Probing dark matter substructure with dusty galaxies

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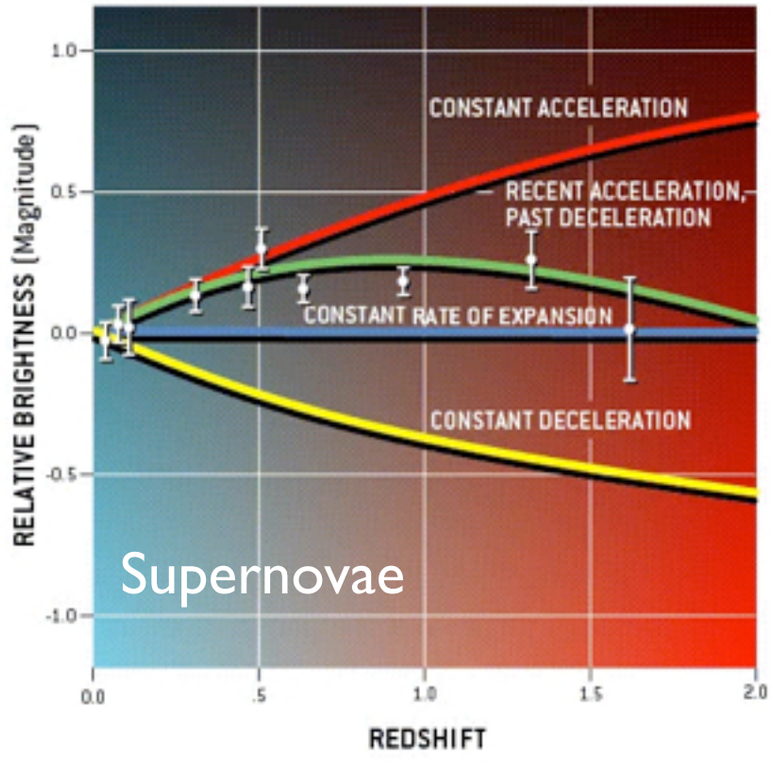
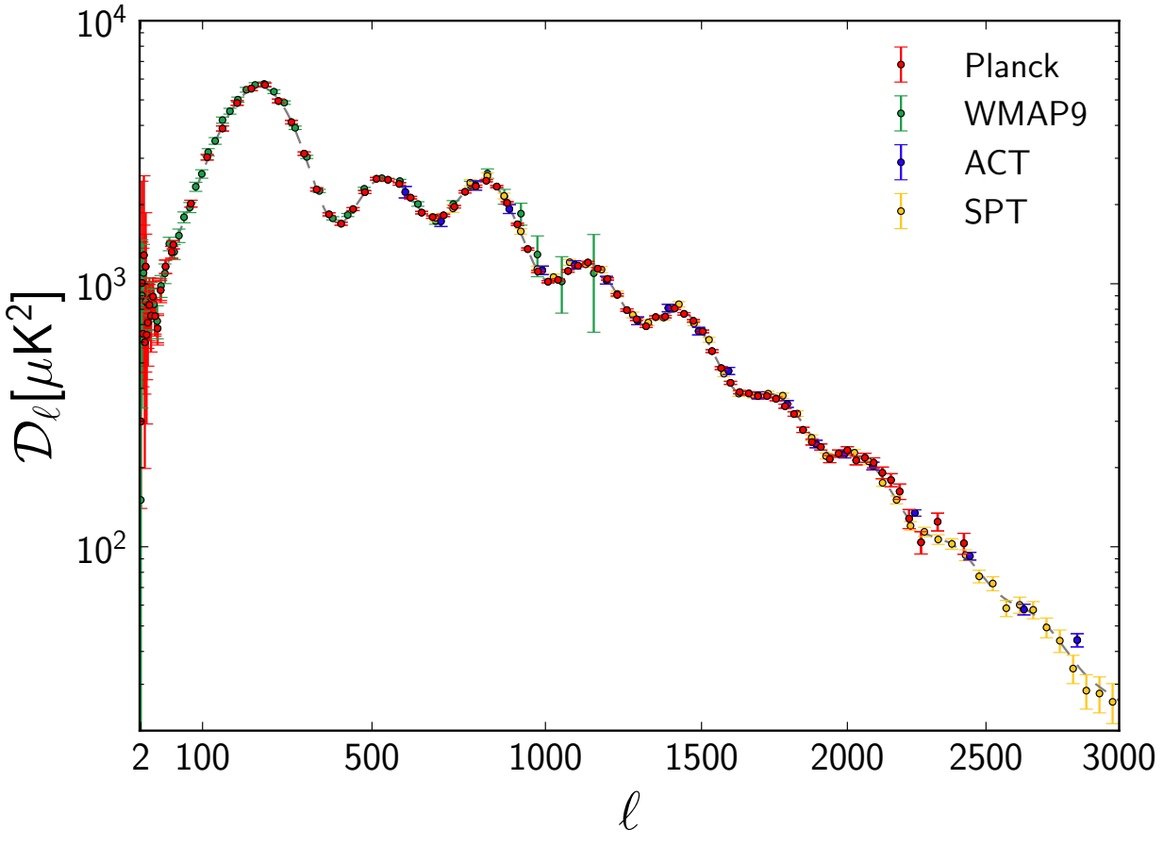
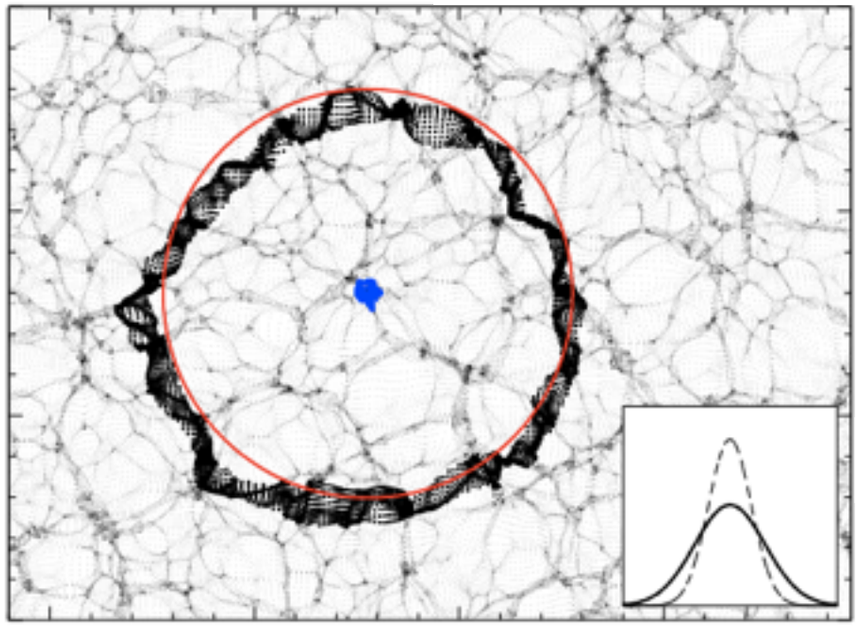
The Standard Model (of Cosmology): ΛCDM

- H_0, Ω_b, Ω_m, Λ, σ_8, n_s, τ
- fits a wealth of data, e.g. :

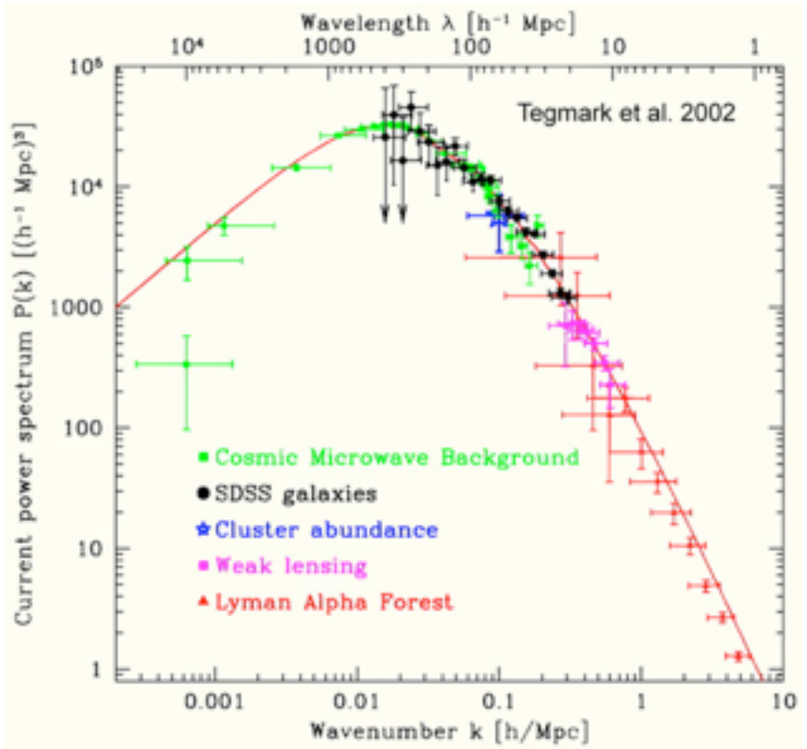






BAO

small-scale structure



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

small-scale P(k) is interesting!

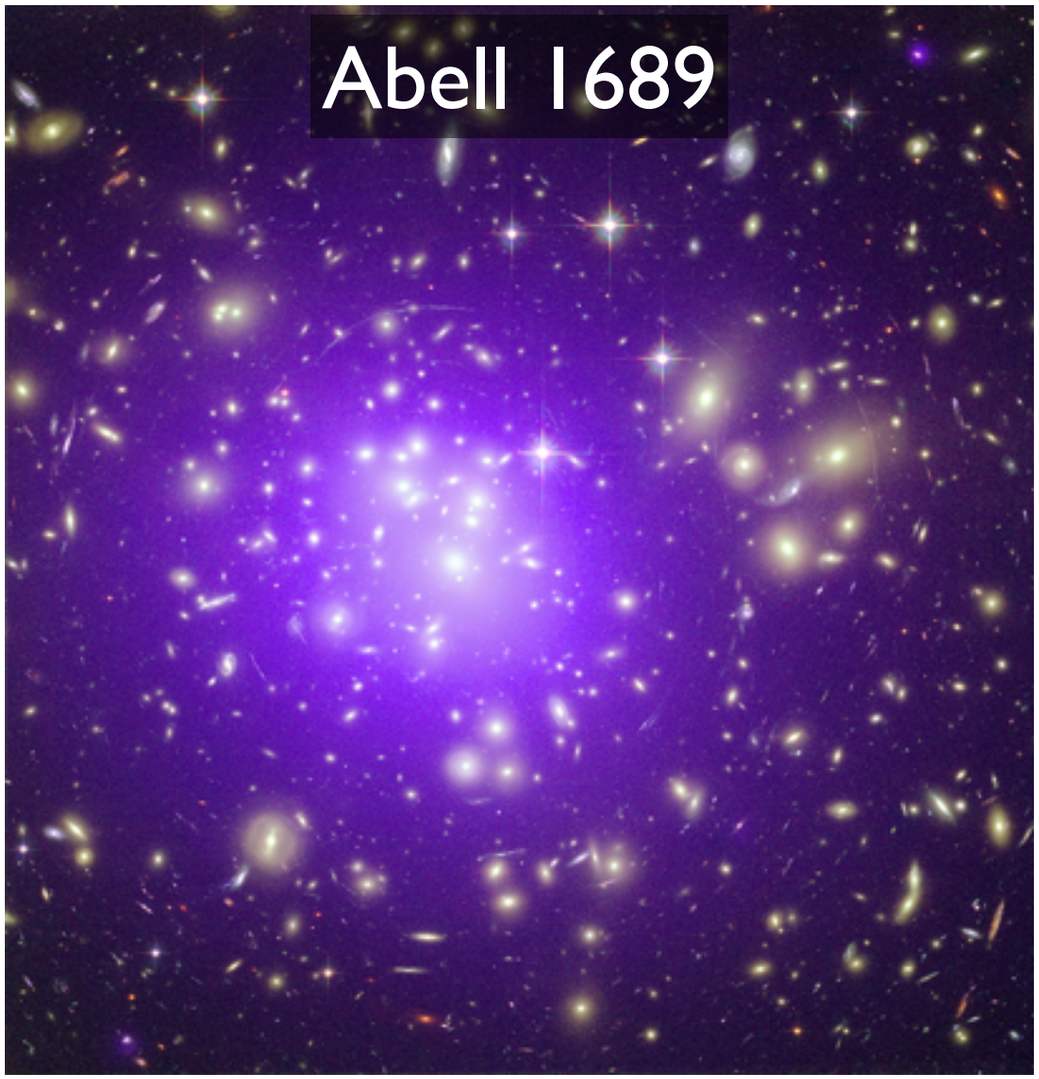
- shape of primordial power spectrum related to shape of inflaton potential (e.g. running $\Longrightarrow V'''$)
- small-scale P(k) sensitive to physics of DM particles

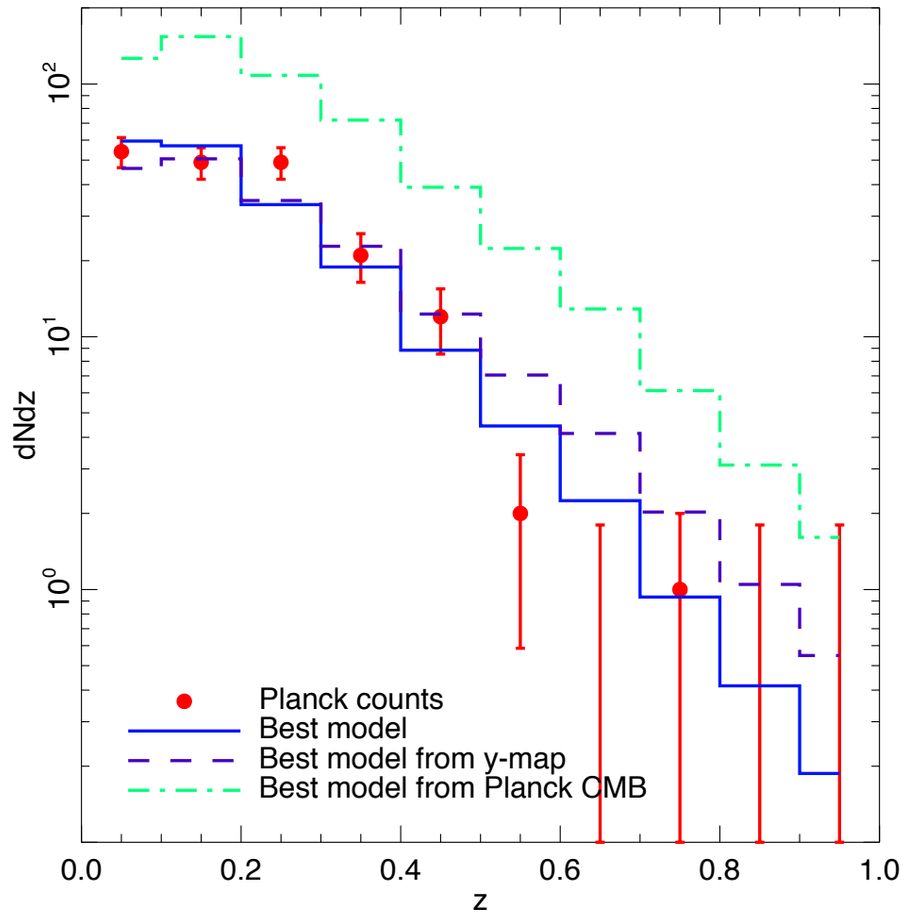
Current best probe is Ly α forest (e.g. Seljak et al. 2006), but already approaching gas Jeans scale!

in future, CMB spectral distortions can probe $k \sim 10^4$

abundances

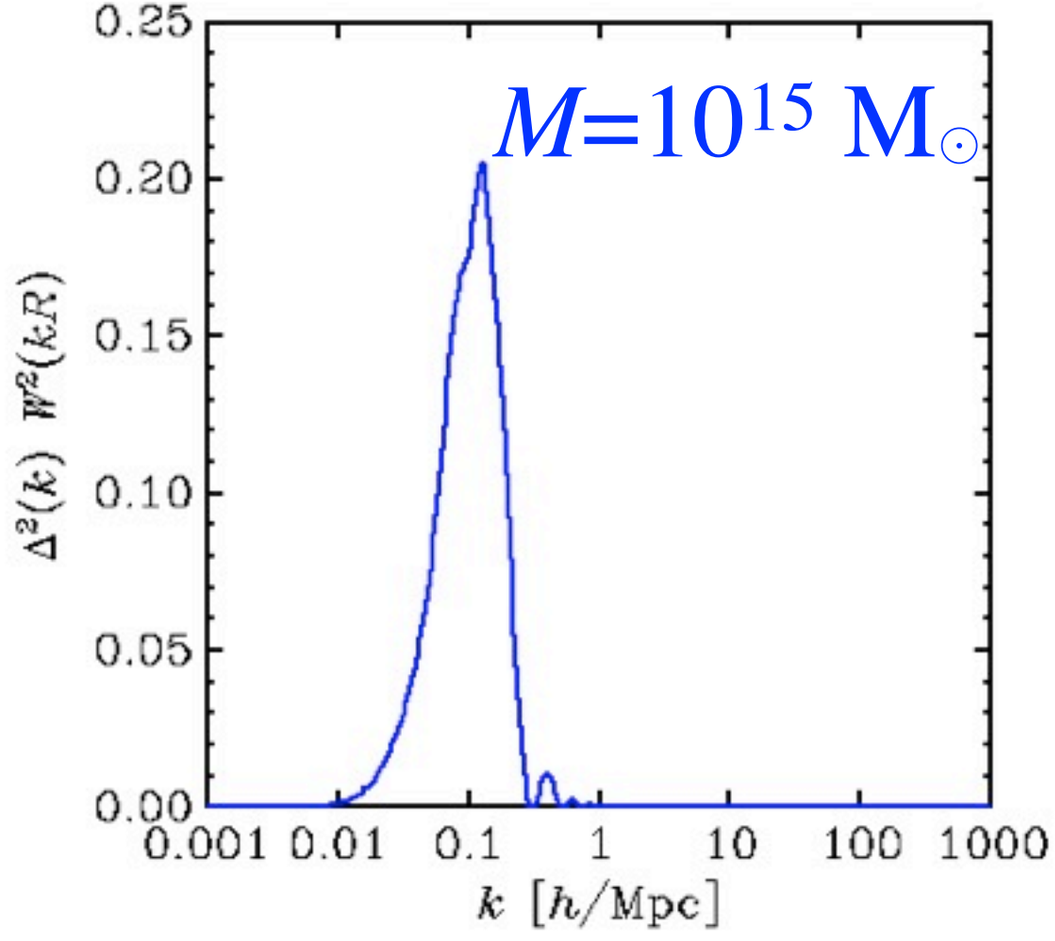
- abundance of objects (e.g. cluster dn/dM) is sensitive to power spectrum

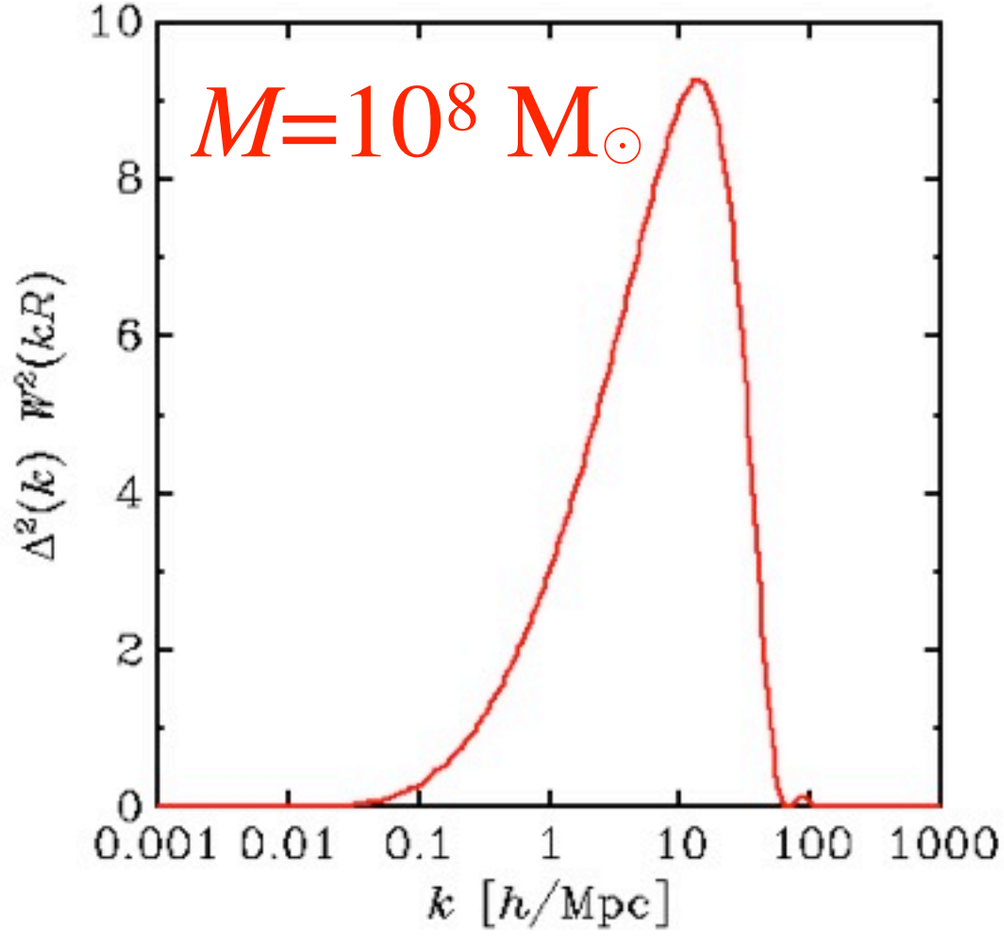




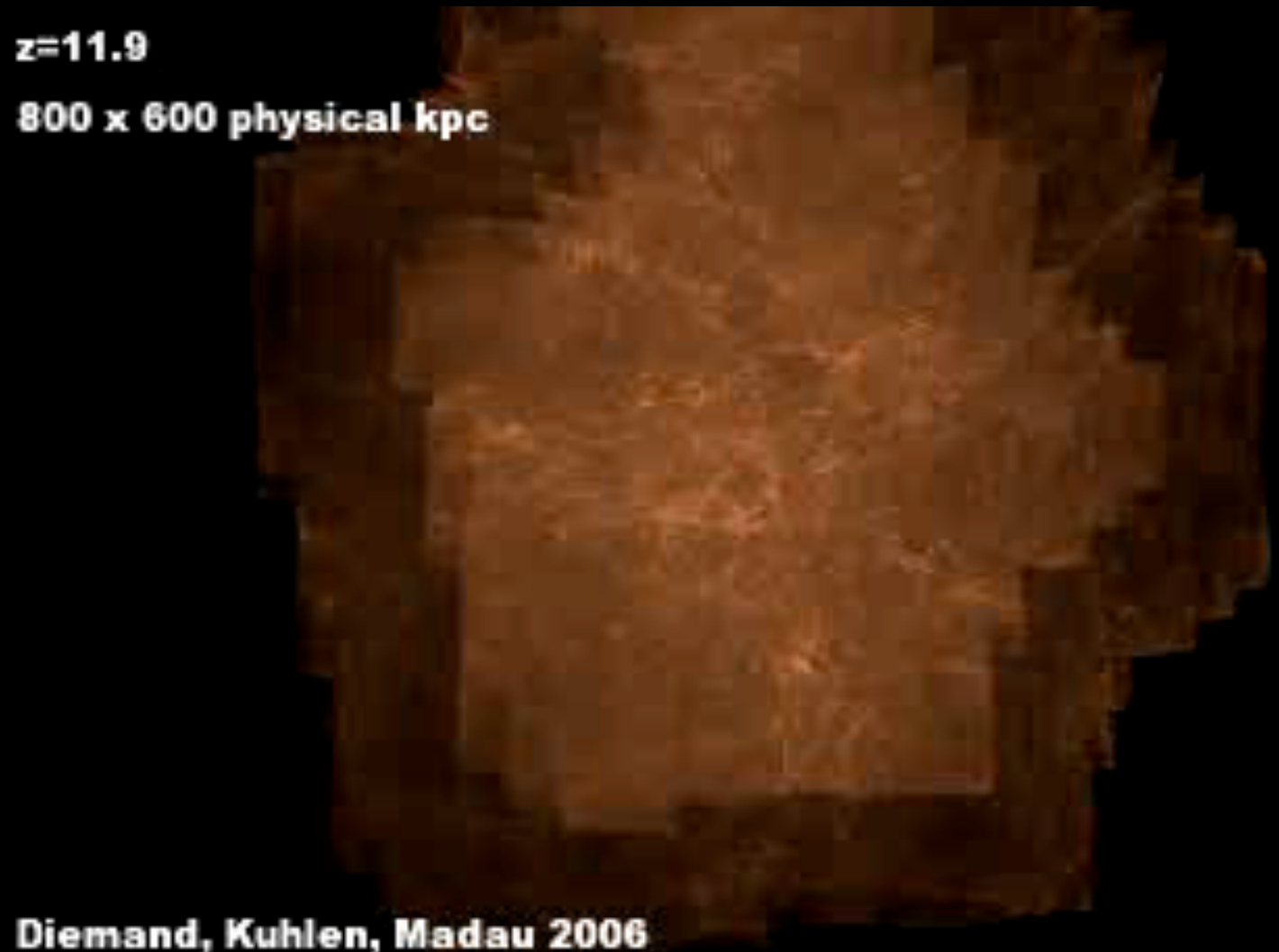
abundances

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





halos and subhalos



“Via Lactea”
Diemand et al. 2006

Diemand, Kuhlen, Madau 2006

subhalos

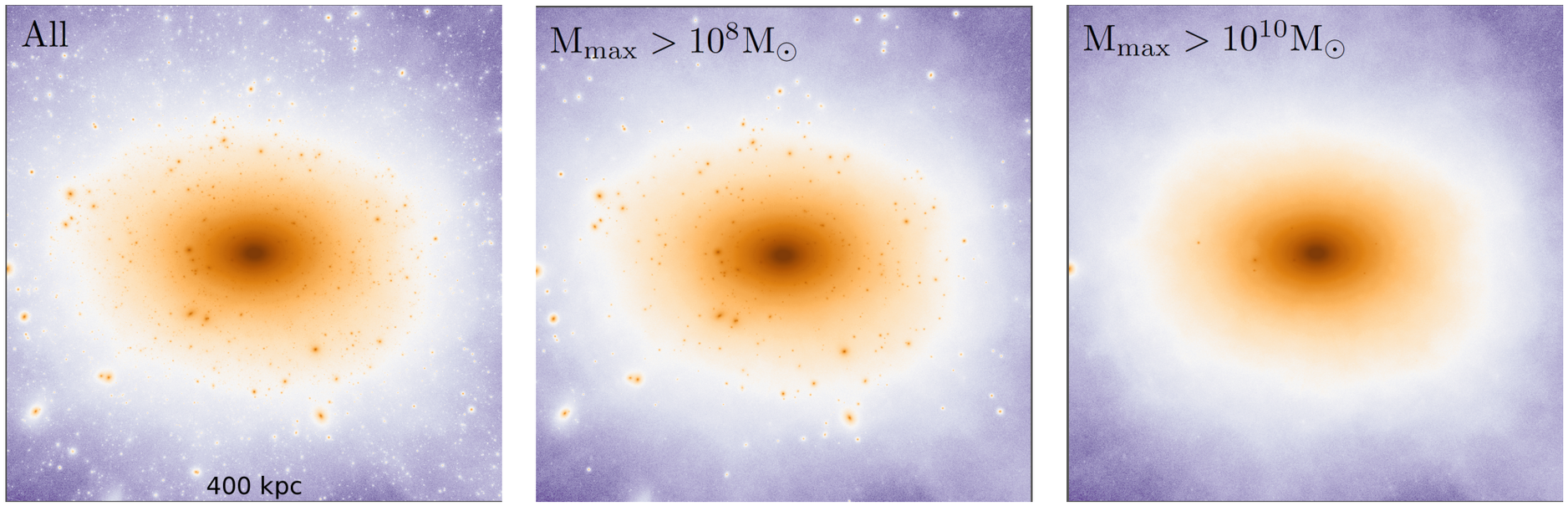
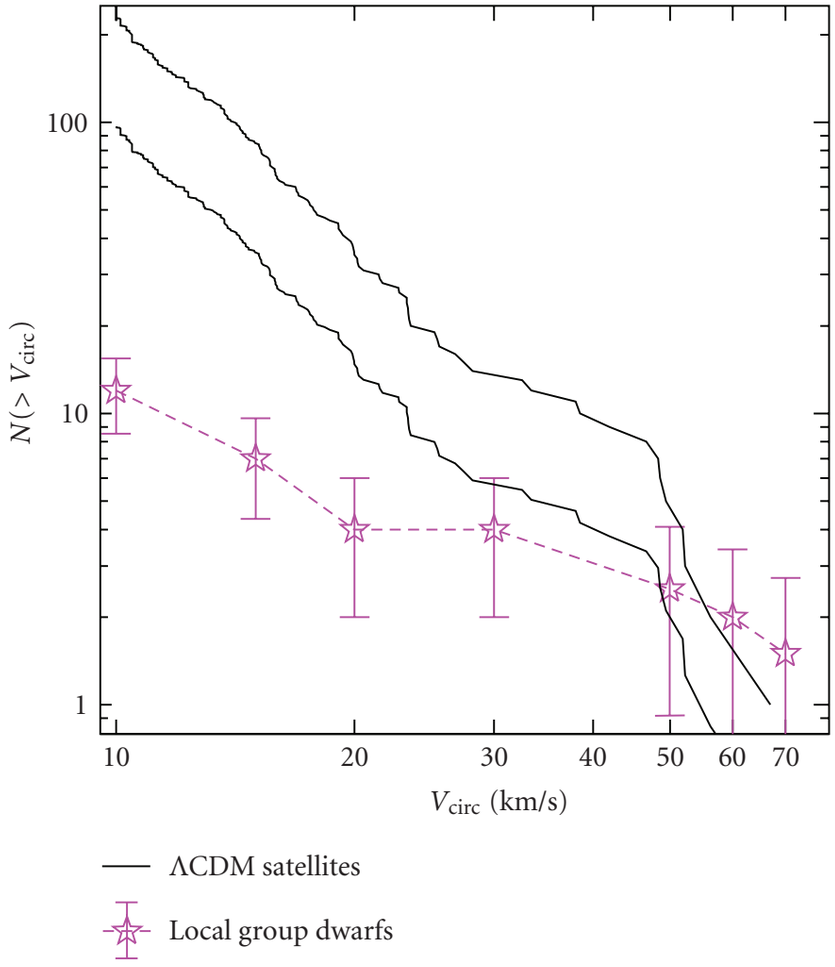


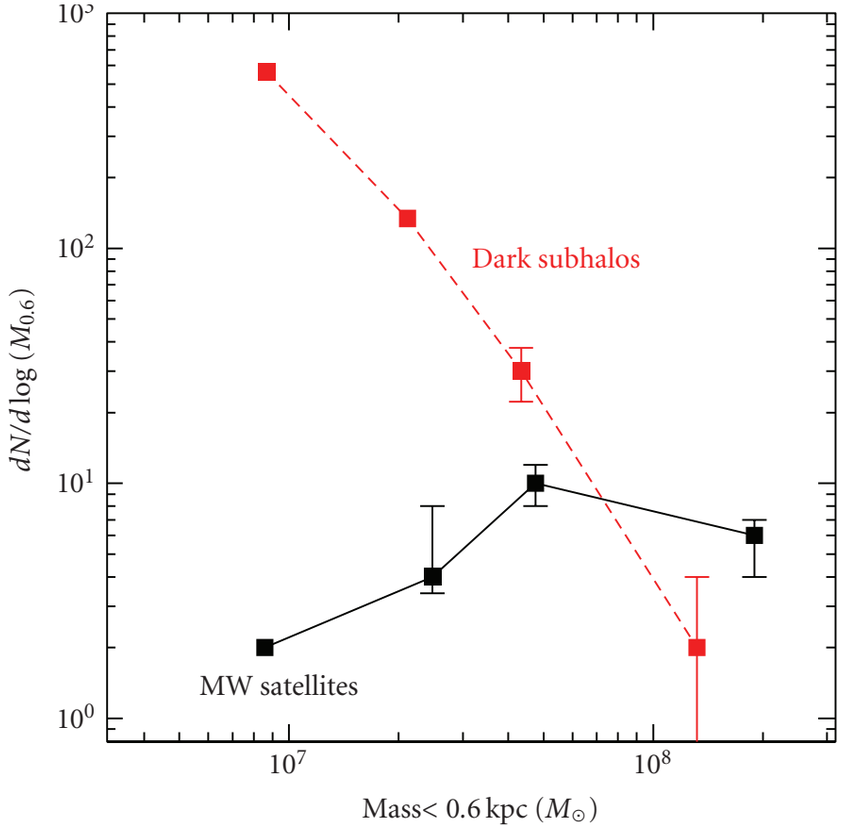
Figure 1: **Left:** Density projection in the Via Lactea-II simulation [18]. **Middle:** Similar, but excluding particles belonging to subhalos whose masses never exceeded $10^8 M_\odot$ any time throughout the simulation. **Right:** Like the middle panel, but excluding subhalos with $M_{\rm max} < 10^{10} M_\odot$. 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!

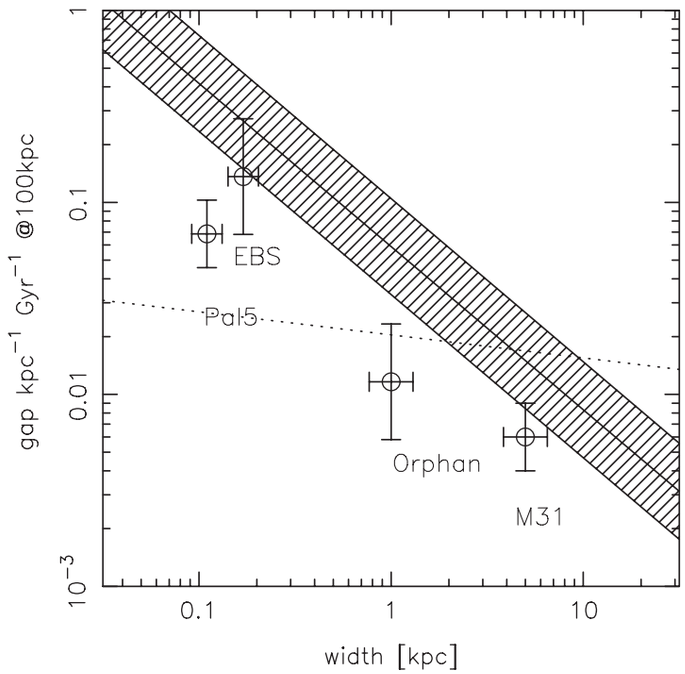
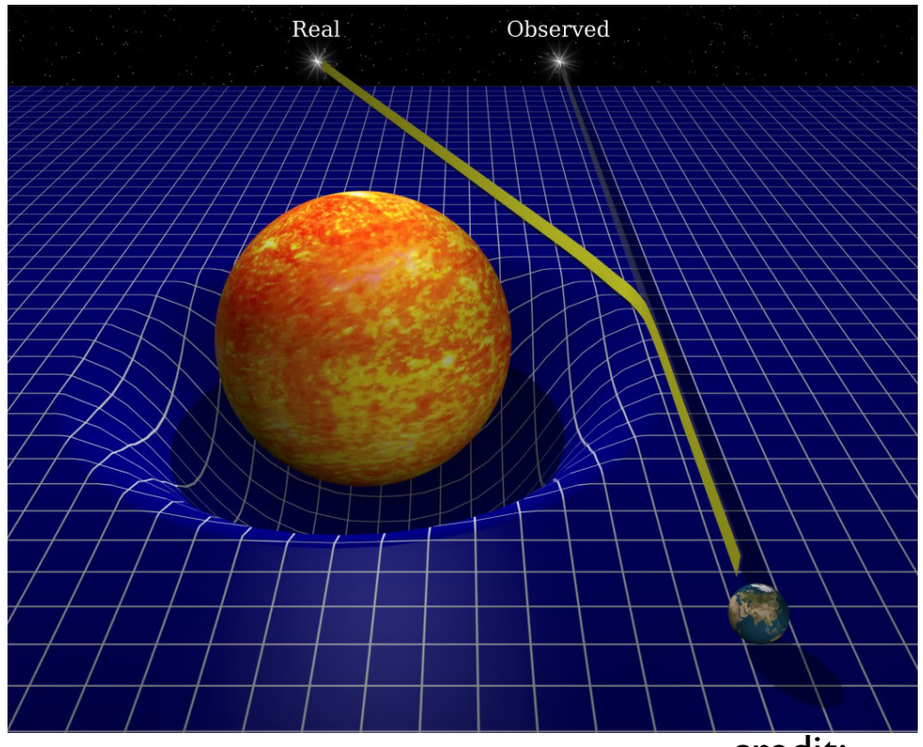


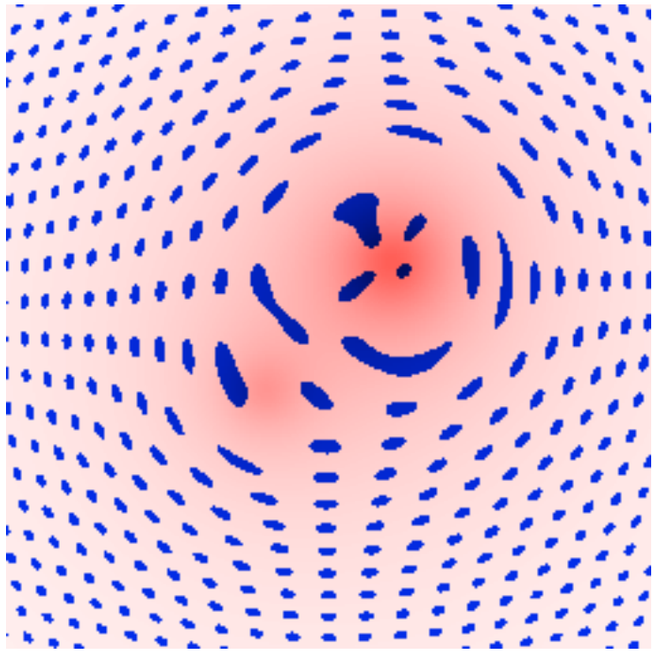
Figure 11. Estimated gap rate vs. stream width relation for M31 NW, Pal 5, the EBS, and the CDM halo prediction. All data are normalized to 100 kpc. The width of the theoretical relation is evaluated from the dispersion in the length–height relation of Figure 8. Predictions for an arbitrary alternative 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*



credit: D. Jarvis



credit: E. Wright

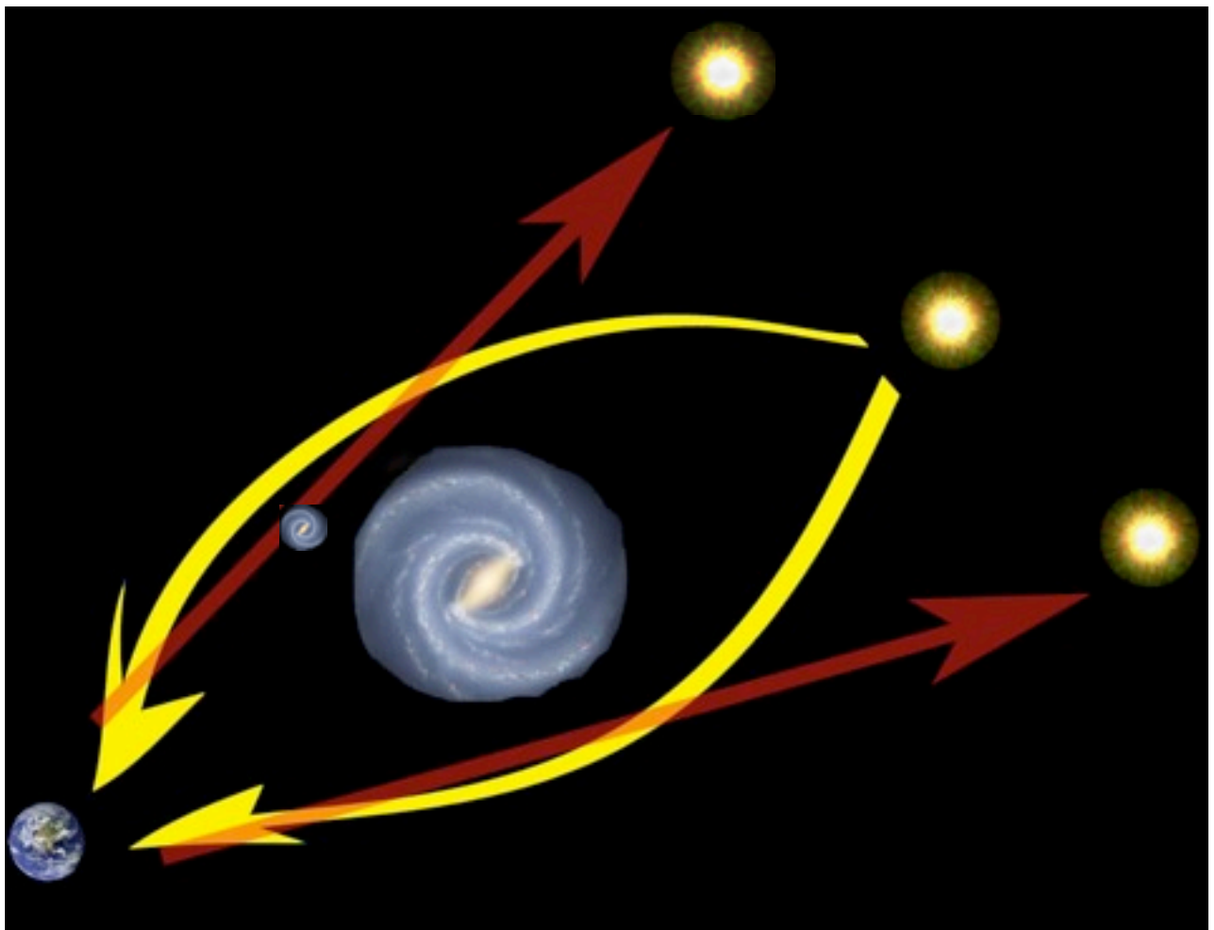
subhalo lensing

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 $\kappa,\gamma \lesssim 0.1$)
- can't stack if they're dark (where to stack?)
- 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

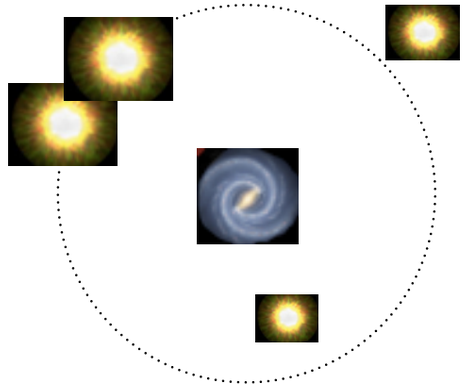


$$\Delta\theta \approx \mathbf{M} \cdot \Delta\alpha$$

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

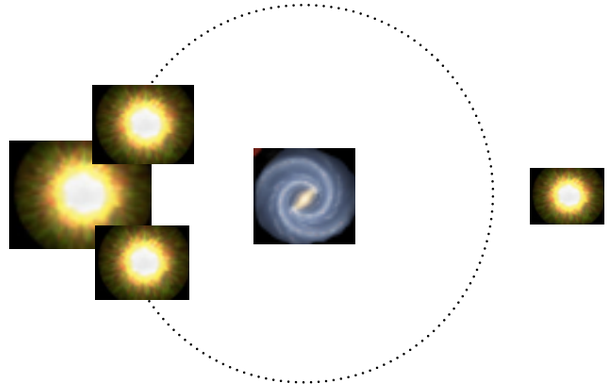
universality relations

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



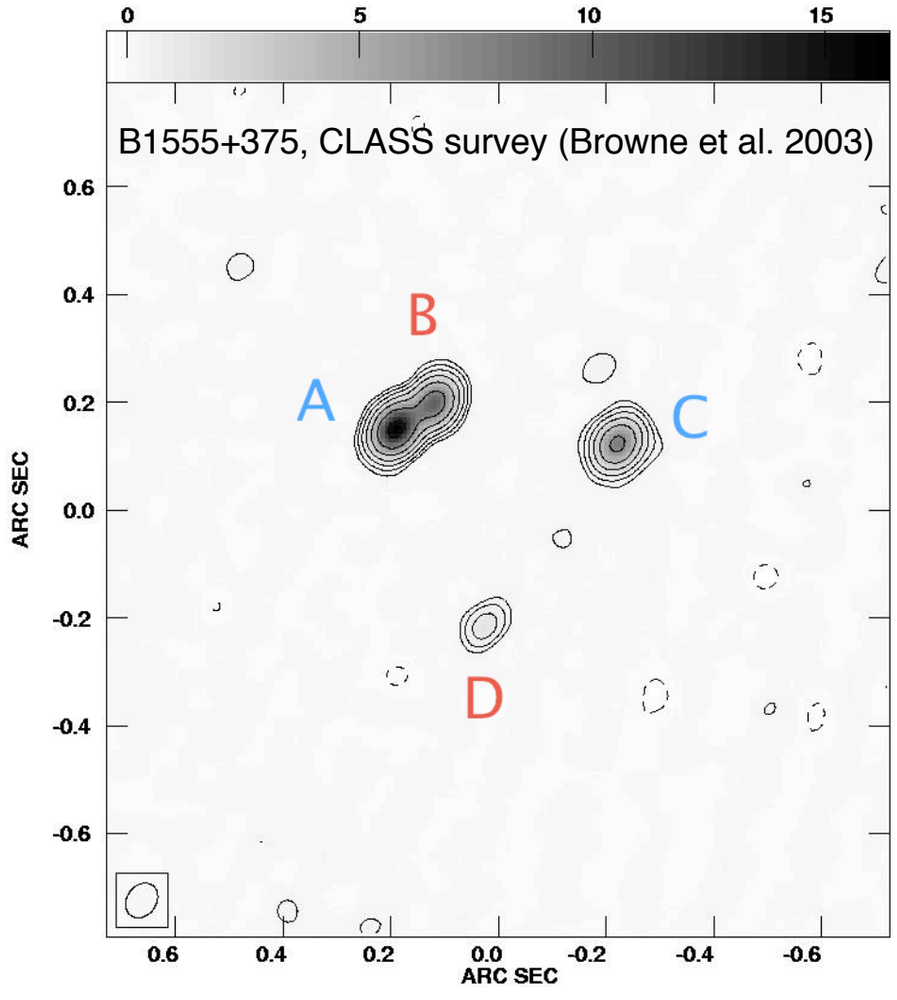
$$\frac{\Delta f}{f} \propto \frac{\Delta r}{r_s}$$

- similar relation when 3 images occur close together:

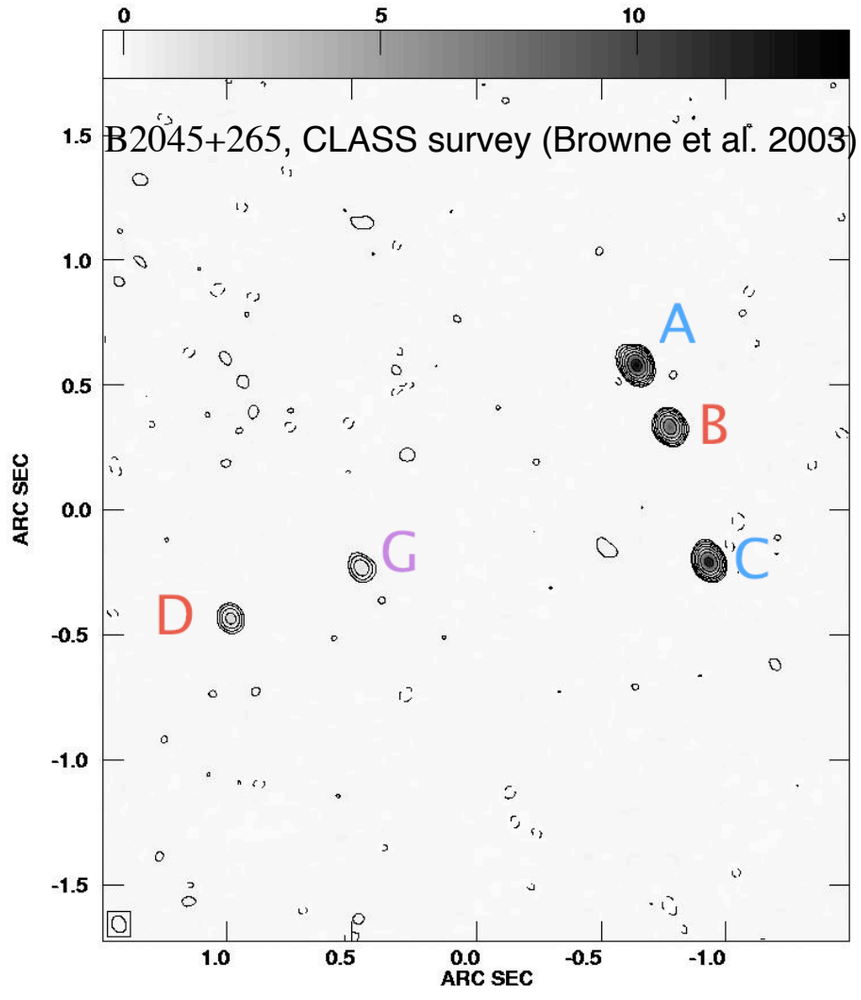


$$\frac{f_A - f_B + f_C}{f_A + f_B + f_C} \propto \frac{\Delta r}{r_s}$$

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?

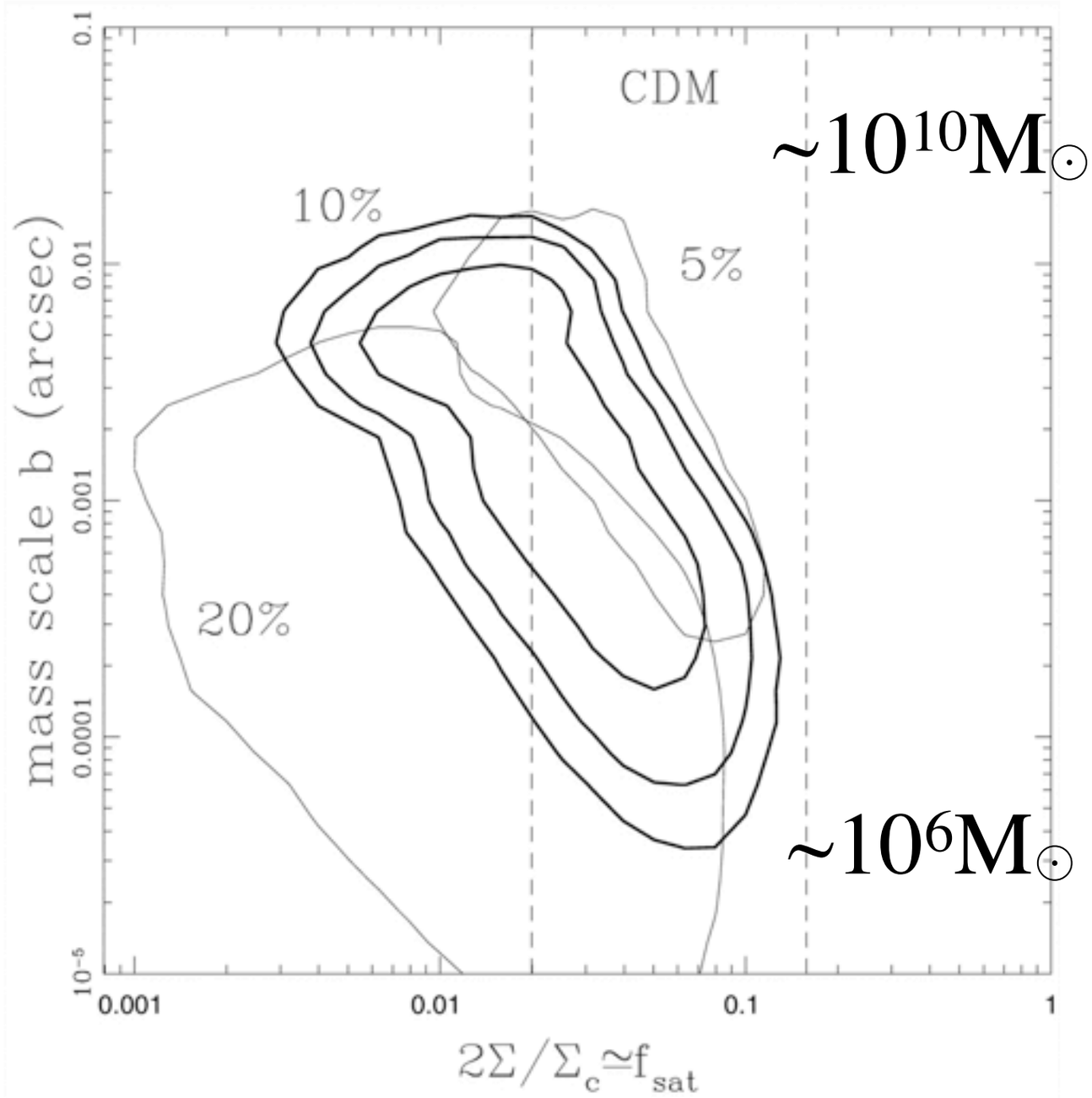
- radio flux ratios independent of λ, as expected for lensing but unlike propagation effects (like scintillation or dust extinction)
- observed **parity** dependence:
  + parity magnified, – parity demagnified
- radio quasars too big to be affected by stellar microlensing, unlike stellar QSO's.
- see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

analysis of radio lenses

- Dalal & Kochanek (2002) analyzed sample of **7** radio lenses

- found that ~ 1% of projected mass at 5kpc is in substructure

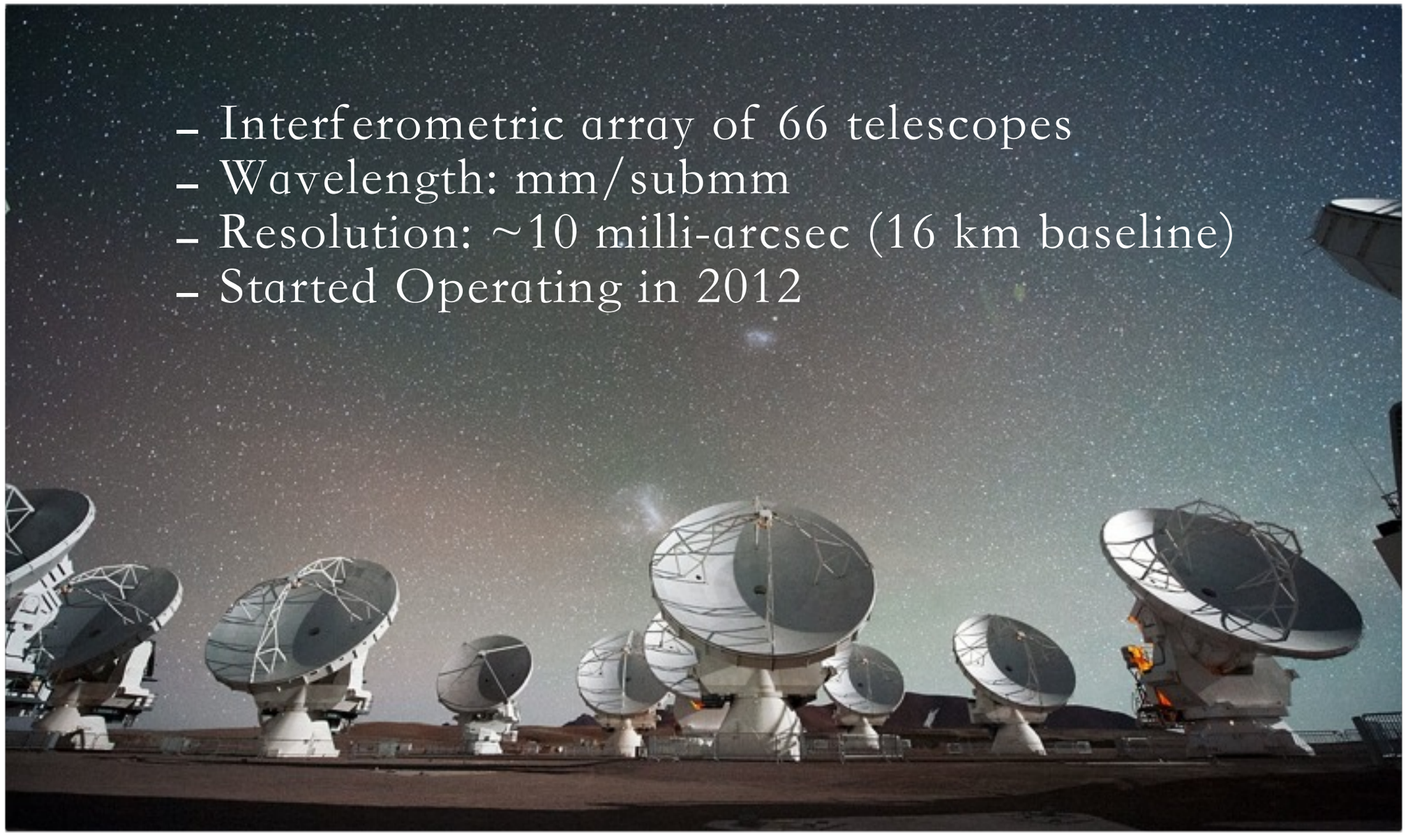
- but uncertainty was about factor of 10!



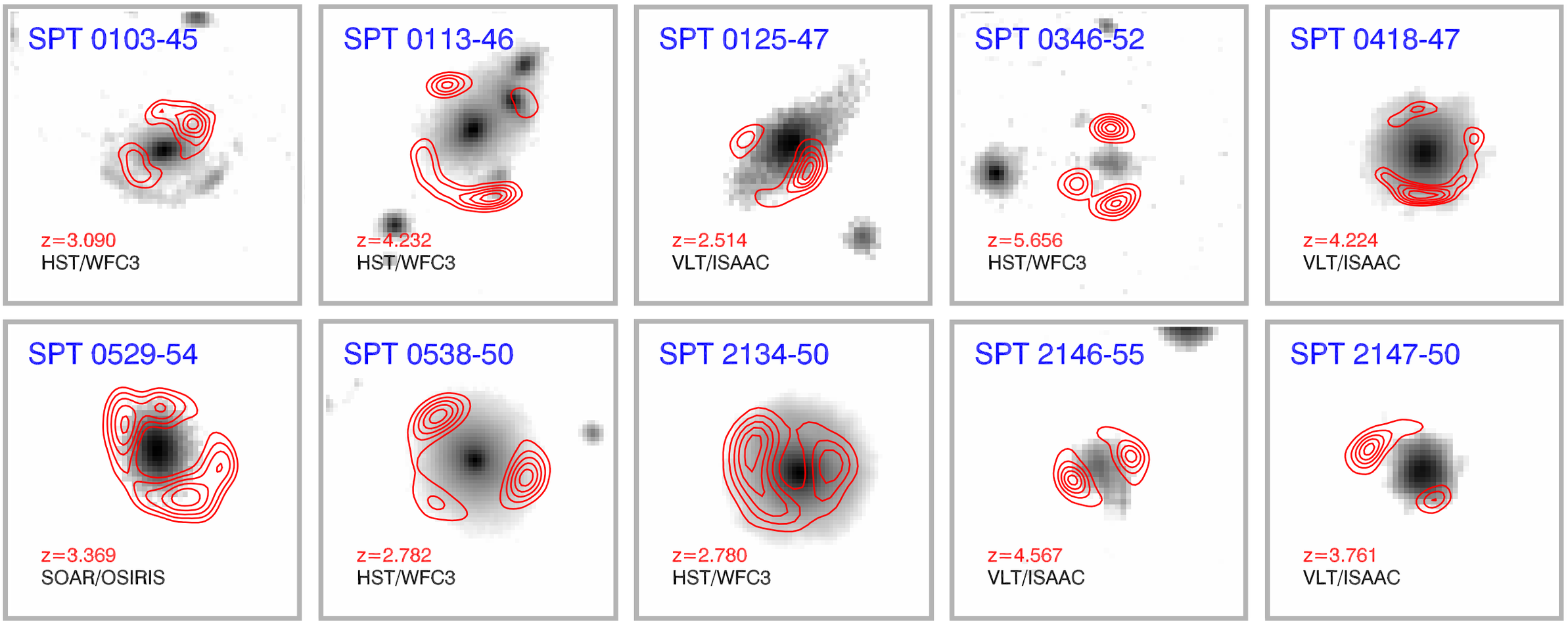
how to improve?

- we need a new class of lensed sources!

ALMA


– Interferometric array of 66 telescopes
– Wavelength: mm/submm
– Resolution: ~10 milli-arcsec (16 km baseline)
– Started Operating in 2012

ALMA Cycle 0 Band 7 350 GHz
2 minute snapshots



8" x 8" boxes

= deep NIR imaging

= 2 minute ALMA 350 GHz snapshot

Note that sources are bright in submm and invisible in visible/IR,
while lenses are invisible in submm and bright in visible/IR.

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

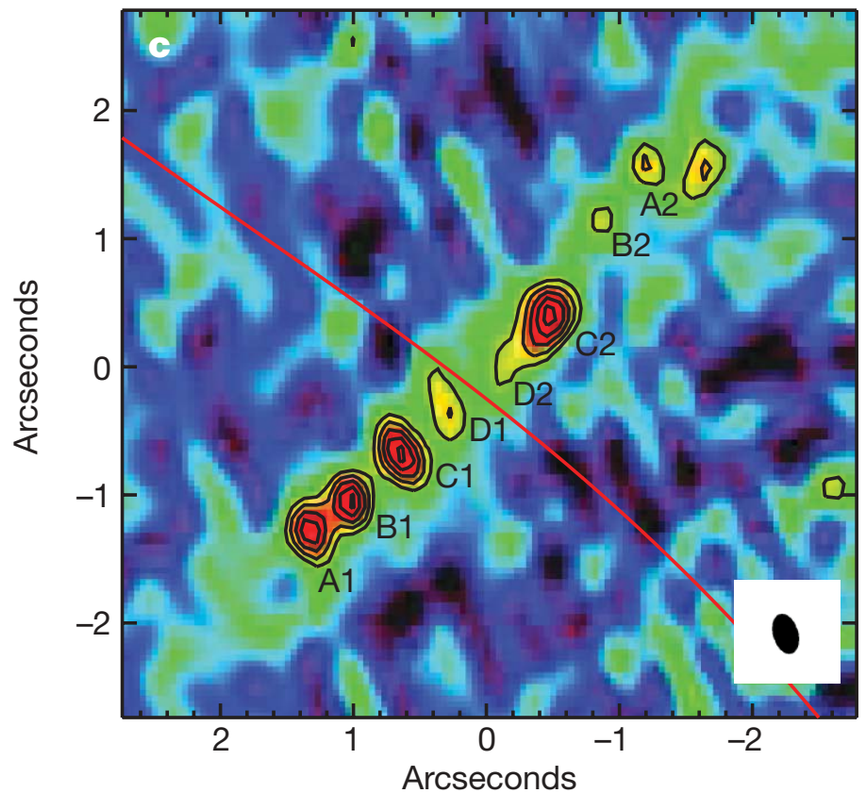
okay.... so what?

- lensed SMG's are *perfect* for detecting substructure!

- theoretically, we expect these galaxies to contain many **compact** star-forming clumps (~100pc) inside much bigger GMC's (~kpc). see also local analogues like Arp 220

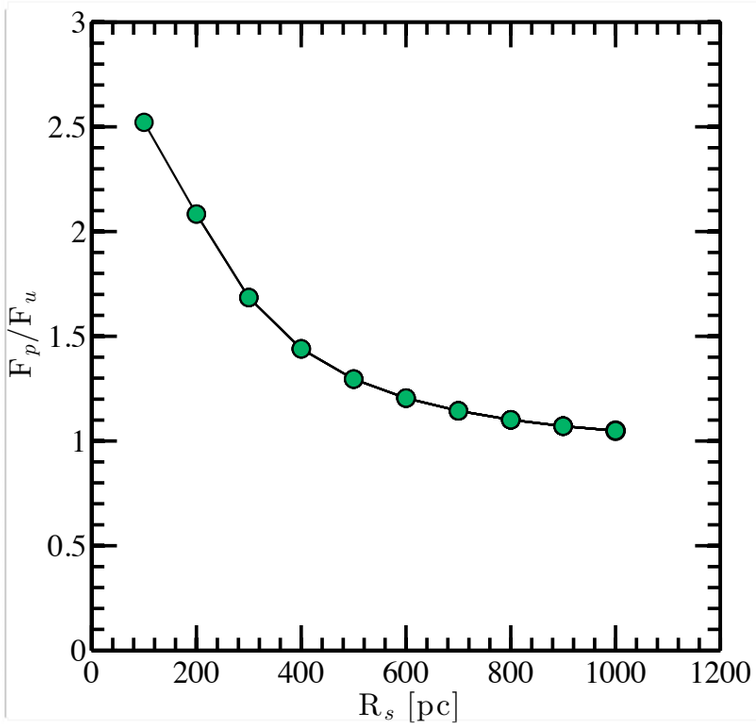
- clumps are extremely bright in lines like CO 7-6

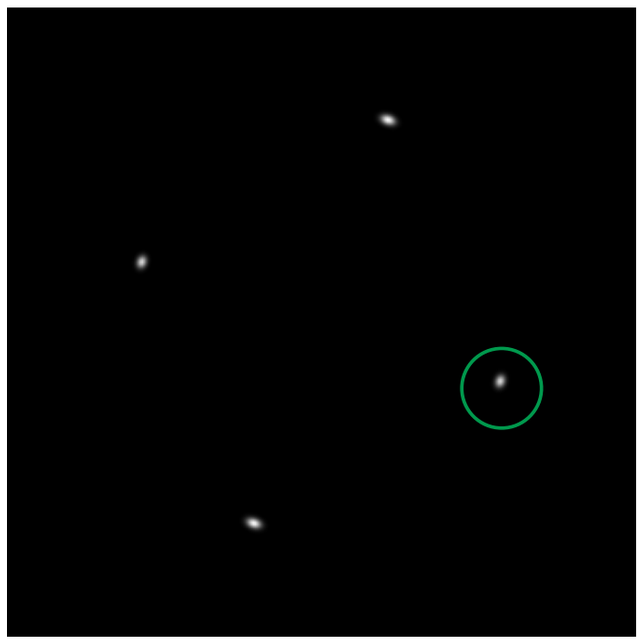
- example: high resolution SMA imaging of lensed SMG reveals compact source clumps (Swinbank et al. 2010)

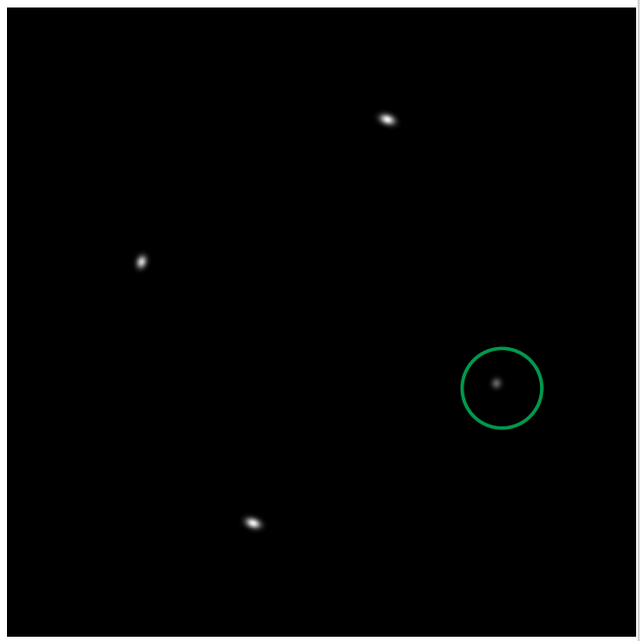


The Strength of Substructure Lensing Signal Depends on the Source Size

Compact Sources Are Perturbed More Strongly







Spatially resolved spectroscopy

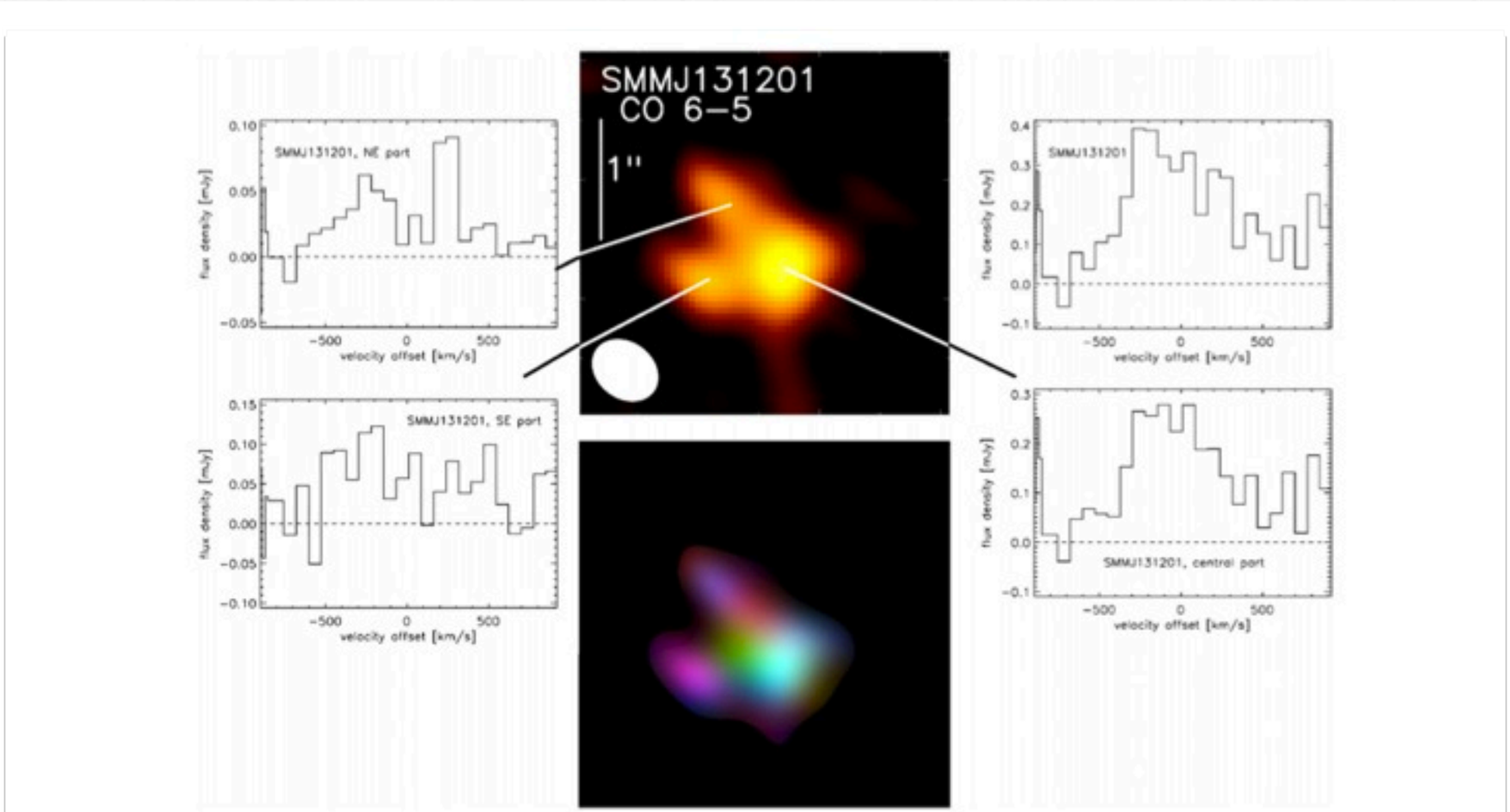
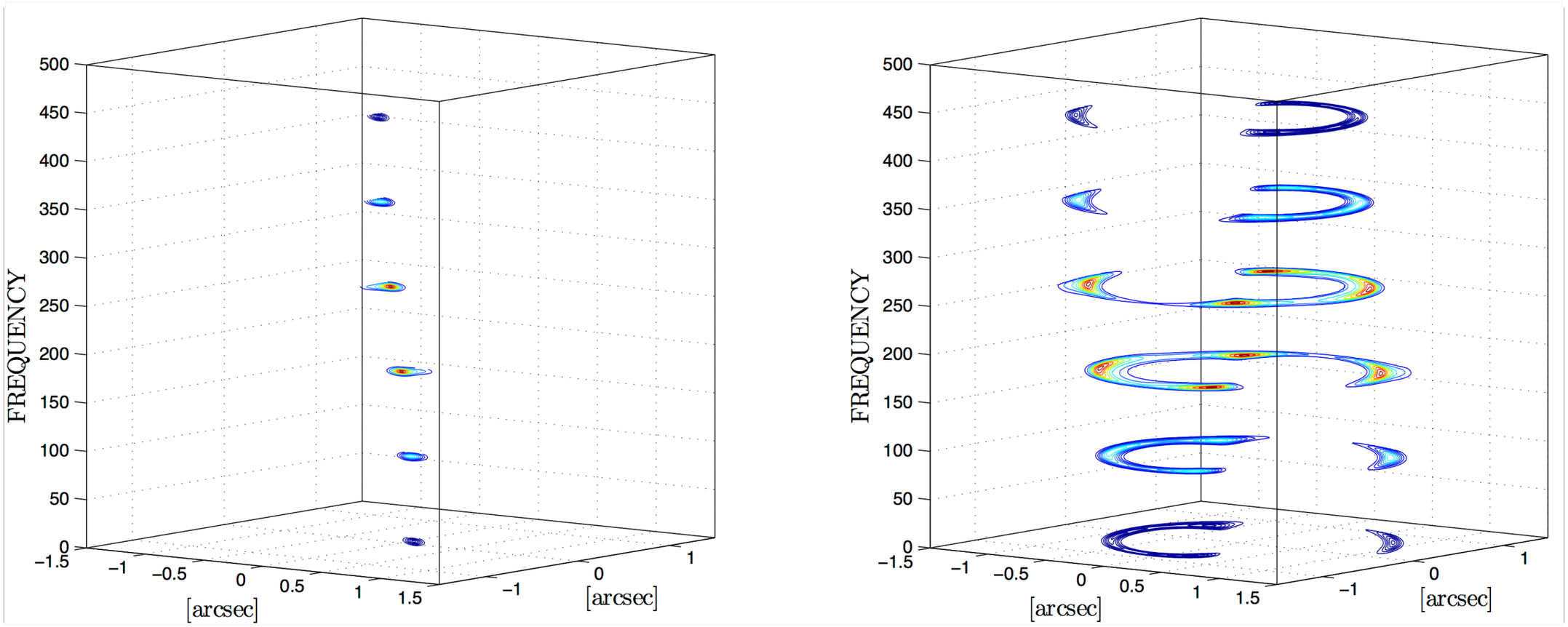


Figure 2. SMM J131201: this system displays a complex, irregular morphology; it most likely is an advanced pre-coalescence merger. The RGB image (mapping red, green, and blue parts of the spectrum) shows no indication of rotation. Spectra are, left: northeast (top) and southeast (bottom) arm, right: entire system (top), and central part (bottom). The beam size (0.″59 × 0.″47, P.A. = 50.°9) 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

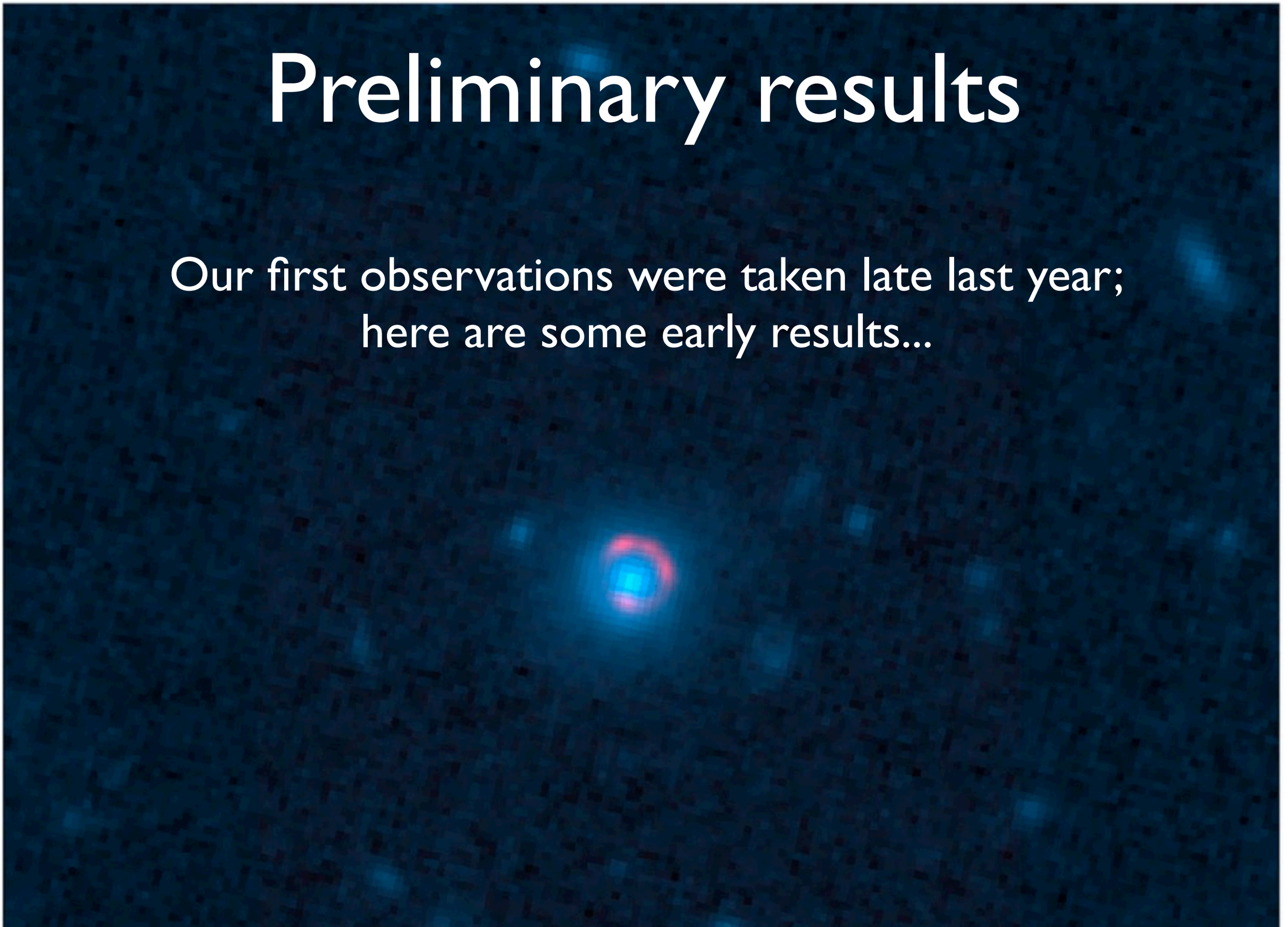


so each SMG is equivalent to having **many** sources behind each lens!

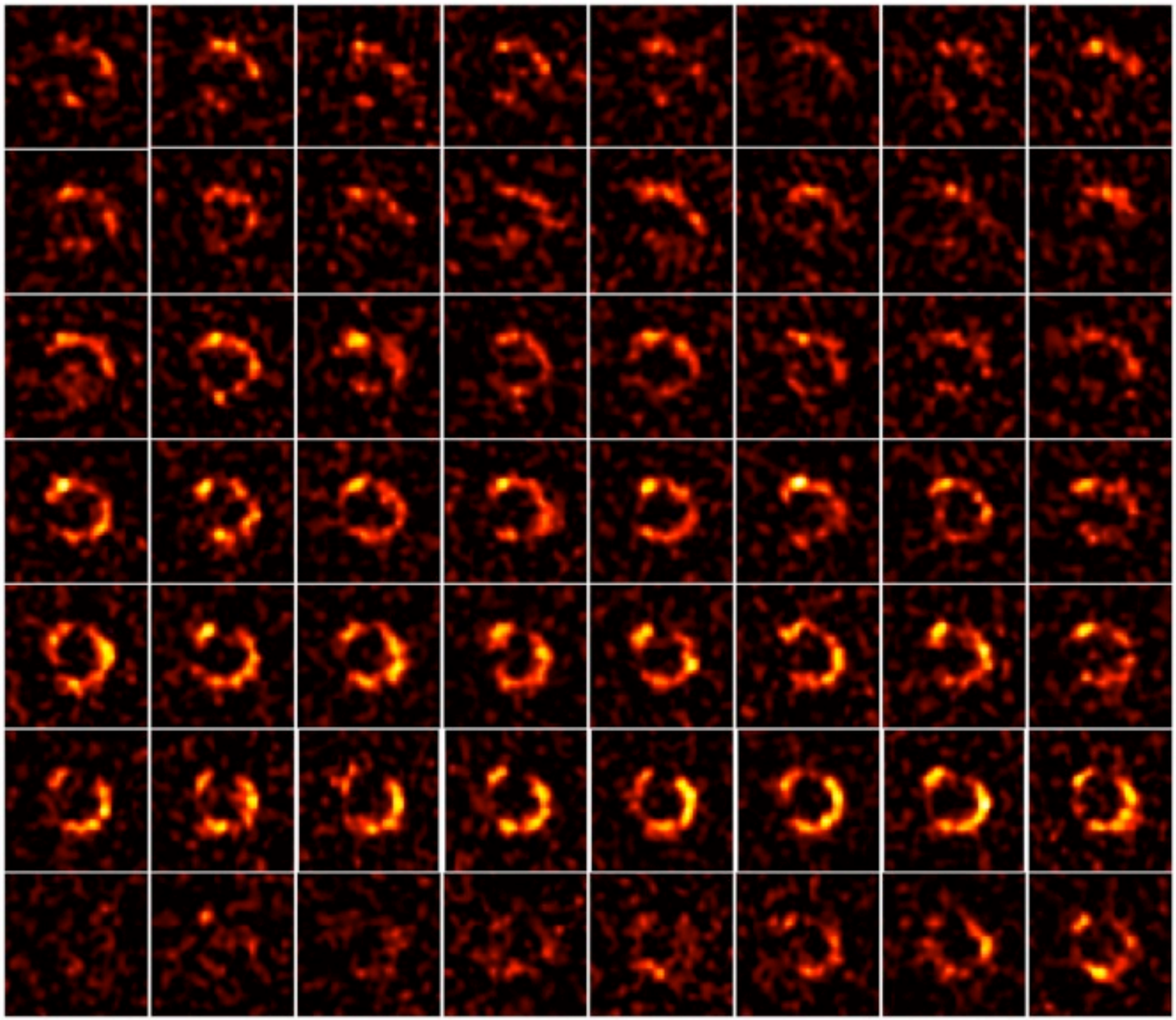
SPT 2134-50

Preliminary results

Our first observations were taken late last year;
here are some early results...



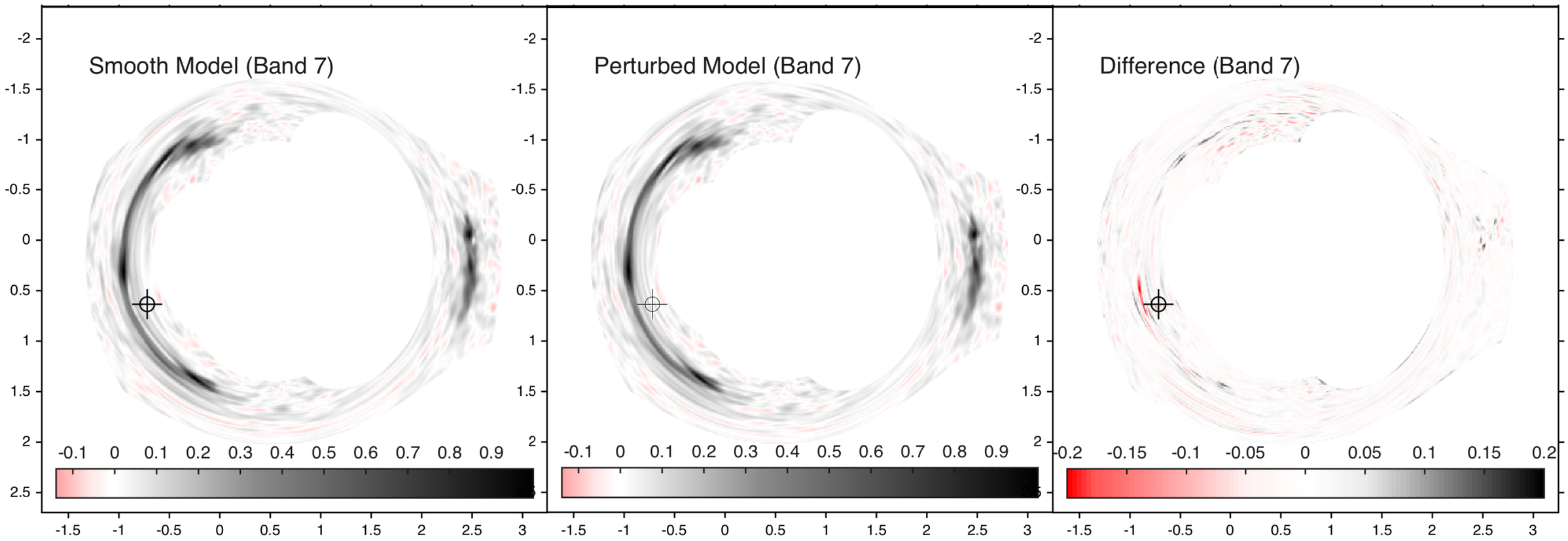
3D structure



Lens modeling

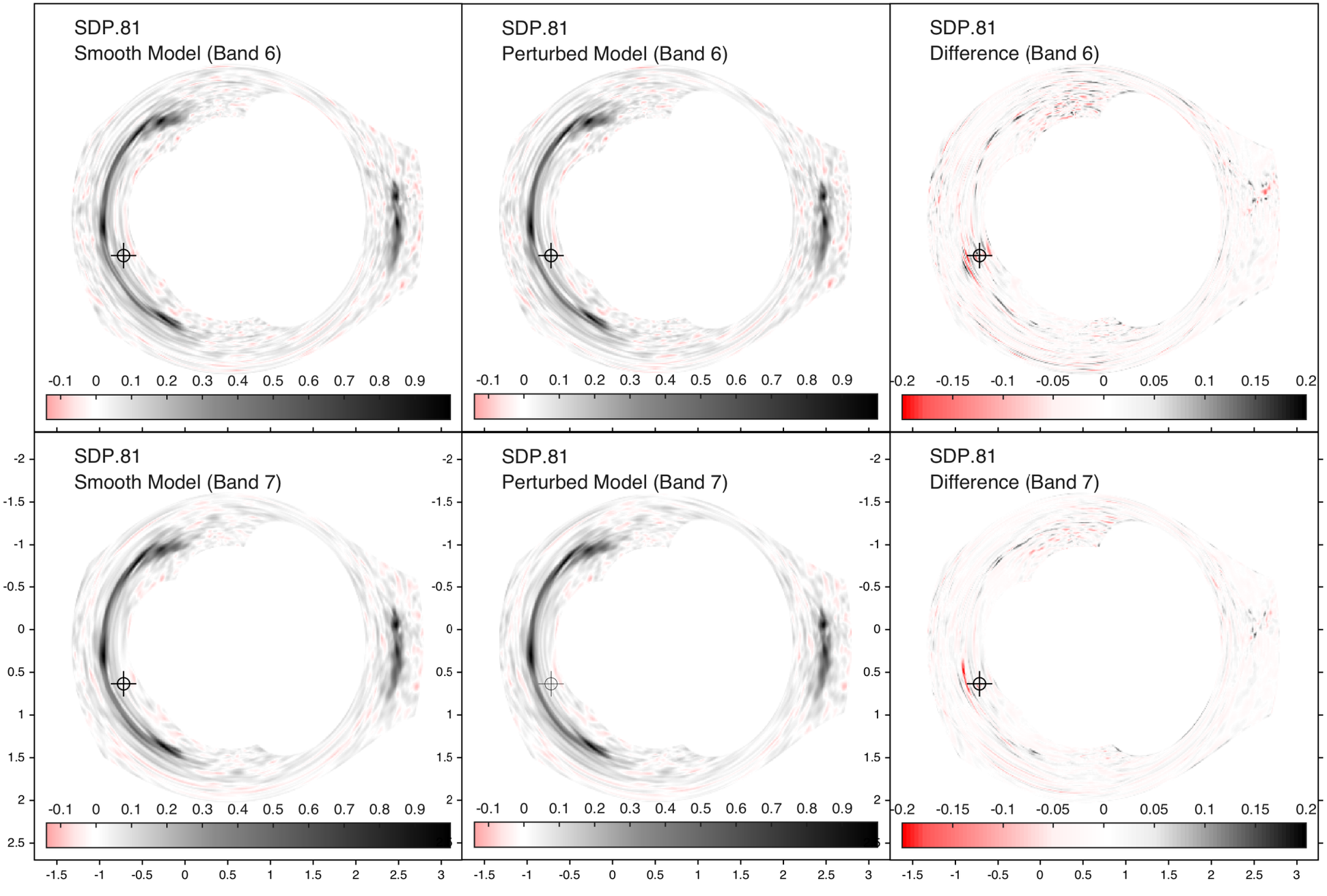
- ALMA is an interferometer, so the observables are (millions of) visibilities in the *uv* plane
- We fit the visibilities, not CLEAN images
- Our model has 10's of thousands of free parameters, including things like time-varying antenna phase errors. We marginalize over all of them.
- This is crucial! Improper treatment of phase errors will lead to spurious detection of subhalos

Subhalo detection

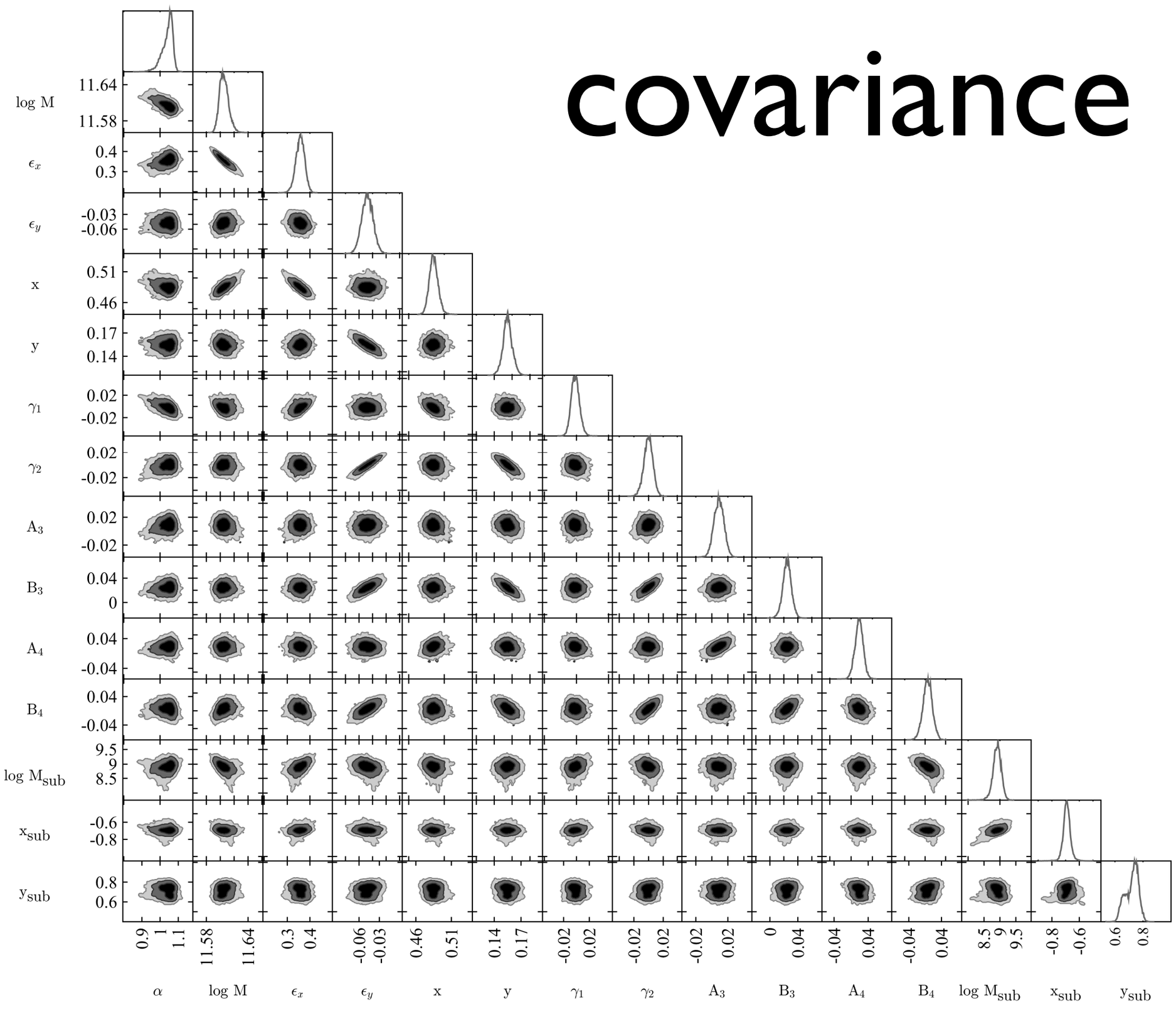


- a $M=10^9\ M_\odot$ subhalo is detected at ~ 7-sigma confidence in the first system we analyzed

detected in multiple bands

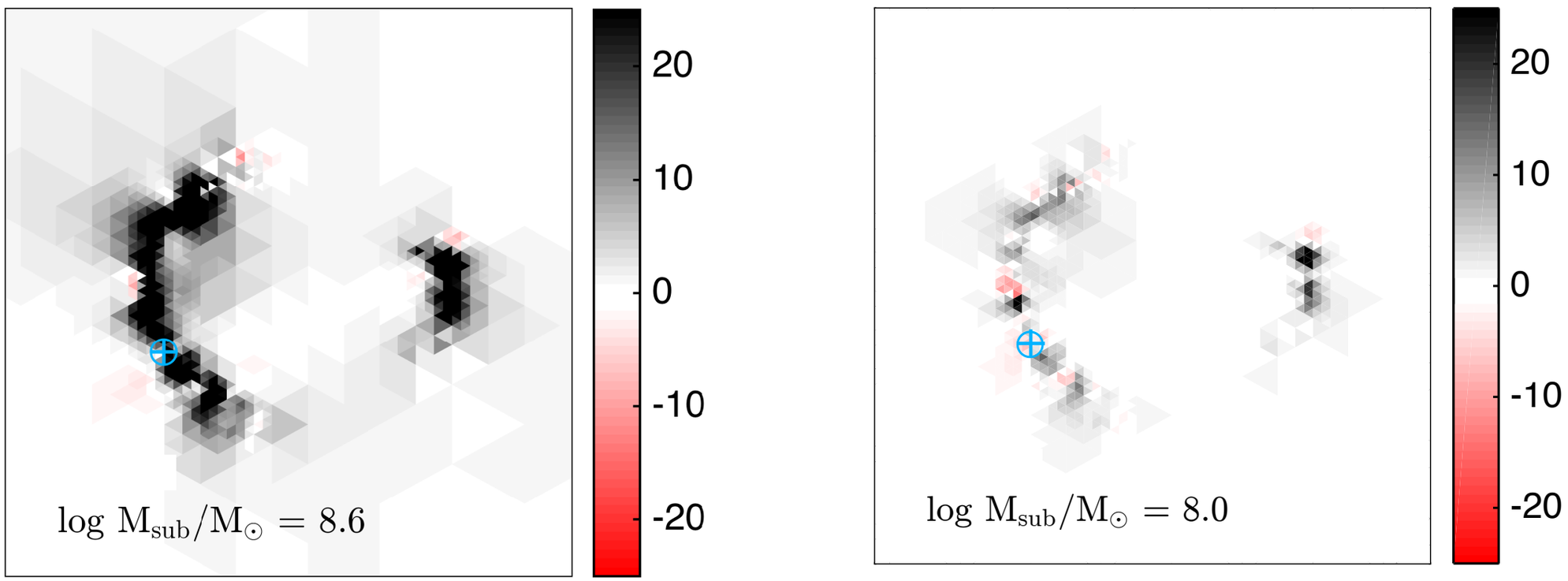


covariance


log M
ϵ_x
ϵ_y
x
y
γ_1
γ_2
A_3
B_3
A_4
B_4
log M_{sub}
x_{sub}
y_{sub}
α

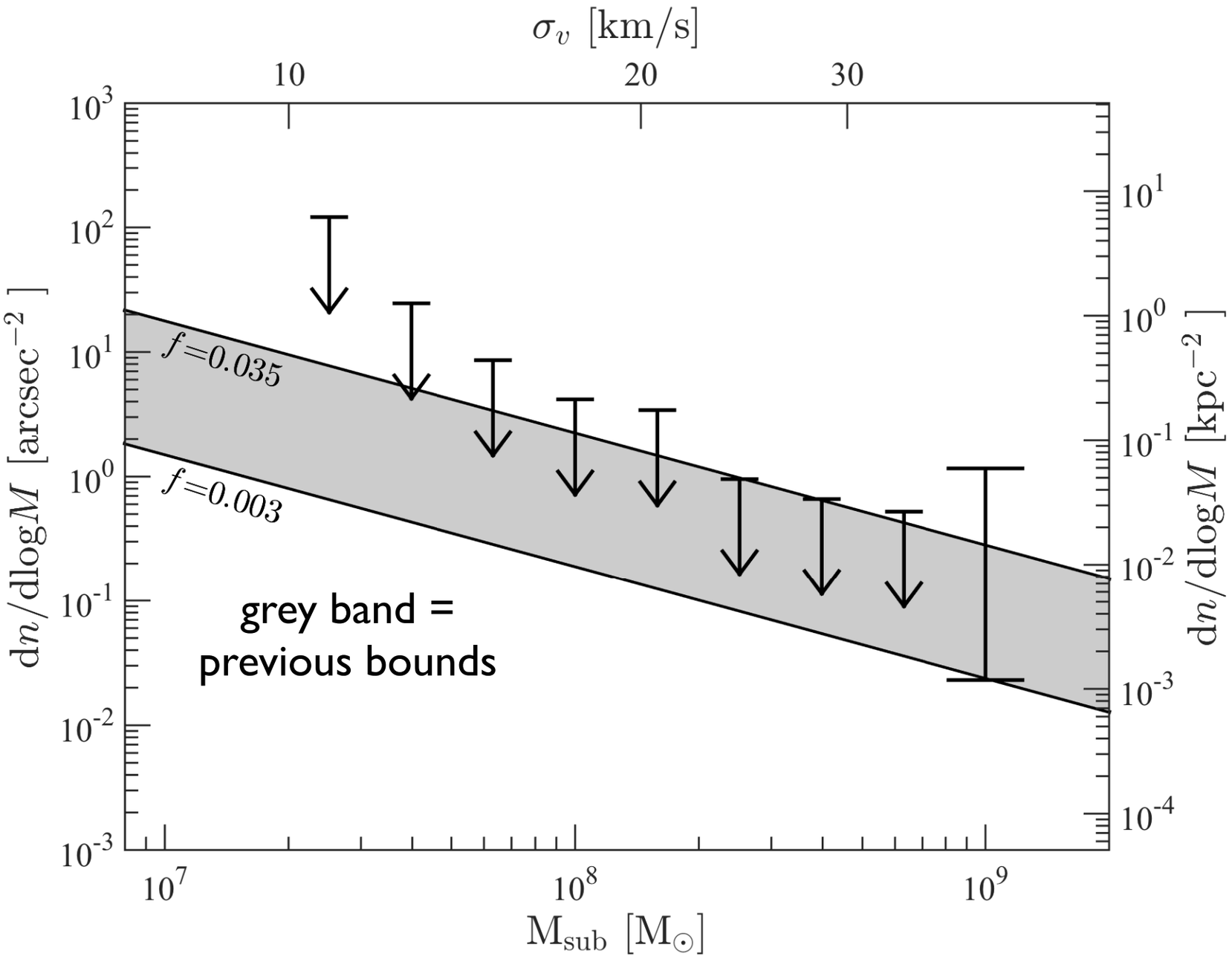
Other subhalos?

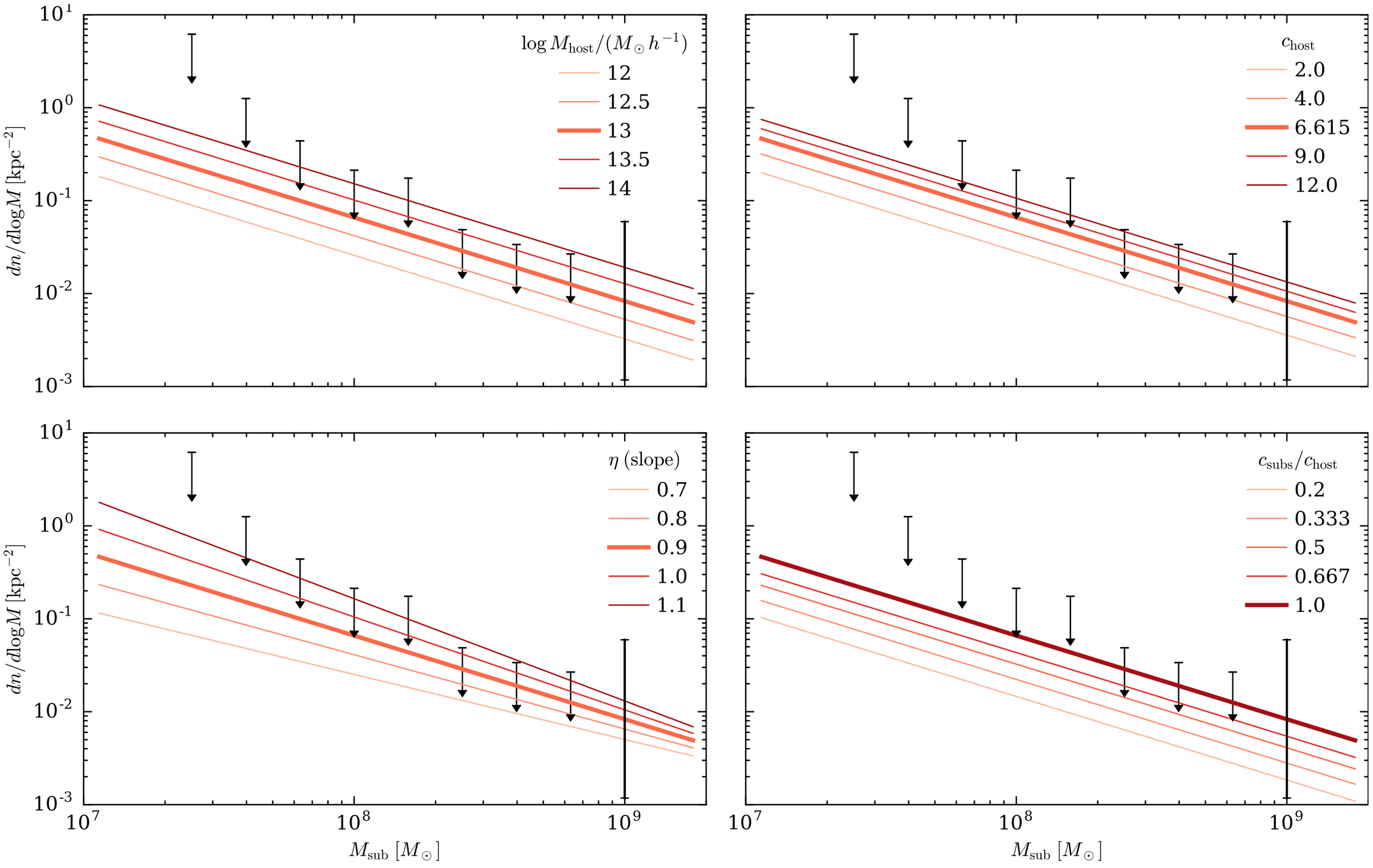
- this map shows how the fit improves ($\Delta\chi^2$) as we add a subhalo at various other locations...



- seems to be ~ 4.5σ hint for an additional subhalo with $M=10^8\ M_\odot$

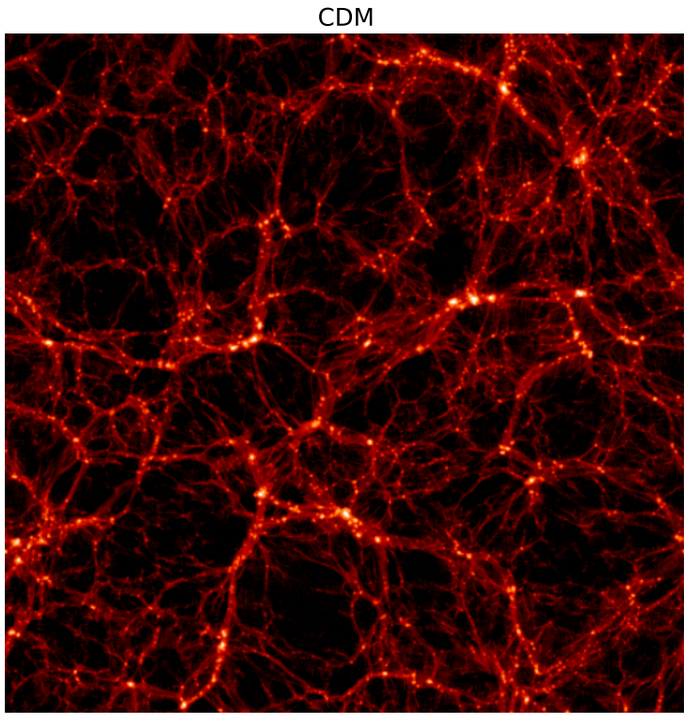
bounds on the subhalo mass function



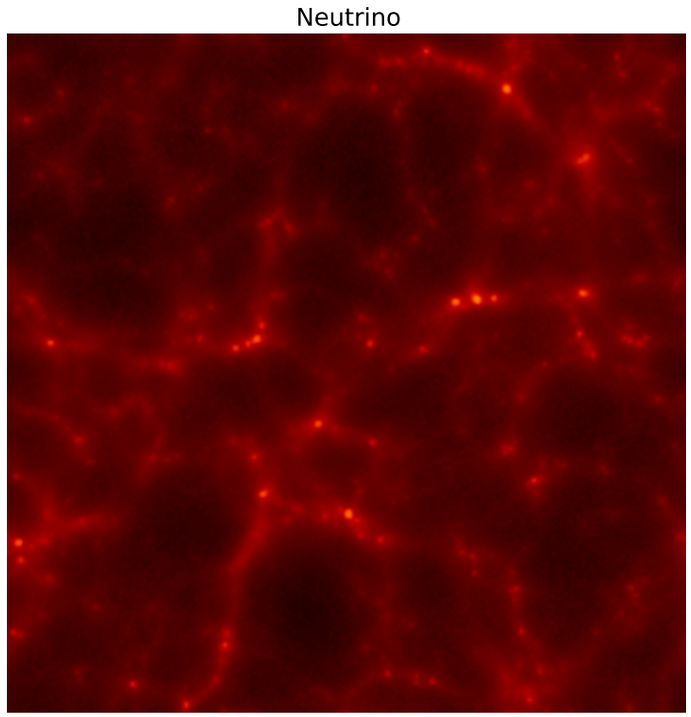

10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$dn/d\log M\ [\mathrm{kpc}^{-2}]$
$\log M_{\mathrm{host}}/(M_\odot\, h^{-1})$
12
12.5
13
13.5
14
c_{host}
2.0
4.0
6.615
9.0
12.0
η (slope)
0.7
0.8
0.9
1.0
1.1
$c_{\mathrm{subs}}/c_{\mathrm{host}}$
0.2
0.333
0.5
0.667
1.0
10^7
10^8
10^9
$M_{\mathrm{sub}}\ [M_\odot]$

New simulation code for hot particles

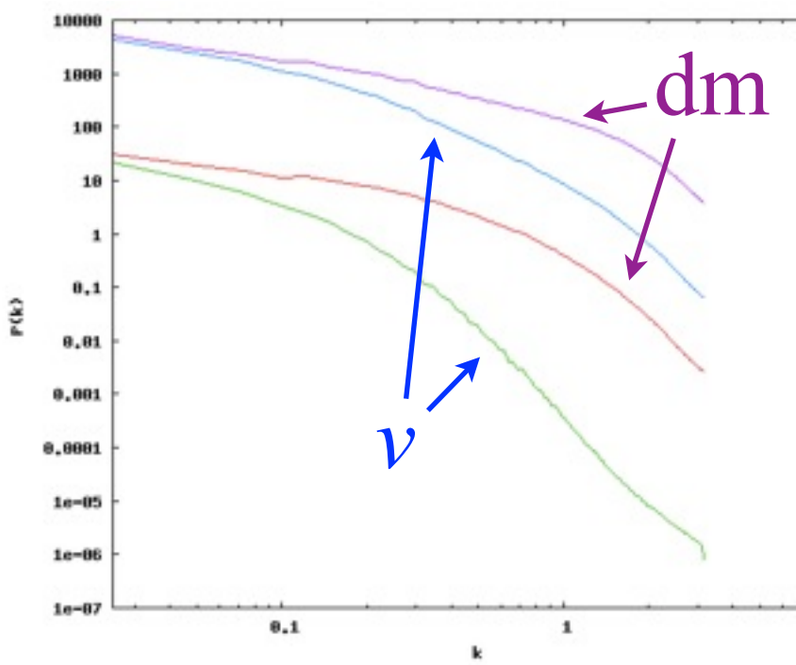
- with Arka Banerjee (student)
- combines elements of Lagrangian (N-body) and Eulerian (hydrodynamic) simulations
- applicable for WDM as well as massive neutrinos; avoid shot noise problems that arise in N-body sims



CDM



neutrinos



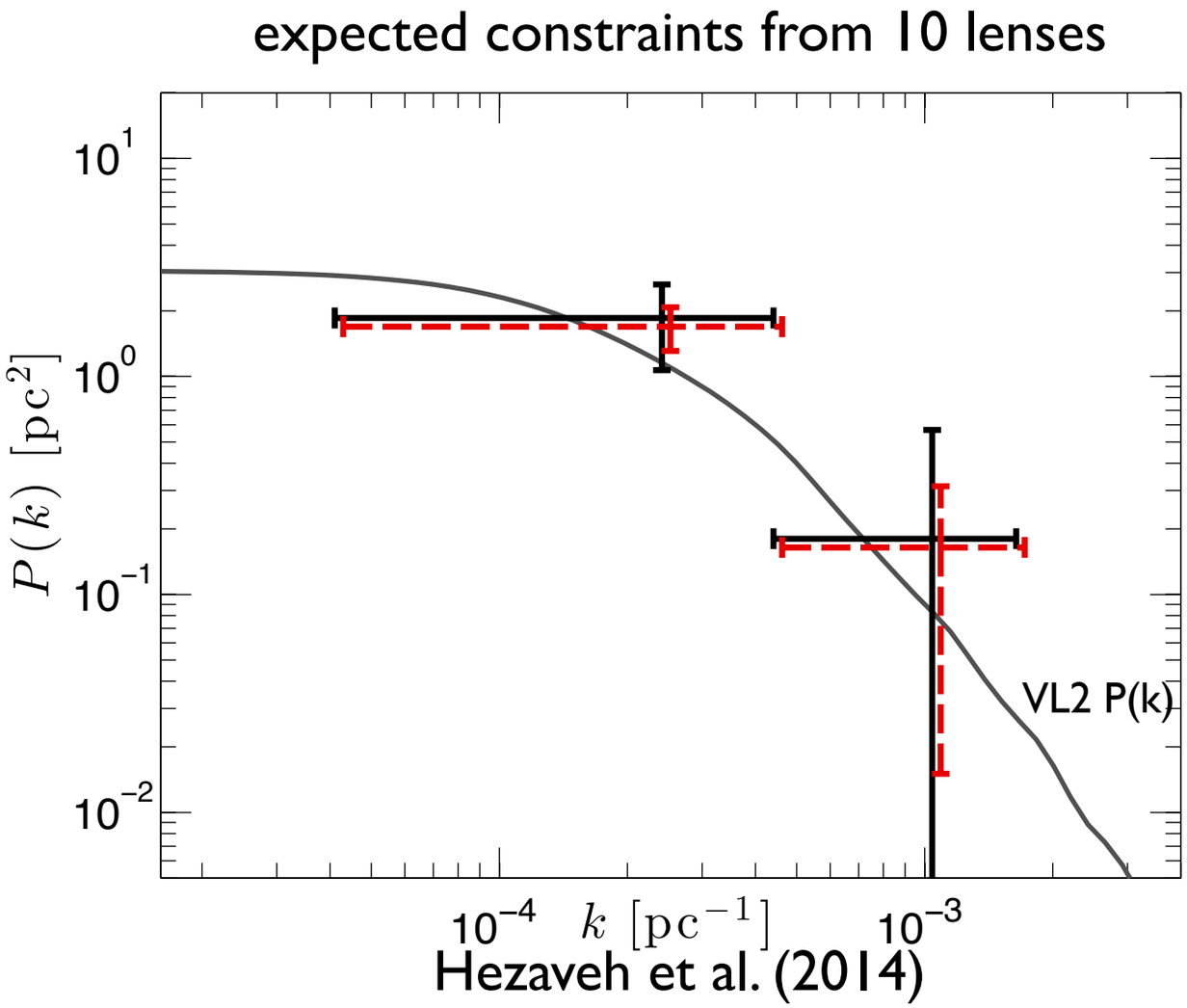
P(k)

Conclusion:

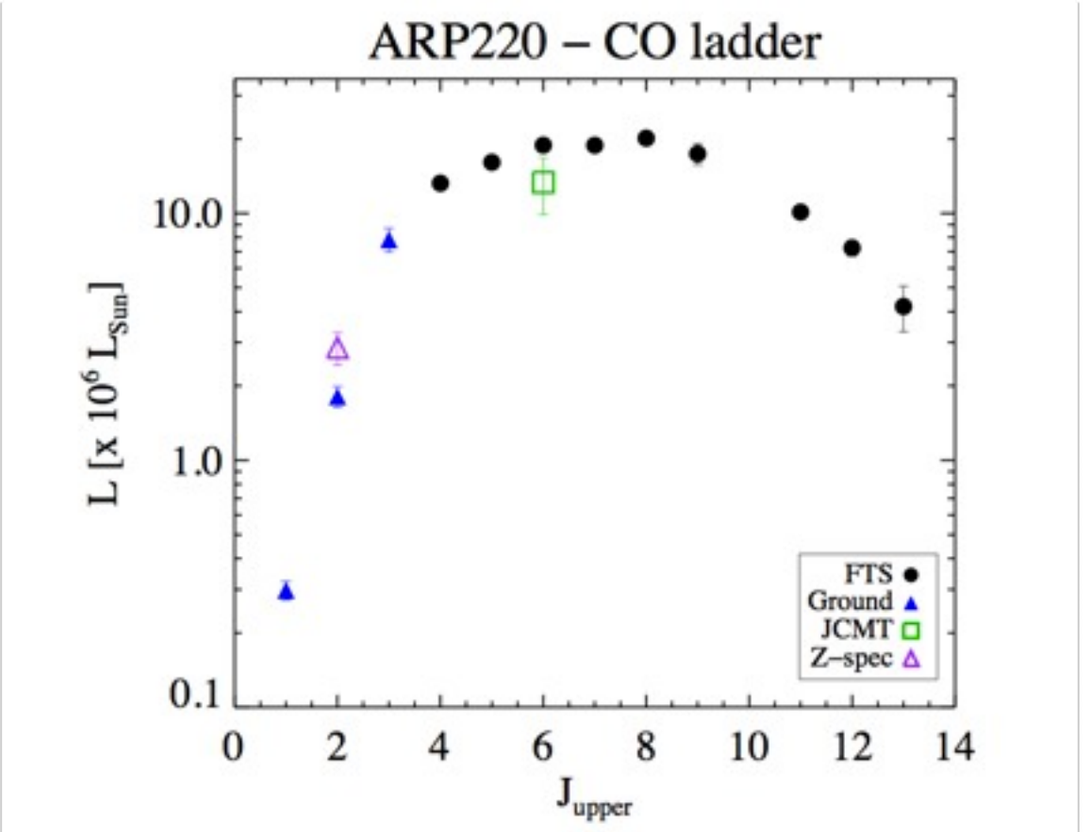
- SMG lensing is great for DM substructure
- stay tuned!

Substructure power spectrum

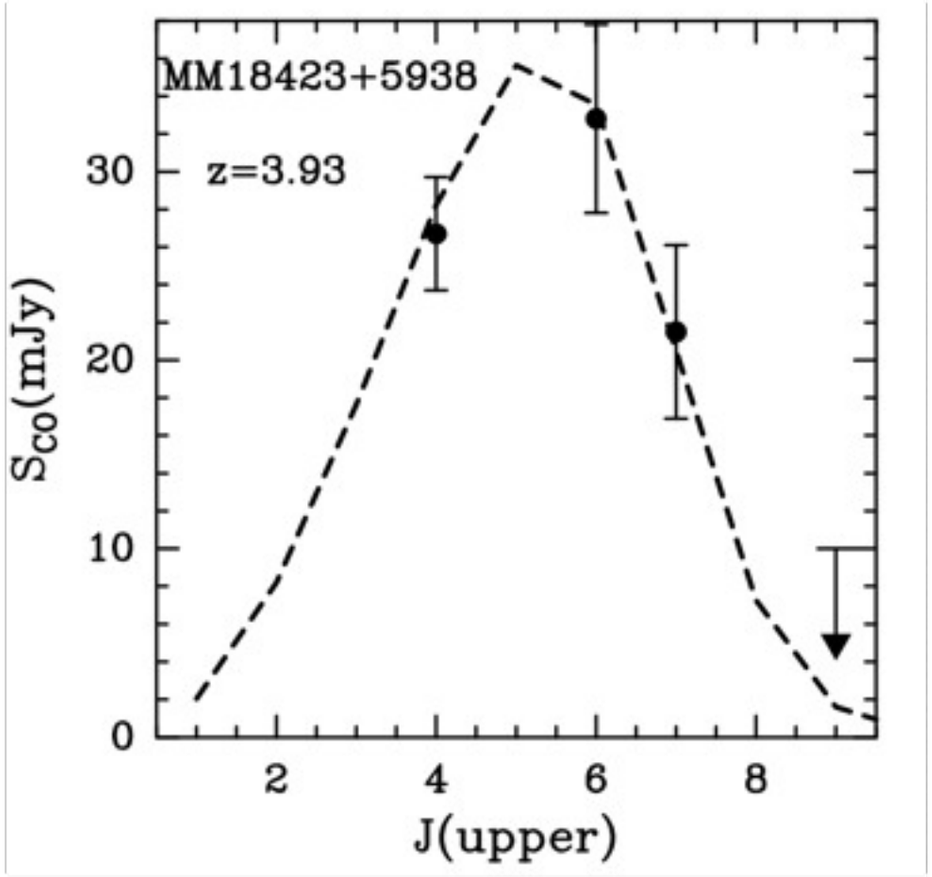
- besides all the big, 5-10σ objects, there are many more subhalos that produce 1-2σ effects.
- although we don't detect them individually, their **collective** effects can be detected
- note: easily distinguishable from measurement noise or source fluctuations



Strength of High-J Lines



RANGWALA ET AL 2011, APJ 743-1



LESTRADE ET AL 2010, A&A 522

⇒ High excitation lines are
1) more compact (more sensitivity to substructure)
2) brighter (higher signal to noise ratios)