GRAVITATIONAL LENSES AS COSMIC TELESCOPES

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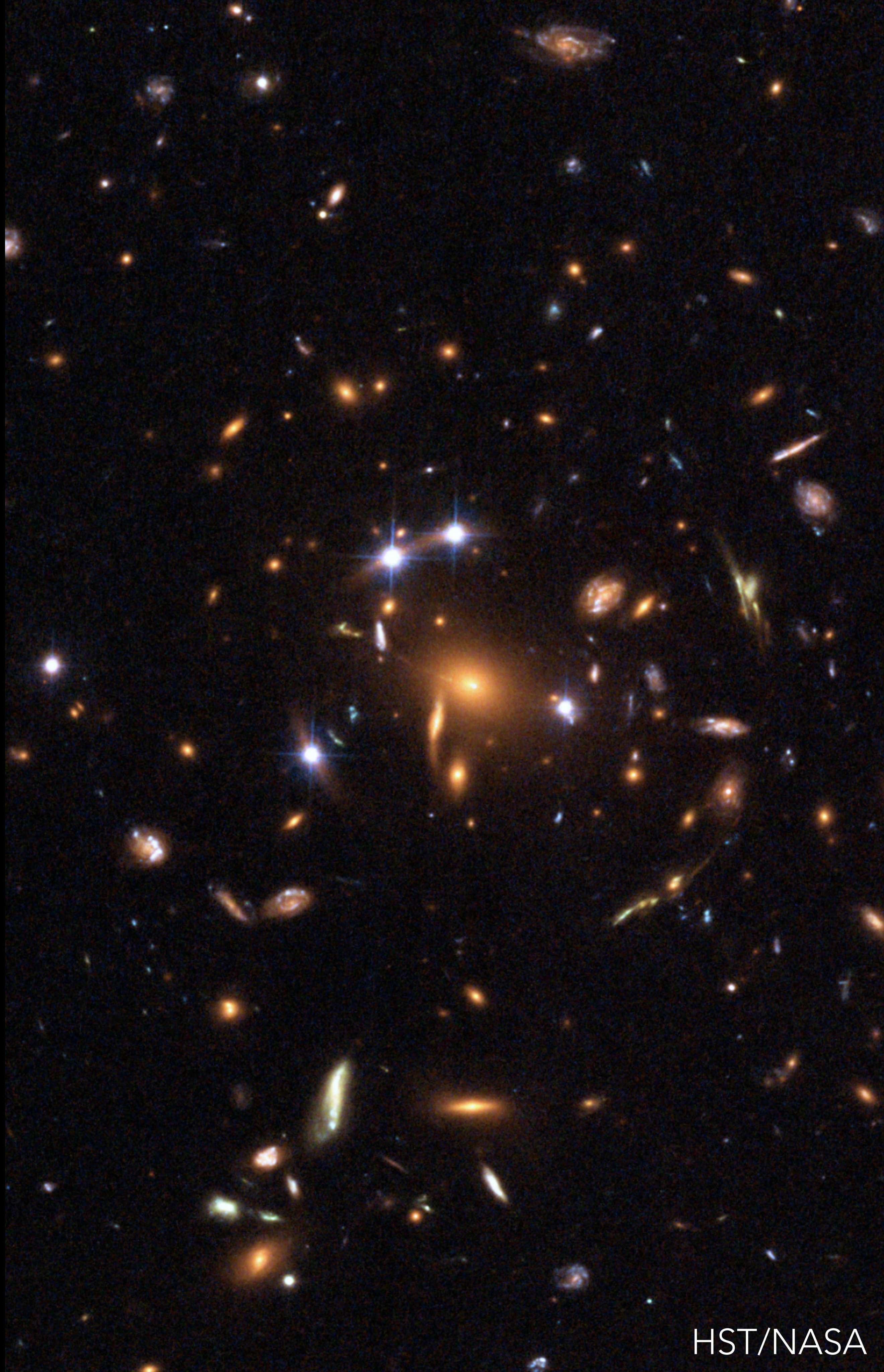
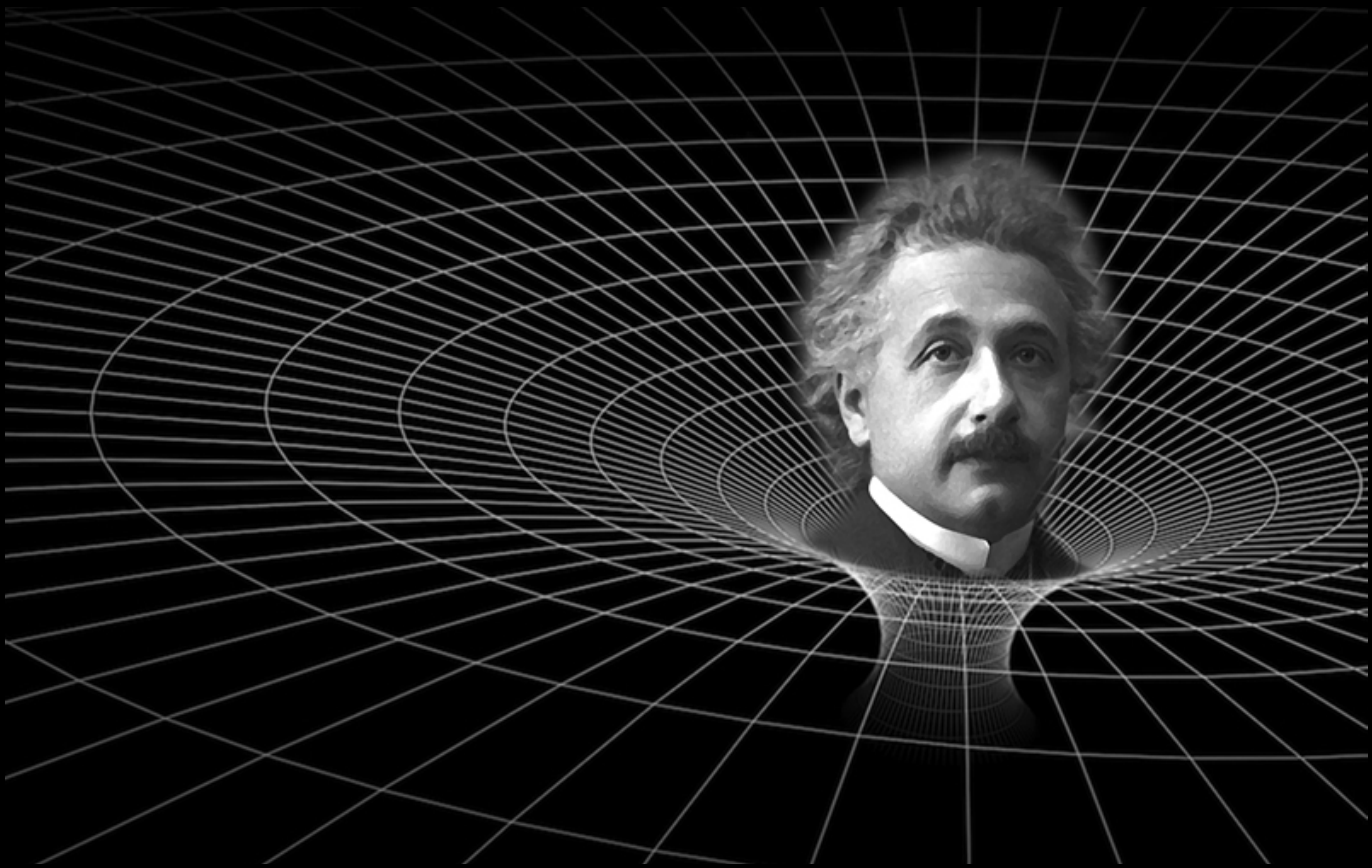
OVERVIEW

- What is a gravitational lens?
- Why are they useful?
- Some examples of applications of strong gravitational lensing
- My research
- Looking to the future



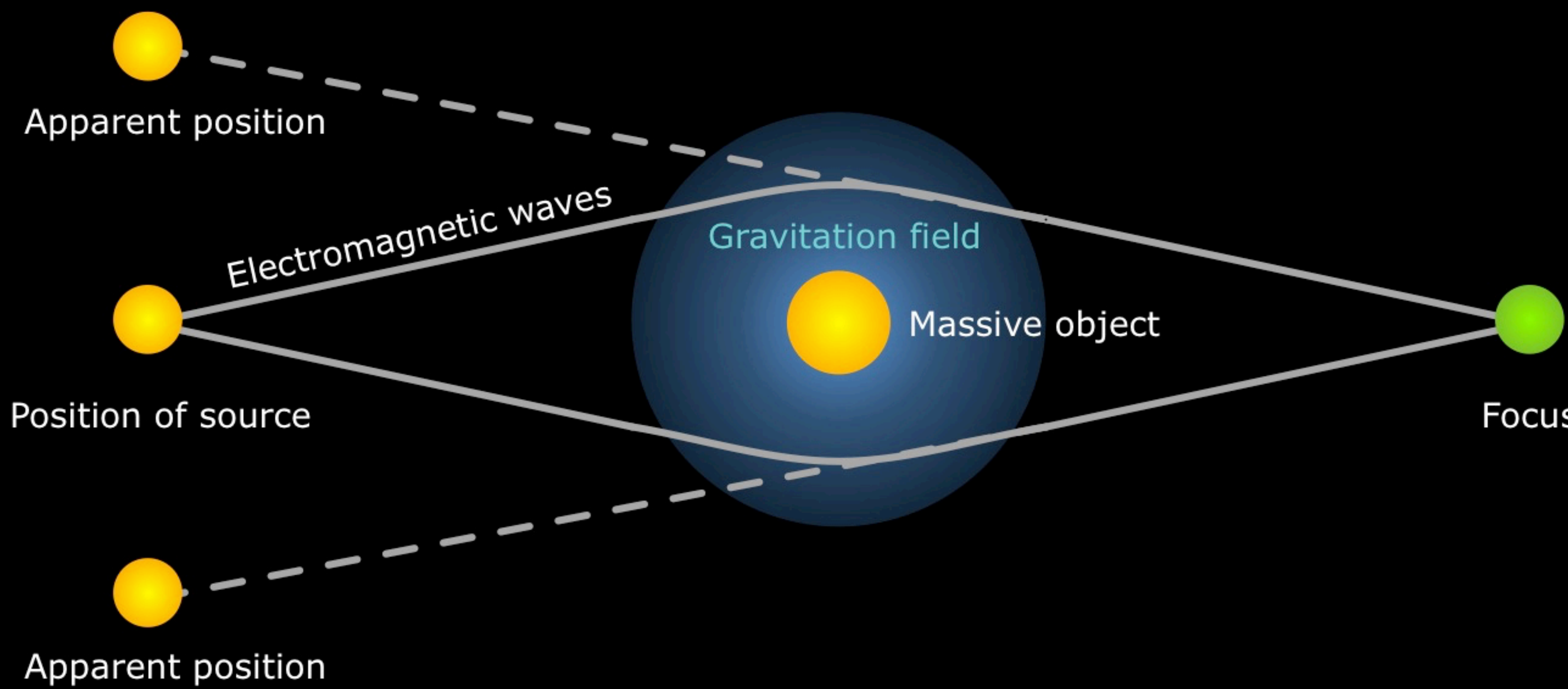
HST/NASA

WHAT IS A GRAVITATIONAL LENS?



Credit: Matt Payne

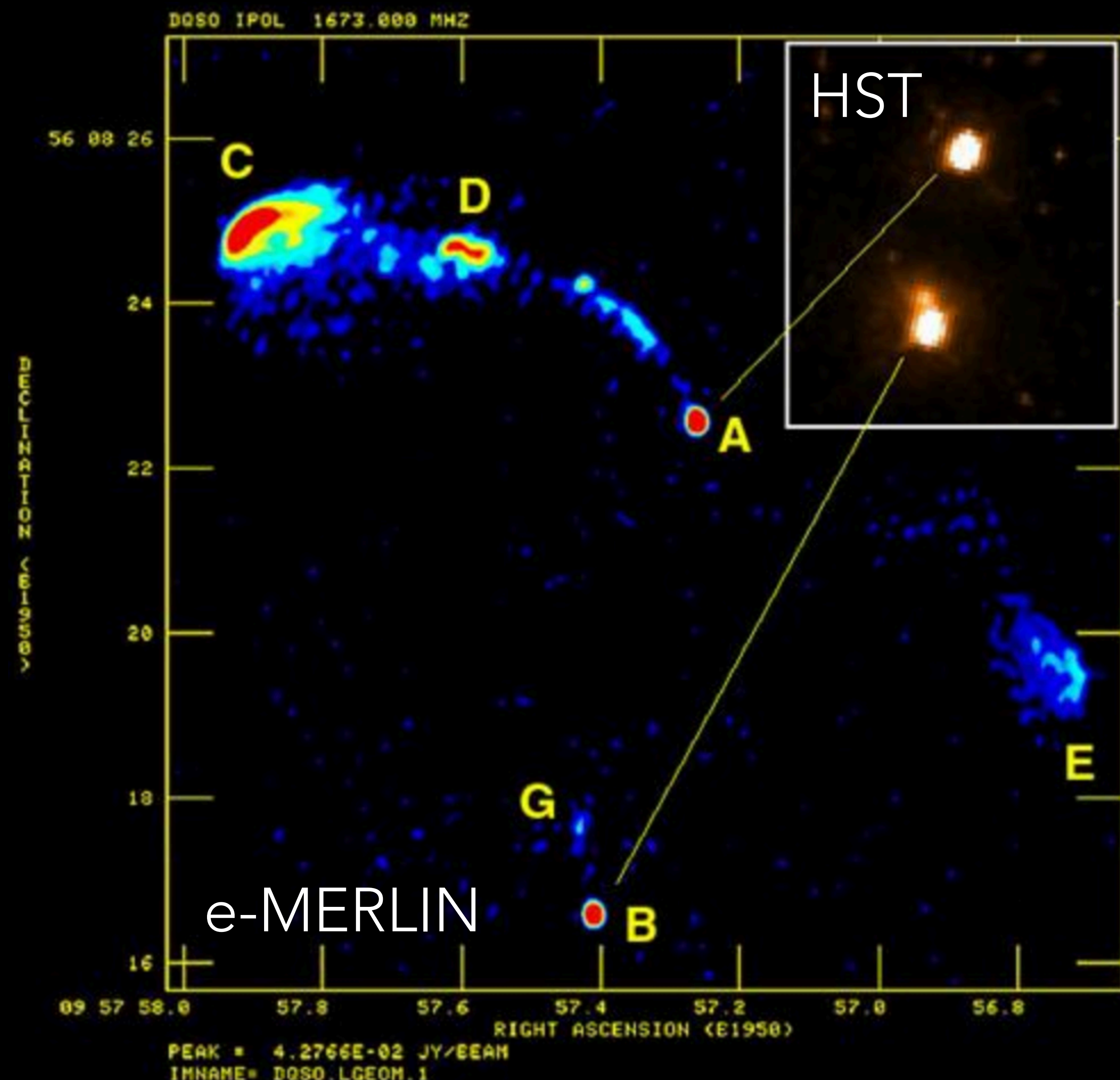
WHAT IS A GRAVITATIONAL LENS?



https://oneminuteastronomer.com/9237/gravitational-lens/

WHAT IS A GRAVITATIONAL LENS?

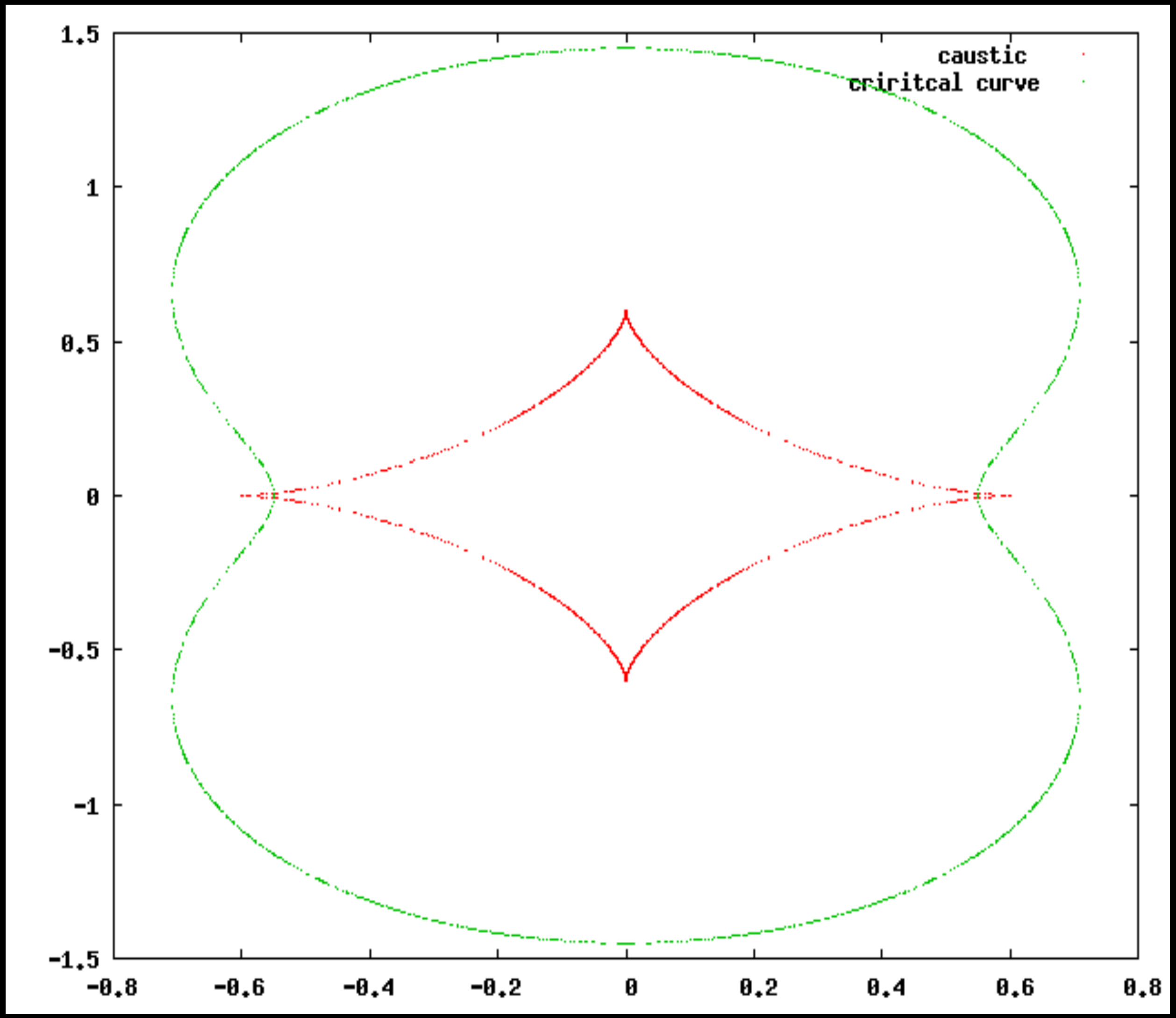
- The first gravitational lens discovered was QSO 0957+561 (Walsh et al. 1979)
- 2 images of the radio core (A and B) can be seen



N. Jackson (probably)

WHAT IS A GRAVITATIONAL LENS?

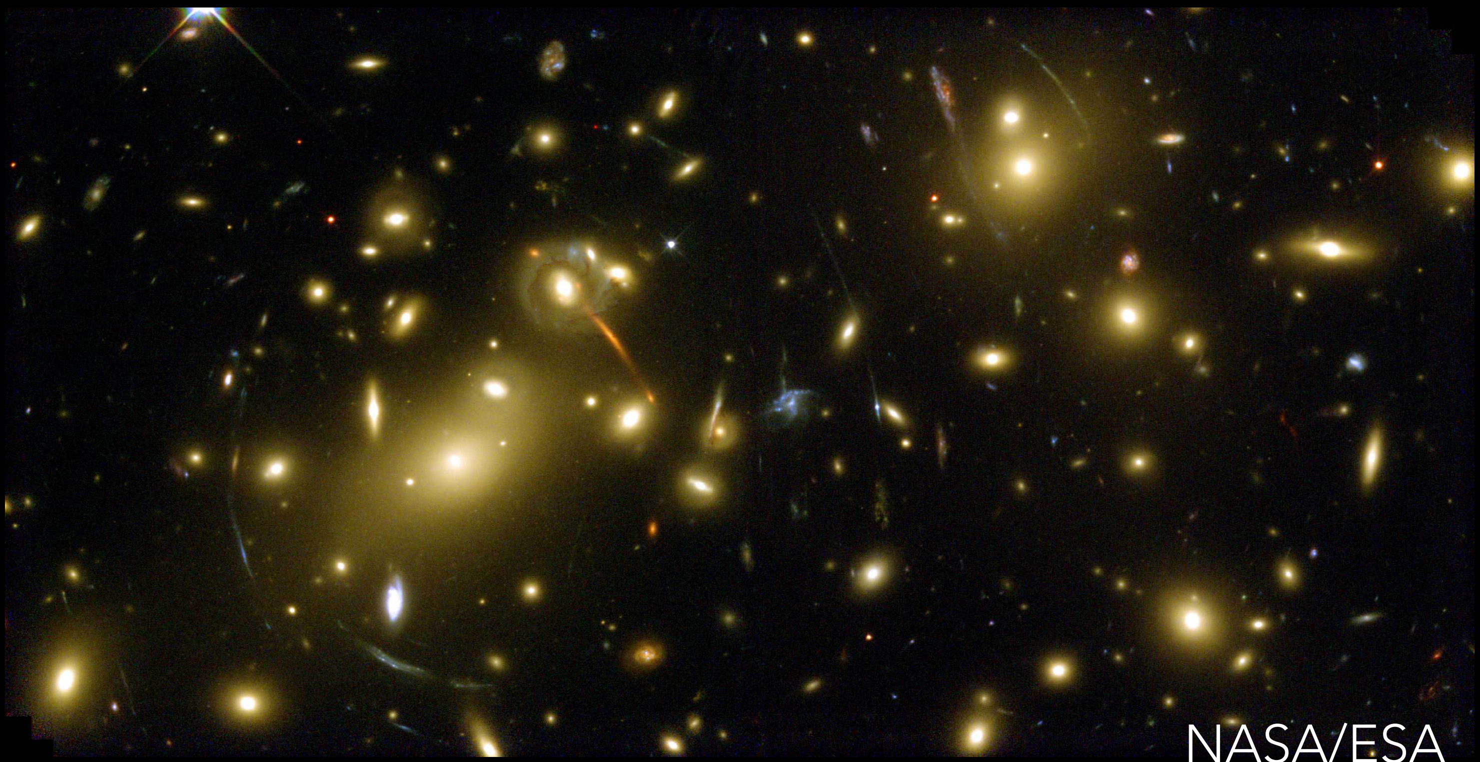
- We can learn about both the **source** (magnification) and the **lensing galaxy** (mass distribution) from the position and brightness of the lensed images



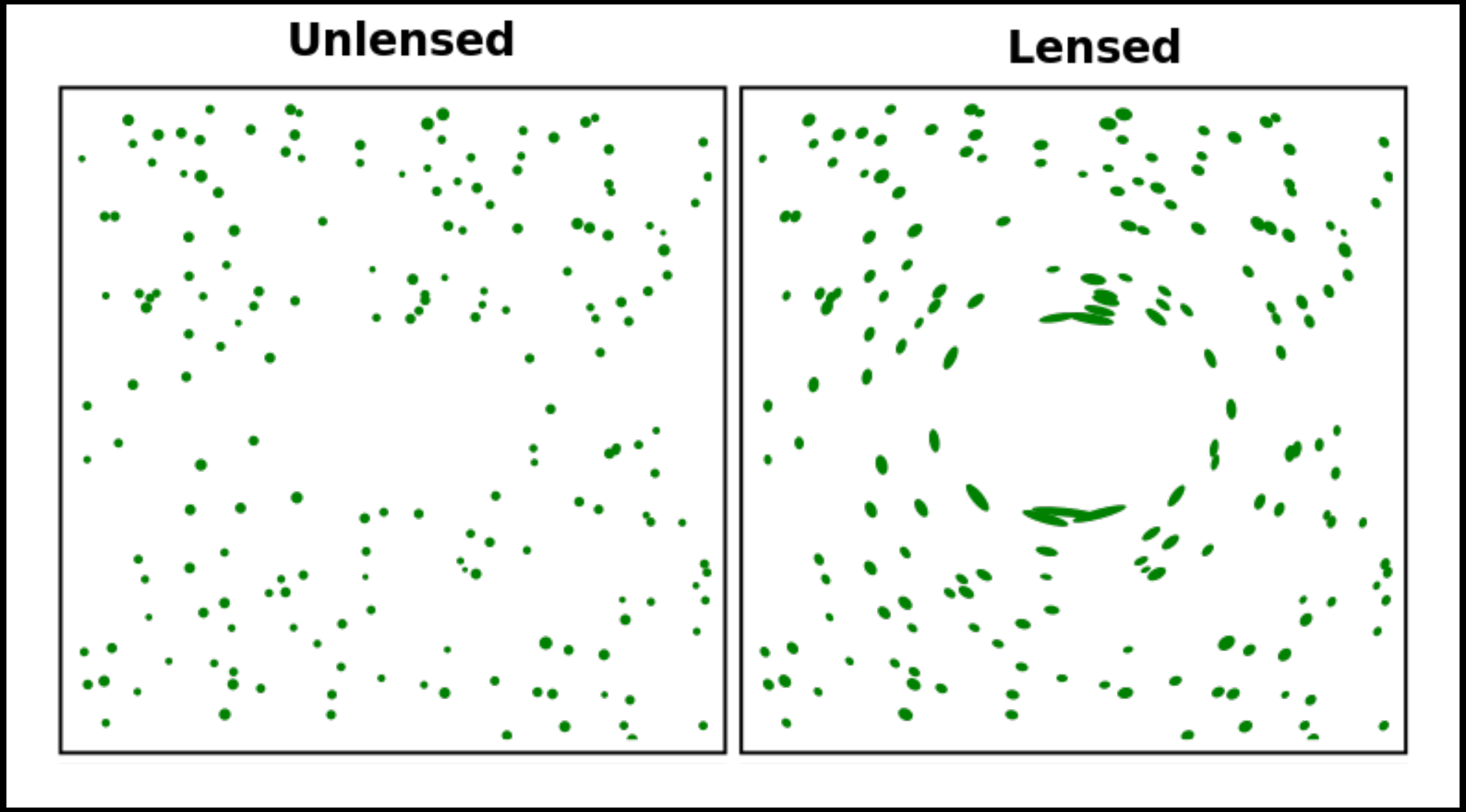
http://homepages.spa.umn.edu/~llrw/a8110

STRONG, WEAK AND MICRO-LENSING

- Weak lensing: the *systematic* lensing effect of the large-scale structure of the universe
- Statistical effect
- Important for cosmology



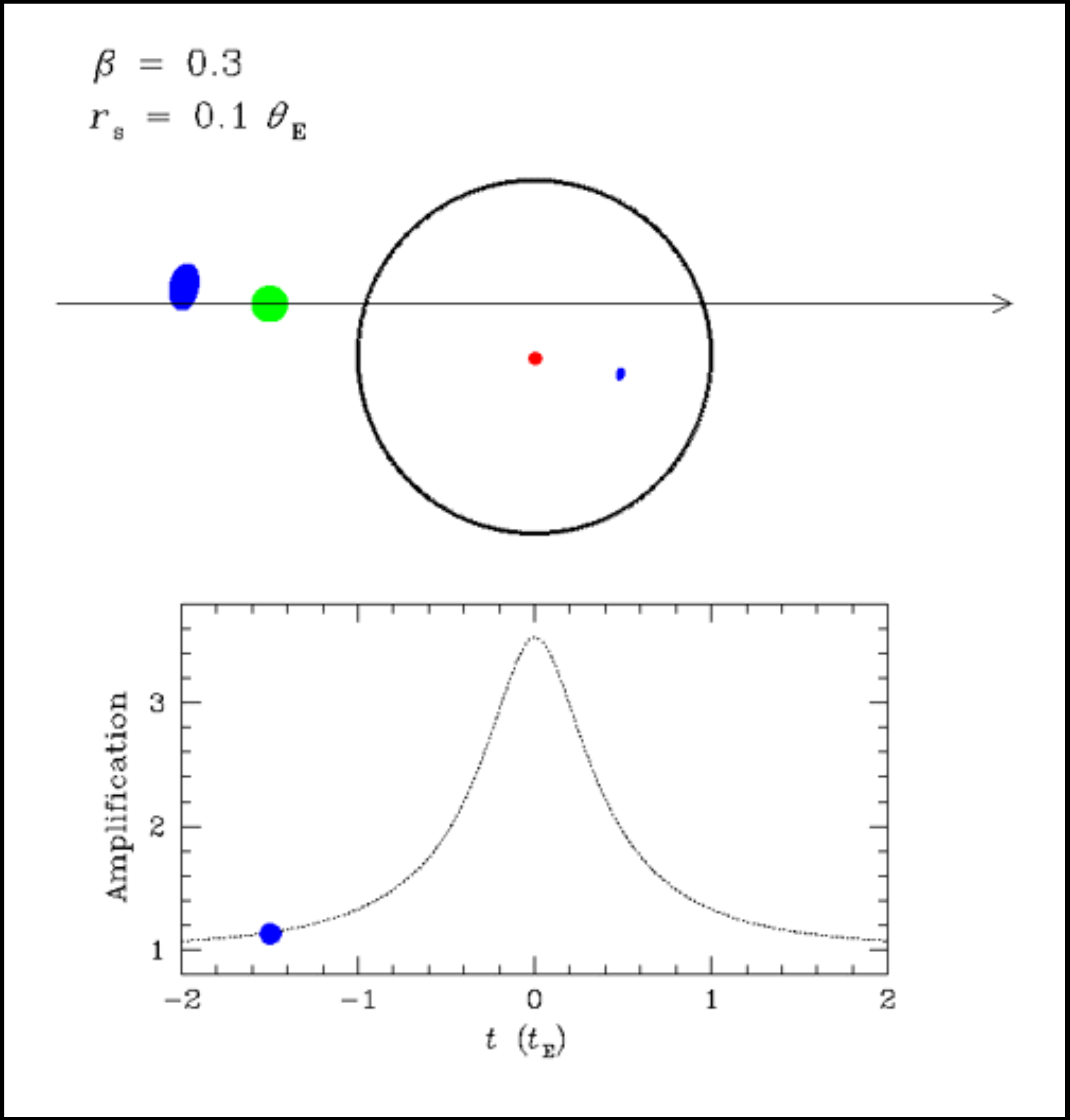
NASA/ESA



Wikipedia

STRONG, WEAK AND MICRO-LENSING

- Microlensing: the differential lensing due to small-scale mass structures like stars or planets
- Timescales of weeks (planets) to months/years (stars)

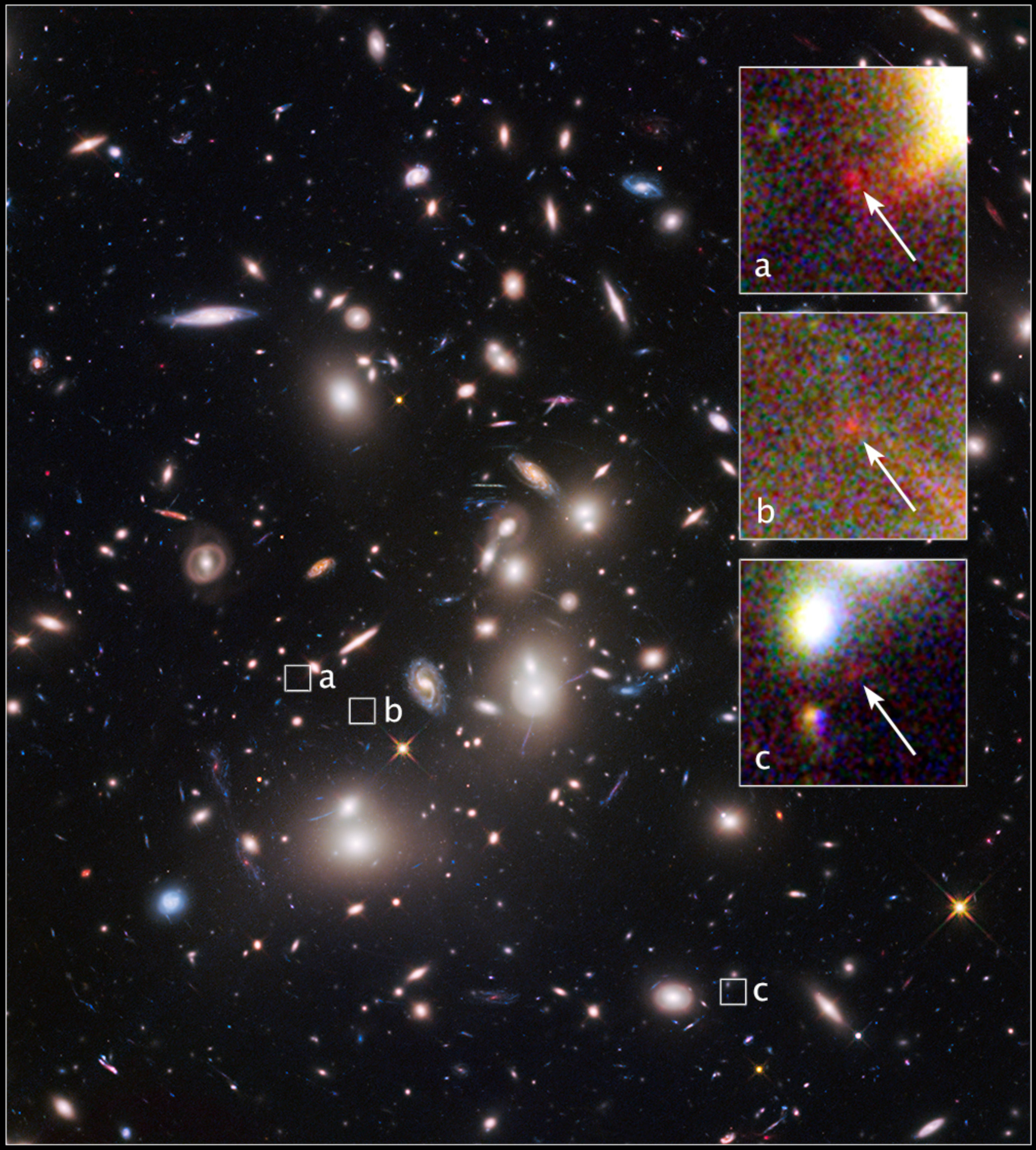


http://stephenkane.net/teaching/as3012/

INVESTIGATING FAINT SOURCE POPULATIONS

- Redshift ~10 galaxies magnified by massive clusters of galaxies
- e.g. Frontier Fields
- What did the first galaxies looks like?
- Extending luminosity functions to high-z, low-luminosities

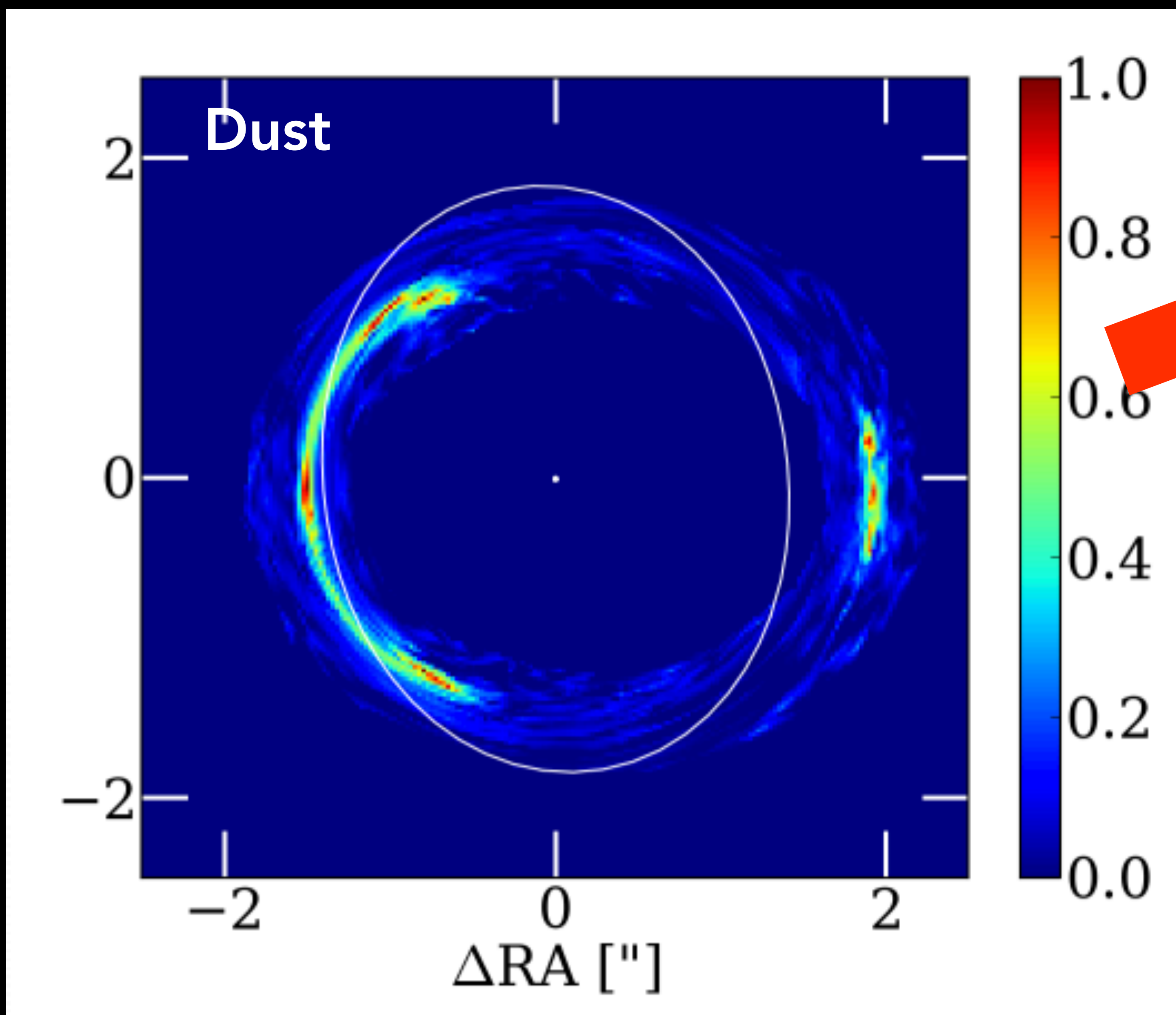
Distant Galaxy in Hubble Frontier Field Abell 2744 *HST* • ACS • WFC3

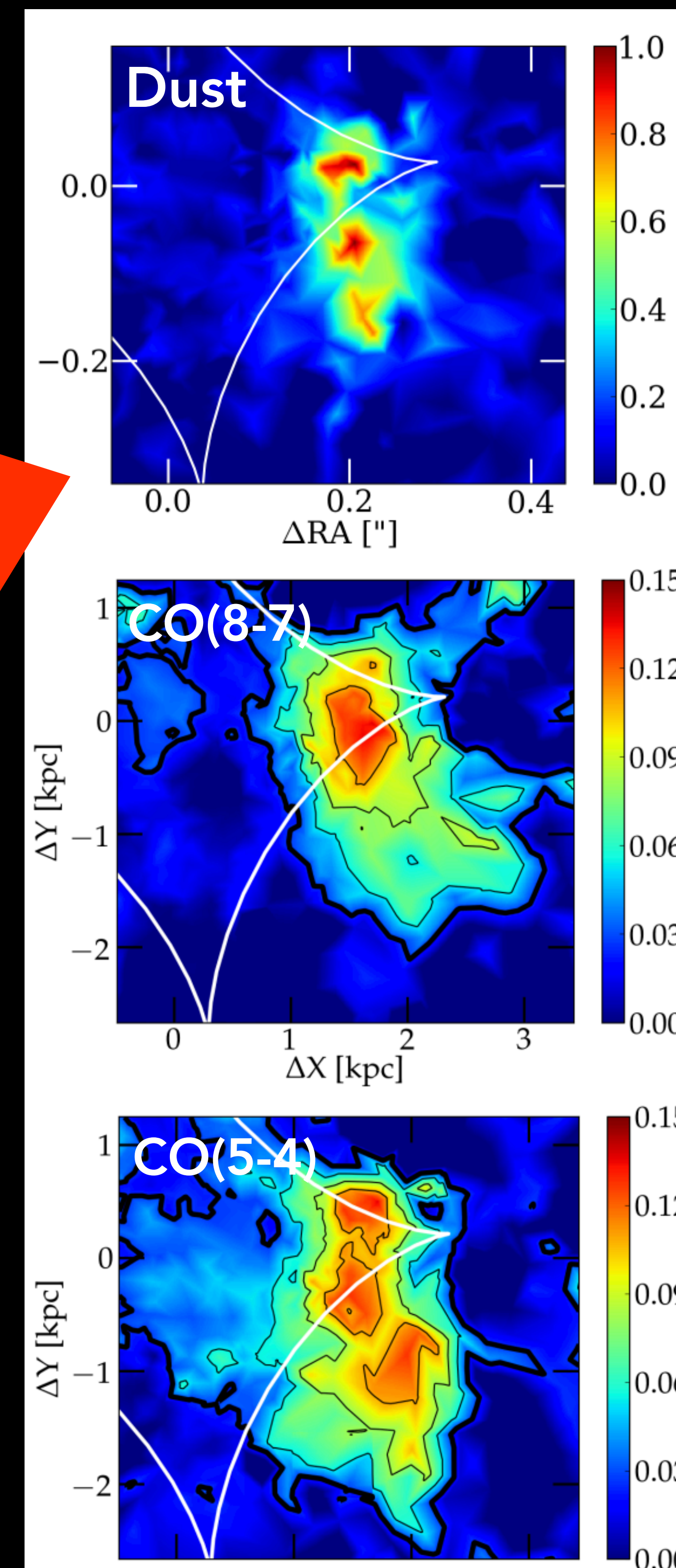


NASA and ESA STScI-PRC14-39a

RESOLVING PROPERTIES OF DISTANT GALAXIES

Star-forming galaxy SDP.81 (observed with ALMA)



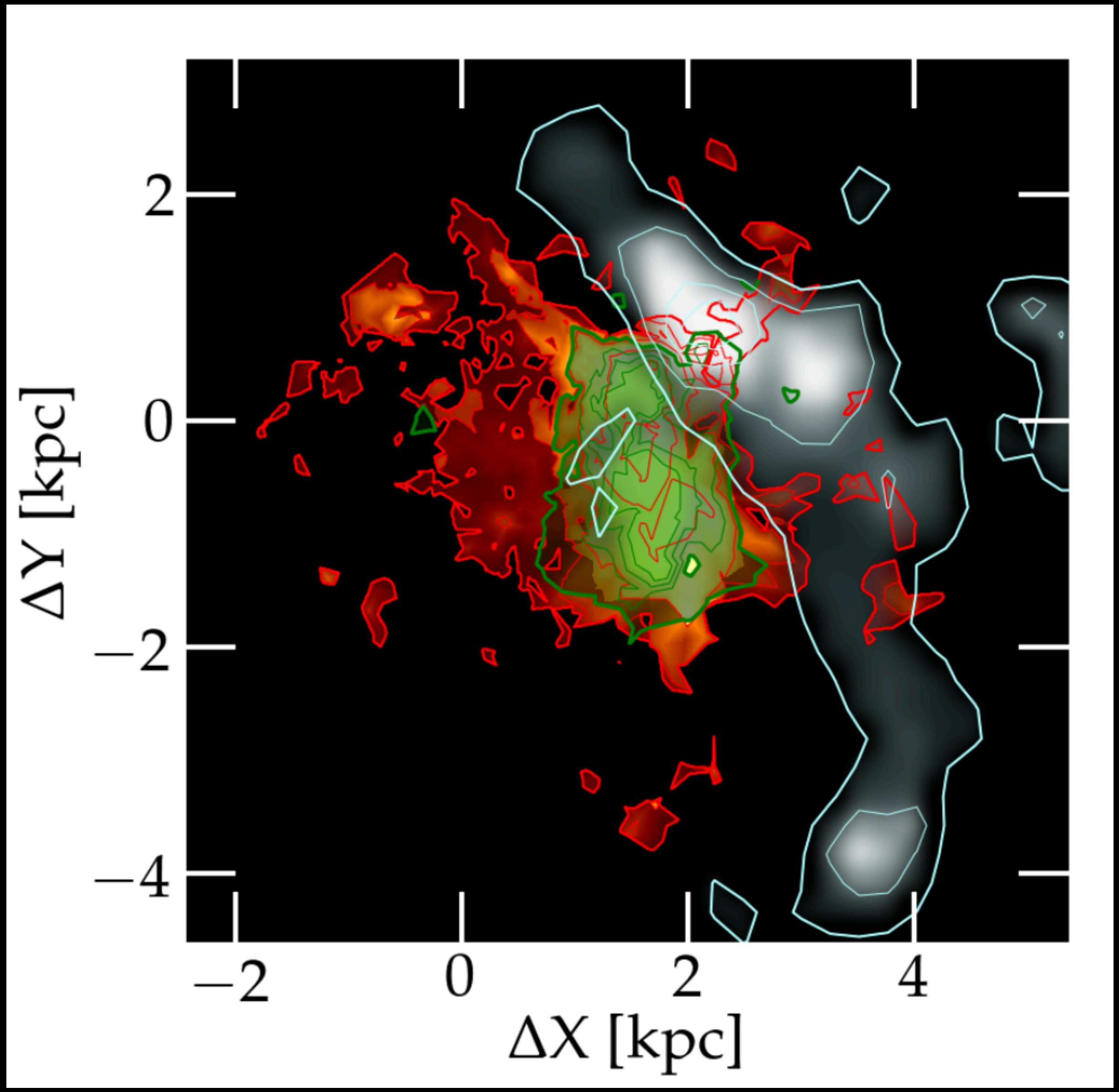


Rybak et al. 2015a,b

RESOLVING PROPERTIES OF DISTANT GALAXIES

- Reconstructing strongly lensed sources
- Magnification -> high-resolution beyond the resolving power of the telescope
- Resolving mergers, interactions, kinematics in at peak of star-formation in the Universe

CO gas tracing different physical states



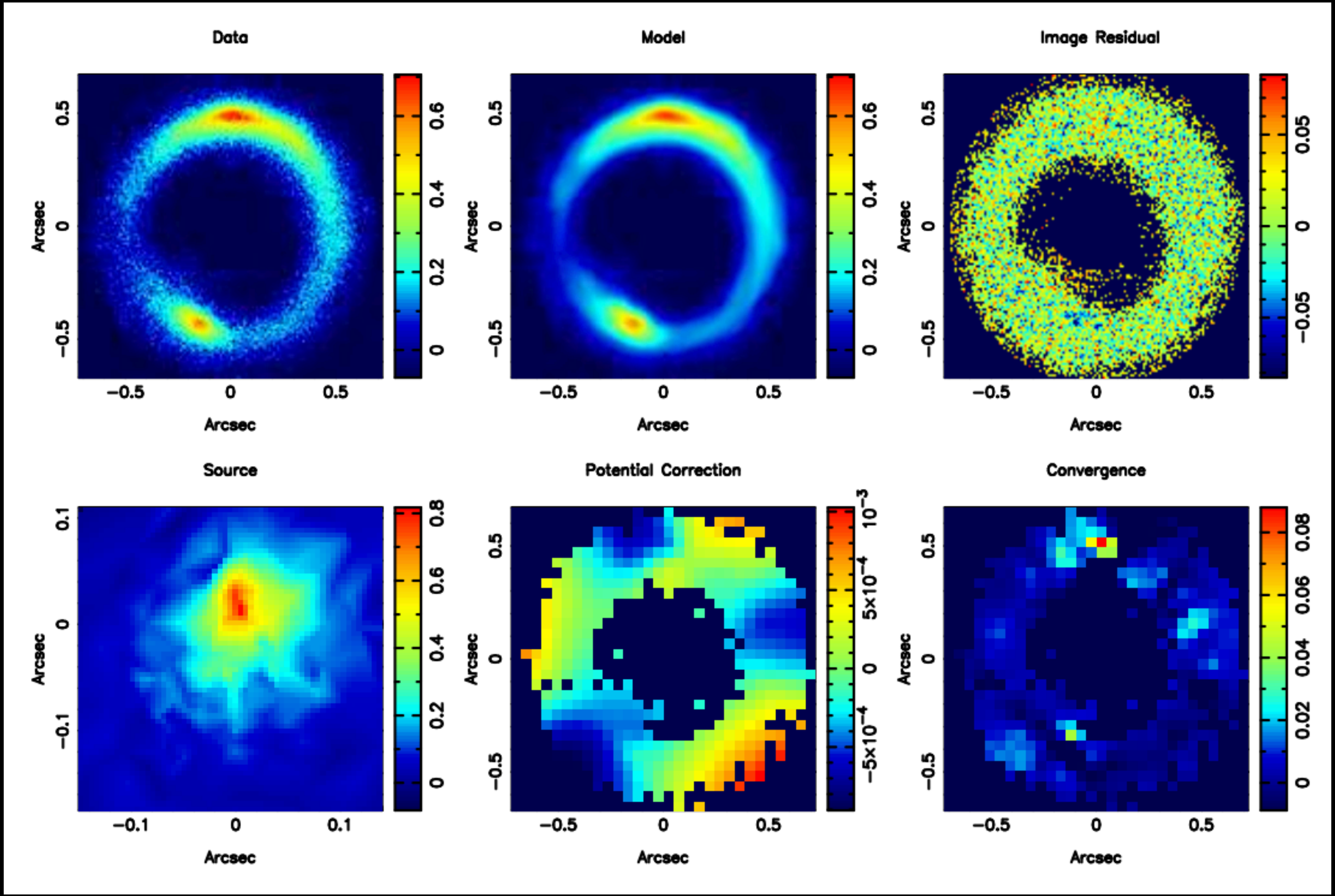
Rybak et al. 2015a,b

DETECTION OF DARK MATTER SUBSTRUCTURES

- Are there enough satellites compared to simulations?
- Can use lensing to detect substructures in other galaxies
- Constraining cosmological models - dark matter, warm matter, or something else?

Illustris Collaboration

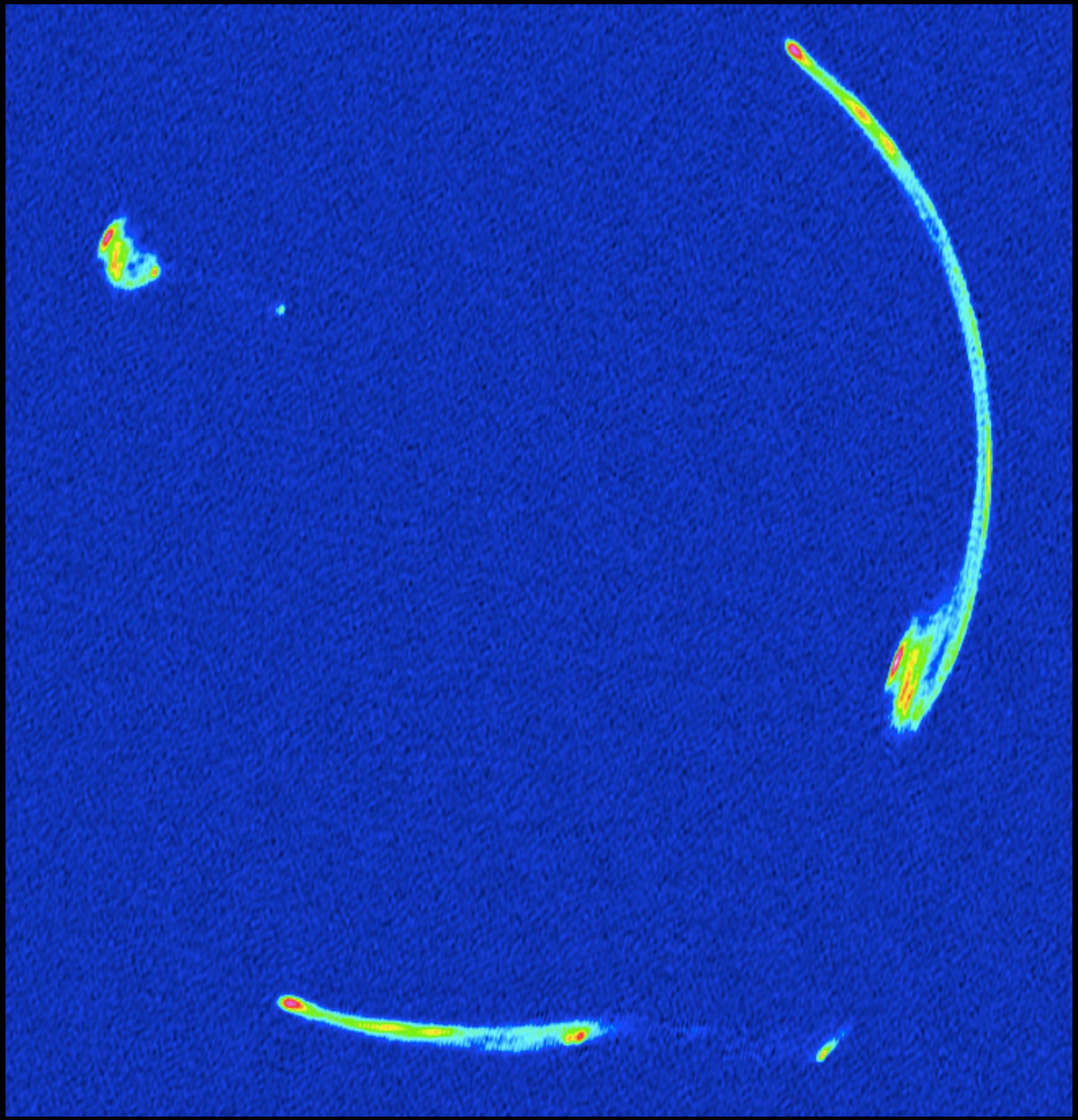
DETECTION OF DARK MATTER SUBSTRUCTURES



Vegetti et al. 2012

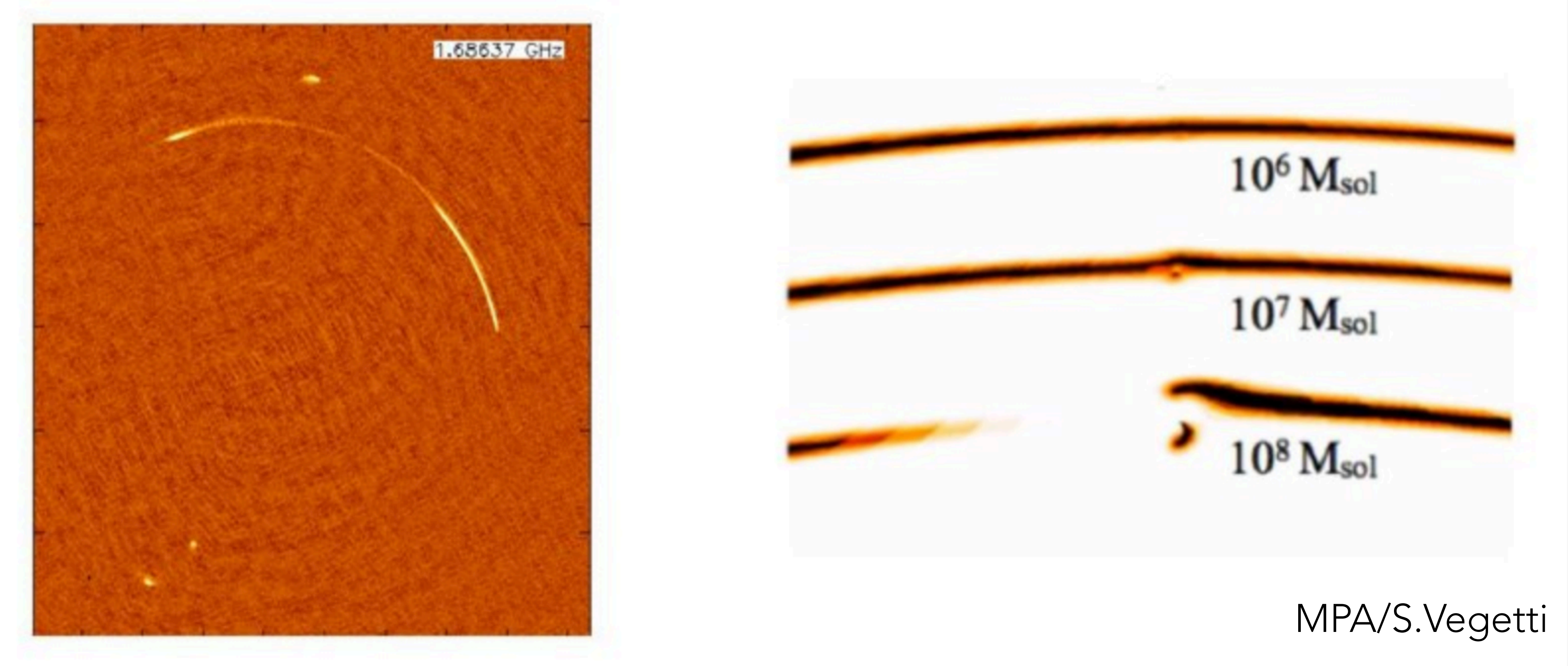
DETECTION OF DARK MATTER SUBSTRUCTURES

- VLBI has high resolution and astrometric precision
- Lensed arcs provide many constraints to find solution to lens model



Spingola et al. 2018

DETECTION OF DARK MATTER SUBSTRUCTURES



MPA/S.Vegetti

- VLBI resolutions are sensitive to smaller perturbations of mass due to substructures

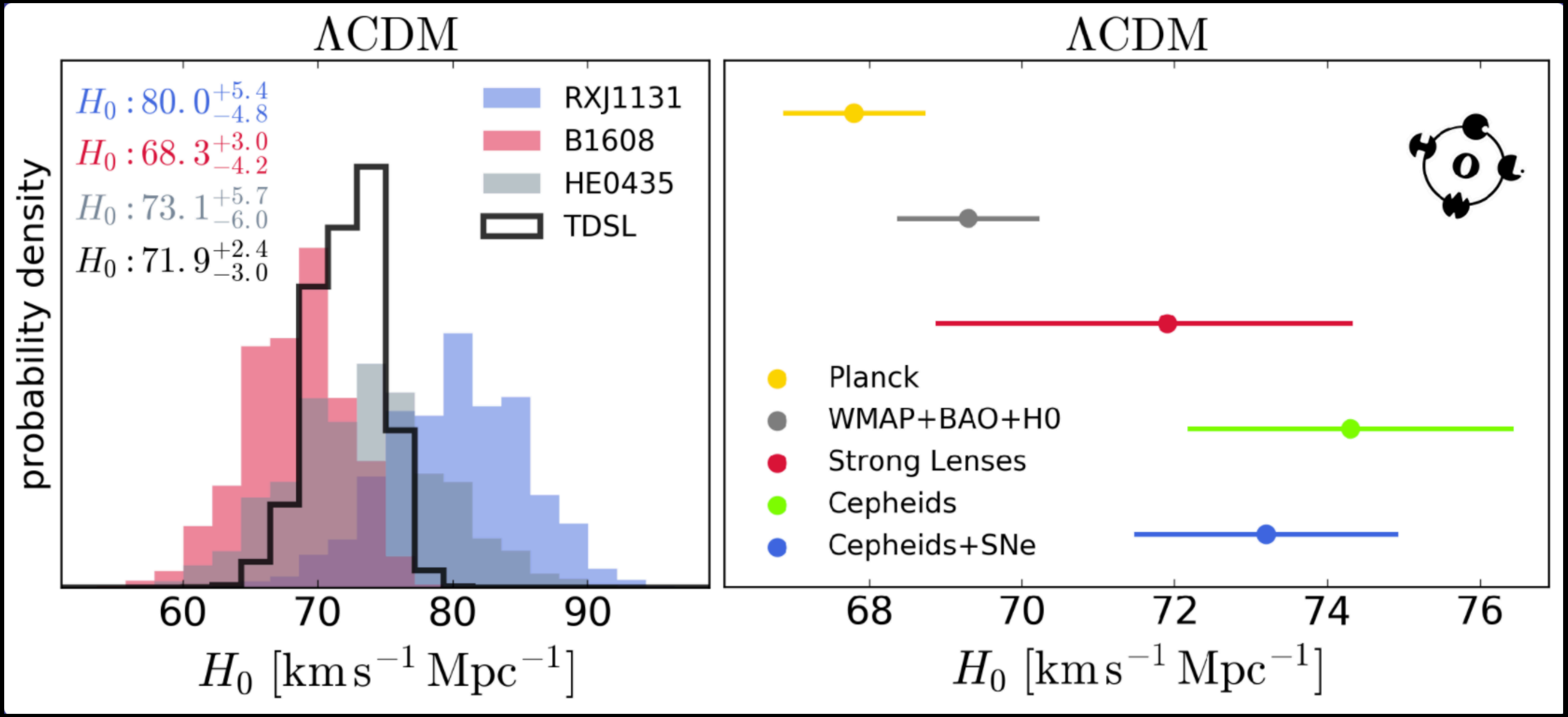
MEASURING THE EXPANSION OF THE UNIVERSE

- Cosmological distance depends on Hubble constant, H_0
- Different path lengths of lensed images
- If the lensed source is variable, we get a time delay between images and can solve for H_0!

Suyu et al.

MEASURING THE EXPANSION OF THE UNIVERSE

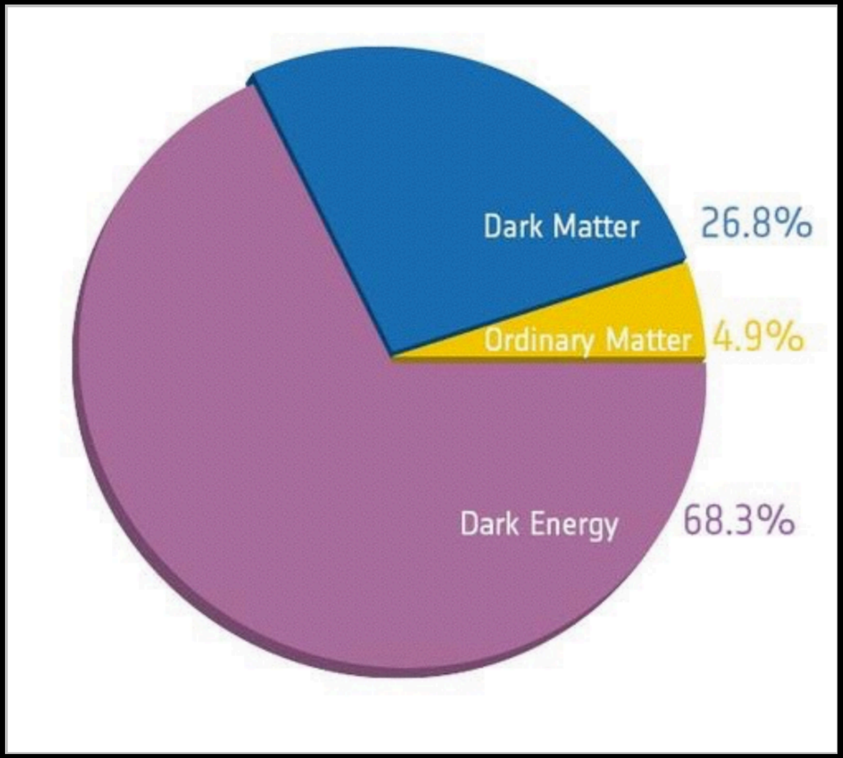
- Tension between different methods of measuring H_0?



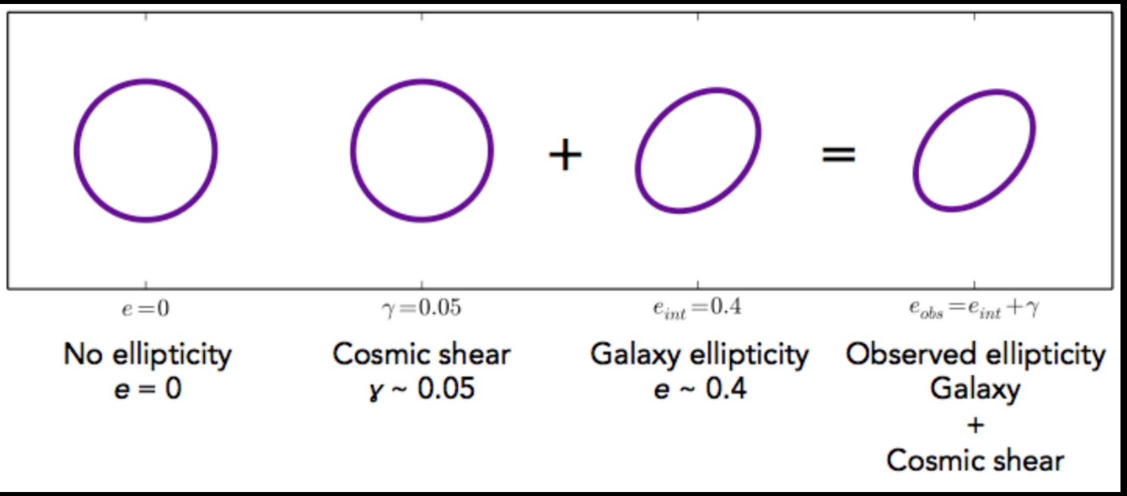
H0LiCoW collaboration

INVESTIGATING THE LARGE-SCALE STRUCTURE OF DARK MATTER

- How much dark matter is hiding in the Universe?
- Can measure the stretching (shear) of galaxies due to weak lensing with a statistical approach (an effect of the order 1%) over > 1 deg^2
- SKA will match future Euclid + LSST optical capabilities to constrain cosmological parameters

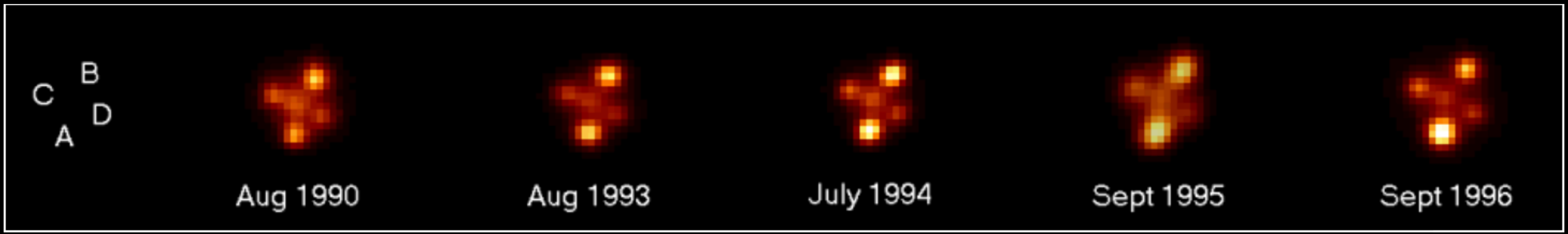


Planck collaboration 2013



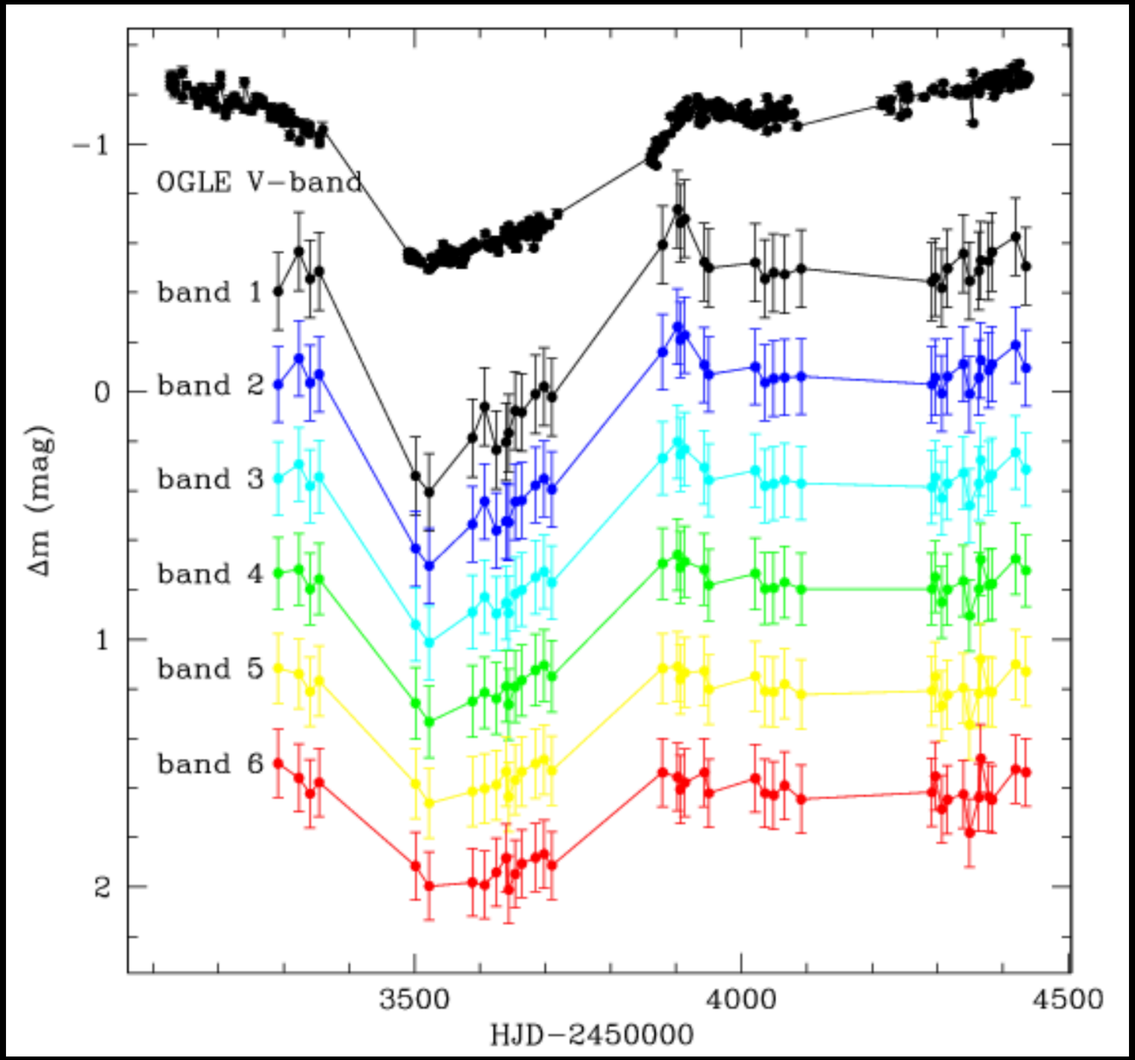
SuperCLASS collaboration 2017

MEASURING THE SIZE AND SHAPE OF BLACK HOLE ACCRETION DISKS



- Different apparent size at different wavelengths due to thermal properties of accretion disk

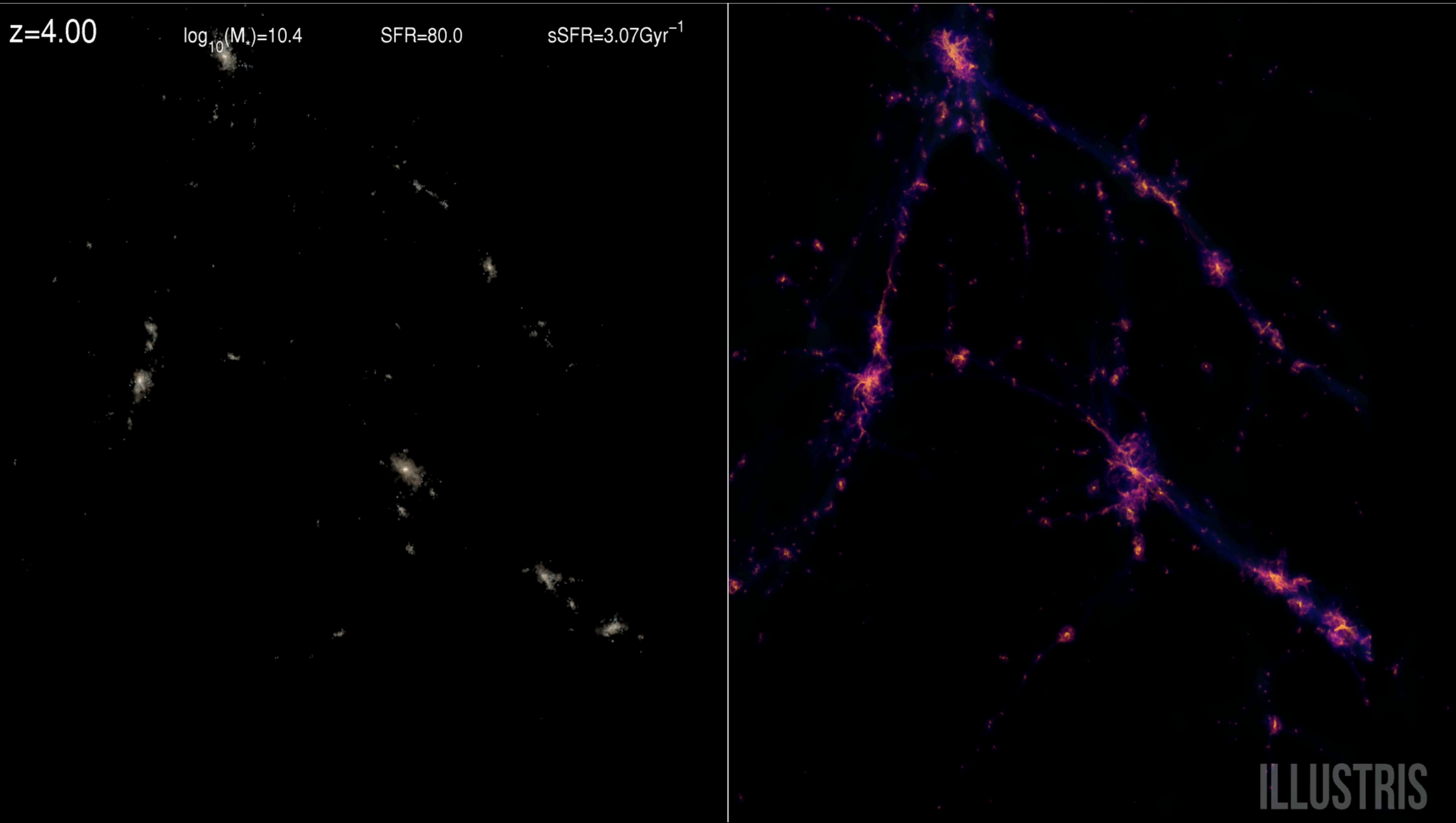
- Magnification will be different for different source sizes - “chromatic microlensing”



Eigenbrod et al. 2008

WHAT DO I DO?

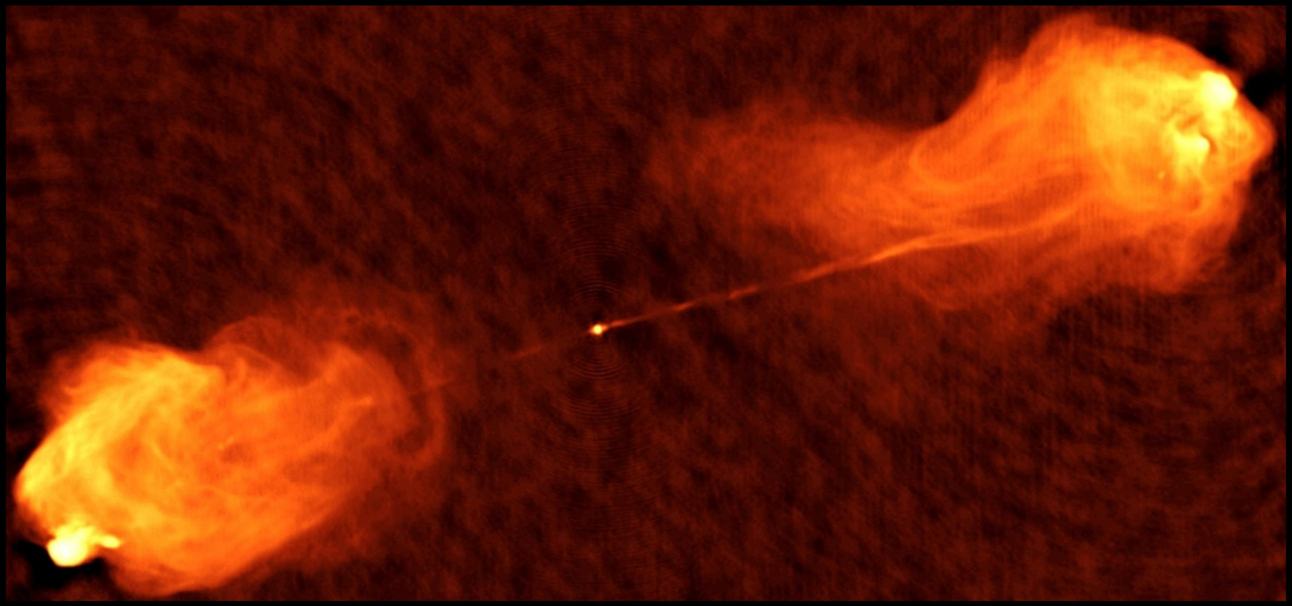
FORMING A MASSIVE ELLIPTICAL GALAXY



ACTIVE GALACTIC NUCLEI (AGN)

- Accreting supermassive black holes at the centre of galaxies
- Accretion produces energy -> extremely luminous sources
- Come in radio-bright and radio-faint flavours

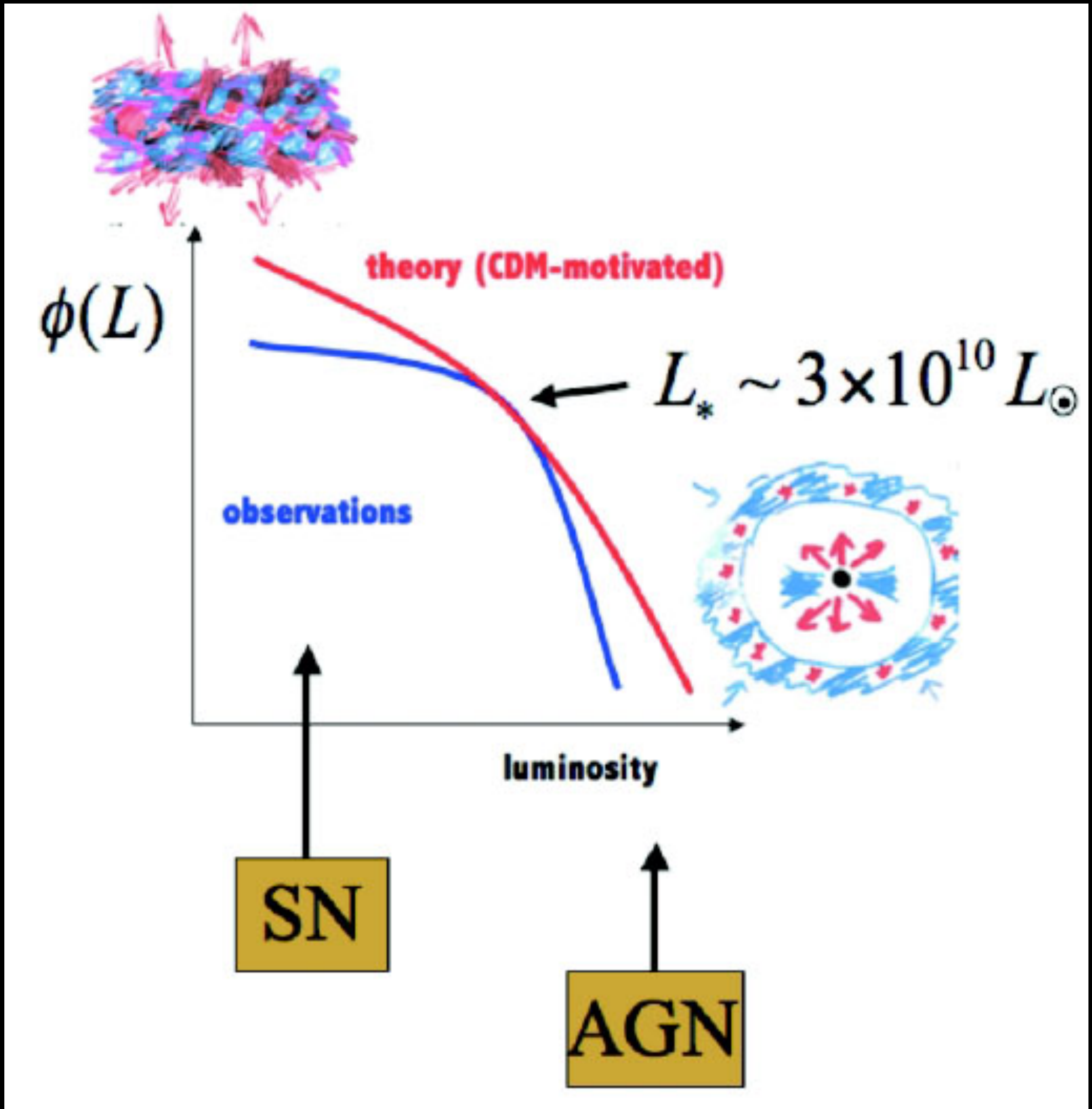
NASA/ESA



NRAO

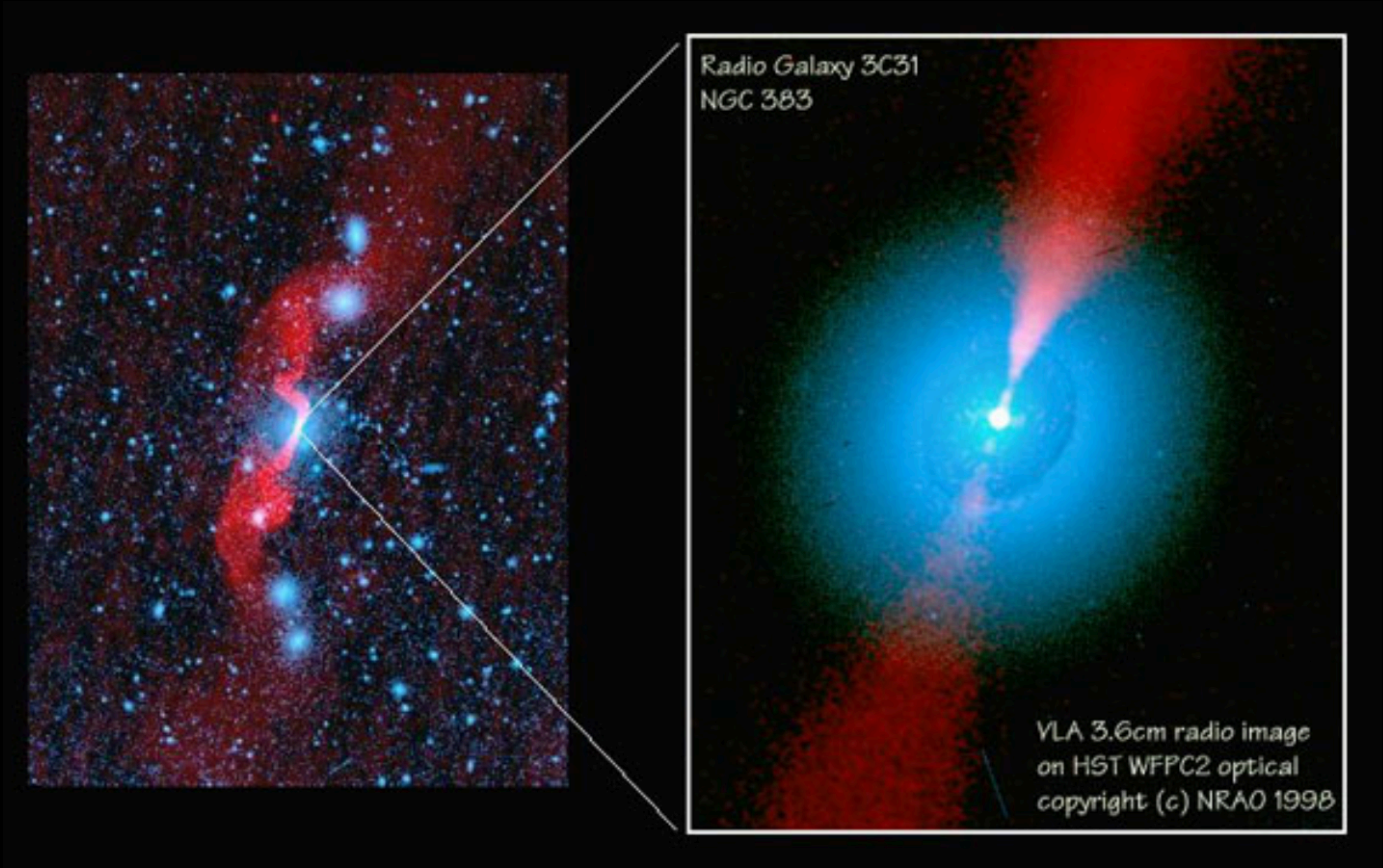
THE ROLE OF AGN FEEDBACK

- Feedback required to suppress star-formation in massive galaxies
- How does the black hole suppress star-formation?
- Jets and winds driving outflows?



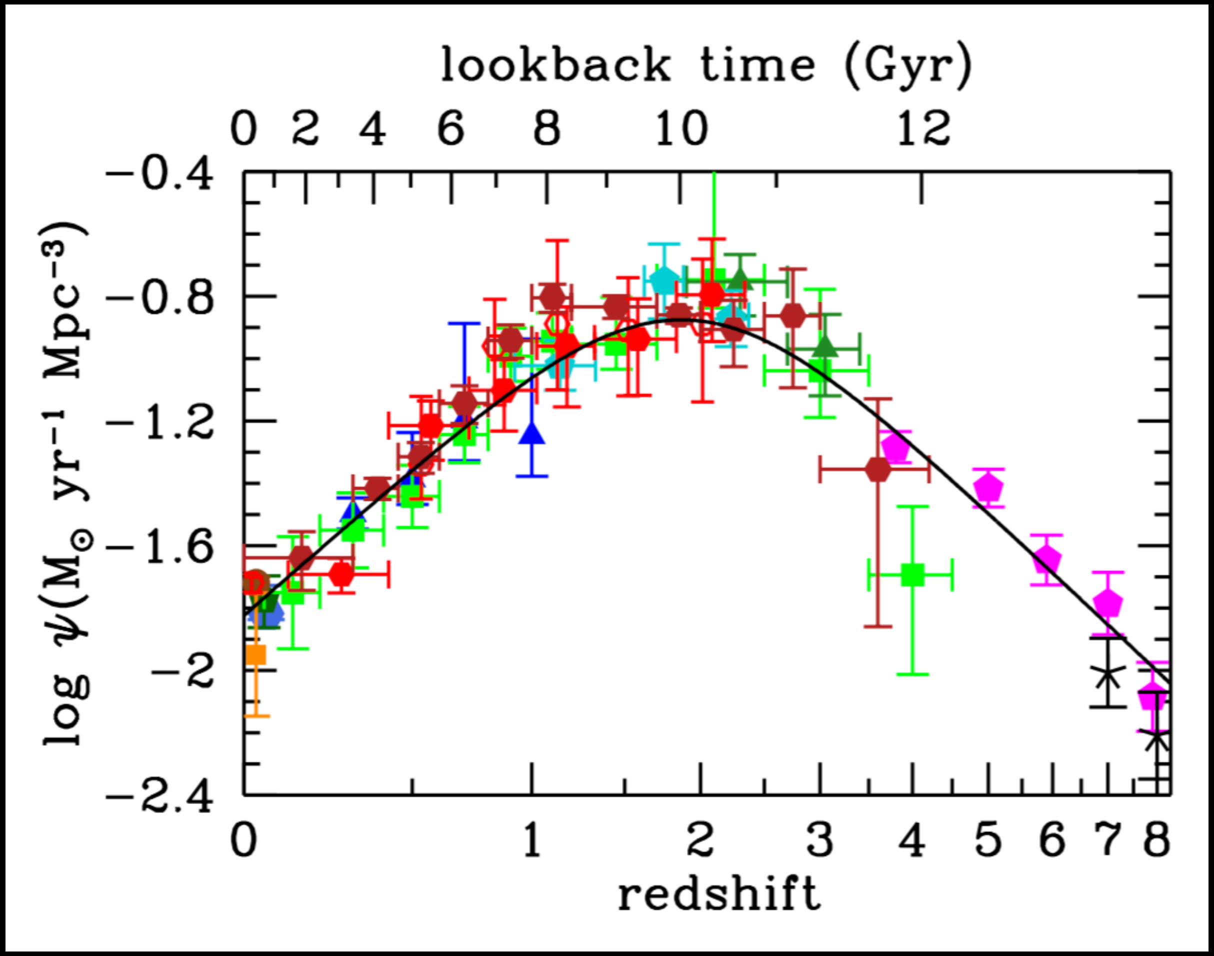
https://ned.ipac.caltech.edu/level5/March11/Silk/Silk2.html

THE ROLE OF AGN FEEDBACK



GRAVITATIONALLY-LENSED QUASARS

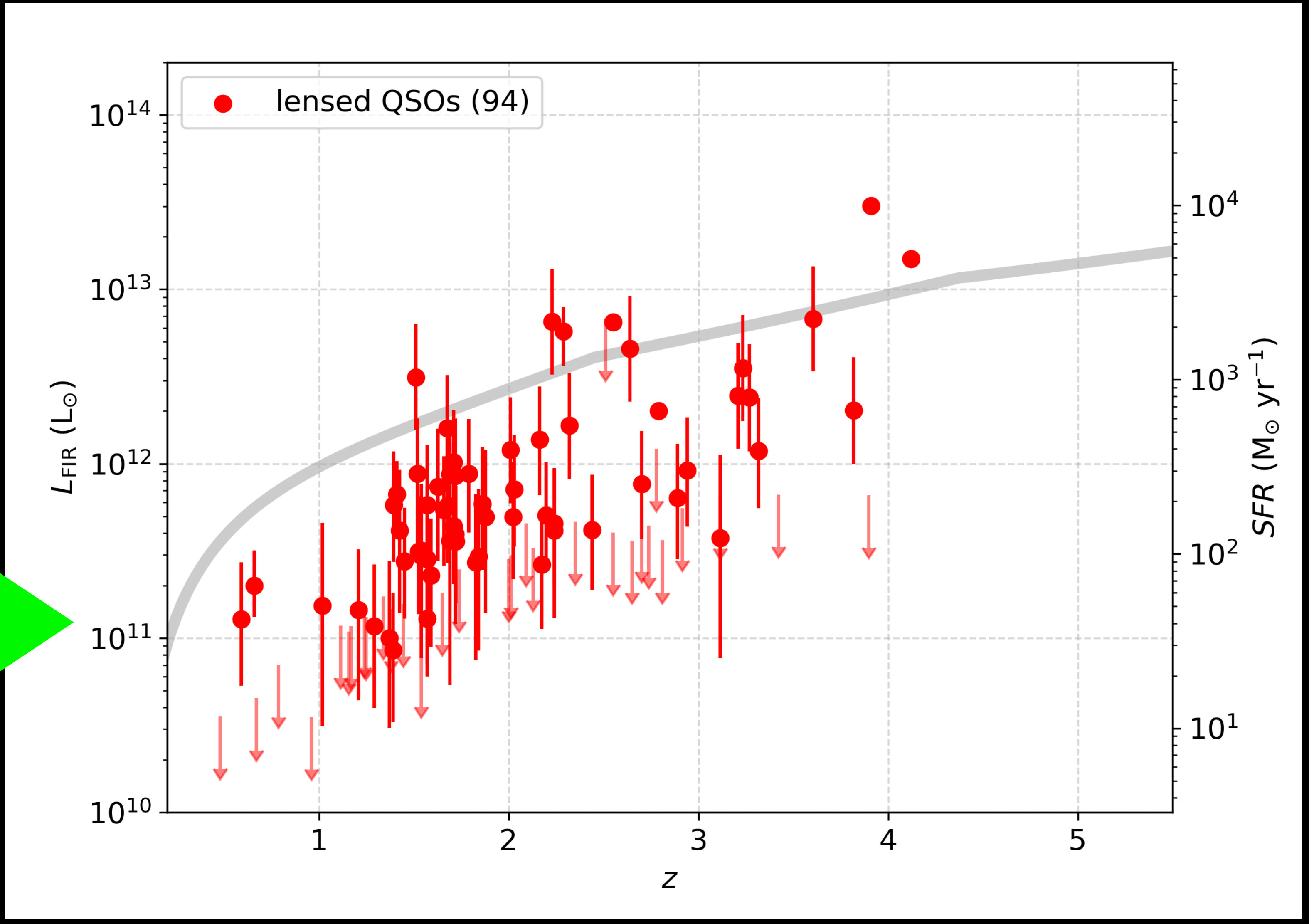
- What is the relationship between AGN and star-formation?
- Lensing magnifies the emission from star-formation in the host galaxies so we can detect them
- Higher effective resolution to resolve feedback effects at high-redshift



Madau & Dickinson (2014)

HOW MUCH STAR-FORMATION IS THERE IN QUASAR HOST GALAXIES?

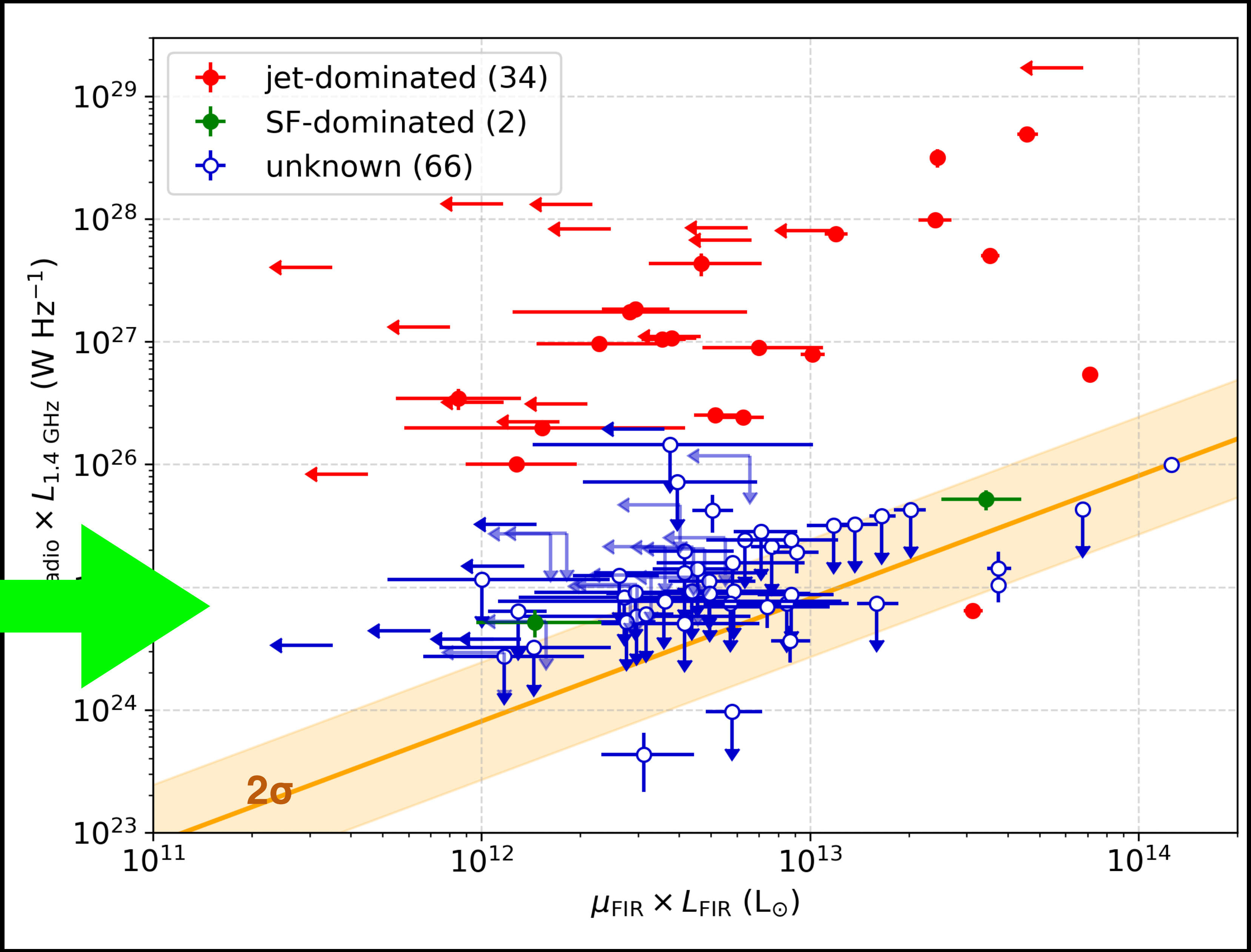
- Measuring sources below the detection limit



Stacey et al. 2018

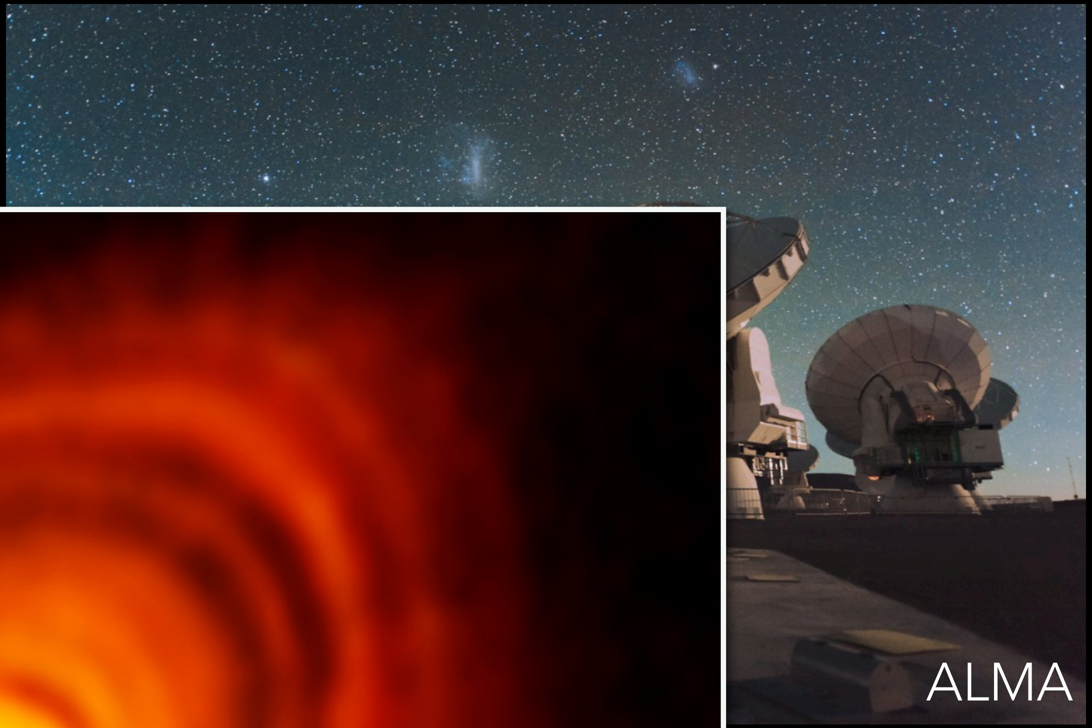
WHAT IS THE ROLE OF RADIO JETS ?

- Do radio-faint quasars also have small-scale radio jets?

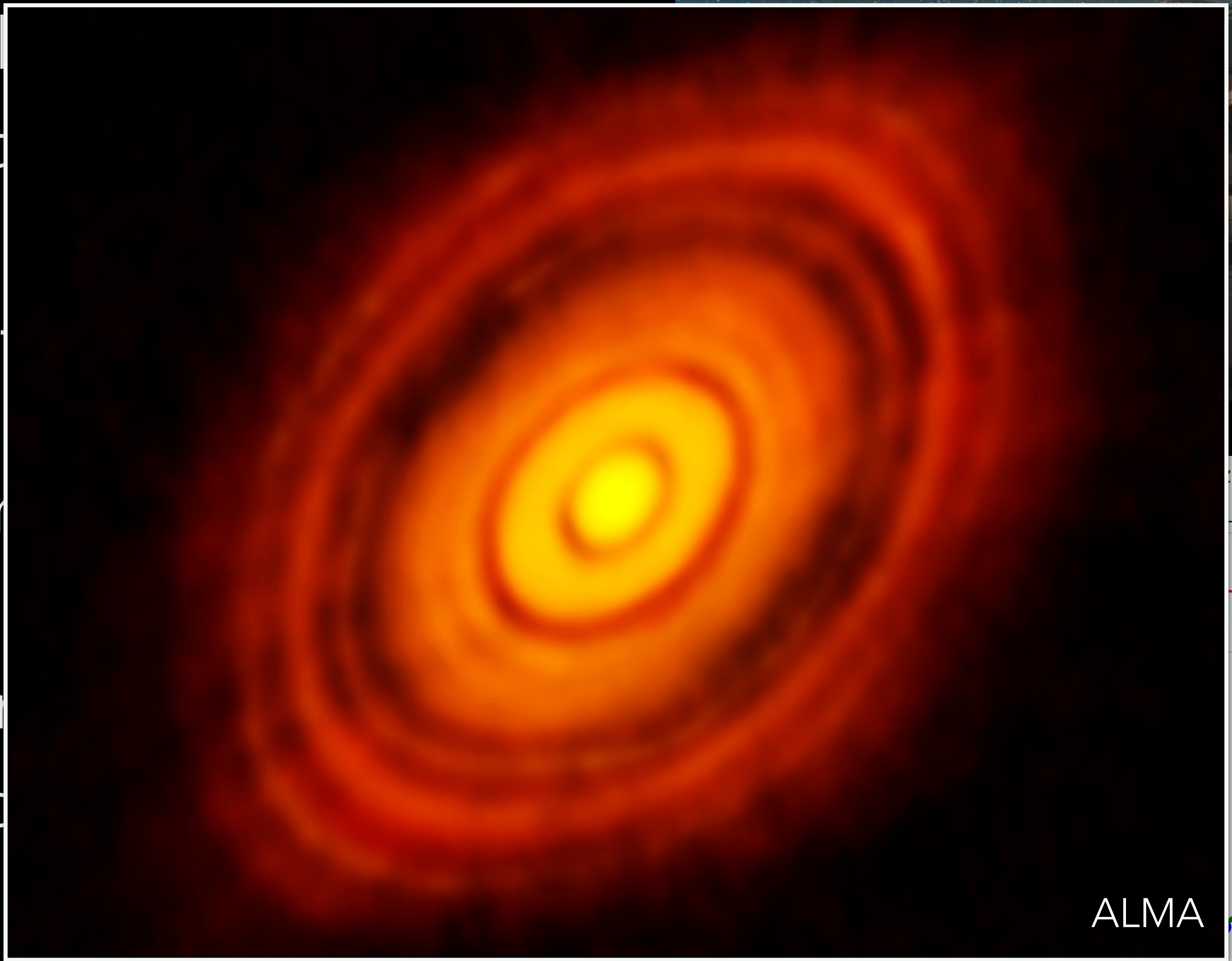


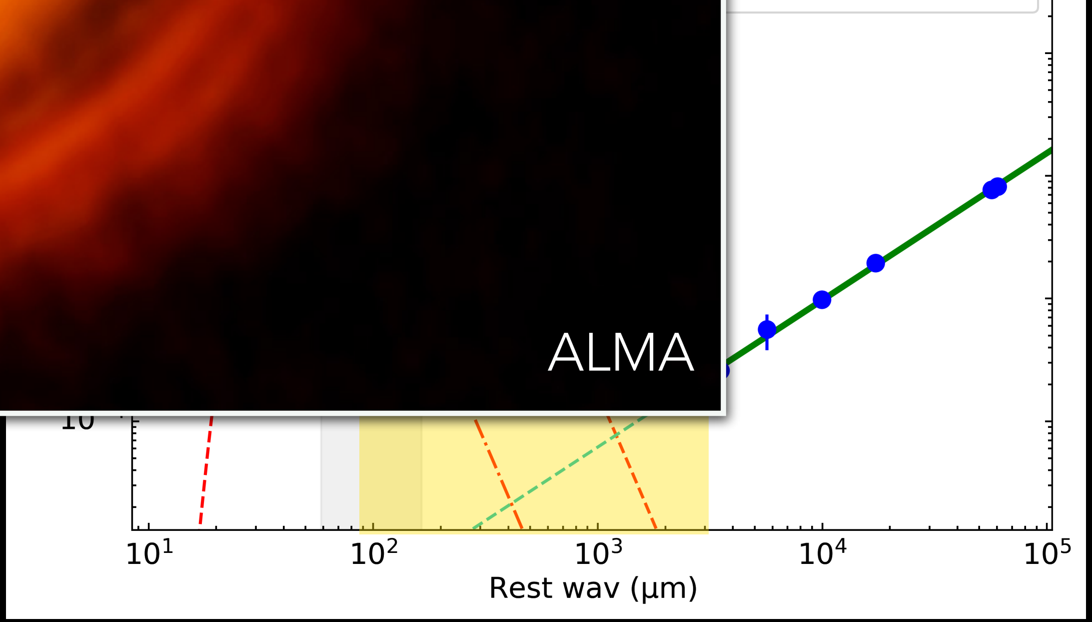
Stacey et al. 2018

ATACAMA LARGE (SUB-)MILLIMETRE ARRAY (ALMA)

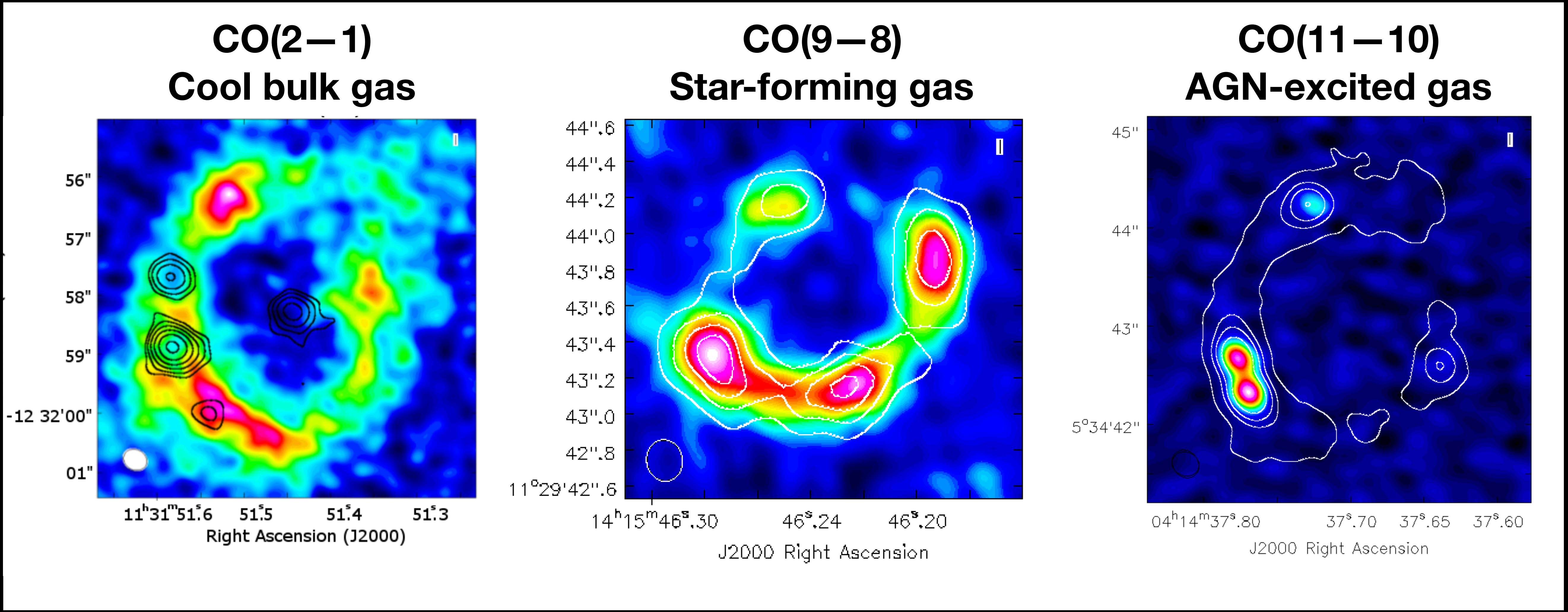


- Sub-mill
  millimet
- 30 GHz -
- Ideal for
  and gas
  with sta
  high-red
- Also other cool things..





TRACING STAR-FORMATION AND AGN AT HIGH-RESOLUTION WITH ALMA



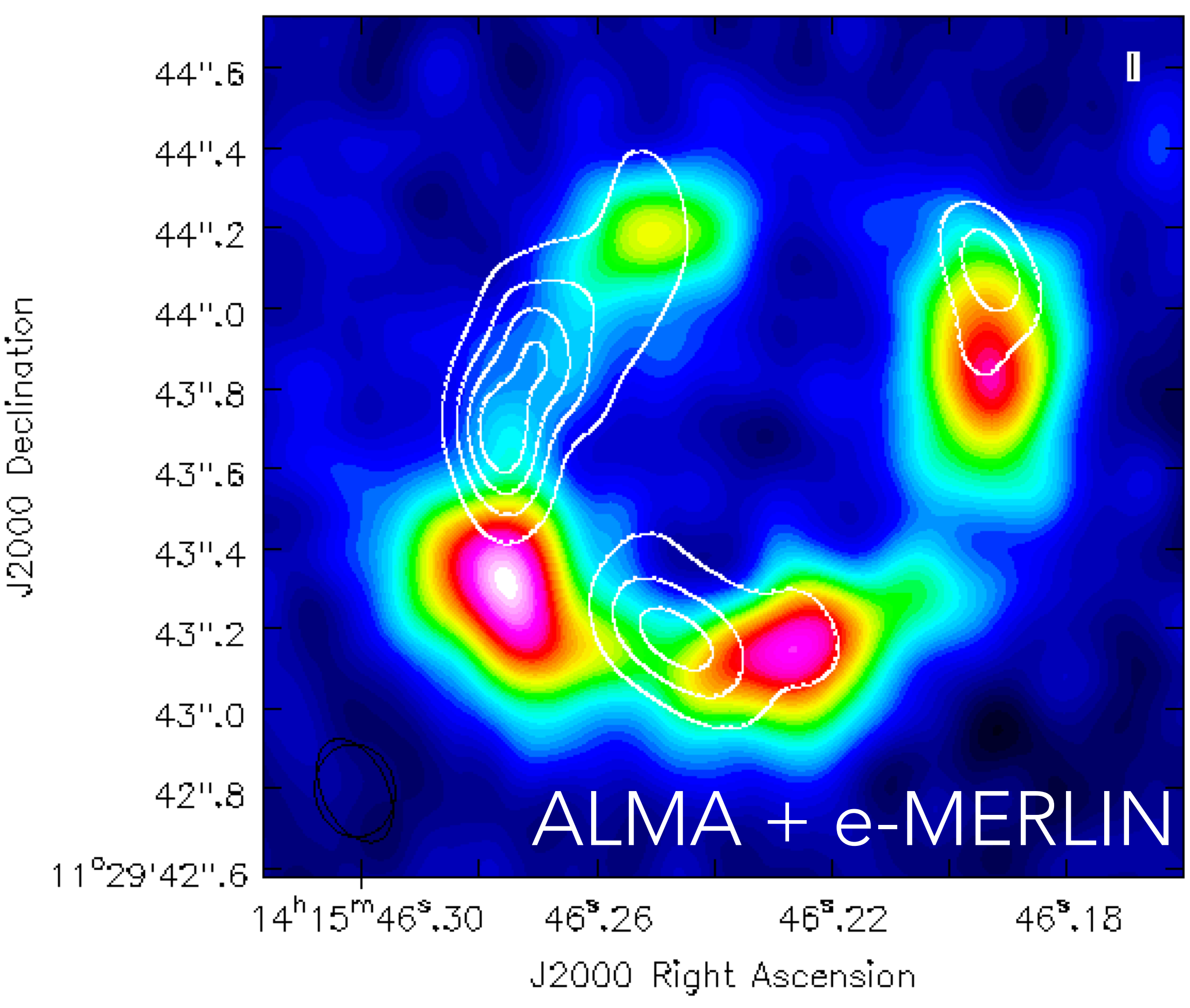
Paraficz et al. 2018

Stacey et al. in prep

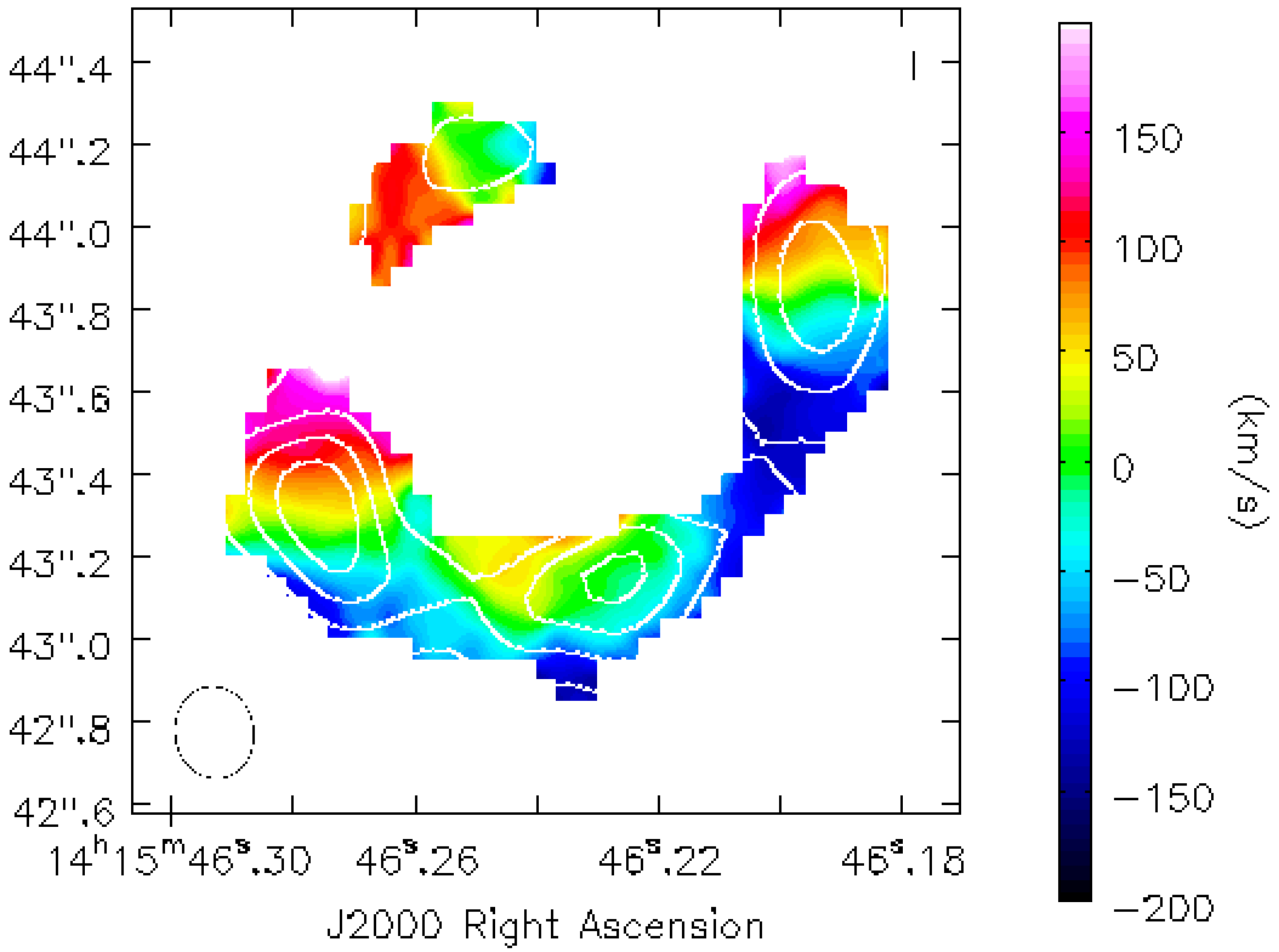
Stacey et al. in prep

CLOVERLEAF: QUASAR/STARBURST

Dust and radio jet(?)

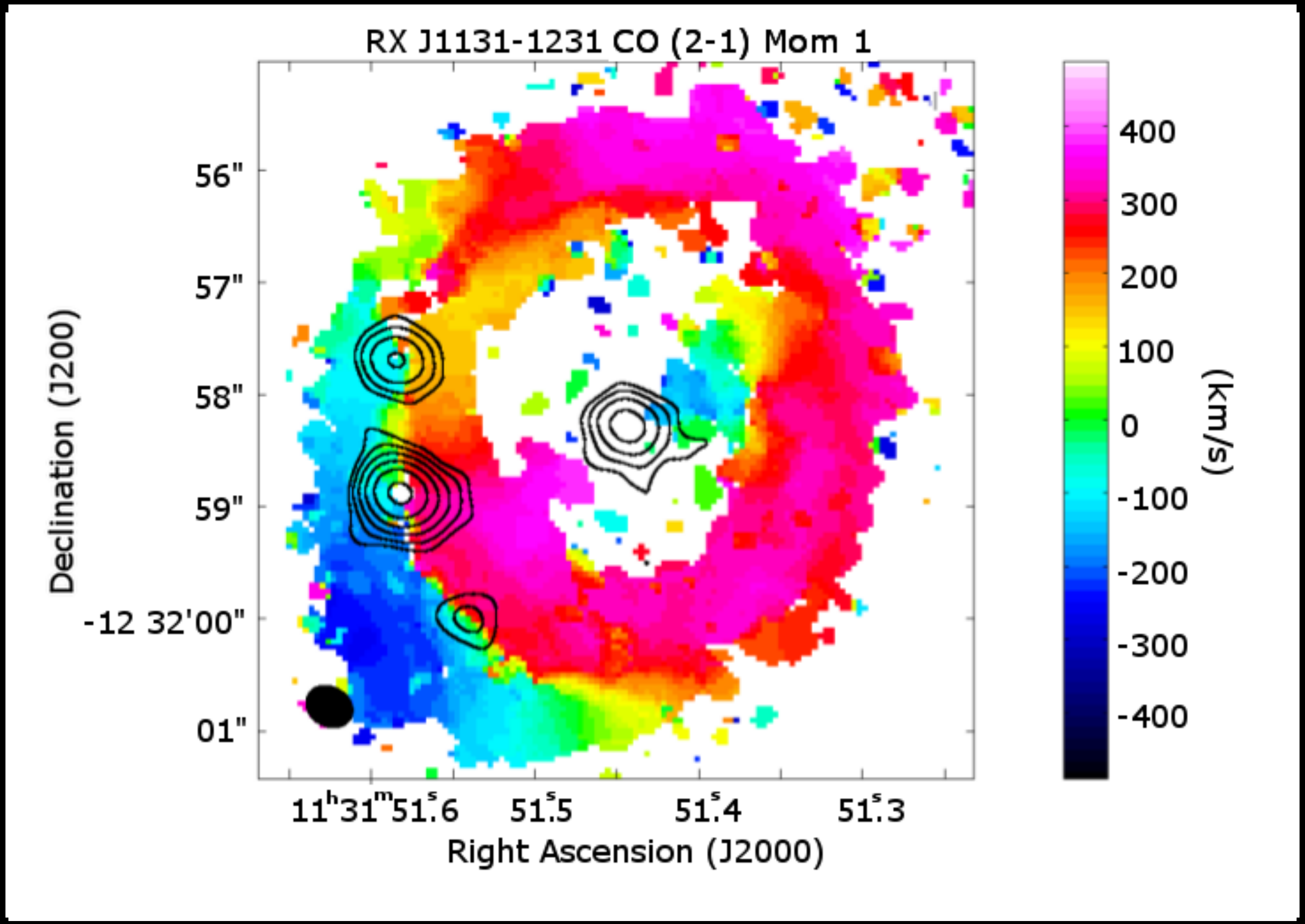


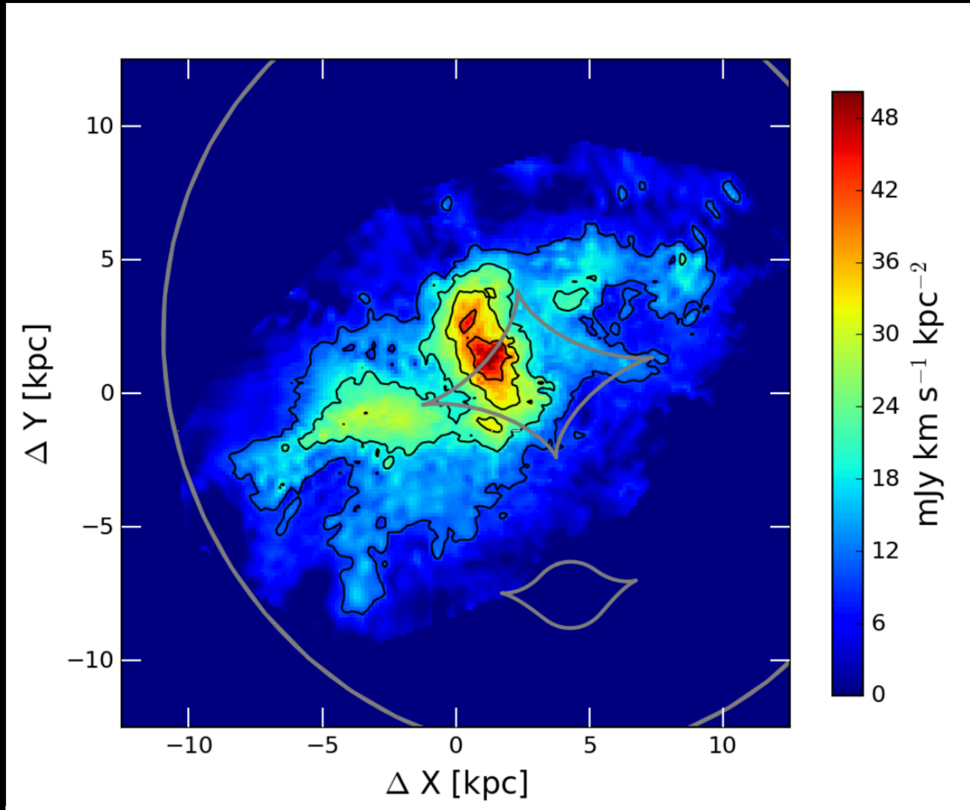
CO gas (star-formation)

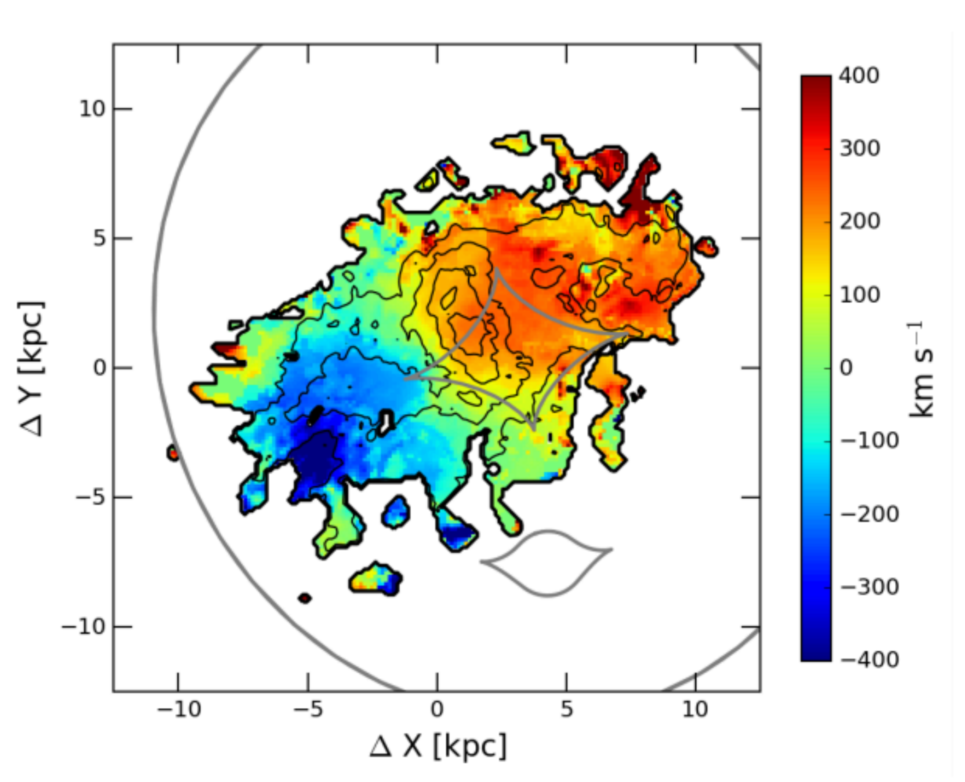


Stacey et al. in prep

RXJ1131–1231: QUASAR IN A SPIRAL GALAXY







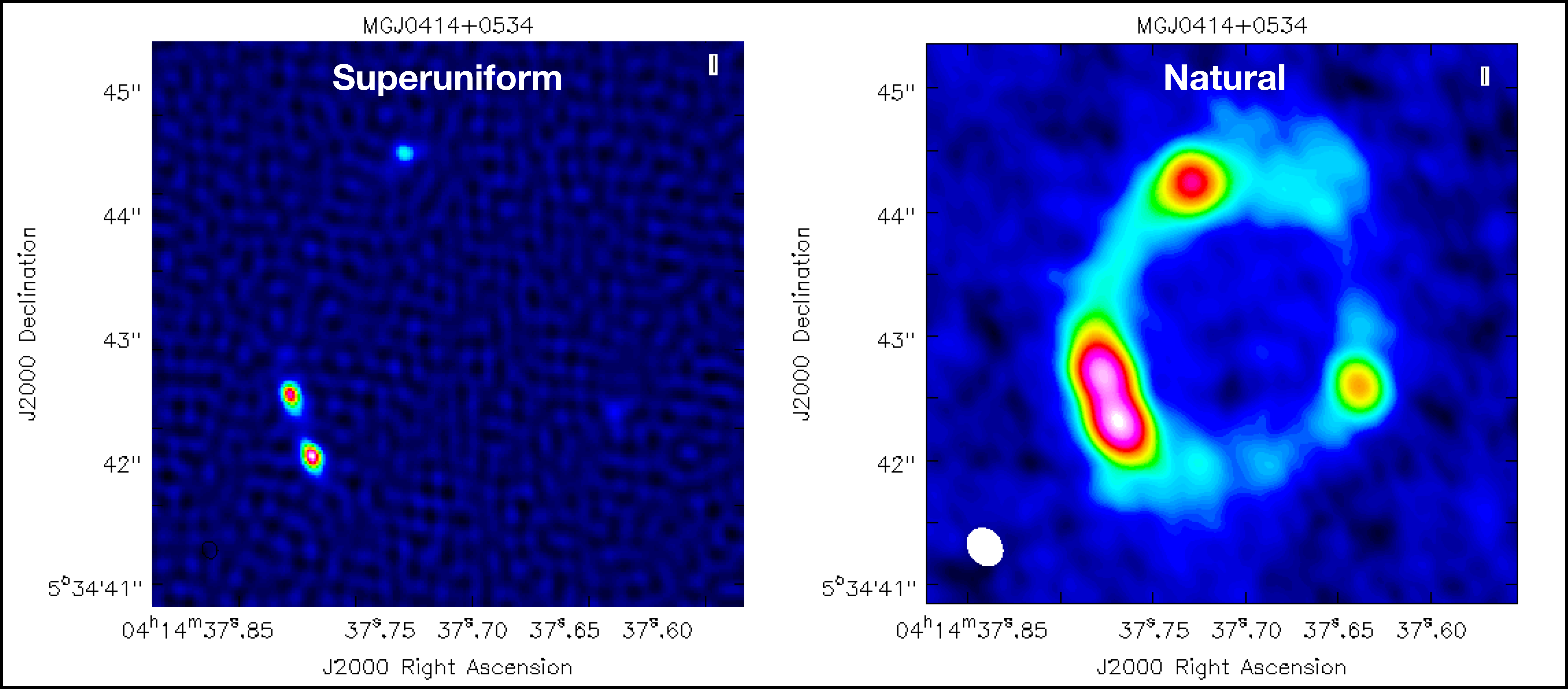
- Resolved kinematics of gas reservoir
- Low star-formation efficiency for its redshift -> an effect of feedback from the black hole?
- Properties of host galaxy seem unaffected by quasar

Paraficz et al. 2018

MGJ0414+0534: LENSED QUASAR/ RADIO GALAXY

AGN (synchrotron)

AGN + dust (thermal)

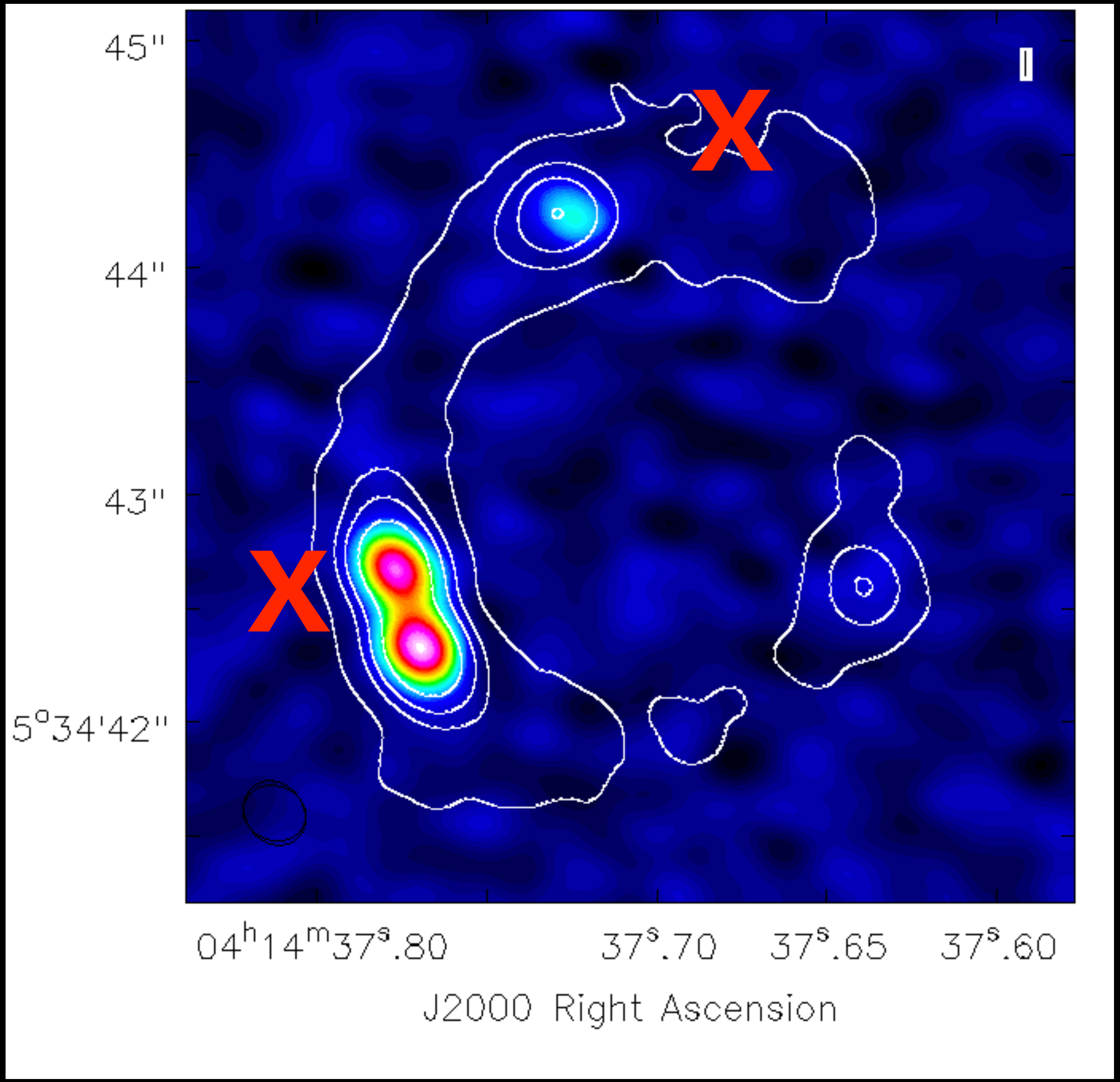


Stacey et al. in prep

MGJ0414+0534: LENSED QUASAR/ RADIO GALAXY

- Combining information from dust ring and CO spectral line to measure substructures in the lensing galaxy?

CO(11–10) and dust (contours)



Stacey et al. in prep

SUMMARY

- Gravitational lensing has many applications in astronomy!
- Gravitational magnification means we can detect fainter sources and resolve scales similar to galaxies at $z<1$
- We can measure massive objects that are otherwise invisible or undetectable and constrain cosmological models
- Lensing + interferometry is a powerful tool to study galaxy evolution
- The future is bright for finding gravitational lenses, and astronomy in general….

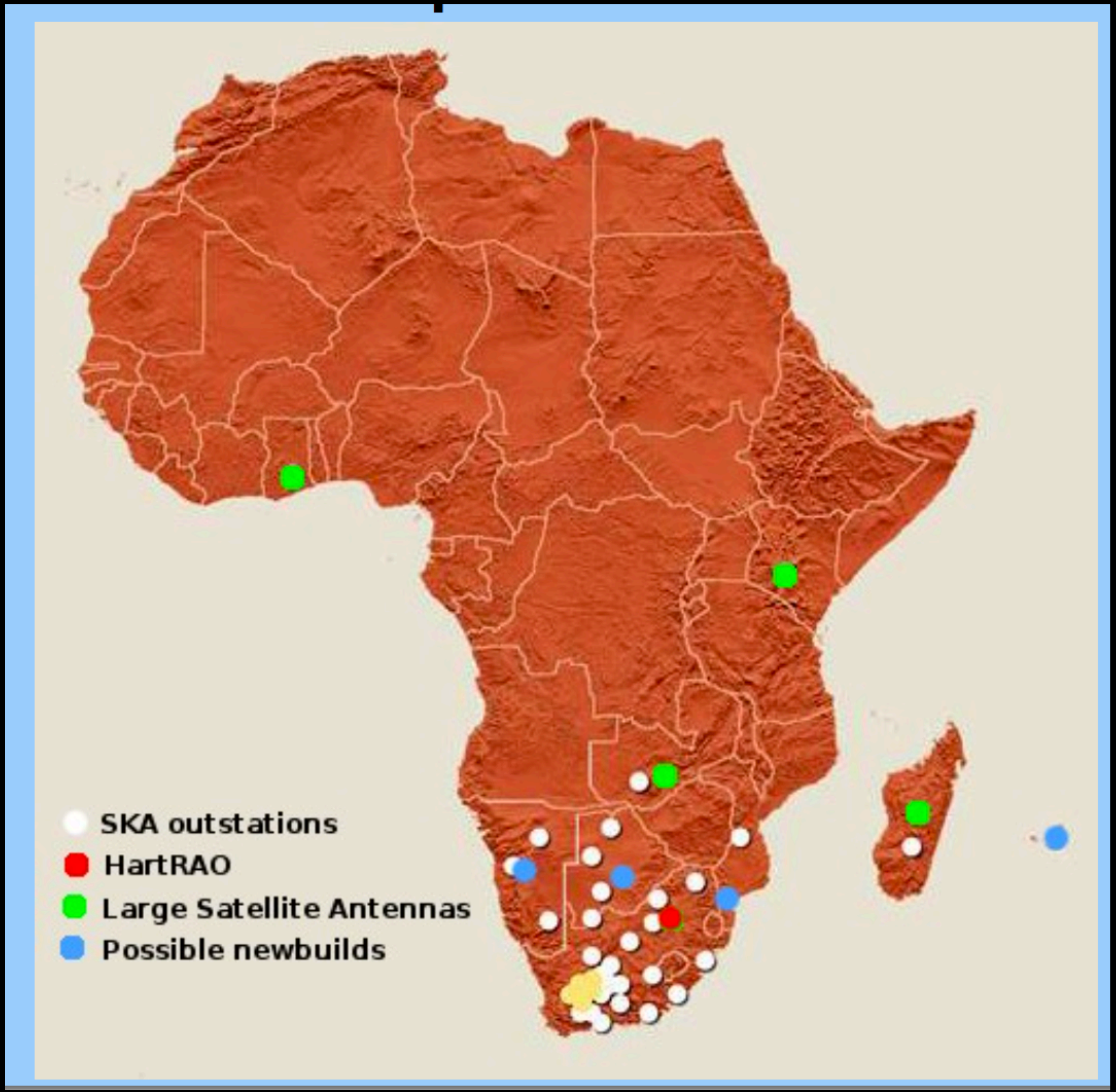
THE FUTURE IS BRIGHT...

THE FUTURE

- **Euclid** (space) & **LSST** (Chile): all-sky surveys in optical will discover ~10 000 gravitational lenses
- **James Webb Space Telescope** (space, infrared) & **European Extremely Large Telescope** (40m optical telescope) for extreme resolution and sensitivity

THE FUTURE

- **African VLBI network** - expanding the global radio network
- Repurposing satellite communications dishes for use in radio astronomy
- Currently Ghana, Kenya, **Zambia**, Botswana & Namibia.. expanding to Madagascar & Mauritius.
- In talks with Mexico, Iraq, Thailand, Indonesia…



THE FUTURE

- **Square Kilometre Array (Africa and Australia)** - many dishes (200—1000s) extreme sensitivity at radio frequencies
- **EVN + SKA + AVN**: current collecting area of EVN antennas is 10% of the SKA! We will get much better sensitivity and image fidelity

SKA-SA

DARA PROJECT

- PI: Melvin Hoare (Univ. Leeds)
- Joint UK-South Africa project funded by the UK's Newton Fund.
- Partner Institutions: University of Manchester, Leeds, Hertfordshire, Oxford, Bristol & UCLAN.
- Uses Overseas Development Assistance money for scientific collaborations with developing countries to promote economic development.
- Consists of two programmes:
  - Basic training (astronomy, dish operations, data reduction + analysis)
  - Advanced training (funded MSc + PhD positions in SA and UK)

See: *www.dara-project.org*

DARA
DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

Newton Fund

DARA Zambia graduates, 2017

JUMPING JIVE

- € 3 million from EU Horizon 2020 EU for the next 4 years, led by JIVE, (the Joint Institute for VLBI ERIC).

- Prioritisation of new VLBI capabilities, including work package for AVN development and global VLBI development projects.

- Also contributing to AVN project. Designed to:
  - Expand DARA to new countries.
  - Bring in EU expertise with extra focus on technical aspects.

See: *www.jive.nl/jumping-jive-global-leap-european-vlbi-network*

Ghana Kutunse (SKA-SA)

SUMMARY

- Gravitational lensing has many applications in astronomy!
- Gravitational magnification means we can detect fainter sources and resolve smaller structures
- We are resolving structure, kinematics at high-redshift on scales similar to galaxies at $z<1$
- We can measure massive objects that are otherwise invisible or undetectable and constrain cosmological models
- Lensing + interferometry is a powerful tool to study galaxy evolution
- The future is bright for finding gravitational lenses, and astronomy in general….

NASA/ESA