Mapping Hot Gas in the Universe using the Sunyaev-Zeldovich Effect

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)

"*Probing Fundamental Physics with CMB Spectral Distortions*", CERN

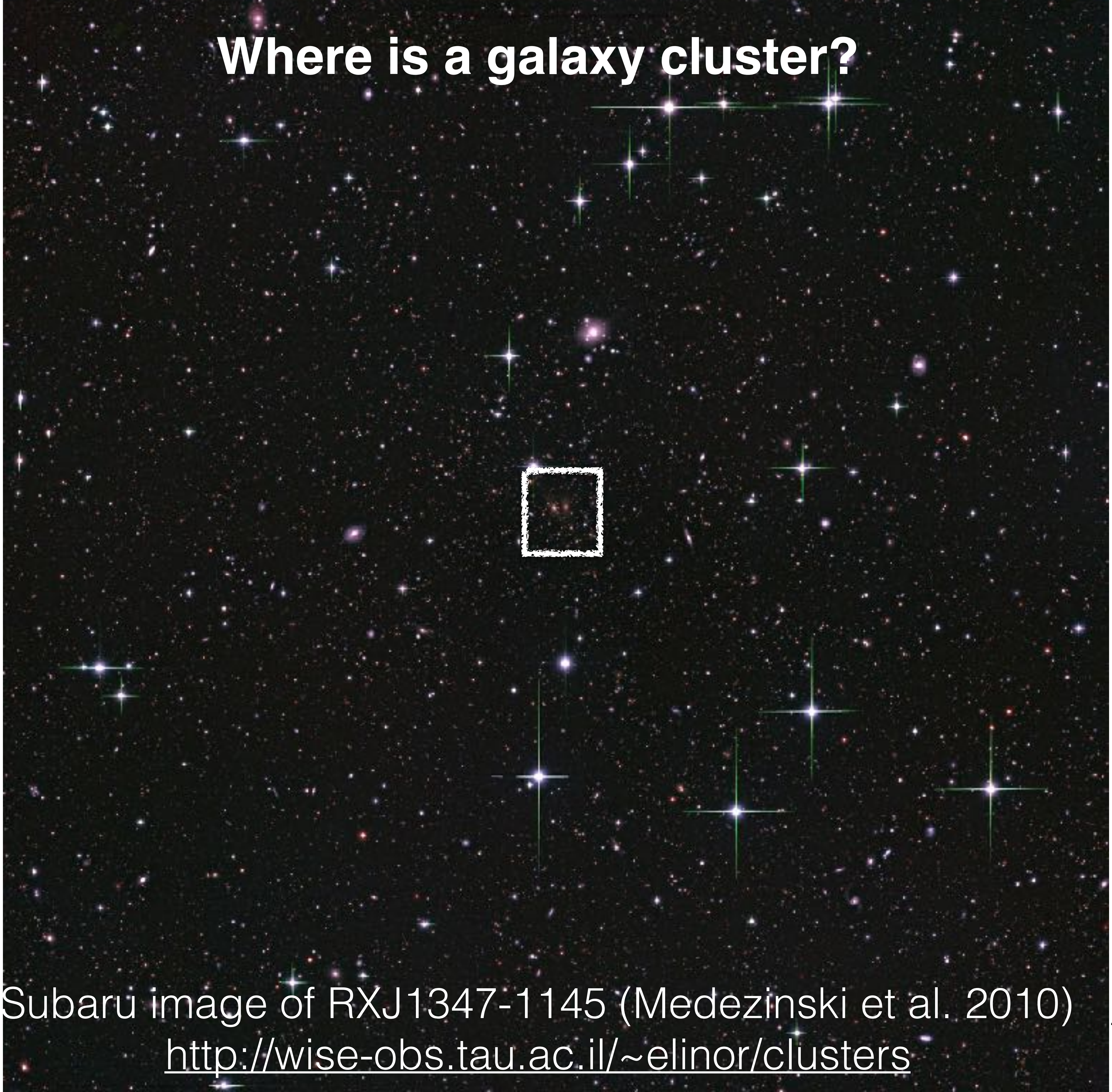
March 12, 2018

Happy (belated; March 1) 75th birthday, Rashid!

Where is a galaxy cluster?

Subaru image of RXJ1347-1145 (Medezinski et al. 2010)
http://wise-obs.tau.ac.il/~elinor/clusters

Where is a galaxy cluster?



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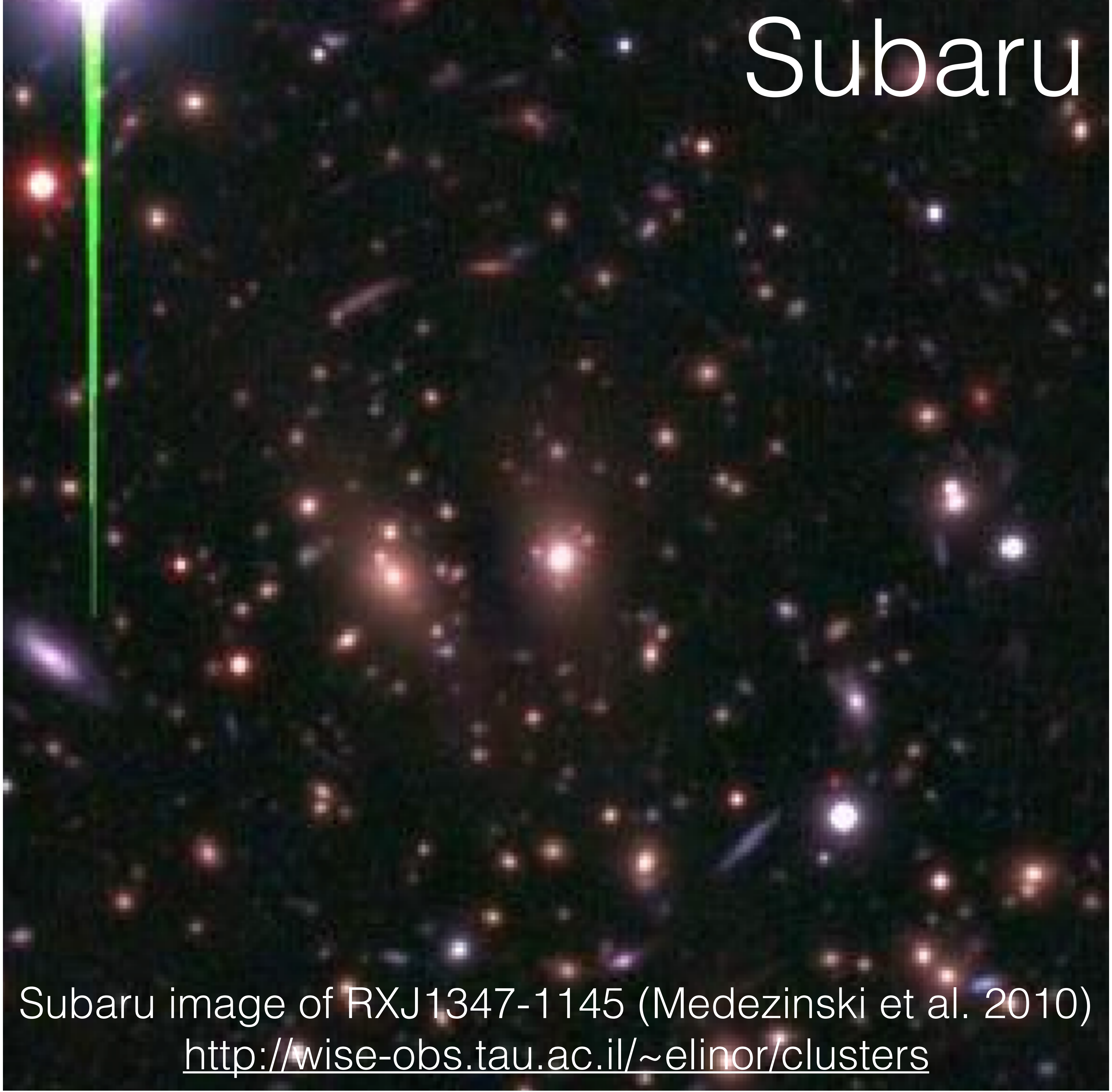
Subaru



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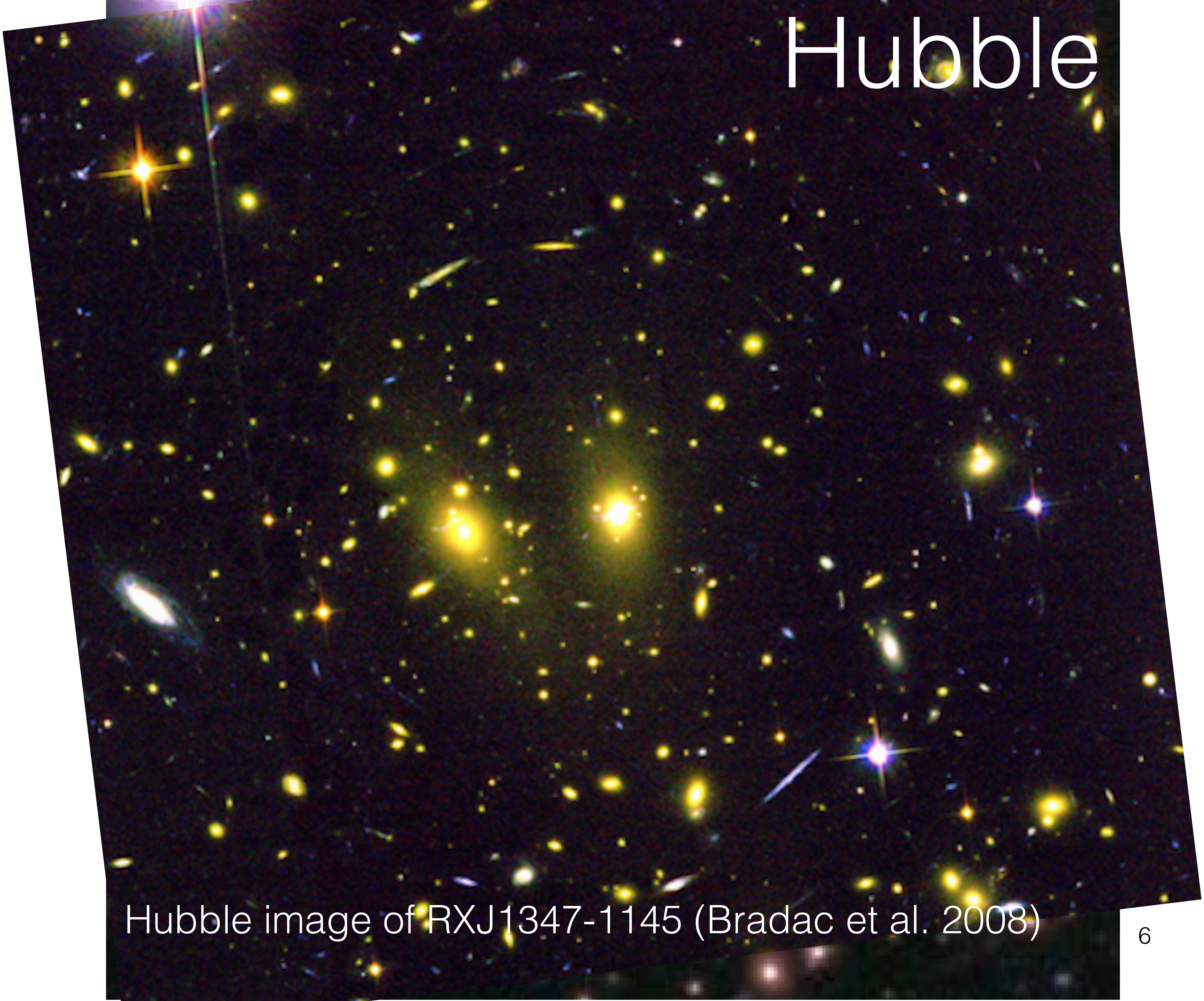
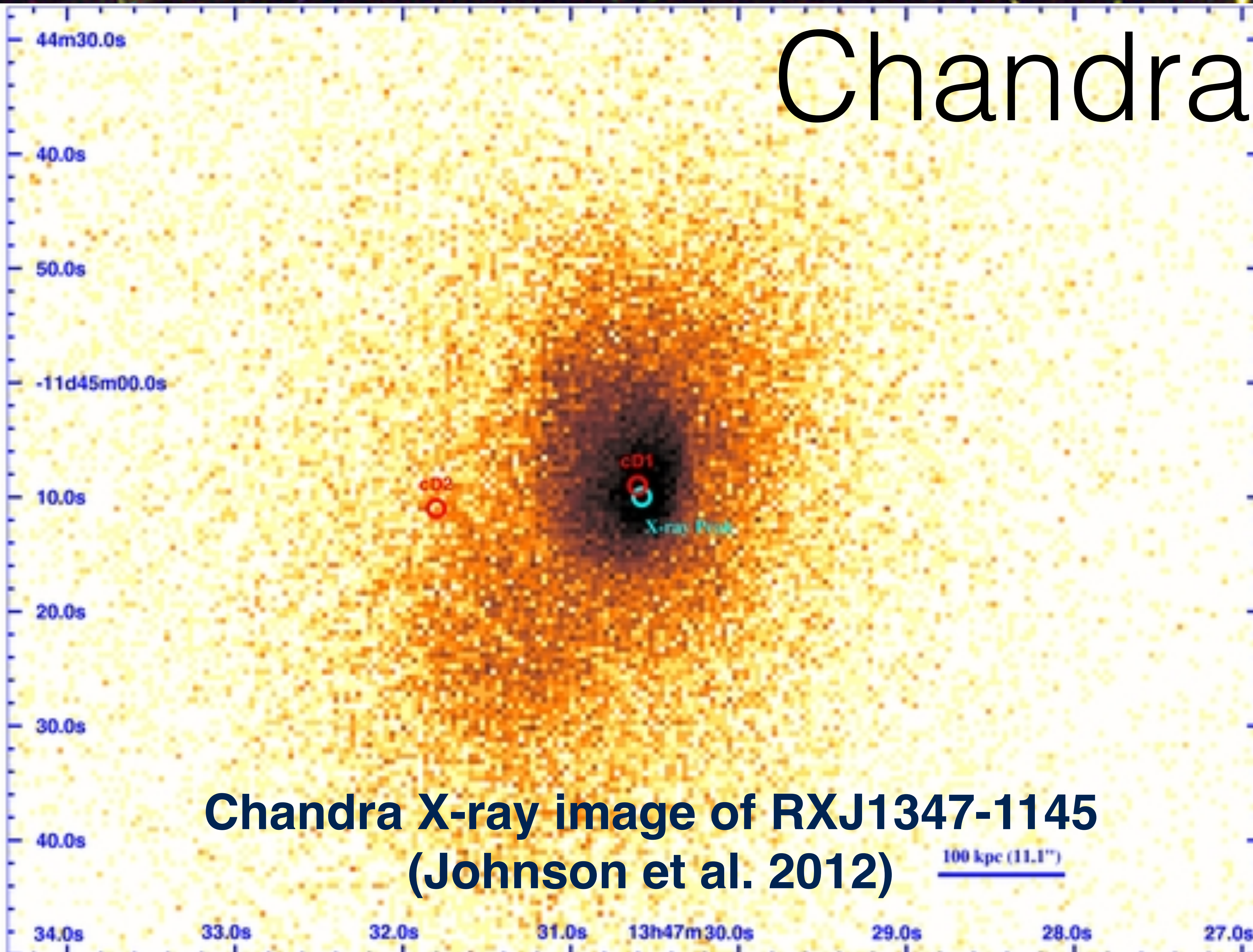
Hubble

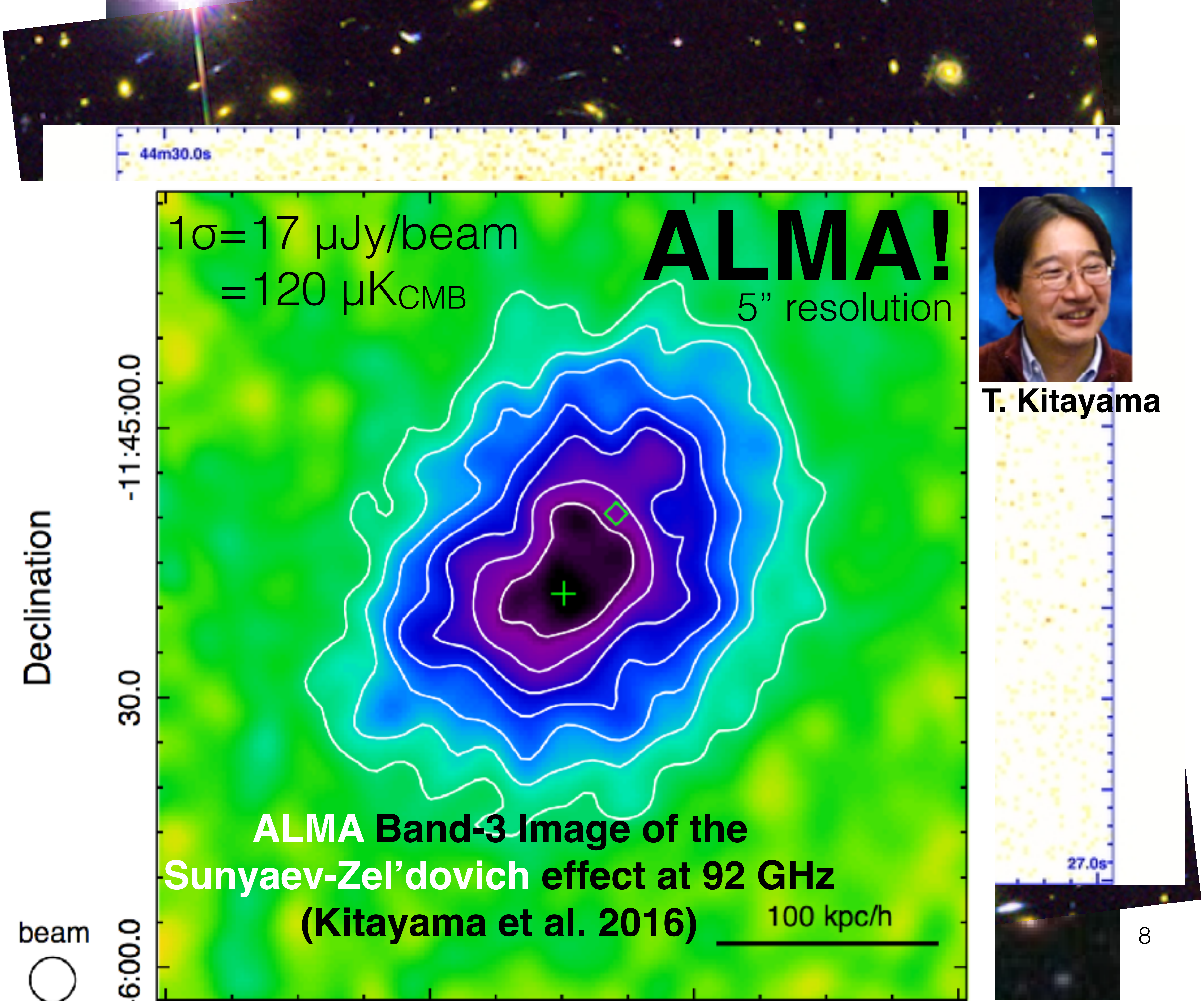


Hubble image of RXJ1347-1145 (Bradac et al. 2008)

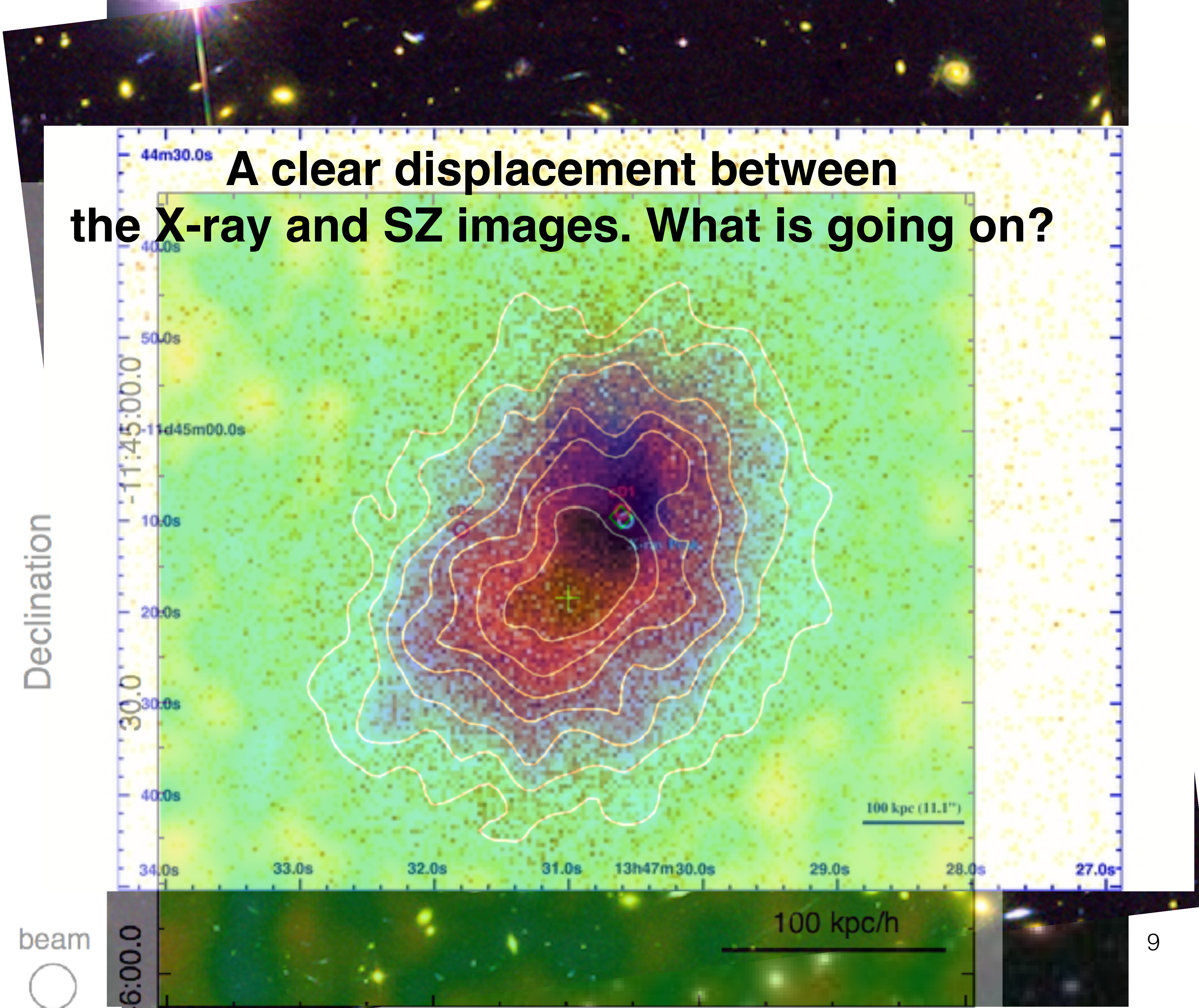
Chandra

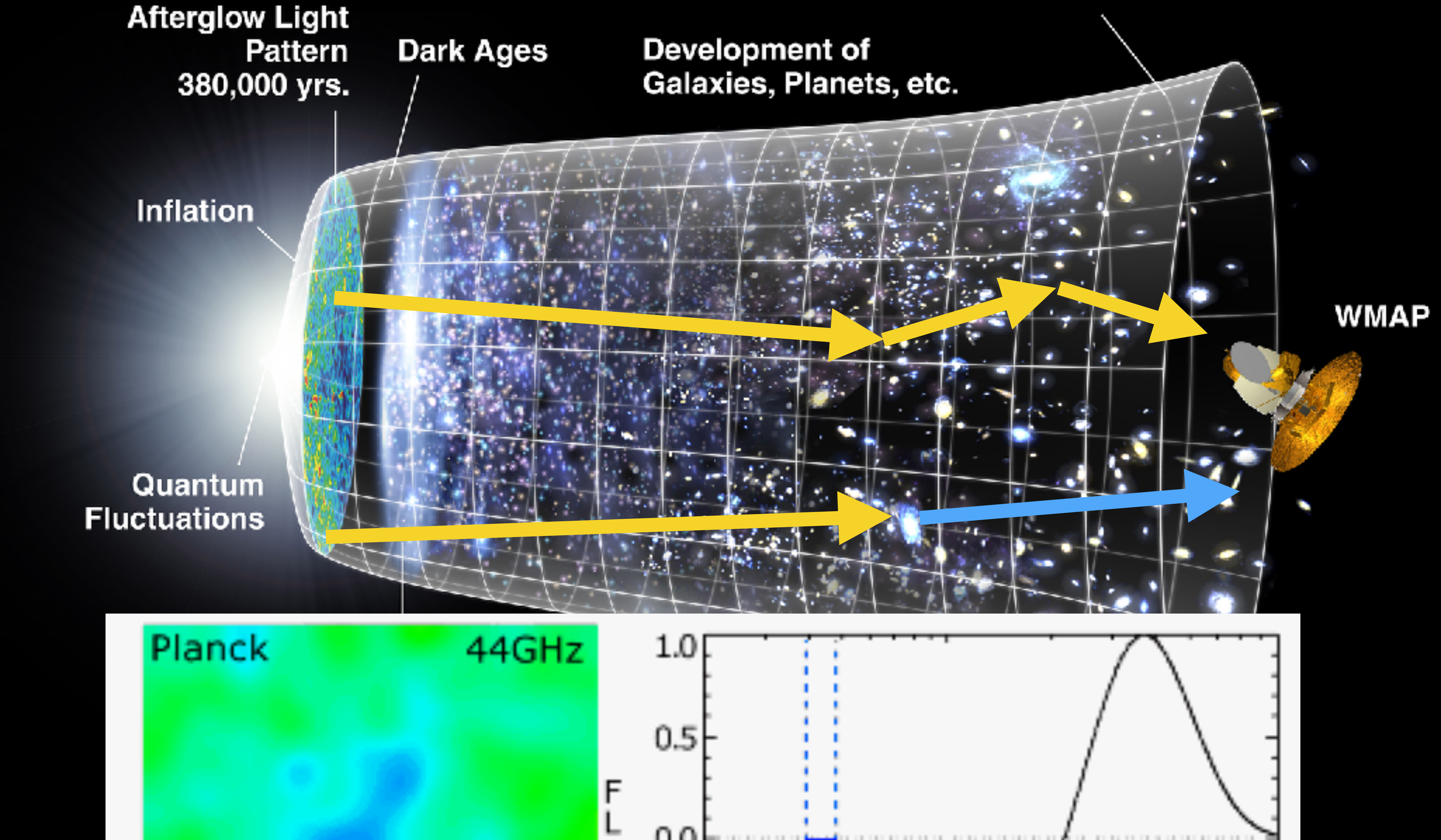


Chandra X-ray image of RXJ1347-1145 (Johnson et al. 2012)

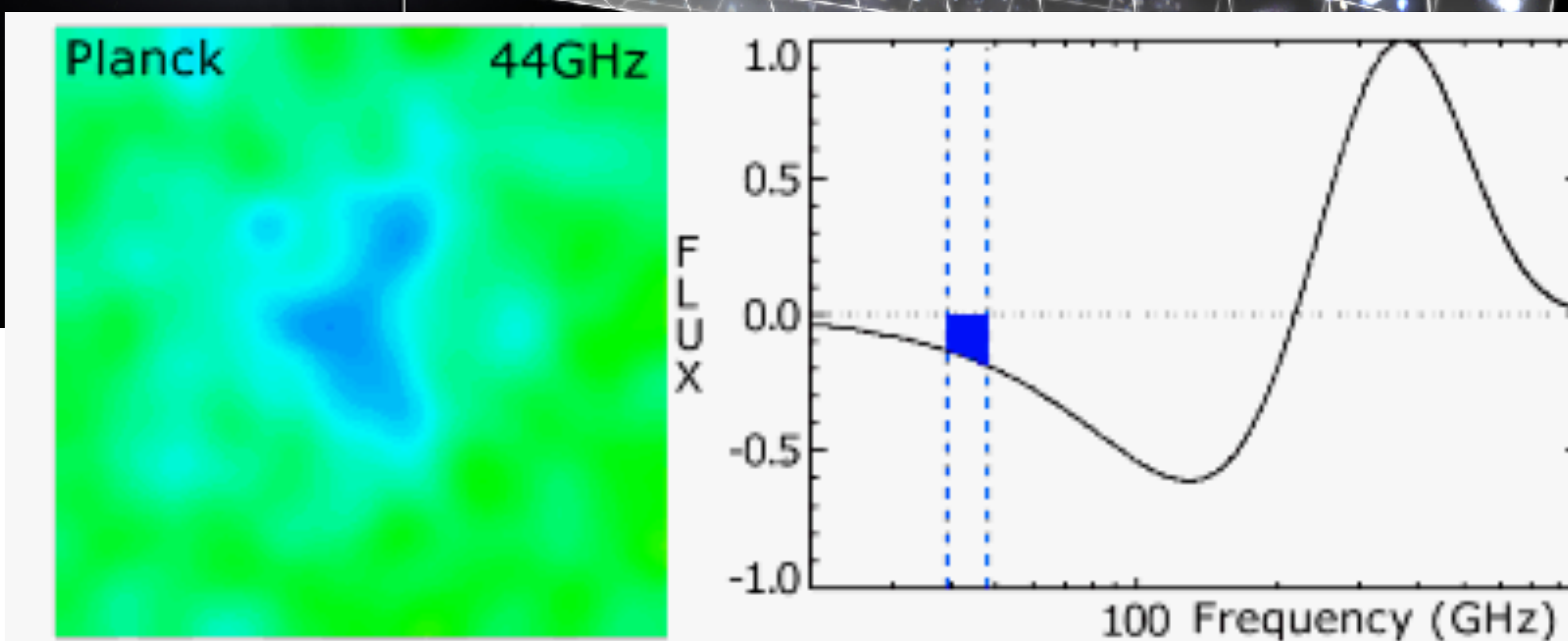

44m30.0s
1σ=17 μJy/beam
=120 μKCMB
ALMA!
5” resolution
T. Kitayama
Declination
-11:45:00.0
30.0
6:00.0
beam
ALMA Band-3 Image of the
Sunyaev-Zel’dovich effect at 92 GHz
(Kitayama et al. 2016)
100 kpc/h
27.0s

A clear displacement between the X-ray and SZ images. What is going on?





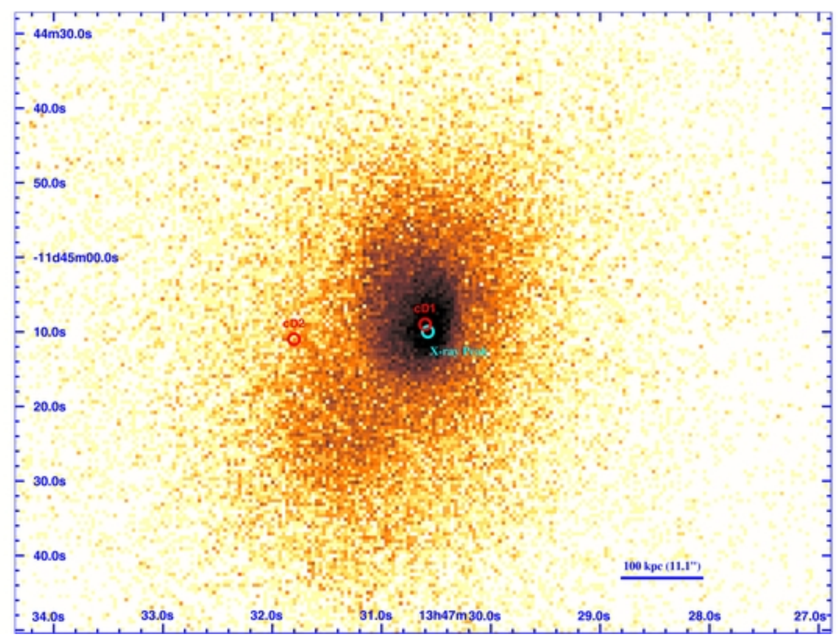
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
Quantum Fluctuations
WMAP

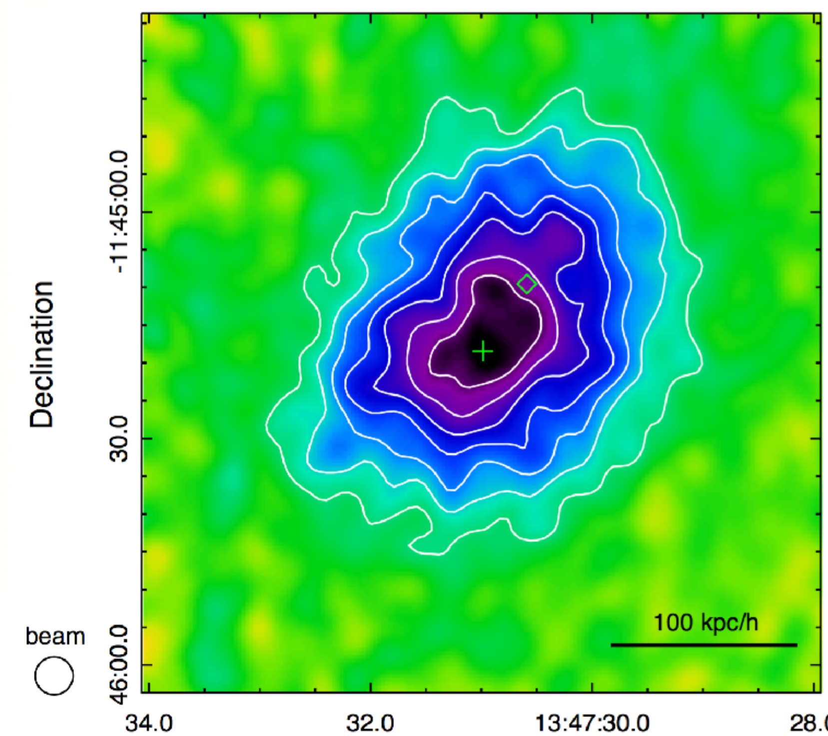


Planck
44GHz
FLUX
1.0
0.5
0.0
-0.5
-1.0
100 Frequency (GHz)

Multi-wavelength Data

$$I_X = \int dl \; n_e^2 \Lambda(T_X) \qquad I_{SZ} = g_\nu \frac{\sigma_T k_B}{m_e c^2} \int dl \; n_e T_e$$





<u>Optical</u>:
- 10^{2-3} galaxies
- velocity dispersion
- gravitational lensing

<u>X-ray</u>:
- hot gas (10^{7-8} K)
- spectroscopic T_X
- Intensity ~ $n_e^2 L$

<u>SZ</u> [microwave]:
- hot gas (10^{7-8} K)
- electron pressure
- Intensity ~ $n_e T_e L$

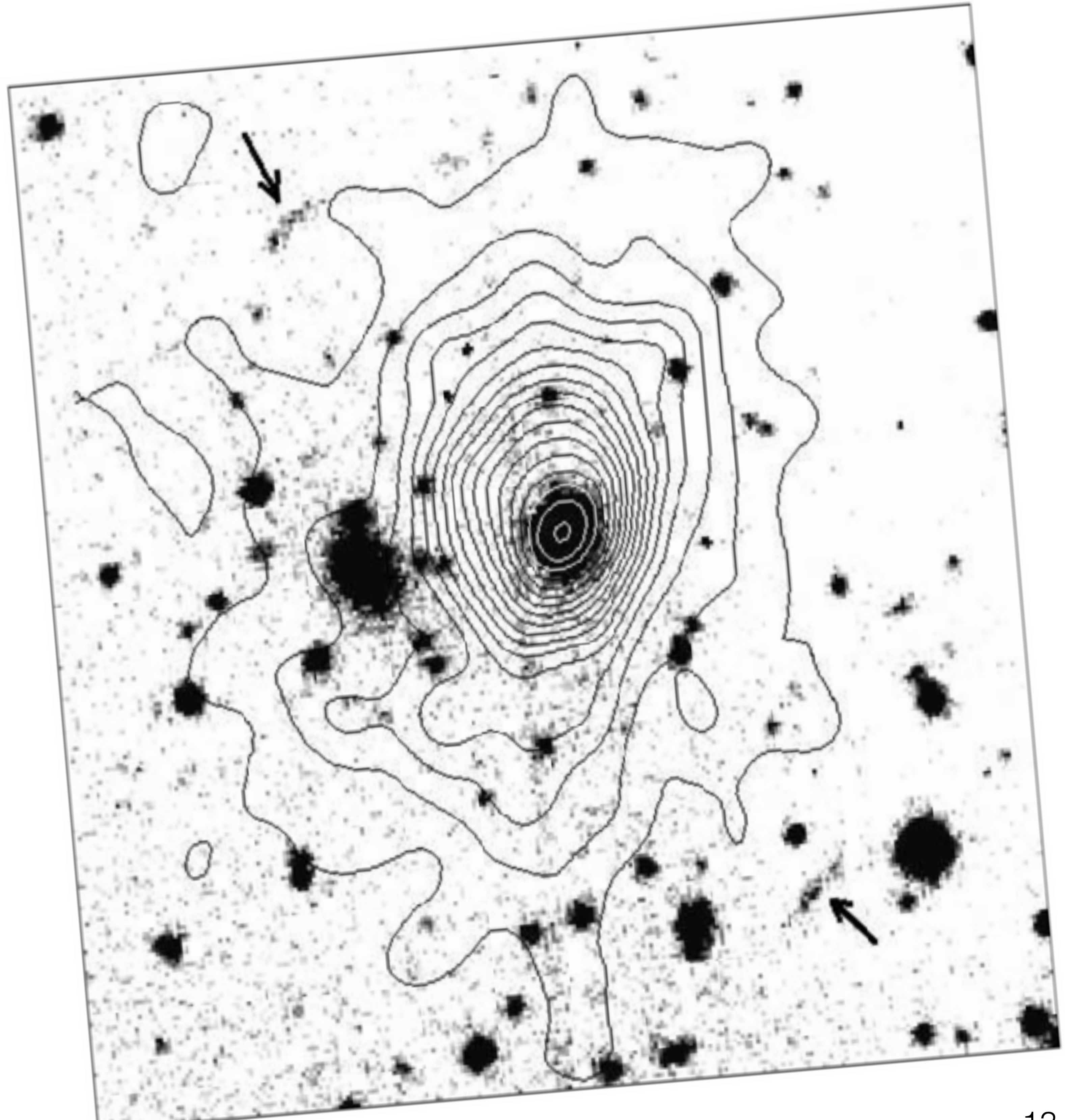
A Story about RXJ1347–1145

- Let me tell you a little story about this particular cluster, which **highlights the unique power of the SZ data to study cluster astrophysics**
    - A massive cluster with 10^{15} M_{sun} at z=0.45
        - *The most X-ray luminous galaxy cluster* found in the ROSAT All Sky Survey
    - Very compact, “cool core” cluster

1997

ROSAT/HRI image
[Schindler et al.]
5” resolution

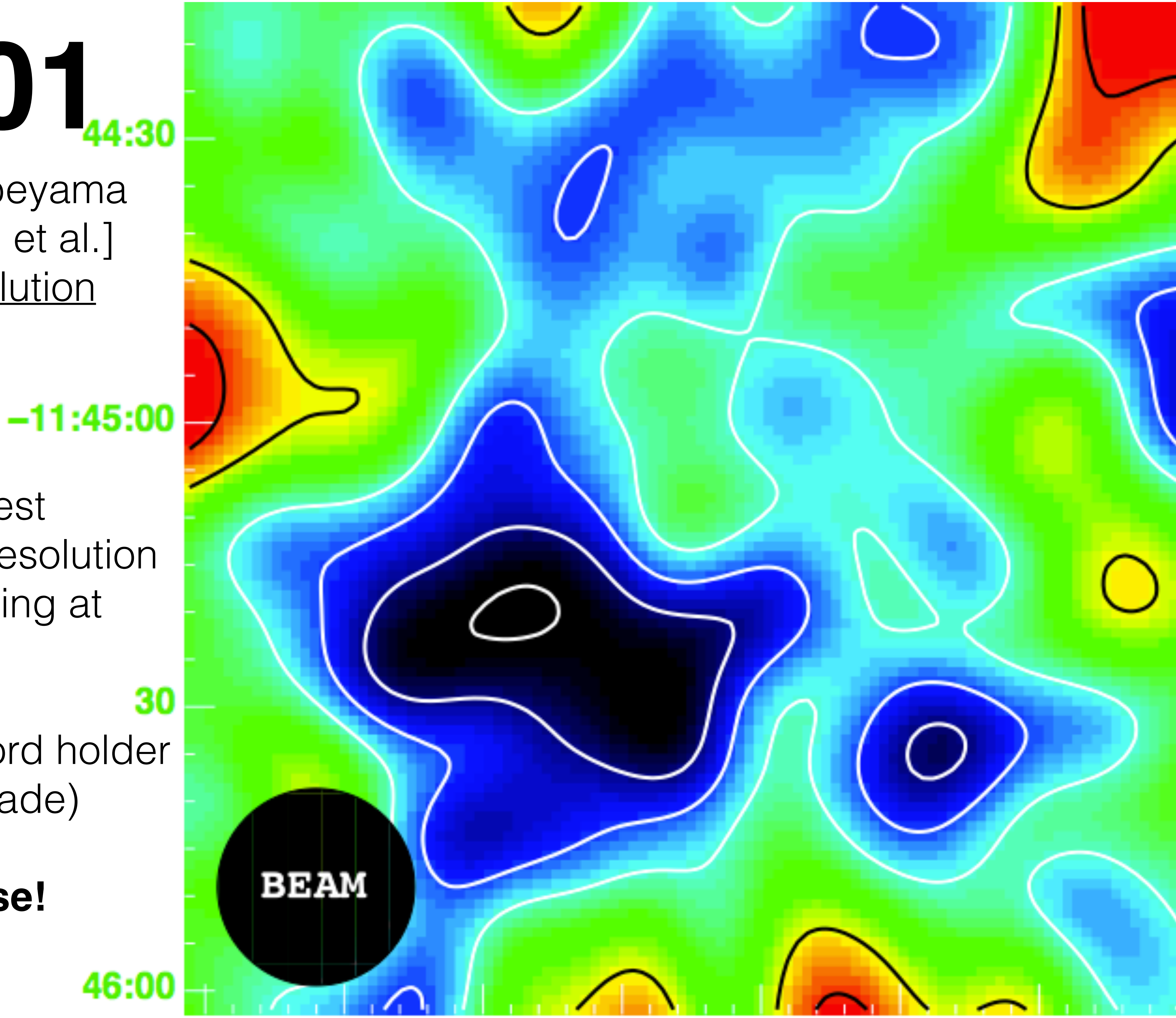
- 0.1–2.4 keV
- Looked pretty “spherical”
- Thought to be a typical, relaxed, cooling-flow cluster



2001

SZ w/ Nobeyama
[Komatsu et al.]
<u>12” resolution</u>

- The highest angular resolution SZ mapping at that time
- (The record holder for a decade)
- **A surprise!**



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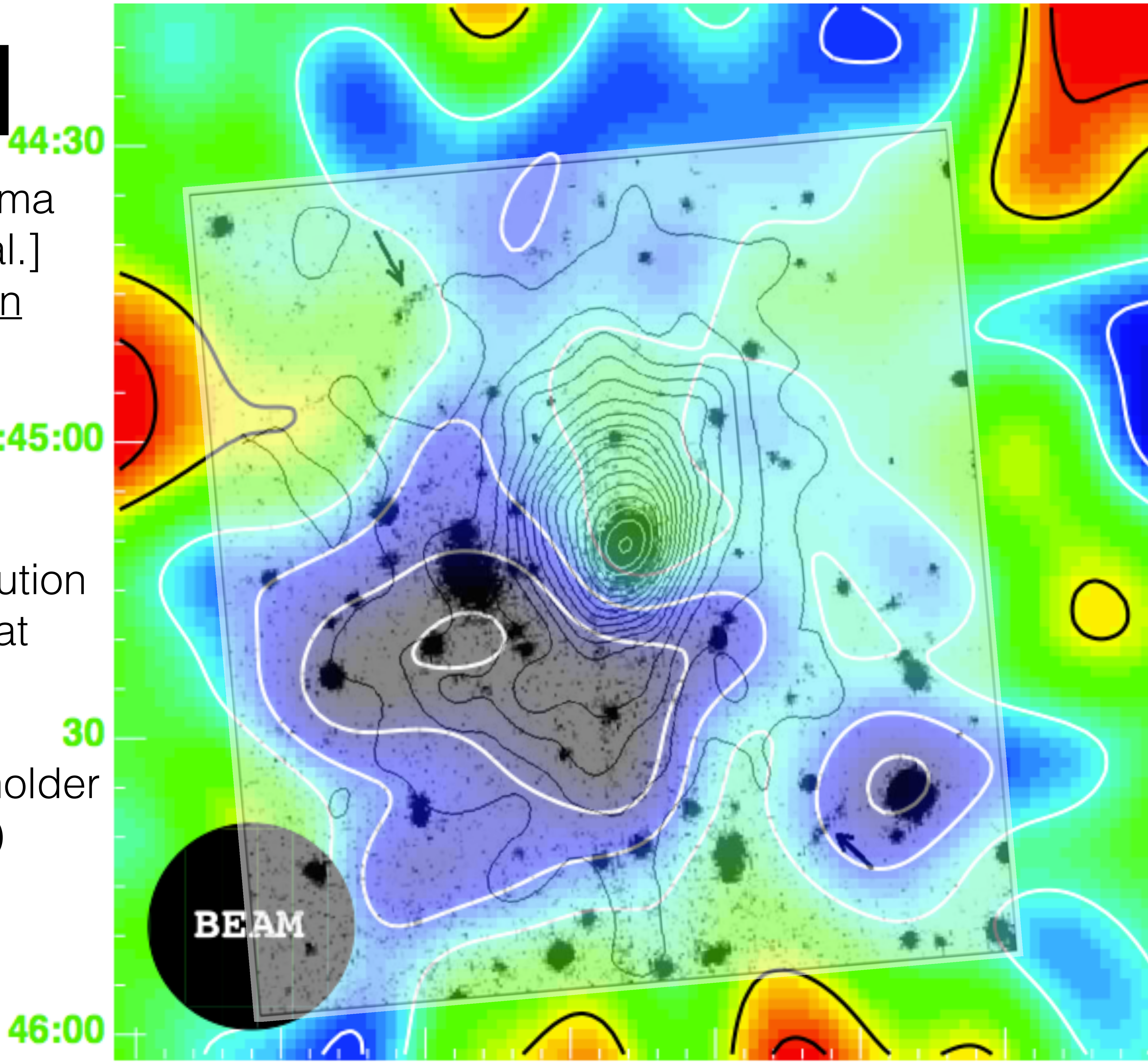
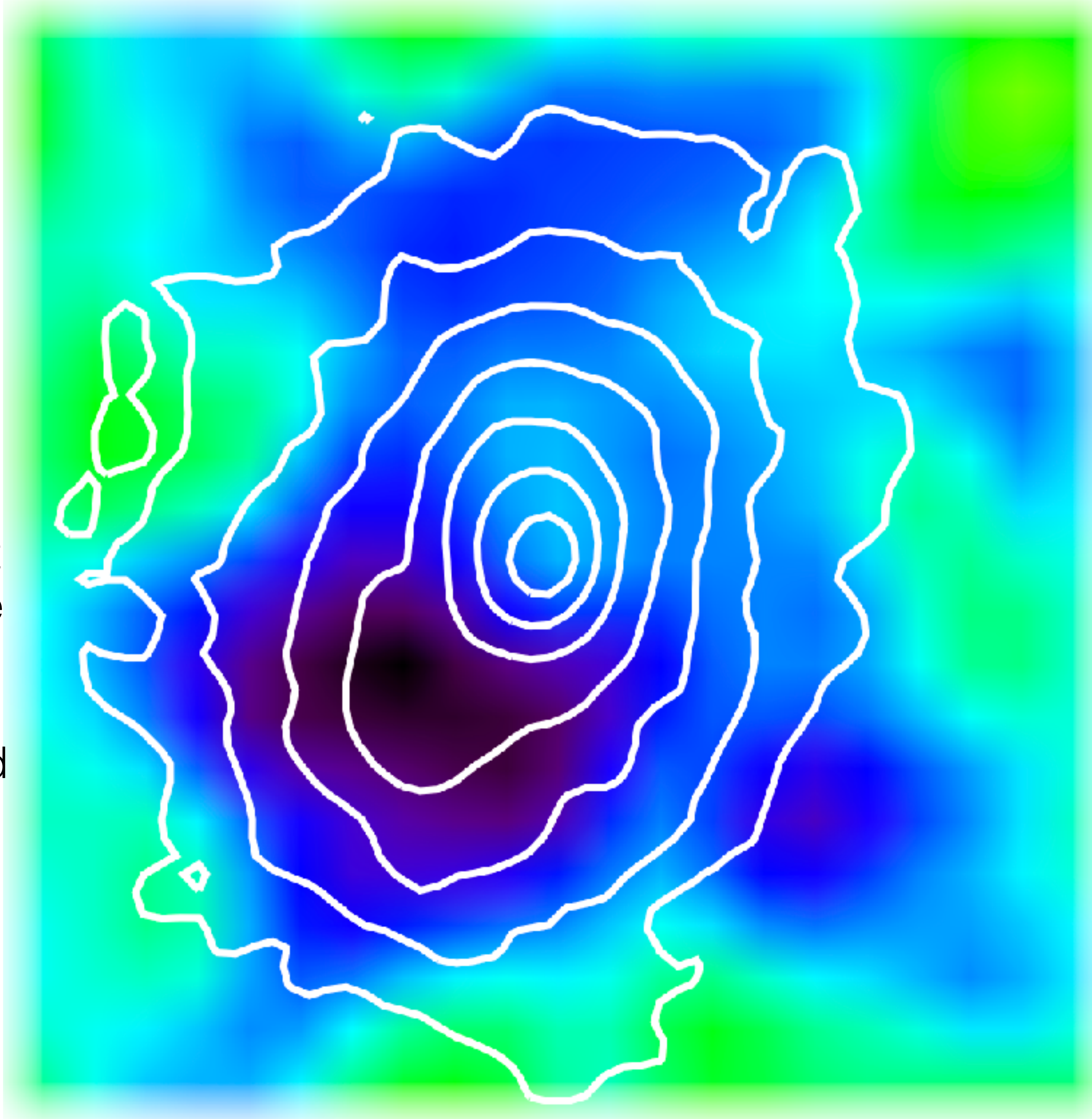


2002

X-ray w/ Chandra
[Allen et al.]

- 0.5–7 keV
- An excess X-ray emission found at the location of the SZ excess
- A hot gas, missed by ROSAT due to the lack of sensitivity at high energies!



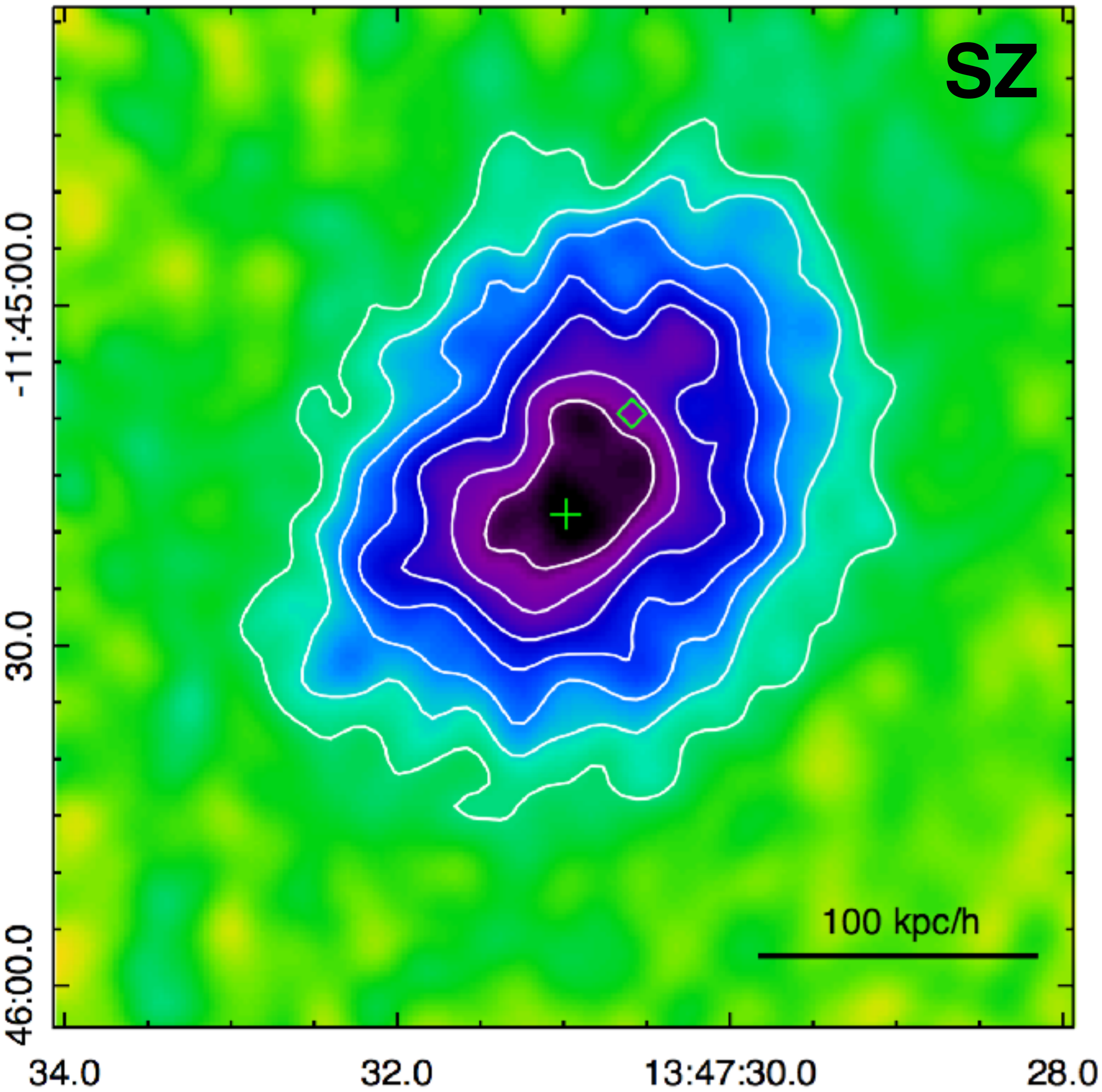
A lesson learned

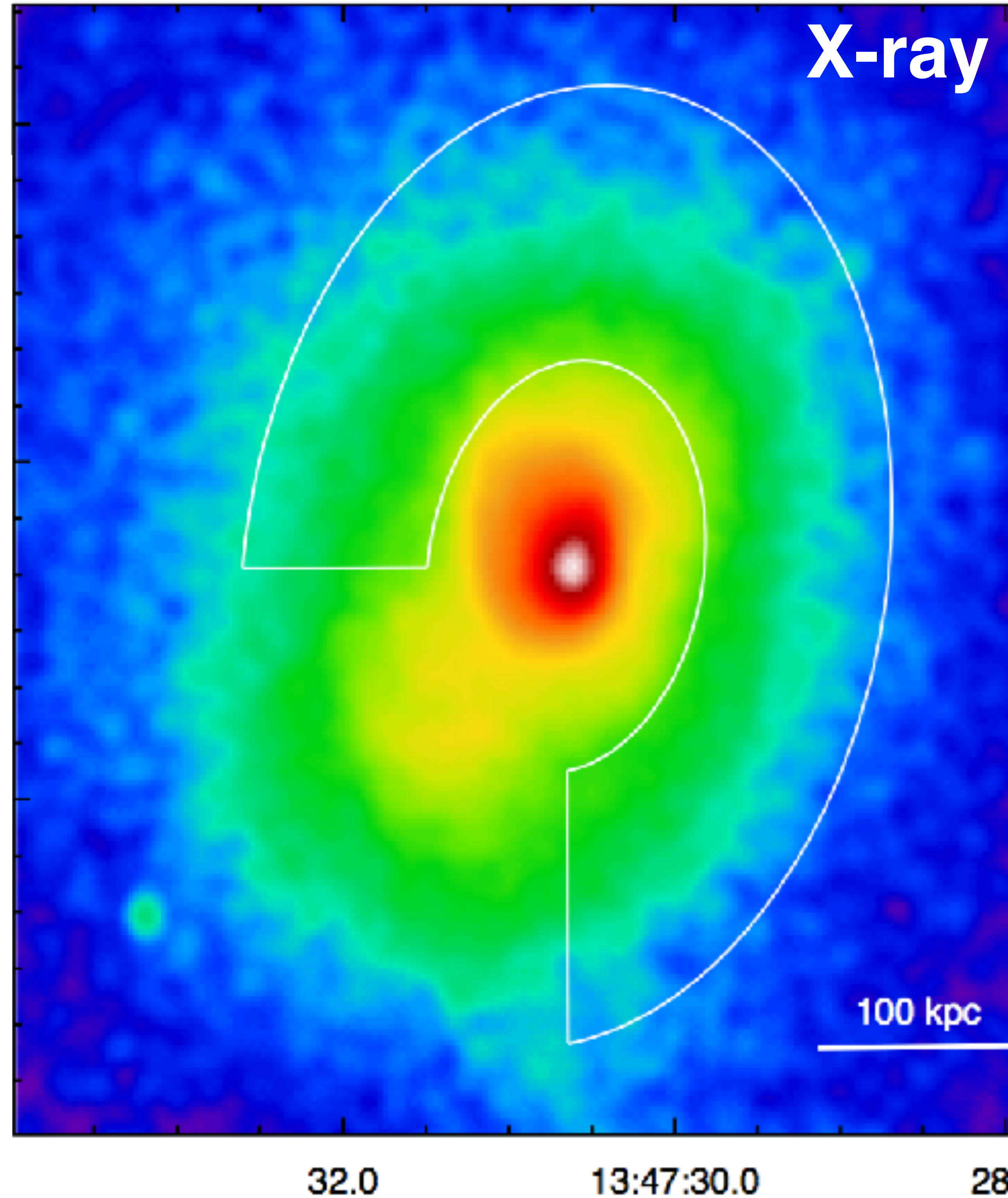
- X-ray observations are band-limited
  - They are not usually not sensitive to very hot gas with temperature >10(1+z) keV
- SZ observations are **not** band-limited
  - They are in principle sensitive to arbitrarily high temperatures (more precisely, pressure)
- SZ data probe electron pressure: a good probe of shock-heated gas due to mergers
  - *RXJ1347–1145 was thought to be a relaxed cluster. Our Nobeyama data challenged it, and now it is accepted that this cluster is a merging system!*

We have ALMA. Now what?

- What is a new science we can do with such high resolution, high sensitivity measurements?
    - Finding shocks and hot clumps is fun, but can we do something new and more quantitative?
- One example: **Pressure fluctuations**

Let's subtract a smooth component

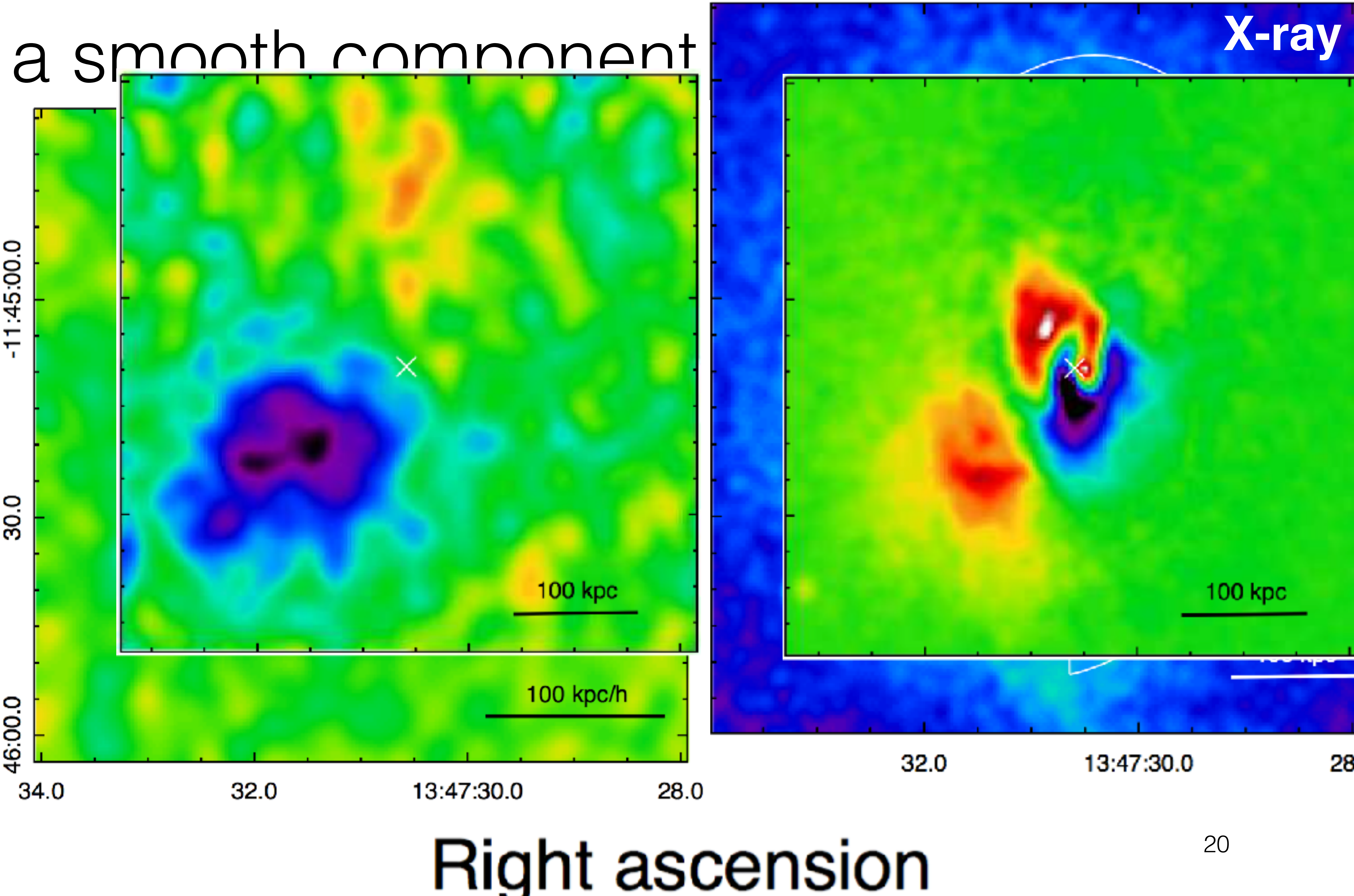




Right ascension

Ueda et al., in prep

Let's subtract a smooth component



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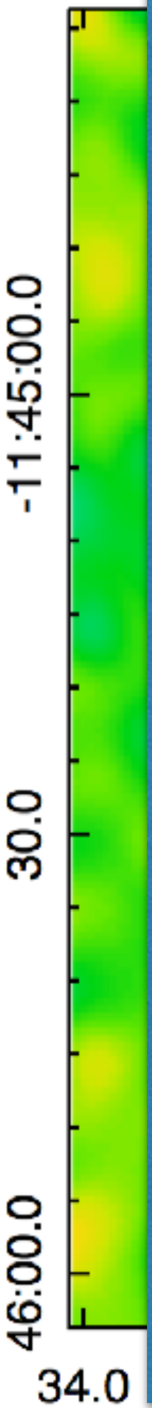
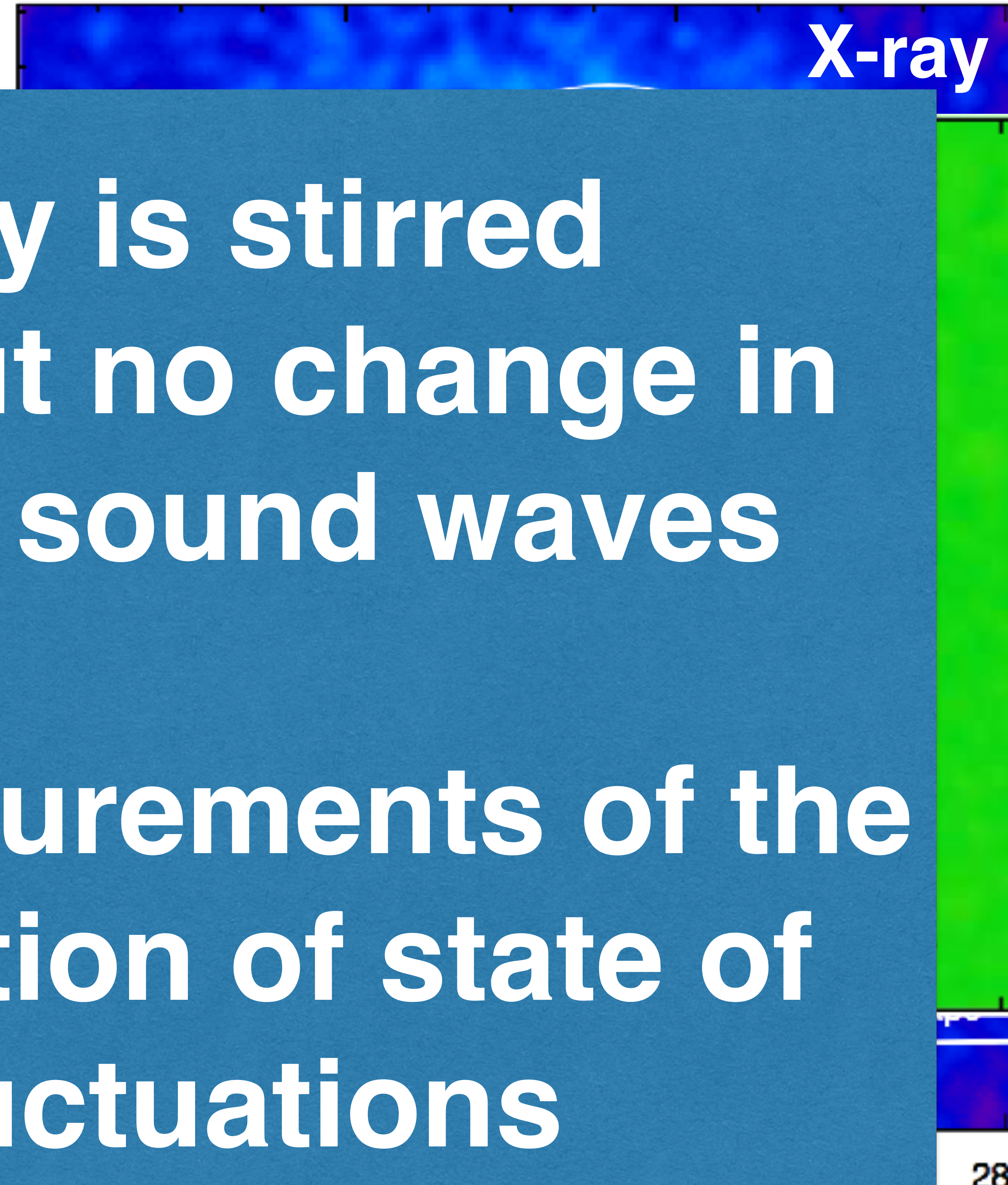




Gas density is stirred (“sloshed”), but no change in pressure! Not sound waves

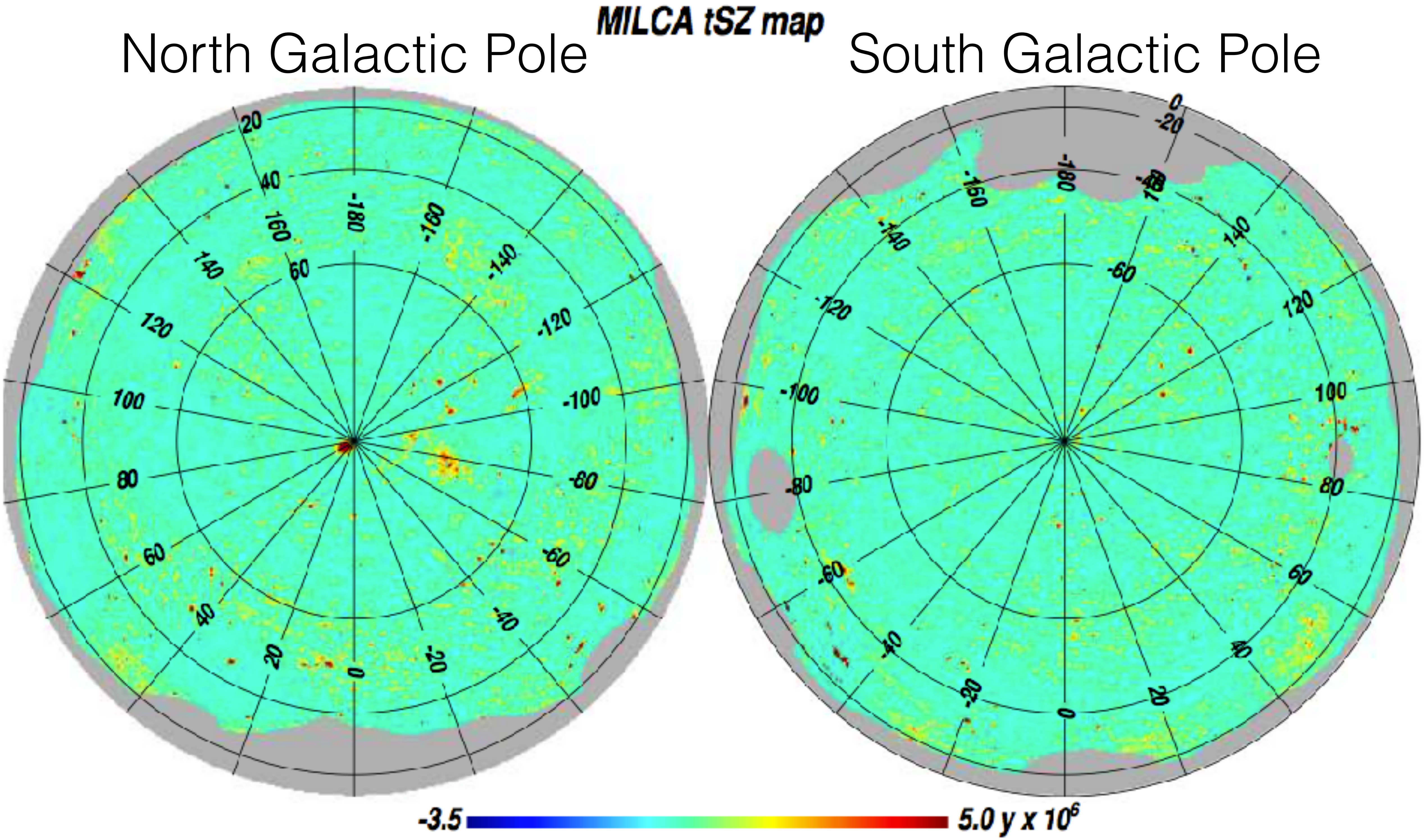
=> Unique measurements of the effective equation of state of density fluctuations

Right ascension

Full-sky Thermal Pressure Map

North Galactic Pole

South Galactic Pole



Planck Collaboration

We can simulate this

Klaus Dolag (MPA/LMU)

arXiv:1509.05134 [MNRAS, **463**, 1797 (2016)]

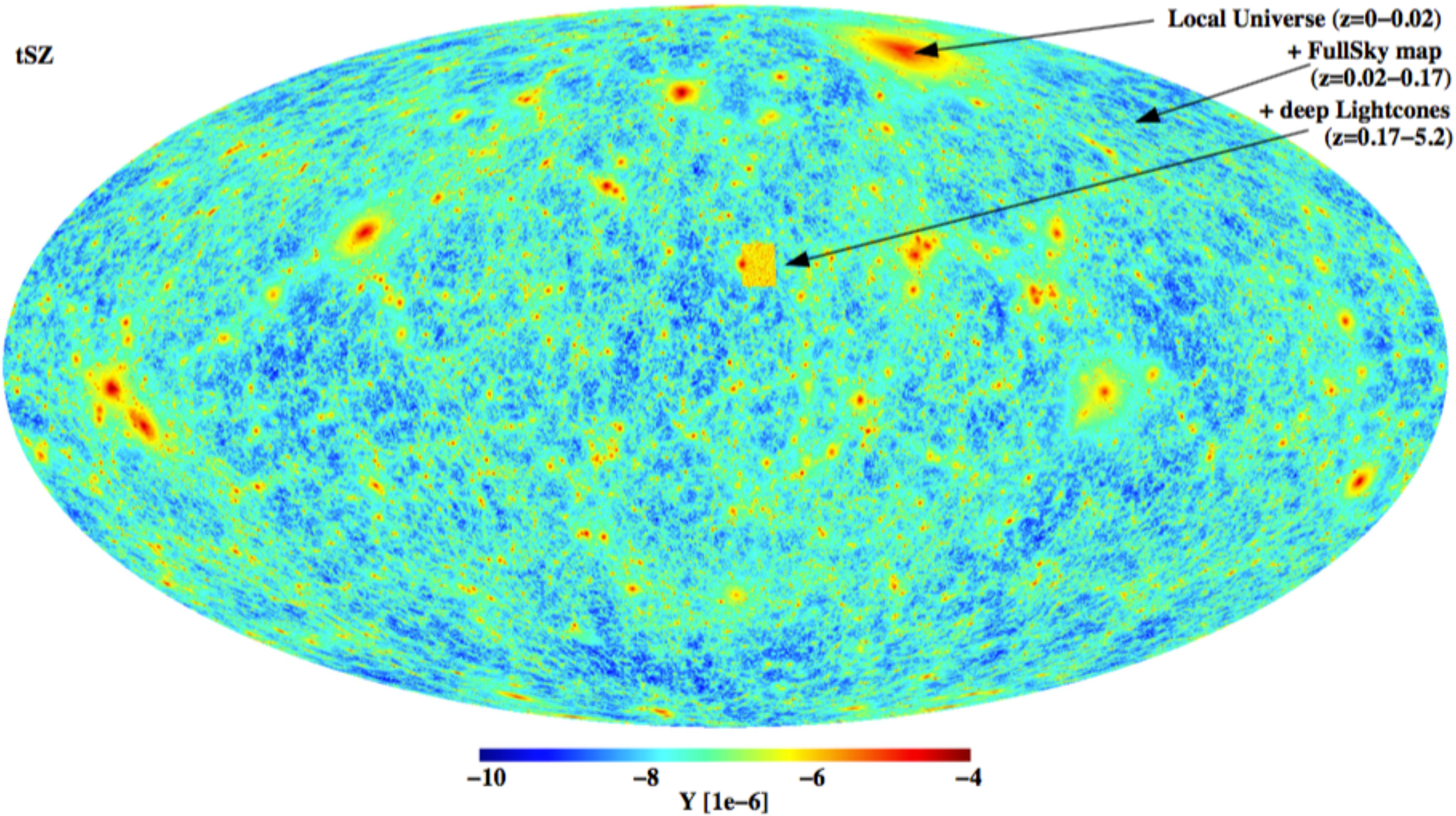
SZ effects in the Magneticum Pathfinder Simulation: Comparison with the Planck, SPT, and ACT results

K. Dolag[1,2]*, E. Komatsu[2,3] and R. Sunyaev[2,4]

[1] *University Observatory Munich, Scheinerstr. 1, 81679 Munich, Germany*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, 85748 Garching, Germany*
[3] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa 277-8583, Japan*
[4] *Space Research Institute (IKI), Russian Academy of Sciences, Profsoyuznaya str. 84/32, Moscow, 117997 Russia*

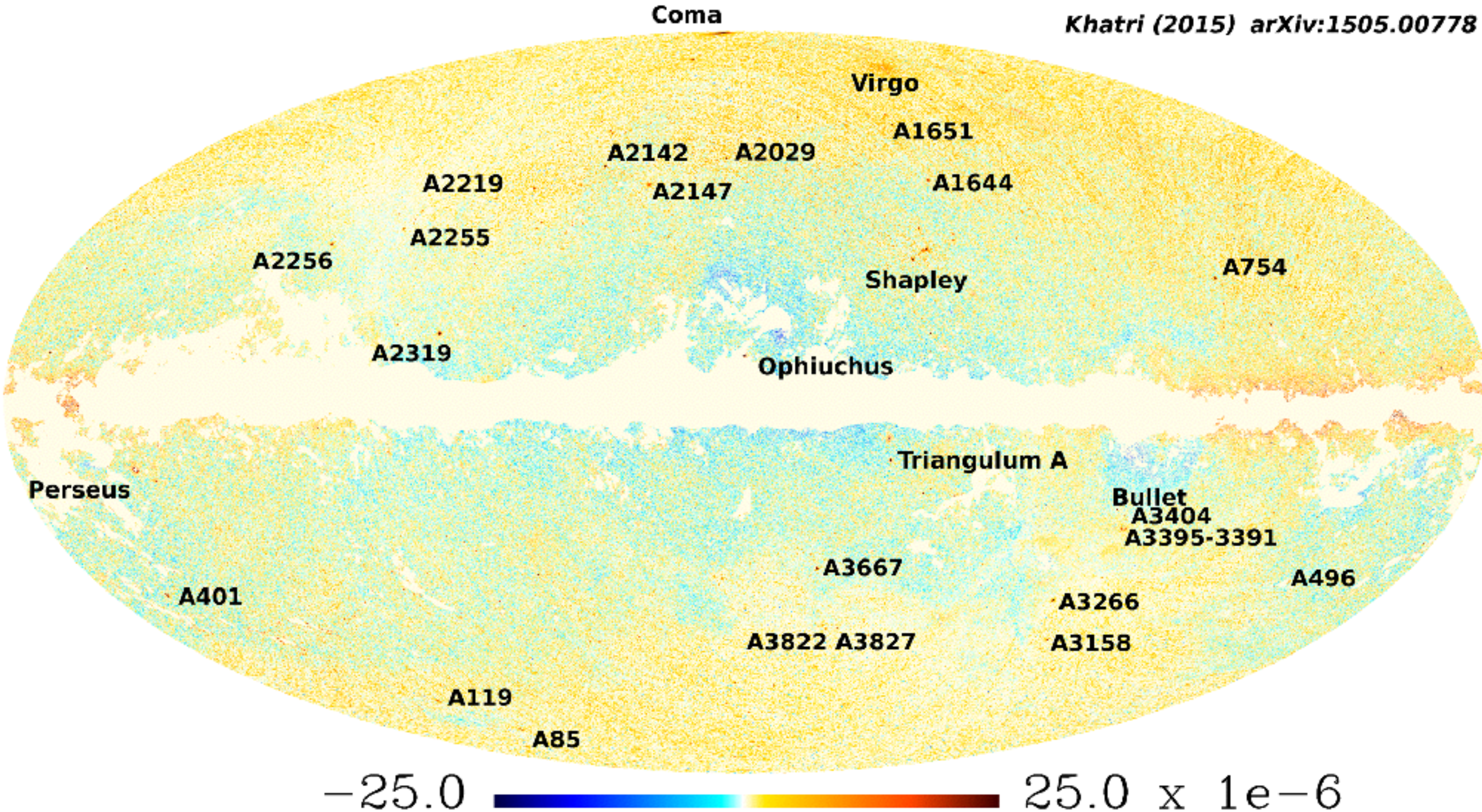
- Volume: $(896\ \mathrm{Mpc}/h)^3$
- Cosmological hydro (P-GADGET3) with star formation and AGN feed back
- 2×1526^3 particles ($m_{DM}=7.5\times10^8\ M_{sun}/h$)

Dolag, EK, Sunyaev (2016)



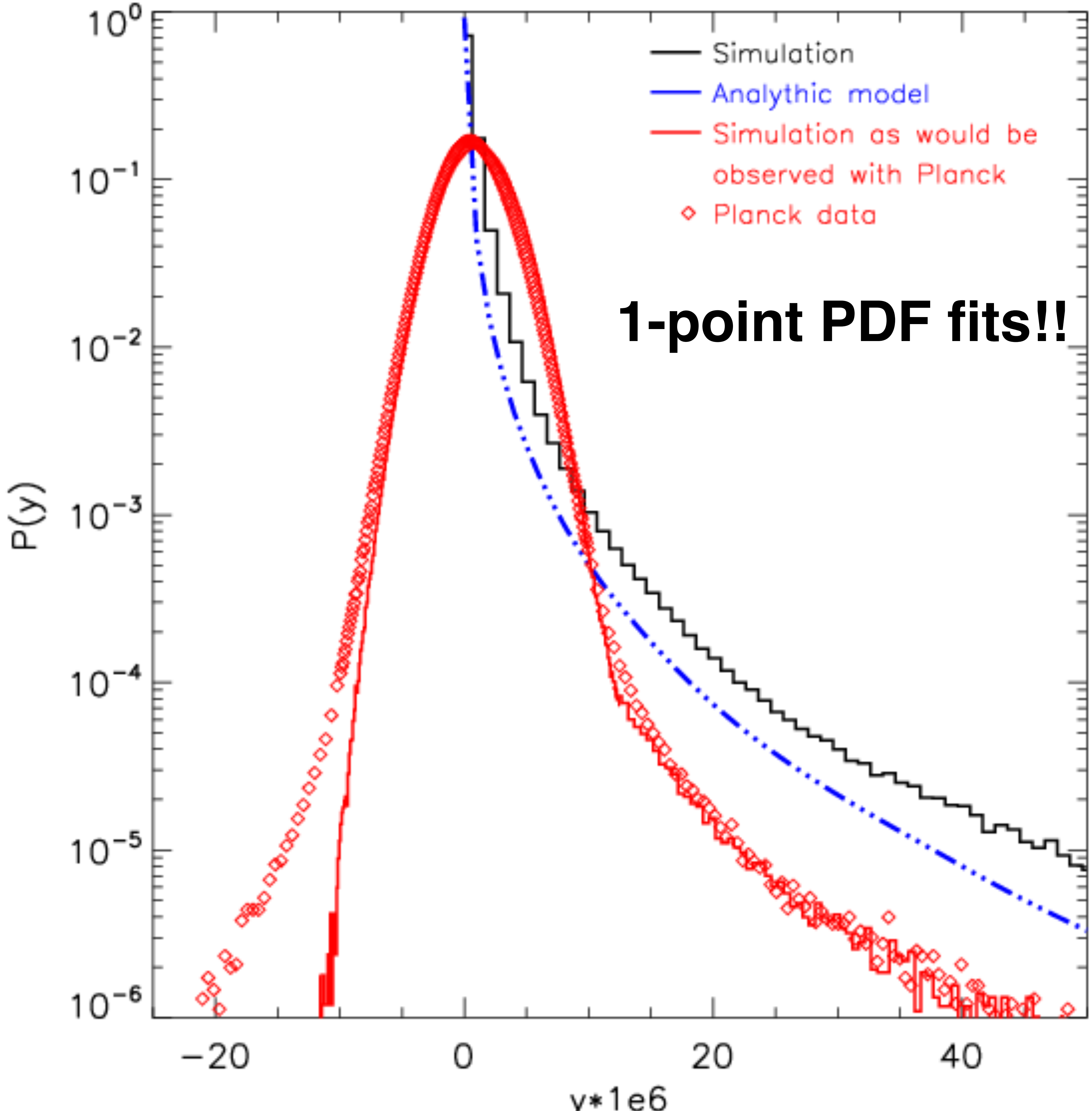
$$Y_{\rm tSZ}(\boldsymbol{\theta}) = \frac{k_B \sigma_T}{m_e c^2} \int {\rm d}l \, n_e(\boldsymbol{\theta}, l) \, T(\boldsymbol{\theta}, l)$$

y−distortion map,10 arcmin

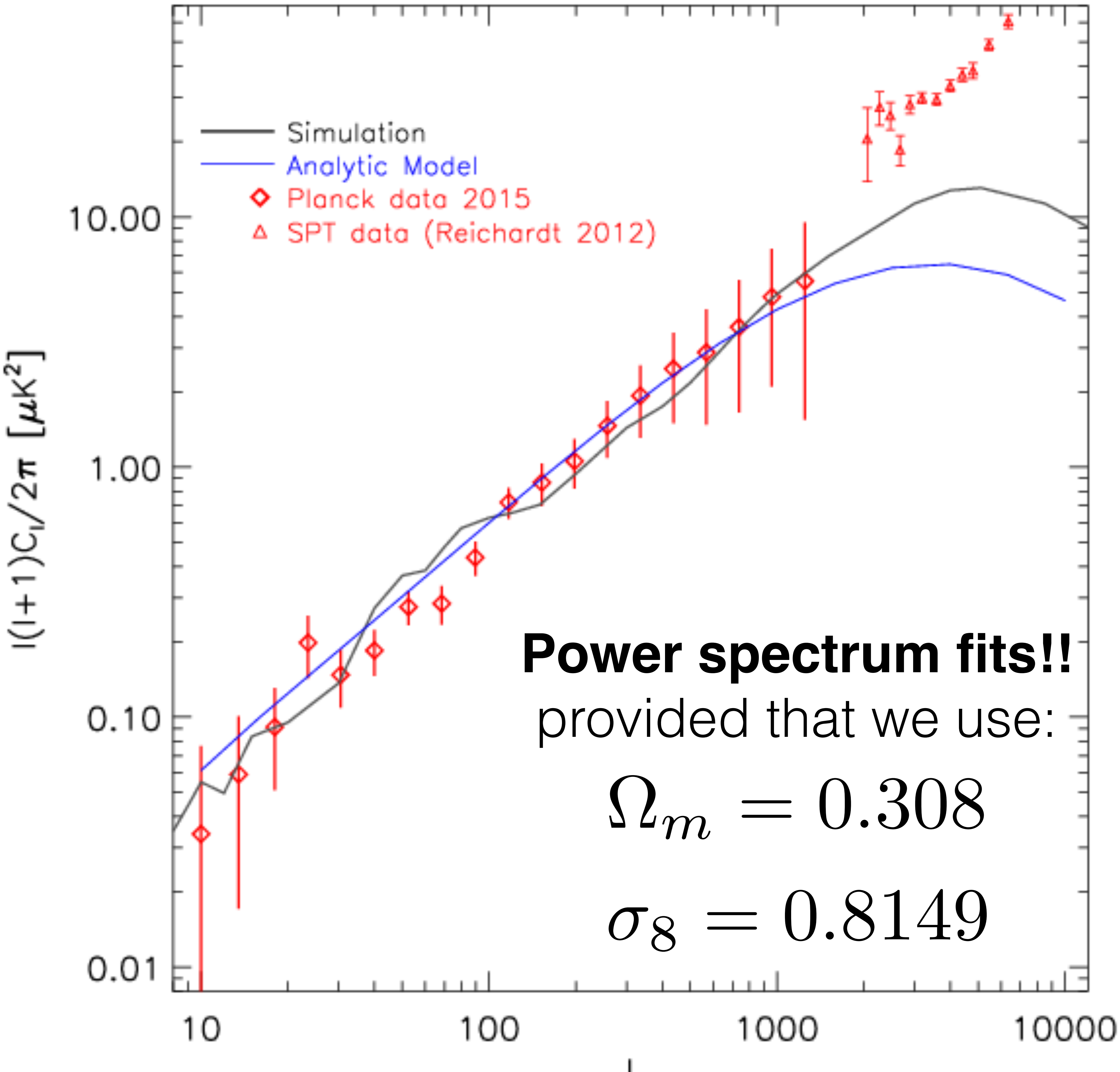


- “The local universe simulation” reproduces the observed structures pretty well

Dolag, EK, Sunyaev (2016)



Dolag, EK, Sunyaev (2016)



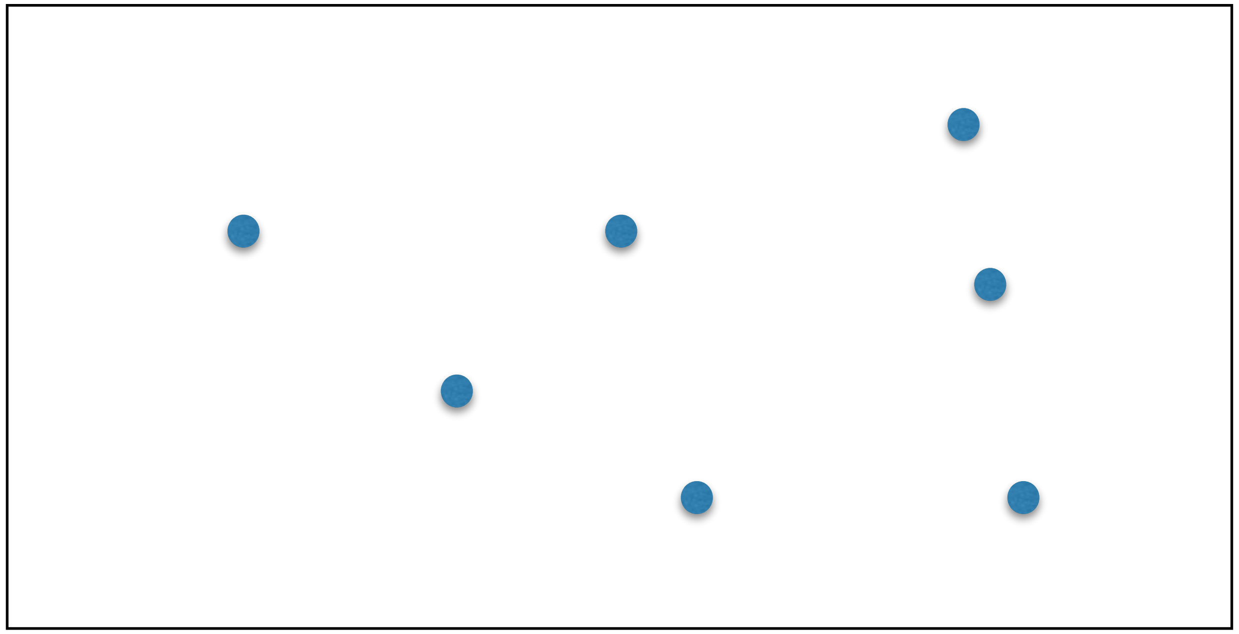
Power spectrum fits!!

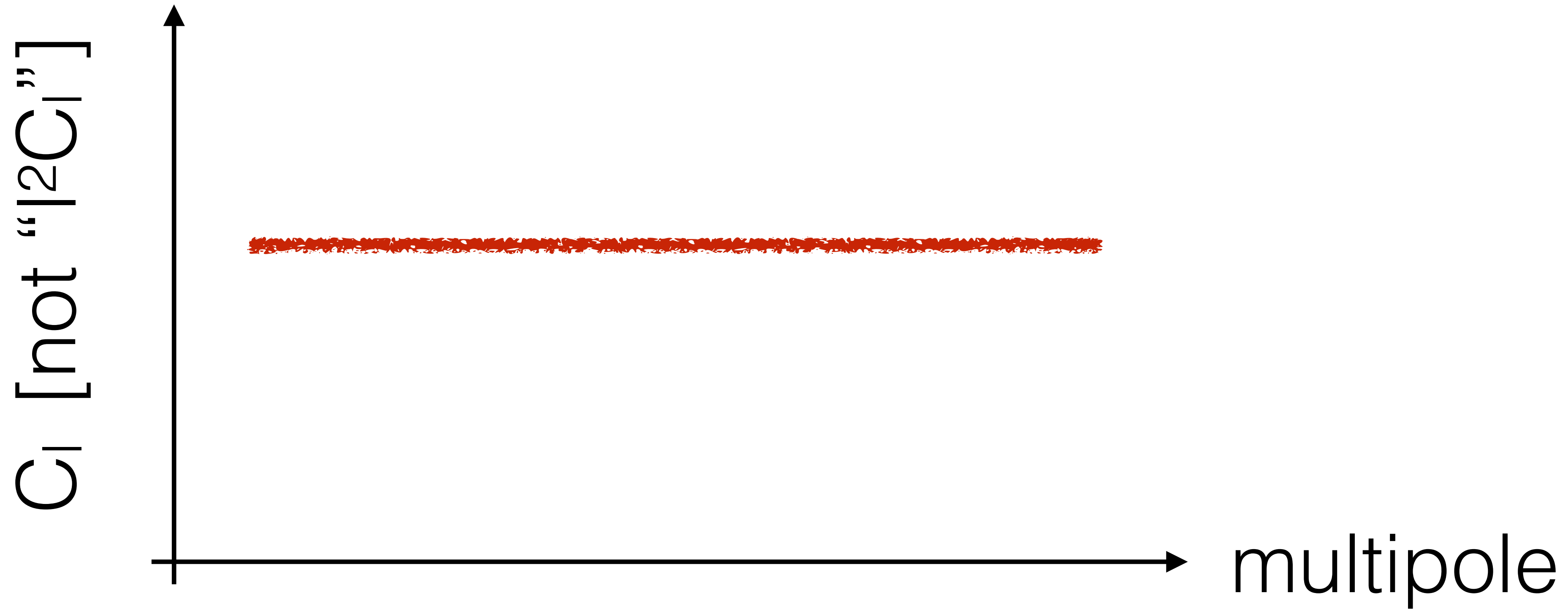
provided that we use:

$$\Omega_m = 0.308$$

$$\sigma_8 = 0.8149$$

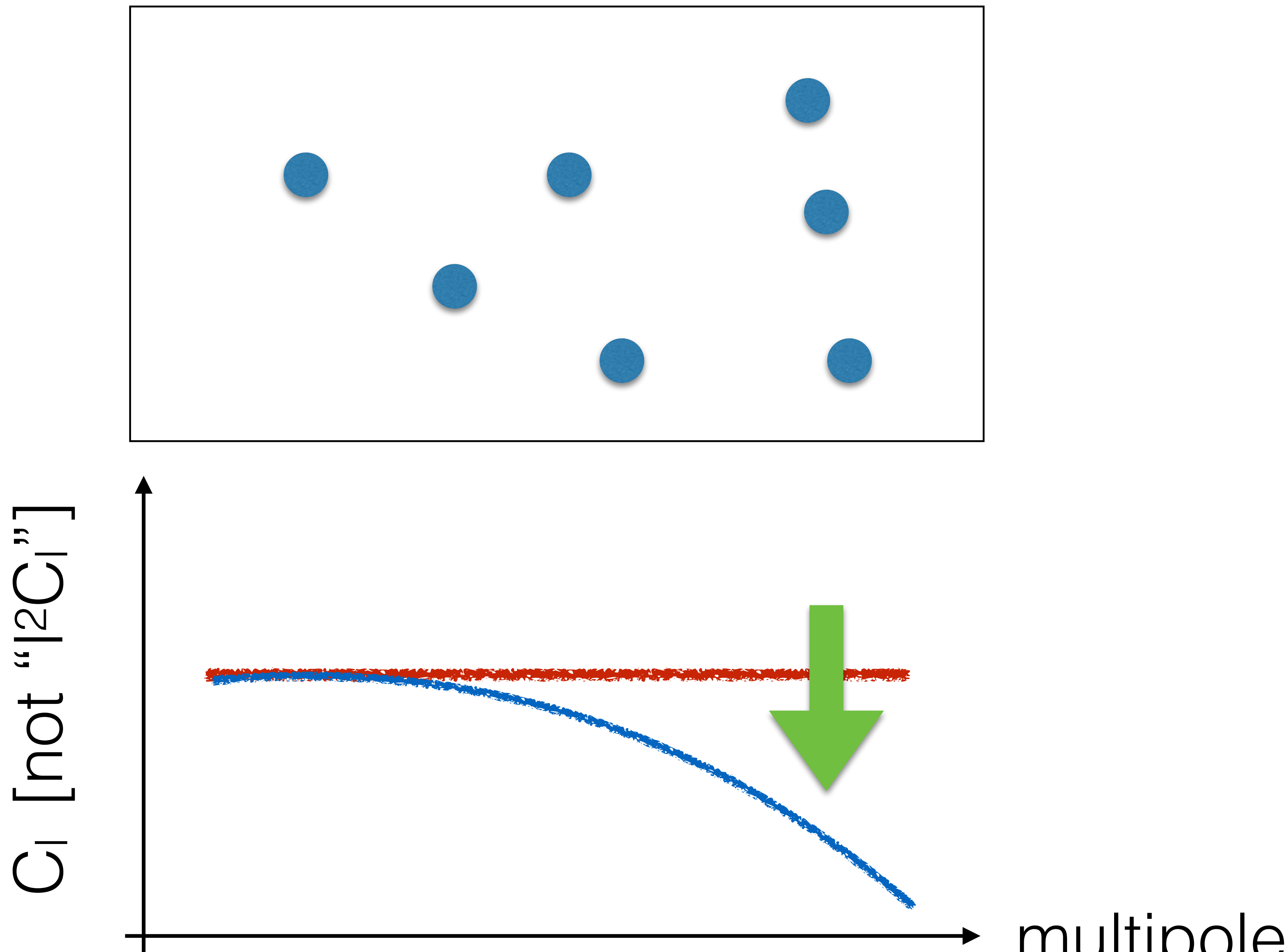
Simple Interpretation



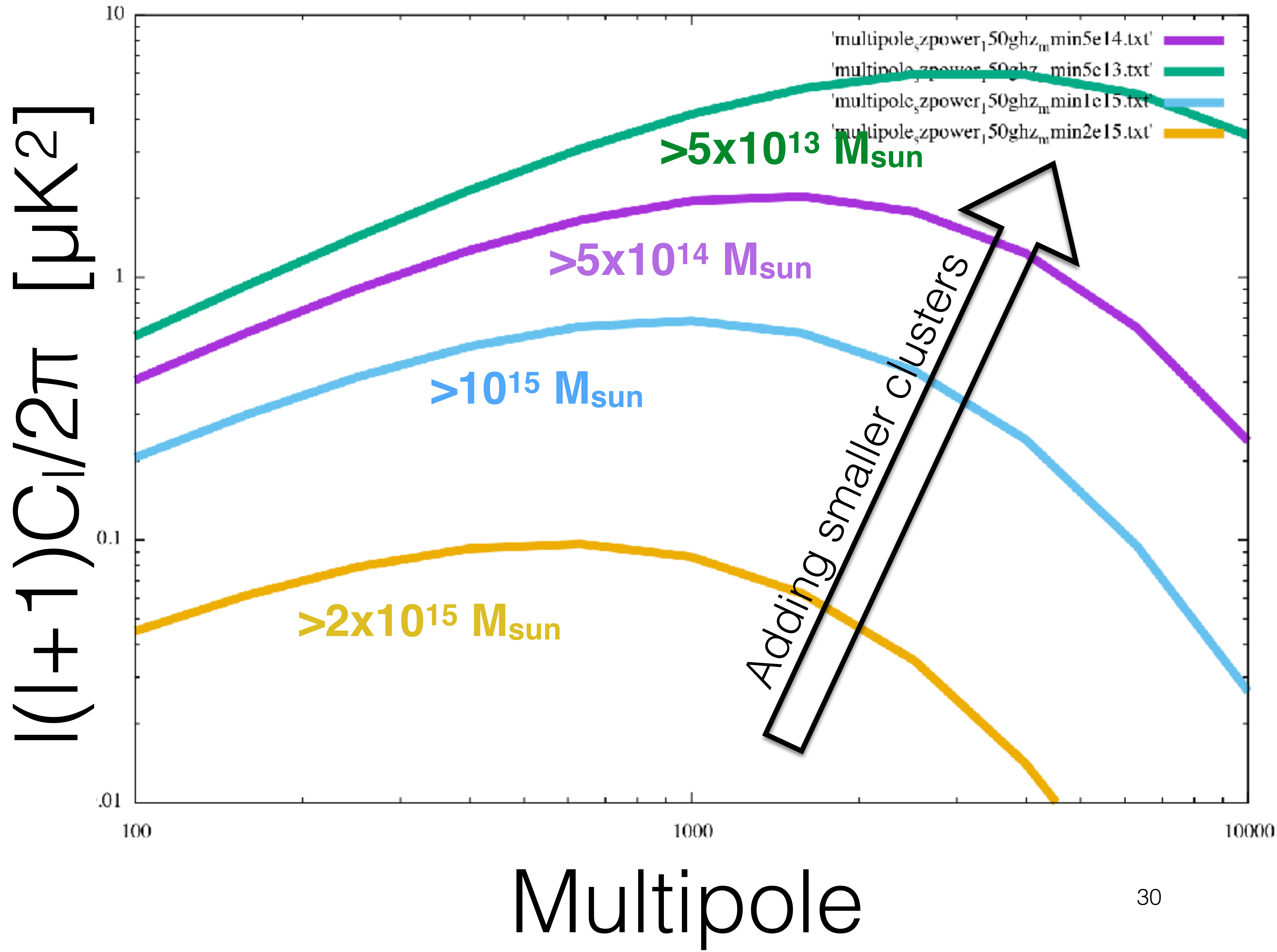


- Randomly-distributed point sources = Poisson spectrum = $\sum_i(\mathrm{flux}_i)^2 / 4\pi$

Simple Interpretation



- Extended sources = the power spectrum reflects intensity profiles


'multipole$_s$zpower$_1$50ghz$_m$min5e14.txt'
'multipole$_s$zpower$_1$50ghz$_m$min5e13.txt'
'multipole$_s$zpower$_1$50ghz$_m$min1e15.txt'
'multipole$_s$zpower$_1$50ghz$_m$min2e15.txt'
>5x10^{13} M$_{sun}$
>5x10^{14} M$_{sun}$
>10^{15} M$_{sun}$
>2x10^{15} M$_{sun}$
Adding smaller clusters
10
1
0.1
.01
100
1000
10000
l(l+1)C$_l$/2π [μK2]
Multipole

Simple Formula

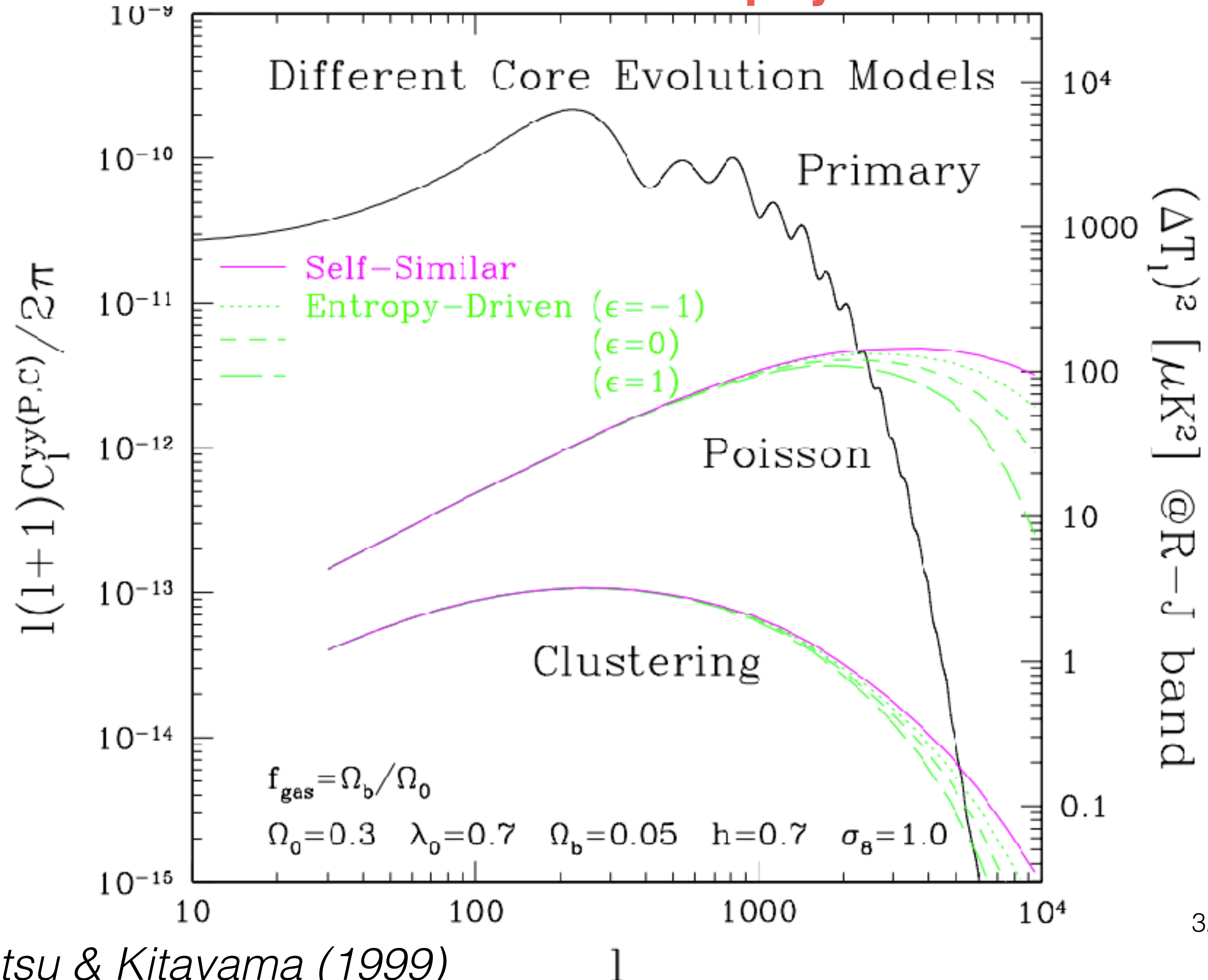
$$C_\ell = \int dz \frac{dV}{dz} \int dM \frac{dn}{dM} |y_\ell(M,z)|^2$$

2d Fourier transform of pressure

- y_l with small l just gives the total thermal pressure, MT ~ $M^{5/3}$
  - Heavily weighted by massive clusters
- The mass function, dn/dM, is sensitive to the amplitude of fluctuations, σ_8

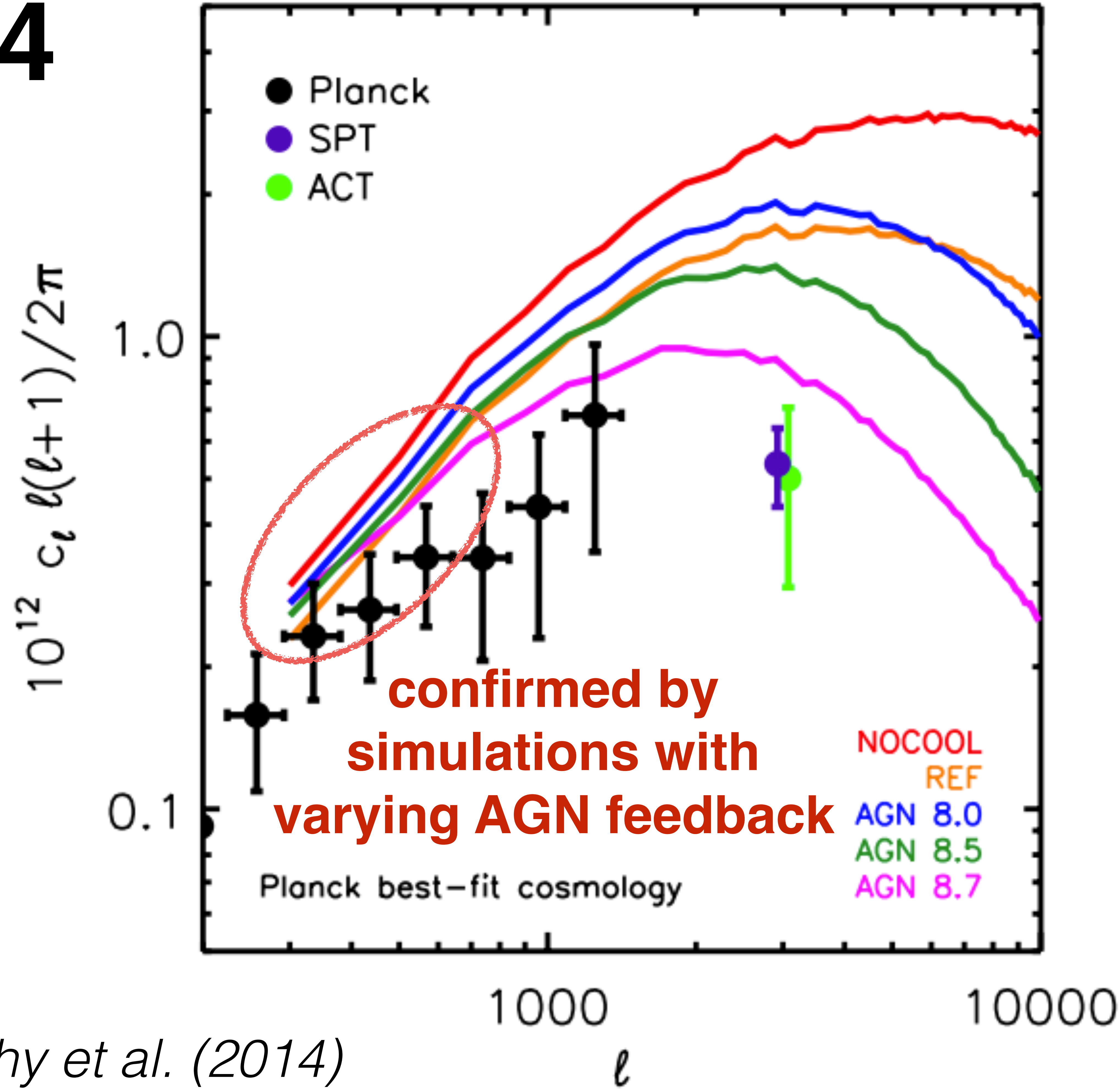
1999

Degree-scale SZ power spectrum is less sensitive to astrophysics in cluster cores



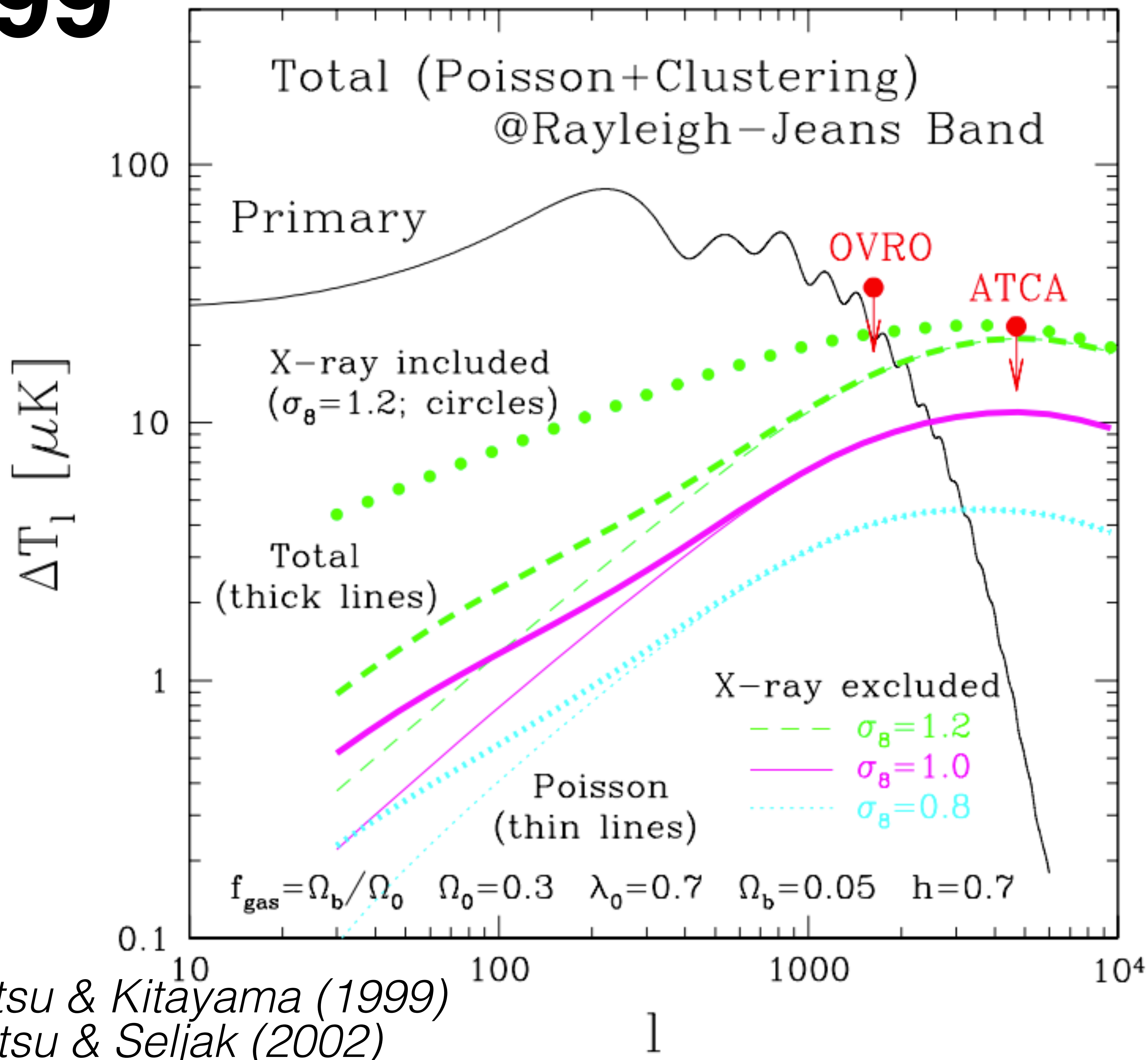
Komatsu & Kitayama (1999)

2014



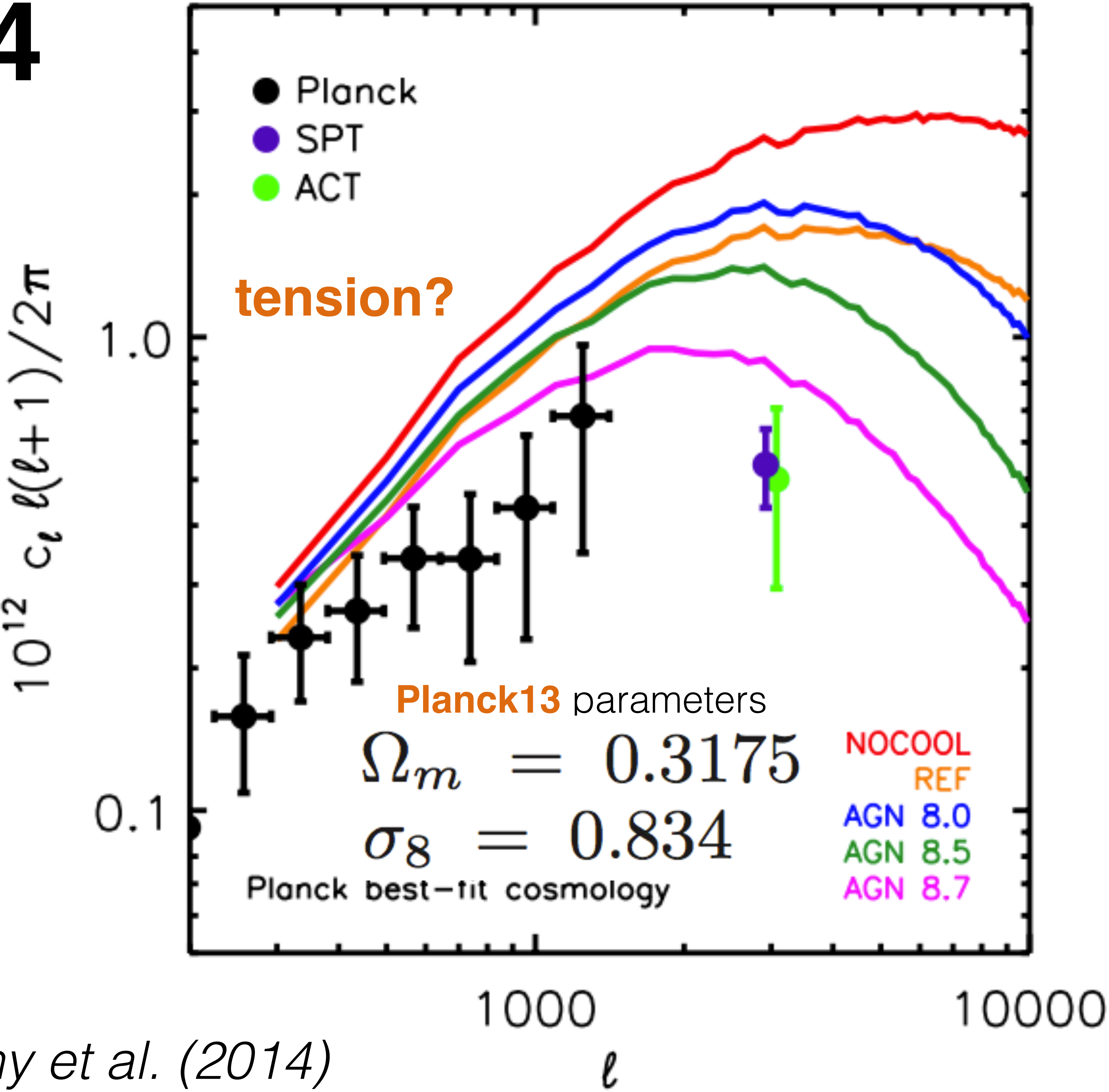
McCarthy et al. (2014)

1999 It is very sensitive to the amplitude of fluctuations



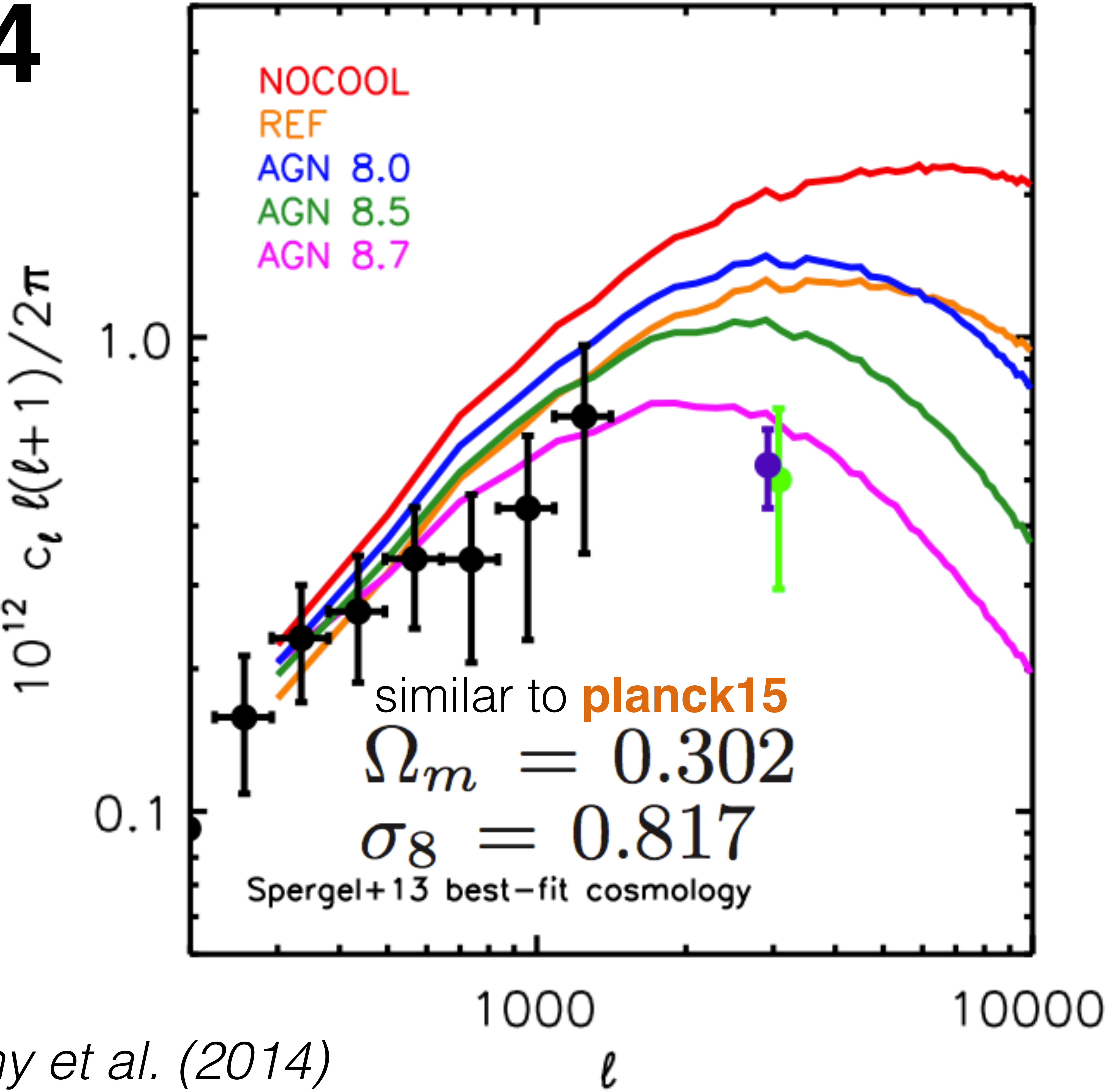
Komatsu & Kitayama (1999)
Komatsu & Seljak (2002)

2014



McCarthy et al. (2014)

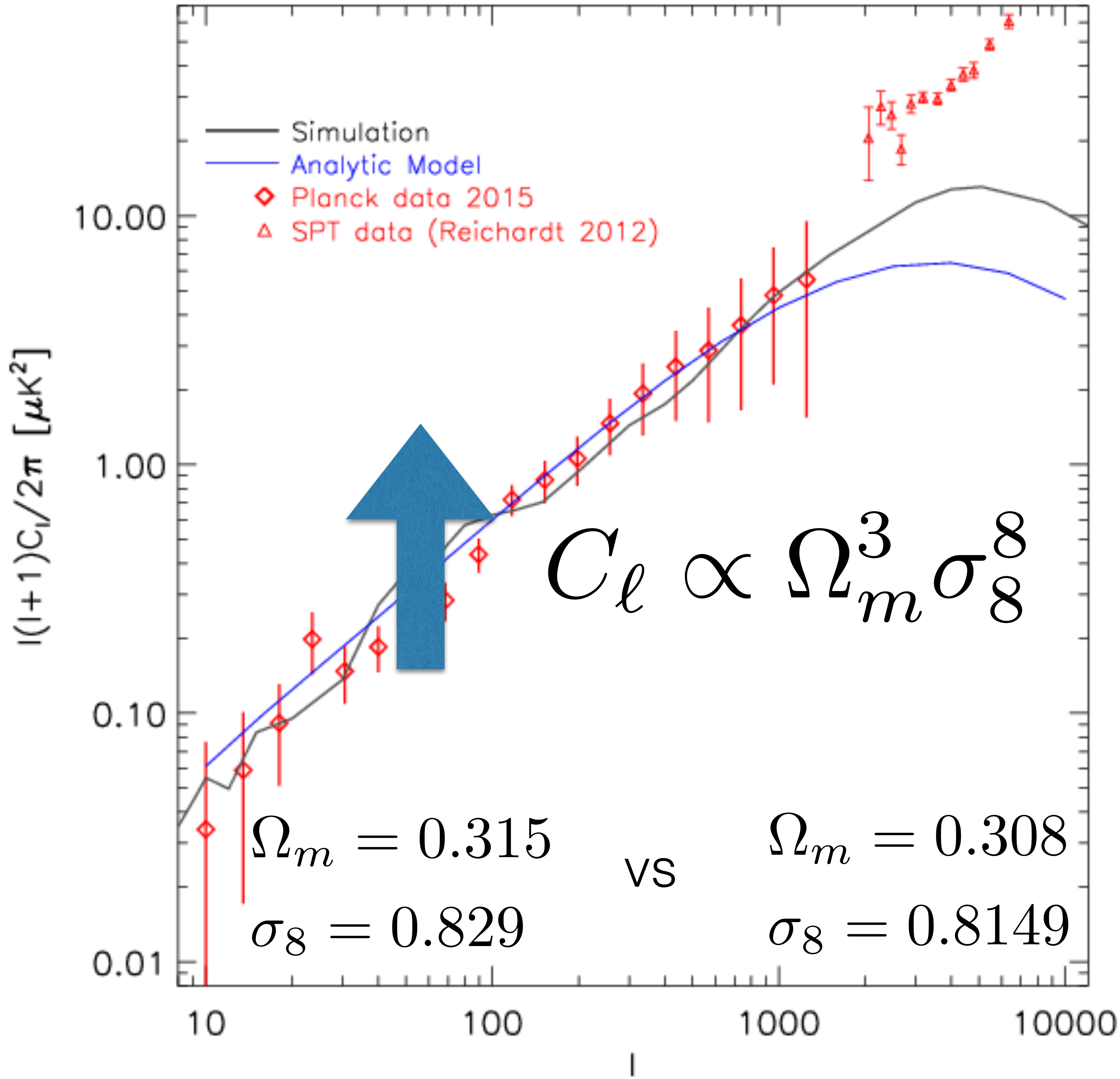
2014



$$\Omega_m = 0.302$$
$$\sigma_8 = 0.817$$

McCarthy et al. (2014)

Dolag, EK, Sunyaev (2016)

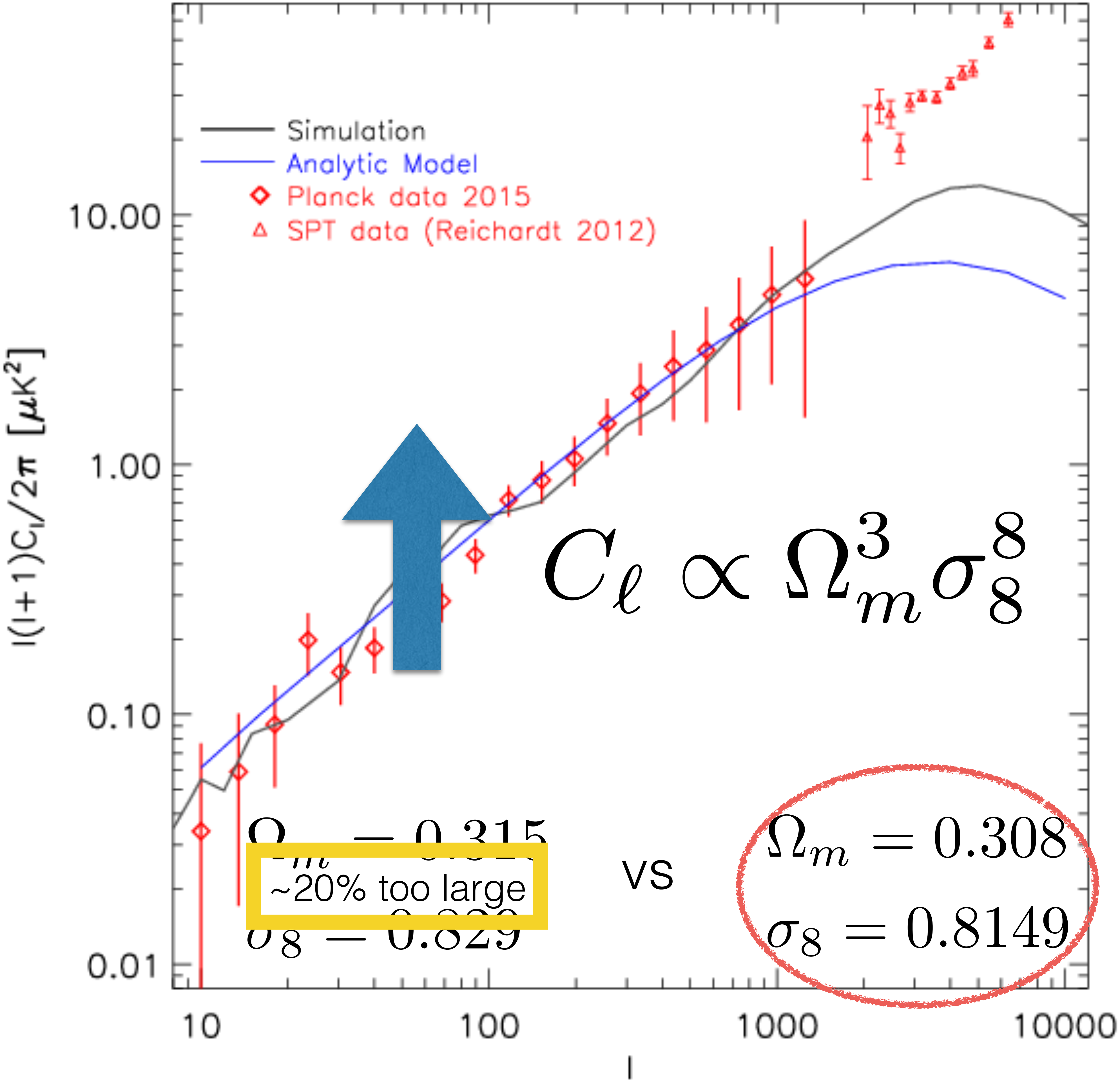


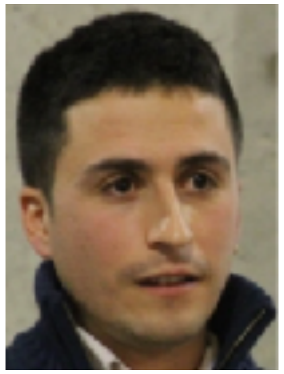
$$C_\ell \propto \Omega_m^3 \sigma_8^8$$

$\Omega_m = 0.315$ vs $\Omega_m = 0.308$

$\sigma_8 = 0.829$ vs $\sigma_8 = 0.8149$

Dolag, EK, Sunyaev (2016)



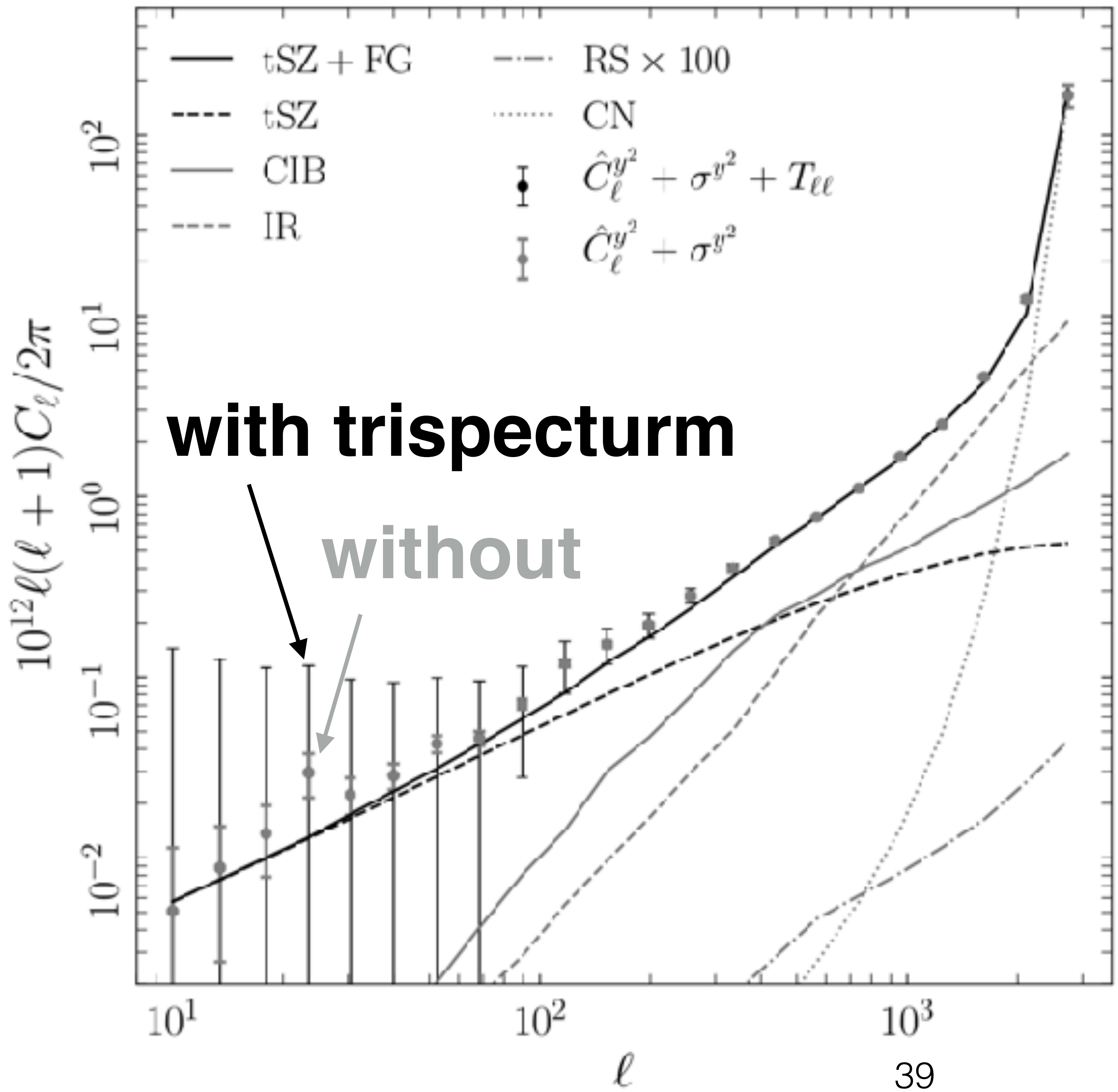


B. Bolliet

Bolliet, Comis, EK, Macias-Perez (2017)

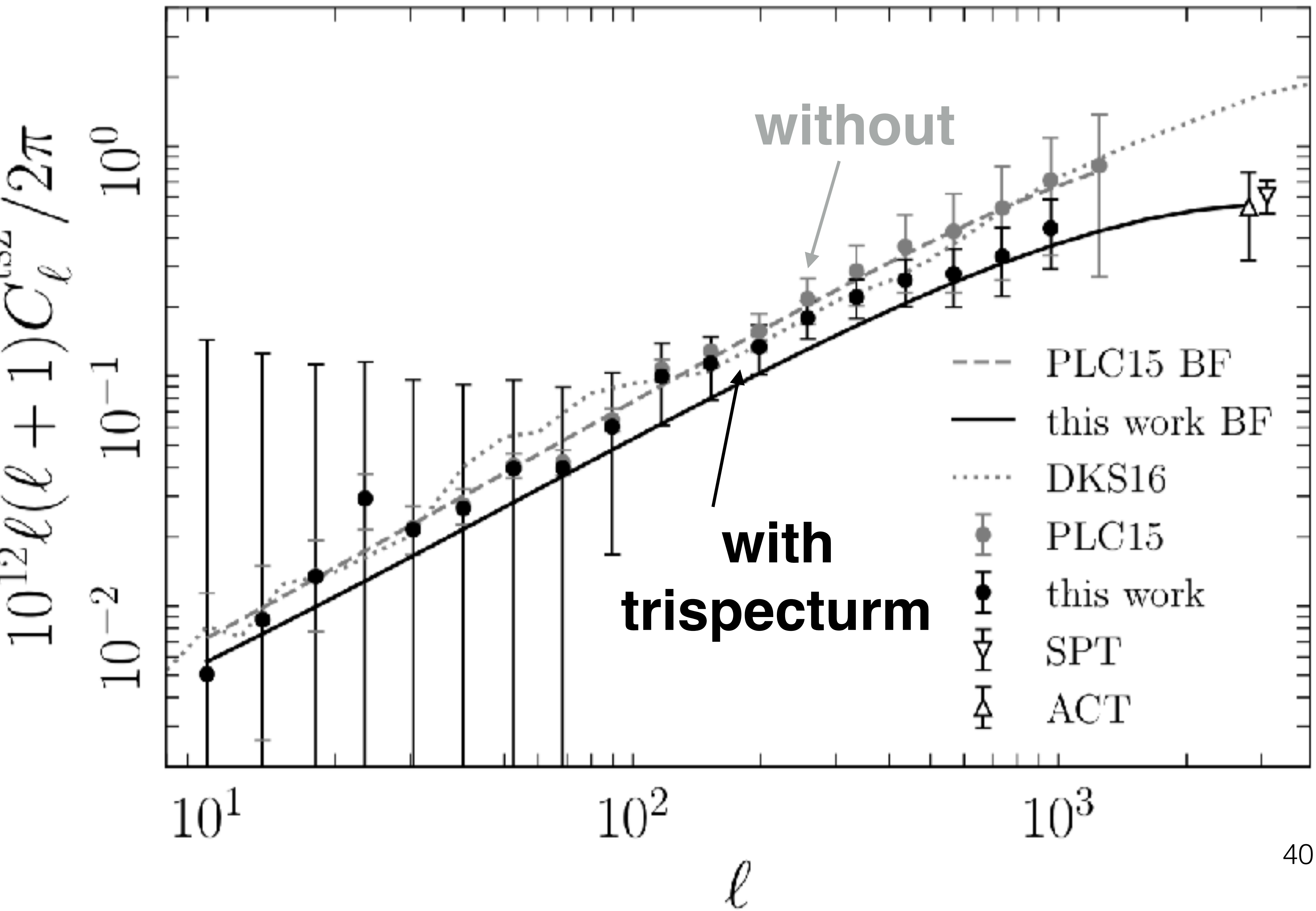
Closer look at the measurements

- The compton-Y power spectrum of Planck contains various foreground sources
- What you saw as the data points were the raw data minus the **best-fitting** foreground components
- When fitting, the Planck team used Gaussian covariance ignoring the trispectrum term
    - How does this affect the results?



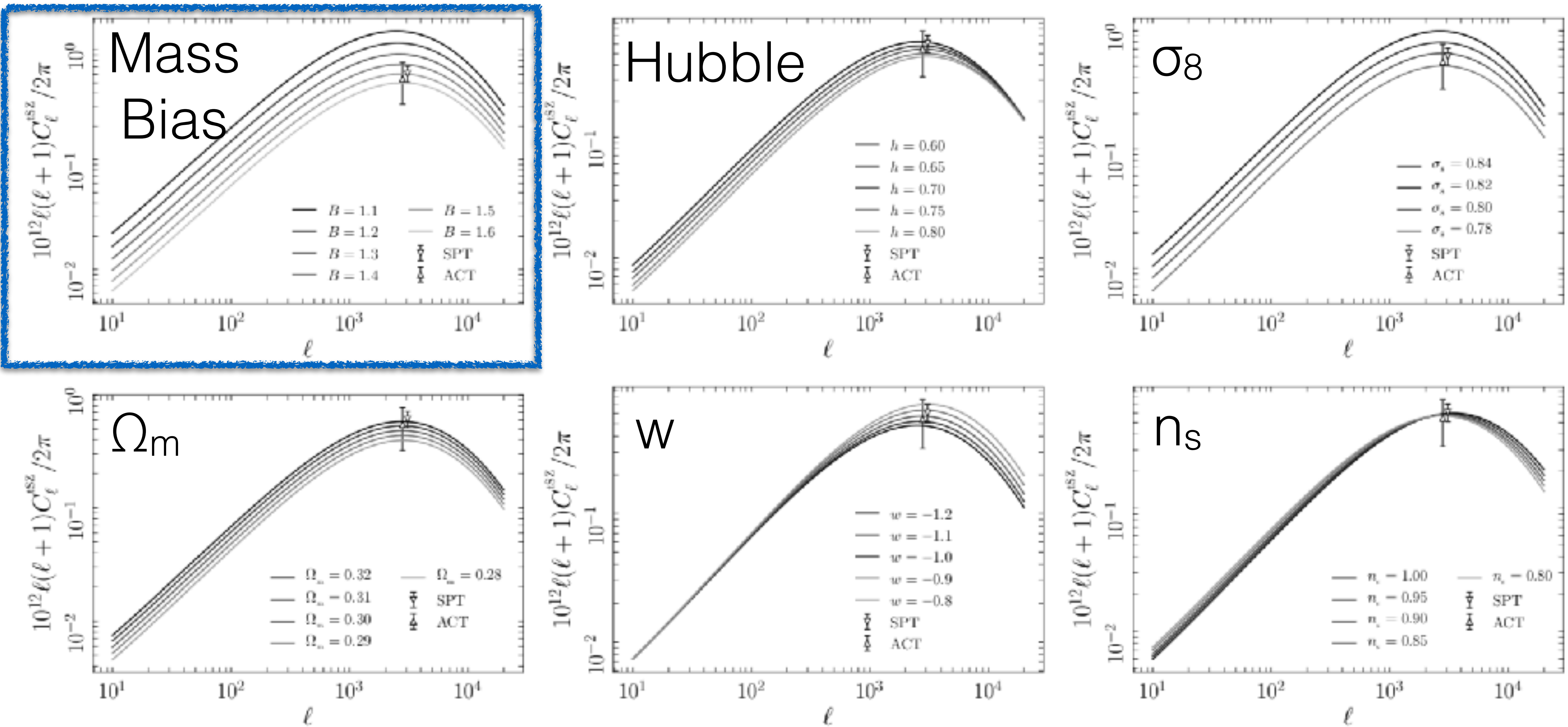
Bolliet, Comis, EK, Macias-Perez (2017)

tSZ power slightly lower



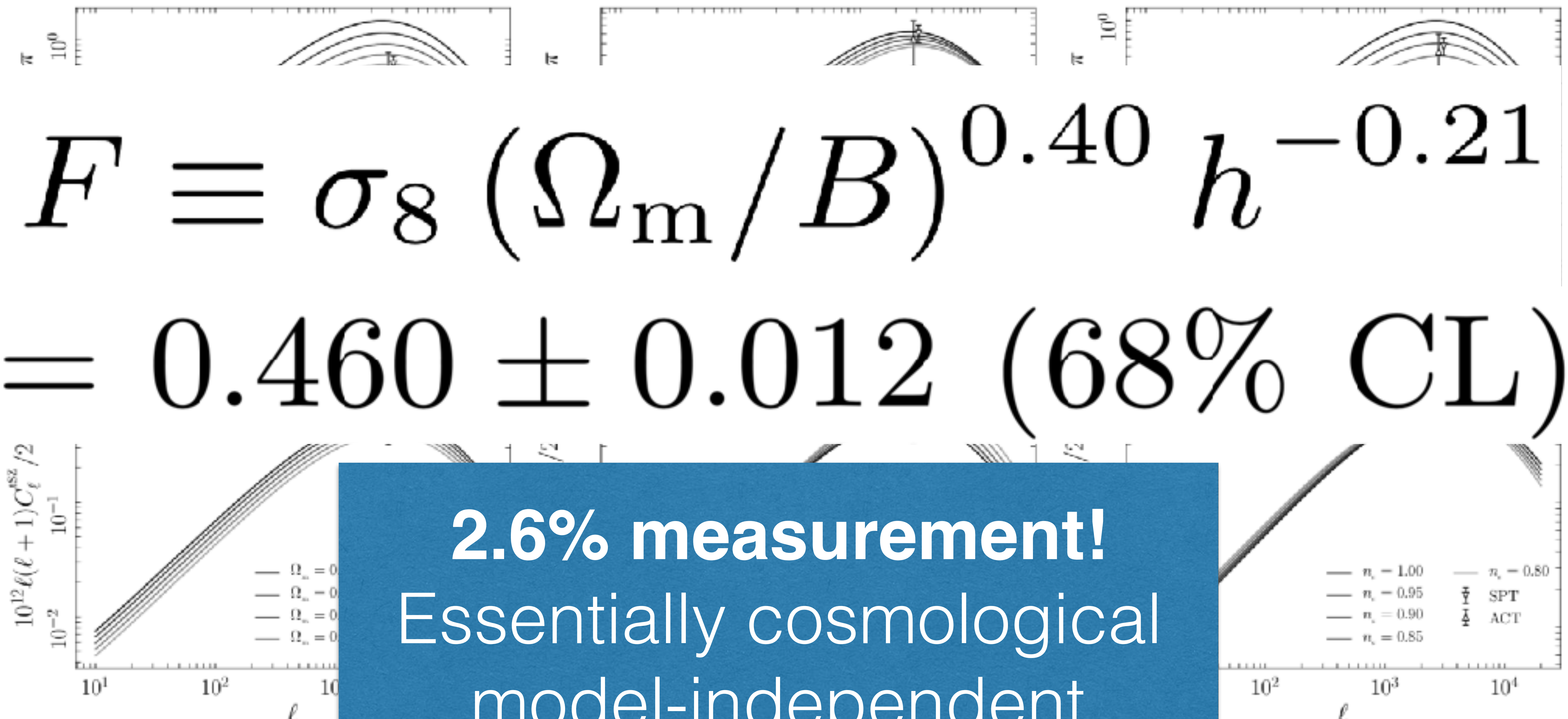
Bolliet, Comis, EK, Macias-Perez (2017)

Closer look at the parameter dependence



Bolliet, Comis, EK, Macias-Perez (2017)

Closer look at the parameter dependence



$$F \equiv \sigma_8 \left(\Omega_{\rm m}/B\right)^{0.40} h^{-0.21}$$

$$= 0.460 \pm 0.012 \ (68\% \ {\rm CL})$$

2.6% measurement!
Essentially cosmological model-independent

Bolliet, Comis, EK, Macias-Perez (2017)

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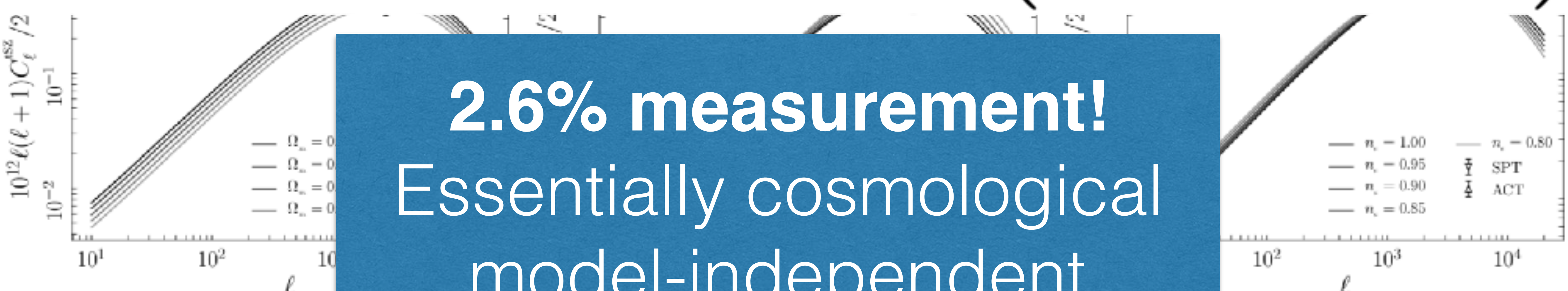


2.6% measurement!

Essentially cosmological model-independent

Planck Mass Bias

$$C_\ell = \int dz \frac{dV}{dz} \int dM \frac{dn}{dM} |y_\ell(M,z)|^2$$

- The key ingredient of the power spectrum is a profile of **thermal pressure of electrons**

$$P_{\mathrm{e}}(x) = C \times P_0 (c_{500} x)^{-\gamma} [1 + (c_{500} x)^{\alpha}]^{(\gamma-\beta)/\alpha}$$

$$C = 1.65 \left(\frac{h}{0.7}\right)^2 \left(\frac{H}{H_0}\right)^{\frac{8}{3}} \left[\frac{(h/0.7)\tilde{M}_{500c}}{3 \times 10^{14} \mathrm{M}_\odot}\right]^{\frac{2}{3}+0.12} \mathrm{eV\,cm^{-3}}$$

$$\tilde{M}_{500c} = M_{500c,\mathrm{true}}/B$$

Mass Bias in ΛCDM

- Constraining the ΛCDM parameters by the Planck (TT+lowP) chain, we find
  - B = 1.71 ± 0.17 (68%CL; Bolliet et al.)
    - or, 1-b = 1/B = 0.58 ± 0.06
- Adding the CMB lensing, we find
  - B = 1.59 ± 0.13 (68%CL; Makiya, Ando & EK, in prep)
- Cf: Simulation by Dolag, EK & Sunyaev: B ~ 1.2.

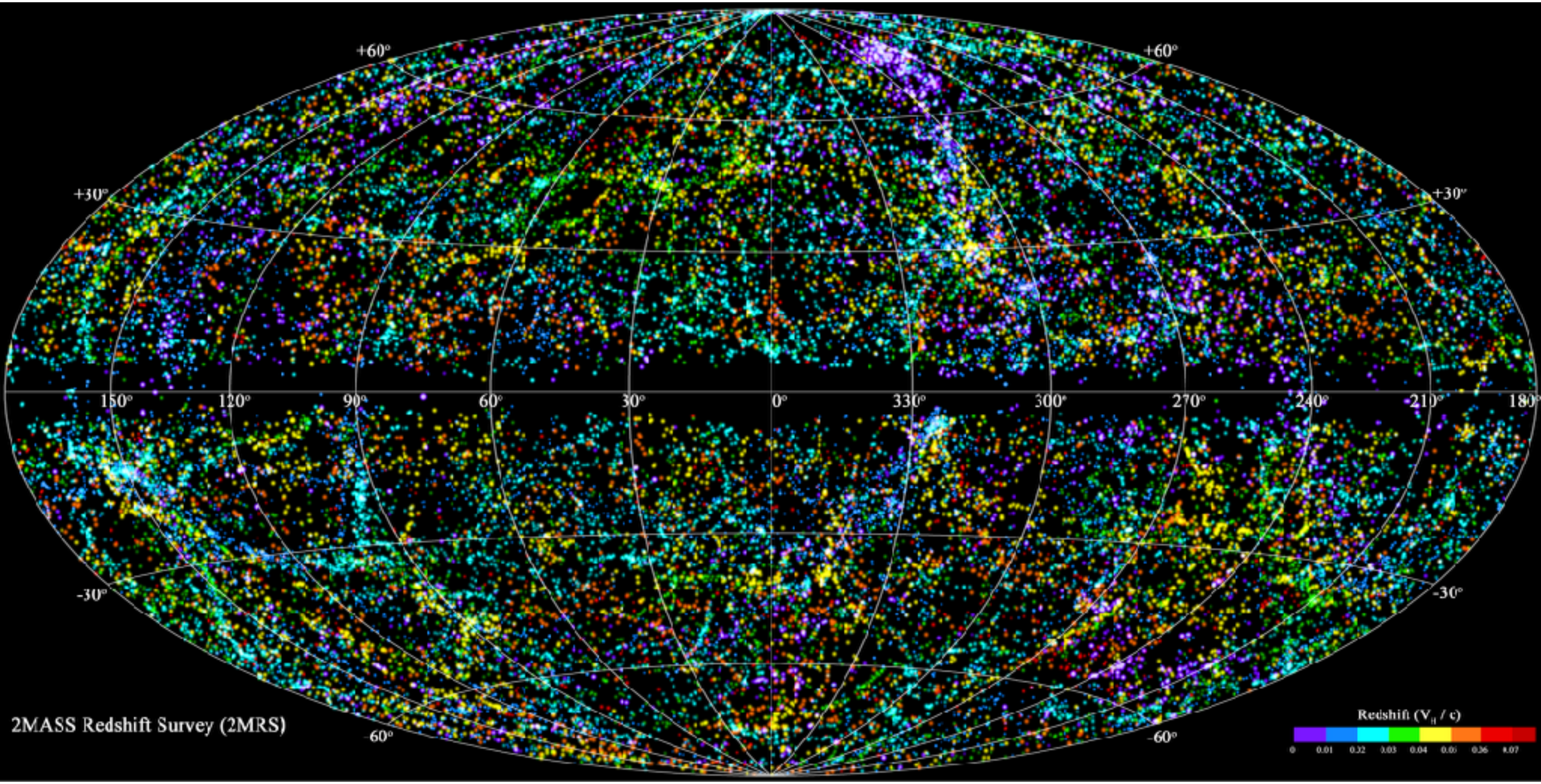
Manifestation that the new Compton-Y power spectrum is lower

Towards “Tomography”

- Cross-correlating the Compton-Y map with galaxies with known redshifts!

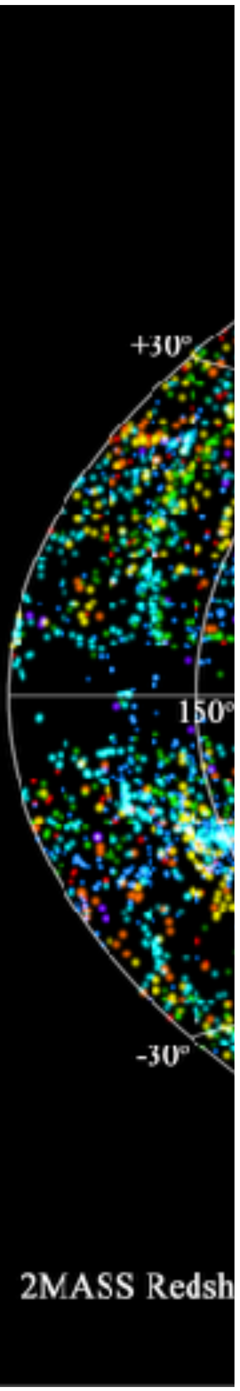
Huchra et al. (2012)

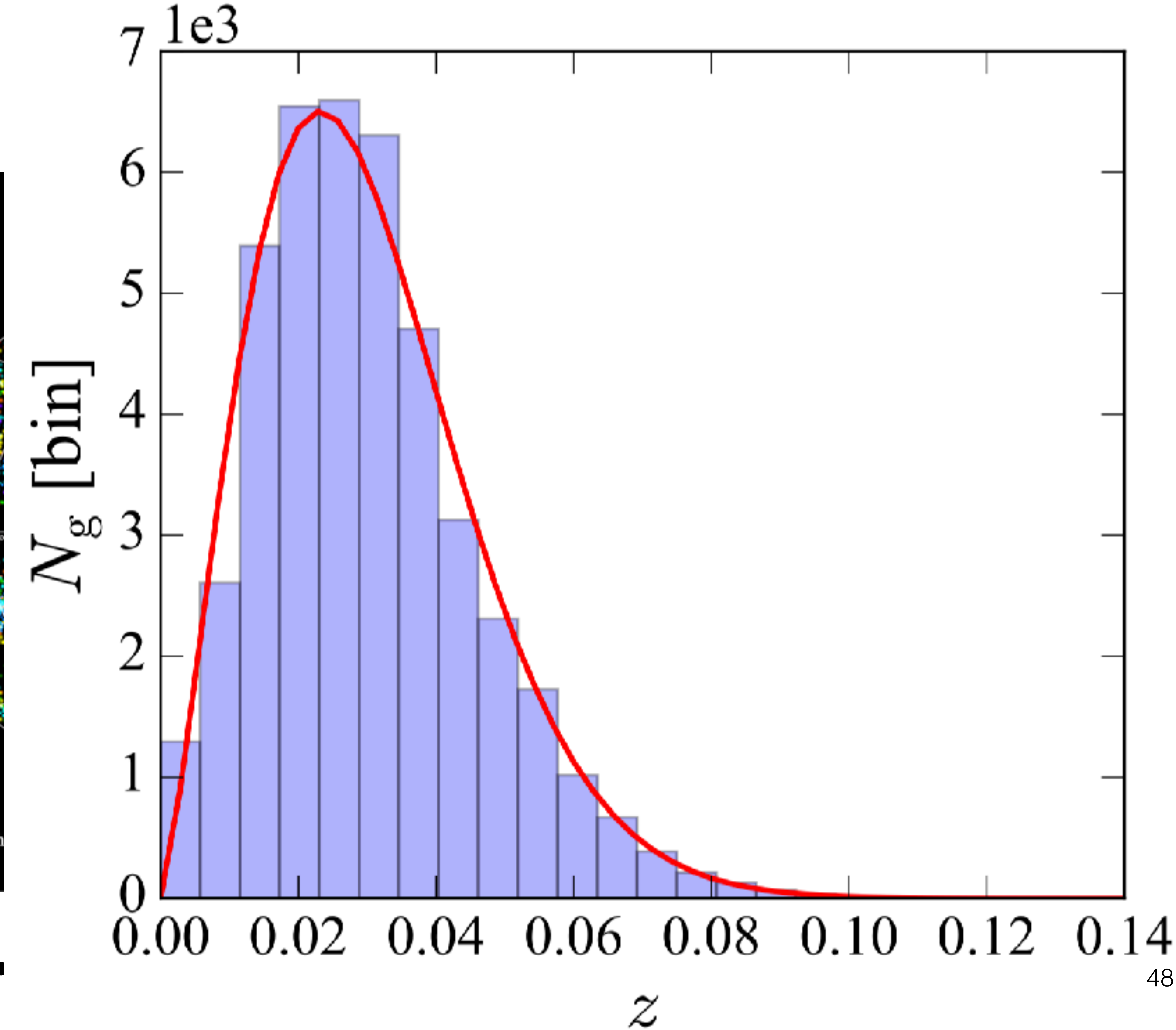
2MASS Redshift Survey

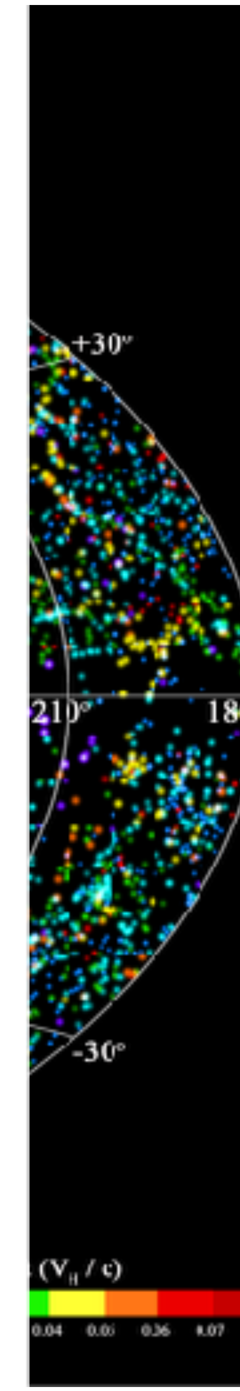


- ~40K galaxies with the median redshift of 0.02

2012)


+30°
150°
-30°
2MASS Redsh


1e3
7
6
5
4
3
2
1
0
N_g [bin]
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
z

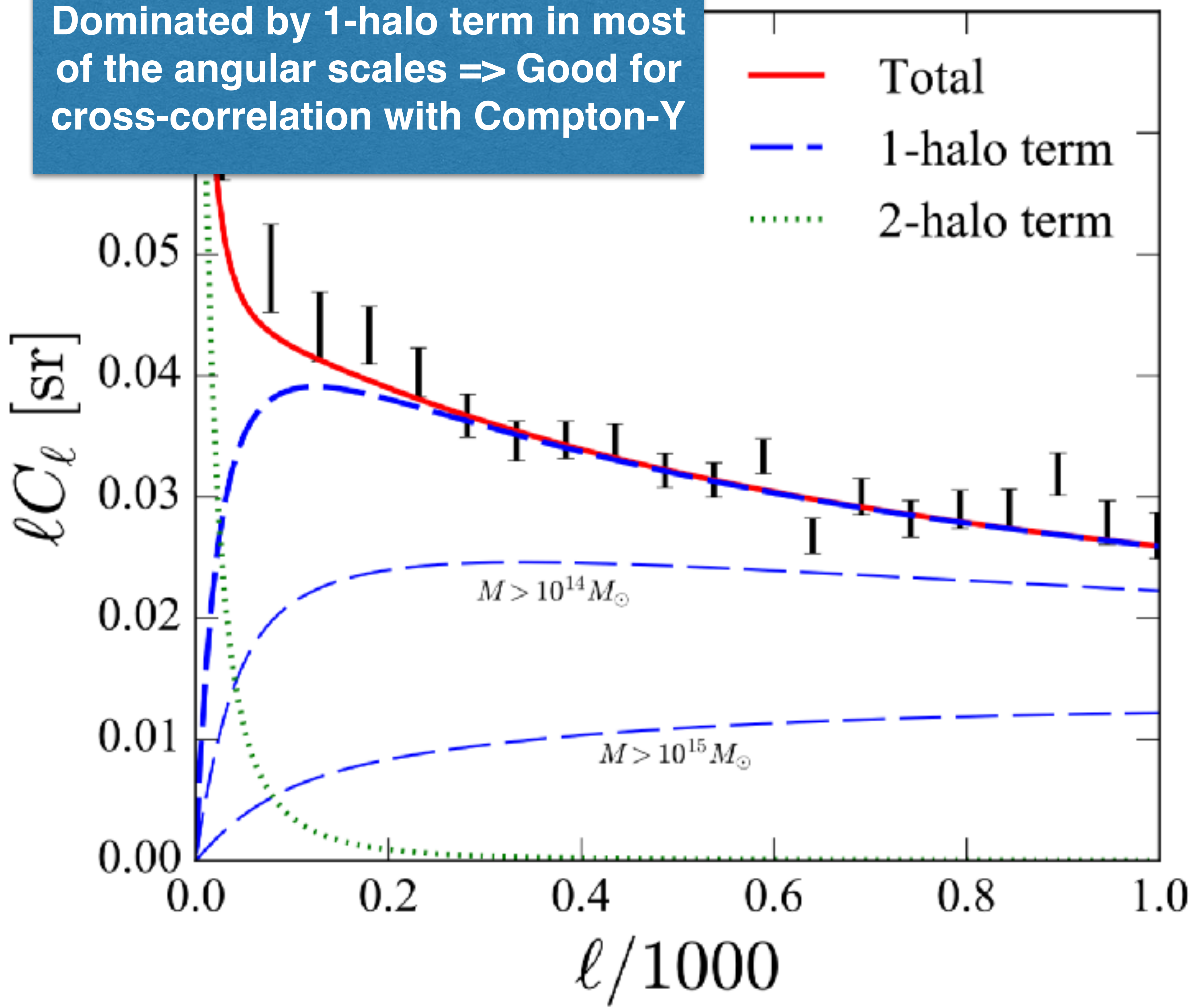

+30°
210°
180°
-30°
(V_H / c)

•

Ando, Benoit-Levy & EK (2018)

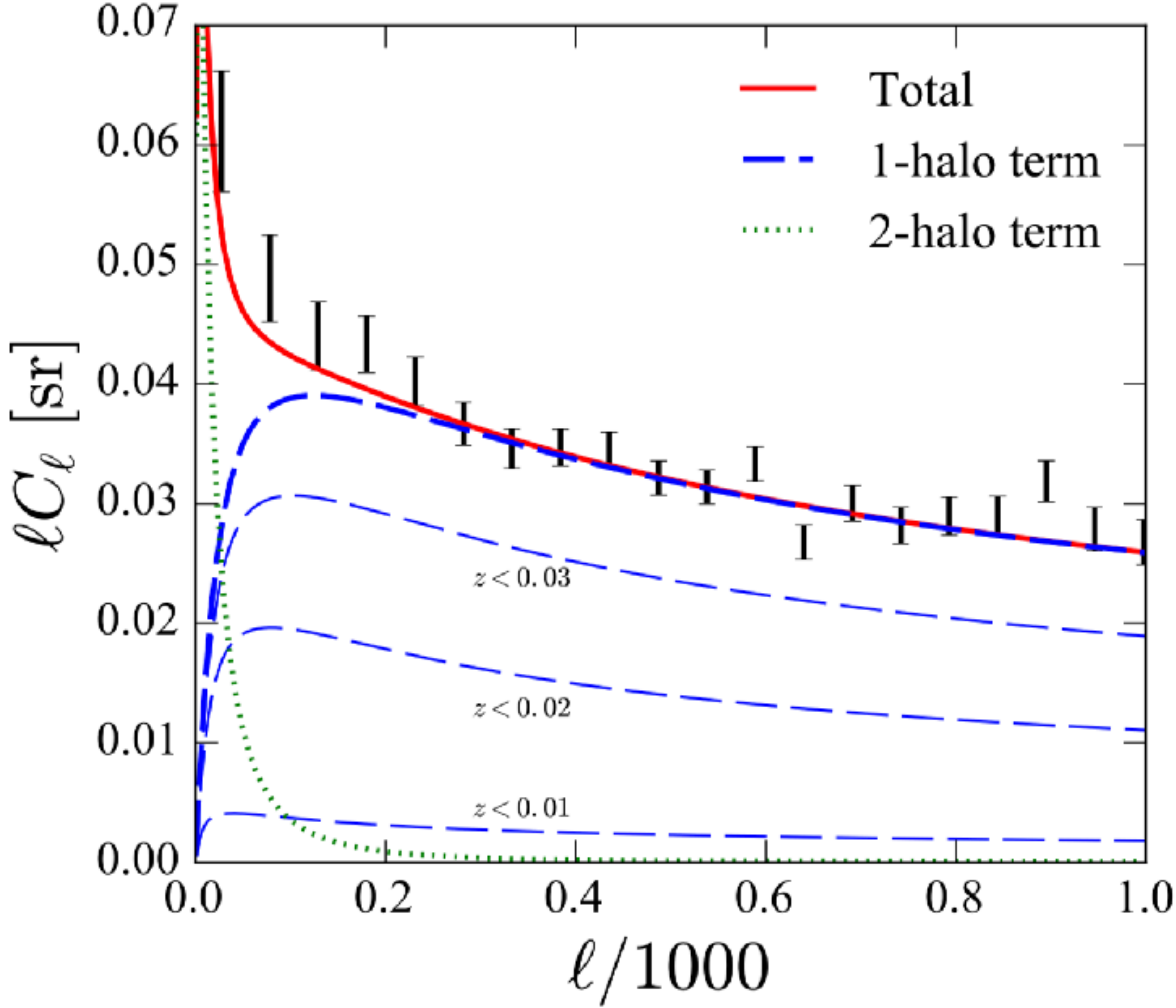
2MRS Auto Power

Dominated by 1-halo term in most of the angular scales => Good for cross-correlation with Compton-Y



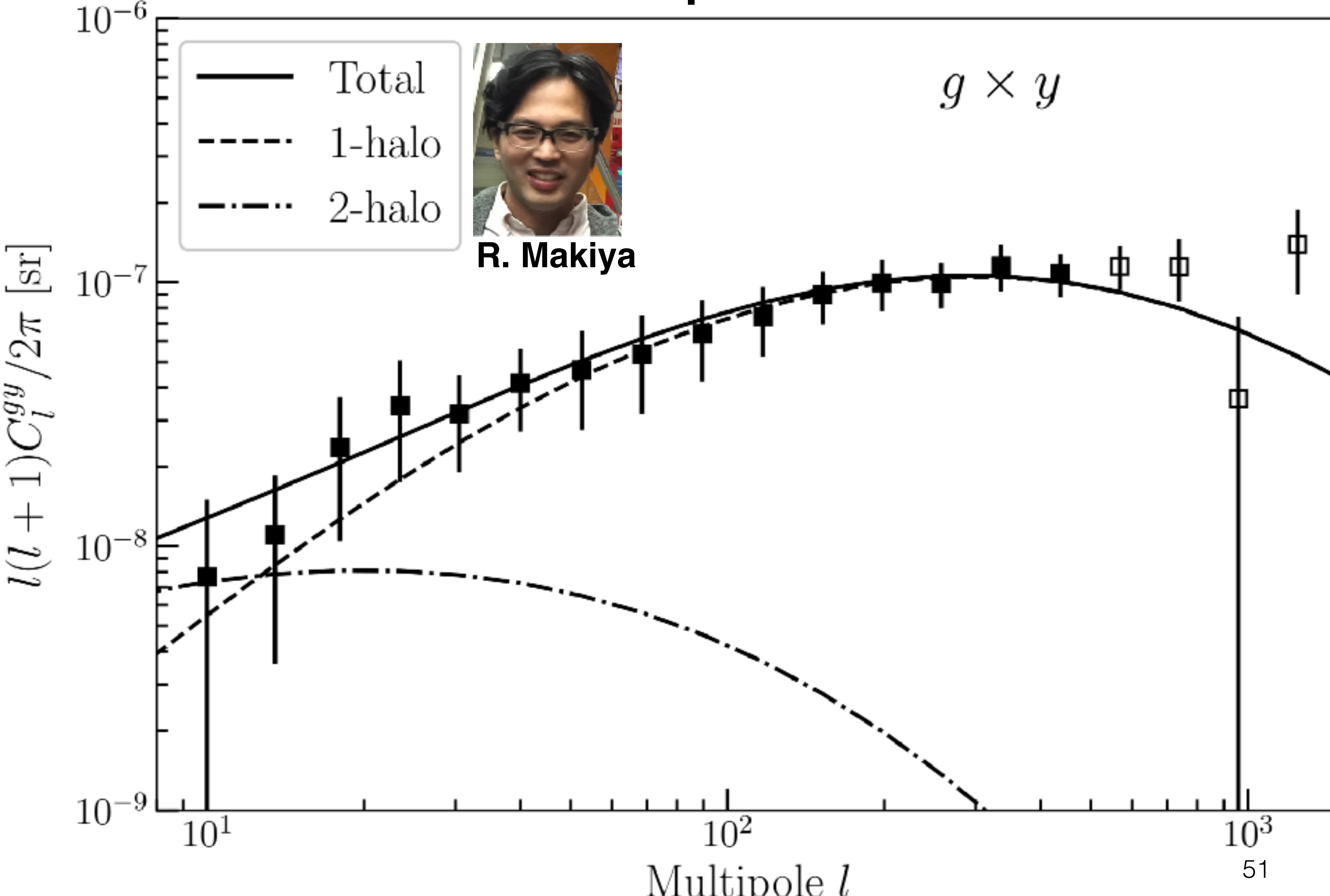
Ando, Benoit-Levy & EK (2018)

2MRS Auto Power



Makiya, Ando & EK, in prep

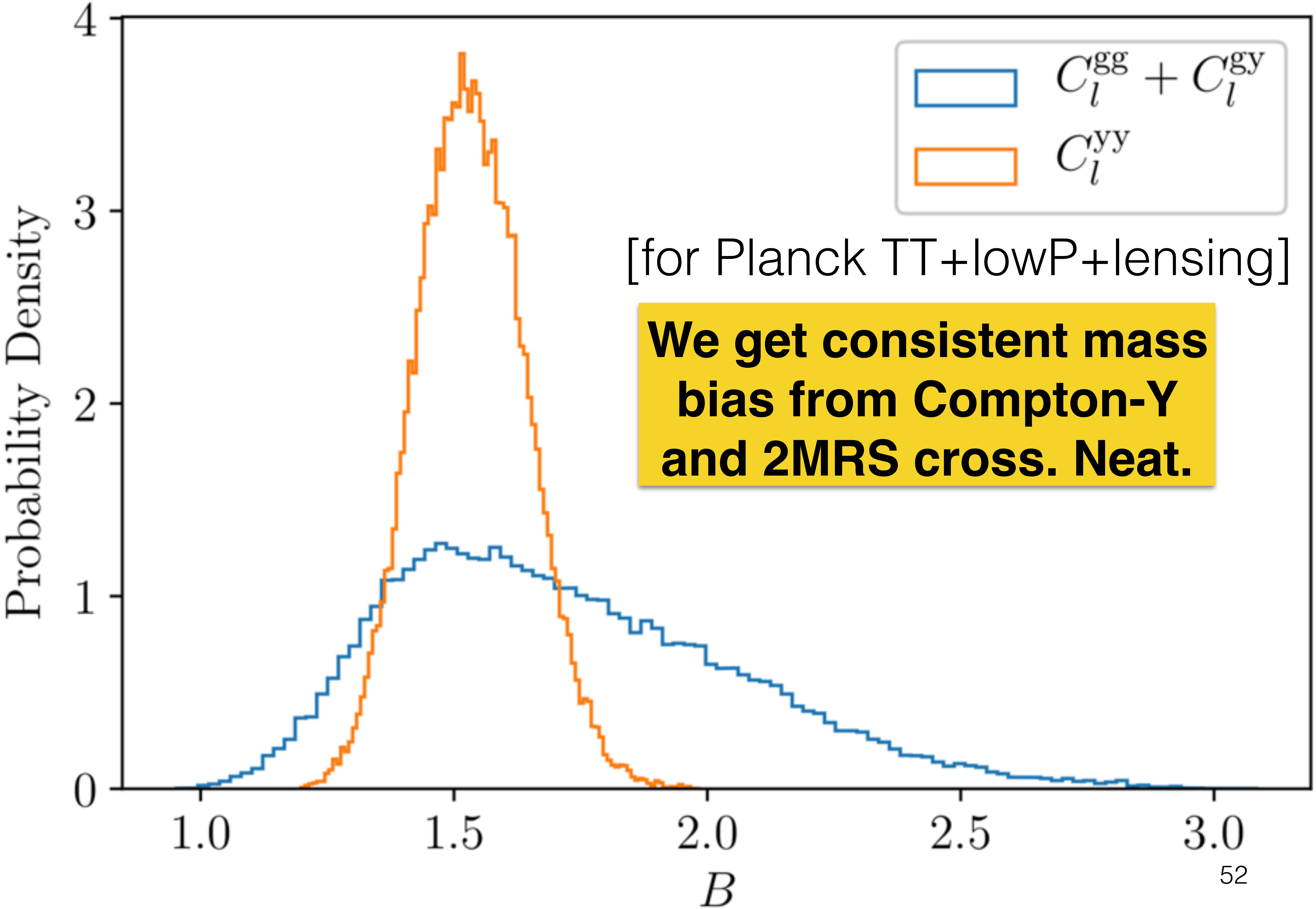
Cross-power!



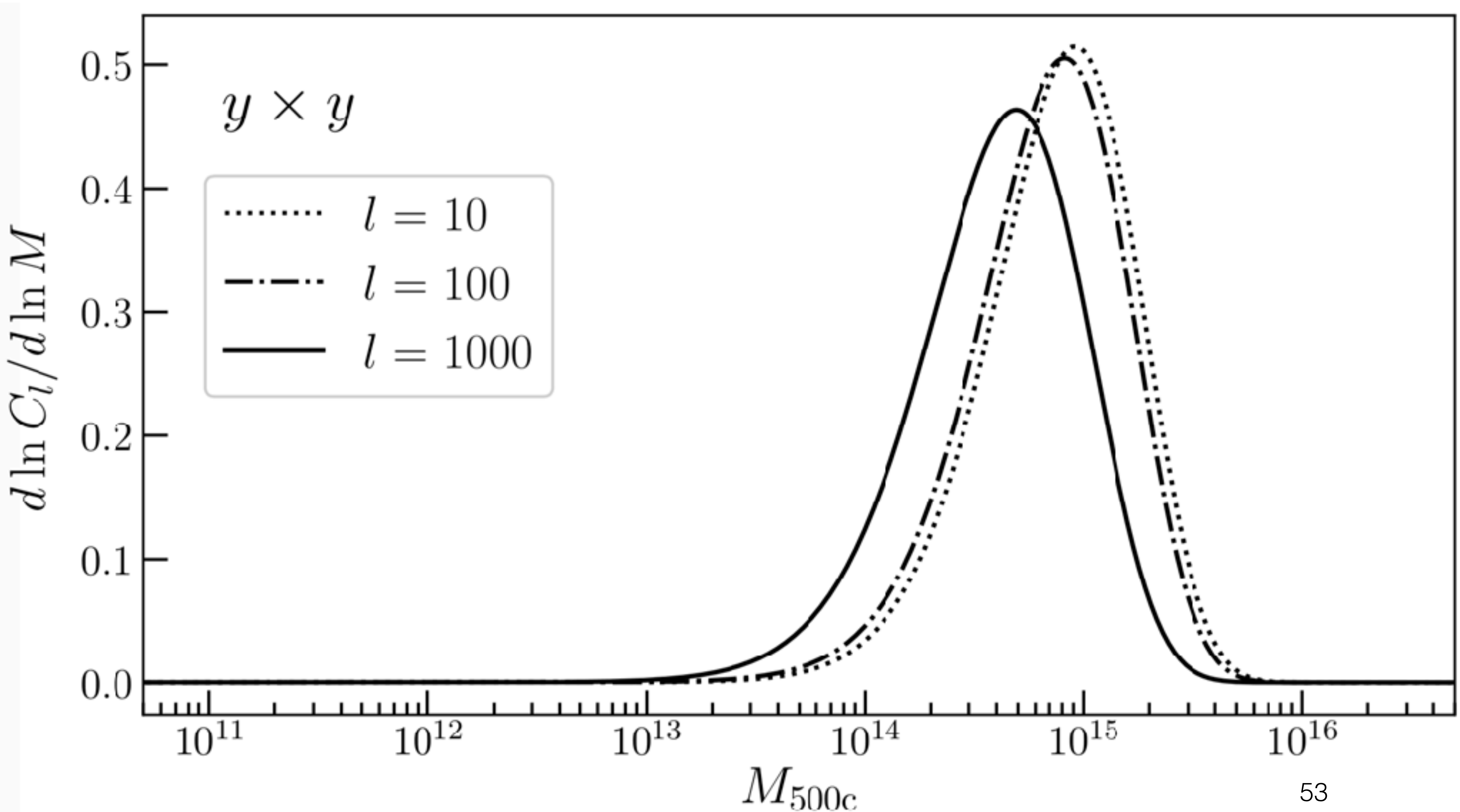
R. Makiya

Makiya, Ando & EK, in prep

Mass-bias Consistency

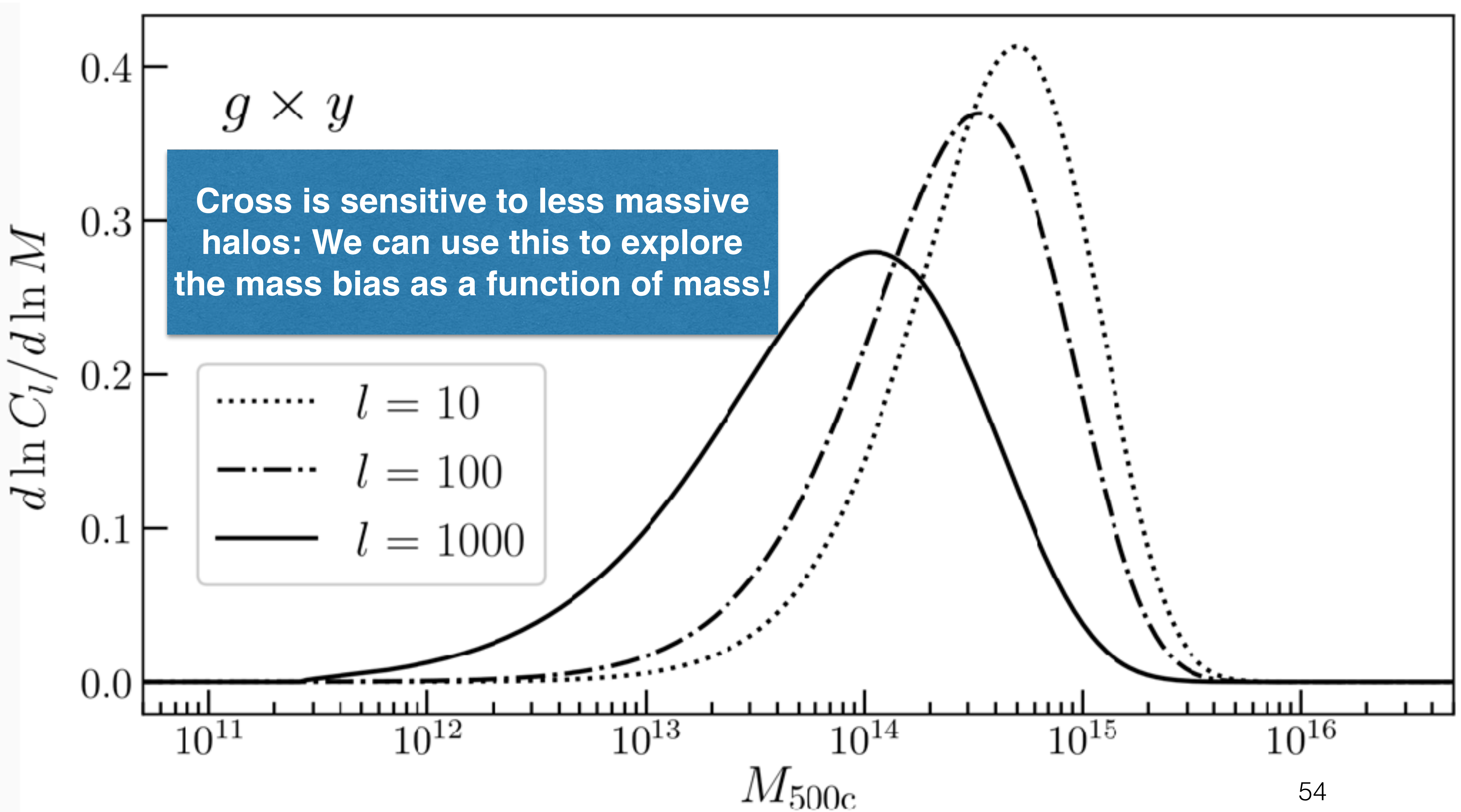


Mass Dependence



Makiya, Ando & EK, in prep

Mass Dependence



Cross is sensitive to less massive halos: We can use this to explore the mass bias as a function of mass!

Planck Mass Bias

$$C_\ell = \int dz \frac{dV}{dz} \int dM \frac{dn}{dM} |y_\ell(M,z)|^2$$

- The key ingredient of the power spectrum is a profile of **thermal pressure of electrons**

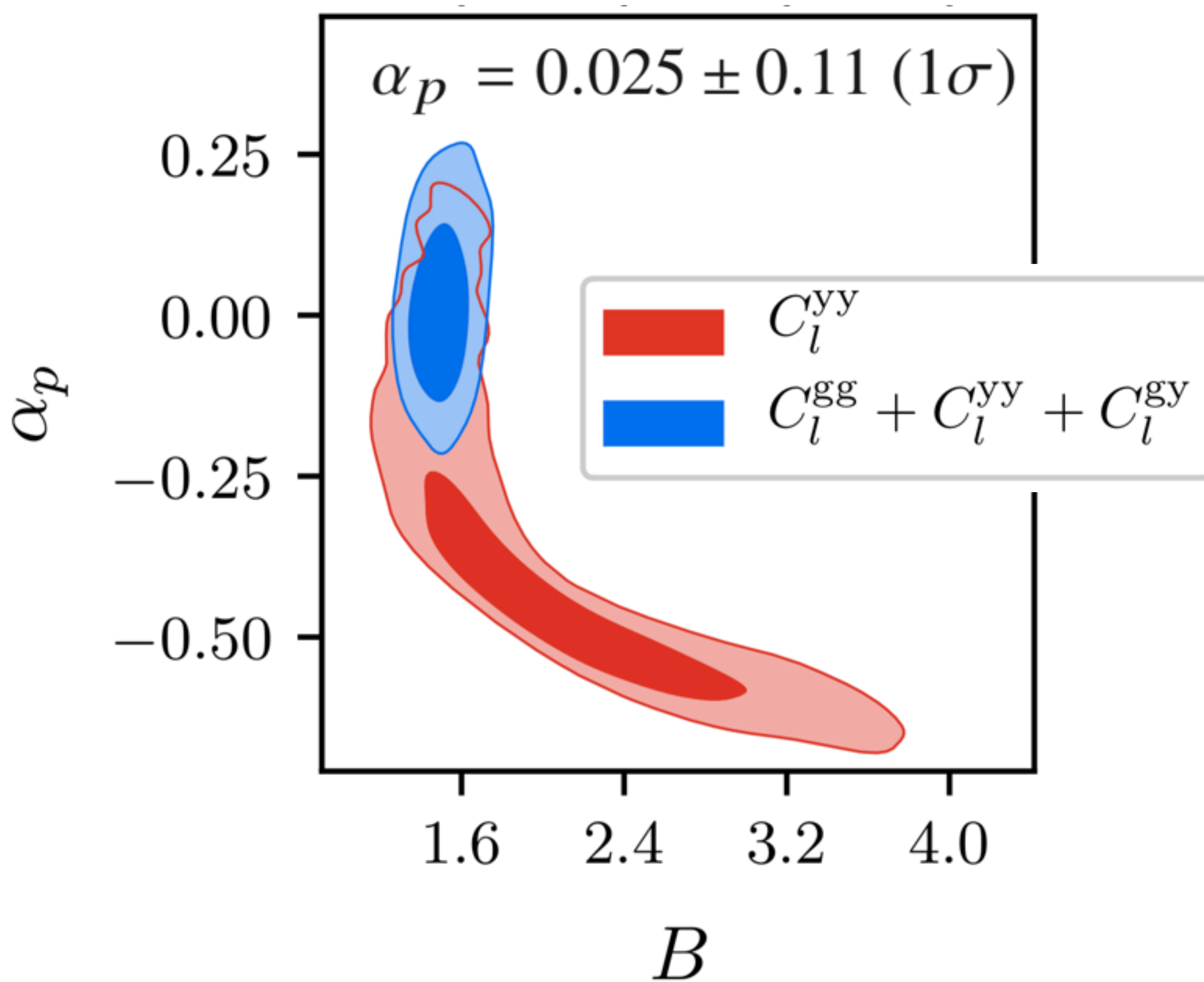
$$P_e(x) = C \times P_0 (c_{500}x)^{-\gamma} [1 + (c_{500}x)^\alpha]^{(\gamma-\beta)/\alpha}$$

$$C = 1.65 \left(\frac{h}{0.7}\right)^2 \left(\frac{H}{H_0}\right)^{\frac{8}{3}} \left[\frac{(h/0.7)\tilde{M}_{500c}}{3 \times 10^{14} M_\odot}\right]^{\frac{2}{3}+\alpha_p} \mathrm{eV\,cm^{-3}}$$

$$\tilde{M}_{500c} = M_{500c,\mathrm{true}}/B$$

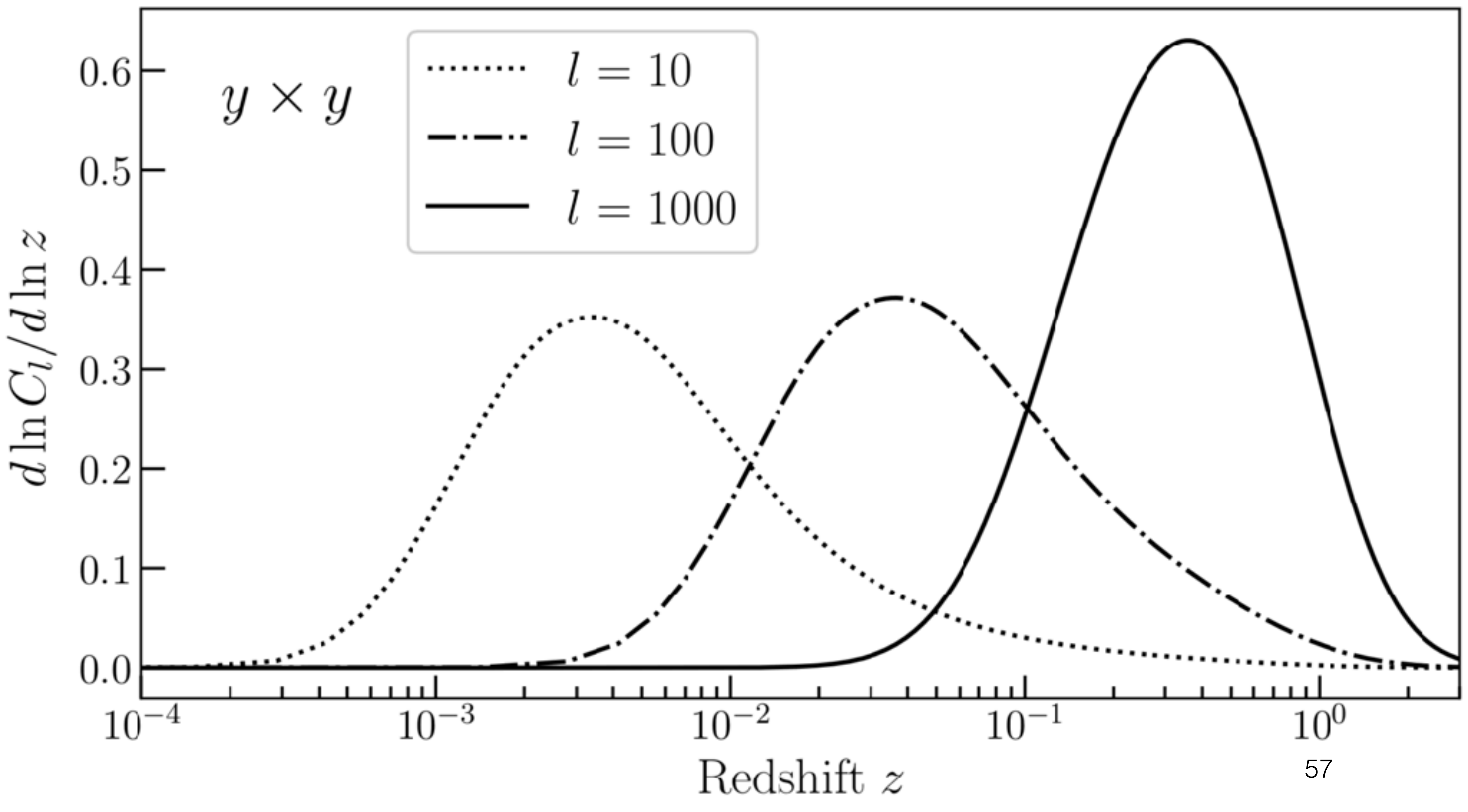
Makiya, Ando & EK, in prep

Mass Dependence Nailed

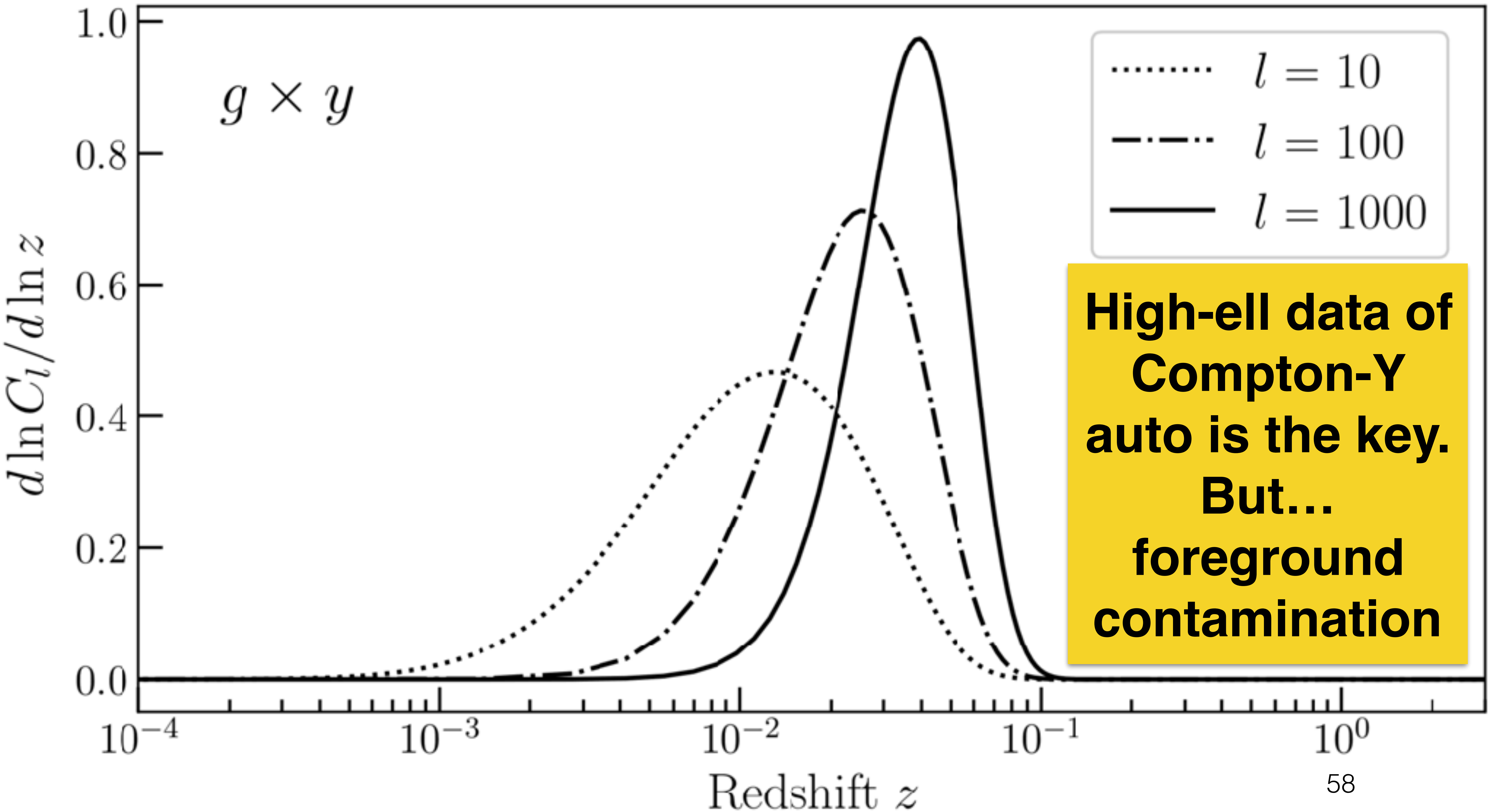


Makiya, Ando & EK, in prep

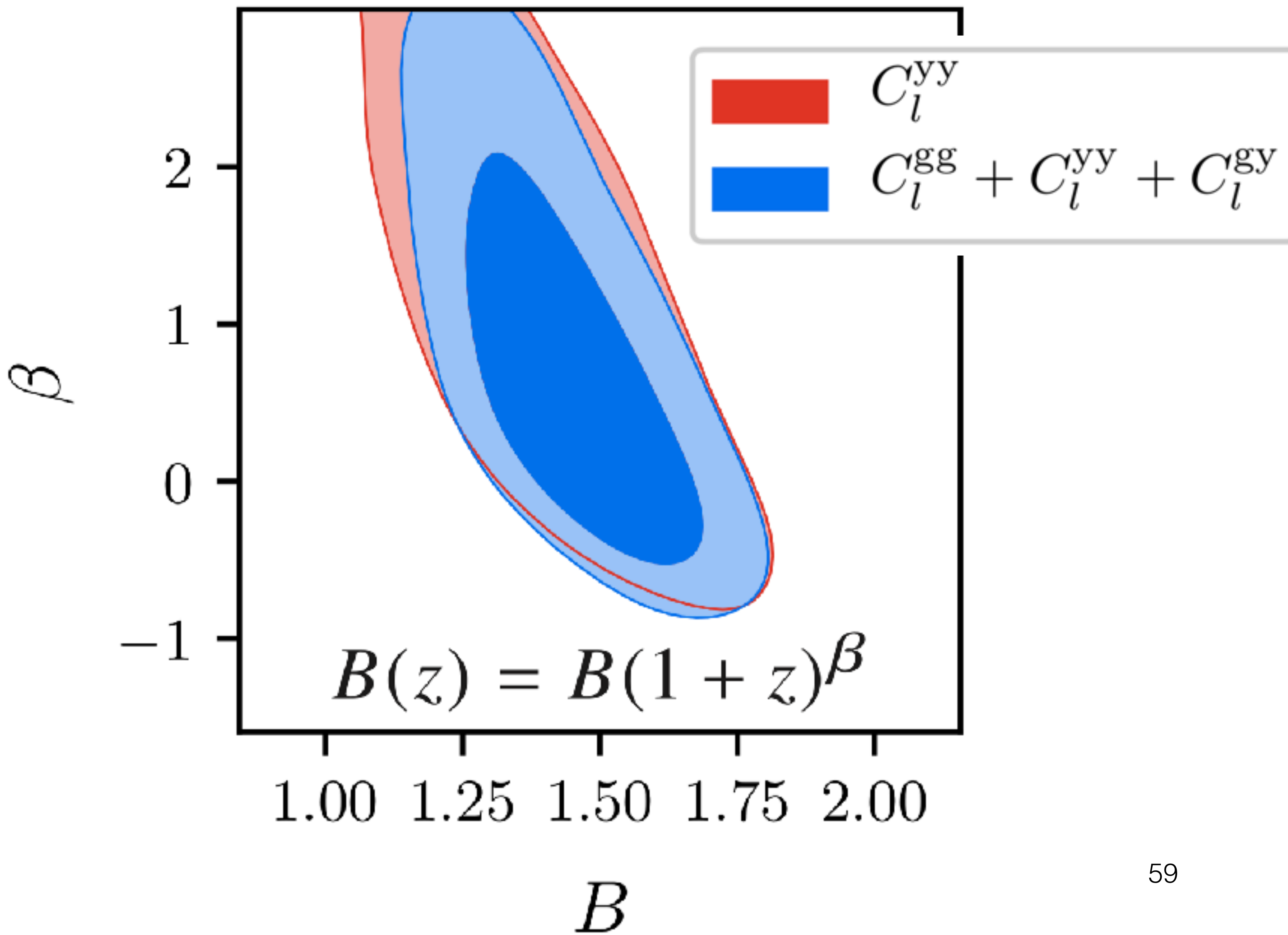
Redshift Dependence



Redshift Dependence



Z-dependence Poorly Constrained



Summary

- New results on the SZ effect, *from small to large:*

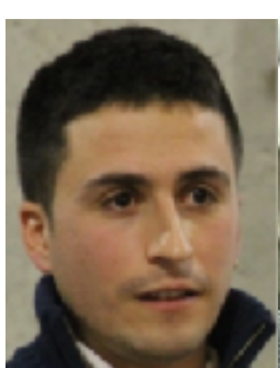
T. Kitayama

1. The first SZ image by ALMA - opening up a new study of cluster astrophysics via pressure fluctuations

K. Dolag

2. The SZ power spectrum at $l<1000$ has been determined finally! And we can simulate it

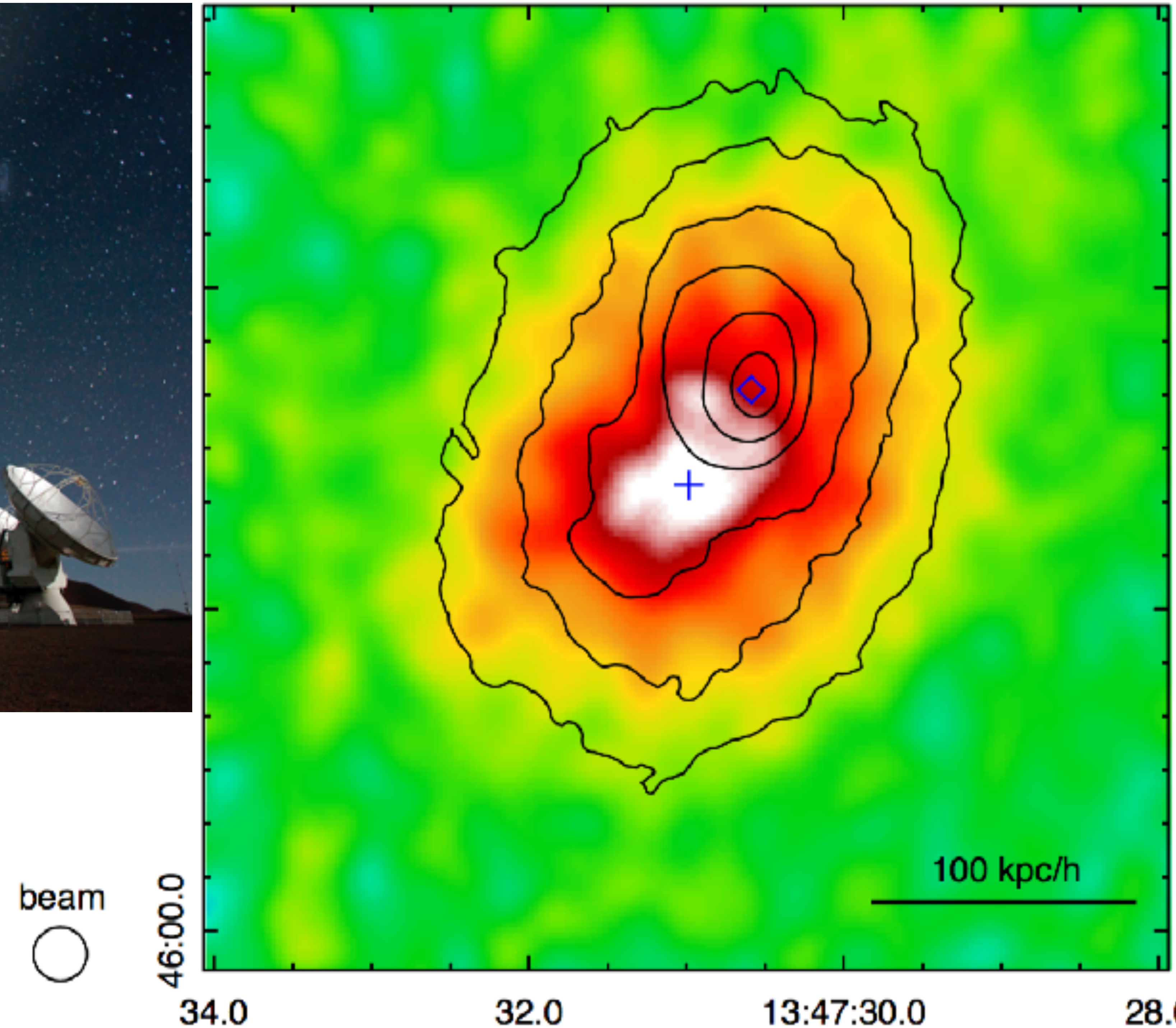
3. Detailed look at mass bias from the SZ power spectrum and cross-correlation tomography



B. Bolliet R. Makiya

- **B = 1.5 ± 0.1 (68%CL)** for Planck TT+lowP+lensing. Expect B ~ 1.2 for hydrostatic mass bias in the simulation. Origin?

Compton Y Map of RXJ1347−1145



<u>on-source integration times</u>

5.6 hours with 7-m array

2.6 hours with 12-m array

Thank you TAC!