The High-redshift Universe, Magnified

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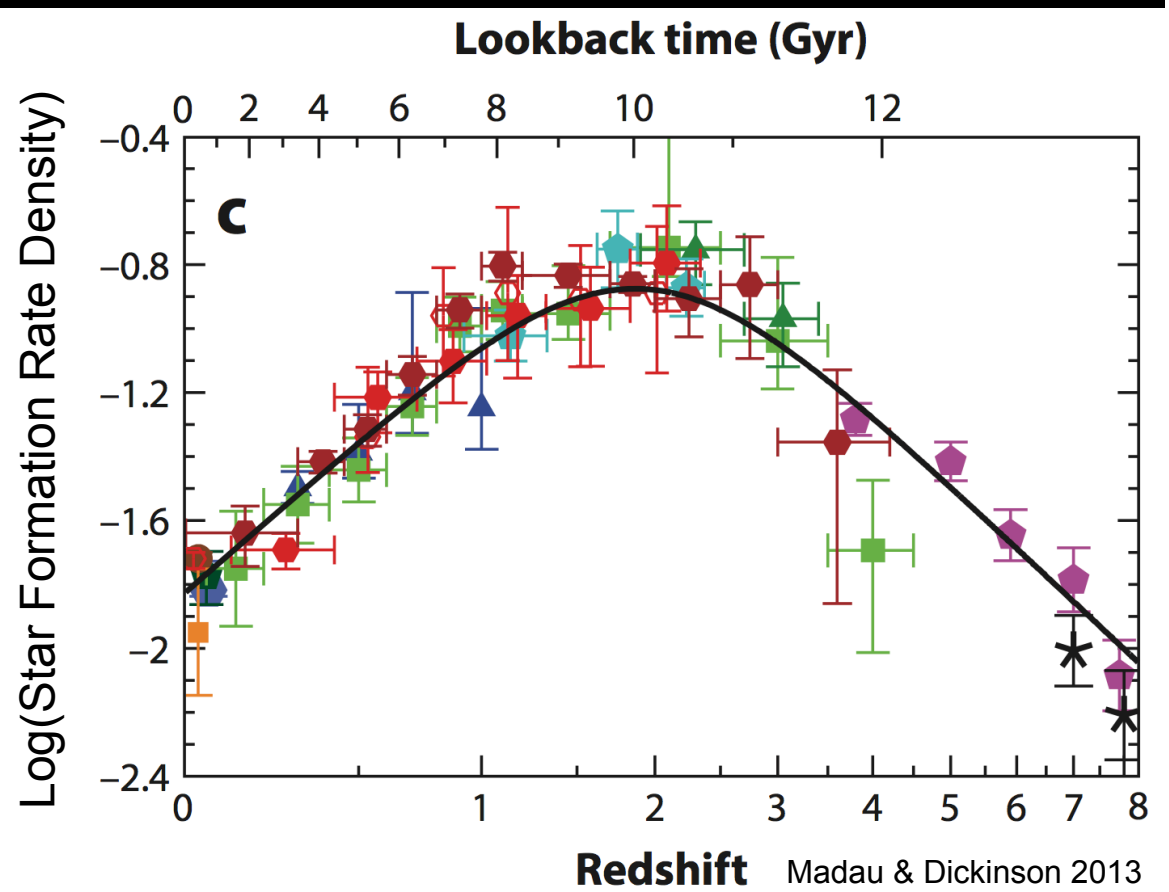
Sixteenth Synthesis Imaging Workshop

16-23 May 2018

High-redshift Galaxy Formation

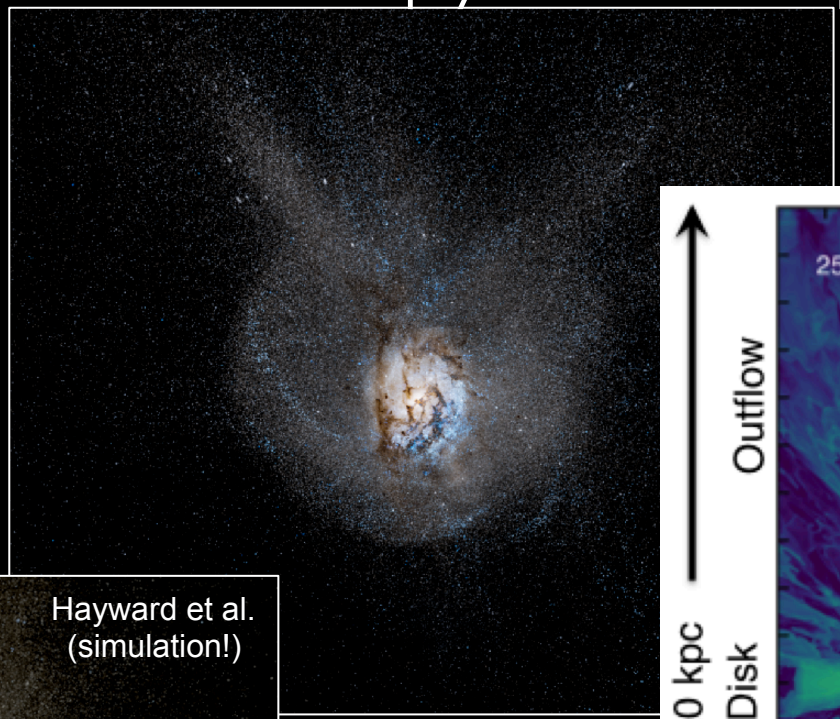
- First few Gyr of cosmic history were a very exciting time!
  - Star formation grows to a peak around z~2, then falls off
  - High density, large gas supplies, active stirring

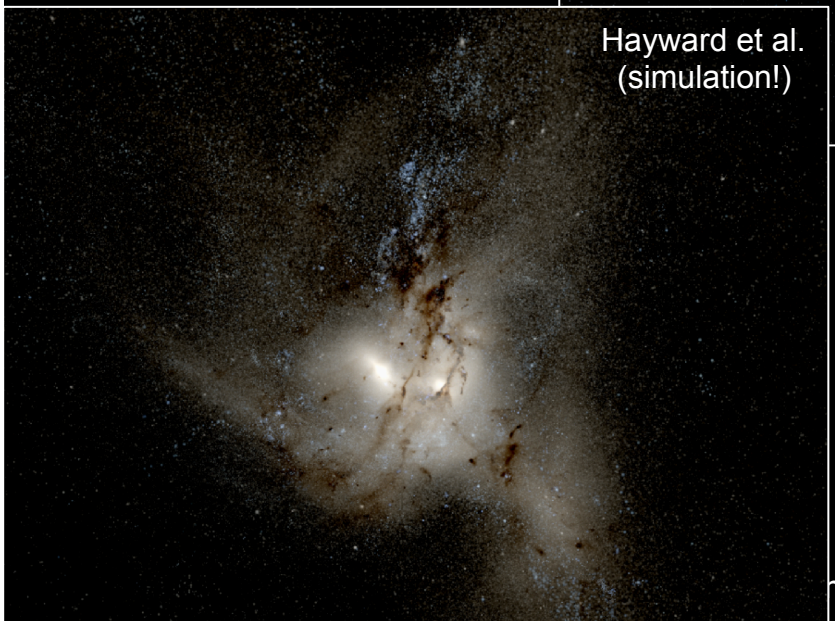


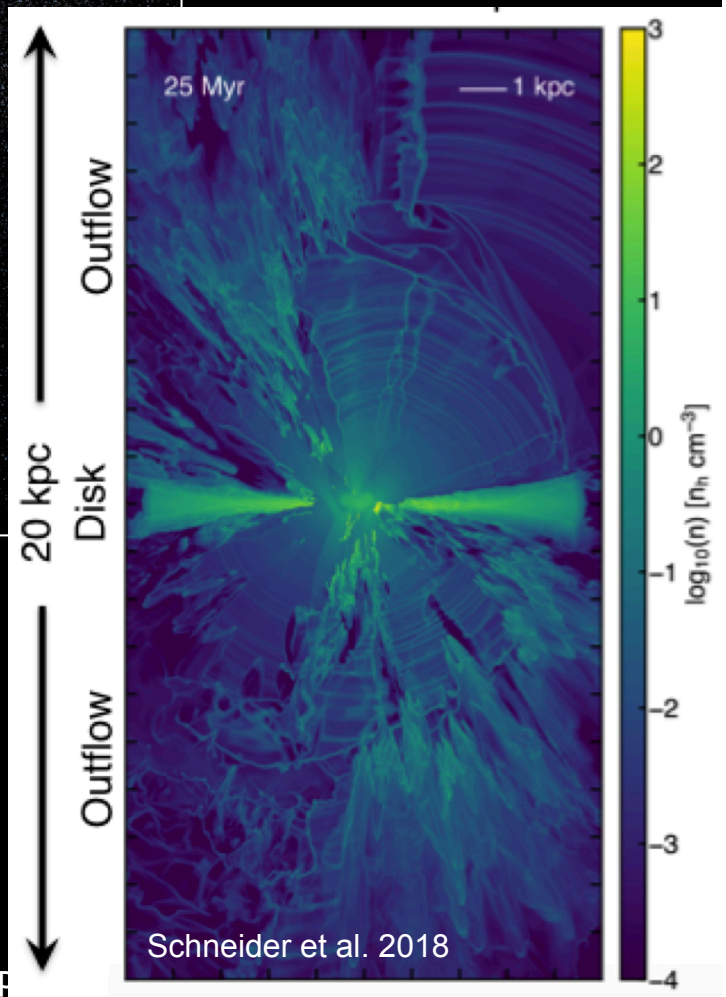
Madau & Dickinson 2013

High-redshift Galaxy Formation

- Detailed simulations now exist but physics are not completely constrained

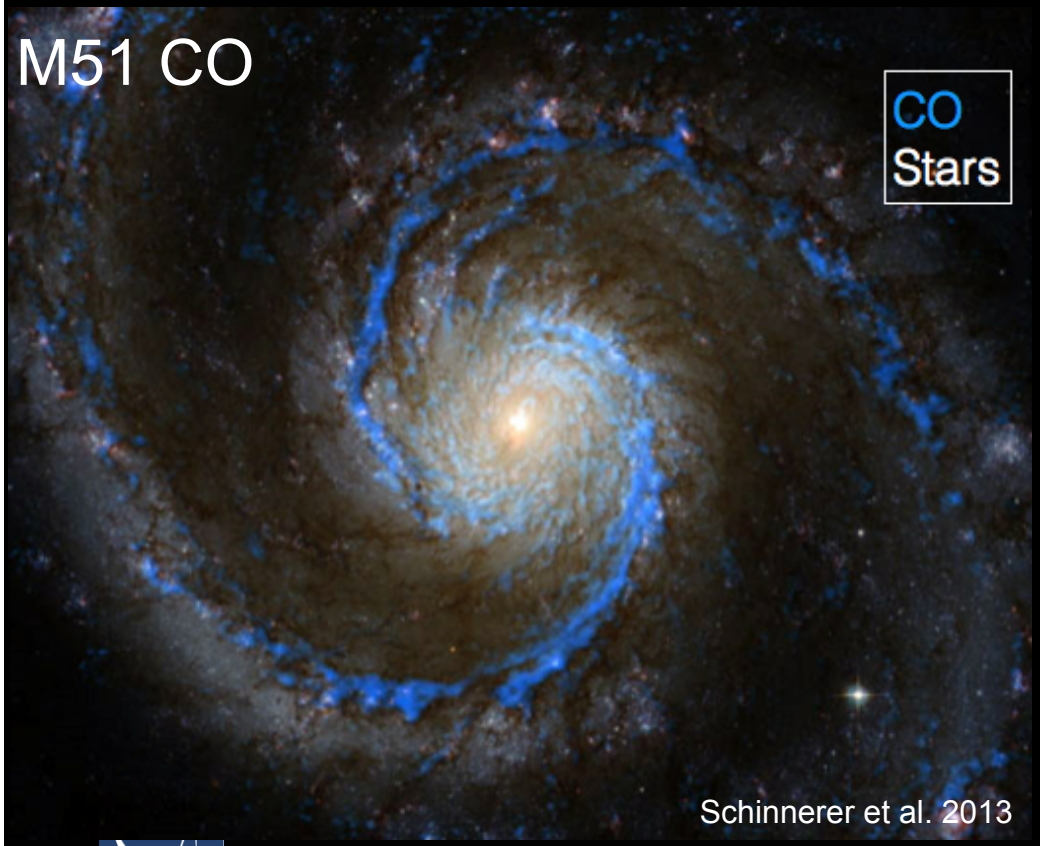


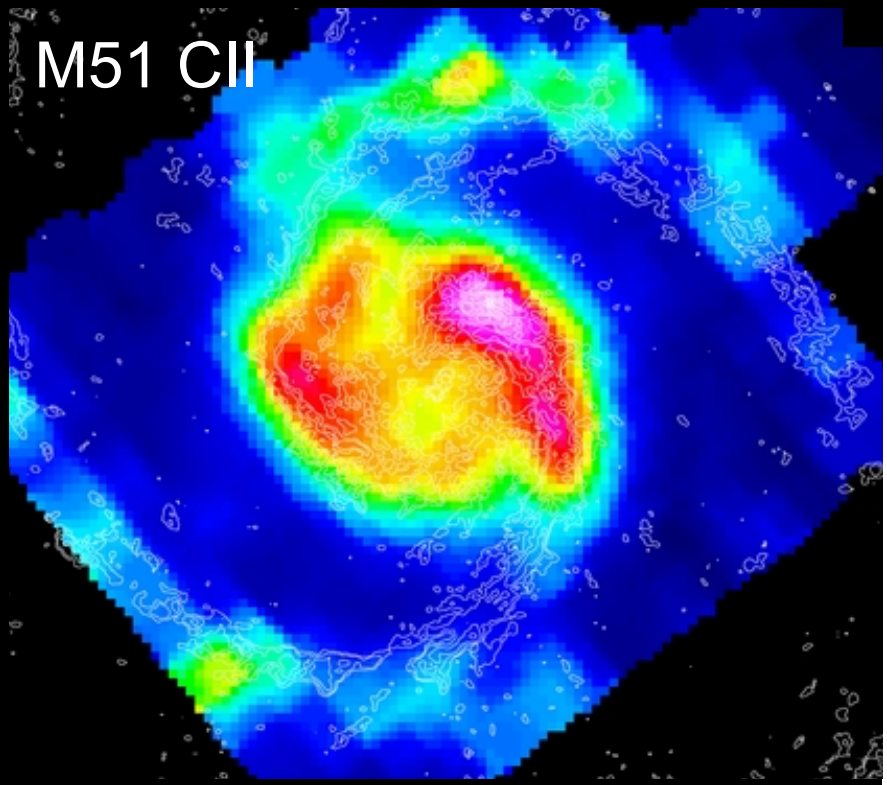




High-redshift Galaxy Formation

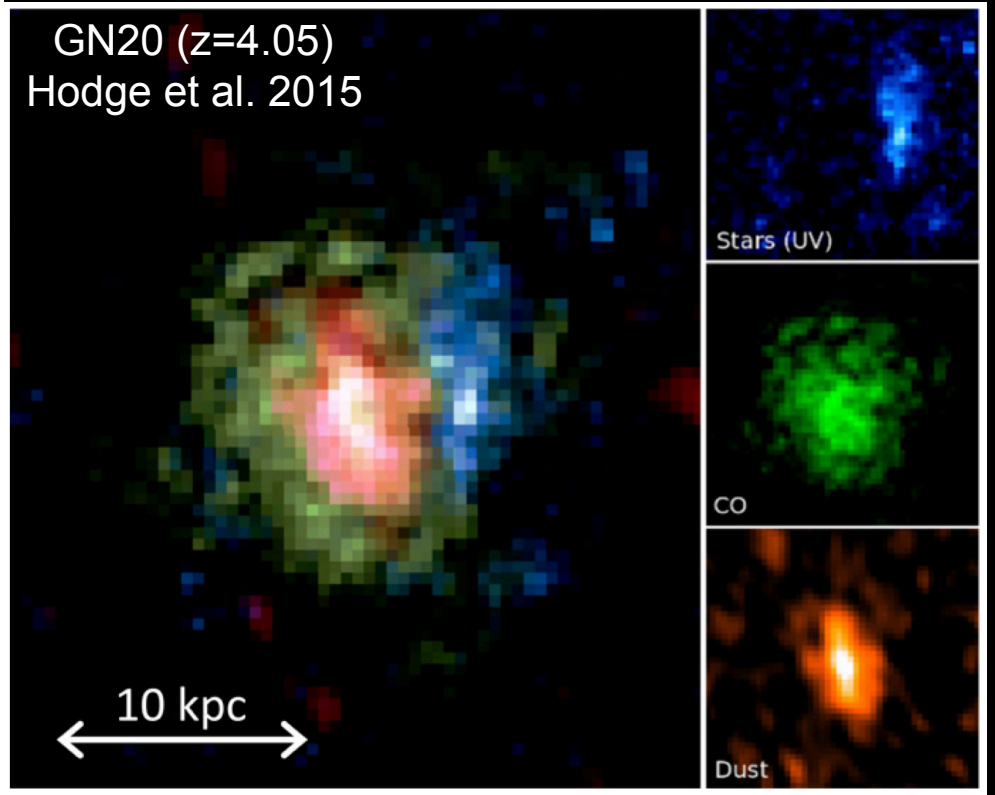
- To understand galaxy formation, we want to approximate local observations
  - In FIR, we may even want to exceed local observations
- This is hard for faint emission from the cool ISM

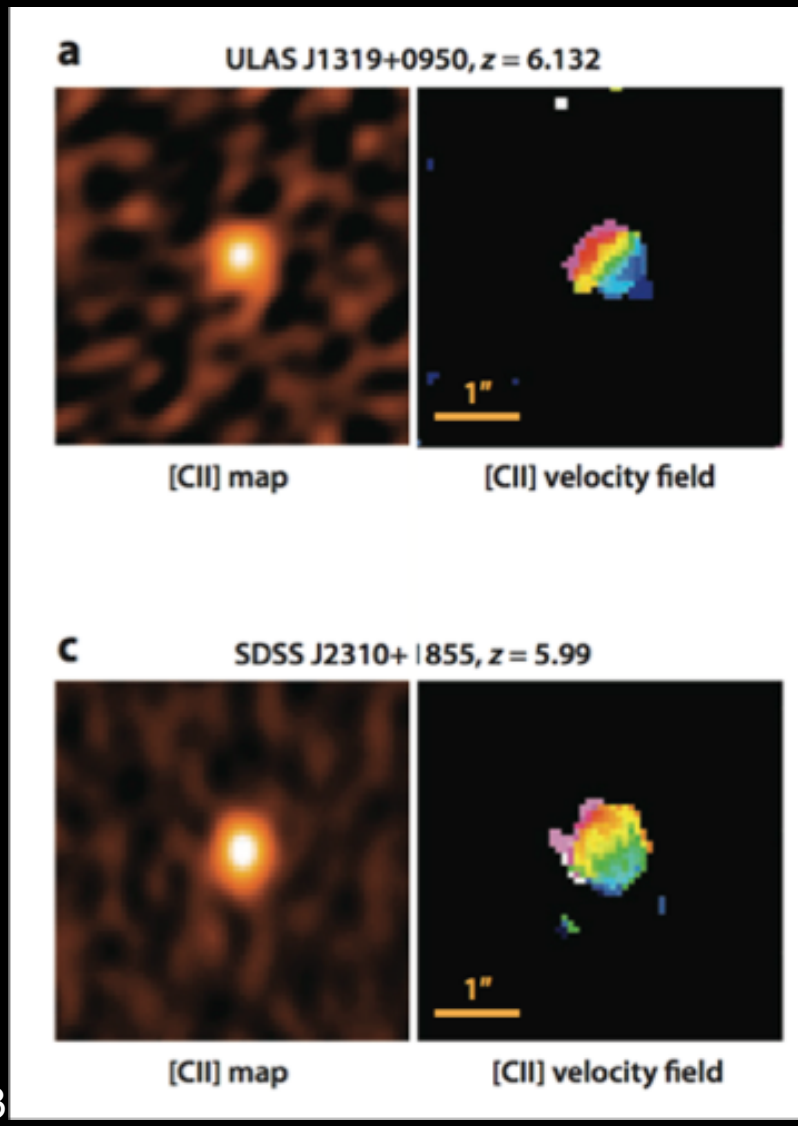




High-redshift Galaxy Formation

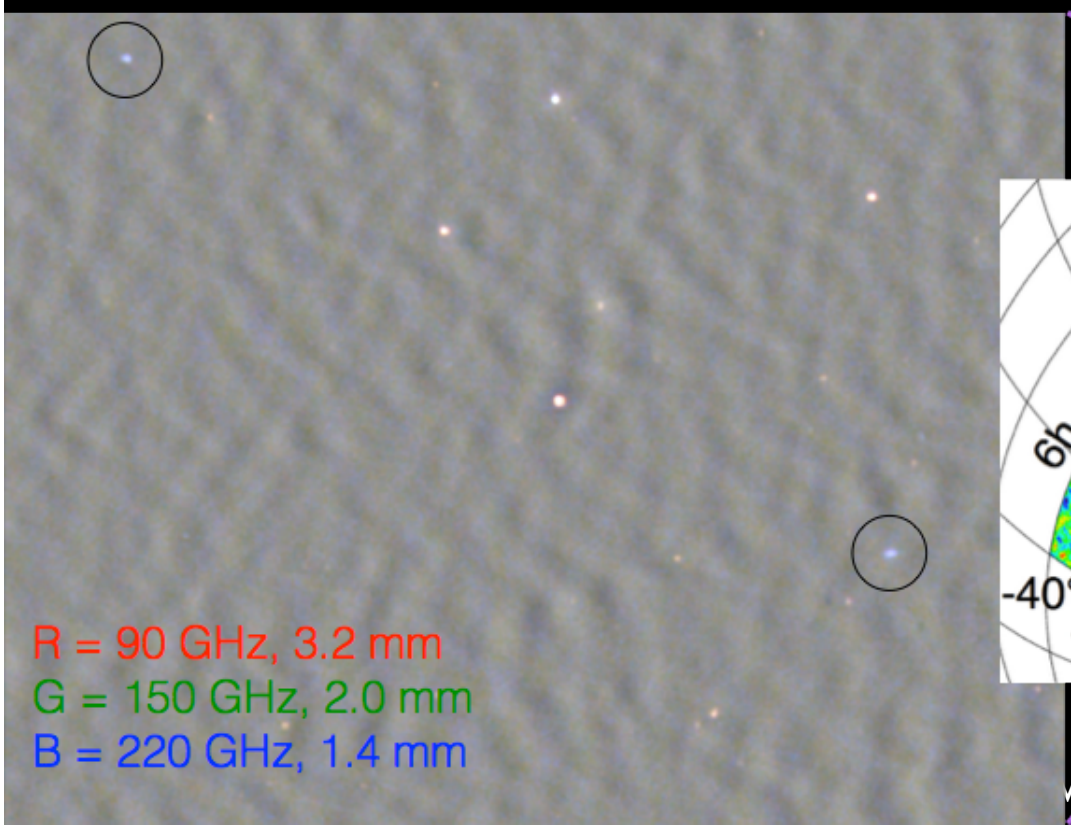
- Our view is less exciting!
  - Still true with ALMA

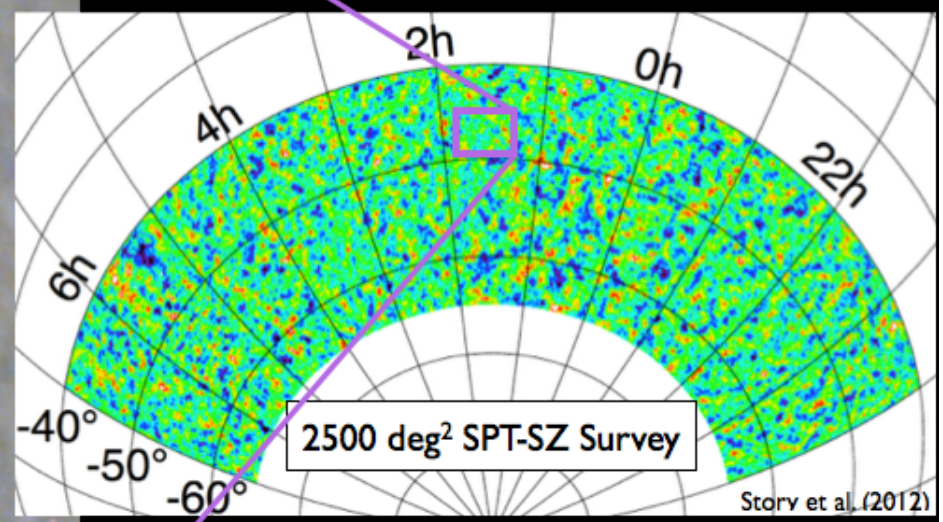




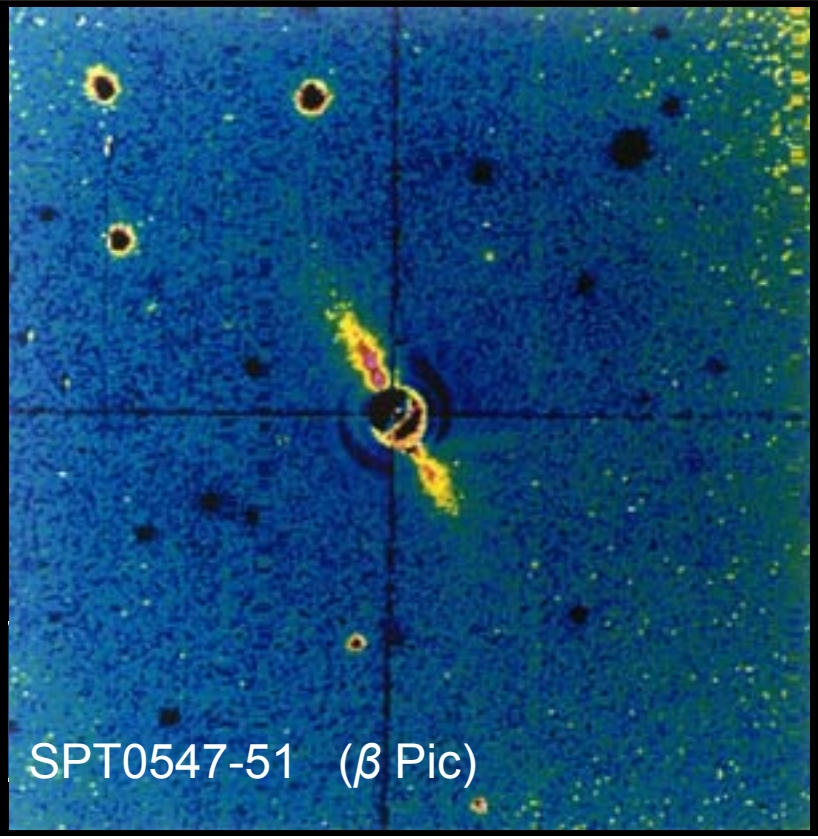
z~6 QSOs
Carilli & Walter 2013

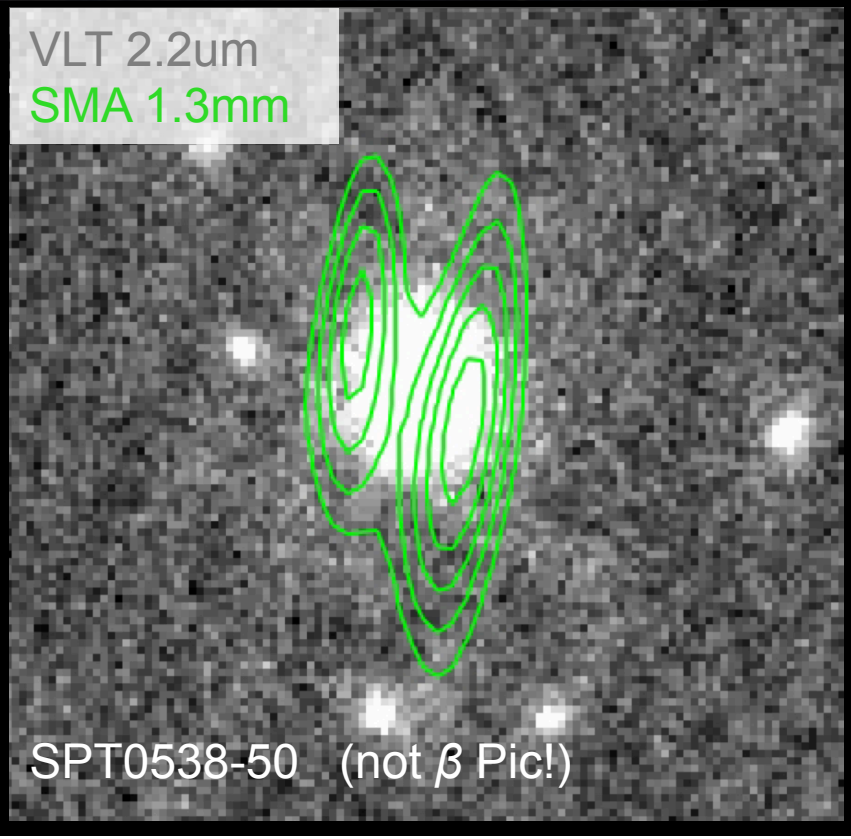
South Pole Telescope



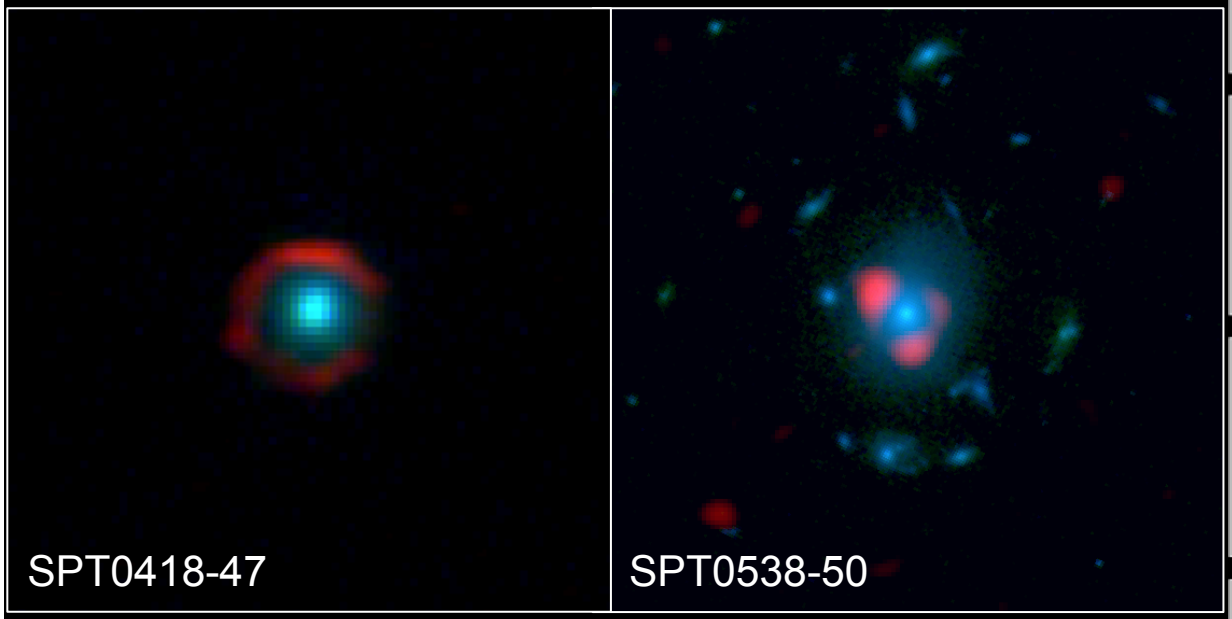



South Pole Telescope

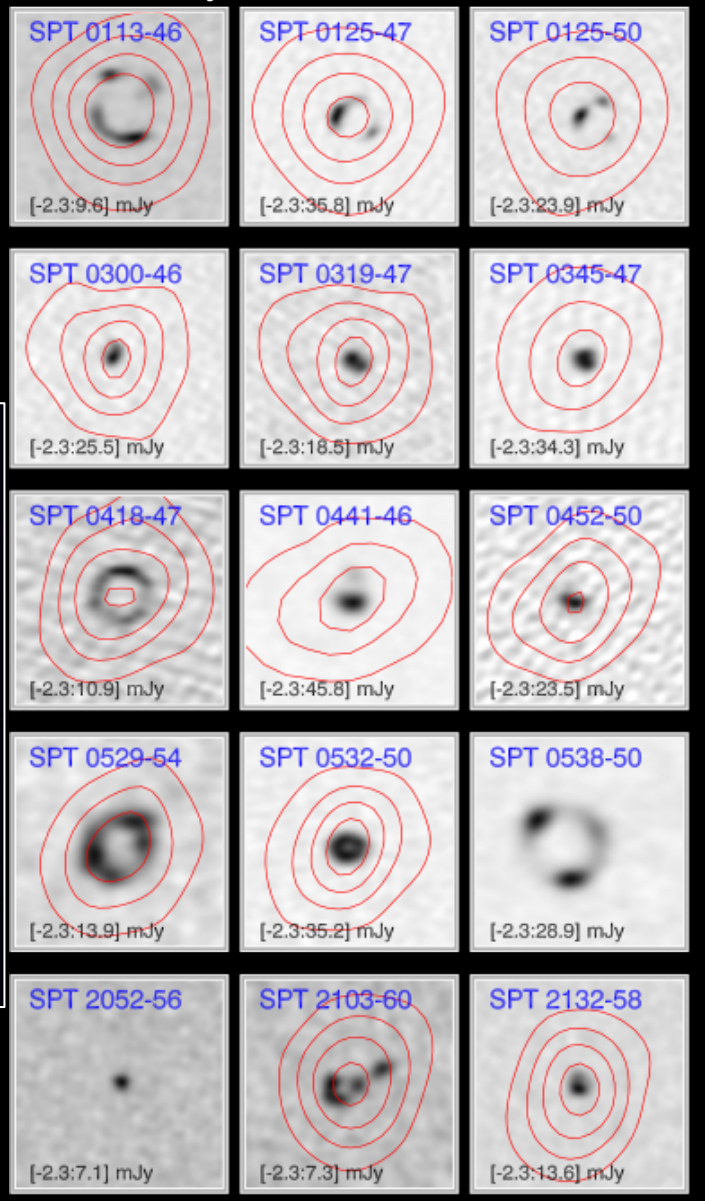

SPT0547-51 (β Pic)


VLT 2.2um
SMA 1.3mm
SPT0538-50 (not β Pic!)

Gravitationally Lensed Galaxies



Cycle 0 – 1min/src



Vieira, DPM et al. 2013

Gravitationally Lensed Galaxies

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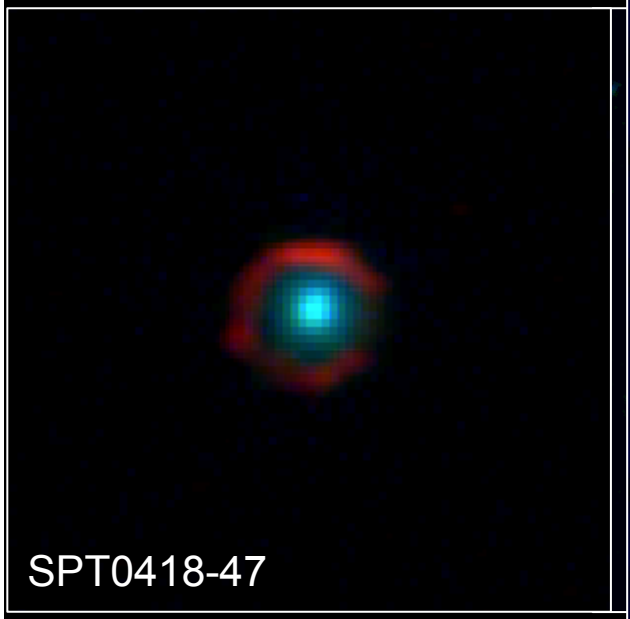

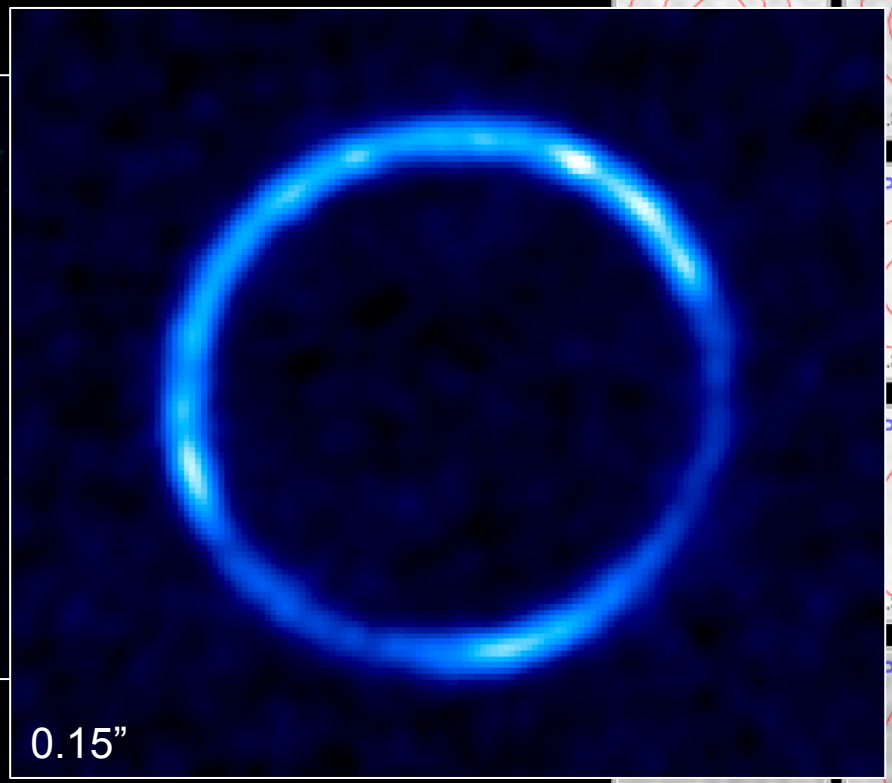

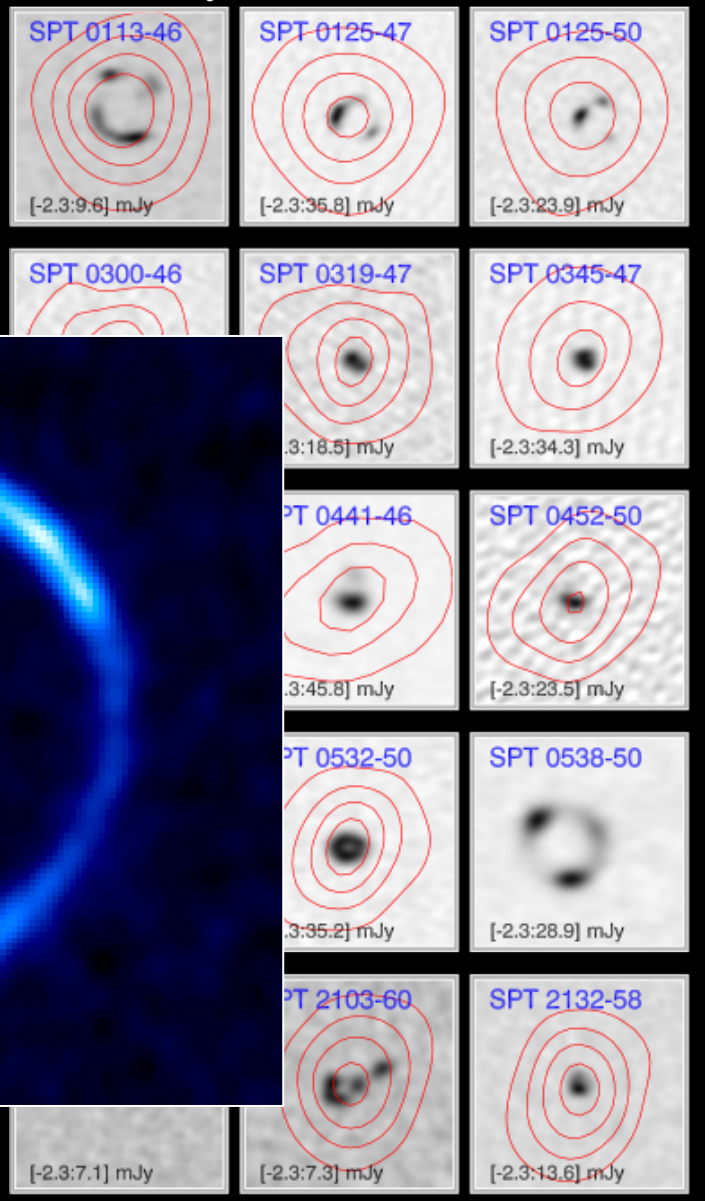

Vieira, DPM et al. 2013

Gravitationally Lensed Galaxies

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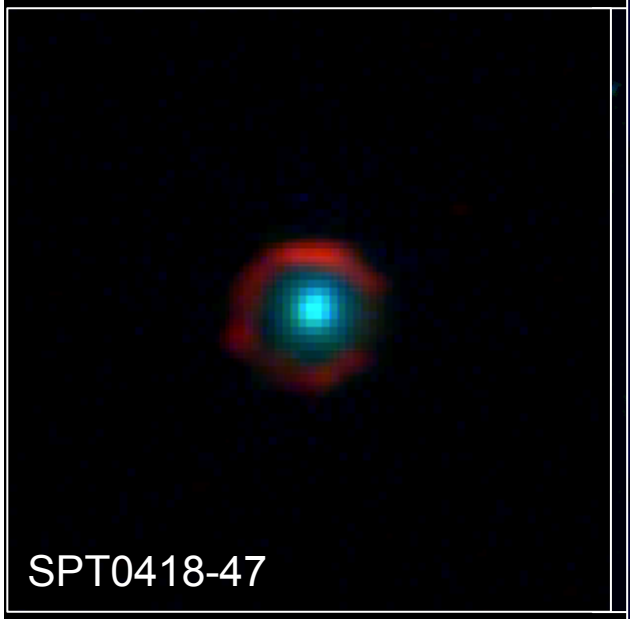
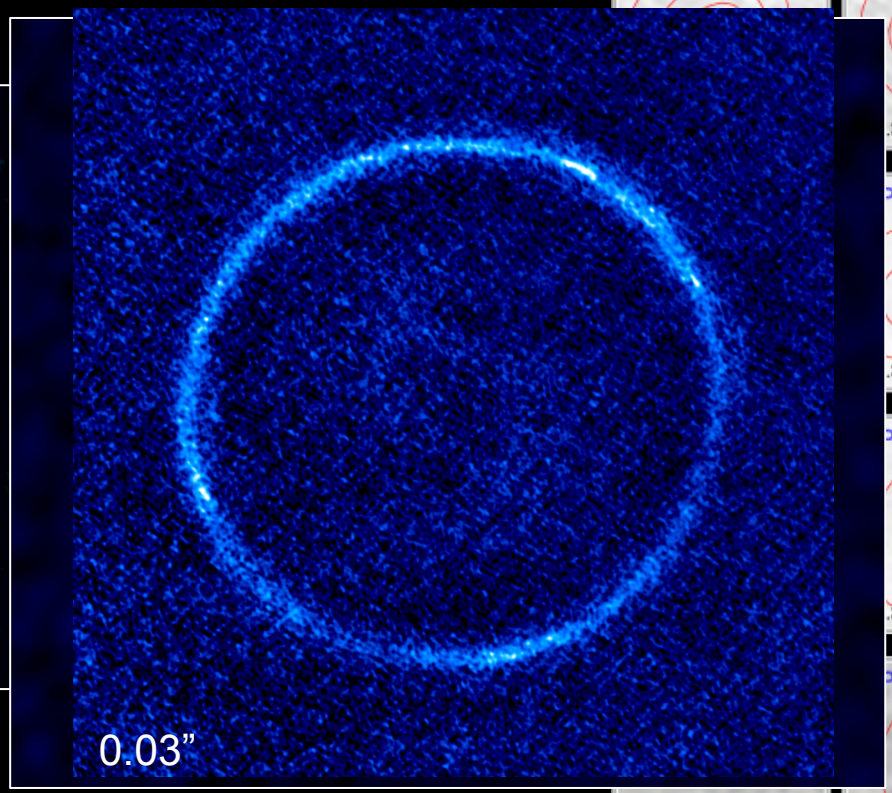
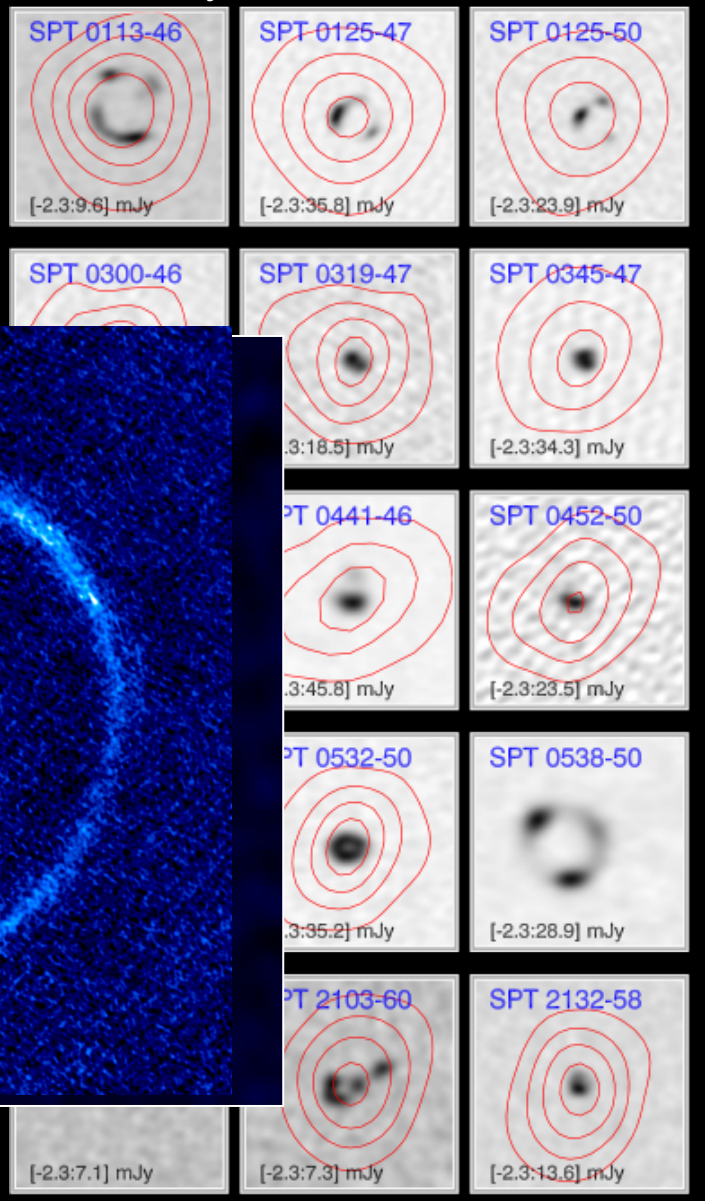


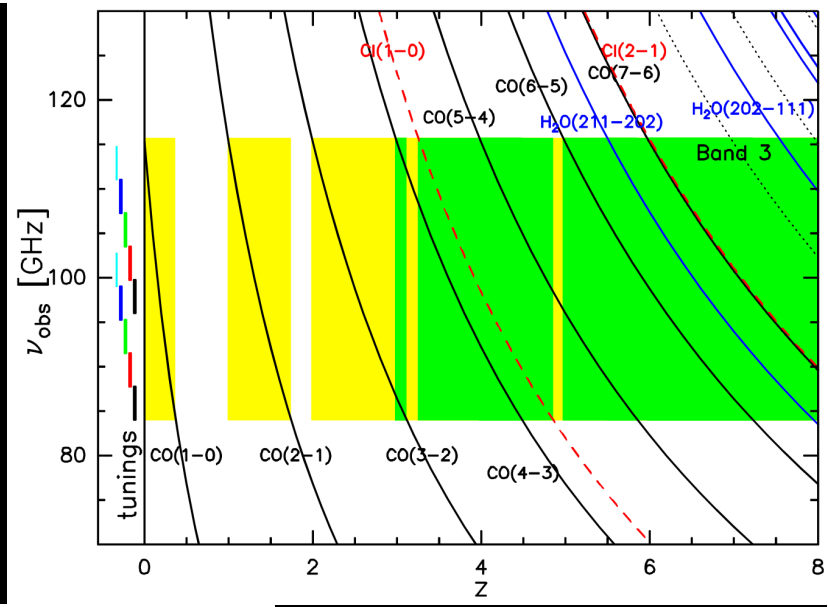




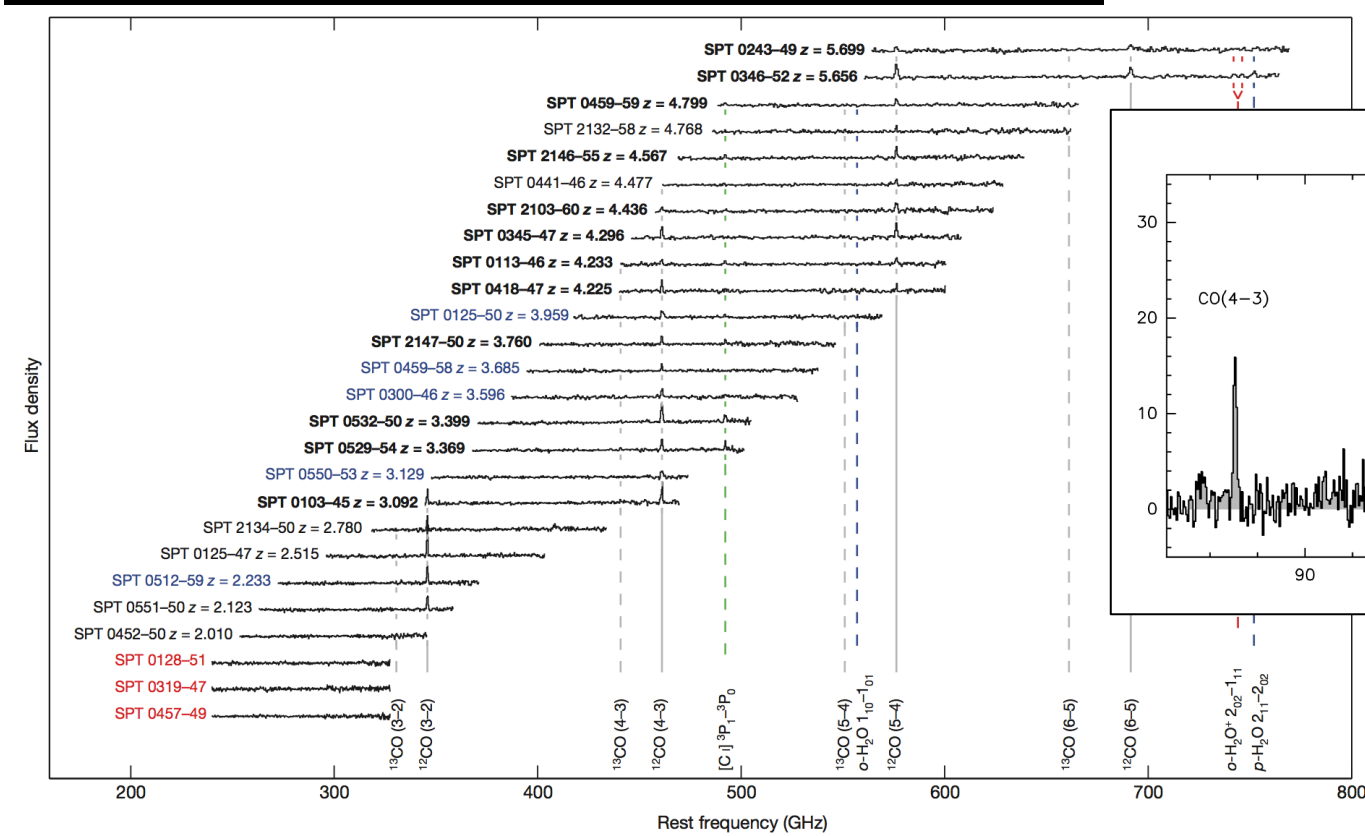
Vieira, DPM et al. 2013

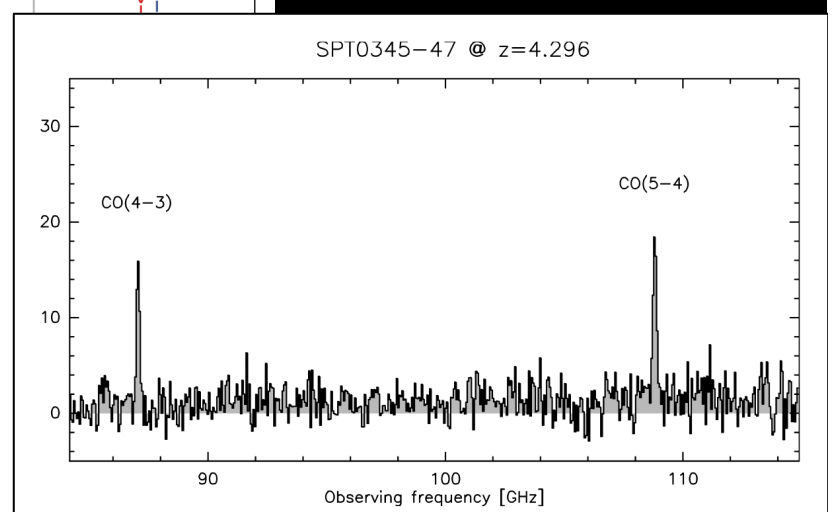
Distant Gravitationally Lensed Galaxies

Cycle 0 - 10min/src



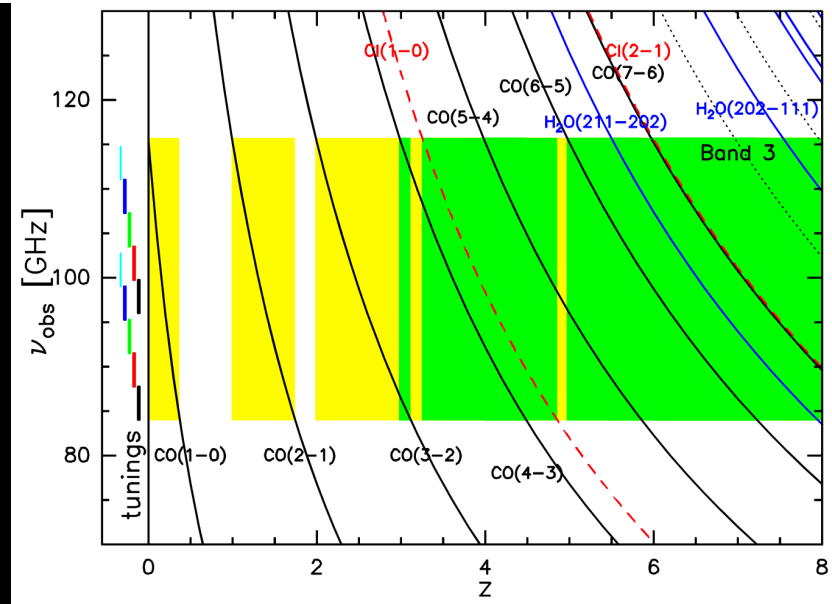
Weiss et al. 2013





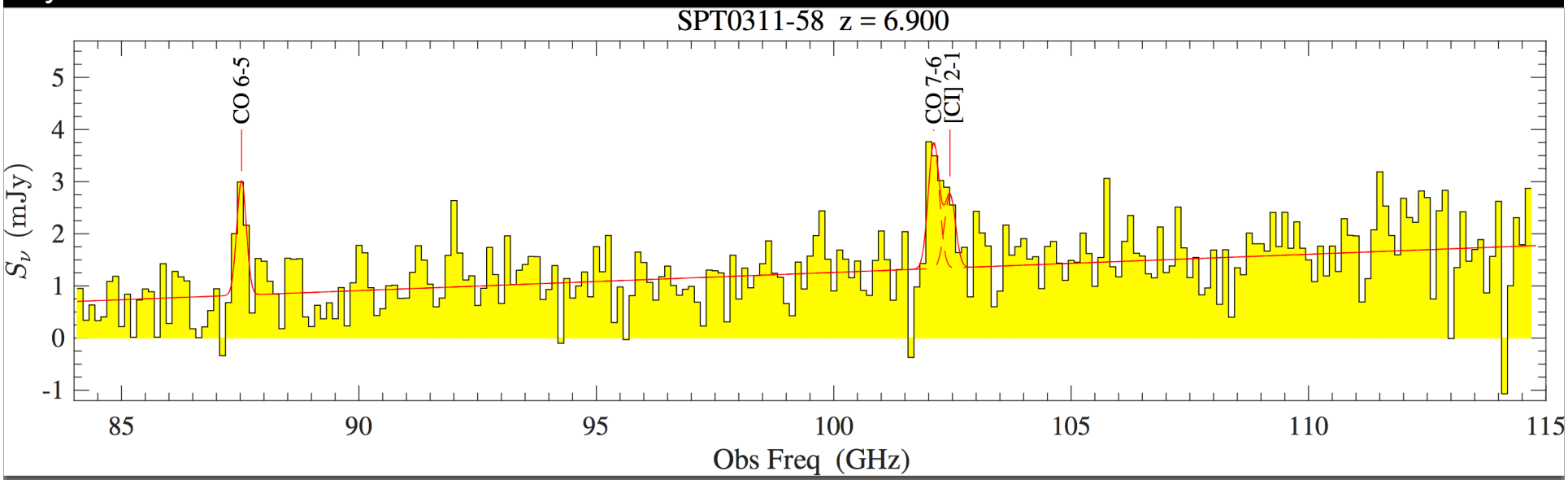
Vieira, DPM et al. 2013

Distant Gravitationally Lensed Galaxies



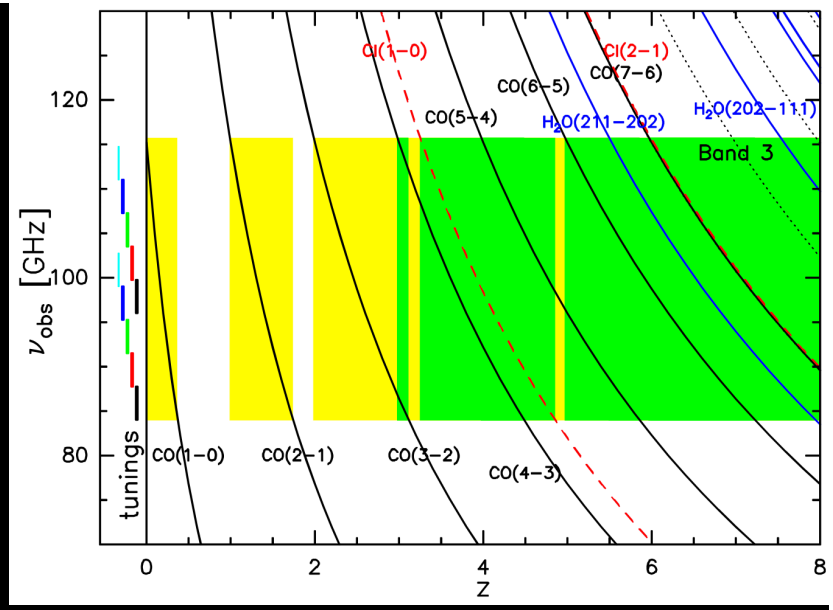
Weiss et al. 2013

Cycle 4 – z=6.9



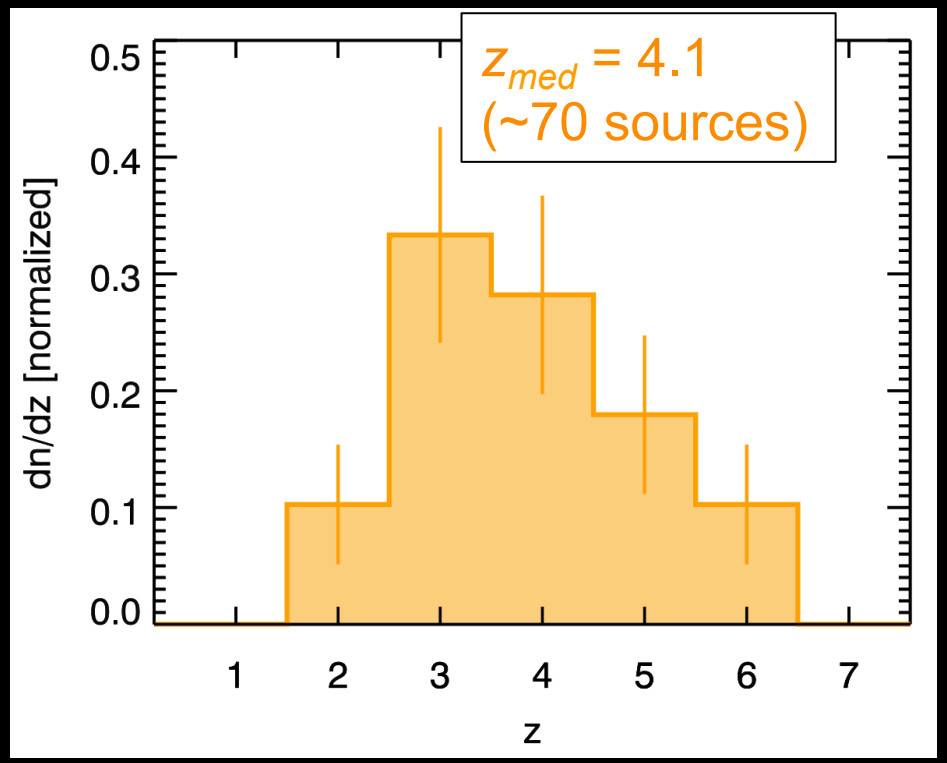
Strandet et al. 2017
Marrone et al. 2018

Distant Gravitationally Lensed Galaxies



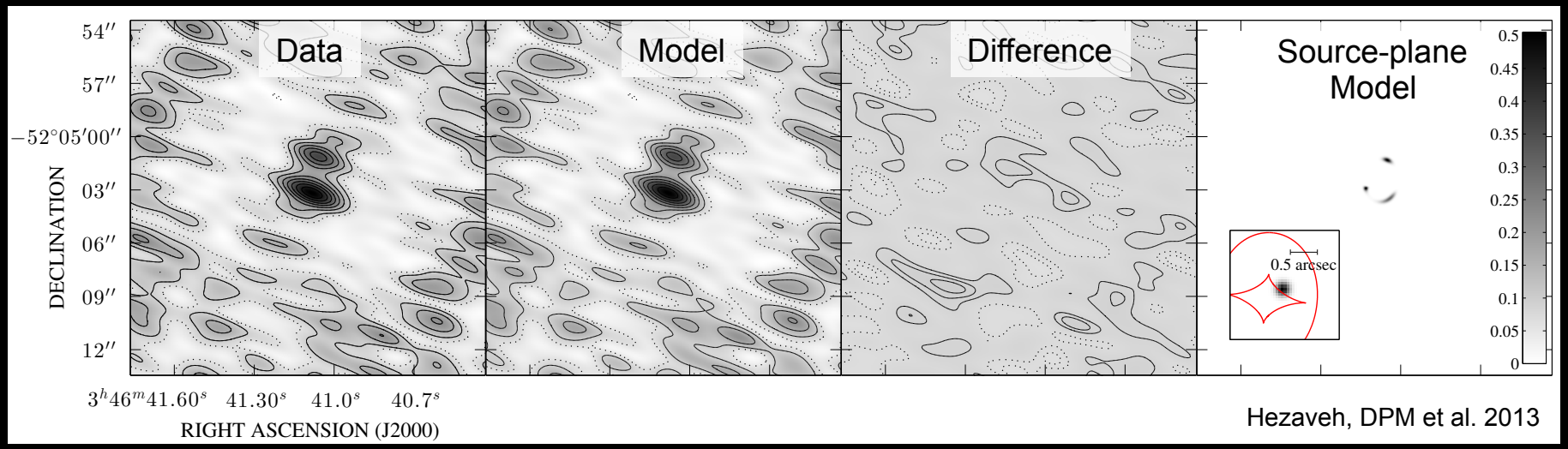
Weiss et al. 2013

Weiss et al. 2013
Strandet et al. 2016



Interferometric Lens Modeling

SPT0346-52

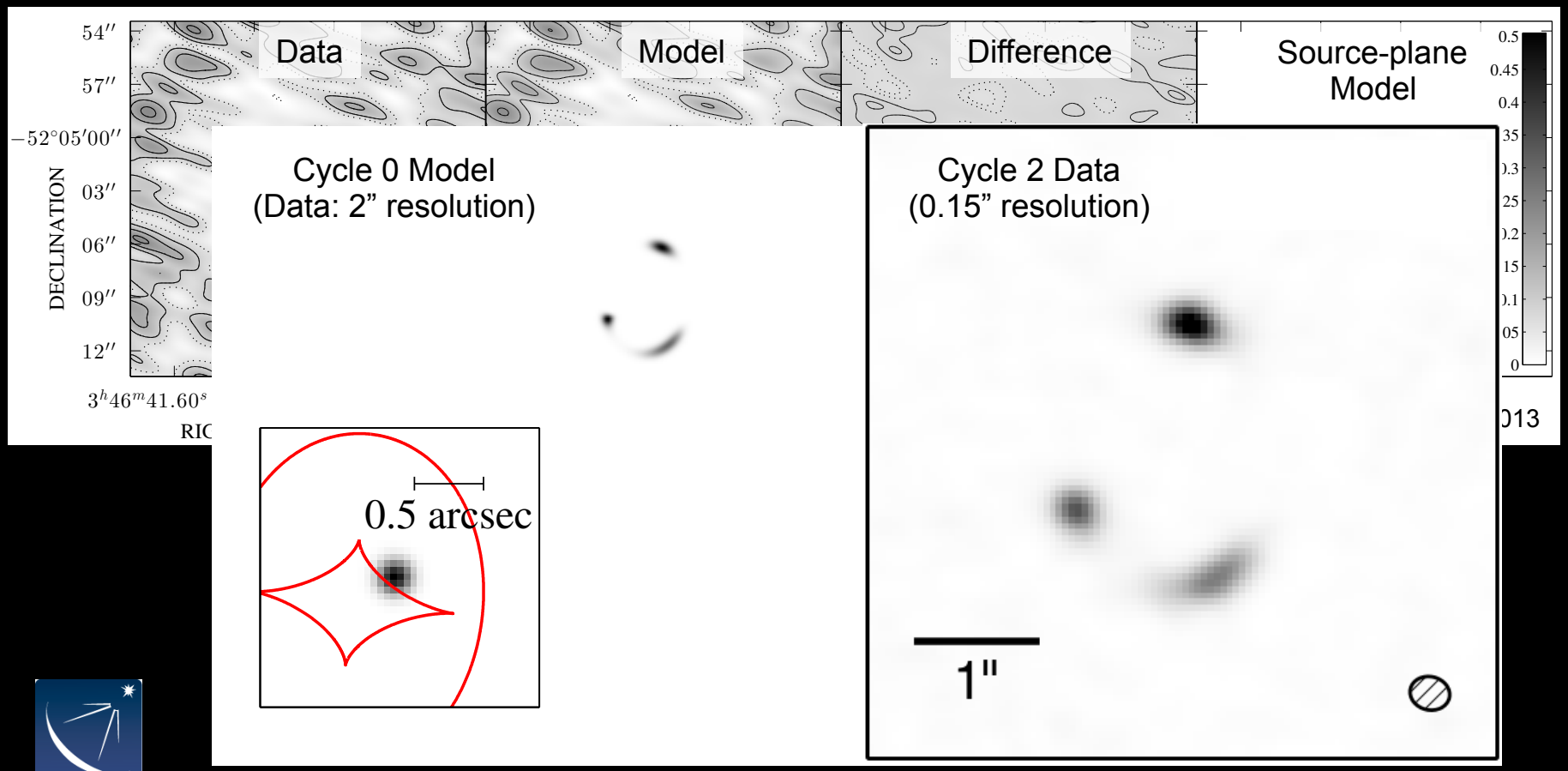


Hezaveh, DPM et al. 2013

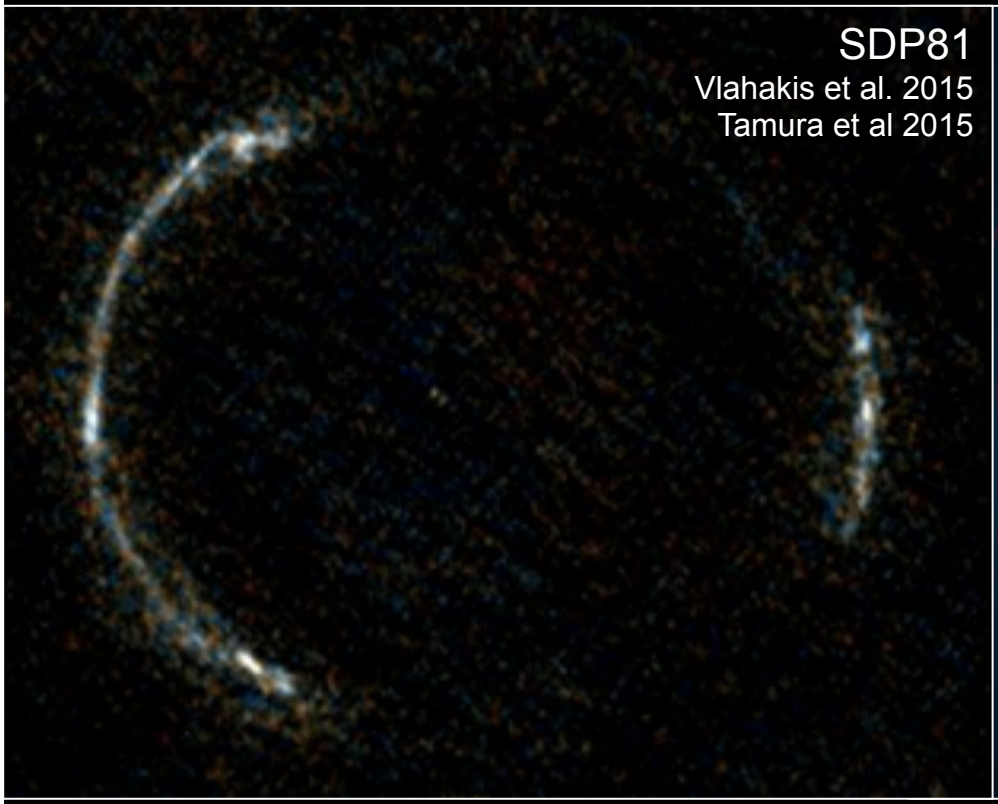
Spilker, DPM et al. 2016

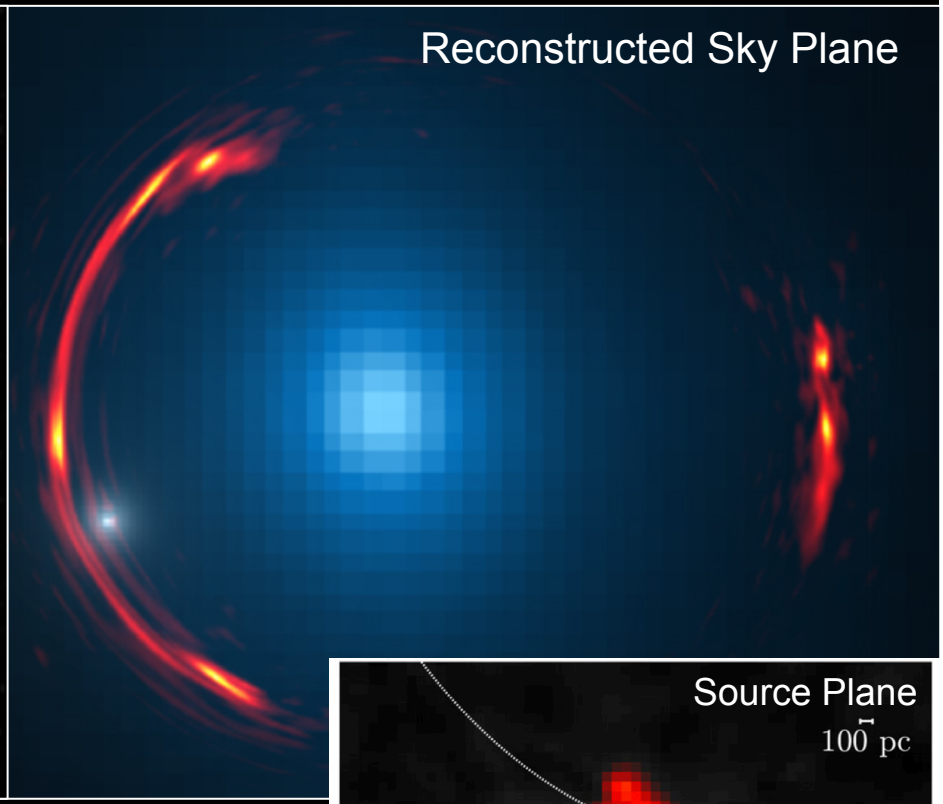
Interferometric Lens Modeling

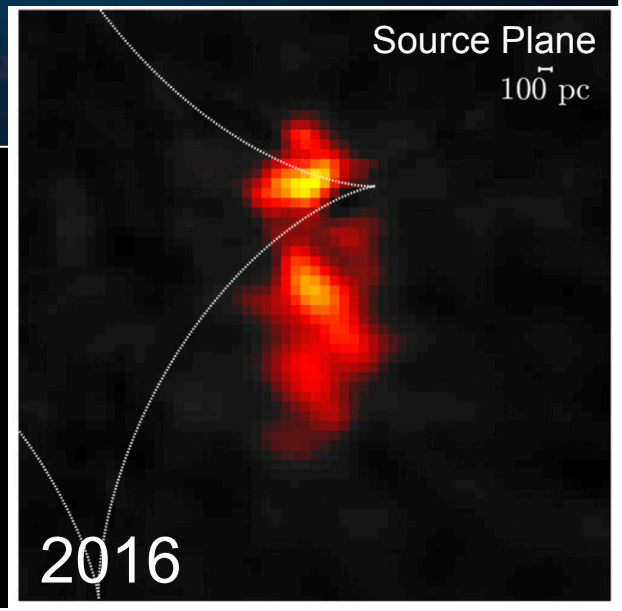
SPT0346-52



Advanced Lens Modeling

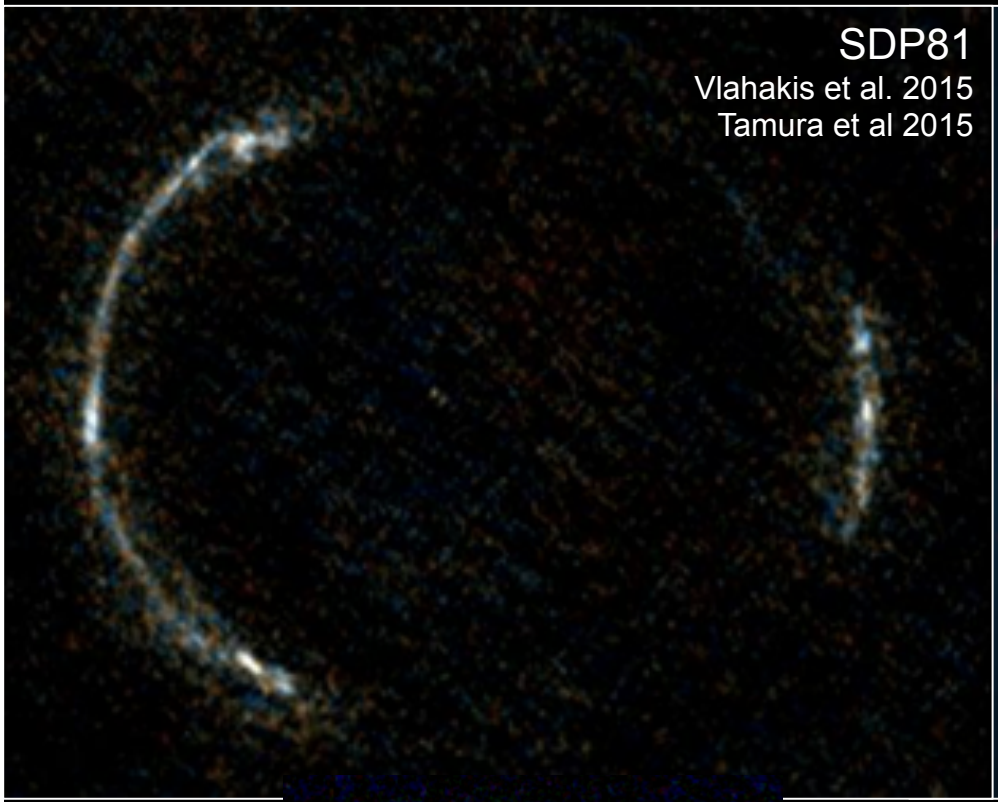


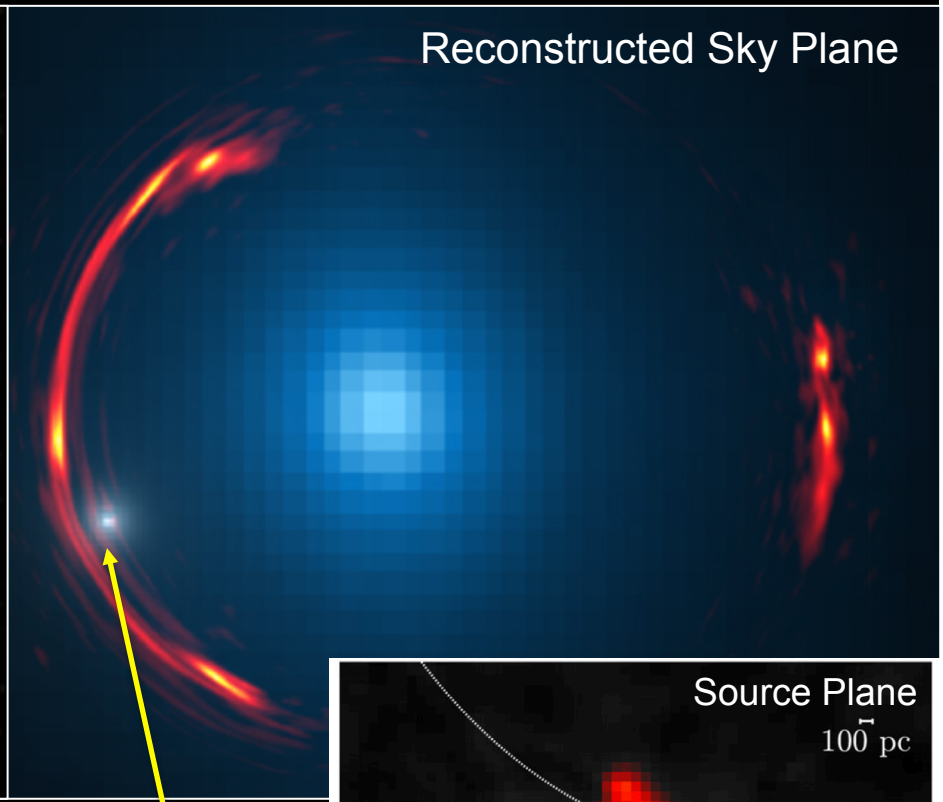


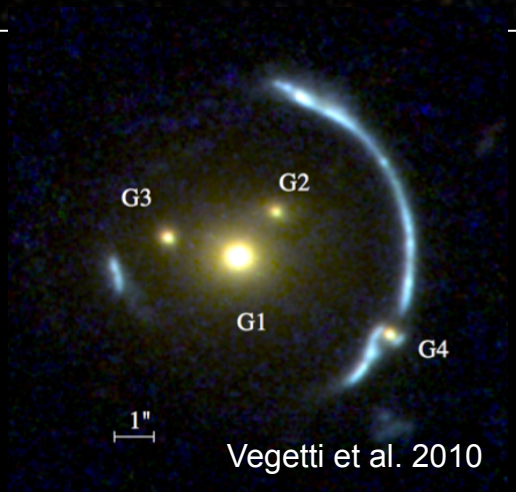


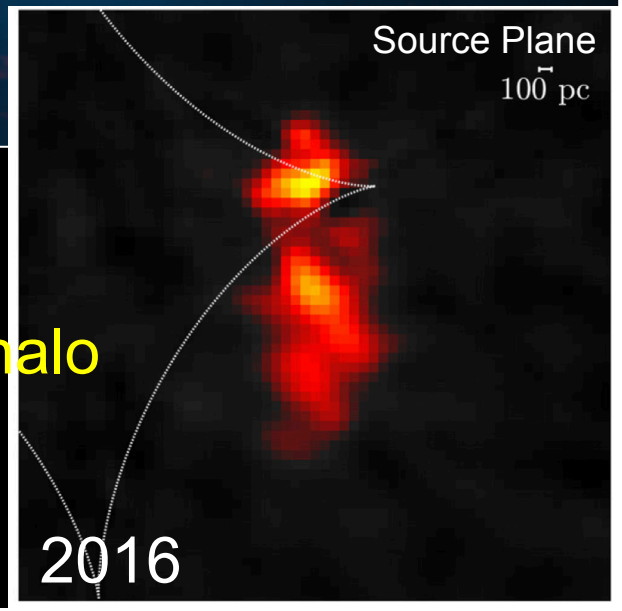
Hezaveh et al 2016

Advanced Lens Modeling









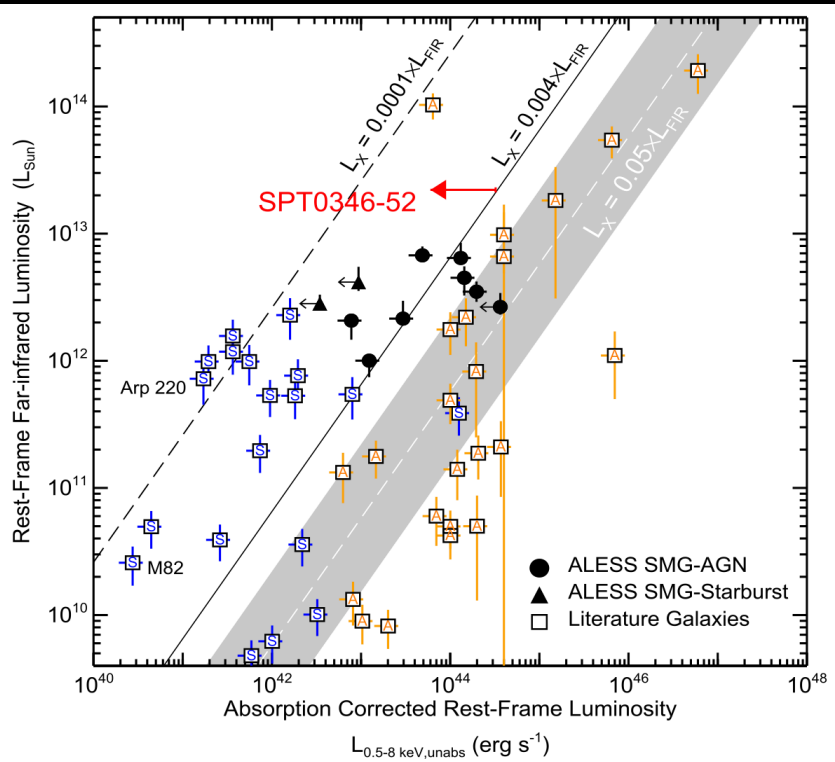
10^9 M_{sun} Subhalo

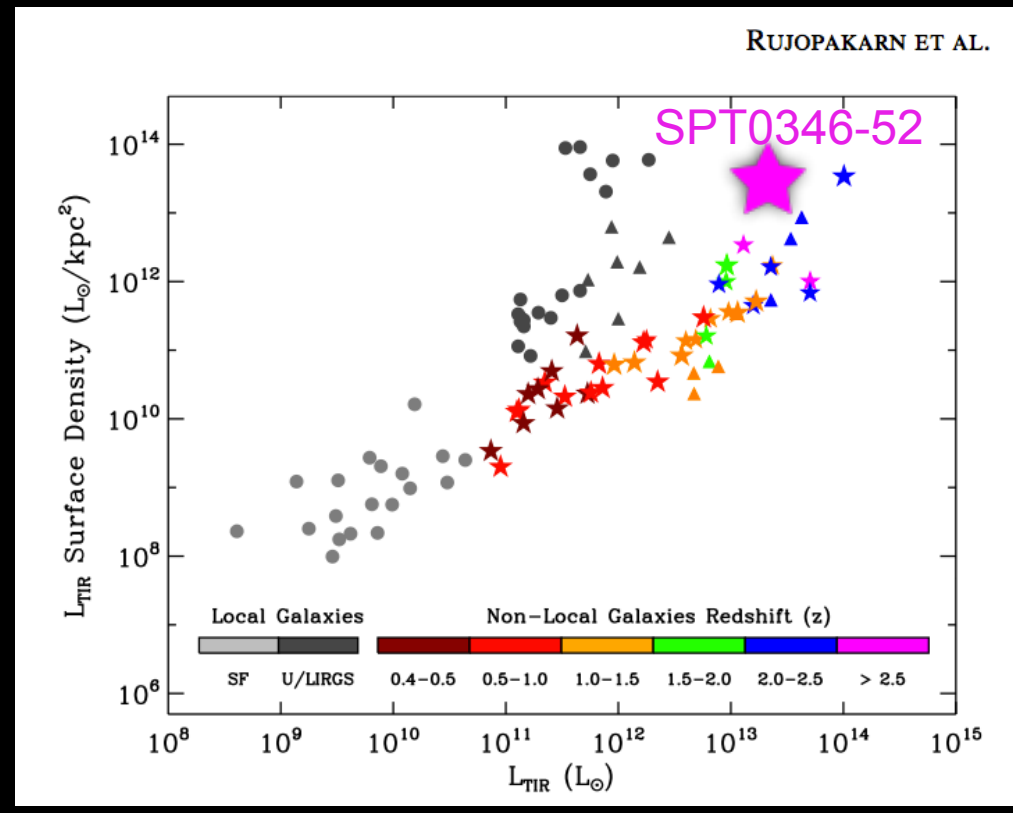
Hezaveh et al 2016

Massive Galaxy Astrophysics: SPT0346-52

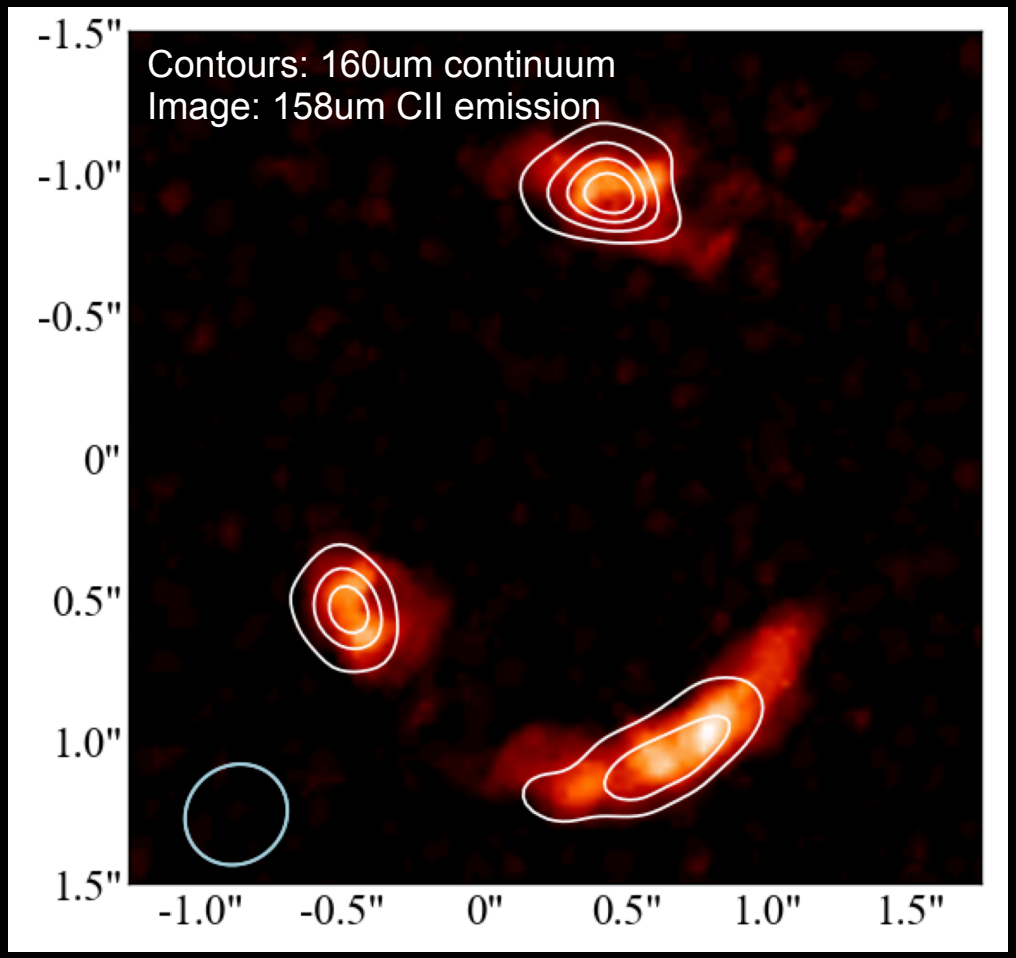
- Most intense galaxy-scale star-formation in the universe!
  - 3×10^{13} Lsun within a 600pc half-light radius
- No evidence for AGN in X-ray
  - This is star-formation powered!

Ma et al. 2016



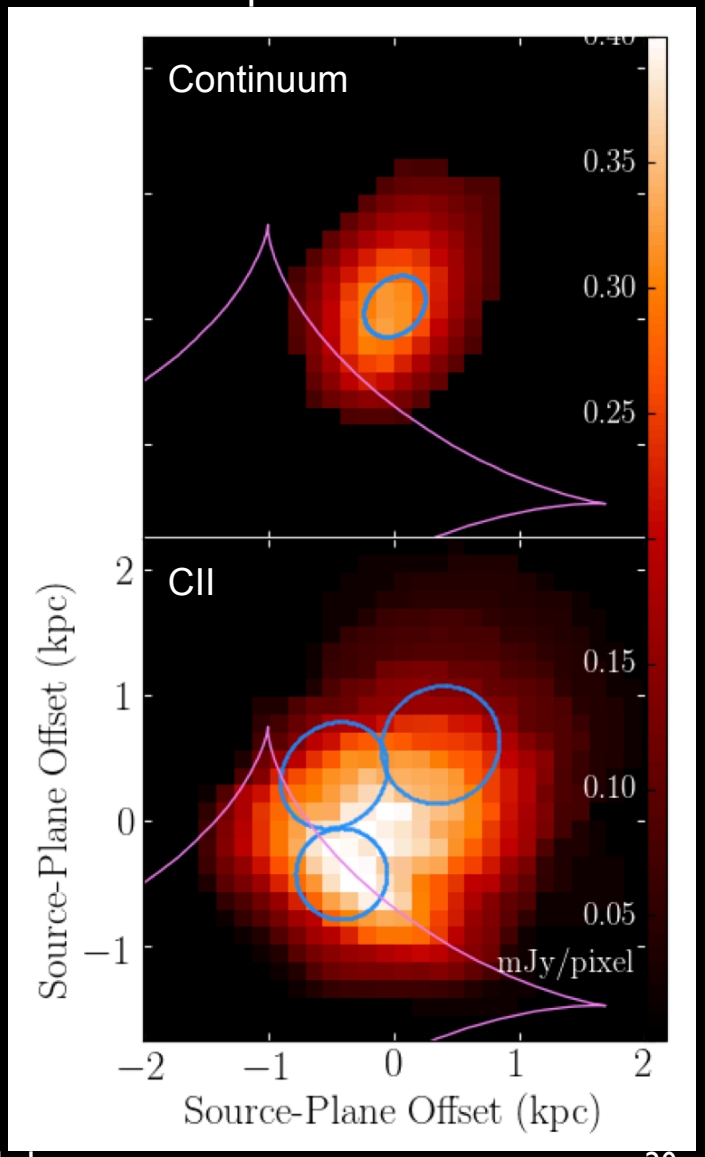


Massive Galaxy Astrophysics: SPT0346-52

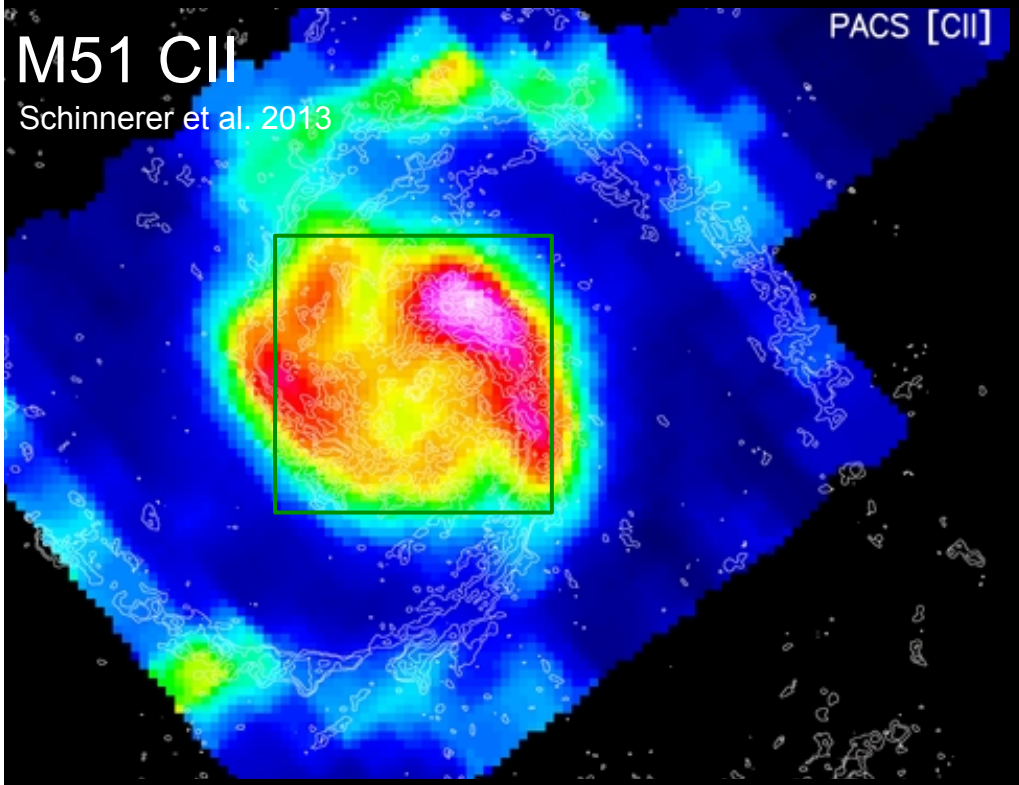


Litke, DPM et al. 2018

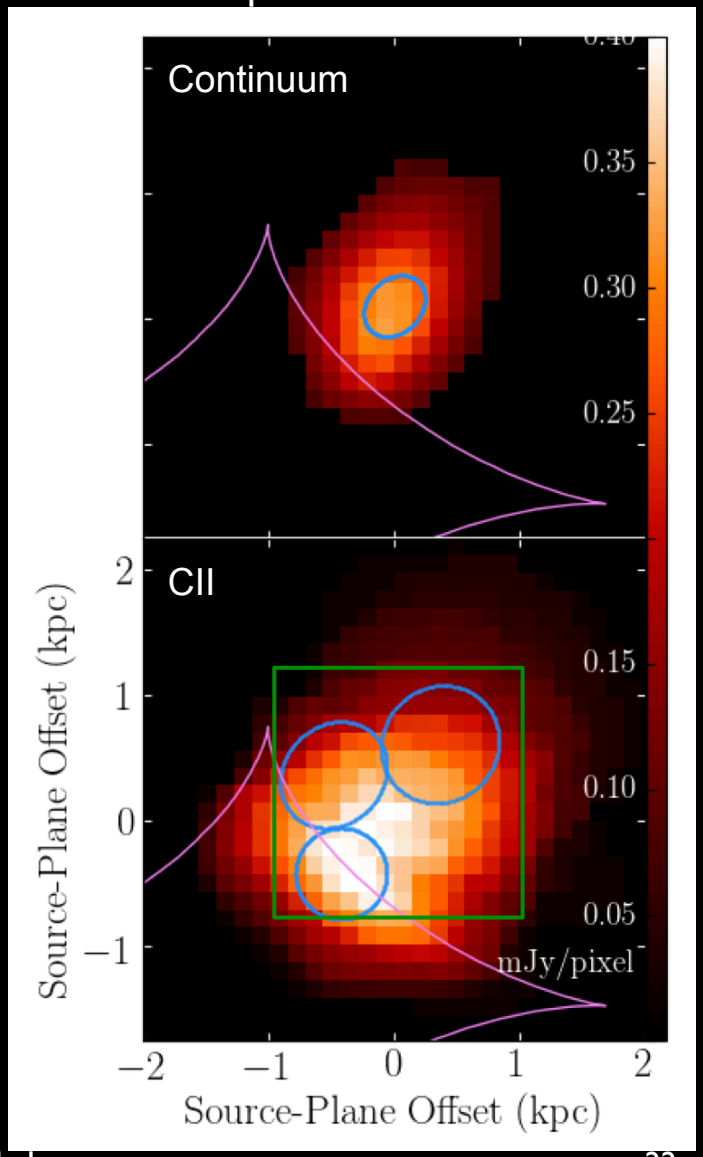
Source-plane reconstruction



Massive Galaxy Astrophysics: SPT0346-52

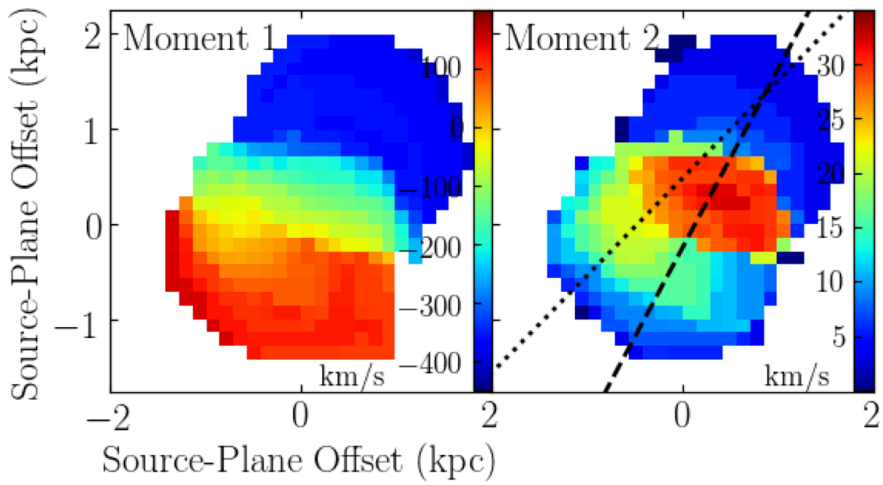


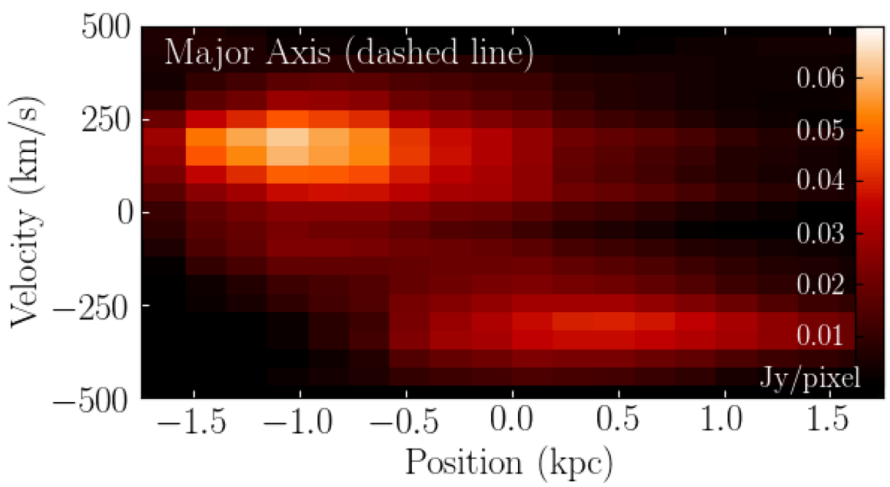
Source-plane reconstruction

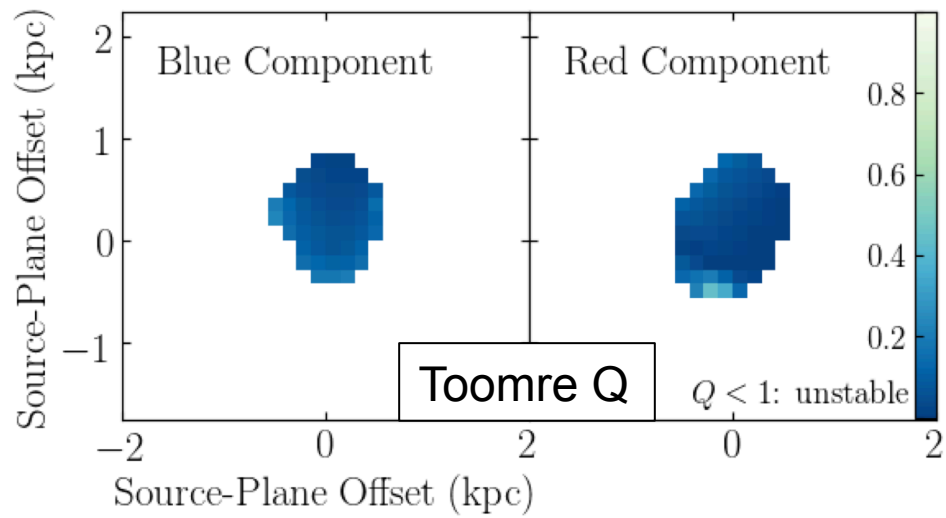


Massive Galaxy Astrophysics: SPT0346-52

- A massive merger
- Two highly unstable components!

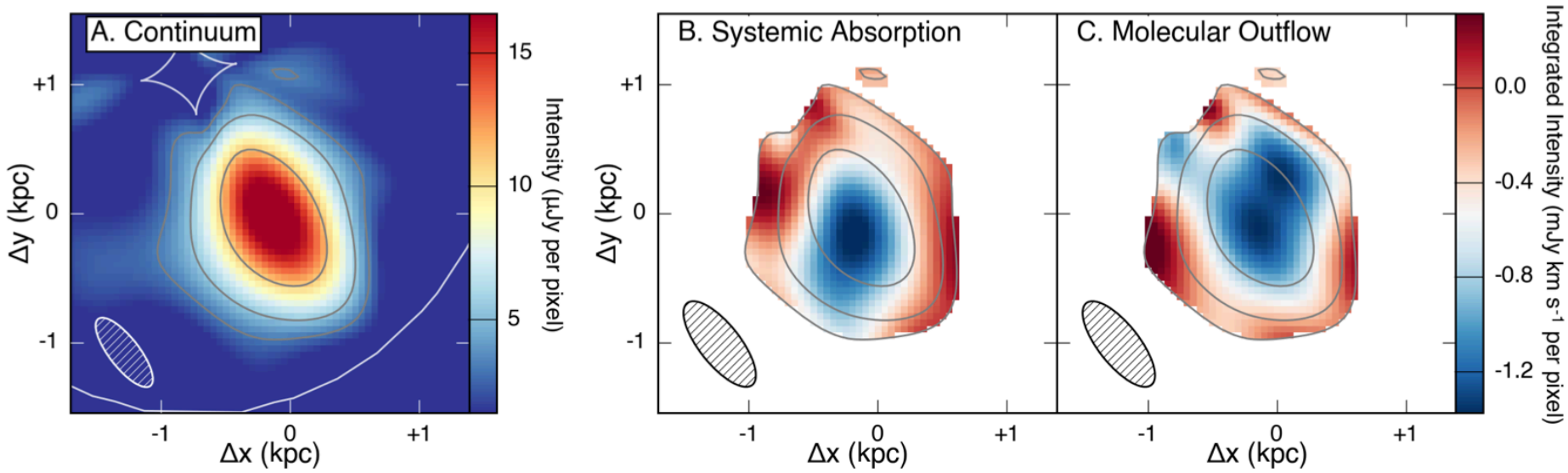






Litke, DPM et al. 2018

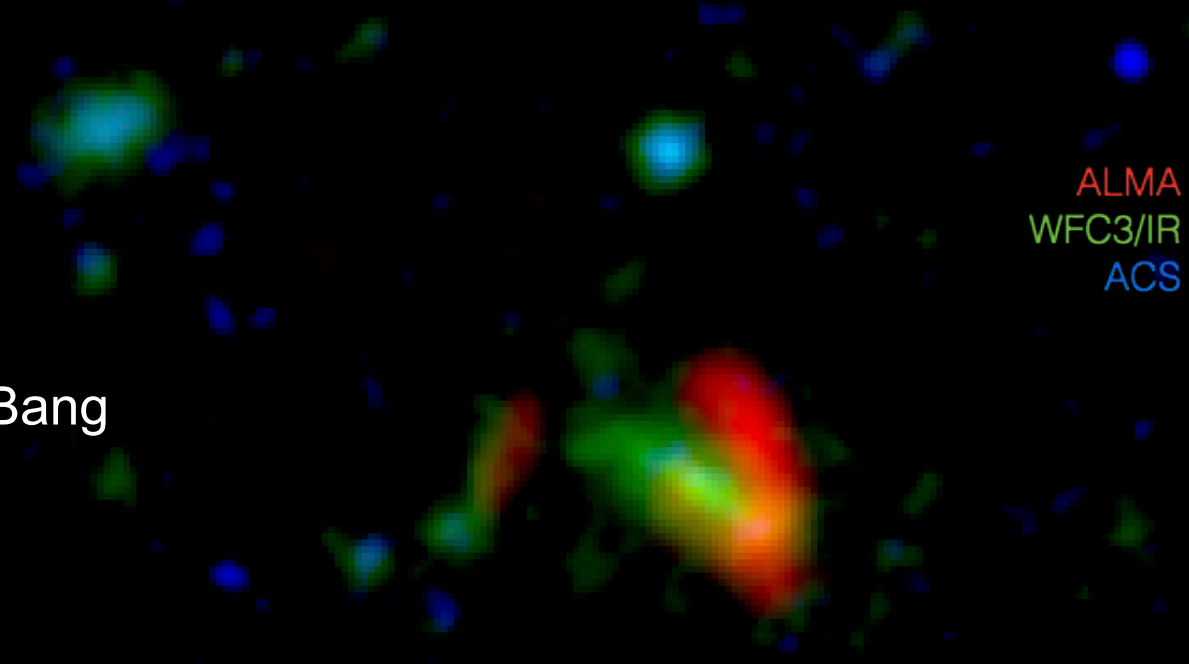
Massive Galaxy Astrophysics: Outflows



Spilker et al. 2018 (submitted)

- OH 119um blue absorption against z=5.3 SMG
- Implied mass outflow is ~500M_{sun}/yr
  - Molecular gas depletion by SF and outflow similar
- Direct observation of quenching in massive galaxy?

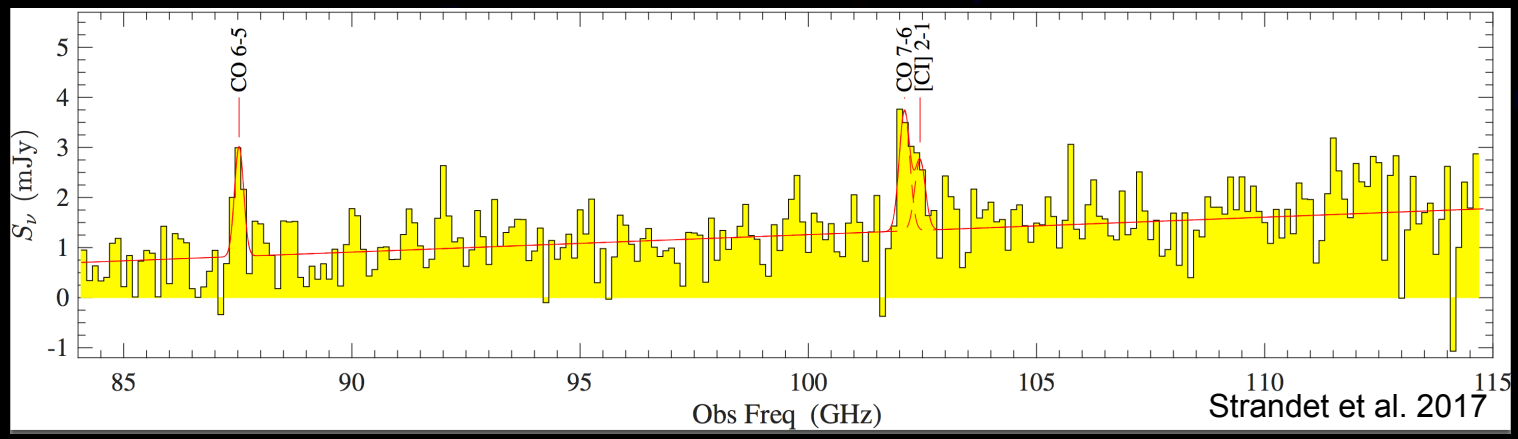
Massive Galaxy Formation: Reionization



SPT0311-58 at z=6.900

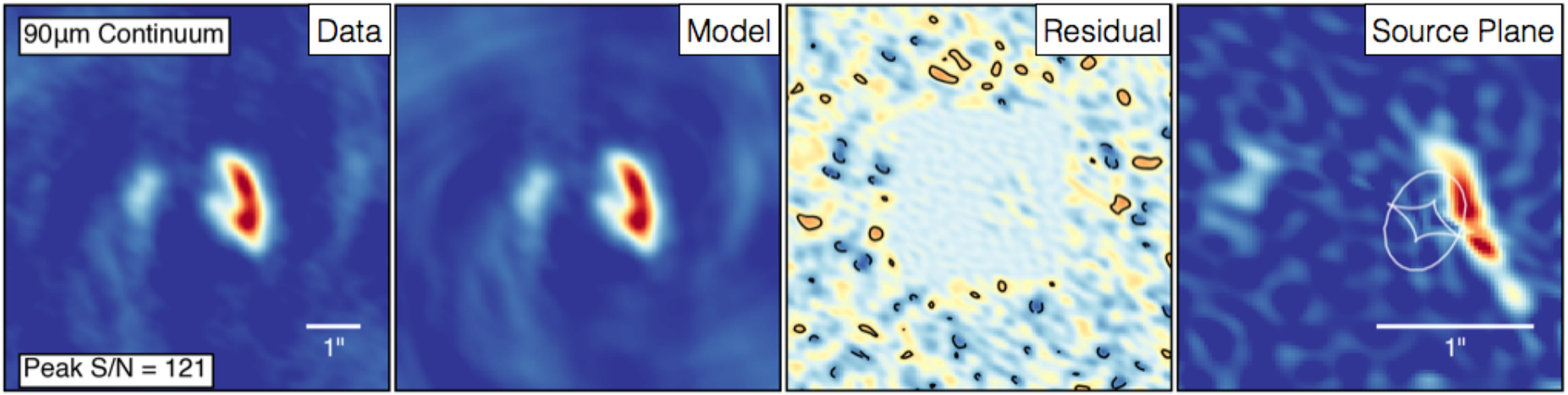
- 780 Myr after the Big Bang
- IGM still 50% neutral

Marrone et al. 2018



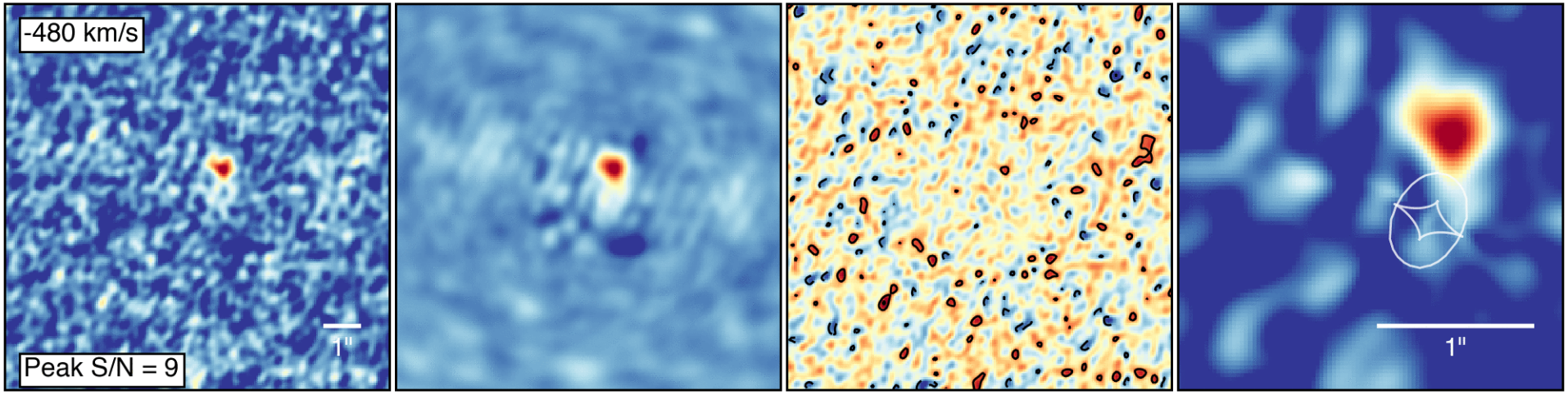
Strandet et al. 2017

Massive Galaxy Formation: Reionization



CII 158μm Data Cube

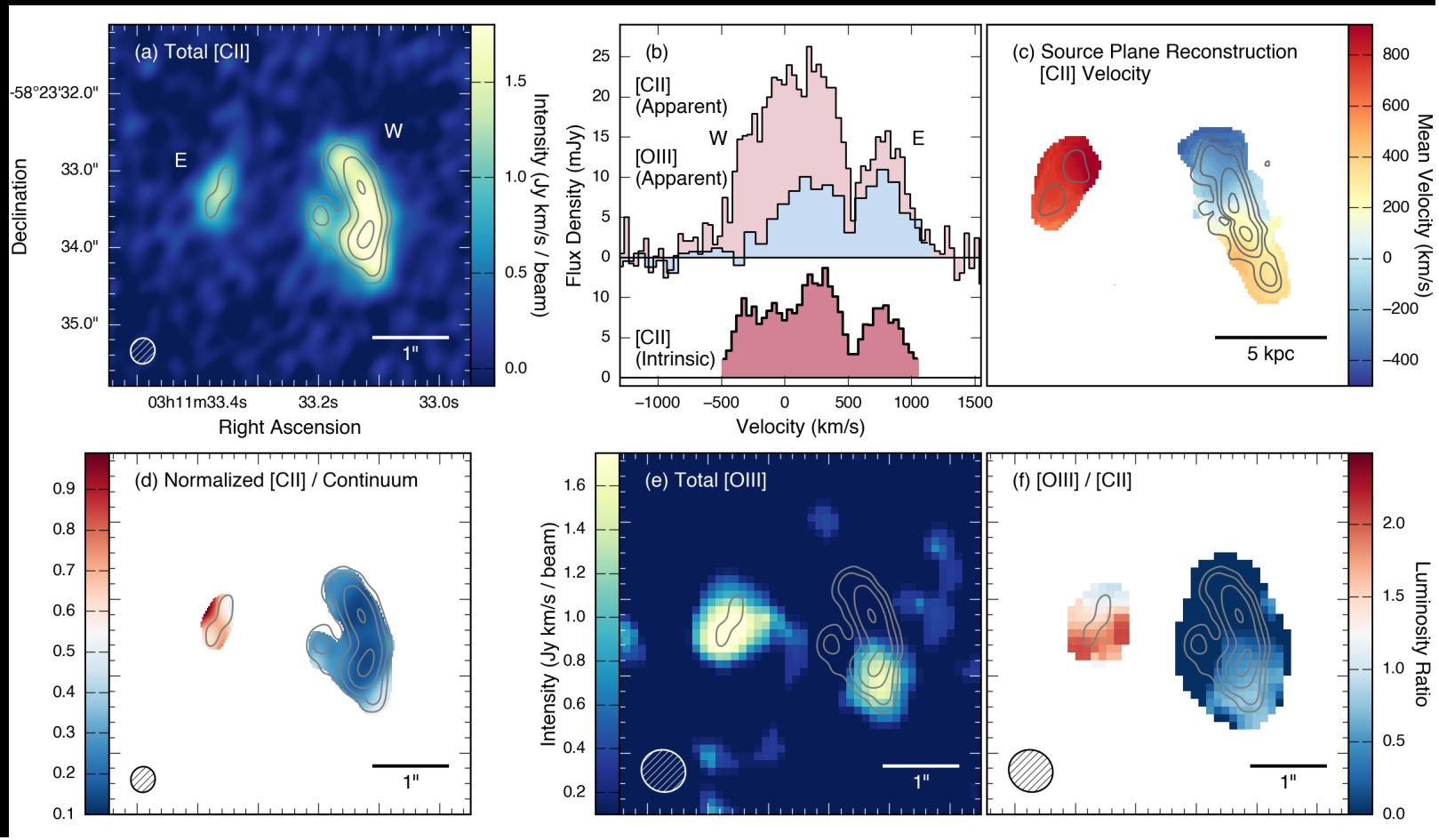
Marrone et al. 2018



Massive Galaxy Formation: Reionization

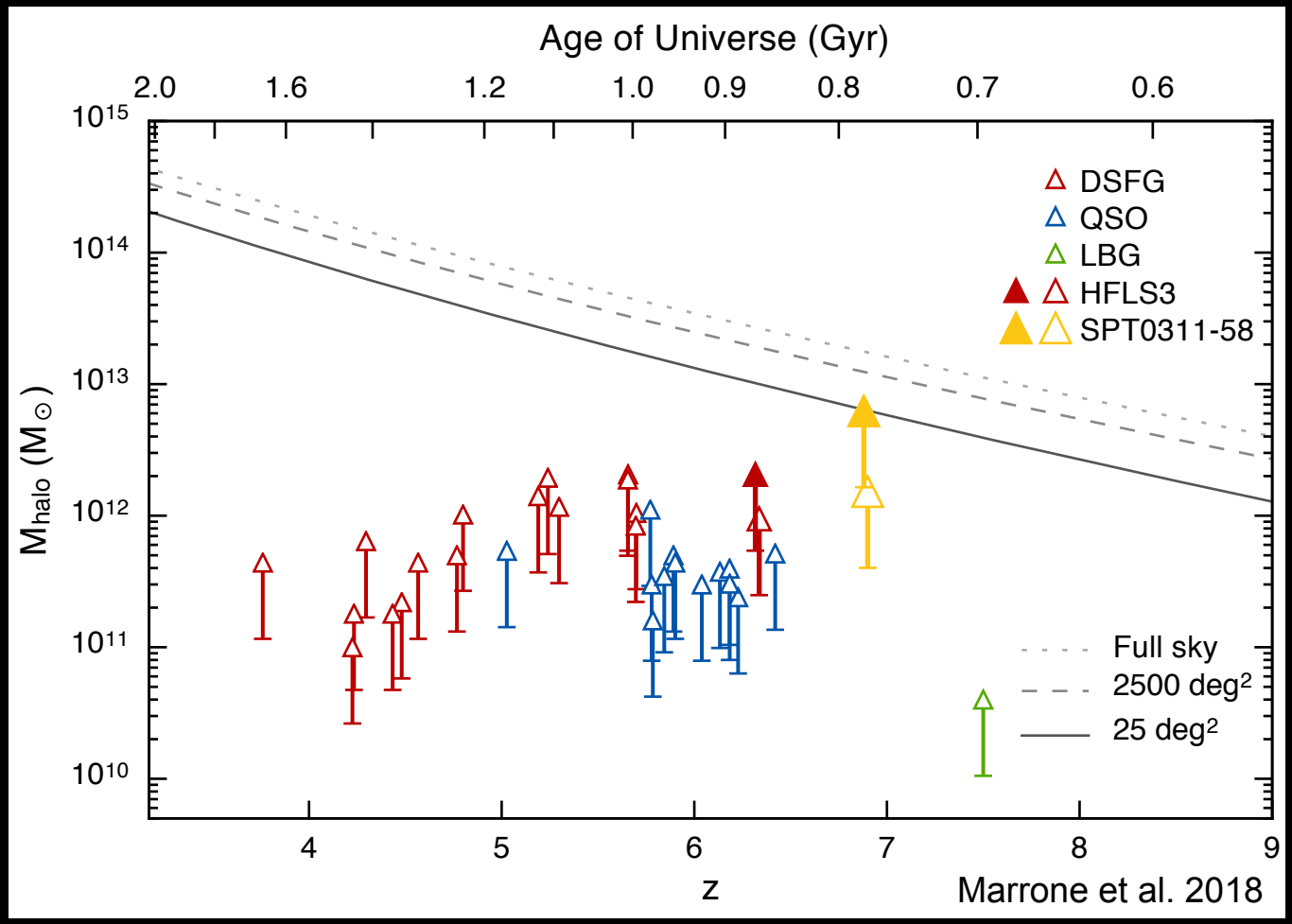
- Two galaxies!
  - Separated by 8kpc and 700 km/s
  - Very different line and continuum properties
  - Large velocity dispersions

Marrone et al. 2018

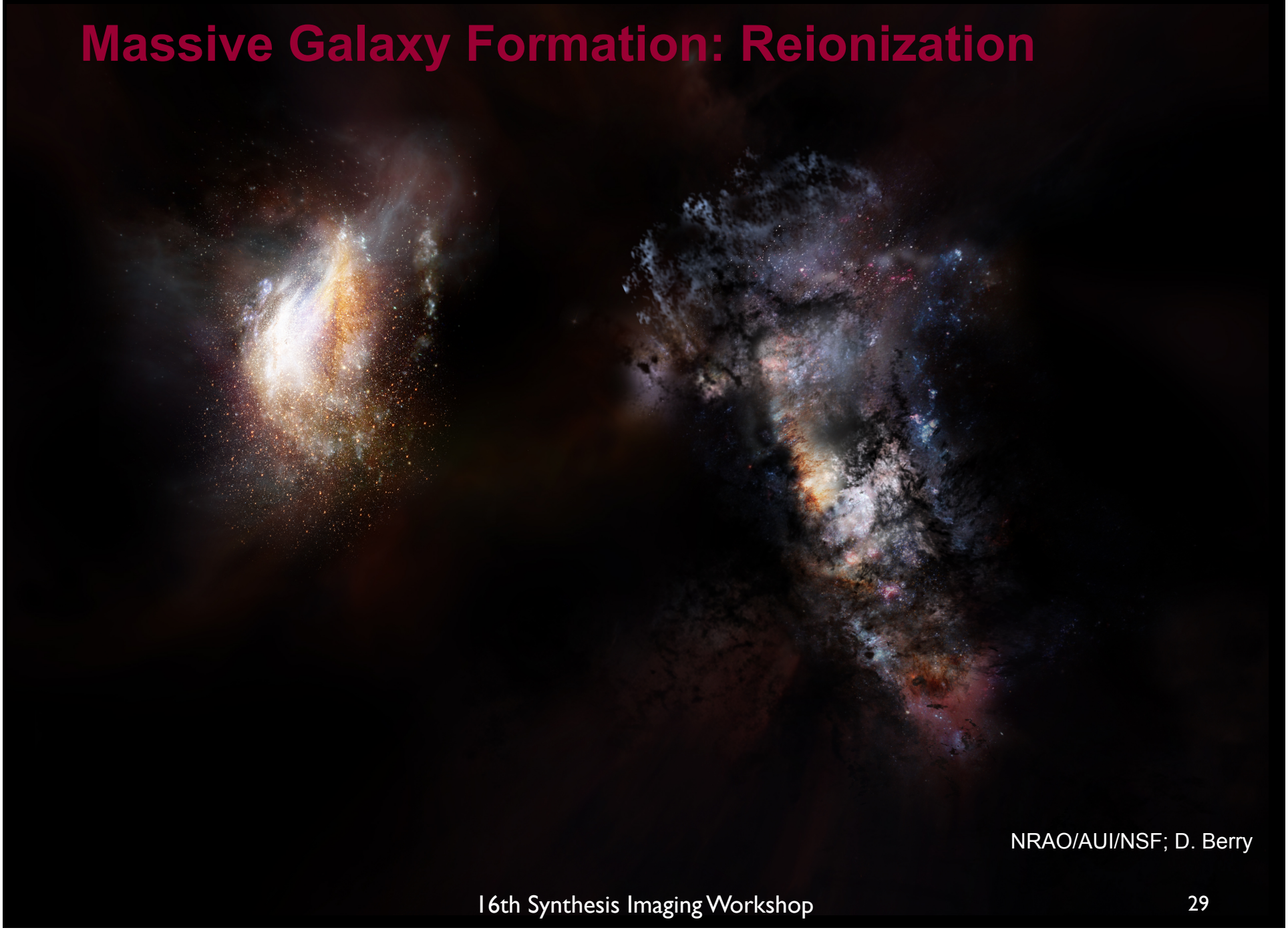


Massive Galaxy Formation: Reionization

- Total halo mass larger than any known at z>5
- Only handful in whole sky

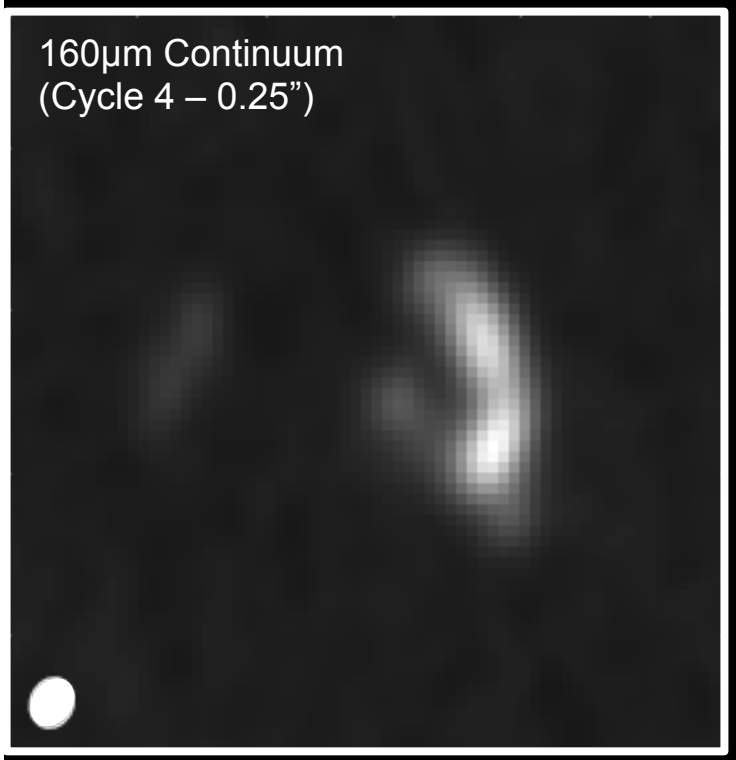


Massive Galaxy Formation: Reionization



NRAO/AUI/NSF; D. Berry

Massive Galaxy Formation: Reionization



(Cycle 5 – 0.06”)