

Title: What Banged?

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URL: <http://pirsa.org/08030033>

Abstract: The evidence that the universe emerged 14 billion years ago from an event called 'the big bang' is overwhelming. Yet the cause of this event remains deeply mysterious. In the conventional picture, the 'initial singularity' is unexplained. It is simply assumed that the universe somehow sprang into existence full of 'inflationary' energy, blowing up the universe into the large, smooth state we observe today. While this picture is in excellent agreement with current observations, it is both contrived and incomplete, leading us to suspect that it is not the final word. In this lecture, the standard inflationary picture will be contrasted with a new view of the initial singularity suggested by string and M-theory, in which the bang is a far more normal, albeit violent, event which occurred in a pre-existing universe. According to the new picture, a cyclical model of the universe becomes feasible in which one bang is followed by another, in a potentially endless series of cosmic cycles. The presentation will also review exciting recent theoretical developments and forthcoming observational tests which could distinguish between the rival inflationary and cyclical hypotheses. <kw> big bang, cosmology, universe, initial singularity, inflation, string theory, M-theory, pre-existing universe, cyclical model, cosmic cycle, particle physics, dark matter, dark energy</kw>



# March 5, 2008

# Upcoming Public Lectures

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**Professor Jeffrey Rosenthal**  
University of Toronto



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**Professor Gerard 't Hooft**  
Nobel Prize, 1999  
Utrecht University



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Nobel Prize, 1999  
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**Professor Bill Phillips**  
Nobel Prize, 1997  
National Institute of Standards and  
Technology



# March 5, 2008

# *What Banged?*



Neil Turok

# March 5, 2008

## *What Banged?*



**Neil Turok**

- Cambridge University

# March 5, 2008

## *What Banged?*



### Neil Turok

- Cambridge University
- James Clerk Maxwell Medal

# March 5, 2008

## *What Banged?*



### Neil Turok

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- AIMS

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## *What Banged?*



### Neil Turok

- Cambridge University
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- TED Prize

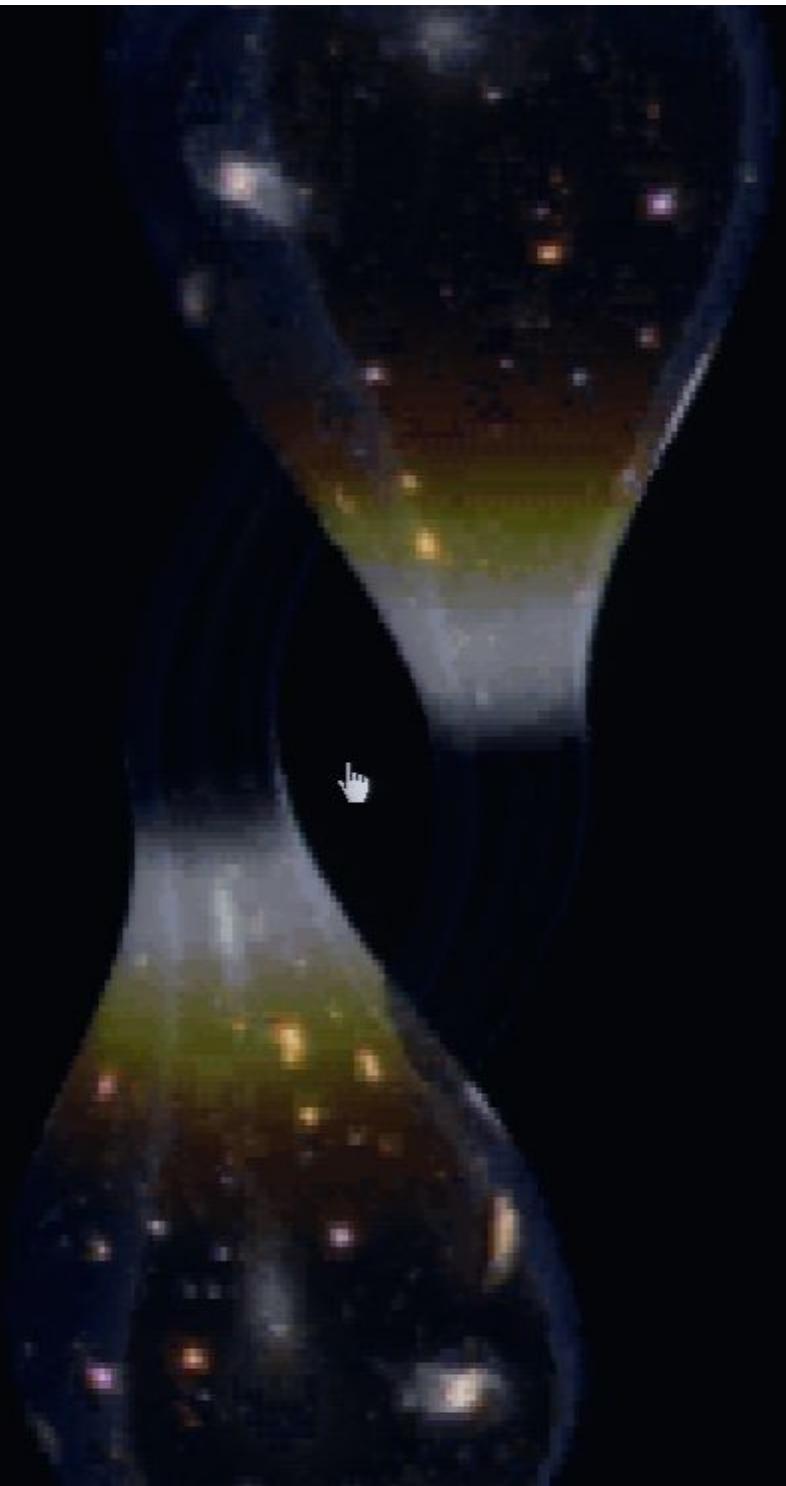
# March 5, 2008

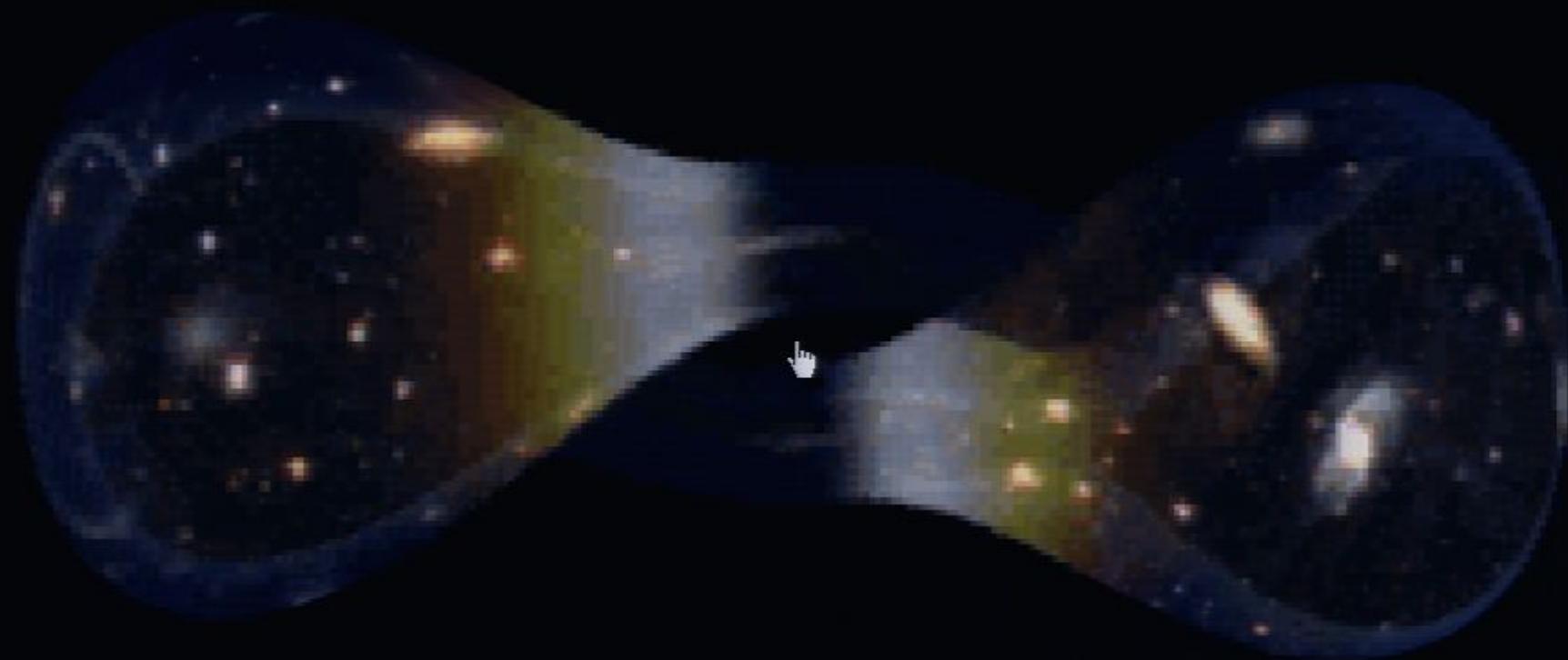
## *What Banged?*

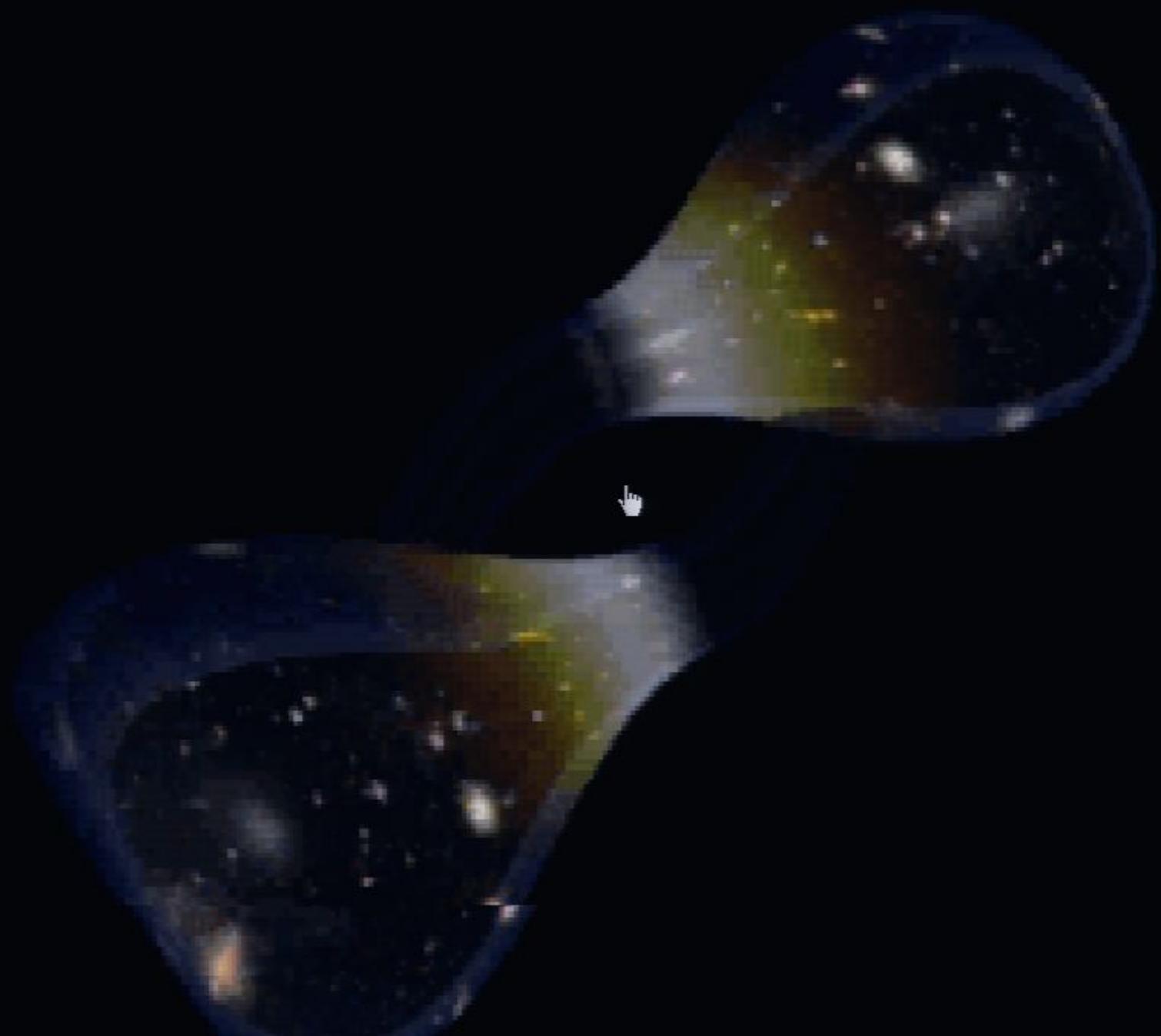


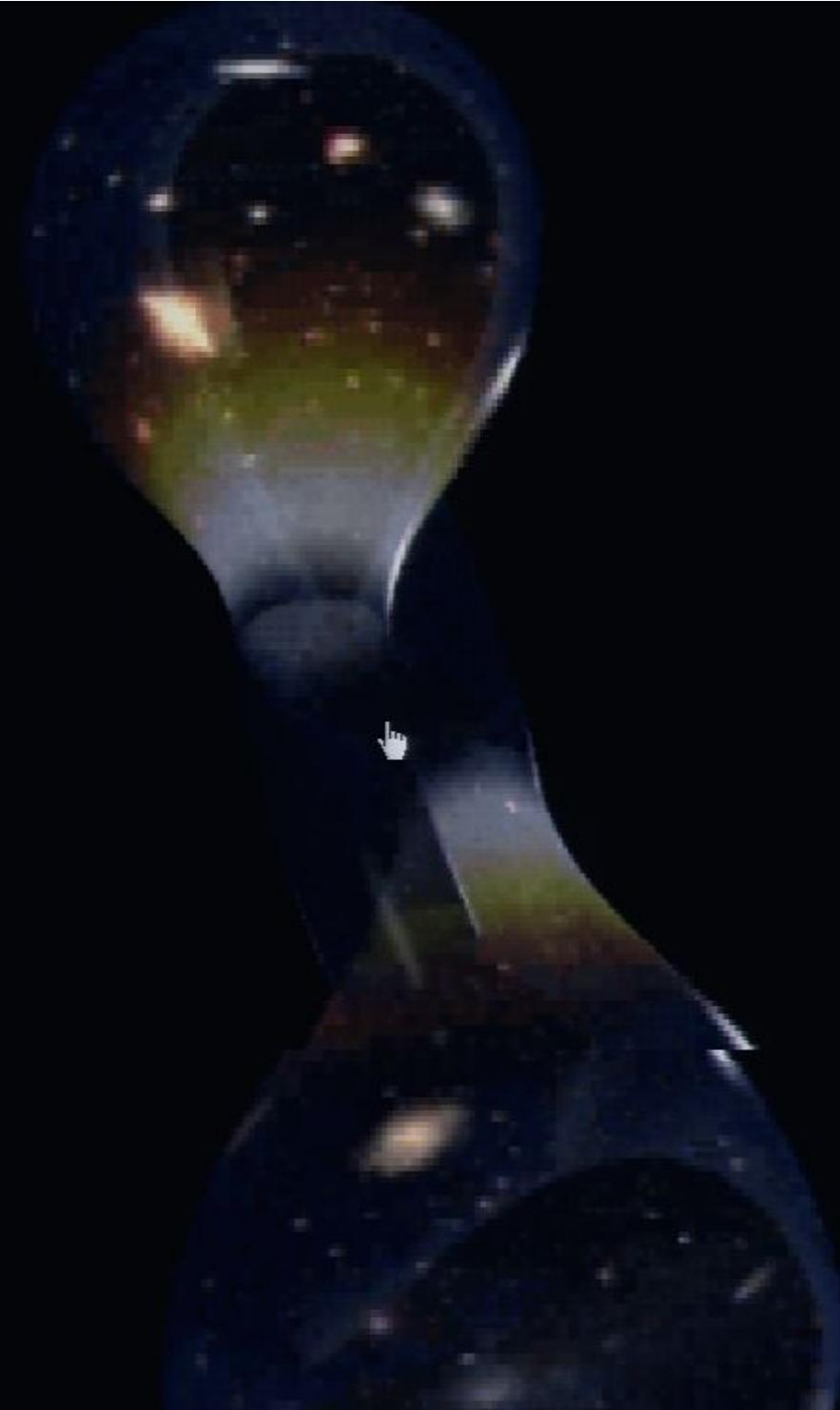
### Neil Turok

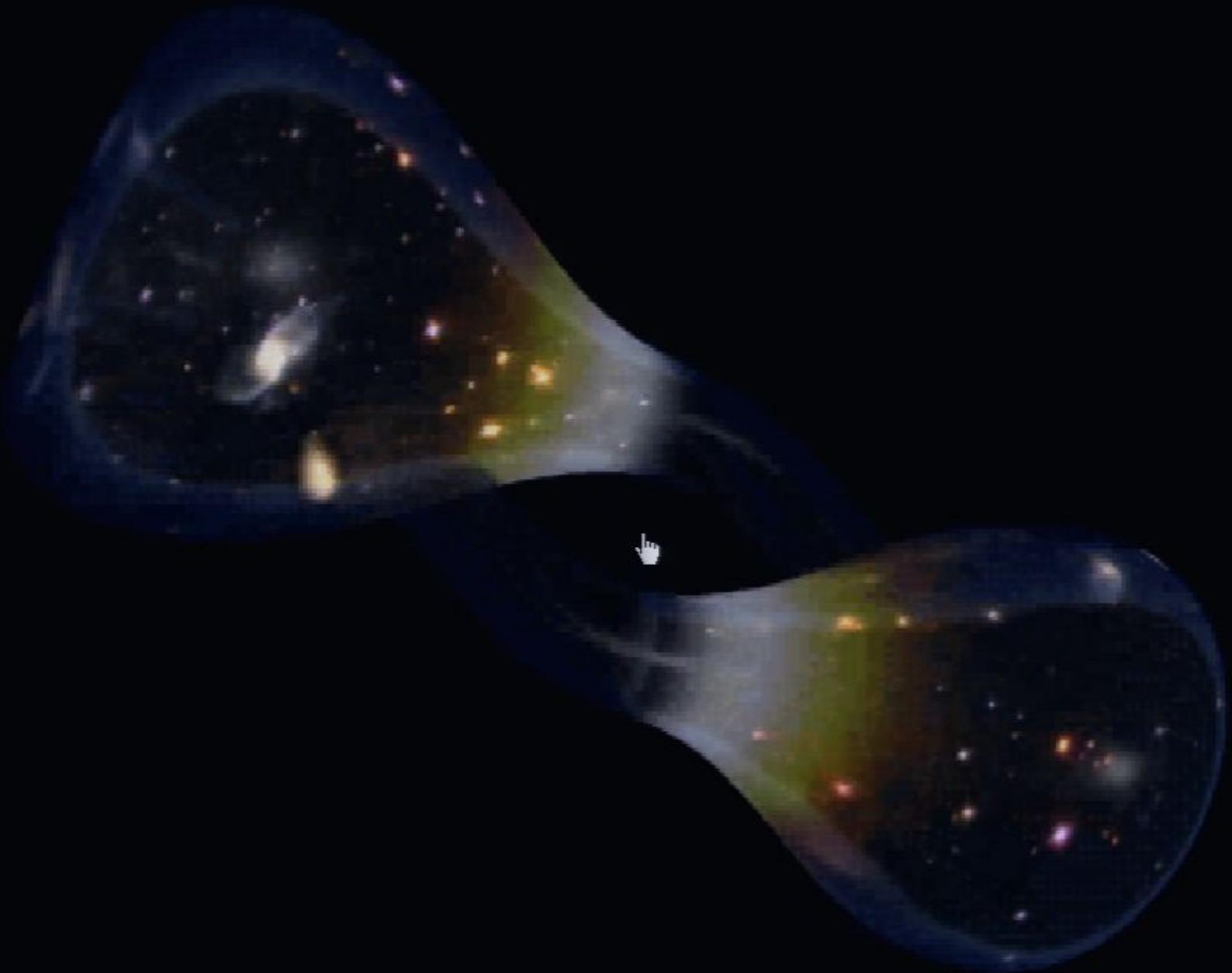
- Cambridge University
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- TED Prize
- PI Scientific Advisory Committee

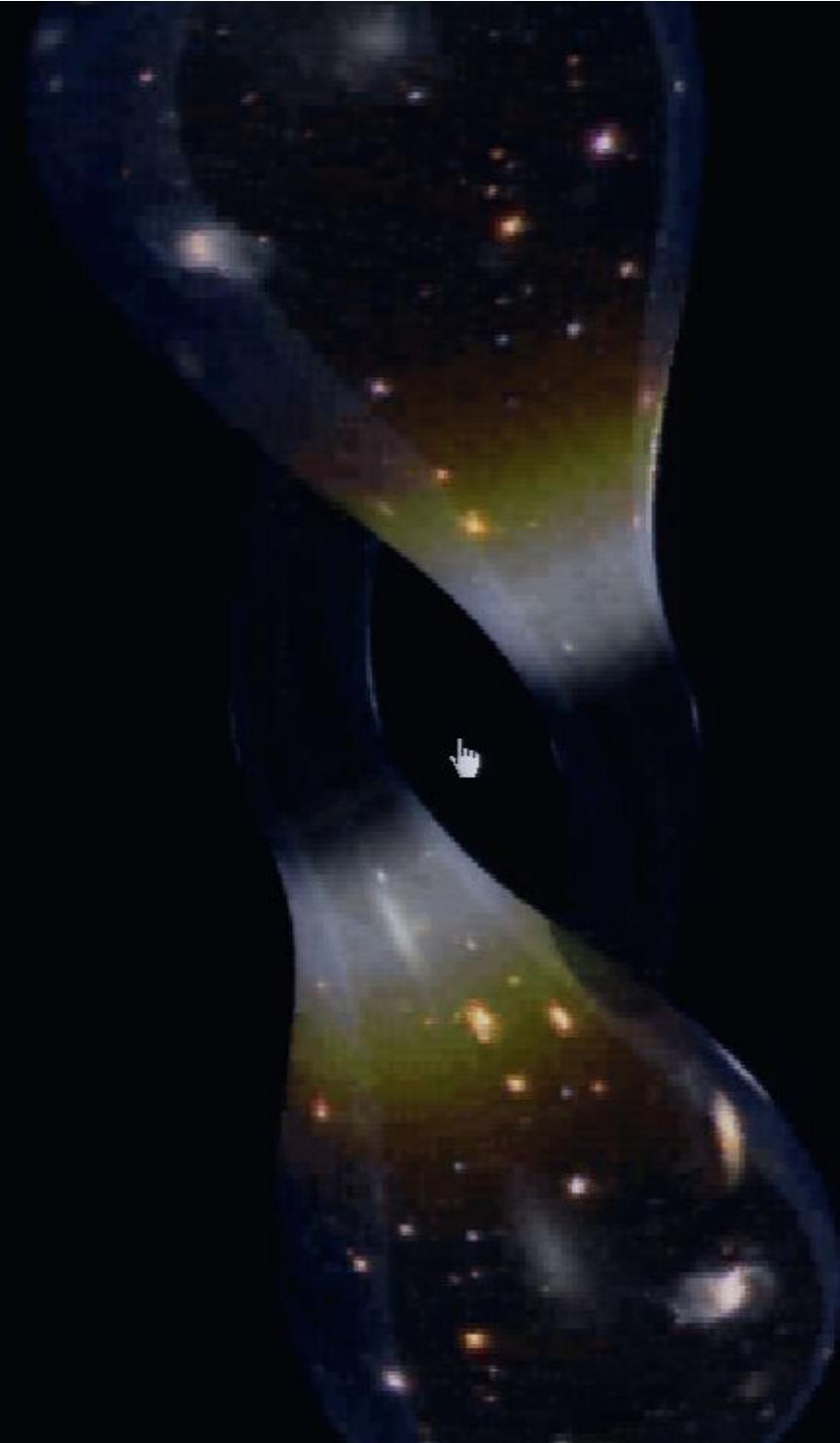


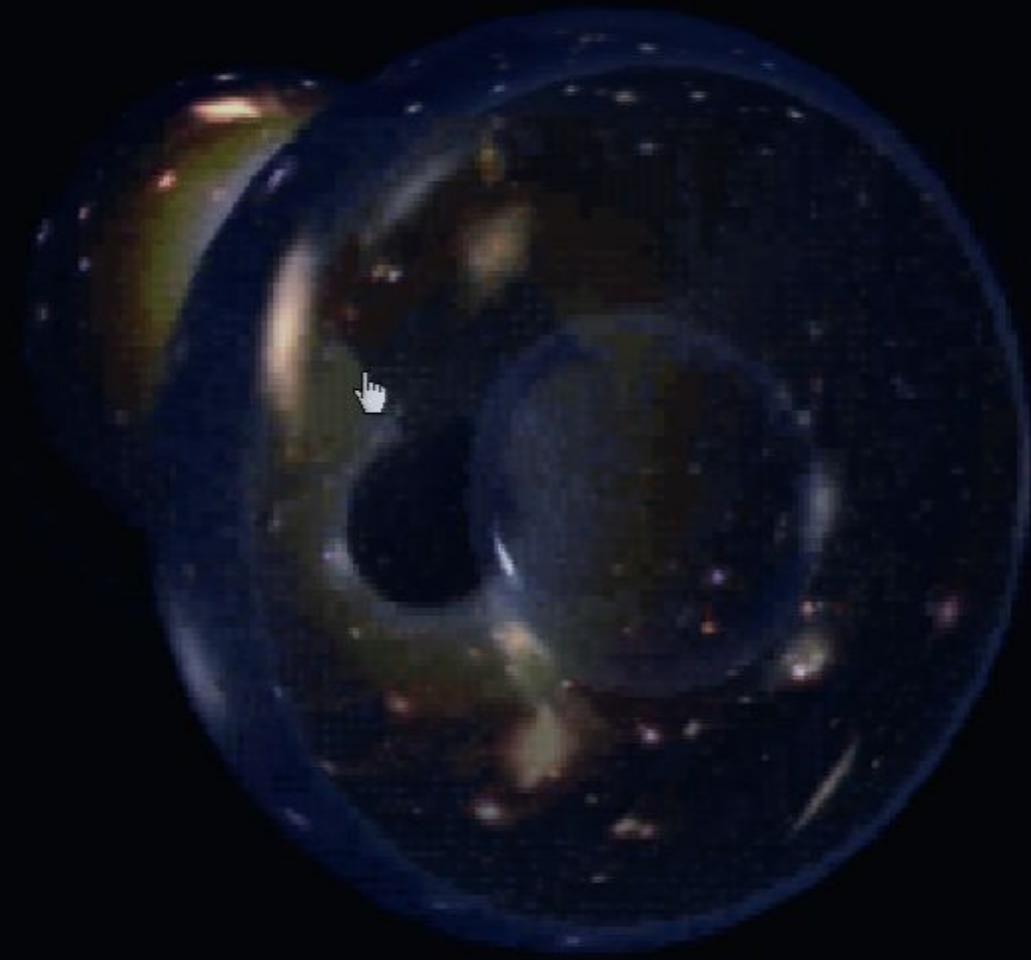


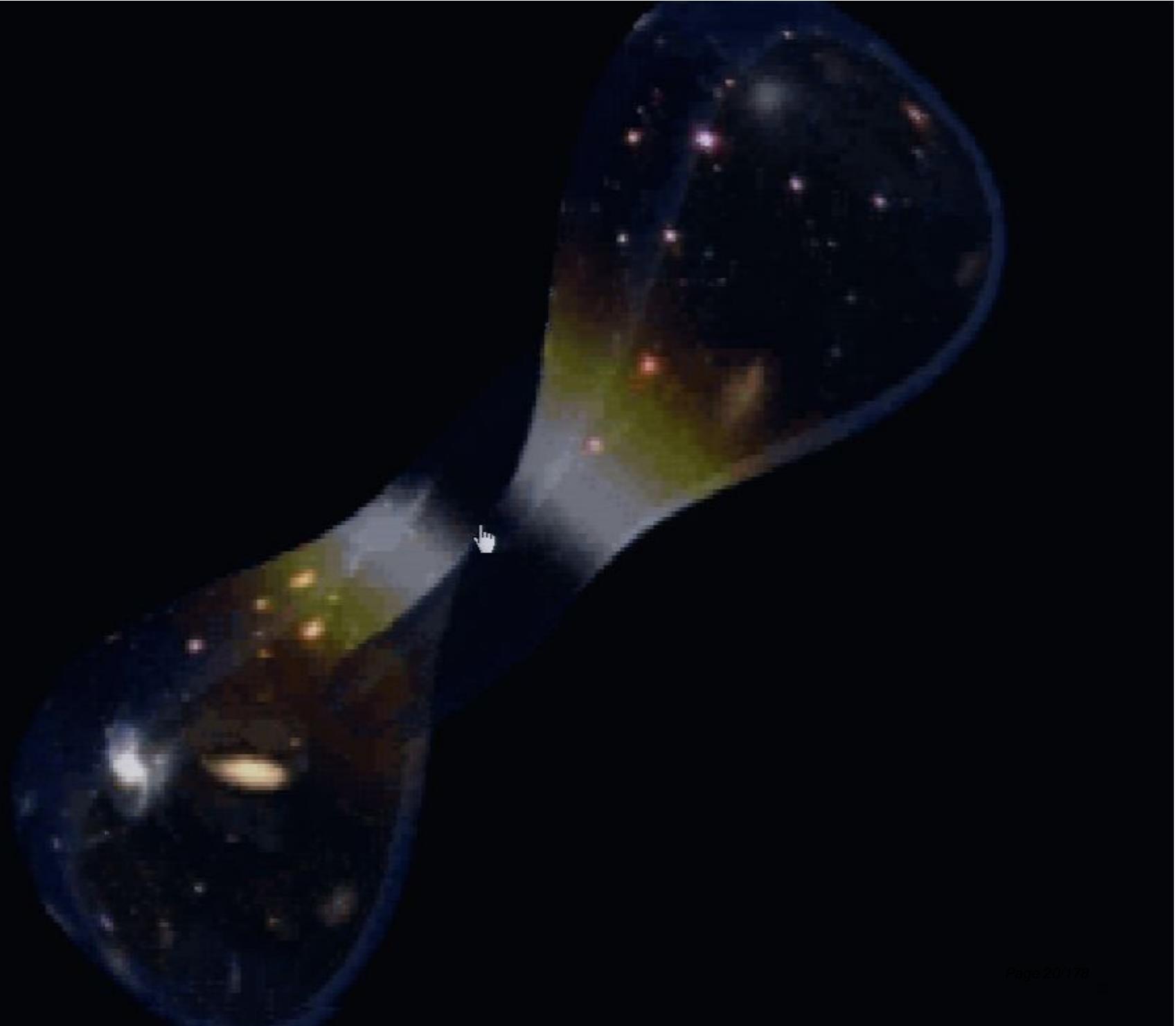




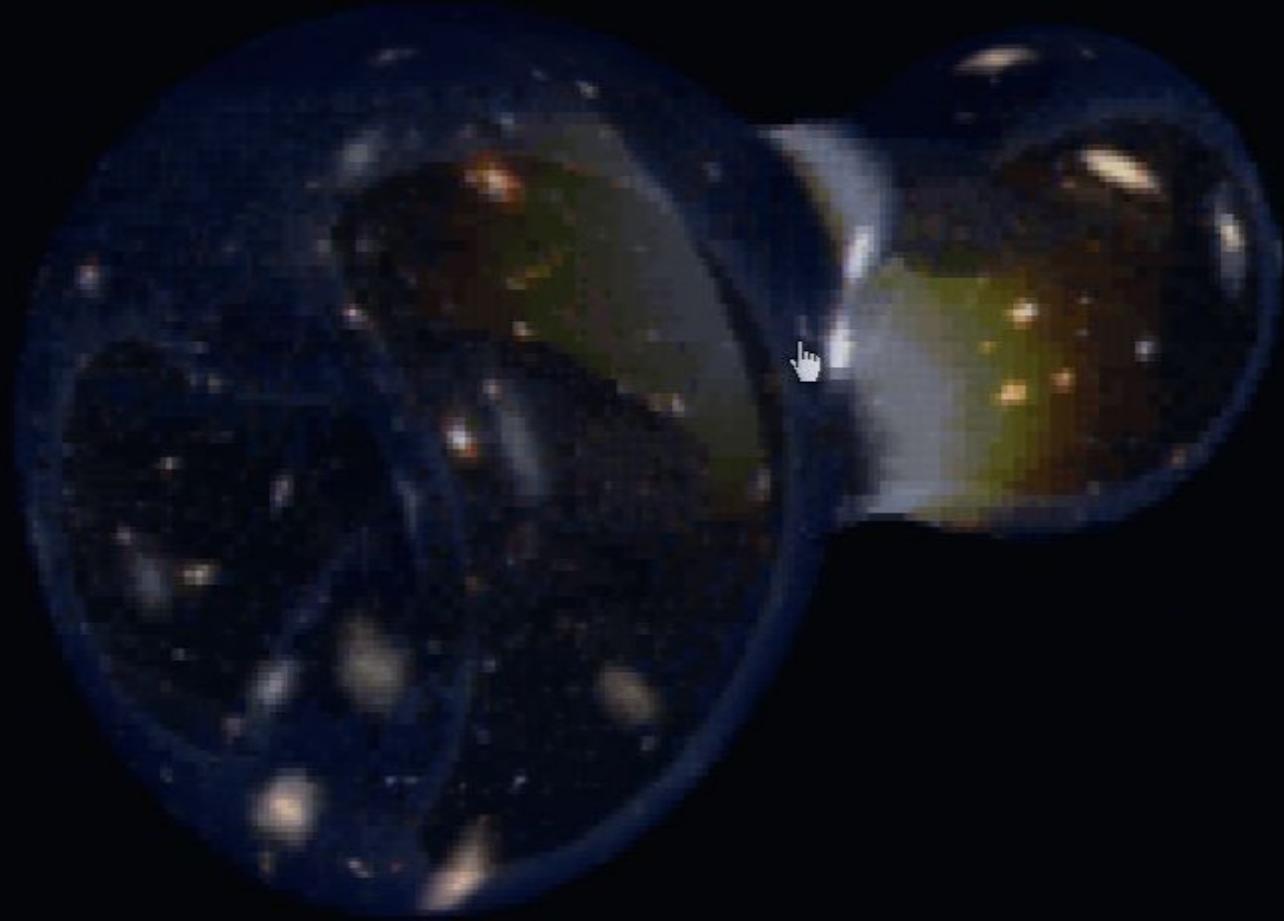


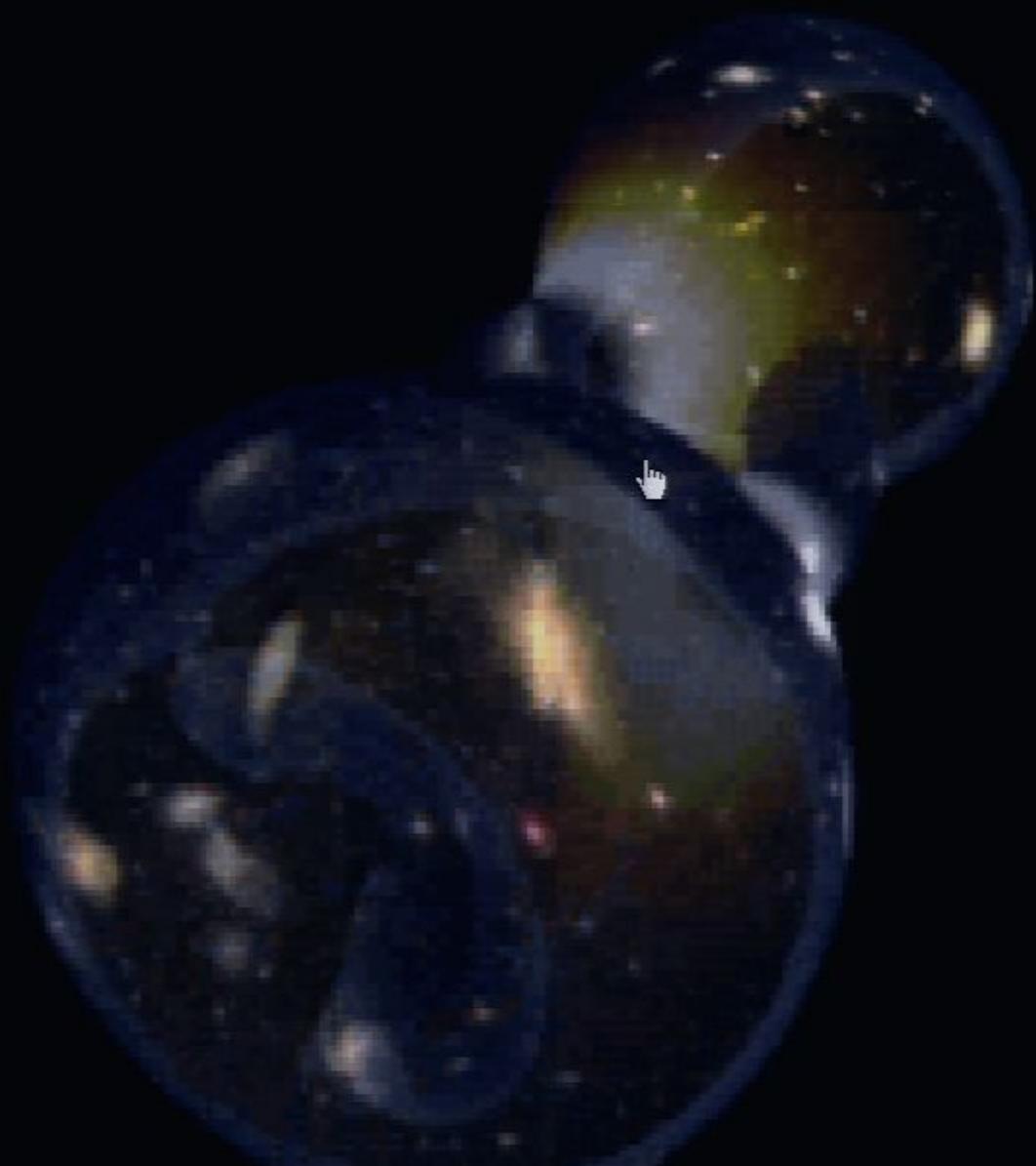


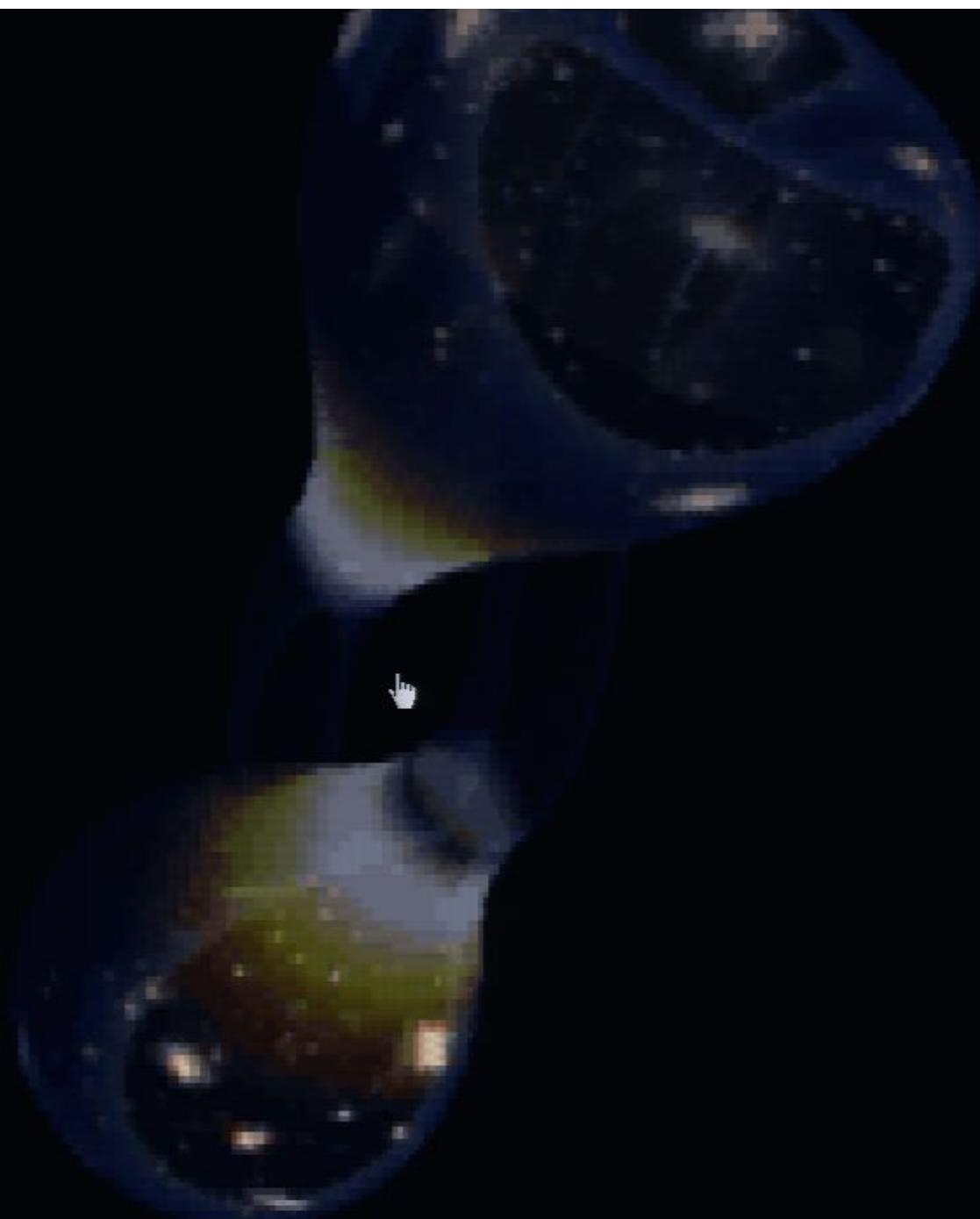


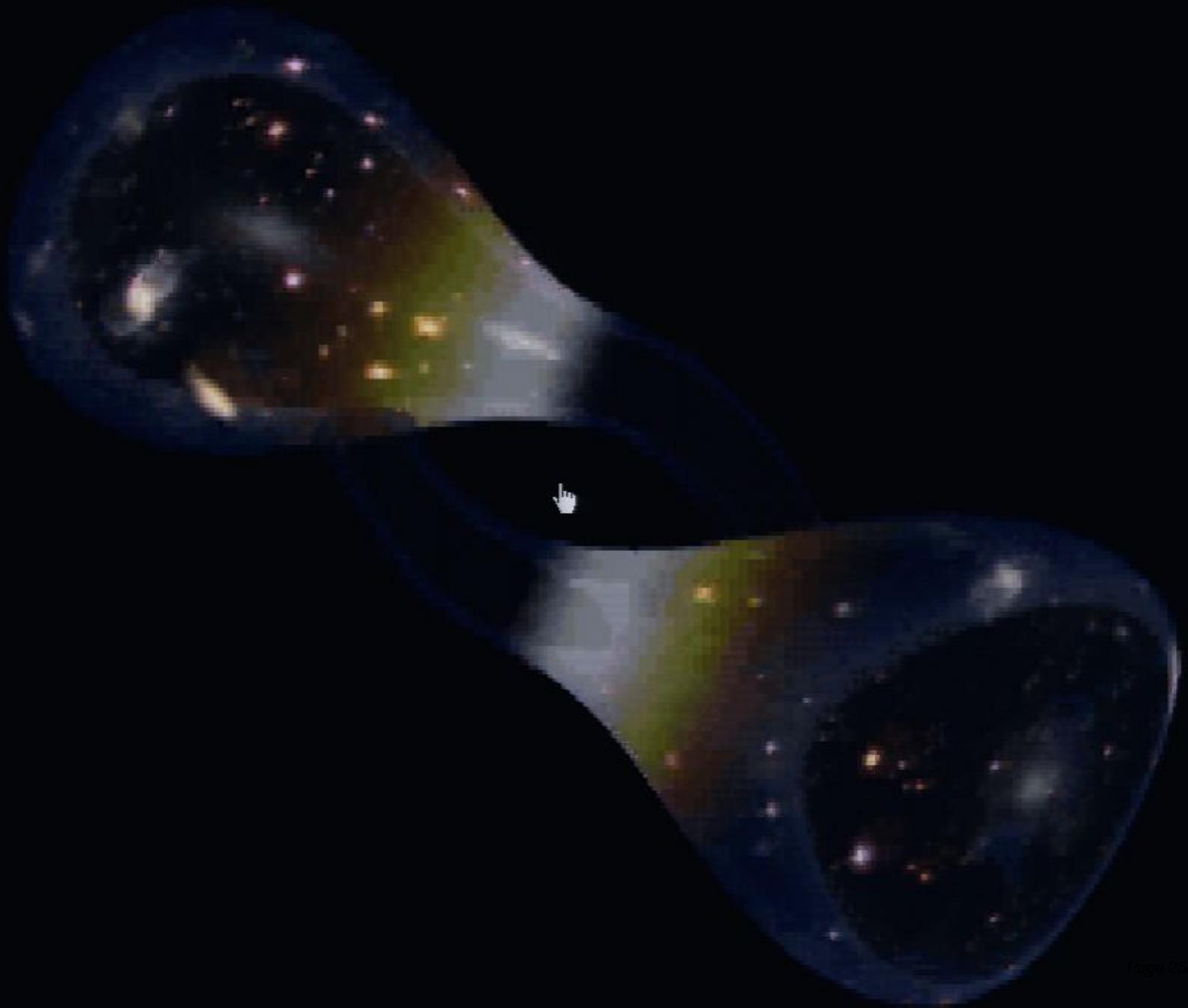




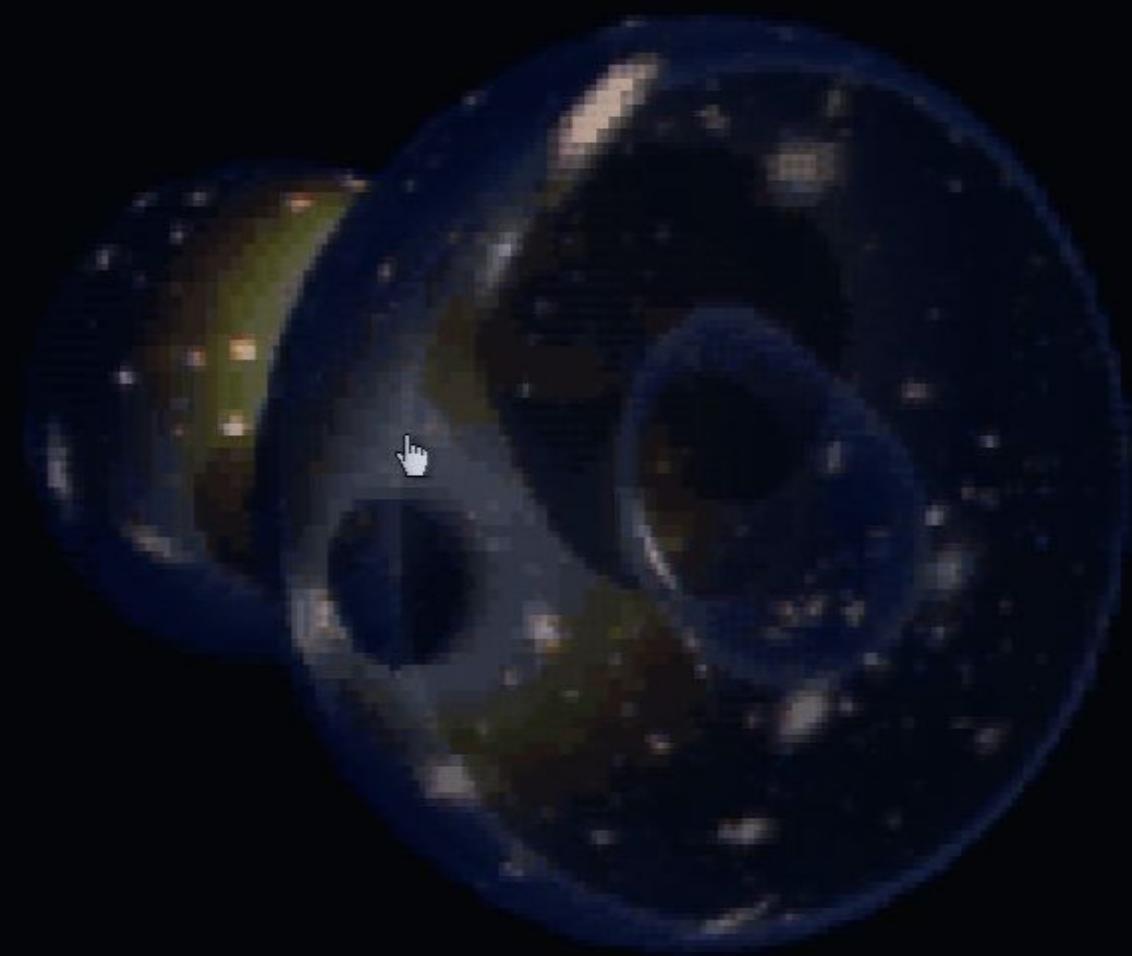


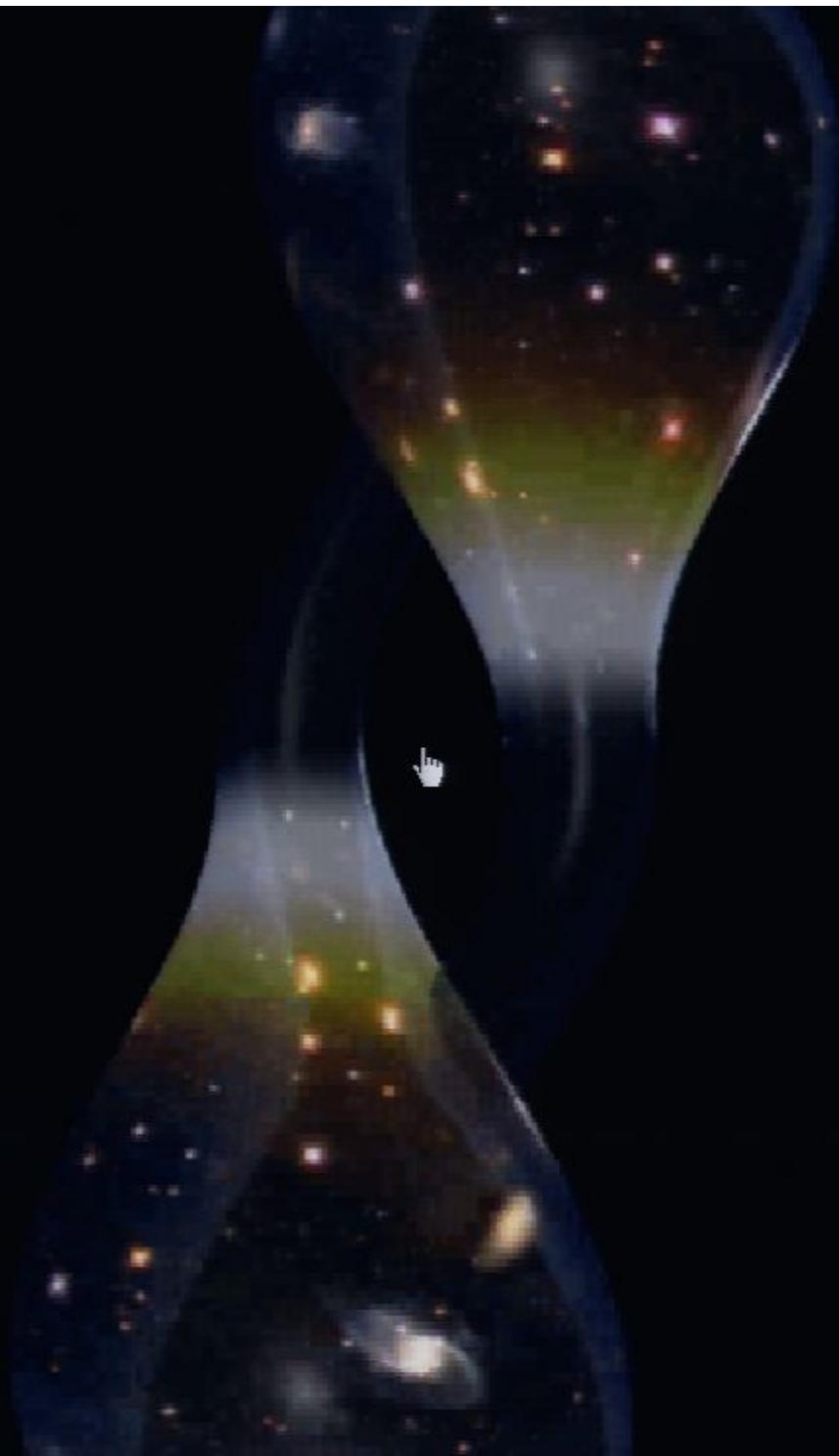


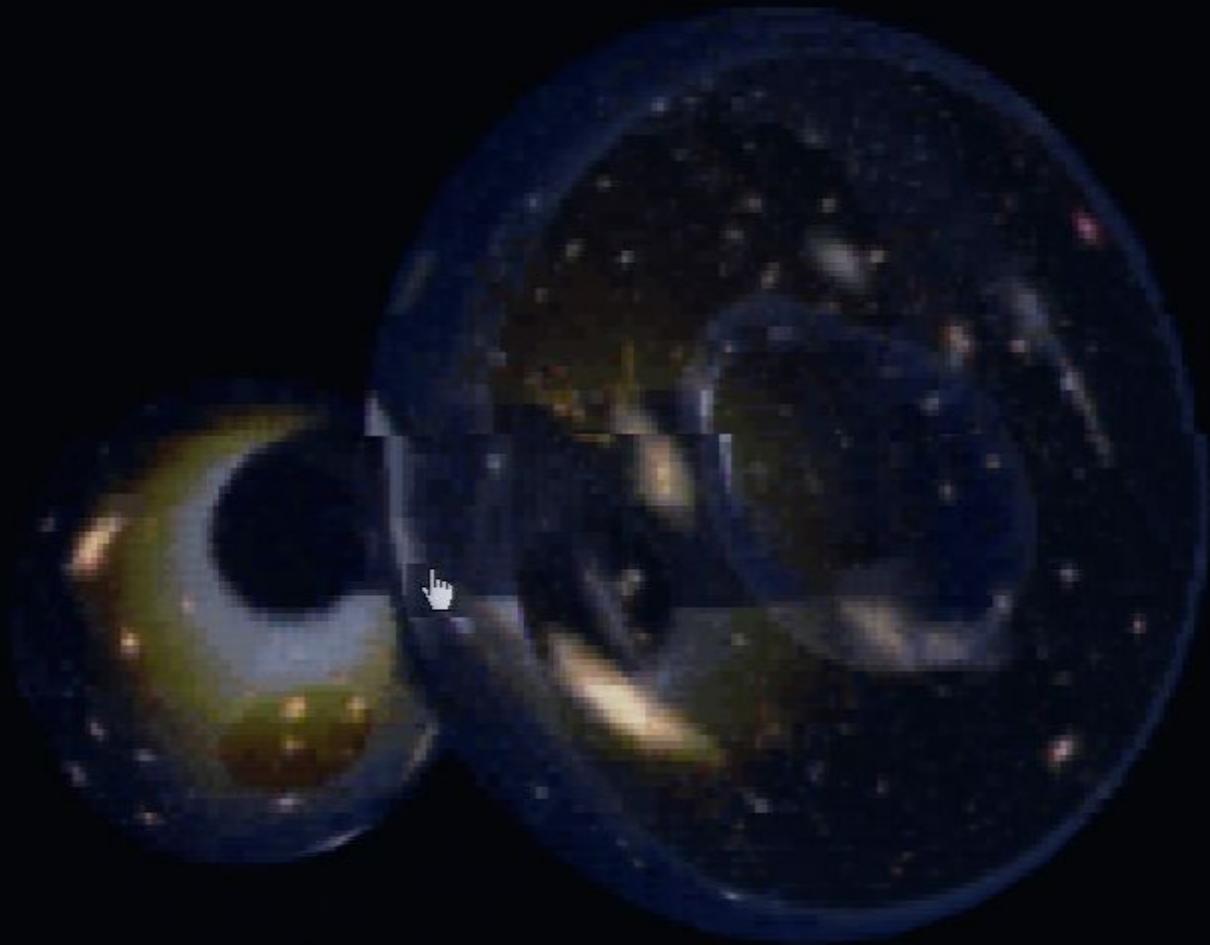


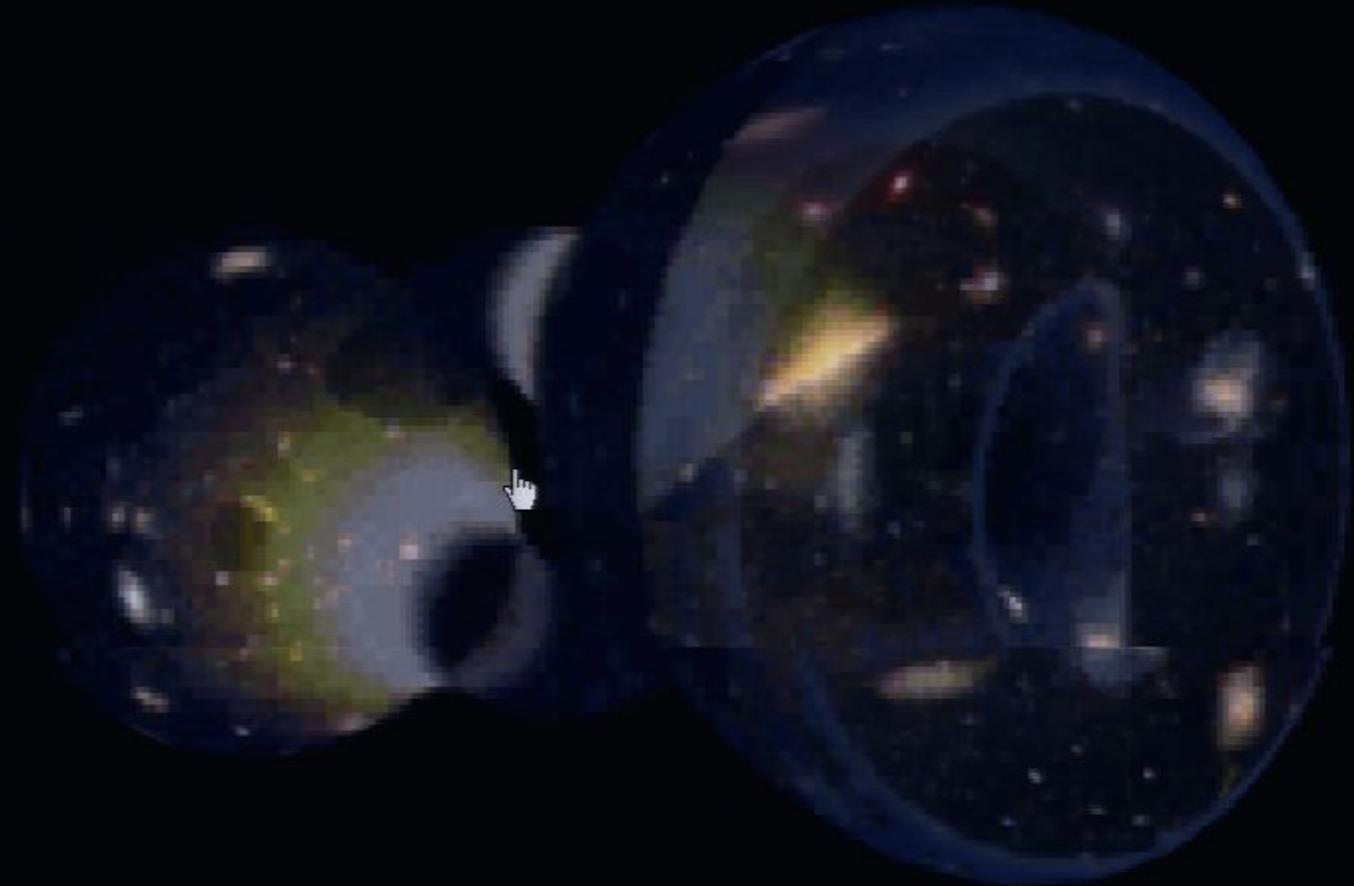


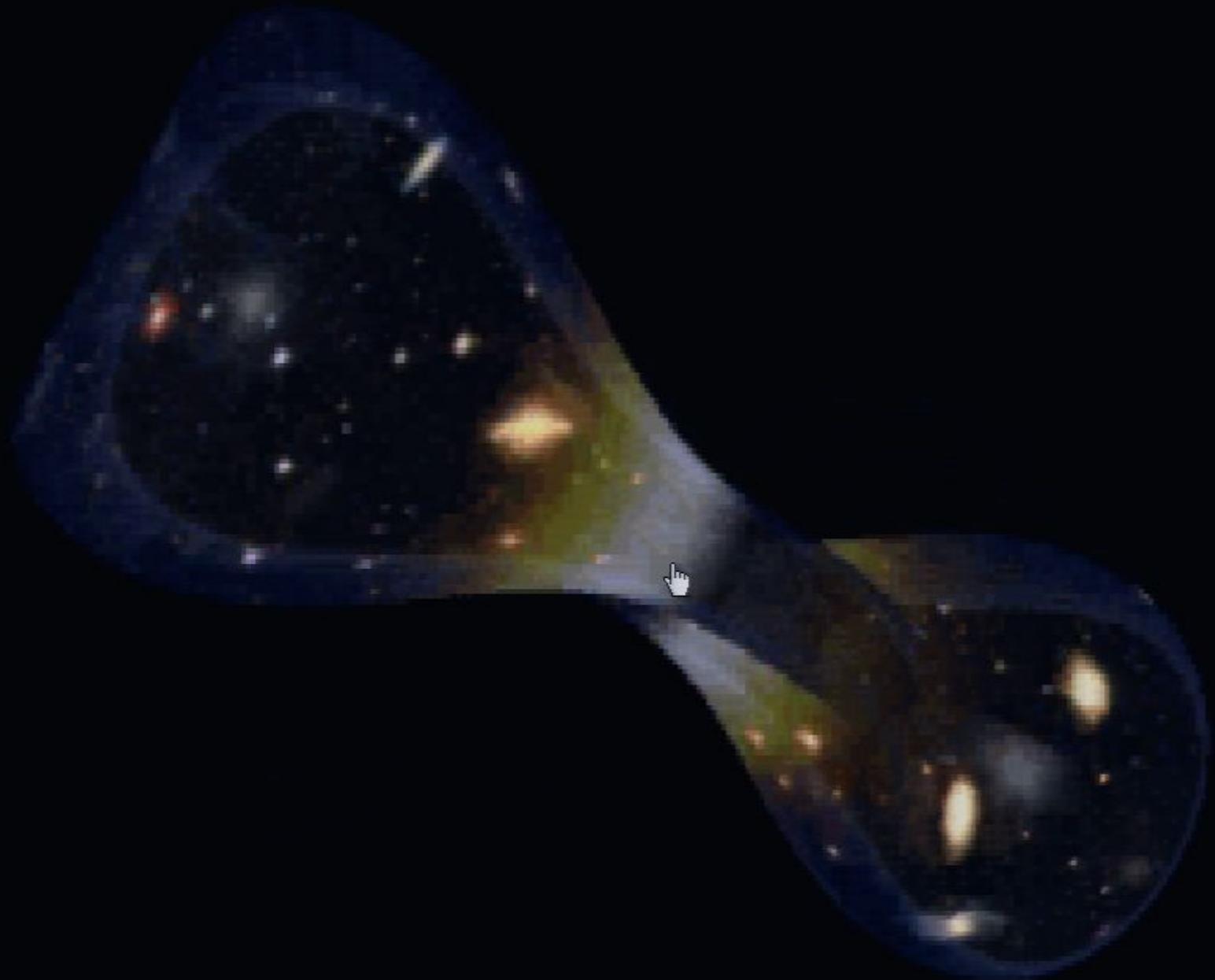


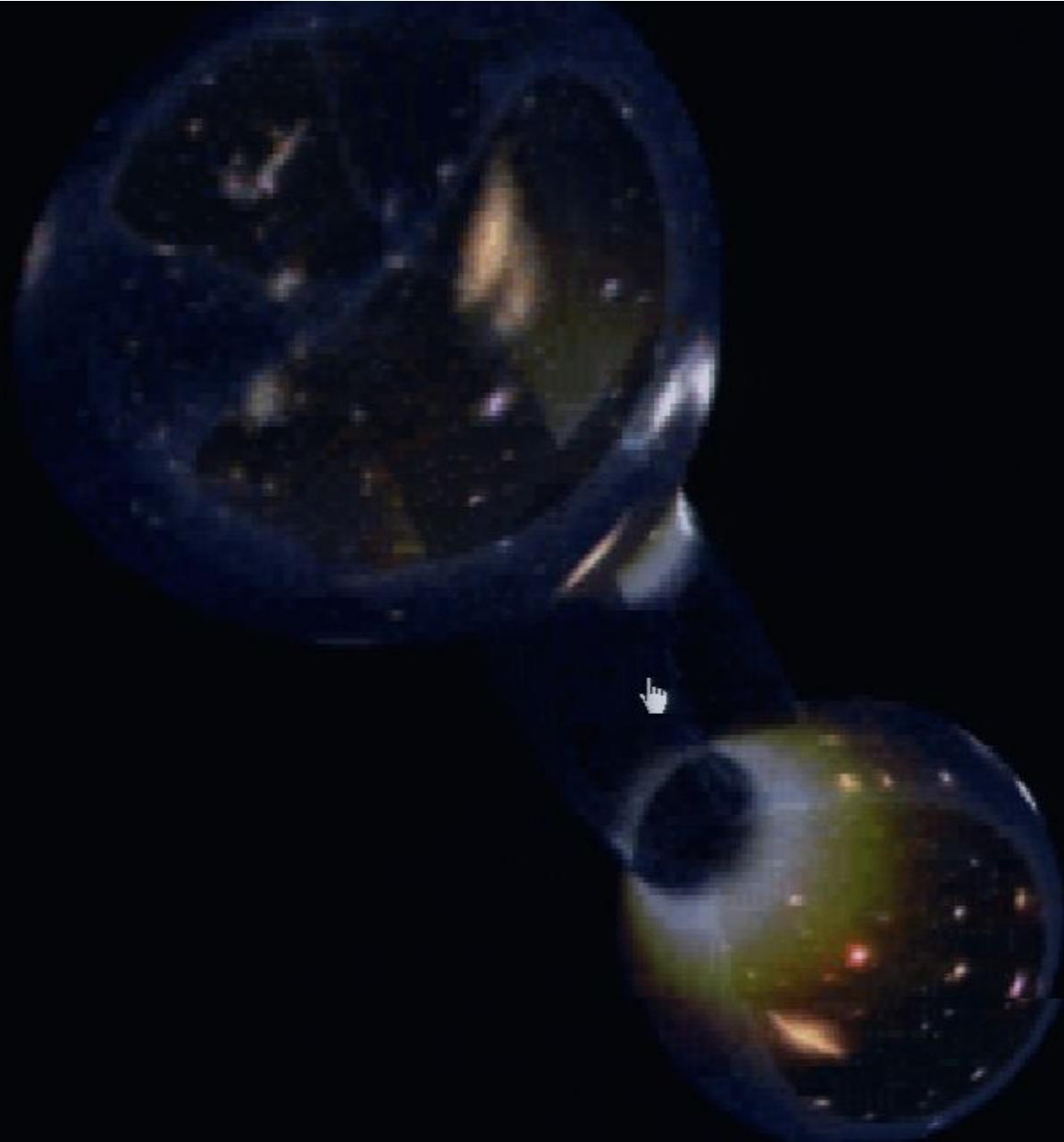




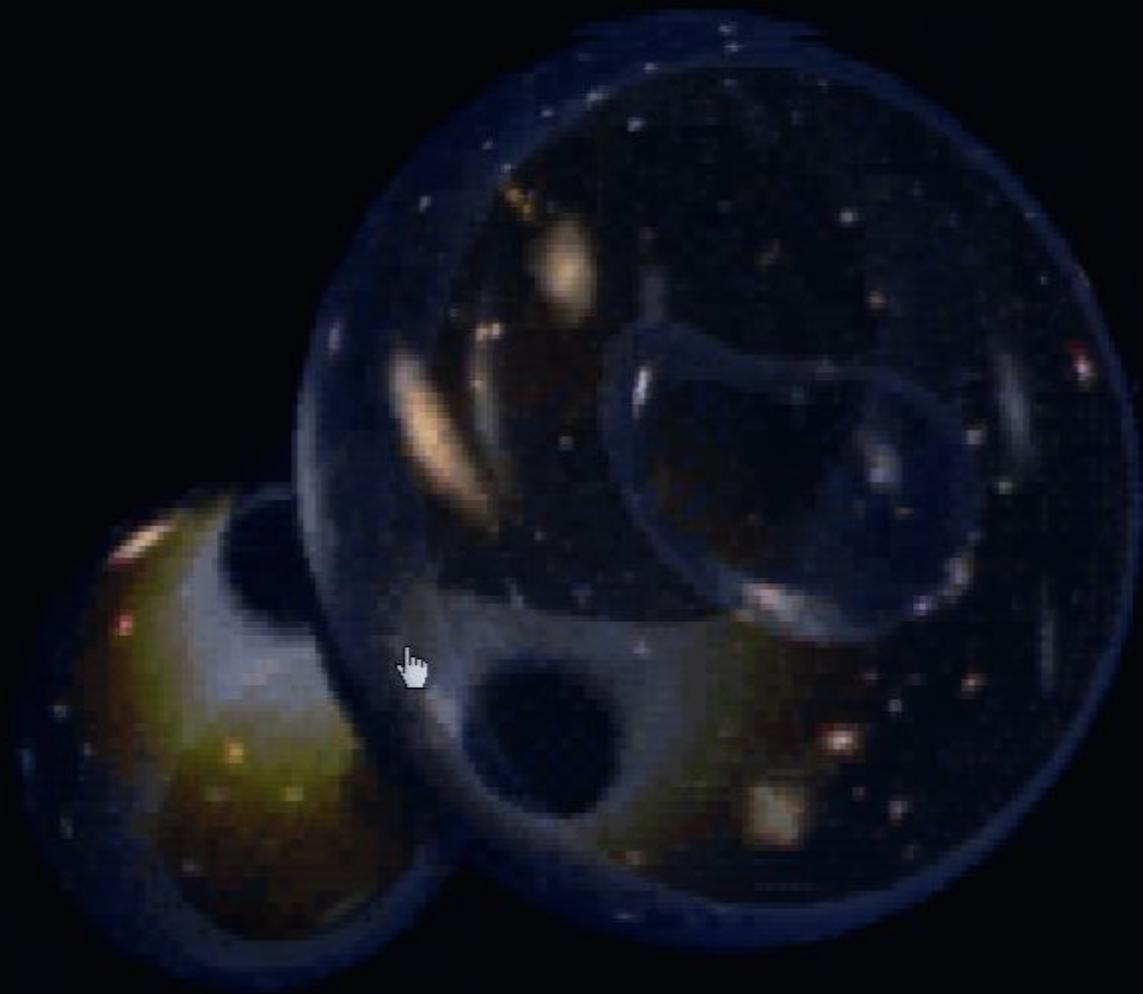


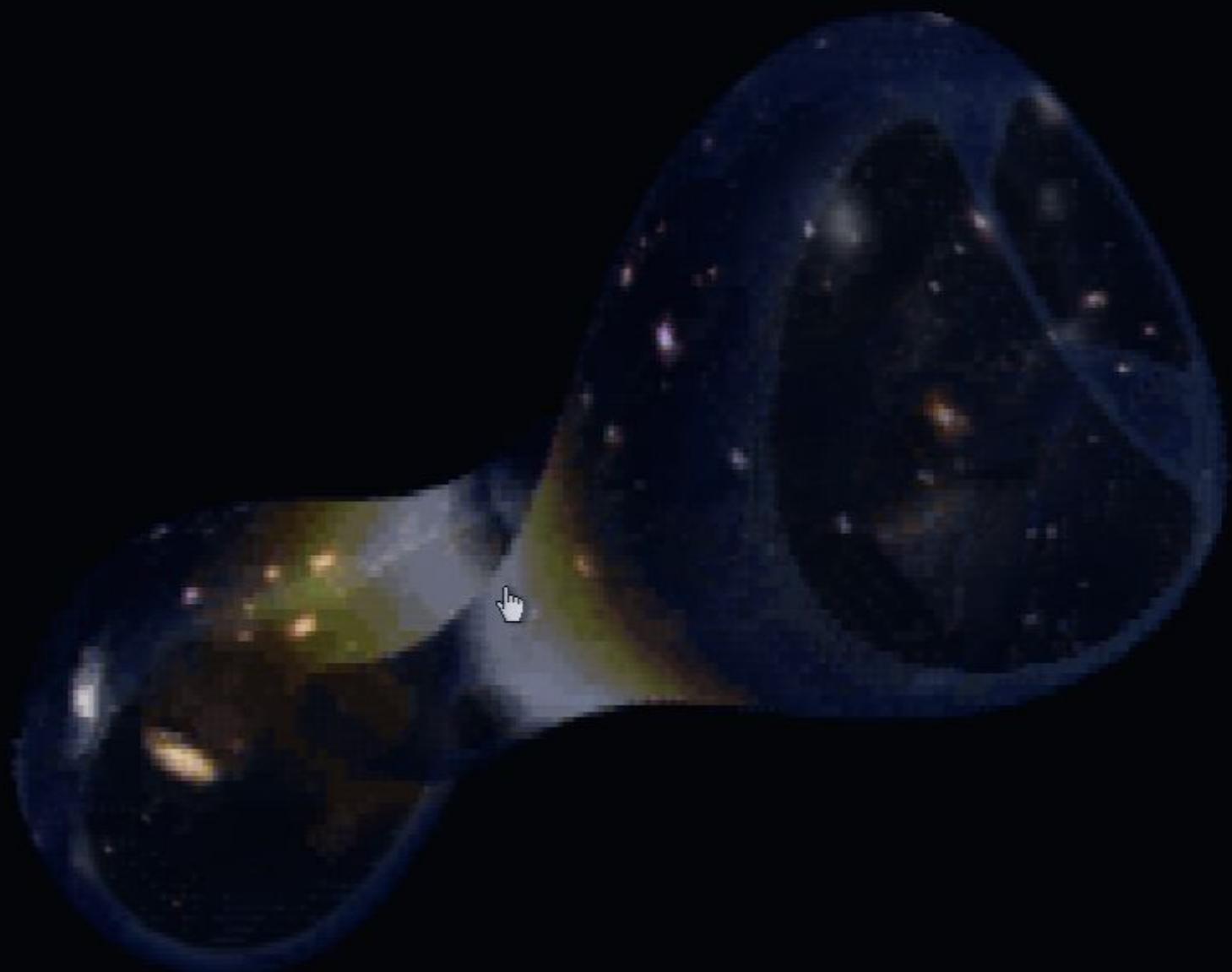


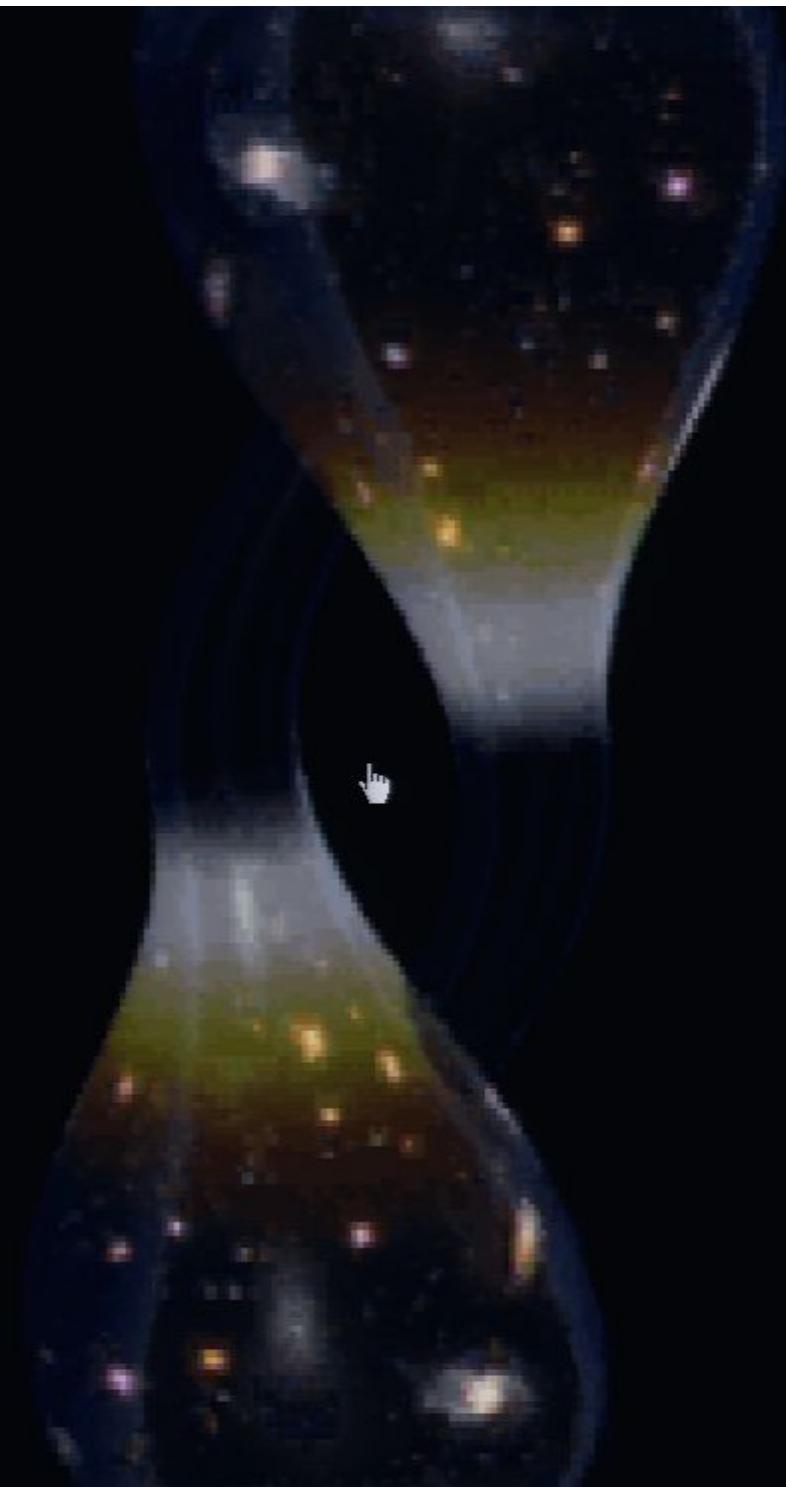


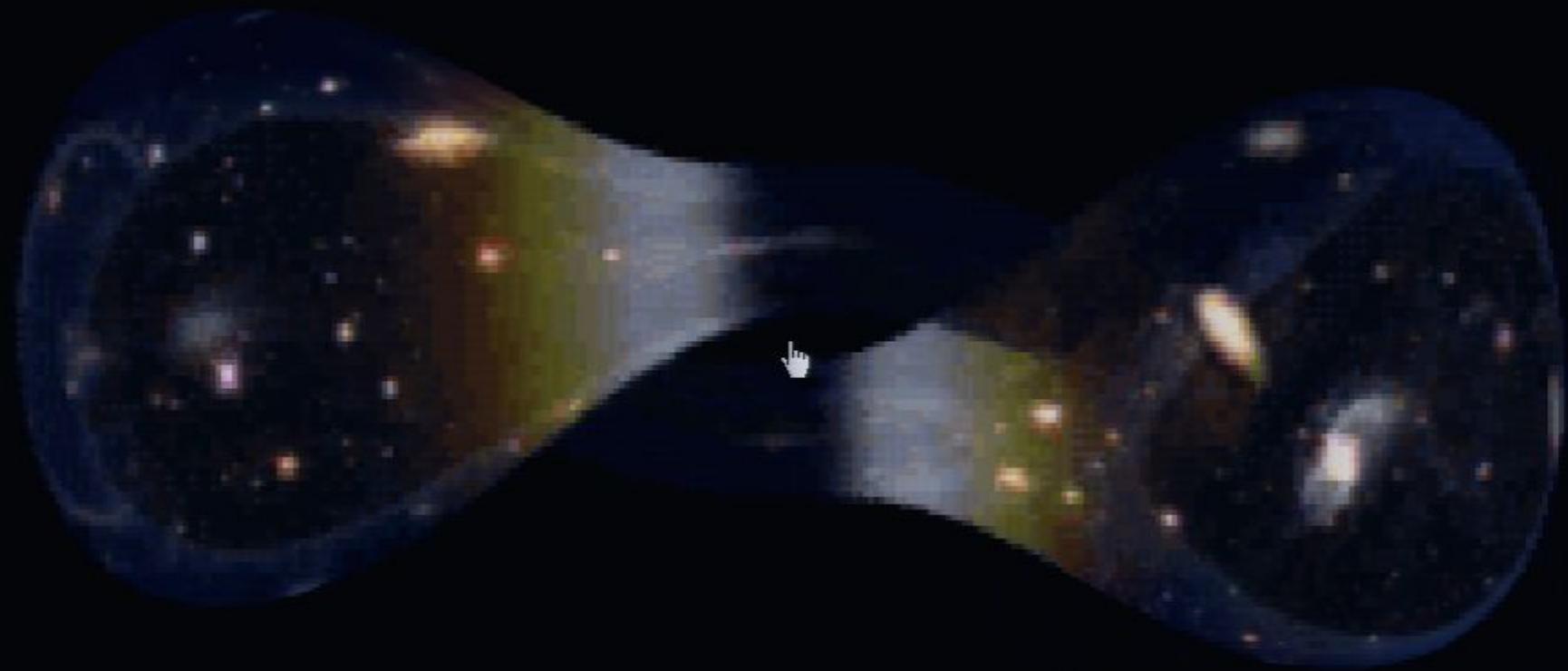


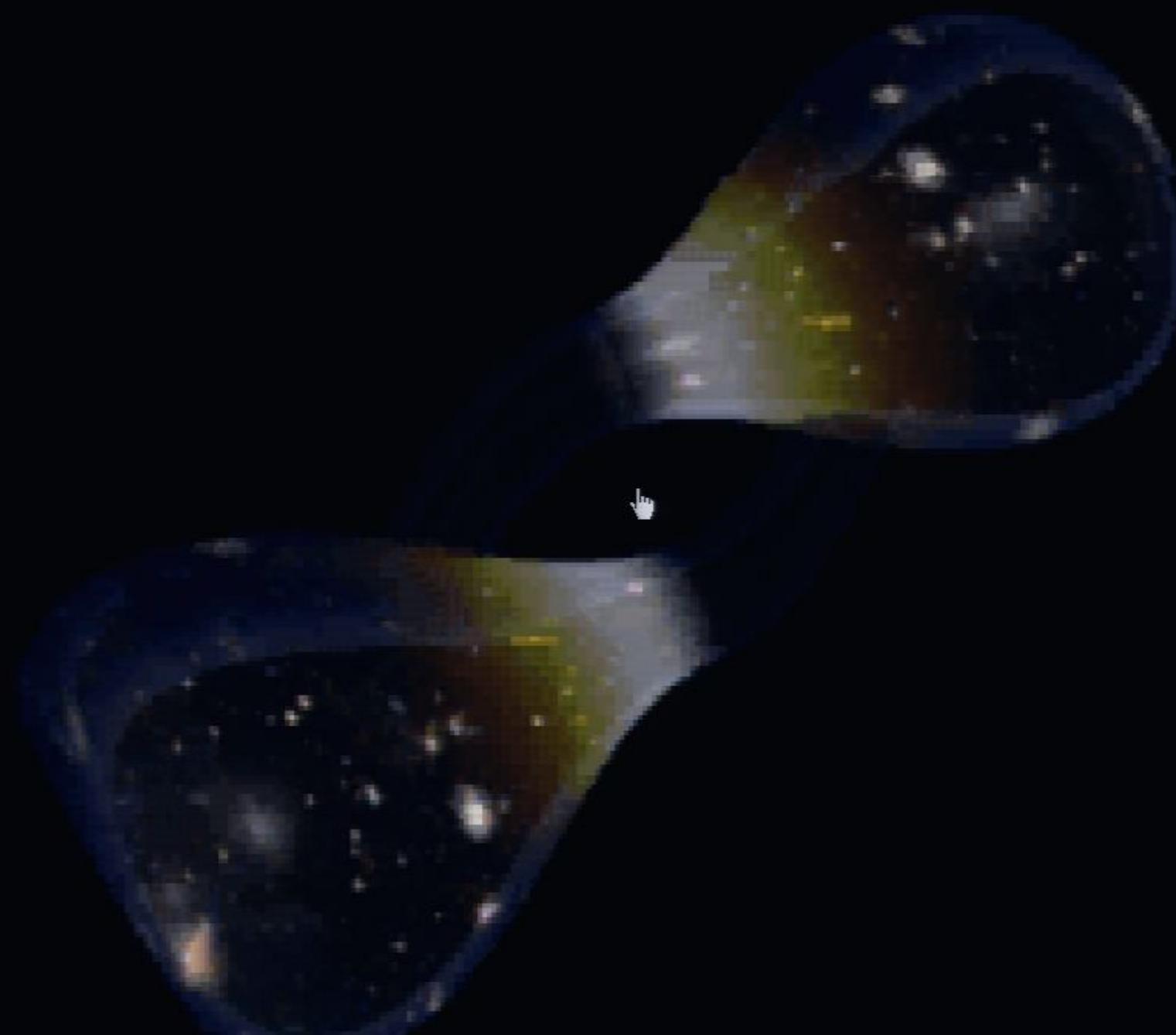


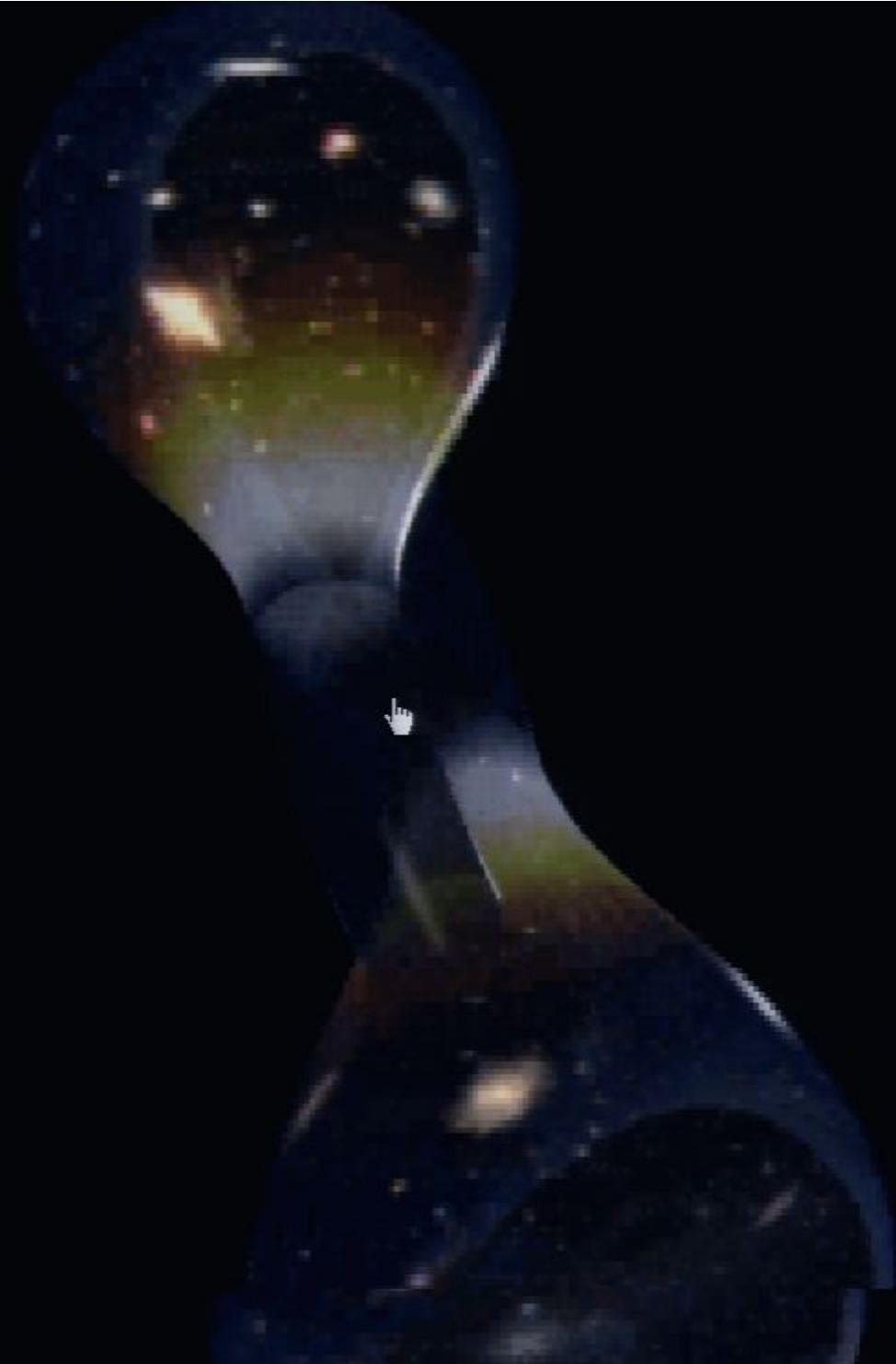


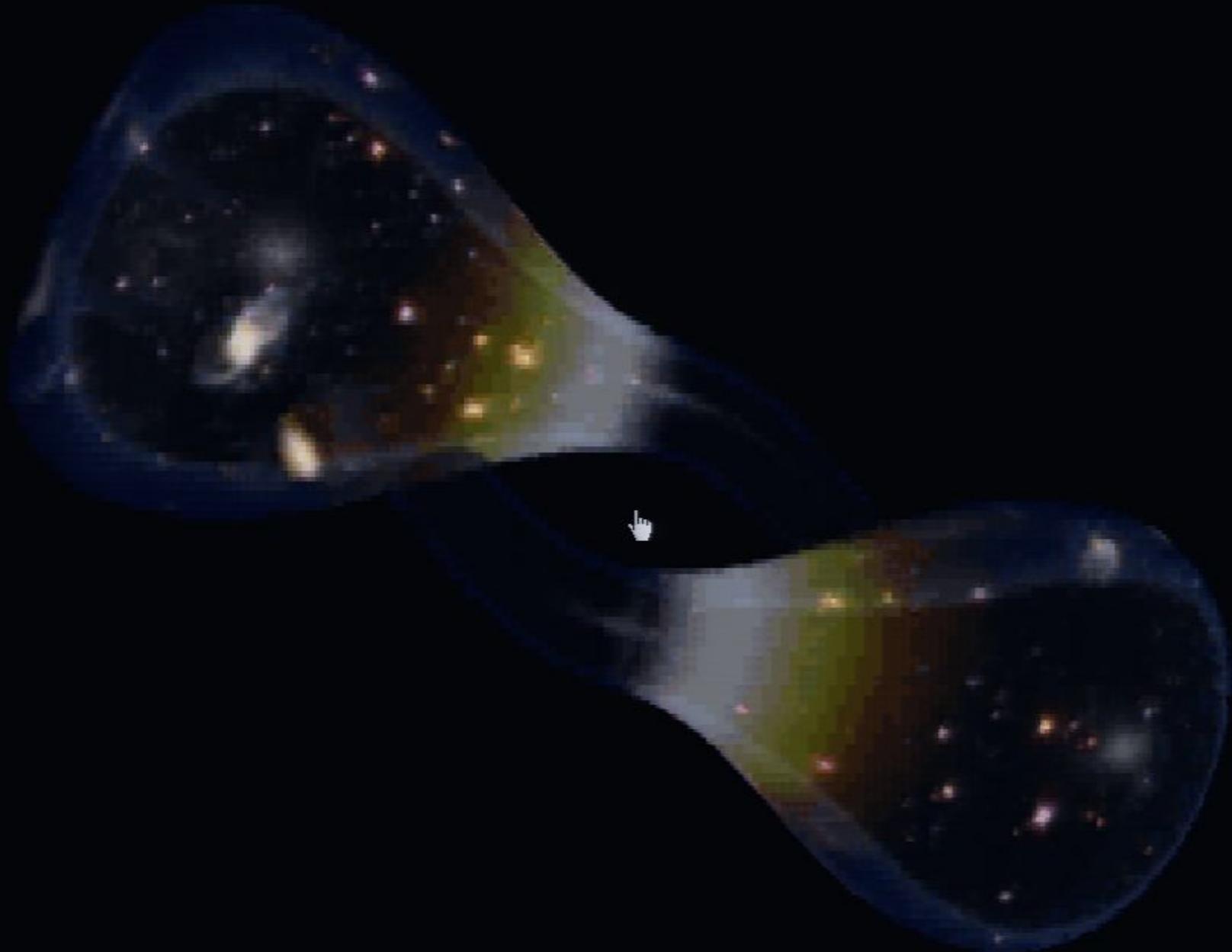




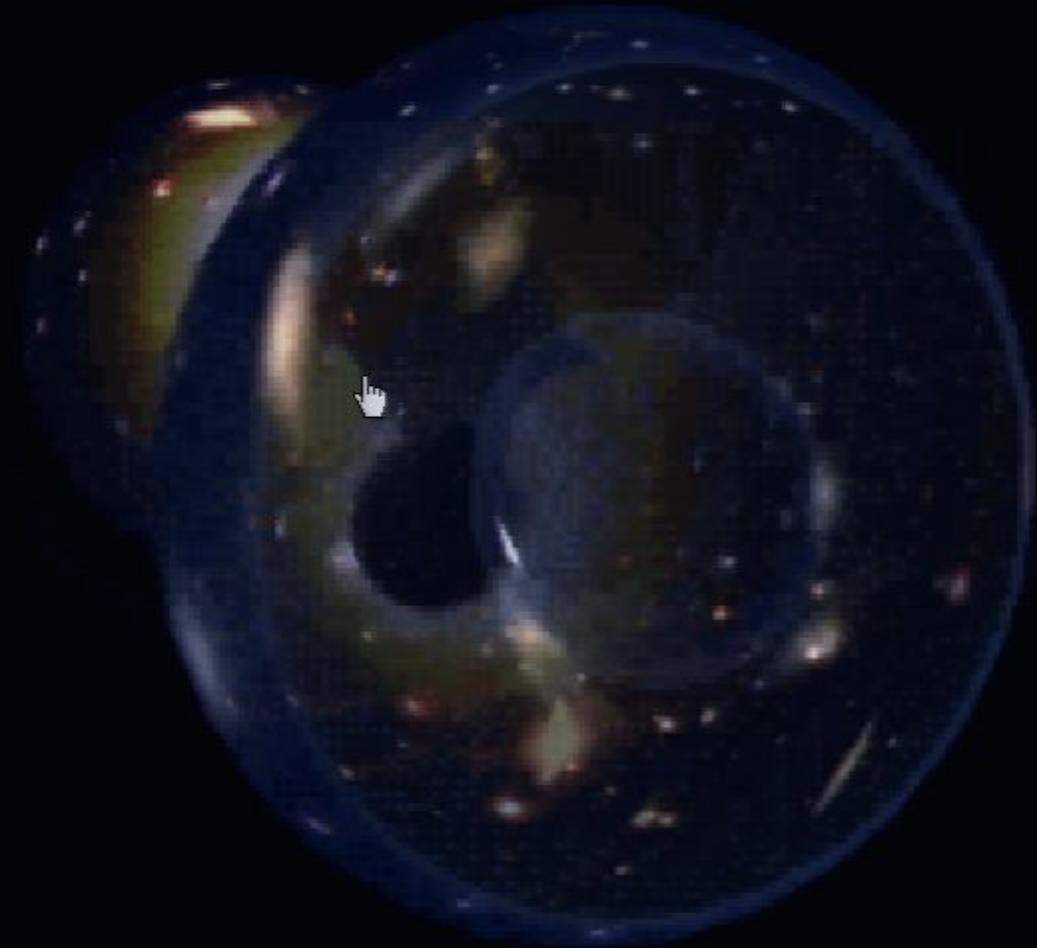






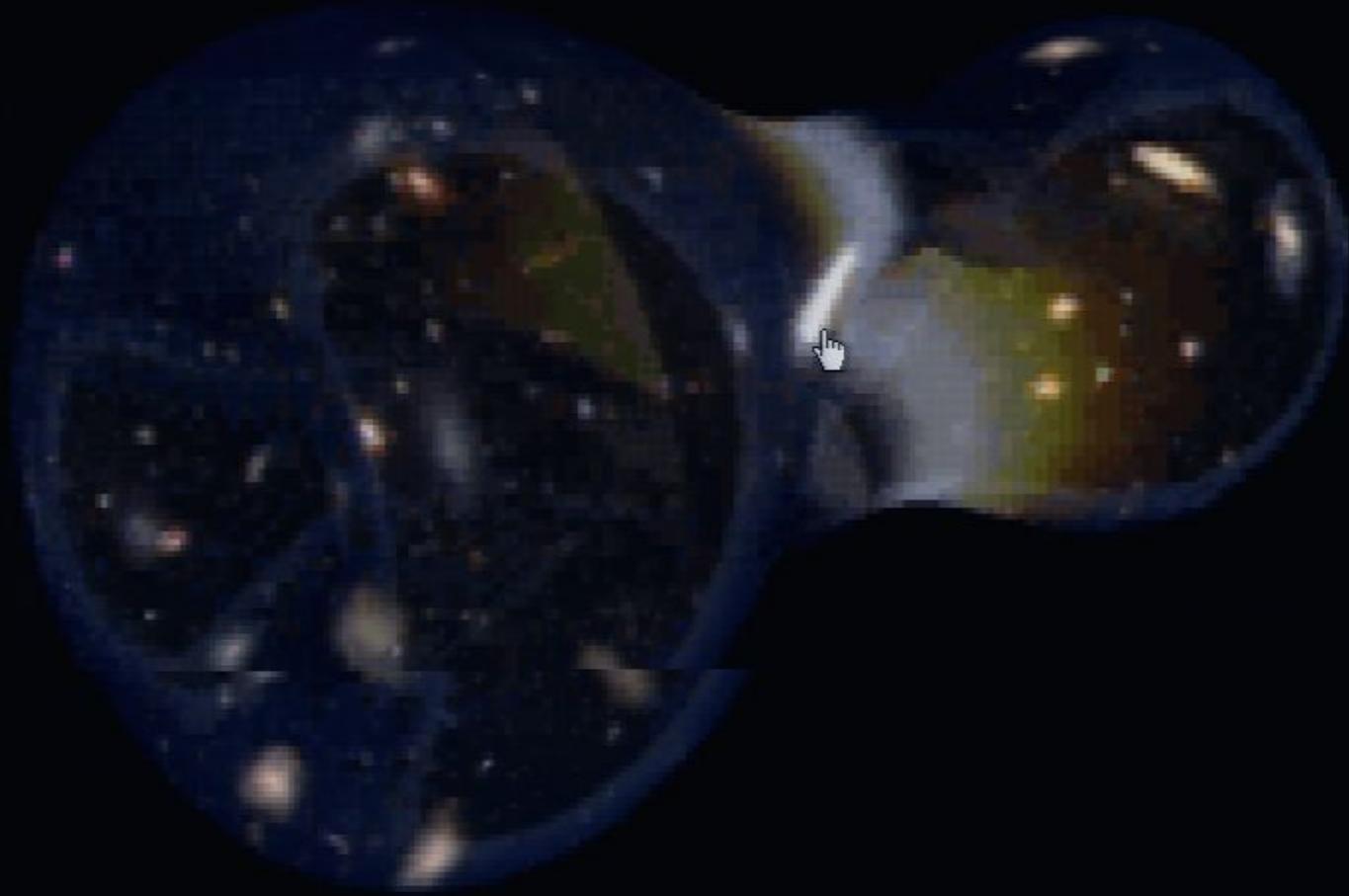


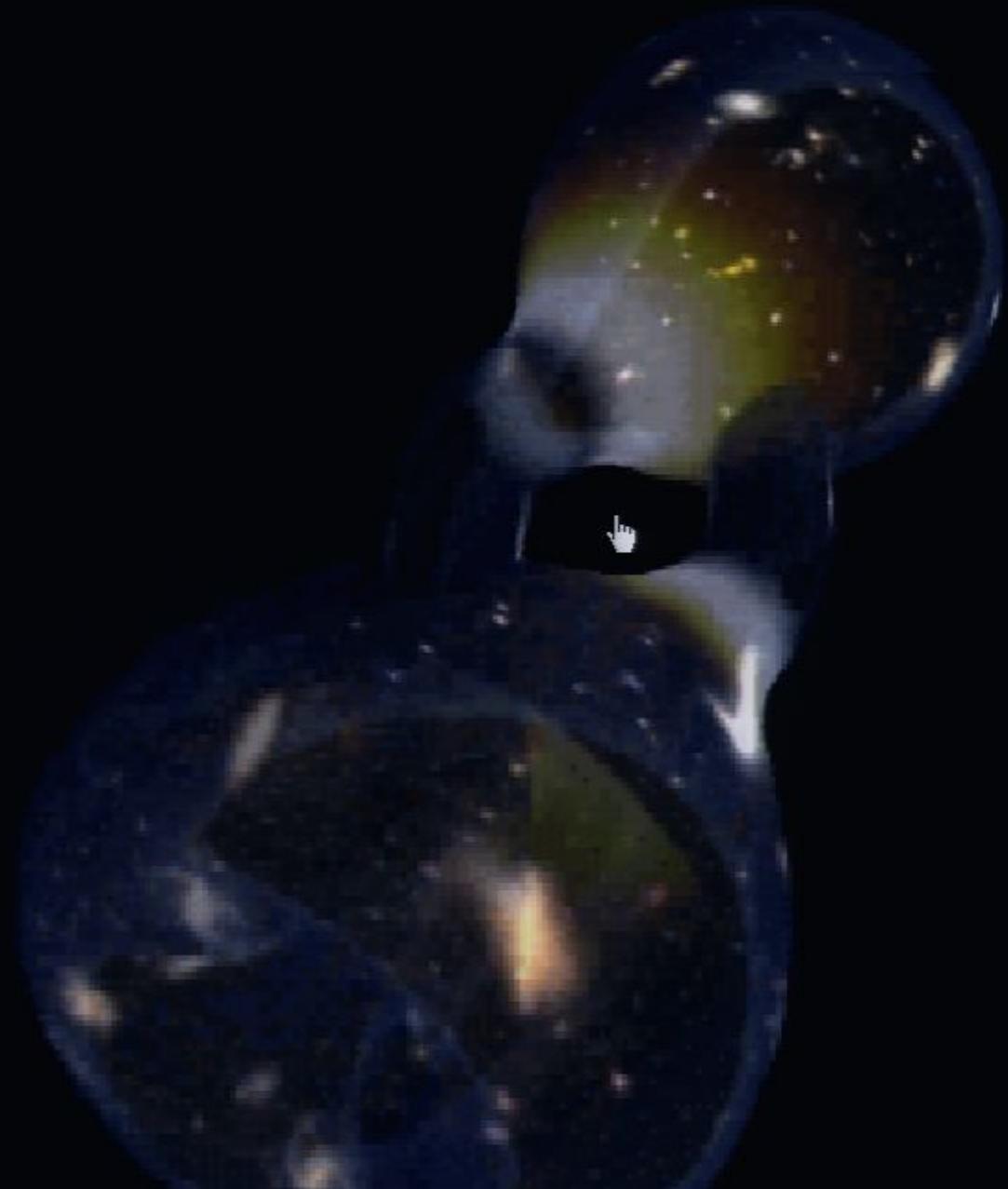


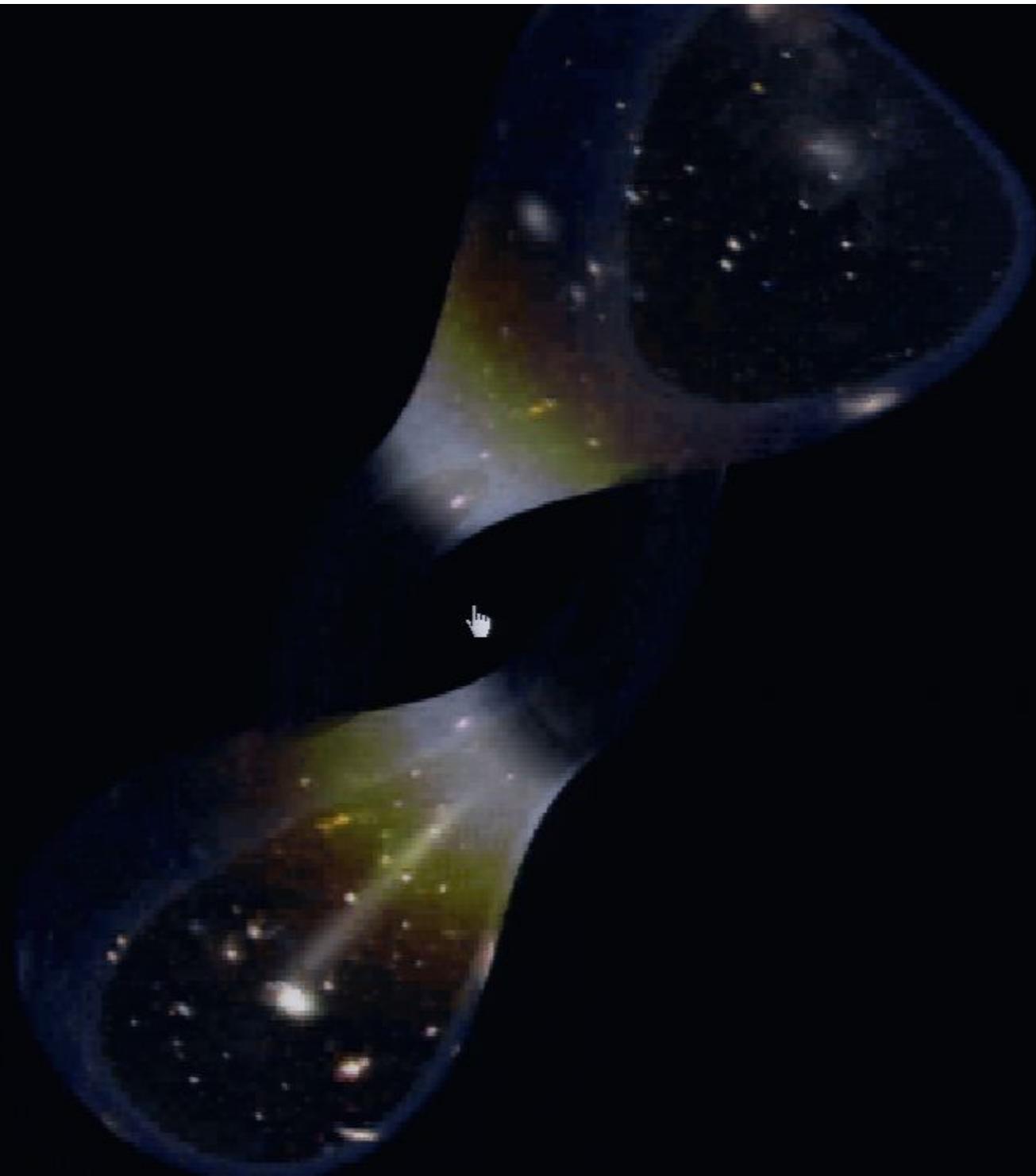


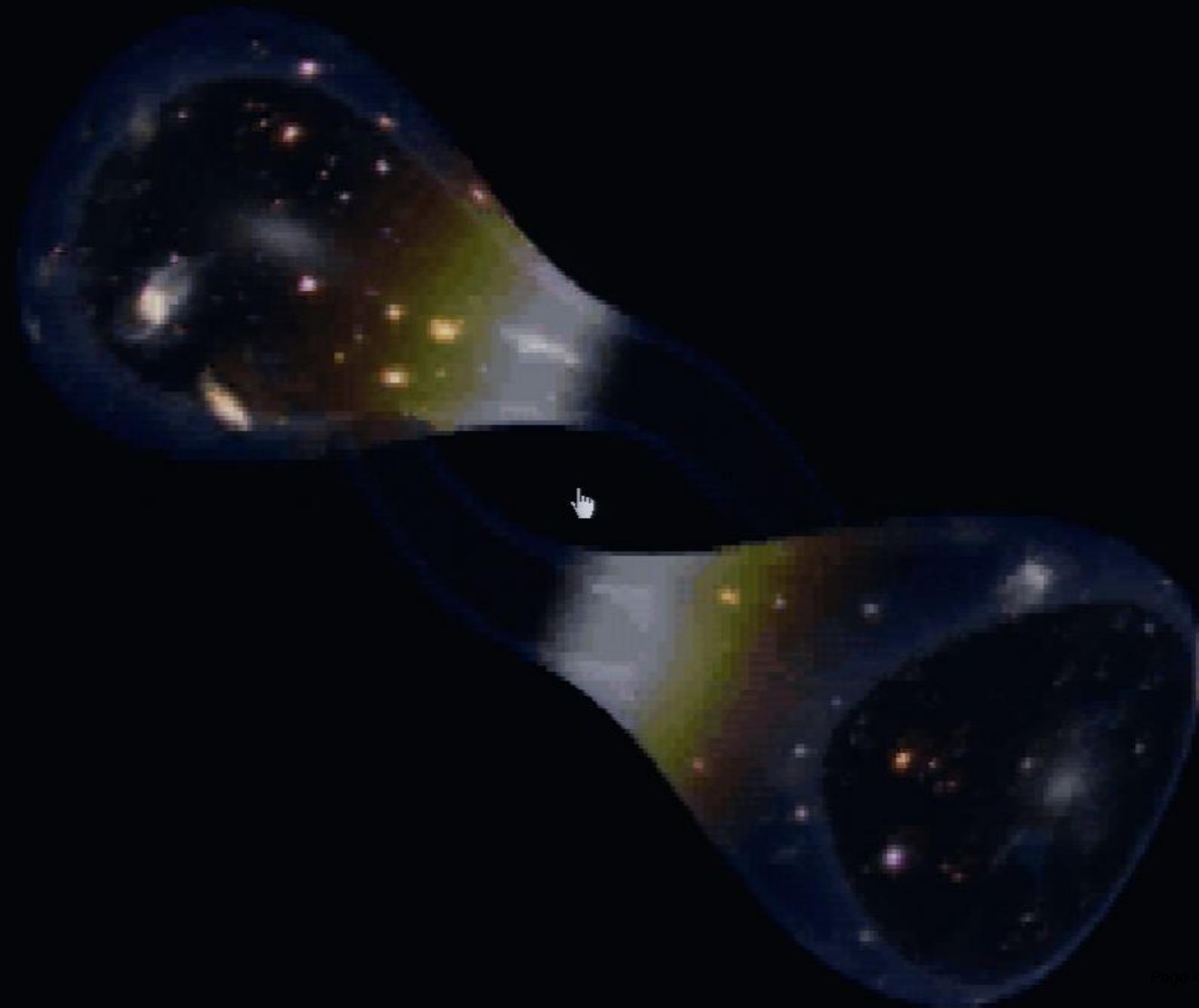














# What Banged?



credits: Paul Steinhardt (Princeton)

Ben Craps (Brussels)

Thomas Hertog (Paris)

# all known physics

$$\Psi = \int e^{\frac{i}{\hbar} \int \left( \frac{R}{16\pi G} - F^2 + \bar{\psi} i \not{D} \psi - \lambda \varphi \bar{\psi} \psi + |D\varphi|^2 - V(\varphi) \right)}$$

schrodinger  
Feynman  
Planck  
Einstein  
Newton  
Maxwell-Yang-Mills  
Dirac  
Yukawa  
Higgs

# all the particles and forces

\* Fermions     $u d c s t b \times 3 \times 4$

90

$e \mu \tau \times 4$

$\nu_e \nu_\mu \nu_\tau \times 2 (+ rh \nu's)$



\* Bosons     $g^a \times 8 \times 2$       strong

30

$W^a \times 3 \times 2$

weak

$A \times 2$

electromag

$H^a \times 4$

higgs ?

$h_{\mu\nu} \times 2$

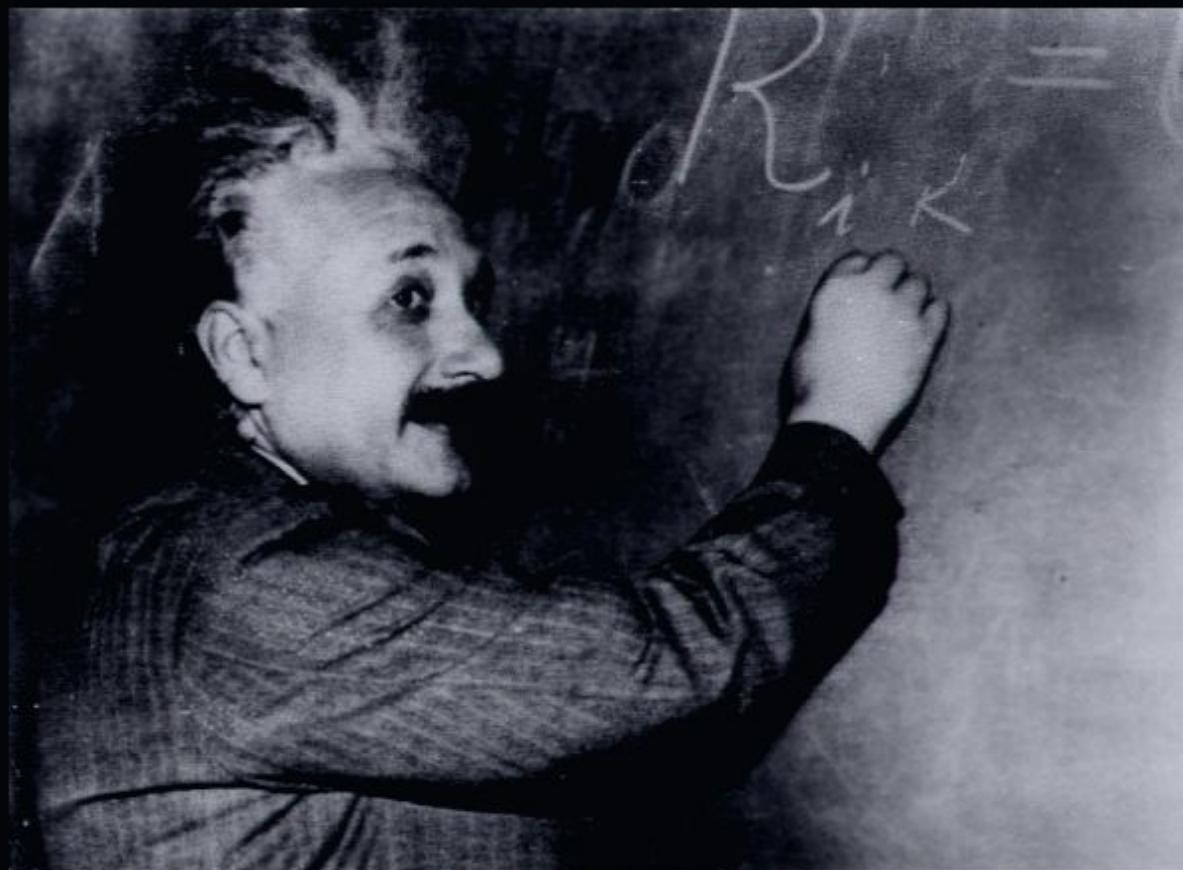
graviton



\* Dark Matter particles?

\* Dark Energy

# the spacetime arena



$$G_{\mu\nu} = 8 \pi G T_{\mu\nu}$$

# all the particles and forces

\* Fermions     $u d c s t b \times 3 \times 4$

90

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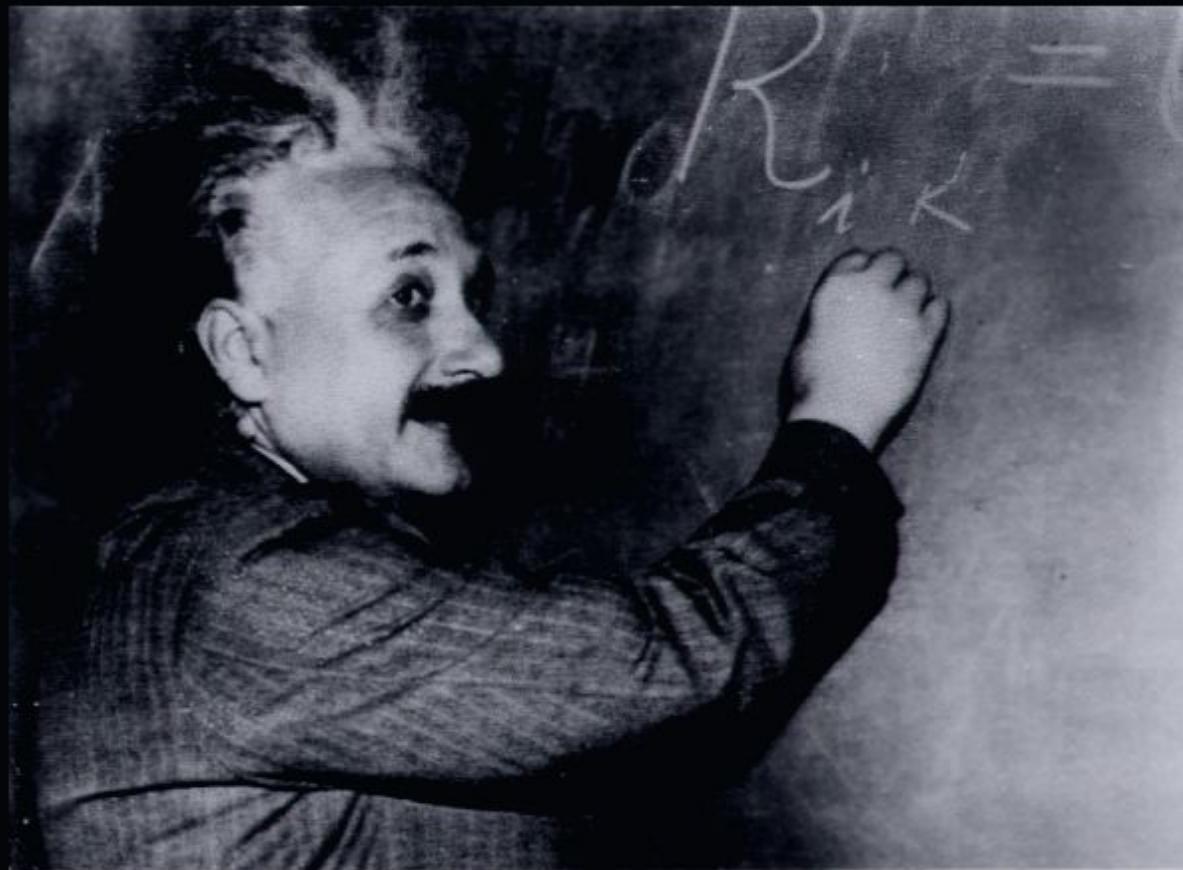
graviton



\* Dark Matter particles?

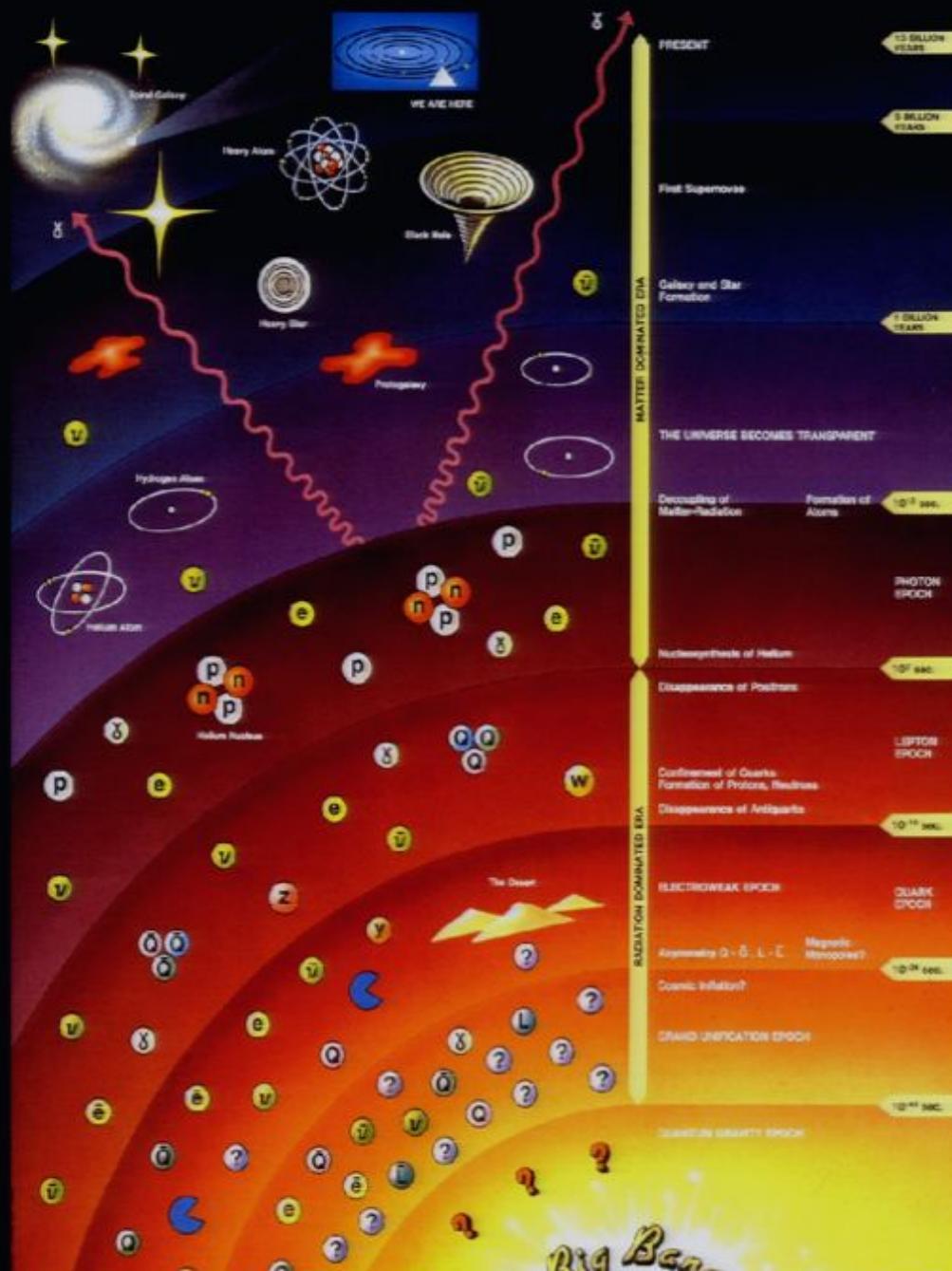
\* Dark Energy

# the spacetime arena



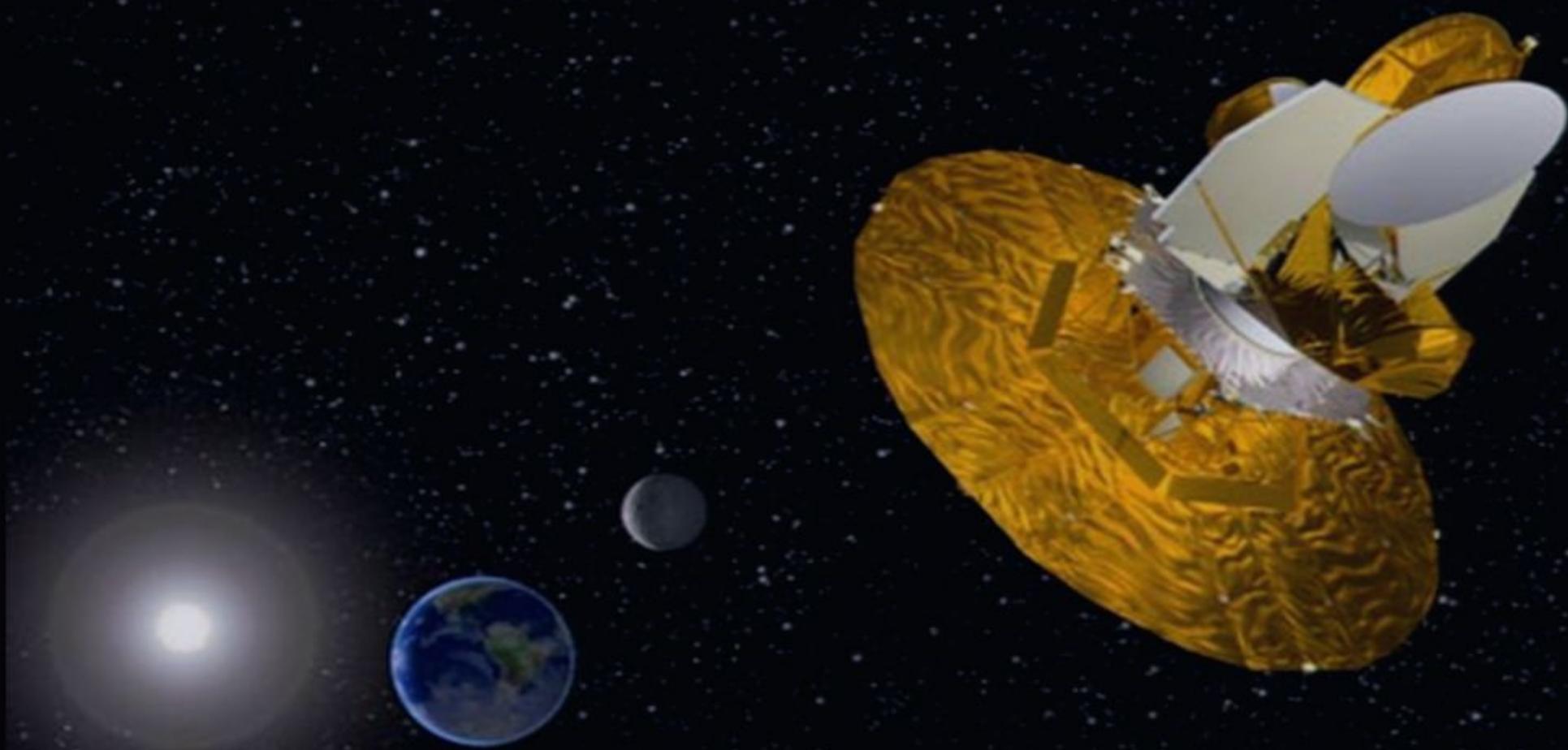
$$G_{\mu\nu} = 8 \pi G T_{\mu\nu}$$

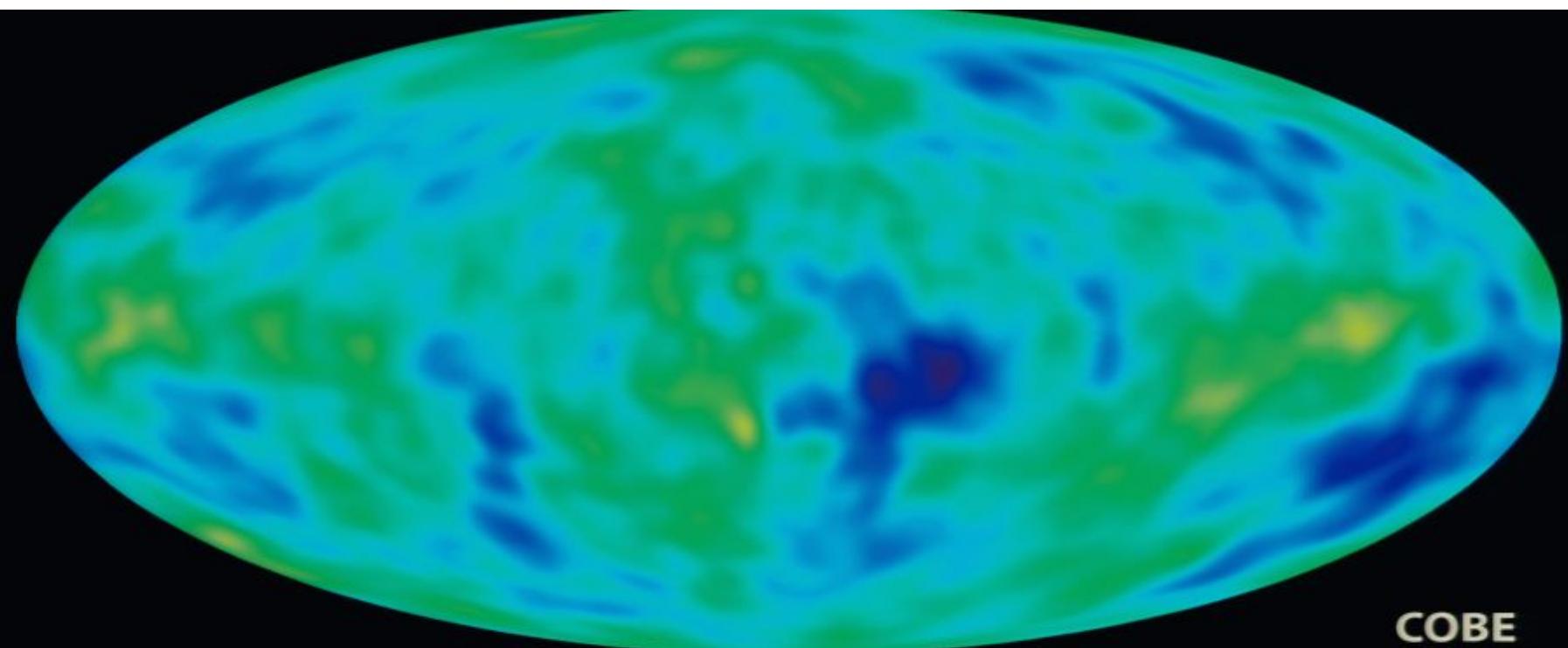
# History of the Universe



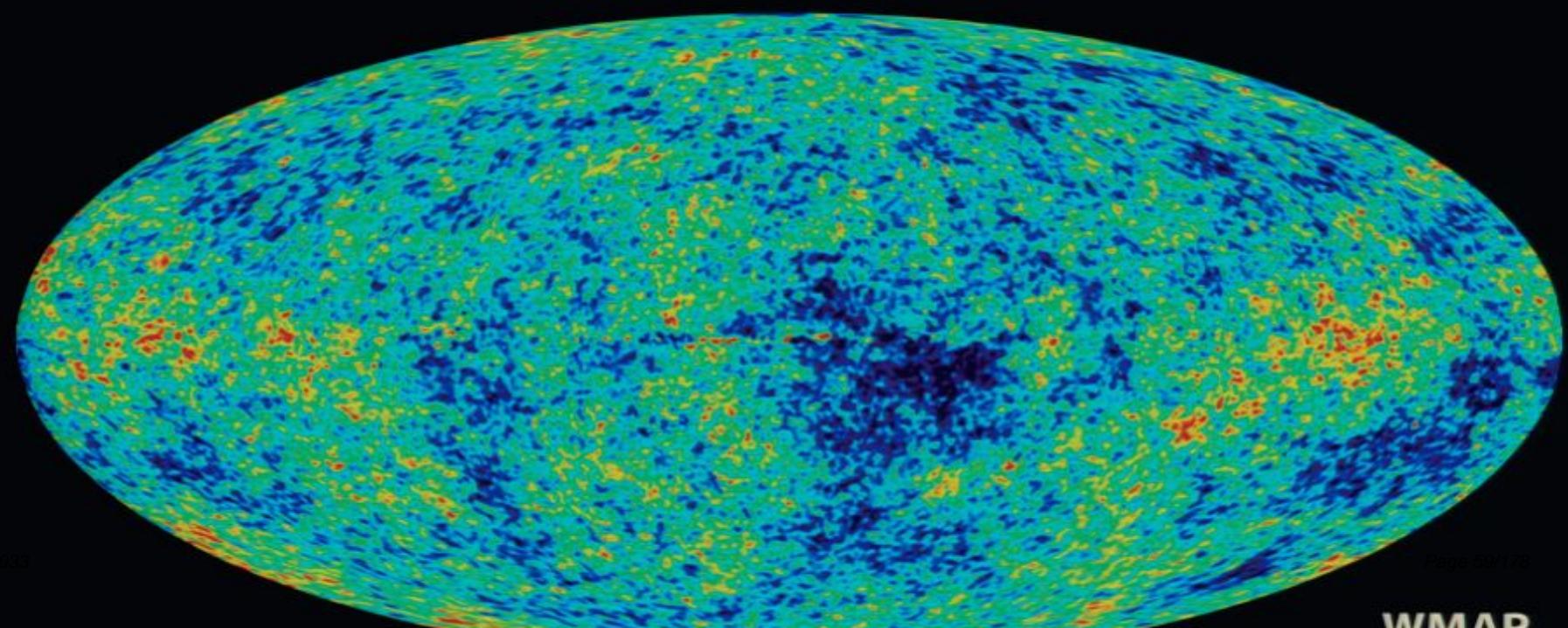
2001

# The Wilkinson-MAP Satellite





COBE



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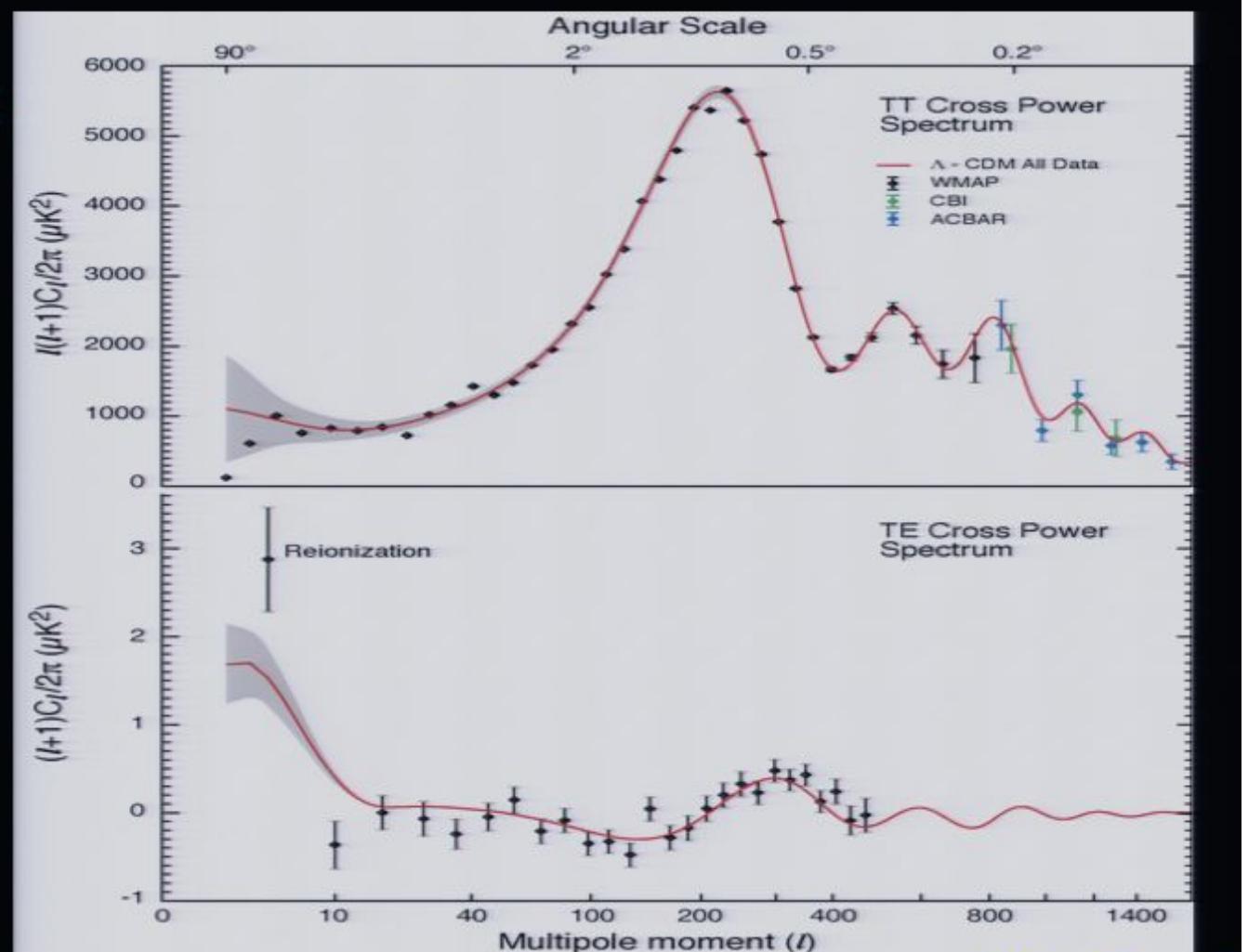
# Theory versus Reality

Fluctuation Level:  
Temperature

Z'eldovich, Peebles+Yu,  
Bond+Efstathiou

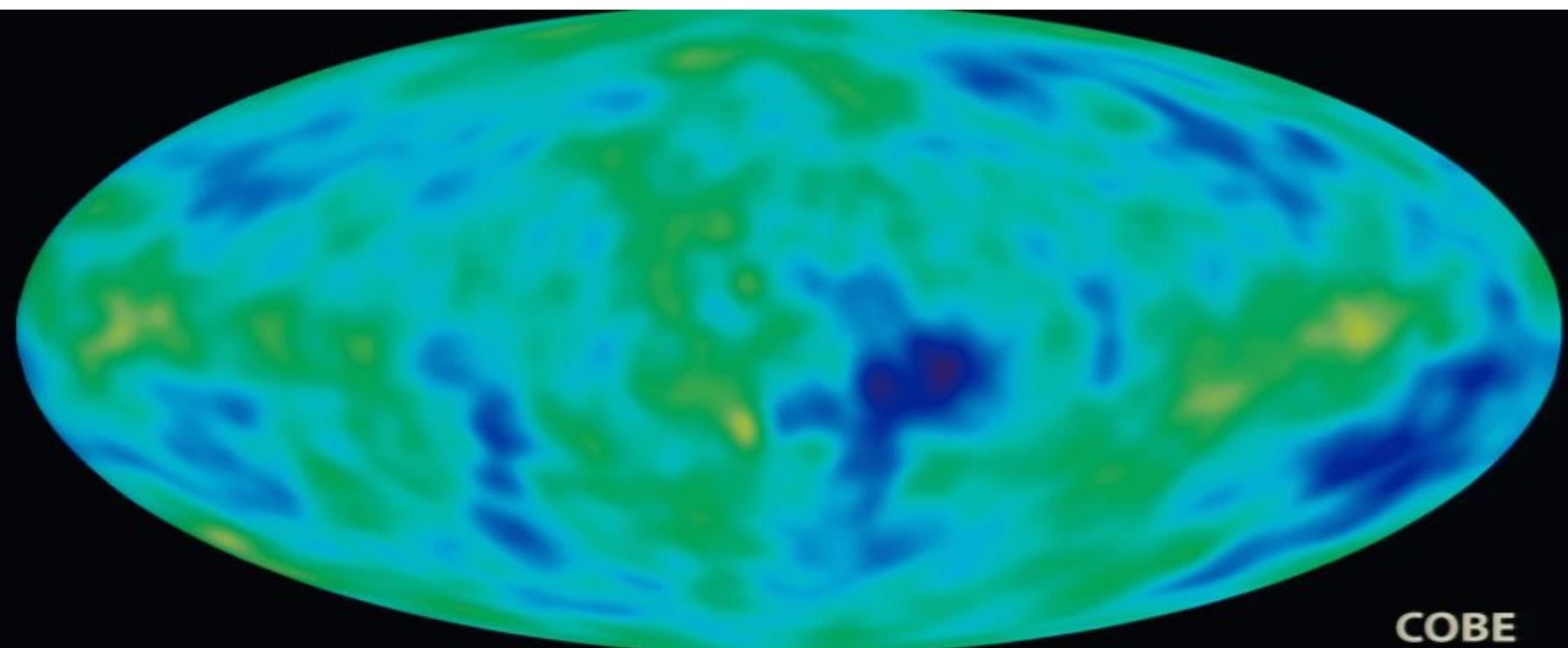
Polarization

Coulson, Crittenden,  
NT (1994)

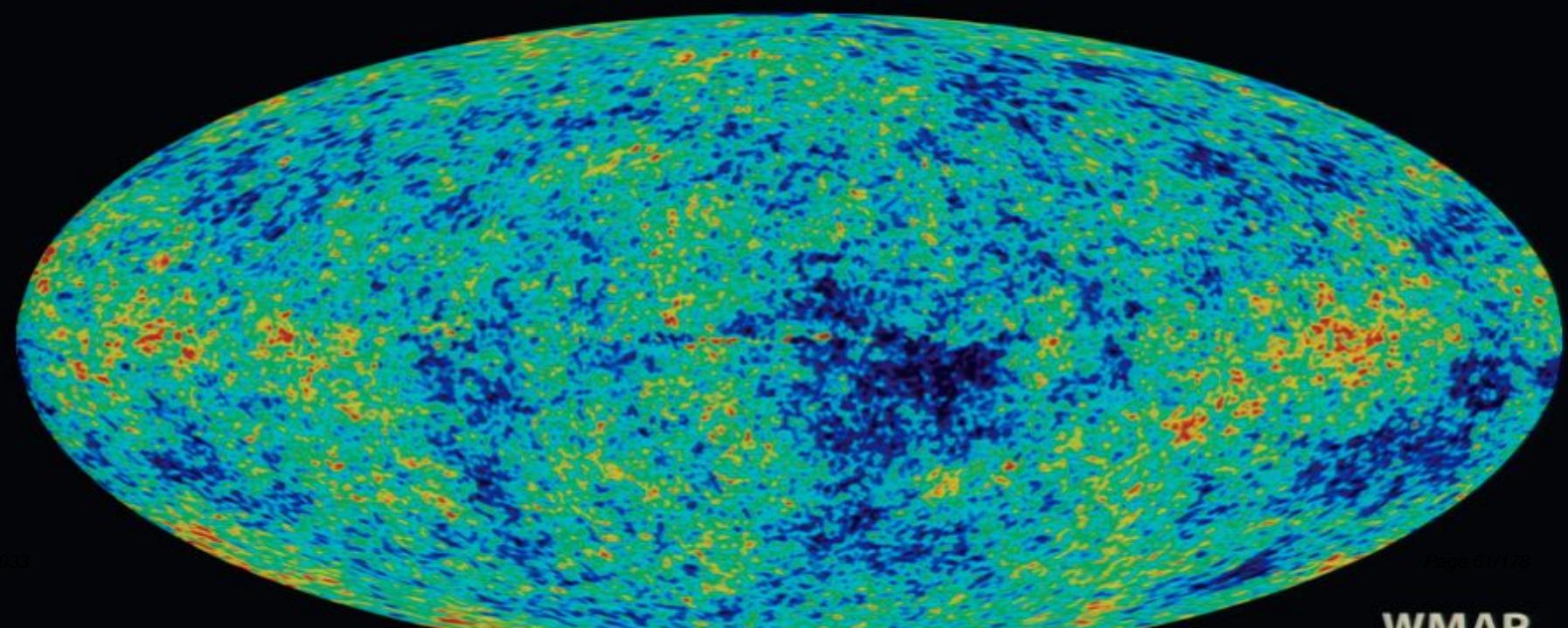


$$100 \quad 10 \quad 1 \quad .1 \quad (l = 2\pi/\theta)$$

Angle on Sky (Degrees)



**COBE**



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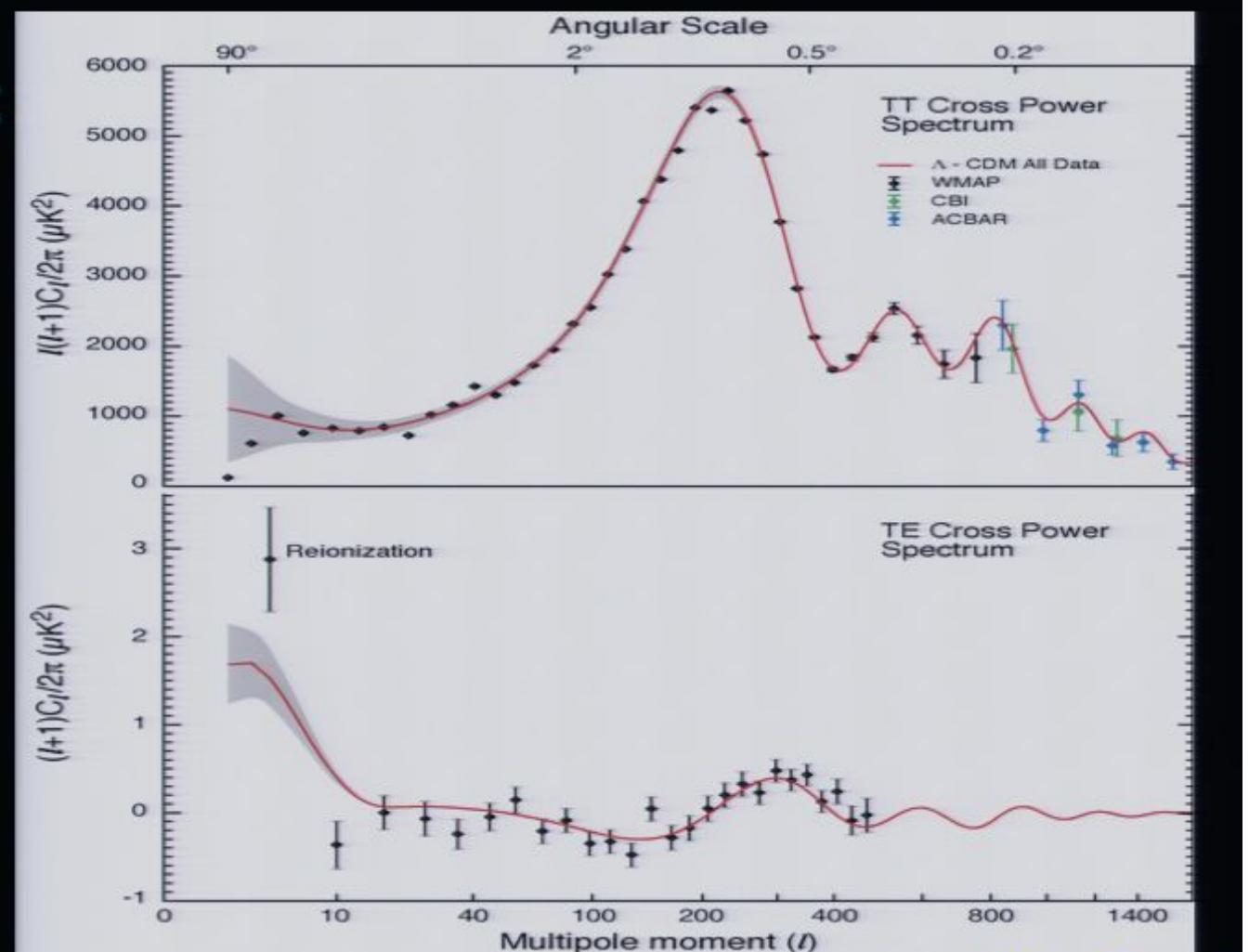
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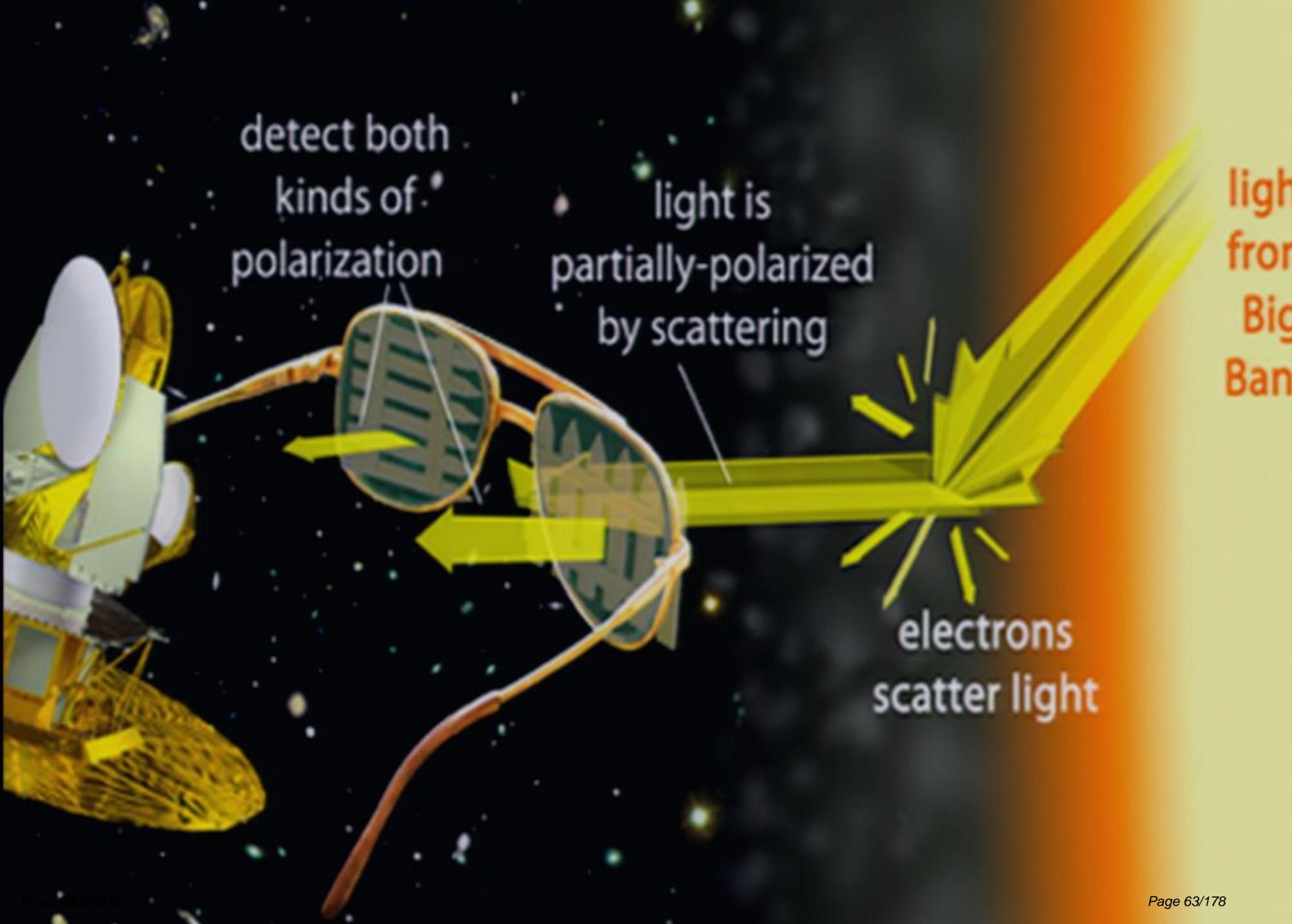
Polarization

Coulson, Crittenden,  
NT (1994)



$$100 \quad 10 \quad 1 \quad .1 \quad (l = 2\pi/\theta)$$

Angle on Sky (Degrees)



detect both  
kinds of  
polarization

- light is  
partially-polarized  
by scattering

electrons  
scatter light

light  
from  
Big  
Bang

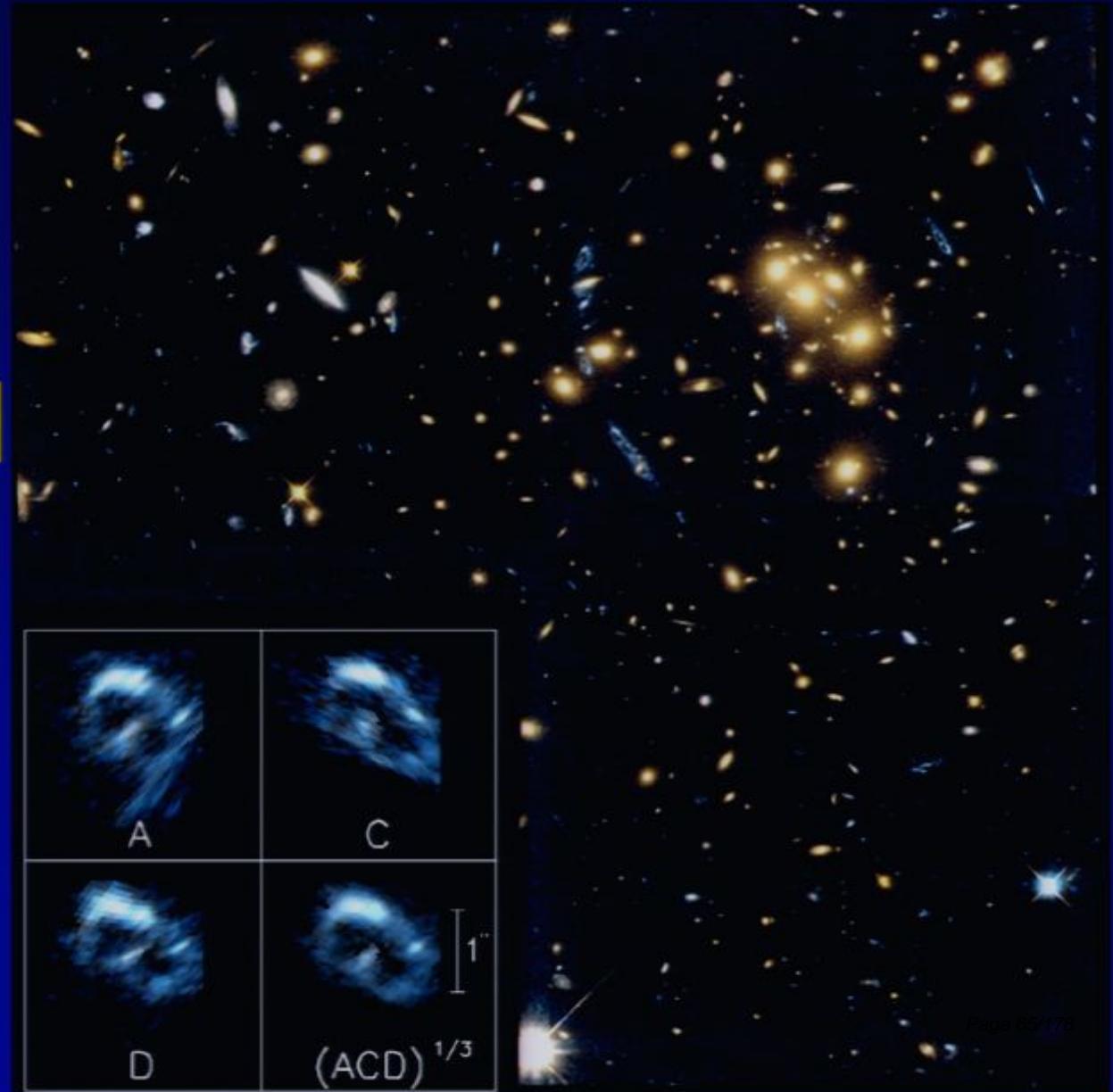
So far, observations are consistent with a spatially flat Universe, and the simplest possible density variations:

- Gaussian random field
- Linear (small amplitude)
- Adiabatic (makeup uniform)
- Scalar (no shear)
- Scale-Invariant (~ same amp on all scales)

BUT BIG PUZZLES REMAIN

# 25% dark matter

gravitational  
lensing



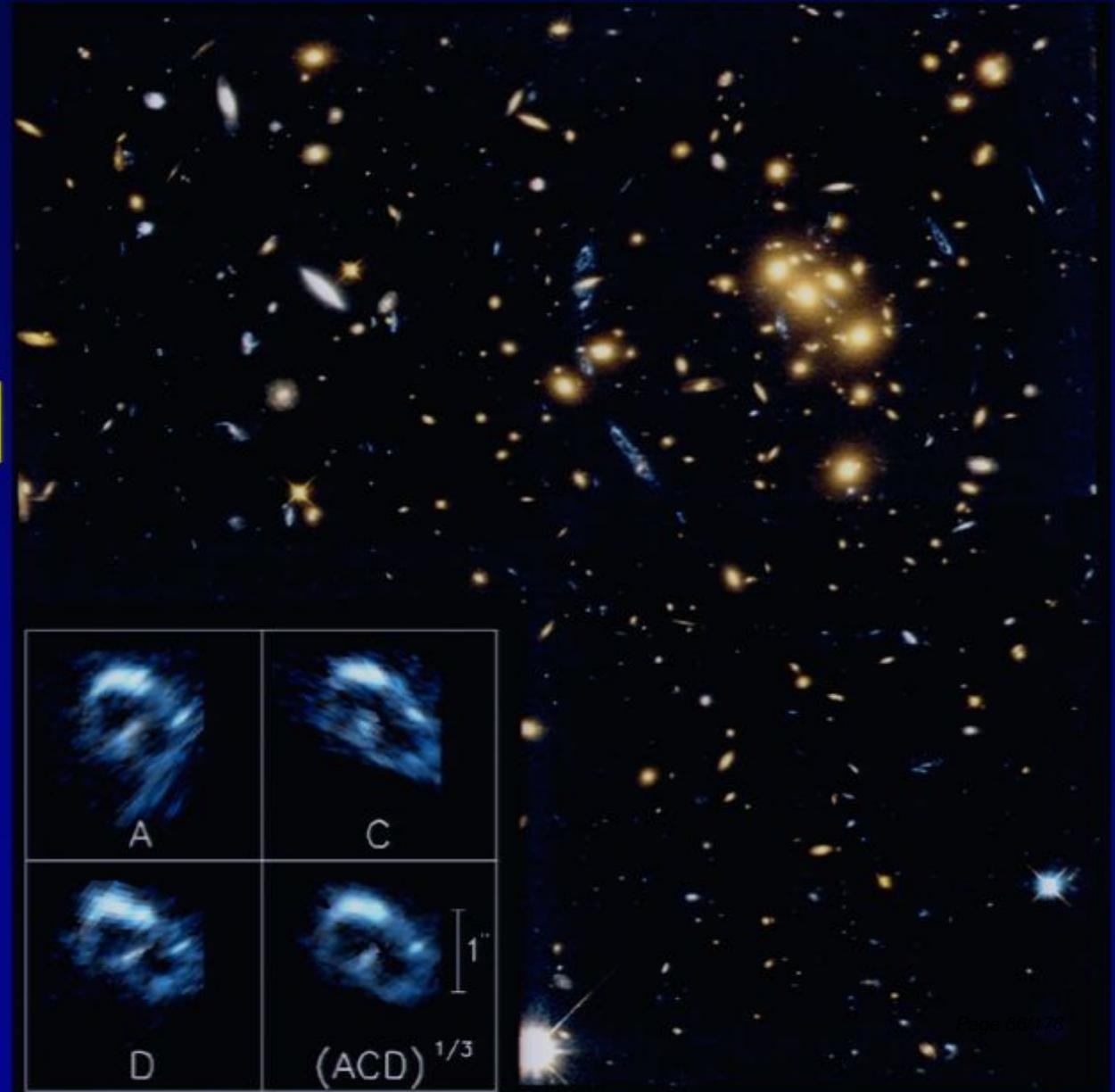
(Tyson et al.  
1995)

Pirsa: 08030033

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# 25% dark matter

gravitational  
lensing



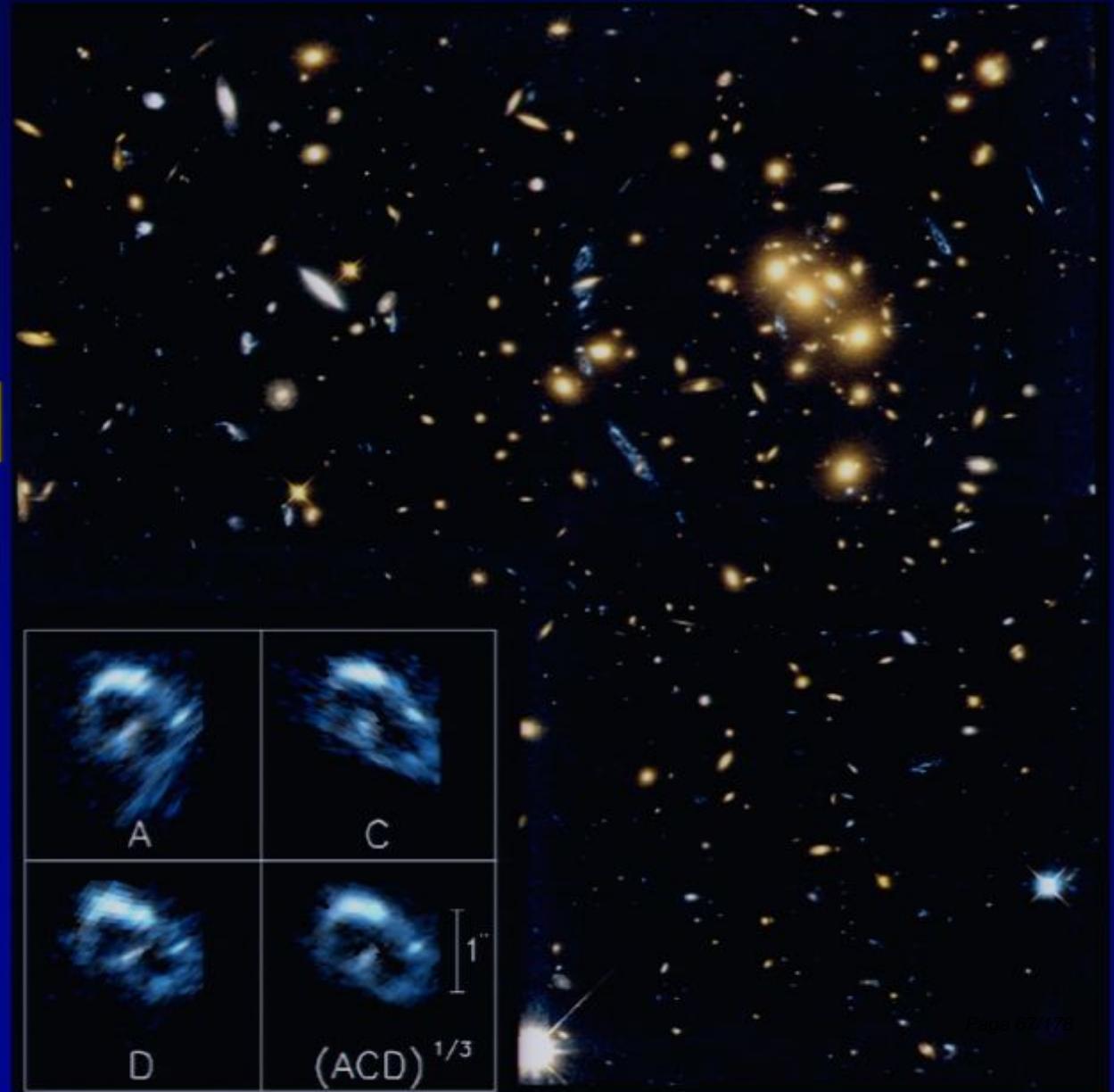
(Tyson et al.  
1995)

Pirsa: 08030033

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# 25% dark matter

gravitational  
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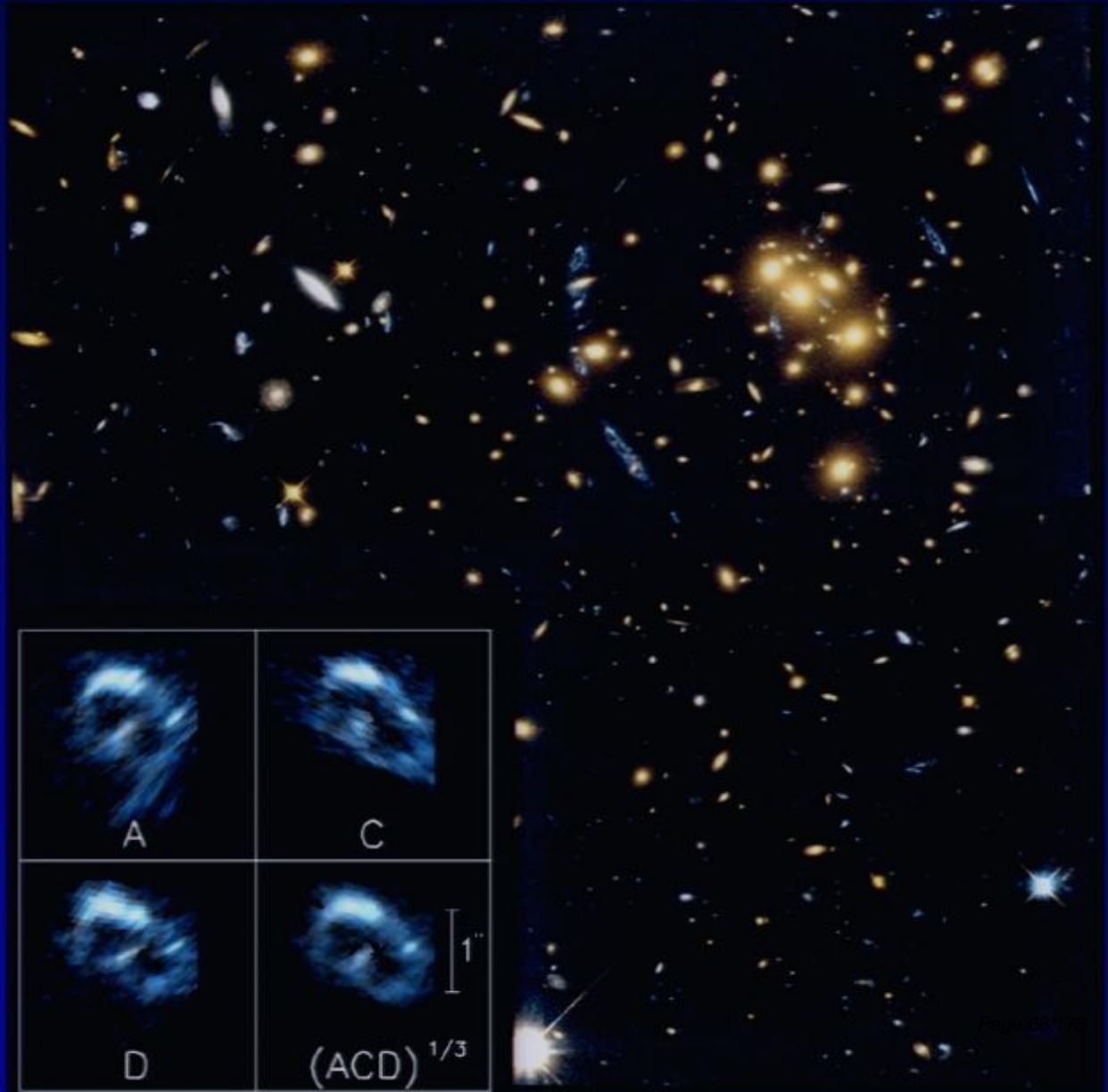
(Tyson et al.  
1995)

Pirsa: 08030033

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# 25% dark matter

gravitational  
lensing



(Tyson et al.  
1995)

Pisa: 08030038

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# 70% dark energy ( $\Lambda$ )

- \* Only gravity feels it
- \* Boost-invariant
- \* Repulsive gravity!  
-> blows up the universe

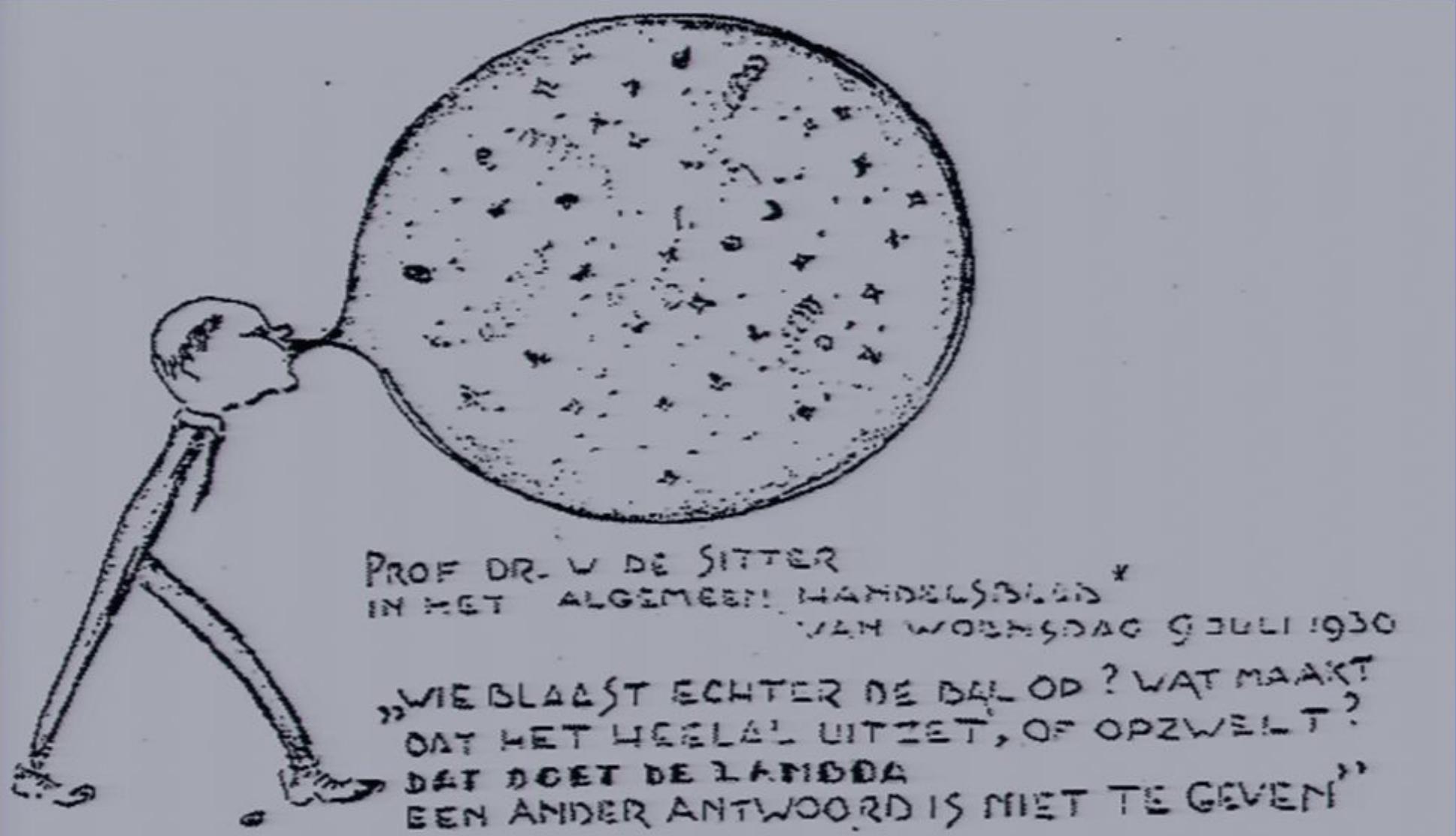


Figure 5.2. This sketch appeared following an interview of de Sitter published in a Dutch newspaper. The quote is translated by van der Laan as: "What, however, blows up the ball? What makes the universe expand or swell up? That is done by the Lambda. Another answer cannot be given."

the beginning .....

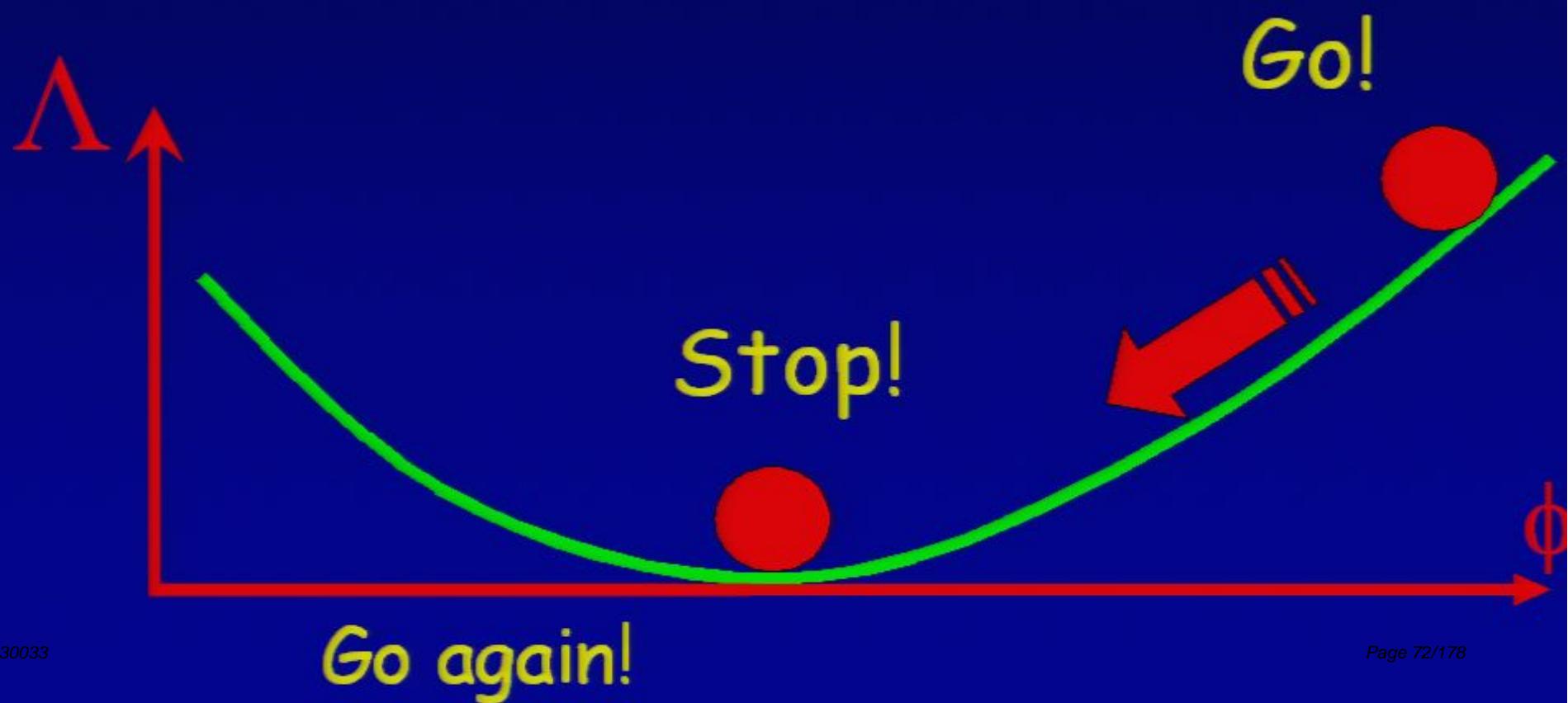
conventional assumption:

the universe somehow sprang into existence full of

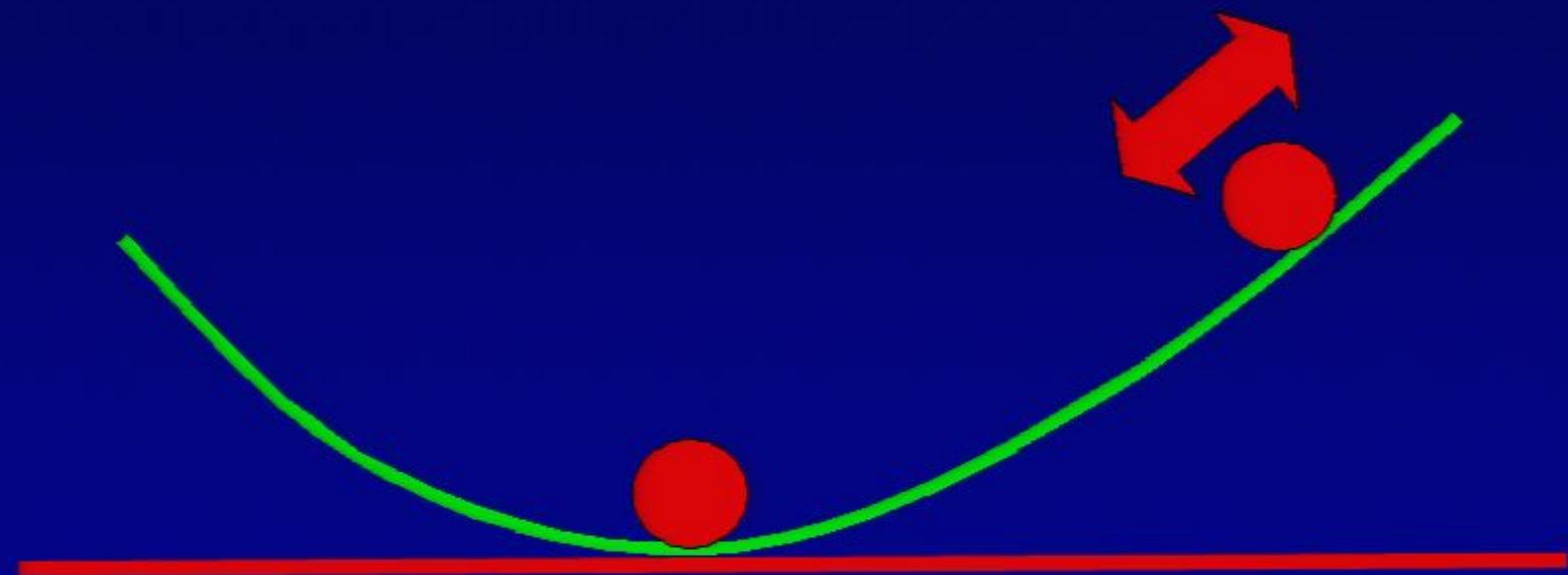
inflationary energy:

- a very high-density version of  $\Lambda$

# Inflation:



# Quantum Jitter:



# why scale-invariant?

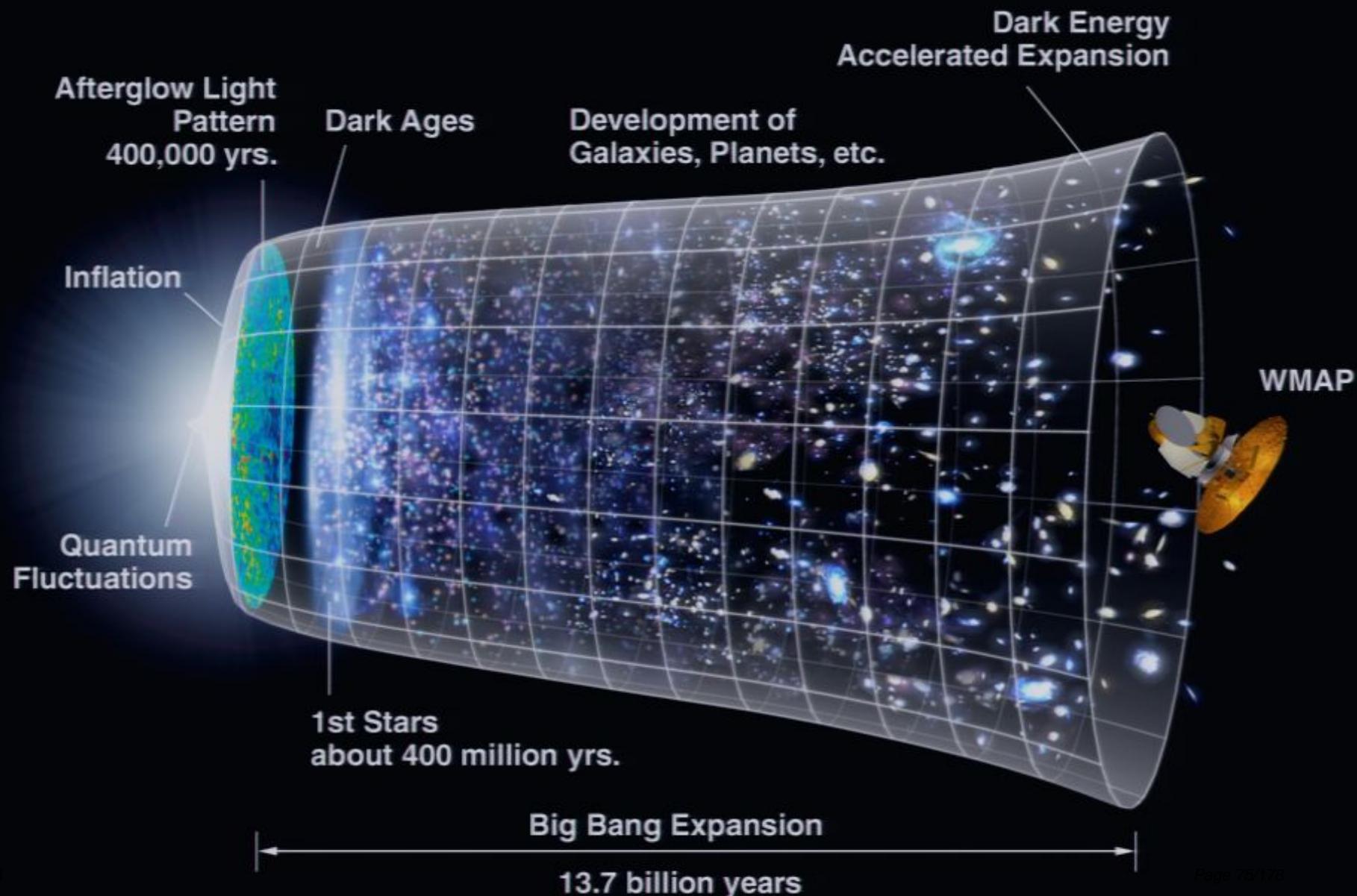
$$ds^2 \sim -dt^2 + e^{2Ht} dx^2$$

Symmetry:

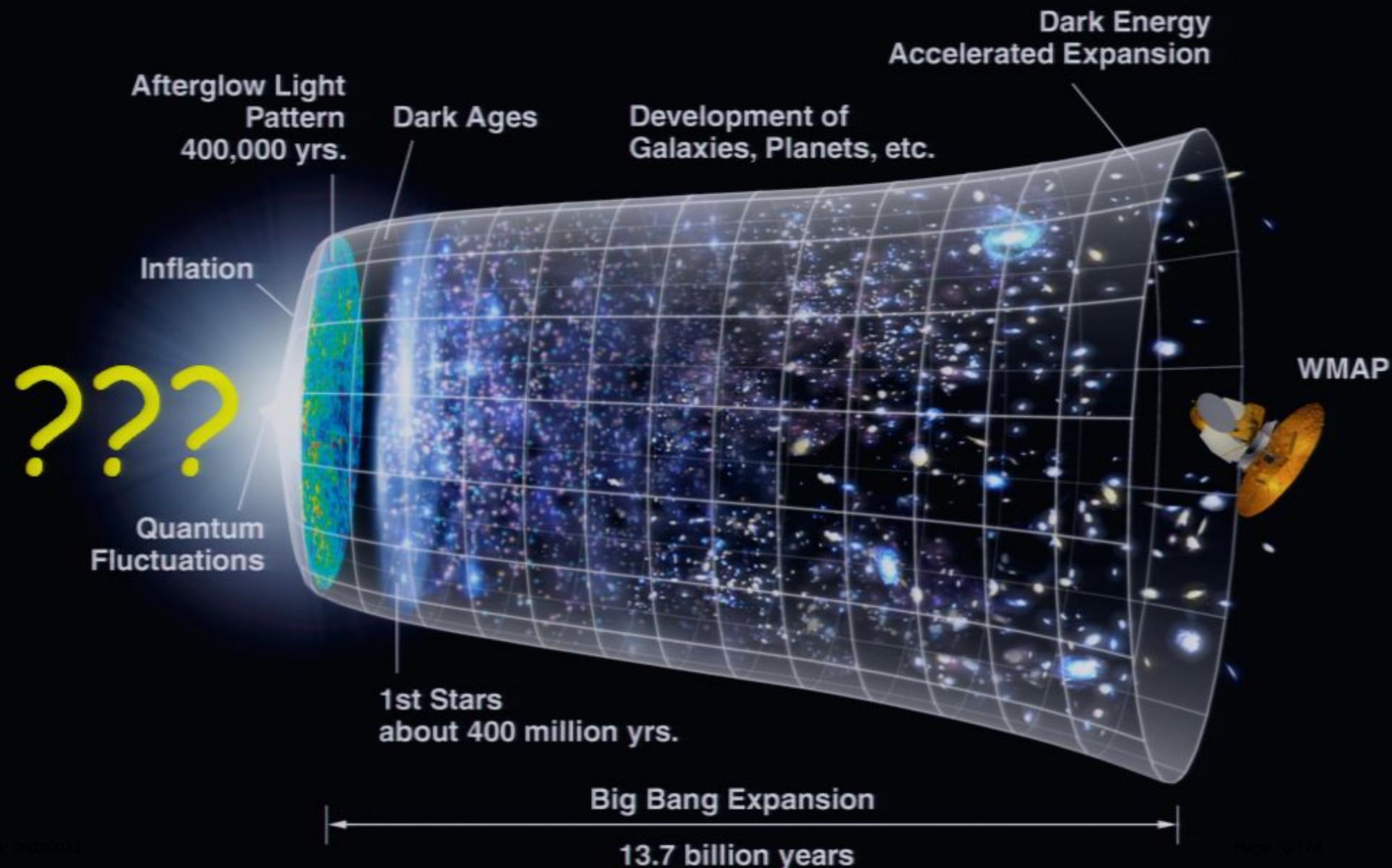
$$t \rightarrow t + \varepsilon$$

$$x \rightarrow e^{-H\varepsilon} x$$

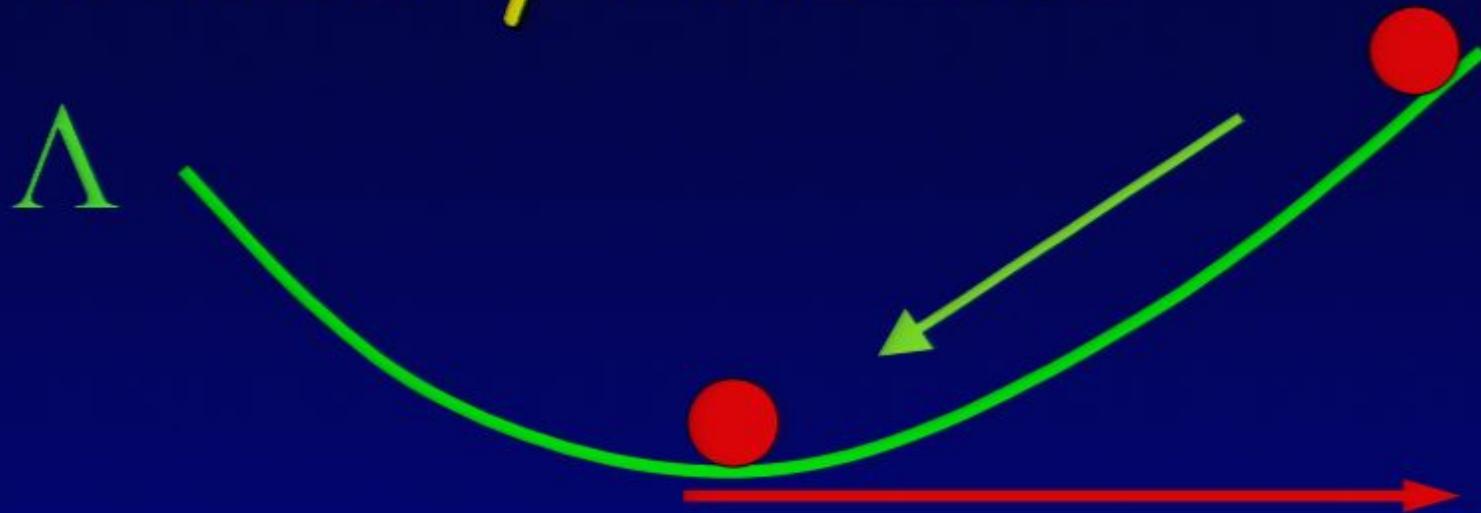
# The Concordance Model



# The Concordance Model

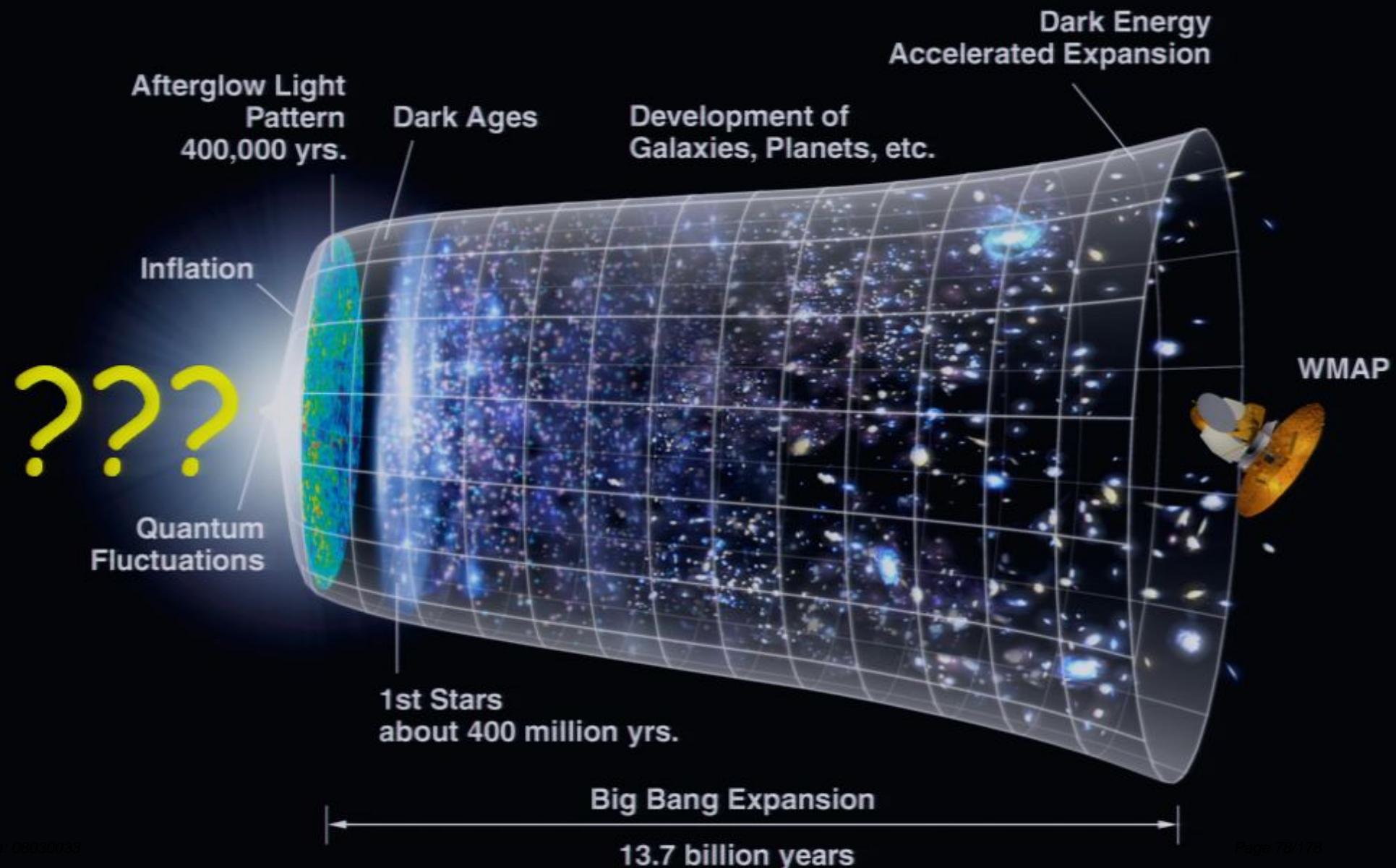


# Inflationary Puzzles

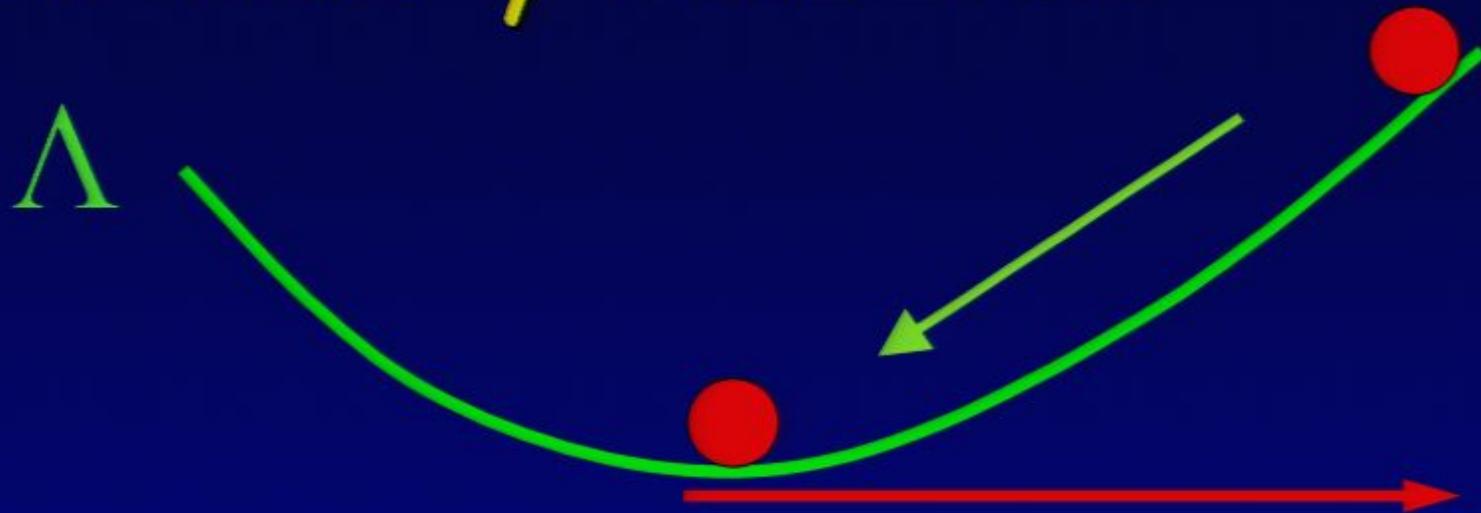


- the beginning
- what is the inflationary energy?
- why did the universe start out inflating?
- $\Lambda_I \sim 10^{100} \Lambda_0$
- how is the singularity resolved?

# The Concordance Model

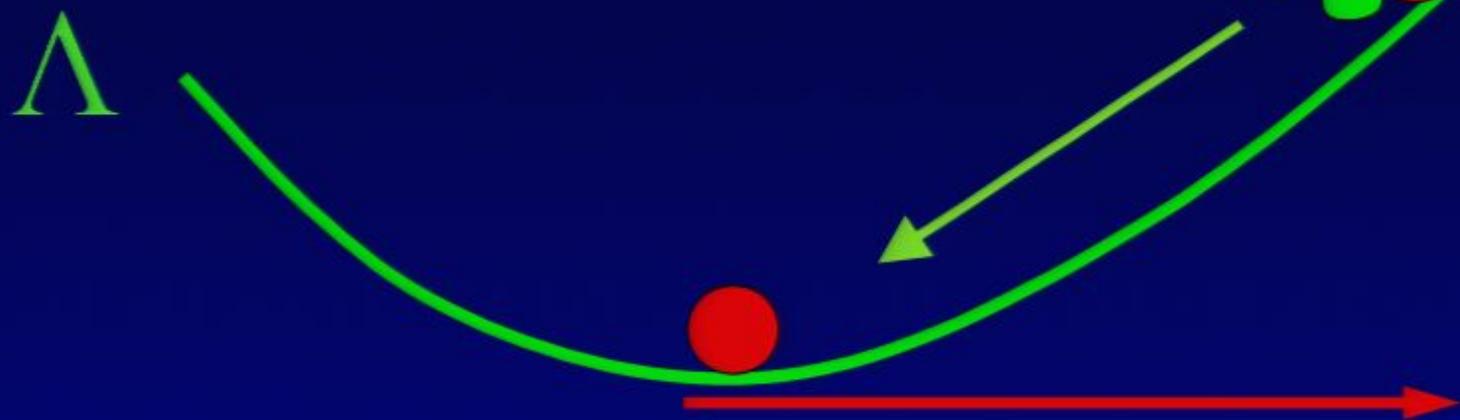


# Inflationary Puzzles



- the beginning
- what is the inflationary energy?
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# Inflationary Puzzles



- the beginning
- what is the inflationary energy?
- why did the universe start out inflating?
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# Theory of a Beginning

Hawking, 1980's

Sphere

$S^4$

$$d\theta^2 + \cos^2\theta d\Omega_3^2$$

$$\theta = -it \downarrow$$

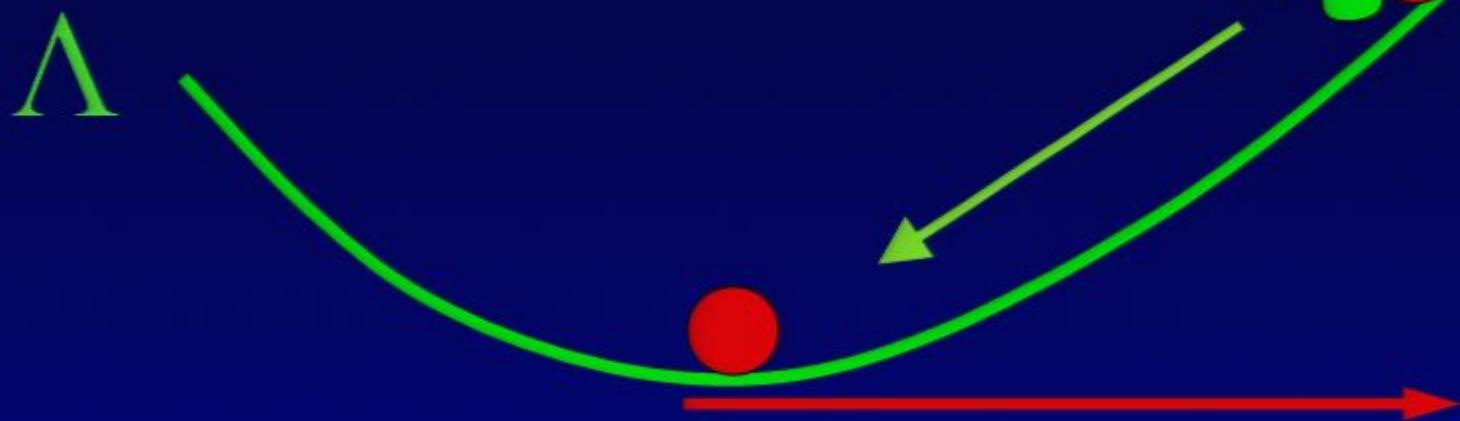
De Sitter

$dS^4$

$$-dt^2 + \cosh^2 t d\Omega_3^2$$



# Inflationary Puzzles



- the beginning
- what is the inflationary energy?
- why did the universe start out inflating?
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# Theory of a Beginning

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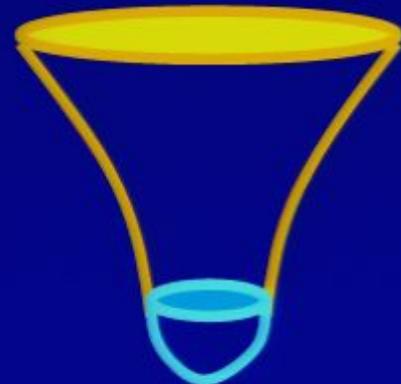
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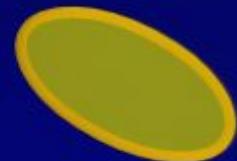
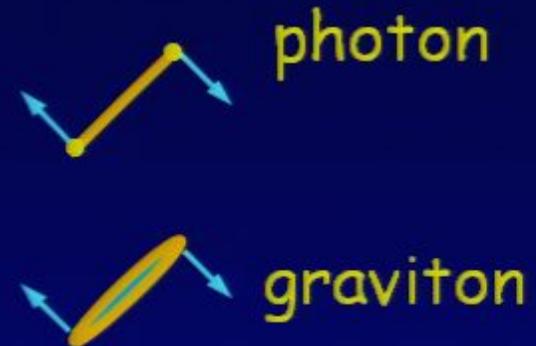
$$-dt^2 + \cosh^2 t d\Omega_3^2$$



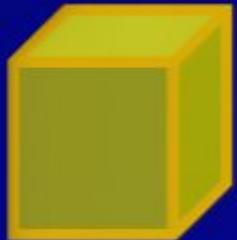
# M Theory



string

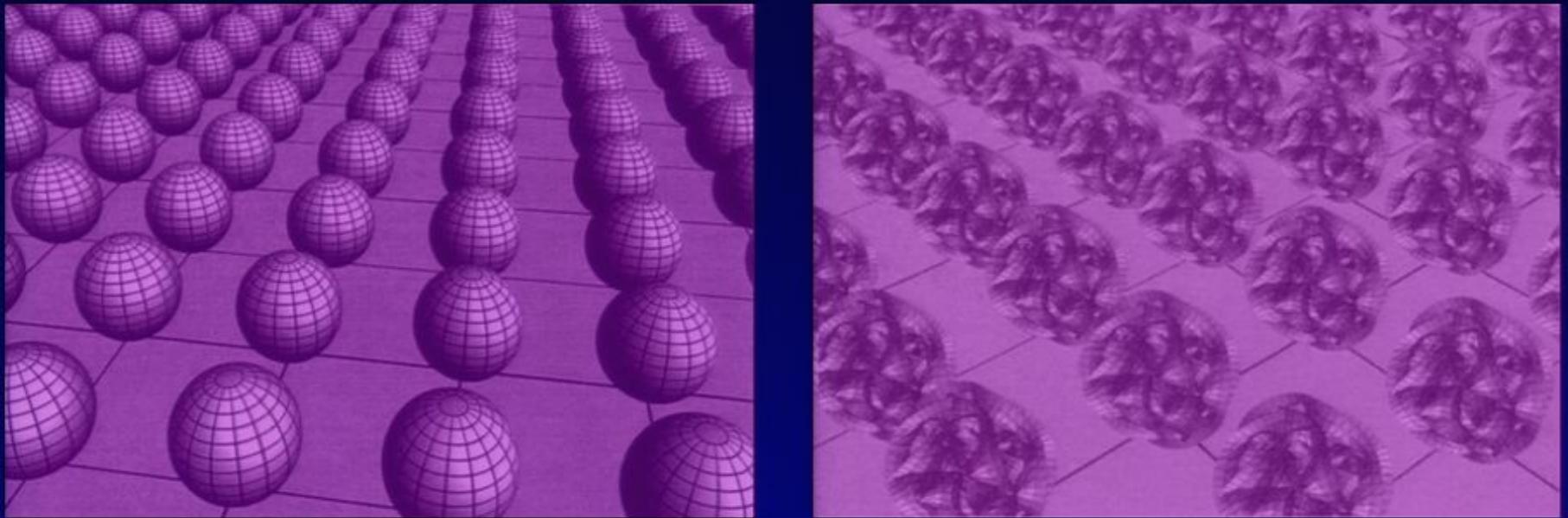


membrane



3-brane

+ 7 extra dimensions of space

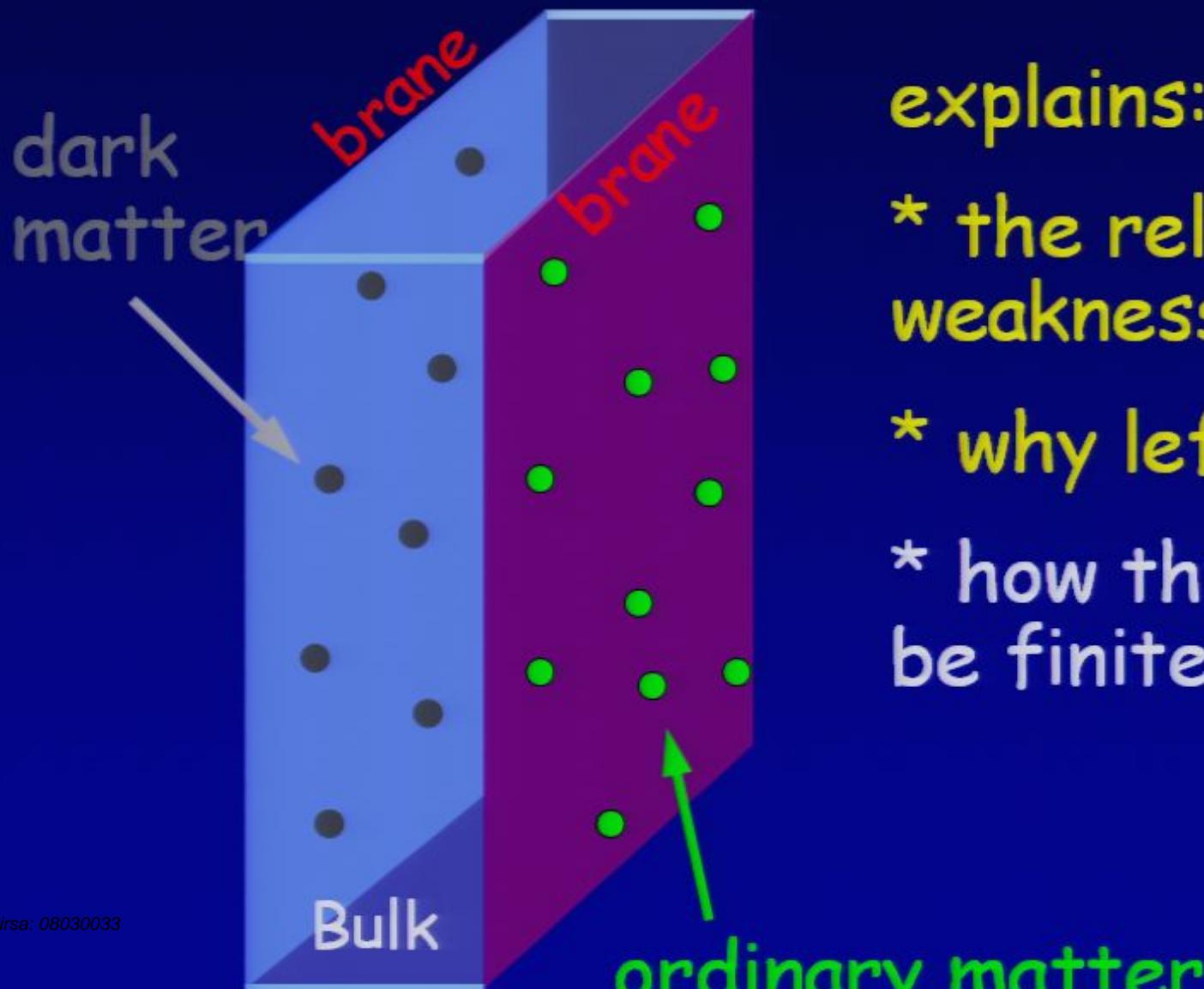


**Six are curled up in a little ball**

**Their size and shape determine the pattern of  
elementary particles and the “constants of nature”**

**So particle physics is just a branch of cosmology!**

**the seventh is a tiny gap between two  
3d brane-worlds**

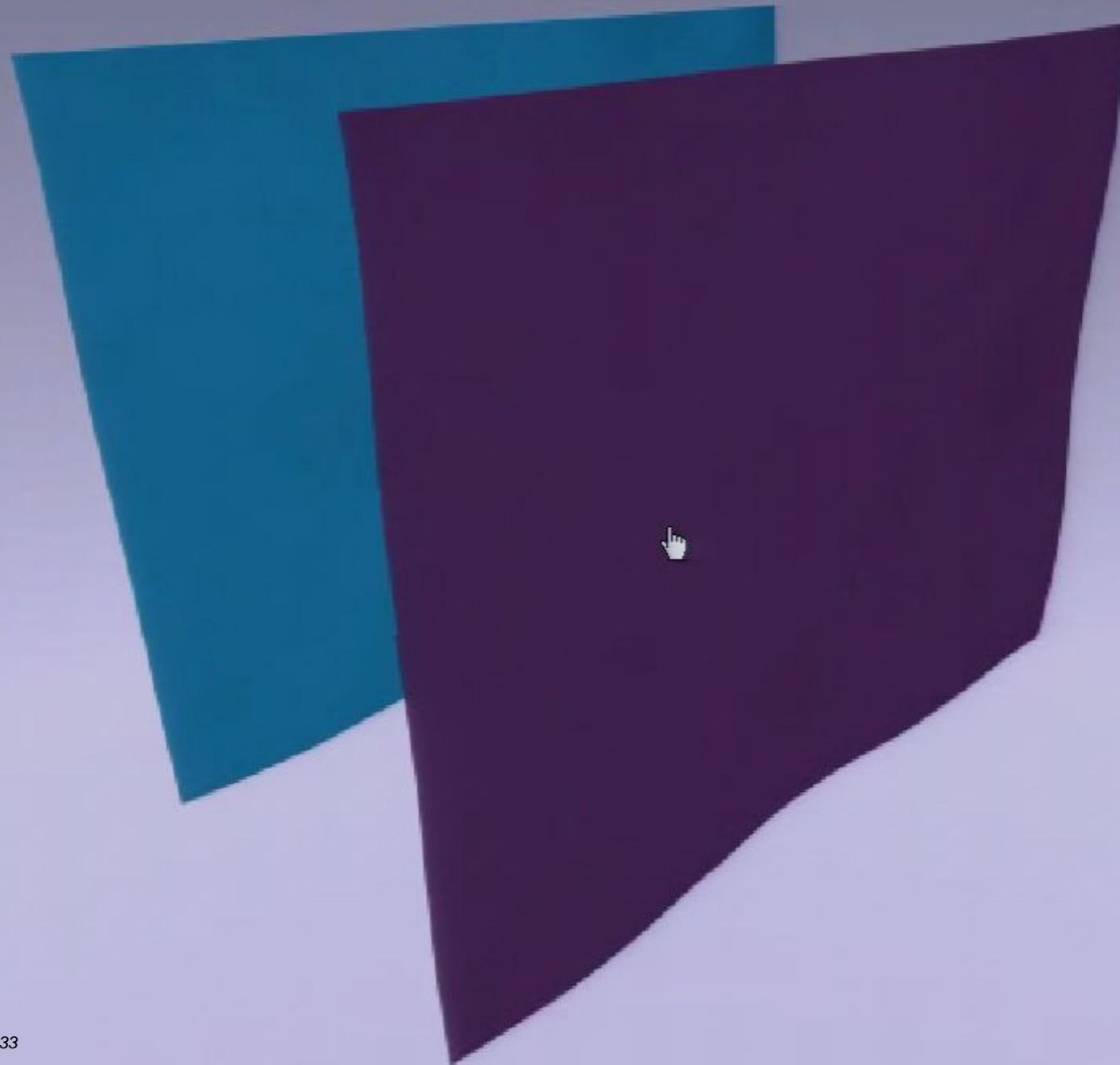


**explains:**

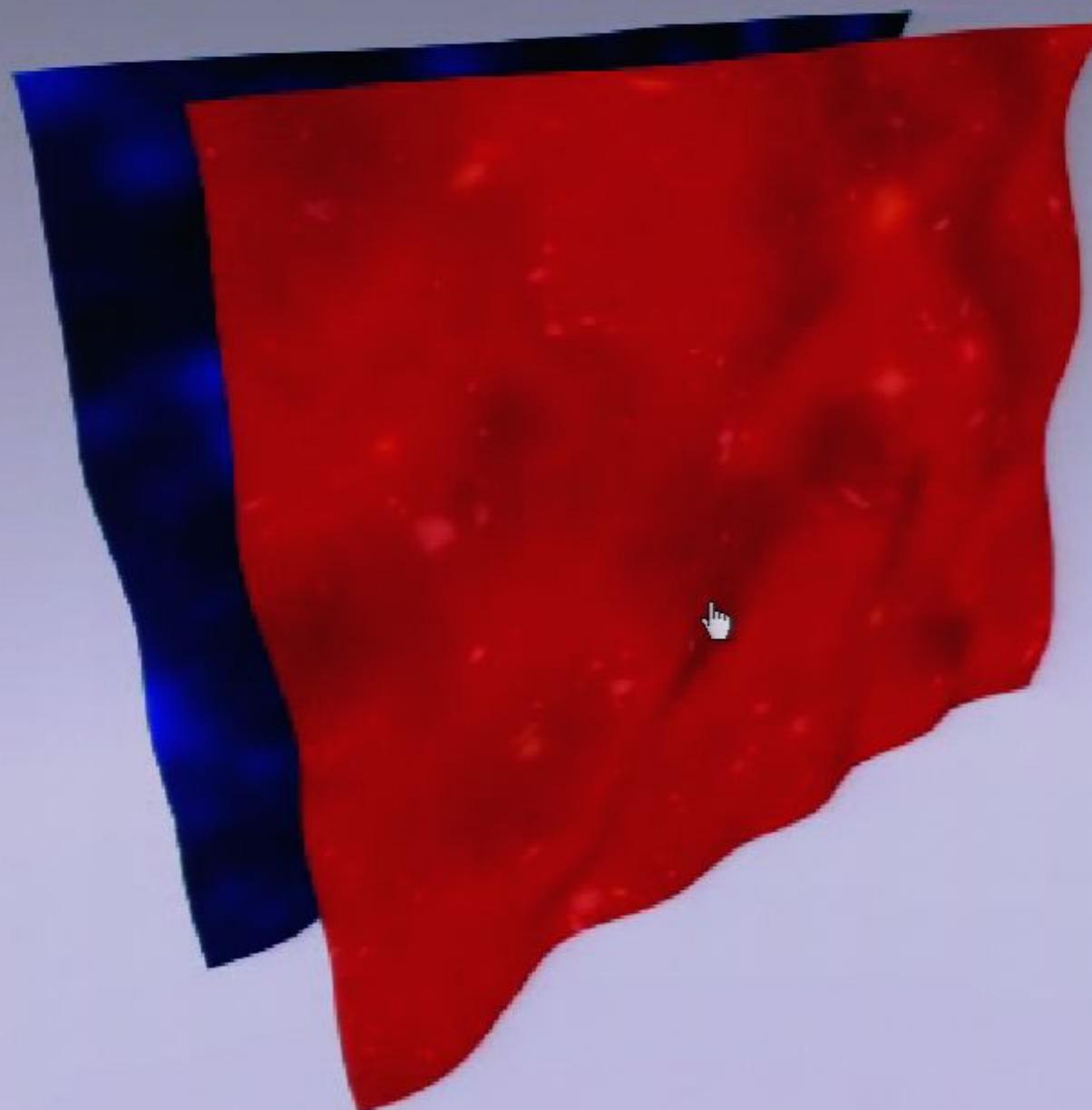
- \* the relative weakness of gravity
- \* why left  $\neq$  right
- \* how the density can be finite at the bang

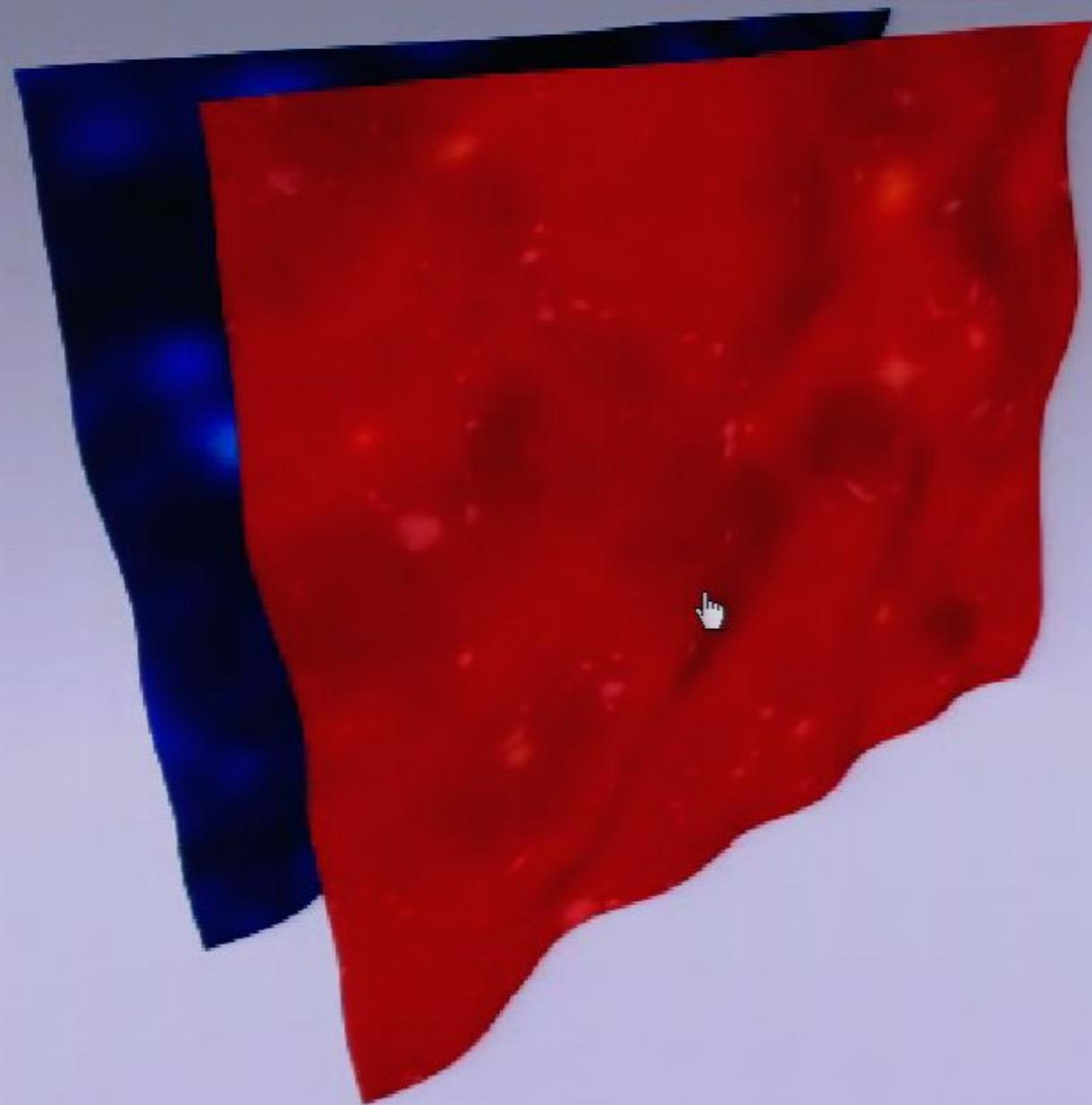
In this picture, the big bang  
is a collision between the two  
brane worlds!

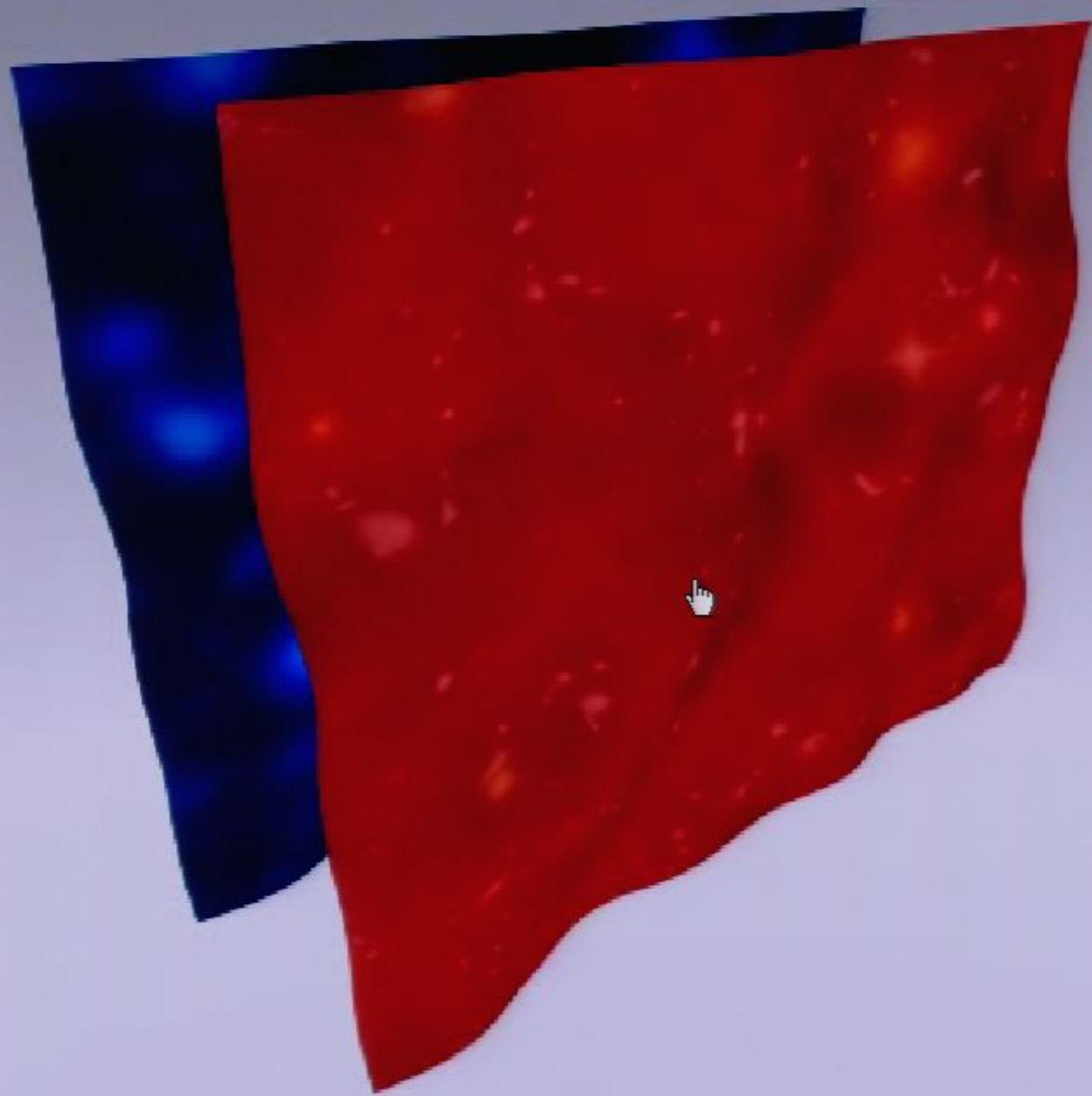


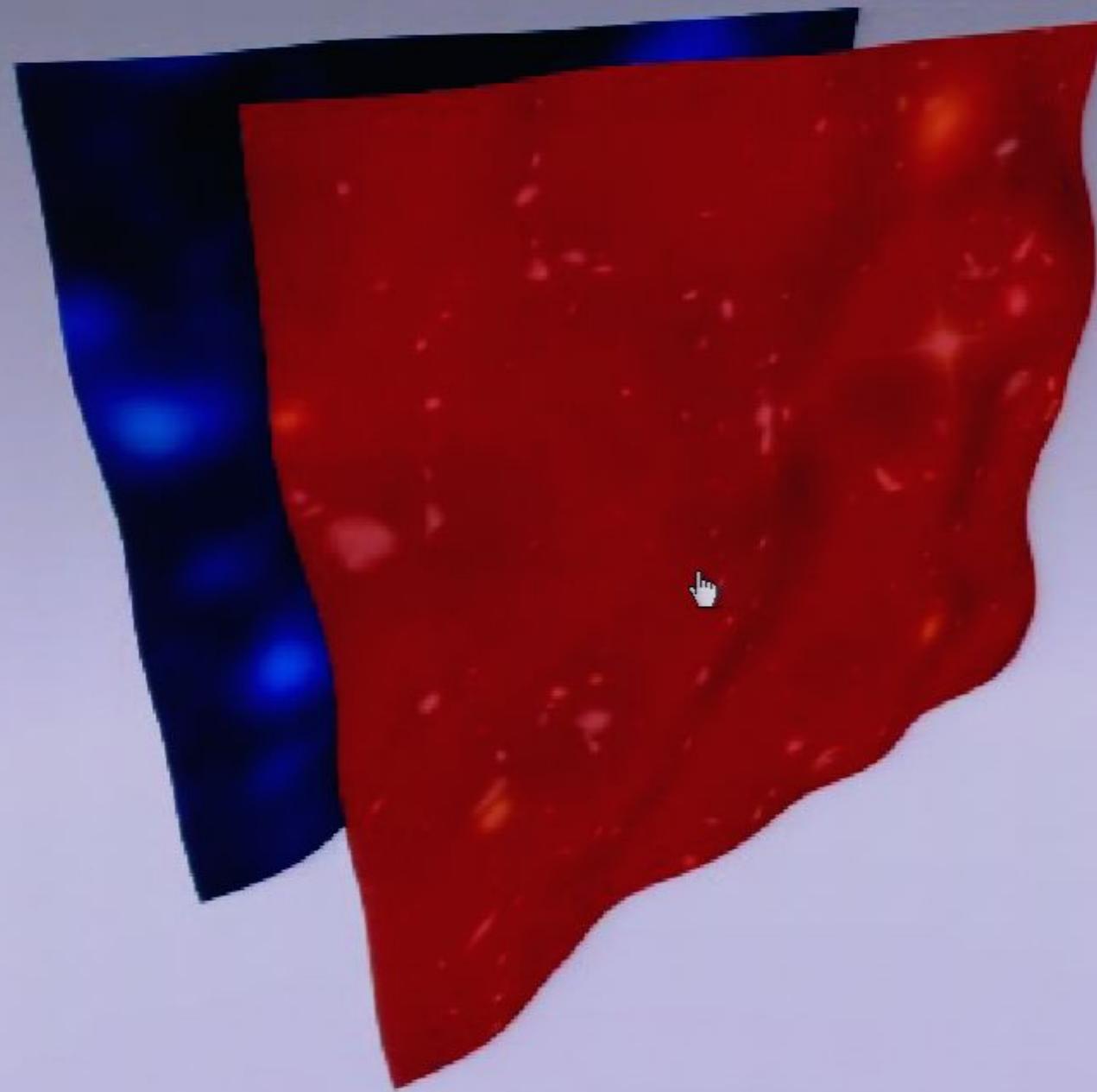


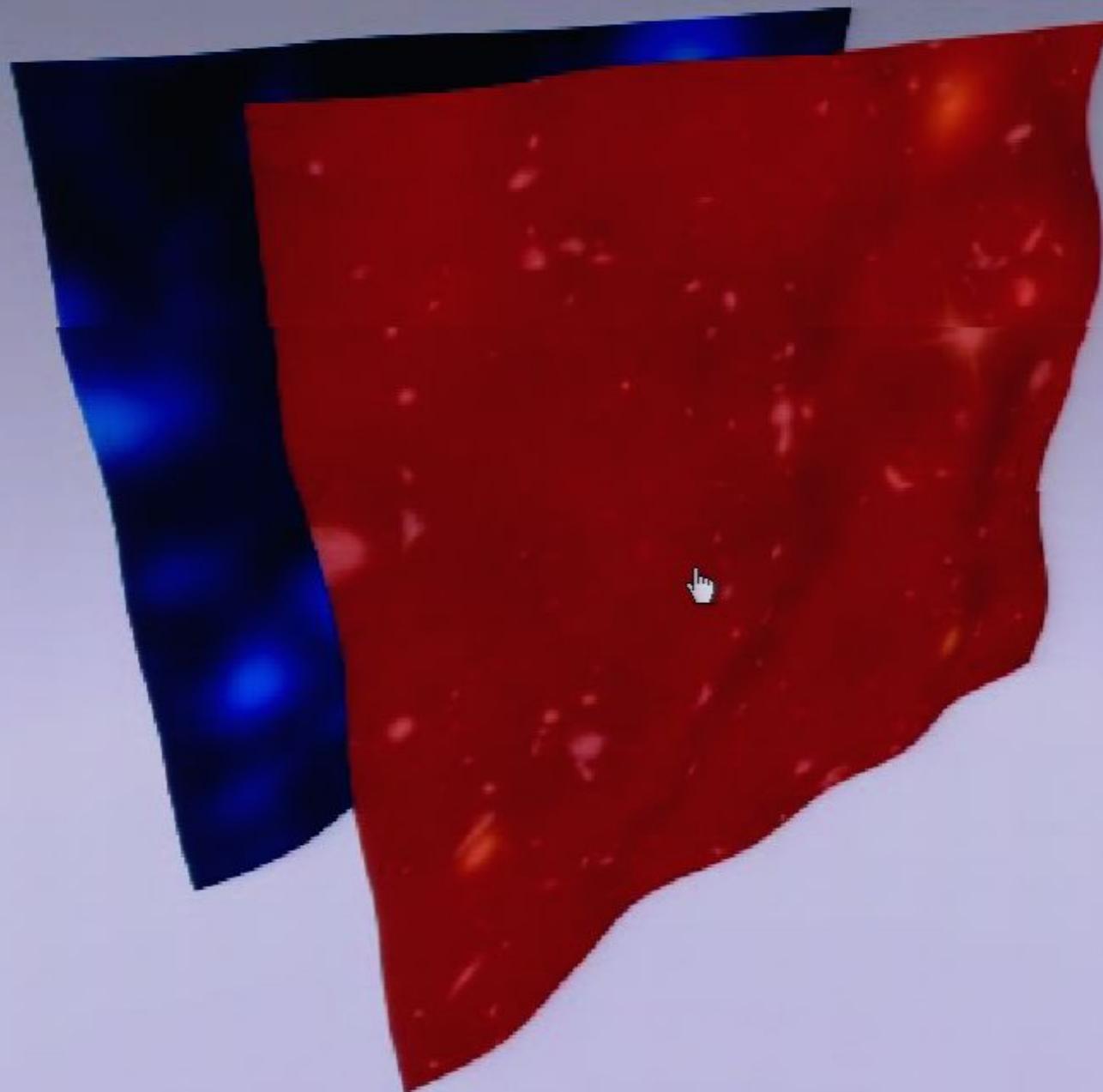


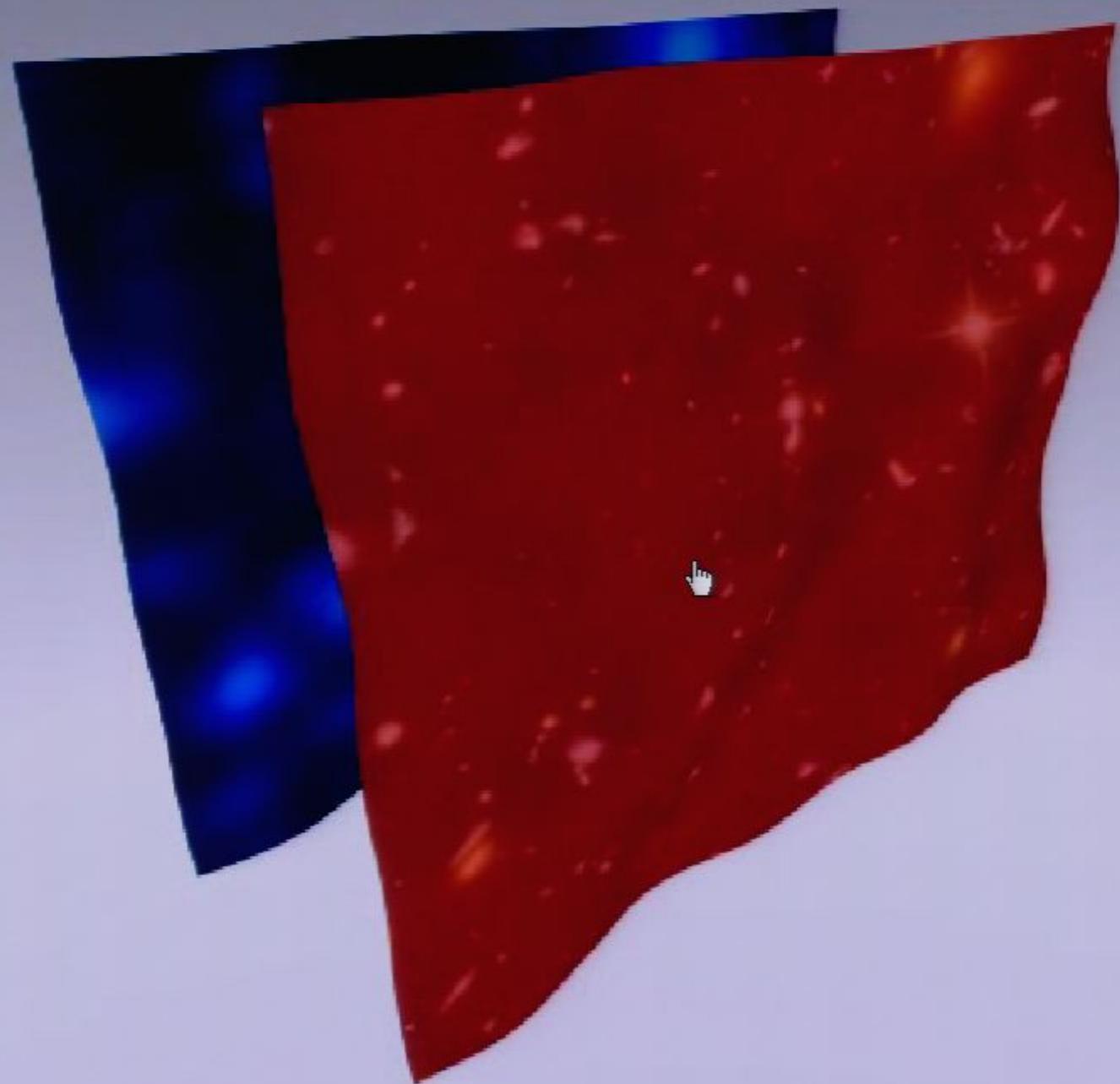


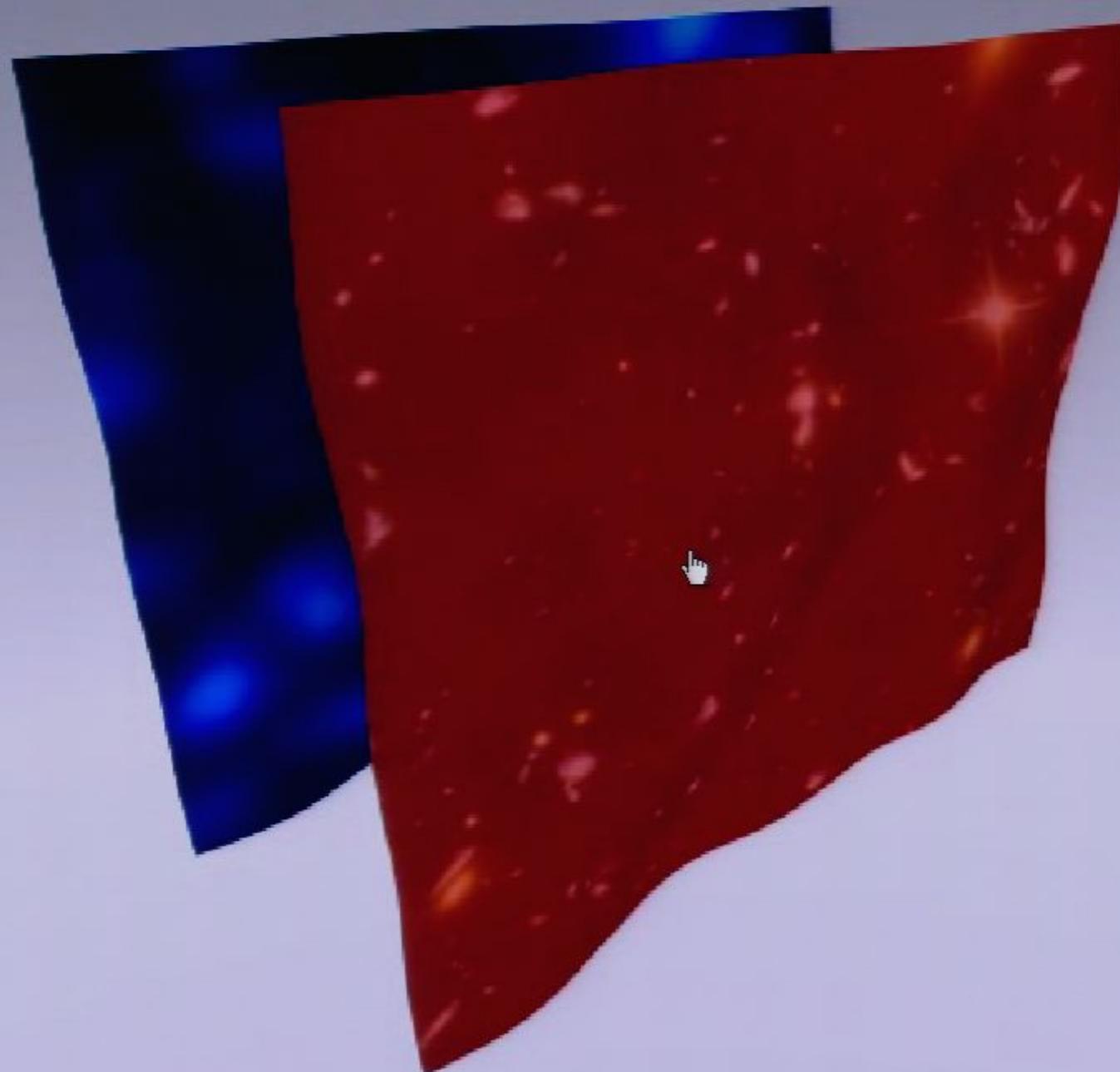


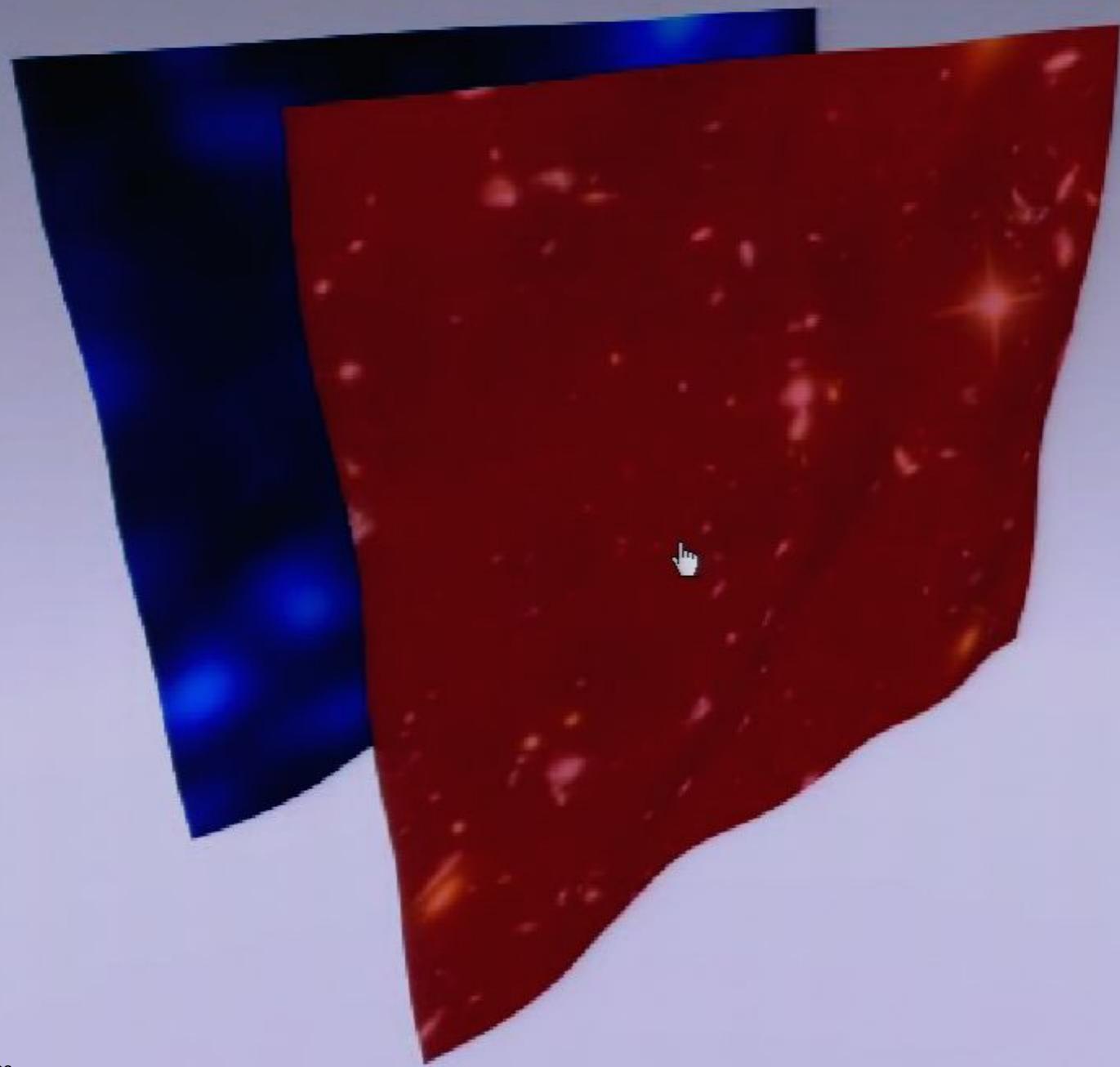


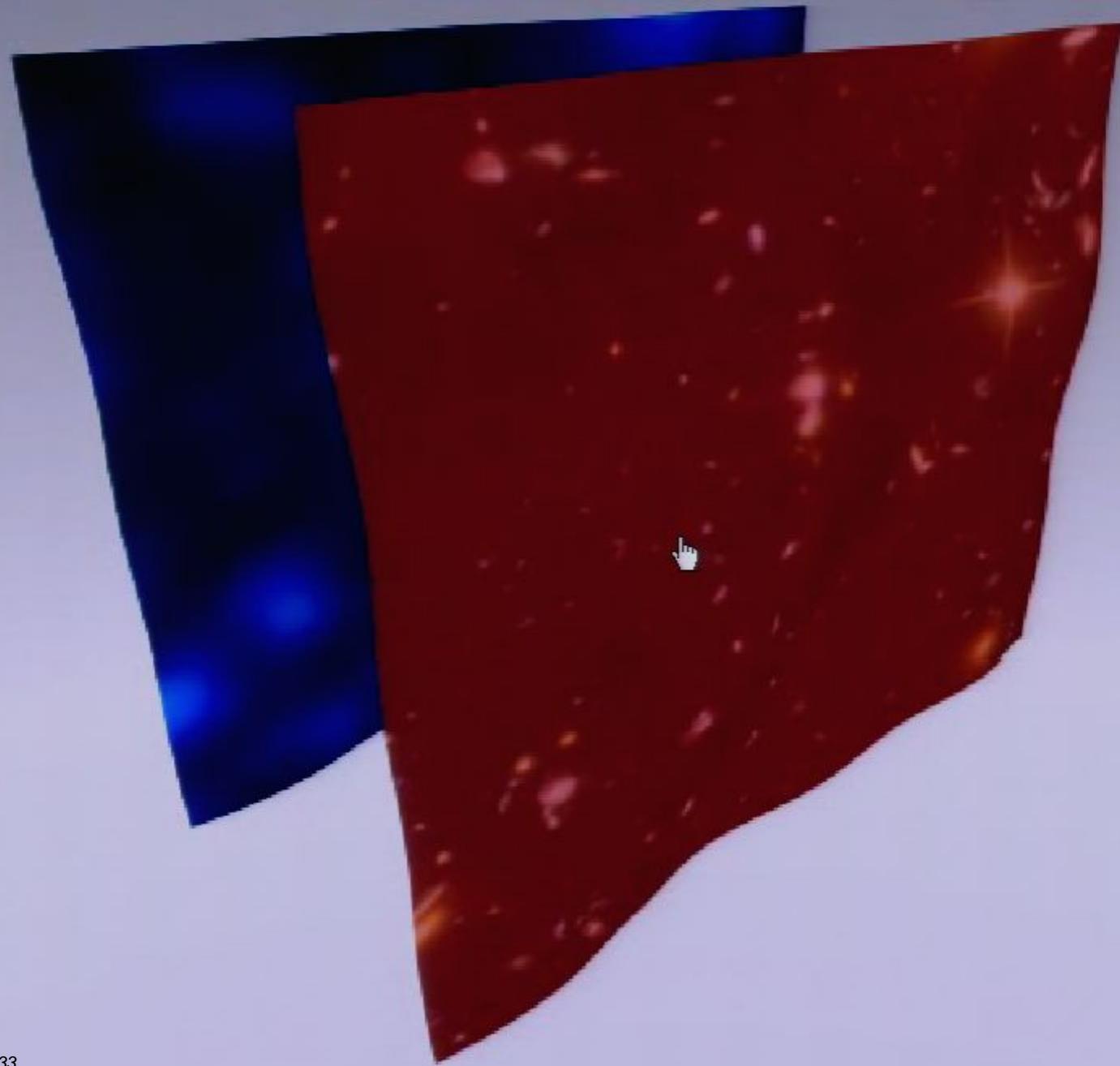


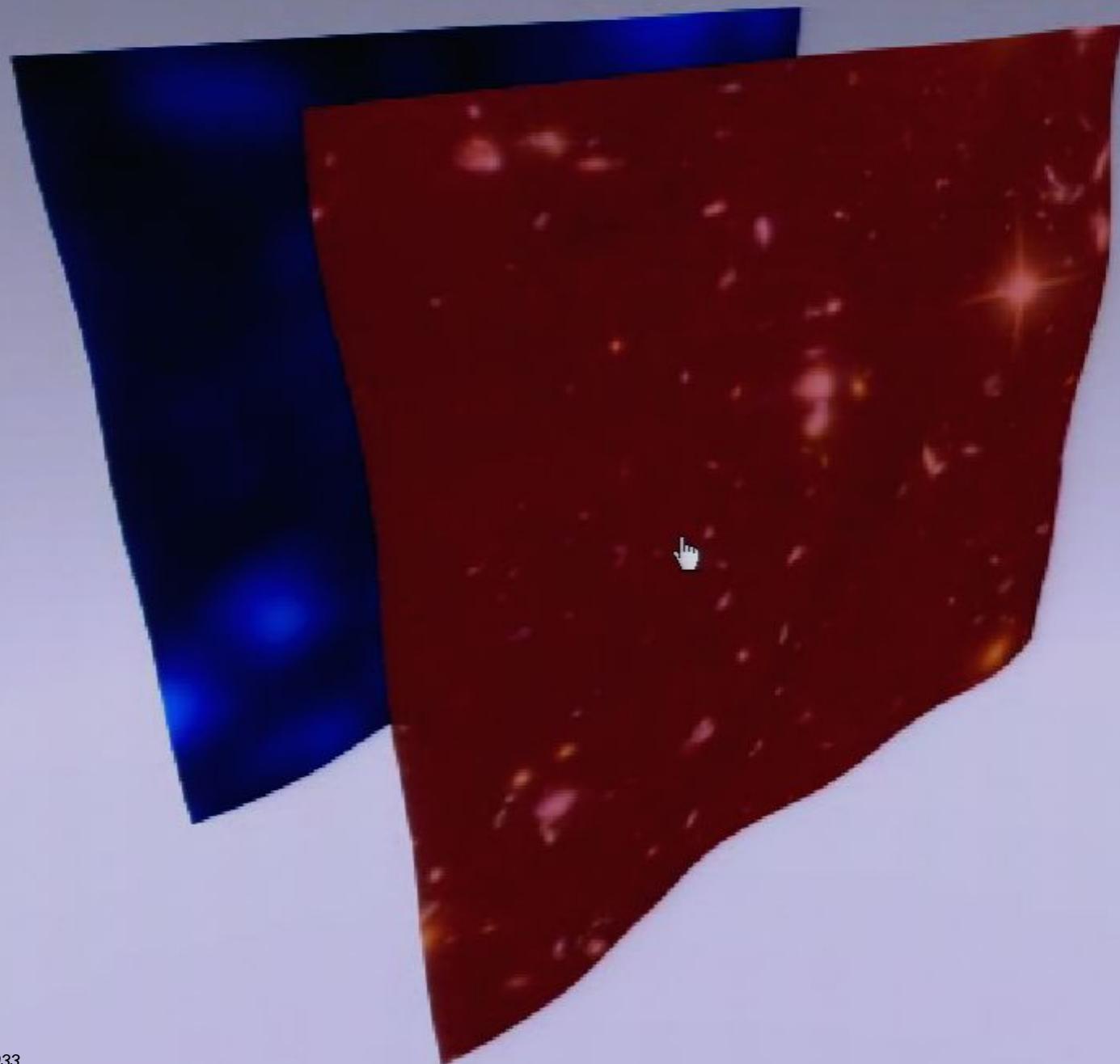


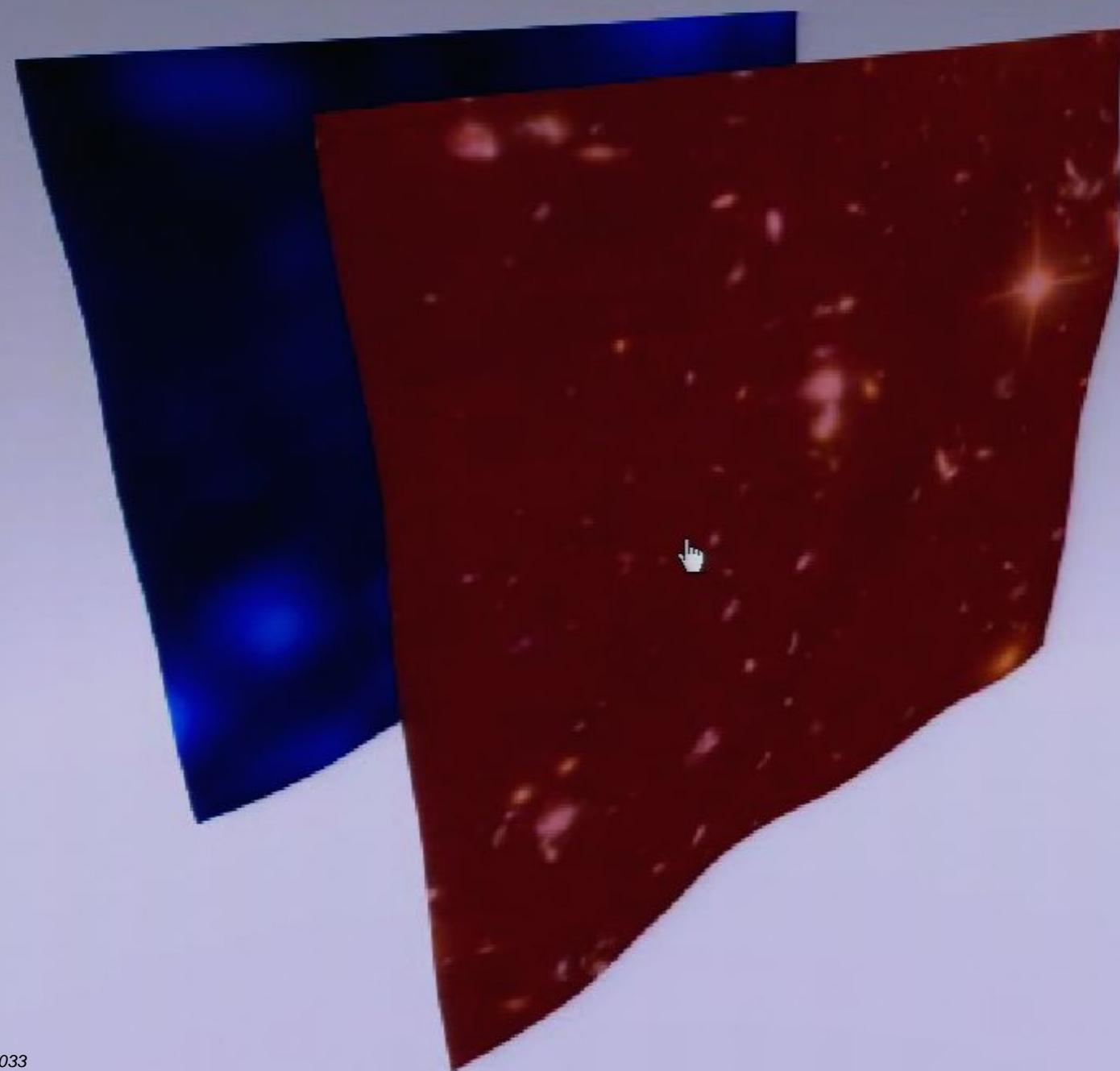


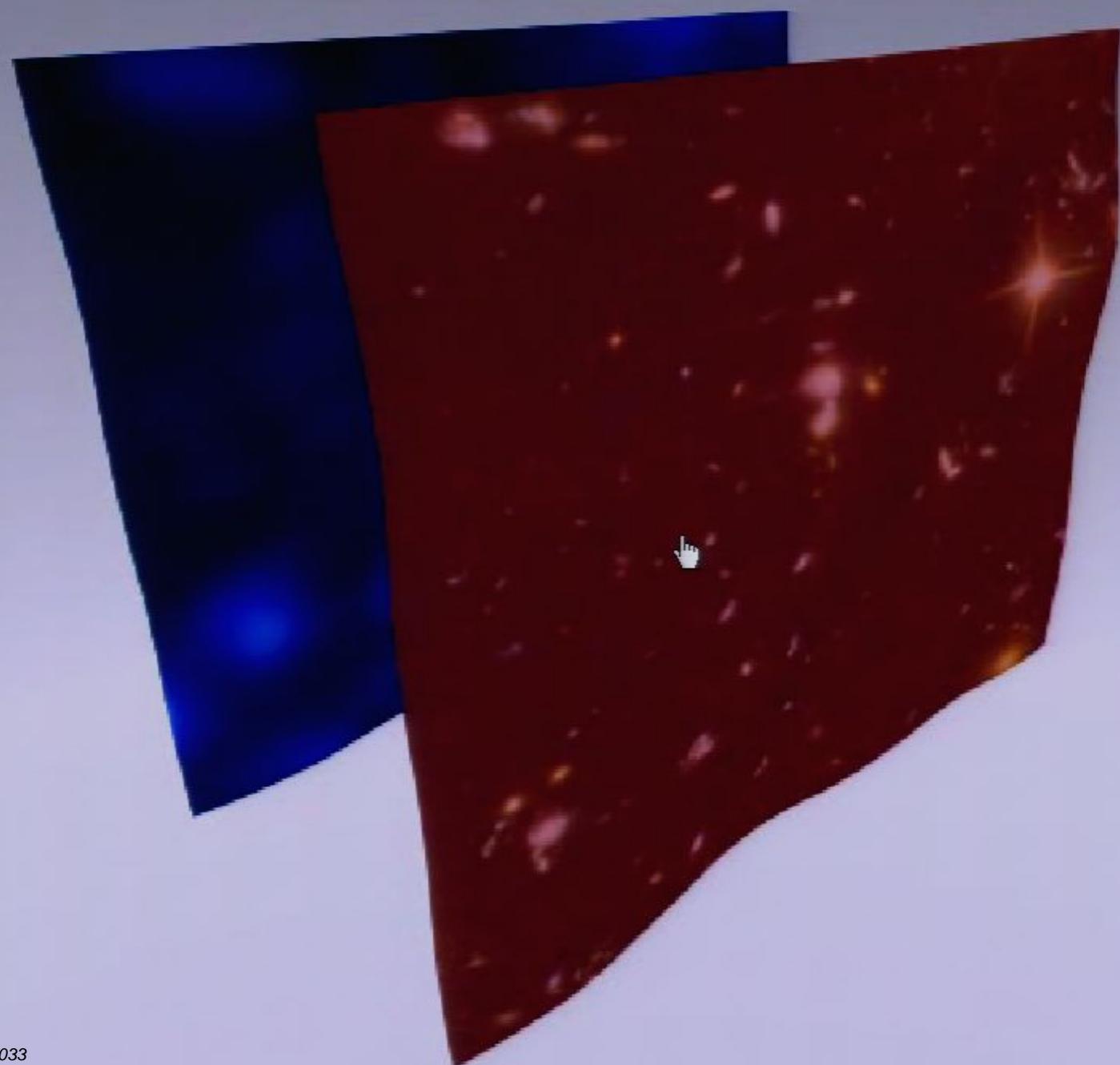


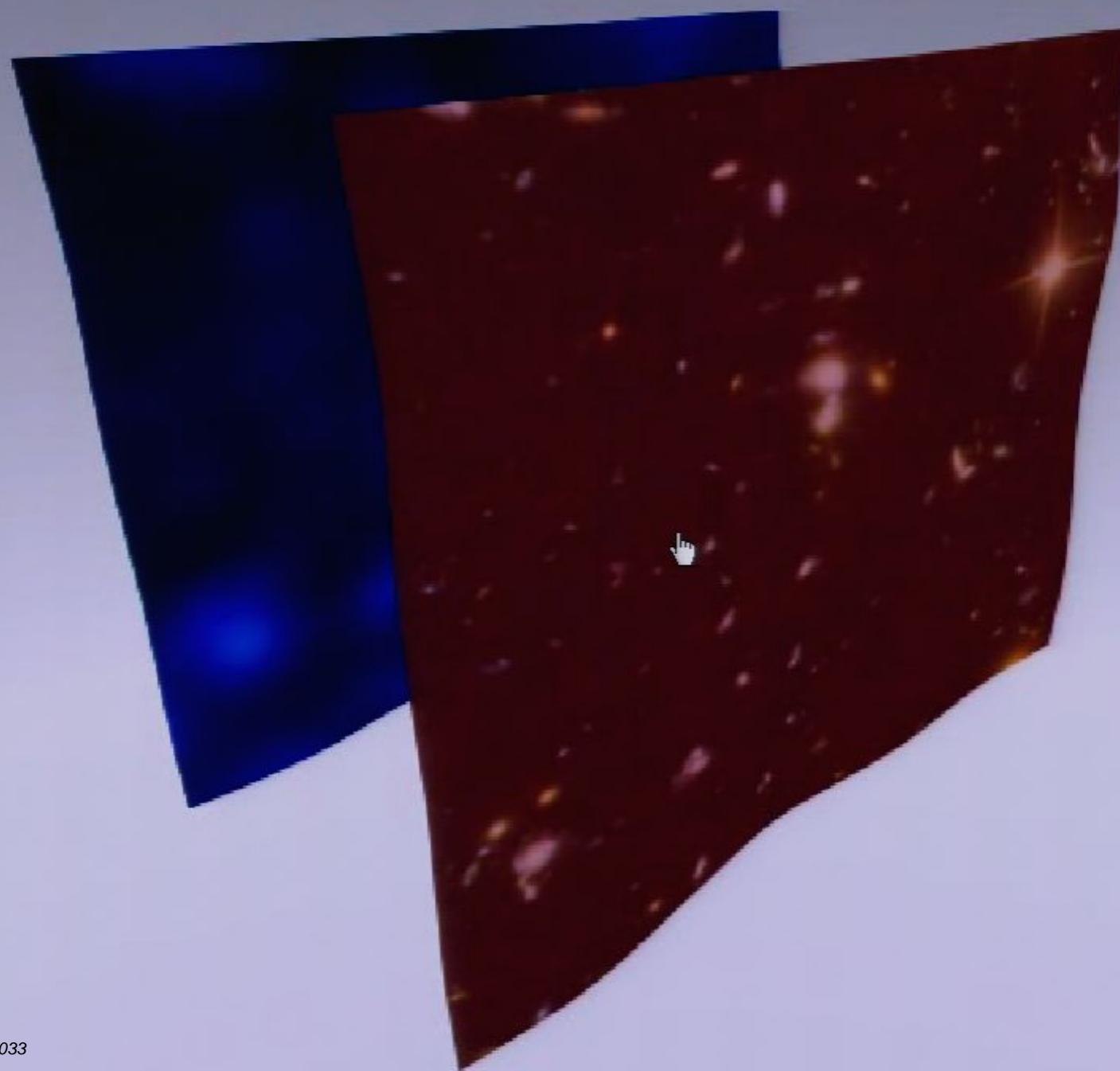


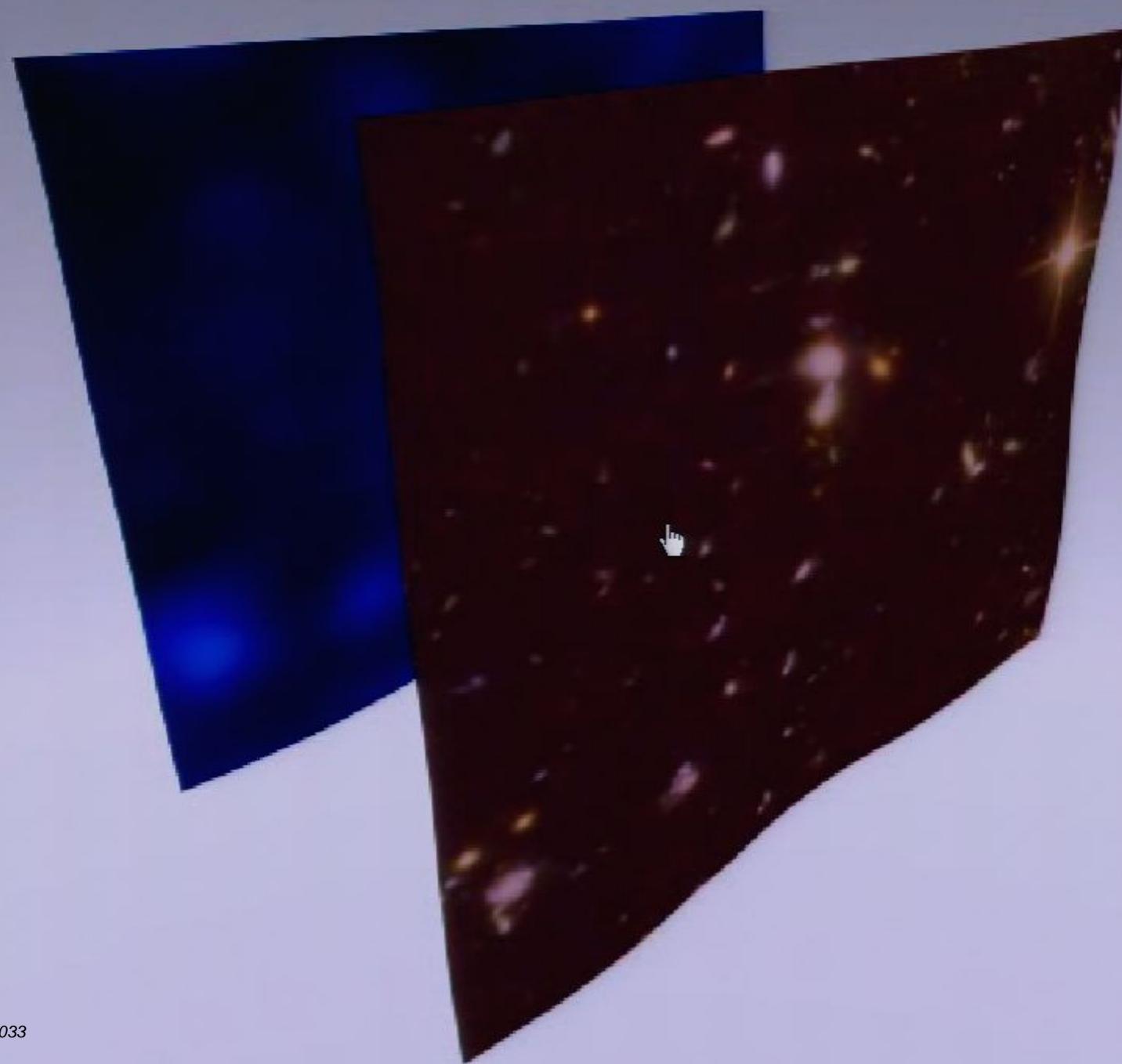


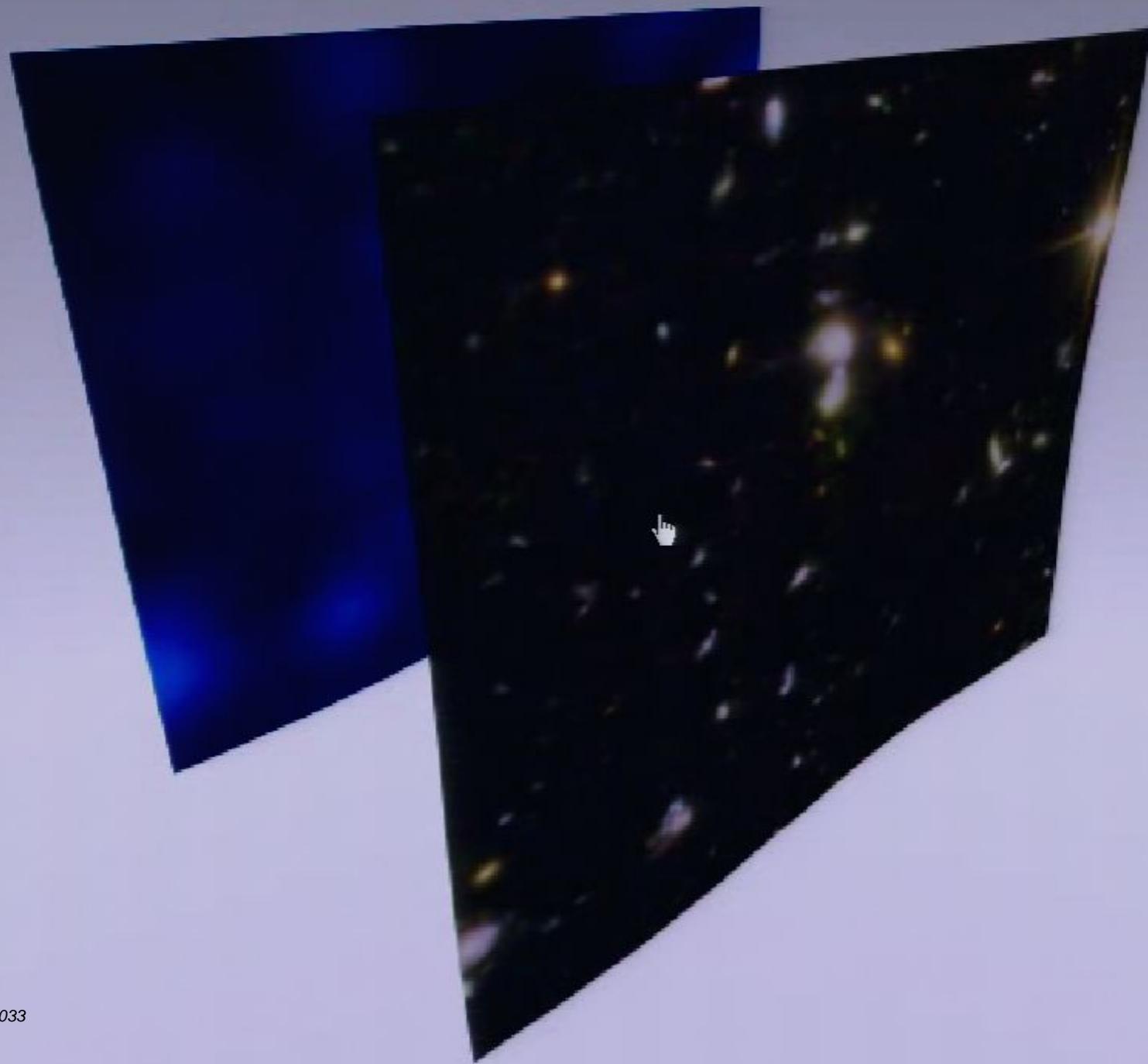


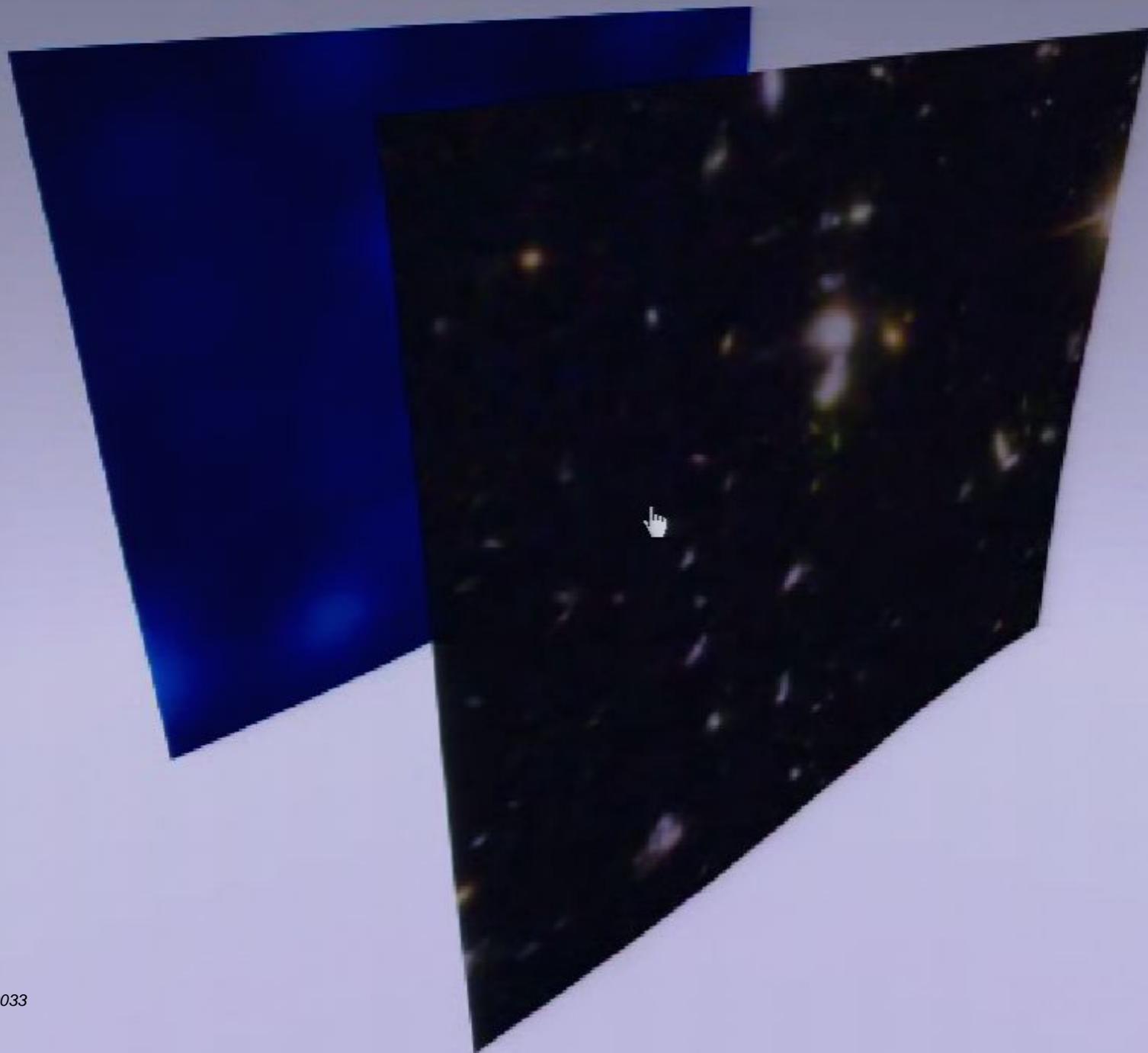


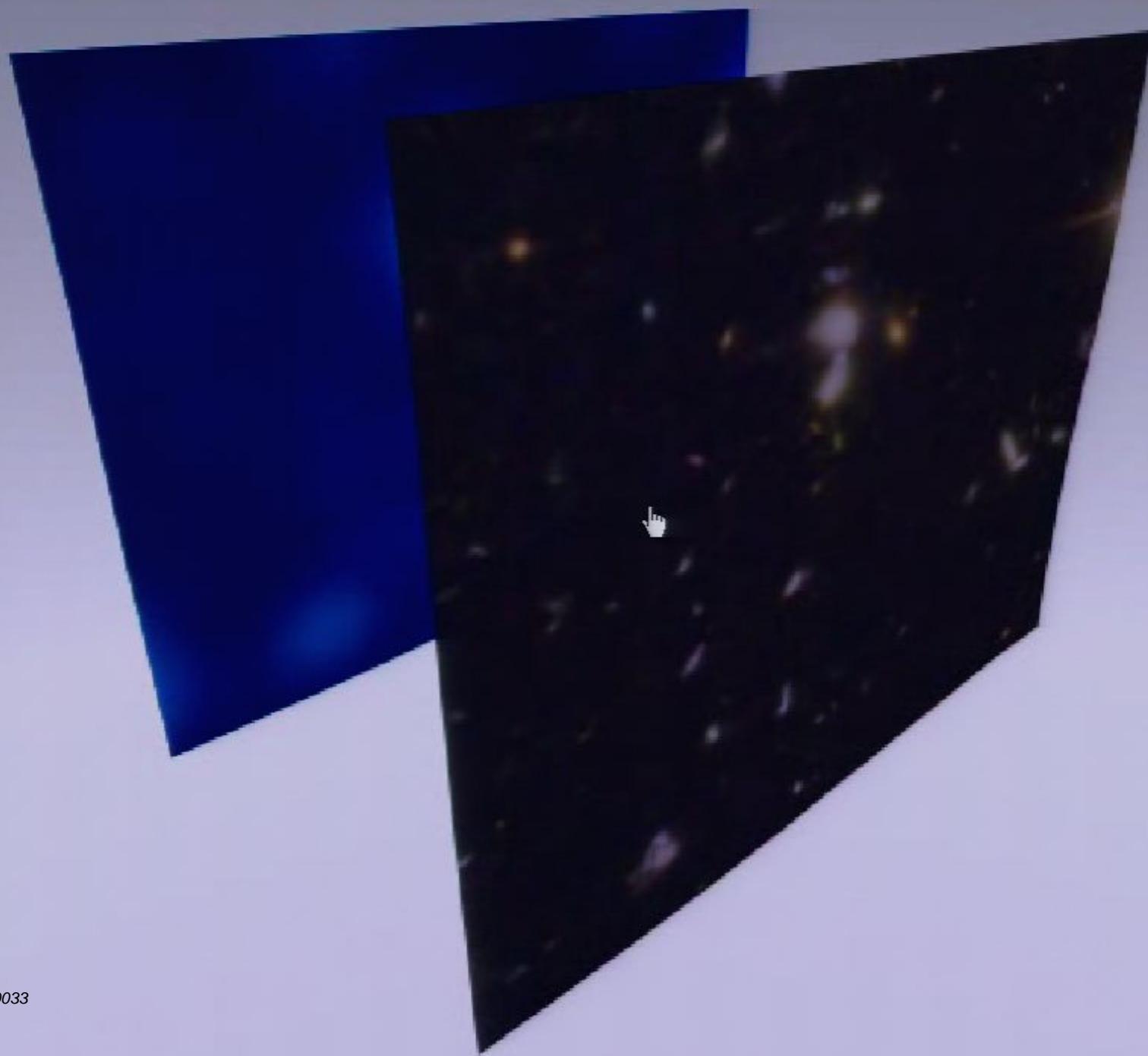


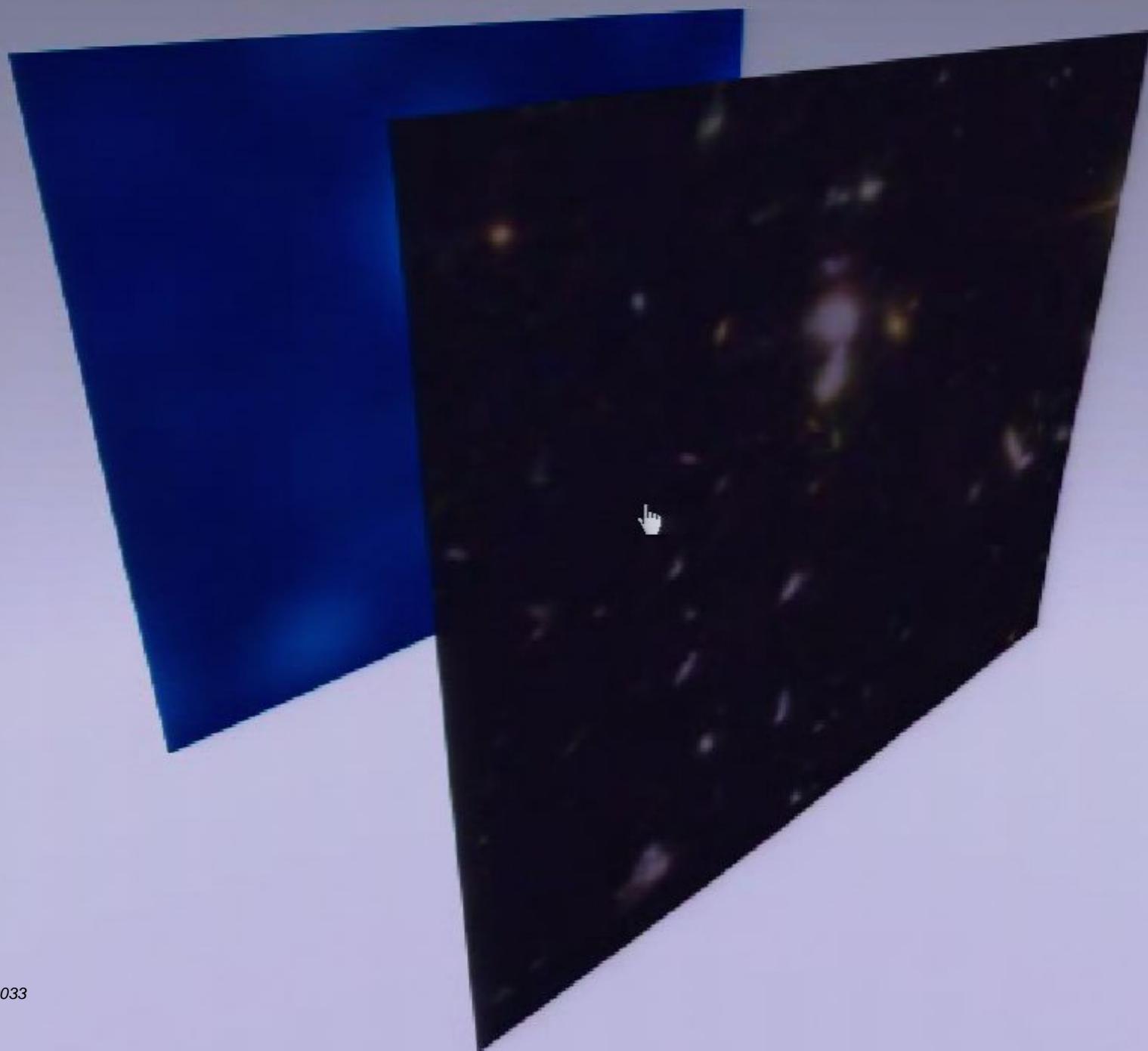


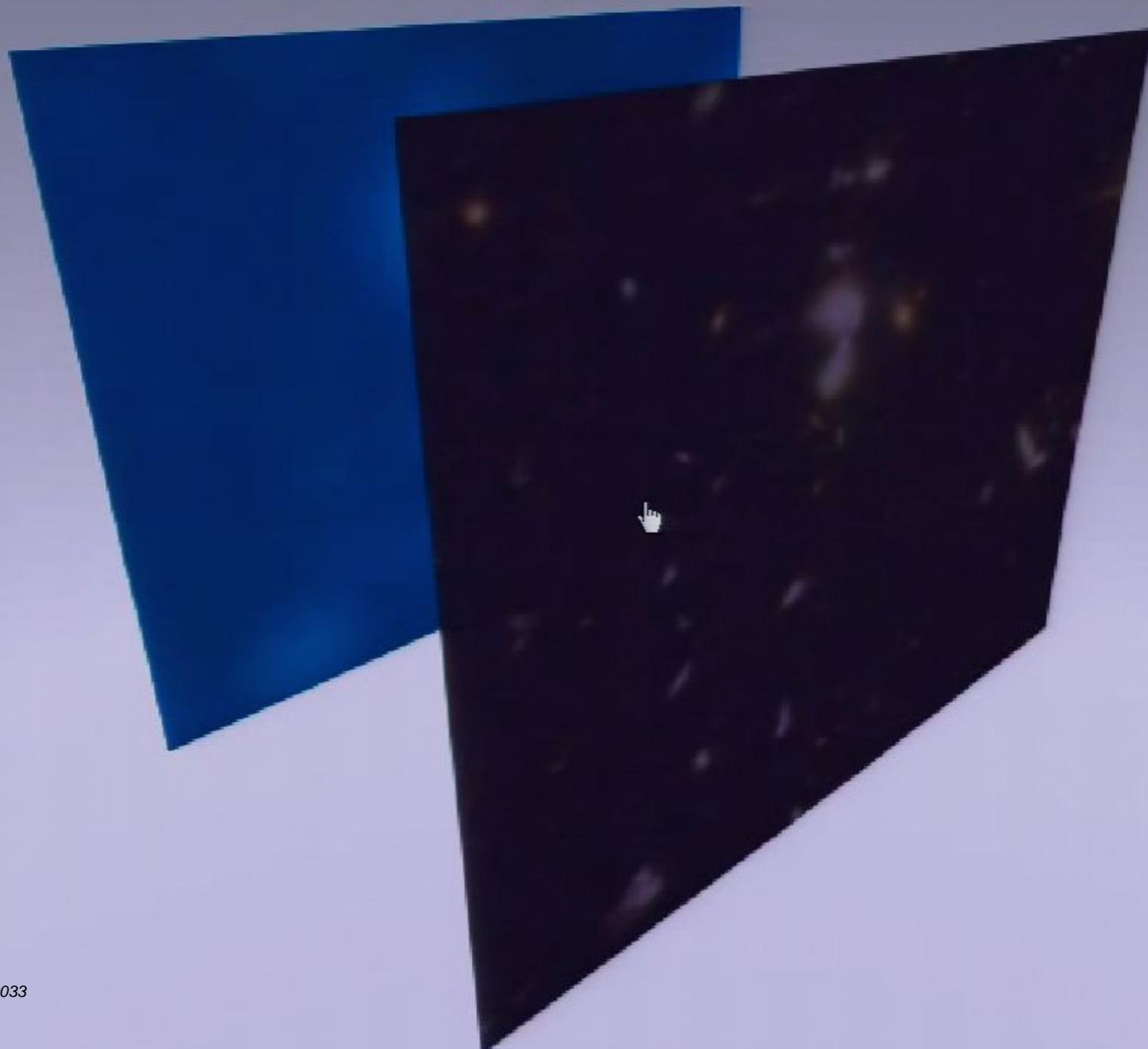


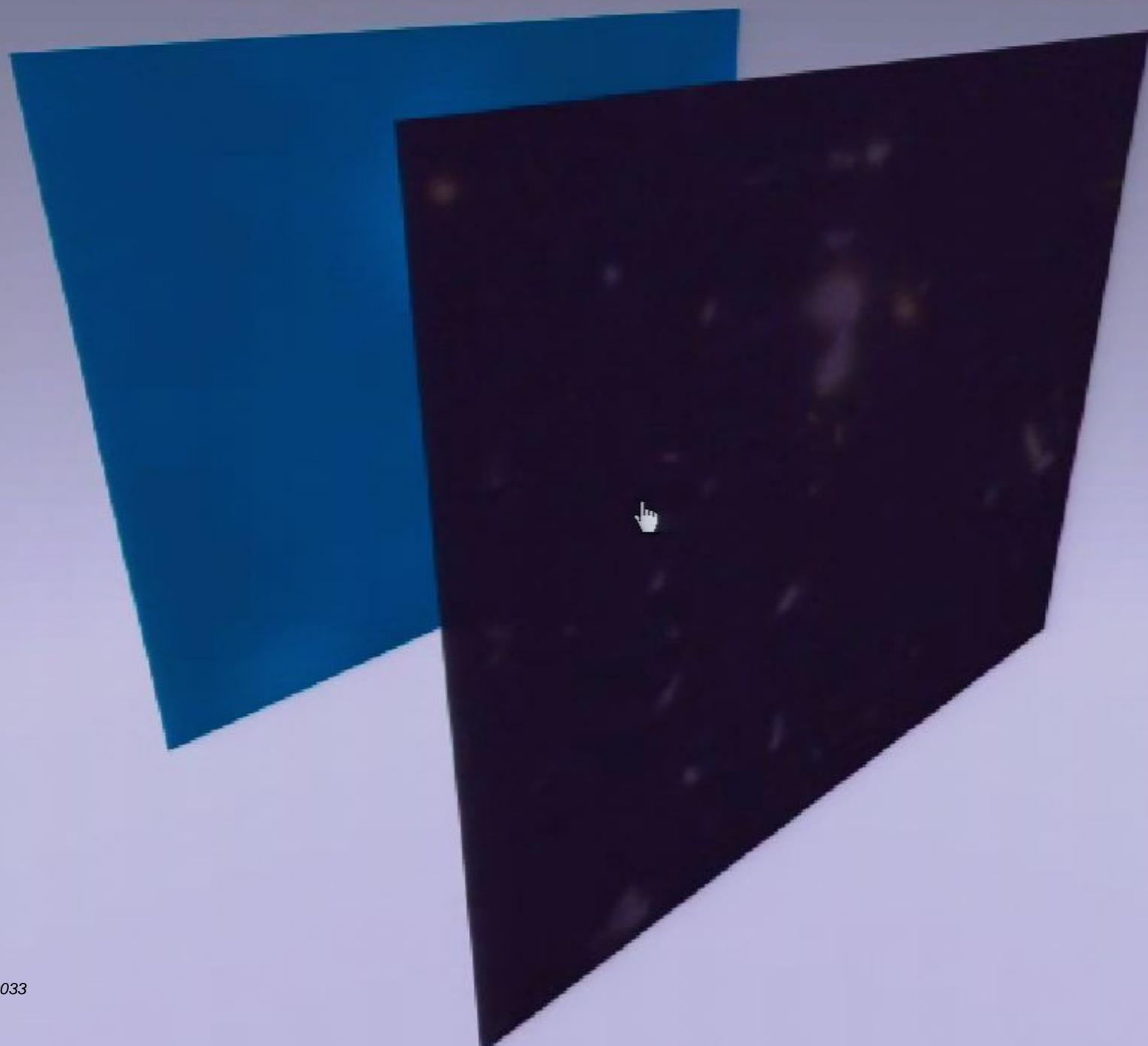


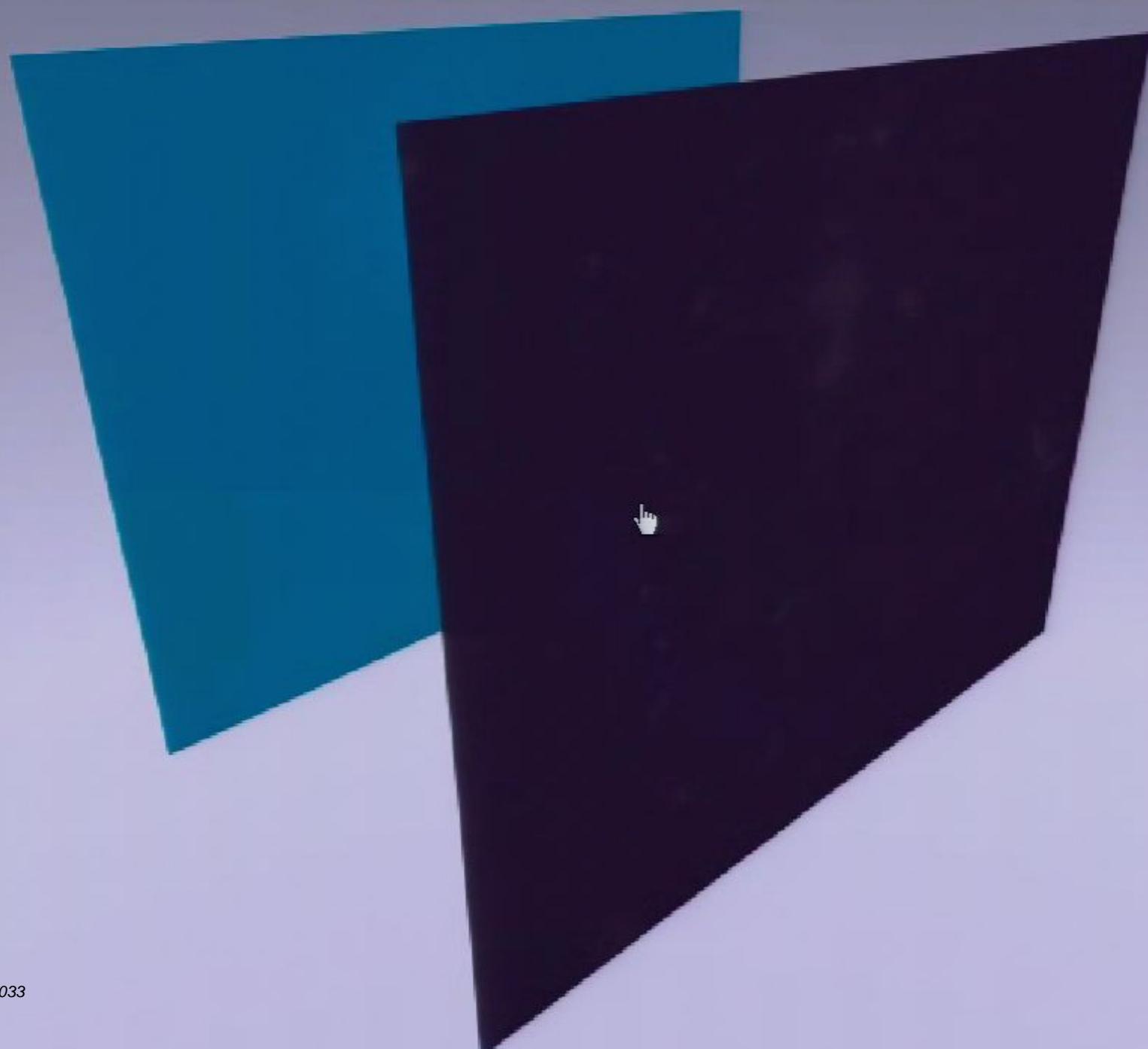


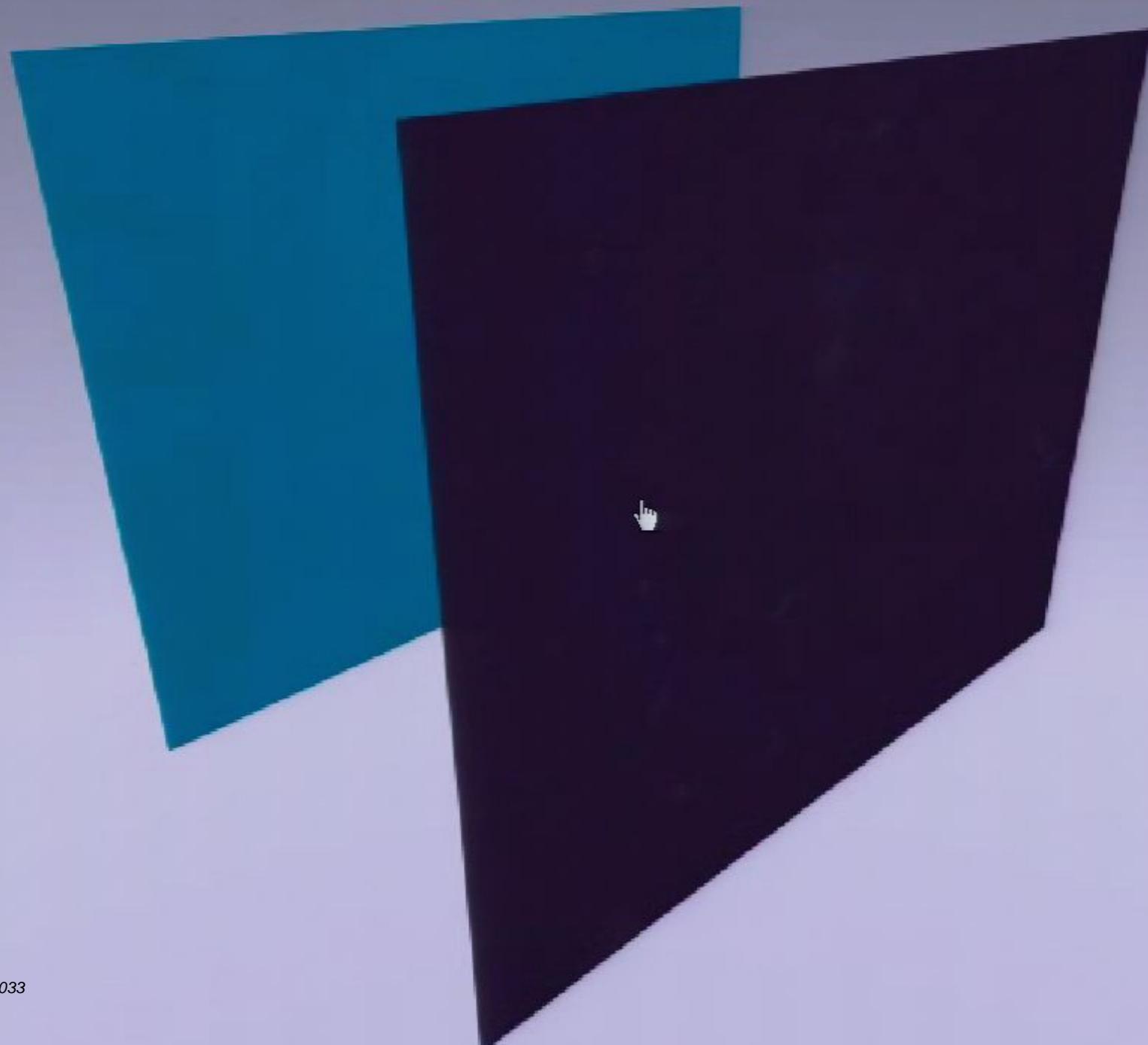


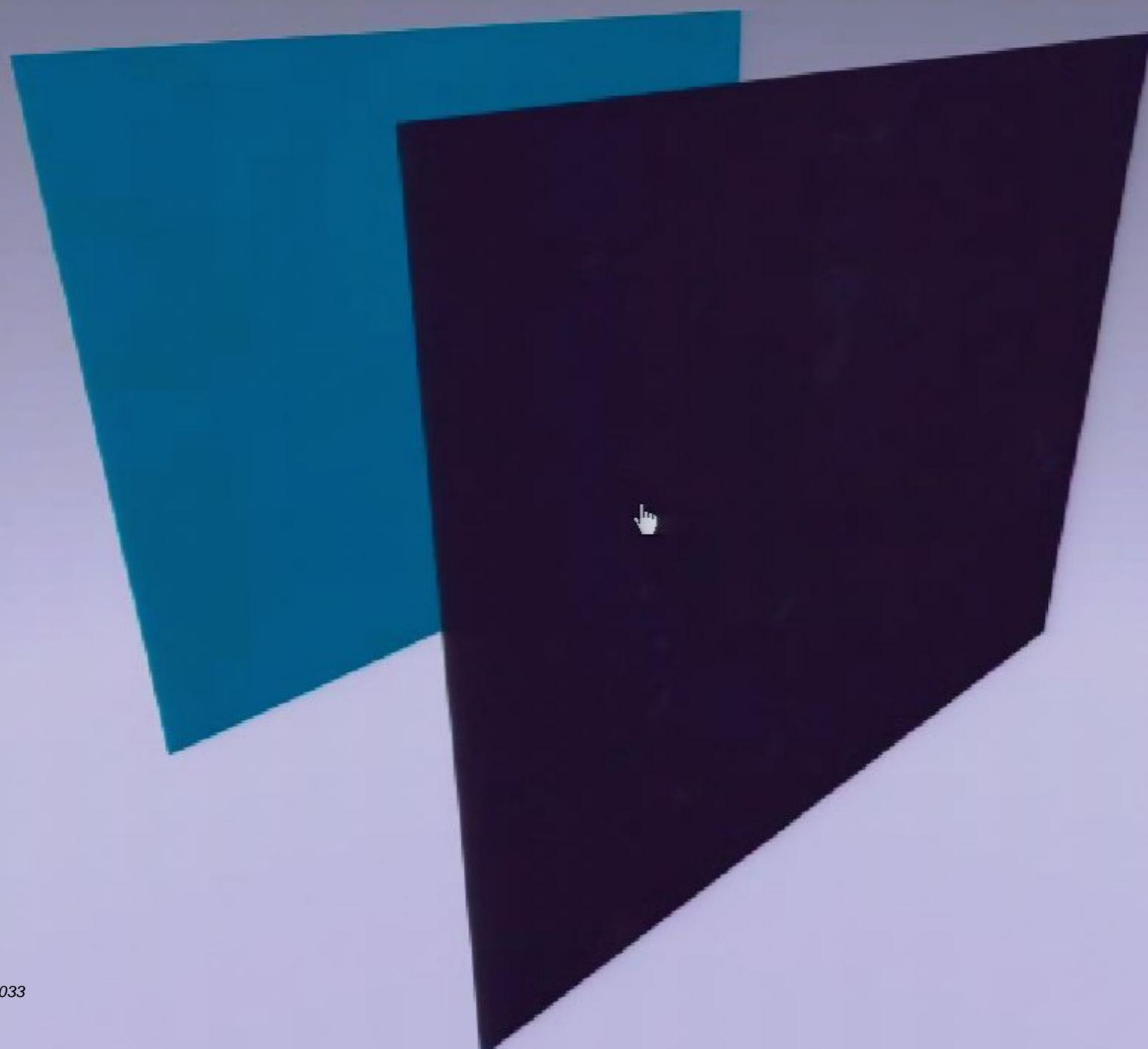


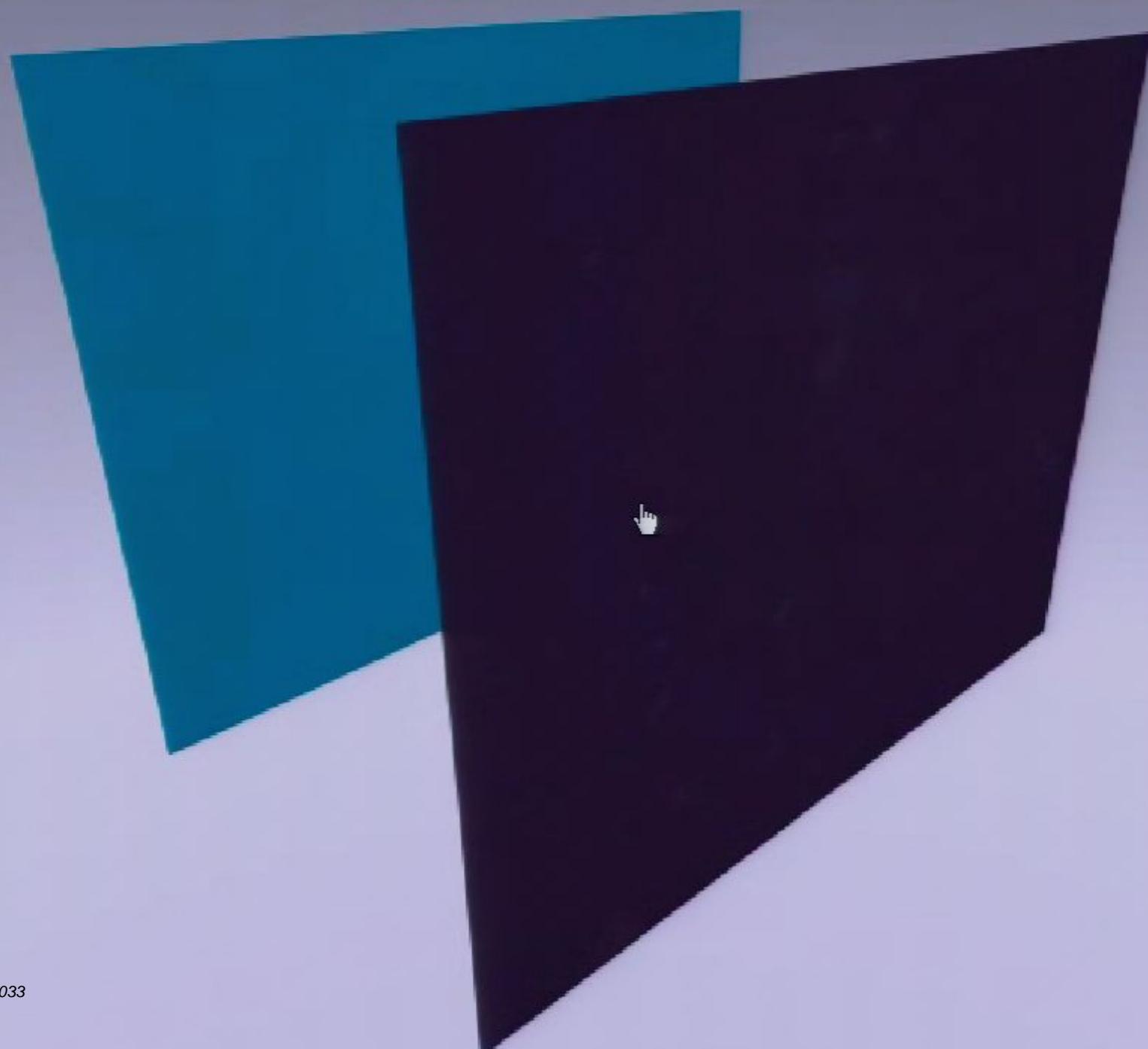


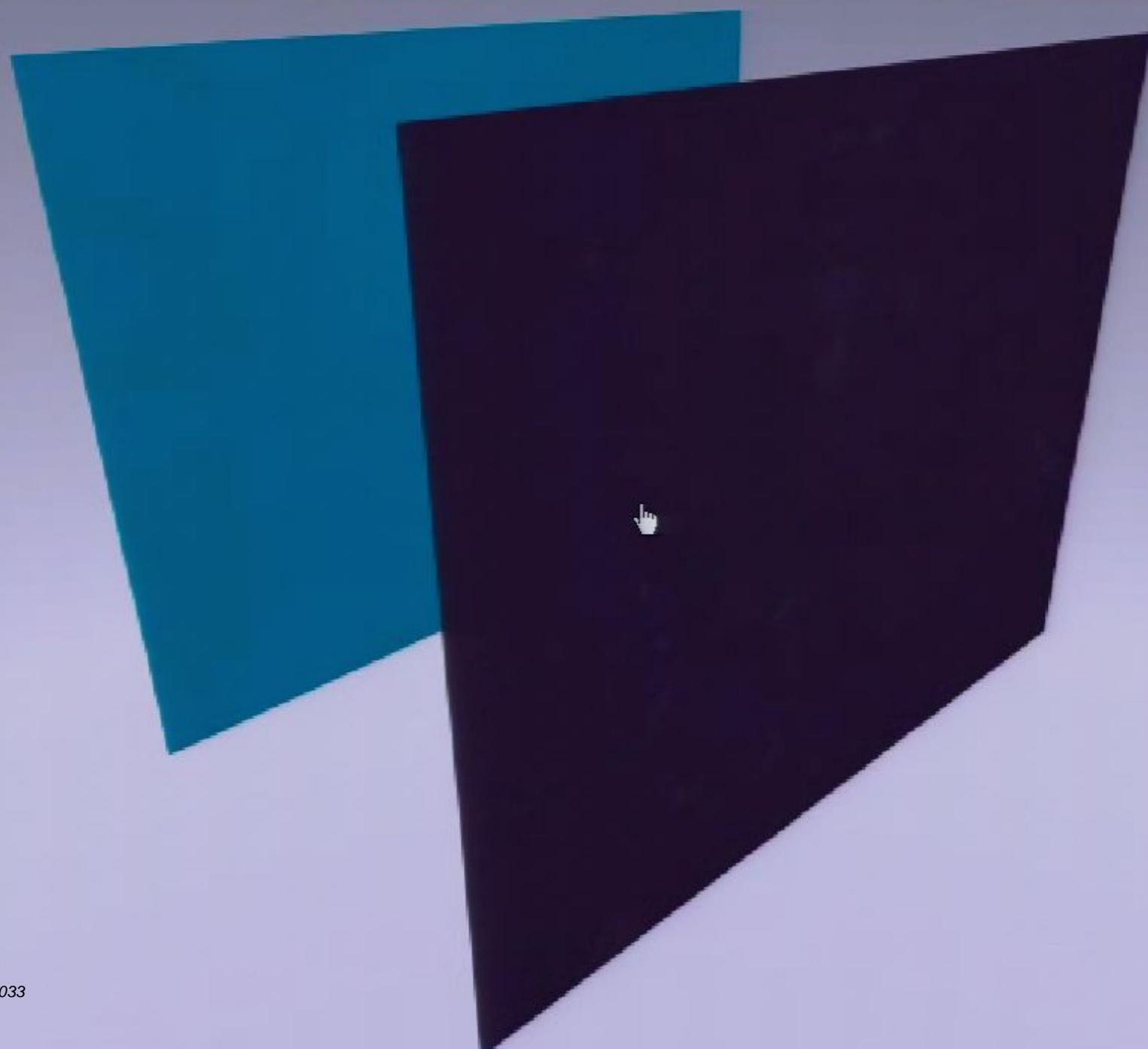


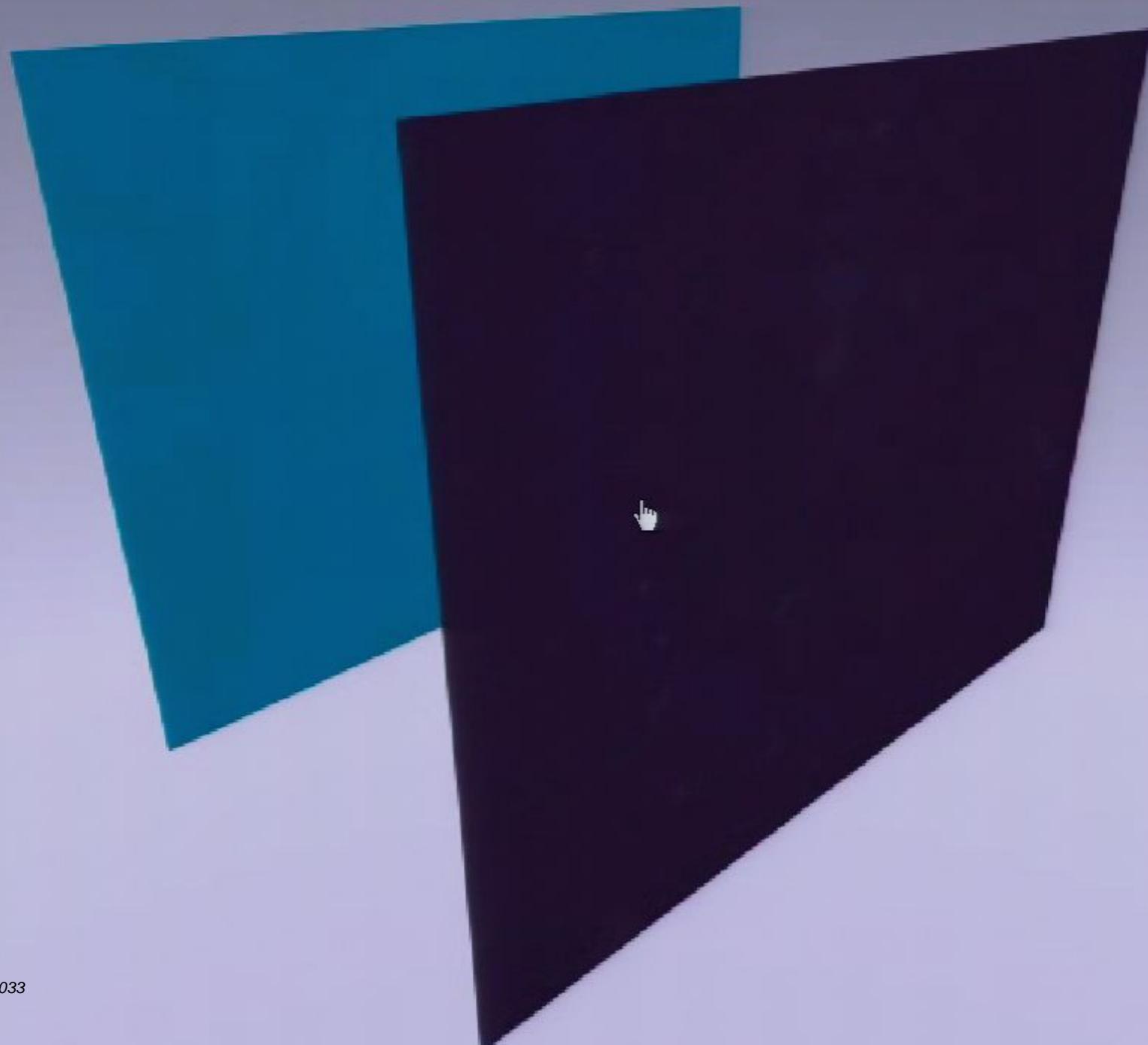


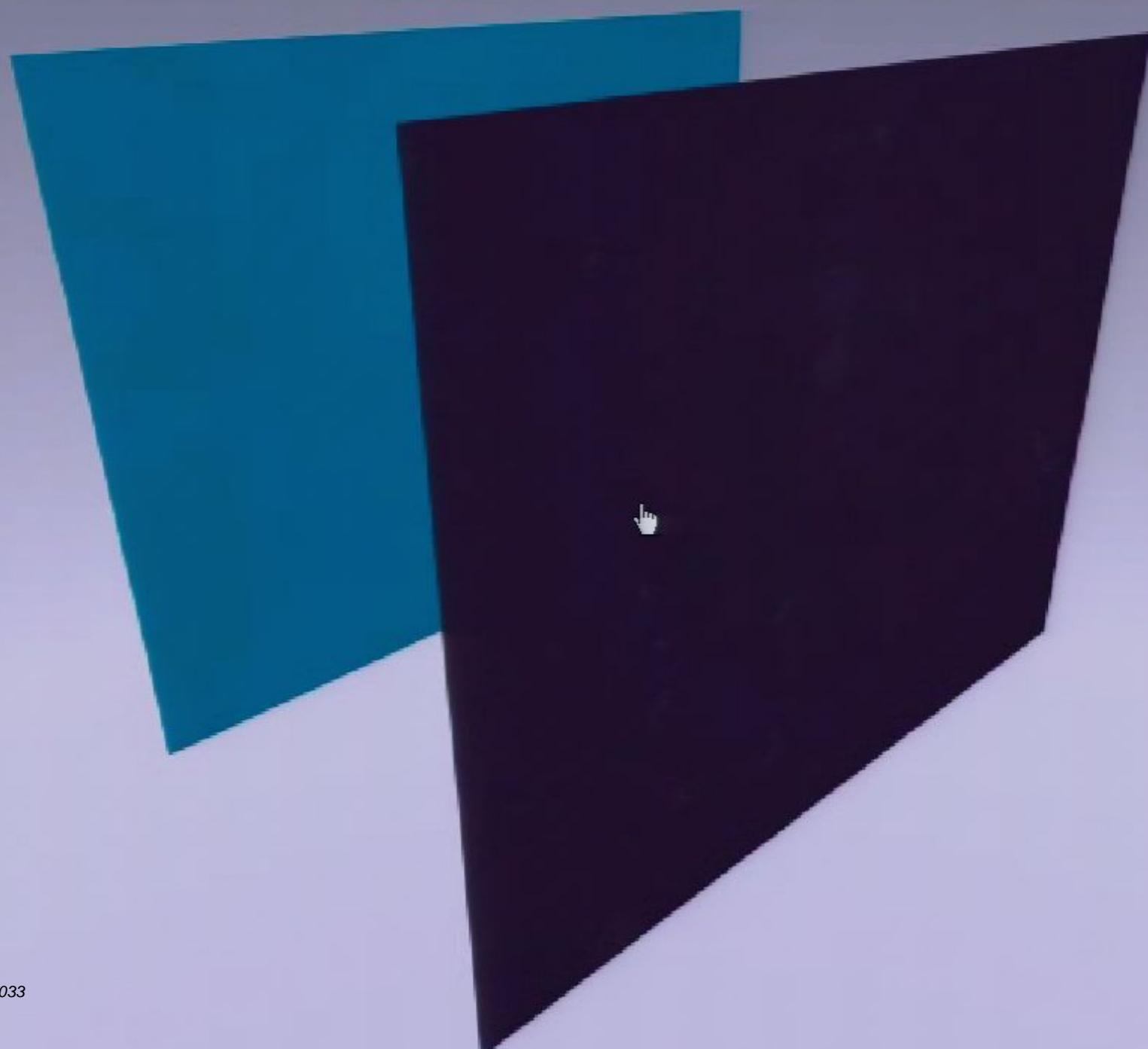


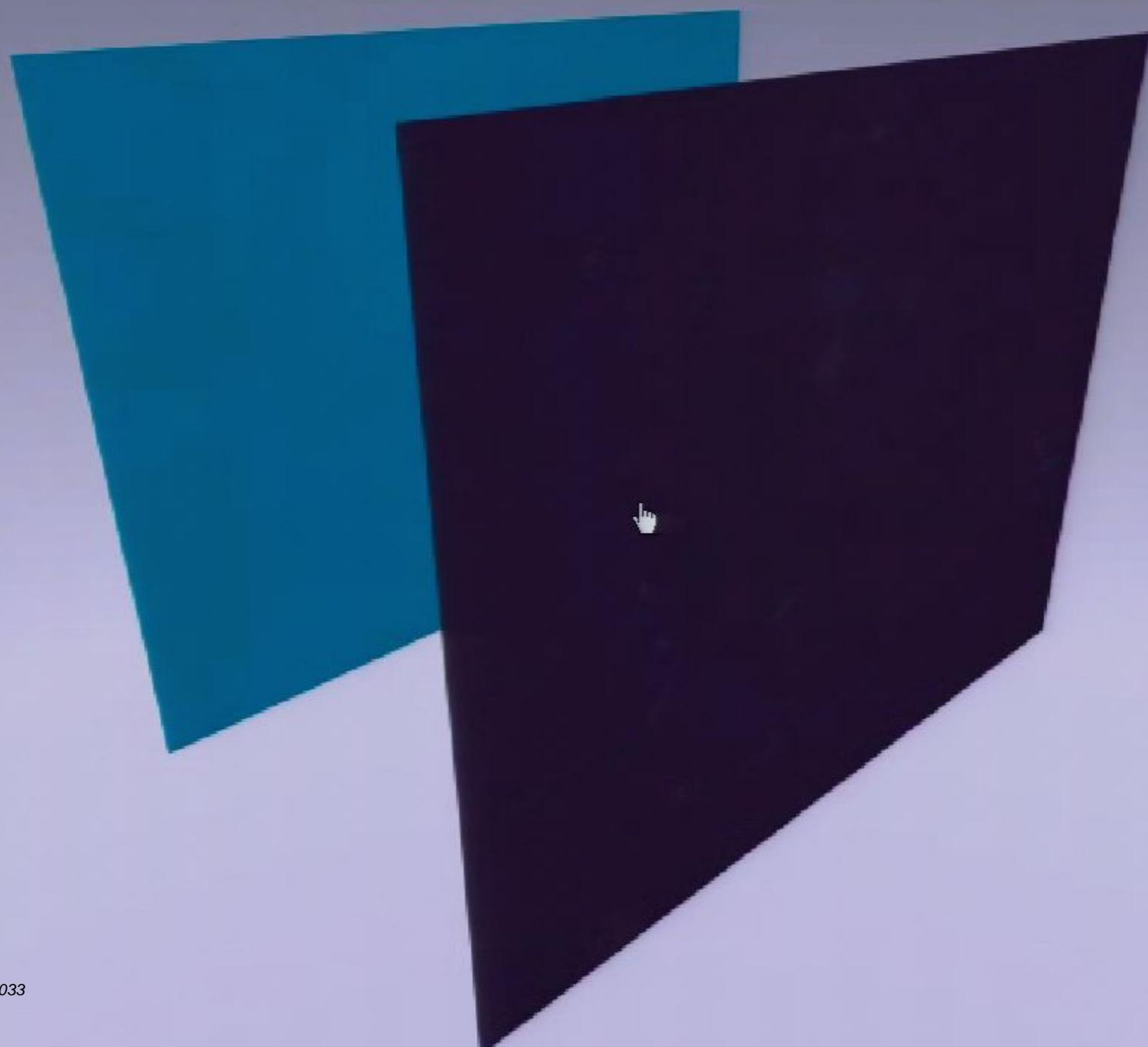




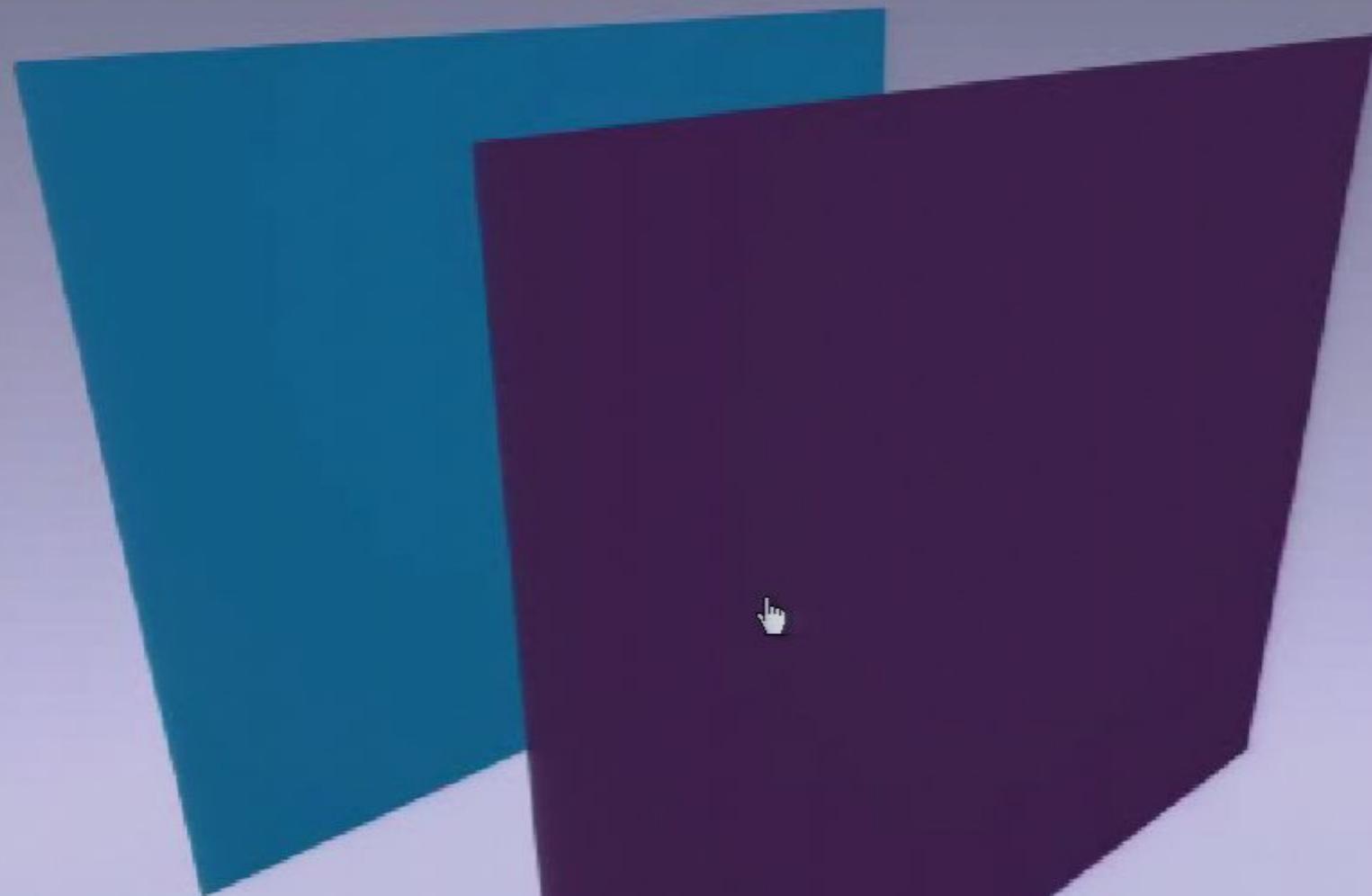


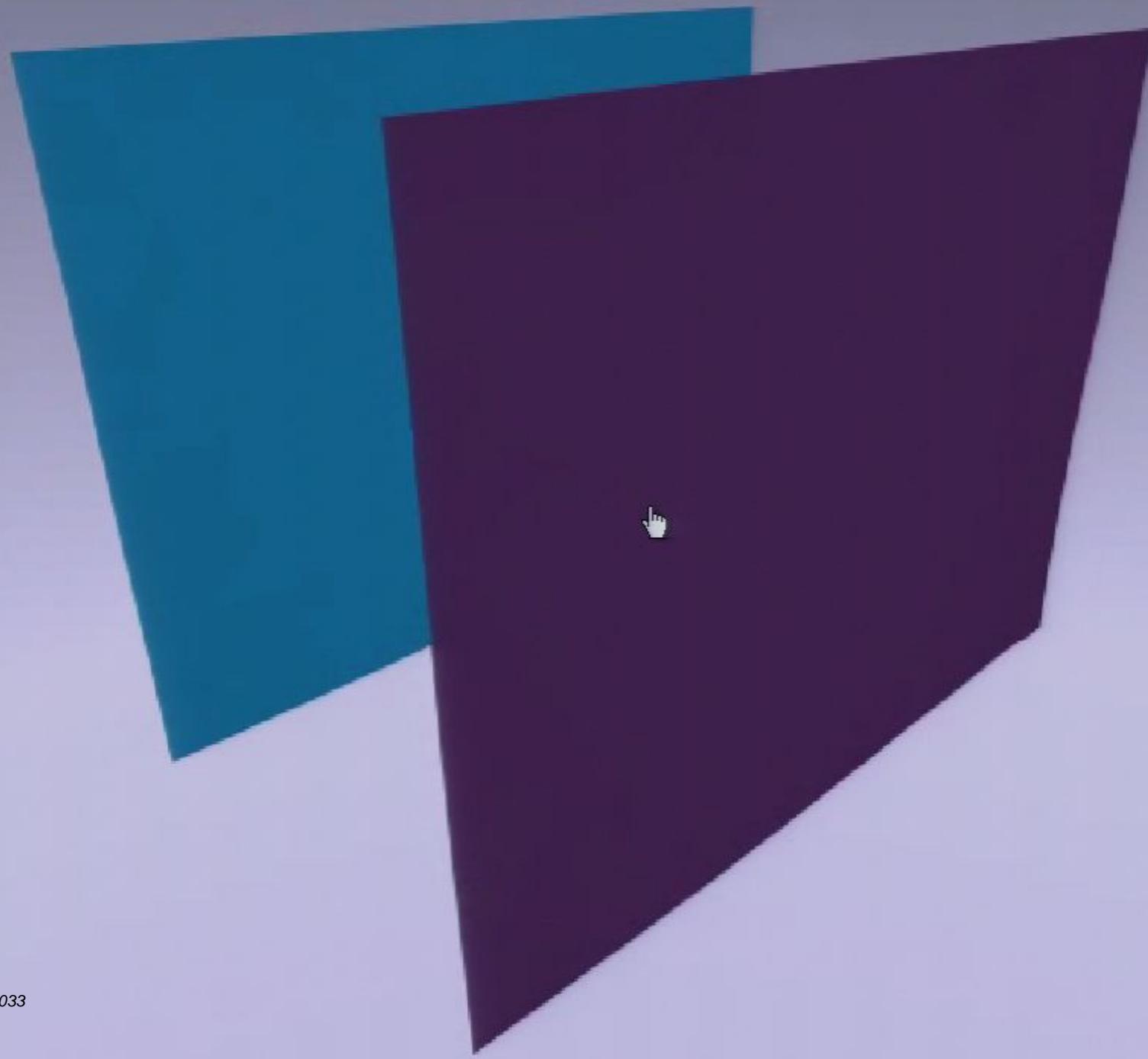


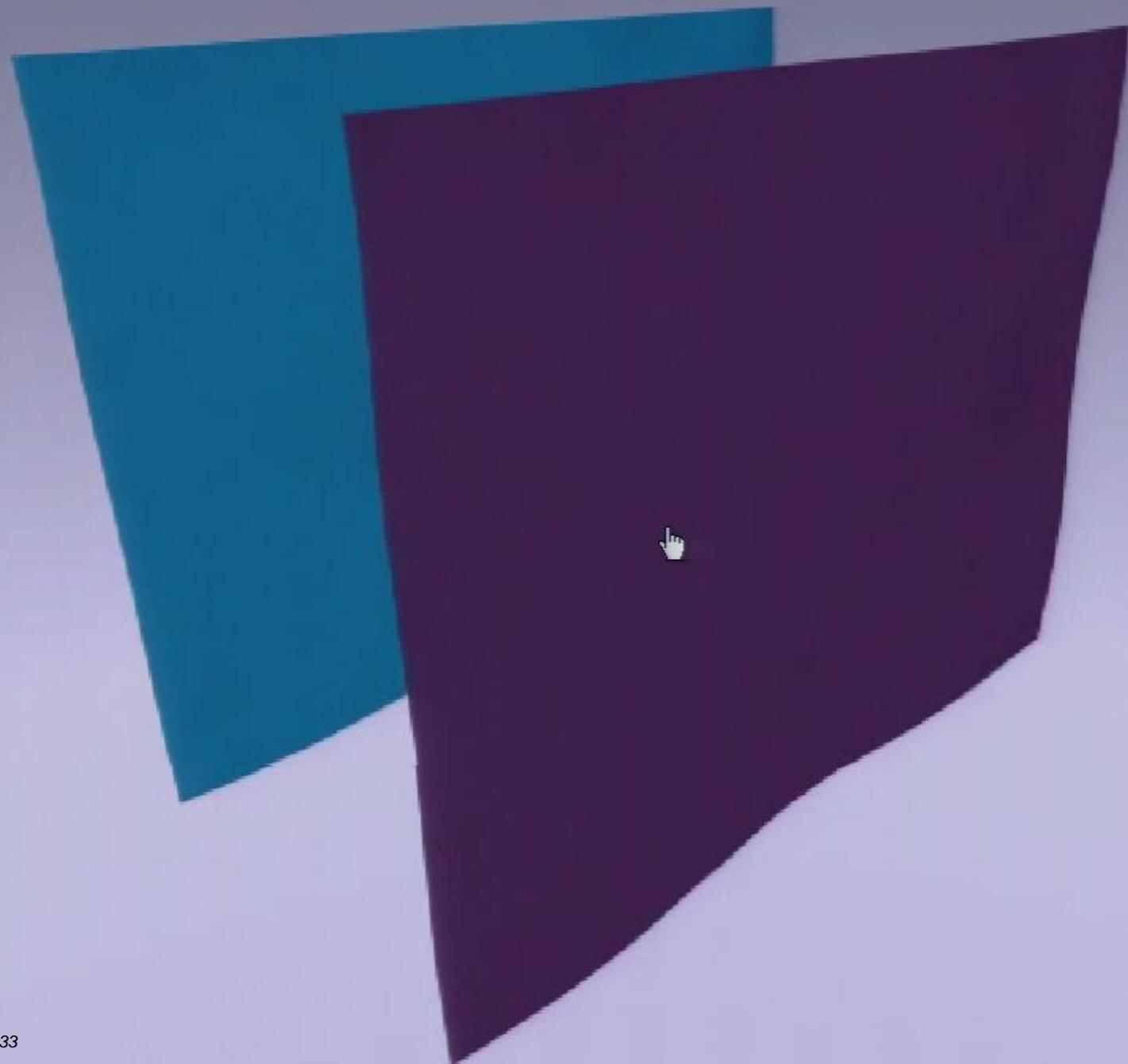


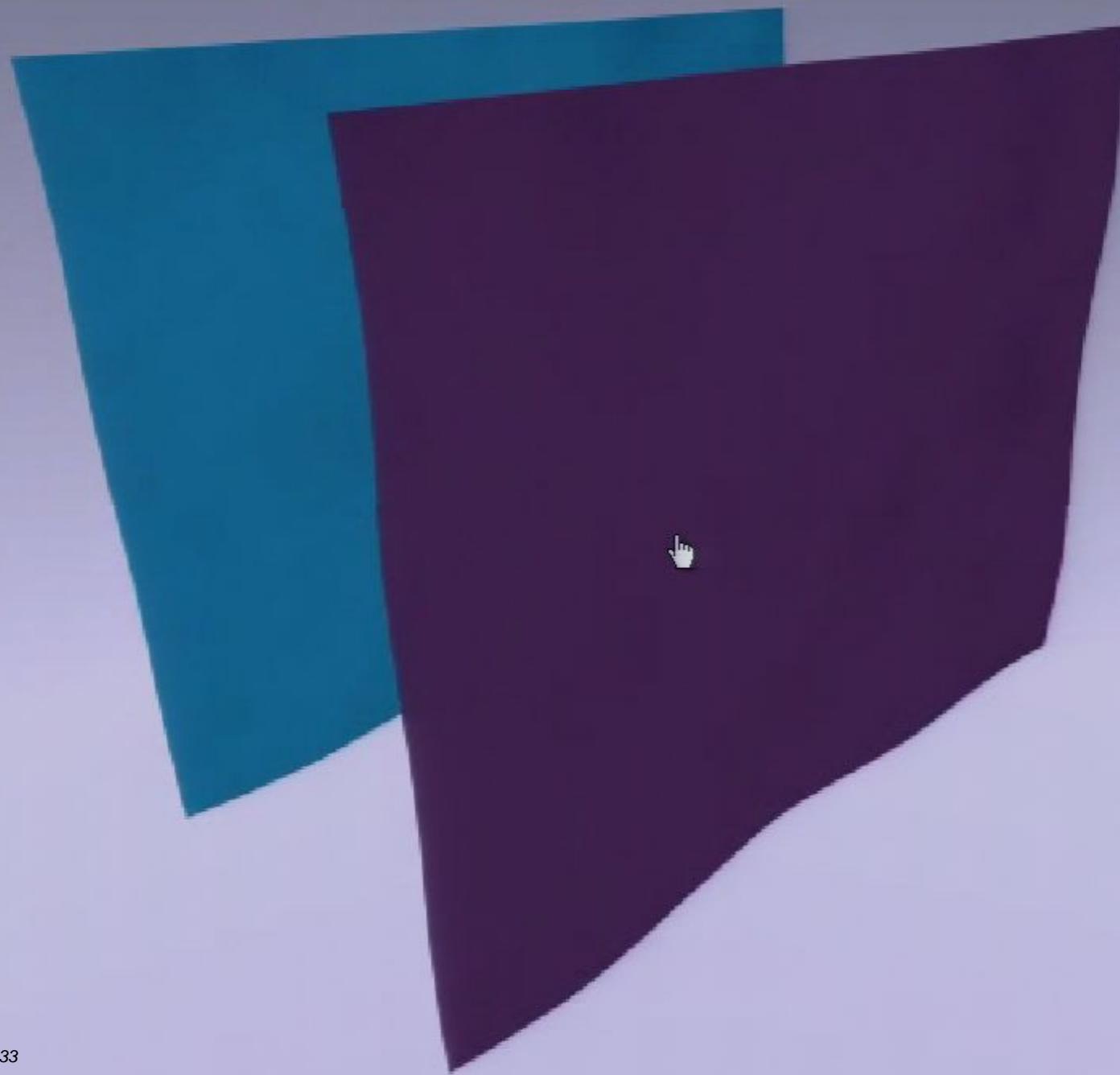


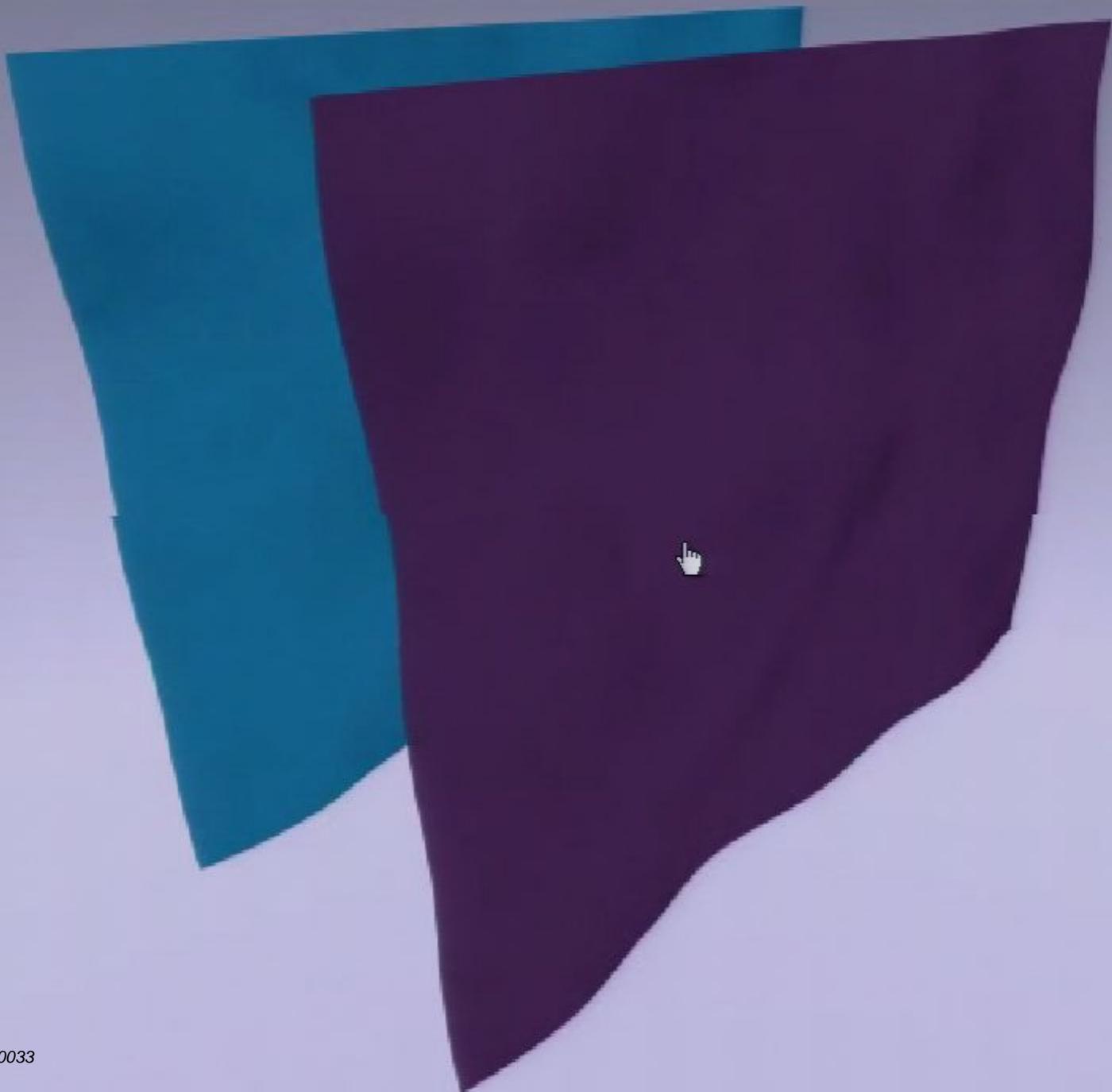








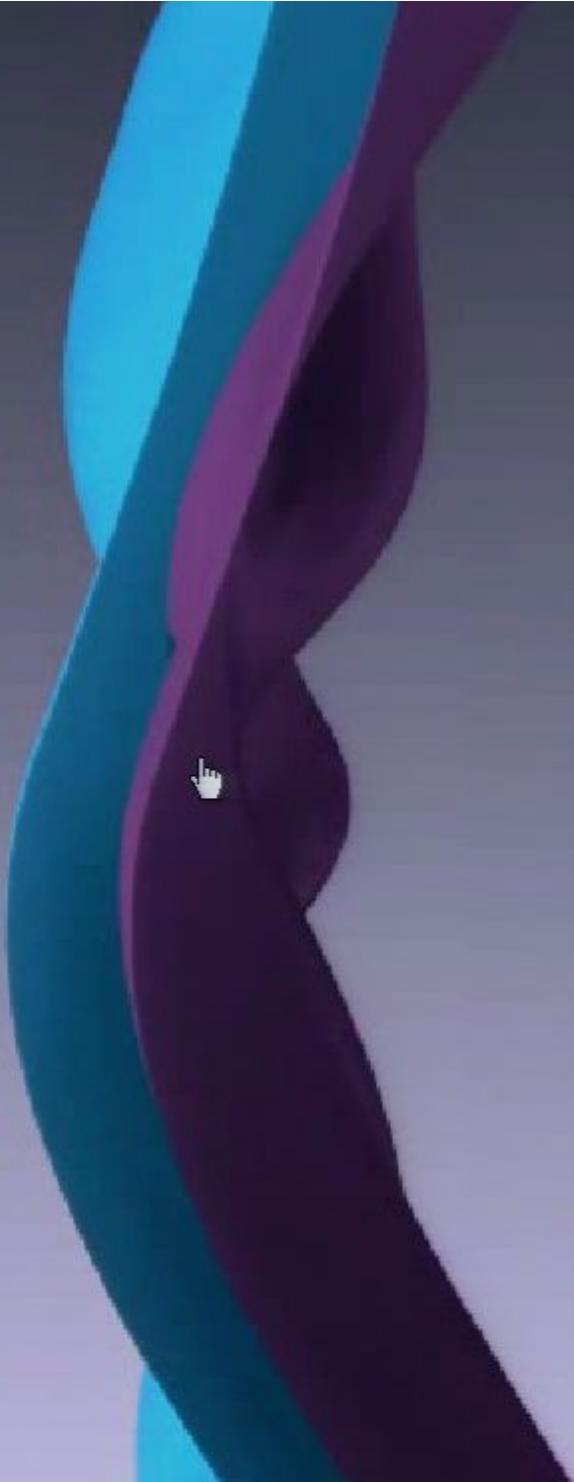




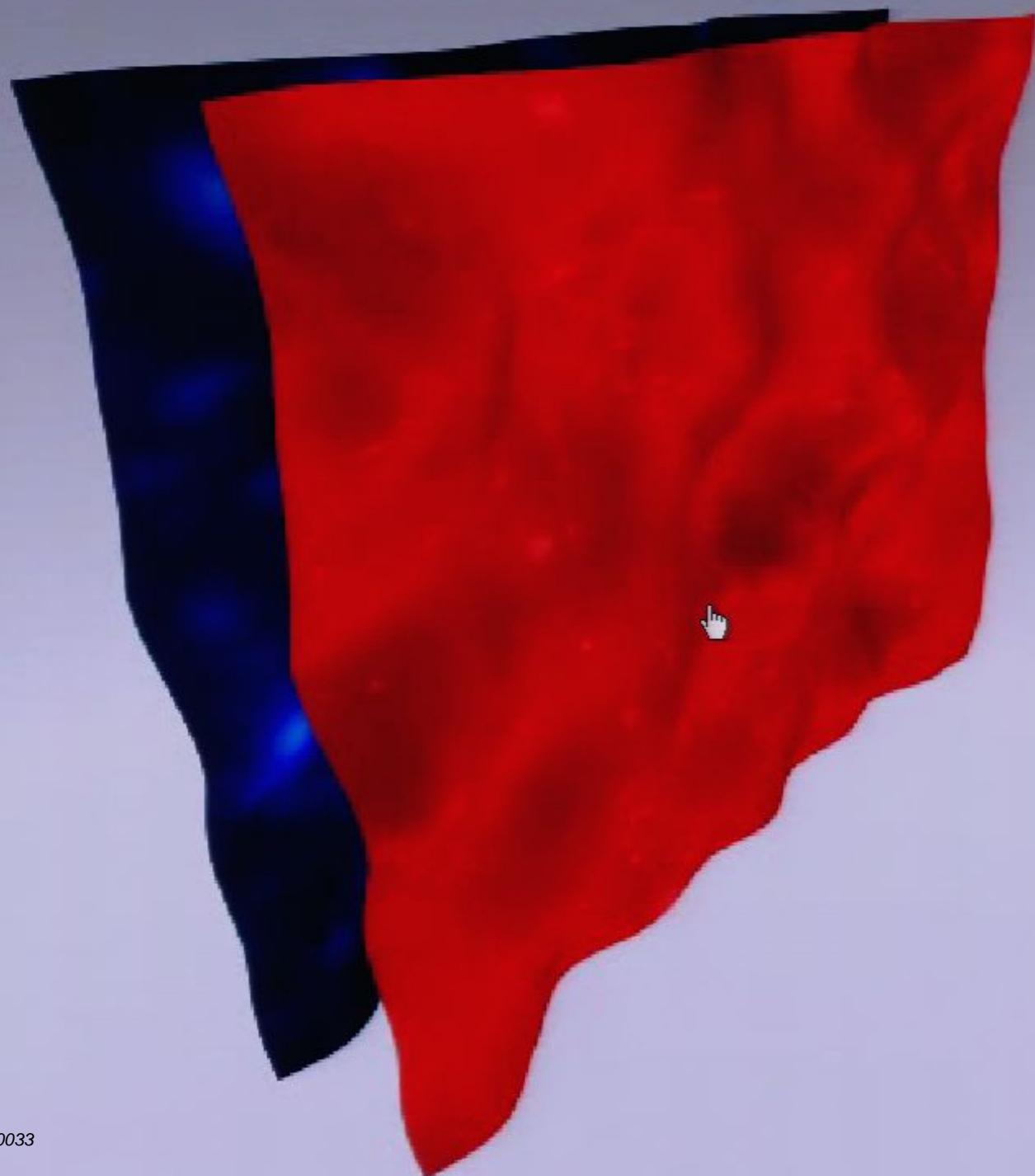


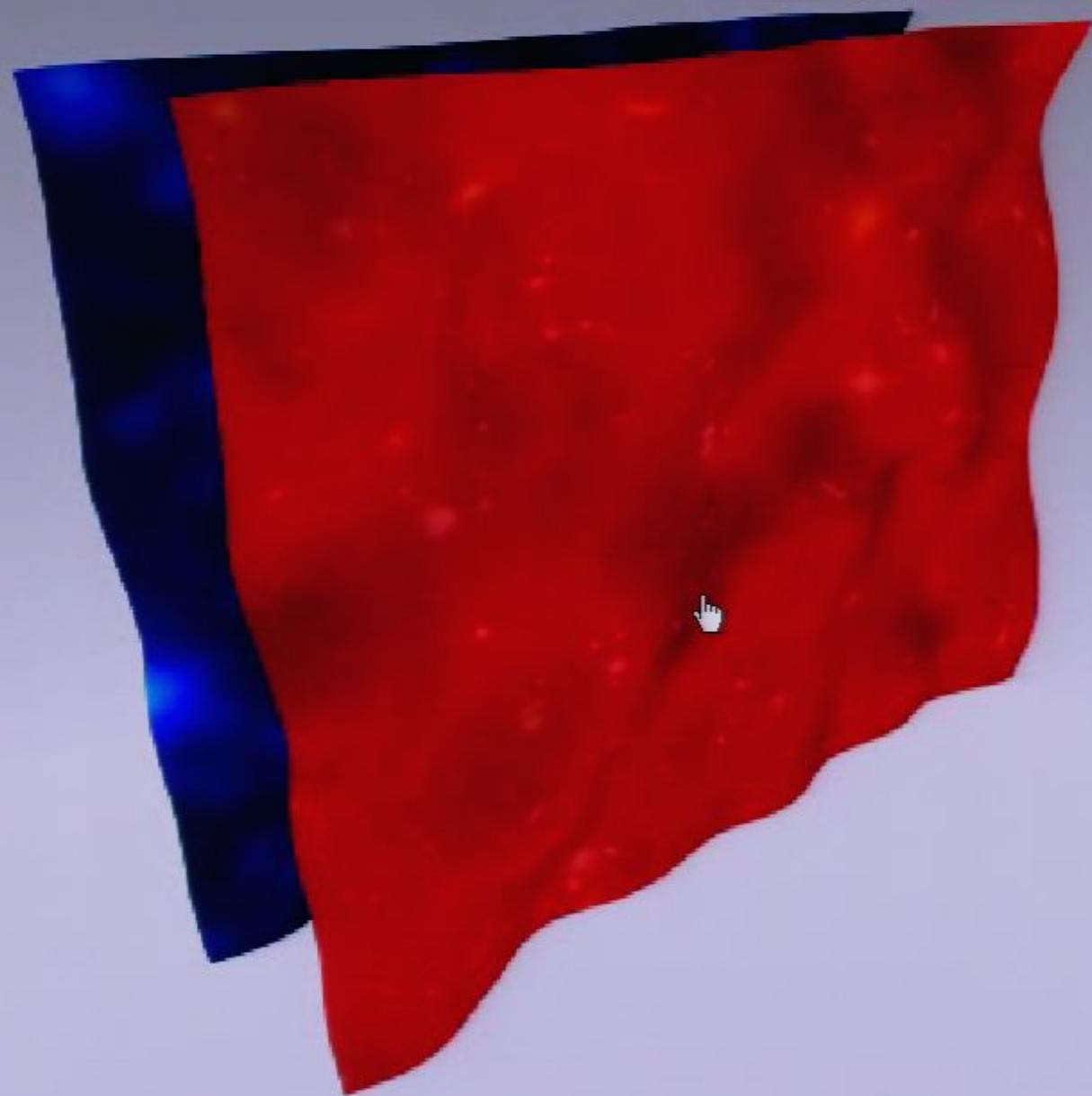


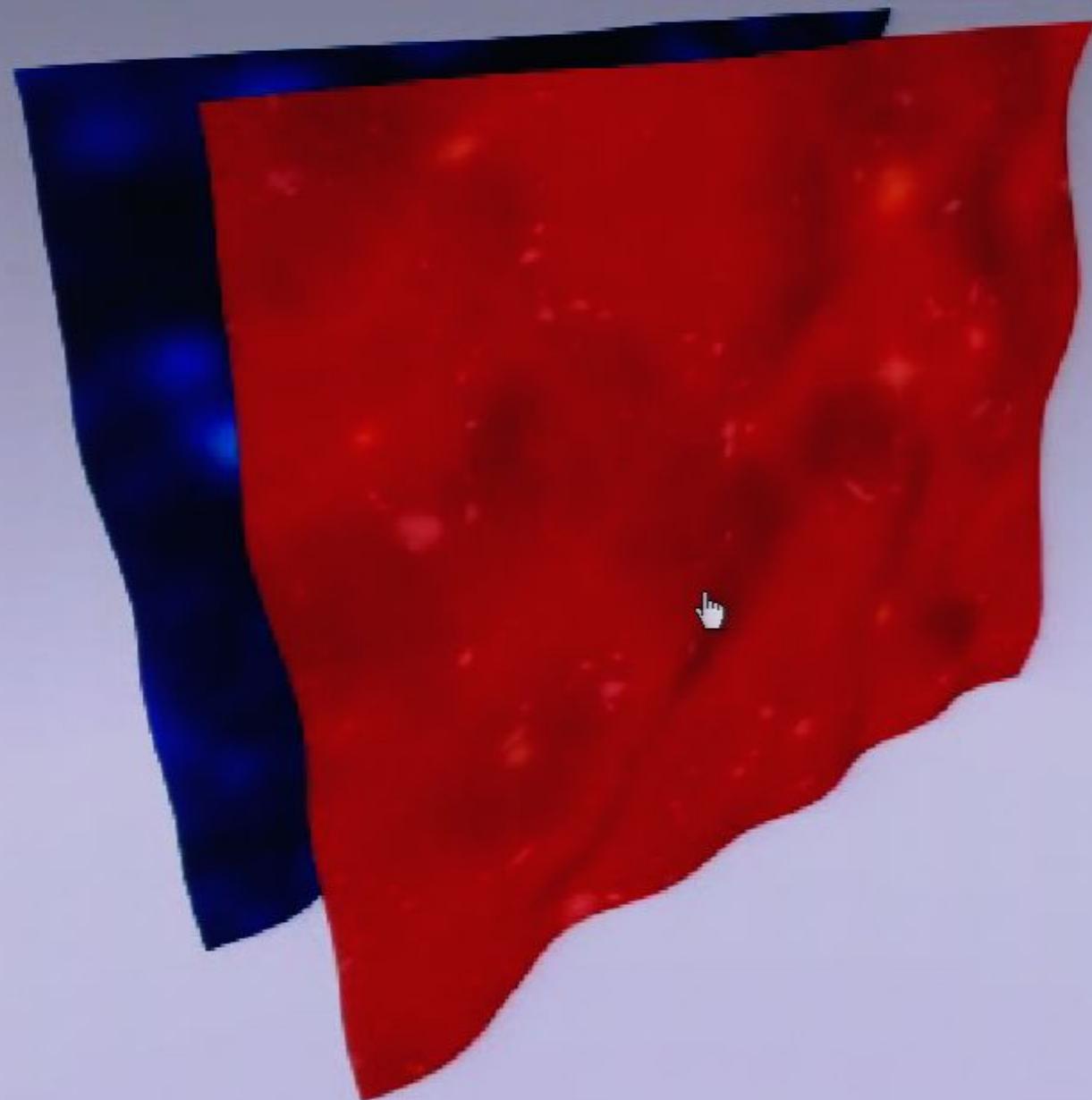


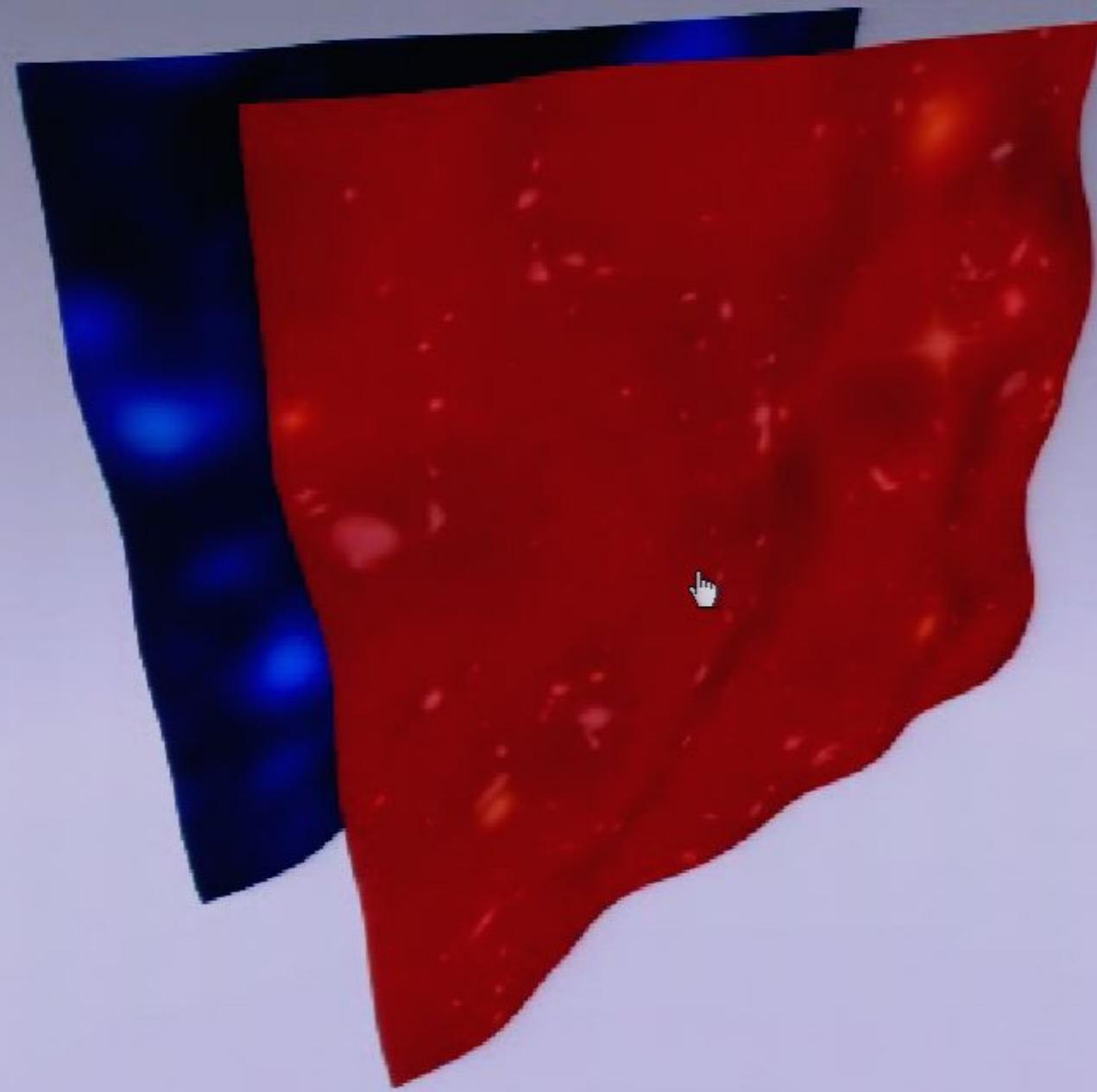


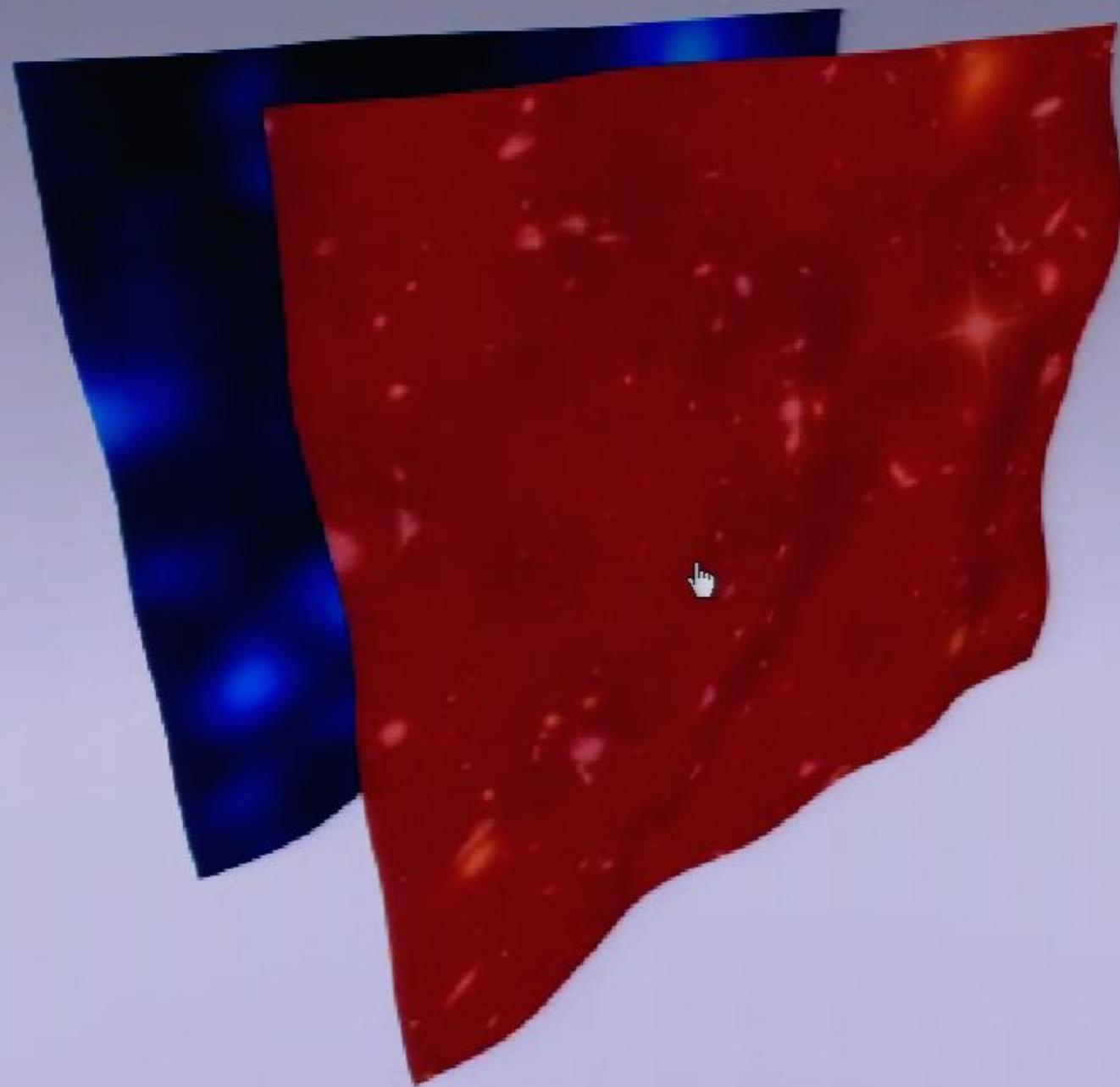


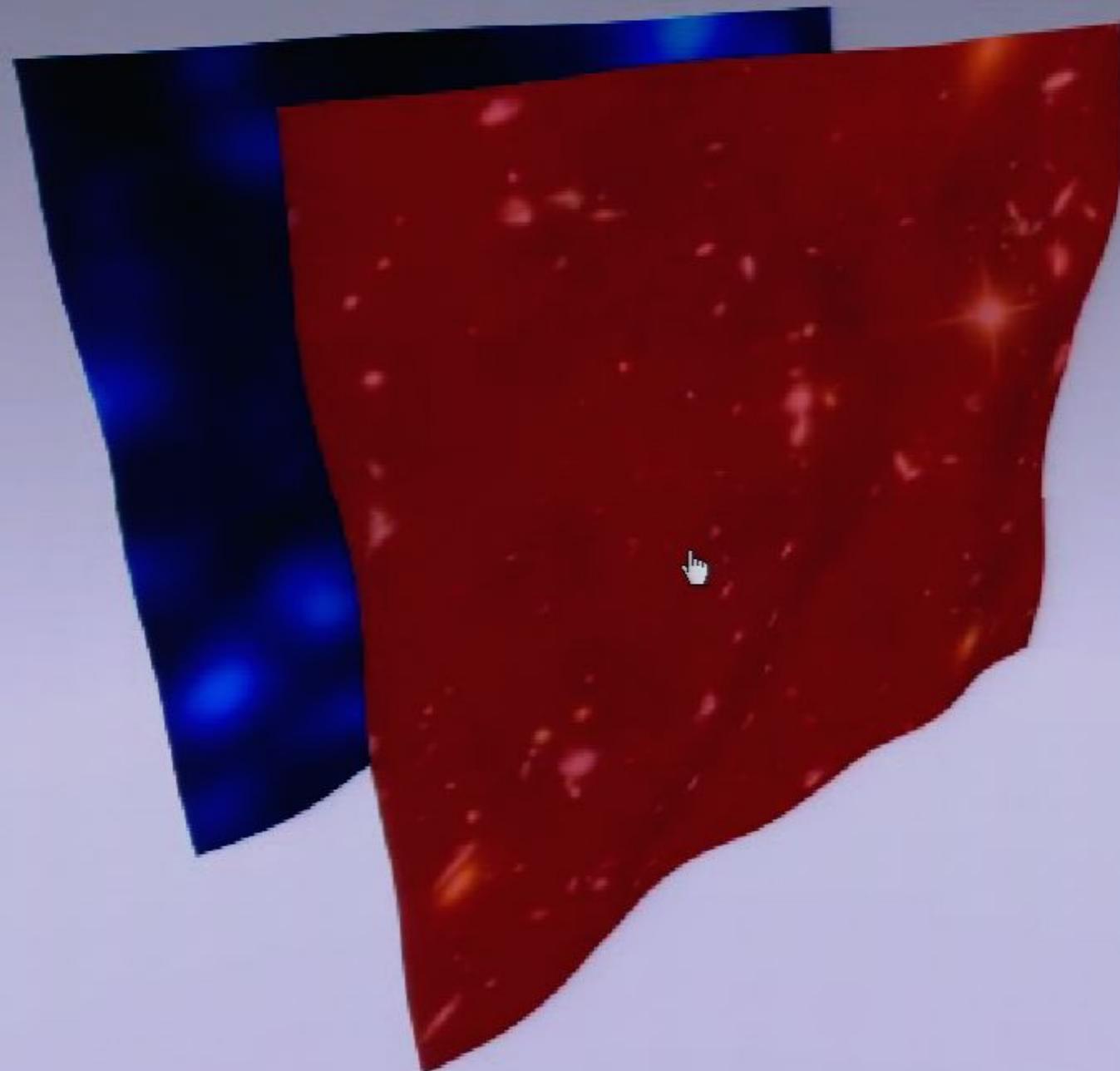


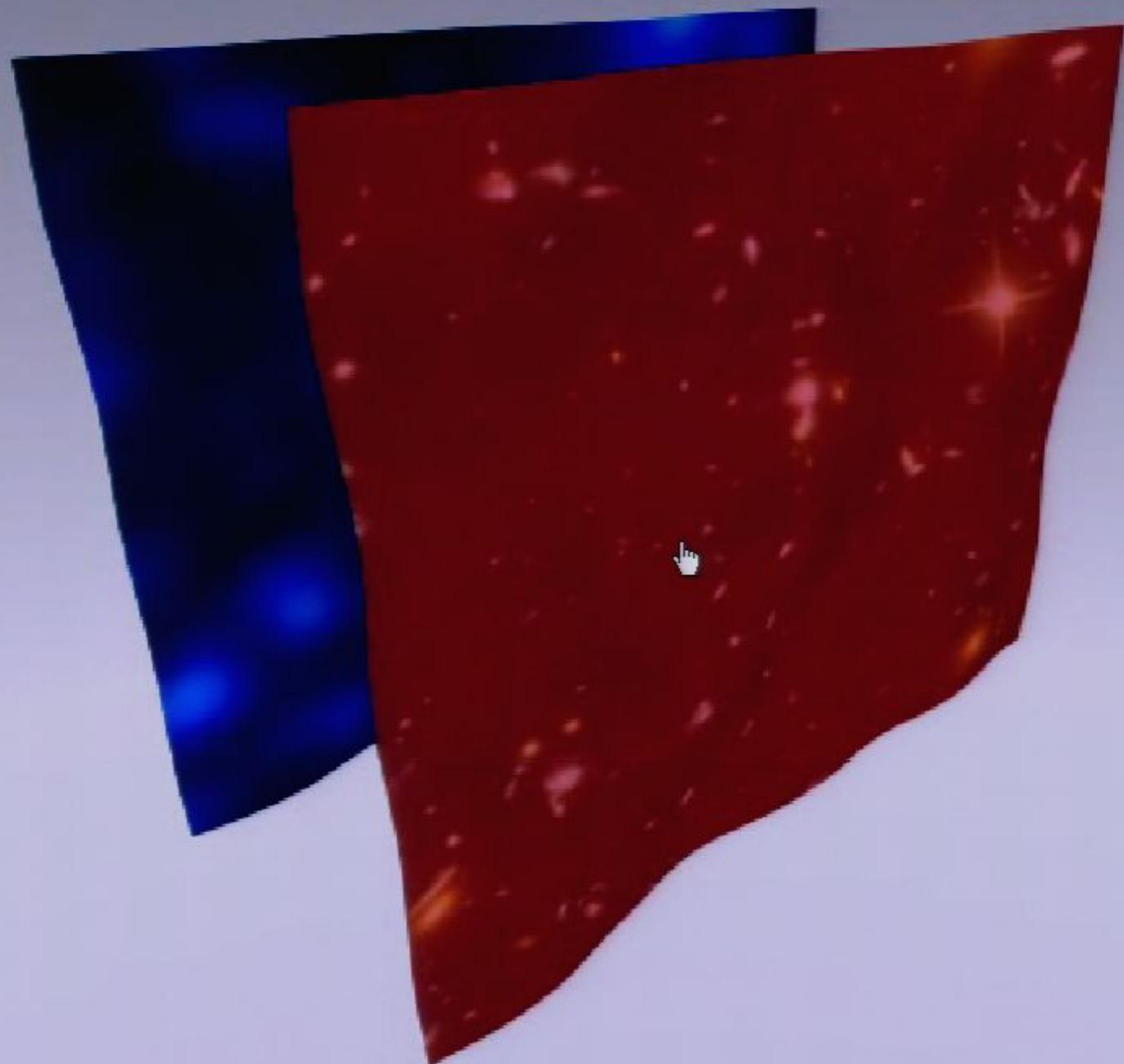


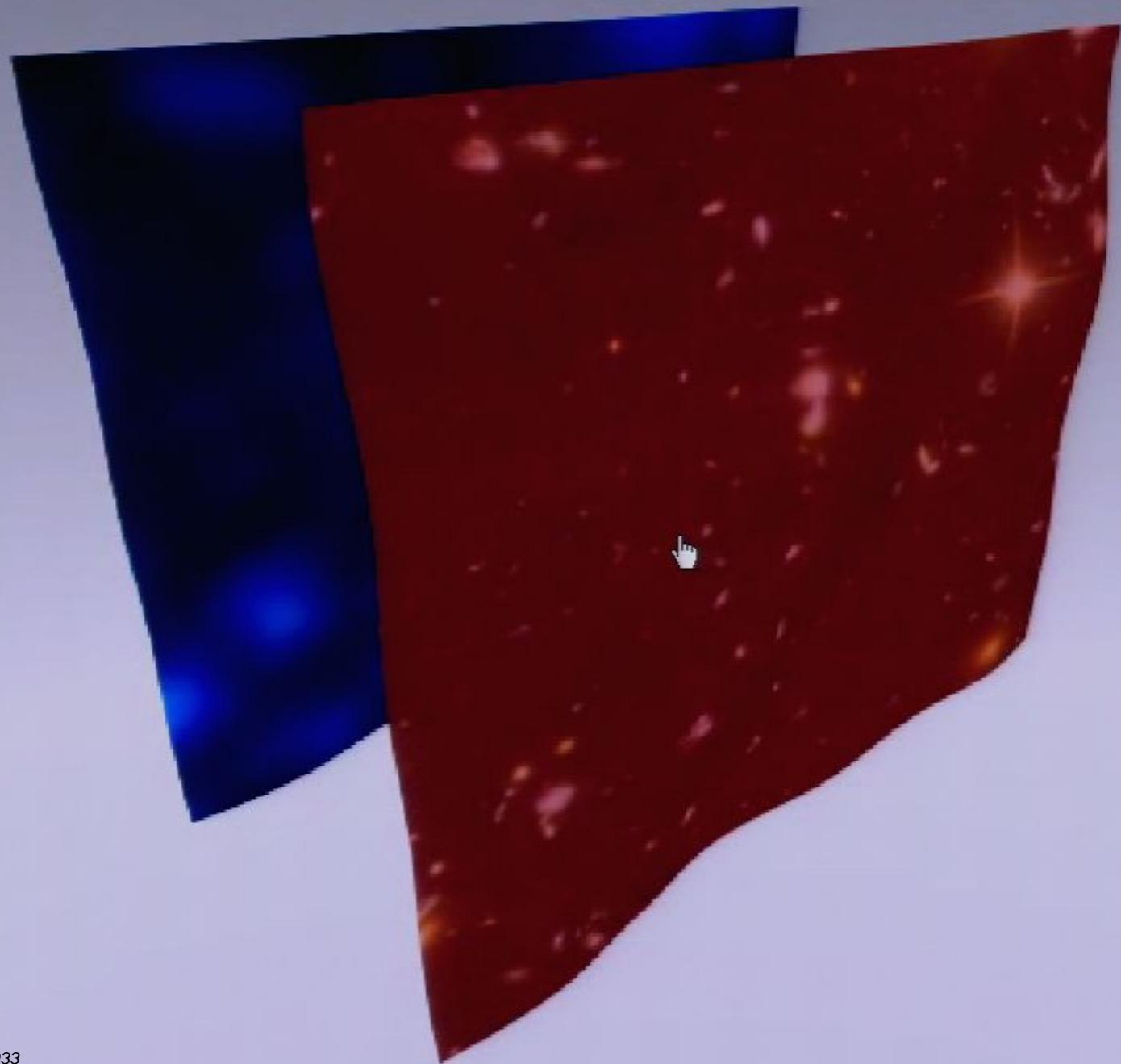


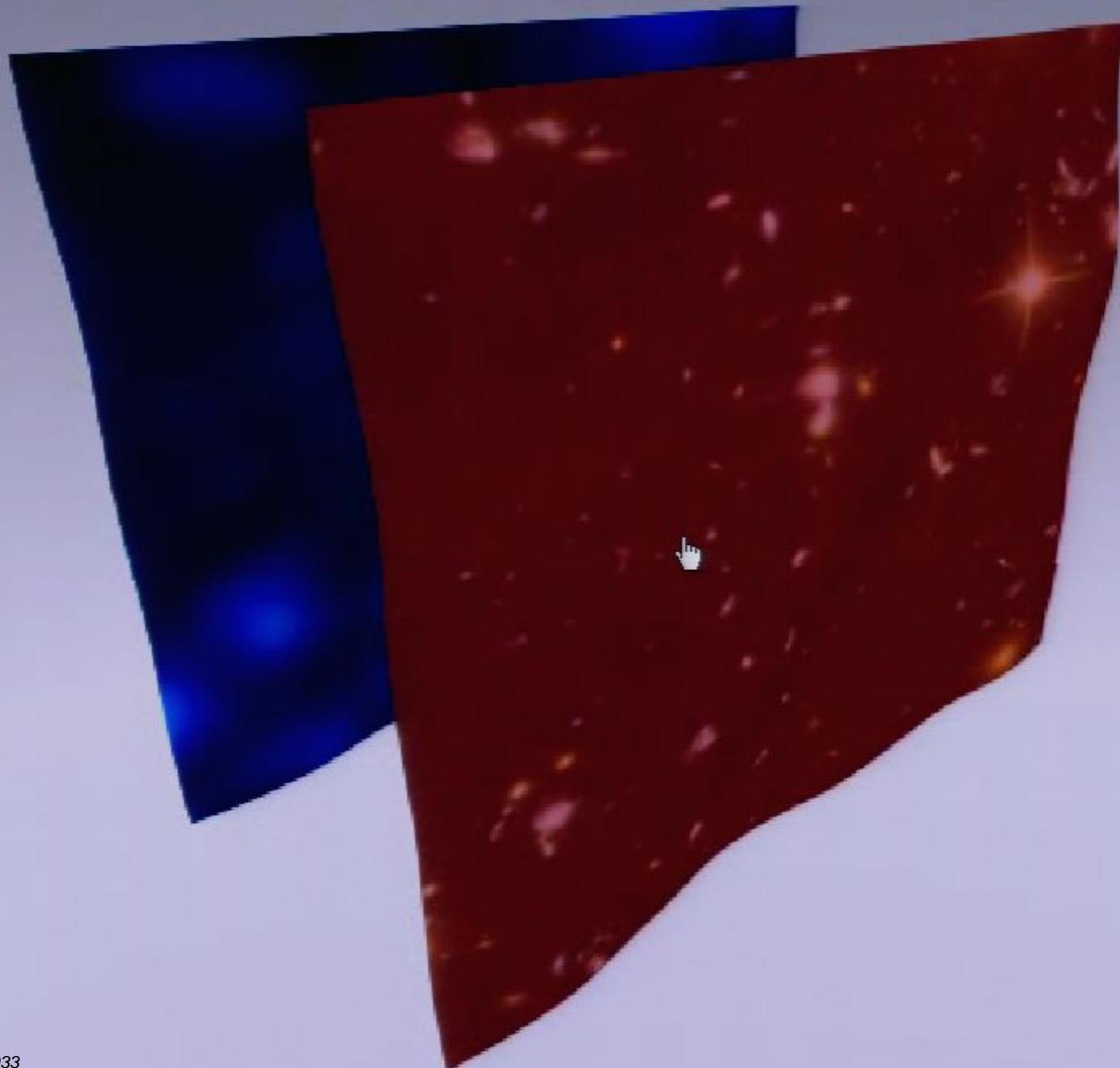


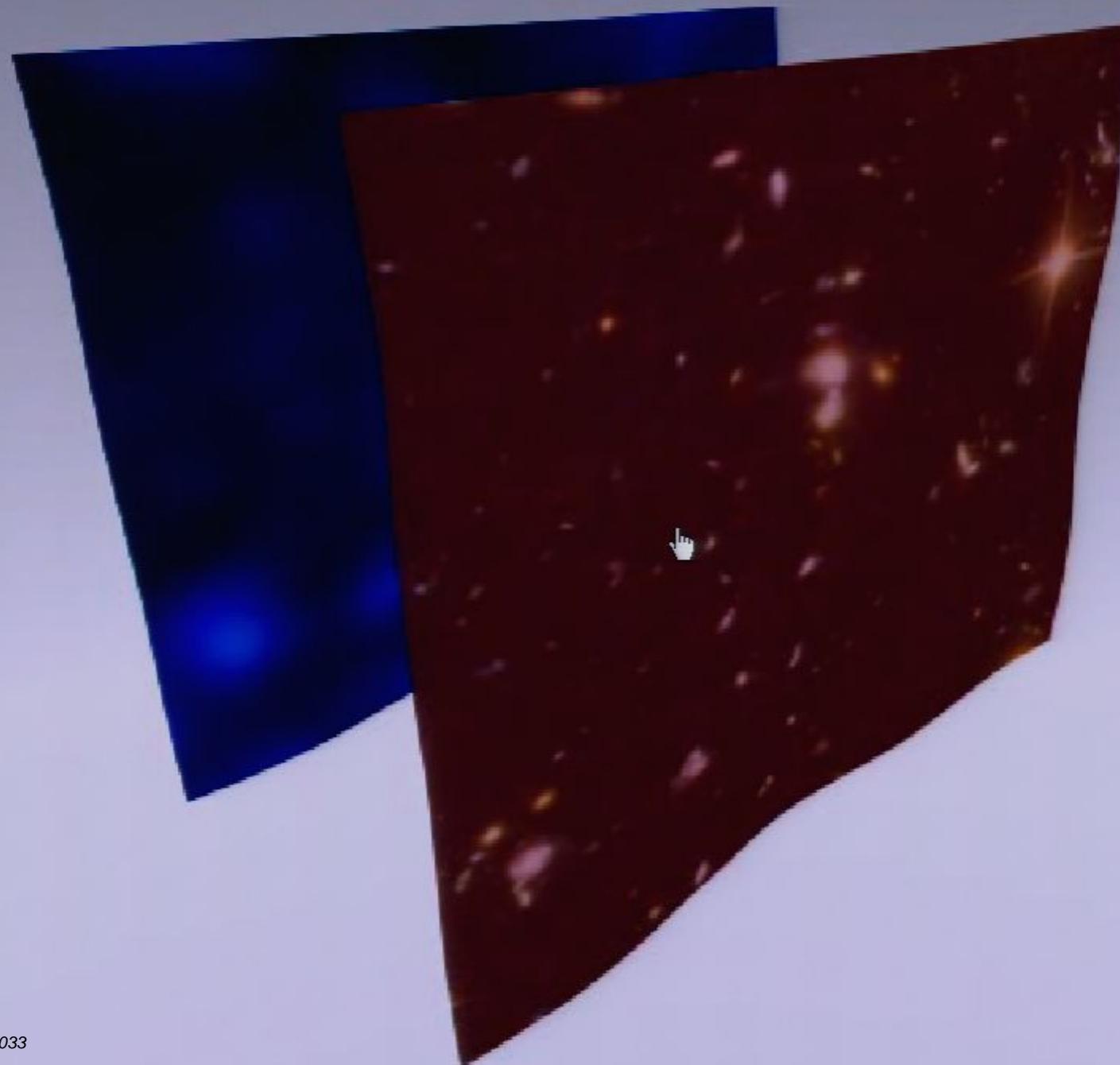


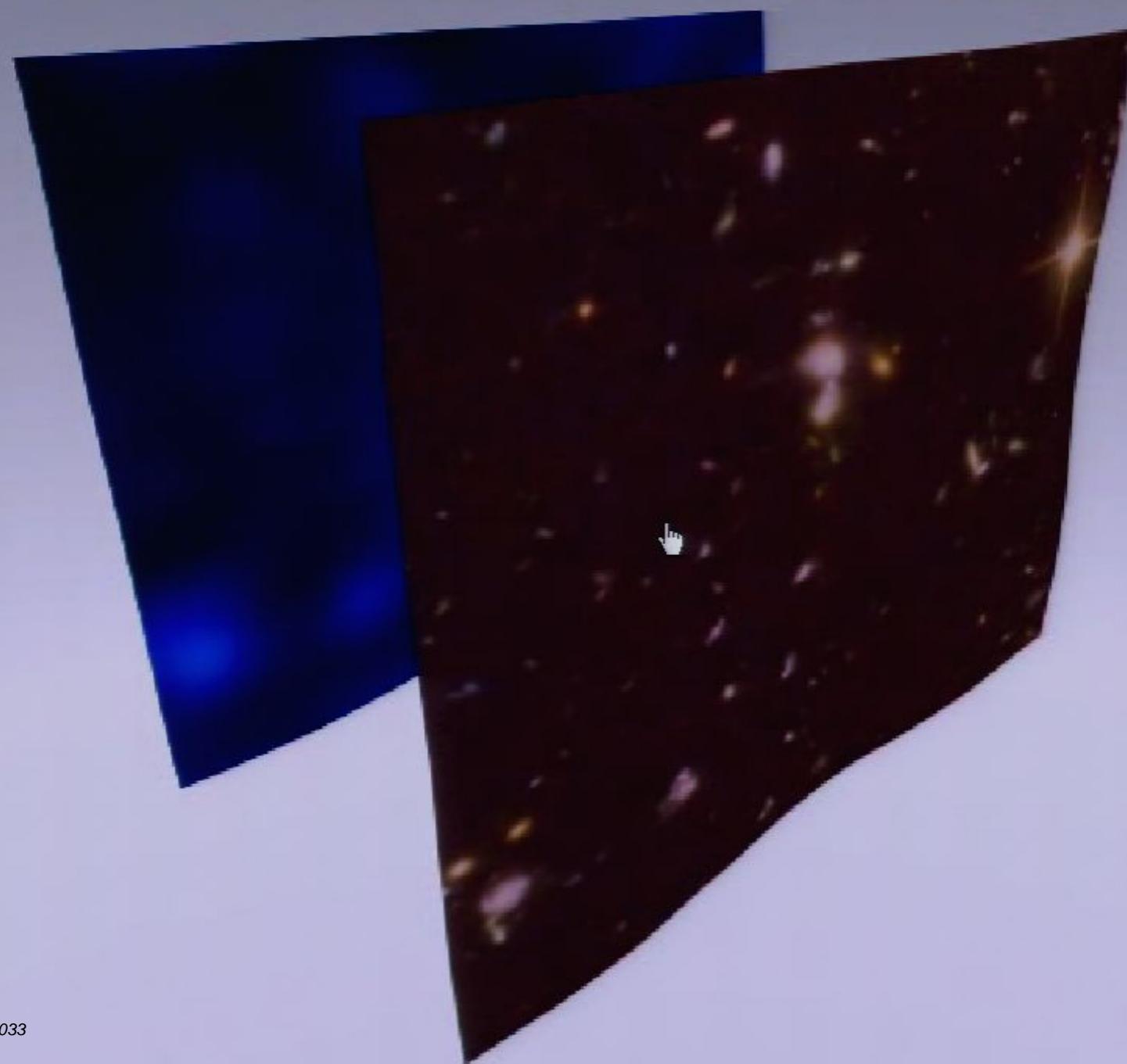


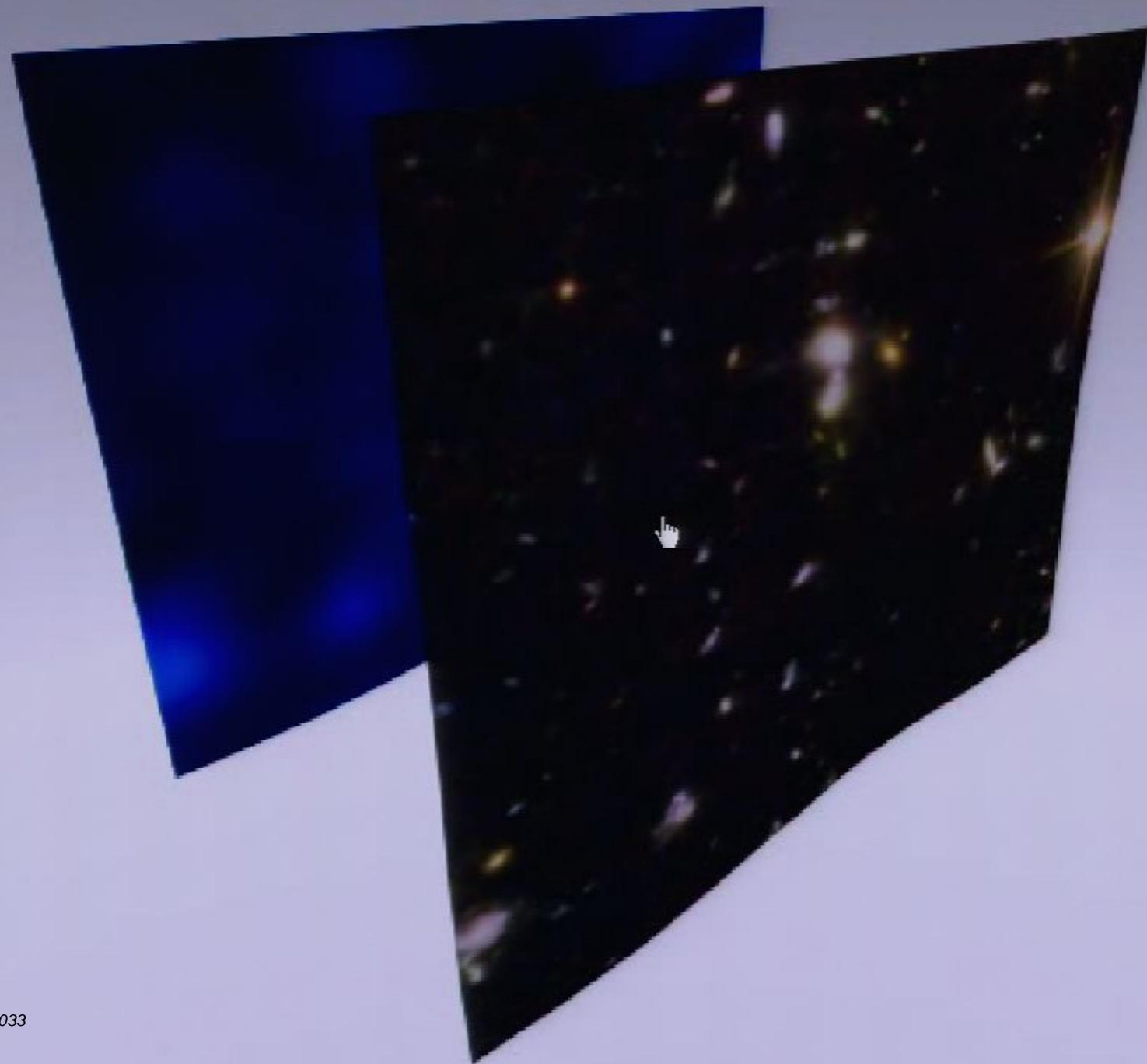


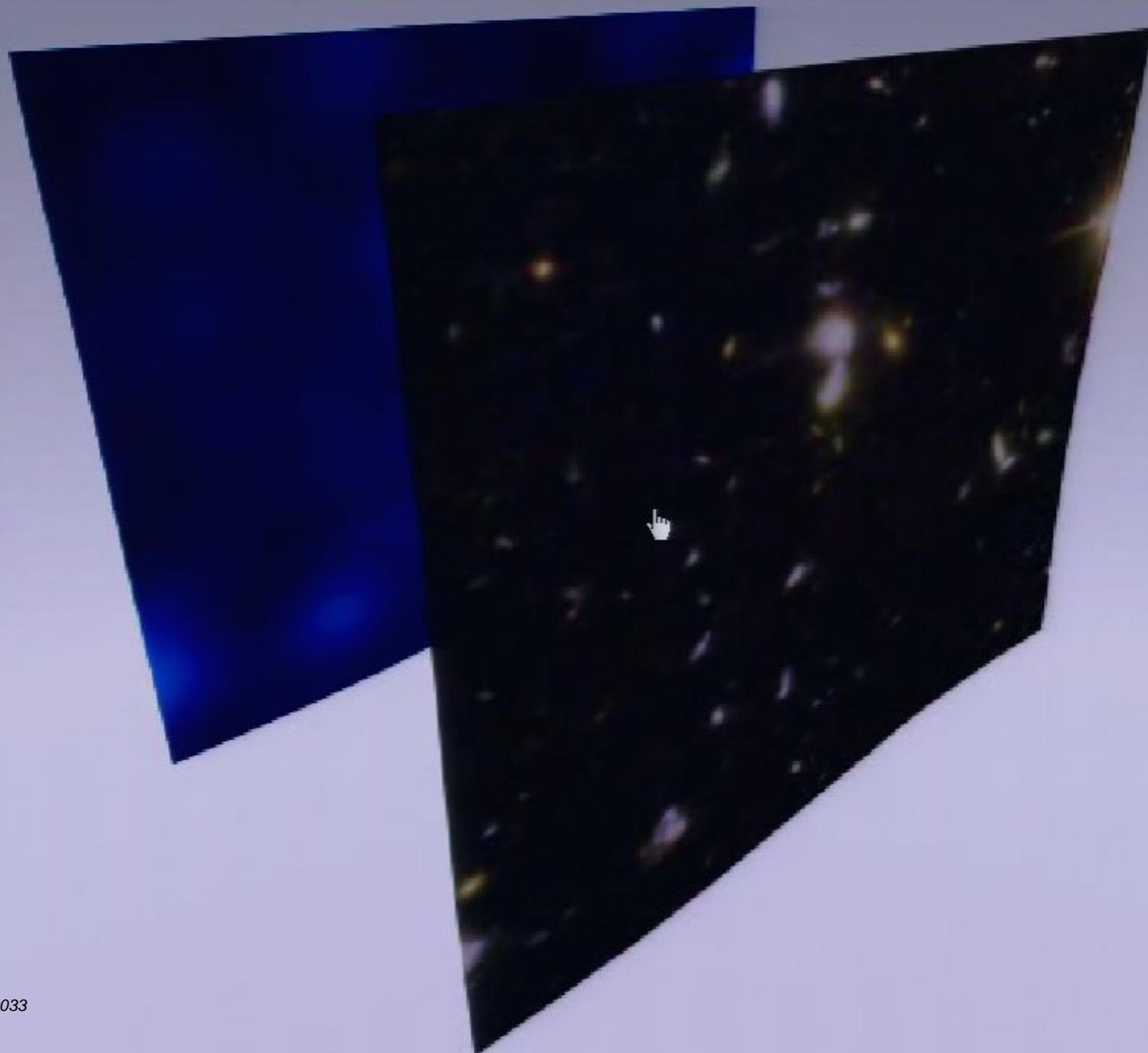


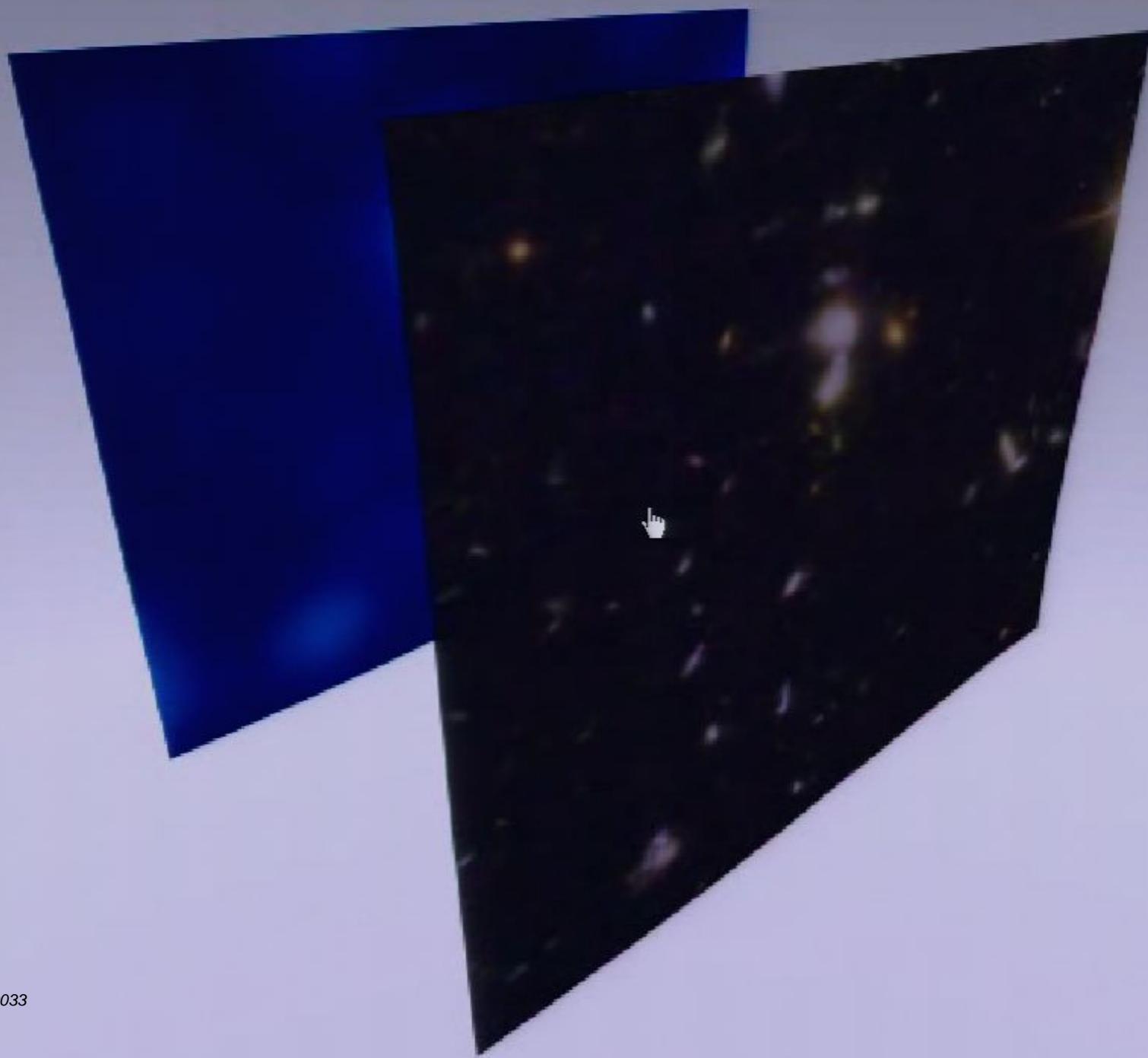


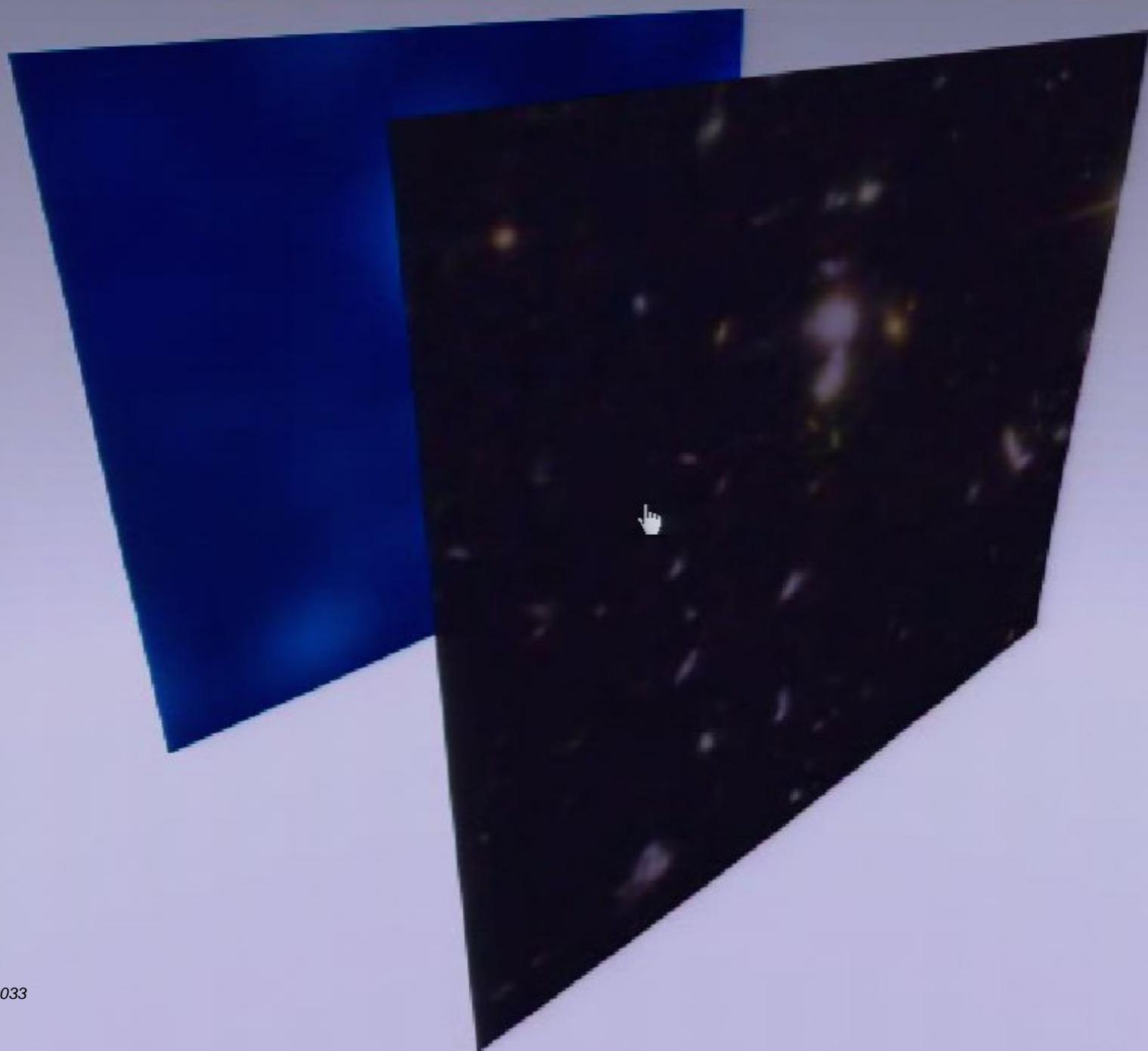


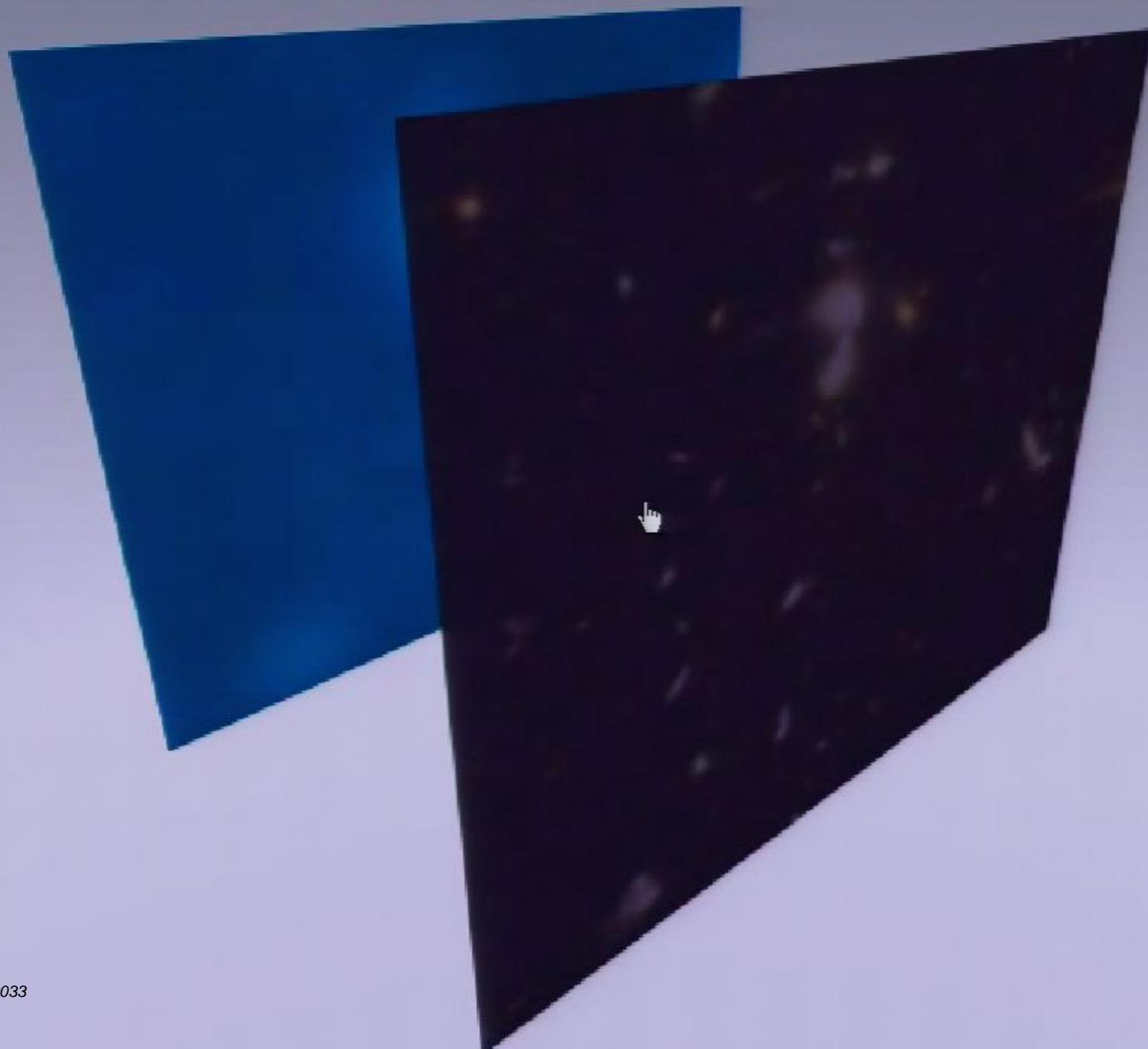


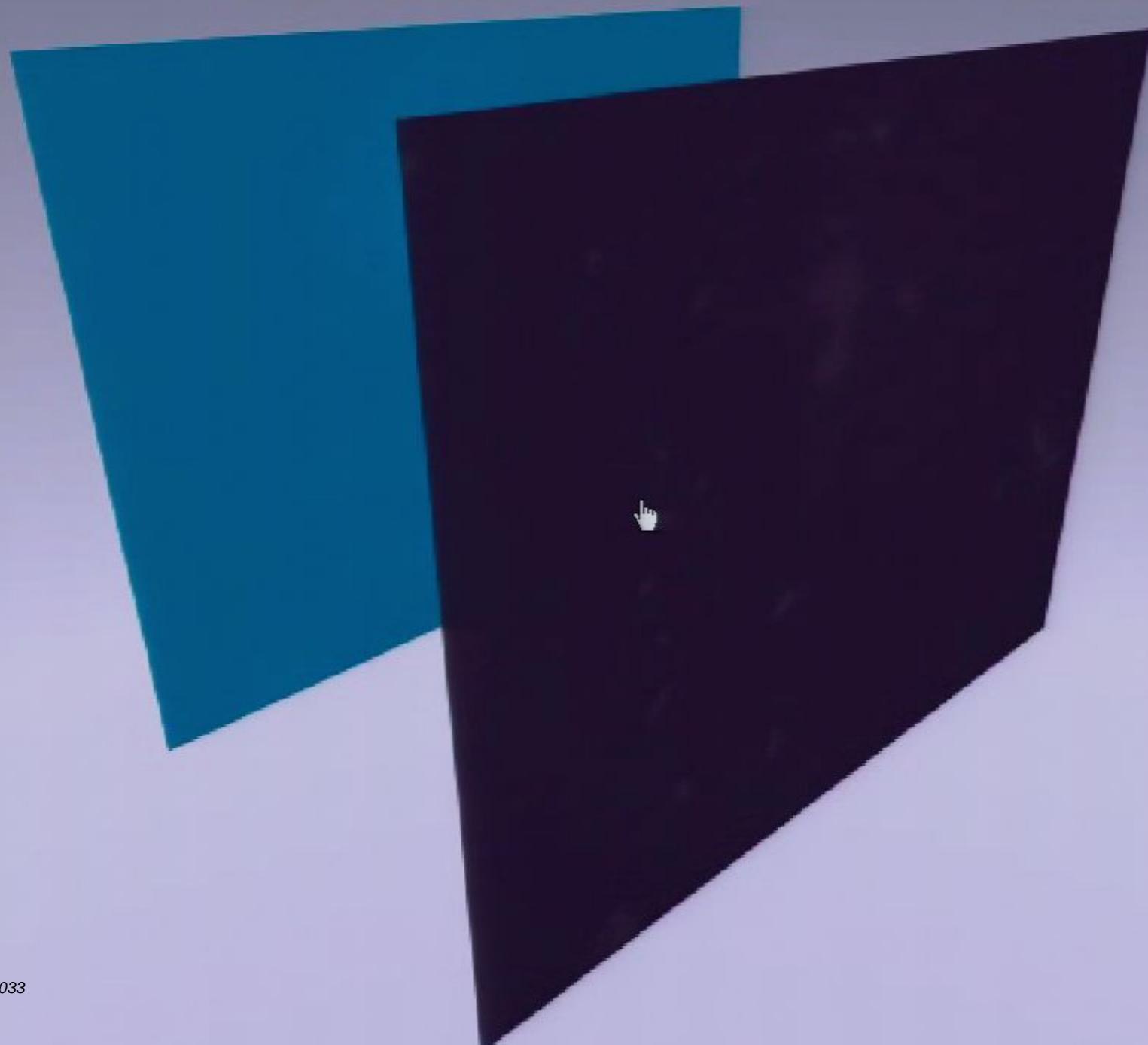


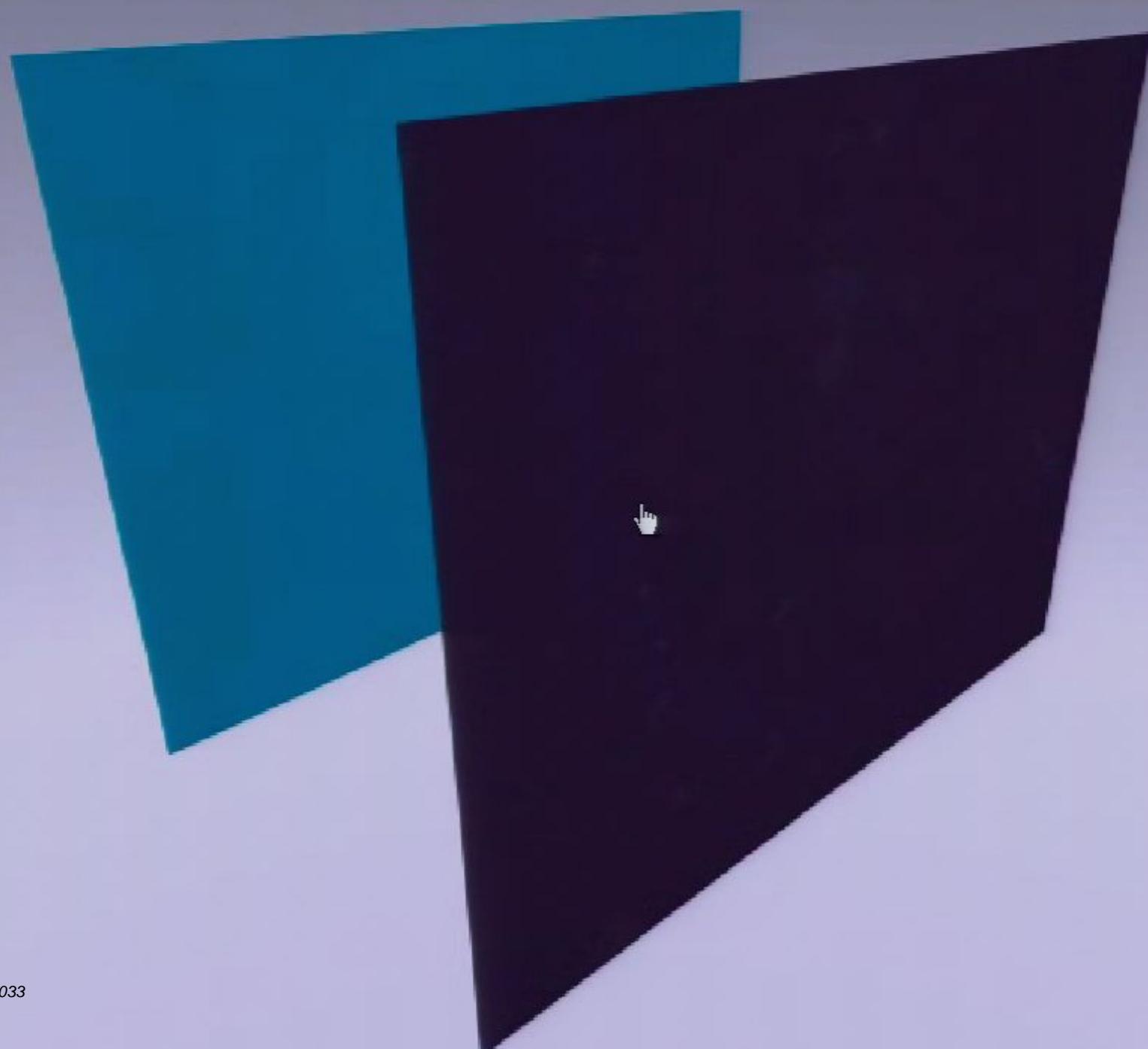




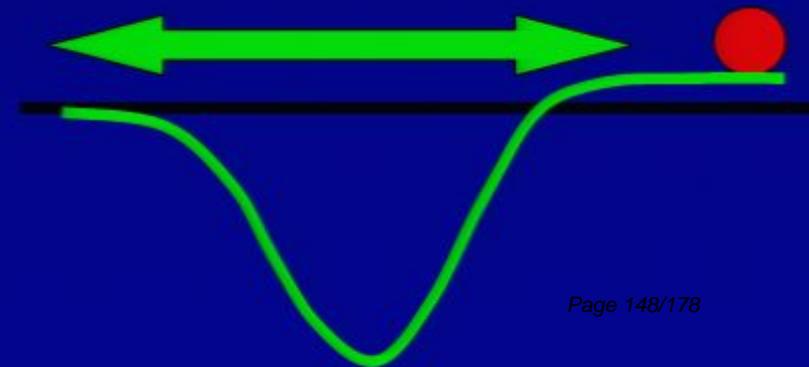
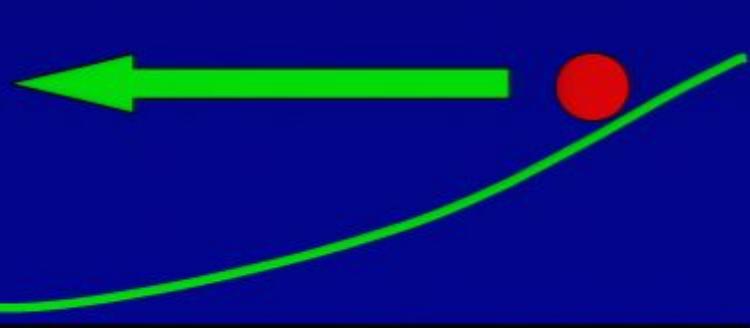
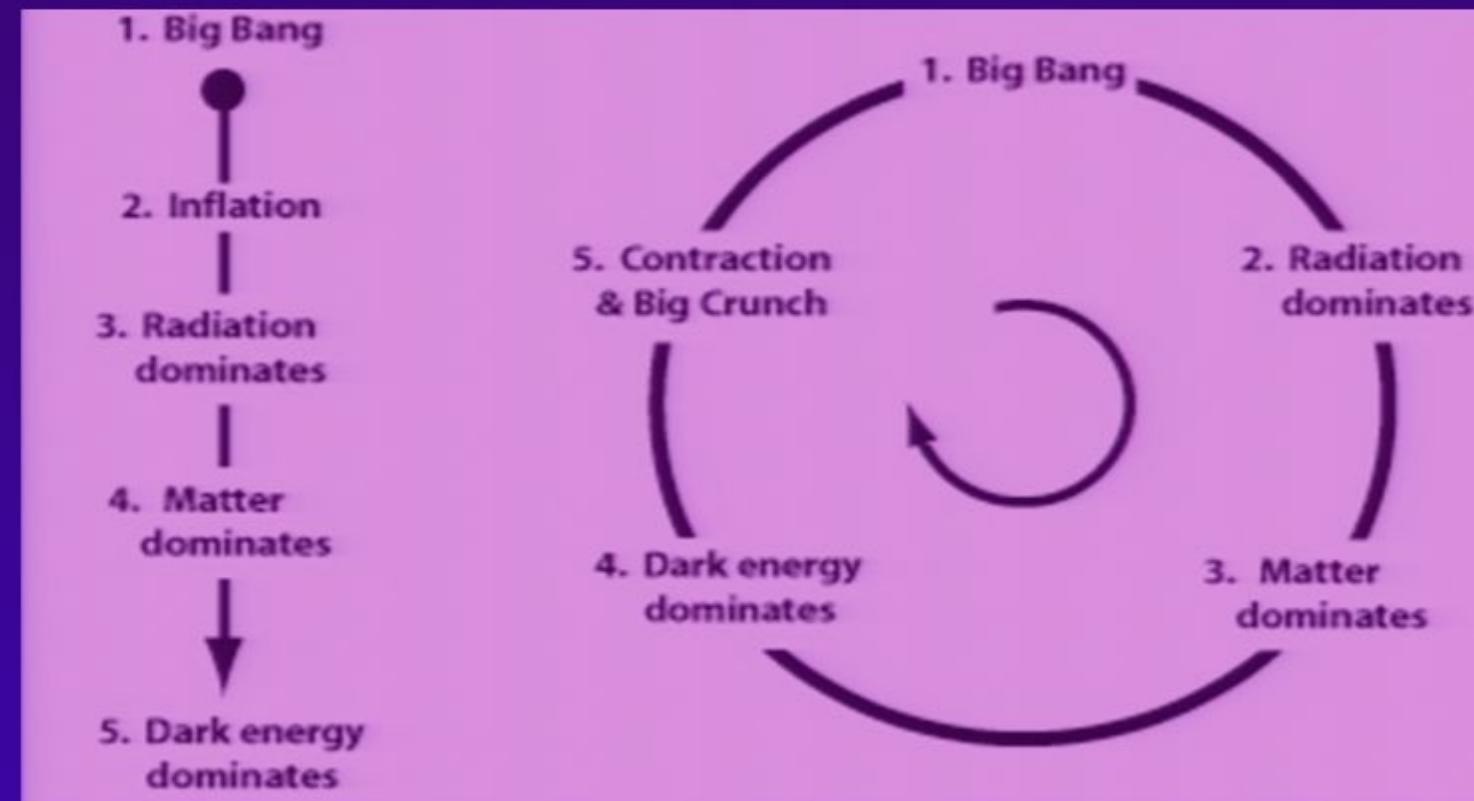








# Inflationary vs Cyclic

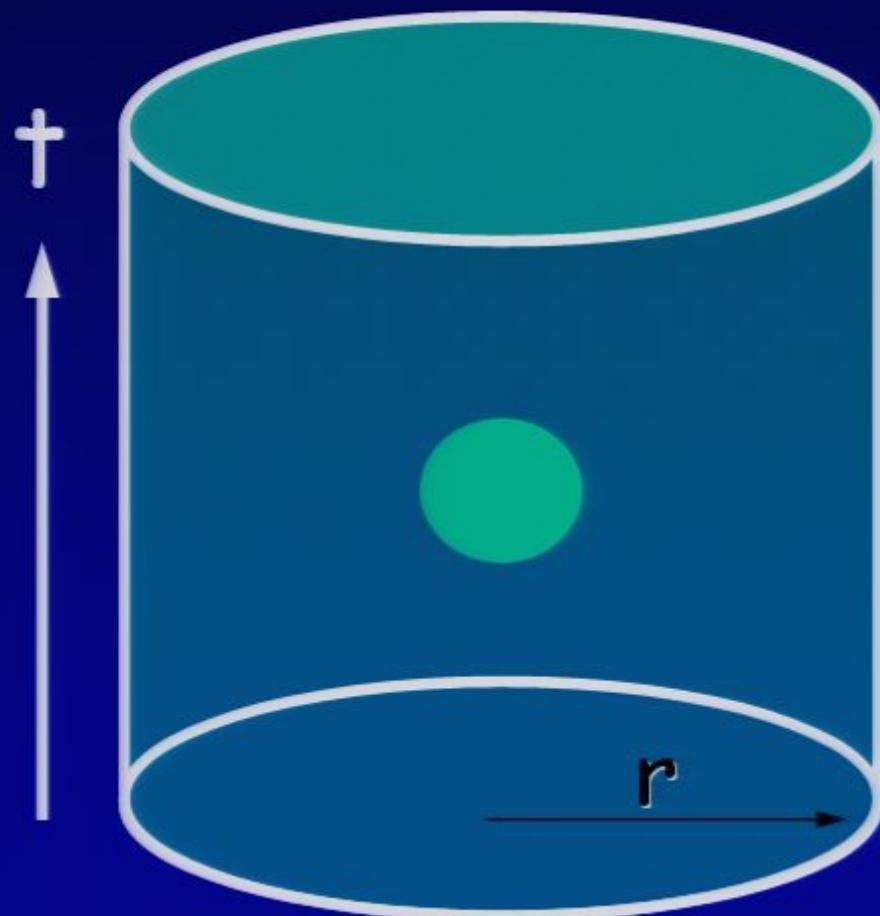


## *Advantages of a cyclic model:*

- no need for inflation:  
dark energy drives the cycling, creates  
density variations*
- extra dimensions may have to take a  
particular form to allow for stable cycling:*
- possible dynamical selection mechanism  
fixing all the constants of nature*

# holographic gravity

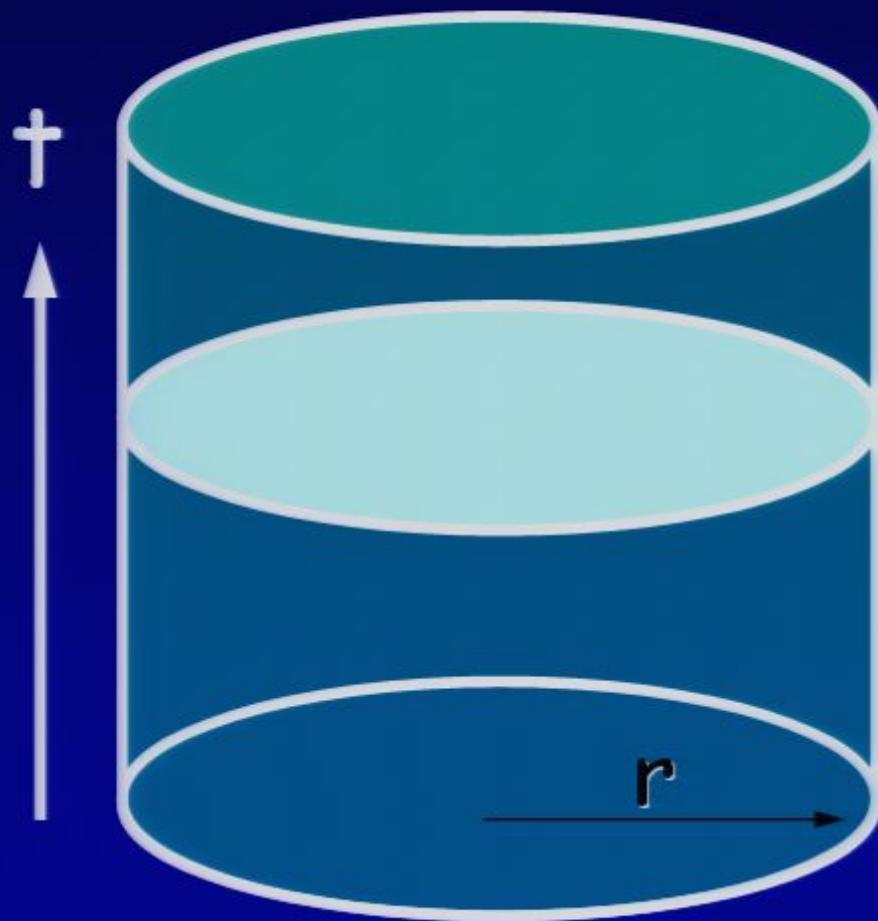
Maldacena



theory with gravity  
in spacetime bulk  
dual to  
a theory with no  
gravity on boundary!  
(scale-invariant)

# holographic cosmology

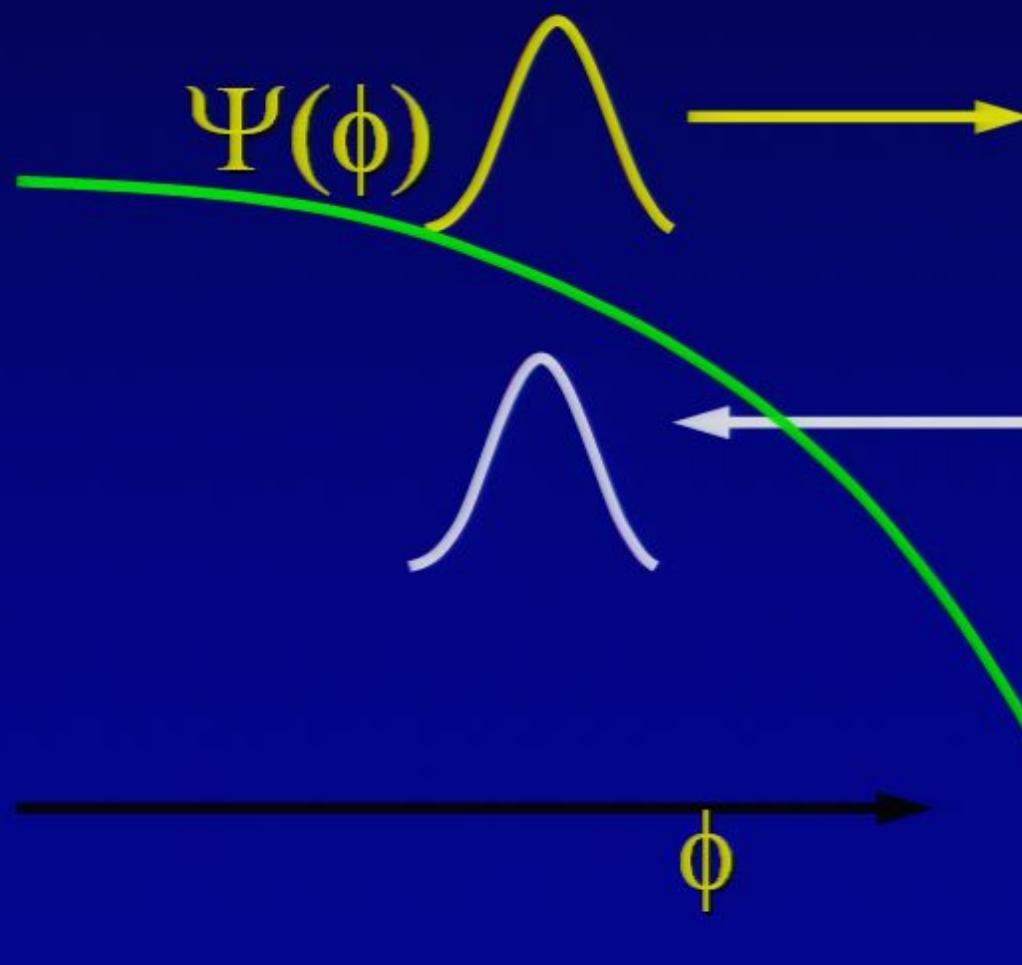
Hertog+Horowitz



can allow the  
bulk to evolve  
towards a  
singularity!  
  
what happens  
next?

# Quantum mechanics of boundary theory

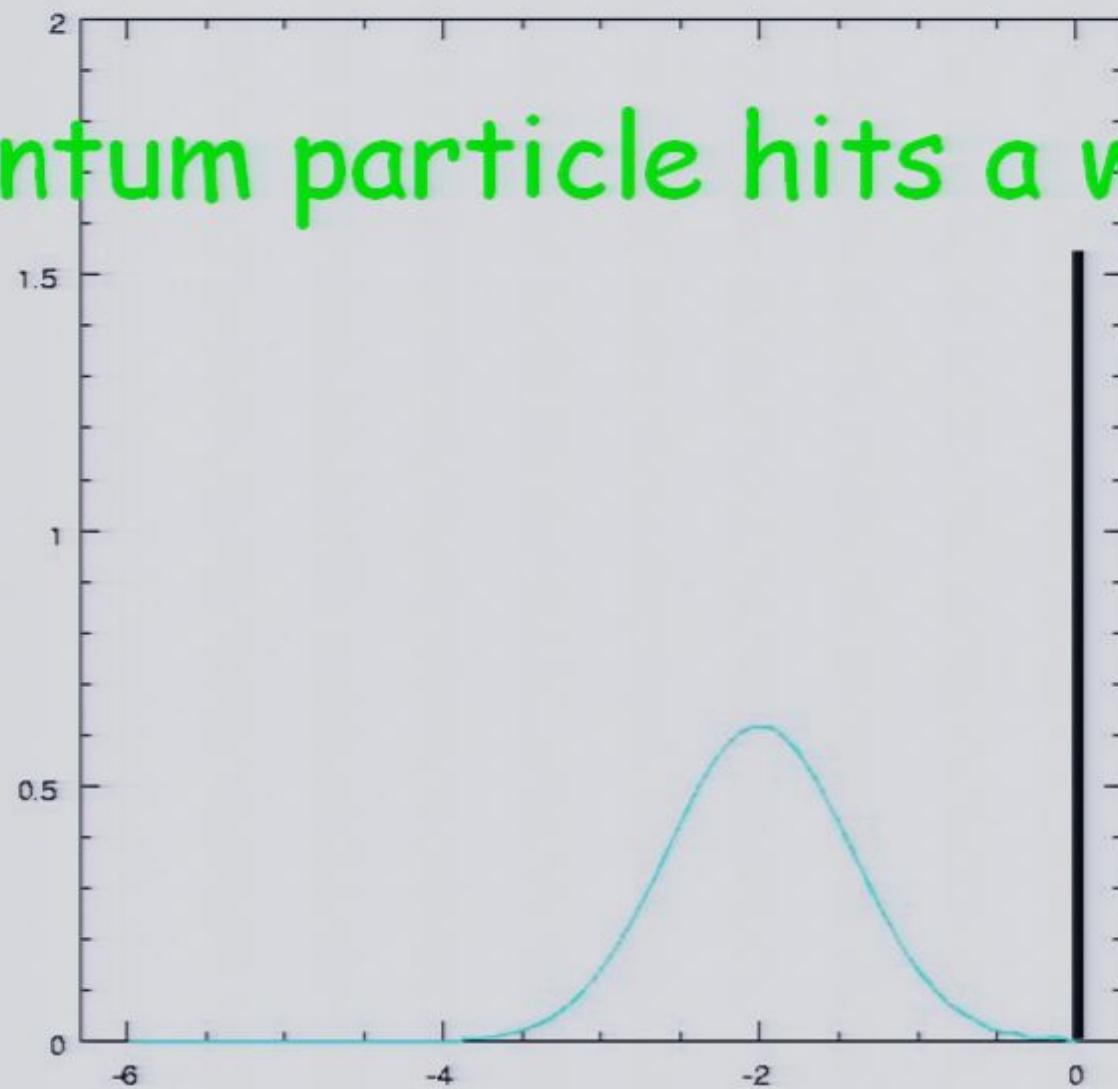
(Reed+Simon 70's)

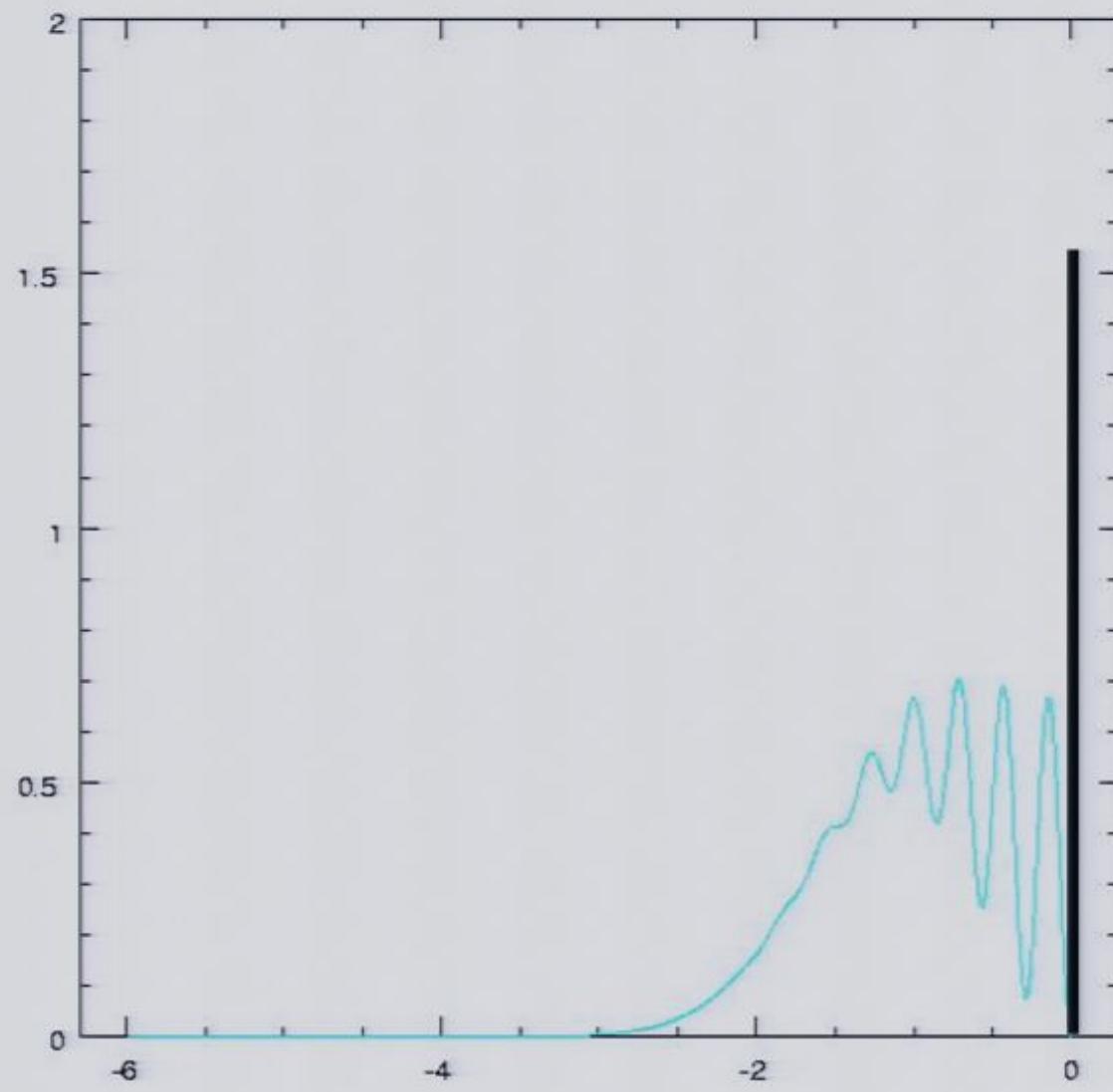


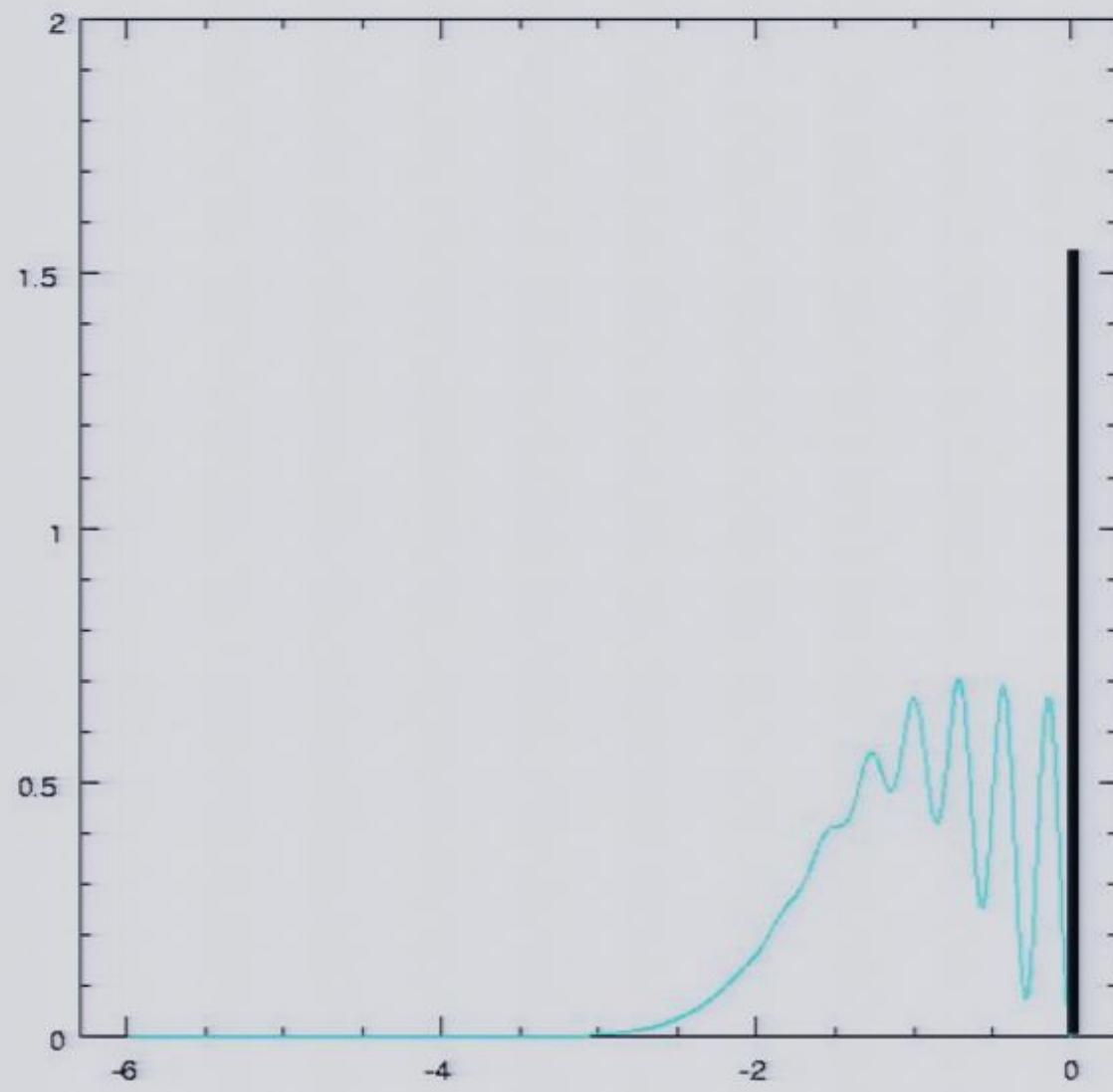
Boundary  
condition at  $\infty$

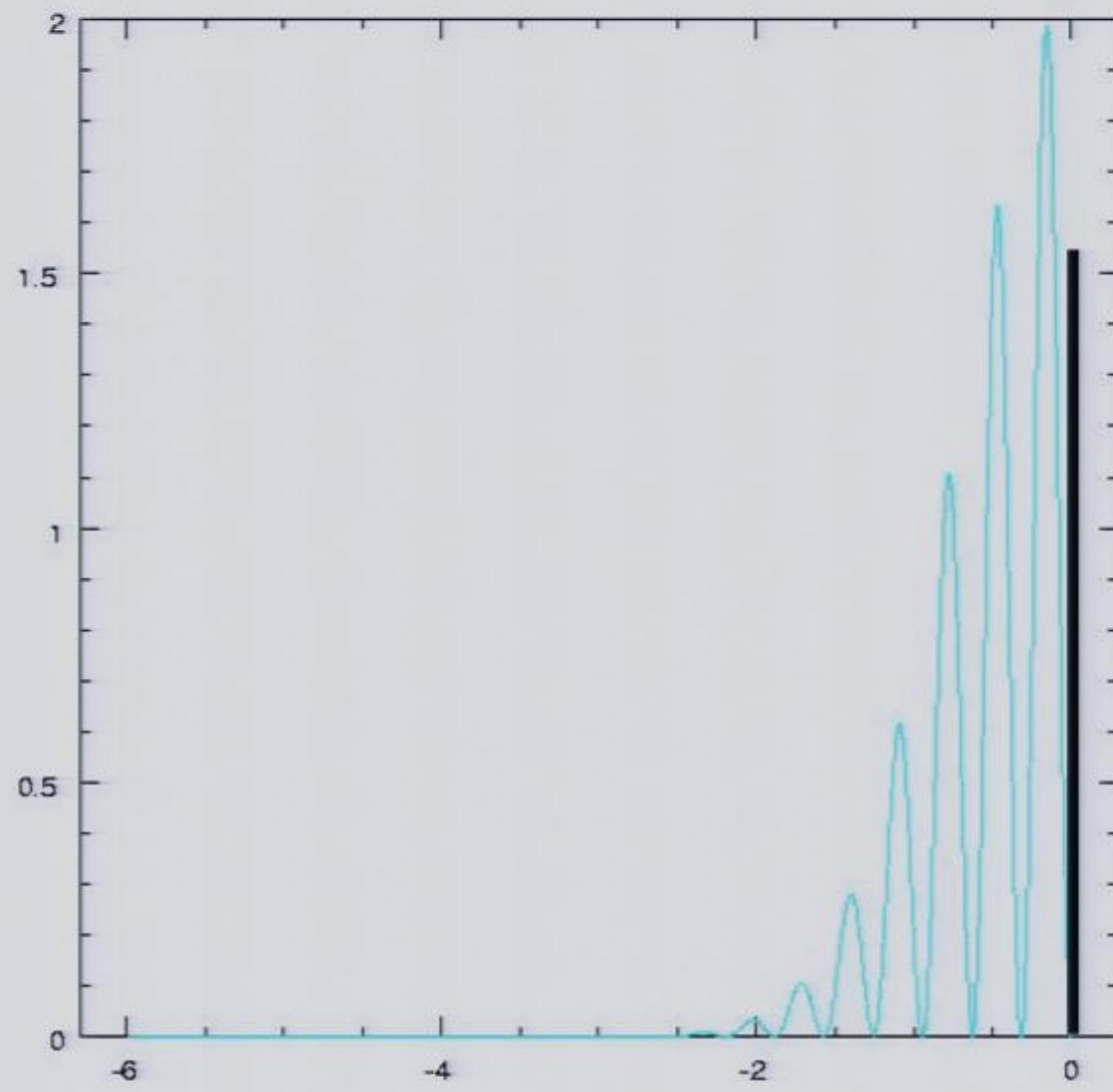
Bottomless  
potential  
reflects  
instability of  
gravity

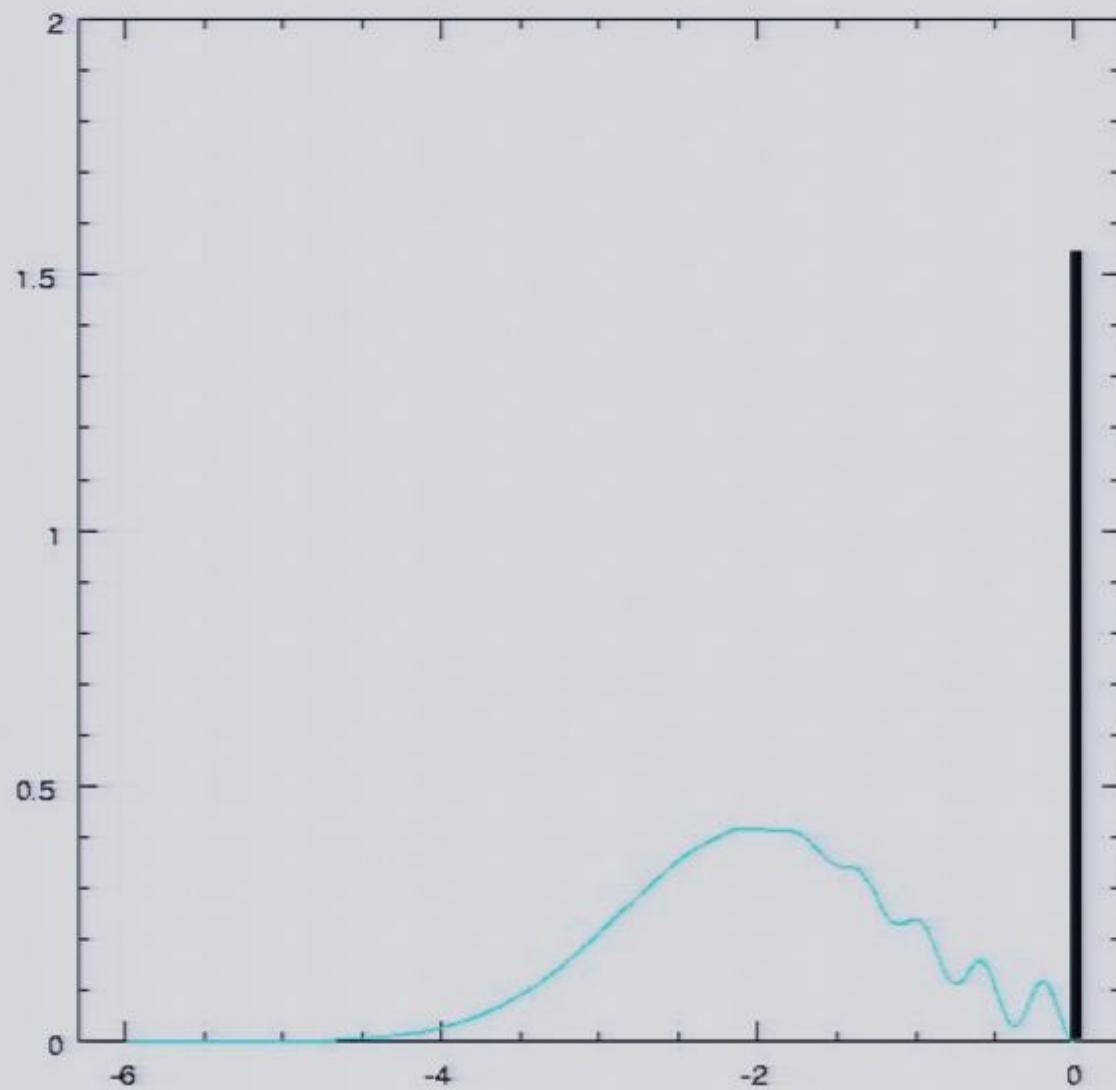
# A quantum particle hits a wall

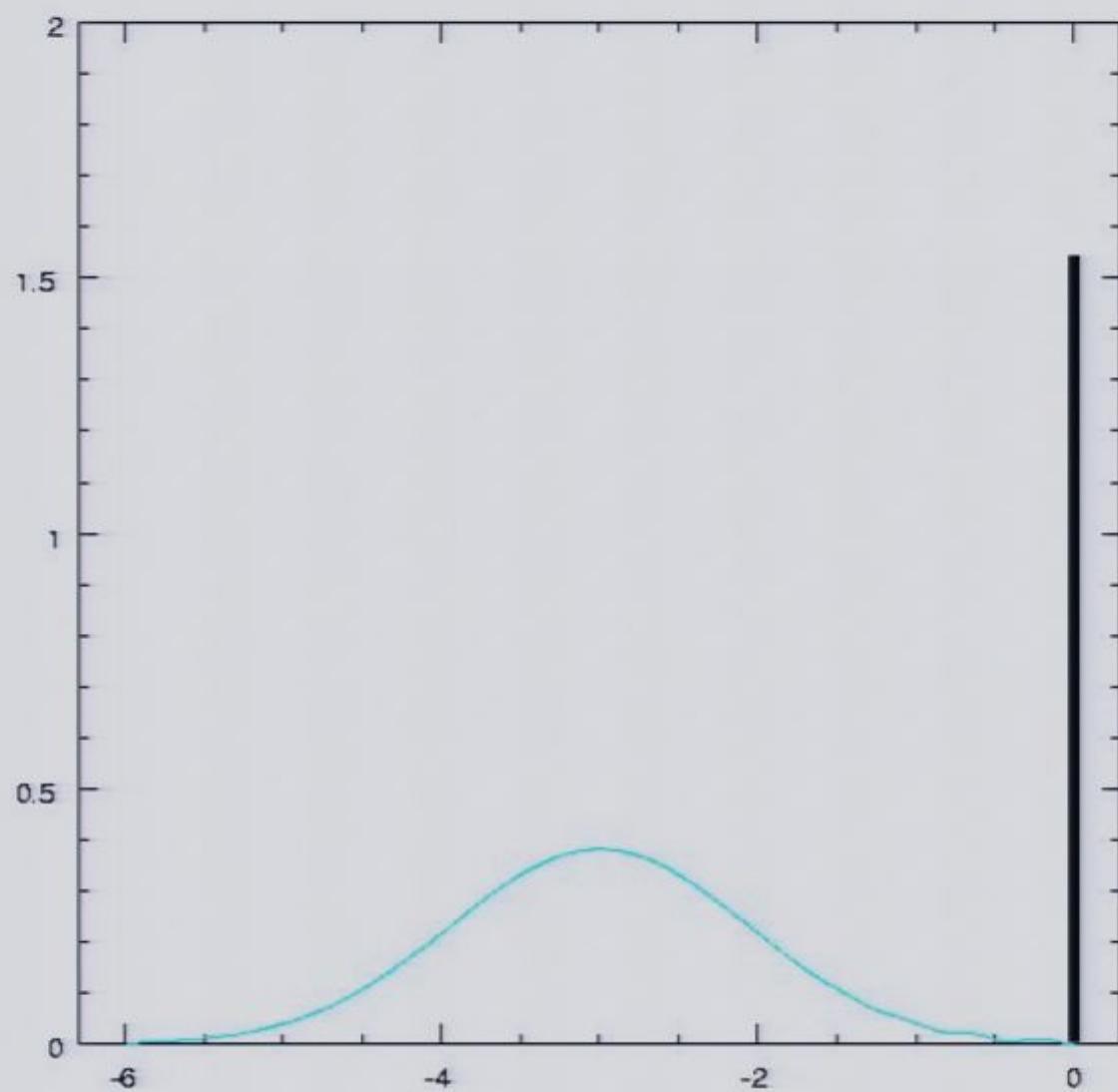












**Result:**

**Roll-down and bounce back leads automatically to**

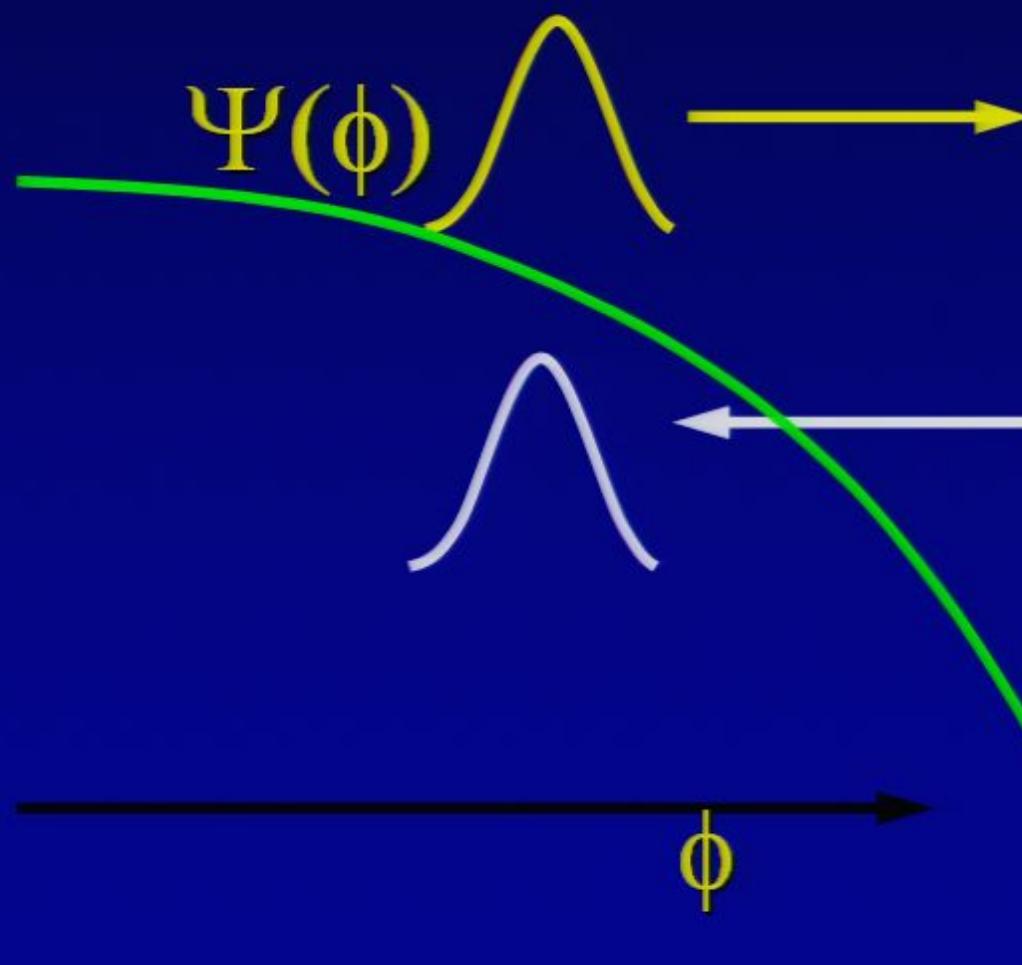
**GLASSy density variations**

**"Scale-Invariance from Scale-Invariance"**

**Caveat: the only model we know how to treat has four space dimensions: but the same principles should apply in three**

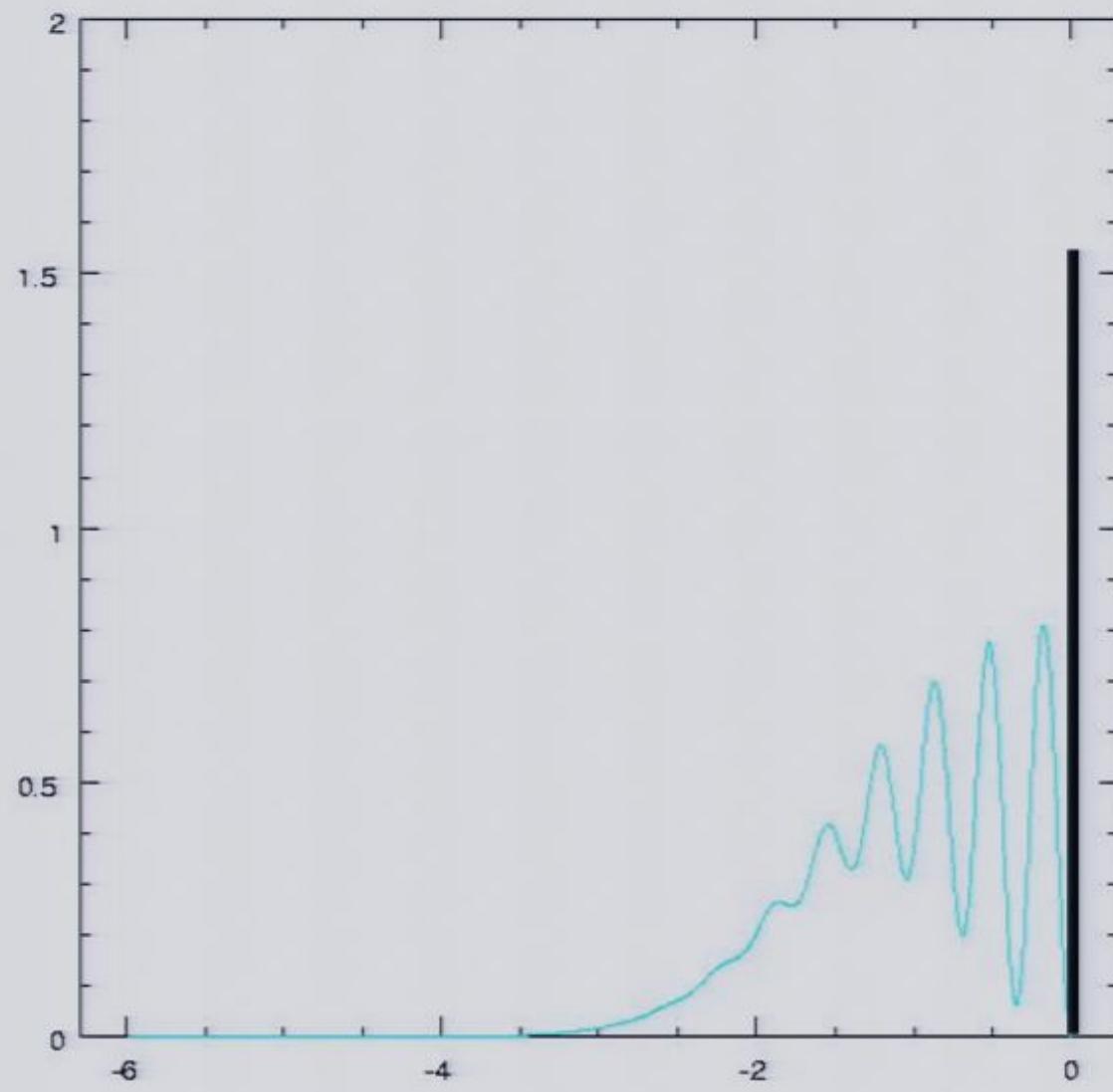
# Quantum mechanics of boundary theory

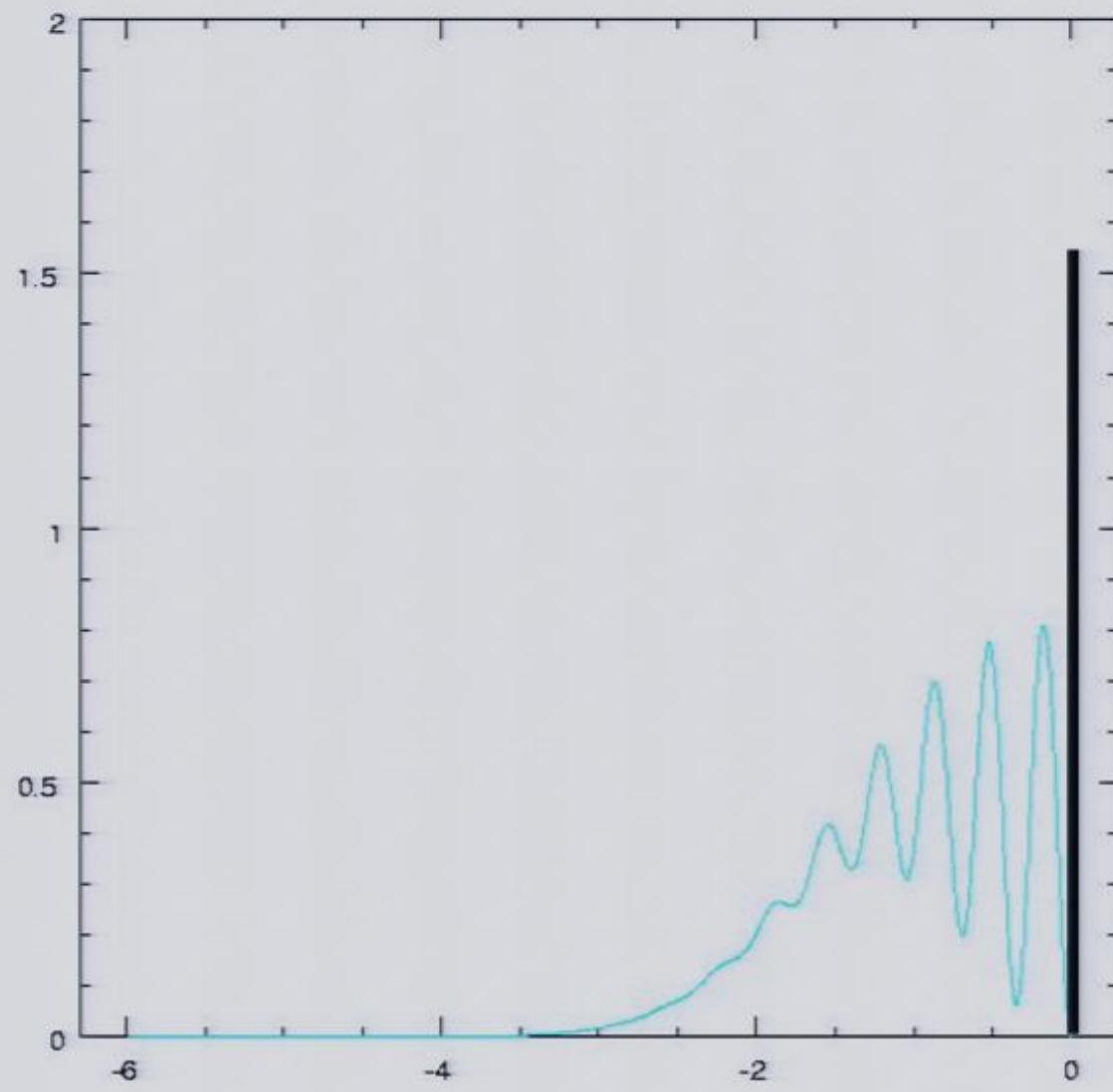
(Reed+Simon 70's)

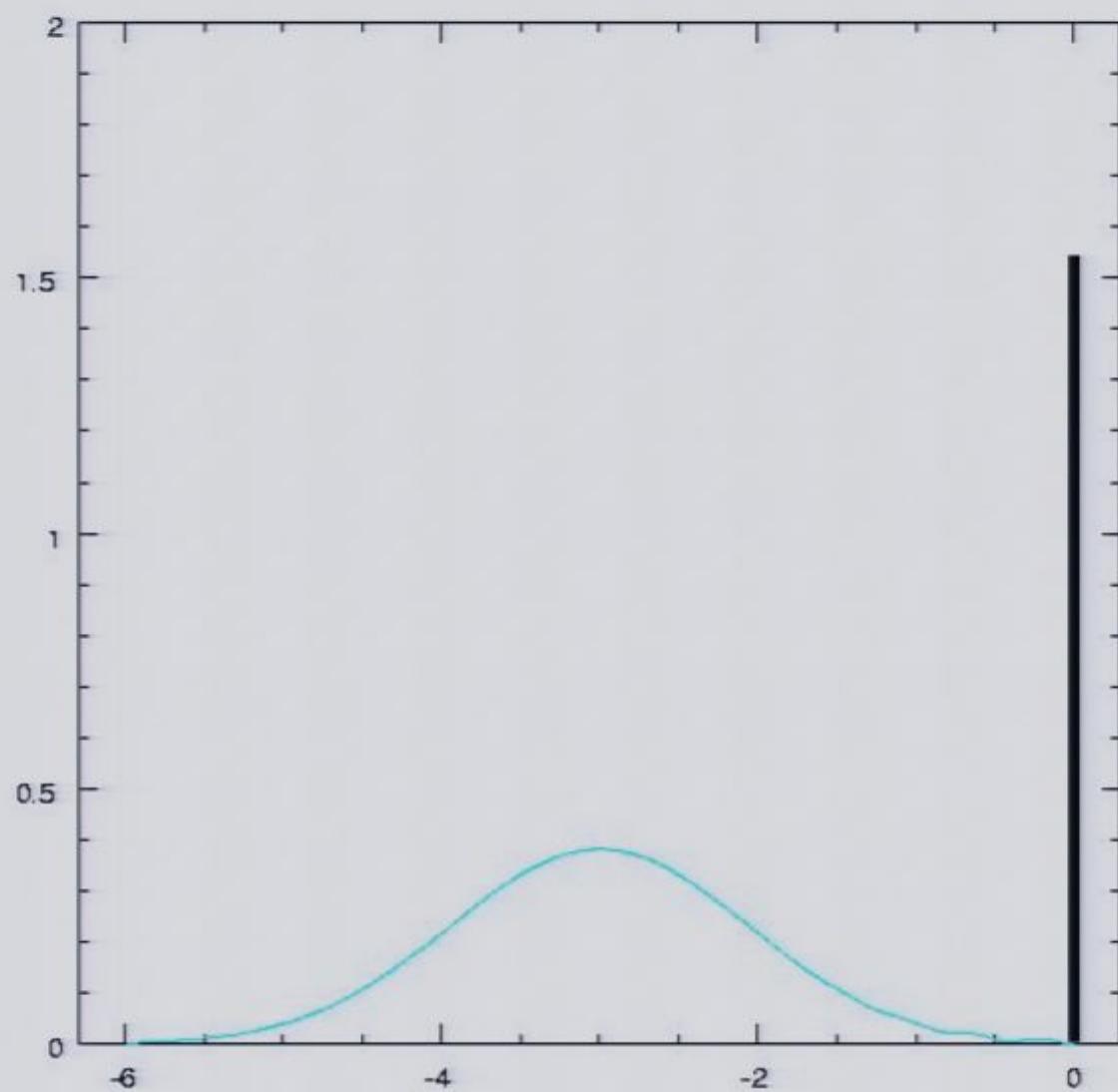


Boundary  
condition at  $\infty$

Bottomless  
potential  
reflects  
instability of  
gravity







**Result:**

**Roll-down and bounce back leads automatically to**

**GLASSy density variations**

**"Scale-Invariance from Scale-Invariance"**

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**Result:**

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# Observational Test

Gravitational  
Waves

**Result:**

**Roll-down and bounce back leads automatically to**

**GLASSy density variations**

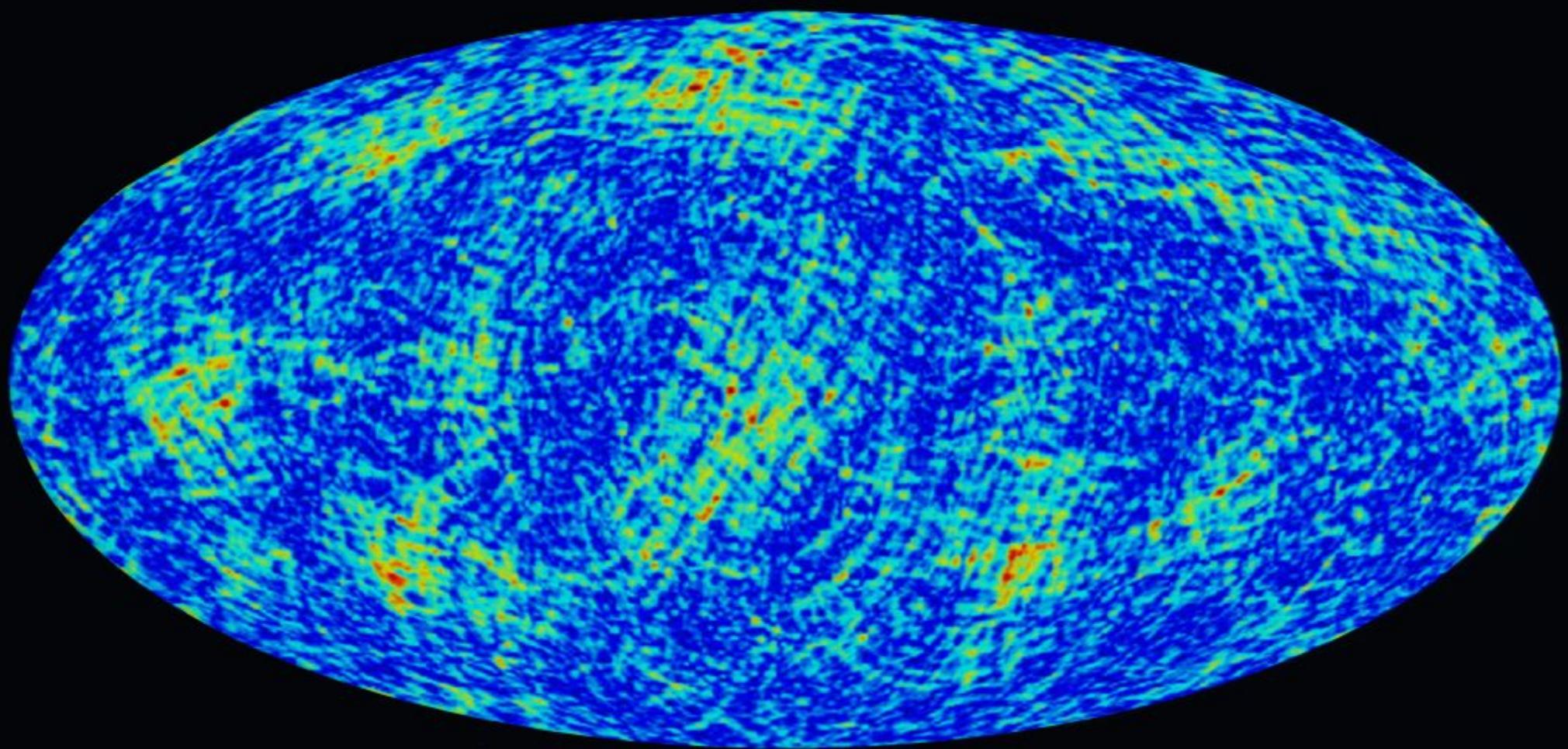
**"Scale-Invariance from Scale-Invariance"**

**Caveat: the only model we know how to treat has four space dimensions: but the same principles should apply in three**

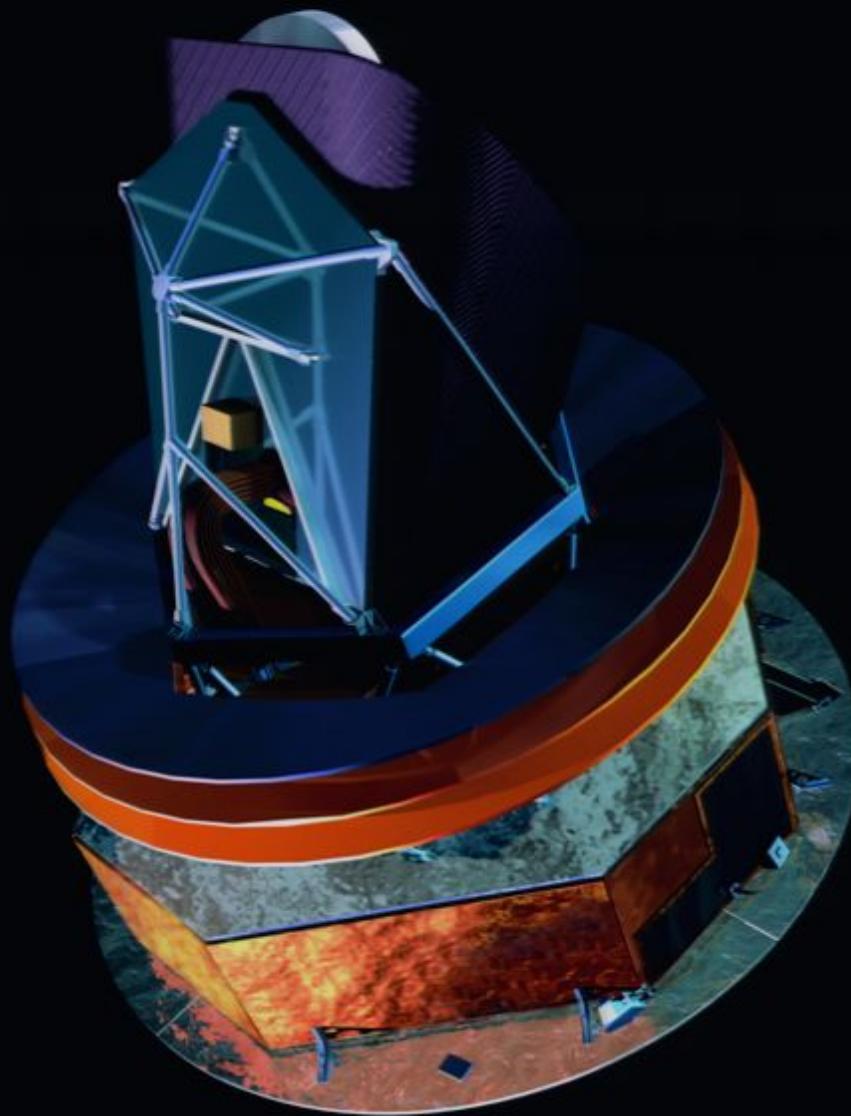
# Observational Test

Gravitational  
Waves

# Gravitational waves from inflation



cause a swirling polarization pattern

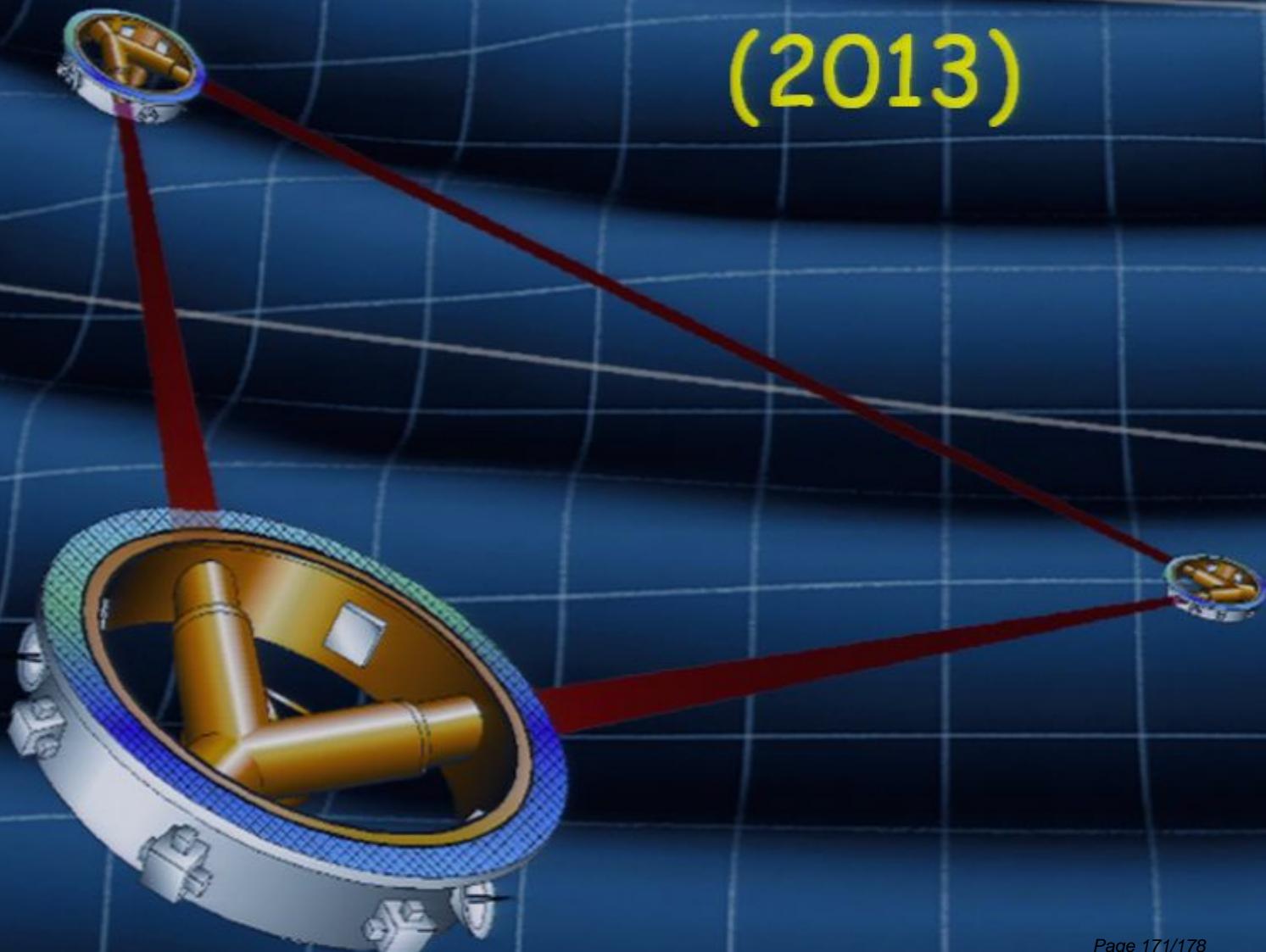


Pinsa: 08030033

ESA Planck satellite (2008)

# Laser Interferometric Space Antenna

(2013)



# Credo

Developing and testing mathematical models of the universe is one of the best ways we have of appreciating it



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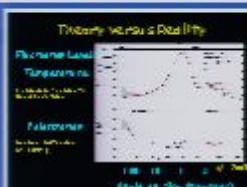
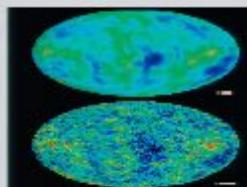
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End Show



2001



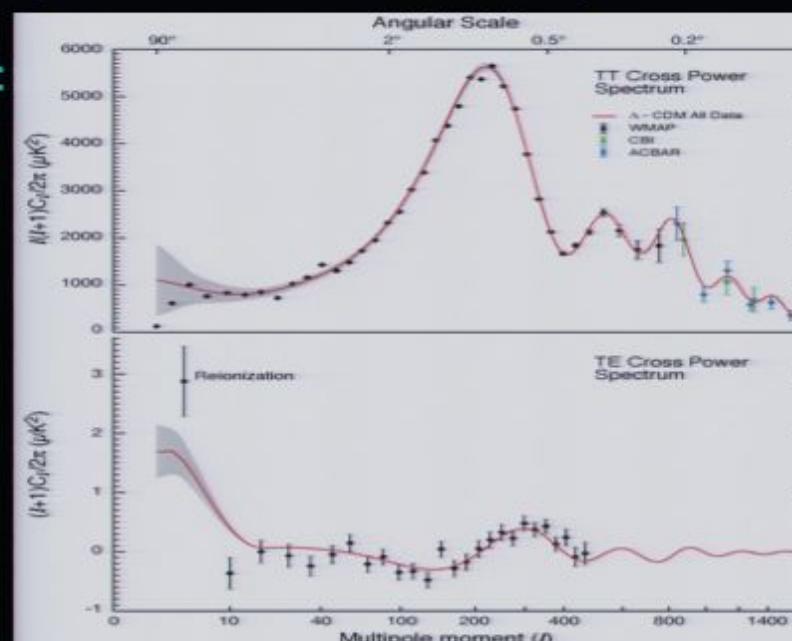
# Theory versus Reality

Fluctuation Level:  
Temperature

Zeldovich, Peebles+Yu,  
Bond+Efstathiou

Polarization

Coulson, Crittenden,  
NT (1994)



100    10    1    .1 ( $l = 2\pi/\theta$ )  
Angle on Sky (Degrees)

Click to add notes

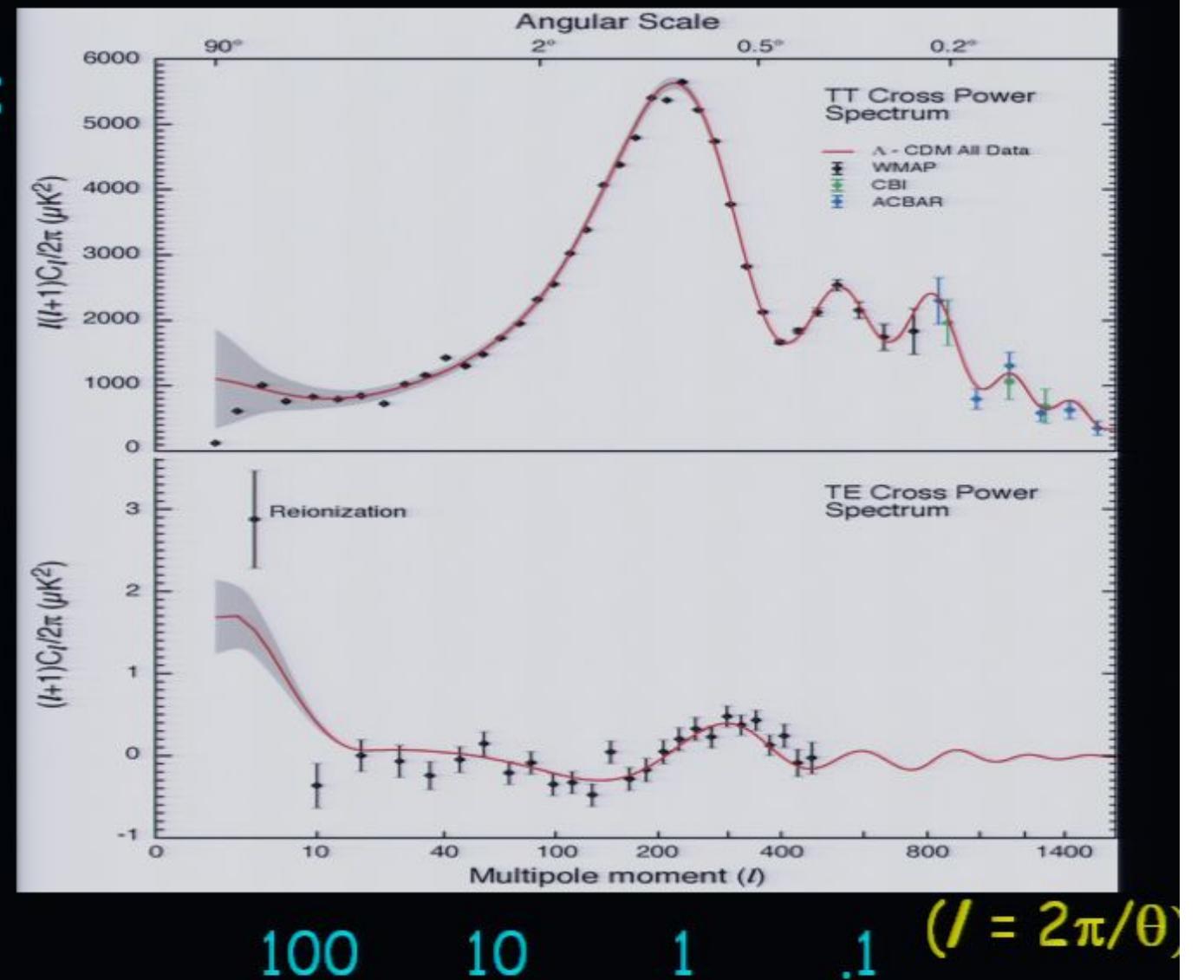
# Theory versus Reality

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Bond+Efstathiou

Polarization

Coulson, Crittenden,  
NT (1994)



Angle on Sky (Degrees)

# all the particles and forces

\* Fermions     $u d c s t b \times 3 \times 4$

90

$e \mu \tau \times 4$

$\nu_e \nu_\mu \nu_\tau \times 2 (+ \text{rh } \nu's)$



\* Bosons     $g^a \times 8 \times 2$     strong

30

$W^a \times 3 \times 2$

weak

$A \times 2$

electromag

$H^a \times 4$

higgs ?

$h_{\mu\nu} \times 2$

graviton



\* Dark Matter particles?

\* Dark Energy

# all known physics

$$\Psi = \int e^{\frac{i}{\hbar} \int \left( \frac{R}{16\pi G} - F^2 + \bar{\psi} i \not{D} \psi - \lambda \varphi \bar{\psi} \psi + |D\varphi|^2 - V(\varphi) \right)}$$

The equation is a complex quantum field theory expression. It includes:  
- A Schrödinger-like term  $\bar{\psi} i \not{D} \psi$ .  
- A Yukawa-like term  $-\lambda \varphi \bar{\psi} \psi$ .  
- A Higgs-like term  $|D\varphi|^2 - V(\varphi)$ .  
- A Planck-like term  $\frac{R}{16\pi G}$ .  
- A Dirac-like term  $F^2$ .  
- A Newton-like term  $\lambda \varphi$ .  
- An Einstein-like term  $i \not{D}$ .  
- A Maxwell-Yang-Mills-like term  $\bar{\psi} \psi$ .