A Review of
High Redshift Galaxies Having Both Their Gas And Dust Components Resolved

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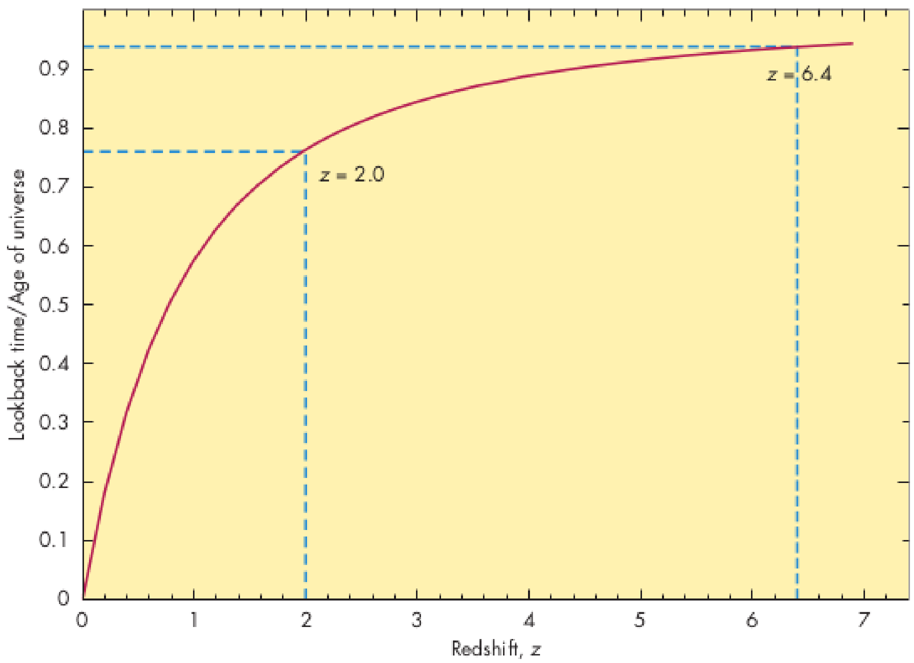
Content

- Introduction
- Strong gravitational lensing
- High redshift galaxies review
- Conclusion

Introduction



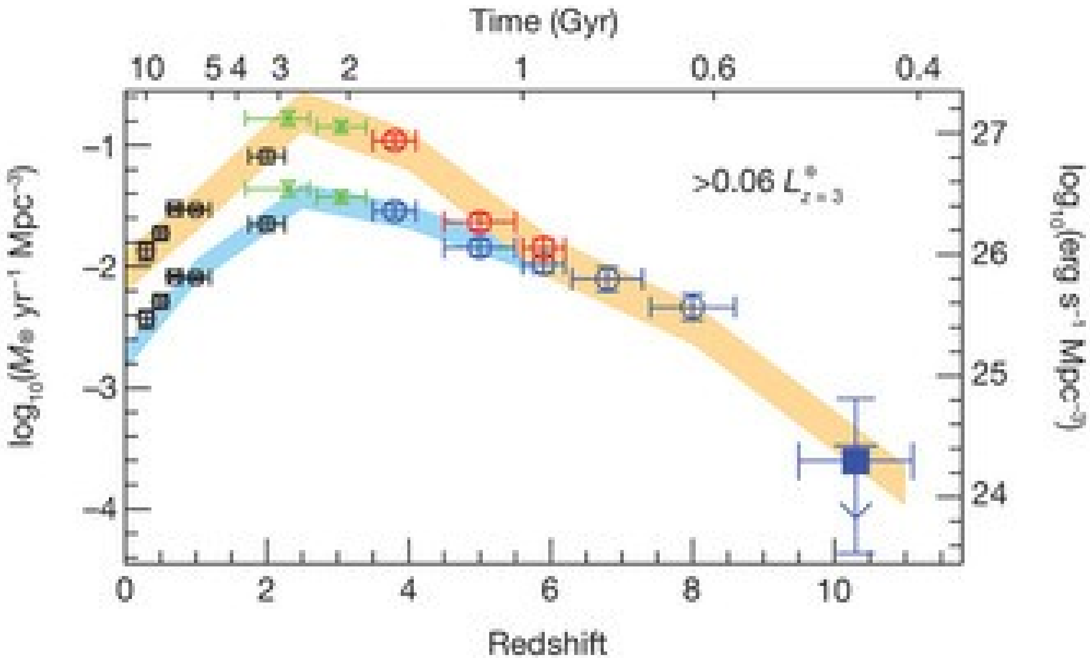
Direct observation of the early Universe from high redshift (z) galaxies:

- High z ↔ high velocity recession → large distance (due to the Universe's expansion)
- Look back time: large fraction of the Universe's age.
- Their difference with the current age tells the age of the Universe when the observed light was emitted

Main contributors at early cosmic times of maximal star formation ($z \sim 2 - 4.5$) can be observed at rest-frame at these typical frequencies:

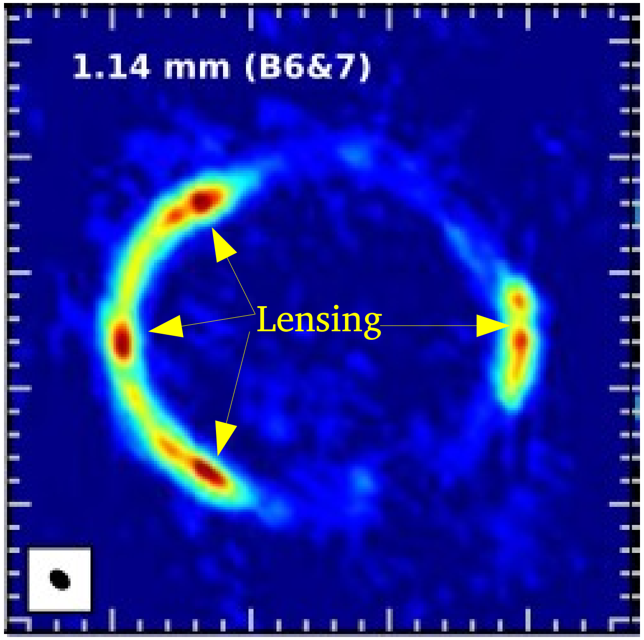
- Central supermassive black hole: optical & X-rays
- Gas reservoir (star formation fuel): mm, sub-mm
- Dust (star formation probe): IR
- Stars: optical
- Dark matter: not directly observed.

  → Quantities that summarize our knowledge of the galaxy: luminosities, masses, star formation rate, ...

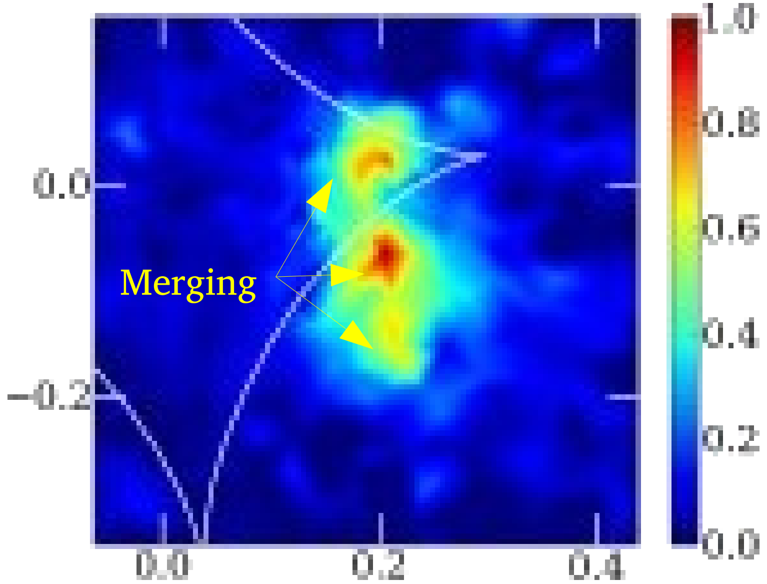


- Only recently that some gas and dust components of (high z) quasar hosts could be spatially resolved
- Usually with the aid of magnification from gravitational lensing

Sky plane



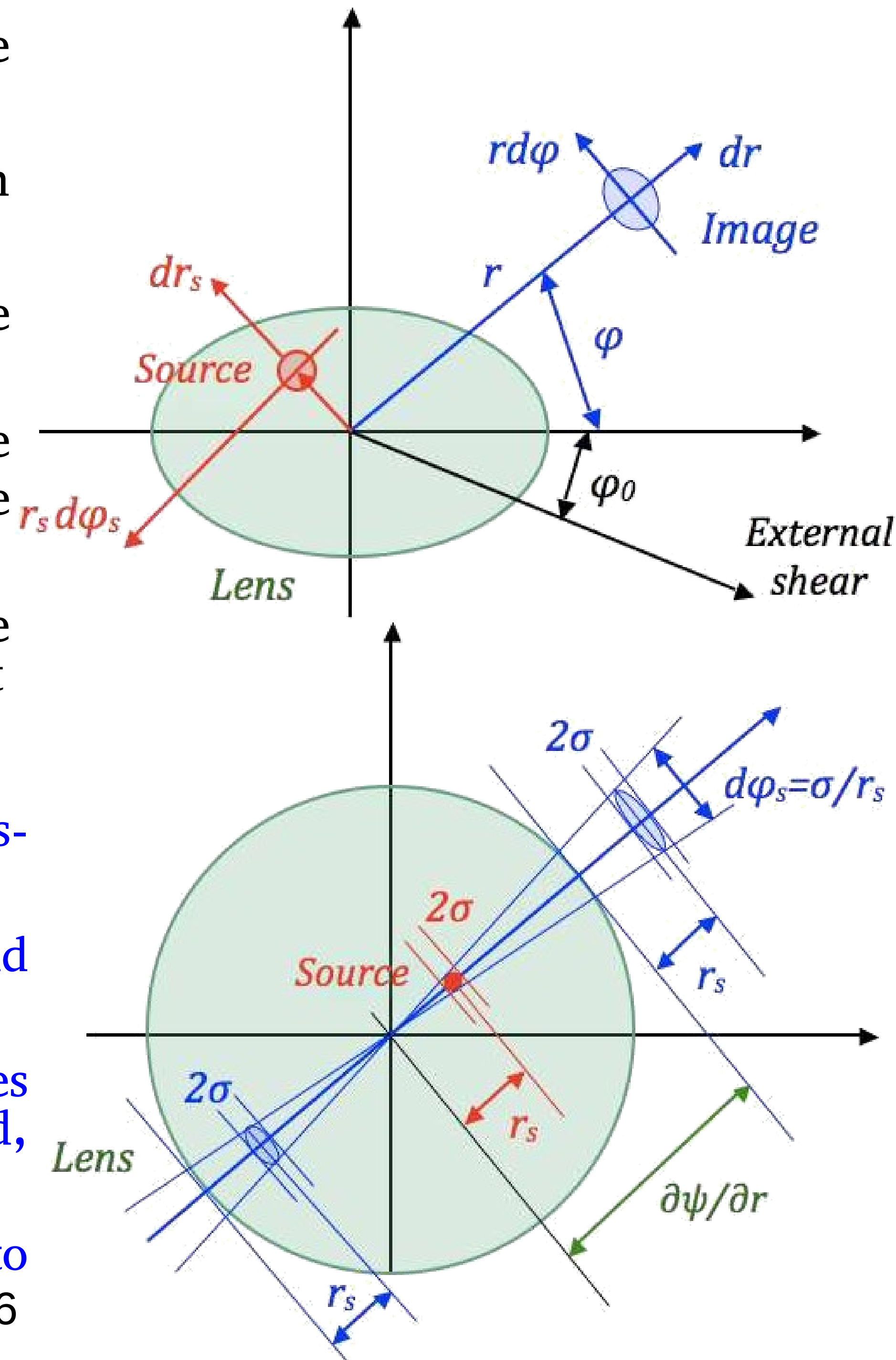
Source plane



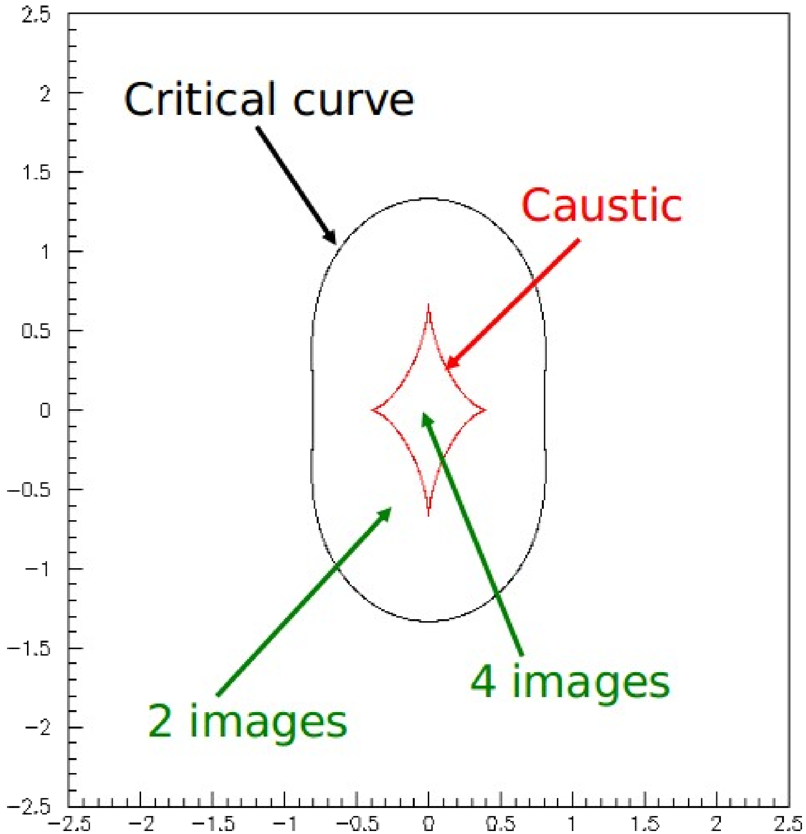
- High z galaxies are often the seat of mergers:
  - By comparing the respective locations of the gas, dust & optical components.
  - Galaxies were smaller & more densely distributed than today
- Mergers → increase gravitational field locally → local gas cloud collapse → starburst (dust source away from the black hole)
- Early galaxy genesis understanding:
  - Observations at different stages → the relative roles of each contributor as a function of time
  - Multiwavelengths observations at each stage:
    - Morphologies of the gas and dust components
    - Locations with respect to the central black hole

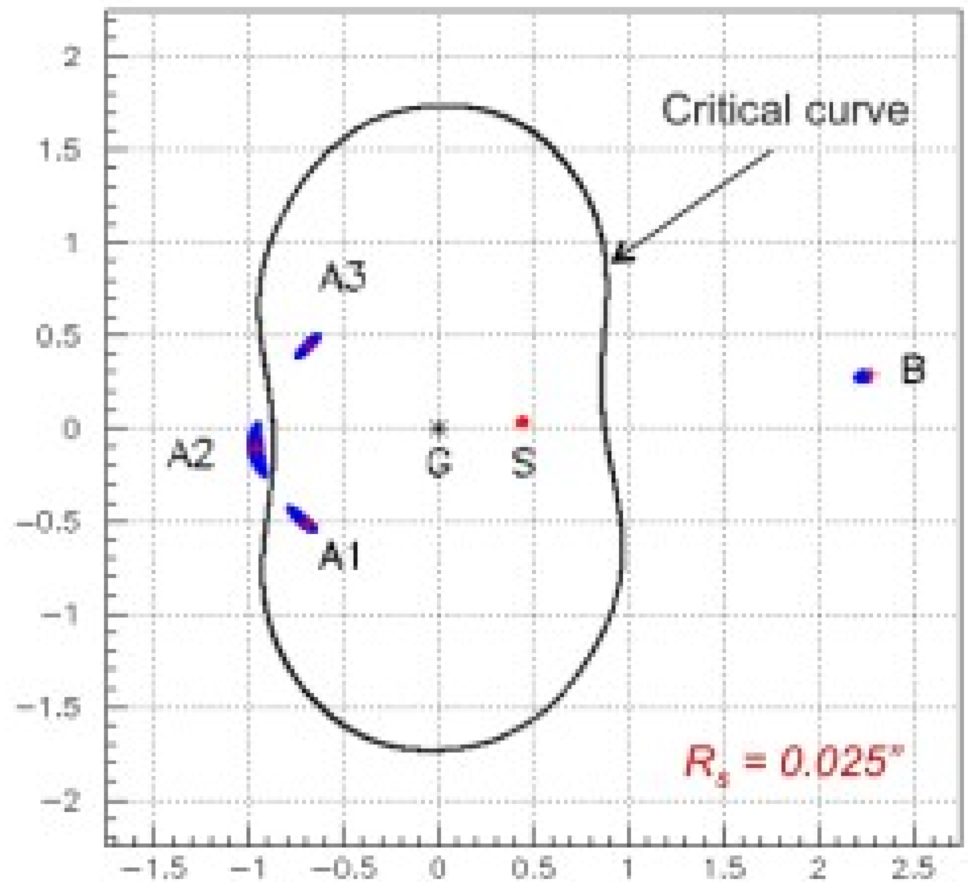
Strong gravitational lensing

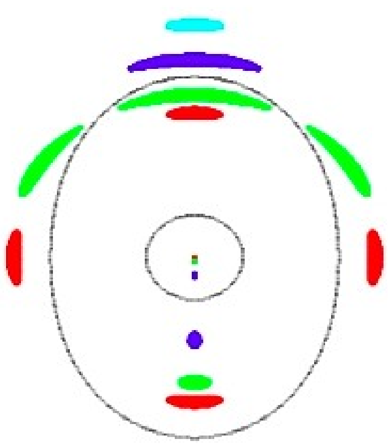
- Photons are deflected by gravity the same way as any other particle
- A large enough mass on the trajectory can act as a lens formation of images
- Fermat principle: Images form where gradient of the time delay t cancels
  - $t = t_{geo} + t_{grav}$, in which an effective potential ψ is introduced to describe the deflection
  - Ψ is proportional to the integral of the gravity potential along the line of sight
- Isotropic lens: Two solutions.
  - Images stretched normally to the lens-image direction
  - Magnification = 1 where the second derivative of the potential cancels.
  - Source closer to lens centre: two images become more tangentially elongated, forming arcs
  - Perfect alignment: The two arcs merge into an Einstein ring.

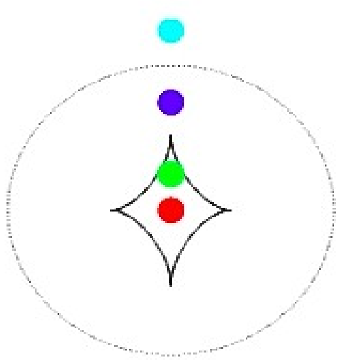


When small perturbations are added to the isotropic potential in the form of an external shear and/or a non-zero eccentricity of the lens, the general picture remains qualitatively valid.





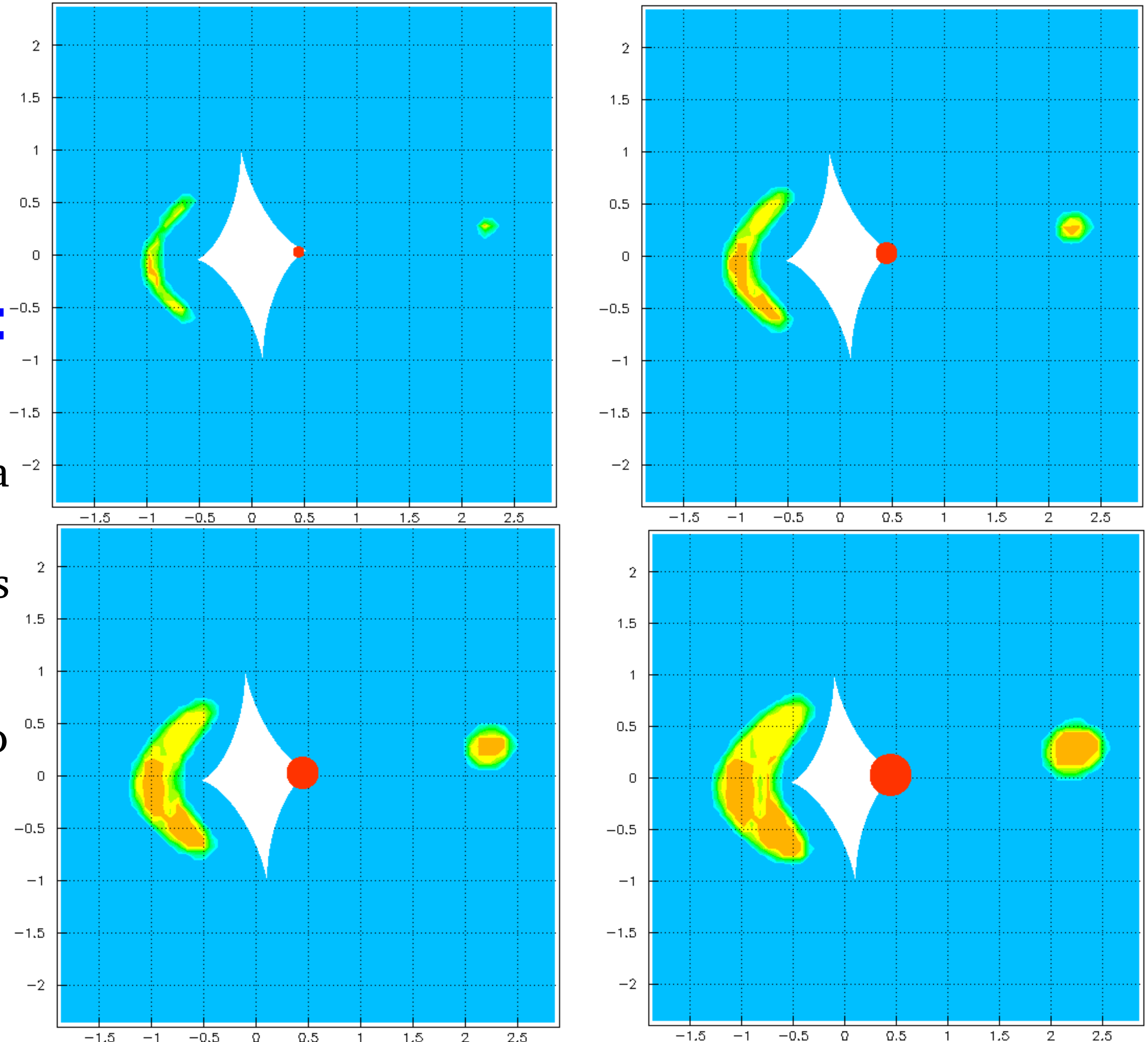




The caustic separates regions of different multiplicities in the source plane. Its image in the image plane is the critical curve, on which magnifications are infinite.

An example: RXJ 0911

- If source exceeds a limit (~ 0.07”):
  - Three A images merge
  - Linear approximation no longer appropriate



- Point-by-point image construction, each point given a weight equal to its magnification.
- The source covers the western cusp of the caustic

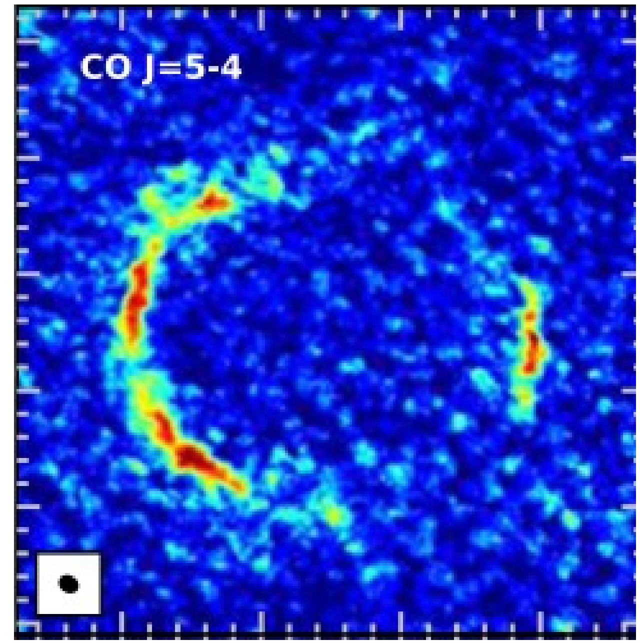
REVIEW OF HIGH REDSHIFT GALAXIES

SDP.81 (z = 3.04)

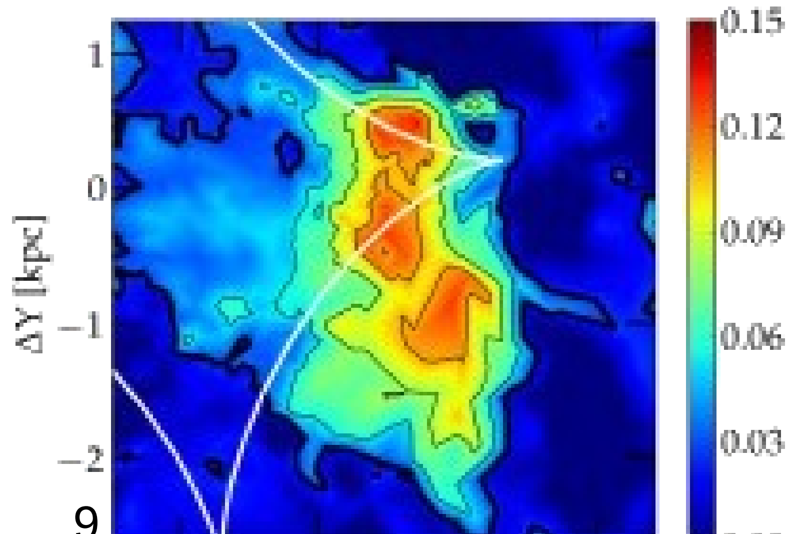
- Best resolved:
  - High spatial resolution & sensitivity observations of gas and dust
  - Accurate HST observations → Greatly help define the lensing potential

- Gravitationally lensed in a typical 'short axis quad' configuration
- Merging evidence from the complex structure of the gas, dust and optical emissions from the source plane

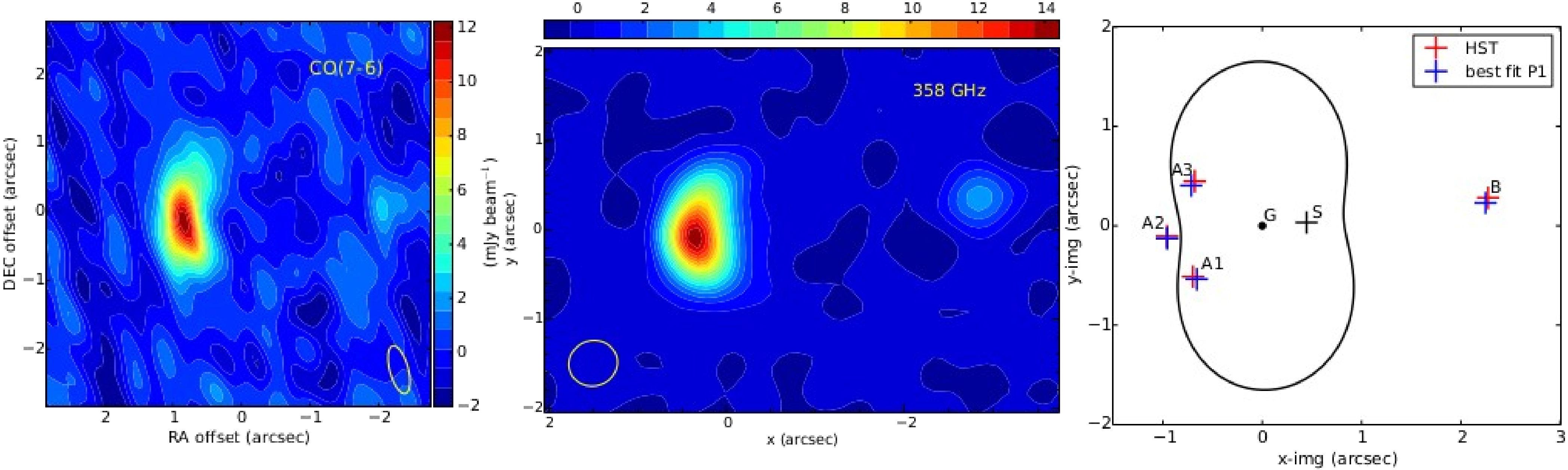
Lens plane



Source plane



RXJ0911.4+0551 ($z = 2.79$)

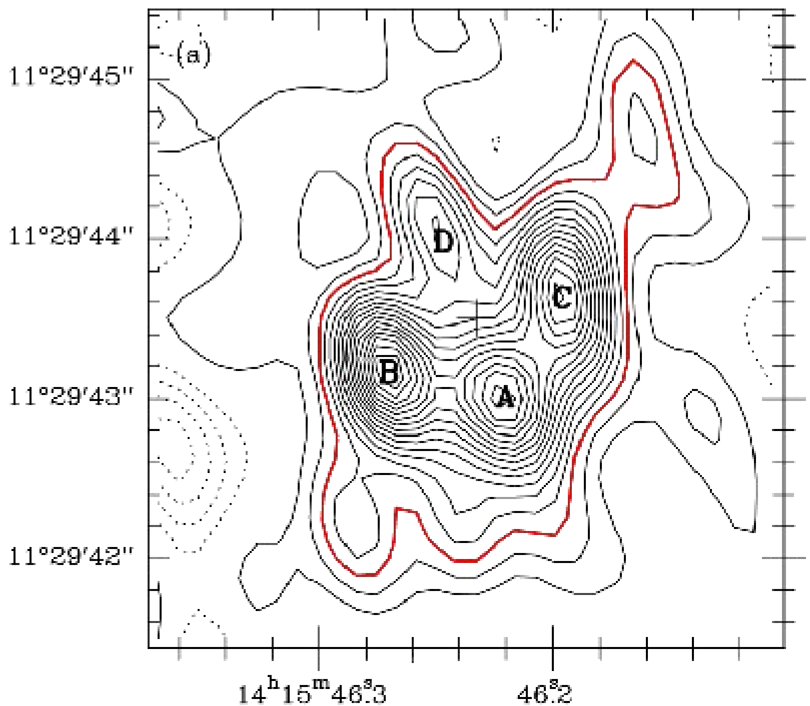


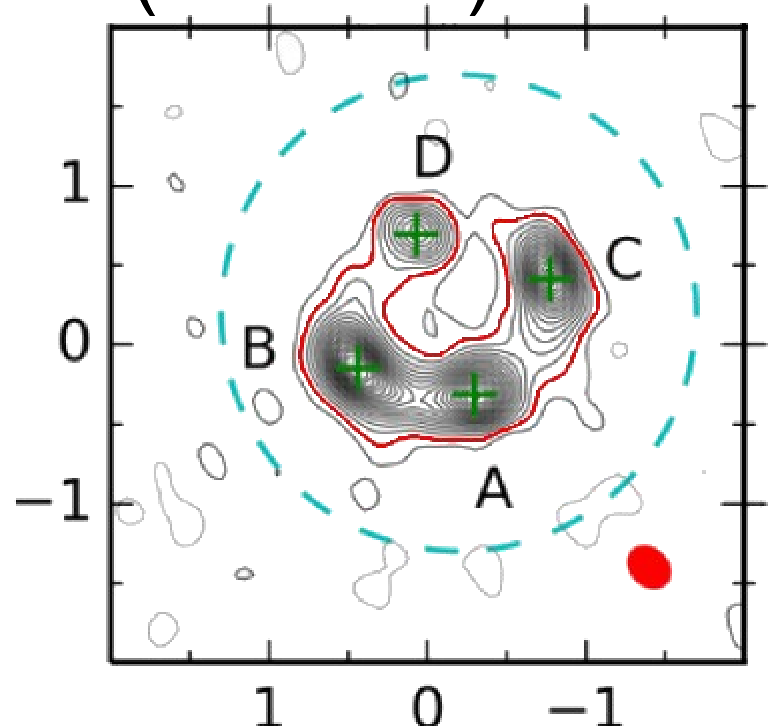
- Gas and dust components are evidenced to be compact and concentric with the black hole:
  - The quasar vs. **358** GHz continuum: concentricity better than **0.31** kpc
  - The quasar vs. CO(**7-6**) emission: concentricity better than **1.10** kpc
  - The gas component is ~ **3.4** ± **0.4** times more extended than the dust component: FWHM_{gas} **= 2.6** ± **0.3**, FWHM_{dust} **= 0.76** ± **0.08** kpc

→ Against a recent merger scenario

→ What may have triggerred the compact starburst?

The Cloverleaf (z = 2.56)

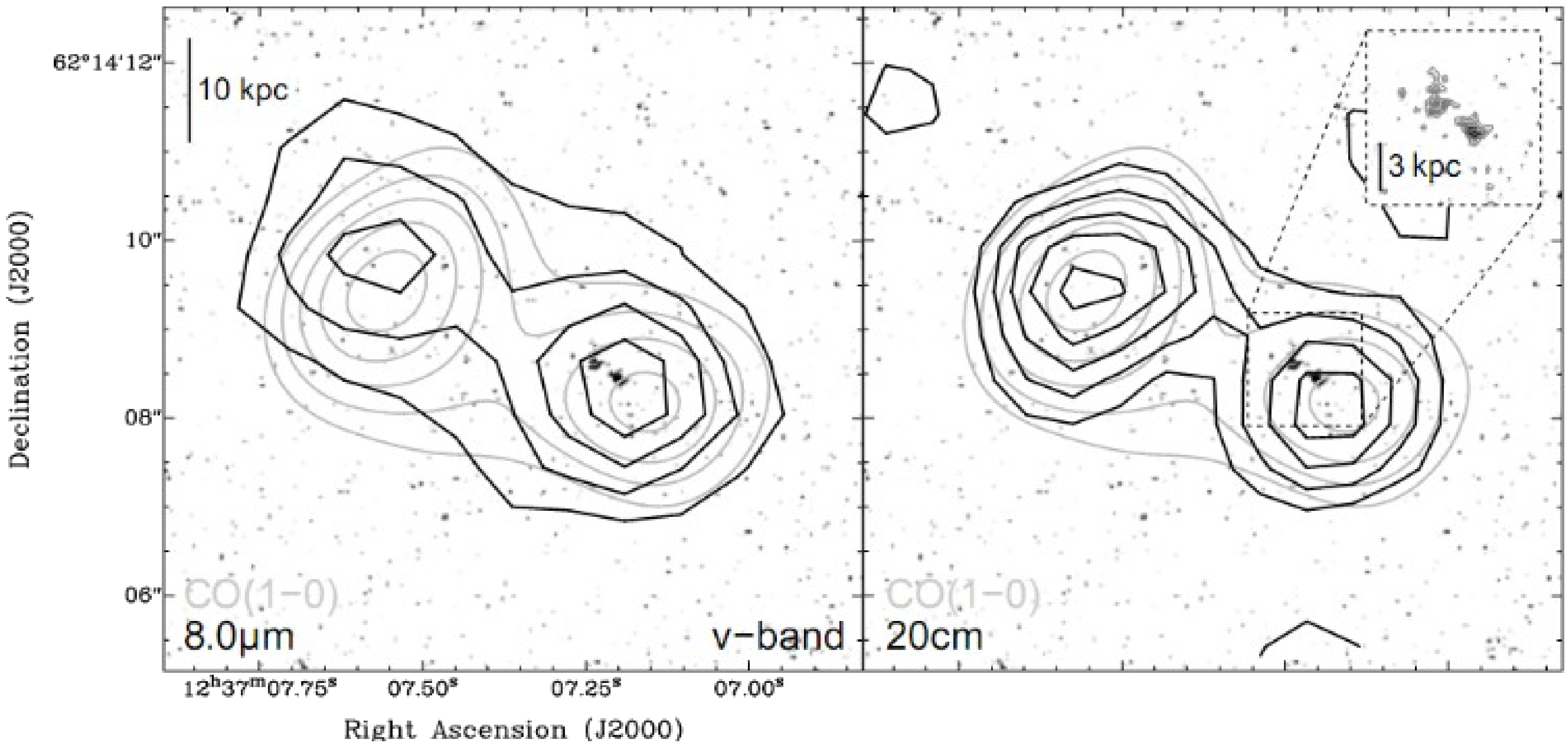




- A gravitationally lensed quasar host having an optical image that would benefit from:
  - Better spatial resolution: better defined lensing potential
  - Better sensitivity: reliably reveal the lens

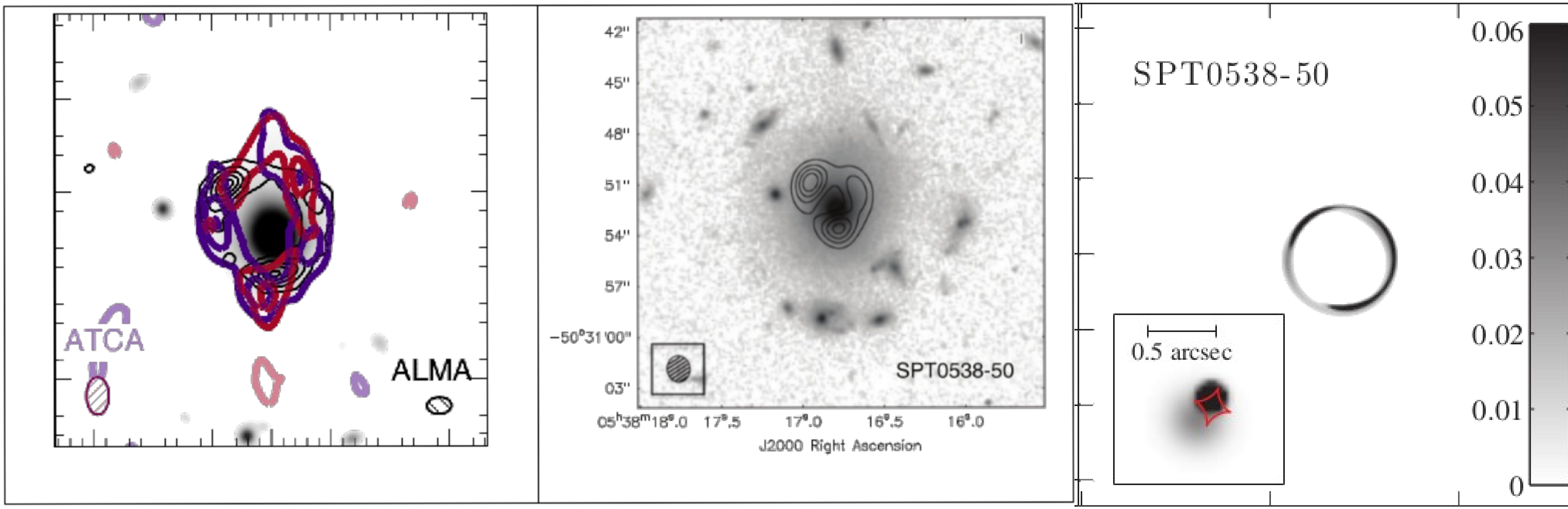
  → Uncertainties remain on the reliability of the lensing model
- Most convincing analysis suggests a size of ~ 0.8 kpc for the gas component.
- The continuum component has not been evaluated precisely but should be on the same scale.

J123707+6214 (z = 2.5)



- **J123707+6214** shows two similar components for both the gas and the dust, of similar sizes and location, separated by $\sim$ **20** kpc, one of which only coincides with the optical image
- No evidence for lensing
- Possible merger

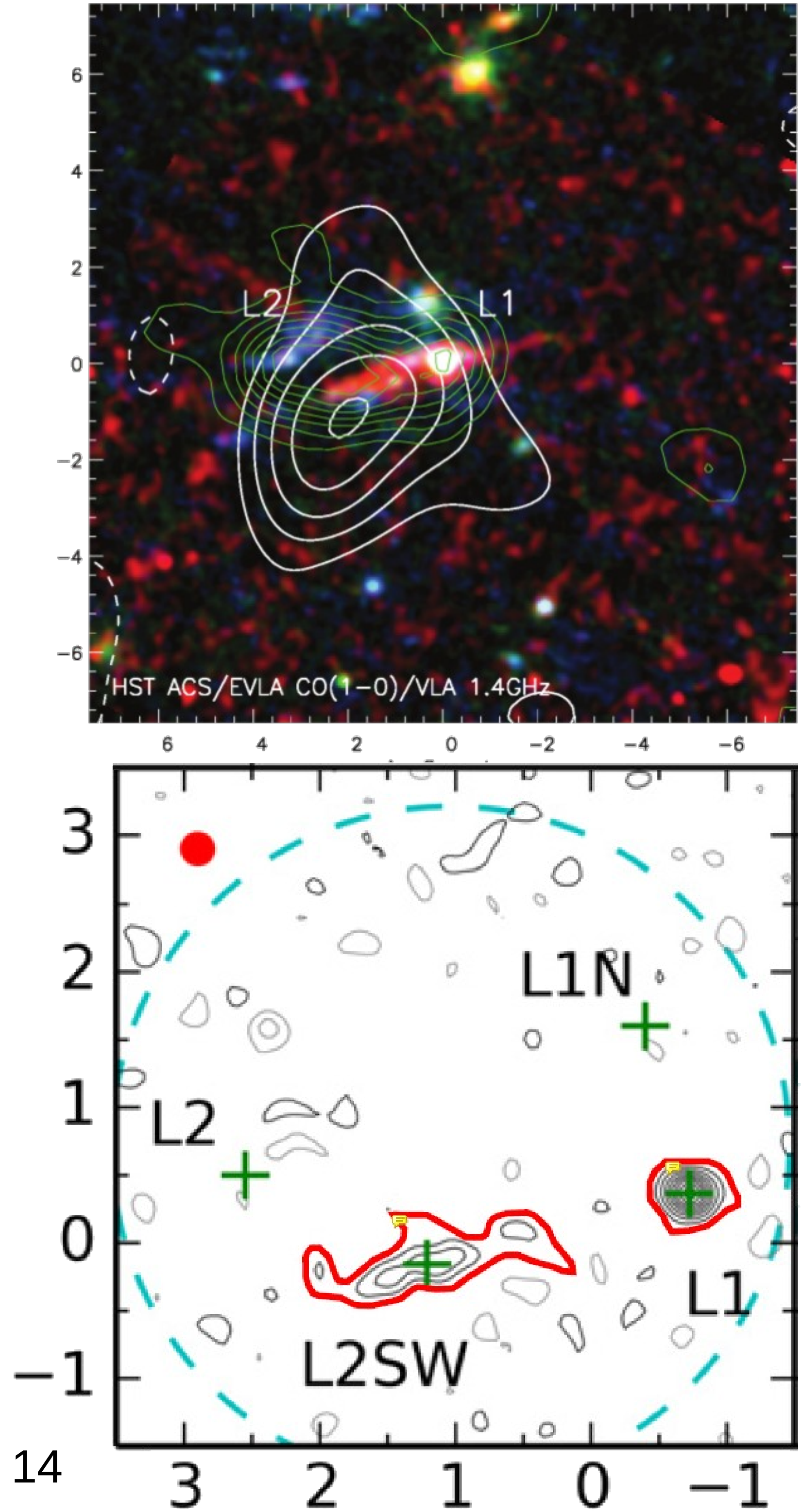
SPT 0538-50 (z = 2.78)



- A dusty star-forming galaxy seen as two components separated in both position and velocity → Possible merger evidence
- Poorly constrained lens model, poorly identified lens
- Evidence for the gas component to be larger than the dust component
- Evidence for the size of the gas component to decrease with J

SMM J02399 (z=2.81)

- Interpretation:
  - A merger of ≥ 2 galaxies separated by ∼ 10 kpc
  - Lensed by a foreground cluster
  - Low magnification (∼2.38)
- Poorly defined lensing mechanism
- Size of dust images ≪ size of gas images
- Difficult detailed interpretation



Summary (Part 1)

Source	Redshift	Comments
A single excellent quality case		
SDP. 81	3.0	High spatial resolution and high sensitivity observations in both gas and dust, accurate HST observations that define the lensing. Gravitationally lensed by a single lens galaxy in the foreground into four images in a typical "short axis quad" configuration. Comparison, in the source plane, of the gas, dust and optical emissions displays a very complex structure giving evidence for merging.
Three relatively clear cases, would benefit from higher resolution/sensitivity observations		
RX J0911	2.8	Well defined lensing, concentric quasar, gas and dust components, dust a factor ~3.4 smaller than gas. No merger.
PSS J2322	4.1	Well defined lensing. Evidence for a star forming disc with a radius of ~2 kpc and a concentric gas reservoir with a radius of ~5 kpc, both concentric with the quasar. A small offset of the gas reservoir is possible (possible merger).
J123707	2.5	No lensing, two distinct components for both dust and gas, one of which hosts the quasar, possible merger.

Summary (Part 2)

Source	Redshift	Comments
Five less clear cases require better quality sensitivity/resolution observations and/or better definition of the lensing mechanism		
APM08279	3.9	Two clear (plus a weaker third) images interpreted as a quad lensed from an inclined unobserved galaxy in the foreground. Suggests a compact source for both gas and dust.
BRI 1335	4.4	Unlensed quasar host with a gas component of a size of ~5 kpc displaying a complex morphology with at least three sub-components suggesting a merging morphology
Cloverleaf	2.6	Poorly defined lensing, similar dust and gas components, no merger
SPT0538-50	2.8	Poortly defined lensing but evidence for two gas and dust components interpreted as a merger
SMMJ0239 9	2.8	Poorly defined lensing (cluster, low magnification). Interpreted as a merger of two or more galaxies