ALMA Imaging of SDP.81

Lens modelling in the age of ALMA

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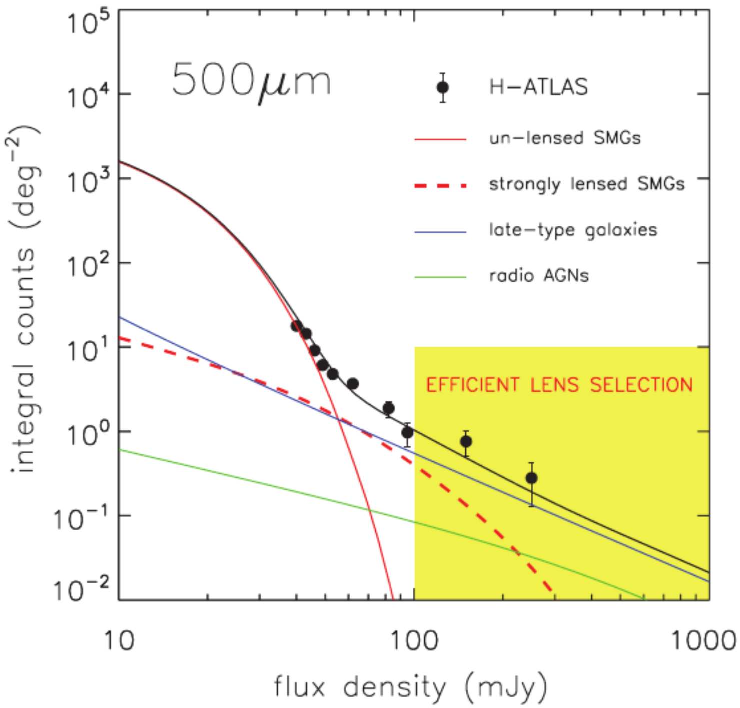
Outline

- Strong lensing at (sub)mm wavelengths
- Lens modelling:
  - **uv** plane or **image** plane?
  - Parametric or pixellated sources?
- SDP.81: continuum – dust distribution, SFR, temperature
- Low-res: ALMA Cycle 0 observations

Strong lensing in (sub)mm

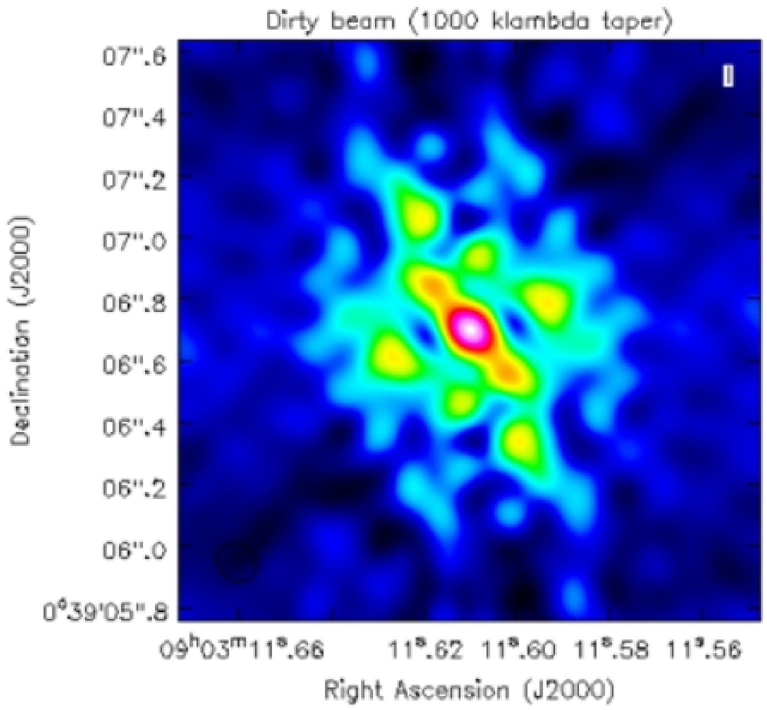
- Brightest sub-mm galaxies detected in high-flux tail of HerMES, H-ATLAS, SPT Survey samples are in fact ***strongly lensed*** (magnification factor of 10-50)
- High-redshift, dust-enshrouded starburst galaxies, $z = 2 – 5$
- Magnification factor of 20 → integration time of 1/400
- Easy to find!
- What can we do with them?
  - Background sources (dust & gas properties)
  - Foreground lenses (cosmology)

Negrello et al., 2010



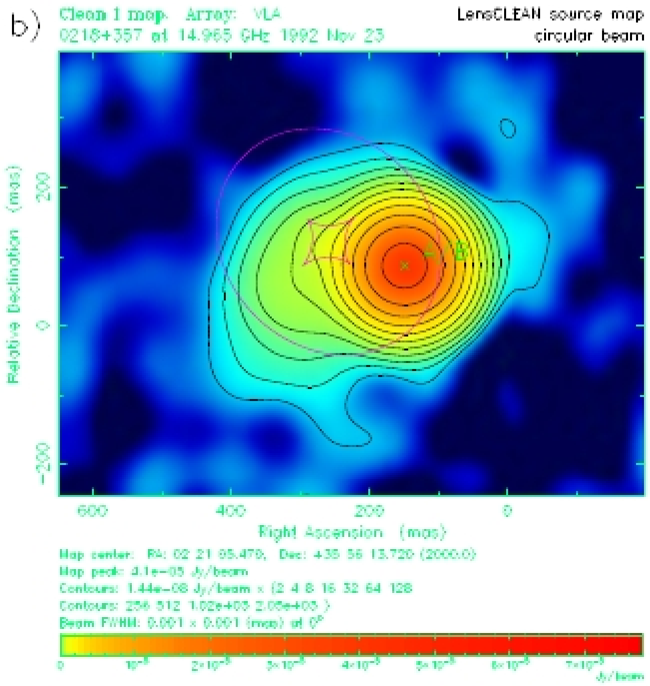
uv plane vs **image** plane

- Interferometric array measures the visibility function **V(u,v,w)**
- Going into the image plane:
  - Sidelobes
  - Extended structures not recovered properly
  - Surface brightness not conserved
  - correlated pixel-by-pixel noise
  - Results depend on deconvolution method, gridding, weighting, taper …
  - Emission lines: lower SNR due to narrower bandwidth → **especially tricky**



uv plane vs **image** plane

- Working in the visibility plane circumvents many of these issues
- Lens modelling via visibility-fitting:
  - **VLA:** LensCLEAN (O. Wucknitz, 2002, 2004)



Wucknitz, 2002

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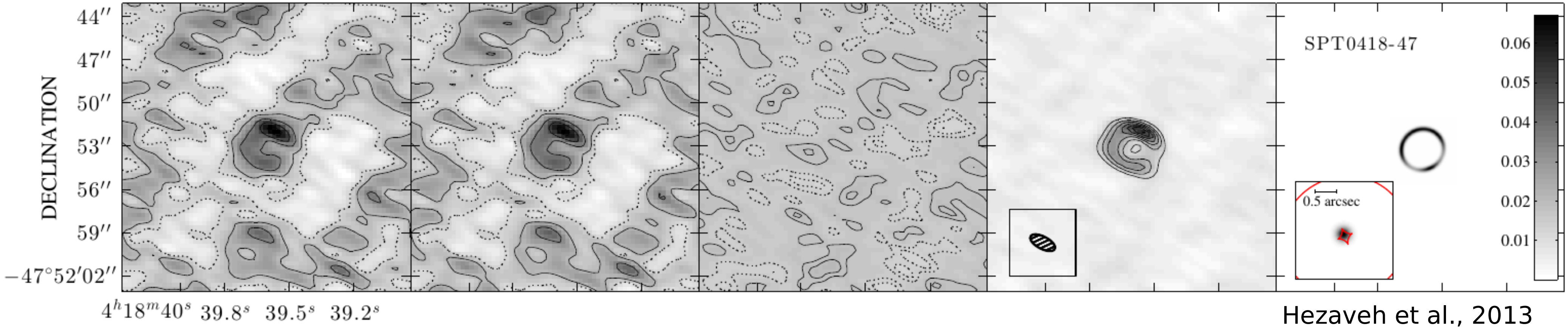
  - **ALMA:** Hezaveh et al., 2012, 2013



Hezaveh et al., 2013

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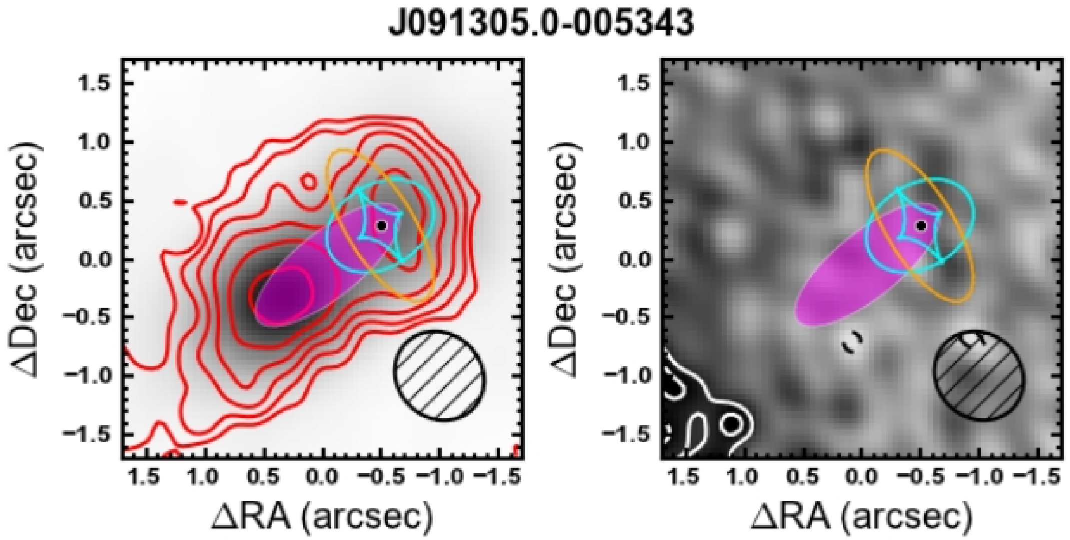

Bussmann et al., 2012

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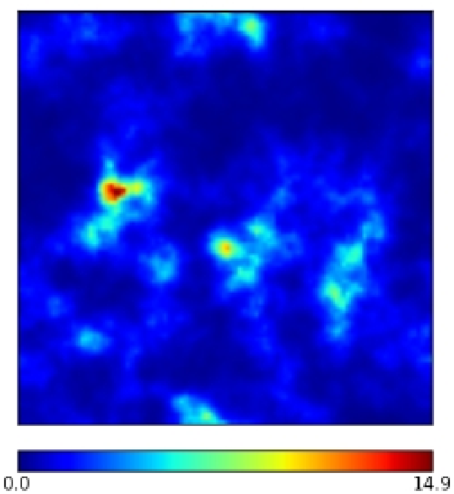
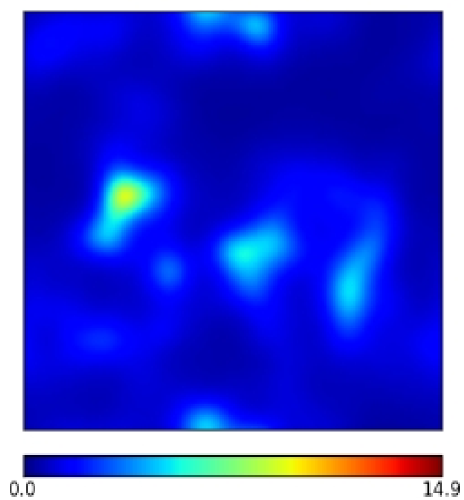
- Imaging: **RESOLVE** (Junklewitz et al., 2014)



(a) Signal.

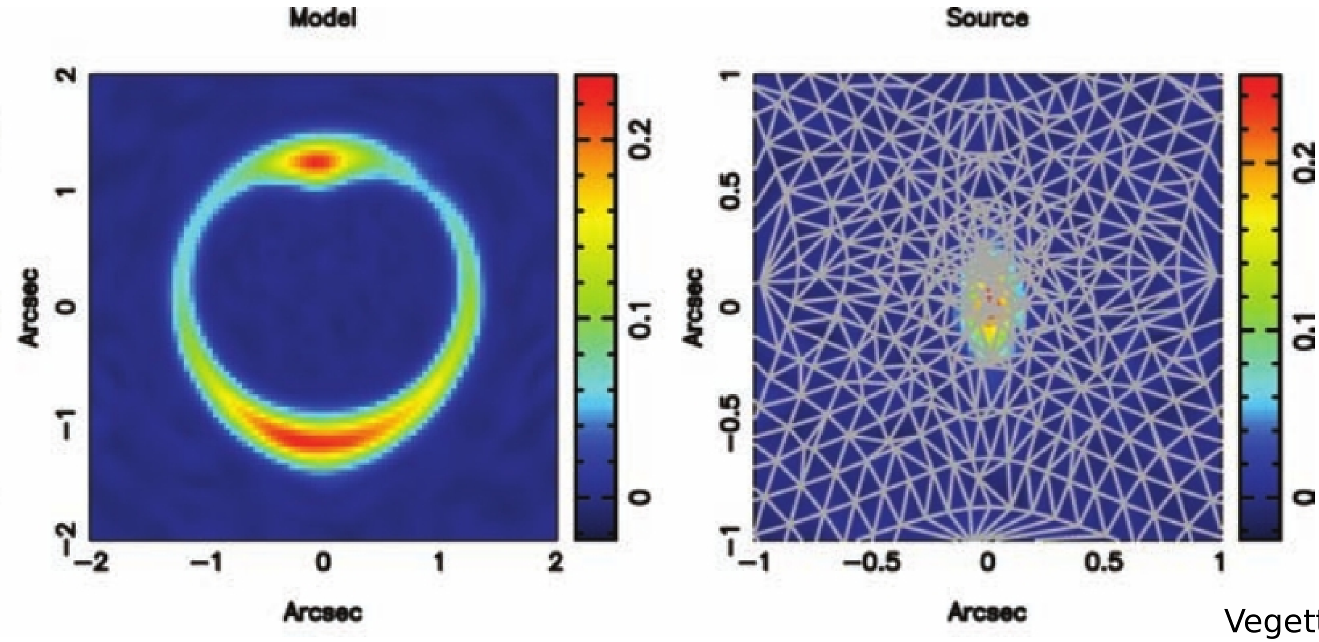


(e) RESOLVE reconstruction with high noise.

Junklewitz et al., 2014

Lens modelling in the **uv-**plane

- Extension of lens modelling technique of Vegetti & Koopmans (2009)
- Compare the model to data directly in the visibility space
- Lens model: Parametric + external shear
- Source surface brightness defined on an adaptive triangular grid → **pixellated source**



Vegetti & Koopmans, 2009

Lens modelling in the *uv* plane

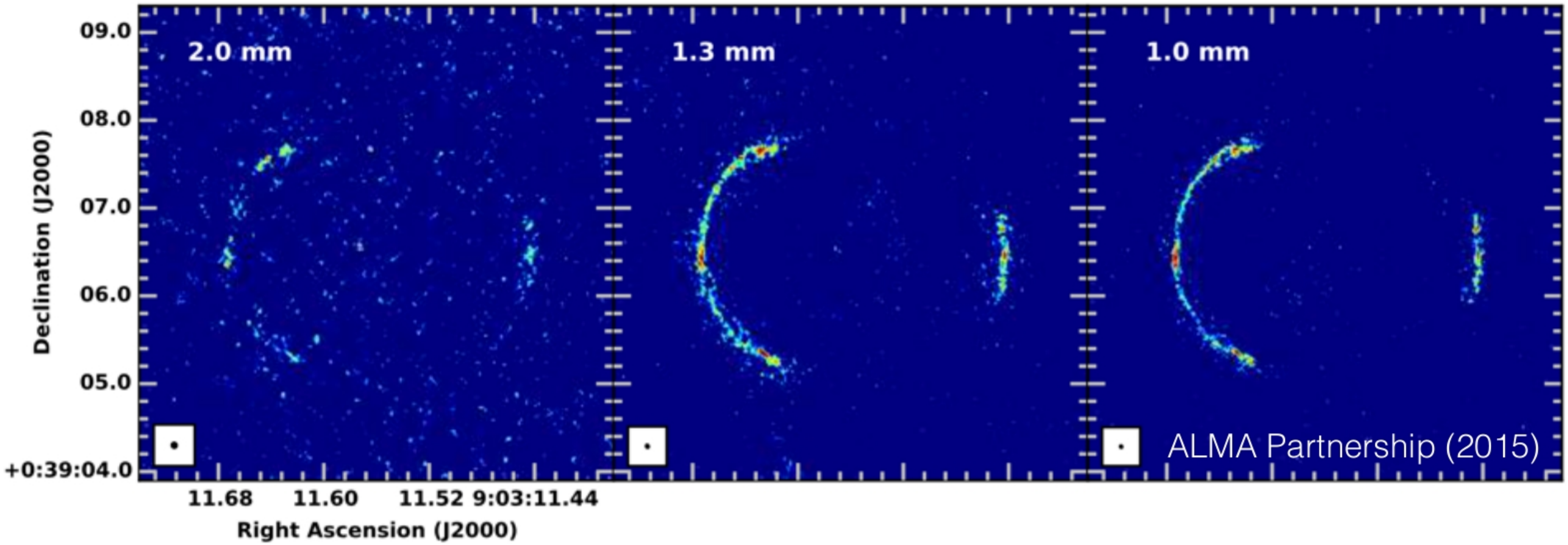
- **Best model: minimize a penalty function = χ^2** (real & imaginary visibilities) **+ regularization** (source/image plane)

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

- Visibility noise: calculated directly from the data, assumed to be Gaussian and non-correlated
- Source regularization: imposes certain degree of smoothness and prevents noise fitting

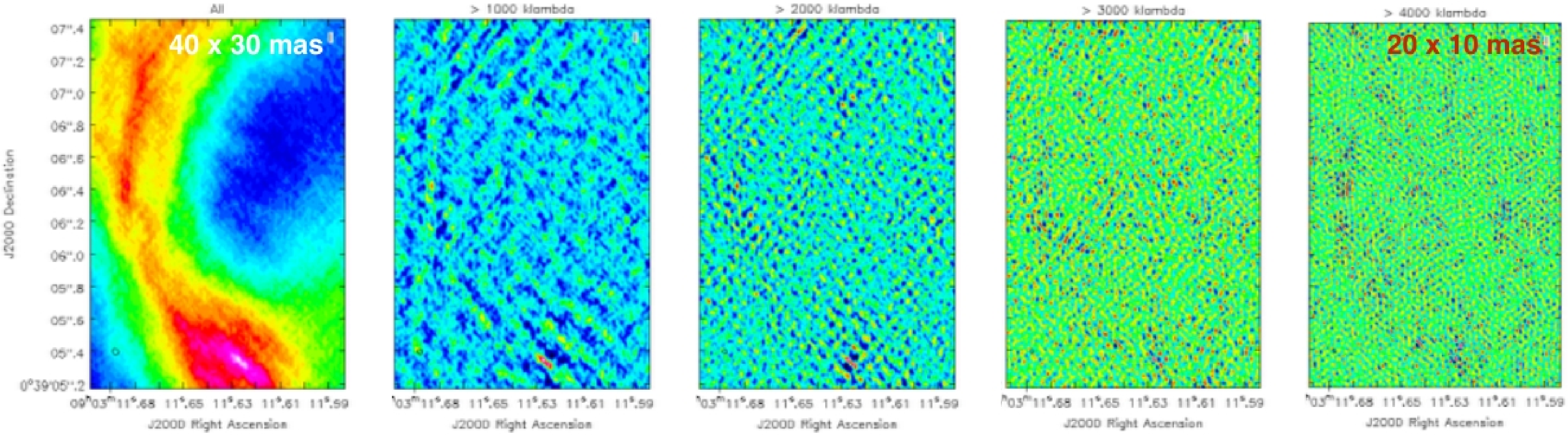
SDP.81 – continuum modelling
(Rybak et al., MNRAS submitted, 2015)

- ALMA Science Verification Long Baseline Campaign, October – November 2014
- Baseline length 15 m - 15 km, 4.5 – 5.5 hours on target
- 31 – 36 antennas
- Continuum: 140, 236, 290 GHz
- Molecular lines: CO (5-4, 8-7, 10-9), H2O (2-1)
- Full dataset contains ~10^8 visibilities



SDP.81 – continuum modelling
(Rybak et al., MNRAS submitted, 2015)

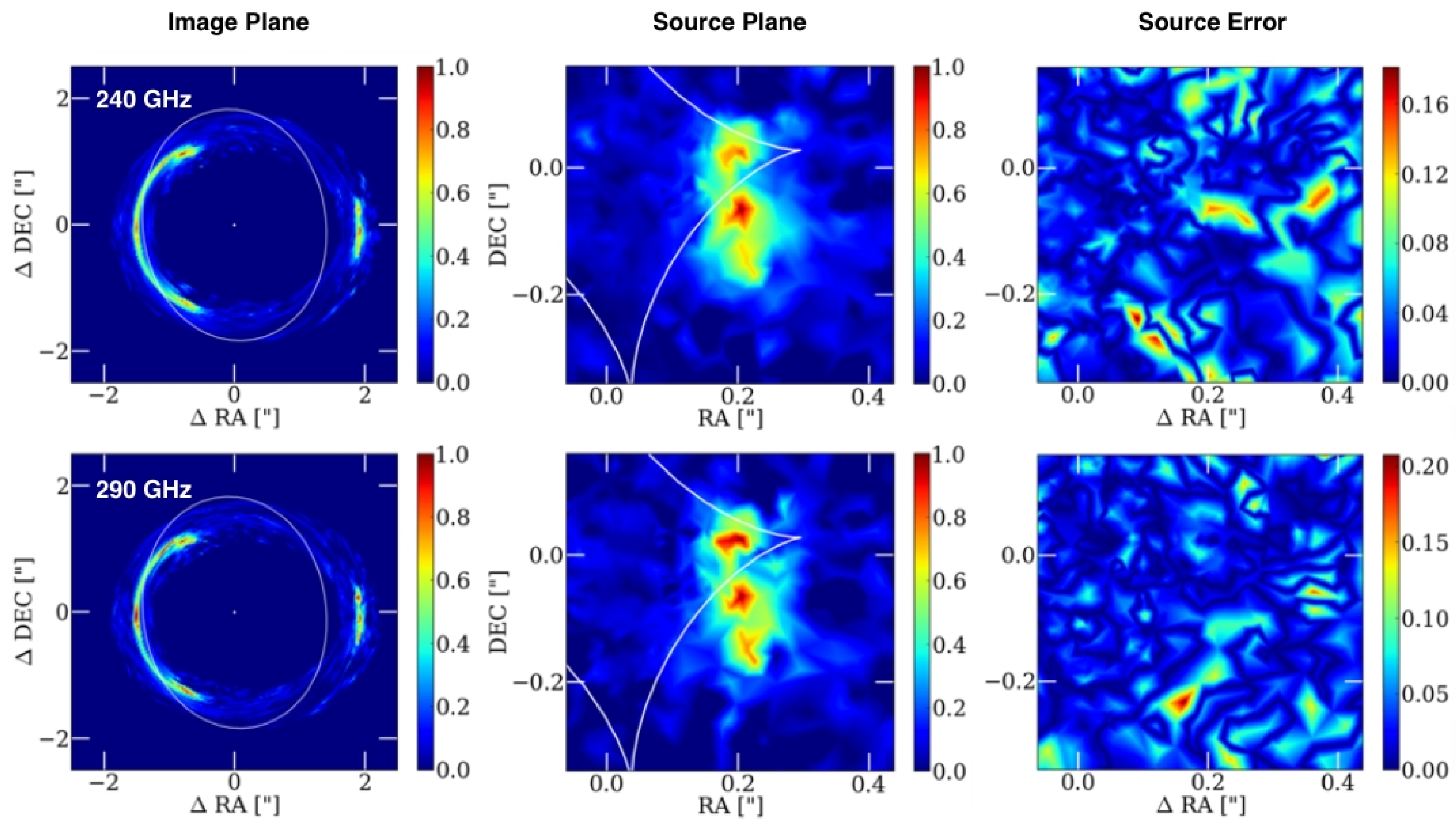
- Most structure is resolved out on the longest baselines (> 5,000 kλ)
- **uv** cut at 2,000 kλ provides a good compromise between SNR and resolution
- Time averaging: 20s, each SPW collapsed into a single channel
- ~10^5 visibilities per SPW left: much more manageable!
- Beam size 95 x 71 mas



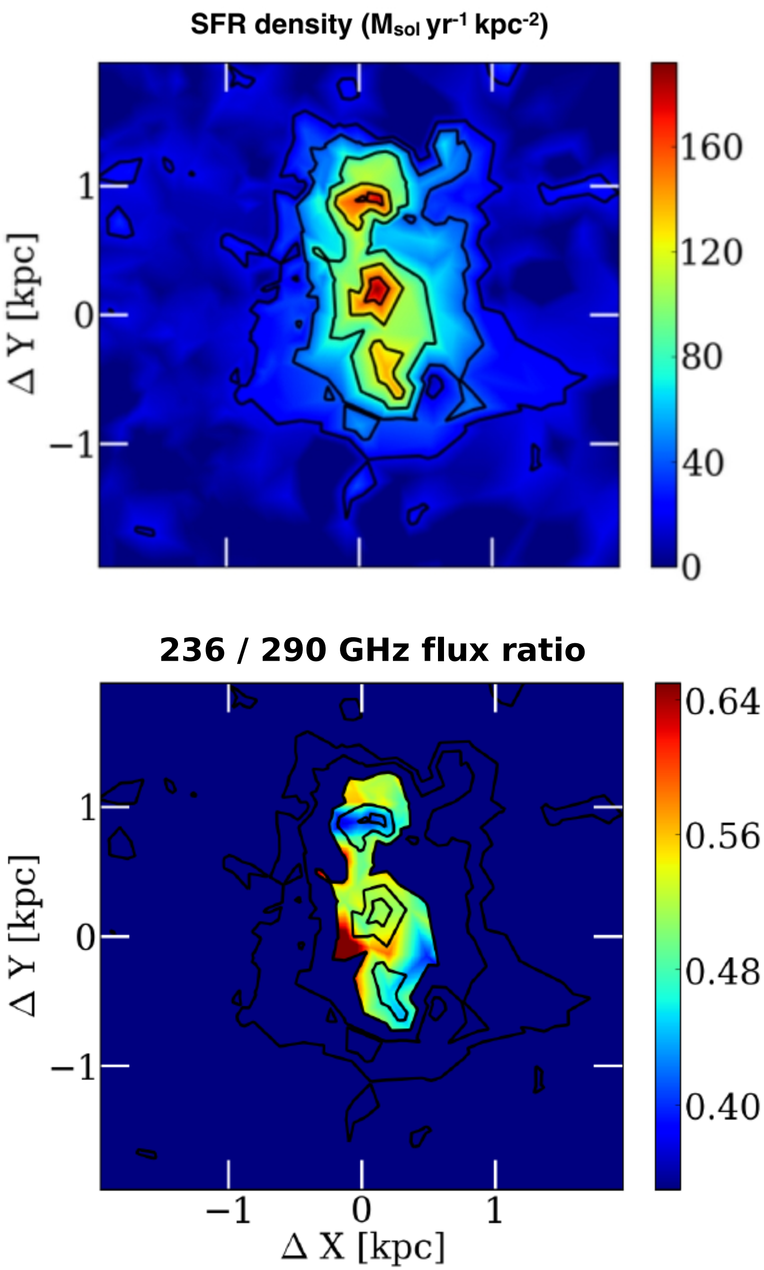
SDP.81 – continuum modelling

- **Lens model:** first guess based on CLEANed data, fine-tuning in the visibility space

κ_0 (arcsec)	q	θ [deg]	γ	Γ	Γ_θ [deg]
1.606±0.005	0.82±0.01	8.3±0.4	2.00±0.03	0.036±0.004	3.0±0.2

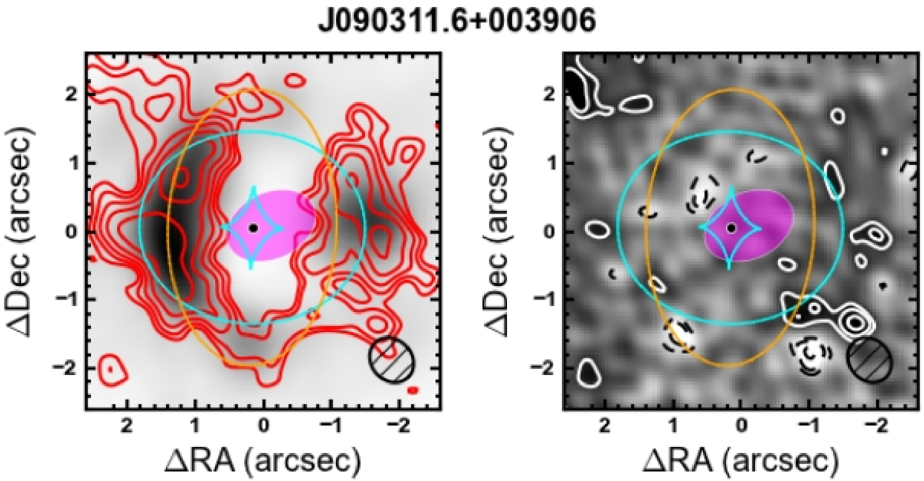


Dust properties



- Bands 6 and 7 (1.3 and 1.0 mm)
- **<50 pc resolution in the source plane**
- Similar morphology
- **μ = 17.6±0.4** (central part: μ = 25.2±2.6)
- Magnification varies across the source!
- Get SFR by correcting the spectral energy distribution fit (Negrello et al., 2010) for magnification + Kennicutt relation
- Total **SFR of 315 = 60 M⊙/yr**
- Extended region with SFR density of 20 – 30 M⊙/yr/kpc^2
- Three clumps of intense star formation (>100 M⊙/yr/kpc^2)
- **236 GHz/290 GHz flux ratio** indicates varying temperature / optical depth across the source

SDP.81 – comparison with previous models

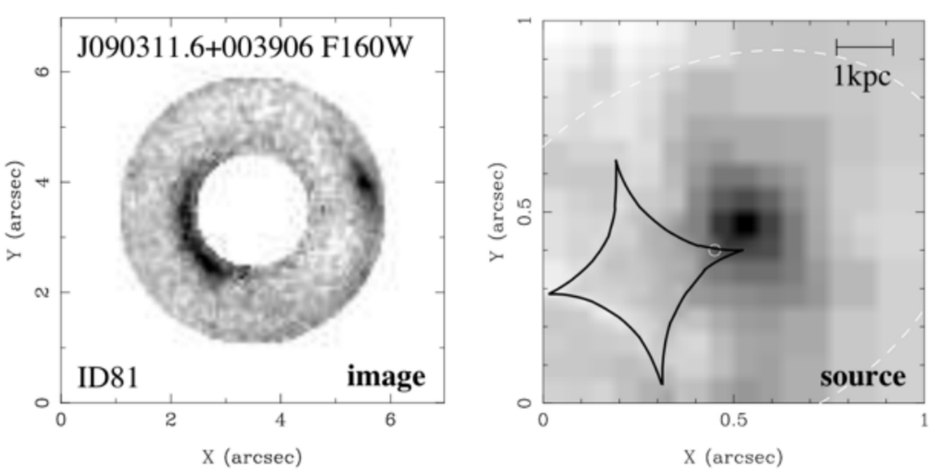


Bussmann et al., 2012

SMA 340 GHz (880 um)

Single Sersic profile, Re = 4 kpc

μ = 11 ± 1



Dye et al., 2015

HST 1.1 & 1.6 um

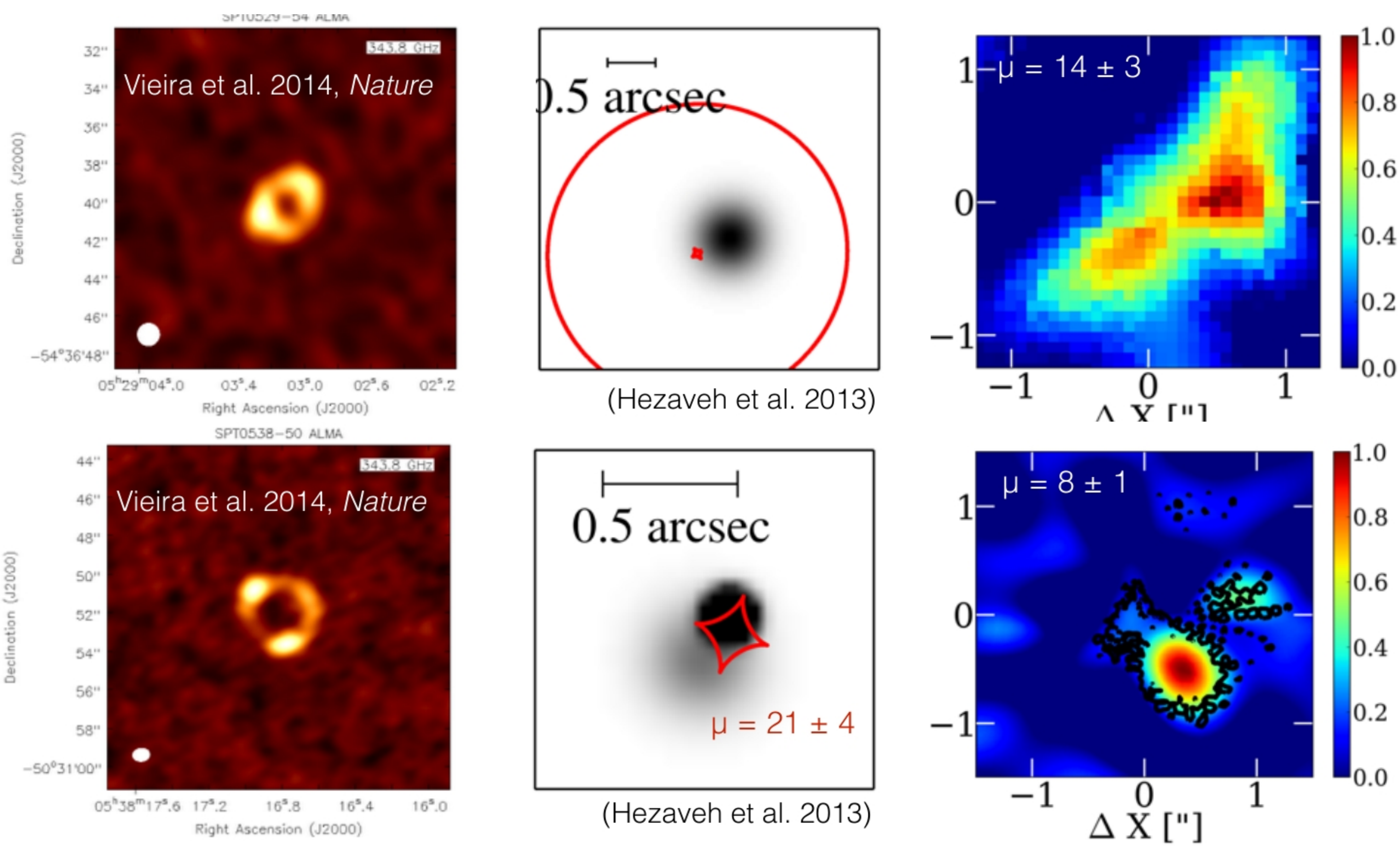
Pixellated source: Re = 1kpc

μ = 10 ± 1

Lower resolution data: ALMA Cycle 0

(Rybak, Vegetti & McKean, in prep.)

- Case study: four SPT lenses, redshift 2.8 – 5.7 (Vieira et al., 2014)
- compact + extended array (resolution 1.0”-2.0” and ~0.5” respectively)
- Reconstructions by Hezaveh et al., 2013: **visibility fitting + parametric sources**



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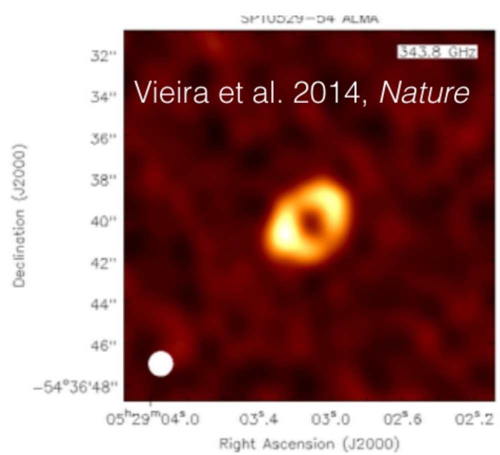

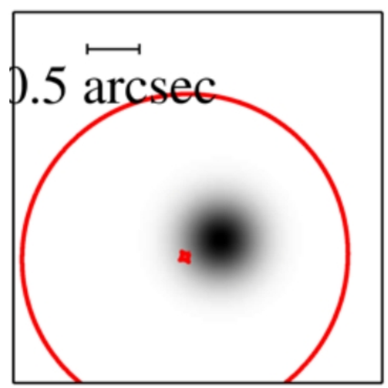

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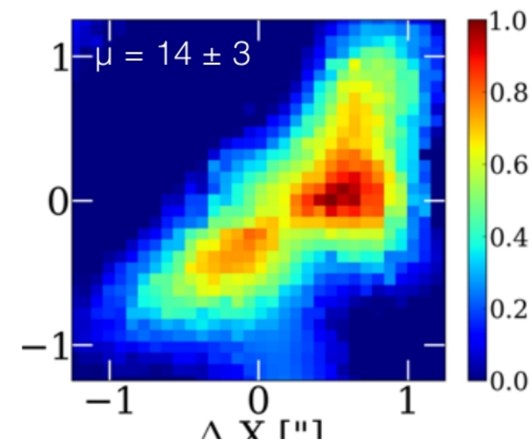

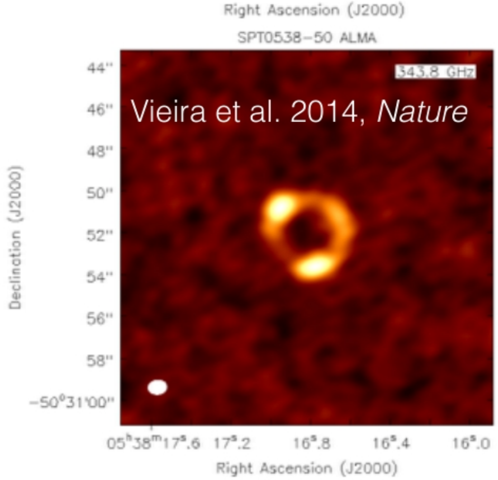

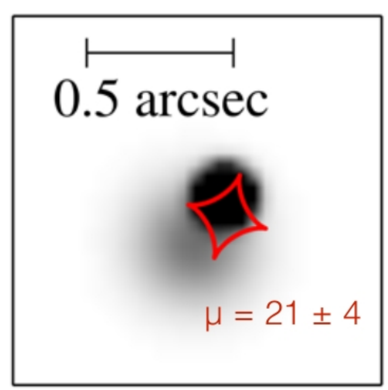

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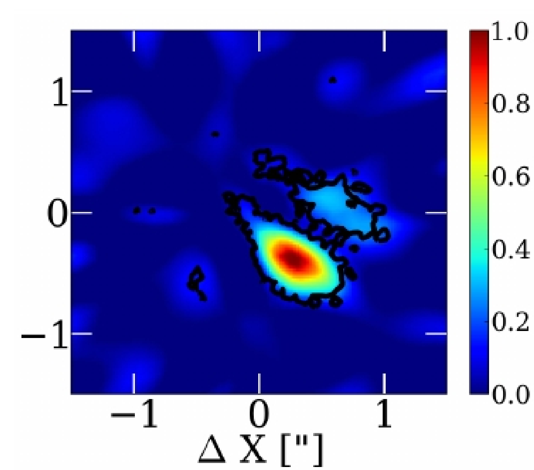

Lower resolution data: ALMA Cycle 0
(Rybak, Vegetti & McKean, in prep.)

- Case study: four SPT lenses, redshift 2.8 – 5.7 (Vieira et al., 2014)
- ALMA Cycle 0, compact + extended array (max. resolution 0.5”)
- Reconstructions by Hezaveh et al., 2013: **visibility fitting + parametric sources**
- Significant source structure in 2 out of 4 cases → mergers?
- **Magnifications estimates modified by up to a factor of 2**
  - Significant changes in intrinsic luminosity and SFR

- Pixellated models allow us to recover source structure and provide better estimates than simple parametric models
- Especially important for high resolution observations

Conclusions

- Strong lensing + interferometry allow us to study high-redshift objects in great detail!
- Lens modelling using CLEANed data introduces severe bias in the source during the deconvolution process: **need to fit the visibilities directly**
- Sources are highly structured → **pixellated sources**
- **SDP.81**
  - Continuum emission reconstructed with ~50 pc resolution.
  - Diffuse and clumpy star forming regions
  - Evidence for different temperature regimes: spectral index, CO lines
- **ALMA Cycle 0**
  - pixellated models lead to significant corrections compared to reconstructions with parametric models

visibility fitting + pixellated sources