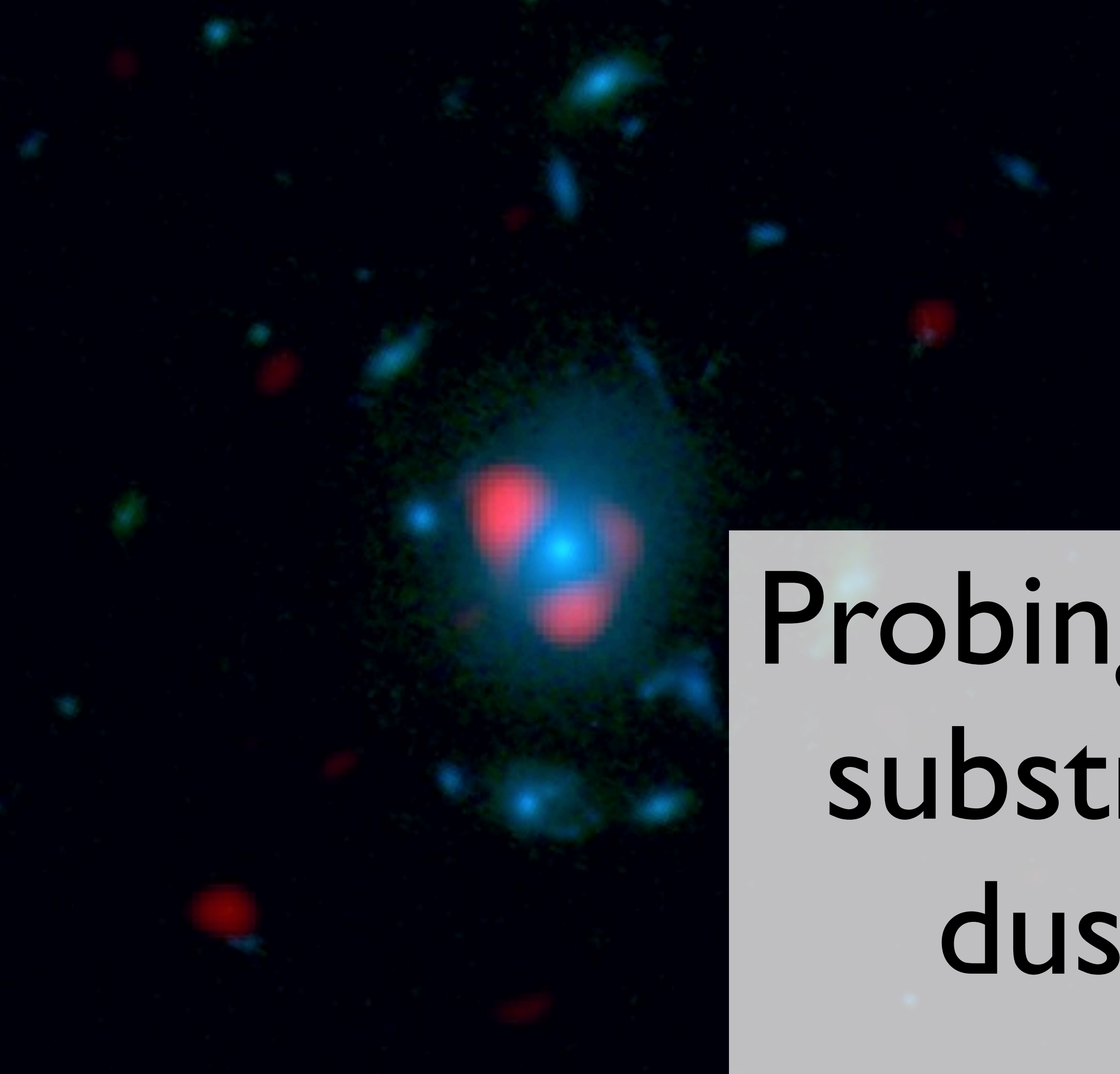
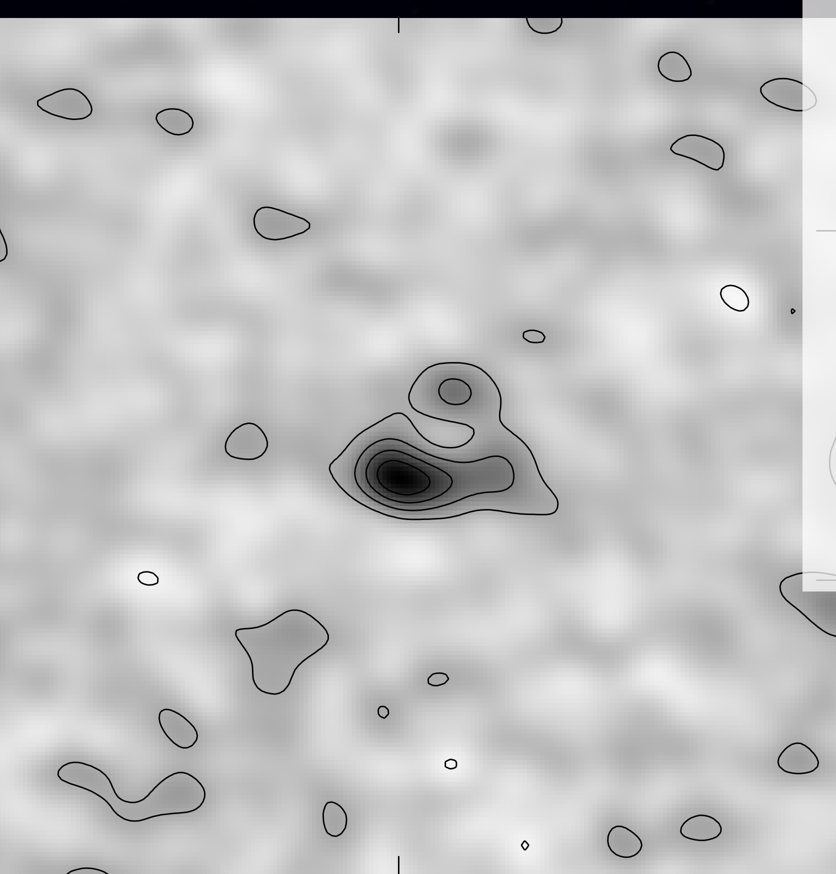
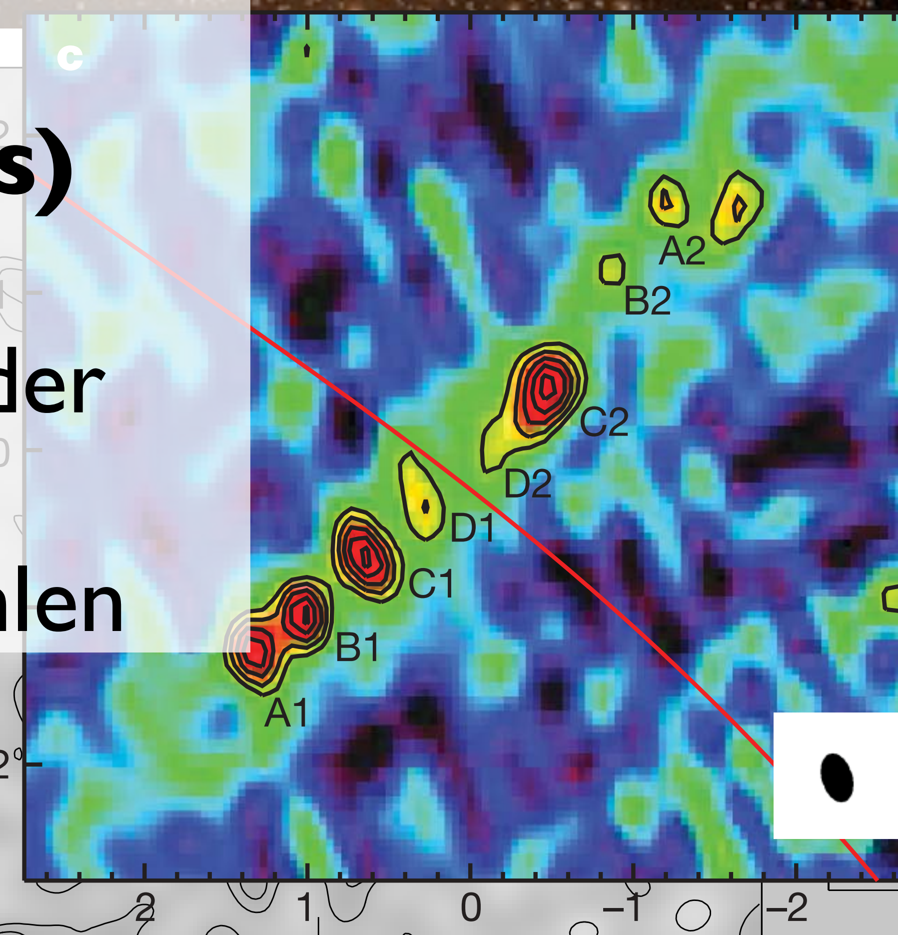


Probing dark matter substructure with dusty galaxies

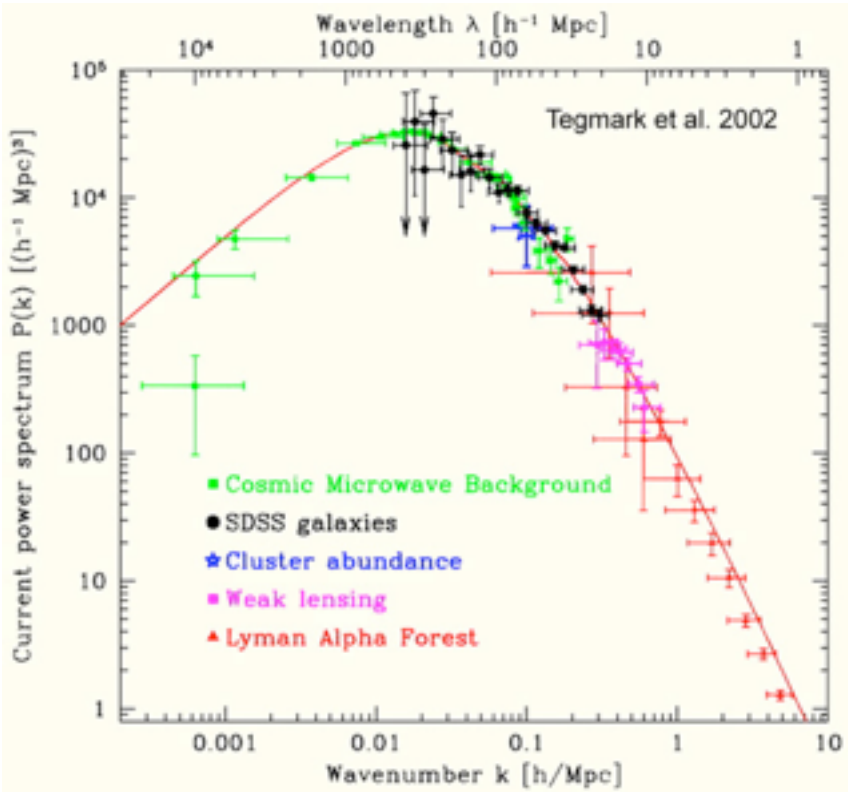
Neal Dalal (Illinois)

Yashar Hezaveh, Gil Holder
Joaquin Vieira [+ SPT]
Norm Murray, Mike Kuhlen





small-scale structure



Millennium-2 simulation (Boylan-Kolchin et al.)

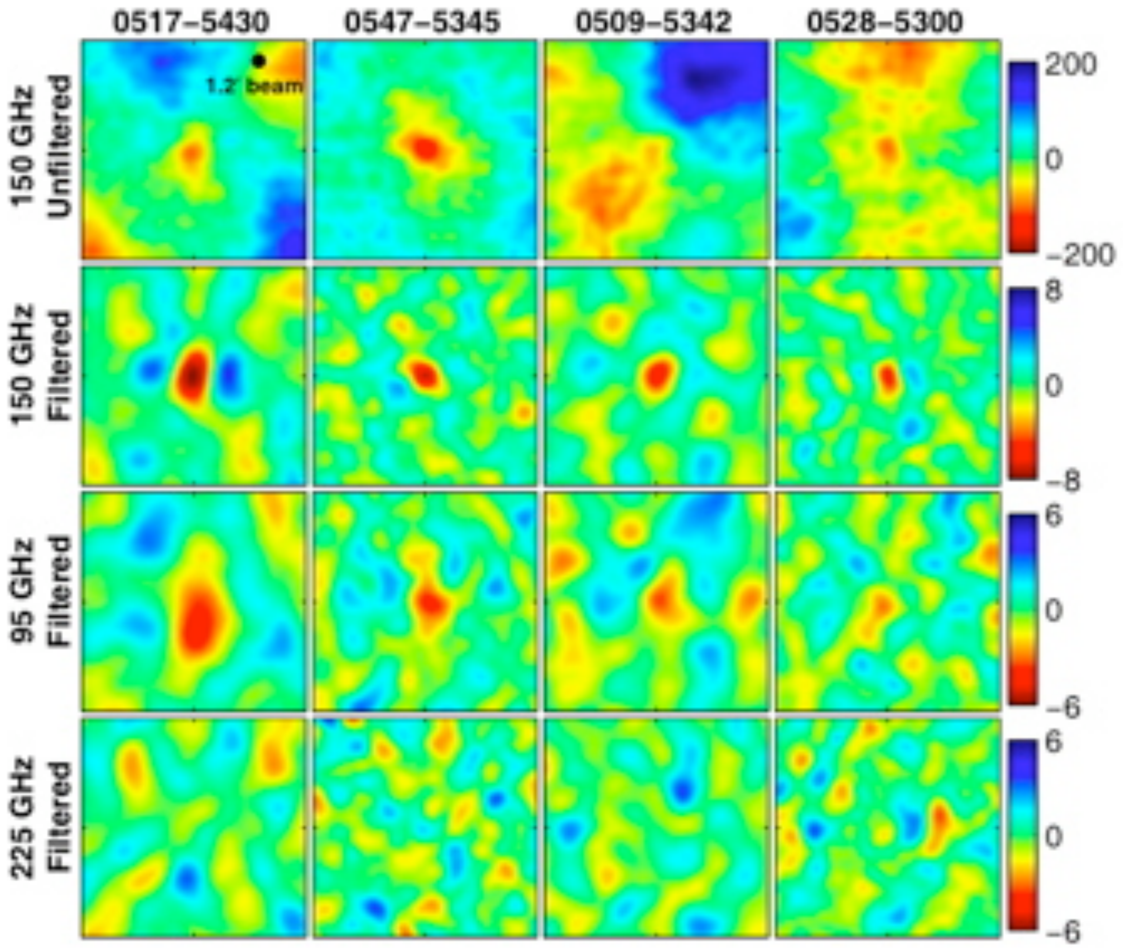
small-scale P(k) is interesting!

- shape of primordial power spectrum related to shape of inflaton potential
- small-scale P(k) sensitive to physics of DM particles

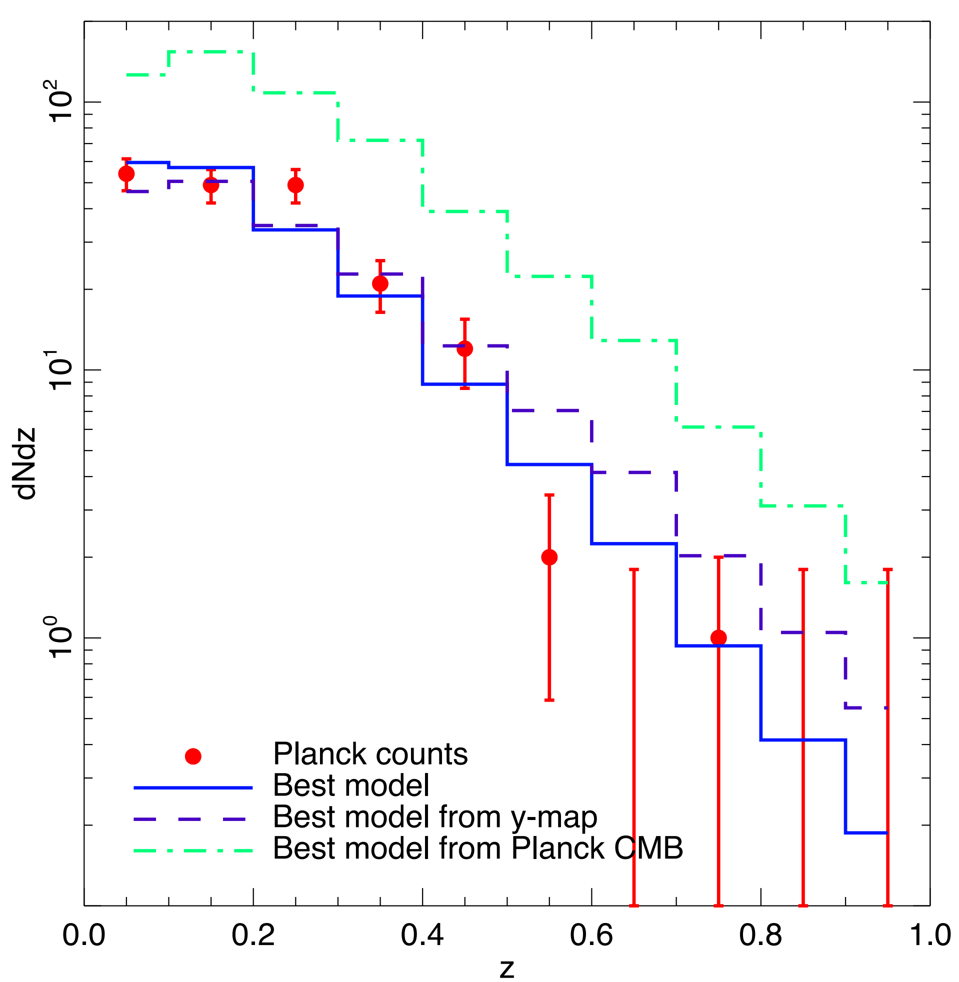
Current best probe is Ly α forest (e.g. Seljak et al. 2006), but already approaching gas Jeans scale!

abundances

- another probe: abundance of objects (e.g. cluster dn/dM)

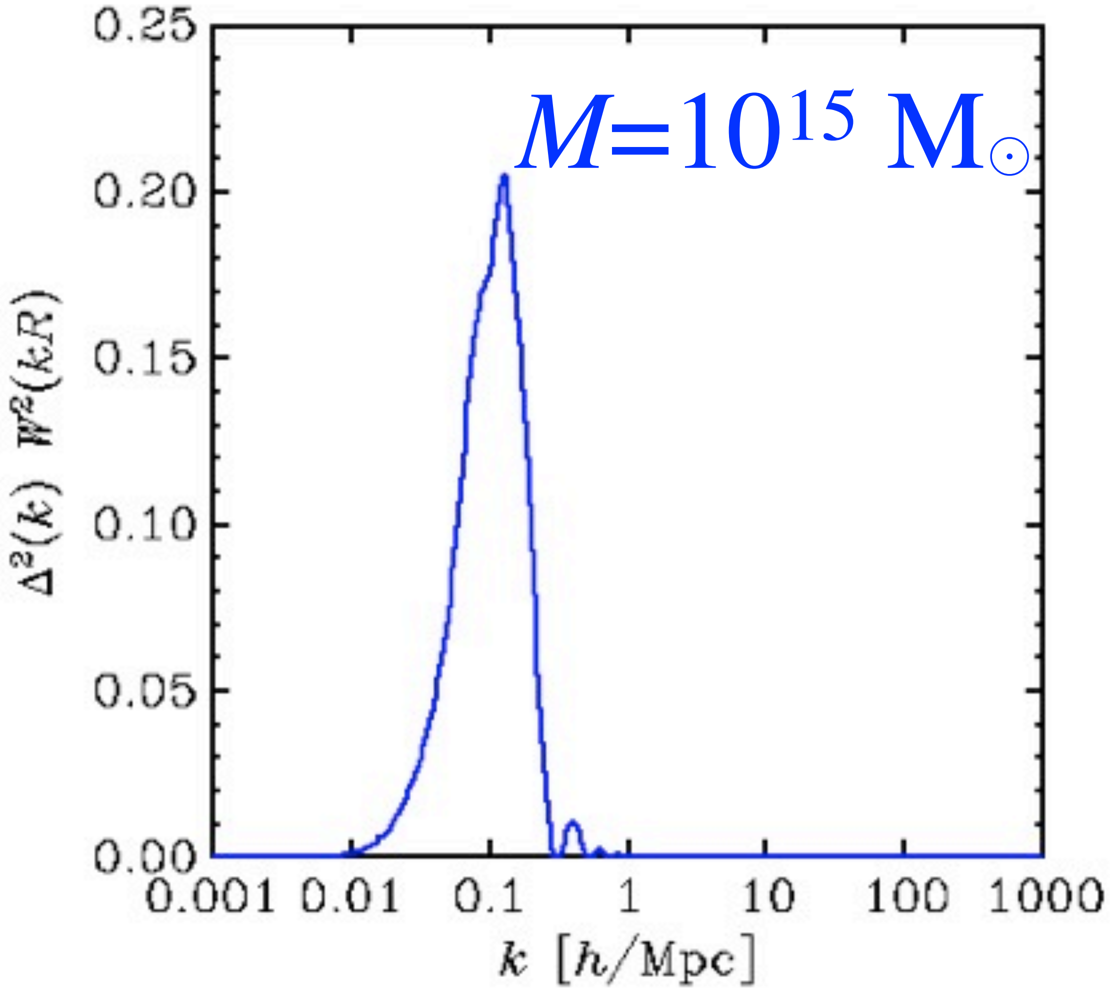


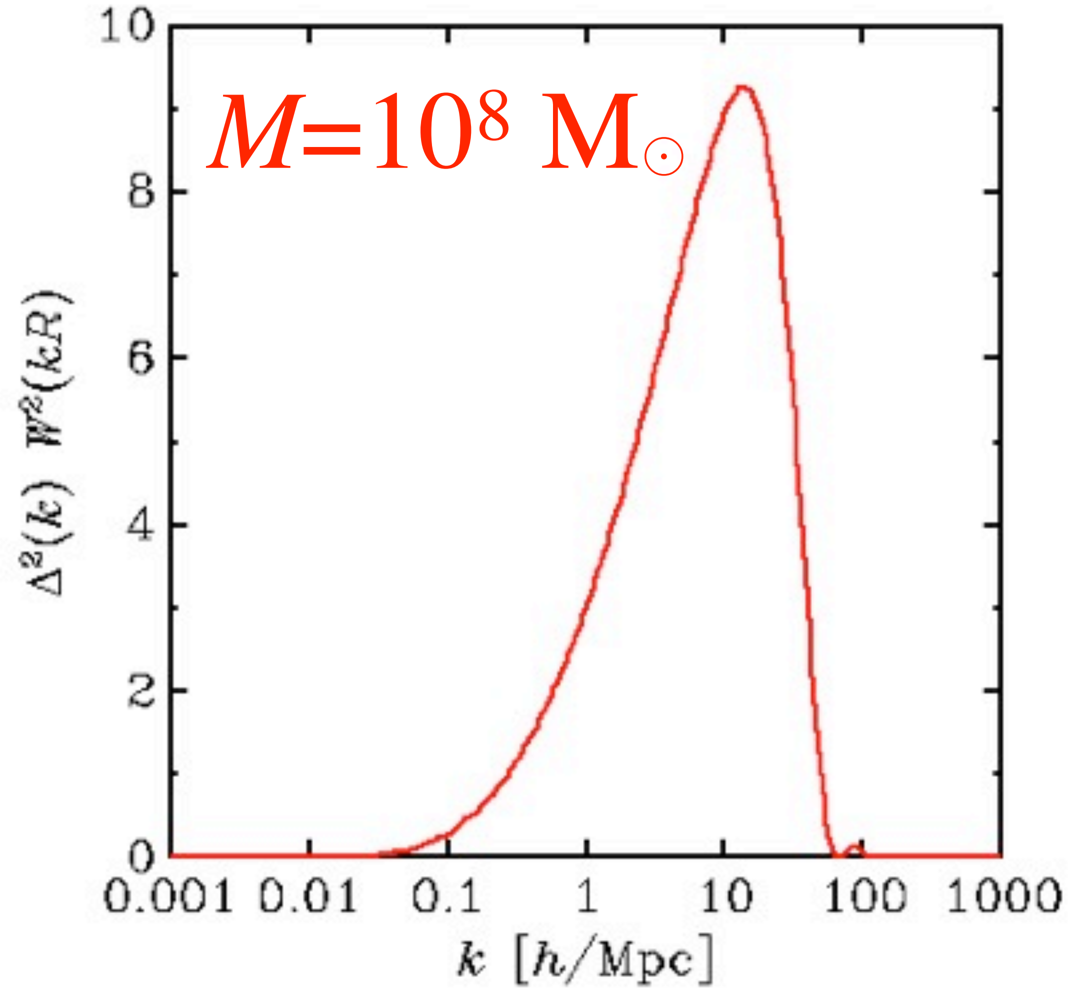
SZ maps



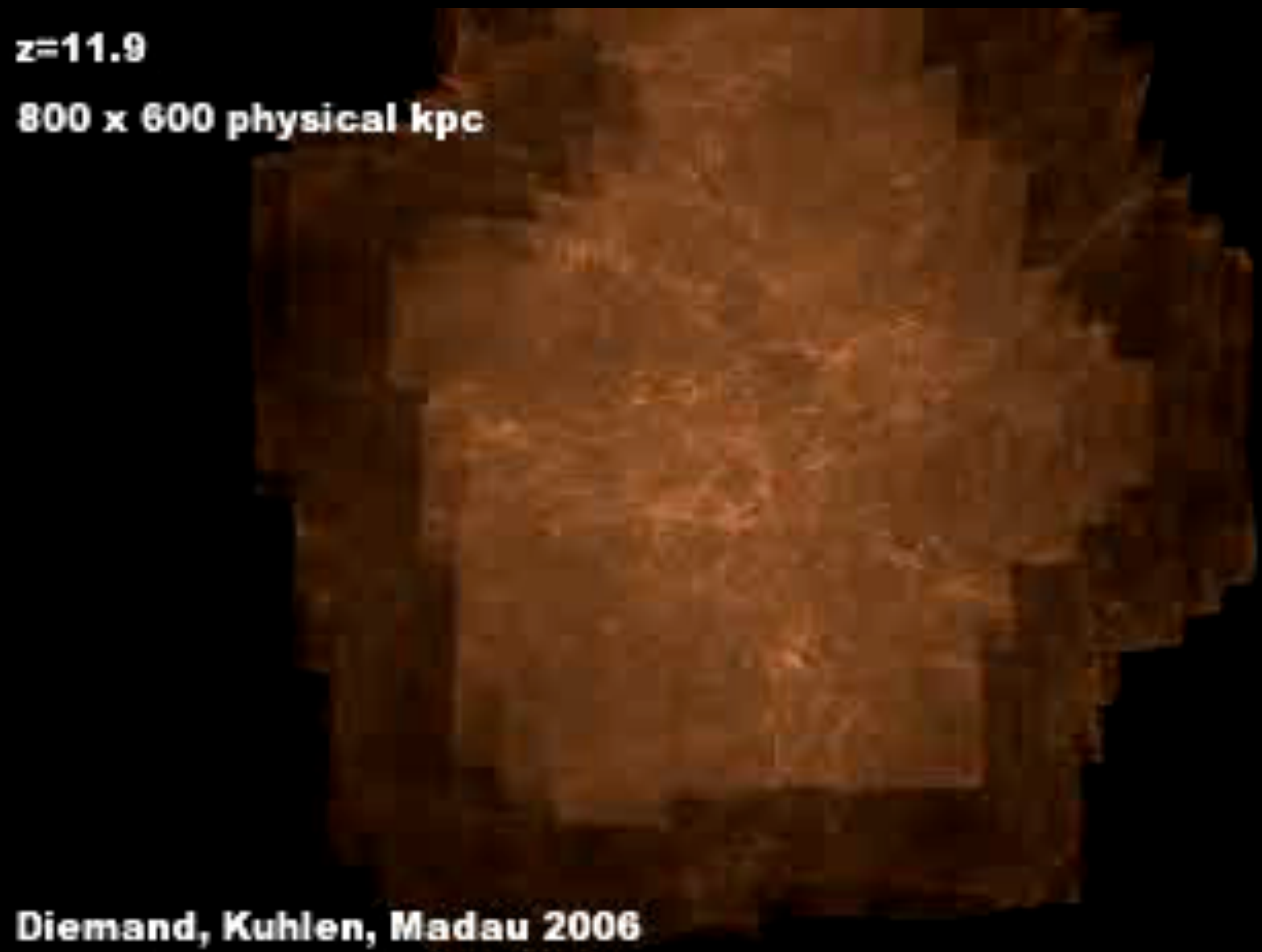
abundances

- another probe: abundance of objects (e.g. cluster dn/dM)
- low mass halos & sub-halos sensitive to small-scale P(k)





halos and subhalos



"Via Lactea"
Diemand et al. 2006

subhalos

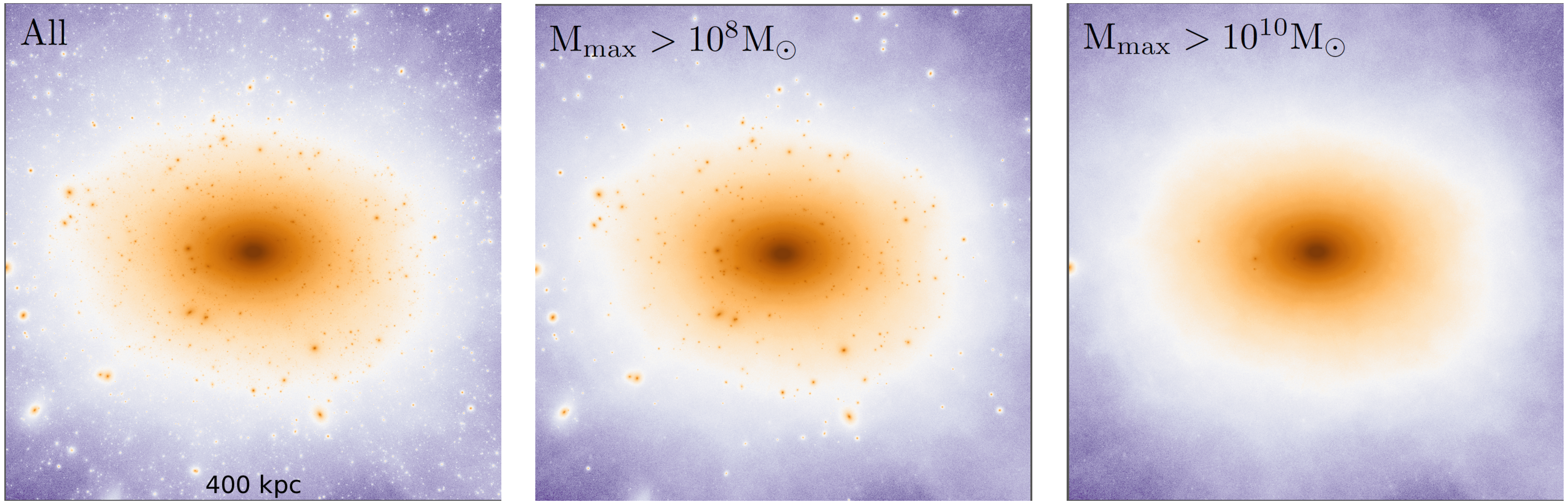
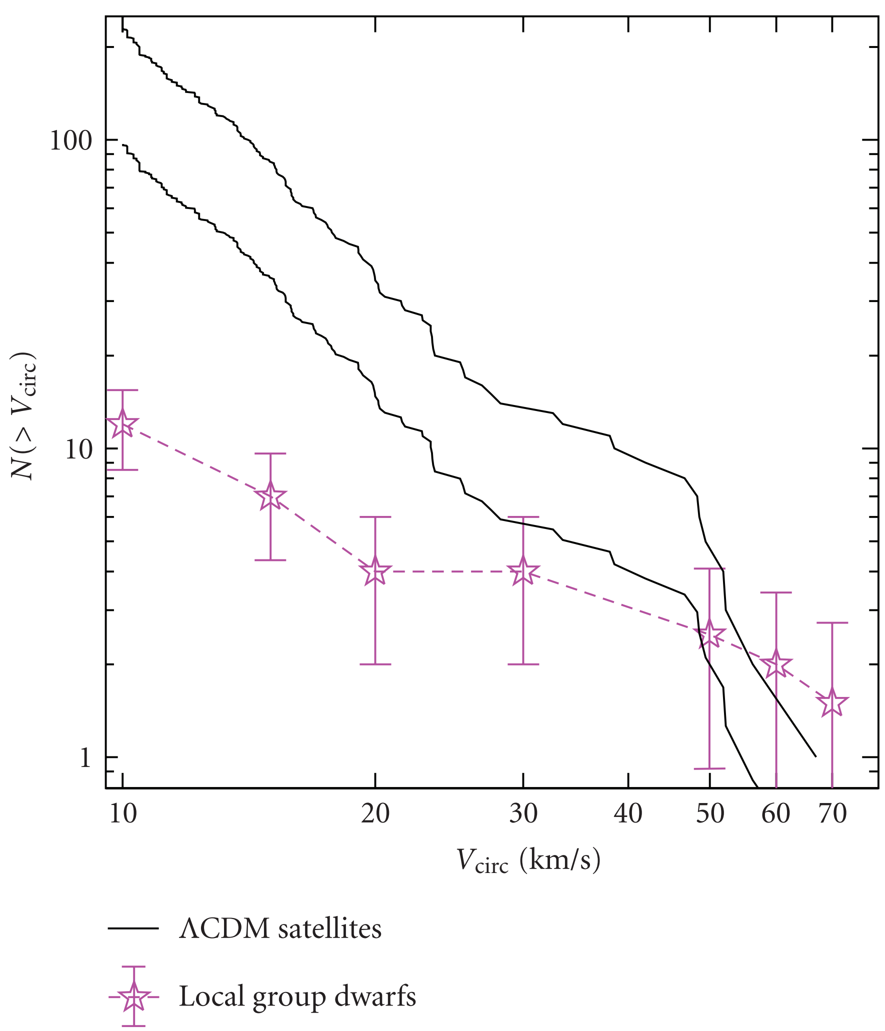


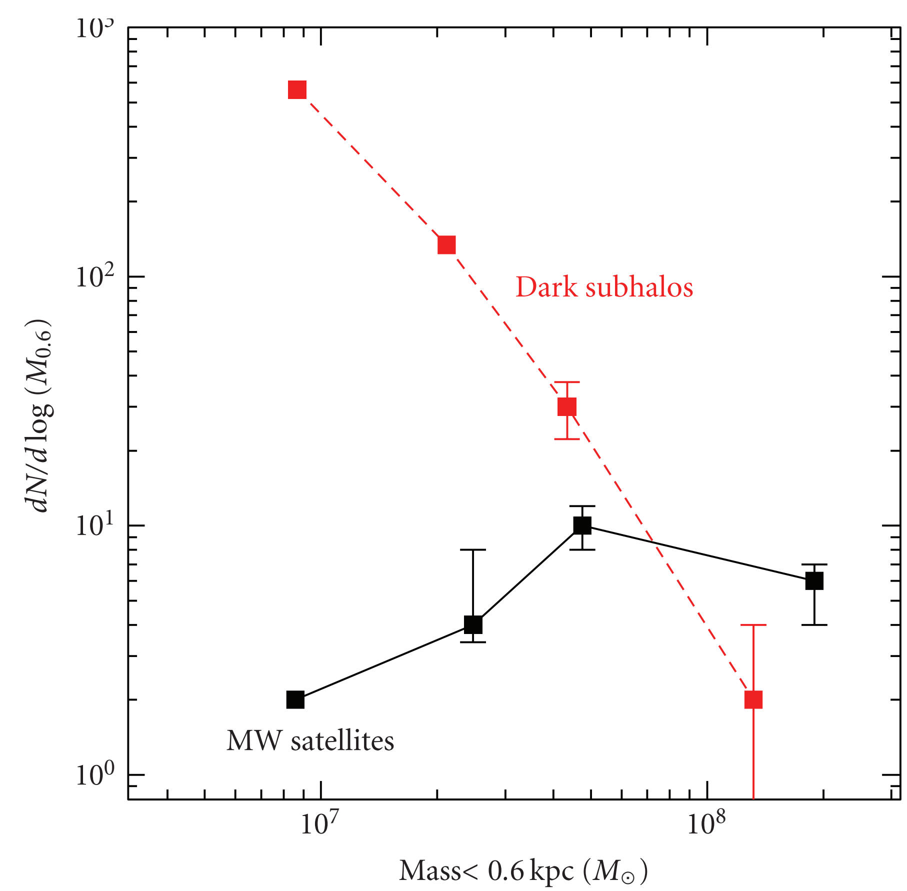
Figure 1: **Left:** Density projection in the Via Lactea-II simulation [18]. **Middle:** Similar, but excluding particles belonging to subhalos whose masses never exceeded $10^8 M_\odot$ any time throughout the simulation. **Right:** Like the middle panel, but excluding subhalos with $M_{\rm max} < 10^{10} M_\odot$. This sequence should qualitatively illustrate the effect of truncating the power spectrum on substructure content in DM halos.

How to measure?

- count small galaxies / satellites

➡ missing satellite problem (see Kravtsov 2012 for recent review)





How to measure?

- count small galaxies / satellites
  - ➡ missing satellite problem (see Kravtsov 2012 for recent review)
  - ➡ but low-mass subhalos could be dark...
- need *gravitational* probe to see dark halos/subhalos
  - heating of tidal streams (e.g. Carlberg 2012)
  - gravitational lensing!

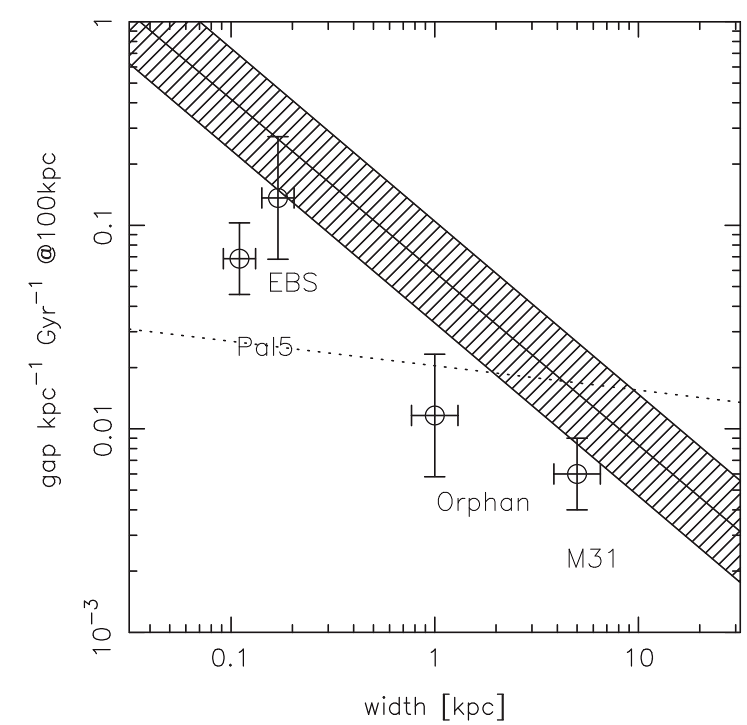
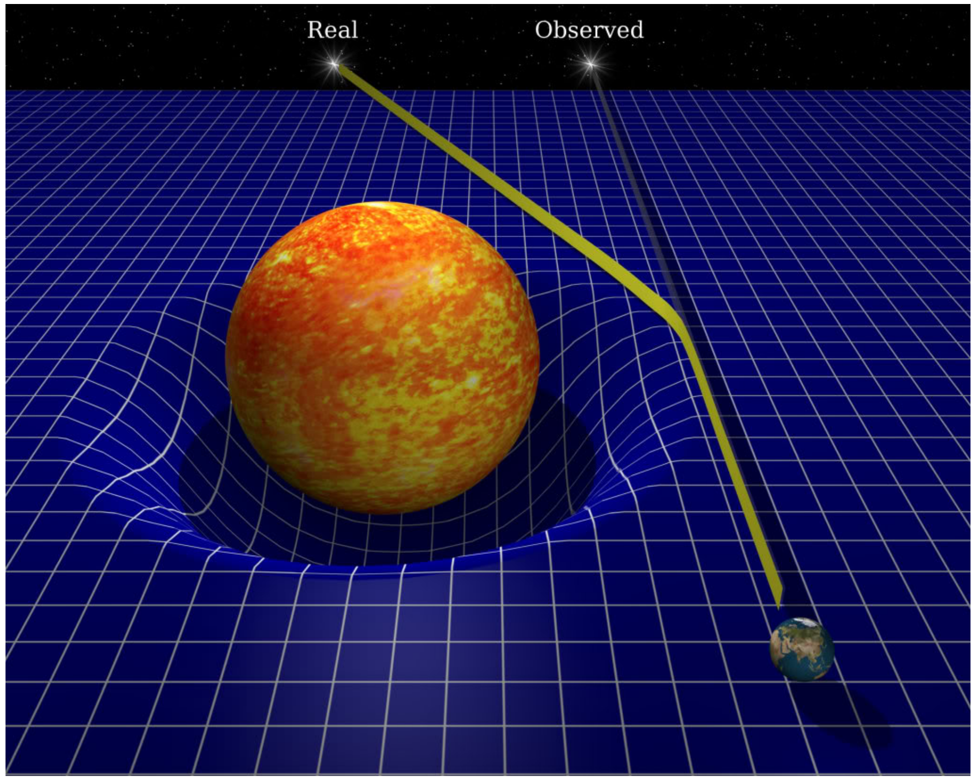
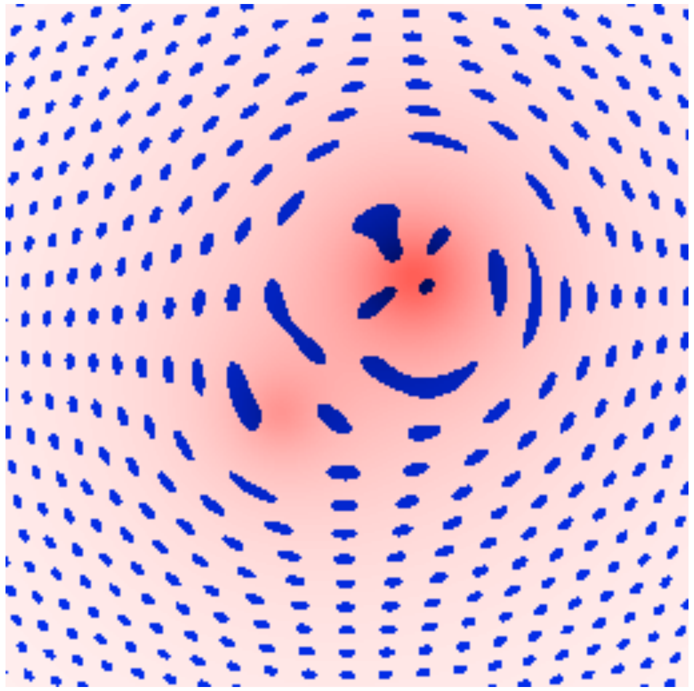


Figure 11. Estimated gap rate vs. stream width relation for M31 NW, Pal 5, the EBS, and the CDM halo prediction. All data are normalized to 100 kpc. The width of the theoretical relation is evaluated from the dispersion in the length–height relation of Figure 8. Predictions for an arbitrary alternative mass functions, $N(M) \propto M^{-1.6}$, normalized to have 33 halos above $10^9 \, M_\odot$ are shown with a dotted line.

Gravitational lensing

- the deflection of light rays caused by inhomogeneities
- also distorts the apparent shapes & sizes of observed sources
- amount of lensing characterized by *convergence* $\kappa \sim \int \delta\rho \, dl$
- Two regimes:
  - ✦ weak lensing ($|\kappa| \ll 1$) : small distortion
  - ✦ strong lensing ($\kappa \gtrsim 1$) : large distortion & *multiple imaging*





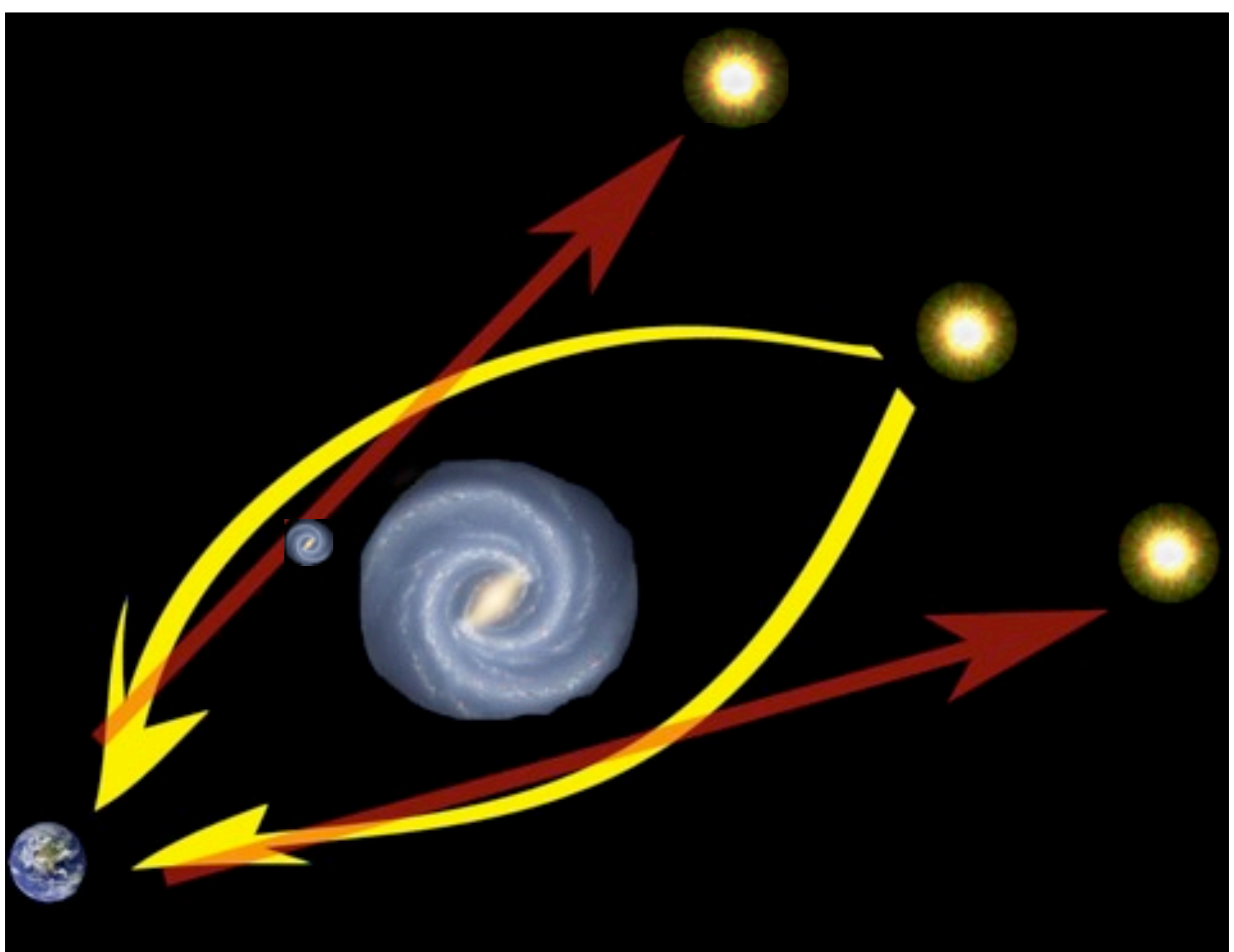
subhalo lensing

small ($M<10^8\ M_\odot$) halos and subhalos are wimpy lenses!

- small size ($\lesssim$ kpc), so each one affects a small fraction of the sky
- lensing amplitude is weak (central $\kappa,\gamma \lesssim 0.1$)
- need a way to boost their effect to detect them...

strong lensing

- if a small halo/subhalo projects near a **strong lens**, then the big lens can magnify the lensing effect of the small halo

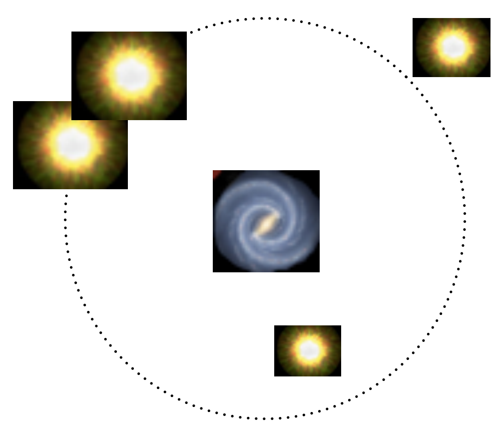


$$\Delta\theta \approx \mathbf{M} \cdot \Delta\alpha$$

if high magnification, then perturbation can have big effect!
(Mao & Schneider 1998)

universality relations

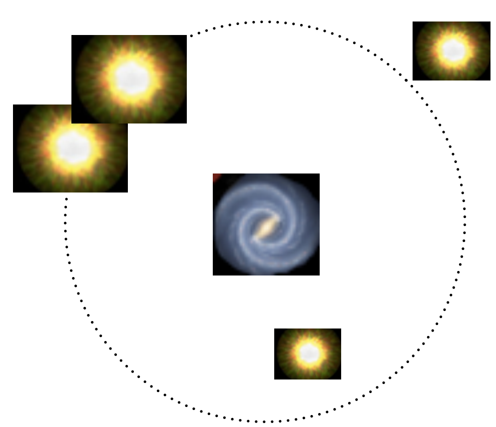
- when 2 images are close together, they *should* have nearly equal brightness

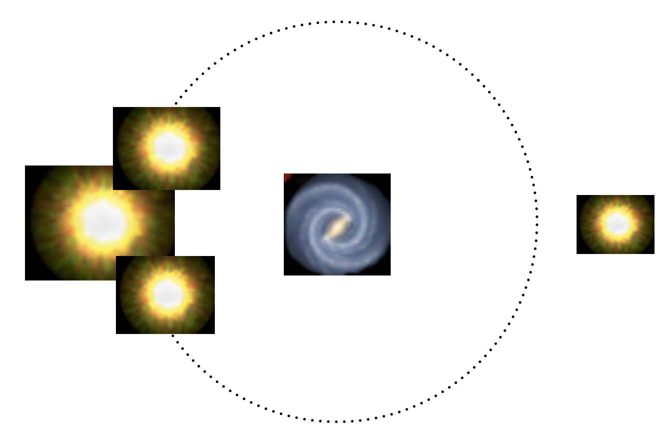


$$\frac{\Delta f}{f} \propto \frac{\Delta r}{r_s}$$

universality relations

- when 2 images are close together, they *should* have nearly equal brightness
- similar relation when 3 images occur close together:

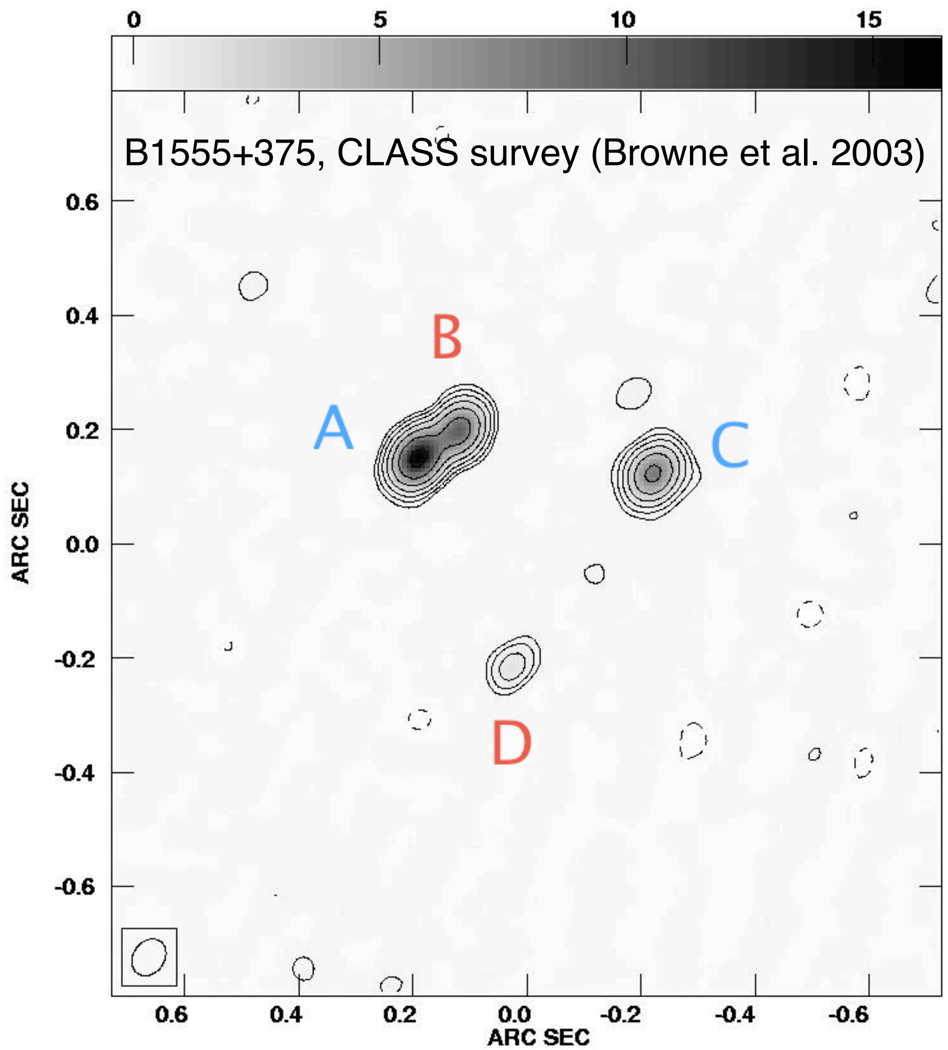


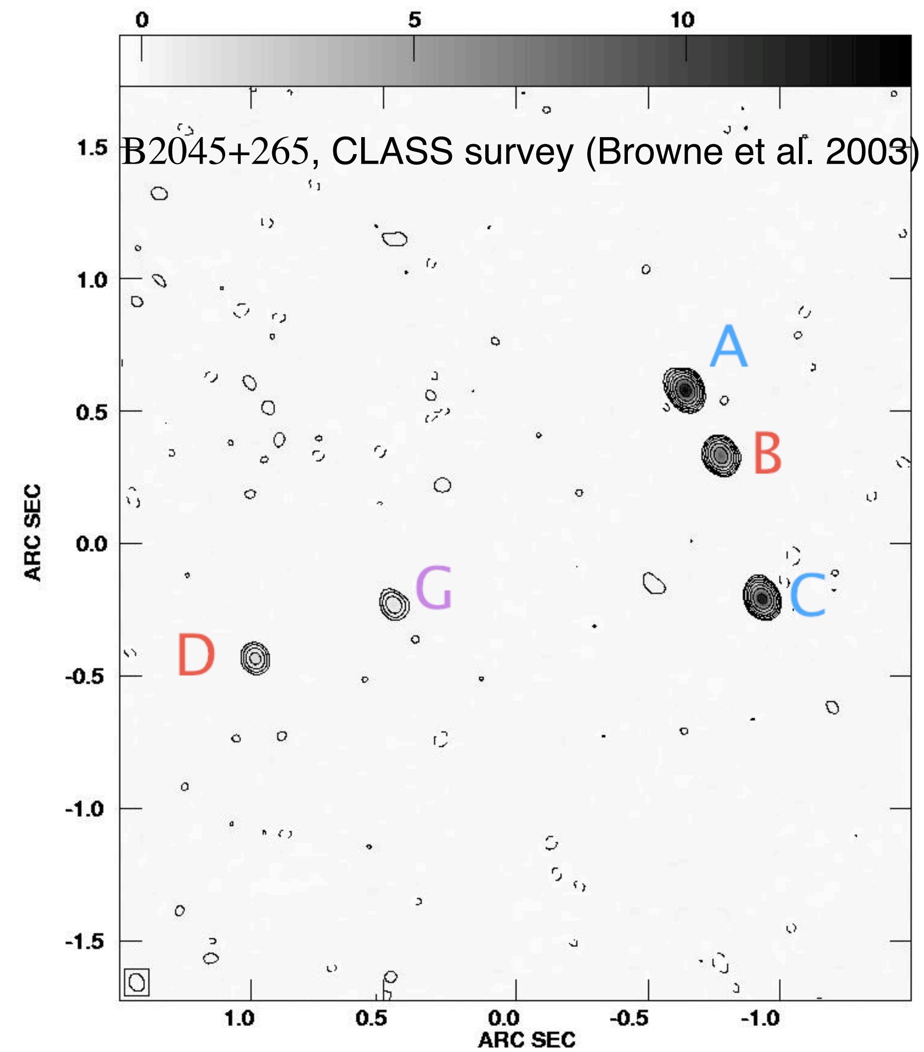


$$\frac{\Delta f}{f} \propto \frac{\Delta r}{r_s}$$

$$\frac{f_A - f_B + f_C}{f_A + f_B + f_C} \propto \frac{\Delta r}{r_s}$$

universality relations





$$\frac{\Delta f}{f} \propto \frac{\Delta r}{r_s}$$

$$\frac{f_A - f_B + f_C}{f_A + f_B + f_C} \propto \frac{\Delta r}{r_s}$$

flux anomalies

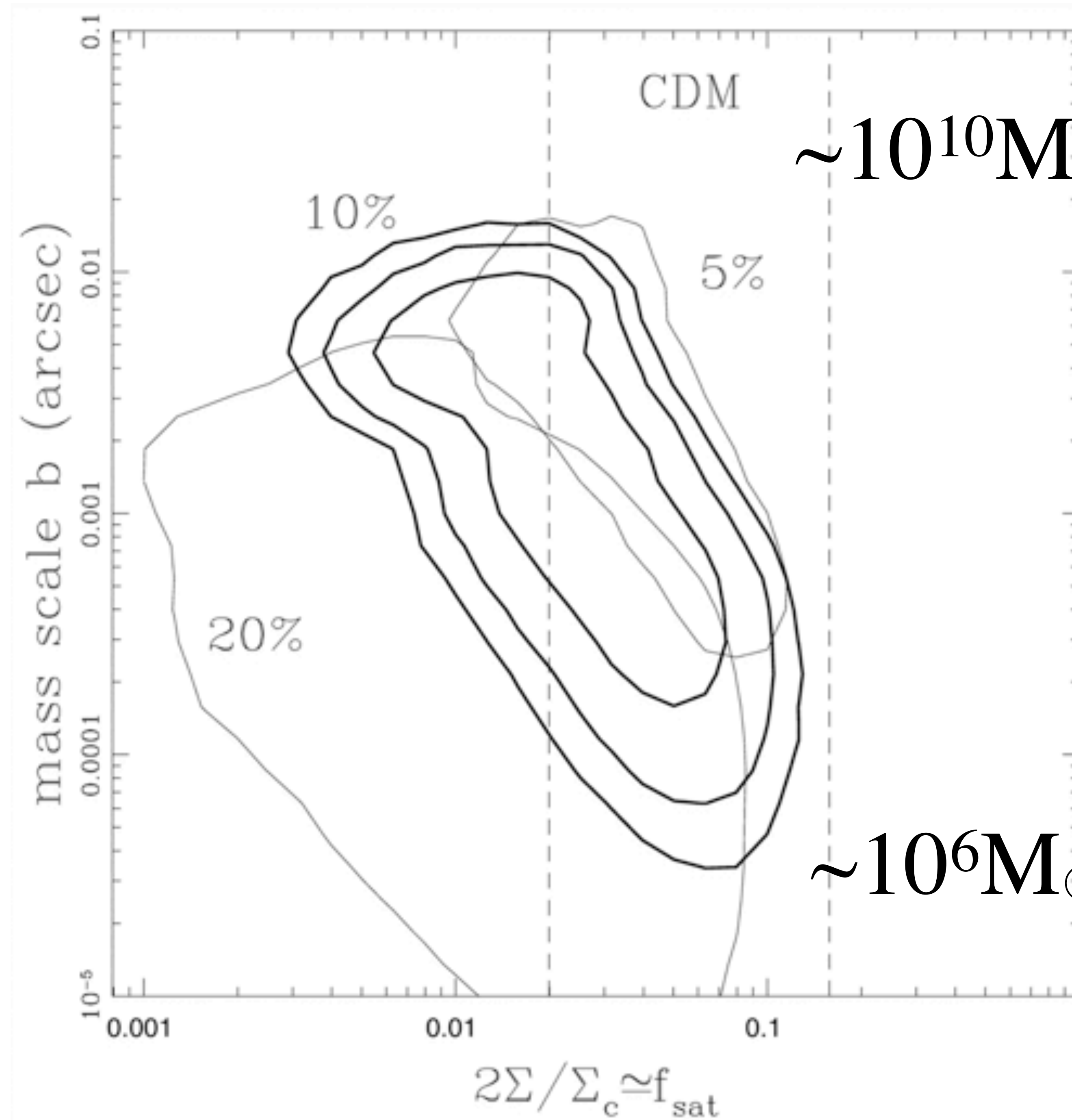
- implication: local scale length r_s is much smaller than size of the system $\Longrightarrow$ **substructure** in the potential
- in radio quasars, flux ratio anomalies can only be caused by mass substructure (not true for optical lenses)
- flux anomalies occur in almost all of the observed quasar lenses $\Longrightarrow$ lots of substructure!

how do we know it's substructure?

- radio flux ratios independent of λ, as expected for lensing but unlike propagation effects (like scintillation or dust extinction)
- observed **parity** dependence: + parity magnified, – parity demagnified
- radio quasars too big to be affected by stellar microlensing, unlike stellar QSO's.
- see Kochanek & Dalal (2003) for more...

analysis of radio lenses

- Dalal & Kochanek (2002) analyzed sample of **7** radio lenses
- found that ~ 1-2% of projected mass at 5kpc is in substructure



$\sim 10^{10} M_\odot$

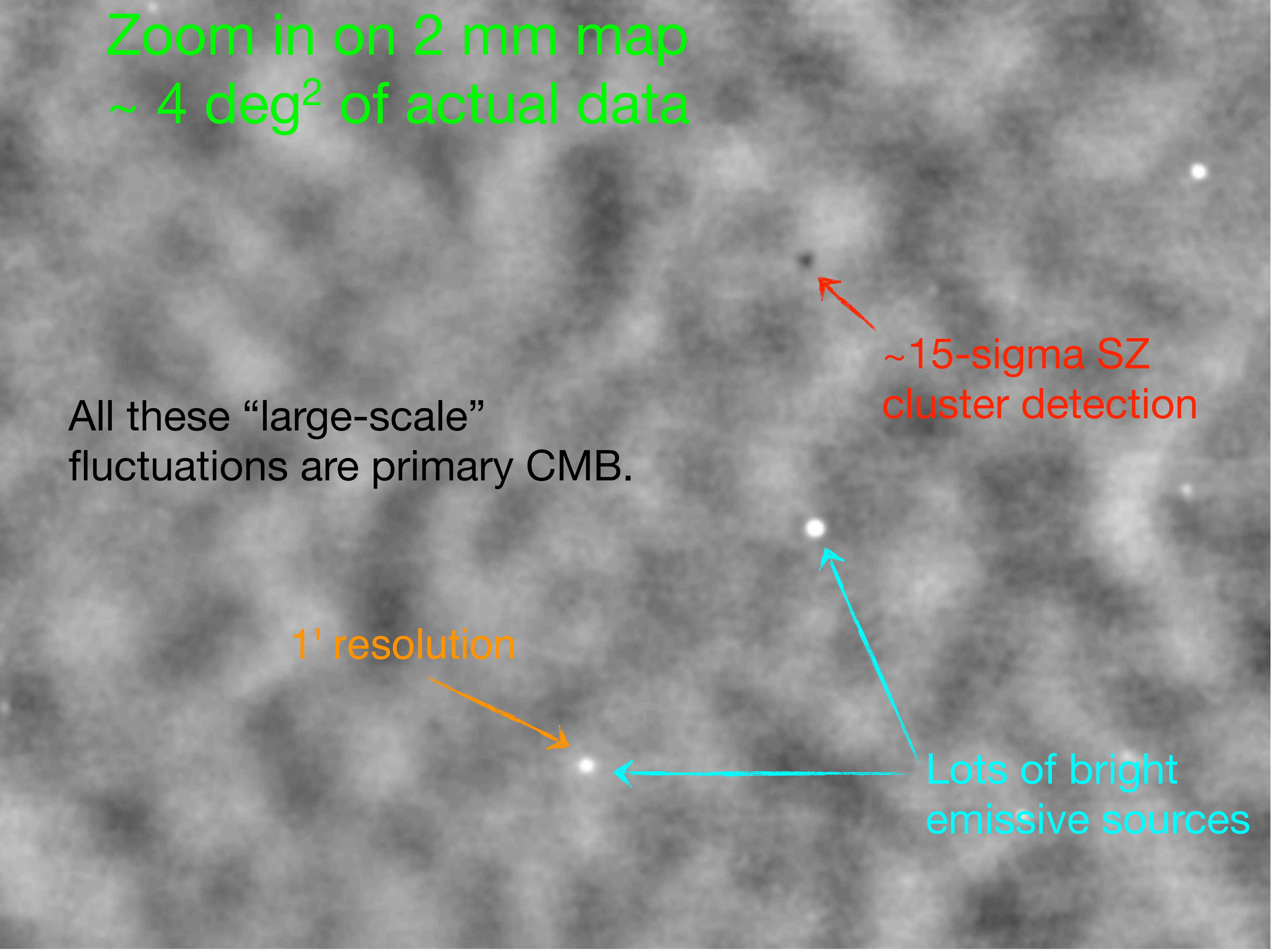
$\sim 10^{6} M_\odot$

how to improve?

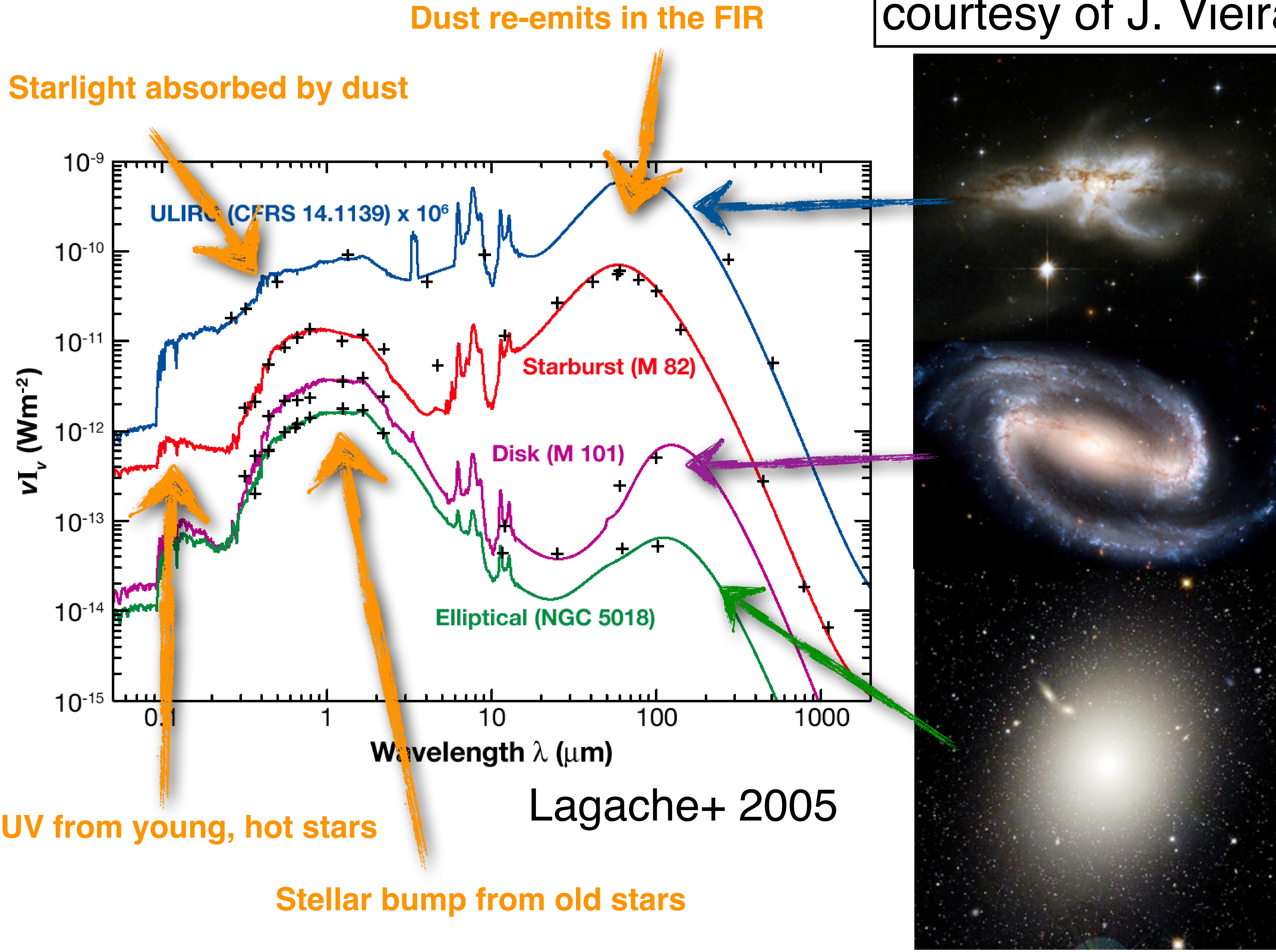
- DK02 analyzed a tiny sample (7 lenses), but many more lenses are known, e.g. >100 optical lenses
- unfortunately, optical QSO's are affected by extinction and stellar microlensing
- can circumvent with mid-IR fluxes, but most QSO's are faint in mid-IR
- galaxy lenses (e.g. SLACS) are **really** challenging (see, e.g., Vegetti et al. 2012)

how to improve?

- we need a new class of lensed sources!

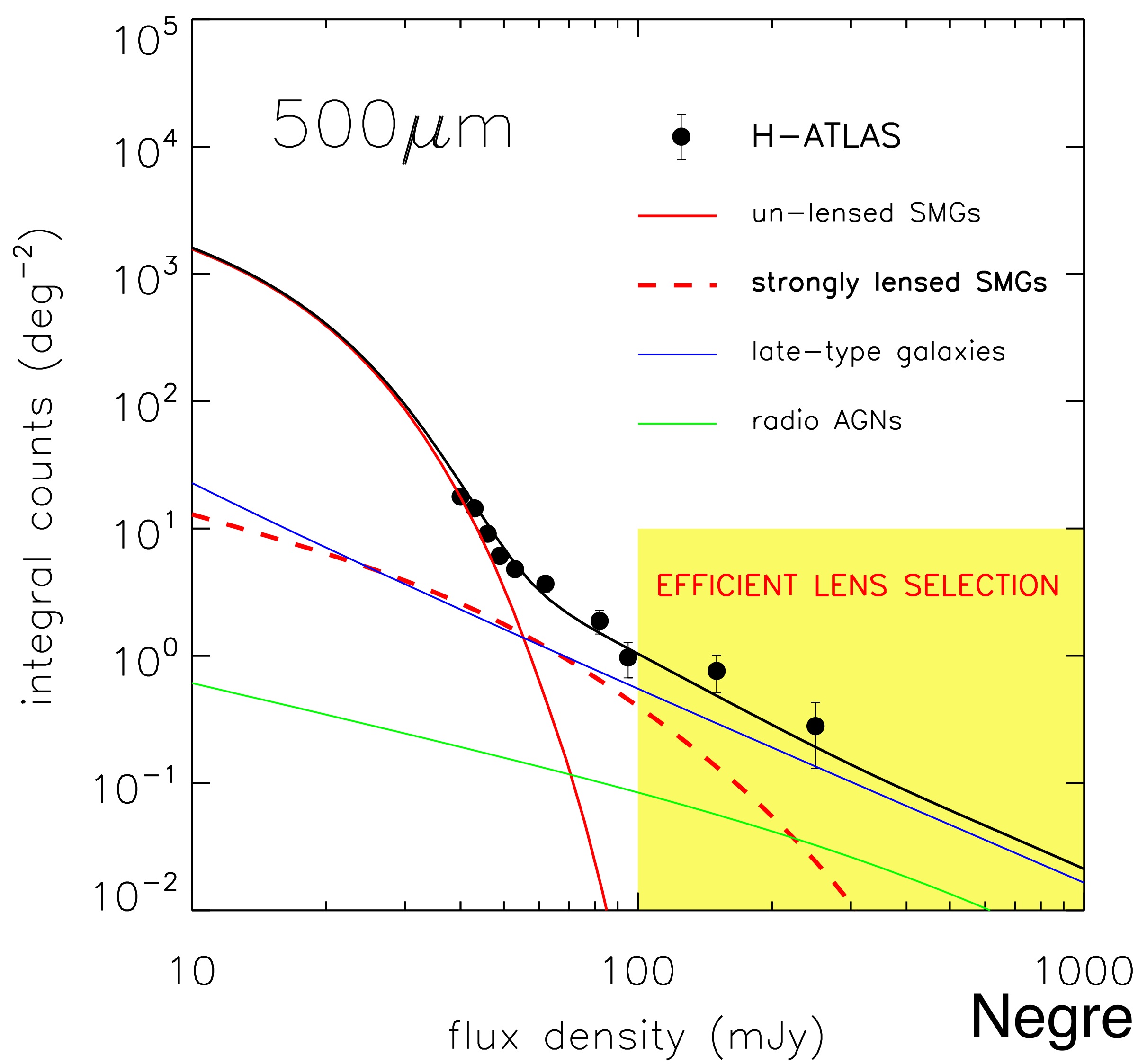

Zoom in on 2 mm map
~ 4 deg² of actual data
All these “large-scale”
fluctuations are primary CMB.
~15-sigma SZ
cluster detection
1' resolution
Lots of bright
emissive sources

courtesy of J. Vieira



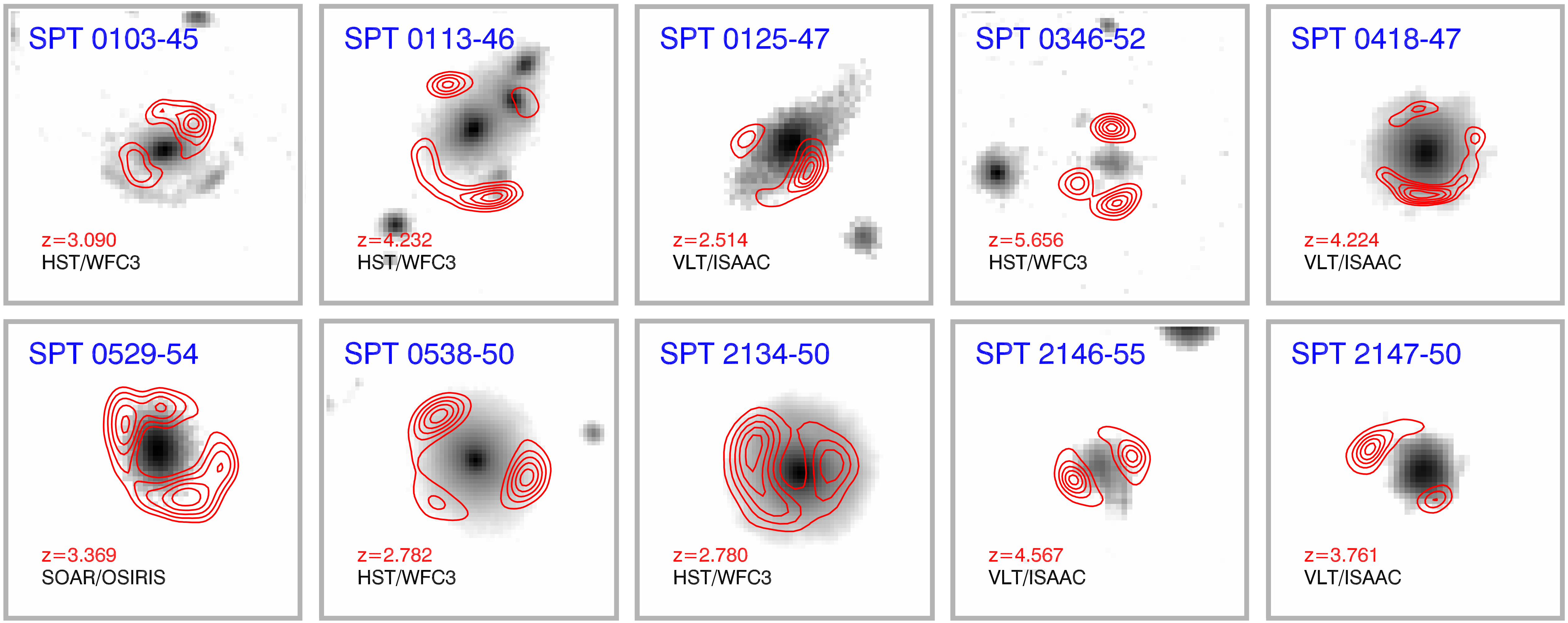
so what?

- why should we care about SPT's SMGs?
- because they're (basically) all lensed!



Negrello et al. (2010)

ALMA Cycle 0 Band 7 350 GHz
2 minute snapshots

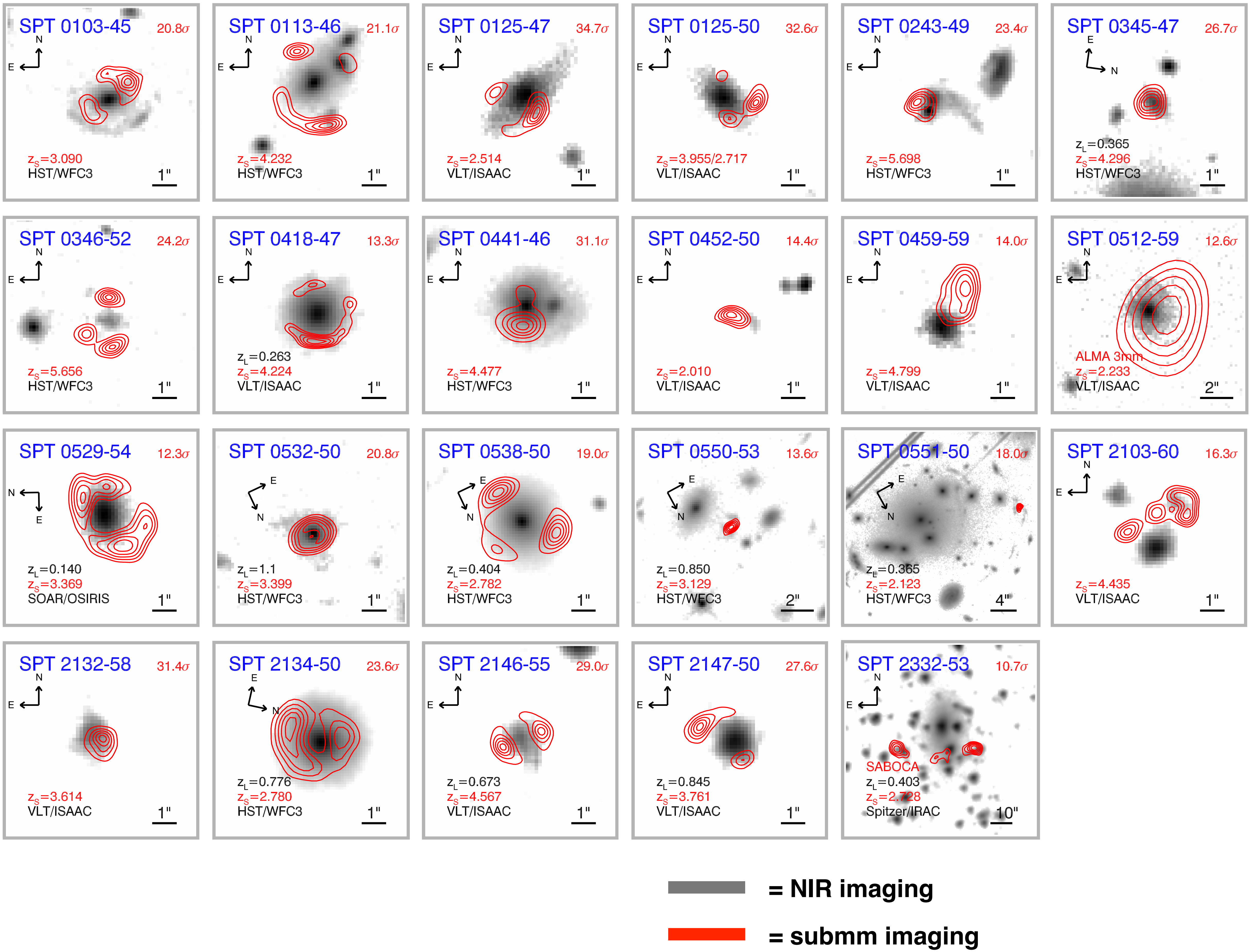


8" x 8" boxes

= deep NIR imaging

= 2 minute ALMA 350 GHz snapshot

Only through the combination of strong gravitational lensing, the SPT selection, and ALMA followup is this result possible


SPT 0103-45
20.8σ
z_S=3.090
HST/WFC3
1"
SPT 0113-46
21.1σ
z_S=4.232
HST/WFC3
1"
SPT 0125-47
34.7σ
z_S=2.514
VLT/ISAAC
1"
SPT 0125-50
32.6σ
z_S=3.955/2.717
VLT/ISAAC
1"
SPT 0243-49
23.4σ
z_S=5.698
HST/WFC3
1"
SPT 0345-47
26.7σ
z_L=0.365
z_S=4.296
HST/WFC3
1"
SPT 0346-52
24.2σ
z_S=5.656
HST/WFC3
1"
SPT 0418-47
13.3σ
z_L=0.263
z_S=4.224
VLT/ISAAC
1"
SPT 0441-46
31.1σ
z_S=4.477
HST/WFC3
1"
SPT 0452-50
14.4σ
z_S=2.010
VLT/ISAAC
1"
SPT 0459-59
14.0σ
z_S=4.799
VLT/ISAAC
1"
SPT 0512-59
12.6σ
ALMA 3mm
z_S=2.233
VLT/ISAAC
2"
SPT 0529-54
12.3σ
z_L=0.140
z_S=3.369
SOAR/OSIRIS
1"
SPT 0532-50
20.8σ
z_L=1.1
z_S=3.399
HST/WFC3
1"
SPT 0538-50
19.0σ
z_L=0.404
z_S=2.782
HST/WFC3
1"
SPT 0550-53
13.6σ
z_L=0.850
z_S=3.129
HST/WFC3
2"
SPT 0551-50
18.0σ
z_L=0.365
z_S=2.123
HST/WFC3
4"
SPT 2103-60
16.3σ
z_S=4.435
VLT/ISAAC
1"
SPT 2132-58
31.4σ
z_S=3.614
VLT/ISAAC
1"
SPT 2134-50
23.6σ
z_L=0.776
z_S=2.780
HST/WFC3
1"
SPT 2146-55
29.0σ
z_L=0.673
z_S=4.567
VLT/ISAAC
1"
SPT 2147-50
27.6σ
z_L=0.845
z_S=3.761
VLT/ISAAC
1"
SPT 2332-53
10.7σ
SABOCA
z_L=0.403
z_S=2.728
Spitzer/IRAC
10"
= NIR imaging
= submm imaging

Lens models

dirty image model image residual source model

SPT 0346-52

$z_S = 5.67$; $z_L \sim 0.8$
$r_E = 1.1$ arcsec
$M_L = 3.7 \times 10^{11}\ M_\odot$
$\mu = 5.4$

$\Sigma_{FIR} = 24\mathrm{x}10^{12}\ L_\odot/\mathrm{kpc}^2$
$R_{1/2} = 0.6$ kpc
$L_{FIR} = 3.7 \times 10^{13}\ L_\odot$
$S_{850\mu m} = 25.5$ mJy

SPT 418-47

$z_S = 4.22$; $z_L = 0.27$
$r_E = 1.4$ arcsec
$M_L = 2.4 \times 10^{11}\ M_\odot$
$\mu = 21$

$\Sigma_{FIR} = 0.74\mathrm{x}10^{12}\ L_\odot/\mathrm{kpc}^2$
$R_{1/2} = 1.1$ kpc
$L_{FIR} = 3.8 \times 10^{12}\ L_\odot$
$S_{850\mu m} = 4.8$ mJy

SPT 0529-54

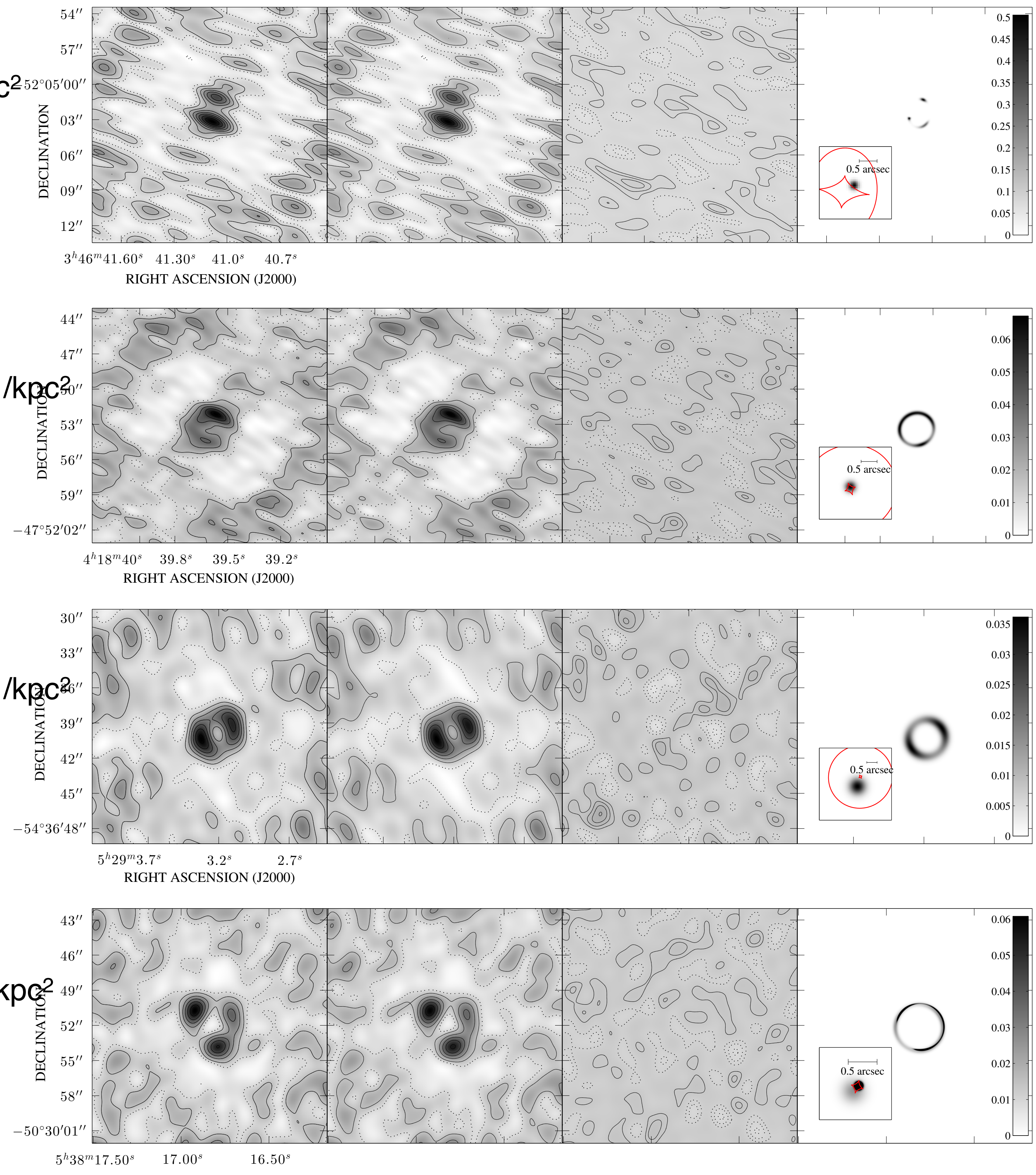
$z_S = 3.37$; $z_L = 0.13$
$r_E = 1.5$ arcsec
$M_L = 1.6 \times 10^{11}\ M_\odot$
$\mu = 9.4$

$\Sigma_{FIR} = 0.15\mathrm{x}10^{12}\ L_\odot/\mathrm{kpc}^2$
$R_{1/2} = 2.4$ kpc
$L_{FIR} = 3.8 \times 10^{12}\ L_\odot$
$S_{850\mu m} = 13$ mJy

SPT 0538-50

$z_S = 2.782$; $z_L = 0.4$
$r_E = 2.0$ arcsec
$M_L = 7.2 \times 10^{11}\ M_\odot$
$\mu = 20.5$

$\Sigma_{FIR} = 1.0\mathrm{x}10^{12}\ L_\odot/\mathrm{kpc}^2$
$R_{1/2} = 1.0$ kpc
$L_{FIR} = 4.5 \times 10^{12}\ L_\odot$
$S_{850\mu m} = 6.1$ mJy

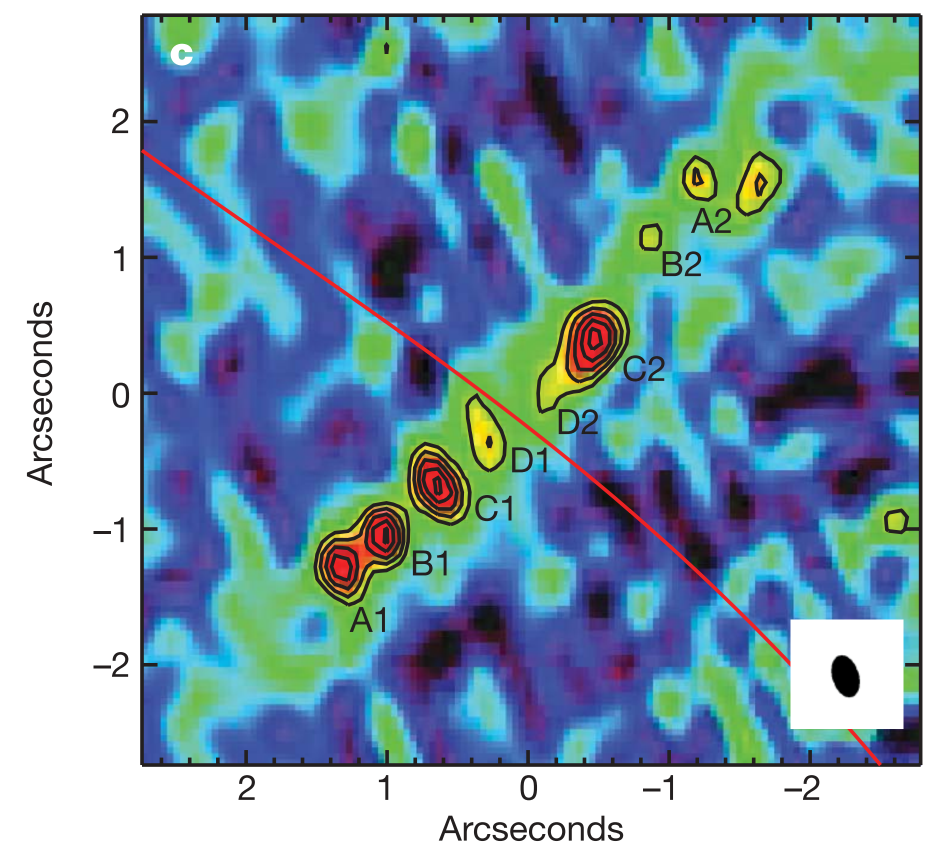


Hezaveh *et al.* (2013)

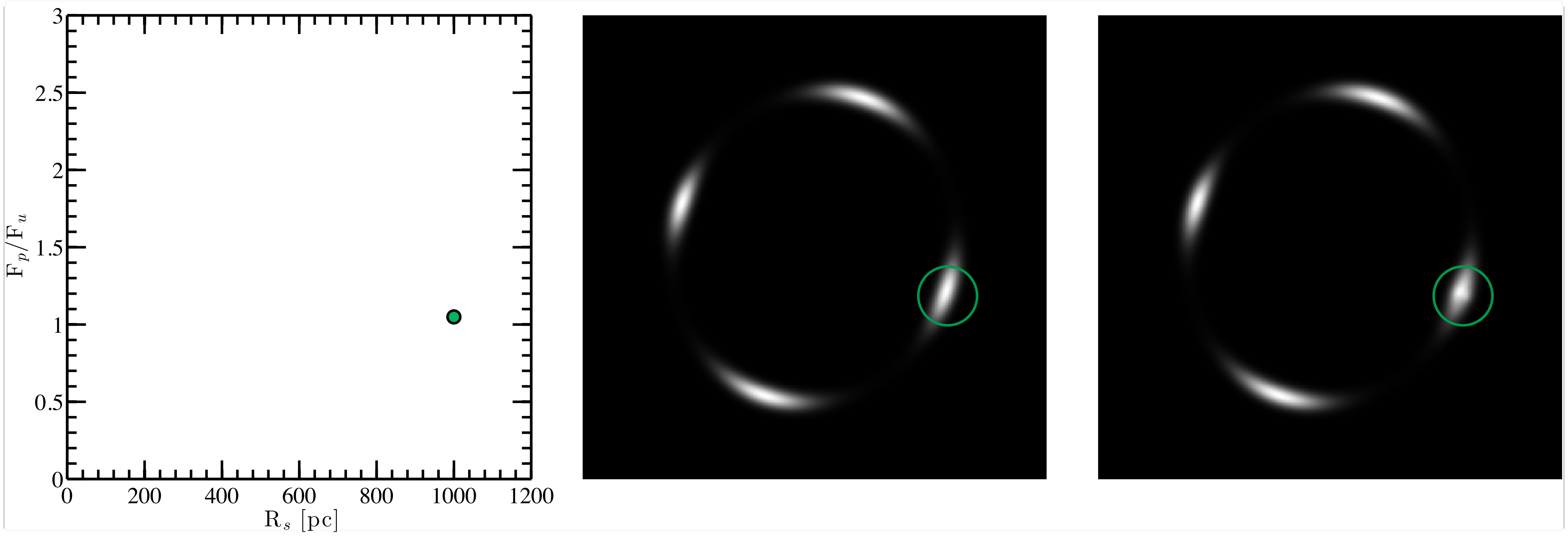
okay.... so what?

- lensed SMG's are *perfect* for detecting substructure!
- theoretically, we expect these galaxies to contain many **compact** star-forming clumps (~10-100pc) inside much bigger GMC's (~kpc). see also local analogues like Arp 220
- clumps are extremely bright in lines like CO 7-6

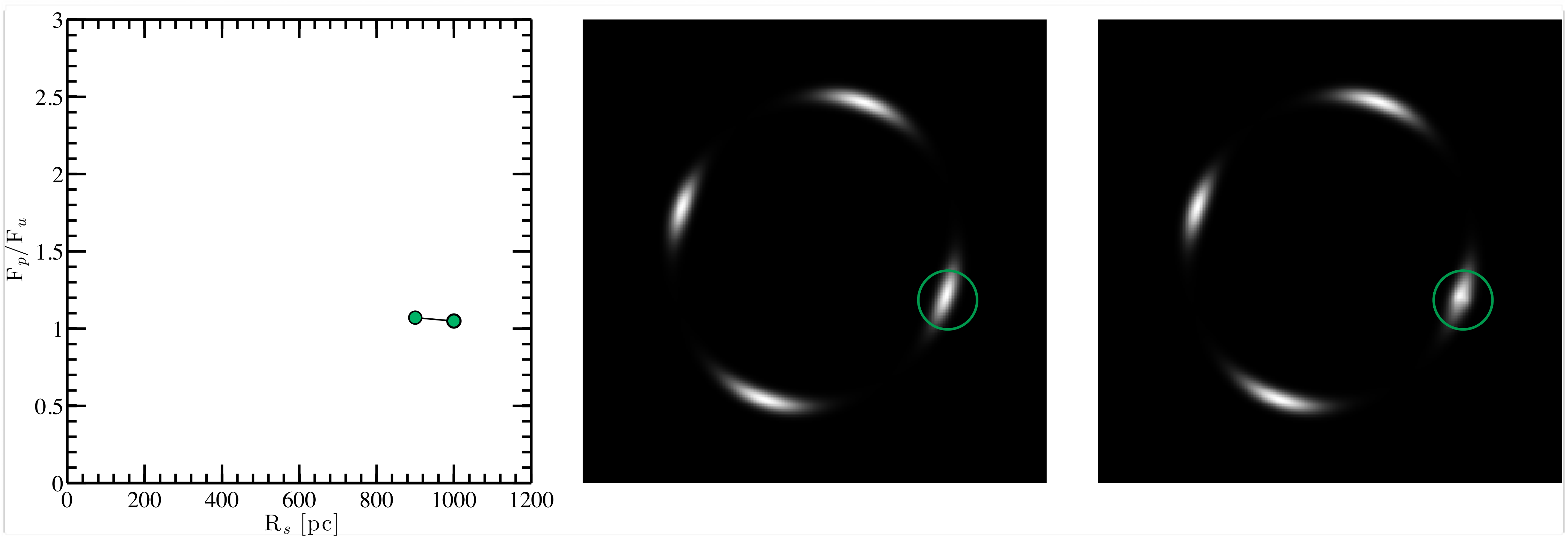
- example: high resolution SMA imaging of lensed SMG reveals compact source clumps (Swinbank et al. 2010)



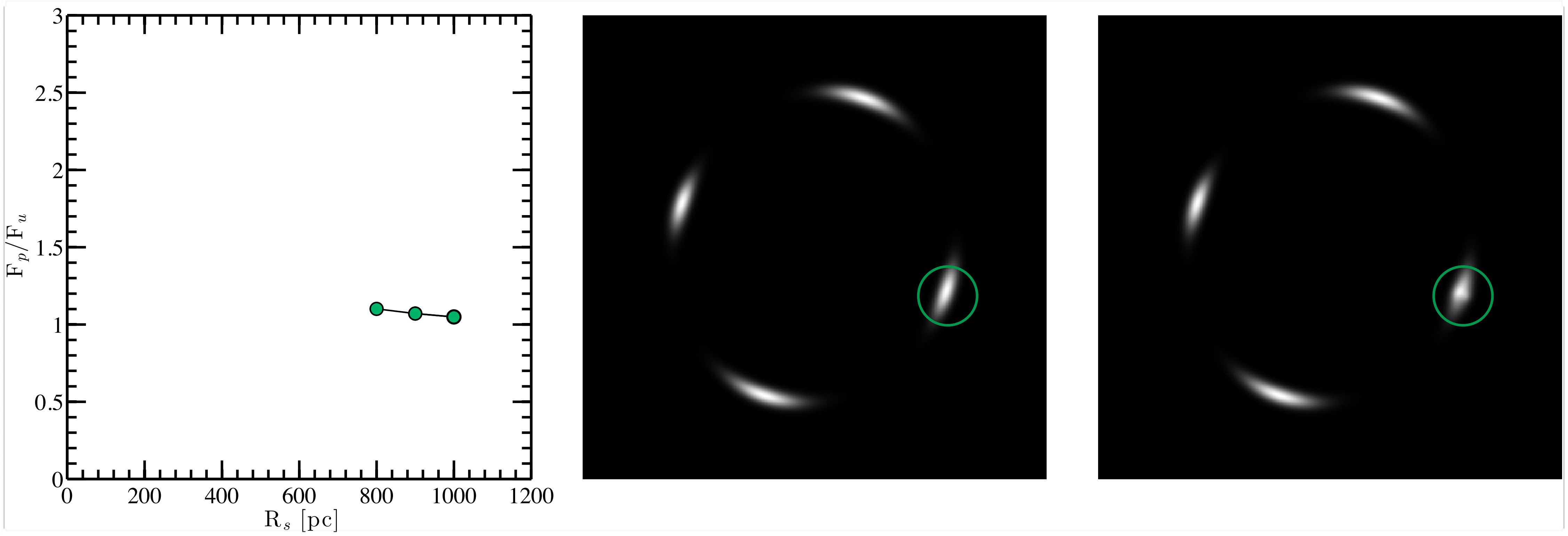
The Strength of Substructure Lensing Signal Depends on the Source Size



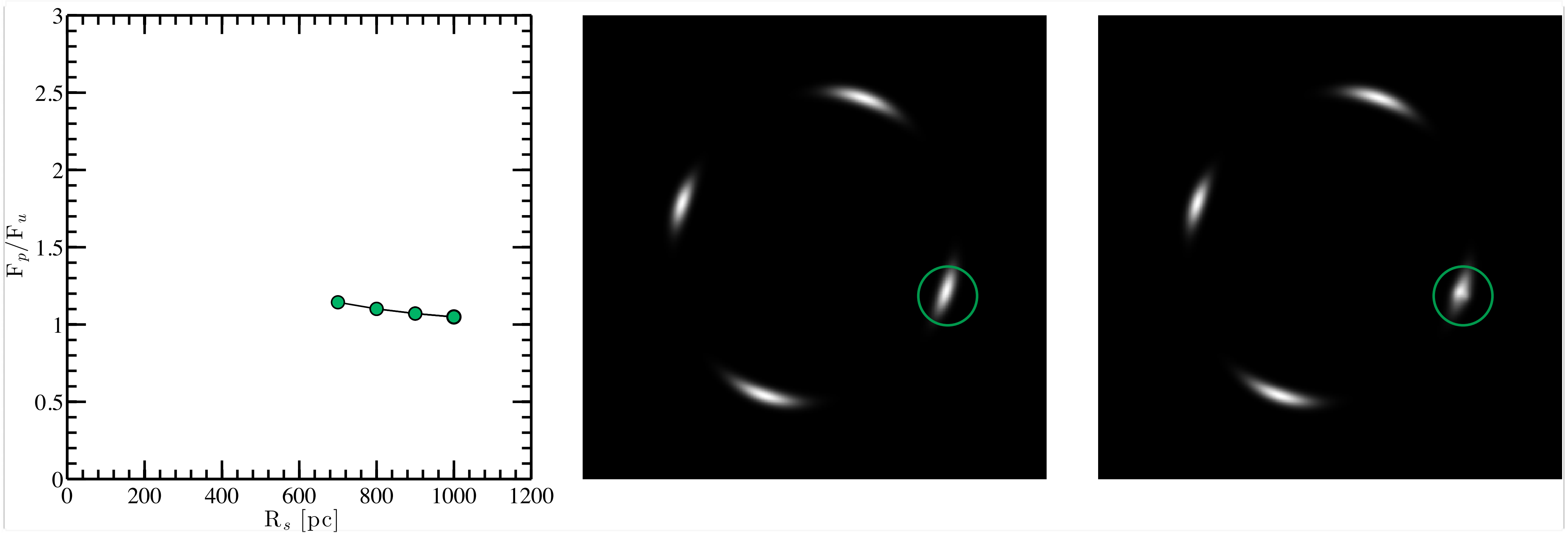
The Strength of Substructure Lensing Signal Depends on the Source Size



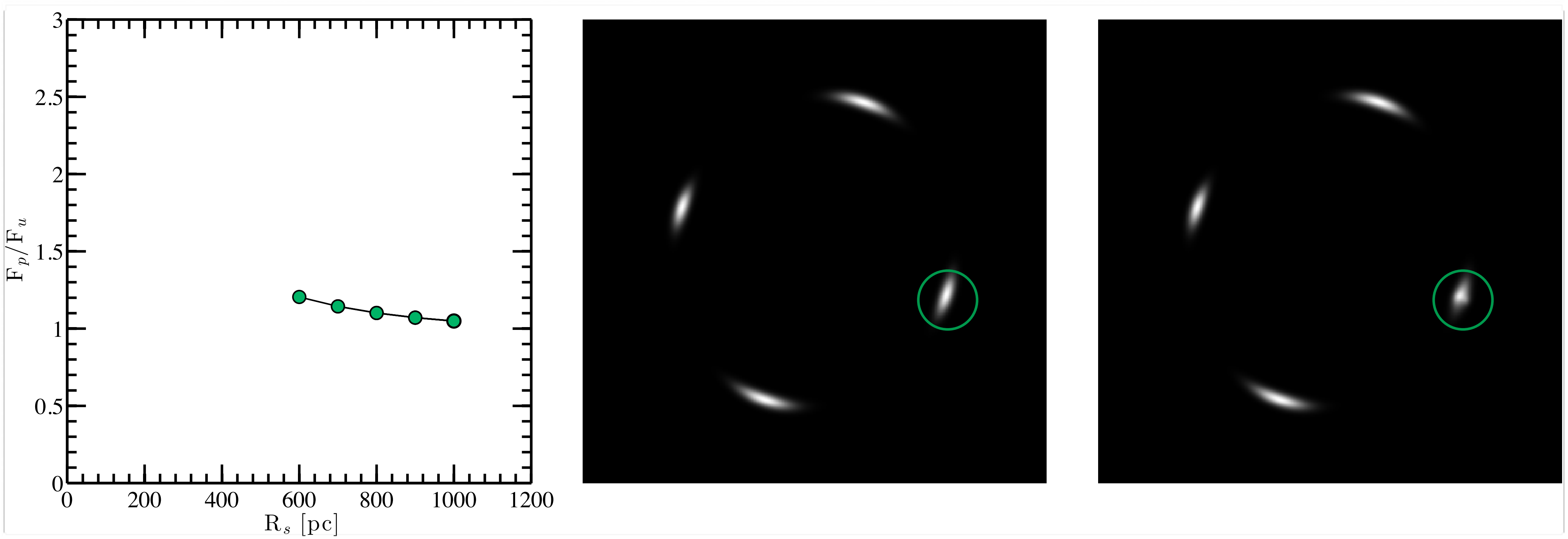
The Strength of Substructure Lensing Signal Depends on the Source Size



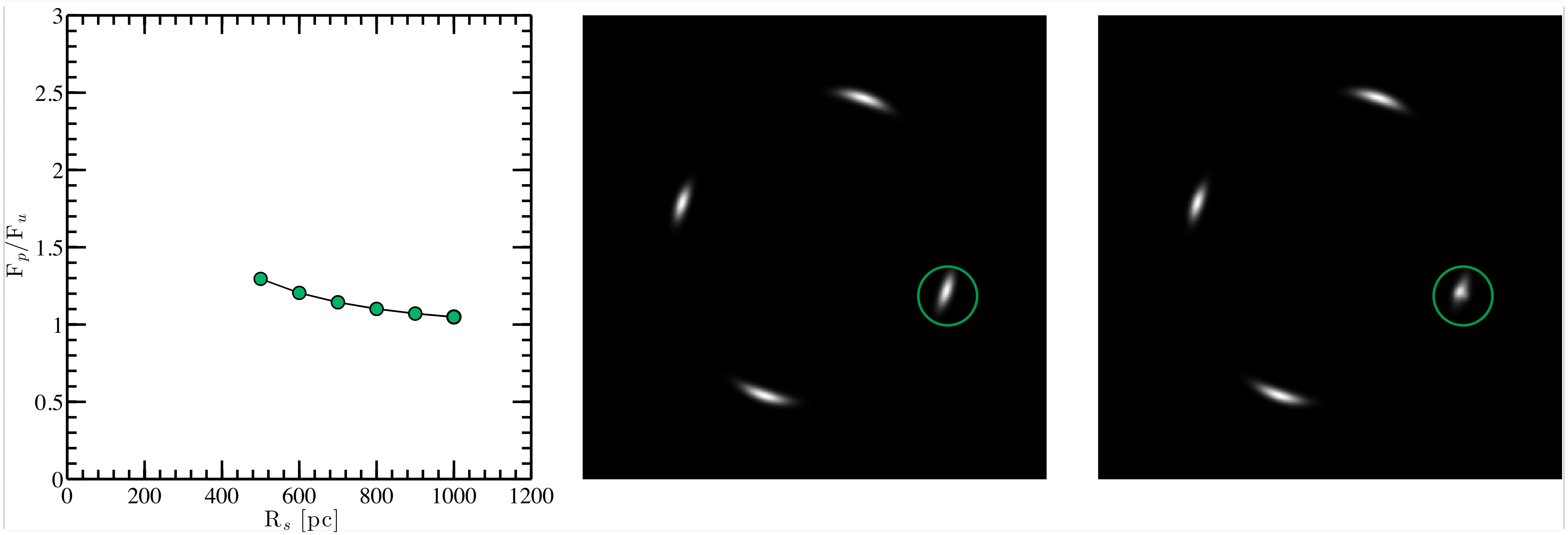
The Strength of Substructure Lensing Signal Depends on the Source Size



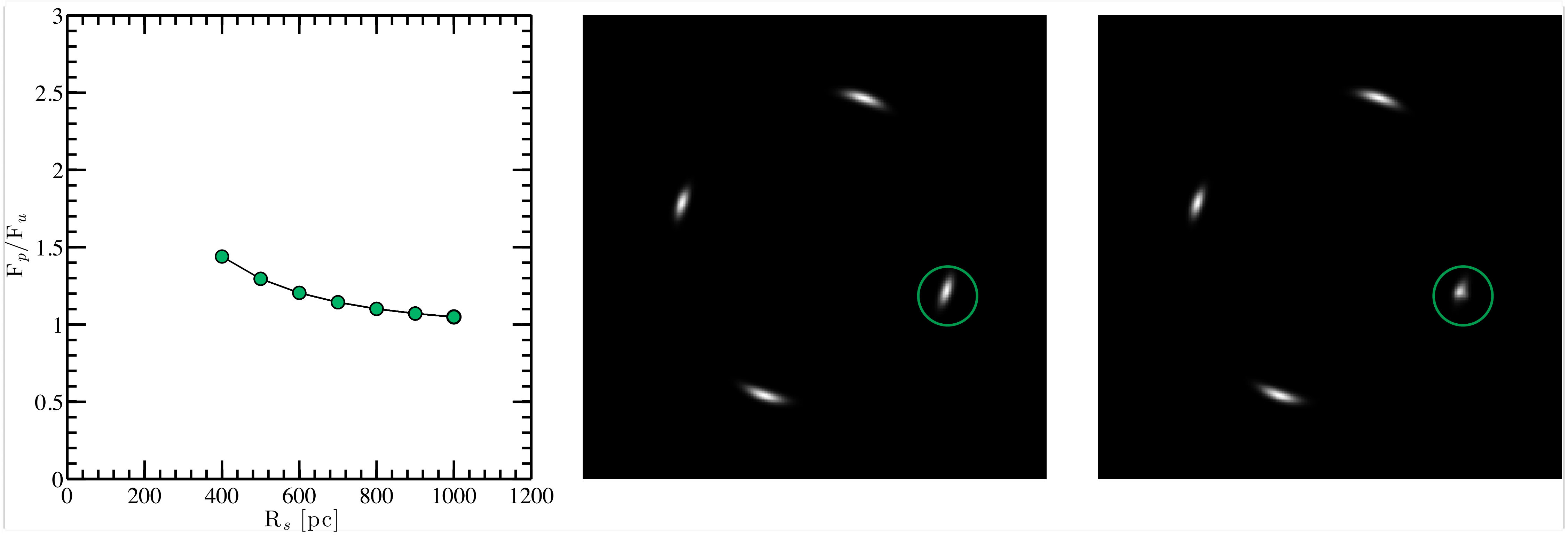
The Strength of Substructure Lensing Signal Depends on the Source Size



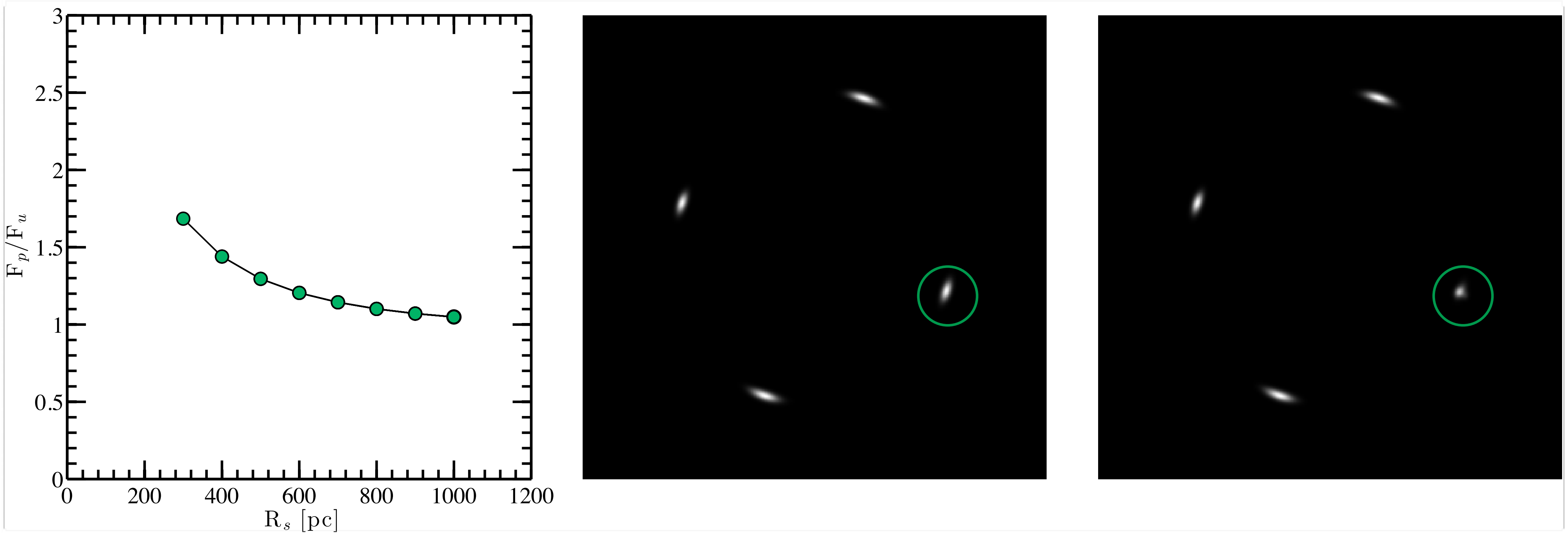
The Strength of Substructure Lensing Signal Depends on the Source Size



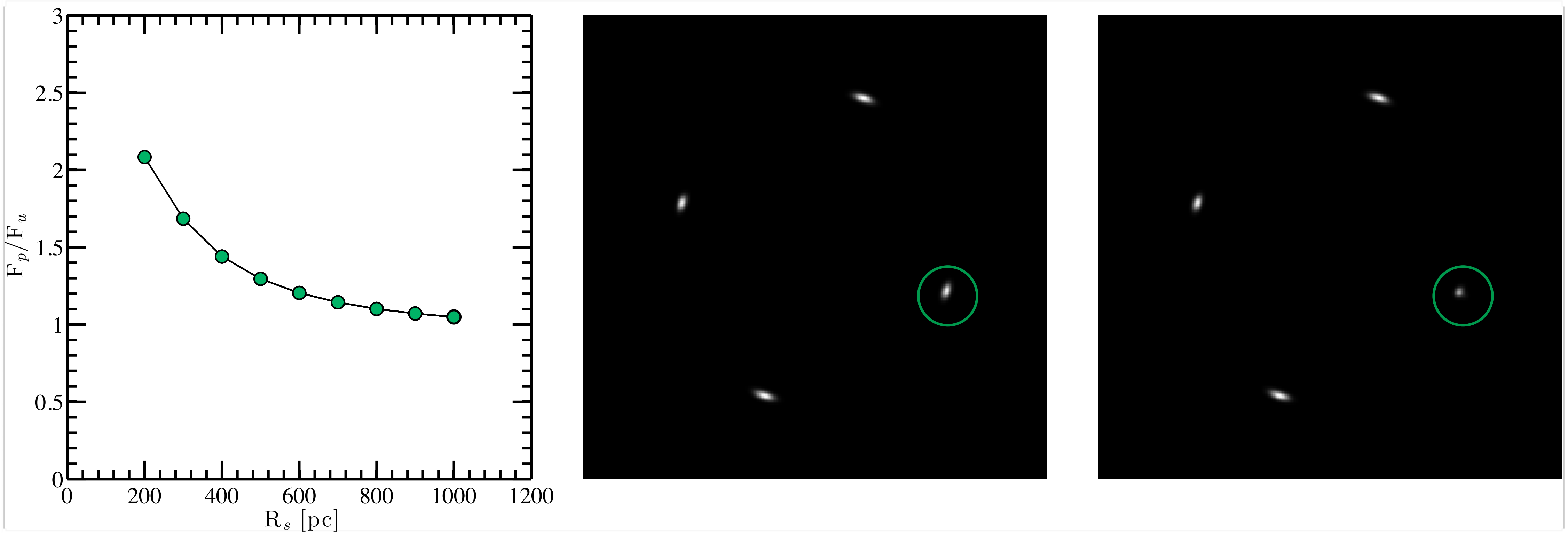
The Strength of Substructure Lensing Signal Depends on the Source Size



The Strength of Substructure Lensing Signal Depends on the Source Size

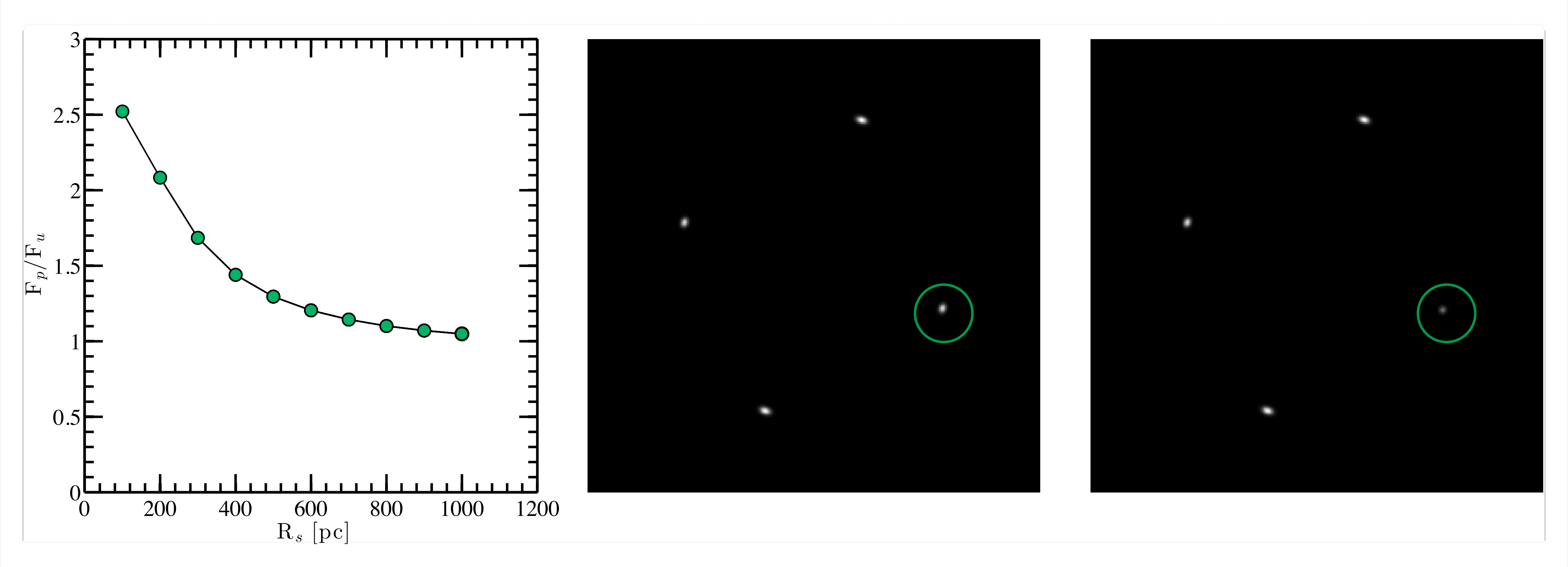


The Strength of Substructure Lensing Signal Depends on the Source Size



The Strength of Substructure Lensing Signal Depends on the Source Size

Compact Sources Are Perturbed More Strongly



Spatially resolved spectroscopy

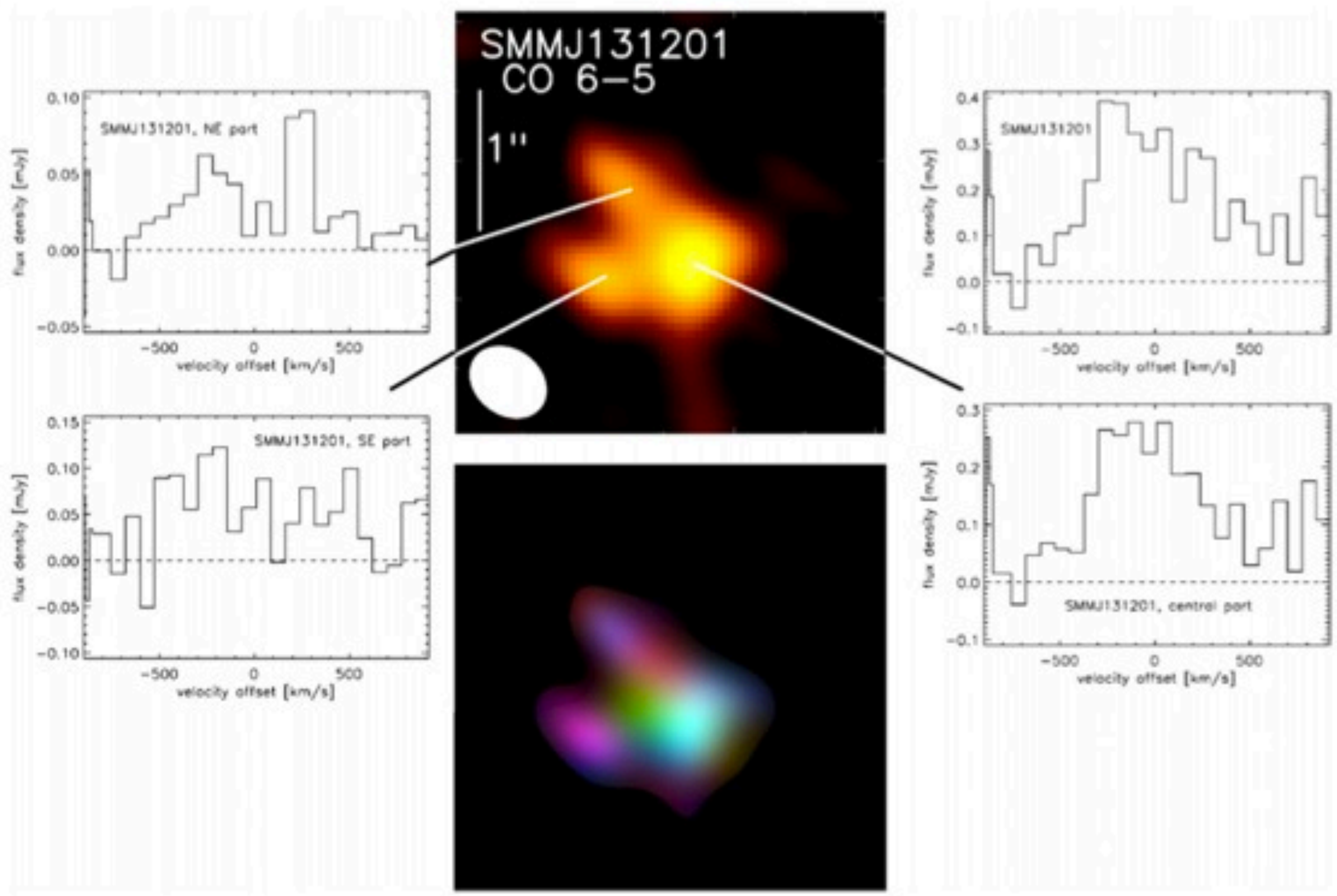
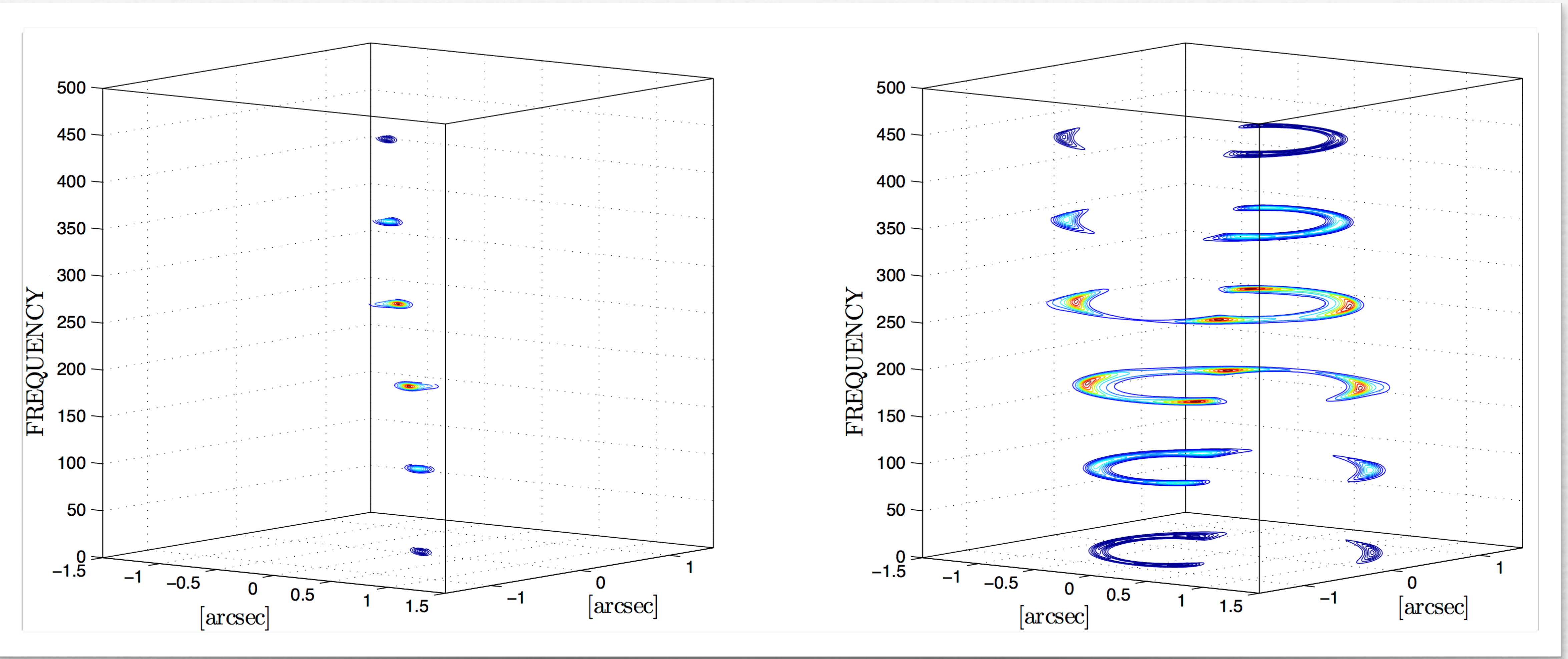


Figure 2. SMM J131201: this system displays a complex, irregular morphology; it most likely is an advanced pre-coalescence merger. The RGB image (mapping red, green, and blue parts of the spectrum) shows no indication of rotation. Spectra are, left: northeast (top) and southeast (bottom) arm, right: entire system (top), and central part (bottom). The beam size ($0\farcs59 \times 0\farcs47$, P.A. = $50\fdg9$) is displayed in the lower left corner of the flux maps. North is up and east is to the left. Scale bar denotes $1''$.

(A color version of this figure is available in the online journal.)

ENGEL ET AL 2010, APJ

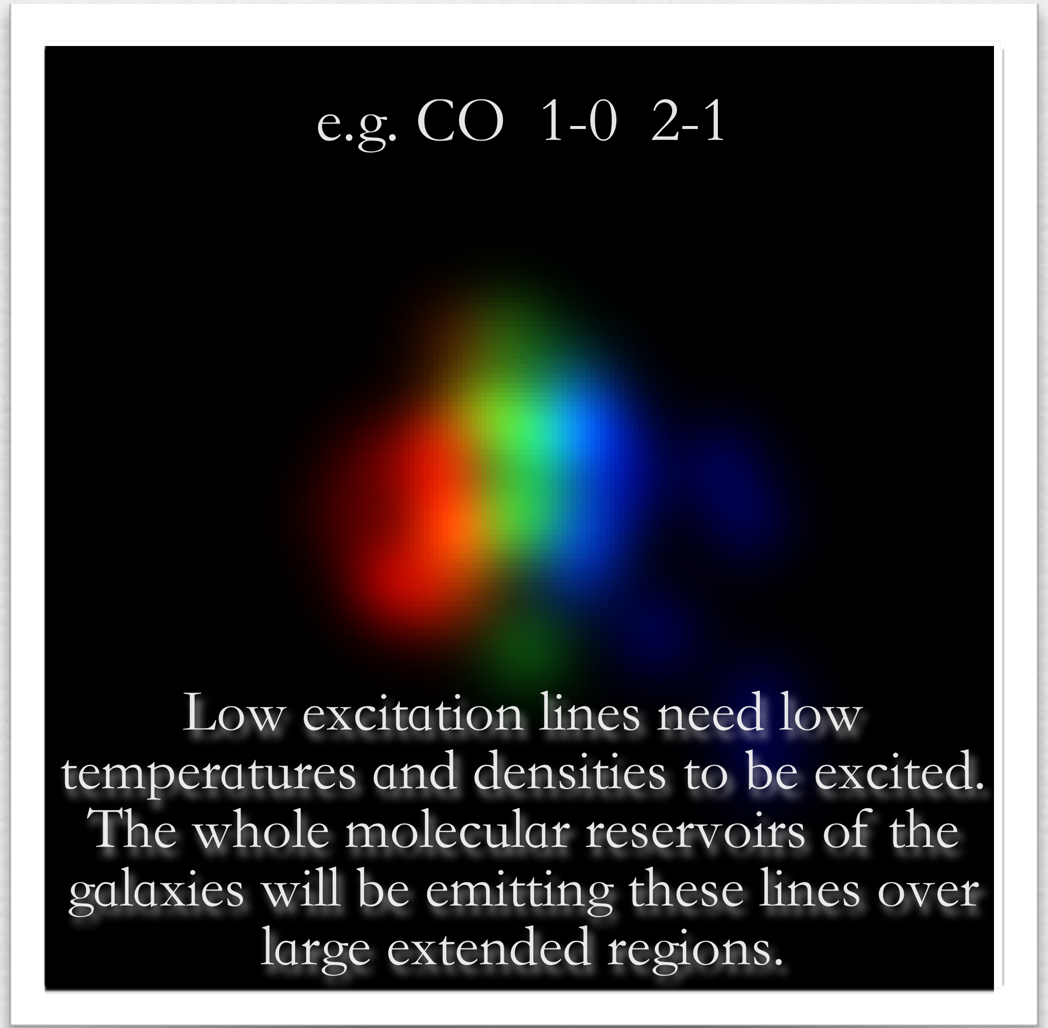
Velocity decomposition can separate small features of the source

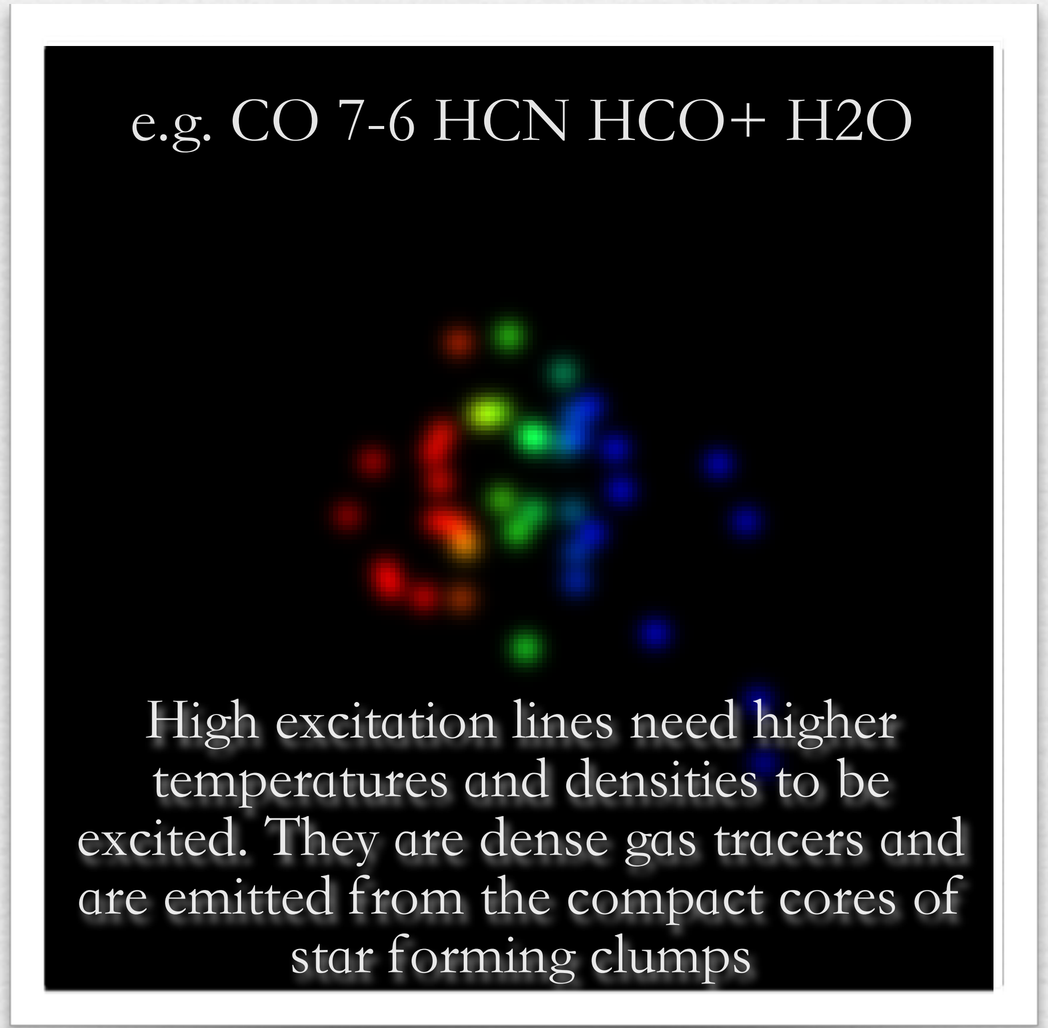


so each SMG is equivalent to having **many** sources behind each lens!

Simulations of ALMA observations

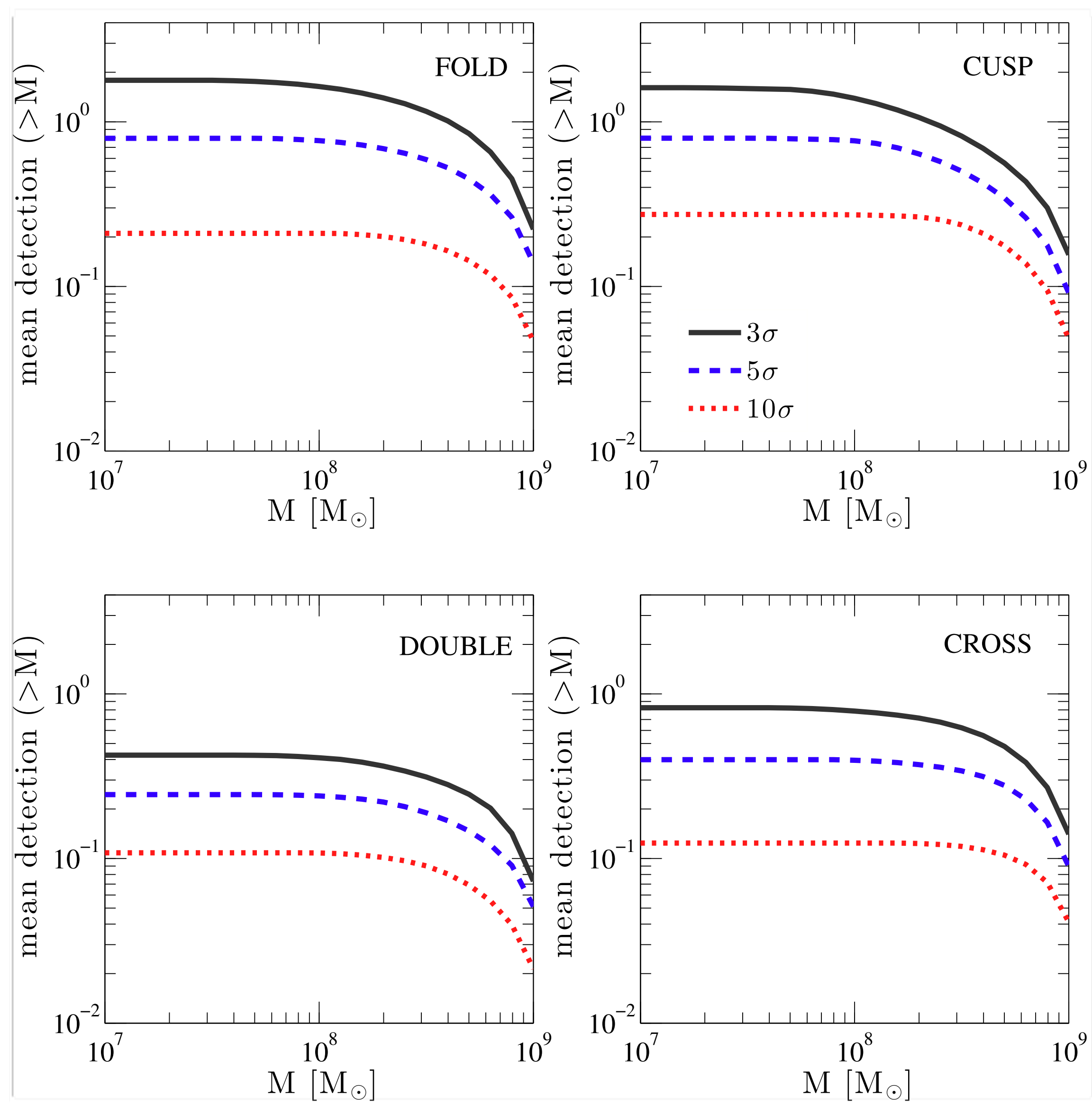
- observe high excitation lines (e.g. CO 7-6)
- use most extended configuration in Cycle 1, one hour total integration





Mean Number of Detections Per Lens (Cycle 1)

expect ~ O(1) detections in **each** lens system



even the low-magnification systems can be useful!

Hezaveh, Dalal et al 2012, ApJ in press

cosmology constraints

- existing sample (DK02) is **7** quasar lenses
- from SPT we expect ~100 SMG lenses, and each SMG lens is **much** more constraining than a quasar
- How do these measurements translate into bounds on cosmology?

cosmology constraints

- existing sample (DK02) is **7** quasar lenses
- from SPT we expect ~100 SMG lenses, and each SMG lens is **much** more constraining than a quasar
- How do these measurements translate into bounds on cosmology?
- We don't know – currently limited by theory! we don't know how to calculate substructure as a function of WDM, etc.
  - we're working on it (Arka Banerjee)
  - other statistics besides mass function might be more useful, e.g. substructure power spectrum

Conclusion:

- SMG lensing is great for DM substructure
- stay tuned!