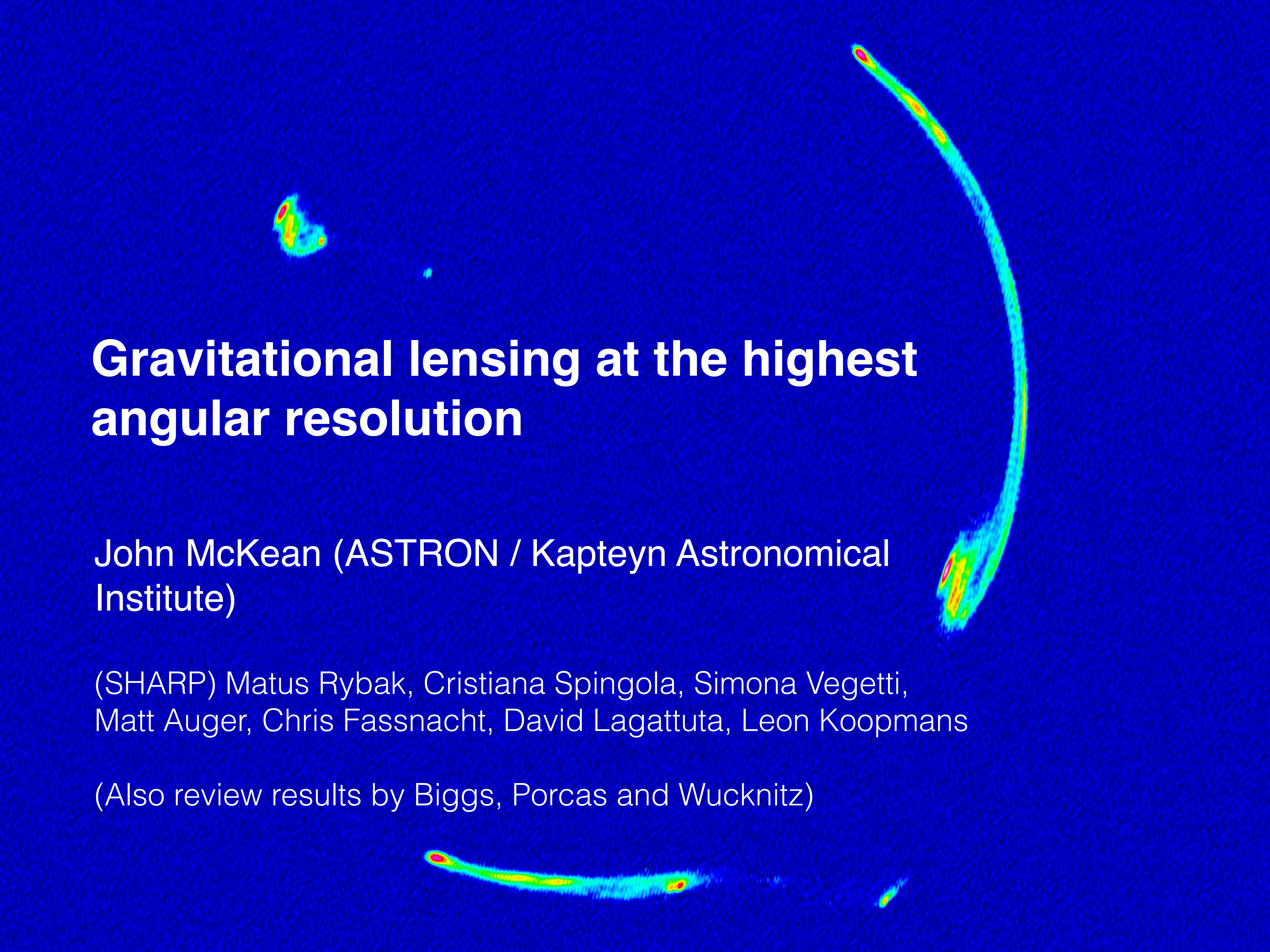


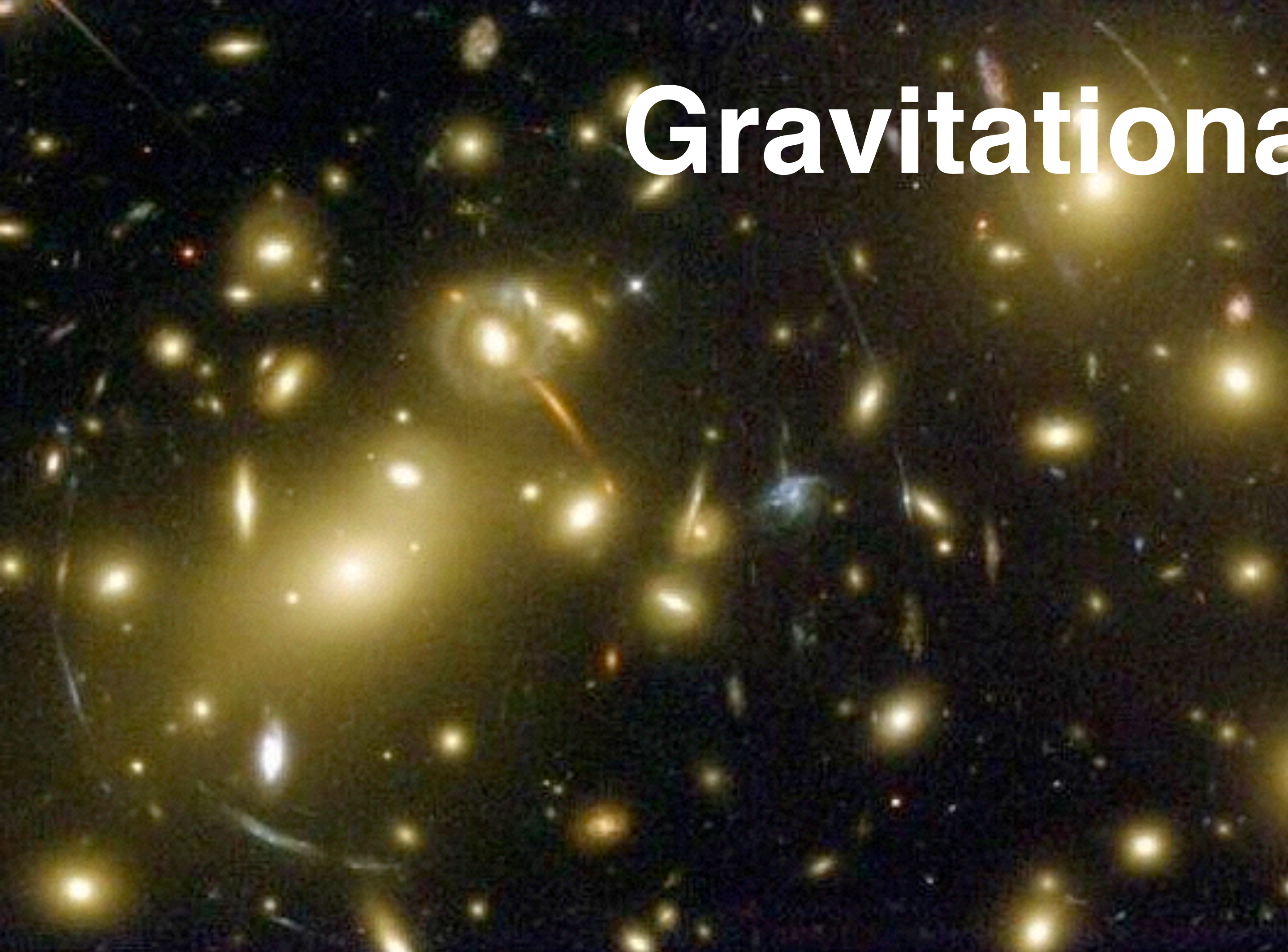
Gravitational lensing at the highest angular resolution

John McKean (ASTRON / Kapteyn Astronomical Institute)

(SHARP) Matus Rybak, Cristiana Spingola, Simona Vegetti,
Matt Auger, Chris Fassnacht, David Lagattuta, Leon Koopmans

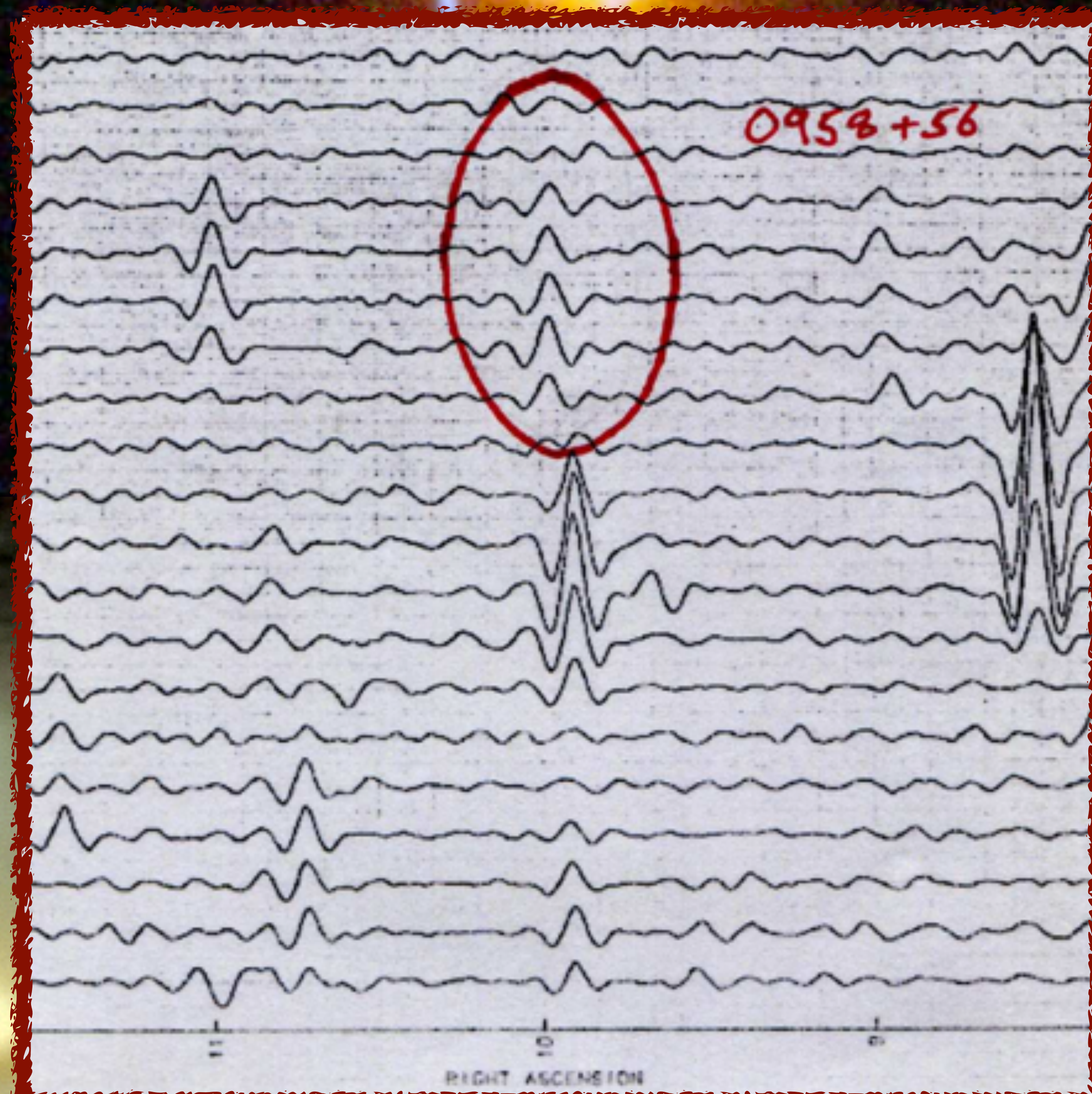
(Also review results by Biggs, Porcas and Wucknitz)

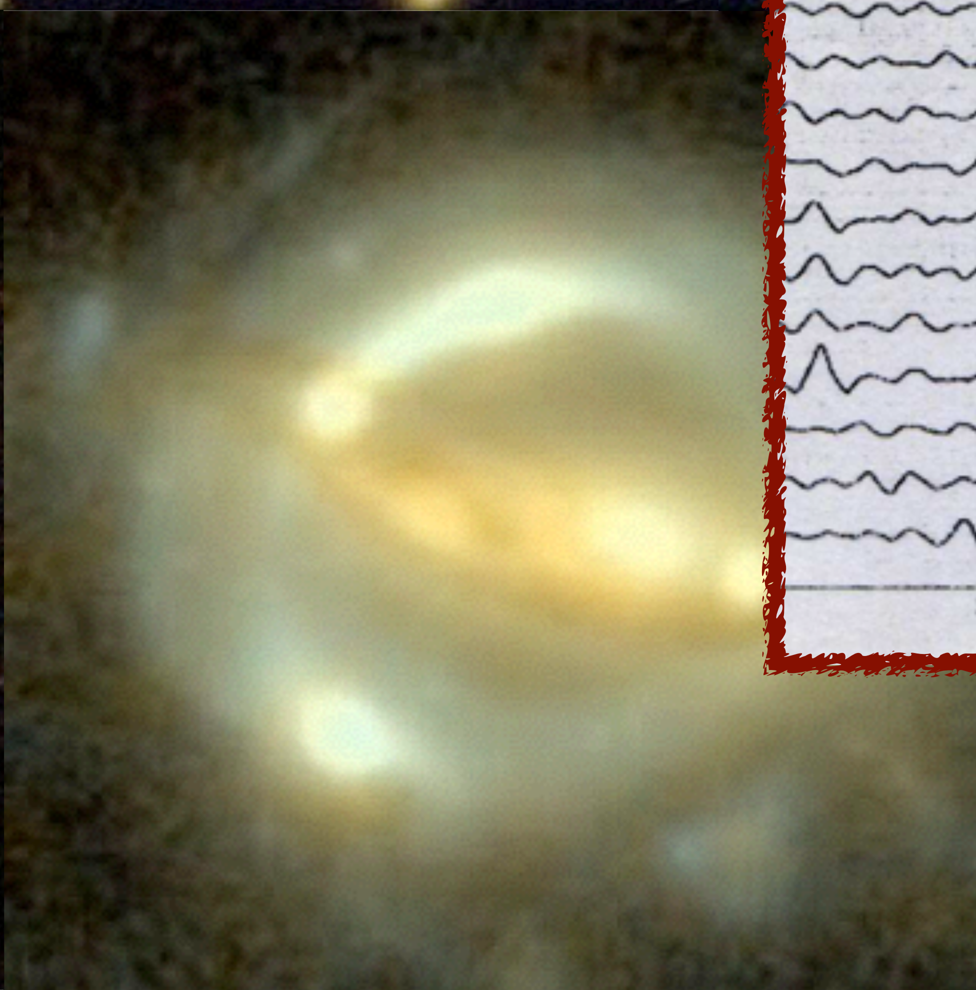
Gravitational lensing



Gravitational lensing

- First gravitational lens found in **radio** from large area survey at 900 MHz (Walsh et al. 1979, *Nature,* Porcas et al. 1979, 1981, *Nature*).
- VLA systematic VLA surveys have found **~40** gravitational lenses.





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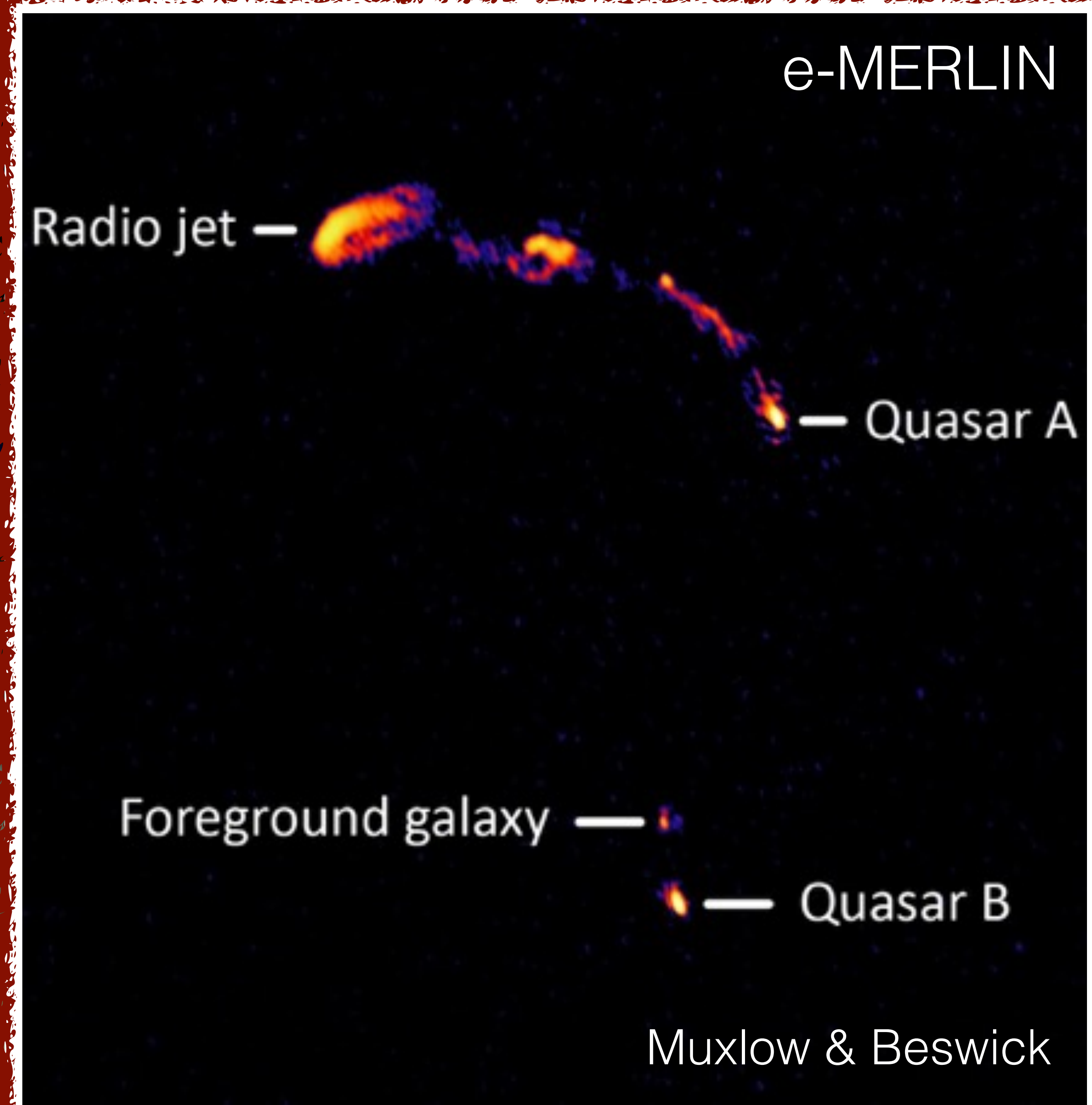
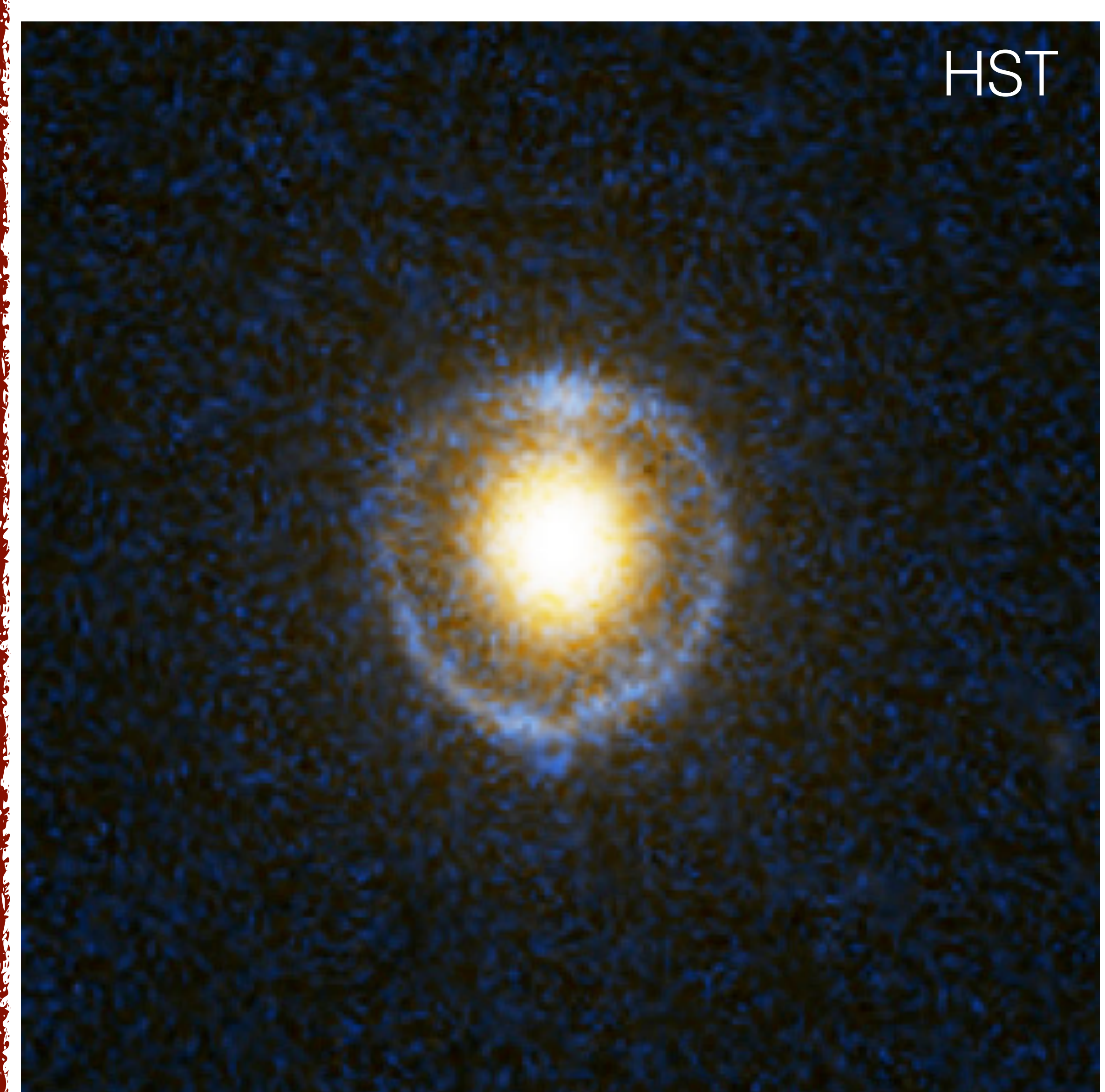


Gravitational lensing

- First gravitational lens found in **radio** from large area survey at 900 MHz (Walsh et al. 1979, *Nature,* Porcas et al. 1979, 1981, *Nature*).
- VLA systematic VLA surveys have found **~40** gravitational lenses.

- Large area imaging and spec. surveys from SDSS have found **$\sim 10^2$** star-forming galaxies and quasars.

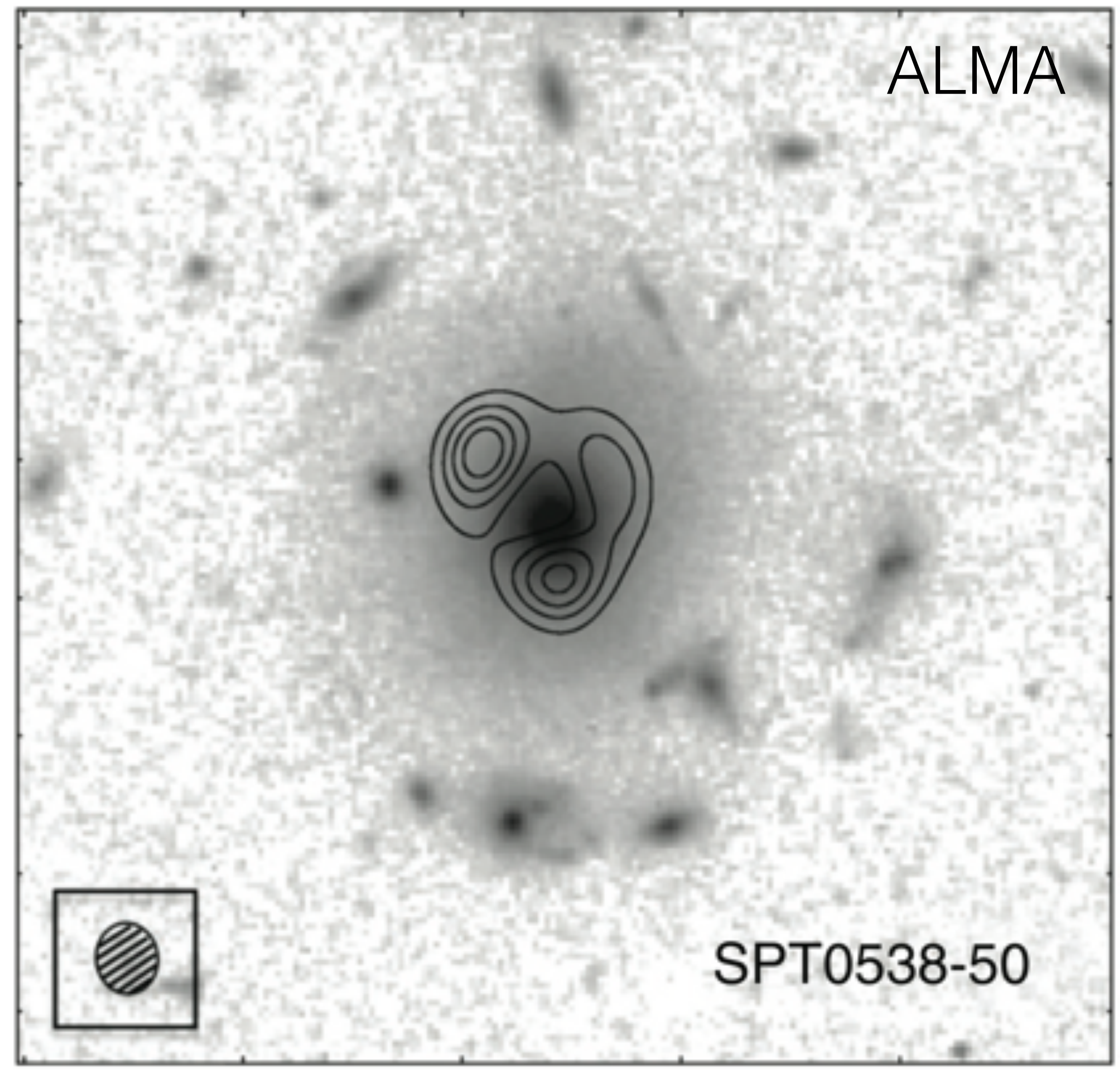


Gravitational lensing

- First gravitational lens found in **radio** from large area survey at 900 MHz (Walsh et al. 1979, *Nature,* Porcas et al. 1979, 1981, *Nature*).
- VLA systematic VLA surveys have found **~40** gravitational lenses.

- Large area imaging and spec. surveys from SDSS have found **~10²** star-forming galaxies and quasars.

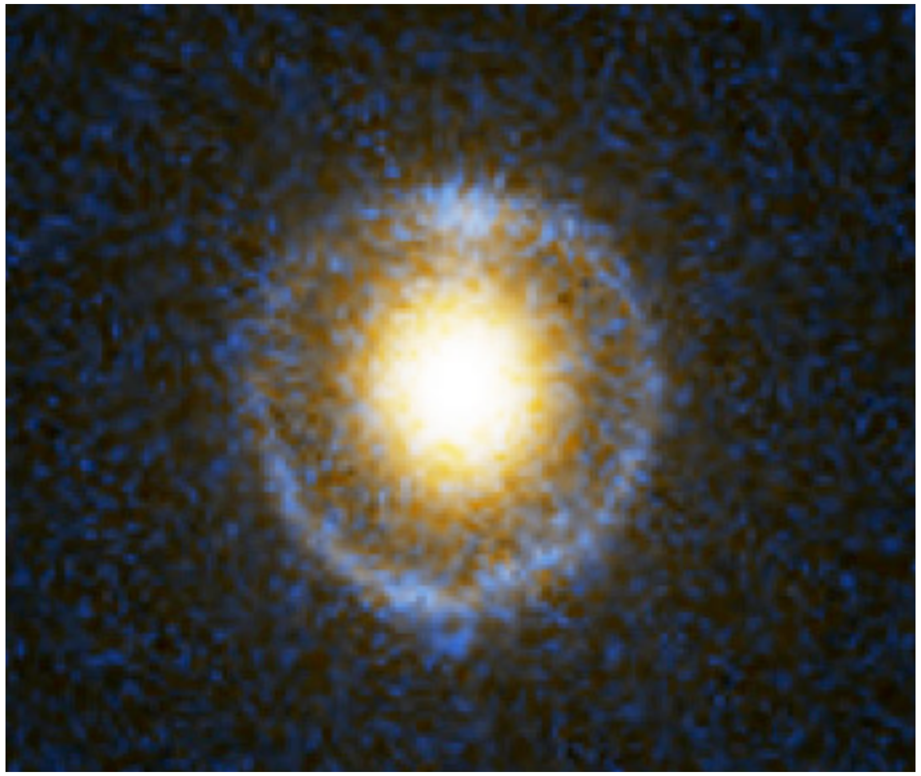
- Steep source counts will lead to **~10²s** lenses in the mm and sub-mm, and detected by ALMA.



Key application: **Mass**

- The most precise (few percent) measurement mass,
  1. Black holes
  2. Galaxies (baryonic and dark)
  3. Clusters (dark)

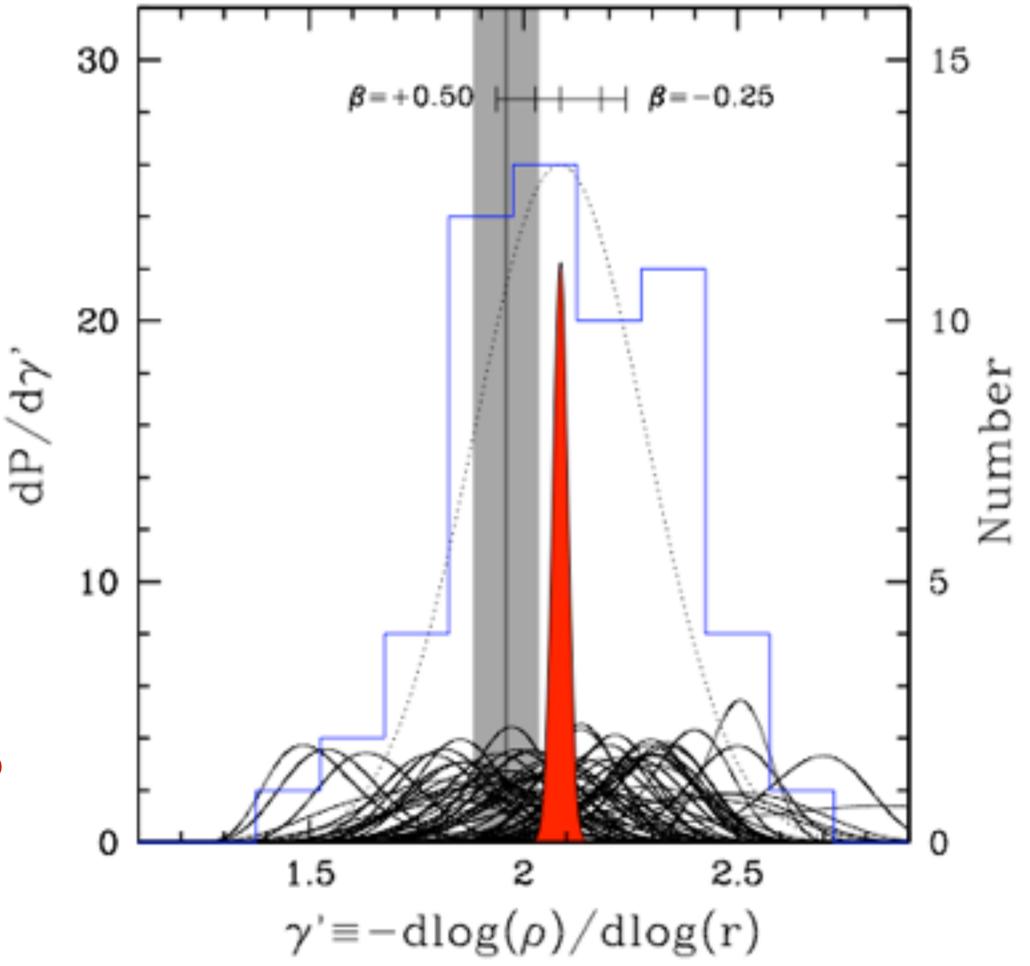
$$\theta_E = \left[\frac{4GM(\theta_E)}{c^2} \frac{D_{ls}}{D_l D_s} \right]^{1/2}$$



- Combine with kinematics to determine mass density profiles.

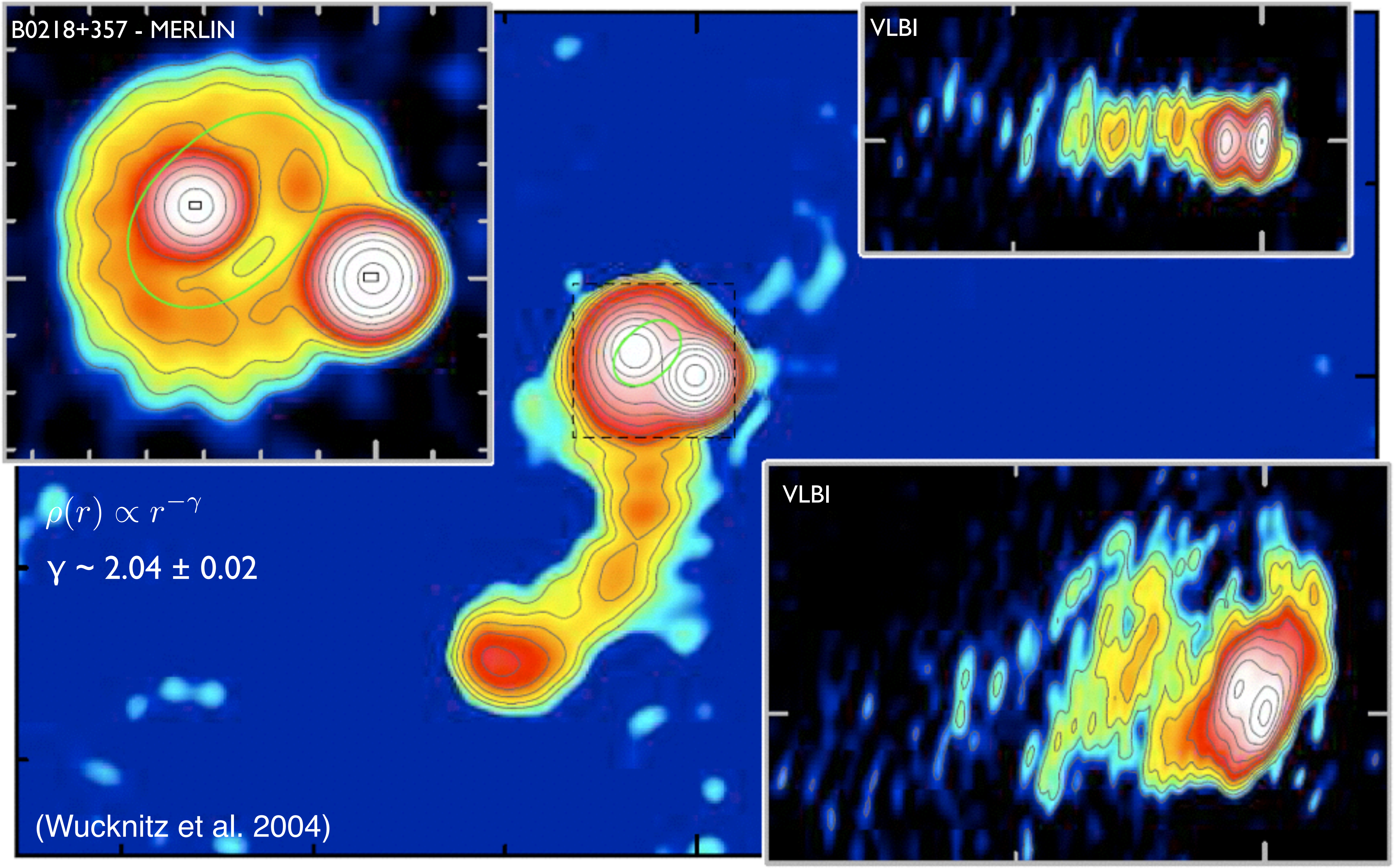
$$\rho(r) \propto r^{\gamma'}$$

- Sample of **58** elliptical lenses at $z \sim 0.2$ selected from SDSS finds inner mass profiles consistent with isothermal (Koopmans et al. 2009).

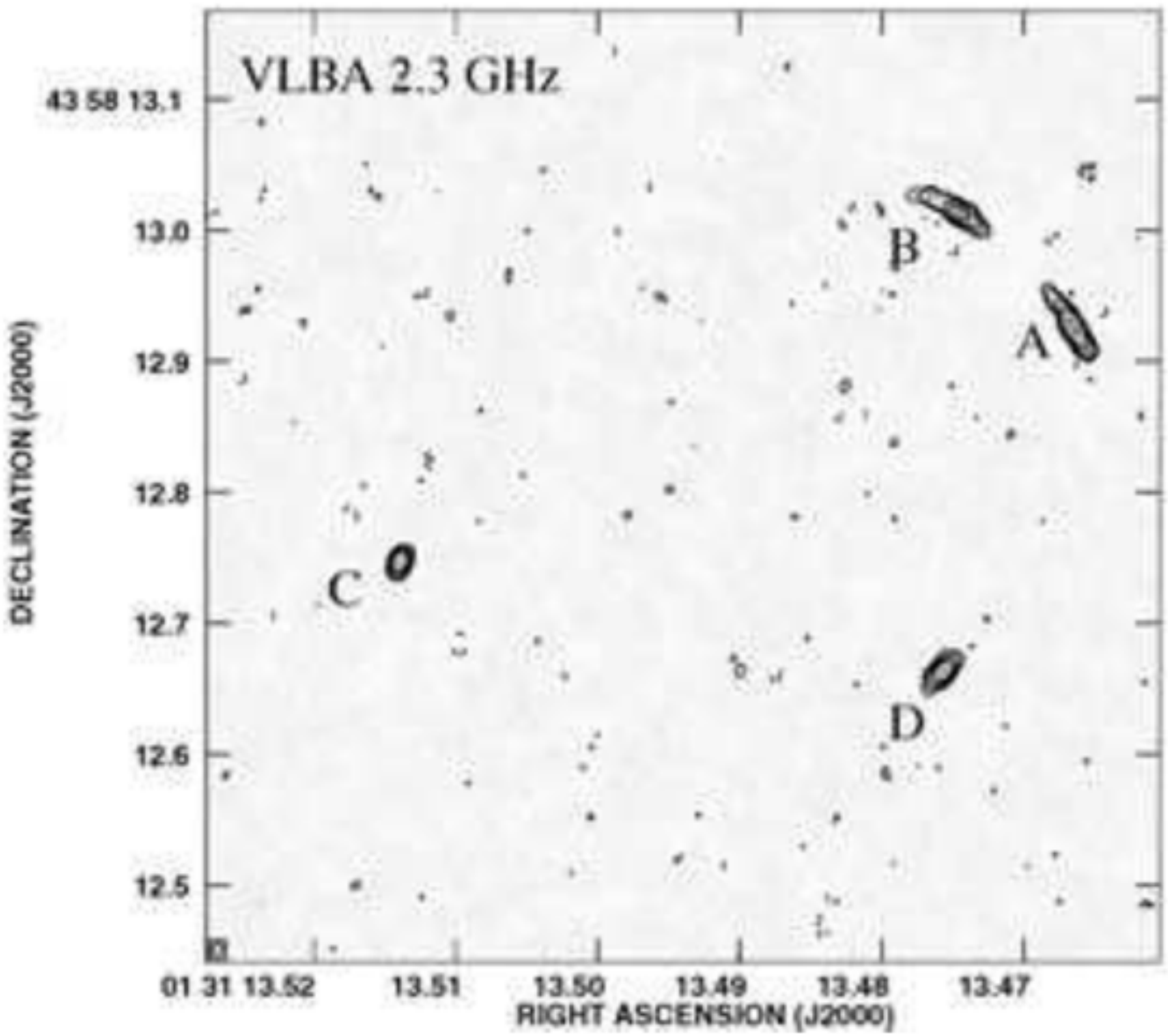


As a function of galaxy type, environment, mass?

Key application: **Mass**

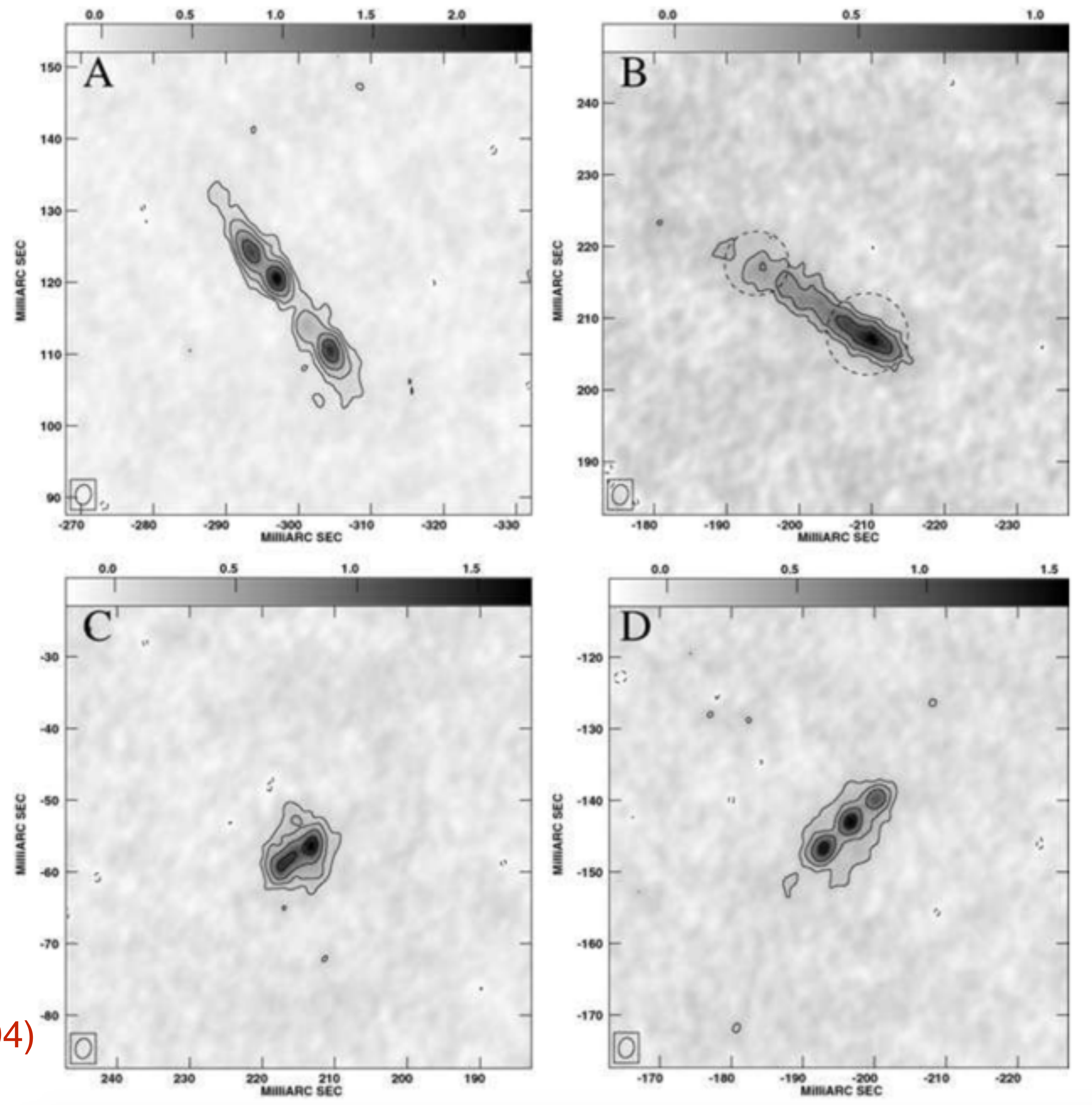


Key application: **Mass**



(Biggs et al. 2004)

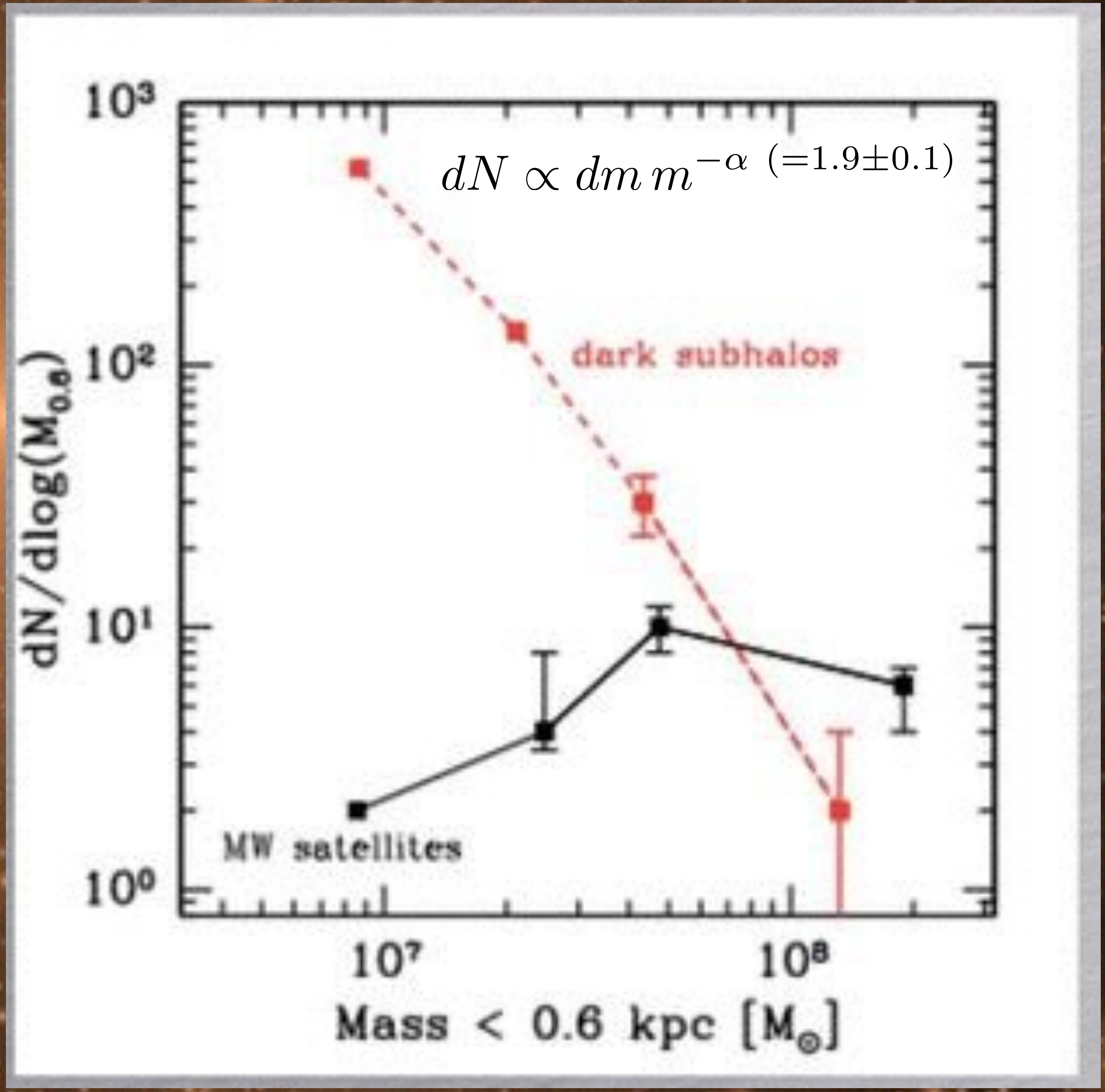
Key application: **Mass**



(Biggs et al. 2004)

Dark matter only simulation of a Milky Way like halo (Diemand et al. 2007) z=0.0

Dark matter only simulation of a Milky Way like halo (Diemand et al. 2007)



80 kpc

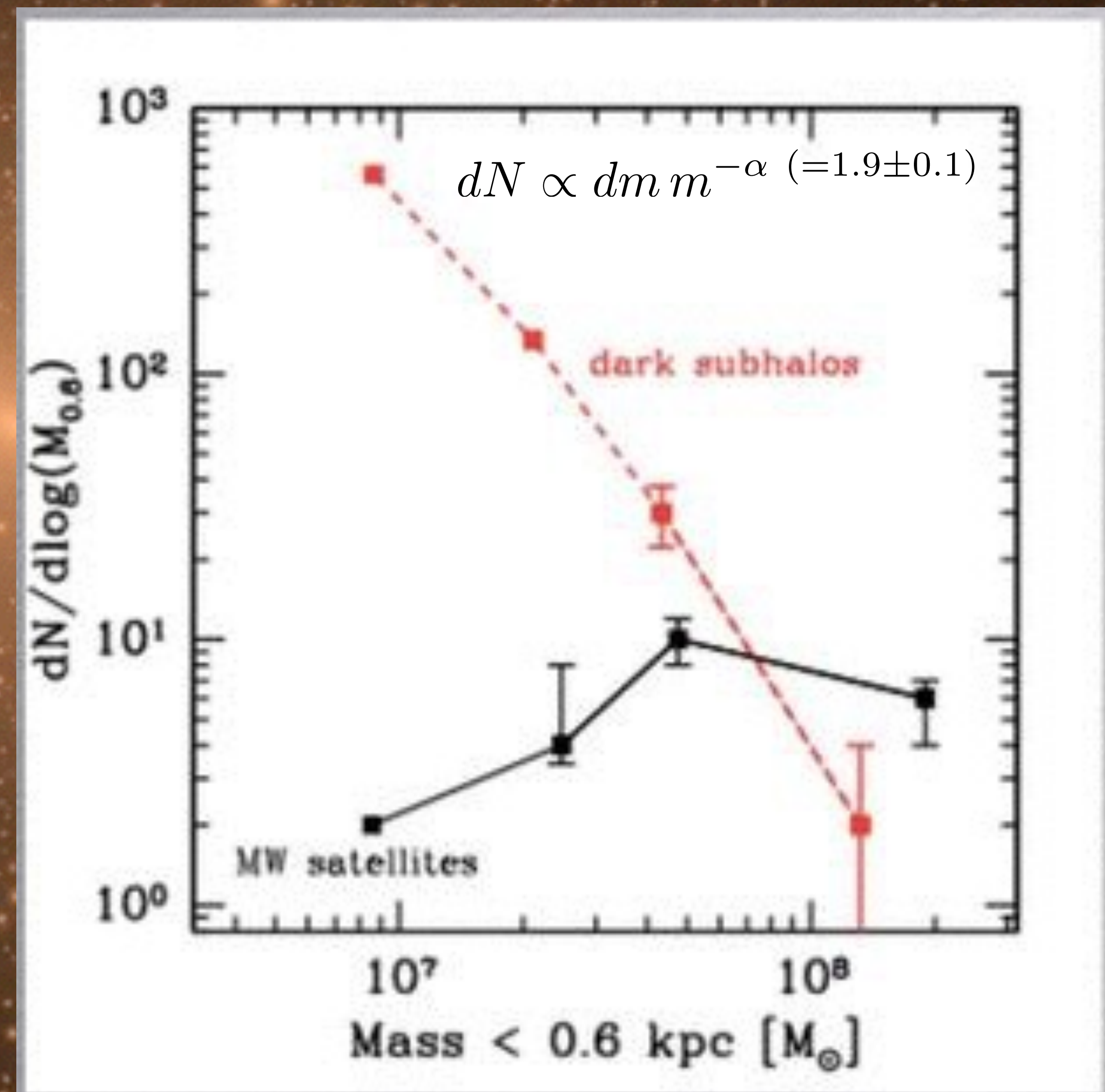
z=0.0

Dark matter only simulation of a Milky Way like halo (Diemand et al. 2007)

i) The low mass dwarfs are dark (did not form stars at early epoch)?

ii) The Milky Way is a special case?

iii) Something wrong with the galaxy formation and/or dark matter model?

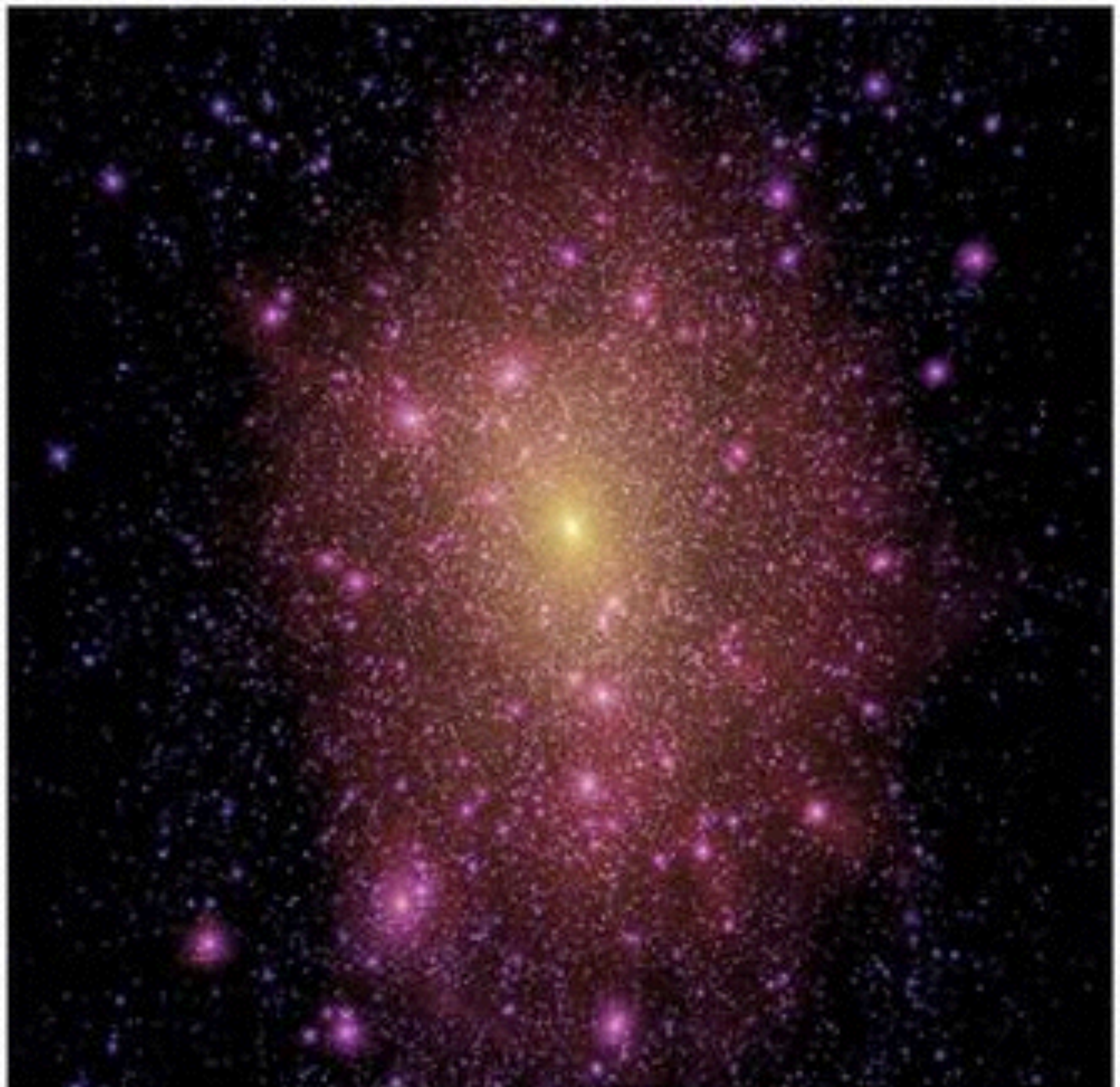


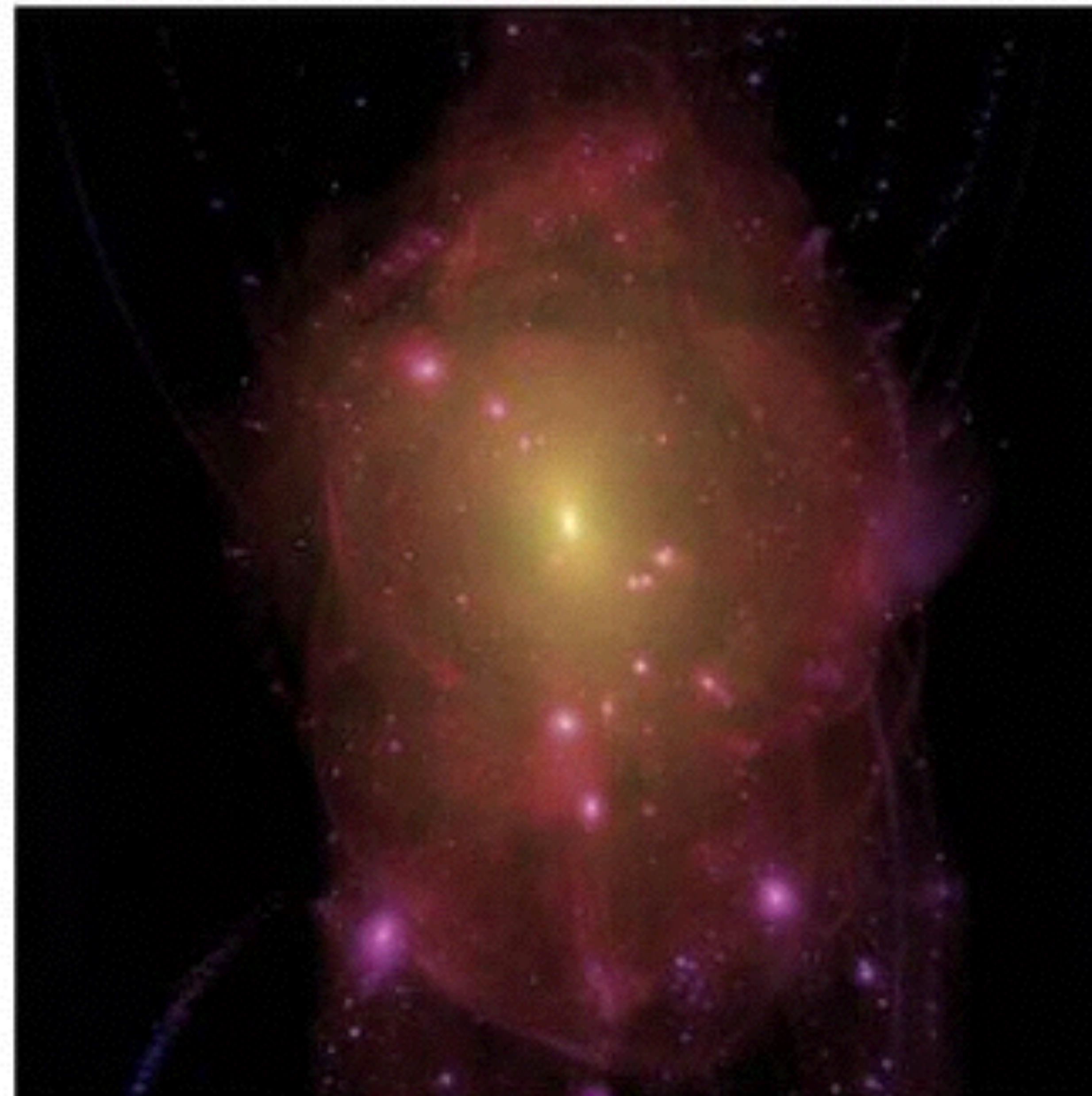
80 kpc

Dark matter halo of mass ~ 10^{12} M_{sun} (Lovell et al. 2012)

Cold dark matter

Warm dark matter





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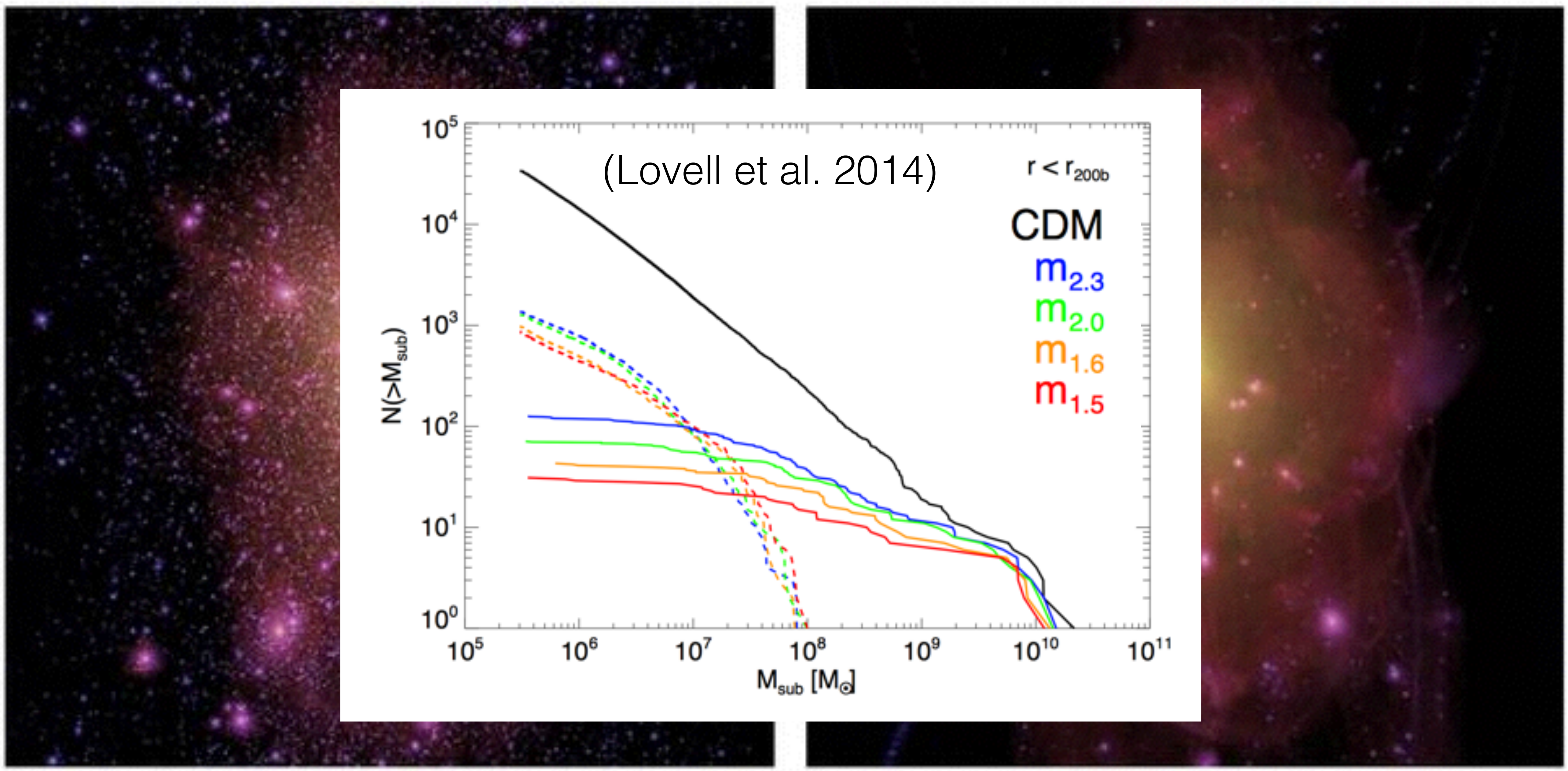
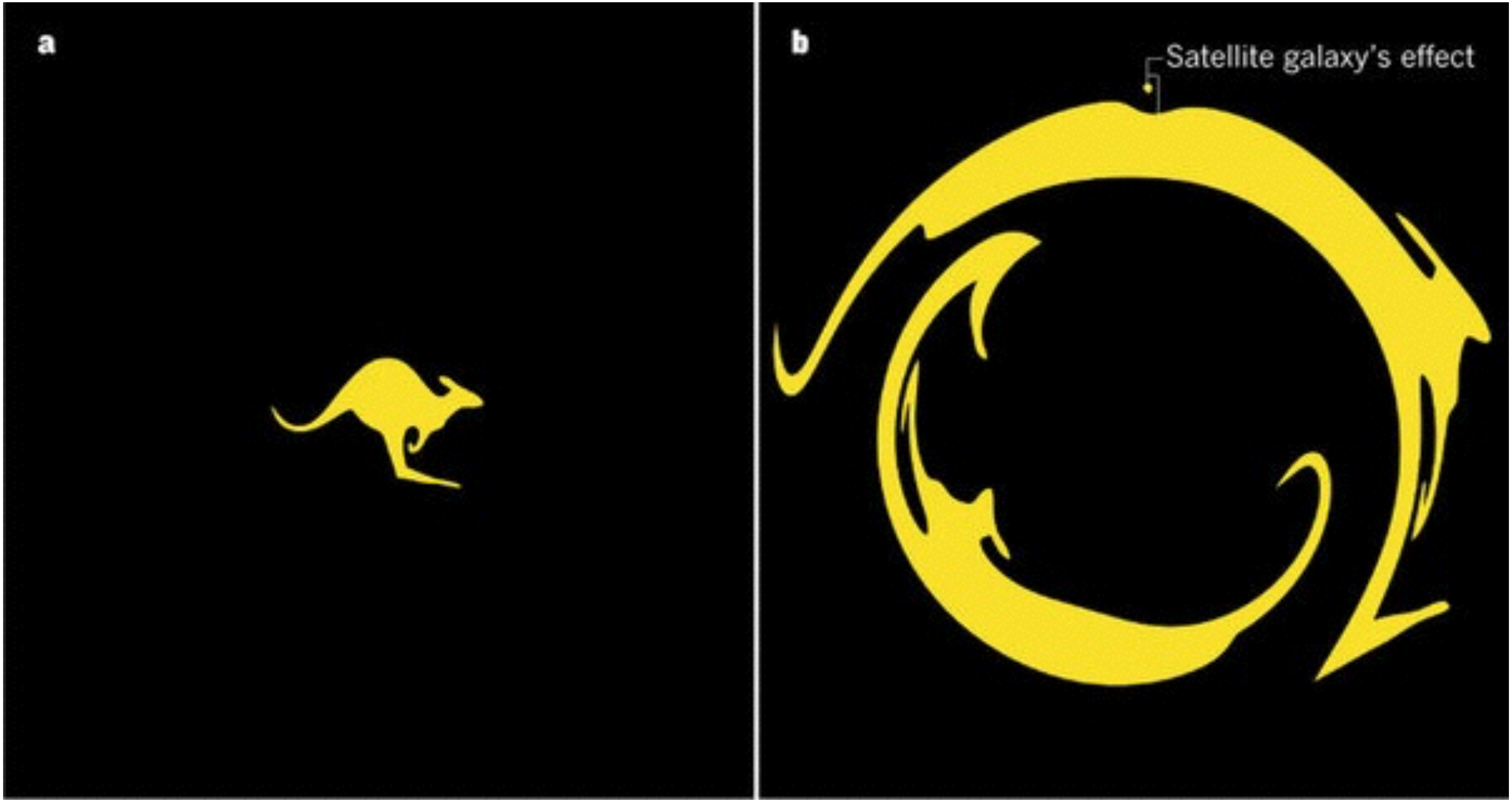
Warm dark matter

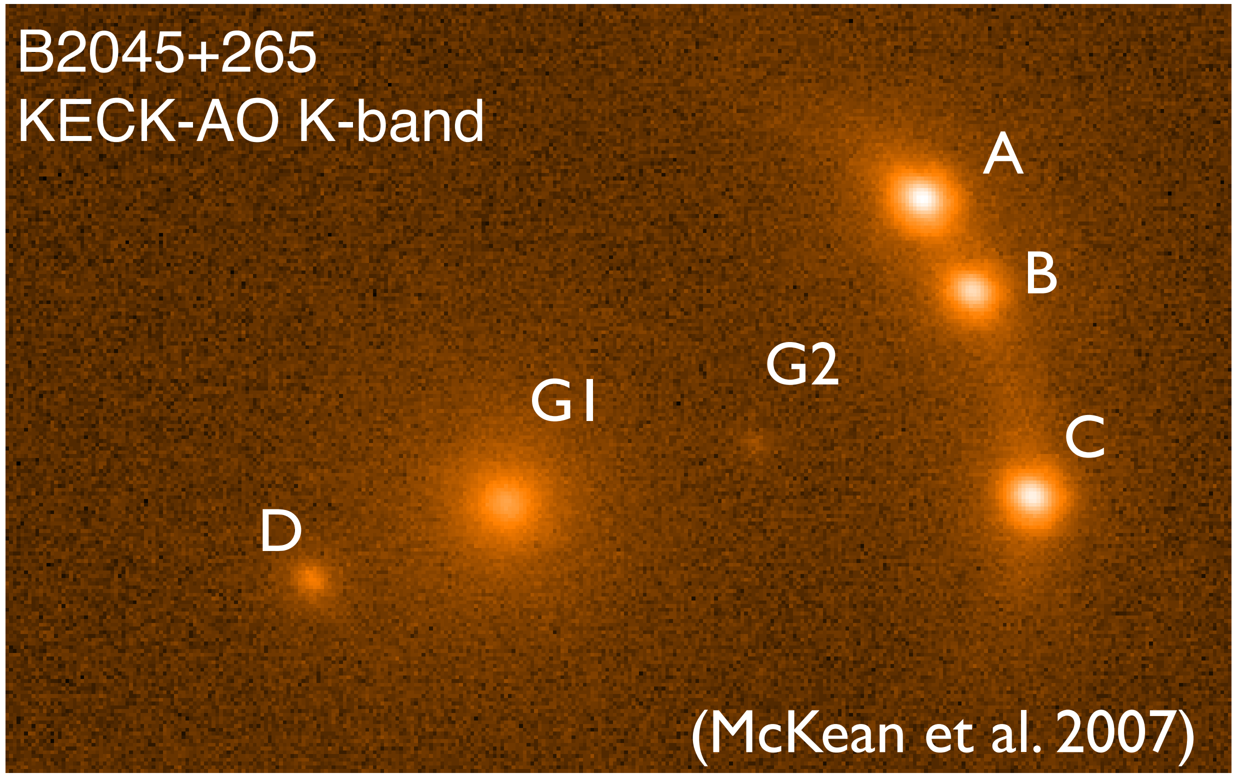


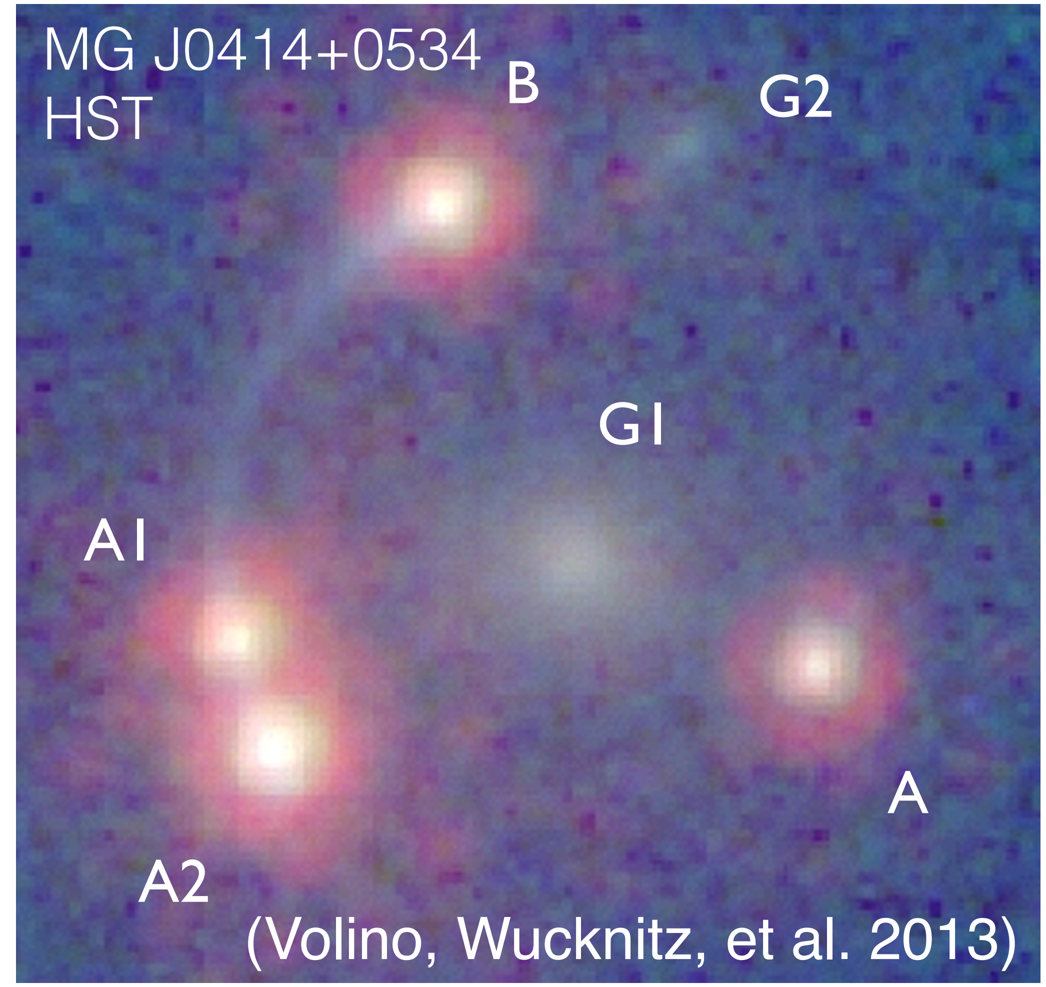
The cut-off in the mass function is directly related to the model for dark matter.

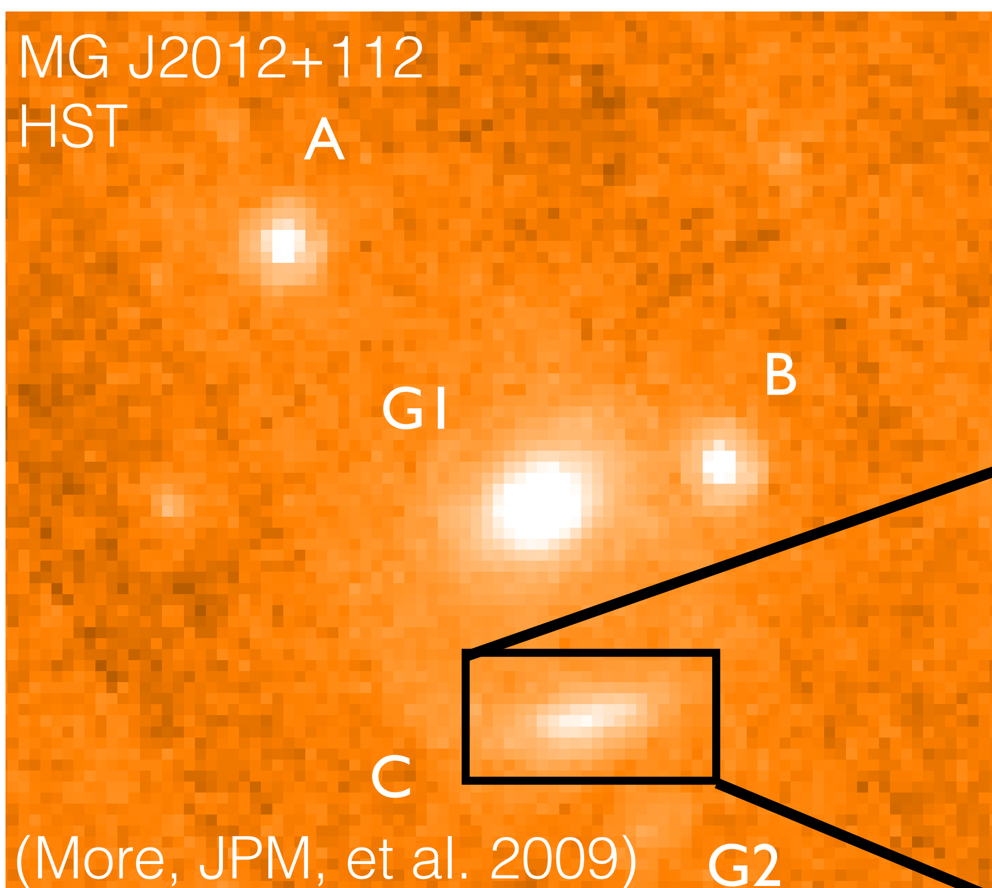
Gravitational lensing by **dark satellites**



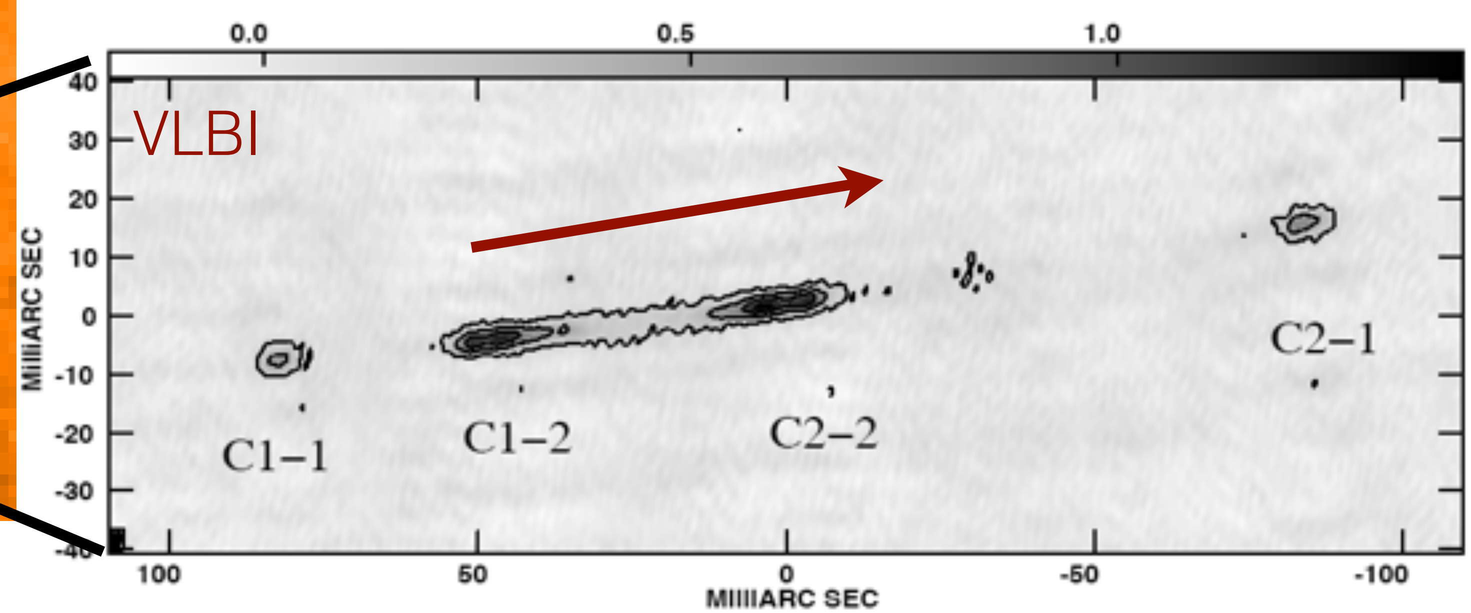
Top end of the **mass-function**



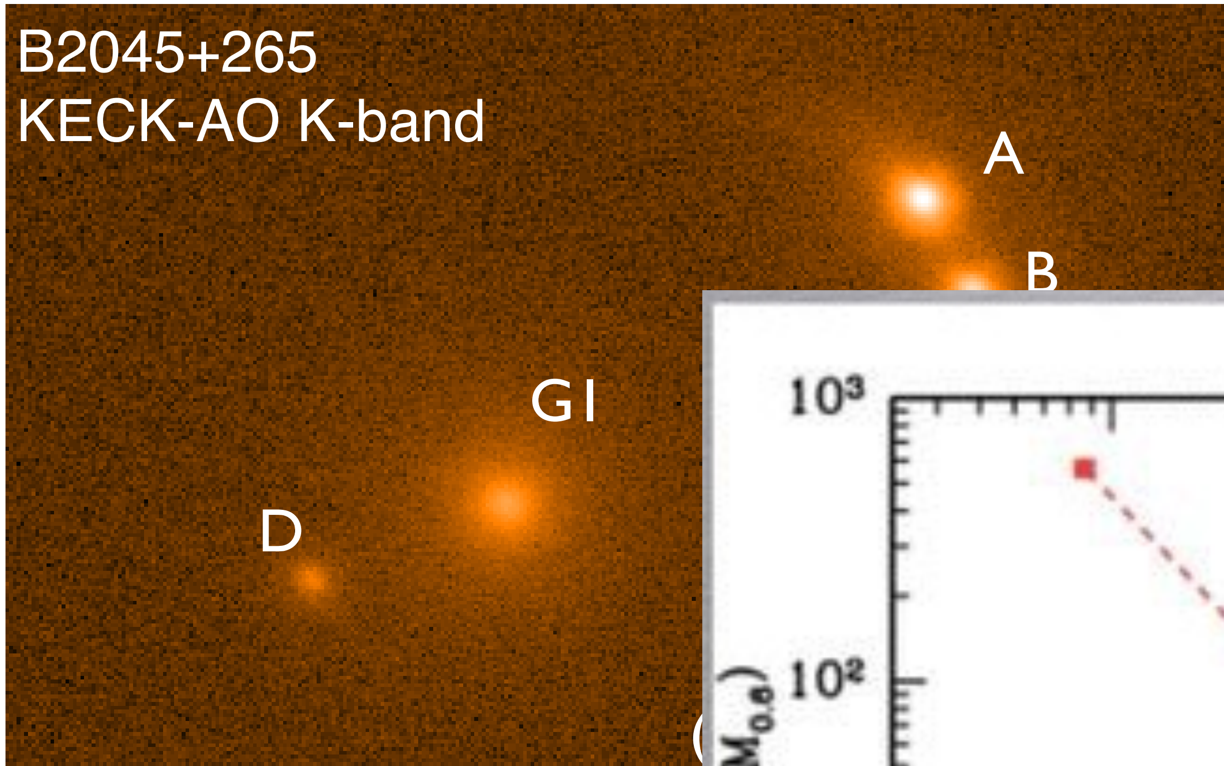


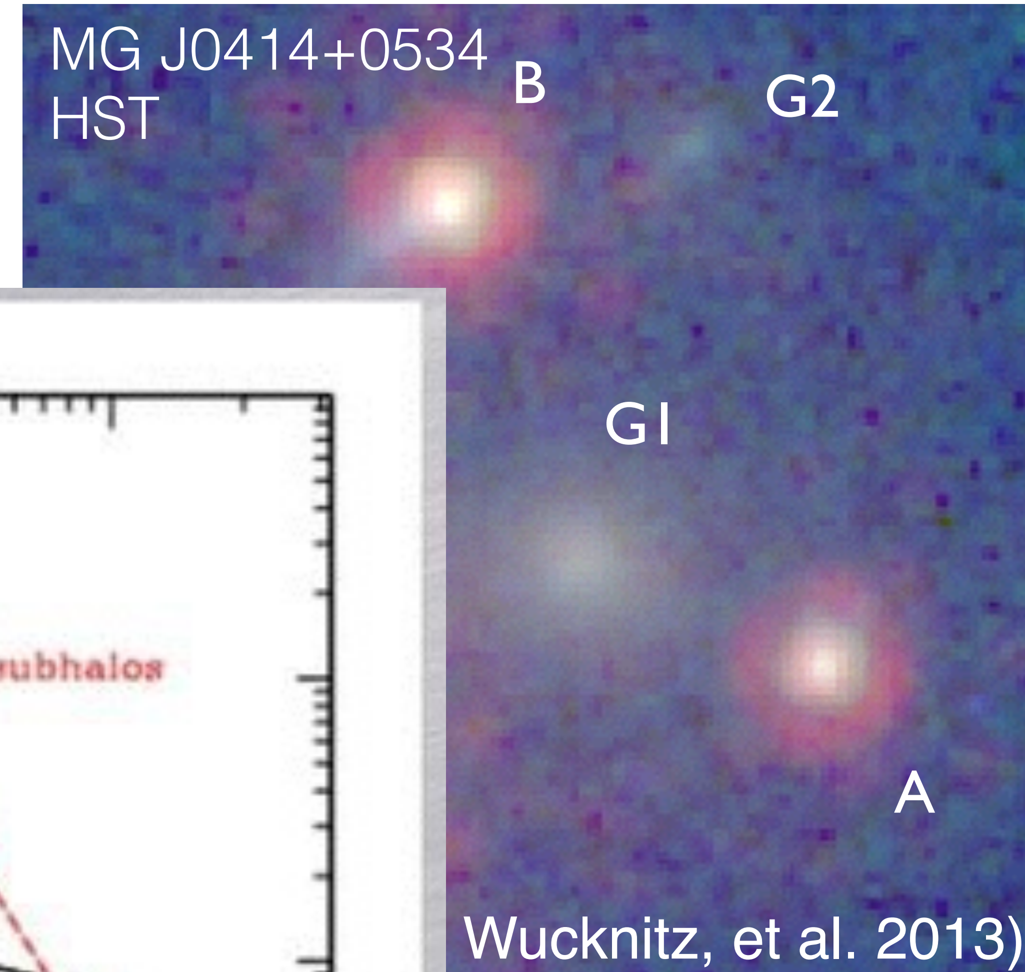


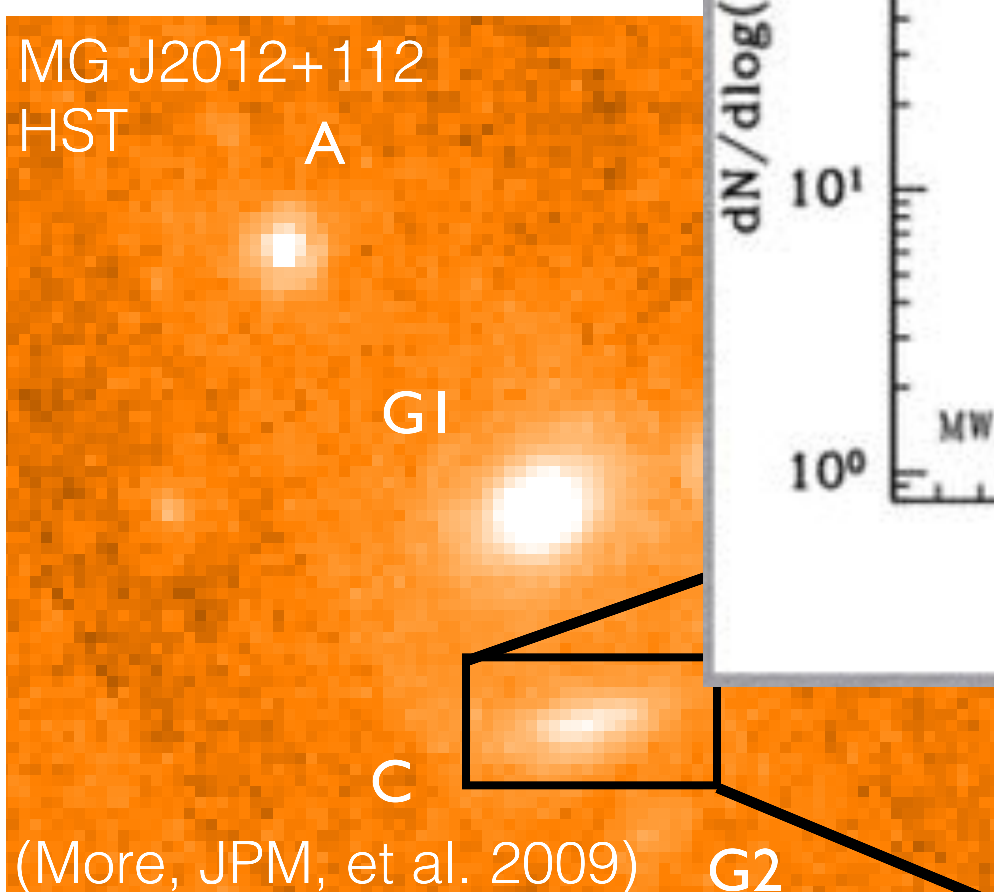
Dwarf companion galaxies (luminous substructures) make up ~1% of total halo mass.

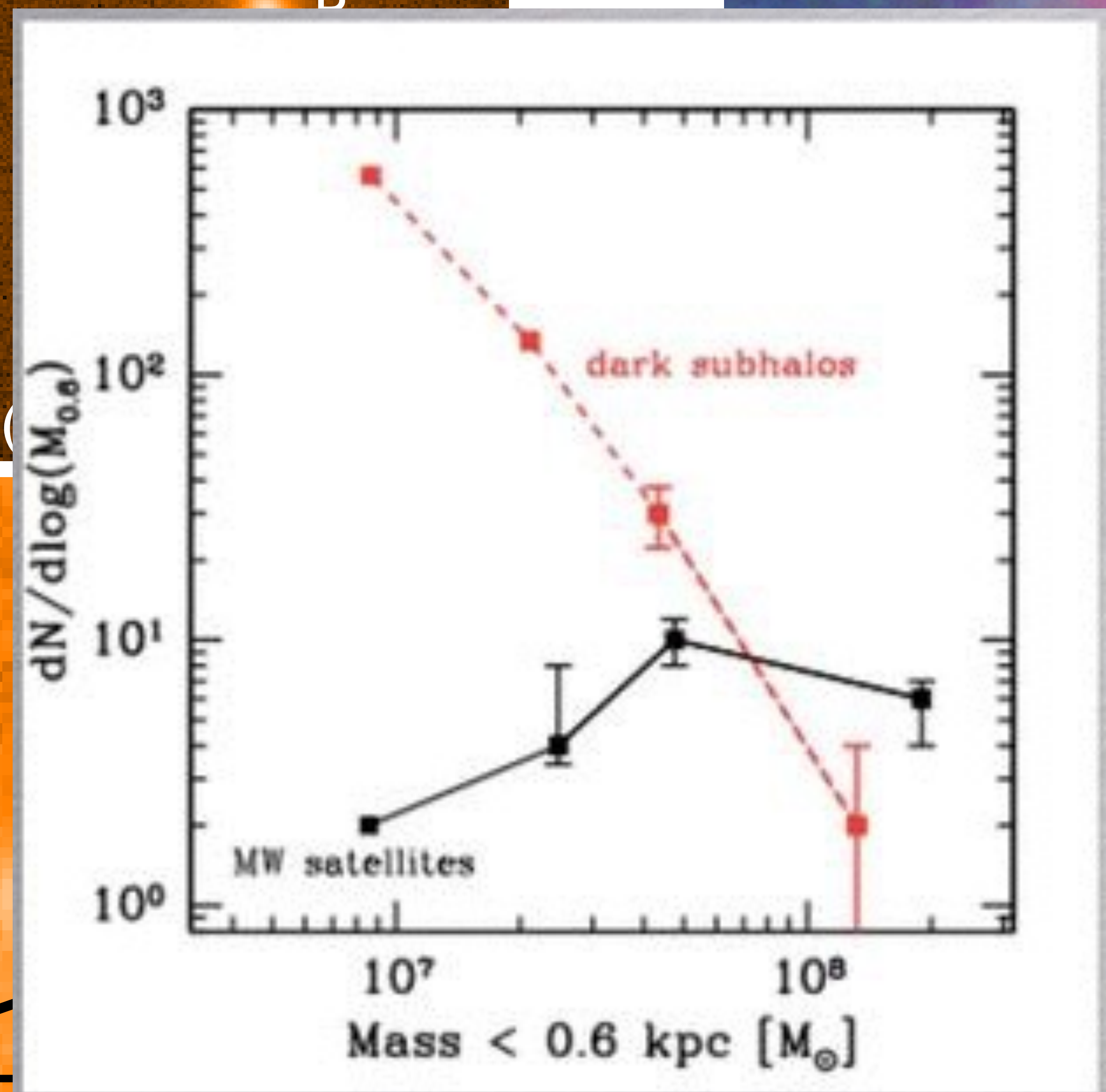


Top end of the **mass-function**

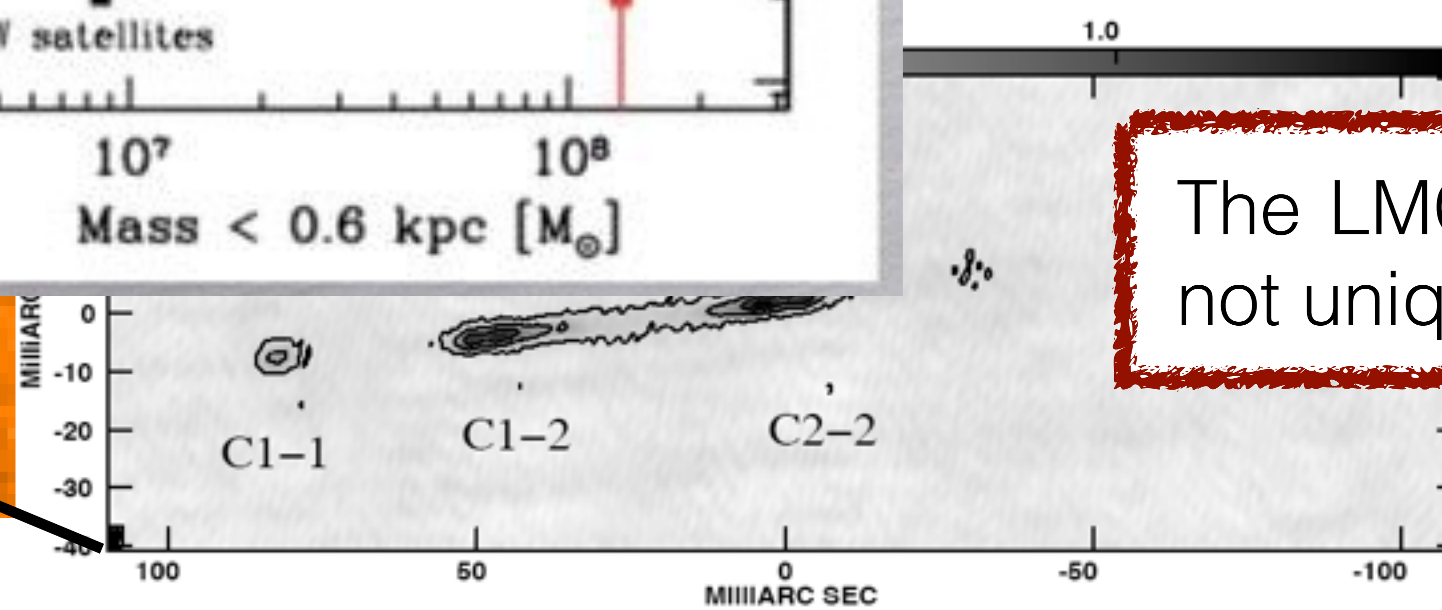






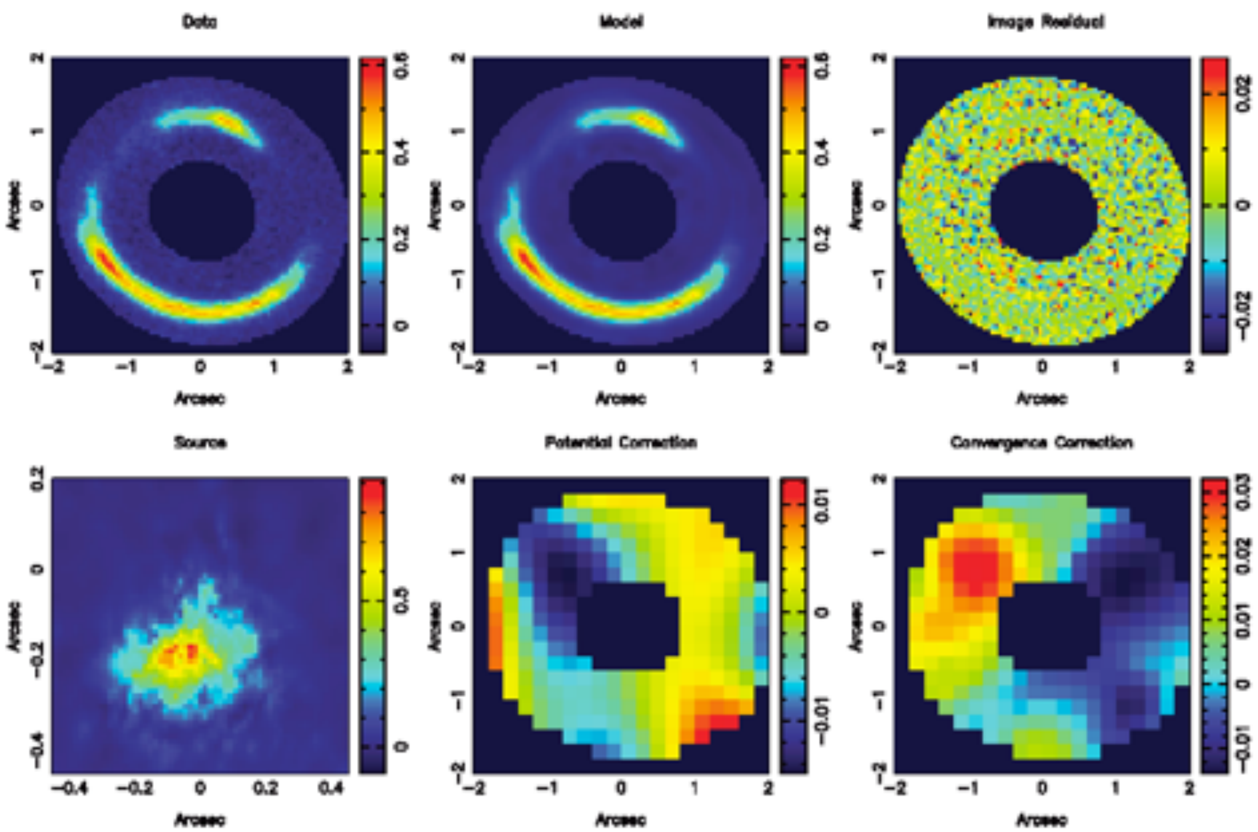


uminous substructures)
ss.



The LMC is not unique!

Middle of the **mass-function**



SDSS J0946+1006 ($z = 0.222$; HST F814W; psf 75 mas)

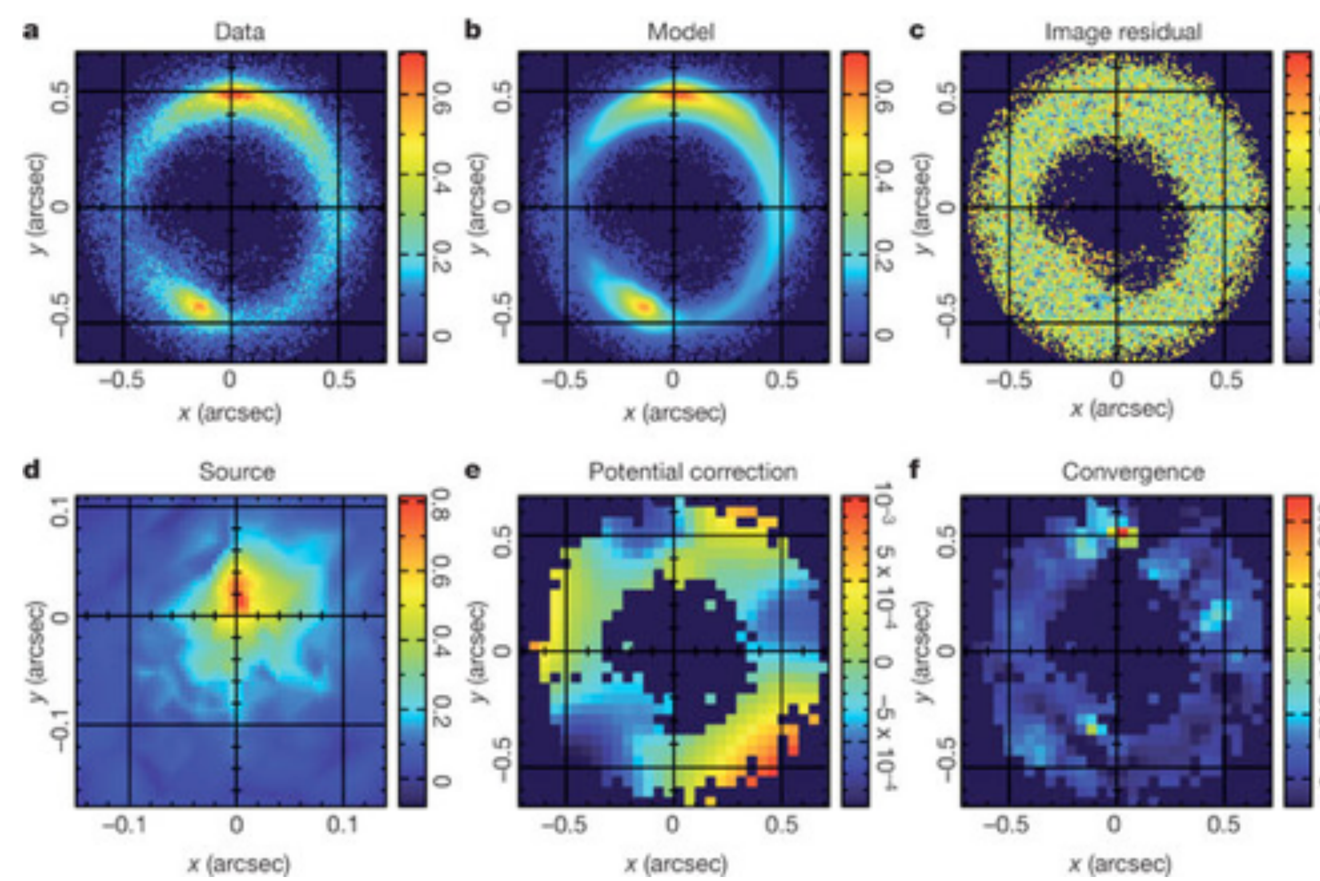
$M_{sub} = (3.5 \pm 0.2 \times 10^9\ M_{sol})$

(Vegetti et al. 2010)

JVAS B1938+666 ($z = 0.881$; Keck adpative optics; psf 65 mas).

$M_{sub} = (1.9 \pm 0.1 \times 10^8\ M_{sol})$

(Vegetti, Lagattuta, McKean et al. 2012, *Nature*)

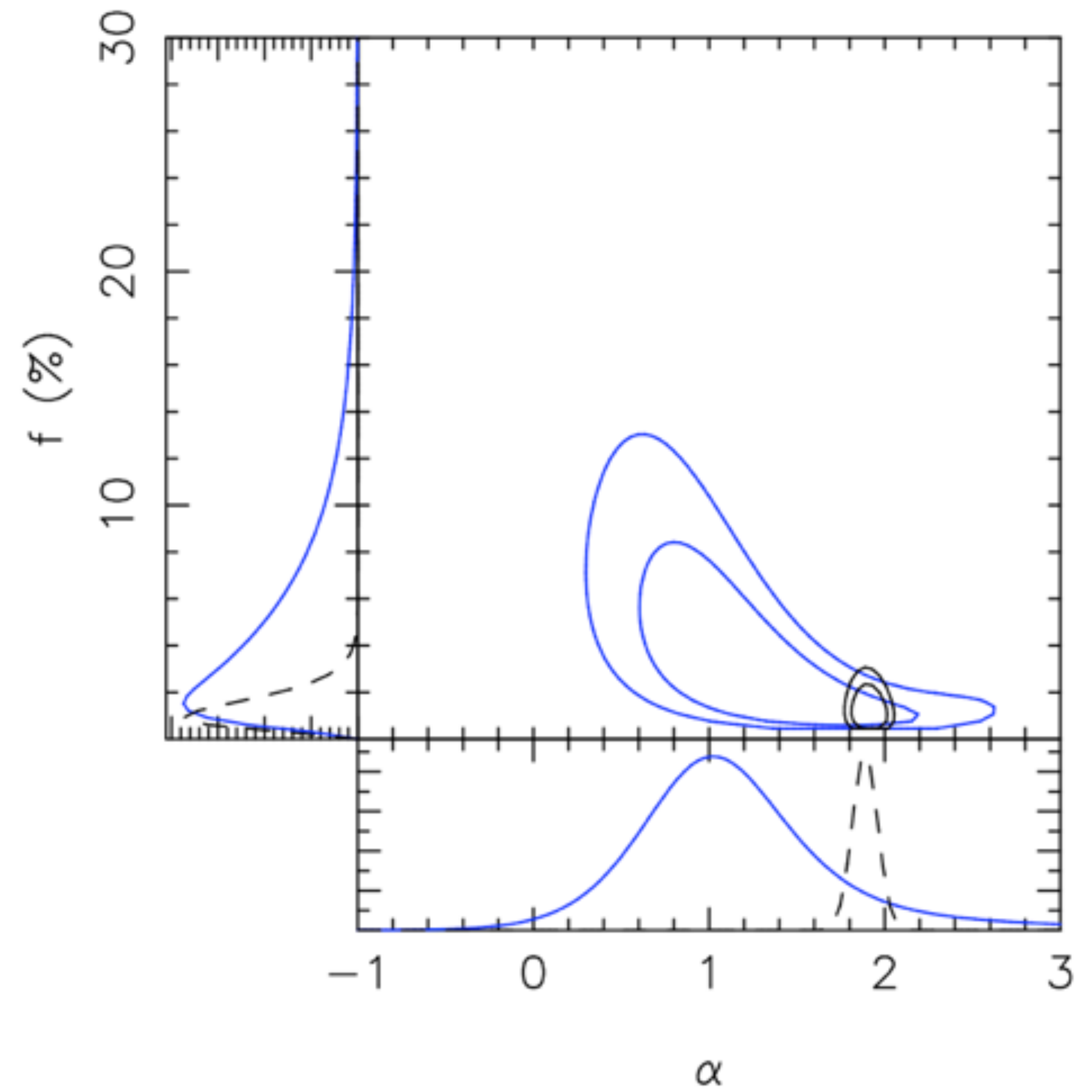


Using the two dark substructures,

$f_{CDM} = 3.3^{+3.6}_{-1.8}$ % and $\alpha = 1.1^{+0.6}_{-0.4}$

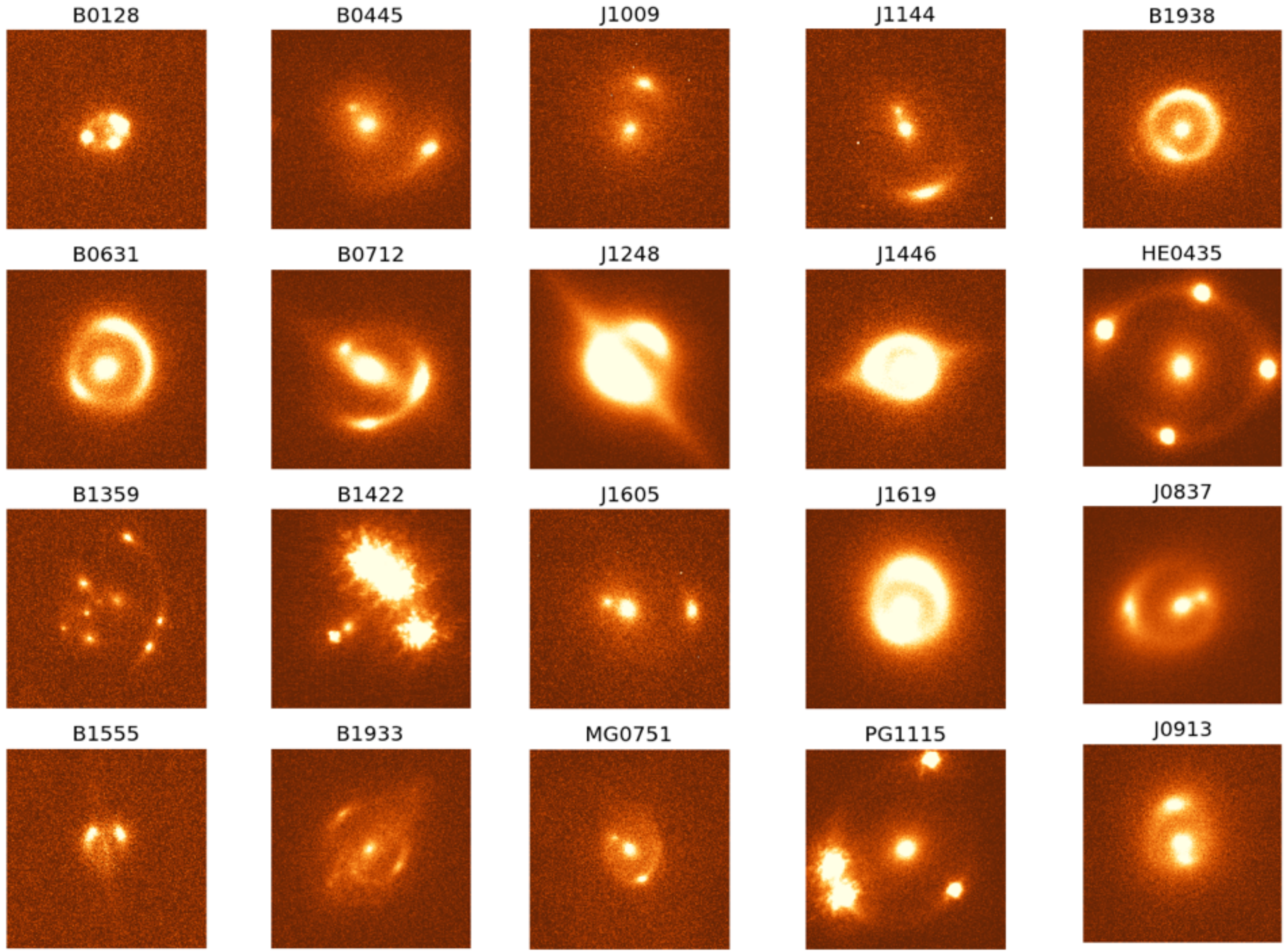
Simulations predict

$f_{CDM} < 0.4$ % and $\alpha = 1.9 \pm 0.1$



Key Result: The mass fraction and the slope of the mass function from 2 lenses are just consistent with what we expect from simulations (95% confidence level).

Can we go orders of magnitude lower in mass to test WDM models? → need mas resolution for 10^6 M_{sol} haloes


B0128
B0445
J1009
J1144
B1938
B0631
B0712
J1248
J1446
HE0435
B1359
B1422
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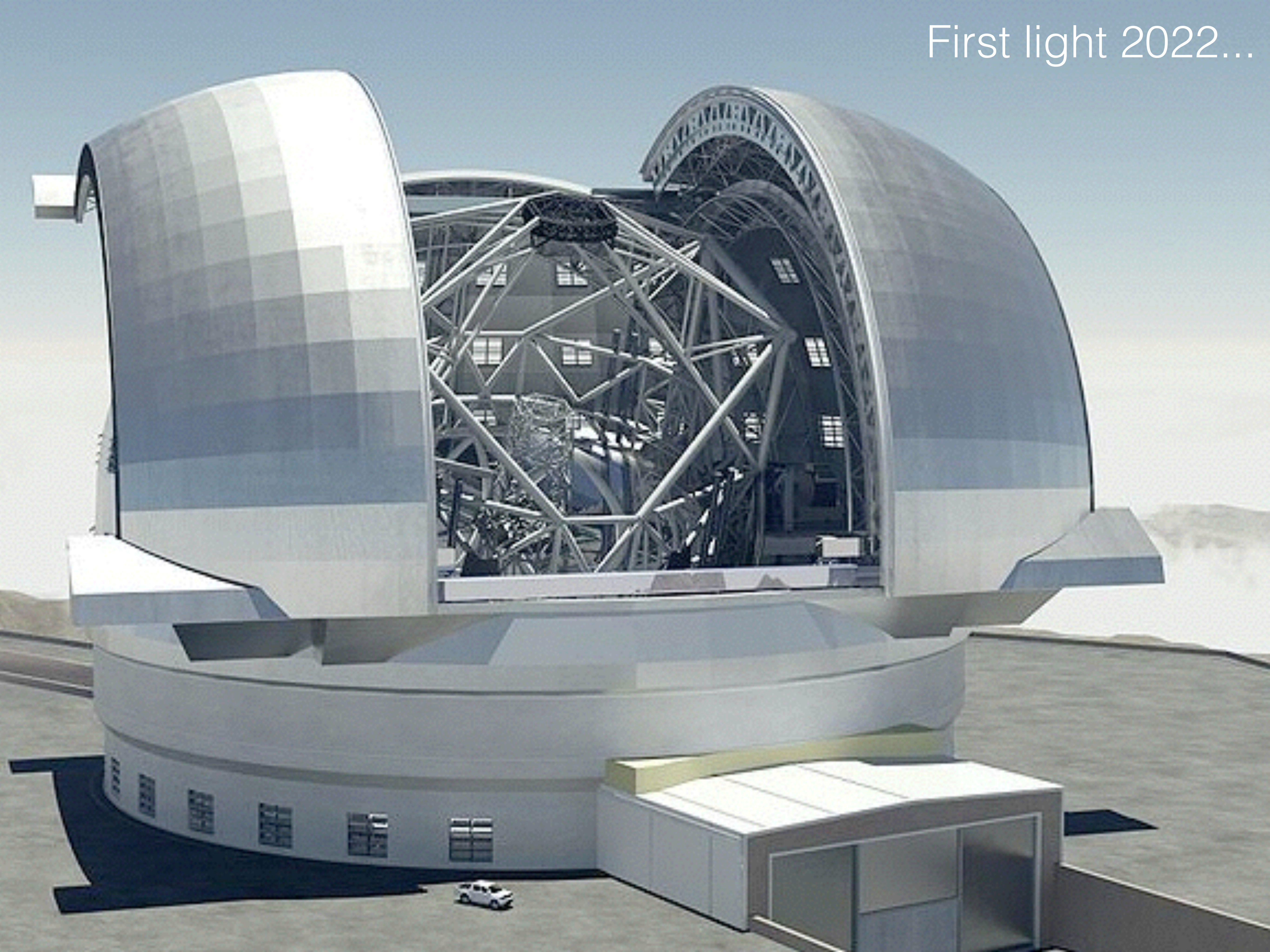
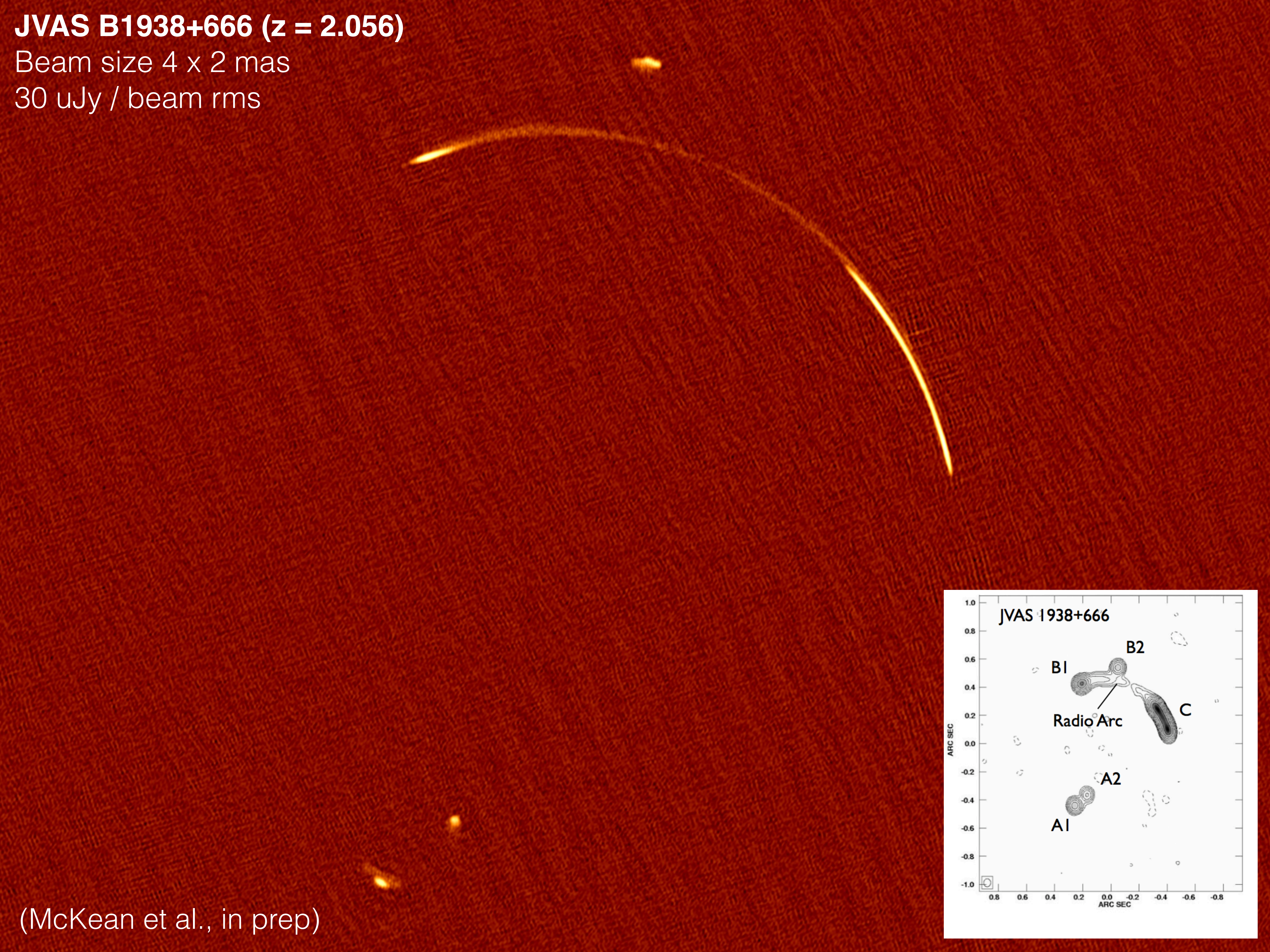
MG0751
PG1115
J0913


First light 2022...

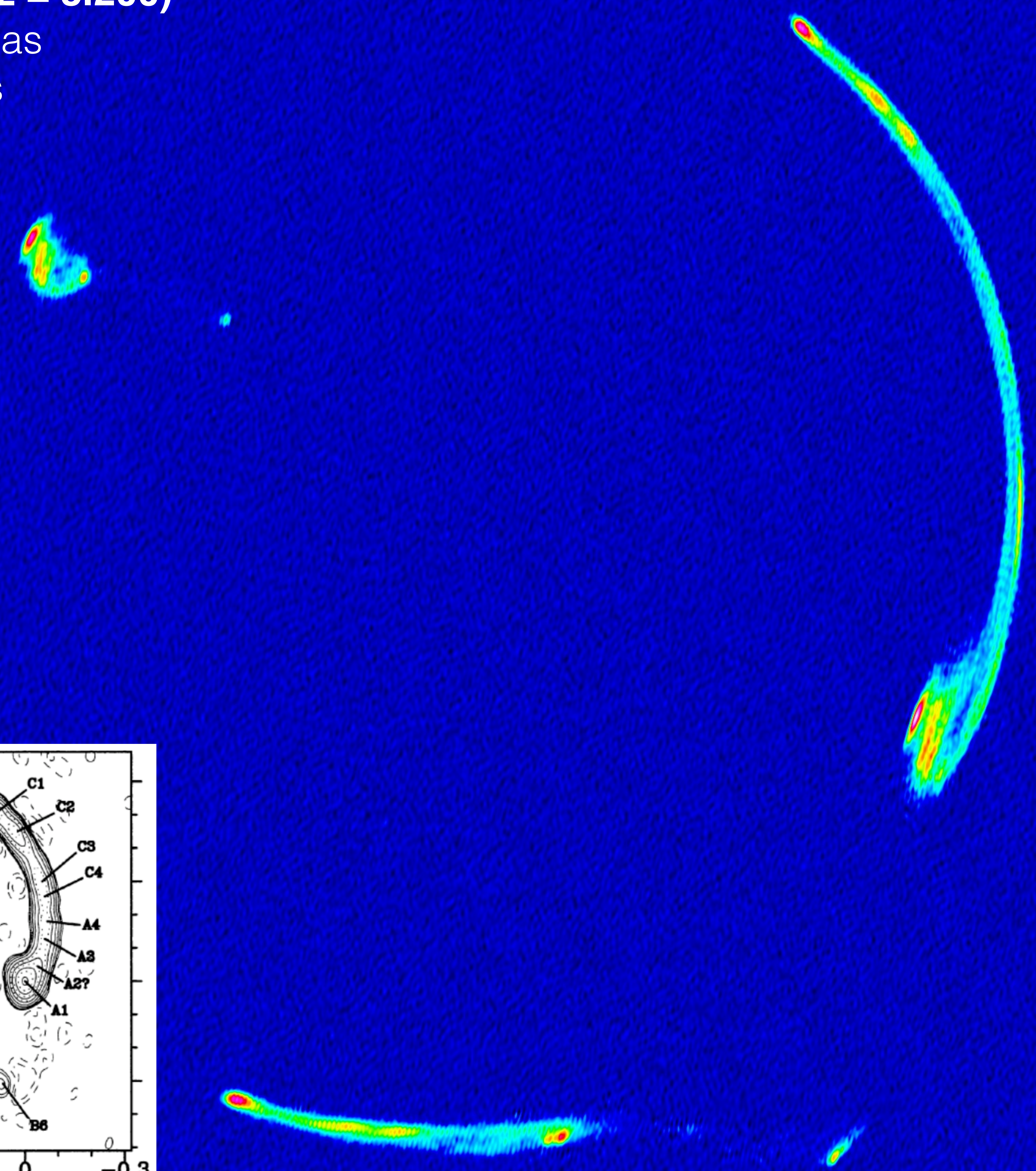
The Global VLBI - Array
NOW!!
Brewster
North Liberty
Hancock
Green Bank
Jodrell Lovell
Jodrell Mk2
Cambridge
Onsala 25m and 20m
Metsähovi
Los Alamos
Owens Valley
Pie Town
Mauna Kea
Kitt Peak
Urumqi
Shanghai
Westerbork
Medicina
Noto
EVN
VLBA
European VLBI Network (EVN)
Very Long Baseline Array (VLBA)
High Sensitivity Array (HSA)
Ft. Davis
St. Croix
V L A
Arecibo
Effelsberg
Yebes
Wettzell
Torun
Hartebeesthoek

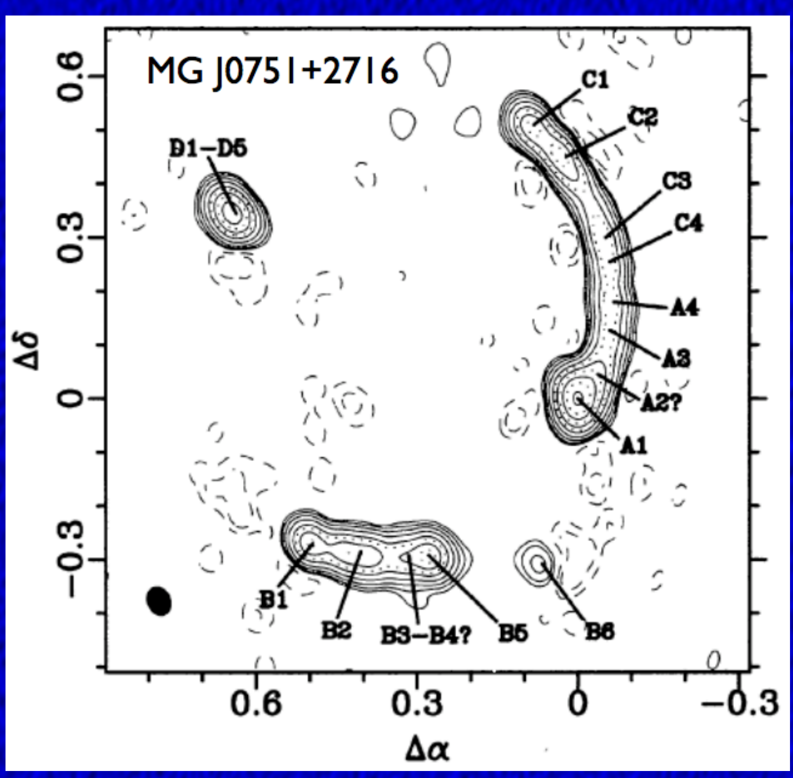

JVAS B1938+666 (z = 2.056)
Beam size 4 x 2 mas
30 uJy / beam rms
JVAS 1938+666
B1
B2
Radio Arc
C
A2
A1
ARC SEC
ARC SEC
(McKean et al., in prep)

MG J0751+2761 (z = 3.200)

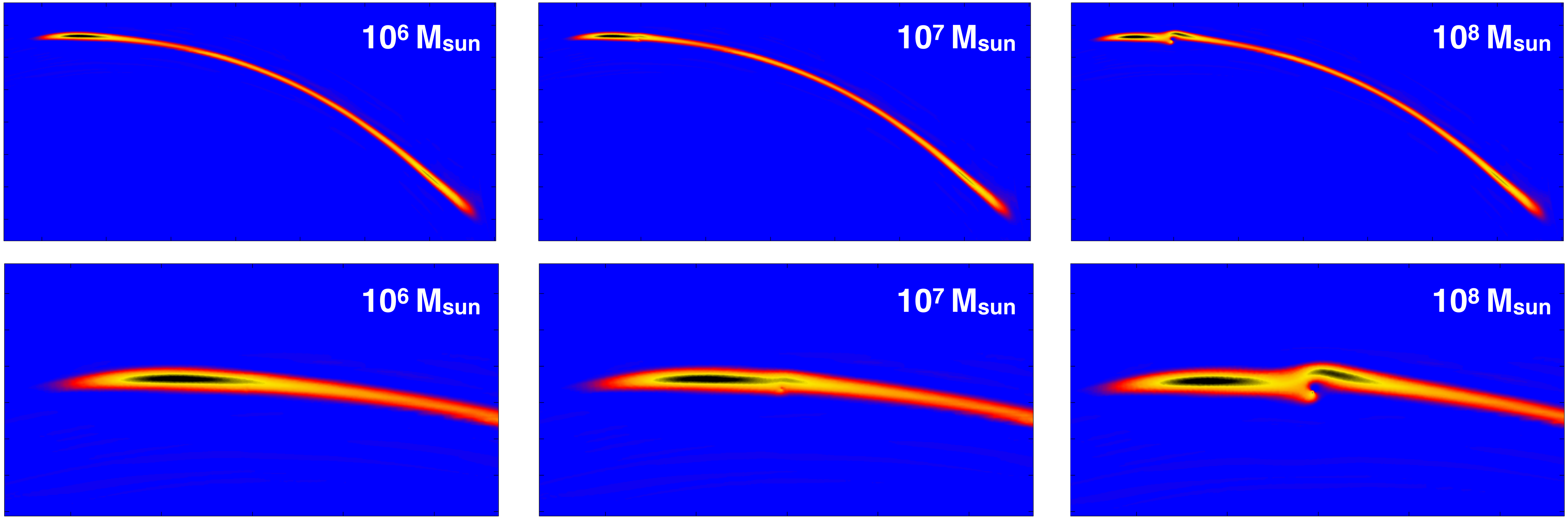
Beam size 7 x 2 mas

10 uJy / beam rms

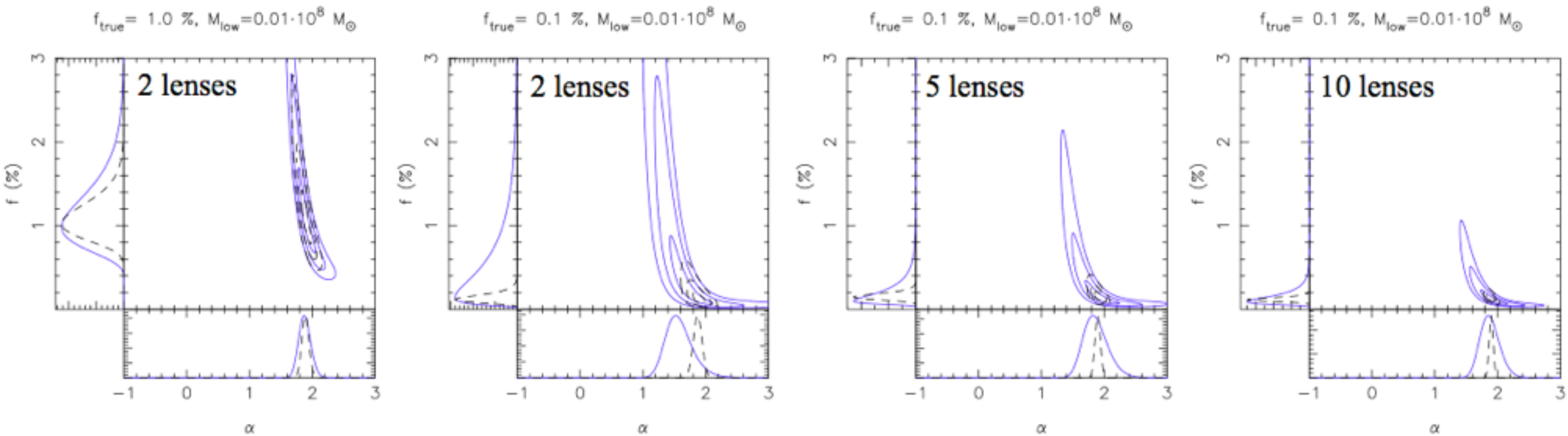




(Spingola et al., in prep)



f_{sub} = 1% f_{sub} = 0.1% f_{sub} = 0.1% f_{sub} = 0.1%



$\alpha = 1.87^{+0.11}_{-0.09}$
$f_{sub} = 1.1^{+0.5}_{-0.3}\%$

$\alpha = 1.57^{+0.23}_{-0.19}$
$f_{sub} = 0.45^{+0.67}_{-0.29}\%$

$\alpha = 1.85^{+0.23}_{-0.17}$
$f_{sub} = 0.18^{+0.18}_{-0.08}\%$

$\alpha = 1.87^{+0.16}_{-0.14}$
$f_{sub} = 0.1^{+0.1}_{-0.05}\%$

Modelling the **visibilities**

Important not to use the image data (unlike for optical/IR observations)

- The visibilities (and errors) are the data
- The noise in the image plane is correlated
- Image plane data dependent on
  - Gridding
  - Weighting of the visibilities (natural / uniform)
  - Tapering
  - Deconvolution (clean, MS-Clean, MEM, CS,…)
  - Human factor

Instead, fit directly to the visibilities (Fourier plane lens modelling)

- The visibilities (and errors) are the data (need a supercomputer).
- Better handle on the noise properties.
- We use a pixellated source model built within a fully Bayesian statistical framework — determines best model, given the data.
- Based on image plane technique devised by Vegetti & Koopmans (2009)
- See Rybak, Vegetti & McKean (2015, submitted) for details.

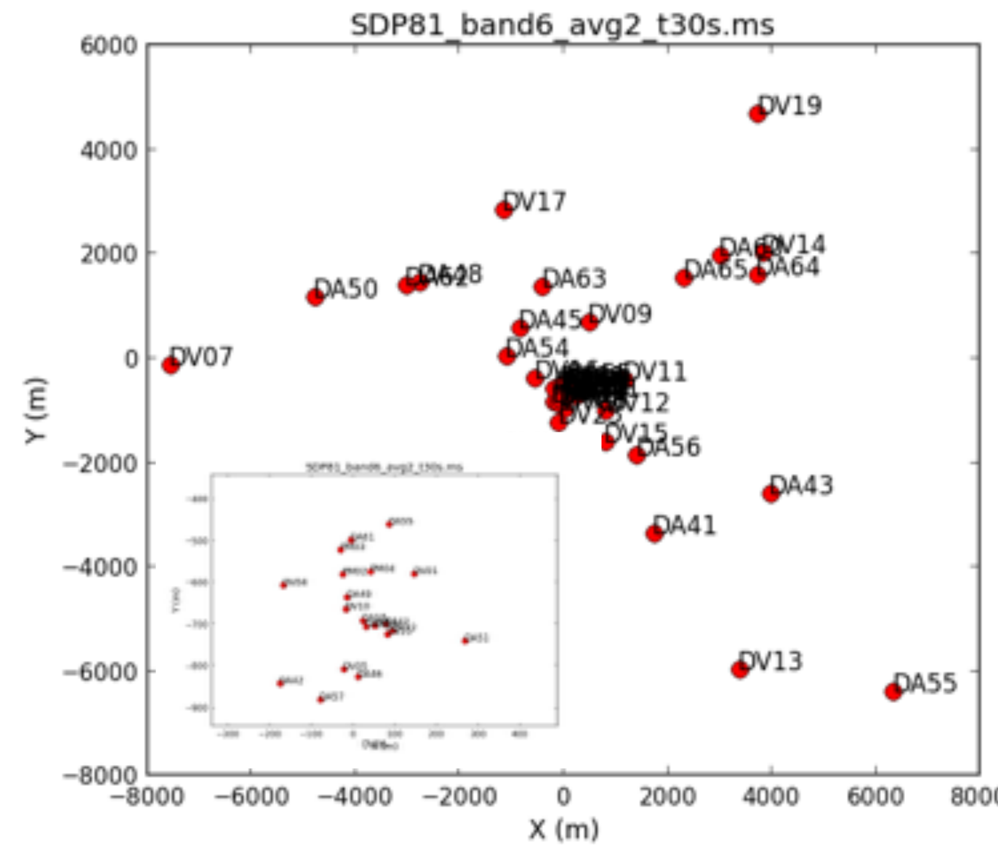
ALMA long baseline observations

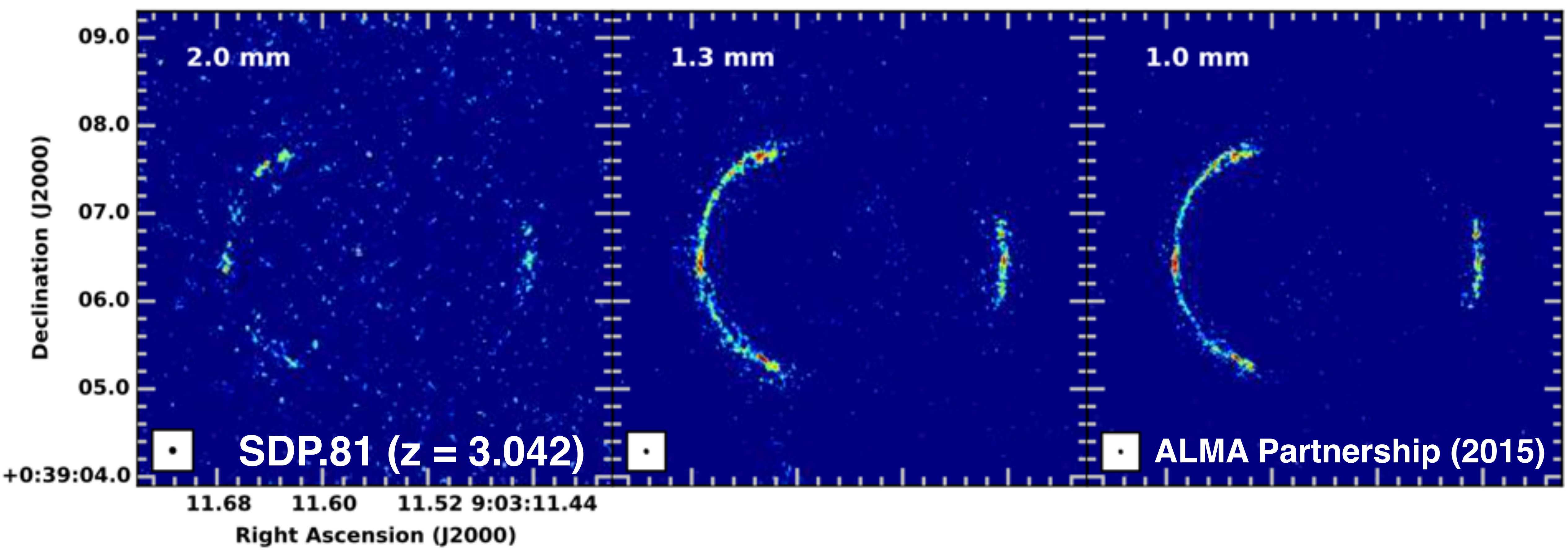
Continuum: 150, 240, 290 GHz
Line: CO (5-4), (8-7), (10-9), H_2O (2-1)

Baselines: 15 m to 15 km
Antennas: 31-36 (10% within 200 m)

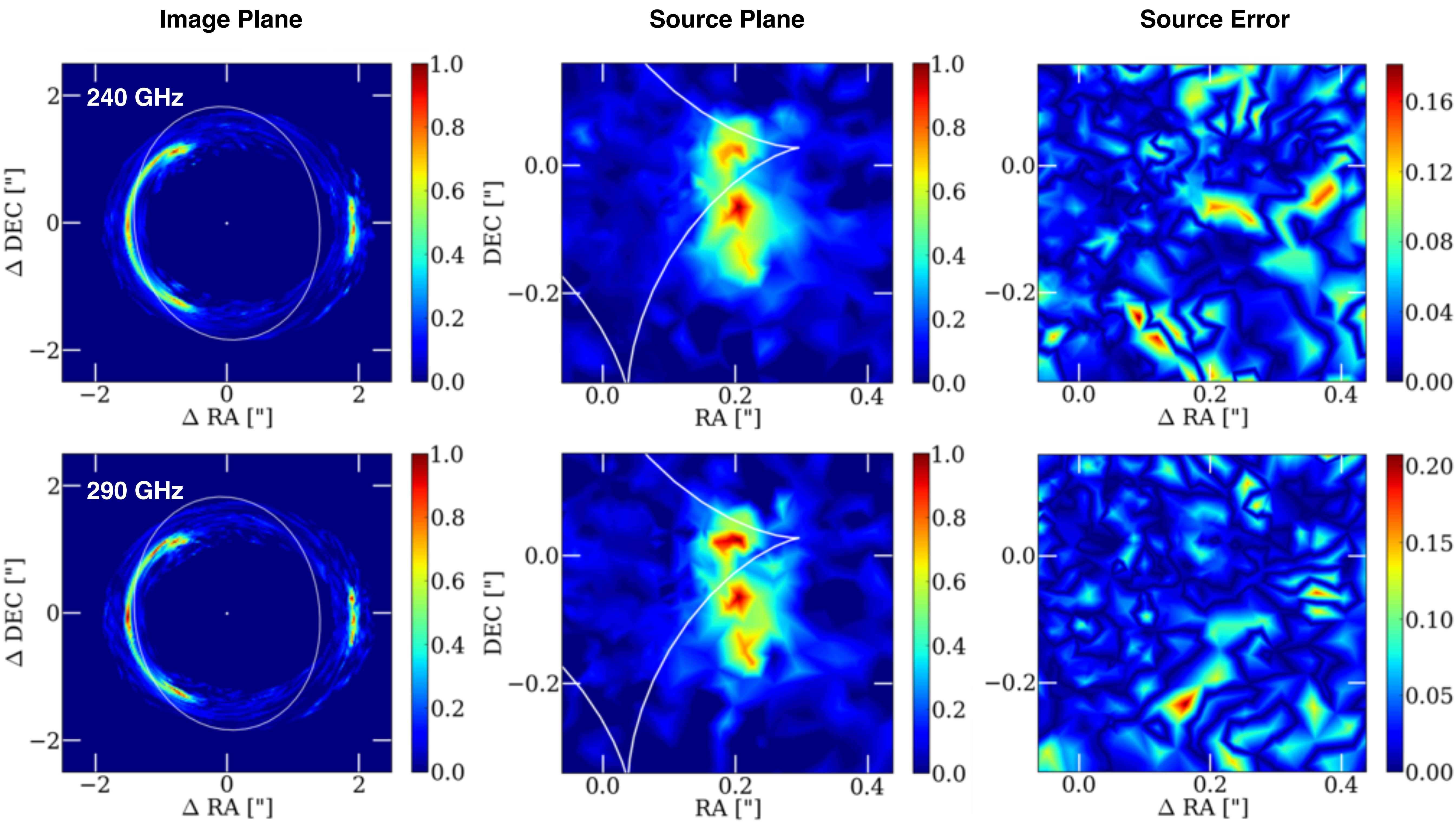
Time: ~4.5 to 5.5 h on-source

Beam-size: 50 x 56 mas to 31 x 23 mas





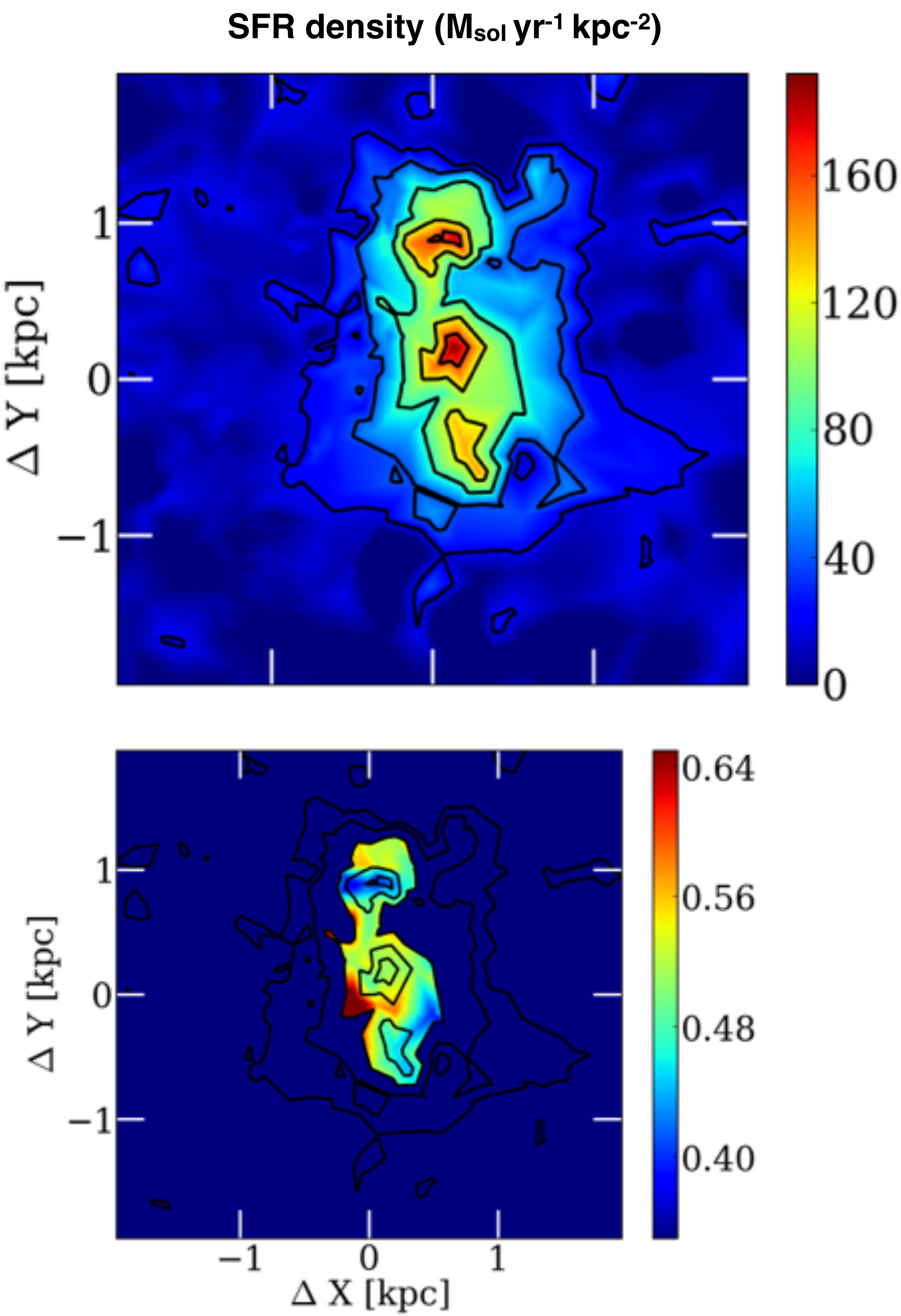
Pixellated source model



- Whole source: μ = 17.6 ± 0.4
- Central region: μ = 25.2 ± 2.6

(Rybak, McKean, Vegetti, Andreani, White, 2015, in press)

Intrinsic properties of the dust



Several star-forming regions:

- Extended and Diffuse structure: 20-30 $M_{sol}\ yr^{-1}\ kpc^{-2}$.
- Central 1.9 x 0.7 kpc structure: 100 $M_{sol}\ yr^{-1}\ kpc^{-2}$ (SMG typically 4-6 kpc in size; Tacconi et al. 2006).
- Intense structures: 100-190 $M_{sol}\ yr^{-1}\ kpc^{-2}$.
- Less than expected for an Eddington-limited star-formation by a pressure supported starburst.

Varying star-formation conditions:

- Flux-ratio map (290 GHz / 240 GHz) shows significant variation.
- Evidence for varying dust temperature and/or optical depth.

Summary

- The level of low mass substructure around massive galaxies is sensitive to the properties of the dark matter particle.
- Gravitational lenses can be used to measure the substructure mass function out to redshift ~ 1 (actually any lens redshift).
- The level of 'high mass' substructure within lenses is consistent with the over abundance seen in the Local Group (e.g. LMC and SMC).
- Current best constraints suggest a total mass fraction and flat-slope to the mass function consistent with CDM (large errors).
- VLBI imaging of a few select gravitational lenses will directly confirm or rule out the CDM model; combining with optical data will test WDM models.
- Gravitational lens modelling of interferometric data should only be carried out in the visibility plane, and pixellated source reconstructions provide more robust source models (and magnifications).
- The reconstructed dust emission of first ALMA target has an extended disk (~2 kpc in size), with diffuse and intense emission regions, consistent with a potential size bias in lensed SF galaxies, but is inconsistent with a pressure-supported starburst.