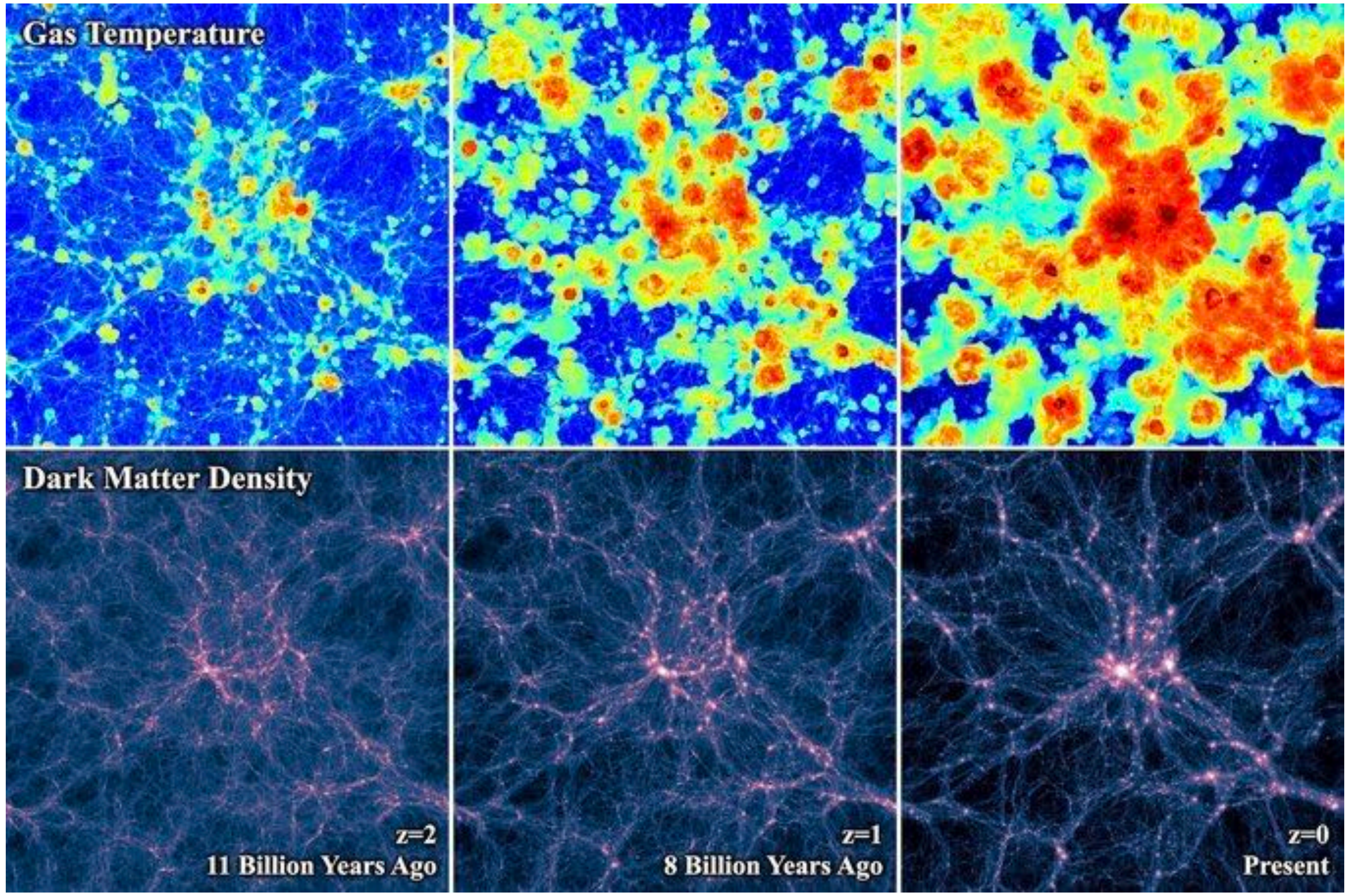
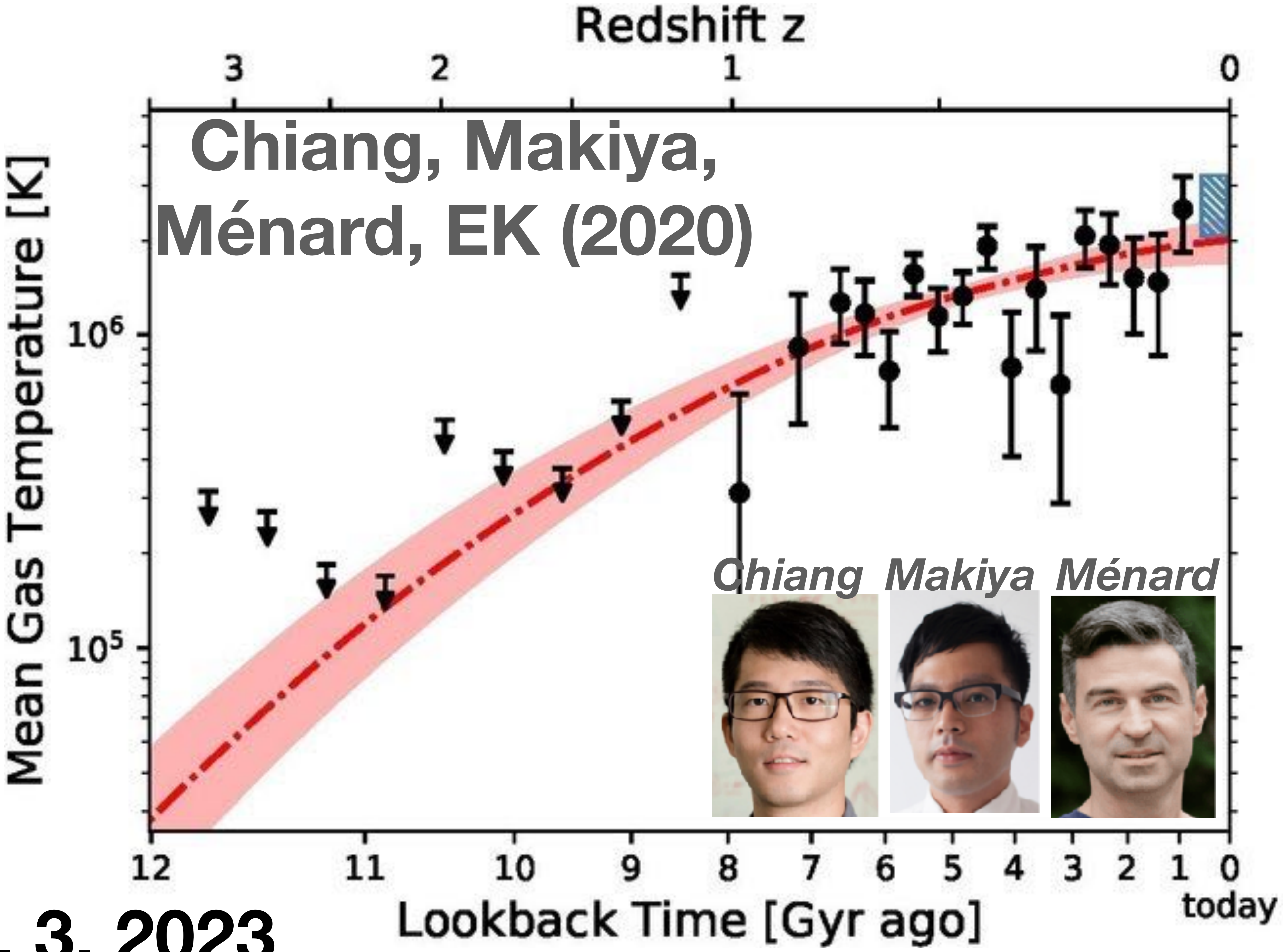
The Temperature of Hot Gas in the Universe

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

Credit: Dylan Nelson, Illustris Collaboration

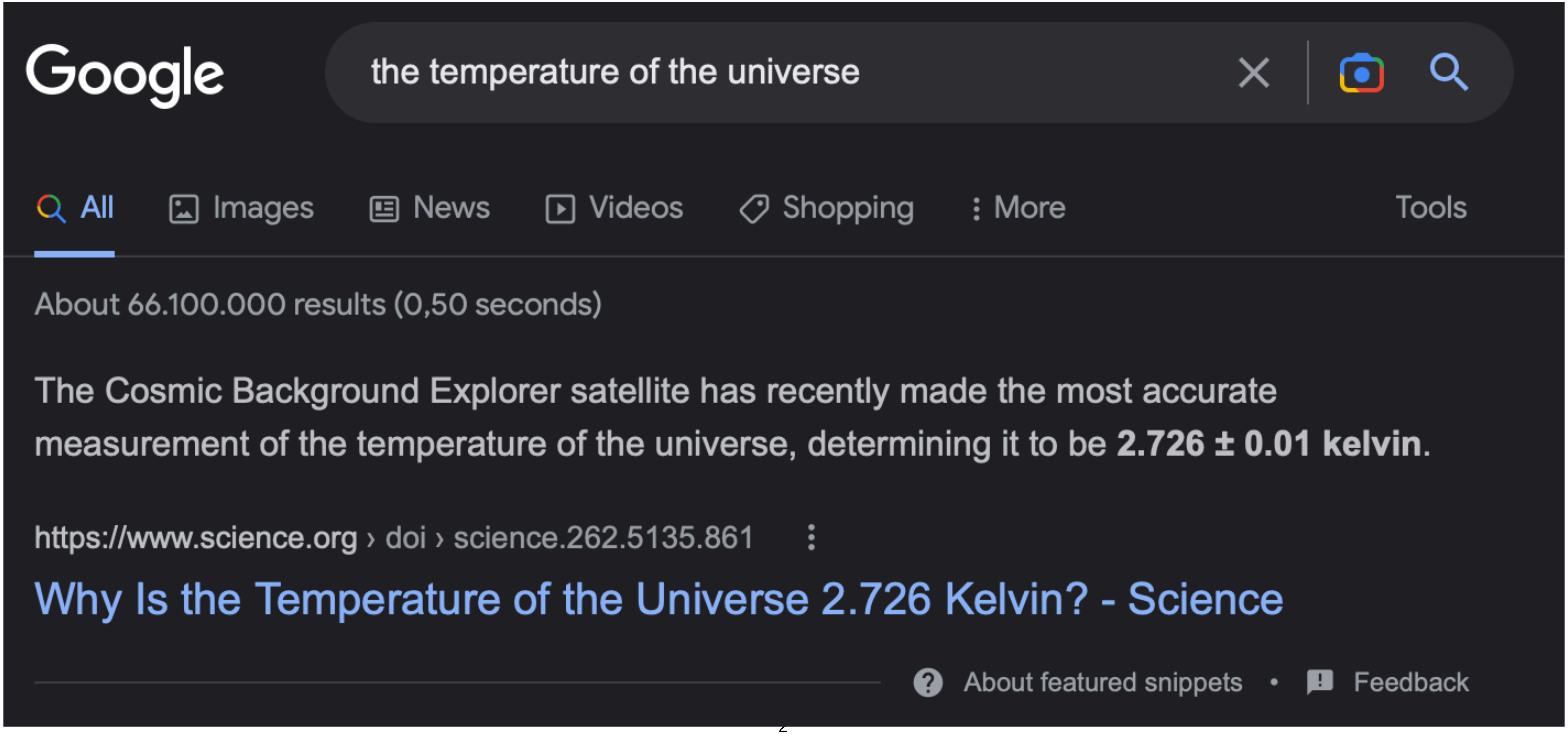




Eiichiro Komatsu, ***CCA Colloquium***, **Feb. 3, 2023**

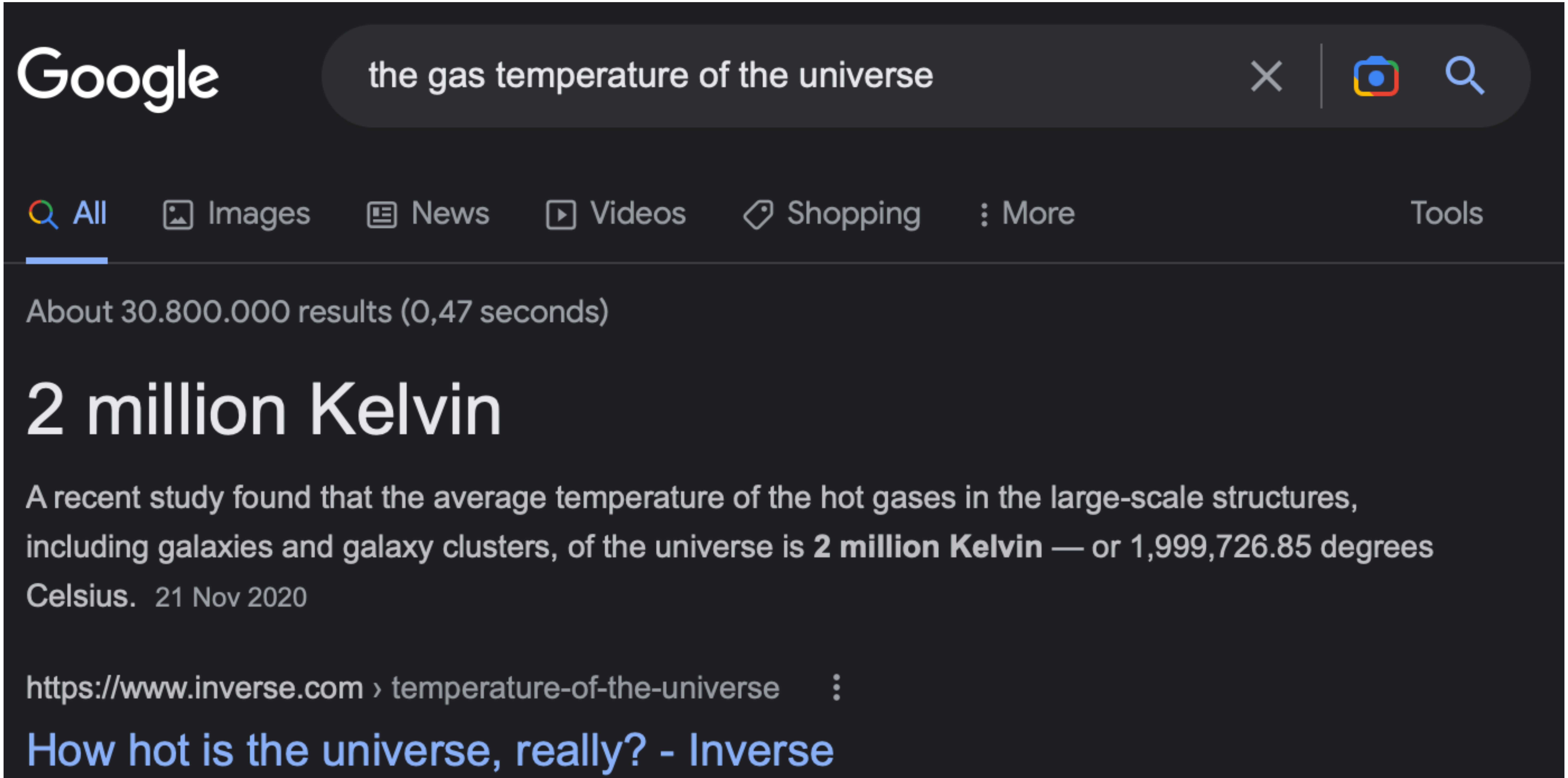
If you ask Google…

“The temperature of the Universe”



If you ask Google…

“The gas temperature of the Universe”



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: **Ω_m ~ 0.3**.
- We also know the mean baryonic mass density of the Universe: **Ω_B ~ 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.

Fukugita & Peebles (2004)

TABLE 1
THE COSMIC ENERGY INVENTORY

Category	Parameter		Components[a]	Totals[a]
1	Dark sector:			0.954 ± 0.003
1.1	Dark energy		0.72 ± 0.03	
1.2	Dark matter		0.23 ± 0.03	
1.3	Primeval gravitational waves		$\lesssim 10^{-10}$	
2	Primeval thermal remnants:			0.0010 ± 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 ± 0.003
3.1	Warm intergalactic plasma		0.040 ± 0.003	
3.1a	Virialized regions of galaxies	0.024 ± 0.005		
3.1b	Intergalactic	0.016 ± 0.005		
3.2	Intracluster plasma		0.0018 ± 0.0007	
3.3	Main-sequence stars: spheroids and bulges		0.0015 ± 0.0004	
3.4	Main-sequence stars: disks and irregulars		0.00055 ± 0.00014	
3.5	White dwarfs		0.00036 ± 0.00008	
3.6	Neutron stars		0.00005 ± 0.00002	
3.7	Black holes		0.00007 ± 0.00002	
3.8	Substellar objects		0.00014 ± 0.00007	
3.9	H I + He I		0.00062 ± 0.00010	
3.10	Molecular gas		0.00016 ± 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[a]	Totals[a]
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–γ-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, Ω_{th}
  - **Let's measure this!**

Our definition of the thermal energy density

nk_BT rather than $(3/2)nk_BT$

- We define the thermal energy from **k_BT**, rather than the kinetic energy, $(3/2)k_BT$.
    - 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:

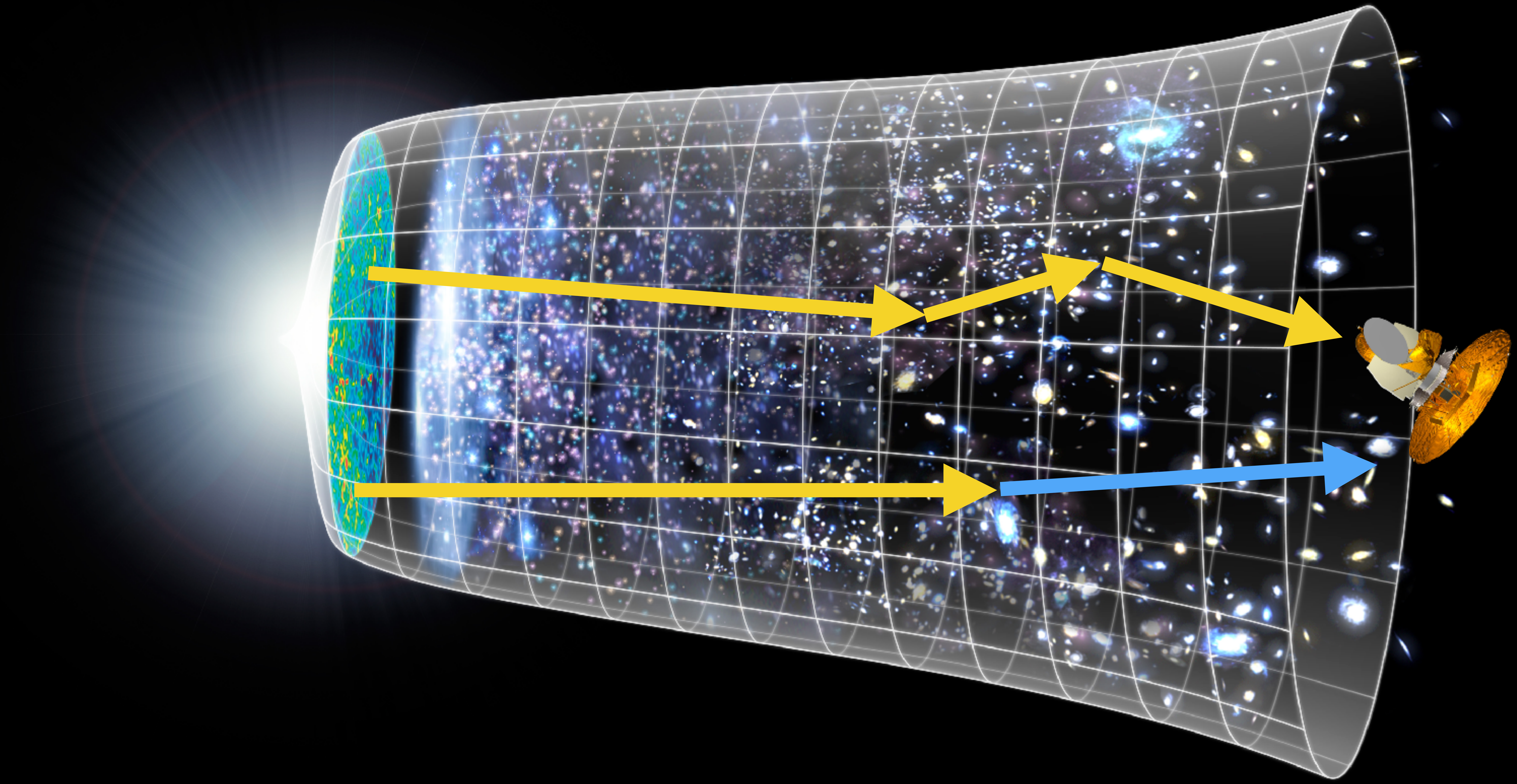
$$\Omega_{\rm th}(z) \equiv \frac{\rho_{\rm th}(z)}{\rho_{\rm crit}} = \frac{\langle P_{\rm th}(z)\rangle}{\rho_{\rm crit}\,(1+z)^3}\,,$$

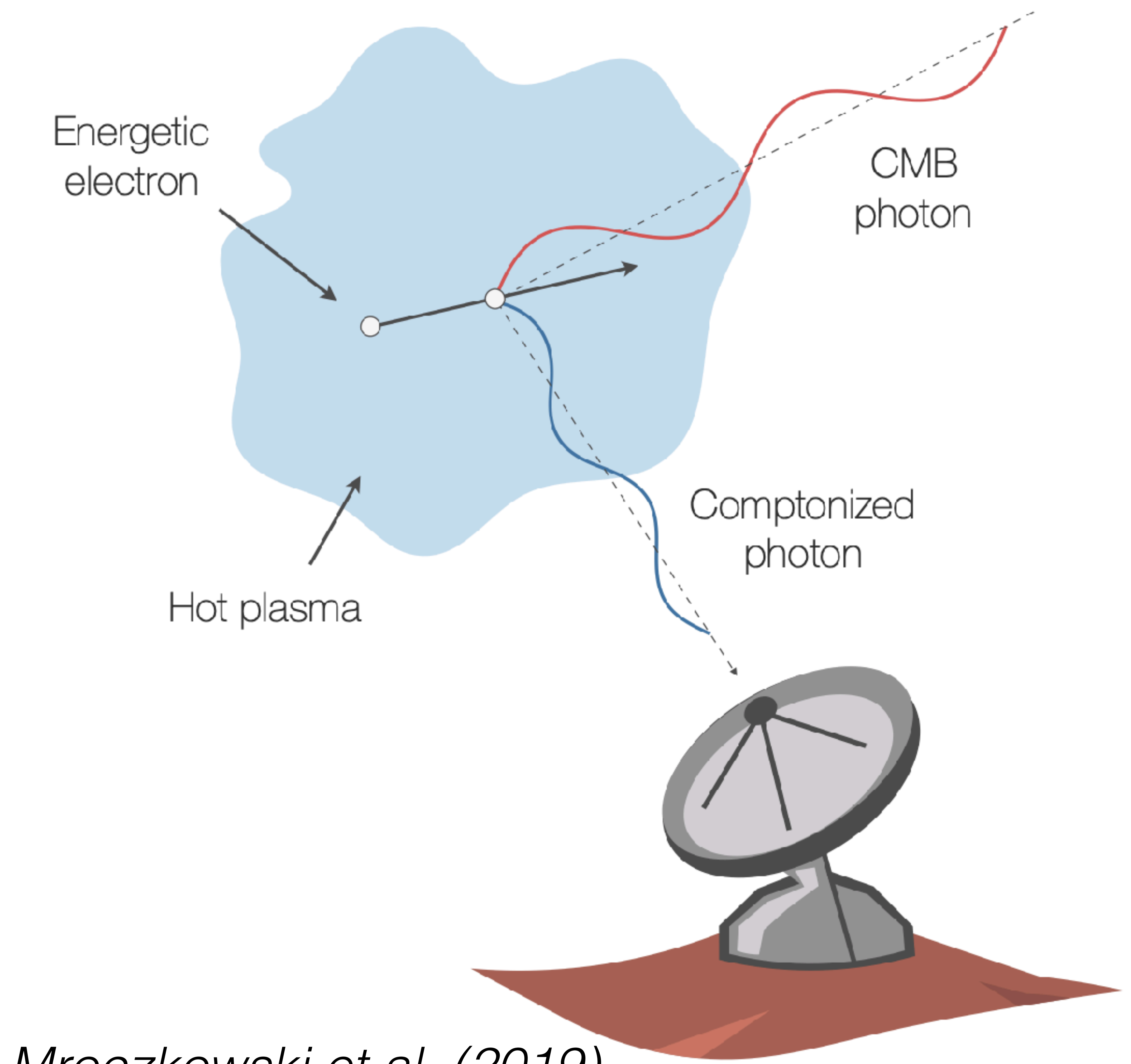
where $\rho_{\rm crit} = 1.054 \times 10^4\ h^2\ {\rm eV\ cm^{-3}}$ is the present-day critical energy density.

Order-of-magnitude estimate

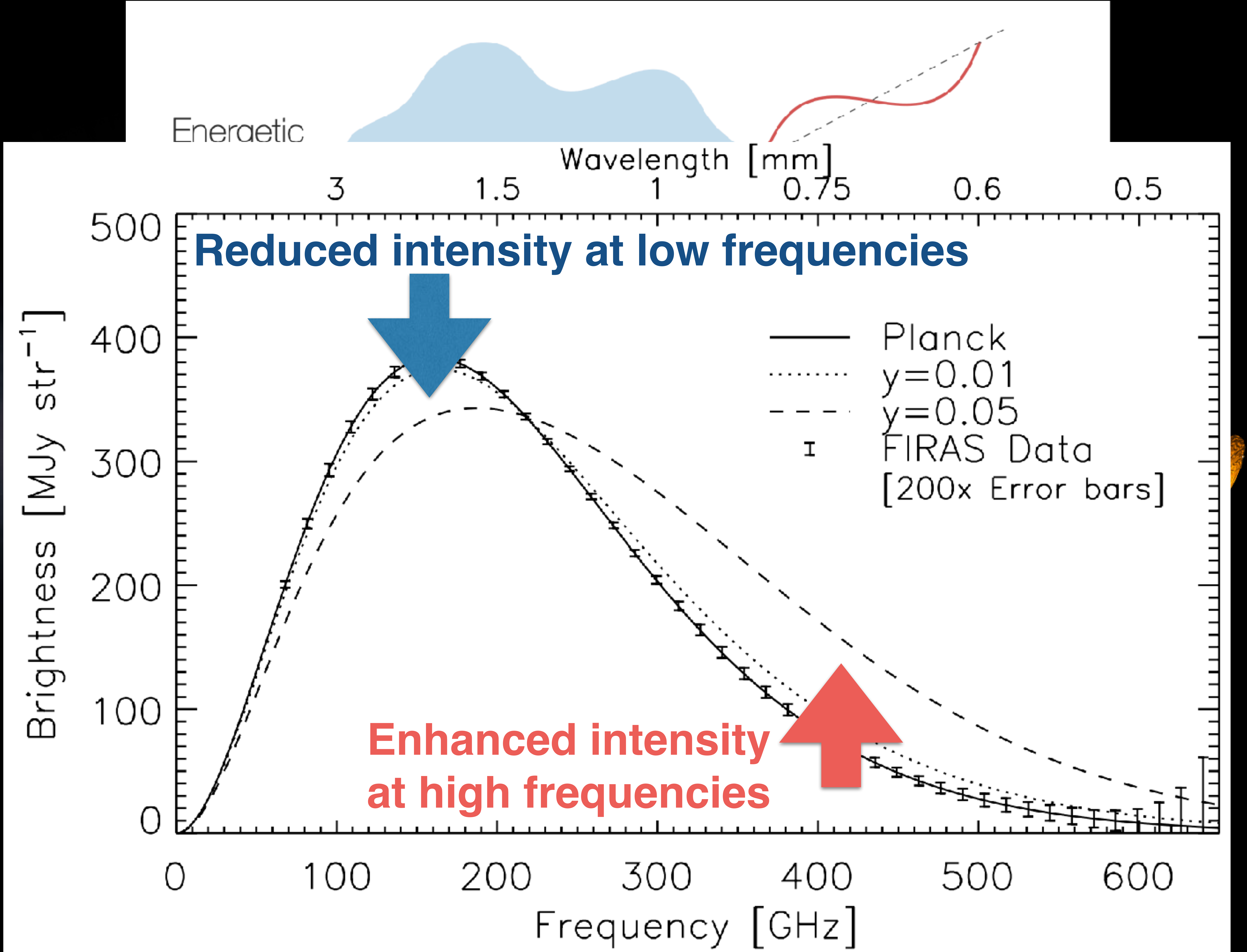
There is more than one way to do this. Here is one example.

- $P_{th} = \rho_{gas}\sigma^2$, where σ^2 is some typical 1D velocity dispersion in the large-scale structure.
- $\Omega_{th} = \Omega_{gas}\sigma^2$ ~ **2×10^{-8}** $(\Omega_{gas}/0.05)(\sigma/200\ \mathrm{km/s})^2$
- *Spoiler: our measurement gives* ***Ω_{th} = (1.7±0.1)x10^{-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.

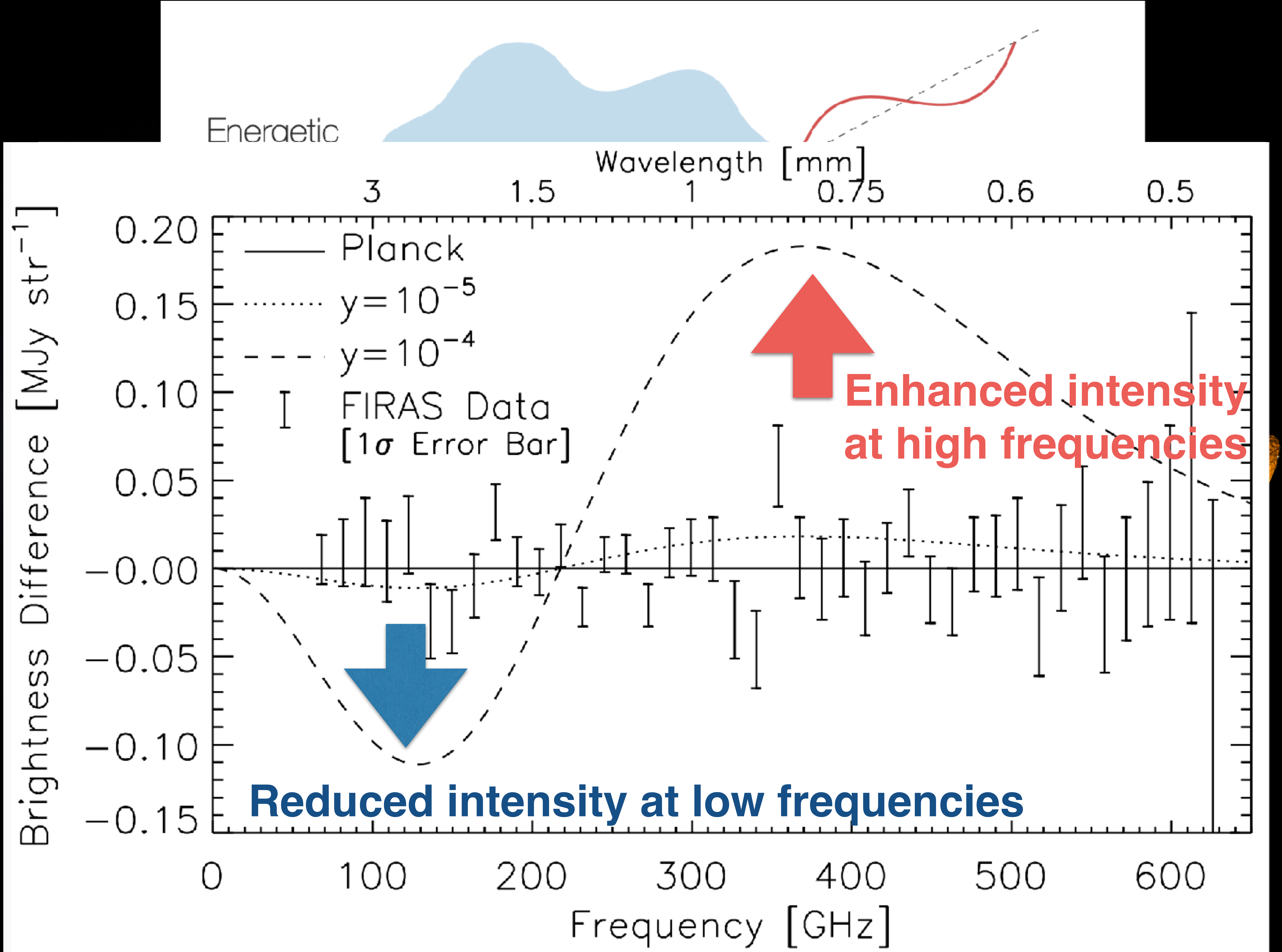




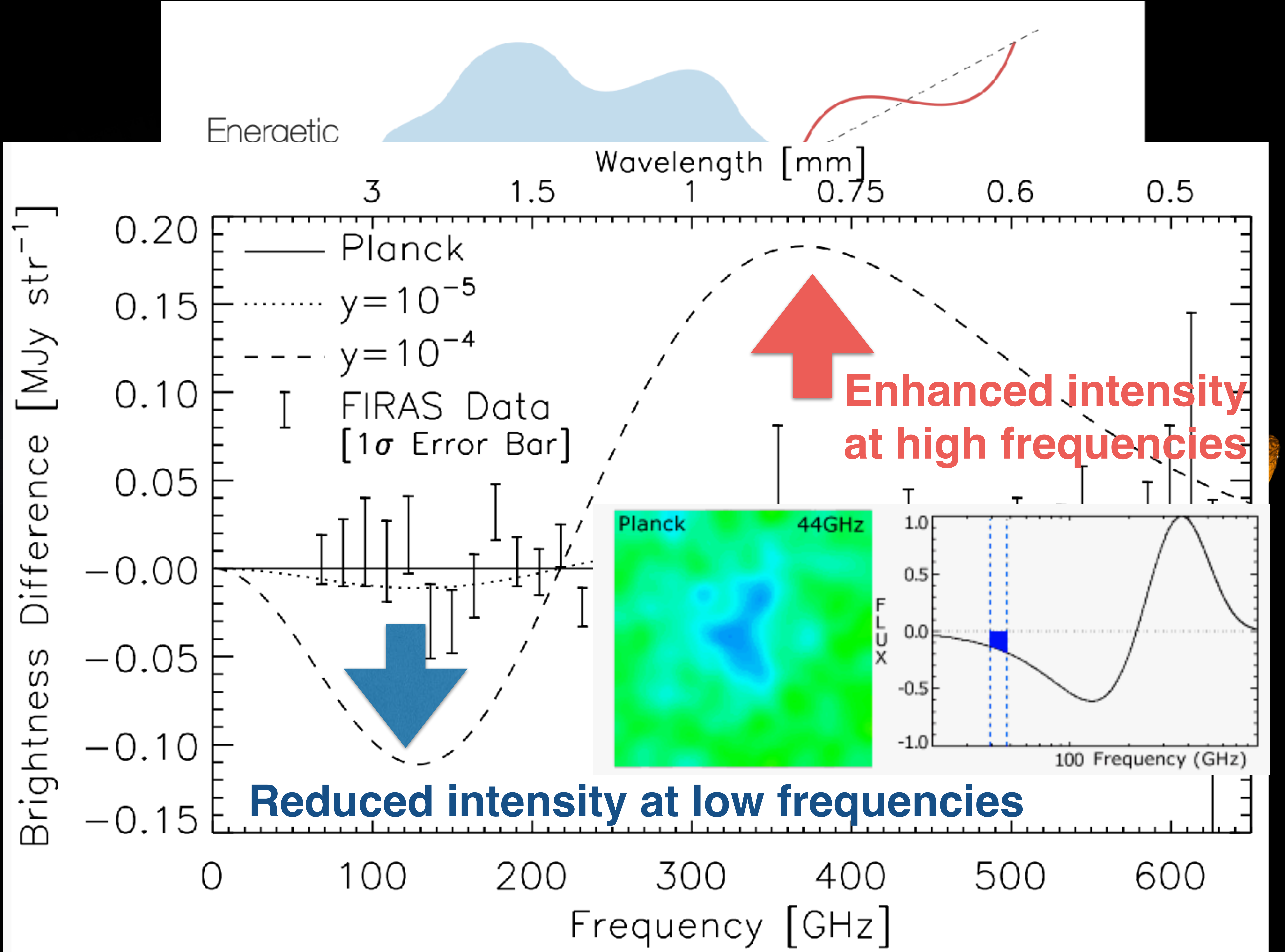
Mroczkowski et al. (2019)



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



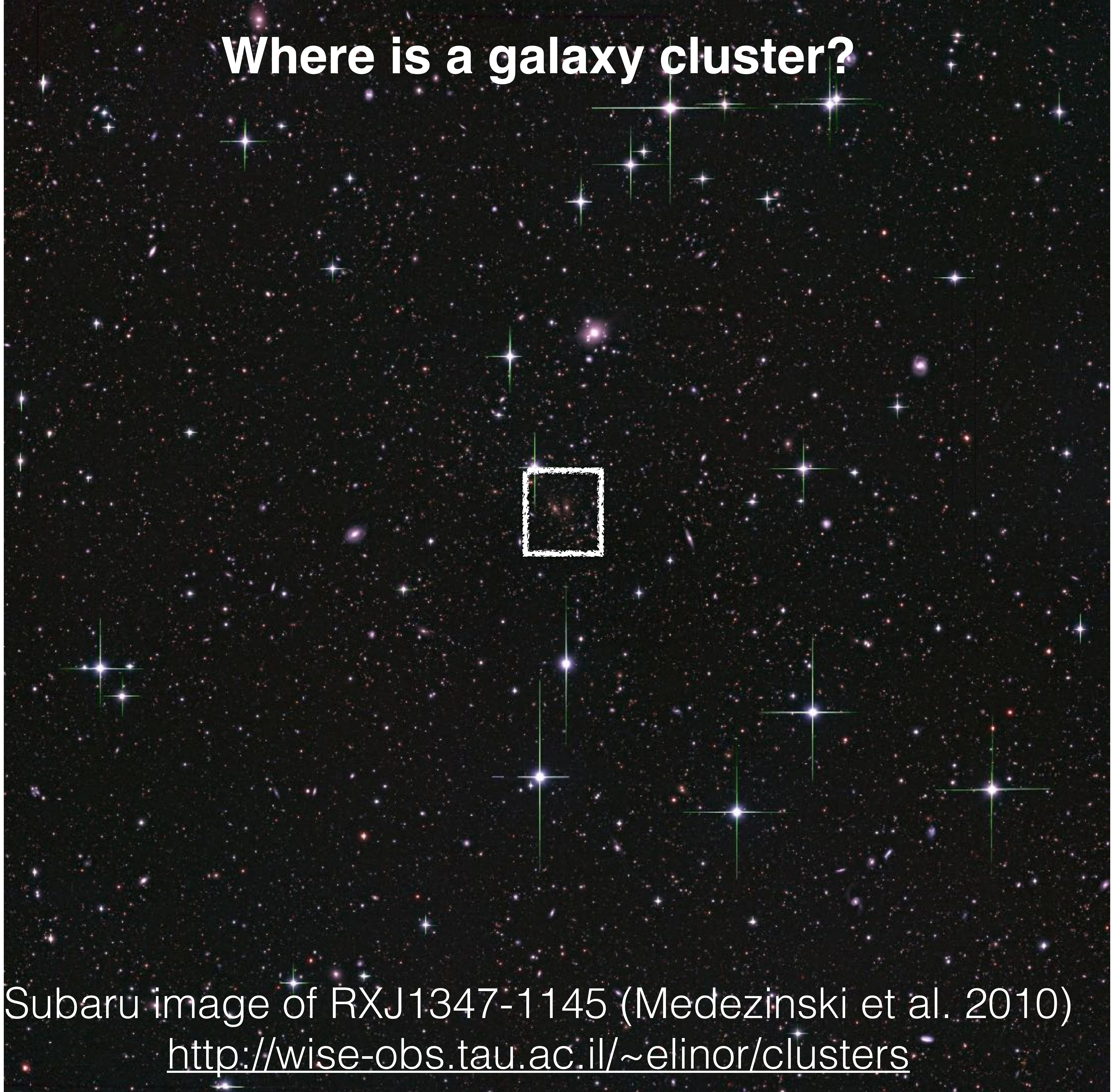
Energetic
Wavelength [mm]
3
1.5
1
0.75
0.6
0.5
Brightness Difference [MJy str^{-1}]
0.20
0.15
0.10
0.05
−0.00
−0.05
−0.10
−0.15
Planck
y=10^{-5}
y=10^{-4}
FIRAS Data
[1σ Error Bar]
Enhanced intensity
at high frequencies
Reduced intensity at low frequencies
0
100
200
300
400
500
600
Frequency [GHz]

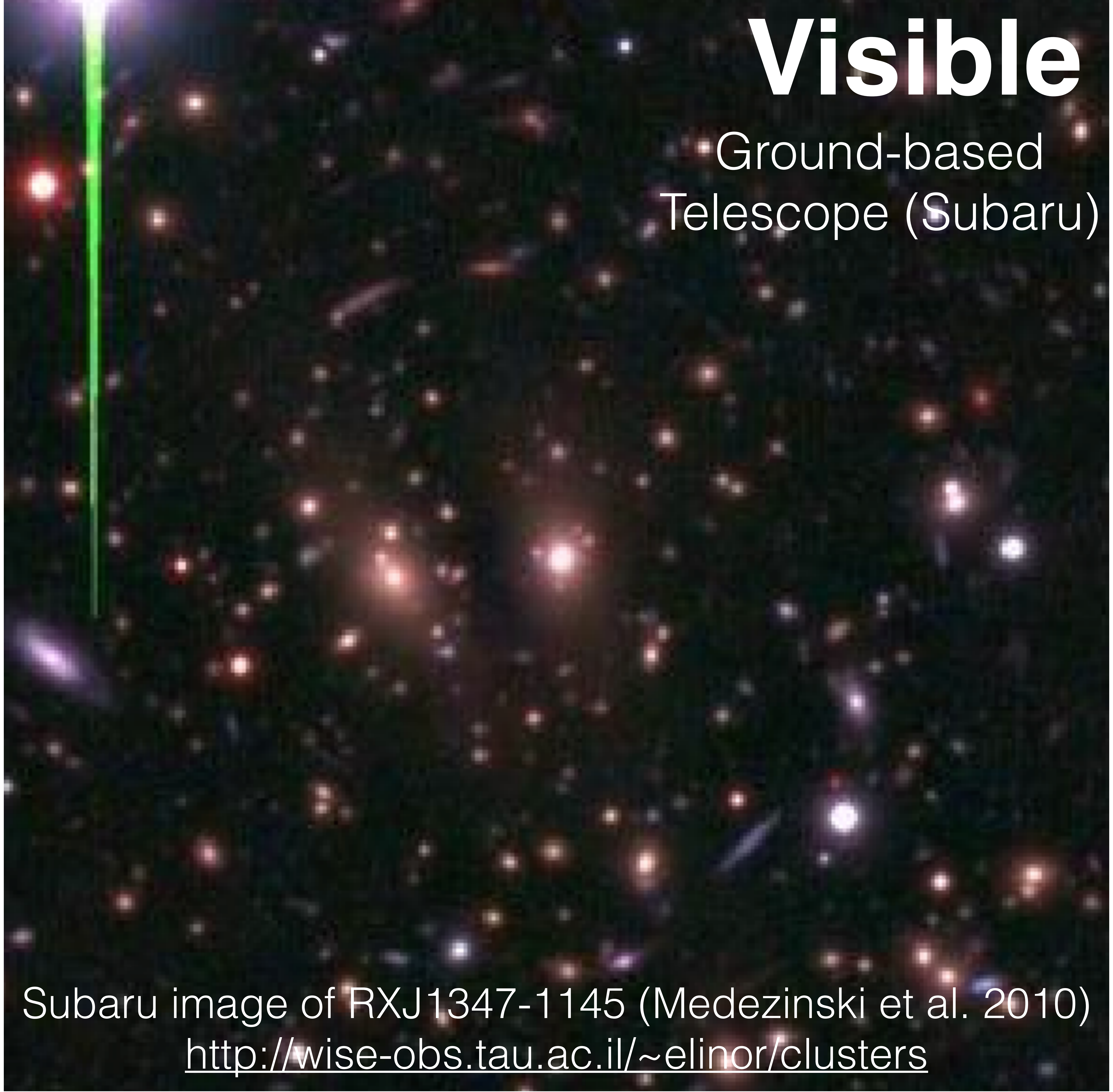


Wavelength [mm]
3
1.5
1
0.75
0.6
0.5
Brightness Difference [MJy str^{-1}]
0.20
0.15
0.10
0.05
−0.00
−0.05
−0.10
−0.15
Planck
y=10^{-5}
y=10^{-4}
FIRAS Data
[1σ Error Bar]
Enhanced intensity
at high frequencies
Planck
44GHz
FLUX
1.0
0.5
0.0
-0.5
-1.0
100 Frequency (GHz)
Reduced intensity at low frequencies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

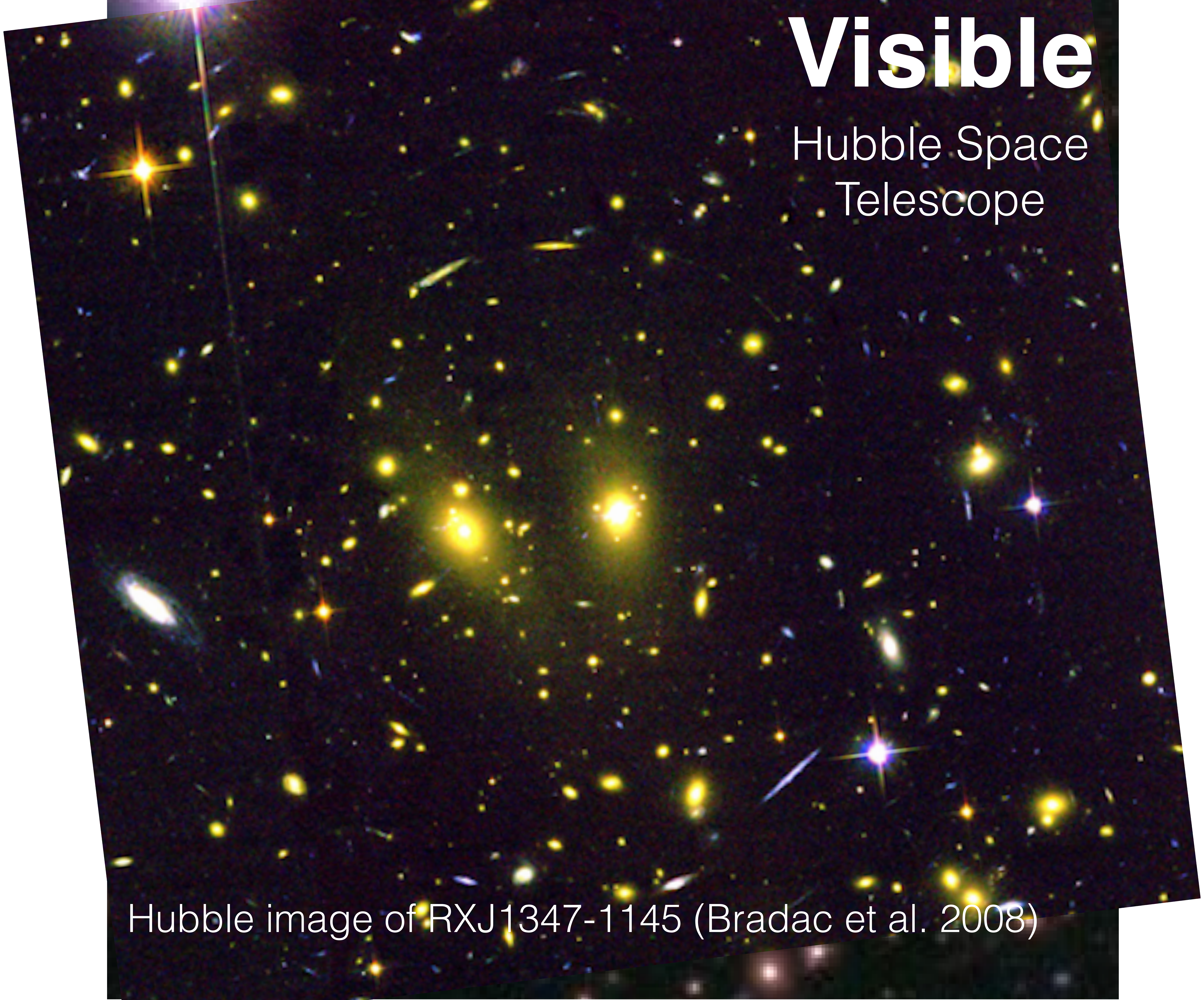
Where is a galaxy cluster?

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

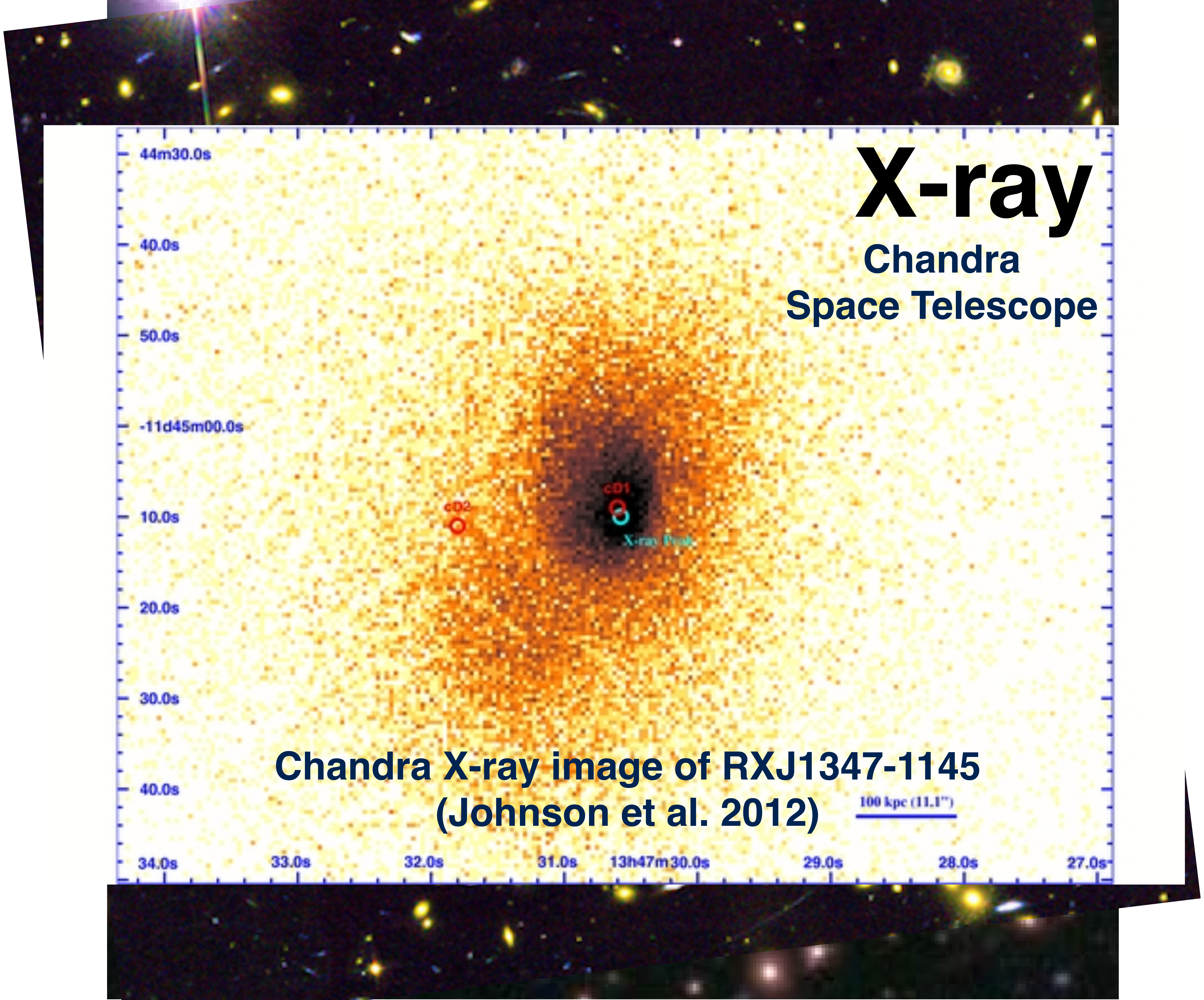


Visible
Ground-based
Telescope (Subaru)
Subaru image of RXJ1347-1145 (Medezinski et al. 2010)
http://wise-obs.tau.ac.il/~elinor/clusters

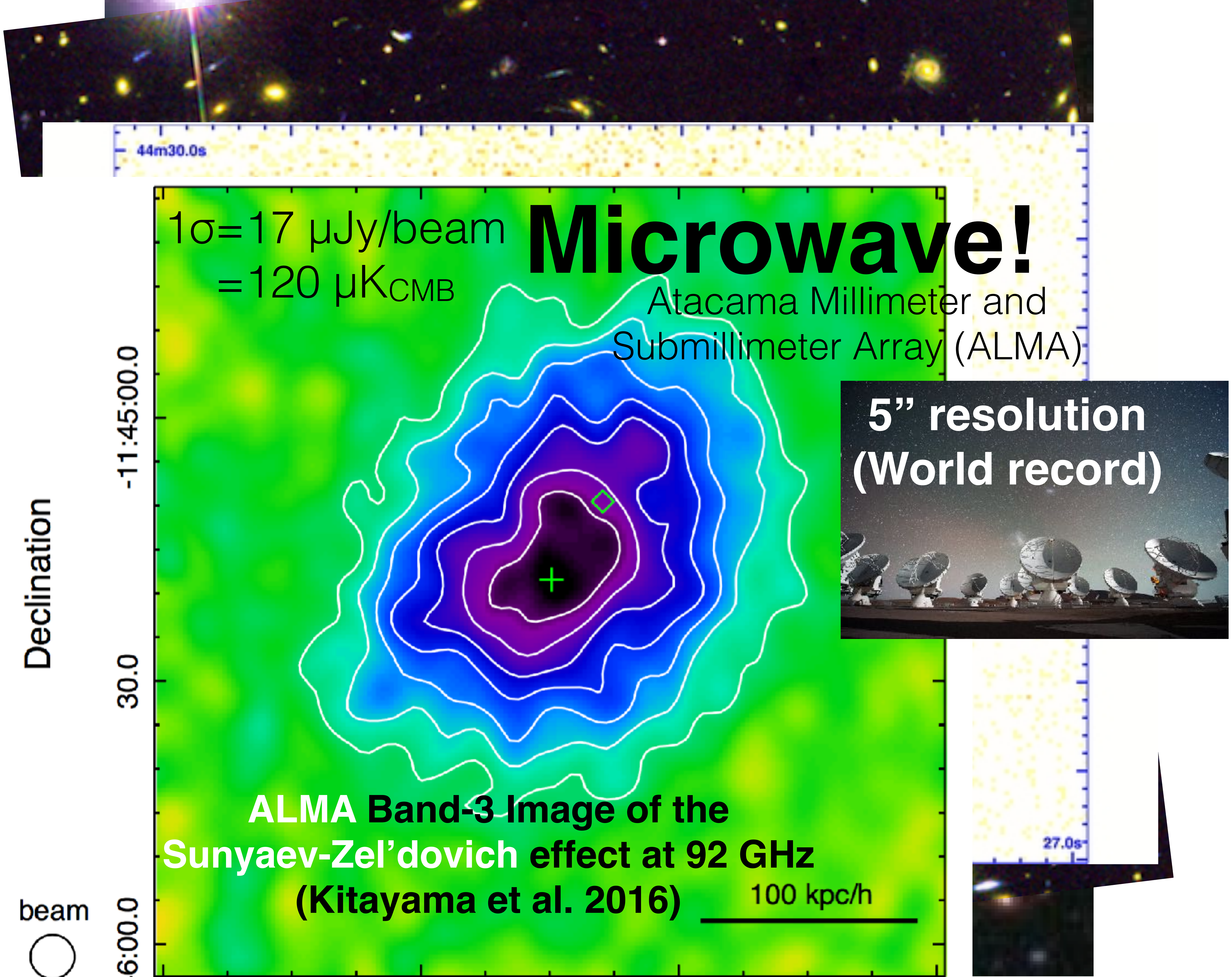

Visible
Hubble Space
Telescope
Hubble image of RXJ1347-1145 (Bradac et al. 2008)

X-ray

Chandra
Space Telescope



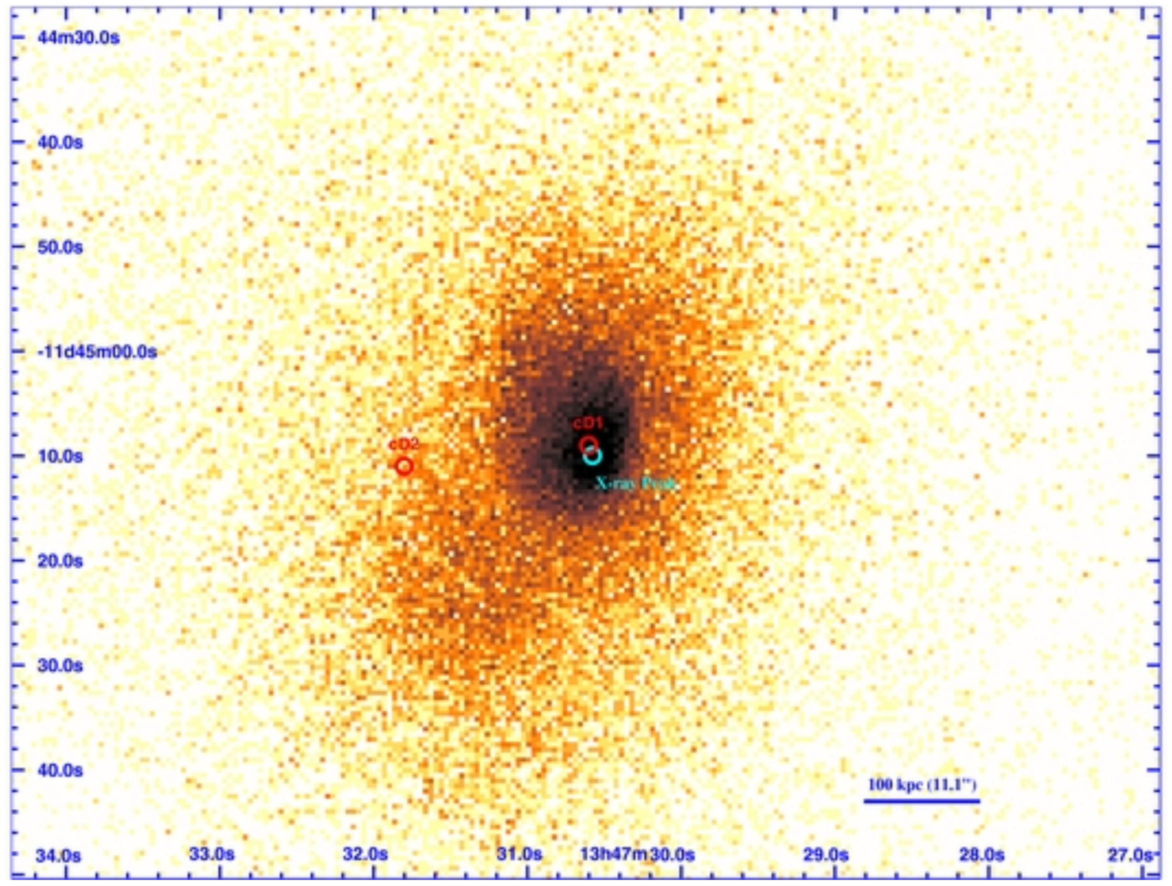
Chandra X-ray image of RXJ1347-1145
(Johnson et al. 2012)

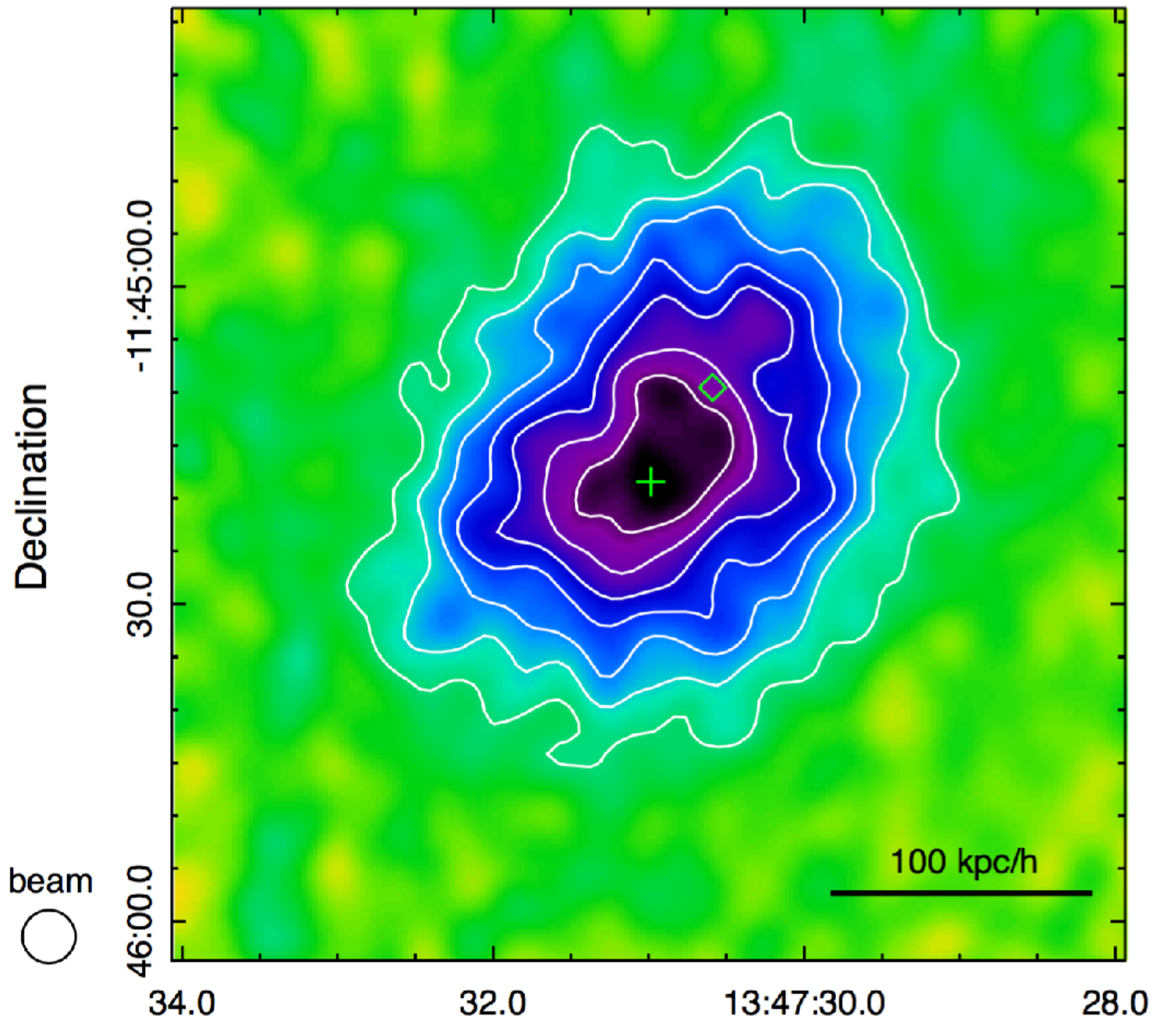


Microwave!
Atacama Millimeter and Submillimeter Array (ALMA)
1σ=17 μJy/beam
=120 μKCMB
5” resolution (World record)
ALMA Band-3 Image of the Sunyaev-Zel’dovich effect at 92 GHz (Kitayama et al. 2016)
100 kpc/h
Declination
-11:45:00.0
30.0
6:00.0
beam
44m30.0s
27.0s

Multi-wavelength Data

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





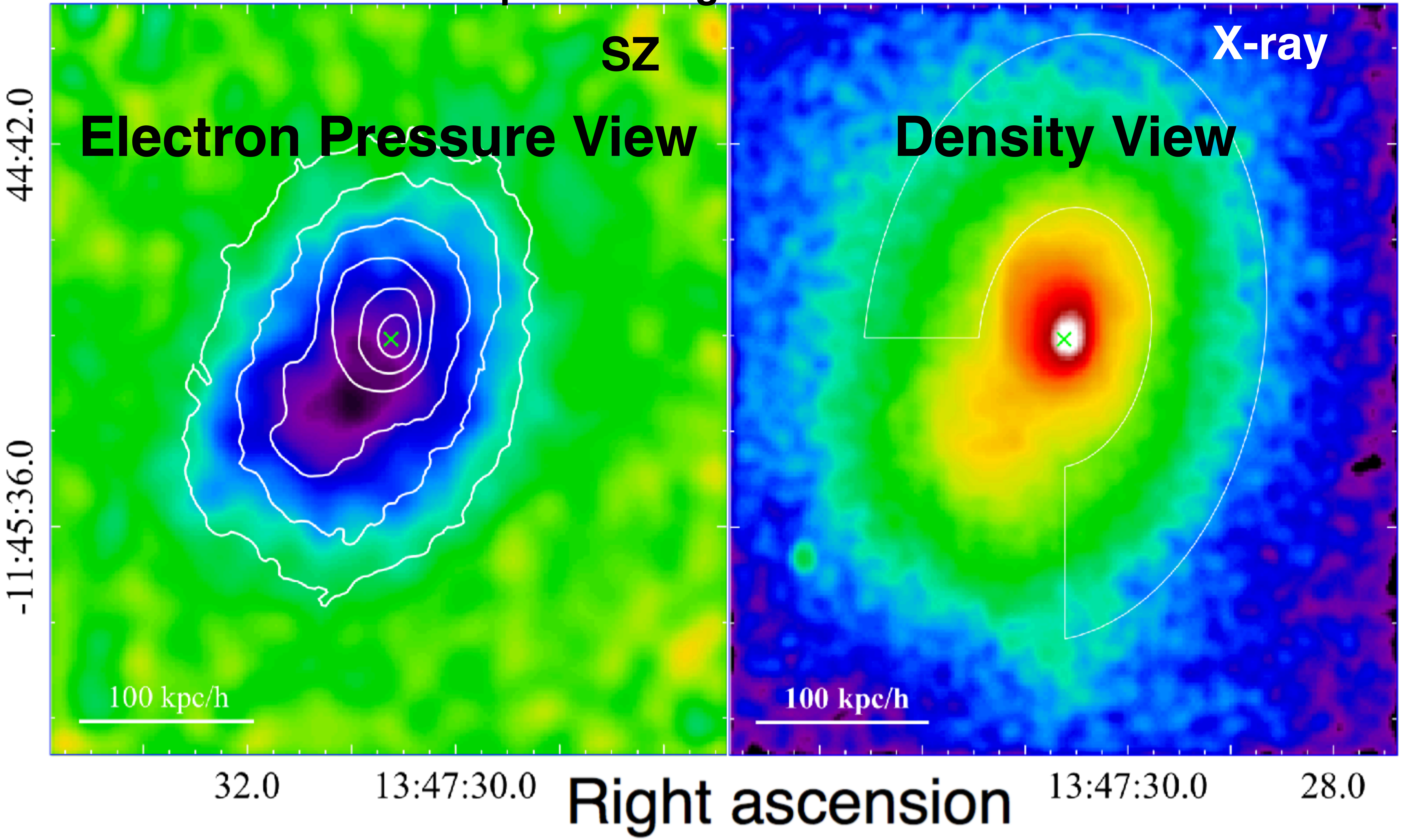
Optical:
- 10^{2-3} galaxies
- velocity dispersion
- gravitational lensing

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

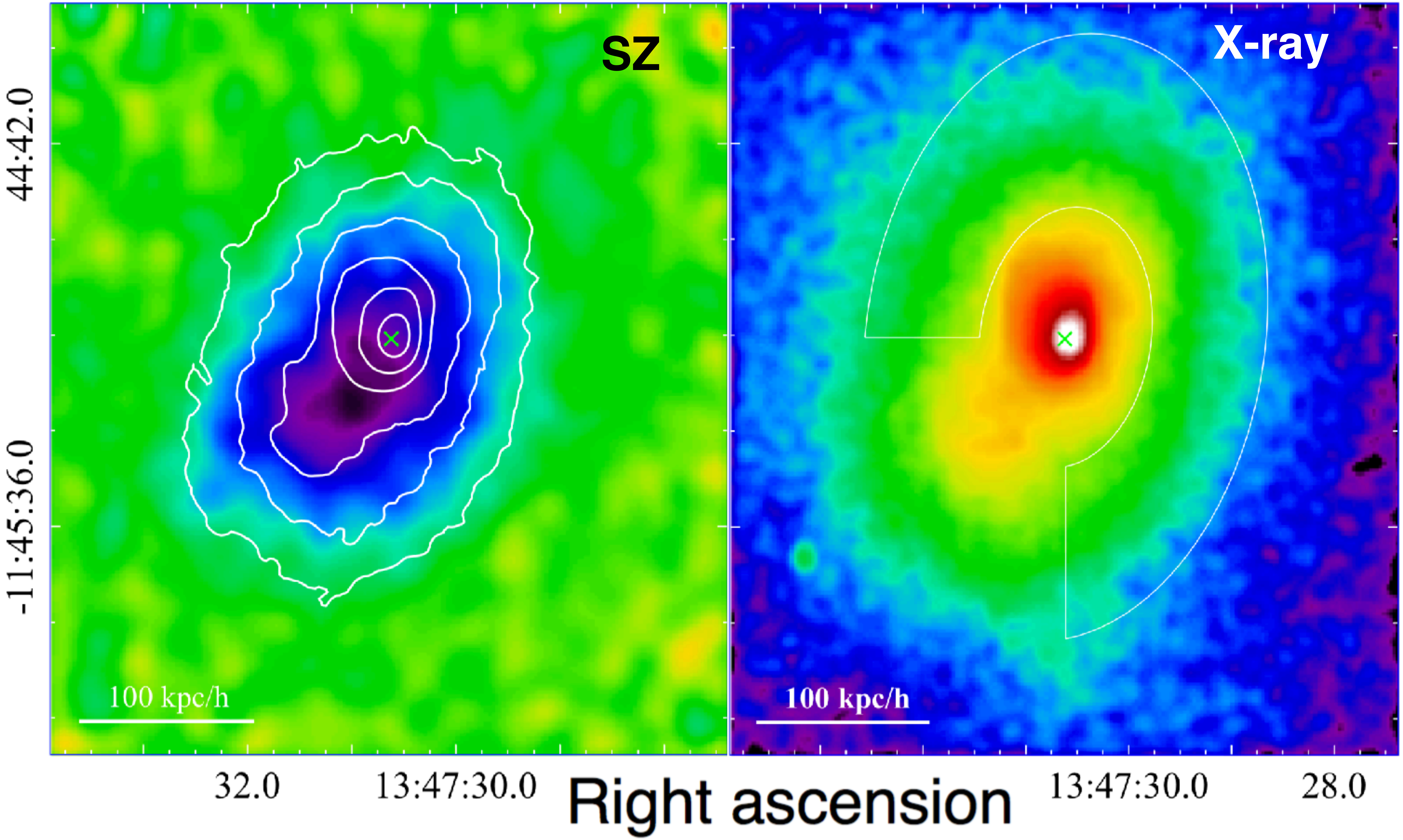
SZ [microwave]:
- hot gas (10^{7-8} K)
- electron pressure
- Intensity ~ $n_e T_e L$

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.

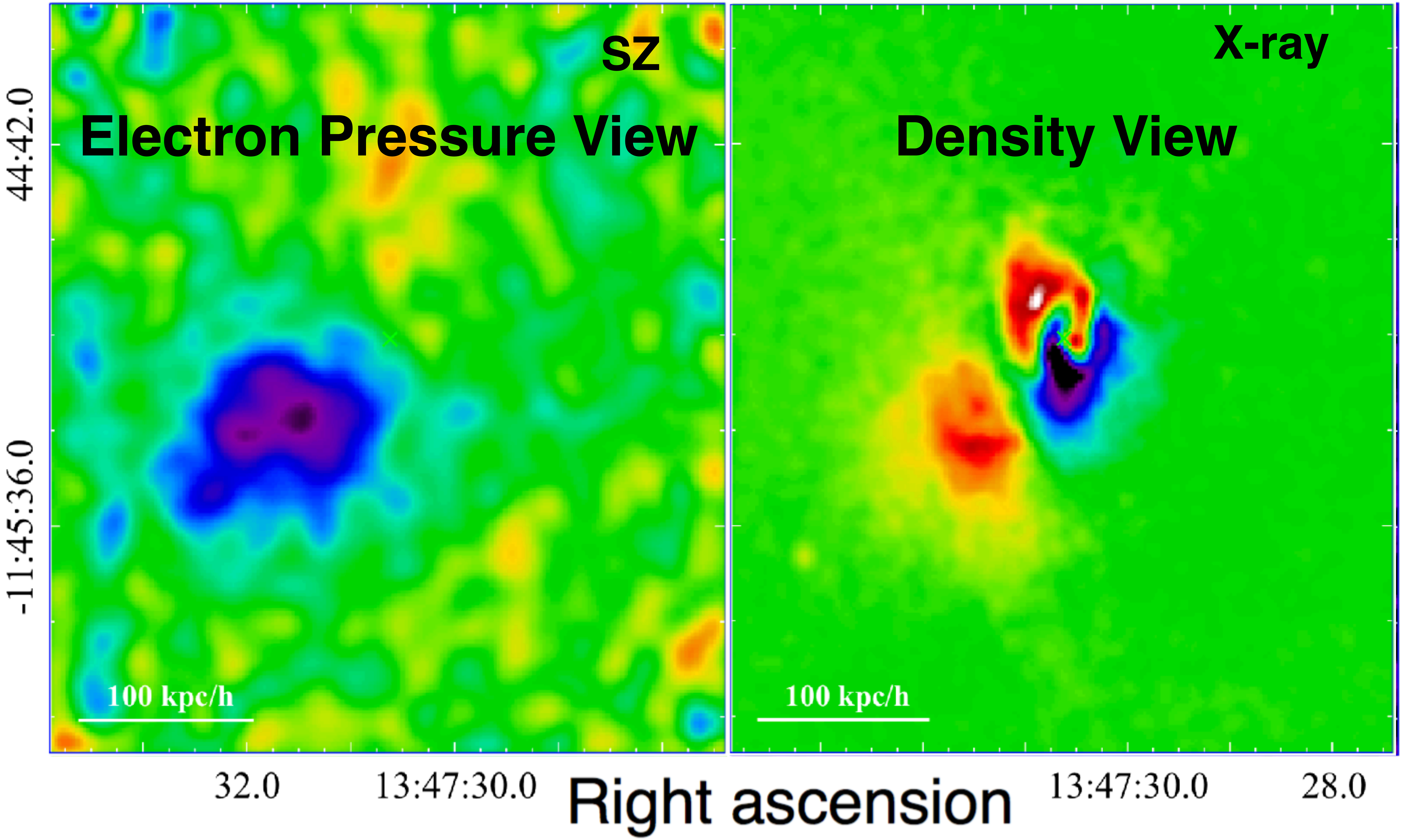


Let's subtract a smooth component



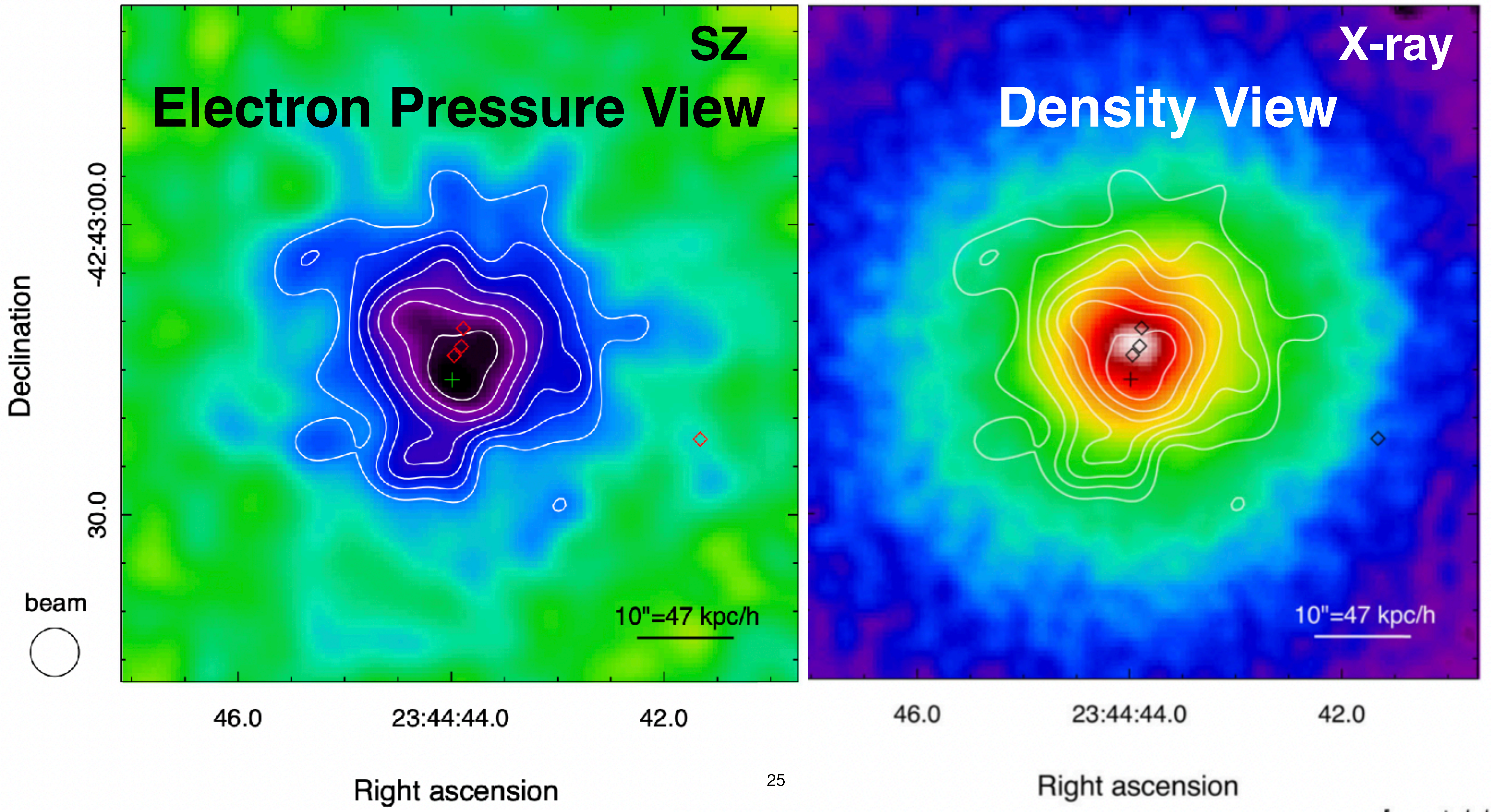
Ueda et al. (2018)

Let's subtract a smooth component



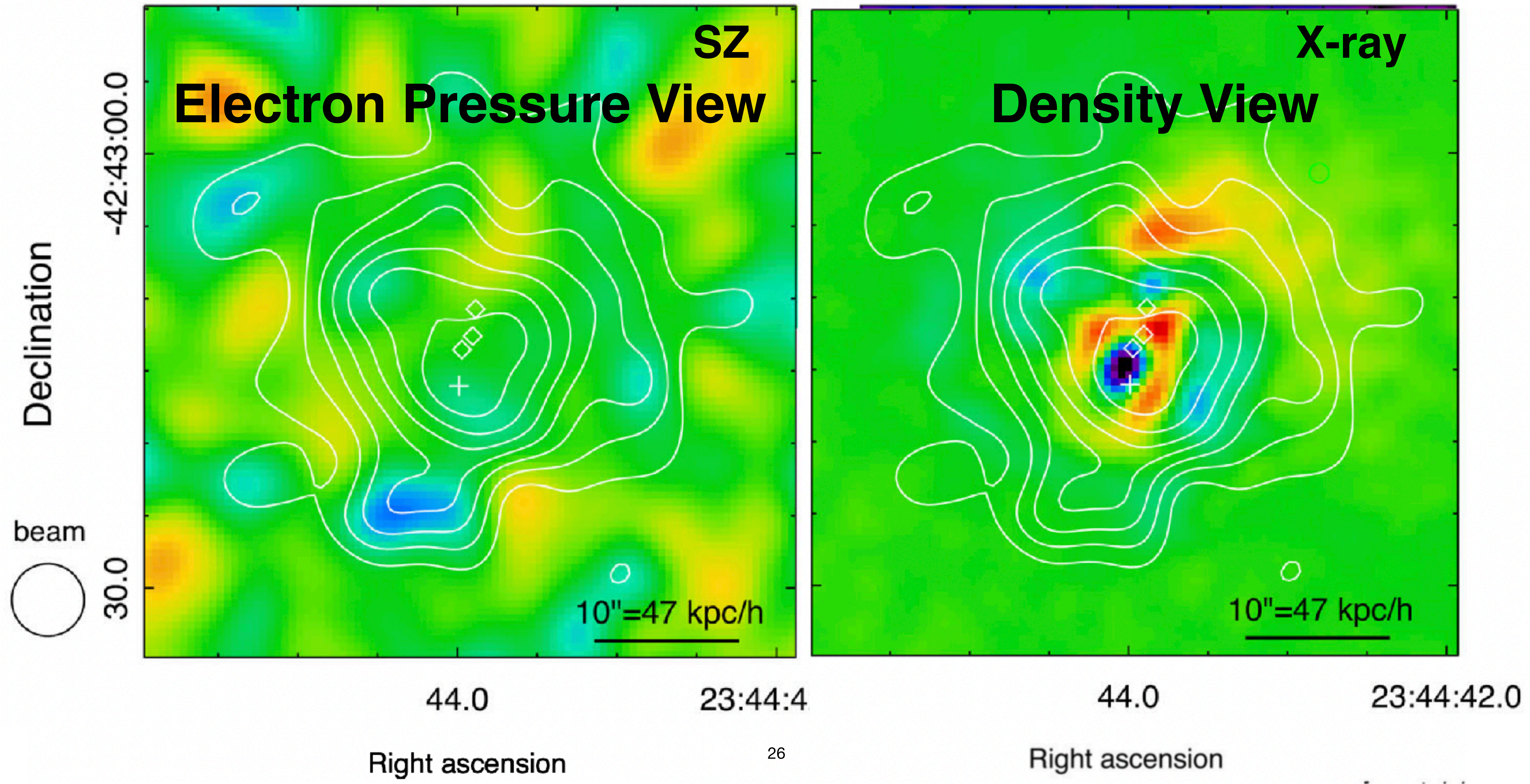
Kitayama et al. (2020)

Another example: Phoenix Cluster (z=0.597)



Kitayama et al. (2020)

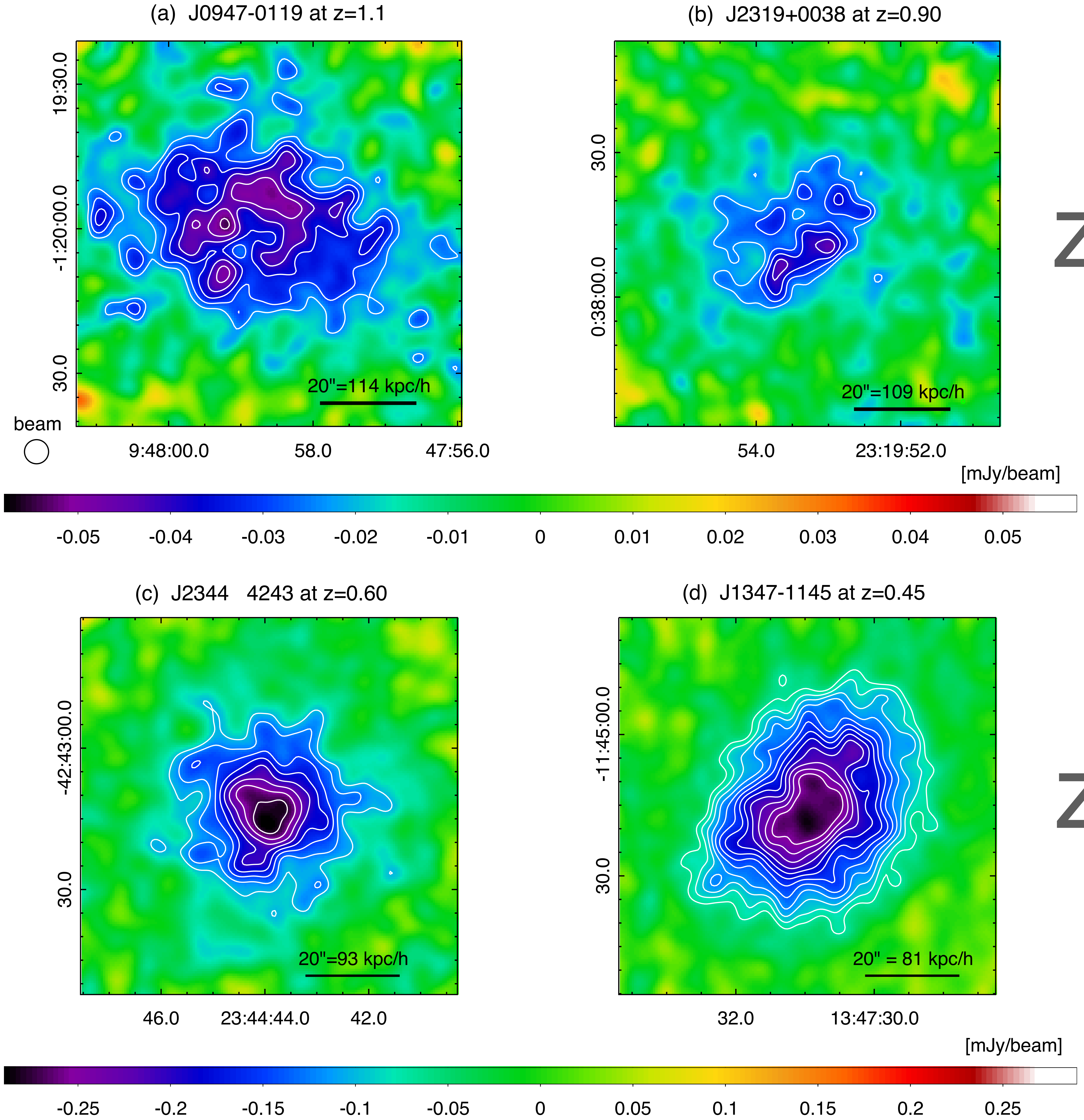
Another example: Phoenix Cluster (z=0.597)



Gallery of the highest-resolution SZ images

z=1.1

z=0.9



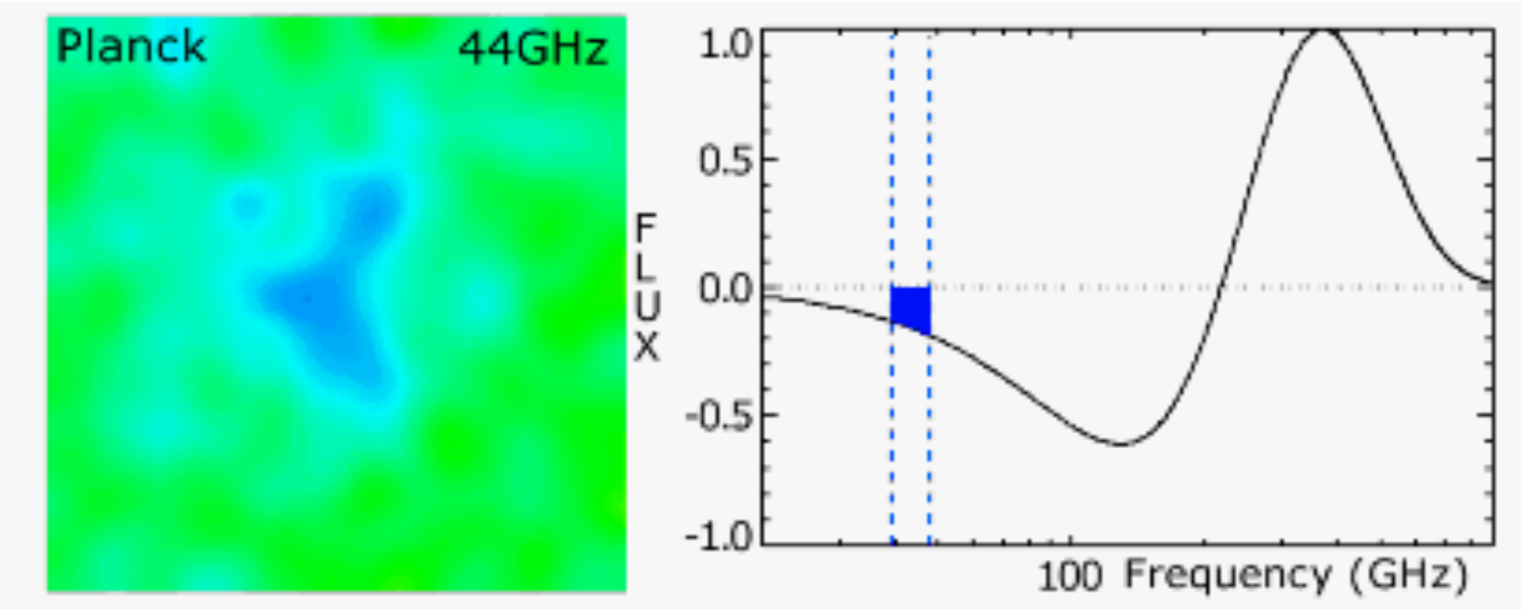
z=0.6

z=0.45

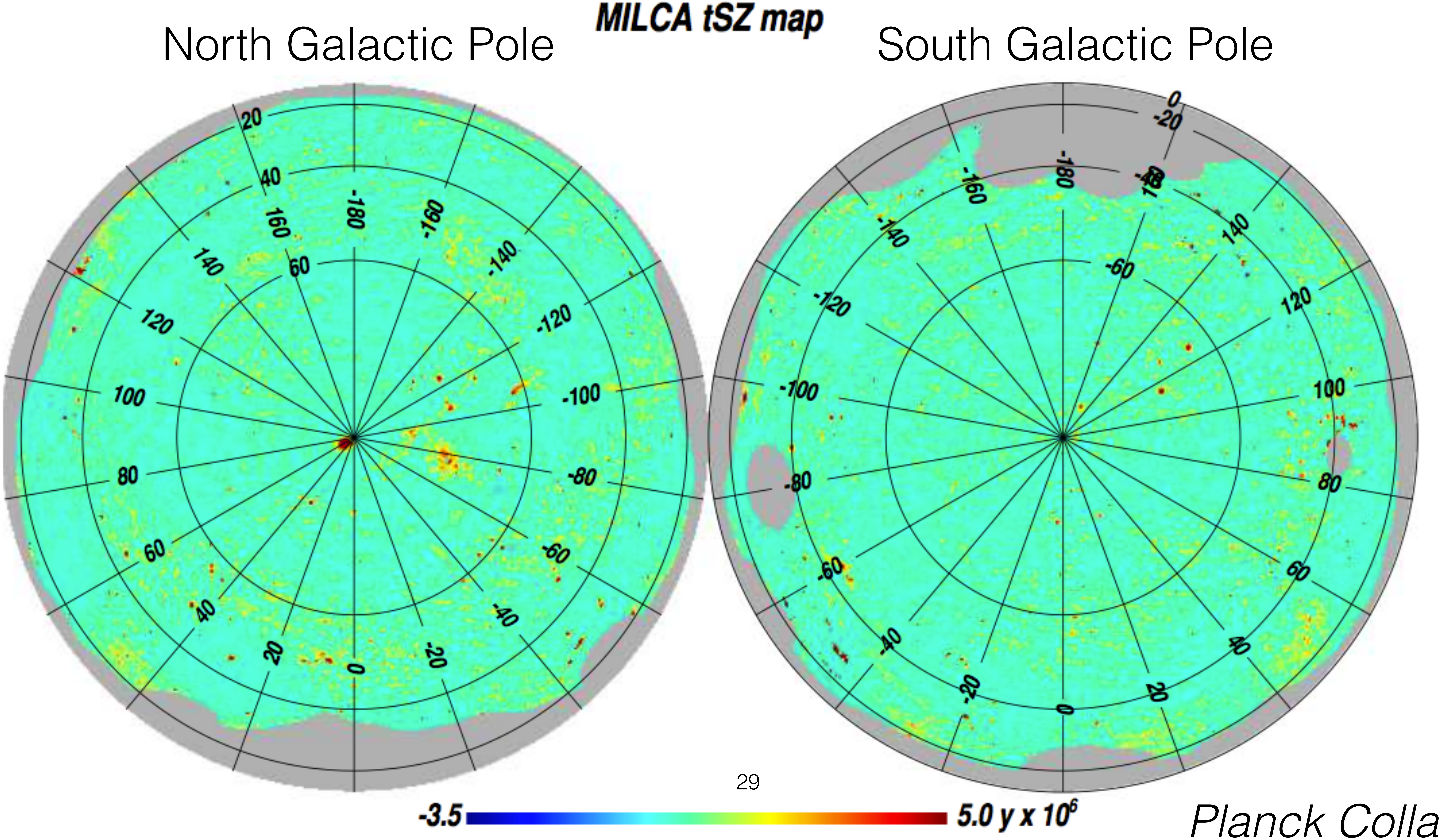
Chiang, Makiya, Ménard, EK, ApJ, 902, 56 (2020)

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



Planck Collaboration

The Limitation of the SZ data

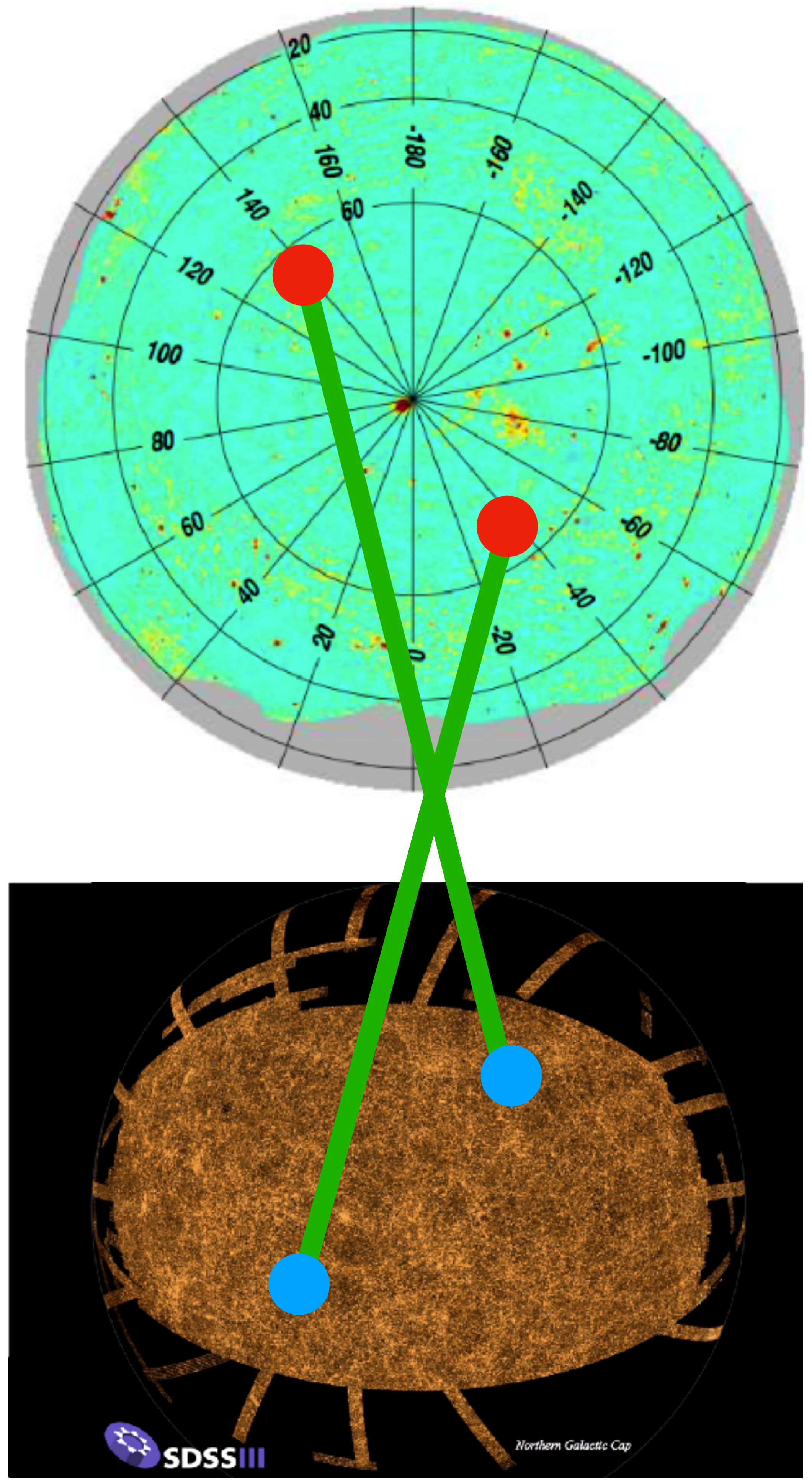
The need for "Tomography"

- 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**.

See Chiang's versatile cross-correlation tool, "*Tomographer*": http://tomographer.org

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 $P_e = \langle P_e \rangle (1 + b_y \delta_{matter})$ and $n_{gal} = \langle n_{gal} \rangle (1 + b_{gal} \delta_{matter})$. Thus, the cross-correlation yields

$$\frac{\langle P_\mathrm{e} n_\mathrm{gal} \rangle}{b_\mathrm{gal} \langle n_\mathrm{gal} \rangle \langle \delta_\mathrm{matter} \delta_\mathrm{matter} \rangle} = b_y \langle P_\mathrm{e} \rangle$$

What we measure from the cross-correlation

What we want in the end

Measured from the auto galaxy correlation

From the ΛCDM model

The first key deliverable

Chiang et al. (2020)

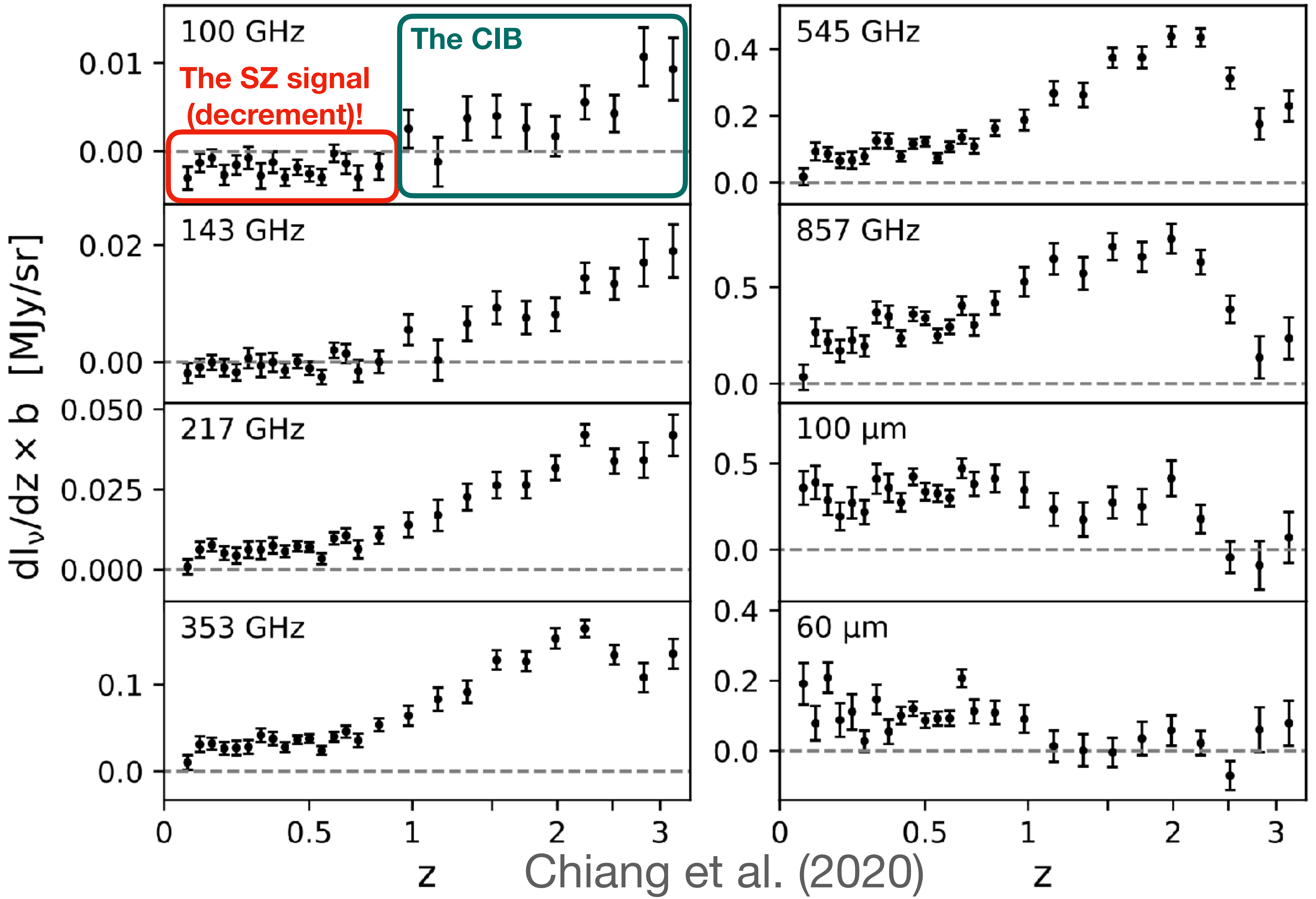
How the measurements look

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.

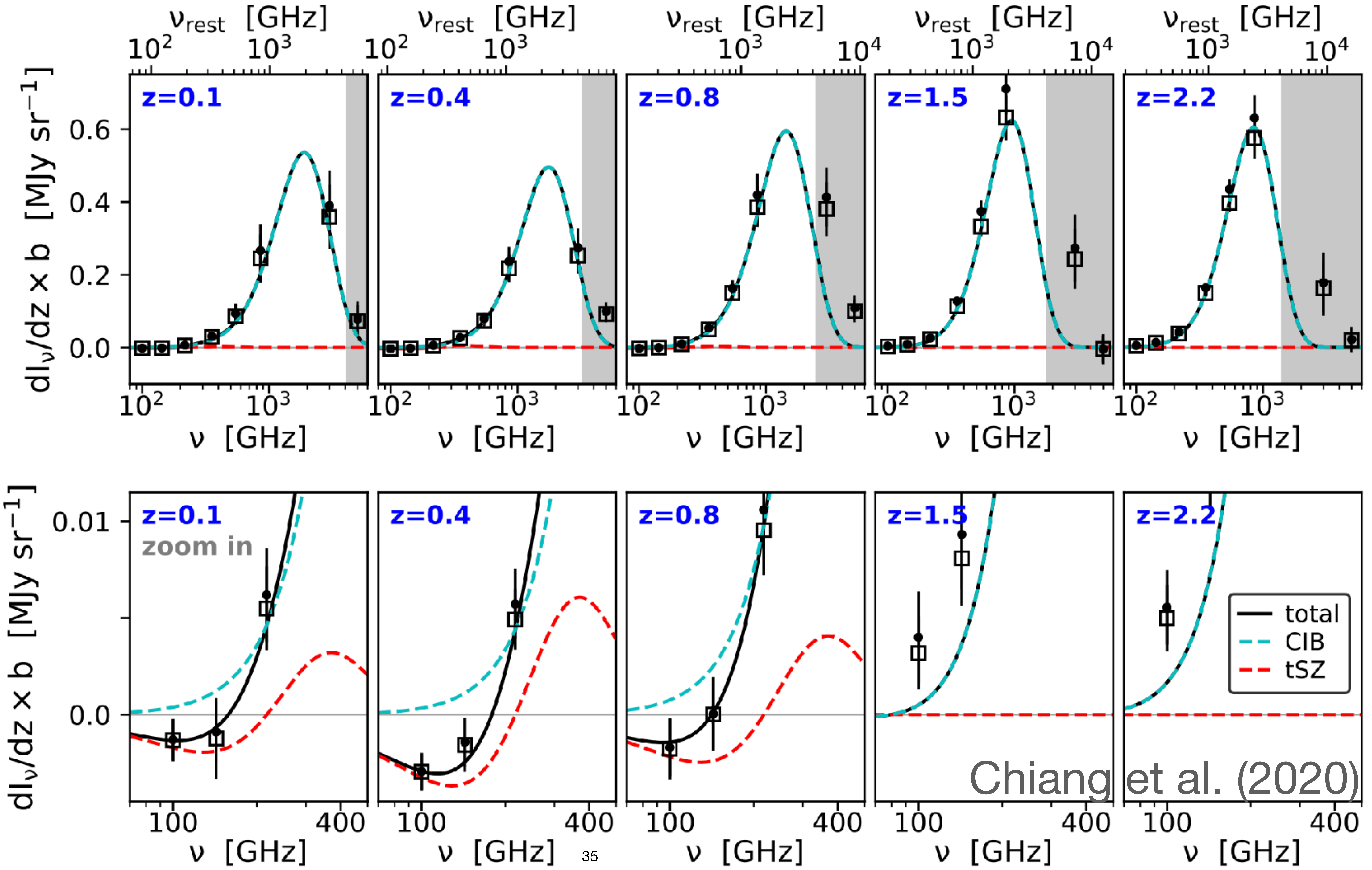
The Planck/IRAS-SDSS cross-correlations

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



Chiang et al. (2020)

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

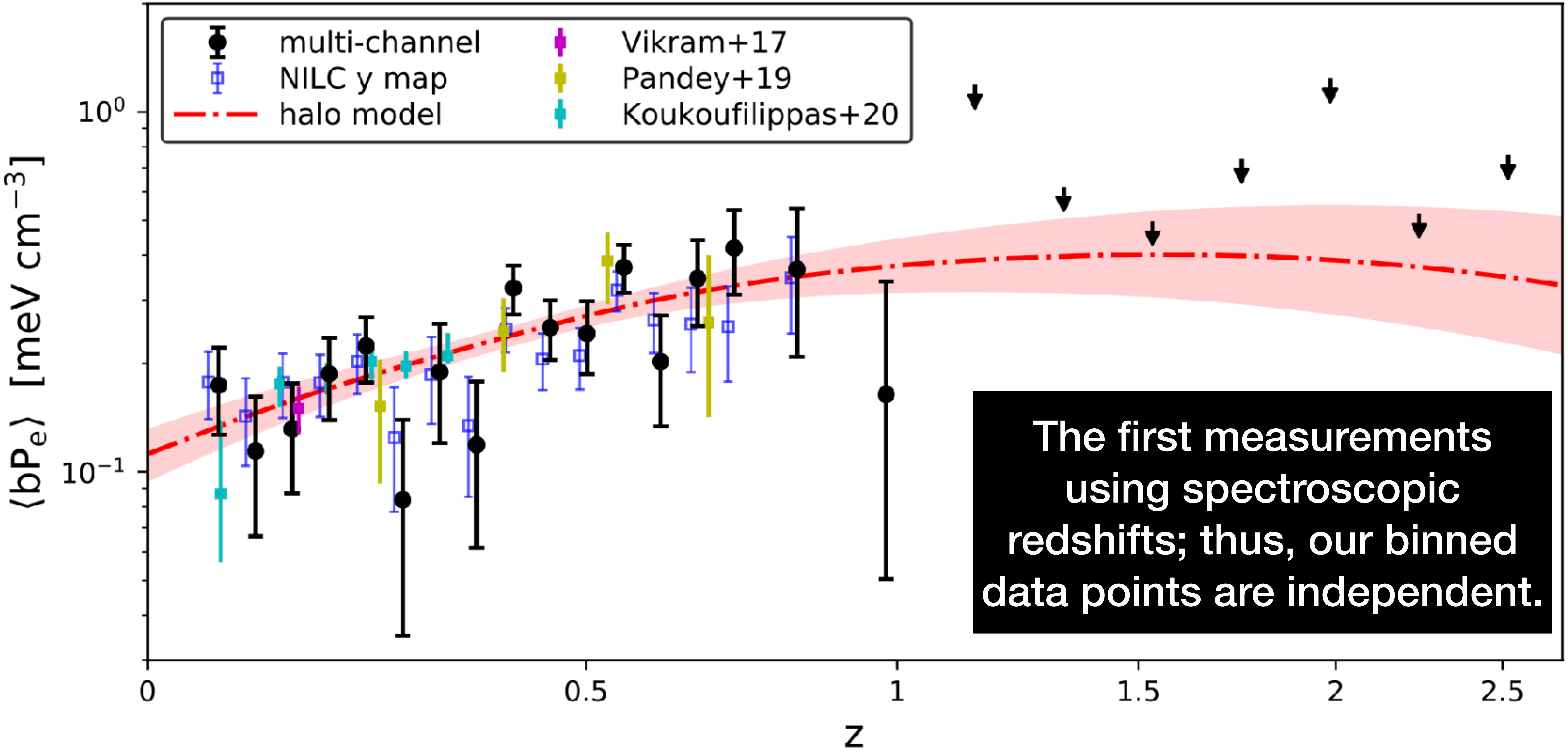


Chiang et al. (2020)

Chiang et al. (2020)

The first main result: Model-independent

Bias-weighted mean electron pressure of the Universe!

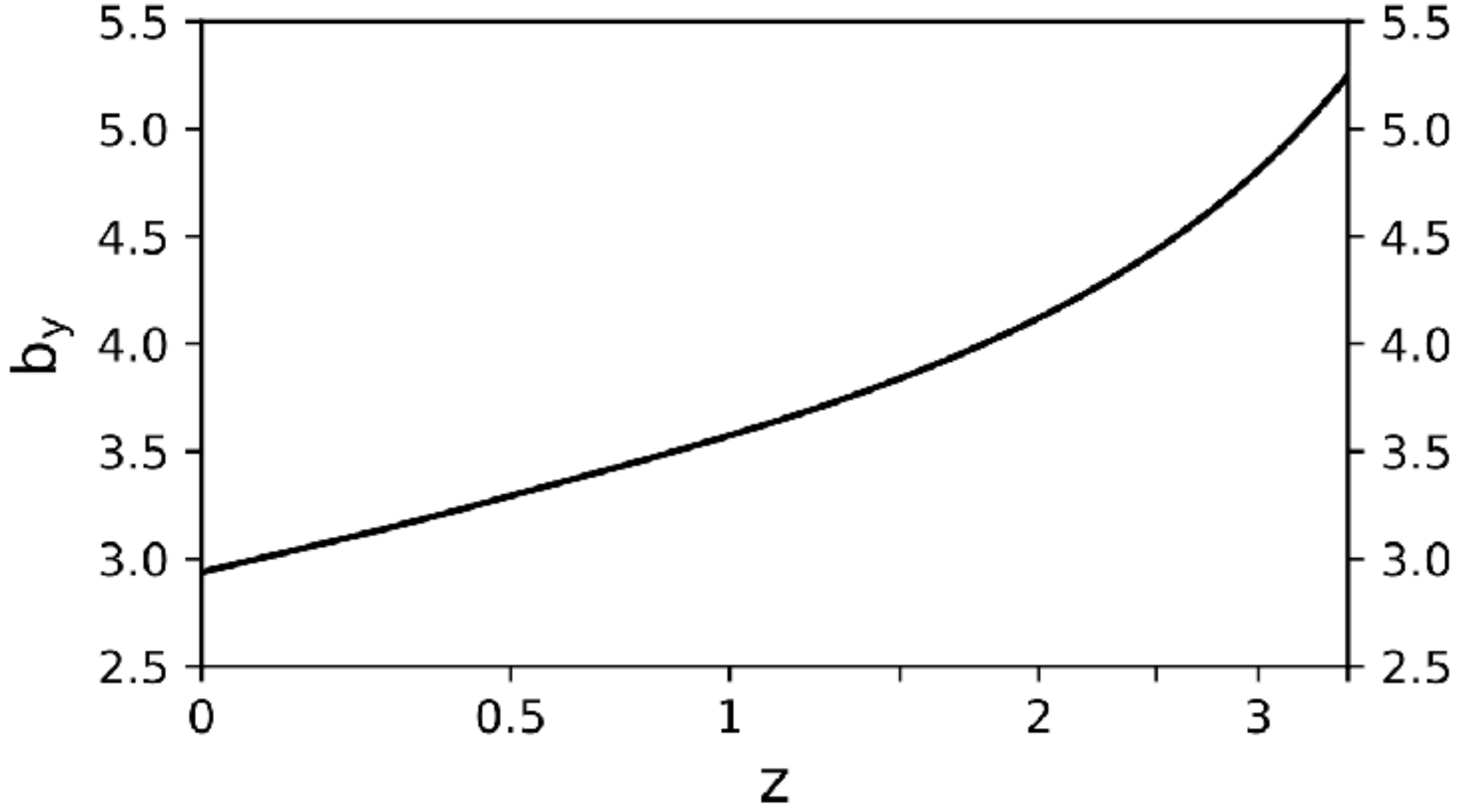


<bPe> -> <Pe>

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

$$b_y(z) = \frac{\langle bP_{\rm e} \rangle}{\langle P_{\rm e} \rangle} = \frac{\int dM \, \frac{dn}{dM} \, M^{5/3+\alpha_P} \, b_{\rm halo}(M, z)}{\int dM \, \frac{dn}{dM} \, M^{5/3+\alpha_P}}$$



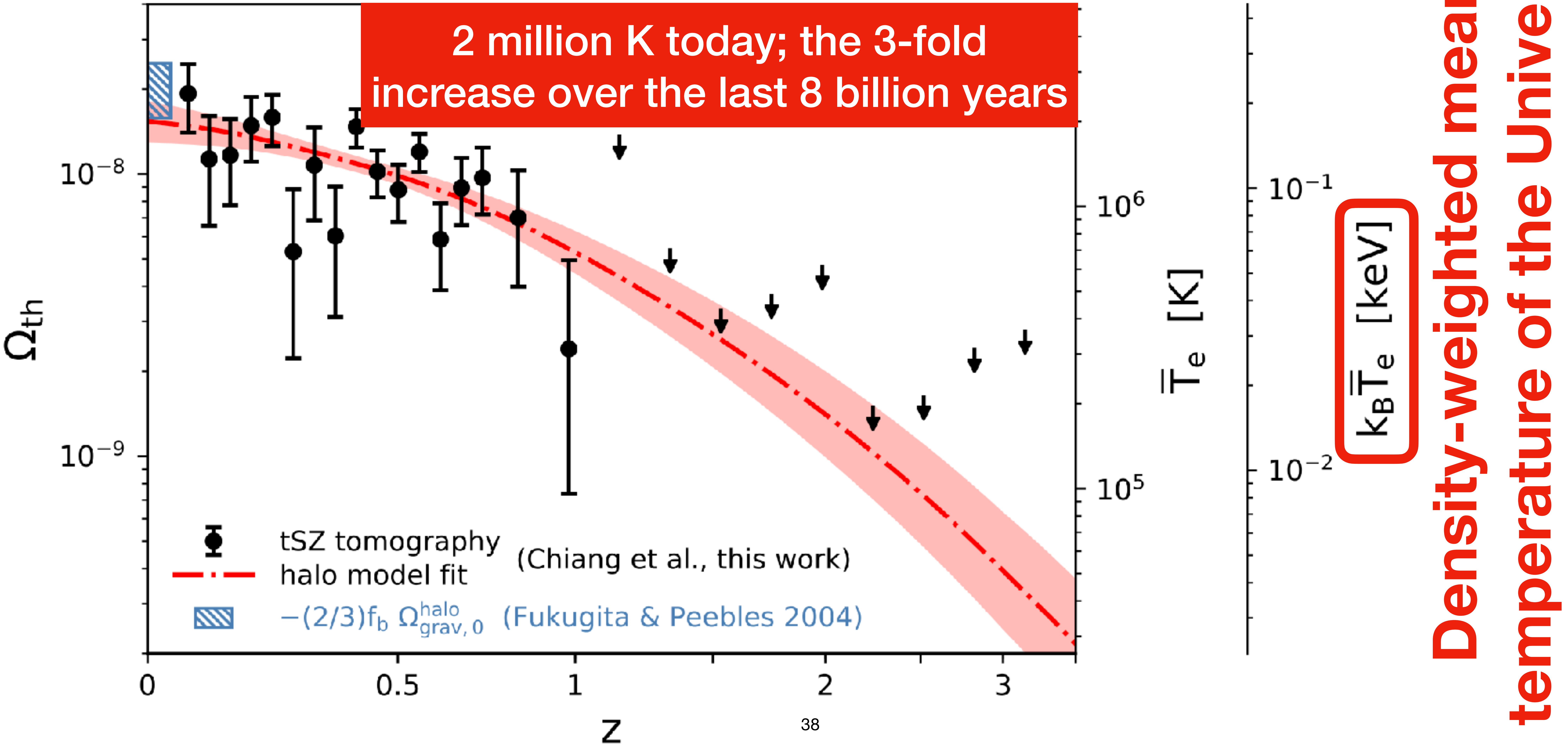
$\alpha_P = 0.12$ is the empirical correction for non-self-similar scaling found by the X-ray data (Arnaud et al. 2010).

Chiang et al. (2020)

$$\Omega_{\rm th}(z) = 1.78 \times 10^{-8} \frac{k_{\rm B}\bar{T}_\rho(z)}{0.2\ {\rm keV}} \frac{\Omega_{\rm b}}{0.049}$$

The second main result

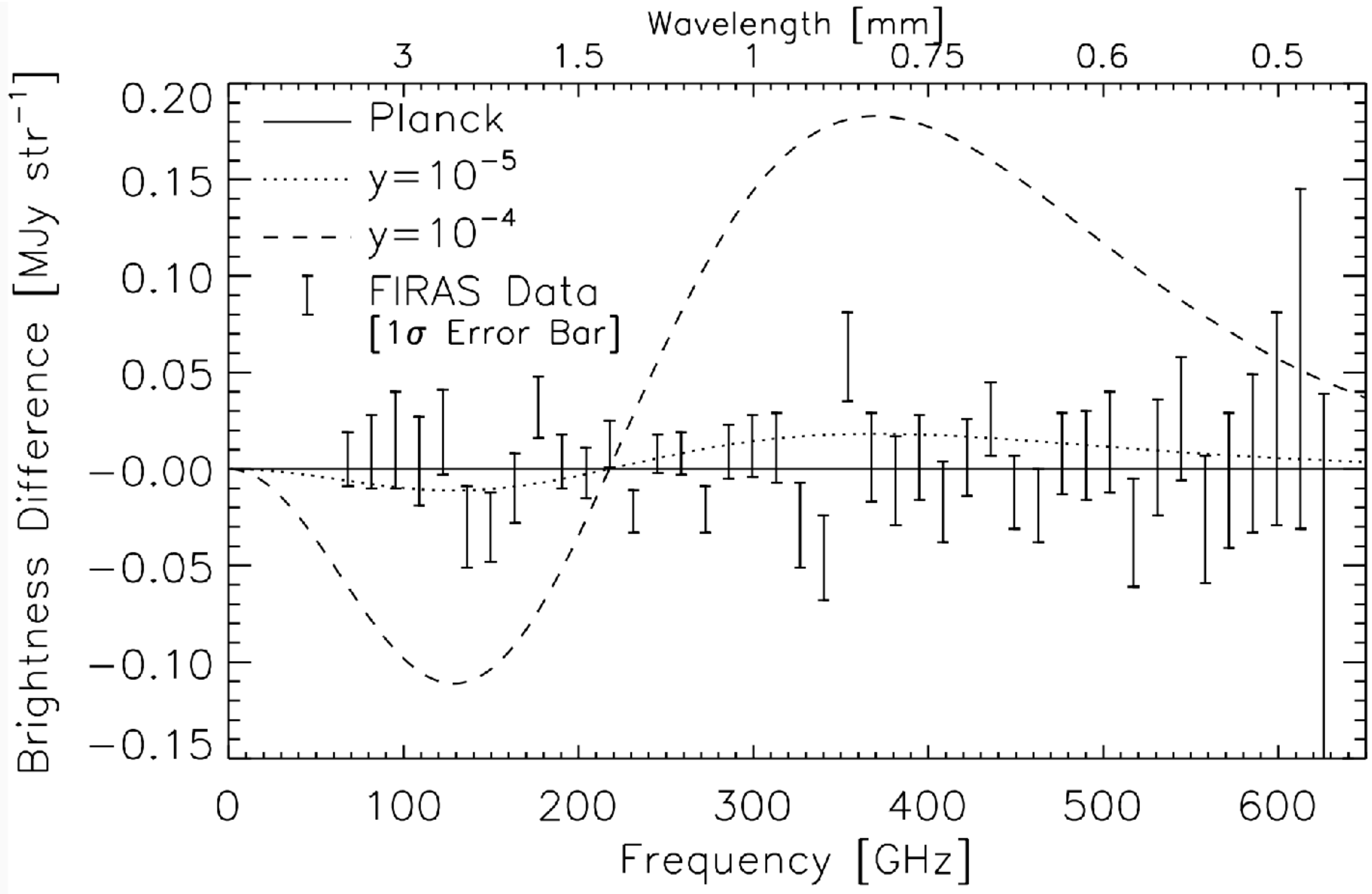
The mean thermal energy density of the Universe!



Chiang et al. (2020)

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 $10^{3\text{–}5}$.
- Such a mission will measure the average distortion from the hot gas in the Universe.
- Our data suggest **$\langle y \rangle = 1.2 \times 10^{-6}$**

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

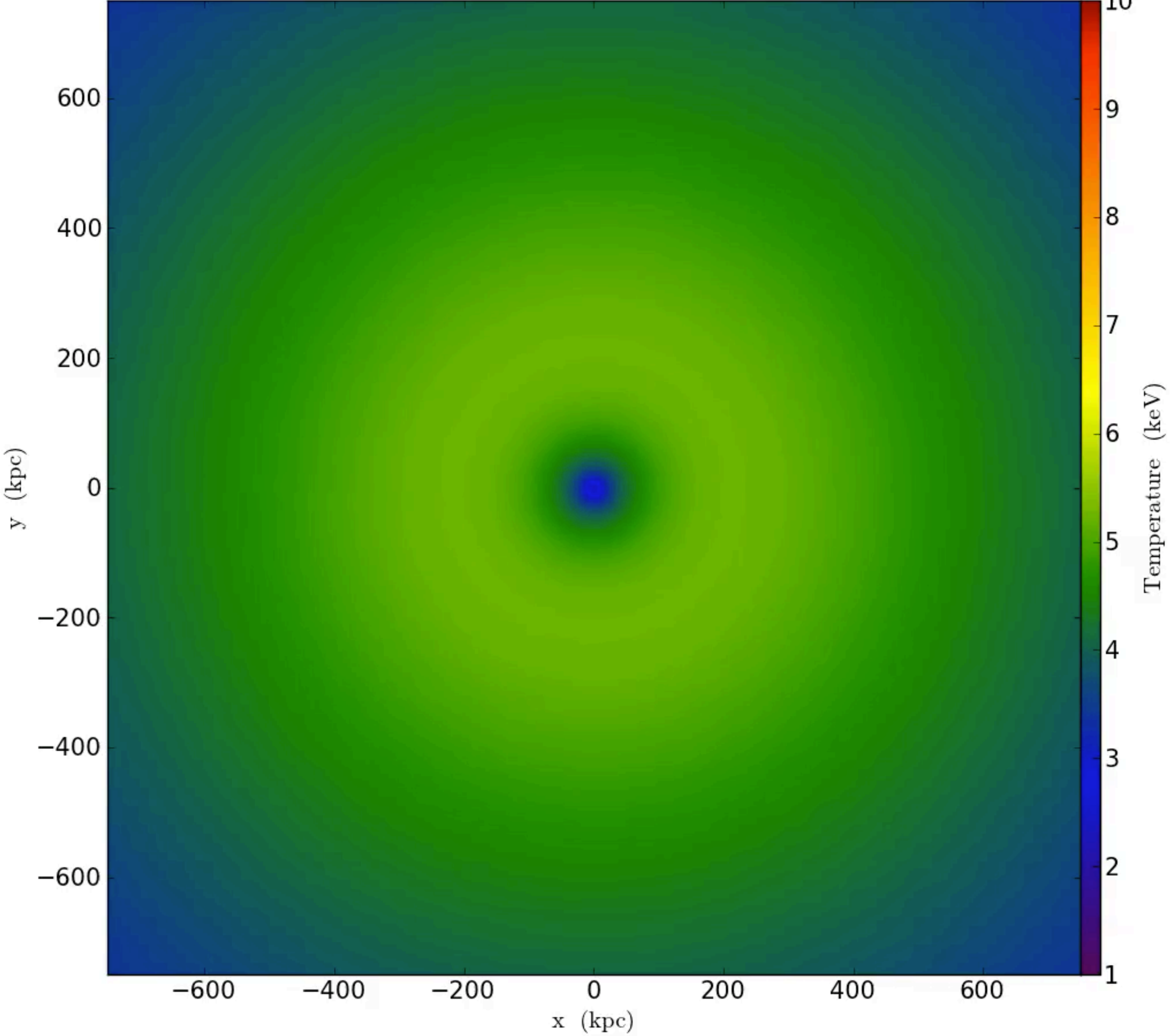
Q2: Where did the thermal energy come from?

Of course you know the answer…

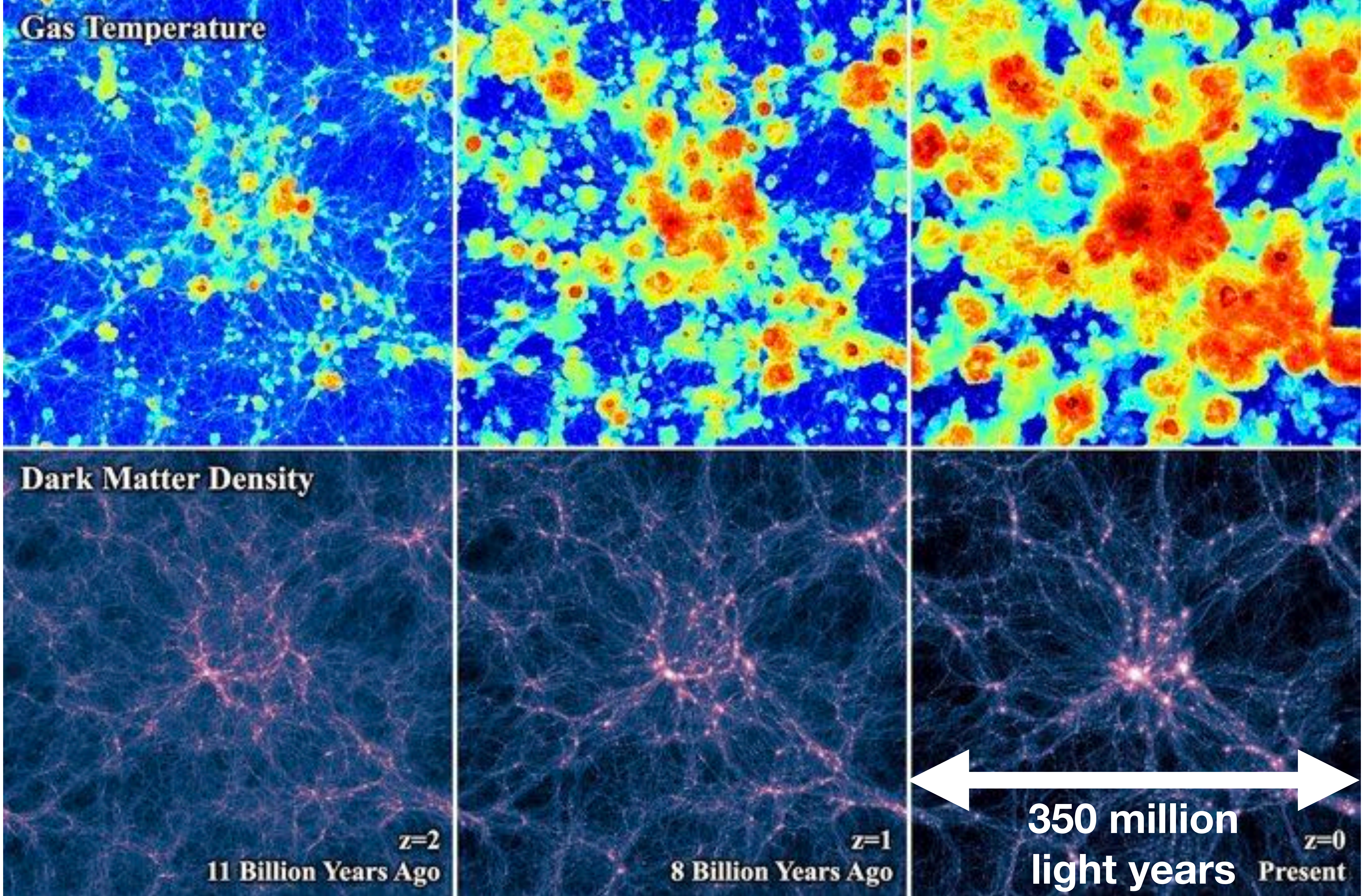
Open any textbook!

- 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 Ω_{th}. We can calculate Ω_{grav} using theory of the structure formation. Let’s compare the two and see if they make sense.

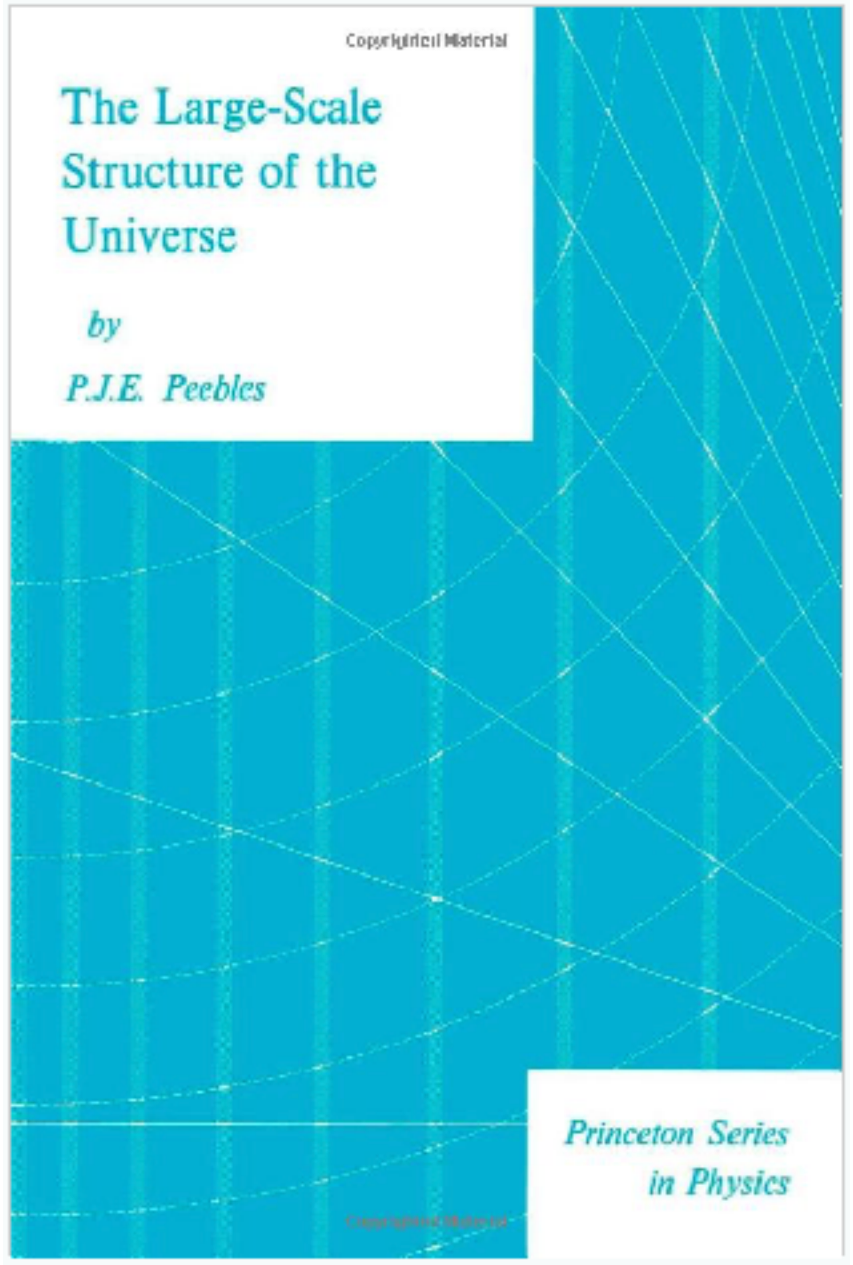
Idealized Simulation of Gas Heating by Shock Waves (Johnson et al. 2012)



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 $M = \sum_i m_i$,

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

$$= -\frac{1}{2}Ga^5\rho_{\rm m}^2(a)\int d^3x\int d^3x'\ \frac{\delta(\mathbf{x},a)\delta(\mathbf{x}',a)}{|\mathbf{x}-\mathbf{x}'|}$$

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

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

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

With the Poisson equation:

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

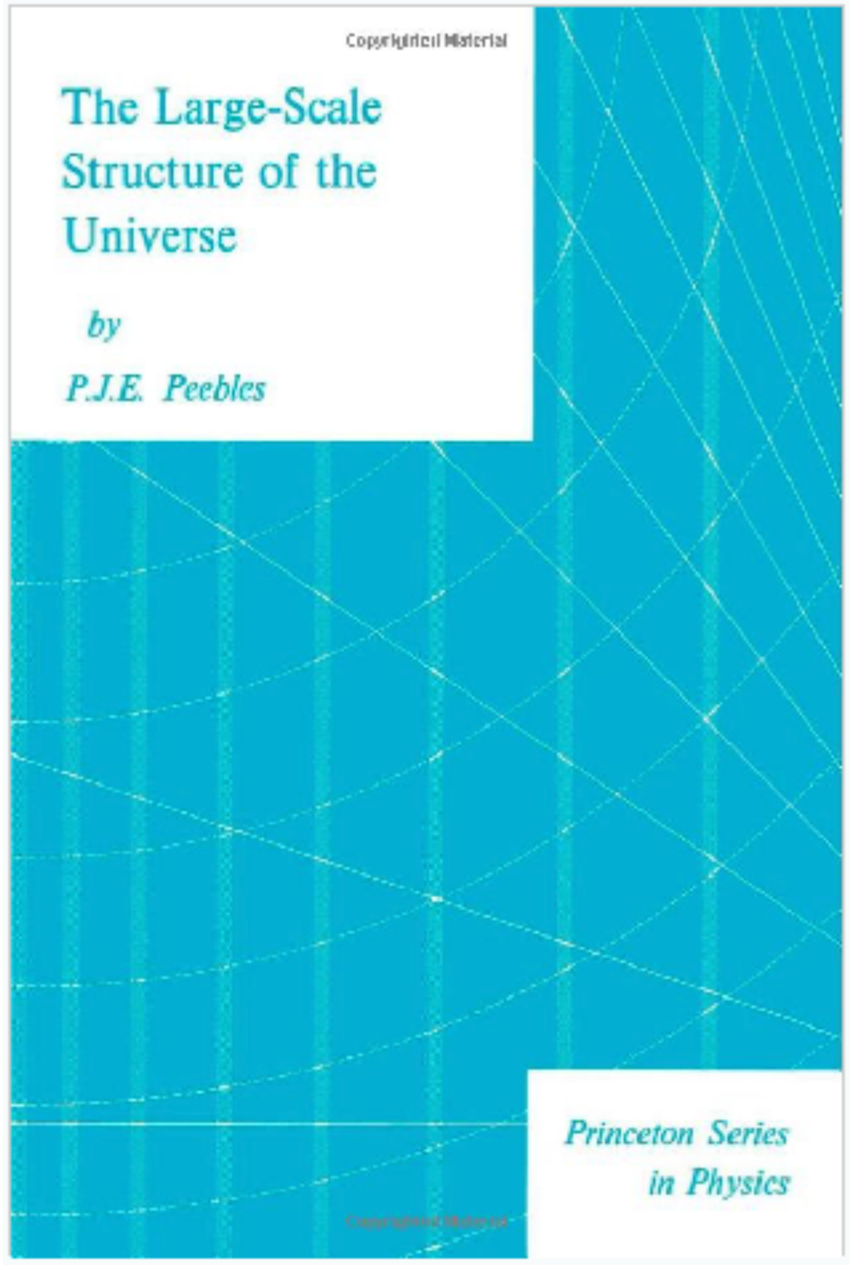
Section 9 of Peebles's Book in 1980

The "W": Gravitational potential energy per unit mass

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

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

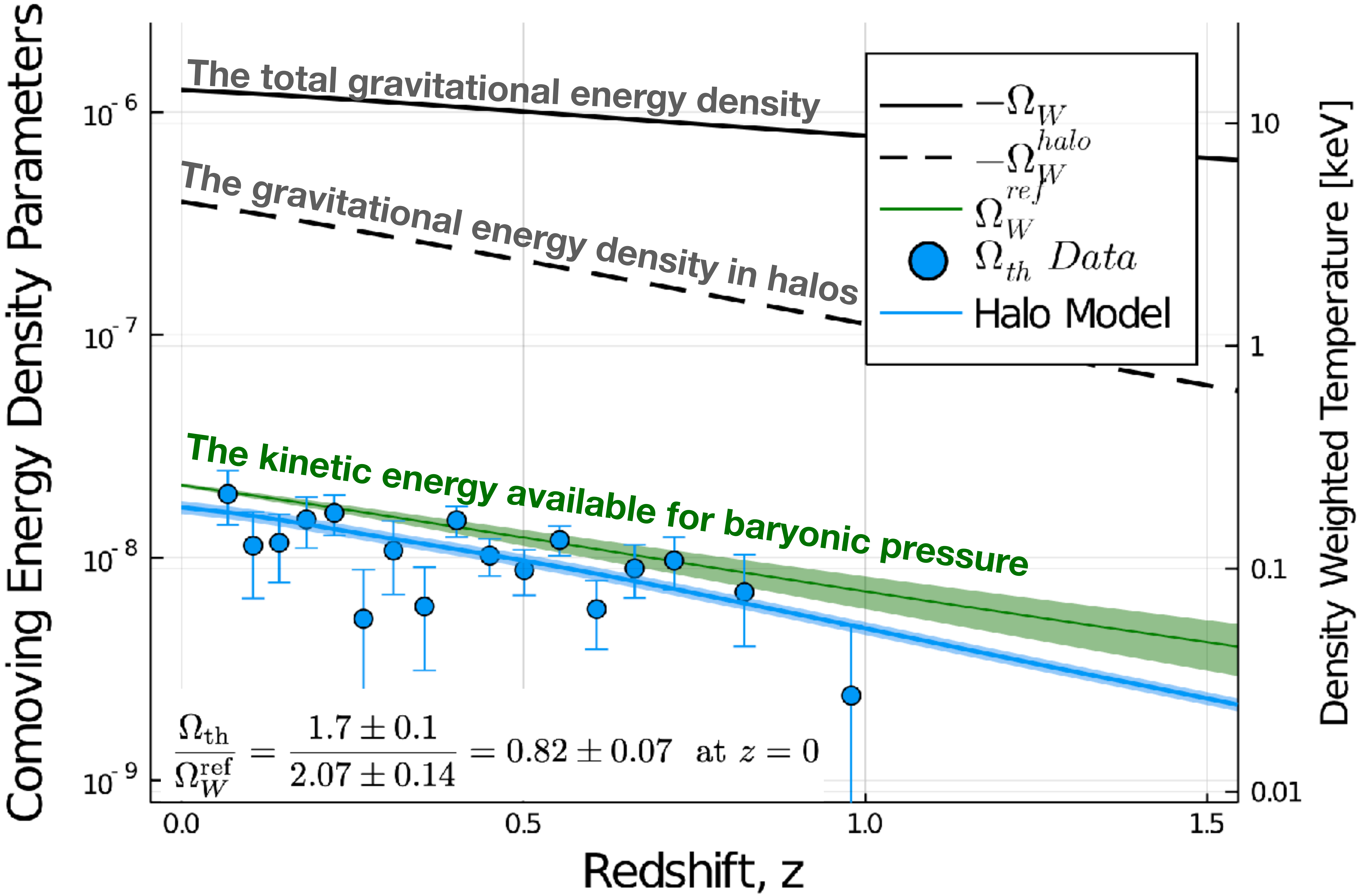
$$W = -\frac{3\Omega_{\rm m}H_0^2}{8\pi^2 a}\int_0^\infty {\rm d}k\ P(k,a)$$



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

Chiang et al. (2021), arXiv:2007.01679

The Energy Balance in the Large-scale Structure



The energy density parameter for W:

$$\Omega_W = \frac{\Omega_{\rm m}}{c^2} W$$

The halo contribution:

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

Pressure available for baryons

$$\Omega_W^{\rm ref} = -\frac{1}{3} f_{\rm b} \, \Omega_W^{\rm halo}$$

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 -> thermal energy conversion in the large-scale structure formation (using the observational data).
- **What is the rest (~20%)?** => 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?

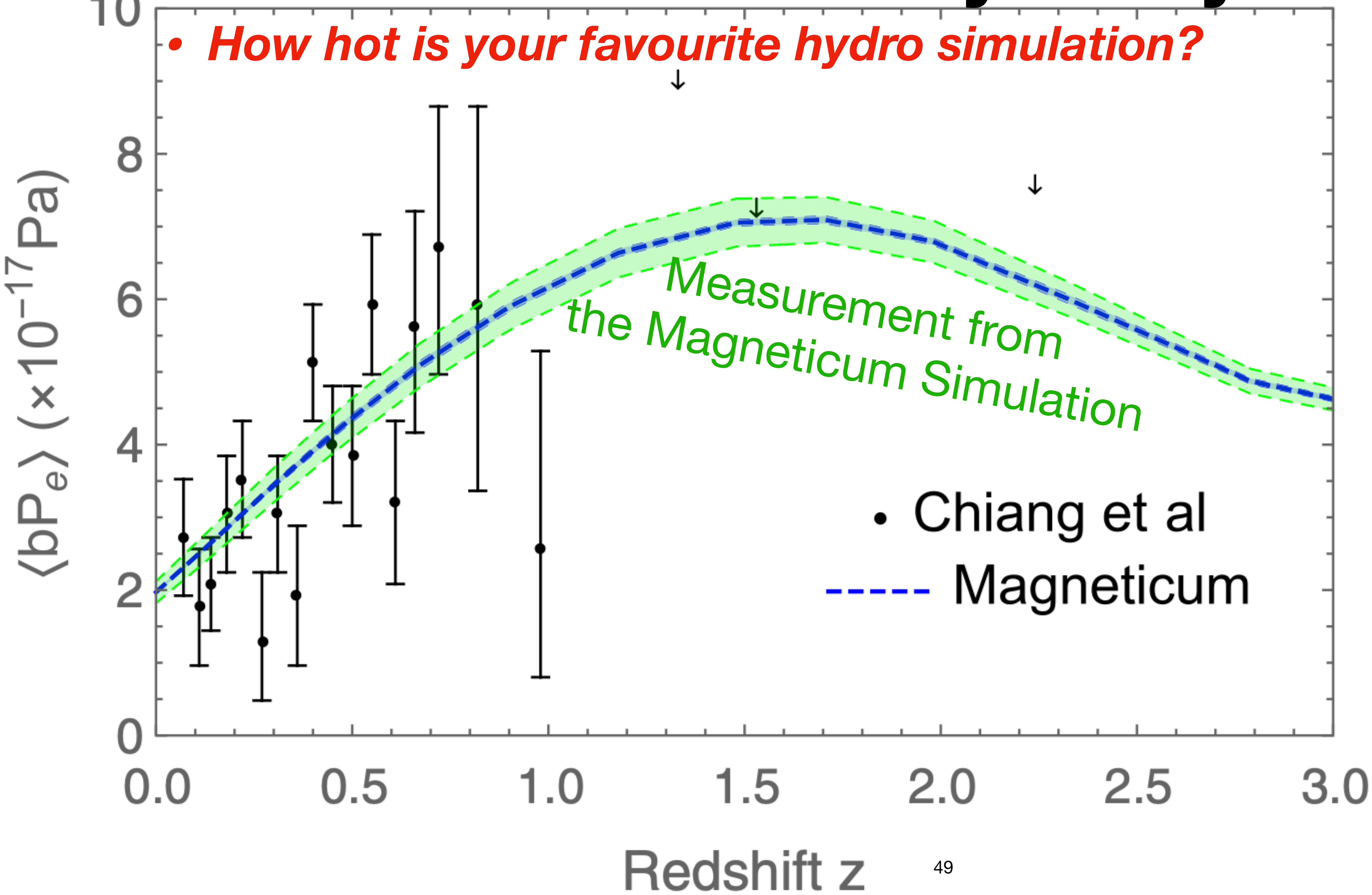
Young, EK, Dolag, PRD, 104, 038538 (2021)

Q3: Is this good for anything?

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

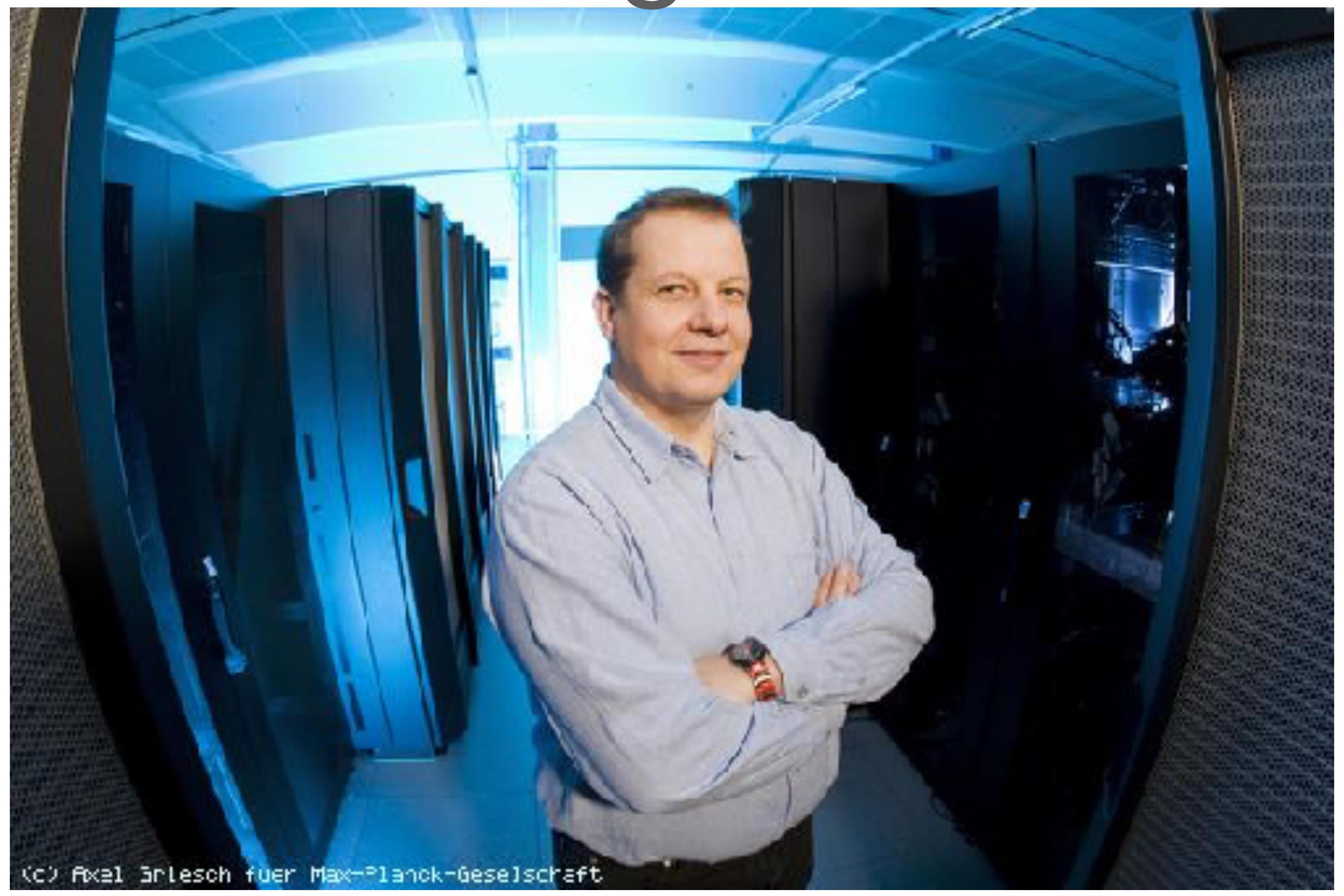
Young, EK, Dolag, PRD, 104, 038538 (2021)

"Thermometer" test of your hydro simulation



Sam Young

Klaus Dolag



Young, EK, Dolag, PRD, 104, 038538 (2021)

"Thermometer" test of your hydro simulation

- ***How hot is your favourite hydro simulation?***

- It is possible that all of the current generation of hydro simulations pass this test; in that case this test is too easy to be useful :)

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~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.**

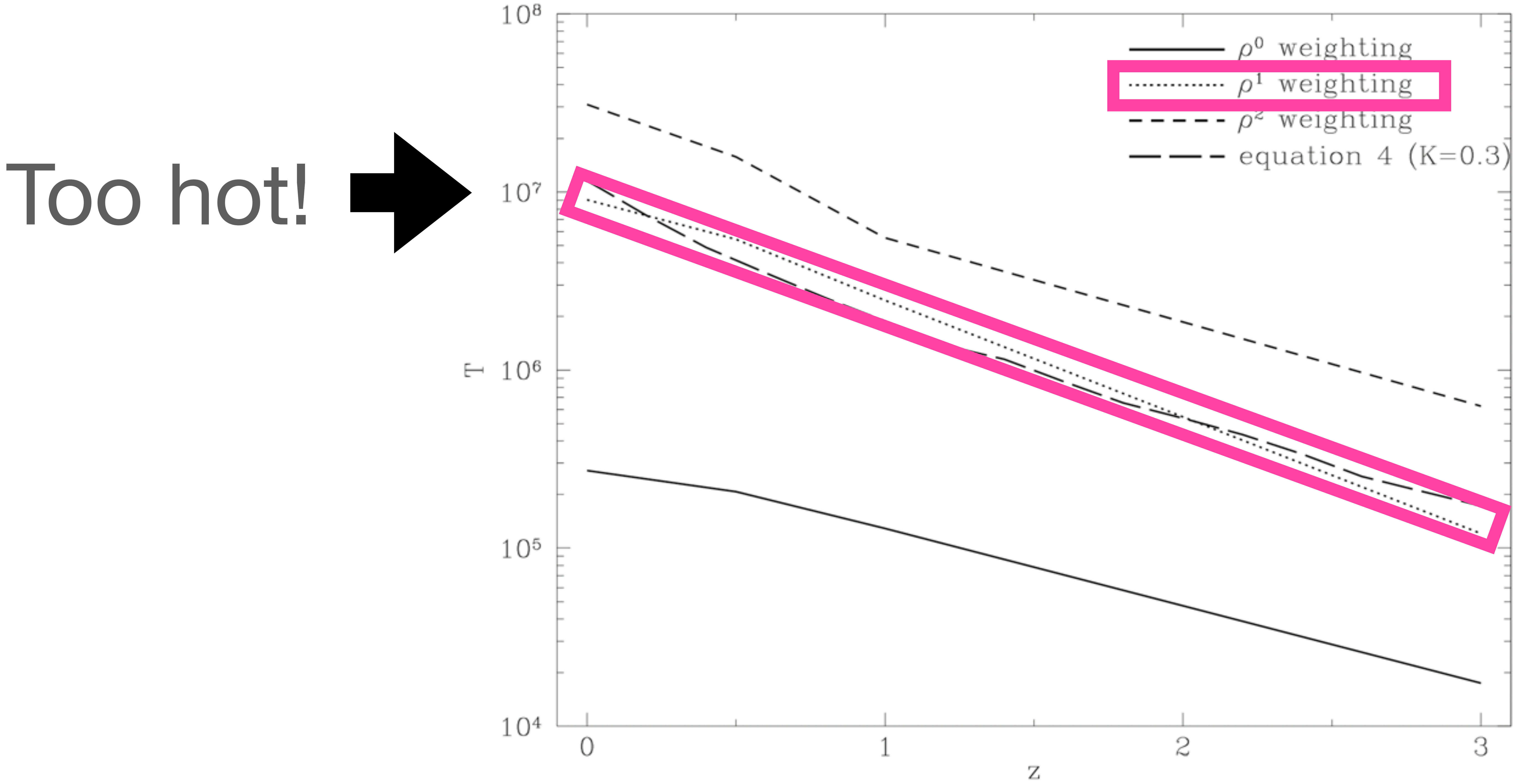
- Detailed comparison to the gravitational energy of the LSS shows that **the thermal energy accounts for ~80% of the kinetic energy available for thermal pressure of collapsed baryons.** The rest can be accounted for easily by non-thermal pressure (*Shi & EK 2014*).

- Is this good for anything? You tell us!

THE ASTROPHYSICAL JOURNAL, 514:1–6, 1999 March 20

WHERE ARE THE BARYONS?

RENYUE CEN AND JEREMIAH P. OSTRIKER
Princeton University Observatory, Princeton University, Princeton, NJ 08544; cen@astro.princeton.edu, jpo@astro.princeton.edu
Received 1998 September 11; accepted 1998 October 29



PHYSICAL REVIEW D, VOLUME 61, 123001

Power spectrum of the Sunyaev-Zel'dovich effect

Alexandre Refregier*
Institute of Astronomy, Madingley Road, University of Cambridge, Cambridge CB3 OHA, England

Eiichiro Komatsu†
Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544

David N. Spergel‡
Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544

Ue-Li Pen§
Canadian Institute of Theoretical Astrophysics, University of Toronto, 60 St. George St., Toronto, Canada
(Received 10 December 1999; published 12 May 2000)

PHYSICAL REVIEW D, VOLUME 61, 123001

Power … effect

Institute of Astronomy, …dge CB3 OHA, England

Department of Astr… , New Jersey 08544

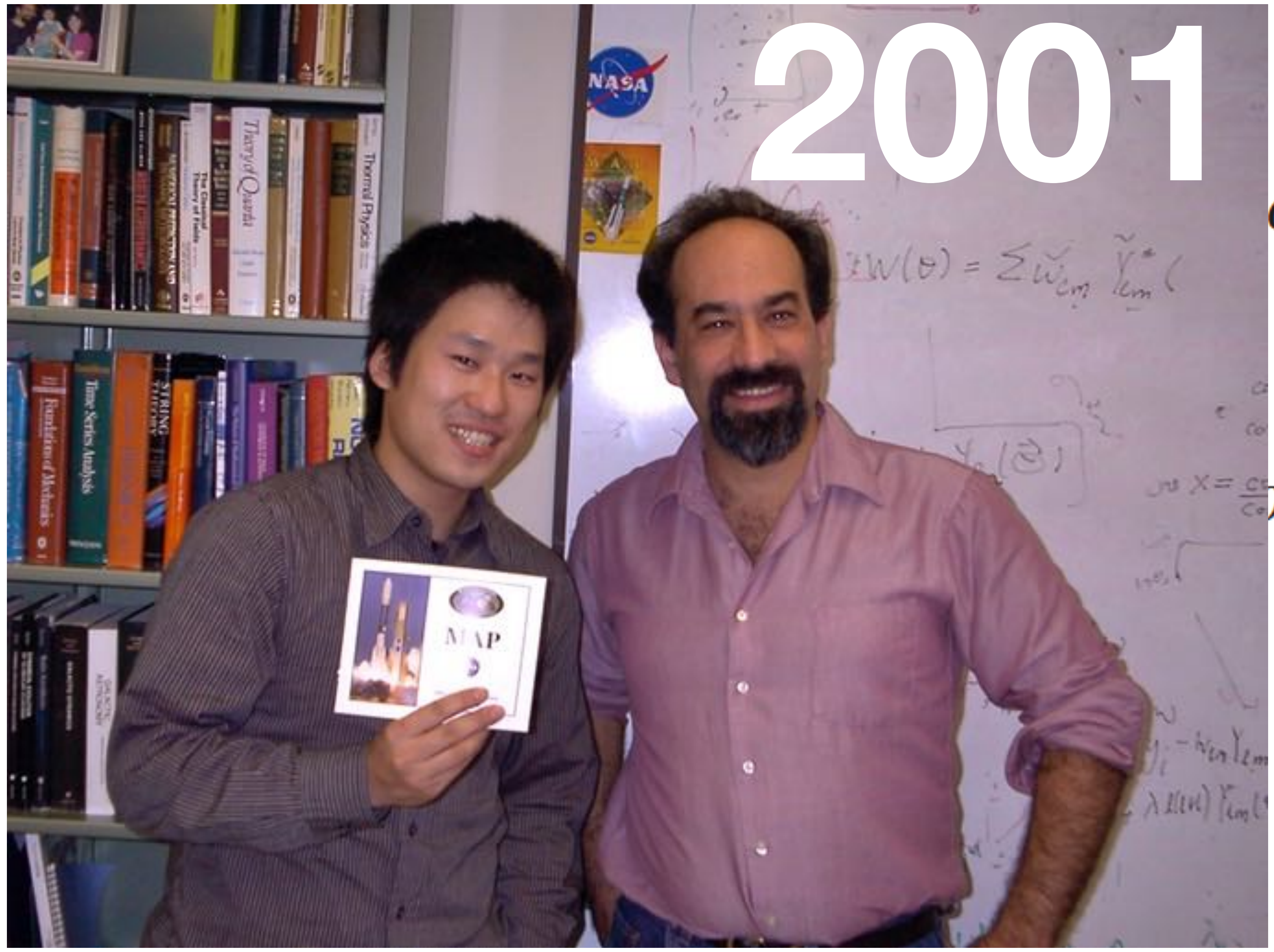
David N. Spergel[‡]

…ciences, Princeton Universit…

Ue-Li Pen[§]

…ophysics, University of Toron…

December 1999; published



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

[a]At $z = 0$.

Not bad!

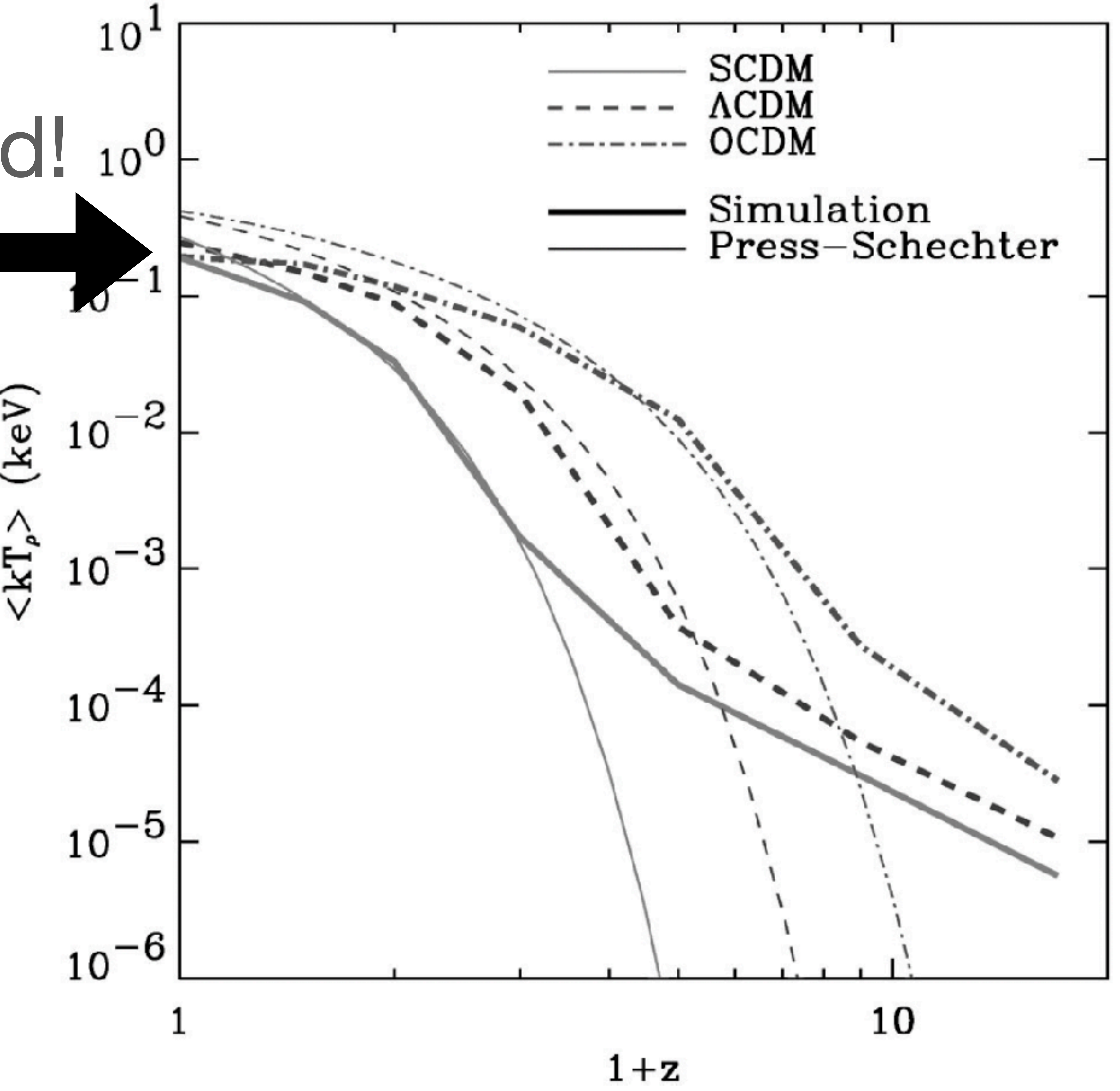


FIG. 4. Temperature history of the gas. For each model, the density weighted temperature T_ρ is shown for the simulations and for the Press-Schechter prediction.

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:

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

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),

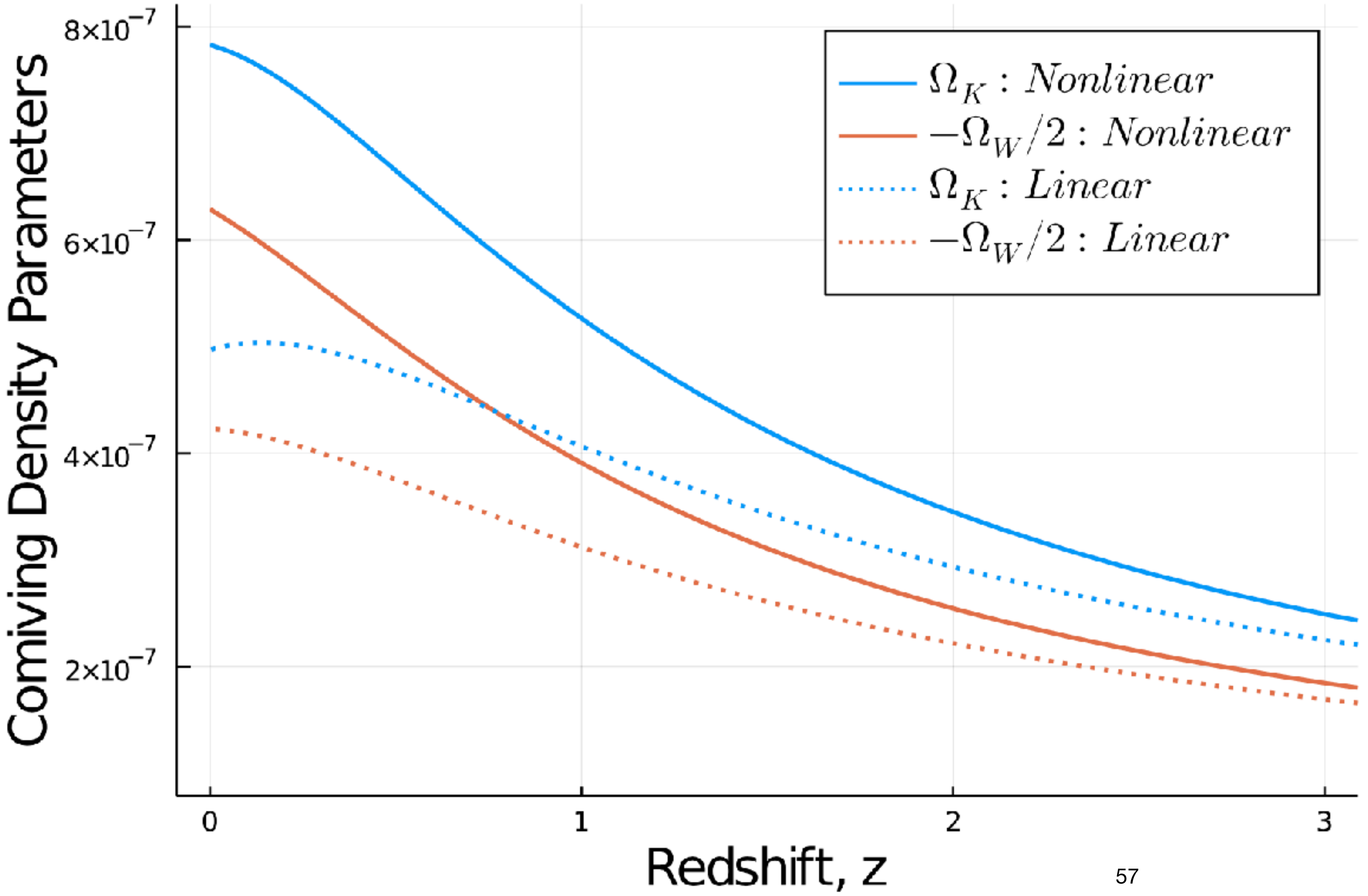
$$K=-\frac{2f^2}{3\Omega_\mathrm{m}(a)}W$$

where $f \equiv \mathrm{d}\ln\delta_1/\mathrm{d}\ln a$ with the linear density contrast δ_1 and $\Omega_\mathrm{m}(a) = \Omega_\mathrm{m}/[a^3E^2(a)]$ is the matter density parameter at a given a.

Chiang et al. (2021), arXiv:2007.01679

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.