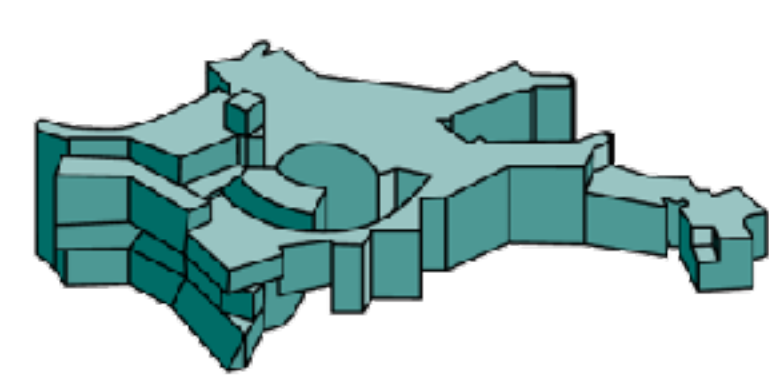
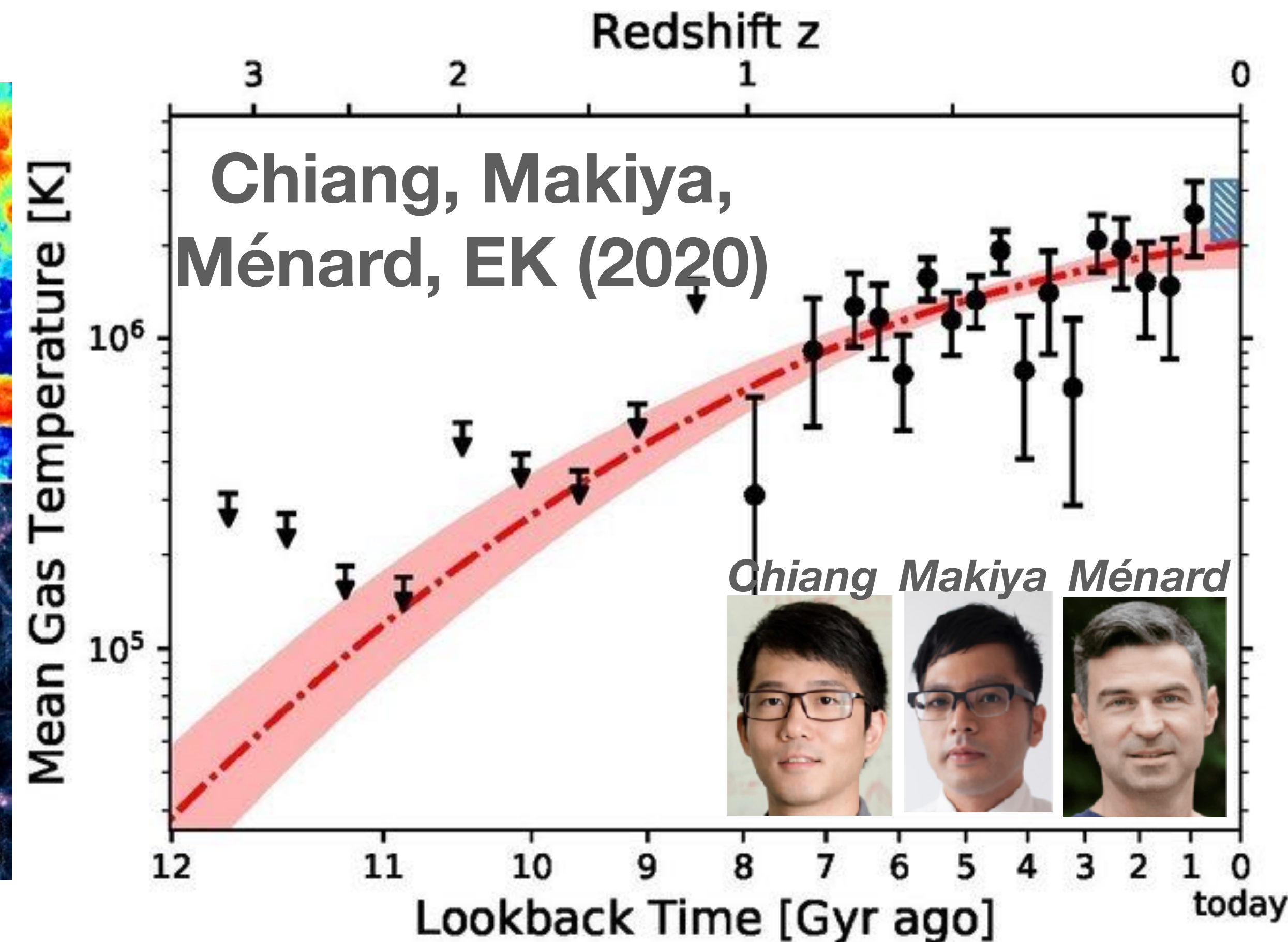
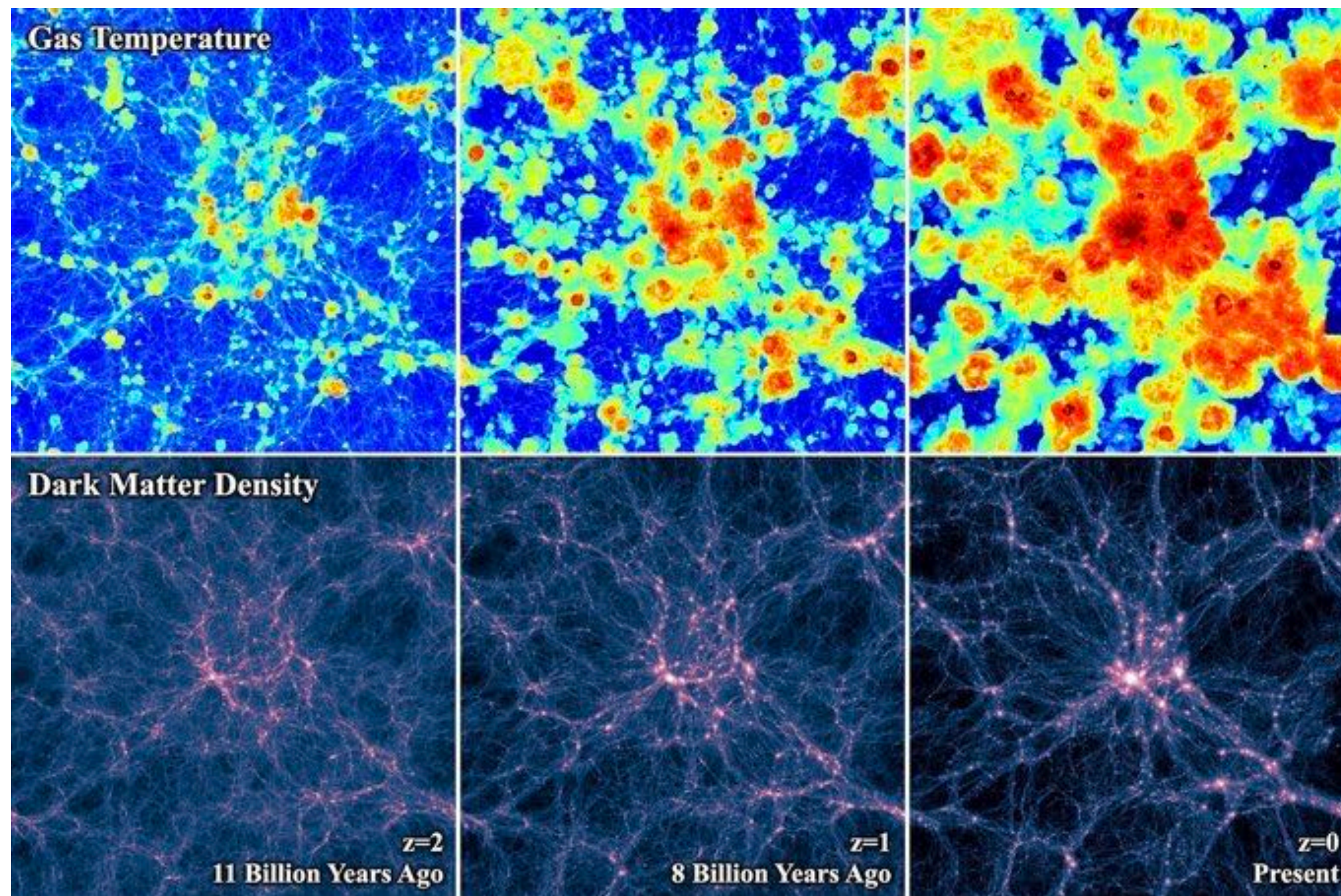


# The Temperature of Hot Gas in the Universe



MAX-PLANCK-INSTITUT  
FÜR ASTROPHYSIK

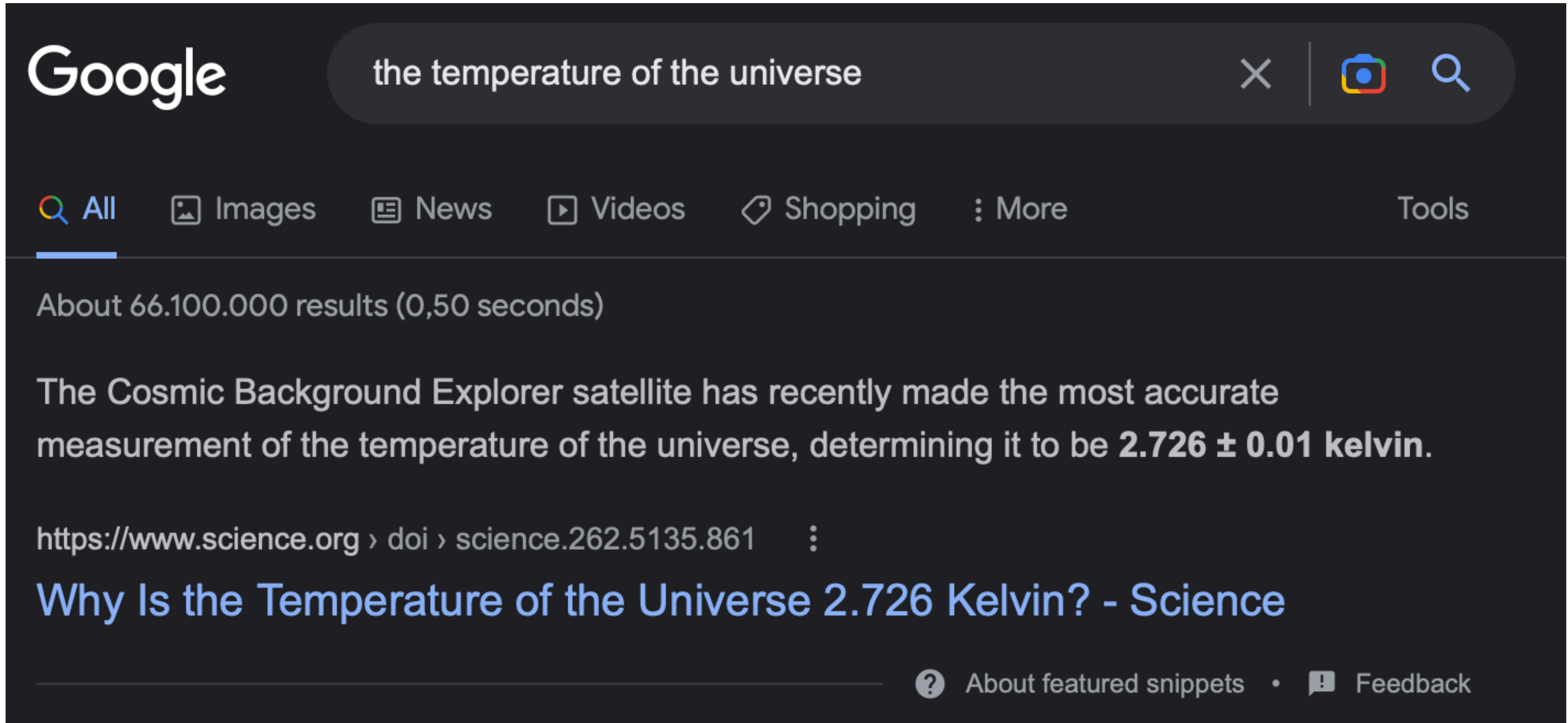
Credit: Dylan Nelson,  
Illustris Collaboration



Eiichiro Komatsu, *Colloquium@Nagoya Univ.*, June 16, 2023

# If you ask Google...

“The temperature of the Universe”



The image shows a screenshot of a Google search interface. At the top left is the Google logo. The search bar contains the text "the temperature of the universe". To the right of the search bar are icons for image search and a magnifying glass. Below the search bar are navigation tabs for "All", "Images", "News", "Videos", "Shopping", and "More", with "All" selected. To the right of these tabs is a "Tools" link. Below the navigation is a line indicating "About 66.100.000 results (0,50 seconds)". The main content area features a featured snippet: "The Cosmic Background Explorer satellite has recently made the most accurate measurement of the temperature of the universe, determining it to be **2.726 ± 0.01 kelvin.**" Below this snippet is the URL "https://www.science.org › doi › science.262.5135.861" and a vertical ellipsis icon. The title of the result is "Why Is the Temperature of the Universe 2.726 Kelvin? - Science". At the bottom right, there are links for "About featured snippets" and "Feedback".

Google

the temperature of the universe

All Images News Videos Shopping More Tools

About 66.100.000 results (0,50 seconds)

The Cosmic Background Explorer satellite has recently made the most accurate measurement of the temperature of the universe, determining it to be **2.726 ± 0.01 kelvin.**

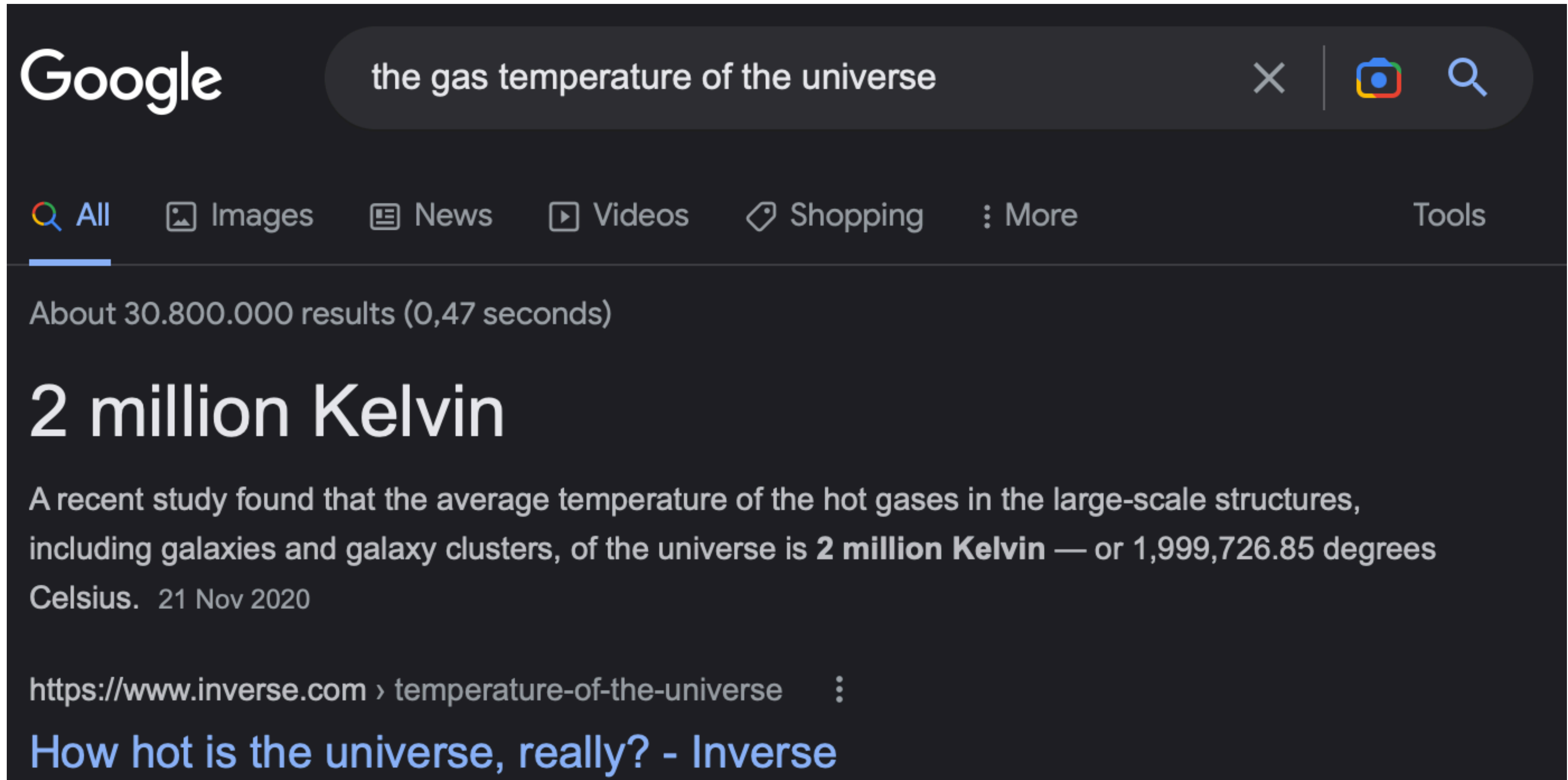
https://www.science.org › doi › science.262.5135.861

Why Is the Temperature of the Universe 2.726 Kelvin? - Science

About featured snippets Feedback

# If you ask Google...

“The **gas** temperature of the Universe”



The image shows a screenshot of a Google search interface. At the top left is the Google logo. The search bar contains the text "the gas temperature of the universe". To the right of the search bar are icons for a close button (X), a camera, and a search icon. Below the search bar are navigation links: "All", "Images", "News", "Videos", "Shopping", and "More", followed by a "Tools" link on the far right. Below the navigation links, it says "About 30.800.000 results (0,47 seconds)". The main result is a large heading "2 million Kelvin". Below this heading is a paragraph of text: "A recent study found that the average temperature of the hot gases in the large-scale structures, including galaxies and galaxy clusters, of the universe is **2 million Kelvin** — or 1,999,726.85 degrees Celsius. 21 Nov 2020". At the bottom, there is a URL "https://www.inverse.com > temperature-of-the-universe" and a blue link "How hot is the universe, really? - Inverse".

Google

the gas temperature of the universe

All Images News Videos Shopping : More Tools

About 30.800.000 results (0,47 seconds)

## 2 million Kelvin

A recent study found that the average temperature of the hot gases in the large-scale structures, including galaxies and galaxy clusters, of the universe is **2 million Kelvin** — or 1,999,726.85 degrees Celsius. 21 Nov 2020

<https://www.inverse.com> > temperature-of-the-universe

[How hot is the universe, really? - Inverse](#)

# Temperature of what?

## The composition of the Universe

- Ordinary stuff that we are familiar with:
  - **Gas of the ordinary matter** (mostly hydrogen and helium) **This colloquium**
  - Photons (cosmic microwave background): 2.7 Kelvin
  - Neutrinos (cosmic neutrino background): 1.9 Kelvin [indirect measurement]
- Extraordinary stuff that we know exists:
  - *Dark matter: ??*
  - *Dark energy: ??*



第12号  
September 2021

宇宙の温暖化

新聞



### \*3 宇宙の温暖化の原因

宇宙の大規模構造の形成にともなって、ガスが引き寄せられるときに生じる衝撃波が、宇宙の加熱源になっている。これは地球で見られる現象と原理的には同じである。たとえば大気圏外からボールを落とすと、位置エネルギーが運動エネルギーに変わる。そしてボールの速度が音速を超えると衝撃波が発生し熱が生じる。同じようなことが宇宙でも起きて、宇宙の温暖化を引き起こしているのだ。

<https://www.ipmu.jp/ja/>

20210929 MonoshiriShimbun12

# Outline

## Three questions to answer during this talk:

1. How hot is the large-scale structure of the Universe today? How was it before?

- *Chiang, Makiya, Ménard, EK, ApJ, 902, 56 (2020)*

2. Where did the thermal energy come from?

- *Chiang, Makiya, EK, Ménard, ApJ, 910, 32 (2021)*

3. What is our result good for?

- Is it just beautiful physics, or is it also useful for something?

- *Young, EK, Dolag, PRD, 104, 083538 (2021)*

# The cosmic energy inventory

Fukugita & Peebles (2004)

- We know the mean total mass density of the Universe:  $\Omega_m \sim 0.3$ .
- We also know the mean baryonic mass density of the Universe:  $\Omega_B \sim 0.05$ .
- We also have estimates for many other energy densities in the Universe:

## THE COSMIC ENERGY INVENTORY

MASATAKA FUKUGITA

Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540; and Institute for Cosmic Ray Research,  
University of Tokyo, Kashiwa 277-8582, Japan

AND

P. J. E. PEEBLES

Joseph Henry Laboratories, Princeton University, Jadwin Hall, P.O. Box 708, Princeton, NJ 08544

*Received 2004 June 3; accepted 2004 August 9*

## ABSTRACT

We present an inventory of the cosmic mean densities of energy associated with all the known states of matter and radiation at the present epoch. The observational and theoretical bases for the inventory have become rich enough to allow estimates with observational support for the densities of energy in some 40 forms. The result is a global portrait of the effects of the physical processes of cosmic evolution.

TABLE 1  
THE COSMIC ENERGY INVENTORY

Category	Parameter	Components <sup>a</sup>	Totals <sup>a</sup>
1.....	Dark sector:		$0.954 \pm 0.003$
1.1.....	Dark energy	$0.72 \pm 0.03$	
1.2.....	Dark matter	$0.23 \pm 0.03$	
1.3.....	Primeval gravitational waves	$\lesssim 10^{-10}$	
2.....	Primeval thermal remnants:		$0.0010 \pm 0.0005$
2.1.....	Electromagnetic radiation	$10^{-4.3 \pm 0.0}$	
2.2.....	Neutrinos	$10^{-2.9 \pm 0.1}$	
2.3.....	Prestellar nuclear binding energy	$-10^{-4.1 \pm 0.0}$	
3.....	Baryon rest mass:		$0.045 \pm 0.003$
3.1.....	Warm intergalactic plasma	$0.040 \pm 0.003$	
3.1a.....	Virialized regions of galaxies	$0.024 \pm 0.005$	
3.1b.....	Intergalactic	$0.016 \pm 0.005$	
3.2.....	Intracluster plasma	$0.0018 \pm 0.0007$	
3.3.....	Main-sequence stars: spheroids and bulges	$0.0015 \pm 0.0004$	
3.4.....	Main-sequence stars: disks and irregulars	$0.00055 \pm 0.00014$	
3.5.....	White dwarfs	$0.00036 \pm 0.00008$	
3.6.....	Neutron stars	$0.00005 \pm 0.00002$	
3.7.....	Black holes	$0.00007 \pm 0.00002$	
3.8.....	Substellar objects	$0.00014 \pm 0.00007$	
3.9.....	H I + He I	$0.00062 \pm 0.00010$	
3.10.....	Molecular gas	$0.00016 \pm 0.00006$	
3.11.....	Planets	$10^{-6}$	
3.12.....	Condensed matter	$10^{-5.6 \pm 0.3}$	
3.13.....	Sequestered in massive black holes	$10^{-5.4}(1 + \epsilon_n)$	
4.....	Primeval gravitational binding energy:		$-10^{-6.1 \pm 0.1}$
4.1.....	Virialized halos of galaxies	$-10^{-7.2}$	
4.2.....	Clusters	$-10^{-6.9}$	
4.3.....	Large-scale structure	$-10^{-6.2}$	
5.....	Binding energy from dissipative gravitational settling:		$-10^{-4.9}$
5.1.....	Baryon-dominated parts of galaxies	$-10^{-8.8 \pm 0.3}$	
5.2.....	Main-sequence stars and substellar objects	$-10^{-8.1}$	



# Fukugita & Peebles (2004)

Category	Parameter	Components <sup>a</sup>	Totals <sup>a</sup>
5.3.....	White dwarfs	$-10^{-7.4}$	
5.4.....	Neutron stars	$-10^{-5.2}$	
5.5.....	Stellar mass black holes	$-10^{-4.2}\epsilon_s$	
5.6.....	Galactic nuclei: early type	$-10^{-5.6}\epsilon_n$	
5.7.....	Galactic nuclei: late type	$-10^{-5.8}\epsilon_n$	
6.....	Poststellar nuclear binding energy:		$-10^{-5.2}$
6.1.....	Main-sequence stars and substellar objects	$-10^{-5.8}$	
6.2.....	Diffuse material in galaxies	$-10^{-6.5}$	
6.3.....	White dwarfs	$-10^{-5.6}$	
6.4.....	Clusters	$-10^{-6.5}$	
6.5.....	Intergalactic	$-10^{-6.2 \pm 0.5}$	
7.....	Poststellar radiation:		$10^{-5.7 \pm 0.1}$
7.1.....	Resolved radio-microwave	$10^{-10.3 \pm 0.3}$	
7.2.....	FIR	$10^{-6.1}$	
7.3.....	Optical	$10^{-5.8 \pm 0.2}$	
7.4.....	X-ray- $\gamma$ -ray	$10^{-7.9 \pm 0.2}$	
7.5.....	Gravitational radiation: stellar mass binaries	$10^{-9 \pm 1}$	
7.6.....	Gravitational radiation: massive black holes	$10^{-7.5 \pm 0.5}$	
8.....	Stellar neutrinos:		$10^{-5.5}$
8.1.....	Nuclear burning	$10^{-6.8}$	
8.2.....	White dwarf formation	$10^{-7.7}$	
8.3.....	Core collapse	$10^{-5.5}$	
9.....	Cosmic rays and magnetic fields		$10^{-8.3^{+0.6}_{-0.3}}$
10.....	Kinetic energy in the IGM		$10^{-8.0 \pm 0.3}$

- But we did not know the mean thermal energy density of the Universe,  $\Omega_{\text{th}}$

- **Let's measure this!**

# Our definition of the thermal energy density

$nk_B T$  rather than  $(3/2)nk_B T$

- We define the thermal energy from  $k_B T$ , rather than the kinetic energy,  $(3/2)k_B T$ .
  - If you do not like this definition, keep this factor of  $3/2$  in your mind.
- Then the mean (comoving) thermal energy density is equal to the mean thermal pressure in the comoving volume:

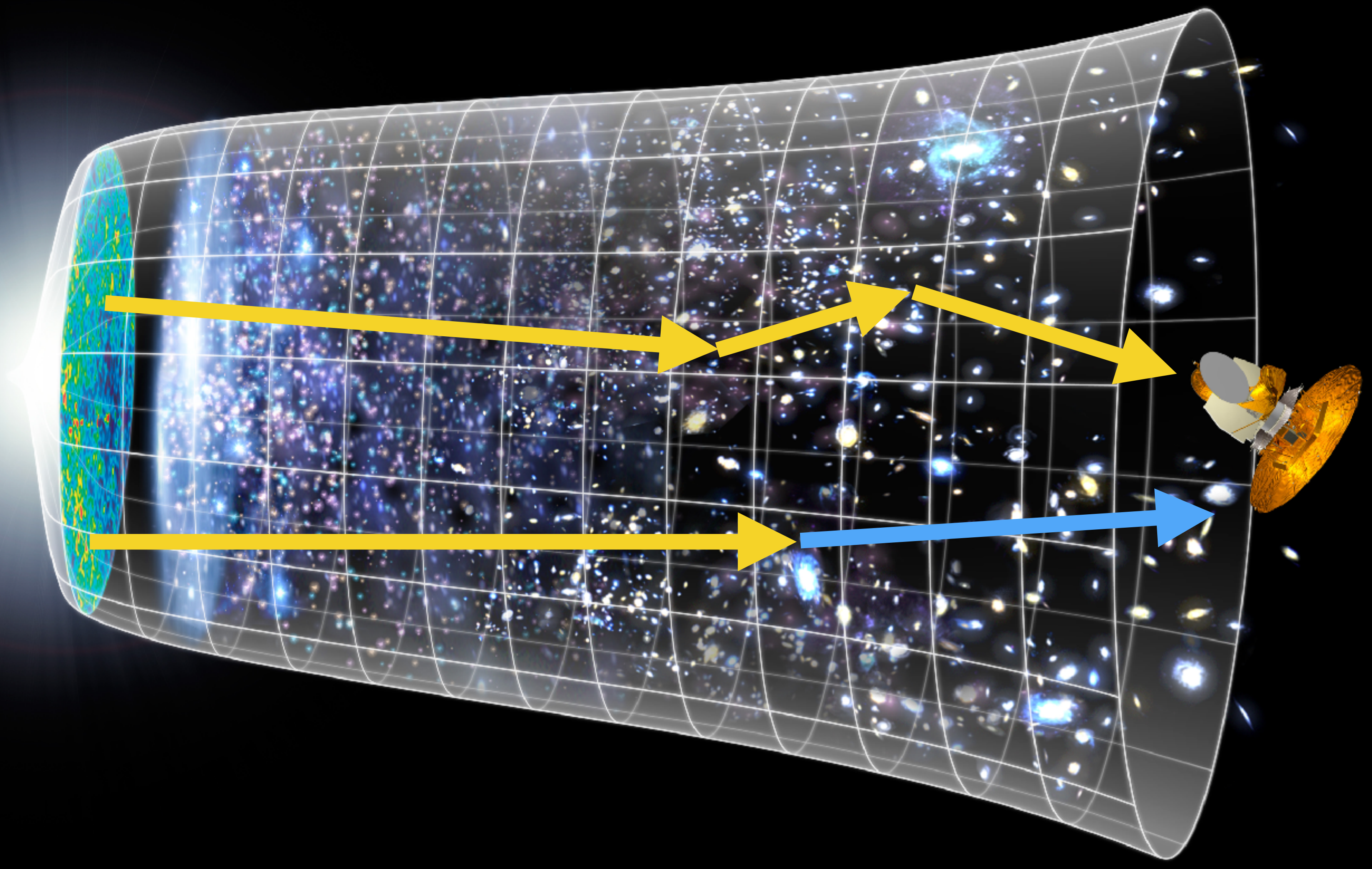
$$\Omega_{\text{th}}(z) \equiv \frac{\rho_{\text{th}}(z)}{\rho_{\text{crit}}} = \frac{\langle P_{\text{th}}(z) \rangle}{\rho_{\text{crit}} (1+z)^3},$$

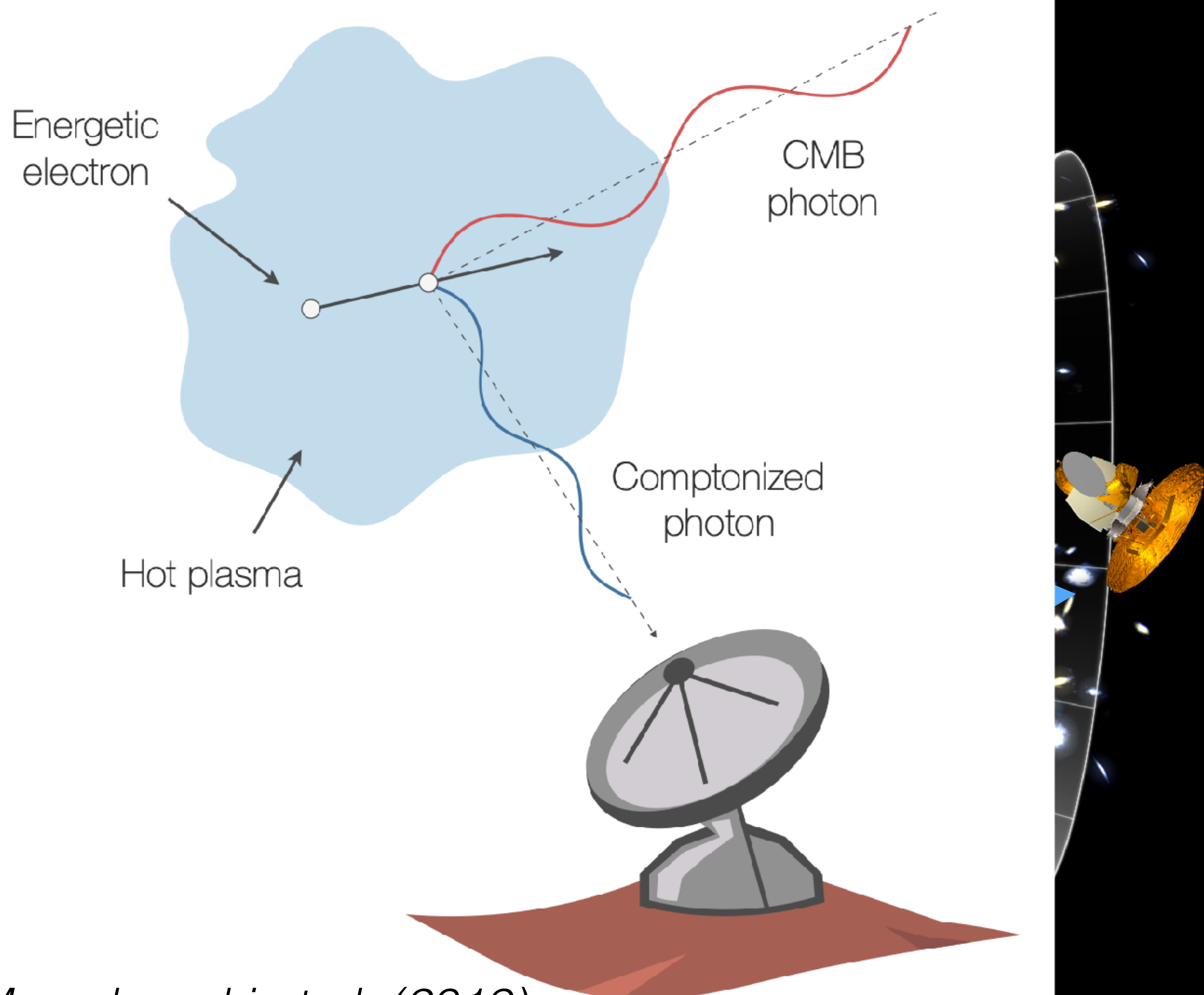
where  $\rho_{\text{crit}} = 1.054 \times 10^4 h^2 \text{ eV cm}^{-3}$  is the present-day critical energy density.

# Order-of-magnitude estimate

There is more than one way to do this. Here is one example.

- $P_{\text{th}} = \rho_{\text{gas}}\sigma^2$ , where  $\sigma^2$  is some typical 1D velocity dispersion in the large-scale structure.
- $\Omega_{\text{th}} = \Omega_{\text{gas}}\sigma^2 \sim \mathbf{2 \times 10^{-8}} (\Omega_{\text{gas}}/0.05)(\sigma/200 \text{ km/s})^2$
- *Spoiler: our measurement gives  $\Omega_{\text{th}} = (1.7 \pm 0.1) \times 10^{-8}$  at  $z=0$ . Not bad, but this isn't actually the right way to do it in detail.*
- OK, let's go. We use the thermal Sunyaev-Zeldovich effect to do this measurement.





*Mroczkowski et al. (2019)*

Energetic

Wavelength [mm]

3

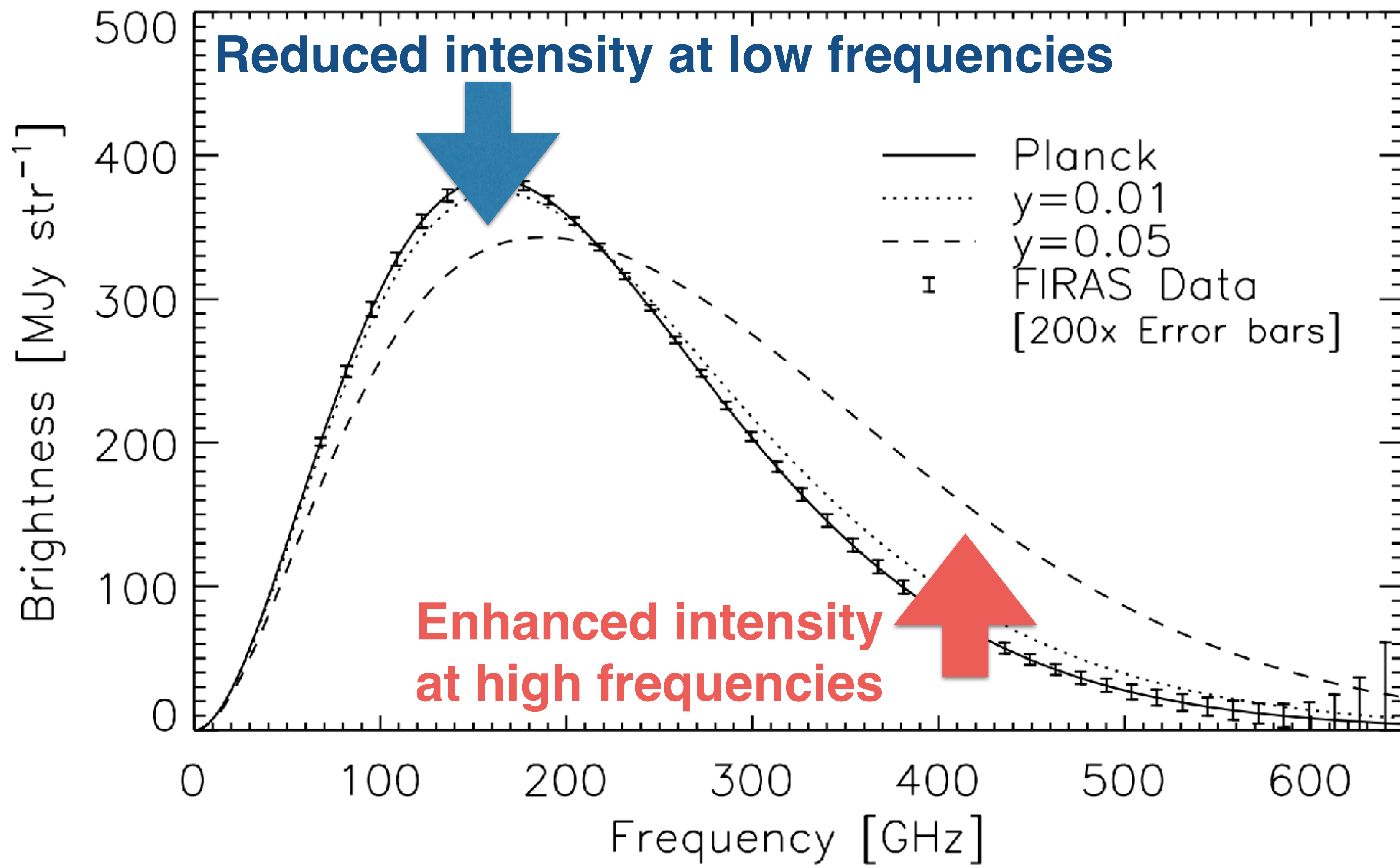
1.5

1

0.75

0.6

0.5



Energetic

Wavelength [mm]

3

1.5

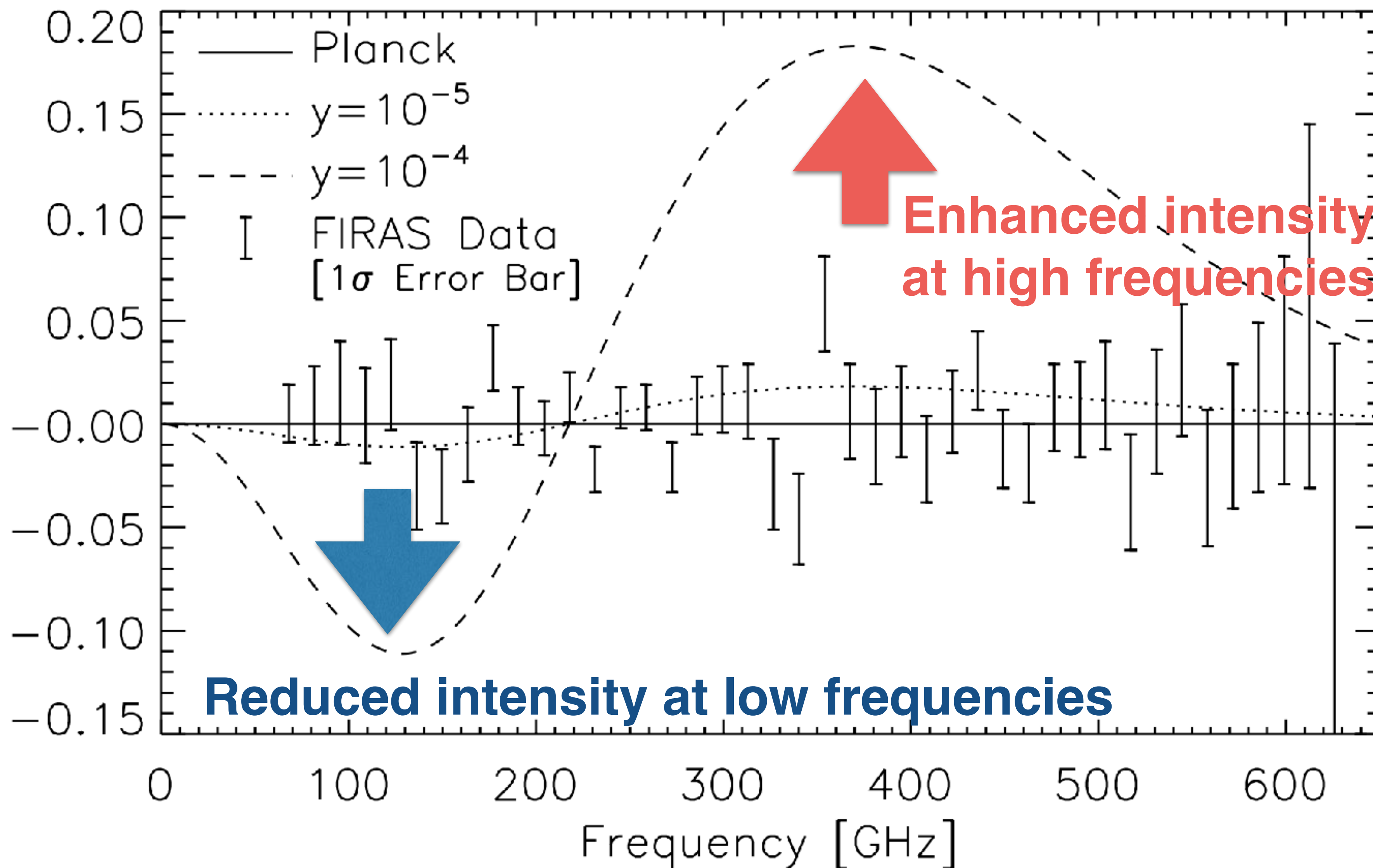
1

0.75

0.6

0.5

Brightness Difference [ $\text{MJy str}^{-1}$ ]



Energetic

Wavelength [mm]

3

1.5

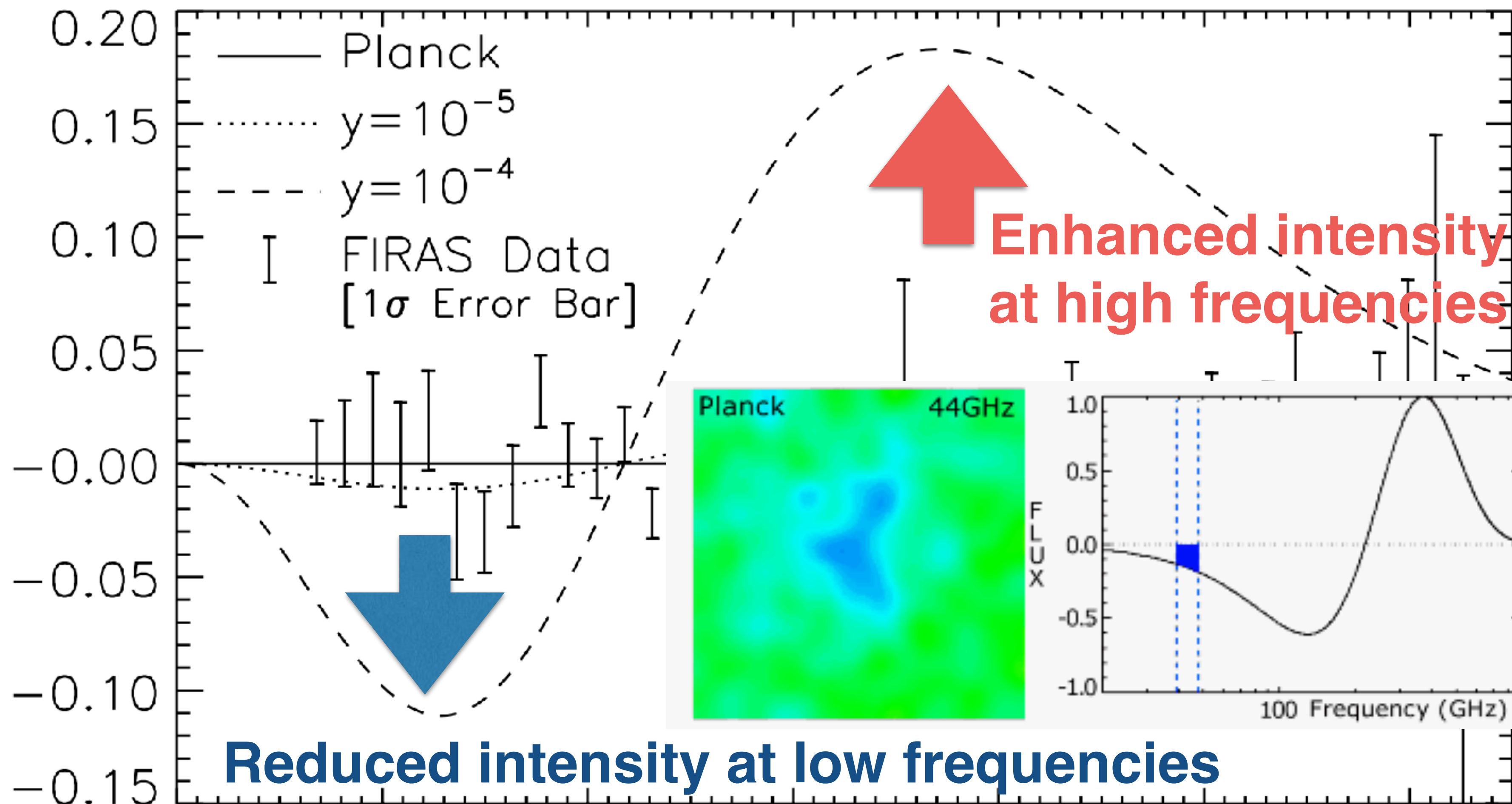
1

0.75

0.6

0.5

Brightness Difference [MJy str<sup>-1</sup>]






# Where is a galaxy cluster?

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

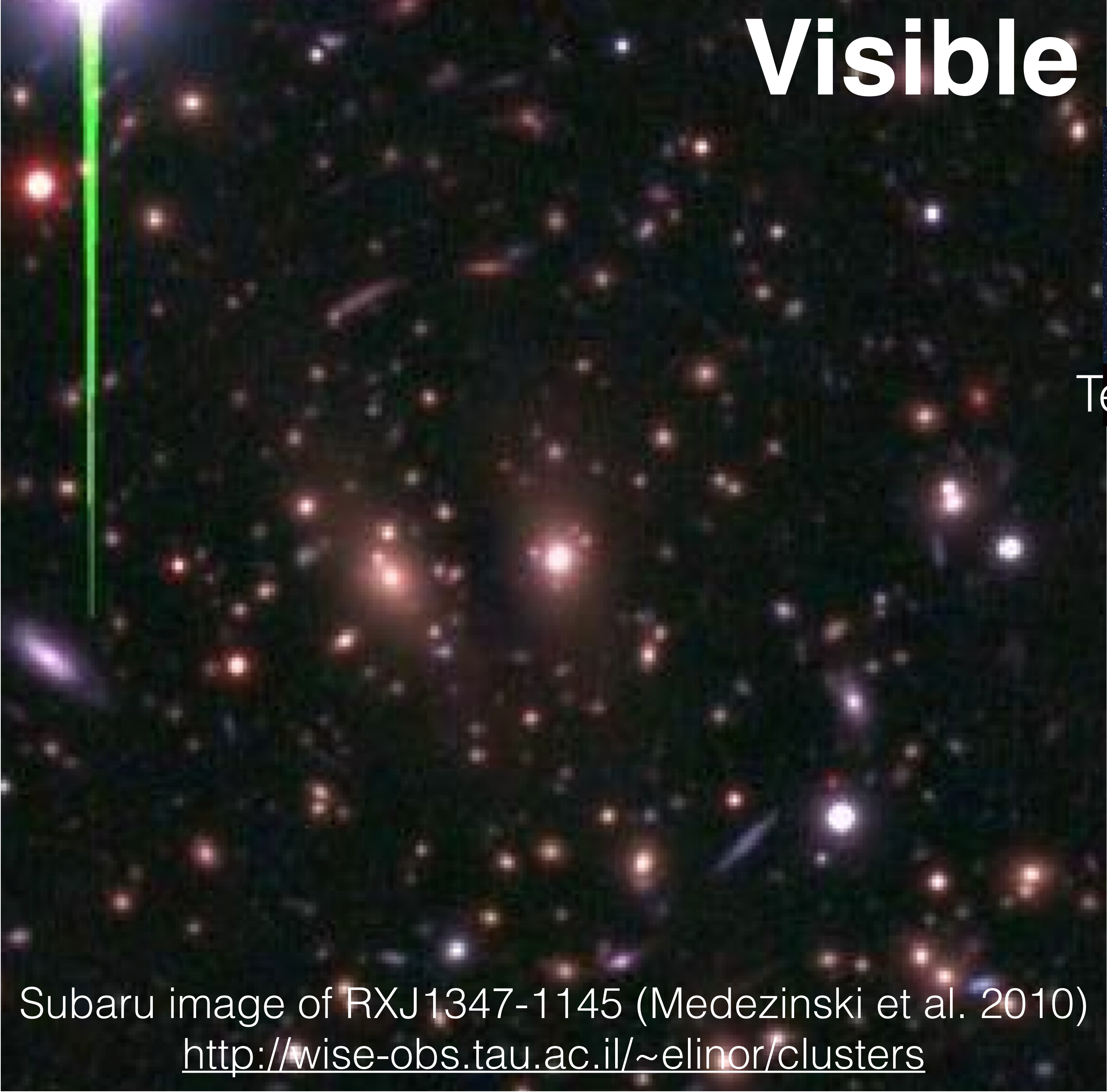
# Where is a galaxy cluster?

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

# Visible

A photograph of the Subaru telescope at night, showing its two large primary mirrors and the surrounding structure against a starry sky.

Ground-based  
Telescope (Subaru)

A large field of view from the Subaru telescope showing a dense cluster of galaxies. The galaxies are mostly red and orange, with some blue and purple ones scattered throughout. A prominent green vertical line is visible on the left side of the image.

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

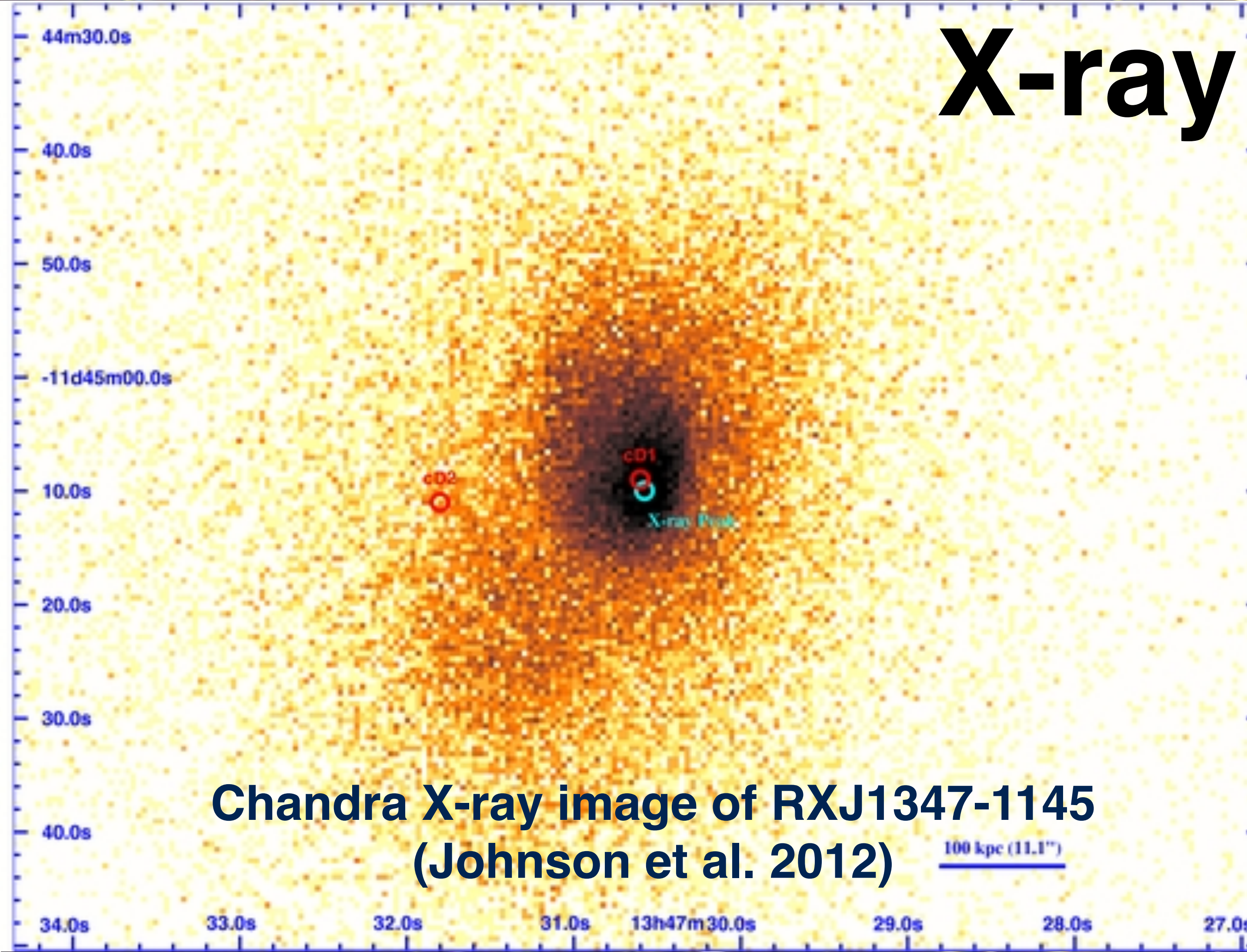
# Visible

Hubble Space  
Telescope



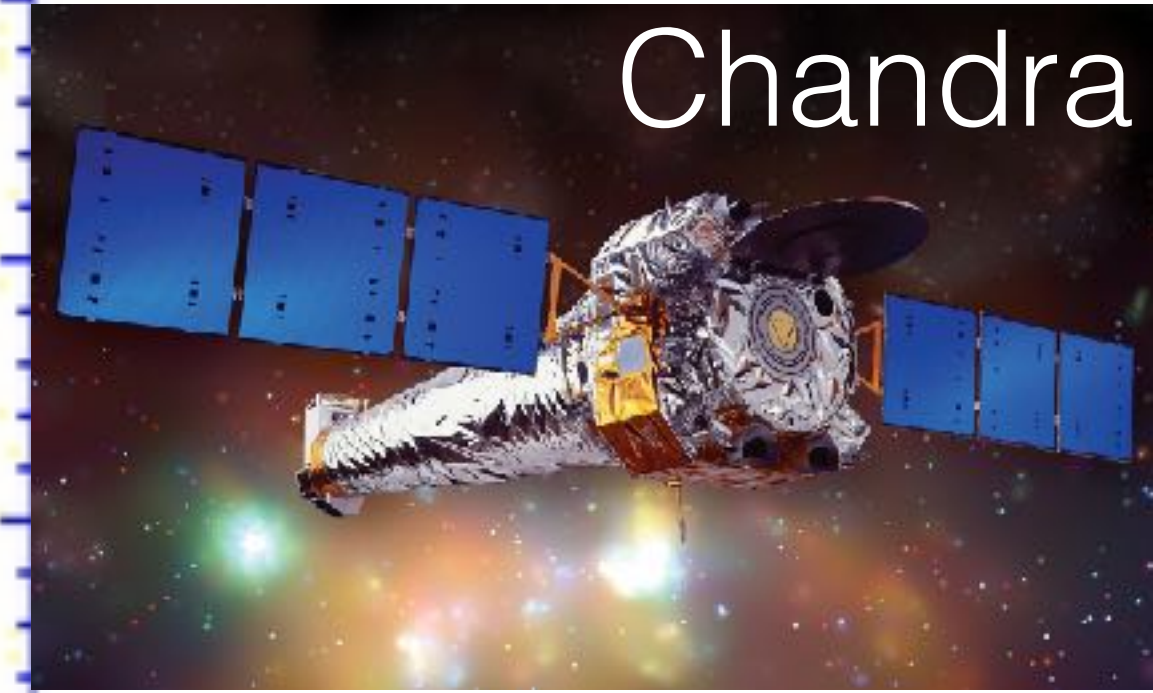
Hubble image of RXJ1347-1145 (Bradac et al. 2008)

# X-ray

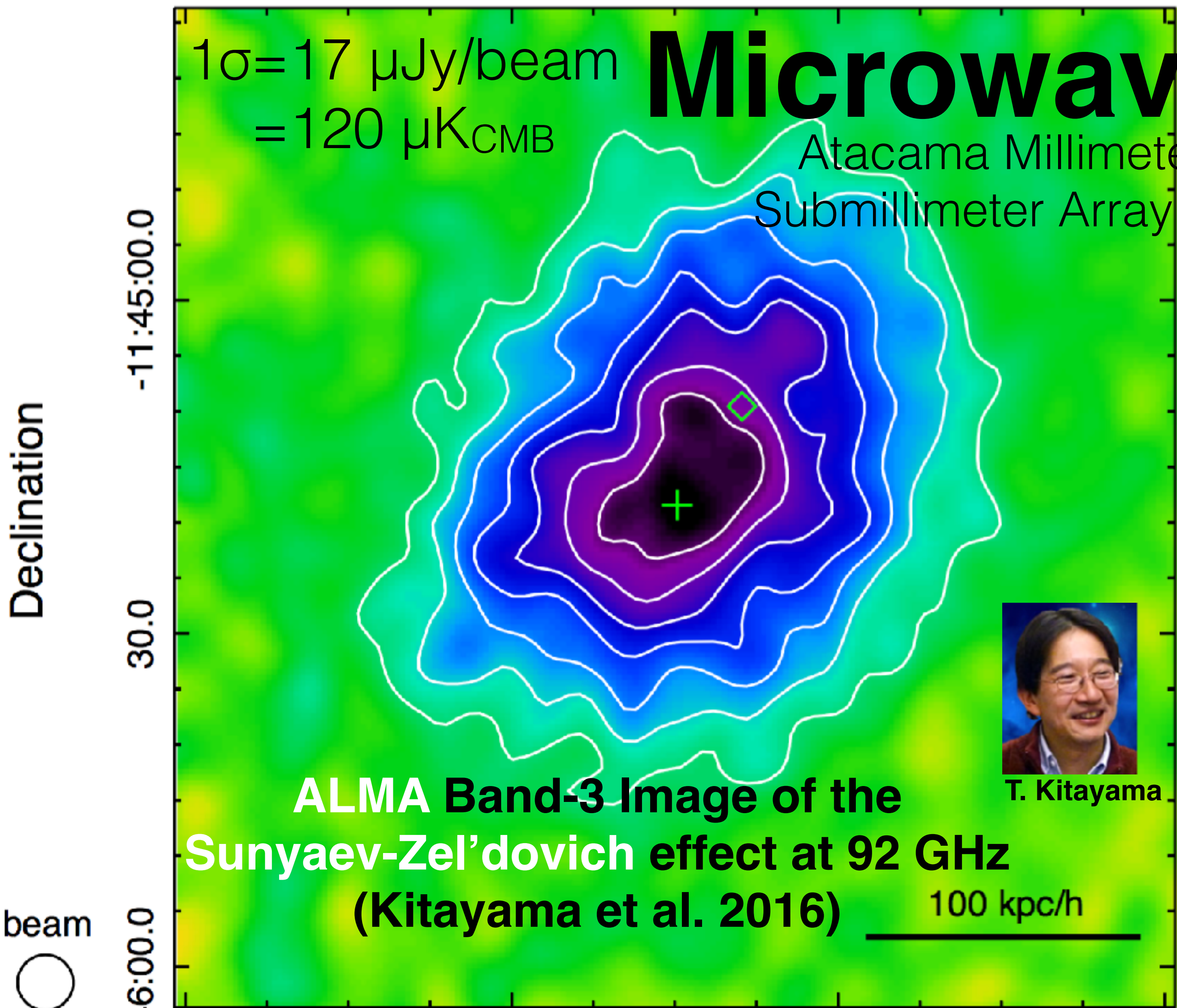


**Chandra X-ray image of RXJ1347-1145  
(Johnson et al. 2012)**

100 kpc (11.1")



Chandra



$1\sigma = 17 \mu\text{Jy}/\text{beam}$   
 $= 120 \mu\text{K}_{\text{CMB}}$

# Microwave!

Atacama Millimeter and  
 Submillimeter Array (ALMA)

**ALMA Band-3 Image of the  
 Sunyaev-Zel'dovich effect at 92 GHz  
 (Kitayama et al. 2016)**



T. Kitayama



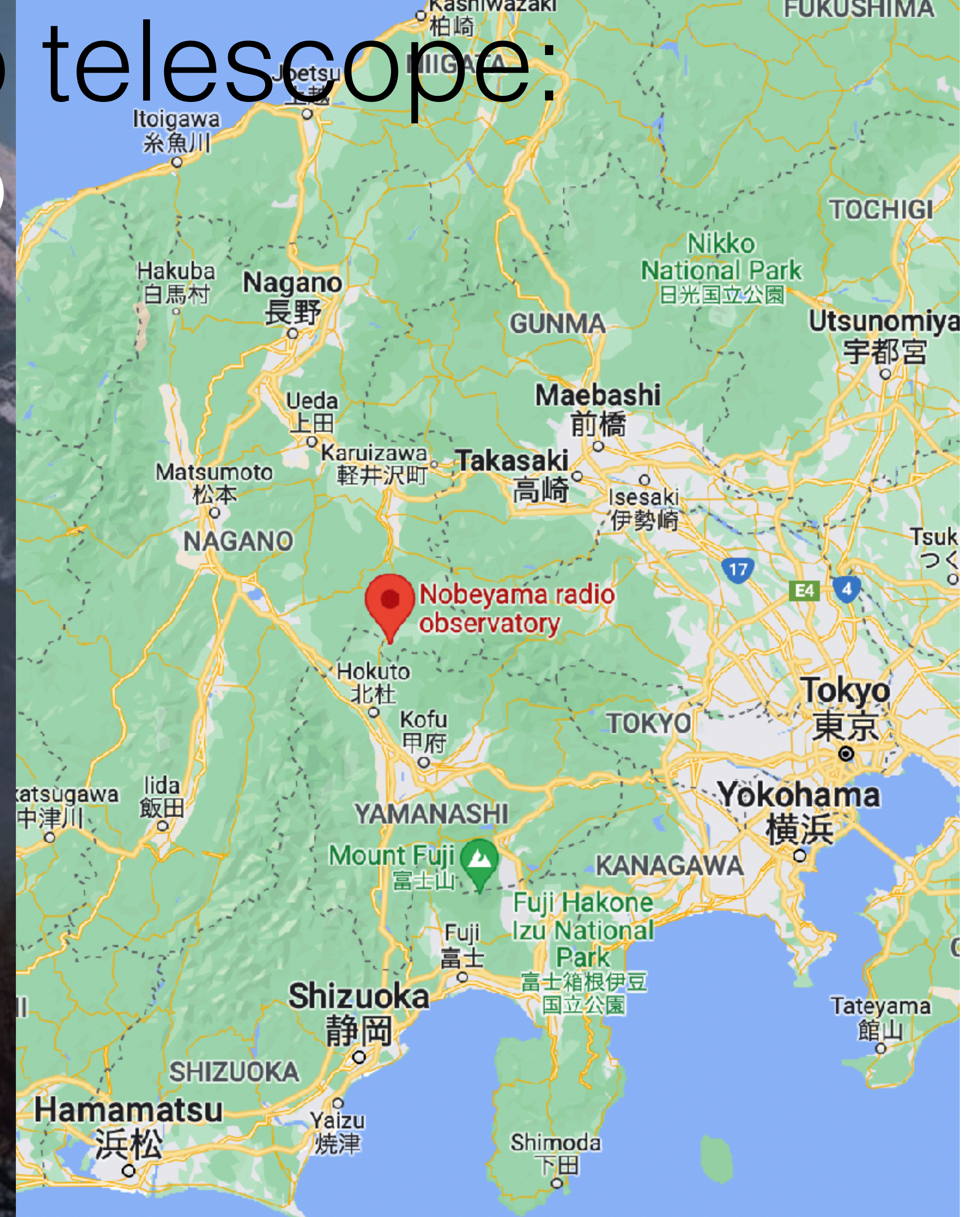
ALMA  
**5'' resolution  
 (World record)**



# My favourite radio telescope: Nobeyama Radio Observatory



我が青春の電波望遠鏡



# SZ Effect@Nobeyama!



我が青春  
In 2001

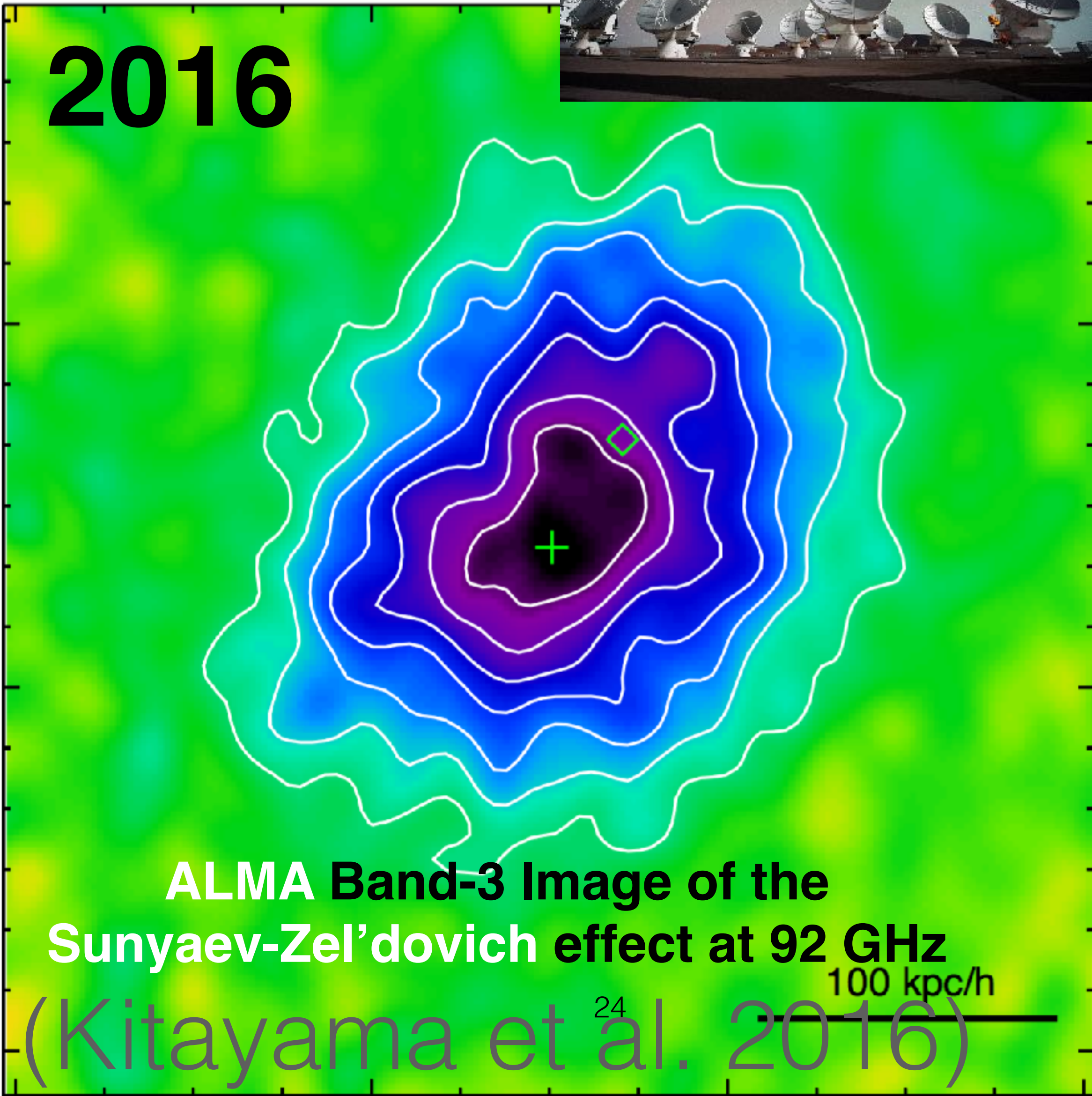
(Komatsu et al. 2001)

Declina  
30.0

beam  
6:00.0



ALMA  
5" resolution  
(World record)



2016

ALMA Band-3 Image of the  
Sunyaev-Zel'dovich effect at 92 GHz

(Kitayama et al. 2016)

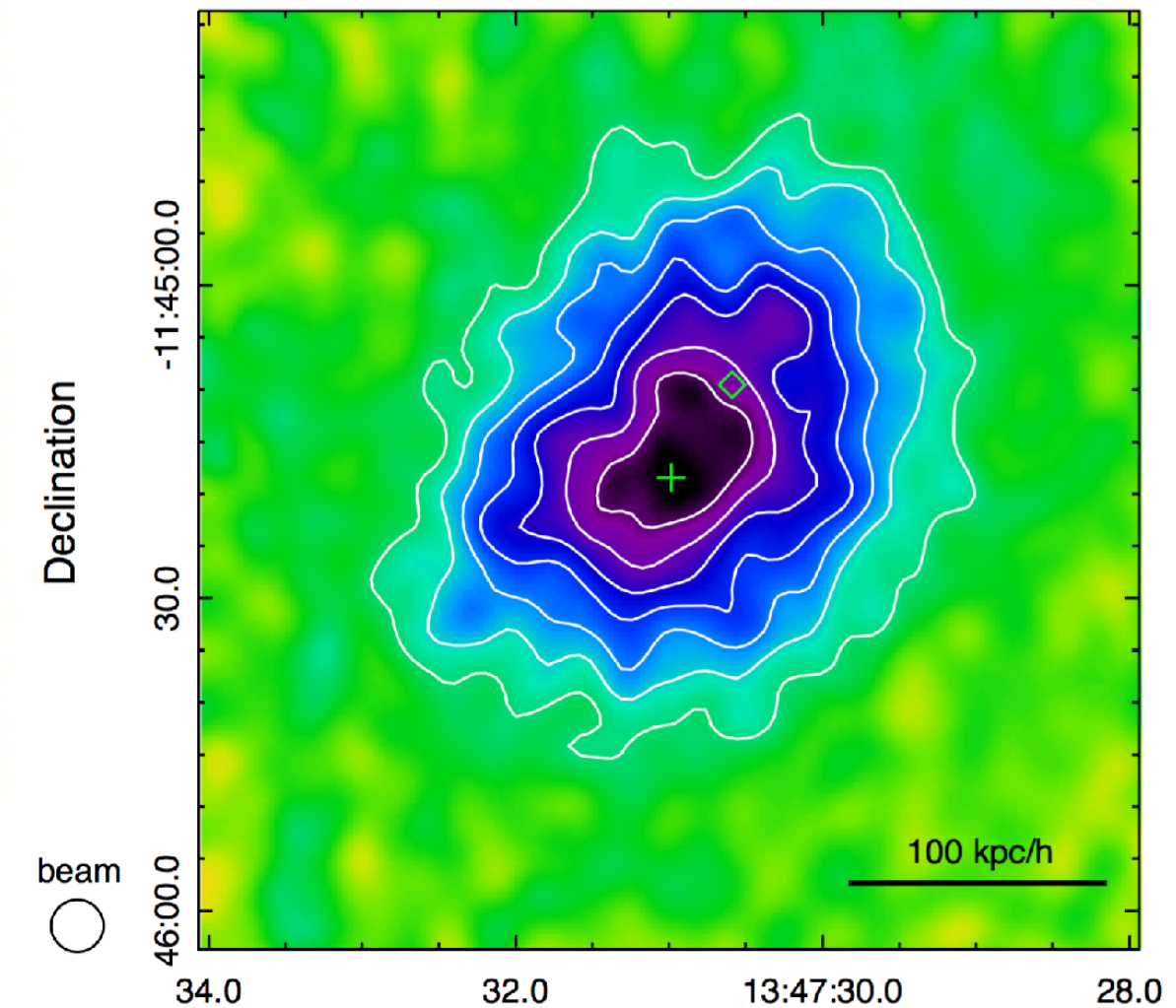
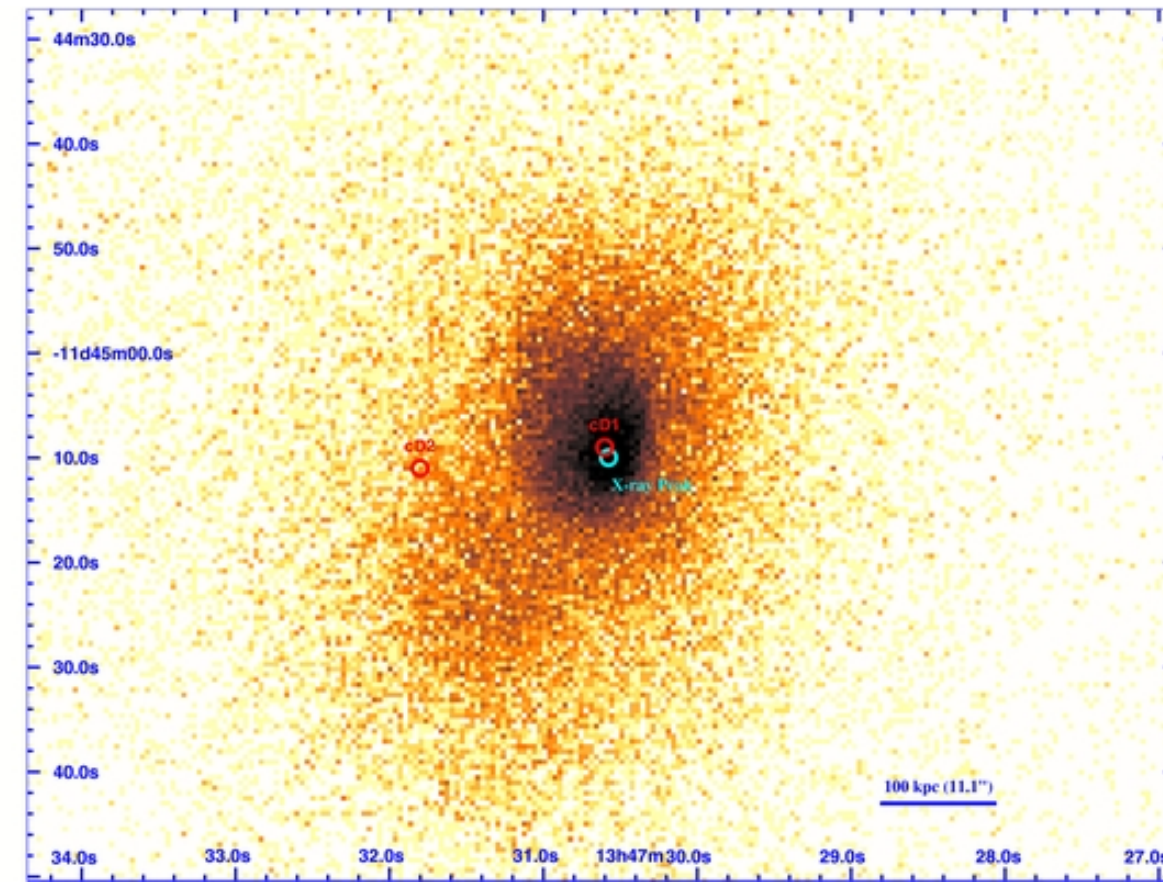
100 kpc/h

24



# Multi-wavelength Data

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



## Optical:

- $10^{2-3}$  galaxies
- velocity dispersion
- gravitational lensing

## X-ray:

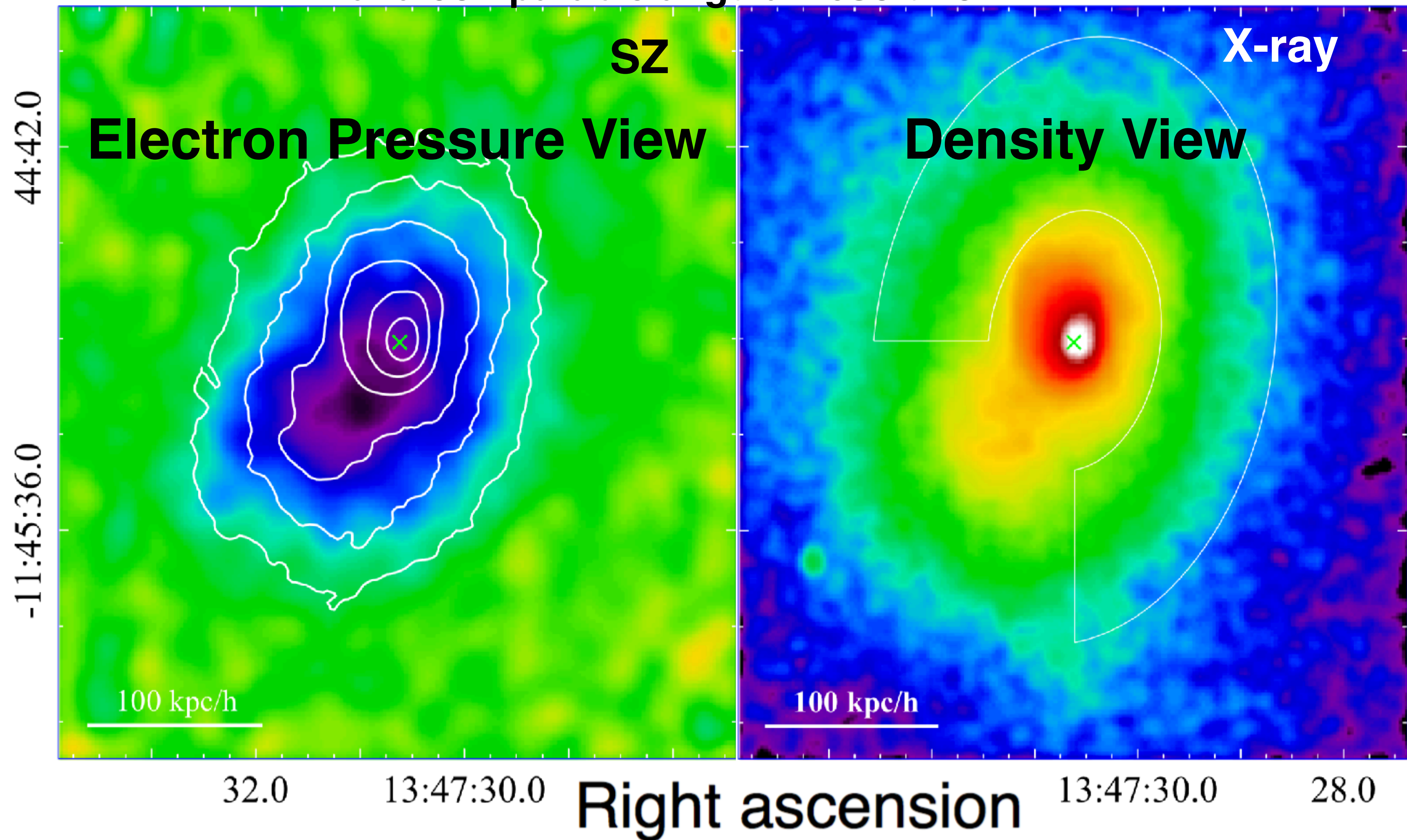
- hot gas ( $10^{7-8}$  K)
- spectroscopic  $T_X$
- Intensity  $\sim n_e^2 L$

## SZ [microwave]:

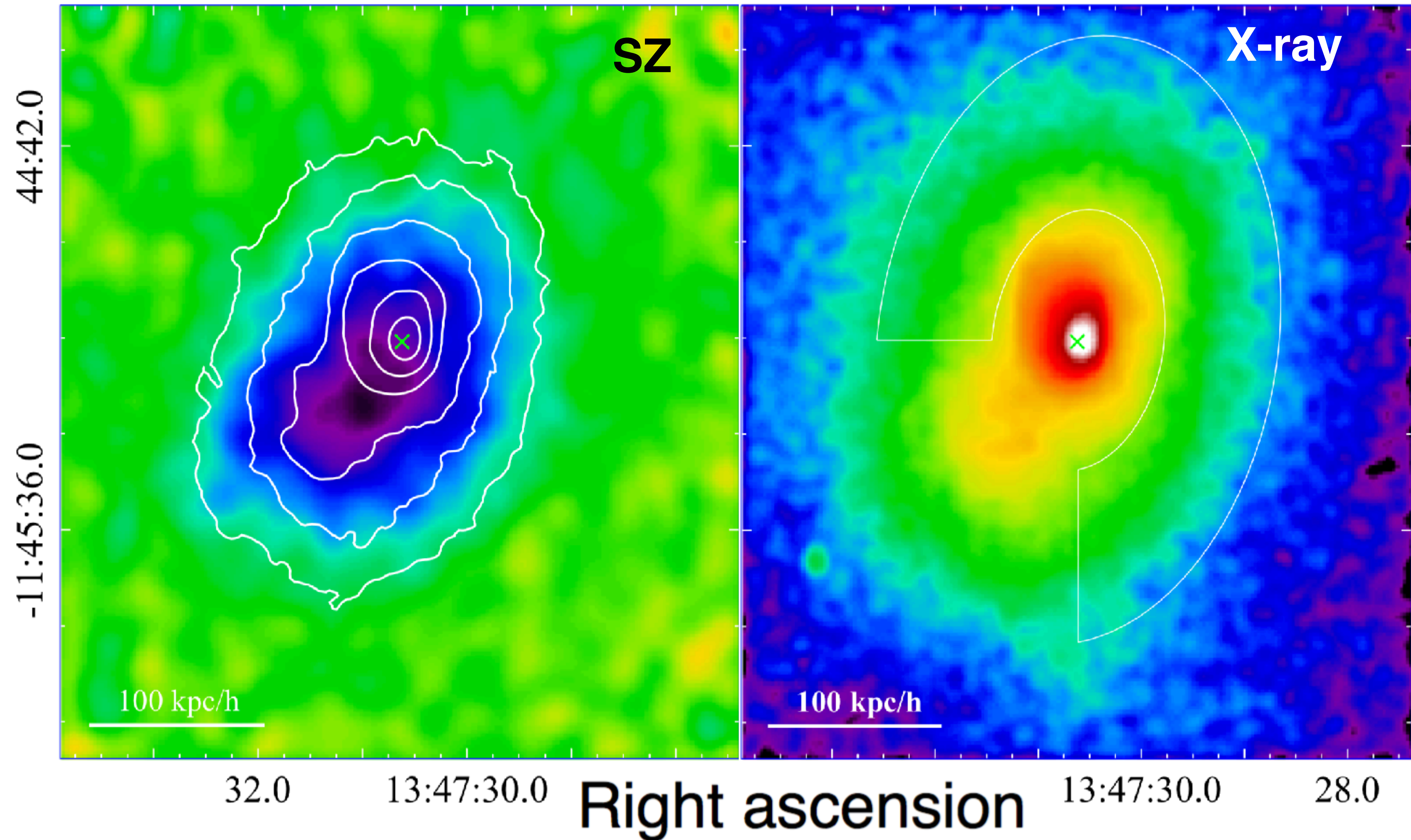
- hot gas ( $10^{7-8}$  K)
- electron pressure
- Intensity  $\sim n_e T_e L$

# They are similar, but not quite the same

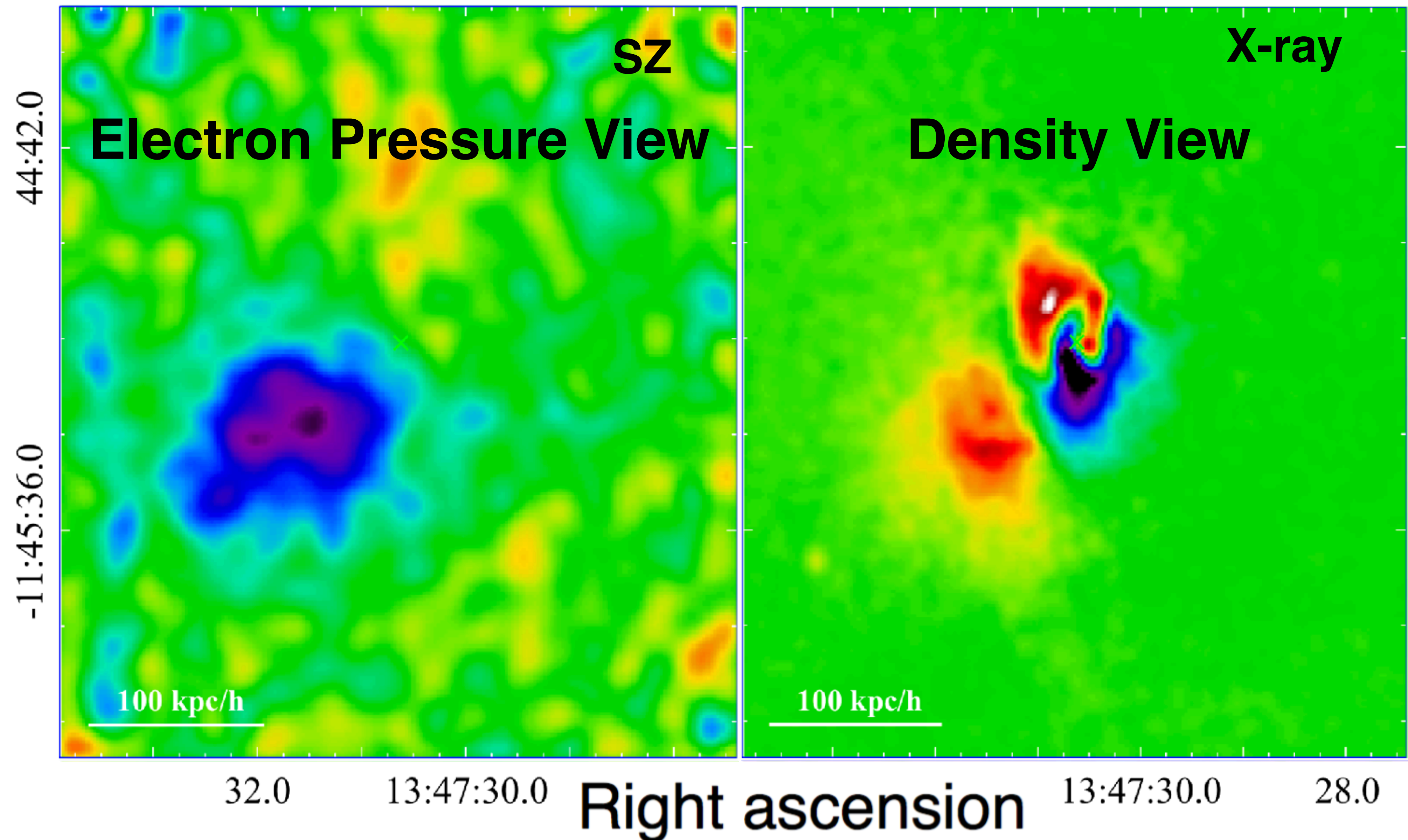
This is the first time to compare SZ and X-ray images  
at a comparable angular resolution.



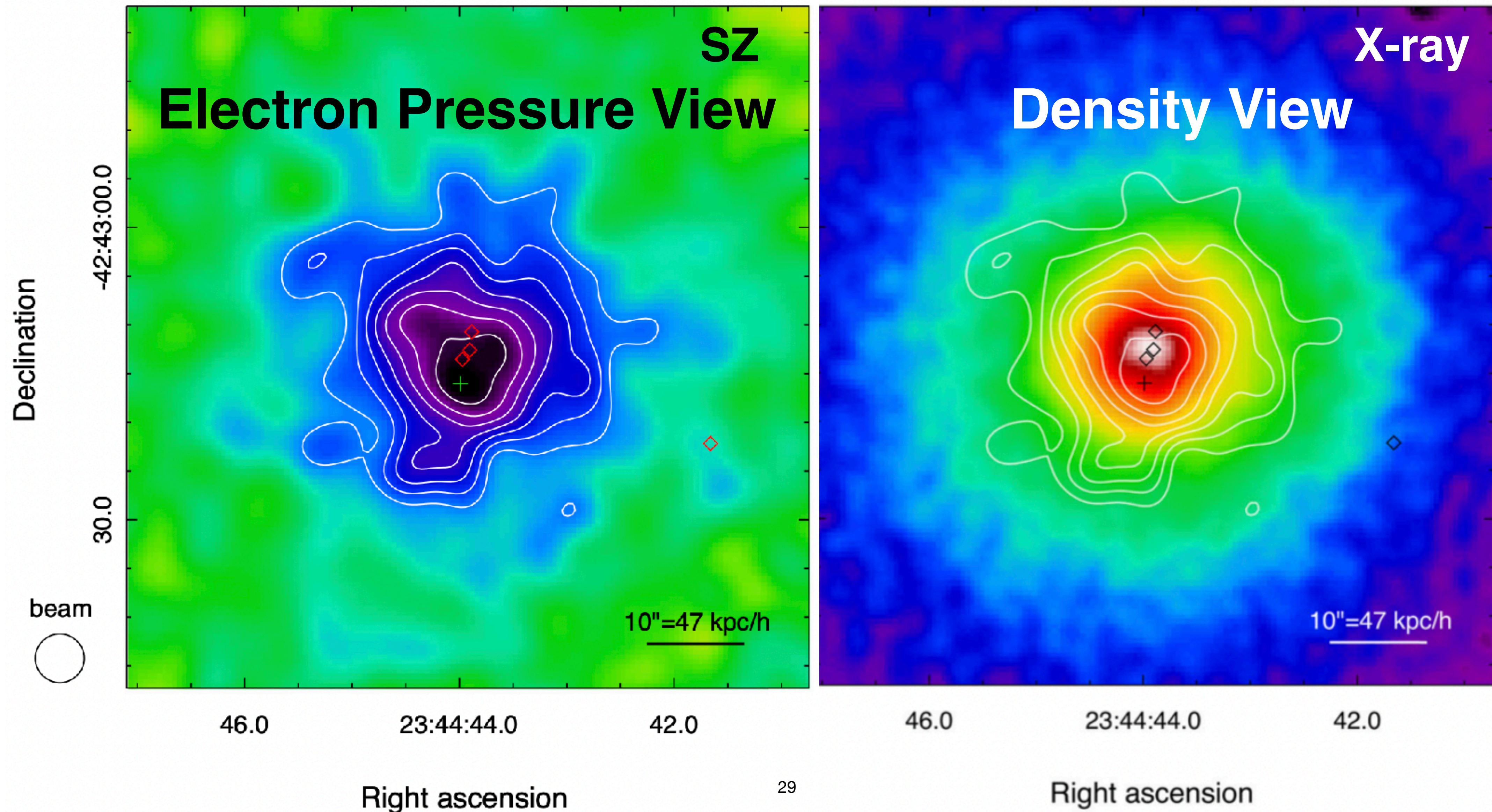
Let's subtract a smooth component



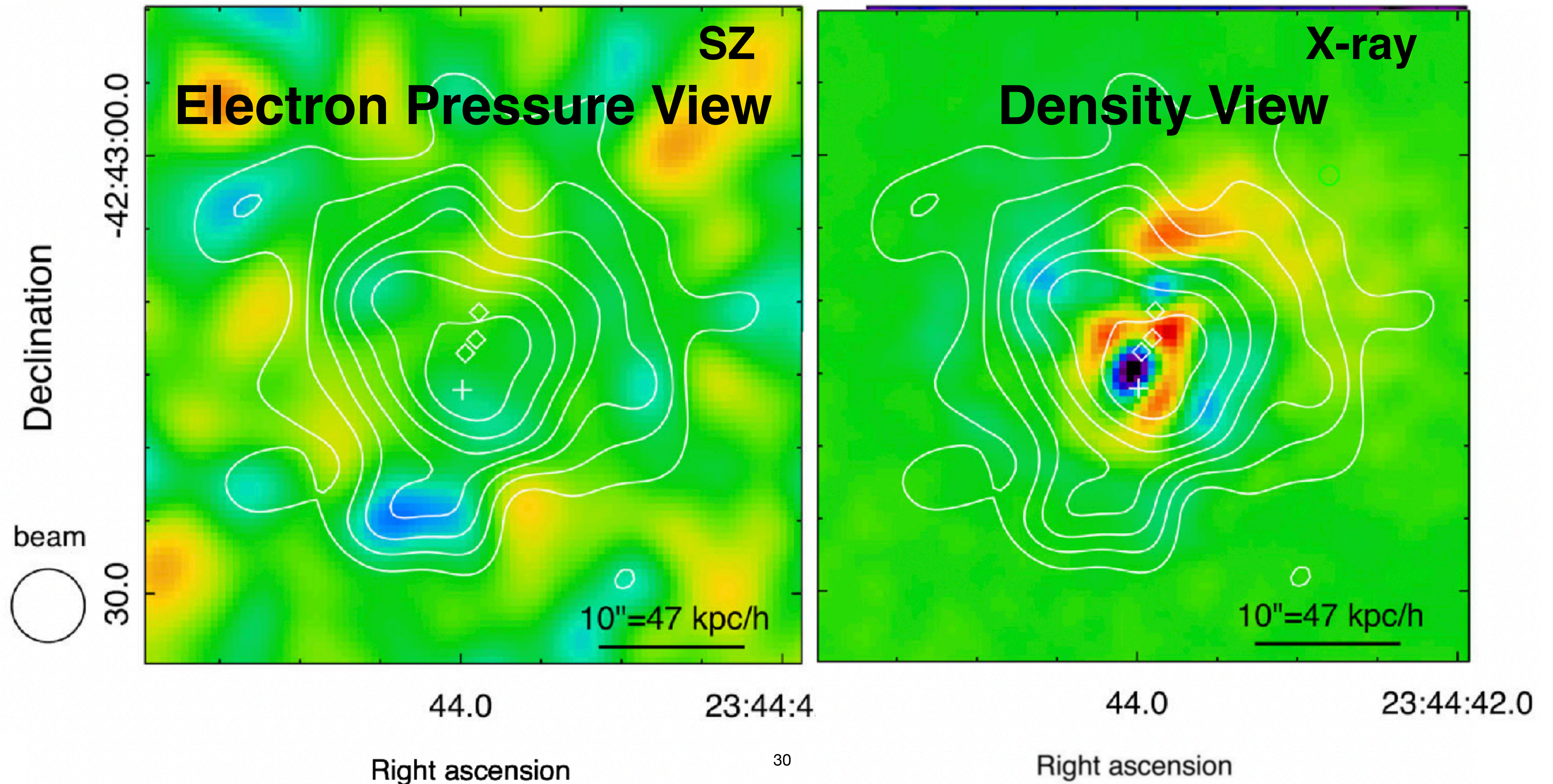
Let's subtract a smooth component



# Another example: Phoenix Cluster ( $z=0.597$ )

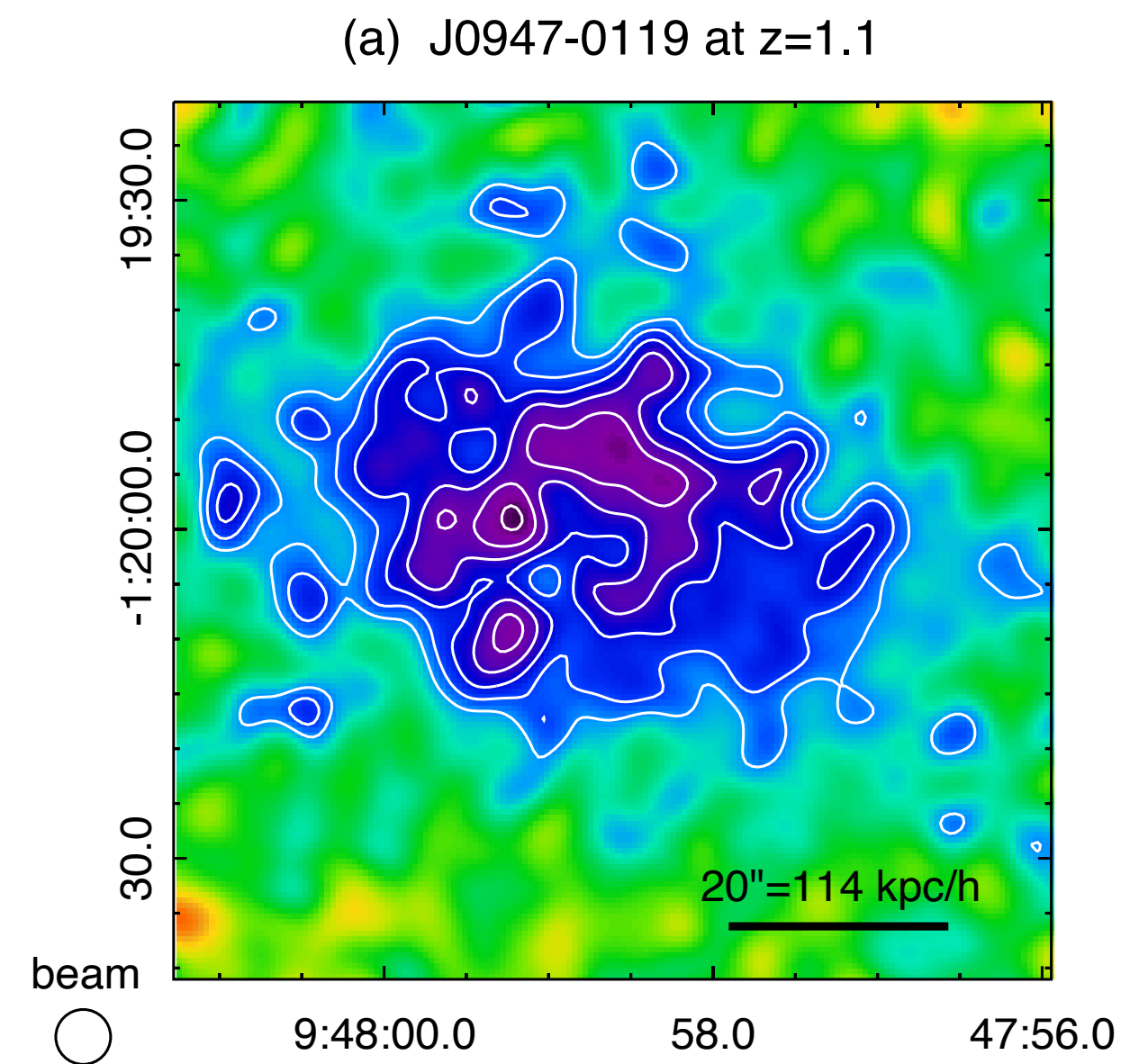


# Another example: Phoenix Cluster ( $z=0.597$ )

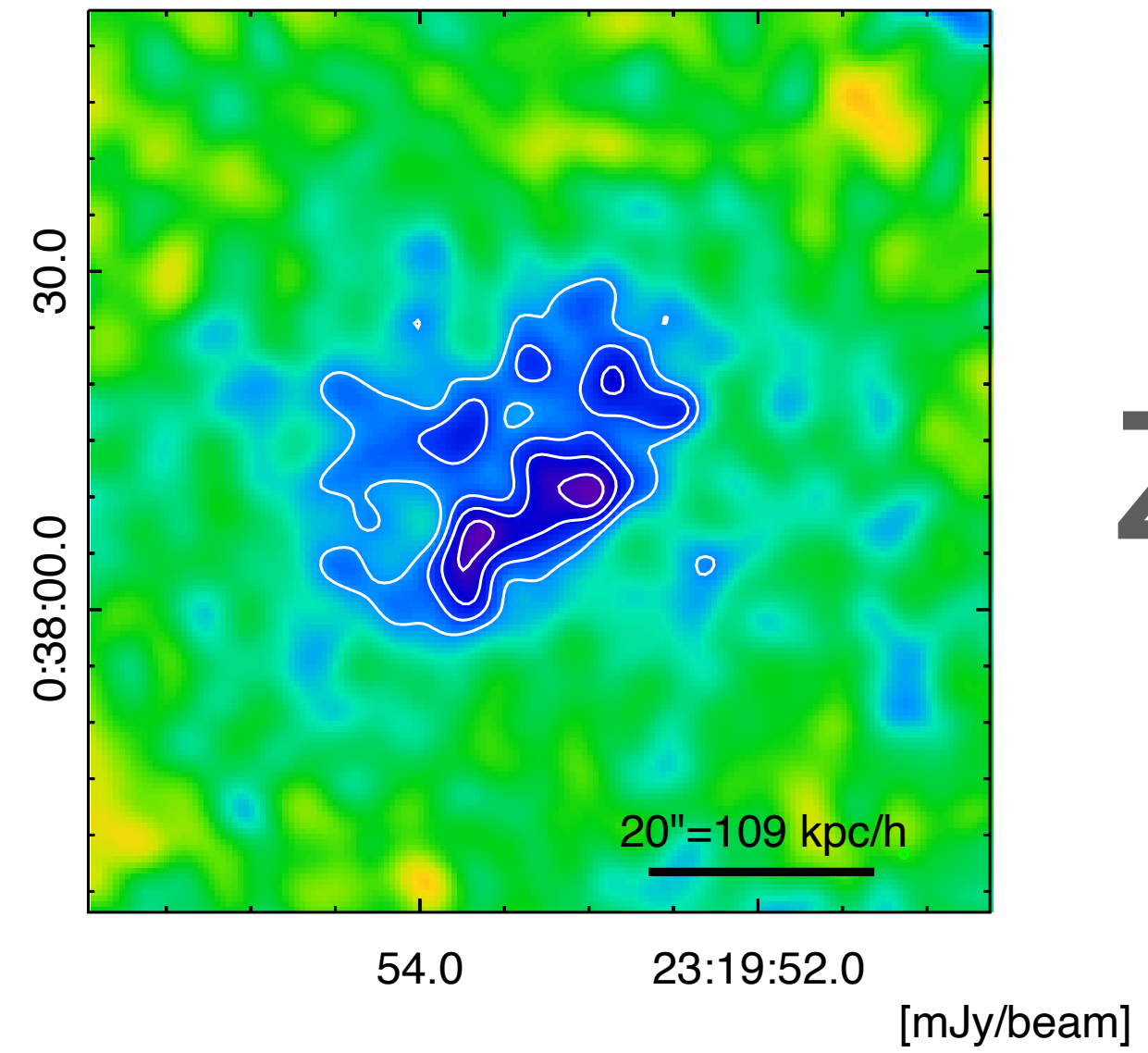


# Gallery of the highest-resolution SZ images

$z=1.1$

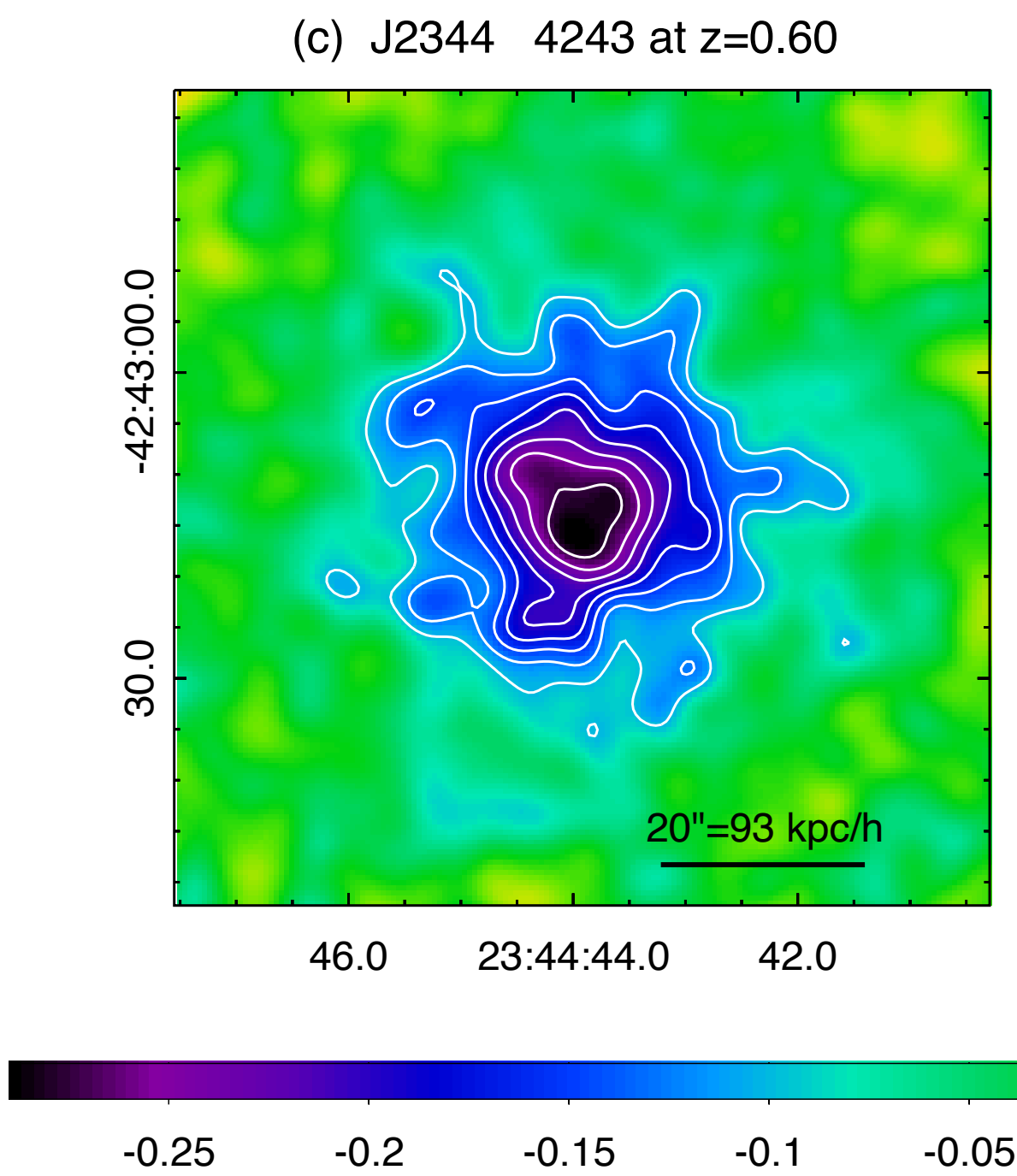


(b) J2319+0038 at  $z=0.90$

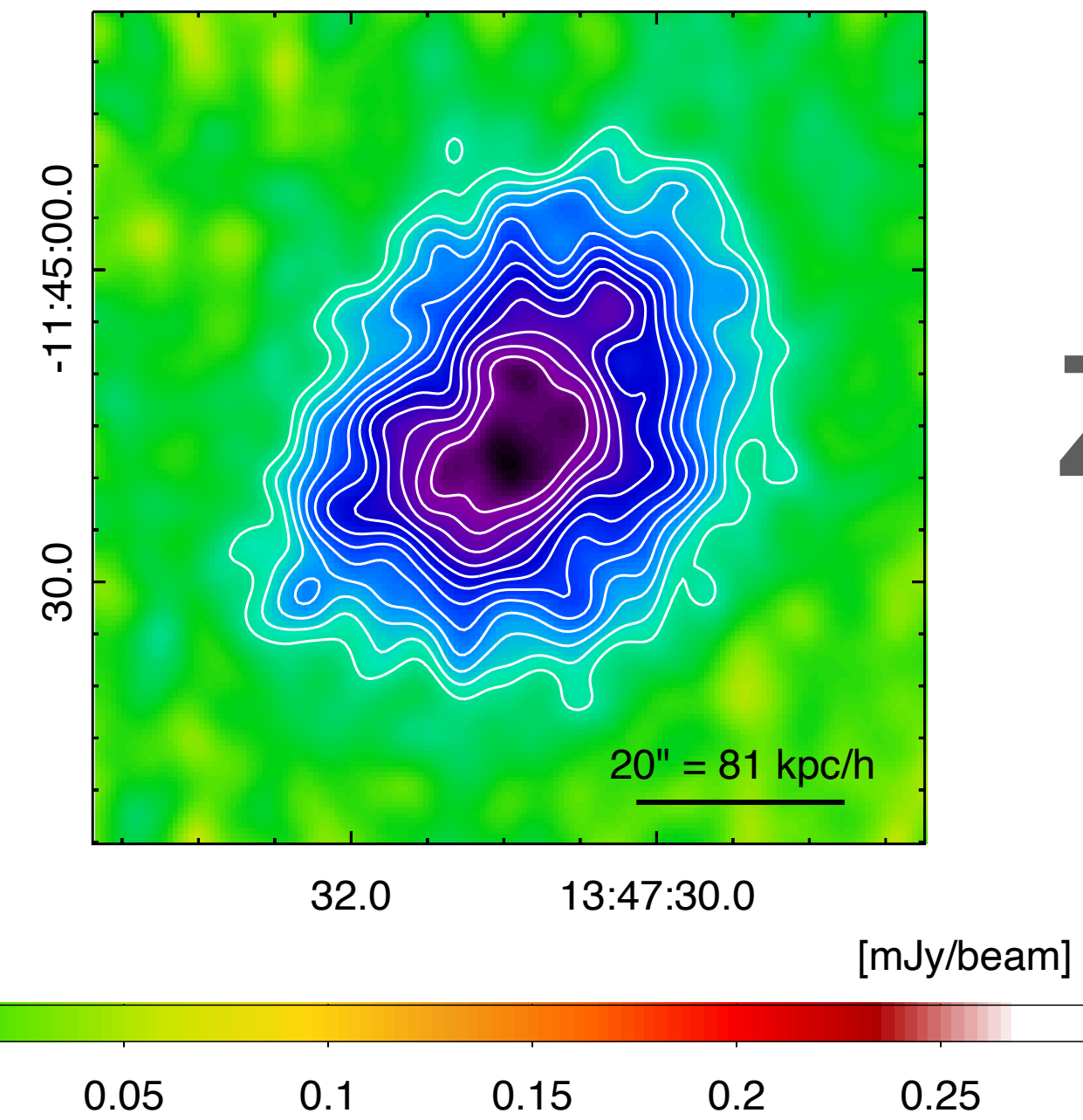


$z=0.9$

$z=0.6$



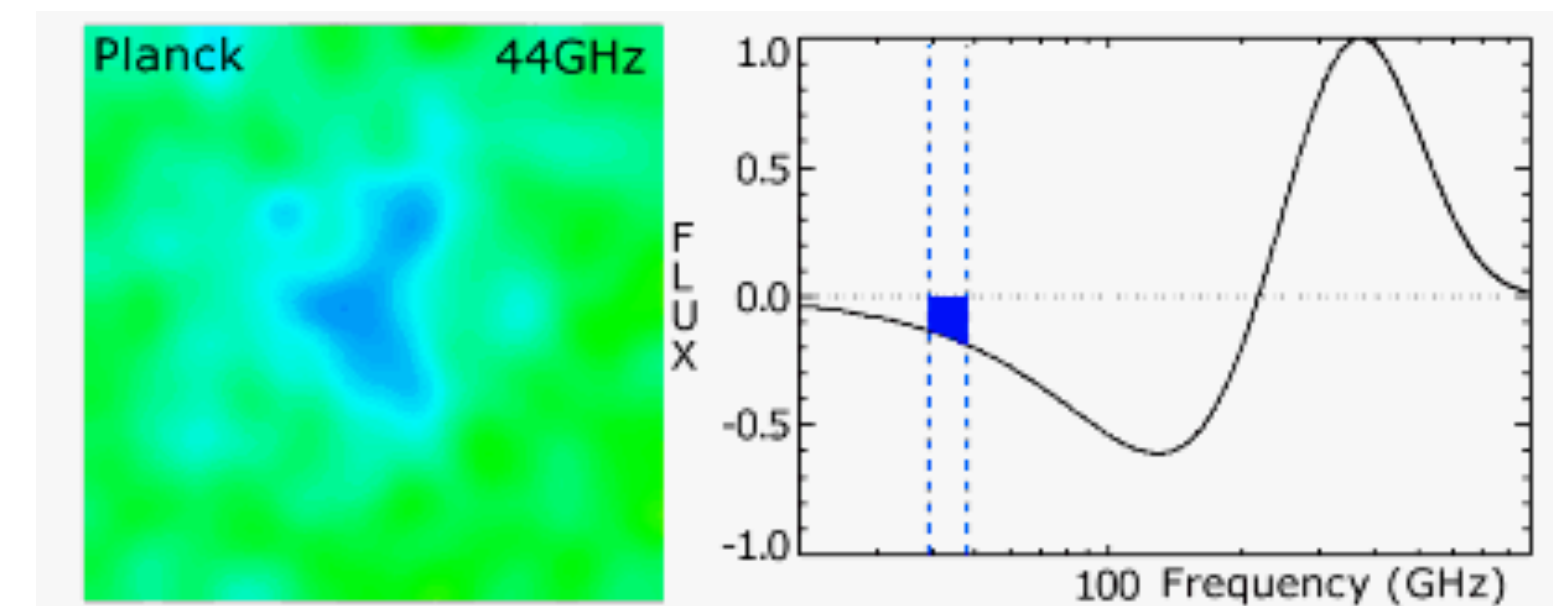
(d) J1347-1145 at  $z=0.45$



$z=0.45$

# Q1: How hot is the large-scale structure of the Universe?

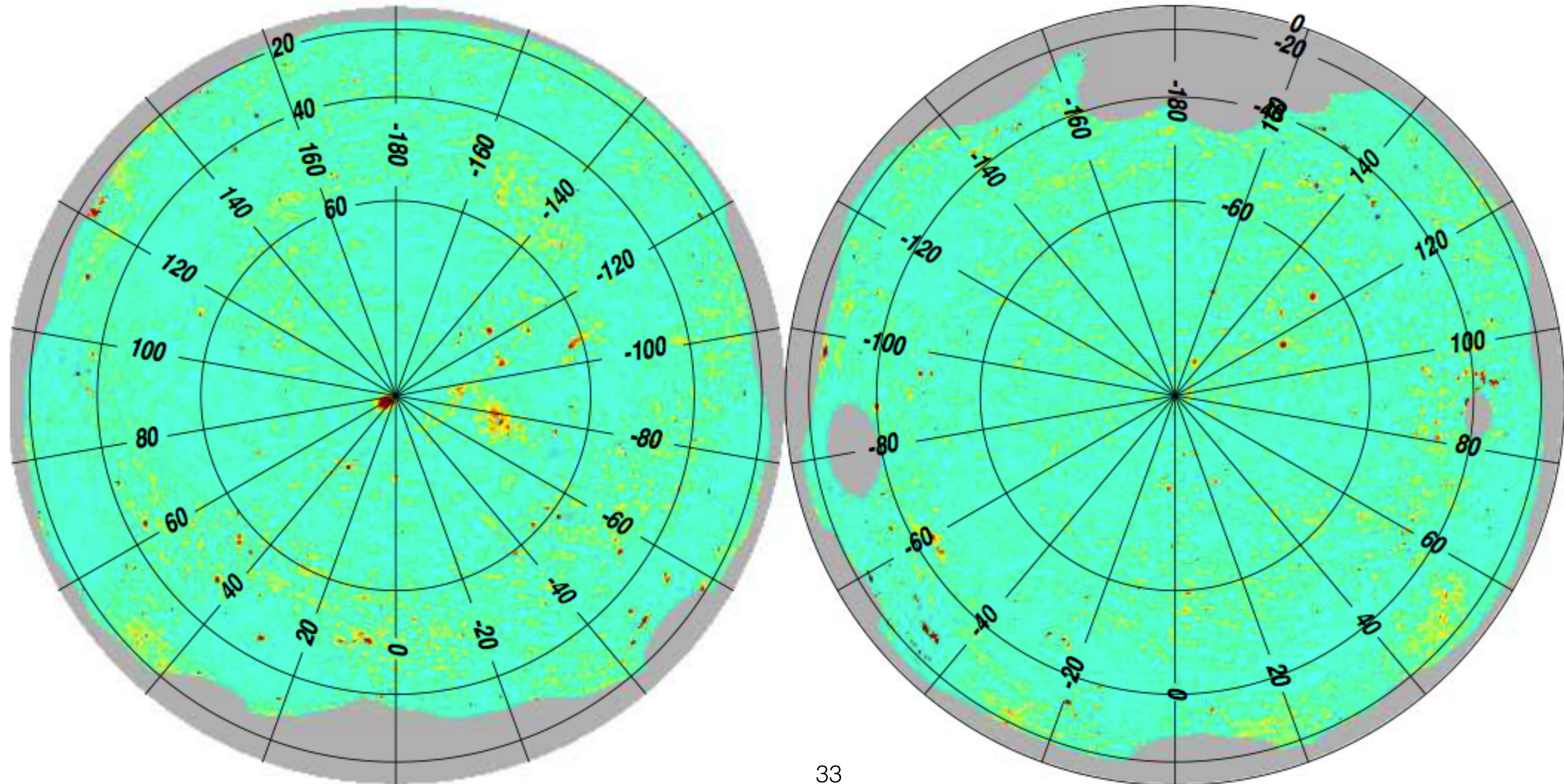
Create a full-sky SZ map using the multi-frequency data!





# Full-sky Electron Pressure Map

North Galactic Pole *MILCA tSZ map* South Galactic Pole

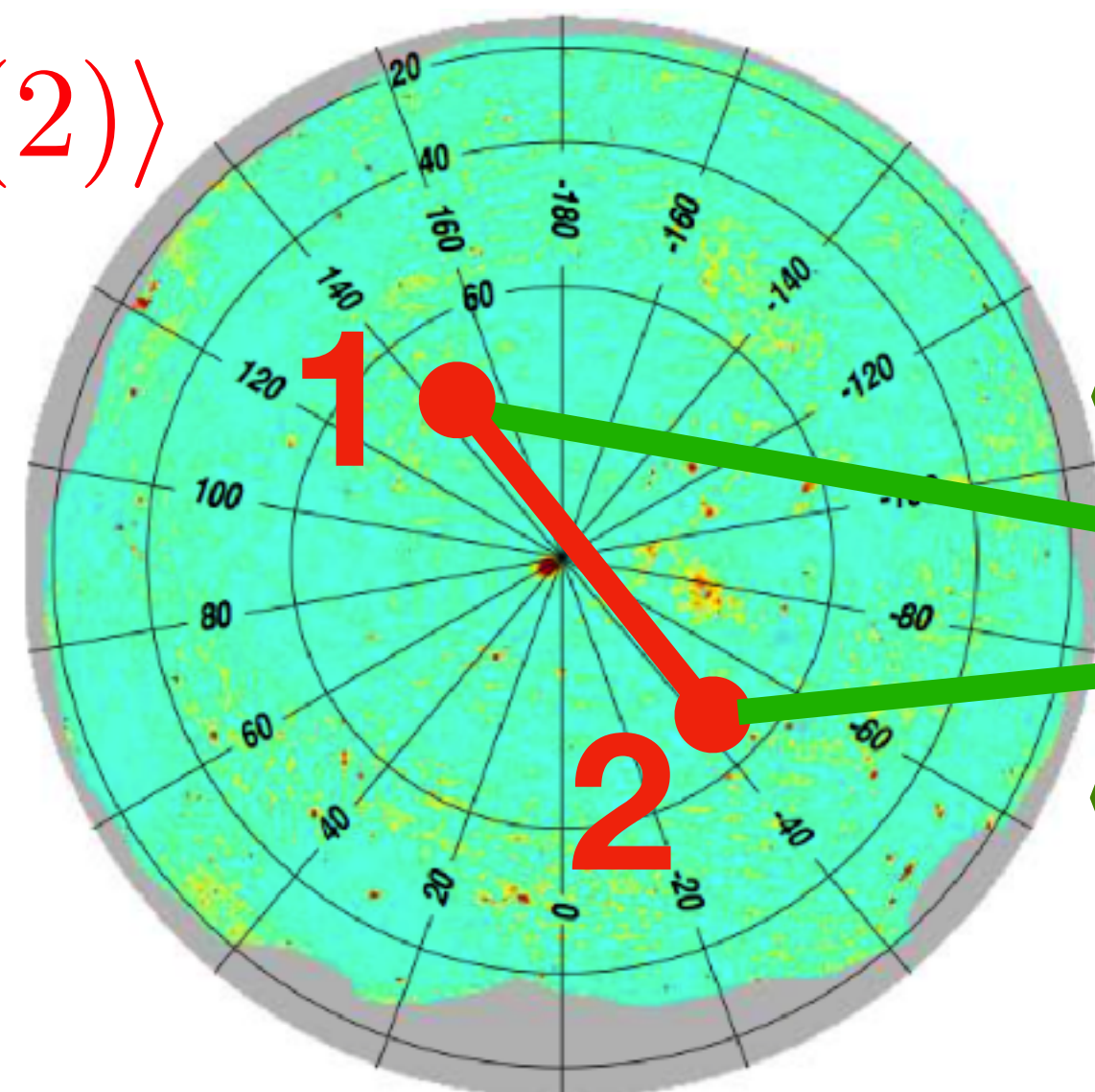


# The Limitation of the SZ data

## The need for “Tomography”

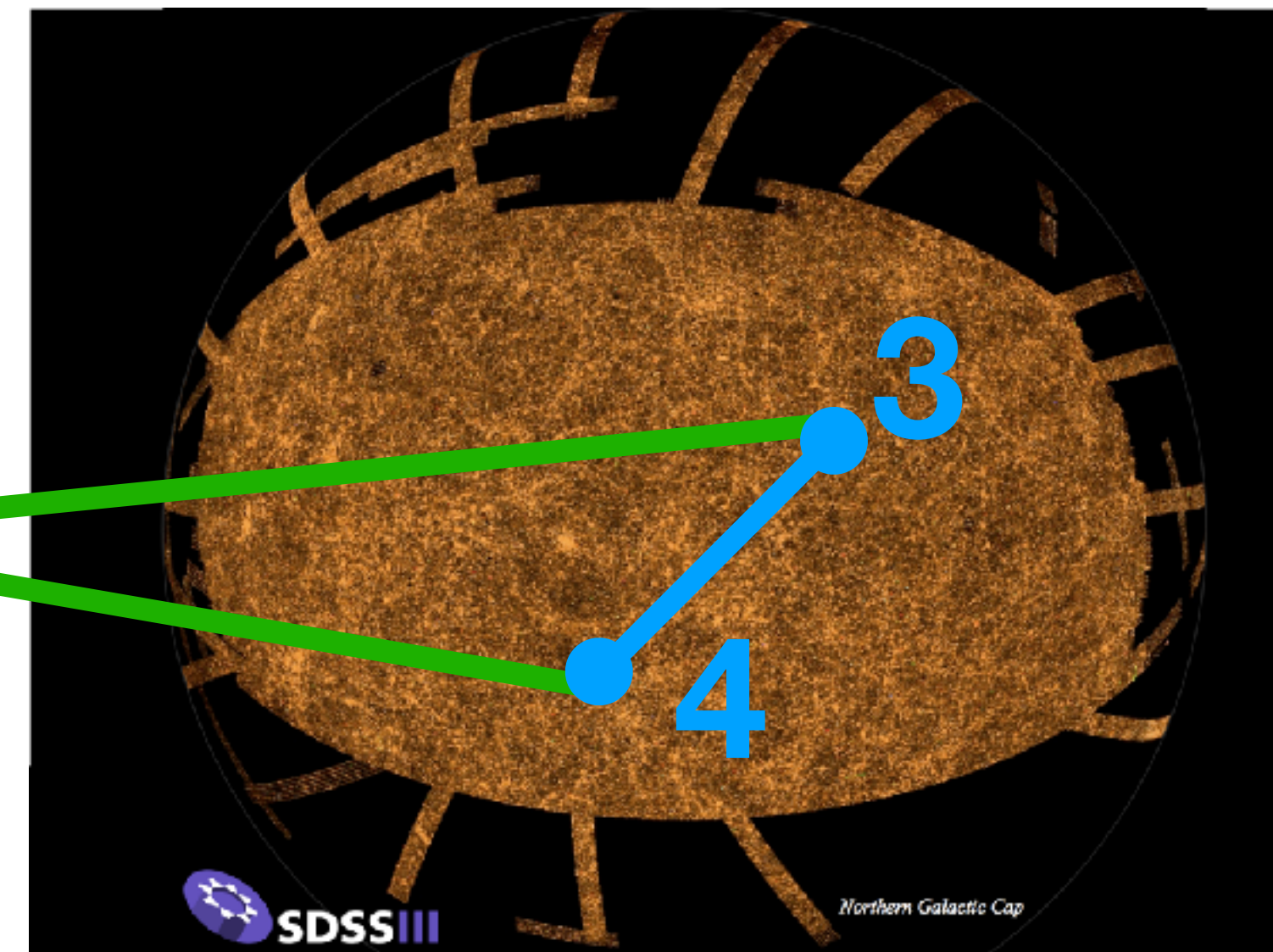
- This map gives us all the hot electron pressure **in projection**.
  - No redshift information.
- We can overcome this limitation by cross-correlating the SZ map with the locations of galaxies with the known redshifts => **the SZ tomography**.

$$\langle \delta_{\text{SZ}}(1) \delta_{\text{SZ}}(2) \rangle$$



$$\langle \delta_{\text{SZ}}(1) \delta_{\text{gal}}(4) \rangle$$

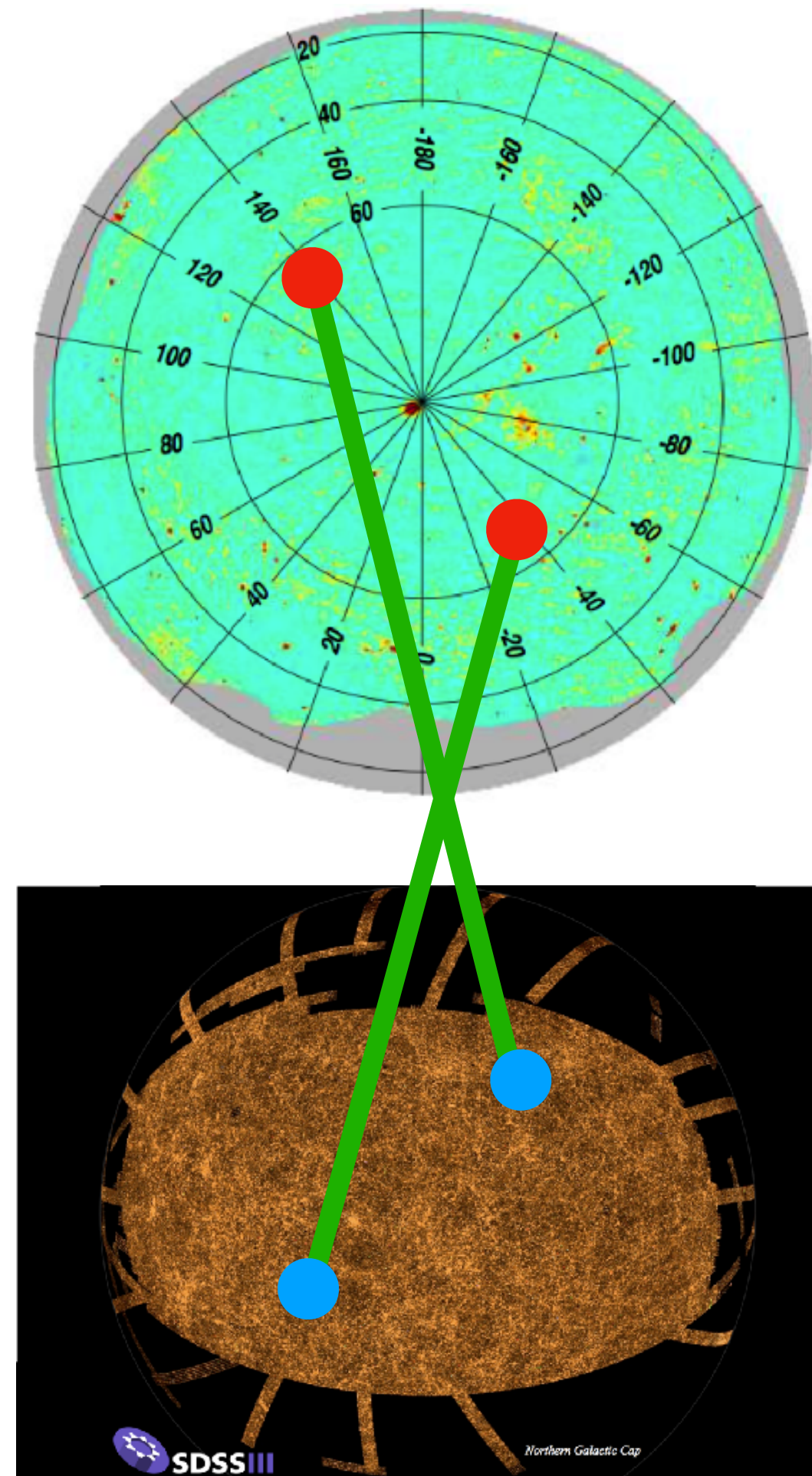
$$\langle \delta_{\text{SZ}}(2) \delta_{\text{gal}}(3) \rangle$$



$$\langle \delta_{\text{gal}}(3) \delta_{\text{gal}}(4) \rangle$$

# The data used

## Planck and SDSS



- **For the SZ: Multi-frequency component separation**

- The Planck High-frequency Instrument (HFI) data at 100, 143, 217, 353, 545 and 857 GHz.
- In addition, we use the IRAS data at 3 and 5 THz for better separating the cosmic infrared background (CIB; from dusty galaxies).

- **For the galaxies and quasars: 2 million redshifts at  $0 < z < 3$**

- The SDSS main, SDSS-III/BOSS, and SDSS-IV/eBOSS data sets.

# The basic methodology: A heuristic description

Vikram, Lids & Jain (2017)

- We focus on the clustering signal at large scales (the so-called “2-halo term” of clustering).
- Ignore non-linear clustering inside dark matter halos, but focus only on clustering between distinct halos.
- In this limit, we can write  $P_e = \langle P_e \rangle (1 + b_y \delta_{\text{matter}})$  and  $n_{\text{gal}} = \langle n_{\text{gal}} \rangle (1 + b_{\text{gal}} \delta_{\text{matter}})$ . Thus, the cross-correlation yields

$$\frac{\langle P_e n_{\text{gal}} \rangle}{b_{\text{gal}} \langle n_{\text{gal}} \rangle \langle \delta_{\text{matter}} \delta_{\text{matter}} \rangle} = b_y \langle P_e \rangle$$

What we measure from the cross-correlation

What we want in the end

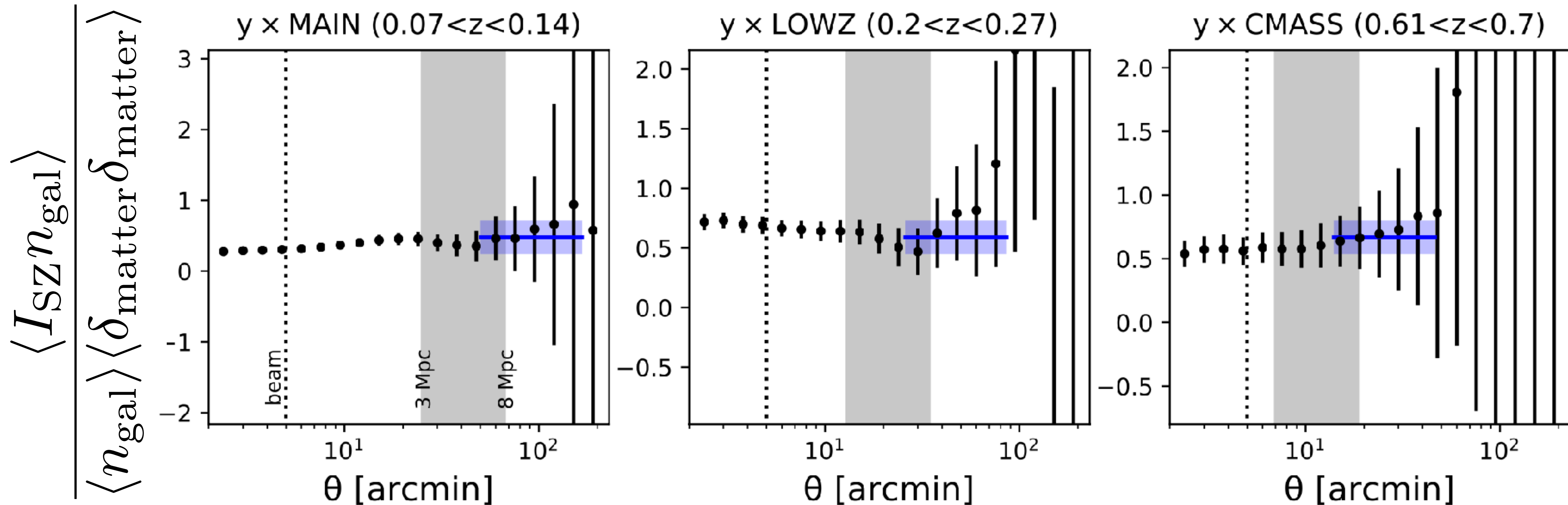
Measured from the auto galaxy correlation

From the  $\Lambda$ CDM model

The first key deliverable

# How the measurements look

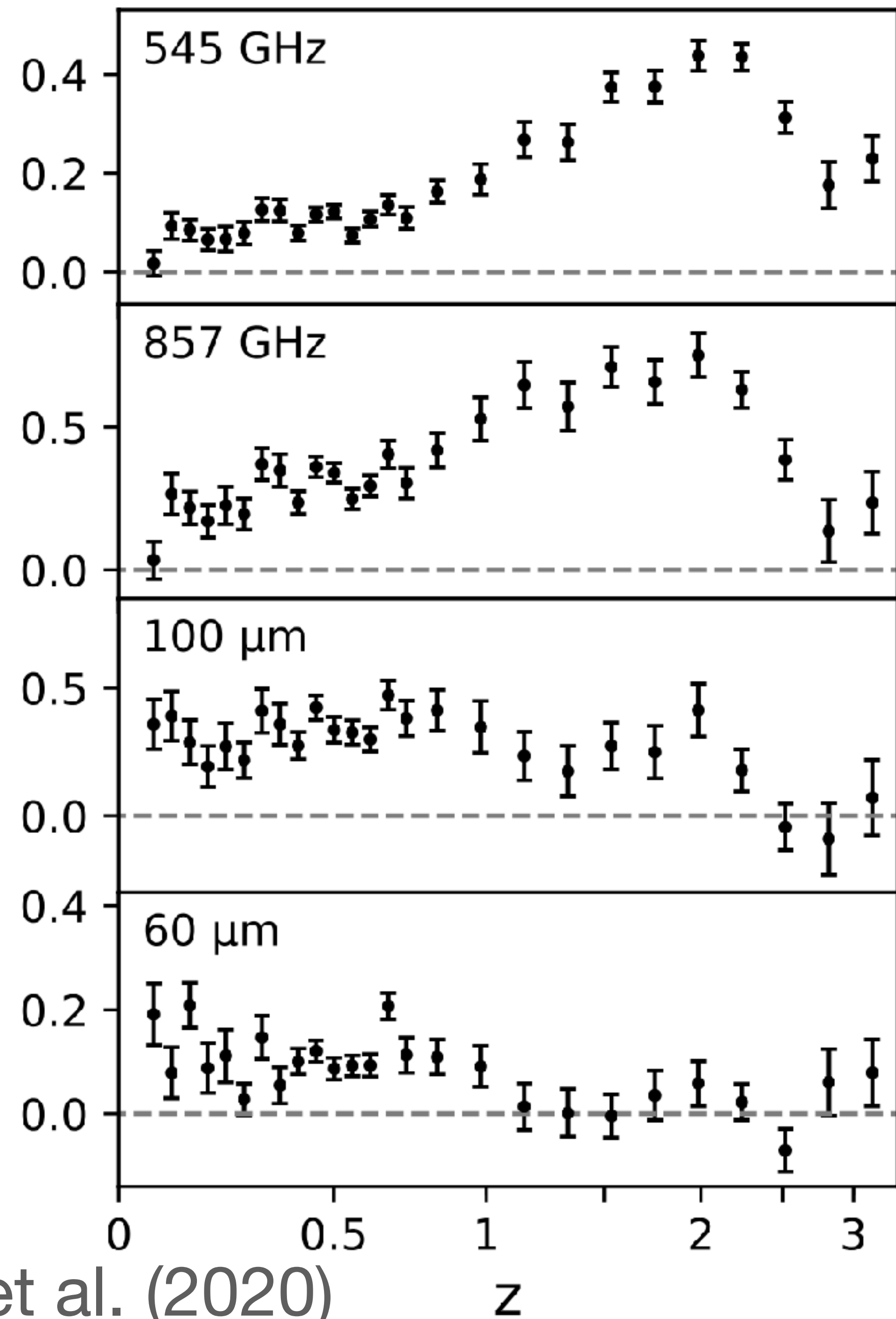
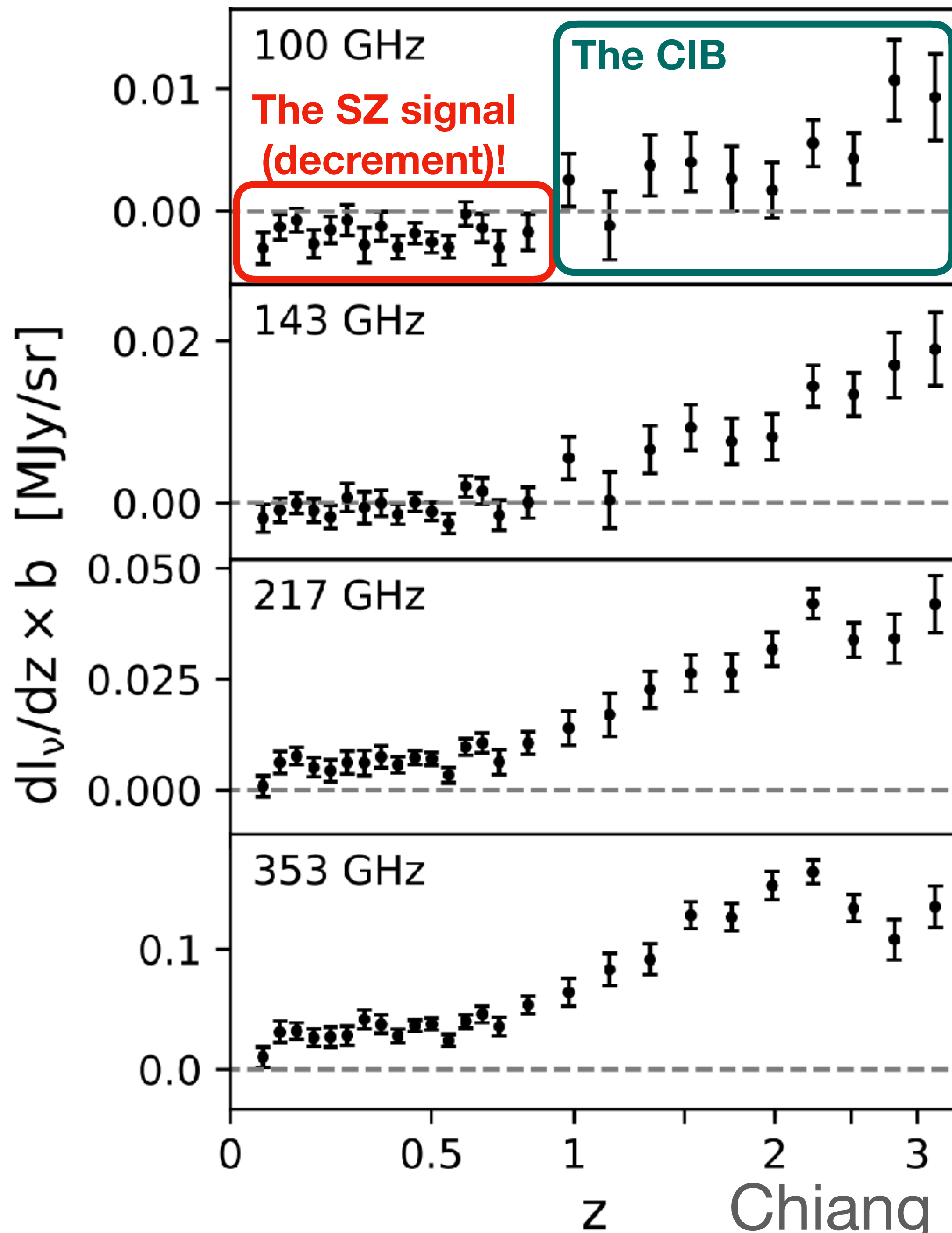
To show that we are in the “linear” regime



- The data within the grey band are used for the analysis, where the ratio is a constant, justifying the extraction of the single constant amplitude in each  $z$  bin.

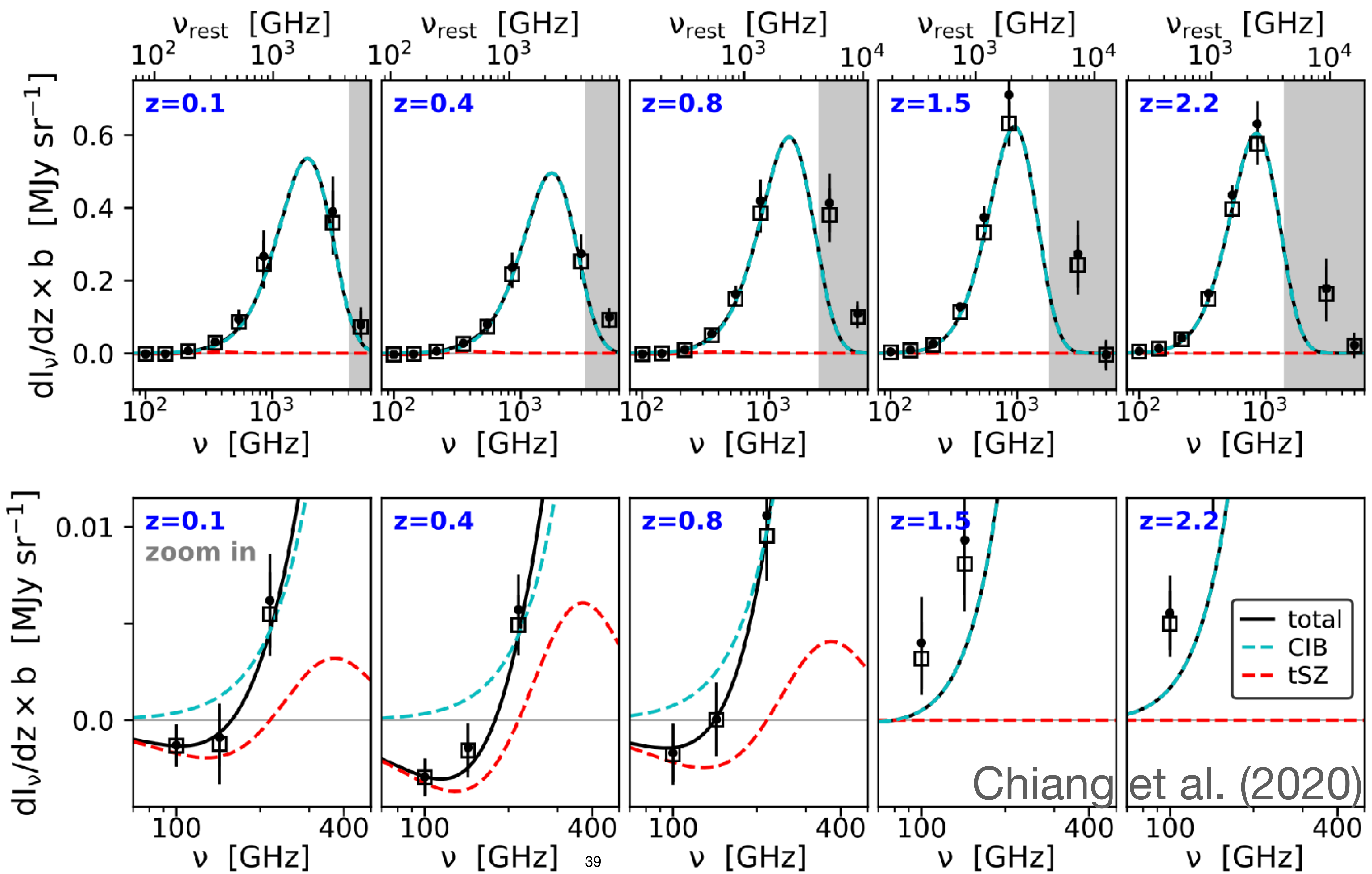
# The Planck/IRAS-SDSS cross-correlations

The need for the multi-component fits (SZ+CIB).

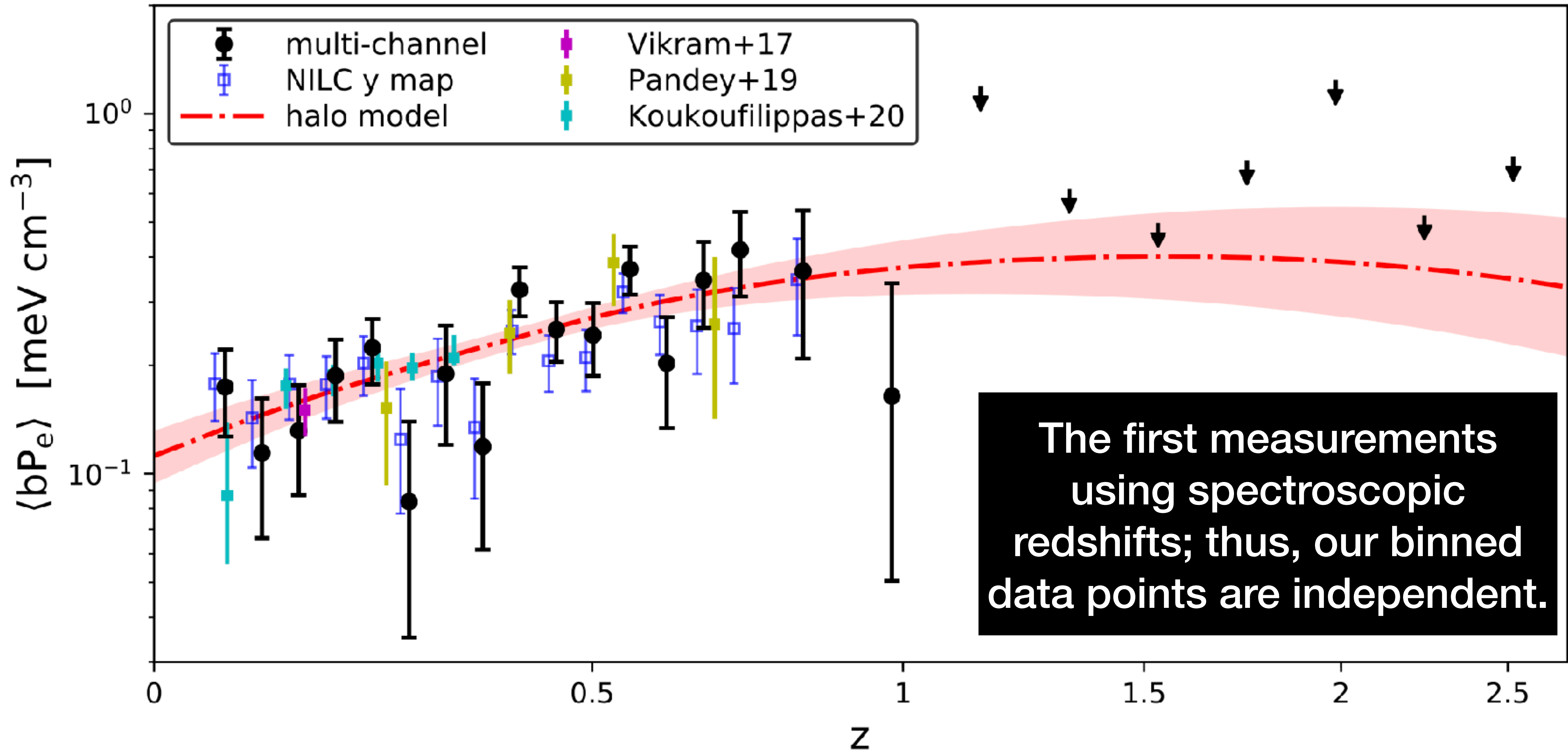


Chiang et al. (2020)

# Tomography of the SED of not only SZ, but also CIB!



# The first main result: Model-independent Bias-weighted mean electron pressure of the Universe!



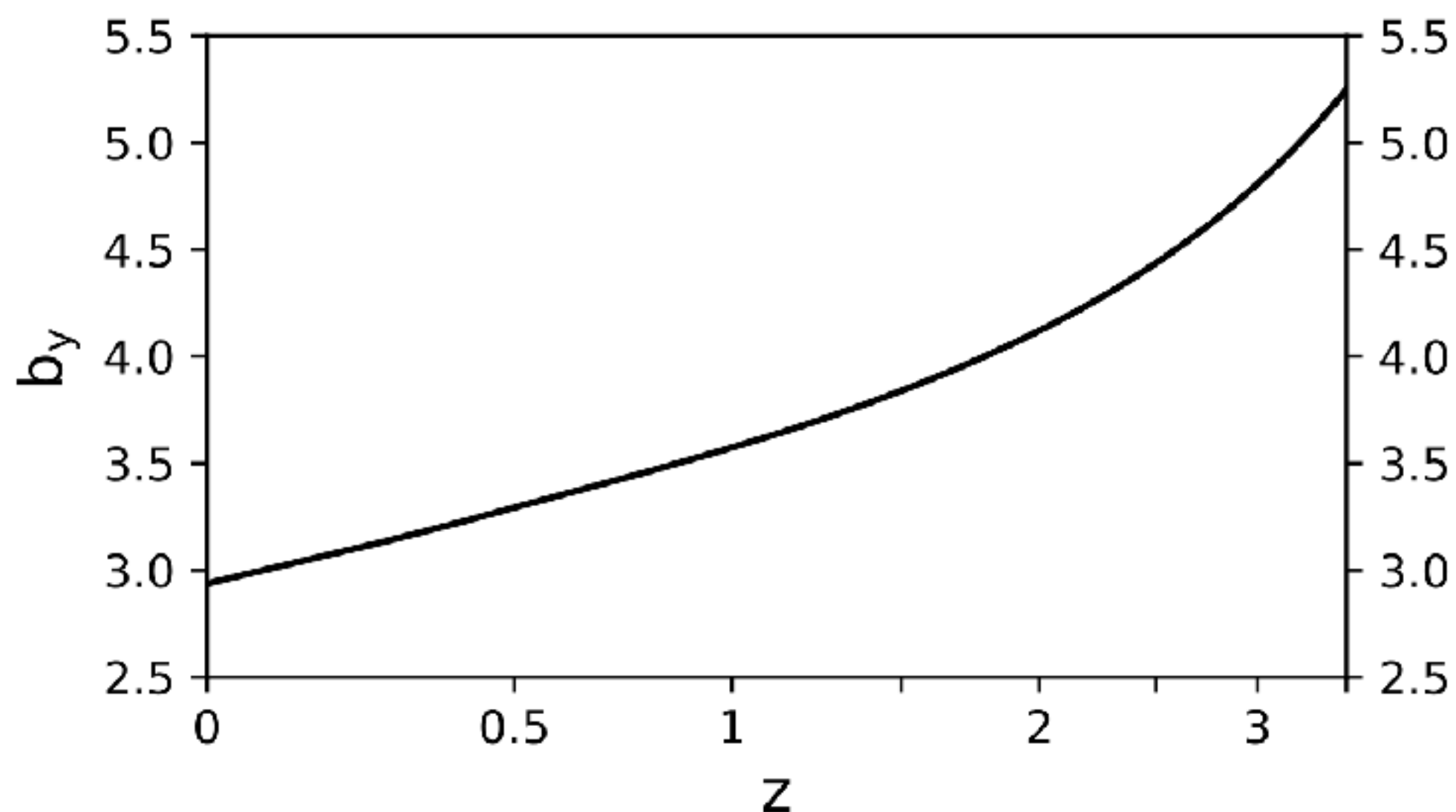


$$\langle bP_e \rangle \rightarrow \langle P_e \rangle$$

## Debiasing by the physical model

- To get the mean pressure, we need to “de-bias”  $\langle bP_e \rangle = b_y \langle P_e \rangle$ . This can be done by computing and dividing by

$$b_y(z) = \frac{\langle bP_e \rangle}{\langle P_e \rangle} = \frac{\int dM \frac{dn}{dM} M^{5/3 + \alpha_P} b_{\text{halo}}(M, z)}{\int dM \frac{dn}{dM} M^{5/3 + \alpha_P}}$$

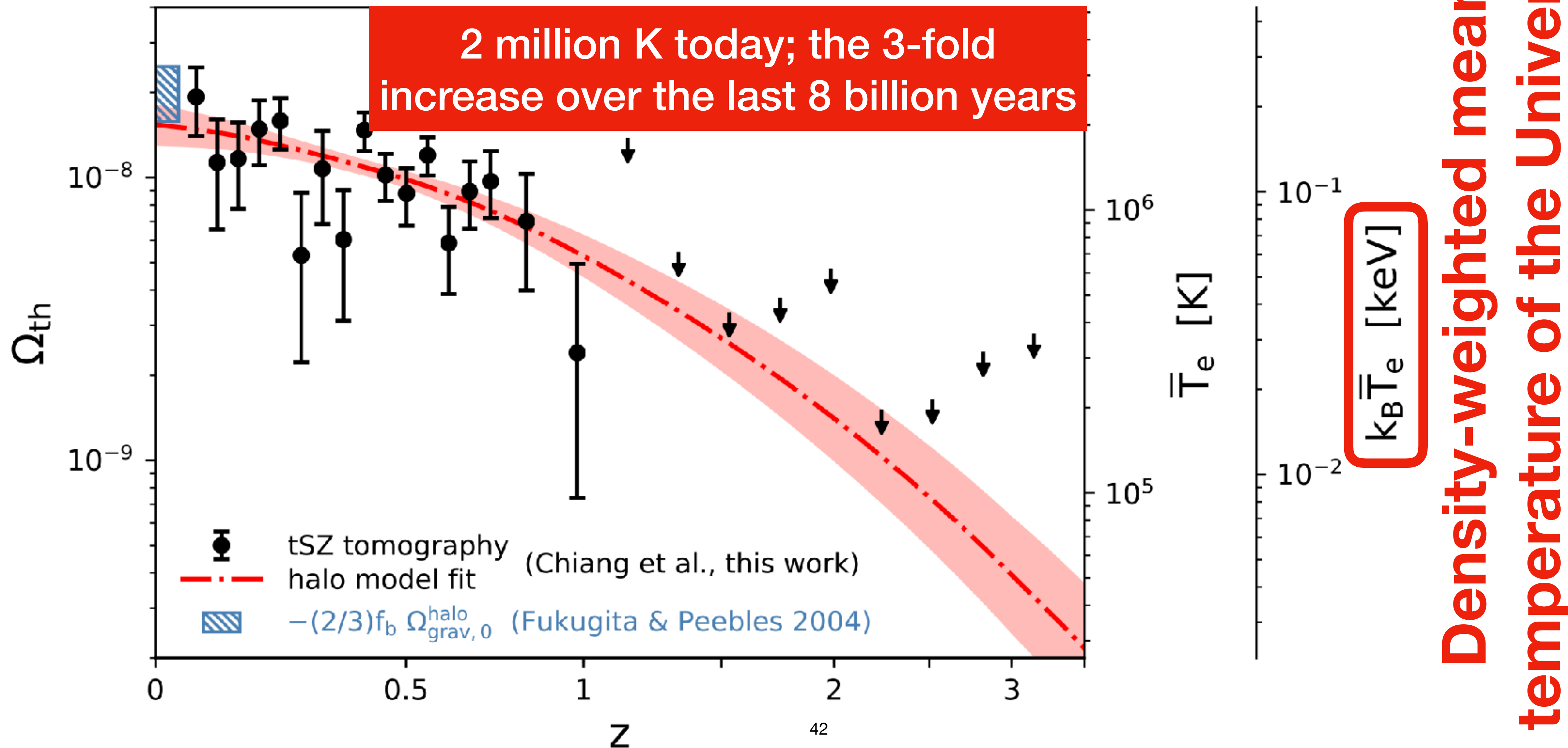


$\alpha_P = 0.12$  is the empirical correction for non-self-similar scaling found by the X-ray data (Arnaud et al. 2010).

$$\Omega_{\text{th}}(z) = 1.78 \times 10^{-8} \frac{k_B \bar{T}_\rho(z)}{0.2 \text{ keV}} \frac{\Omega_b}{0.049}$$

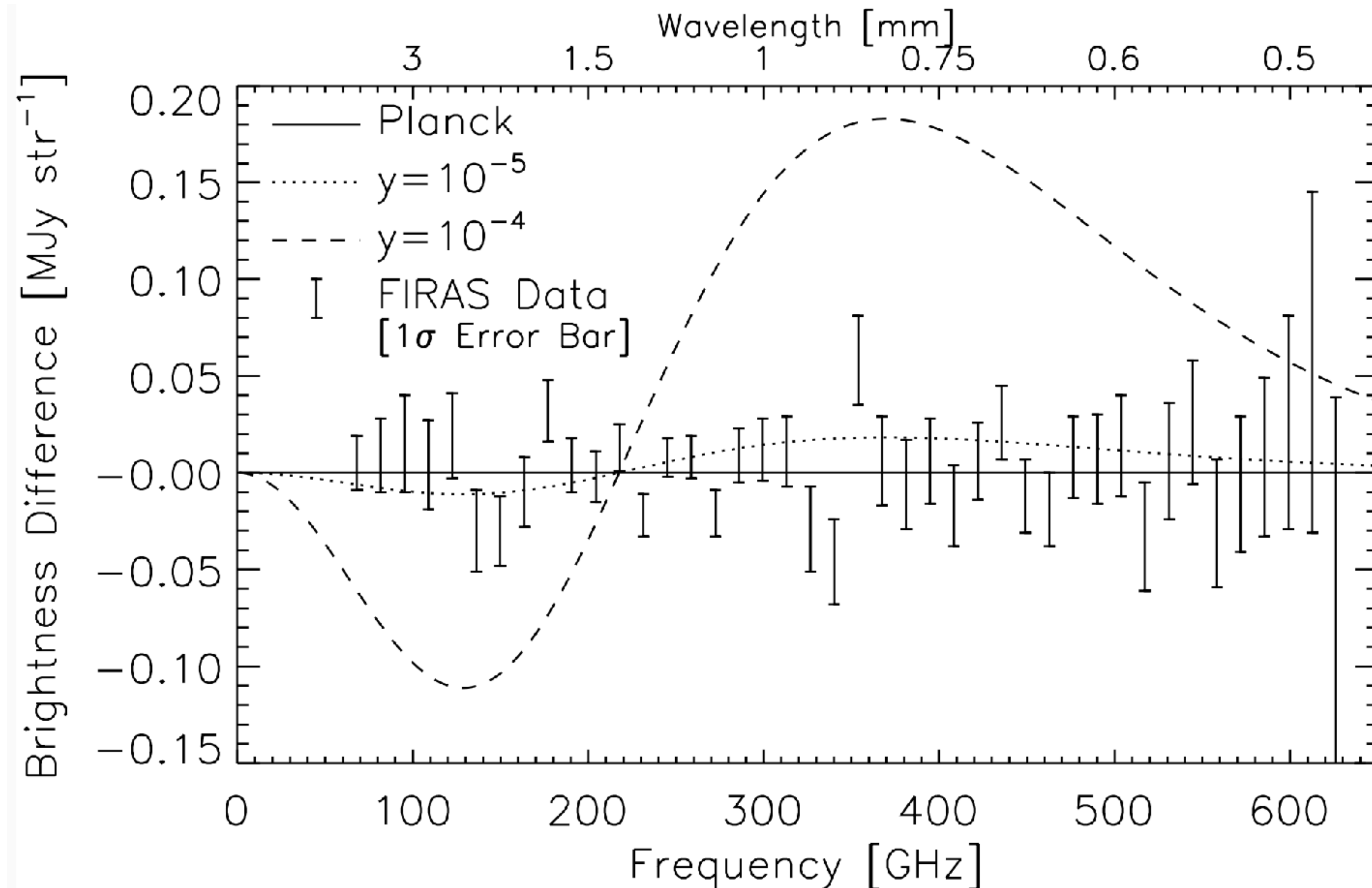
# The second main result

The mean thermal energy density of the Universe!



# The prediction for the future space mission

## The sky-averaged Compton $y$ parameter



- Sometime in future, there will be a space mission measuring the sky-averaged (monopole) spectrum of the CMB, improving upon COBE/FIRAS by a factor of  $10^3-5$ .
- Such a mission will measure the average distortion from the hot gas in the Universe.
- Our data suggest  **$\langle y \rangle = 1.2 \times 10^{-6}$**

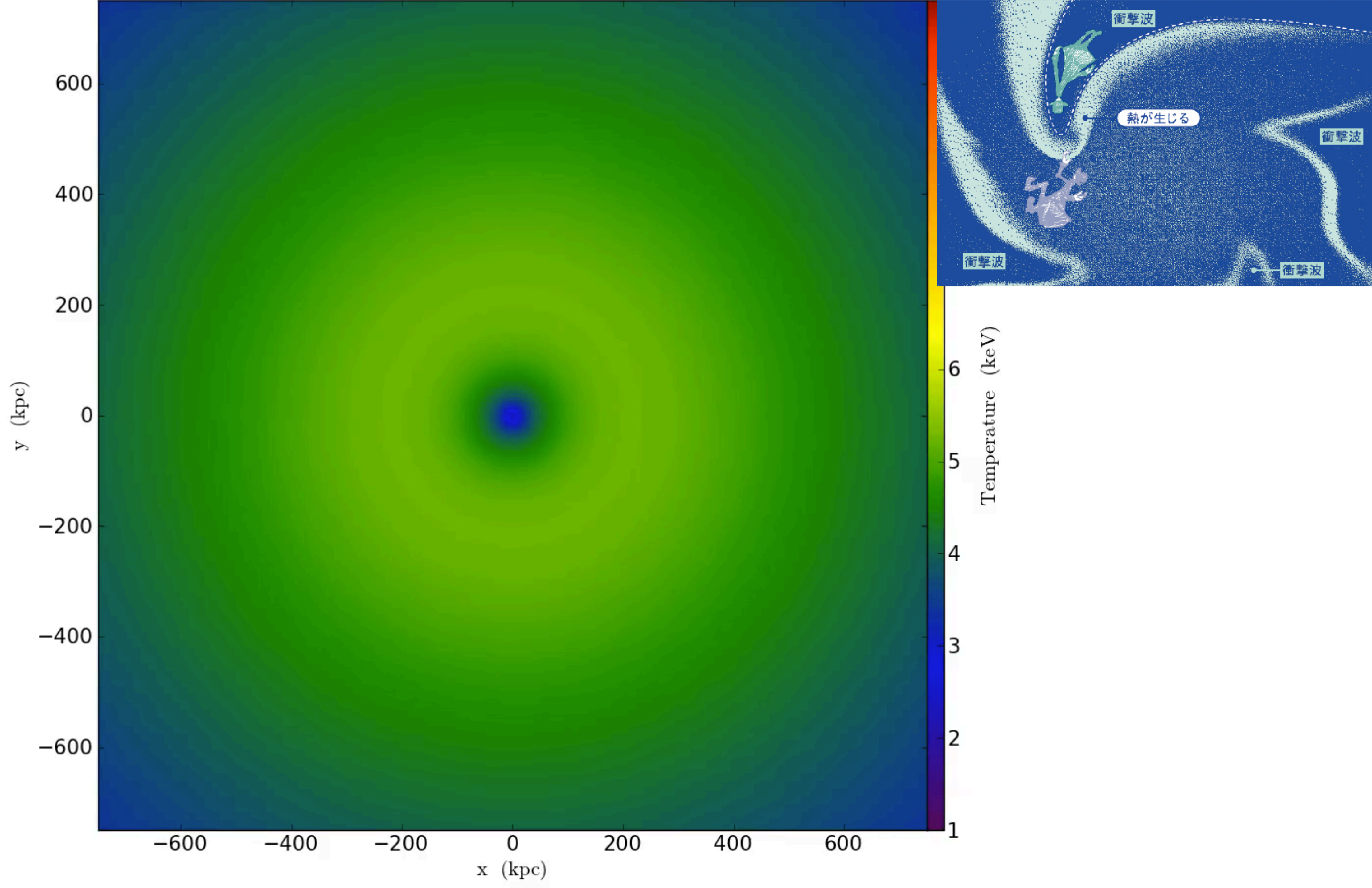
**Q2: Where did the thermal energy come from?**

# Of course you know the answer...

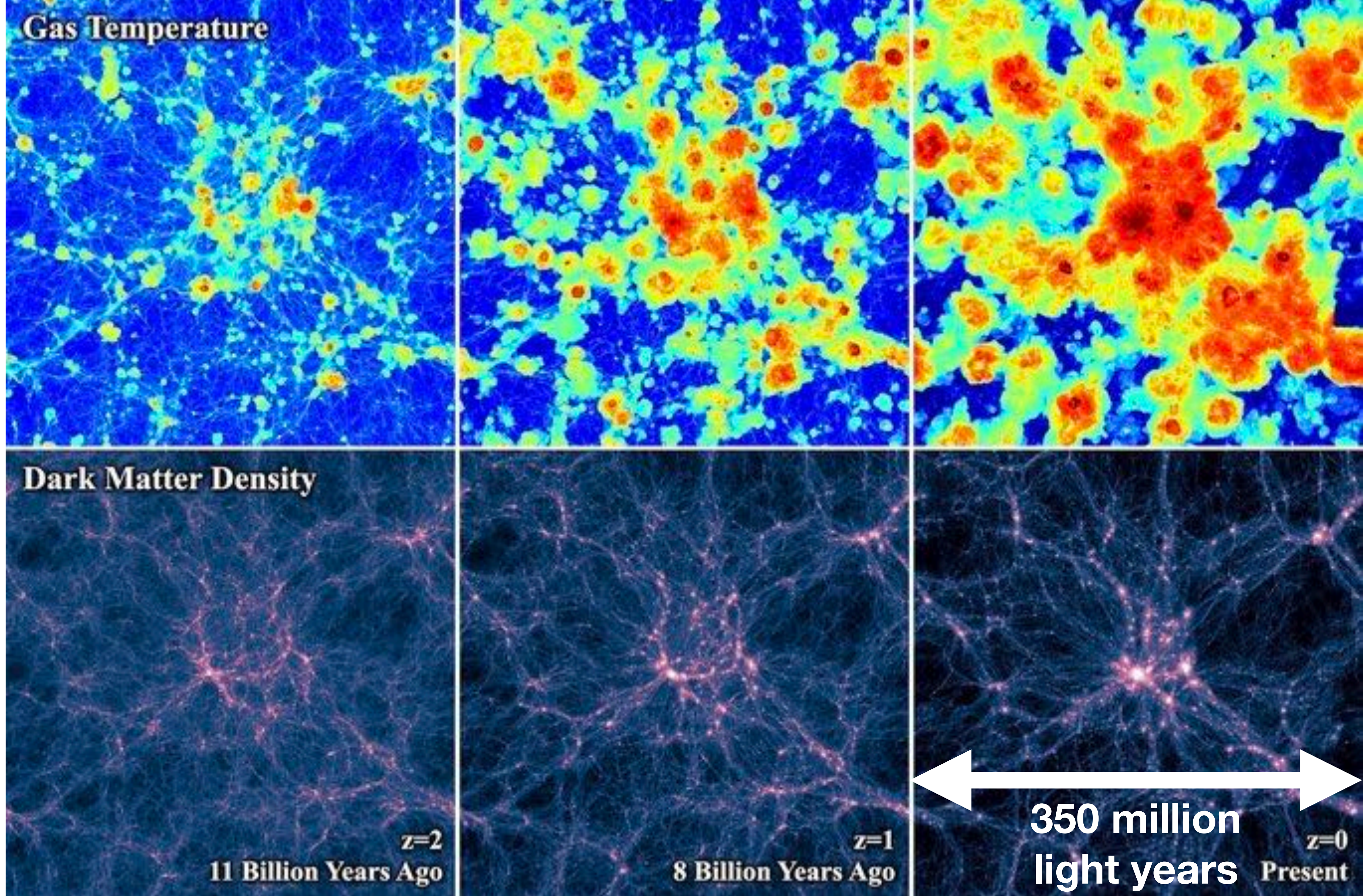
## Open any textbook!

- You can find a statement like, “*As the large-scale structure forms and the matter density fluctuation collapses, the gravitational energy is converted into the thermal energy via a shock.*”
  - Yes, of course this picture is correct. However, how much do we know about this energy conversion **quantitatively**?
  - To my knowledge, no quantitative assessment of this statement has been made before.
- Our approach: We have measured  $\Omega_{\text{th}}$ . We can calculate  $\Omega_{\text{grav}}$  using theory of the structure formation. Let's compare the two and see if they make sense.

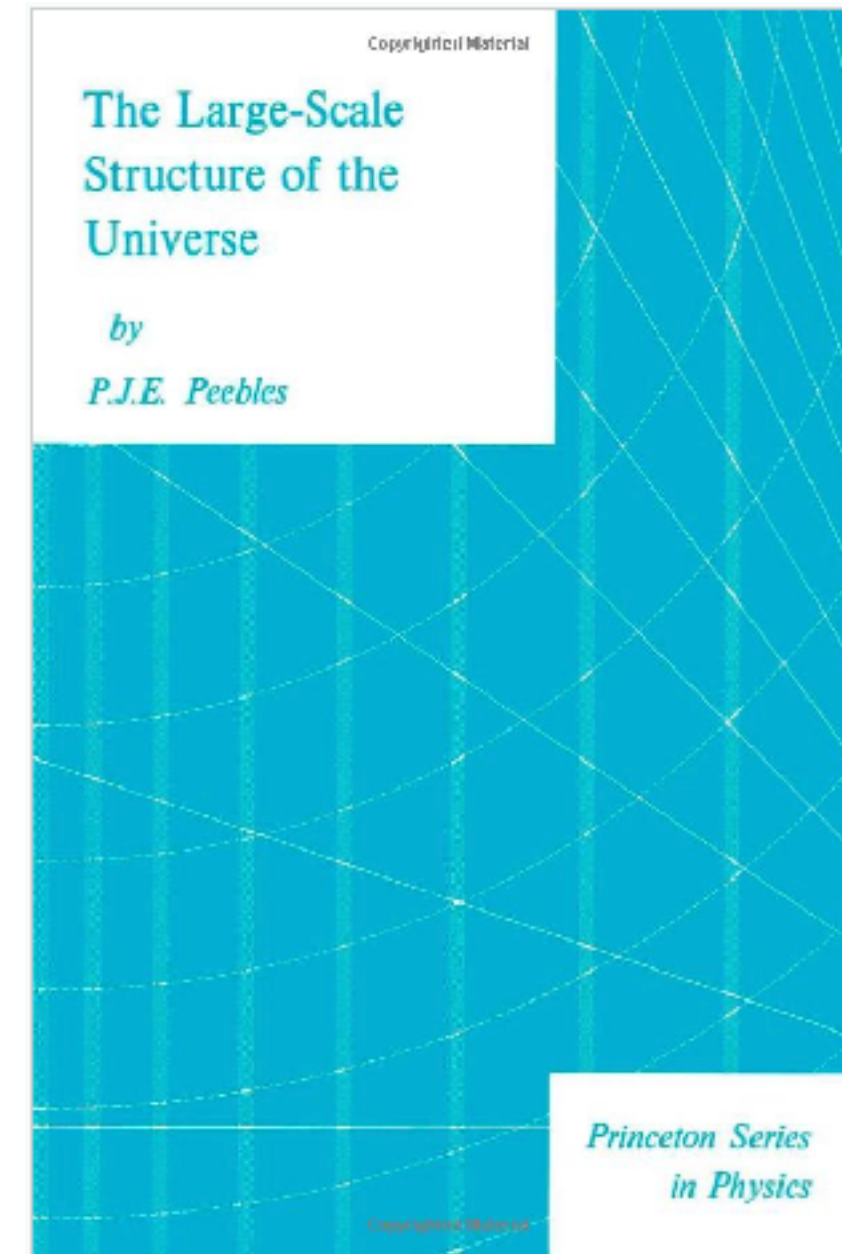
# Idealized Simulation of Gas Heating by Shock Waves (Johnson et al. 2012)



# More sophisticated simulation (Credit: Illustris Collaboration)



# The "W": Gravitational potential energy per unit mass



Considering a system of mass  $M$  consisting of particles with mass  $m_i$ , such that  $M = \sum_i m_i$ ,

$$\begin{aligned}
 MW &= -\frac{1}{2}a^3 \rho_m(a) \int d^3x \delta(\mathbf{x}, a) \phi(\mathbf{x}, a) \\
 &= -\frac{1}{2}Ga^5 \rho_m^2(a) \int d^3x \int d^3x' \frac{\delta(\mathbf{x}, a)\delta(\mathbf{x}', a)}{|\mathbf{x} - \mathbf{x}'|}
 \end{aligned}$$

- The ensemble average is given by the density-potential cross power spectrum:

$$\overline{MW} = -\frac{1}{2}\rho_{m0} \left( \int d^3x \right) \int \frac{d^3k}{(2\pi)^3} P_{\phi\delta}(k, a)$$

With the Poisson equation:

$$P_{\phi\delta}(k, a) = -4\pi G \frac{\rho_{m0}}{a} \frac{P(k, a)}{k^2}$$

$$M = \rho_{m0} \int d^3x$$



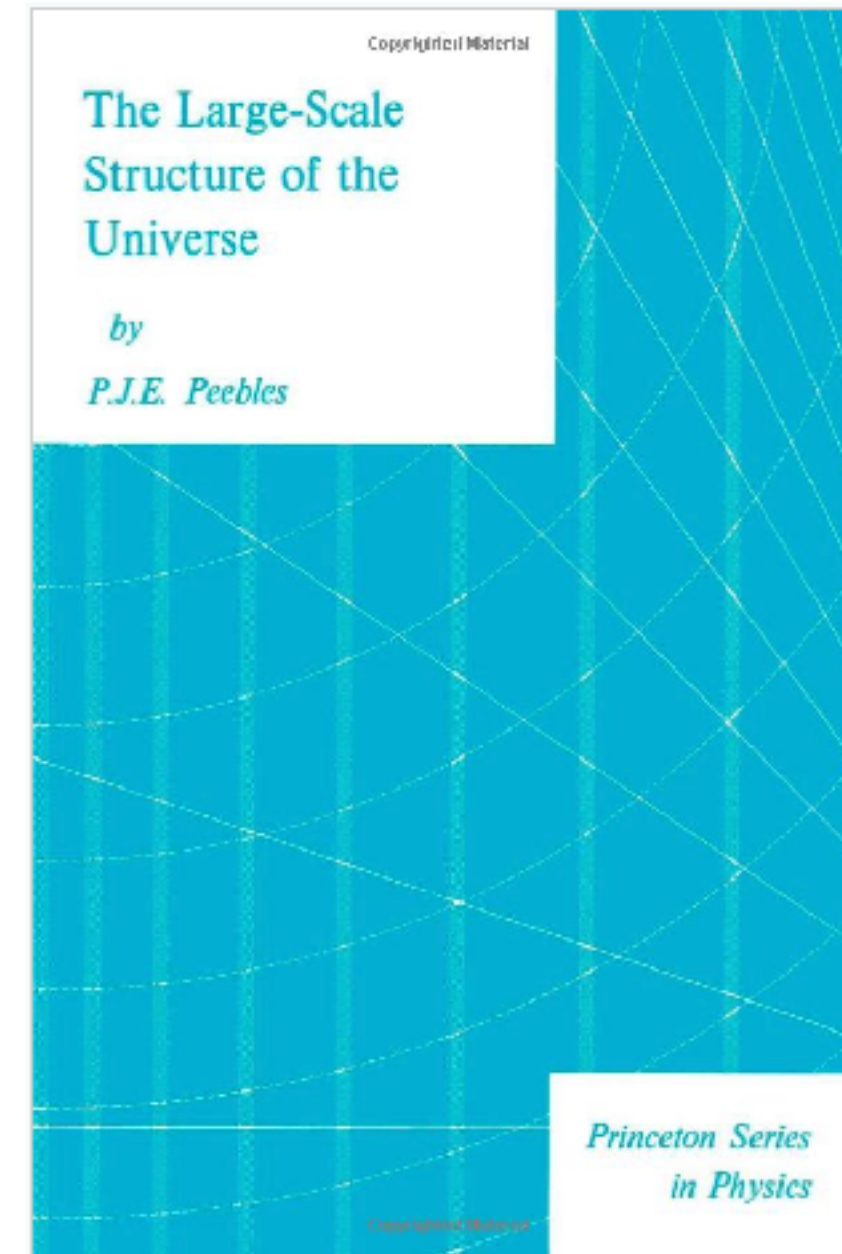
# The “W”: Gravitational potential energy per unit mass

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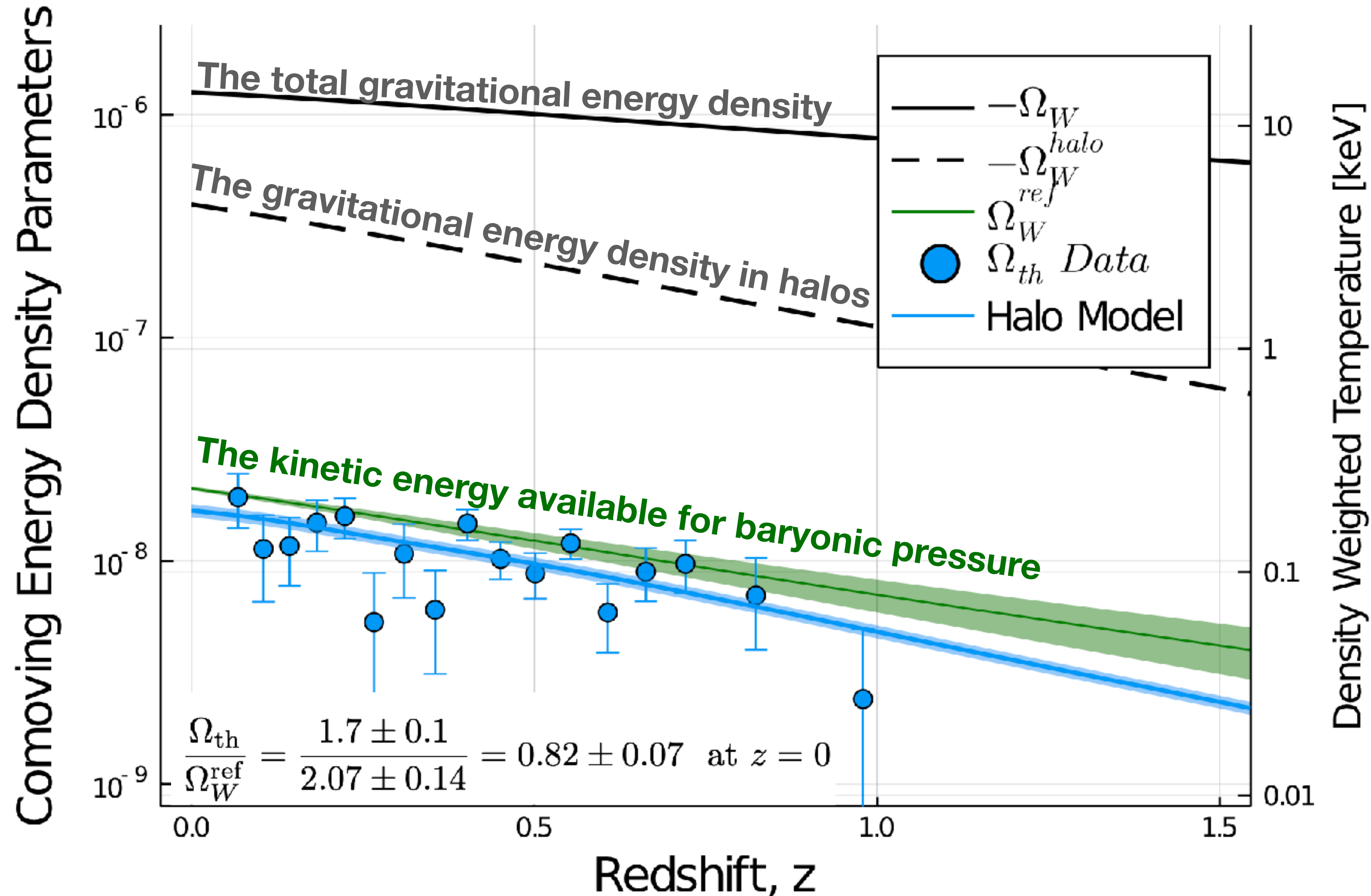
$$MW = -\frac{1}{2}a^3 \rho_m(a) \int d^3x \delta(\mathbf{x}, a) \phi(\mathbf{x}, a)$$

$$W = -\frac{3\Omega_m H_0^2}{8\pi^2 a} \int_0^\infty dk P(k, a)$$

This is the exact formula for  $W$  (in the Newtonian limit).



# The Energy Balance in the Large-scale Structure



The energy density parameter for W:

$$\Omega_W = \frac{\Omega_m}{c^2} W$$

The halo contribution:

$$\frac{\Omega_W^{halo}}{\Omega_W^{tot}} \simeq 0.3 \quad \text{at } z = 0$$

Pressure available for baryons

$$\Omega_W^{ref} = -\frac{1}{3} f_b \Omega_W^{halo}$$

# Conclusion from the second part

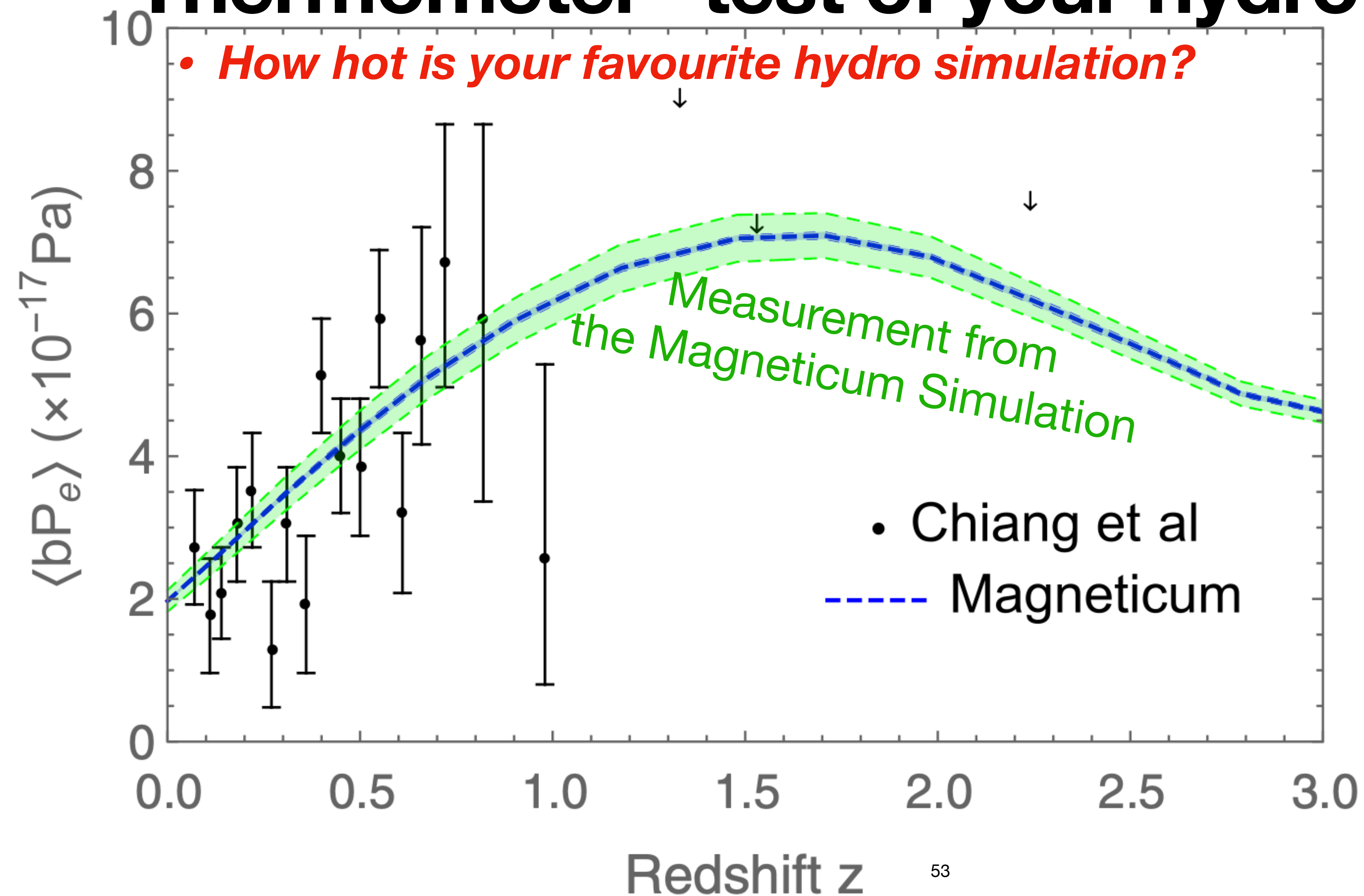
The energy balance does work, but where is the rest of the K.E.?

- We can now make the following statement:
  - **The measured thermal energy density accounts for ~80% of the gravitational potential energy available for kinetic energy of collapsed baryons.**
  - This is the first quantitative assessment of the textbook statement on gravitational  $\rightarrow$  thermal energy conversion in the large-scale structure formation (using the observational data).
- **What is the rest (~20%)?**  $\Rightarrow$  Non-thermal pressure due to the mass accretion!  
[Shi and EK (2014); Shi et al. (2015; 2016)]
- There is a lot more (x3) kinetic energy available in the LSS beyond collapsed baryons. **Where/how can we find it? Kinetic SZ effect?**

# **Q3: Is this good for anything?**

Is this just beautiful physics, or actually useful for anyone?

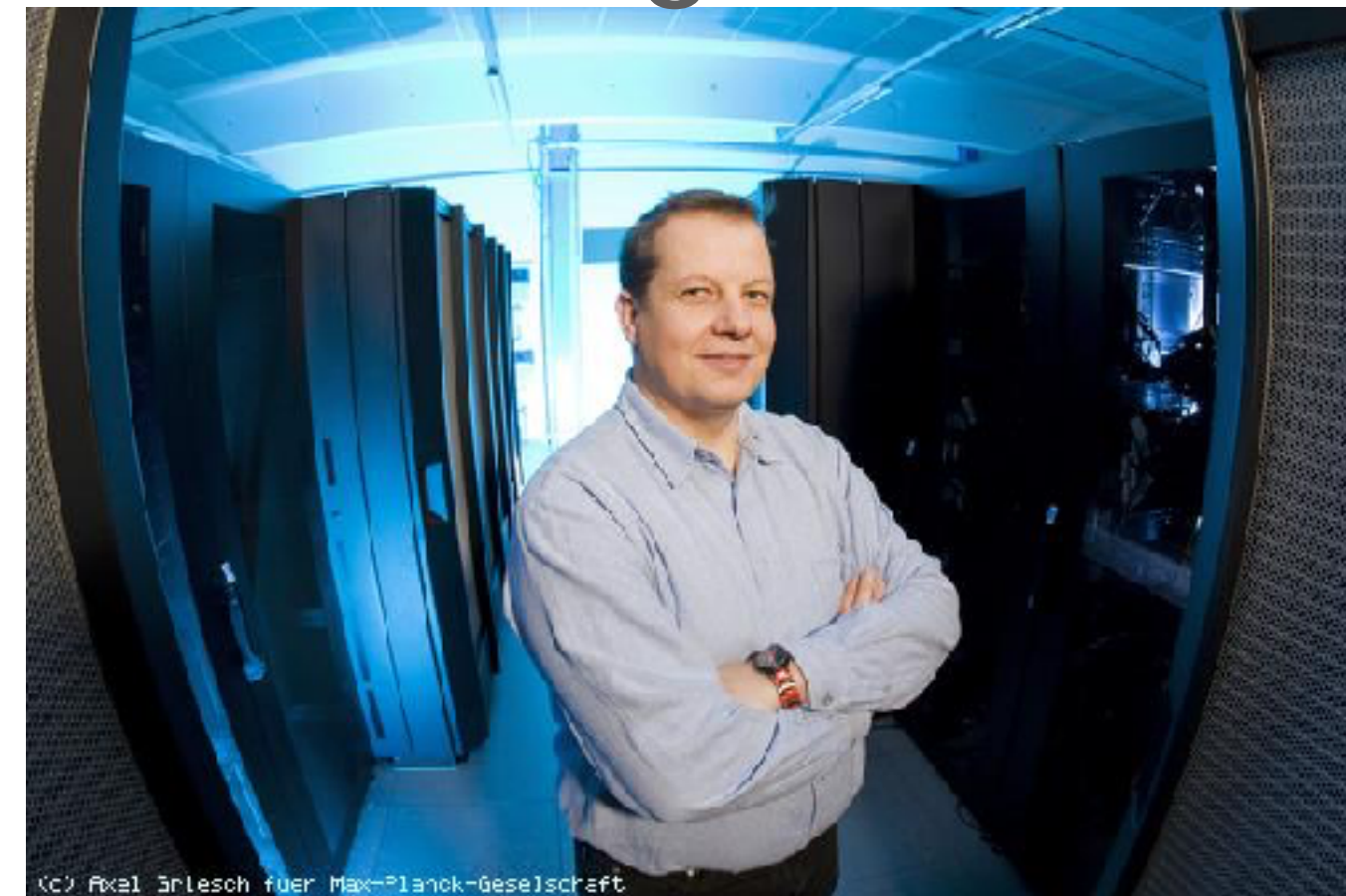
# “Thermometer” test of your hydro simulation



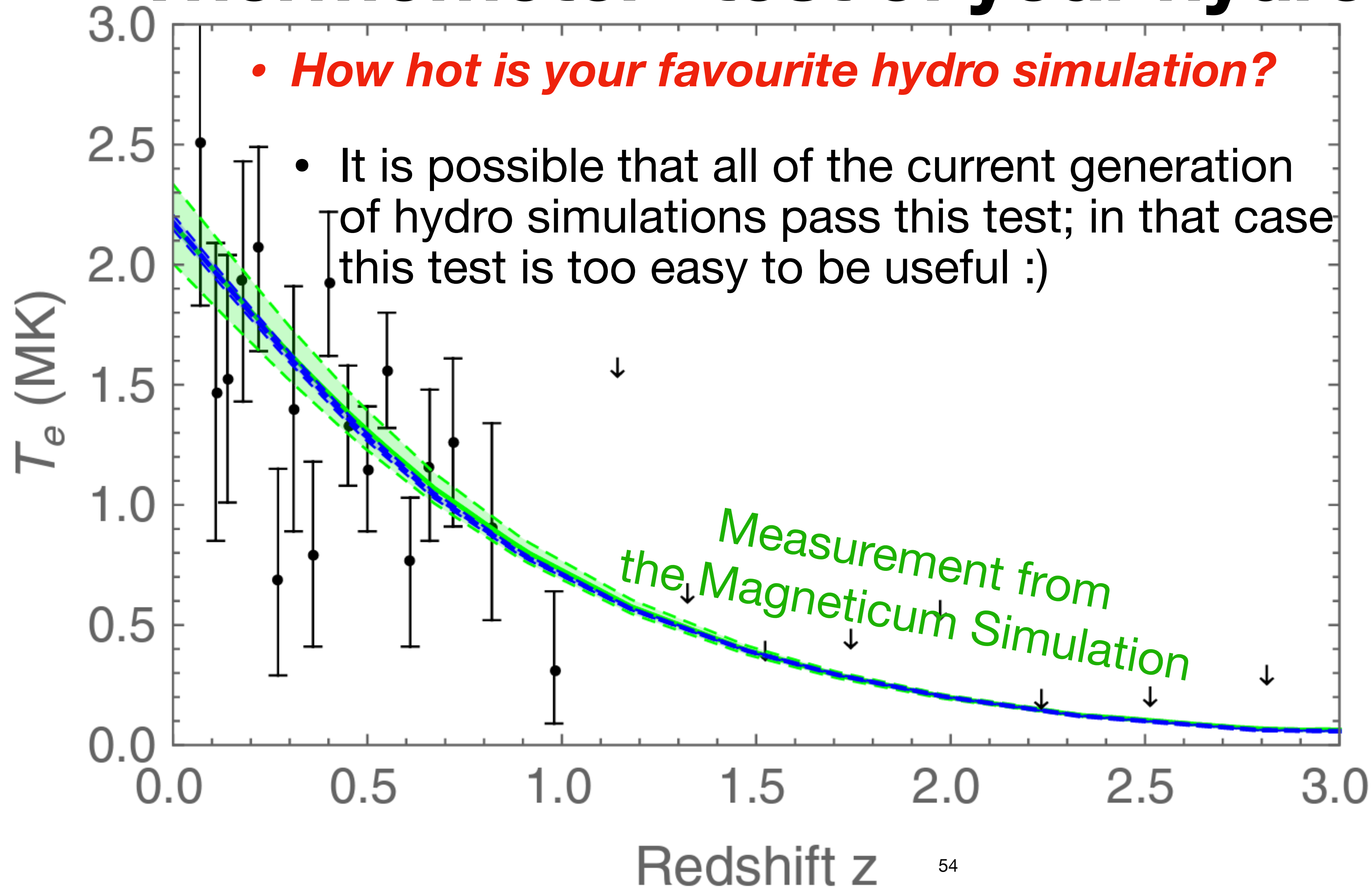
Sam Young



Klaus Dolag



# “Thermometer” test of your hydro simulation



# Conclusion: Home work done.

## The energy balance seems to work in the Universe

- We have measured the evolution of the mean thermal energy density (equivalently the density-weighted mean temperature) of the large-scale structure of the Universe out to  $z \sim 1$ .
- **Personally:** This is the completion of the 20 years of homework since *Refregier, EK, Spergel, Pen (2000)* [Also see Cen & Ostriker (1999)].
  - We used Ue-Li Pen's moving mesh hydro code to predict the evolution of the density-weighted mean temperature. **We finally measured this.**
- Detailed comparison to the gravitational energy of the LSS shows that **the thermal energy accounts for ~80% of the kinetic energy available for thermal pressure of collapsed baryons.** The rest can be accounted for easily by non-thermal pressure (*Shi & EK 2014*).
- Is this good for anything? You tell us! <sup>55</sup>

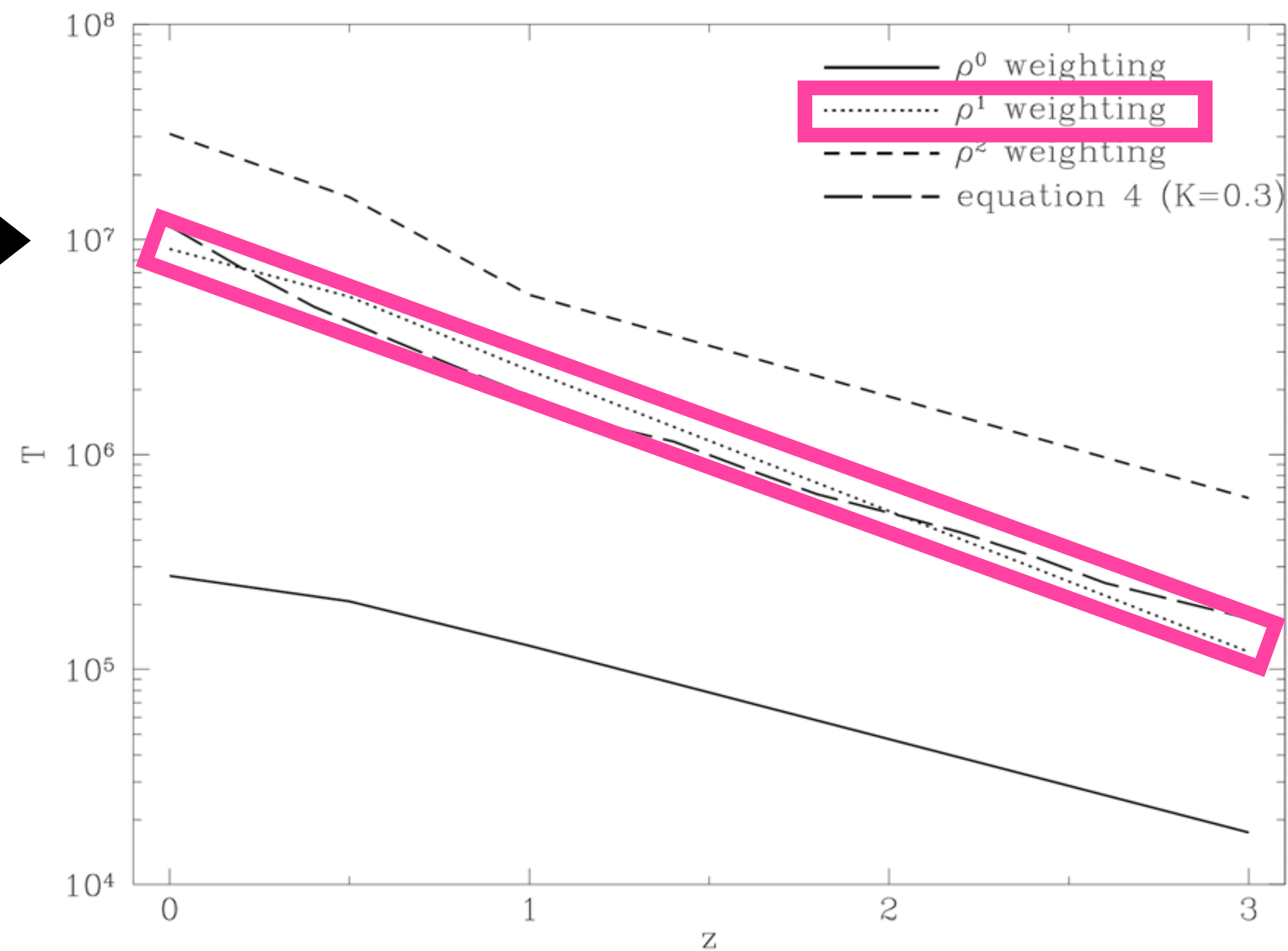
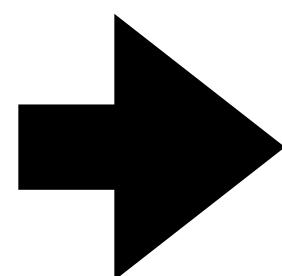
## WHERE ARE THE BARYONS?

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*Received 1998 September 11; accepted 1998 October 29*

Too hot!





# Power spectrum of the Sunyaev-Zel'dovich effect

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(Received 10 December 1999; published 12 May 2000)

Model	$\bar{T}_\rho^a$ (keV)
SCDM	0.19 (2.2 mil. K)
$\Lambda$ CDM	0.25 (2.9 mil. K)
OCDM	0.19 (2.2 mil. K)

Not bad!  


<sup>a</sup>At  $z=0$ .

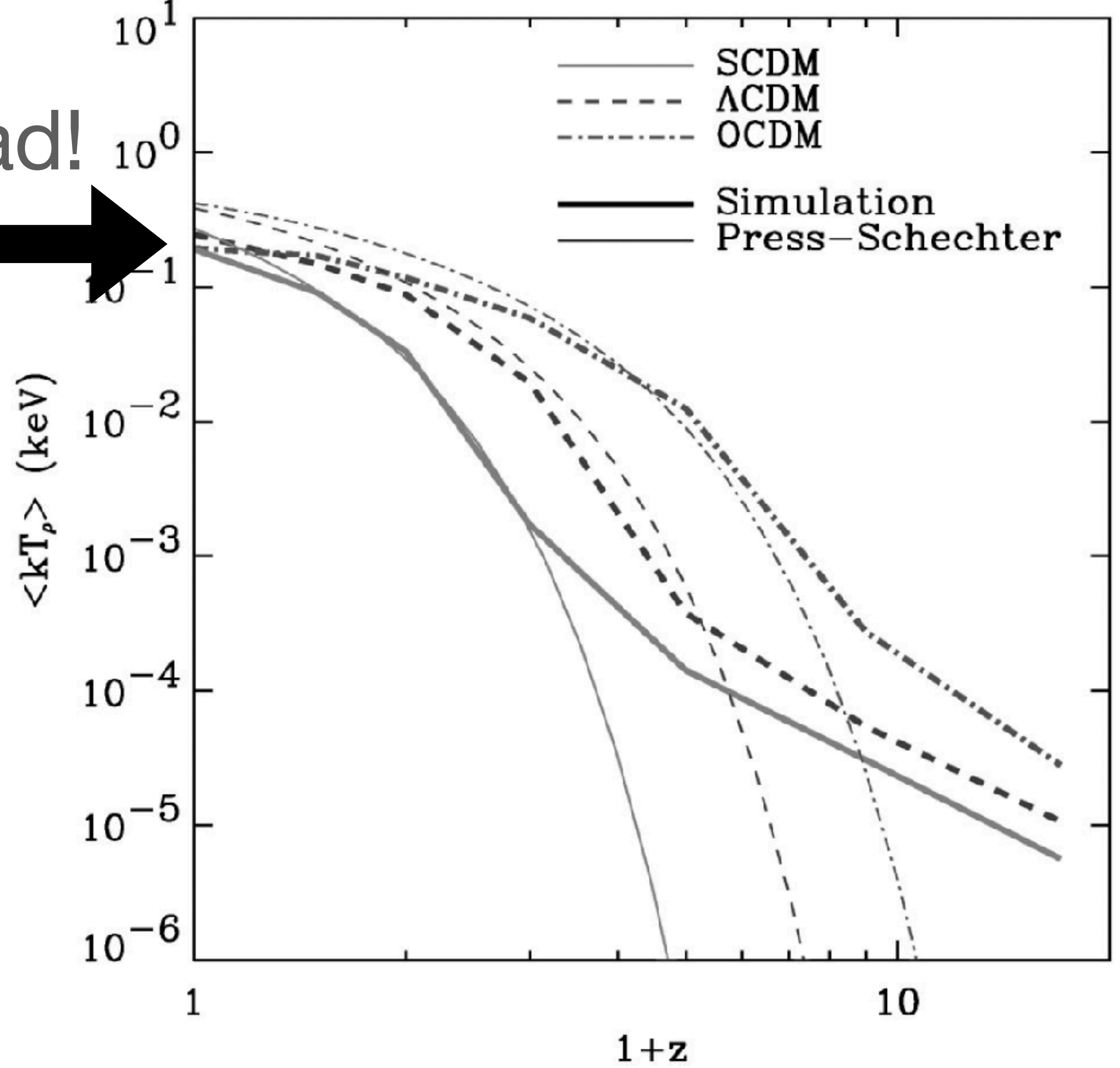


FIG. 4. Temperature history of the gas. For each model, the density weighted temperature  $T_\rho$  is shown for the simulations and for the Press-Schechter prediction.

**Back up slides**

# W to K: the mean kinetic energy per unit mass

Layzer-Irvine equation (Layzer 1963; Irvine 1961; Dmitriev & Zeldovich 1964)

- Given the knowledge of  $W$ , we can calculate the mean kinetic energy per unit mass,  $K$ , using the Layzer-Irvine equation:

$$\frac{d}{dt}(K + W) + \frac{\dot{a}}{a}(2K + W) = 0$$

where  $K$  is the mean kinetic energy per unit mass,  $K = \sum_i m_i v_i^2 / (2 \sum_i m_i)$ .

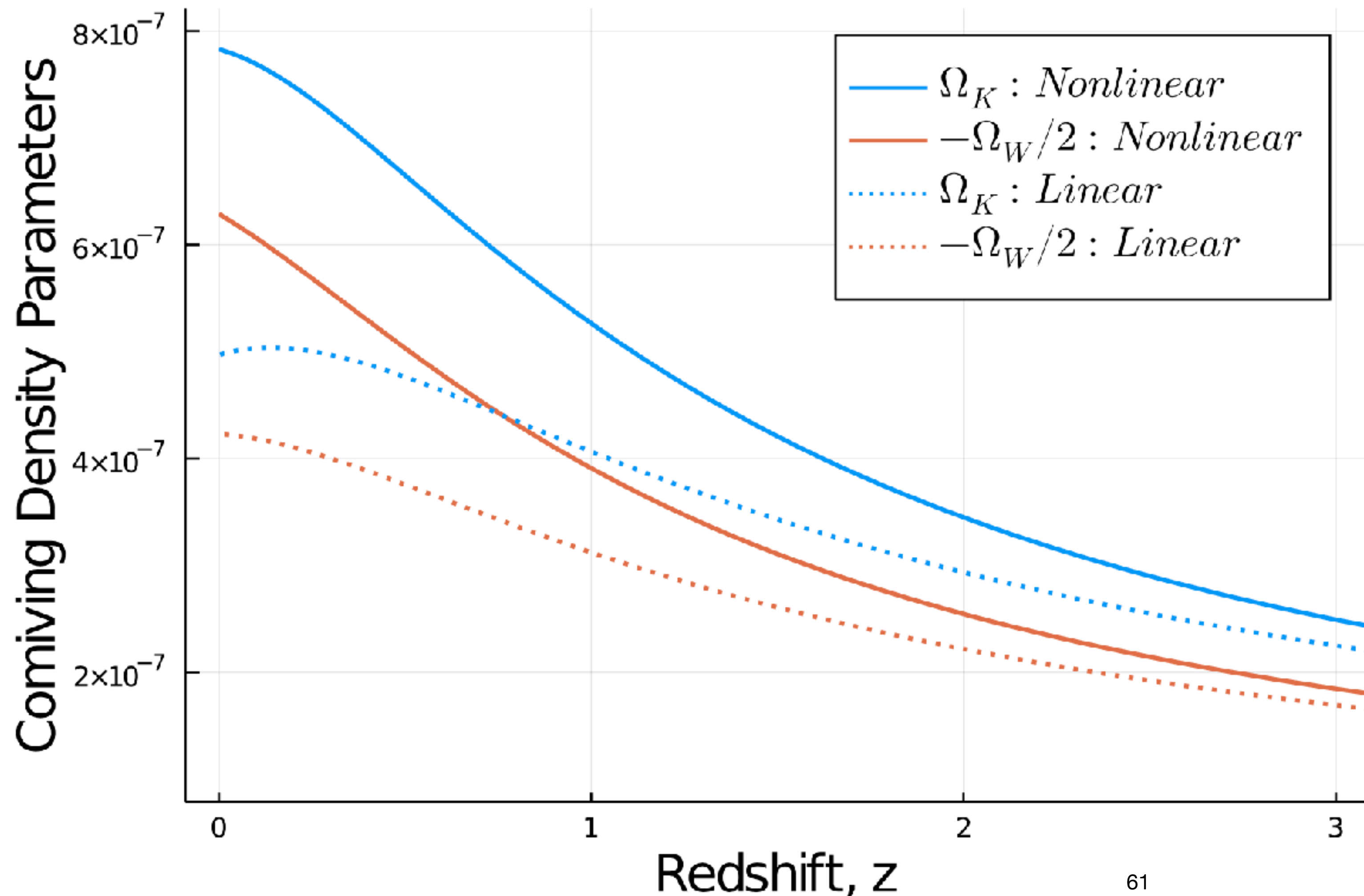
- The initial condition for  $K$  can be set using the linear theory result at sufficiently early time (Davis et al. 1997),

$$K = -\frac{2f^2}{3\Omega_m(a)}W$$

where  $f \equiv d \ln \delta_1 / d \ln a$  with the linear density contrast  $\delta_1$  and  $\Omega_m(a) = \Omega_m / [a^3 E^2(a)]$  is the matter density parameter at a given  $a$ .

# W to K: The Result

**More kinetic energy is available than the virial theorem  $K = -W/2$**



- This result captures the kinetic energy of all structures.
- Here, we do not separate random and bulk motion of collapsed and non-collapsed structures, respectively.
- For comparison to the thermal energy, we used the virial relationship,  $K = -W/2$ .