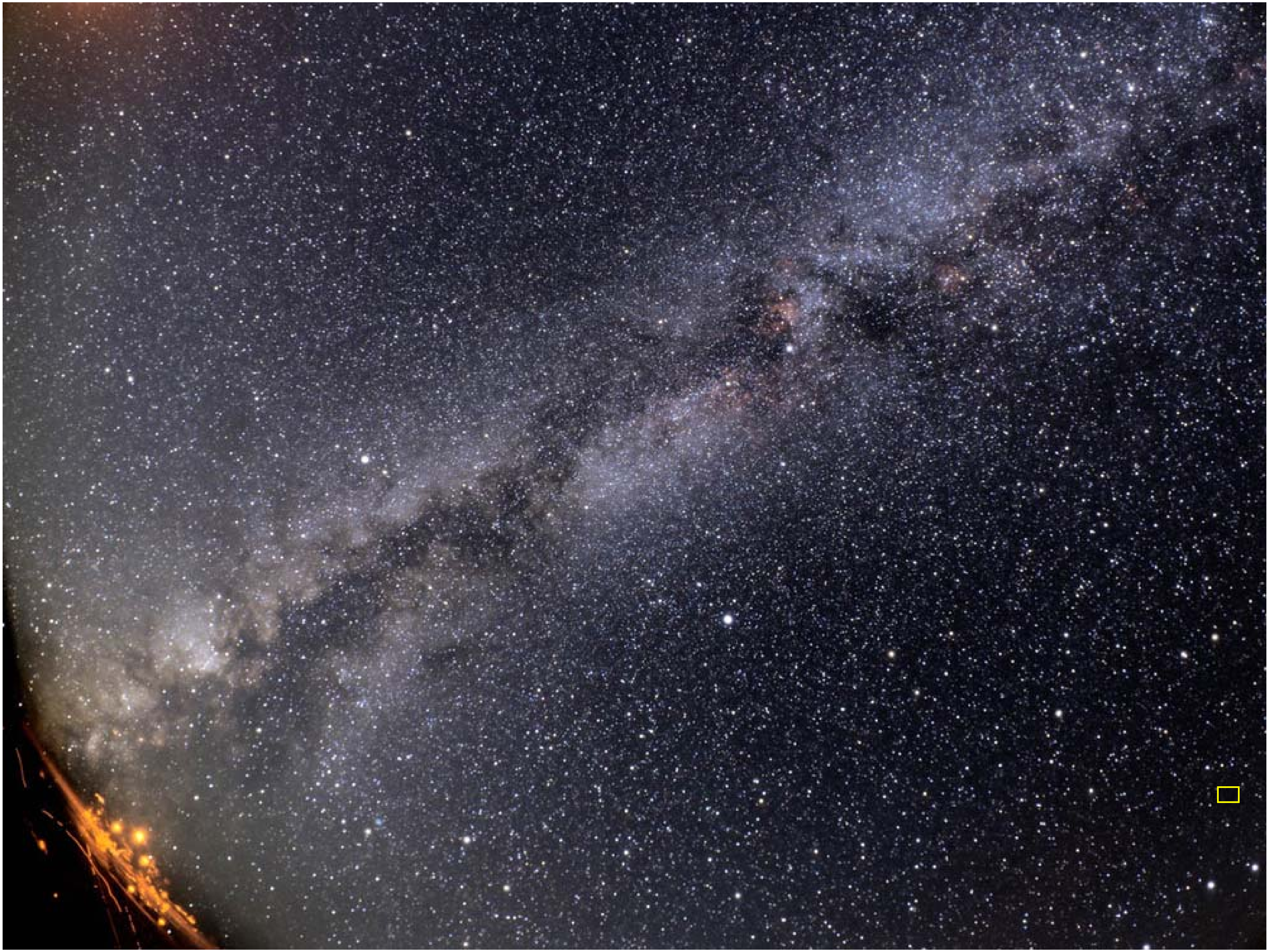
The light from beyond the stars

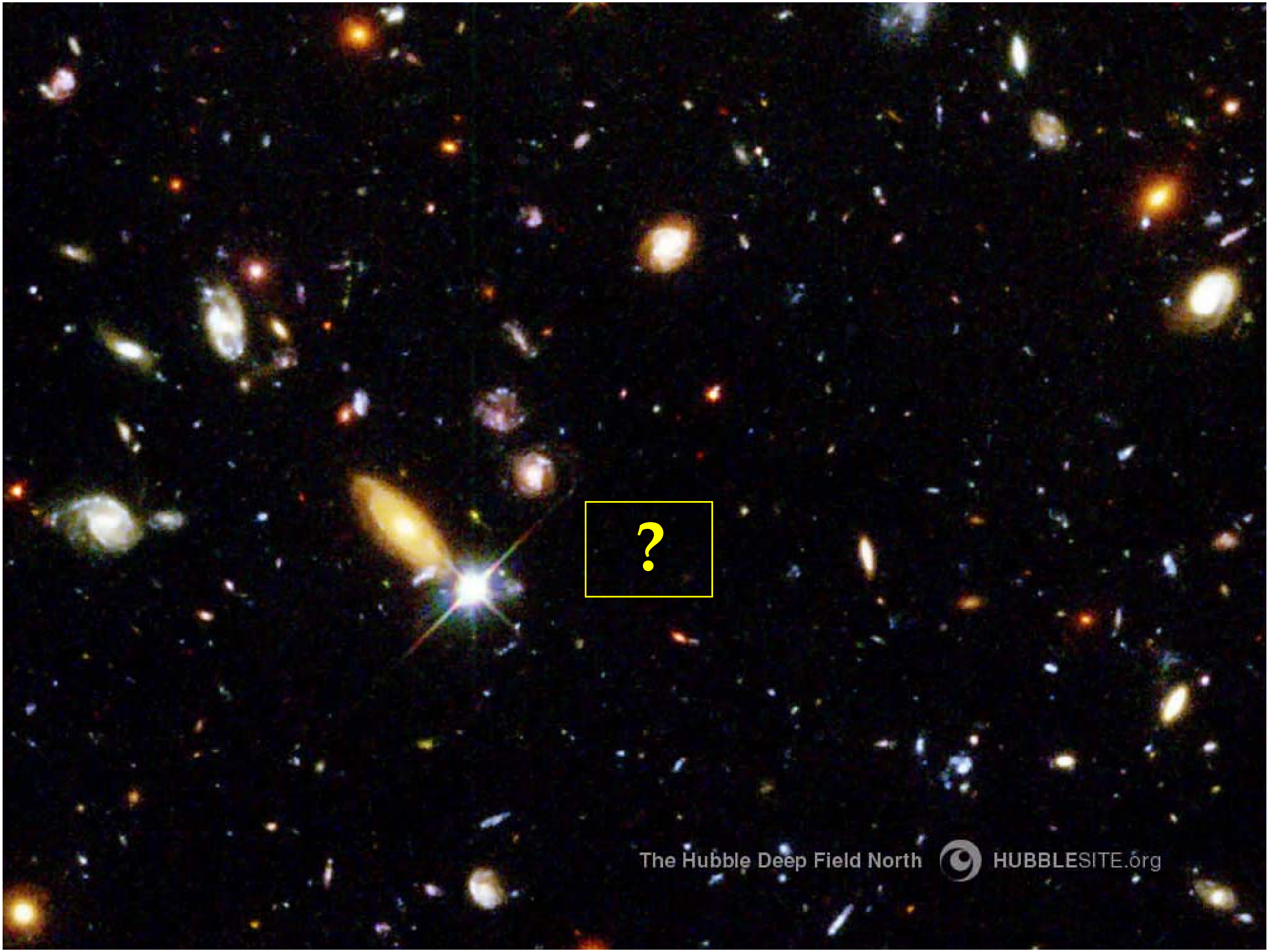
presented by

Hael Collins

“I’m astounded by people who
want to ‘know’ the universe
when it's hard enough to find
your way around Chinatown”

Woody Allen




?
The Hubble Deep Field North
HUBBLESITE.org

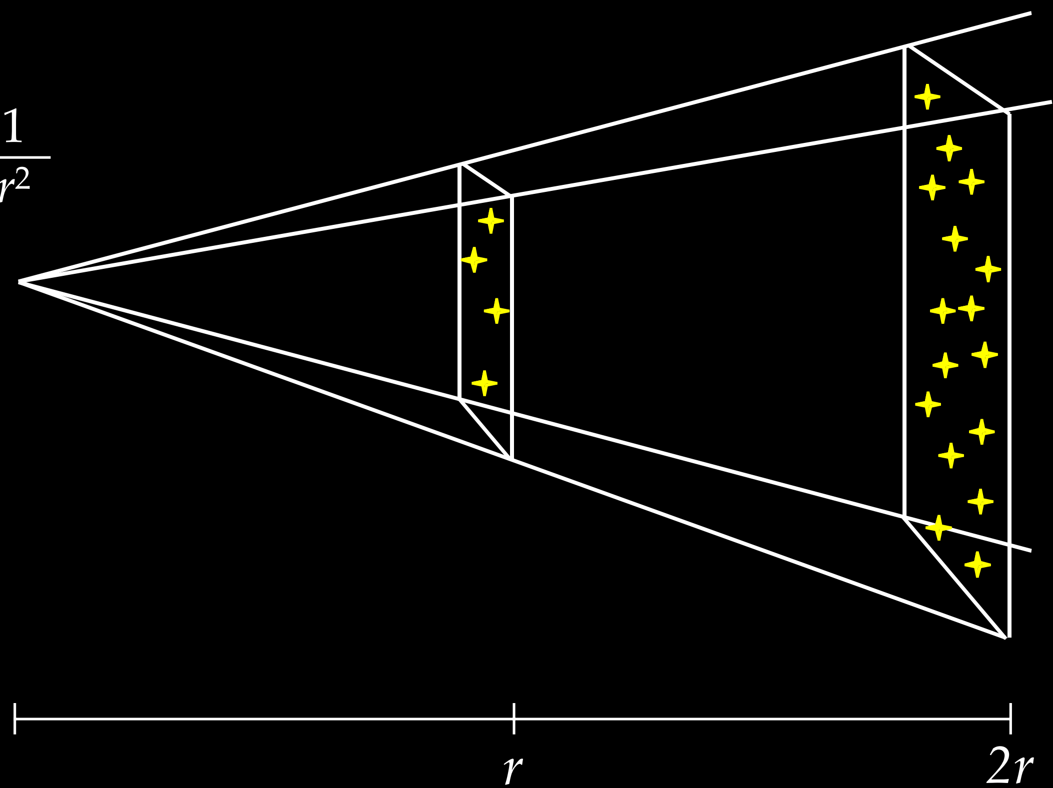

Why is the night sky dark?
Is it perfectly dark?
?
The Hubble Deep Field North
HUBBLESITE.org

Heinrich Wilhelm Olbers
(1758–1840)

Oblers' Paradox

(or "Why is the night sky dark?")

$$\frac{\text{Light}}{\text{Star}} \propto \frac{1}{r^2}$$



$$\frac{\text{Stars}}{\text{Slice}} \propto r^2$$

Oblers’ Paradox

(or “Why is the night sky dark?”)

$$\left(\frac{\text{Light}}{\text{Star}} \propto \frac{1}{r^2}\right) \times \left(\frac{\text{Stars}}{\text{Slice}} \propto \ r^2\right) = \left(\frac{\text{Light}}{\text{Slice}} \propto \text{constant}\right)$$

Resolution:

1. Finite size?
   (the average density of stars far away falls off faster than $1/r^2$)
2. Finite time?
   (the universe had a beginning)
3. Dilution?
   (some additional effect weakens the light at great distances)

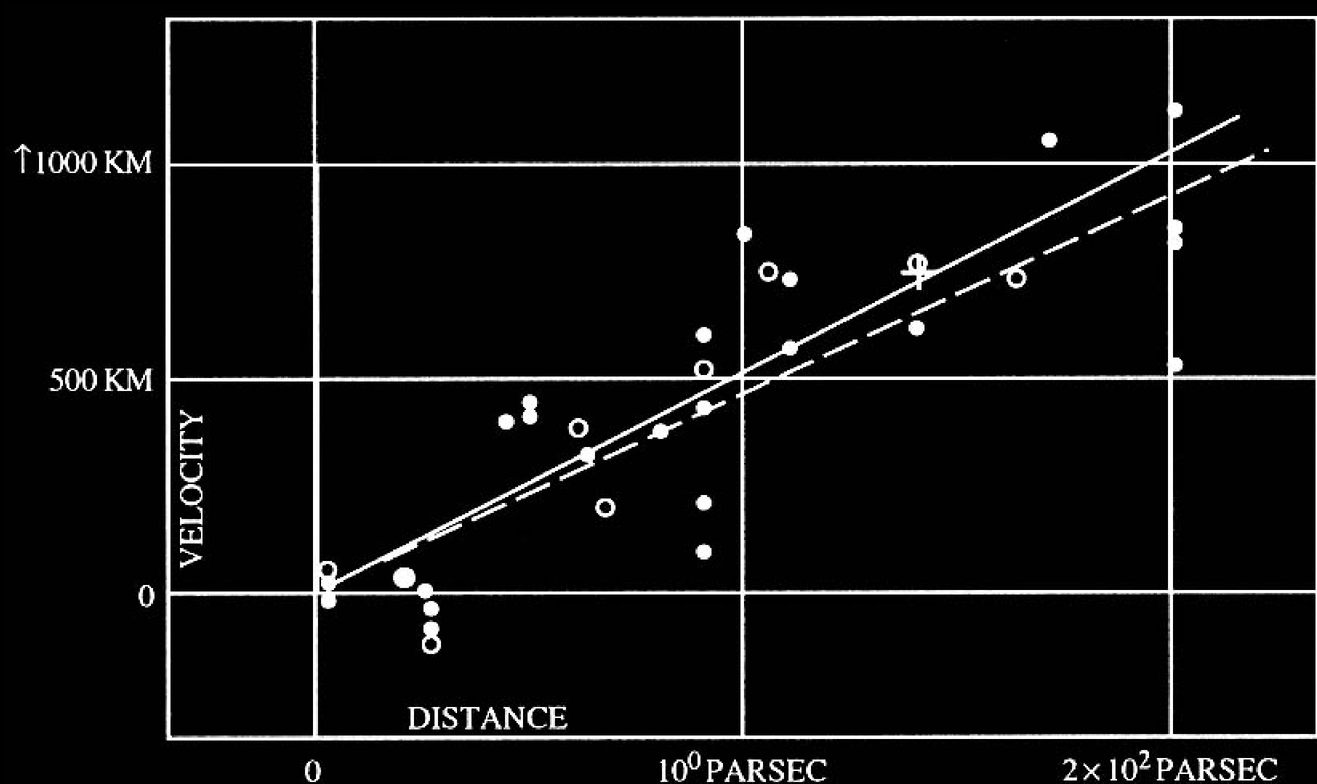
“[I] chucked the law for astronomy, and I knew that even if I were second-rate or third-rate it was astronomy that mattered.”

Edwin Hubble

Edwin Powell Hubble
(1889–1953)

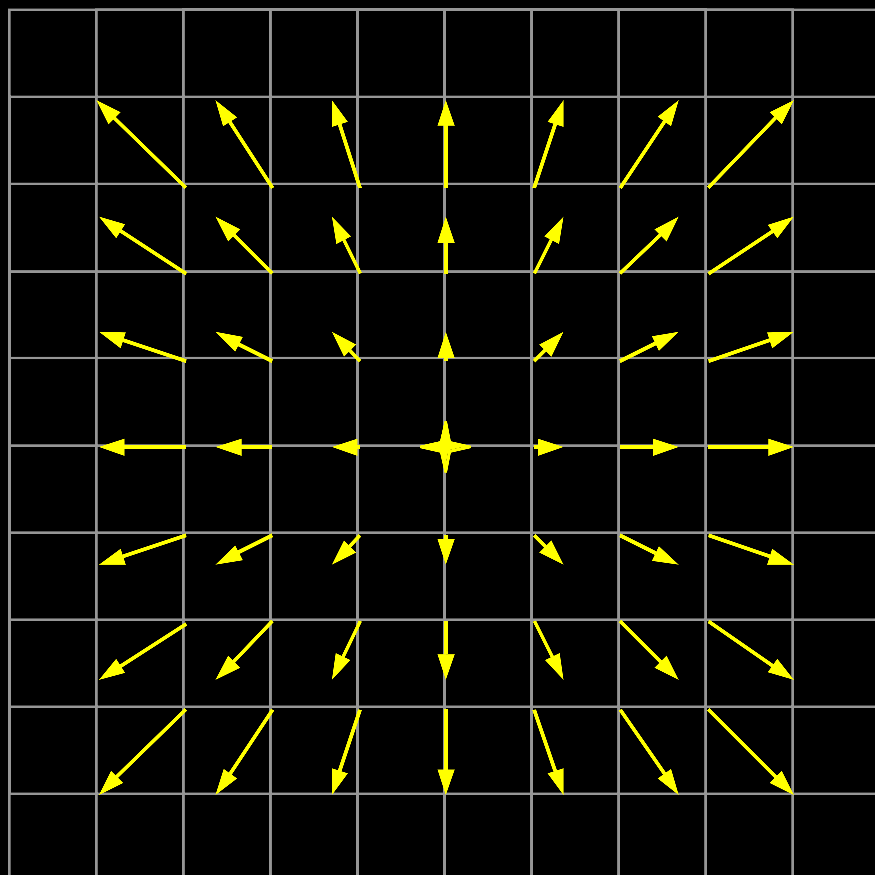
Hubble's Discovery
(1929)

The farther away something is from us,
the faster it is moving away



Do we live in a special part of the universe?

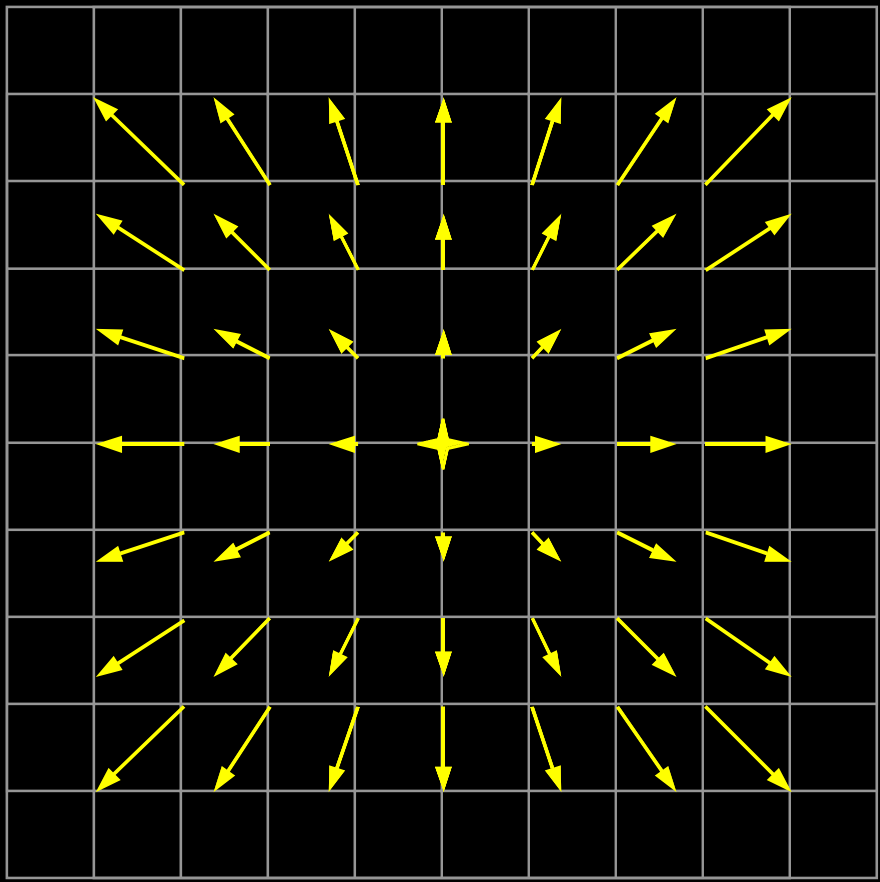
(and what about the Copernican Principle?)

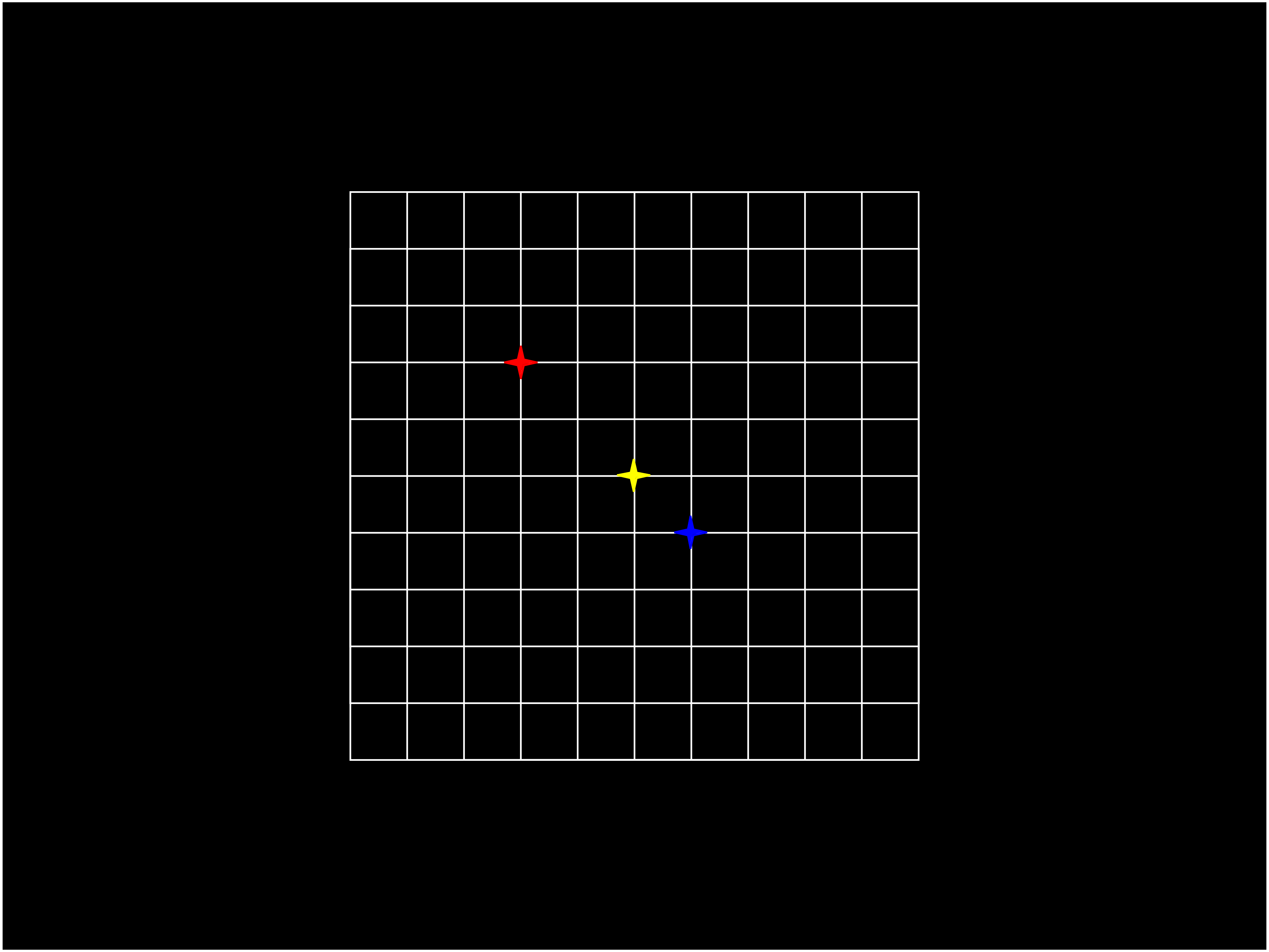


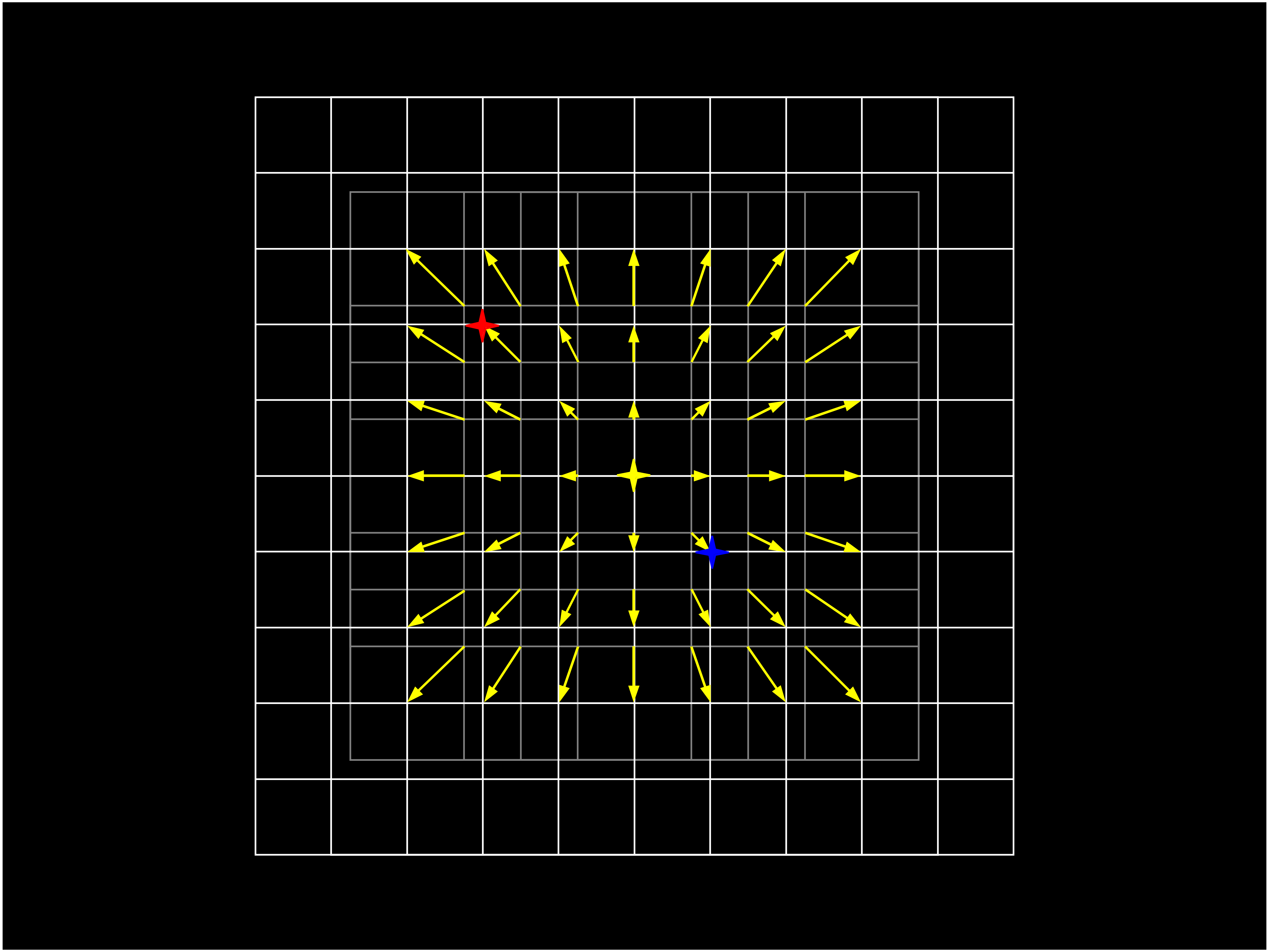
Two possibilities:

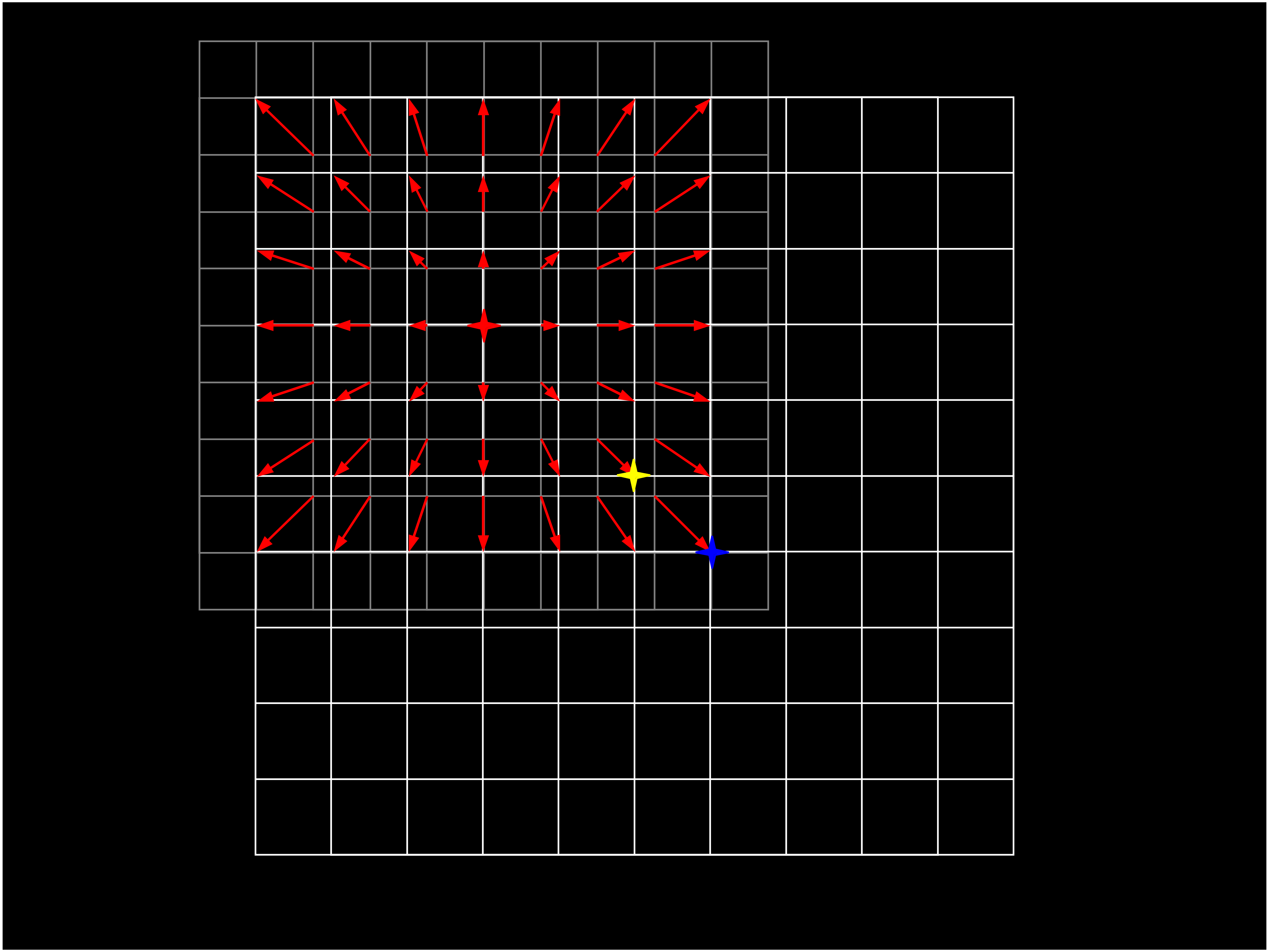
1. Space is fixed, and the galaxies move

2. Space itself is expanding and the galaxies are more or less fixed



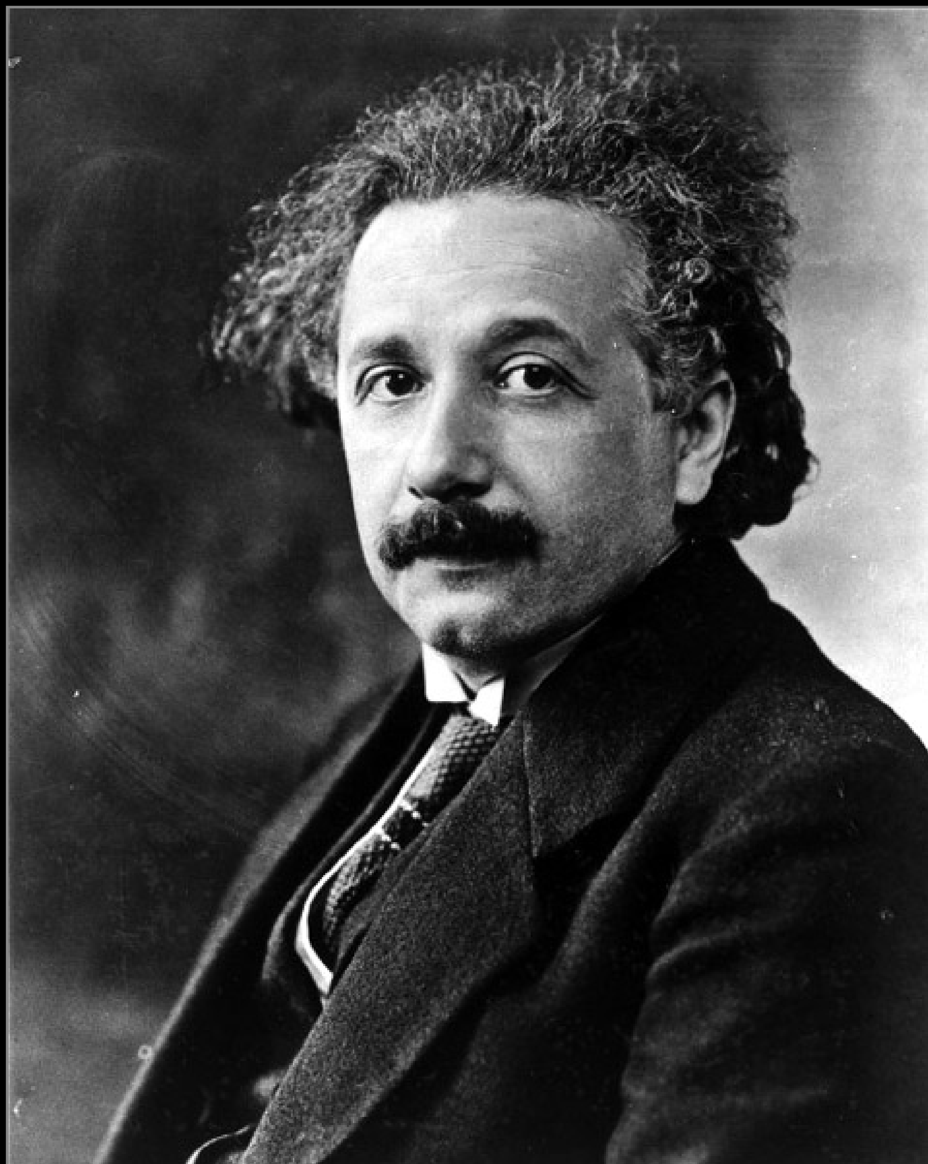






"I think and think for months and years.
Ninety-nine times, the conclusion is false.
The hundredth time I am right."

Albert Einstein

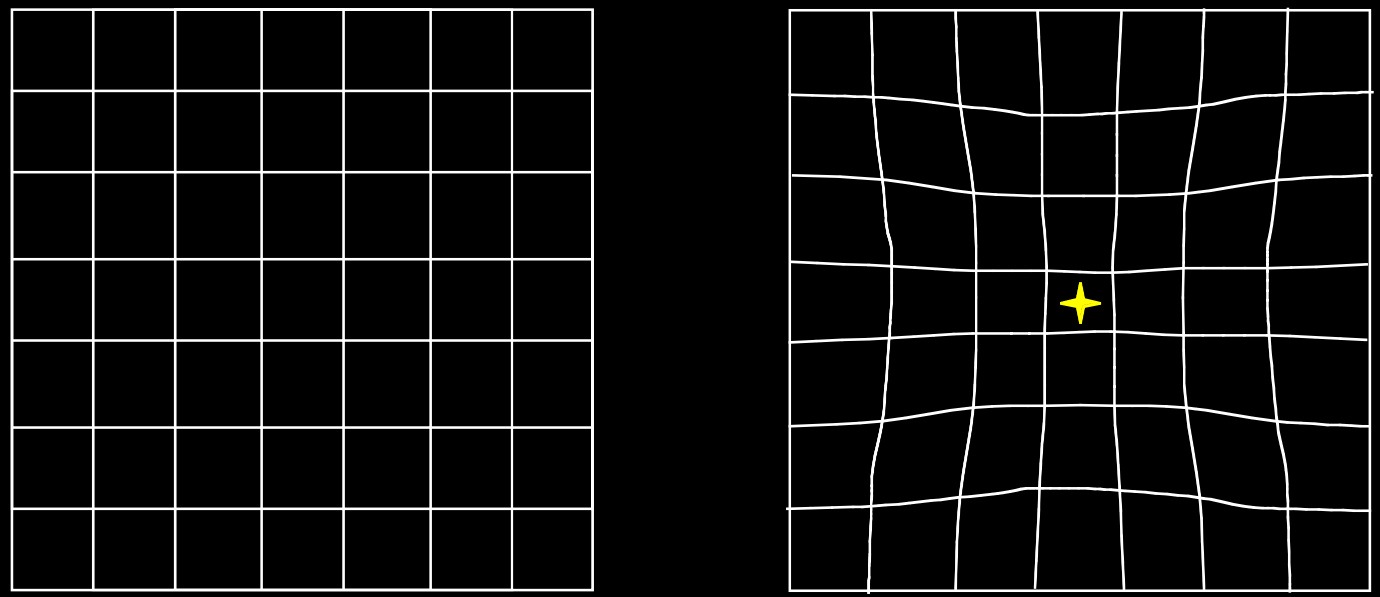


Albert Einstein
(1879–1955)

General Relativity

"Die Grundlage der allgemeinen Relativitätstheorie"
A. Einstein (1916)

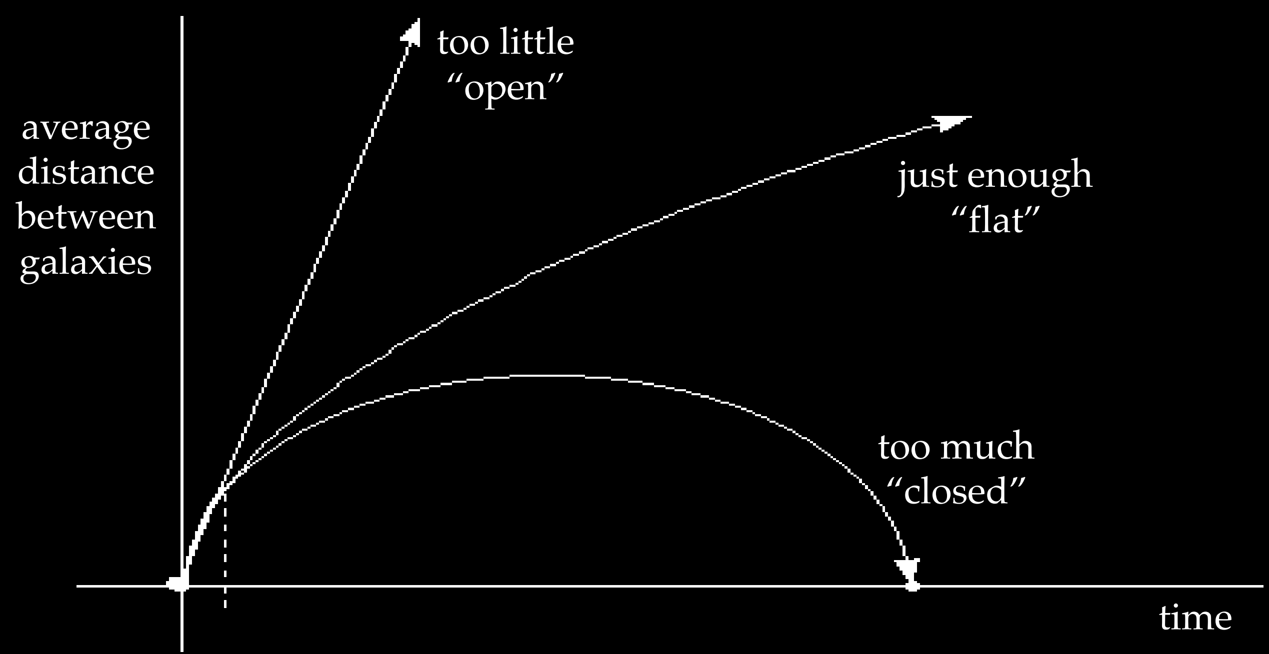
Gravity = Geometry of space-time



Gravity (energy/momentum of the stuff in the universe)

General Relativity & Cosmology

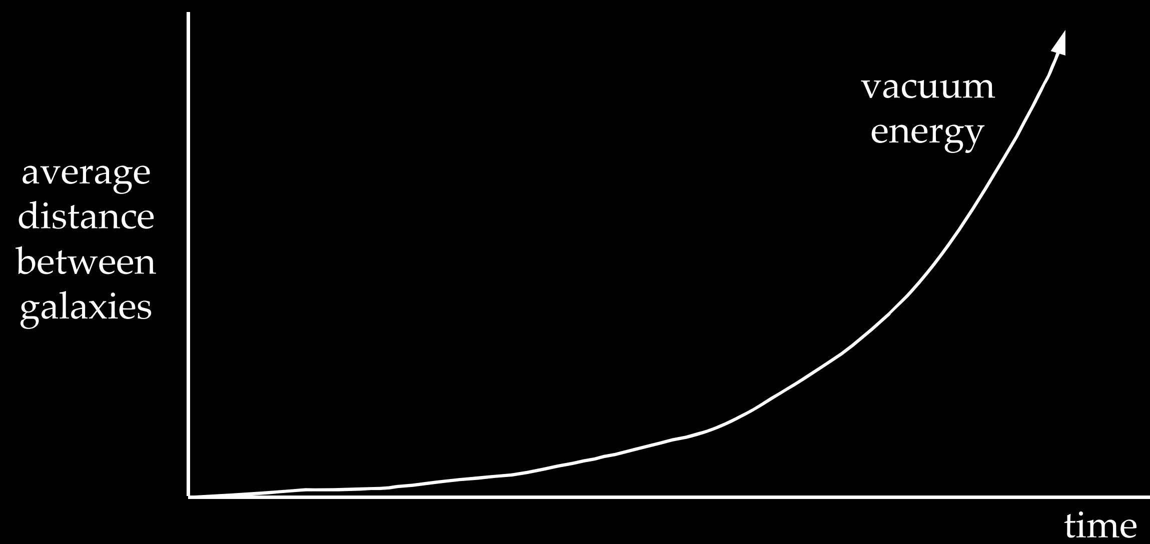
Given an initial impulse, space-time could expand
A. Friedmann (1922) – H.-G. Lemaître (1927)



matter or radiation ⇒ act to retard expansion

A Mysterious Ingredient

General Relativity also allows a self-repulsive material
W. de Sitter (1917)

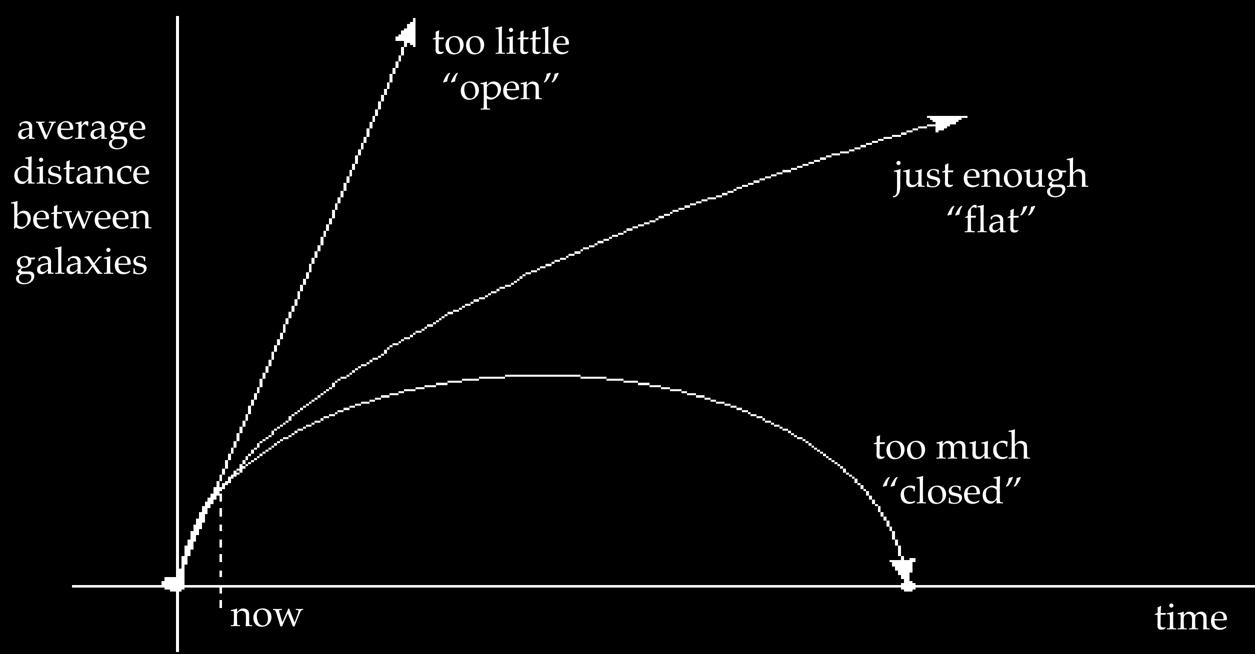


matter or radiation ⇒ act to retard expansion

"vacuum energy" (Λ) ⇒ acts to heighten expansion

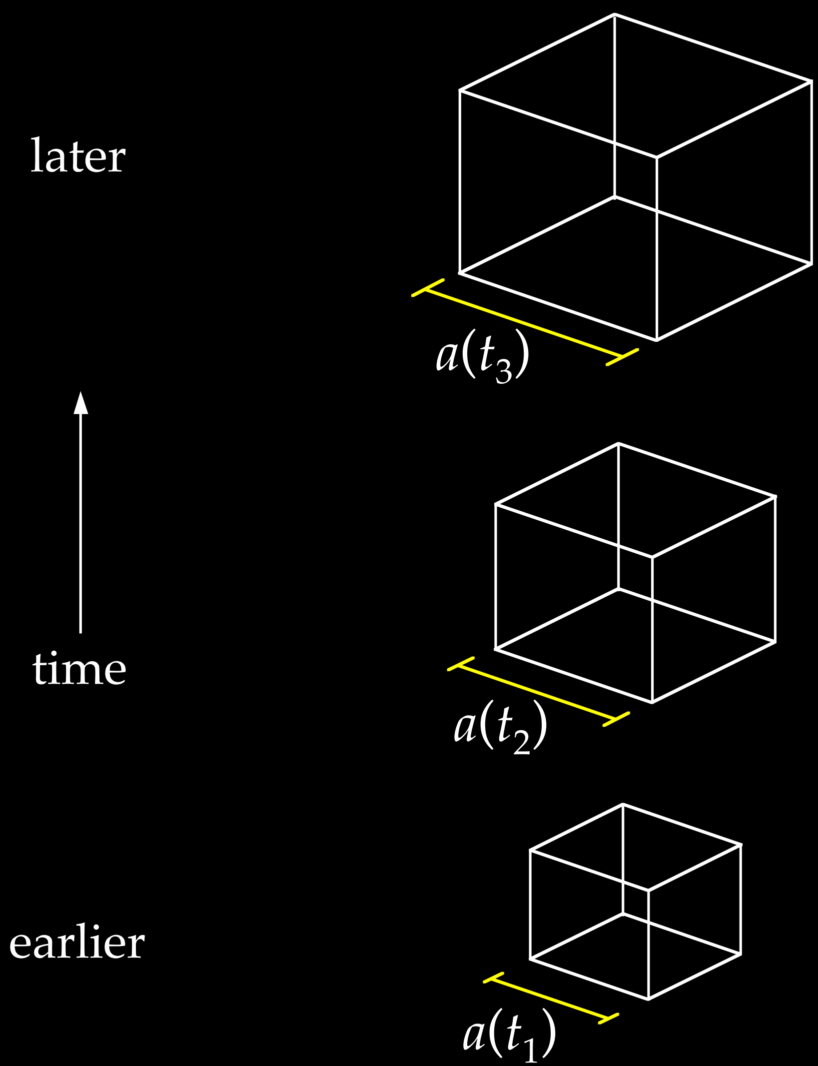
General Relativity & Cosmology

If the universe is expanding now,
then it must have been smaller in the past



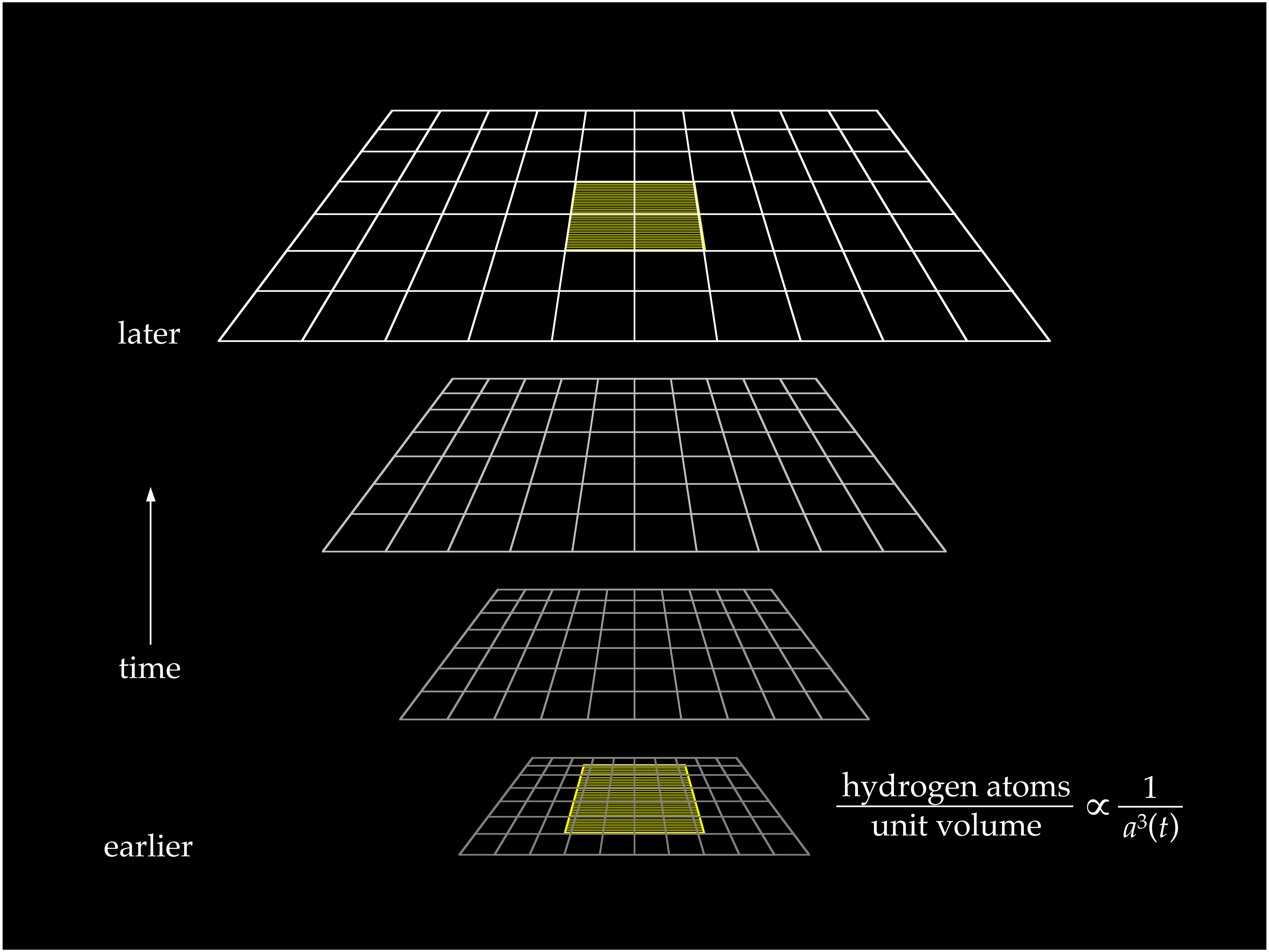
But space is not perfectly empty

The scale factor: $a(t)$



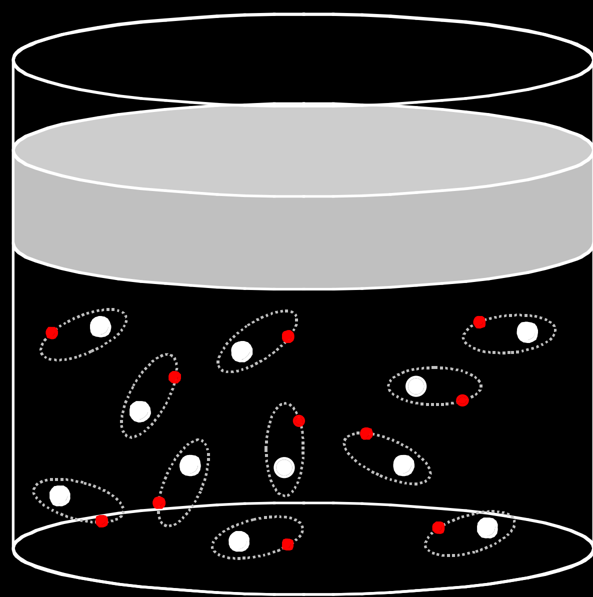
$a(t)$ = how much lengths change with time

What happens to the number of hydrogen atoms per unit volume as the universe evolves?


later
time
earlier
$\frac{\text{hydrogen atoms}}{\text{unit volume}} \propto \frac{1}{a^3(t)}$

What happens when you adiabatically compress a gas?

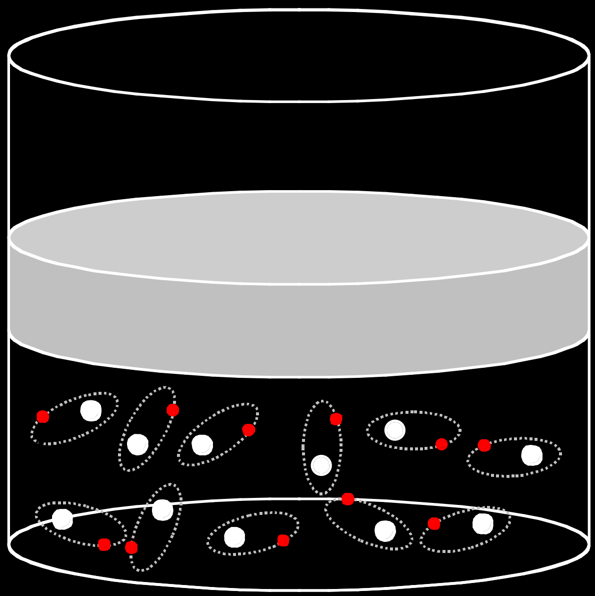
It gets denser and hotter



neutral hydrogen

What happens when you adiabatically compress a gas?

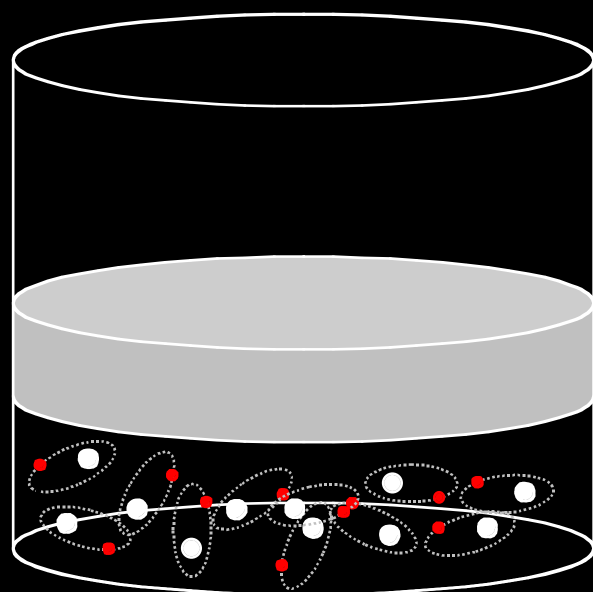
It gets denser and hotter



neutral hydrogen (hotter)

What happens when you adiabatically compress a gas?

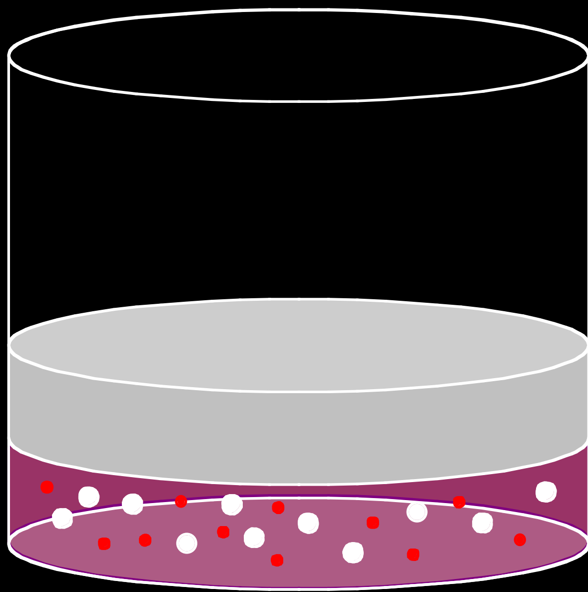
It gets denser and hotter



neutral hydrogen (still hotter)

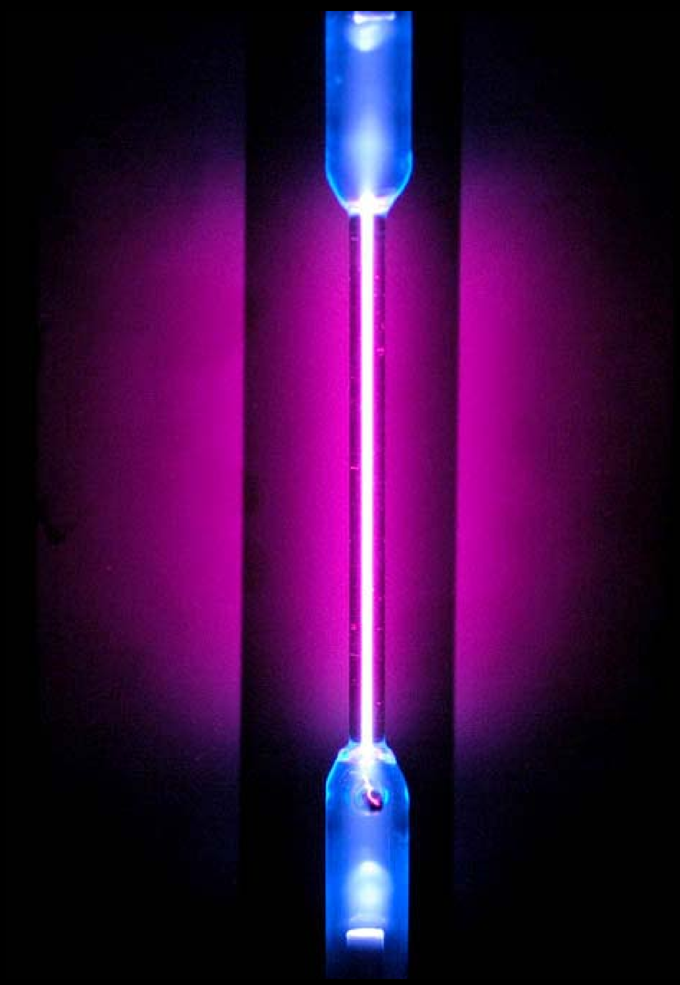
What happens when you adiabatically compress a gas?

It gets denser and hotter



a hydrogen plasma

What happens when you
adiabatically compress a gas?



So at some early stage,
the universe should have
been filled with a hot,
opaque gas

Where did the light go?

Oblers' Paradox Redux

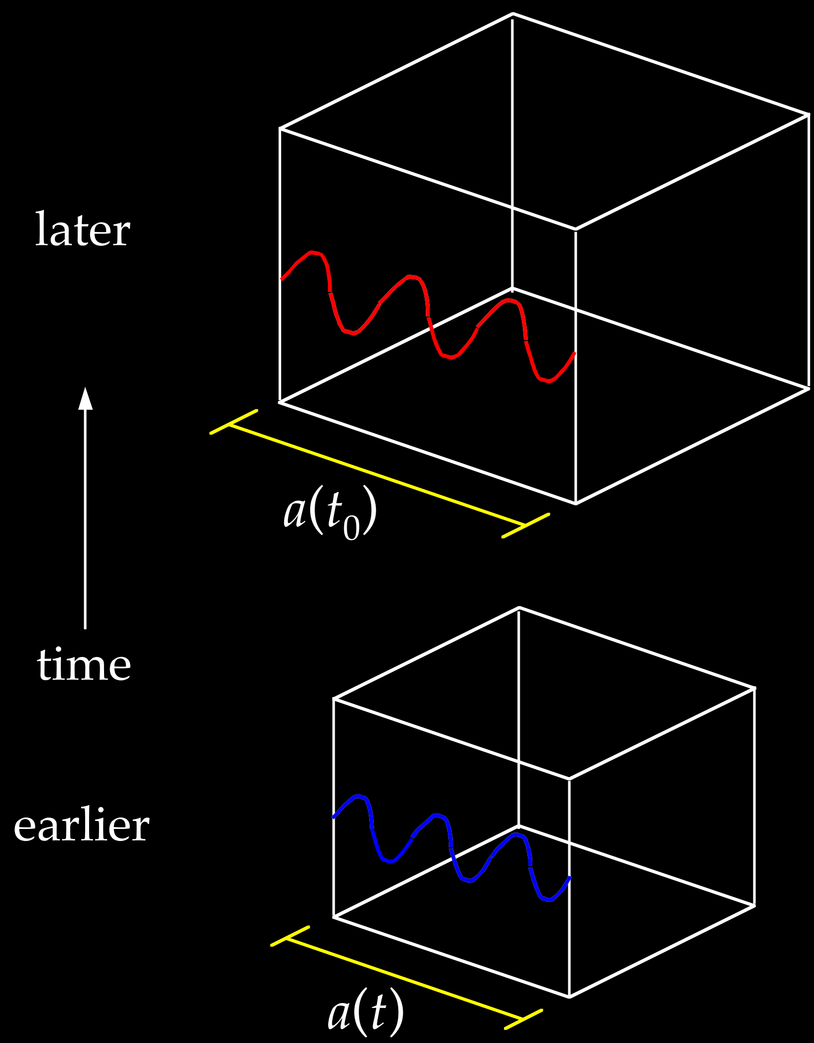
(or "Why isn't the night sky purple?")

Resolution:

1. Finite size?
   (the average density of stars far away falls off faster than $1/r^2$)
2. Finite time?
   (the universe had a beginning)
3. Dilution?
   (some additional effect weakens the light at great distances)

What happens to light in an expanding universe?

Gravitational redshifting



The wavelength (λ) of light is stretched by the expansion of space

$$\text{Energy}(t) = \frac{h}{\lambda(t)}$$

$$= \frac{h}{\lambda(t_0)} \frac{a(t_0)}{a(t)}$$

$$= \frac{a(t_0)}{a(t)} \text{Energy}(t_0)$$

$$\text{temperature}(t_0) = \frac{a(t)}{a(t_0)} \text{temperature}(t)$$

Prediction!

Lemaître (1931), Tolman (1934), Alpher & Gamow

1. If general relativity is correct and

2. If the universe has been expanding since its "beginning"

The universe should be filled with
a cold, faint relic glow left
when the early plasma cooled
and became transparent —

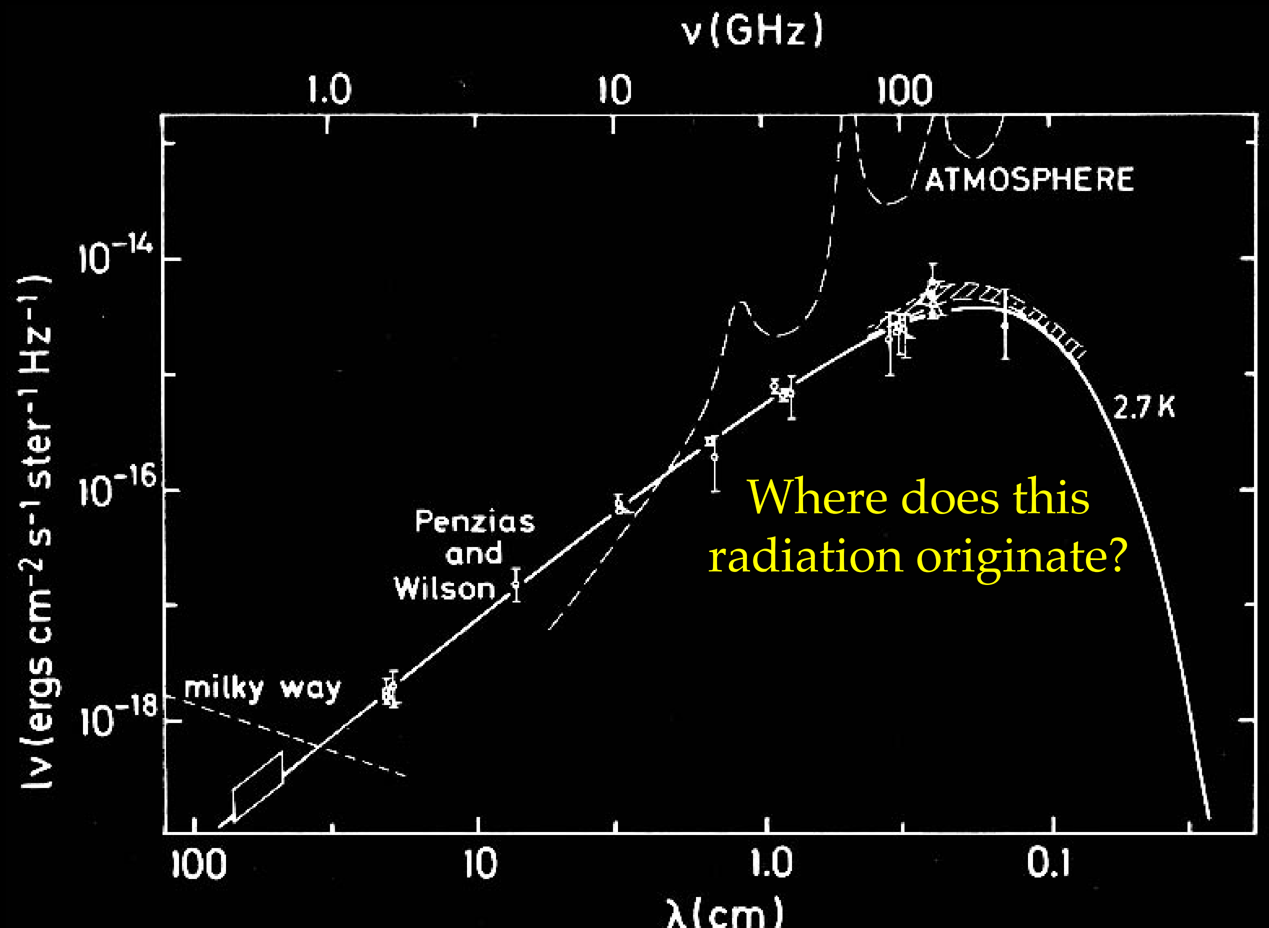
The Cosmic Microwave Background (CMB) Radiation

"There is nothing like looking, if you want to find something. You certainly usually find something, if you look, but it is not always quite the something you were after."

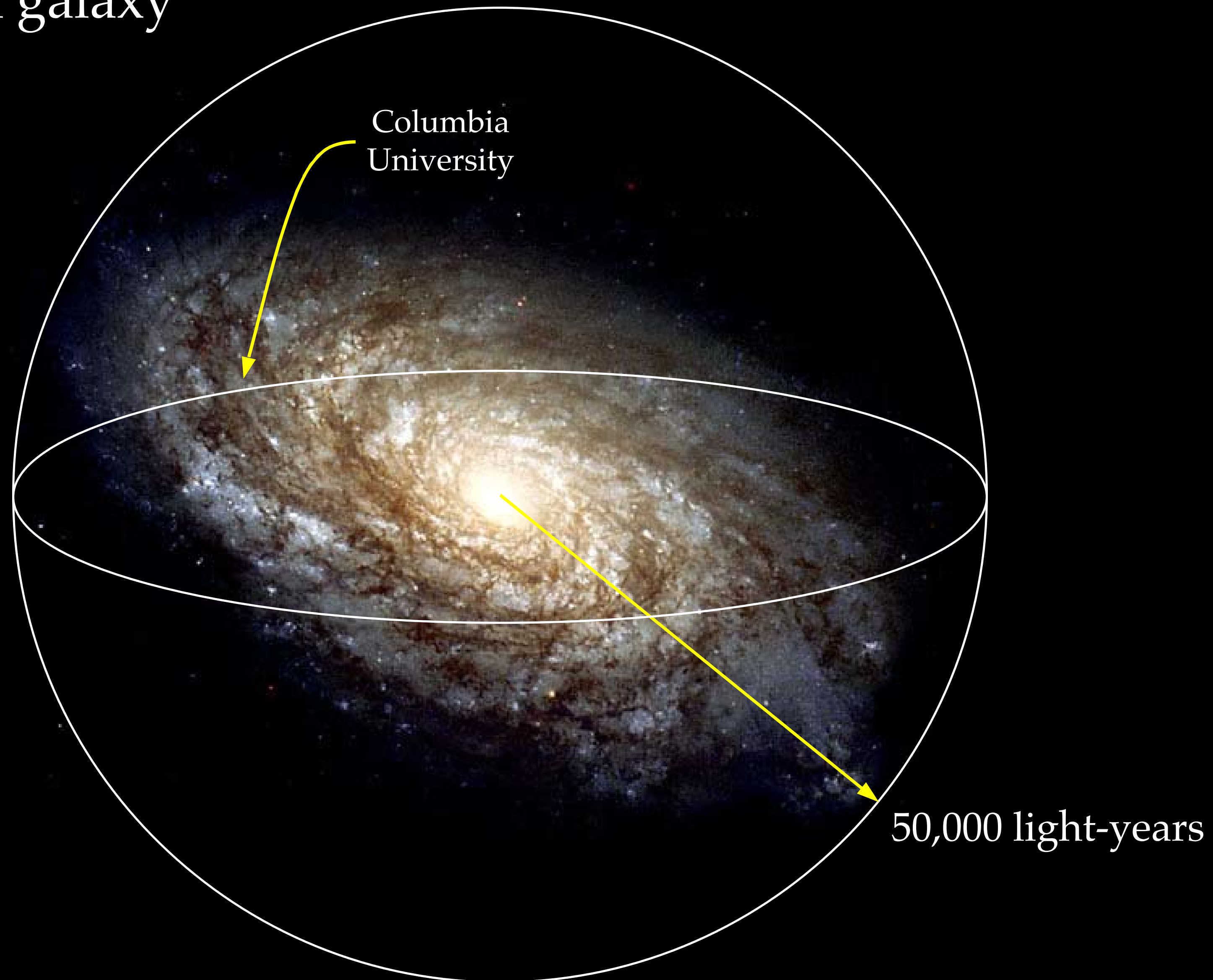
J. R. R. Tolkien

Penzias and Wilson's Discovery
(1965)

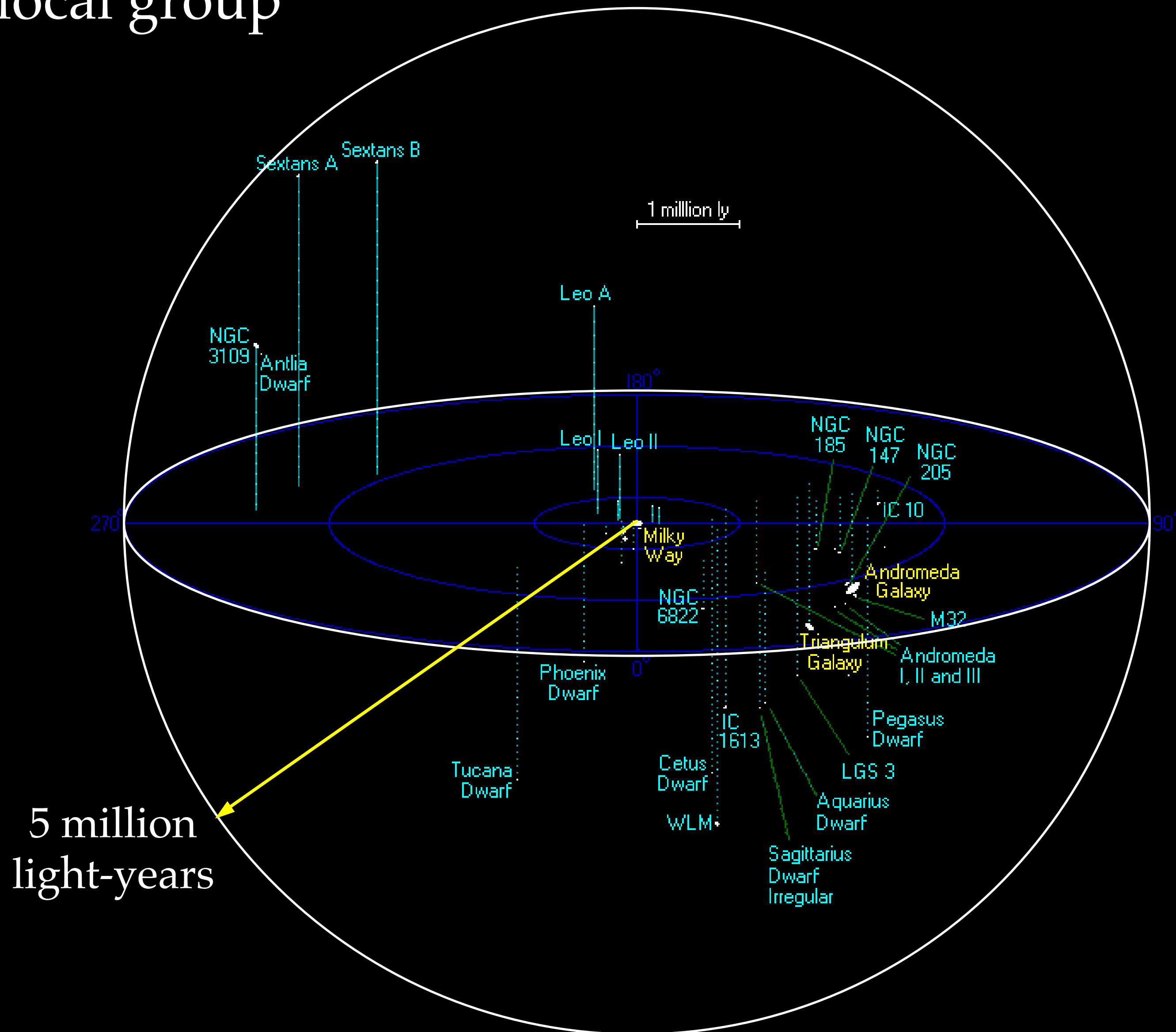
The universe is filled with the faint radiation
of a 2.7 K (nearly) perfect blackbody



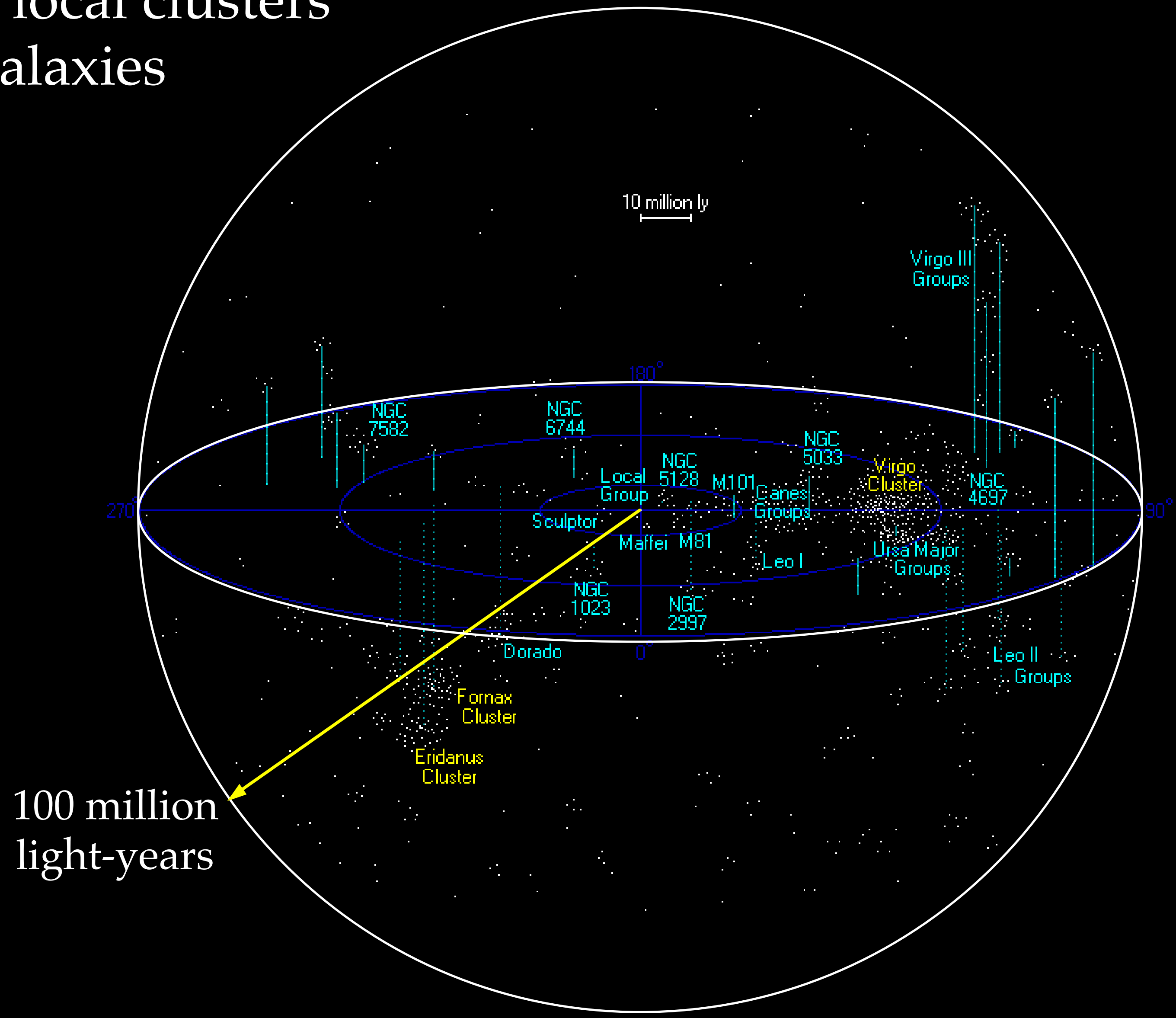
Our own galaxy



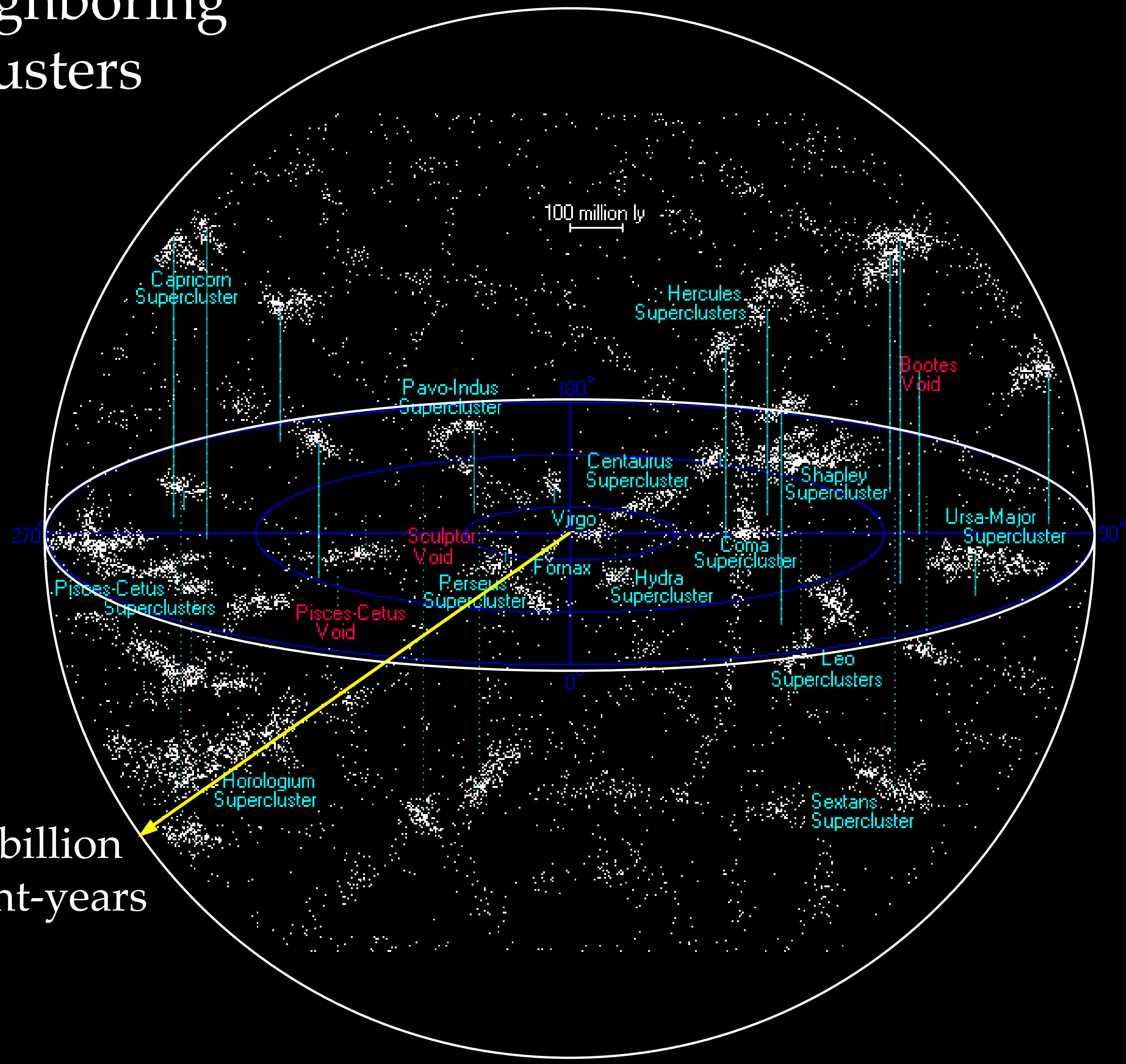
The local group

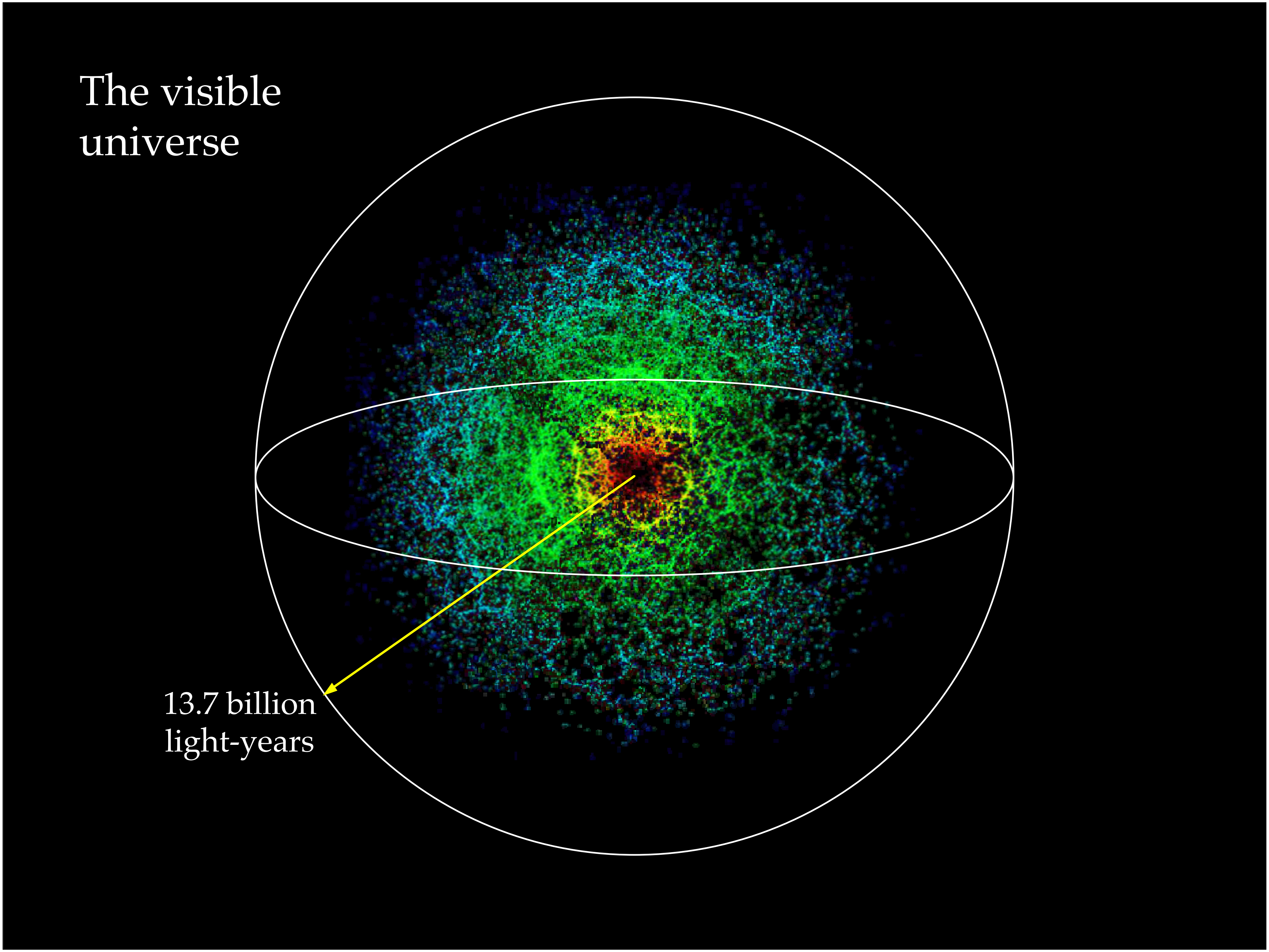


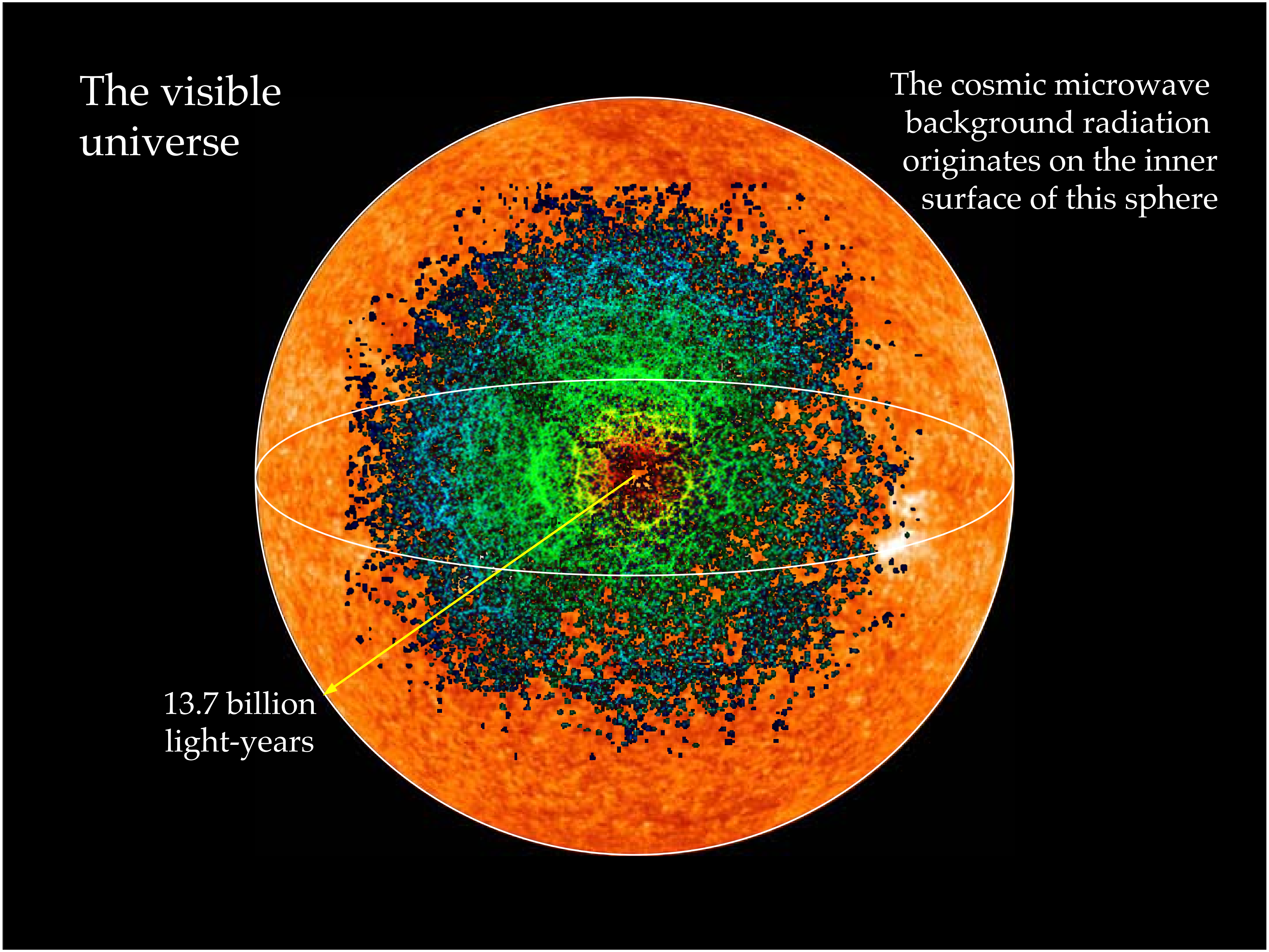
The local clusters of galaxies



The neighboring superclusters



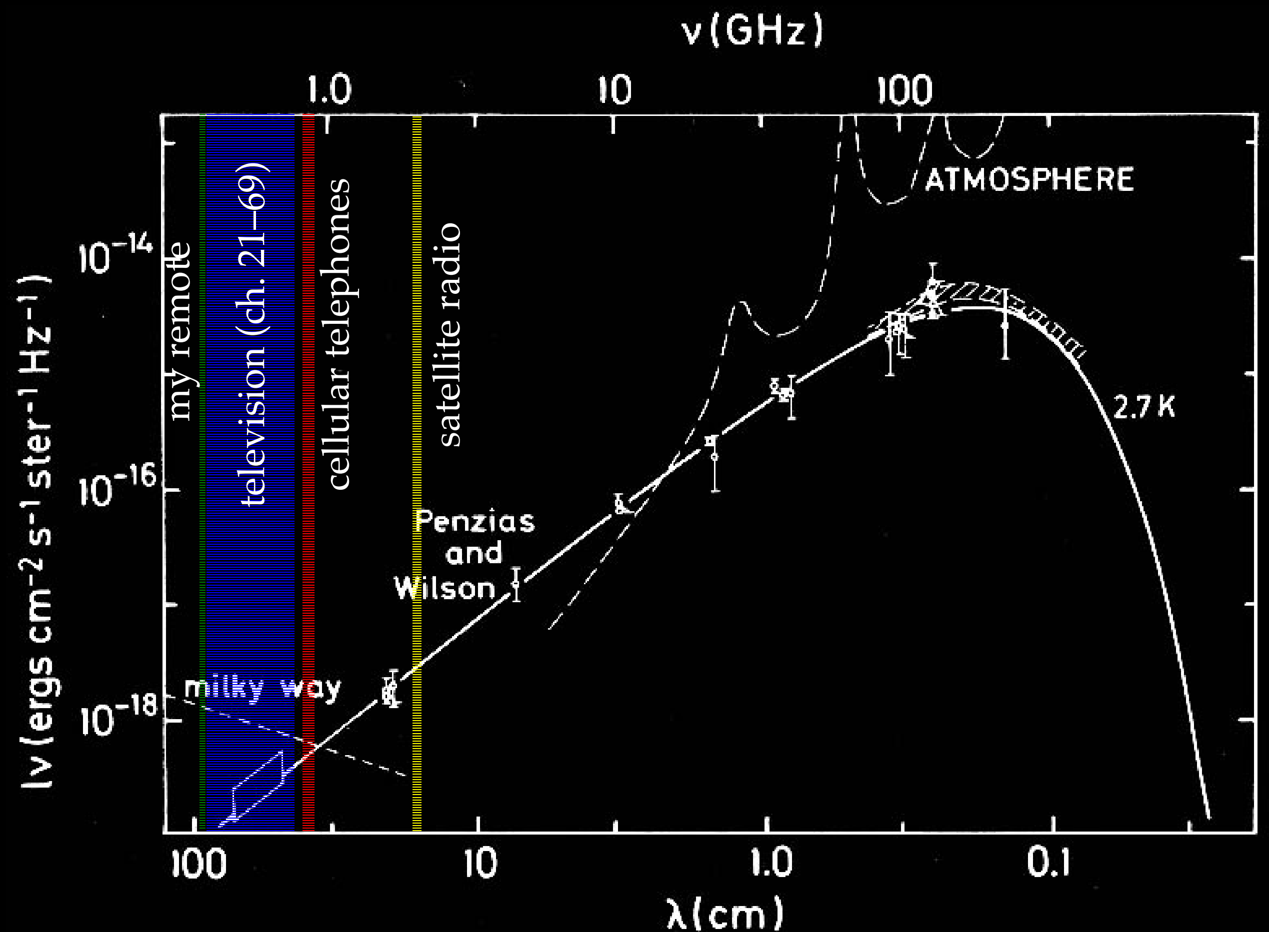

The visible
universe
13.7 billion
light-years


The visible universe
The cosmic microwave background radiation originates on the inner surface of this sphere
13.7 billion light-years

Penzias and Wilson's Discovery

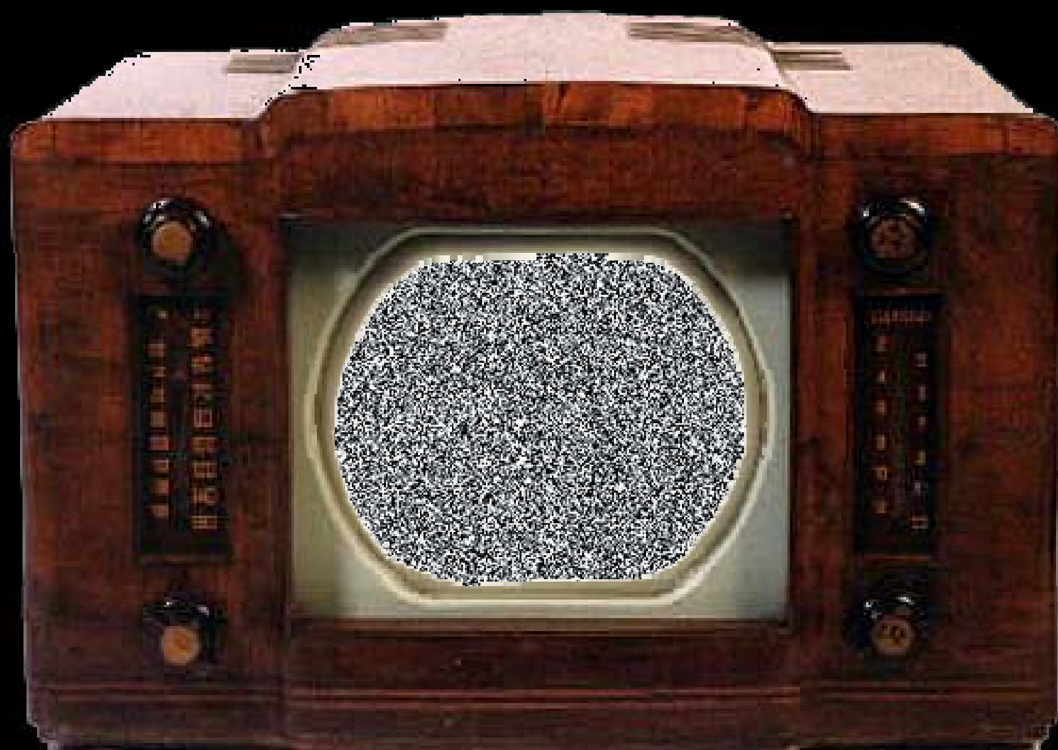
(1965)

The universe is filled with the faint radiation
of a 2.7 K (nearly) perfect blackbody

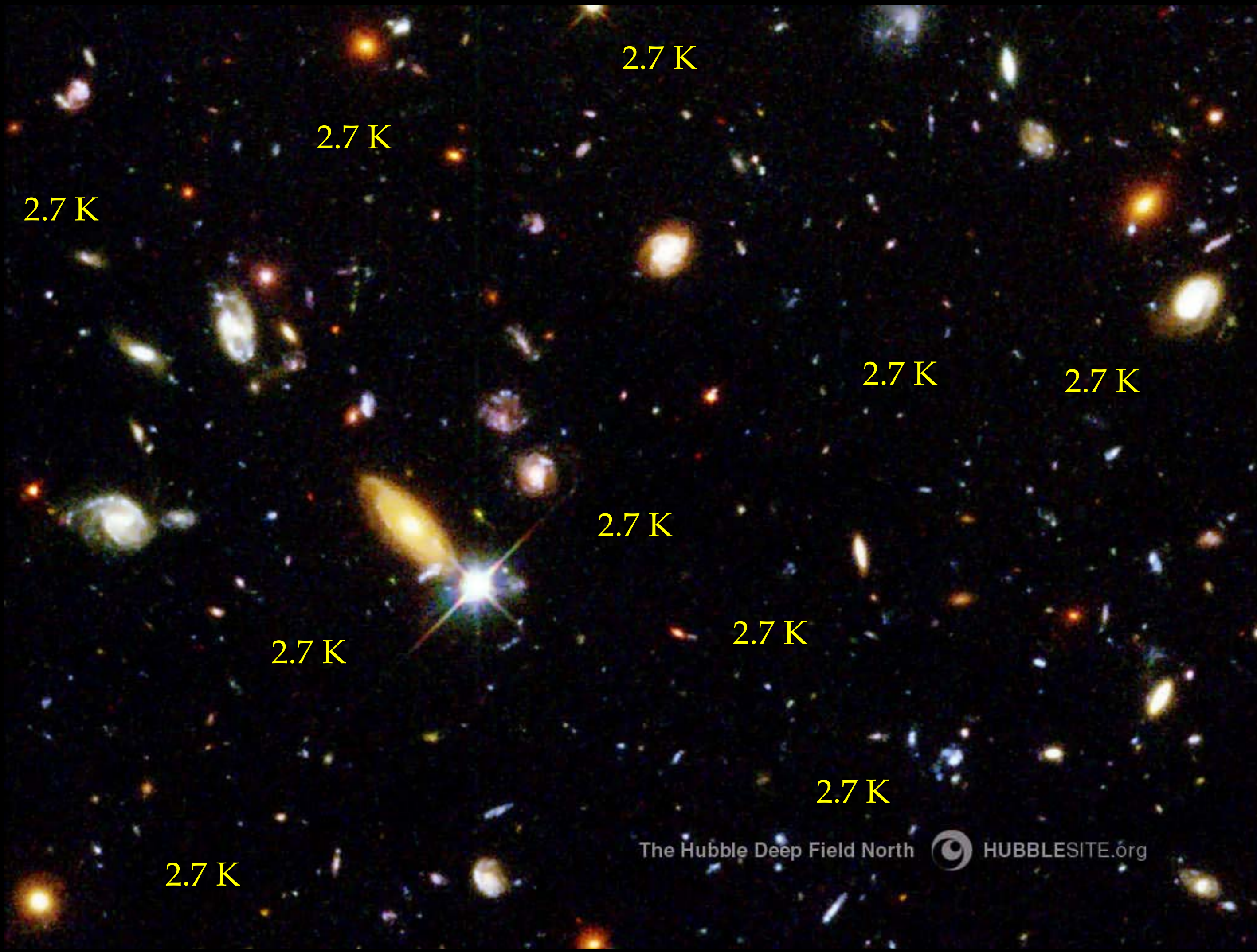


A Homemade CMB Detector

About 1% of the noise on an old television
set is due to that cosmic radiation



Where did it all come from?

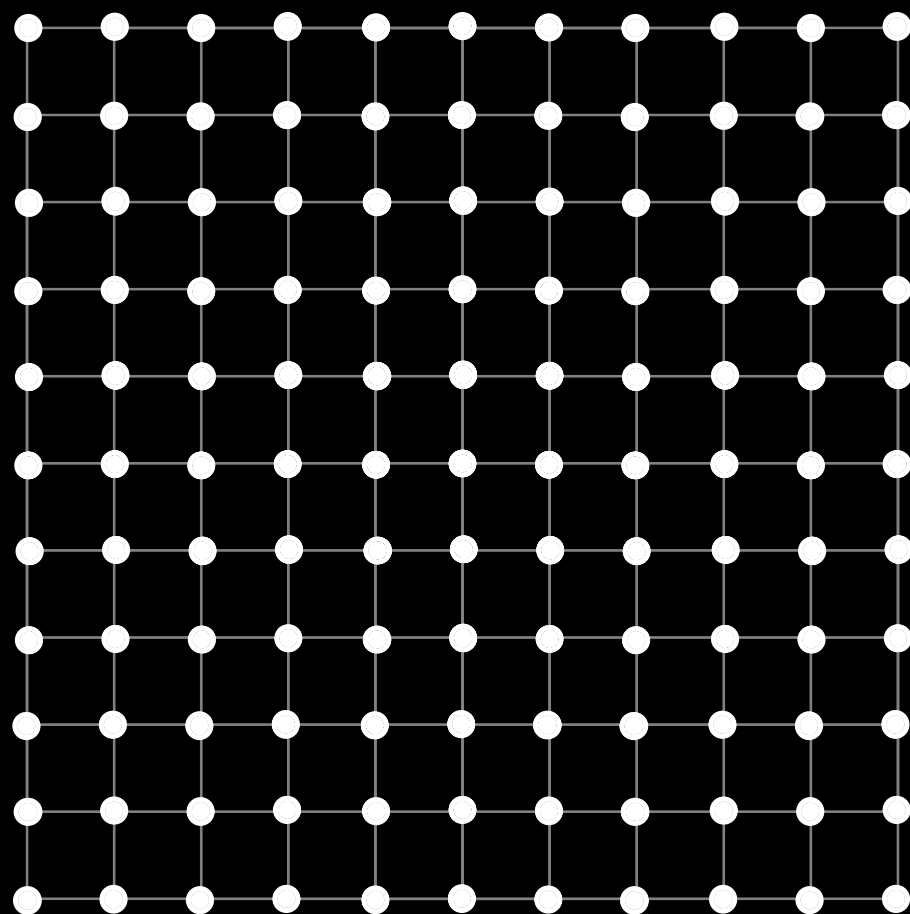


"Faultily faultless, icily regular, splendidly null,
Dead perfection, no more. . ."

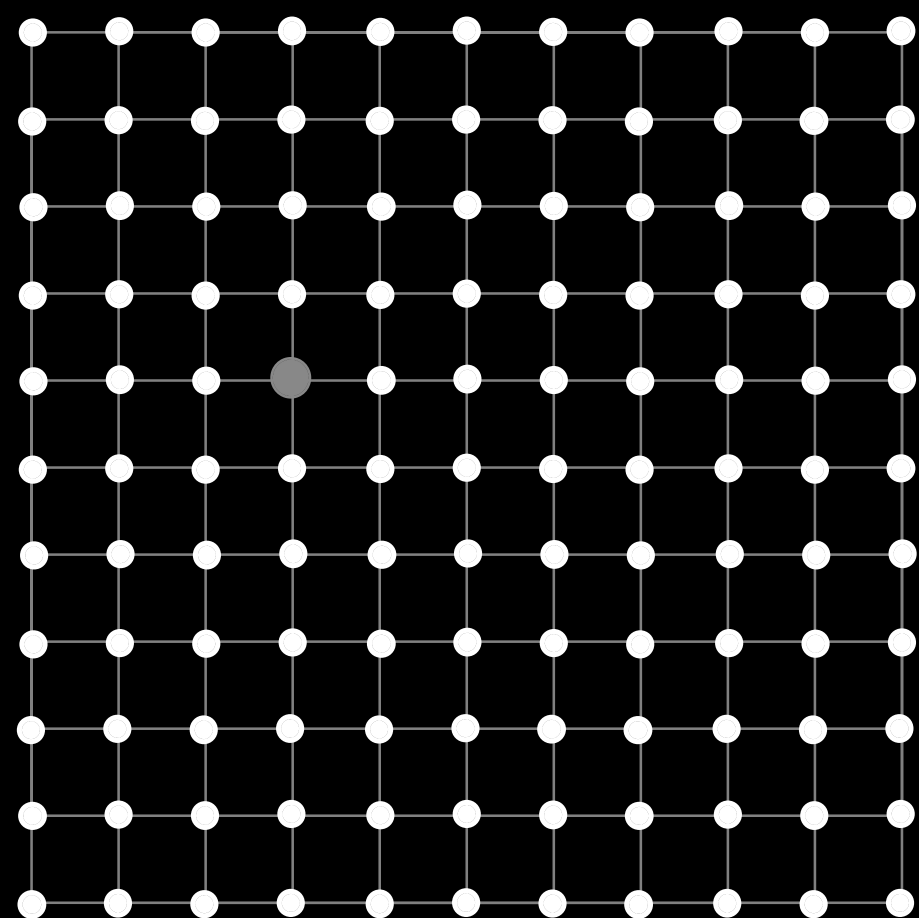
Alfred Tennyson

(from *Maud*)

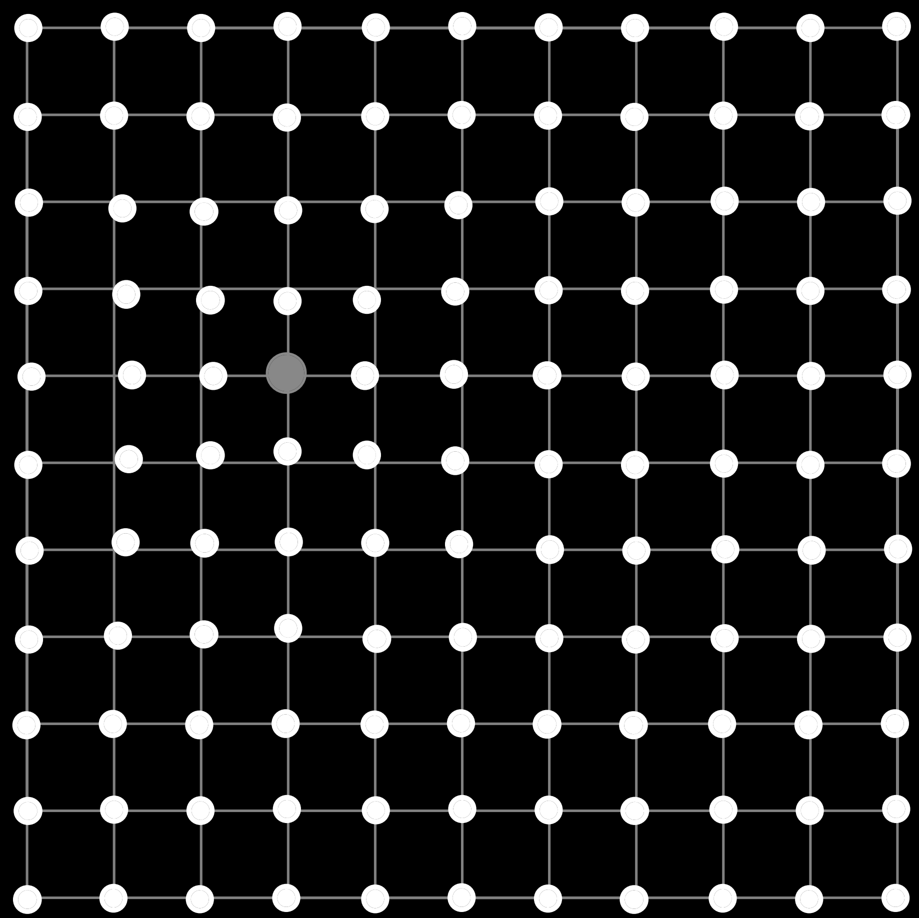
Too much symmetry is a bad thing



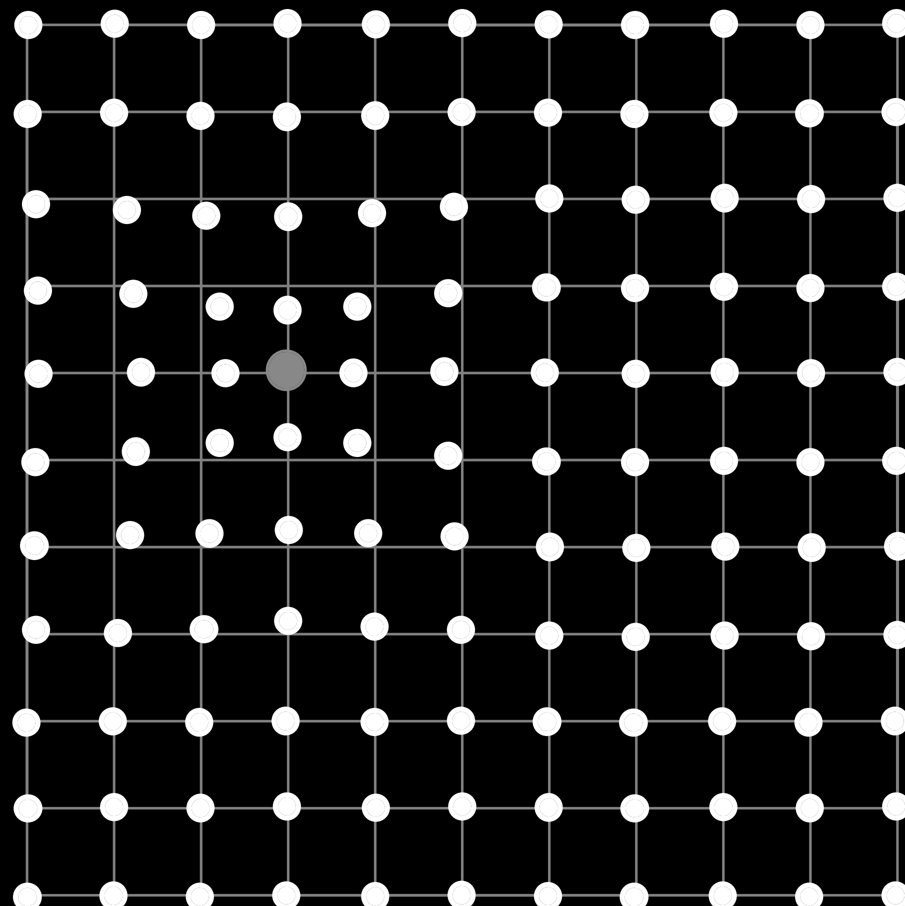
But little asymmetry can be good



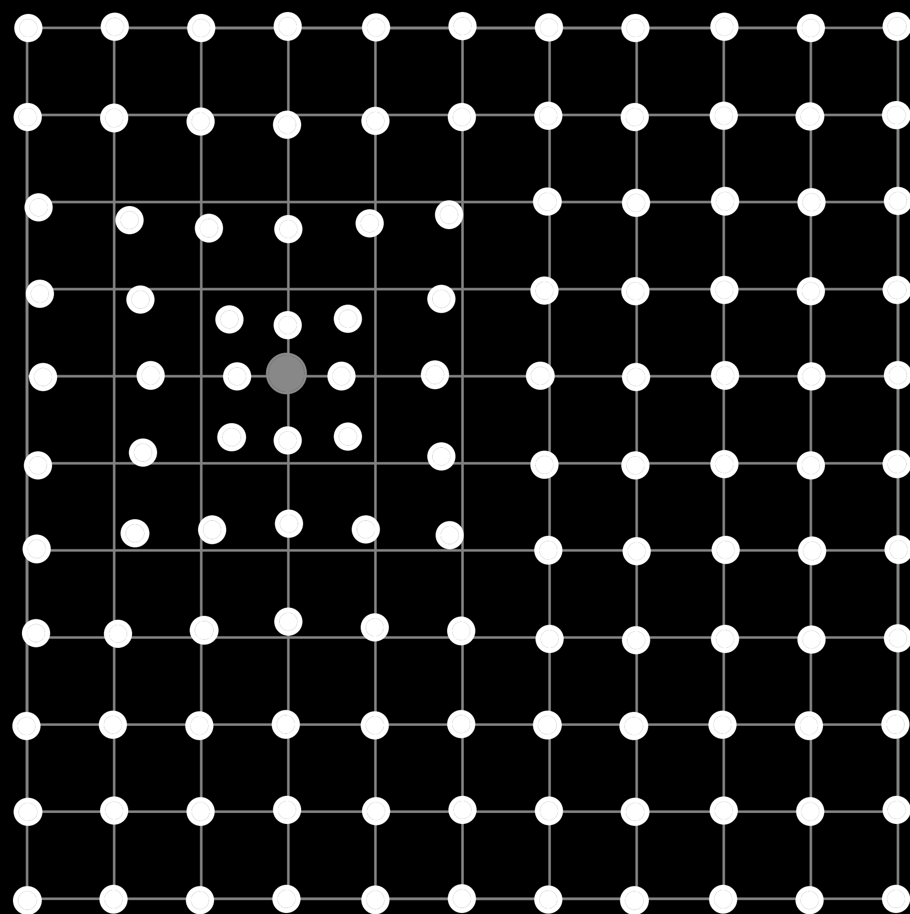
But little asymmetry can be good



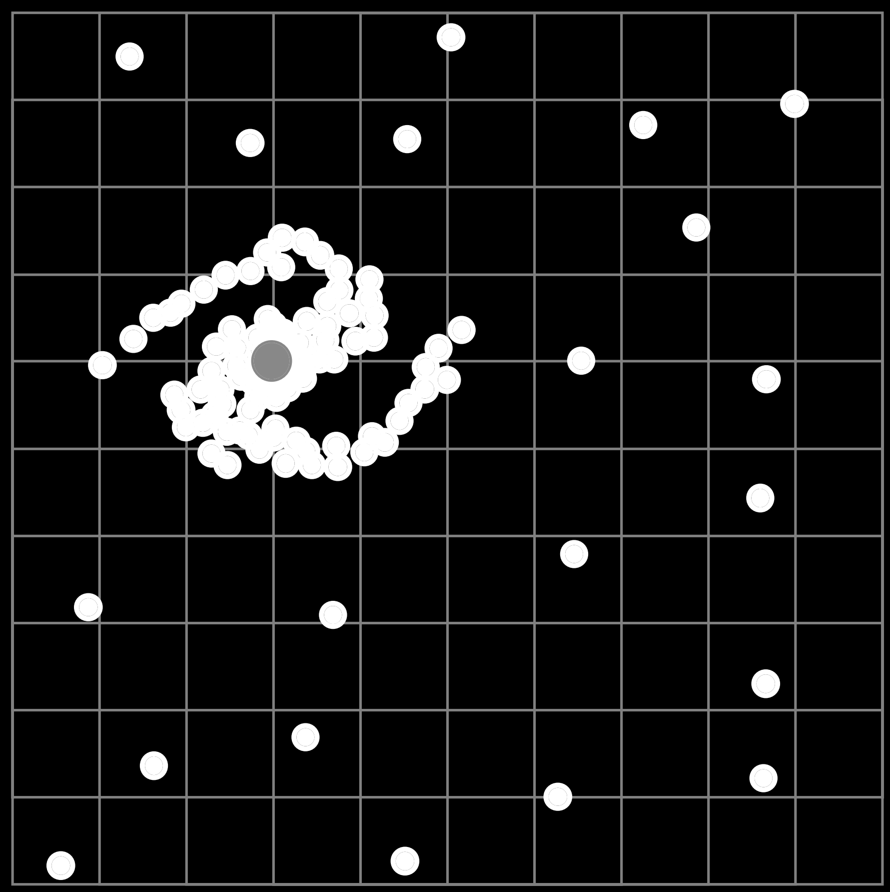
But little asymmetry can be good



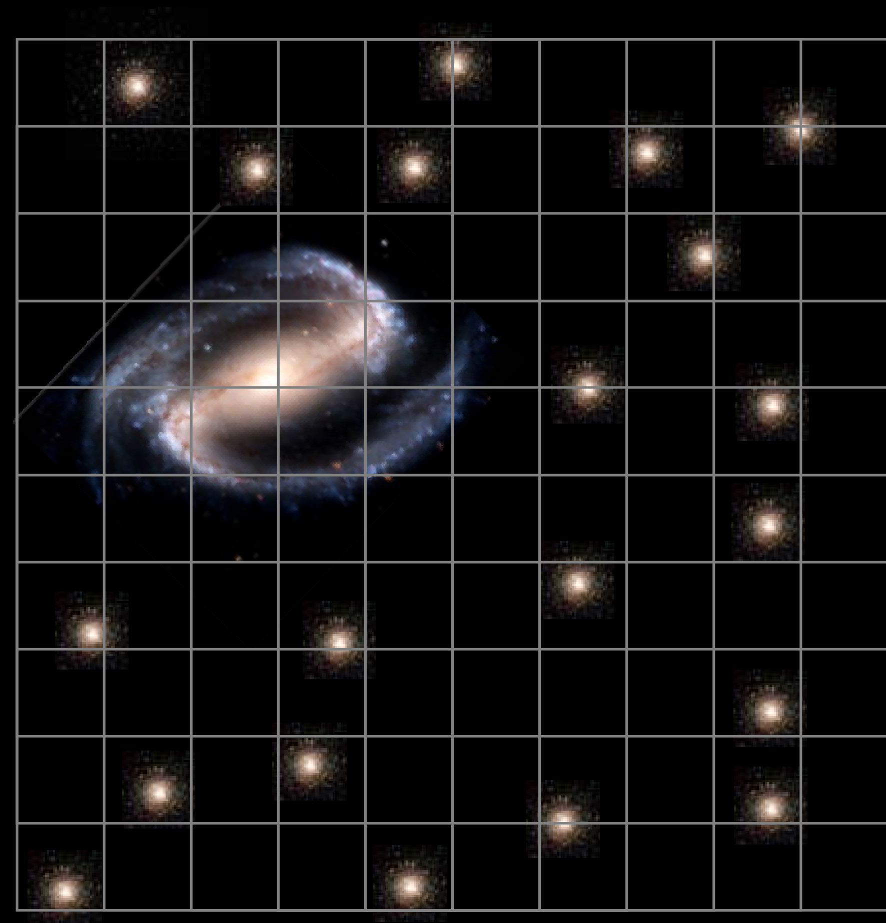
But little asymmetry can be good



Gravity causes little asymmetries to become big asymmetries



Gravity causes little asymmetries
to become big asymmetries



How uniform is the Cosmic Background?

From 1965 to the beginning of the 1990's,
the faint relic radiation looked perfectly uniform

But the asymmetries that grew into stars and galaxies
and clusters of galaxies had to be there in the
microwave background

With gravity and time, the tiniest of asymmetries
(a part in 100,000) would have been enough

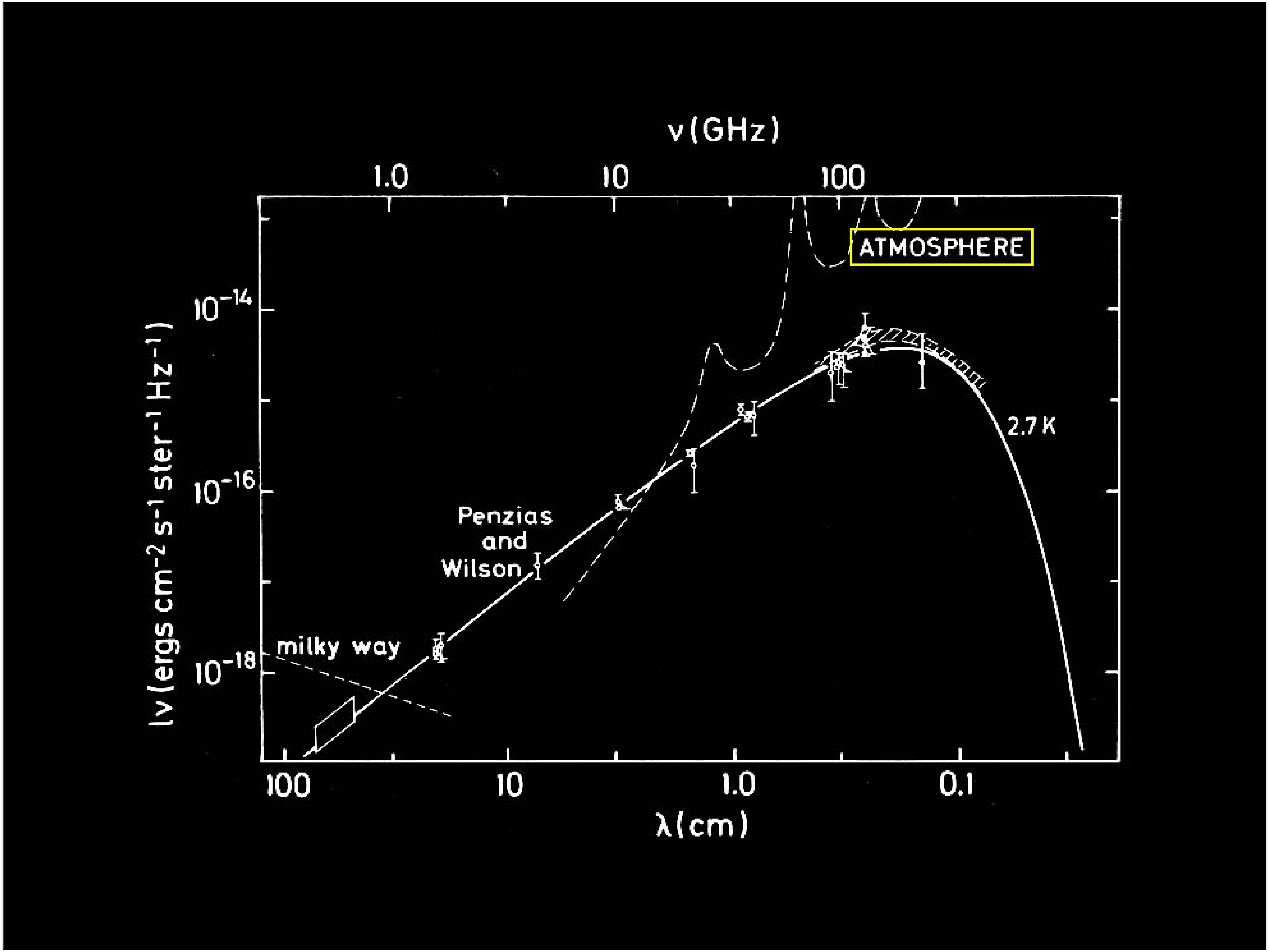
Prediction!

1. If general relativity is correct and

2. If the stars and galaxies formed from tiny asymmetries

The cold, faint relic glow left when the early plasma cooled and became transparent should not be perfectly uniform

Measure the temperature of the cosmic background very carefully


ν (GHz)
1.0
10
100
ATMOSPHERE
Iν (ergs cm^{-2} s^{-1} ster^{-1} Hz^{-1})
10^{-14}
10^{-16}
10^{-18}
2.7 K
Penzias and Wilson
milky way
100
10
1.0
0.1
λ (cm)

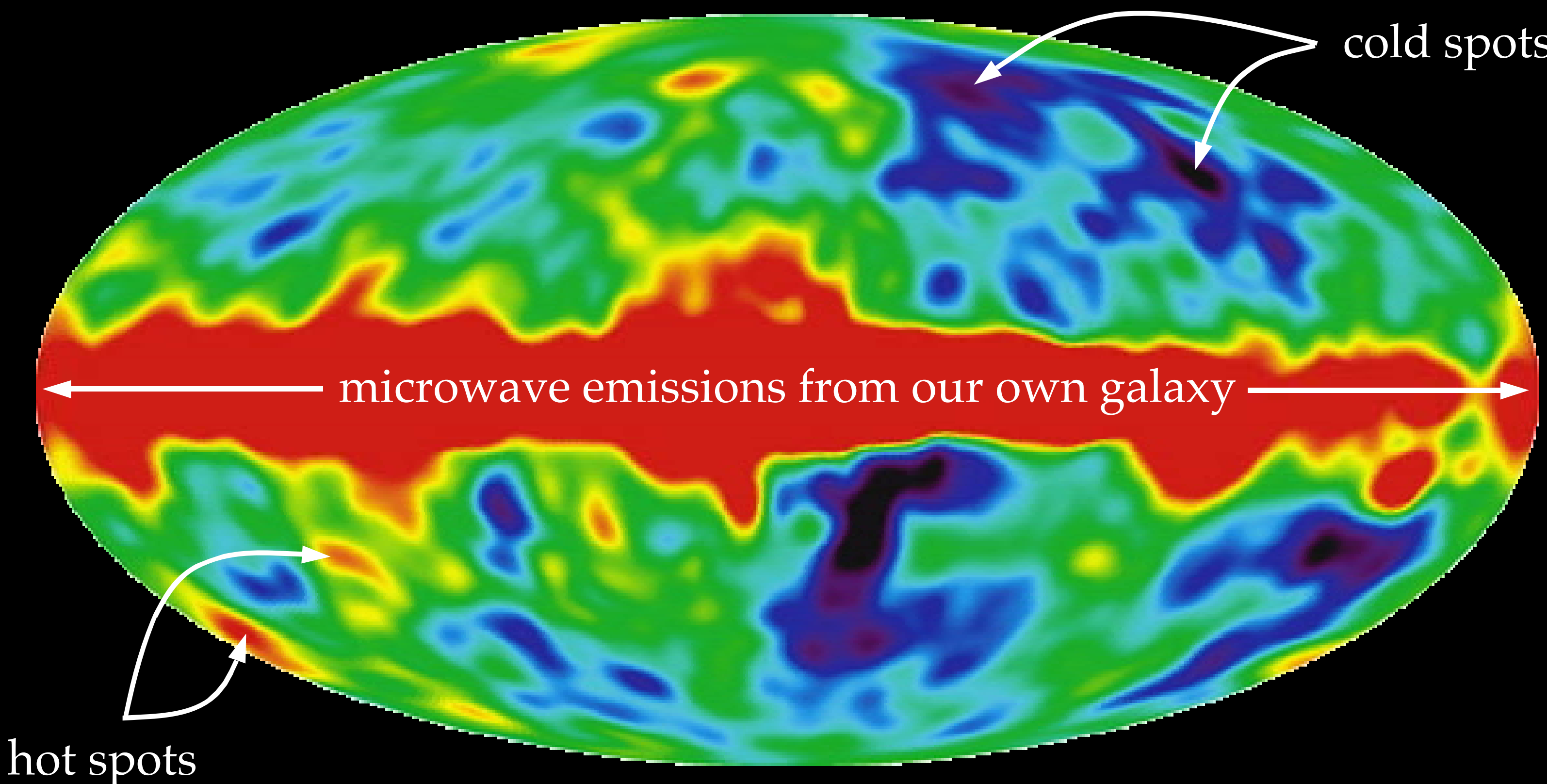
The COsmic Background Explorer (COBE)

launched November 18, 1989

COBE's Discovery

(ca. 1992 – launched in 1989)

Saw small variations of the temperature of the CMB in different parts of the sky

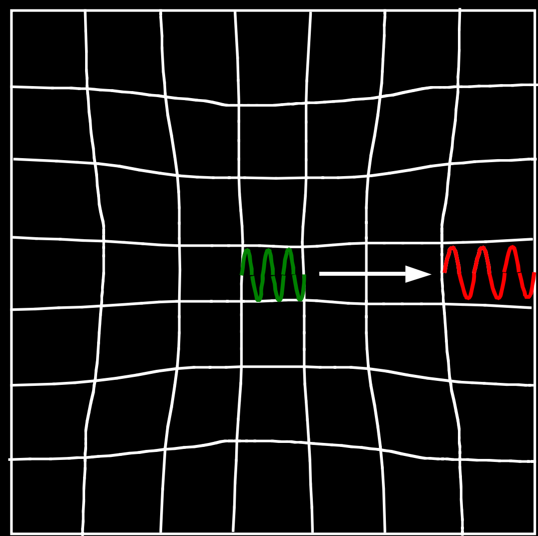


COBE's temperature map of the sky (only 7° resolution)

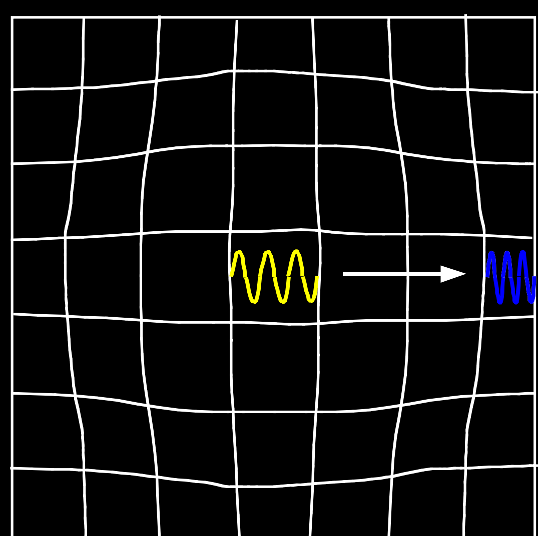
What makes the hot and cold spots?

Two competing effects —

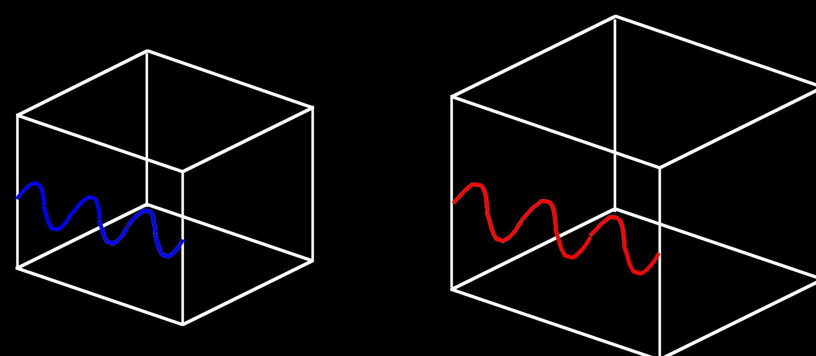
1. A more (less) dense region is hotter (colder)
2. But light cools (warms) as it emerges from a more (less) dense region



dense region



thin region

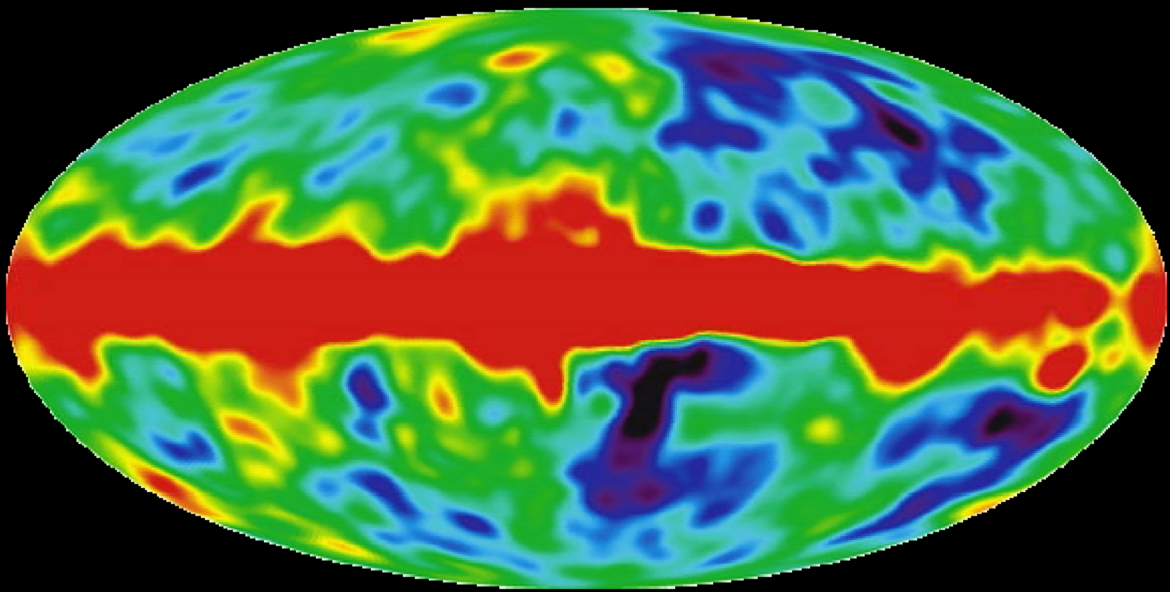


gravitational redshifting

Beyond COBE
(1990's)

COBE told us that our basic picture of the universe was right

complicated structures growing gravitationally from a very uniform early plasma



COBE's temperature map of the sky (only 7° resolution)

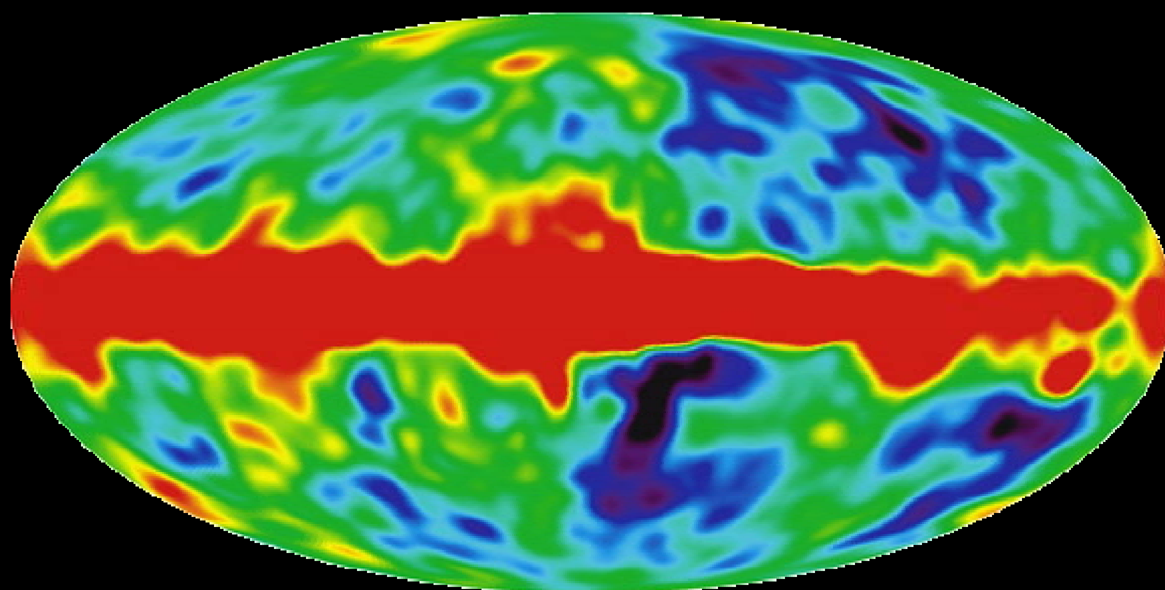
Beyond COBE
(1990's)

Can we do better?

1. how did the asymmetries arise?
2. what is the shape of the universe?
3. what composes the universe?
4. are we missing something?

more resolution

ordinary matter,
dark matter,
radiation

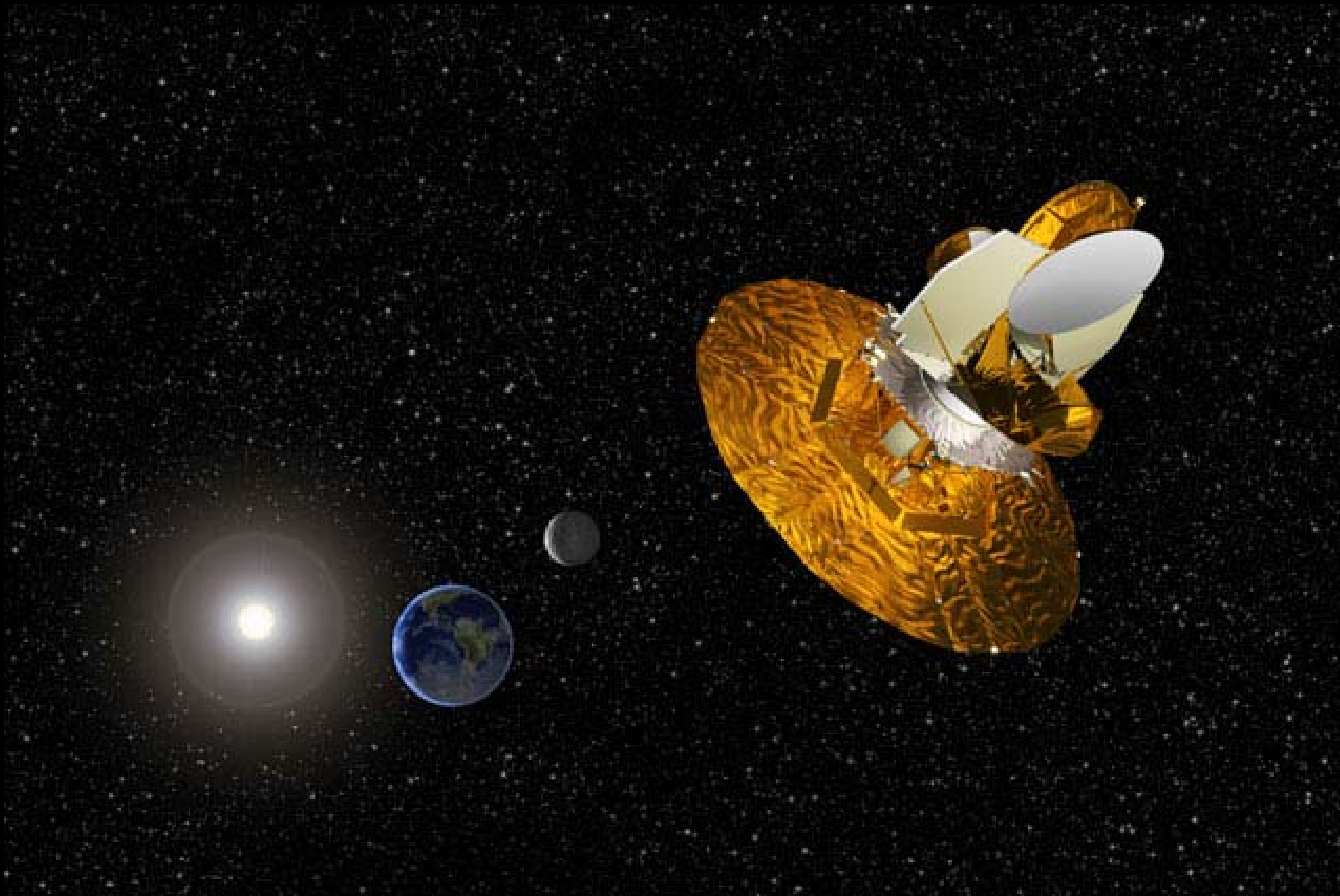


COBE's temperature map of the sky (only 7° resolution)

"Anything you can do, I can do better.
I can do anything better than you."

Irving Berlin

(from *Annie Get Your Gun*)



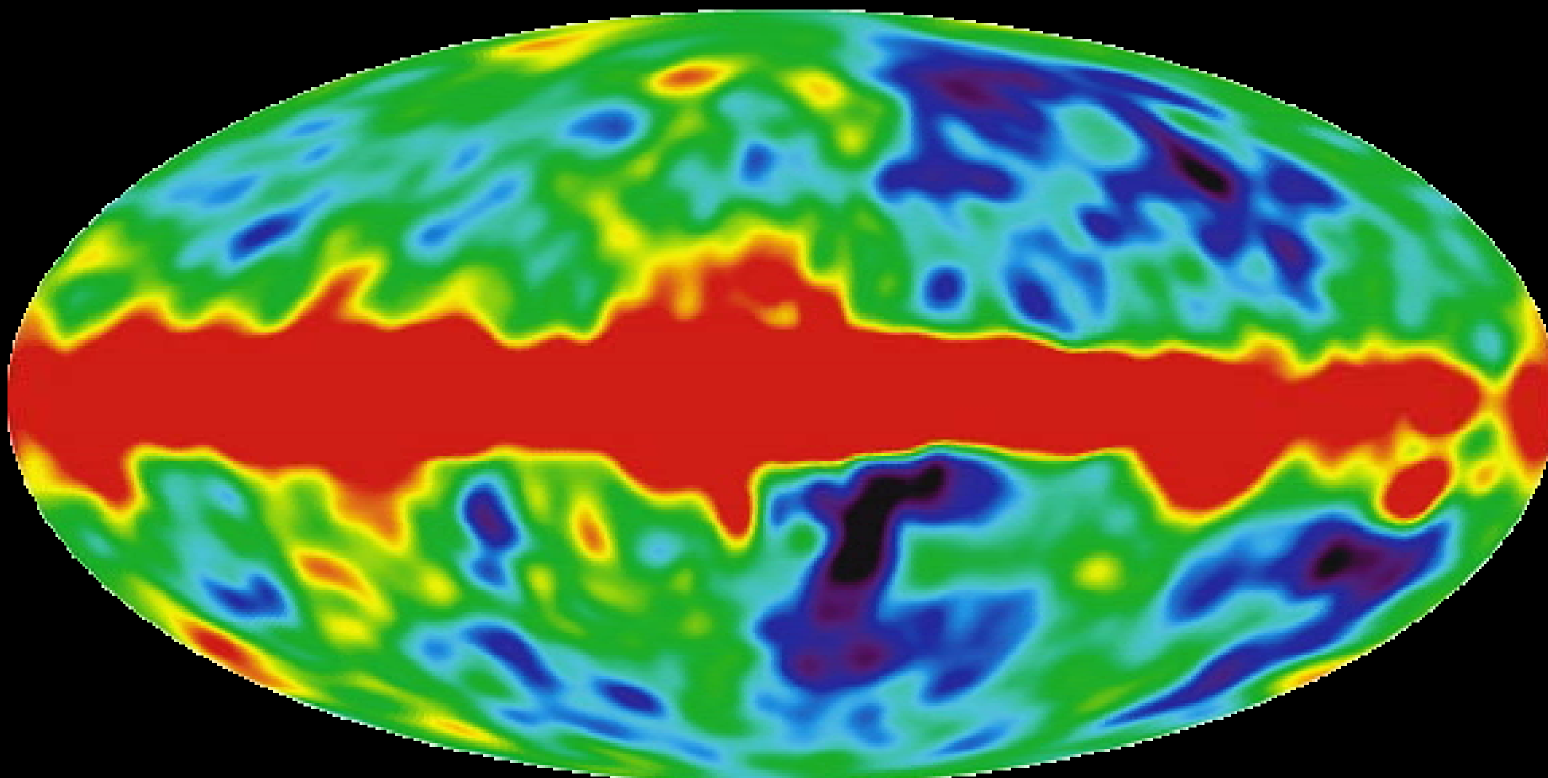
Wilkinson Microwave Anisotropy Probe (WMAP)

launched June 30, 2001

WMAP's Discovery

(2003 – ongoing)

Precisely measured the temperature and polarization of the earliest relic light

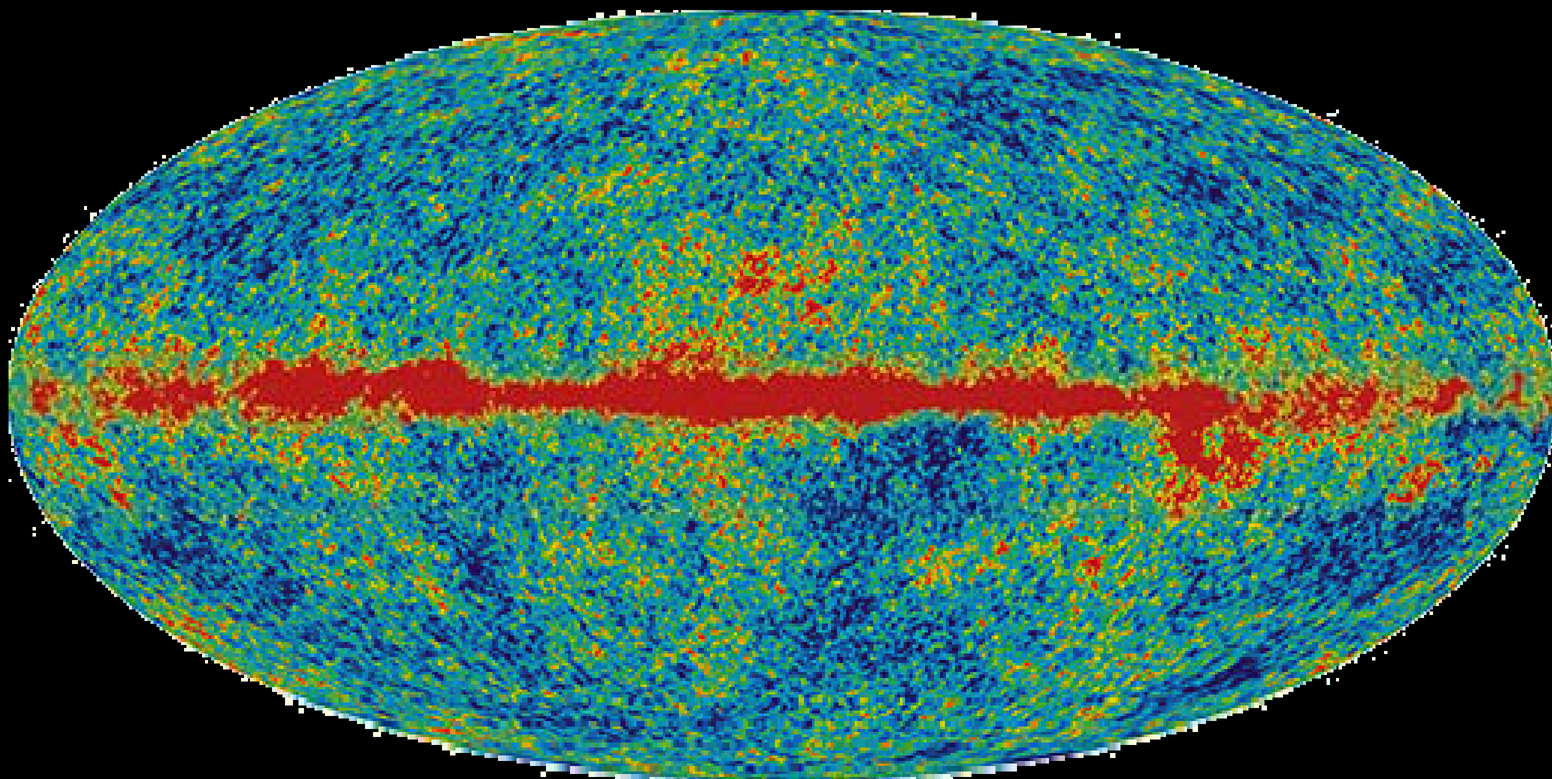


COBE's temperature map of the sky (only a 7° resolution)

WMAP's Discovery

(2003 – ongoing)

Precisely measured the temperature and polarization of the earliest relic light

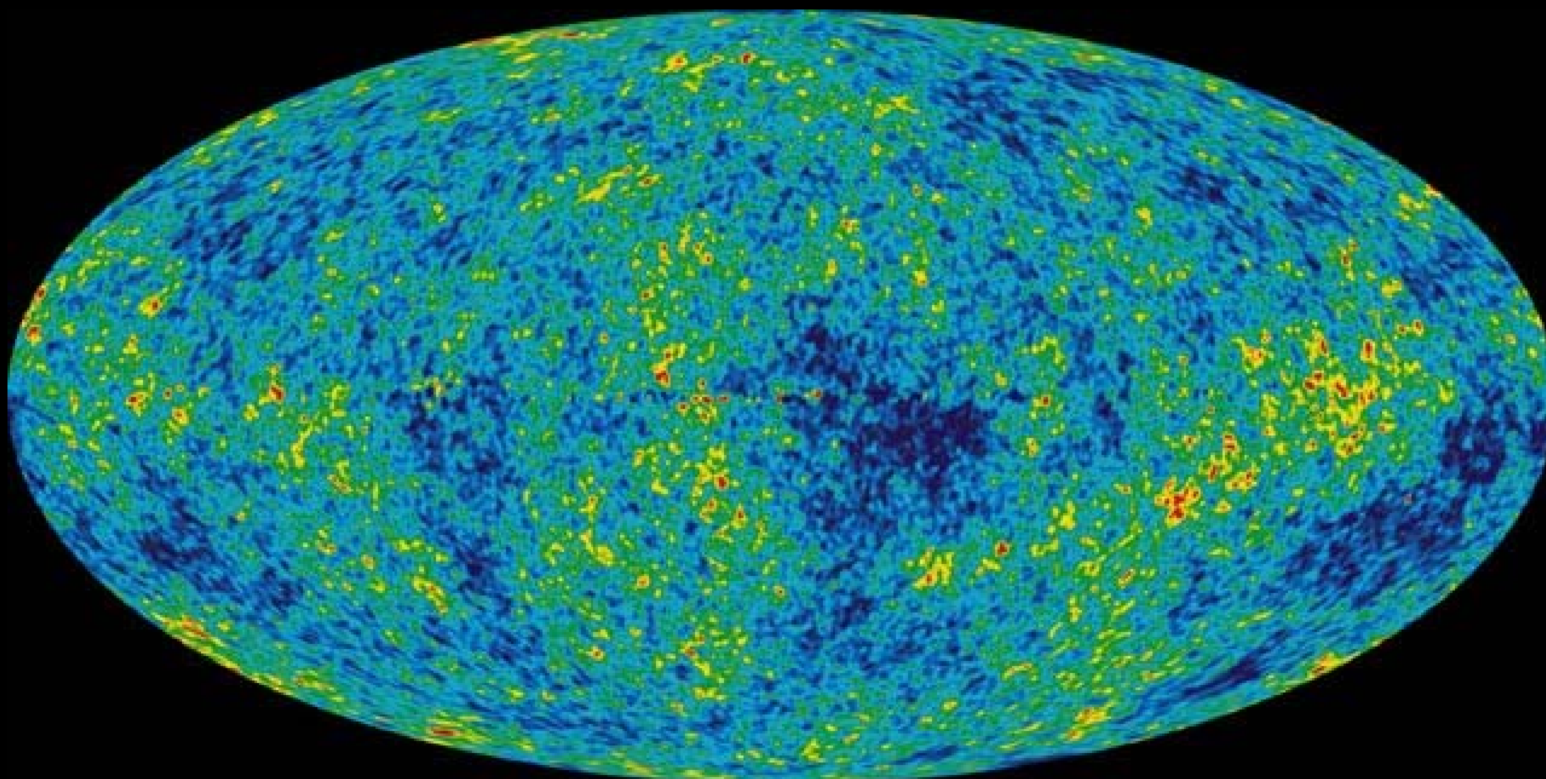


WMAP's temperature map of the sky (about a 0.2° resolution)

WMAP's Discovery

(2003 – ongoing)

Precisely measured the temperature and polarization of the earliest relic light



WMAP's temperature map of the sky (about a 0.2° resolution)

WMAP's Discoveries
(2003 – ongoing)

1. The universe is $13.73^{+0.13}_{-0.17}$ billion years old

2. The first stars formed 13.3 billion years ago

3. The universe is flat (just enough ± 2 %)

4. The universe is made of
   a) dark energy: 72 %
   b) dark matter: 24 %
   c) ordinary matter: 4 %

5. The entire universe is filled with distortions of space (nearly featureless noise)

6. Many further discoveries

“ ‘And – and – what comes next?’
‘Oh, yes, yes, what the dickens
does come next? *C’est la question,
ma très chère demoiselle!’ ”*

Thomas Mann

(from *Buddenbrooks*)

Open Questions

1. What is the dark matter?

2. What is the dark energy?

3. What made those primordial distortions of space?

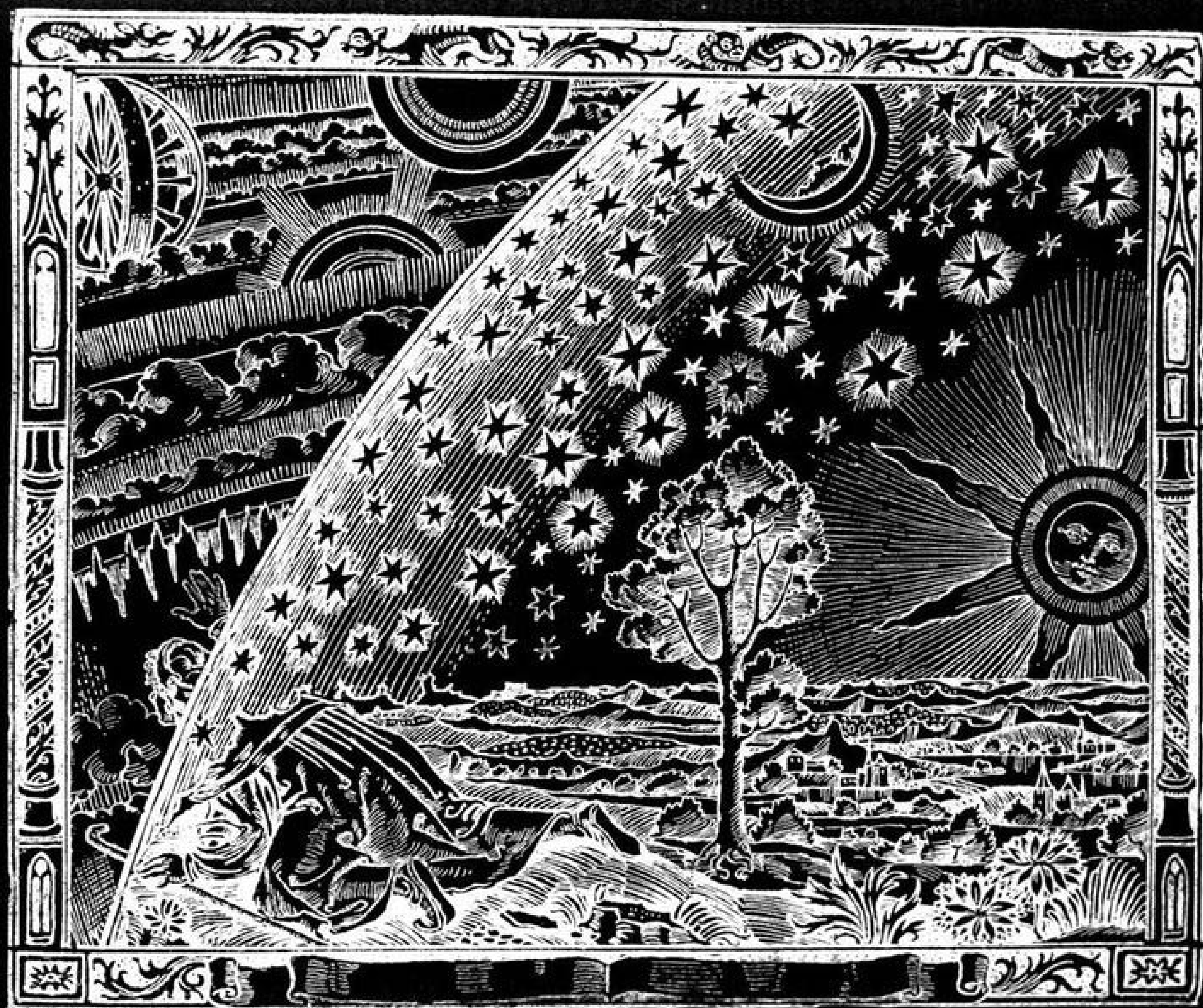
   (inflation?)

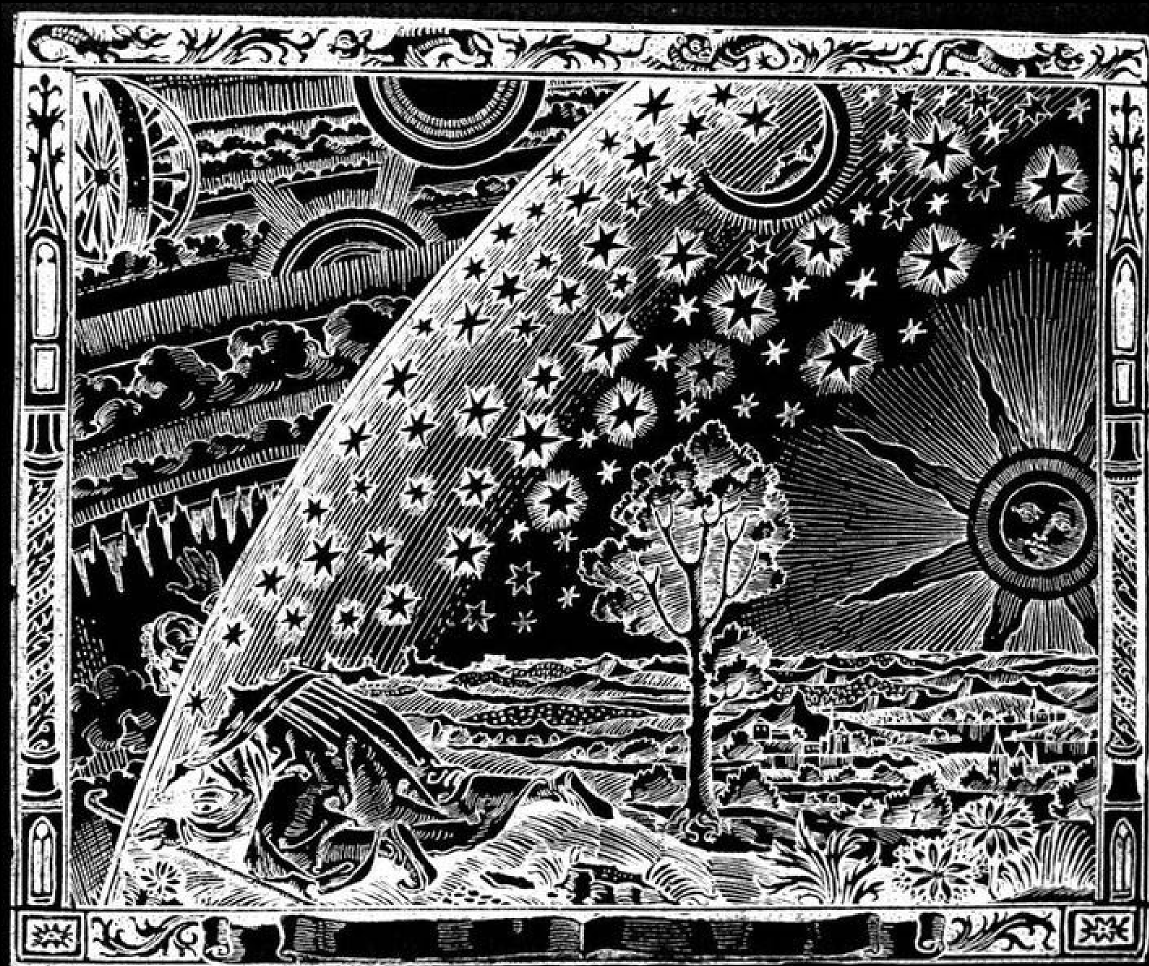
4. What produced that initial impulse that caused the universe to expand?

5. How far ultimately can we peer behind the cosmic background radiation?

   (nucleosynthesis)

6. and many, many more





The End