

Title: What is the universe made of? The case for dark energy and dark matter.

Date: Jul 07, 2006 01:10 PM

URL: <http://pirsa.org/06070013>

Abstract: Currently, most physicists believe that only a small fraction of all the matter and energy in the universe is visible and can be seen through our most powerful telescopes. The remaining majority of the universe is thought to consist of elusive dark matter and dark energy, two substances about which we know very little. This presentation will explore the evidence in supporting the dark matter and dark energy theories and discuss some of their implications for how our universe will evolve.



What is the Universe Made of?

*The Case for Dark Energy
and Dark Matter*

Cliff Burgess

Outline

- The Hot Big Bang
 - *Evidence for an Expanding Universe*
 - *Evidence for a Hot Big Bang*
 - *Evidence for Dark Matter and Dark Energy*
- Contact With Fundamental Physics
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- Outlook

Outline

- The Hot Big Bang
 - *Evidence for an Expanding Universe*
 - *Evidence for a Hot Big Bang*
 - *Evidence for Dark Matter and Dark Energy*
- Contact With Fundamental Physics
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- Outlook

Outline

- The Hot Big Bang
 - *Evidence for an Expanding Universe*
 - *Evidence for a Hot Big Bang*
 - *Evidence for Dark Matter and Dark Energy*
- Contact With Fundamental Physics
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- Outlook

Outline

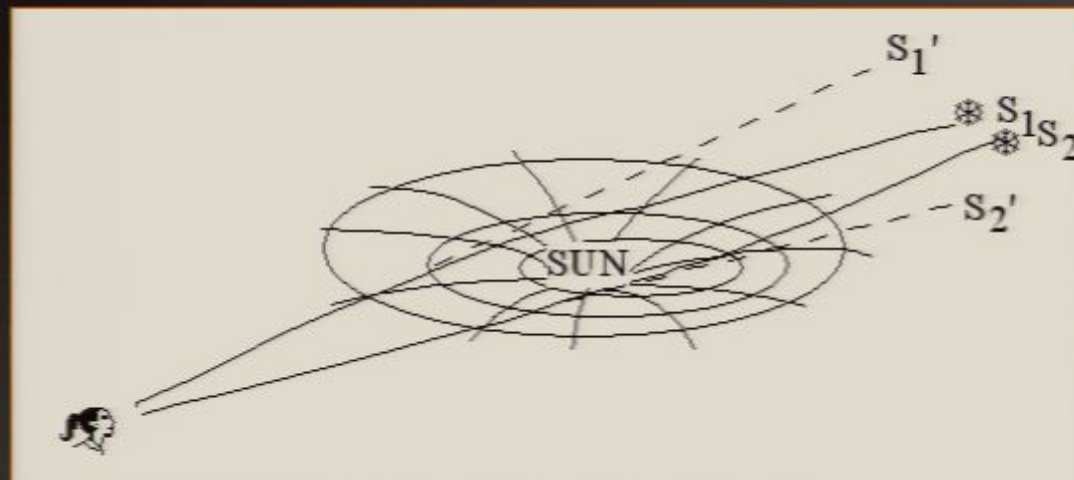
- The Hot Big Bang
 - *Evidence for an Expanding Universe*
 - *Evidence for a Hot Big Bang*
 - *Evidence for Dark Matter and Dark Energy*
- Contact With Fundamental Physics
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- Outlook

Gravity, Matter & Geometry

“Only two things are infinite, the universe and human stupidity, and I’m not sure about the former.”

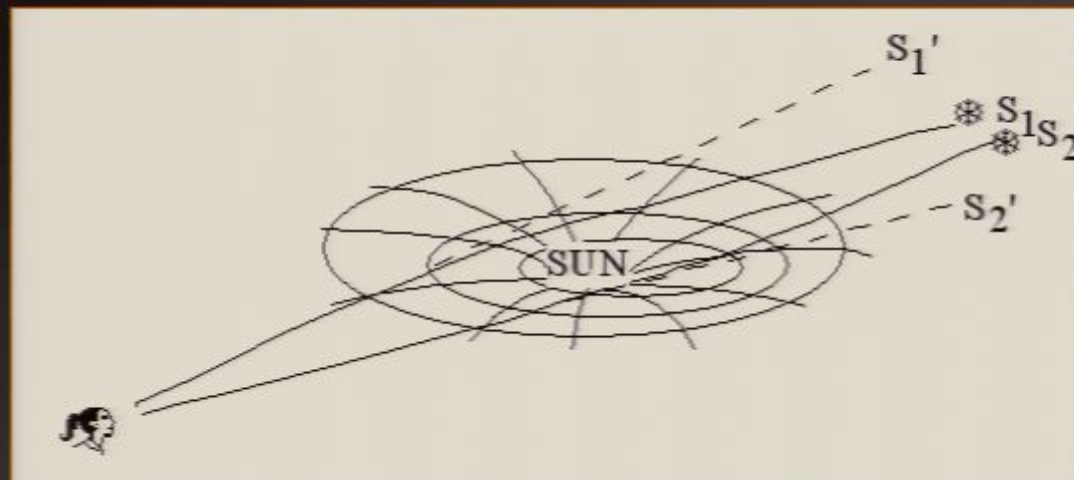
Albert Einstein

Gravity, Matter & Geometry



- According to Einstein gravity is really the response of space and time to the presence of matter.
 - The presence of energy curves space and time.
 - The curvature of space changes how objects move.

Gravity, Matter & Geometry

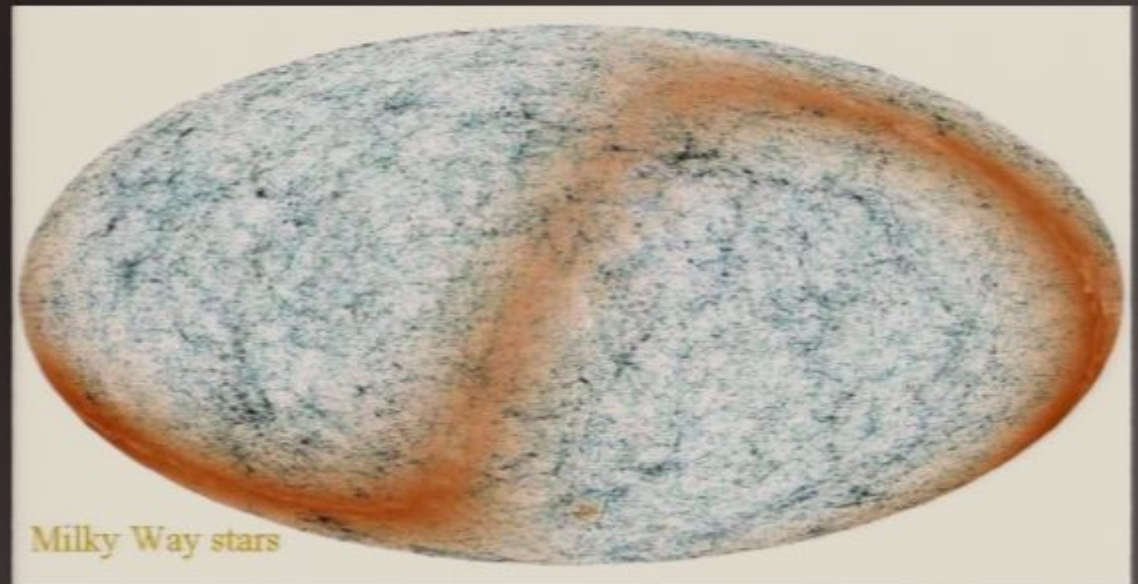


- According to Einstein gravity is really the response of space and time to the presence of matter.
 - The presence of energy curves space and time.
 - The curvature of space changes how objects move.
- *Knowing how matter is distributed over large scales tells us the shape and evolution of the Universe!*

Visible Matter in the Universe

2MASS Galaxy Survey

- Visible matter is distributed as stars and gas within galaxies and clusters of galaxies.
- These appear to be distributed roughly isotropically and homogeneously about us.



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



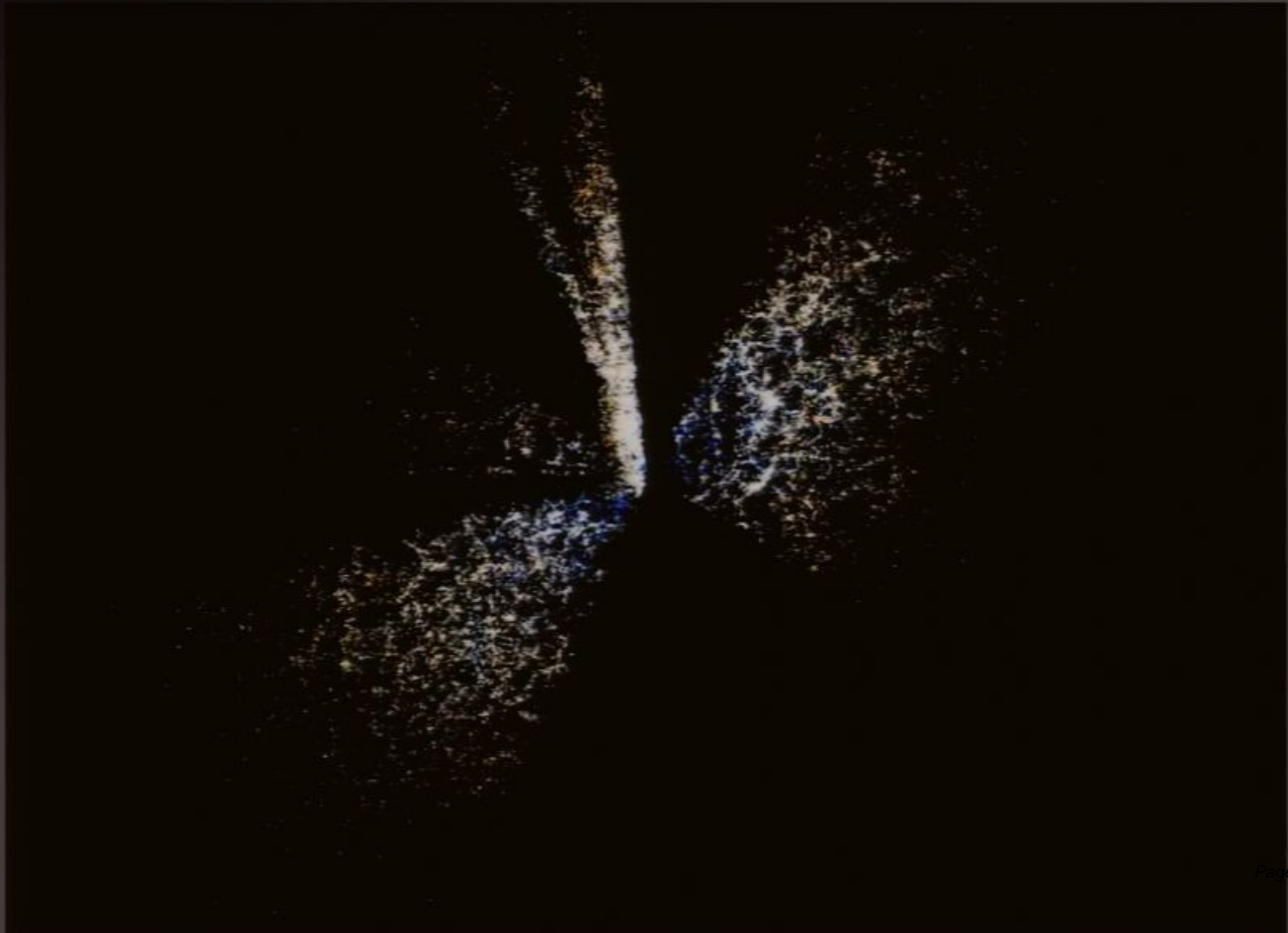
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



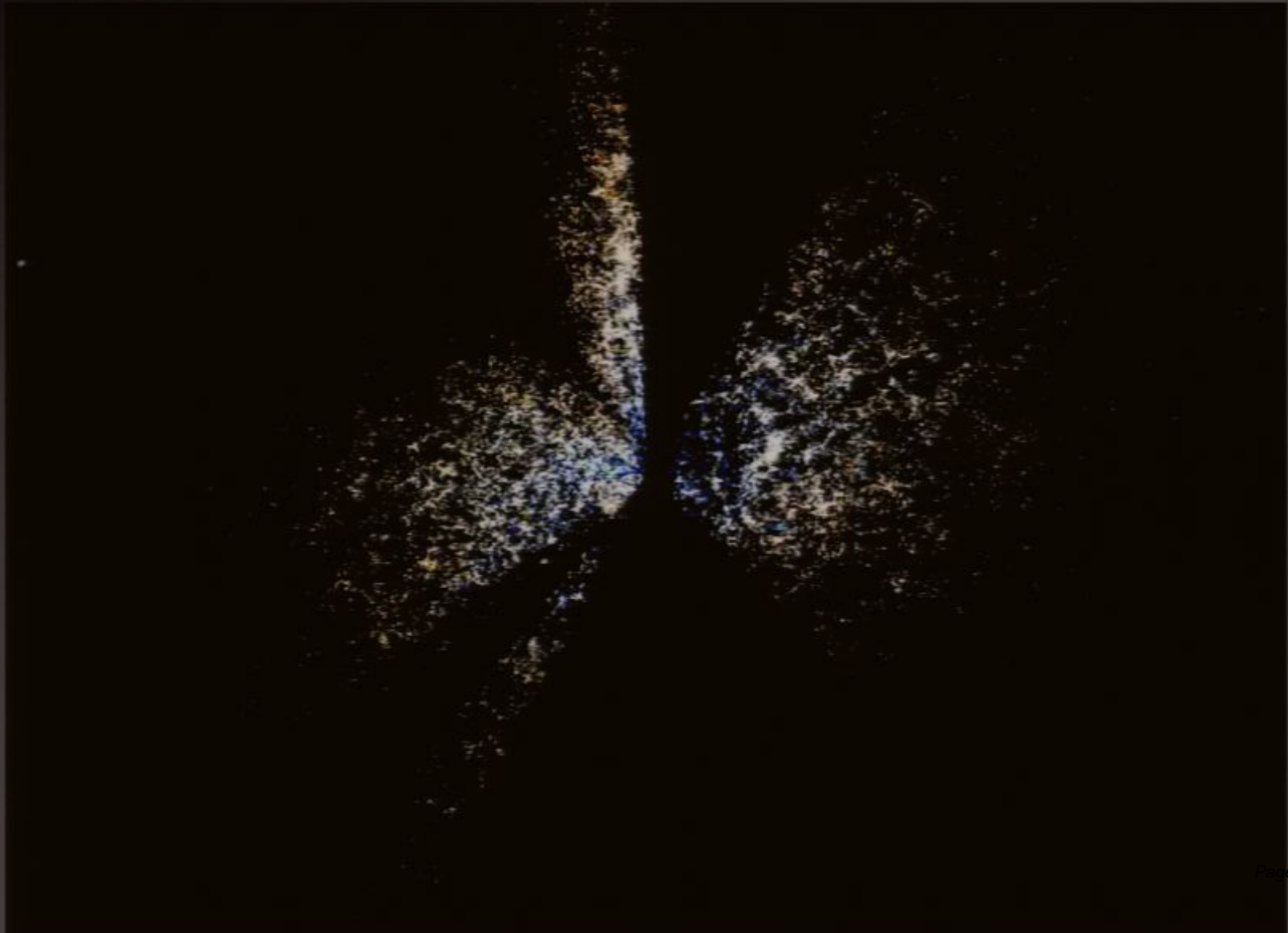
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



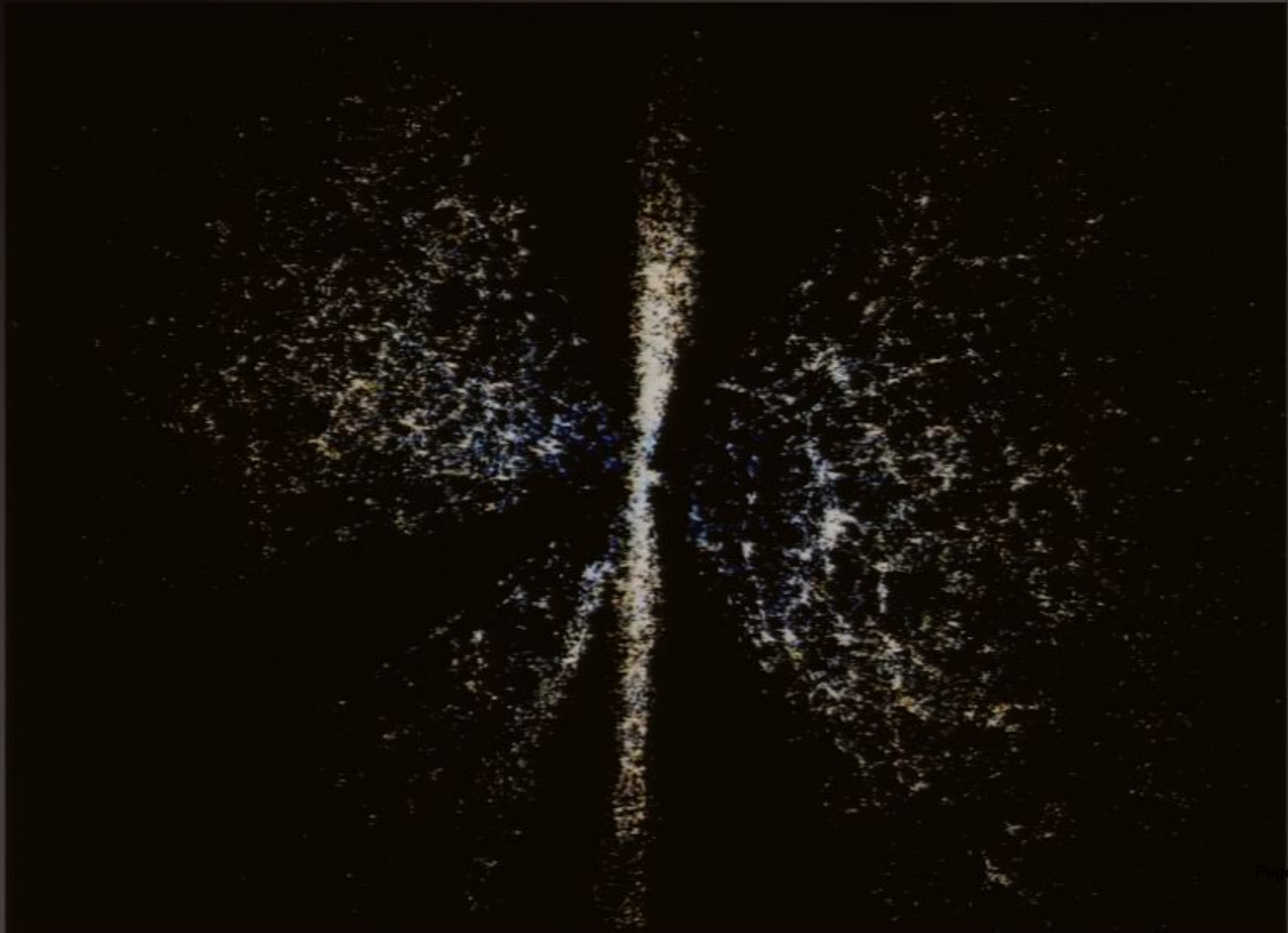
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



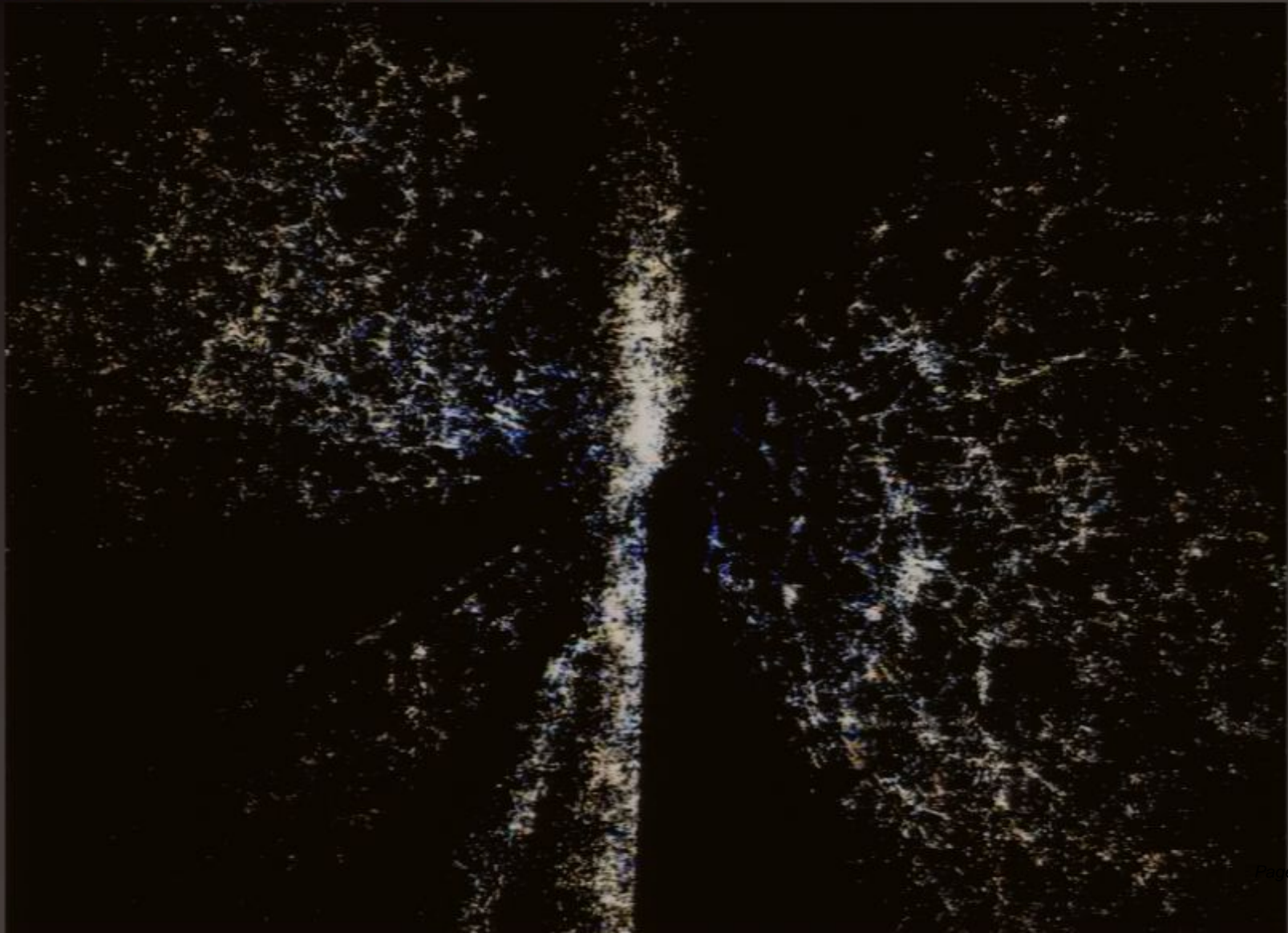
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



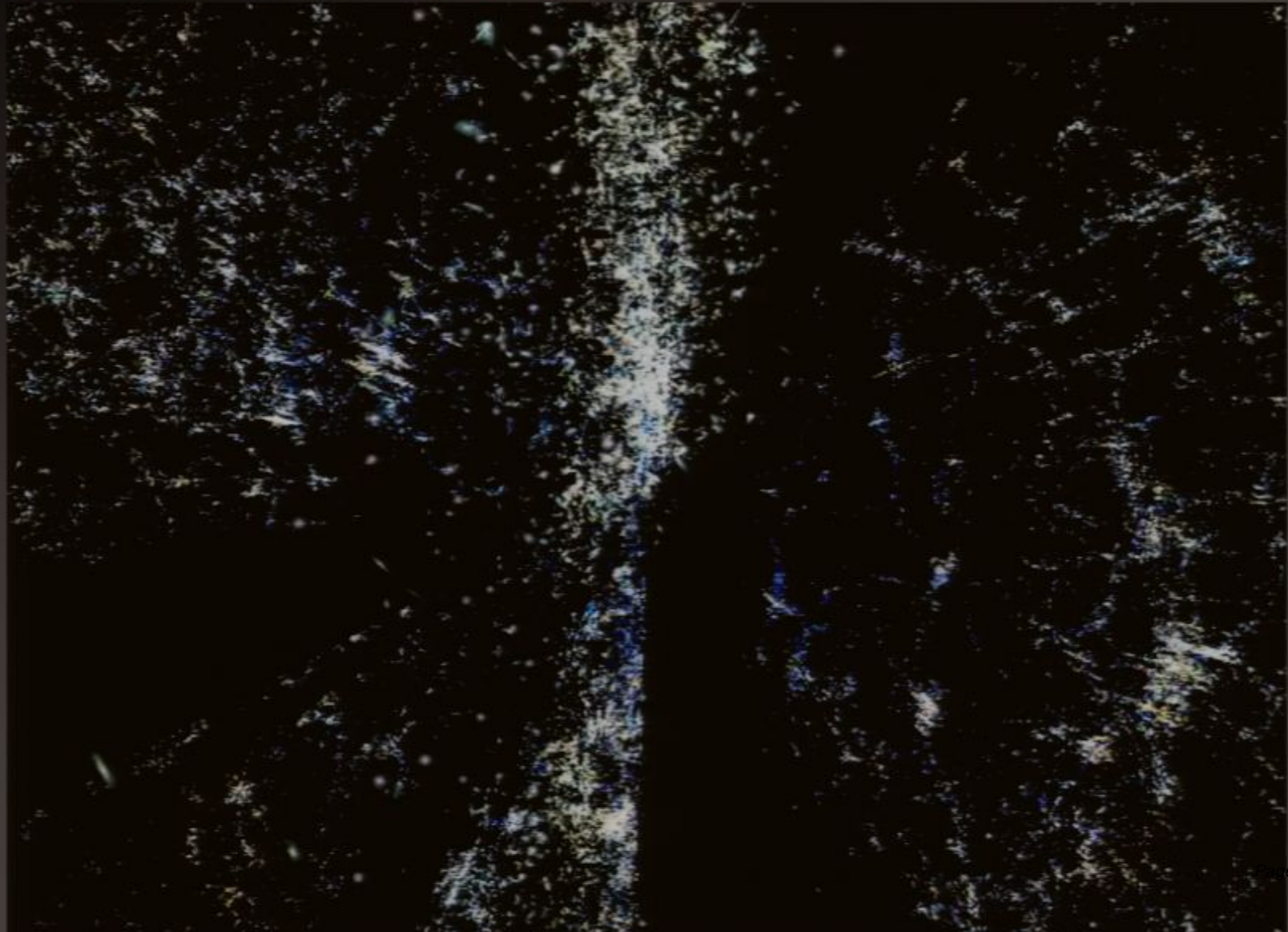
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



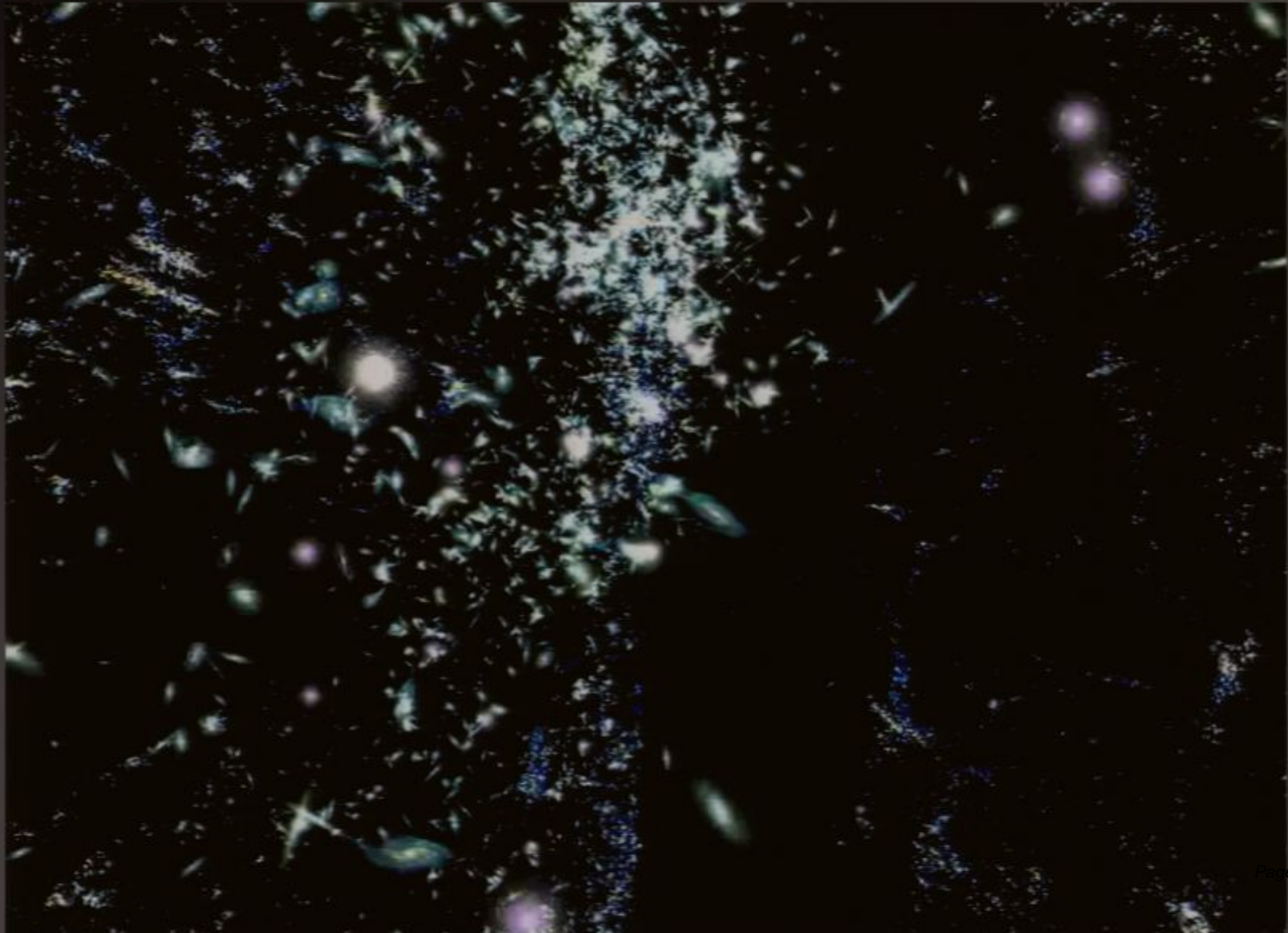
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



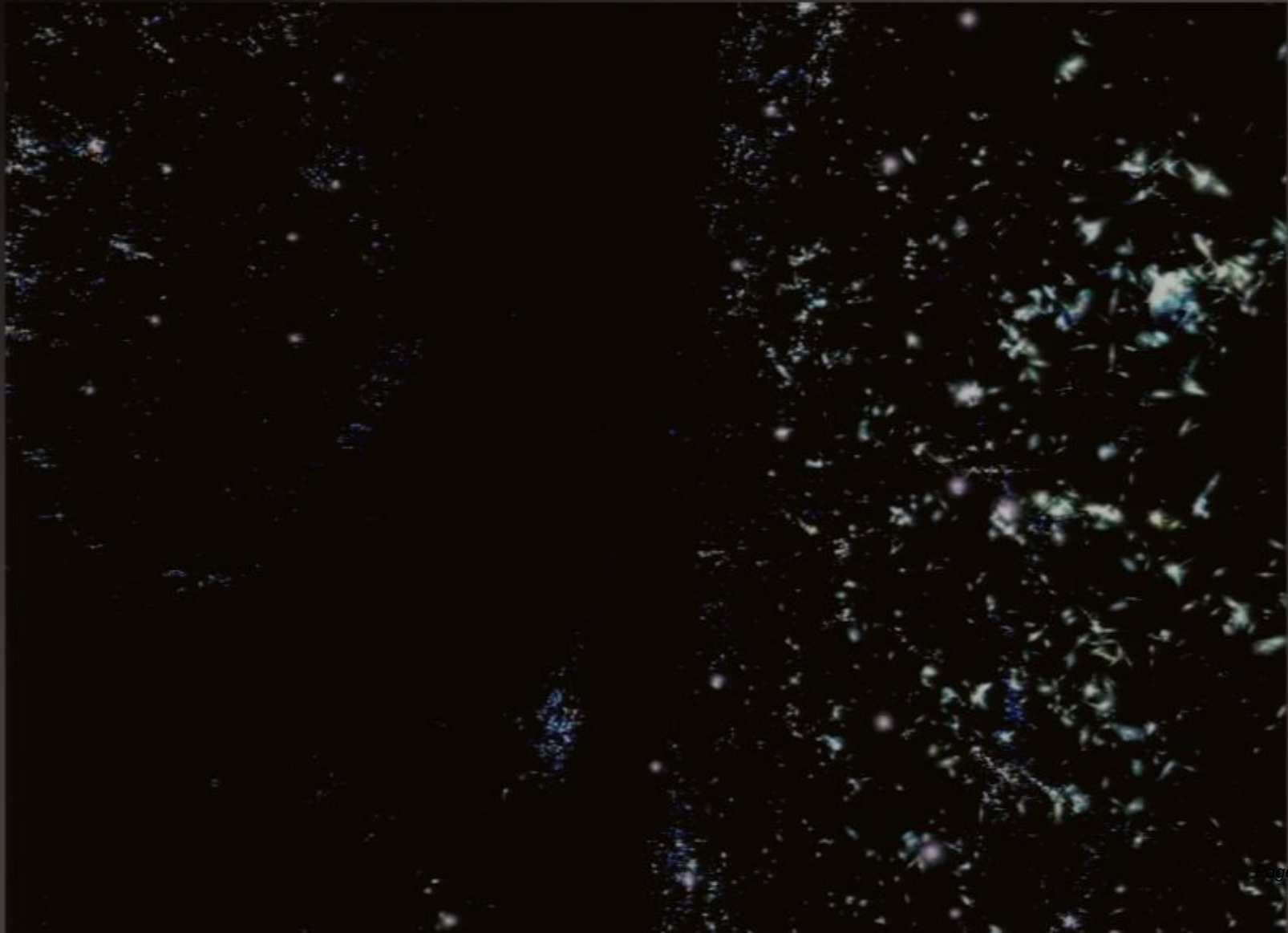
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



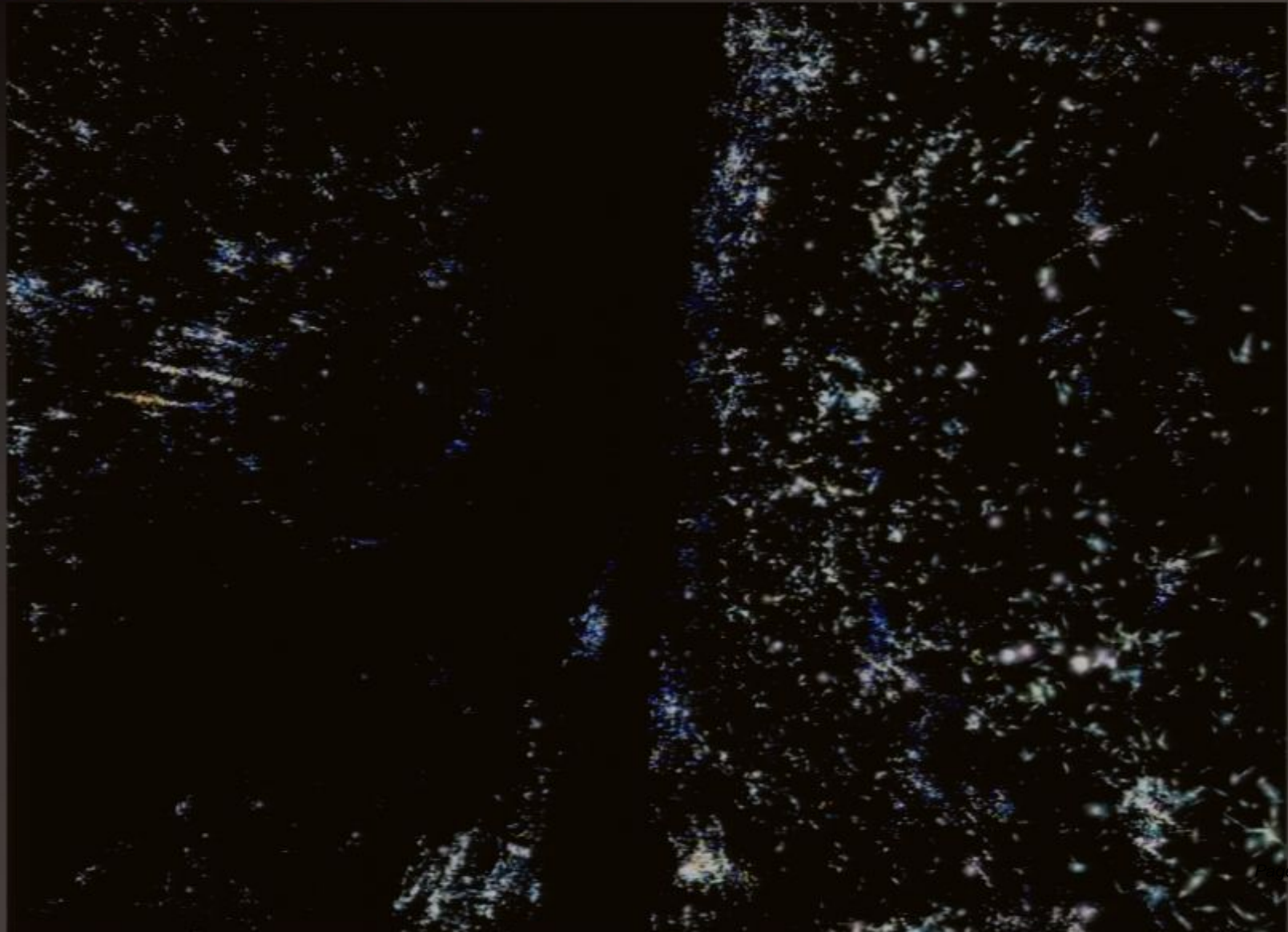
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



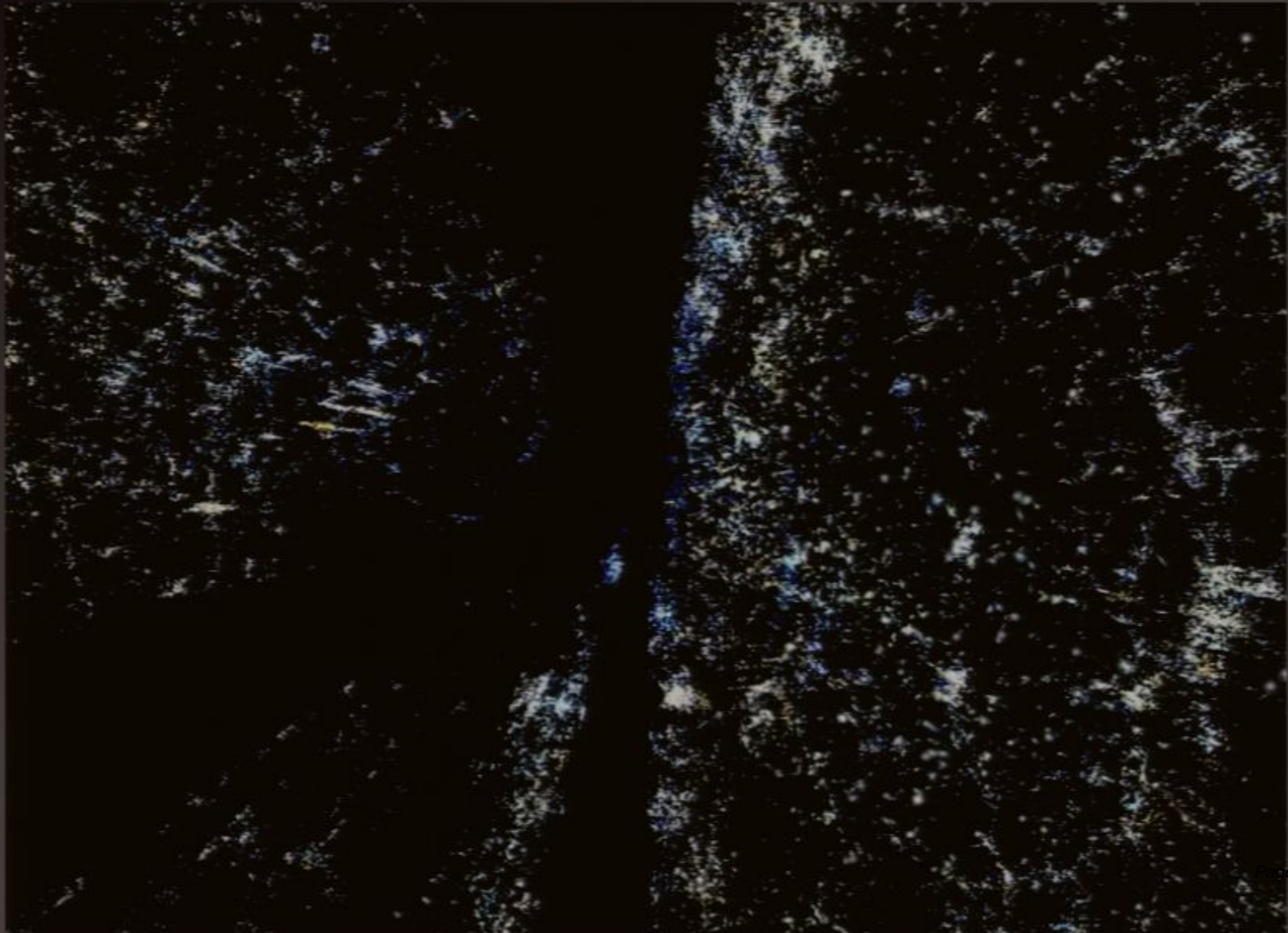
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



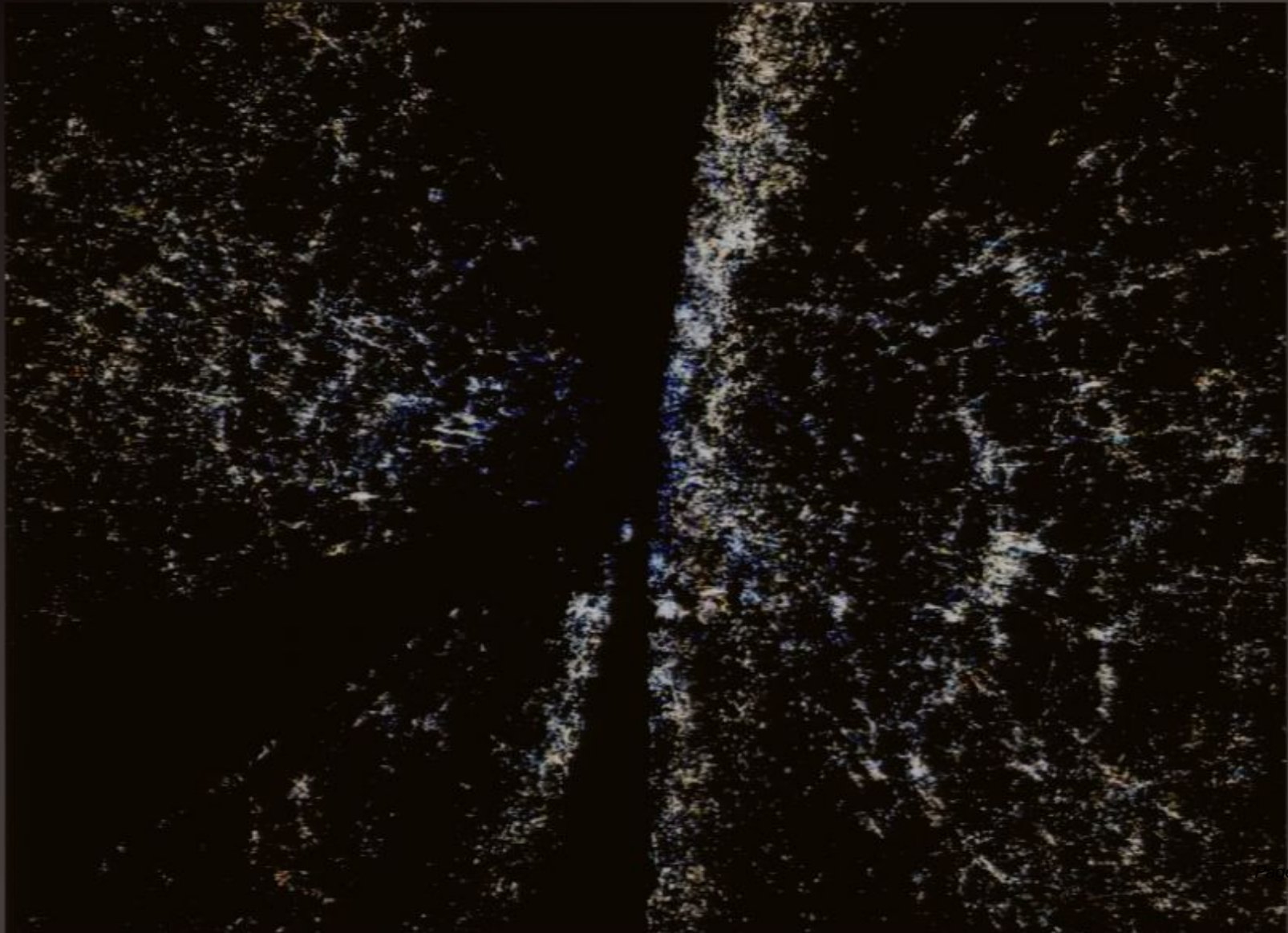
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



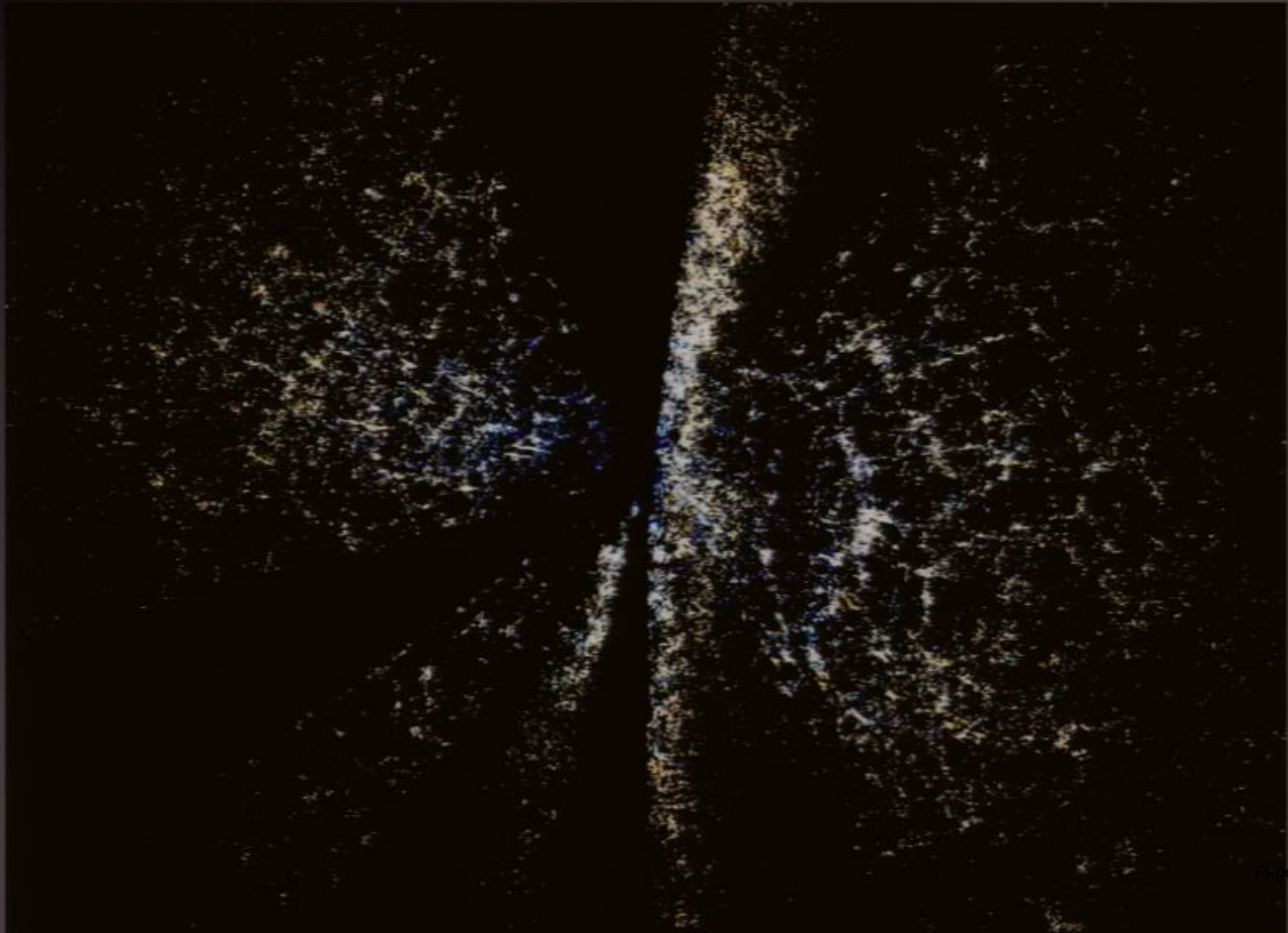
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



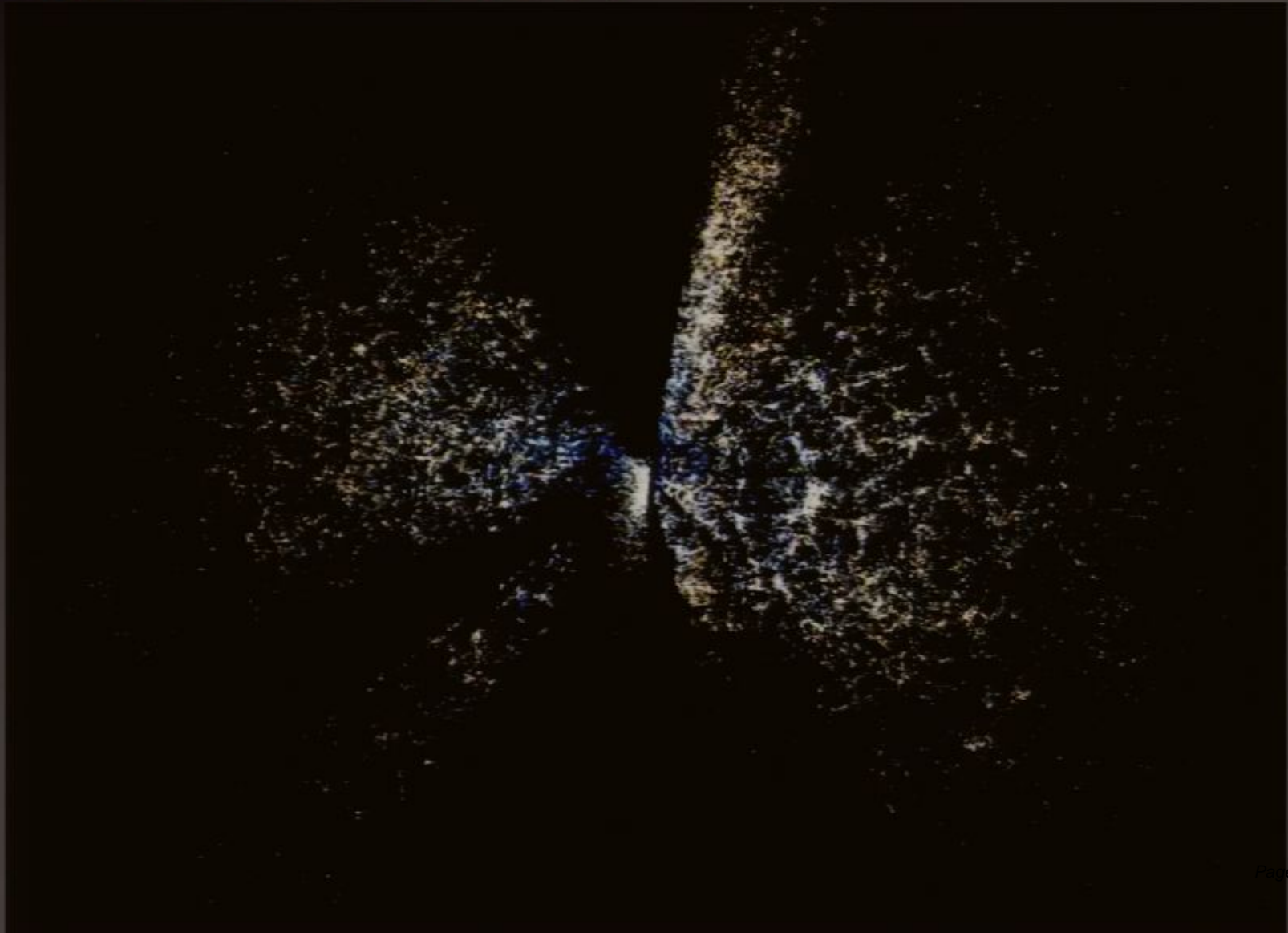
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



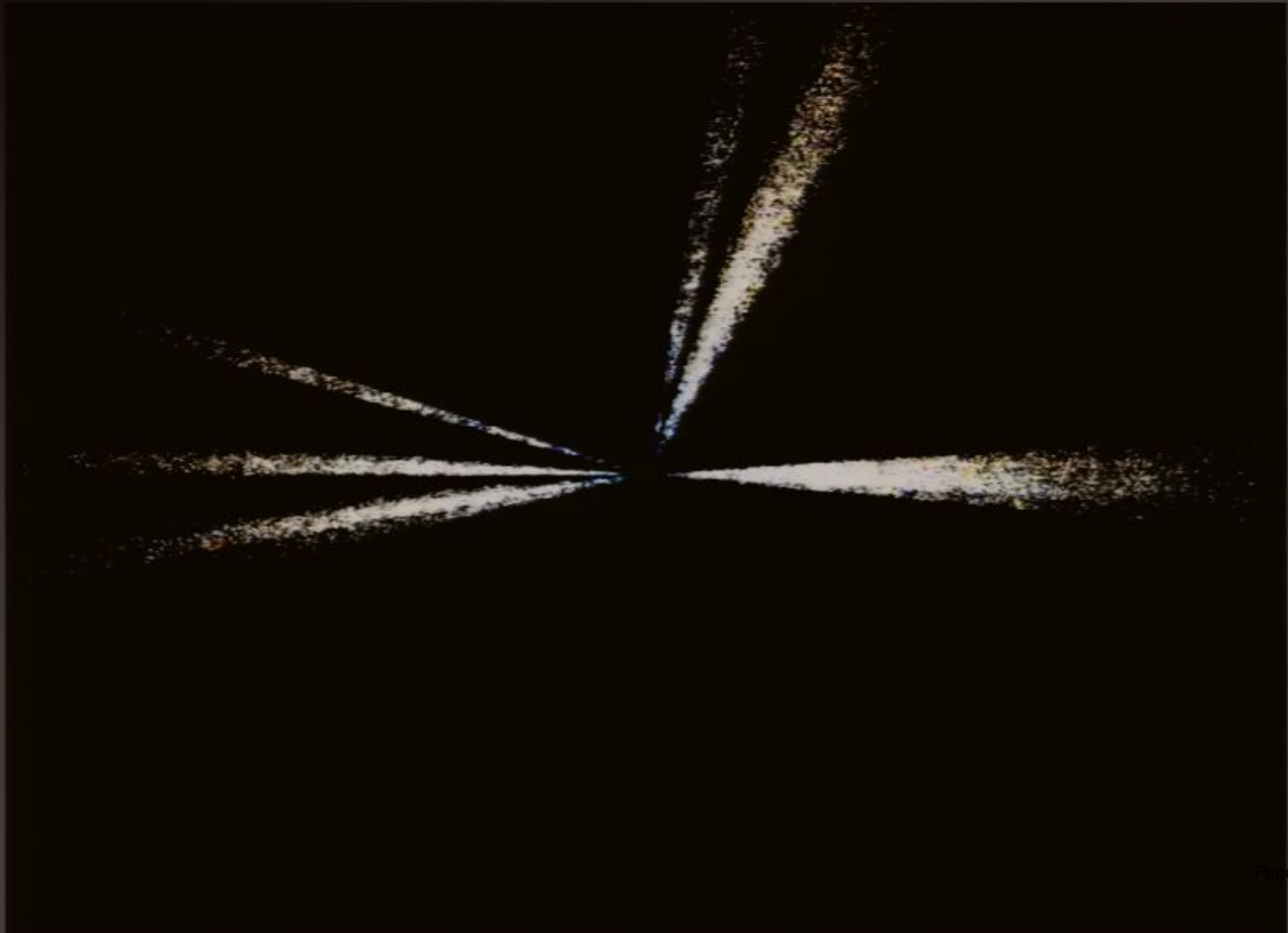
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



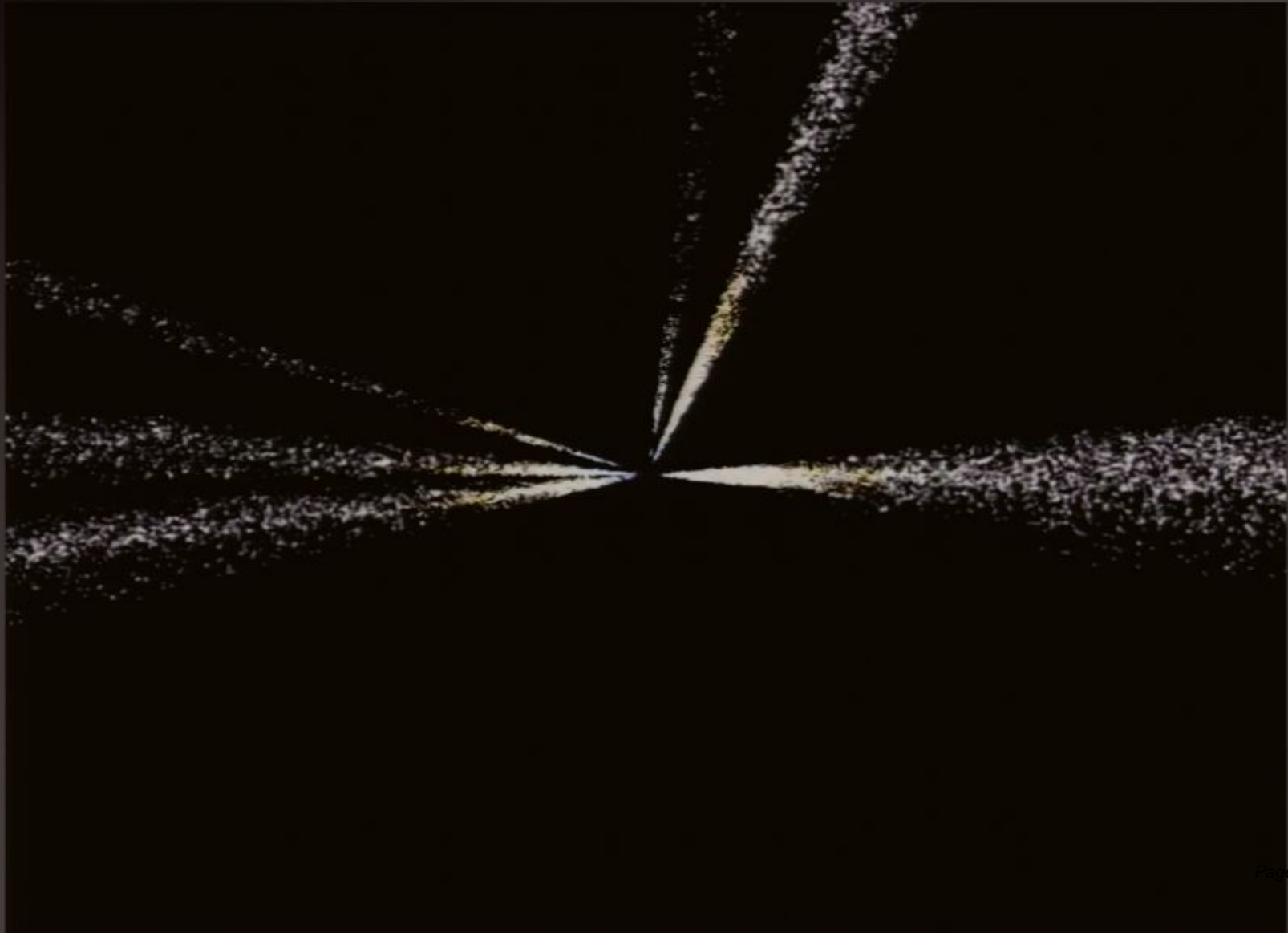
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



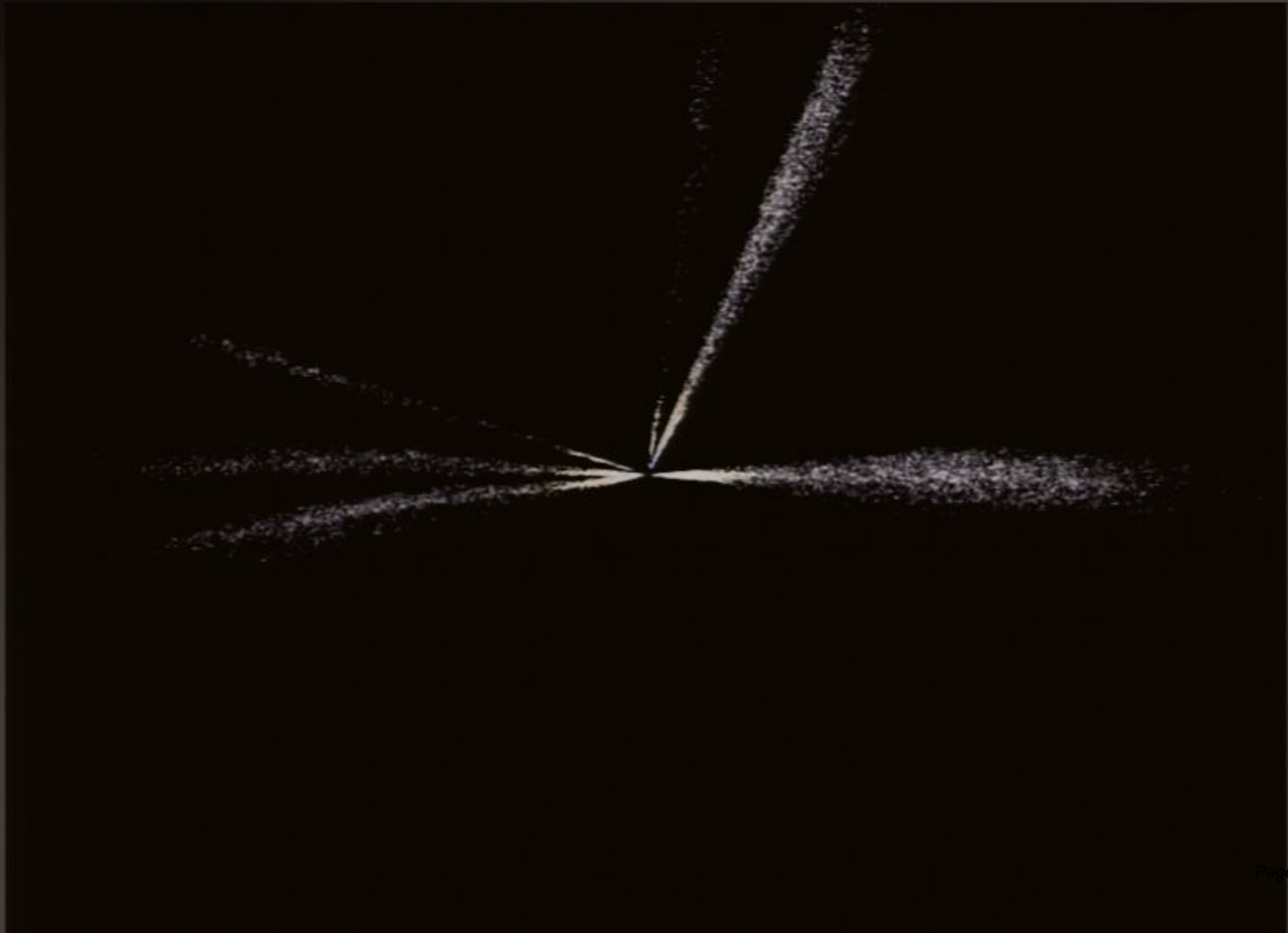
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



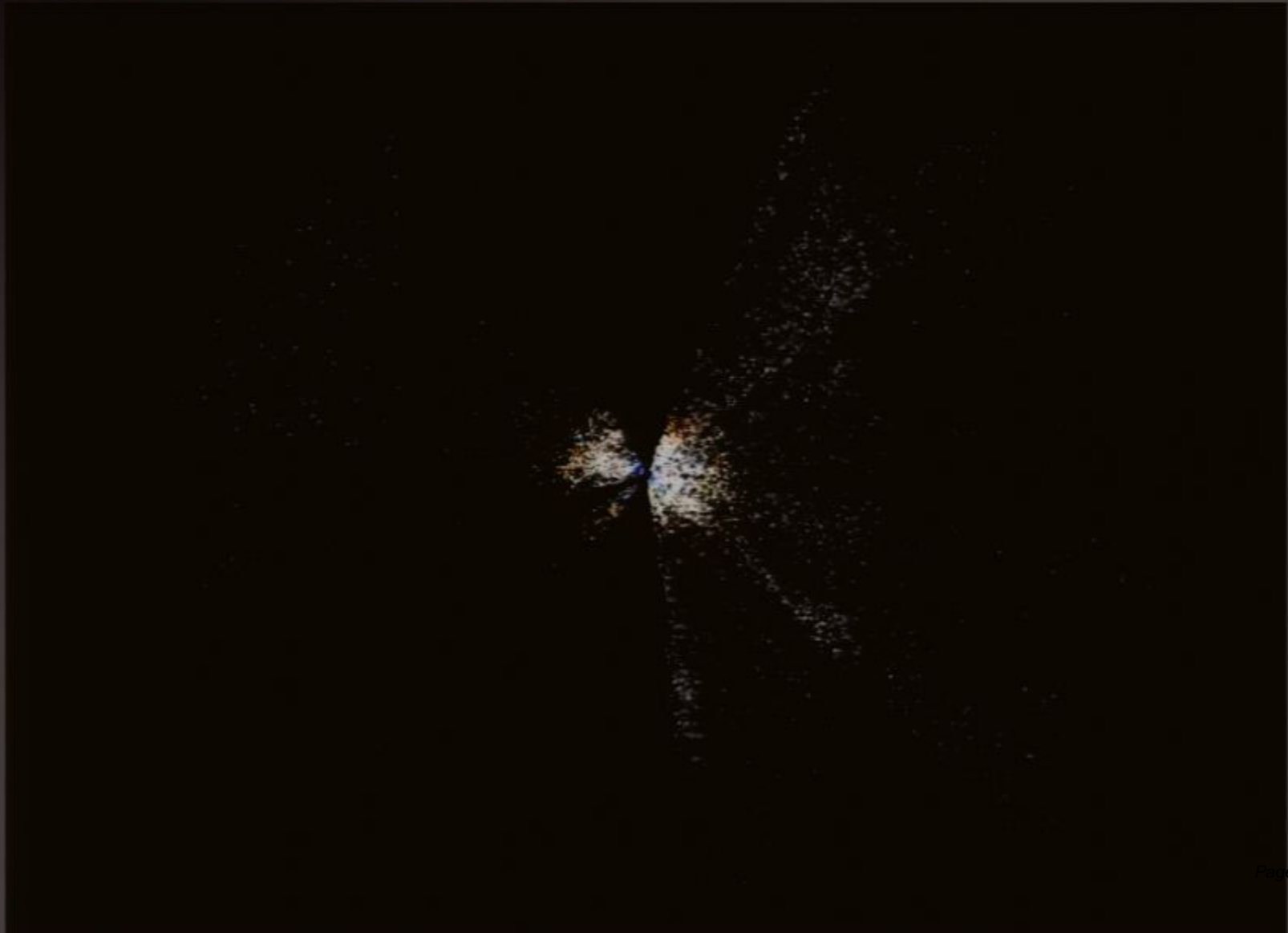
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



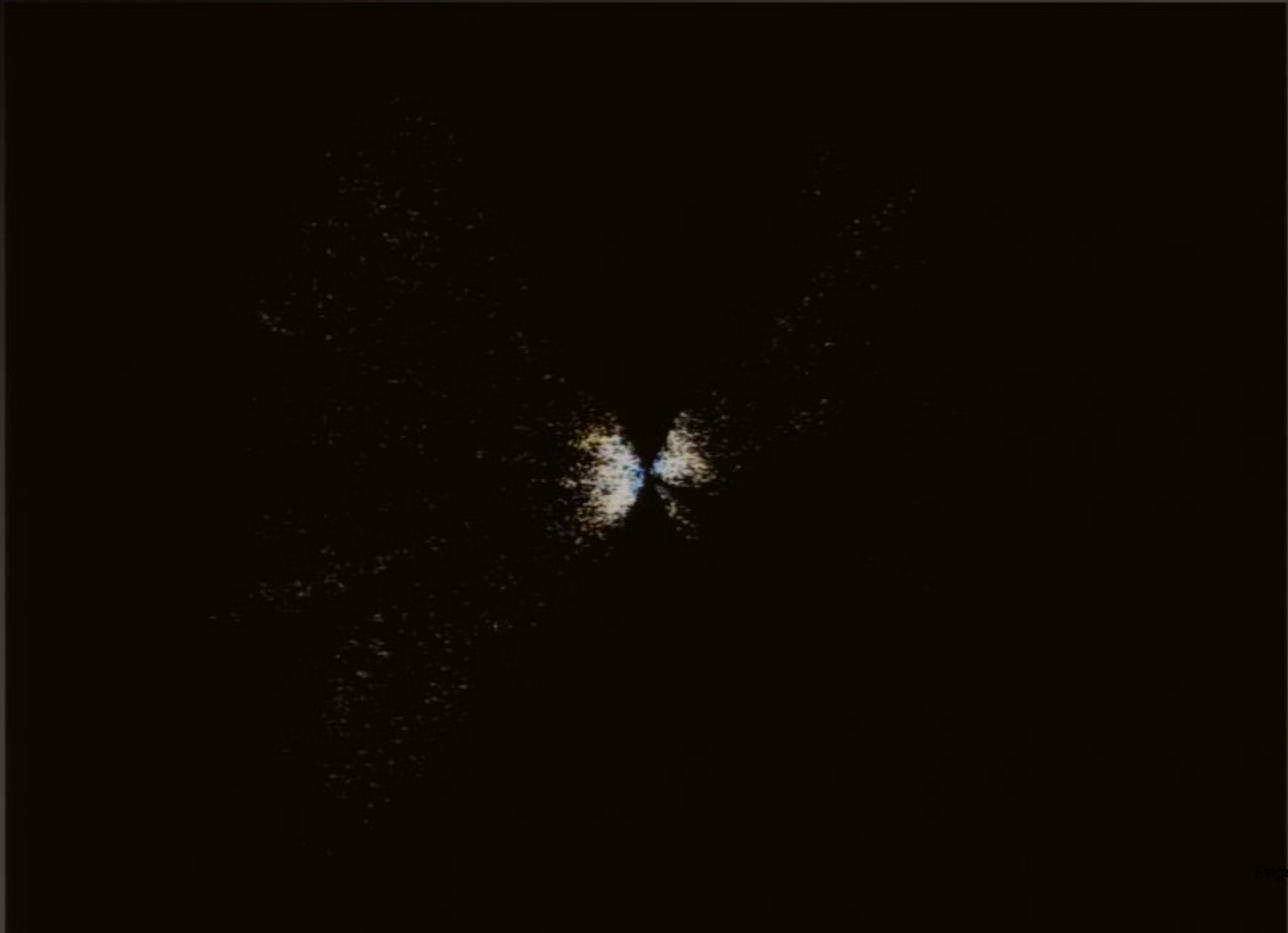
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



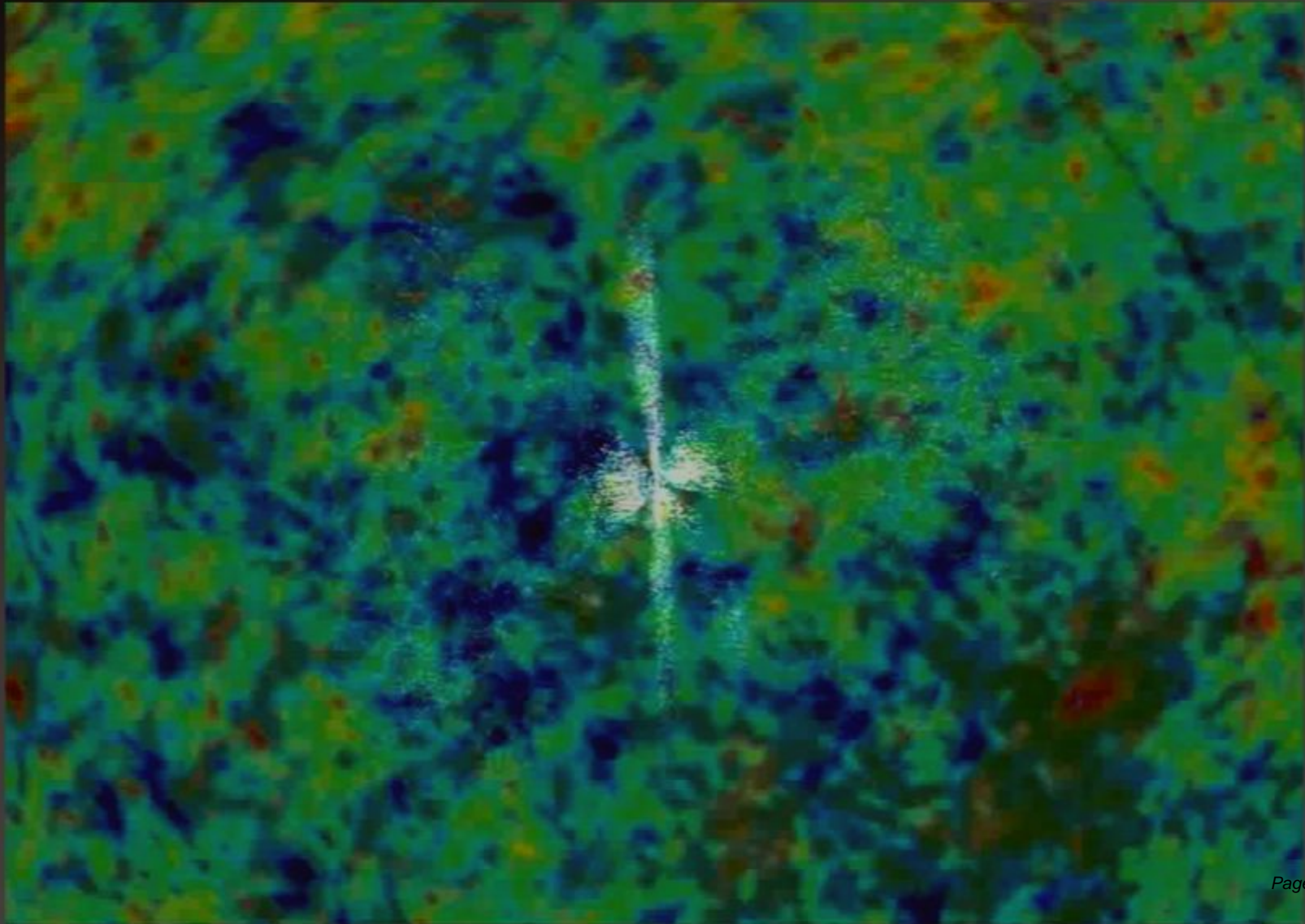
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



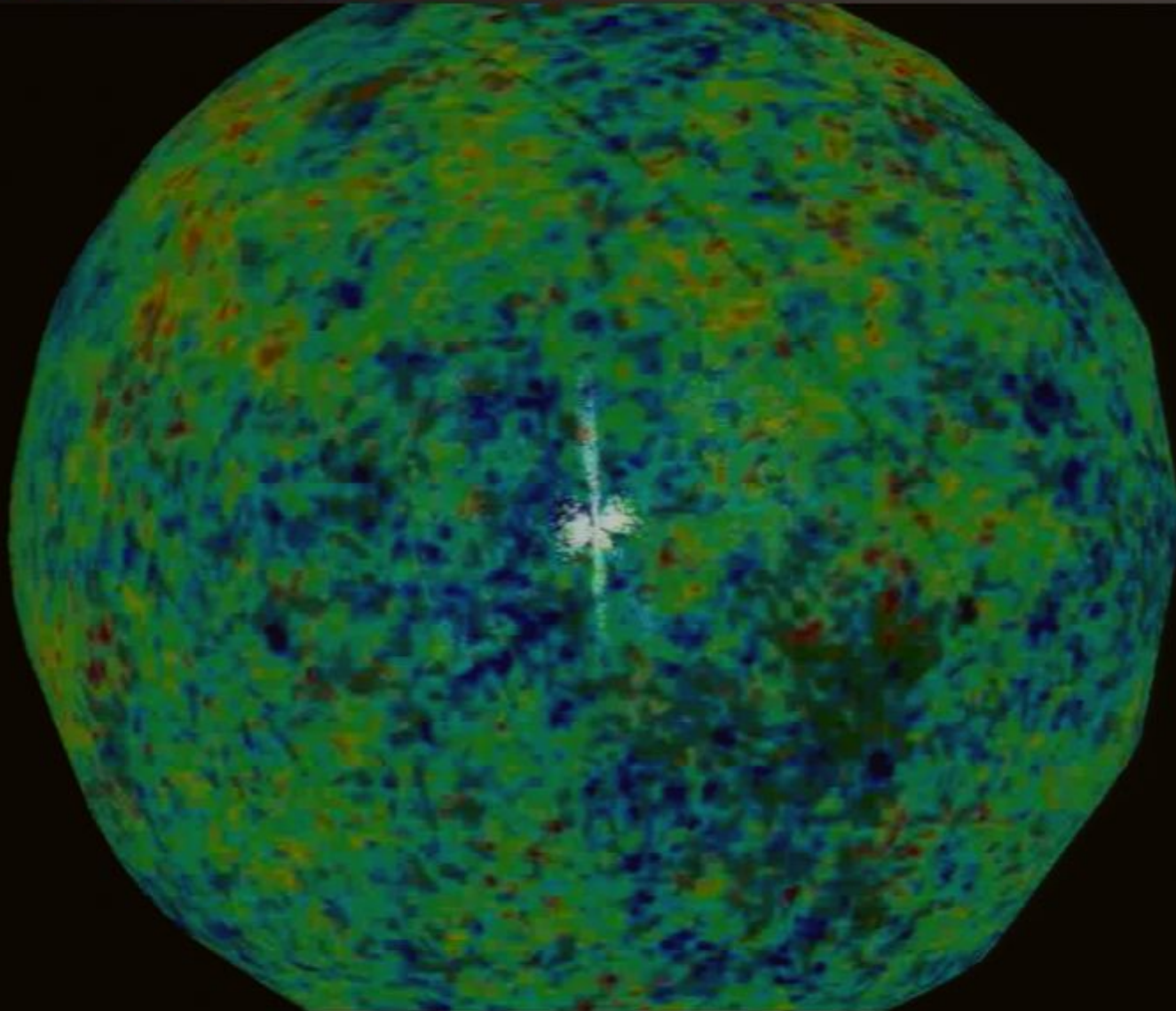
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



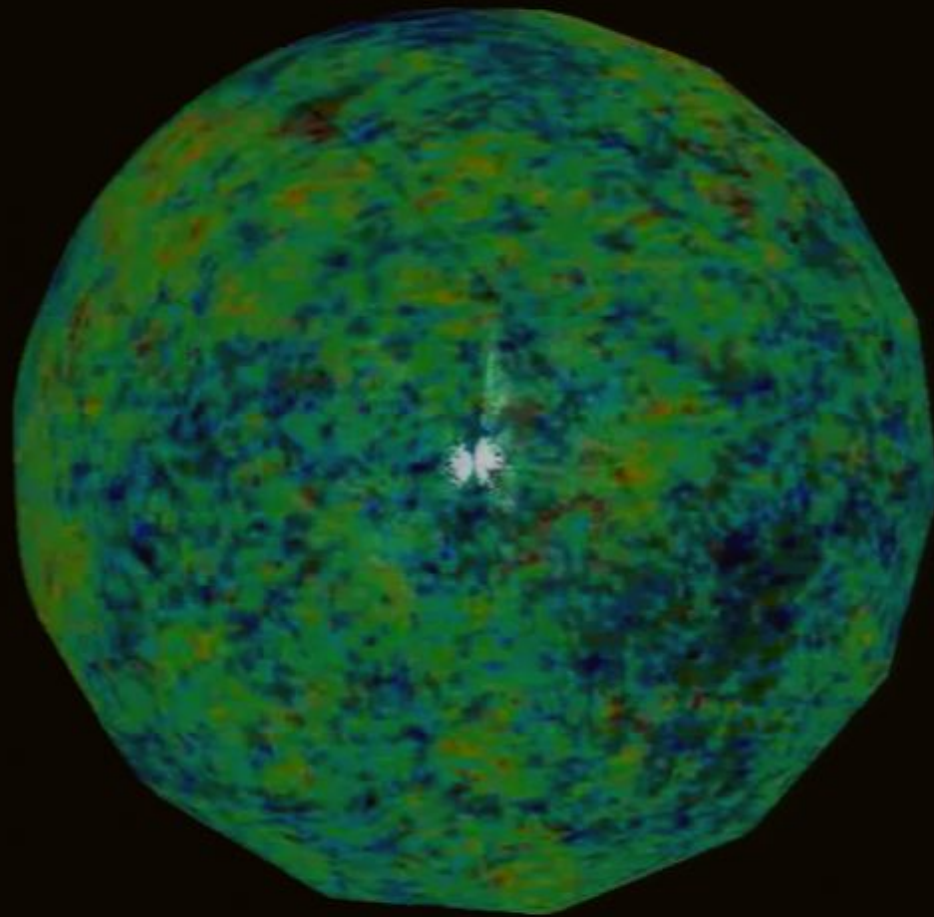
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



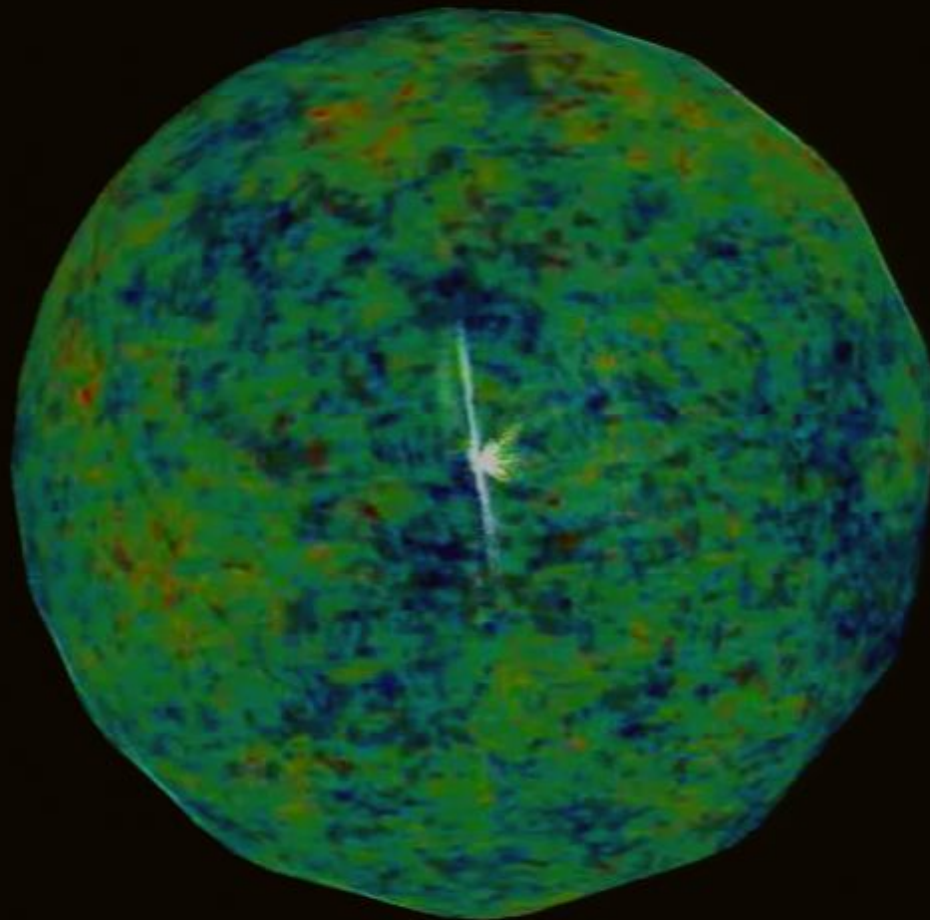
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



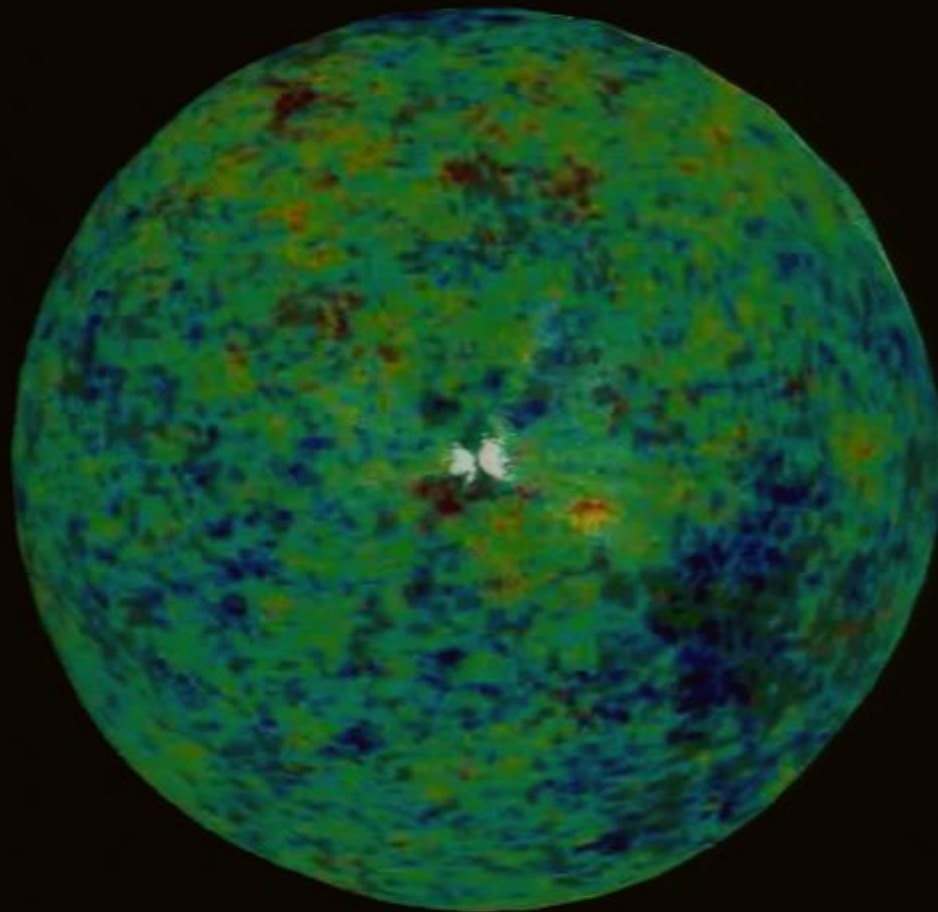
A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*

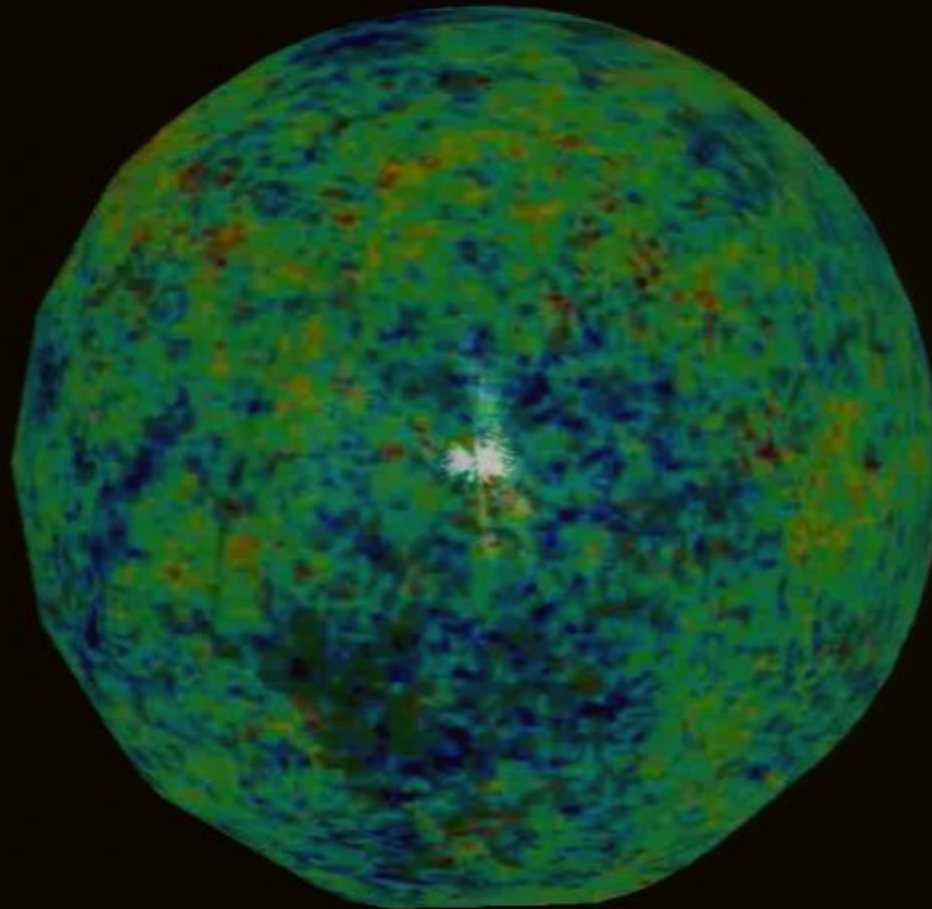


A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*

Galaxy and Quasar positions from the Sloan Digital Sky Survey (SDSS)

Cosmic Microwave Background from the Wilkinson Microwave Anisotropy Probe (WMAP)

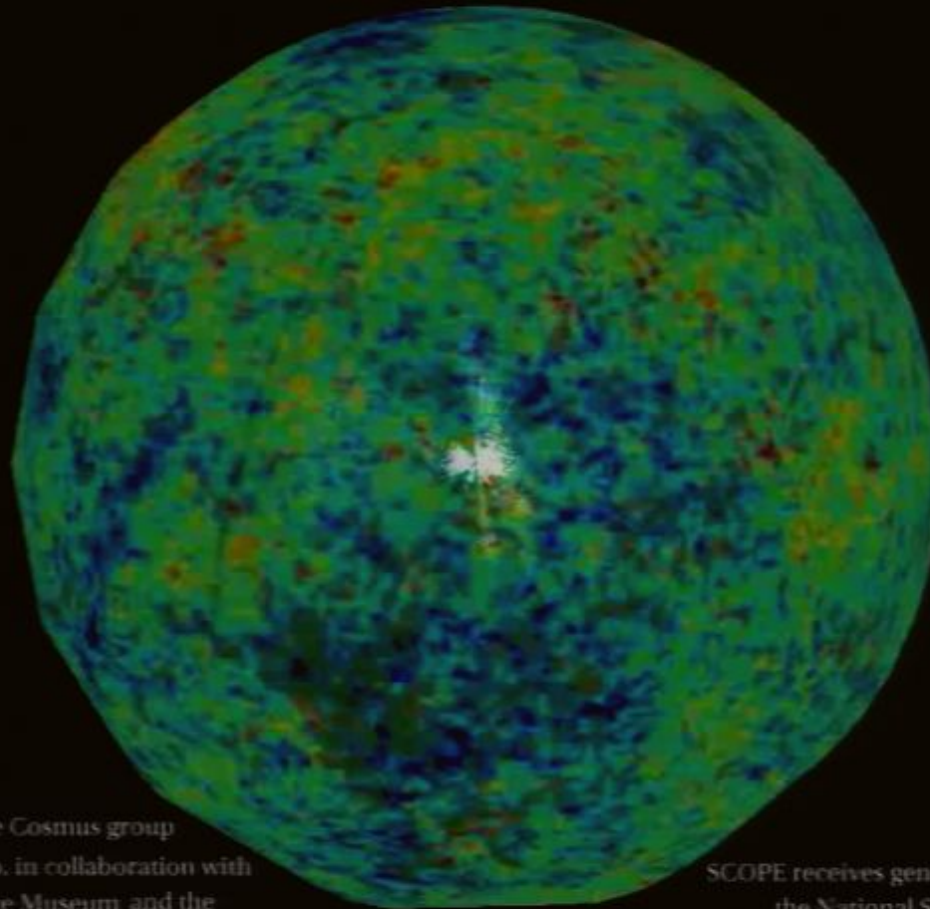


A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*

Galaxy and Quasar positions from the Sloan Digital Sky Survey (SDSS)

Cosmic Microwave Background from the Wilkinson Microwave Anisotropy Probe (WMAP)



Animation produced by the Cosmos group
at the University of Chicago, in collaboration with
SciTech Hands-on Science Museum and the
Adler Planetarium and Science Museum.

SCOPE receives generous financial support from
the National Science Foundation,
the Center for Cosmological Physics,
the Materials Research Science and Engineering Center
and the University of Chicago.

Evidence for an Expanding Universe

- The sky is dark
- The Hubble Law
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae

Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae

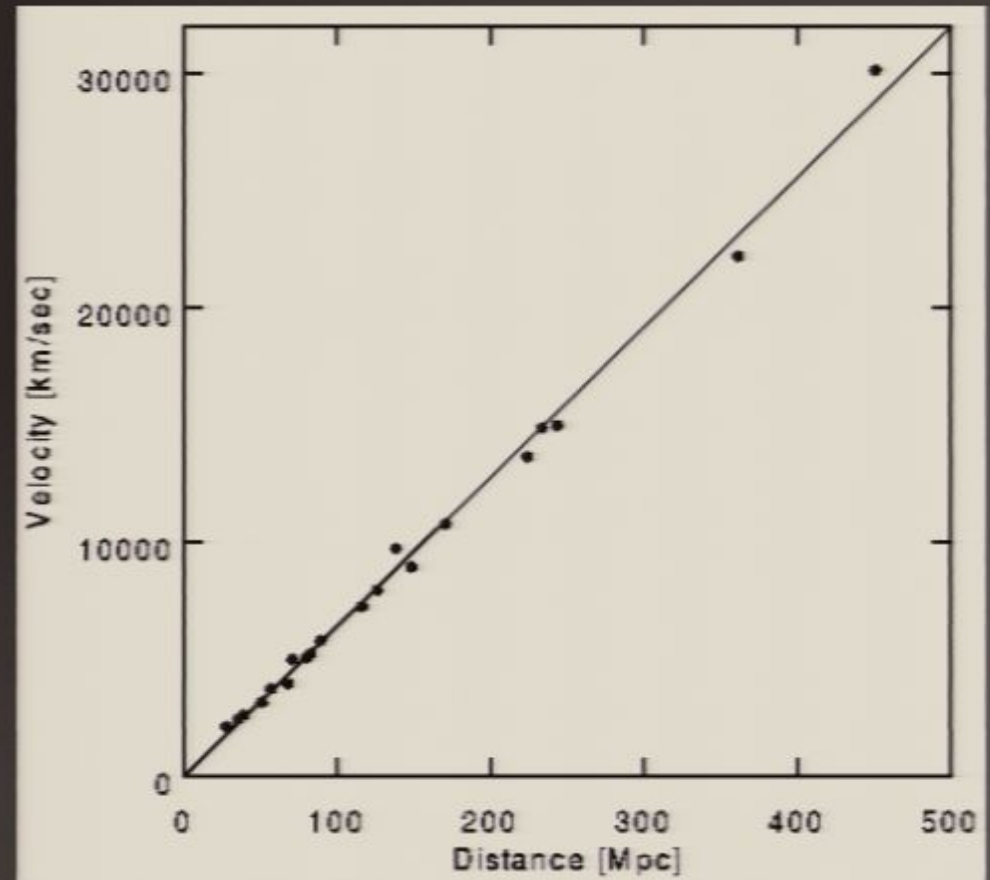
In all directions galaxies are seen to be receding from us with a speed which is proportional to their distance from us:

As expected if all started at the same point at the same instant.

$$v = H_0 d$$

Evidence for an Expanding Universe

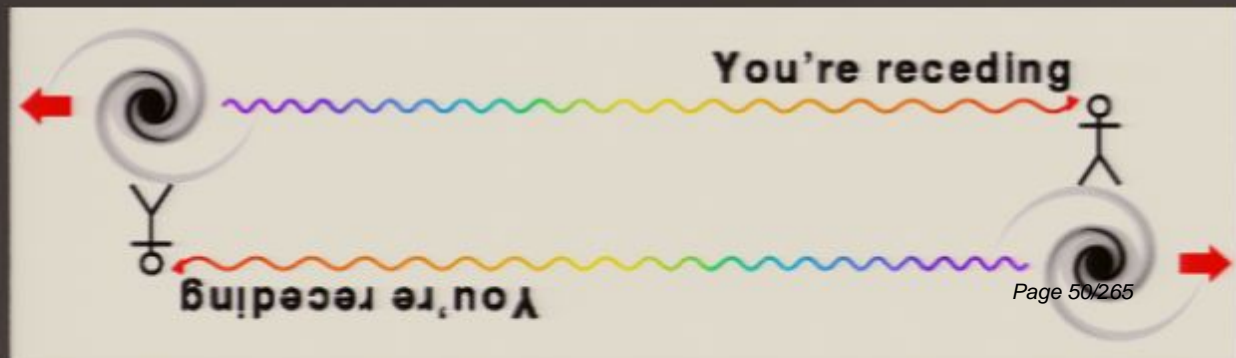
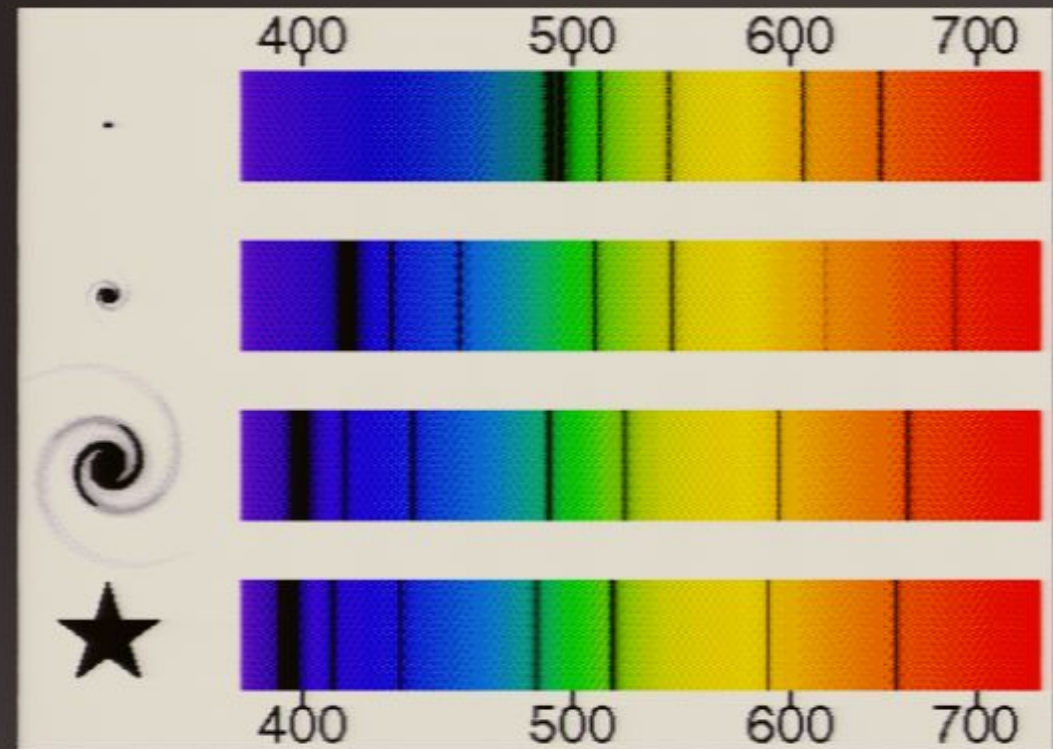
- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



$$v = H_0 d$$

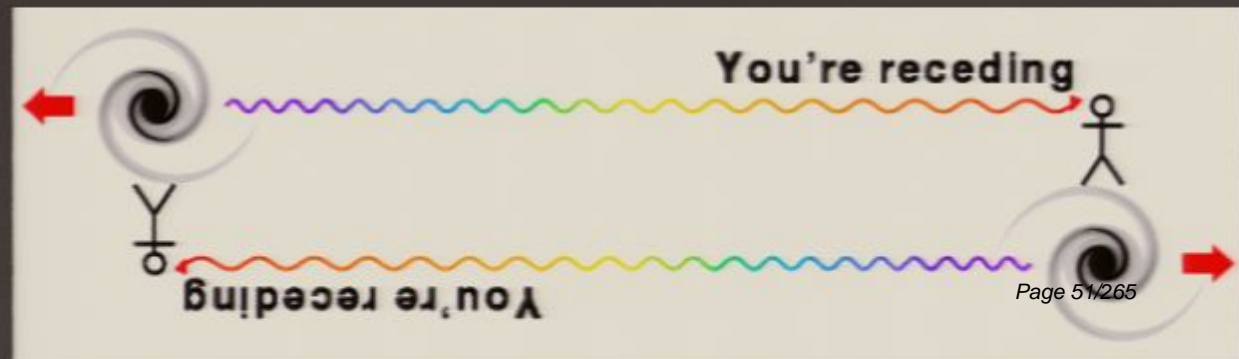
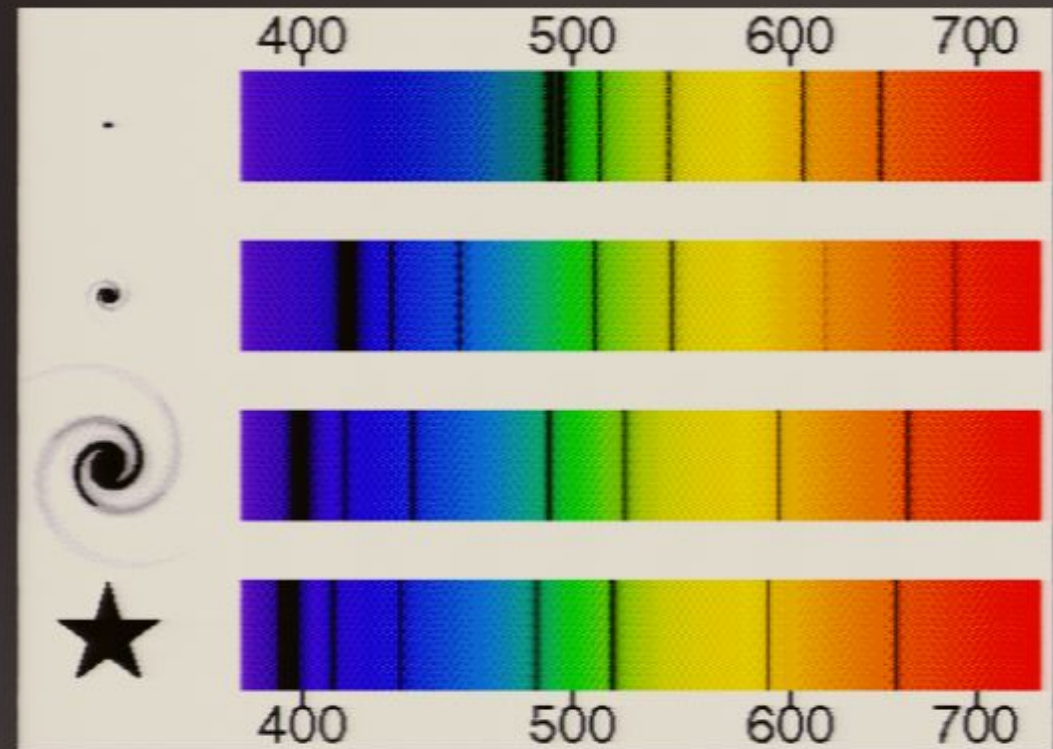
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



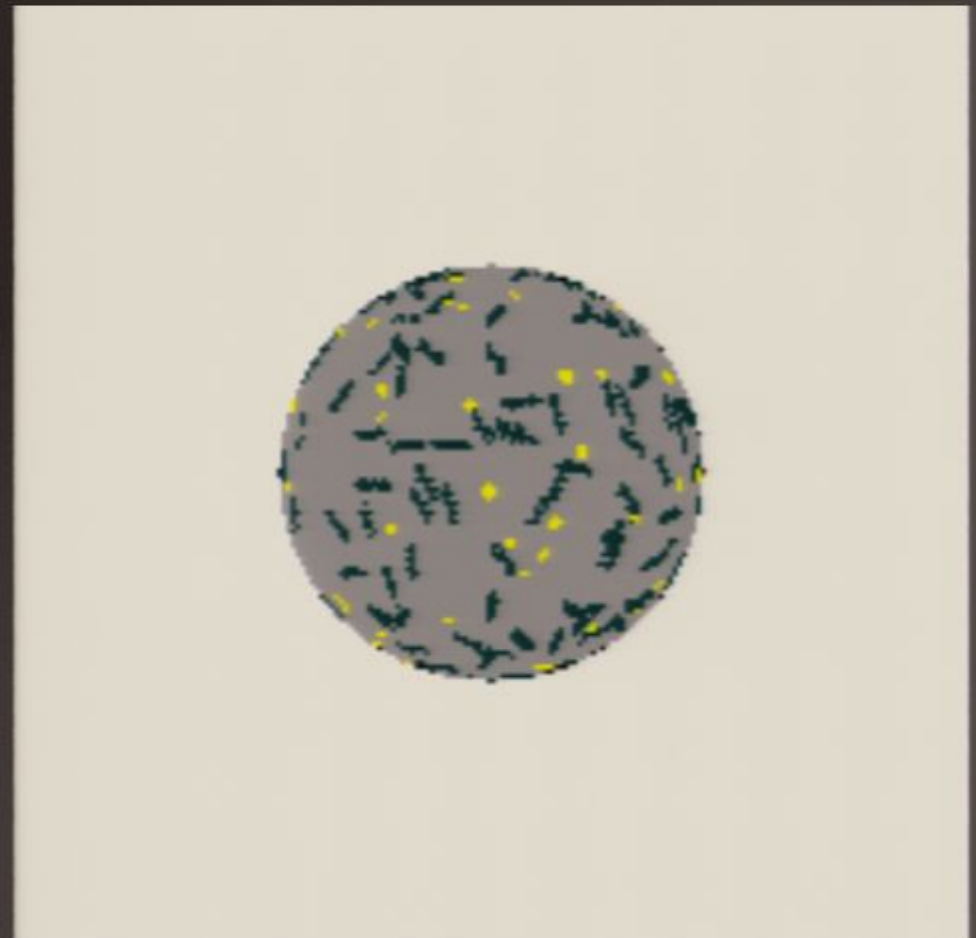
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



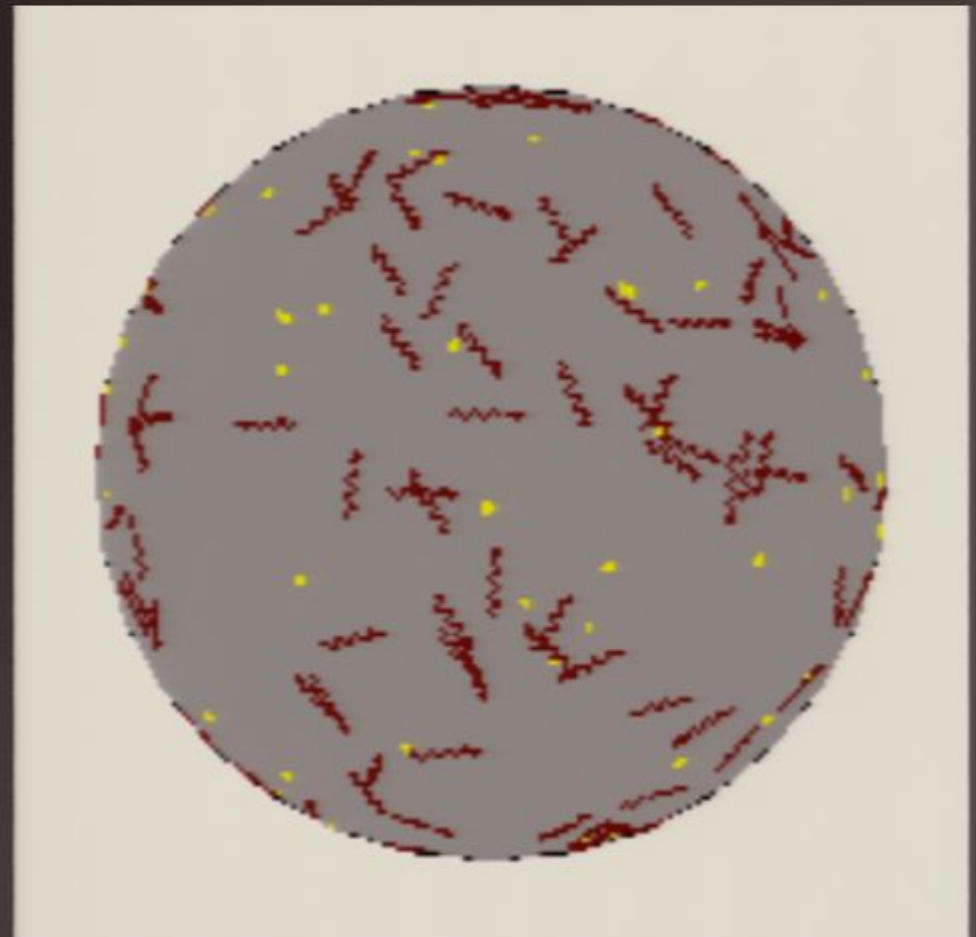
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



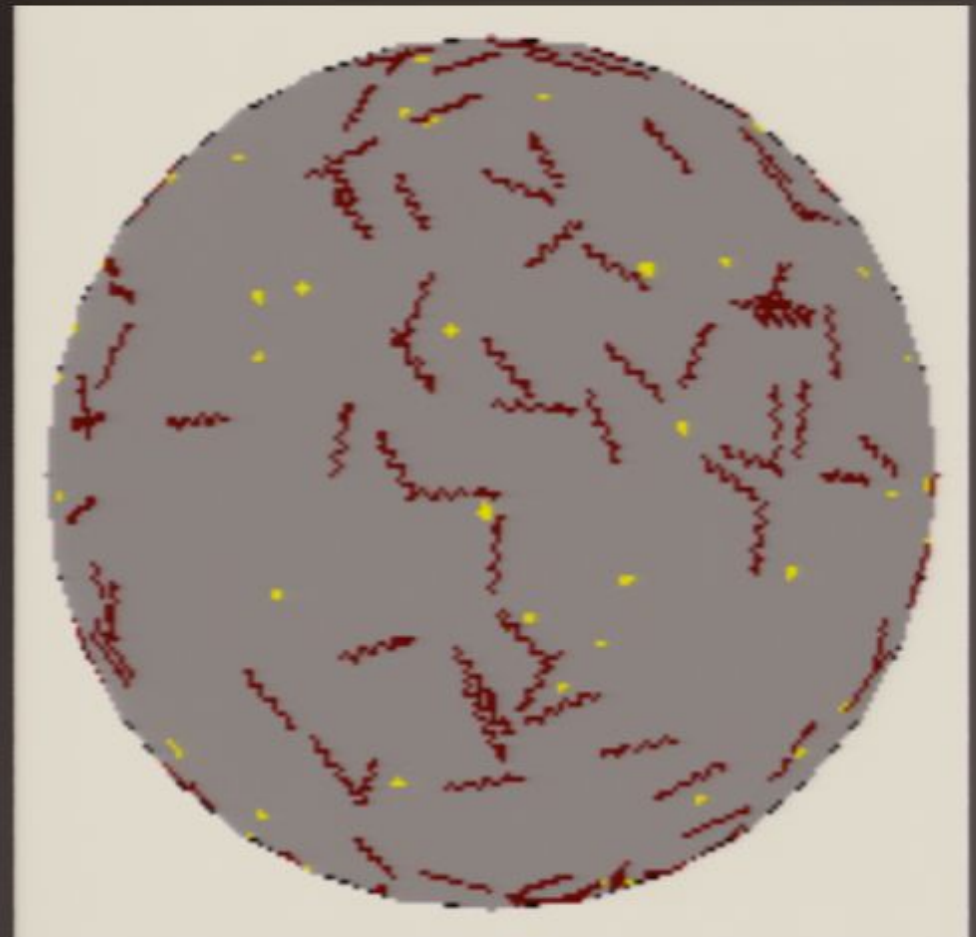
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



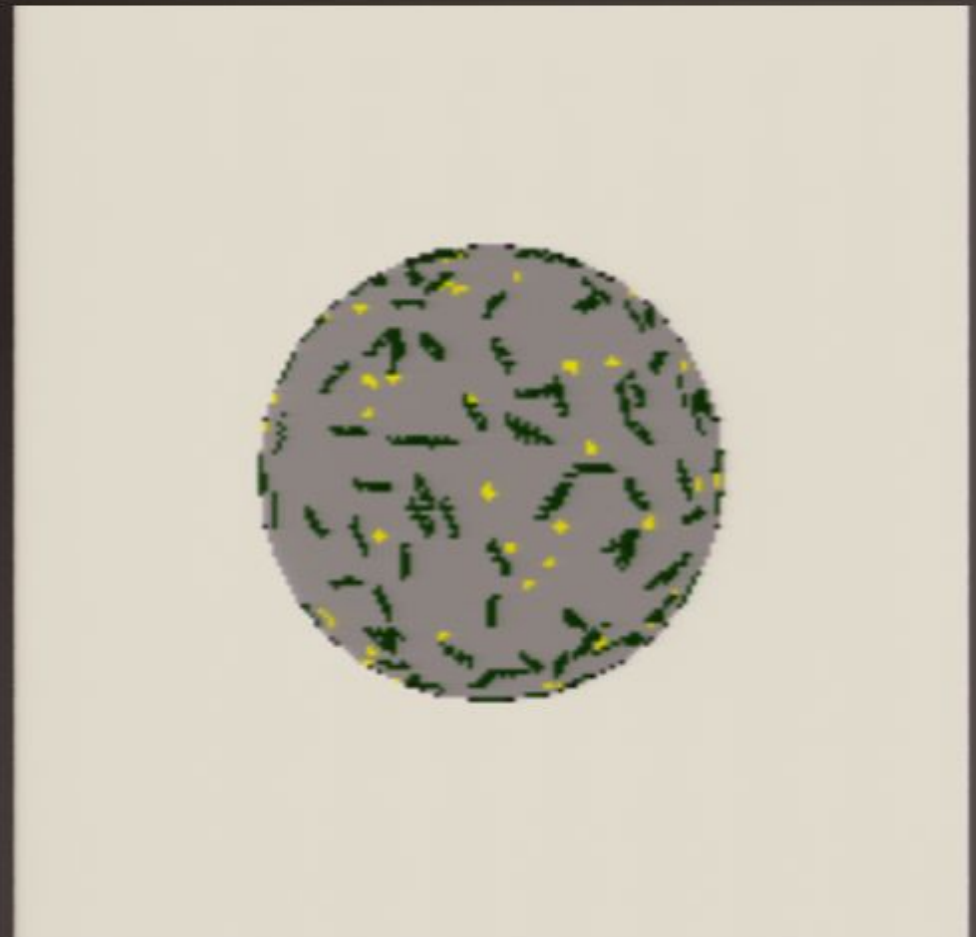
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



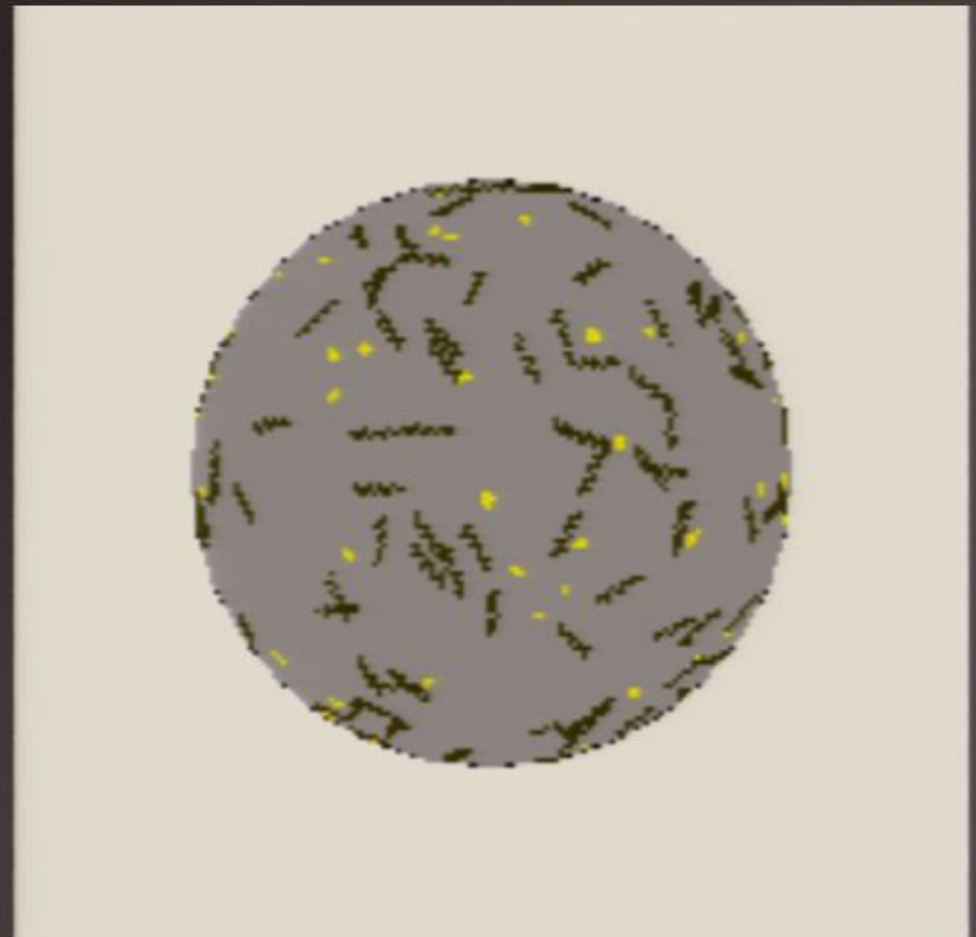
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



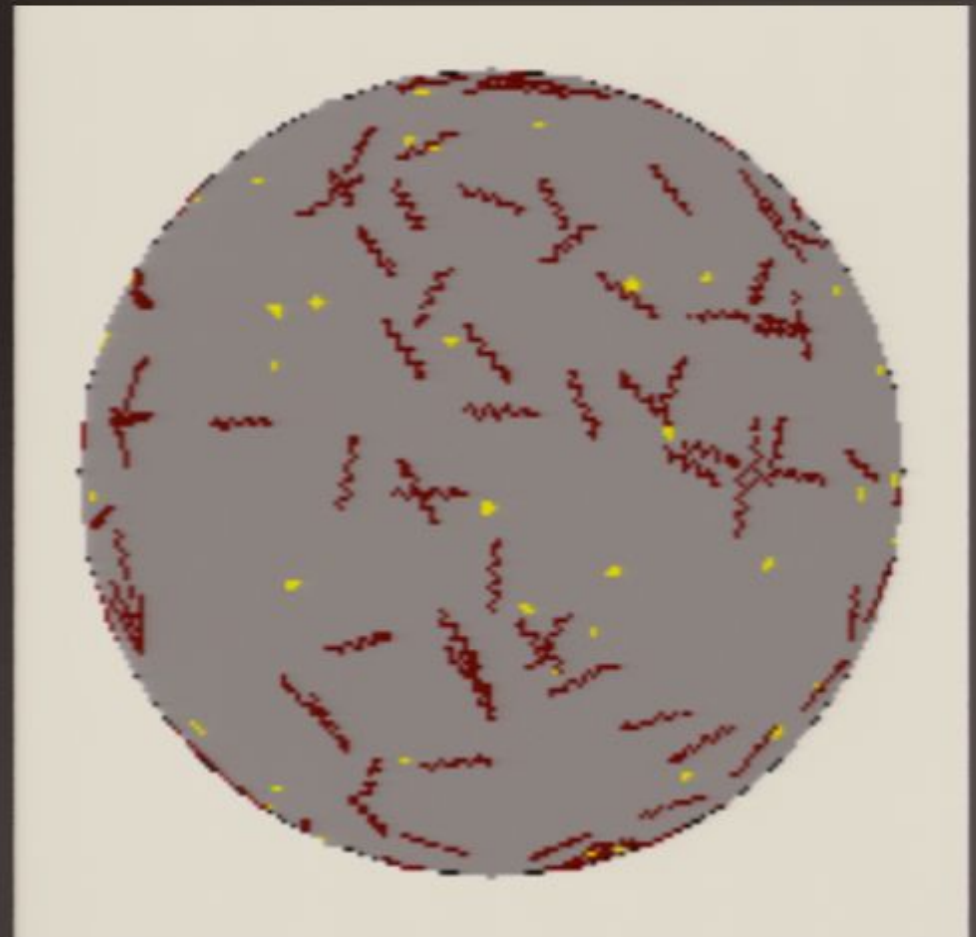
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



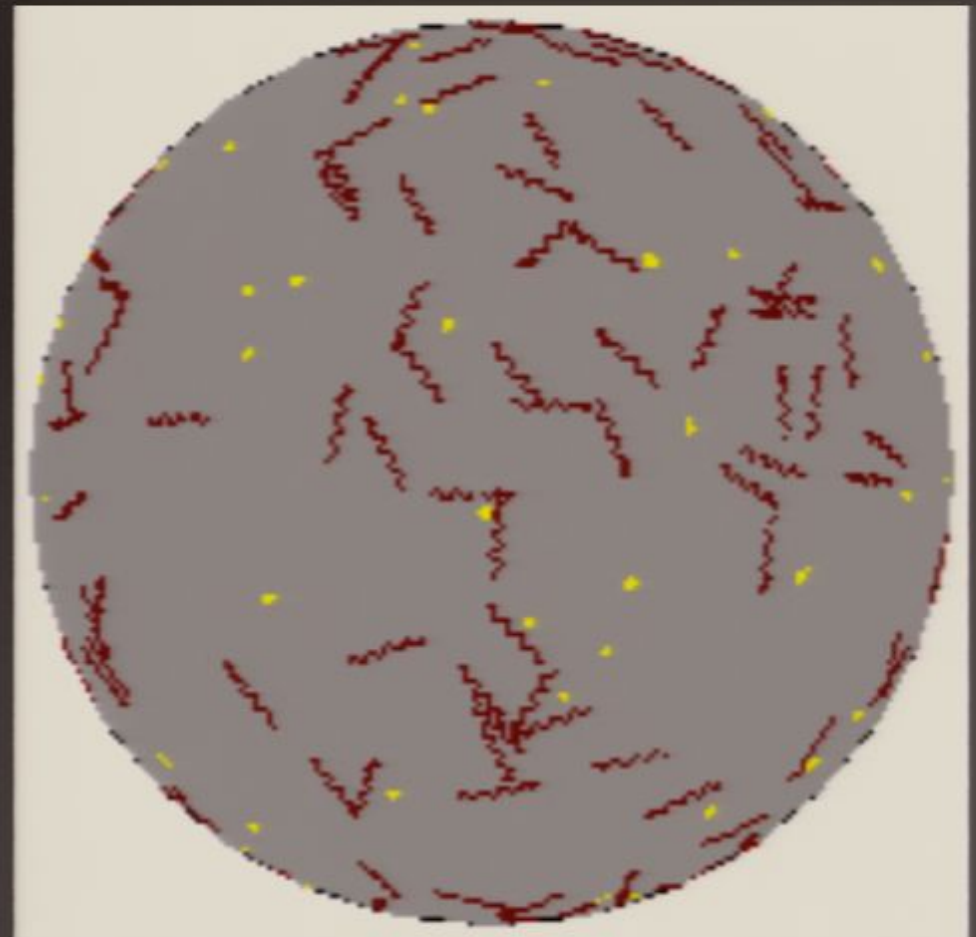
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



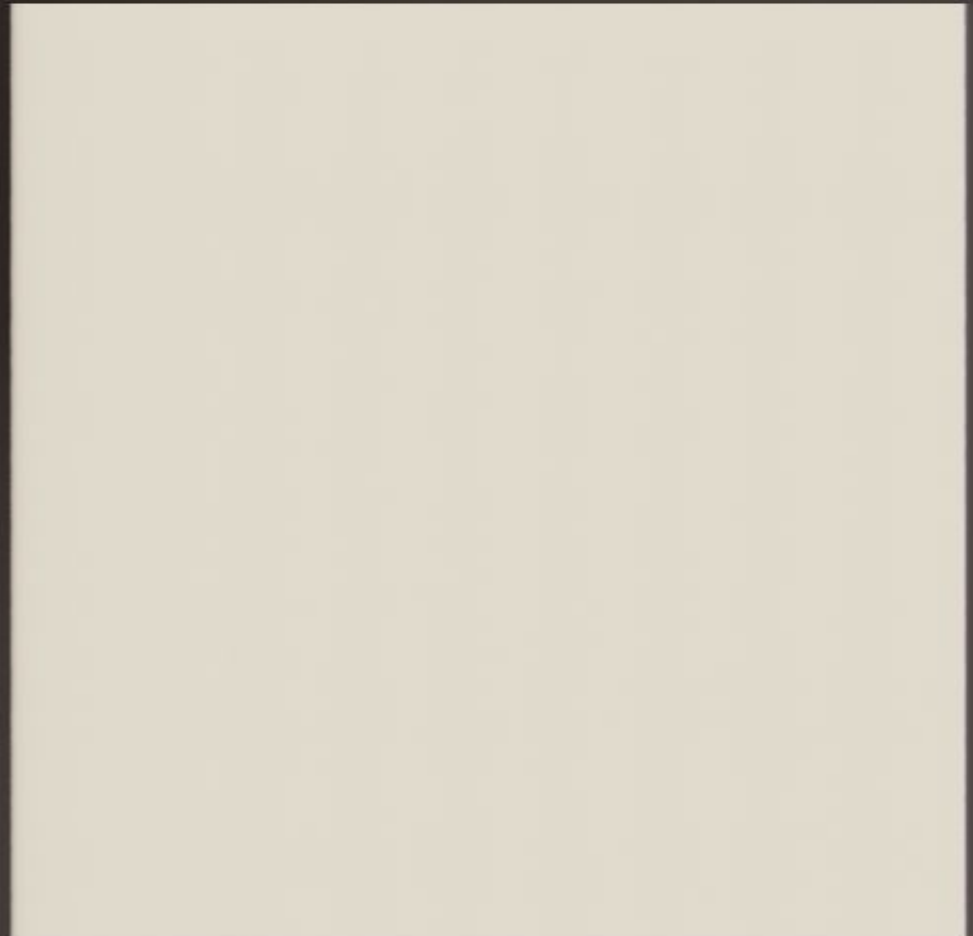
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



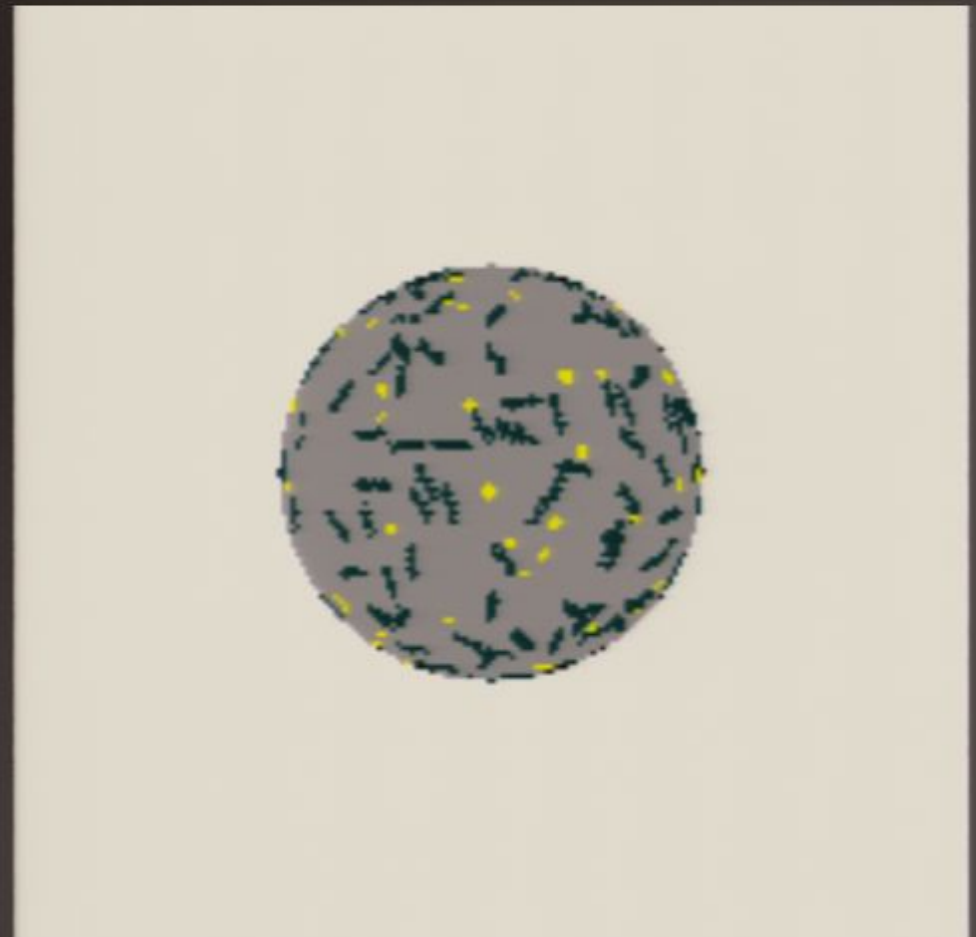
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



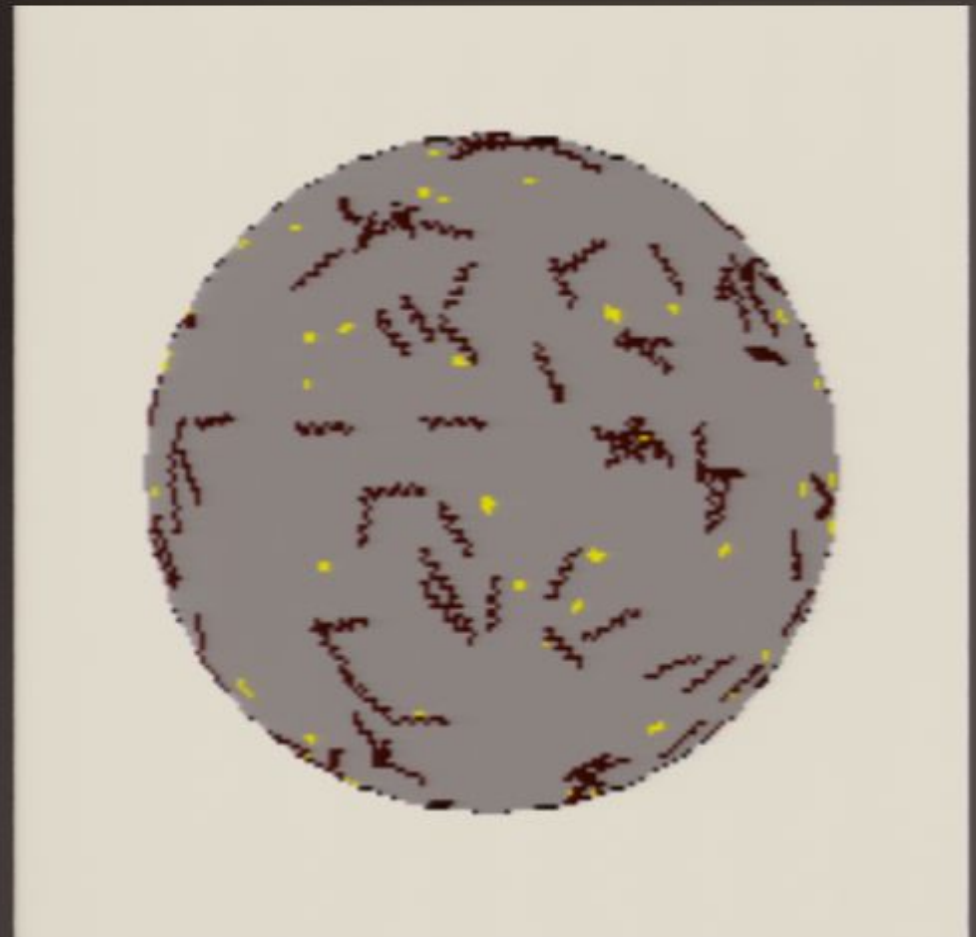
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



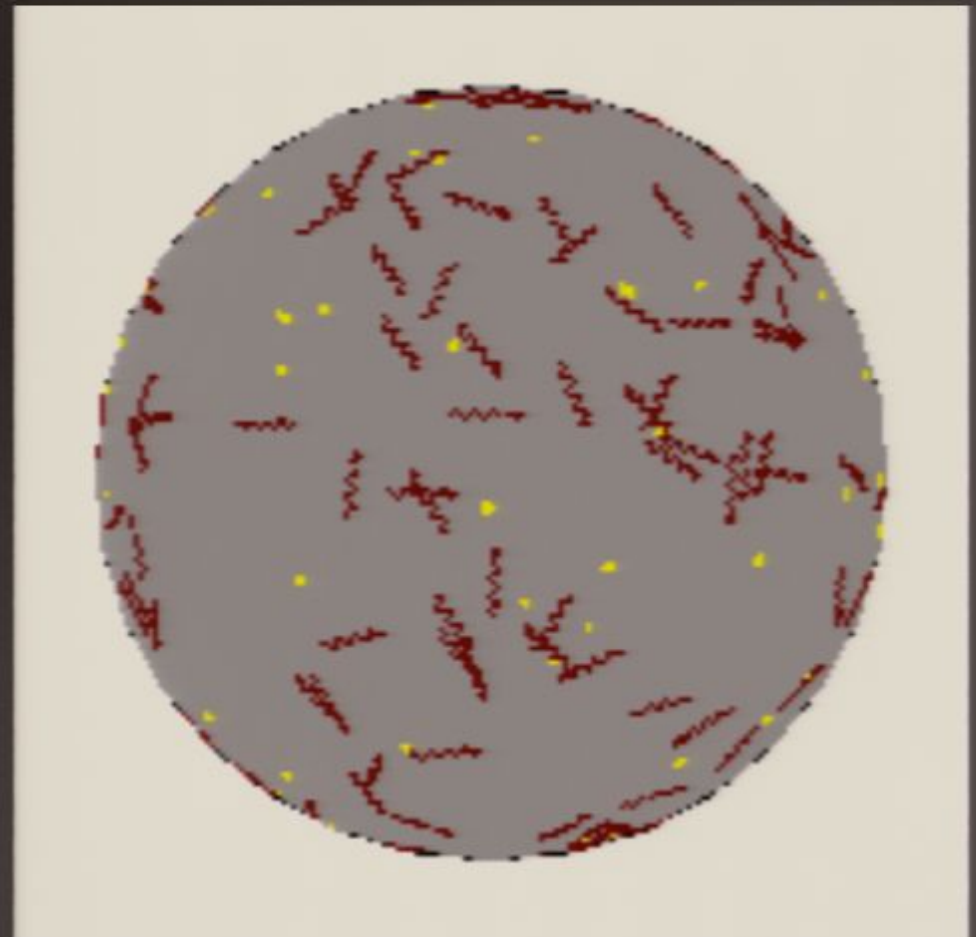
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



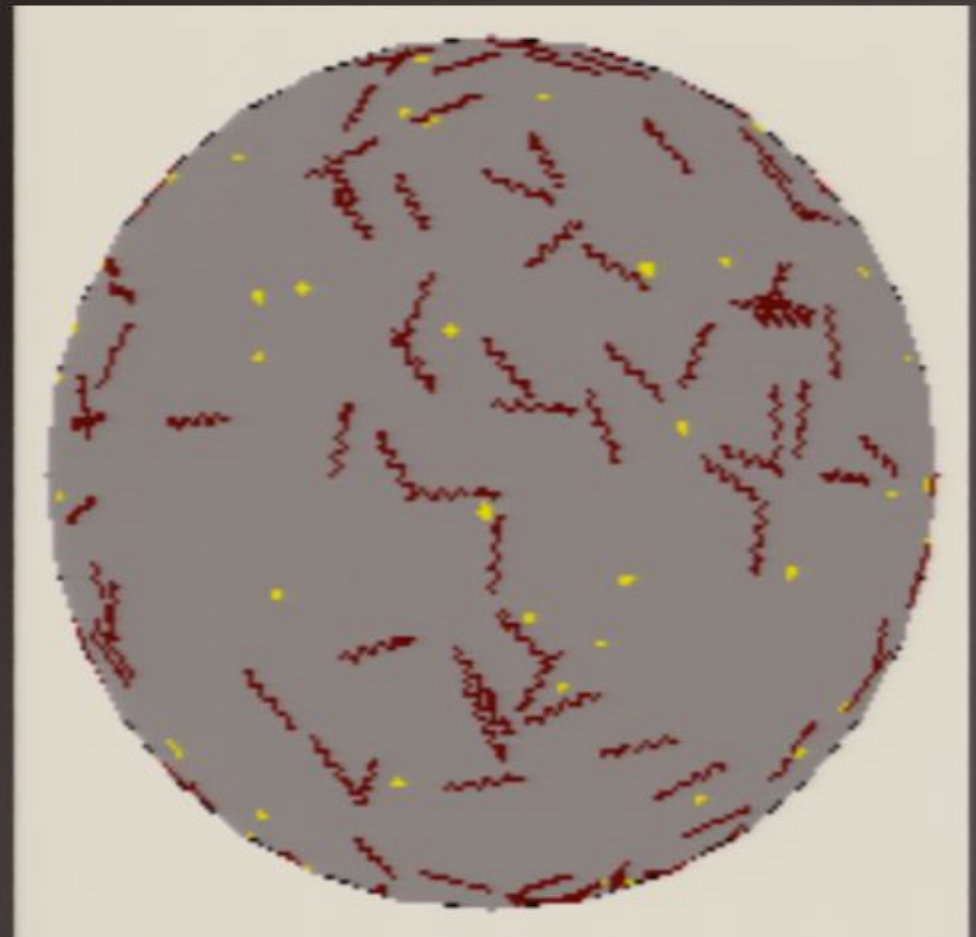
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



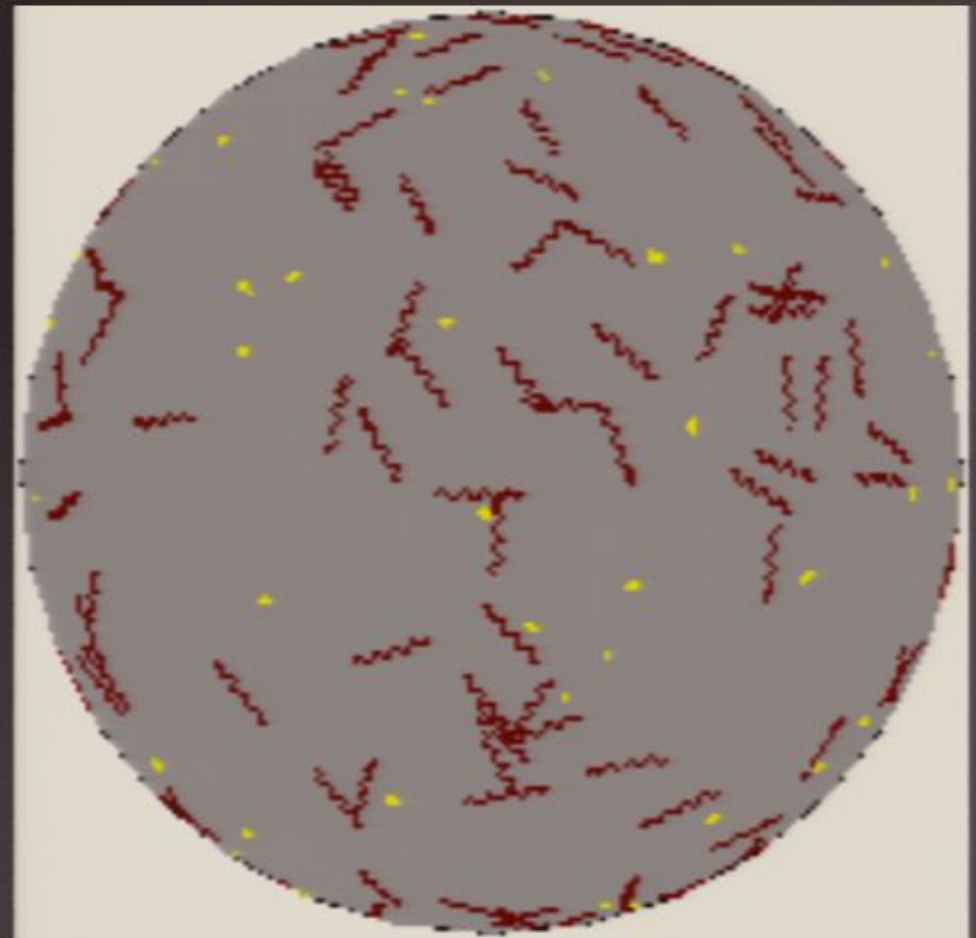
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



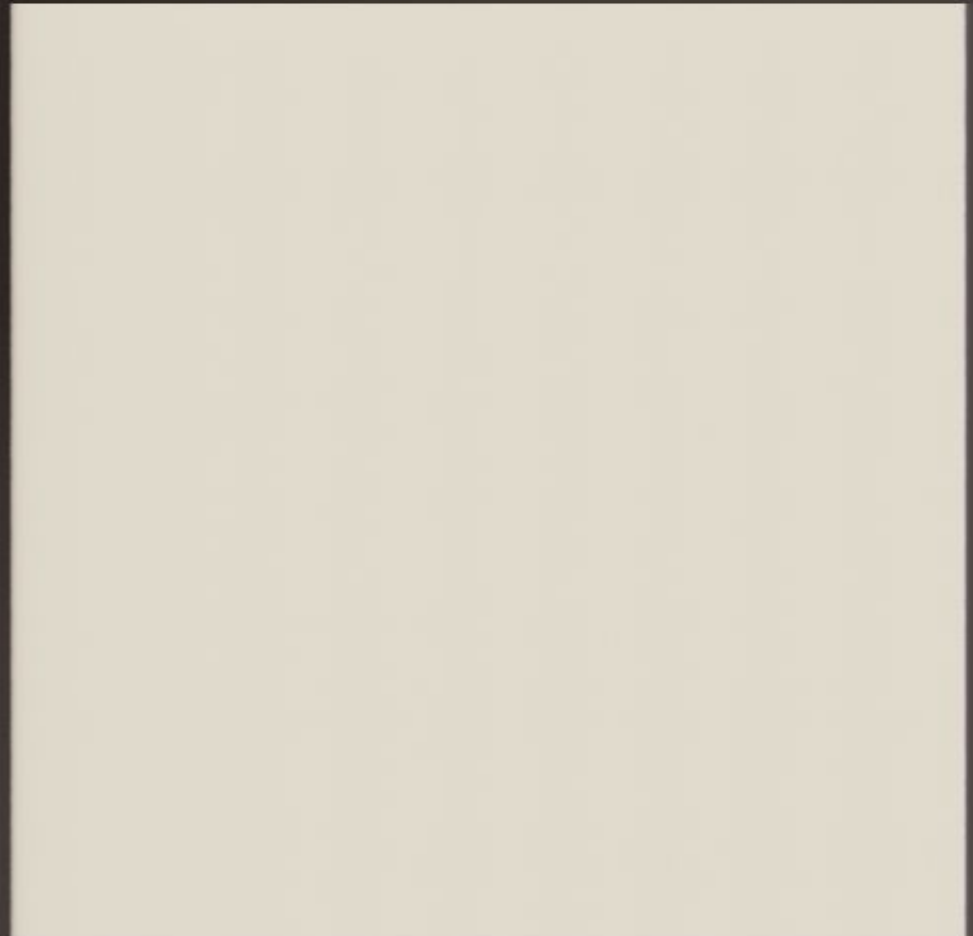
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



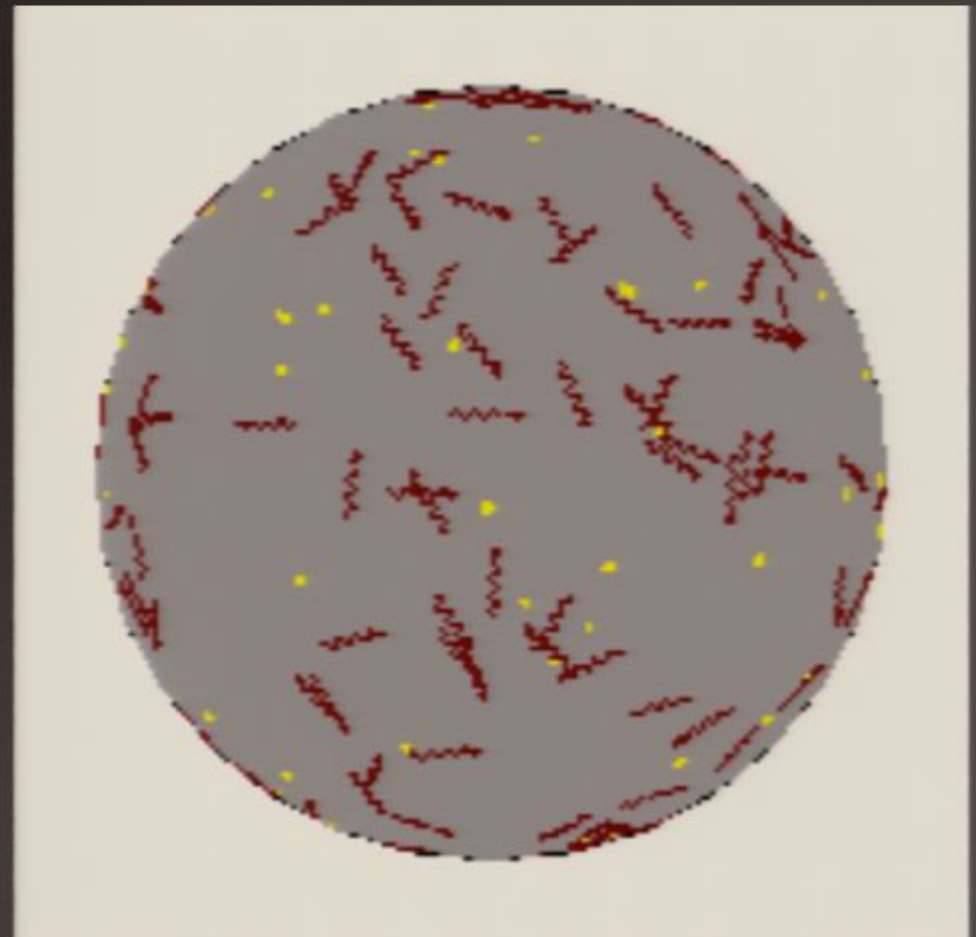
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



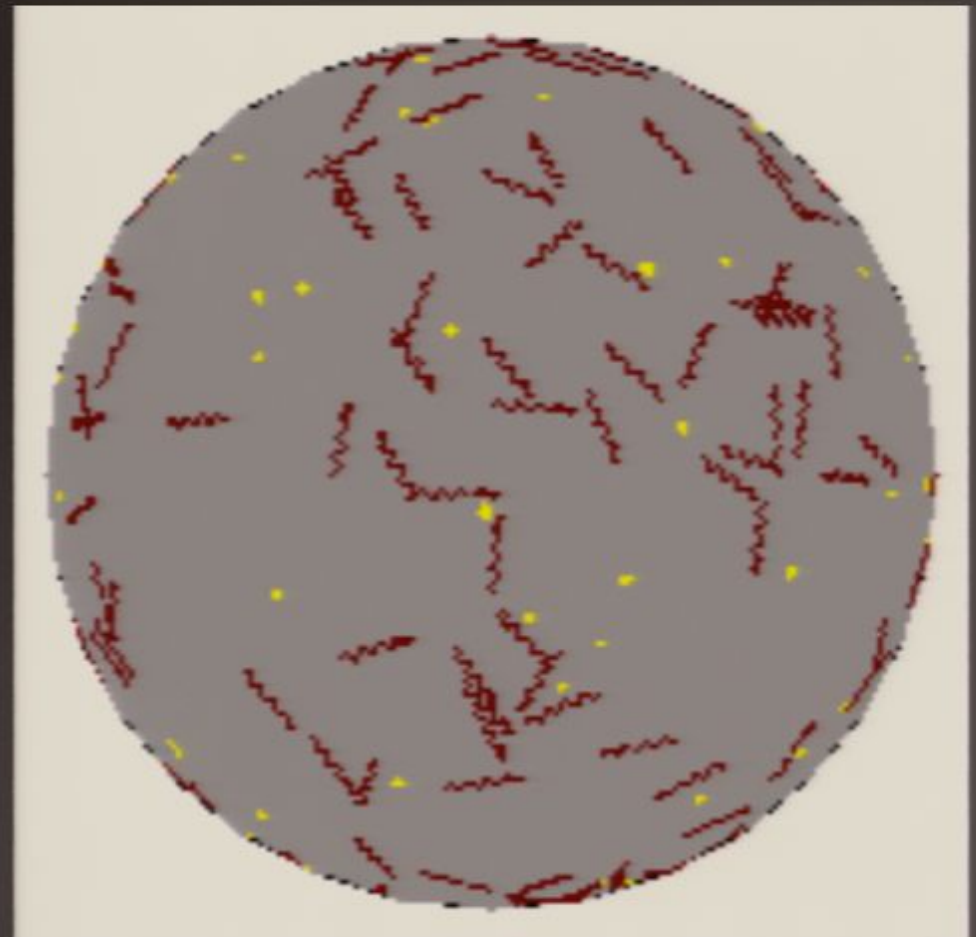
Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



Evidence for an Expanding Universe

- The sky is dark
- *The Hubble Law*
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae



The Hot Big Bang

- Matter in an expanding container cools.
 - Extrapolating back in time suggests the Universe was once very small and very hot.
- The Hot Big Bang theory assumes the Universe was initially a small, hot soup of elementary particles.
- *This theory is just now being redundantly tested.*
 - *Surprise! Most of the matter in the Universe is in two completely unknown forms!*

How Would We Know?

- The Universe being hot *means* that the particles within it are randomly moving with higher speeds.
- At high enough temperatures particles get knocked apart into their constituents.



How Would We Know?

- The Universe being hot *means* that the particles within it are randomly moving at higher speeds.
- At high enough temperatures particles get knocked apart into their constituents.



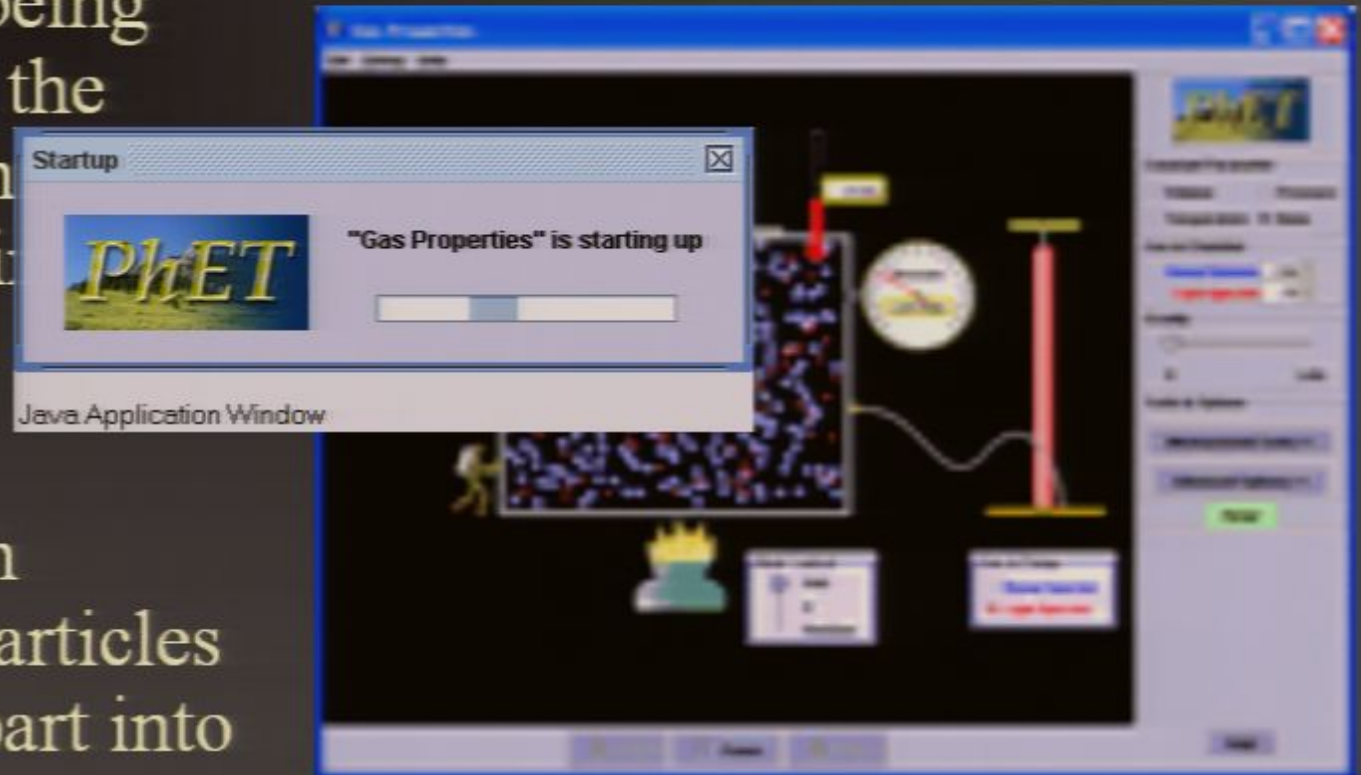
How Would We Know?

- The Universe being hot *means* that the particles within it are randomly moving at higher speeds.
- At high enough temperatures particles get knocked apart into their constituents.



How Would We Know?

- The Universe being hot *means* that the particles within it are moving at higher speeds.
- At high enough temperatures particles get knocked apart into their constituents.





Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

- Heavy Species: 0
- Light Species: 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Help!

Pump the handle!



Heat Control

Add

0

Remove

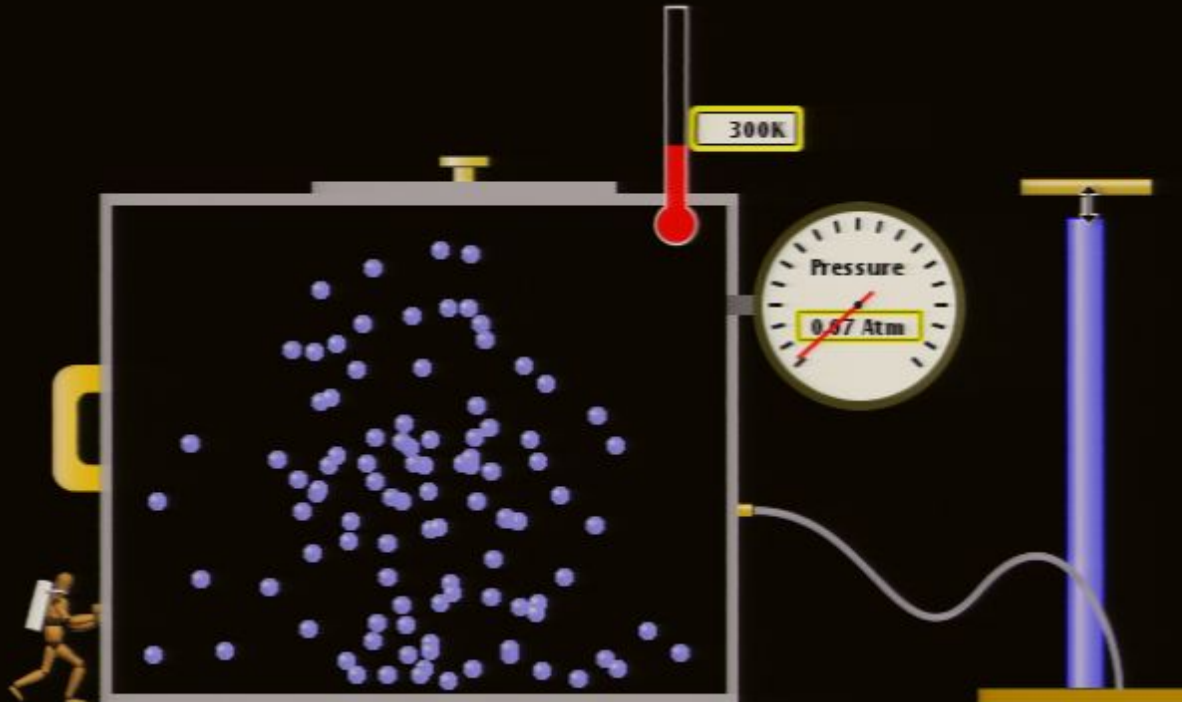
Gas in Pump

- Heavy Species
- Light Species

Play

Pause

Stop



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species: 100

Light Species: 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

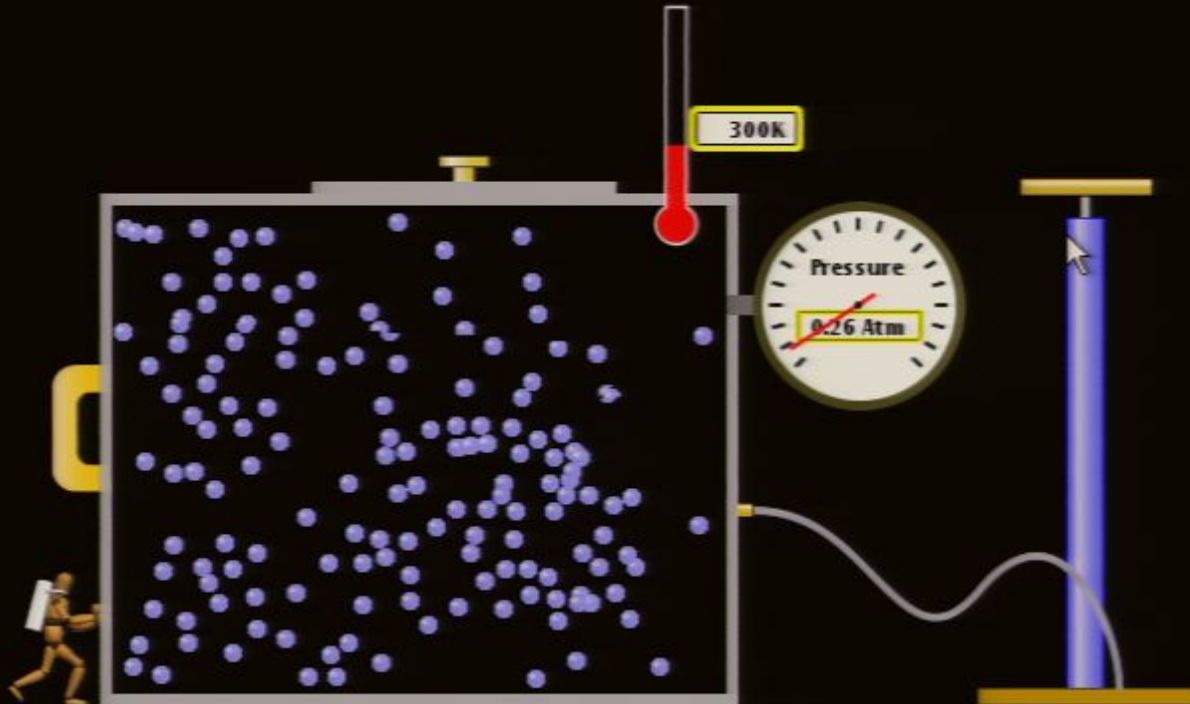
Gas in Pump

Heavy Species

Light Species

Play Pause Stop

Help!



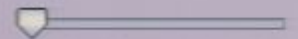
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 152
Light Species 0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

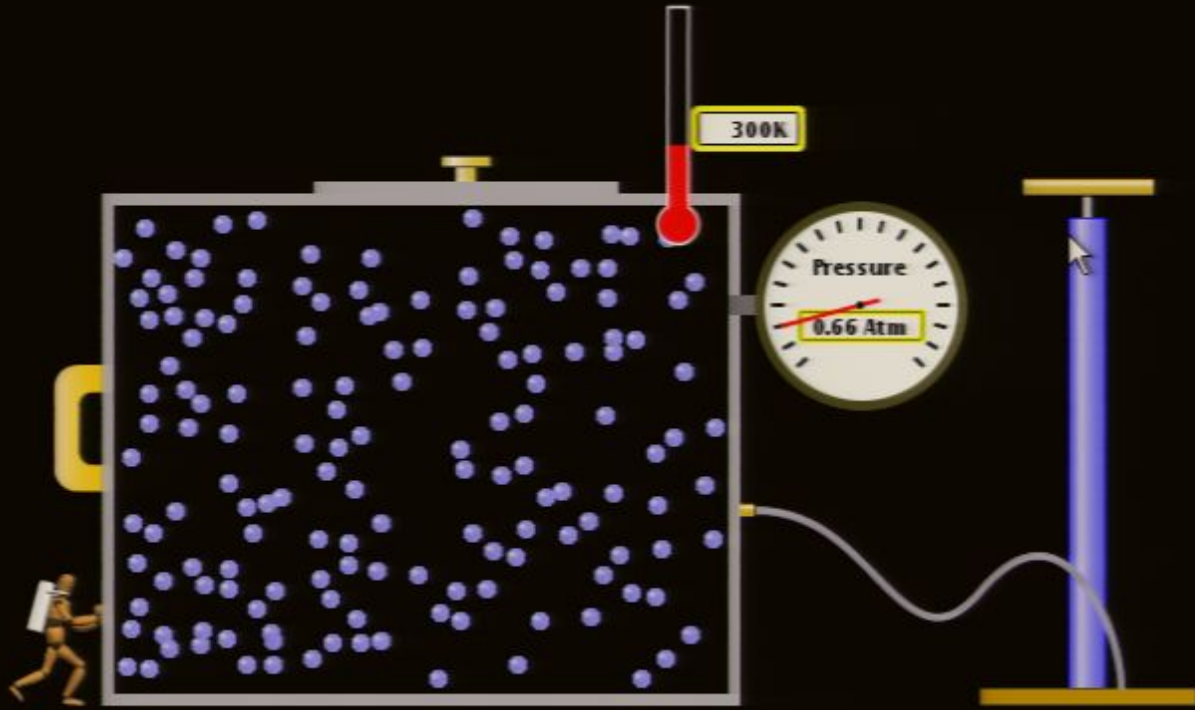
Add
0
Remove

Gas in Pump

- Heavy Species
- Light Species

Play Pause Stop

Help!



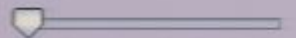
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

Gas in Pump

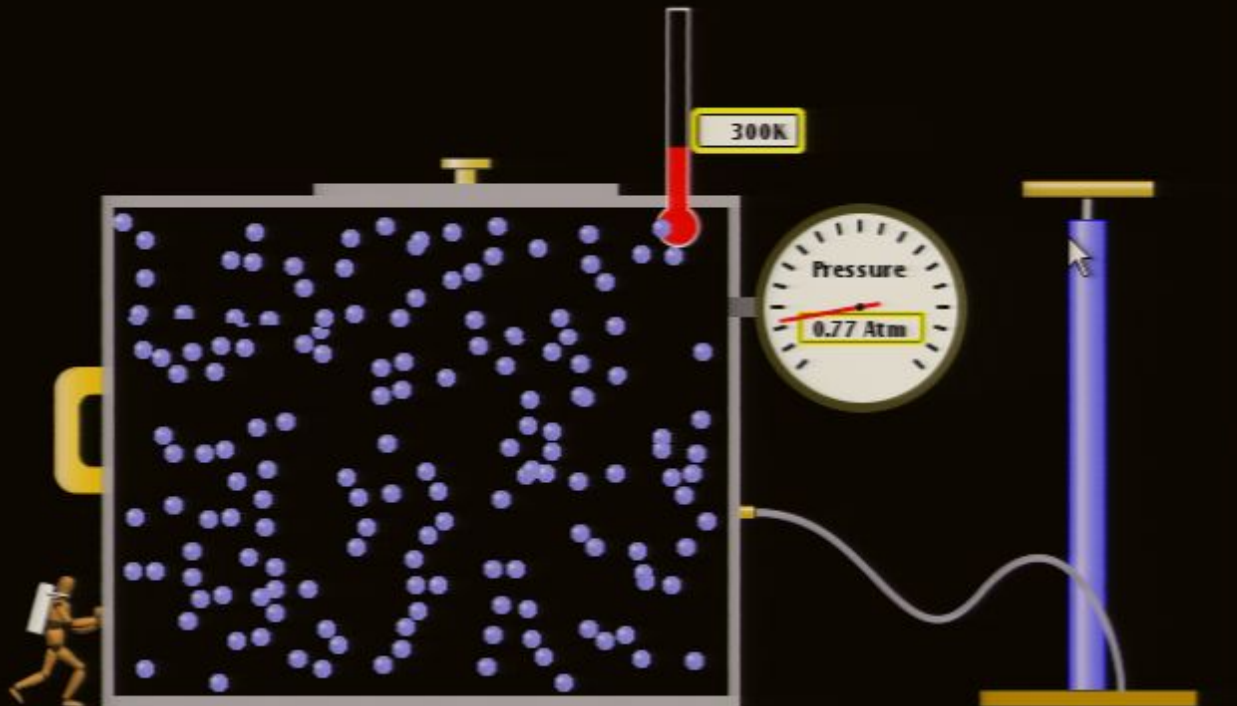
- Heavy Species
- Light Species

Play

Pause

Step

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 152
Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

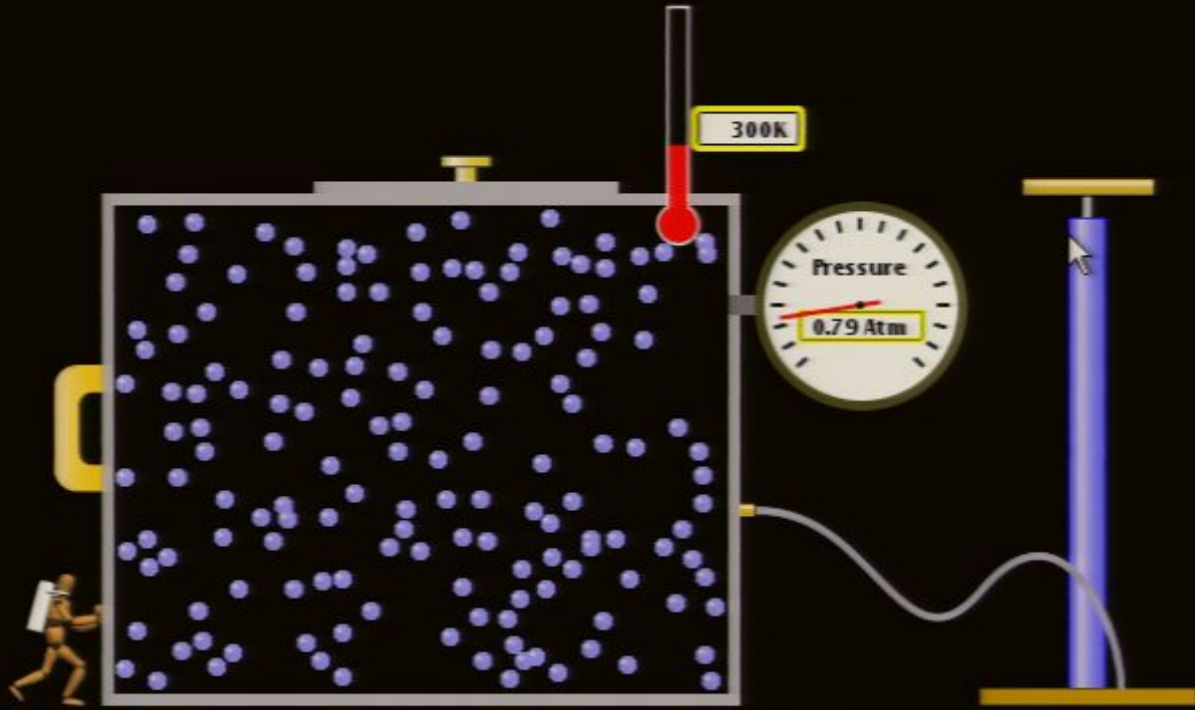
Add
0
Remove

Gas in Pump

Heavy Species
 Light Species

Play Pause Stop

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

Gas in Pump

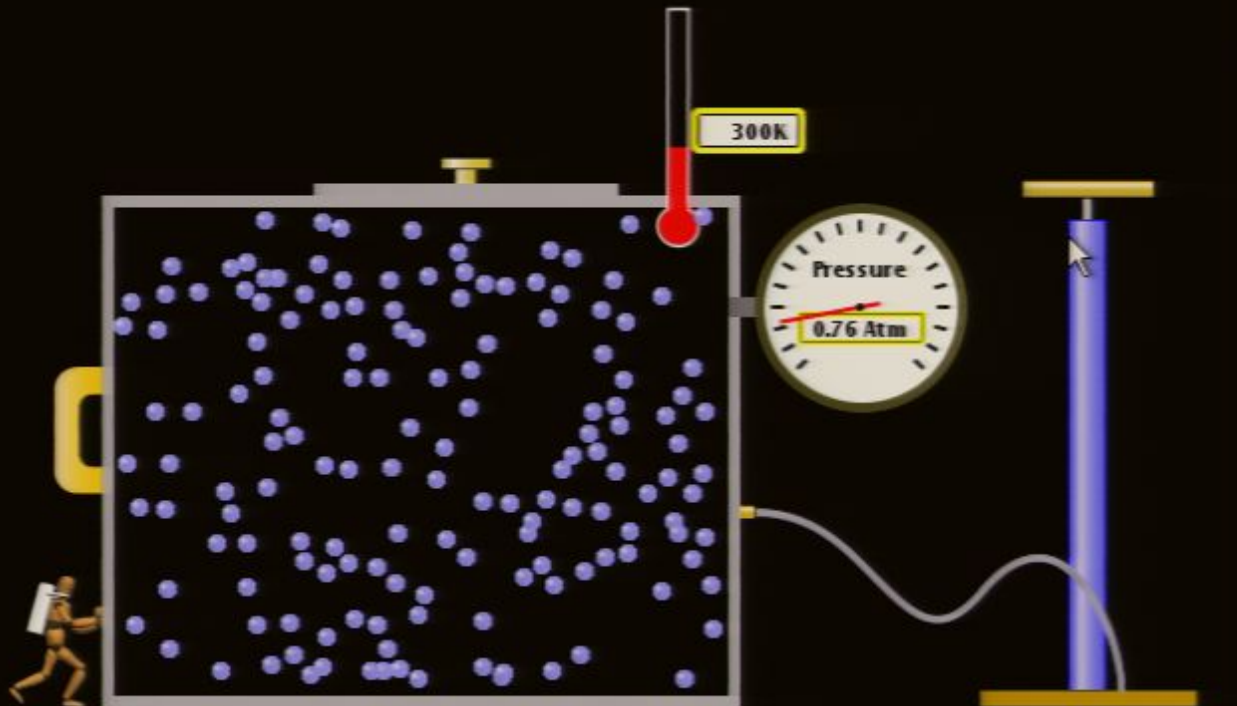
- Heavy Species
- Light Species

Play

Pause

Stop

Help!



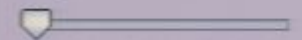
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 152
Light Species 0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

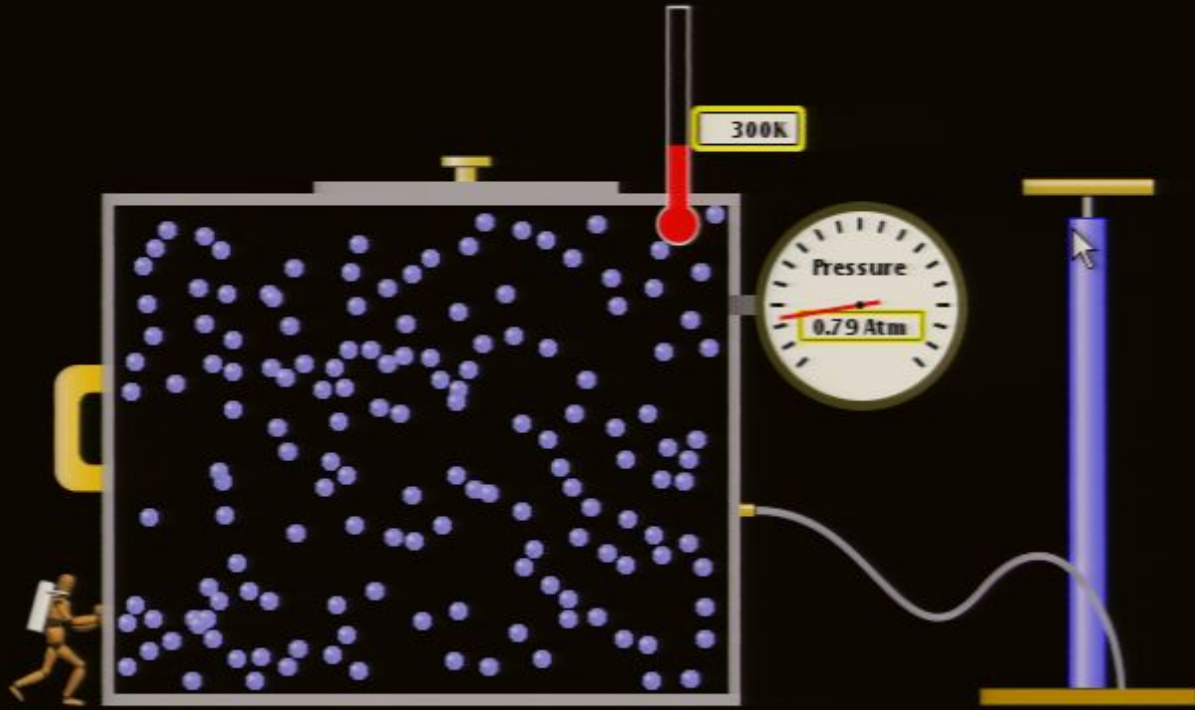
Add
0
Remove

Gas in Pump

Heavy Species
 Light Species

Play Pause Step

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

Gas in Pump

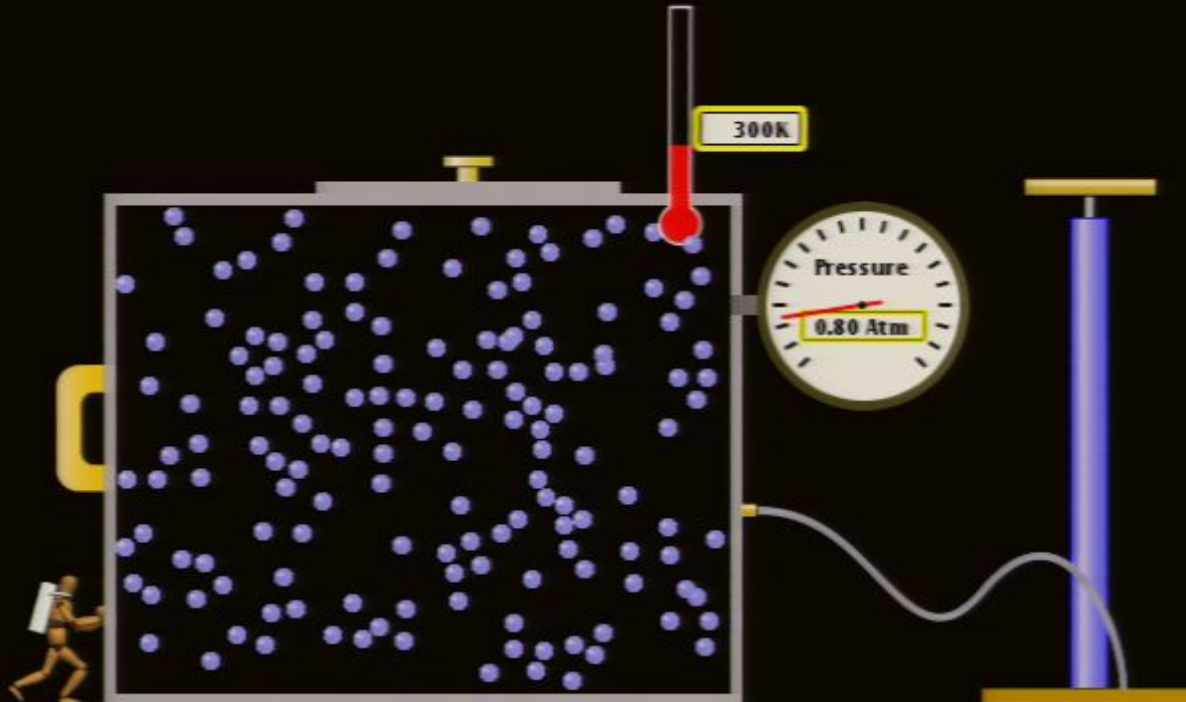
- Heavy Species
- Light Species

Play

Pause

Stop

Help!



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity

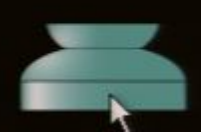
0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset



Heat Control

Add

0

Remove

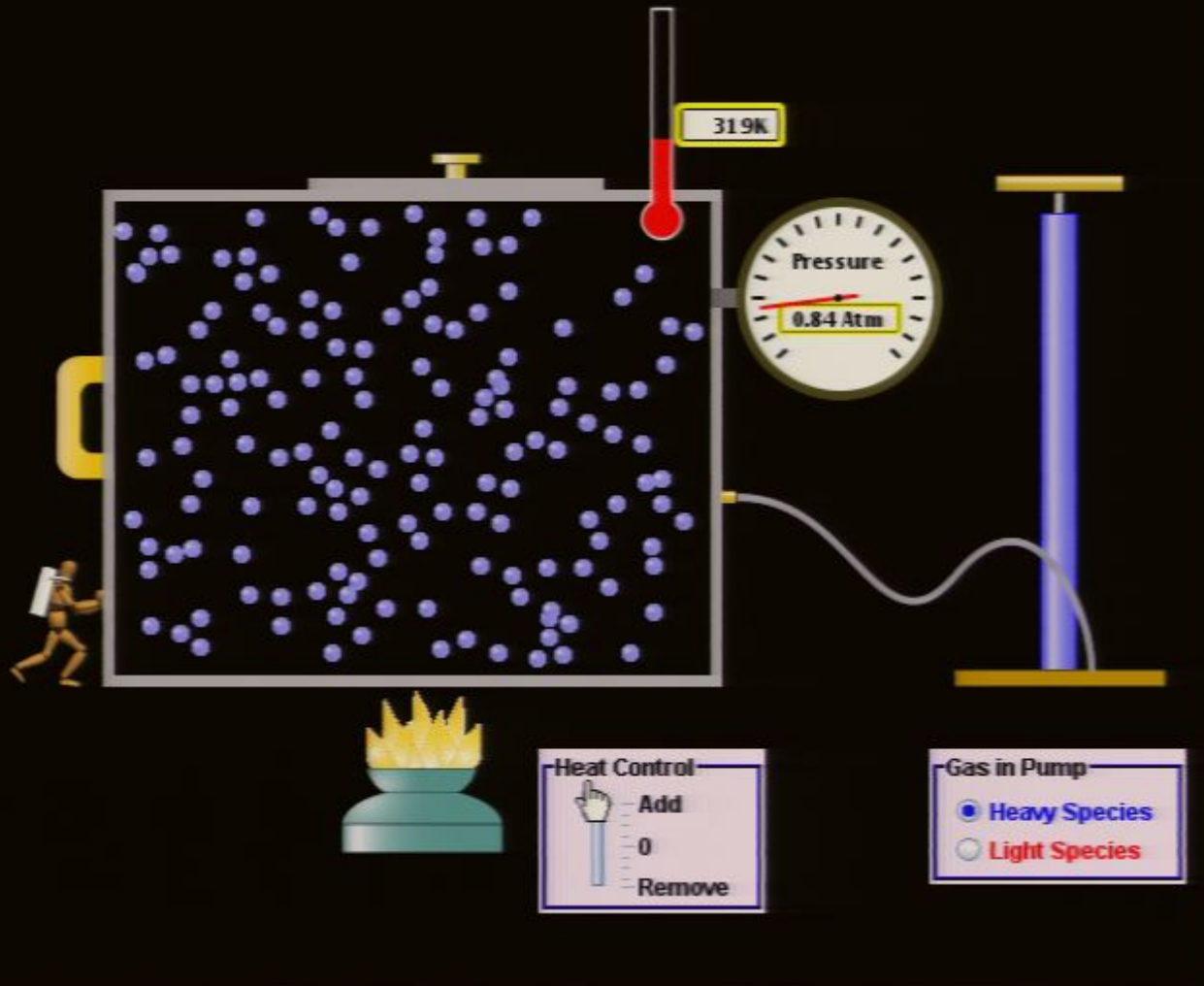
Gas in Pump

Heavy Species

Light Species

Play Pause Stop

Help!



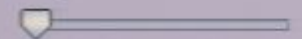
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity



0 Lots

Tools & Options

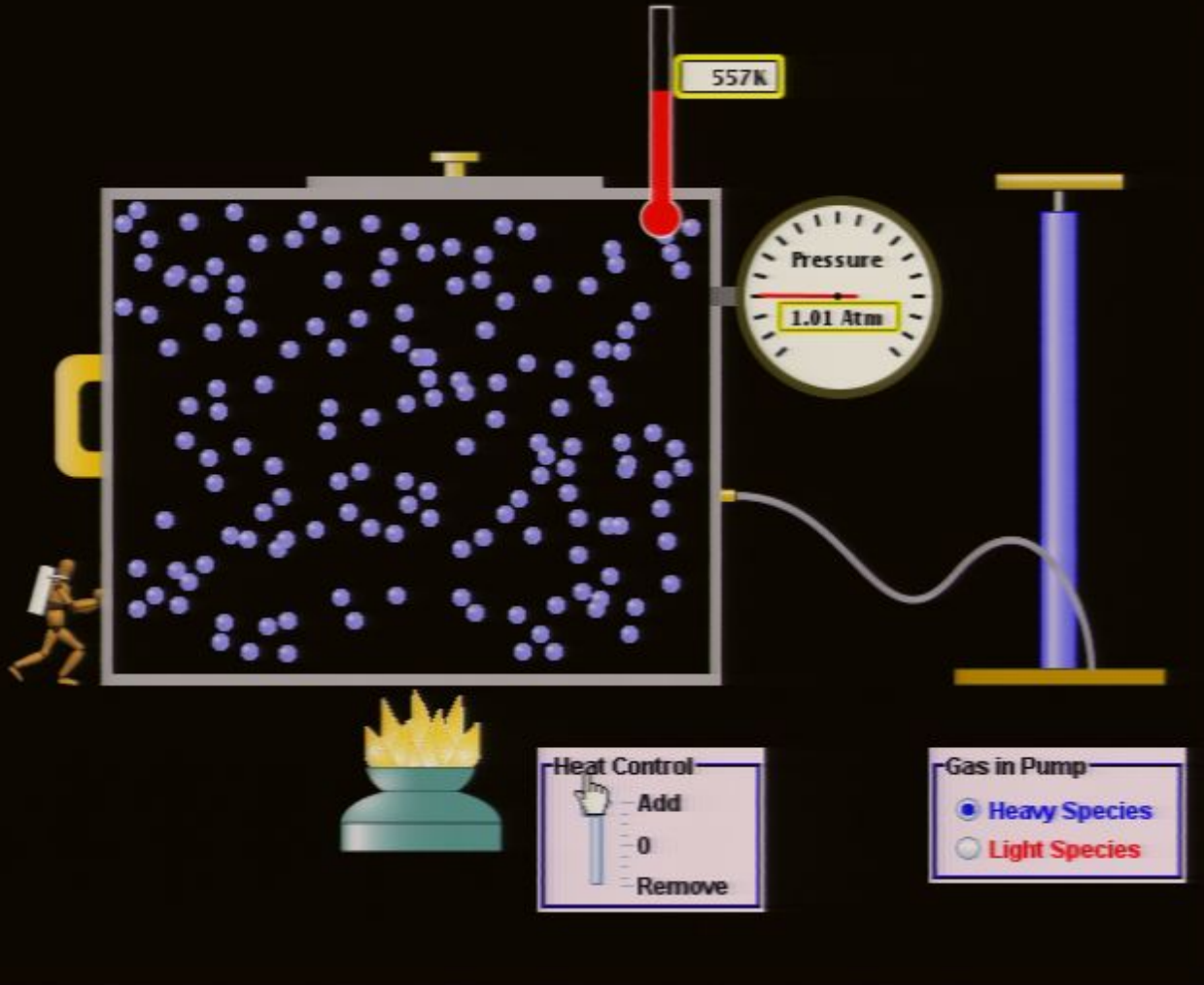
Measurement Tools >>

Advanced Options >>

Reset

Play Pause Stop

Help!



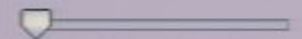
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Play Pause Stop

Help!

Gas Properties (3.03)

File Help

The main simulation area features a central rectangular chamber filled with numerous blue particles. To the left of the chamber, a small figure of a person wearing a white backpack is walking. Above the chamber, a red thermometer is attached, displaying a temperature of 893K. To the right of the chamber, a circular pressure gauge is connected, showing a pressure of 1.66 Atm. Further to the right, a blue vertical pump is connected to the chamber via a grey tube. The background is black, making the particles and equipment stand out.



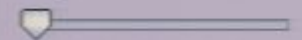
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add
0
Remove

Gas in Pump

- Heavy Species
- Light Species

Play Pause Step

Help!

Gas Properties (3.03)

File Help

The main simulation area features a central rectangular chamber filled with numerous small blue spheres representing gas particles. To the left of the chamber, a small orange figure with a white backpack is walking. Above the chamber, a red thermometer is connected to the top, displaying a temperature of 883K. To the right of the chamber, a circular pressure gauge is connected to the side, showing a pressure of 2.13 Atm. Further to the right, a blue vertical pump is connected to the chamber via a white tube. Below the chamber, there is a green heat source and a 'Heat Control' panel with a vertical slider ranging from 'Remove' at the bottom to 'Add' at the top, currently set at 0. To the right of the heat control is a 'Gas in Pump' panel with two radio buttons: 'Heavy Species' (selected) and 'Light Species'.



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 152
Light Species 0

Gravity

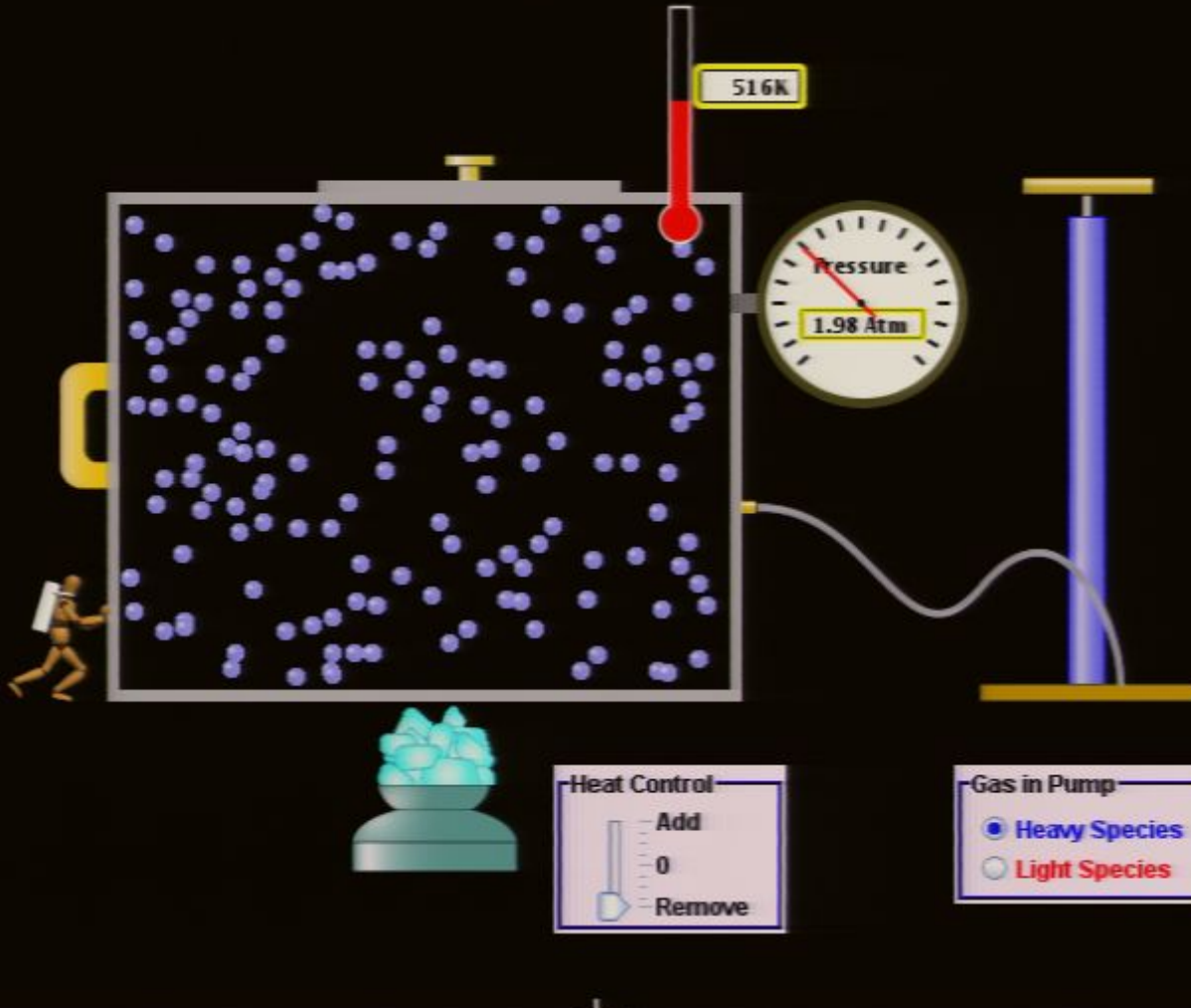
0 Lots

Tools & Options

Measurement Tools >>
Advanced Options >>
Reset

Play Pause Stop

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 152
Light Species 0

Gravity

0 Lots

Tools & Options

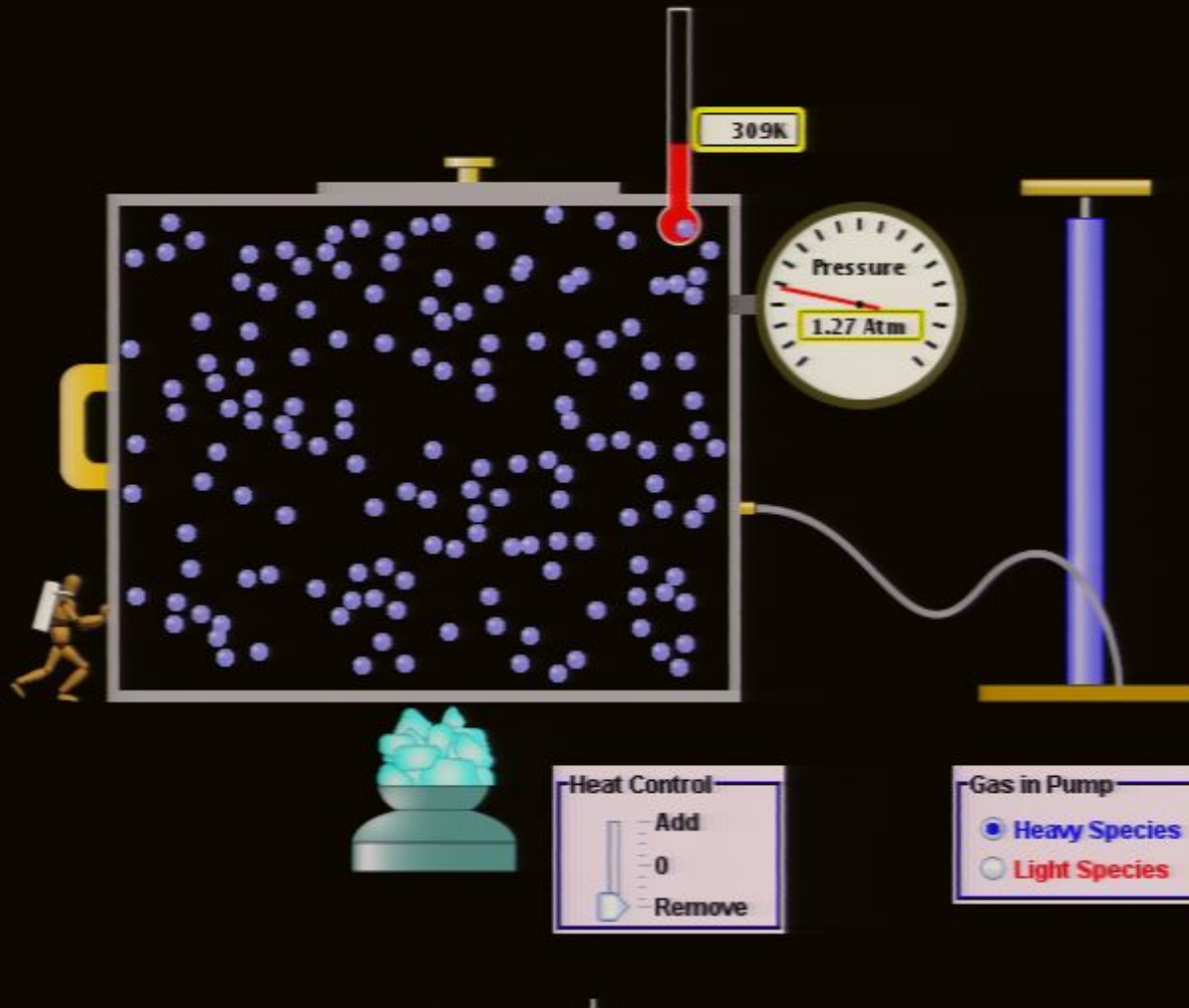
Measurement Tools >>

Advanced Options >>

Reset

Help!

Play Pause Step



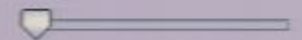
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity



0 Lots

Tools & Options

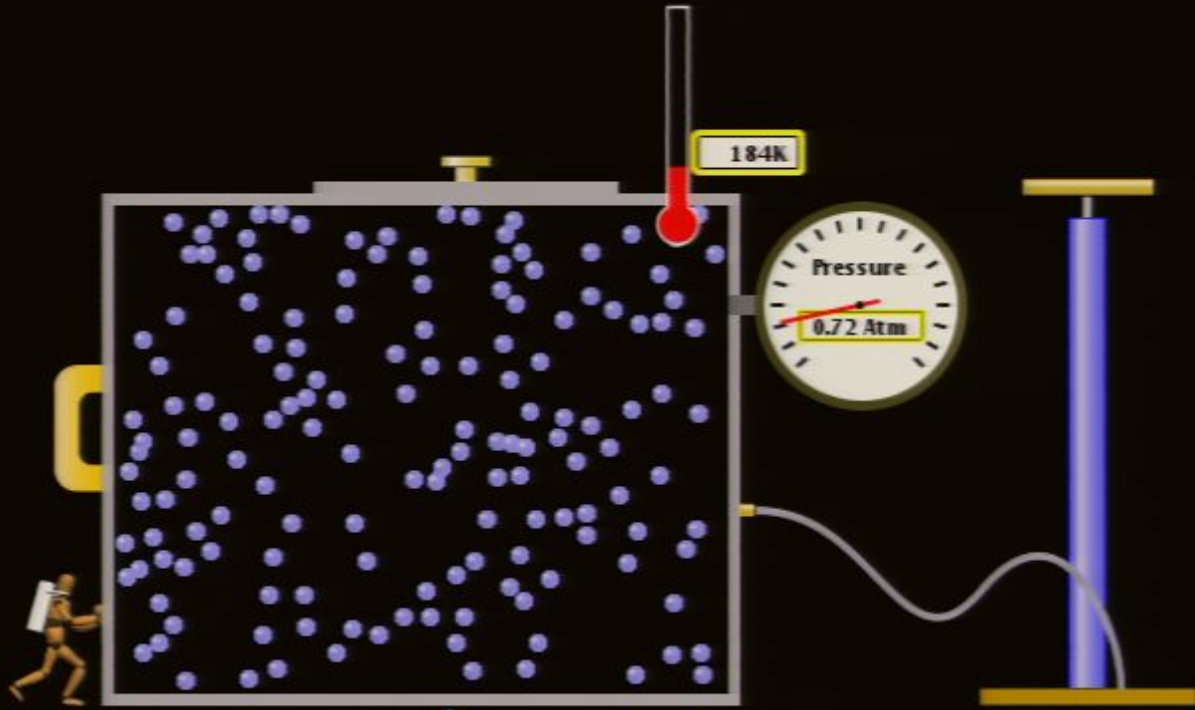
Measurement Tools >>

Advanced Options >>

Reset

Play Pause Step

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity

0 Lots

Tools & Options

- Measurement Tools >>
- Advanced Options >>
- Reset



Heat Control

Add

0

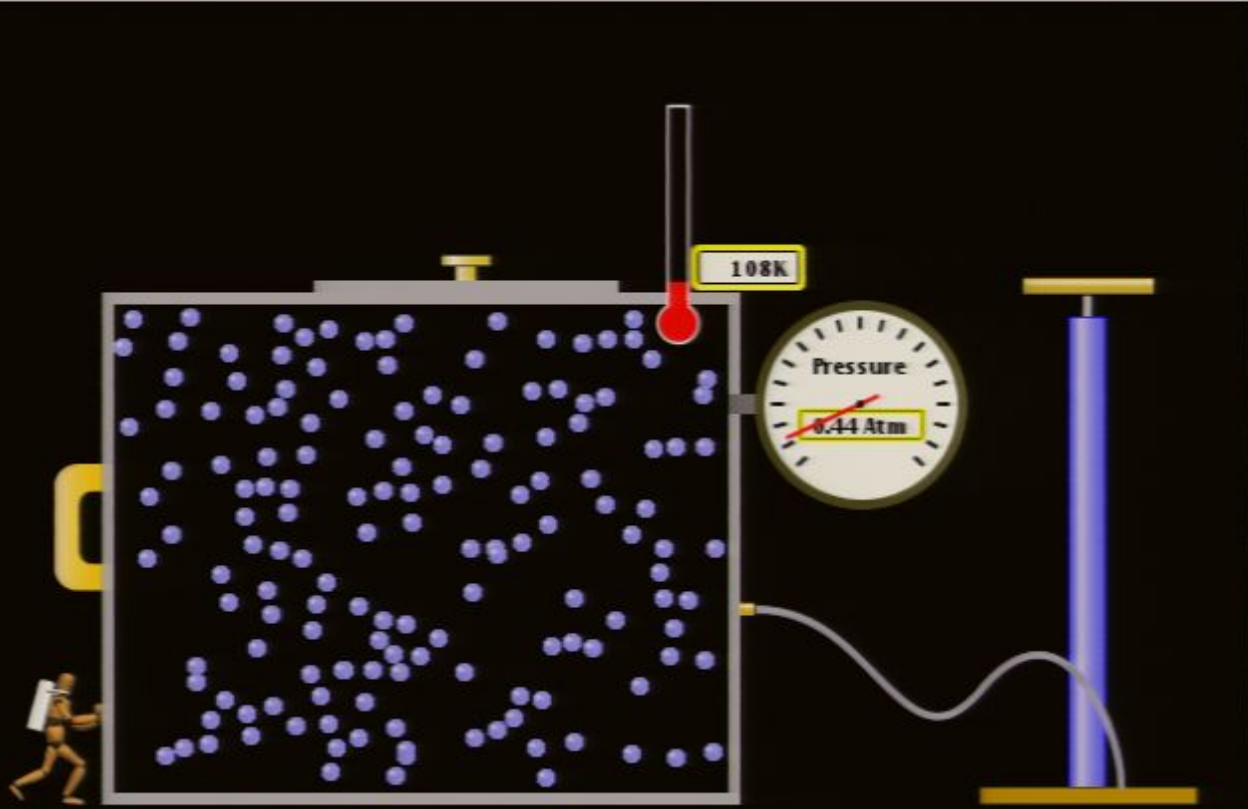
Remove

Gas in Pump

- Heavy Species
- Light Species

- Play
- Pause
- Stop

Help!



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species 152

Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

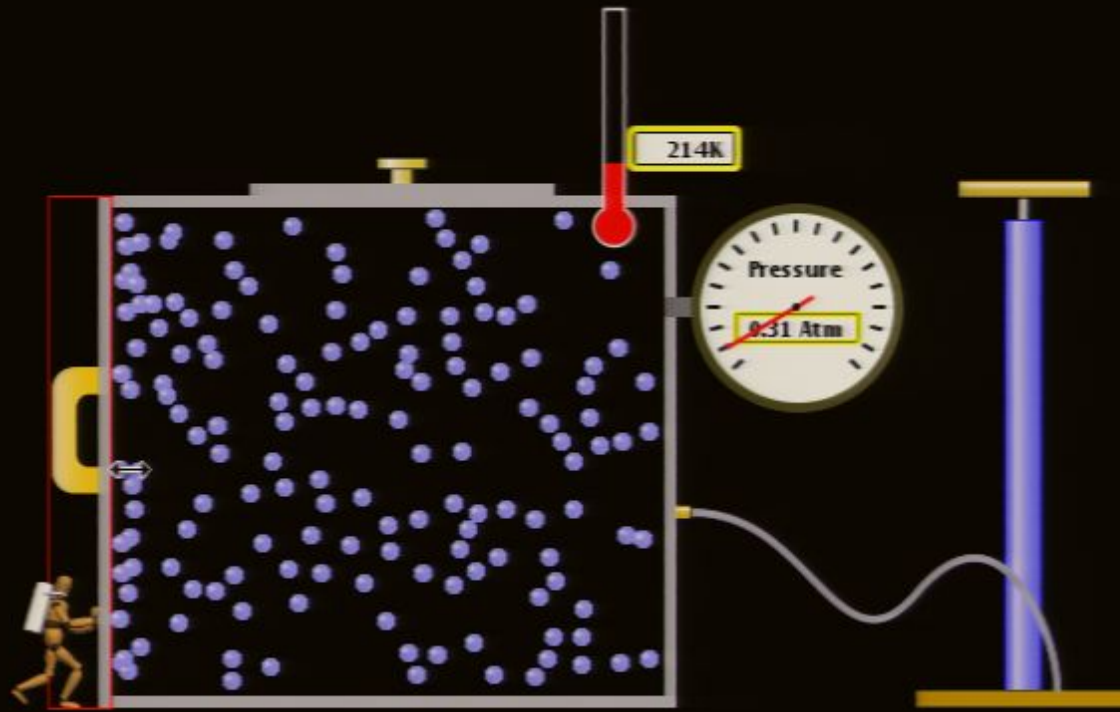
Gas in Pump

Heavy Species

Light Species

Play Pause Step

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 152
Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

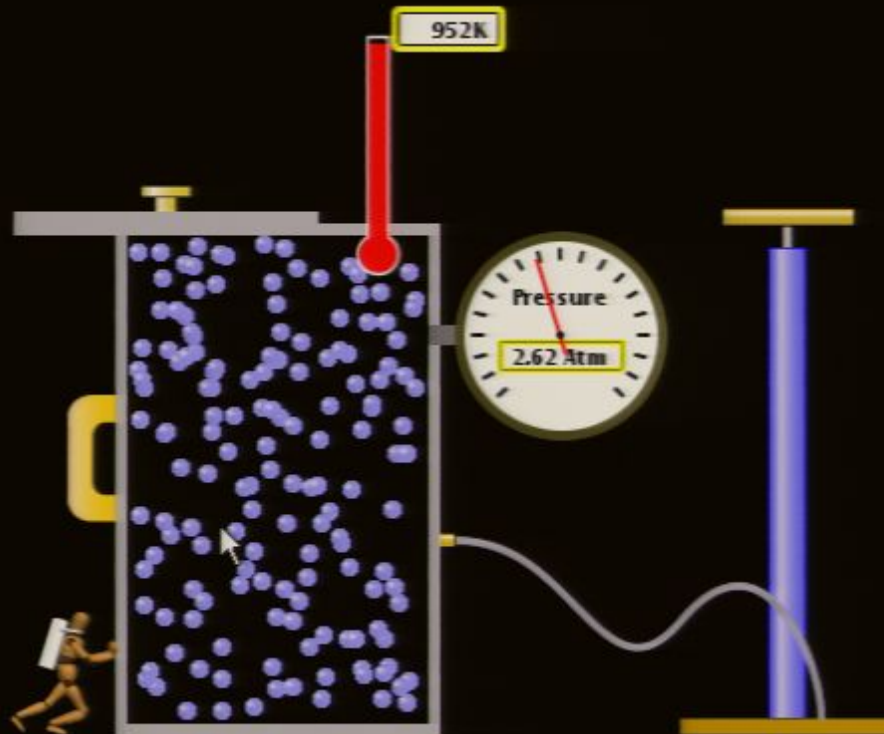
Add
0
Remove

Gas in Pump

Heavy Species
 Light Species

Play Pause Stop

Help!



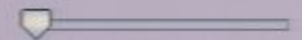
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	152
Light Species	0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

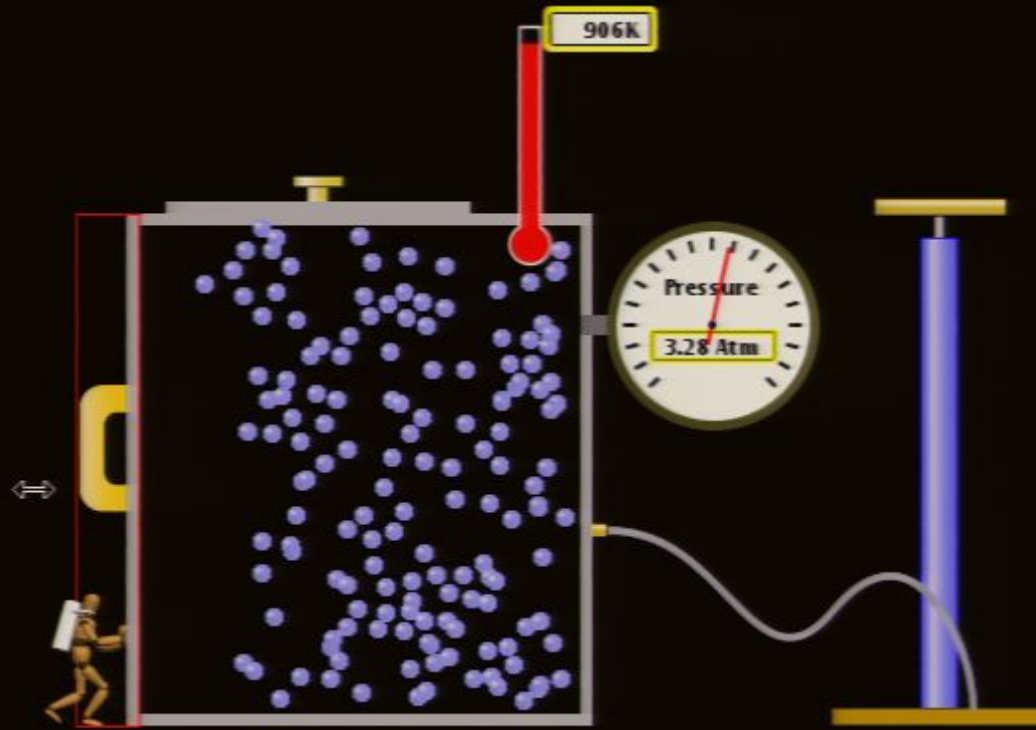
Remove

Gas in Pump

- Heavy Species
- Light Species

Play Pause Stop

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	150
Light Species	0

Gravity

0 Lots

Tools & Options

- Measurement Tools >>
- Advanced Options >>
- Reset

Heat Control

Add

0

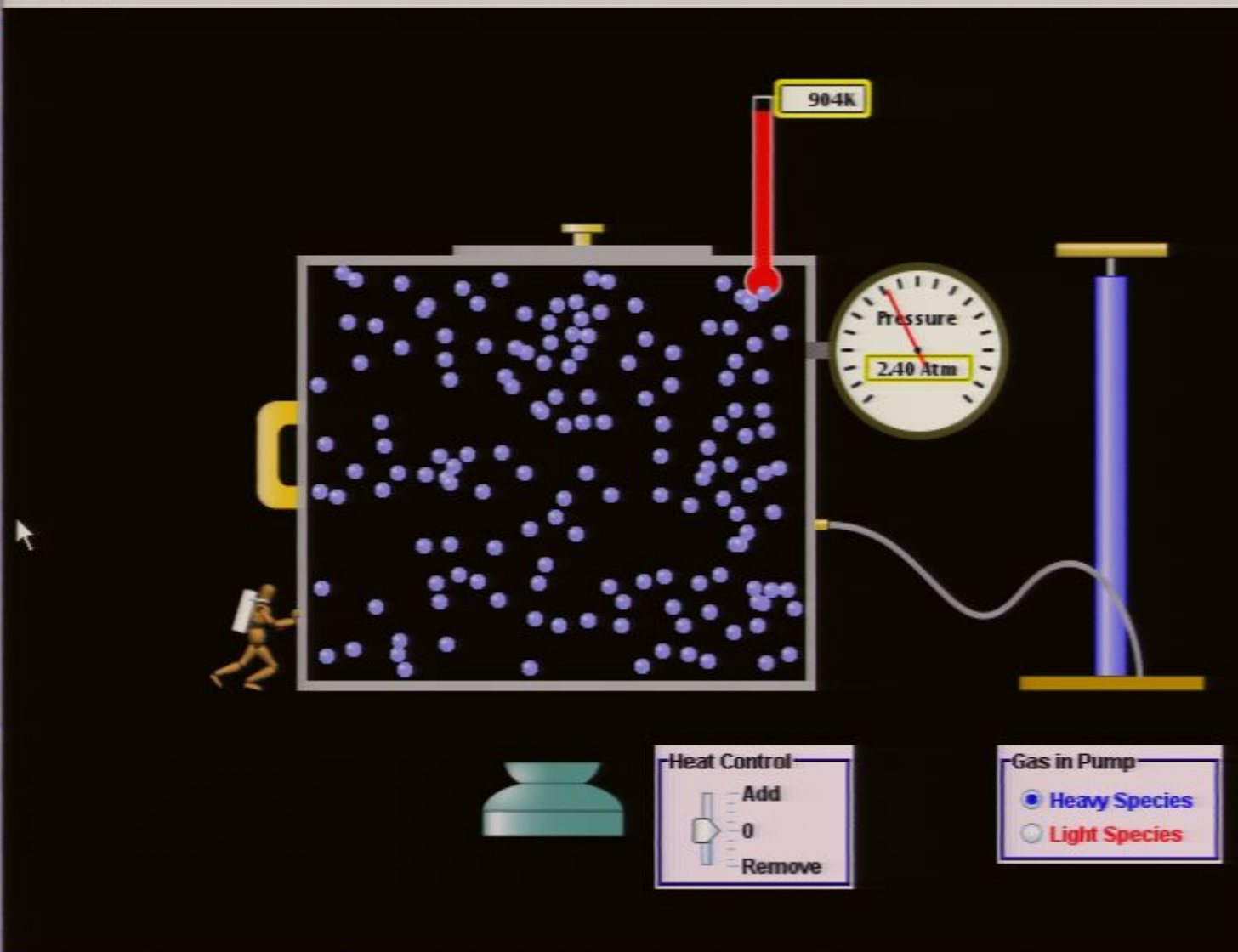
Remove

Gas in Pump

- Heavy Species
- Light Species

- Play
- Pause
- Stop

Help!



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species 150

Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

Gas in Pump

Heavy Species

Light Species

Play Pause Stop

Help!

The main simulation area features a central rectangular chamber filled with numerous small blue spheres representing gas particles. To the left of the chamber, a small human figure stands next to a yellow handle. Above the chamber, a red thermometer is connected to the top, displaying a temperature of 901 K. To the right of the chamber, a circular pressure gauge is connected to the side, showing a pressure of 2.43 Atm. Further to the right, a blue vertical pump is connected to the chamber via a grey tube. The background is black, making the particles and instruments stand out.



Constant Parameter

Volume Pressure
 Temperature None

Gas in Chamber

Heavy Species	149
Light Species	0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add
0
Remove

Gas in Pump

Heavy Species
 Light Species

Play Pause Stop

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	149
Light Species	0

Gravity

0 Lots

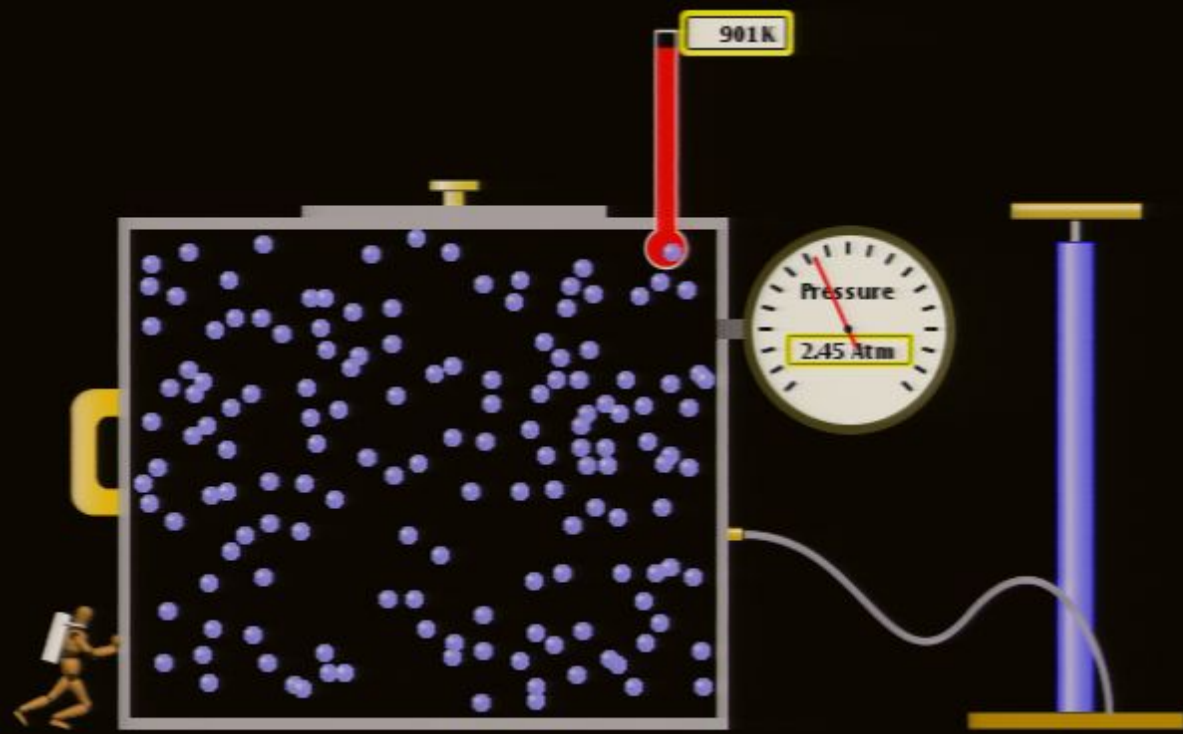
Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Help!



Heat Control

Add

0

Remove

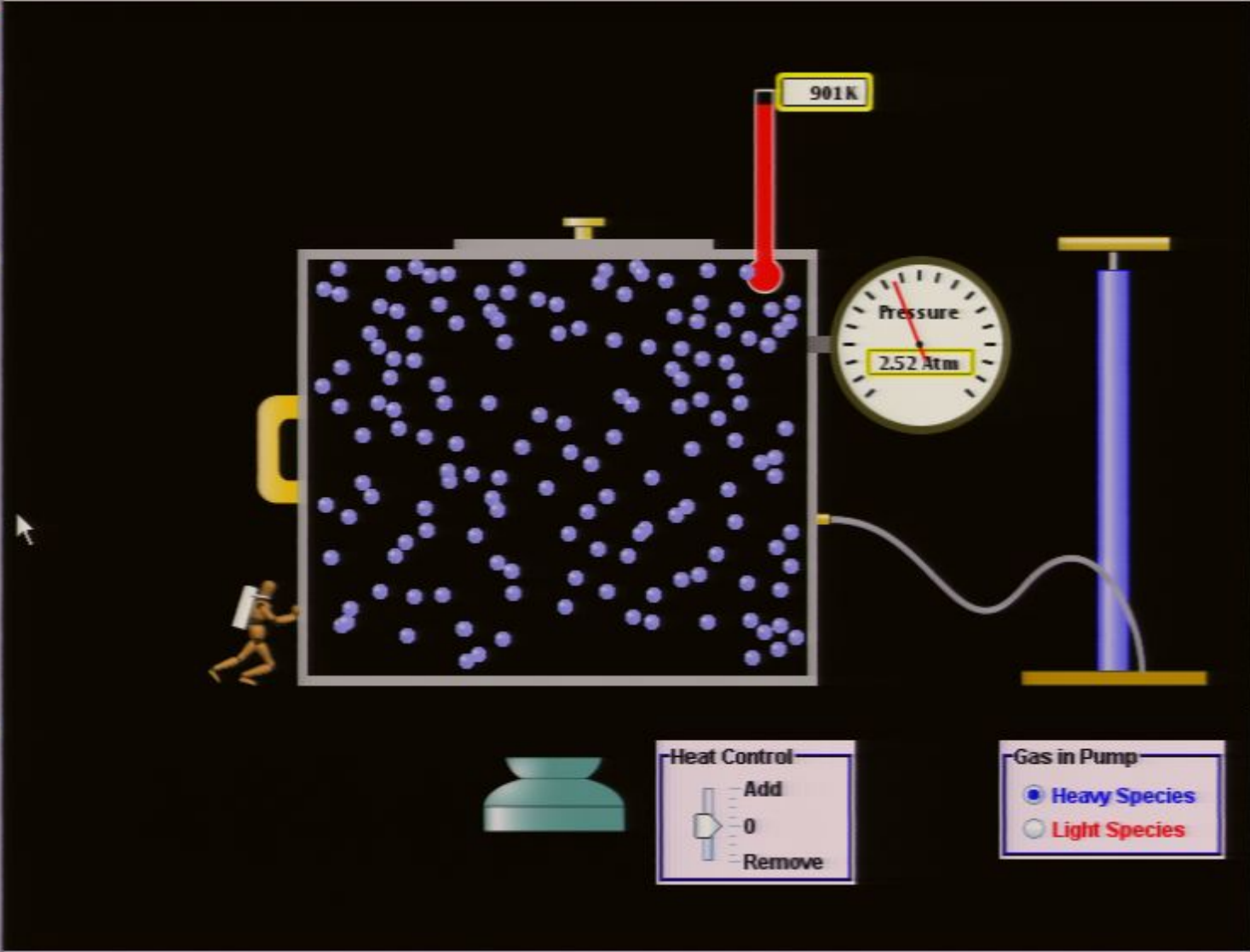
Gas in Pump

- Heavy Species
- Light Species

Play

Pause

Step



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species	149
Light Species	0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

Gas in Pump

Heavy Species

Light Species

Play Pause Stop

Help!

The main simulation area features a central rectangular chamber filled with numerous small blue spheres representing gas particles. To the left of the chamber, a small human figure is carrying a white box. Above the chamber, a red thermometer is connected to the top, displaying a temperature of 895 K. To the right of the chamber, a circular pressure gauge is connected to the side, showing a pressure of 2.46 Atm. Further to the right, a blue vertical pump is connected to the chamber via a grey tube. The background is black, making the particles and instruments stand out.



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 148
Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

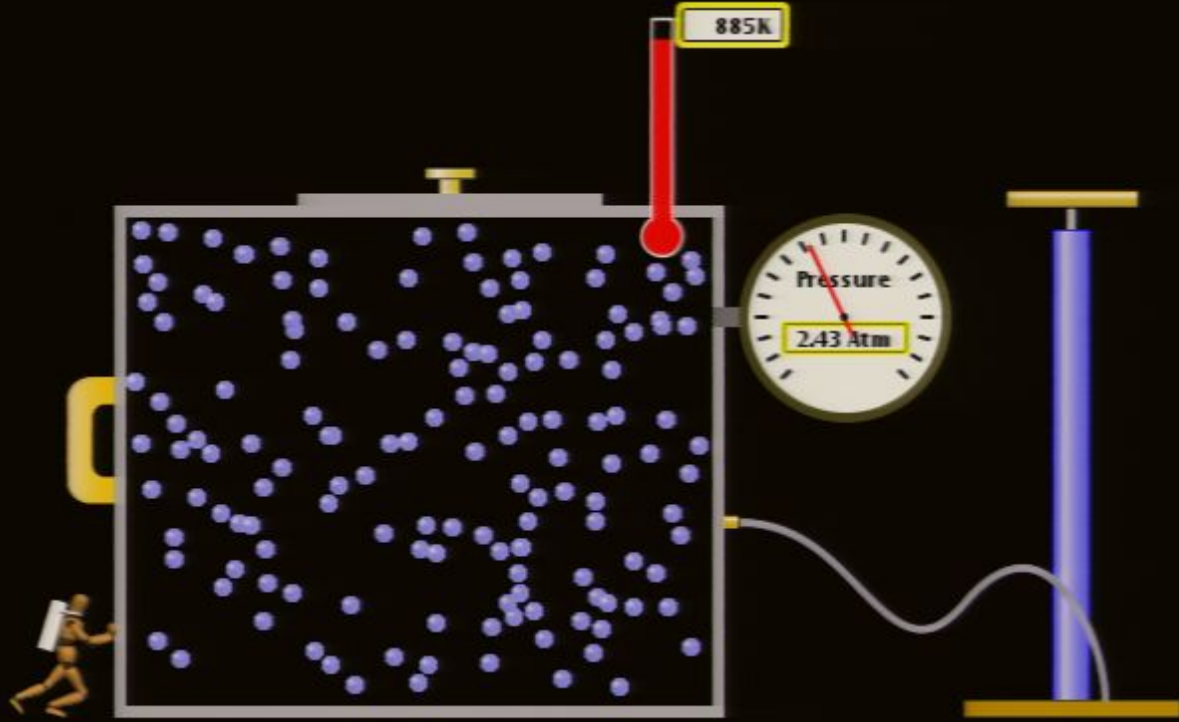
Add
0
Remove

Gas in Pump

- Heavy Species
- Light Species

Play Pause Stop

Help!



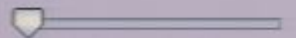
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 147
Light Species 0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

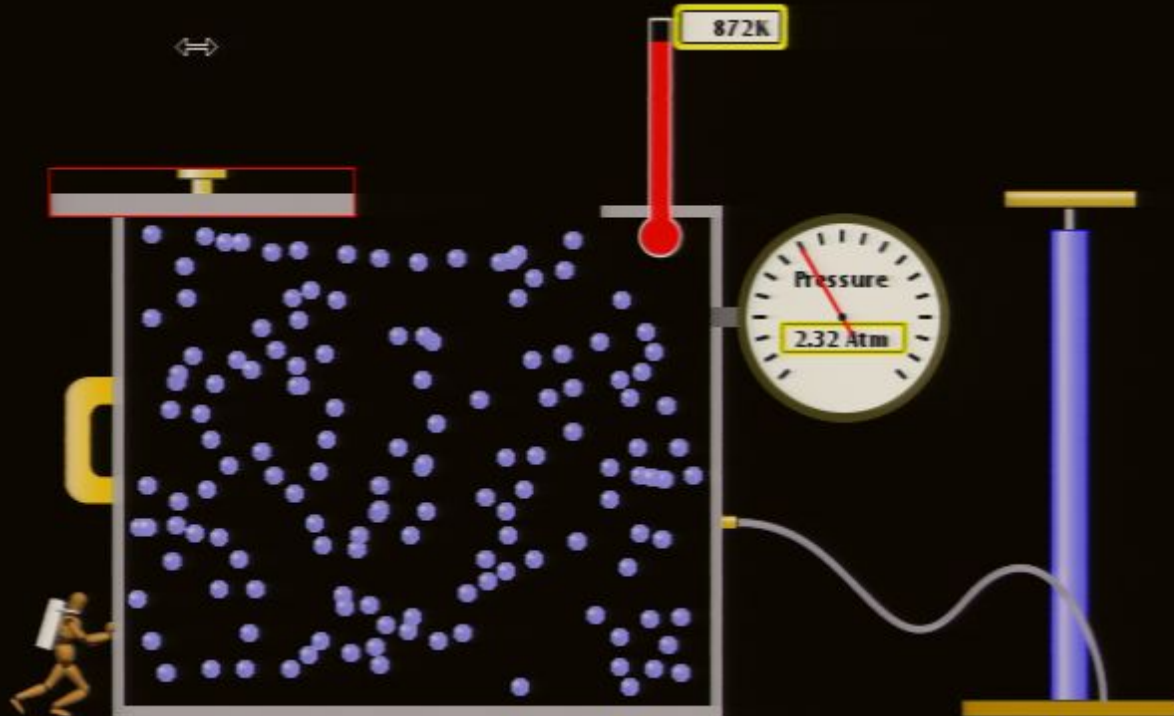
Add
0
Remove

Gas in Pump

- Heavy Species
- Light Species

Play Pause Step

Help!



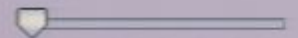
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	142
Light Species	0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

Gas in Pump

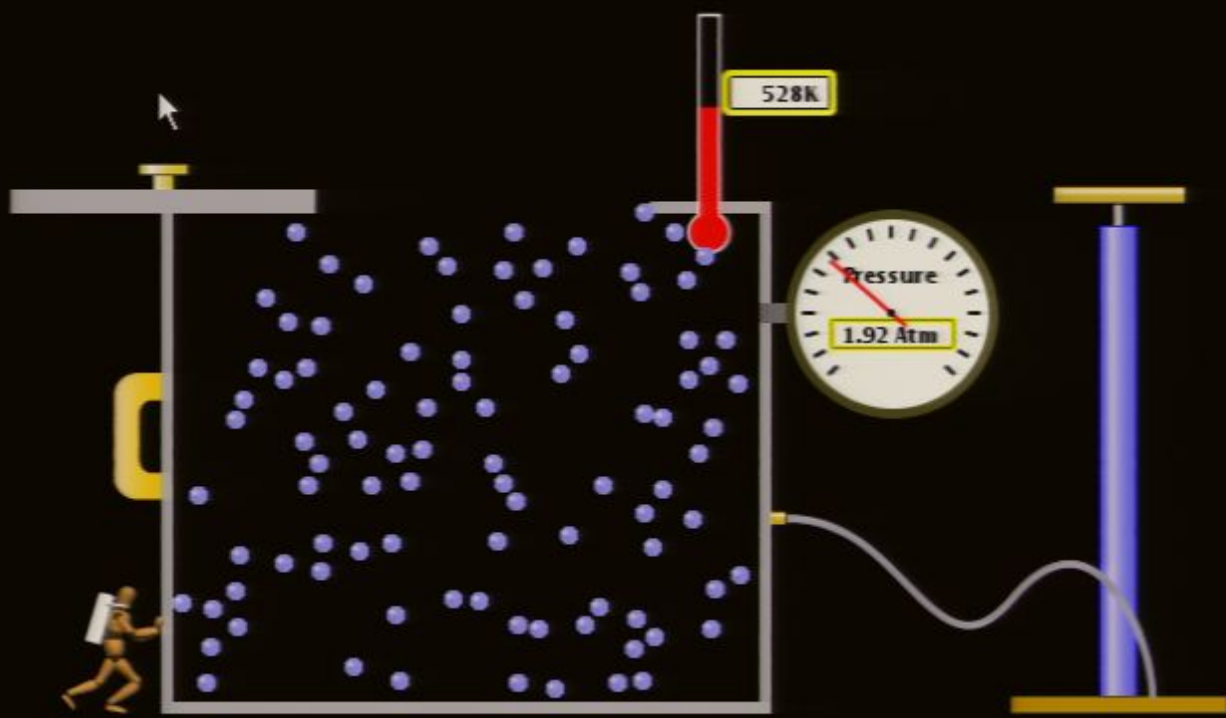
- Heavy Species
- Light Species

Play

Pause

Step

Help!



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species 93

Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

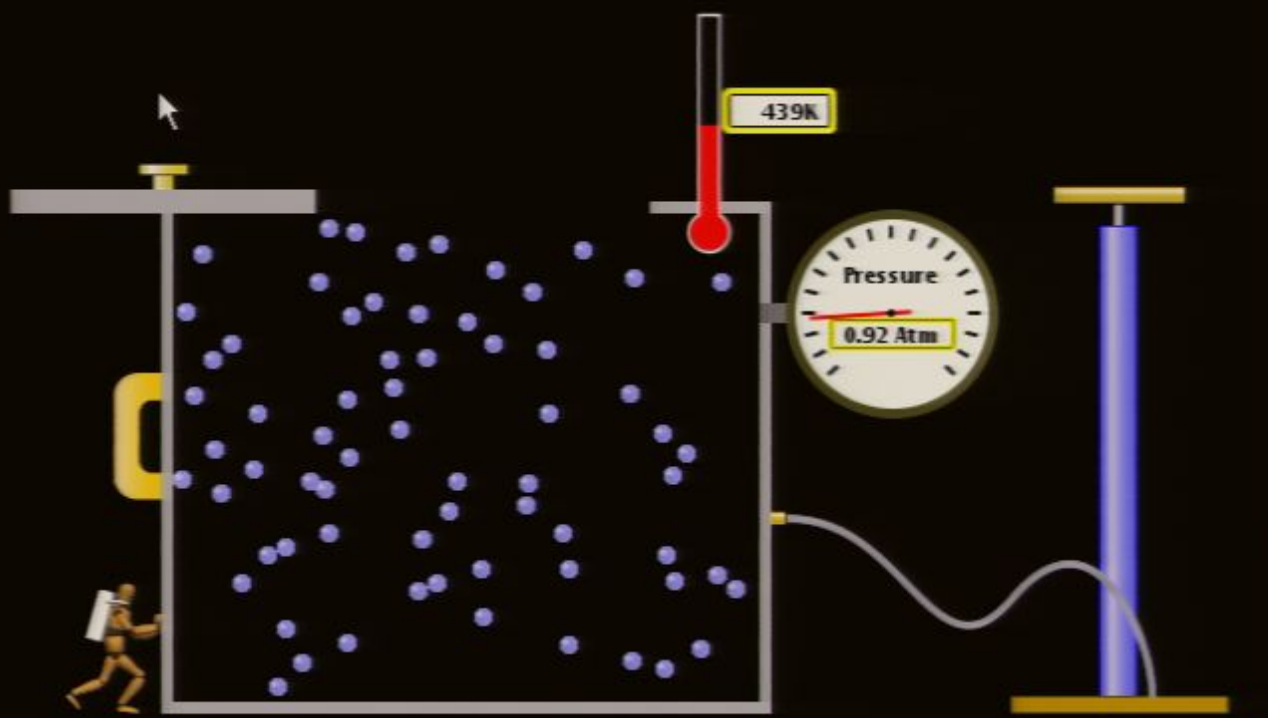
Gas in Pump

Heavy Species

Light Species

Play Pause Stop

Help!



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species	67
Light Species	0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

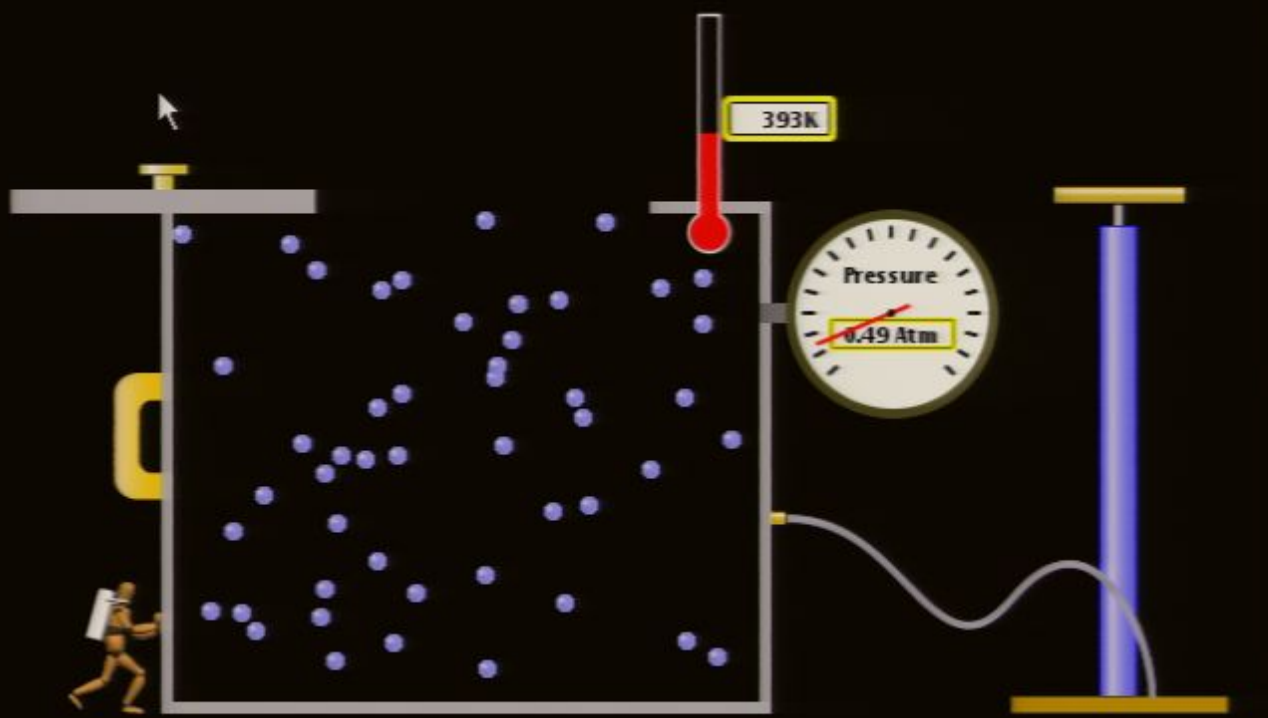
Gas in Pump

Heavy Species

Light Species

Play Pause Stop

Help!



Constant Parameter

Volume Pressure

Temperature None

Gas in Chamber

Heavy Species	48
Light Species	0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

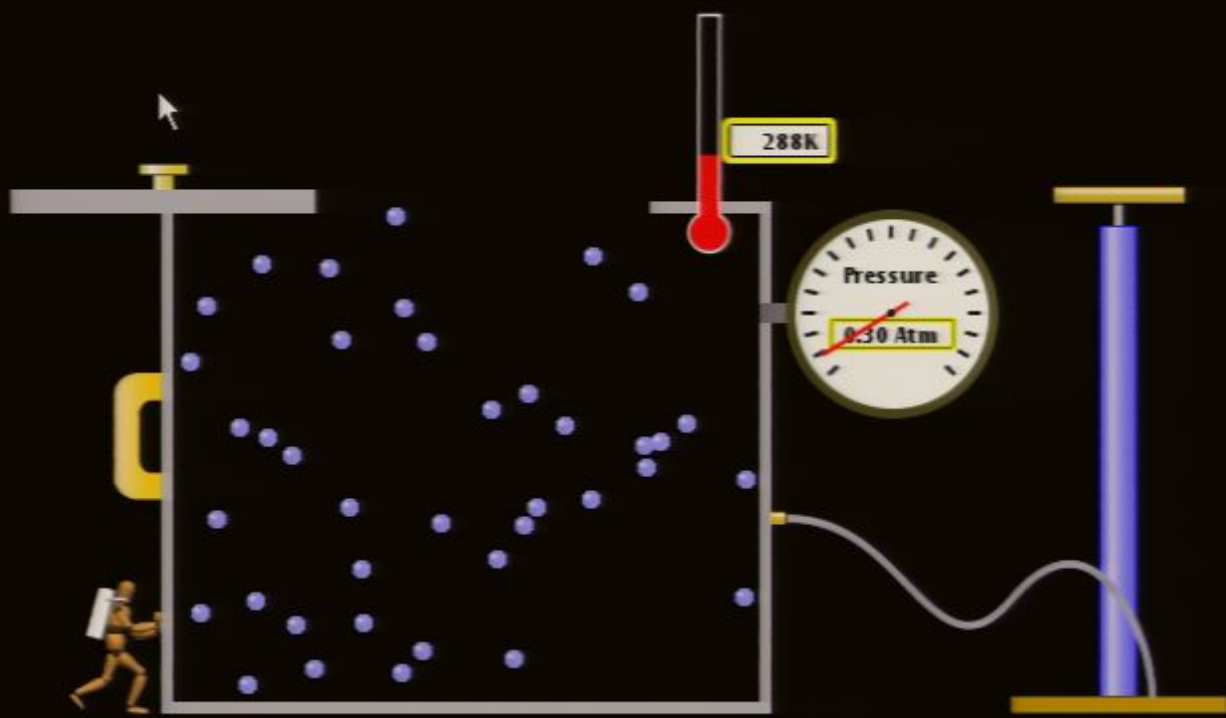
Gas in Pump

Heavy Species

Light Species

Play Pause Stop

Help!



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species	39
Light Species	0

Gravity

0 Lots

Tools & Options

- Measurement Tools >>
- Advanced Options >>
- Reset

Heat Control

Add

0

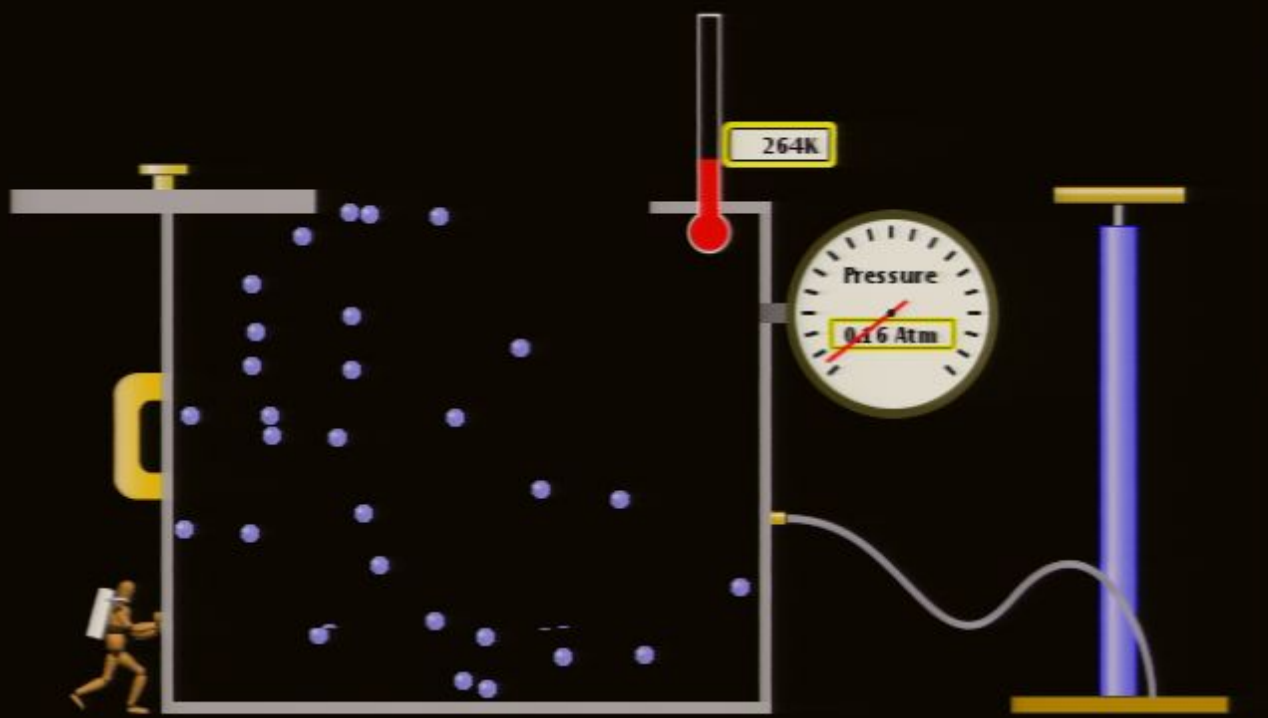
Remove

Gas in Pump

- Heavy Species
- Light Species

- Play
- Pause
- Stop

Help!



- Constant Parameter
- Volume
 - Pressure
 - Temperature
 - None

Gas in Chamber

Heavy Species	28
Light Species	0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

Add

0

Remove

Gas in Pump

- Heavy Species
- Light Species

Play

Pause

Stop

Help!

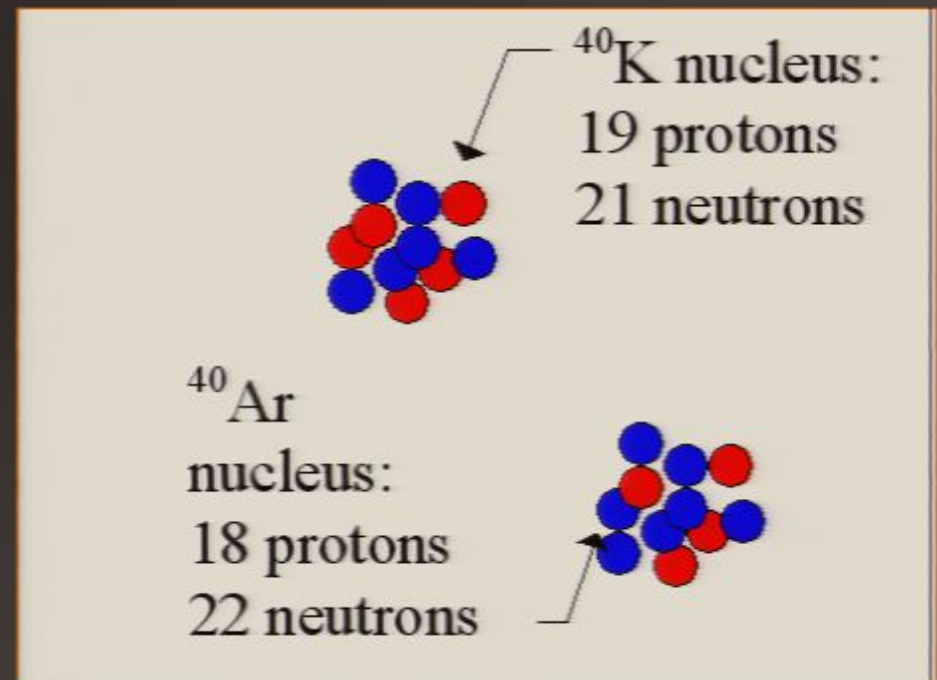
How Would We Know?

- The Universe being hot *means* that the particles within it are randomly moving with higher speeds.
- At high enough temperatures particles get knocked apart into their constituents.



How Would We Know?

- Atoms can survive once the Universe cools below 1000 degrees.
 - Charged electrons and nuclei combine to form neutral atoms.
- Nuclei can survive below 10 billion degrees.
 - Protons and neutrons combine to form nuclei.



Evidence for a Hot Big Bang

- Primordial element abundances
- The cosmic microwave background
- T_{CMB} vs distance

Evidence for a Hot Big Bang

- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance

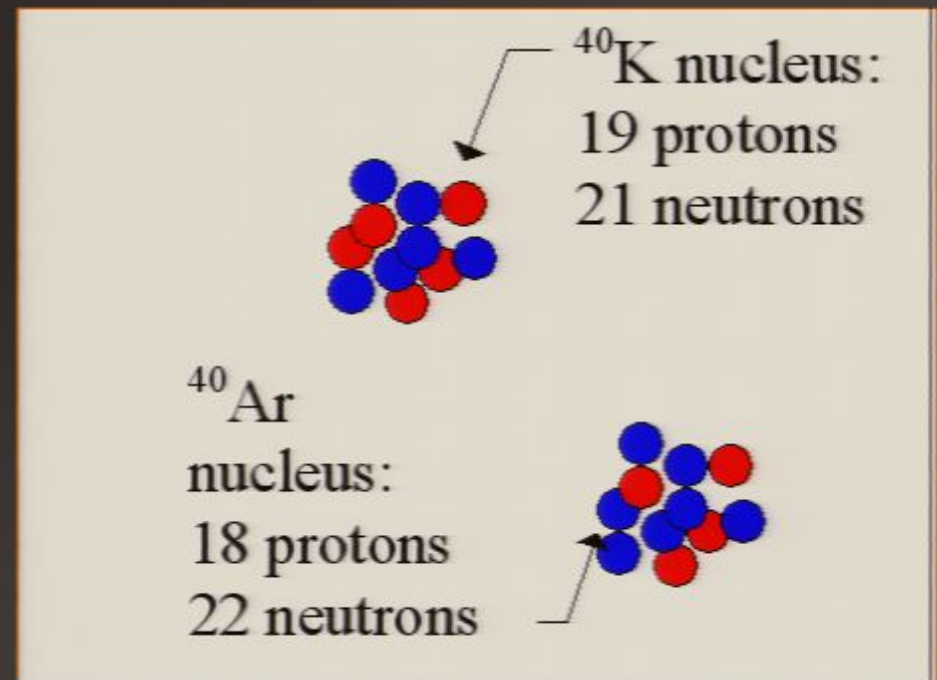
When the universe cools to the point where nuclei can form (around 10^{10} K) then the relative abundances of the light elements can be calculated.

The predictions for the isotopes of H, He, Li and Be agree with the measured abundances.

Agreement is very sensitive to the total number of atoms present.

How Would We Know?

- Atoms can survive once the Universe cools below 1000 degrees.
 - Charged electrons and nuclei combine to form neutral atoms.
- Nuclei can survive below 10 billion degrees.
 - Protons and neutrons combine to form nuclei.



Evidence for a Hot Big Bang

- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance

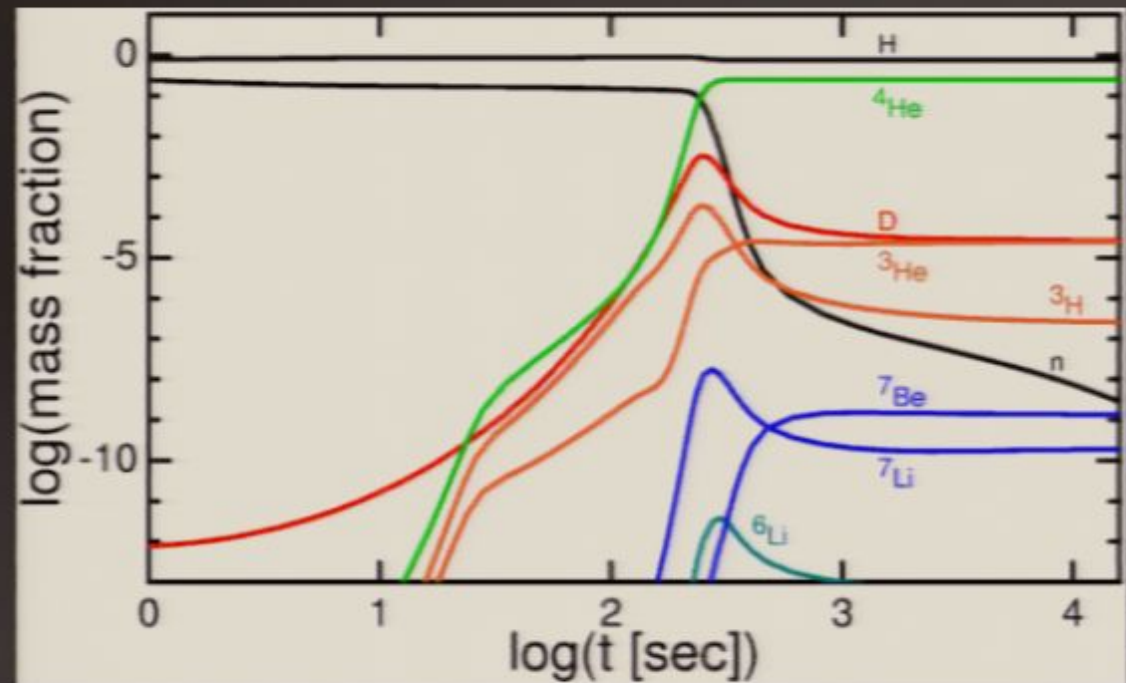
When the universe cools to the point where nuclei can form (around 10^{10} K) then the relative abundances of the light elements can be calculated.

The predictions for the isotopes of H, He, Li and Be agree with the measured abundances.

Agreement is very sensitive to the total number of atoms present.

Evidence for a Hot Big Bang

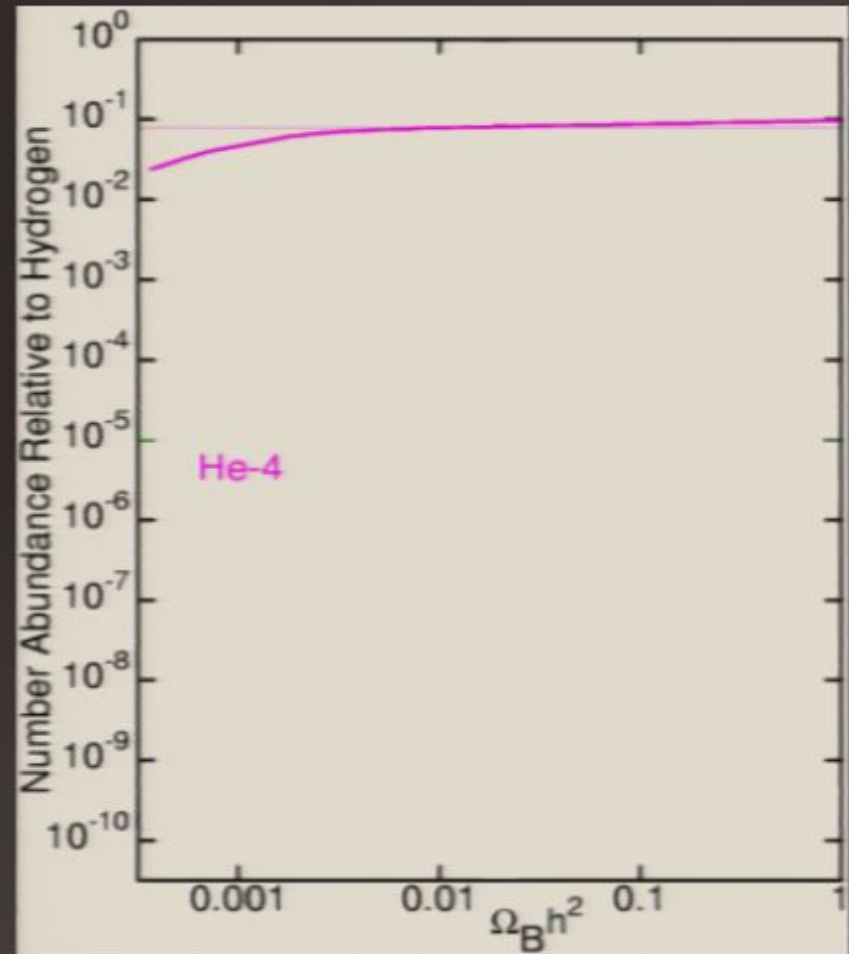
- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance



Burles, Nolette & Turner, 1999

Evidence for a Hot Big Bang

- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance

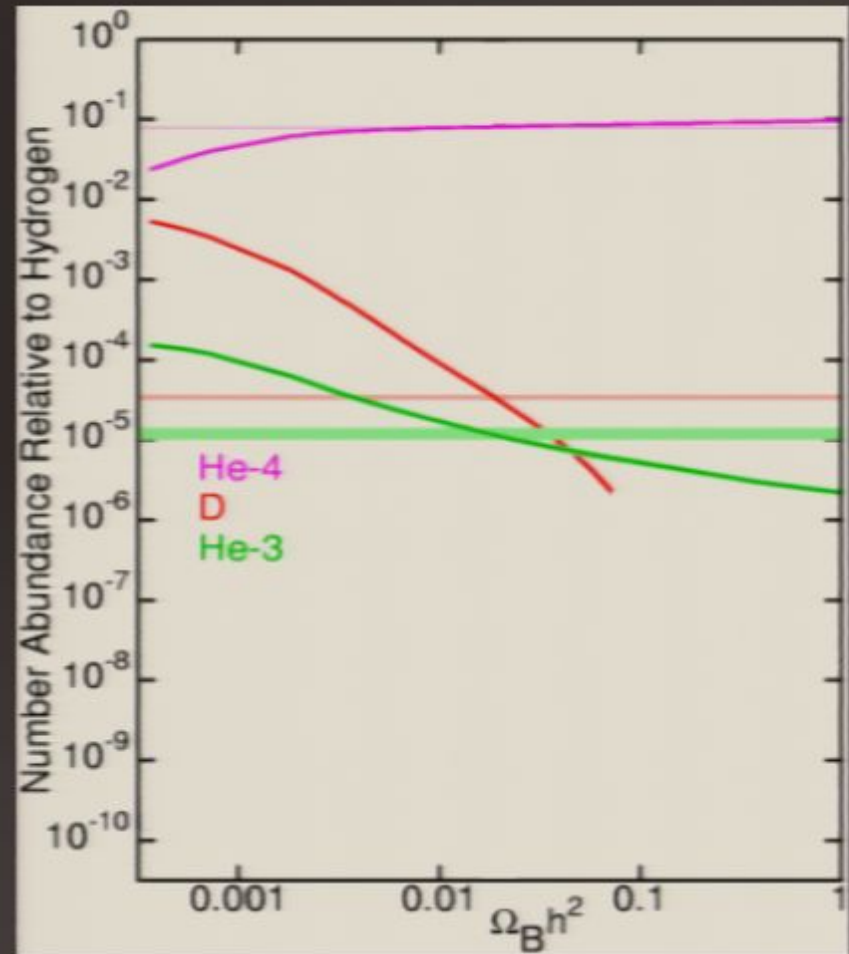


Total Mass Density of Atoms

Burles, Nolette & Turner, 1999

Evidence for a Hot Big Bang

- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance

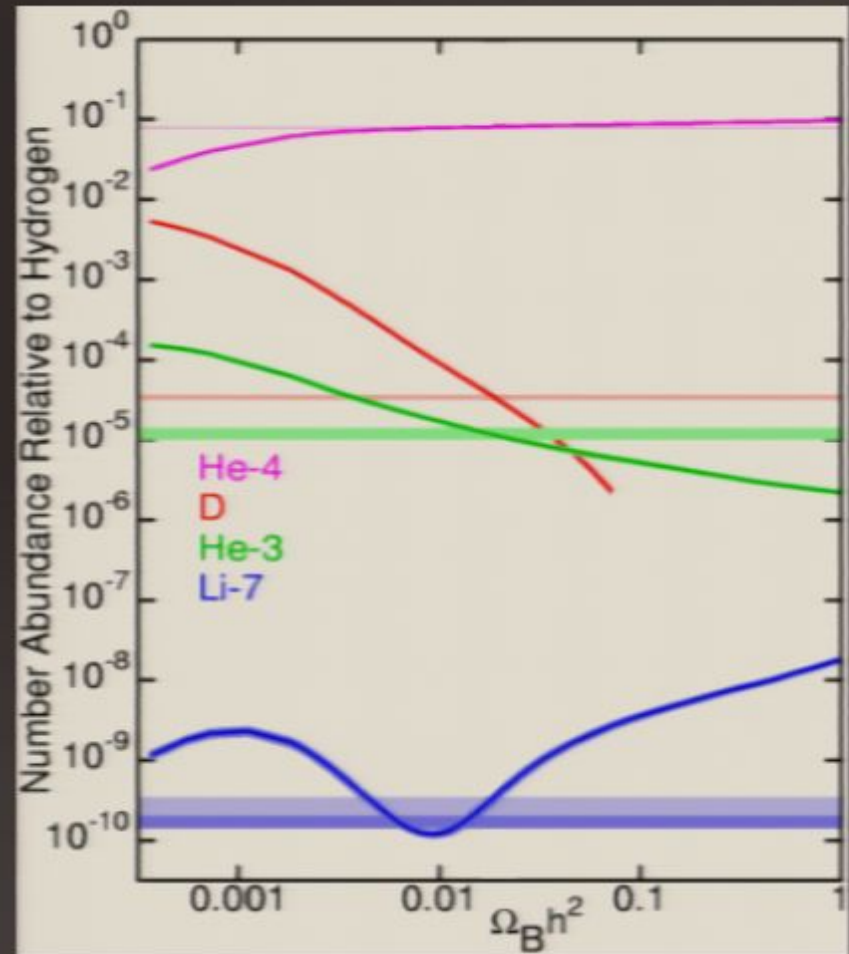


Total Mass Density of Atoms

Burles, Nolette & Turner, 1999

Evidence for a Hot Big Bang

- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance

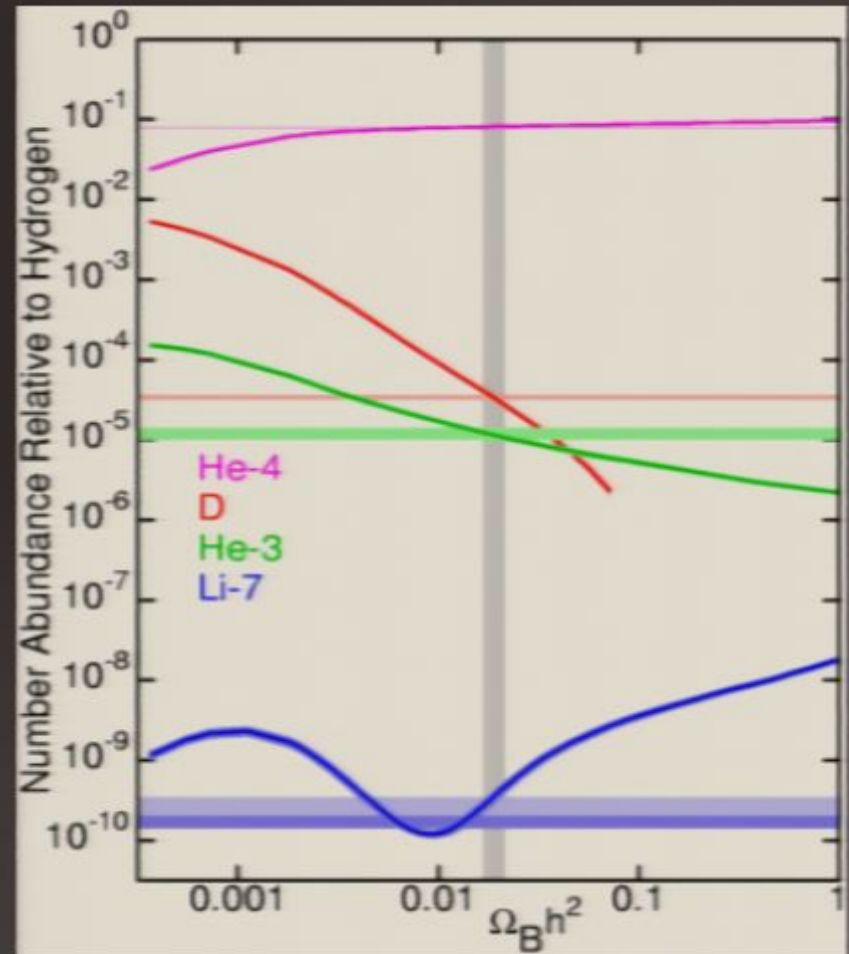


Total Mass Density of Atoms

Burles, Nolette & Turner, 1999

Evidence for a Hot Big Bang

- *Primordial element abundances*
- The cosmic microwave background
- T_{CMB} vs distance



Total Mass Density of Atoms

Burles, Nolette & Turner, 1999

Evidence for a Hot Big Bang

- Primordial element abundances
- *The cosmic microwave background*
- T_{CMB} vs distance

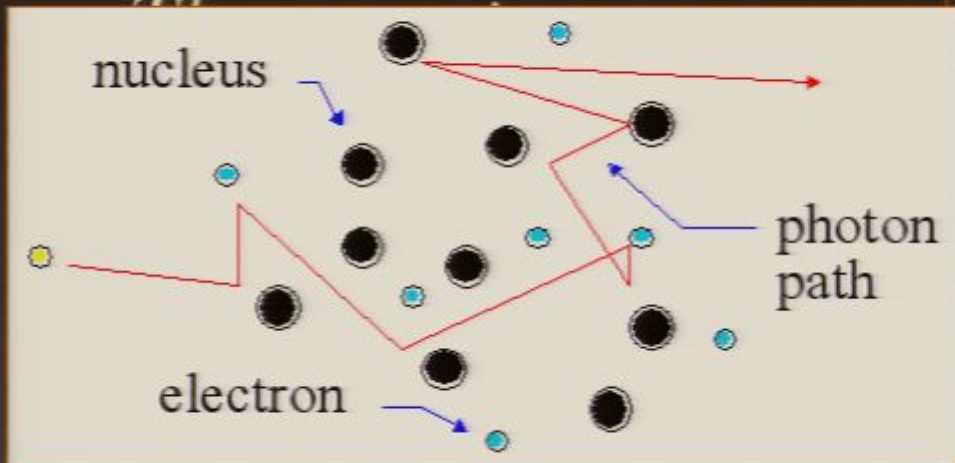
When the universe cools enough for atoms to form (around 10^3 K) it becomes transparent to light.

The light present at this time is still running around the universe.

This light is now seen as microwaves due to the intervening expansion of the universe.

Evidence for a Hot Big Bang

- Primordial element abundances



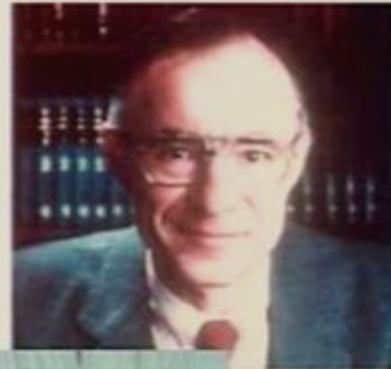
When the universe cools enough for atoms to form (around 10^3 K) it becomes transparent to light.

Above 1000 degrees atoms break up into electrons and nuclei.

Unlike atoms, electrons and nuclei carry electric charge and so scatter light very efficiently.

Evidence for a Hot Big Bang

- Primordial element abundances
- *The cosmic microwave background*
- T_{CMB} vs distance



Arno Penzias



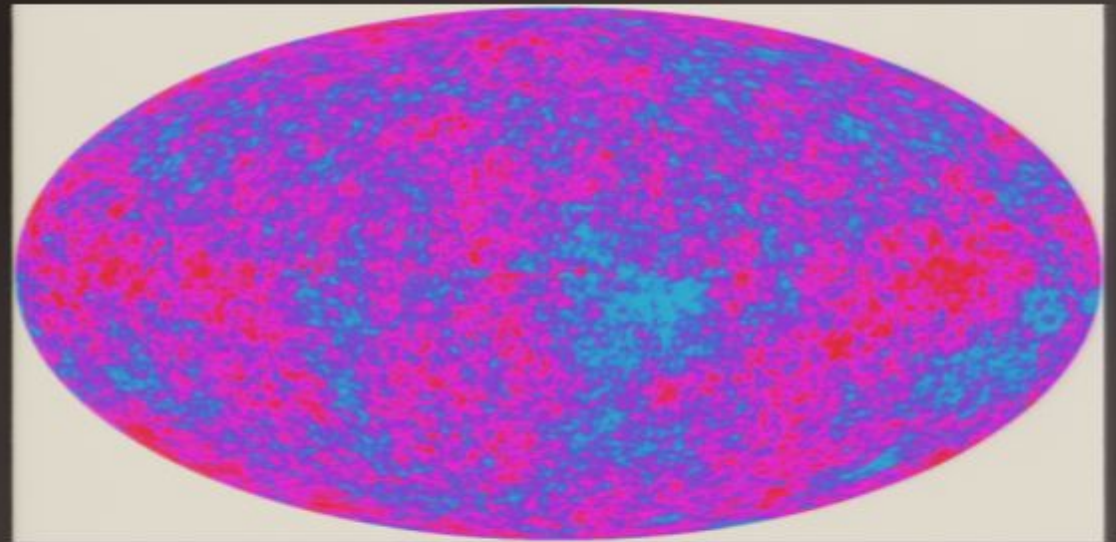
Robert Wilson



Evidence for a Hot Big Bang

- Primordial element abundances
- *The cosmic microwave background*
- T_{CMB} vs distance

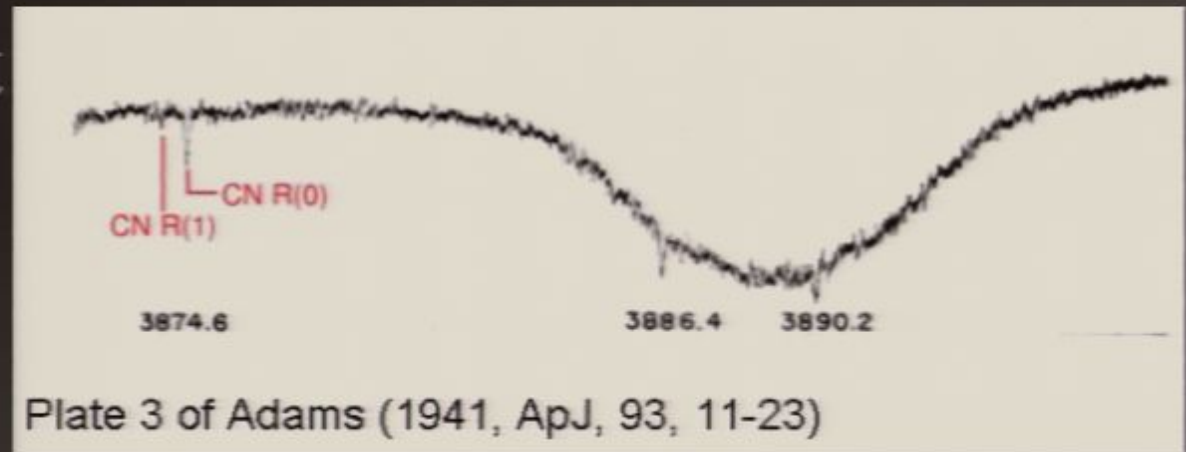
CMB Temperature vs Direction



WMAP collaboration

Evidence for a Hot Big Bang

- Primordial element abundances
- *The cosmic microwave background*
- T_{CMB} vs distance



Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:
"From the intensity ratio of the lines with $K=0$ and $K=1$ a rotational temperature of 2.3° K follows, which has of course only a **very restricted meaning.**"

Outline

- The Hot Big Bang
 - *Evidence for a Hot Expanding Universe*
 - *Dark Matter and Dark Energy*
- Contact With Fundamental Physics
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- Outlook

Evidence for Dark Matter

- Mass in galaxies
- Mass in clusters of galaxies
- Temperature fluctuations in the CMB
- Start of galaxy formation.

Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



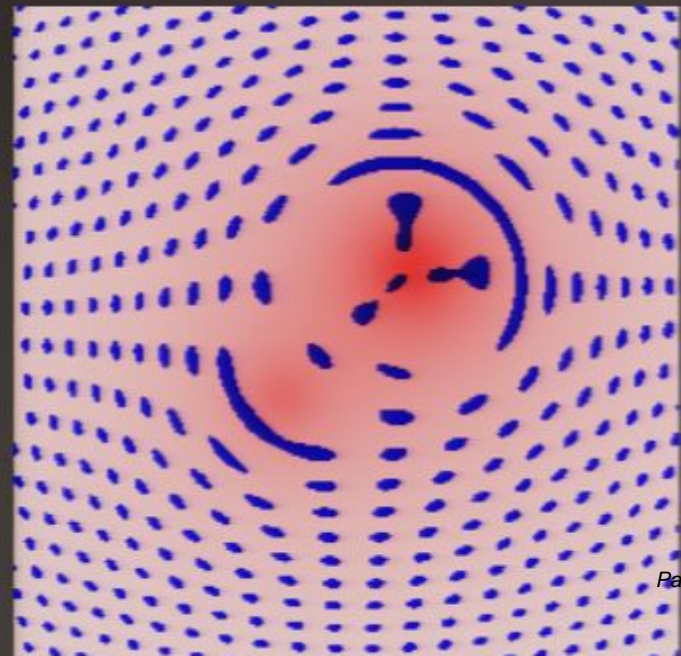
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



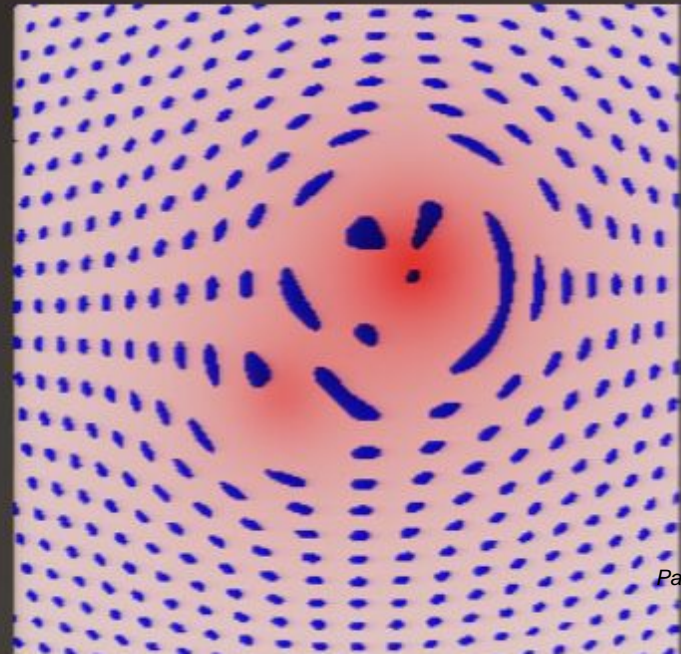
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



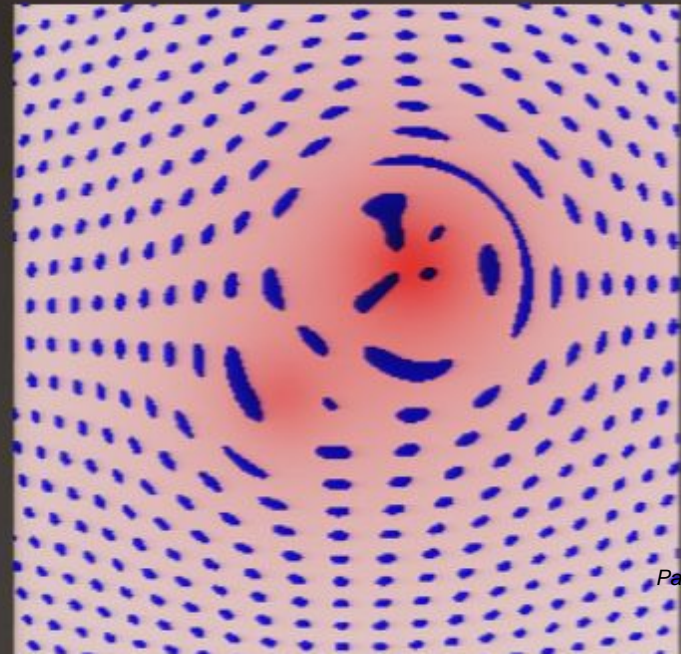
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



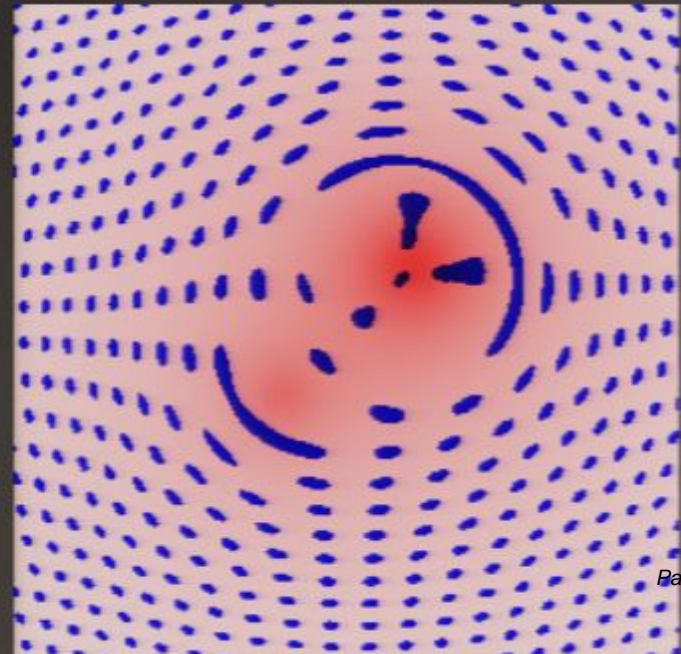
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



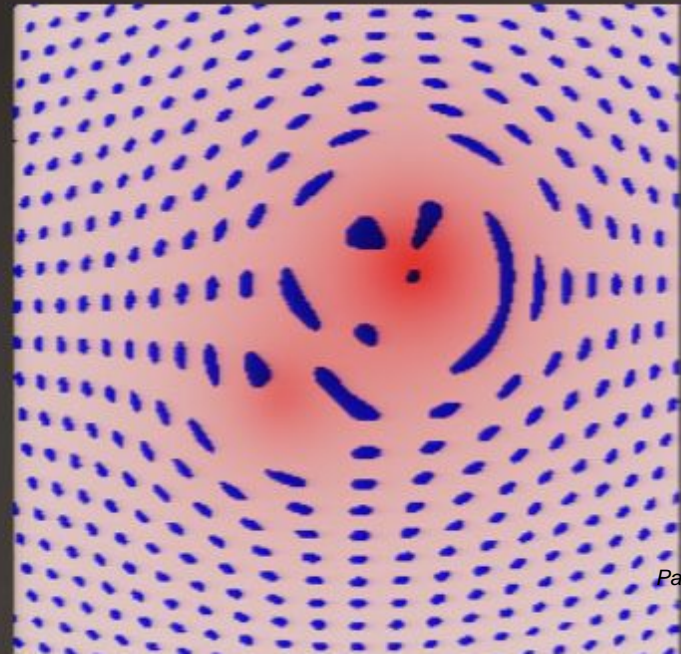
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



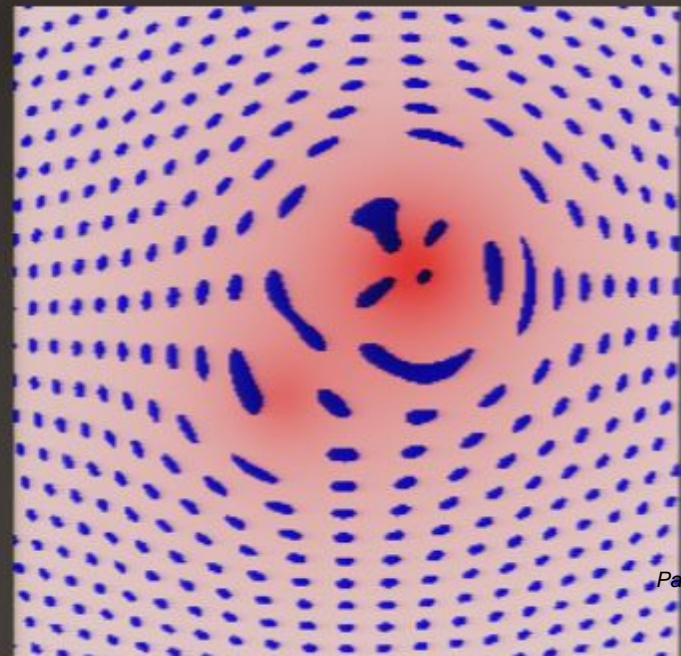
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



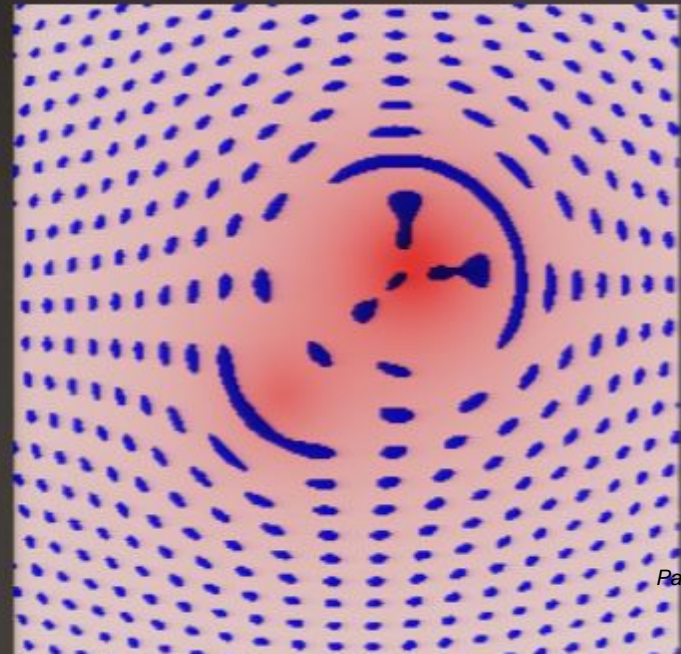
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



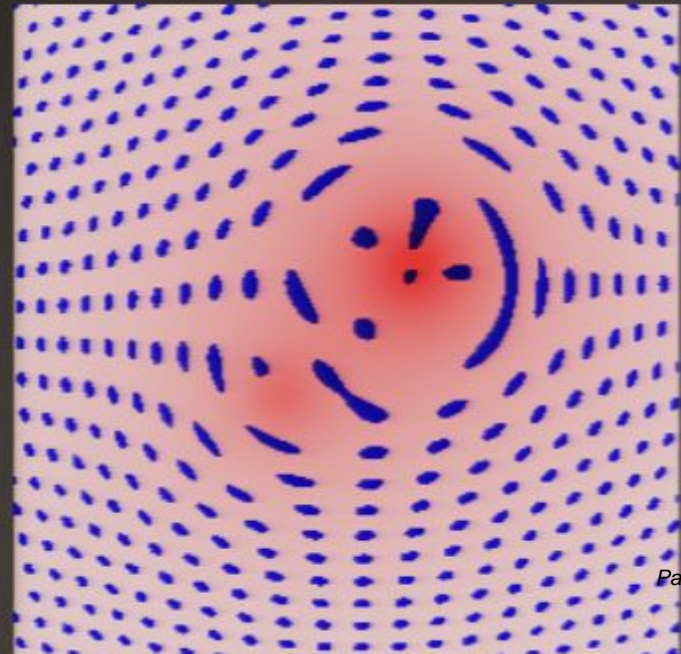
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



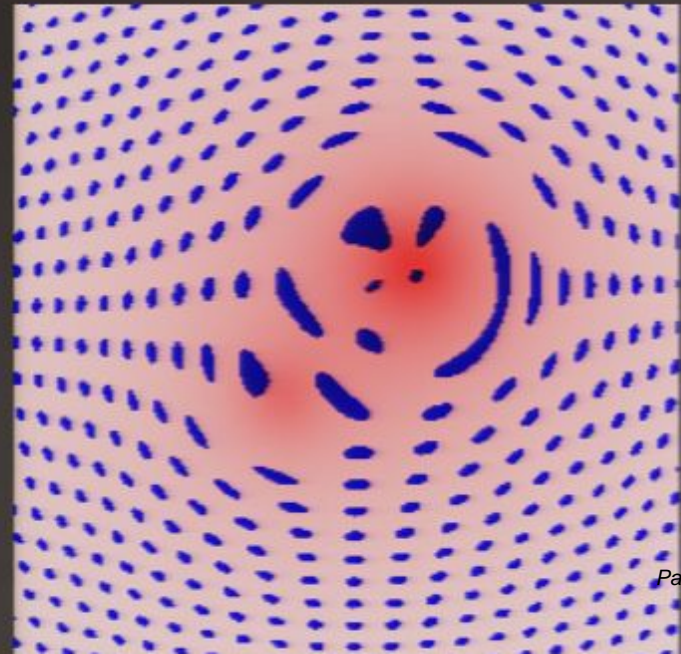
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



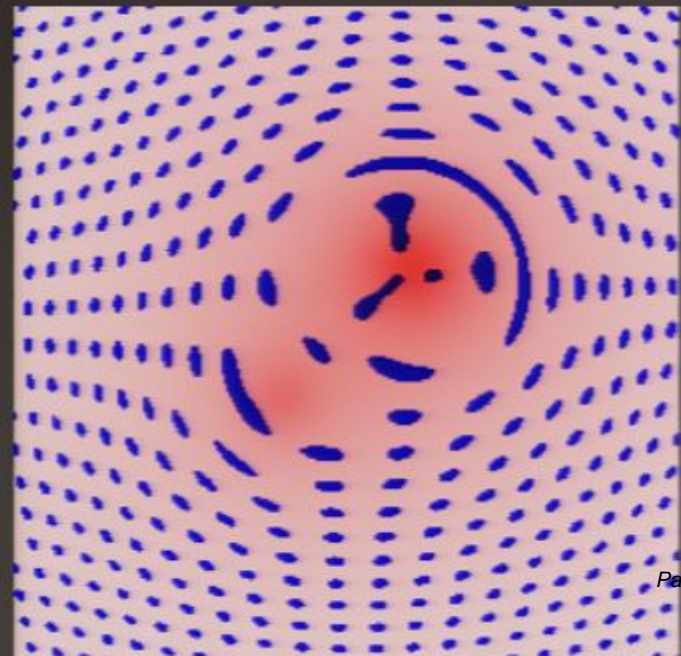
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



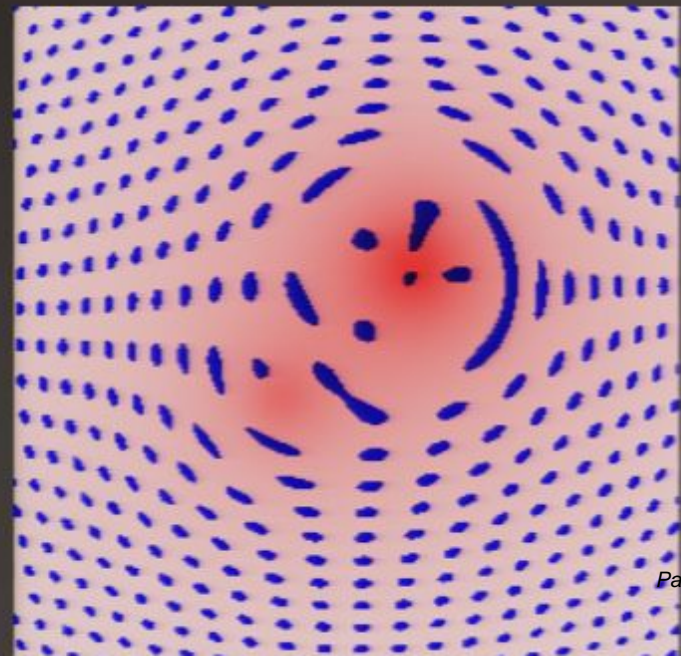
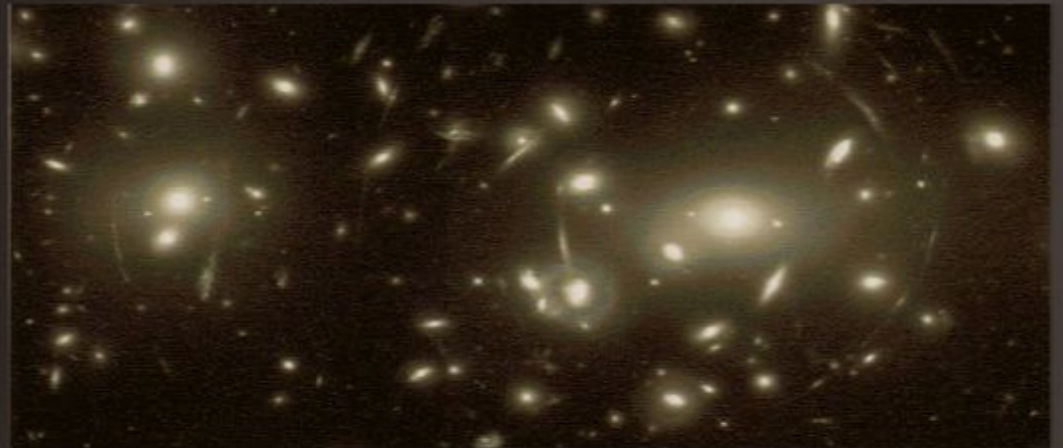
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



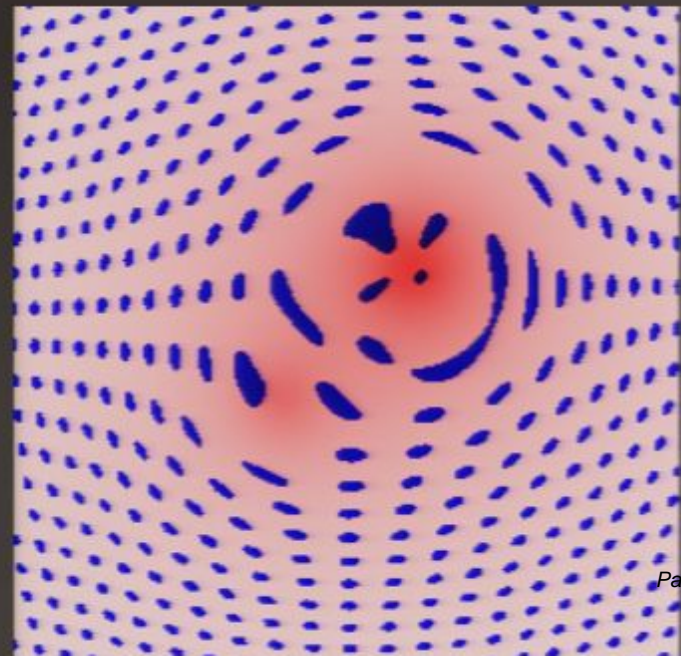
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



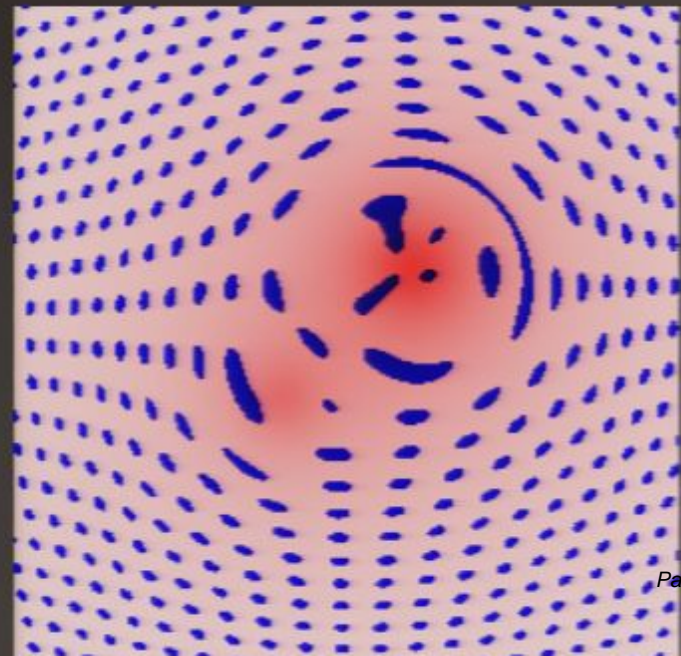
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



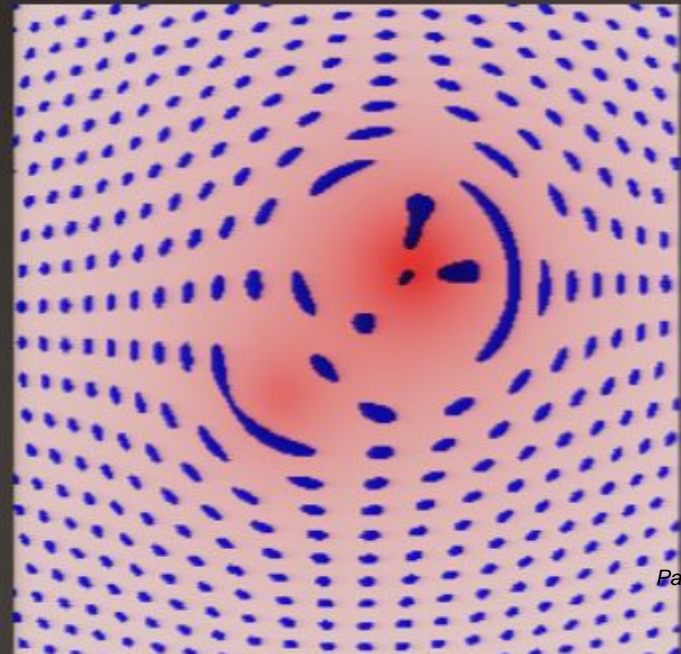
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



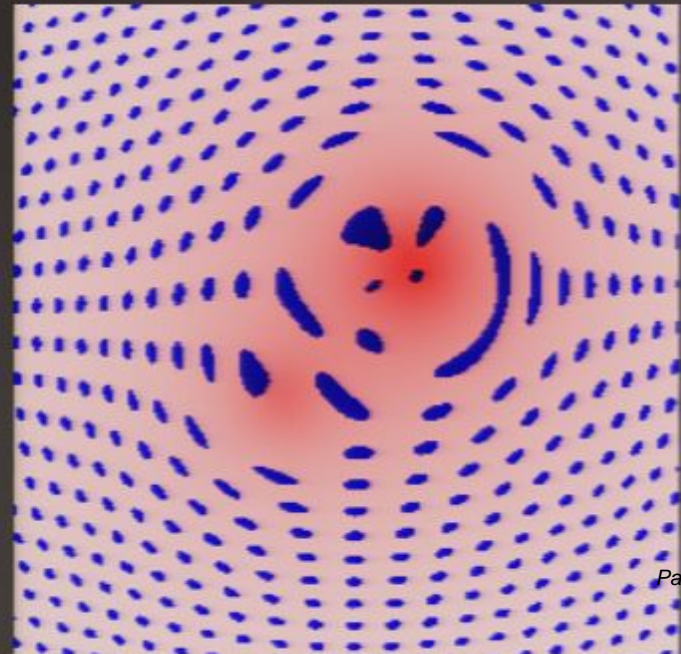
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



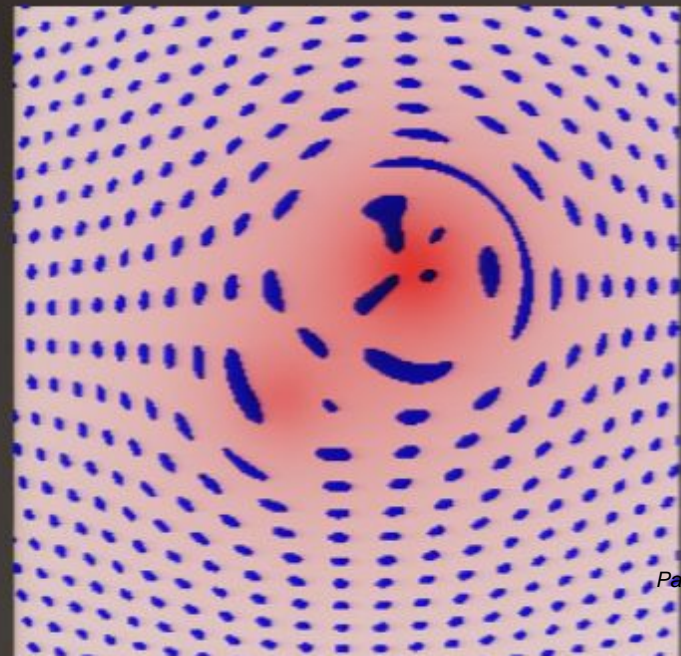
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



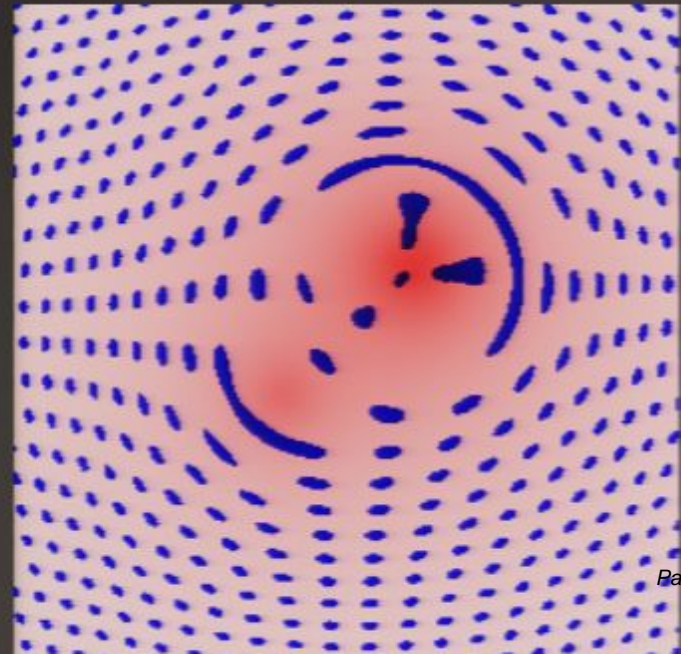
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



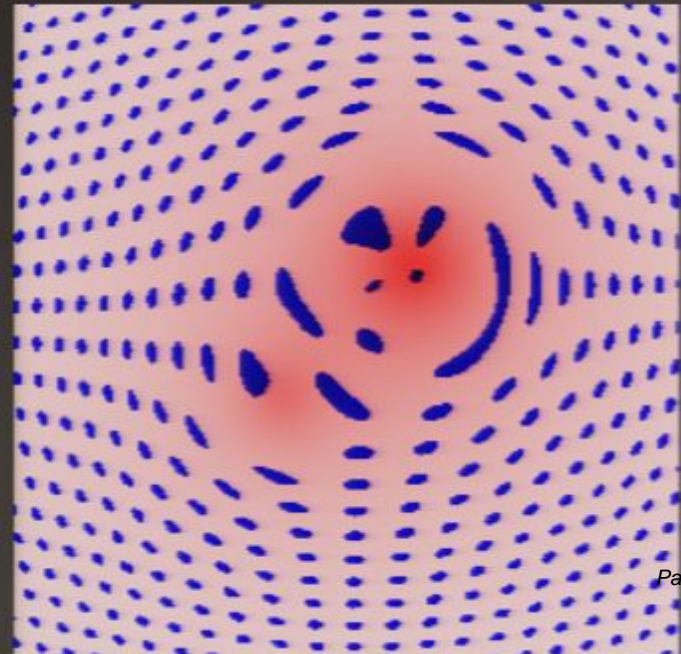
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



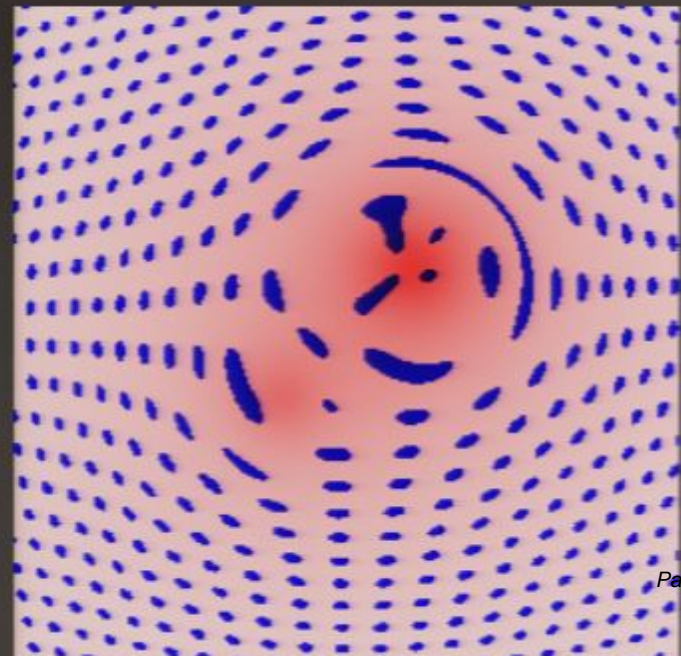
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



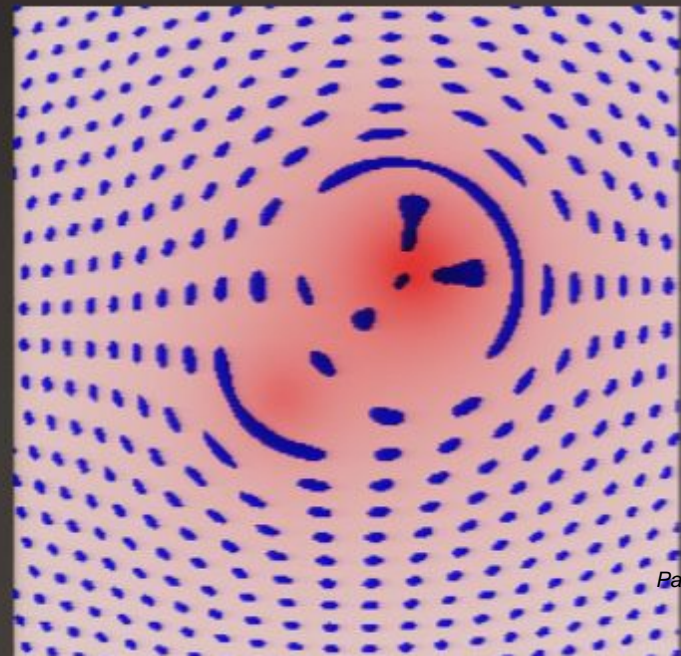
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



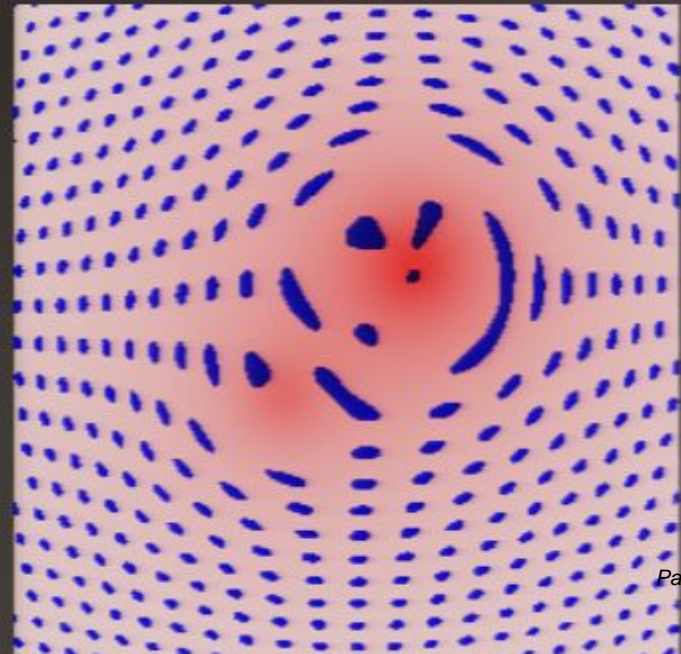
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



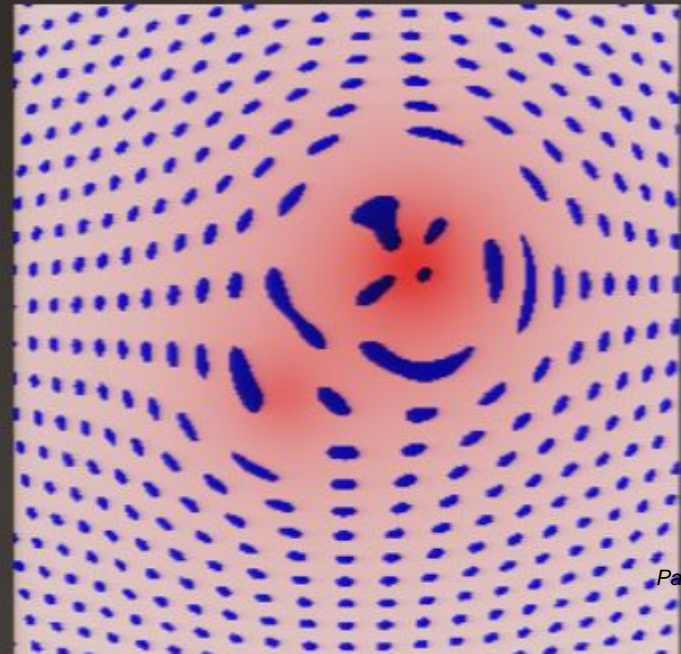
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



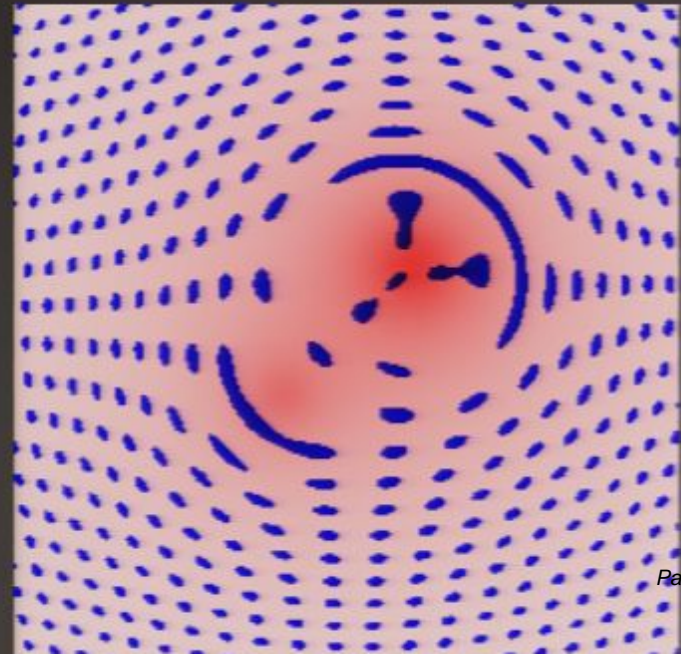
Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



Evidence for Dark Matter

- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation.



Evidence for Dark Energy

- Brightness of very distant supernovae
- Flatness of the universe as a whole

Evidence for Dark Energy

- *Brightness of very distant supernovae*
- Flatness of the universe as a whole

Very distant objects should not precisely follow Hubble's Law because gravitational attraction should decelerate the universal expansion.

This can be tested by looking for deviations from Hubble's Law for very distant supernovae.

Evidence for Dark Energy

- *Brightness of very distant supernovae*
- Flatness of the universe as a whole



Evidence for Dark Energy

- *Brightness of very distant supernovae*
- Flatness of the universe as a whole

Very distant objects should not precisely follow Hubble's Law because gravitational attraction should decelerate the universal expansion.

This can be tested by looking for deviations from Hubble's Law for very distant supernovae.

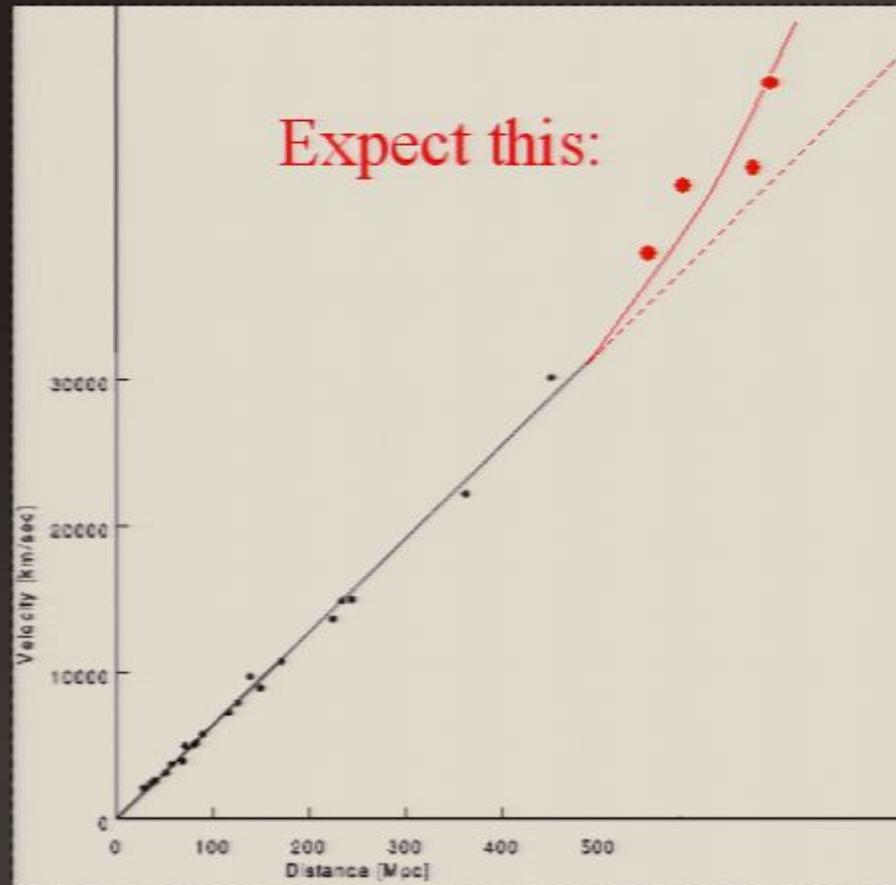
Evidence for Dark Energy

- *Brightness of very distant supernovae*
- Flatness of the universe as a whole



Evidence for Dark Energy

- *Brightness of very distant supernovae*
- *Flatness of the universe as a whole*

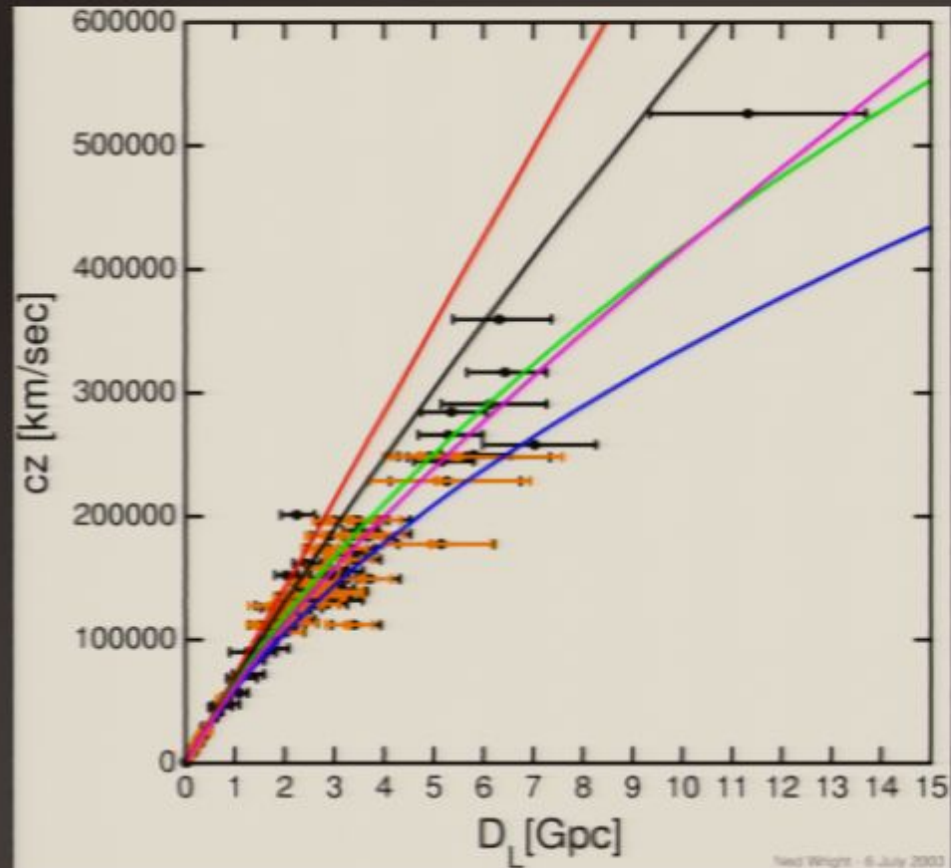


The universal expansion should be decelerating due to gravitational attraction

Evidence for Dark Energy

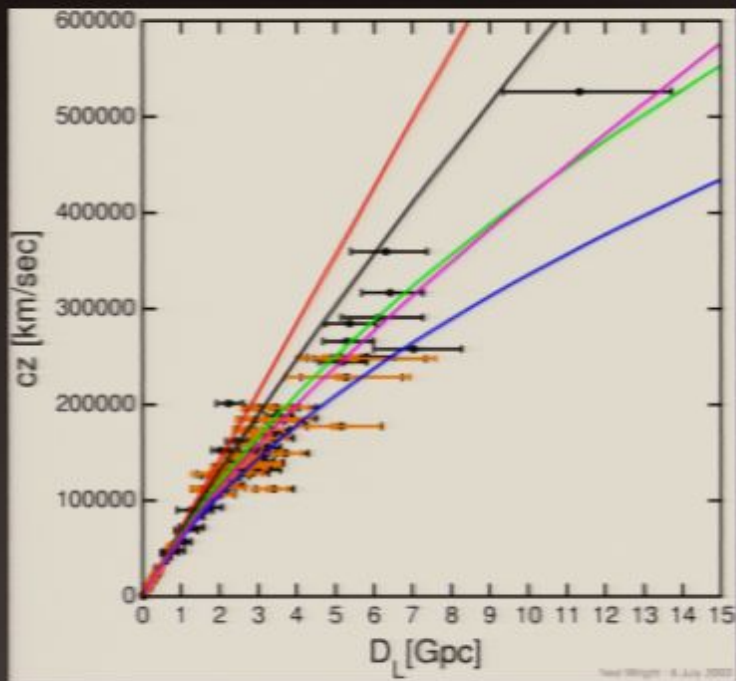
Tonrey et.al., 2003

- *Brightness of very distant supernovae*
- Flatness of the universe as a whole

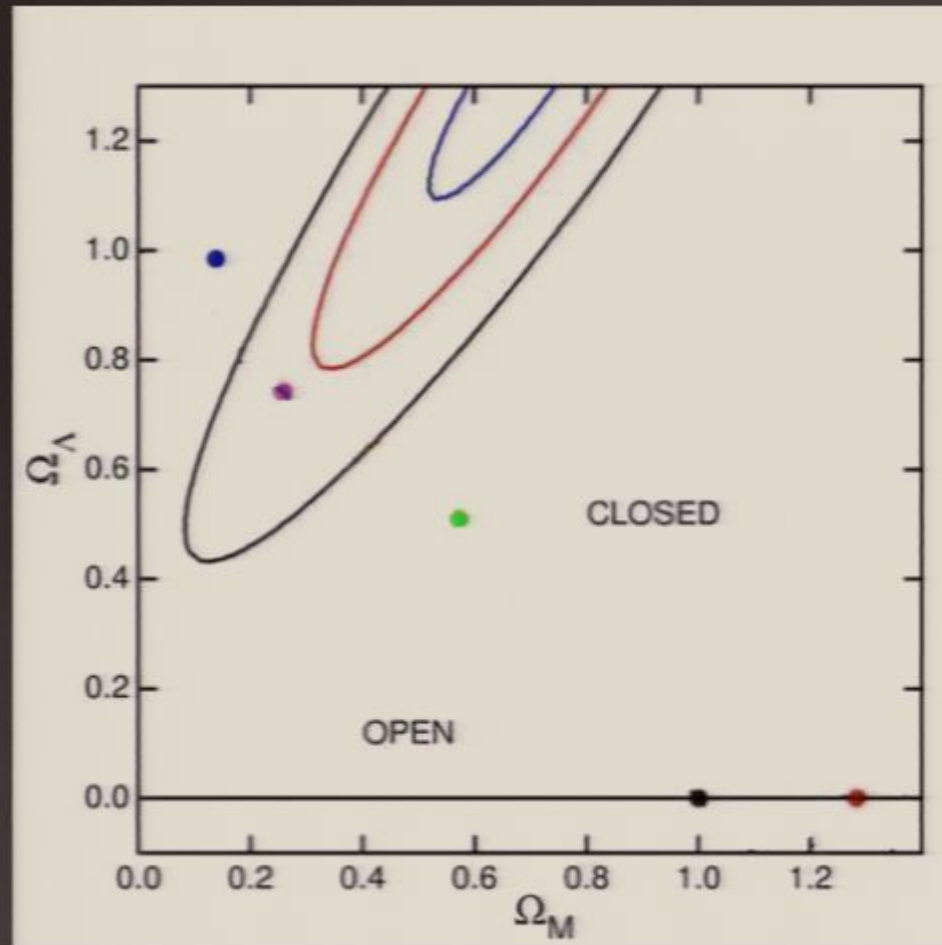


Evidence for Dark Energy

Tonrey et.al., 2003



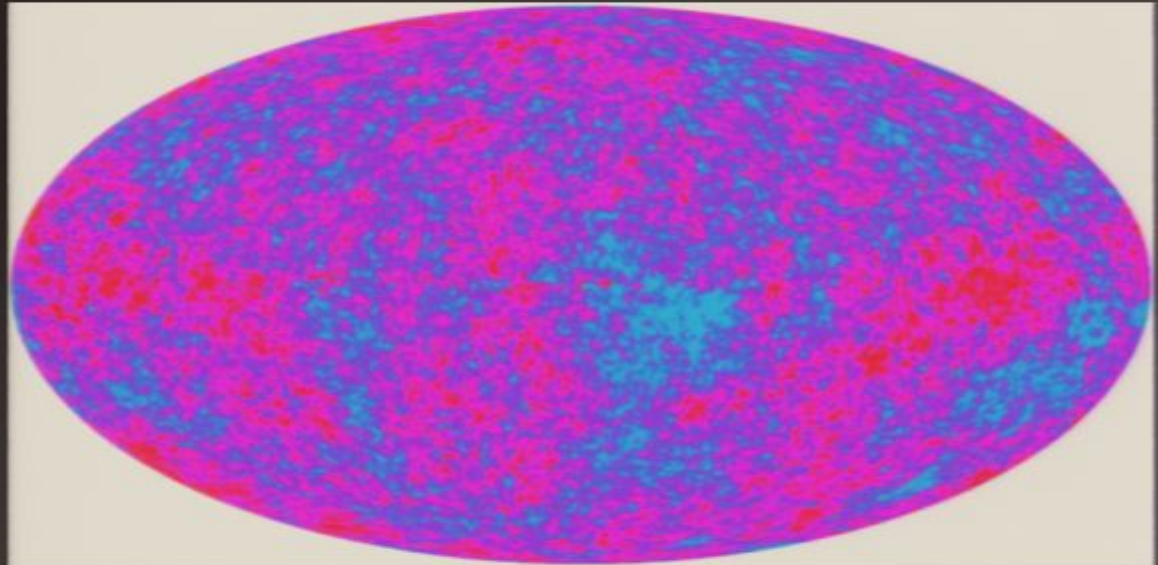
Amount of Dark Energy



Amount of Dark Matter

Evidence for Dark Energy

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*

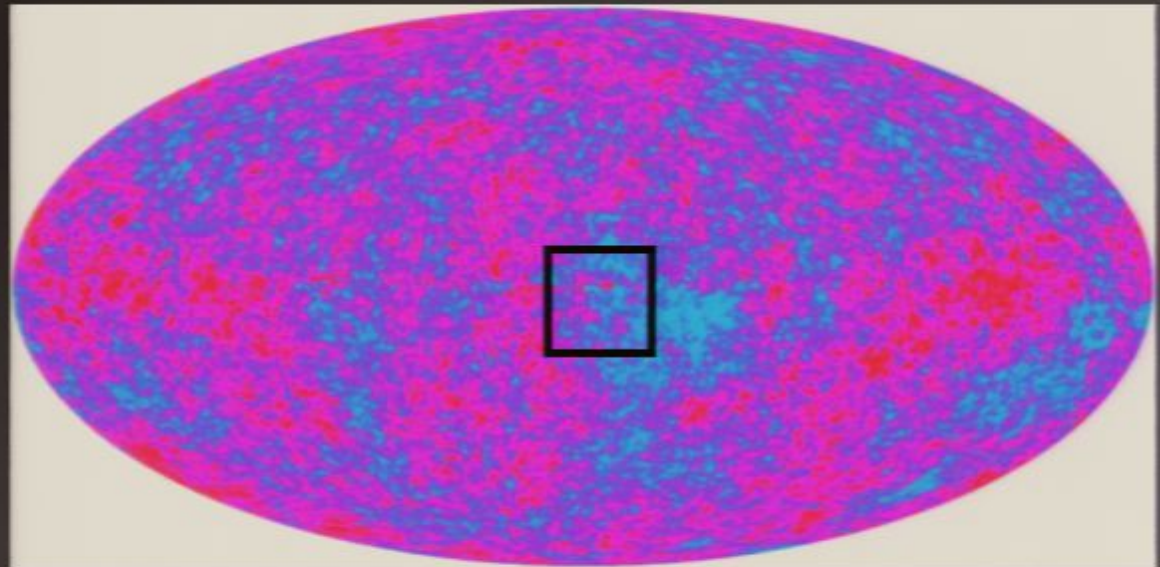


WMAP collaboration

Small temperature variations, at the level of one part in 100,000, are visible in the CMB

Evidence for Dark Energy

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*

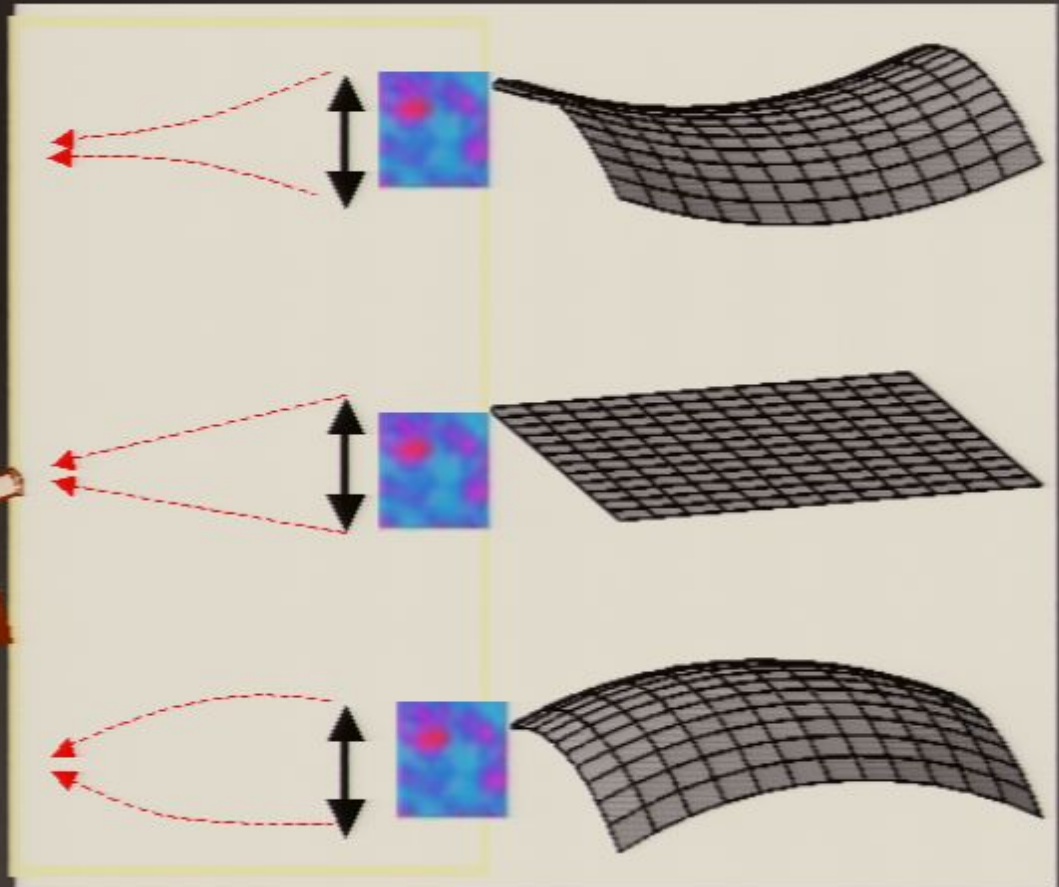


WMAP collaboration

These are due to sound waves in the primordial gas which emitted this light.

Evidence for Dark Energy

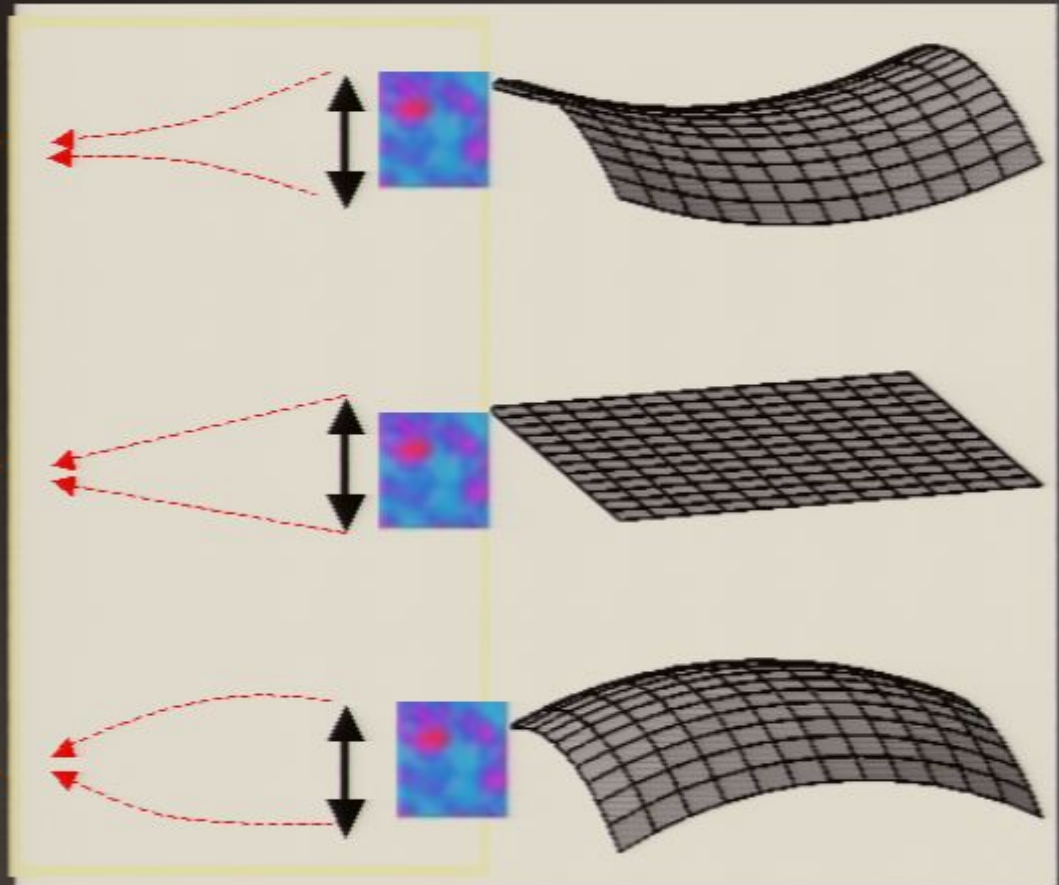
- Brightness of very distant supernovae
- *Flatness of the universe as a whole*



Size of the CMB fluctuations depends on the geometry of space the light traverses.

Evidence for Dark Energy

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*



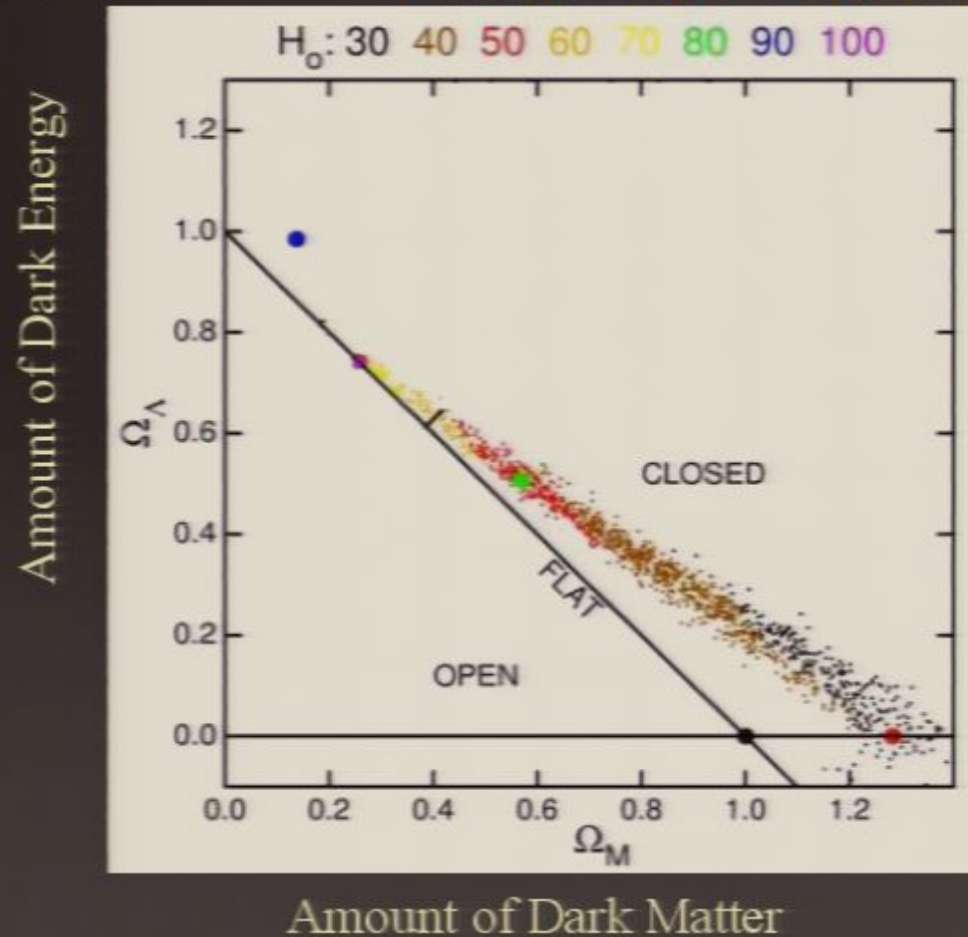
... but the geometry of space depends on the amount and kind of matter it contains

Evidence for Dark Energy

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*

Courtesy: Ned Wright's Cosmology Page

WMAP collaboration



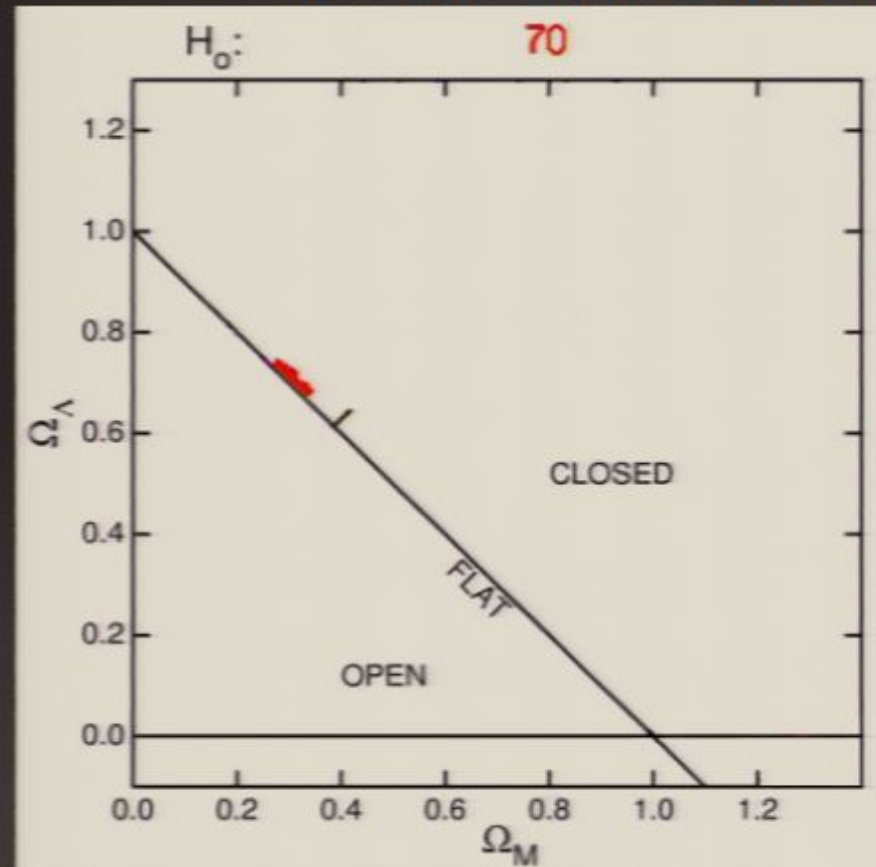
Measurement of CMB fluctuations correlate flatness with the universal expansion rate, H_0

Evidence for Dark Energy

WMAP collaboration

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*

Amount of Dark Energy



Amount of Dark Matter

Courtesy: Ned Wright's Cosmology Page

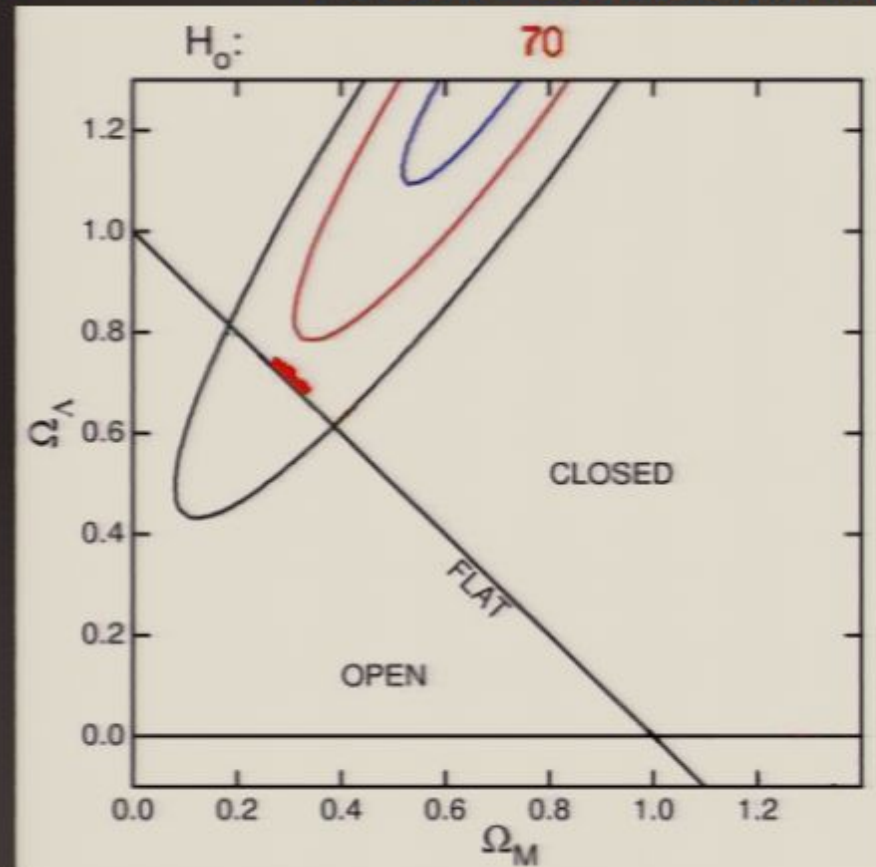
Measured H_0 with CMB fluctuations prefers a flat universe.

Evidence for Dark Energy

WMAP collaboration

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*

Amount of Dark Energy



Amount of Dark Matter

Courtesy: Ned Wright's Cosmology Page

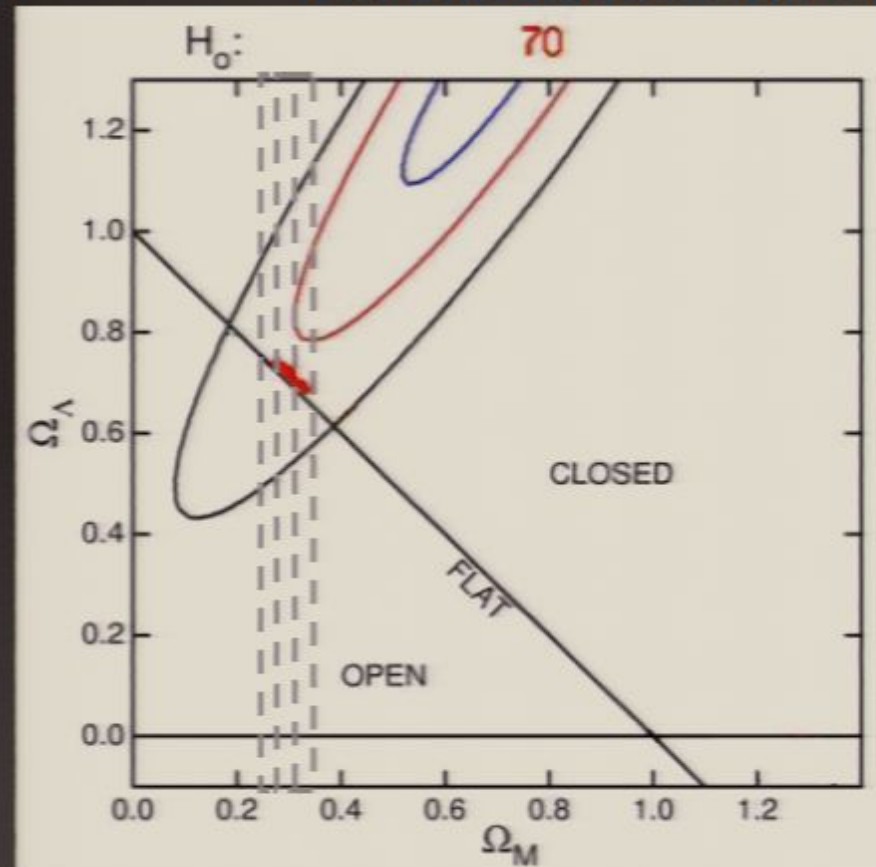
Dark Energy required to explain CMB is consistent with what universal acceleration requires.

Evidence for Dark Energy

WMAP collaboration

- Brightness of very distant supernovae
- *Flatness of the universe as a whole*

Amount of Dark Energy

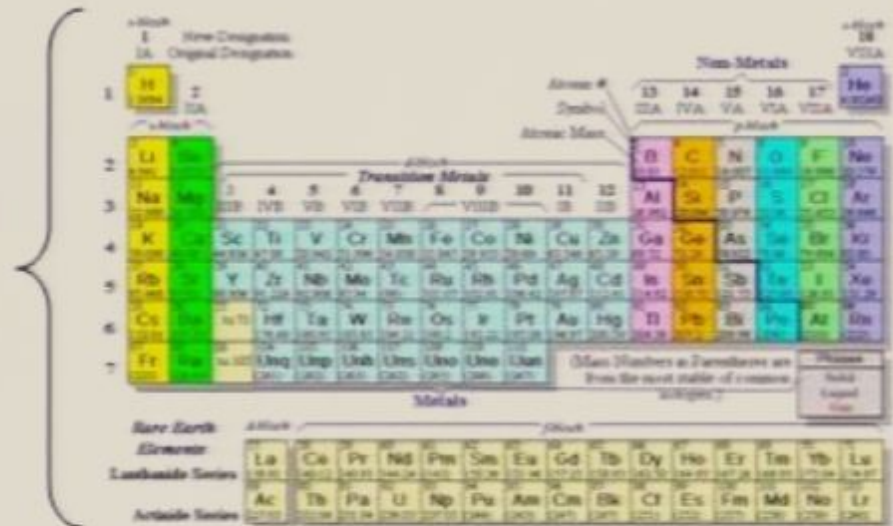


Amount of Dark Matter

Courtesy: Ned Wright's Cosmology Page

Dark Energy required to explain CMB is consistent with the measured amount of Dark Matter

Concordance Cosmology



From best fits to the 'Concordance Cosmology'

Outline

- The Hot Big Bang
 - *Evidence for a Hot Expanding Universe*
 - *Dark Matter and Dark Energy*
- Contact With Fundamental Physics
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- Outlook

Contact With Fundamental Physics

“If you are out to describe the truth, leave elegance to the tailor.”

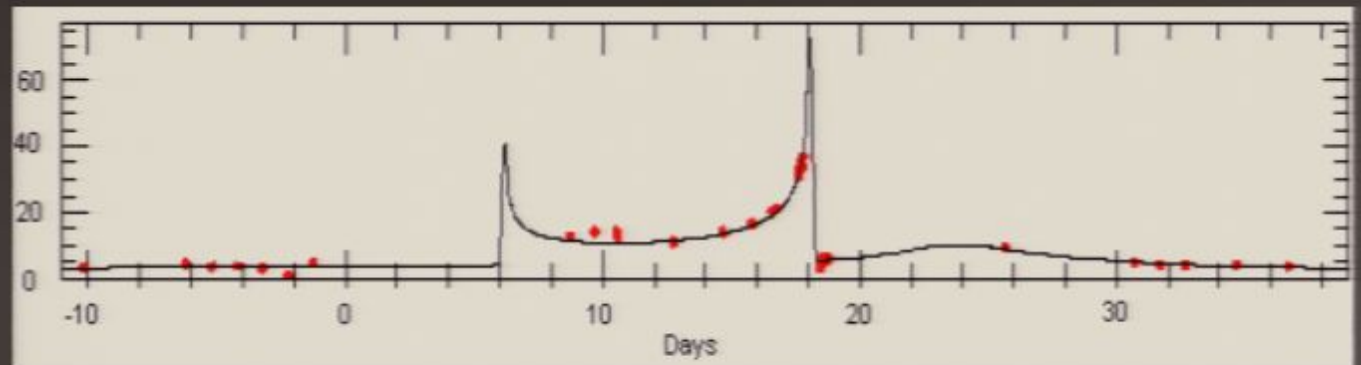
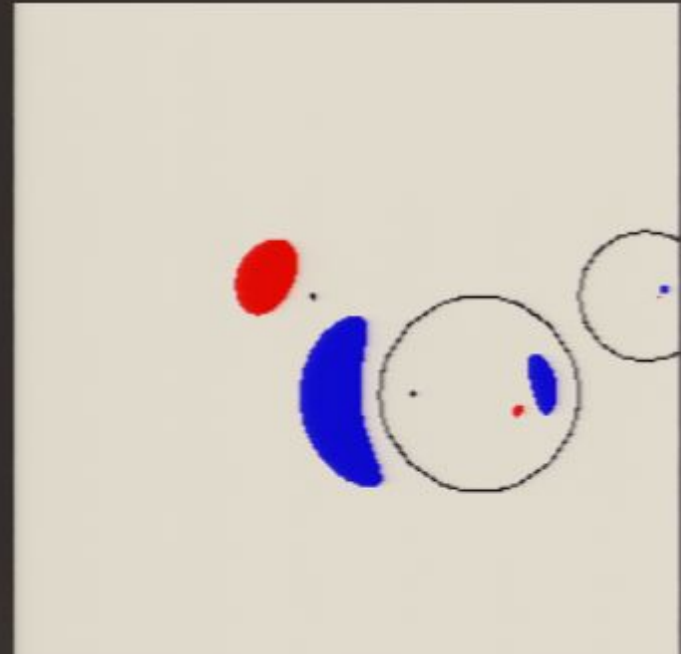
Albert Einstein

What is the Dark Matter?


- Ordinary atoms?
- Modifications to the Law of Gravity?
- New kind of particles?

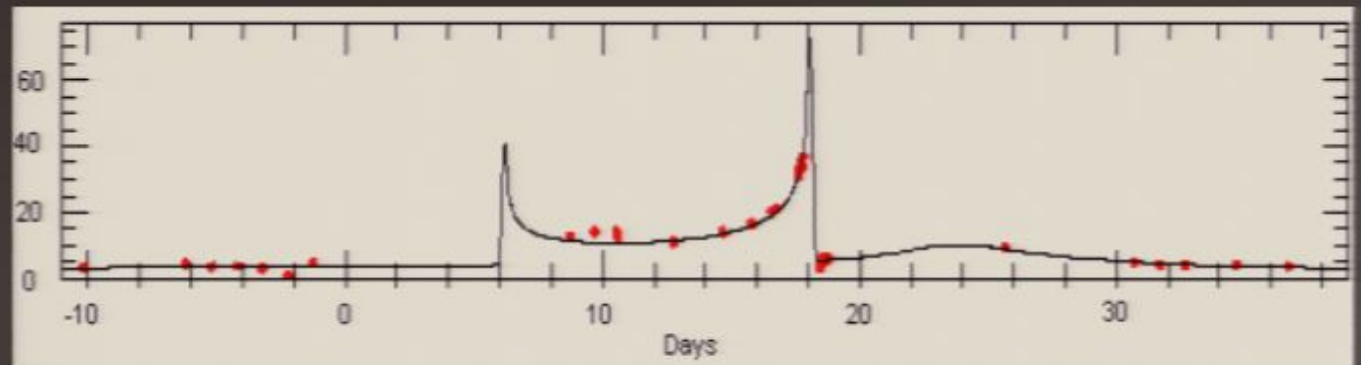
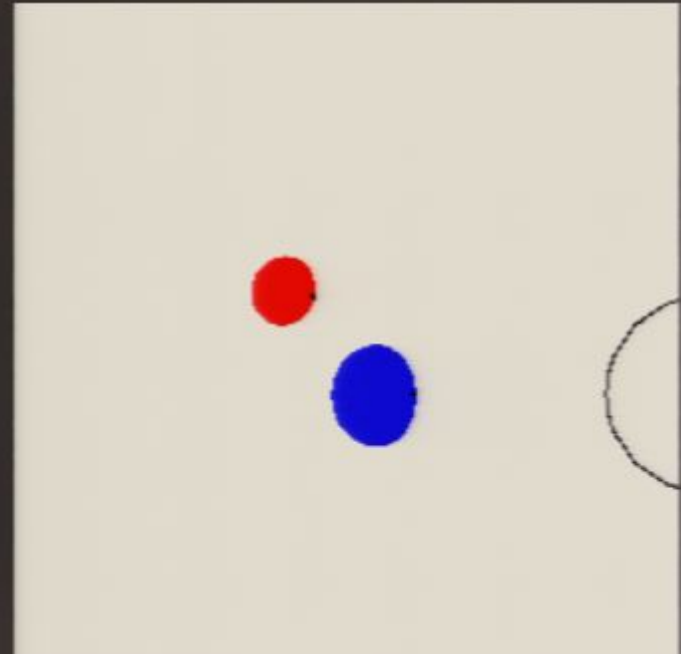
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



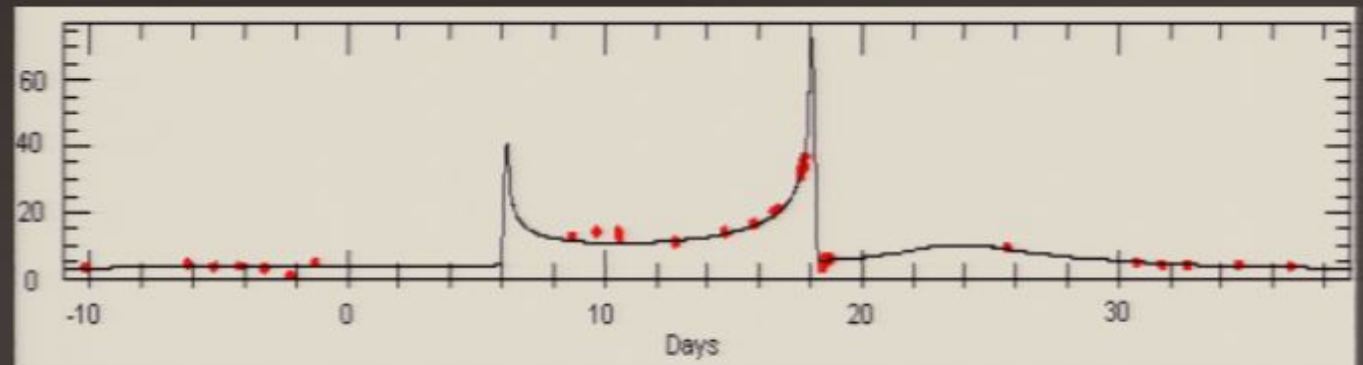
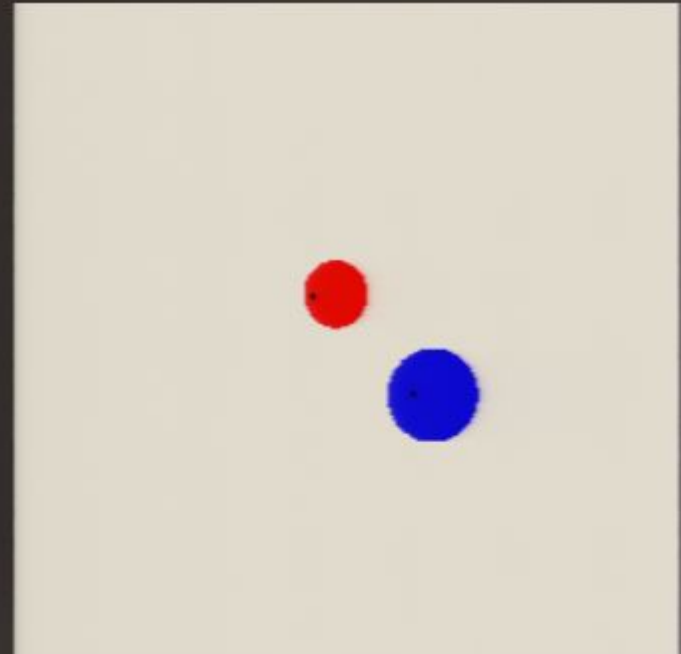
What is the Dark Matter?

- *Ordinary atoms?* 
- Modifications to the Law of Gravity?
- New kind of particles?



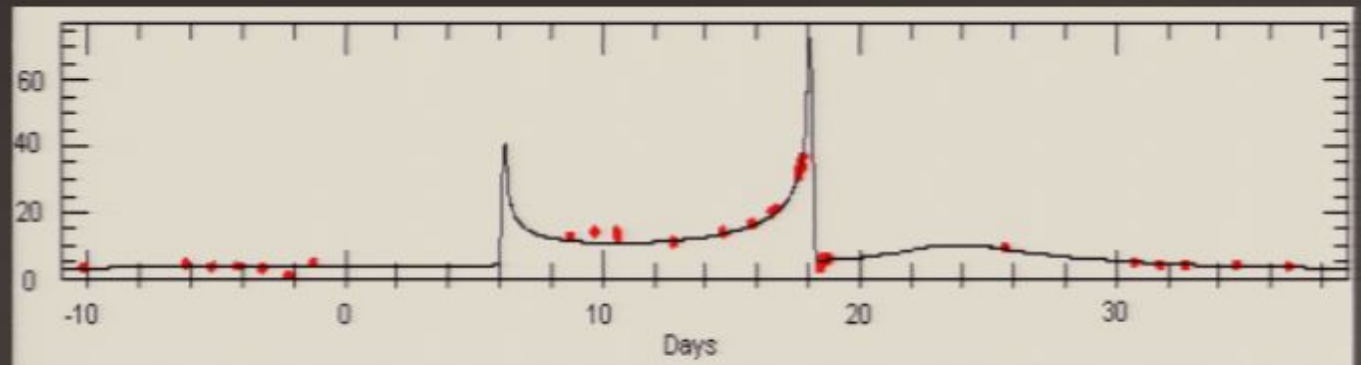
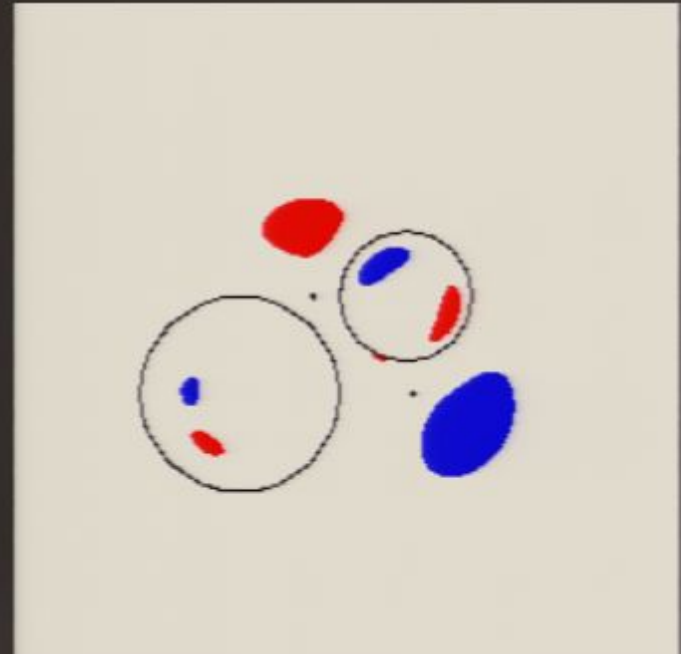
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



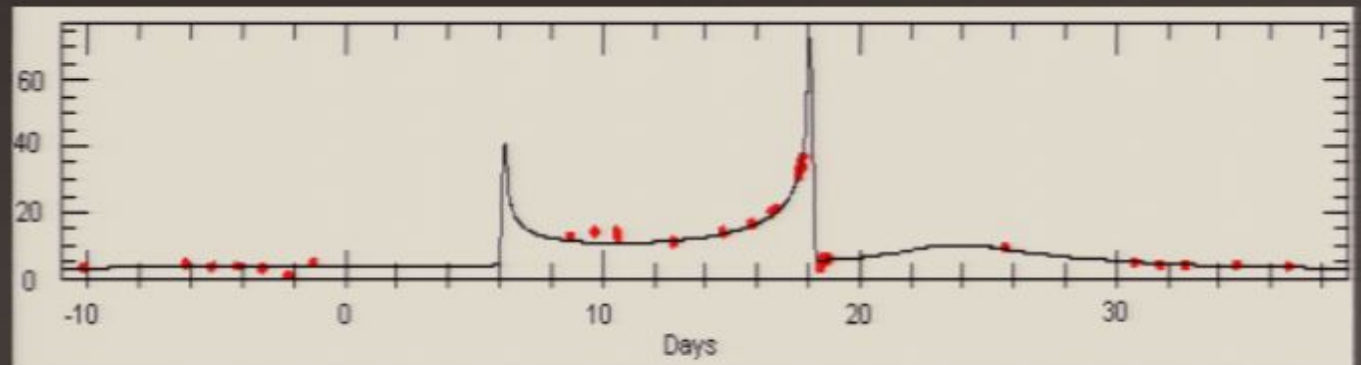
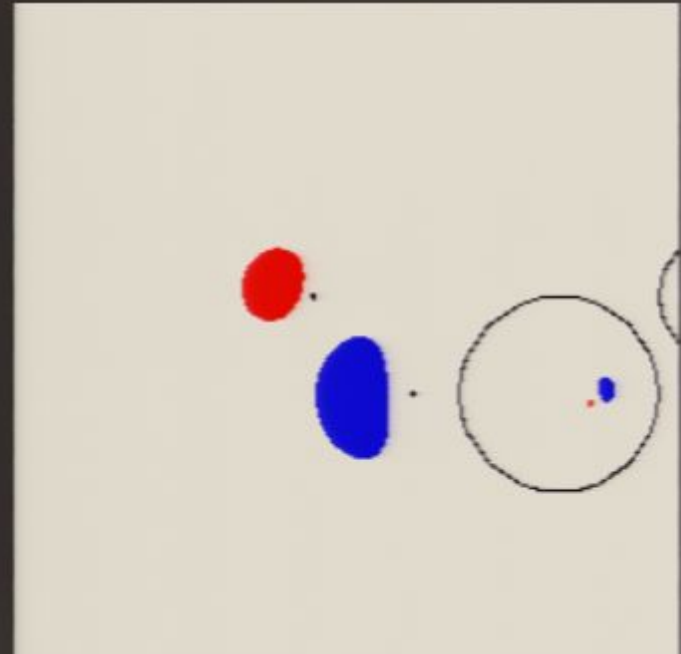
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



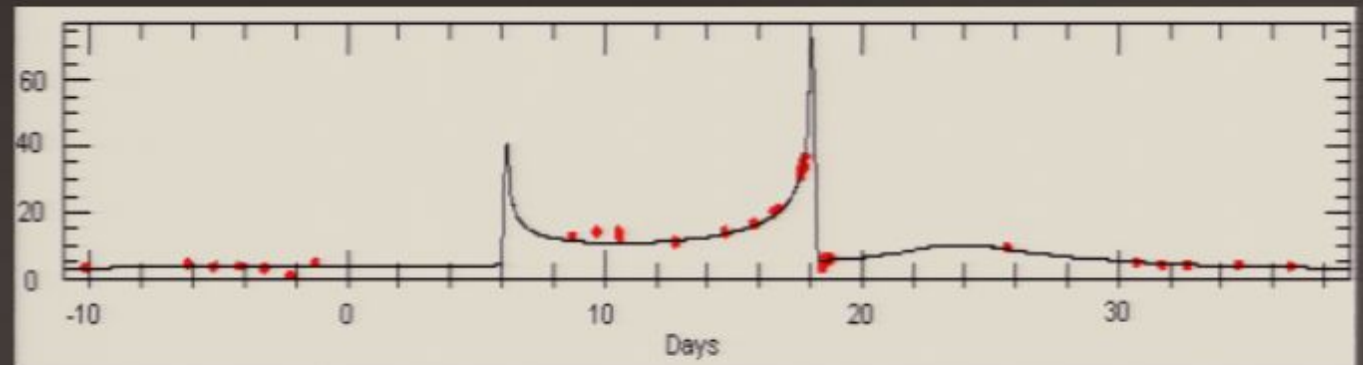
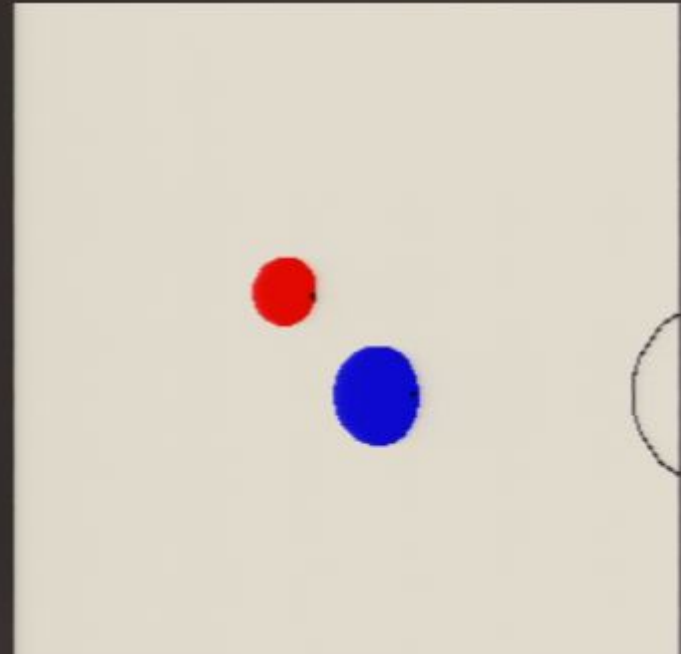
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



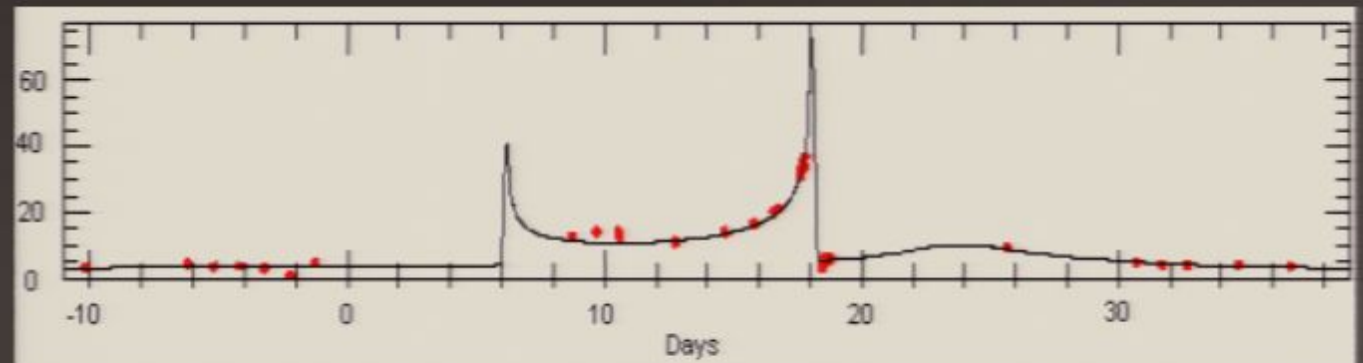
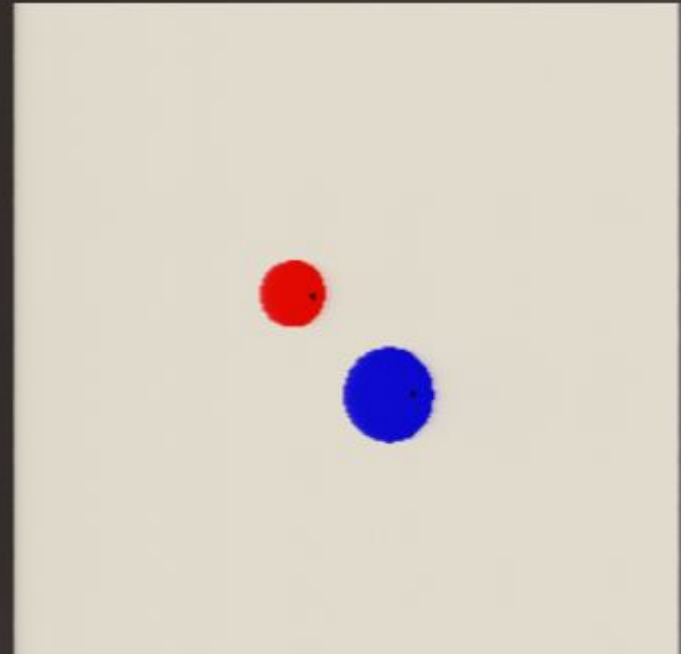
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



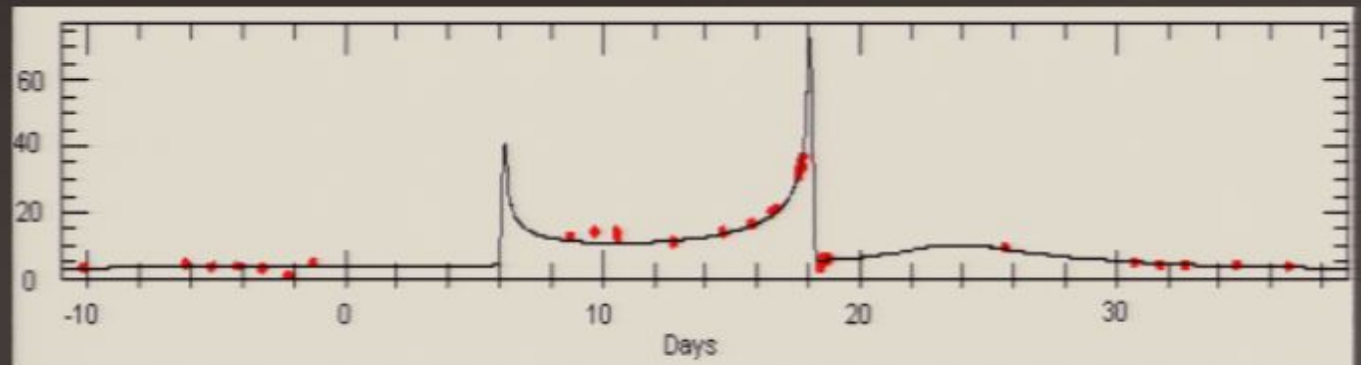
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?




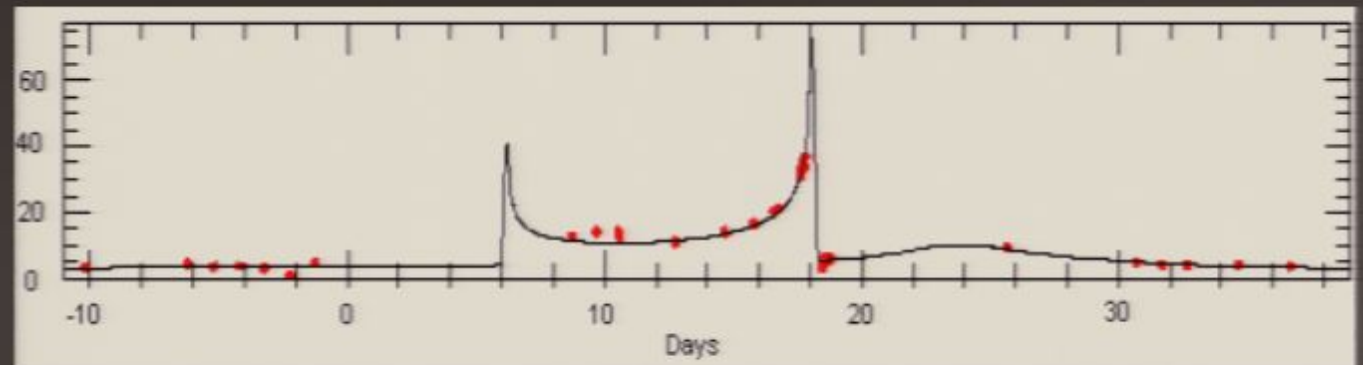
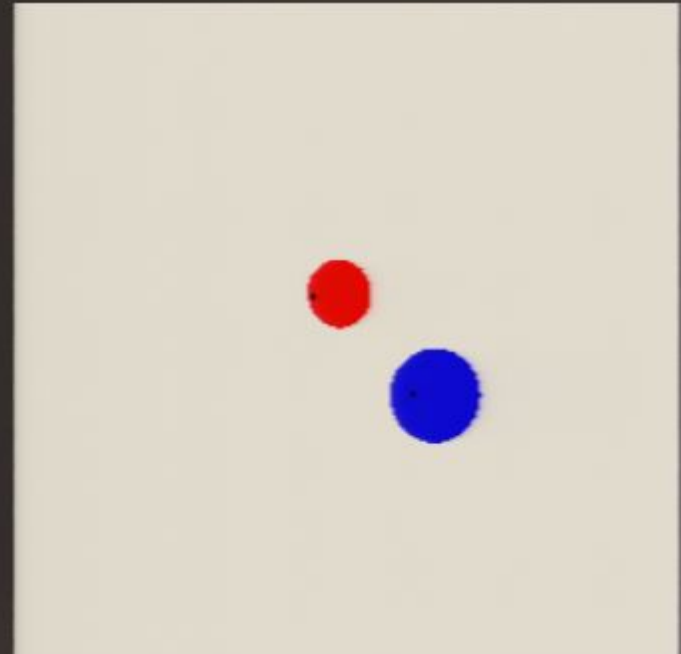
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



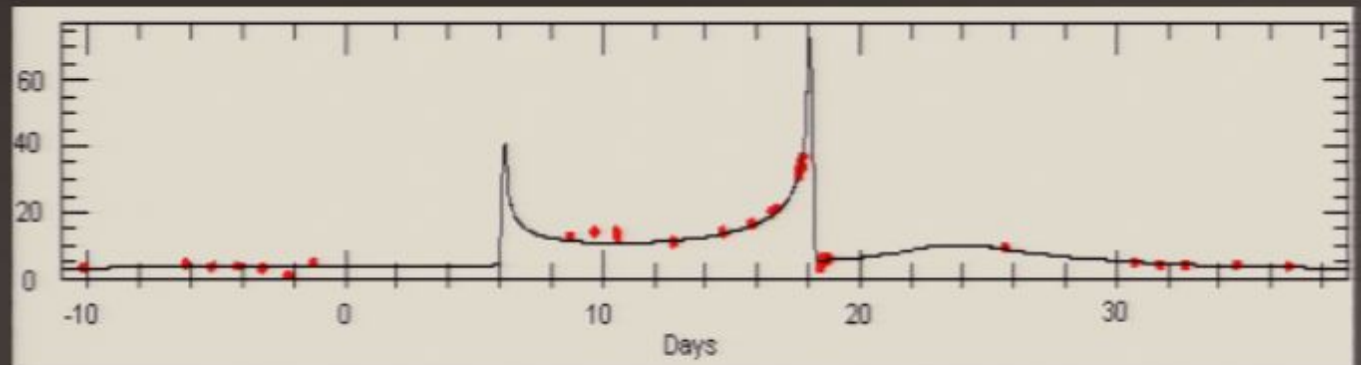
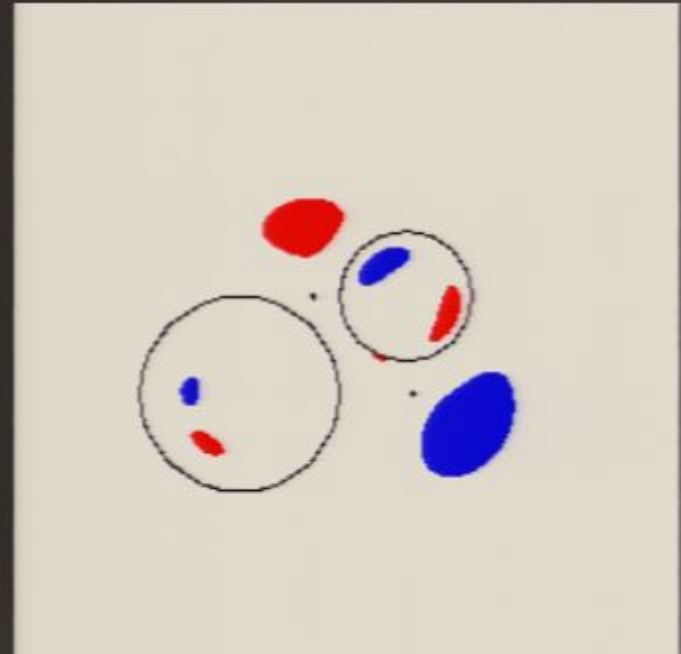
What is the Dark Matter?

- *Ordinary atoms?* 
- Modifications to the Law of Gravity?
- New kind of particles?



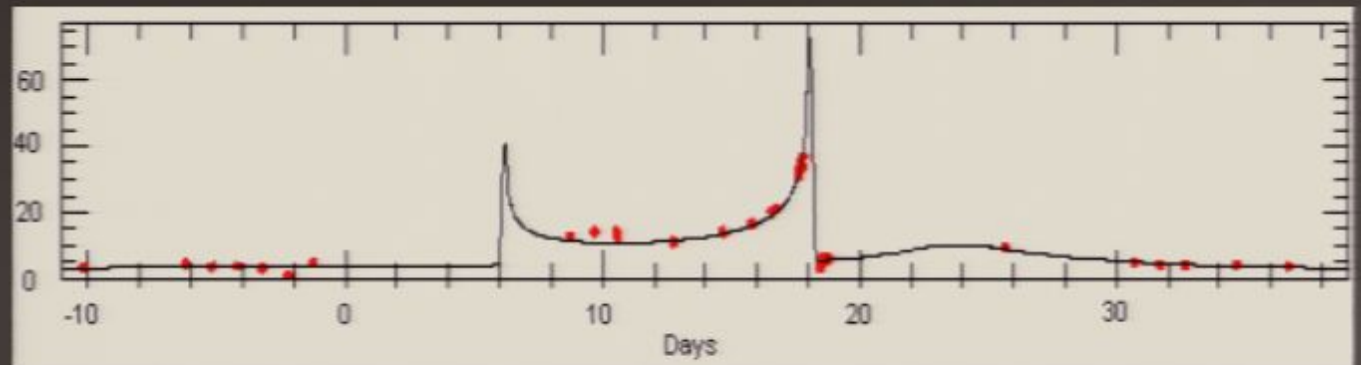
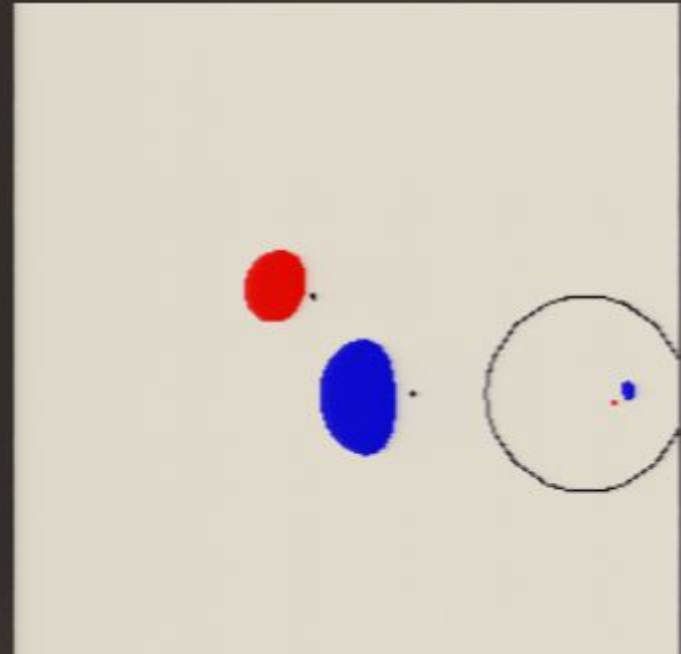
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



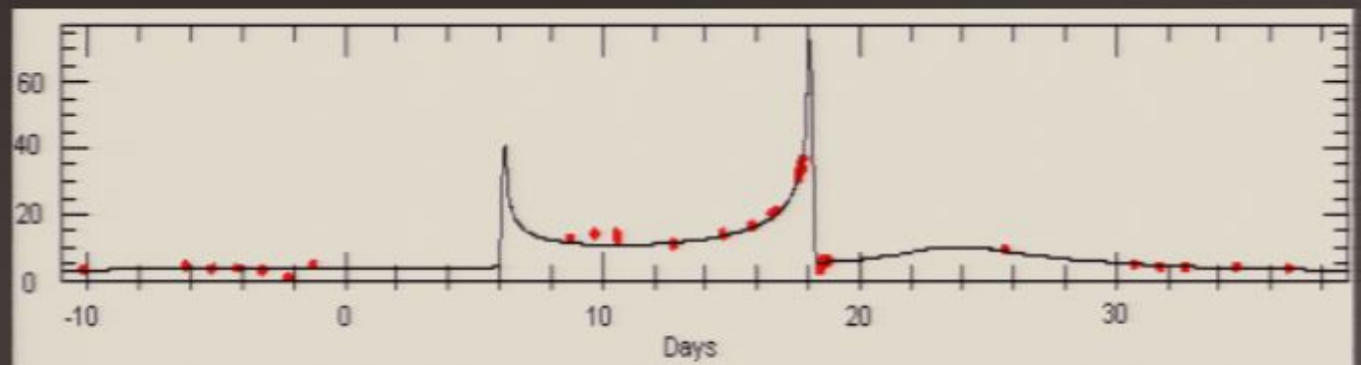
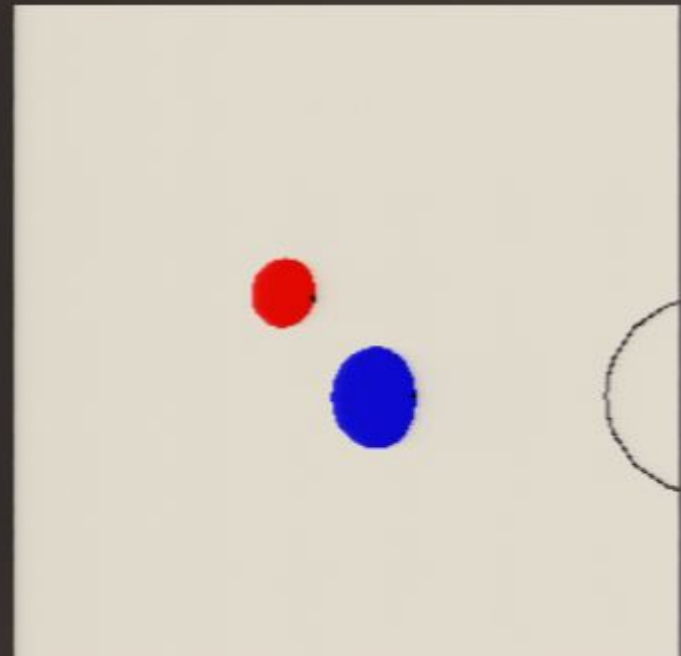
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



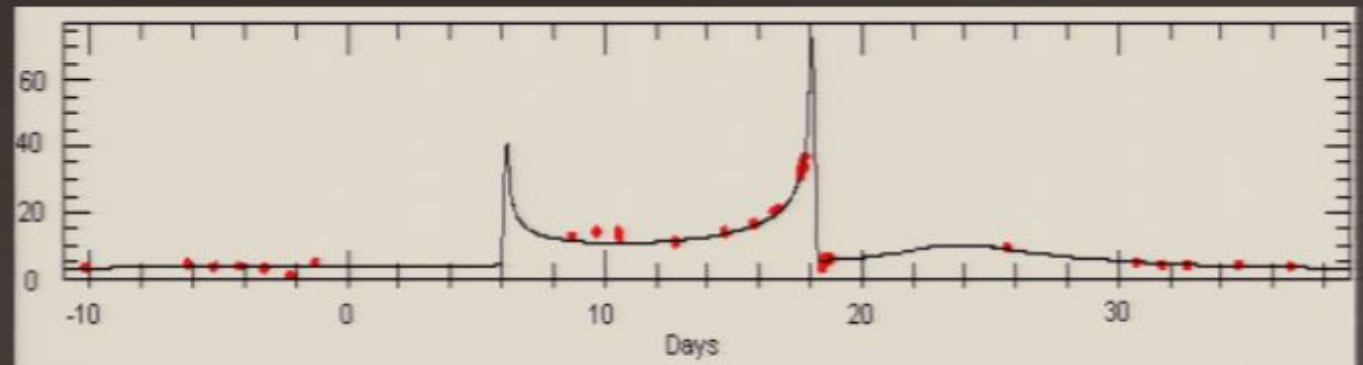
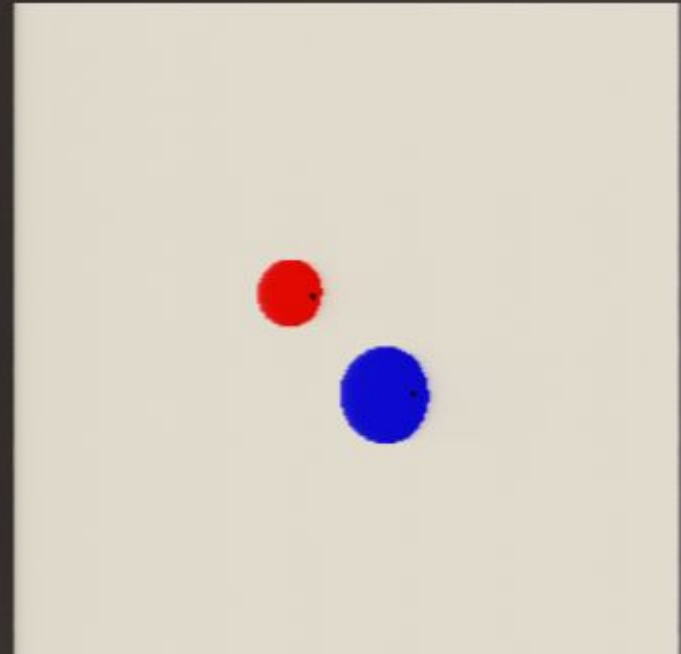
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



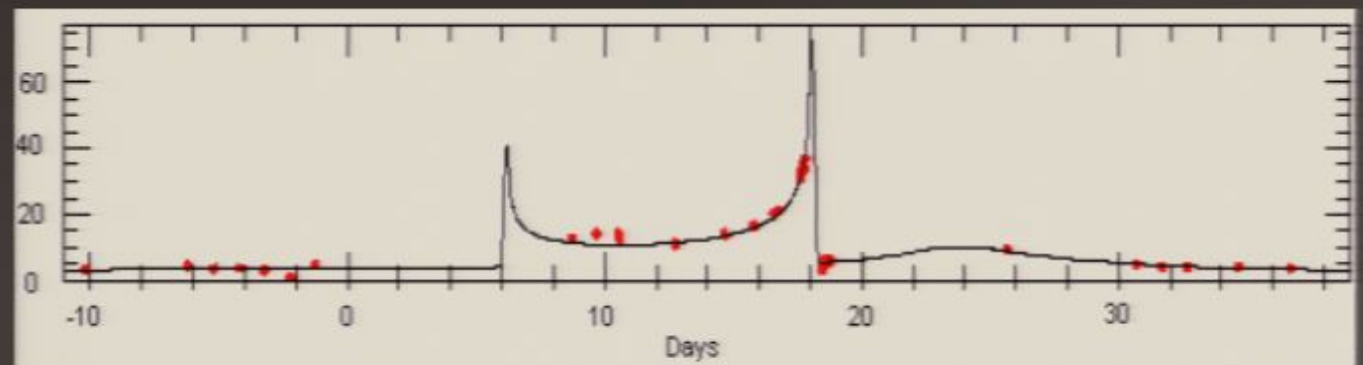
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



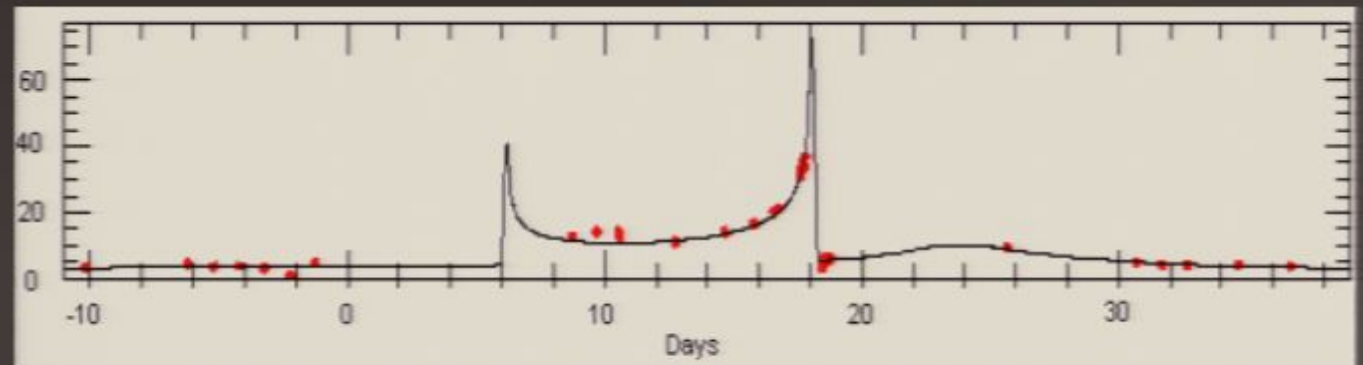
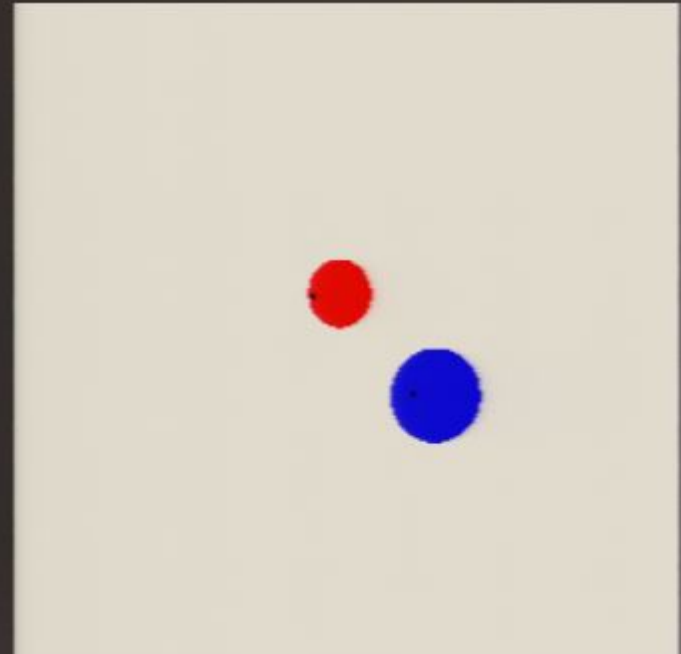
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



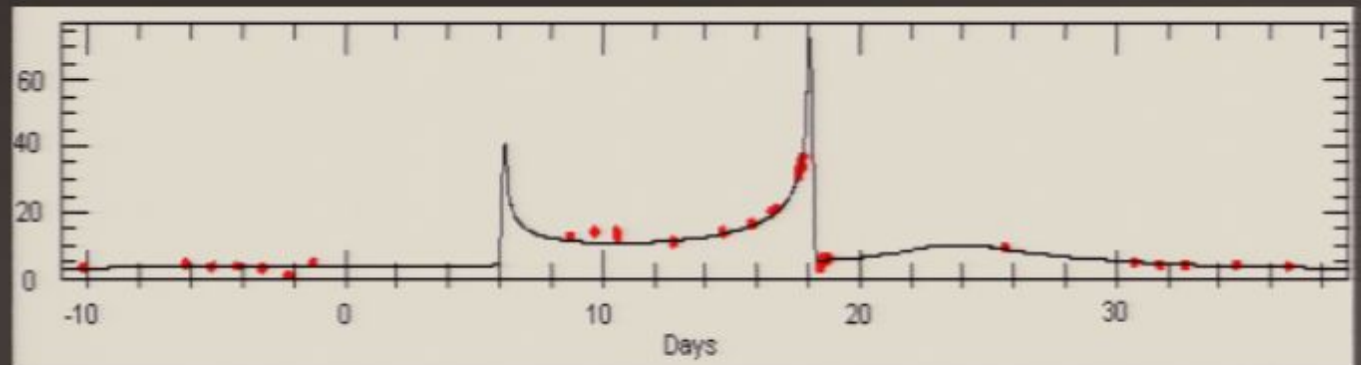
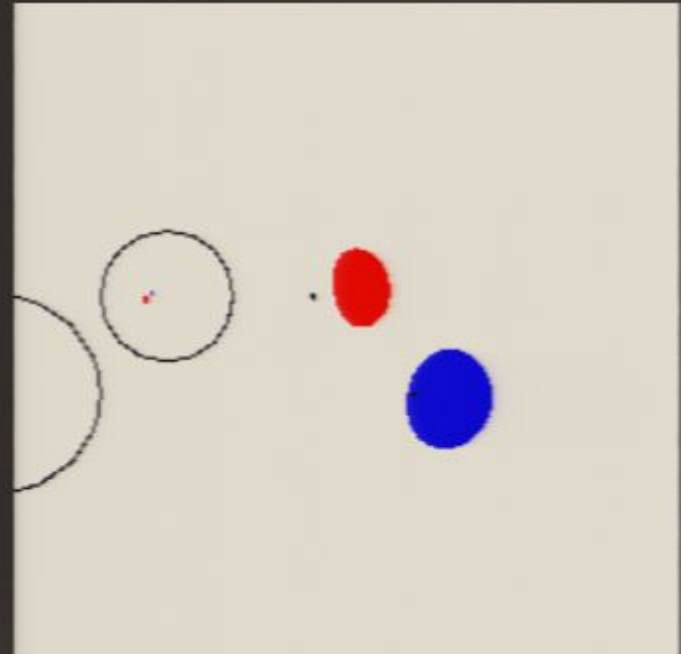
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



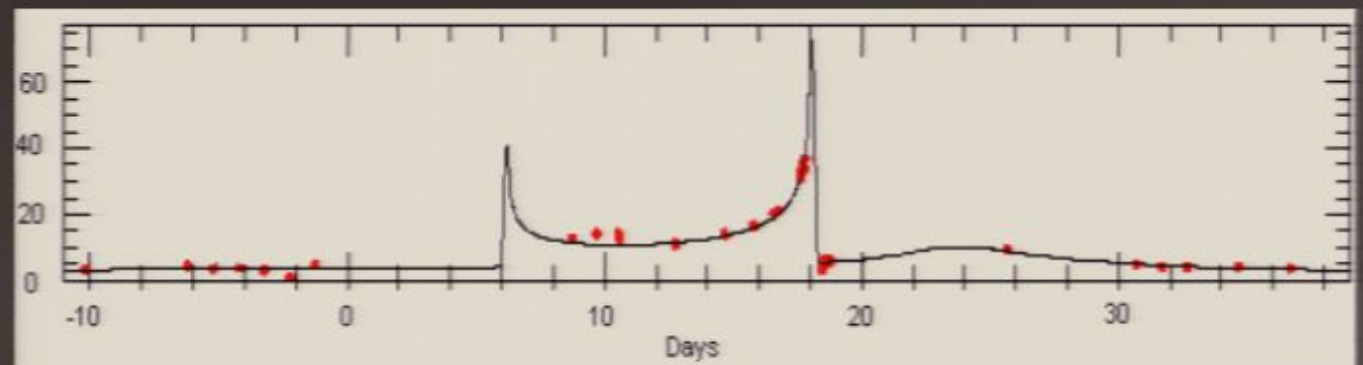
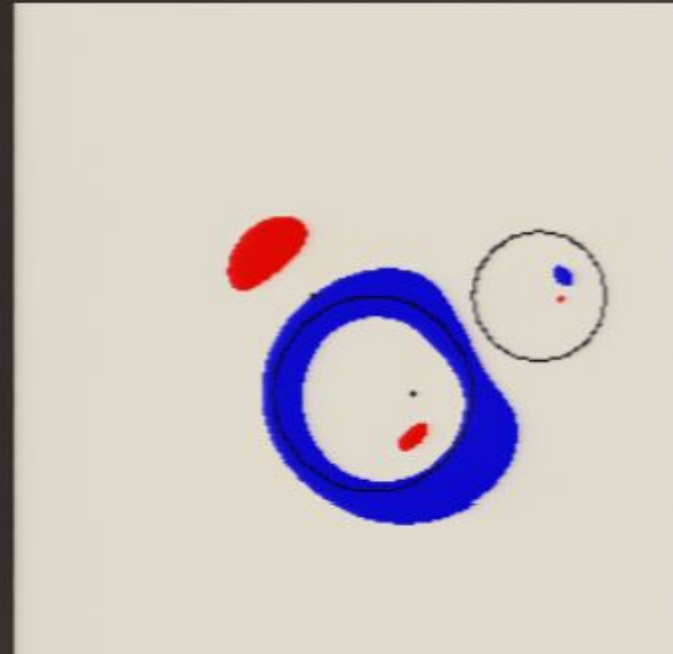
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?




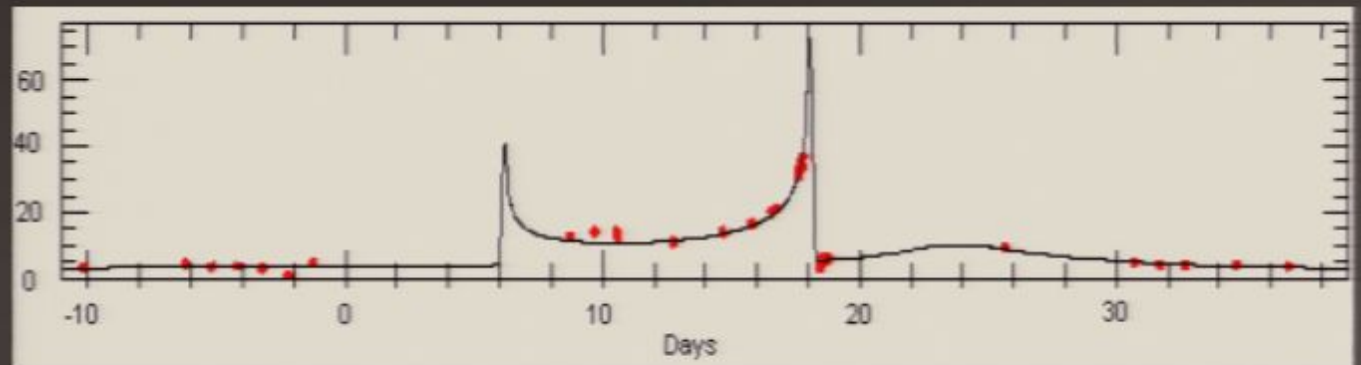
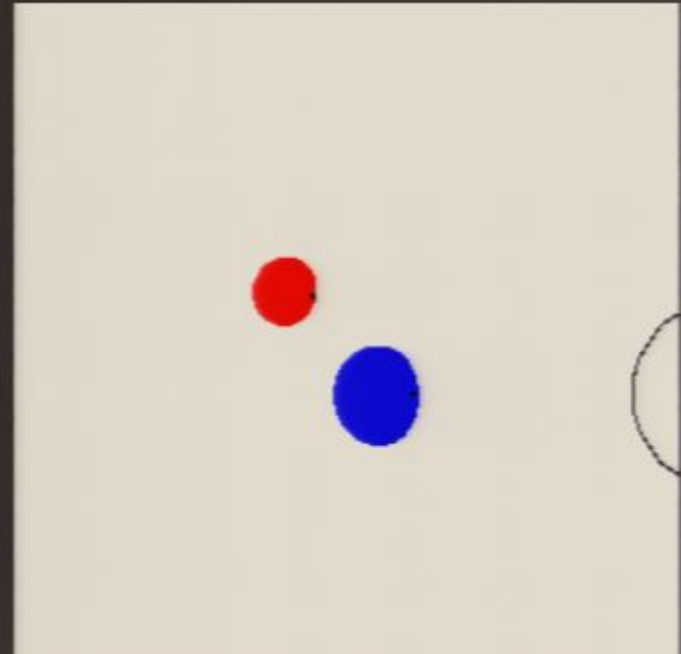
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



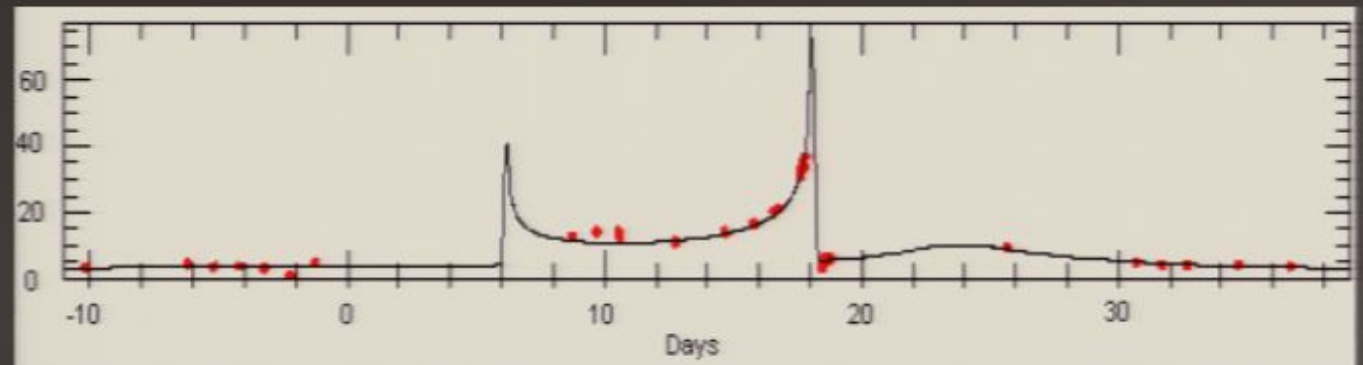
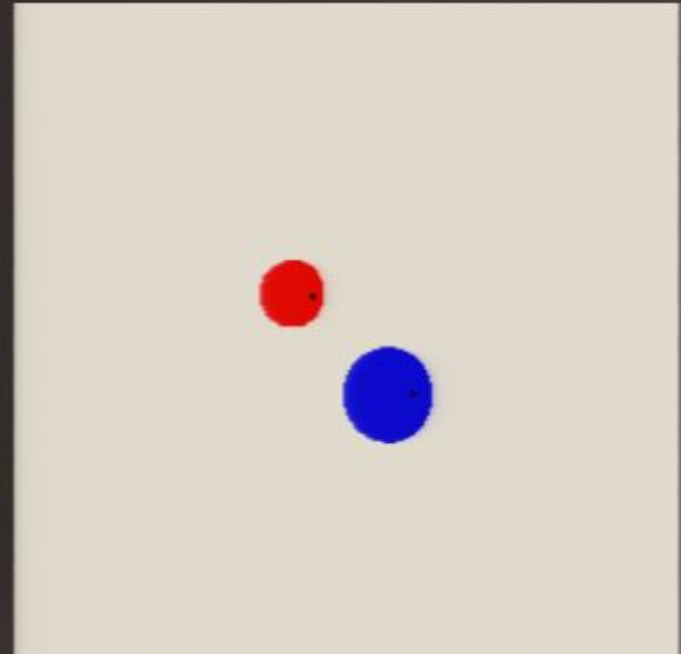
What is the Dark Matter?

- *Ordinary atoms?* 
- Modifications to the Law of Gravity?
- New kind of particles?



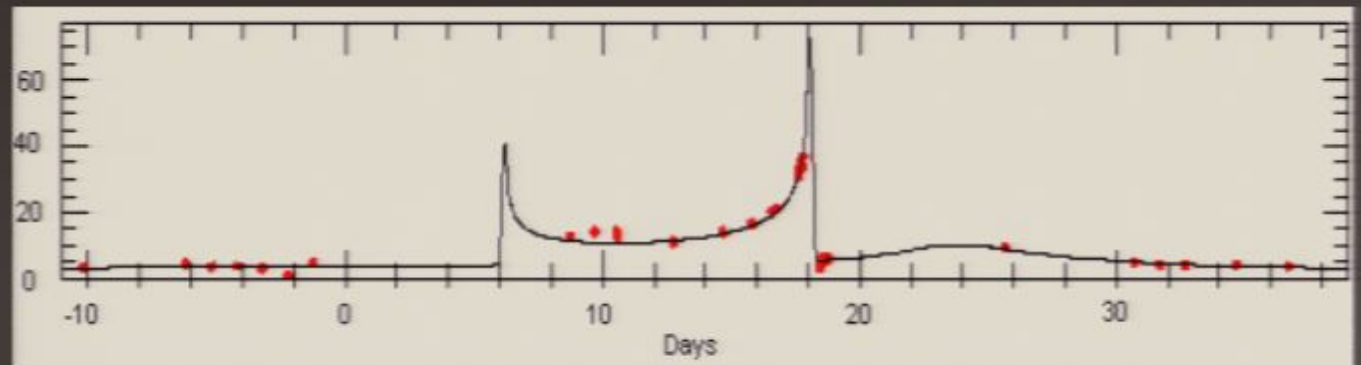
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



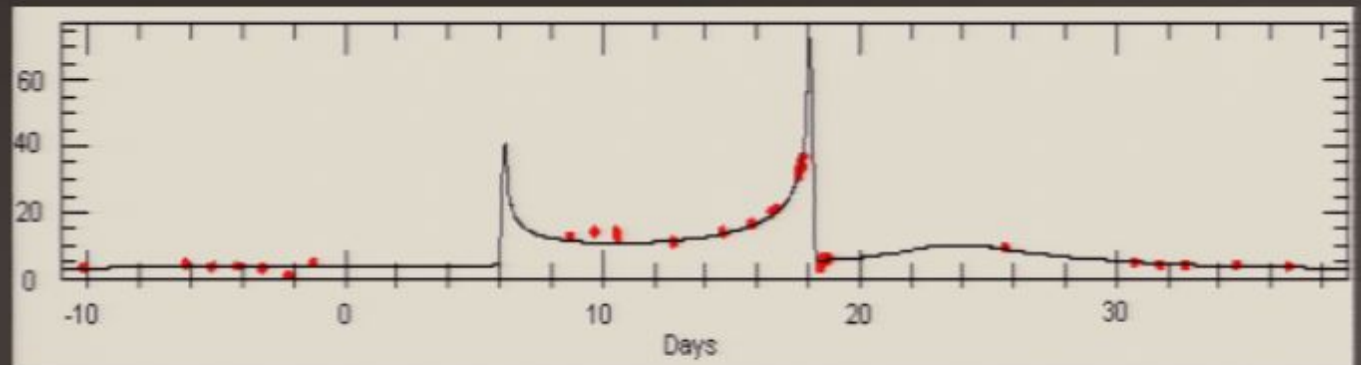
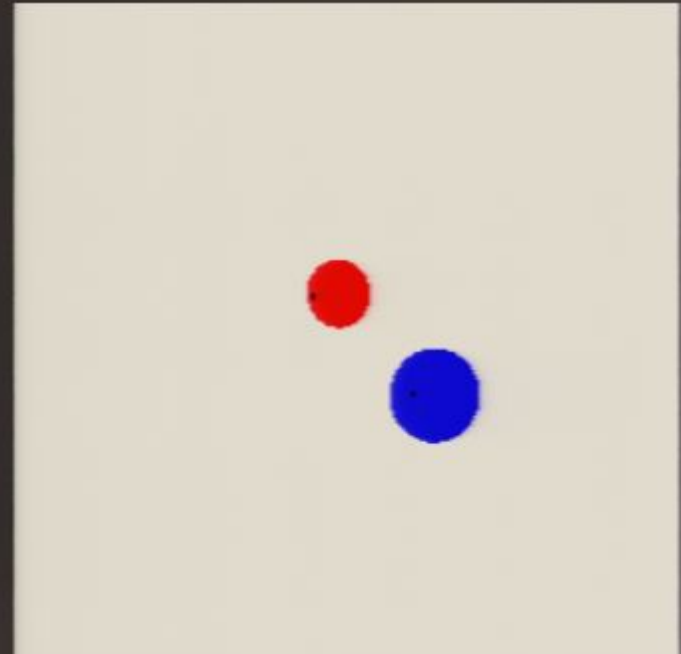
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



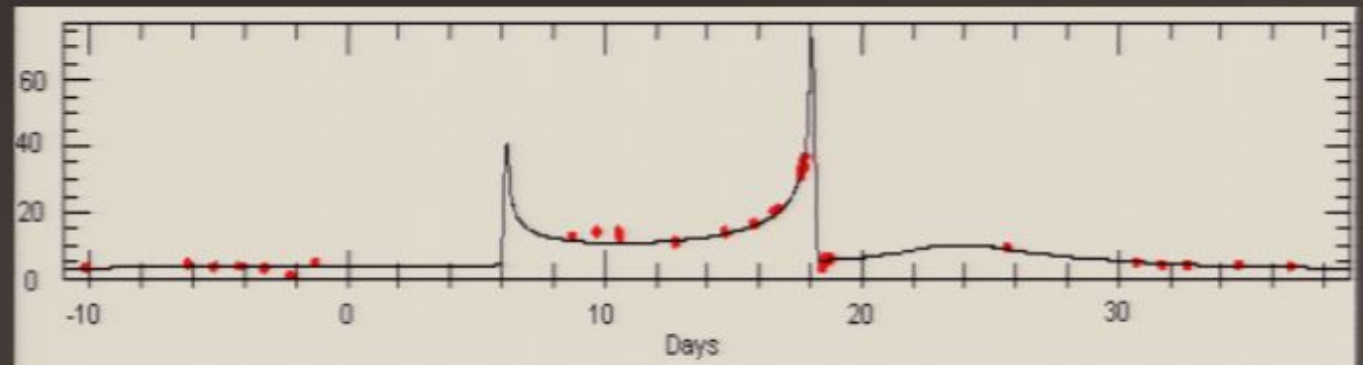
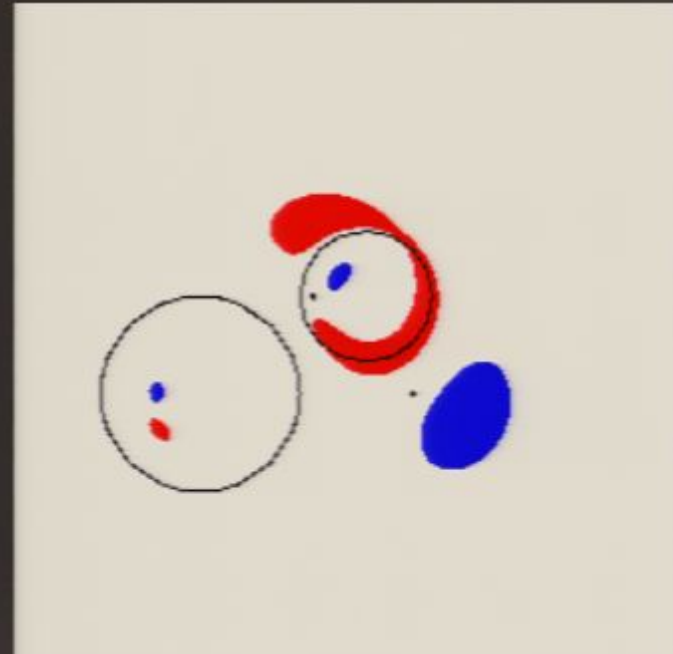
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



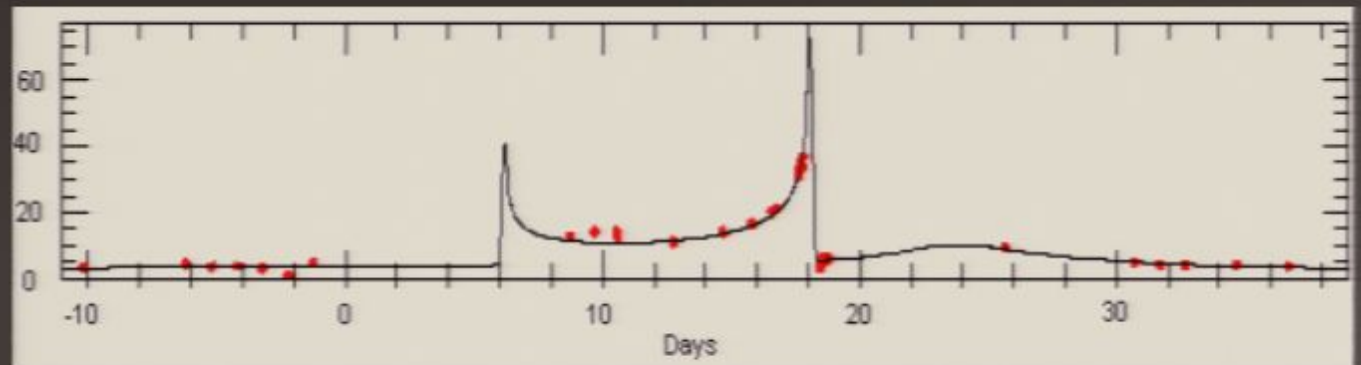
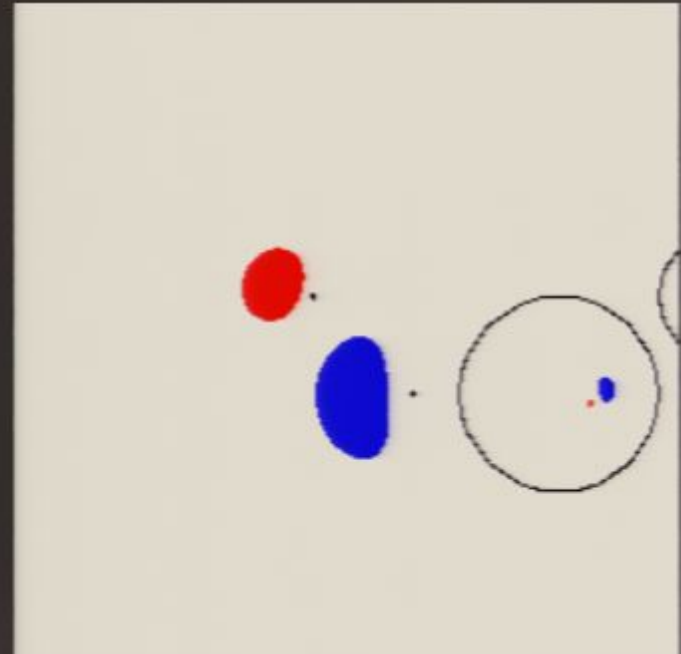
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



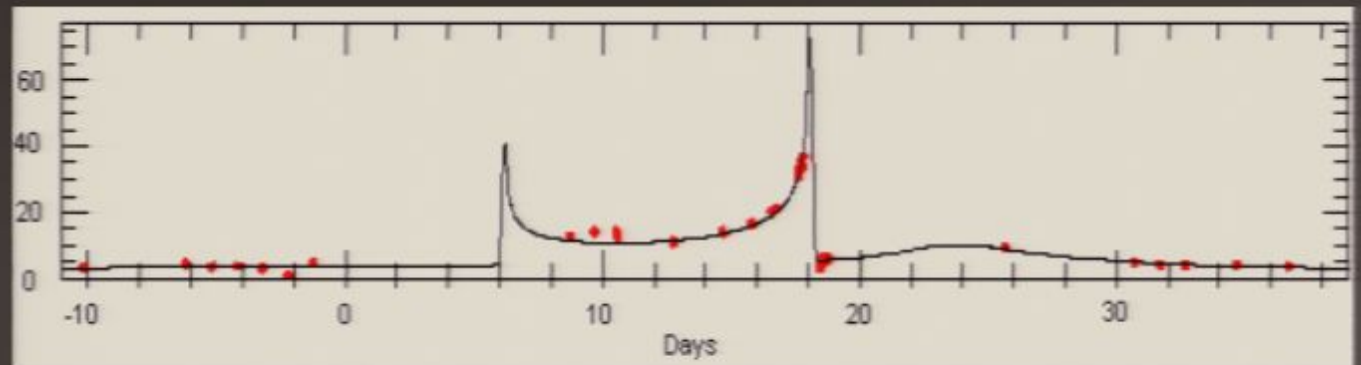
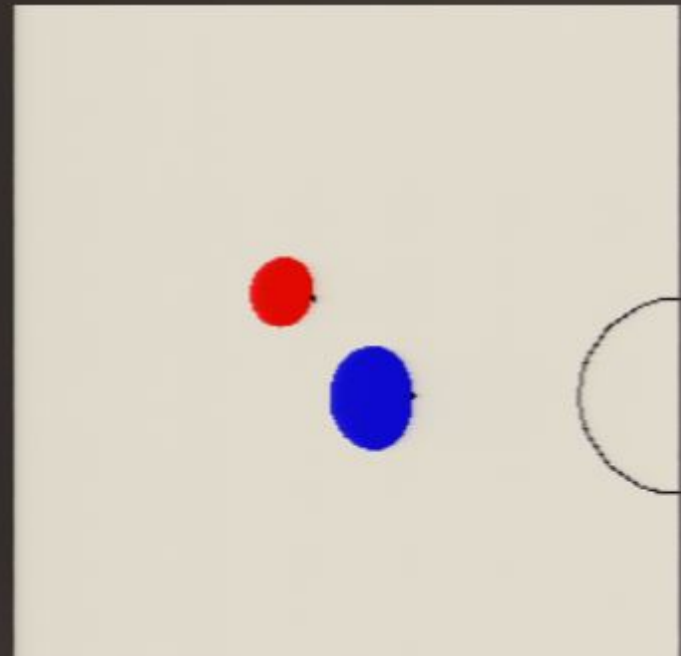
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



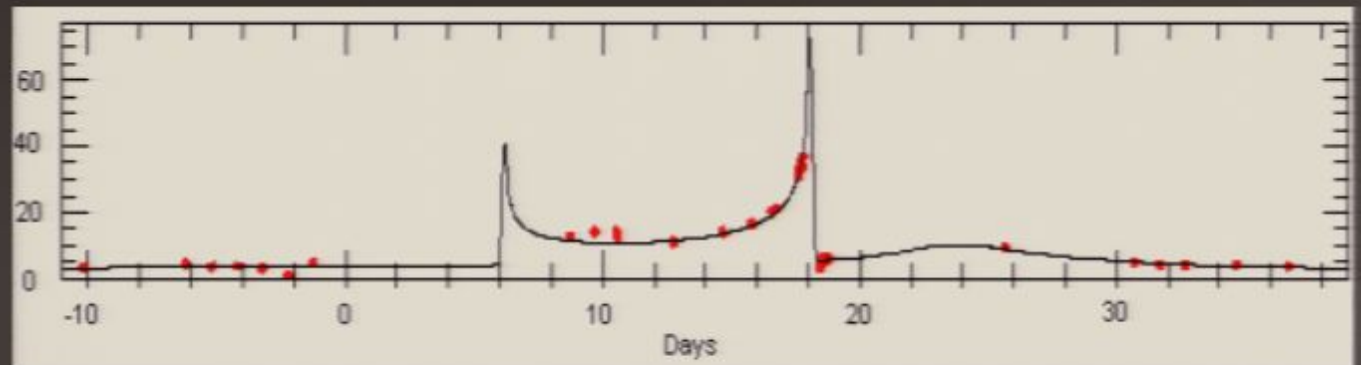
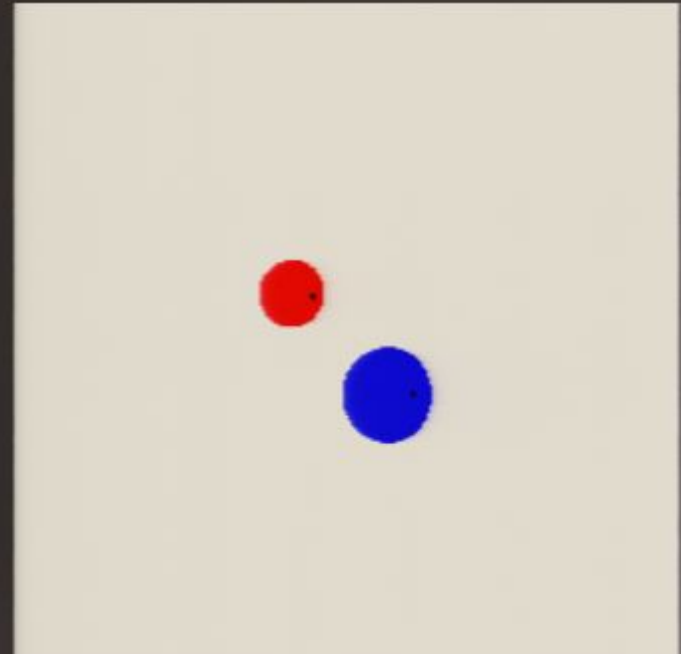
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



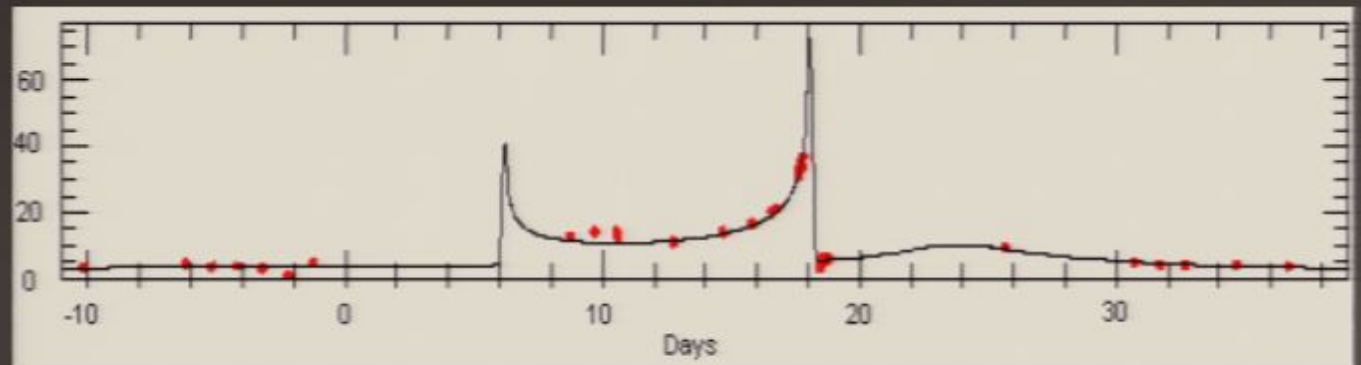
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



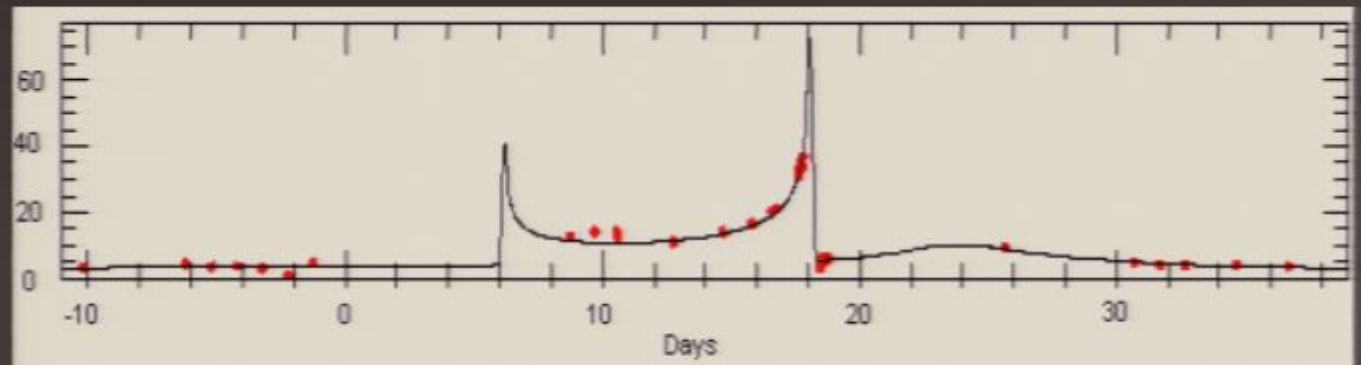
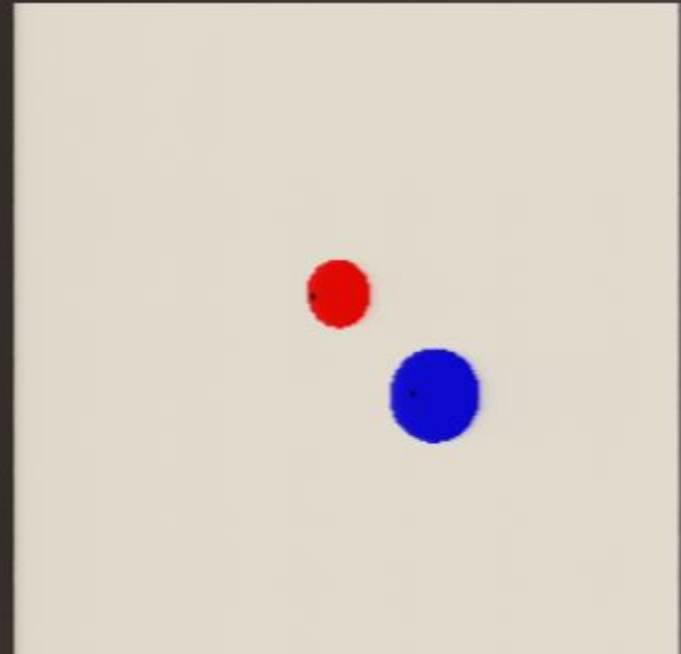
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



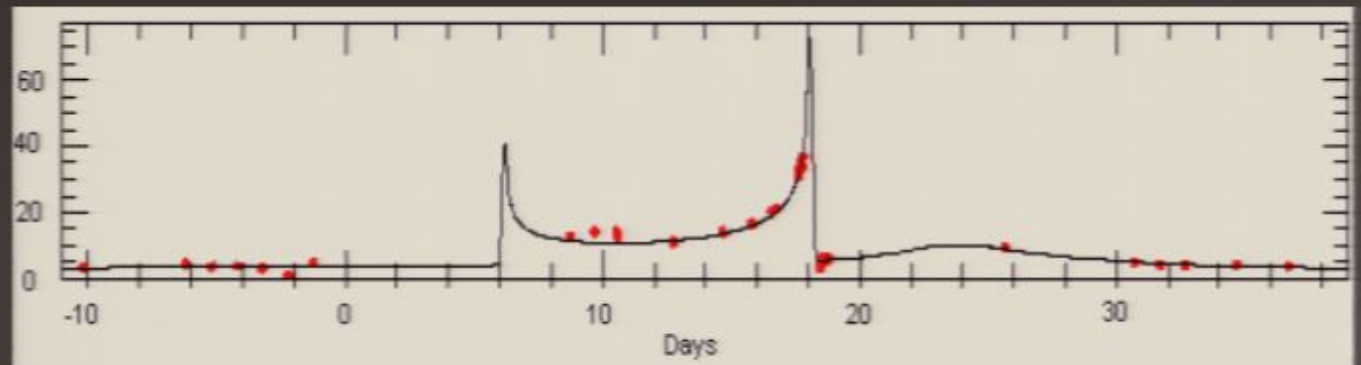
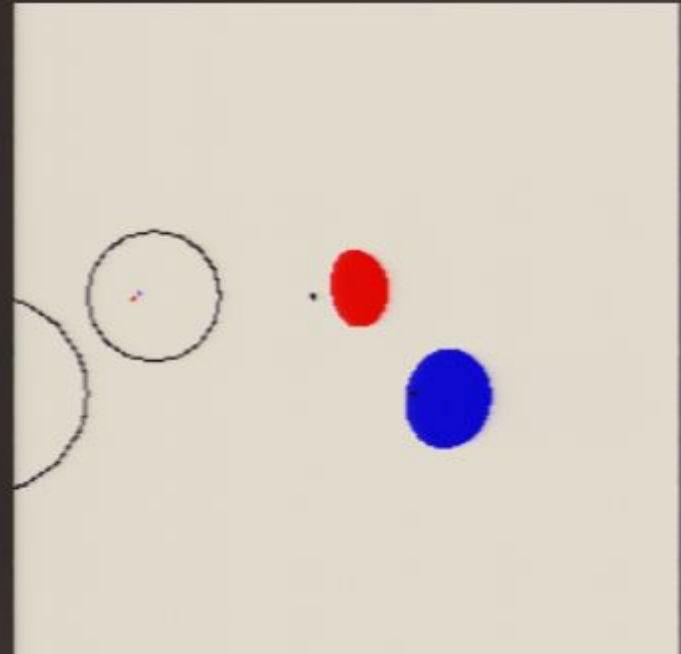
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



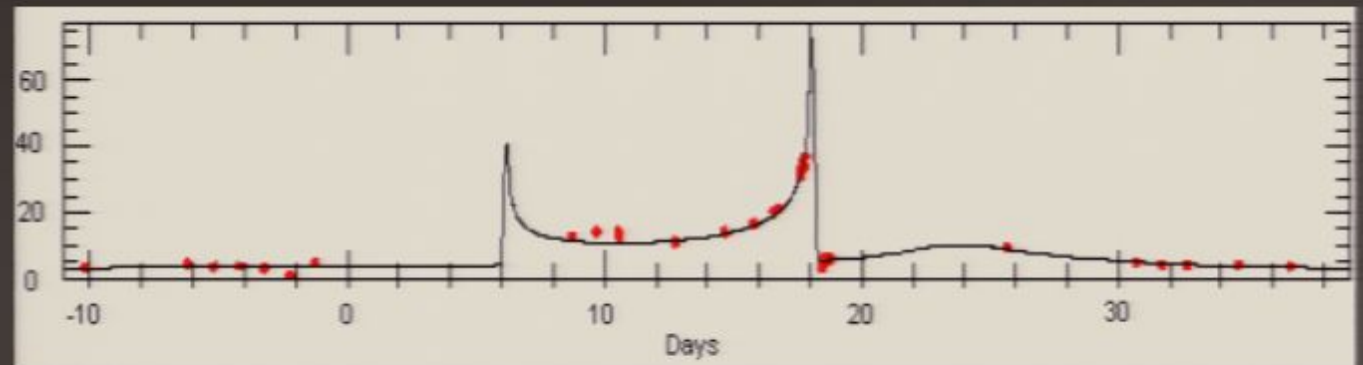
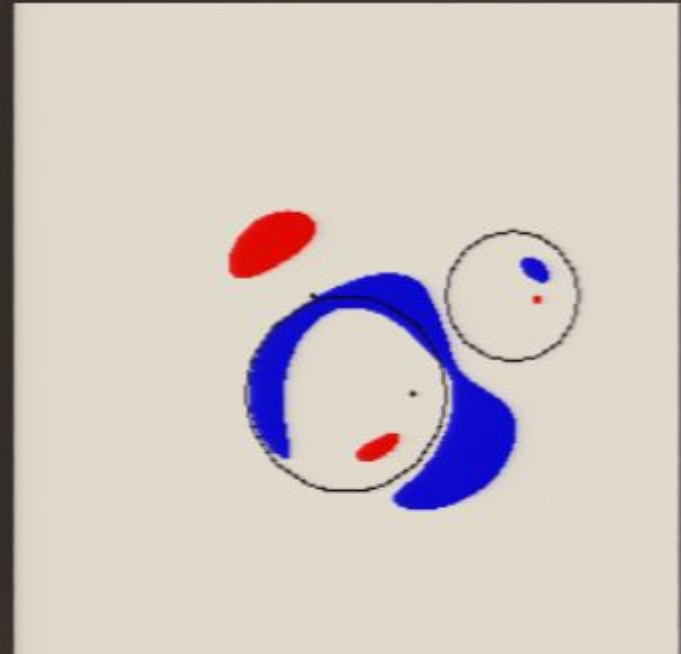
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



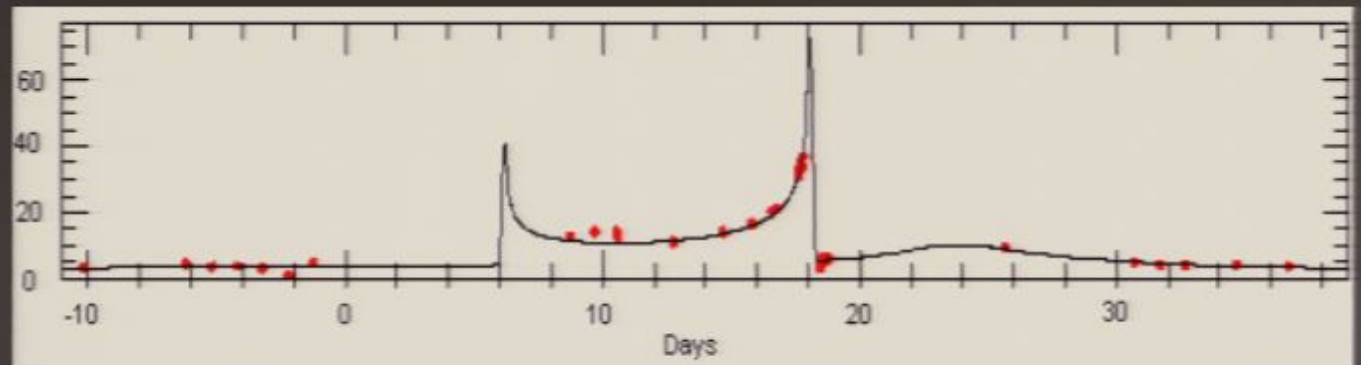
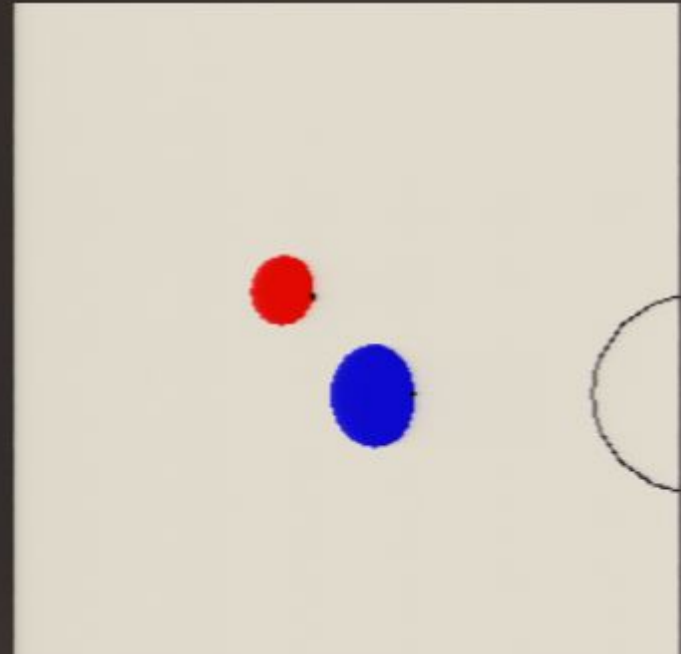
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



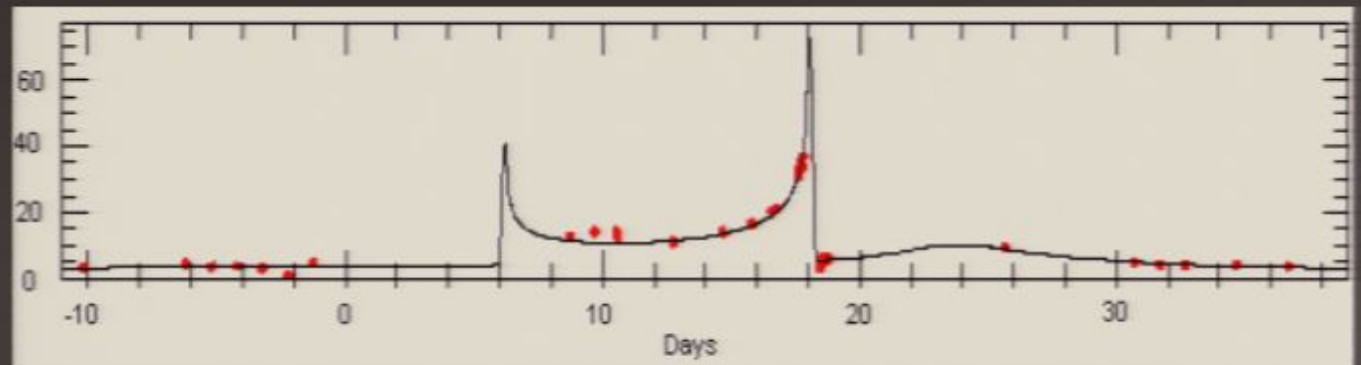
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



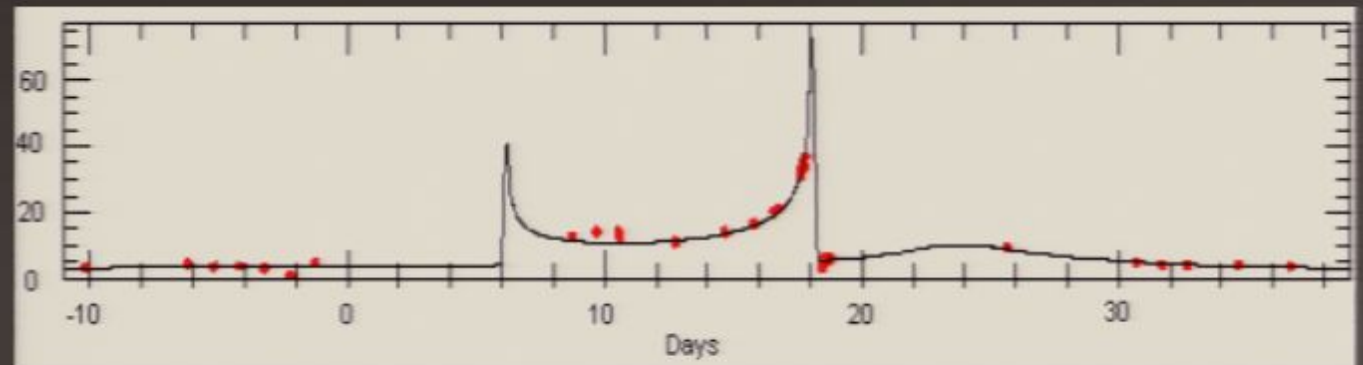
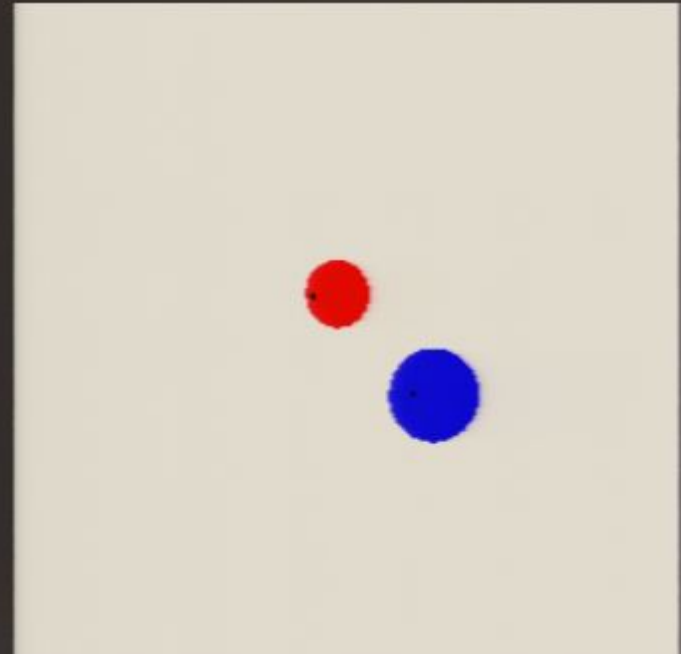
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



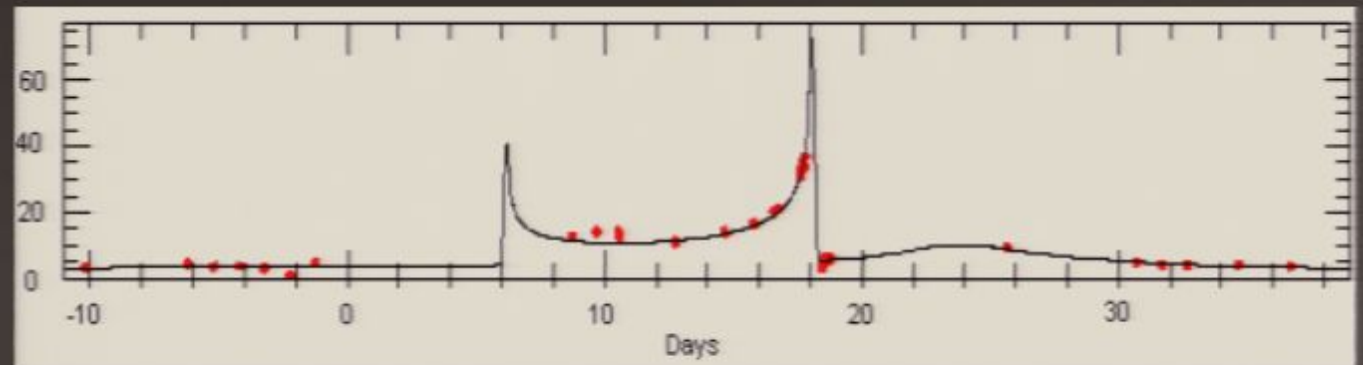
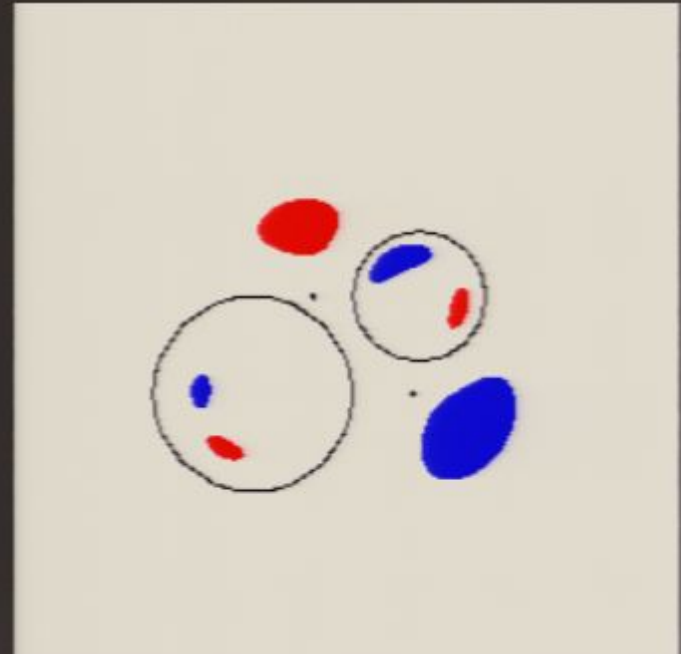
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



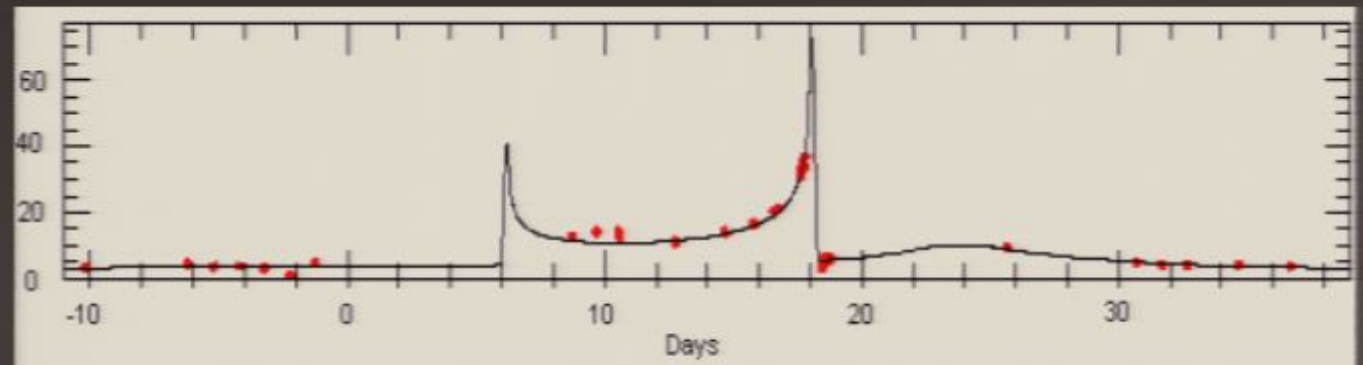
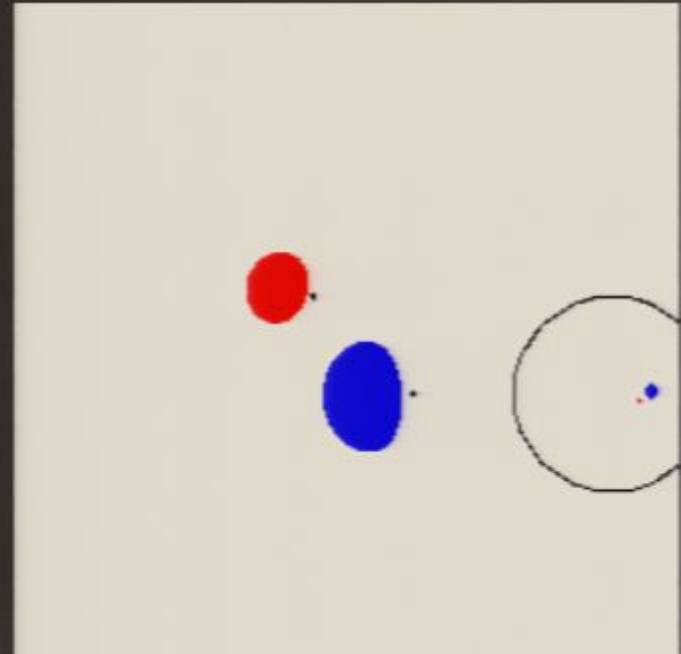
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



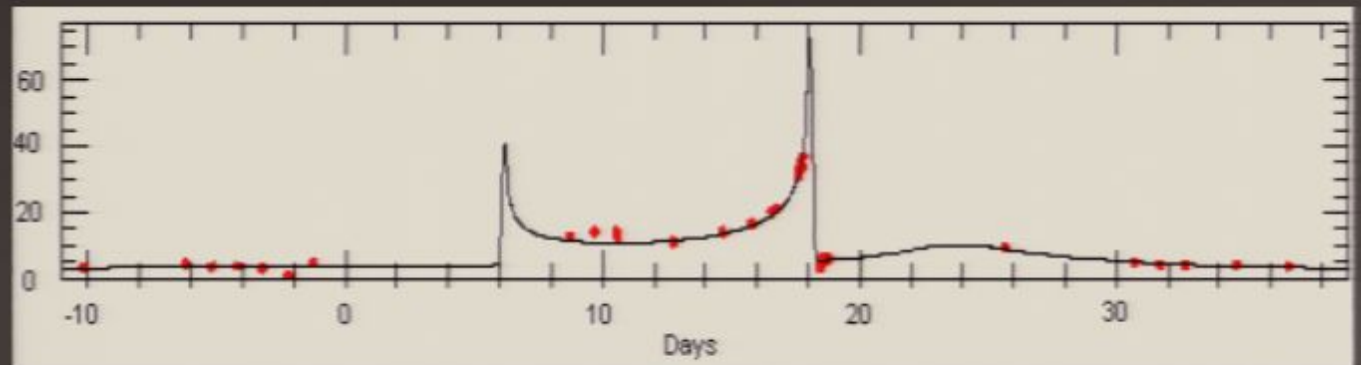
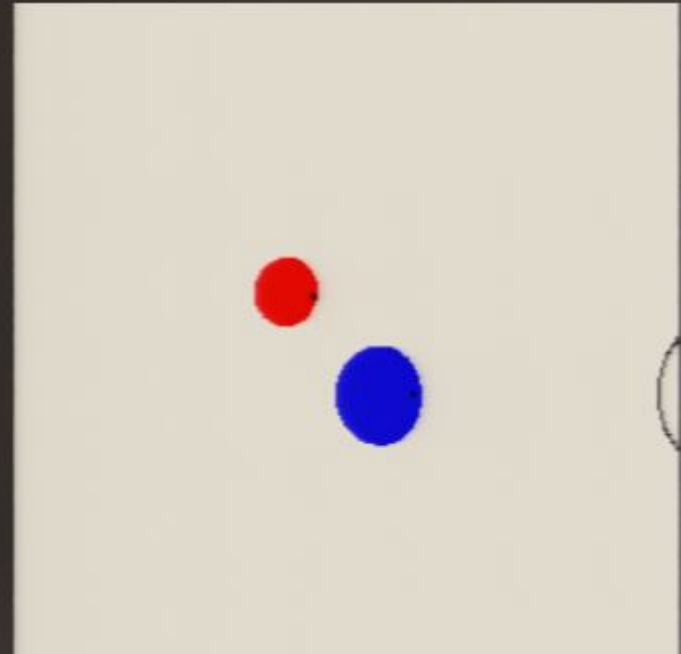
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



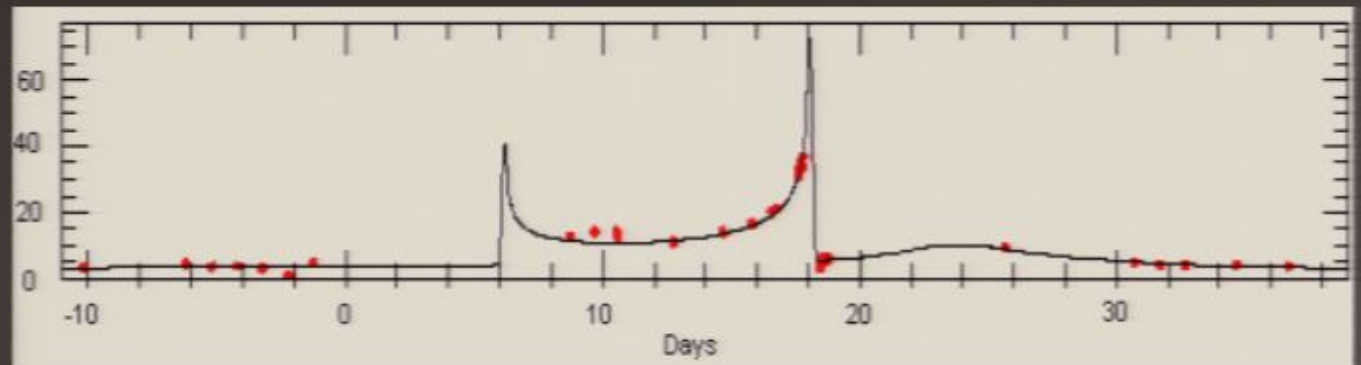
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



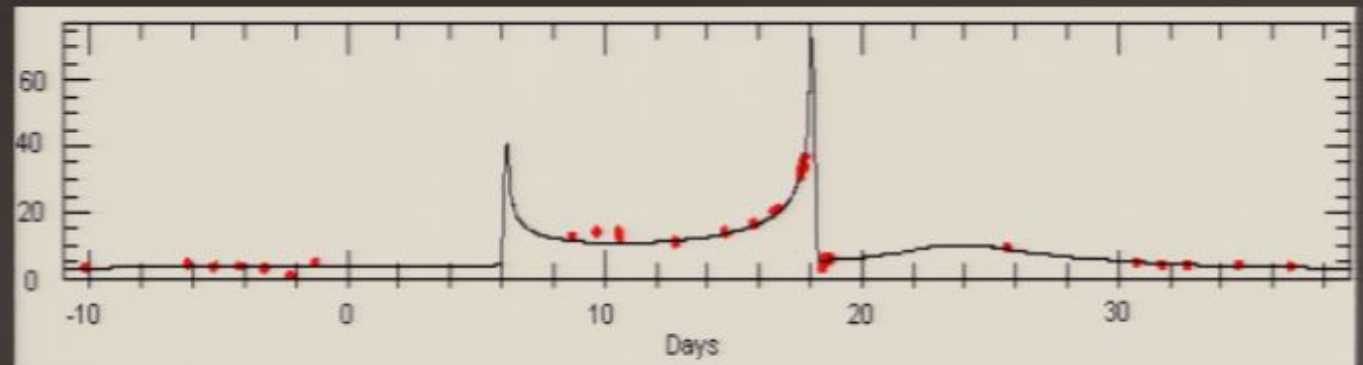
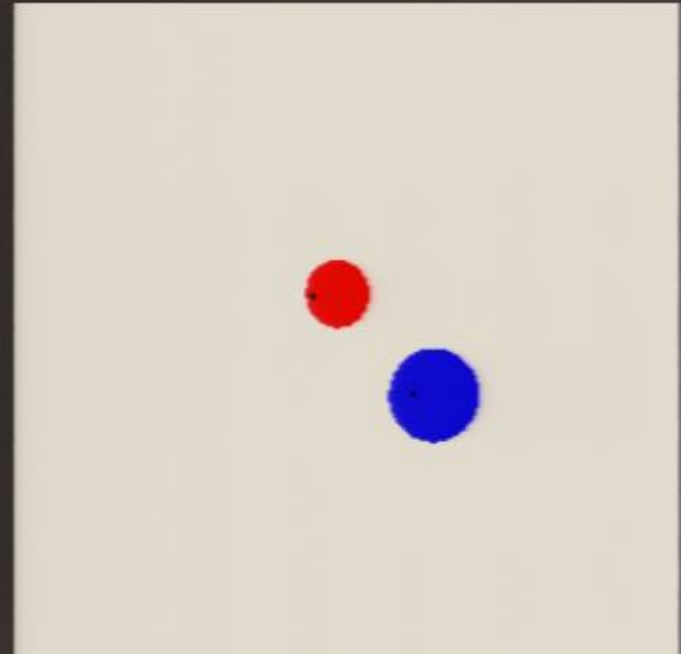
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



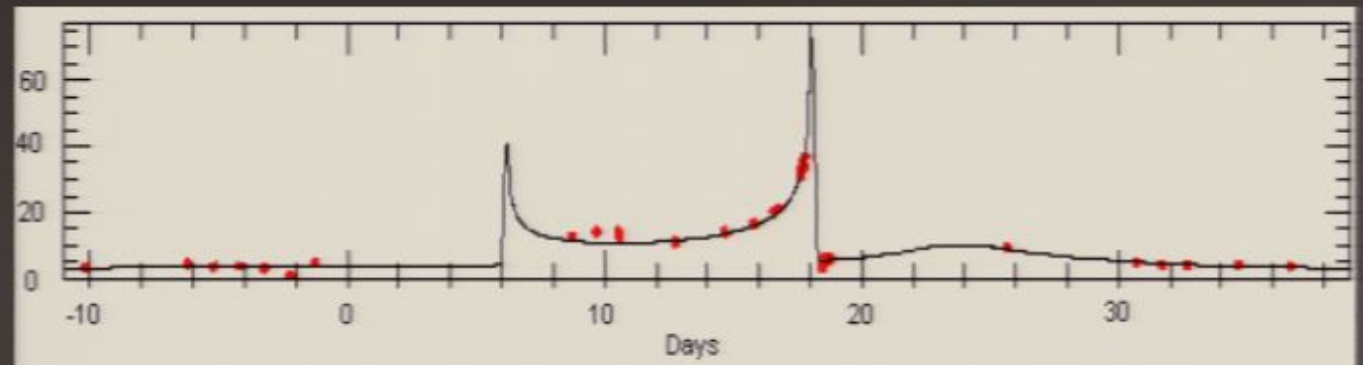
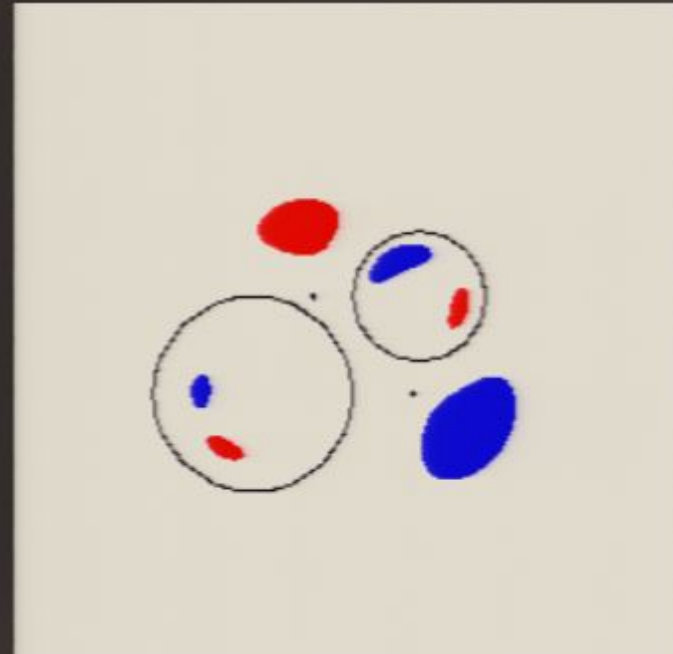
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



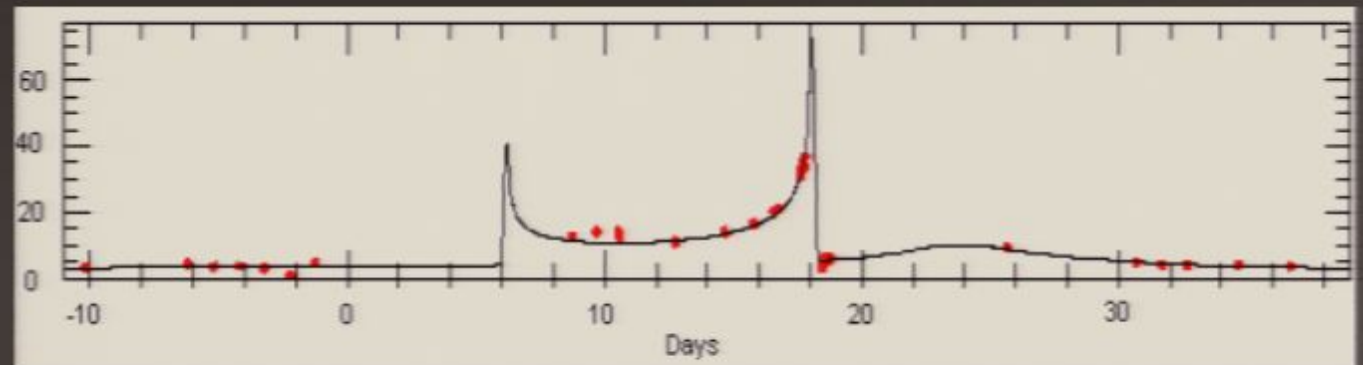
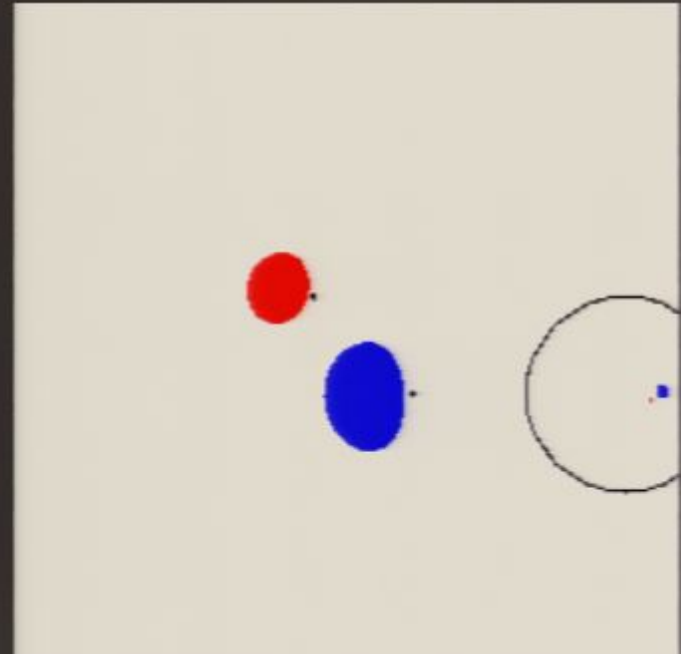
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



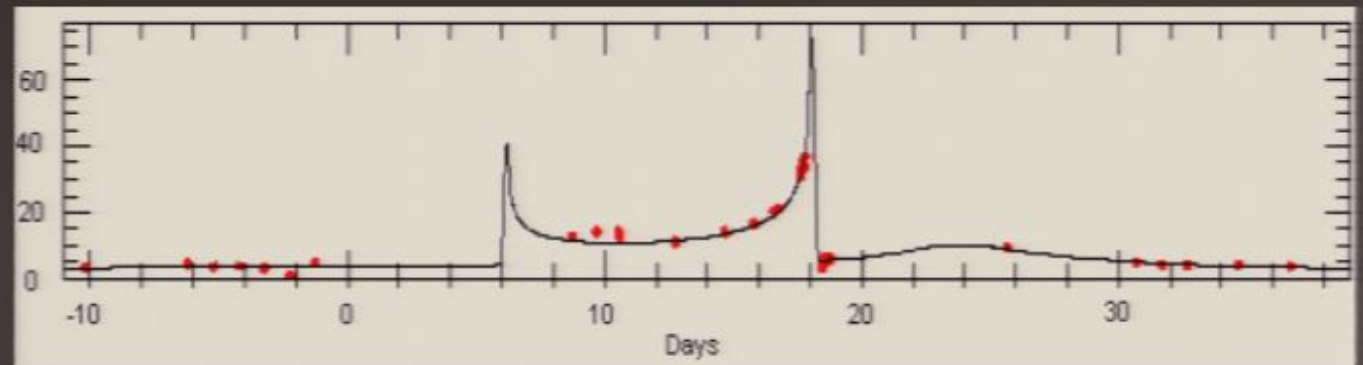
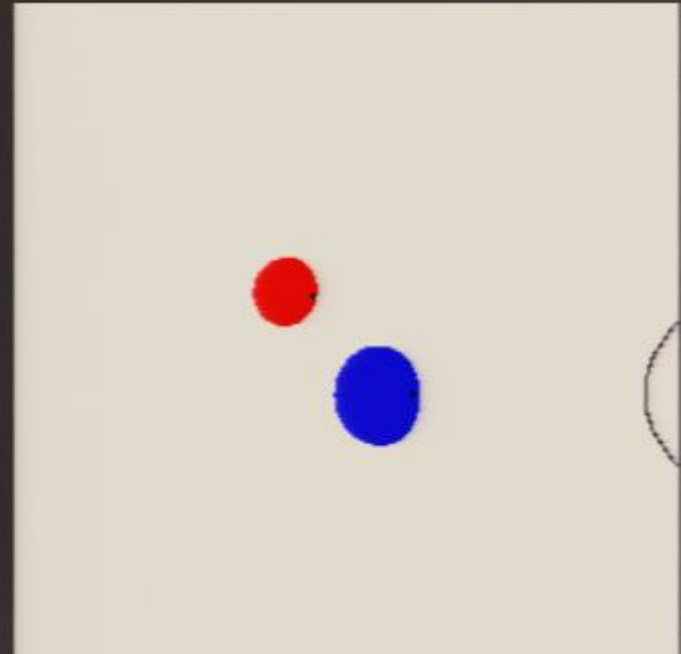
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



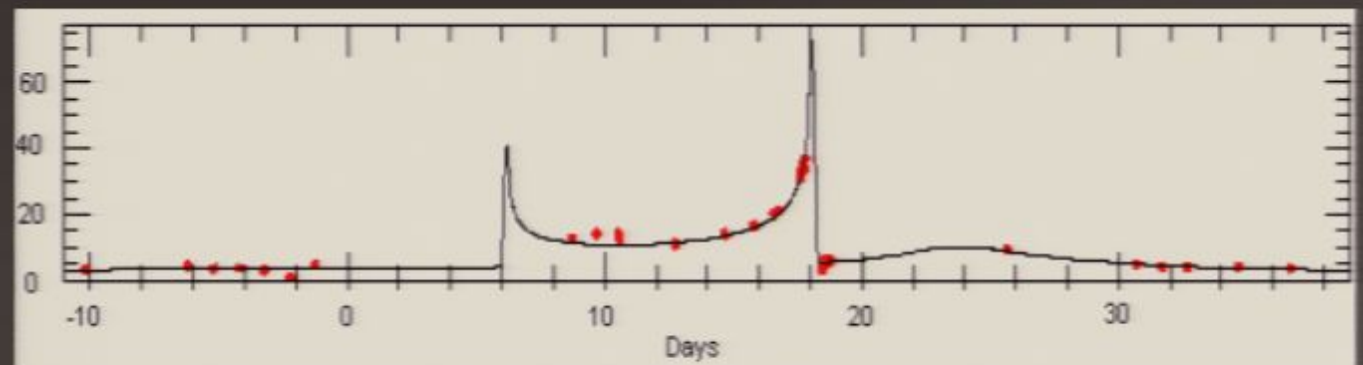
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



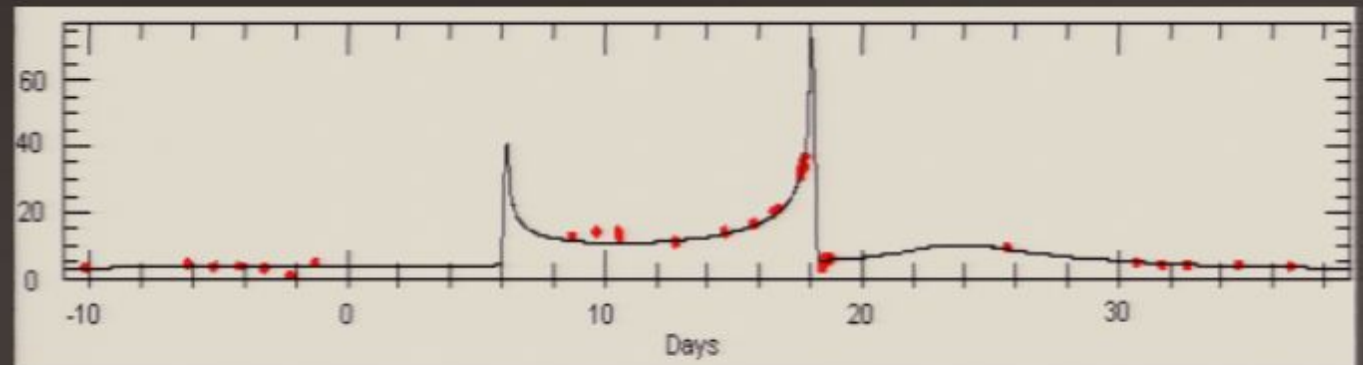
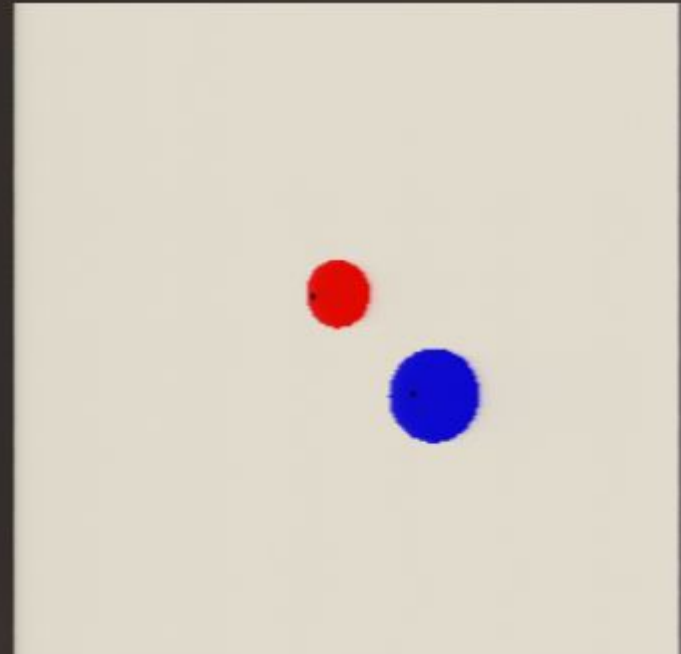
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



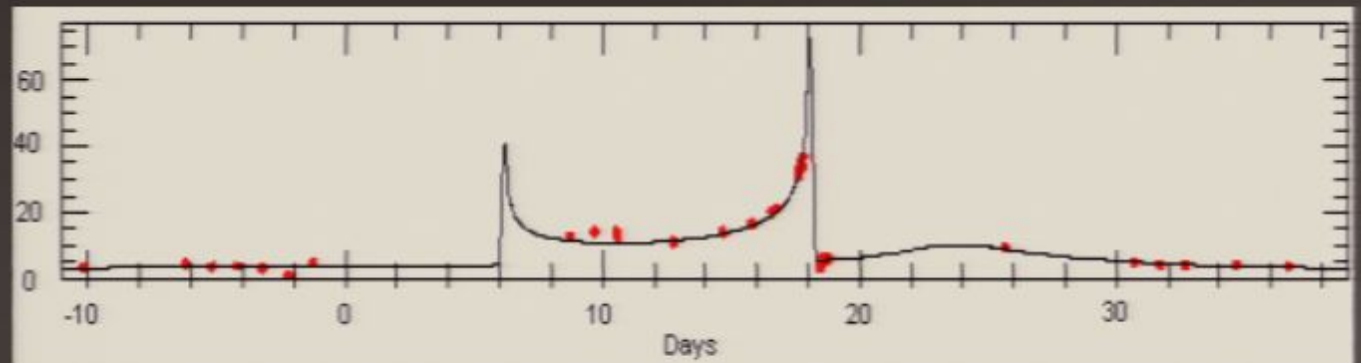
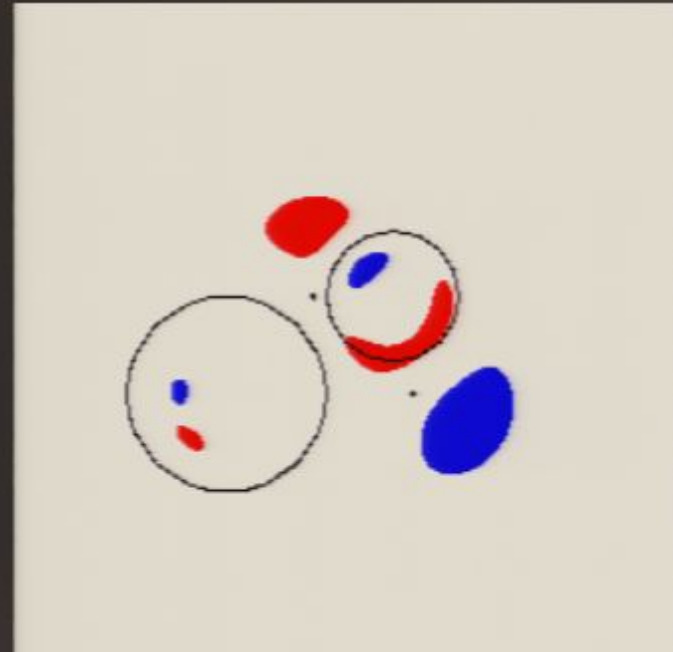
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



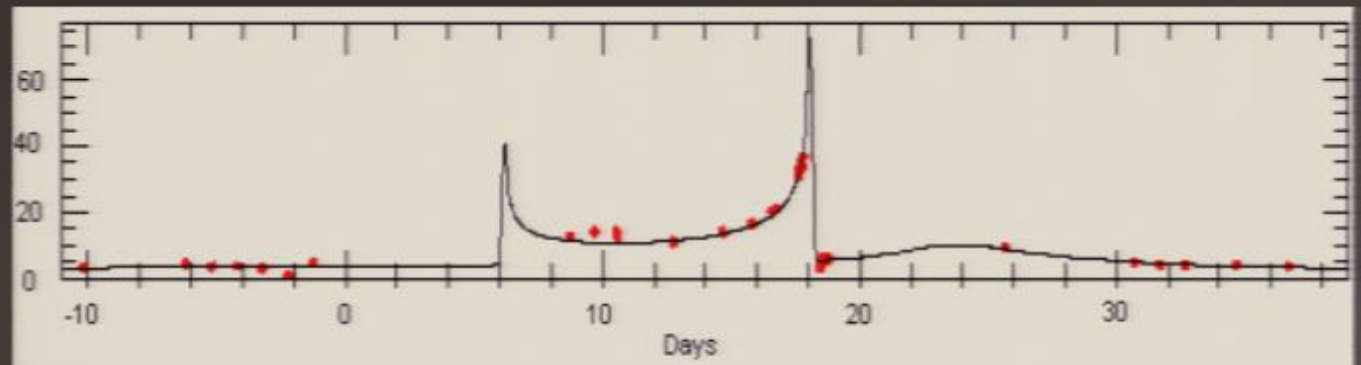
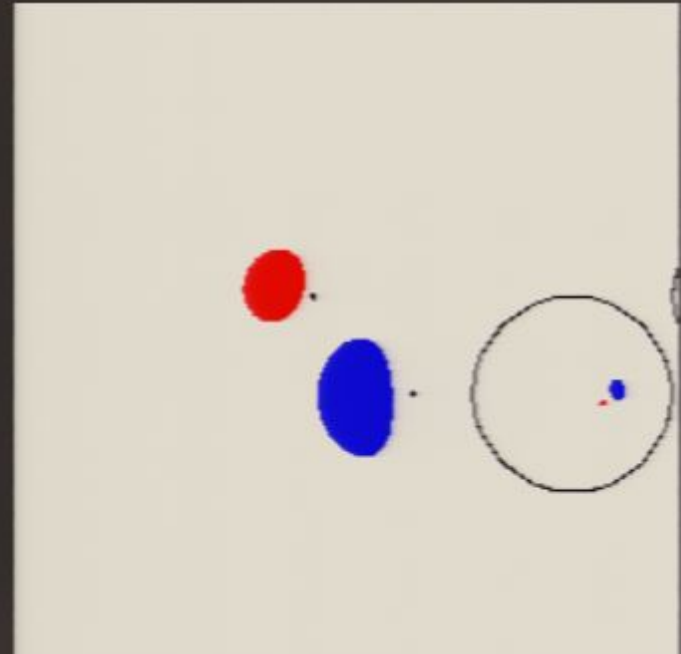
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



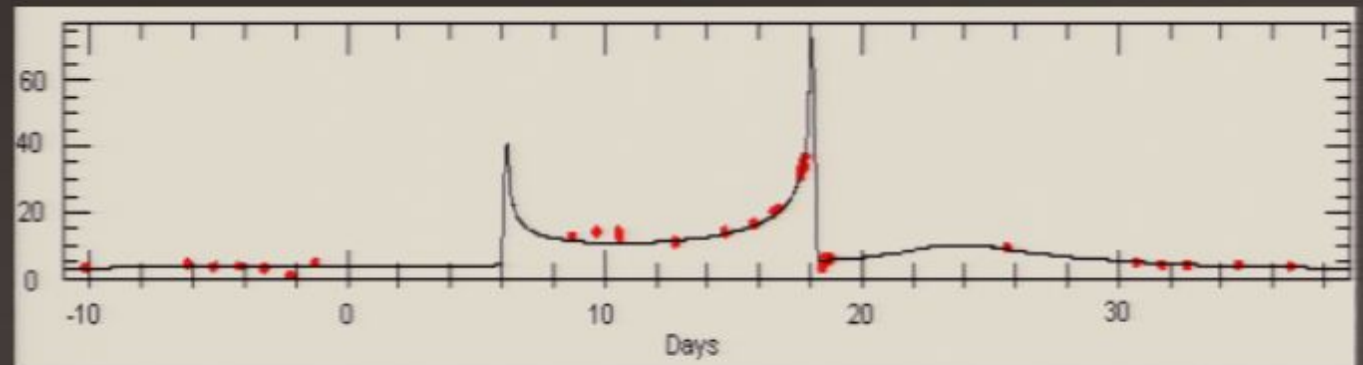
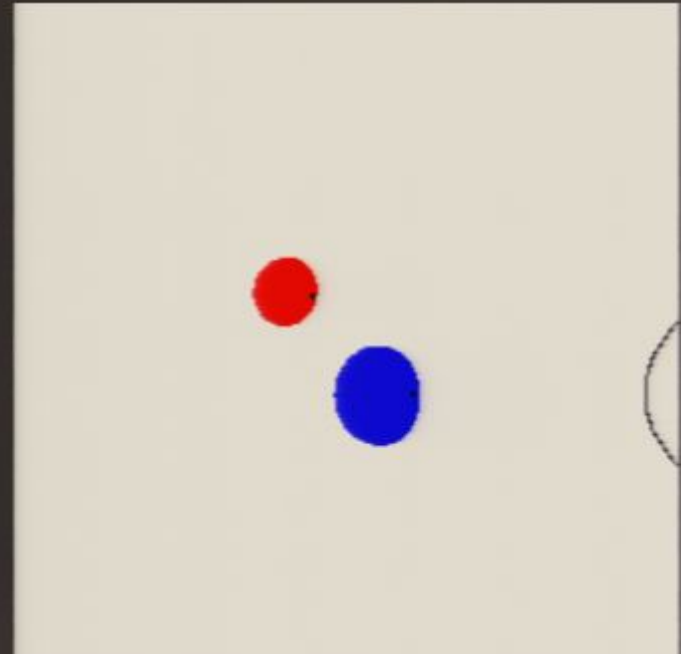
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



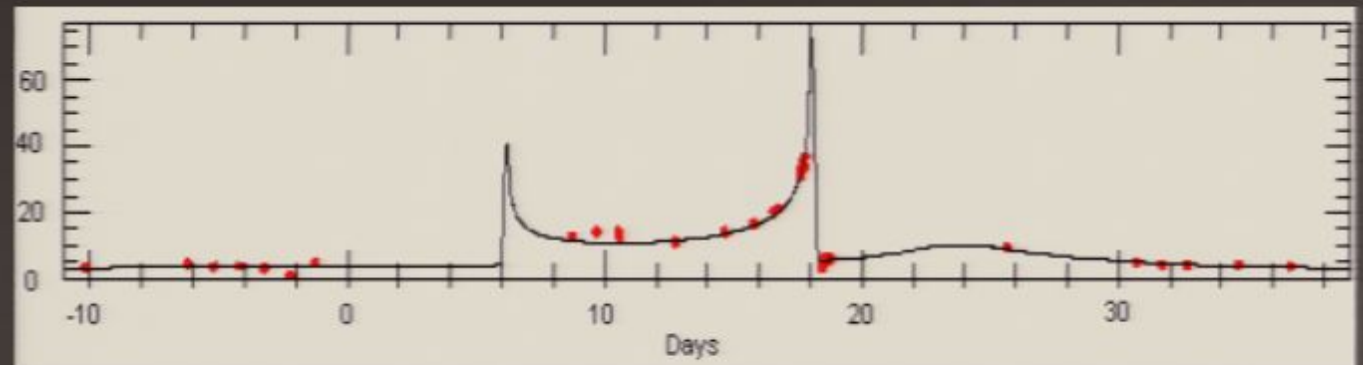
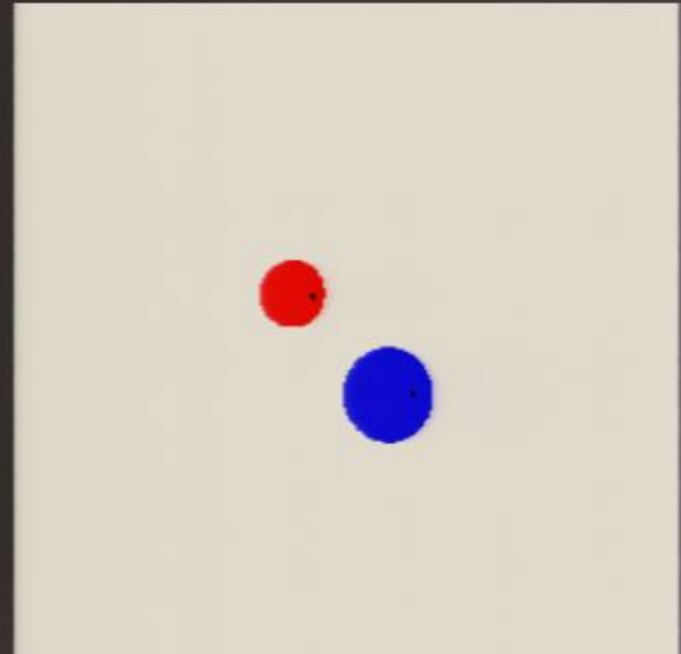
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



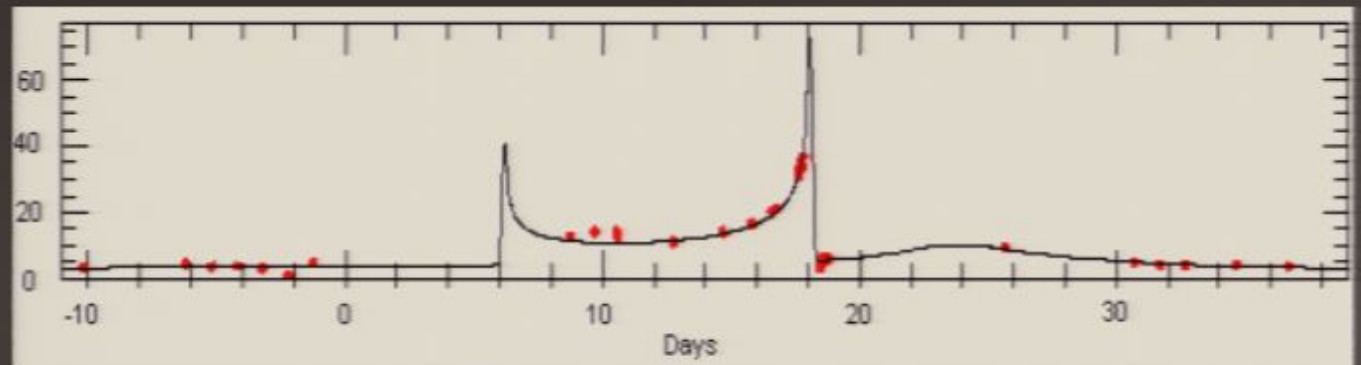
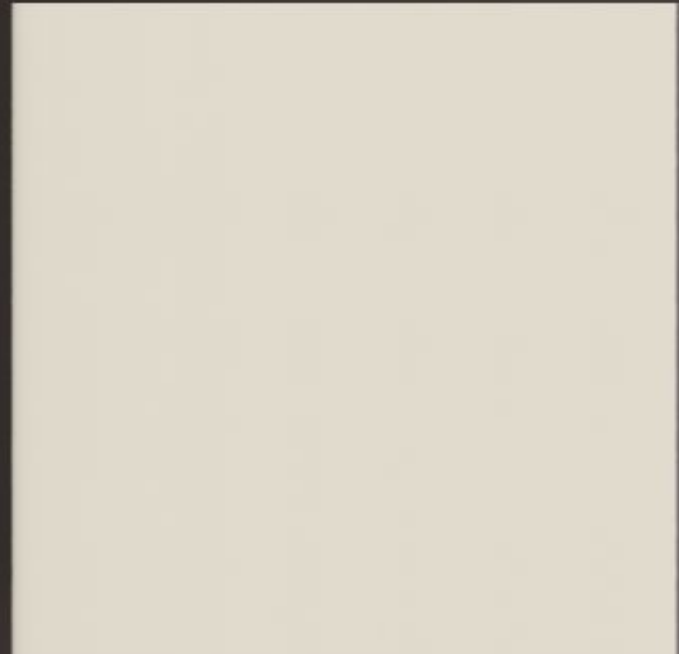
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



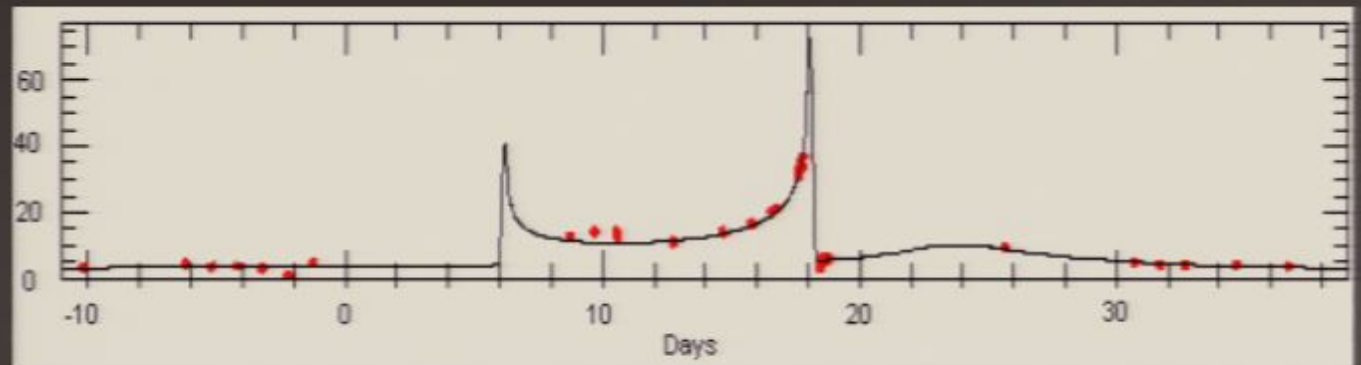
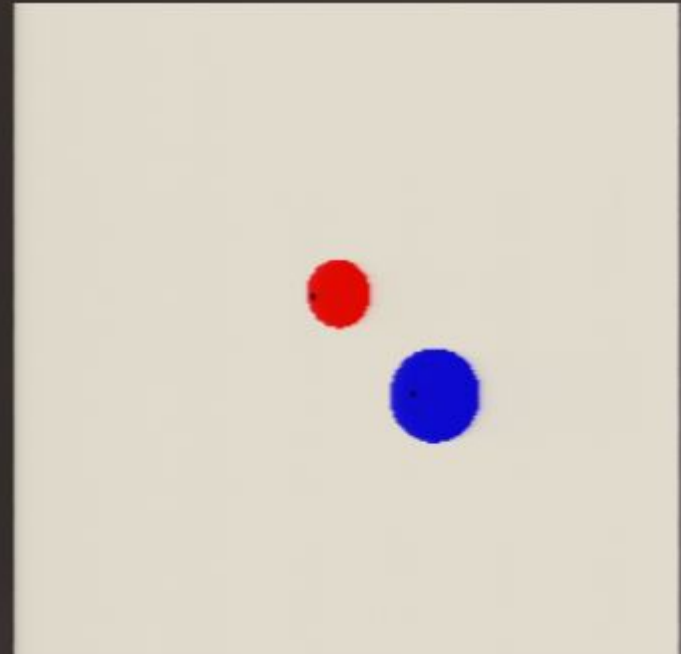
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



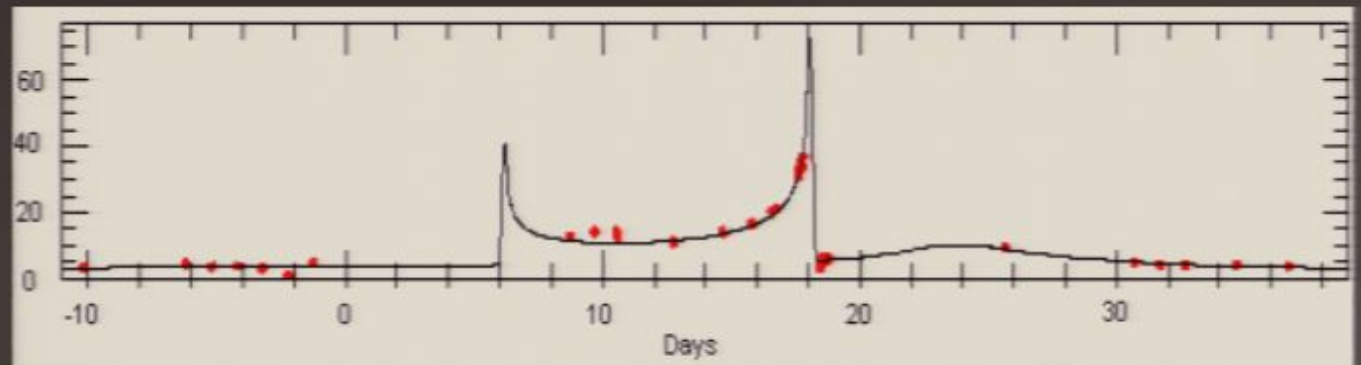
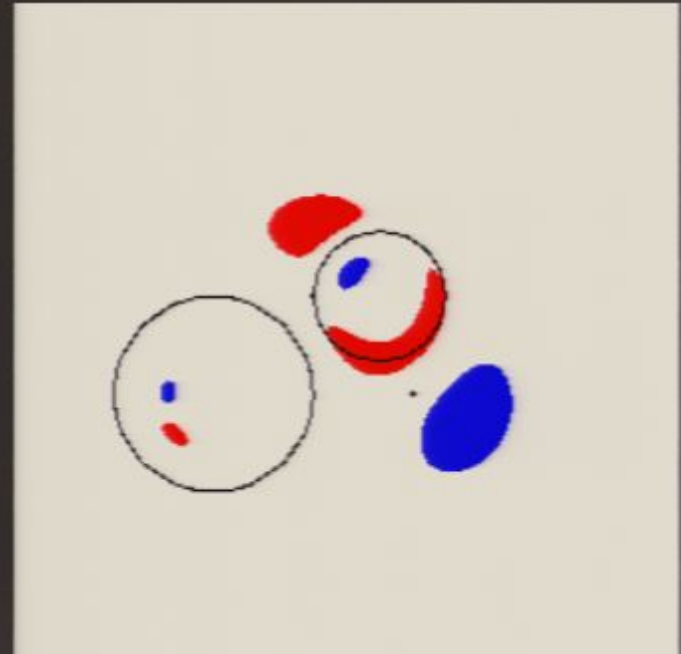
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



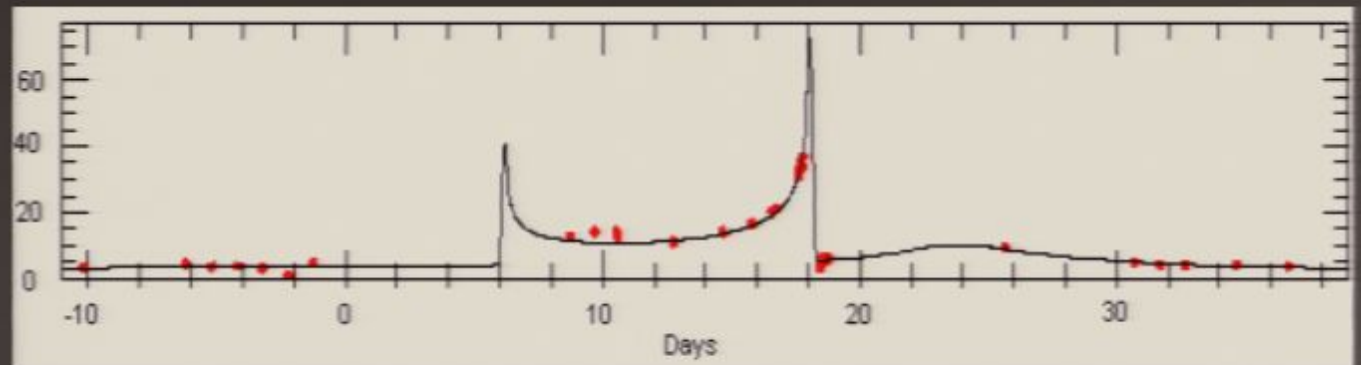
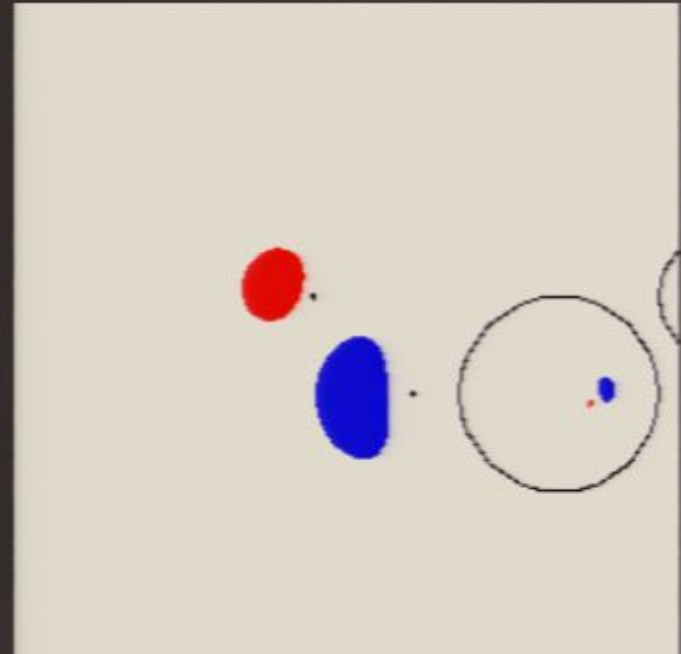
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



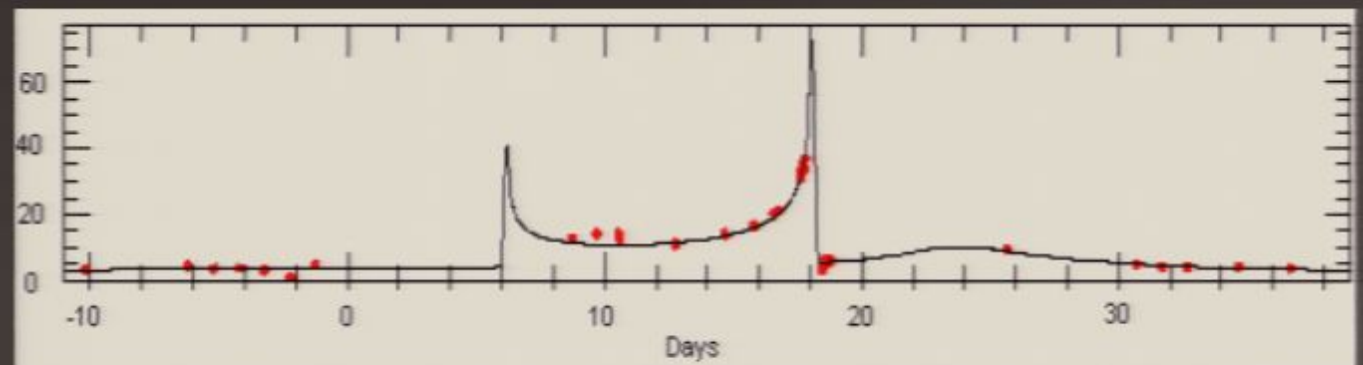
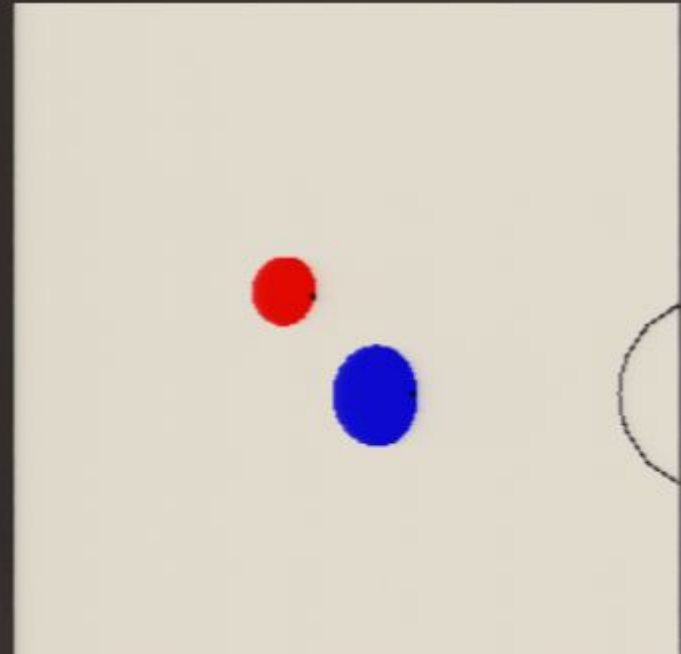
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



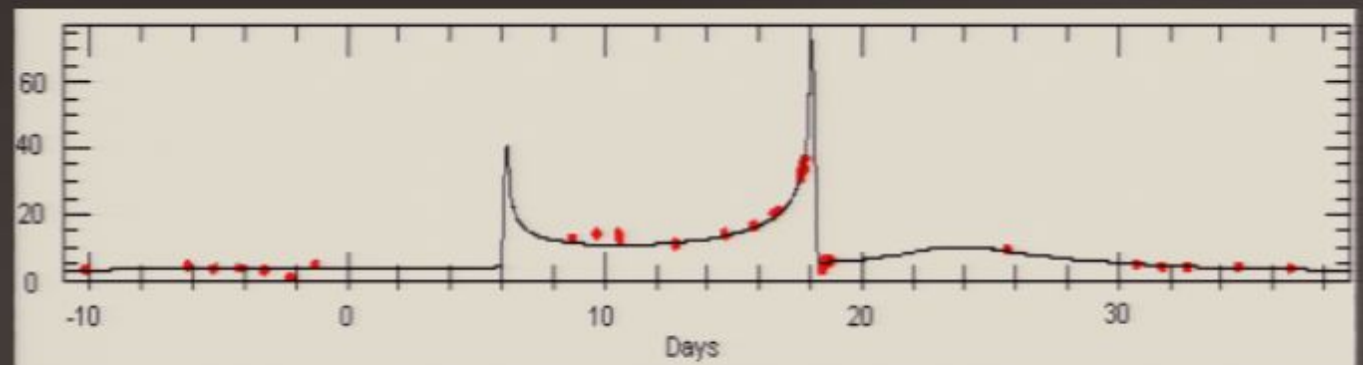
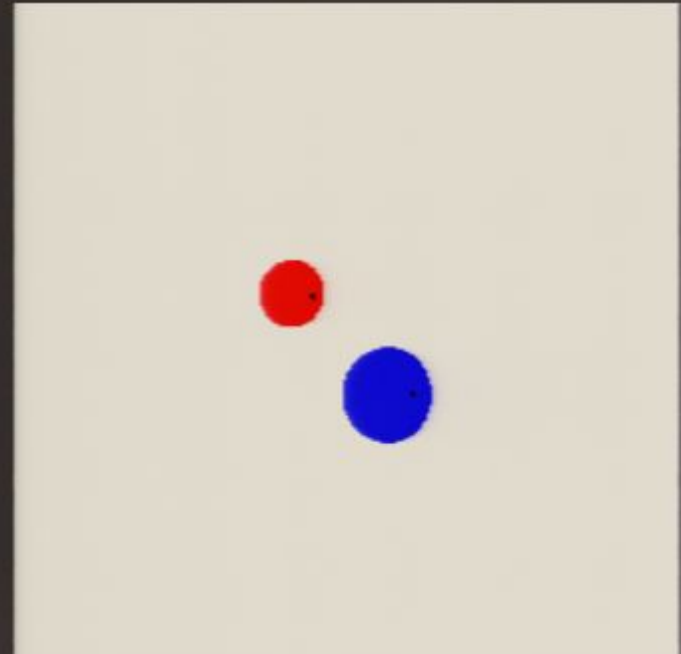
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



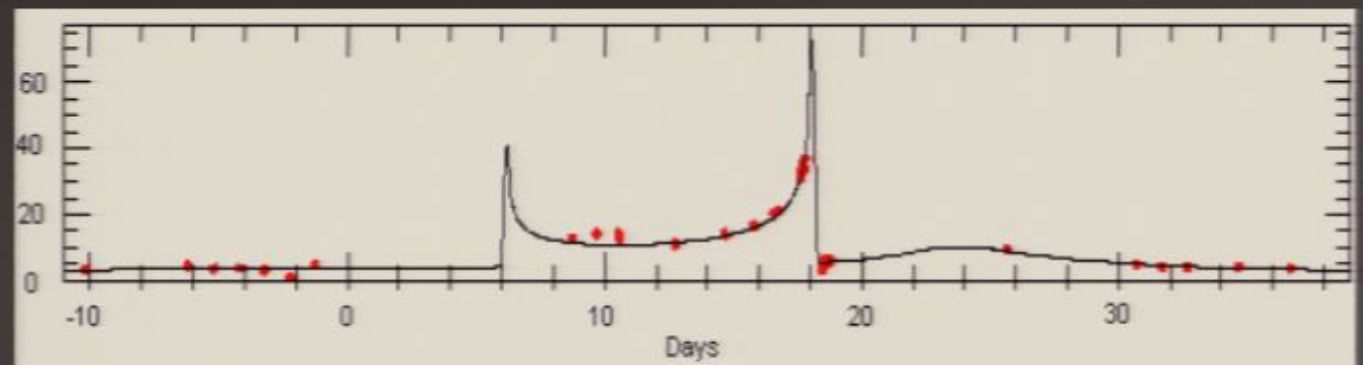
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



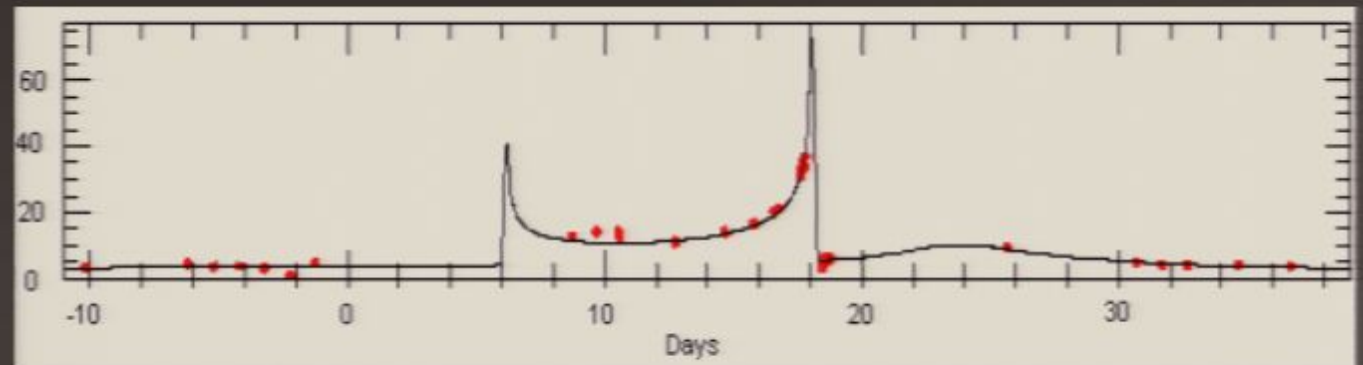
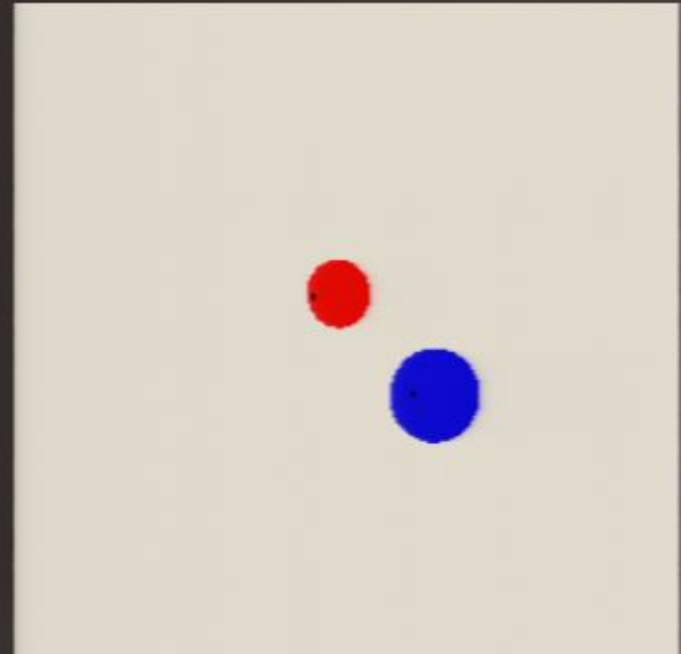
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



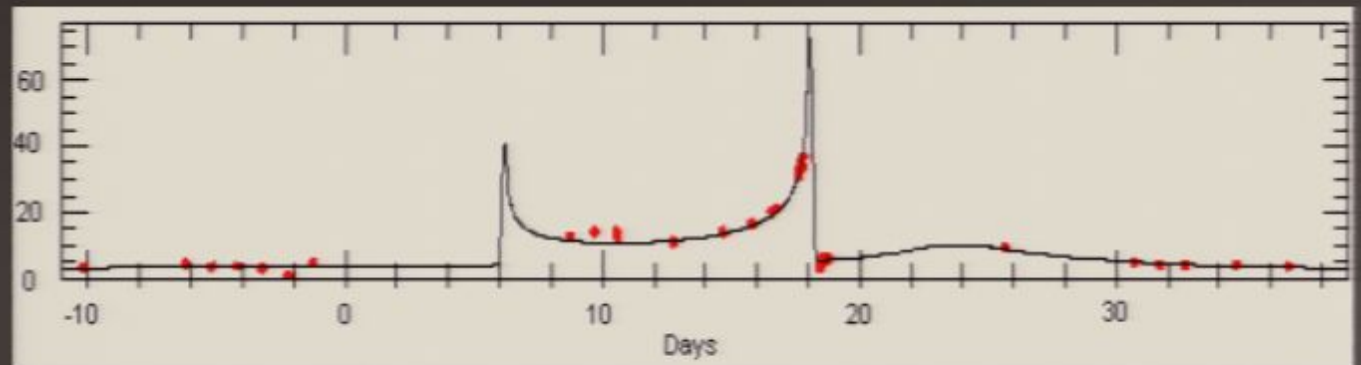
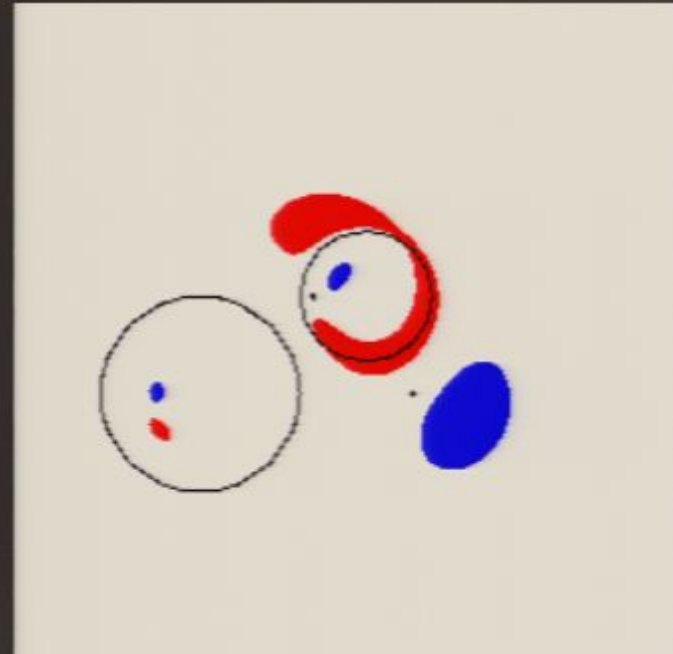
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



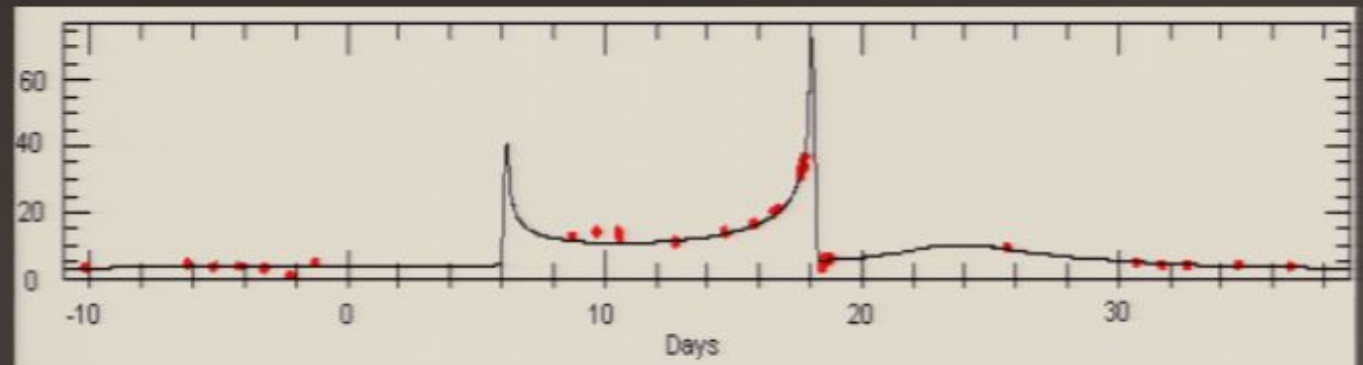
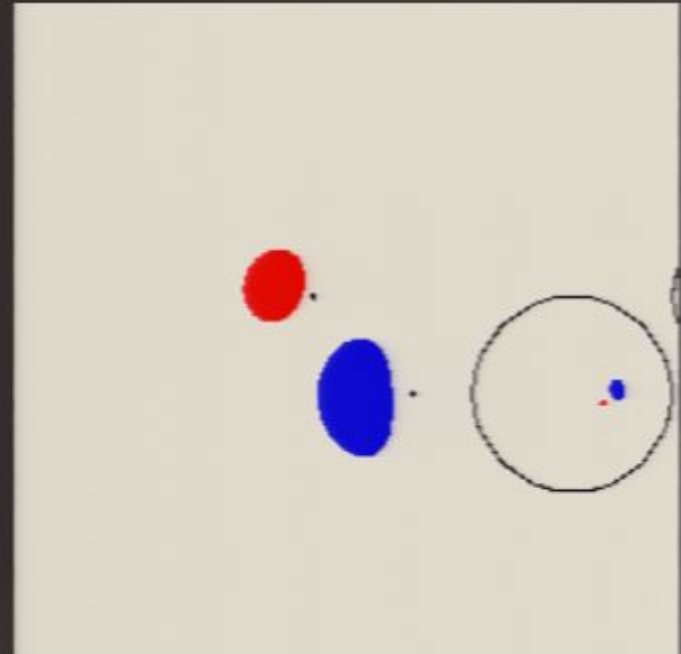
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



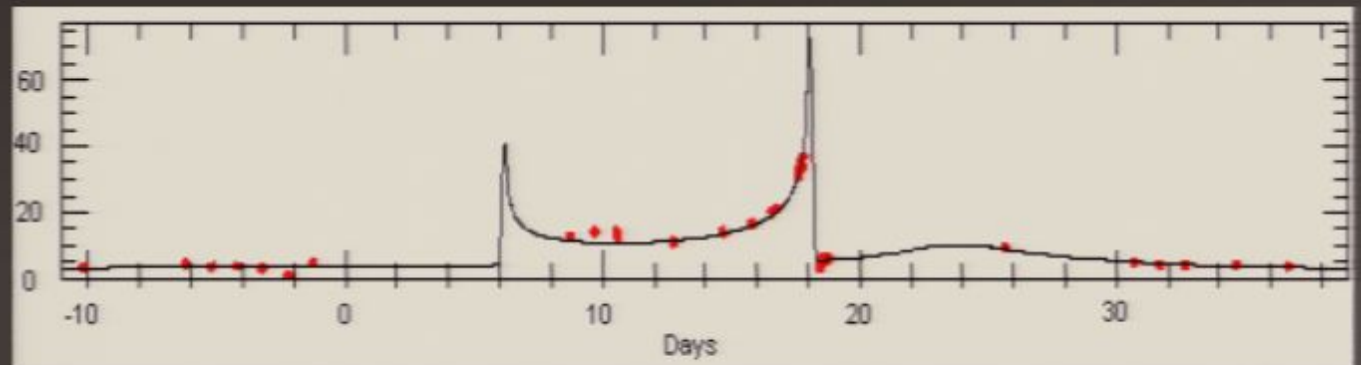
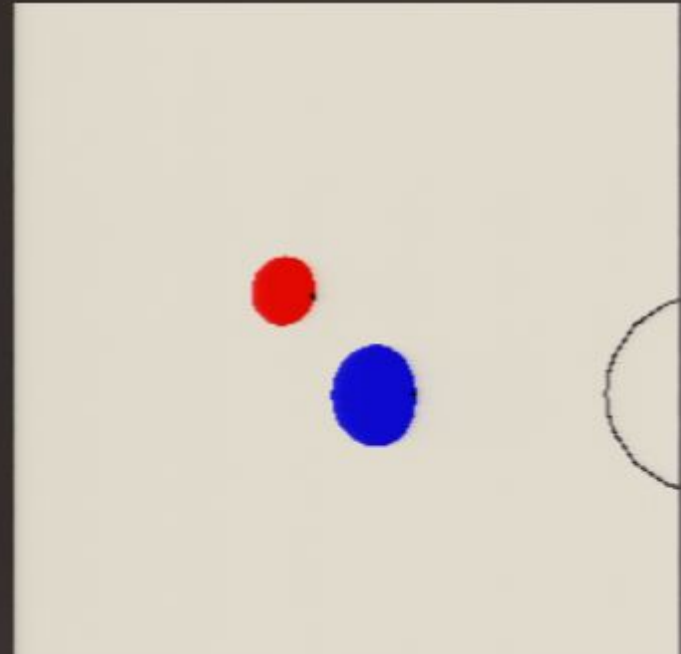
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



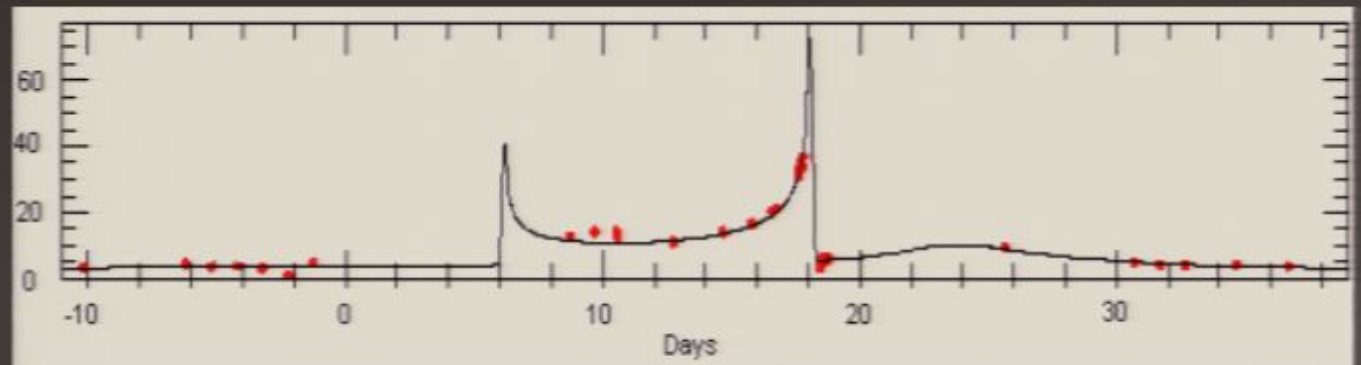
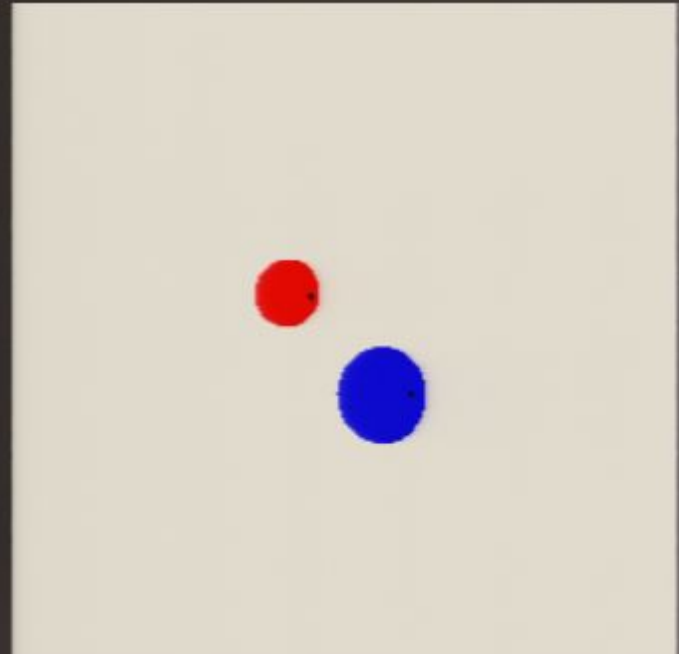
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



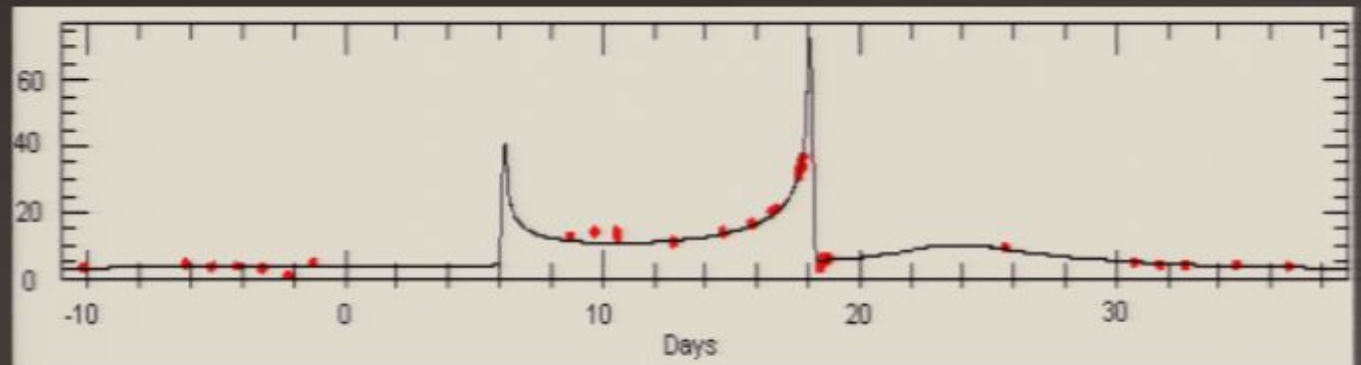
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



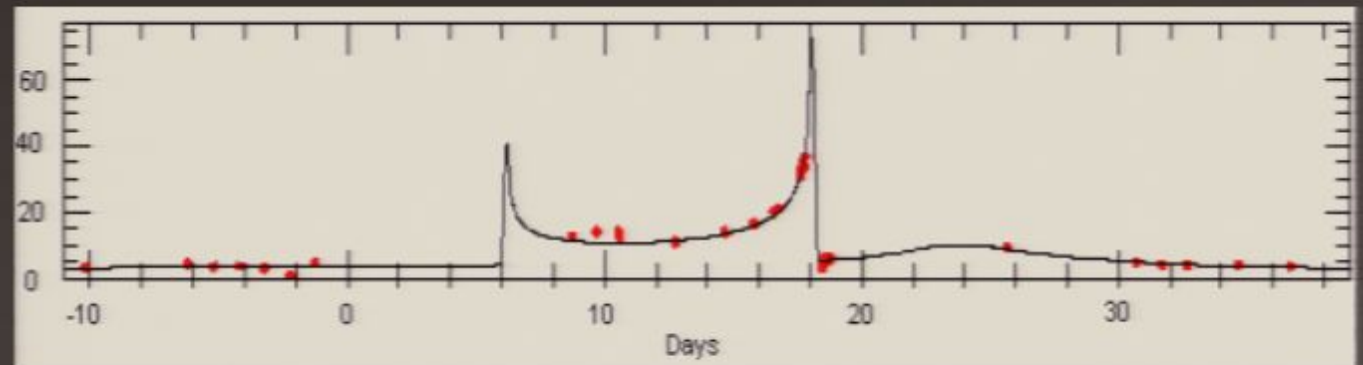
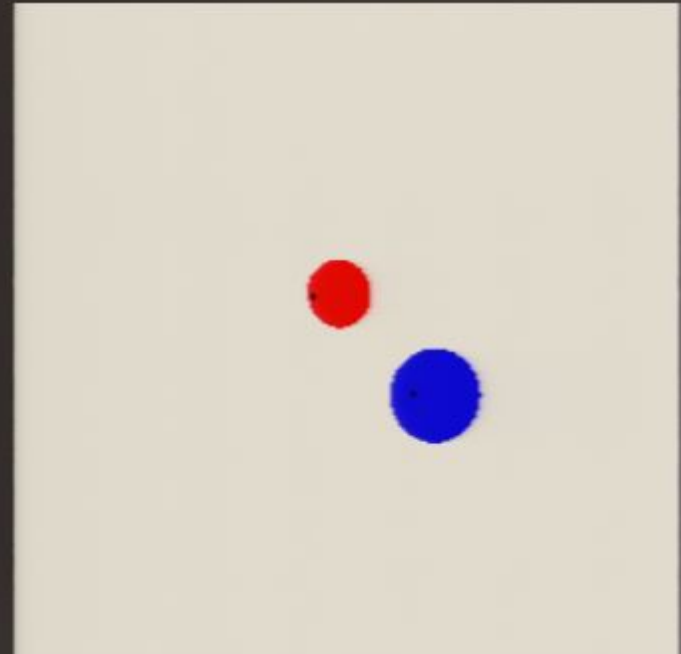
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



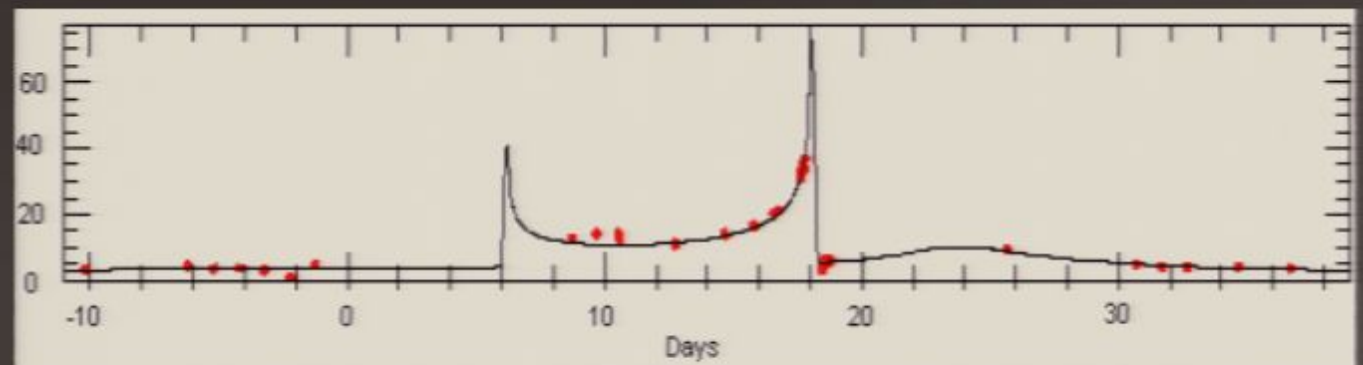
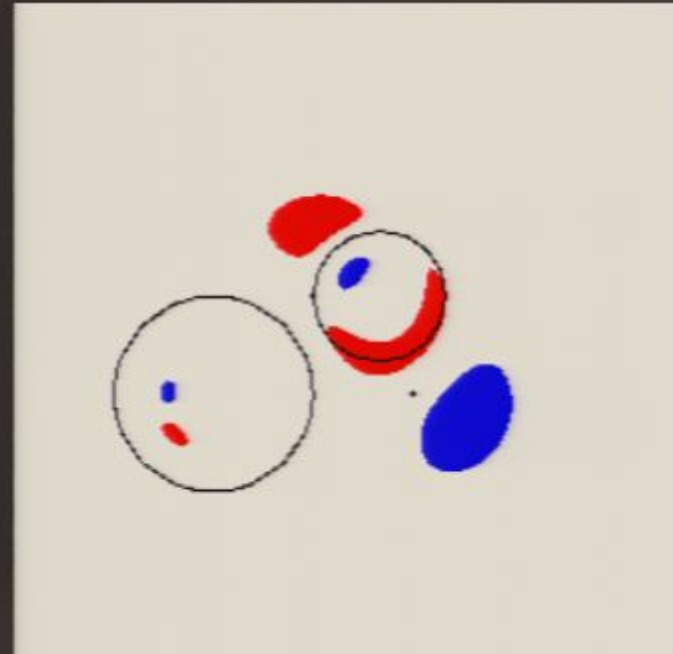
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



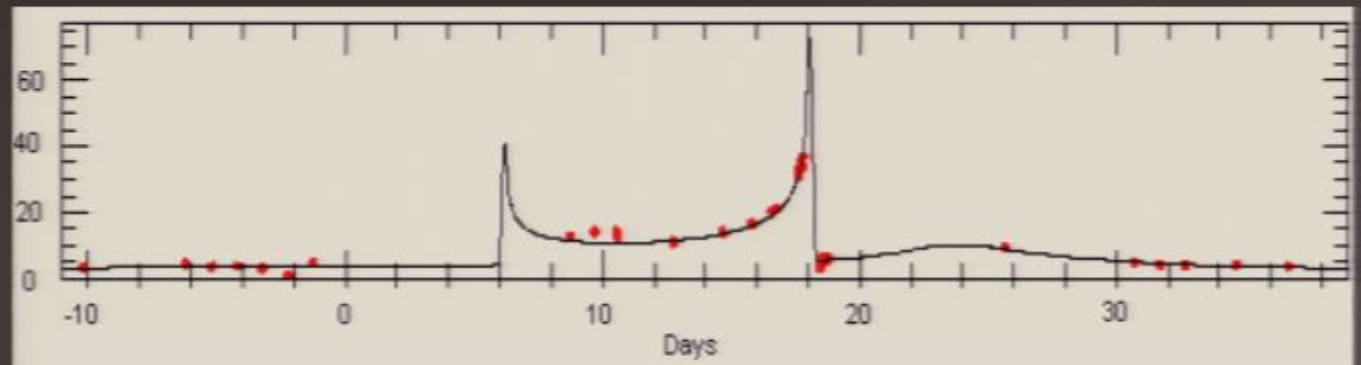
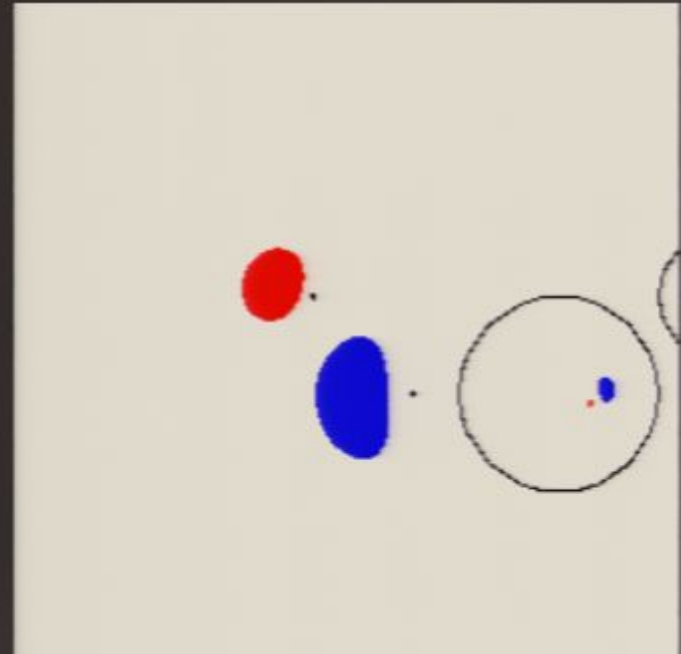
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



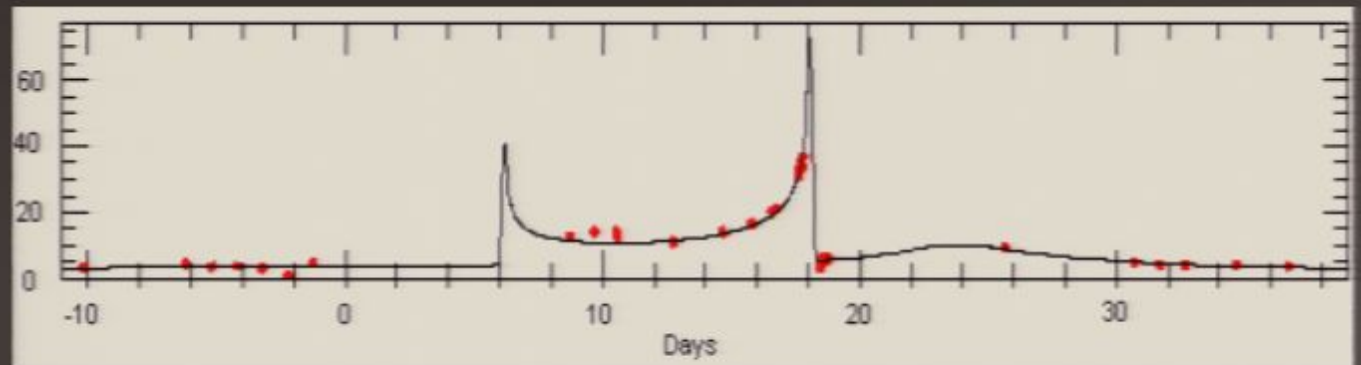
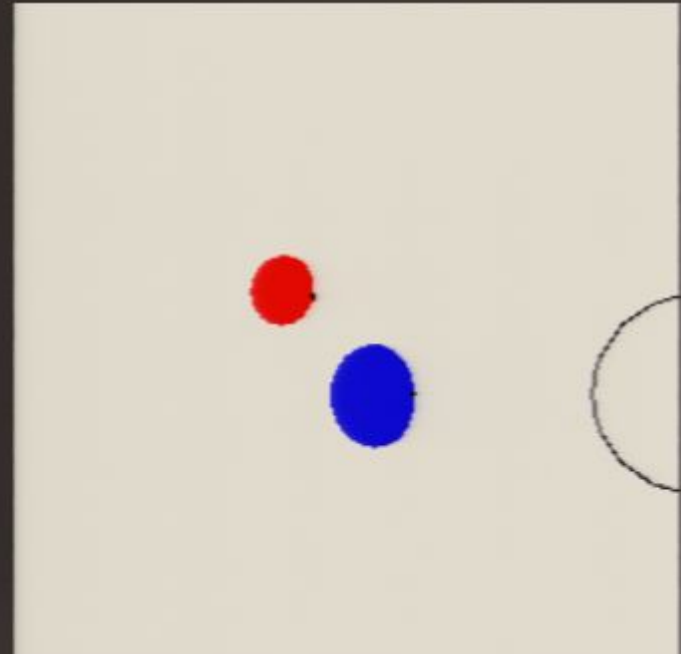
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



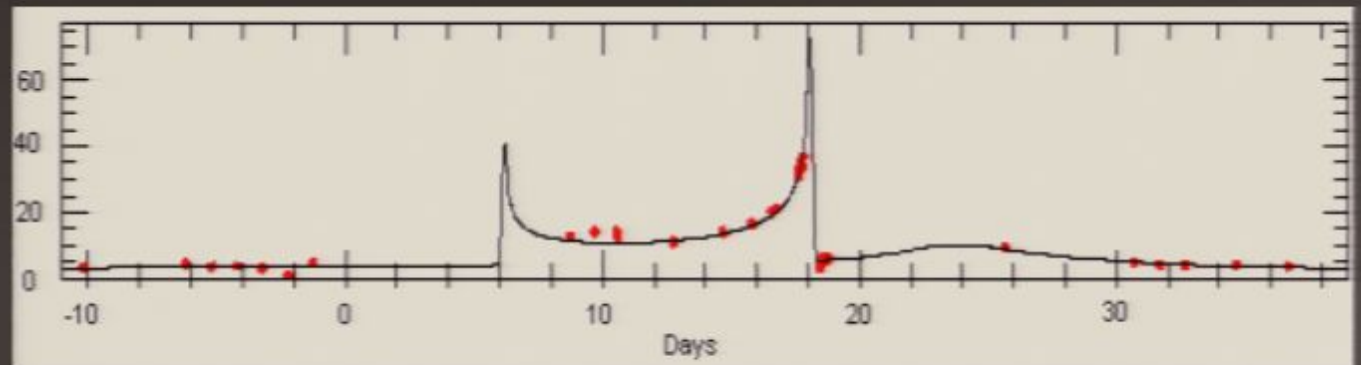
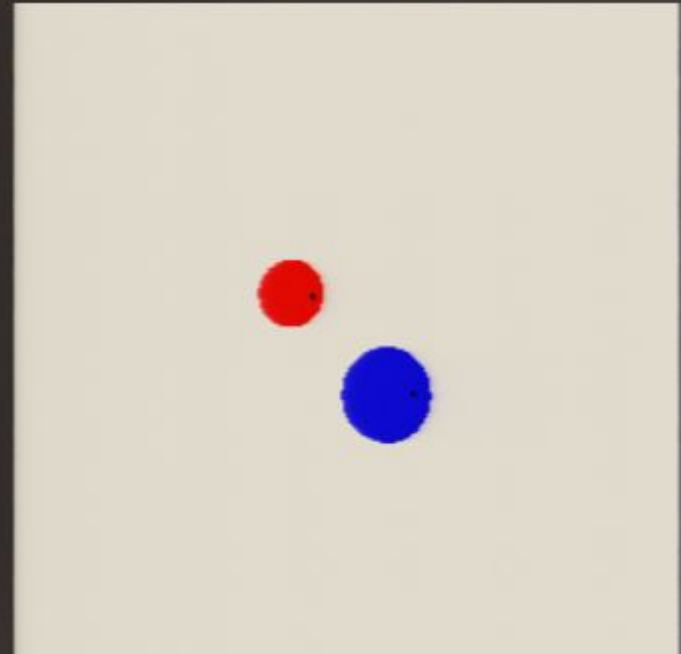
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



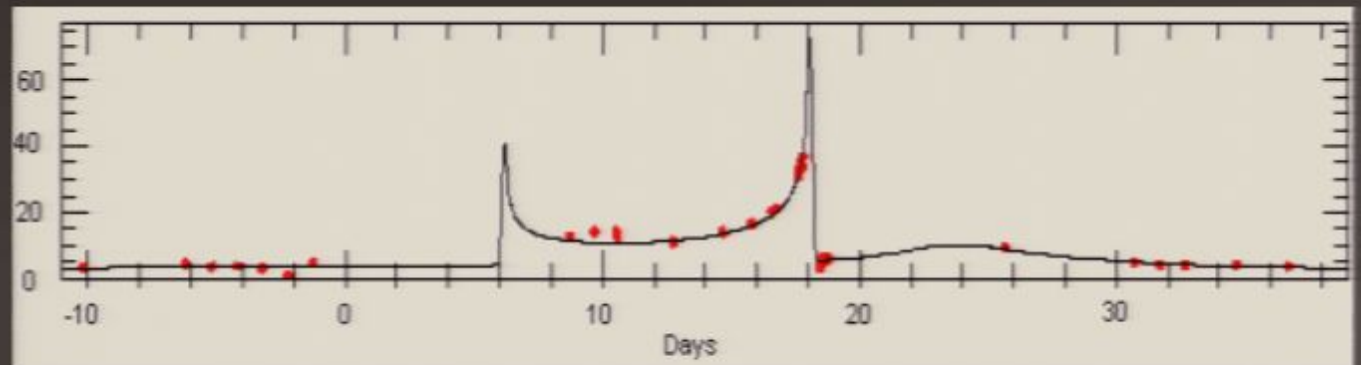
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



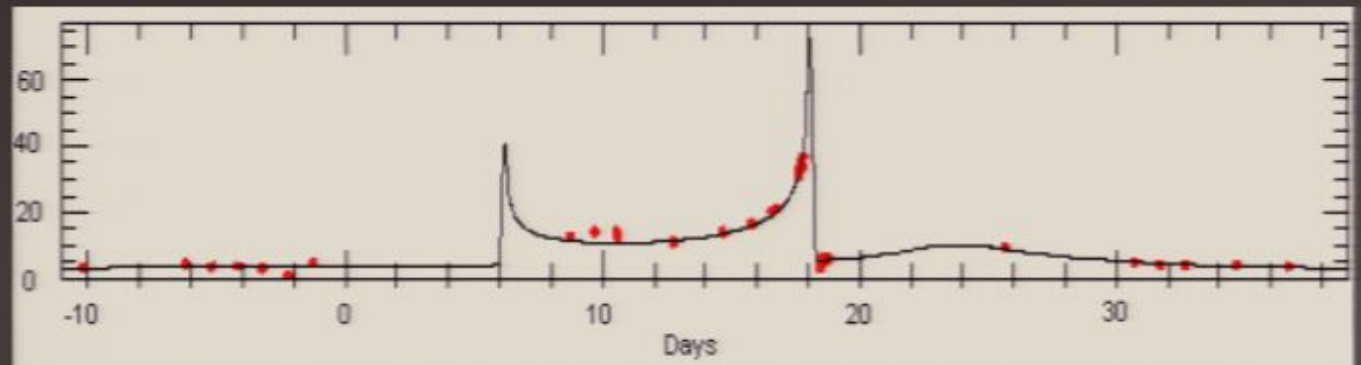
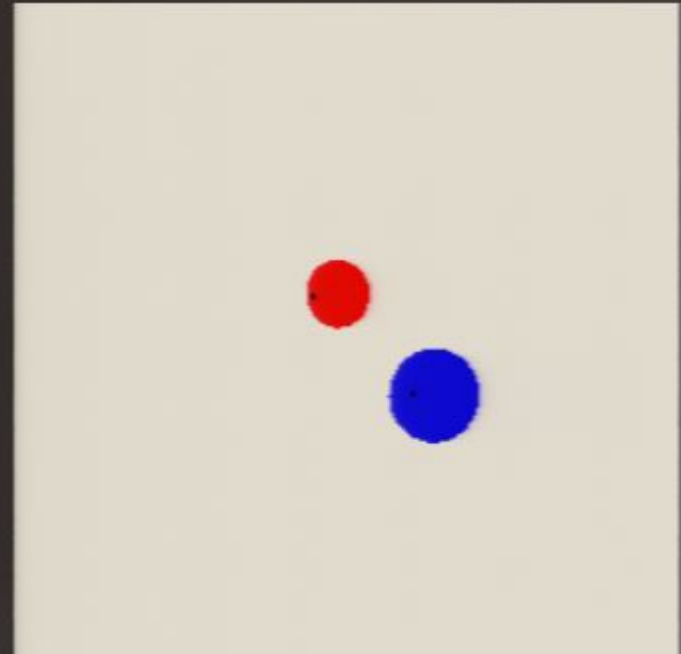
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



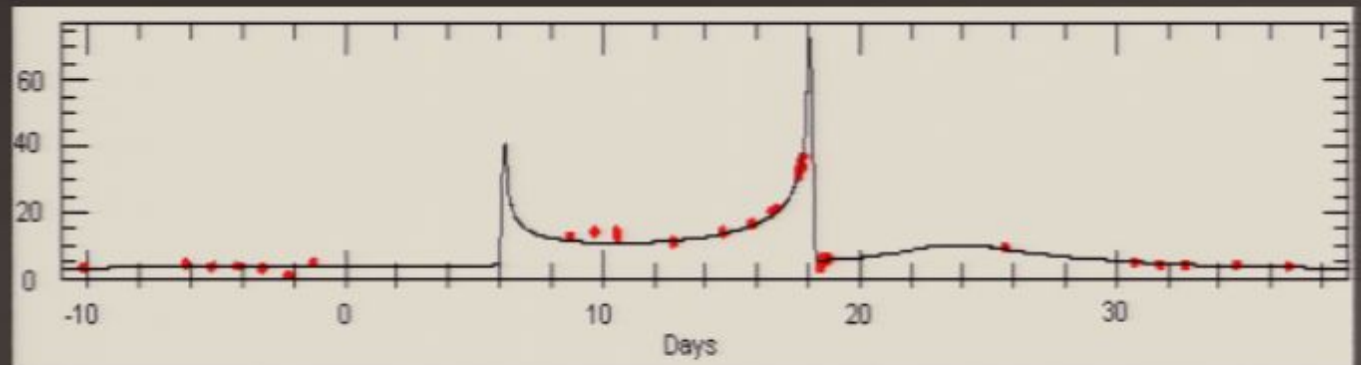
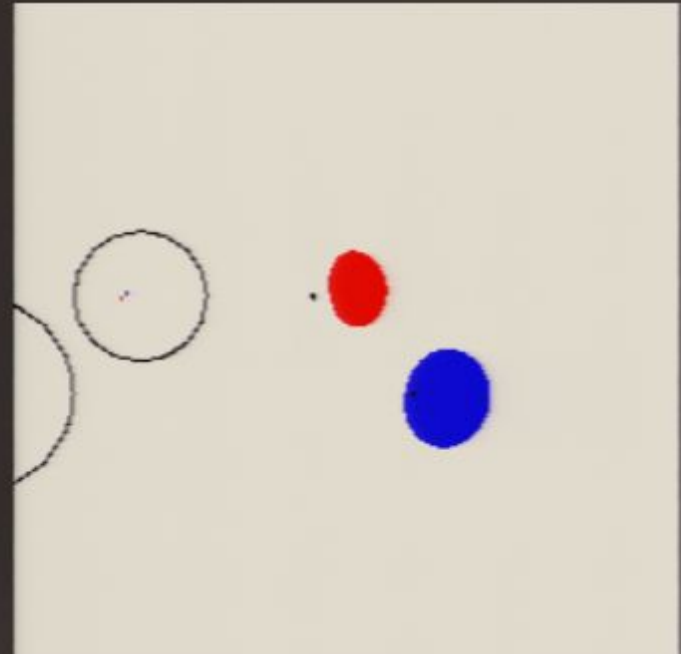
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



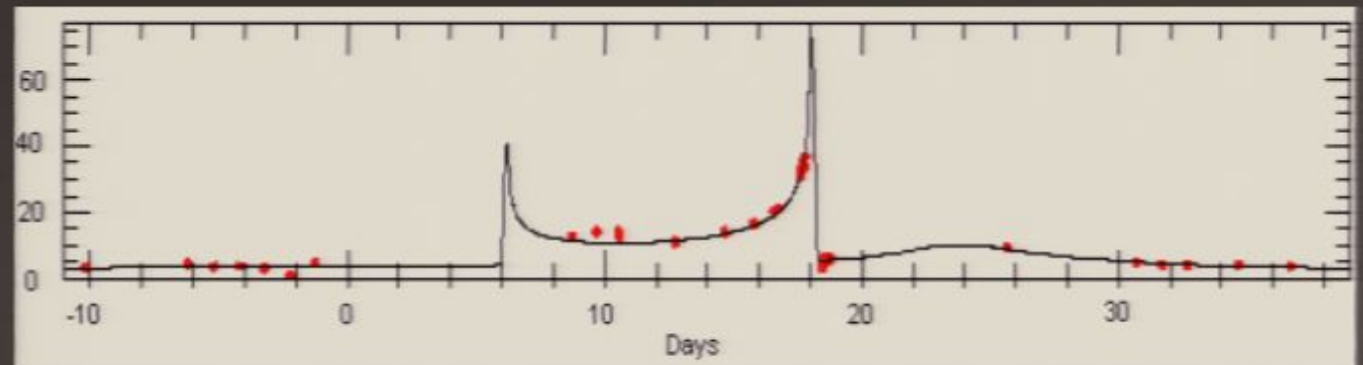
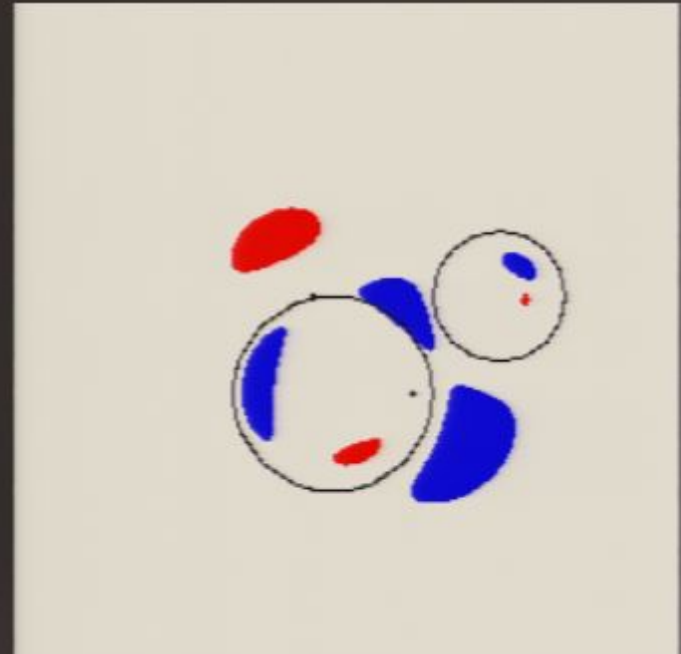
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



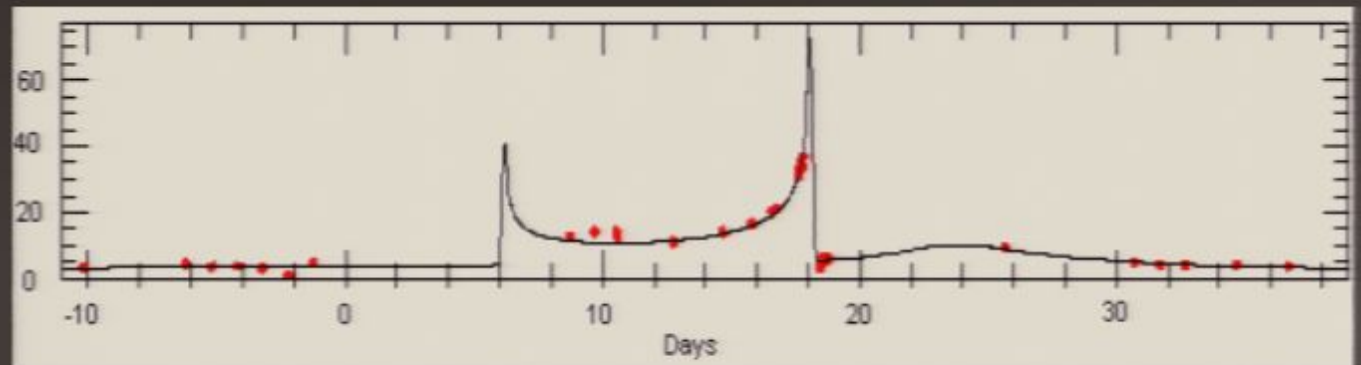
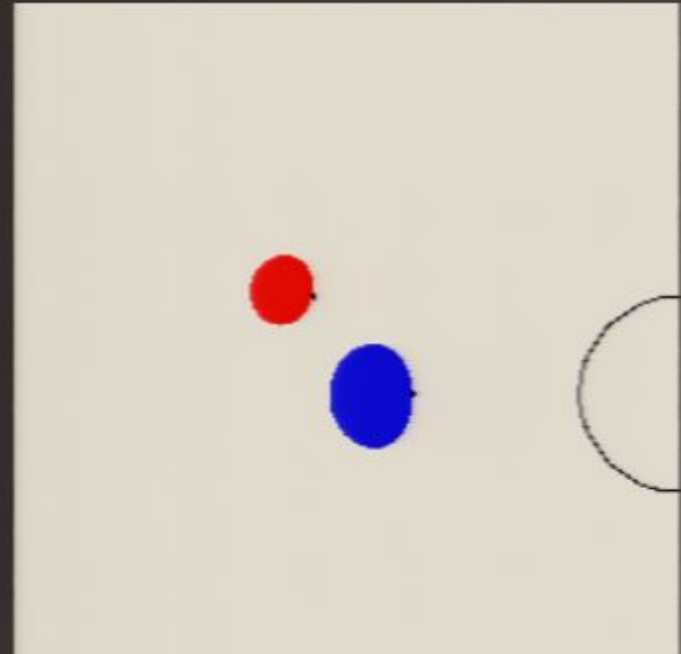
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



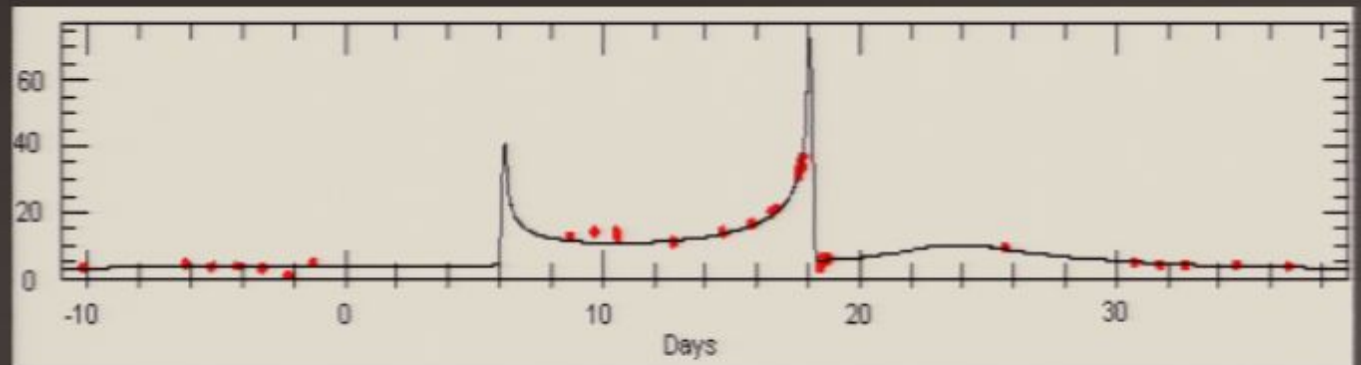
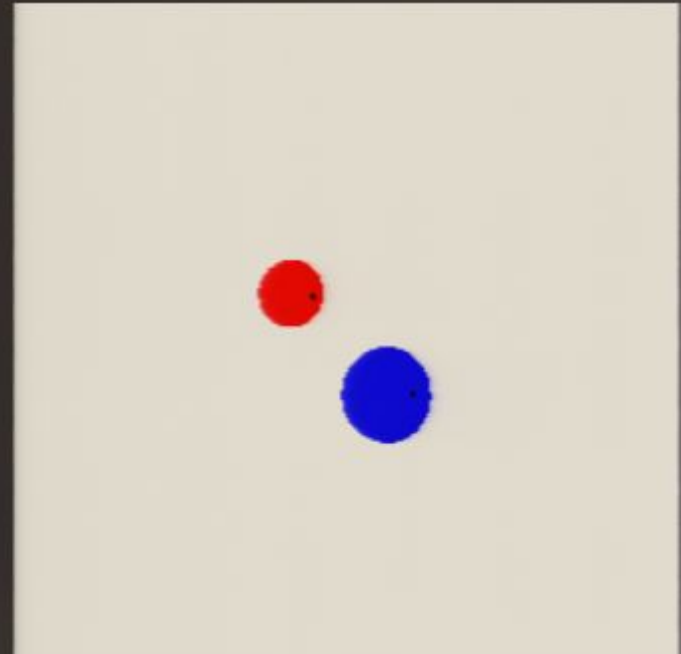
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



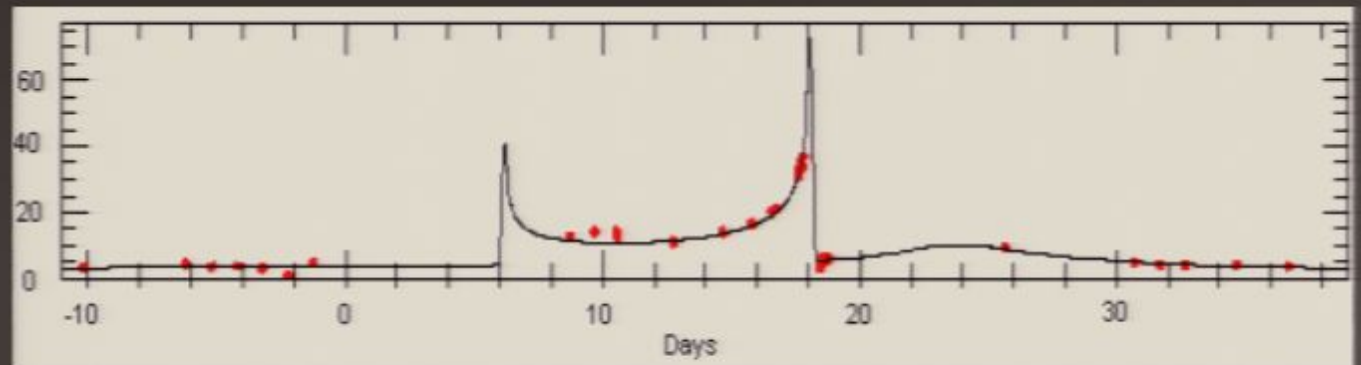
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



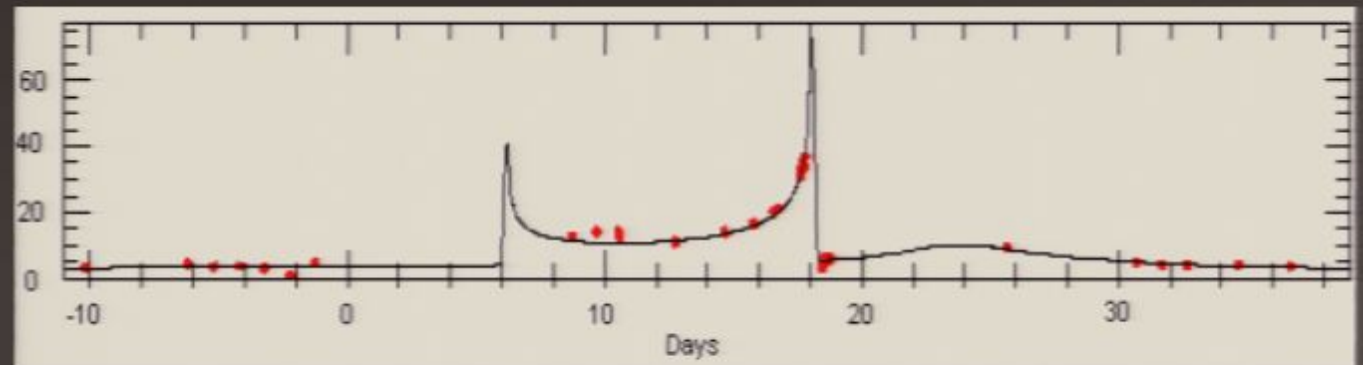
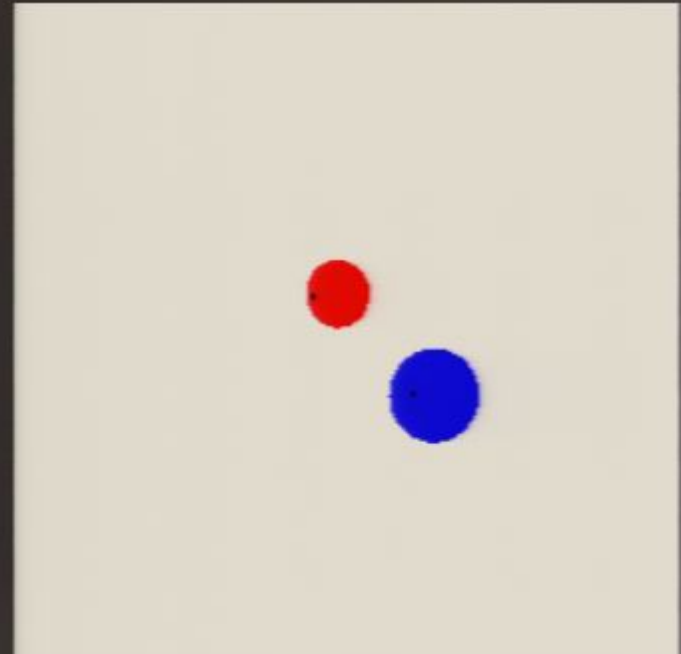
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



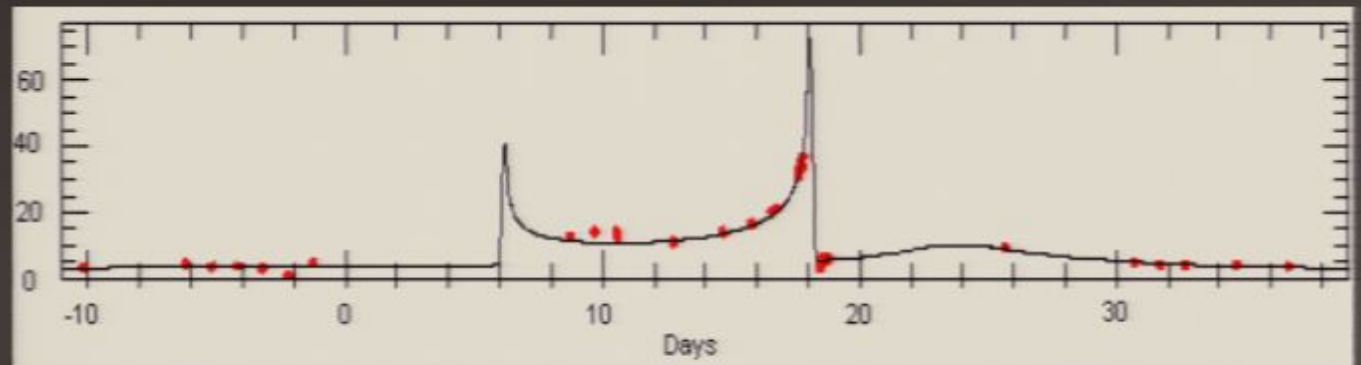
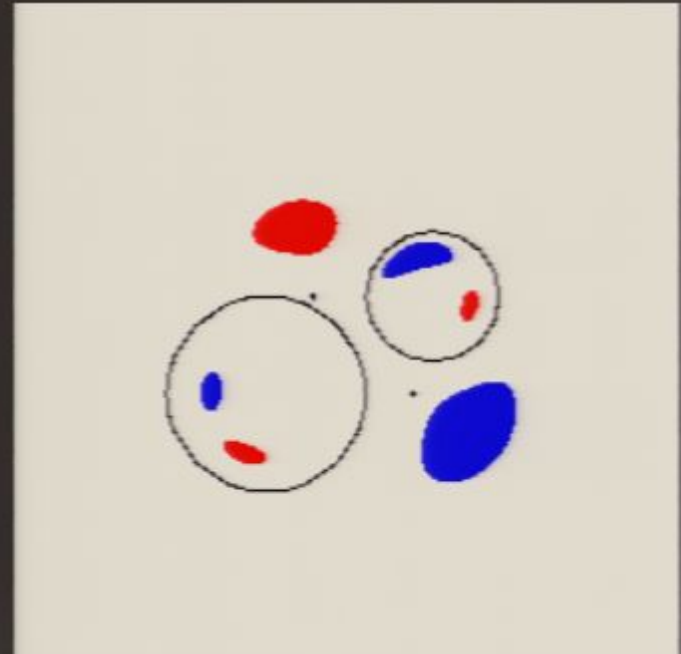
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



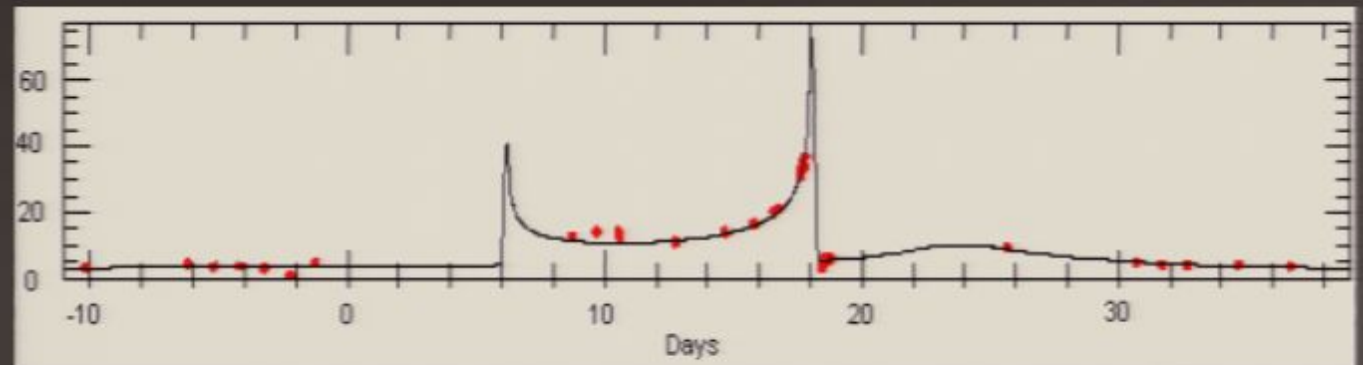
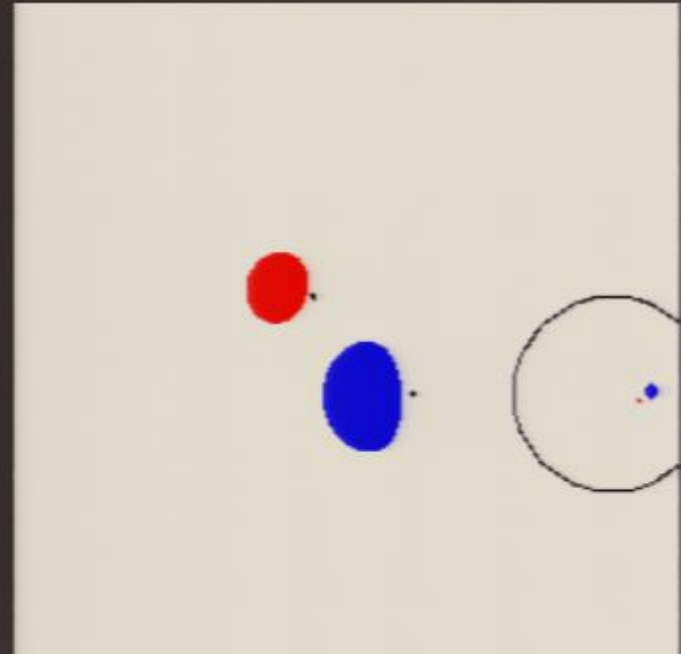
What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



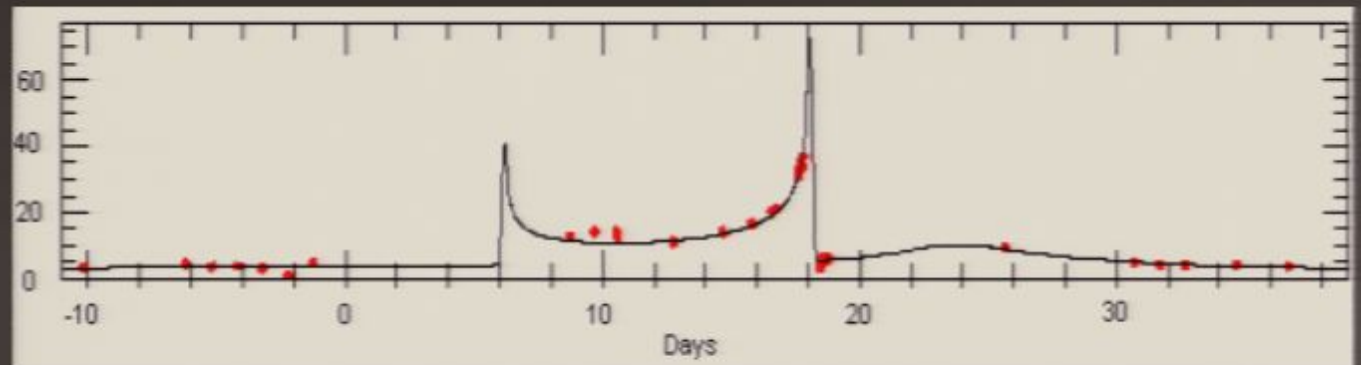
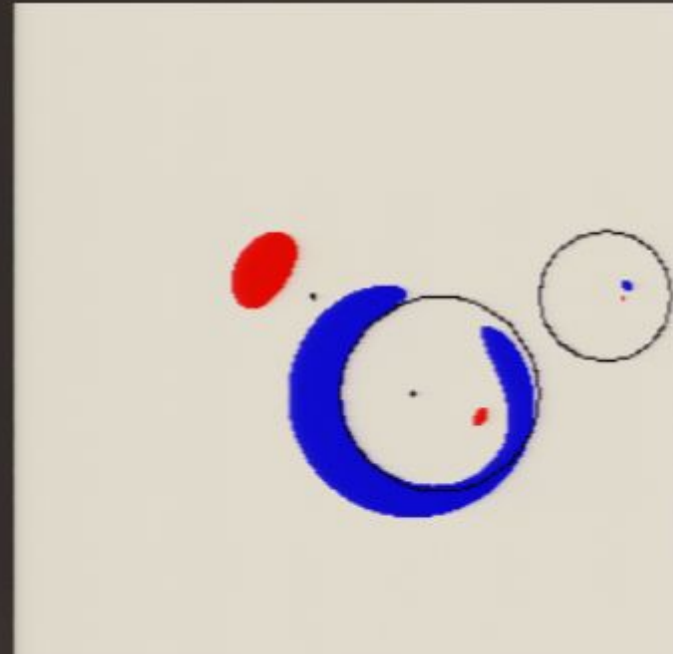
What is the Dark Matter?

- *Ordinary atoms?* X
- Modifications to the Law of Gravity?
- New kind of particles?



What is the Dark Matter?

- *Ordinary atoms?* ✗
- Modifications to the Law of Gravity?
- New kind of particles?



What is the Dark Matter?

- Ordinary atoms?
- *Modifications to the Law of Gravity?*
- New kind of particles?



The devil is in the details:



No proposals yet succeed for galaxies and clusters and the CMB.

Very difficult to modify gravity at long distances without having problems with fundamental principles.

What is the Dark Matter?

- Ordinary atoms?
- Modifications to the Law of Gravity?
- *New kind of particles?*



Weakly Interacting Massive Particles arise in most theories of microscopic physics.

Their residual cosmic abundance is naturally the right size to agree with the observed amount of Dark Matter.

What is the Dark Matter?

- Ordinary atoms?
- Modifications to the Law of Gravity?
- *New kind of particles?*



Weakly Interacting Massive Particles arise in most theories of microscopic physics.

Their residual cosmic abundance is naturally the right size to agree with the observed amount of Dark Matter.

Outline

- The Hot Big Bang
 - *Evidence for a Hot Expanding Universe*
 - *Dark Matter and Dark Energy*
- Contact With Fundamental Physics
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- Outlook

What Cosmology Requires

- *Small, positive energy density*

$$\rho \approx 10^{-29} \text{ g/cc} \approx (3 \times 10^{-3} \text{ eV})^4$$

What Cosmology Requires

- Small, positive energy density

$$\rho \approx 10^{-29} \text{ g/cc} \approx (3 \times 10^{-3} \text{ eV})^4$$

- *Negative pressure:*
 $p < -\rho/3$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

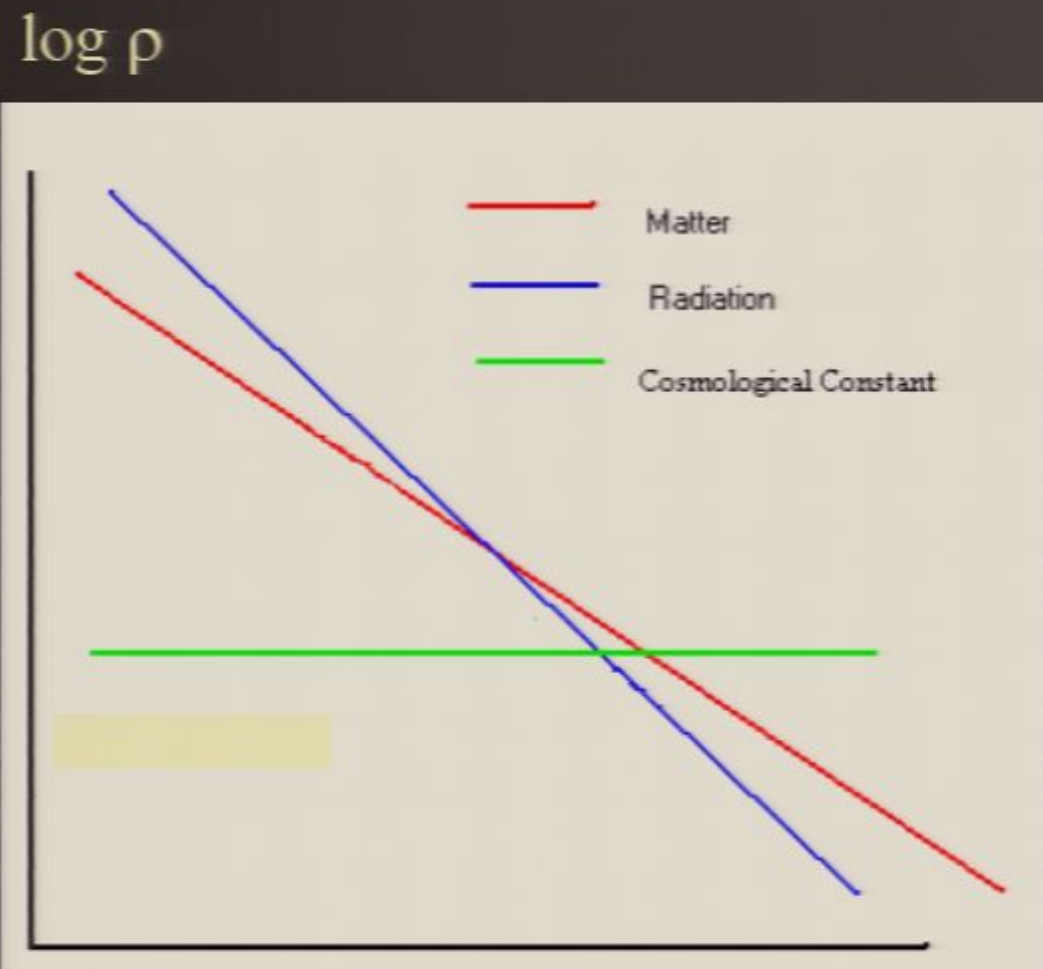


This expresses how the universal acceleration depends on the Dark Energy's energy and pressure according to Einstein.

Vacuum Energy as Dark Energy

- The energy, λ , of the vacuum has the negative pressure required to be the Dark Energy.
 - The vacuum energy is only observable through gravity because non gravitational measurements only see energy differences.

$$\rho = -p = \lambda > 0$$



The Cosmological Constant Problem

- The vacuum energy is *calculable* within any theory of elementary particles, such as the Standard Model of particle physics.
- All elementary particles contribute quantum zero-point energy to the vacuum energy, λ .
 - Each particle of mass m contributes $\lambda \approx m^4$
 - Since, for example, even the electron has $m \sim 5 \times 10^5 \text{ eV} \gg 10^{-3} \text{ eV}$, how can the vacuum have such a small energy density: $\lambda \ll m^4$?

Outlook


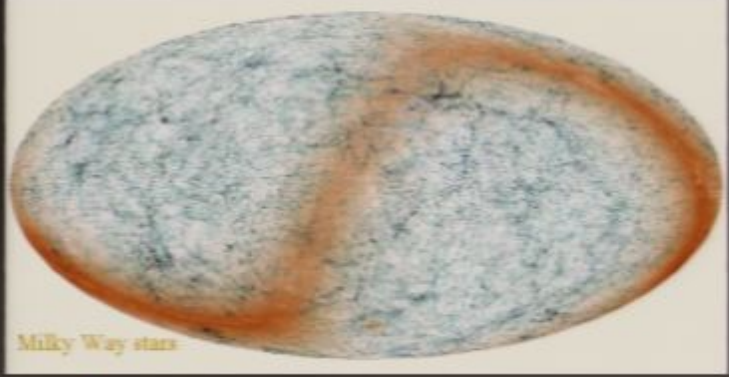
“If I had only known, I’d have become a locksmith.”

Albert Einstein



Evidence for an Expanding Universe

- The sky is dark
- The Hubble Law
- *The homogeneity and isotropy of the universe*
- The slower decay of more distant supernovae



Milky Way stars

The slide features a dark grey background with a list of evidence points. To the right of the list, there are two images. The top image is a photograph of the Milky Way galaxy, showing a dense field of stars with a reddish-brown band across the center. Below it is a dark field of stars, which is a photograph of a distant galaxy cluster. An orange arrow points from the dark field image up to the Milky Way image.

Outlook

- Cosmological observations are now redundantly testing the Hot Big Bang model.
 - Observations support the ‘Concordance Cosmology’.
- The concordance involves several lines of independent evidence for both Dark Matter and Dark Energy.
 - Neither can be dark forms of ordinary atoms.
- Dark Matter may be new kinds of elementary particles, but Dark Energy is more difficult to embed into a fundamental theory (although a few proposals do exist).
 - If so we’ll know from a variety of observational tests.