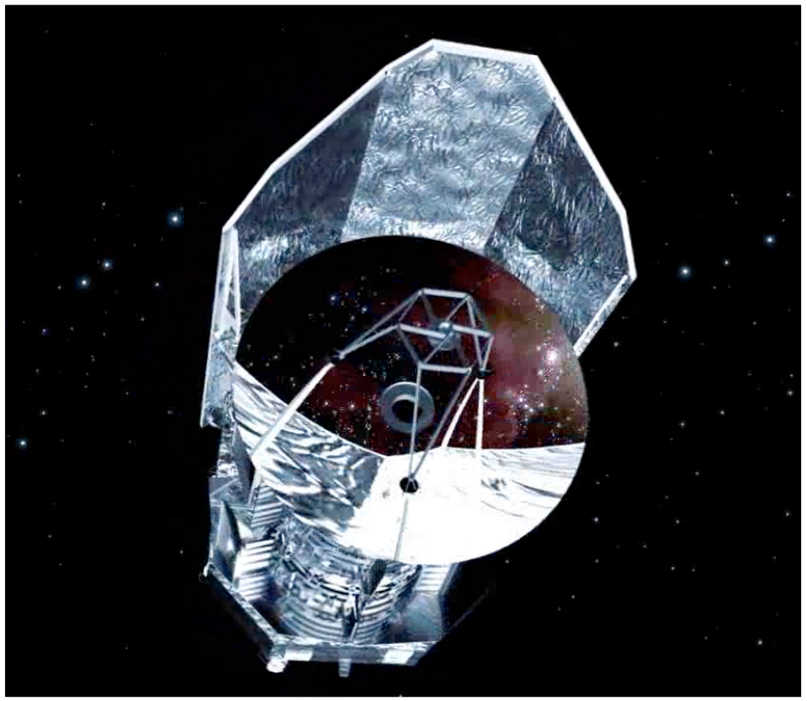
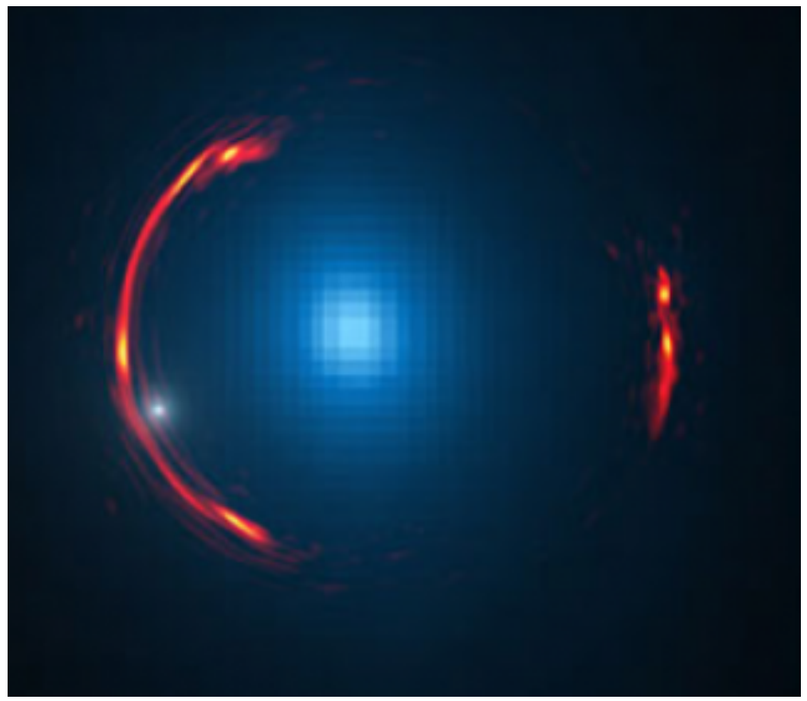
STRONG LENSING AND ALMA: RESOLVING THE NATURE OF HIGH-REDSHIFT GALAXIES DETECTED BY HERSCHEL





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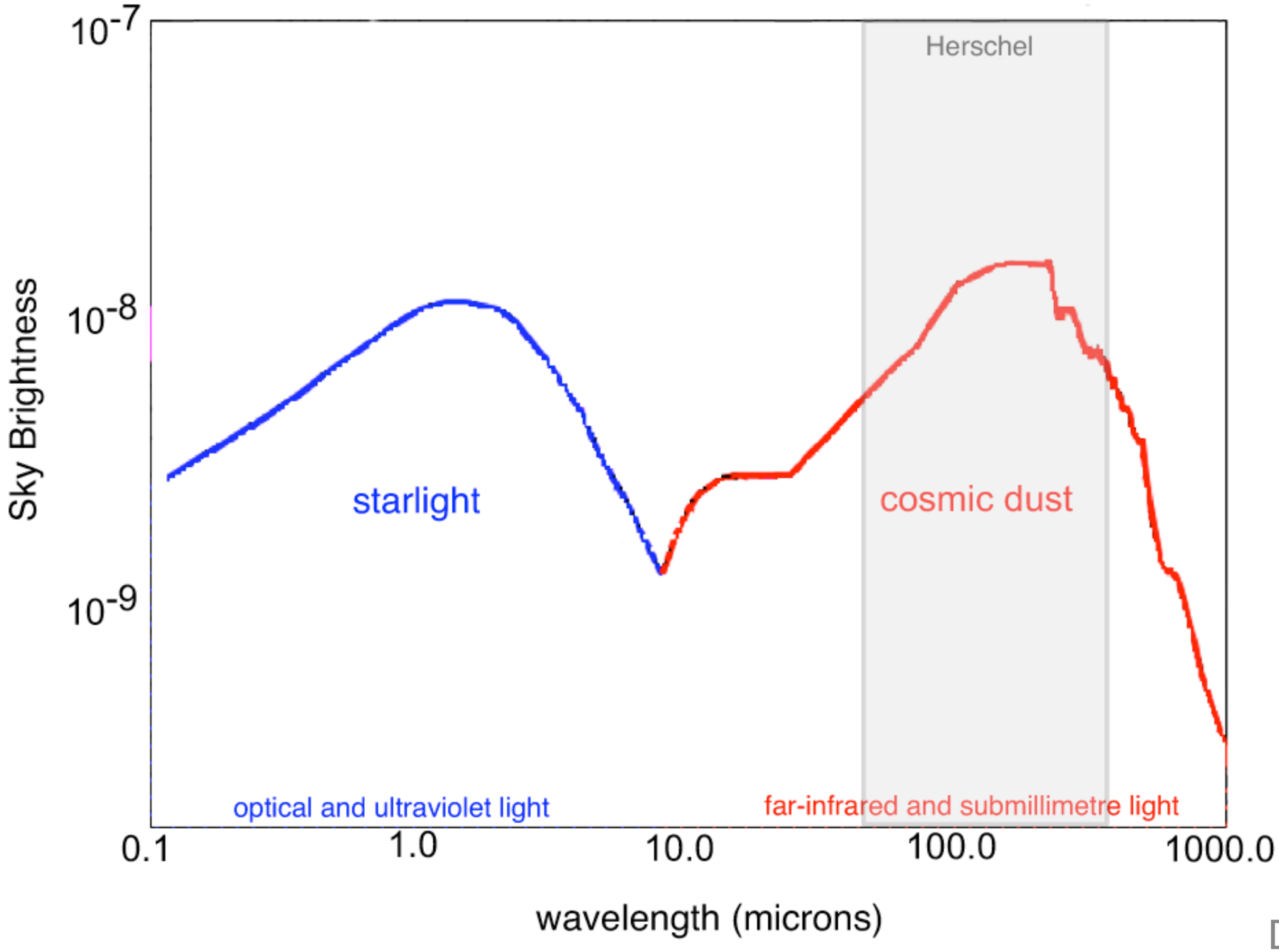
OUTLINE

- Submillimeter galaxies
- Candidate lens selection
- SDP.81: a showcase for strong lensing with ALMA
- Modelling high-resolution ALMA observations of lensed highly star-forming galaxies detected by Herschel
- Conclusions

INTRODUCTION



Dole et al. (2006)

SUBMILLIMETER GALAXIES

- Massive: 10^{11} - 10^{12} $M_{\odot}$, median redshift $z > 2.5$, SFR ~500 $M_{\odot}\,yr^{-1}$

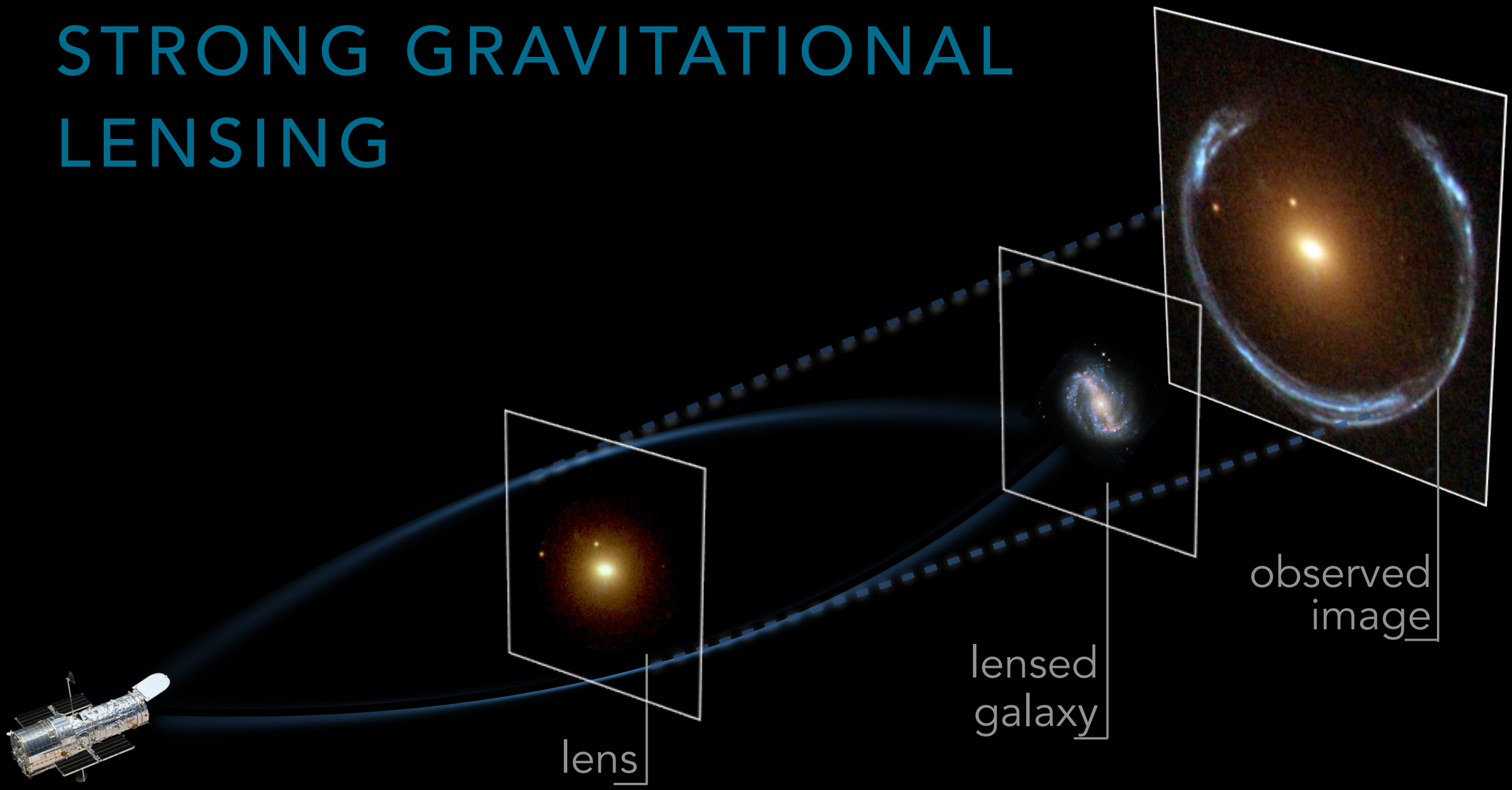
- Are a more energetic version of more local ultra-luminous infrared galaxies (ULIRGs) and the likely progenitors of massive elliptical galaxies

- Opportunity to study an important phase in galaxy evolution at the peak of cosmic star-formation

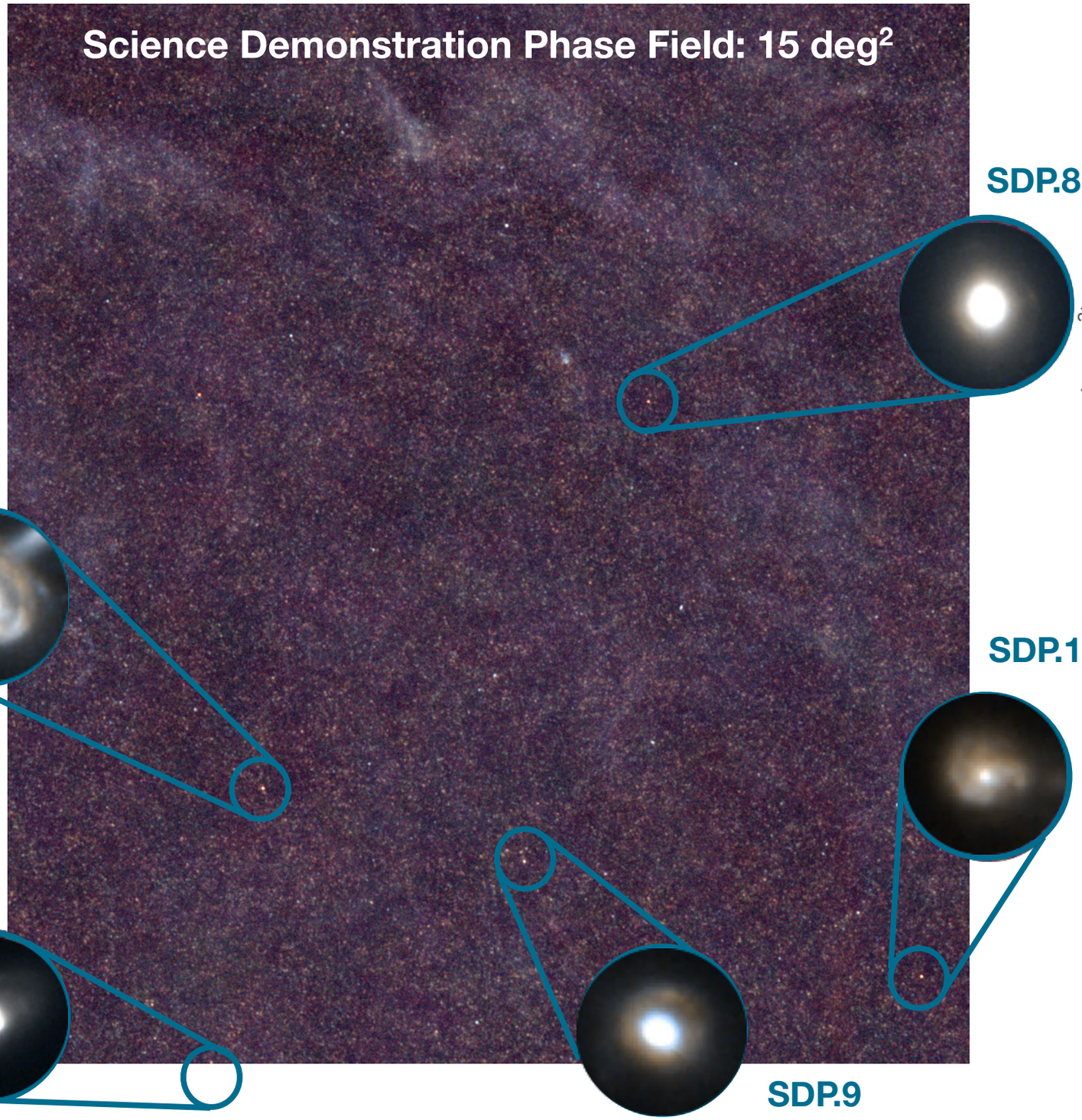
- Studies with early instruments are limited by poor spatial resolution, insufficient sensitivity, or both

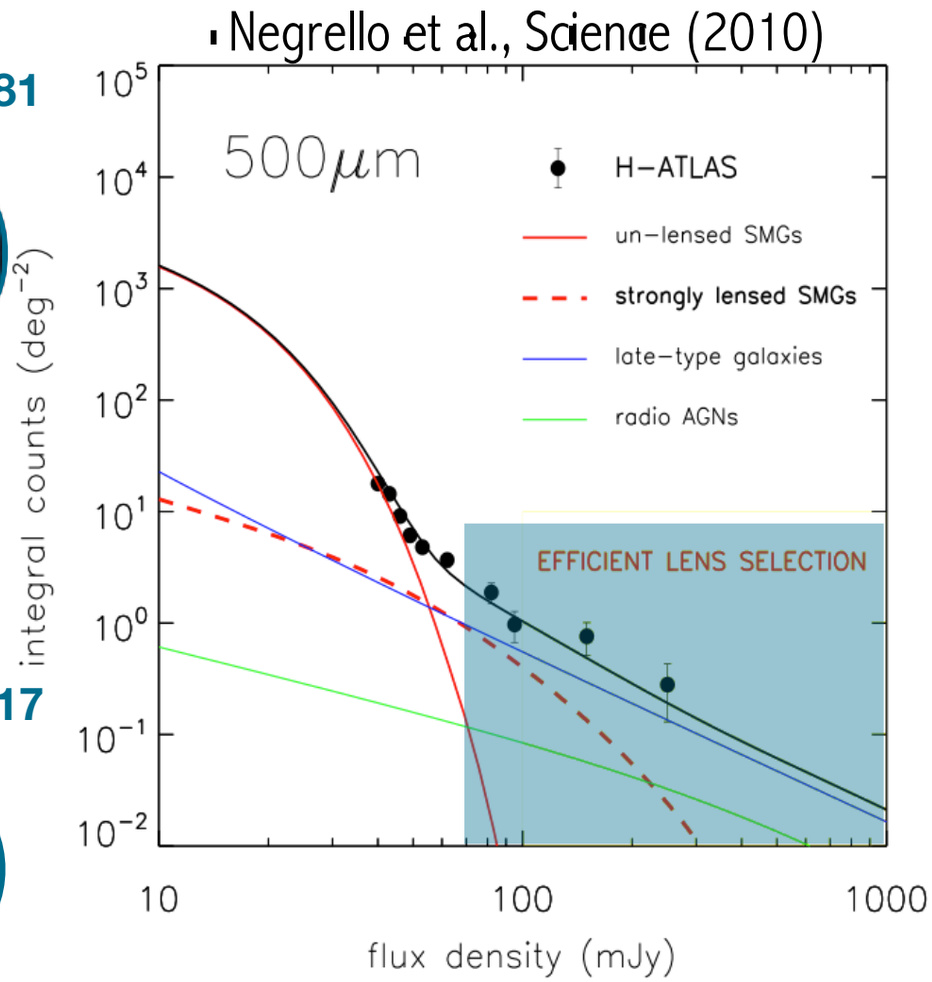
- Gravitational lensing provides a solution to both of these problems

STRONG GRAVITATIONAL LENSING



HERSCHEL-ATLAS AND SELECTION OF LENSES





- 250 μm
- 350 μm
- 500 μm

SPIRES

WHY DO WE NEED INTERFEROMETRY?

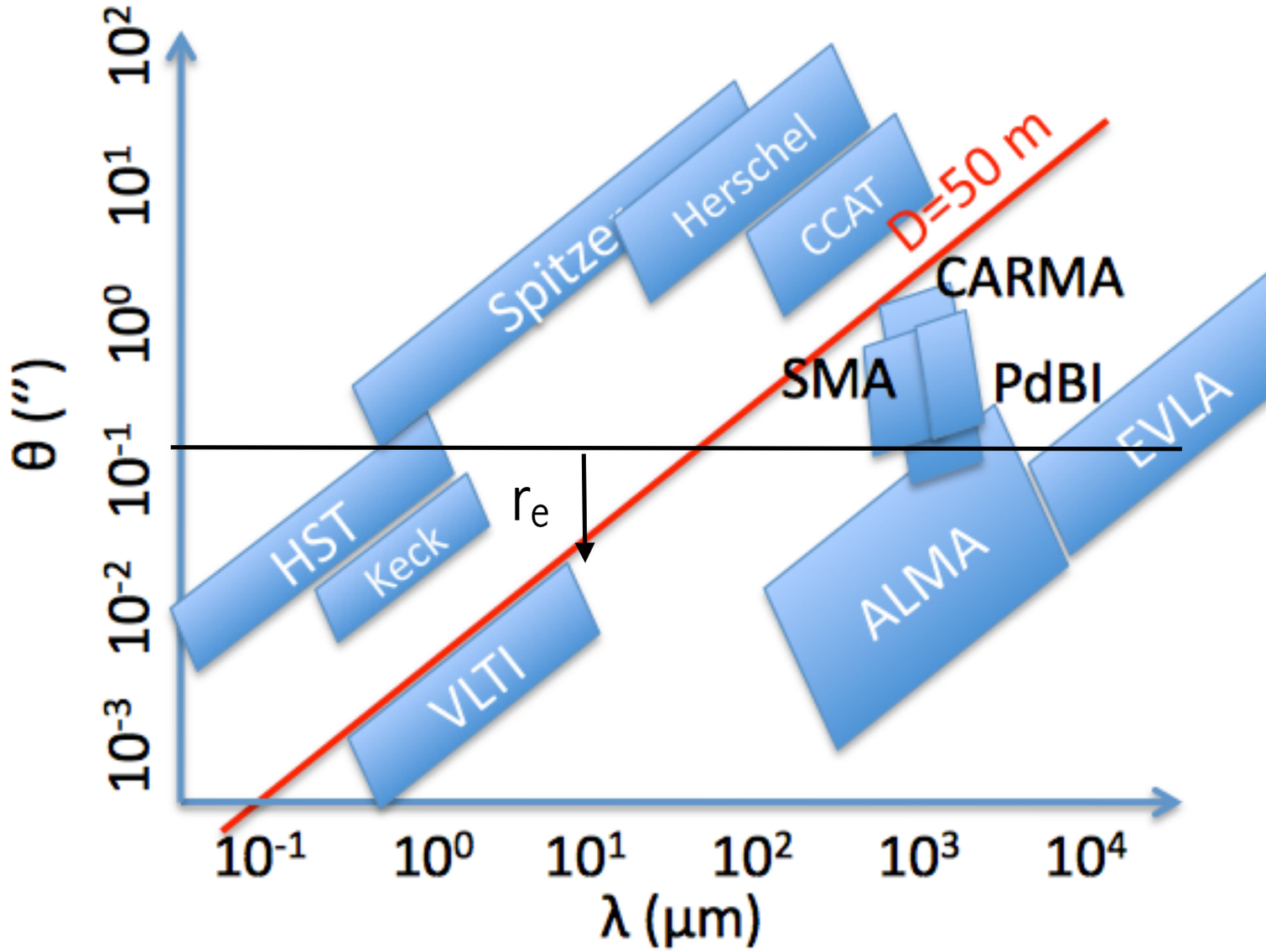
- Angular separation of multiple images: Einstein radius (r_E)

- Detection limit

$$r_E \sim \theta$$

- Longer baselines ⟹ higher resolution

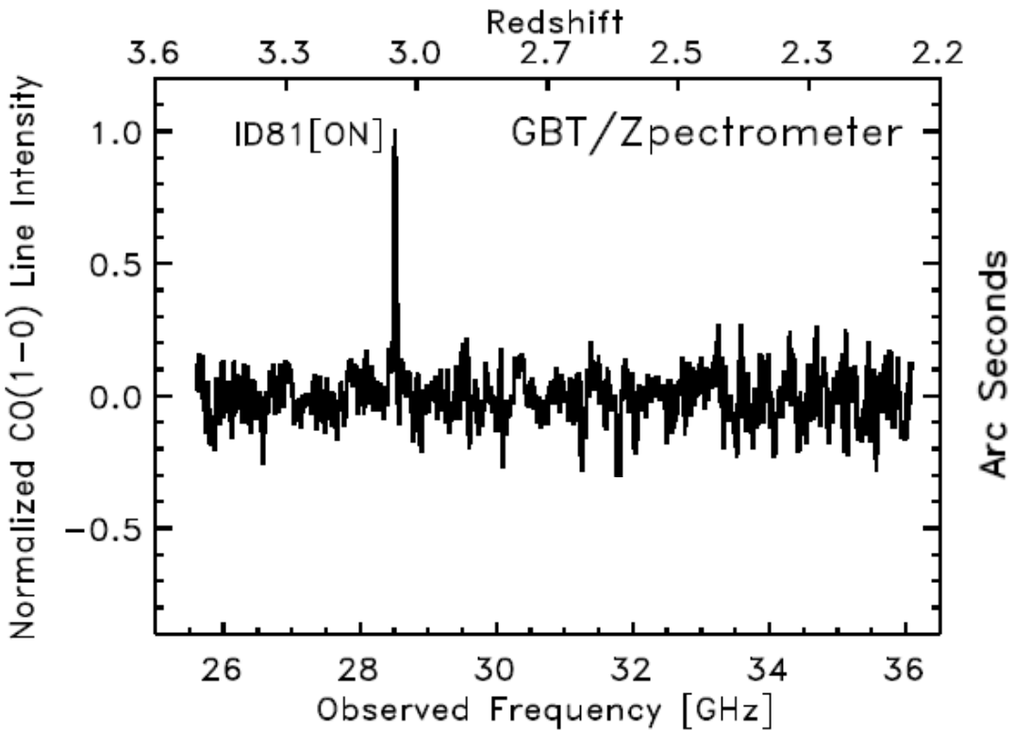
$$\theta = \lambda / B$$



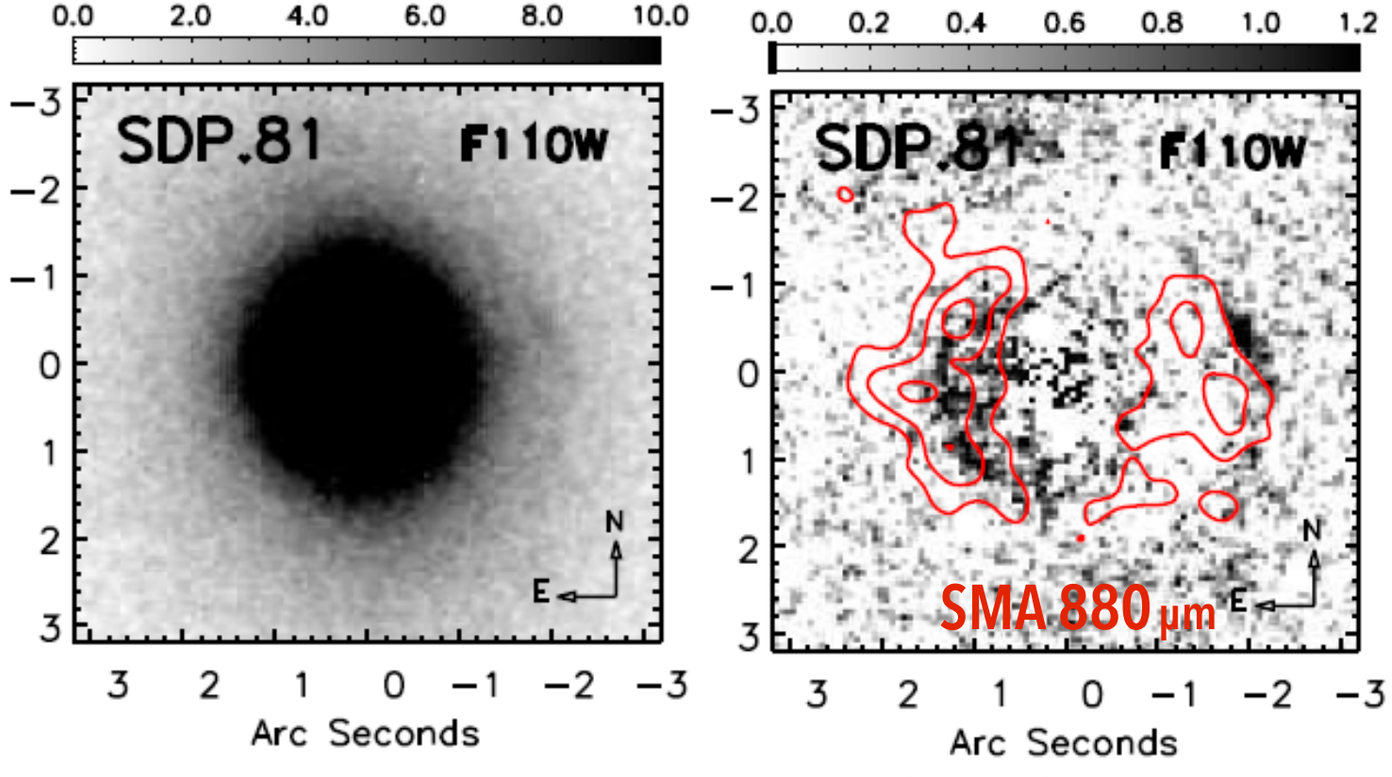
https://science.nrao.edu

SDP.81: A SHOWCASE FOR STRONG LENSING WITH ALMA

- SDP.81 is one of the first five strongly lensed submm sources detected in the H-ATLAS (Negrello et al., 2010)
- Source at z=3.042 (CO spectroscopy with GBT)
- Lens at z=0.3 (from SDSS spectrum)

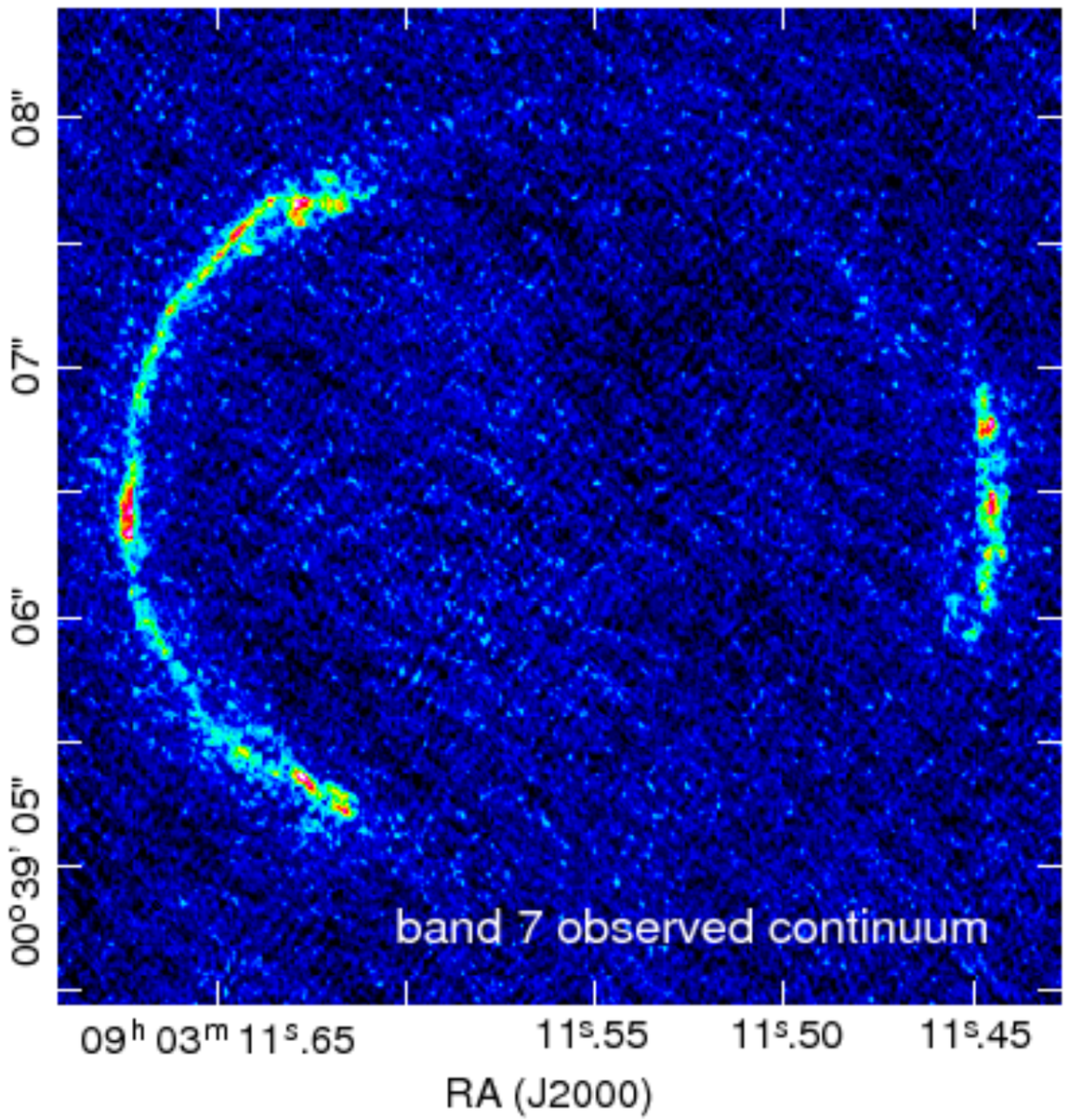


Frayer et al. (2011)



Negrello et al. (2014)

SDP.81: ALMA DATA



Vlahakis et al. (2015)

ALMA Long Baseline Campaign

22–36 antennas (~15m–15km baselines)

Observation in 3 bands:
B4 – 2.0 mm (151 GHz)
B6 – 1.3 mm (236 GHz)
B7 – 1.0 mm (290 GHz)

On-source integration times: ~4–6 hours

Continuum + molecular lines
CO (5-4, 8-7, 10-9)

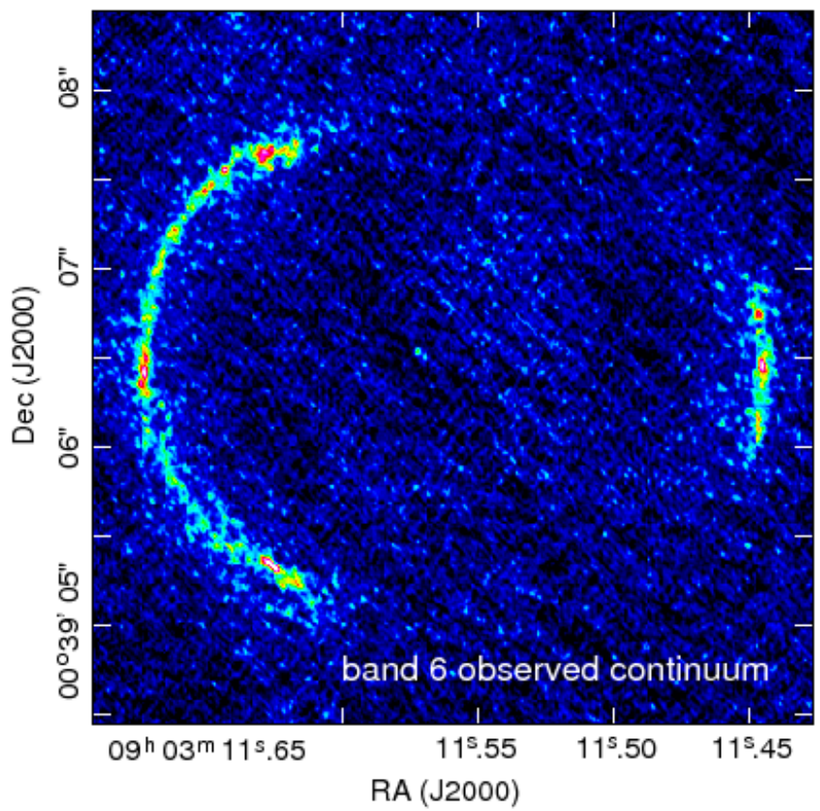
Angular resolution: 23–170 mas

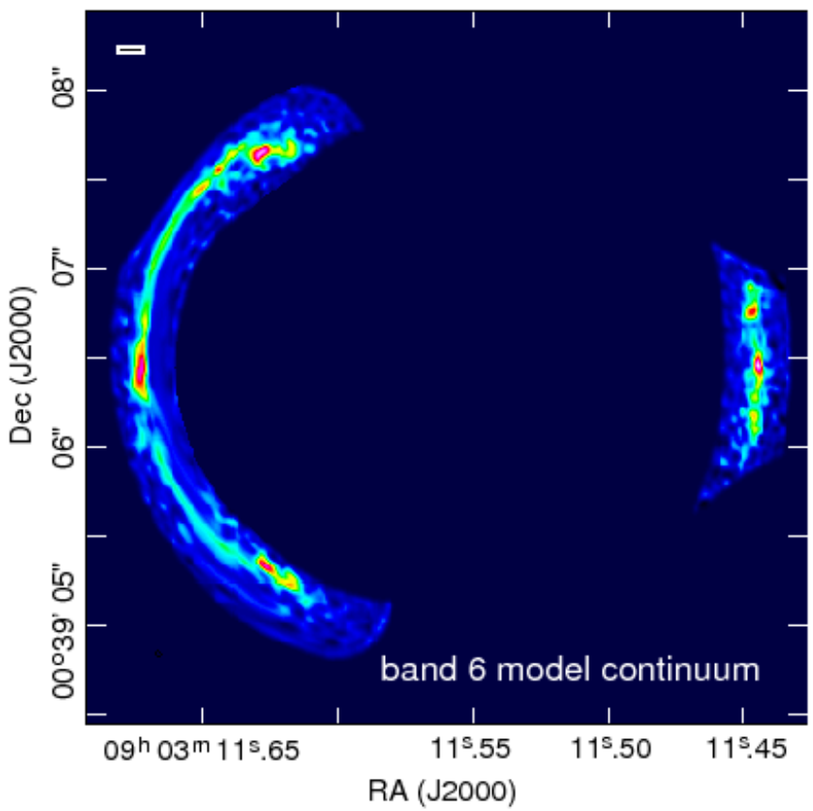
SDP.81: LENS MODELLING OF ALMA DATA

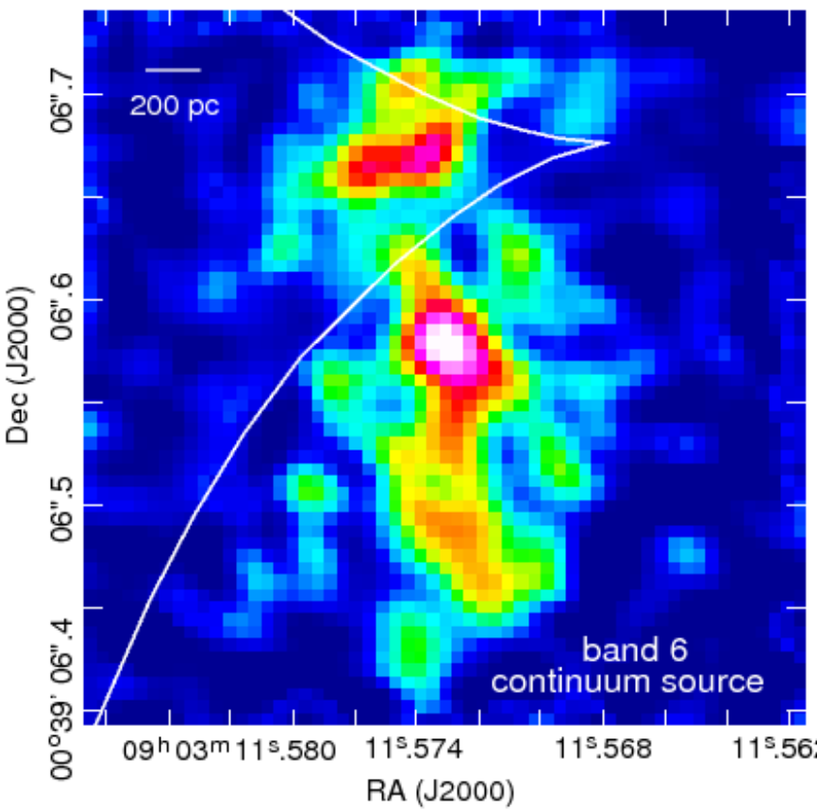
observed

model

reconstructed source







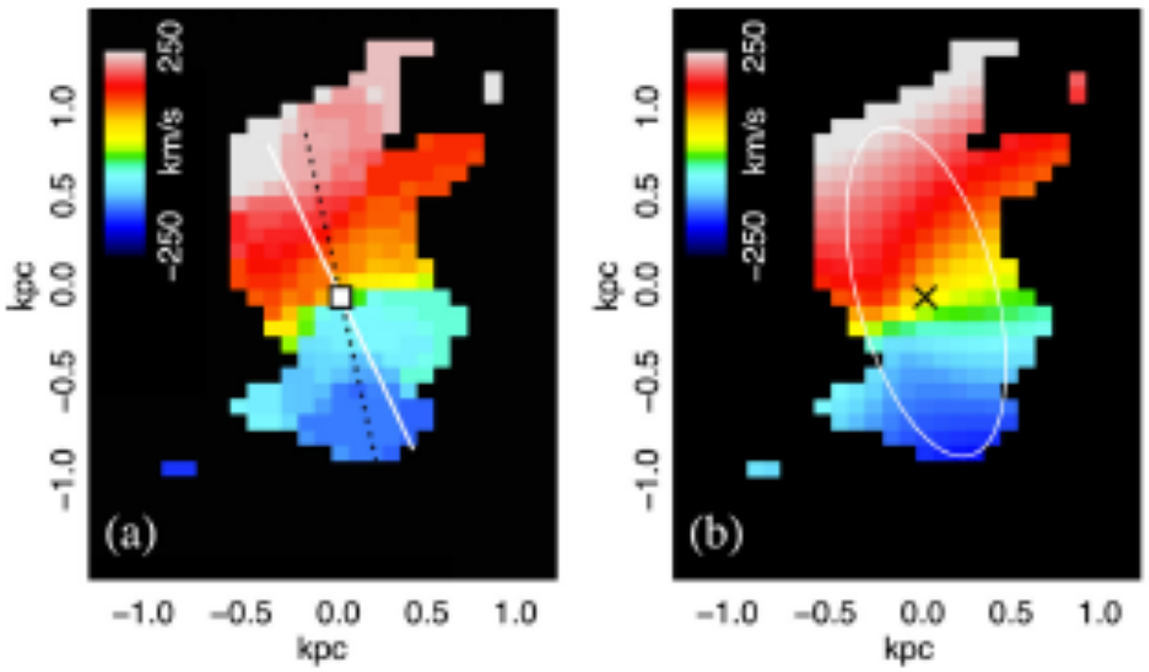
Dye, Furlanetto et al. (2015)

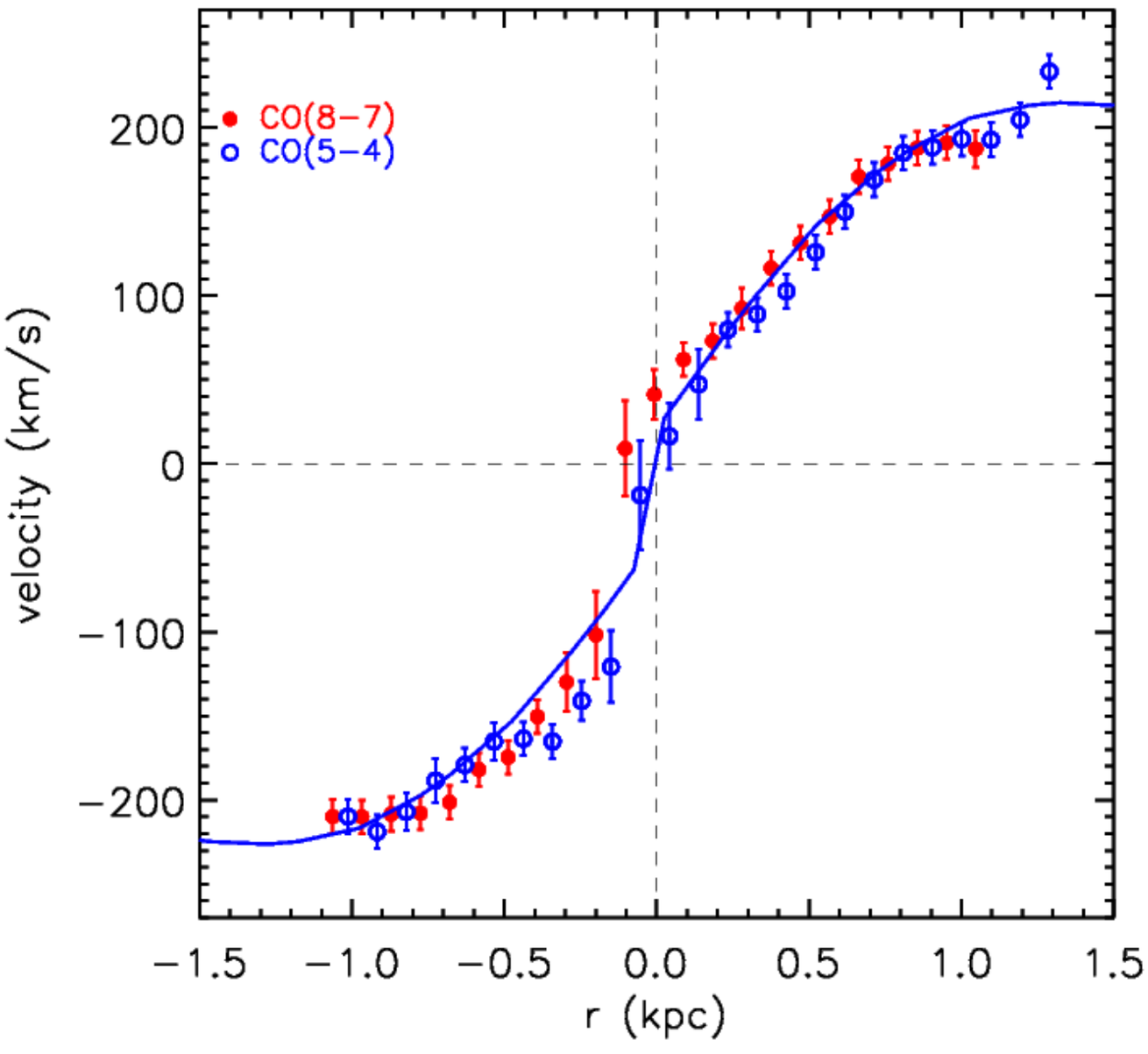
SDP.81: KINEMATICS

Swinbank et al. (2015)

observed velocity field

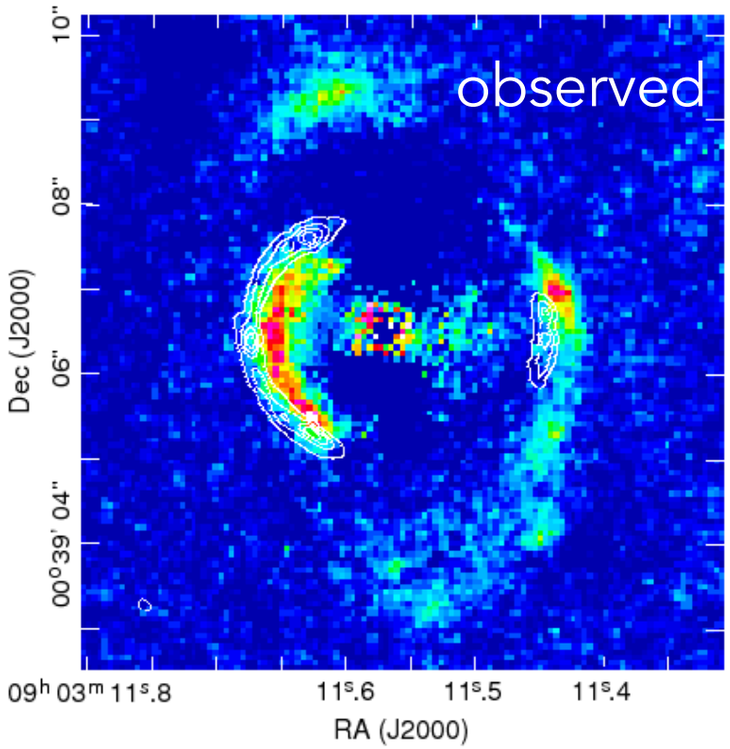
model

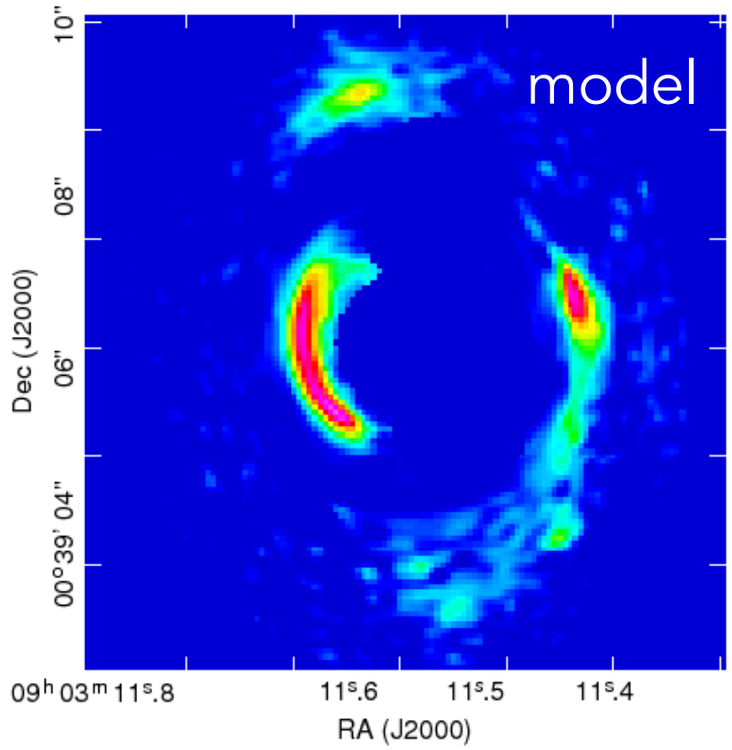




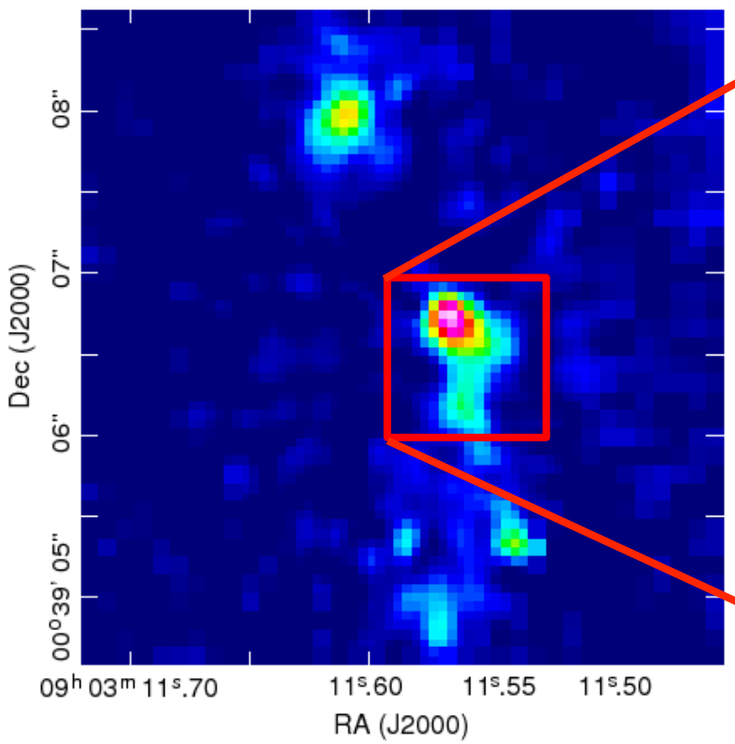
Dynamical mass consistent with gas and dust mass.

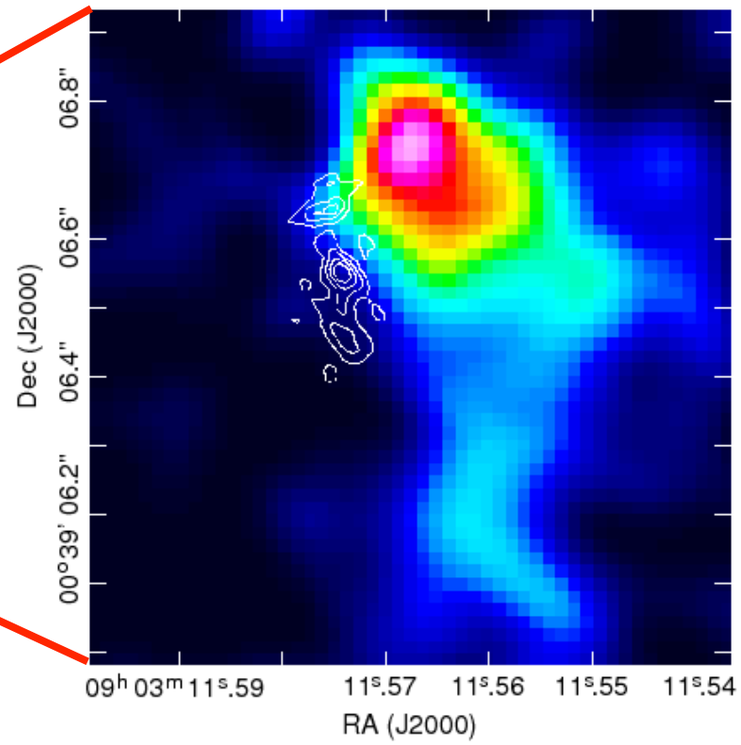
SDP.81: LENS MODELLING OF HST DATA



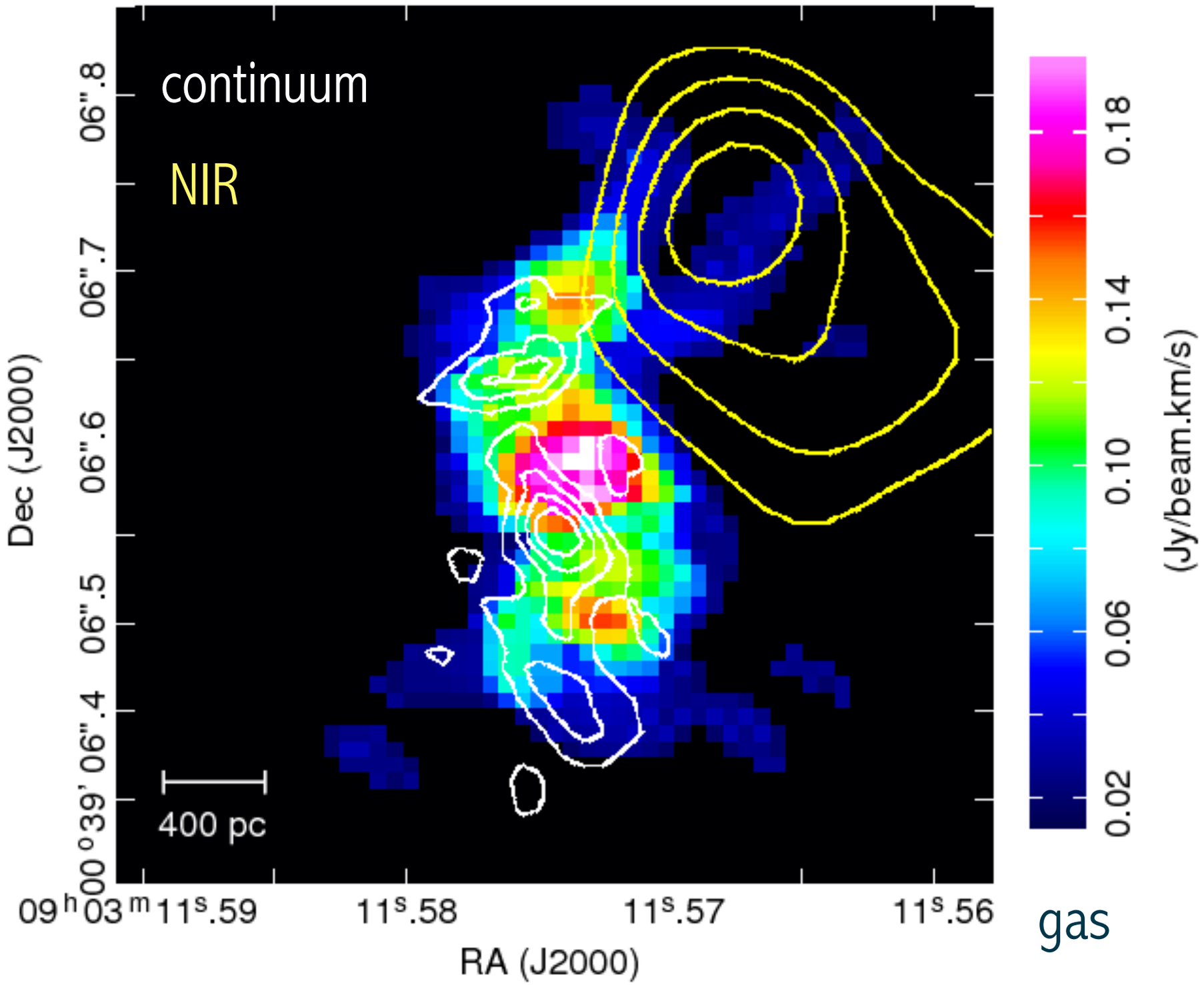


reconstructed source

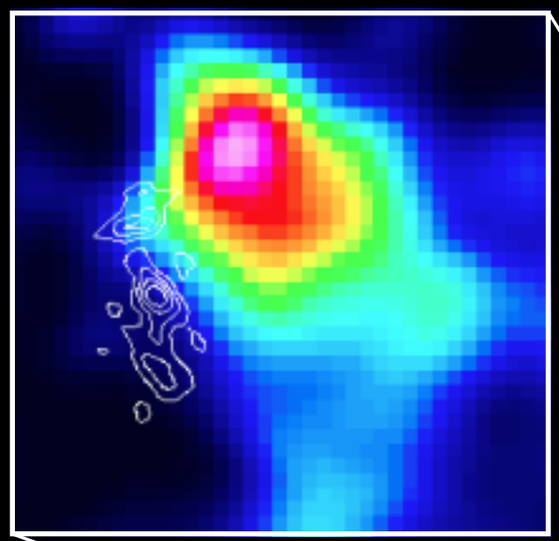


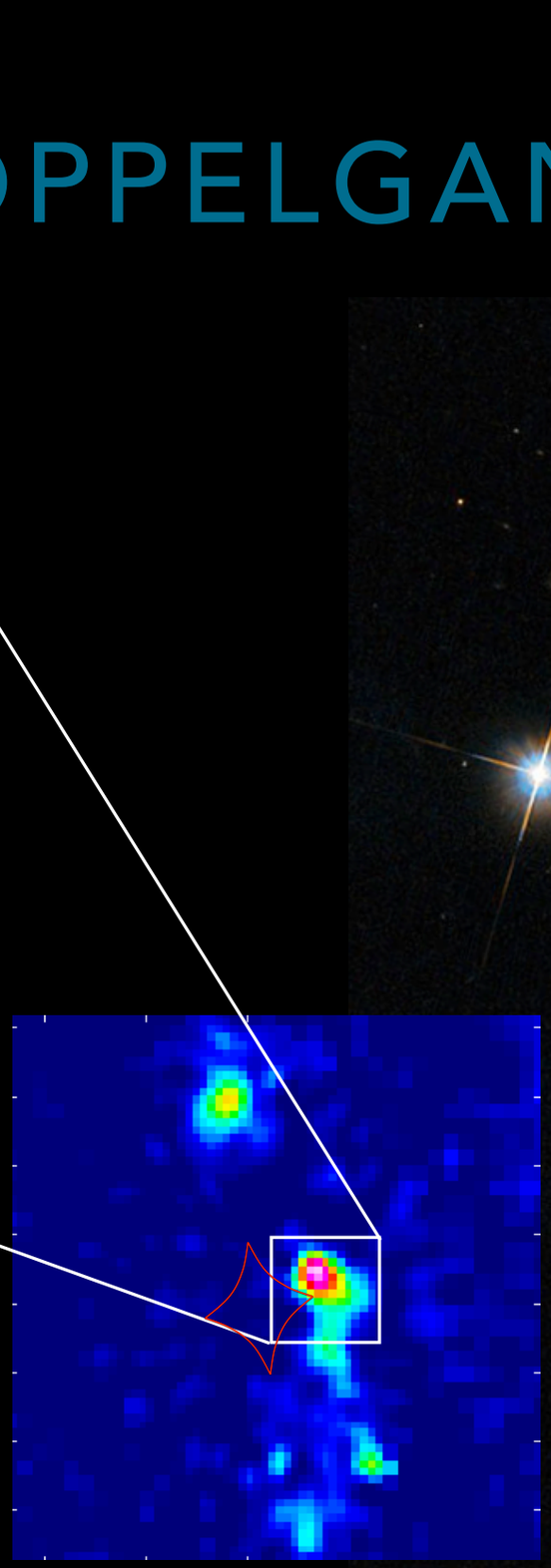


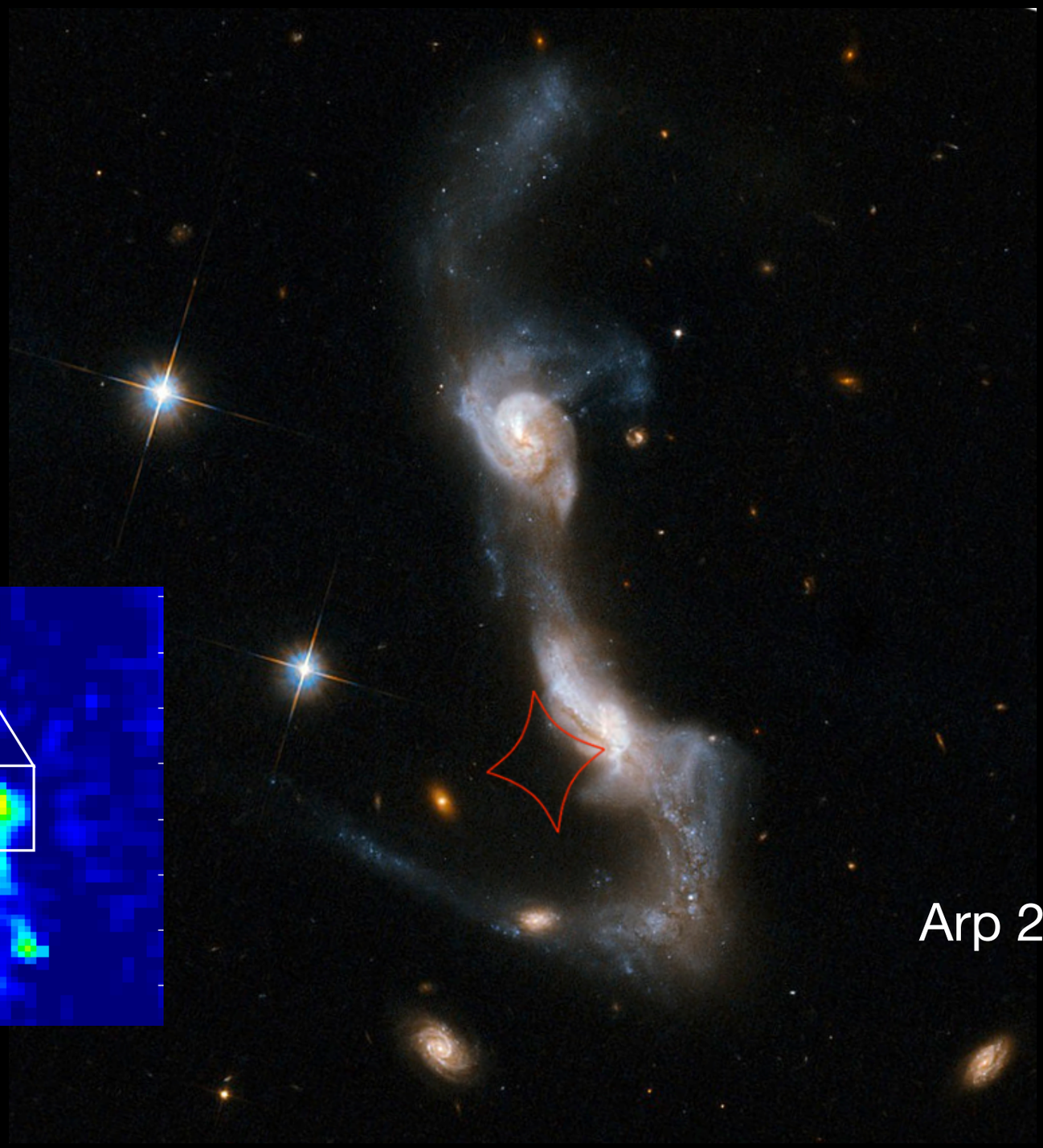
SDP.81: SOURCE MORPHOLOGY



SDP.81 DOPPELGANGER?







Arp 238

SEMI-LINEAR INVERSION

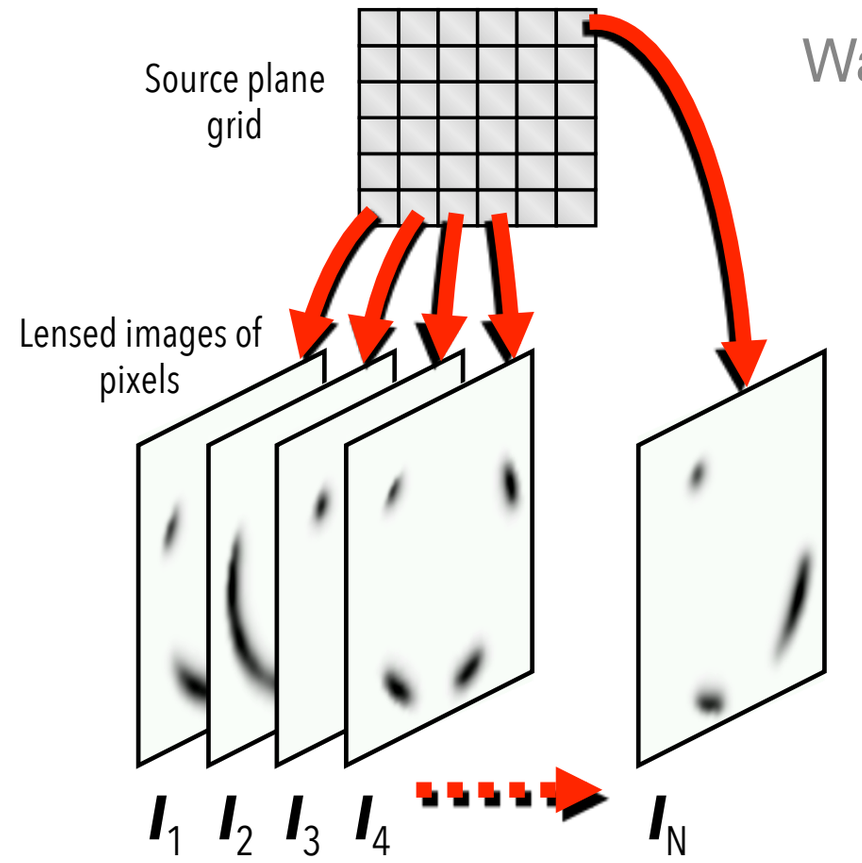
Pixellated source

+

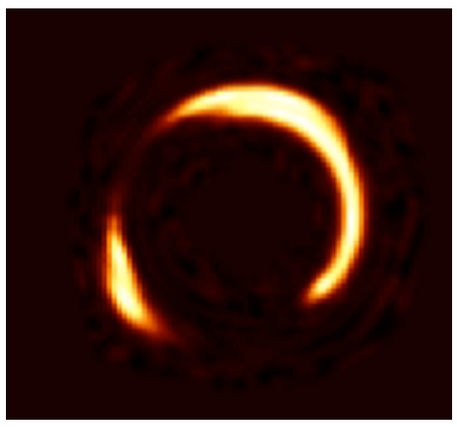
Parametric lens model

+

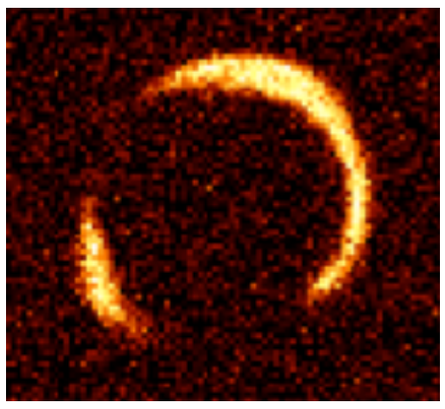
Image fitting



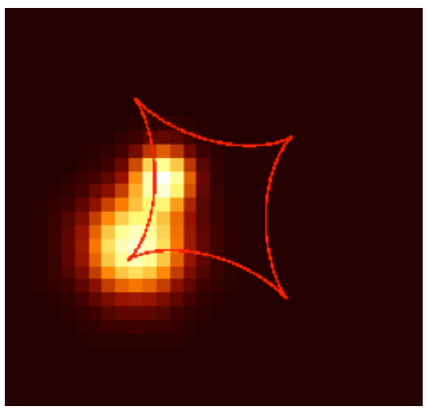
Warren & Dye (2003)



model



observed



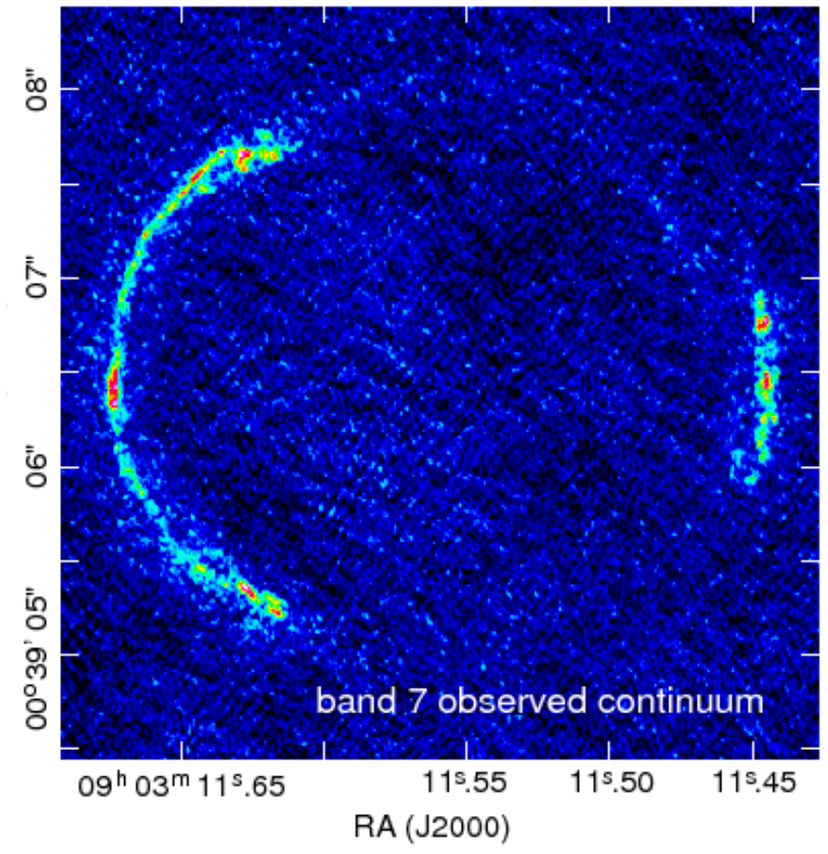
reconstructed source

LENS MODELLING: INTERFEROMETRIC DATA

Interferometers measure visibilities, not images.

Image:

- correlated pixel-to-pixel noise
- results depend on the methods used to create the images (gridding, weighting, deconvoltution, etc)



Visibility space:

- Noise assumed to be Gaussian

SEMI-LINEAR INVERSION - VISIBILITY SPACE

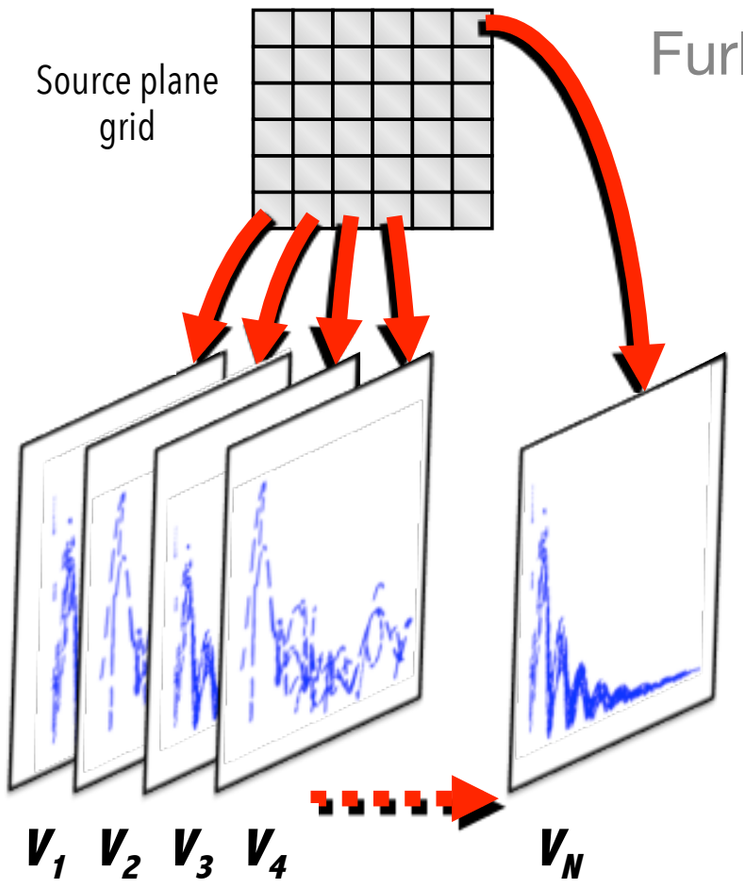
Pixellated source

+

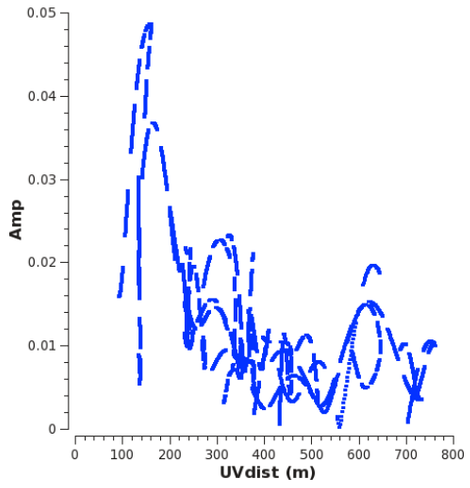
Parametric lens model

+

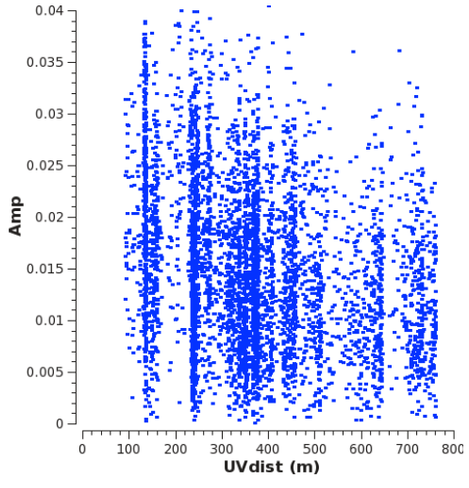
Fitting visibilities



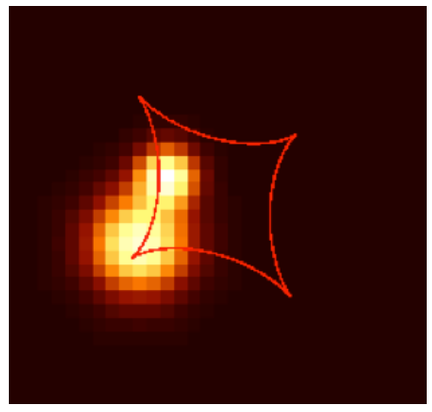
Furlanetto & Dye (in prep.)



model

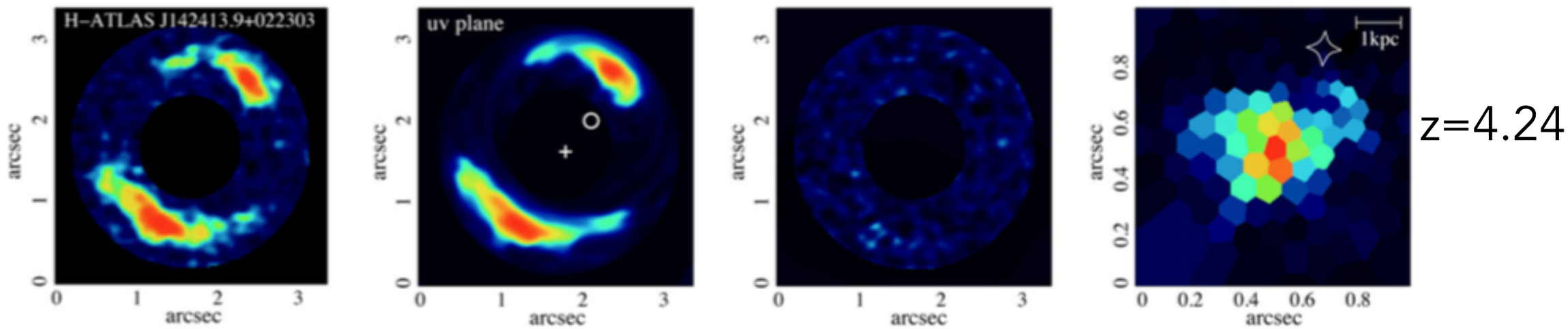


observed

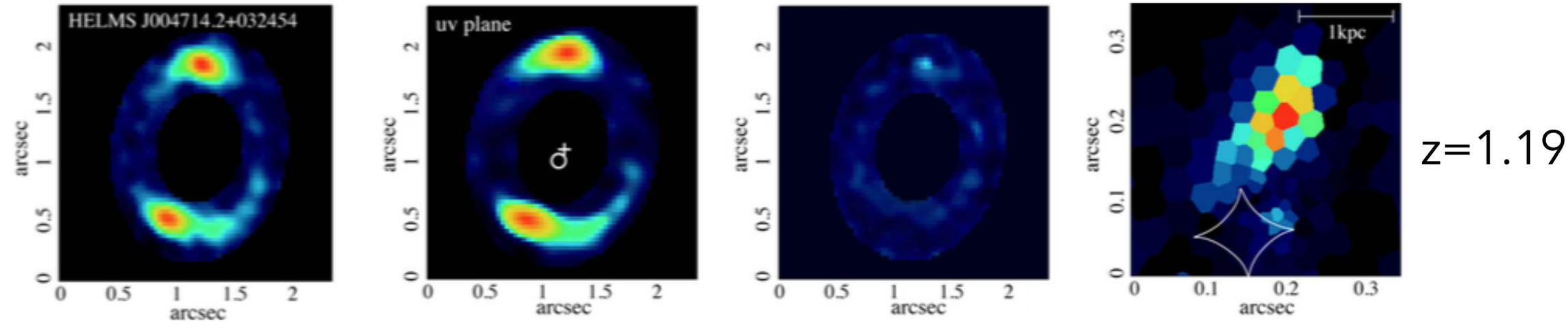


reconstructed source

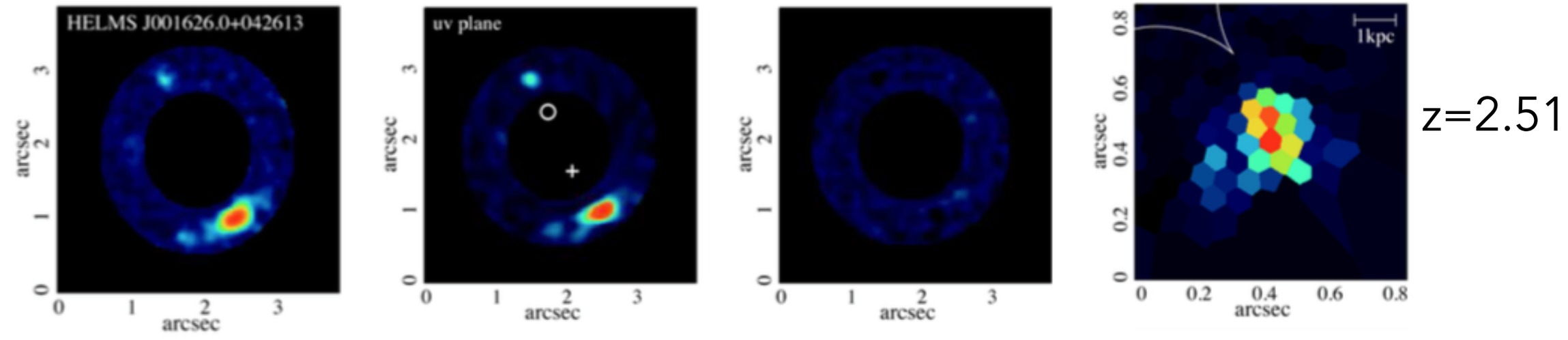
MODELLING ALMA DATA OF LENSED HIGHLY SF GALAXIES DETECTED BY HERSCHEL



z=4.24

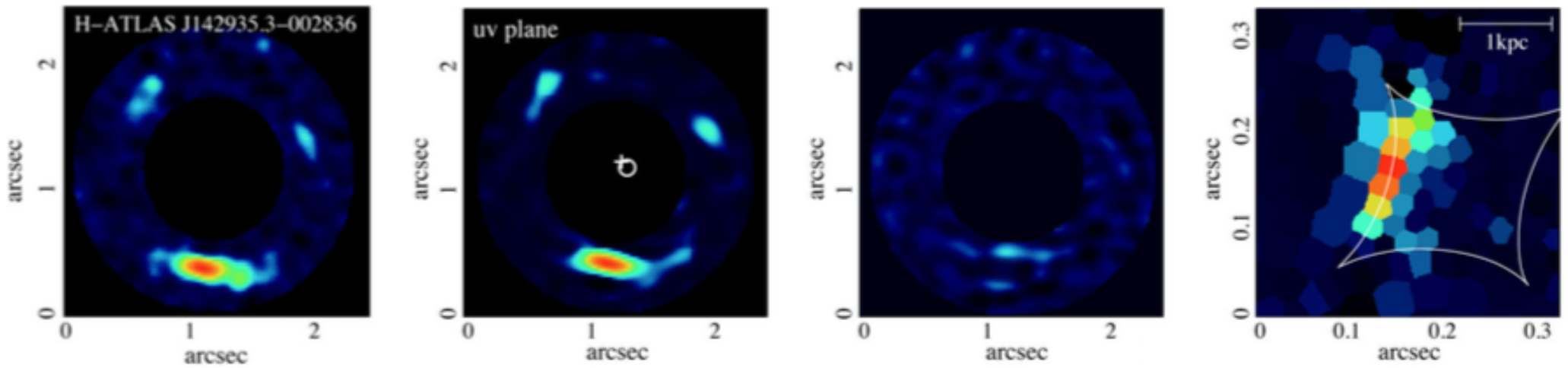


z=1.19

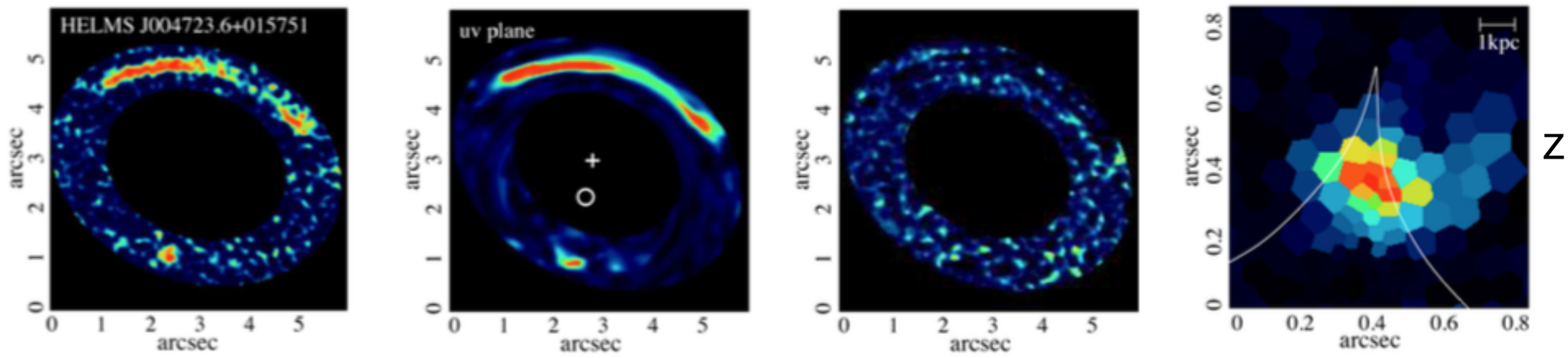


z=2.51

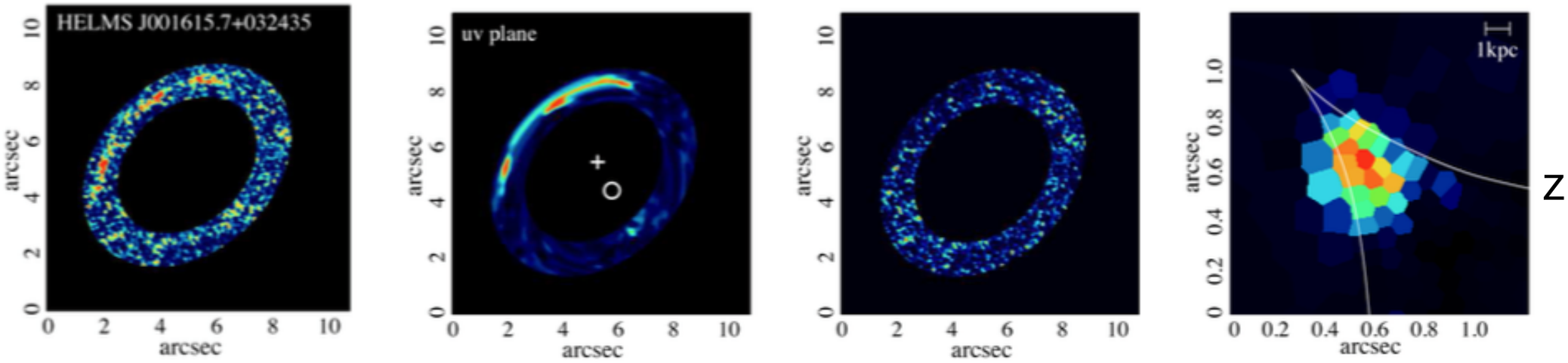
MODELLING ALMA DATA OF LENSED HIGHLY SF GALAXIES DETECTED BY HERSCHEL



z=1.03



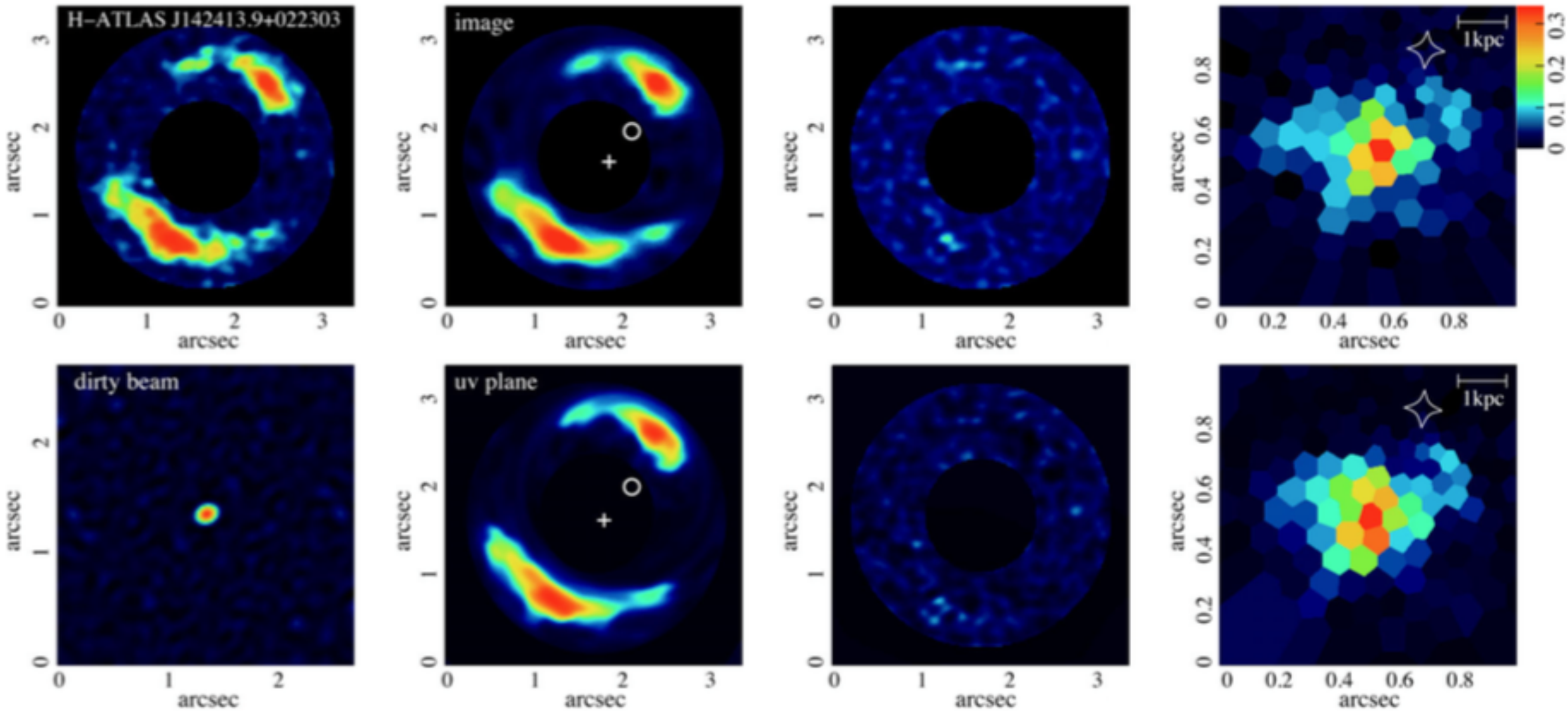
z=1.44



z=2.76

IMAGE-PLANE VS. UV-PLANE RECONSTRUCTION

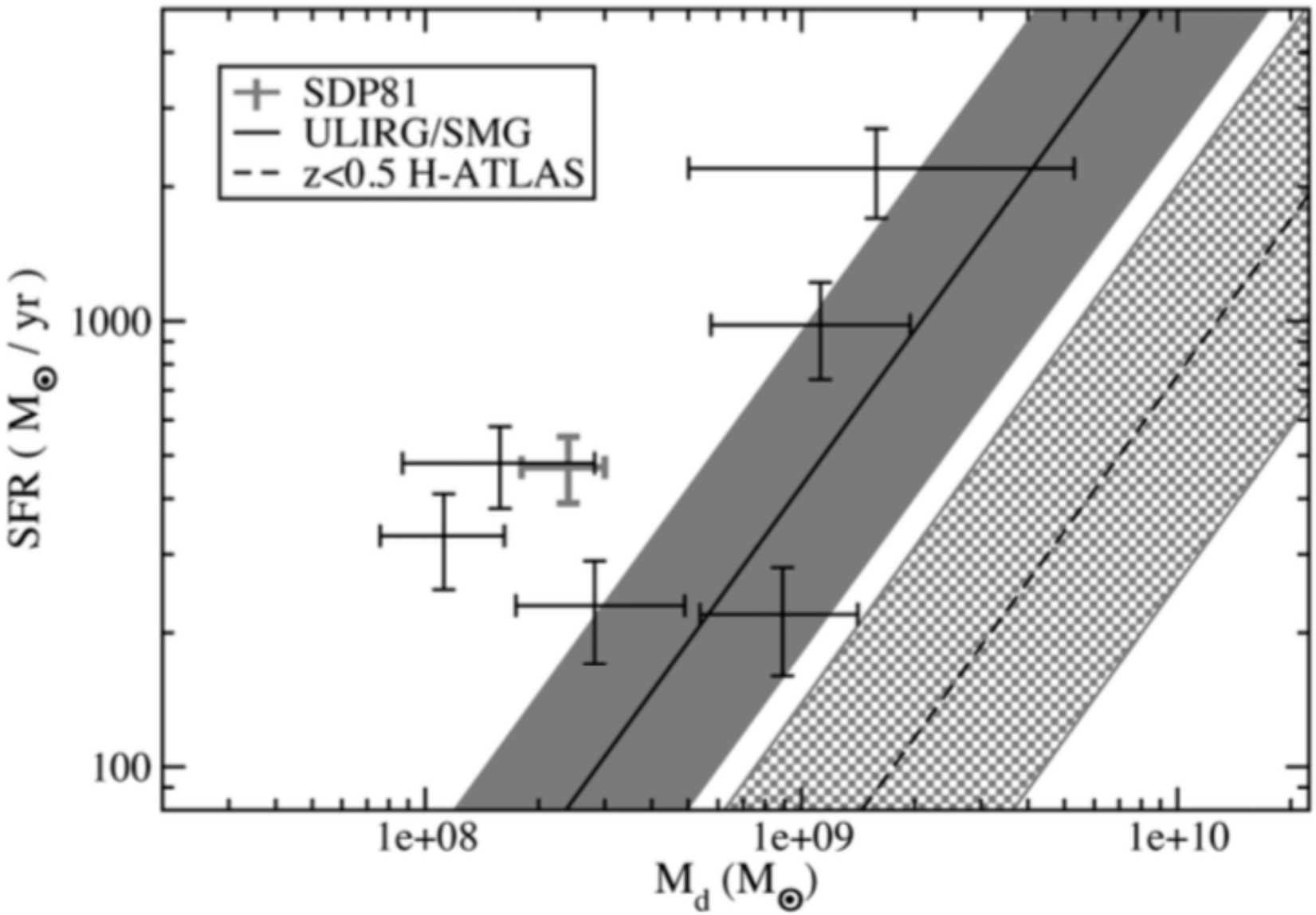
observed | model | residual | reconstructed source



Dye, Furlanetto et al. (2018)

INTRINSIC SOURCE PROPERTIES

Majority of lensed sources in this work have higher dense molecular gas fractions than the average ULIRG/SMG



Star formation rate determined using the method of Kennicutt & Evans 2012.

CONCLUSIONS

- Strong lensing and interferometry: powerful combination to study of high-z objects in great detail

- SDP.81 analysis:

  - two objects which appear to be interacting, with the rotating disc of gas and dust revealed by ALMA distinctly offset from the near-infrared emission

- Complexity in high-z SMGs when they are studied at the high angular resolution now made possible by ALMA's incredible long baseline capability

- We can model smooth lenses and pixellated sources by directly fitting the visibility data

THANK YOU!