Title: Keynote Presentation - How the universe began

Date: Jul 11, 2006 10:35 PM

URL: http://pirsa.org/06070021

Abstract:

HOW DID THE UNIVERSE BEGIN?

Justin Khoury
(Perimeter Institute)

How the universe began, what happened at the big bang, did the universe exist before the bang, are some of the most profound questions.

But an even more mysterious question is:

How the universe began, what happened at the big bang, did the universe exist before the bang, are some of the most profound questions.

But an even more mysterious question is:

WHAT TICKED OFF ZIDANE????

What is Cosmology?

What is Cosmology?

"Cosmology is concerned with the makeup of the universe. Cosmetology is concerned with the universe of makeup."

- Prof. Rocky Kolb

Hot Big Bang Model:

- Some 14 billion yrs ago, the Universe began in a hot and dense state. It has been cooling down as it expands.

- Through gravitational attraction, small overdense regions became denser and denser, and eventually formed galaxies where life could exist.

Hot Big Bang Model:

- Some 14 billion yrs ago, the Universe began in a hot and dense state. It has been cooling down as it expands.

- Through gravitational attraction, small overdense regions became denser and denser, and eventually formed galaxies where life could exist.

Disclaimer: "Big Bang Theory" is a misleading name since the model says nothing about the "bang" itself. It is a theory that purports to explain everything that happened after a fraction of a second after the bang.

My list of FAQs:

1. Where did the bang happen? There must be a center for the explosion, no?
2. What is the universe expanding into?
3. Is the Earth expanding? Is my body expanding? (YES, but not the fault of cosmic expansion)
4. How do we know that the universe is expanding?
5. Is the universe infinite?

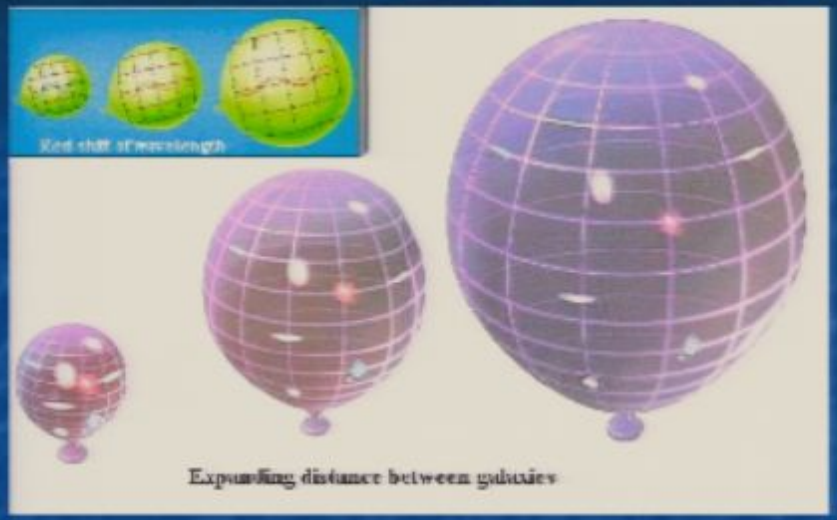
My list of FAQs:

1. Where did the bang happen? There must be a center for the explosion, no?
2. What is the universe expanding into?
3. Is the Earth expanding? Is my body expanding? (YES, but not the fault of cosmic expansion)
4. How do we know that the universe is expanding?
5. Is the universe infinite?

Are there alien life forms and can we get in touch with them?

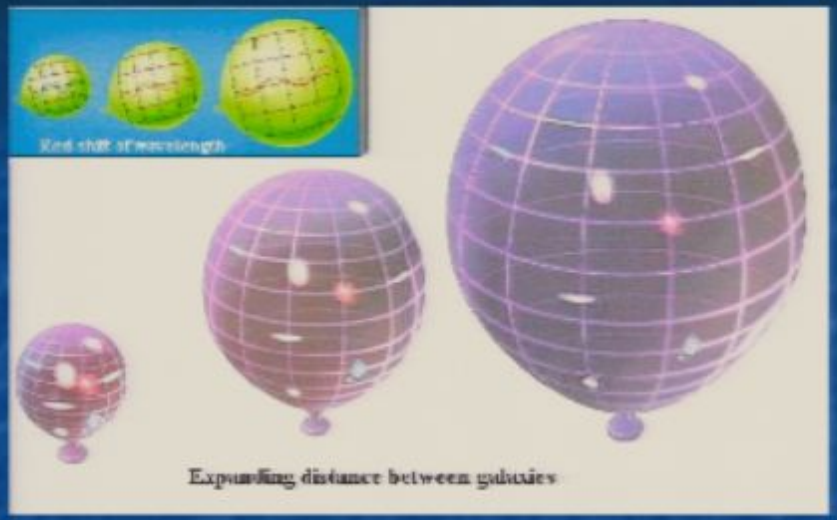
1. Where did the bang happen? 2. What is the universe expanding into?
3. Is the Earth expanding?

"Balloon" analogy:

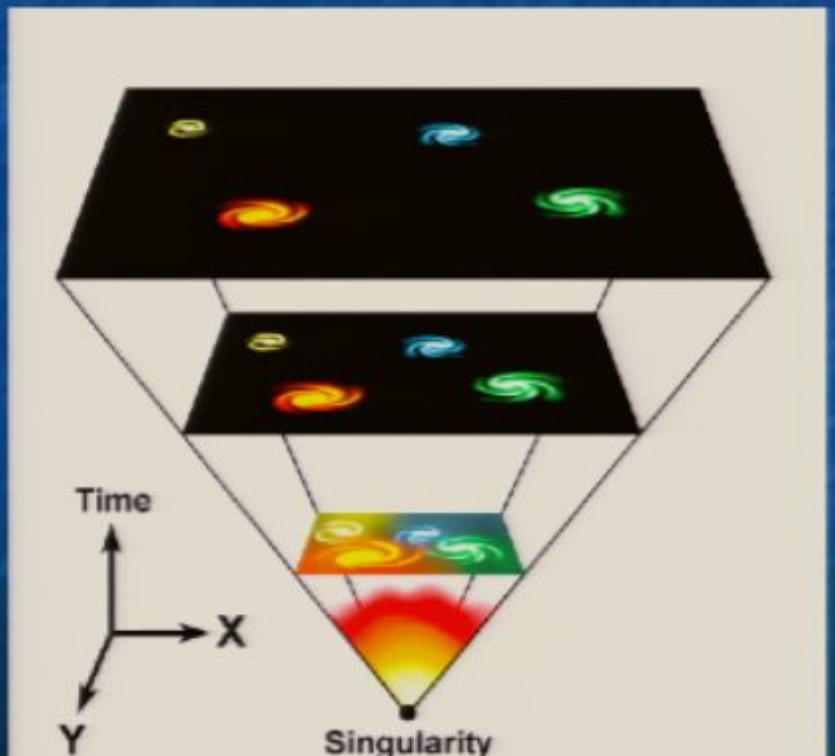


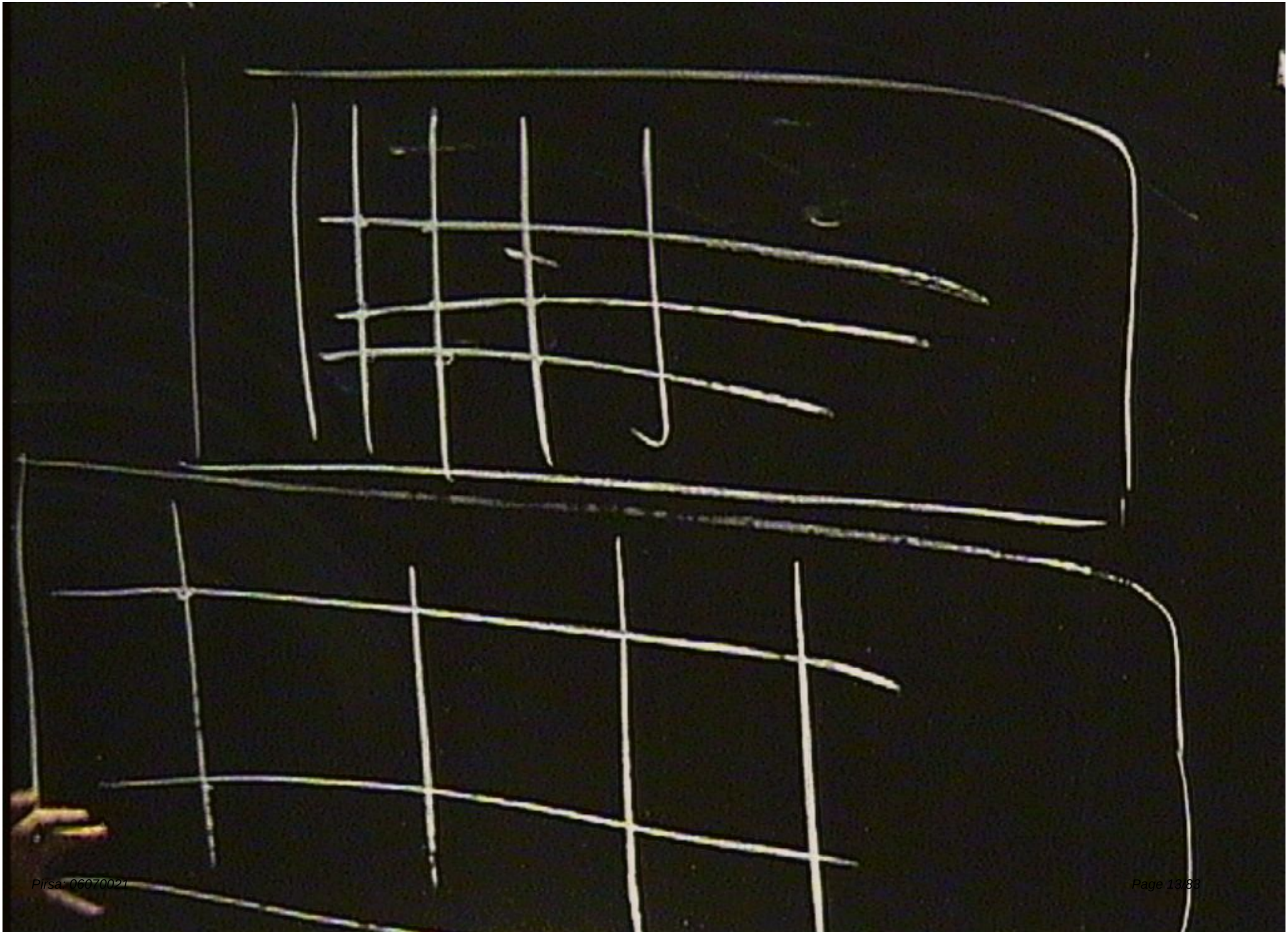
1. Where did the bang happen? 2. What is the universe expanding into?
3. Is the Earth expanding?

"Balloon" analogy:



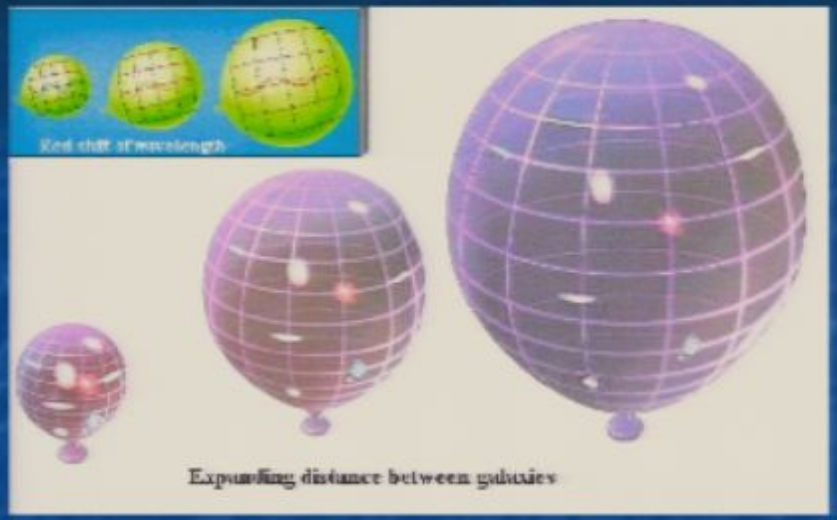
A better picture:



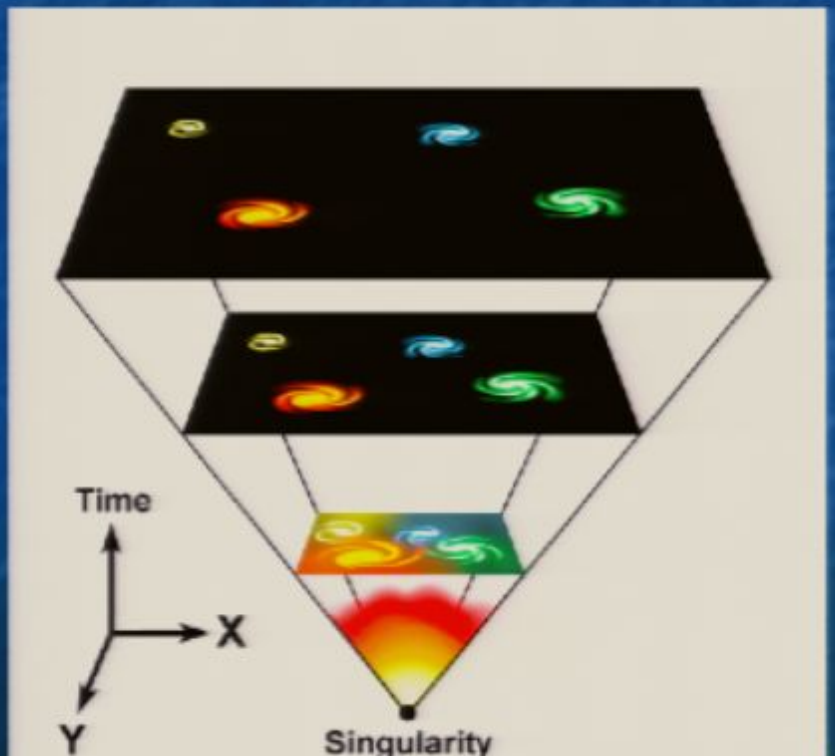


1. Where did the bang happen? 2. What is the universe expanding into?
3. Is the Earth expanding?

"Balloon" analogy:



A better picture:



4. How do we know that the universe is expanding?

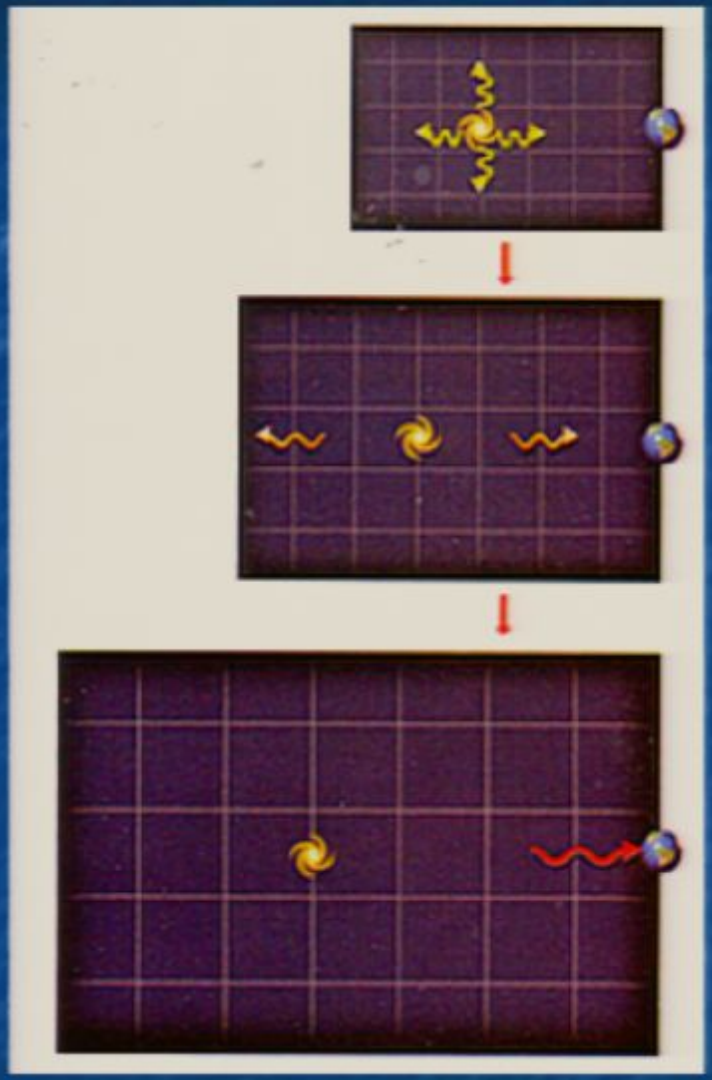
- Atoms absorb and emit light at specific wavelengths or frequencies

- As light travels from distant galaxy to us, its wavelength gets stretched by expansion of universe (redshift)

- Comparing emitted and observed wavelengths, we can determine the redshift.

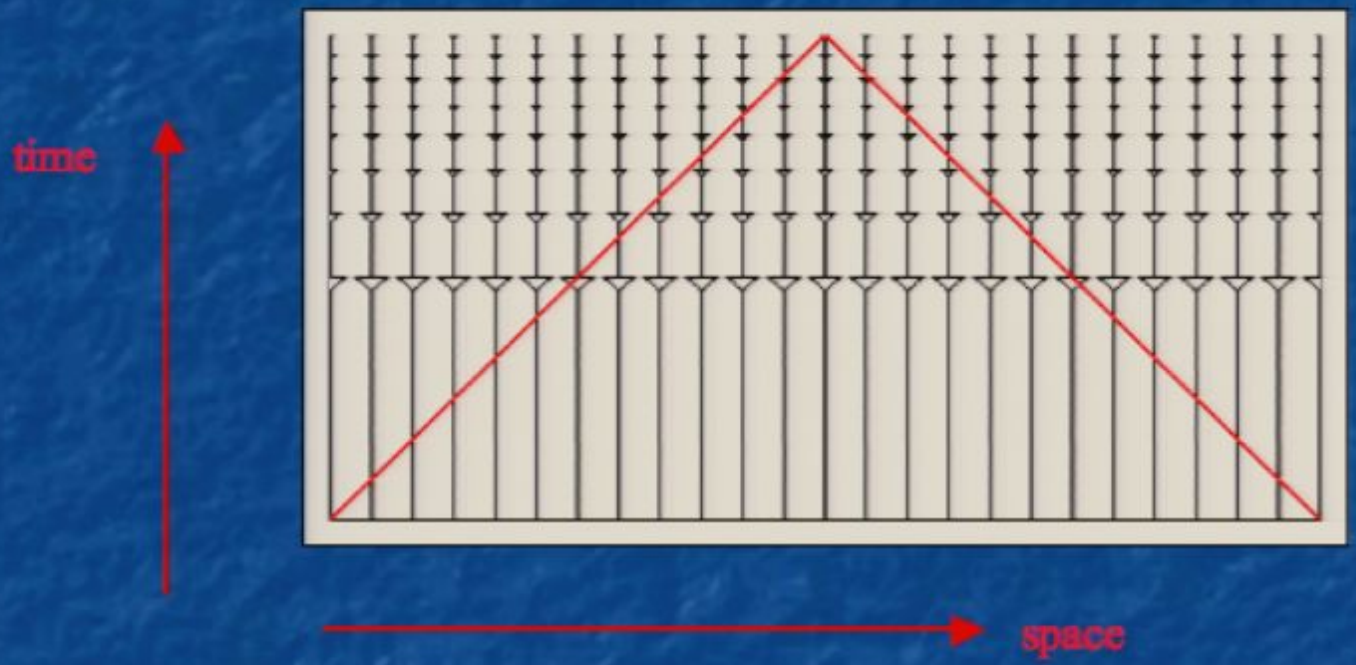
- On average, find overall redshift. Moreover, galaxies satisfy on average the Hubble law:

$$z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{Hd}{c}$$



5. Is the universe infinite?

• Because light travels at a finite speed, and because there is a finite amount of time since the big bang (14 billion years), we only see a *finite* portion of the universe : the observable universe.

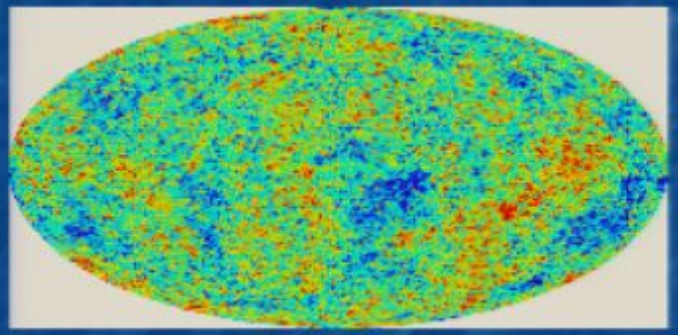


• So we don't know for sure what's "out there", beyond what we can see. Inflationary theory, however, predicts that the universe is exponentially larger than what we can see, consisting predominantly of empty space.

Successes of the Big Bang model:

- Accurately predicts relative abundance of light elements (through nucleosynthesis, about 1s after big bang)

- Predicts remnant thermal radiation at around 3K from the moment when universe became neutral -- this is the cosmic microwave background radiation



- Explains how small inhomogeneities can grow over time through gravitational attraction to eventually form stars and galaxies.

Still not everyone is convinced…

Still not everyone is convinced…

How the universe began: modern theories of early universe

A few paradoxes:

- As mentioned earlier, big bang model accounts exquisitely well for what happened 1s after the big bang onwards, but says nothing about the bang itself.
- In particular, what caused the universe to expand? The expansion of space is a gravitational effect, yet we know gravity is attractive ?!?!
- And how did all the matter and radiation in the universe get created?

Still not everyone is convinced…

How the universe began: modern theories of early universe

A few paradoxes:

- As mentioned earlier, big bang model accounts exquisitely well for what happened 1s after the big bang onwards, but says nothing about the bang itself.
- In particular, what caused the universe to expand? The expansion of space is a gravitational effect, yet we know gravity is attractive ?!?!
- And how did all the matter and radiation in the universe get created?

How the universe began: modern theories of early universe

A few paradoxes:

- As mentioned earlier, big bang model accounts exquisitely well for what happened 1s after the big bang onwards, but says nothing about the bang itself.
- In particular, what caused the universe to expand? The expansion of space is a gravitational effect, yet we know gravity is attractive ?!?!
- And how did all the matter and radiation in the universe get created?

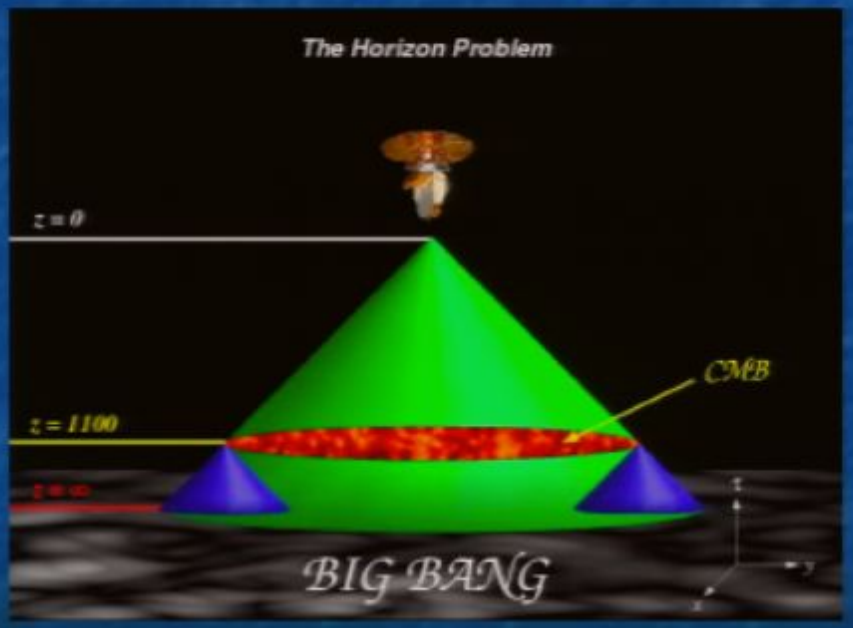
These profound questions find (partial) answers in an important addendum to the big bang model, which is called *inflation*.

Inflation proposes that, a fraction of a second after the big bang, the universe underwent a burst of tremendously rapid expansion. The size of the universe grew by a factor of 10^{26} in 10^{-32} seconds!

Brief motivation for inflation: smoothness (horizon) problem

- Microwave background is highly homogeneous -- same temperature to 1 part in 100000!!

- But distant parts of the sky were not in causal contact at the time when the radiation was emitted



when radiation was emitted

(from Will Kinney)

So how did these different parts of the sky get the same temperature to such accuracy?

How the universe began: modern theories of early universe

A few paradoxes:

- As mentioned earlier, big bang model accounts exquisitely well for what happened 1s after the big bang onwards, but says nothing about the bang itself.
- In particular, what caused the universe to expand? The expansion of space is a gravitational effect, yet we know gravity is attractive ?!?!
- And how did all the matter and radiation in the universe get created?

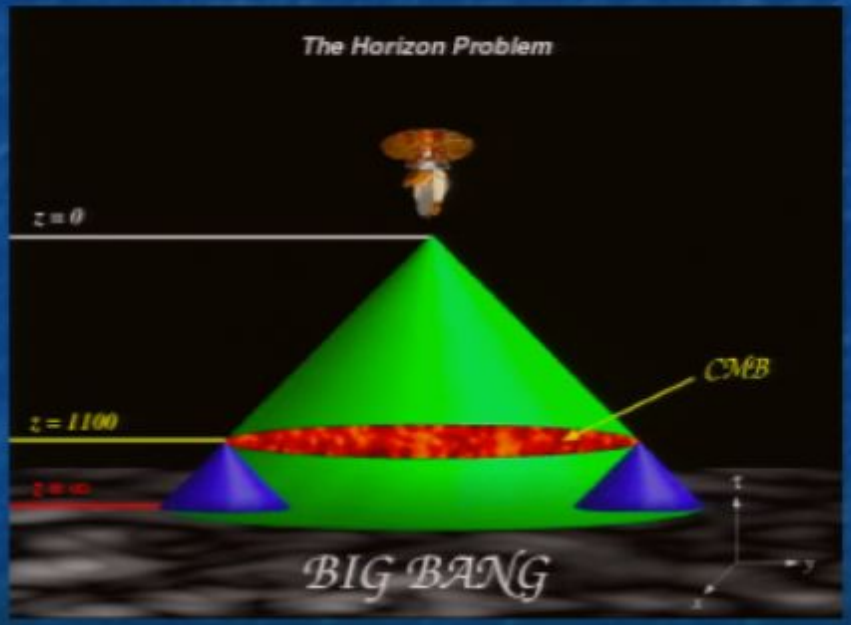
These profound questions find (partial) answers in an important addendum to the big bang model, which is called *inflation*.

Inflation proposes that, a fraction of a second after the big bang, the universe underwent a burst of tremendously rapid expansion. The size of the universe grew by a factor of 10^{26} in 10^{-32} seconds!

Brief motivation for inflation: smoothness (horizon) problem

- Microwave background is highly homogeneous -- same temperature to 1 part in 100000!!

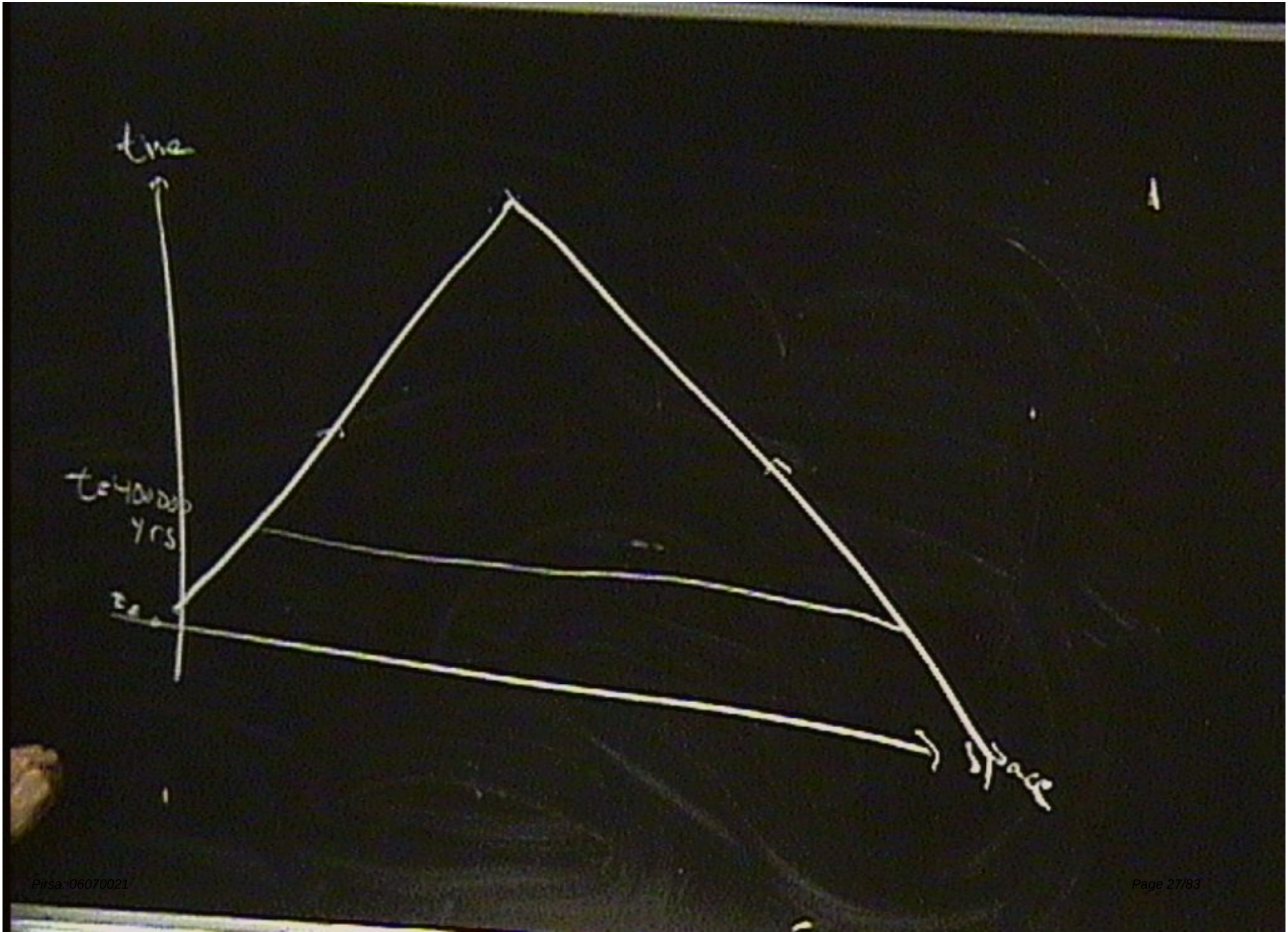
- But distant parts of the sky were not in causal contact at the time when the radiation was emitted

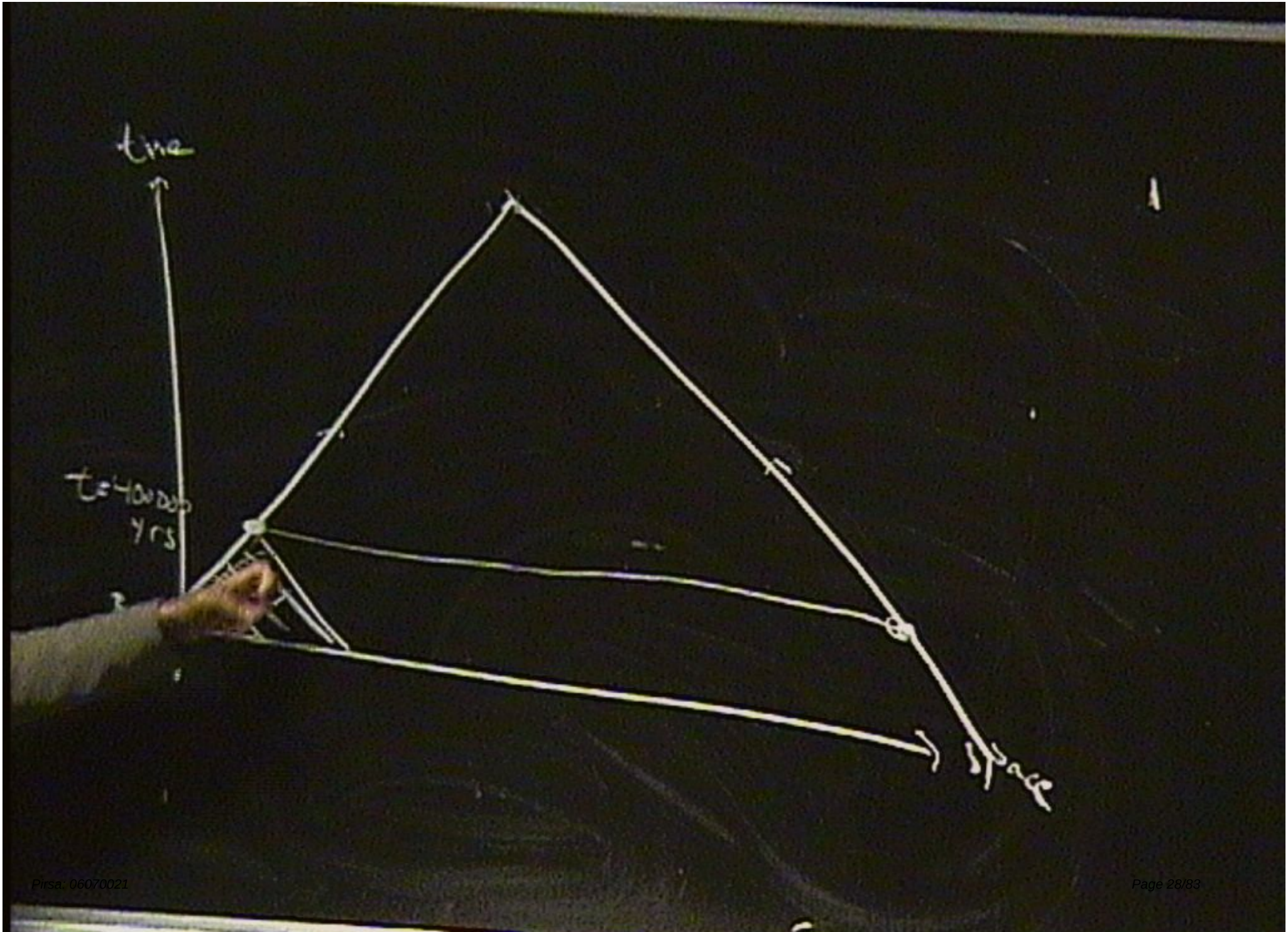


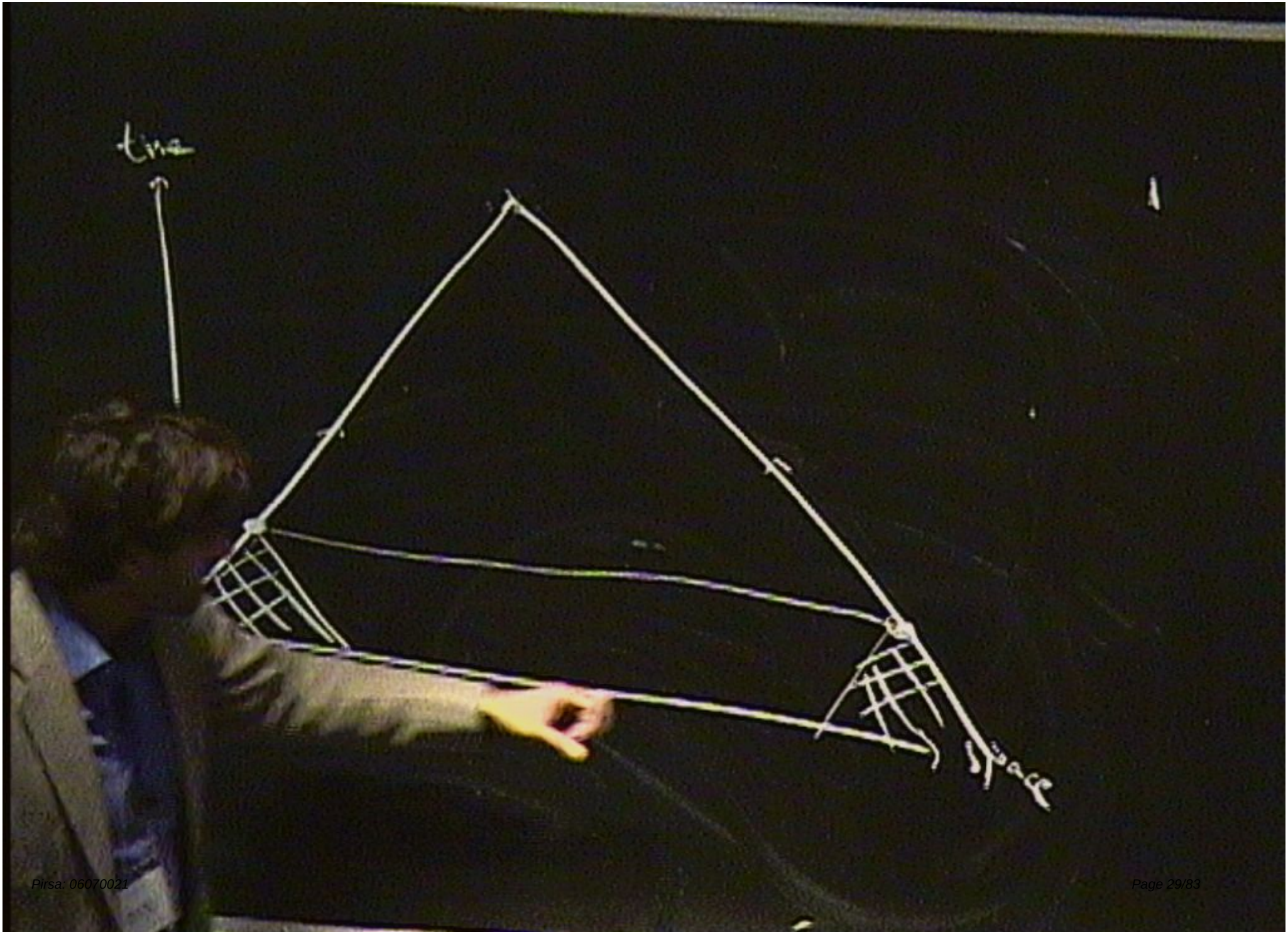
when radiation was emitted

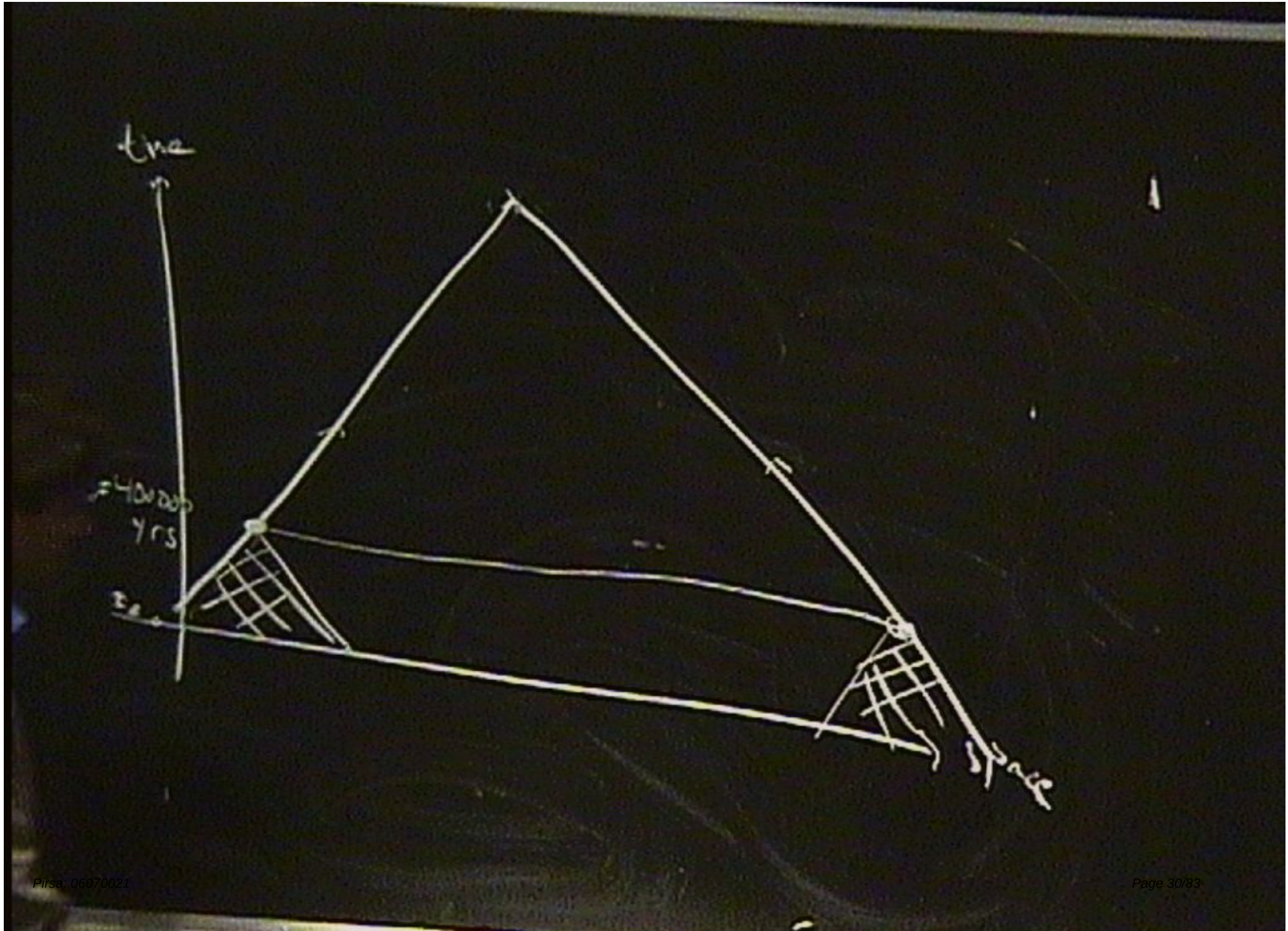
(from Will Kinney)

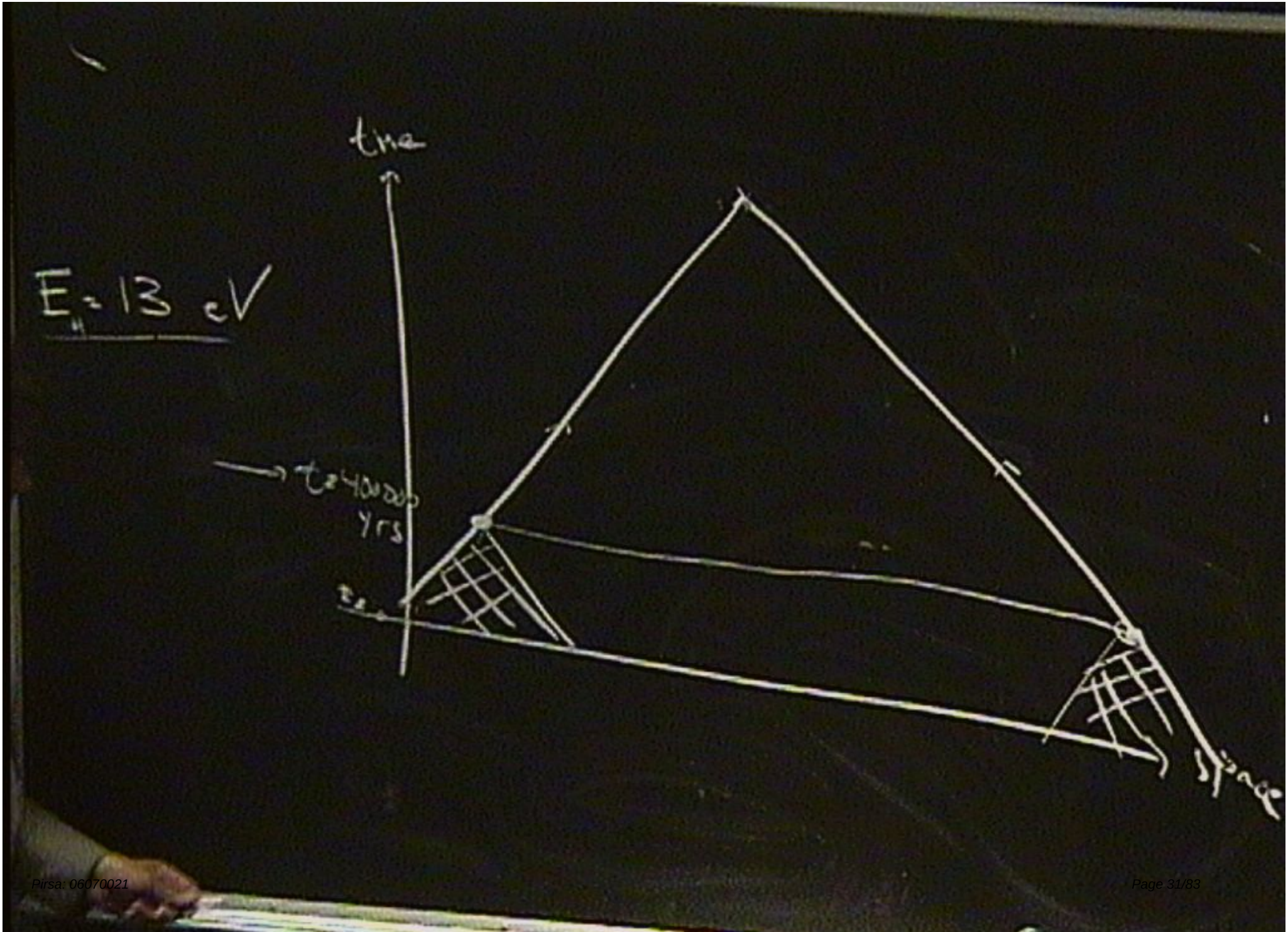
So how did these different parts of the sky get the same temperature to such accuracy?

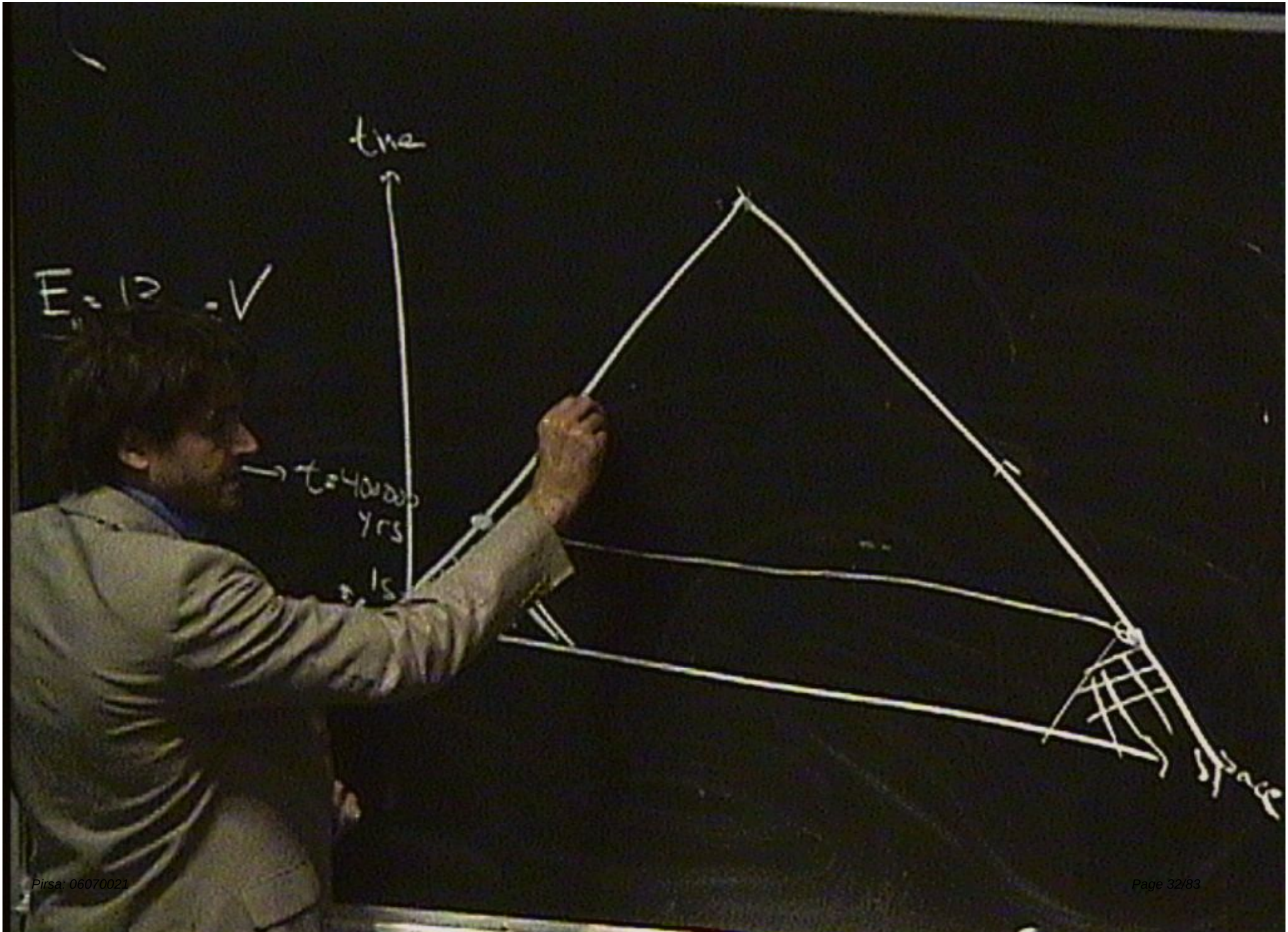

time
today
yrs

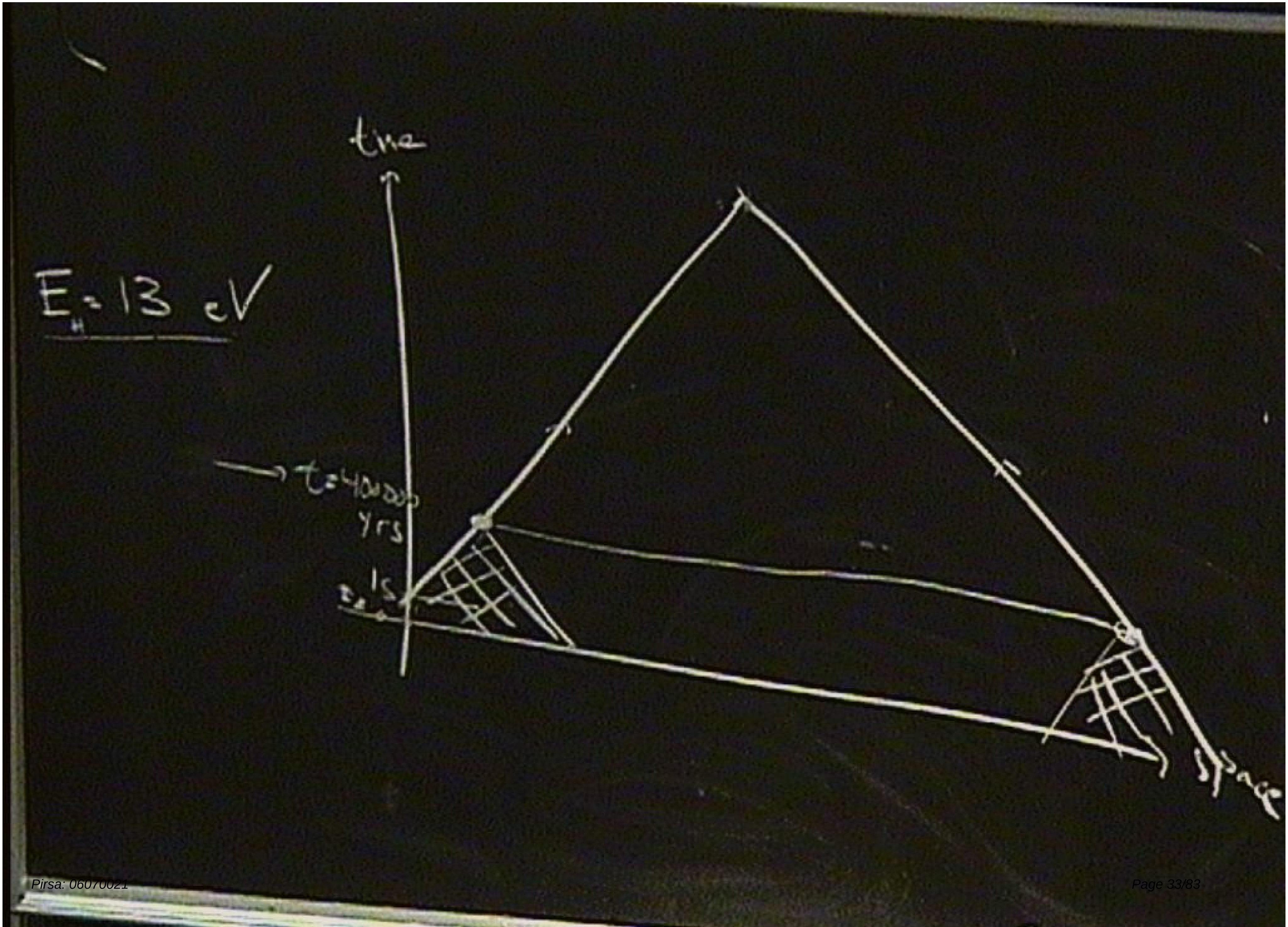

time
Pirsa: 06070021
Page 28/83


time

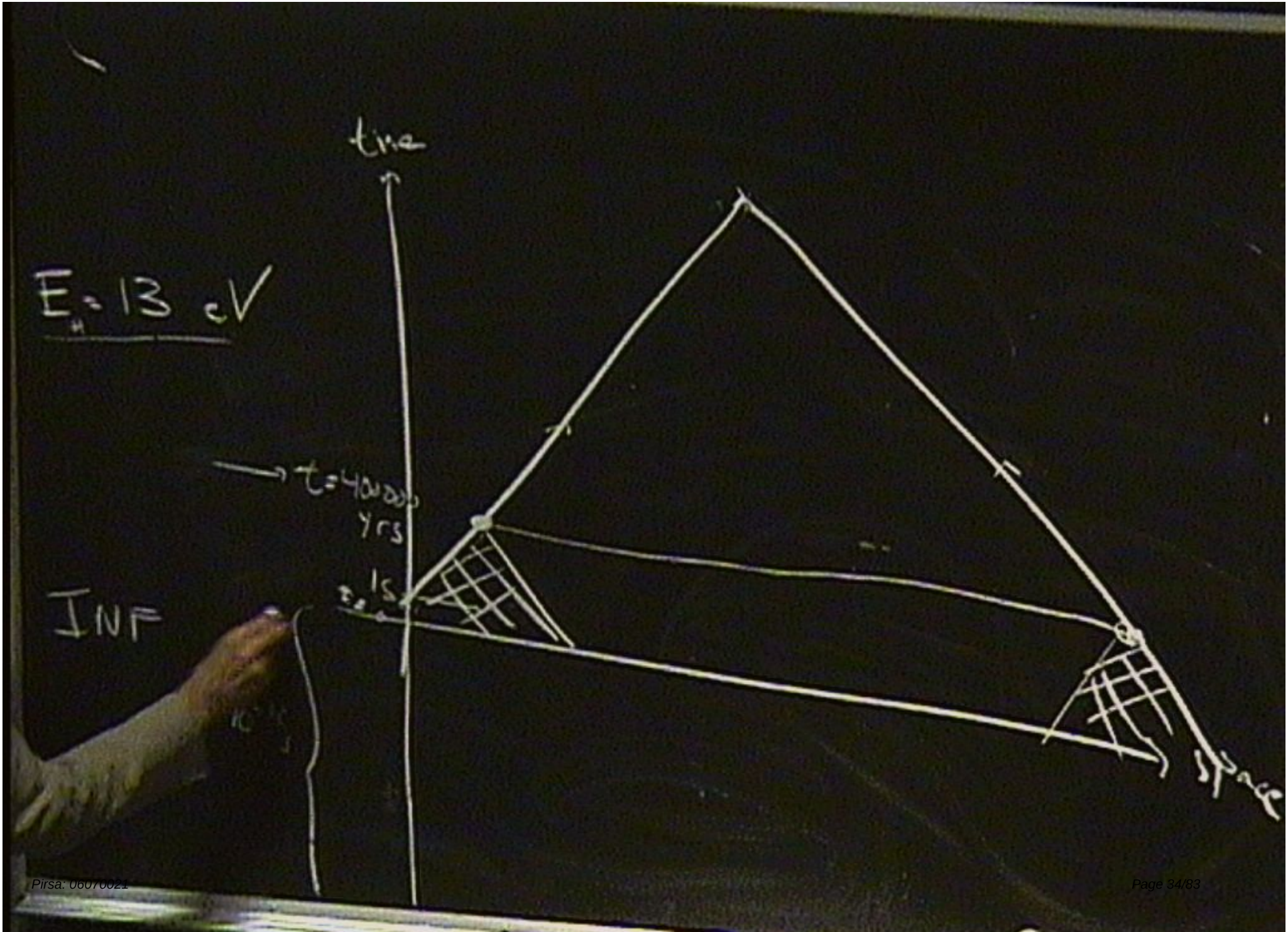

time

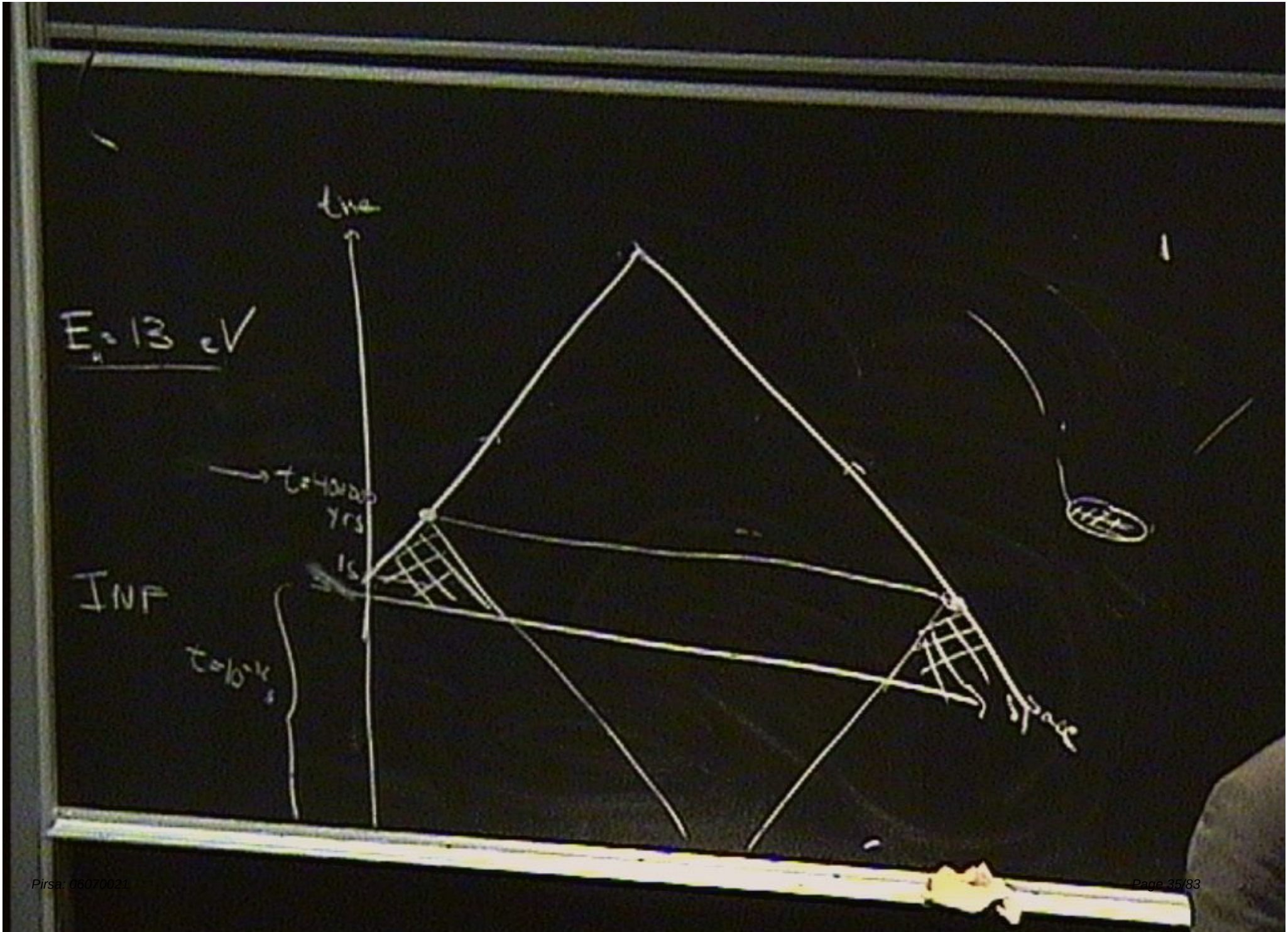

time
$E_H = 13$ eV
$t_{re} \approx 400{,}000$ yrs
t_{re}
Today


time
E = 12 · V
→ t = 40,000 yrs
≈ 1s



time
$E_H = 13$ eV
t=400000
yrs
1s
space


time
$E_H = 13$ eV
$t = 4 \times 10^{10}$ yrs
INF


time
E_0 13 eV
INF
space

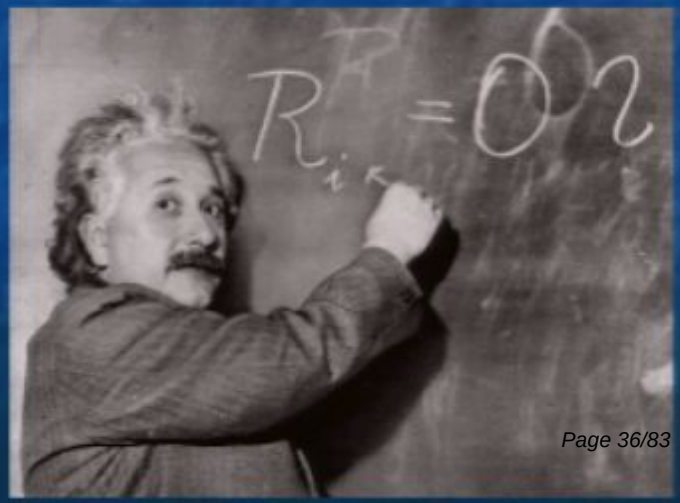
What causes this burst of exponential growth?

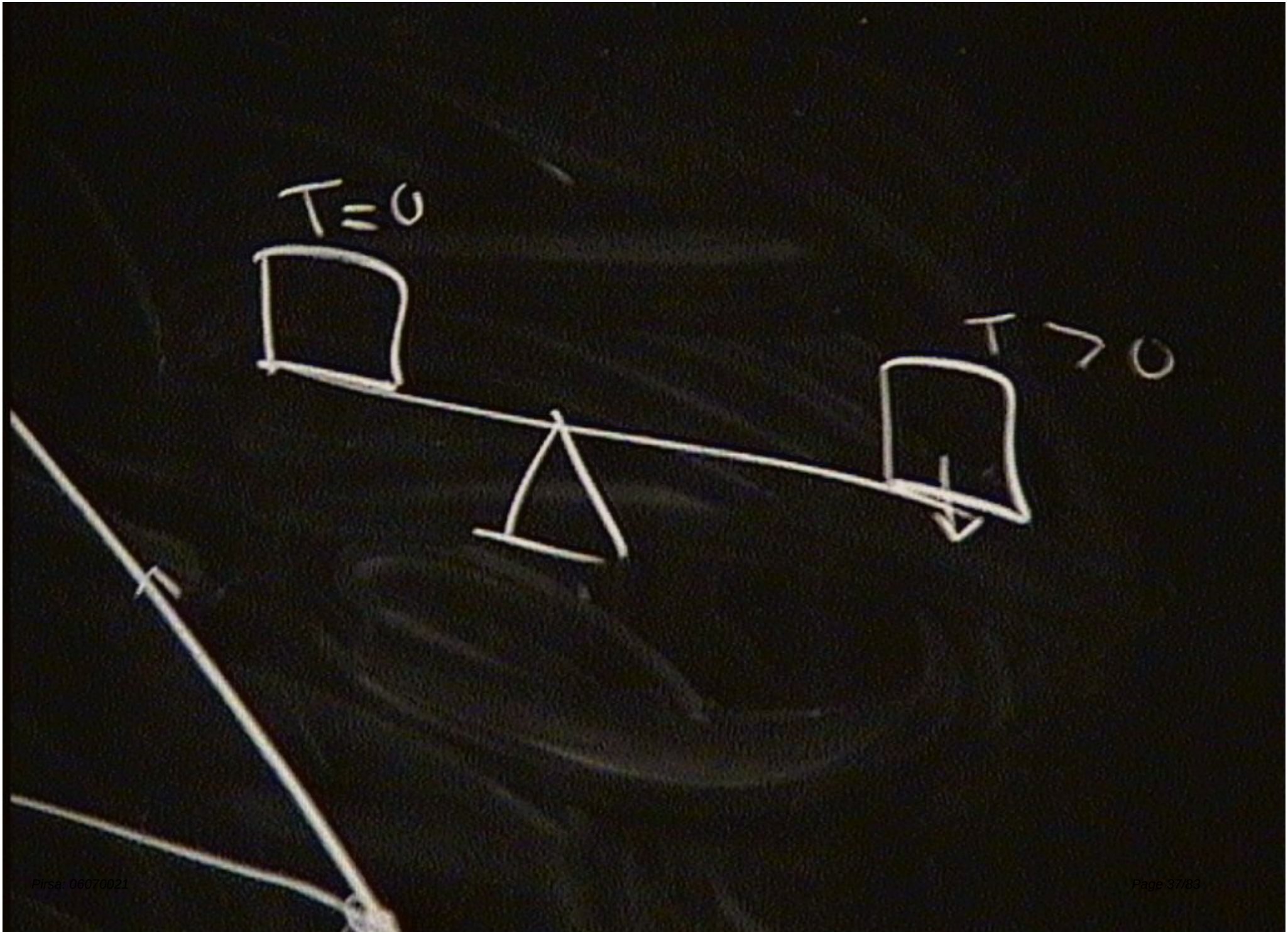
- Newtonian: gravitational force between two objects depends on their mass and the distance between them

- Einstein: gravitational force also depends on energy…

(not surprising since $E=mc^2$ equates mass and energy)

…but also on pressure!

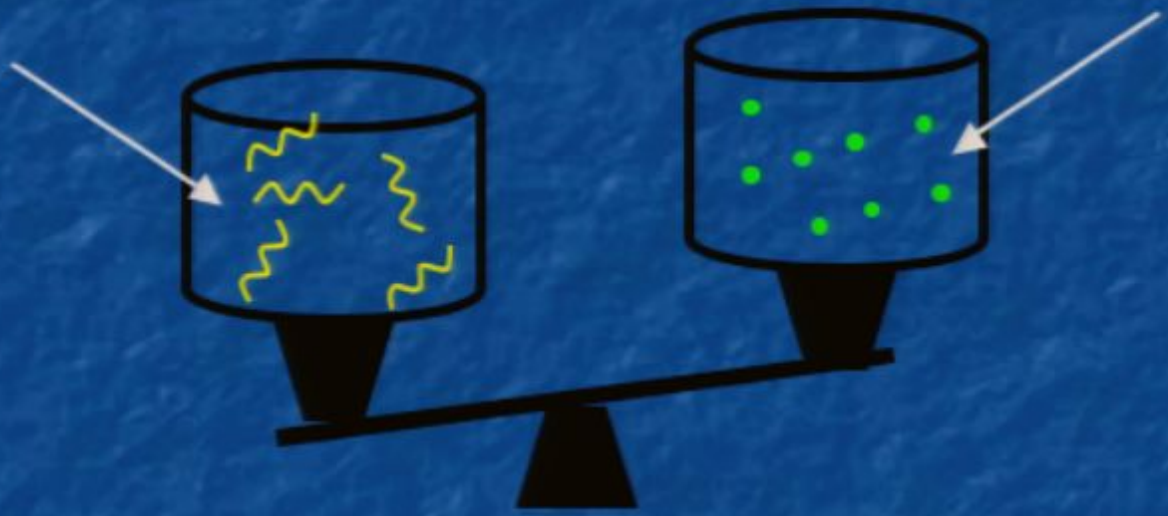



T=0
T>0

E.g.: consider 2 boxes filled with gas, same total energy

Box 1: Gas of photons => significant pressure

Box 2: Gas of massive particles => near zero pressure



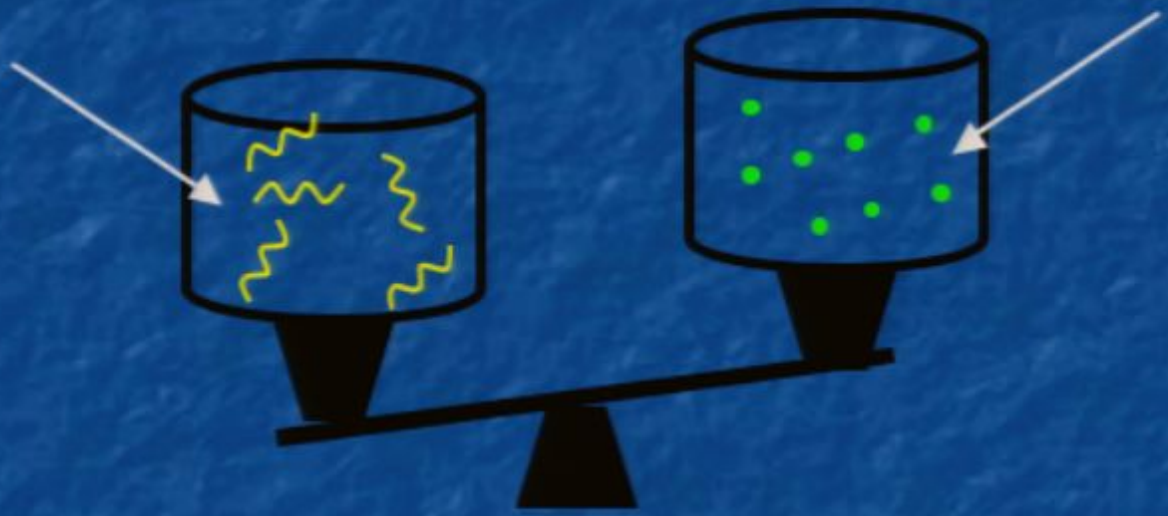
- Positive pressure contributes to greater attraction
- Negative pressure contributes to repulsion!!!!

Gravity can be repulsive!!

E.g.: consider 2 boxes filled with gas, same total energy

Box 1: Gas of photons => significant pressure

Box 2: Gas of massive particles => near zero pressure



- Positive pressure contributes to greater attraction
- Negative pressure contributes to repulsion!!!!

Gravity can be repulsive!!

Another way to understand how pressure gravitates:

Newtonian says: acceleration of particle due to big sphere of dust is

$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2} = -\frac{G}{R^2}\left(\frac{4\pi R^3}{3}\rho\right)$$

$$\Longrightarrow \boxed{\frac{1}{R}\frac{d^2R}{dt^2} = -\frac{4\pi G}{3}\rho}$$

(Thinking of R(t) as radius of sphere, then this describes the cosmological expansion according to Newton)

Another way to understand how pressure gravitates:

Newtonian says: acceleration of particle due to big sphere of dust is

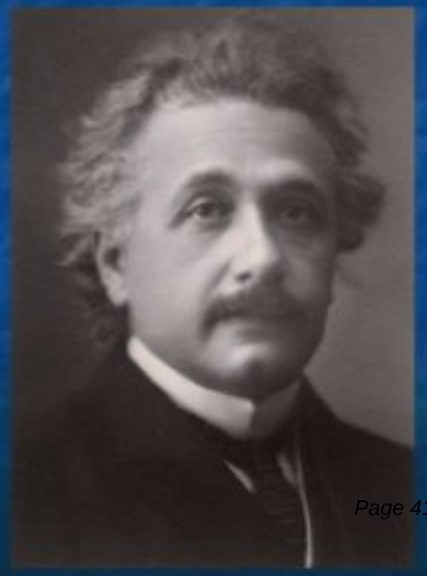
$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2} = -\frac{G}{R^2}\left(\frac{4\pi R^3}{3}\rho\right)$$

$$\Longrightarrow \boxed{\frac{1}{R}\frac{d^2R}{dt^2} = -\frac{4\pi G}{3}\rho}$$

(Thinking of R(t) as radius of sphere, then this describes the cosmological expansion according to Newton)

Einstein says: pressure gravitates too!

$$\boxed{\frac{1}{R}\frac{d^2R}{dt^2} = -\frac{4\pi G}{3}(\rho + 3P)}$$



So in this precise sense pressure gravitates!

How negative pressure leads to inflation:

$$\frac{1}{R}\frac{d^2R}{dt^2} = -\frac{4\pi G}{3}(\rho + 3P)$$

If pressure is sufficiently negative, then have accelerated expansion

$$\frac{1}{R}\frac{d^2R}{dt^2} = const > 0$$

and exponential expansion:

$$R(t) \sim e^{Ht}$$

This phase of exponential expansion is what we call inflation!

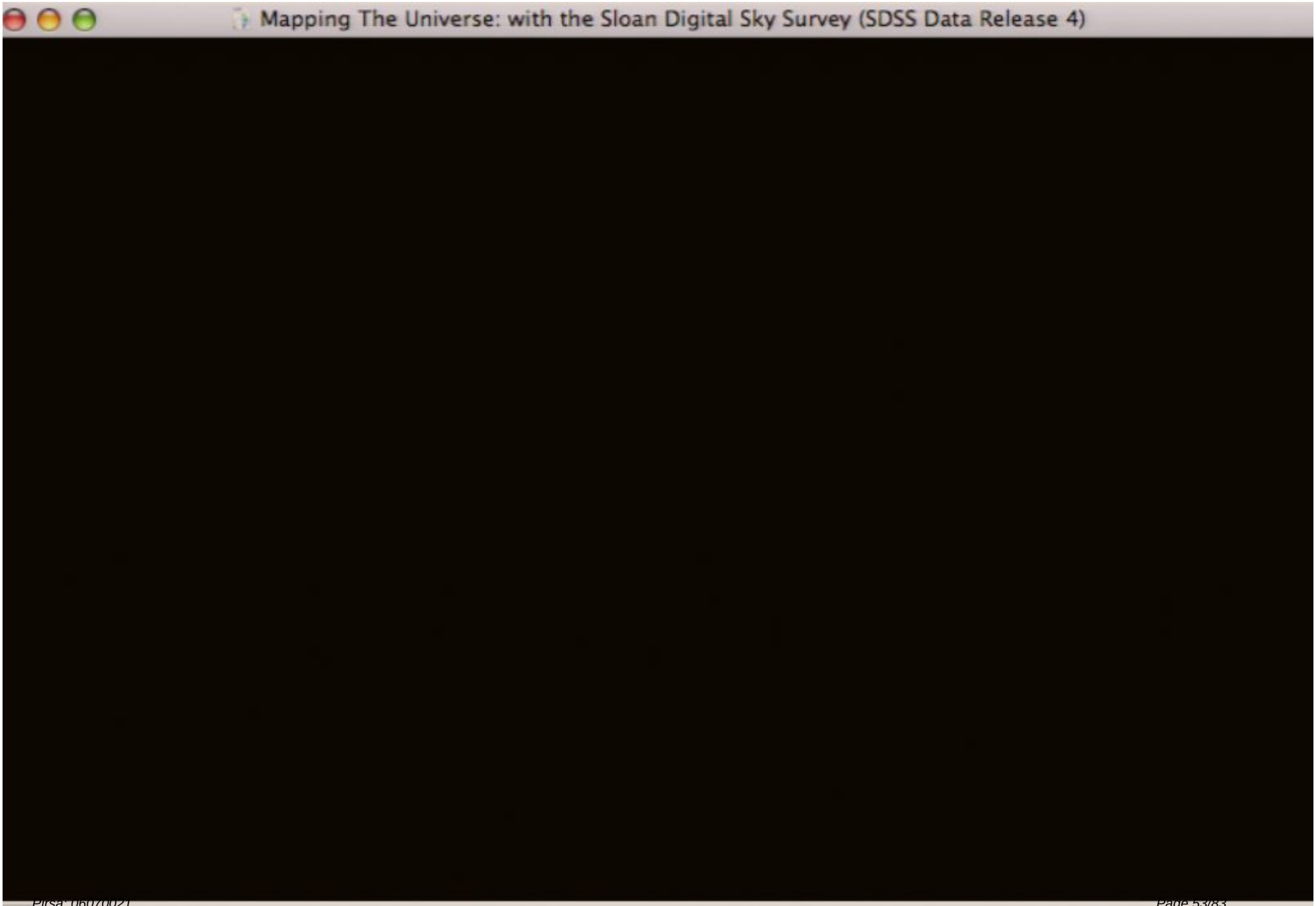
All that remains is to explain what's the stuff with negative pressure…

niverse: with the Sloan Digital Sky Survey (SDSS Data Release 4)

niverse: with the Sloan Digital Sky Survey (SDSS Data Release 4)

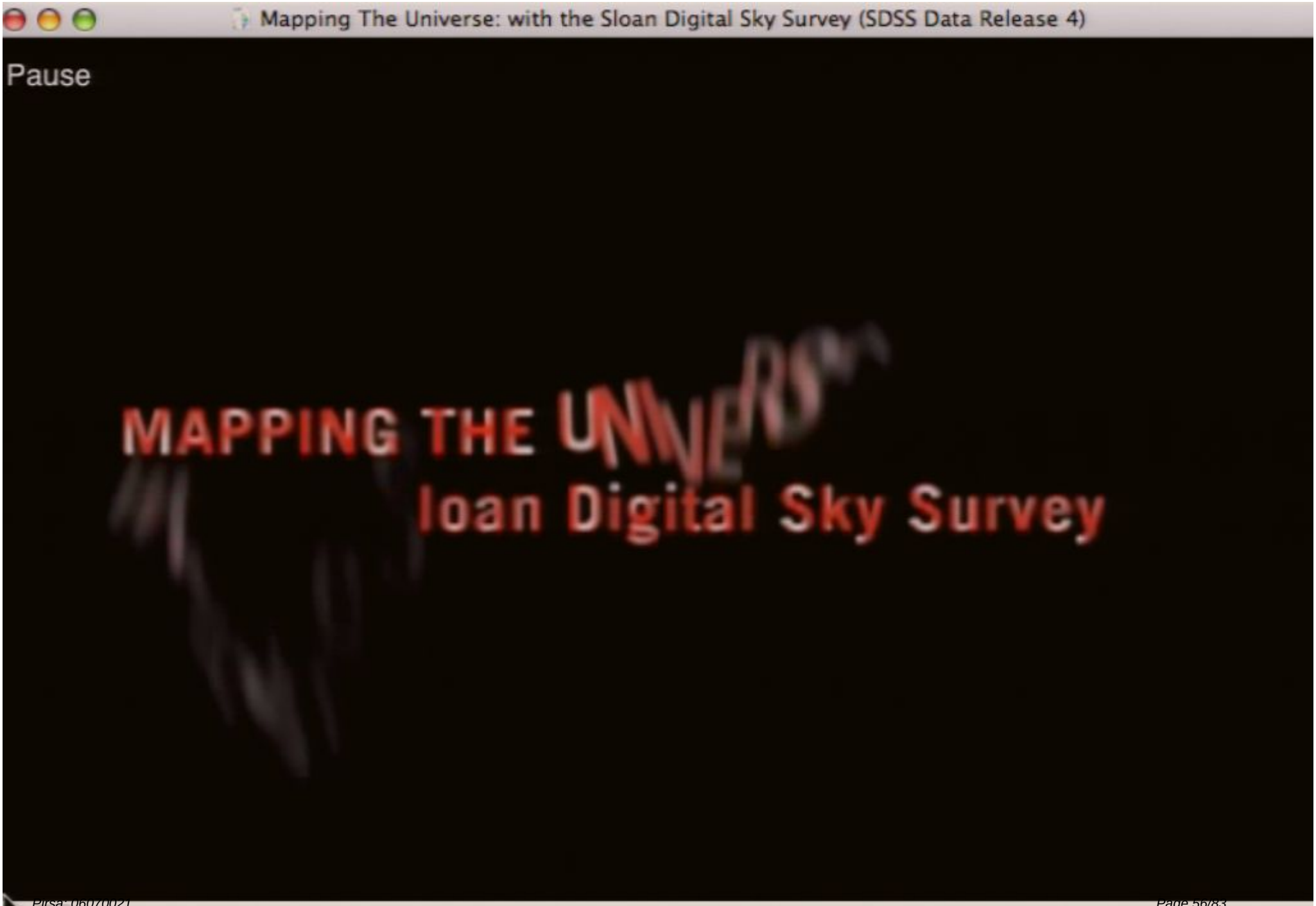
niverse: with the Sloan Digital Sky Survey (SDSS Data Release 4)

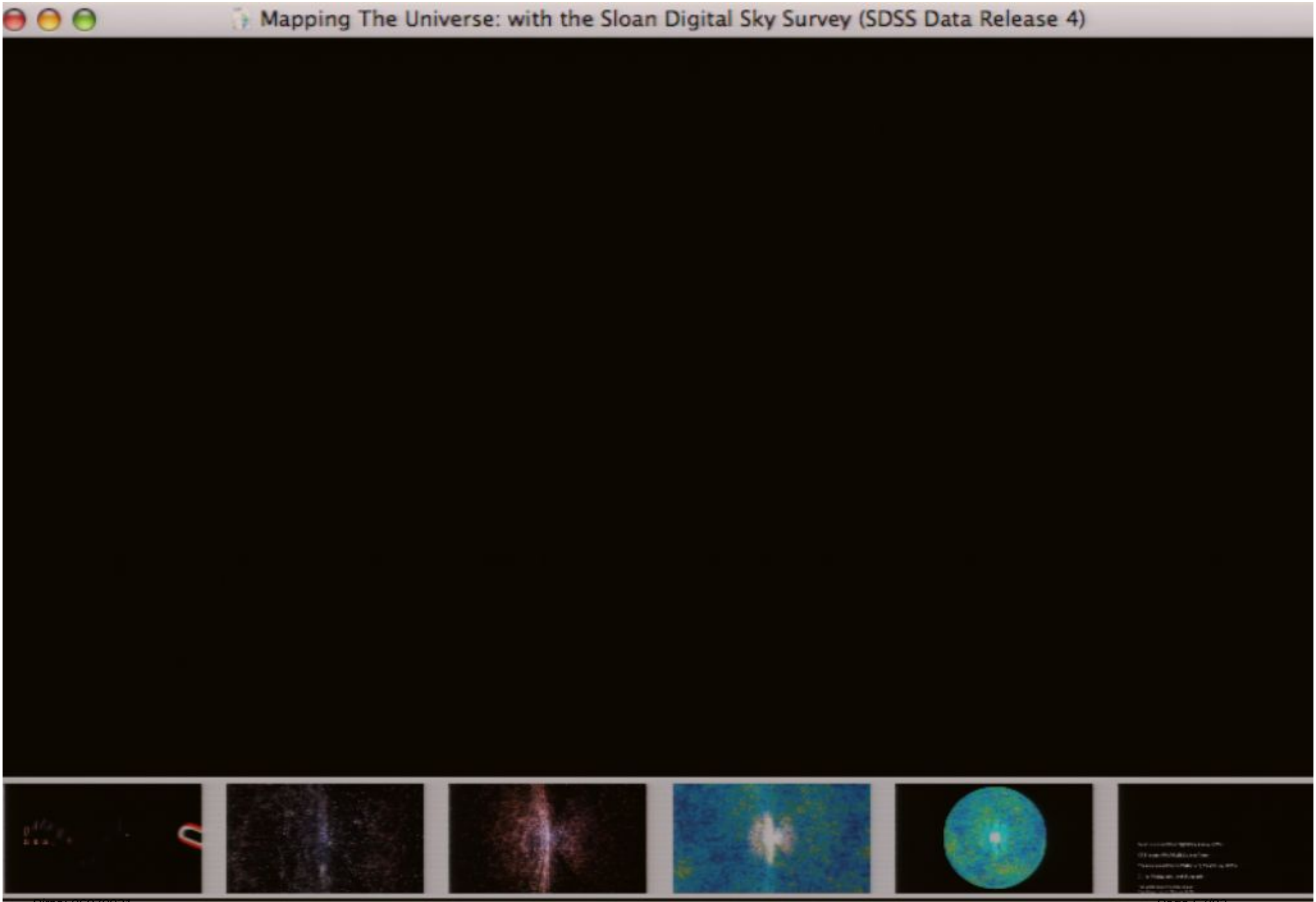
Mapping The Universe: with the Sloan Digital Sky Survey (SDSS Data Release 4)

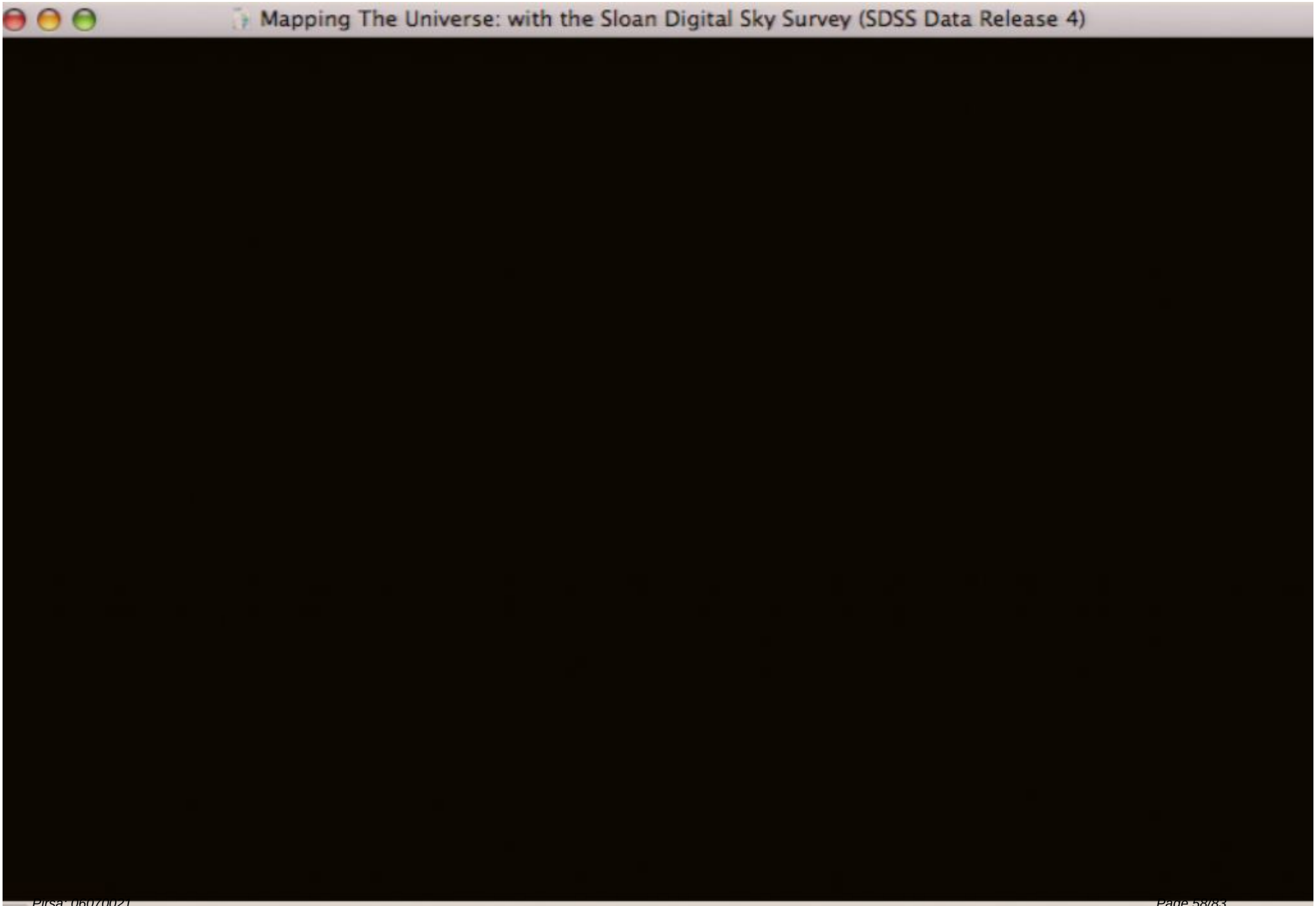

Mapping The Universe: with the Sloan Digital Sky Survey (SDSS Data Release 4)


Mapping The Universe: with the Sloan Digital Sky Survey (SDSS Data Release 4)

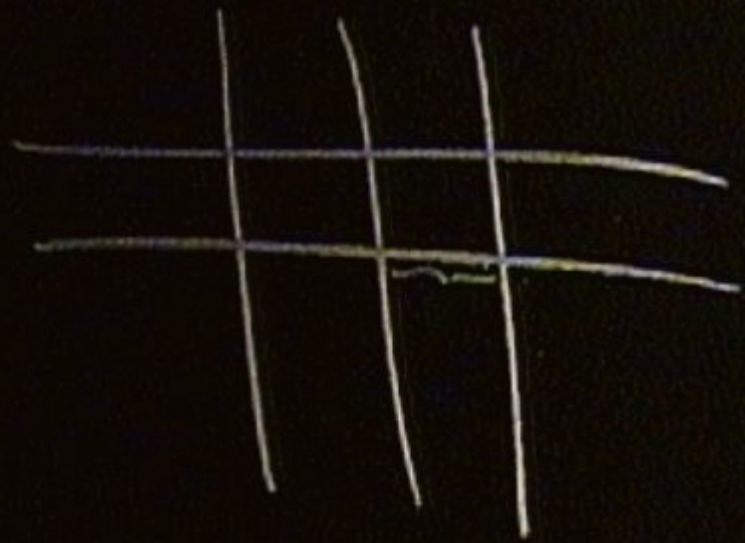

Mapping The Universe: with the Sloan Digital Sky Survey (SDSS Data Release 4)


Mapping The Universe: with the Sloan Digital Sky Survey (SDSS Data Release 4)
Pause
MAPPING THE UNIVERSE
loan Digital Sky Survey

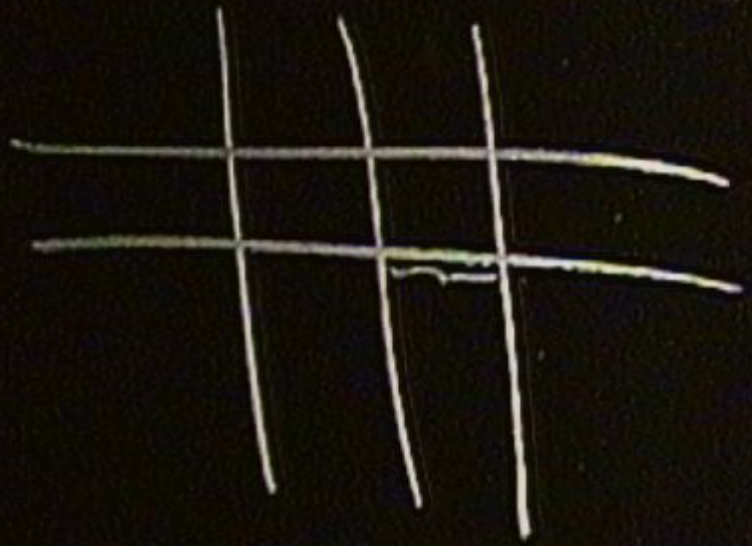

Mapping The Universe: with the Sloan Digital Sky Survey (SDSS Data Release 4)


Mapping The Universe: with the Sloan Digital Sky Survey (SDSS Data Release 4)

$$R(t) = e^{-Ht} = e^{-60}$$



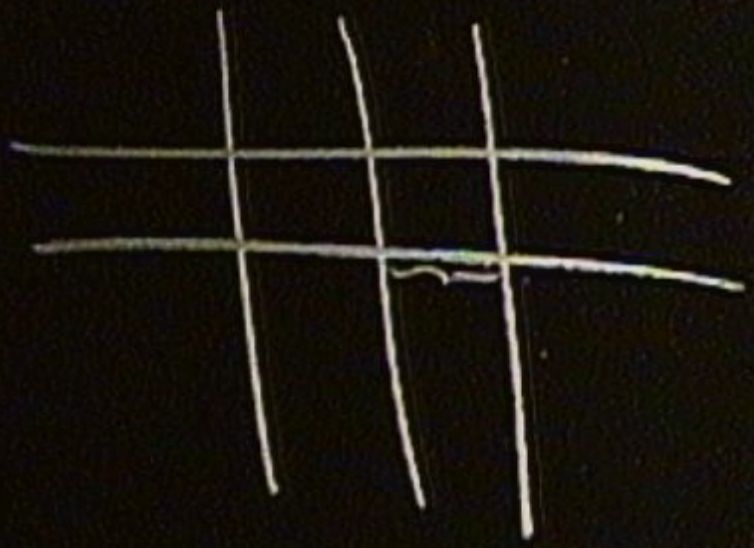
$$R(t) = e^{H t} = e^{60}$$



$$R(t) = e^{H t} \qquad t \sim 10^{-32}\,\text{s}$$

$$= e^{60} \approx 10^{26}$$

!



INTERLUDE: “Google Universe”

http://astro.uchicago.edu/cosmus/projects/sloanmovie/

INTERLUDE: “Google Universe”

http://astro.uchicago.edu/cosmus/projects/sloanmovie/

TO RECAP:

Einstein teaches two important lessons:

1. Not only mass and energy gravitate, but also pressure

2. Energy can't be negative, but pressure can. And negative pressure leads to exponential expansion.

TO RECAP:

Einstein teaches two important lessons:

1. Not only mass and energy gravitate, but also pressure

2. Energy can't be negative, but pressure can. And negative pressure leads to exponential expansion.

But all forms of matter we are familiar with have *positive* pressure.

TO RECAP:

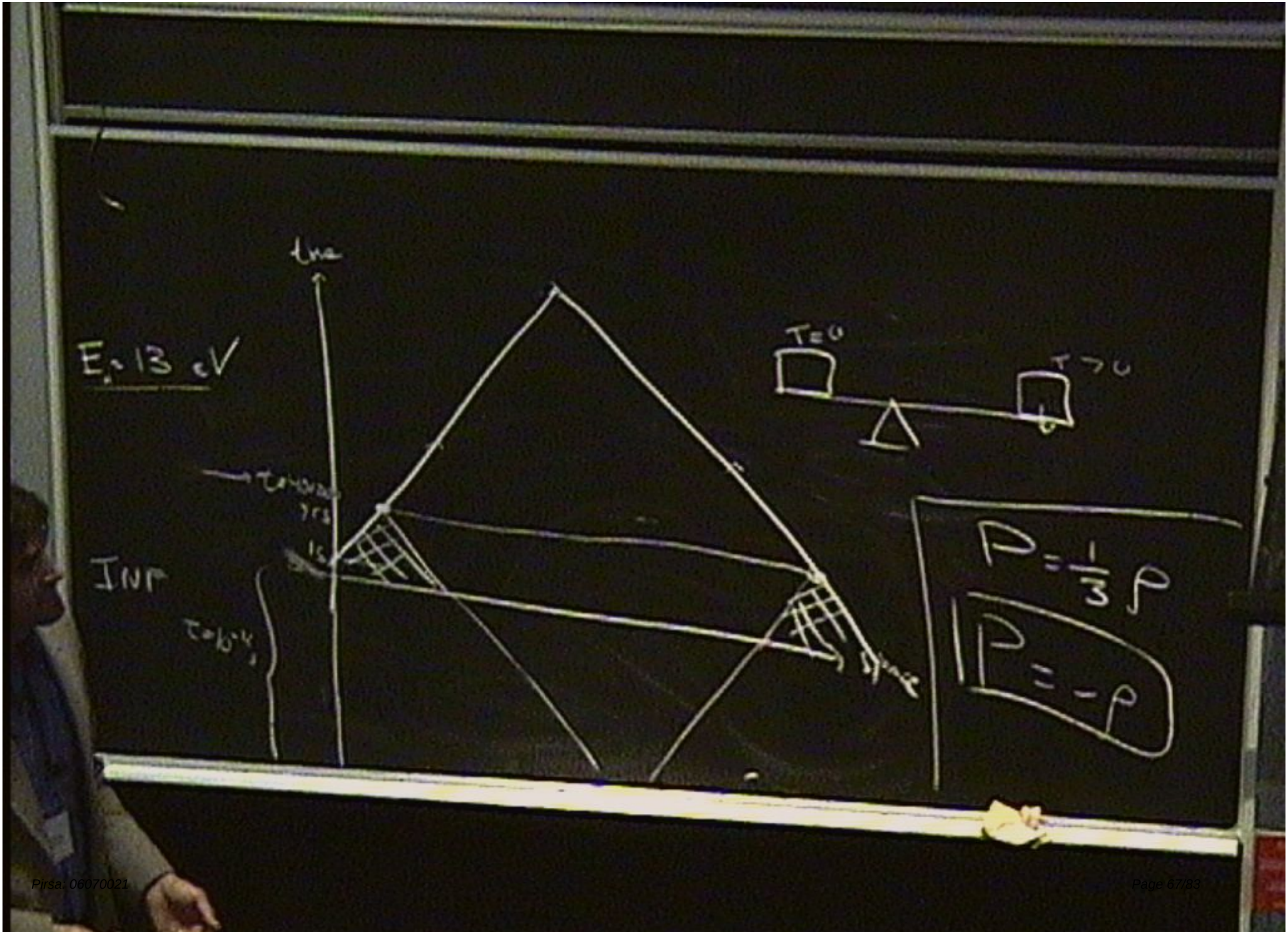
Einstein teaches two important lessons:

1. Not only mass and energy gravitate, but also pressure

2. Energy can't be negative, but pressure can. And negative pressure leads to exponential expansion.

But all forms of matter we are familiar with have *positive* pressure.

So where's the beef ?....


E ~ 13 eV
INF
P = 1/3 ρ
P = -ρ

TO RECAP:

Einstein teaches two important lessons:

1. Not only mass and energy gravitate, but also pressure

2. Energy can't be negative, but pressure can. And negative pressure leads to exponential expansion.

But all forms of matter we are familiar with have *positive* pressure.

So where's the beef ?....

Recall the optimism of those who are used to searching…

Recall the optimism of those who are used to searching…

"The absence of evidence
is not evidence of absence."

To understand the "beef", we will walk through a few abstract but crucial concepts.

1. Fields: We are used to electric and magnetic fields. They carry energy and permeate space. *The culprit for inflation is a new hypothetical field, which we call the "inflaton".*

Not as crazy as it sounds. String theory, for instance, is infested with such fields, some of which can lead to successful inflation.

To understand the "beef", we will walk through a few abstract but crucial concepts.

1. Fields: We are used to electric and magnetic fields. They carry energy and permeate space. *The culprit for inflation is a new hypothetical field, which we call the "inflaton".*

Not as crazy as it sounds. String theory, for instance, is infested with such fields, some of which can lead to successful inflation.

2. Potential energy: In mechanics, potential energy is associated with interactions. Fields that interact therefore also have potential energy. Since fields permeate space, so does their potential energy. *The potential energy associated with our hypothetical field arises from interactions with itself.*

3. Potential energy is a form of energy with negative pressure. *The potential energy of the inflaton is what causes inflation.*

Alan Guth (MIT)

Paul Steinhardt (Princeton)

Andrei Linde (Stanford)

Andy Albrecht (UC Davis)

3. Potential energy is a form of energy with negative pressure. *The potential energy of the inflaton is what causes inflation.*

Alan Guth (MIT)

Paul Steinhardt (Princeton)

Andrei Linde (Stanford)

Andy Albrecht (UC Davis)

4. If there is any matter present early on, it will rapidly get diluted by the exponential expansion of inflation. So an inflating universe is nearly empty.

As usual, potential energy can be converted into other forms of energy. *The potential energy of our inflaton gets converted into matter and radiation. This marks the end of inflation, and the model matches on to the standard big bang story.*

As an analogy, consider particle with potential $V(x)$, which starts "at the top of the hill":

- Initially, particle rolls slowly
  => total E is mostly potential

- When it rolls off the flat part, potential gets converted to kinetic energy.

As an analogy, consider particle with potential $V(x)$, which starts "at the top of the hill":

- Initially, particle rolls slowly
  => total E is mostly potential
- When it rolls off the flat part, potential gets converted to kinetic energy.

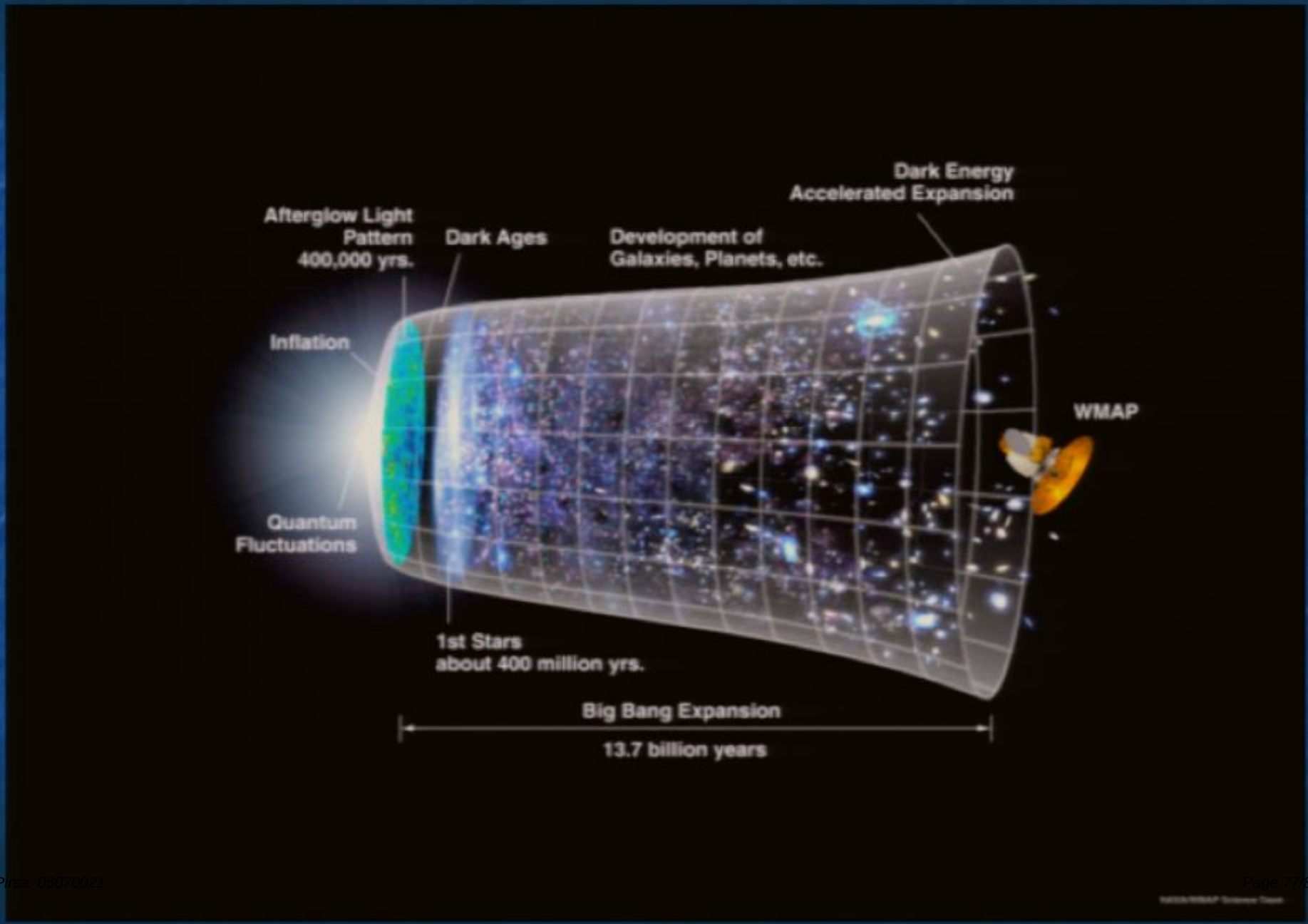
Our inflaton field behaves very much like this particle, except that it and its potential energy are at every point in space. Apart from this subtle difference, the story is virtually the same:

Potential energy => Kinetic energy => Matter and radiation

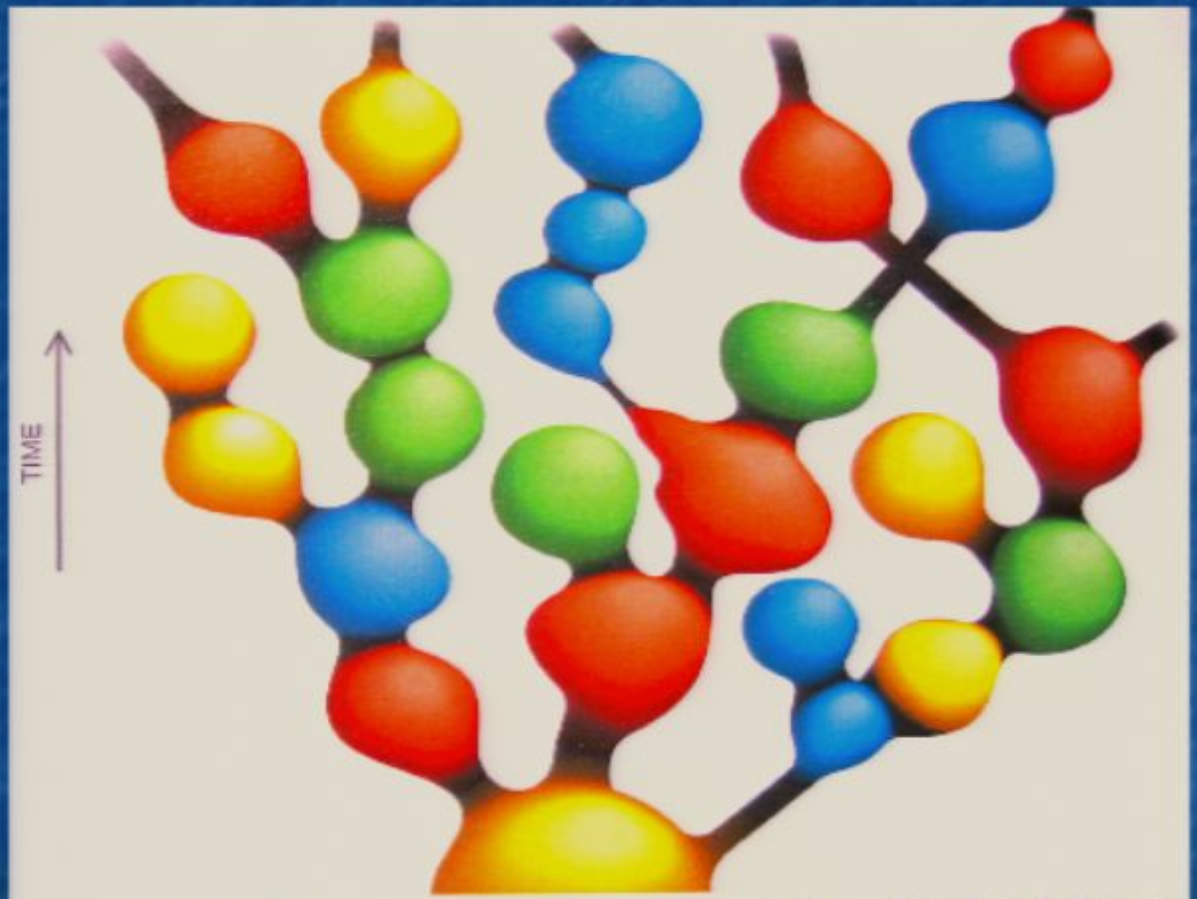
Drives inflation

Standard big bang story

The story of our observable universe:



Then add quantum mechanics to the story: it is possible for inflaton to fluctuate up the hill. This keeps inflation going. Although our observable universe stopped inflating, "out there" space is still inflating, creating (infinitely-many) other pocket universes.



SELF-REPRODUCING COSMOS appears as an extended branching of inflationary bubbles. Changes in color represent "mutations" in the laws of physics from parent universes. The properties of space in each bubble do not depend on the time when the bubble formed. In this sense, the universe as a whole may be stationary, even though the interior of each bubble is described by the big bang theory.

(from Andrei Linde)

As an analogy, consider particle with potential $V(x)$, which starts "at the top of the hill":

- Initially, particle rolls slowly
  => total E is mostly potential
- When it rolls off the flat part, potential gets converted to kinetic energy.

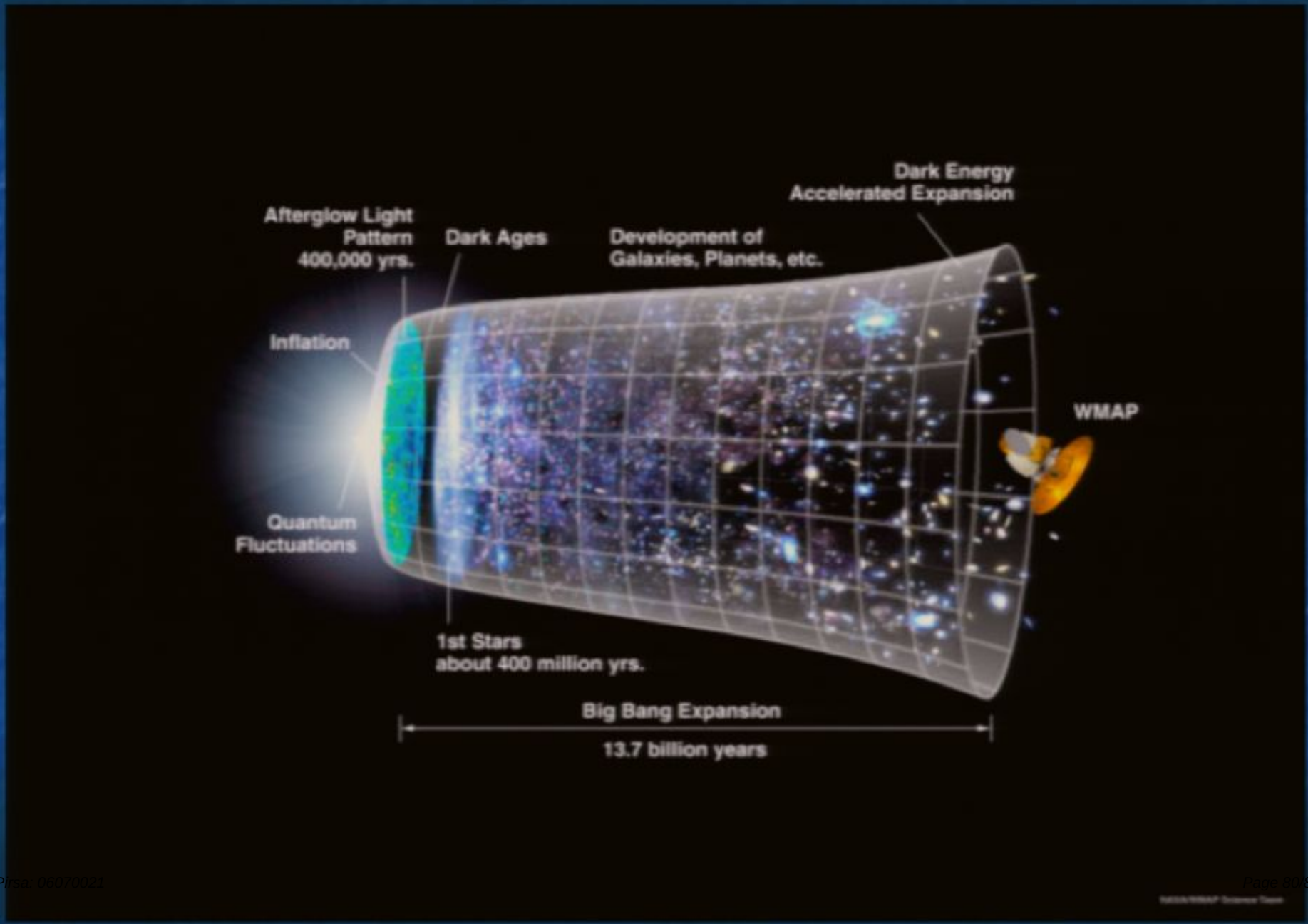
Our inflaton field behaves very much like this particle, except that it and its potential energy are at every point in space. Apart from this subtle difference, the story is virtually the same:

Potential energy => Kinetic energy => Matter and radiation

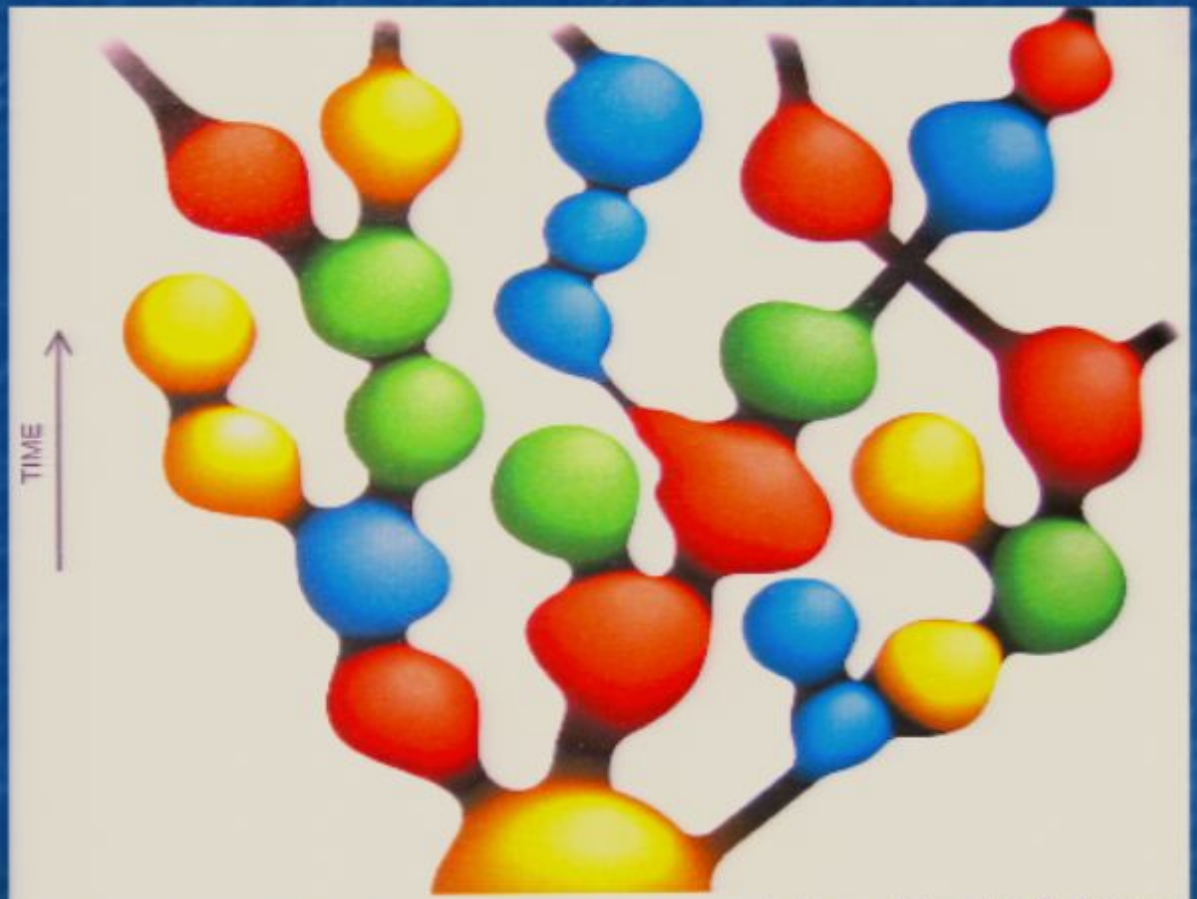
Drives inflation

Standard big bang story

The story of our observable universe:



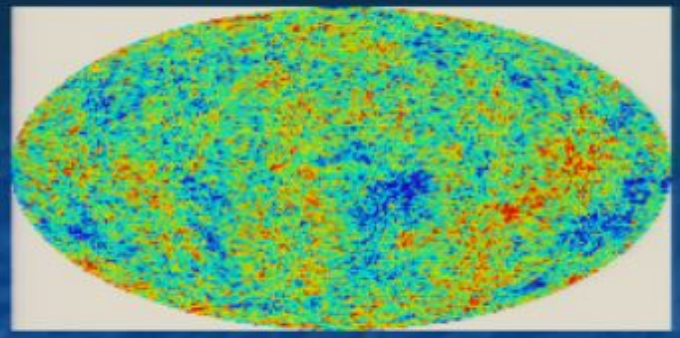
Then add quantum mechanics to the story: it is possible for inflaton to fluctuate up the hill. This keeps inflation going. Although our observable universe stopped inflating, "out there" space is still inflating, creating (infinitely-many) other pocket universes.



SELF-REPRODUCING COSMOS appears as an extended branching of inflationary bubbles. Changes in color represent "mutations" in the laws of physics from parent universes. The properties of space in each bubble do not depend on the time when the bubble formed. In this sense, the universe as a whole may be stationary, even though the interior of each bubble is described by the big bang theory.

(from Andrei Linde)

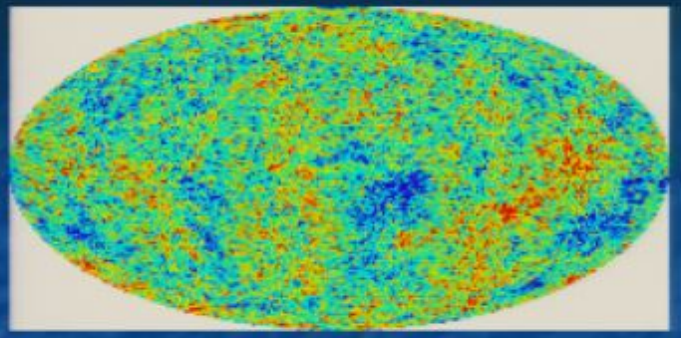
A few remarks to conclude:



- Observations are testing inflation.
- Inflation does not answer the question of how the universe started. In the past of every observer, there is still a big bang.
- Alternative ideas propose that big bang is a bridge between contracting and expanding universe (ekpyrotic/cyclic models). Big bang is collision between parallel universes (branes).

http://www.physics.princeton.edu/~steinh/

A few remarks to conclude:



- Observations are testing inflation.
- Inflation does not answer the question of how the universe started. In the past of every observer, there is still a big bang.
- Alternative ideas propose that big bang is a bridge between contracting and expanding universe (ekpyrotic/cyclic models). Big bang is collision between parallel universes (branes).

http://www.physics.princeton.edu/~steinh/