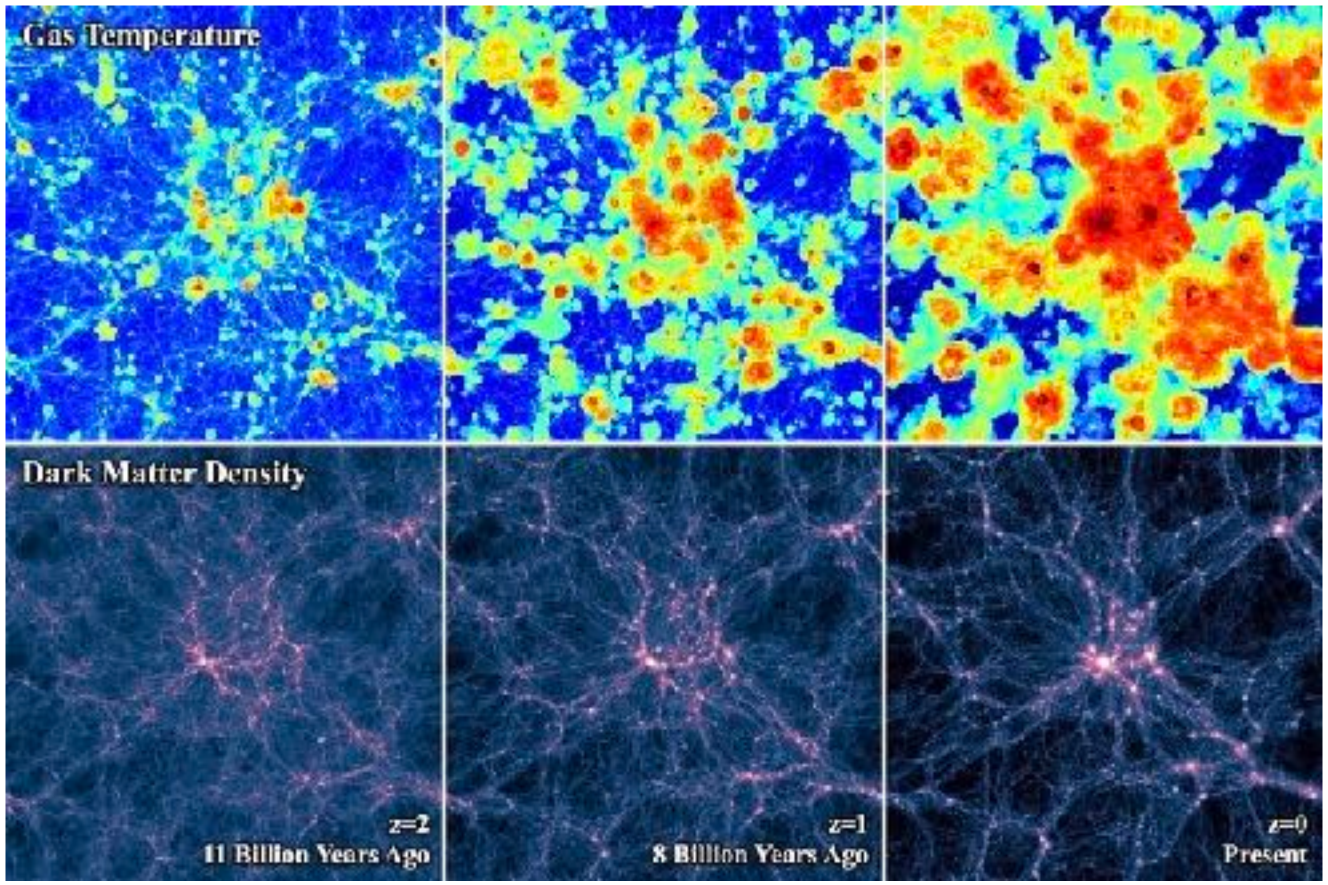
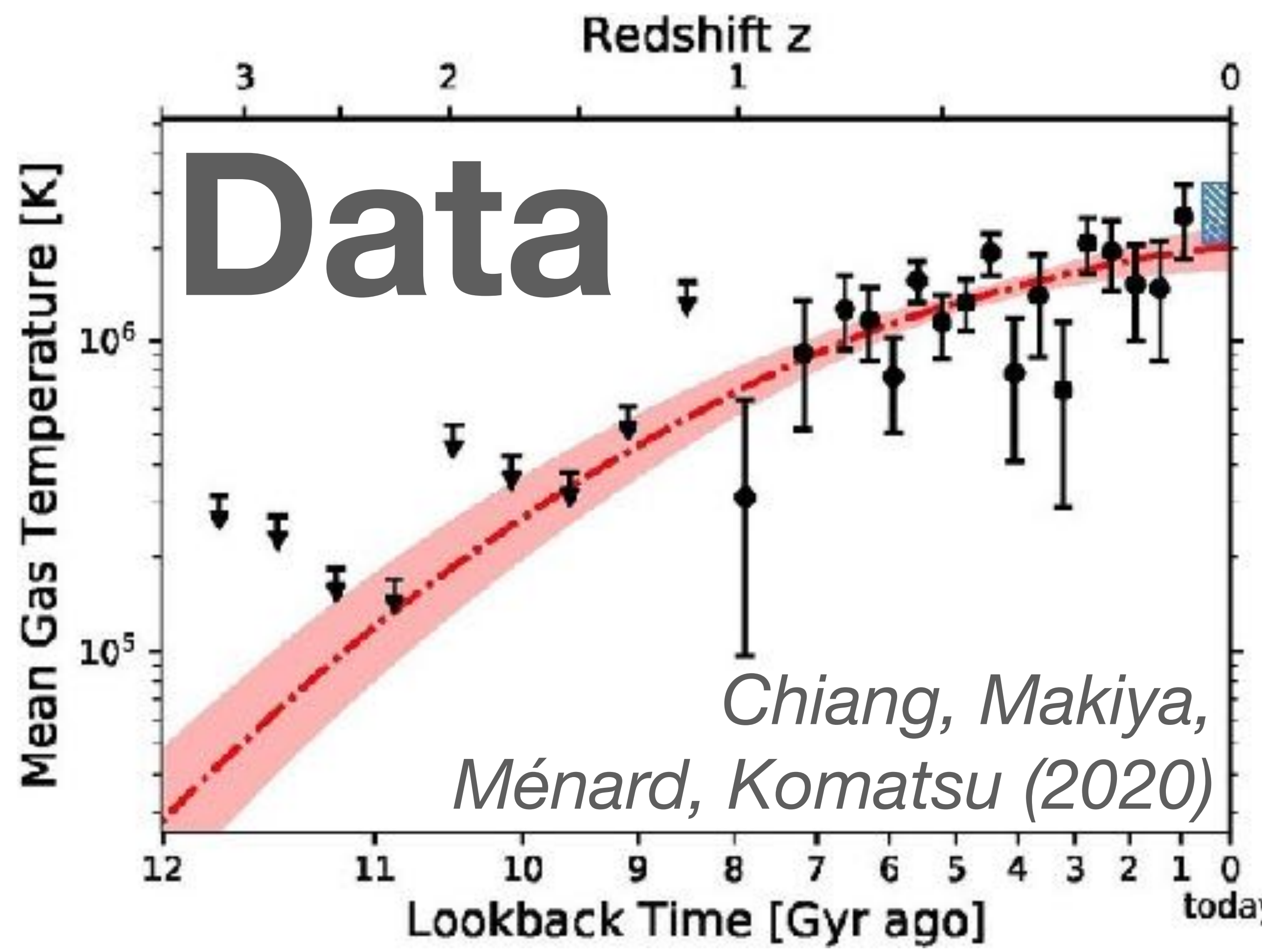
“*Global warming*” of hot gas in the Universe over the last 8 billion years





Simulation

Credit: Dylan Nelson, Illustris Collaboration

Eiichiro Komatsu
(Max Planck Institute for Astrophysics)
***Space Cafe Tokyo*, August 23, 2022**

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

What is the temperature of the Universe?

How hot is the Universe?

Google's answer: "2.725 Kelvin"

Search "temperature of the universe"

Google

temperature of the universe

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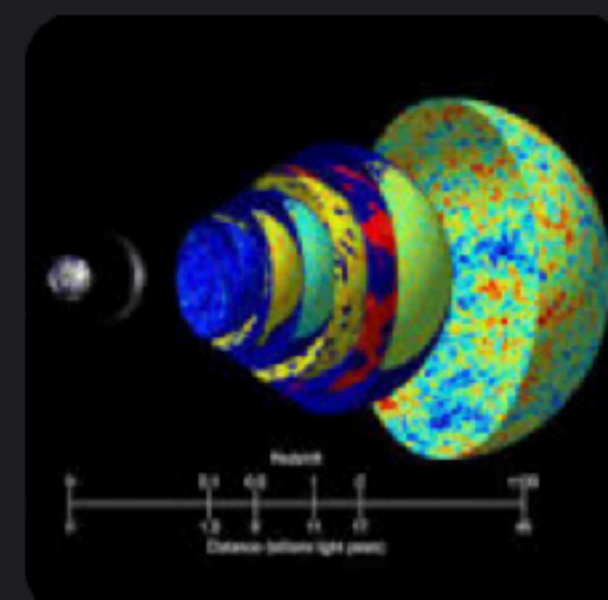
0 kelvin | in Celsius | in Fahrenheit

2.725 K.

From measuring the temperature of the radiation left over from the Big Bang , observable today as the cosmic microwave background, we infer that the Universe is just a few degrees above absolute zero: **2.725 K.** 14 Jan 2022

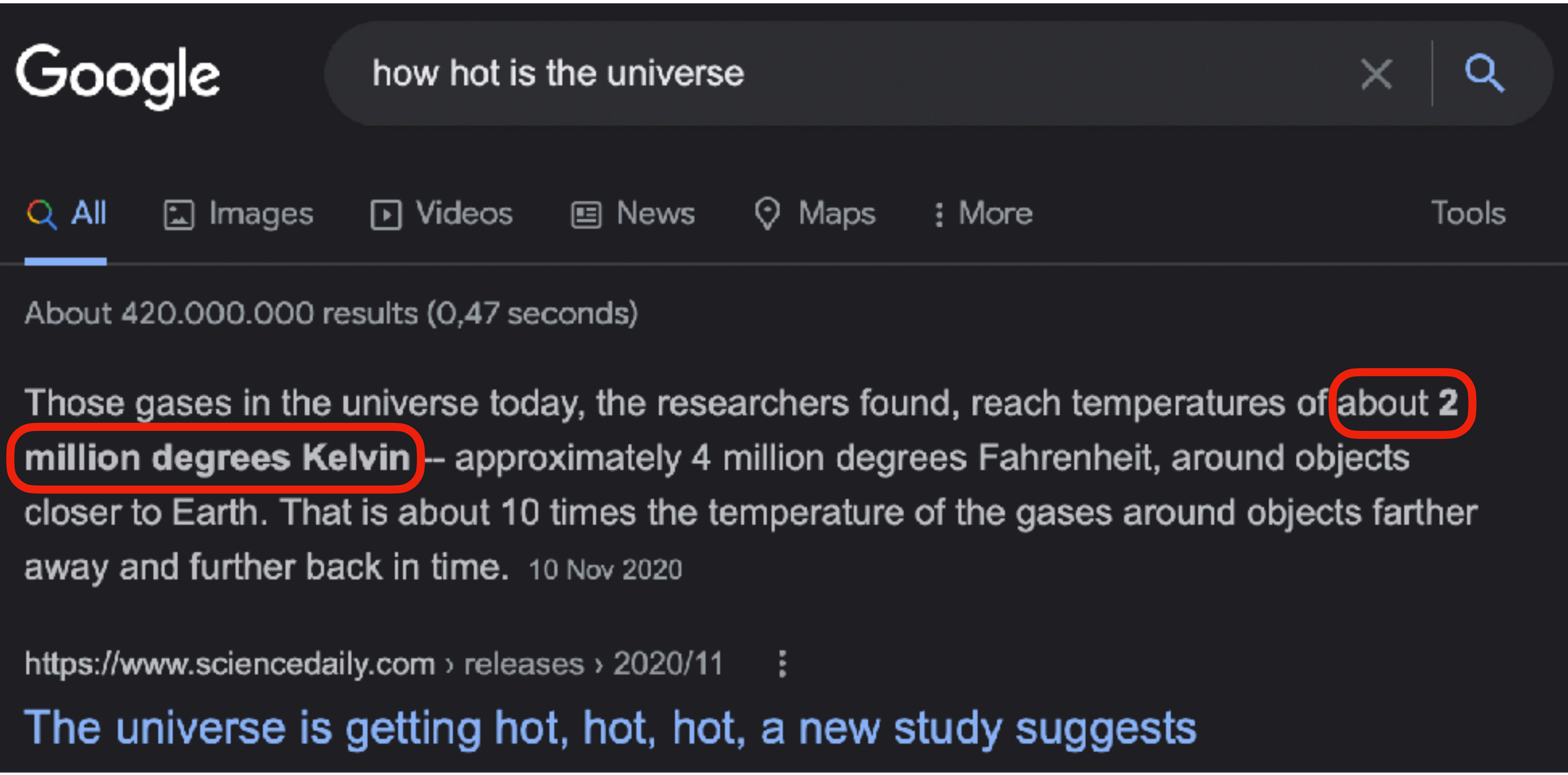


https://bigthink.com › universe-temperature

Ask Ethan: How do we know the Universe's temperature?

Google's answer: "2 million Kelvin"

Search "how hot is the universe"

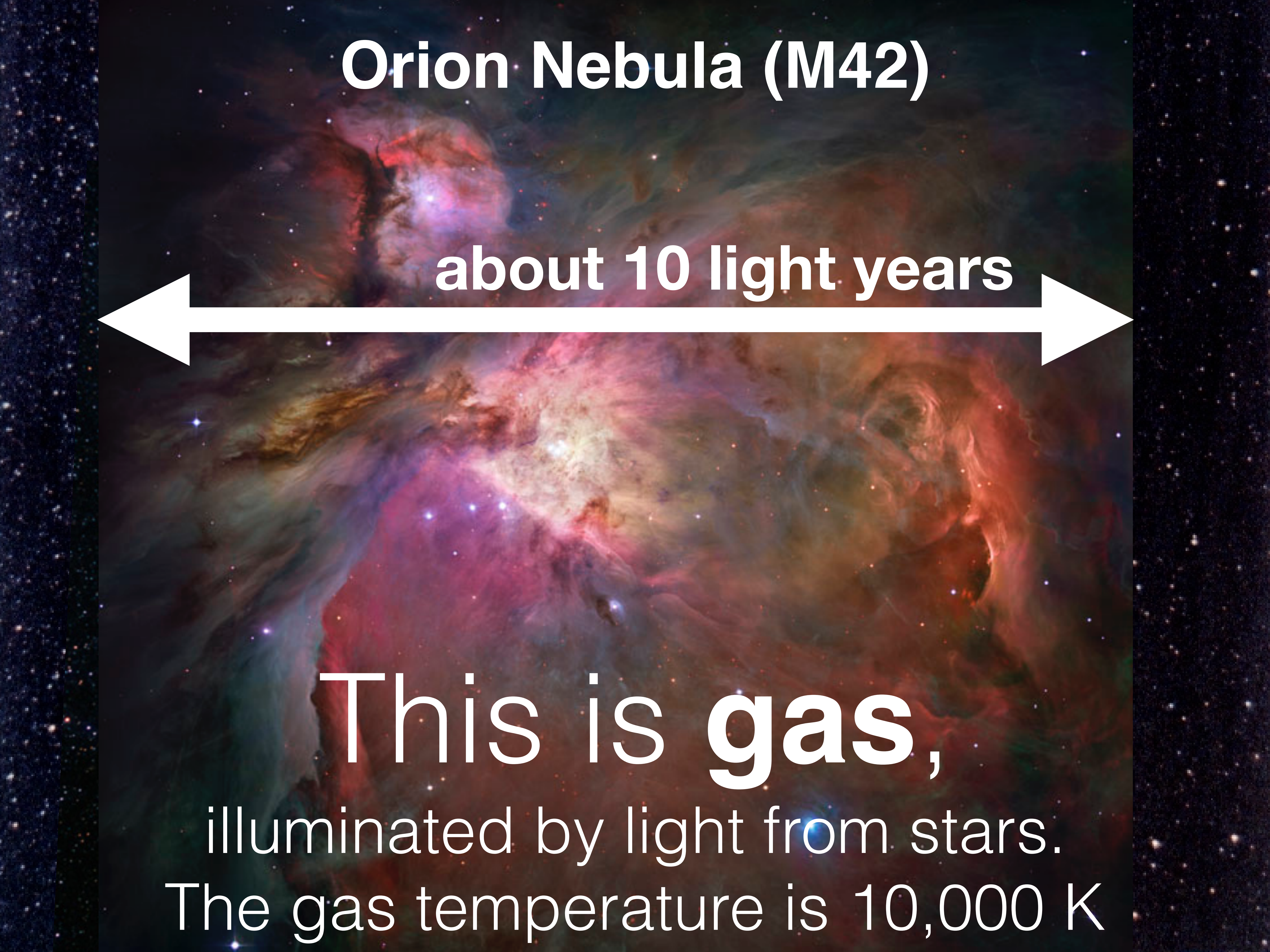


This is our result. So, *which answer is right?*

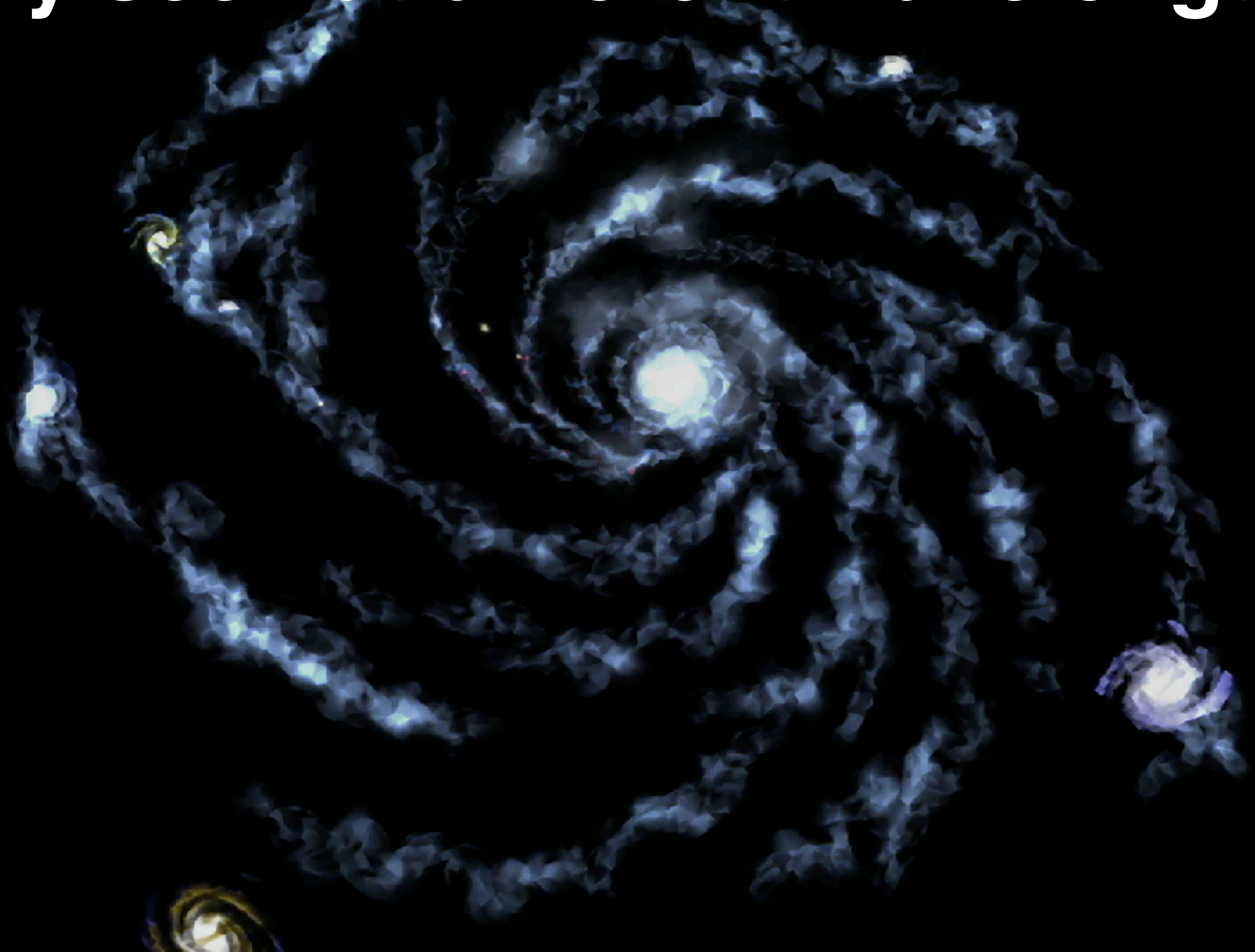
Temperature of *what*?

What is there in space?

- You see stars in the sky.
    - Stars are really hot!
    - But stars occupy such a small volume in space.
    - Maybe it is not correct to use them for the "temperature of the Universe".
- Space between stars is *vast*. Is that space empty?
    - No. **Space is full of stuff!**

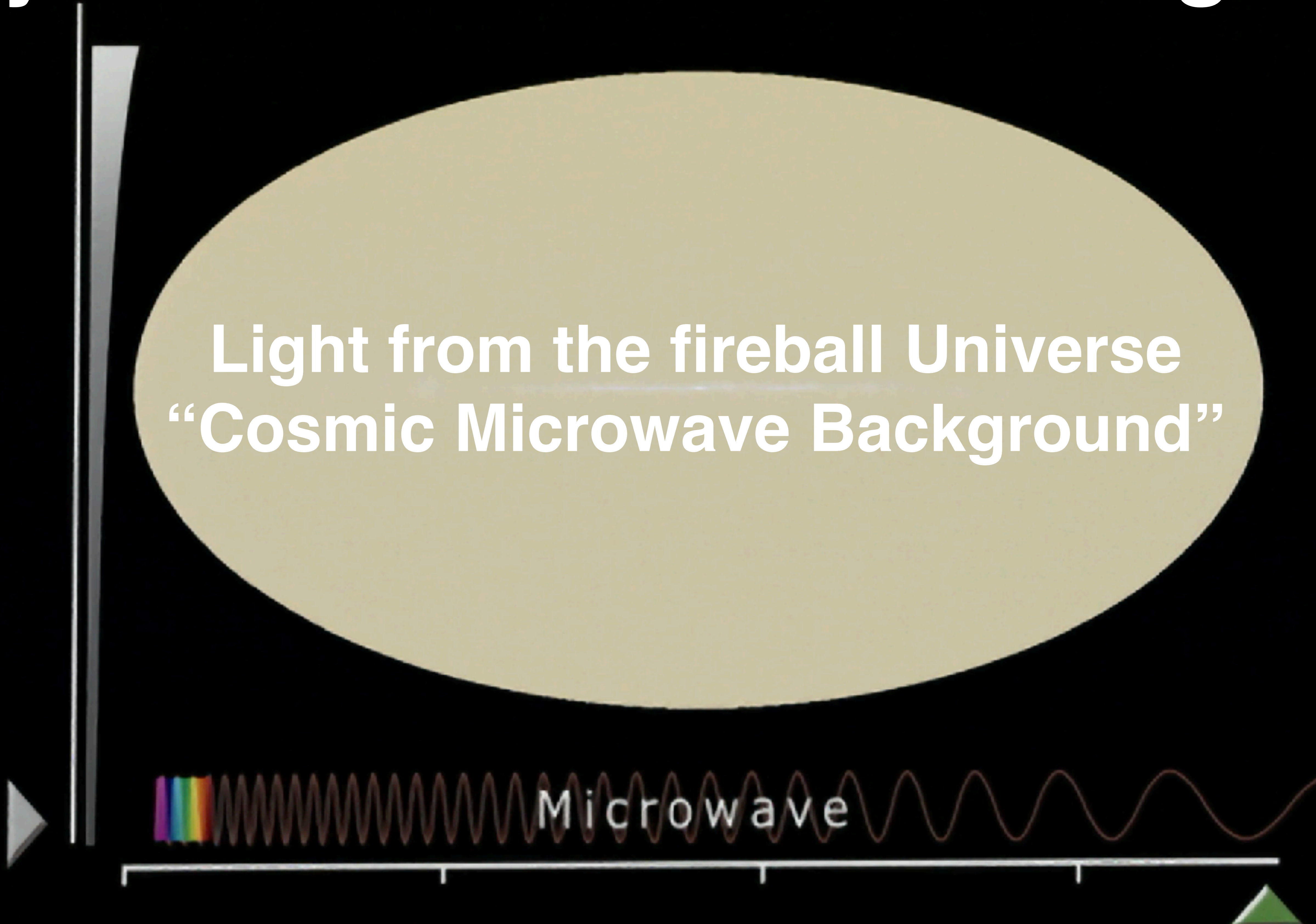

Orion Nebula (M42)
about 10 light years
This is **gas**,
illuminated by light from stars.
The gas temperature is 10,000 K

Sky seen at different wavelengths



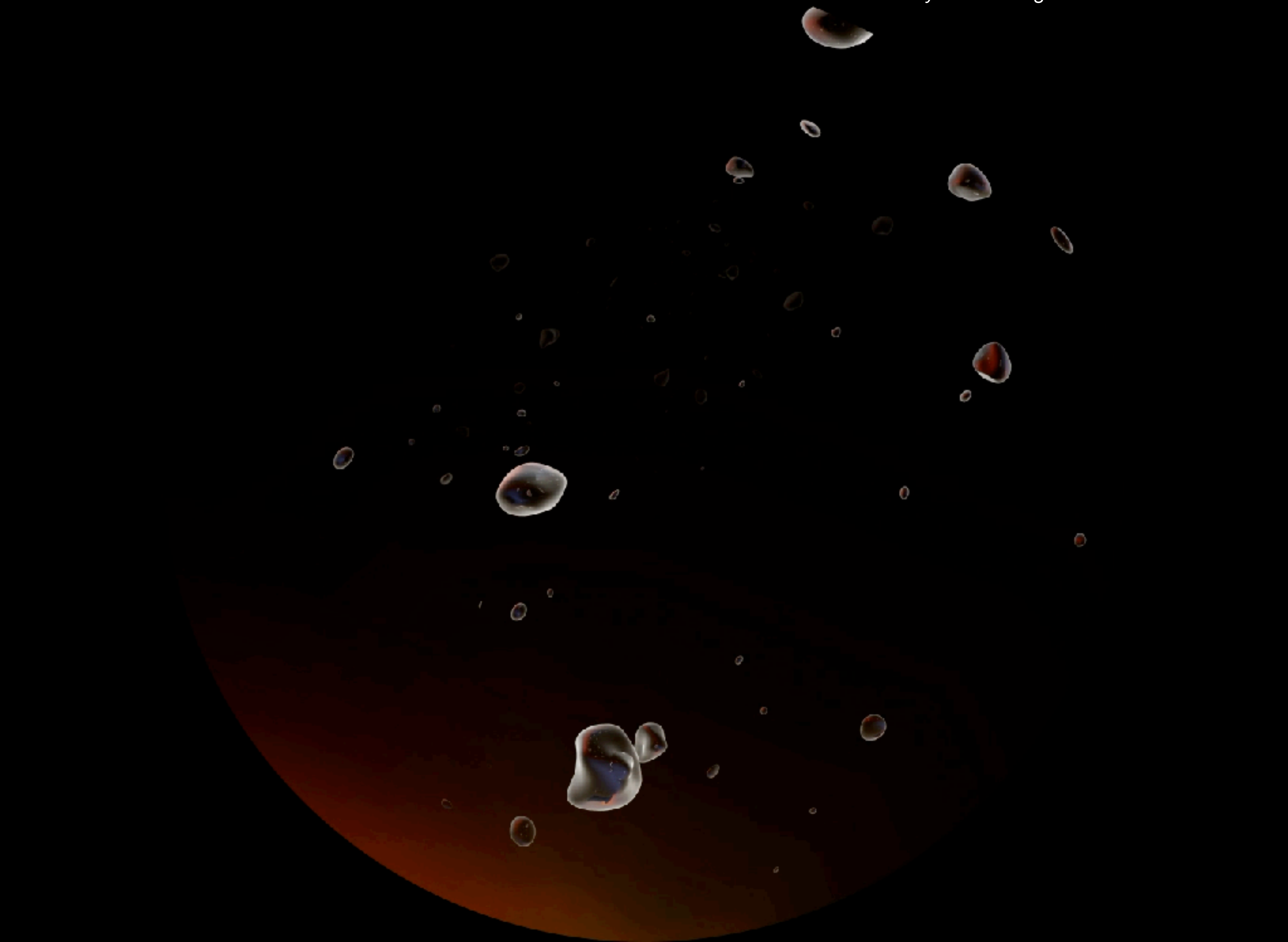
Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave

Sky seen at different wavelengths



Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave

From *HORIZON ~Beyond the Edge of the Visible Universe~*



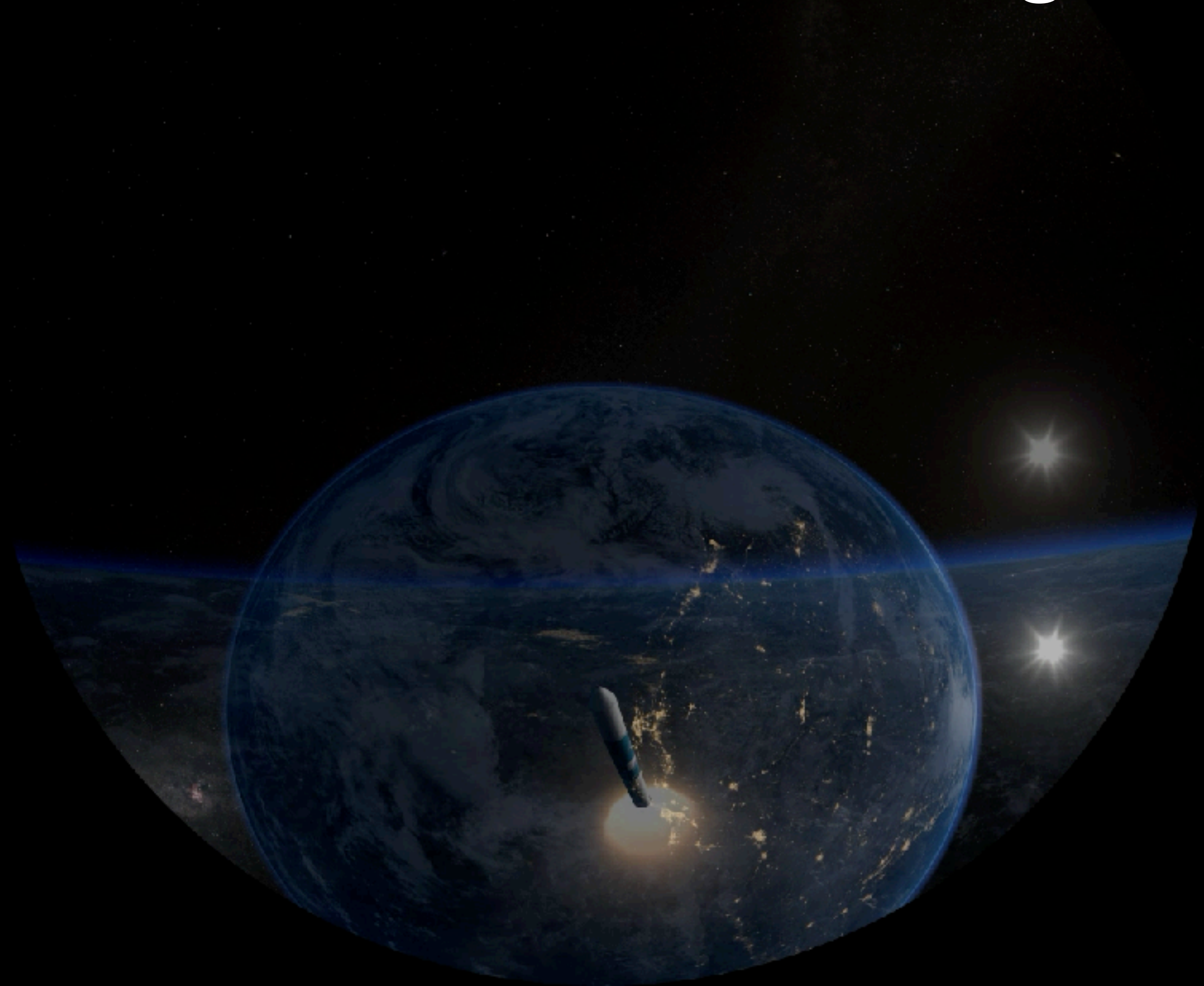
What is in the space?

The composition of the Universe

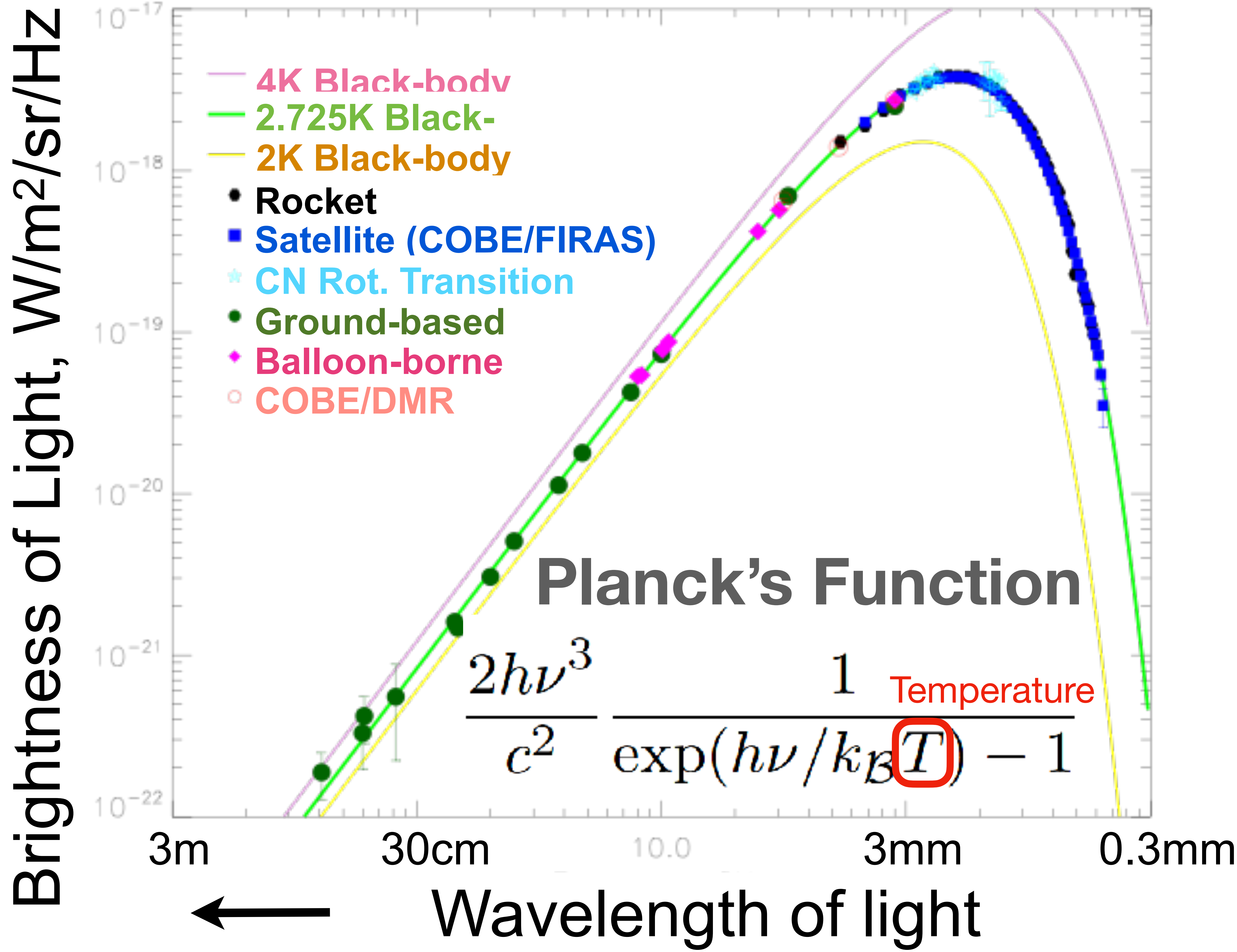
- Ordinary stuff that we are familiar with:
  - **Gas** of the ordinary matter (mostly hydrogen and helium)
  - **Photons** (cosmic microwave background)
  - **Neutrinos** (cosmic neutrino background)
- Extraordinary stuff that we know exists:
  - **Dark matter**
  - **Dark energy**
- **What is their temperature…???**

From *HORIZON ~Beyond the Edge of the Visible Universe~*

How to measure the temperature of the cosmic microwave background



c: speed of light; $\nu = c$ / wavelength; h: Planck's constant; k_B: Boltzmann's constant



(from Samtleben et al. 2007)

Google's answer: "2.725 Kelvin"

Search "temperature of the universe"

Google

temperature of the universe

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0 kelvin | in Celsius | in Fahrenheit

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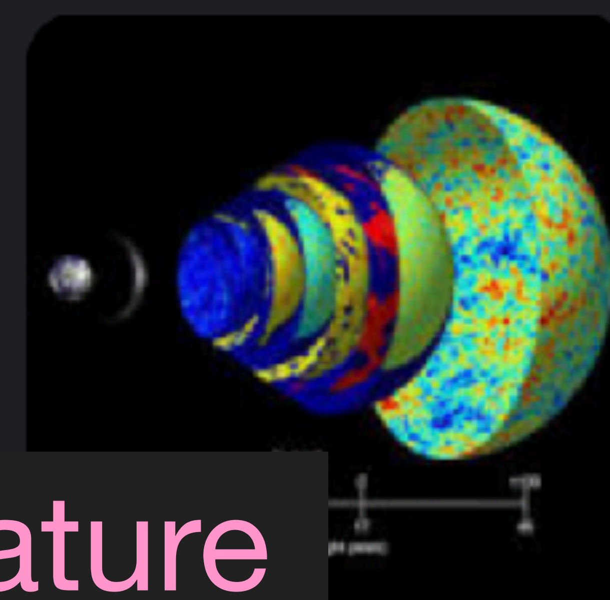

This is true only for the temperature of *photons* filling the Universe

Ask Ethan: How do we know the Universe's temperature?

What is in the space?

The composition of the Universe

- Ordinary stuff that we are familiar with:
  - **Gas** of the ordinary matter (mostly hydrogen and helium)
  - ✓ Photons: 2.7 Kelvin
  - (✓) Neutrinos: 1.9 Kelvin [indirect determination]
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- **What is their temperature…???**

A lot of galaxies!

What is in the space between galaxies?

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

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

A lot of galaxies!

What is in the space between galaxies?

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

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

Subaru Telescope

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

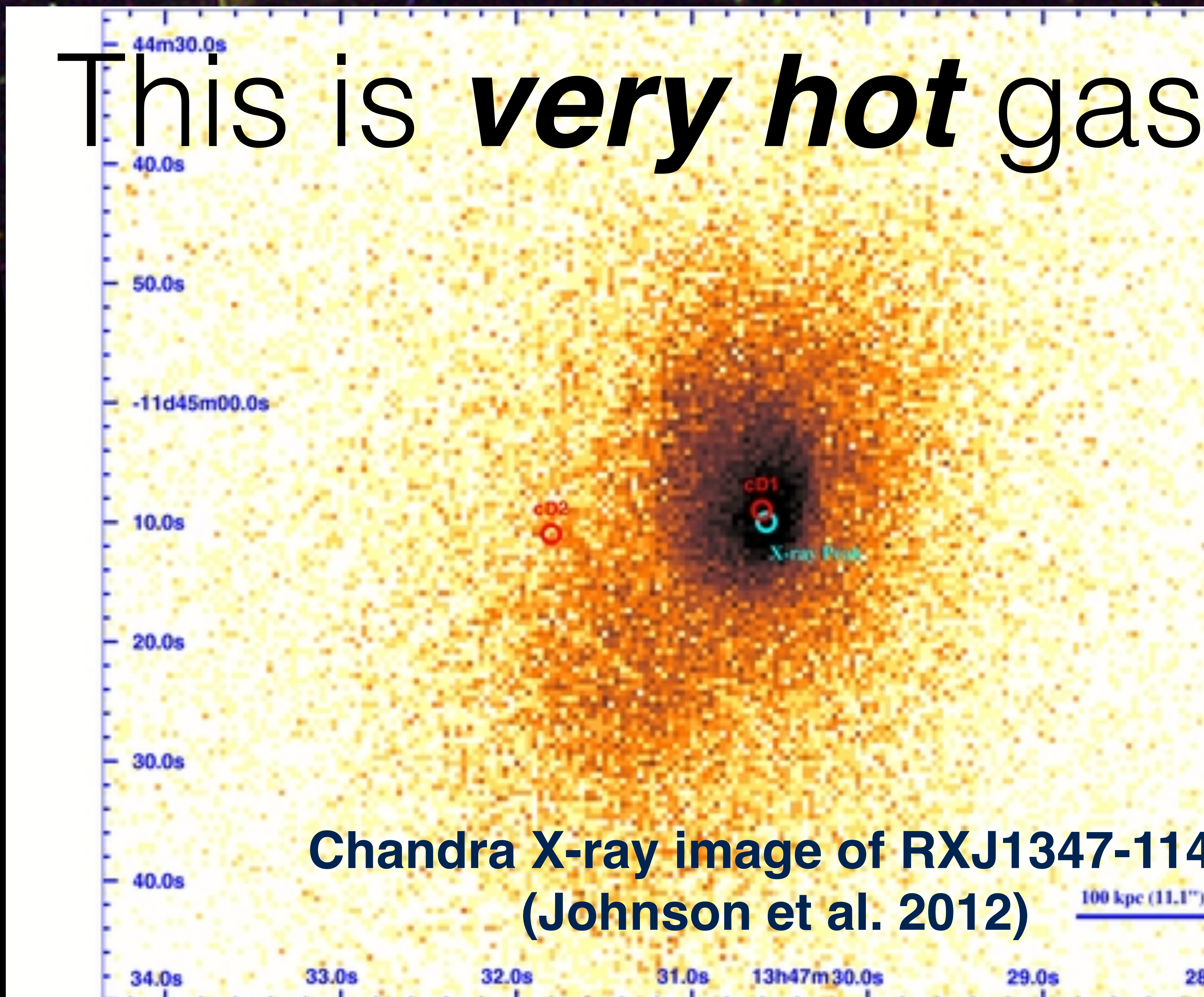
Hubble Space Telescope

This is a "cluster of galaxies".
What is in the space between galaxies?

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

Chandra's **X-ray** Image

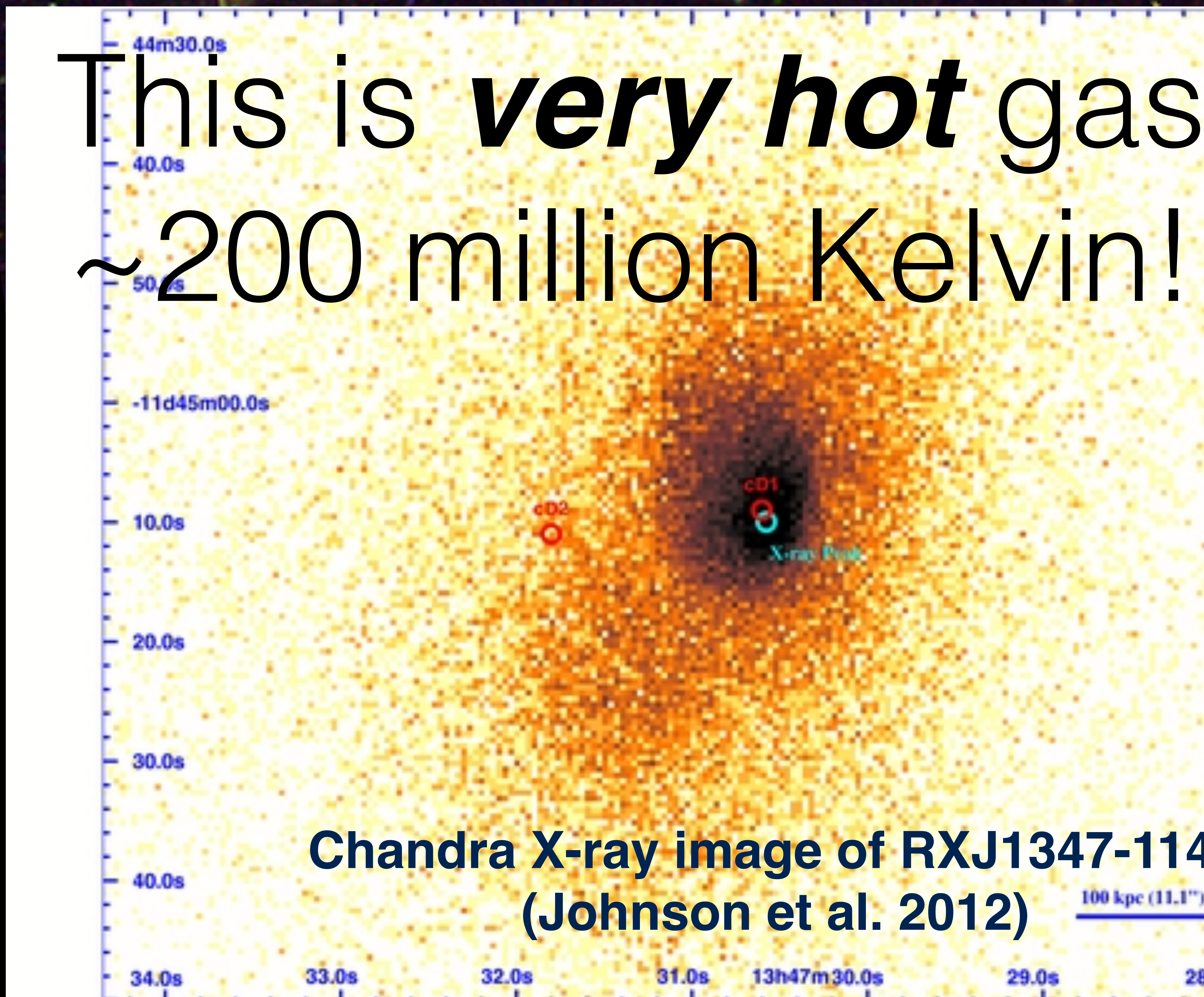
This is ***very hot*** gas



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

Chandra's **X-ray** Image

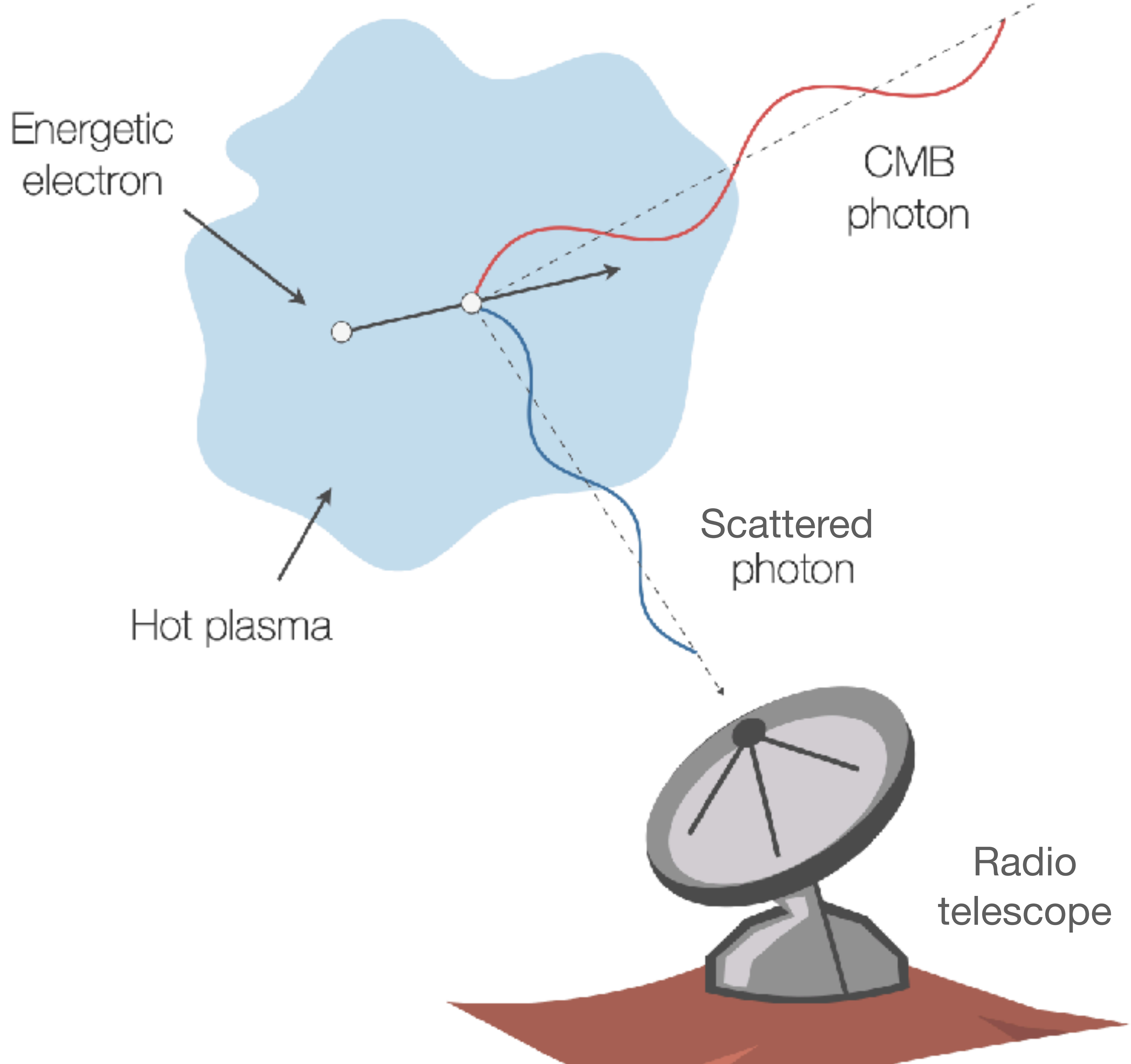
This is ***very hot*** gas
~200 million Kelvin!



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

A new technique:

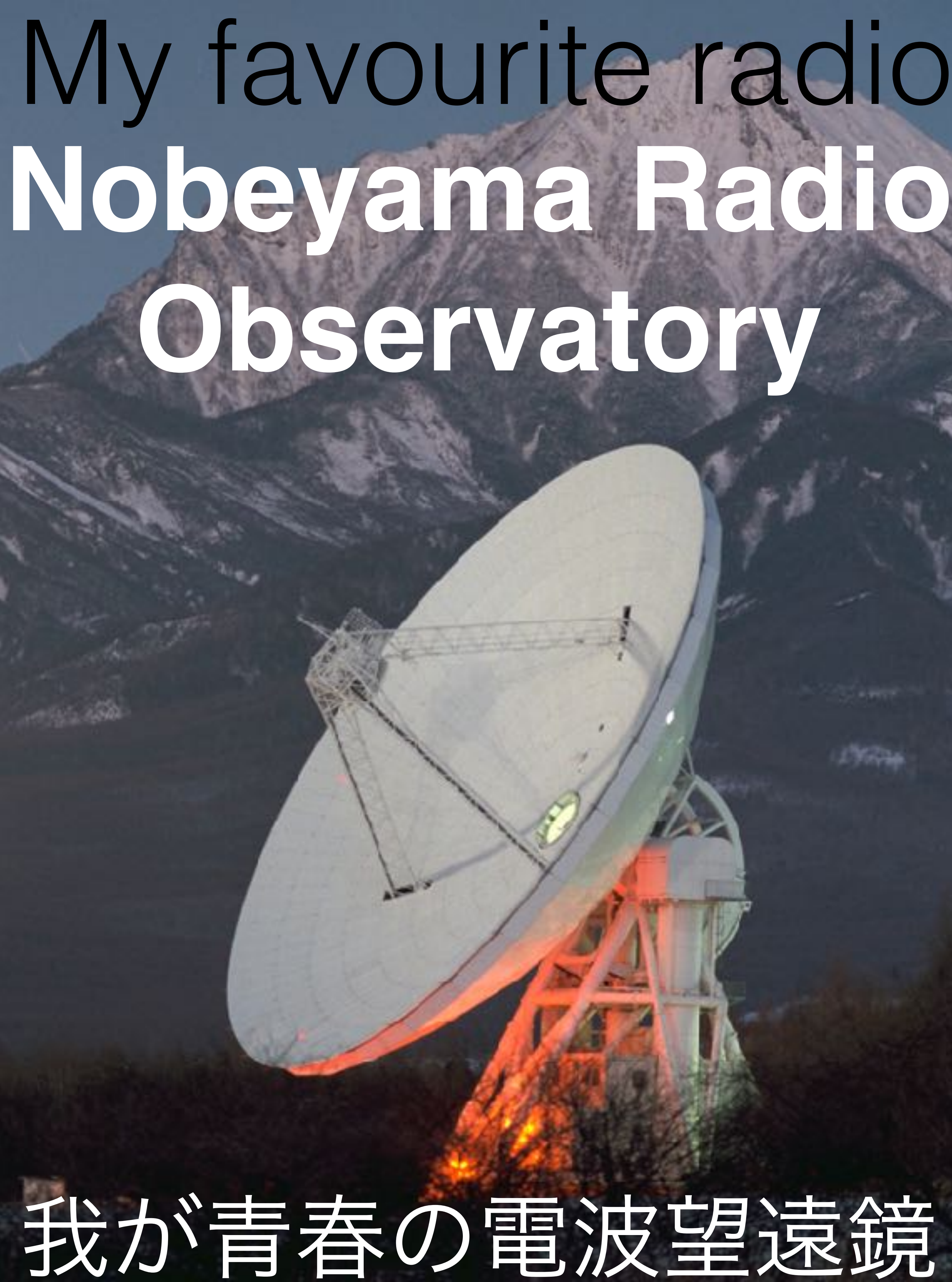
Use the cosmic microwave background as *back light!*



Mroczkowski et al. (2019)

My favourite radio telescope:

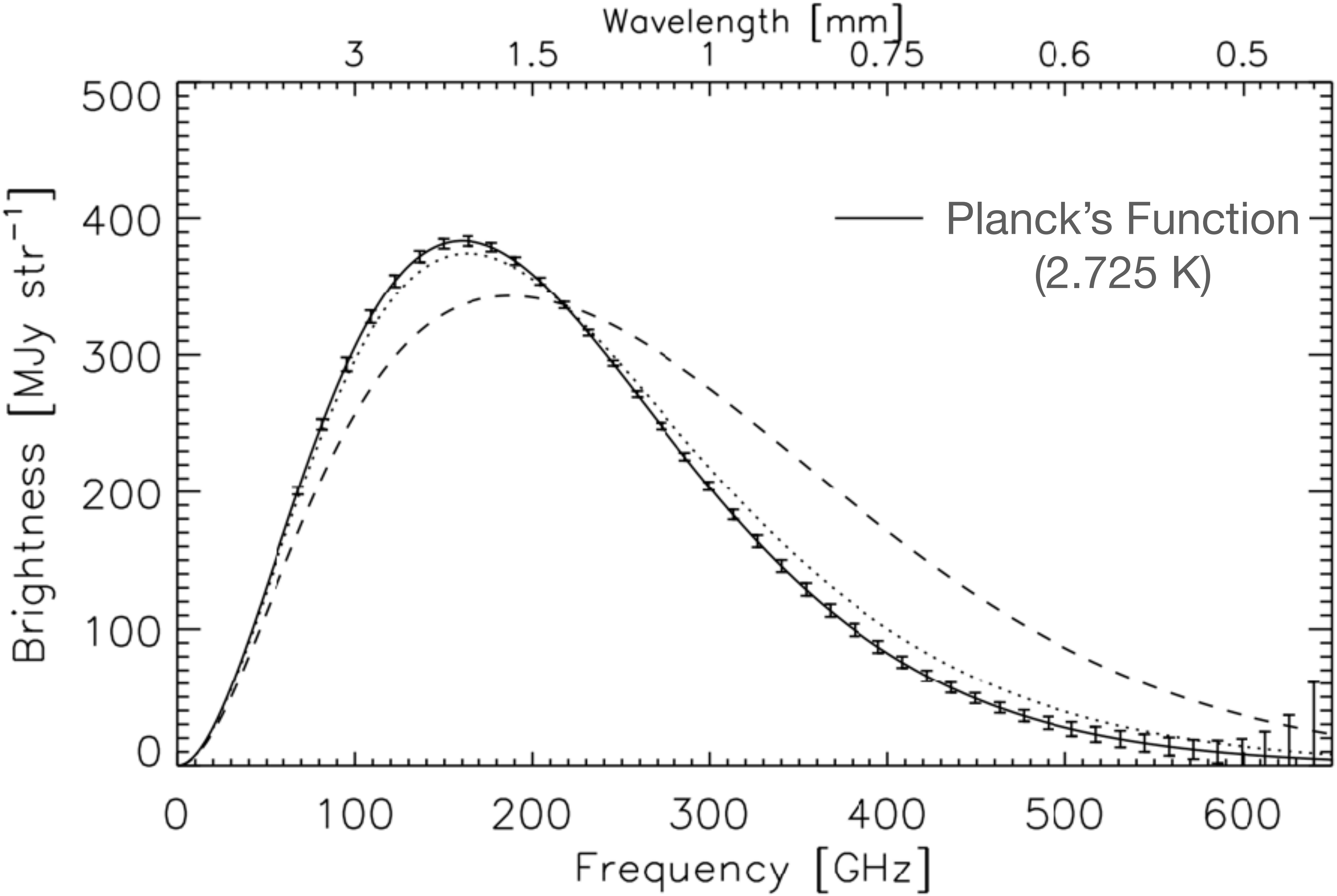
Nobeyama Radio Observatory



我が青春の電波望遠鏡

我が青春の
The “Sunyaev-Zeldovich Effect”

A new technique to measure the gas temperature



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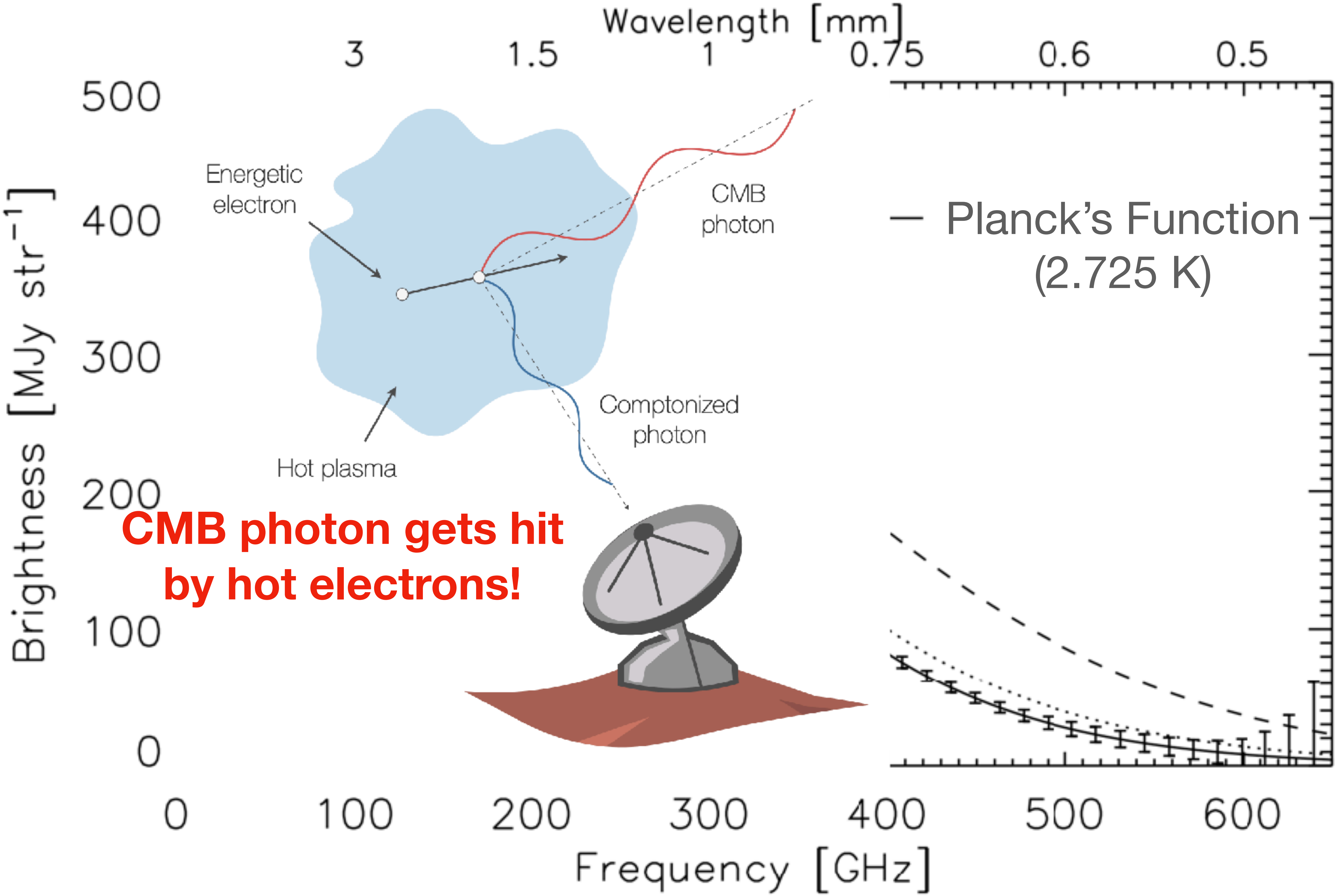

The “Sunyaev-Zeldovich Effect”

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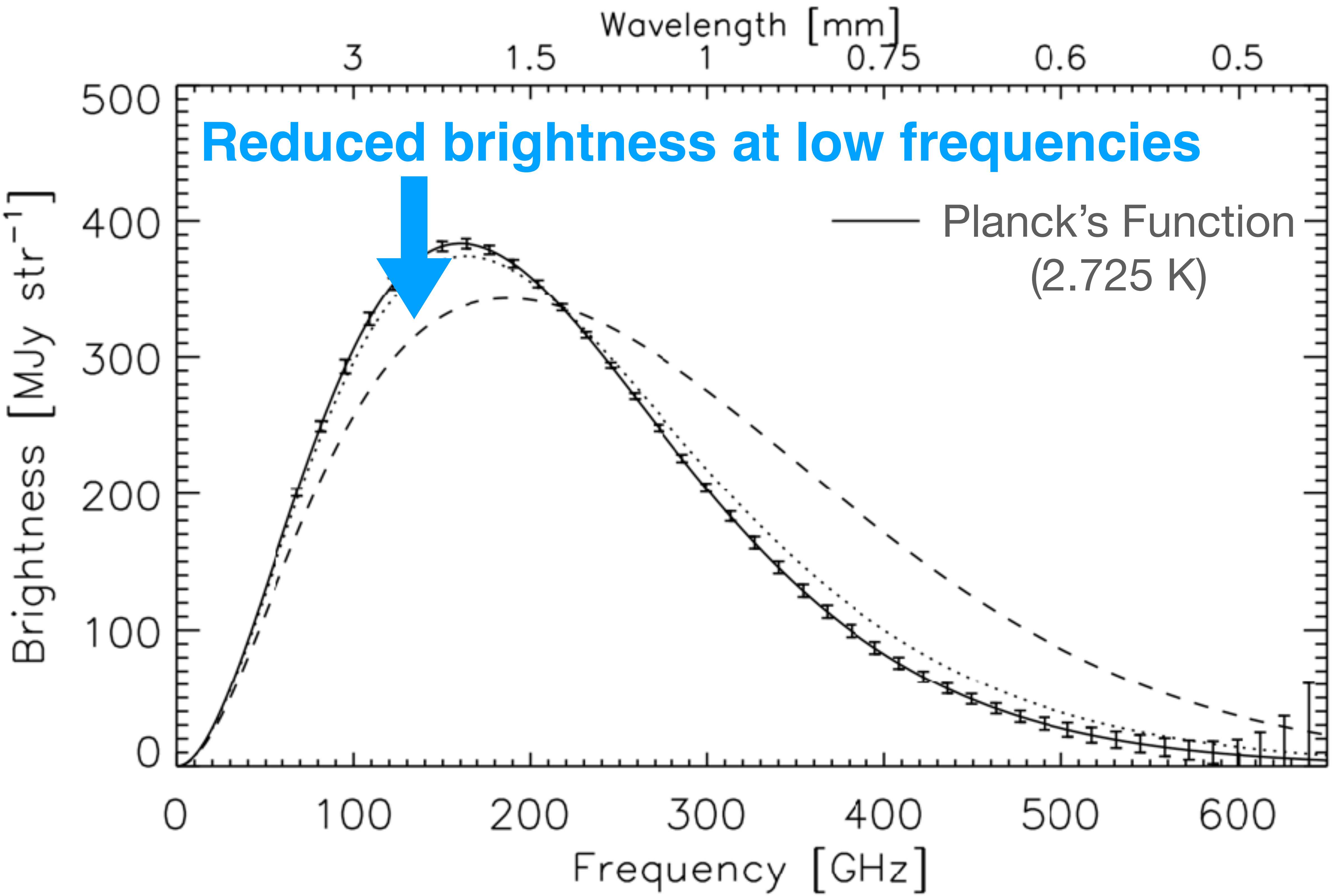

The “Sunyaev-Zeldovich Effect”

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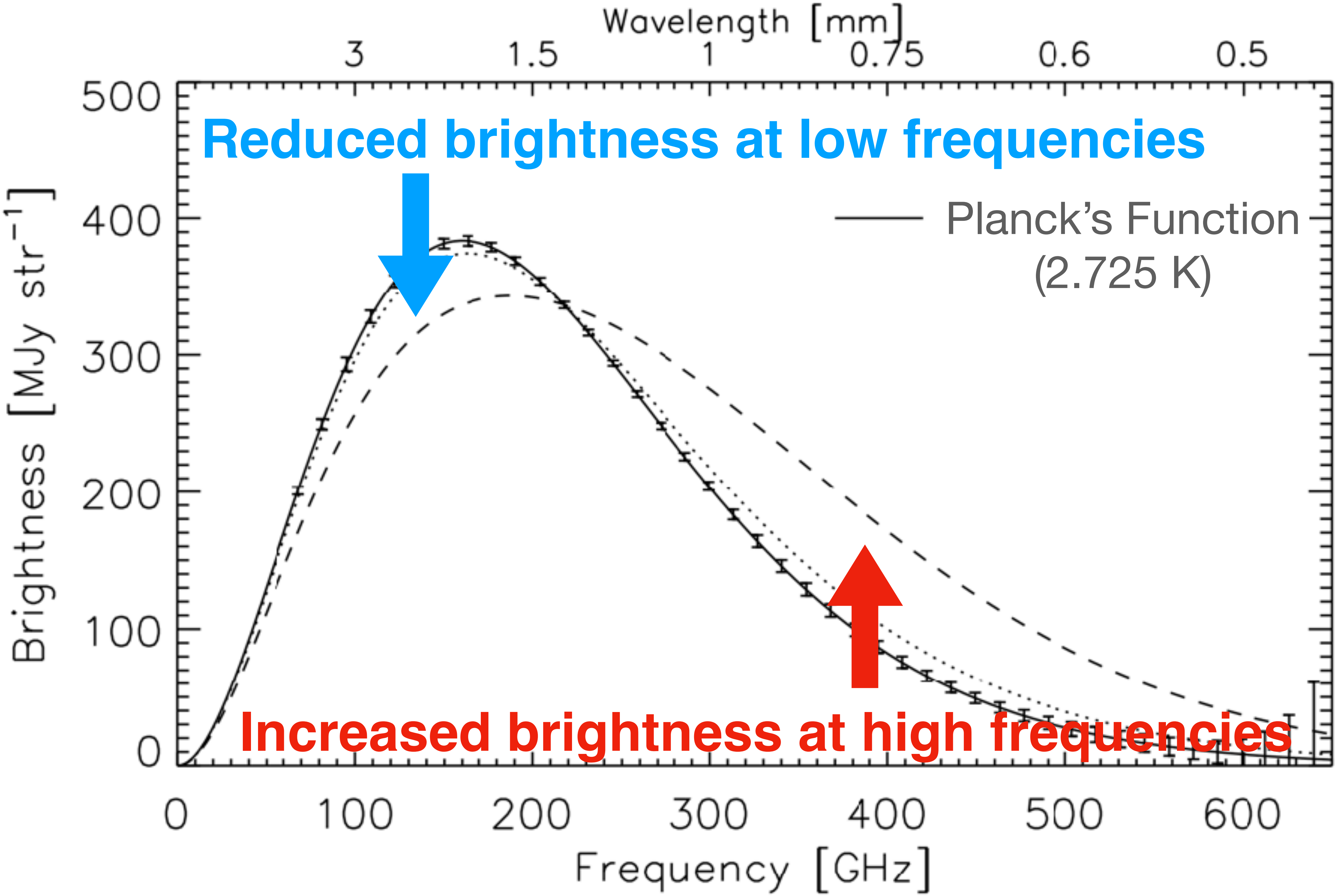
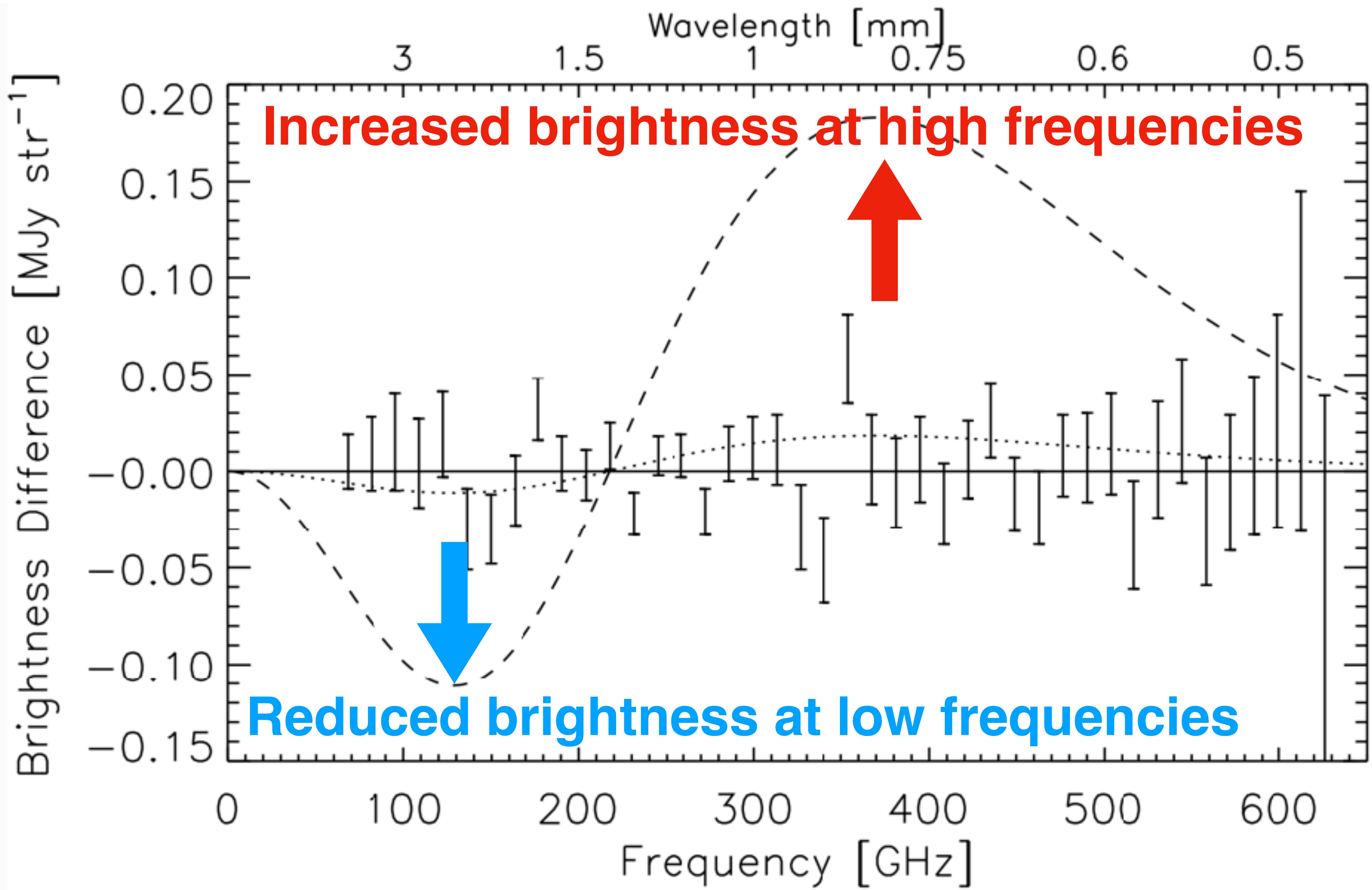


The "Sunyaev-Zeldovich Effect"

A new technique to measure the gas temperature



The “Sunyaev-Zeldovich Effect”

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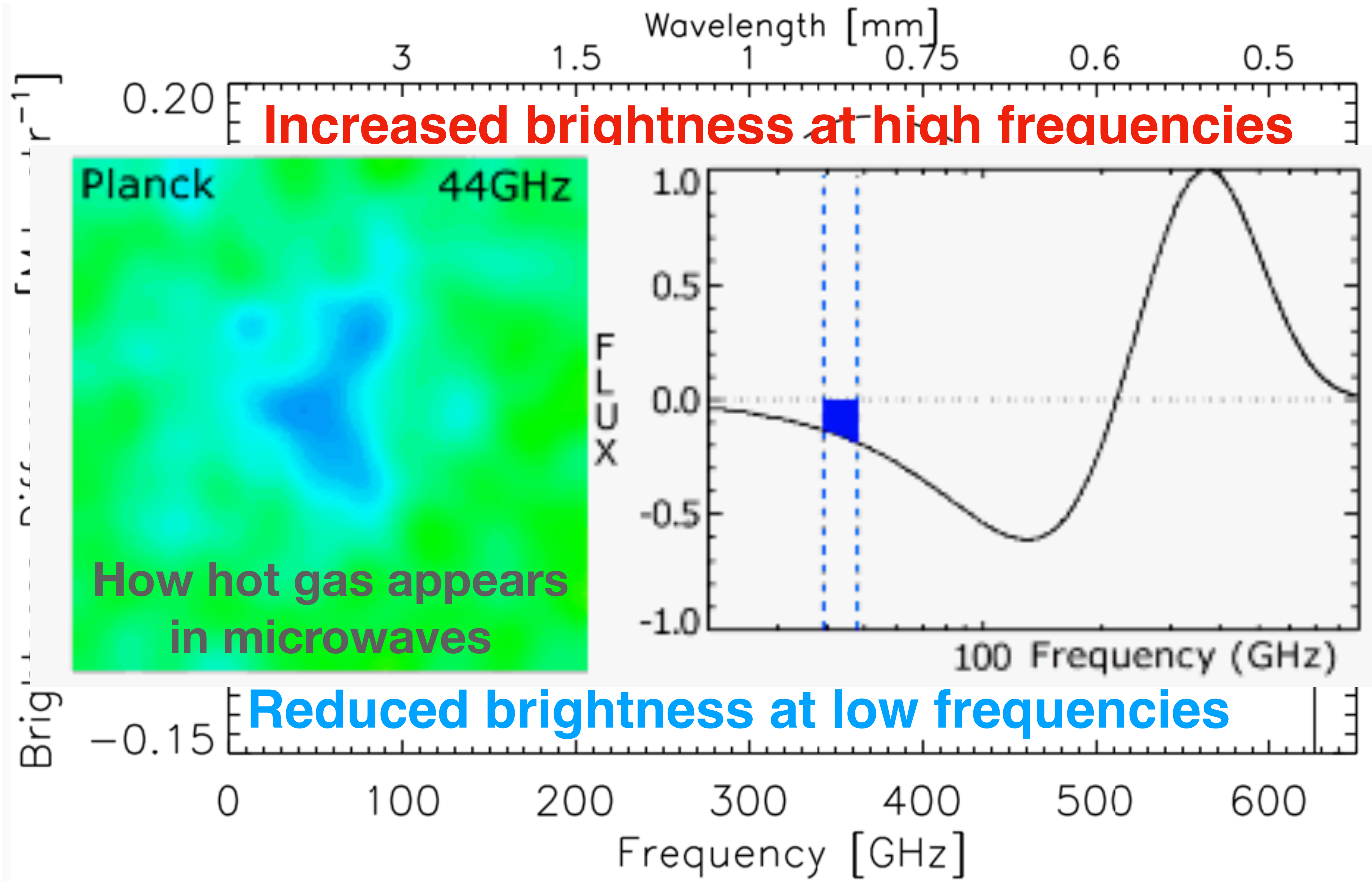
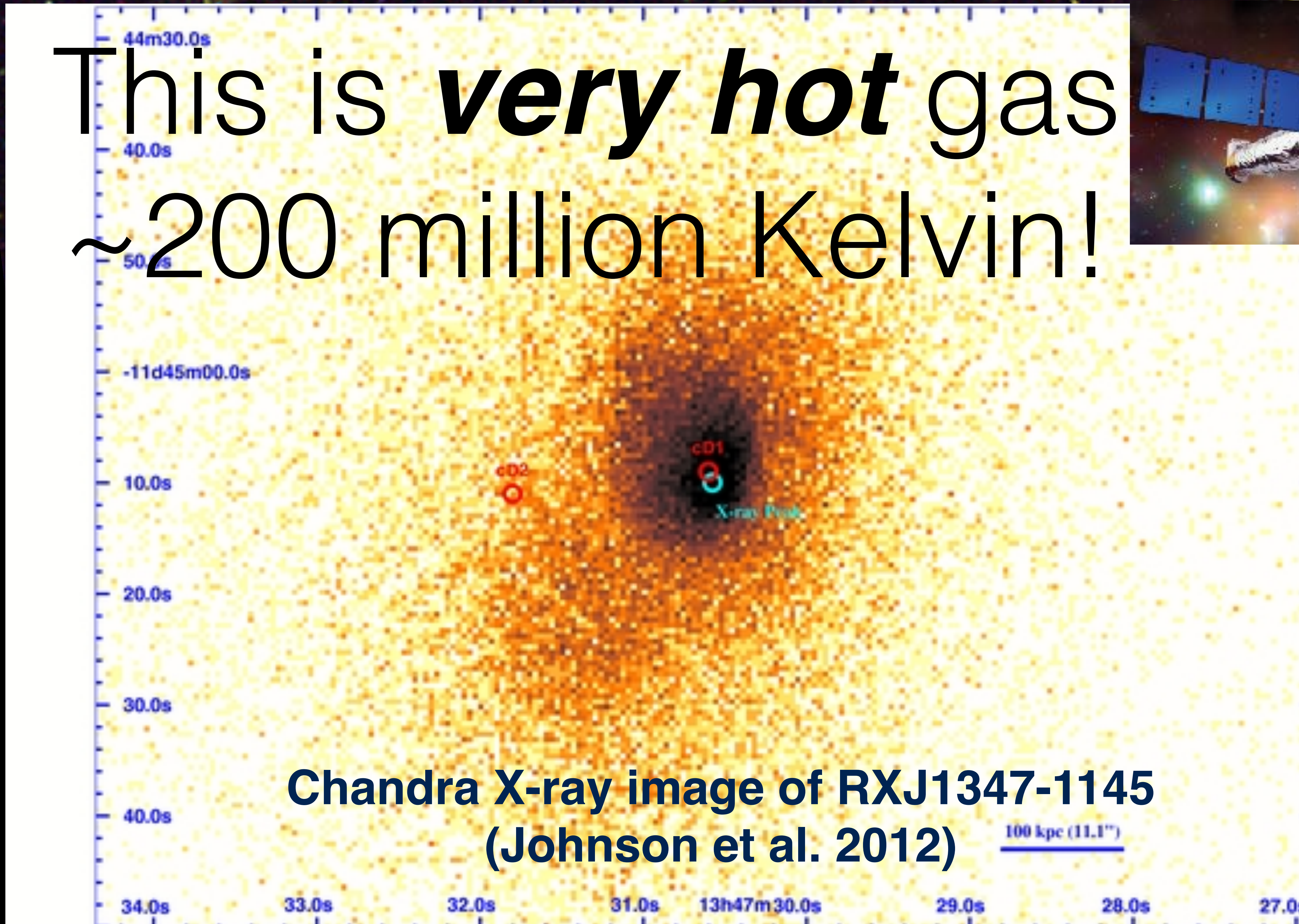


Chandra's **X-ray** Image



This is ***very hot*** gas
~200 million Kelvin!

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

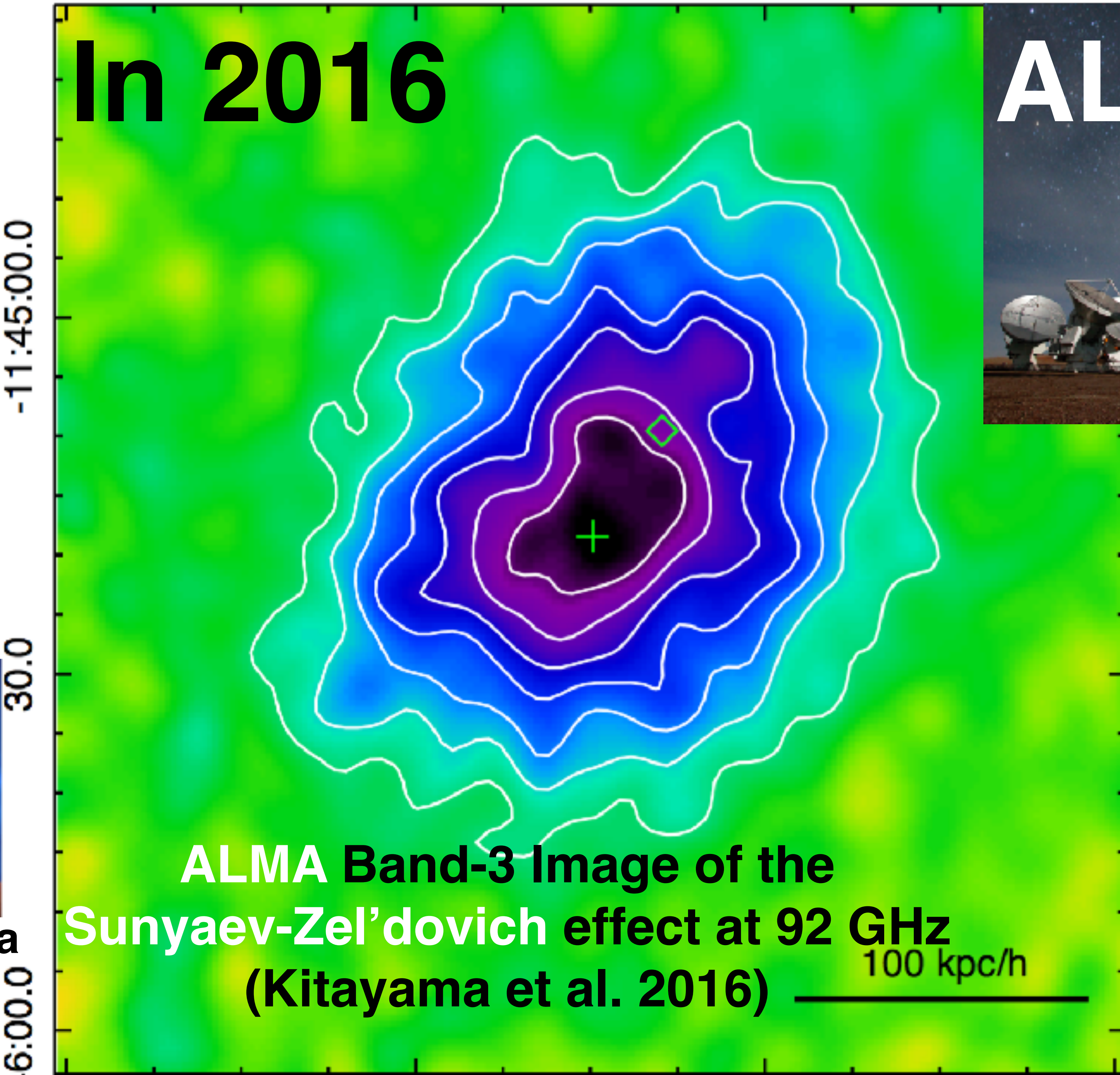
SZ Effect@Nobeyama!

我が青春
In 2001

Su

(Kitayama et al. 2016)

In 2016

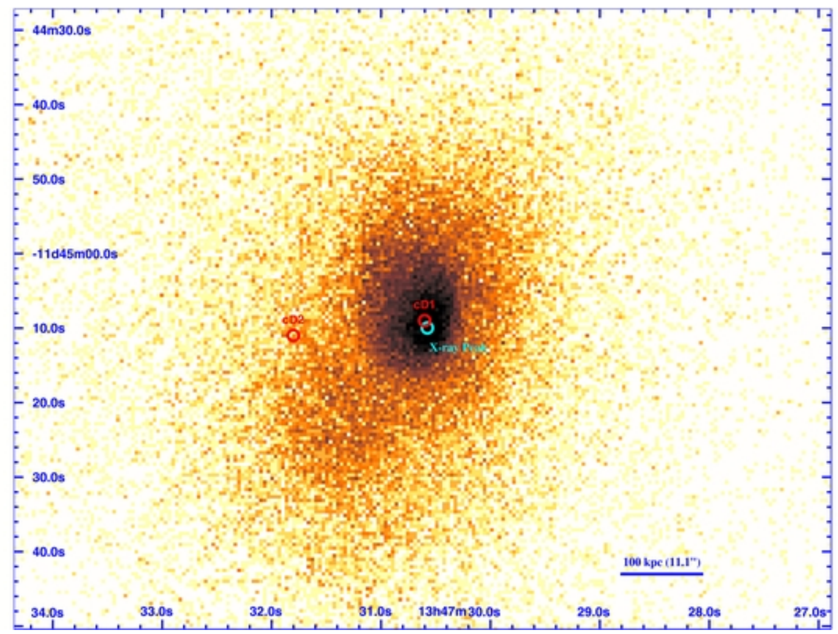


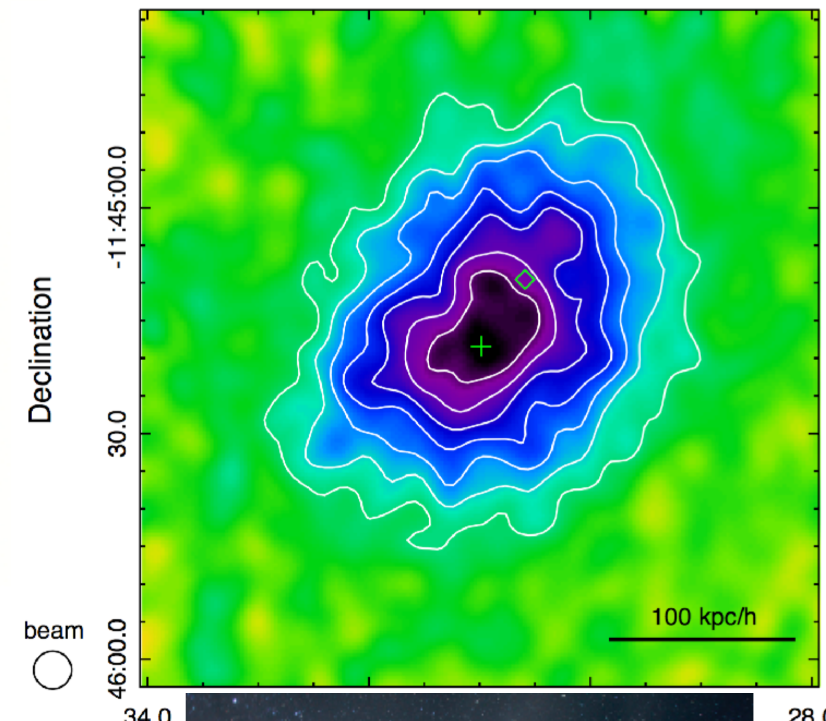
ALMA Band-3 Image of the Sunyaev-Zel'dovich effect at 92 GHz (Kitayama et al. 2016)

ALMA!

T. Kitayama

Multi-wavelength Views of clusters of galaxies





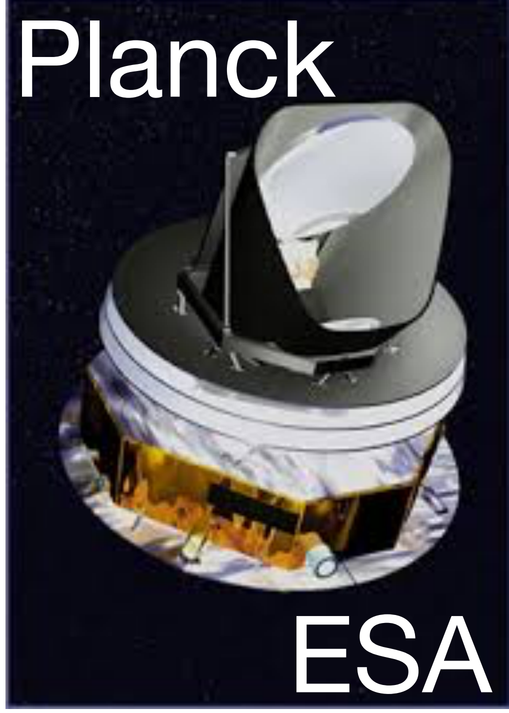
<u>Visible</u>:
- 100-1000 galaxies

<u>X-ray</u>:
- hot gas (10^{7-8} K)

<u>SZ</u> [microwave]:
- hot gas (10^{7-8} K)

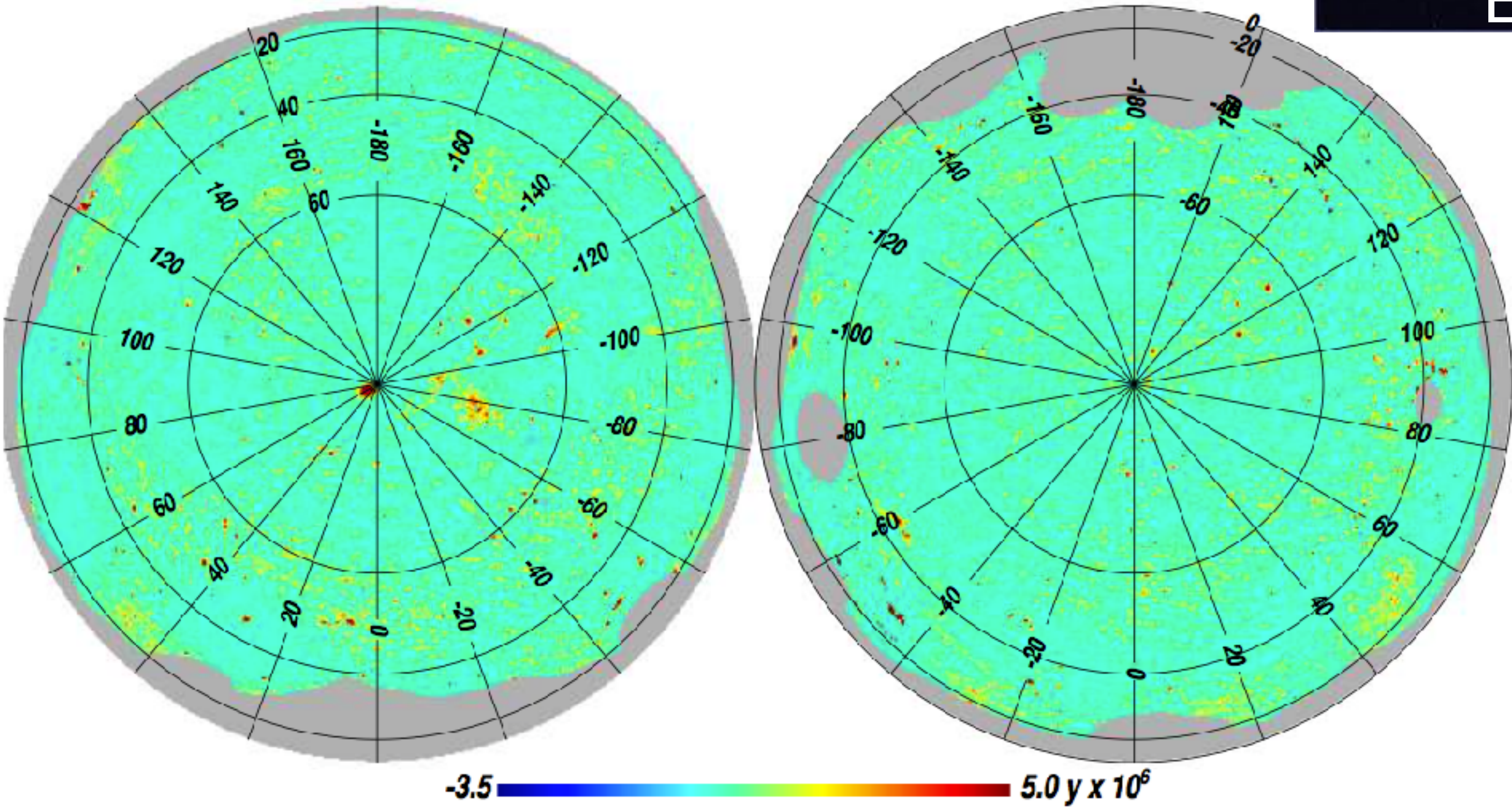
Now, the whole Universe!

The SZ effect from the Planck satellite



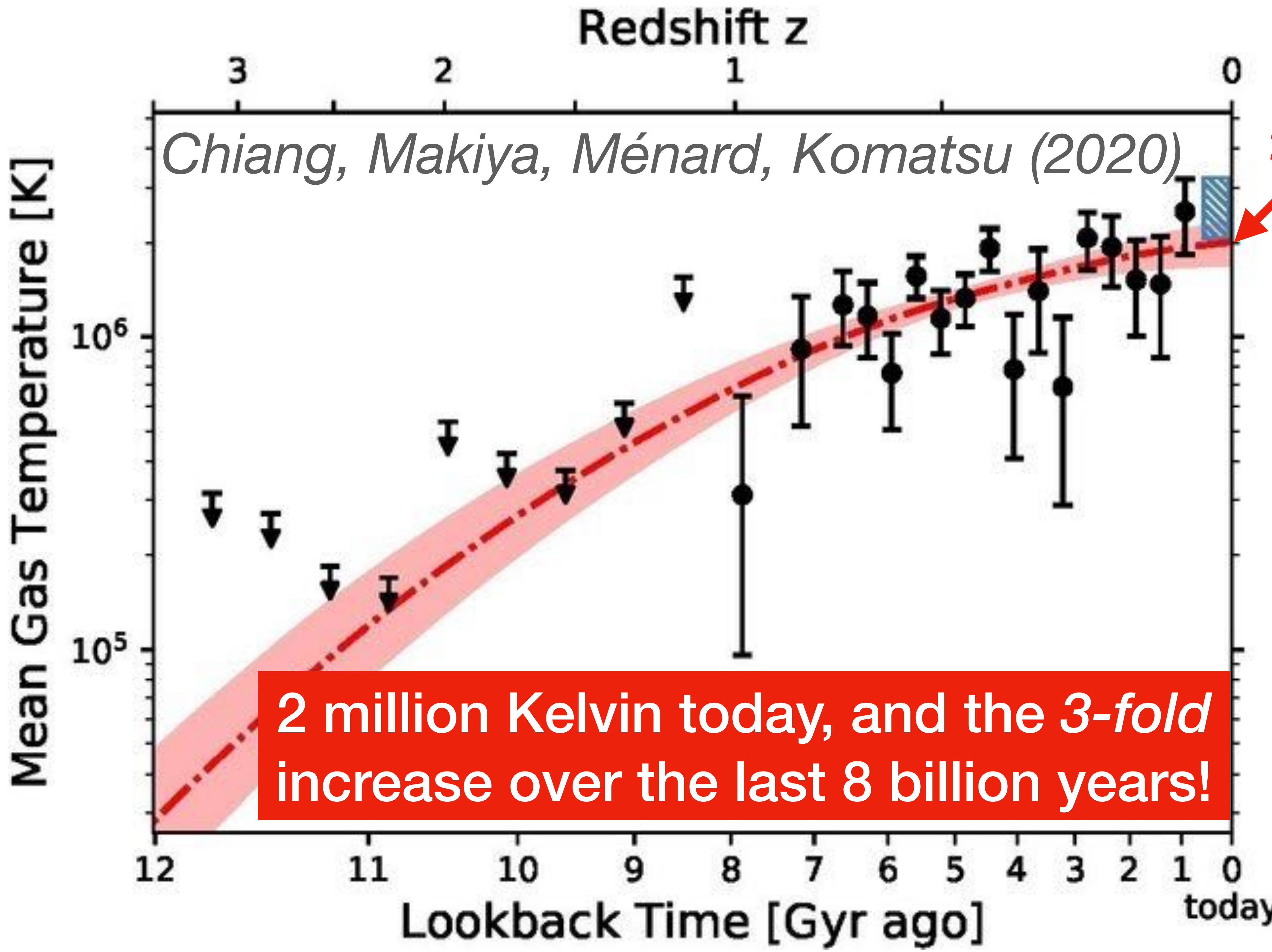
Northern Sky

Southern Sky



Mean Gas Temperature of the Universe

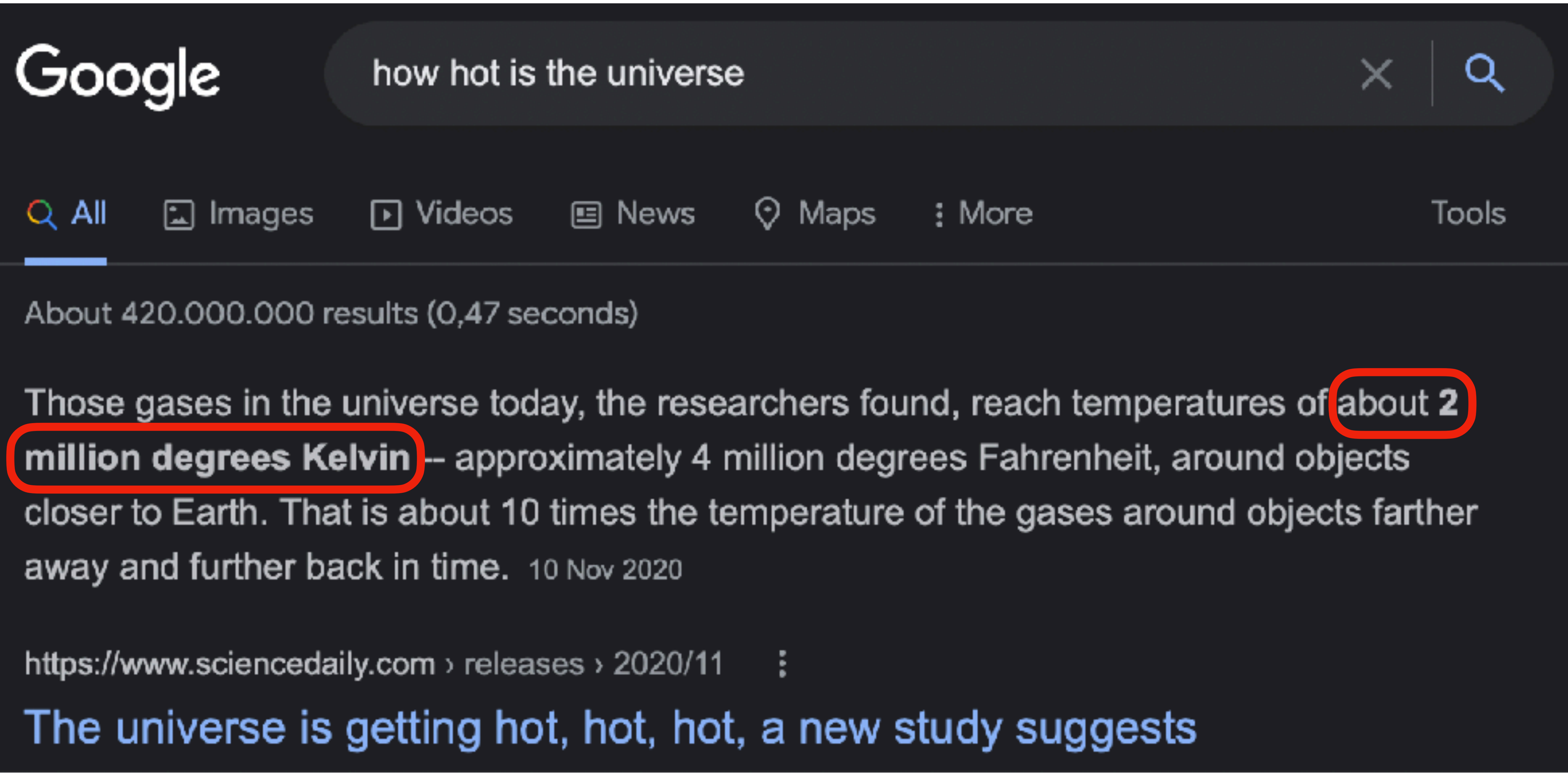
Measured for the first time!



2 million Kelvin Today

Google’s answer: “2 million Kelvin”

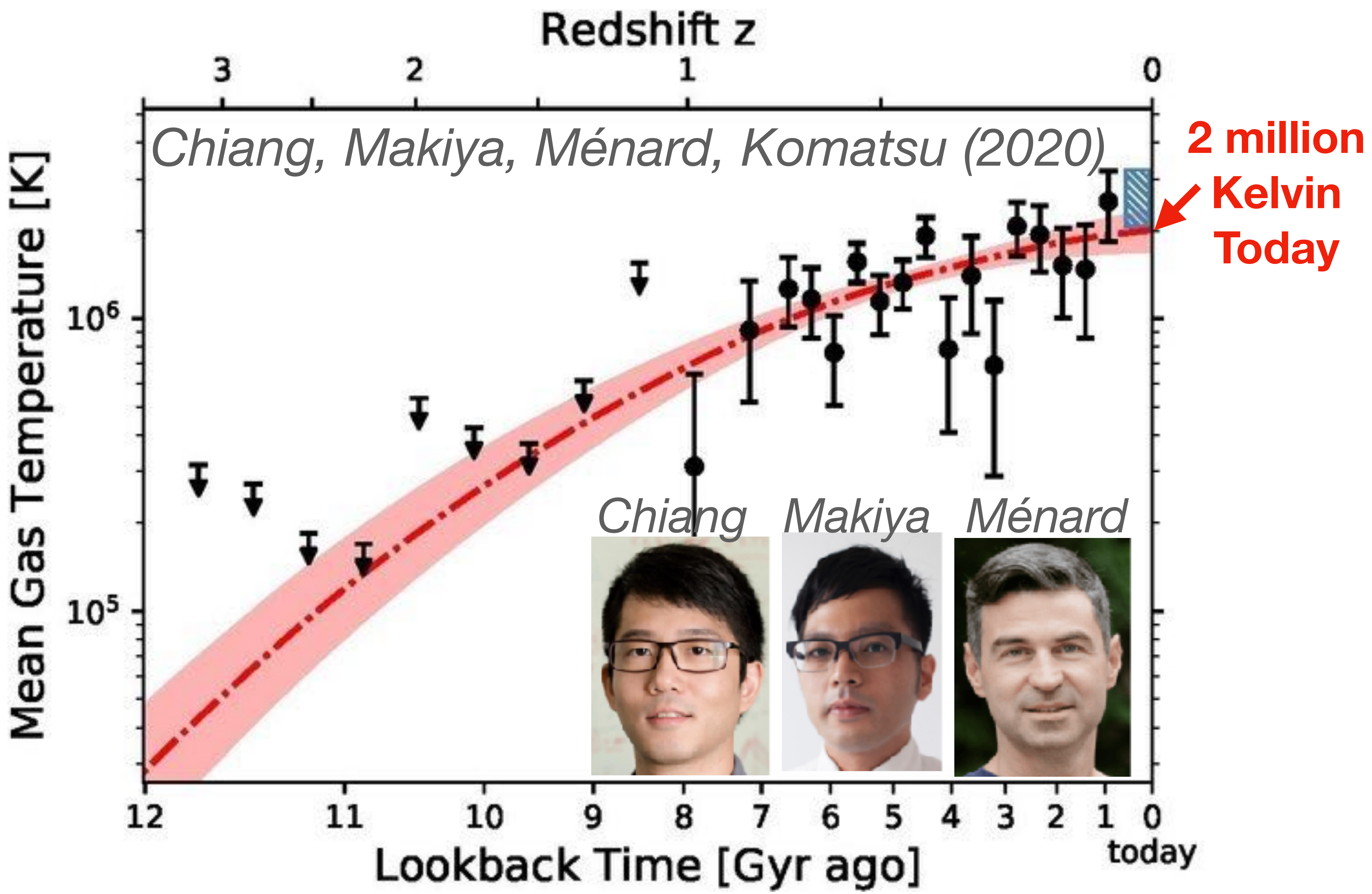
Search “how hot is the universe”



This is our result, for the temperature of **gas**!

Mean Gas Temperature of the Universe

Measured for the first time!

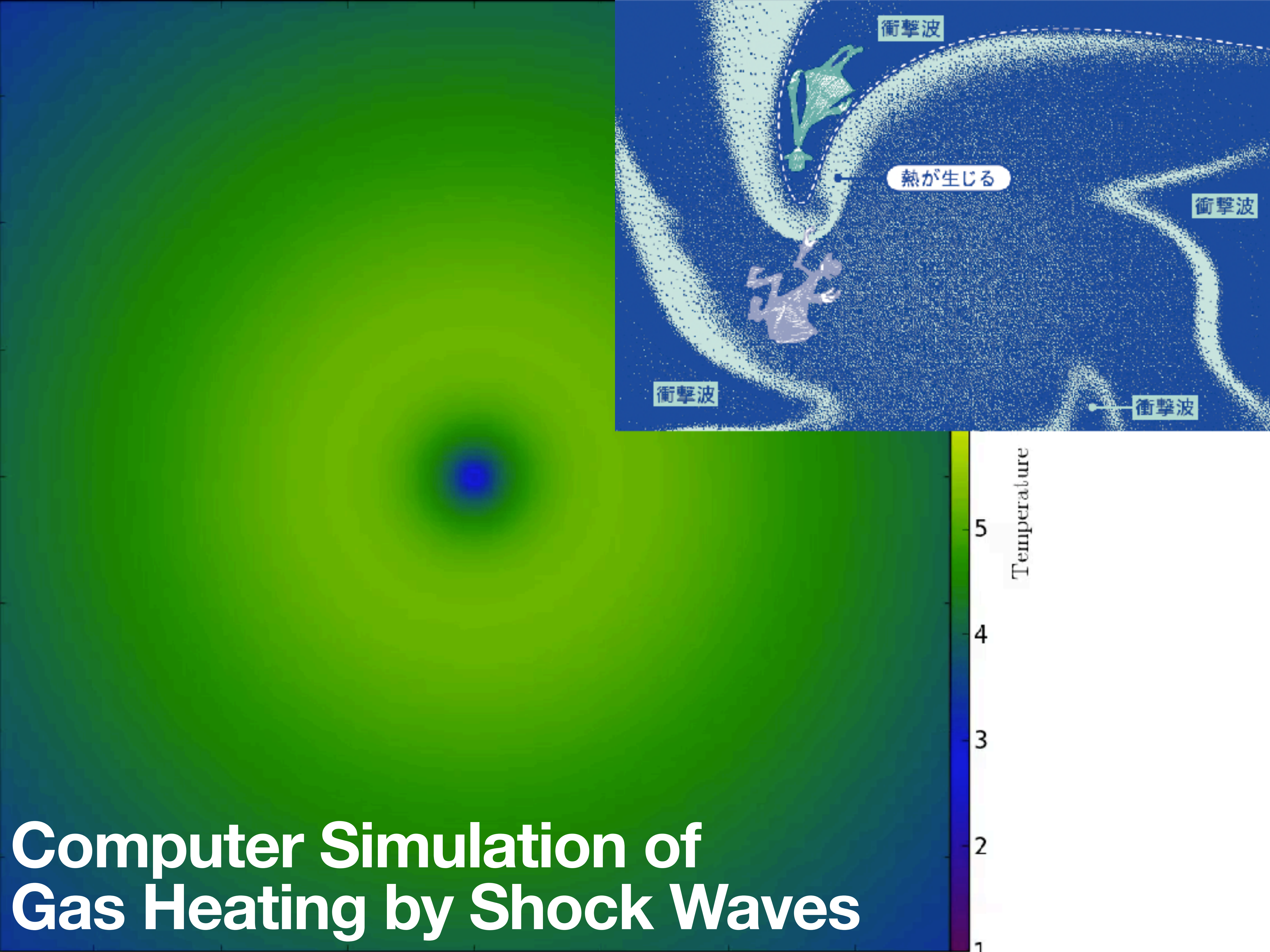


Q: What caused this "global warming" of gas?

A: It's a shock wave!

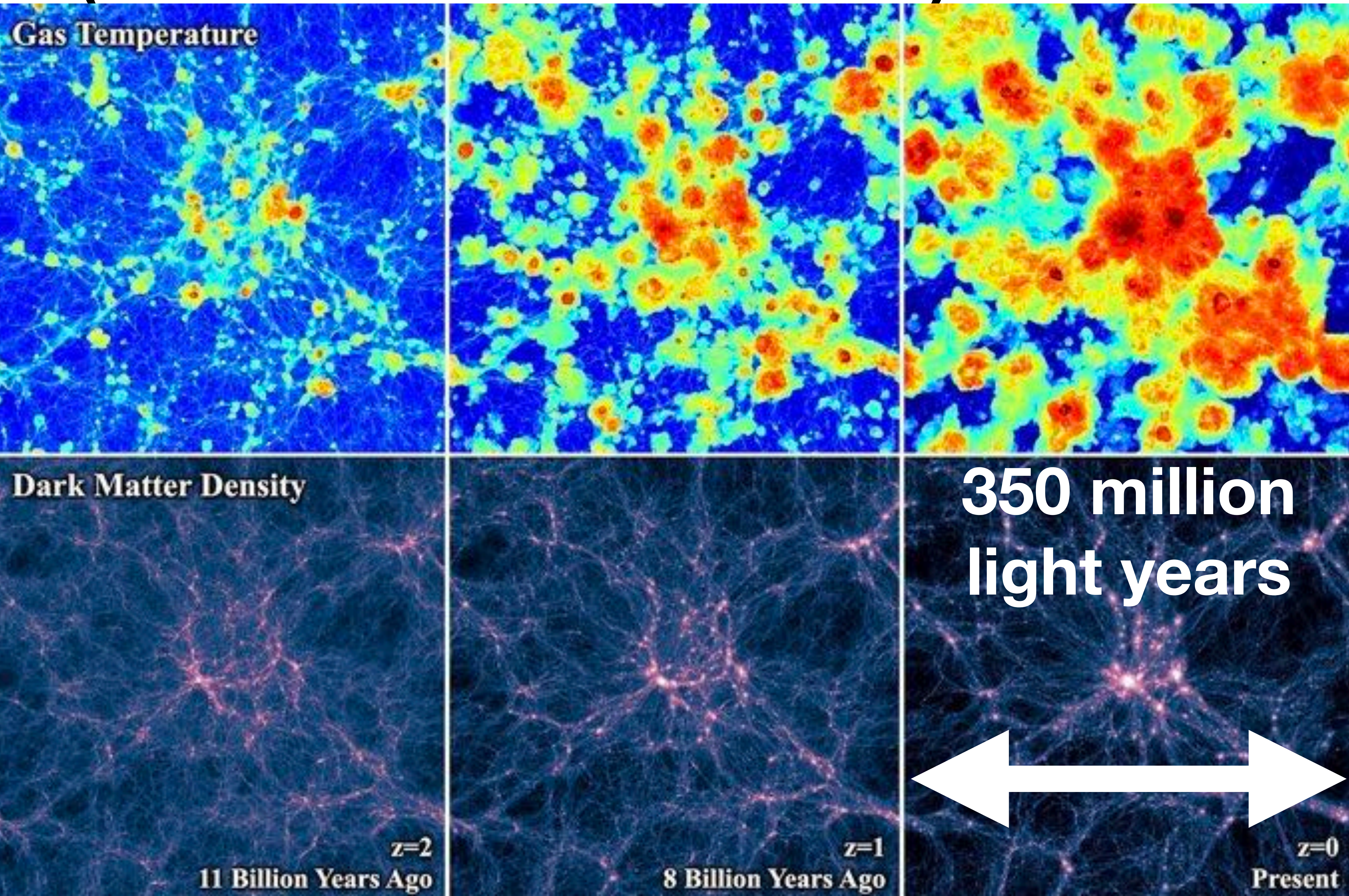
Small clumps collide, merge, and form bigger structures

From “*Cosmic Voyage*” (1996)



Computer Simulation of Gas Heating by Shock Waves

Sophisticated simulation of the Universe (Credit: Illustris Collaboration)



Summary

Gas in the Universe is getting hotter

- We used a new technique called “Sunyaev-Zeldovich Effect” to measure the time evolution of the mean **gas** temperature of the Universe.

- We discovered two things:

    - Today’s mean gas temperature is **2 million Kelvin.** Very hot!

    - The temperature increased 3 times over the last 8 billion years.

- We can explain this “global warming” of gas by **shock-wave heating** associated with formation of structures in the Universe.

The remaining questions

Big questions are not yet answered

- Ordinary stuff that we are familiar with:
  - ✓ Gas of the ordinary matter: 2 million Kelvin
  - ✓ Photons: 2.7 Kelvin
  - (✓) Neutrinos: 1.9 Kelvin [indirect determination]
- Extraordinary stuff that we know exists:
  - **Dark matter: ????**
  - **Dark energy: ????**
- **Can we even define their temperature…???**

The remaining questions

Big questions are not yet answered

•

✓

✓

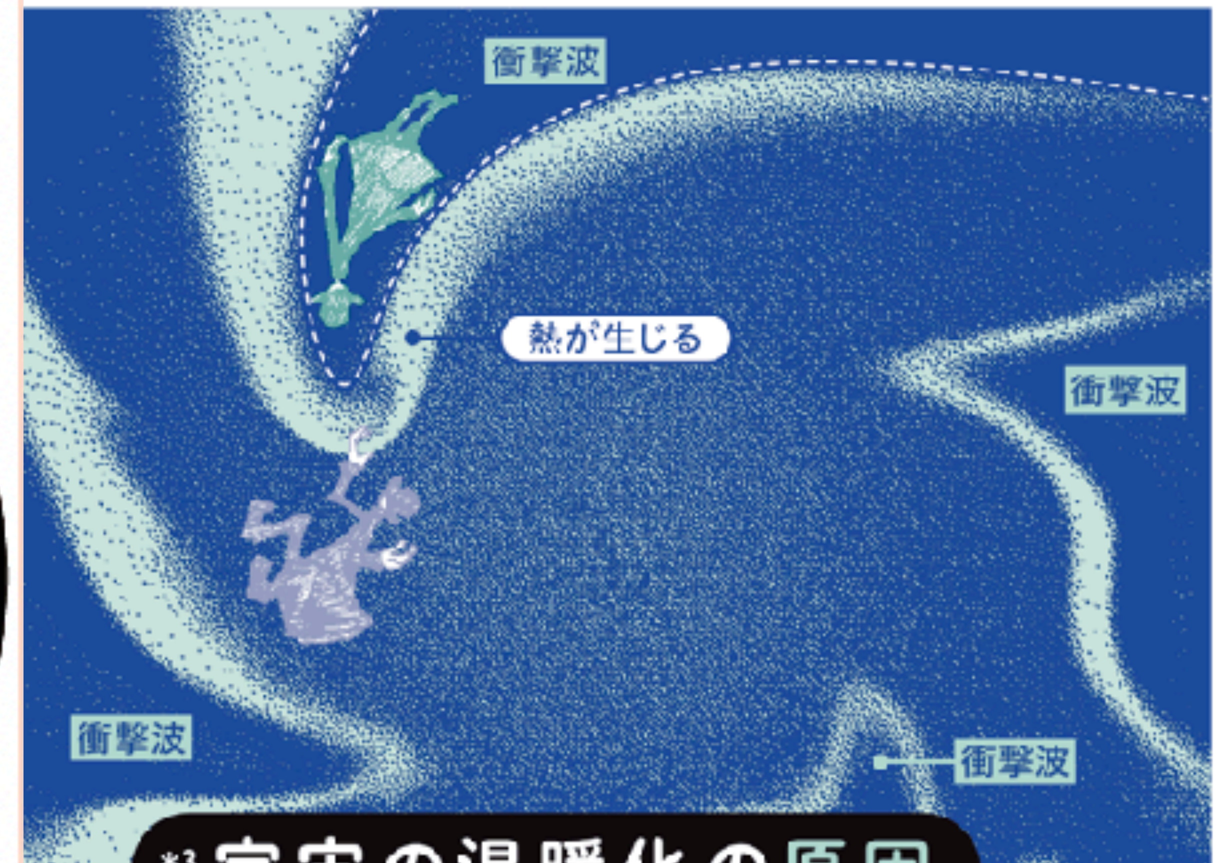
(✓)

•

So, the research continues.
Thank you very much
for your support.
This is also <u>your</u> research result,
supported by <u>your</u> tax!

- **Dark matter: ????**
- **Dark energy: ????**

- **Can we even define their temperature…???**



*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。

たくさん持ってきていますので、
ご自由にお取りください。