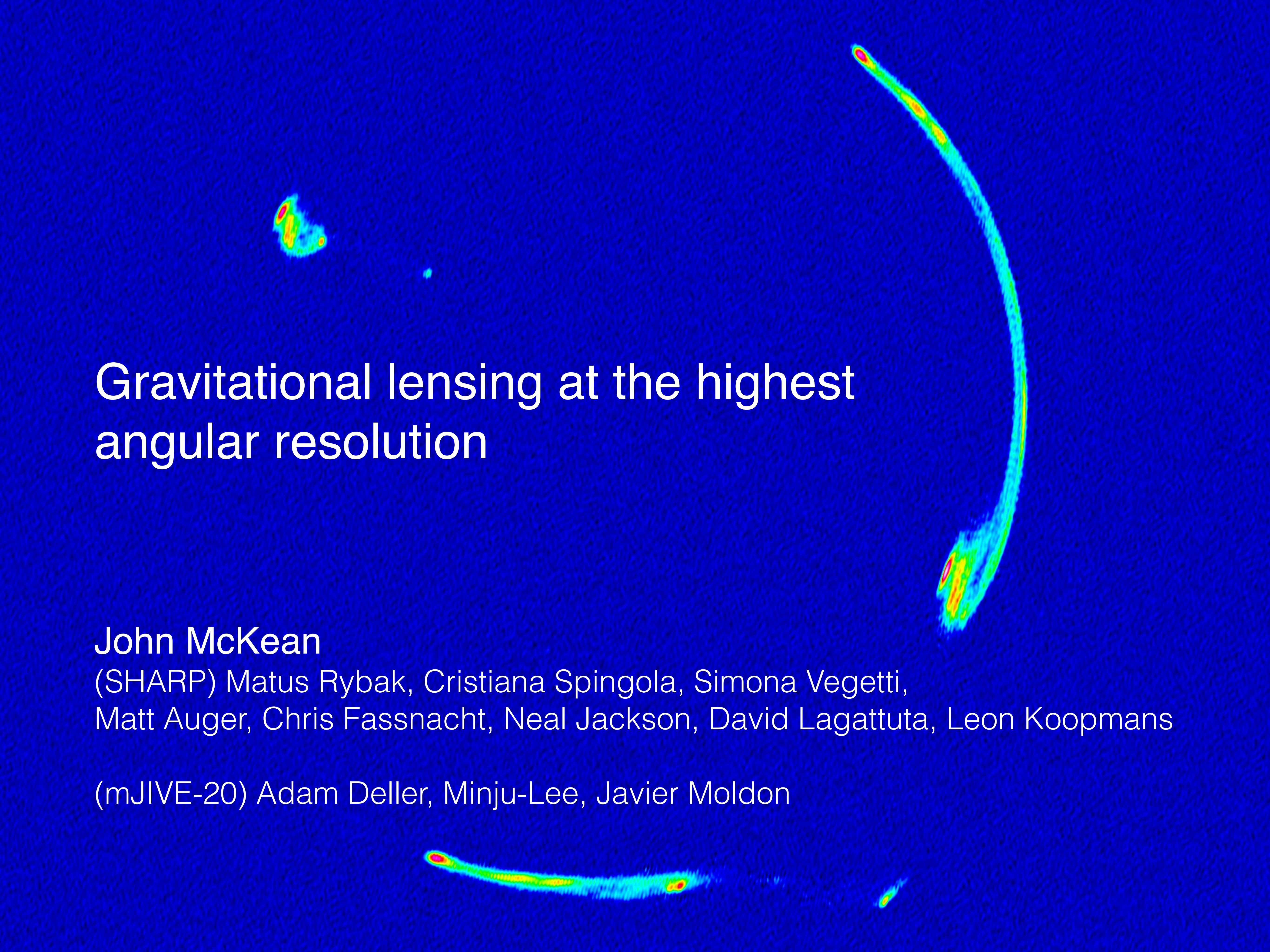


Gravitational lensing at the highest angular resolution

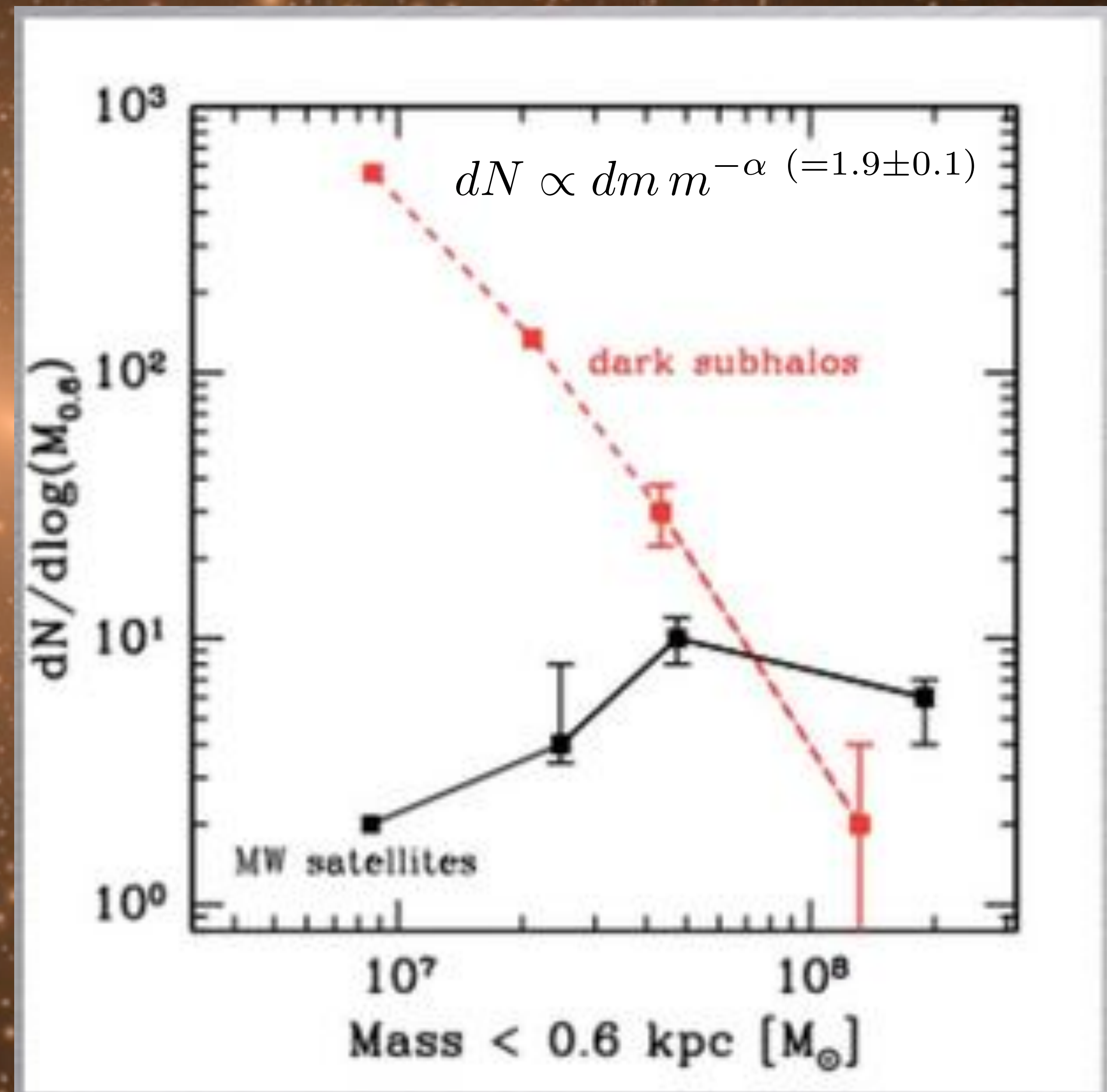
John McKean

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

(mJIVE-20) Adam Deller, Minju-Lee, Javier Moldon

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

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



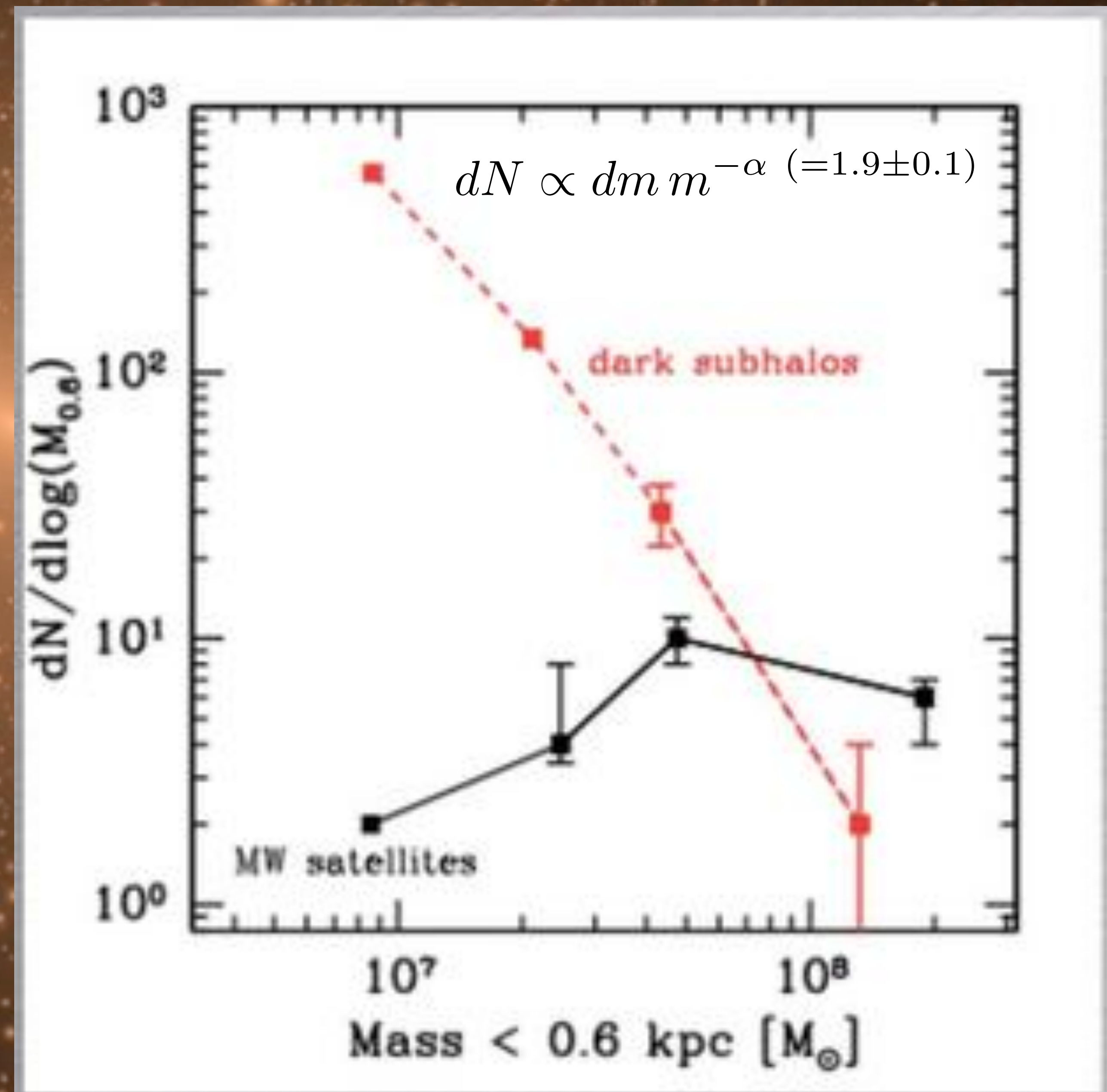
z=0.0

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

i) Something wrong with the galaxy formation model?

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

iii) The Milky Way is a special case?



80 kpc

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

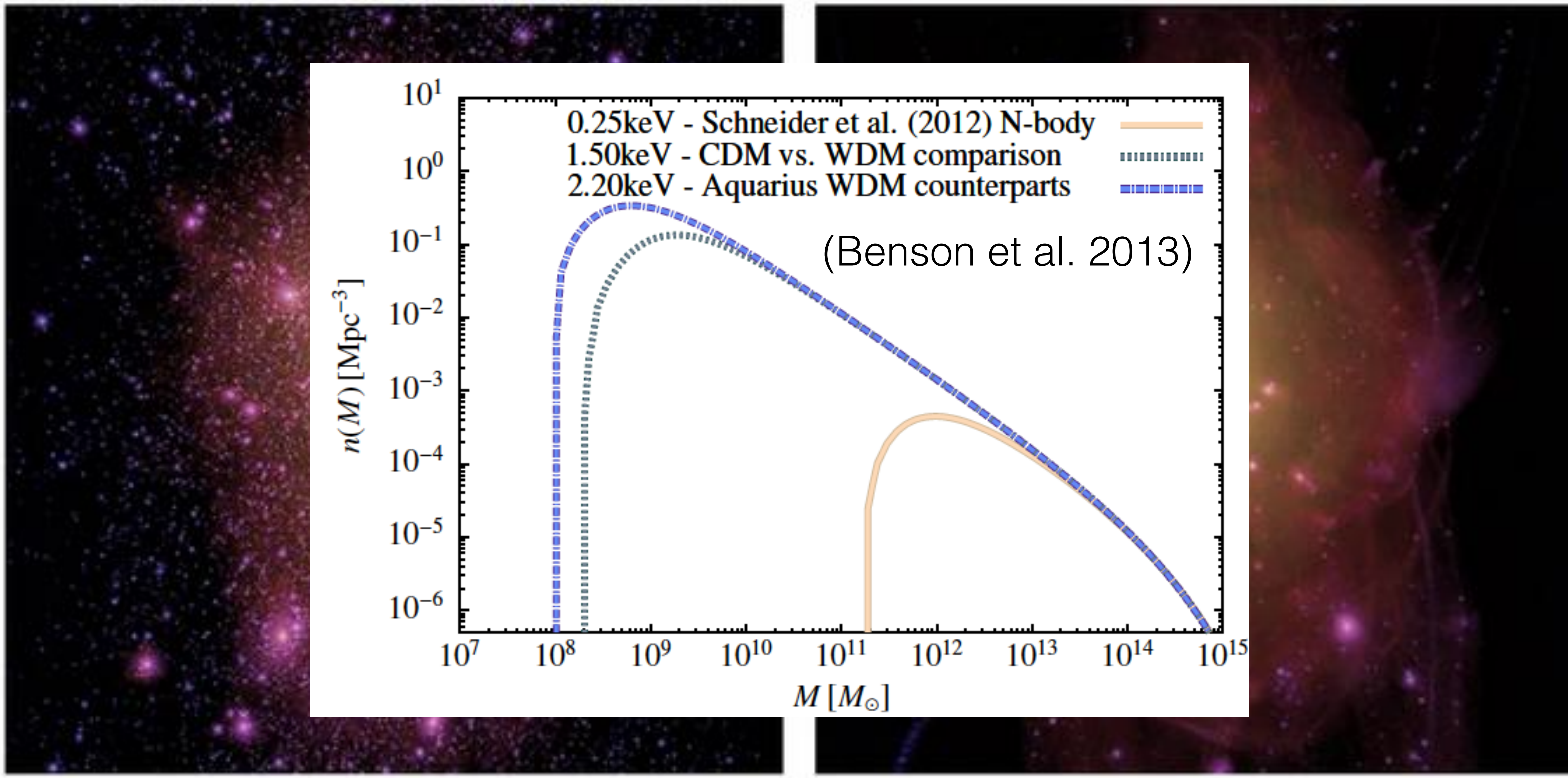
Cold dark matter

Warm dark matter

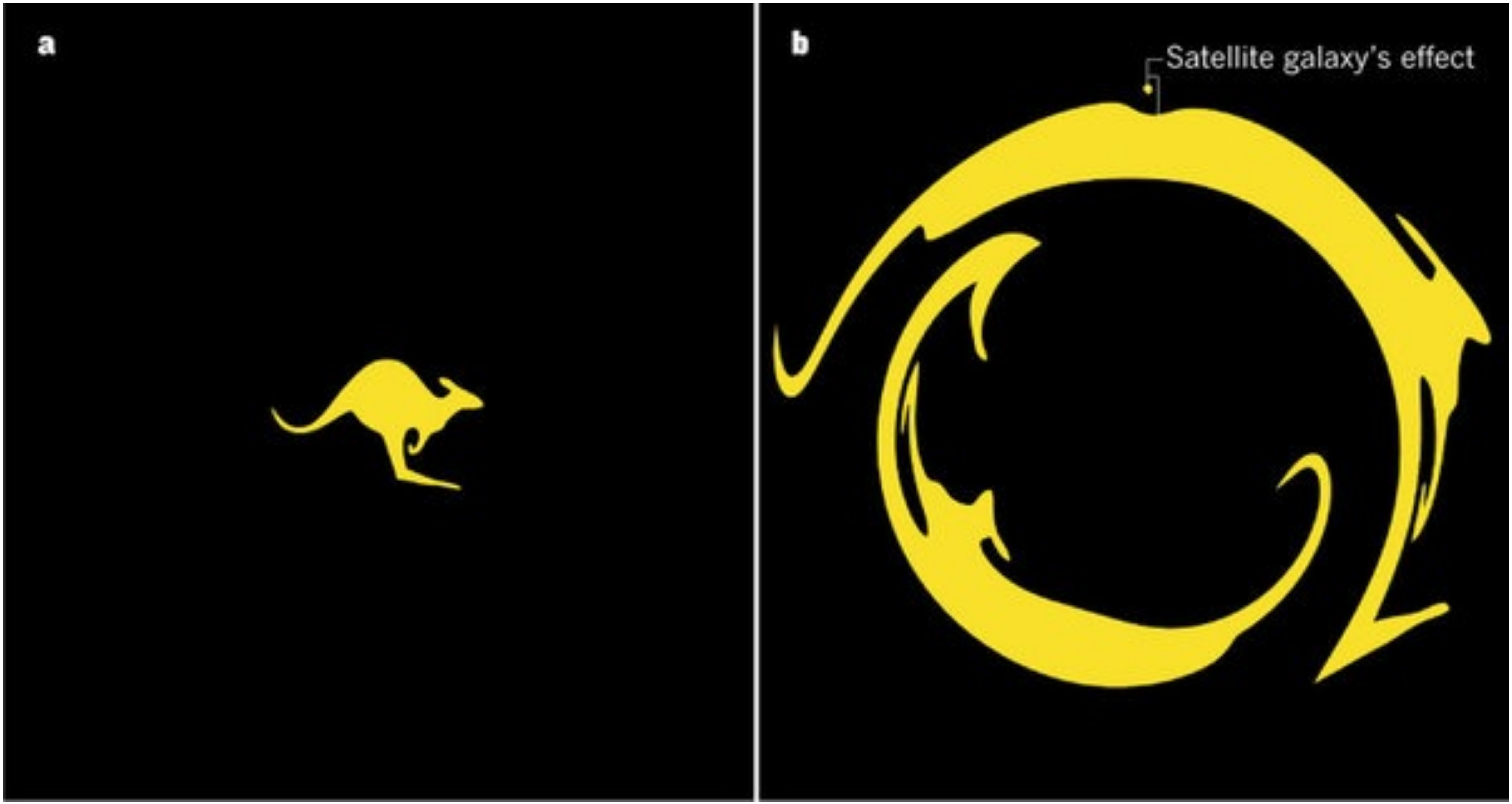
Dark matter halo of mass ~ 10^{12} M_{sun} (Lovell et al. 2012)

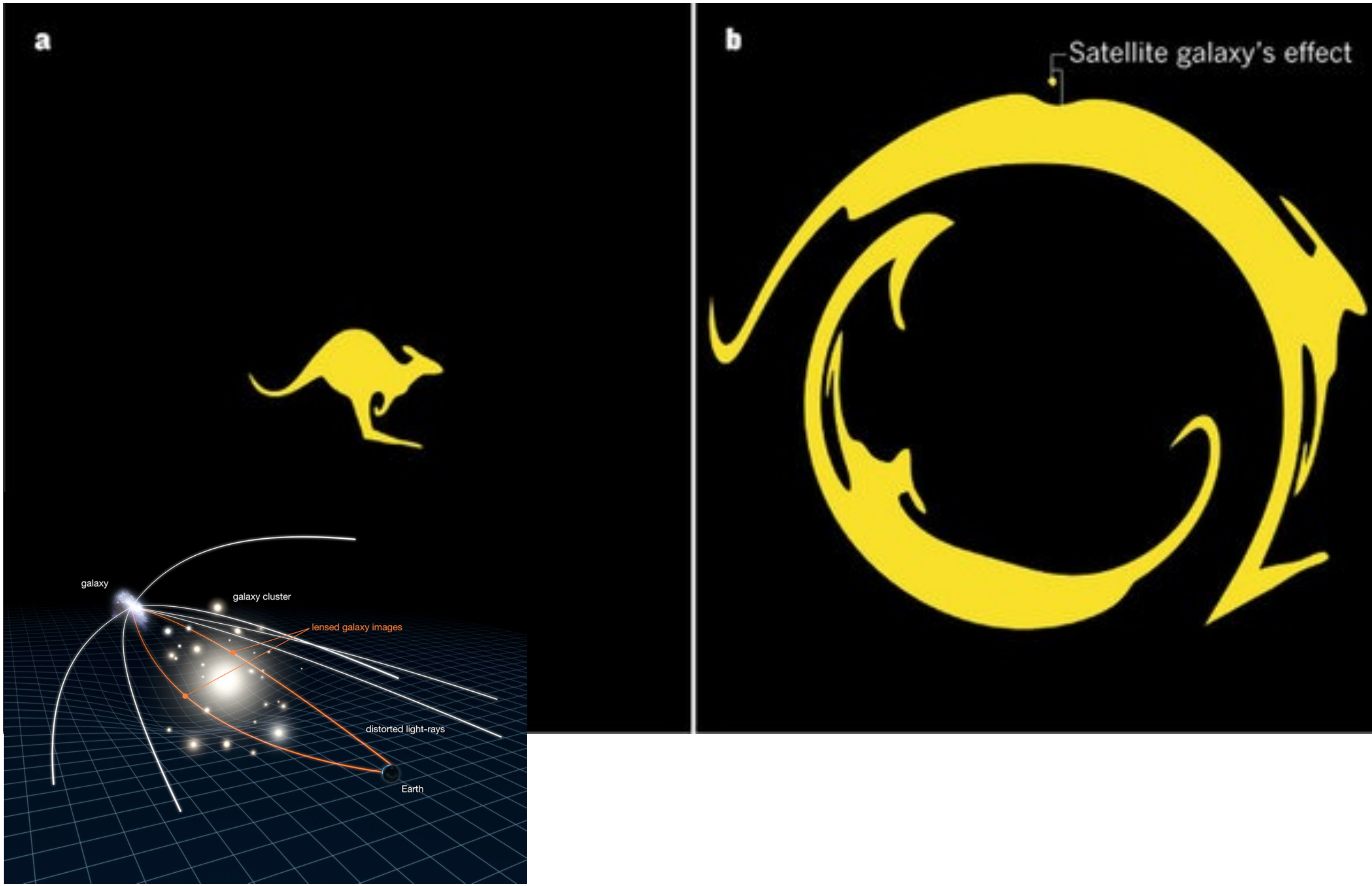
Cold dark matter

Warm dark matter

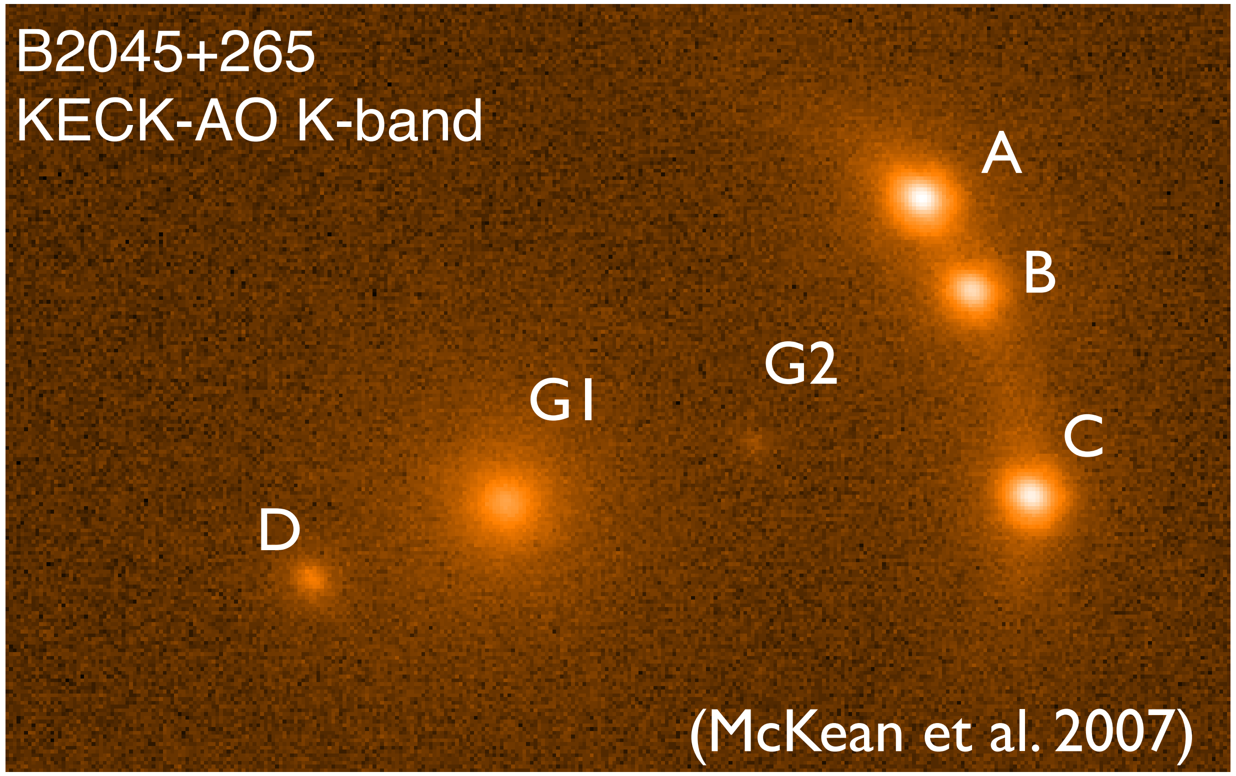


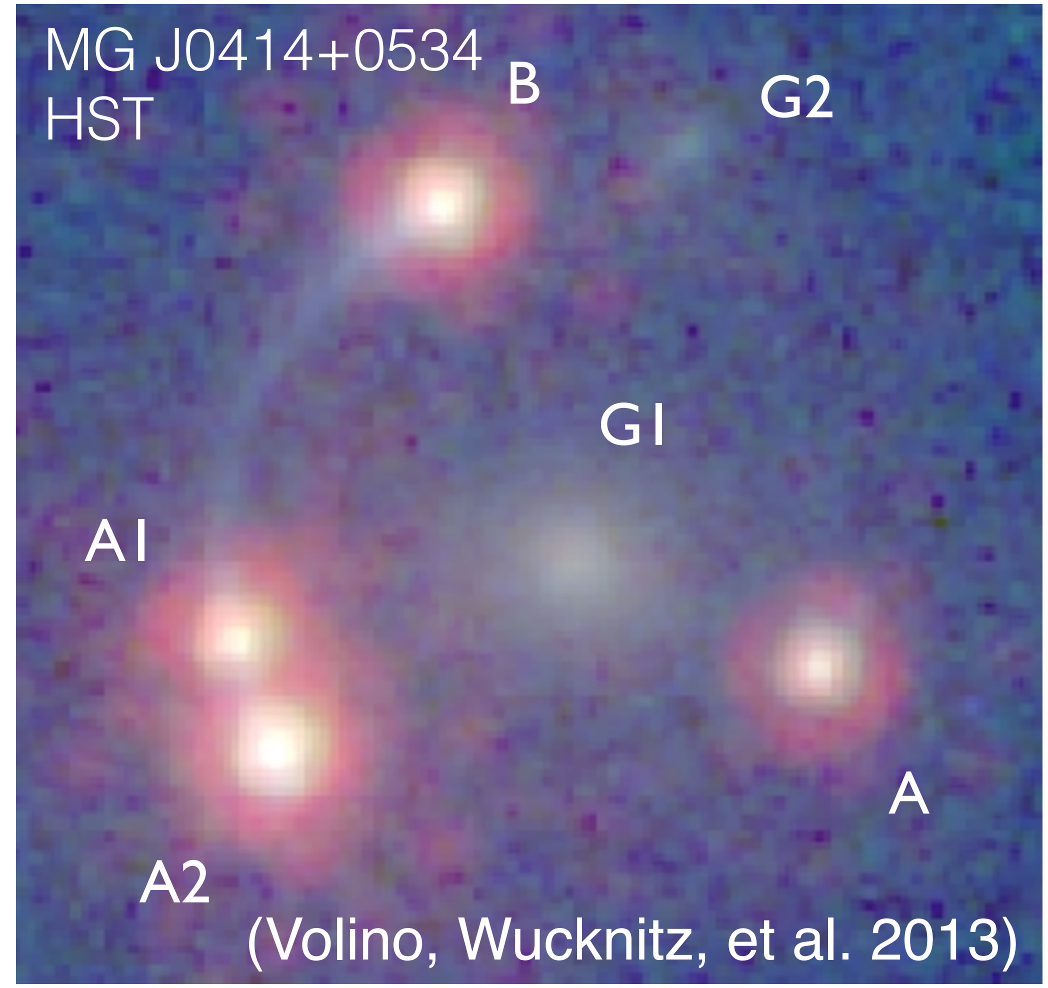
The cut-off in the mass function is directly related to the model for dark matter.

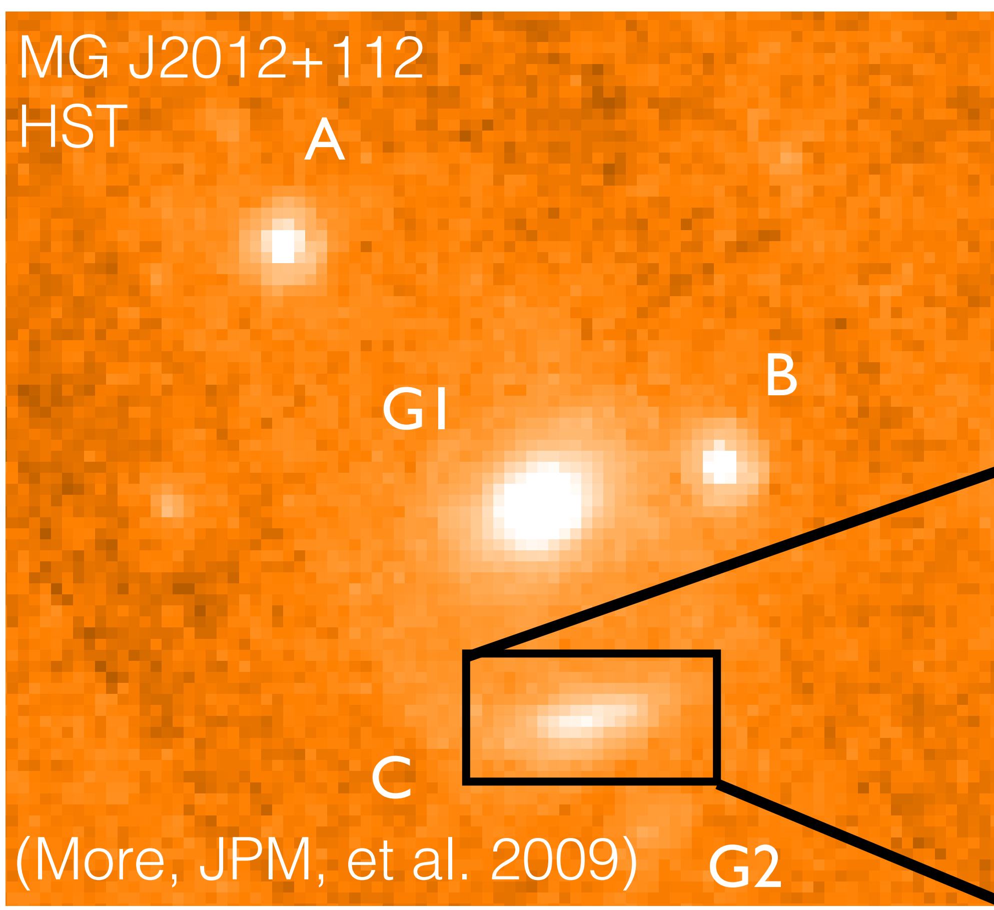

a
b
Satellite galaxy's effect


a
b
Satellite galaxy's effect
galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

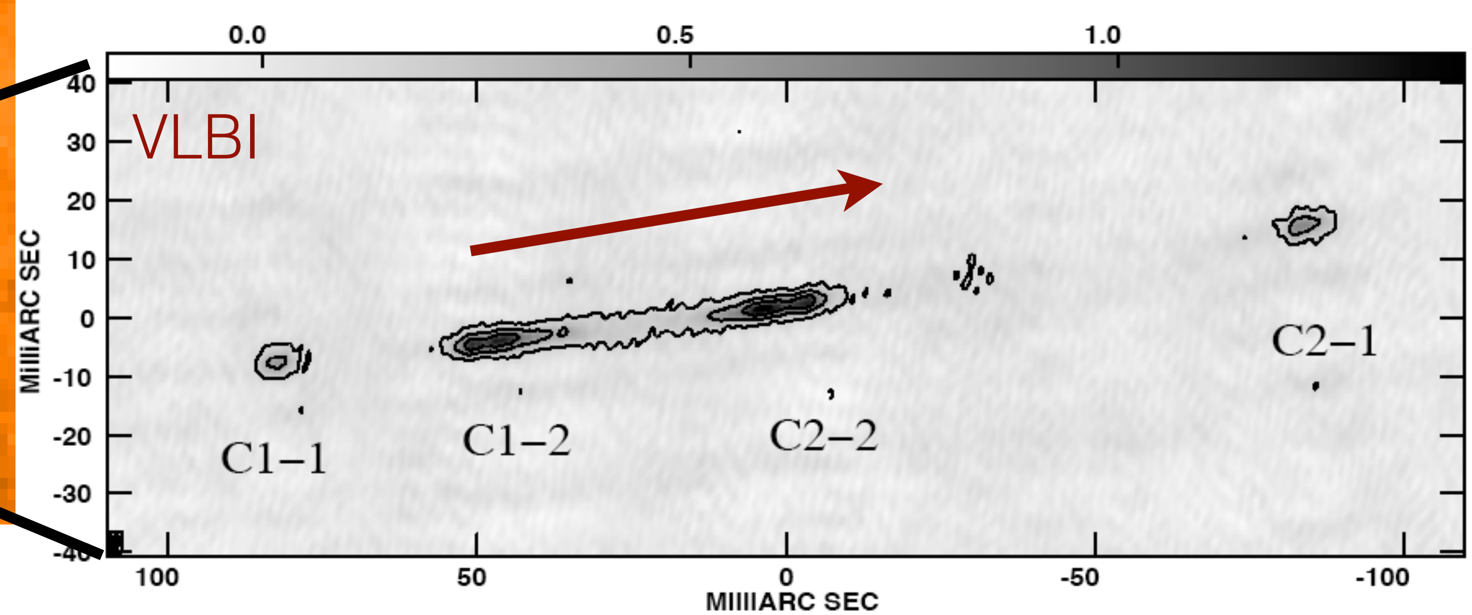
Top end of the substructure mass function



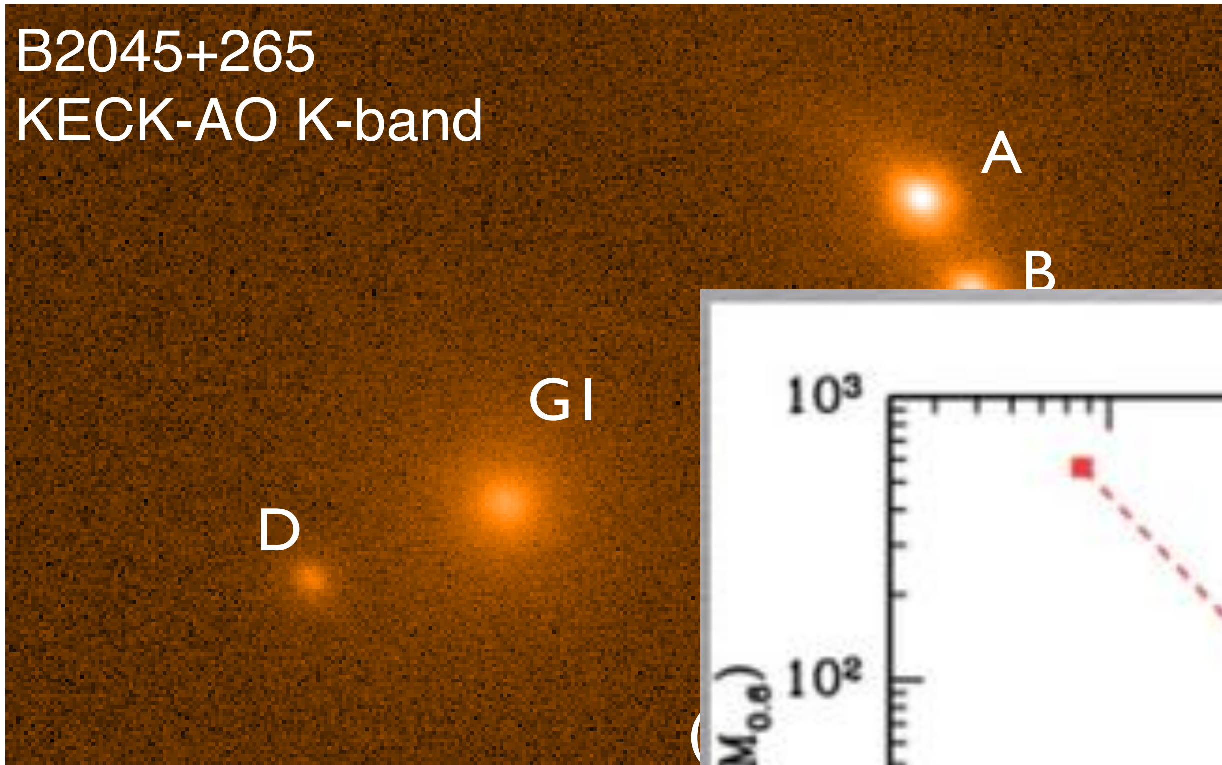


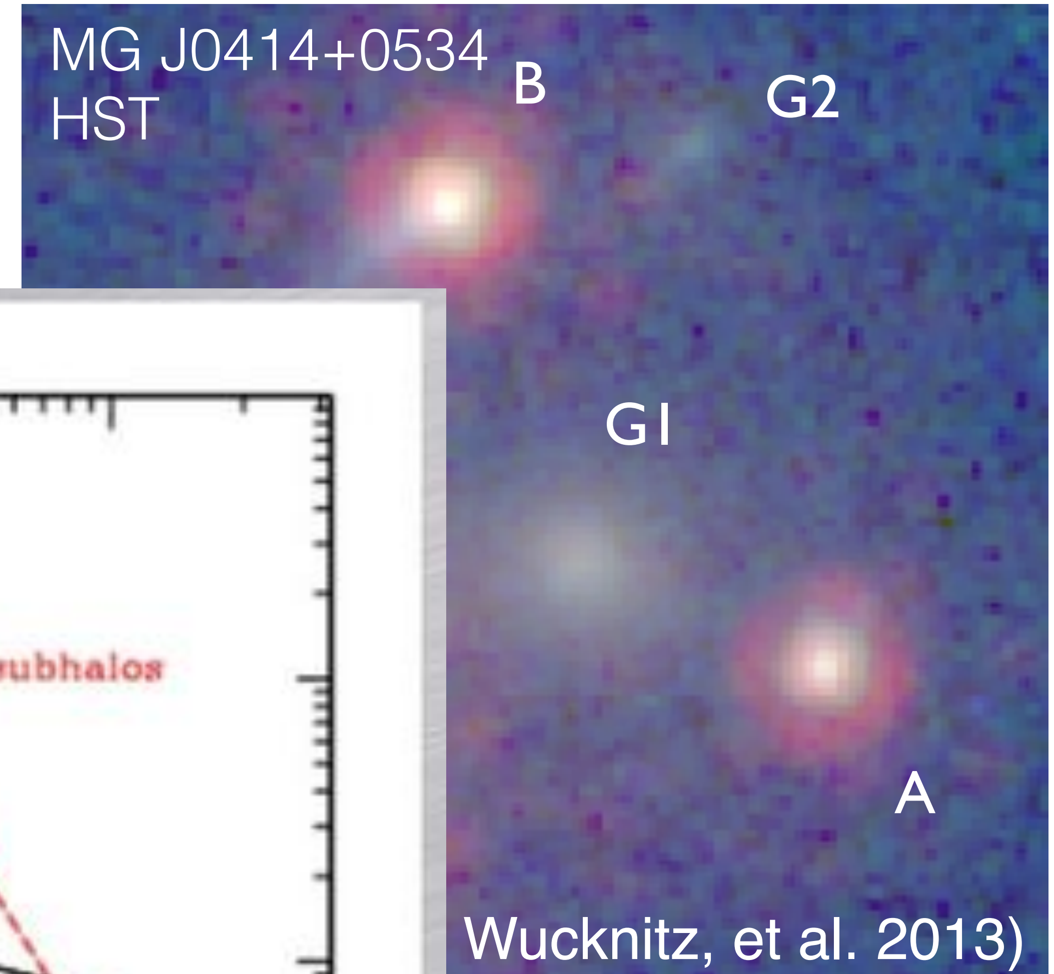


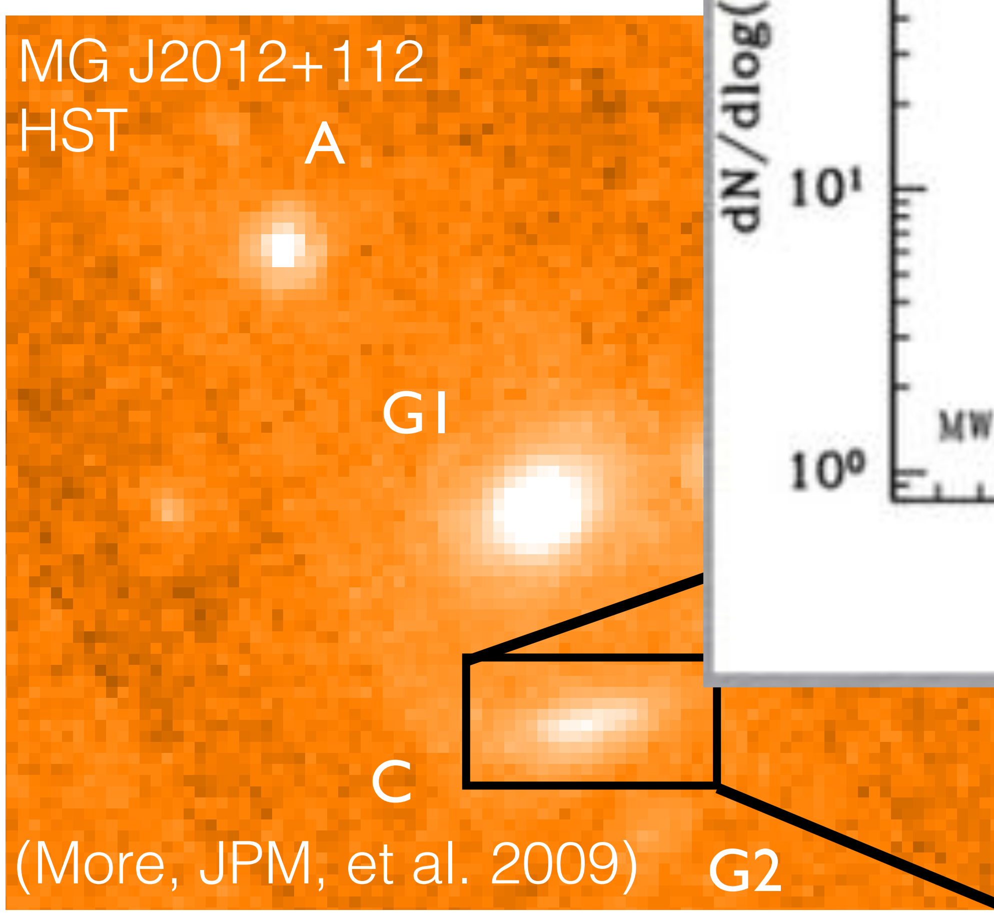
Dwarf companion galaxies (luminous substructures) make up ~1% of total halo mass.

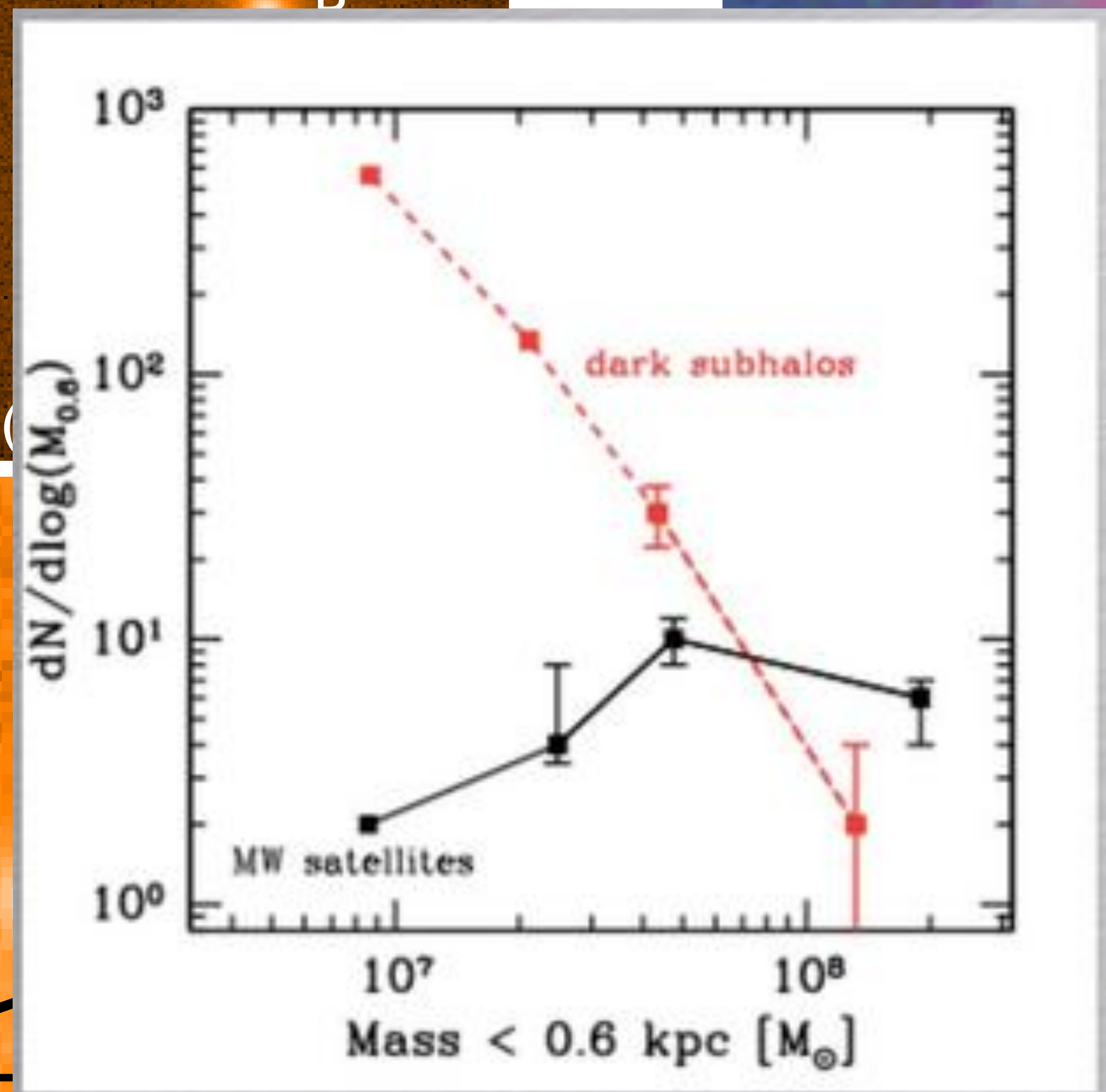


Top end of the substructure mass function

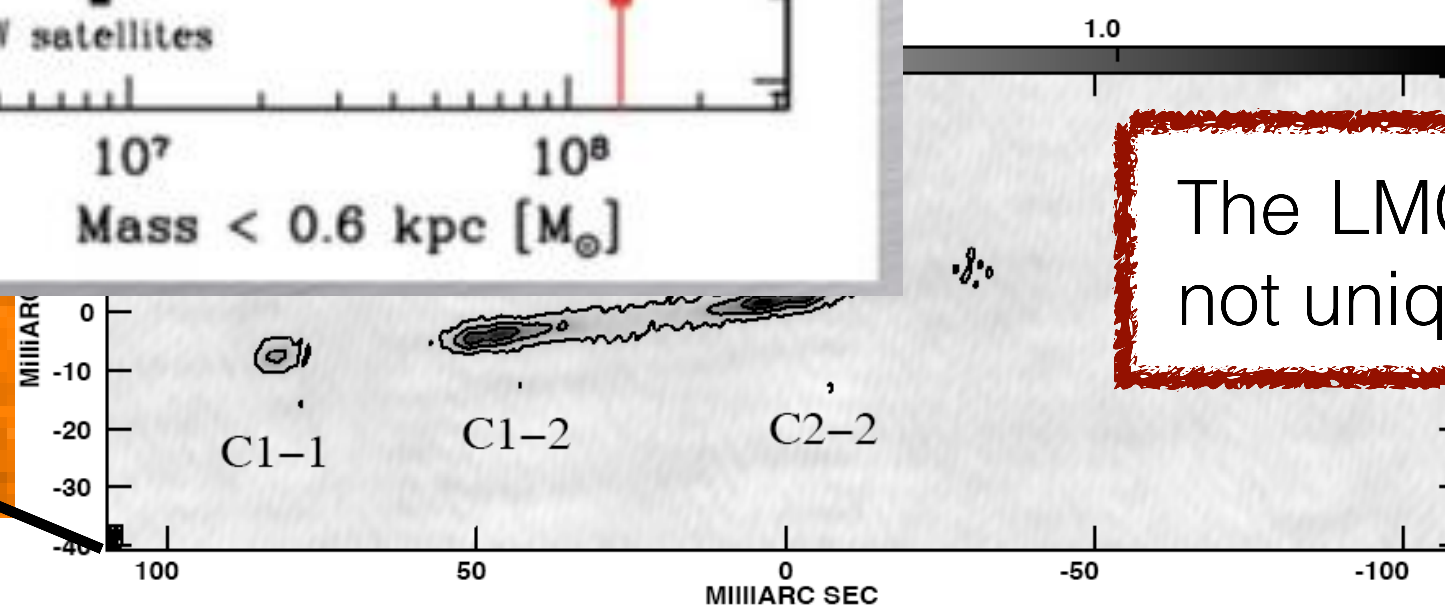




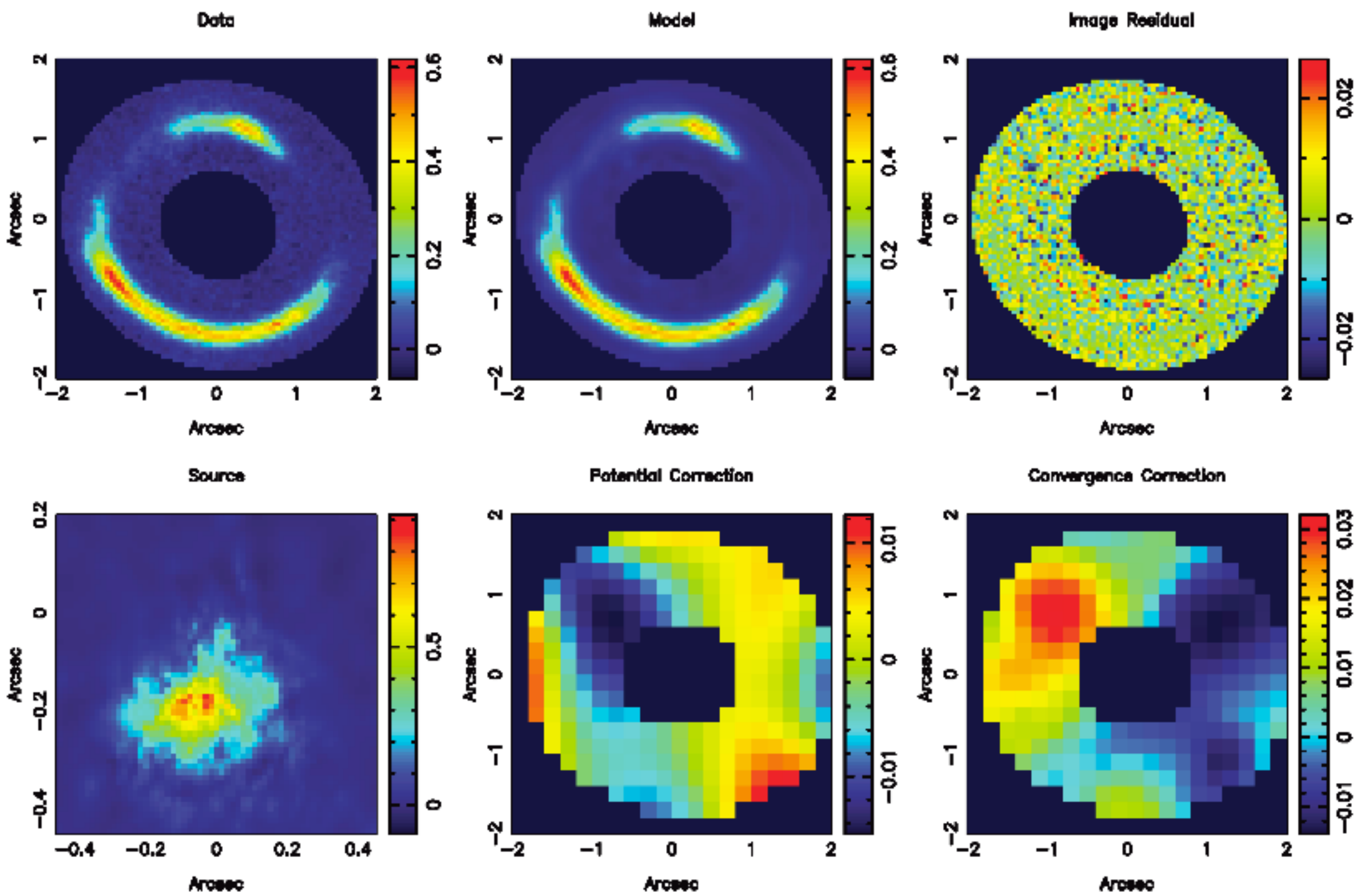




uminous substructures)
ss.



The LMC is not unique!



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

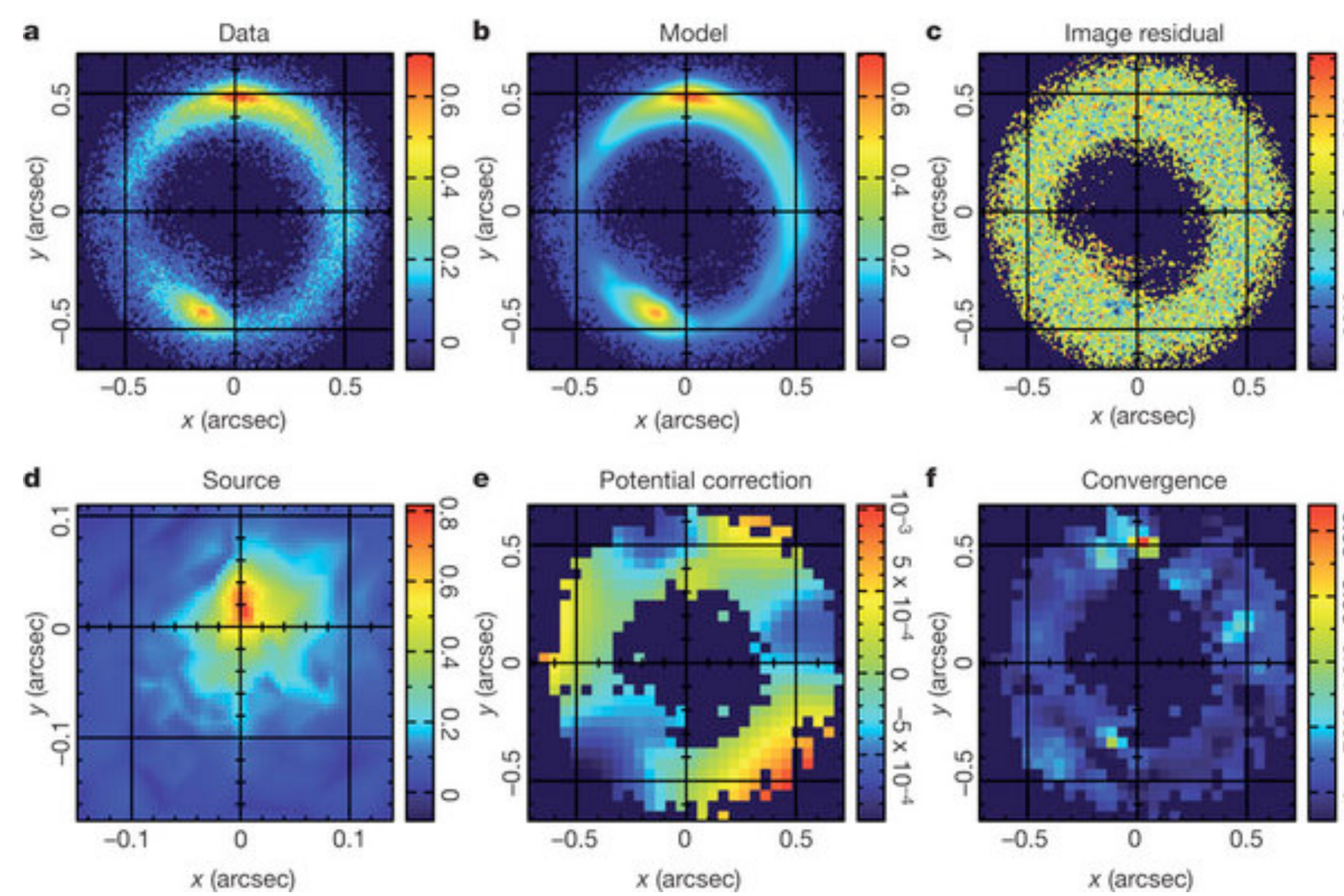
$M_{sub} = (3.5 \pm 0.2 \times 10^9\ M_{sol})$

(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, JPM et al. 2012, Nature)

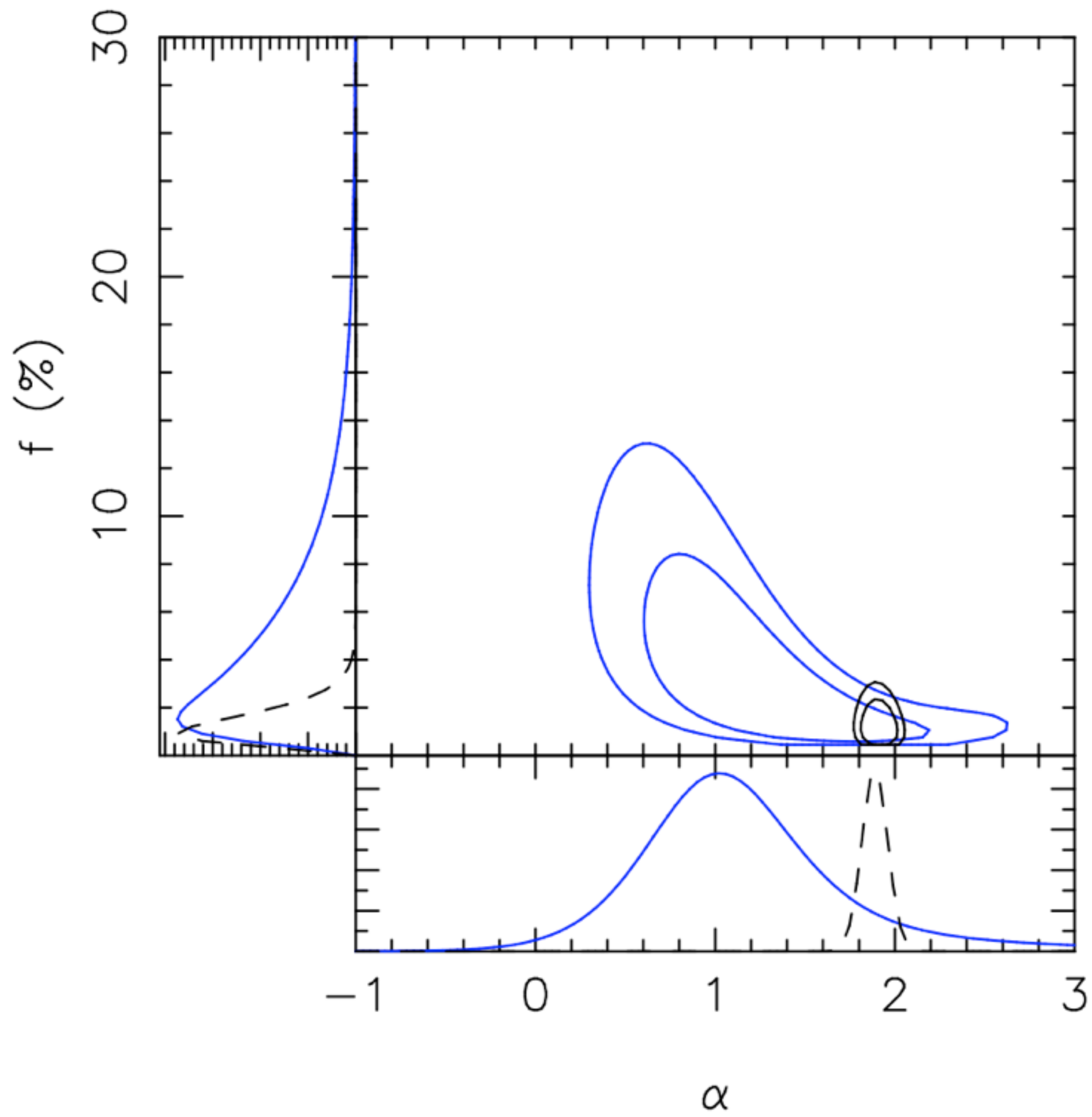


Using the two dark substructures,

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

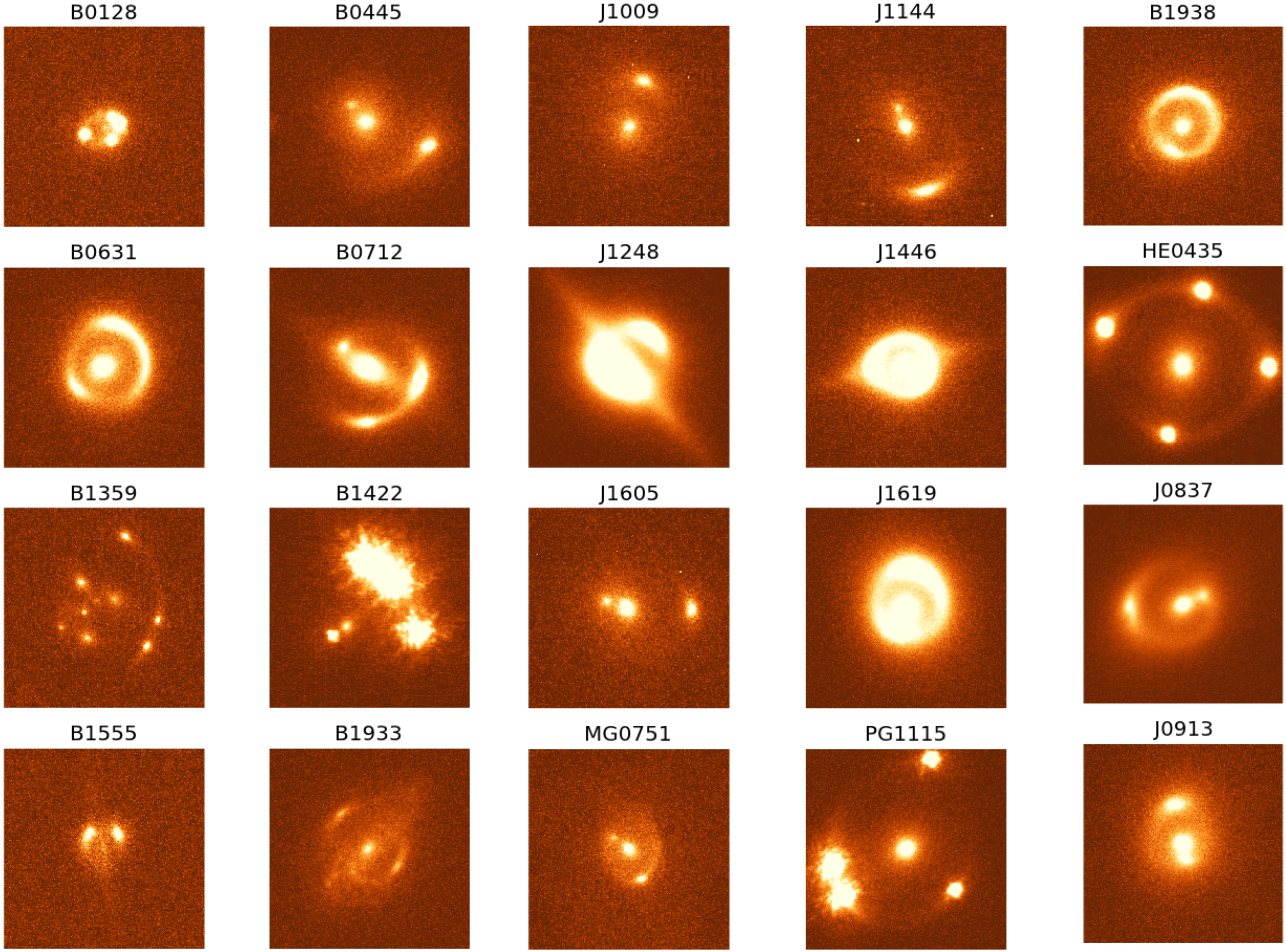
Simulations predict

$f_{CDM} < 0.4$ % 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
J1605
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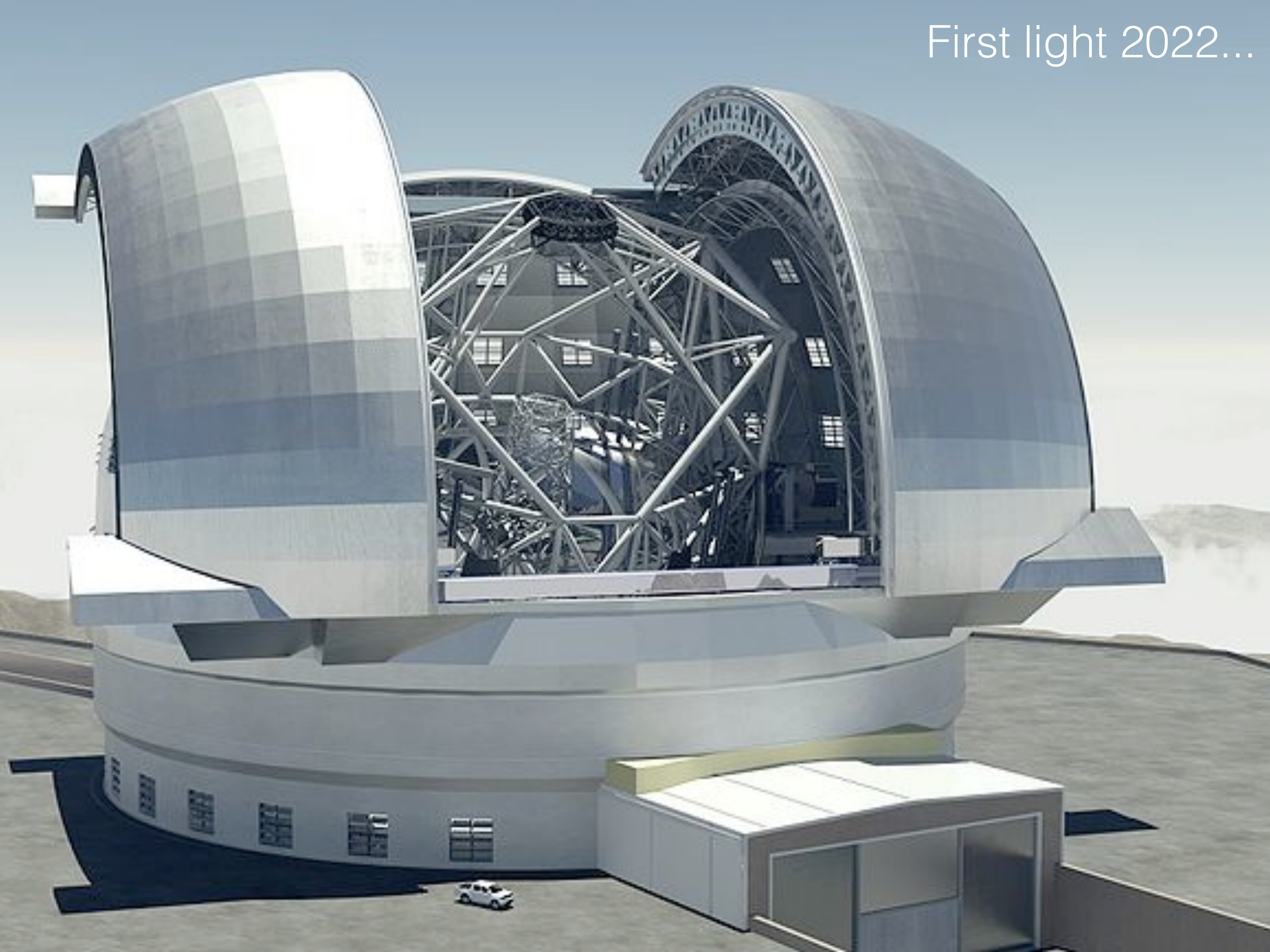
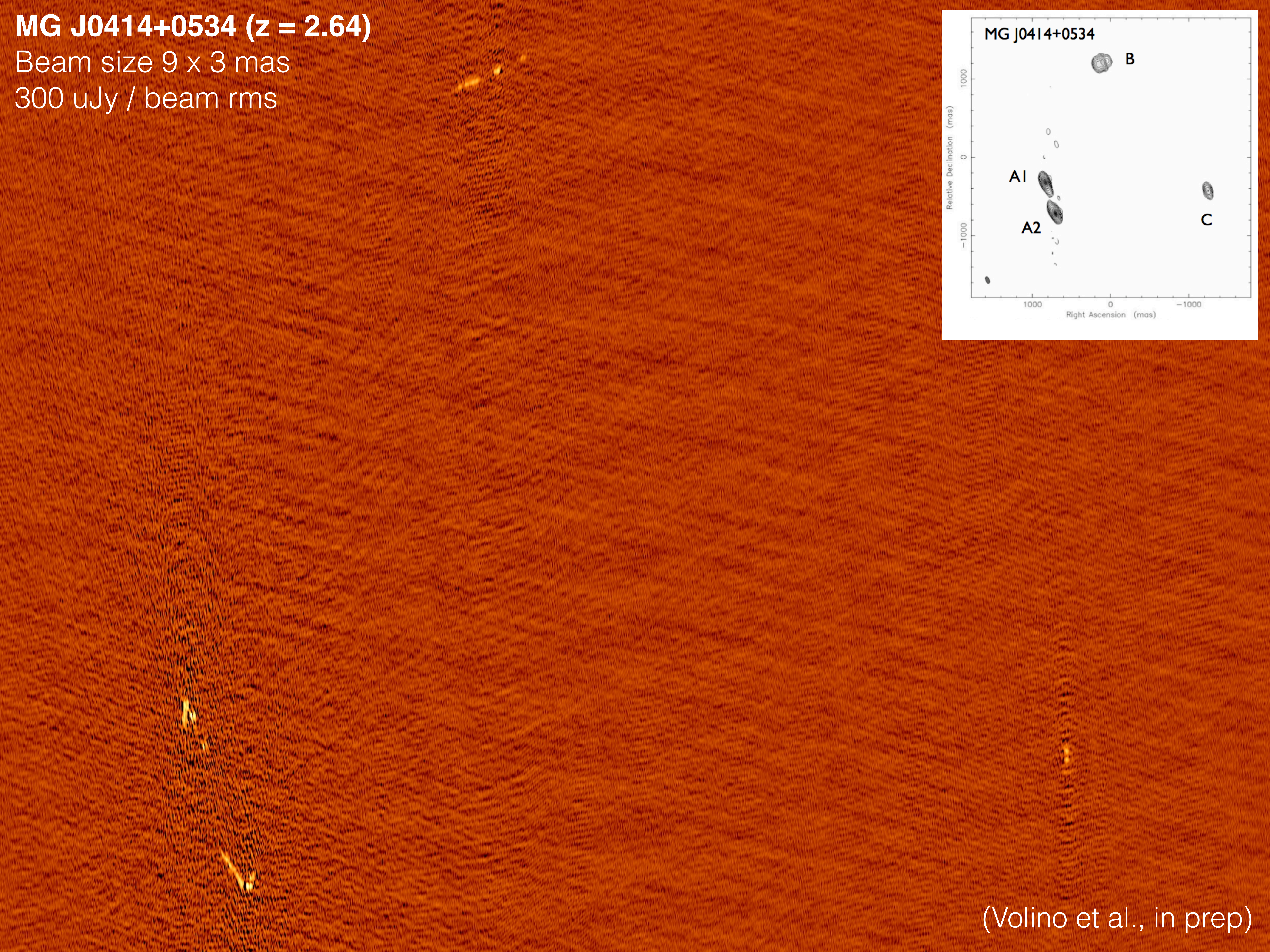
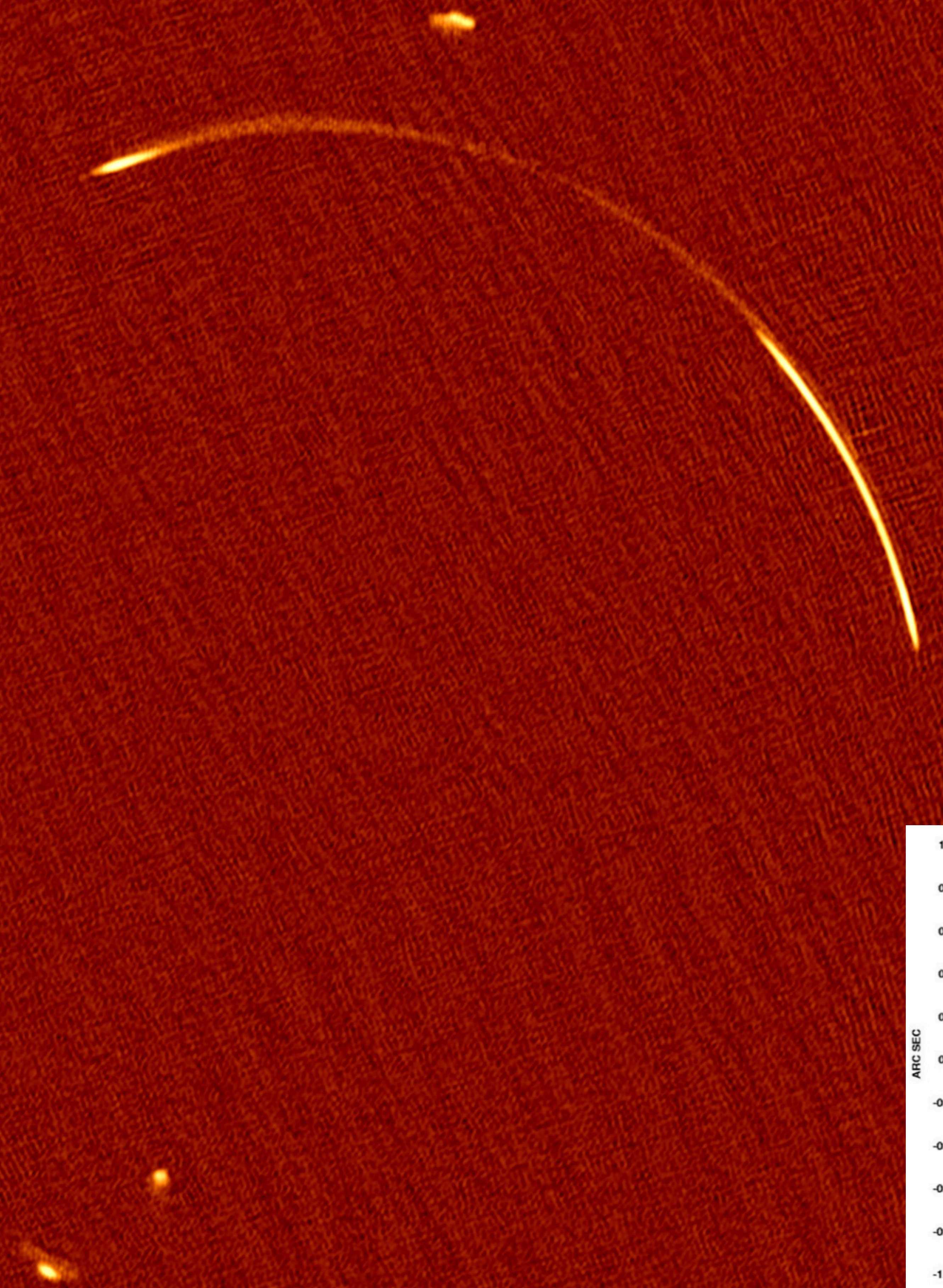
B1555
B1933
MG0751
PG1115
J0913

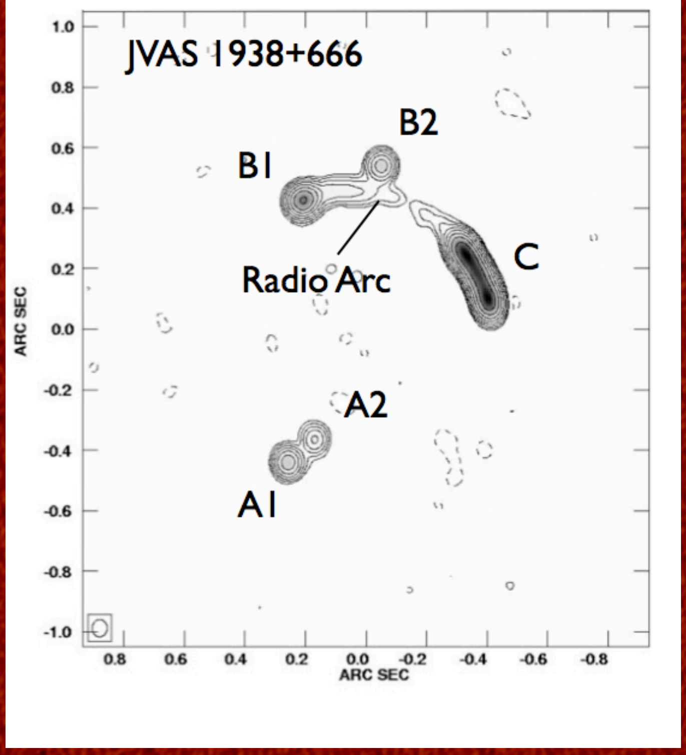

First light 2022...


The Global VLBI - Array
NOW!!
Brewster
North Liberty
Hancock
Green Bank
Jodrell Lovell
Jodrell Mk2
Cambridge
Onsala 25m and 20m
Metsähovi
Urumqi
Shanghai
Westerbork
Medicina
Noto
Los Alamos
Owens Valley
Pie Town
Mauna Kea
Kitt Peak
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


MG J0414+0534 (z = 2.64)
Beam size 9 x 3 mas
300 uJy / beam rms
(Volino et al., in prep)
MG J0414+0534
B
A1
A2
C
Relative Declination (mas)
Right Ascension (mas)
1000
0
−1000

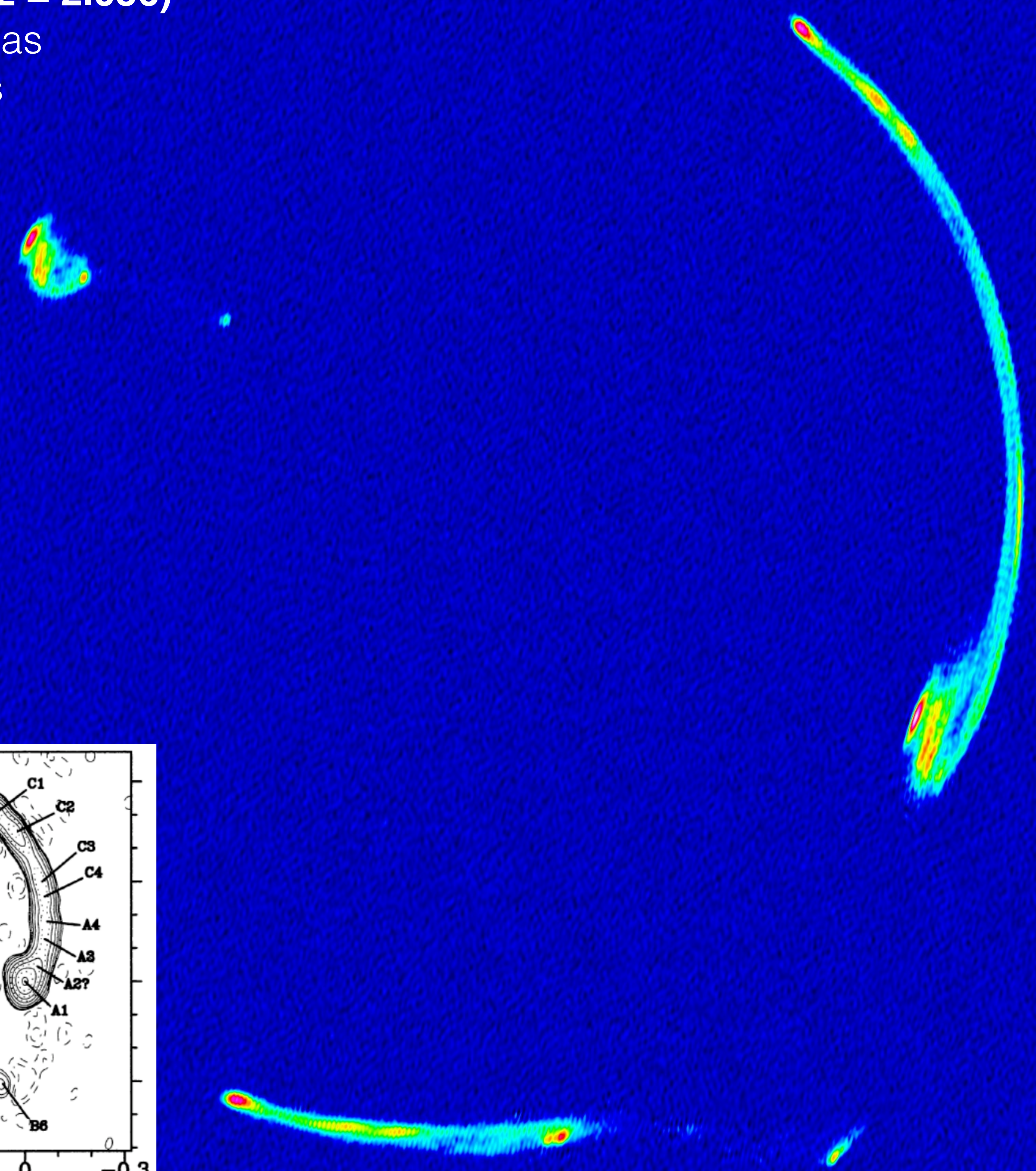
JVAS B1938+666 (z = 2.056)
Beam size 4 x 2 mas
30 uJy / beam rms

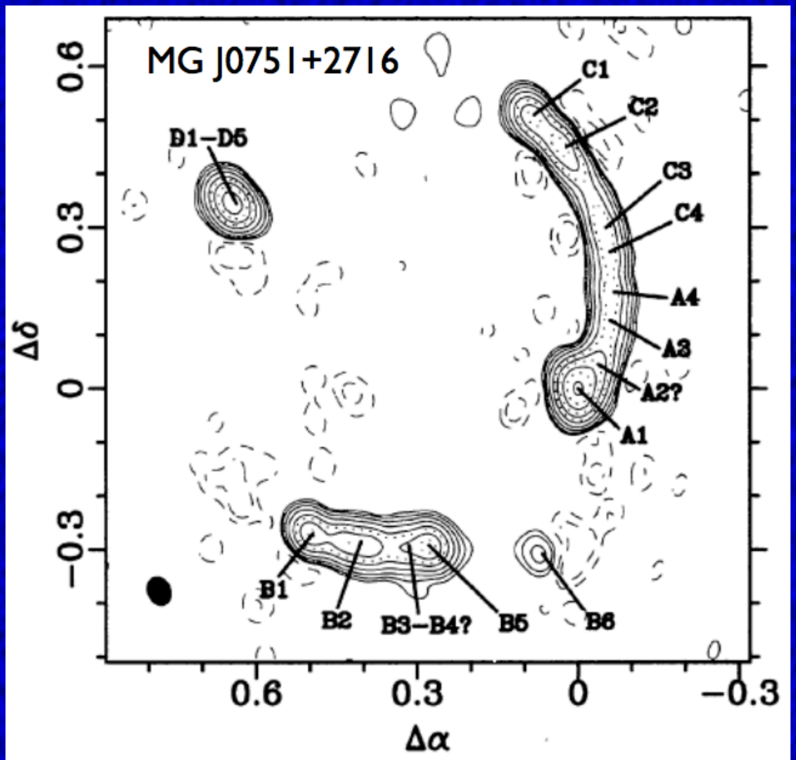




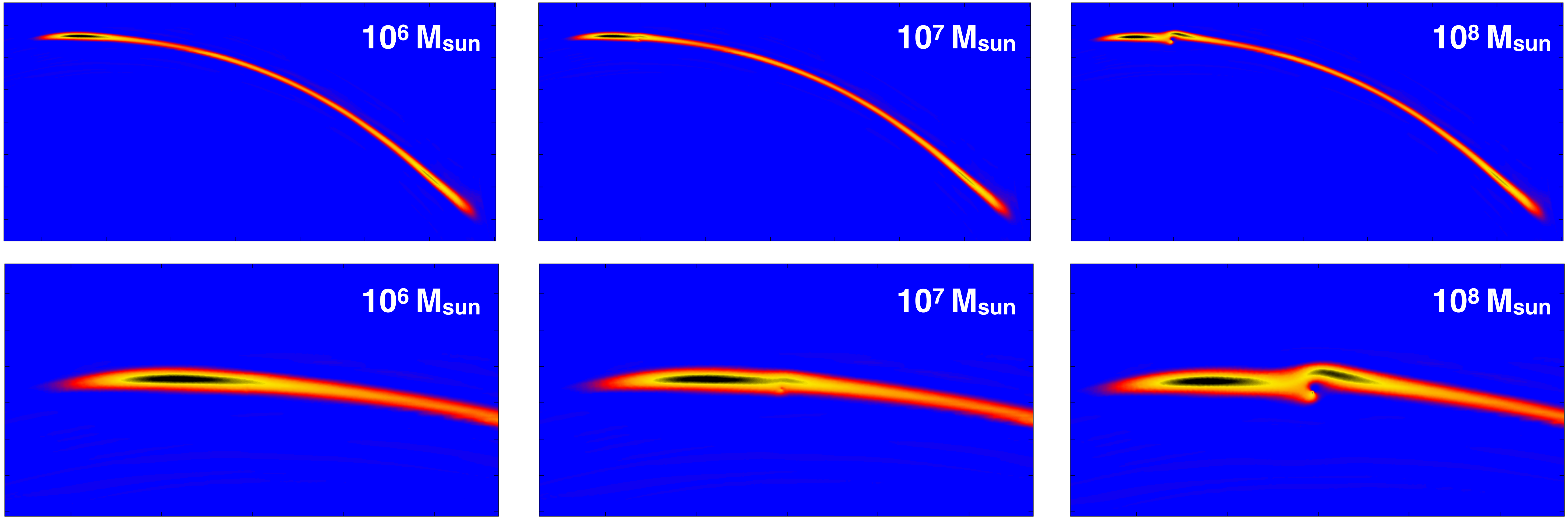
(McKean et al., in prep)

MG J0751+2761 (z = 2.056)
Beam size 7 x 2 mas
10 uJy / beam rms

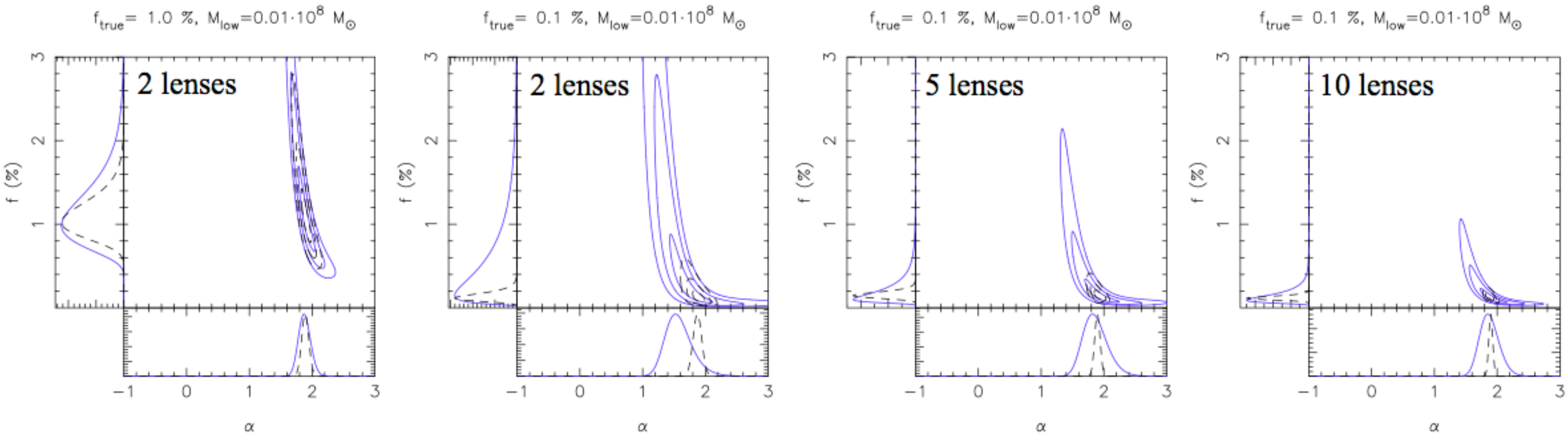




(McKean et al., in prep)



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



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

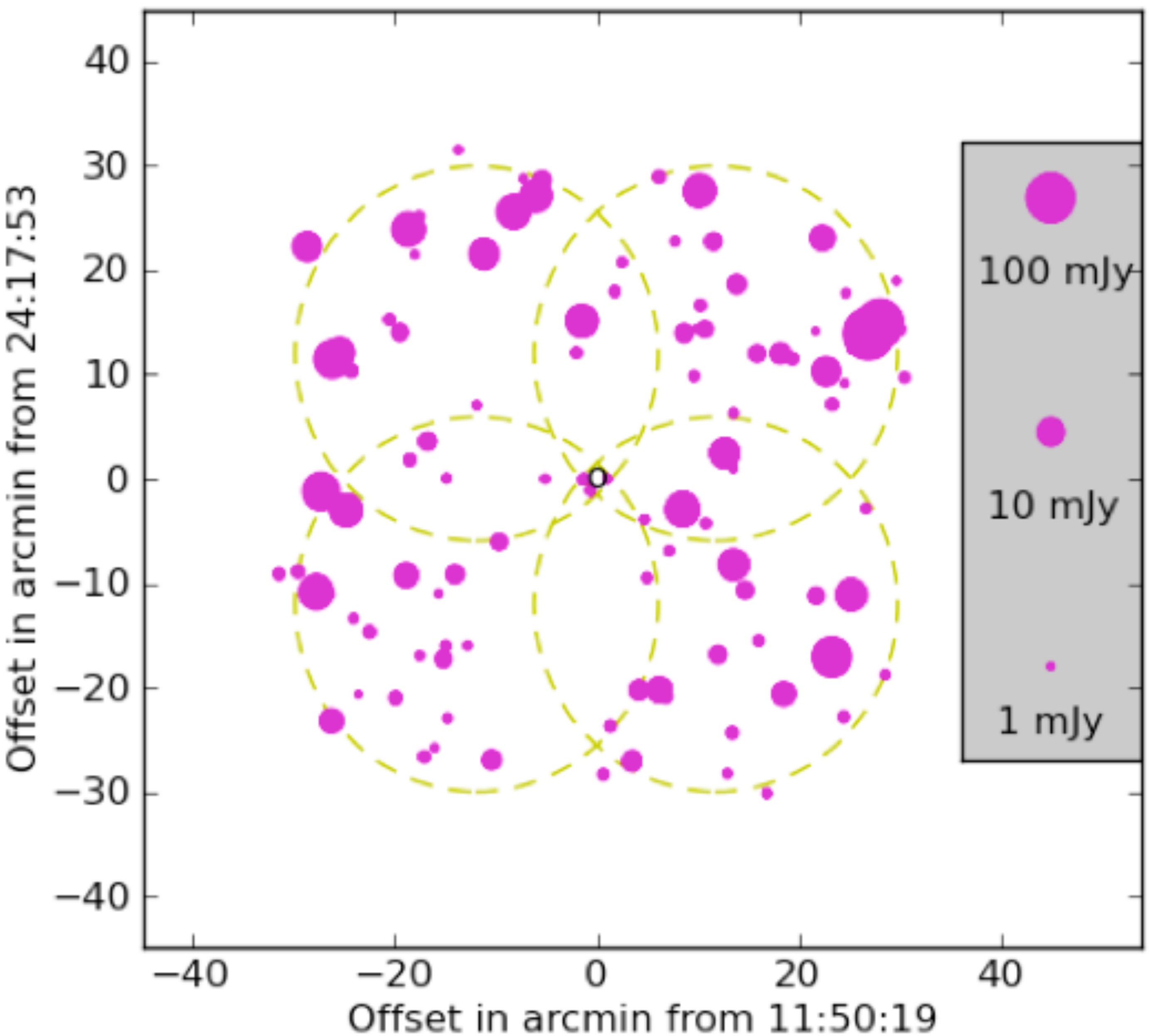
$\alpha = 1.57^{+0.23}_{-0.19}$
$f_{sub} = 0.45^{+0.67}_{-0.29}$%

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

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

Need to find more lenses in the radio with extended structure!

mJIVE-20: The mJy Imaging VLBI Exploration at 20 cm (Deller & Middelberg 2013).



Instrument: VLBA (filler time)

Area: 200 deg^2 (200 h)

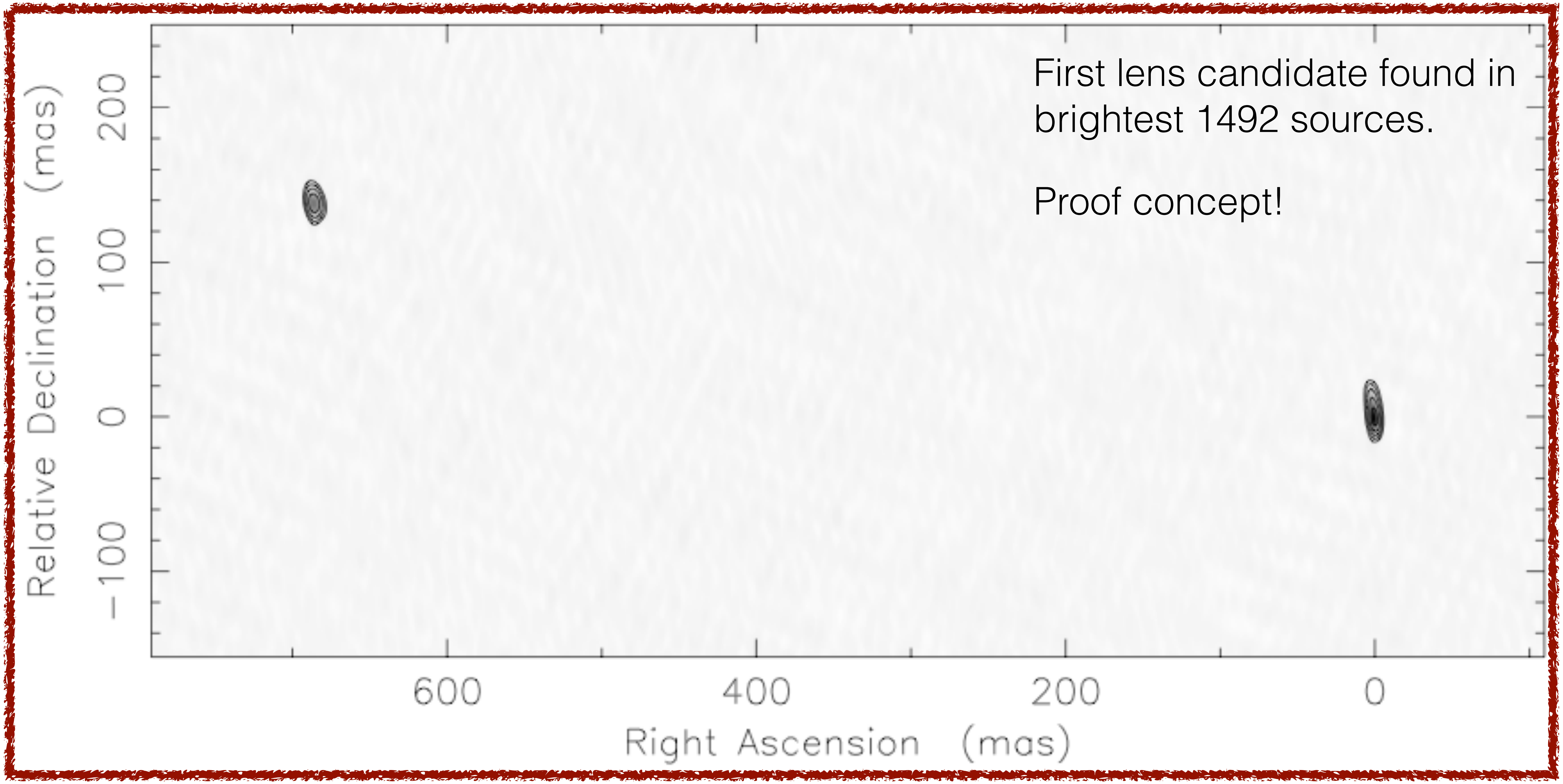
Resolution: 5--10 mas

Sources: 14812 (FIRST)

Detections: 3057

Potential lenses: 4 ± 2

mJIVE-20: The mJy Imaging VLBI Exploration at 20 cm (Deller & Middelberg 2013).



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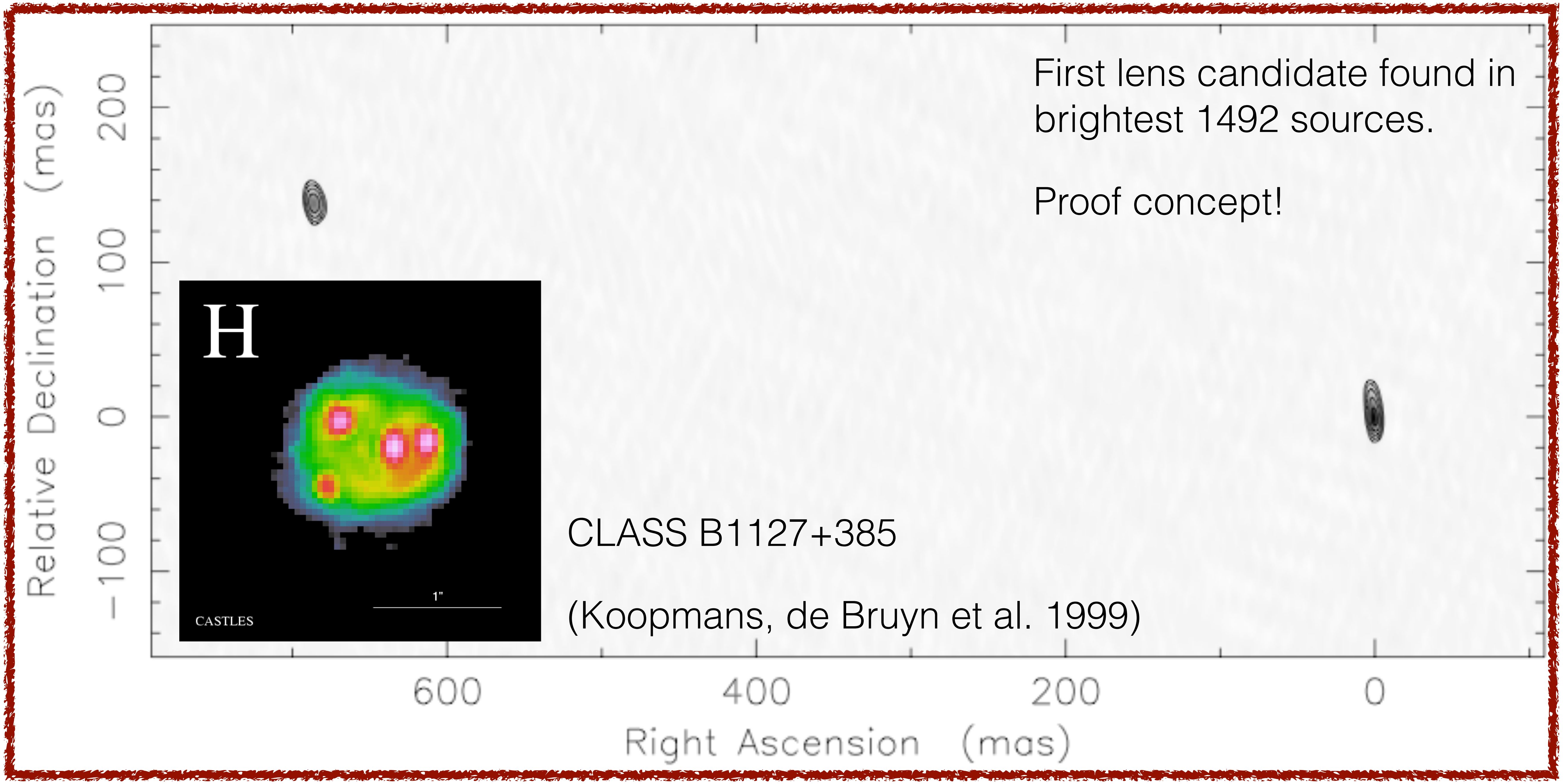
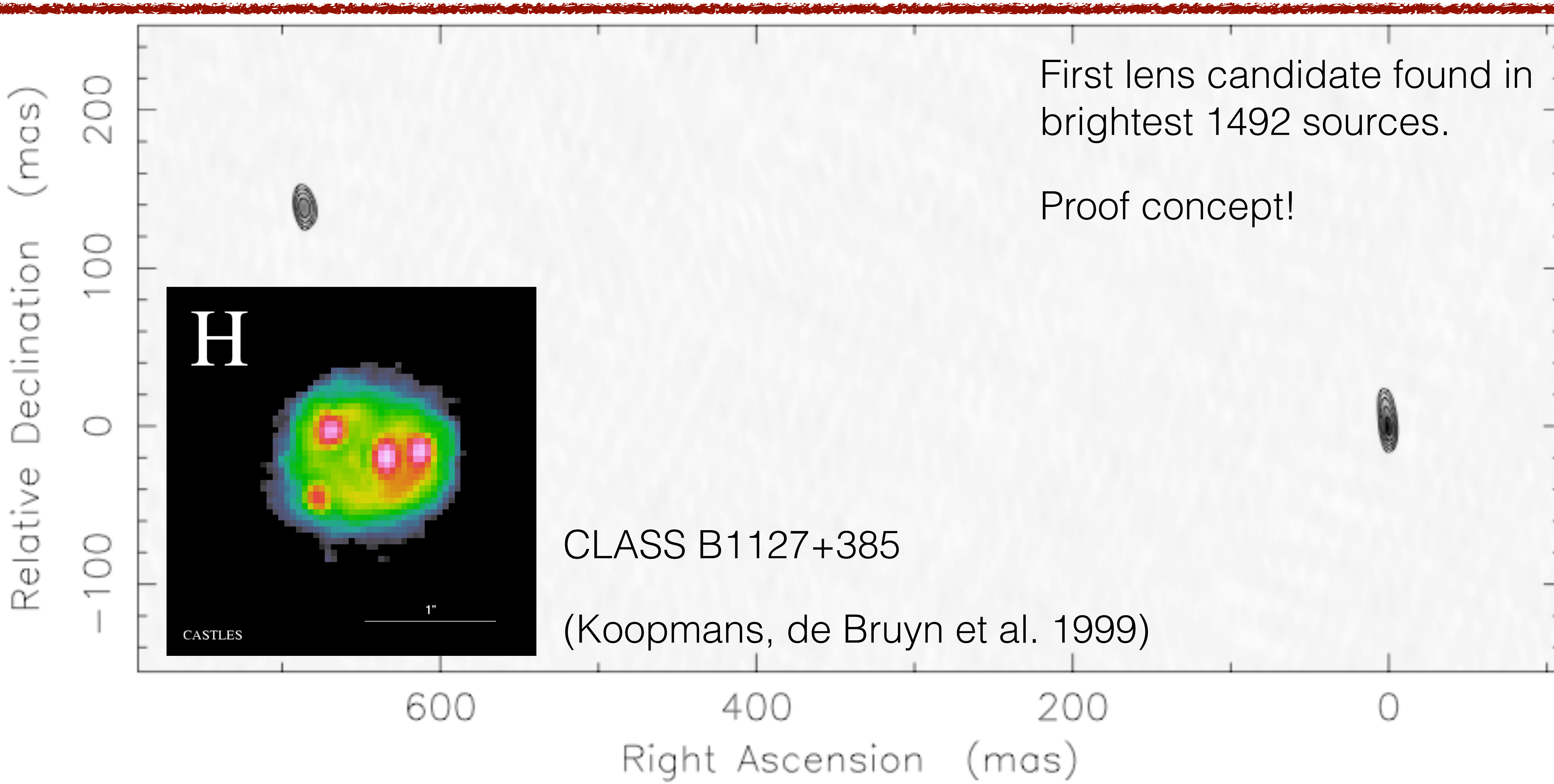


mJIVE-20: The mJy Imaging VLBI Exploration at 20 cm (Deller & Middelberg 2013).



Proposal for a 8000 deg² survey to be completed in VLBA filler time being prepared.

Expect to find ~ 150 new radio-loud gravitational lenses.

Summary

- The level of low mass substructure around massive galaxies is sensitive to the nature 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.
- Wide-field VLBI surveys have the potential to quickly increase the number of radio-loud lenses by factors ~ 5.