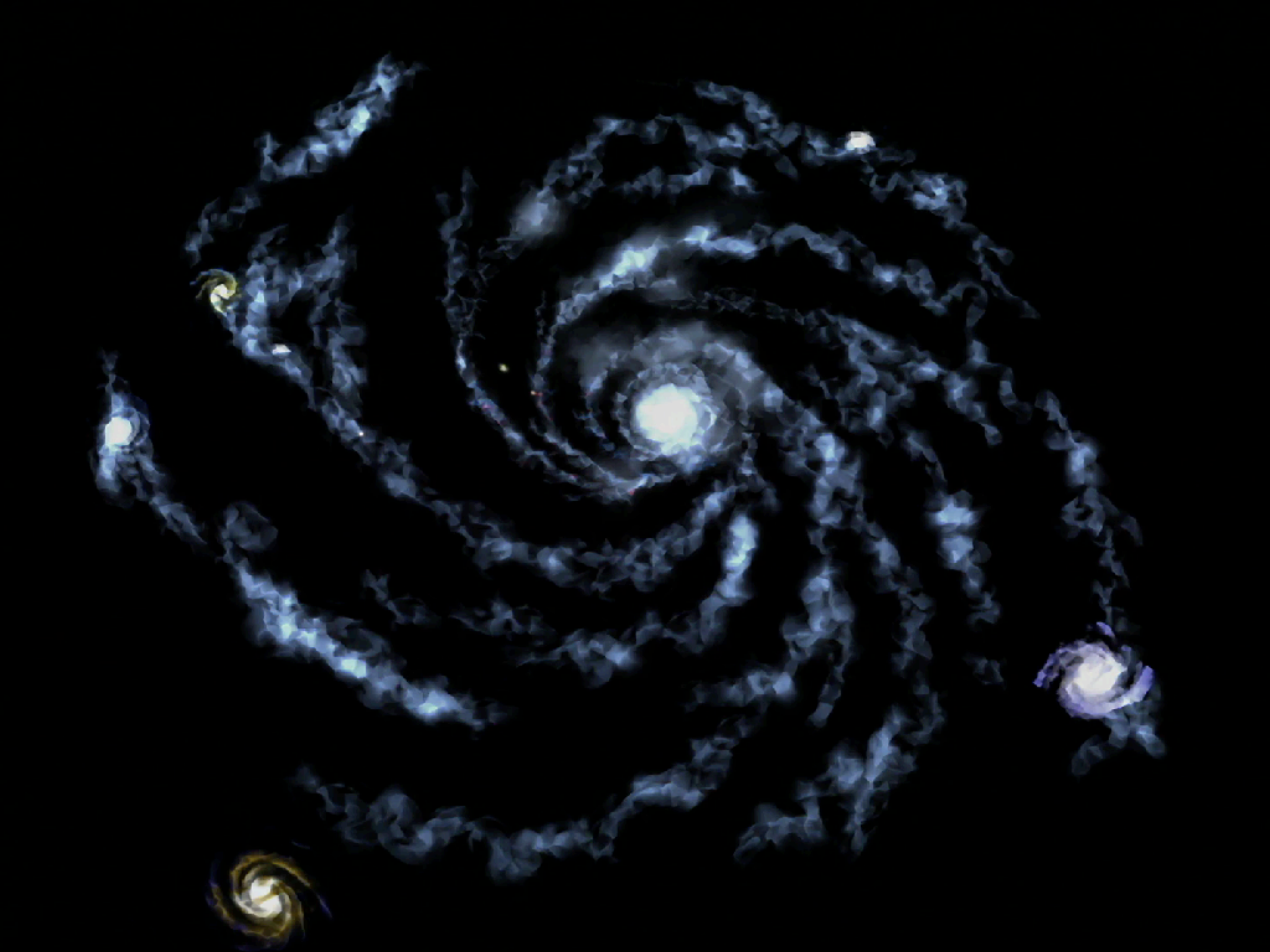
# Cosmic Microwave Background as the Backlight:

## *Mapping Hot Gas in the Universe with the Sunyaev-Zeldovich Effect*

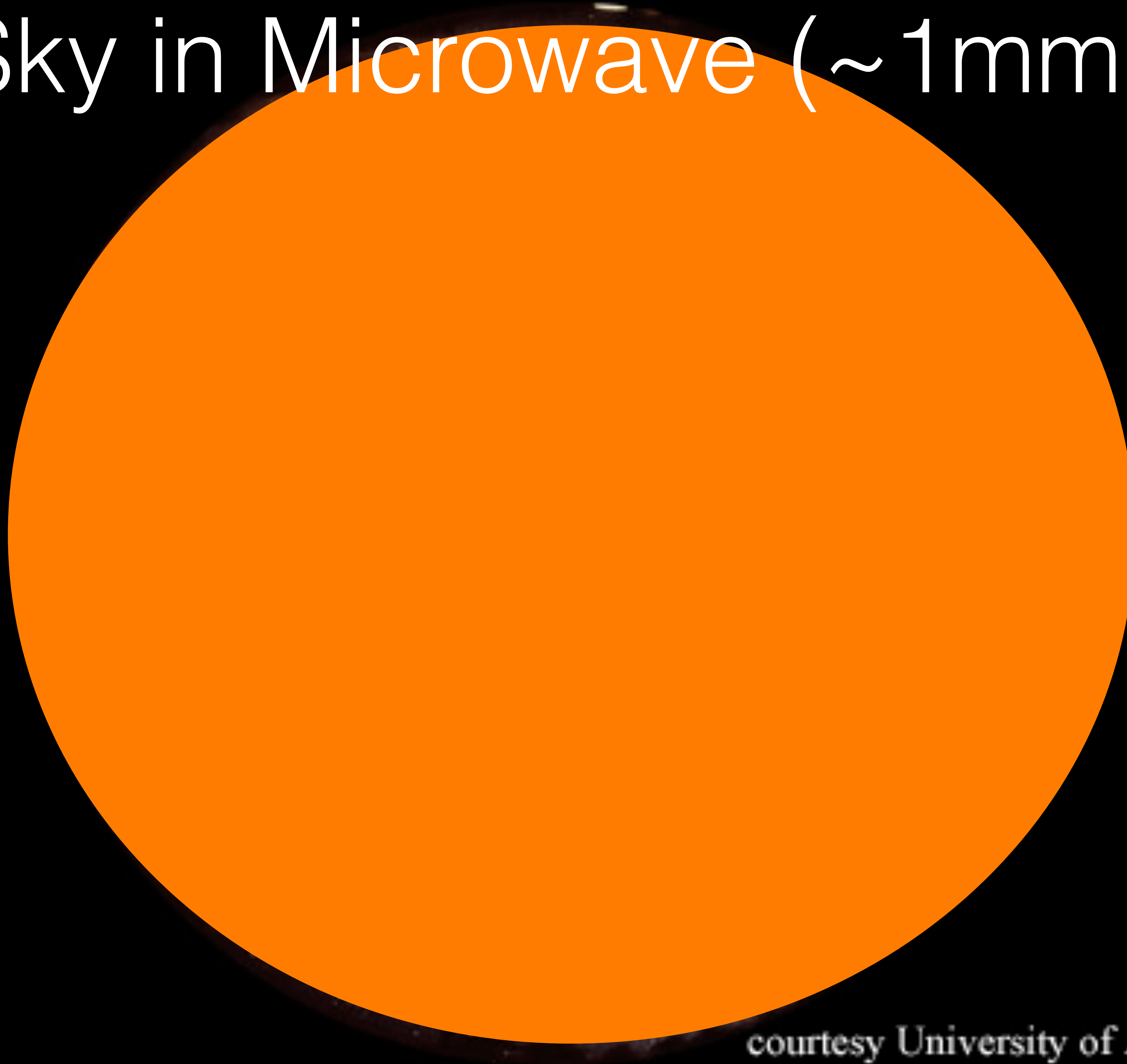
Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
Physikalisches Kolloquium, Universität Bonn
6. Dezember, 2019



# Sky in Optical (~0.5μm)

courtesy University of Arizona

# Sky in Microwave (~1mm)

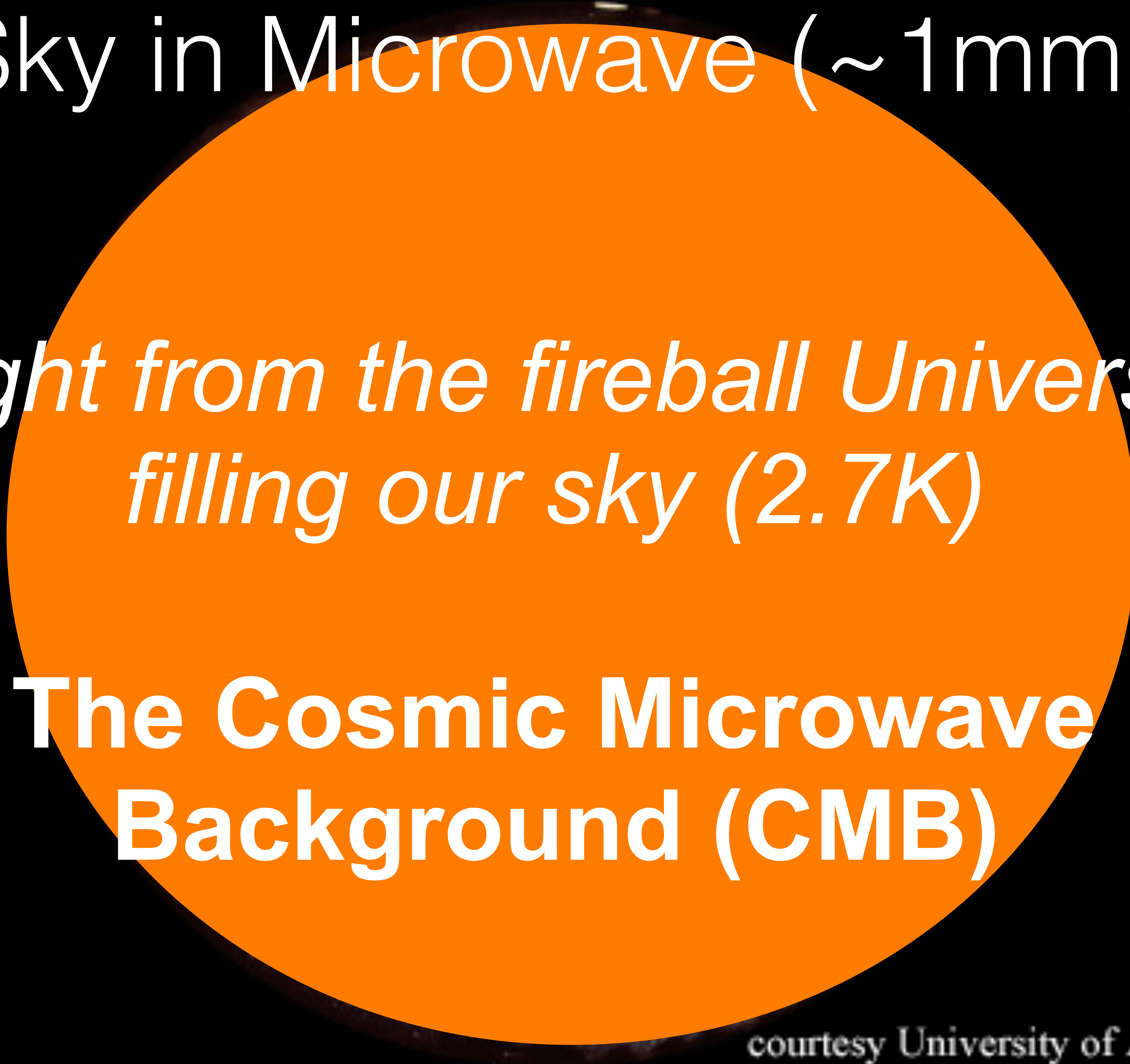


courtesy University of Arizona

# Sky in Microwave (~1mm)

*Light from the fireball Universe filling our sky (2.7K)*

**The Cosmic Microwave Background (CMB)**



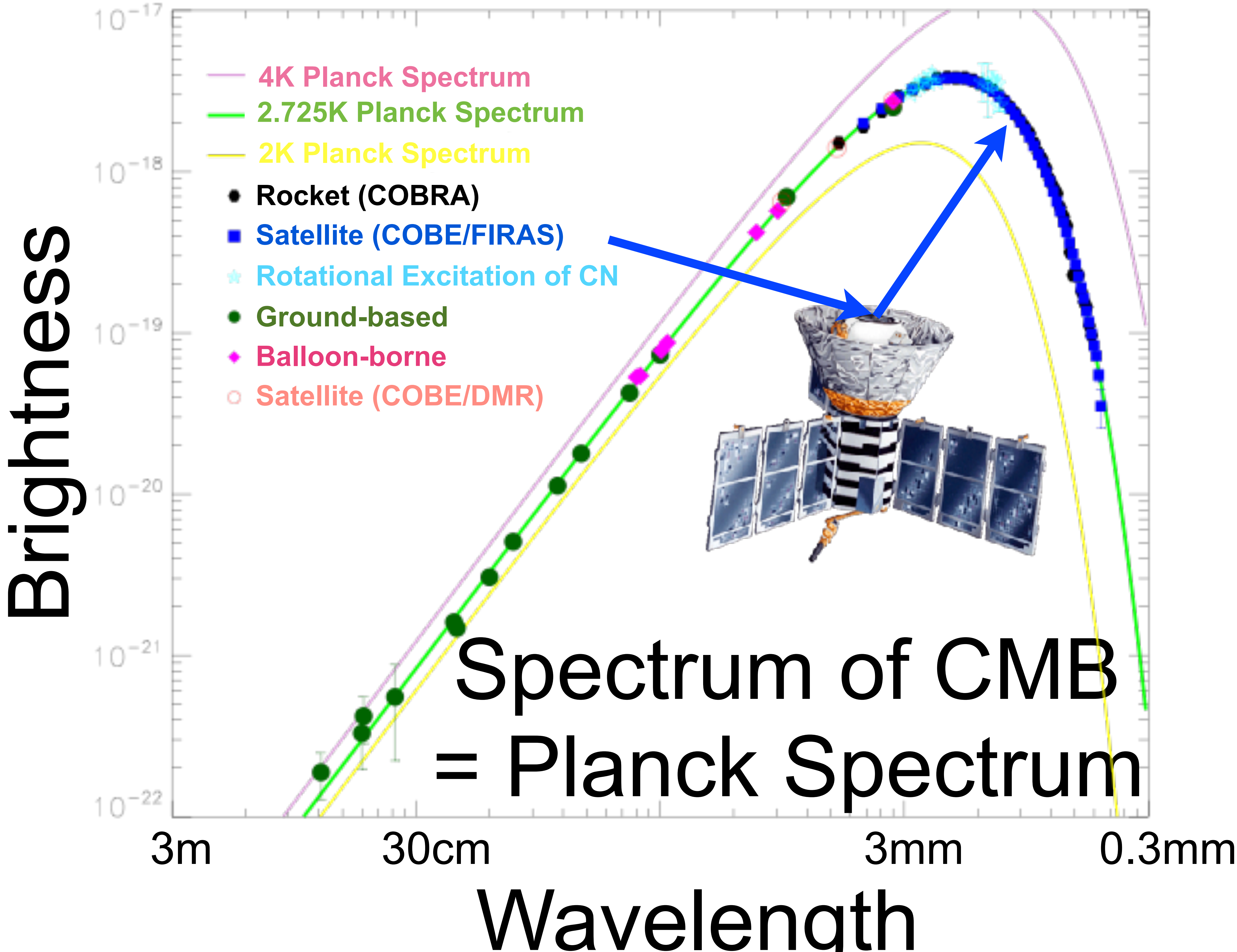
courtesy University of Arizona

**410 photons**

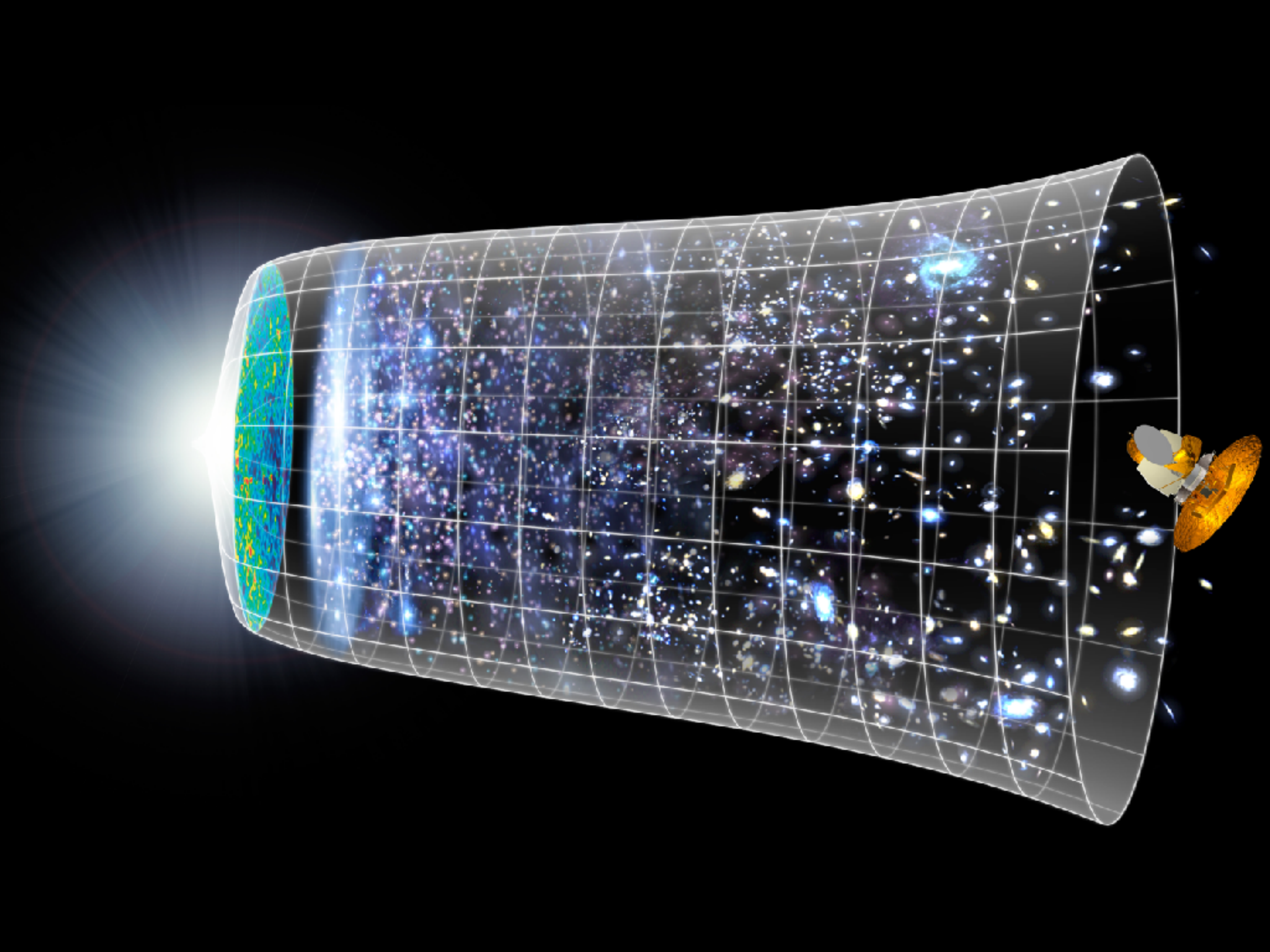
per

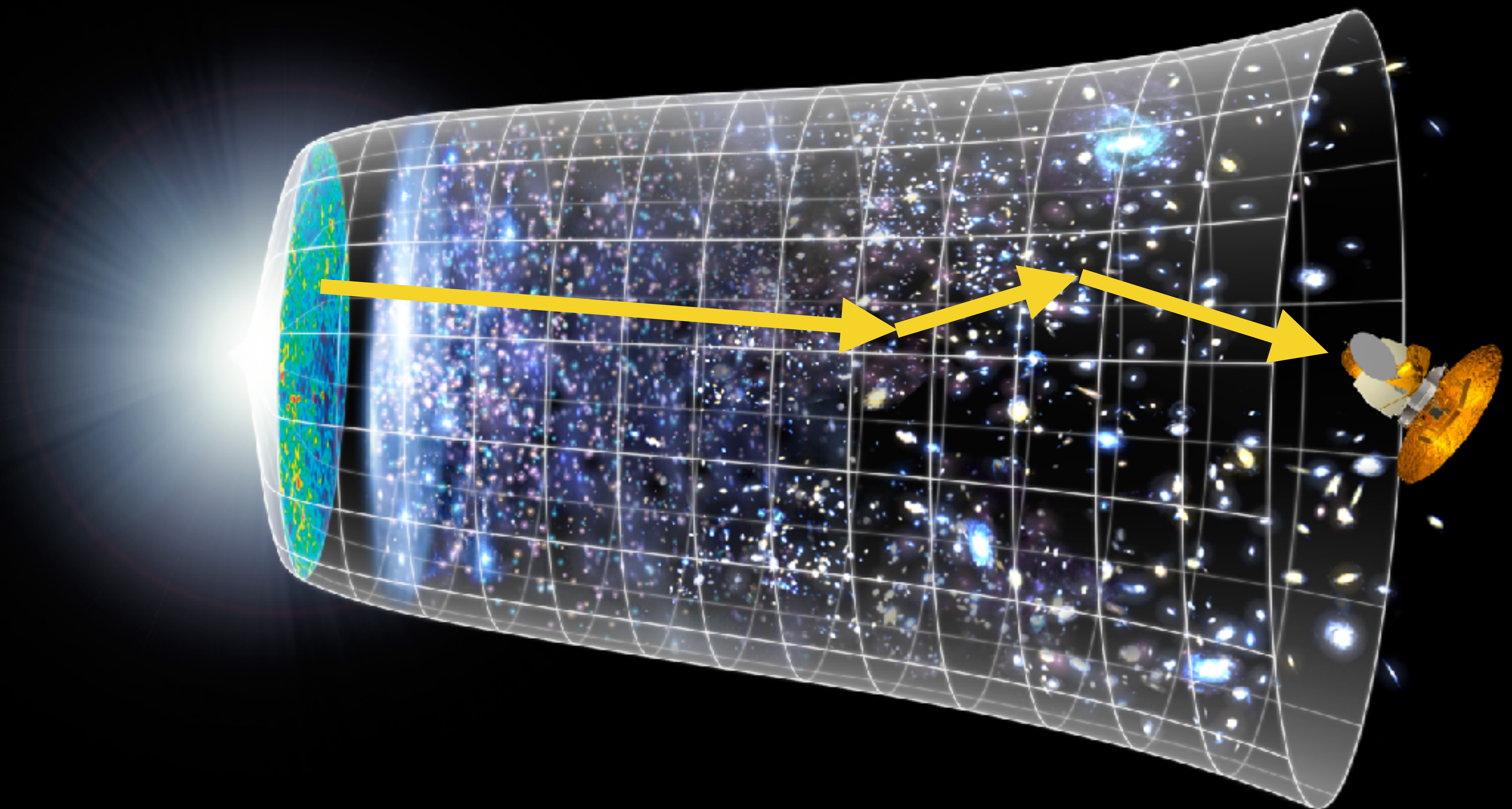
cubic centimeter!!

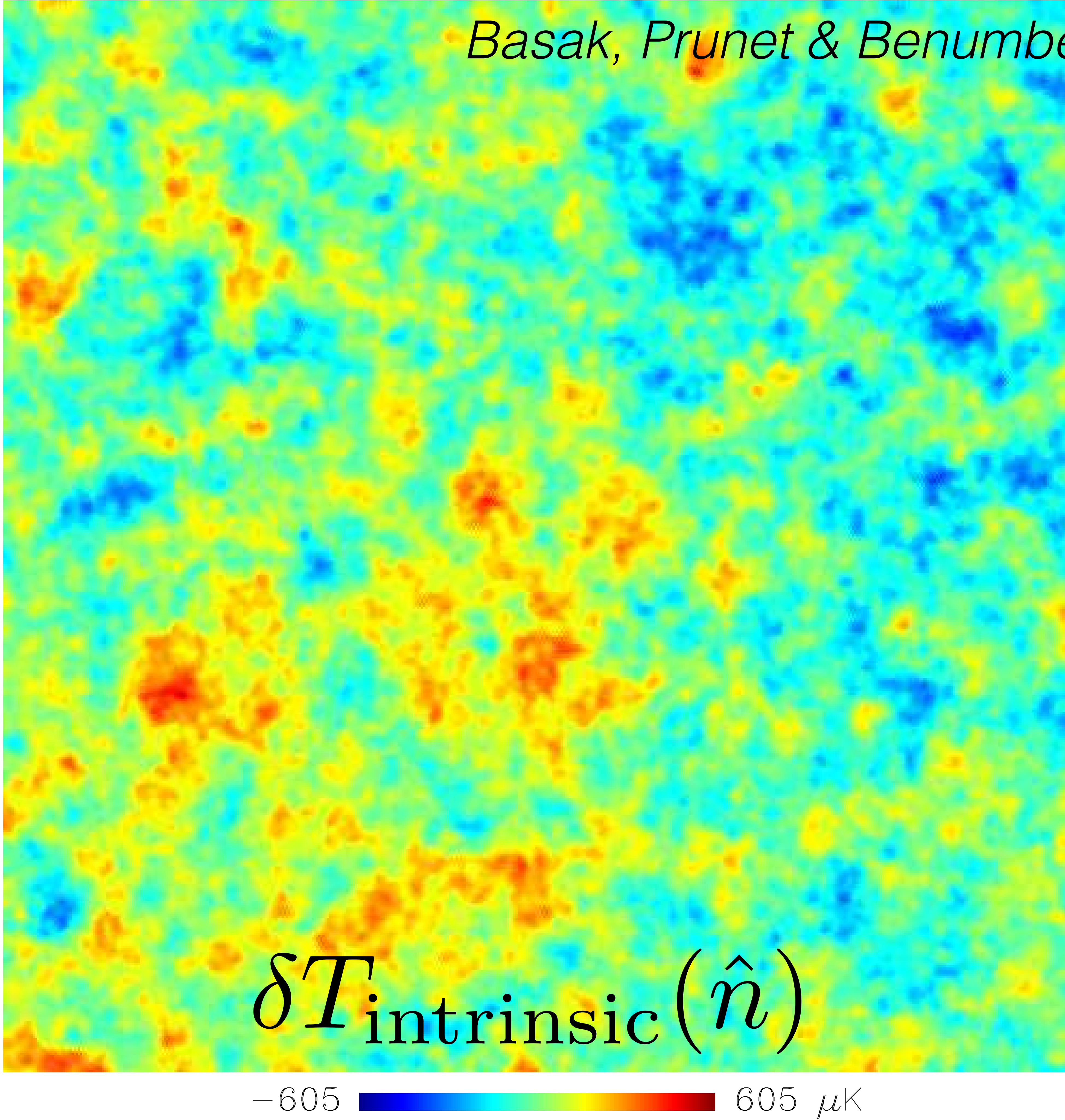
courtesy University of Arizona



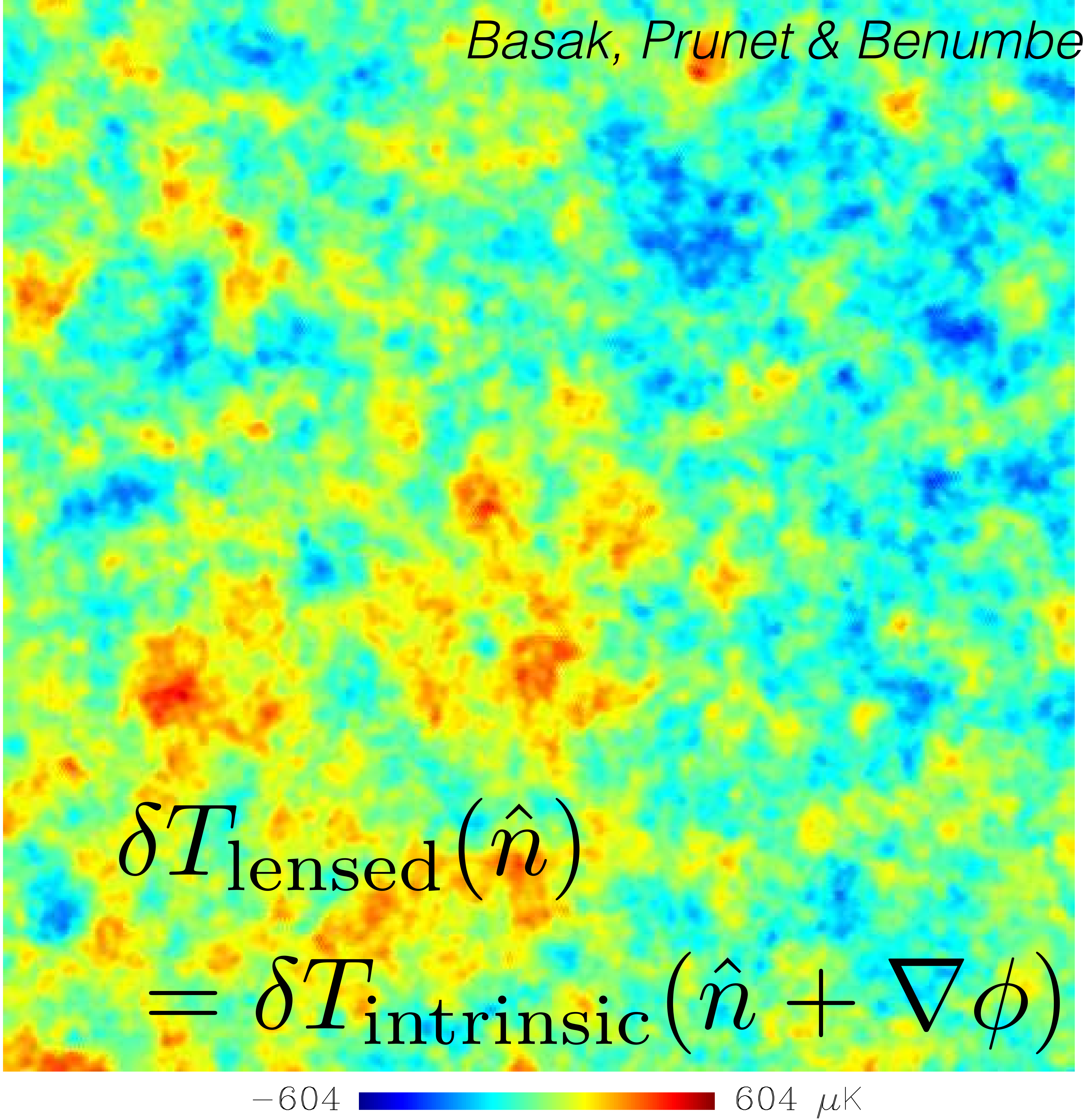
Brightness
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
4K Planck Spectrum
2.725K Planck Spectrum
2K Planck Spectrum
Rocket (COBRA)
Satellite (COBE/FIRAS)
Rotational Excitation of CN
Ground-based
Balloon-borne
Satellite (COBE/DMR)
Spectrum of CMB
= Planck Spectrum
3m
30cm
3mm
0.3mm
Wavelength





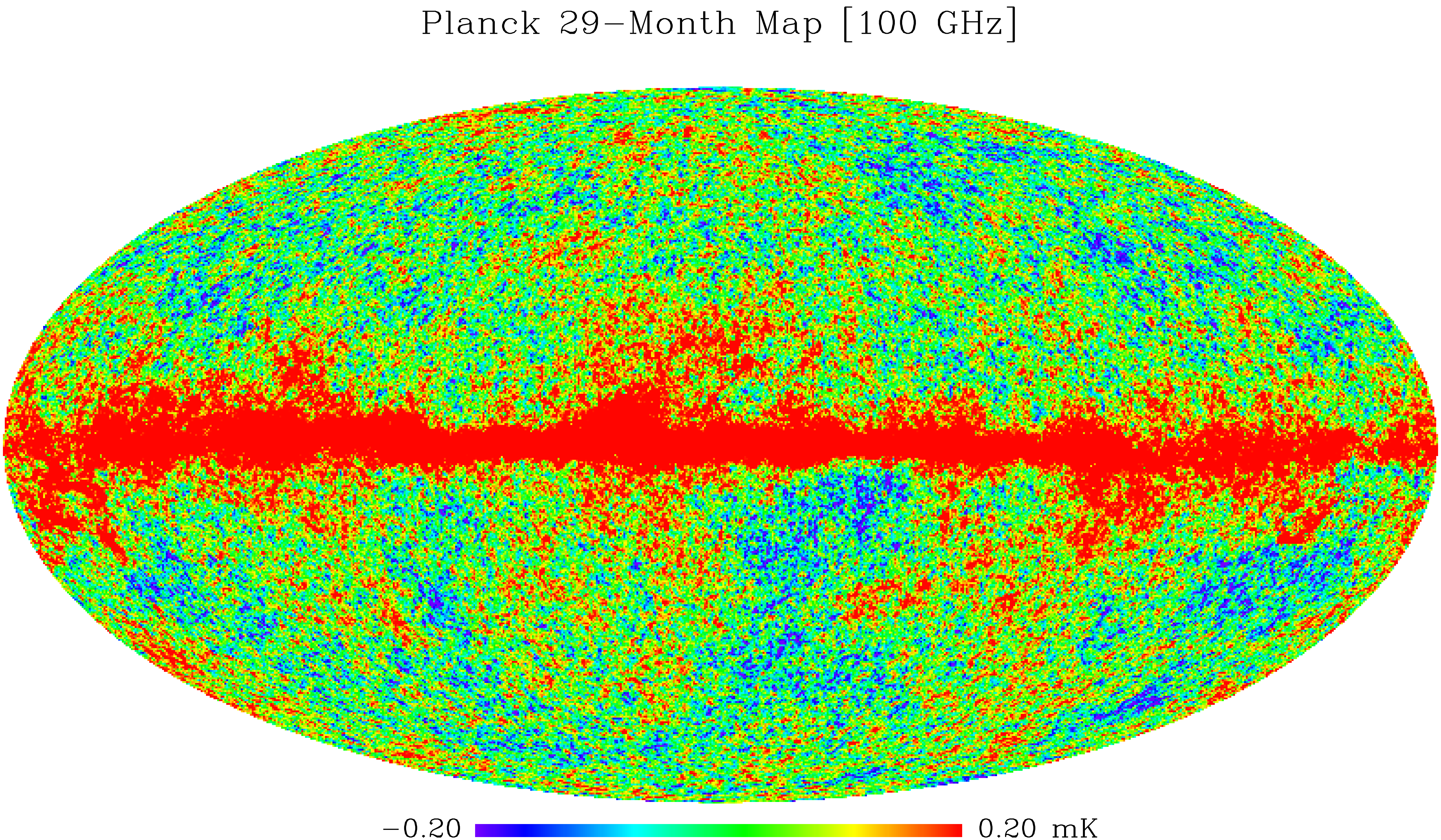

Basak, Prunet & Benumbed (2008)
$\delta T_{\text{intrinsic}}(\hat{n})$
−605
605 μK

*Basak, Prunet & Benumbed (2008)*



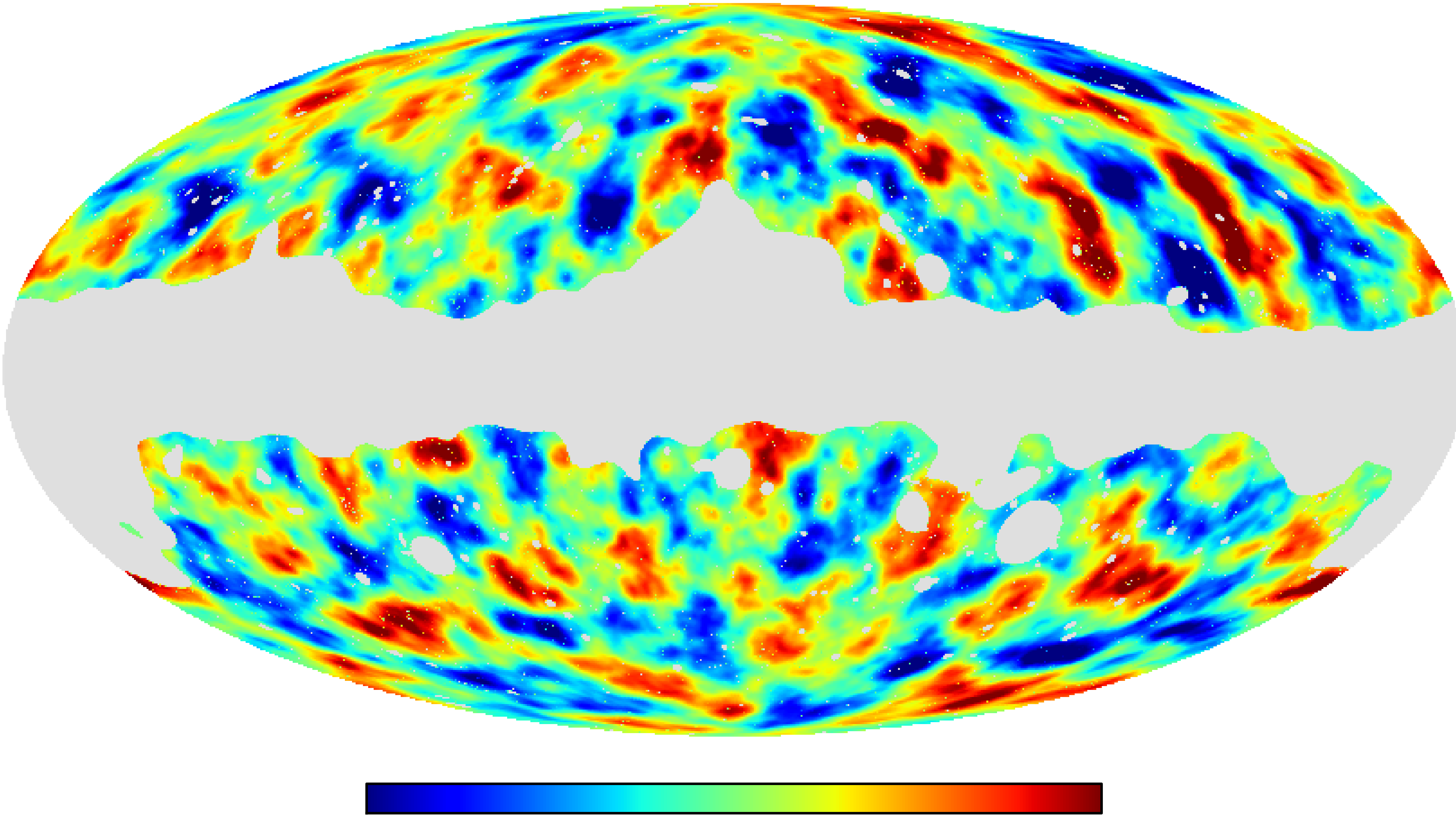

$$\delta T_{\mathrm{lensed}}(\hat{n}) = \delta T_{\mathrm{intrinsic}}(\hat{n} + \nabla\phi)$$

*Planck Collaboration*

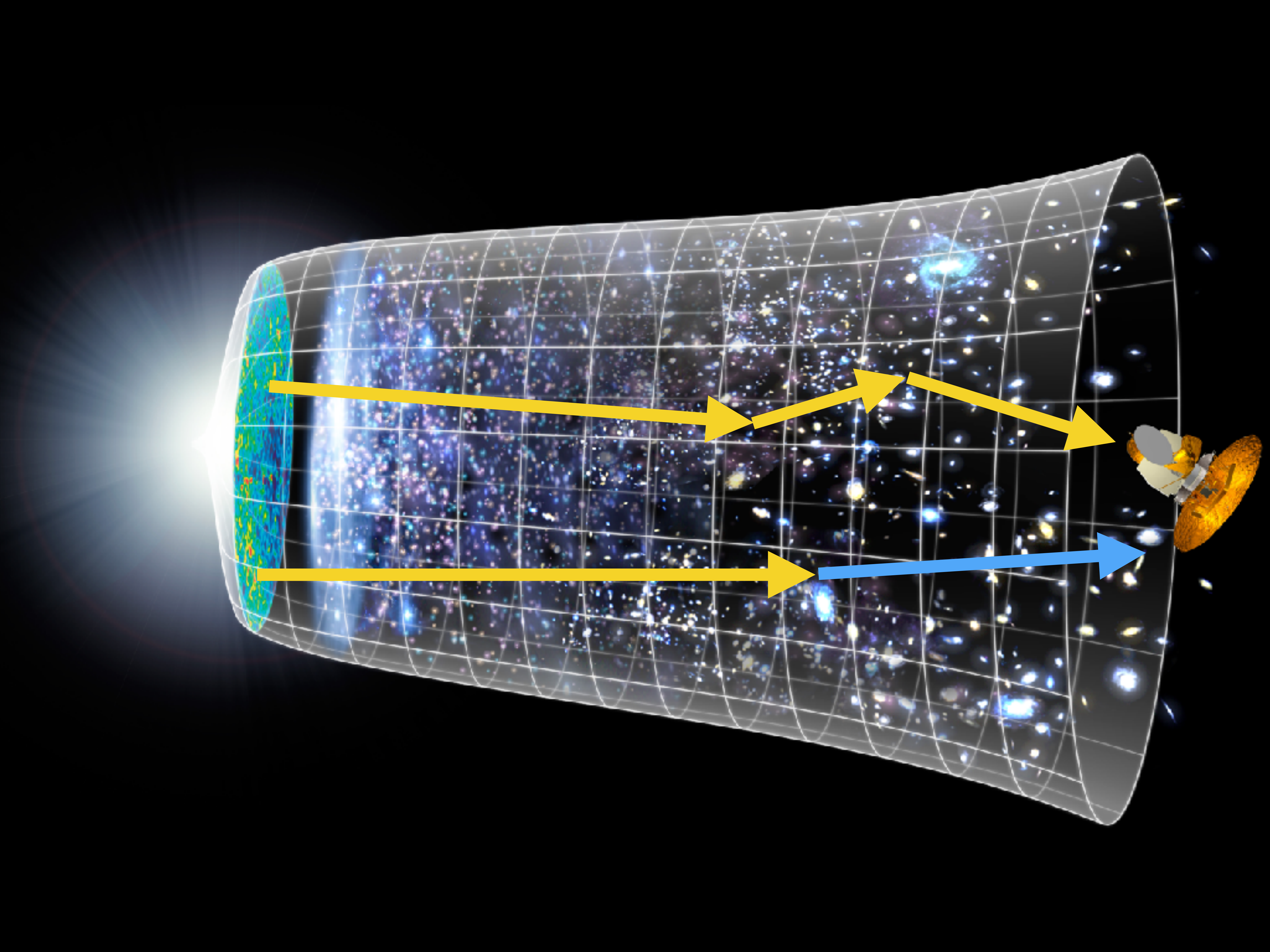


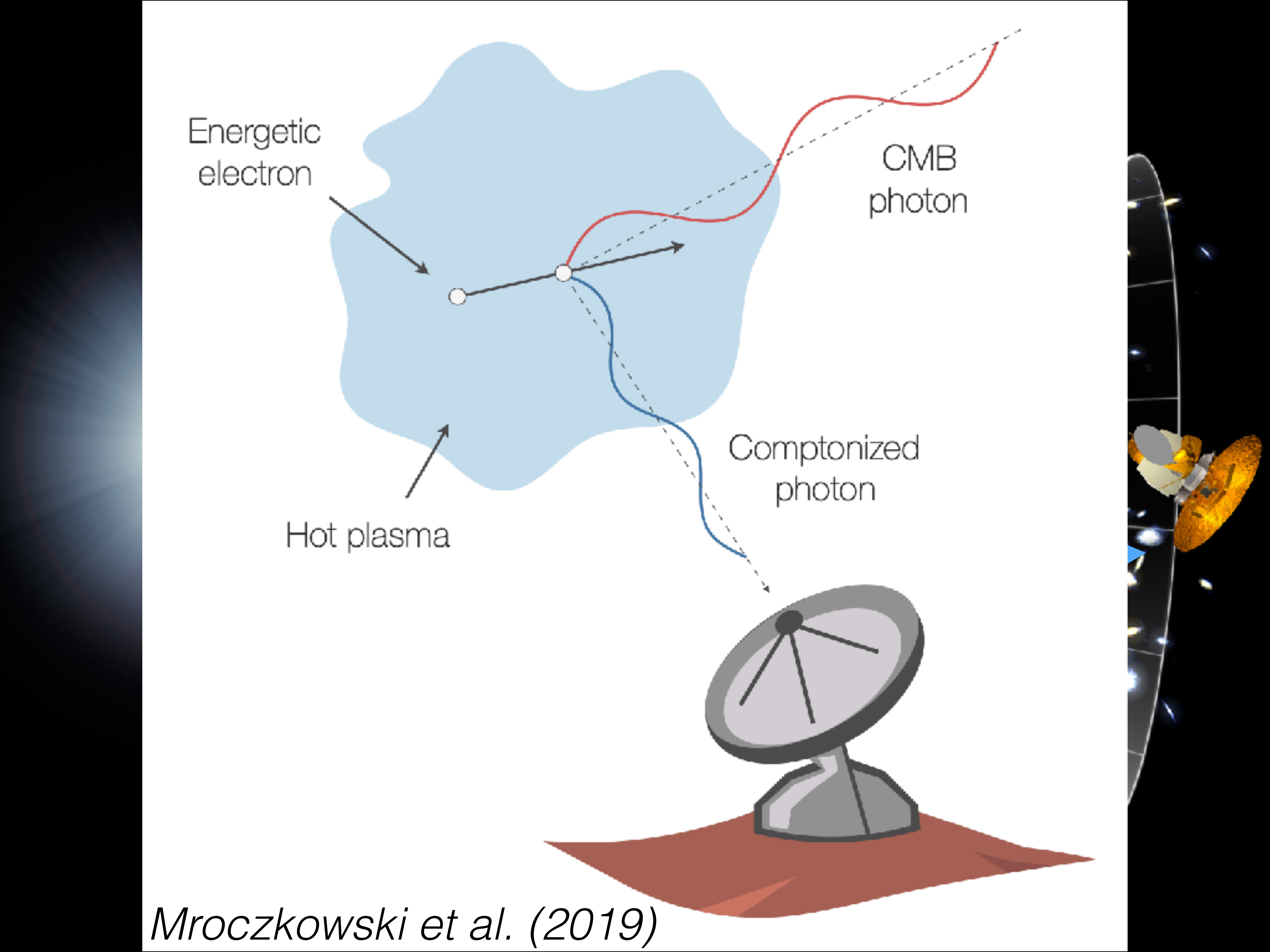

**From full-sky temperature maps to…**

*Planck Collaboration*

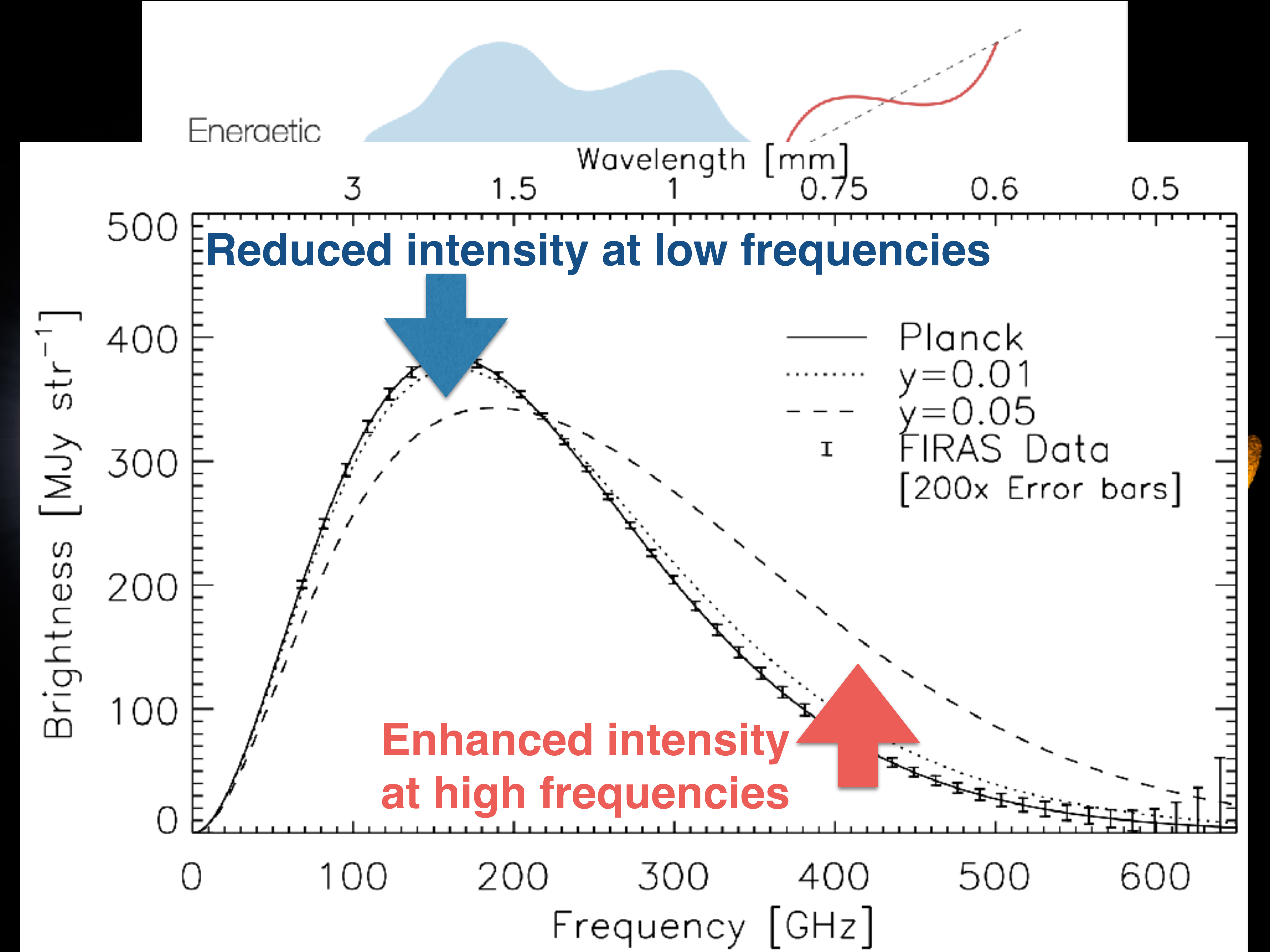


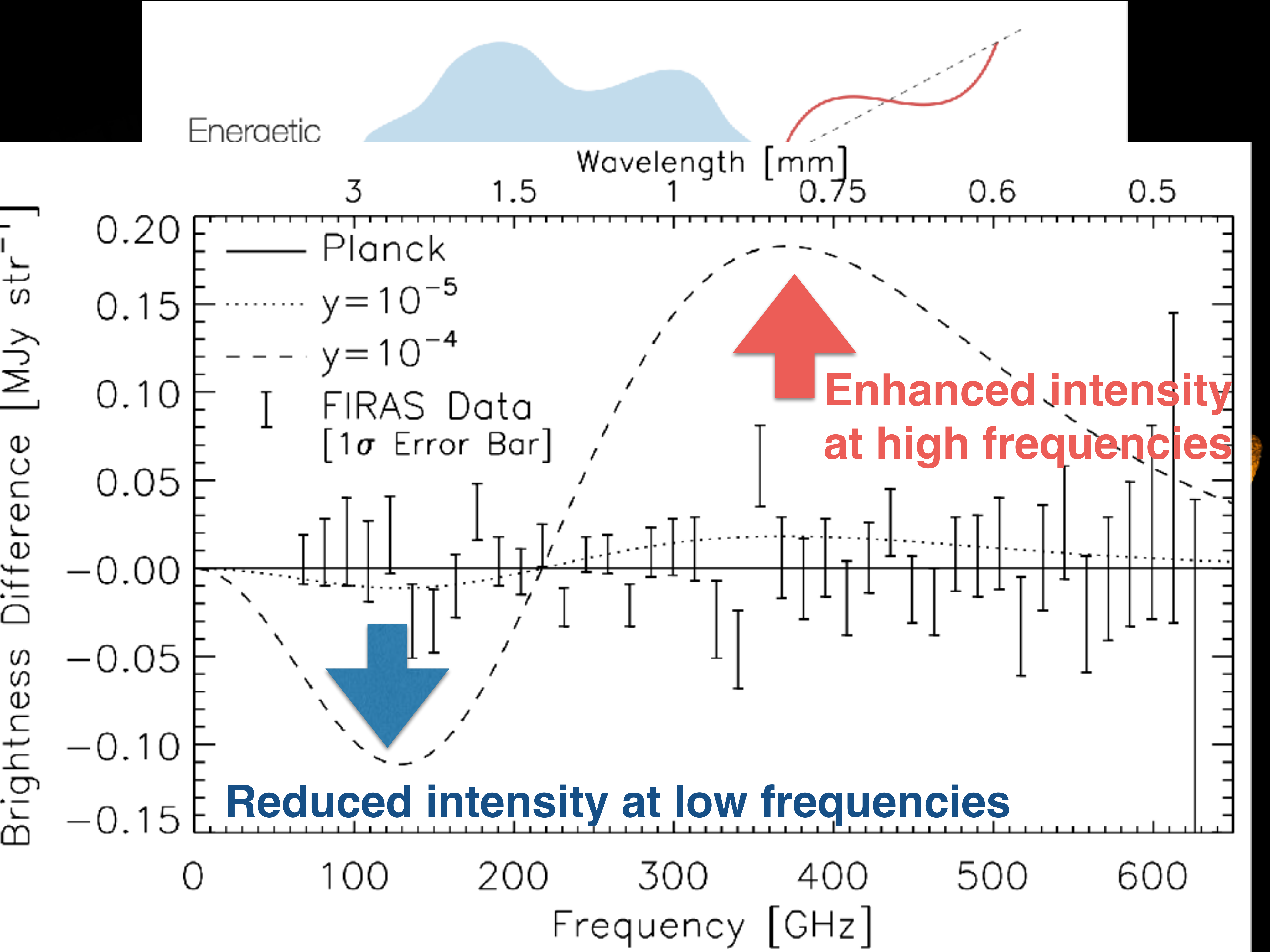

**A full-sky lensing potential map!**



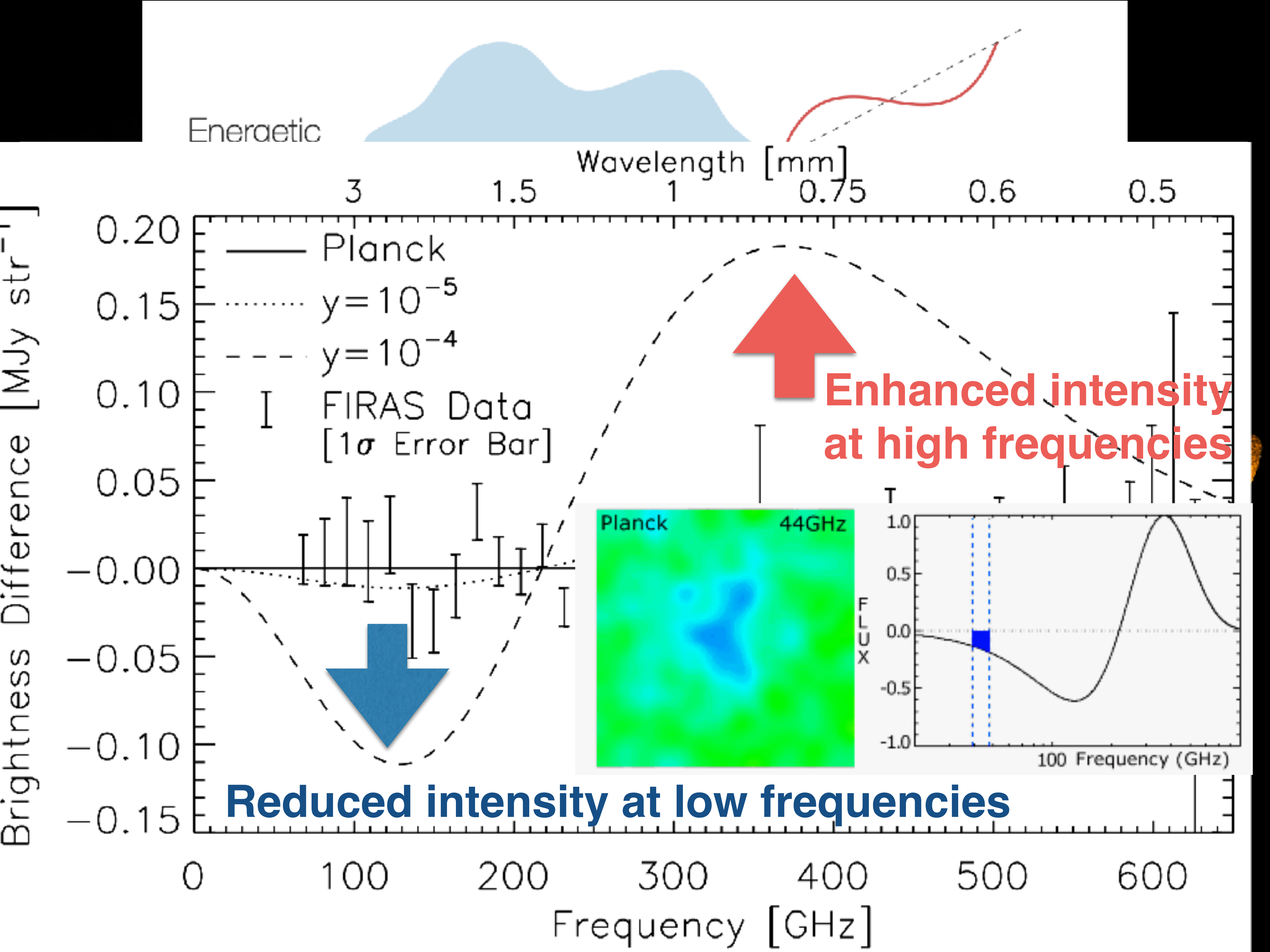



*Mroczkowski et al. (2019)*

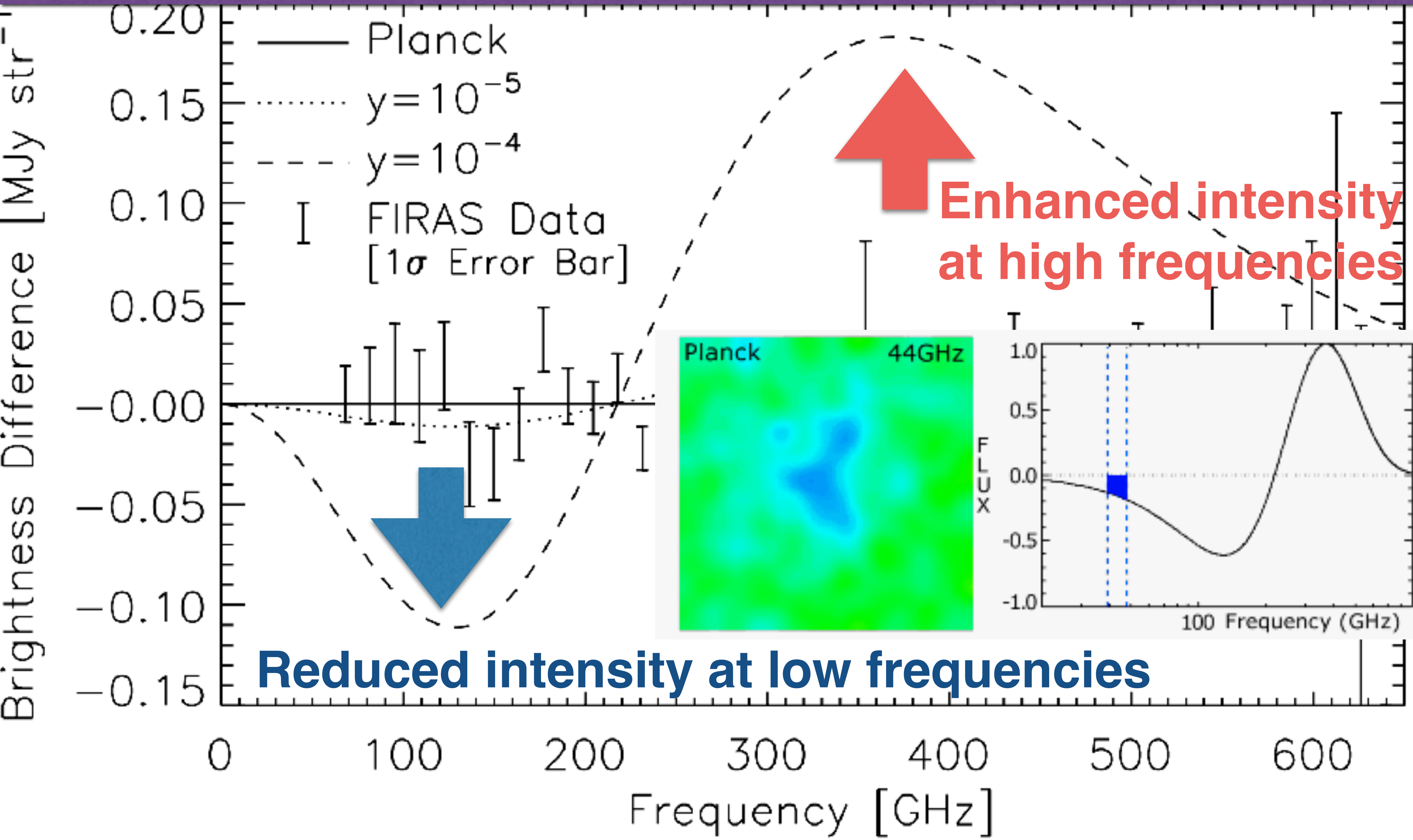

Energetic
Wavelength [mm]
3
1.5
1
0.75
0.6
0.5
Reduced intensity at low frequencies
Planck
y=0.01
y=0.05
FIRAS Data
[200x Error bars]
Enhanced intensity
at high frequencies
Brightness [MJy str$^{-1}$]
500
400
300
200
100
0
0
100
200
300
400
500
600
Frequency [GHz]



Energetic
Wavelength [mm]
3
1.5
1
0.75
0.6
0.5
Planck
y=10^-5
y=10^-4
FIRAS Data
[1σ Error Bar]
Enhanced intensity at high frequencies
Reduced intensity at low frequencies
Brightness Difference [MJy str^-1]
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
0
100
200
300
400
500
600
Frequency [GHz]


Wavelength [mm]
3
1.5
1
0.75
0.6
0.5
Planck
y=10^-5
y=10^-4
FIRAS Data
[1σ Error Bar]
Enhanced intensity
at high frequencies
Planck
44GHz
FLUX
1.0
0.5
0.0
-0.5
-1.0
100 Frequency (GHz)
Reduced intensity at low frequencies
Brightness Difference [MJy str^-1]
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
0
100
200
300
400
500
600
Frequency [GHz]

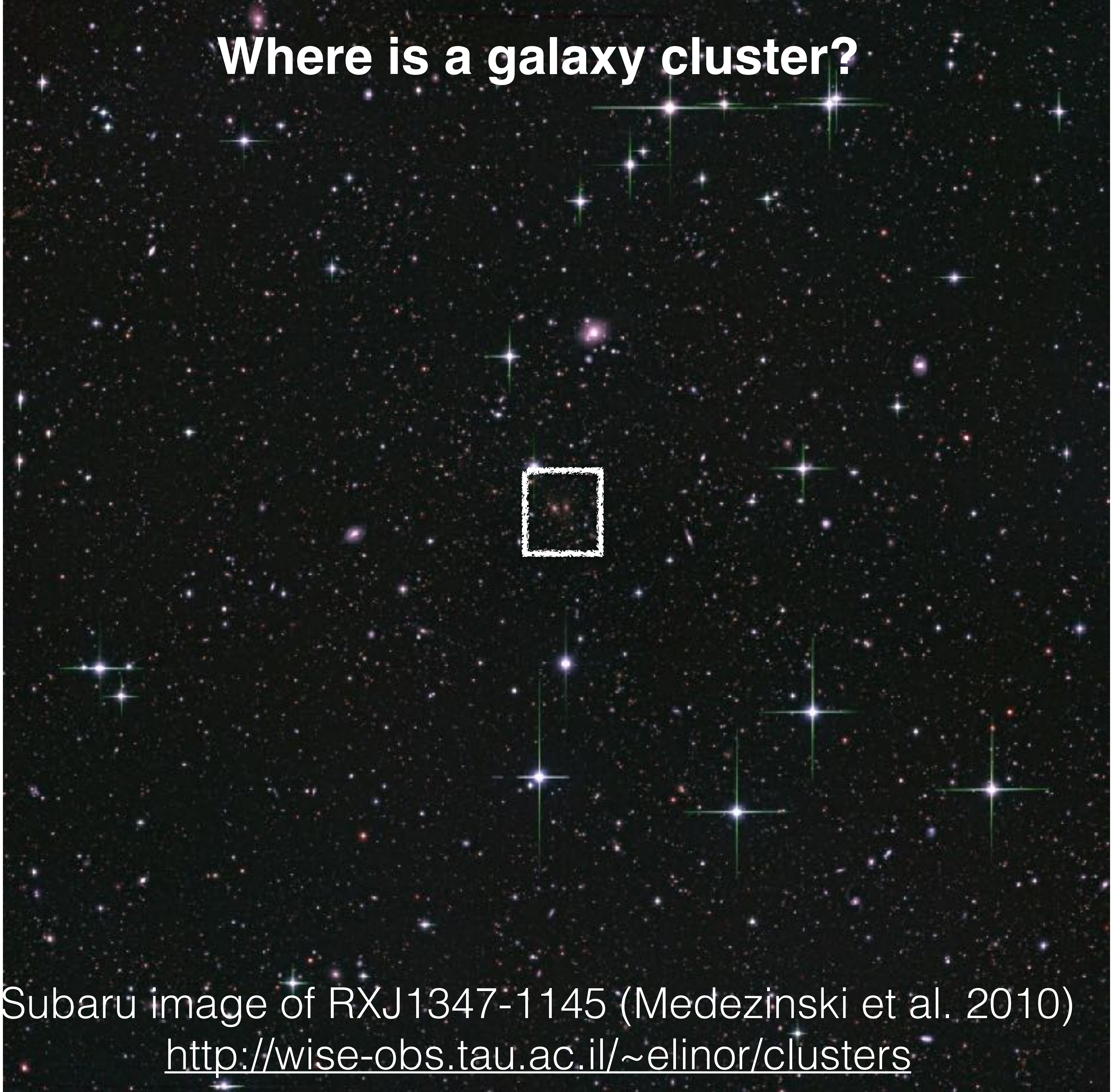
# Sunyaev-Zeldovich (SZ) Effect (Sunyaev & Zeldovich 1972)



# Where is a galaxy cluster?

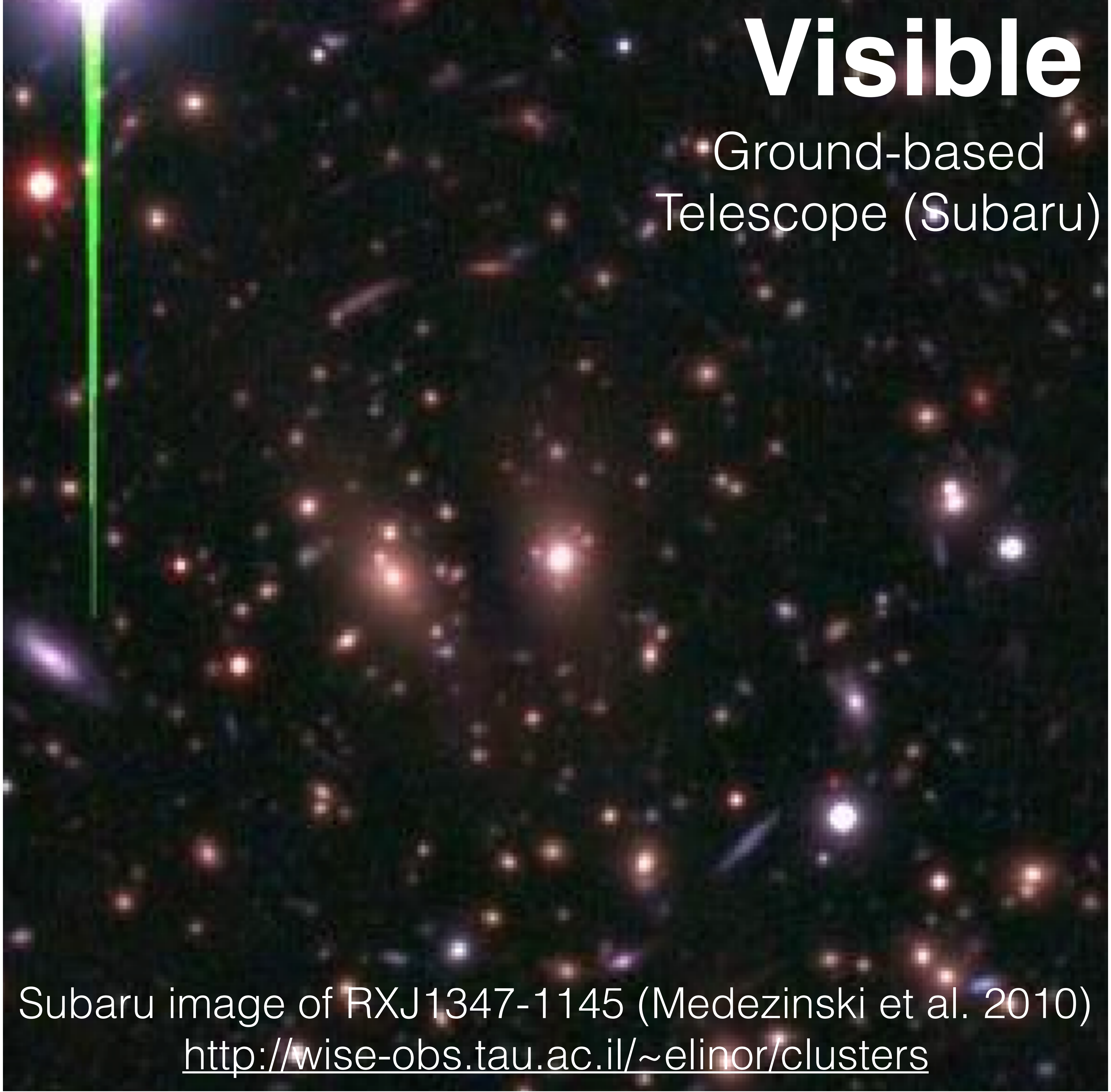
Subaru image of RXJ1347-1145 (Medezinski et al. 2010)
http://wise-obs.tau.ac.il/~elinor/clusters

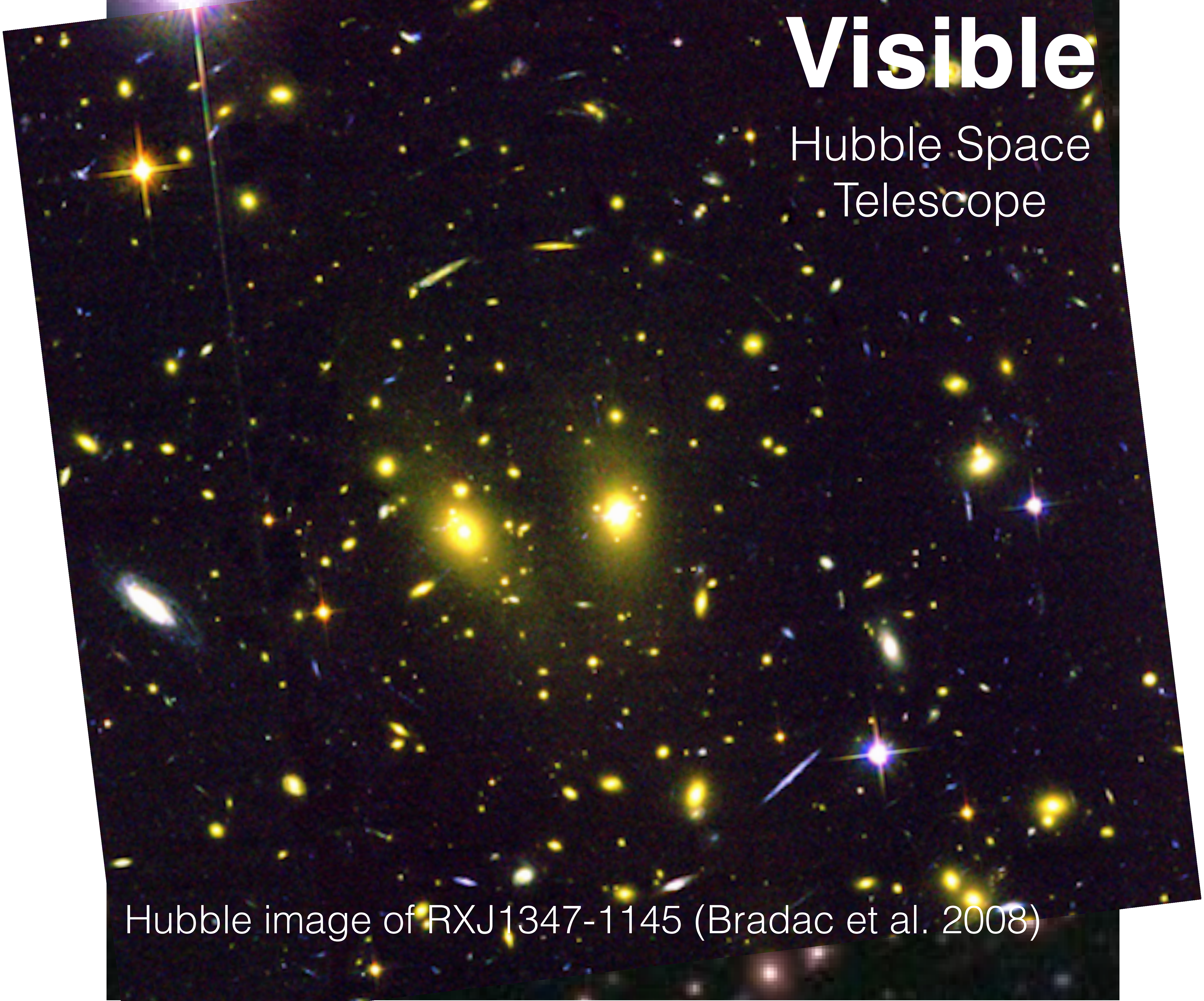
# Where is a galaxy cluster?

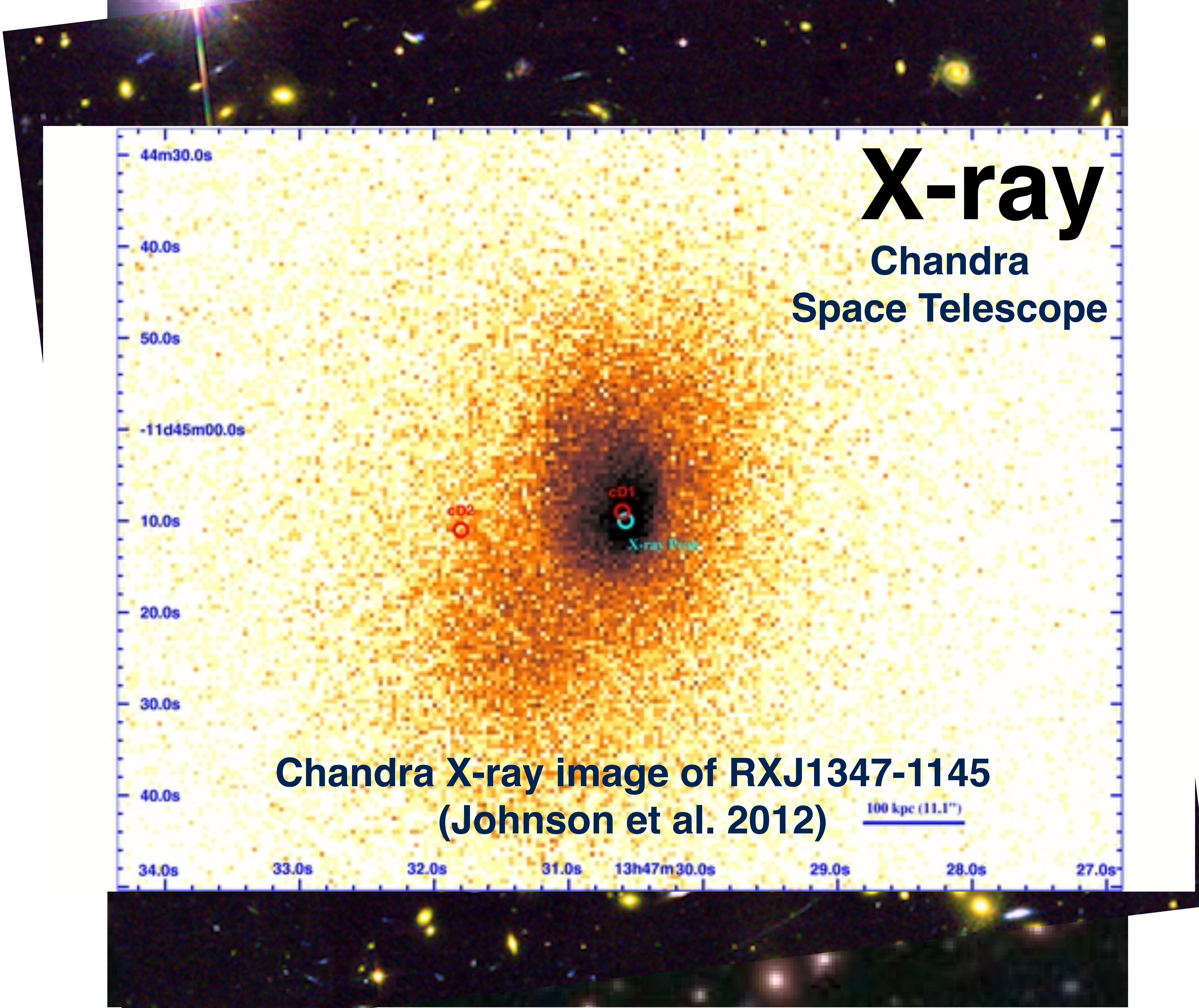


Subaru image of RXJ1347-1145 (Medezinski et al. 2010)

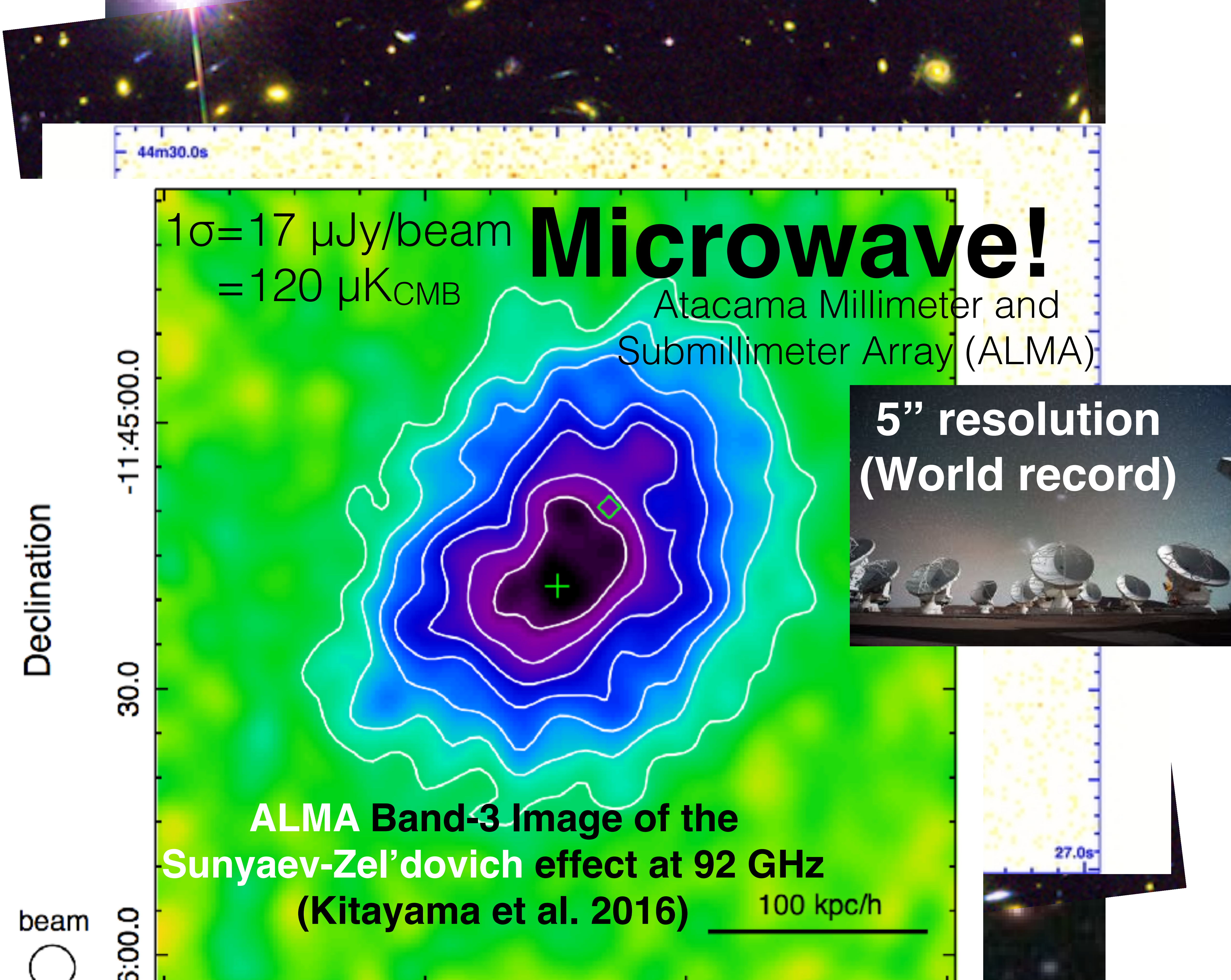
http://wise-obs.tau.ac.il/~elinor/clusters


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


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

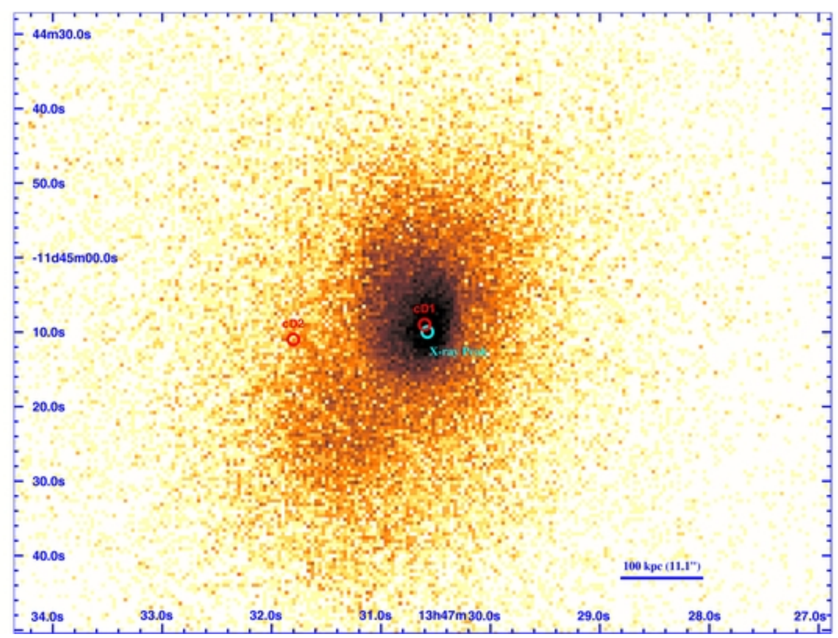


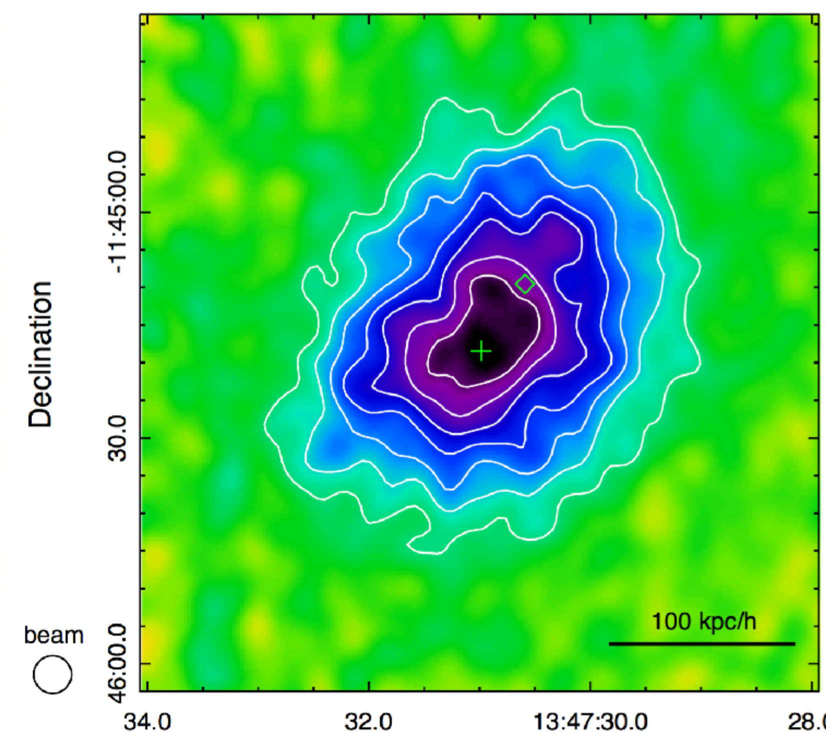

Chandra X-ray image of RXJ1347-1145
(Johnson et al. 2012)


Microwave!
Atacama Millimeter and
Submillimeter Array (ALMA)
1σ=17 μJy/beam
=120 μK_CMB
5" resolution
(World record)
ALMA Band-3 Image of the
Sunyaev-Zel'dovich effect at 92 GHz
(Kitayama et al. 2016)
100 kpc/h
Declination
-11:45:00.0
30.0
46:00.0
beam
44m30.0s
27.0s

# 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 ~ $n_e T_e L$

# Multi-wavelength Astrophysics Rocks!

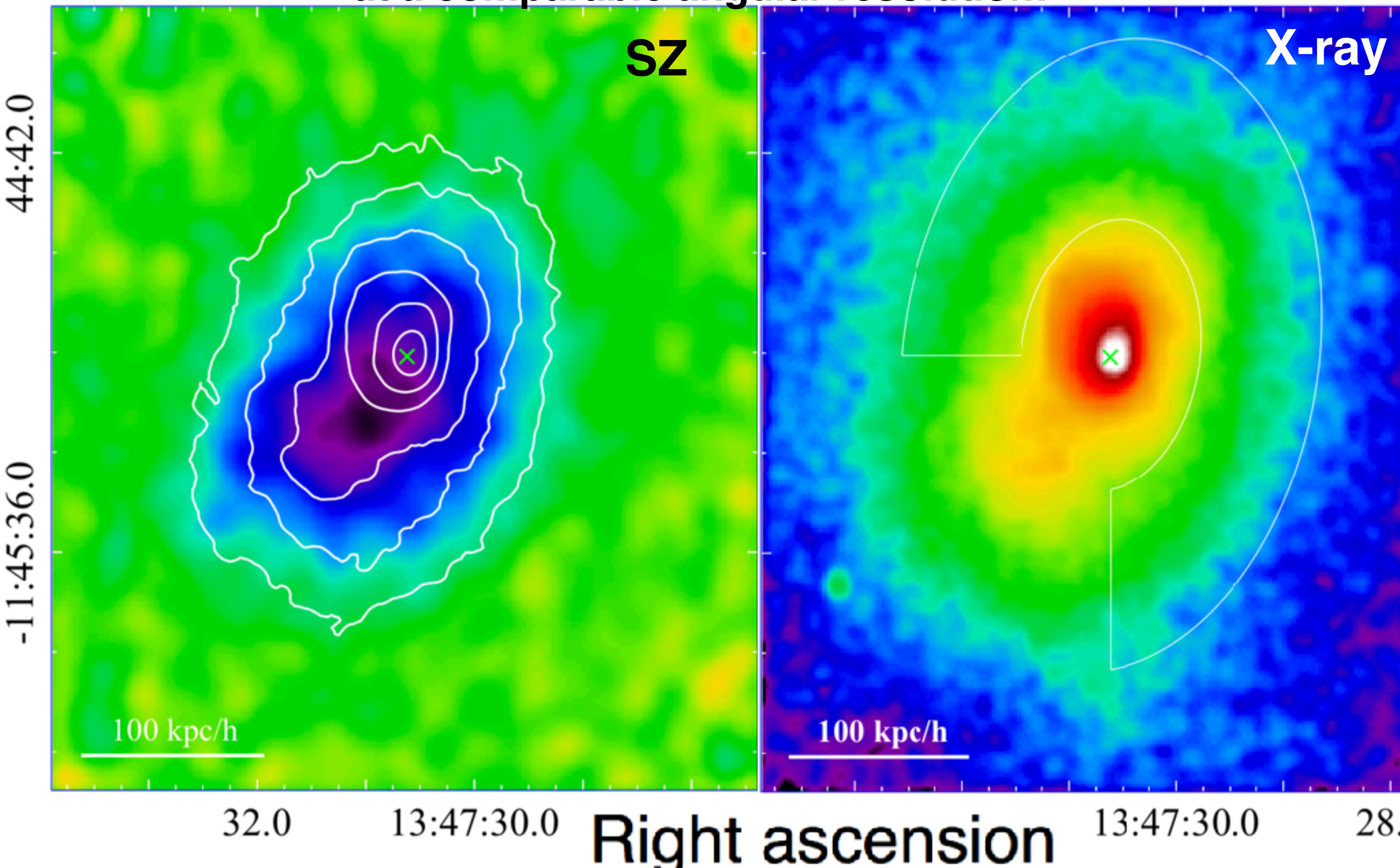
- One electromagnetic wavelength tells only a limited story!
- The X-ray intensity measures the electron **density** (squared) $I_X = \int dl\ n_e^2 \Lambda(T_X)$
- The SZ intensity measures the electron **pressure**

$$I_{SZ} = g_\nu \frac{\sigma_T k_B}{m_e c^2} \int dl\ n_e T_e$$

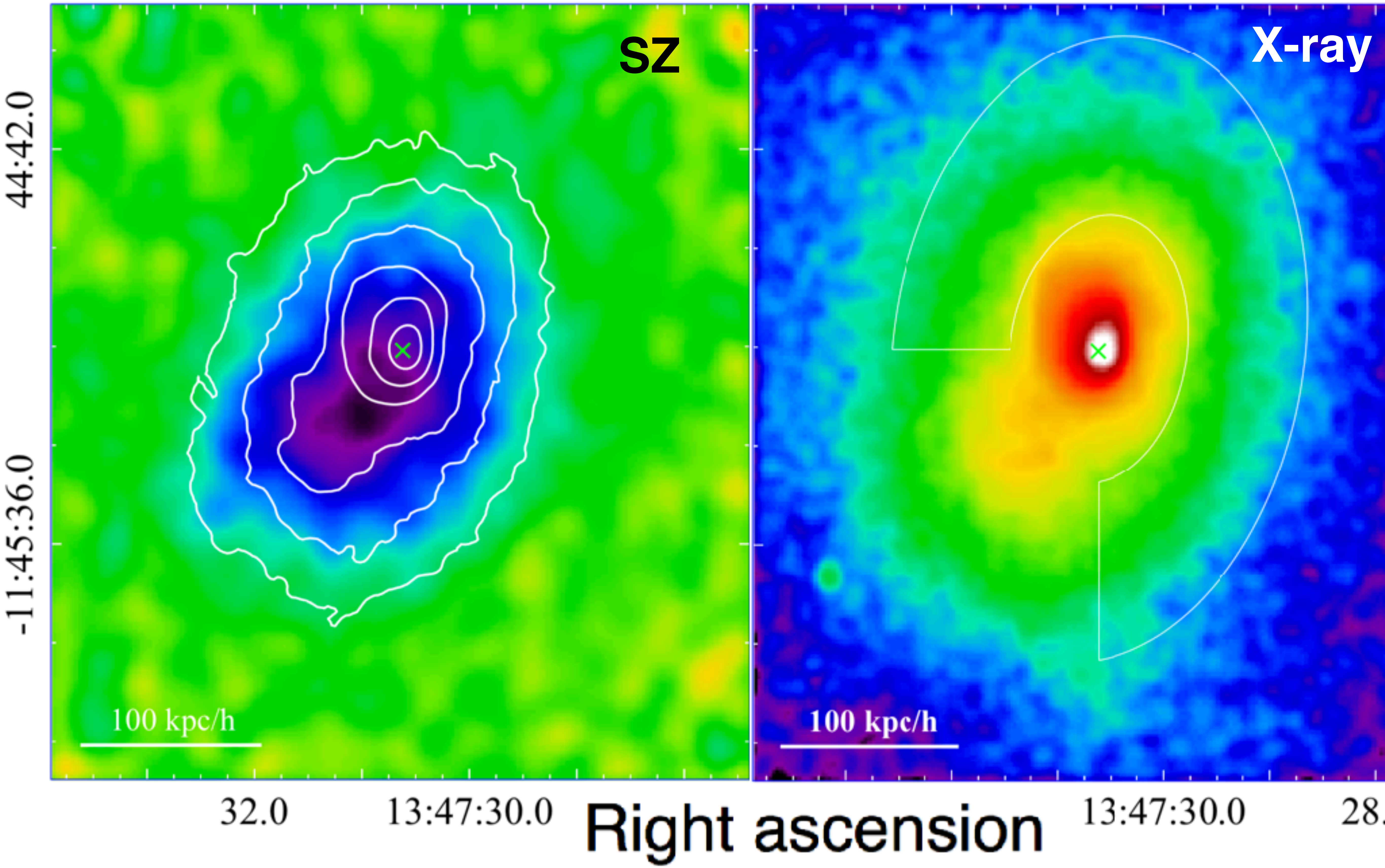
- **How do they the compare?**

# They are similar, but not quite the same

**Interesting! This is the first time to compare SZ and X-ray images at a comparable angular resolution!**

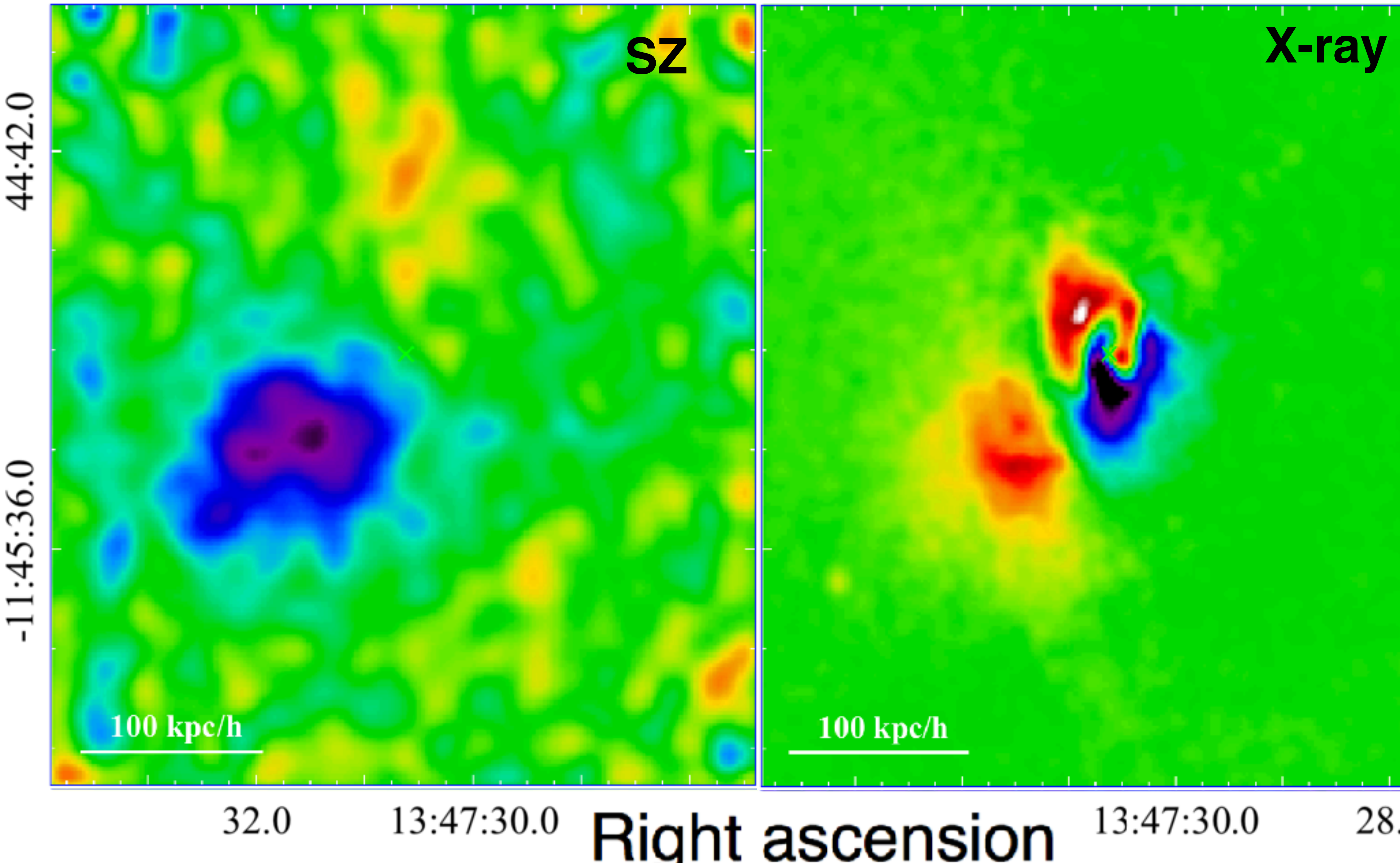


# Let's subtract a smooth component



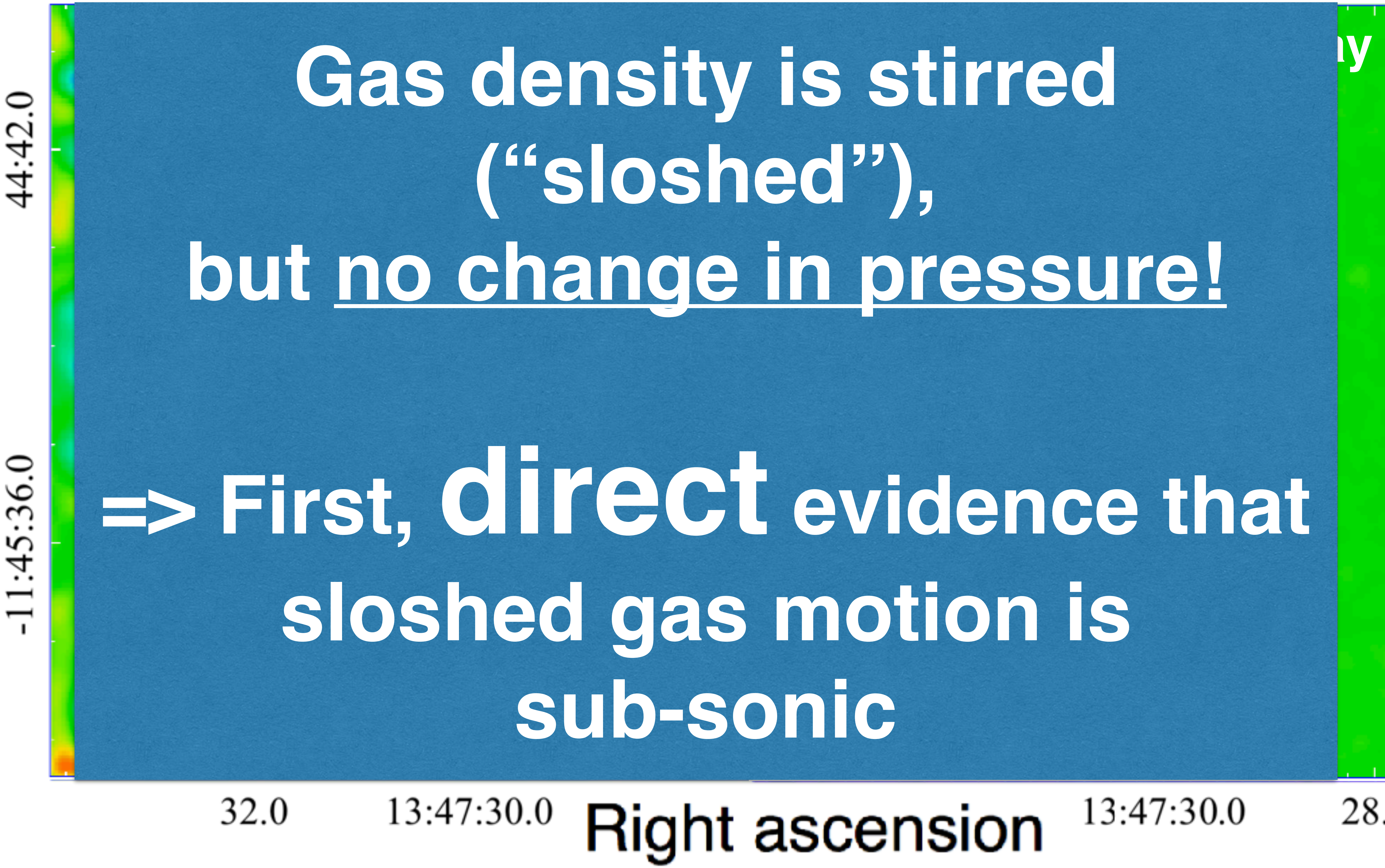
Ueda et al. (2018)

# Let's subtract a smooth component



*Ueda et al. (2018)*

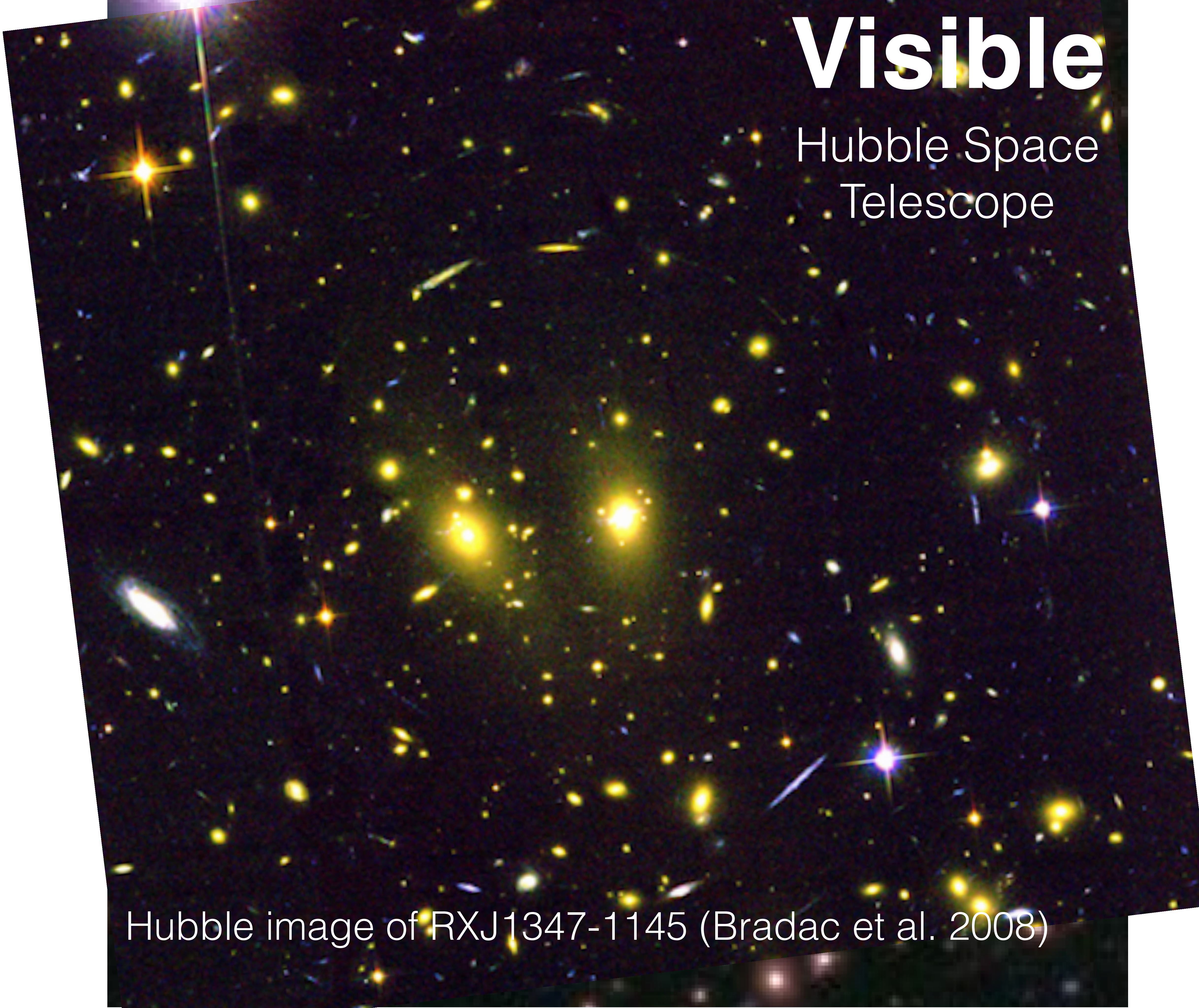
# Let's subtract a smooth component




**Gas density is stirred (“sloshed”), but <u>no change in pressure!</u>**

**=> First, direct evidence that sloshed gas motion is sub-sonic**

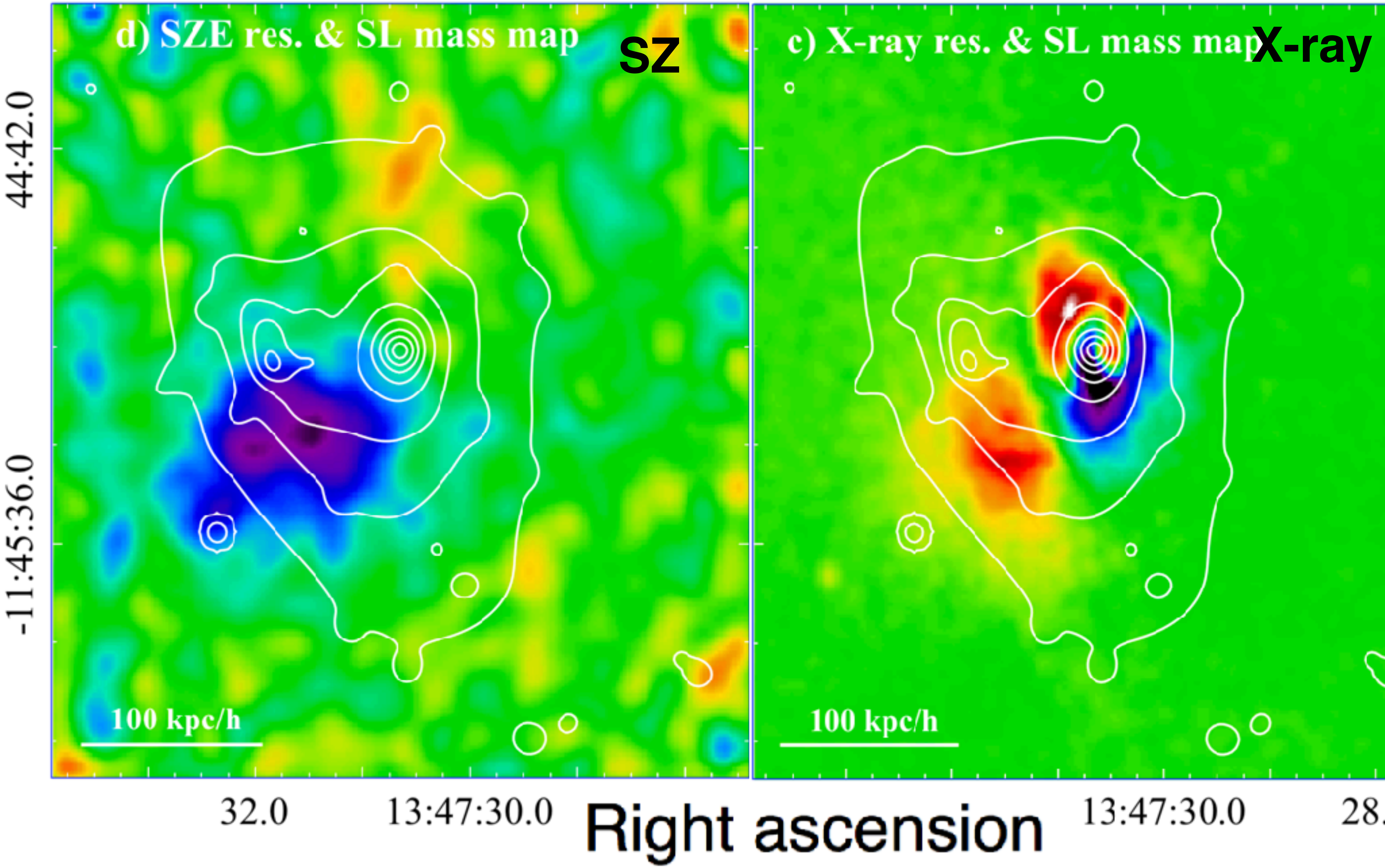
www.spacetelescope.org




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

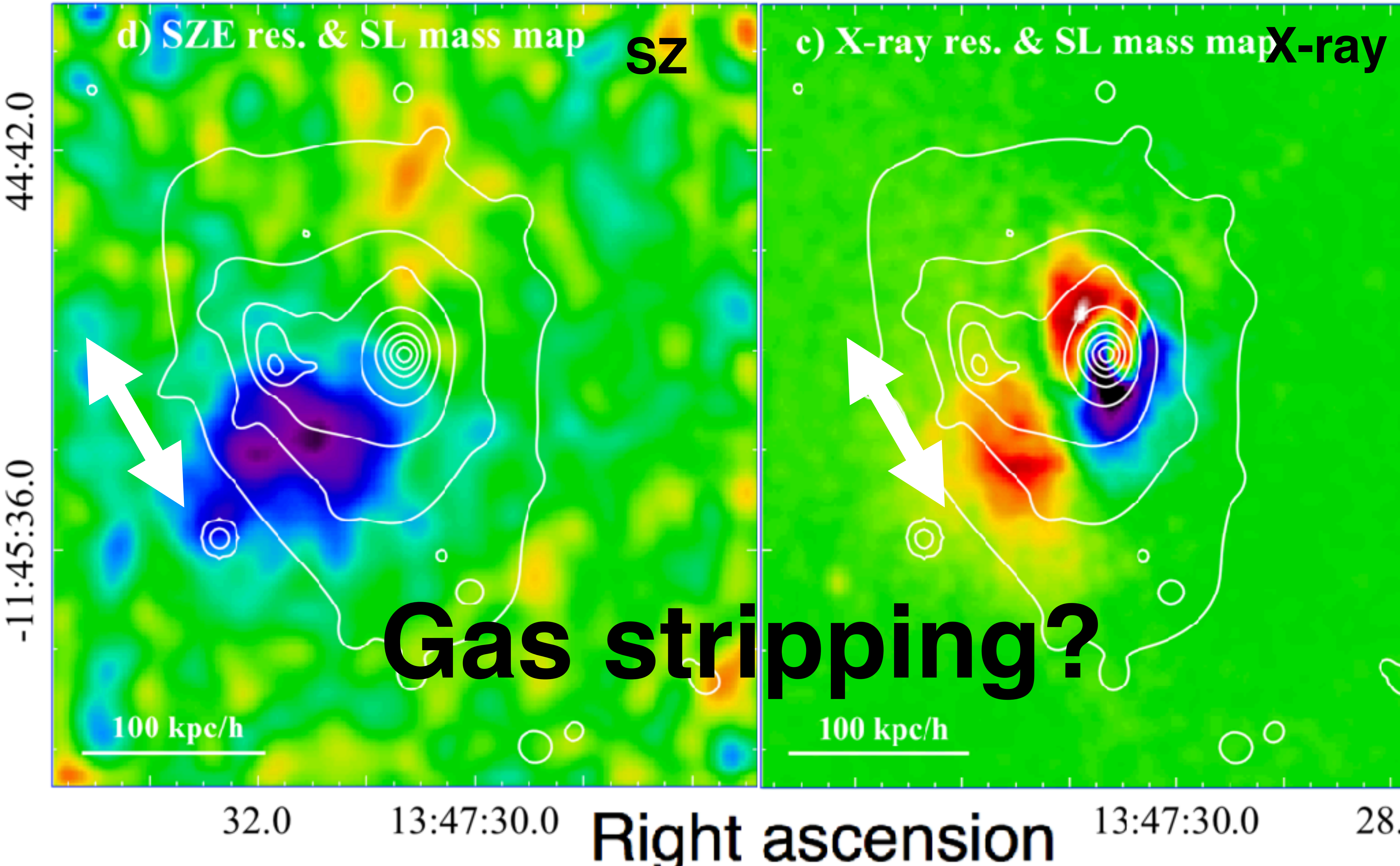
*Ueda et al. (2018)*

# Contours: Mass map from lensing!



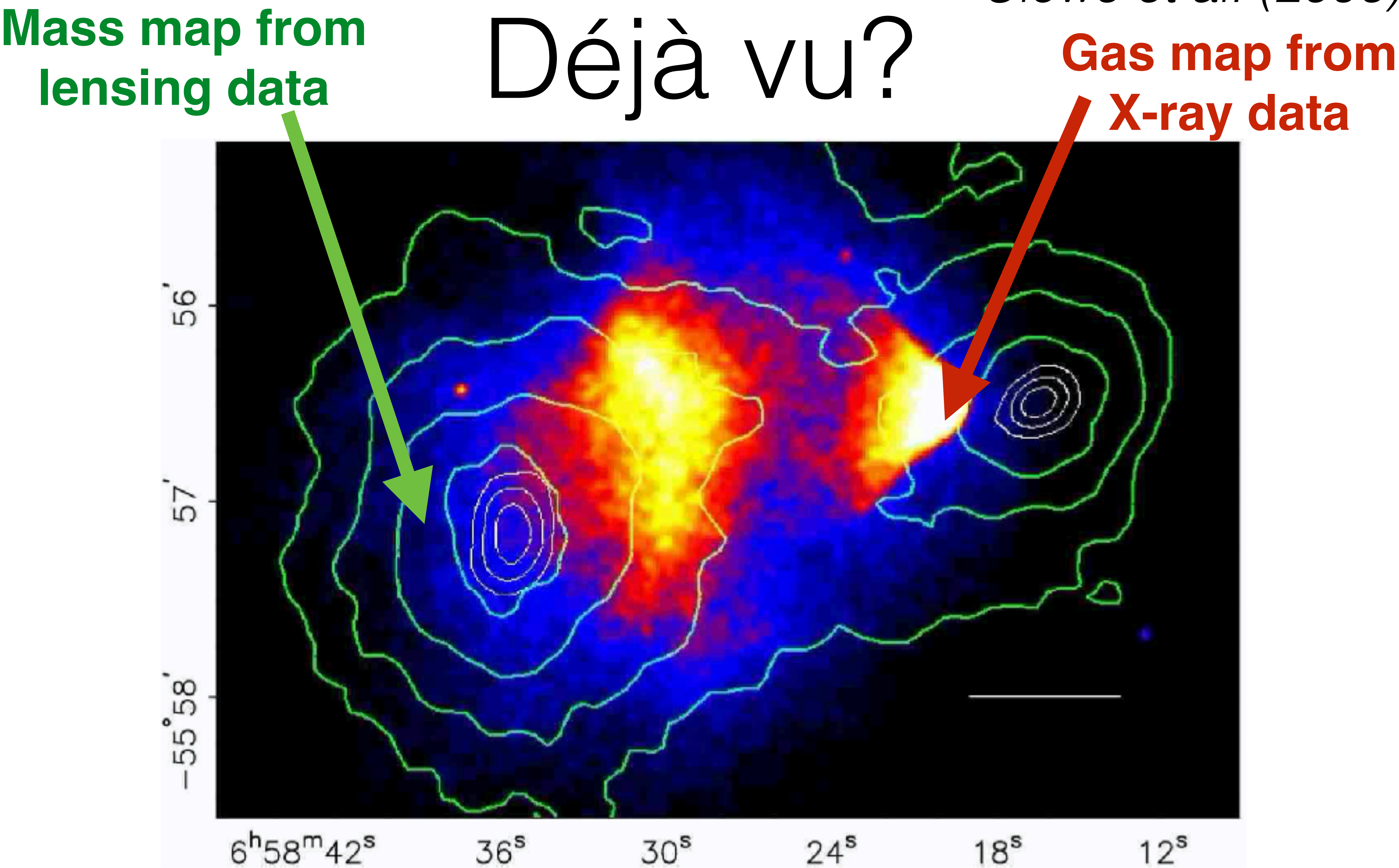
*Ueda et al. (2018)*

# Contours: Mass map from lensing!



*Clowe et al. (2006)*

# Déjà vu?

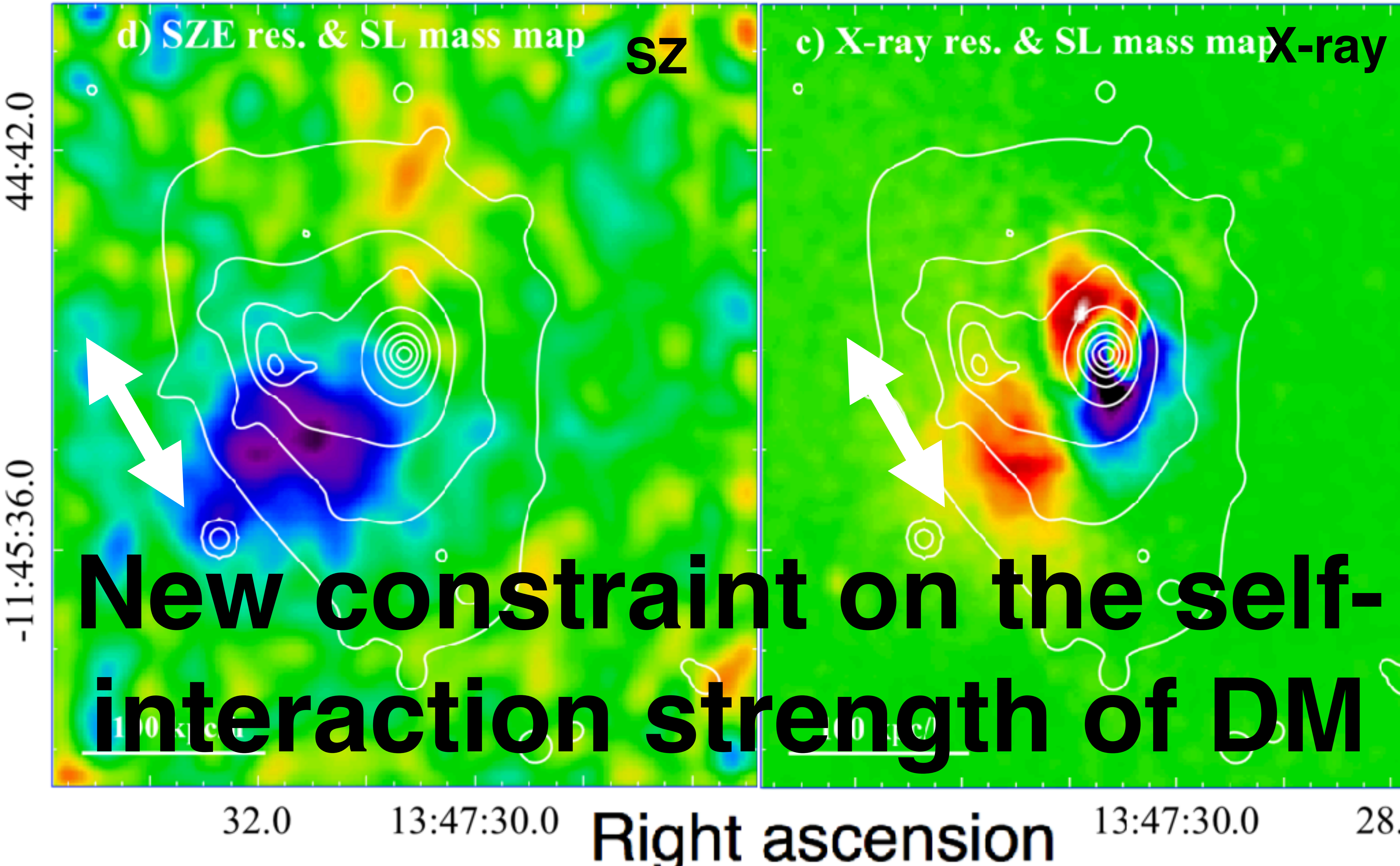



- **Dark matter is collisionless!**

$$\sigma_{\rm DM}/m < 5\ h^{-1}\ {\rm cm}^2\ {\rm g}^{-1}\ (95\%\ {\rm CL})$$

*Ueda et al. (2018)*

$$\sigma_{\rm DM}/m < 3.7\,h^{-1}\,{\rm cm}^2\,{\rm g}^{-1}\ (95\%\ {\rm CL})$$




**New constraint on the self-interaction strength of DM**

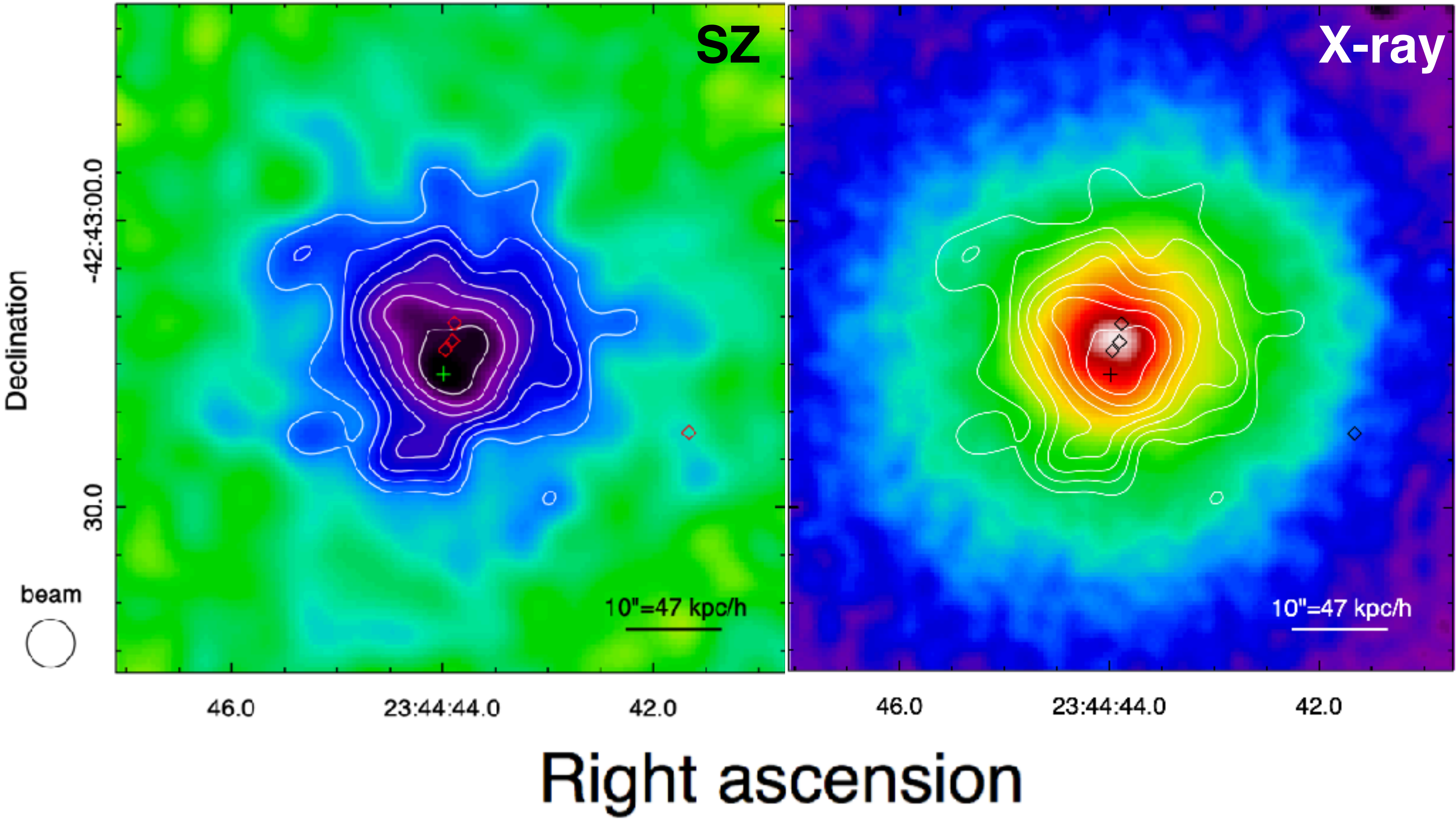
# One more cluster!

*Kitayama et al., submitted on November 22*

## Deeply cooled core of the Phoenix galaxy cluster imaged by ALMA with the Sunyaev-Zel'dovich effect

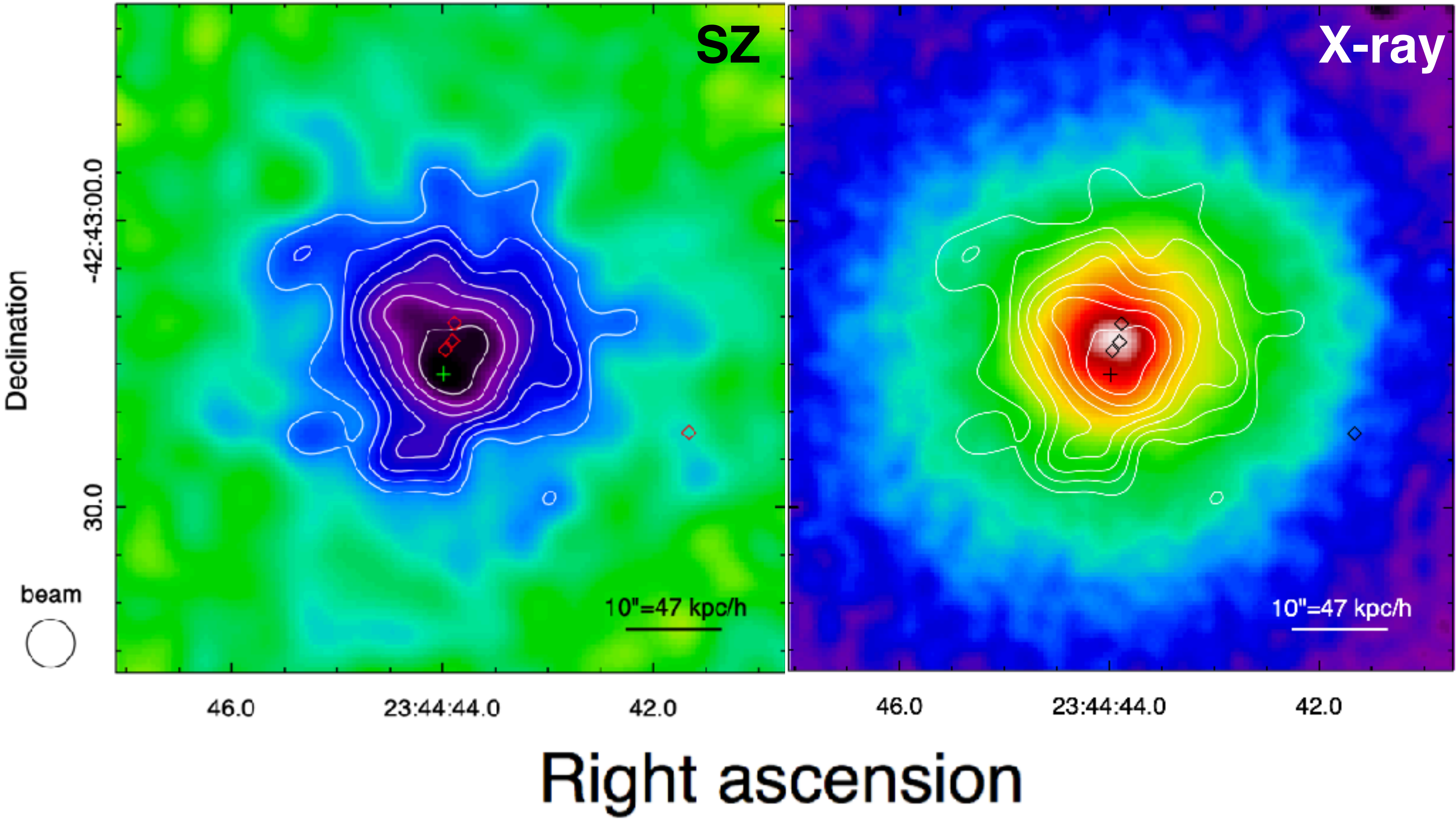
**Tetsu KITAYAMA[1], Shutaro UEDA[2], Takuya AKAHORI[3], Eiichiro KOMATSU[4,5], Ryohei KAWABE[6,7,8], Kotaro KOHNO[9,10], Shigehisa TAKAKUWA[11], Motokazu TAKIZAWA[12], Takahiro TSUTSUMI[13], and Kohji YOSHIKAWA[14]**

*Kitayama et al., submitted*



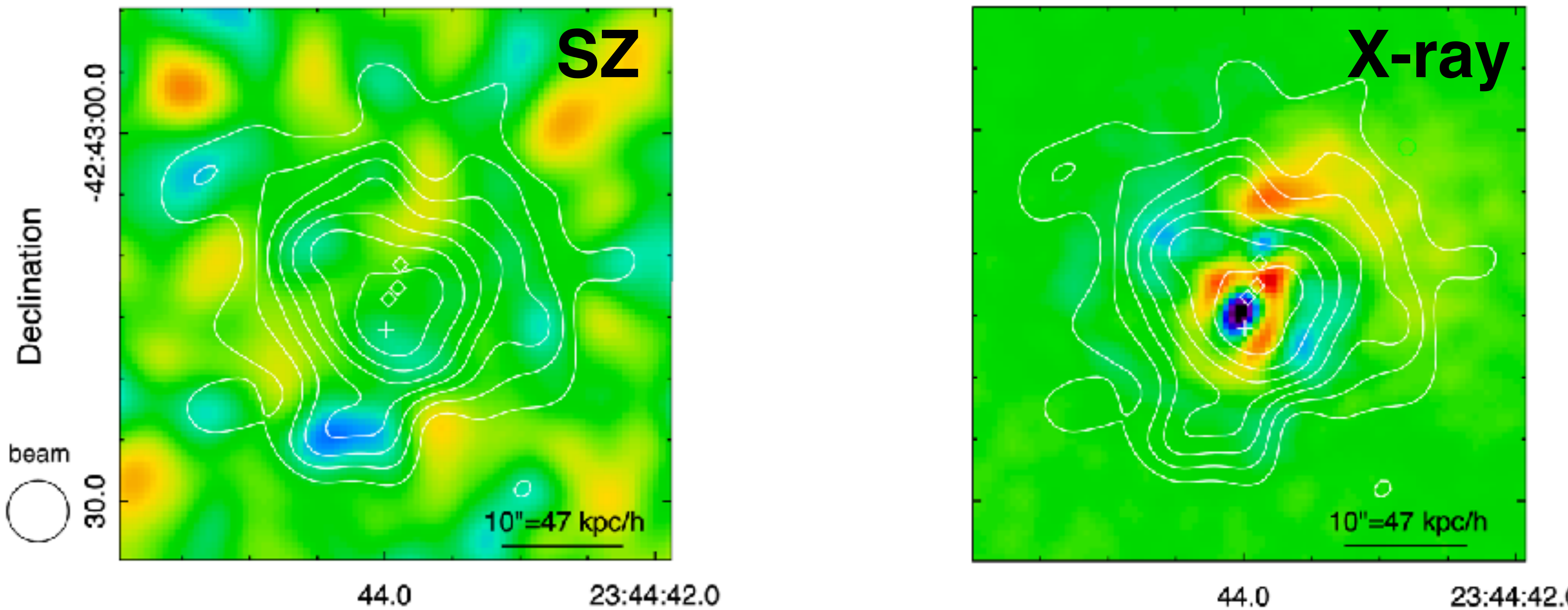

SZ and X-ray images look more alike than the previous cluster

*Kitayama et al., submitted*




# Let’s subtract a smooth component

*Kitayama et al., submitted*



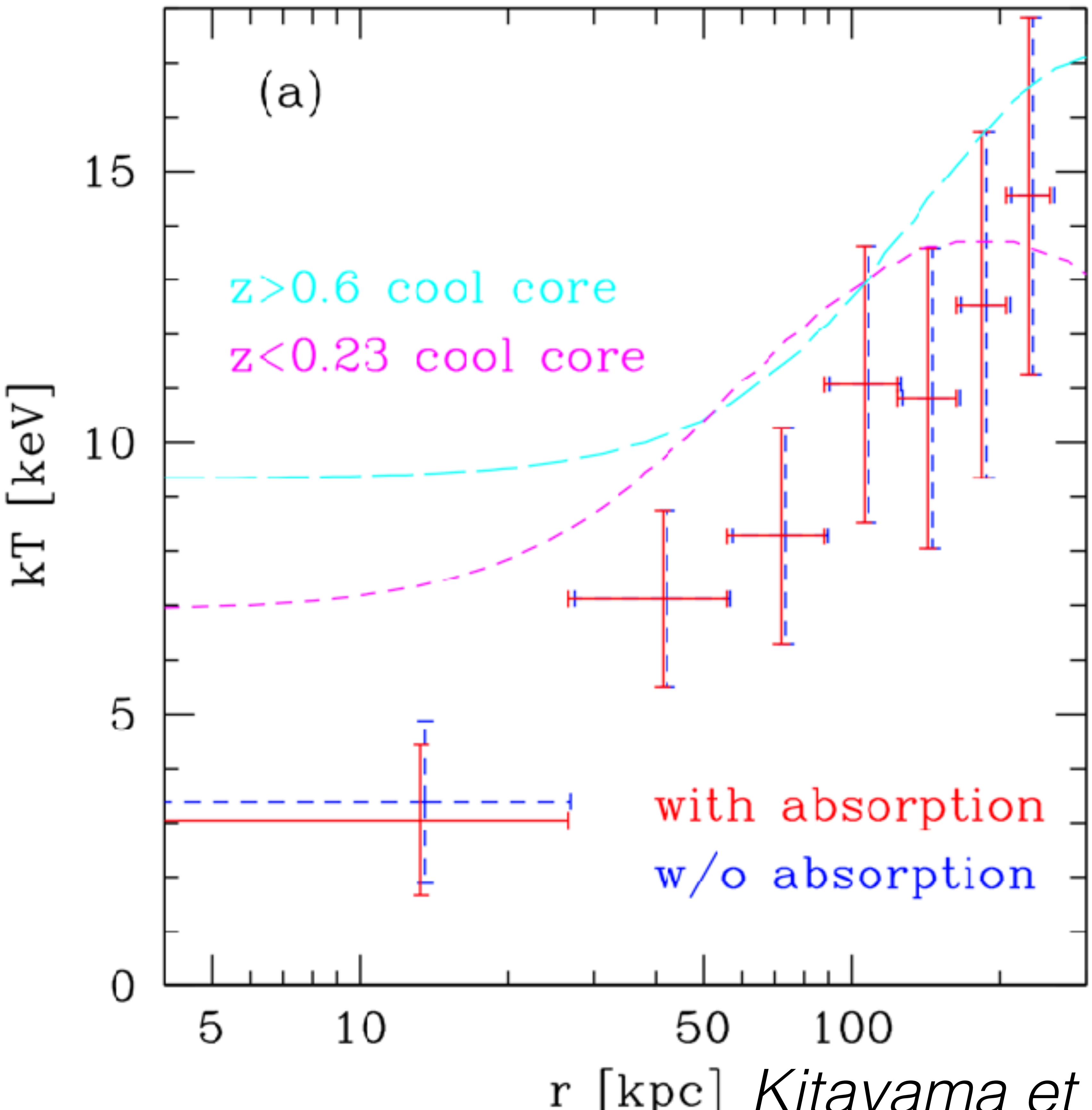

- Structures in the X-ray residual image indicate that gas is pushed by **jets** from the central galaxy
- Once again, **no structure in the SZ residual!** The gas motion is sub-sonic

# SZ + X-ray = Thermometer

- SZ gives the electron pressure, while X-ray gives the electron density

- **Combination = Electron temperature!**

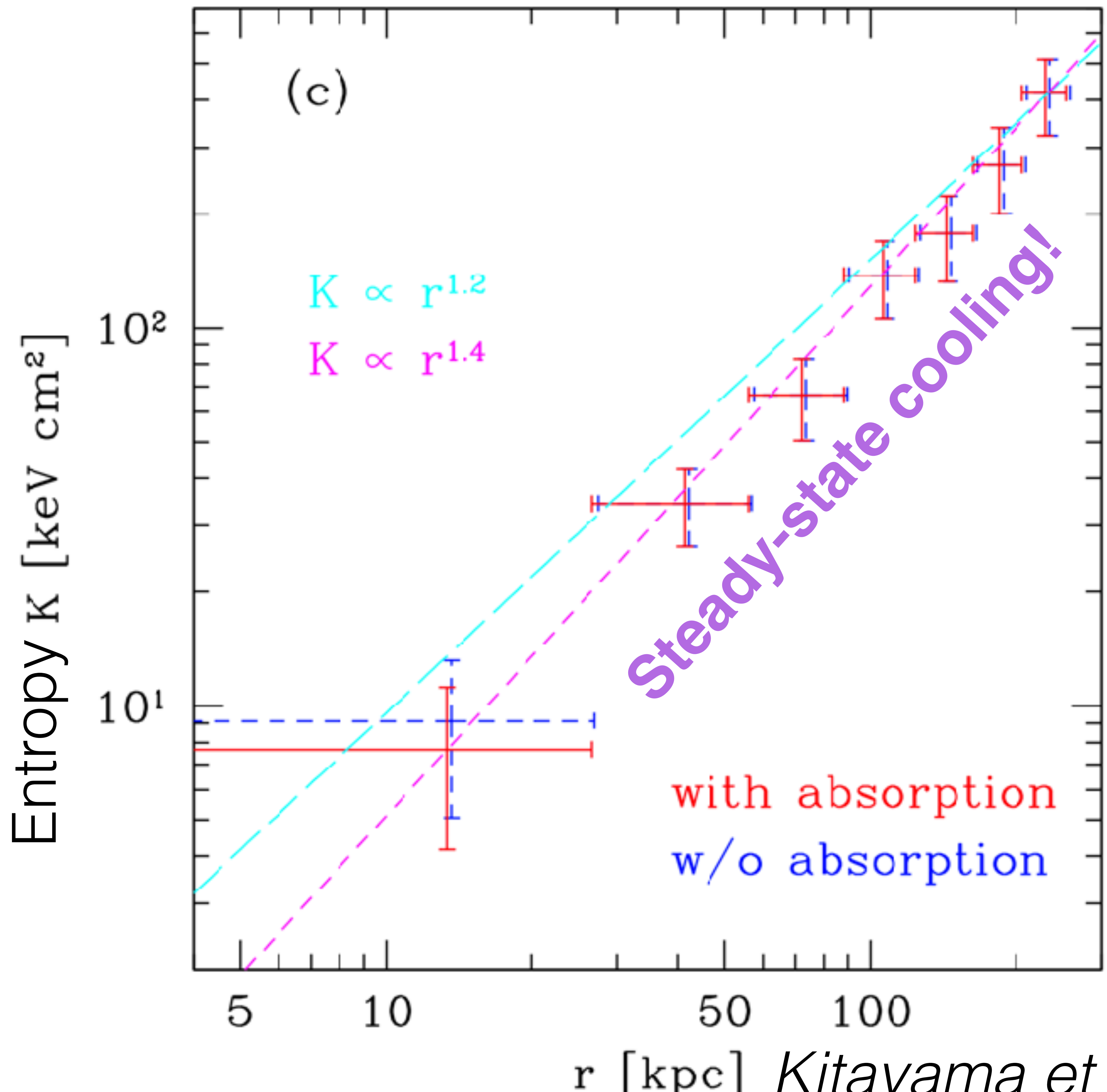
# Deeply cooling core?




*Kitayama et al., submitted*

- **Temperature continues to fall towards the center**
- <u>Highly unusual</u>: In other clusters, temperature stabilises in the core

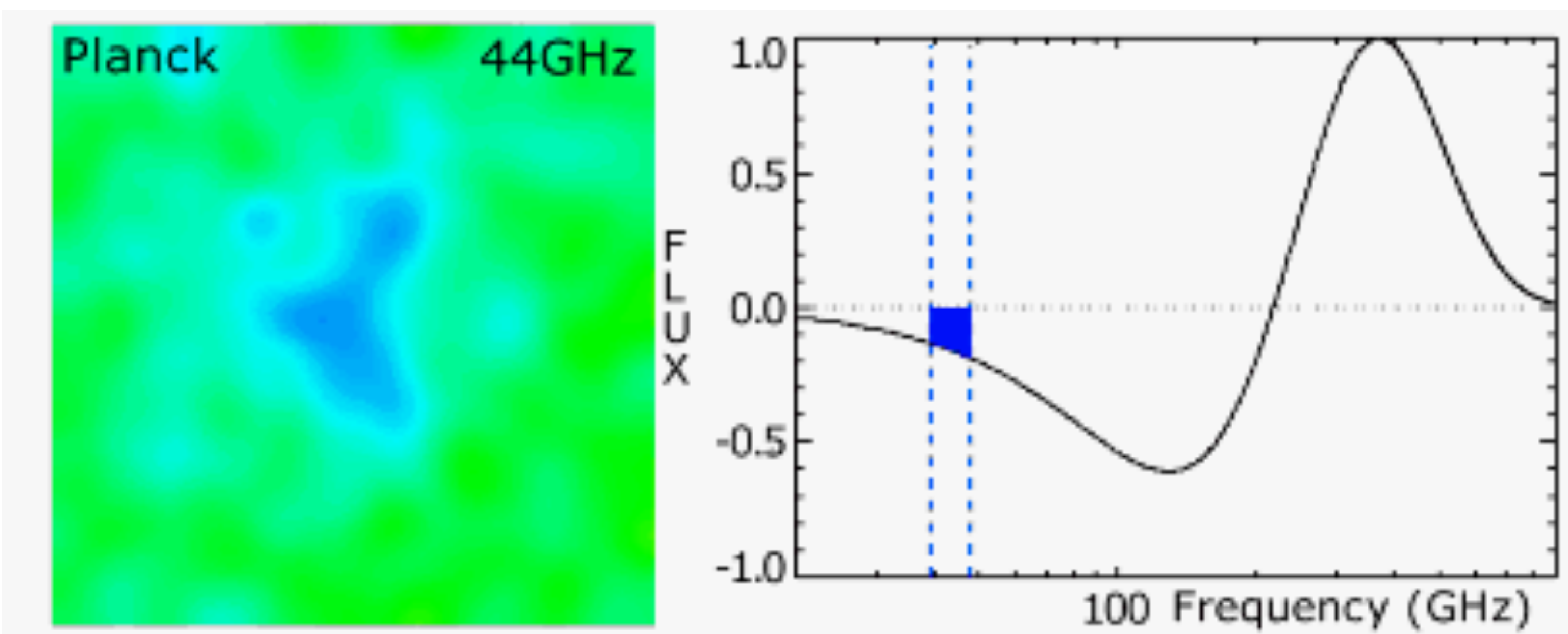
# Deeply cooling core?



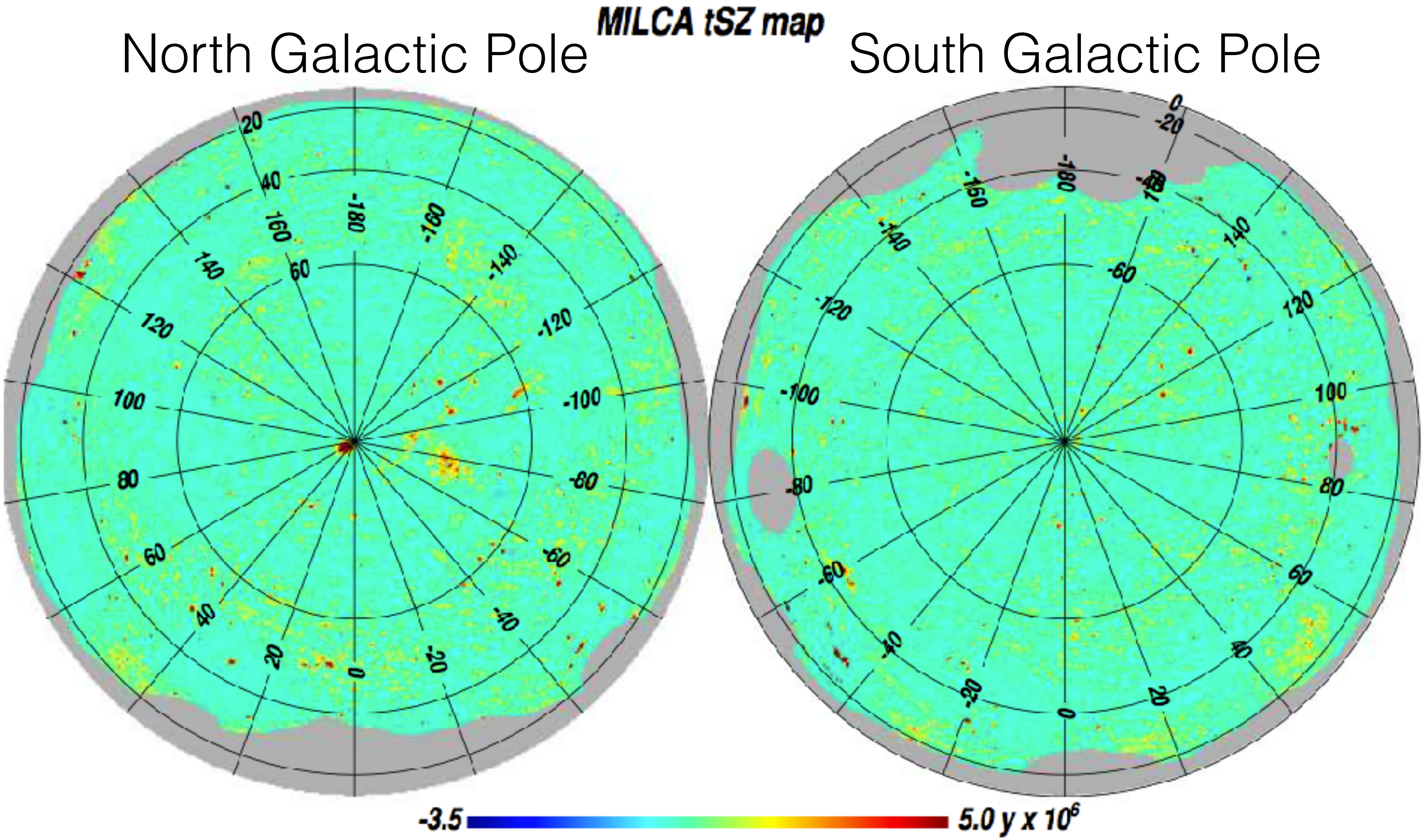

*Kitayama et al., submitted*

- **Entropy of gas also continues to fall towards the center**
- Highly unusual also: In other clusters, entropy stabilises in the core, or the slope is more like $r^{1.2}$

# Full-sky SZ Map



# Full-sky Thermal Pressure Map




*Planck Collaboration*

# We can simulate this in (super)computers

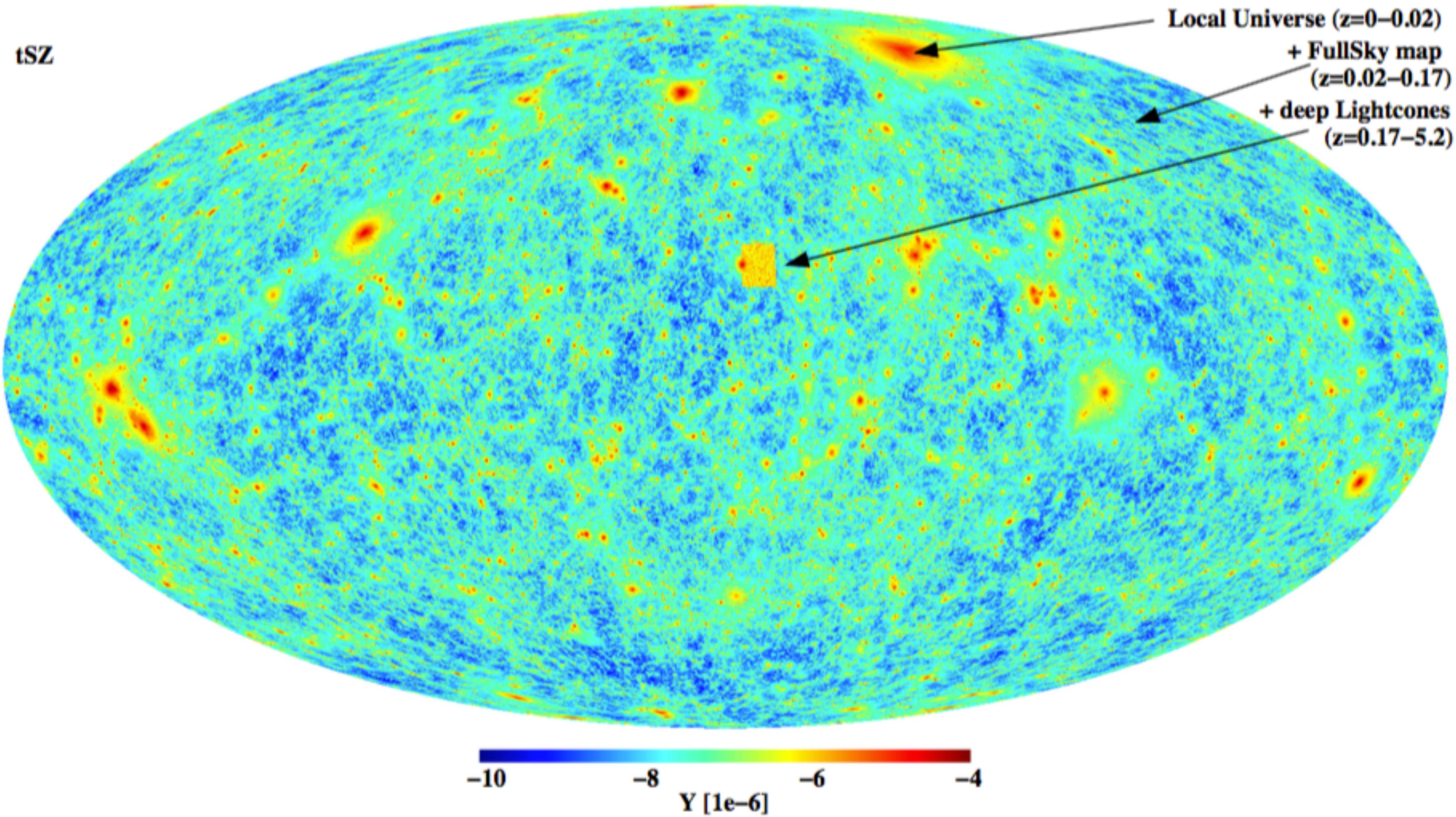
**arXiv:1509.05134** [MNRAS, **463**, 1797 (2016)]

**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*

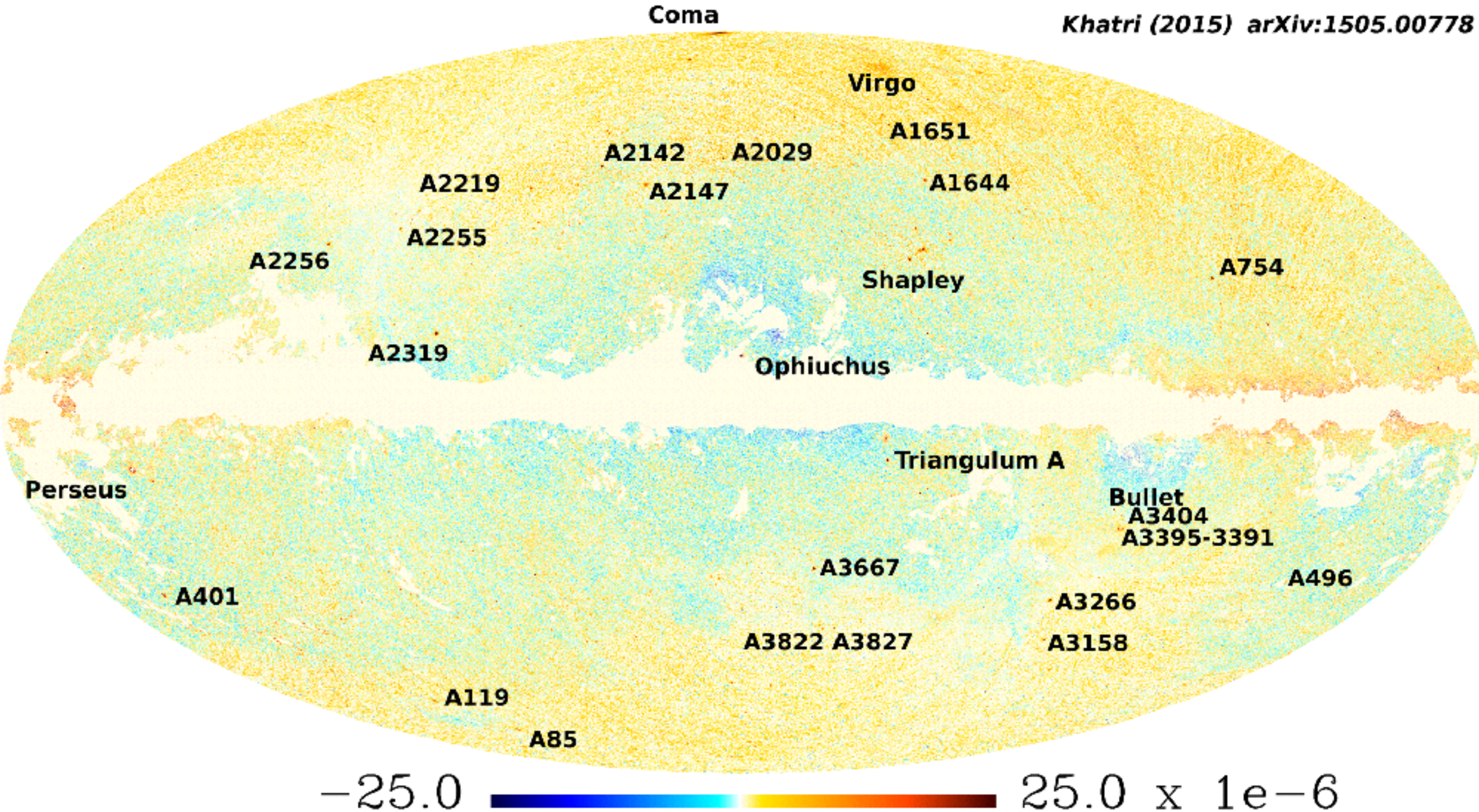
- Volume: $(896\ \mathrm{Mpc}/h)^3$
- Cosmological hydro (P-GADGET3) with star formation and AGN feed back
- $2 \times 1526^3$ particles ($m_{DM}=7.5\times10^8\ M_{sun}/h$)

*Dolag, EK, Sunyaev (2016)*



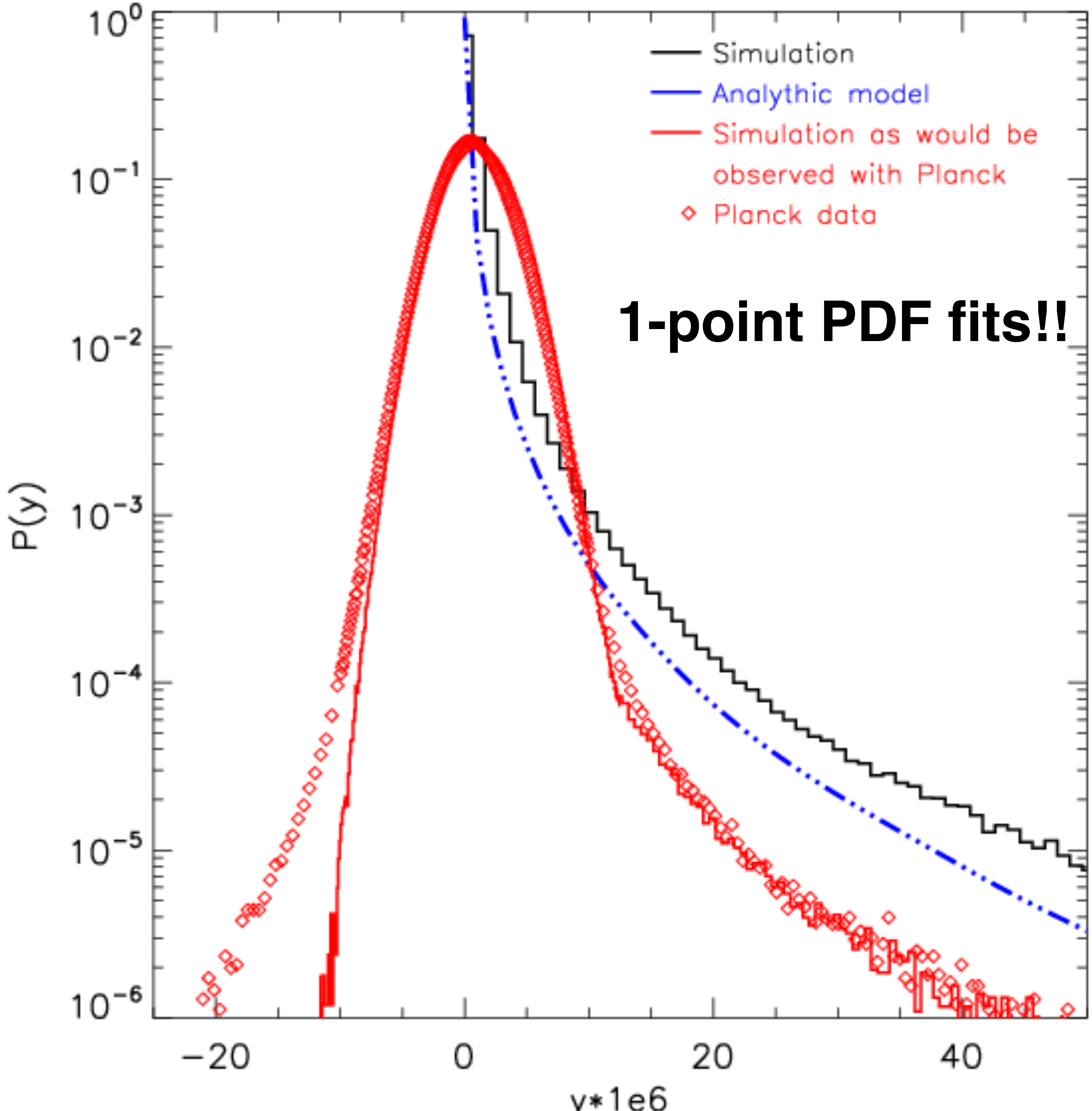

$$Y_{\mathrm{tSZ}}(\boldsymbol{\theta}) = \frac{k_B \sigma_T}{m_e c^2} \int \mathrm{d}l \, n_e(\boldsymbol{\theta}, l) \, T(\boldsymbol{\theta}, l)$$

# y−distortion map,10 arcmin

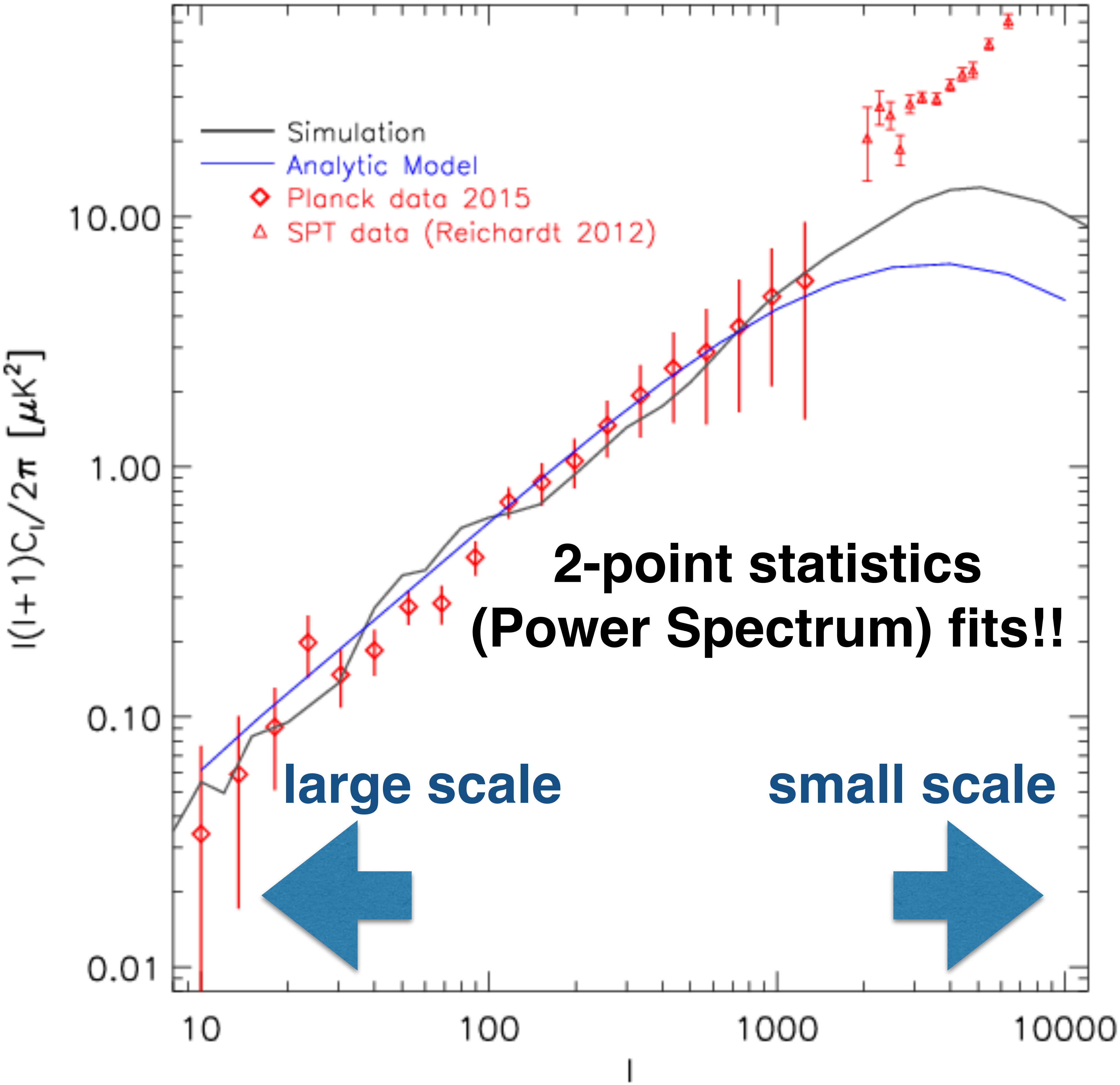



- "The local universe simulation" reproduces the observed structures pretty well

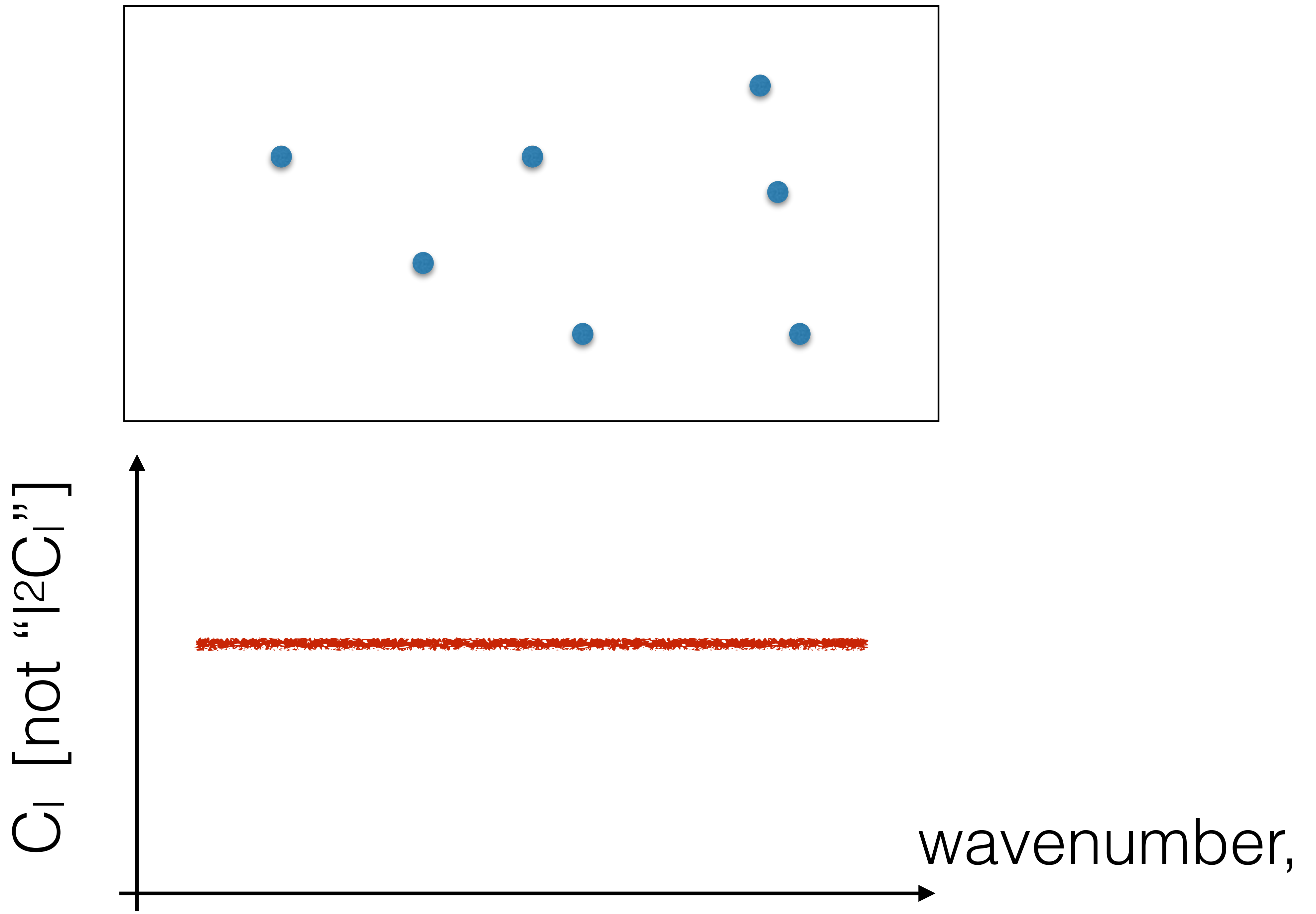
*Dolag, EK, Sunyaev (2016)*



*Dolag, EK, Sunyaev (2016)*

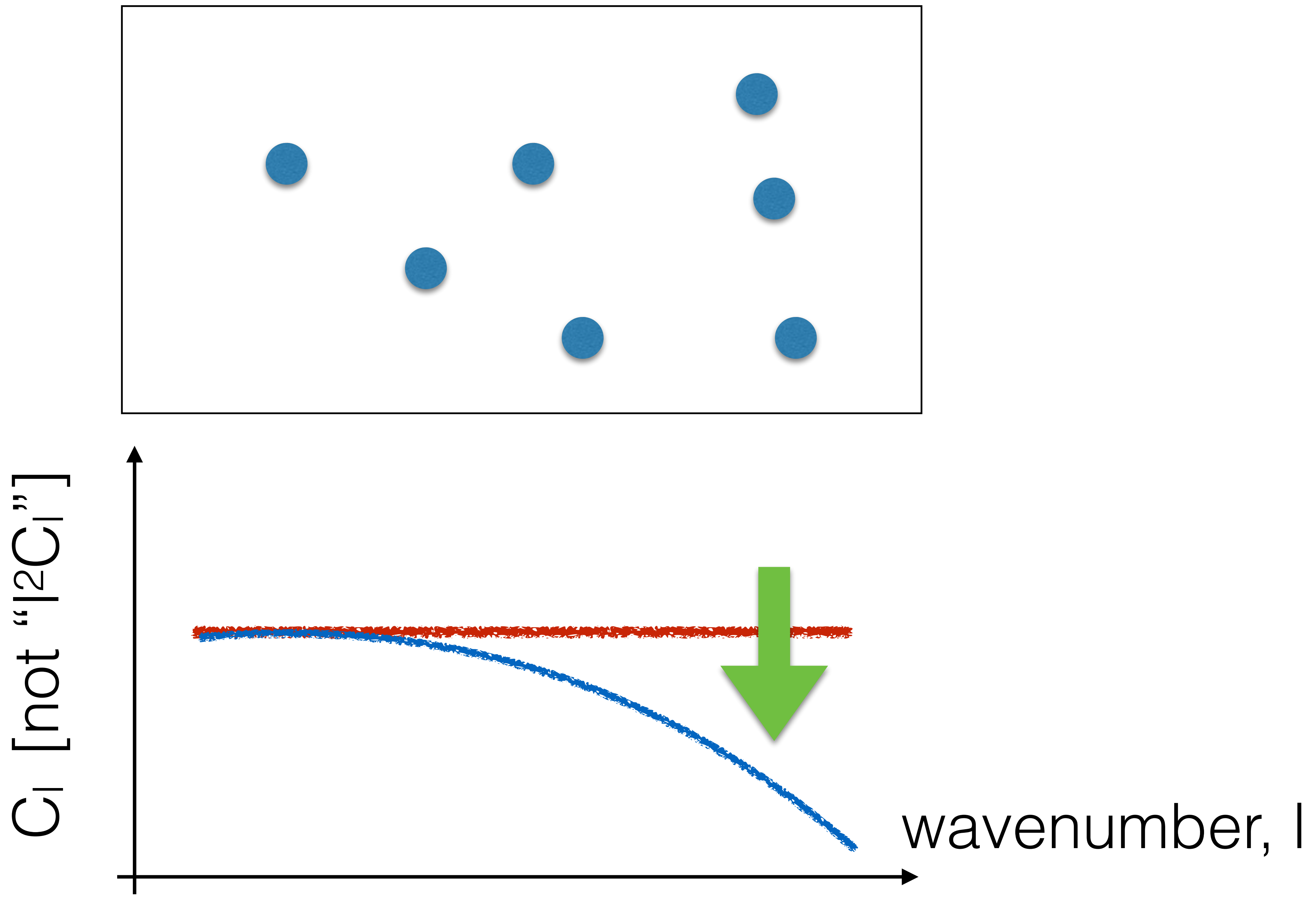


# Simple Interpretation

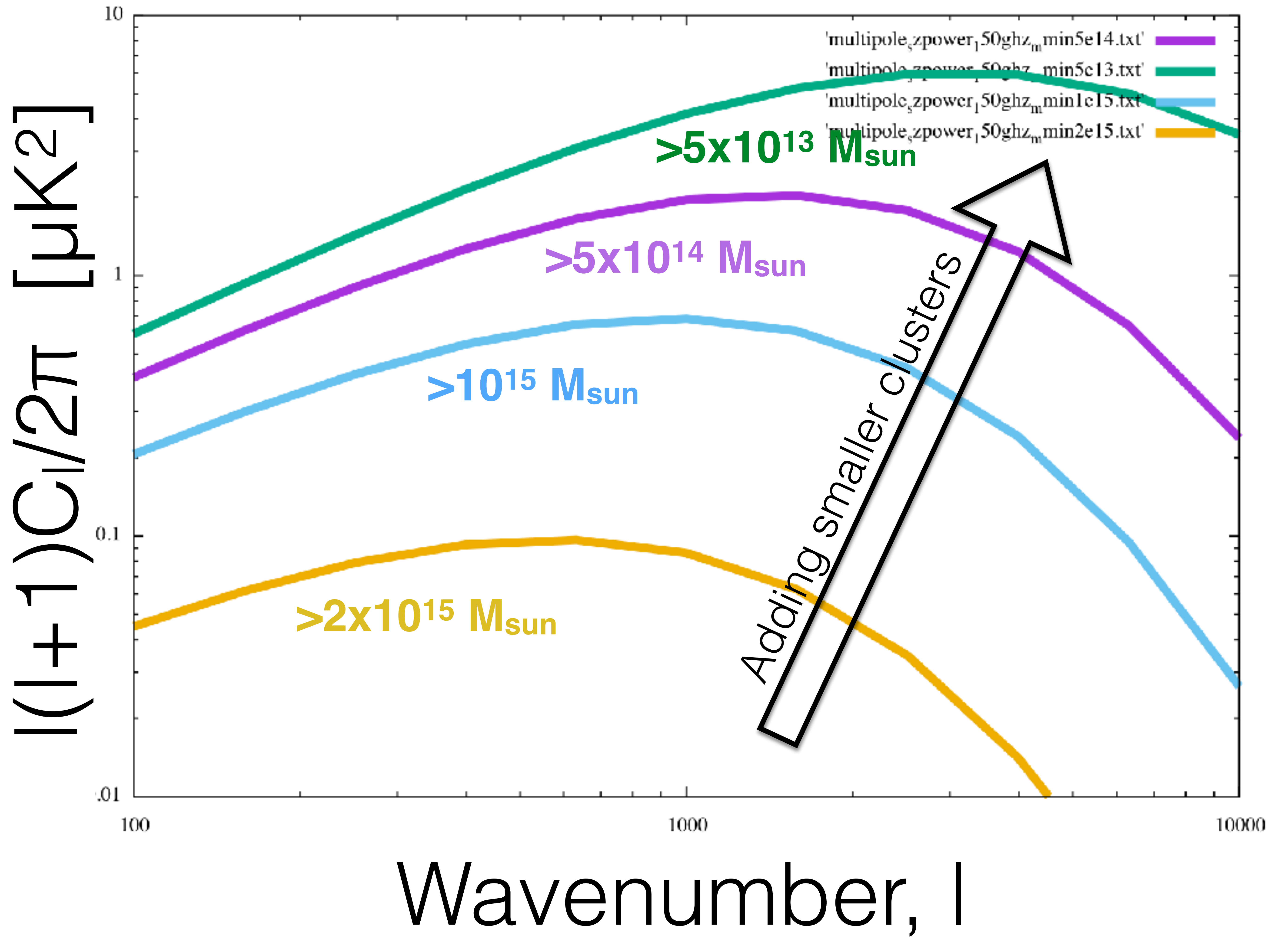



- Randomly-distributed point sources = Poisson spectrum = $\sum_i(\text{flux}_i)^2 / 4\pi$

# Simple Interpretation




- Extended sources = the power spectrum reflects intensity profiles

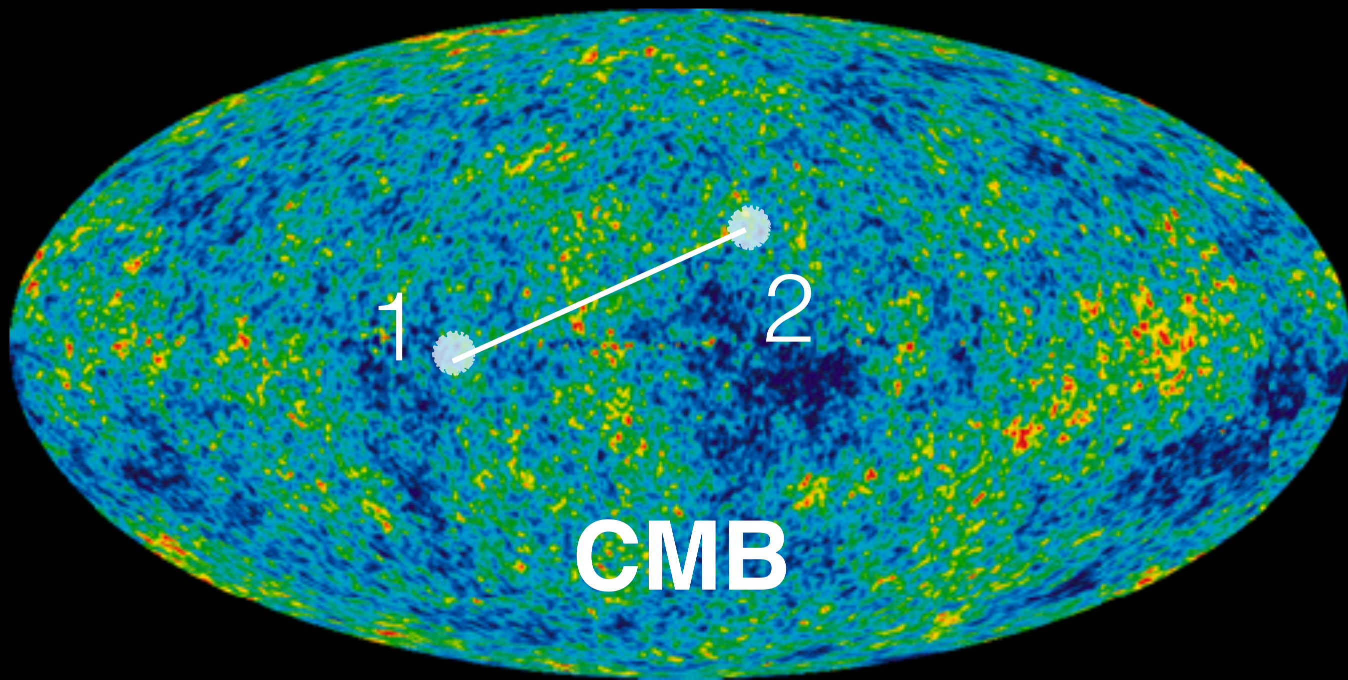


'multipole,zpower,50ghz,min5e14.txt'
'multipole,zpower,50ghz,min1e15.txt'
'multipole,zpower,50ghz,min2e15.txt'
>5x10^13 Msun
>5x10^14 Msun
>10^15 Msun
>2x10^15 Msun
Adding smaller clusters
10
1
0.1
.01
100
1000
10000
l(l+1)Cl/2π [μK2]
Wavenumber, l

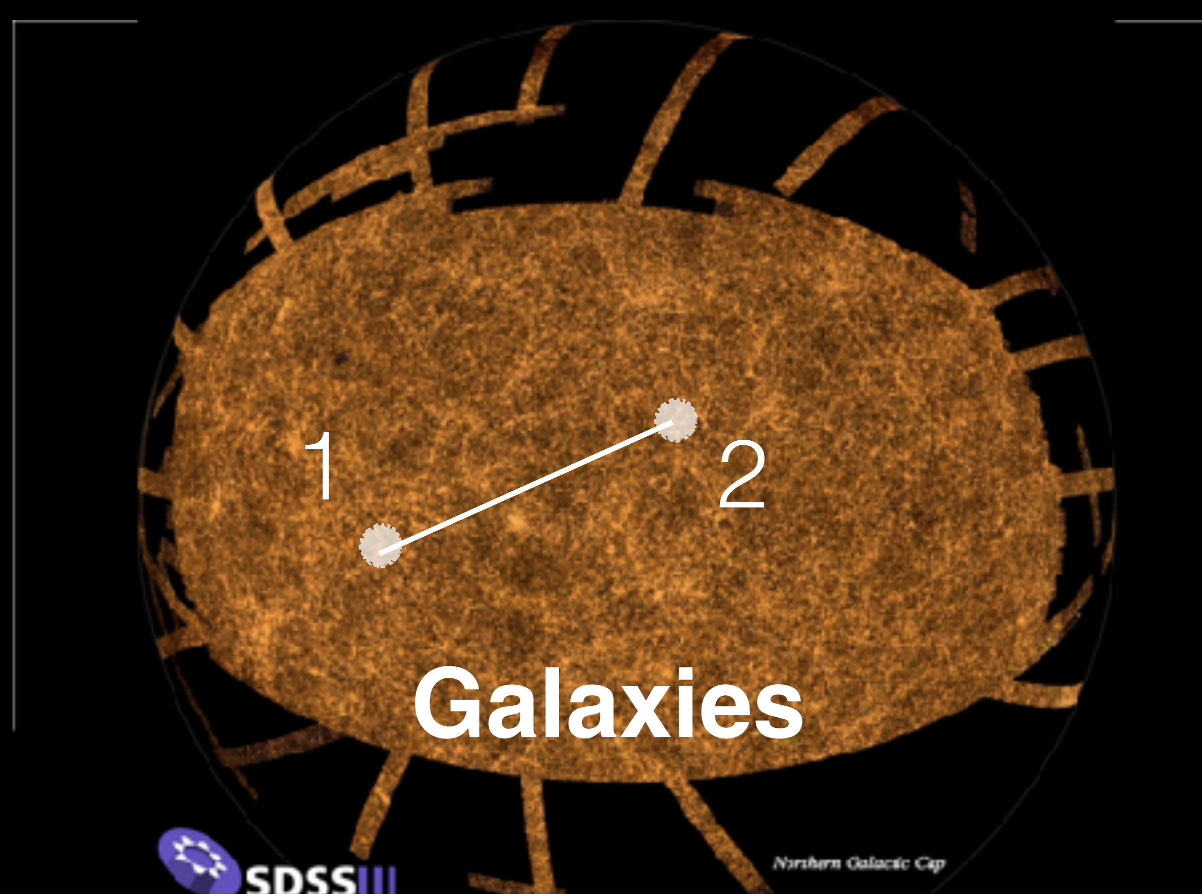
# Tomography of all hot gas pressure in the Universe!

- The SZ map does not tell us redshifts (or distances from us)
- By cross-correlating the SZ map with galaxies with known redshifts, **we can identify the amount of gas pressure as a function of redshifts (distances)**

# Auto 2-point Correlation

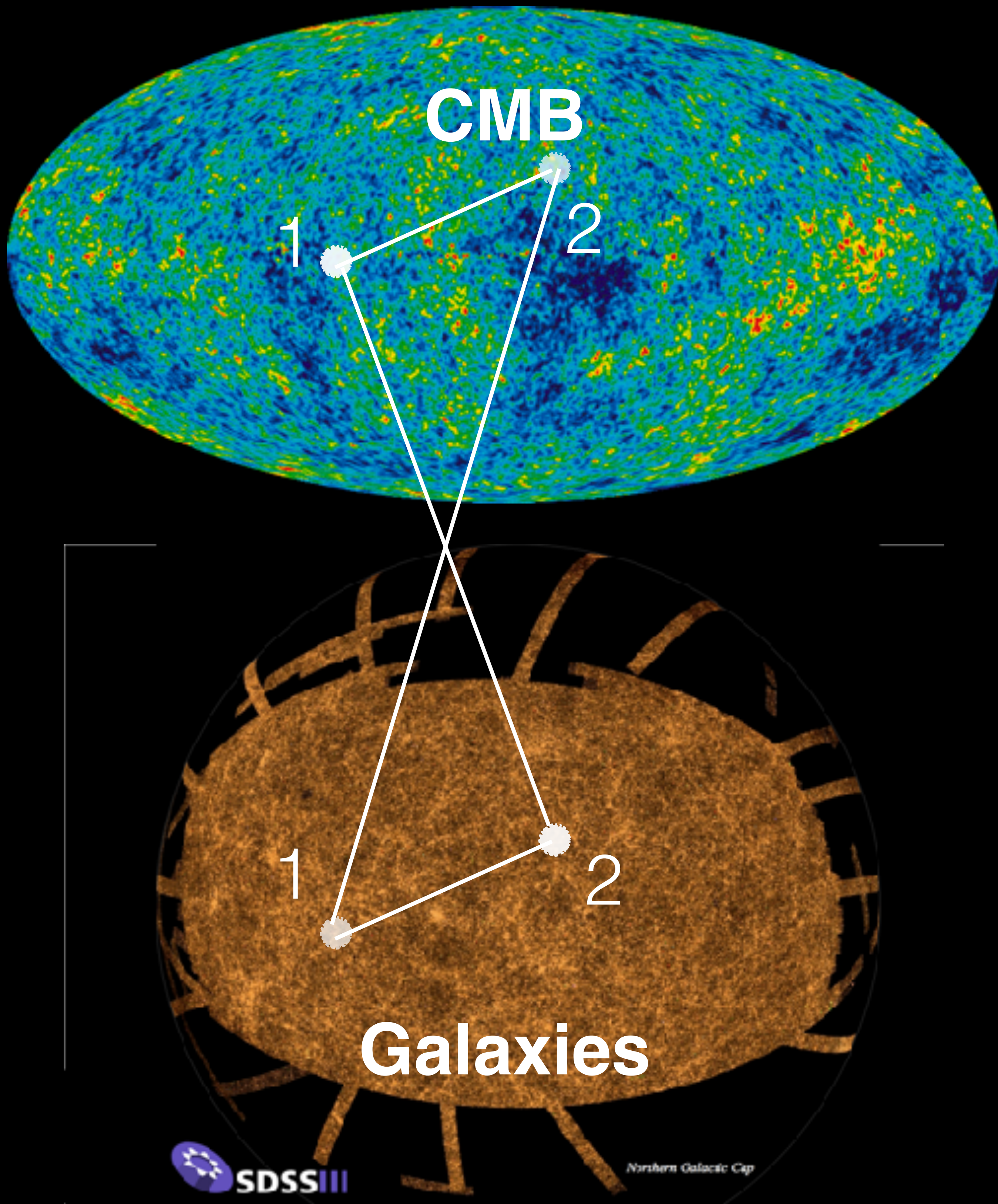



$T_{CMB}(1) \times T_{CMB}(2)$




$n_{gal}(1) \times n_{gal}(2)$

# Cross 2-point Correlation



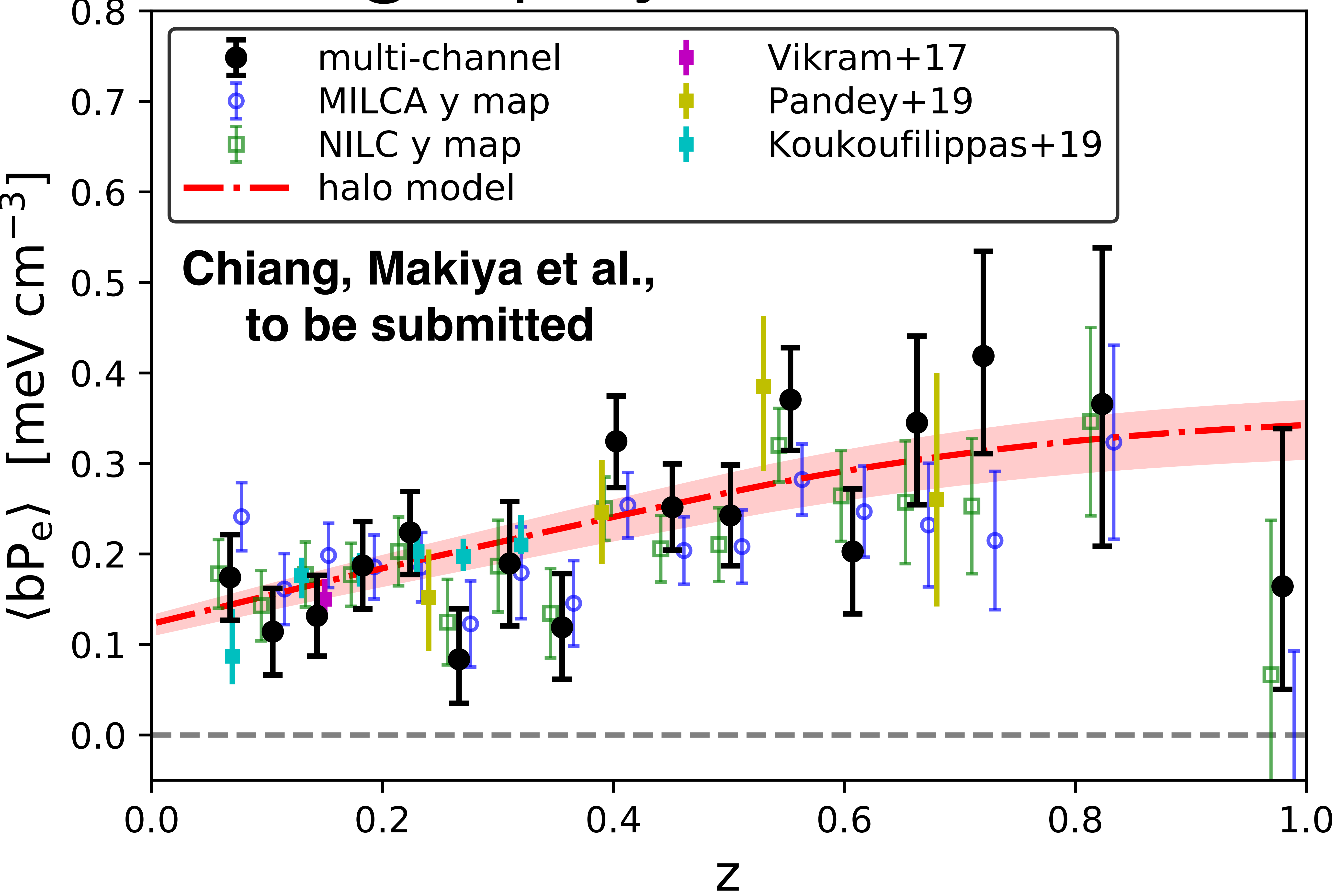

$T_{CMB}(1) \times T_{CMB}(2)$

$\mathbf{T_{CMB}(1) \times n_{gal}(2)}$

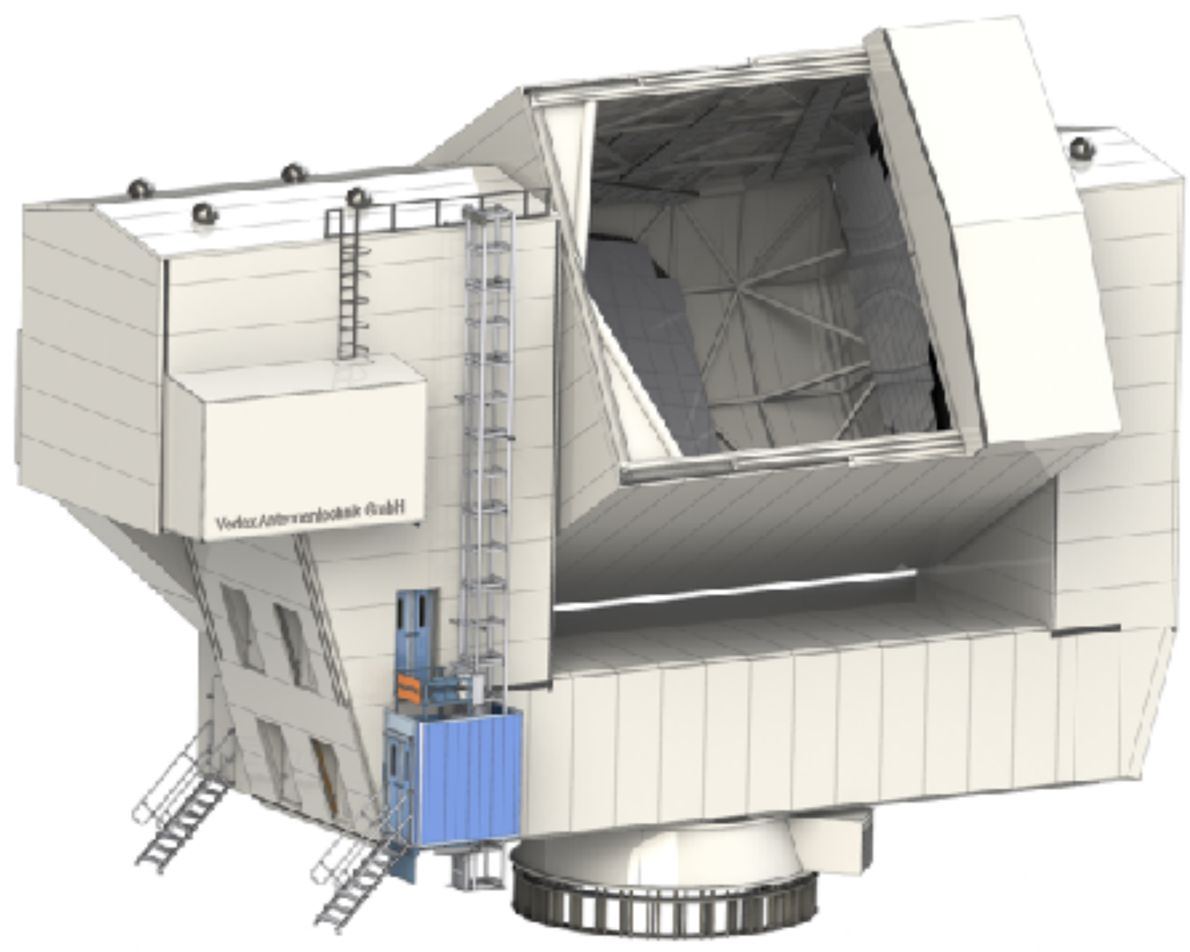
$\mathbf{n_{gal}(1) \times T_{CMB}(2)}$

$n_{gal}(1) \times n_{gal}(2)$

# Tomography of Pressure



# Near Future?
# CCAT-prime



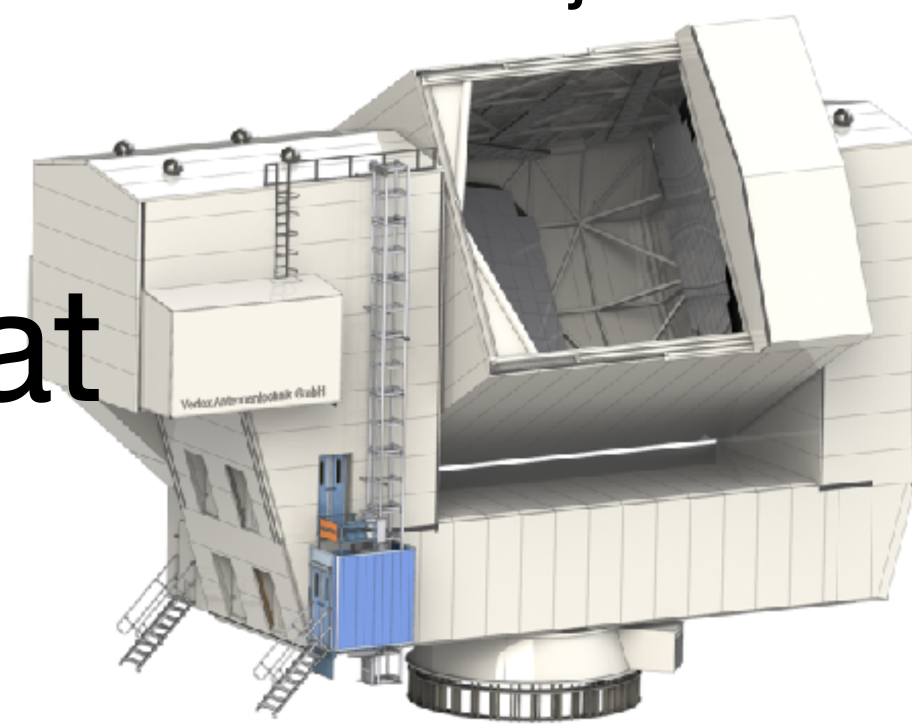
*Frank's slide from the Florence meeting*

# Where is CCAT-p?

## Cerro Chajnantor at 5600 m w/ TAO

# A Game Changer

- **CCAT-prime**: 6-m telescope on Cerro Chajnantor (5600 m)



- Germany makes great telescopes!

- Design study completed, the contract signed by “VERTEX Antennentechnik GmbH”, and the **construction has begun**

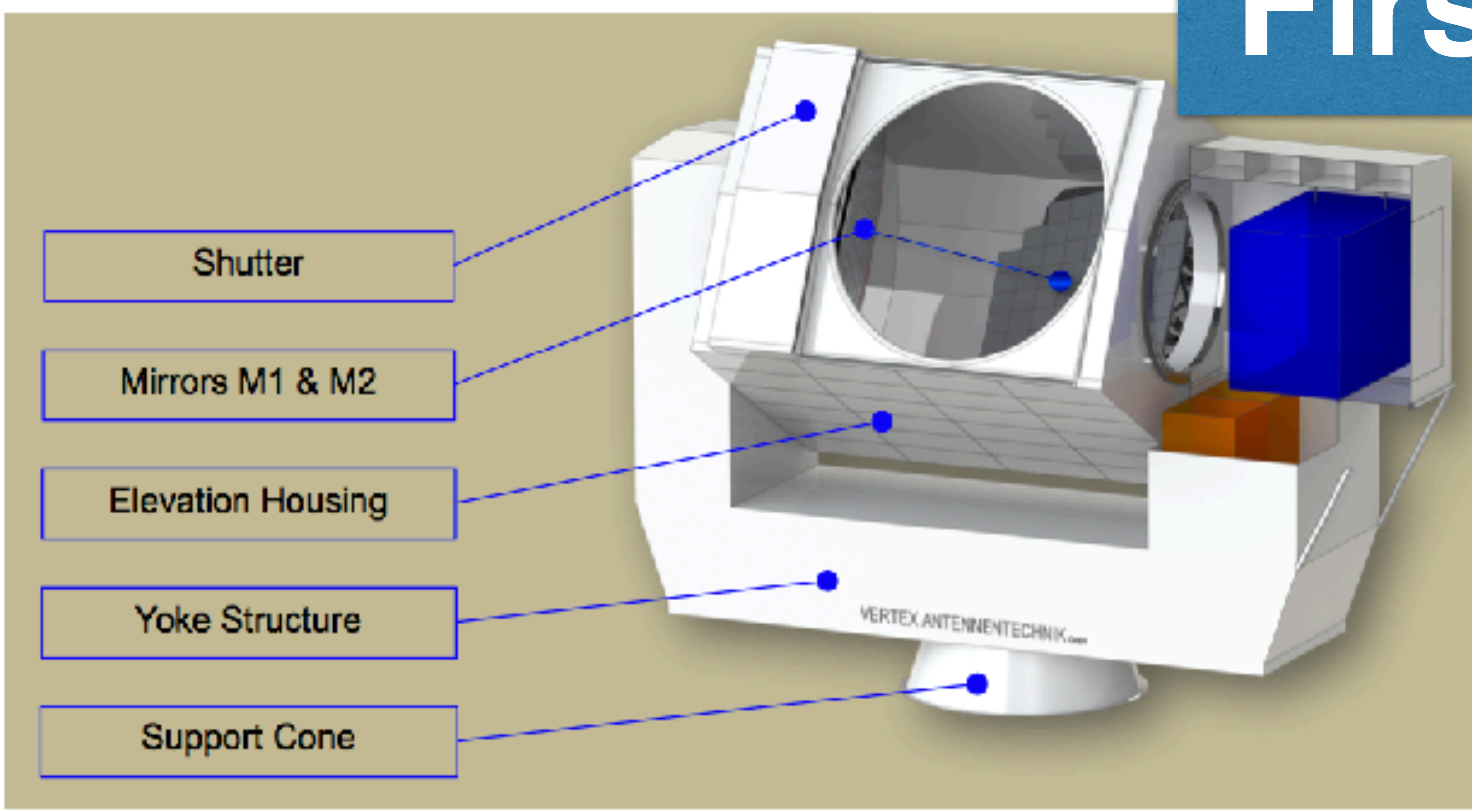
*Frank's slide from the Florence meeting*

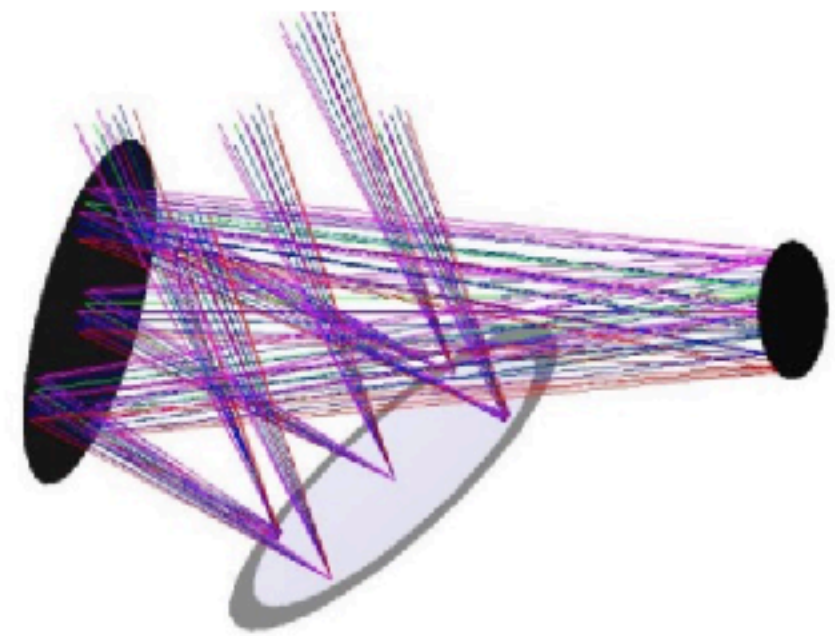
# What is CCAT-p?

CCAT-p

CCAT-prime is a high surface accuracy / throughput 6 m submm (0.3-3mm) telescope

**First light: 2021**

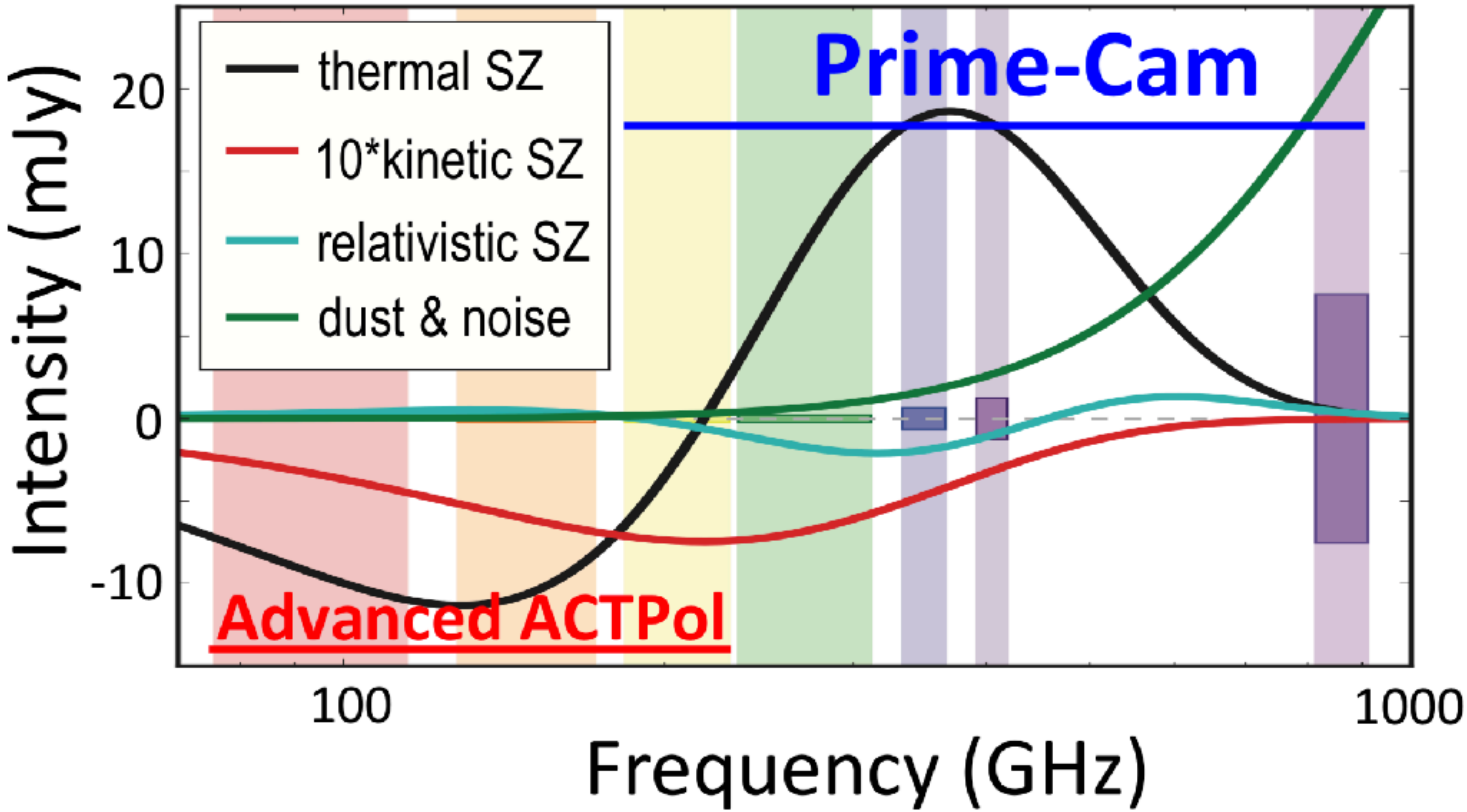


Cornell U. + German consortium + Canadian consortium + …

*CCAT-prime Collaboration*

# Clean SZ component separation



# Summary

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

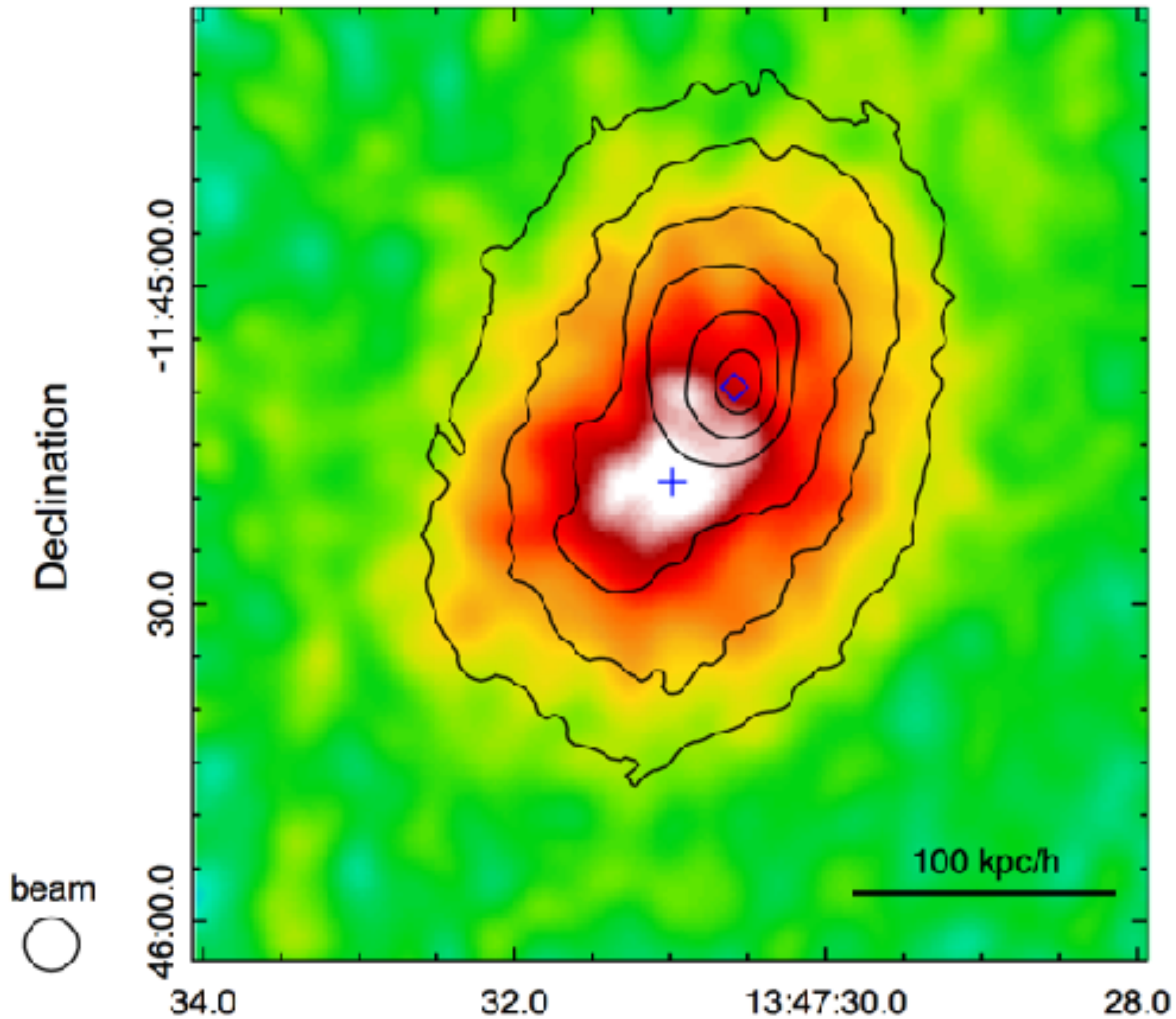
1. ***Highest* angular resolution images of the SZ effect by ALMA** - opening up a new study of cluster astrophysics via pressure fluctuations and "thermometer"

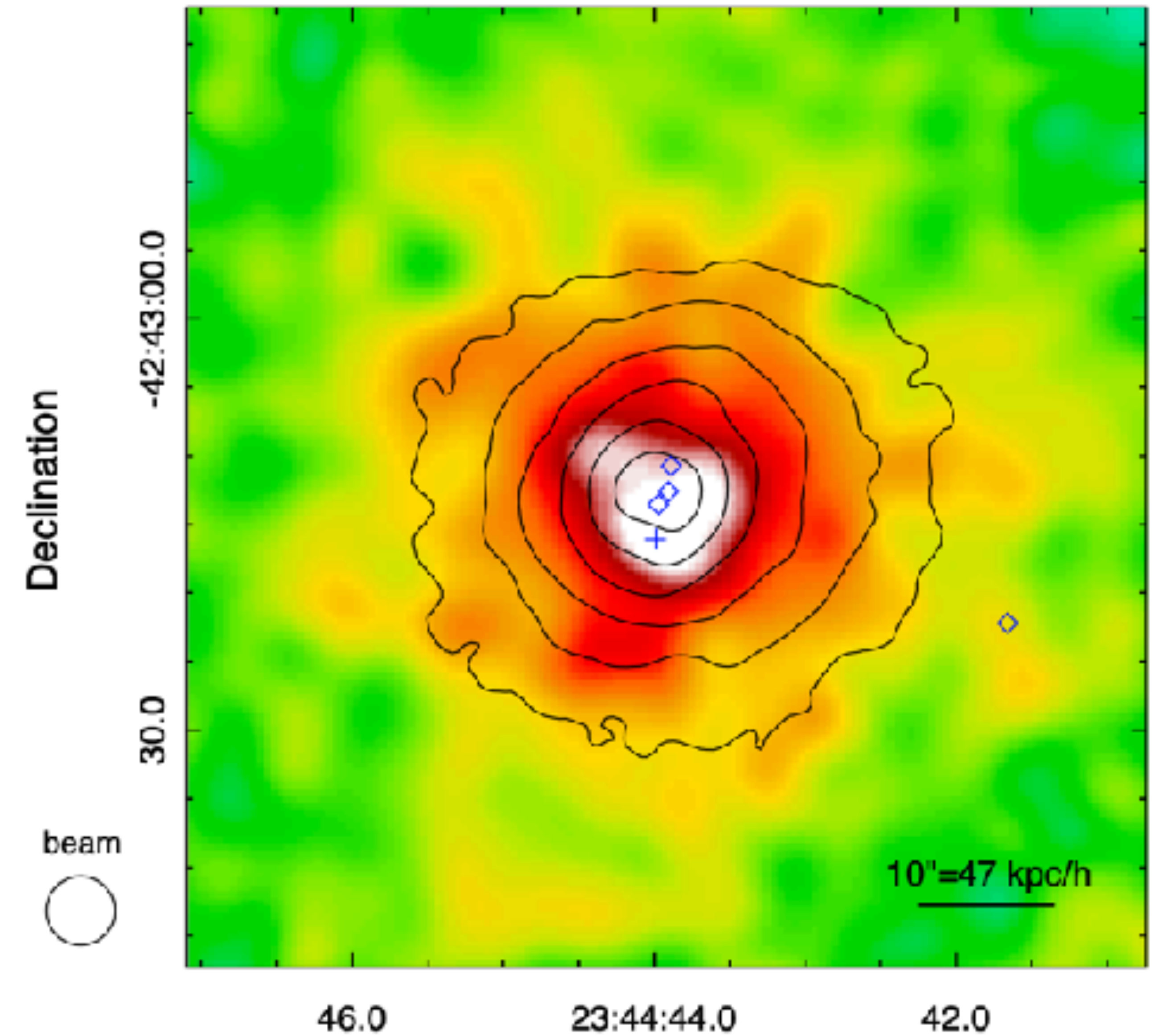
2. Computer simulations are able to reproduce the **low-order statistics (1-point and 2-point PDF) of pressure fluctuations in the Universe**. We (roughly) understand how gas works in the Universe

3. Tomography of gas pressure! This is **the thermal history of the whole Universe**

4. Near future: **CCAT-prime** to more cleanly separate dust emission from the SZ effect

# SZ Maps by ALMA




**5.6 hours** with 7-m array
**2.6 hours** with 12-m array

**8.1 hours** with 7-m array
**3.2 hours** with 12-m array

**Thank you Time Allocation Committee (TAC)!**