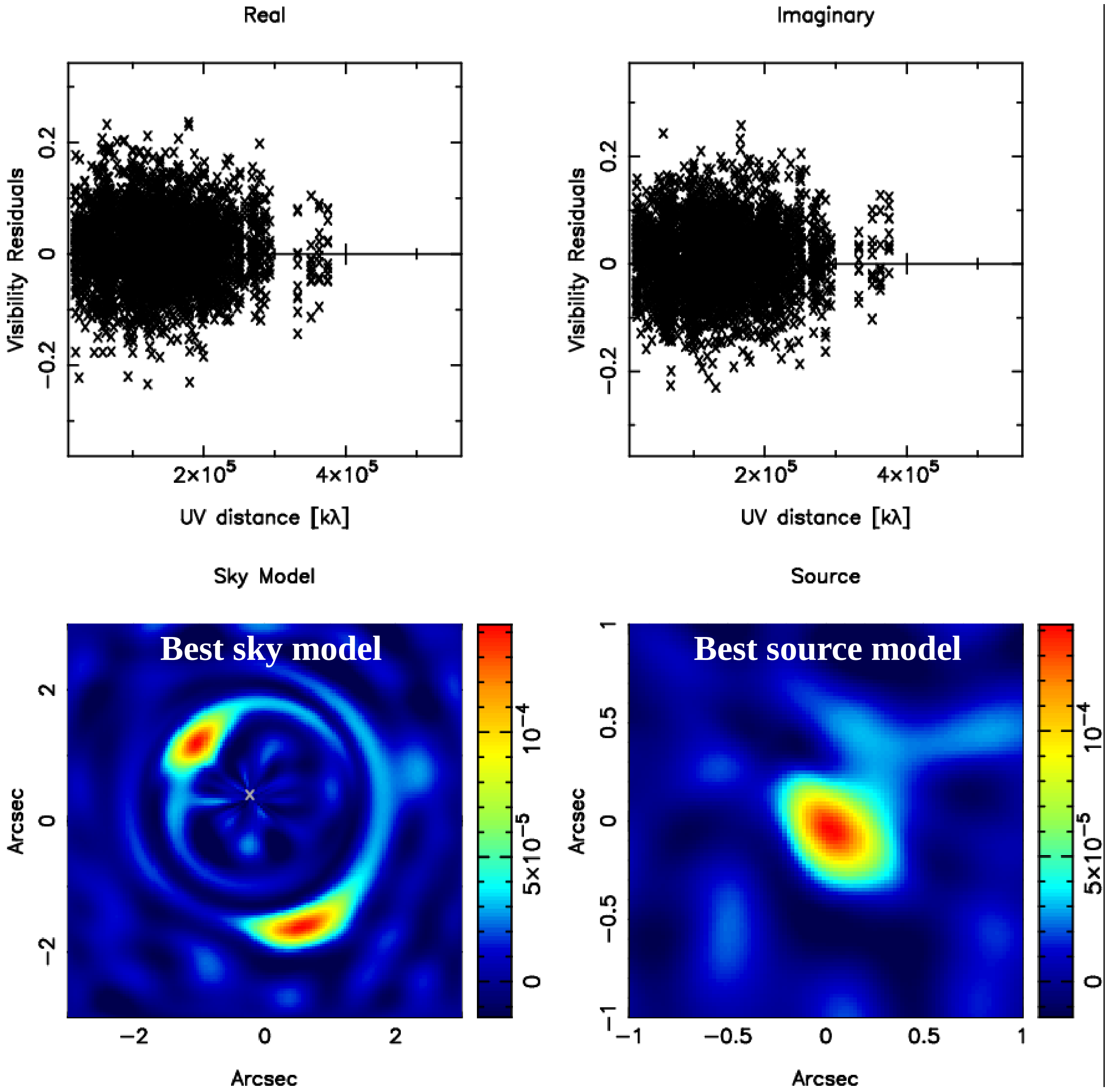
Lens modeling in the *UV*-plane

- Starting point: Vegetti & Koopmans, 2009

- **Best model: minimize a penalty function = χ^2** (real & imaginary visibilities) **+ regularization** (source/image plane)

$$P(s \mid \eta, \lambda, s_{n-1}, \psi_{n-1}) = \chi^2 + \lambda_s \parallel H_s s \parallel_2^2$$

- *V(u,v)* noise: assumed to be Gaussian and non-correlated
- Can be extended to account for the beam profile, non-coplanar arrays etc.


Real
Imaginary
Visibility Residuals
UV distance [kλ]
Sky Model
Source
Best sky model
Best source model
Arcsec
10^−4
5×10^−5
0

Real data! - ALMA Cycle 0

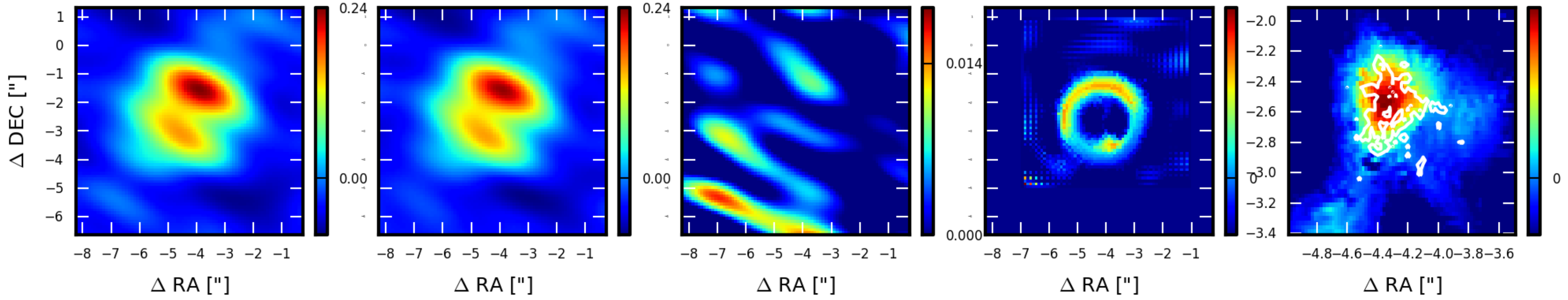
- ALMA Cycle 0 @ 350 GHz, Project No: 2011.00958.S,
- 30+ dusty star-forming galaxies, $z = 2 - 5$

- **Hezaveh et al., 2013**
  - **lens modelling with visibility fitting** (compact array)
  - sources are symmetric Gaussians blobs, lens: SIE

- 14-16 antennas, 2 resolution levels:
  - Compact configuration: $\Delta\theta \approx 1.5''$, 60-90 s integration
  - Extended Configuration: $\Delta\theta \approx 1.0''$, 60 s integration
- Redshifts, multiband analysis etc.: Vieira et al., 2013, Bothwell et al., 2013

SPT 0418-47, z = 4.224

Compact array, $\Delta\theta \approx$ 2.0”x1.0”, ~90 s integration

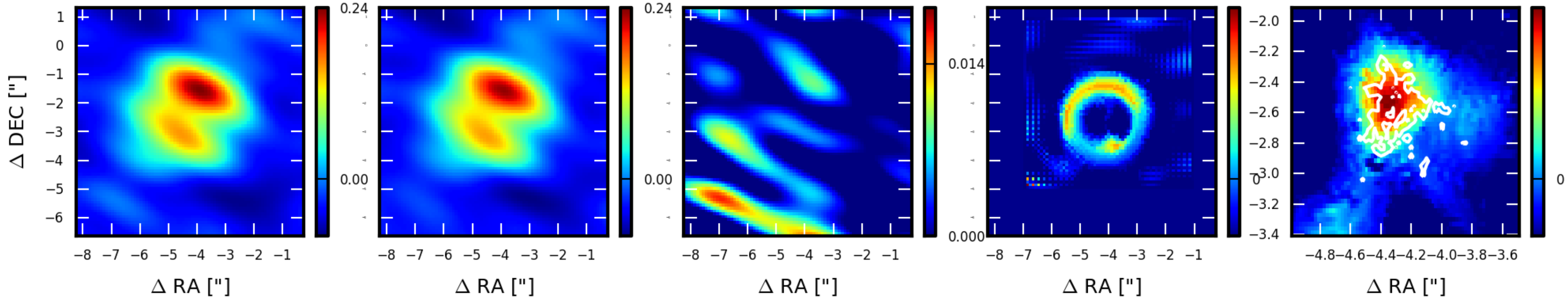


Dirty image data | **Dirty image model** | **Dirty image residuals** | **Best model - sky** | **Best model – Source + 95% confidence contour**

$$I^D(l,m) = \sum_k V(u_k, v_k) e^{+2\pi i [u_k l + v_k m]}$$

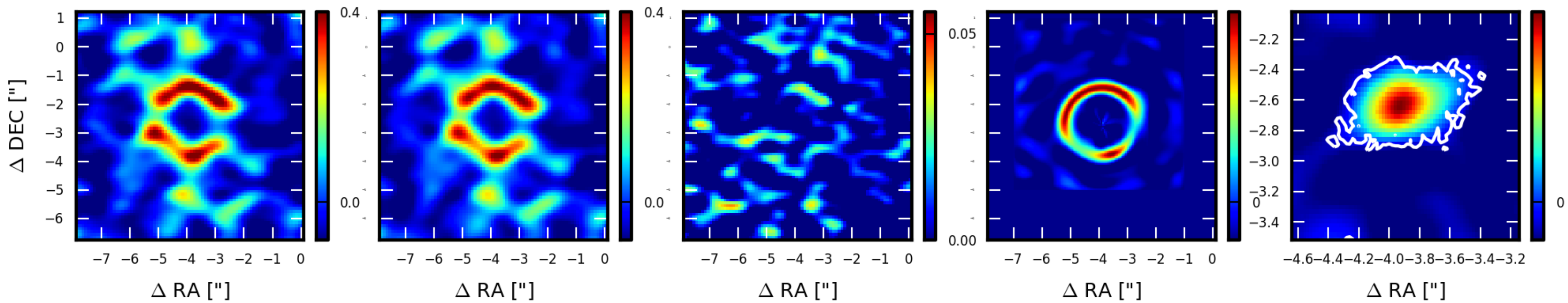
SPT 0418-47, *z* = 4.224

Compact array, *Δθ* ≈ 2.0”x1.0”, ~90 s integration



Object	z_L	z_S	b ["]	f	θ [deg]	γ	μ
SPT 0418-47	0.265	4.225	1.31±0.06 (1.390±0.012)	0.67±0.04 (0.80±0.03)	19	1.96	25.6 (21.0±3.5)

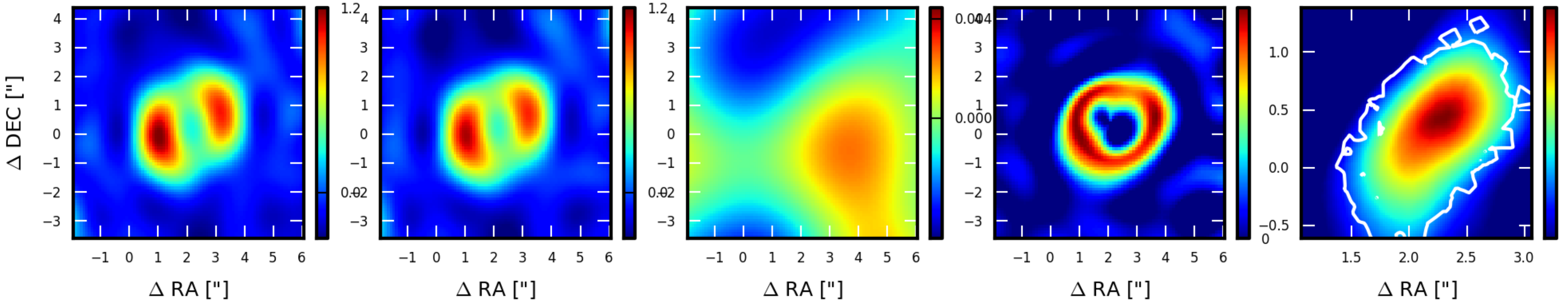
Extended array, *Δθ* ≈ 1.0”x0.6”, ~60 s integration



Object	z_L	z_S	b [arcsec]	f	θ [deg]	γ	μ
SPT 0418-47	0.265	4.225	1.26	0.75	22	1.93	16.8

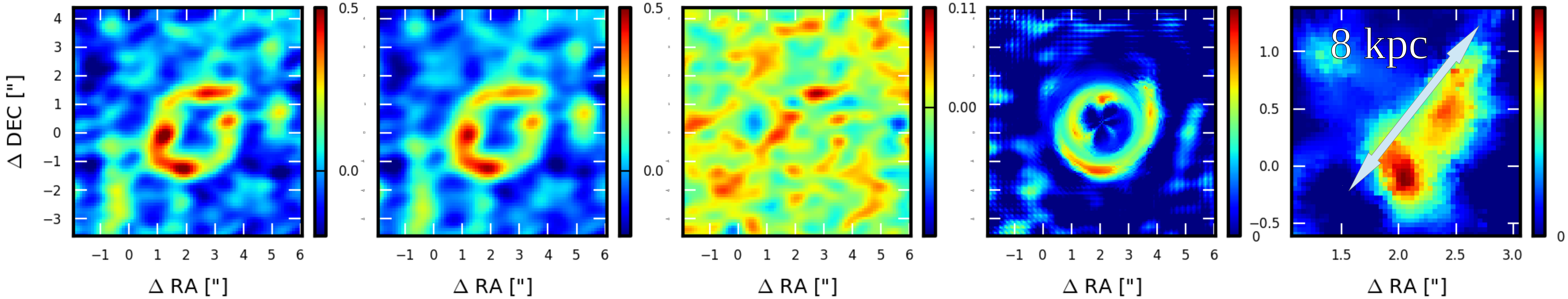
SPT 0529-54, z = 3.369

Extended array, $\Delta\theta \approx$ 1.5”x1.0”, ~60 s integration



Object	z_L	z_S	b ["]	f	θ [deg]	γ	μ
SPT 0529-54	0.140	3.369	1.34±0.06 (1.536±0.017)	0.93±0.03 (0.90±0.03)	3	2.00	8.3 (9.4±1.0)

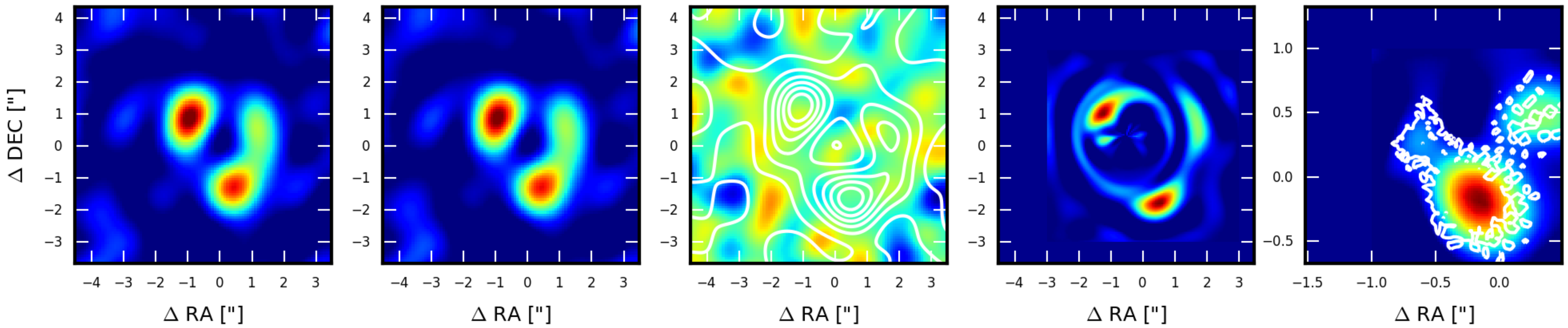
Extended array, $\Delta\theta \approx$ 1.0”x0.6”, ~60 s integration, poor SNR



Merger?

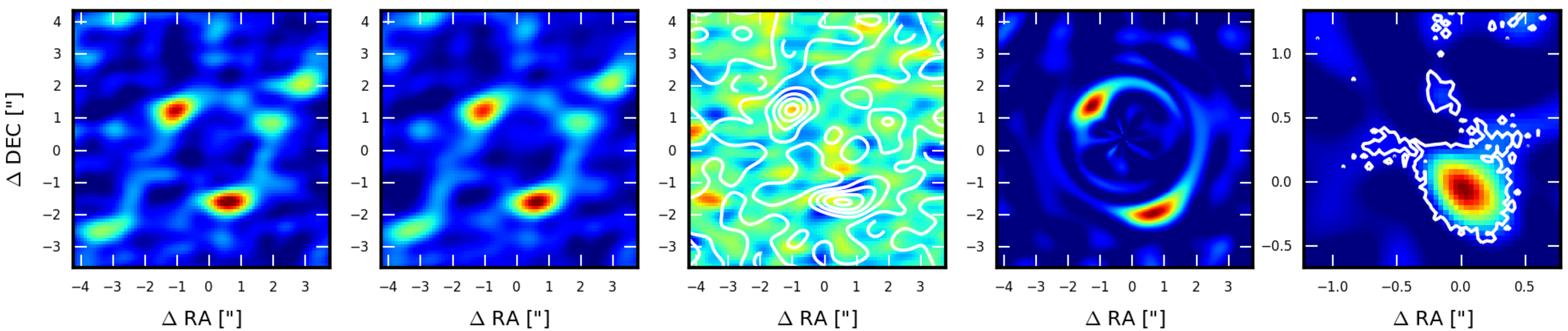
SPT 0538-50 (z=2.873)

Compact array, beam size ~1.5”x1.0”, ~90 s integration



Object	z_L	z_S	b ["]	f	θ [deg]	γ	μ
SPT 0538-50	0.404	2.782	1.59±0.05 (1.987±0.009)	0.89±0.02 (0.87±0.02)	92±6	2.02	9.3 (20.5±4.0)

Extended array, beam size ~1.0”x0.6”, ~60 s integration

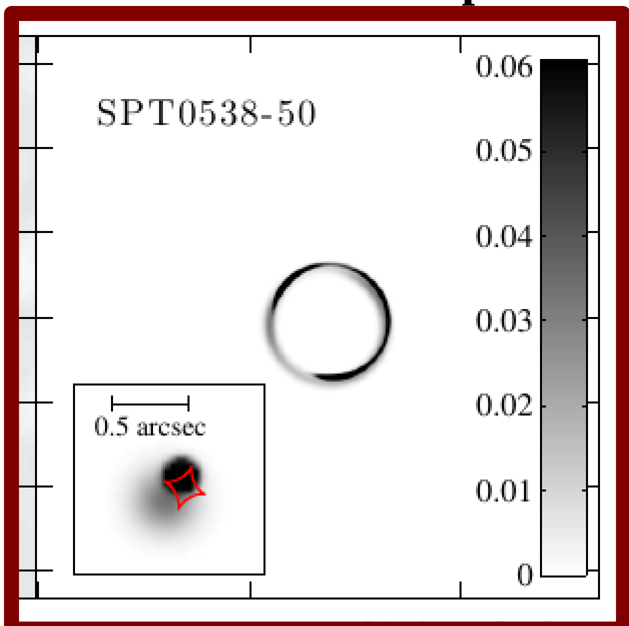


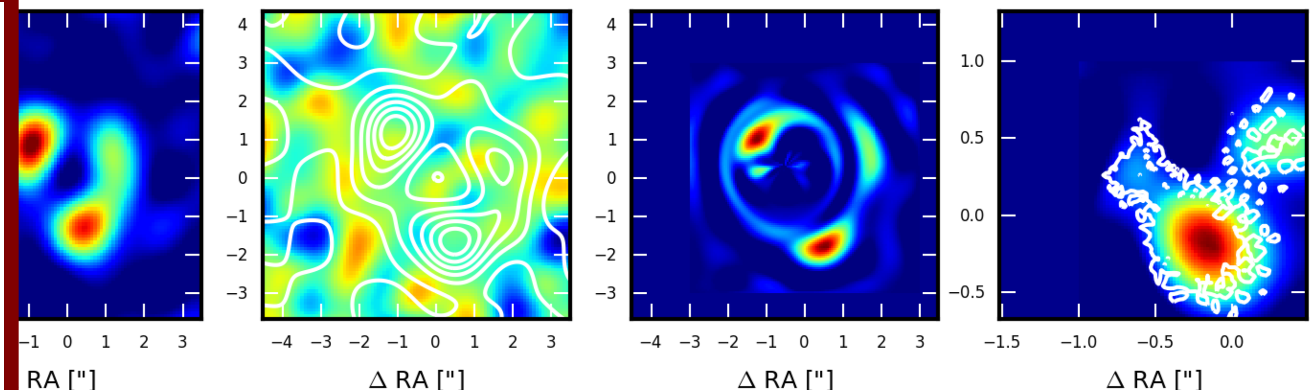
Object	z_L	z_S	b [arcsec]	f	θ [deg]	γ	μ
SPT 0538-50	0.404	2.782	1.62	0.88	85	2.02	8.9

SPT 0538-50 (*z*=2.873)

Compact array, beam size ~1.5”x1.0”, ~90 s integration

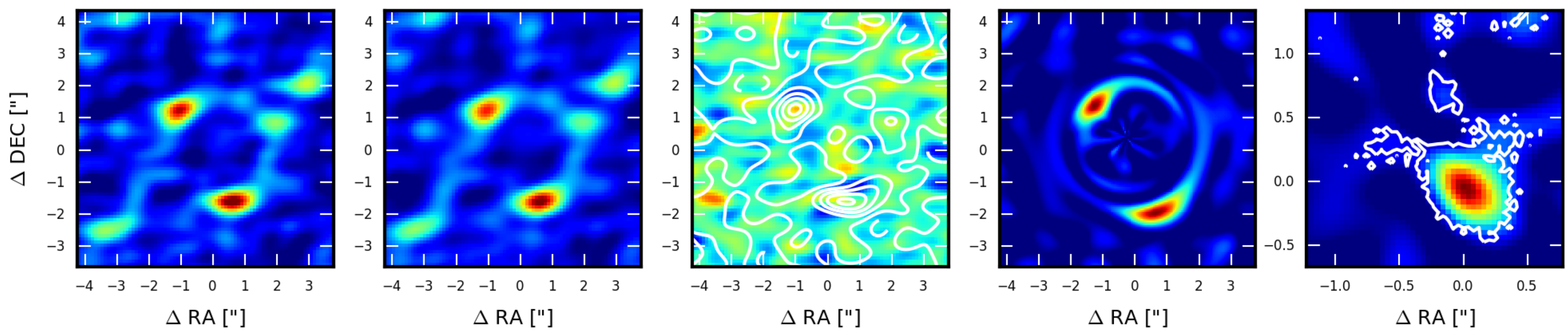
Hezaveh et al., 2013





b ["]	f	θ [deg]	γ	μ
±0.05 (1.987±0.009)	0.89±0.02 (0.87±0.02)	92±6	2.02	9.3 (20.5±4.0)

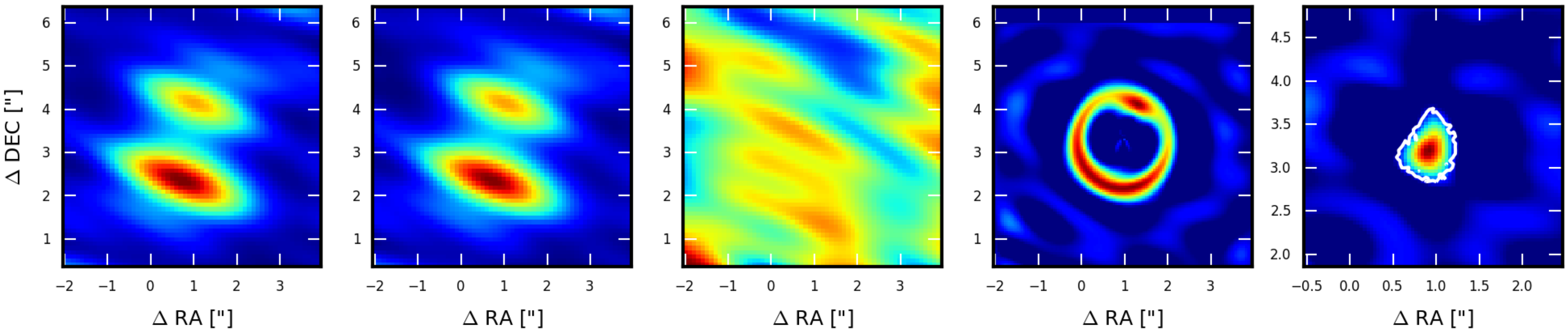
Extended array, beam size ~1.0”x0.6”, ~60 s integration



Object	z_L	z_S	b [arcsec]	f	θ [deg]	γ	μ
SPT 0538-50	0.404	2.782	1.62	0.88	85	2.02	8.9

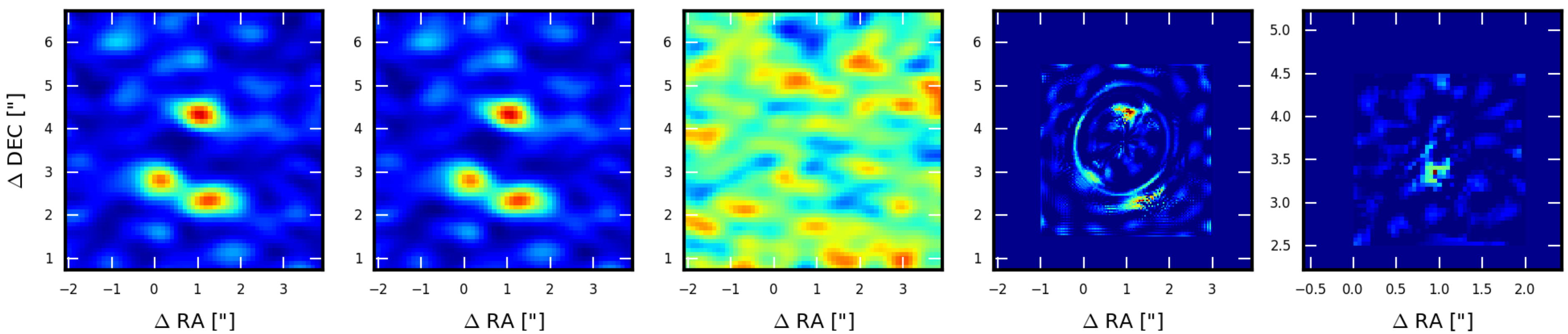
SPT 0346-52 (z = 5.656): when things go awry

Compact array, beam size ~1.5”x1.0”, ~90 s integration



Object	z_L	z_S	b [″]	f	θ [deg]	γ	μ
SPT 0346-52	? (0.8)	5.656	1.10±0.07(1.124 ± 0.004)	0.74±0.01(0.55 ± 0.01)	-22	1.99	13.9 (5.4±0.2)

Extended array, beam size ~1.0”x0.6”, ~60 s integration



Object	z_L	z_S	b [arcsec]	f	θ [deg]	γ	μ
SPT 0346-52	? (0.8)	5.656	1.08	0.68	-31	2.00	14.2

Comparison with Hezaveh et al., 2013

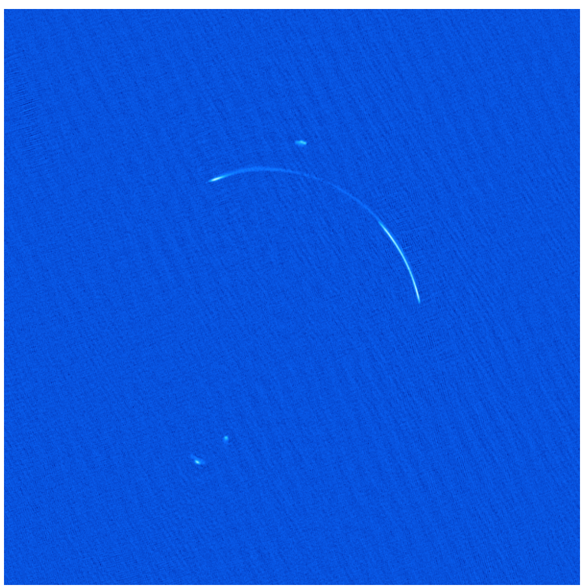
- Lens models largely agree within errors
- Different magnifications, similar lens models → non-symmetric and structures sources
- SPT 0346-52: two self-consistent lens solutions (f = 0.7 vs. f = 0.45)
  - ***f* - source position - Γ** degeneracy?
  - data quality too low to constrain models effectively?

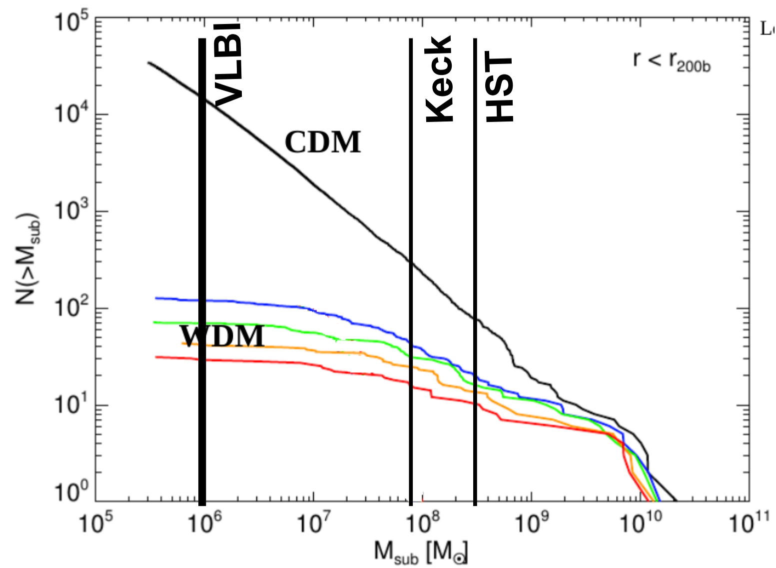
Back to the substructure!

- Adding pixellated potential perturbations:

$$P(s, \delta\psi \mid \eta, \lambda, s_{n-1}, \psi_{n-1}) = \chi^2 + \lambda_s \parallel H_s s \parallel_2^2 + \lambda_{\delta\psi} \parallel H_{\delta\psi} \delta\psi \parallel_2^2$$

- *VLBI* data - huge datasets: (10^8 vs. 10^4 for ALMA)
  - Multi-threading
  - Interim solution: Average & split the data





Conclusions & future

- We can model smooth lenses & pixellated sources by directly fitting the visibility data
- Smooth modelling: starburst galaxies from ALMA Cycle 0, our results largely match previous work
- Near future: VLBI data – need to deal with very large datasets
  - In the meantime: try splitting/averaging