

Title: What is the Universe Made Of?

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Abstract:



What is the Universe Made of?

*The Case for Dark Energy
and Dark Matter*

Cliff Burgess



What is the Universe Made of?

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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

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Outline

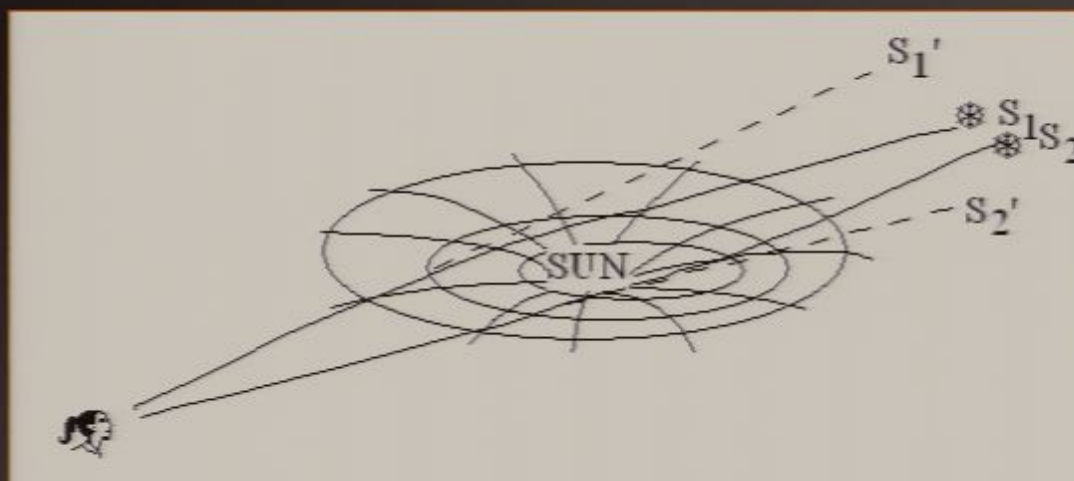
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Gravity, Matter & Geometry

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

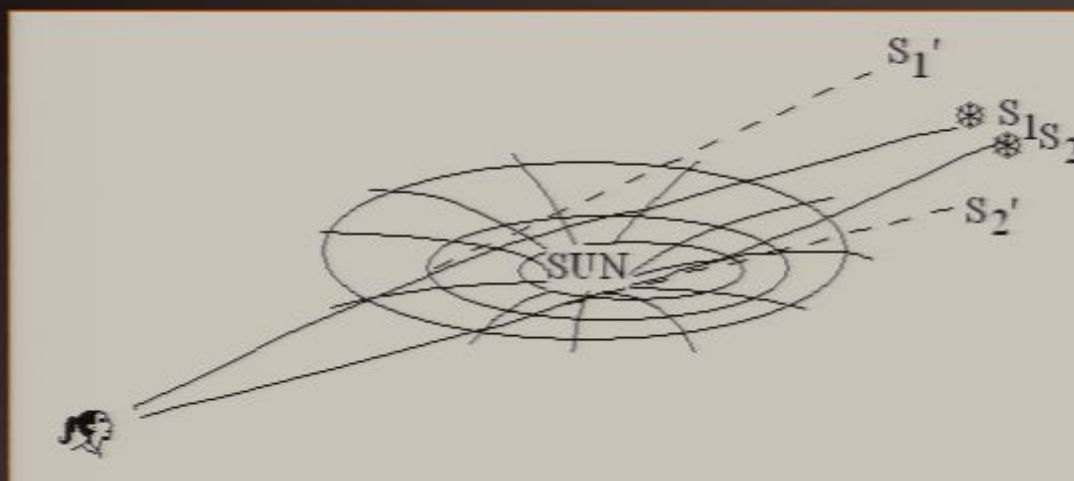
Albert Einstein

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

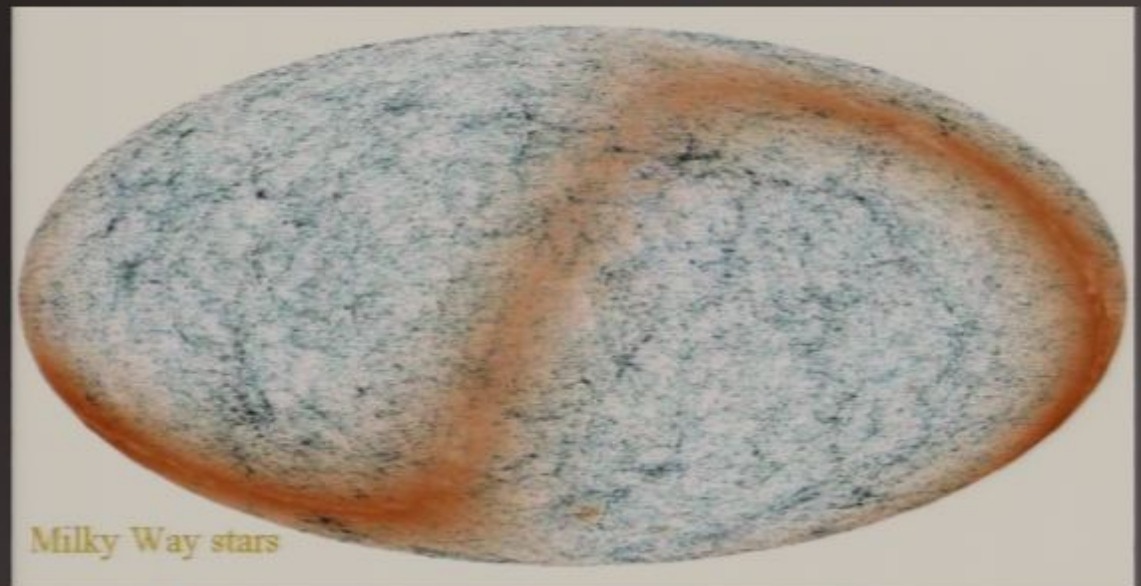


- According to Einstein gravity is really the response of space and time to the presence of matter.
 - The presence of energy curves space and time.
 - The curvature of space changes how objects move.
- *Knowing how matter is distributed over large scales tells us the shape and evolution of the Universe!*

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*



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WMAP*



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WMAP*



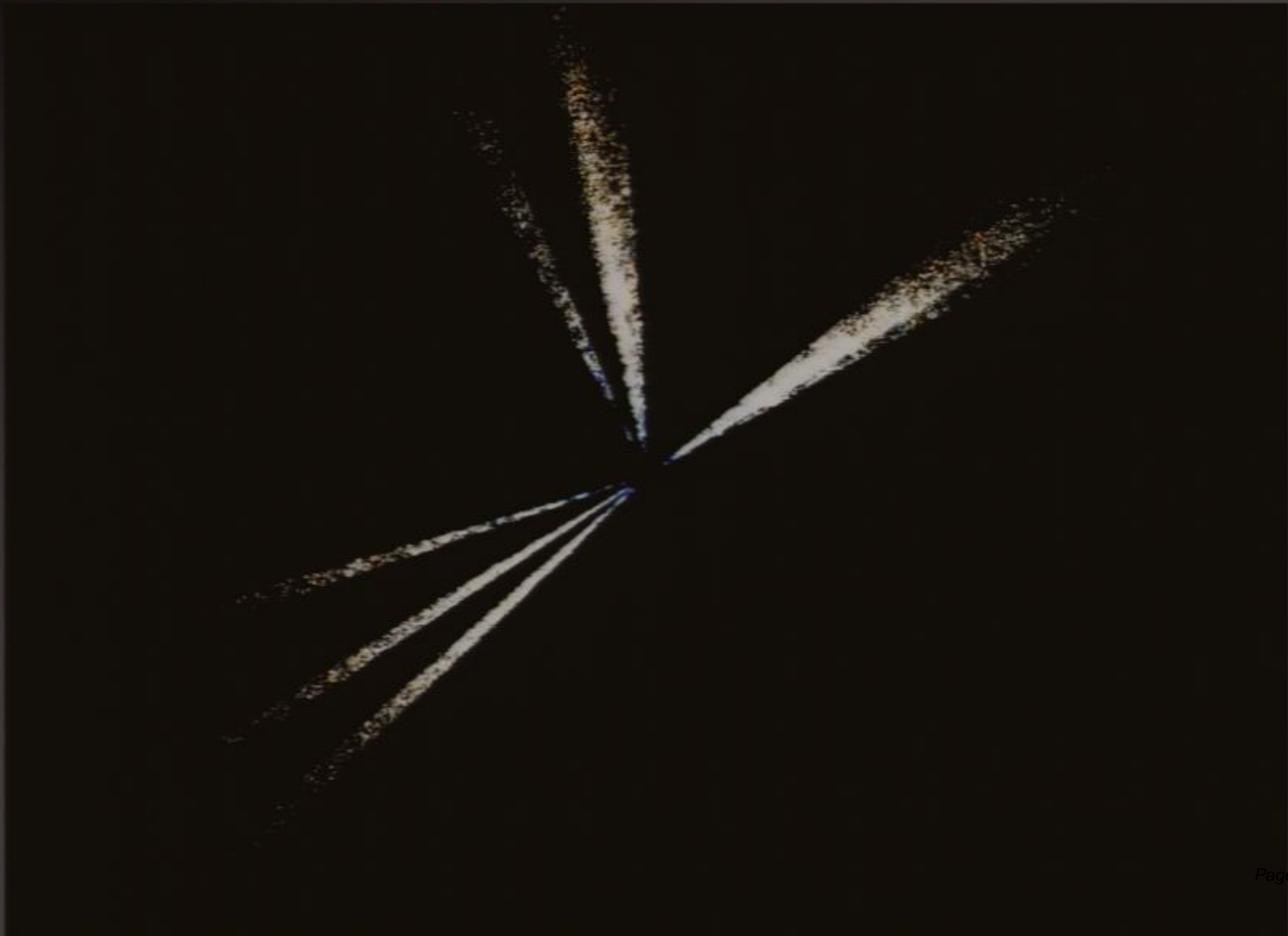
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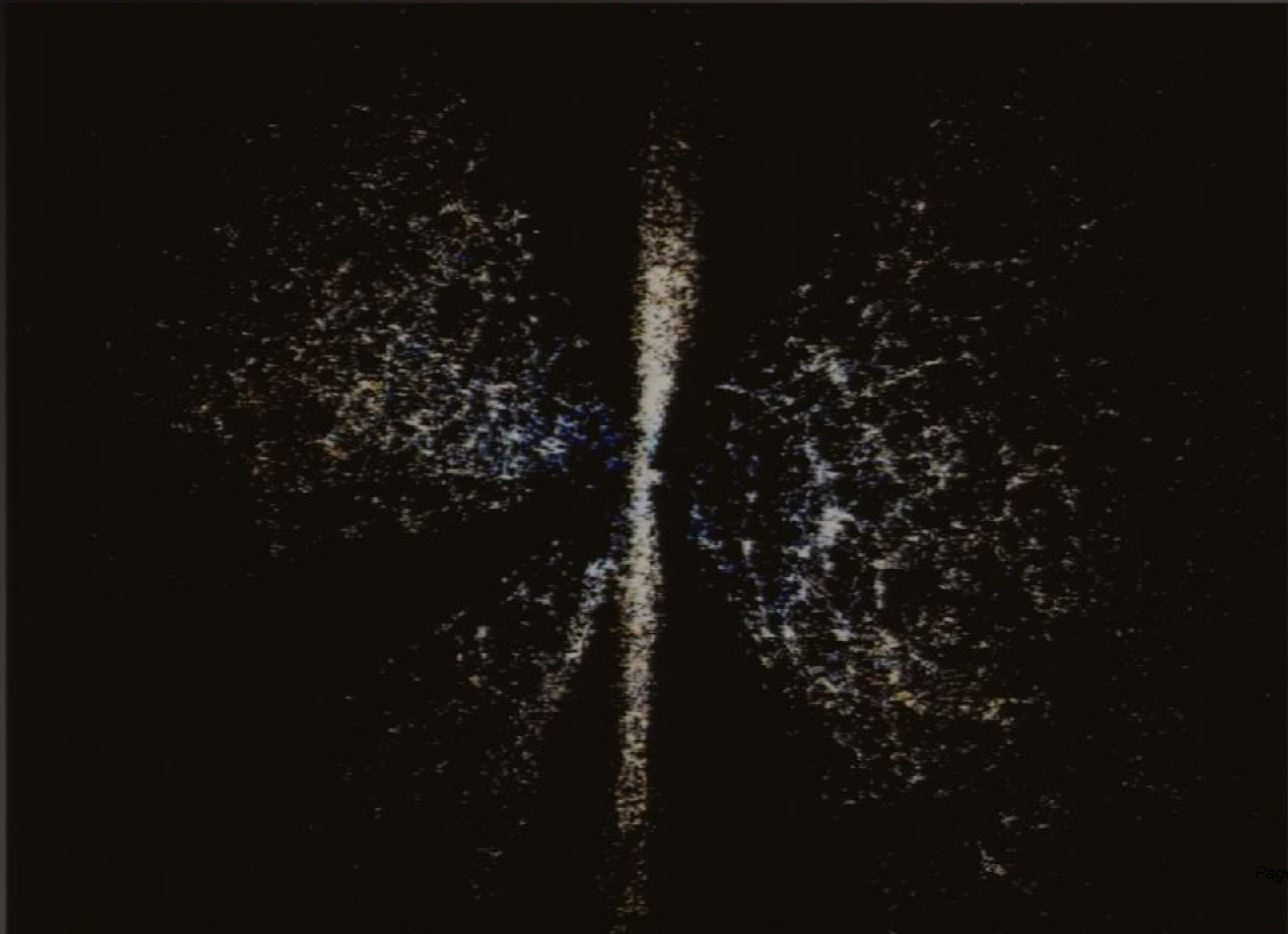
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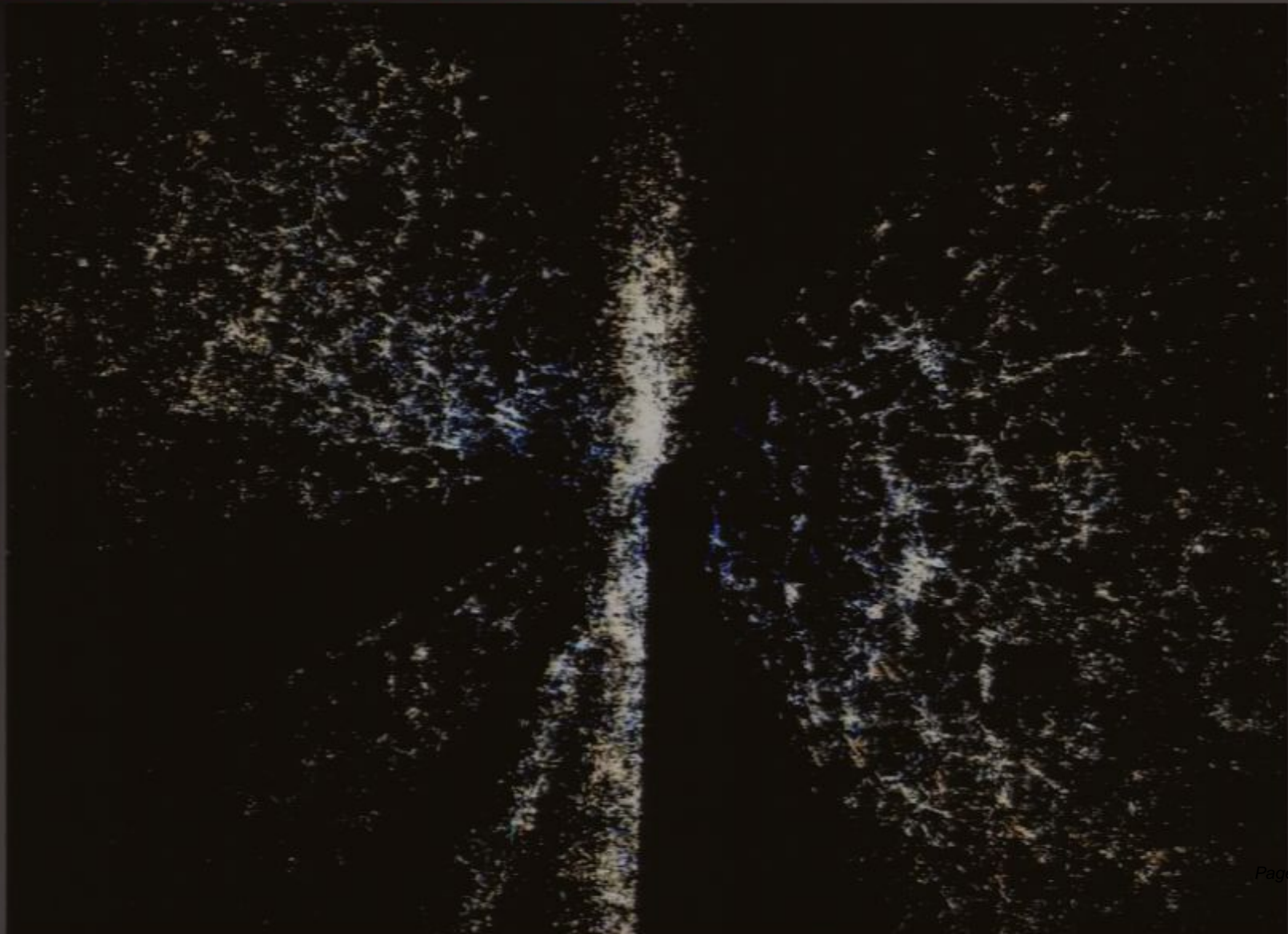
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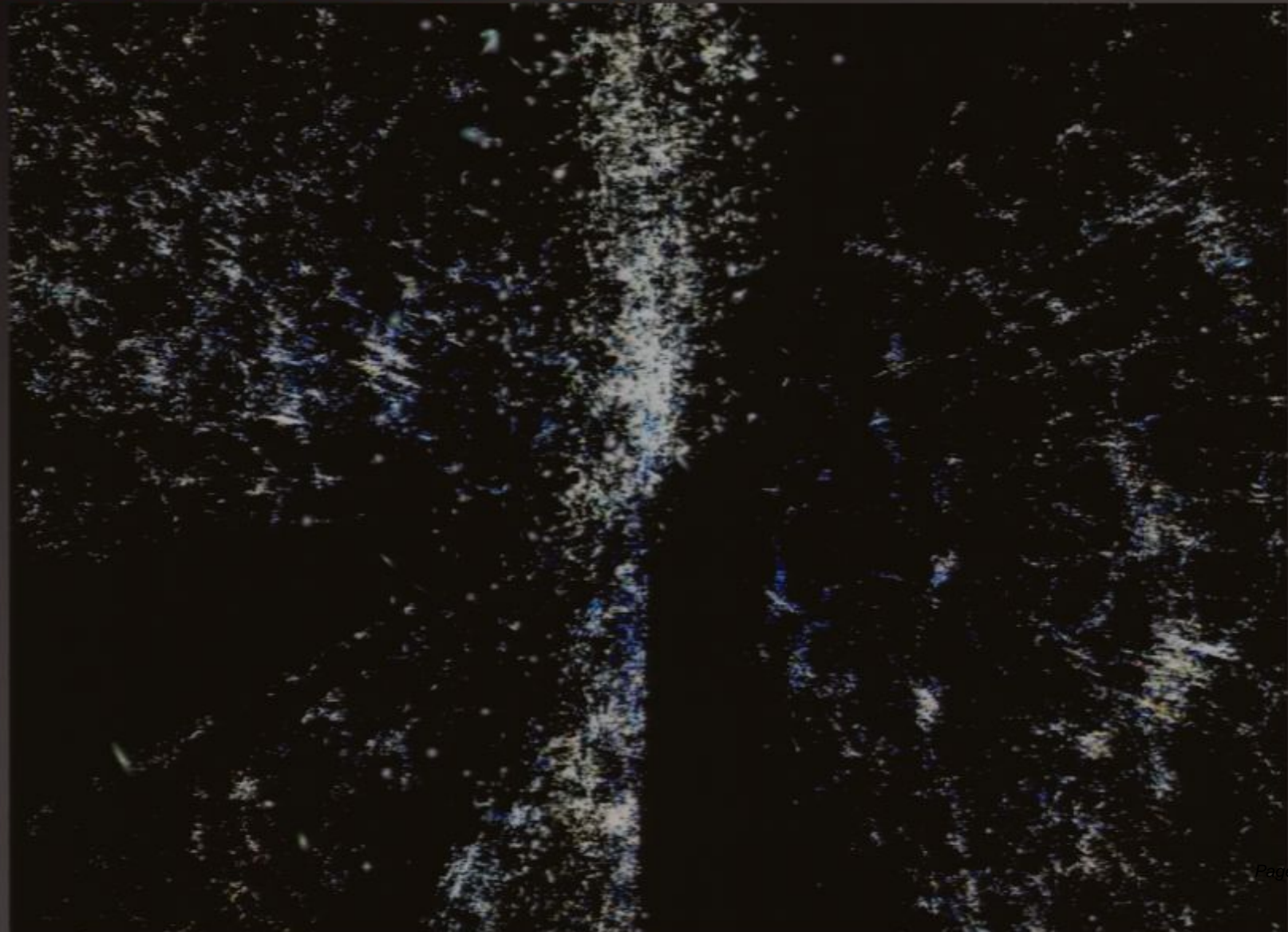
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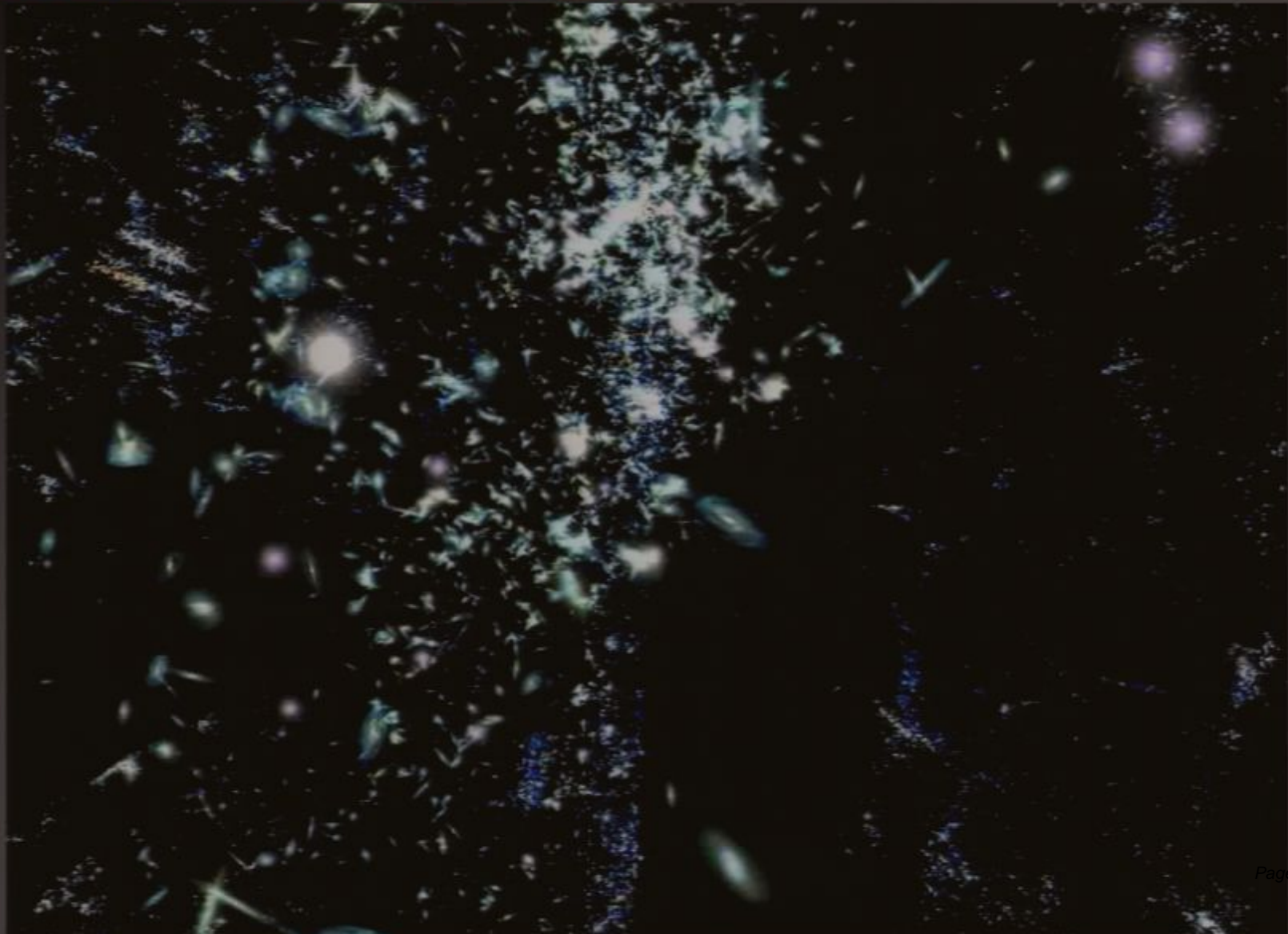
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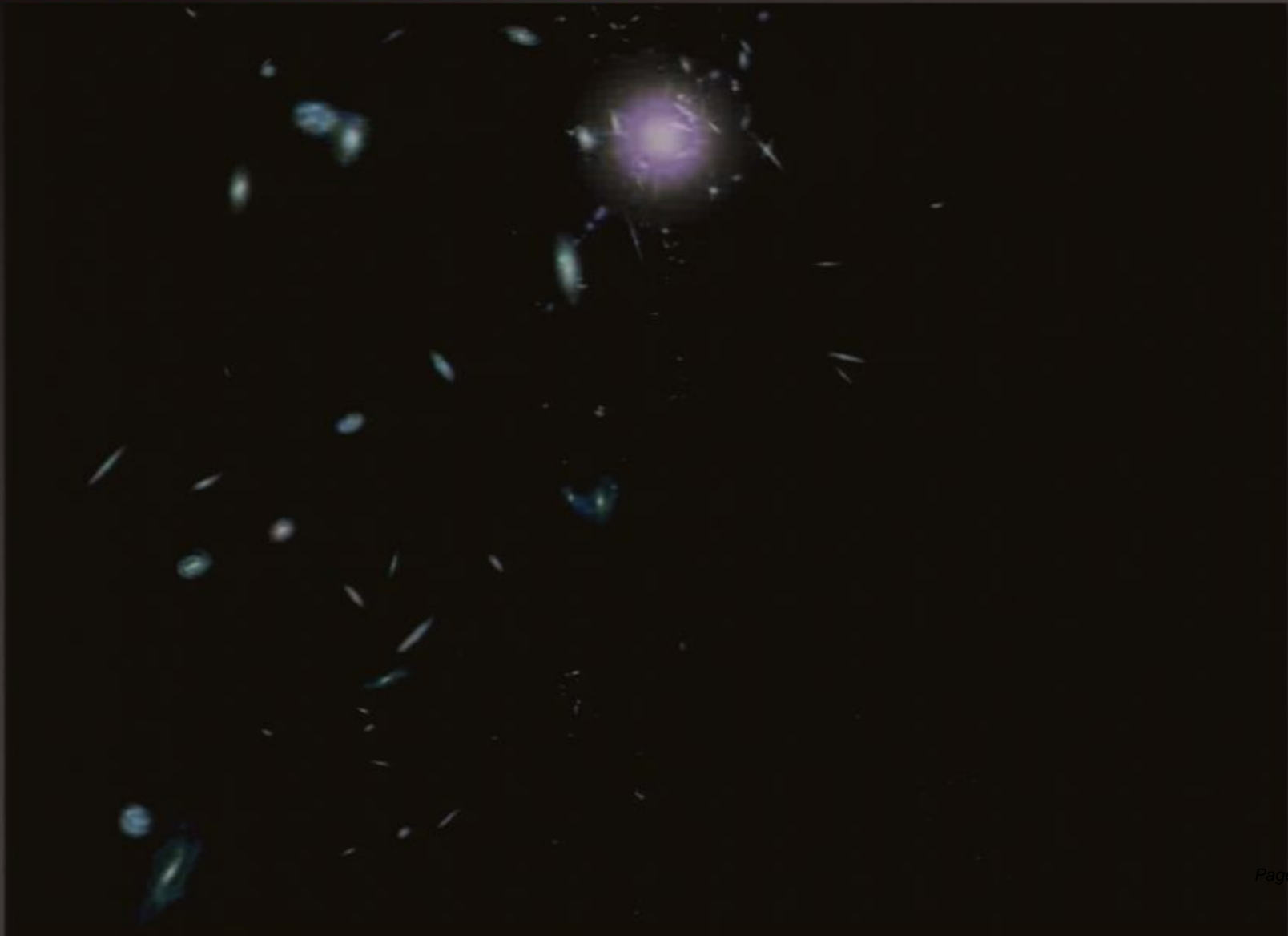
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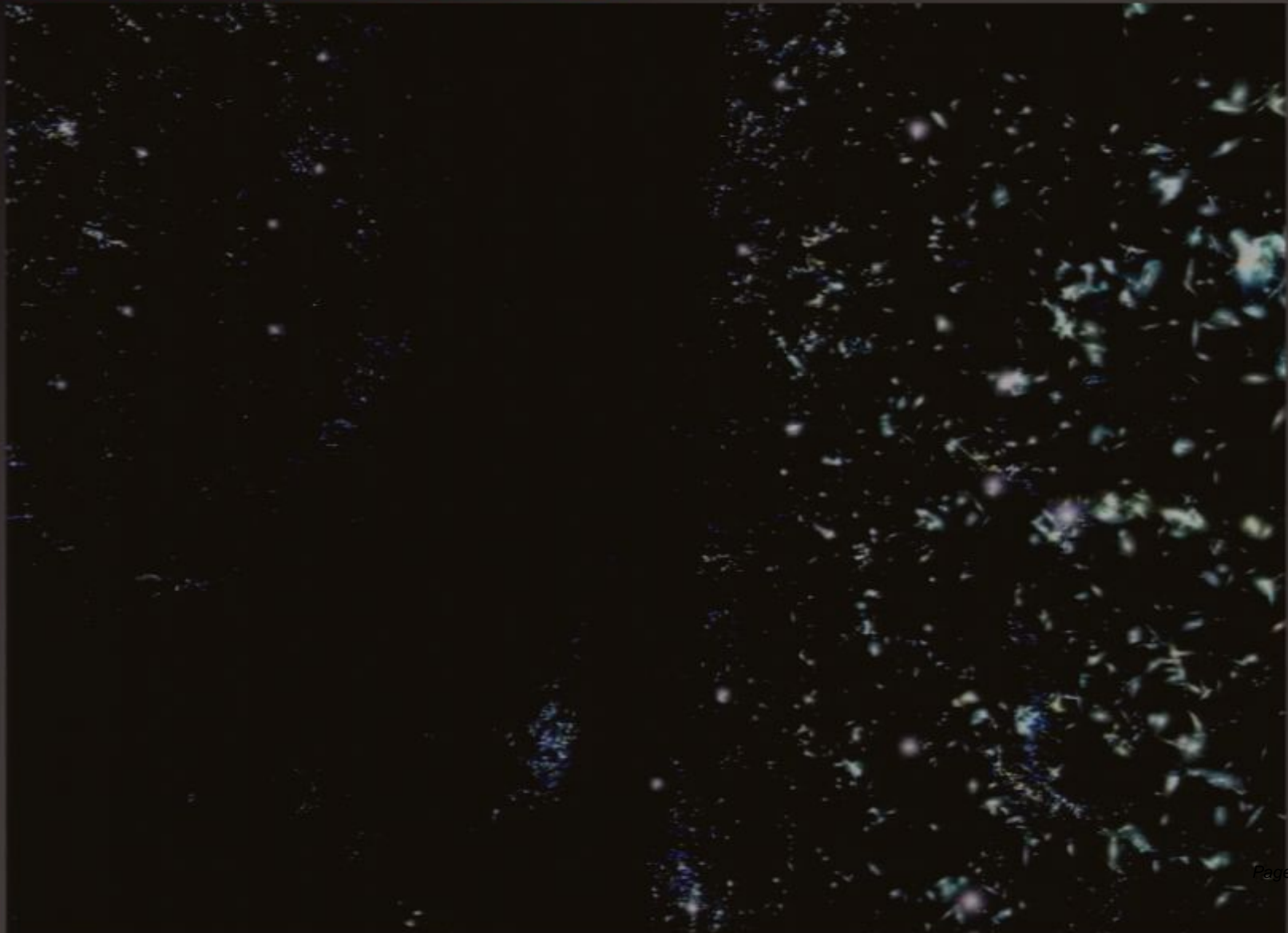
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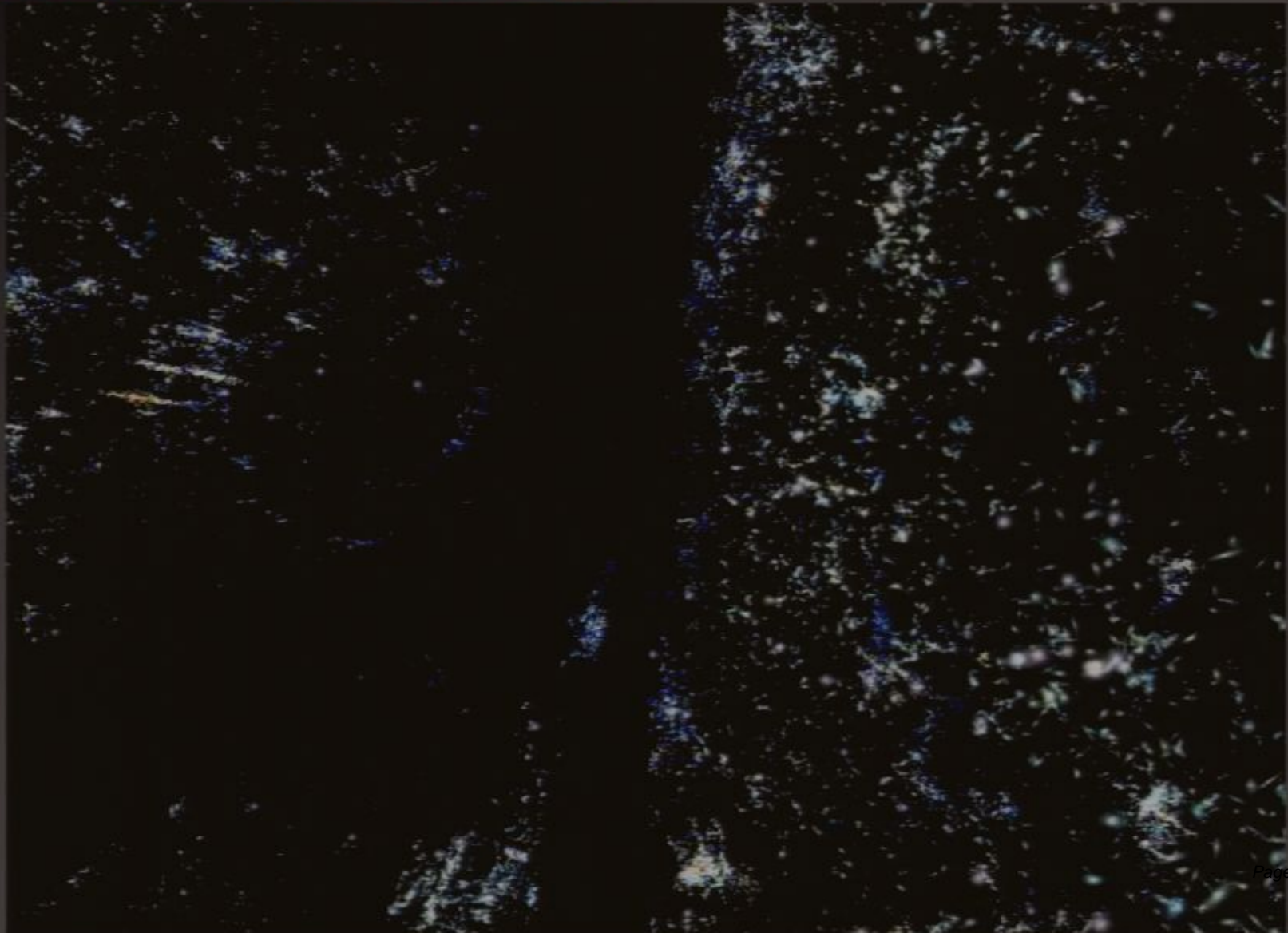
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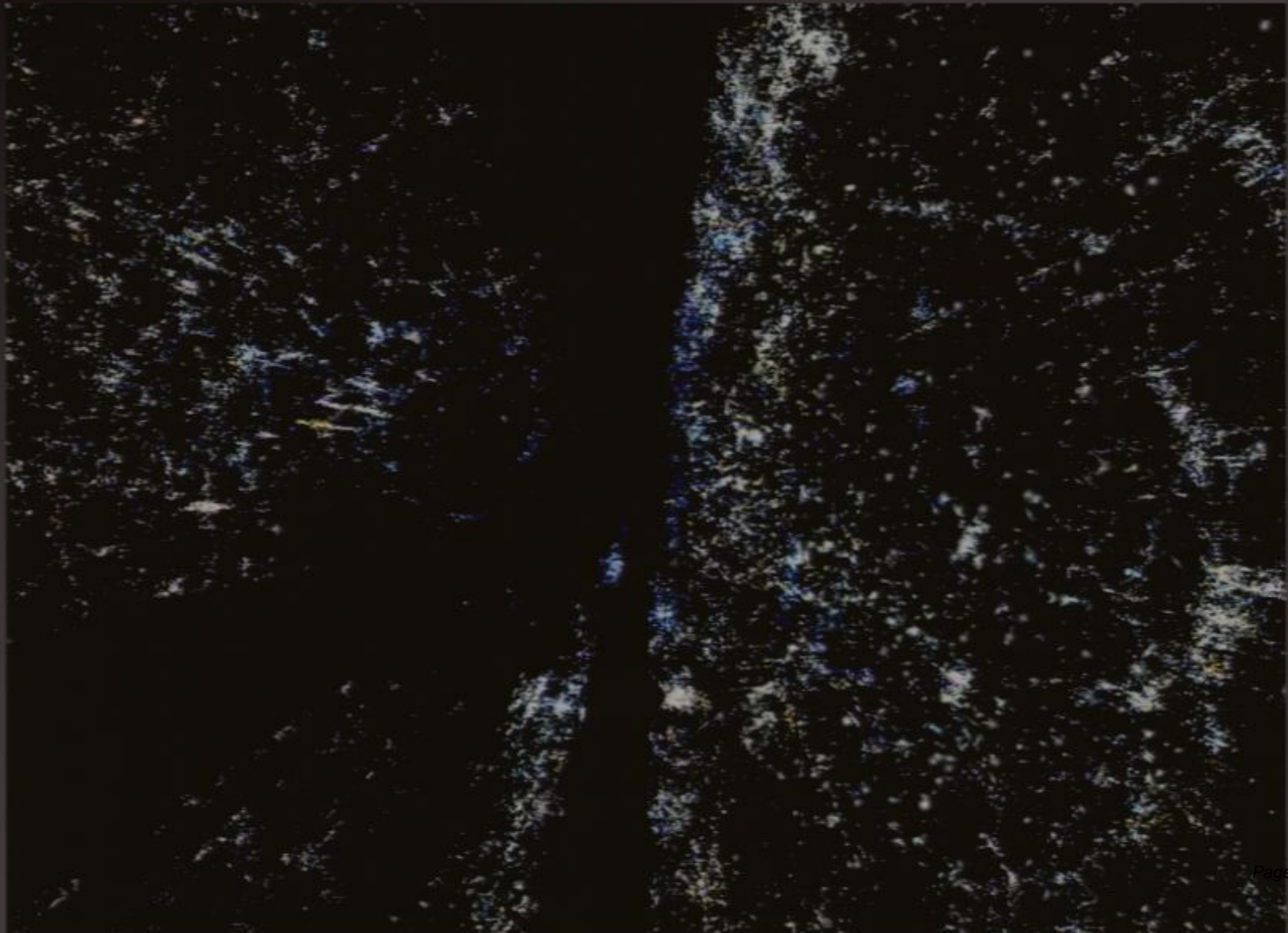
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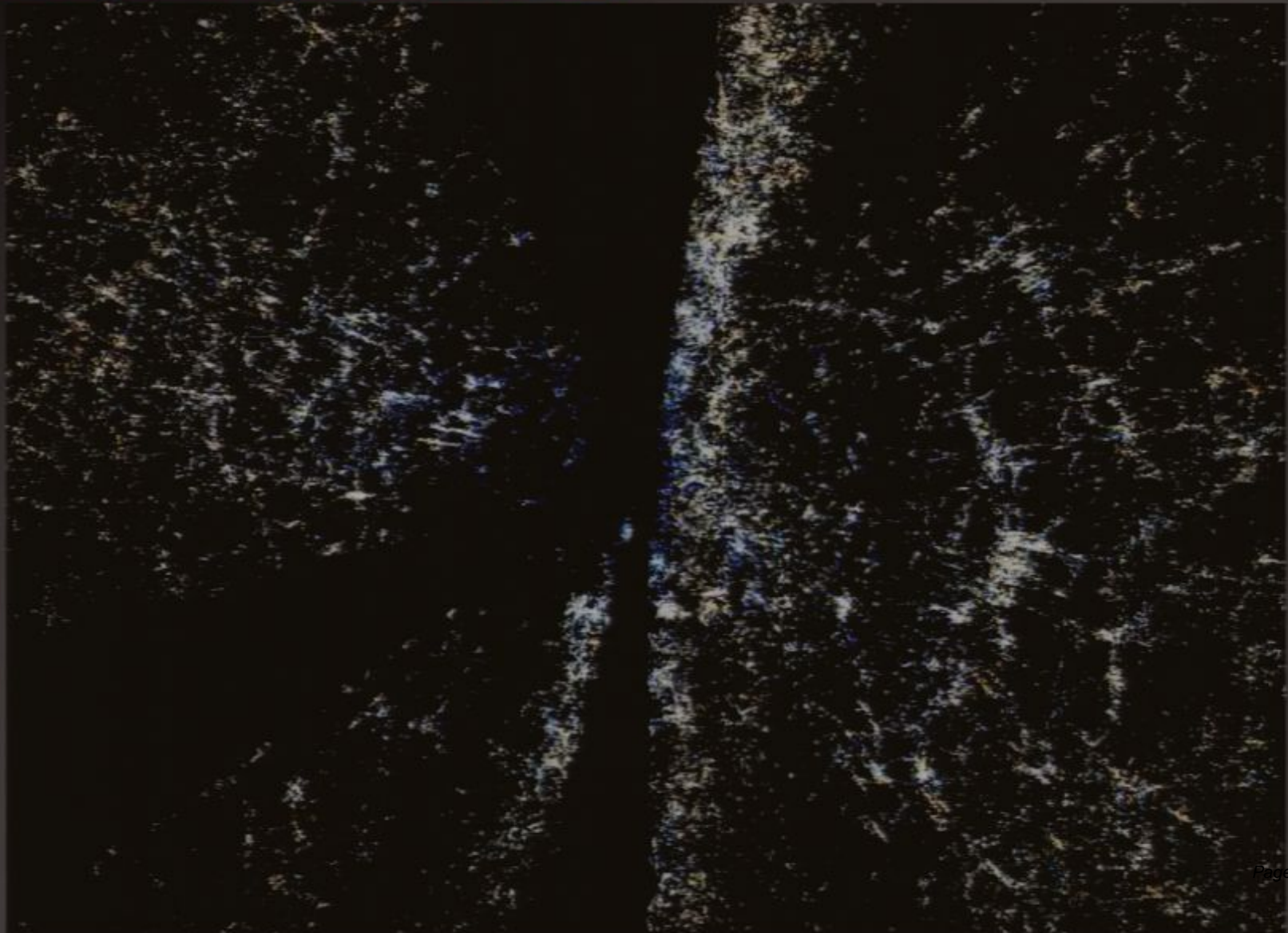
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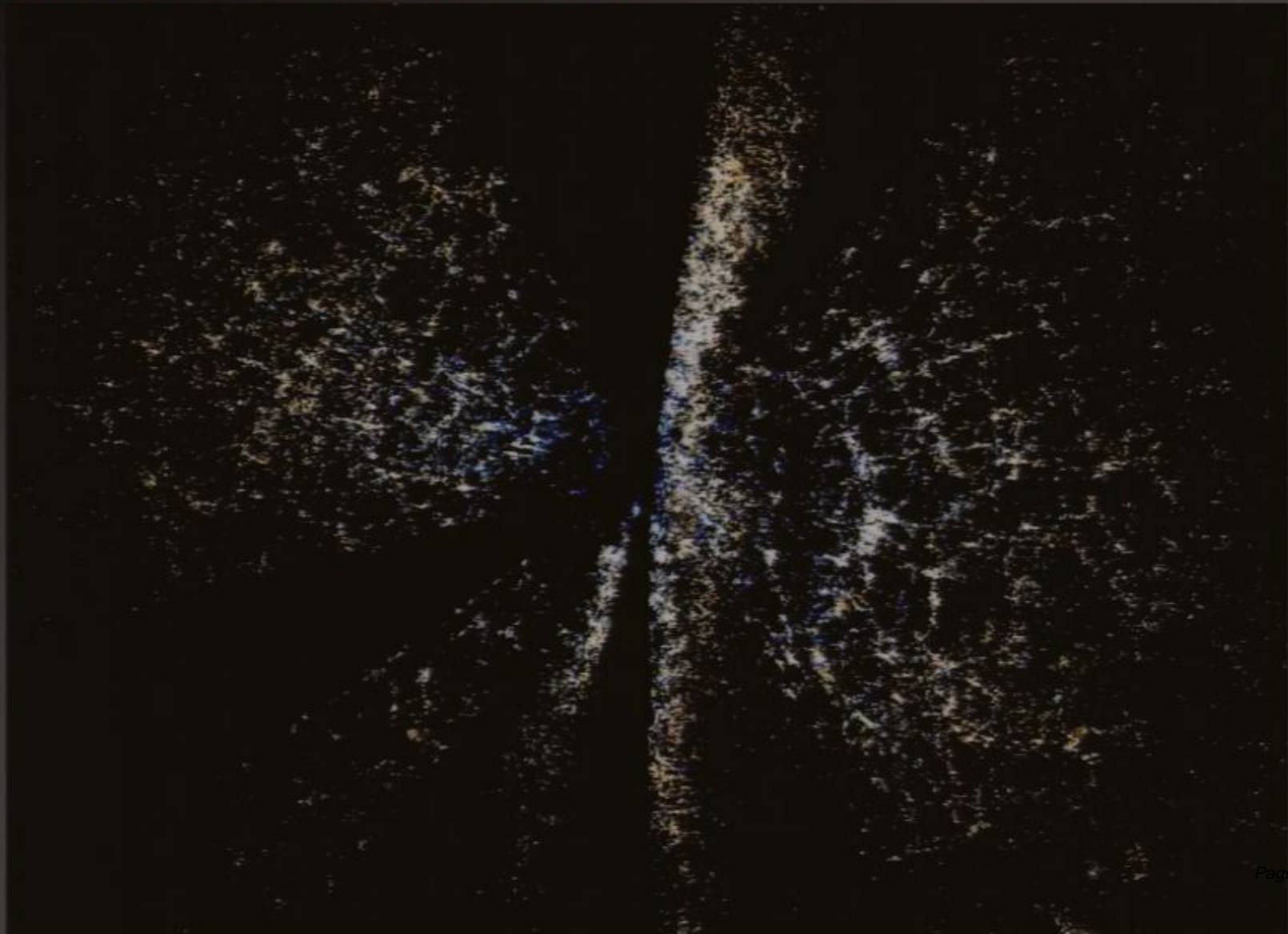
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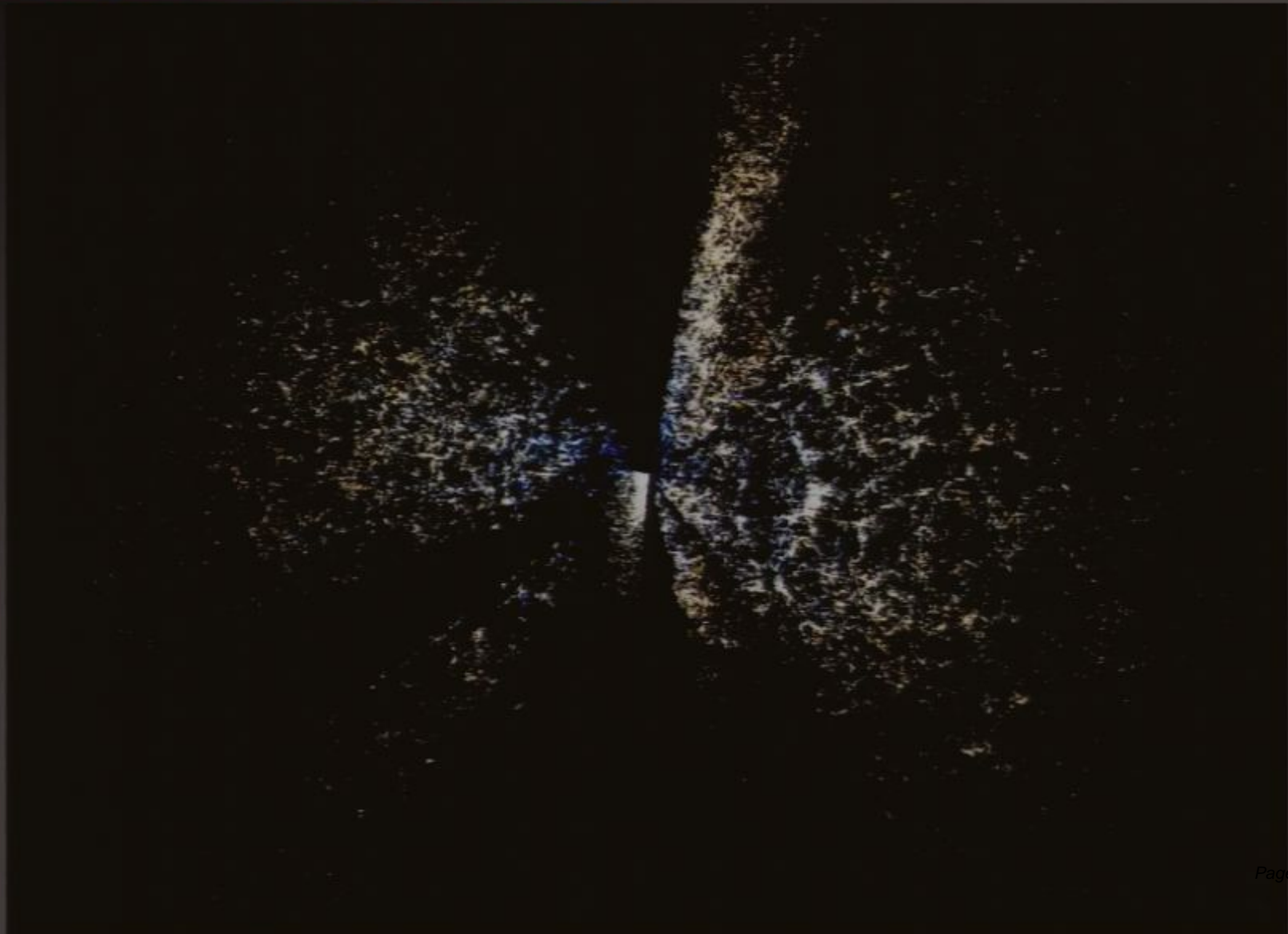
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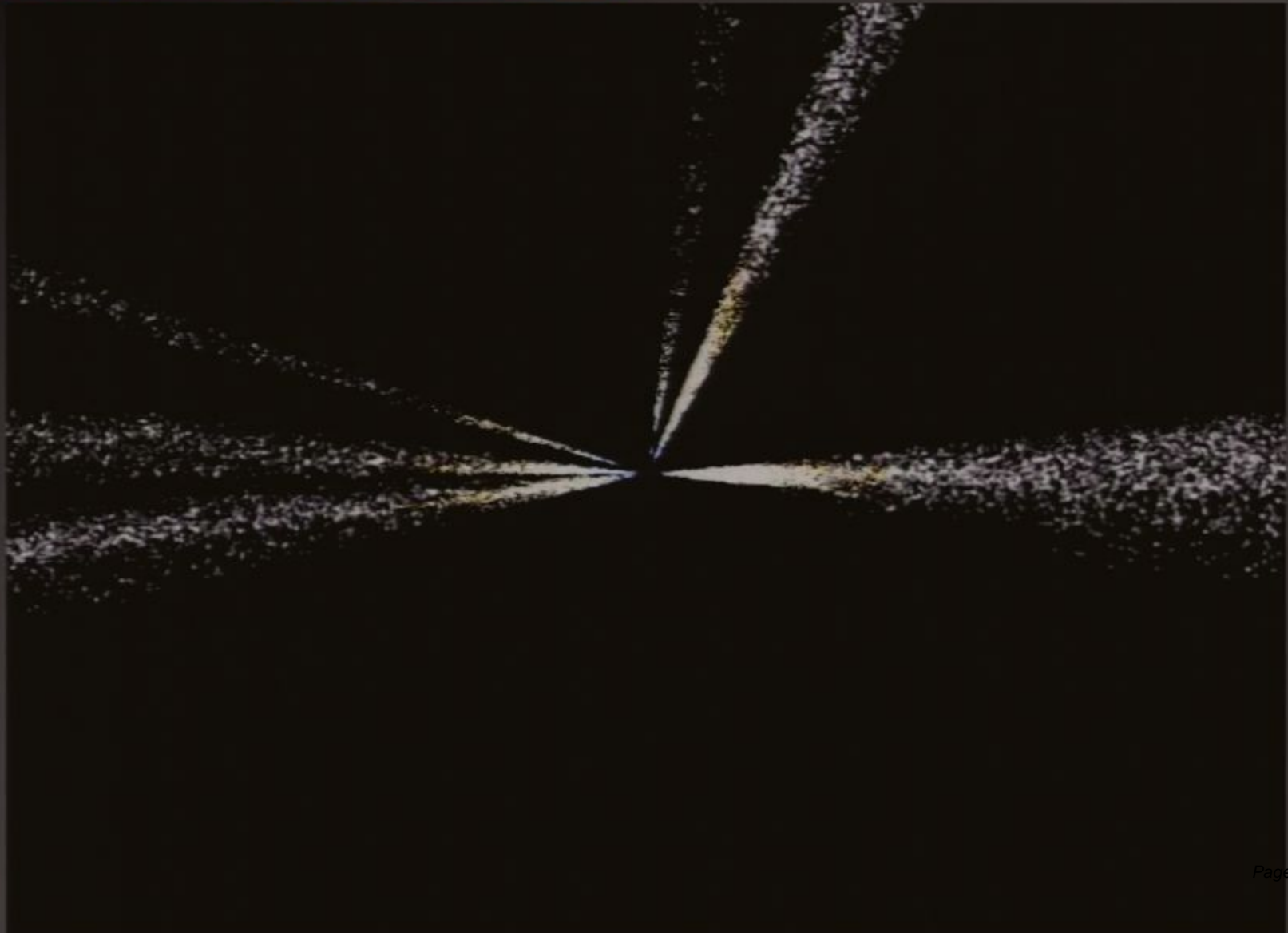
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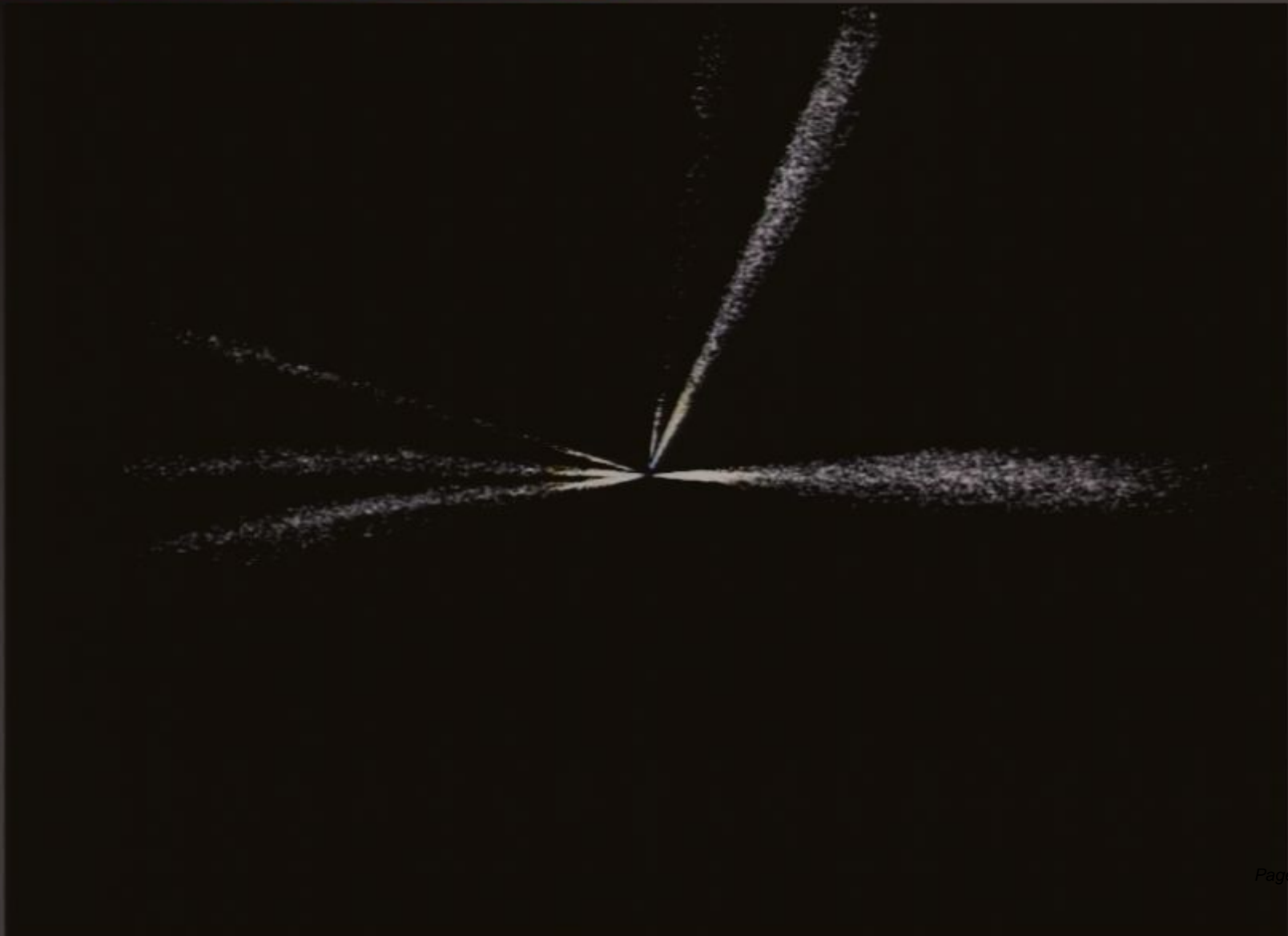
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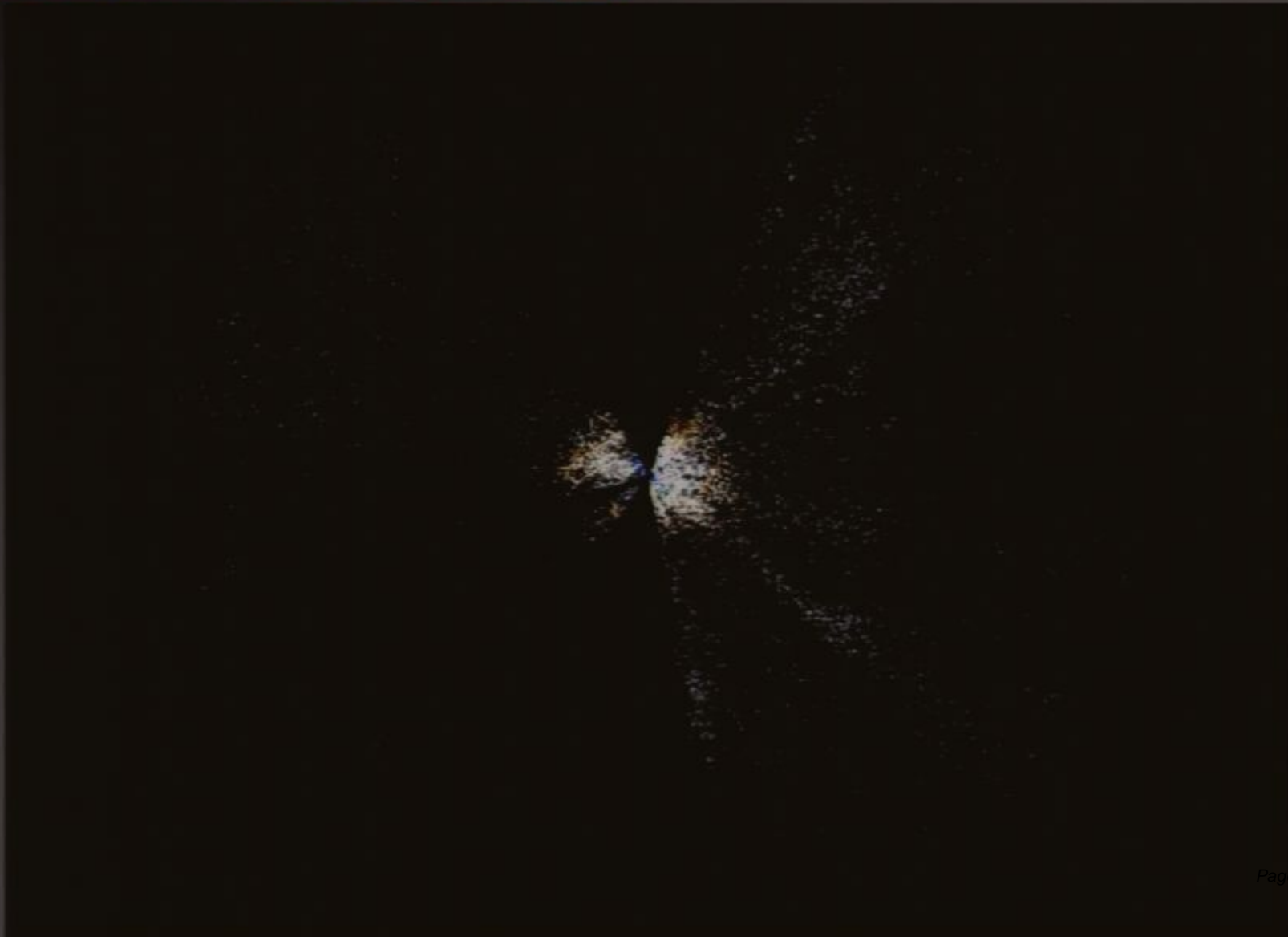
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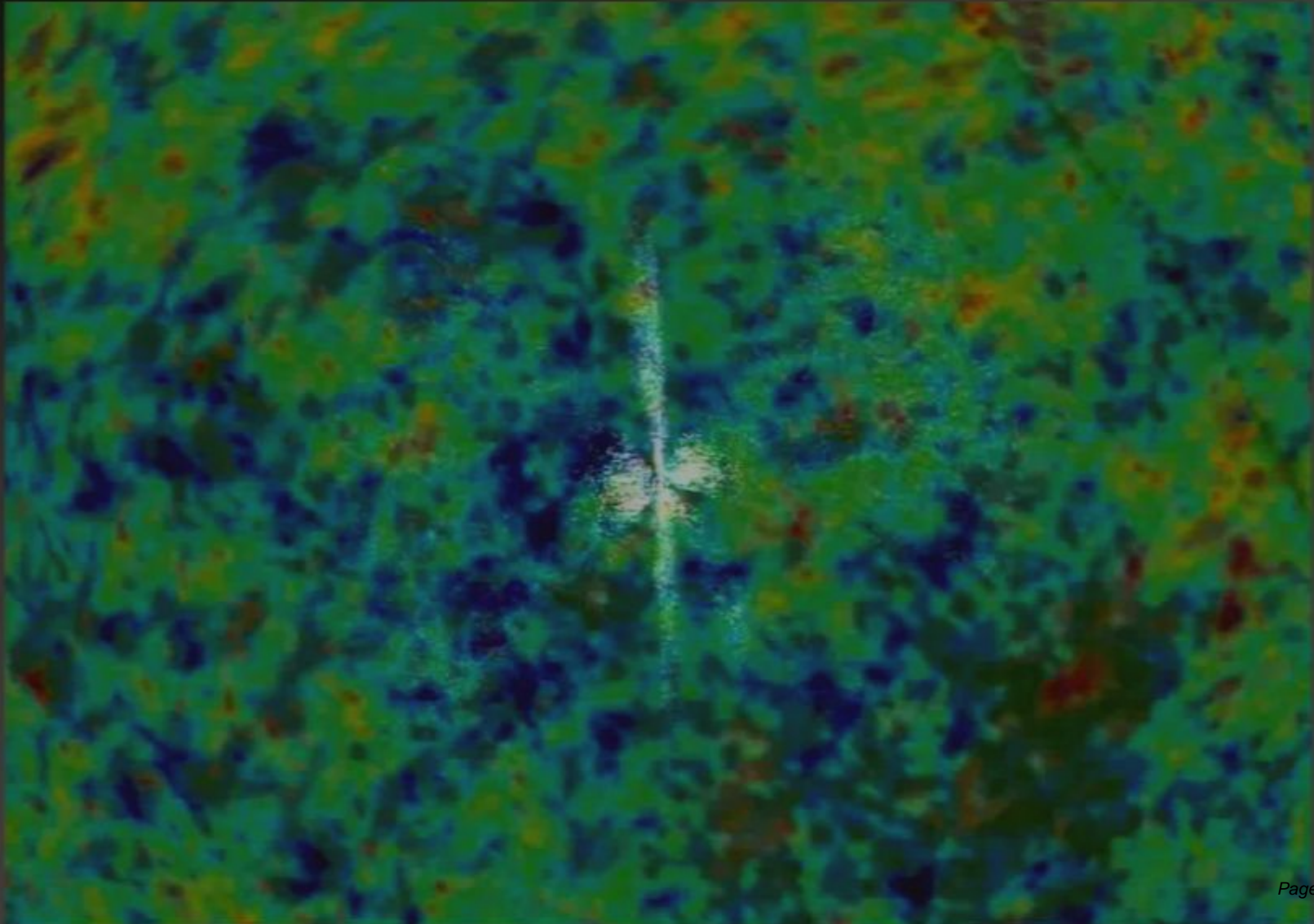
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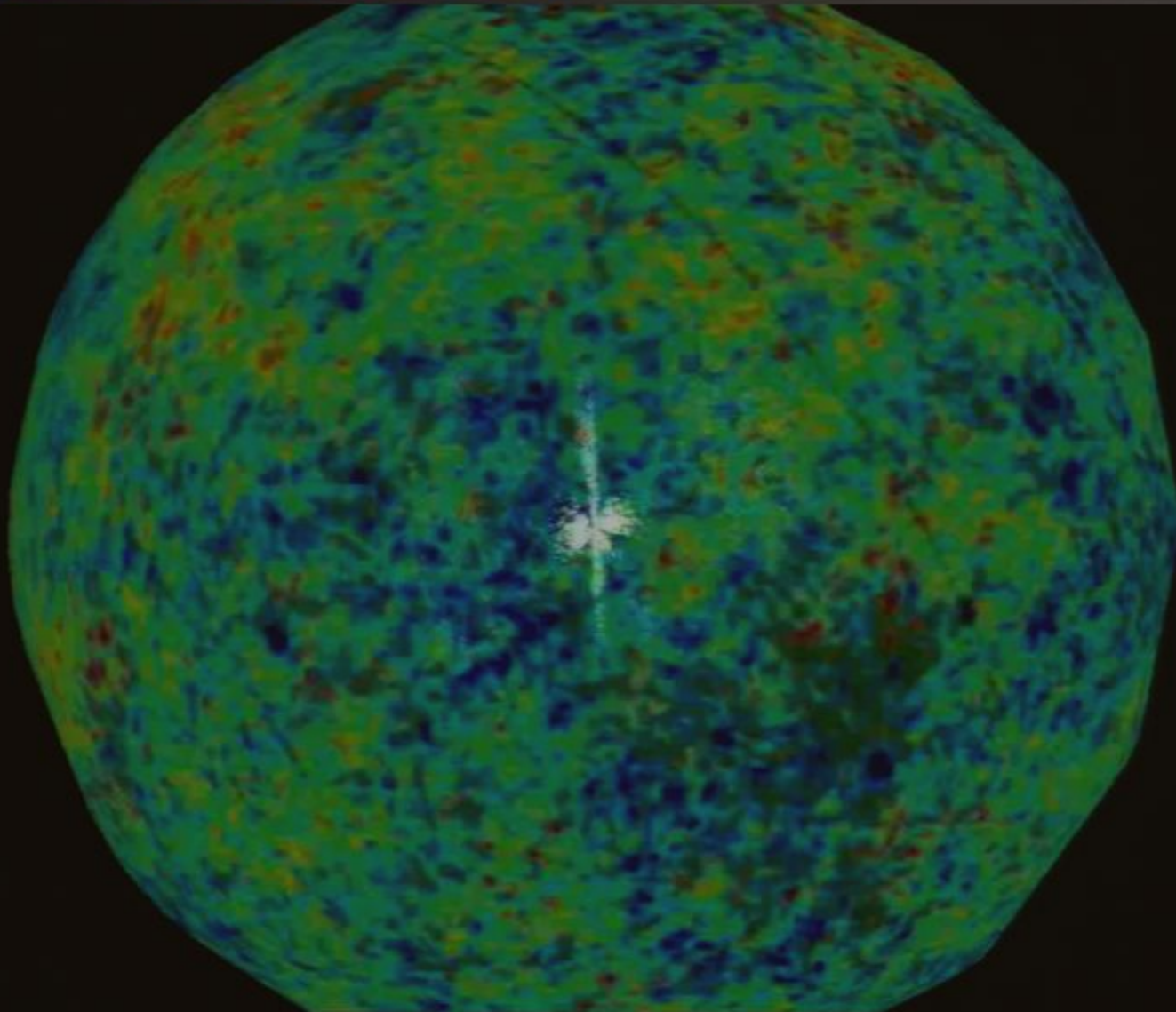
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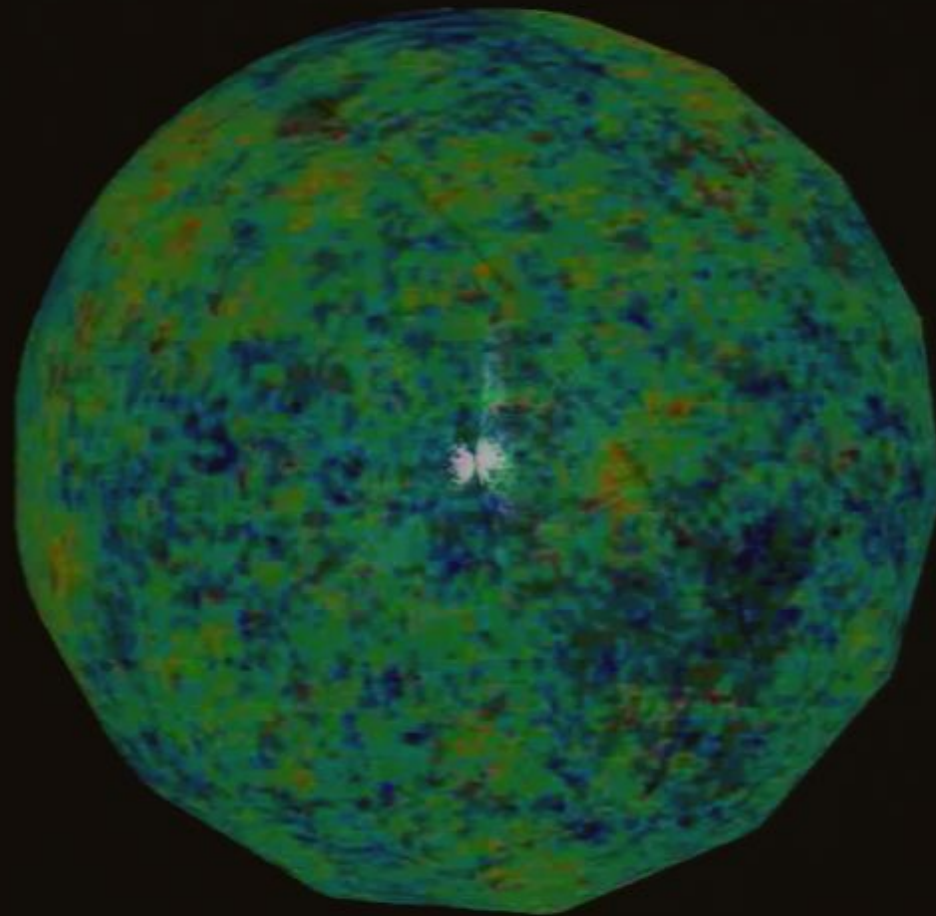
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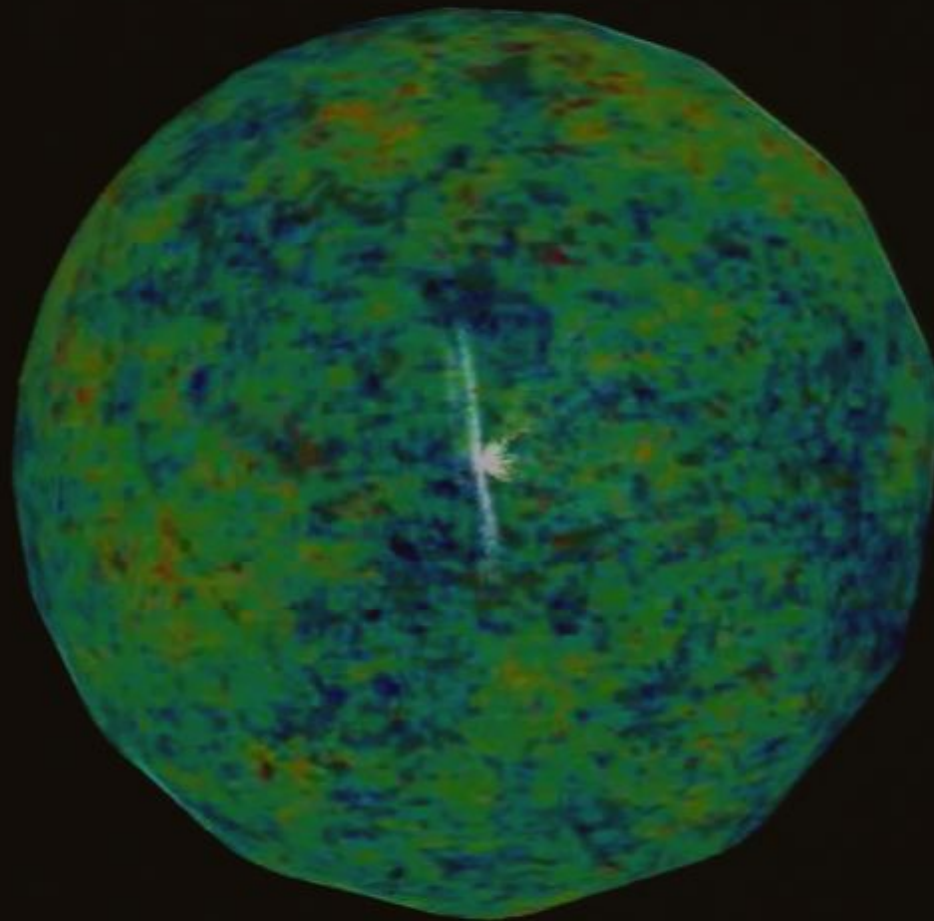
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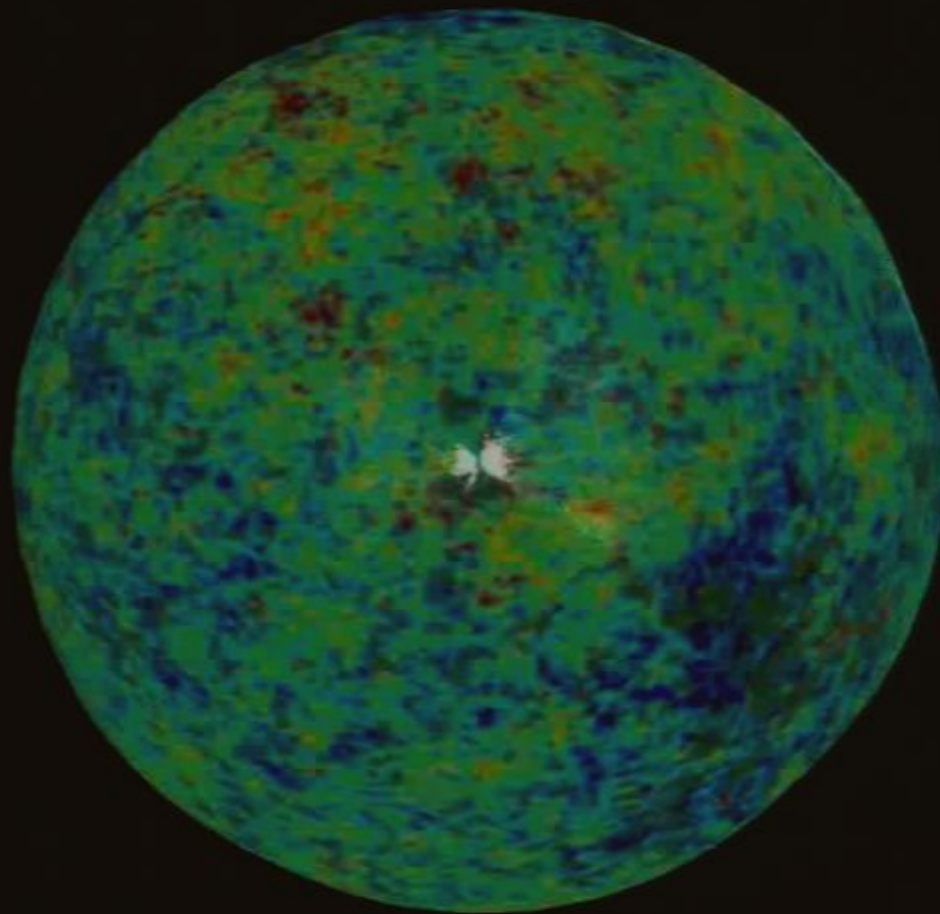
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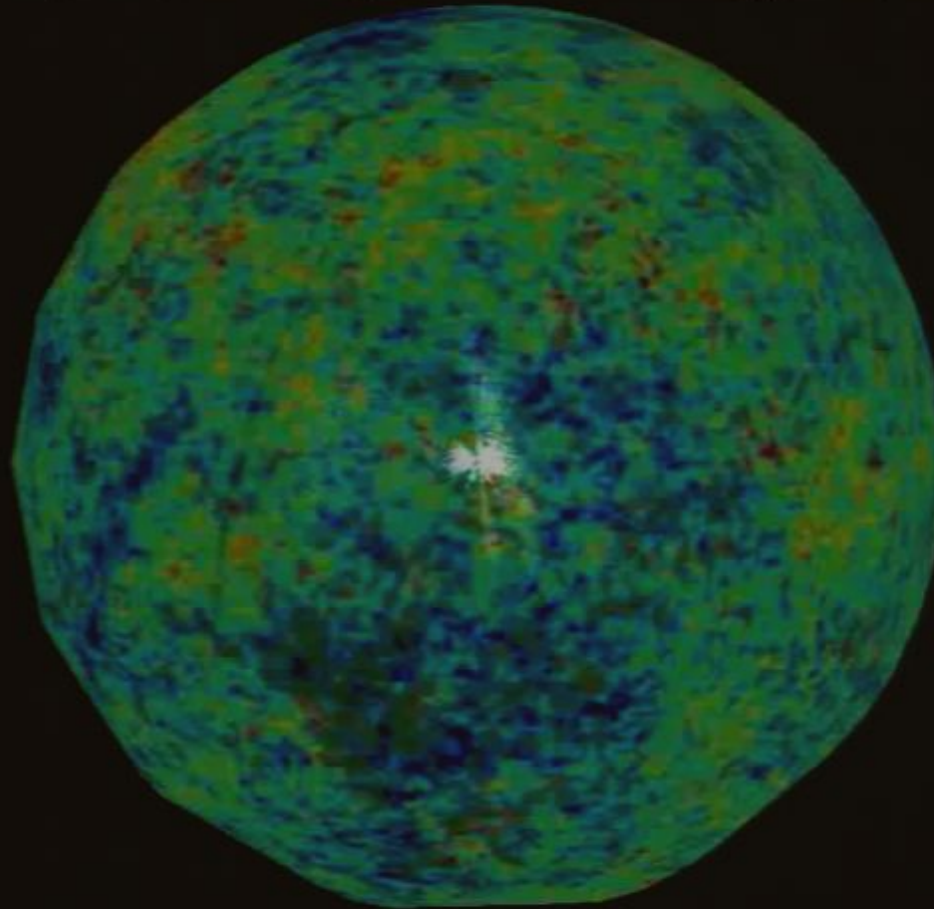


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Galaxy and Quasar positions from the Sloan Digital Sky Survey (SDSS)

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

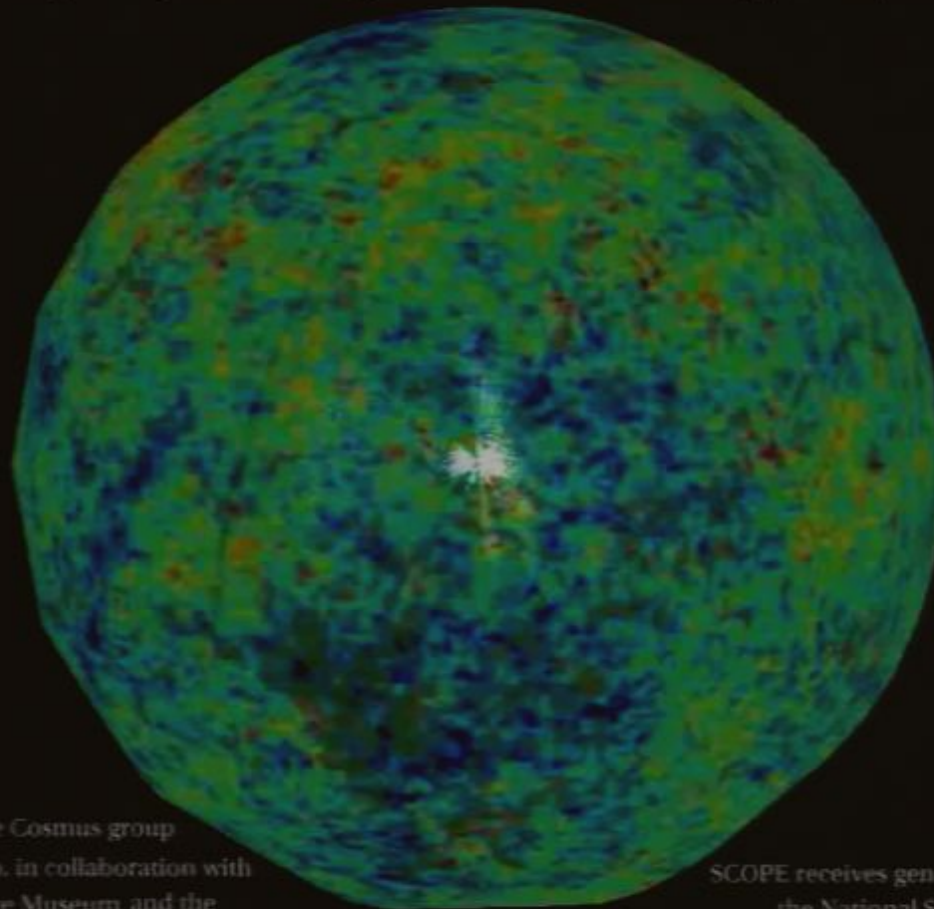


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Animation produced by the Cosmus group at the University of Chicago, in collaboration with SciTech Hands-on Science Museum and the Adler Planetarium and Science Museum.

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

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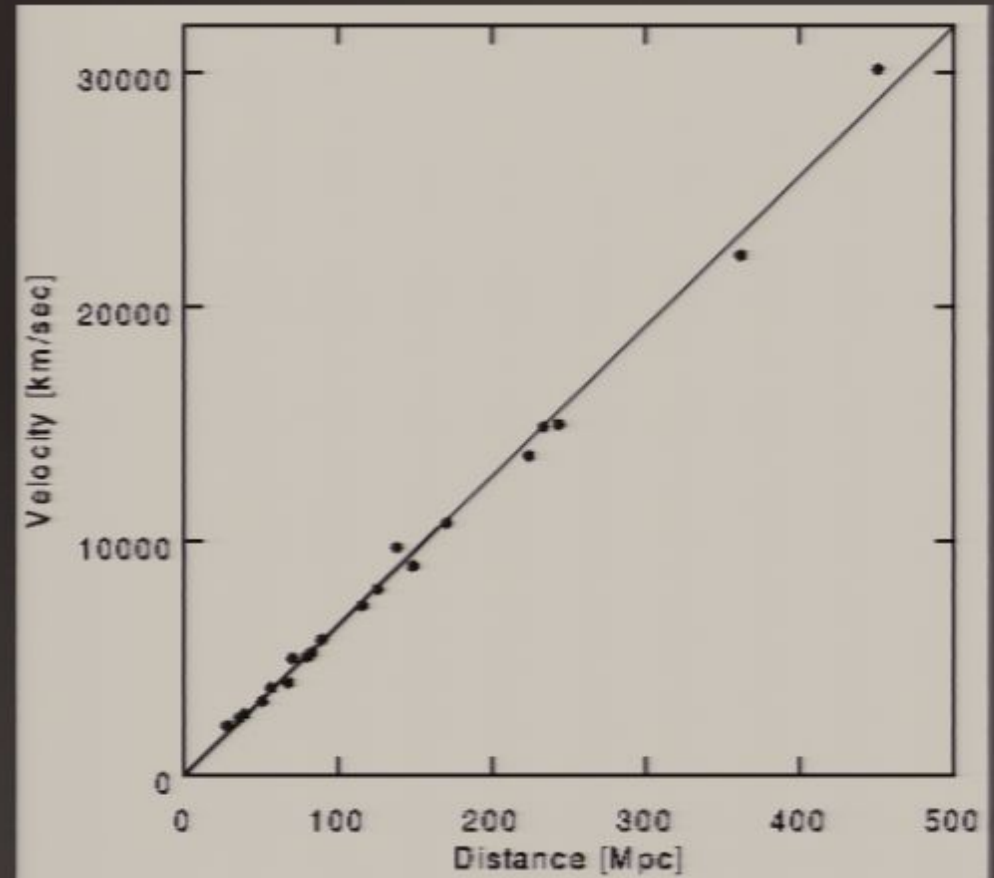
In all directions galaxies are seen to be receding from us with a speed which is proportional to their distance from us:

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

$$v = H_0 d$$

Evidence for an Expanding Universe

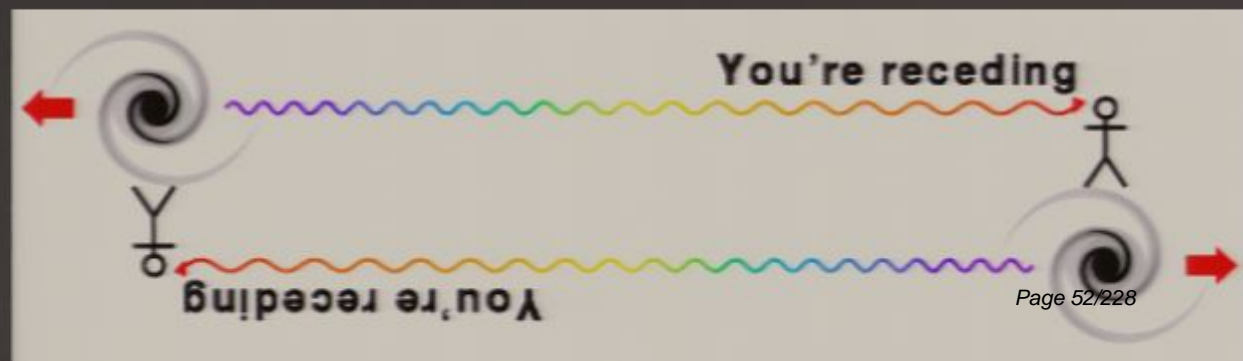
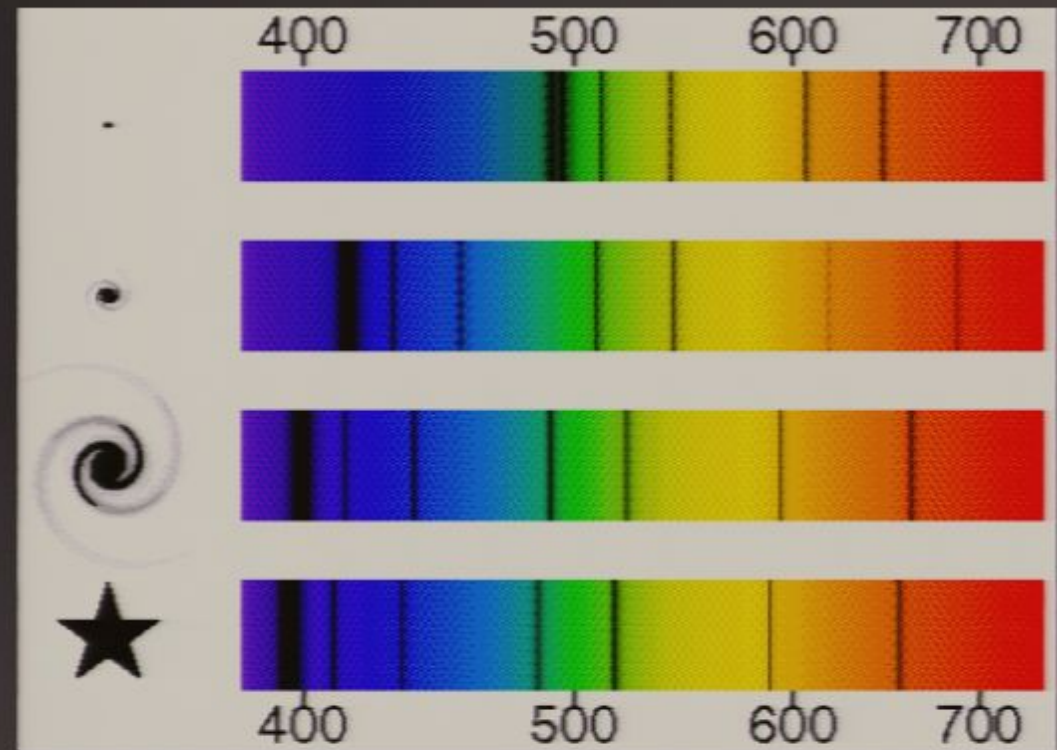
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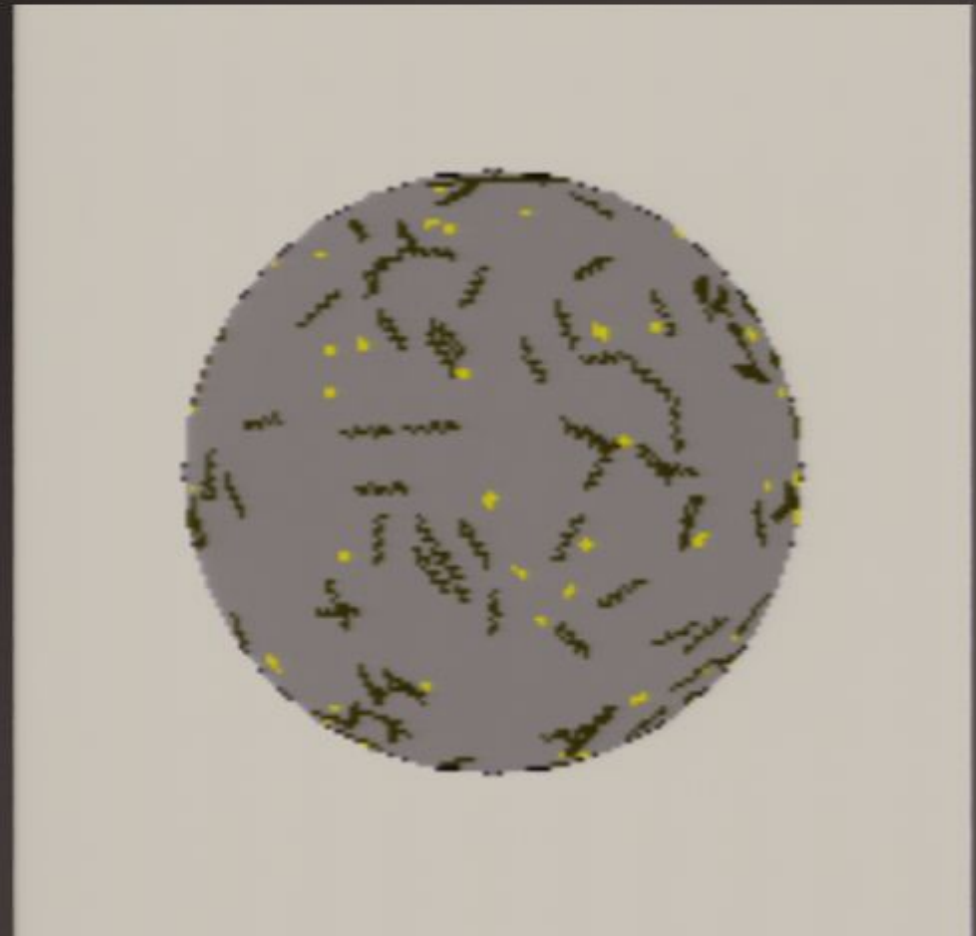
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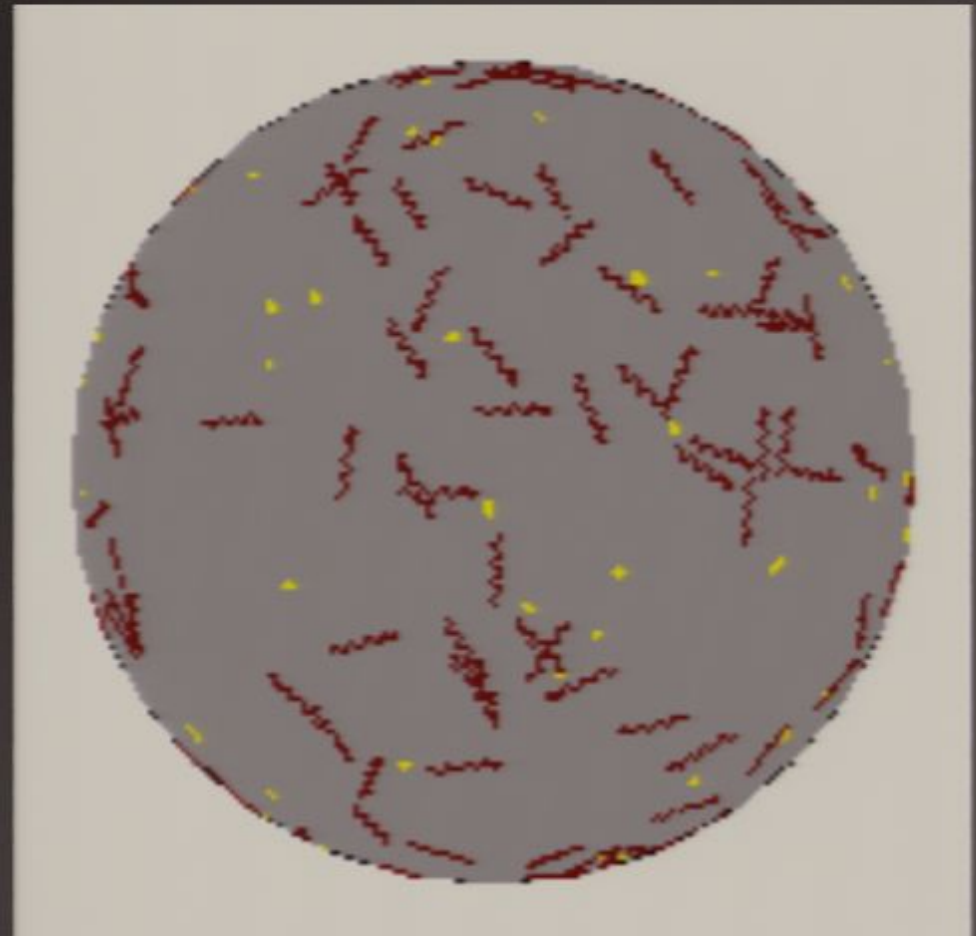
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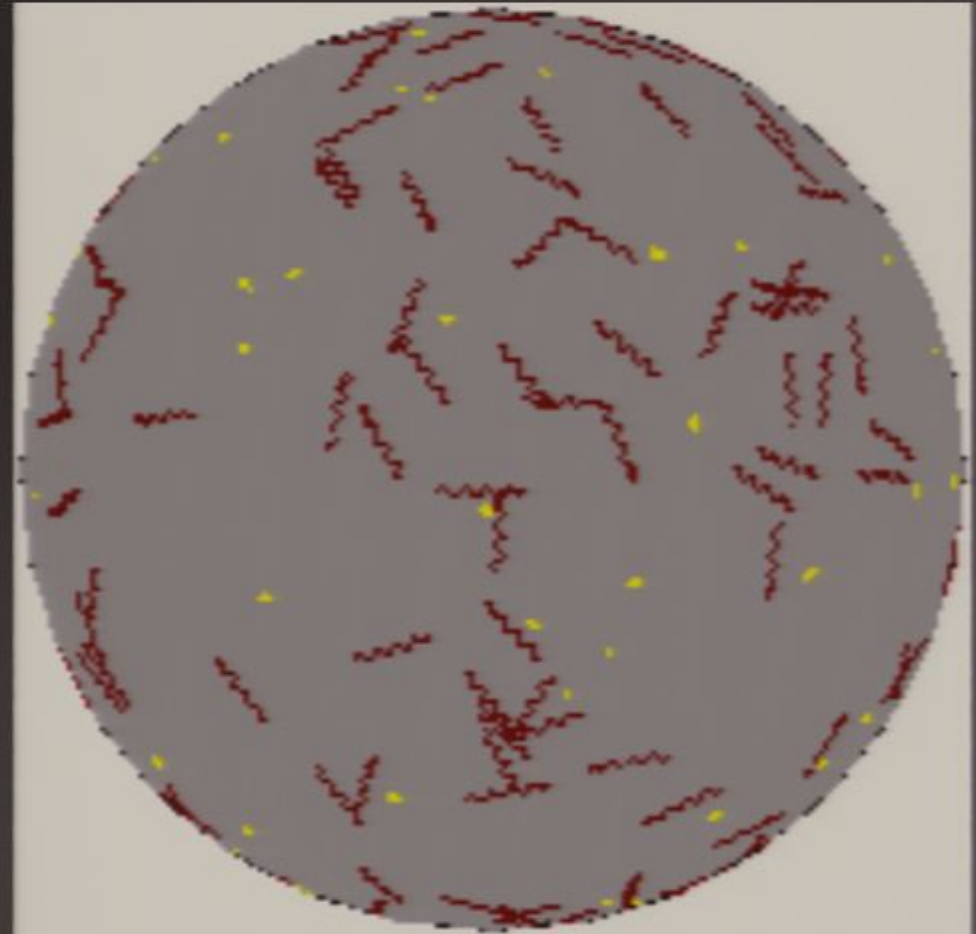
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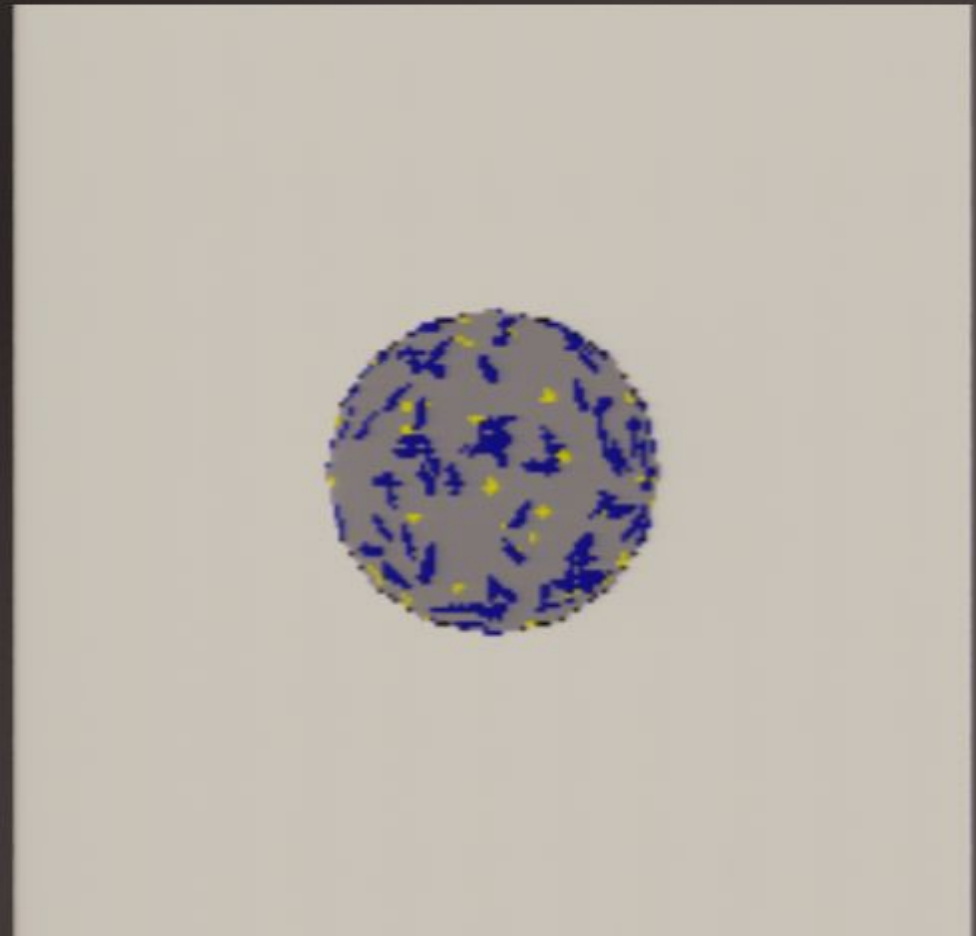
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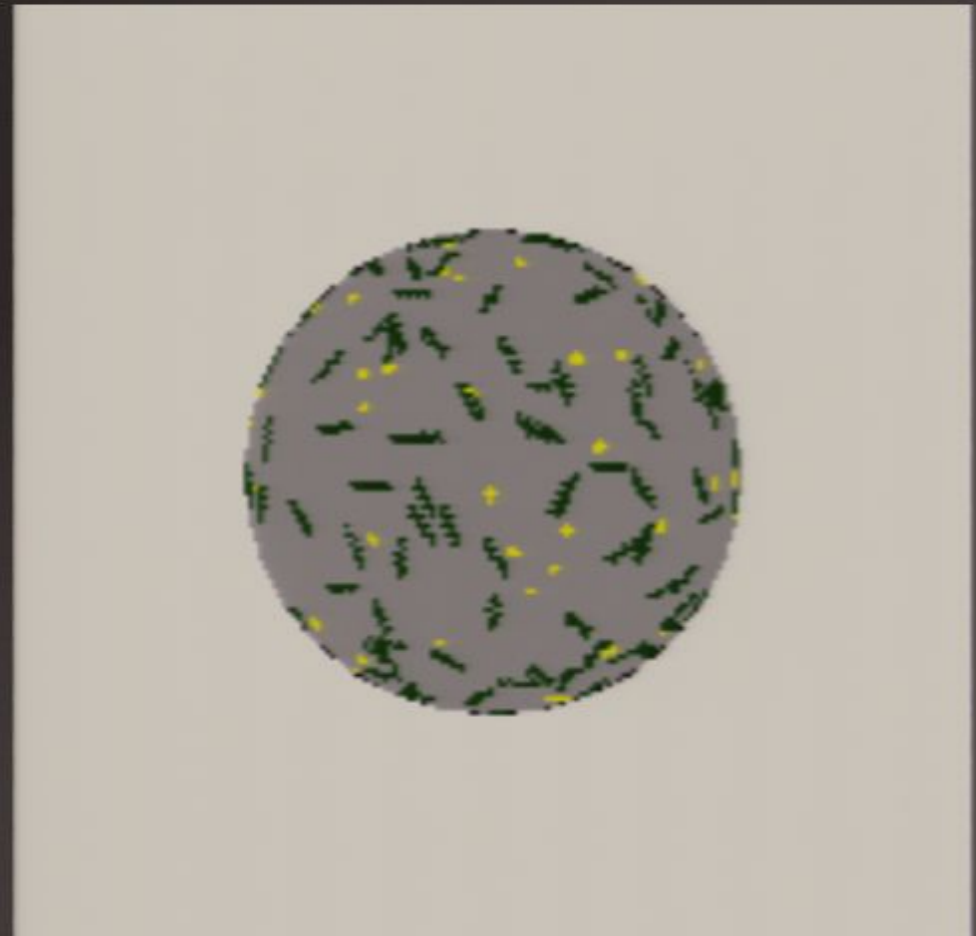
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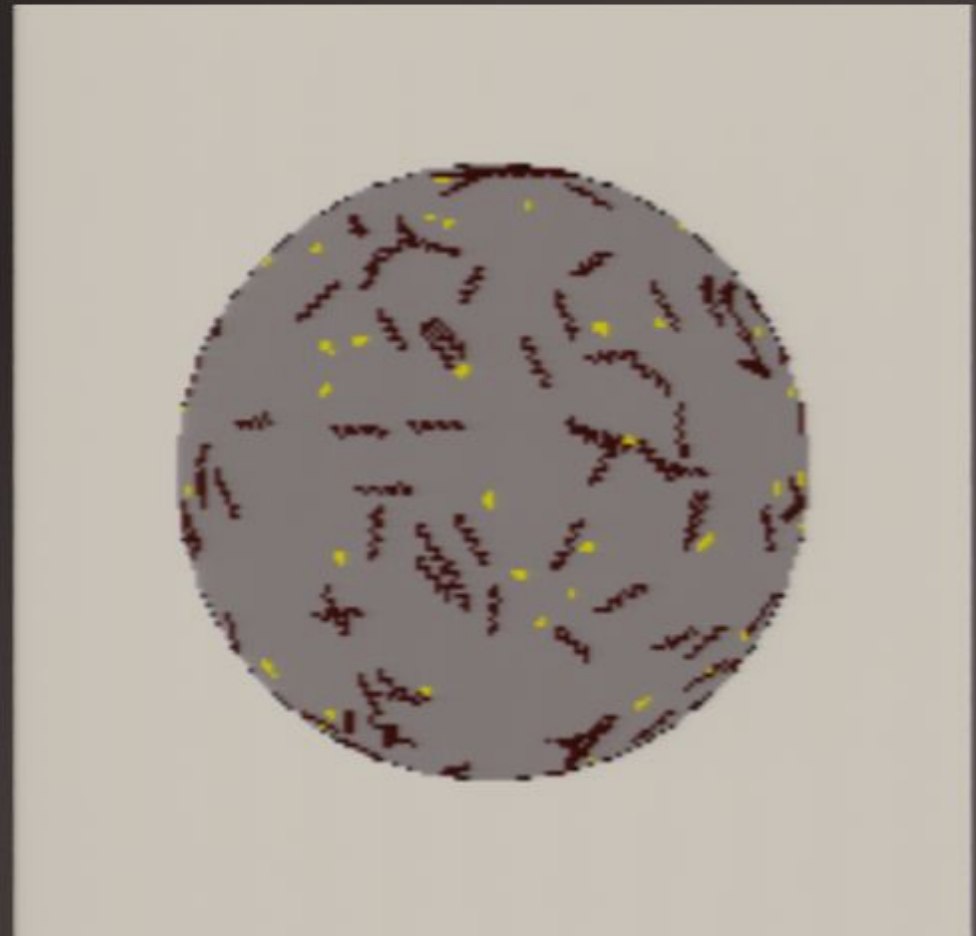
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The Hot Big Bang

- 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!*

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- *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.



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21

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22

- The sky is dark
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No evidence that galaxies outside local system is fixed space
The universe is expanding!

23

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27

Evidence for an Expanding Universe

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28

The Hot Big Bang

- Matter was expanding and cooling.
 - Expecting that it was so hot that the universe was ionized 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 independently tested.
 - Supernova observations indicate that the Universe is still expanding at an accelerating rate.

29

How Would We Know?

- The Universe being hot means that the particles within it are constantly moving with higher speeds.
- At high enough temperatures particles get close together faster than one time out.

30

How Would We Know?

- At low temperatures since the Universe cools to below 1000 K gas.
 - Charged particles and nuclei combine into atoms, neutral atoms.
- If the Universe cooled below 10 billion K gas.
 - Protons and neutrons combine into deuterium.

31

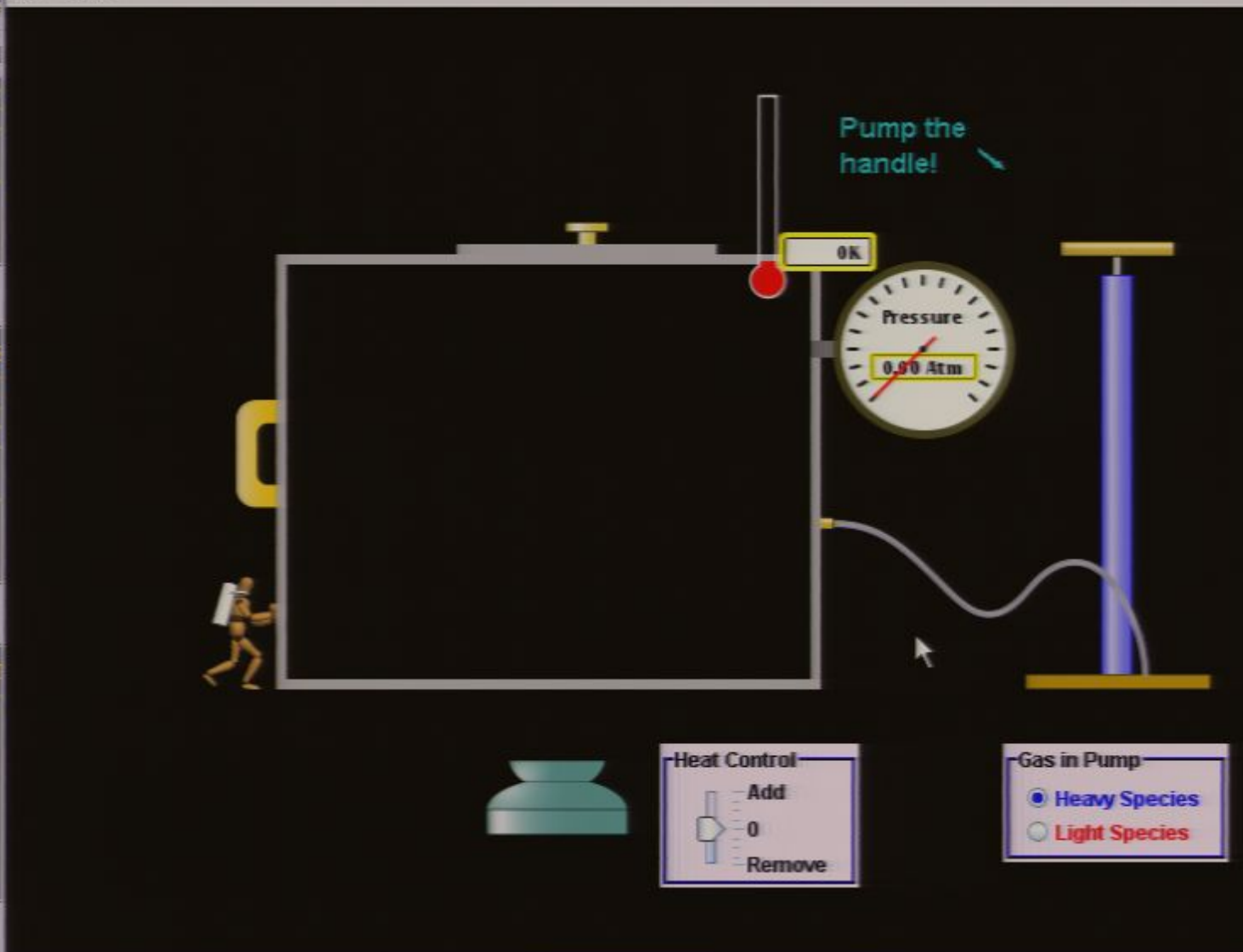
Evidence for a Hot Big Bang

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

32

Gas Properties (3.03)

File Help



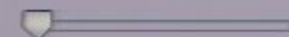
Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 0
Light Species 0

Gravity



0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

Heat Control

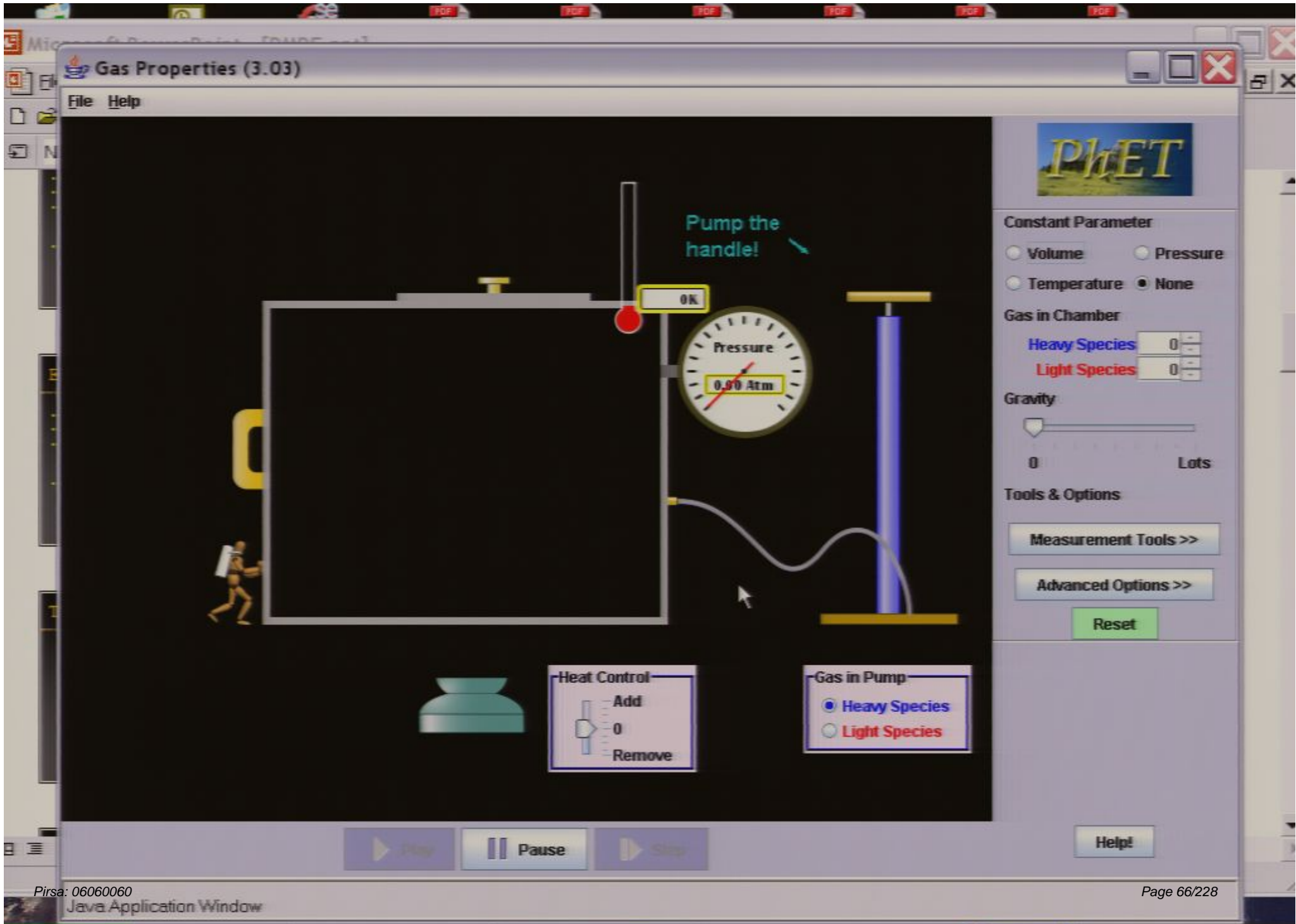
Add
0
Remove

Gas in Pump

Heavy Species
 Light Species

Play Pause Stop

Help!



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

- Heavy Species
- Light Species

Gravity

0 Lots

Tools & Options

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

Pump the handle!



Heat Control

Add

0

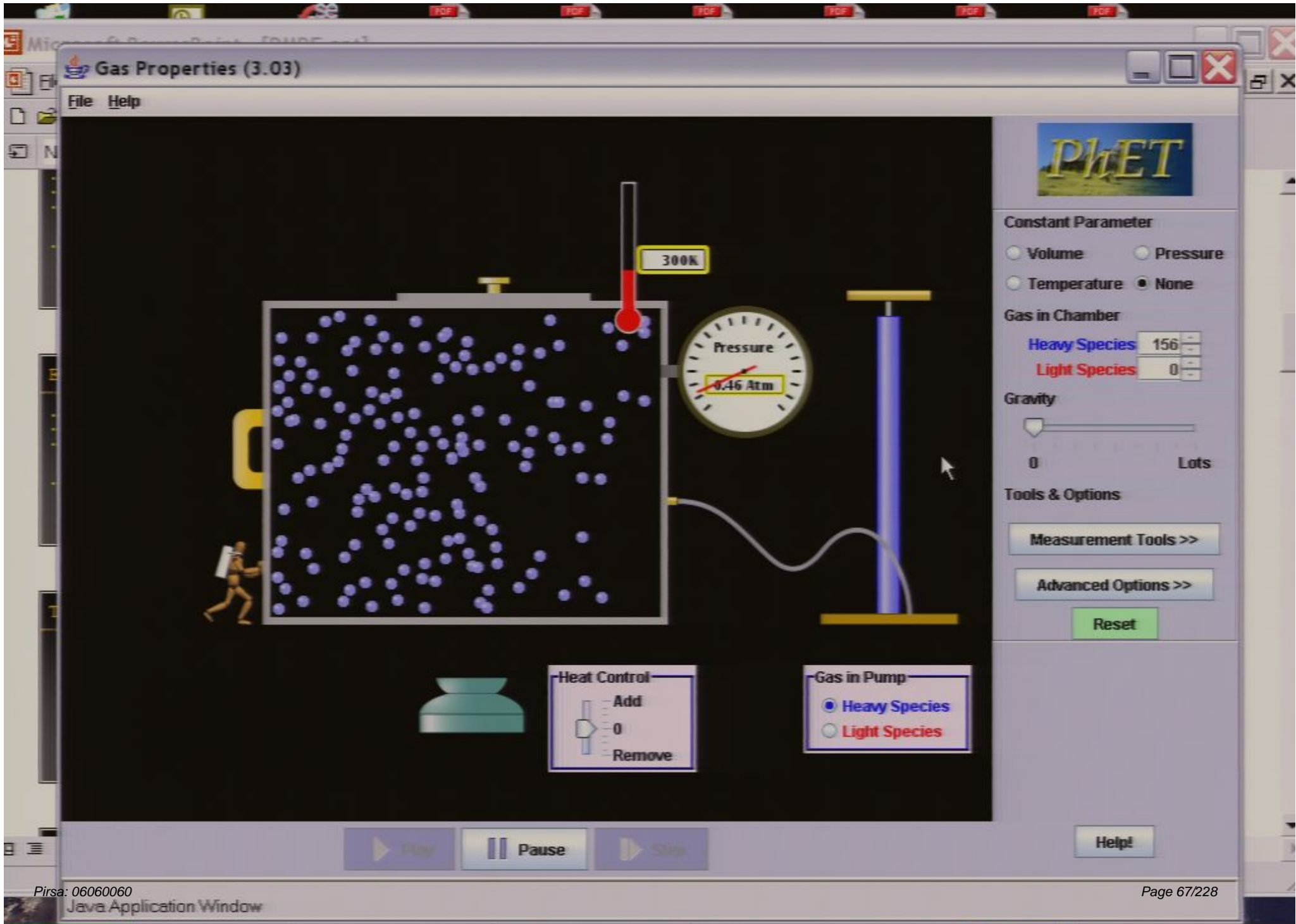
Remove

Gas in Pump

- Heavy Species
- Light Species

- Play
- Pause
- Stop

Help!



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 156

Light Species 0

Gravity

0 Lots

Tools & Options

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

300K

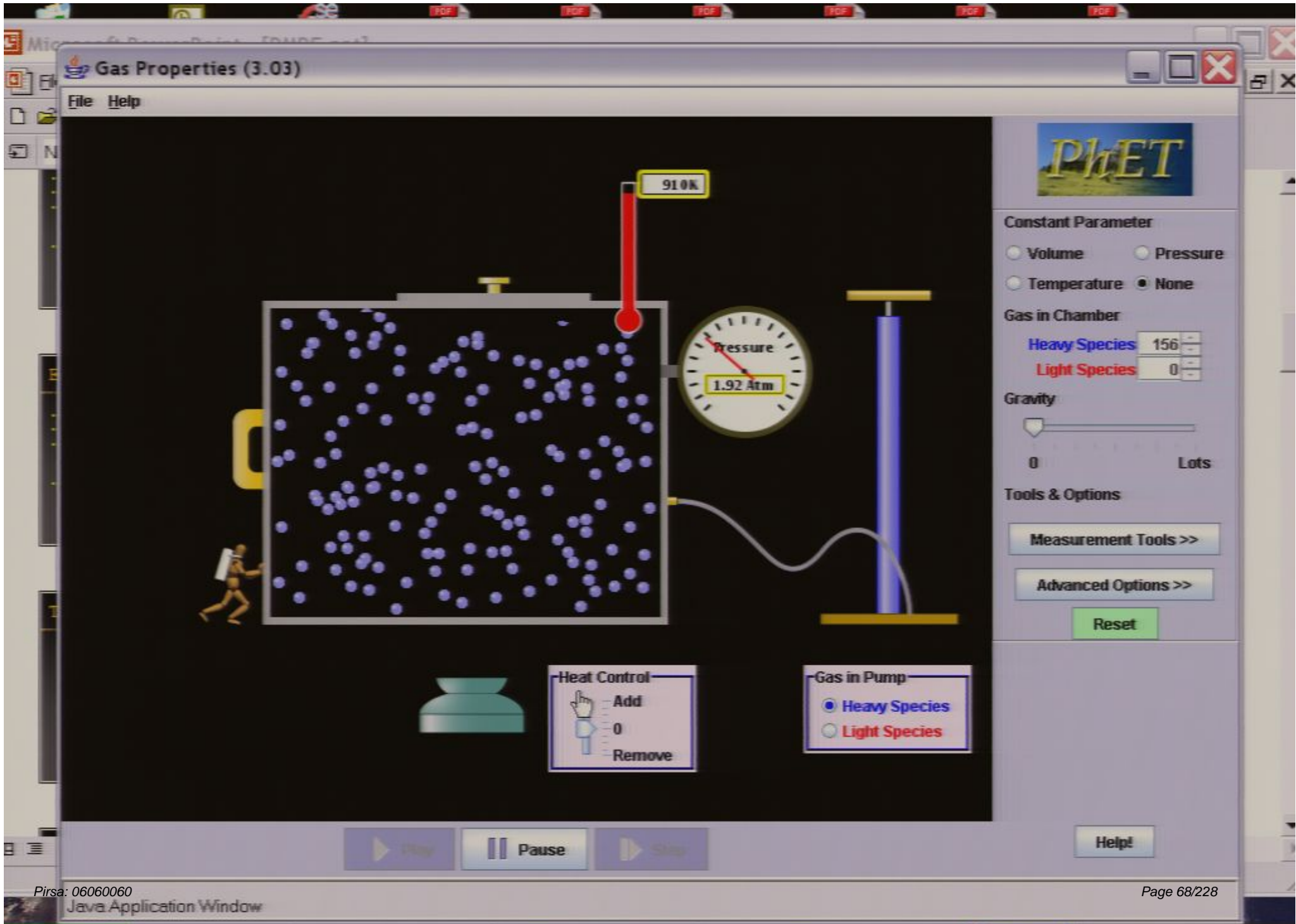
Pressure 0.46 Atm

Heat Control: Add, 0, Remove

Gas in Pump: Heavy Species, Light Species

Play Pause Stop

Help!



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 156

Light Species 0

Gravity

0 Lots

Tools & Options

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

910K

Pressure

1.92 Atm

Heat Control

Add

0

Remove

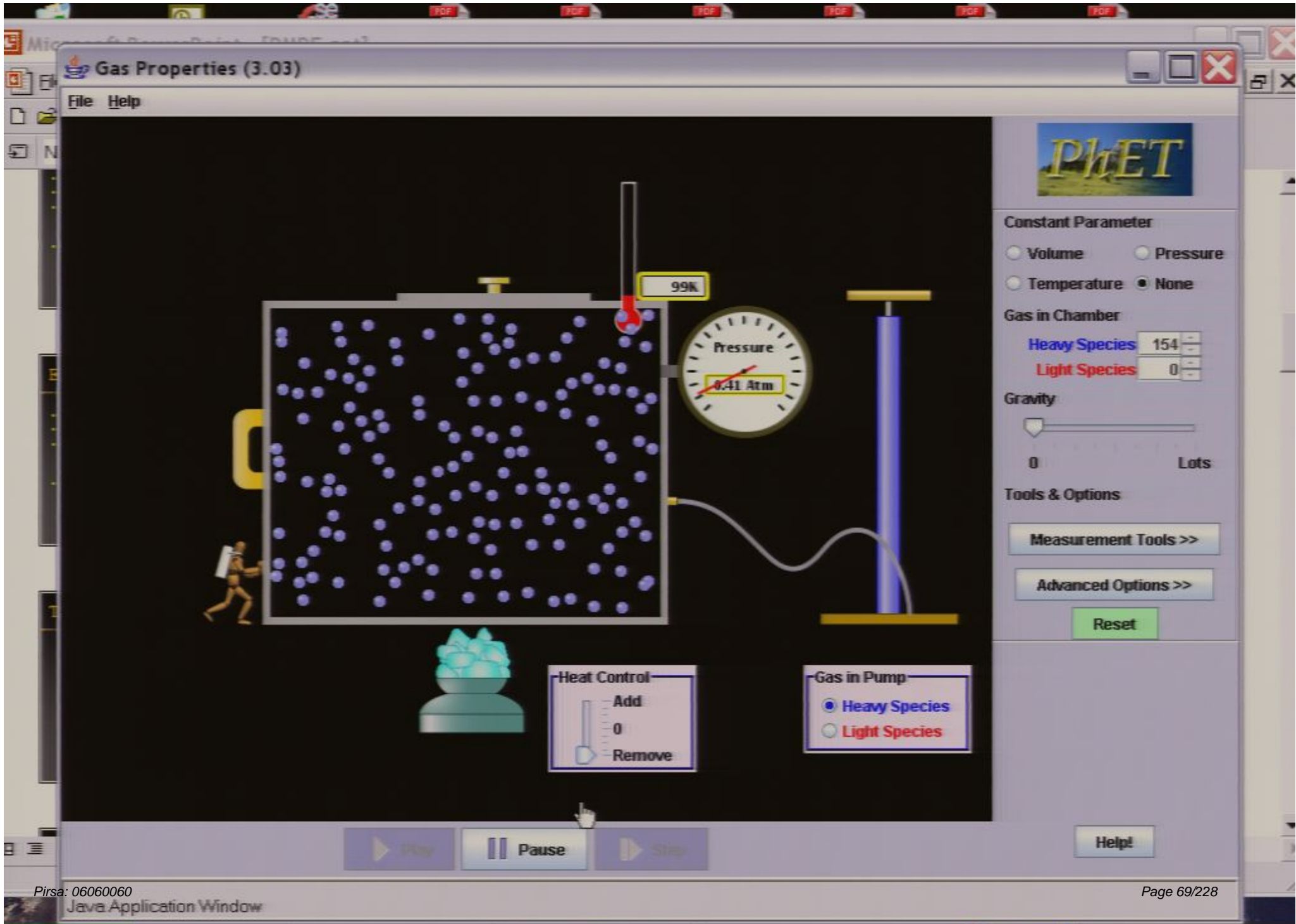
Gas in Pump

Heavy Species

Light Species

- Play
- Pause
- Stop

Help!



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 154

Light Species 0

Gravity

0 Lots

Tools & Options

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

99K

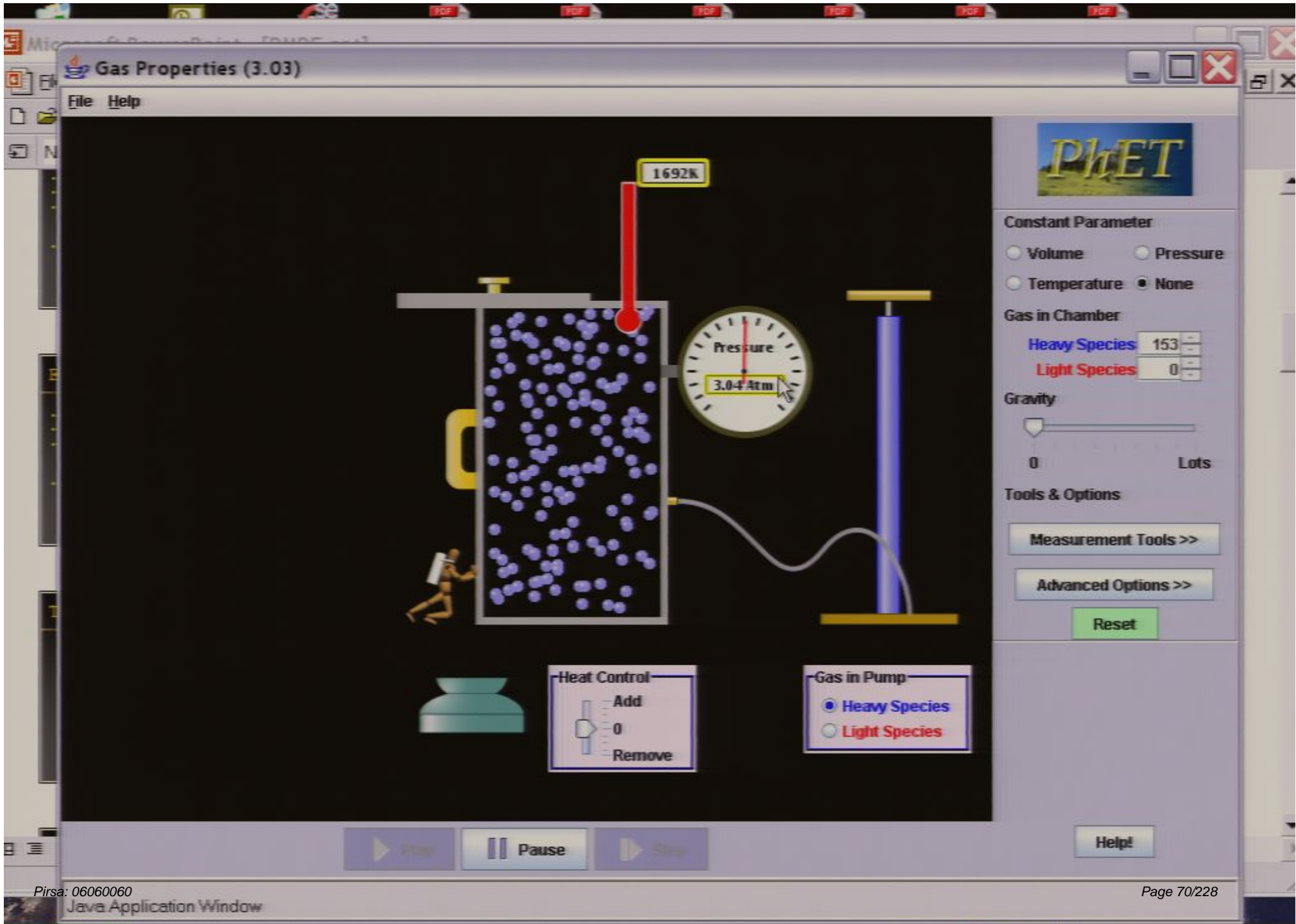
Pressure 0.41 Atm

Heat Control: Add, 0, Remove

Gas in Pump: Heavy Species, Light Species

Play Pause Stop

Help!



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 153

Light Species 0

Gravity



0 Lots

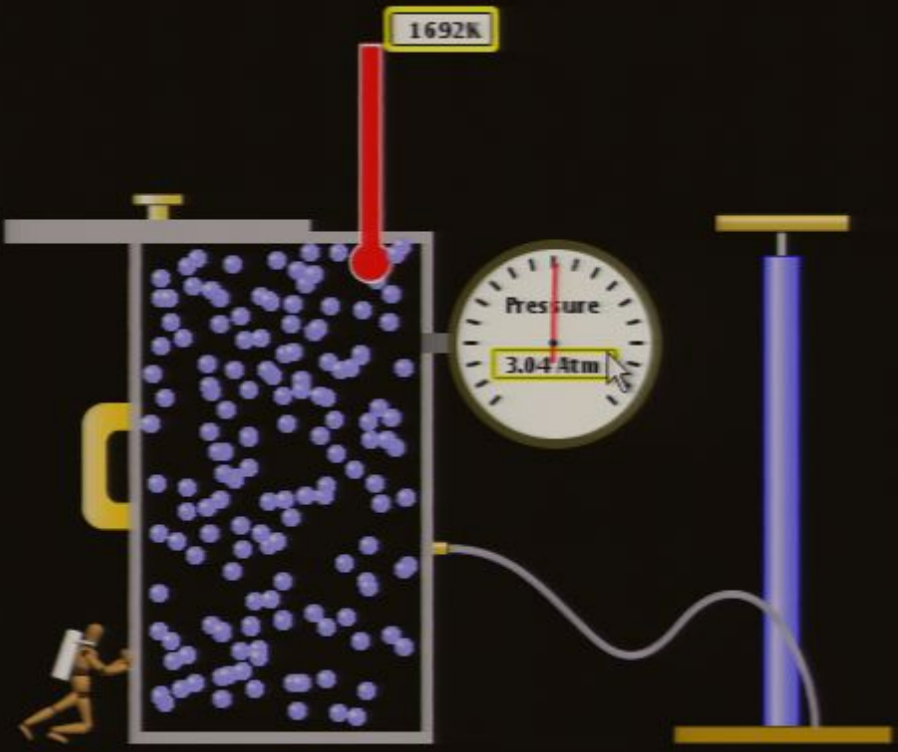
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Advanced Options >>

Reset

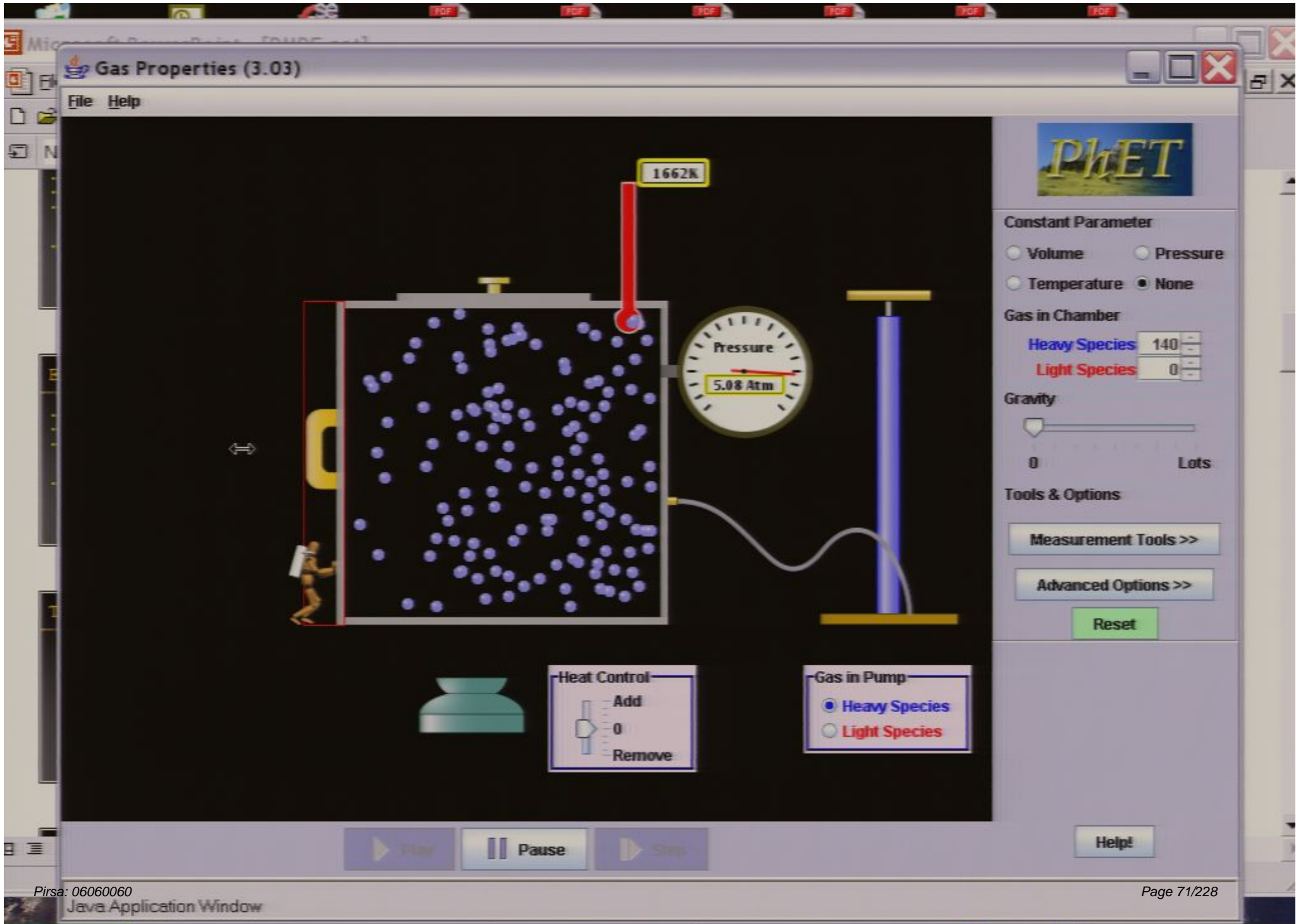
Help!



Play

Pause

Slow



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 140

Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

1662K



Heat Control

Add

0

Remove

Gas in Pump

Heavy Species

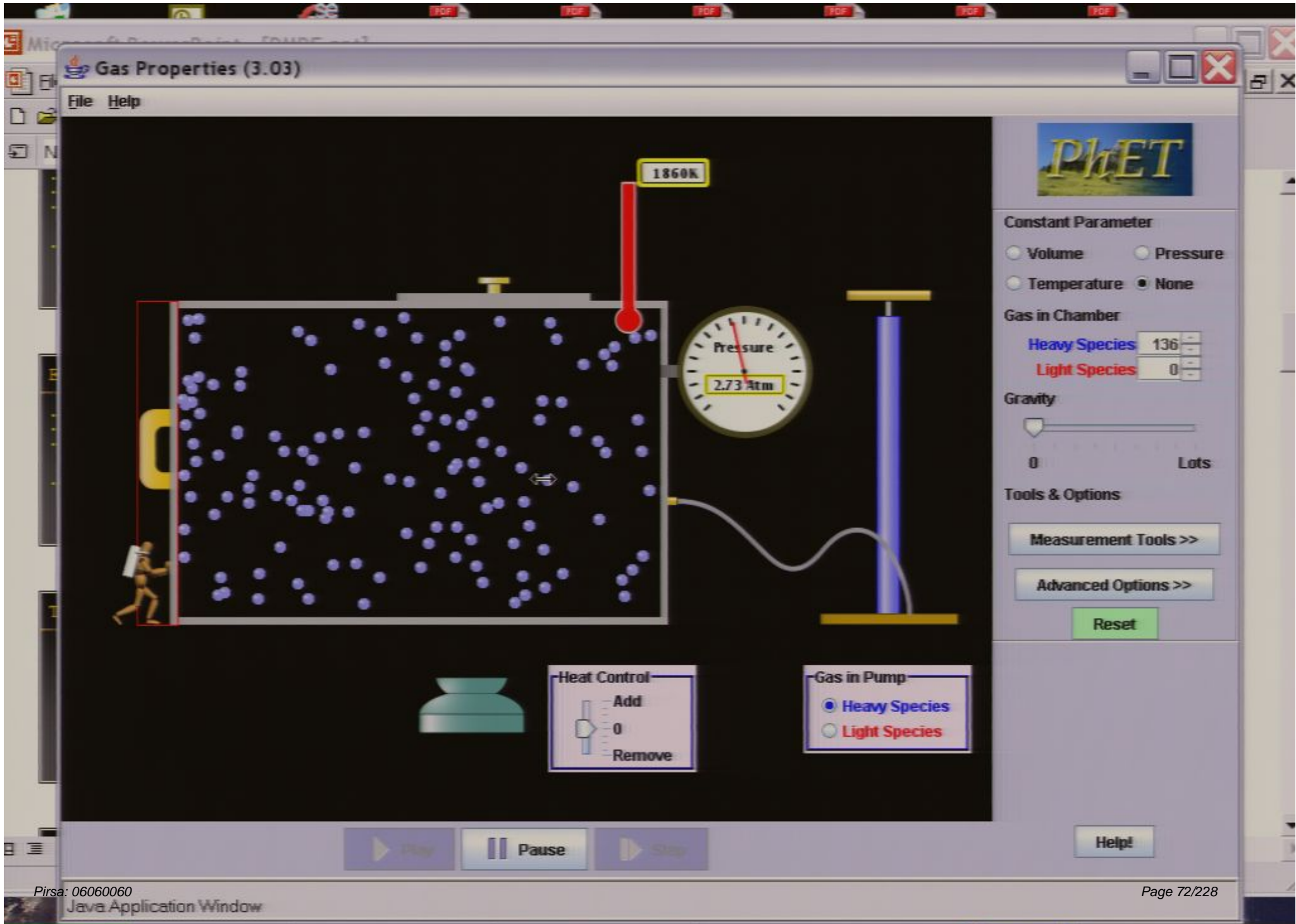
Light Species

Play

Pause

Step

Help!



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species 136

Light Species 0

Gravity

0 Lots

Tools & Options

Measurement Tools >>

Advanced Options >>

Reset

1860K



Heat Control

Add

0

Remove

Gas in Pump

Heavy Species

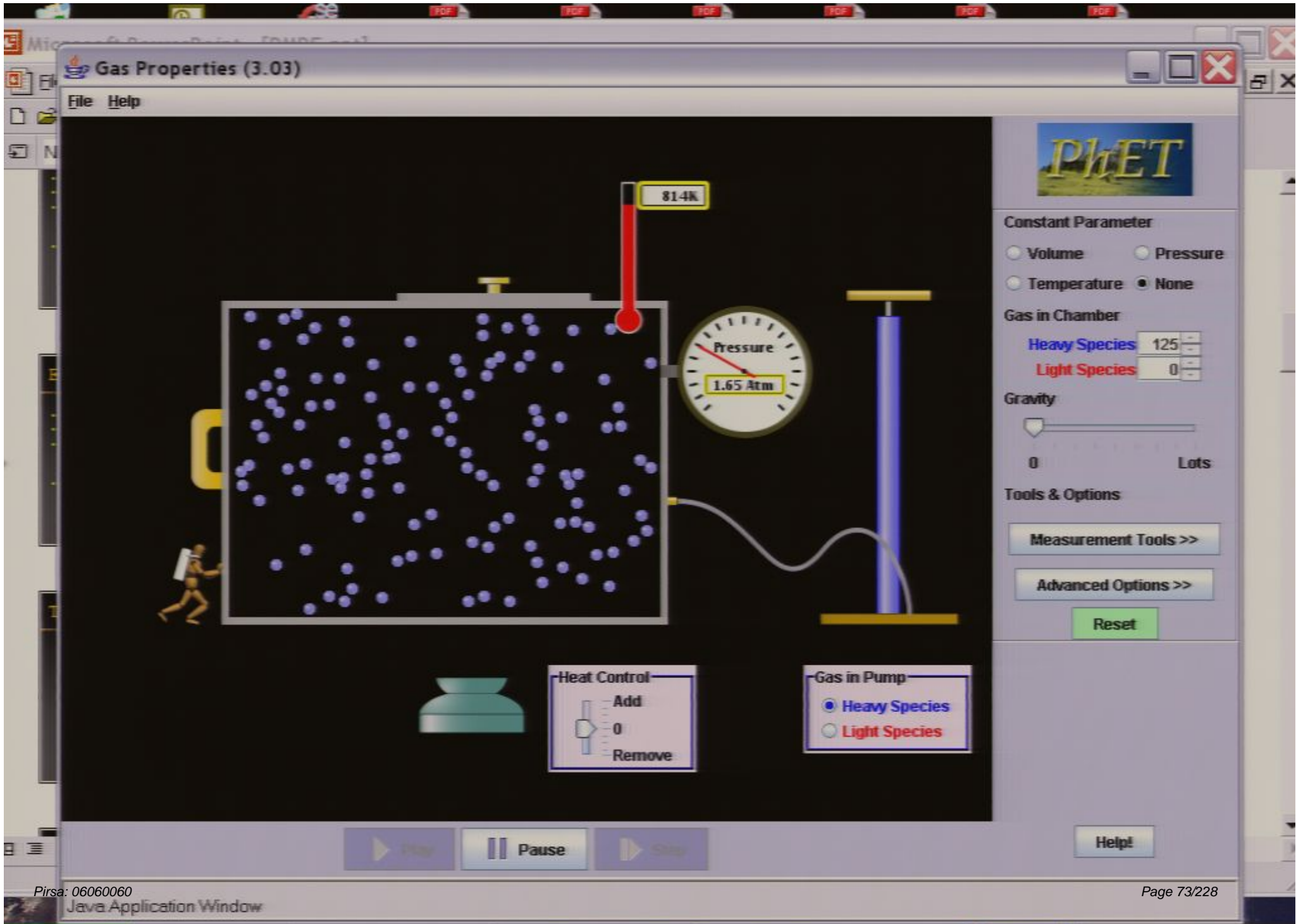
Light Species

Play

Pause

Stop

Help!



Gas Properties (3.03)

File Help



Constant Parameter

- Volume
- Pressure
- Temperature
- None

Gas in Chamber

Heavy Species

Light Species

Gravity

0 Lots

Tools & Options

[Measurement Tools >>](#)

[Advanced Options >>](#)

[Reset](#)

81.4K

Pressure

1.65 Atm

Heat Control

Add

0

Remove

Gas in Pump

Heavy Species

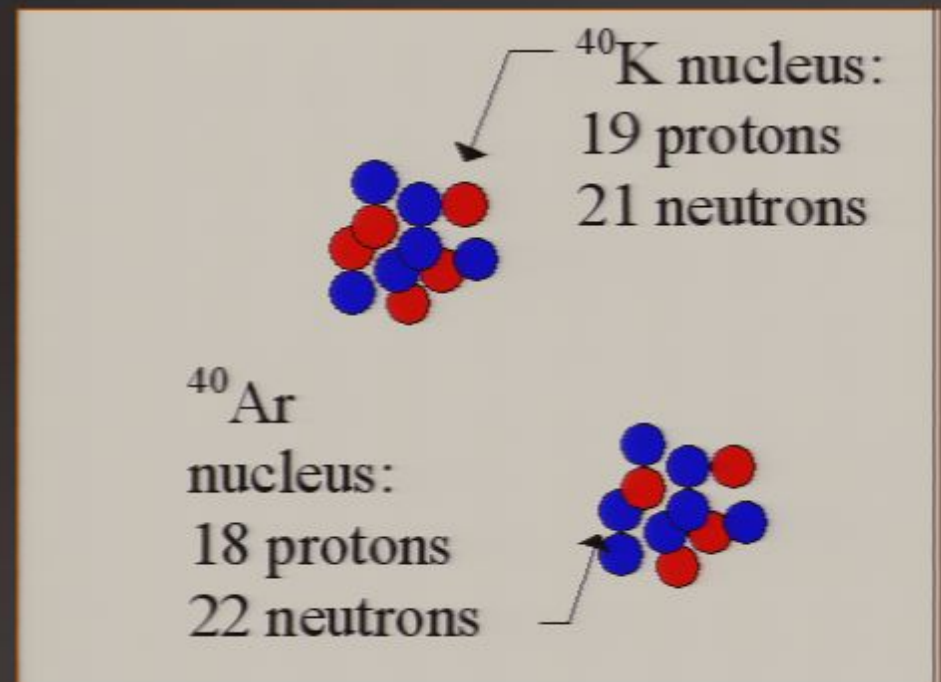
Light Species

[Play](#) [Pause](#) [Skip](#)

[Help!](#)

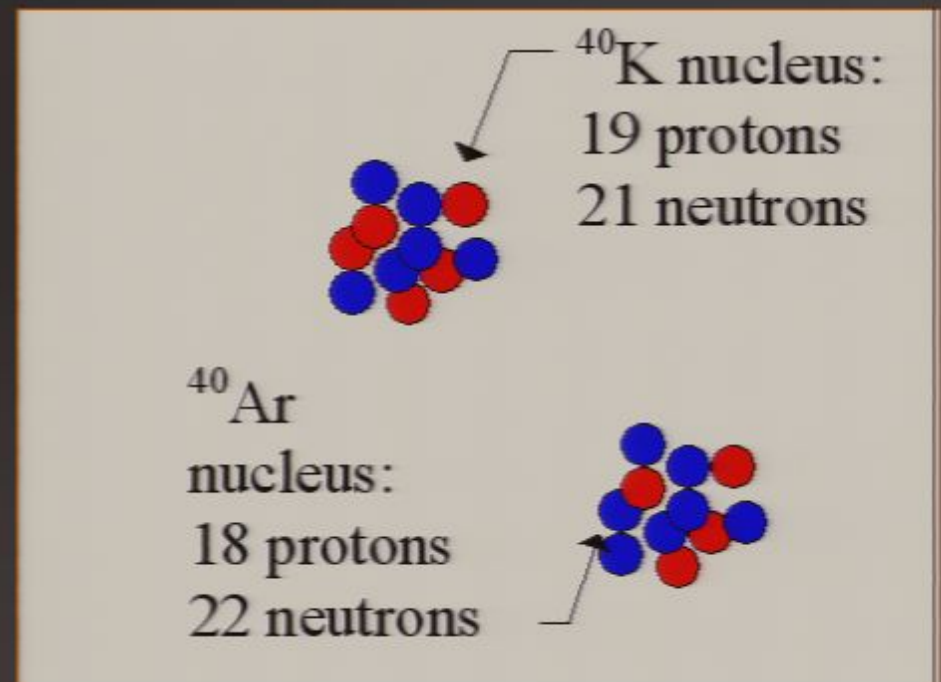
How Would We Know?

- 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.



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Evidence for a Hot Big Bang

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

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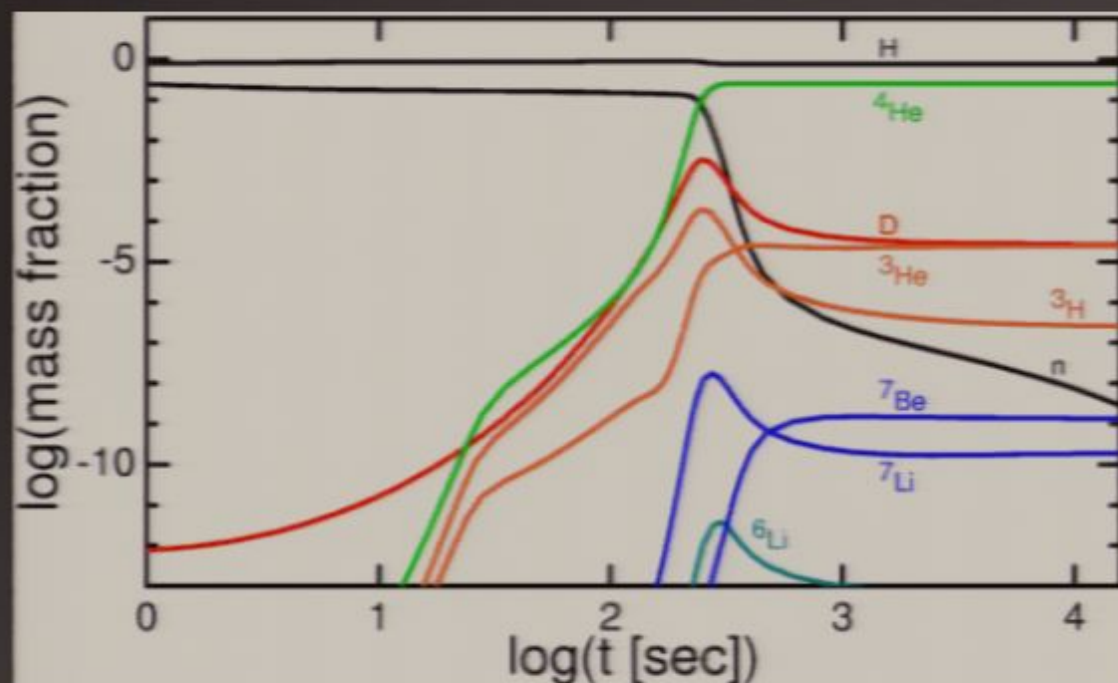
When the universe cools to the point where nuclei can form (around 10^{10} K) then the relative abundances of the light elements can be calculated.

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

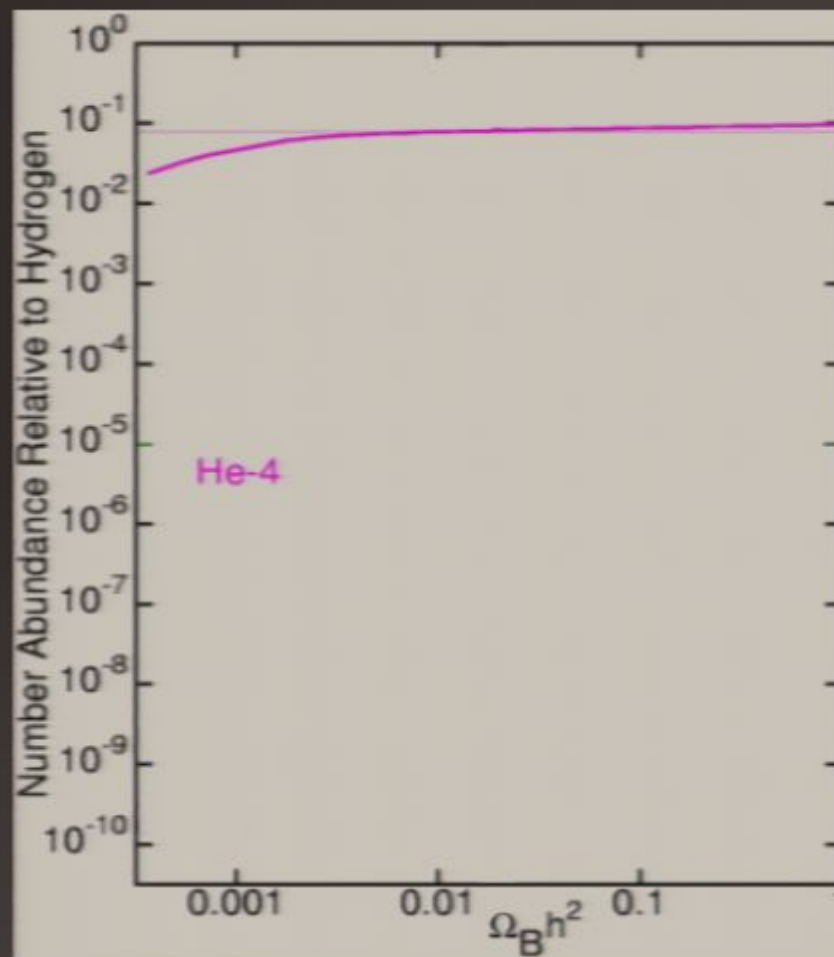
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Burles, Nolette & Turner, 1999

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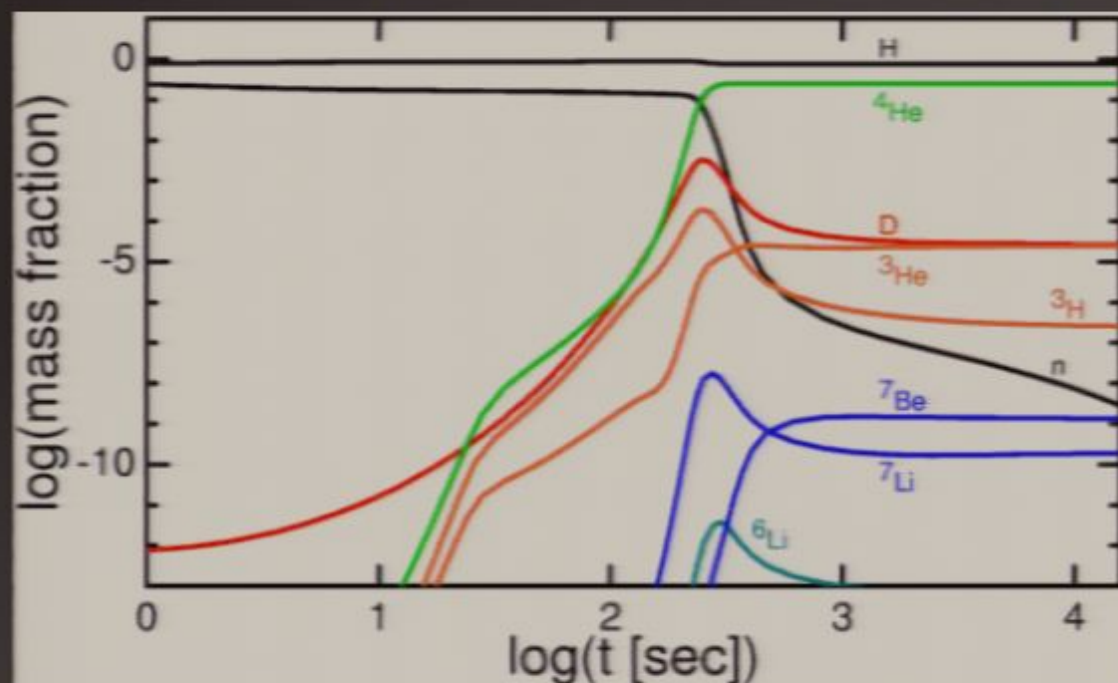


Total Mass Density of Atoms

Burles, Nolette & Turner, 1999

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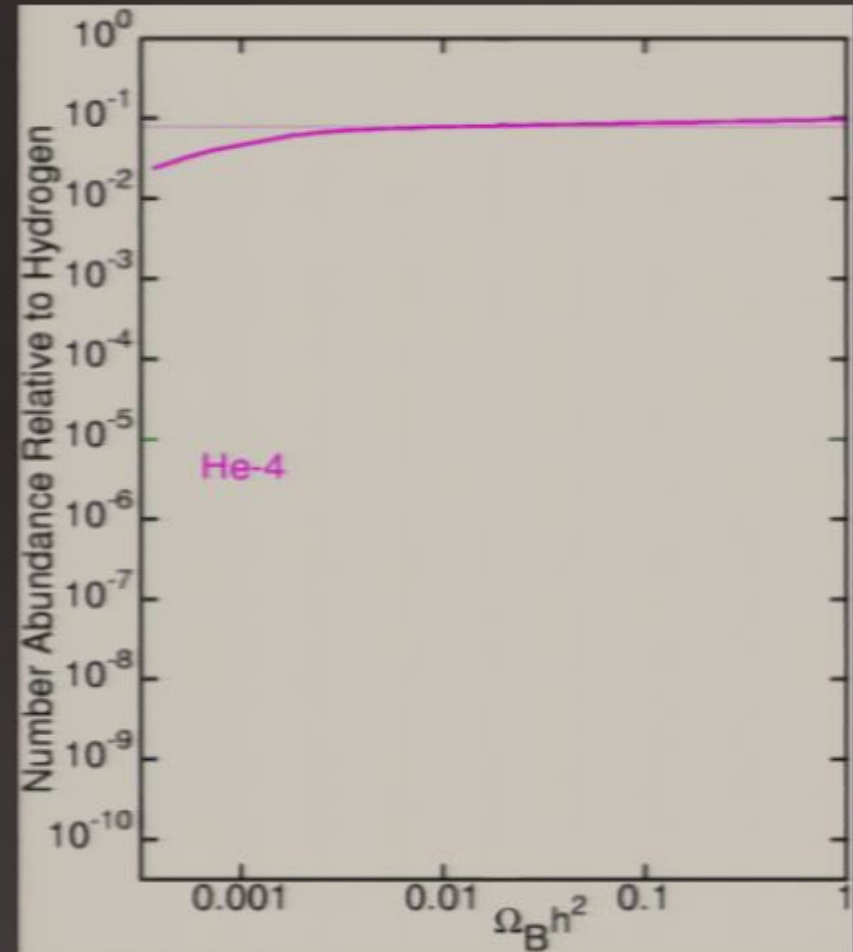
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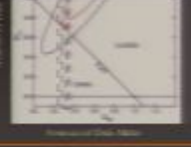


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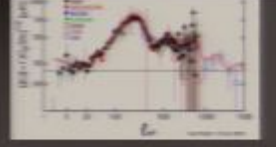
very distant superimpose

- Flattens of the universe as a whole



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

77



Good fit to CMB fluctuations requires both Dark Matter and Dark Energy

78



Flattest fit to the 'Cosmological Observations'

79

- Contact With Fundamental Physics
- Dark Matter
- Why Dark Energy is Harder
- Outline

80

Contact With Fundamental Physics

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

Albert Einstein

81

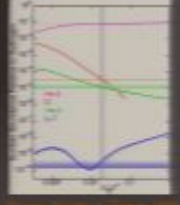
What is the Dark Matter?

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

82

What is the Dark Matter?

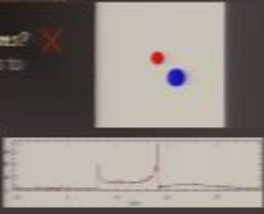
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83

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84

What is the Dark Matter?

- Ordinary atoms?
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Weakness is a Weakness

No proposals yet advanced for particles and observers and the CMB

General Relativity modify gravitation long distance without being problems with fundamental principles

85

What is the Dark Matter?

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

Weakly Interacting Massive Particles seem to most favored of many cosmologists

Their required cosmic abundance is naturally the right order of magnitude for the observed amount of Dark Matter

86

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
- Outline

87

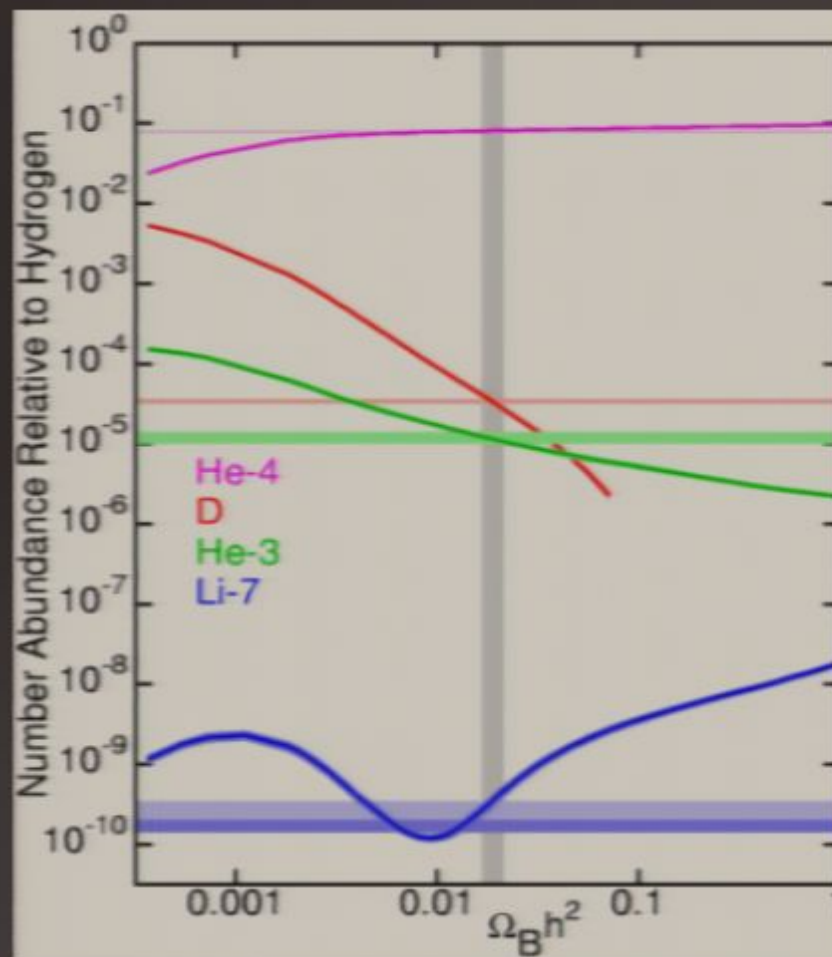
What Cosmology Requires

- Small positive energy density $\rho = 10^{-27} \text{ g/cc} = (3 \times 10^{-11} \text{ eV})^4$

88

Evidence for a Hot Big Bang

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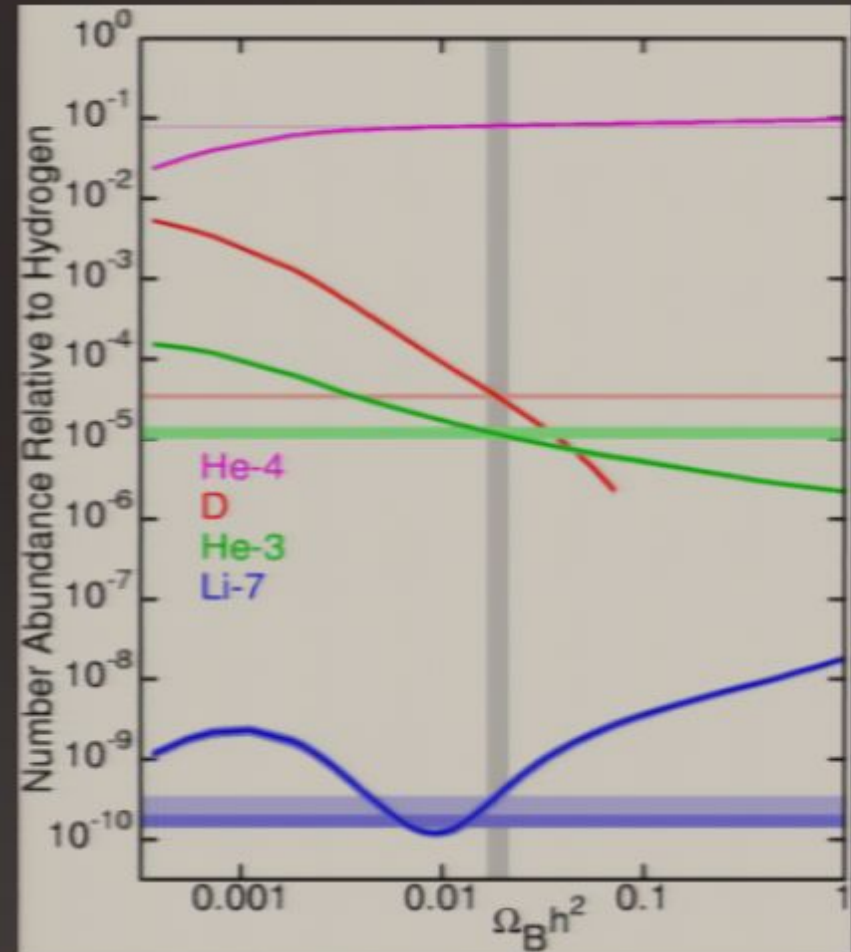


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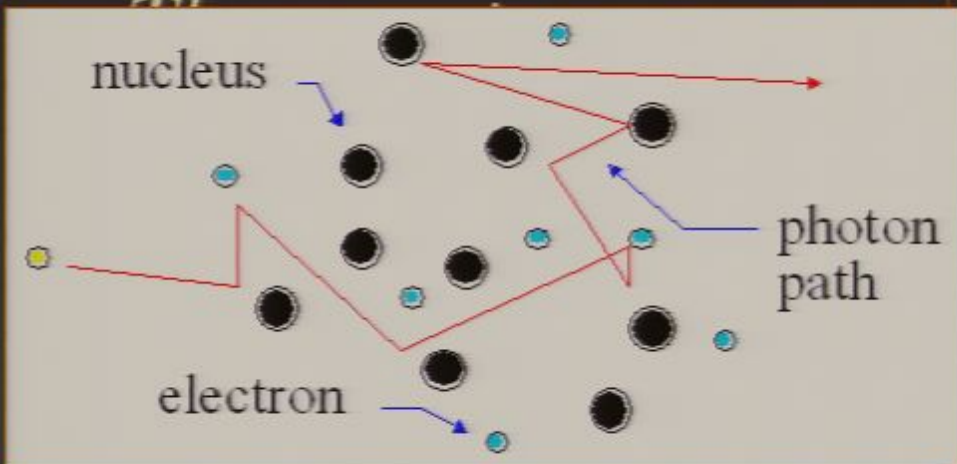
When the universe cools enough for atoms to form (around 10^3 K) it becomes transparent to light.

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



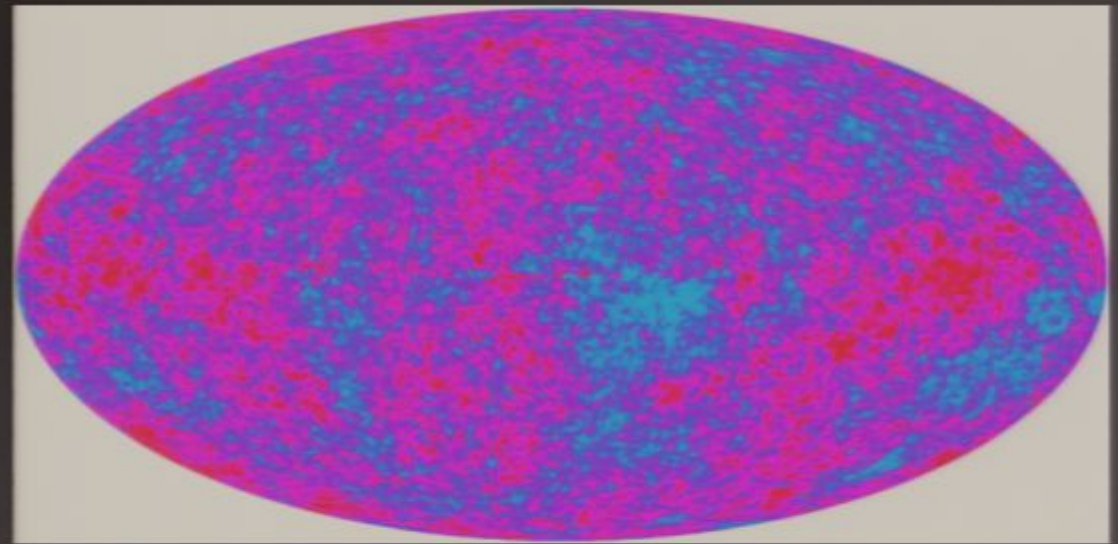
Robert Wilson



Evidence for a Hot Big Bang

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CMB Temperature vs Direction



WMAP collaboration

Outline

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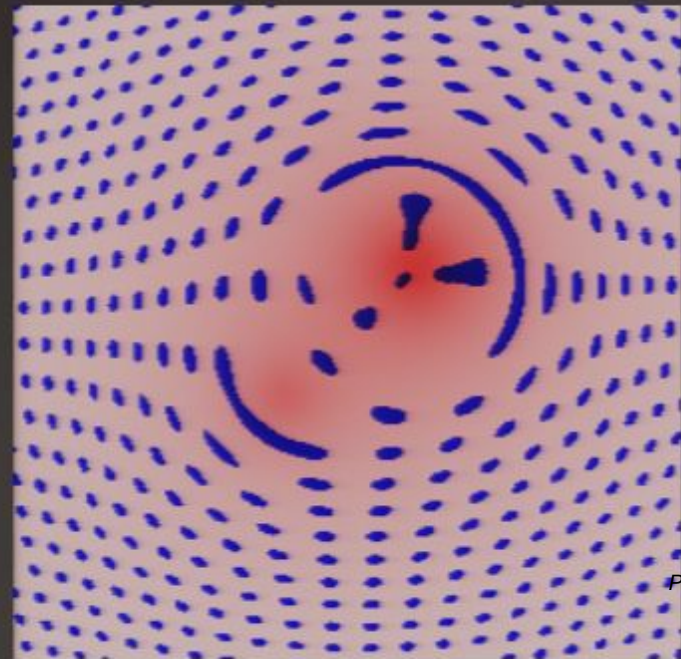
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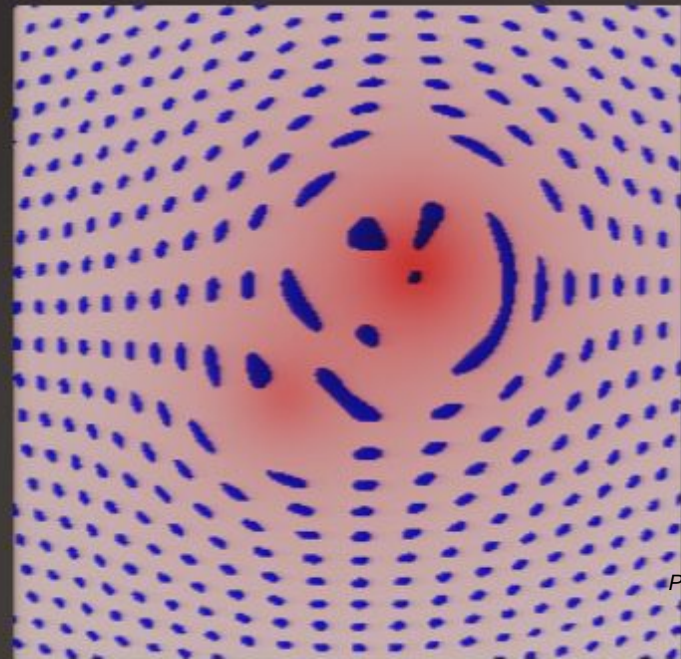
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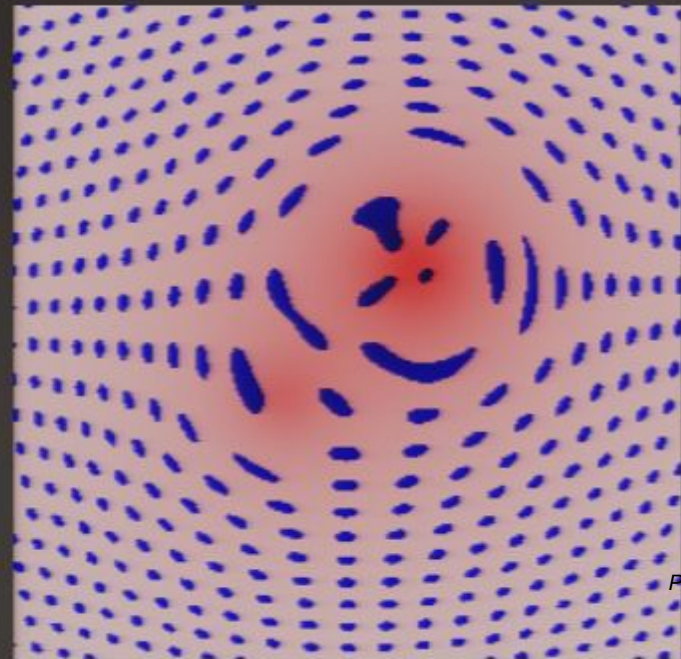
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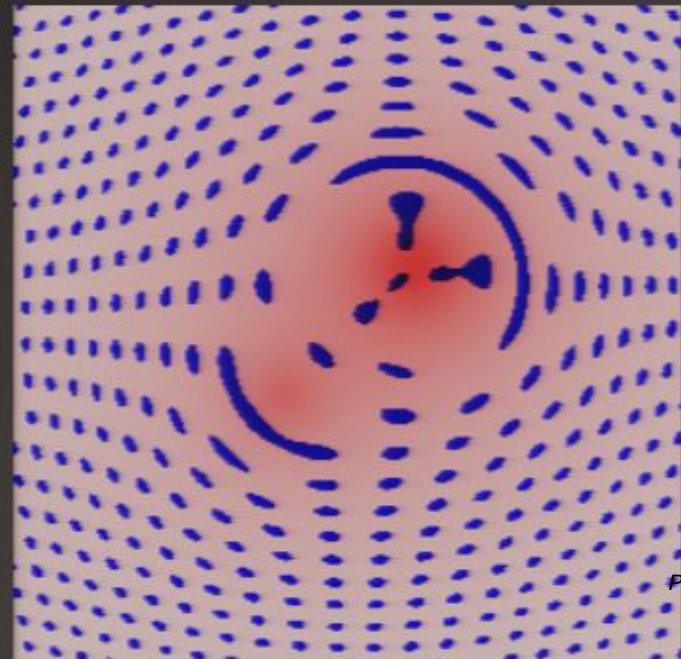
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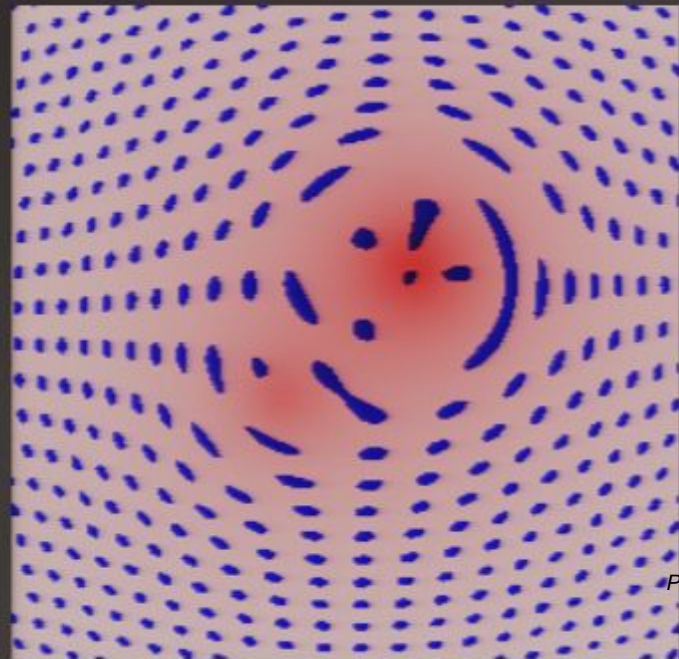
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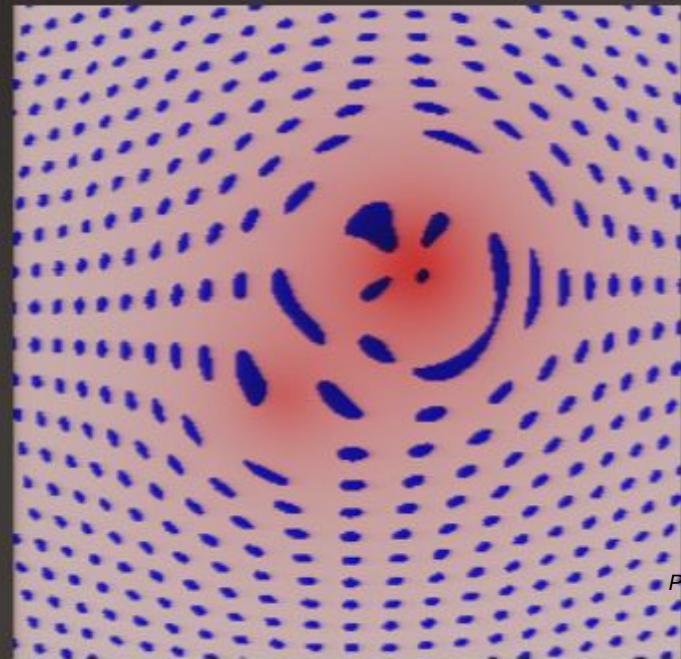
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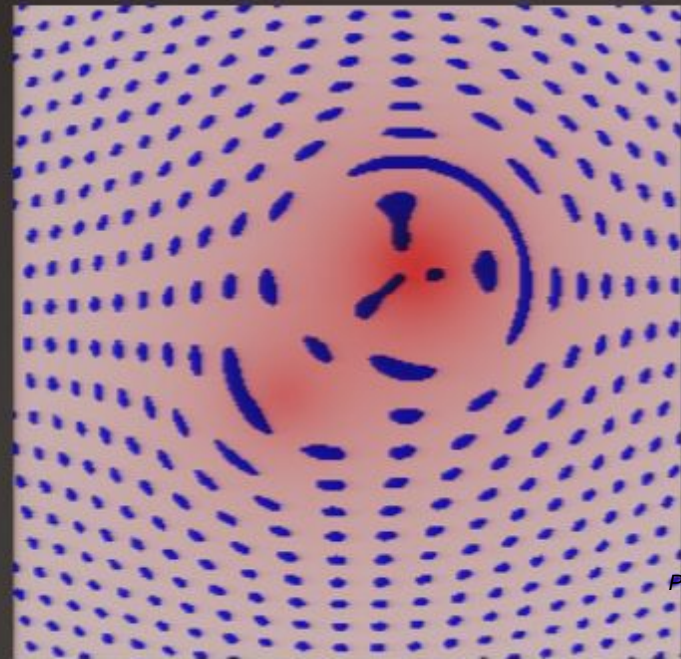
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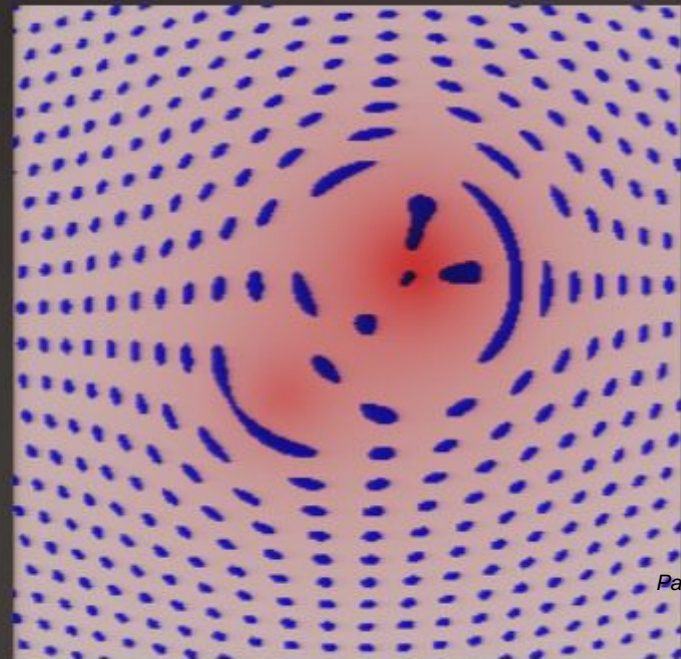
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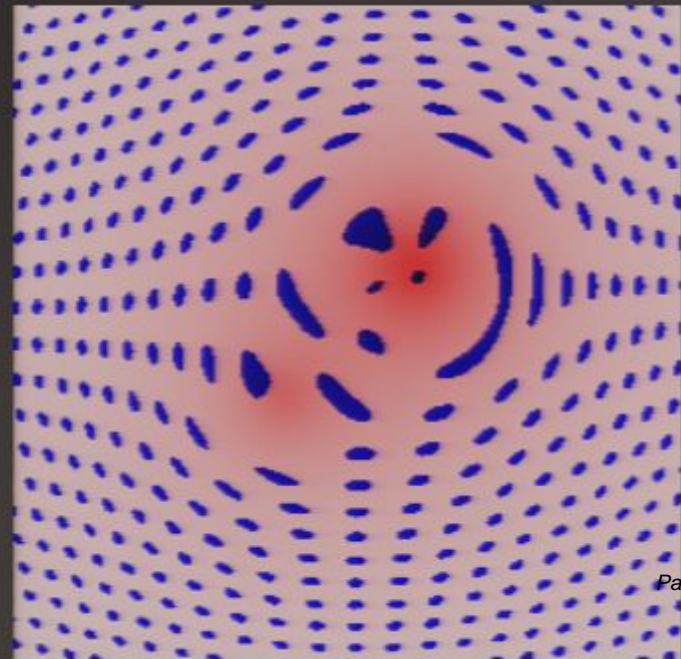
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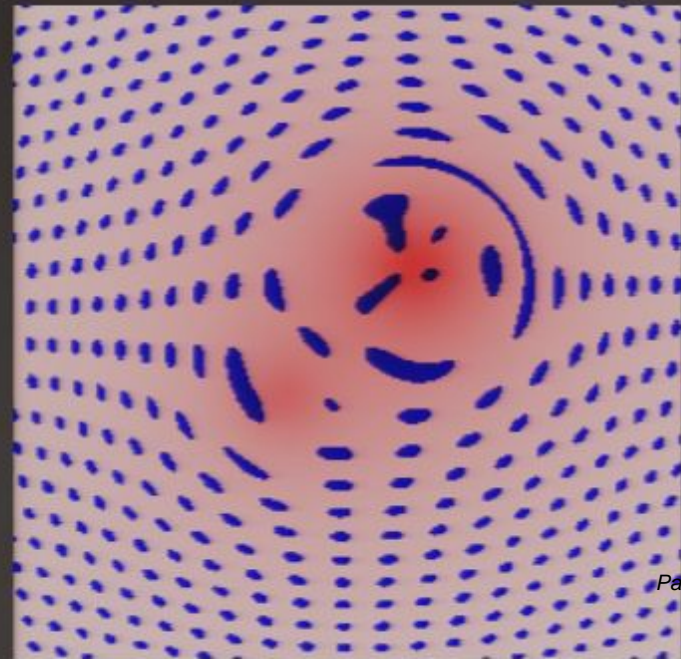
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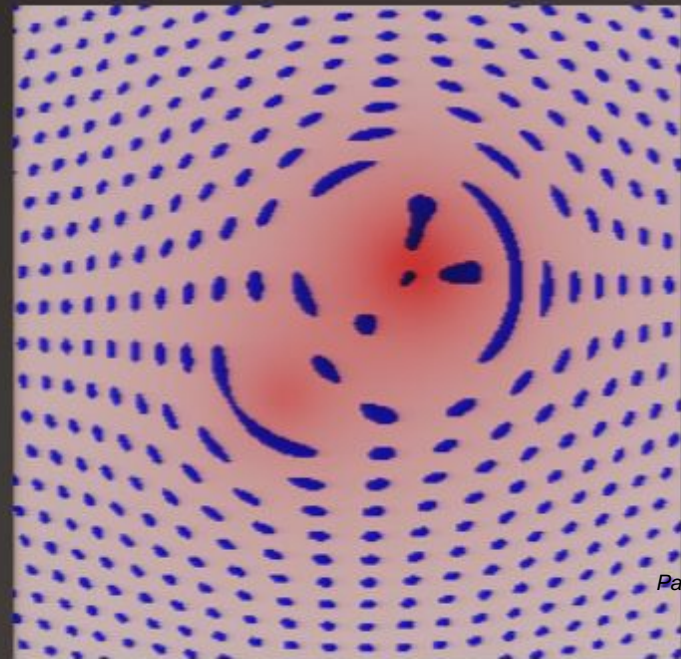
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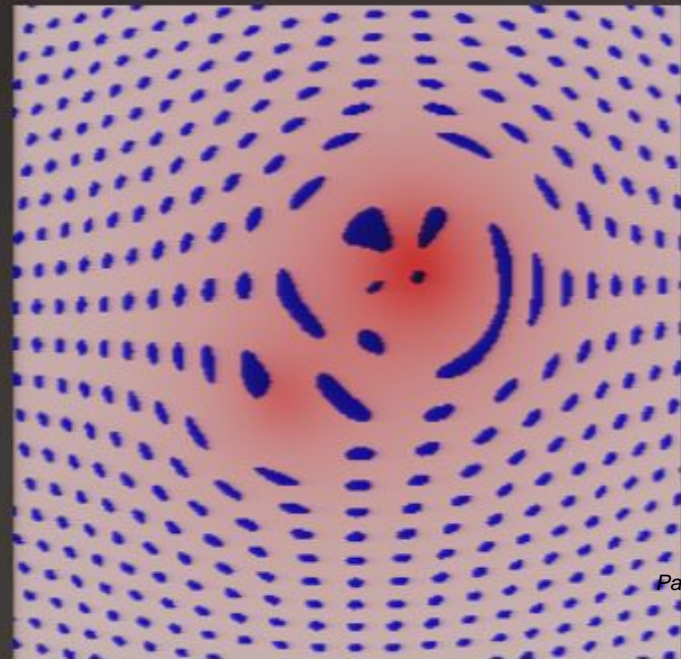
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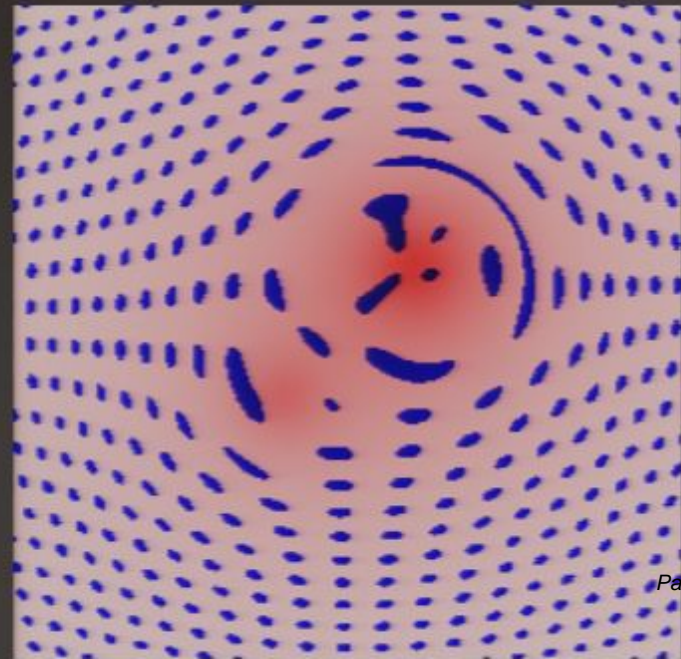
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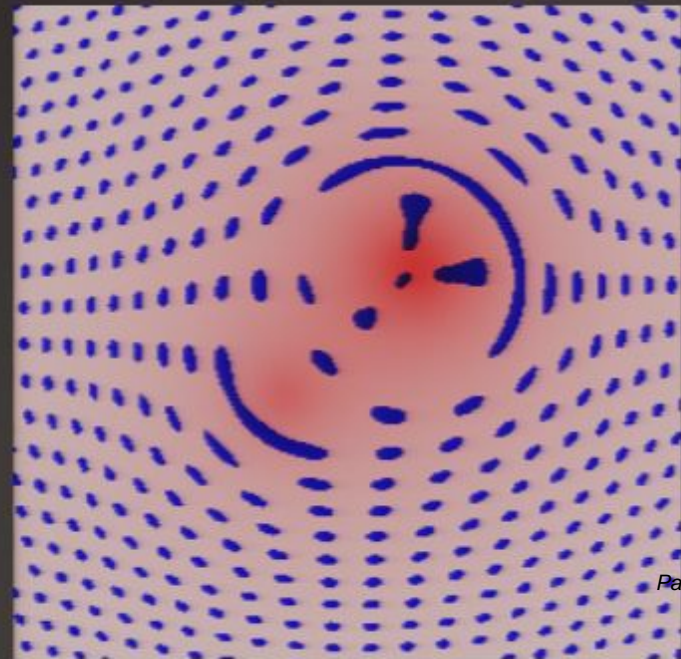
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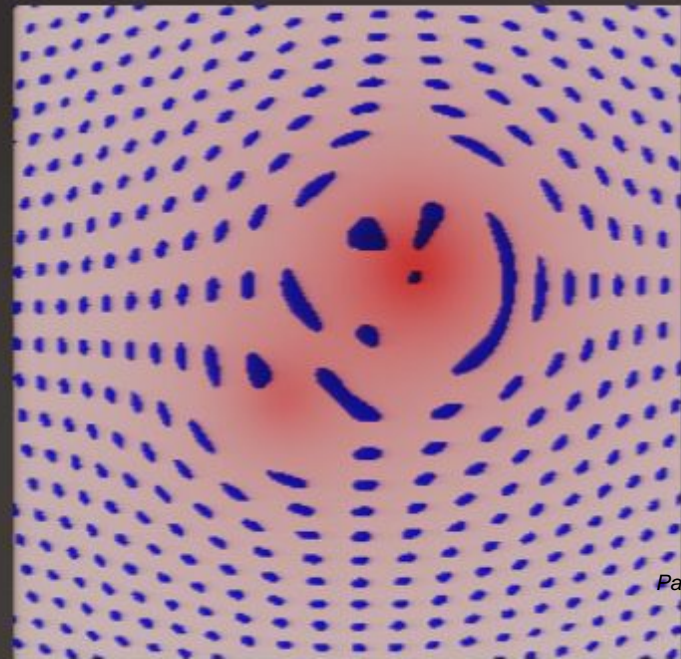
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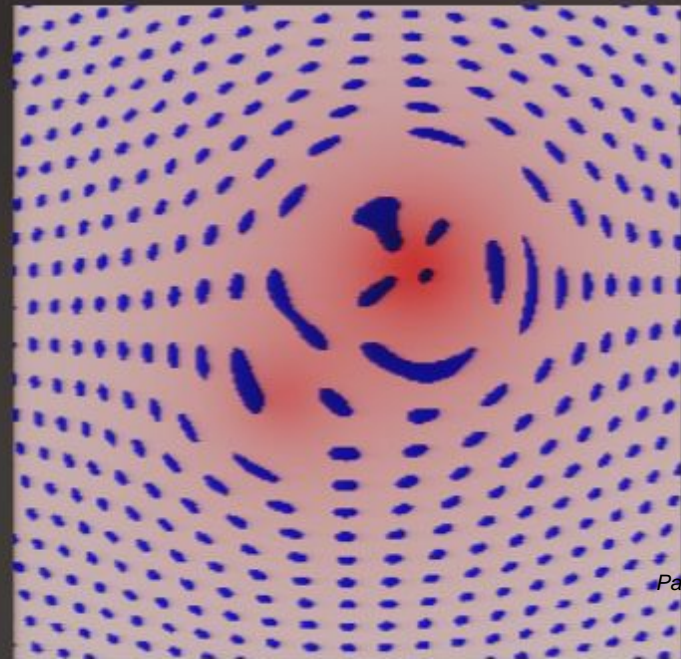
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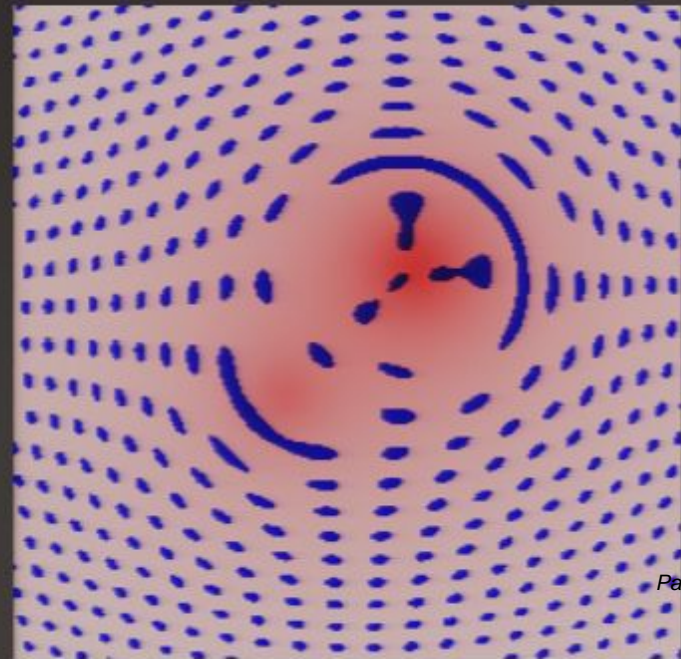
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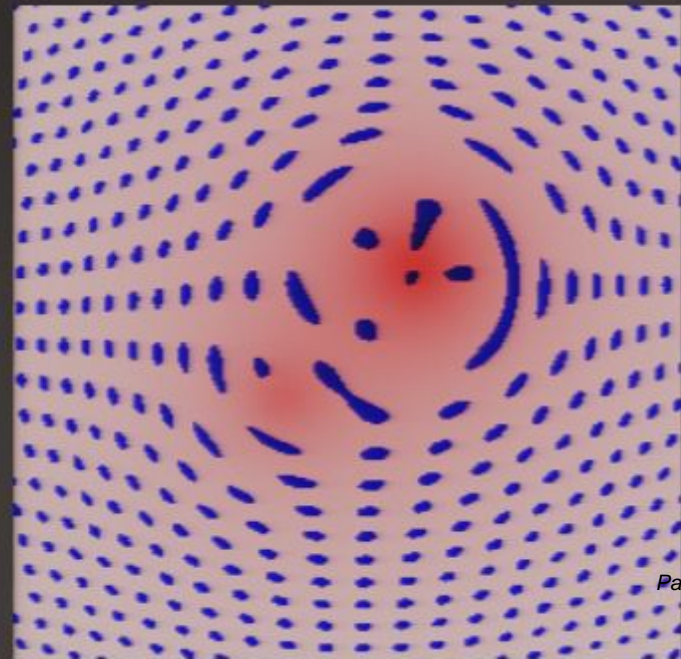
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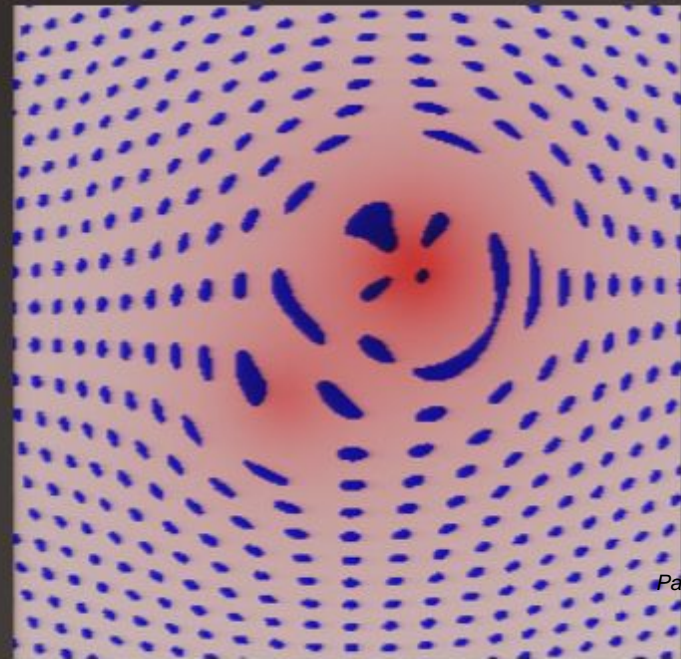
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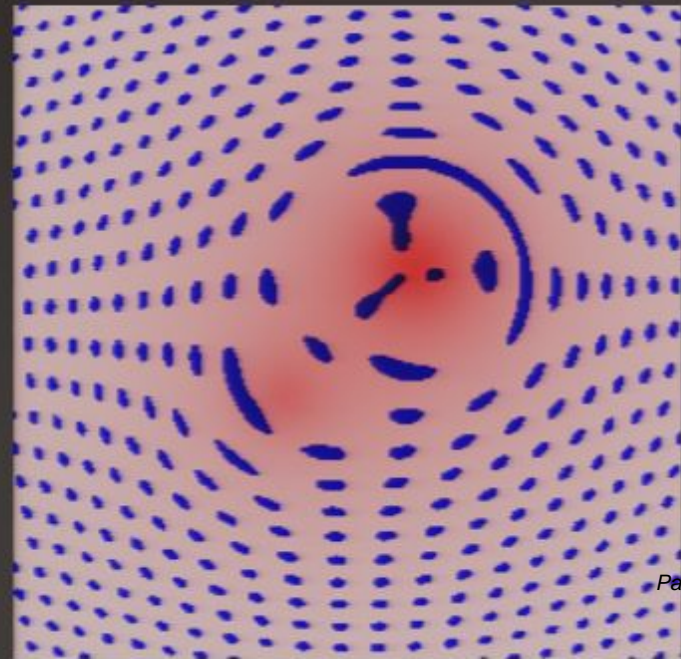
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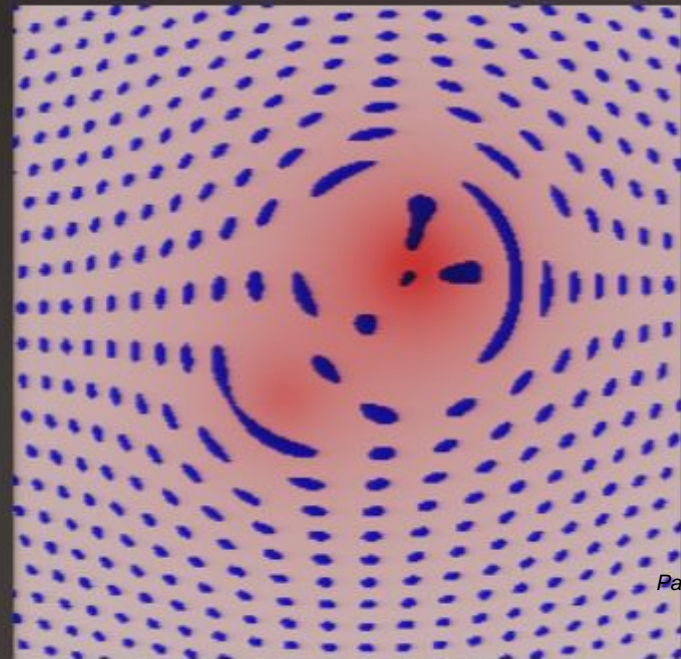
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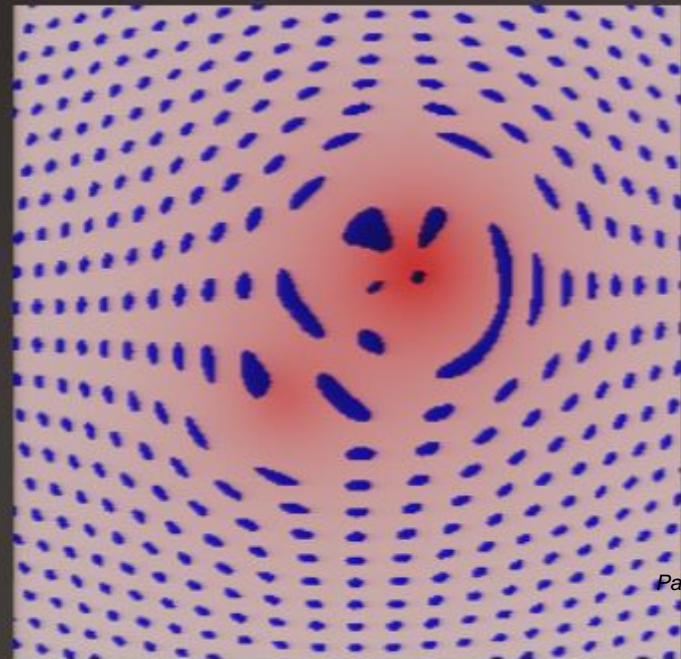
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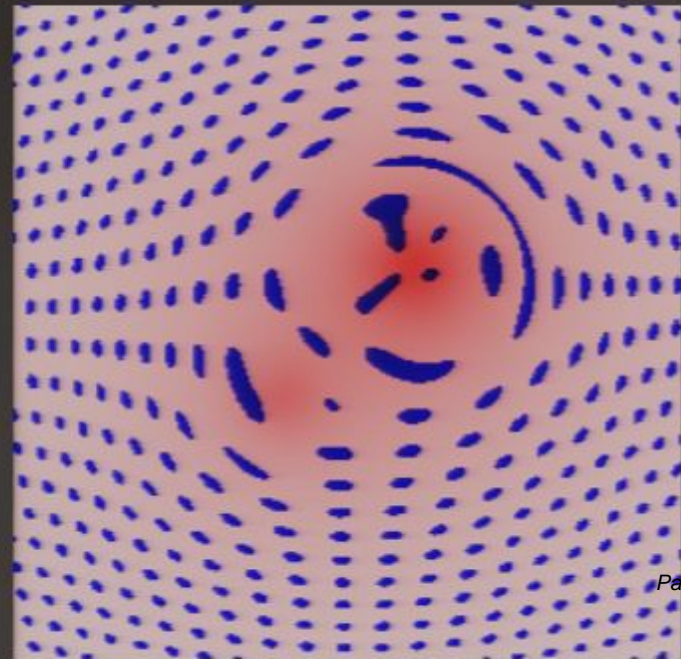
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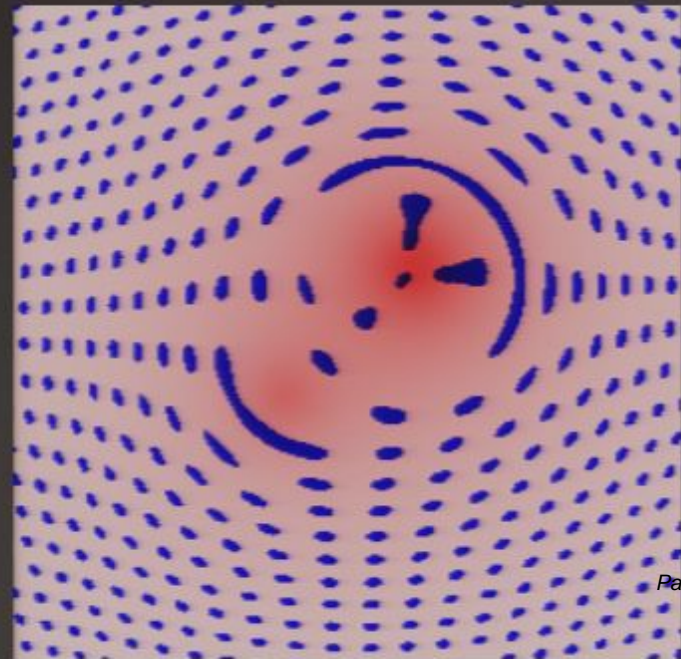
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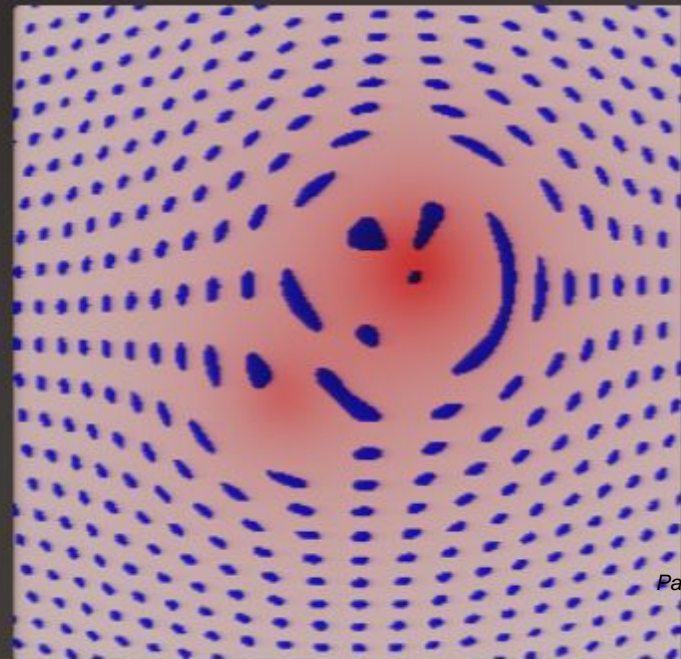
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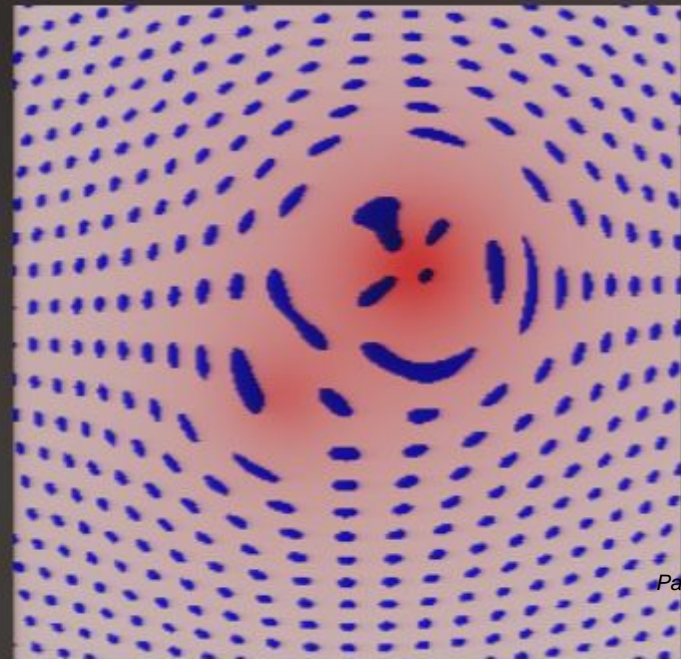
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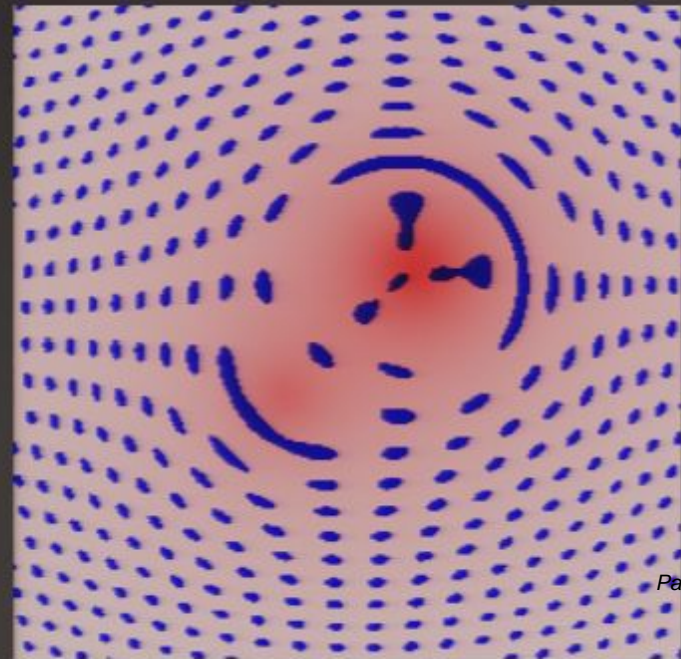
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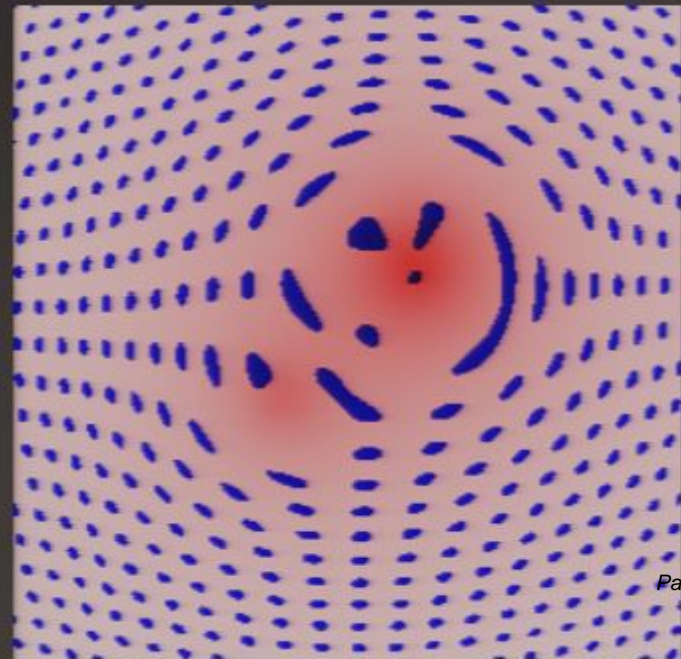
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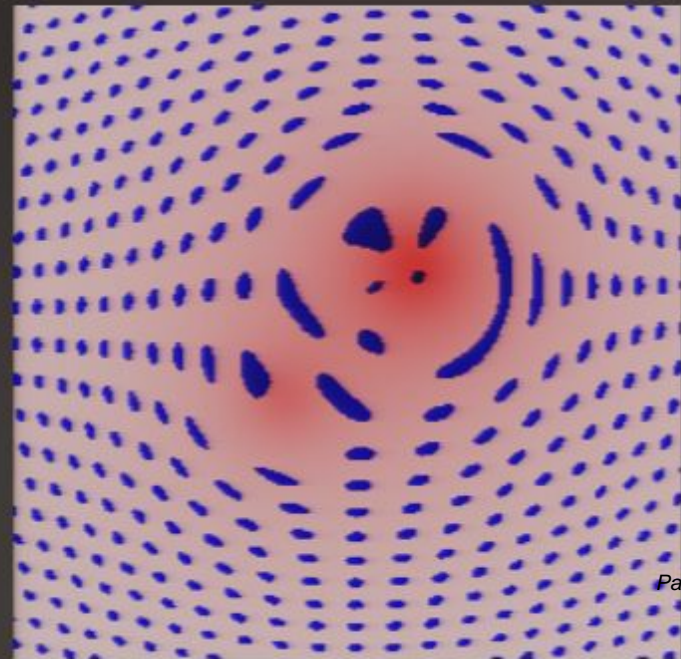


Evidence for Dark Energy

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

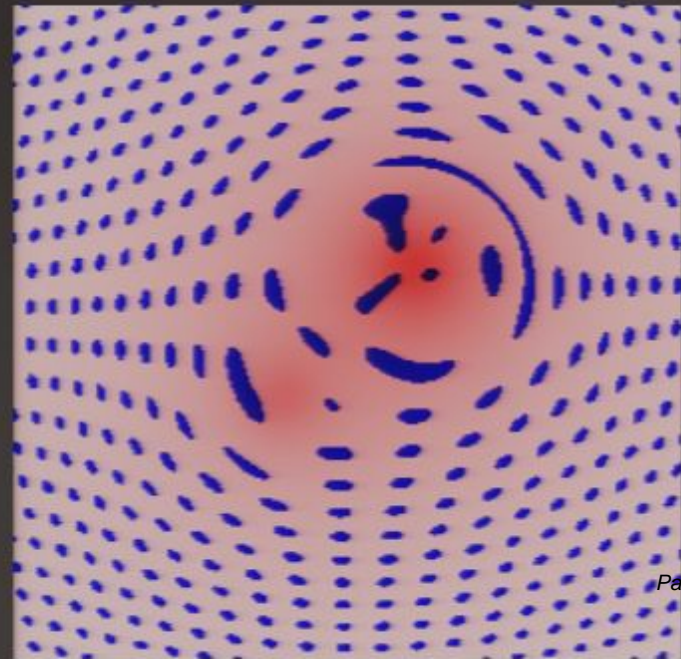
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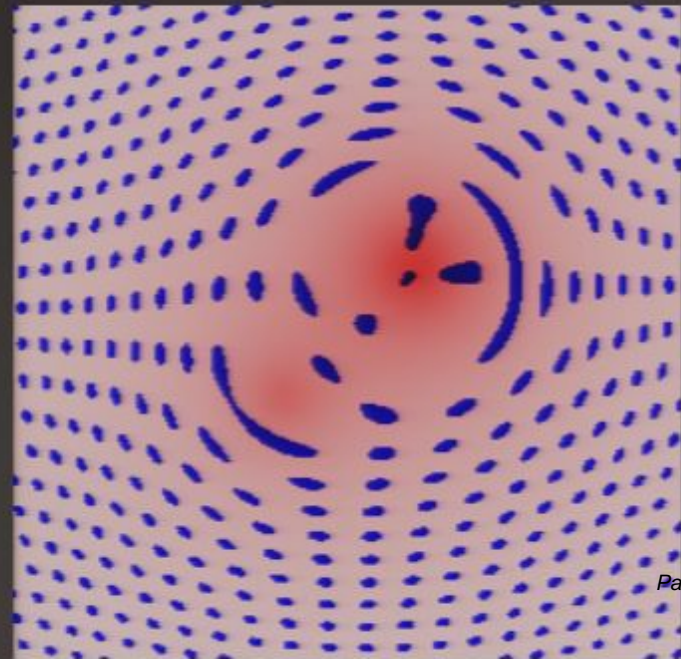
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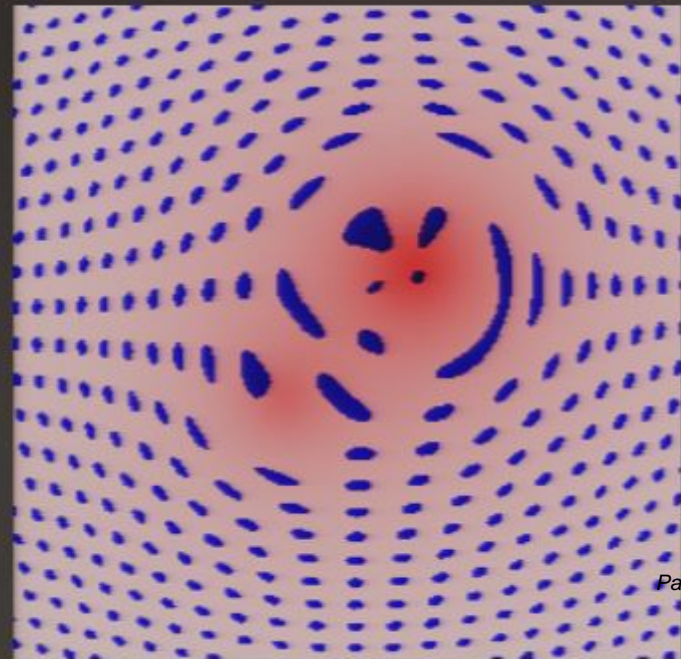
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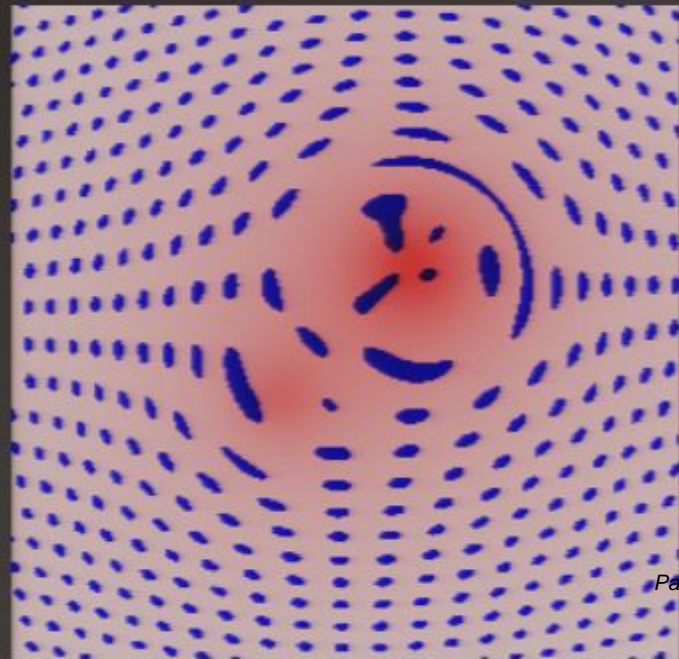
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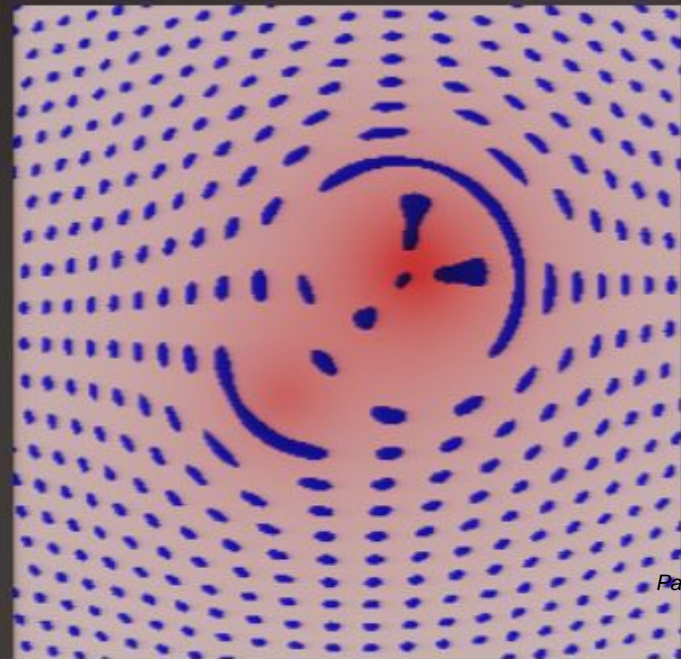
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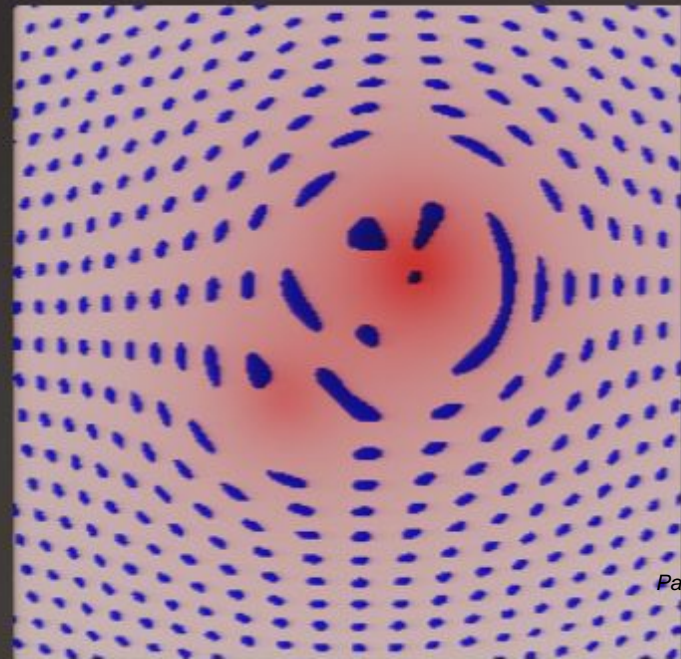
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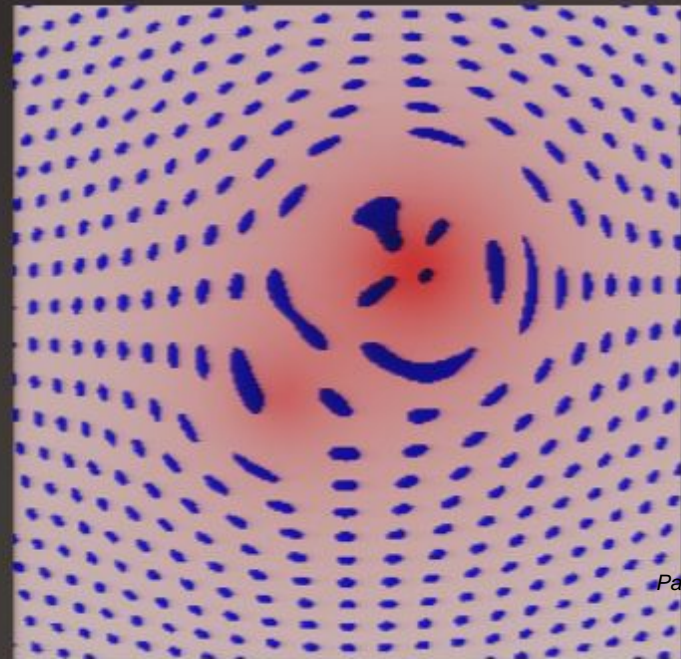
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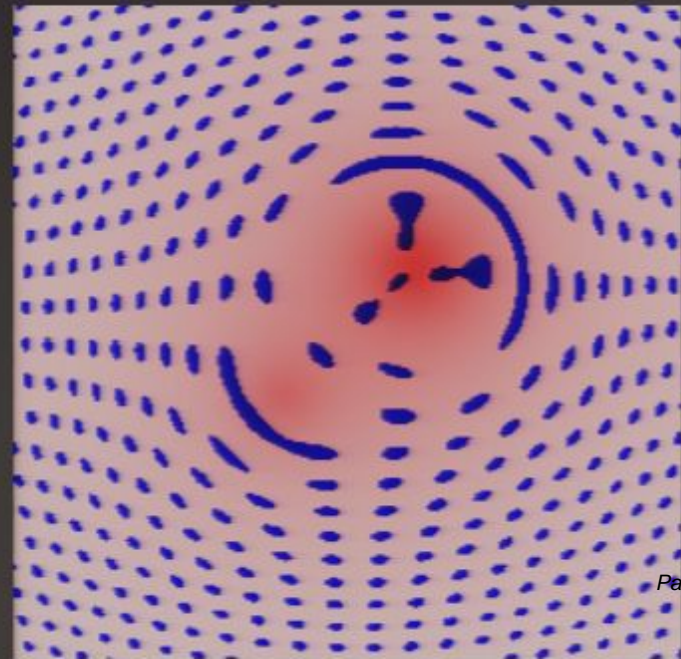
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- Flatness of the universe as a whole

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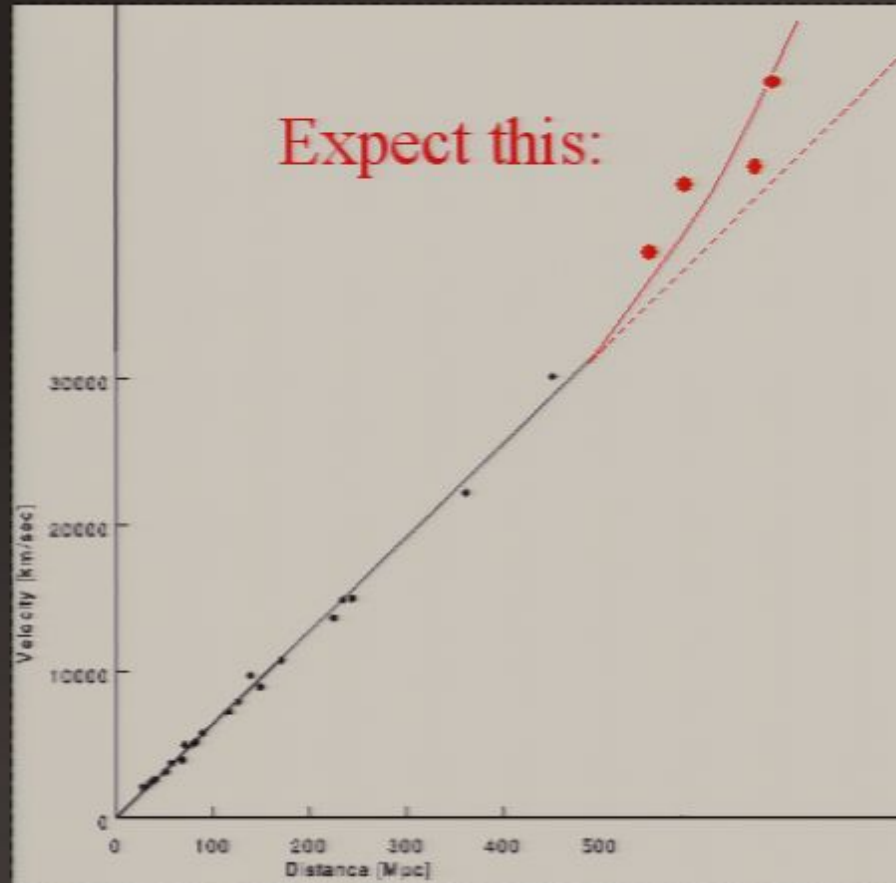
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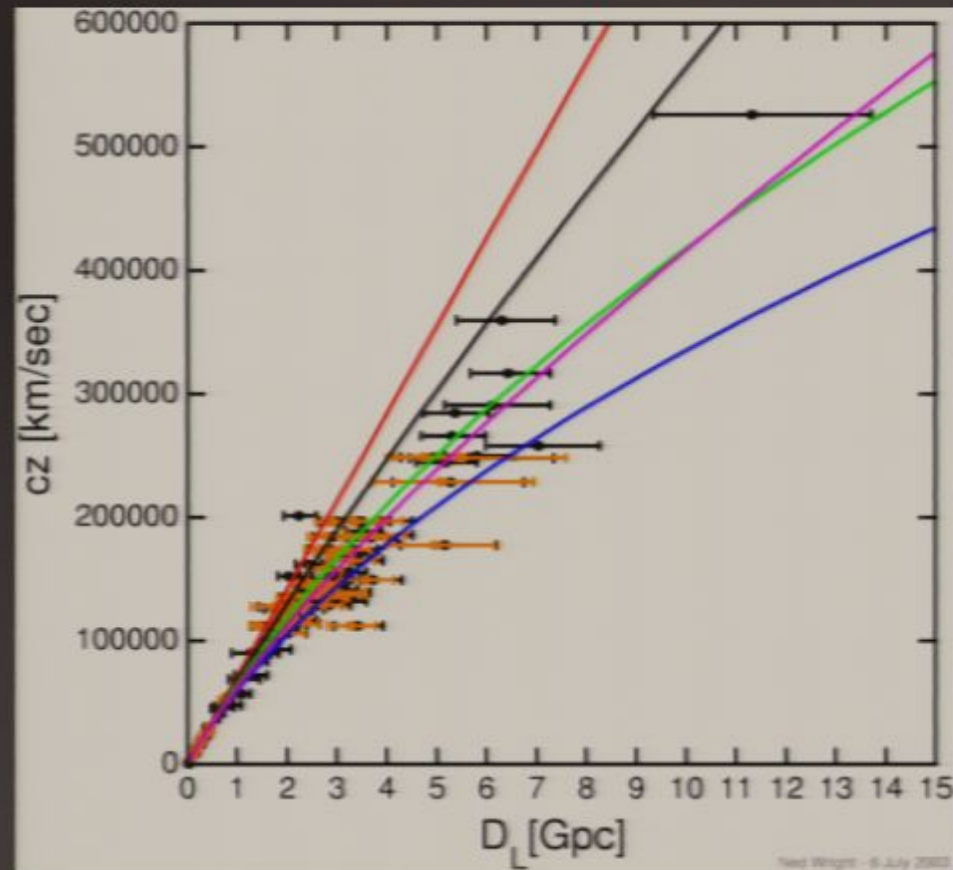


The universal expansion should be decelerating due to gravitational attraction

Evidence for Dark Energy

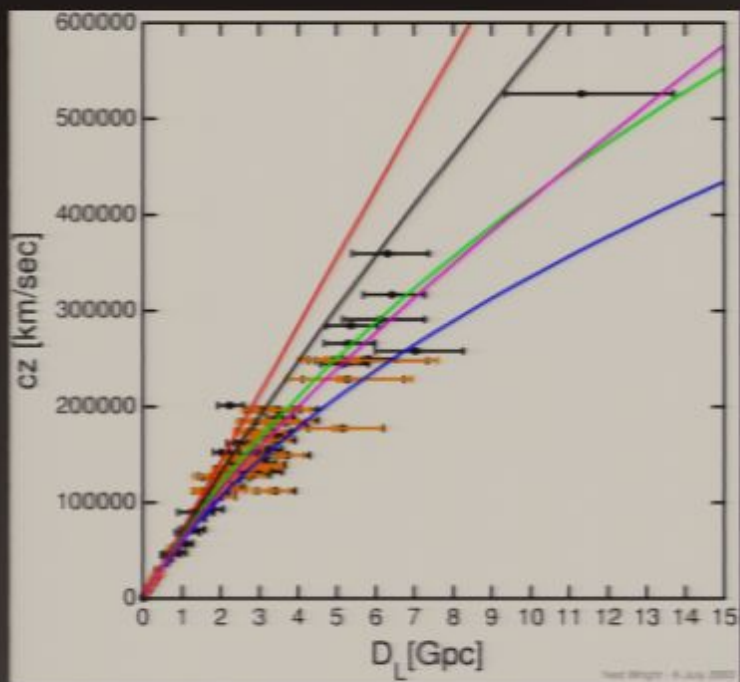
Tonrey et.al., 2003

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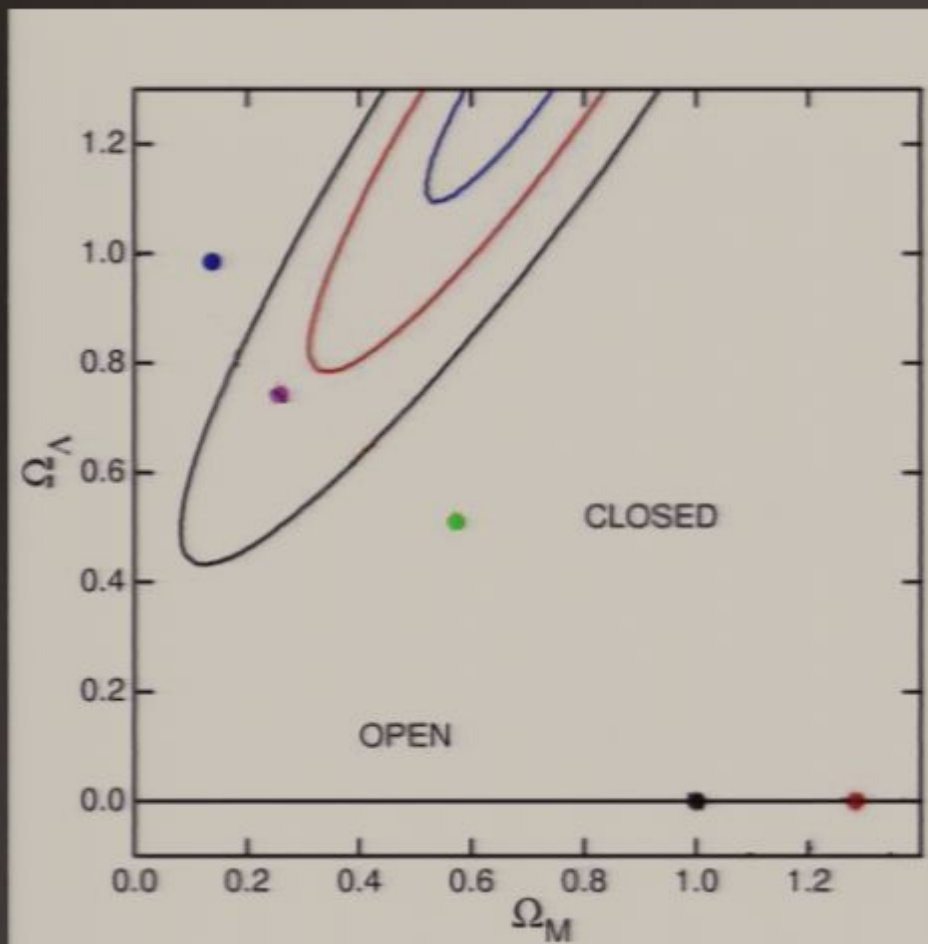


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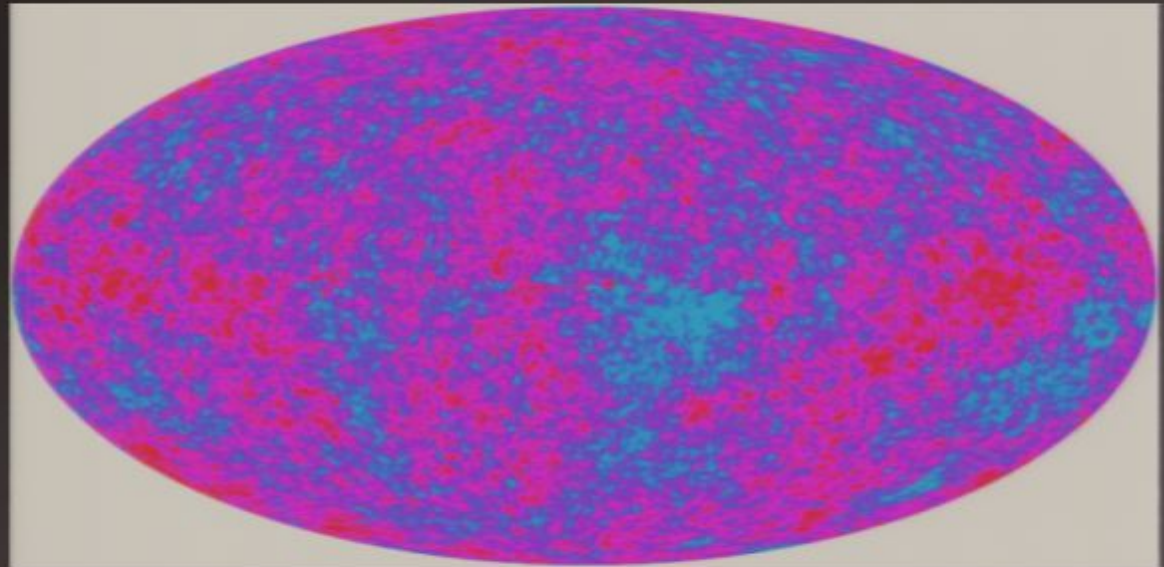
Amount of Dark Energy



Amount of Dark Matter

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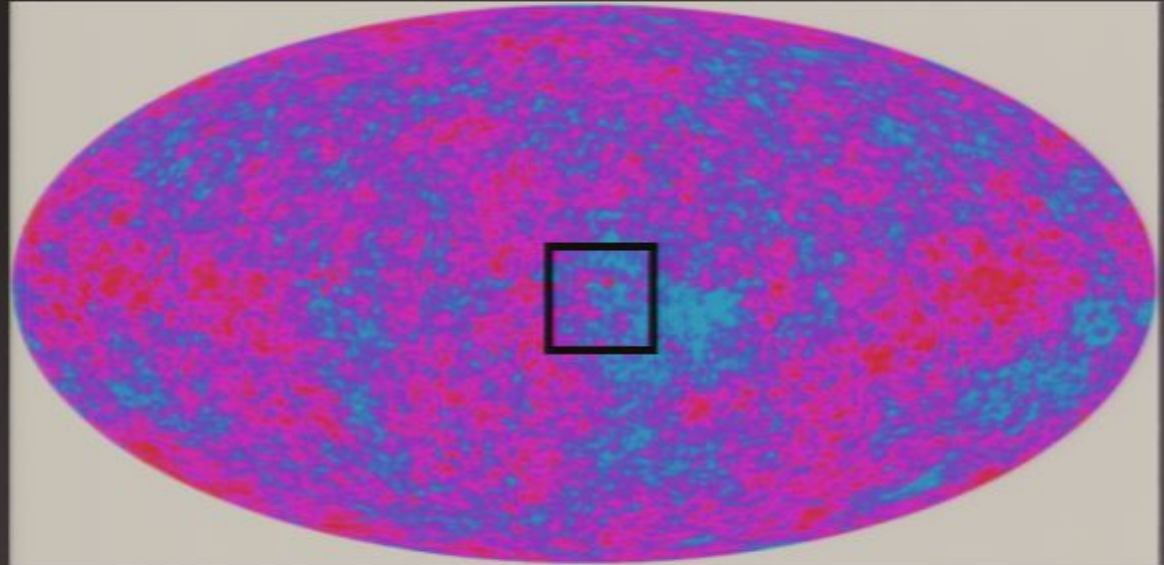


WMAP collaboration

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*

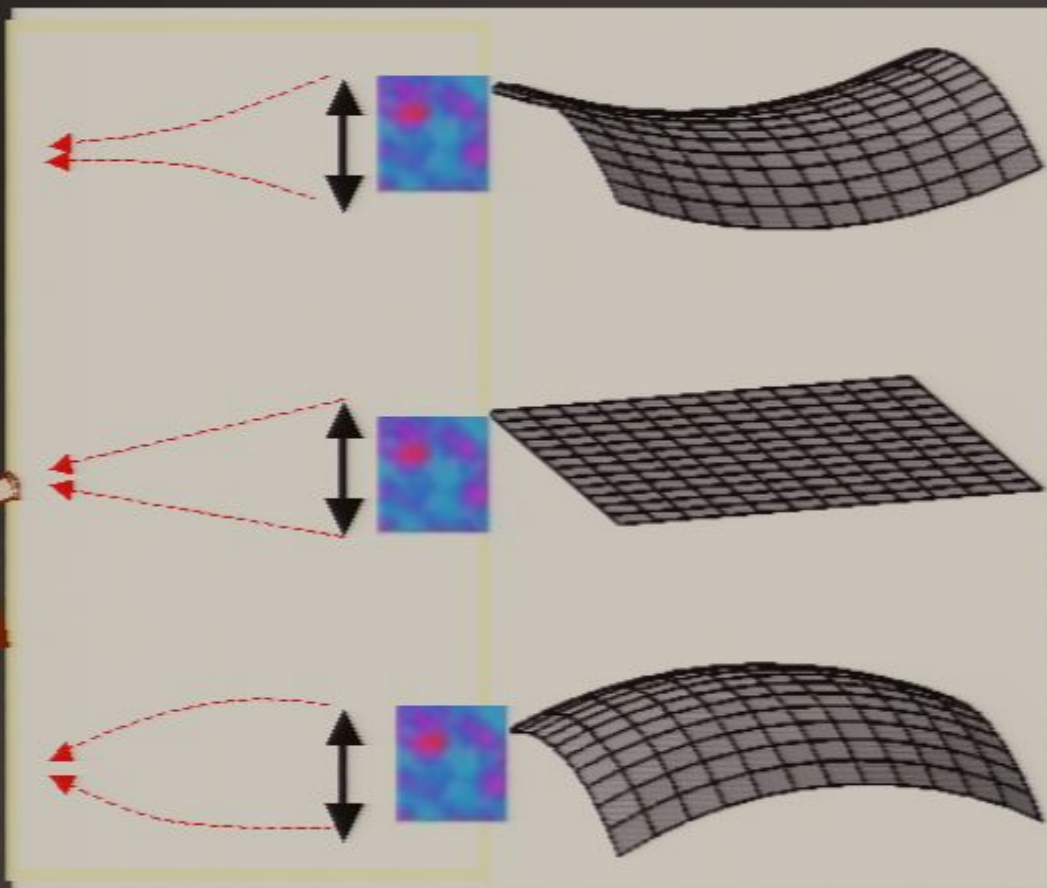


WMAP collaboration

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*



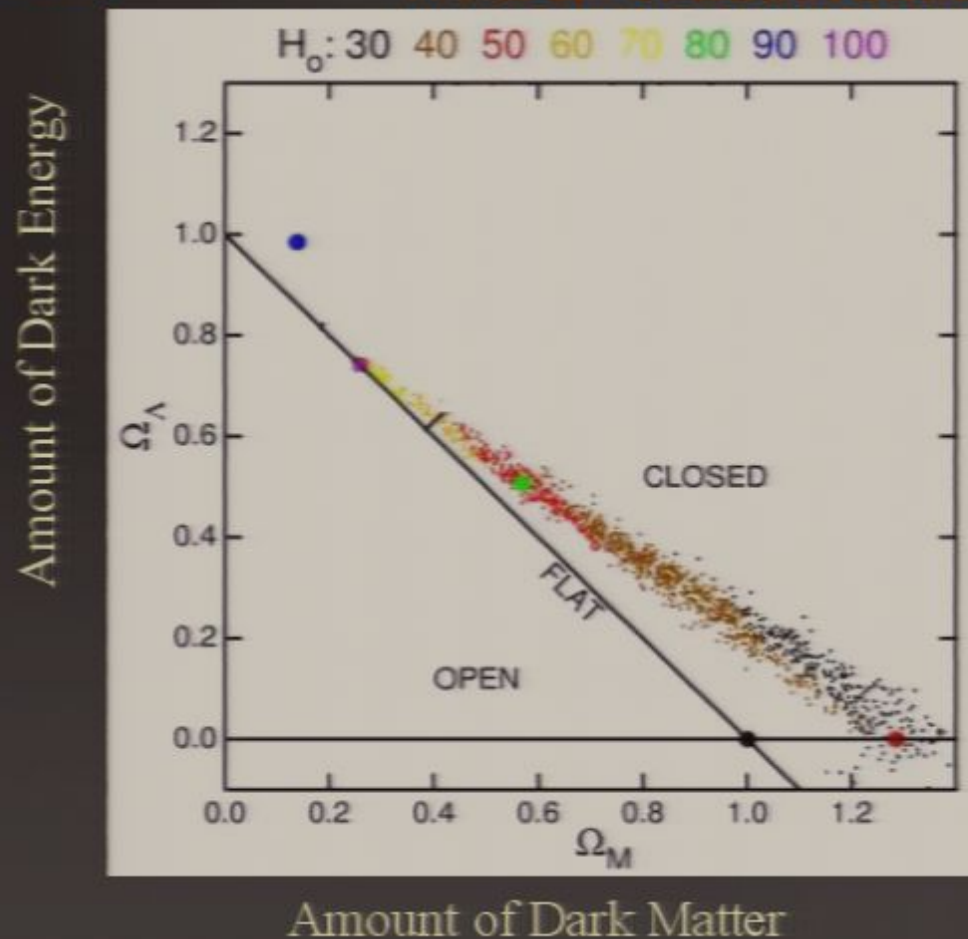
Size of the CMB fluctuations depends on the geometry of space the light traverses.

Evidence for Dark Energy

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

Courtesy: Ned Wright's Cosmology Page

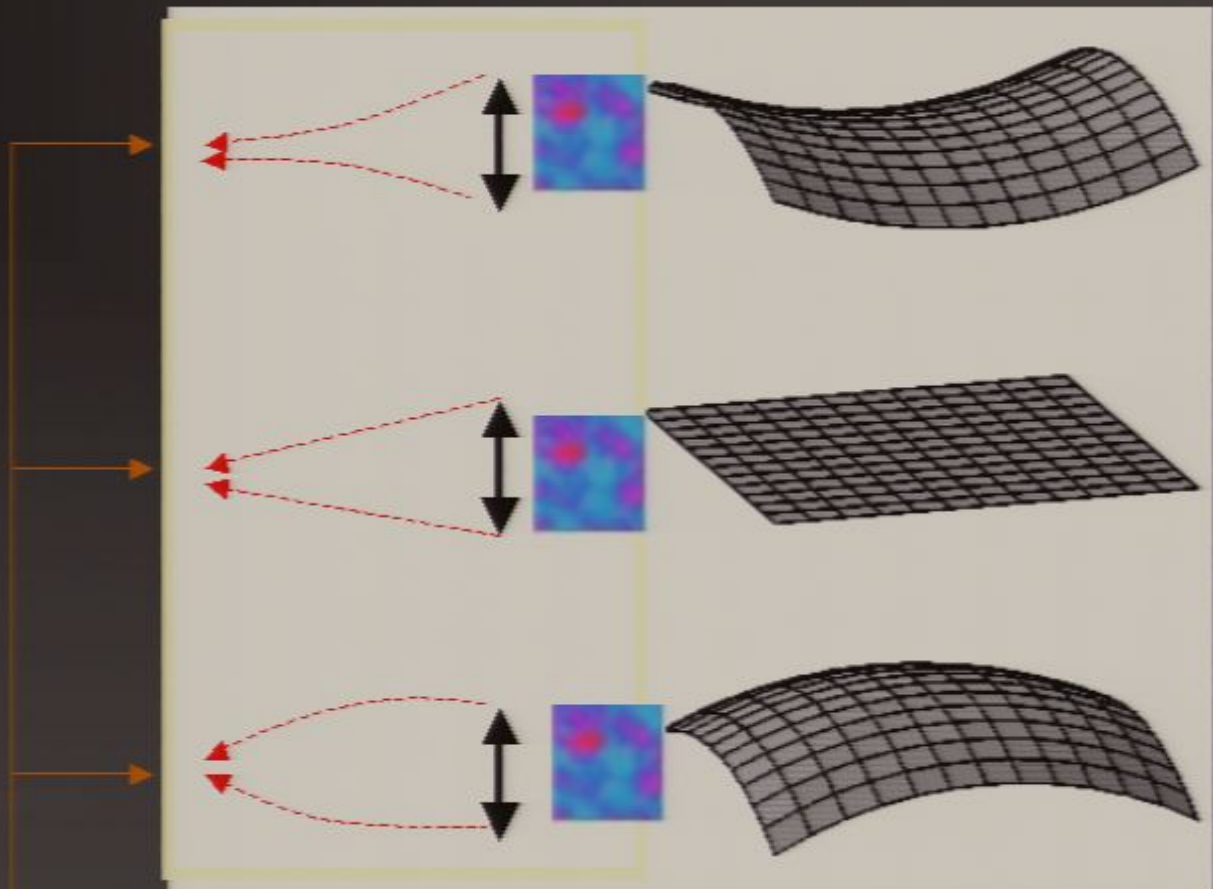
WMAP collaboration



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

Evidence for Dark Energy

- Brightness of very distant supernovae
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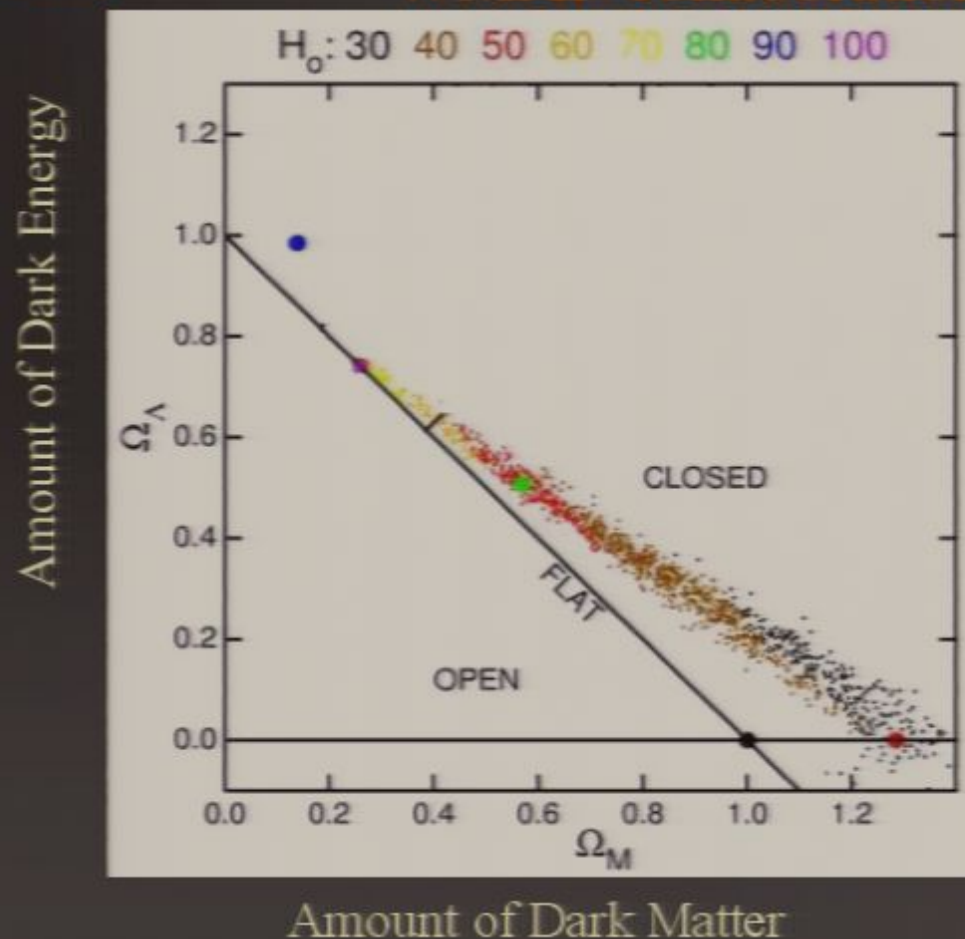
... but the geometry of space depends on the amount and kind of matter it contains

Evidence for Dark Energy

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

Courtesy: Ned Wright's Cosmology Page

WMAP collaboration



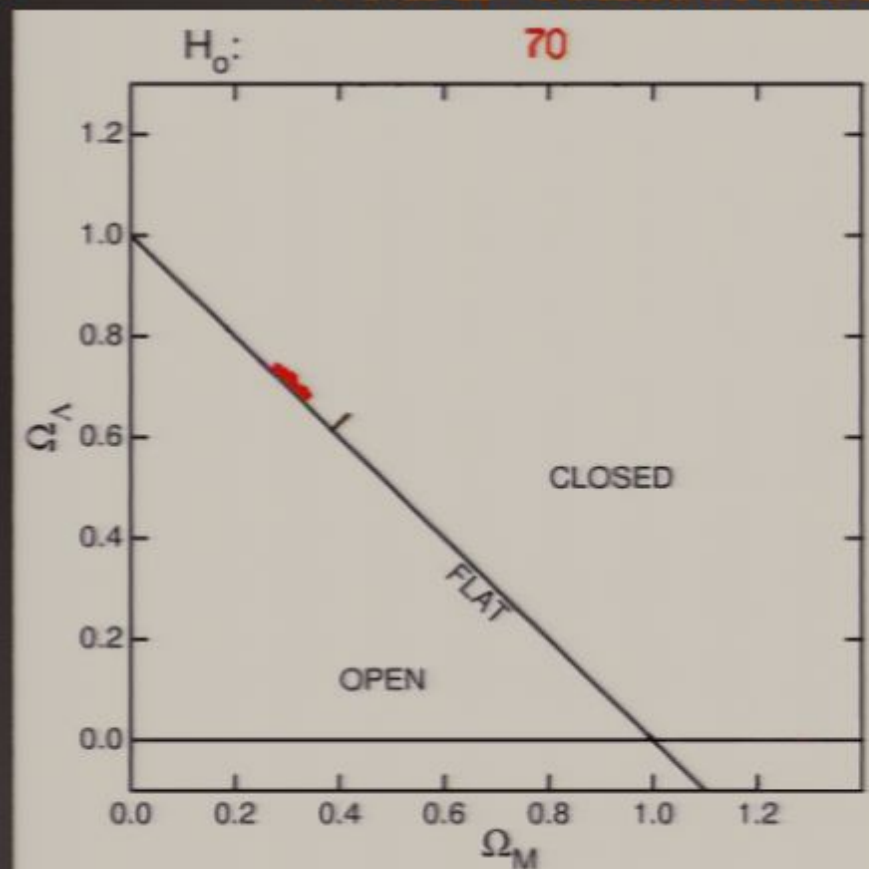
Measurement of CMB fluctuations correlate flatness with the universal expansion rate, H_0

Evidence for Dark Energy

WMAP collaboration

- Brightness of very distant supernovae
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Amount of Dark Energy



Courtesy: Ned Wright's Cosmology Page

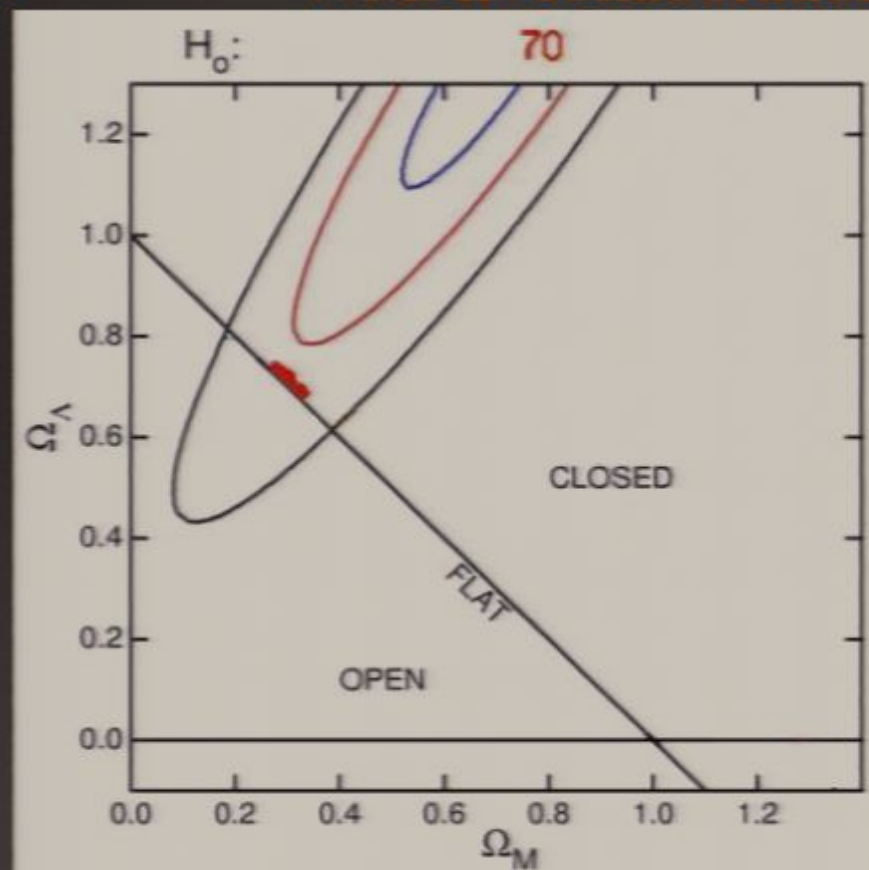
Measured H_0 with CMB fluctuations prefers a flat universe.

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

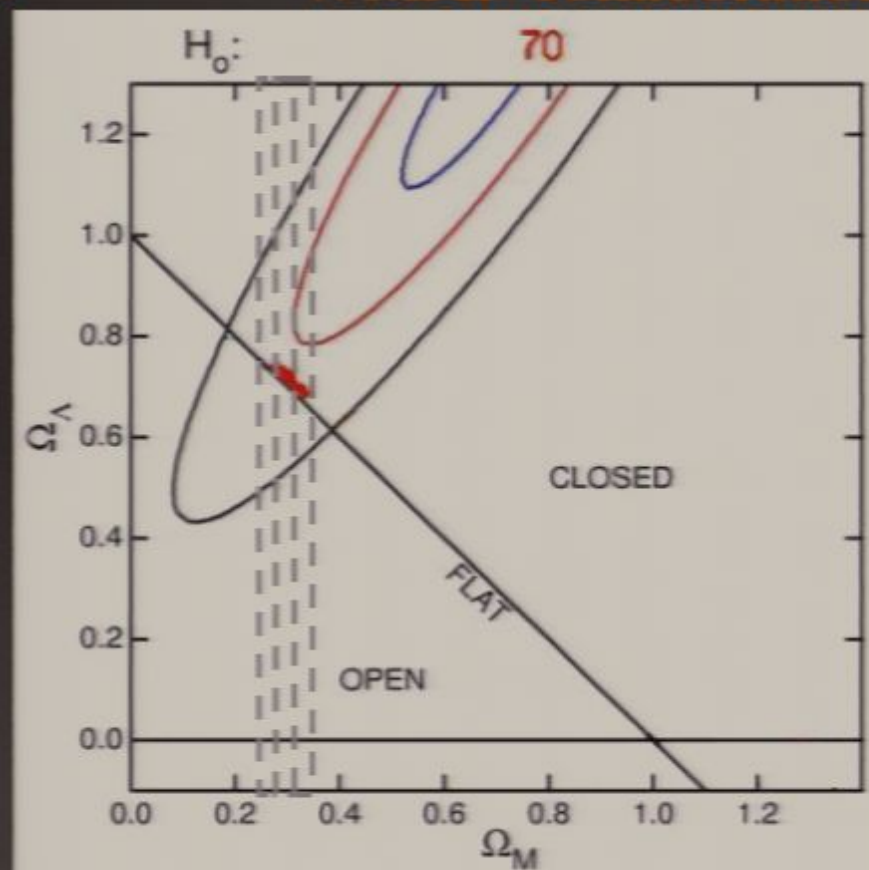
Dark Energy required to explain CMB is consistent with what universal acceleration requires.

Evidence for Dark Energy

WMAP collaboration

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- *Flatness of the universe as a whole*

Amount of Dark Energy

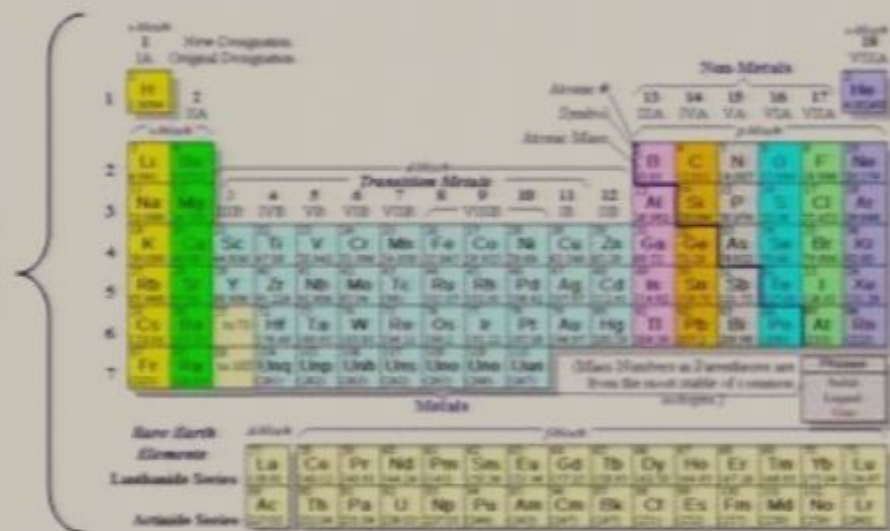


Amount of Dark Matter

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?

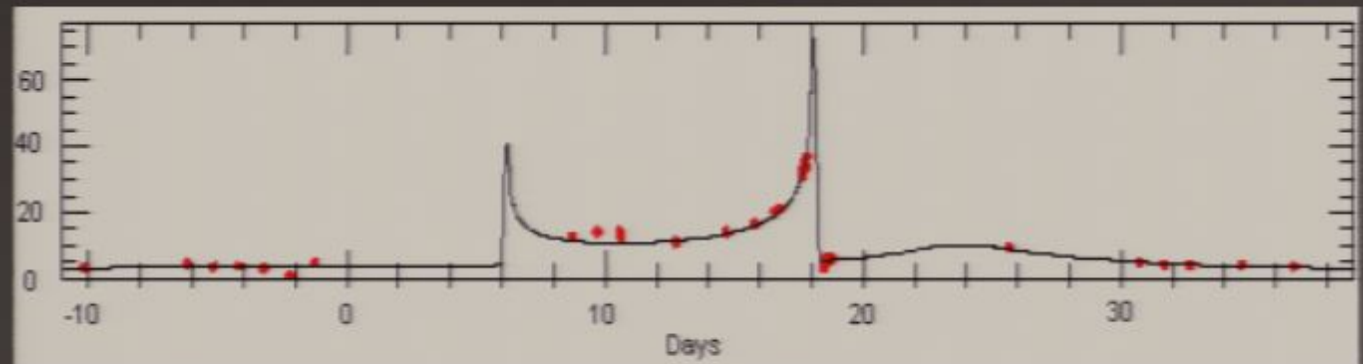
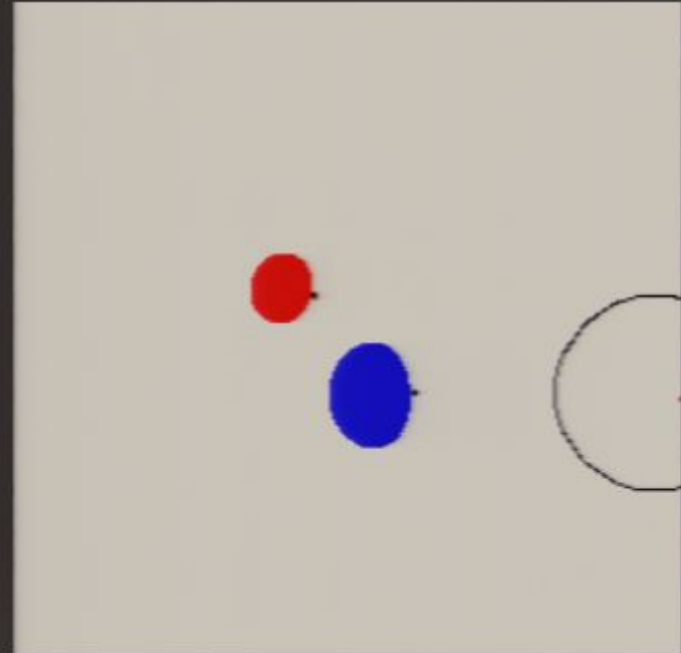
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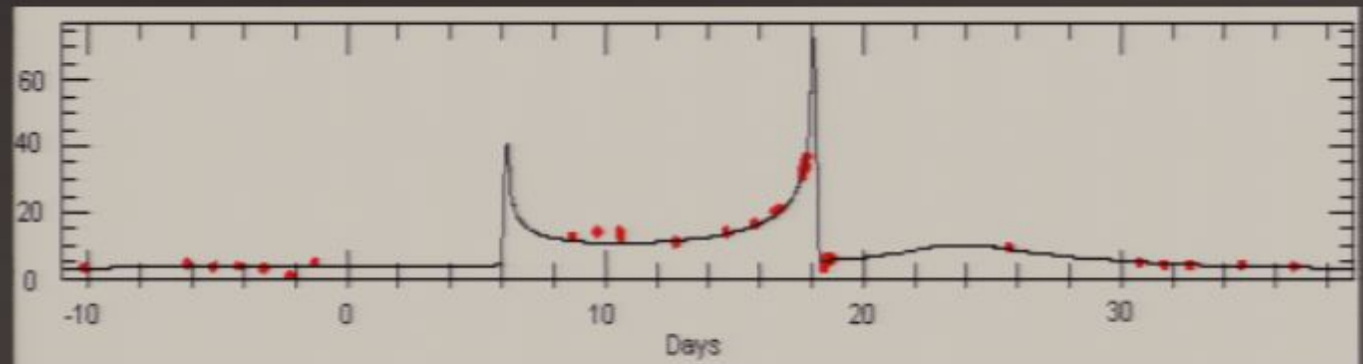
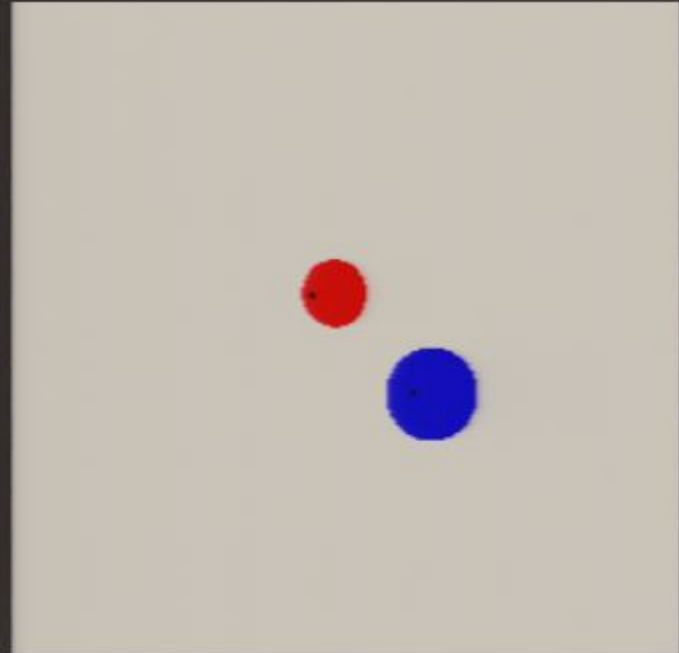
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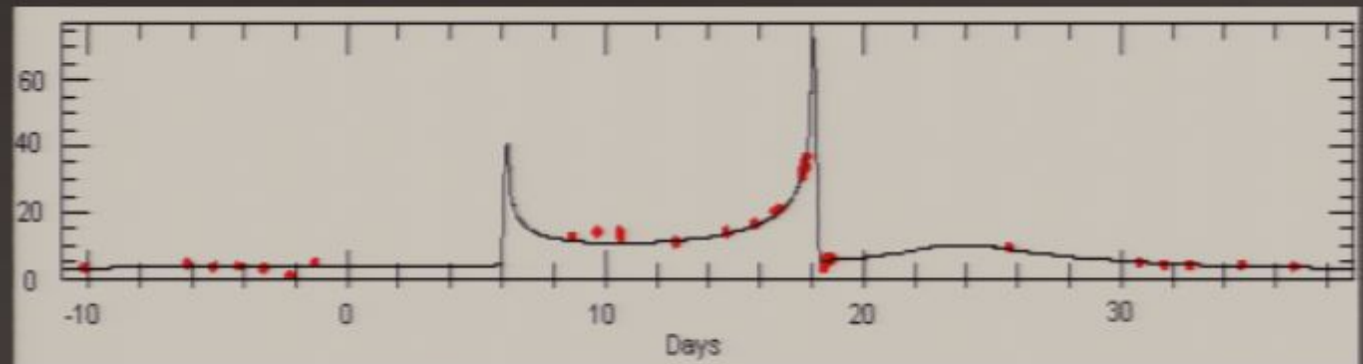
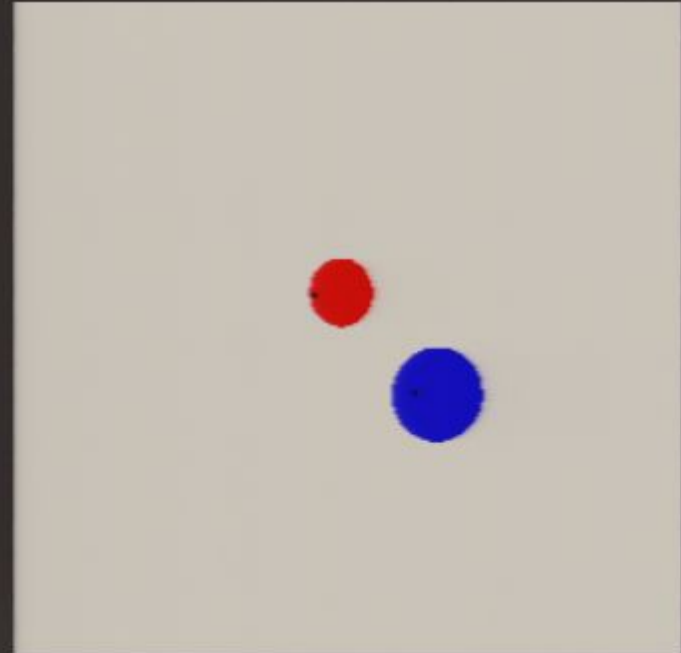
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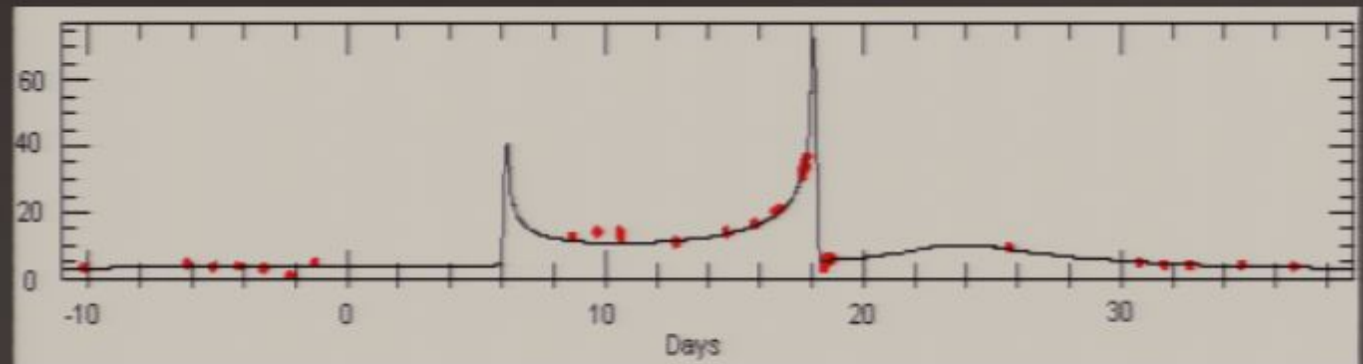
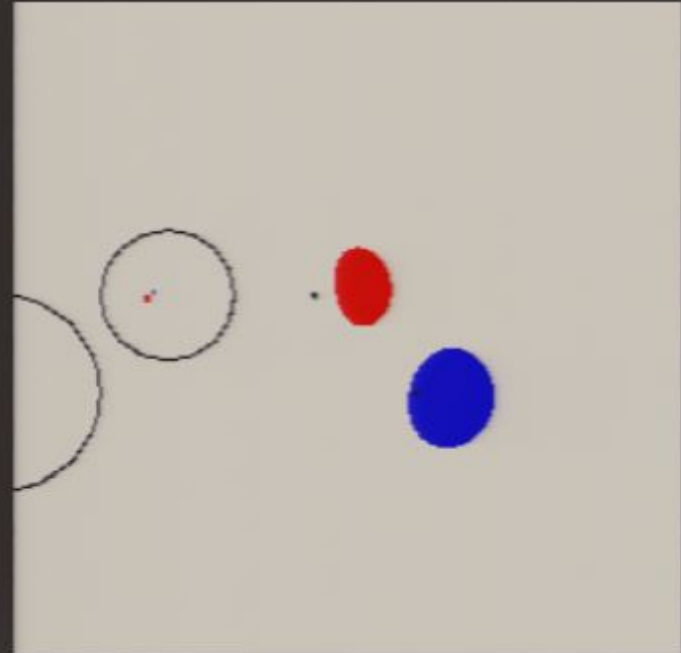
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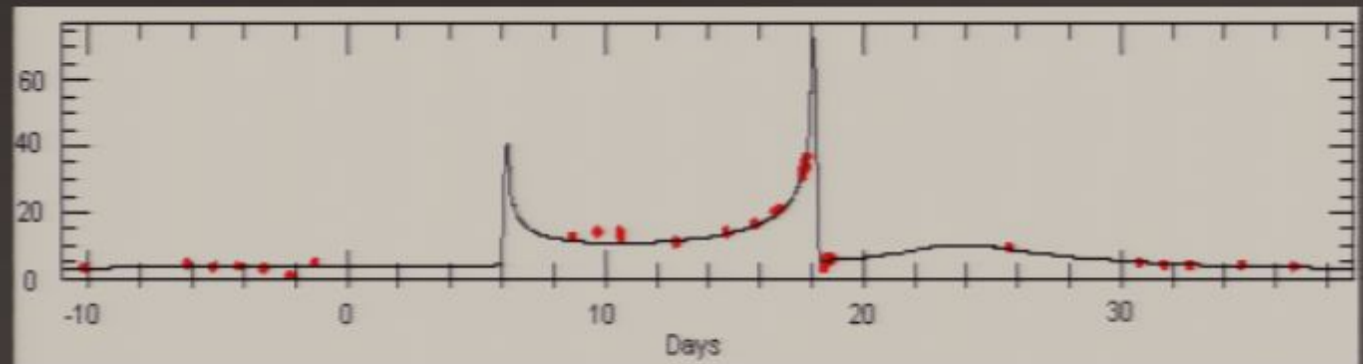
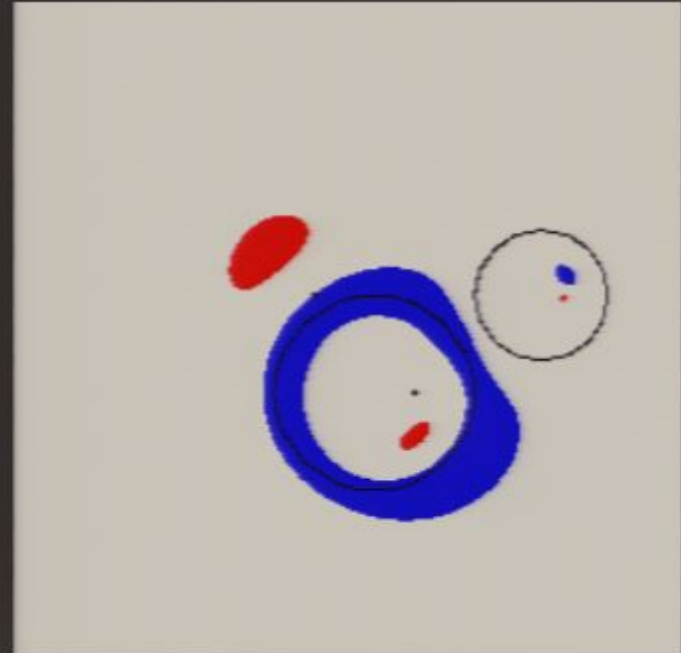
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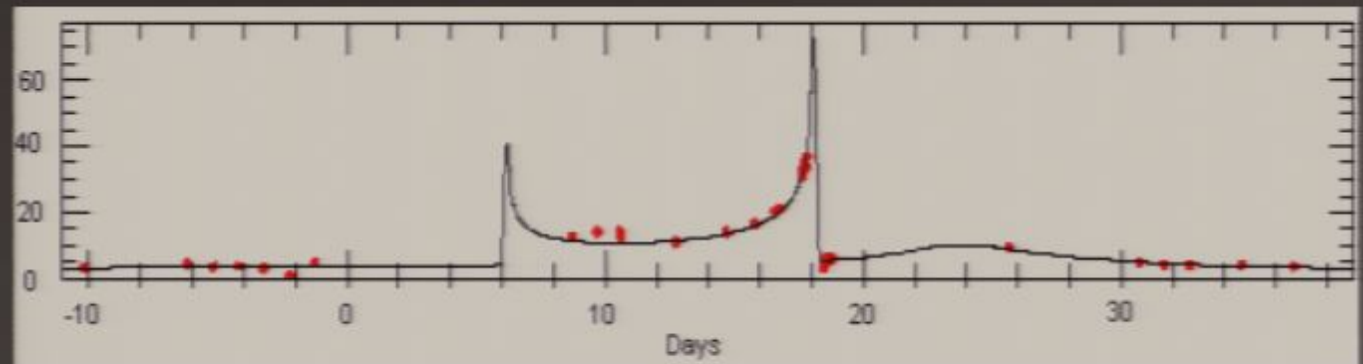
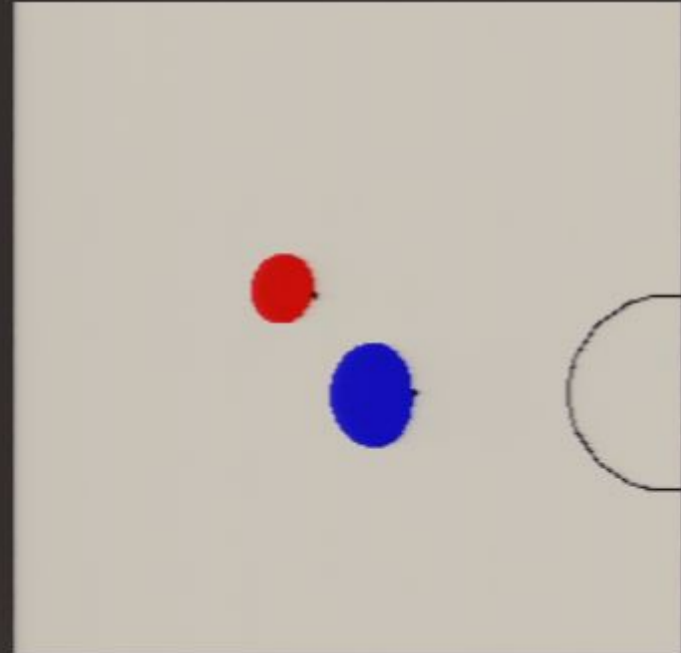
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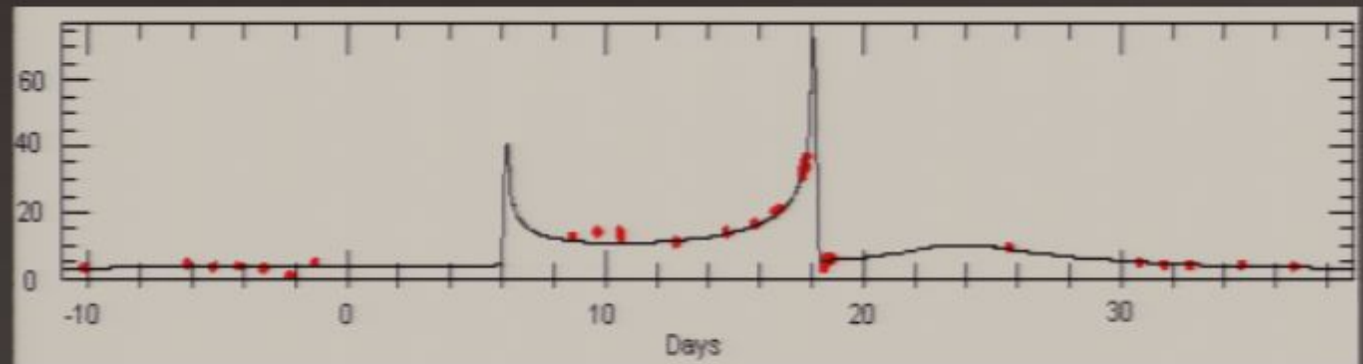
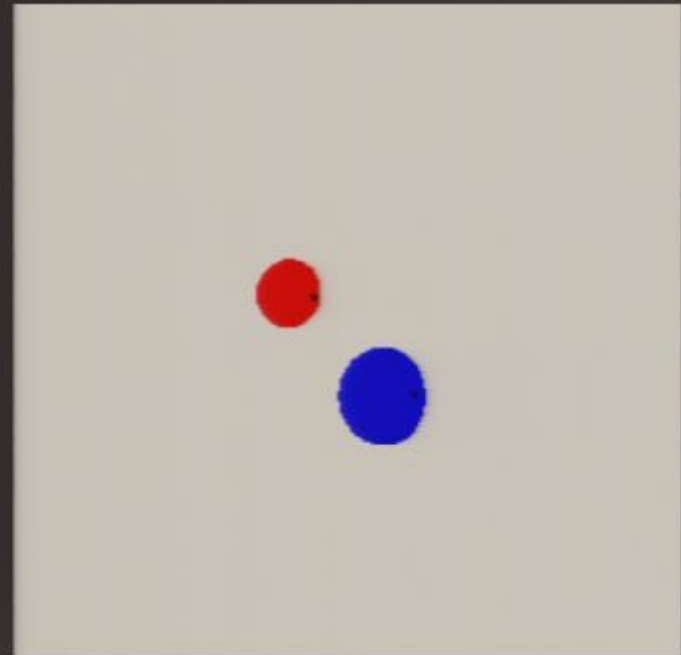
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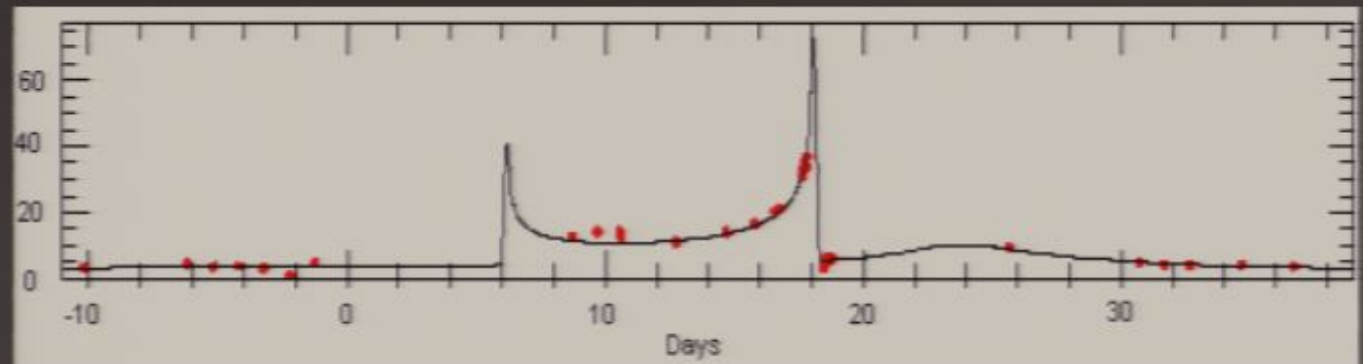
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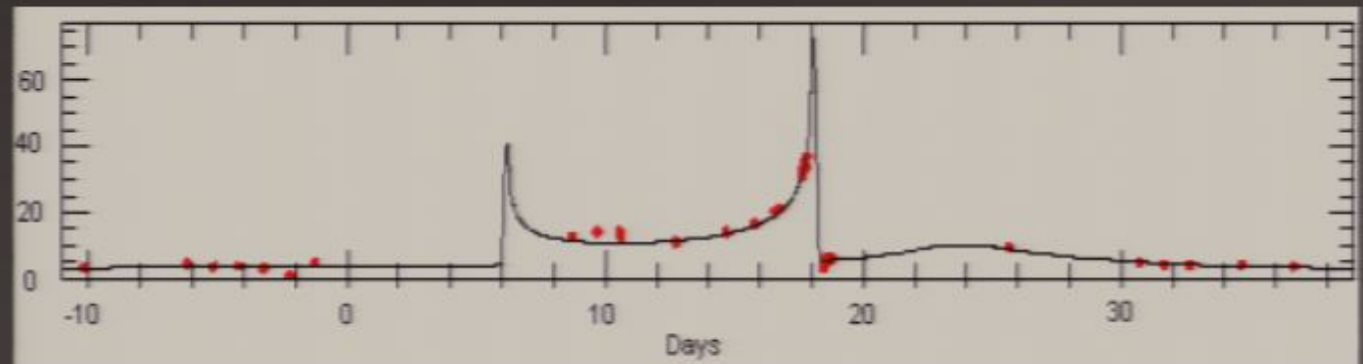
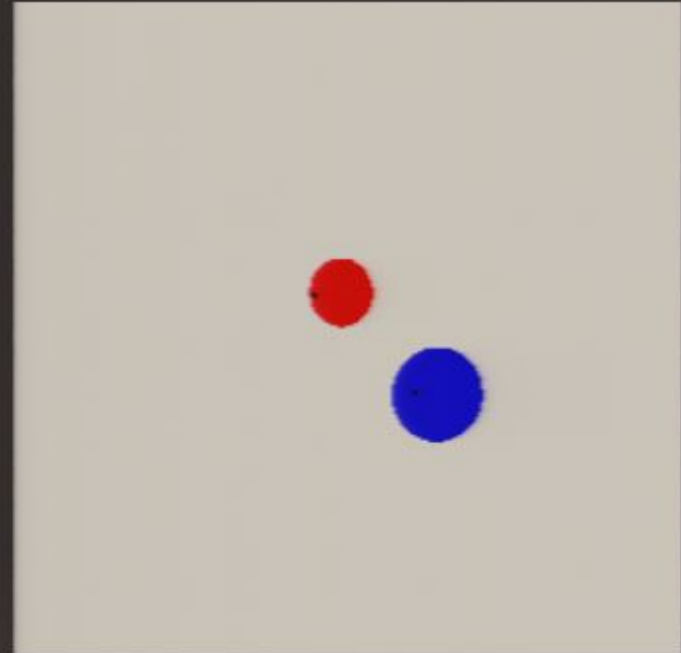
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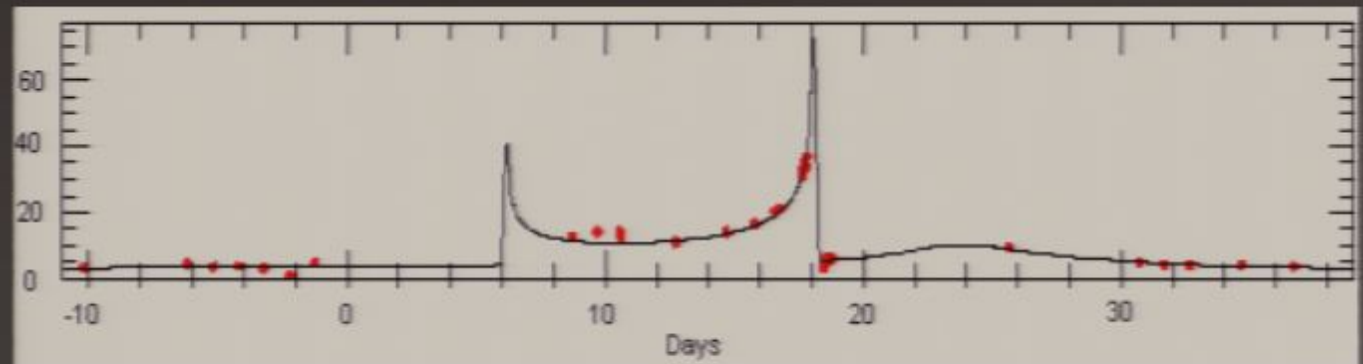
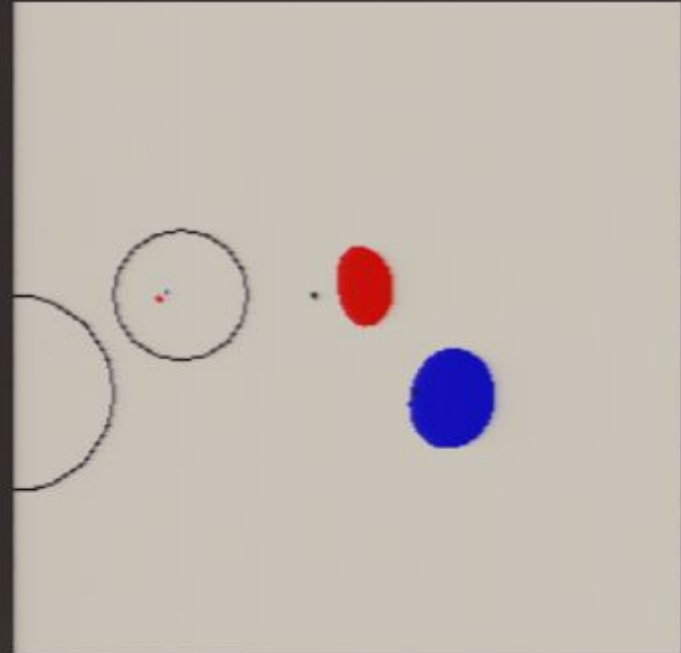
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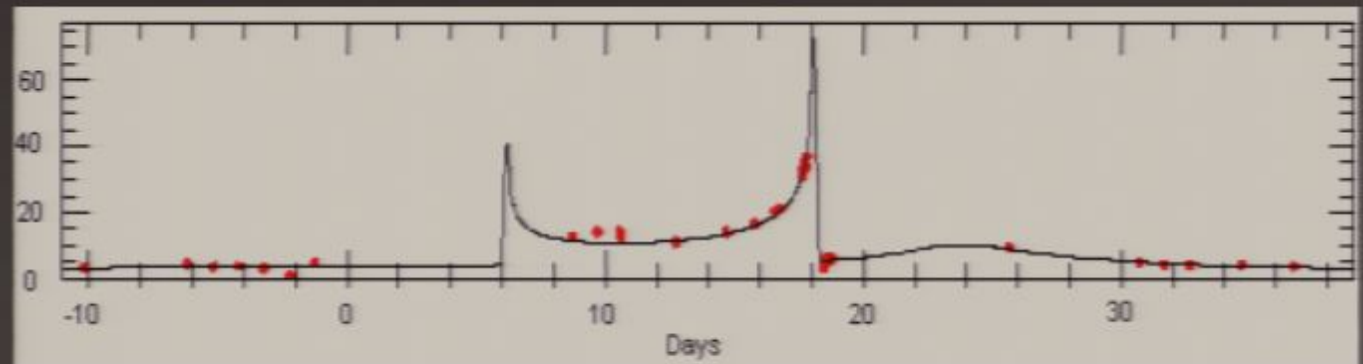
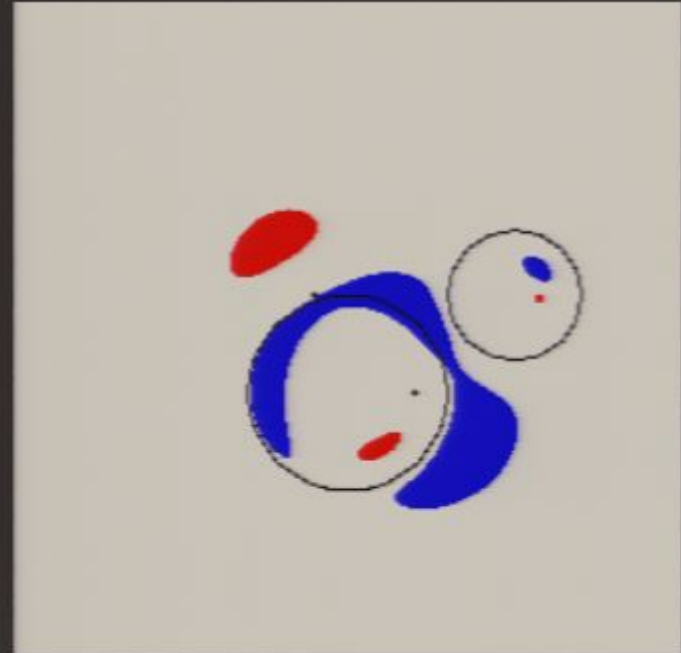
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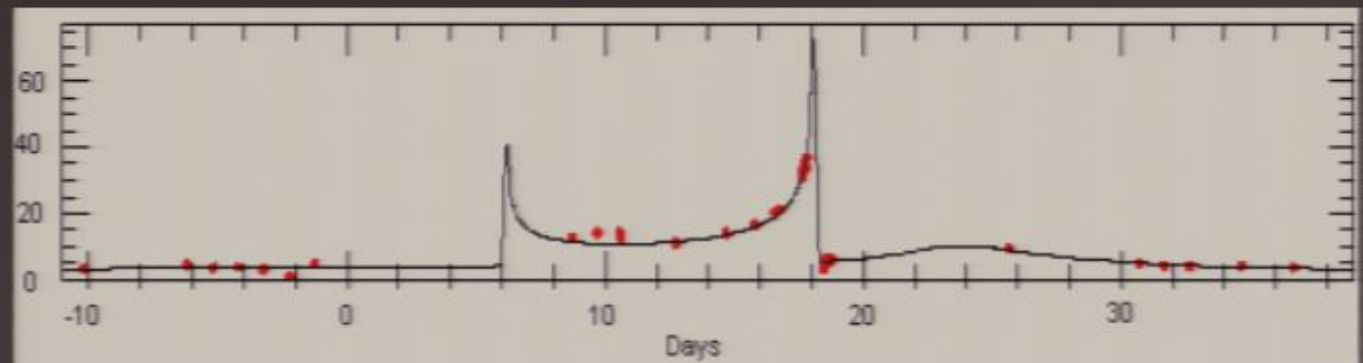
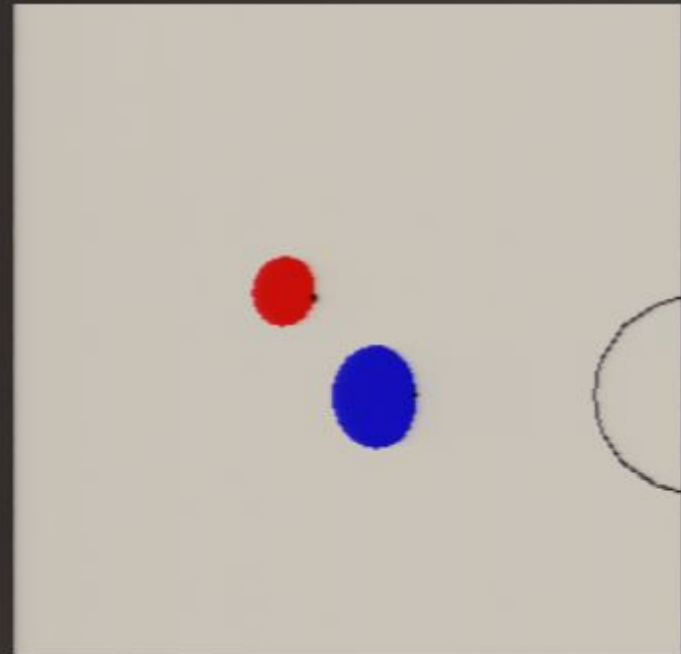
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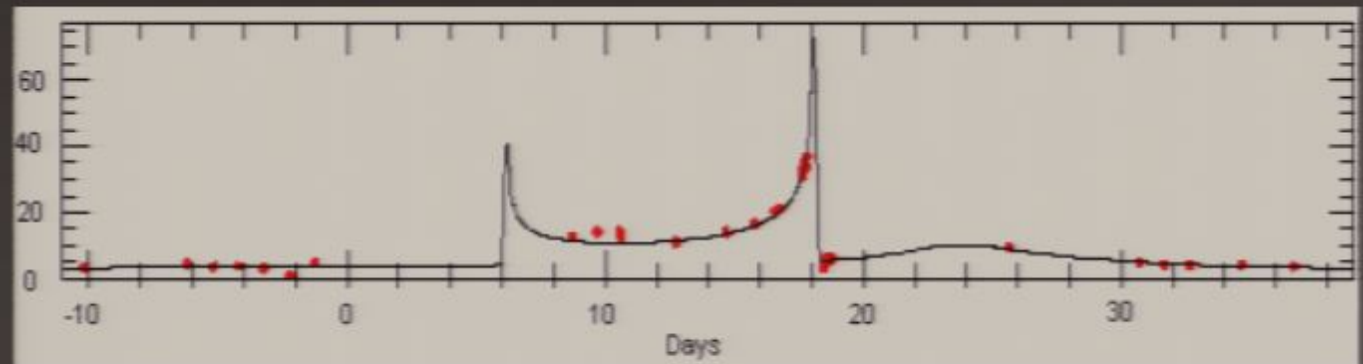
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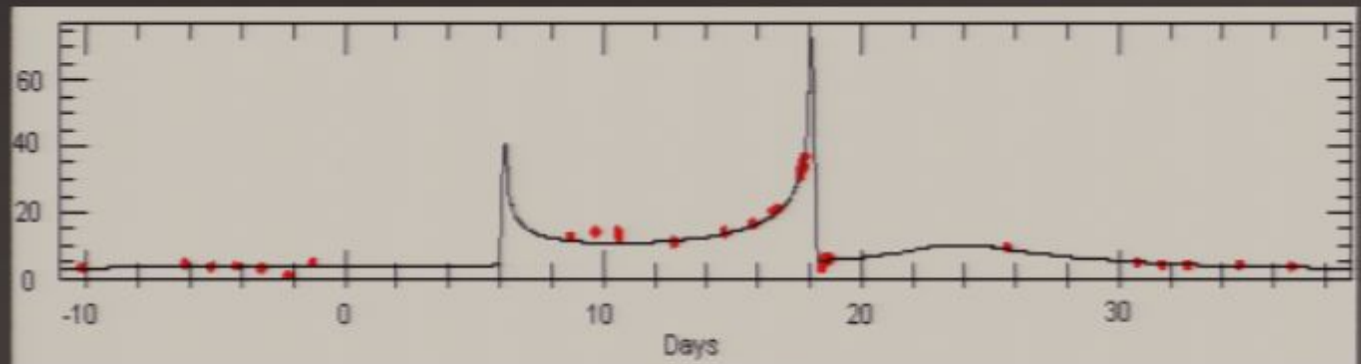
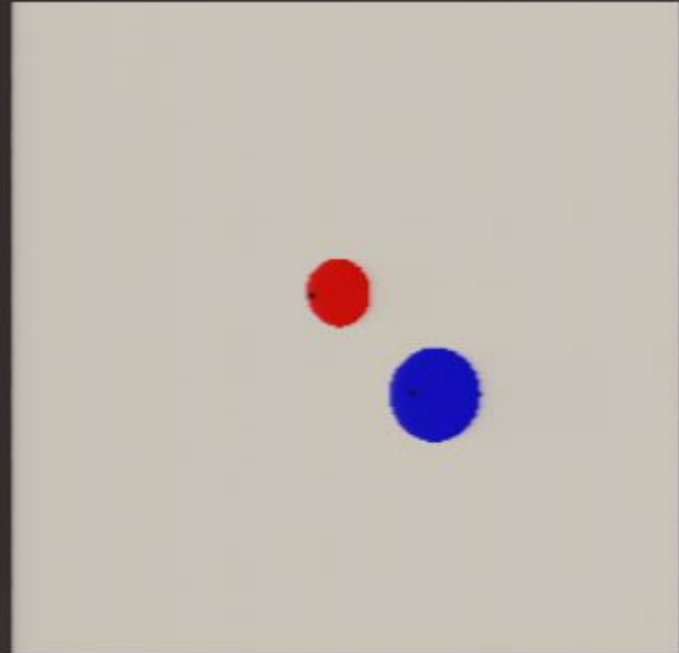
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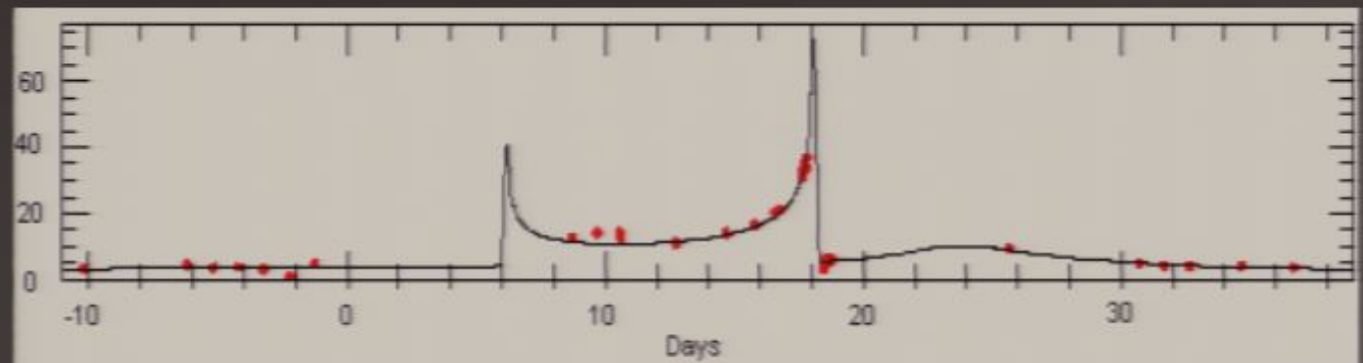
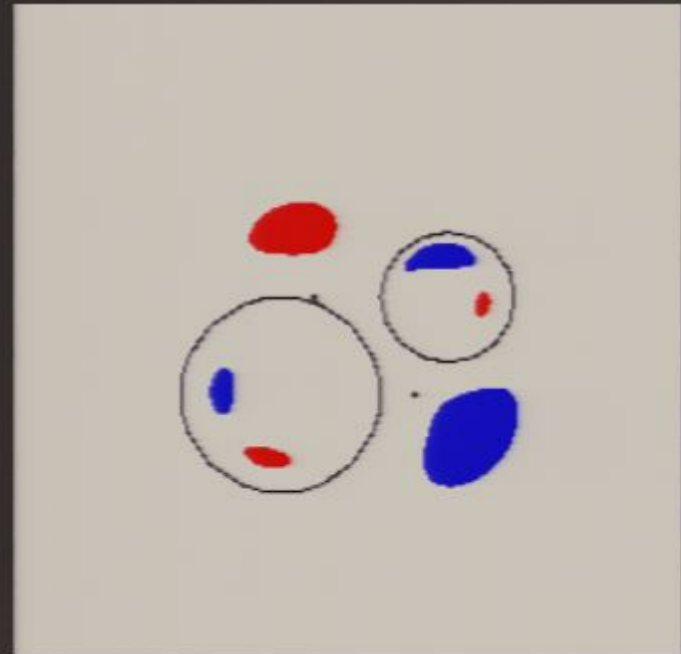
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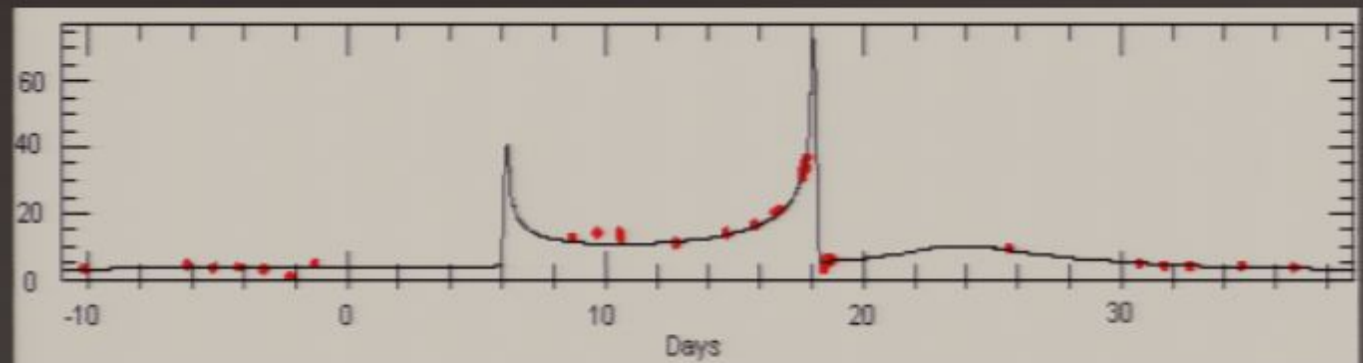
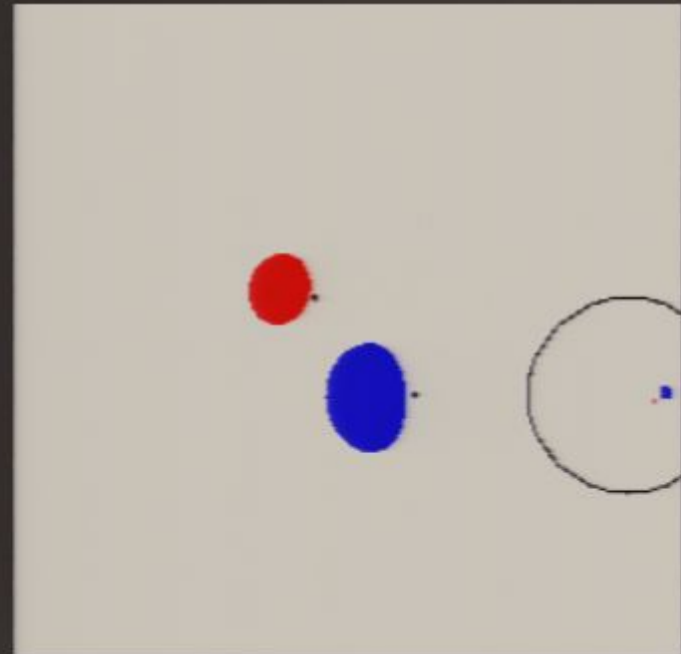
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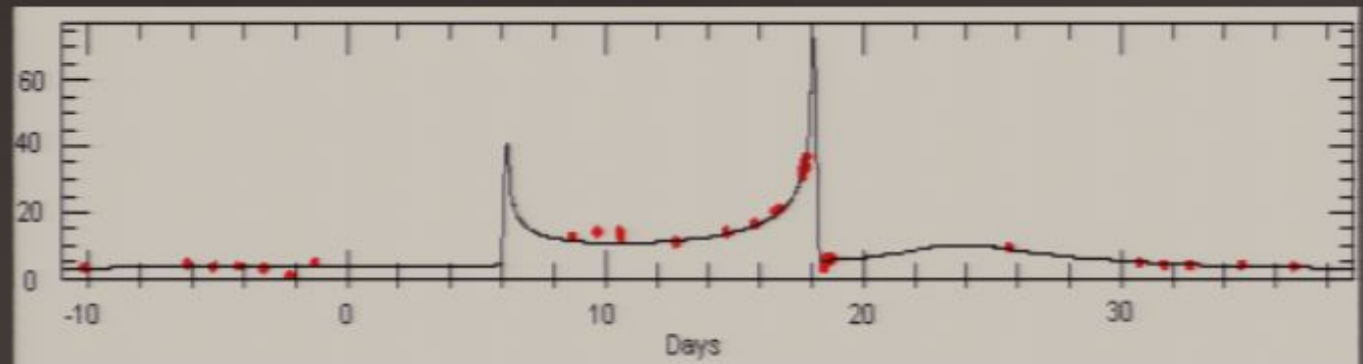
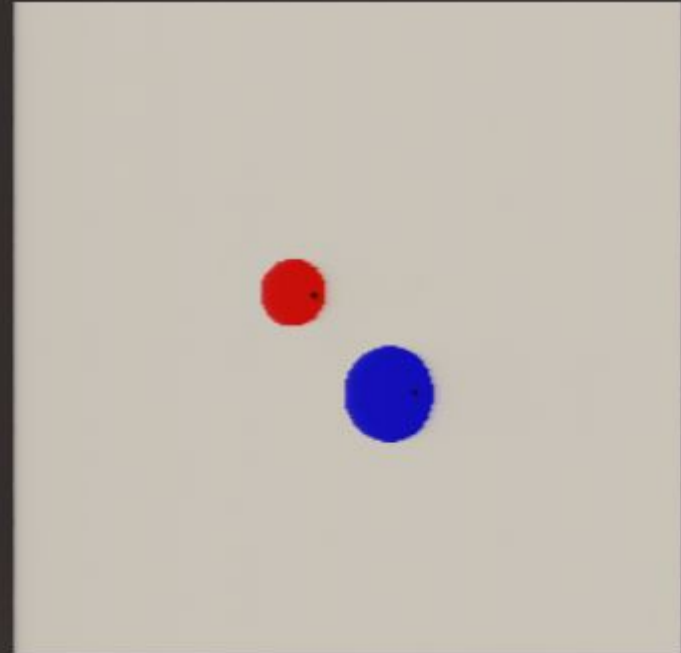
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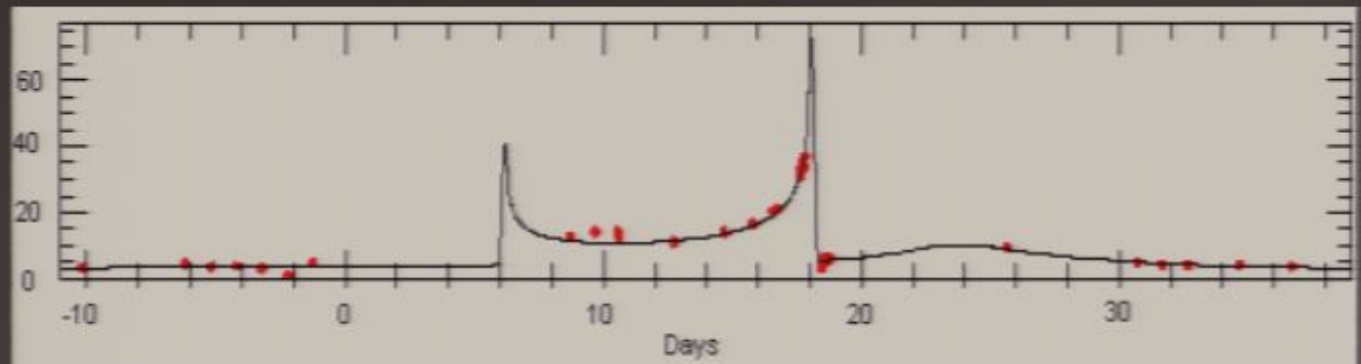
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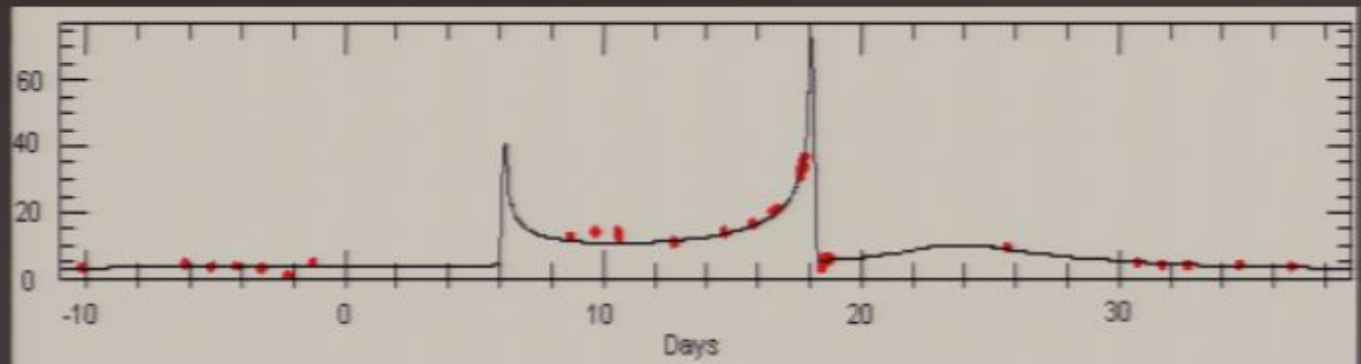
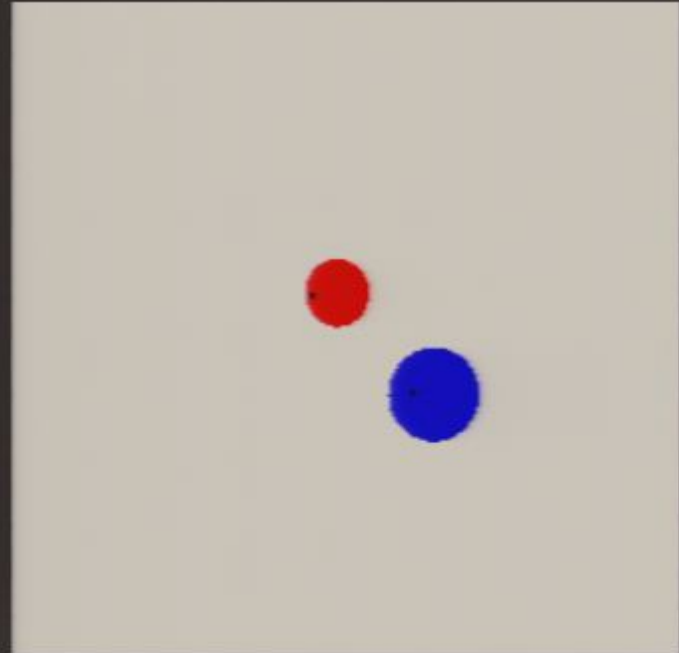
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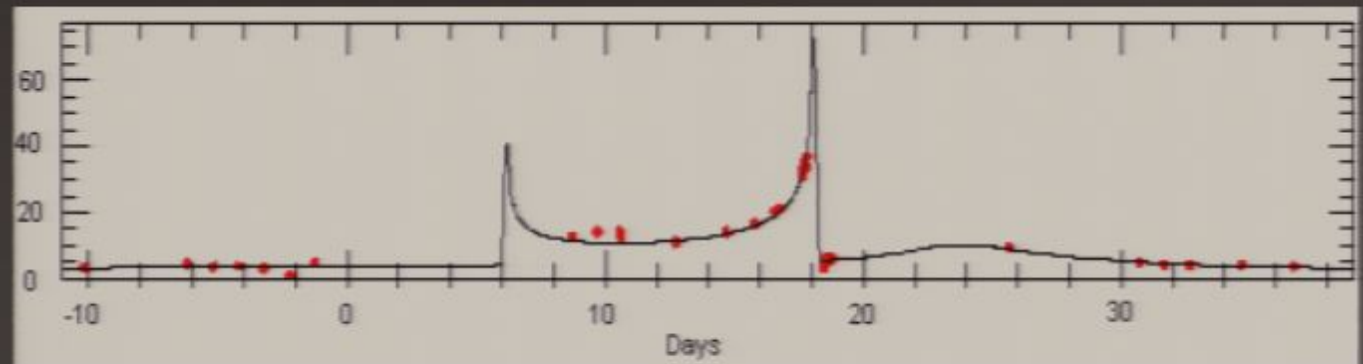
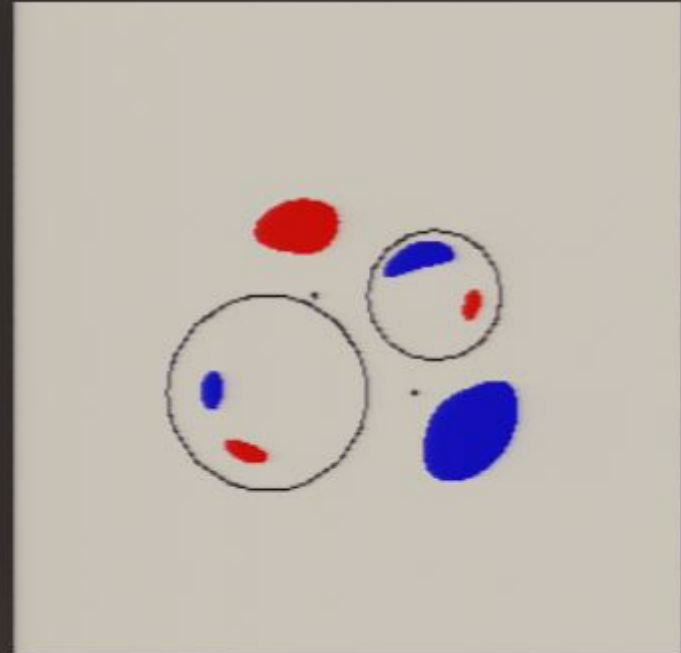
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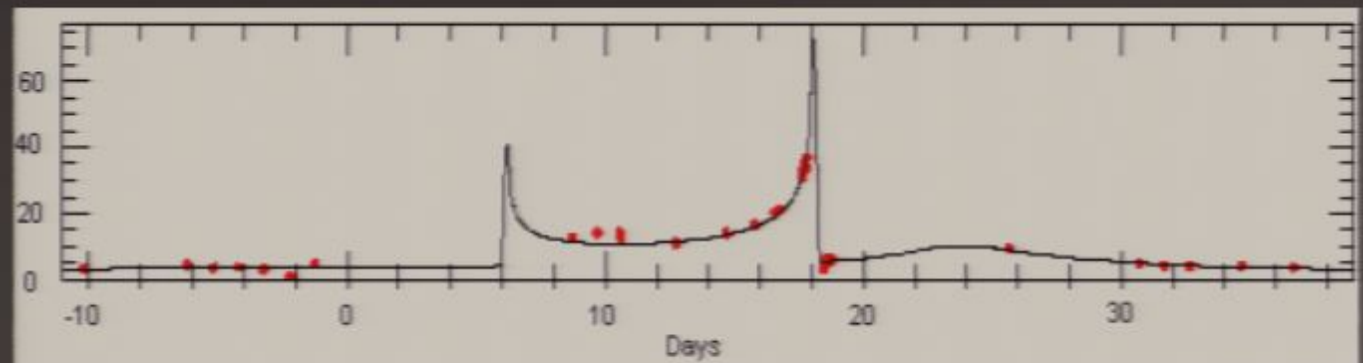
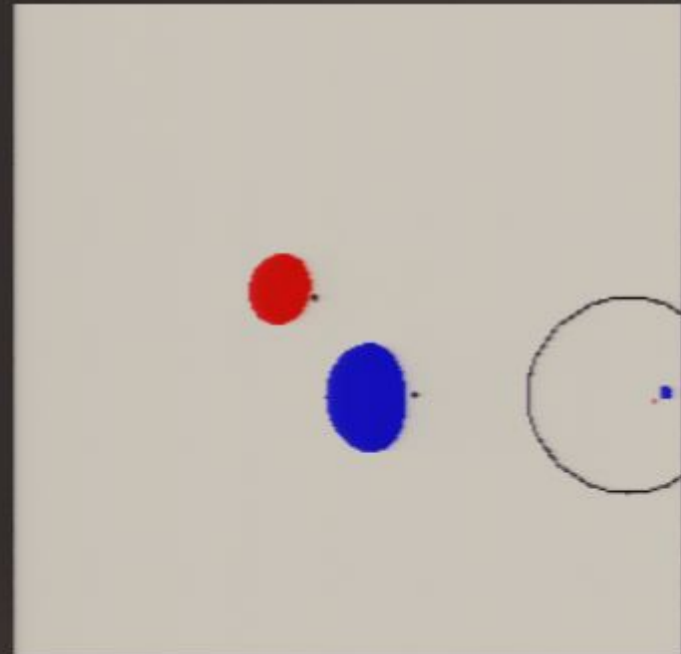
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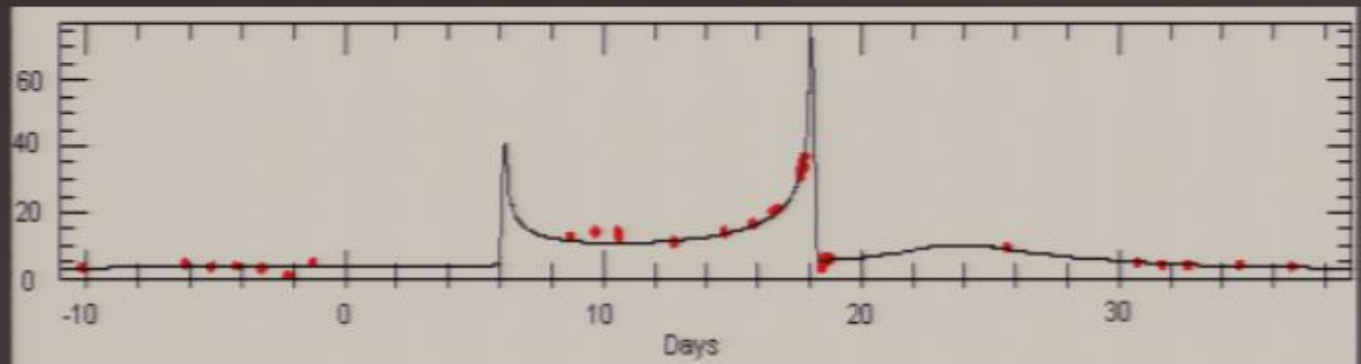
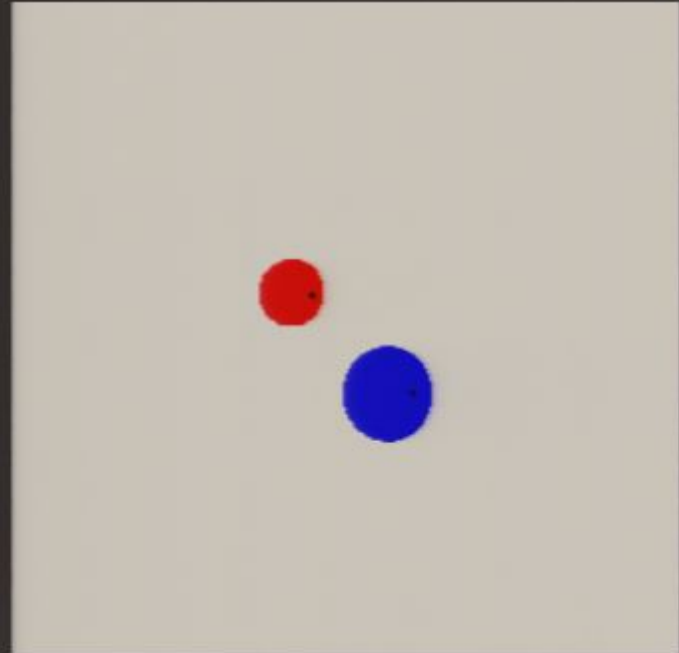
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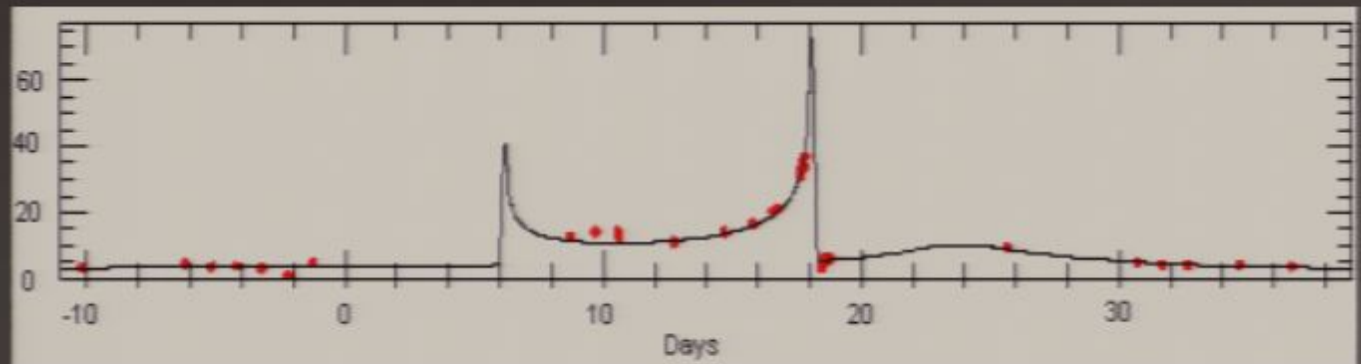
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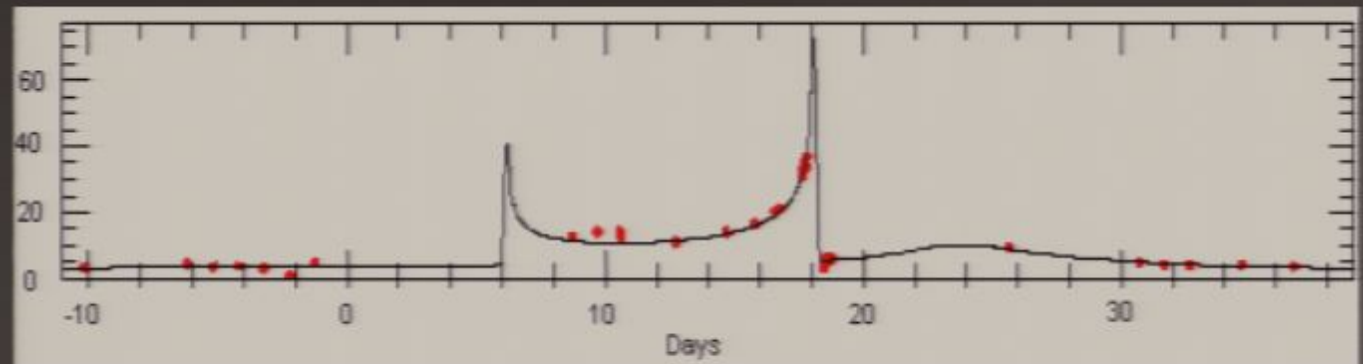
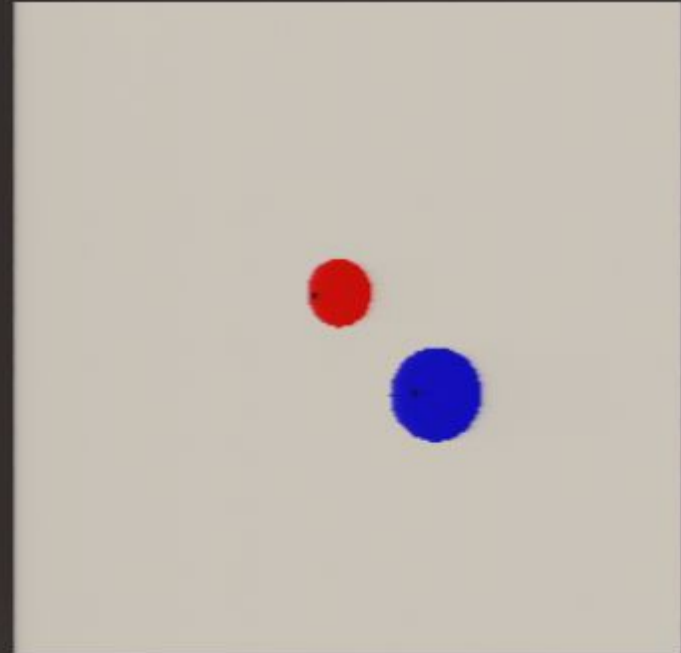
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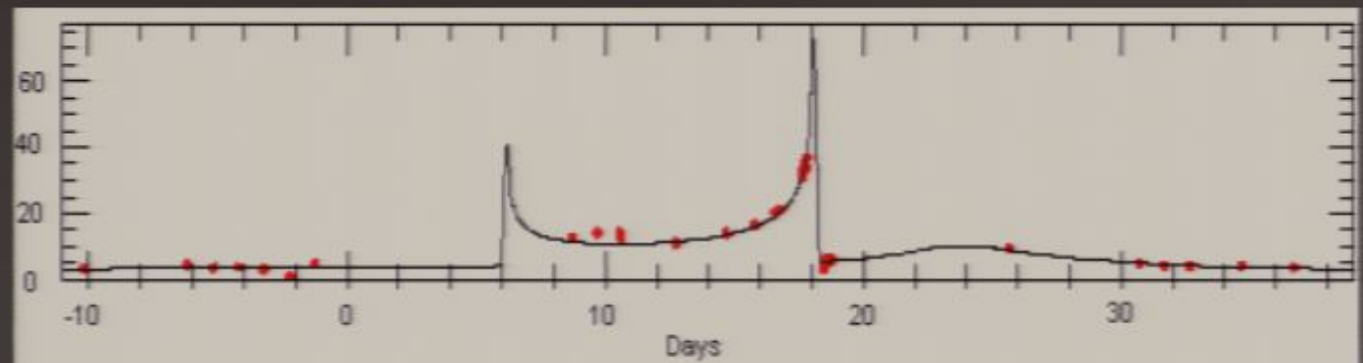
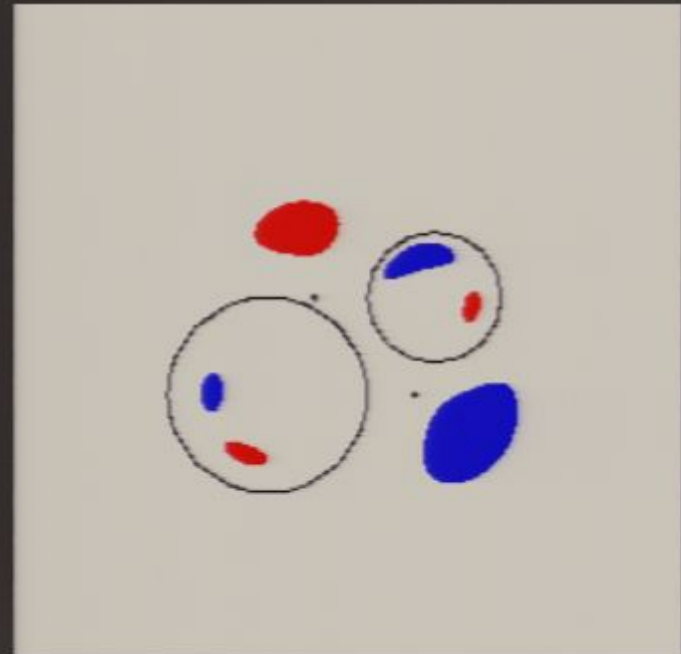
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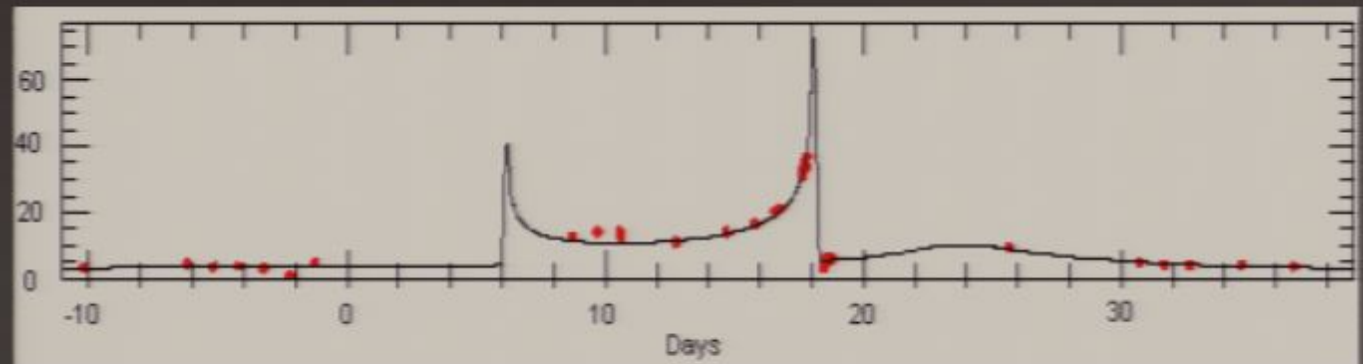
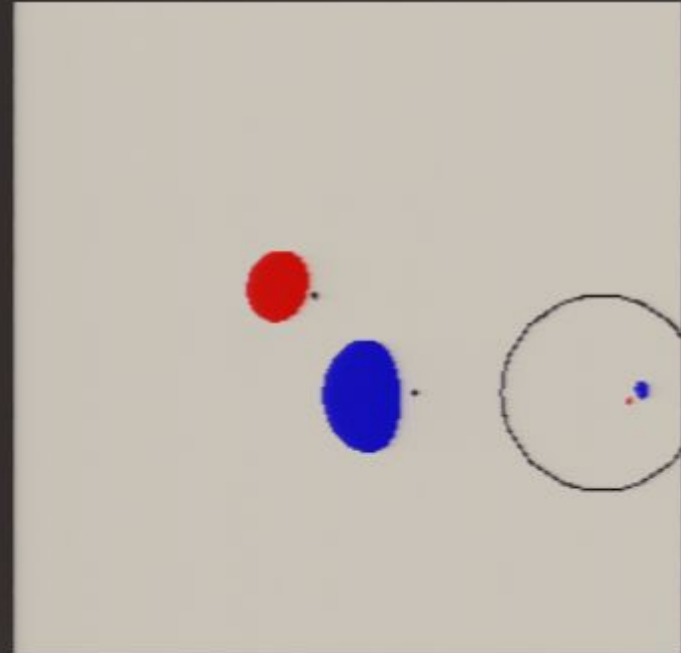
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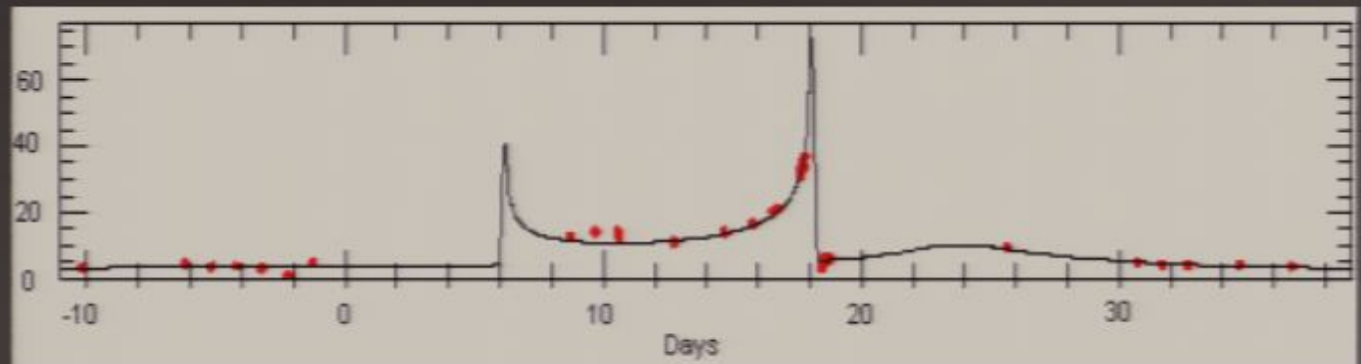
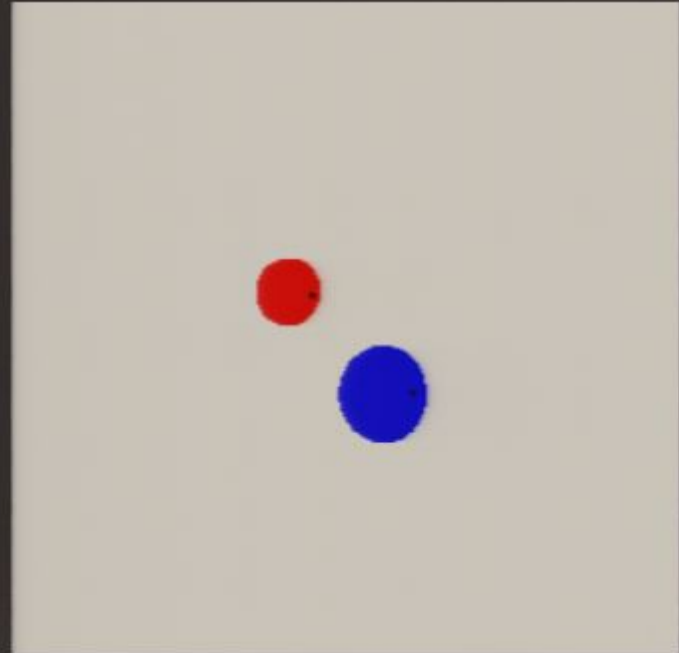
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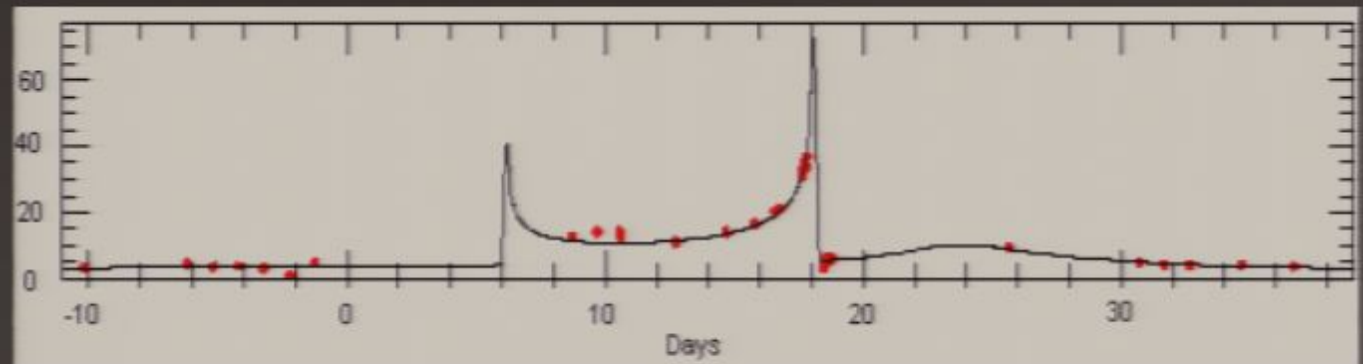
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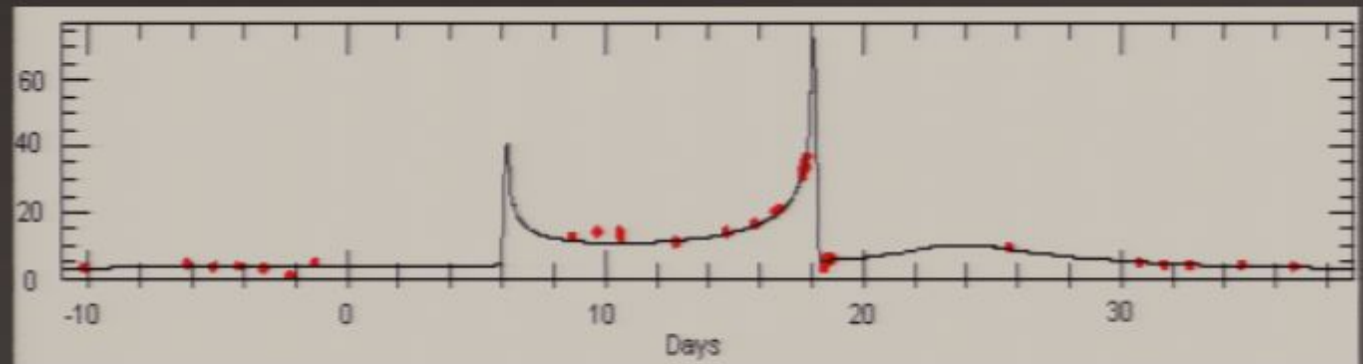
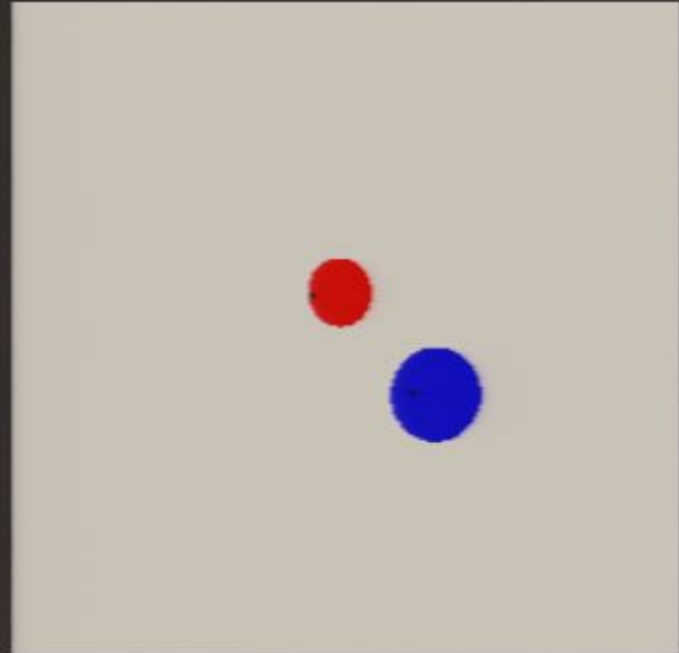
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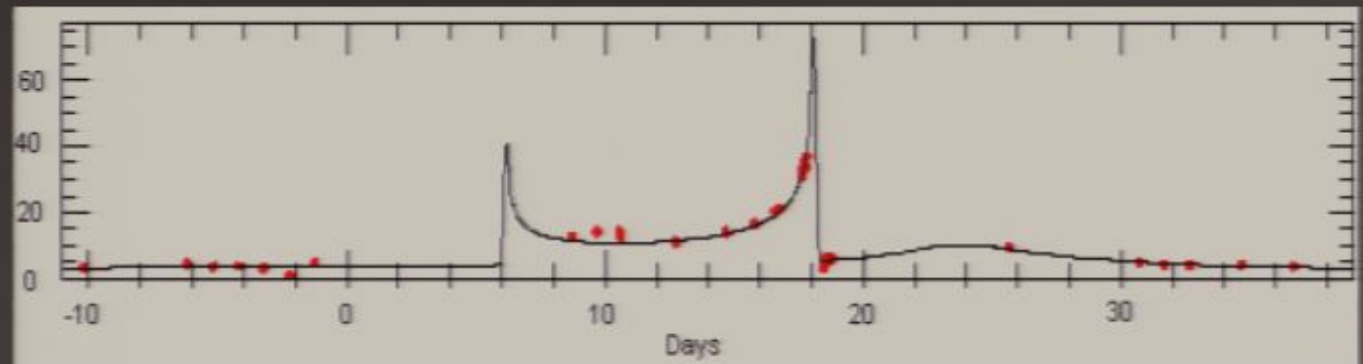
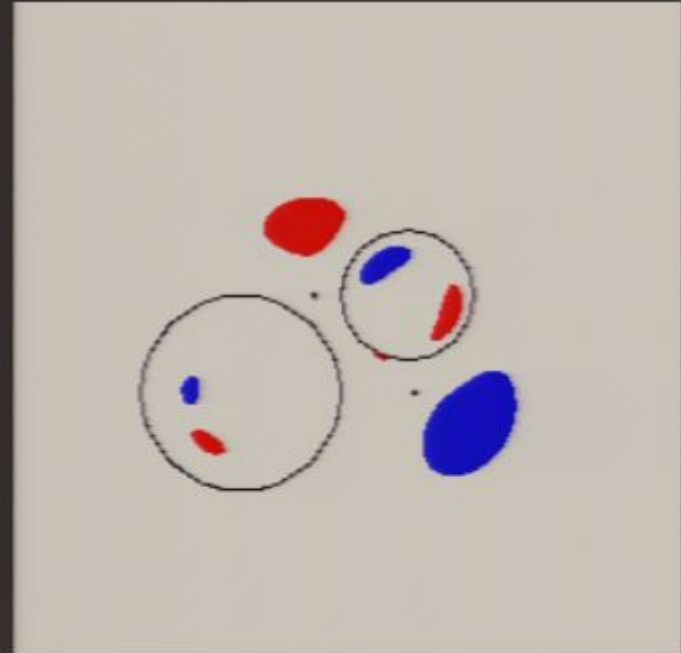
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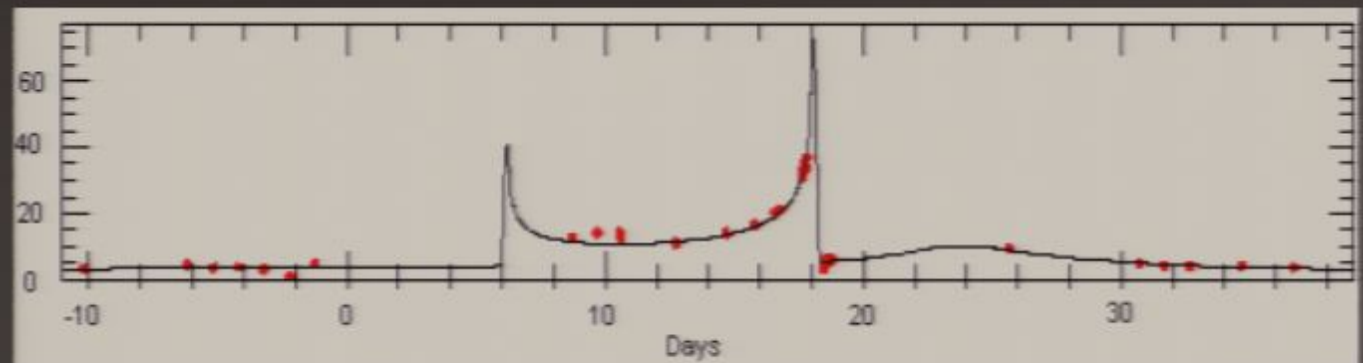
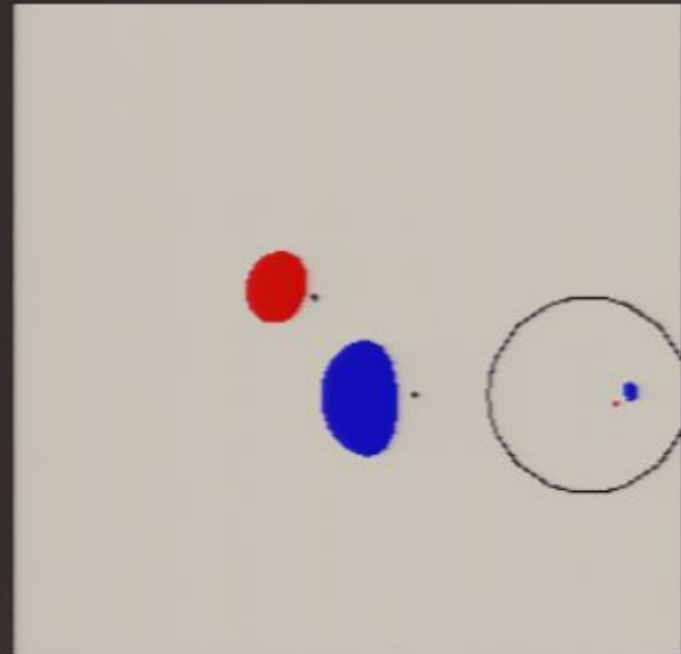
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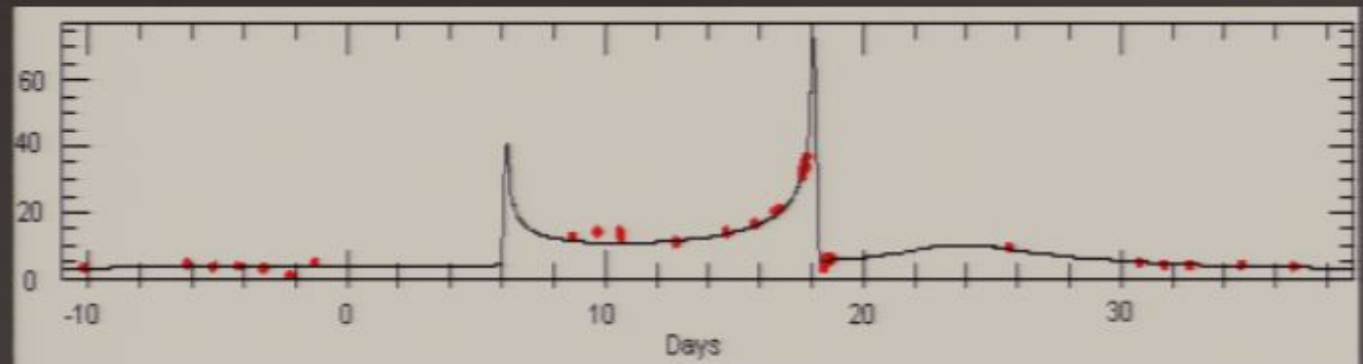
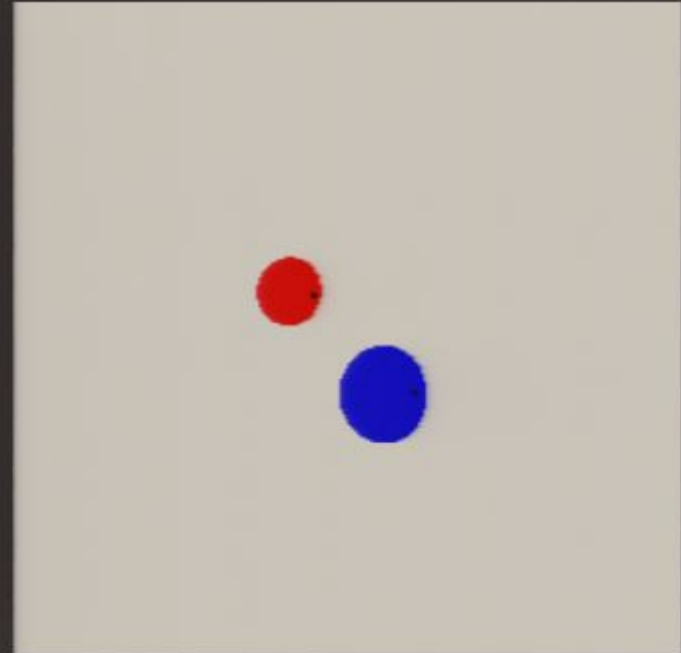
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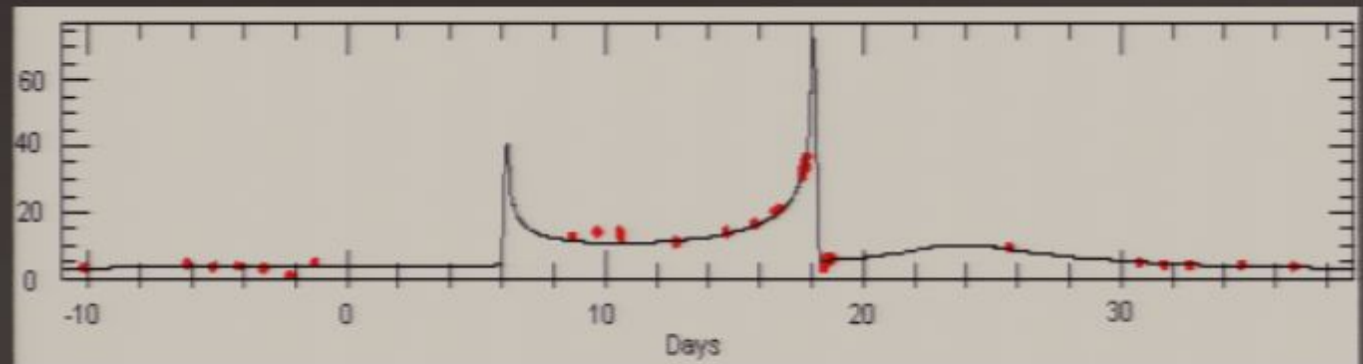
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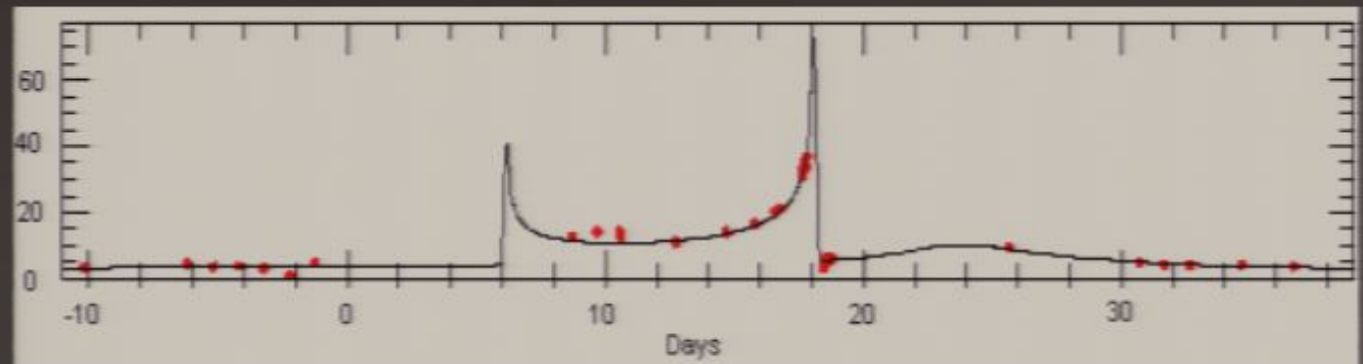
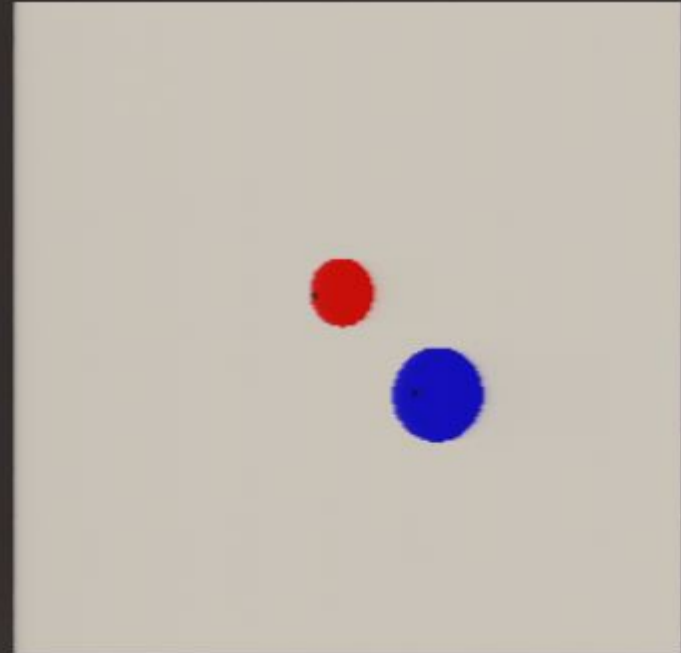
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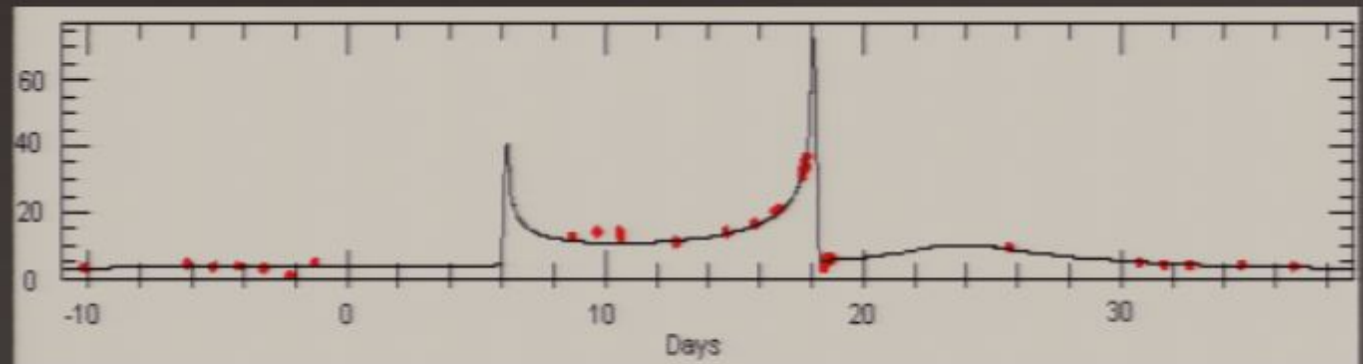
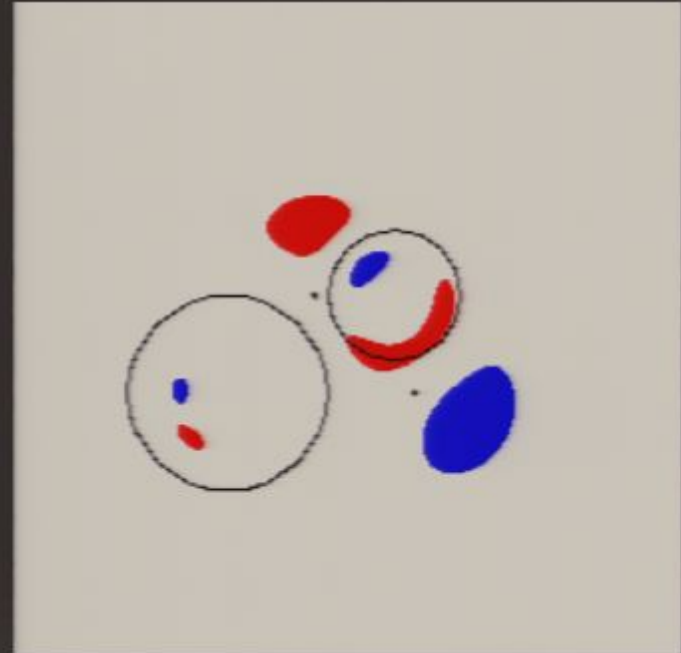
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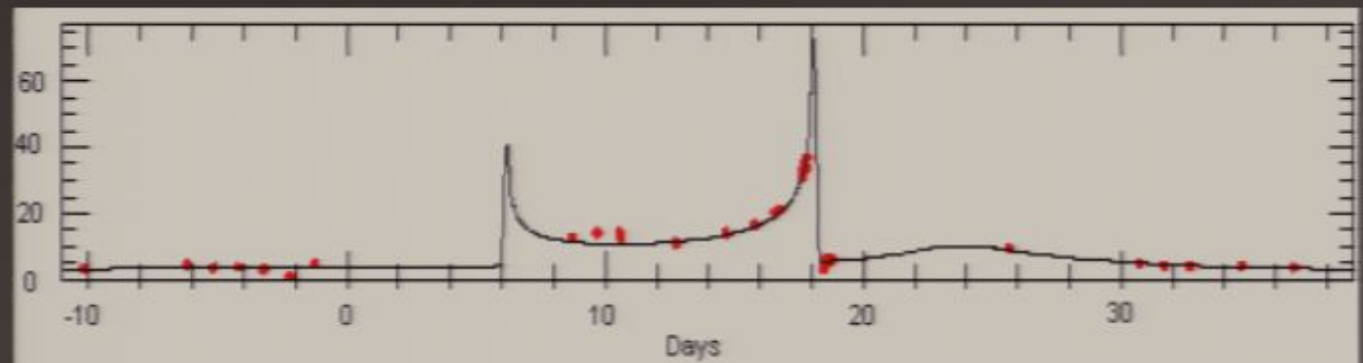
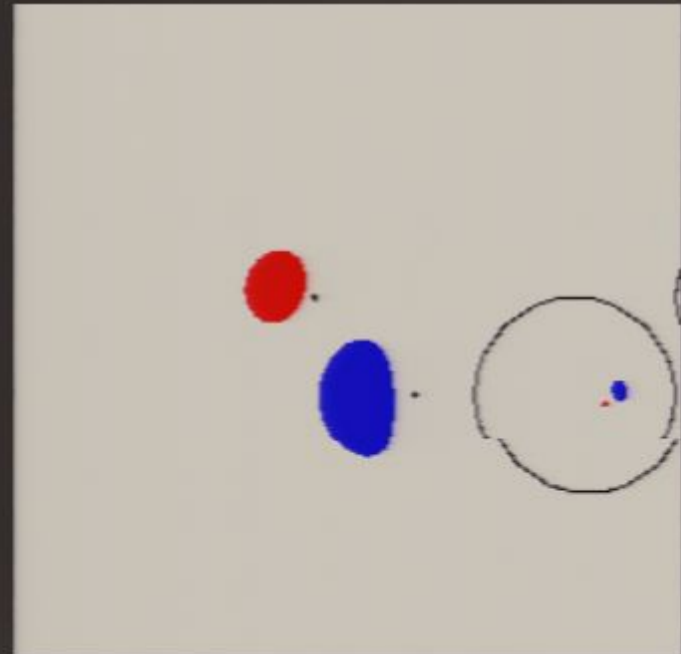
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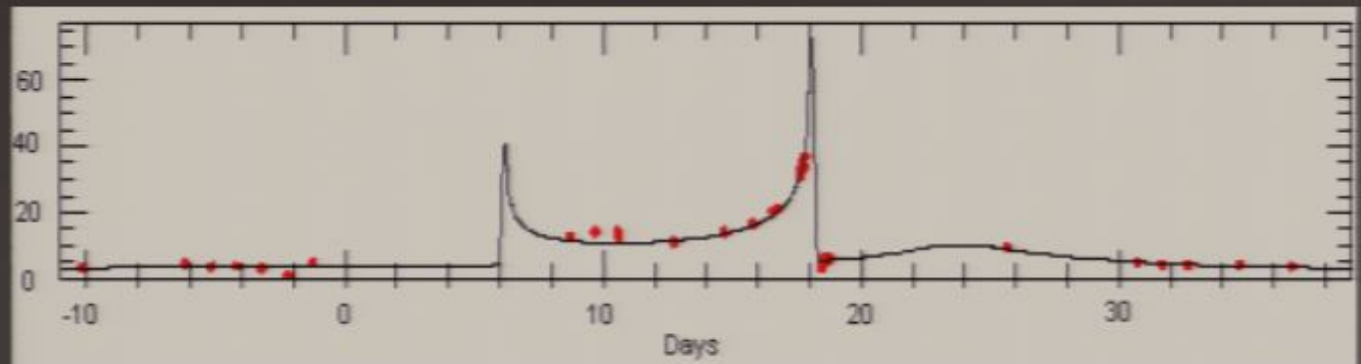
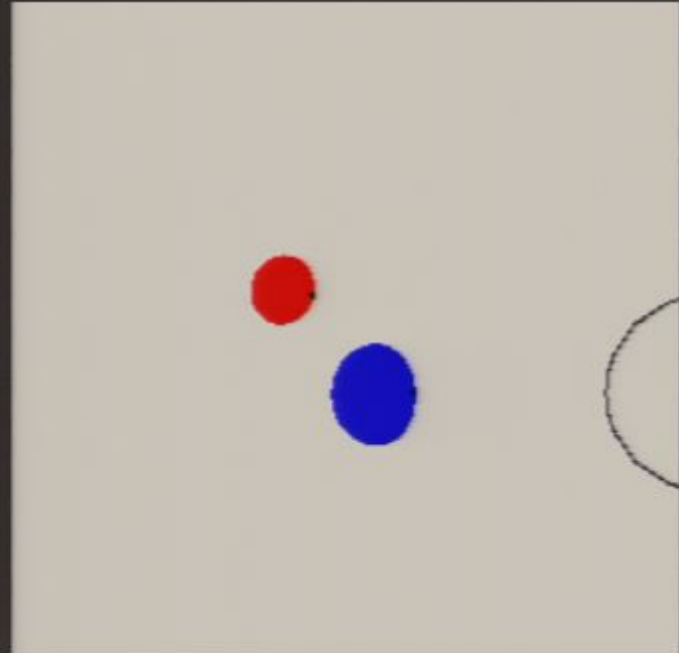
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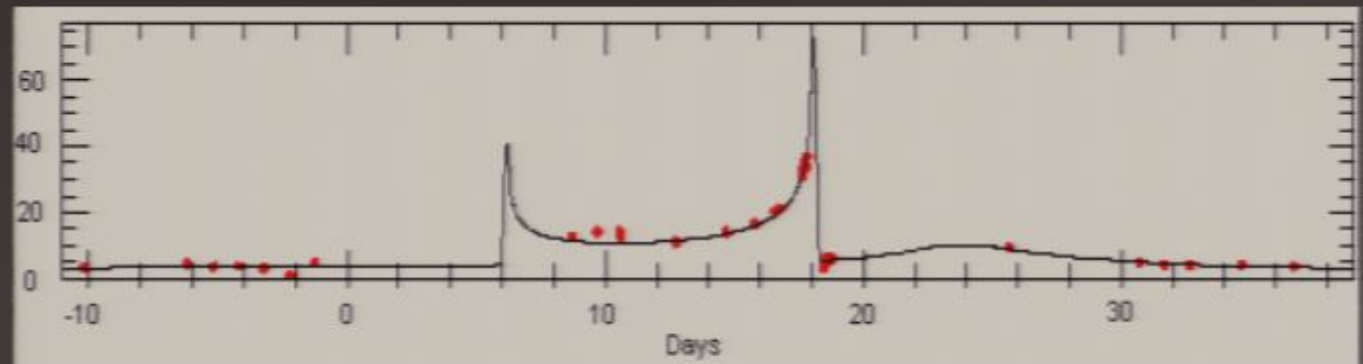
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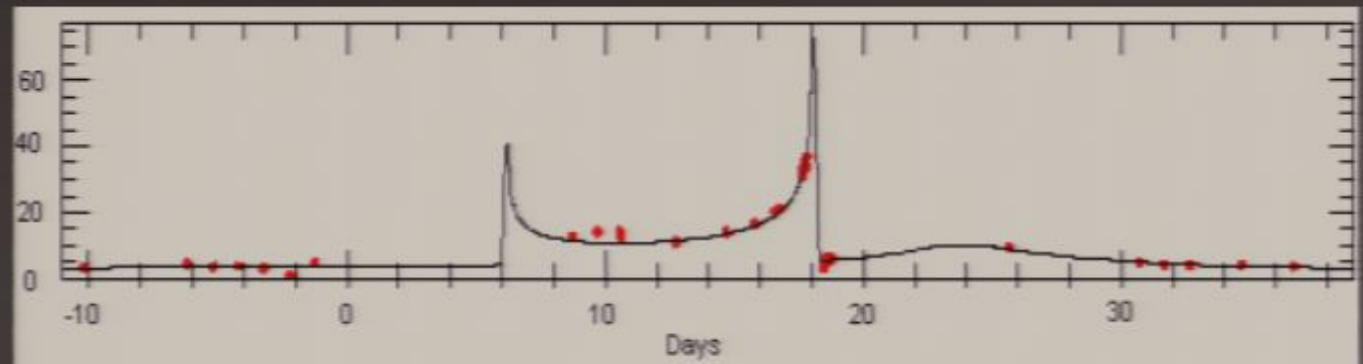
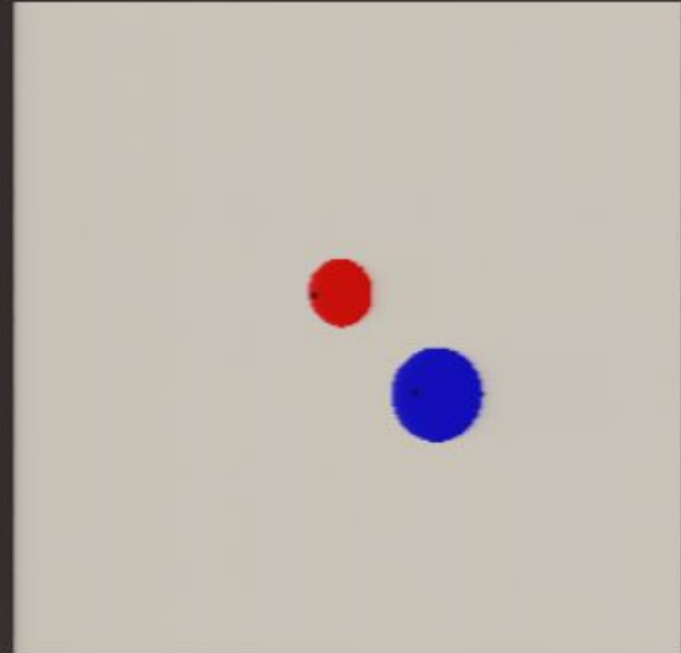
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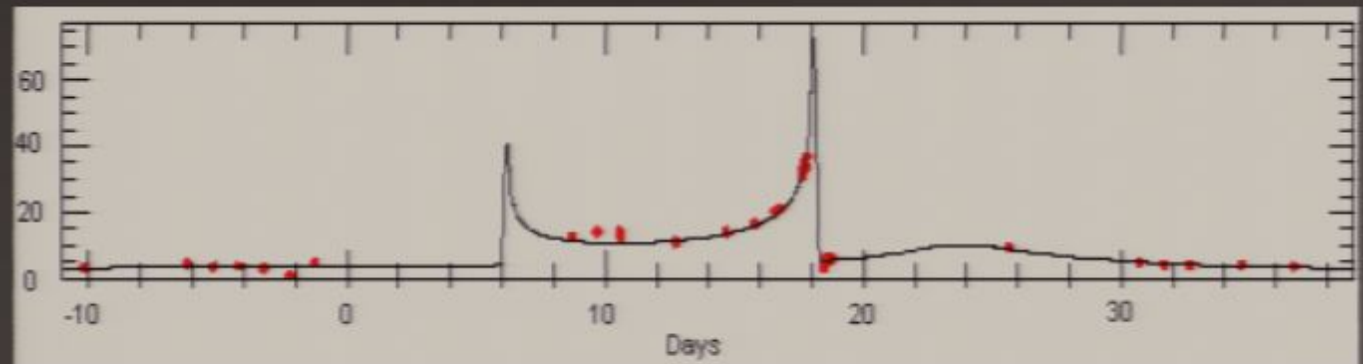
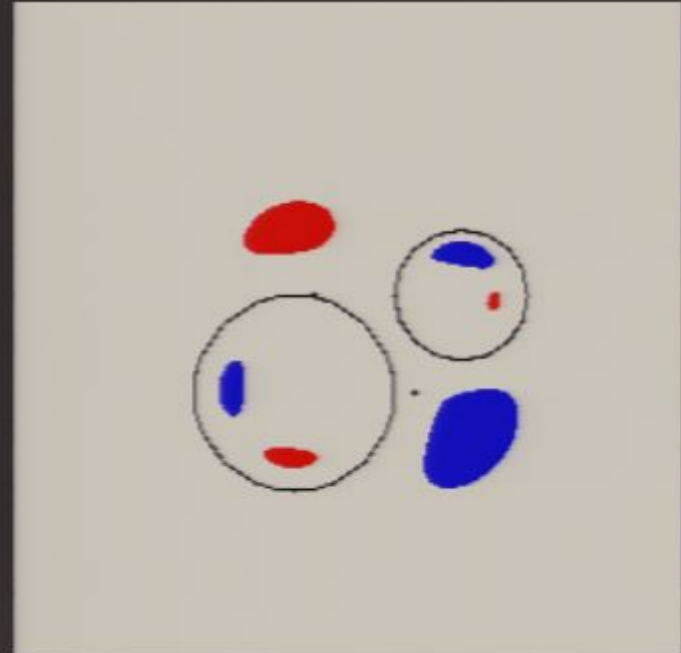
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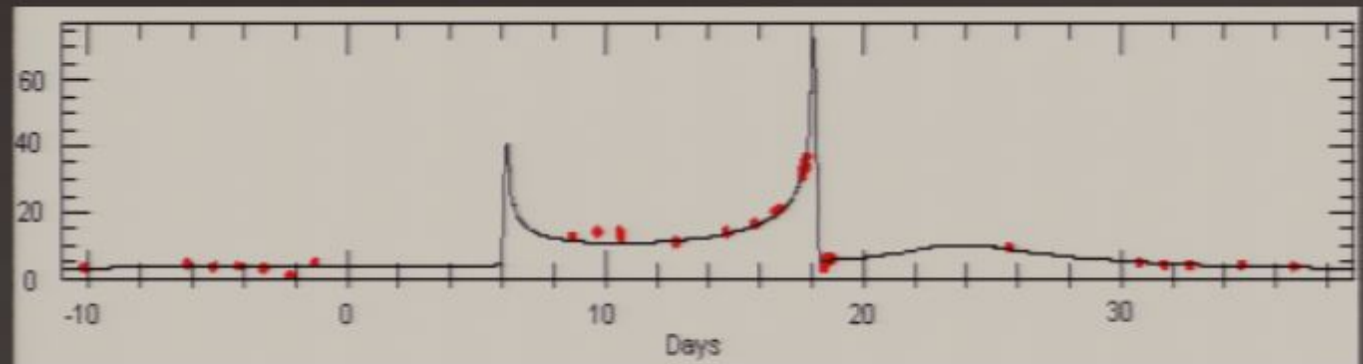
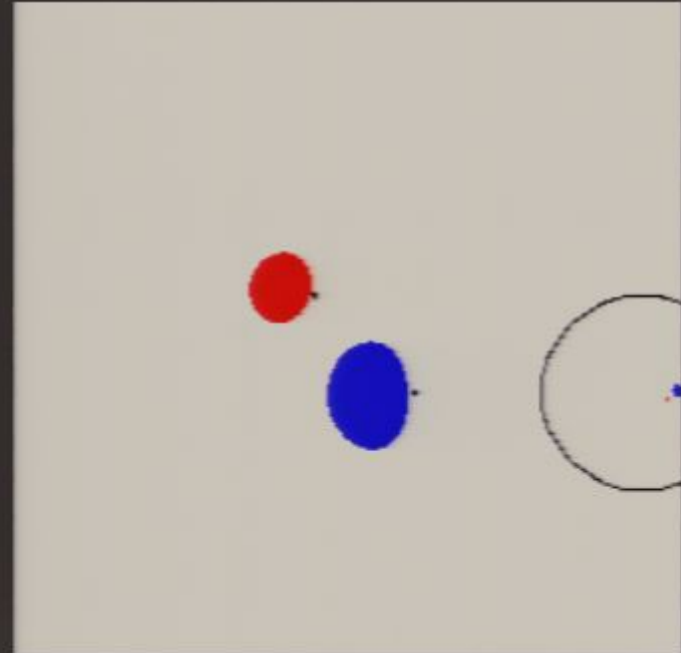
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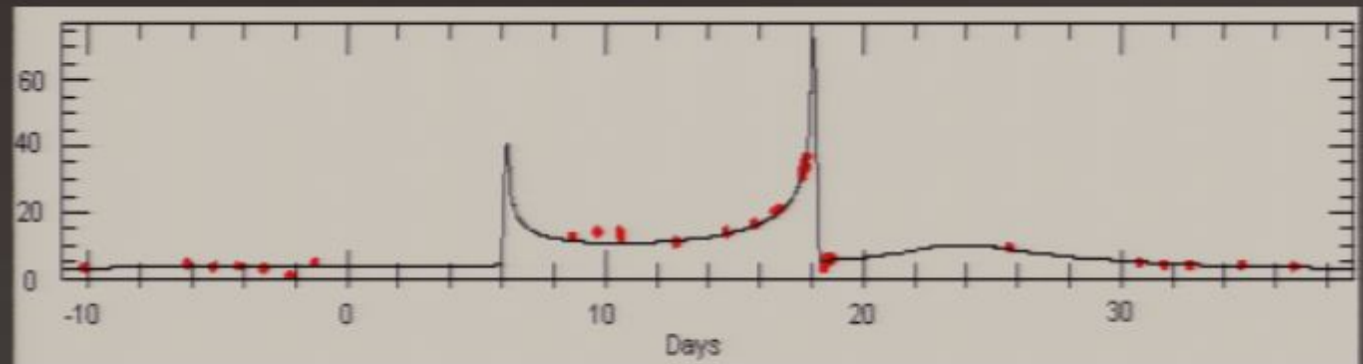
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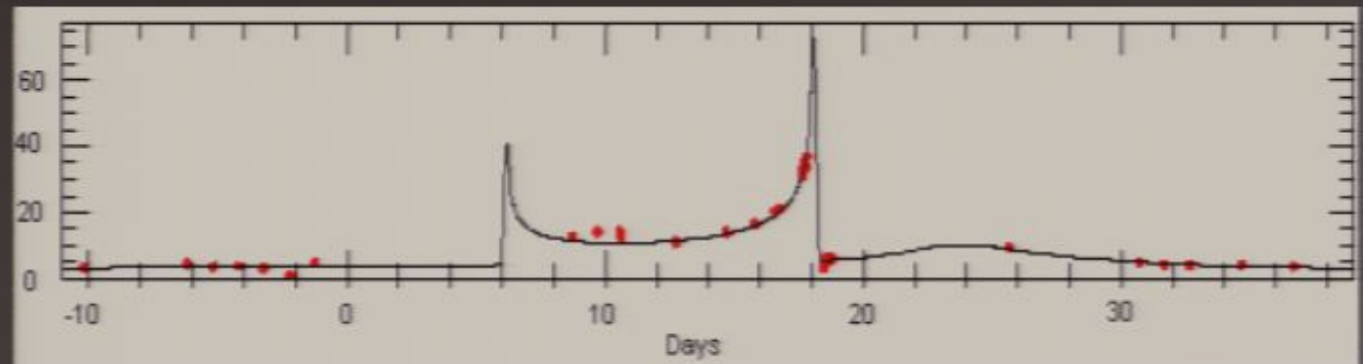
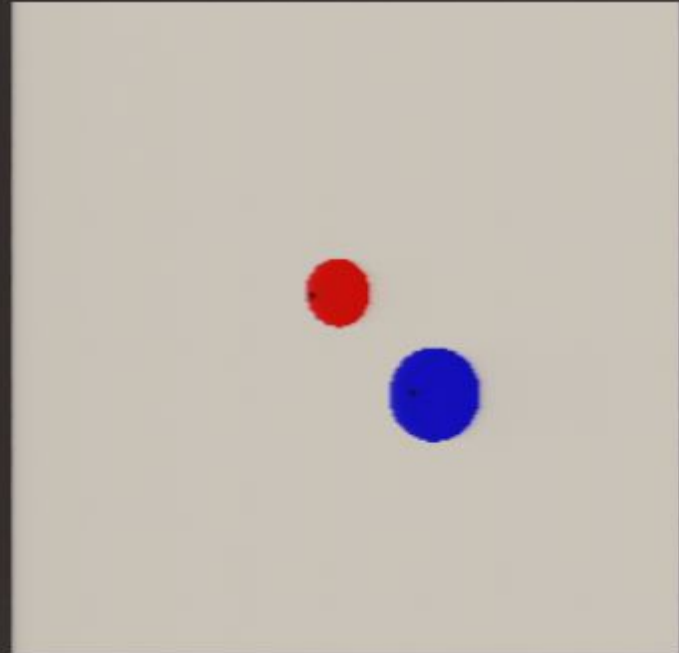
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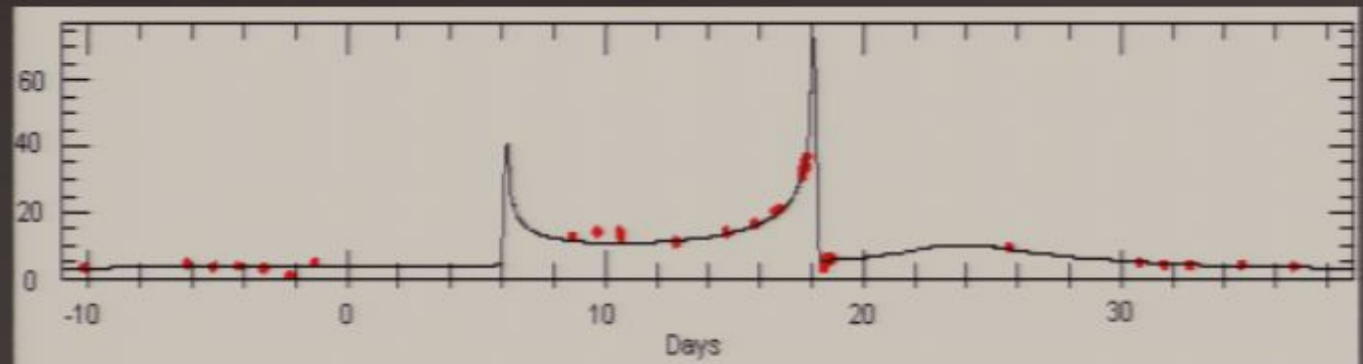
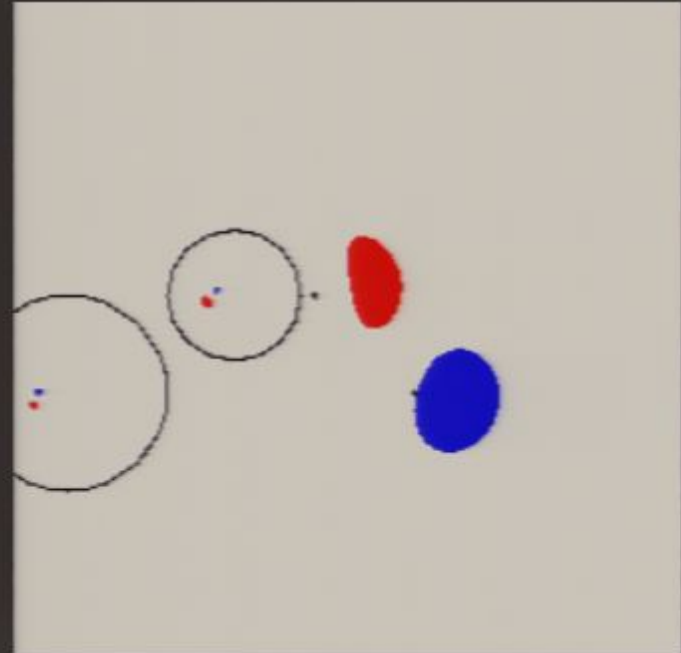
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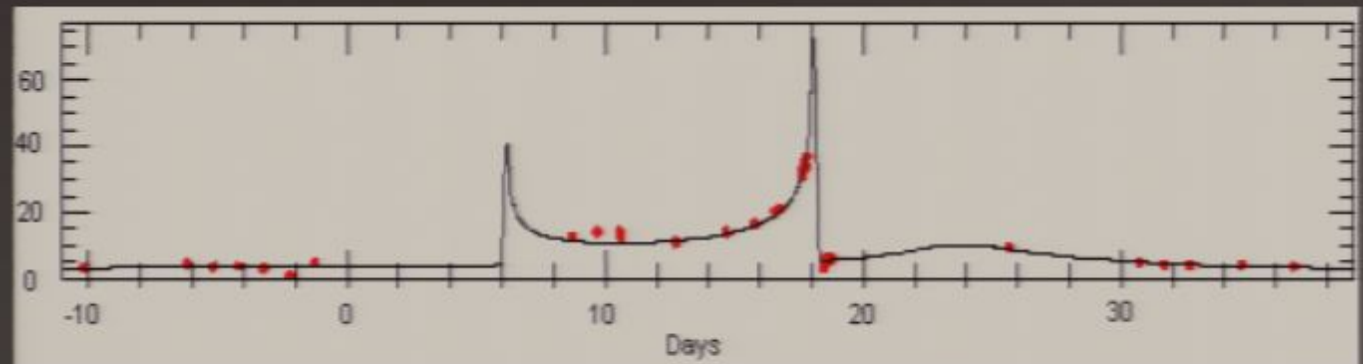
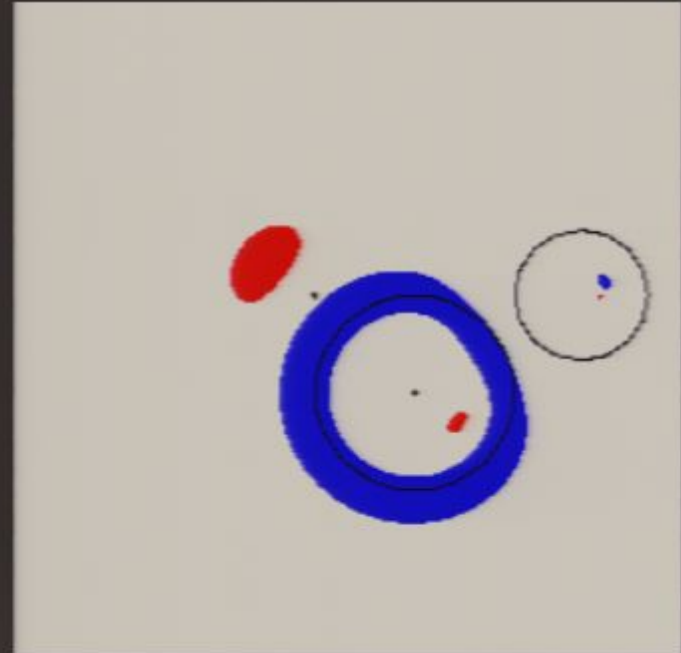
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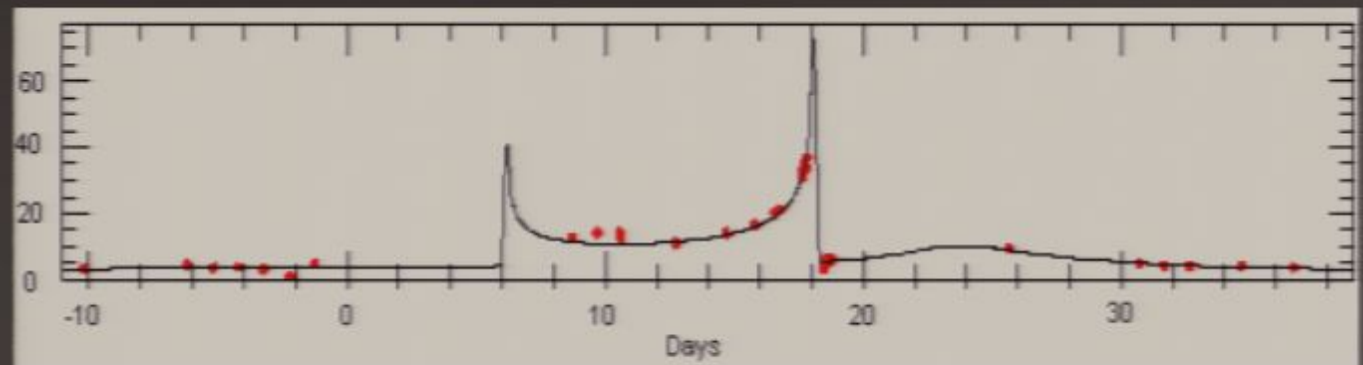
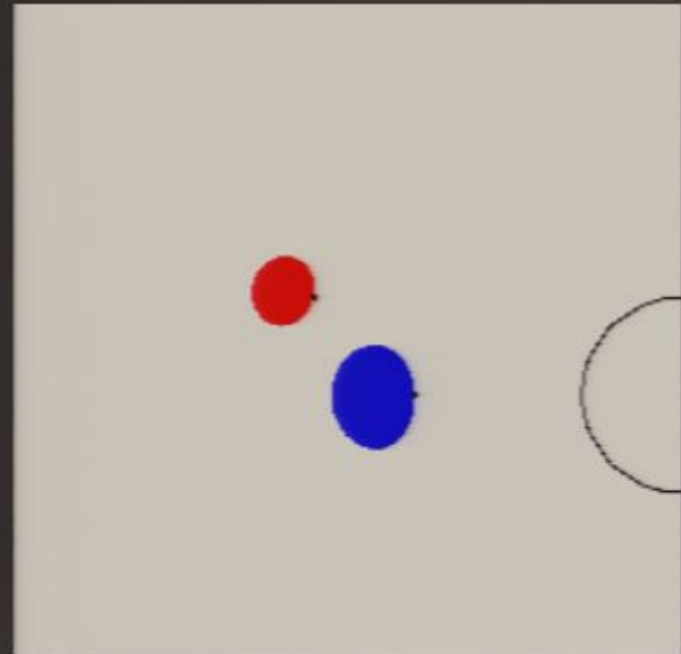
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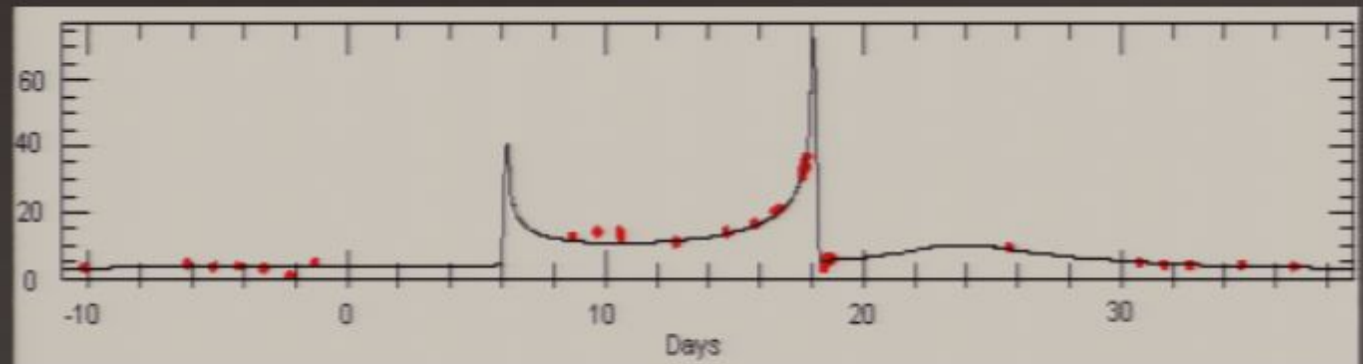
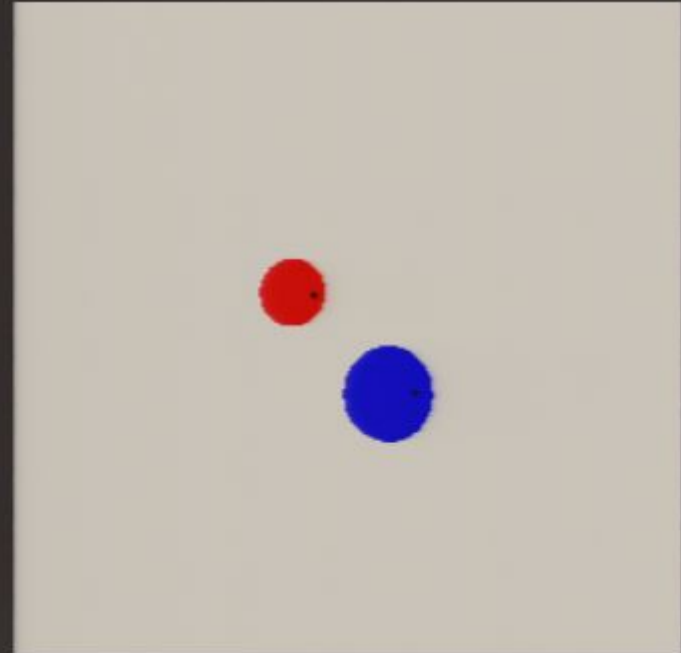
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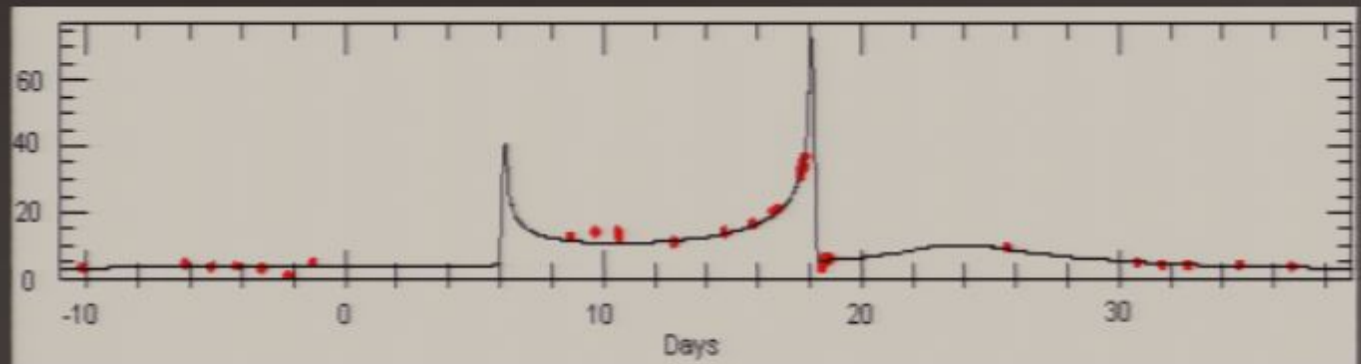
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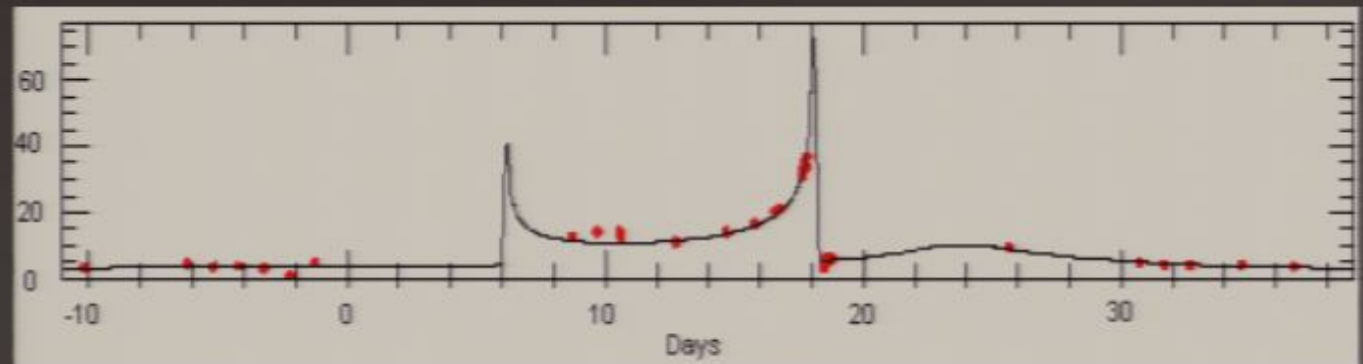
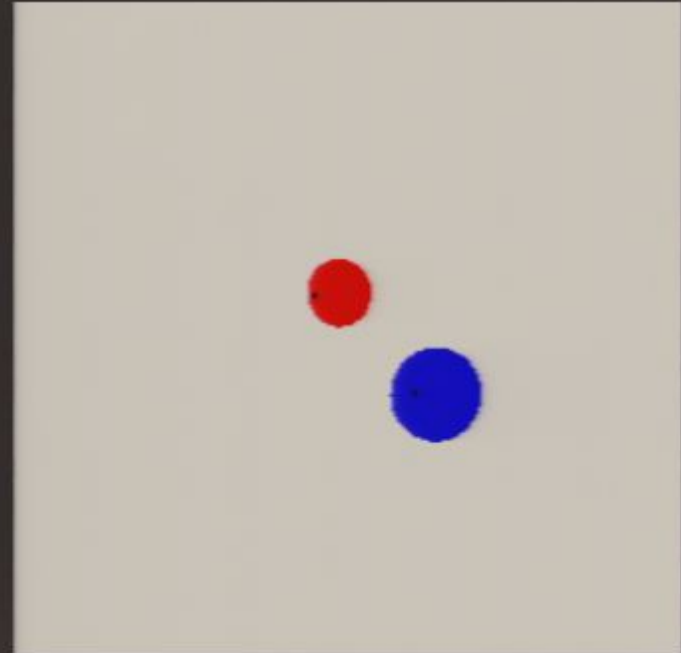
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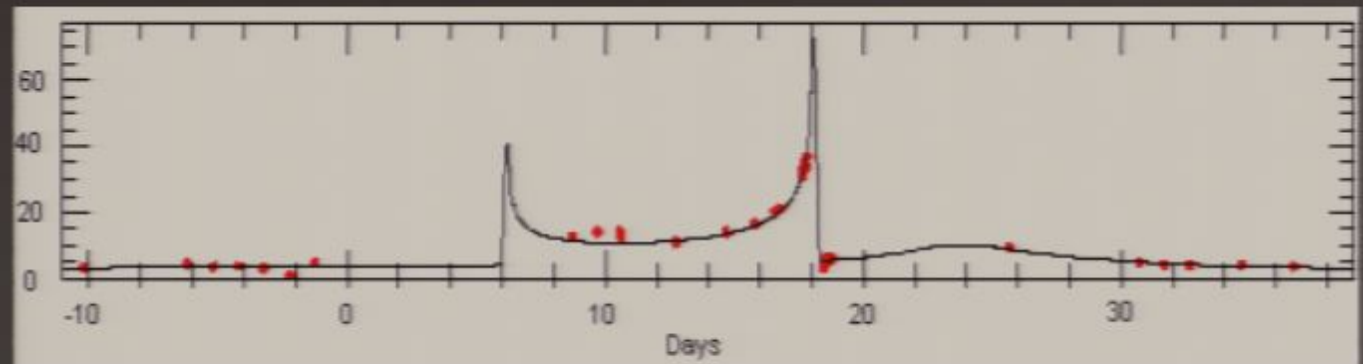
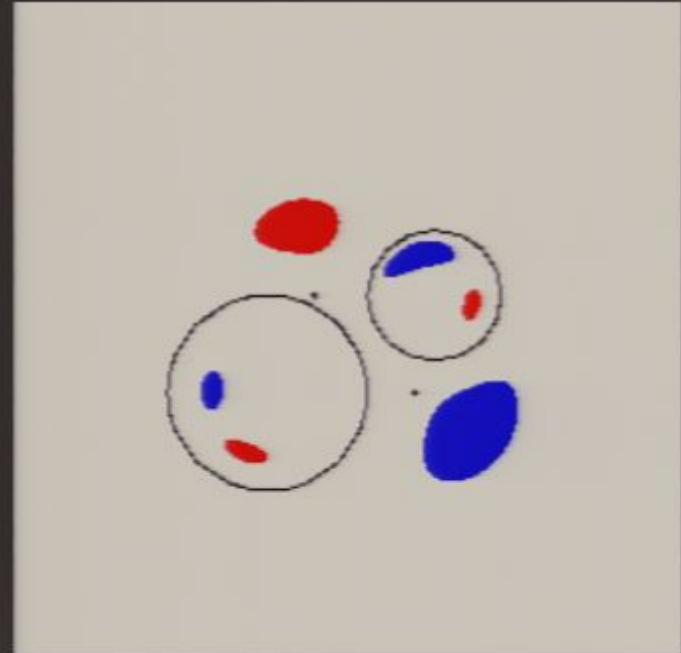
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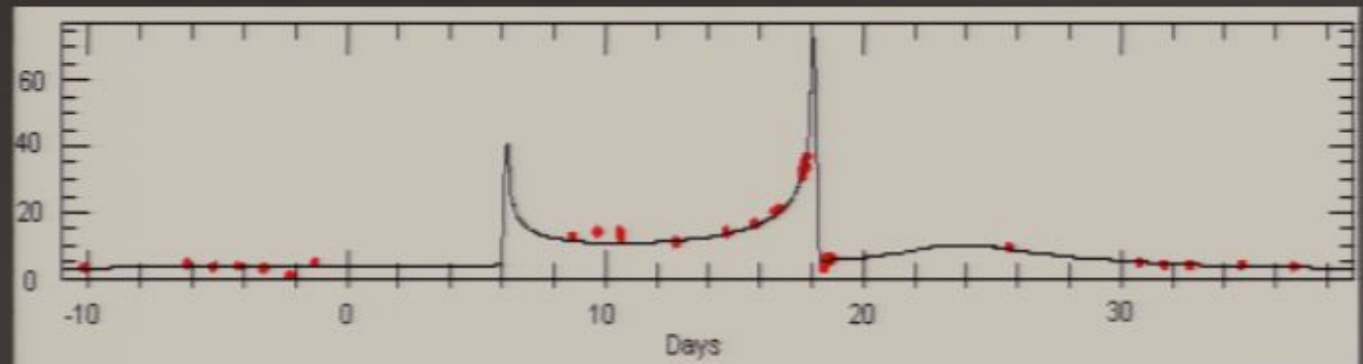
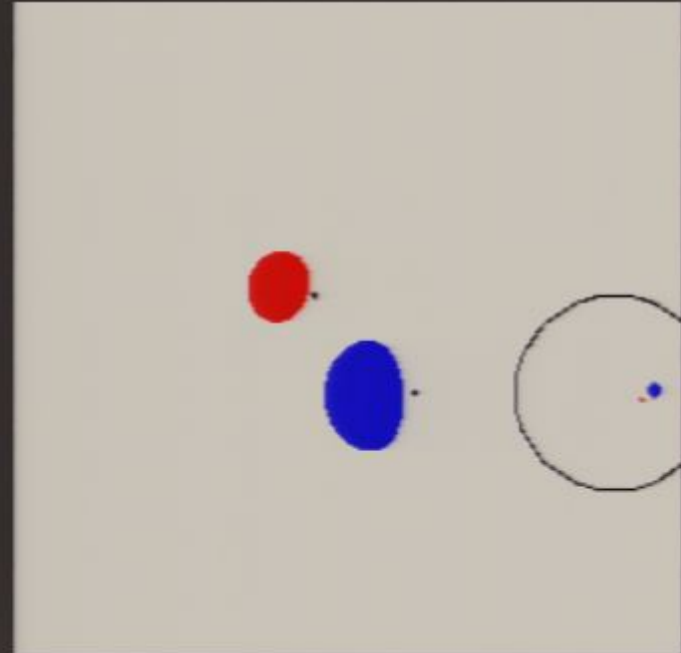
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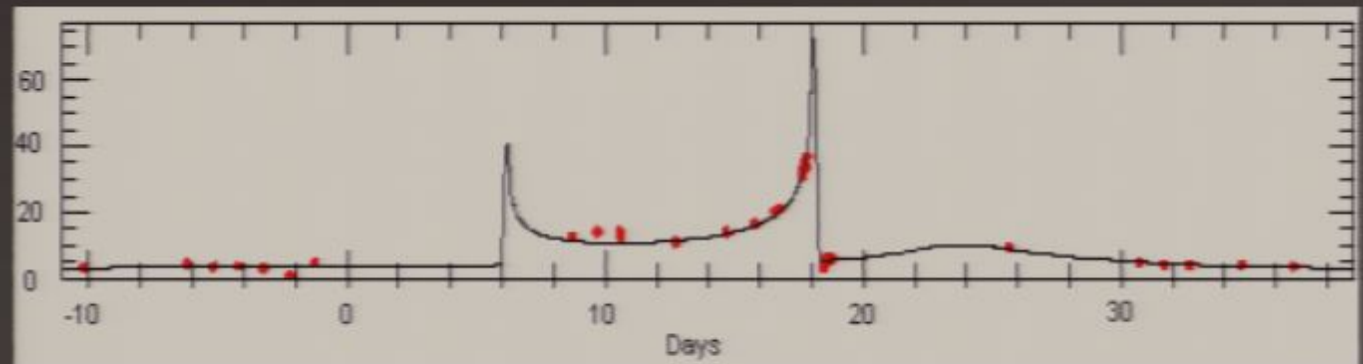
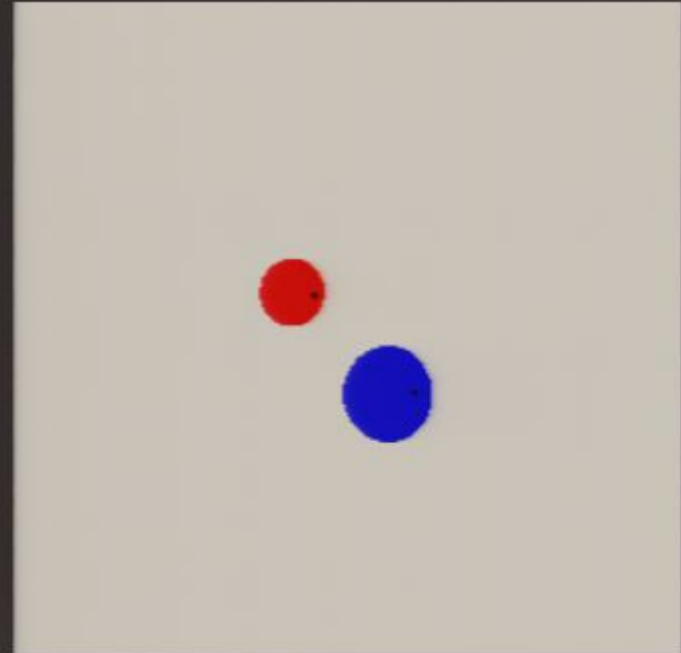
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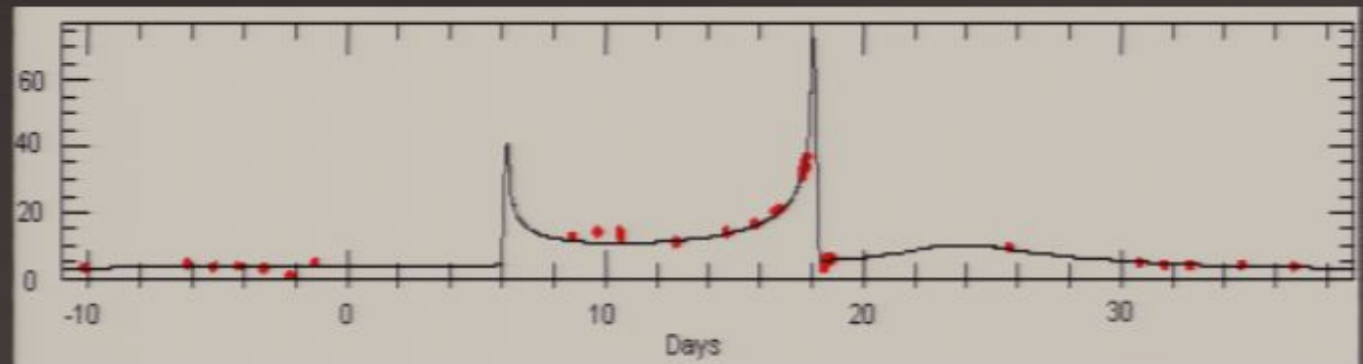
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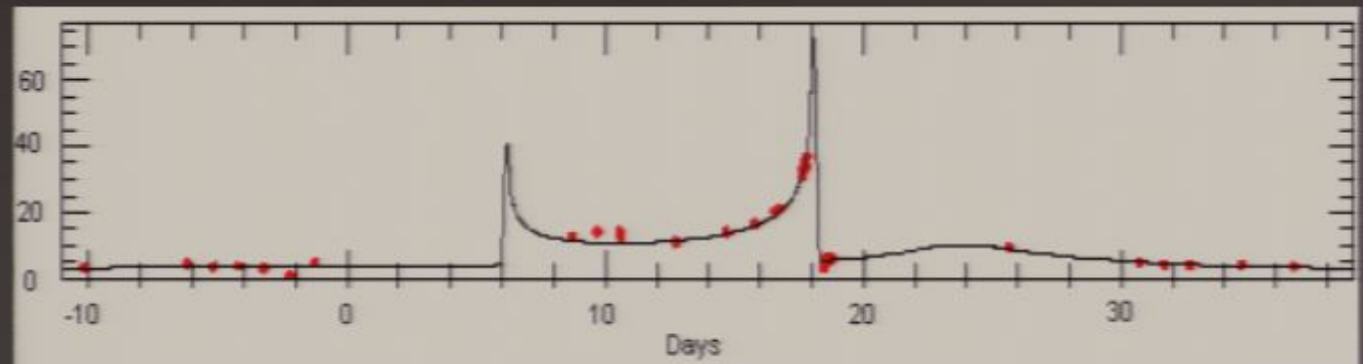
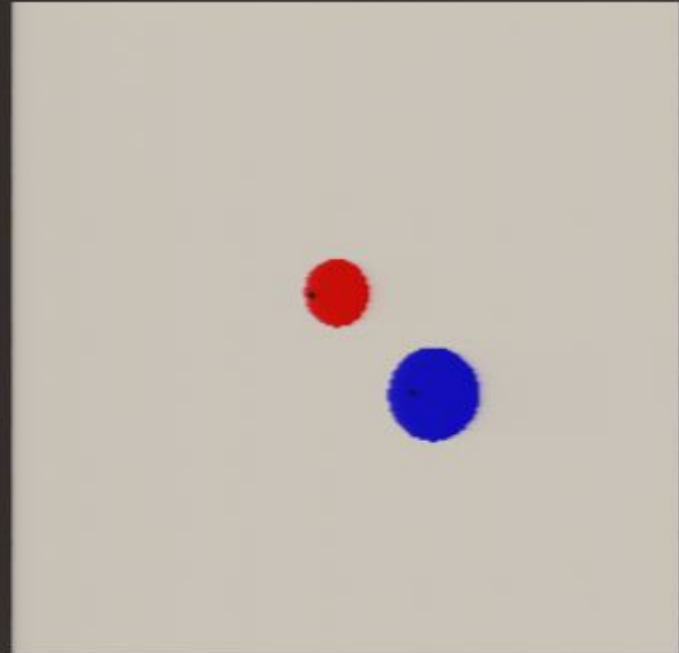
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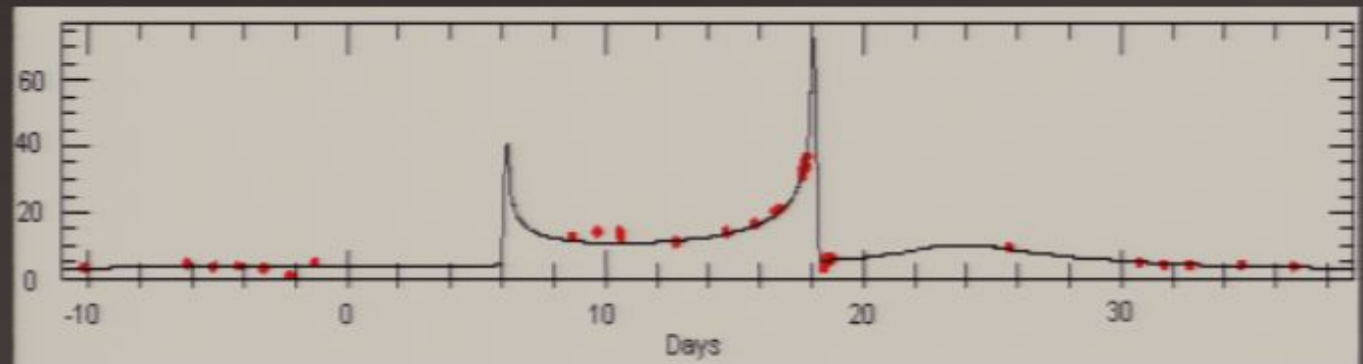
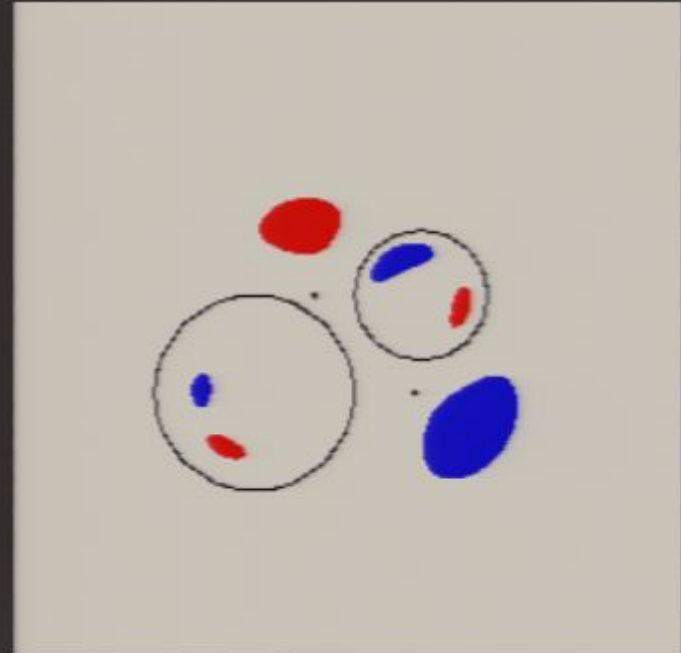
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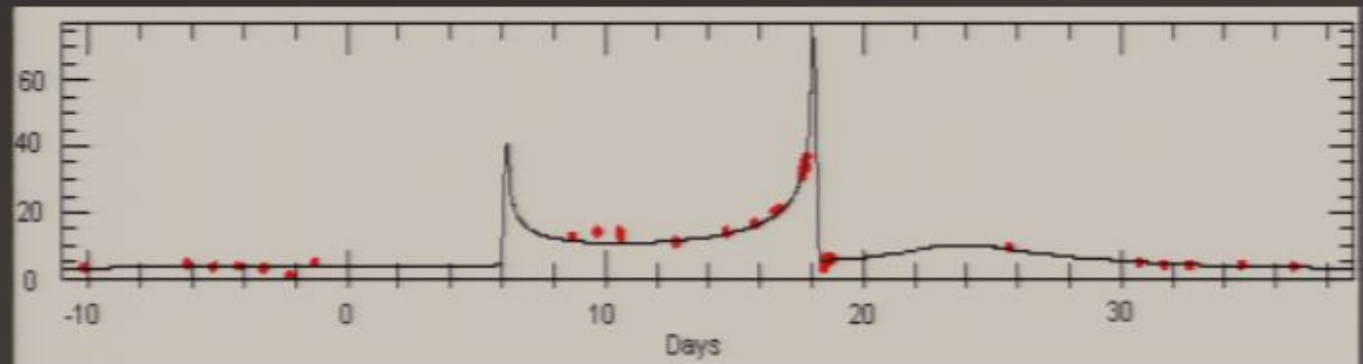
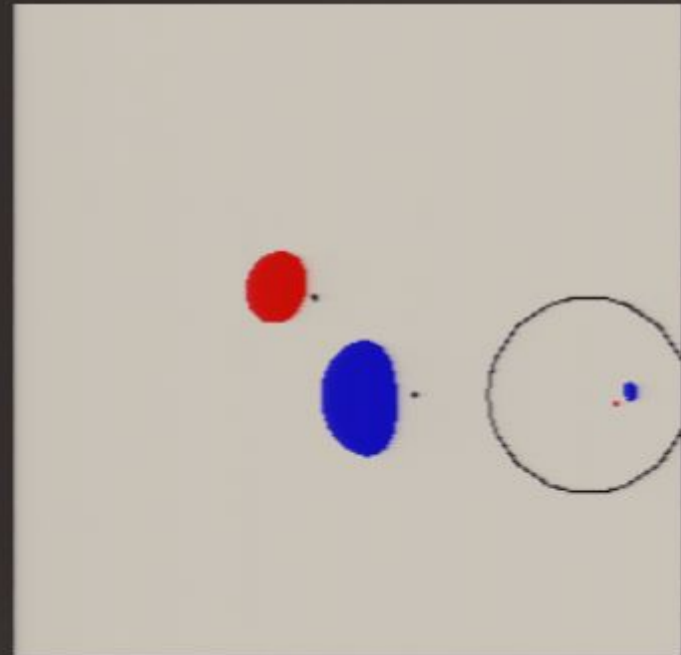
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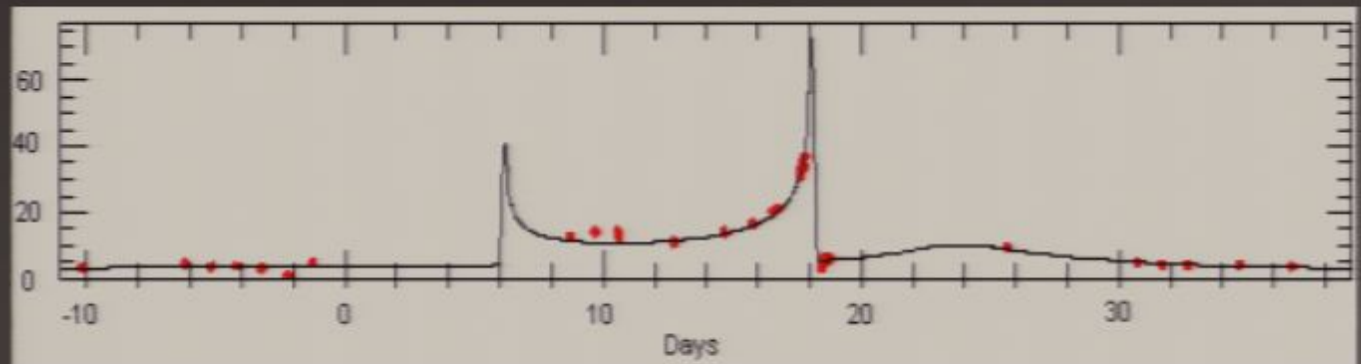
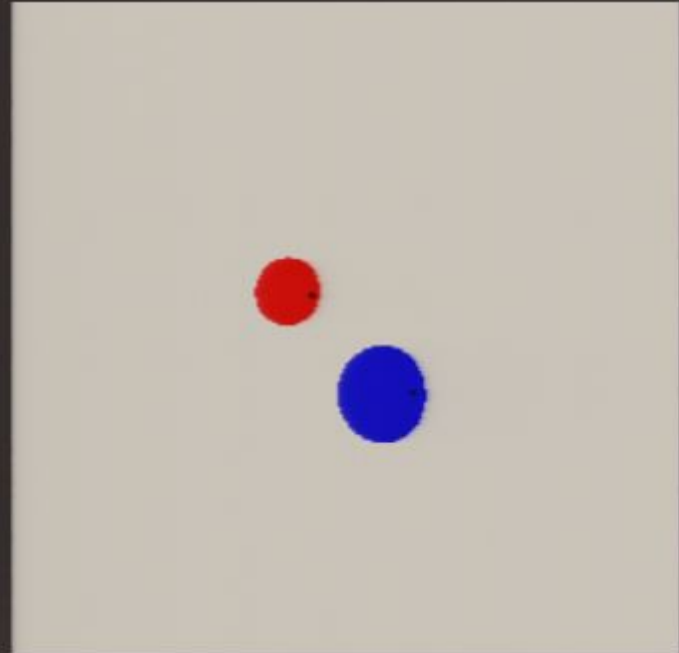
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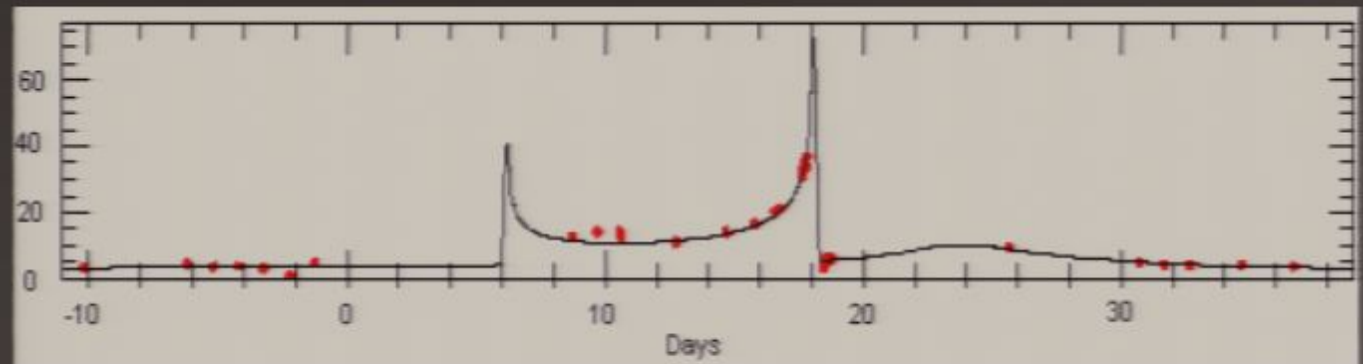
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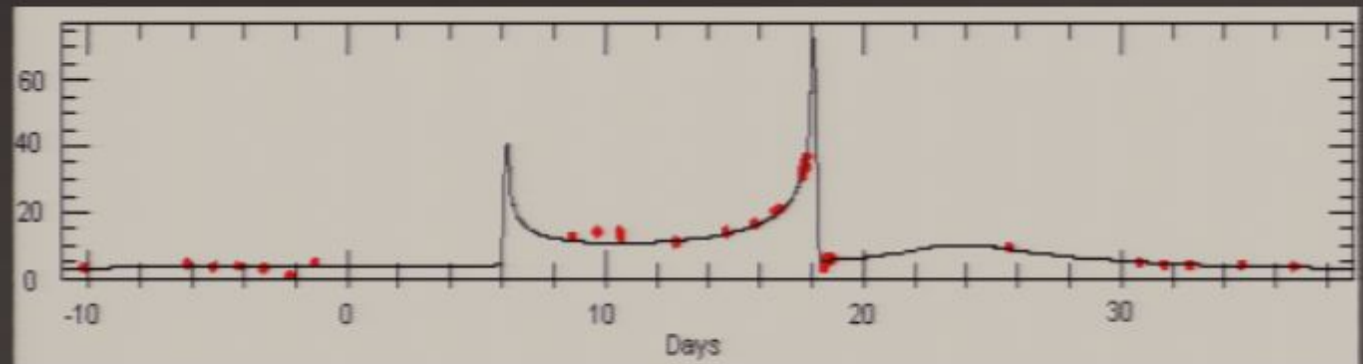
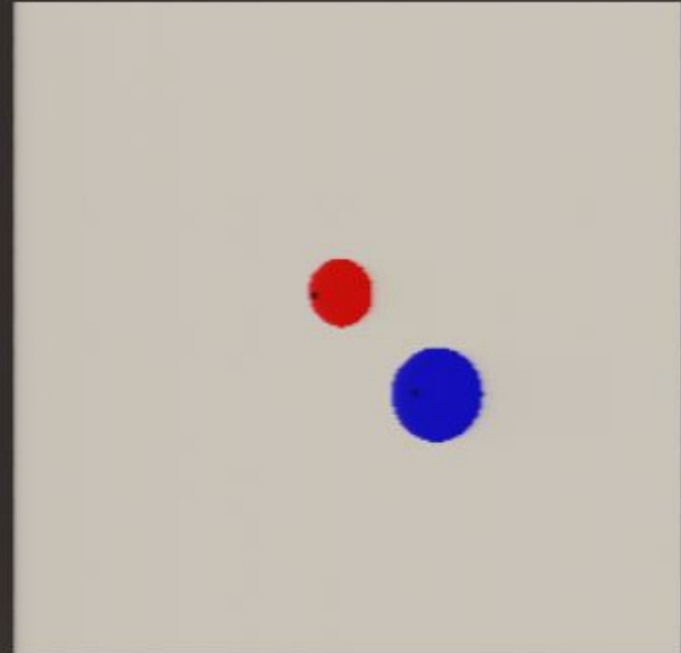
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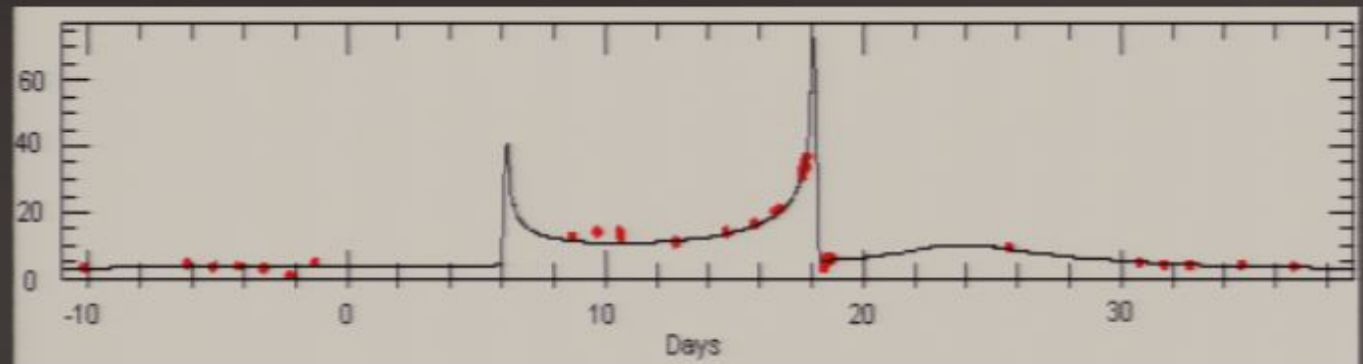
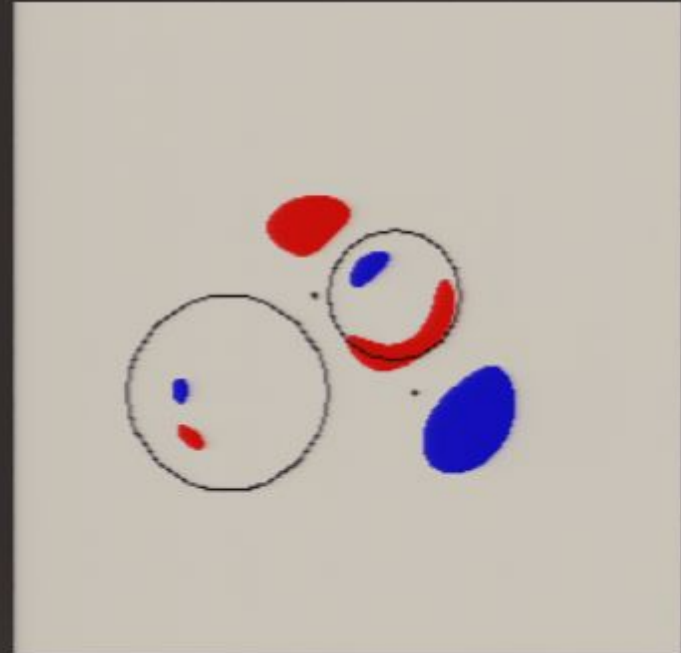
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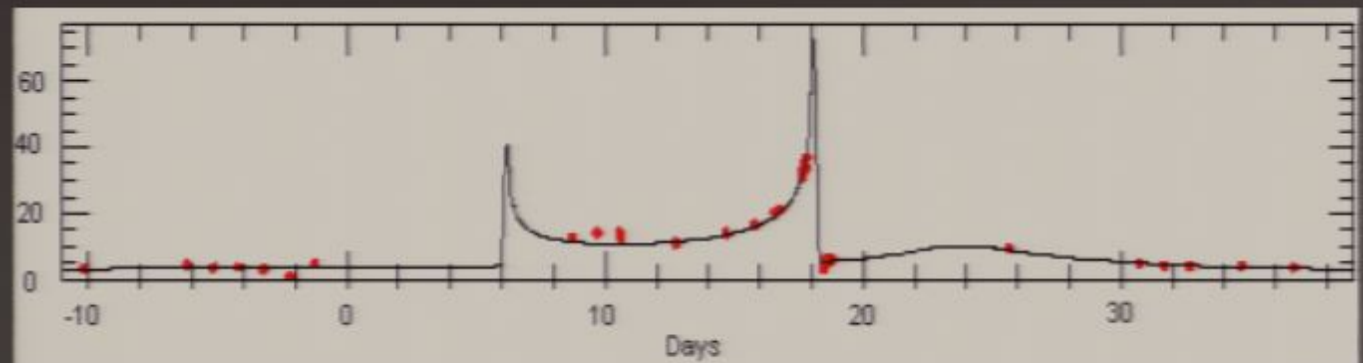
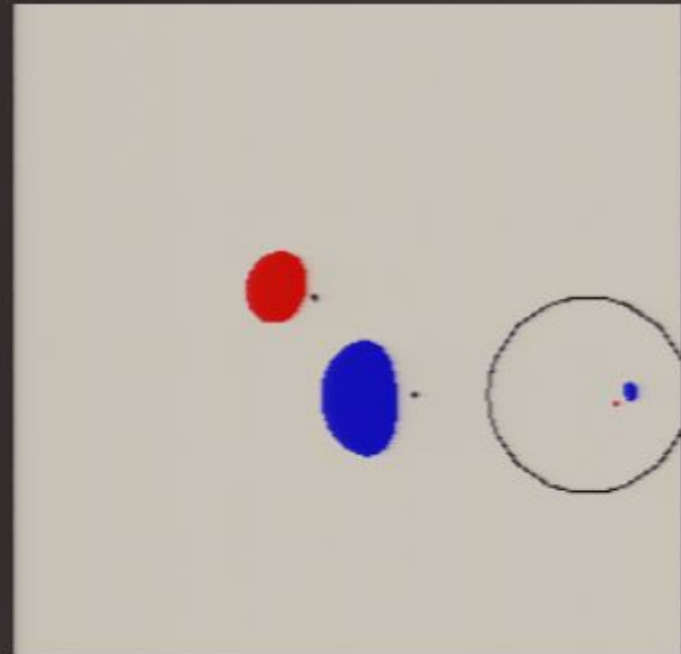
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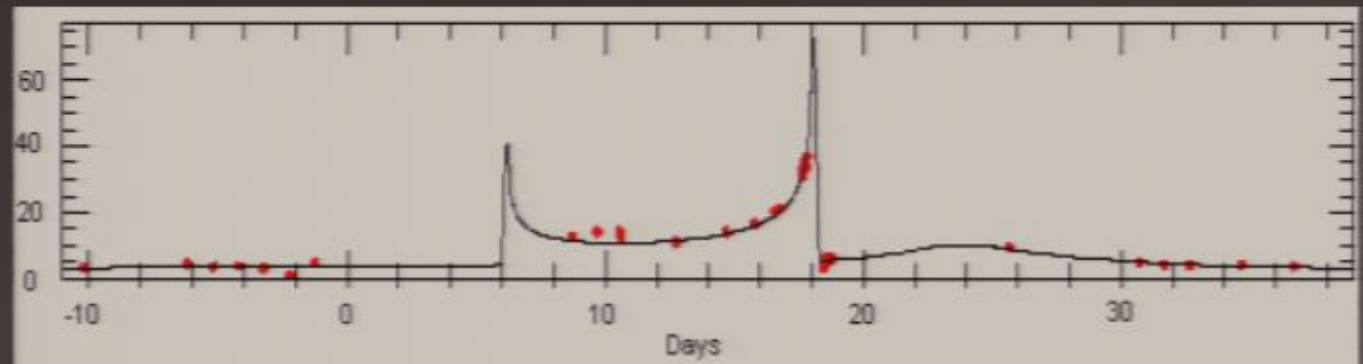
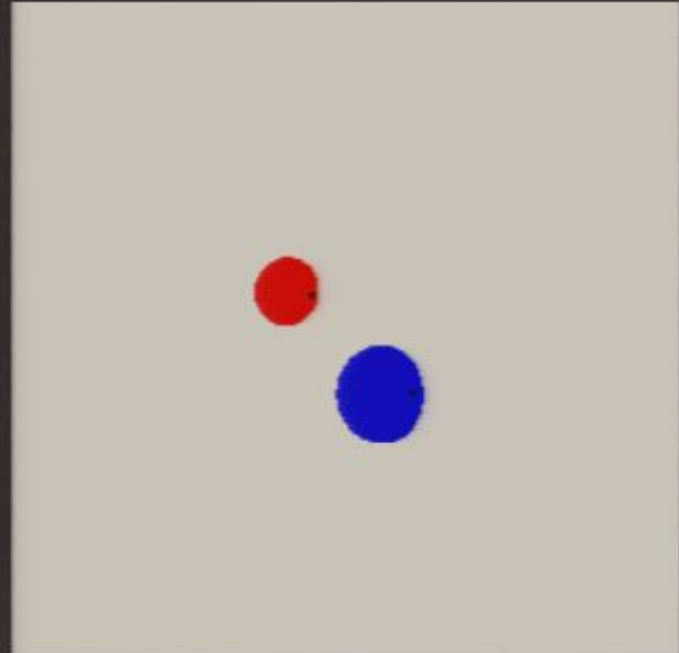
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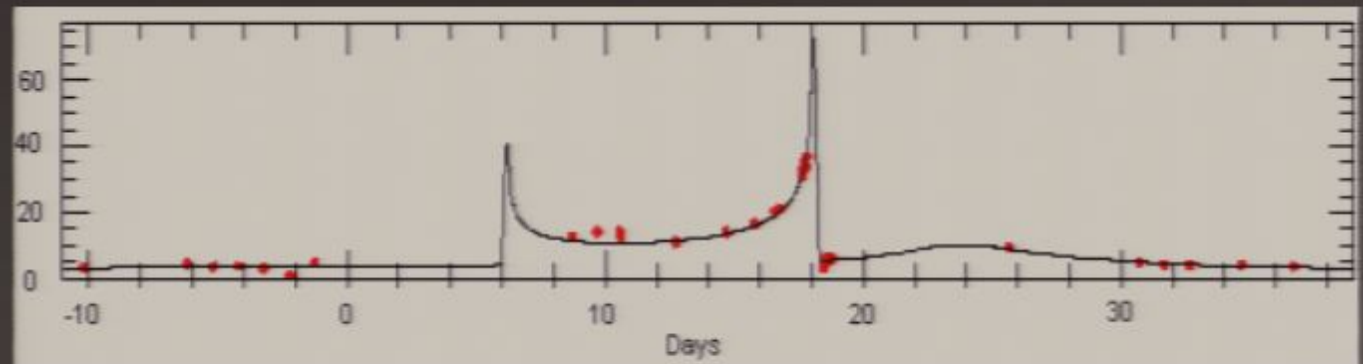
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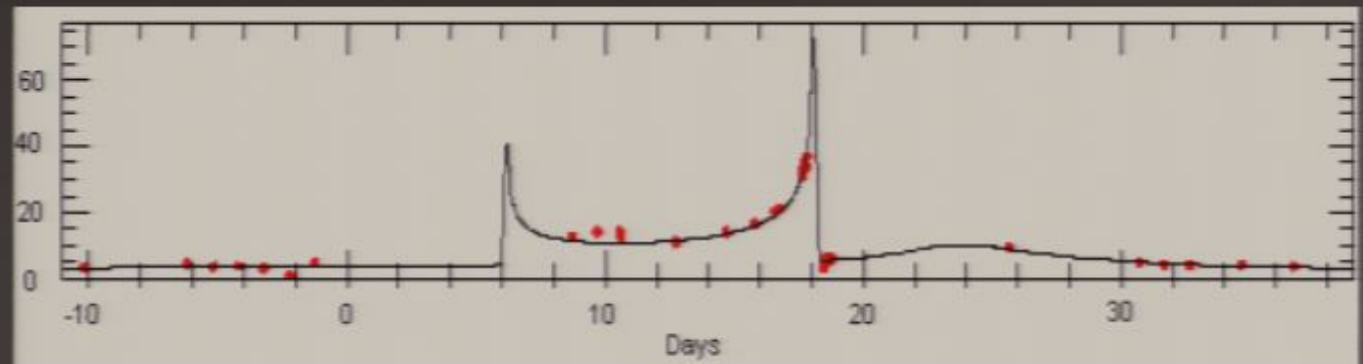
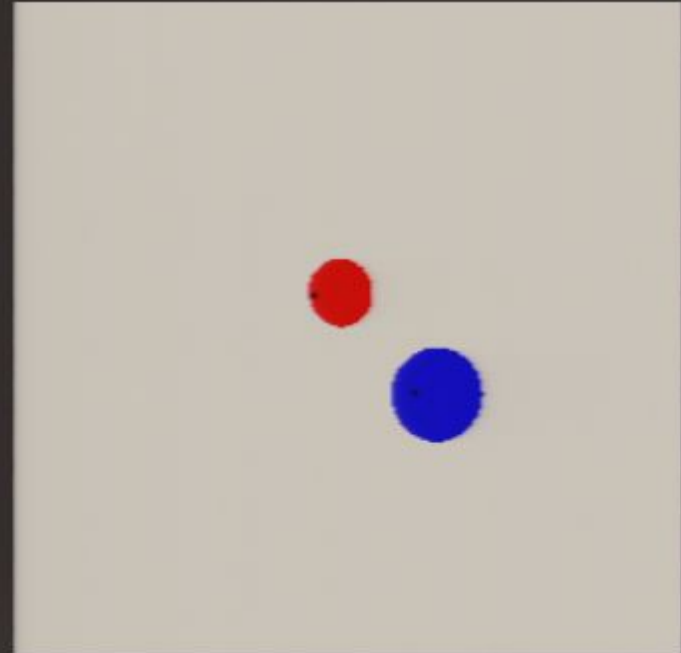
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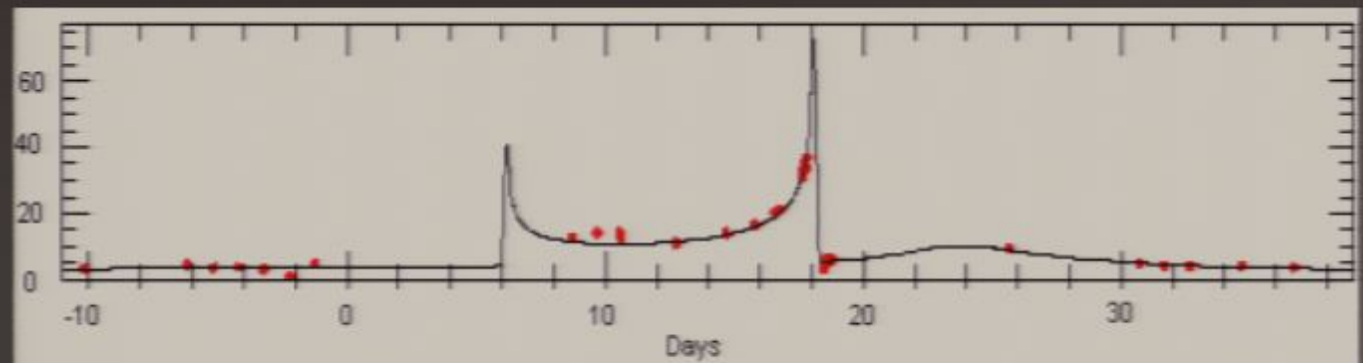
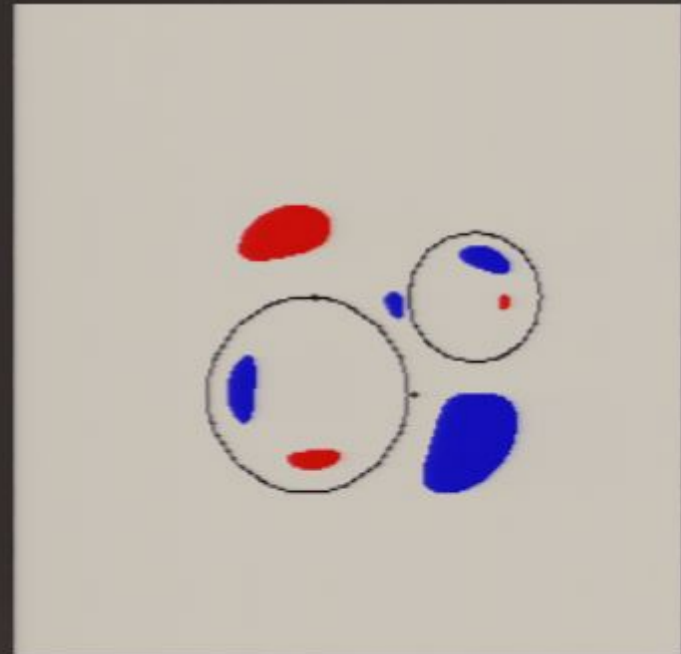
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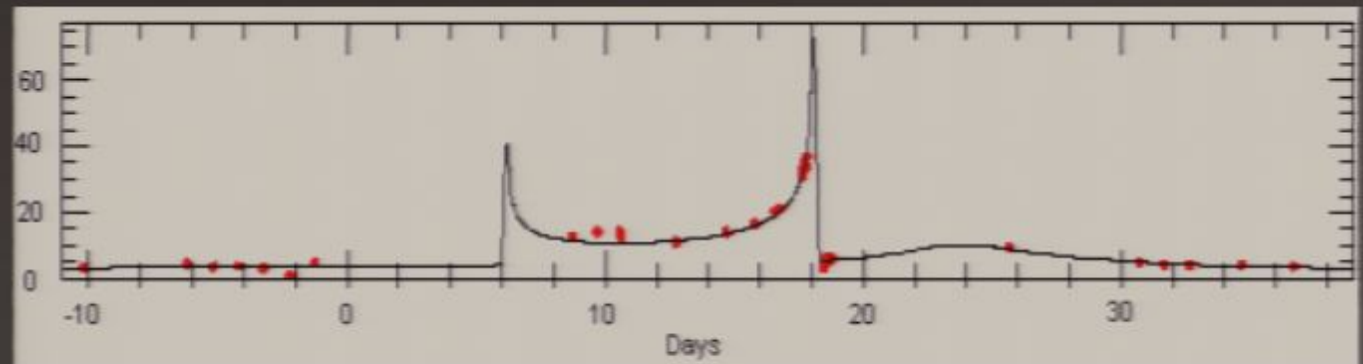
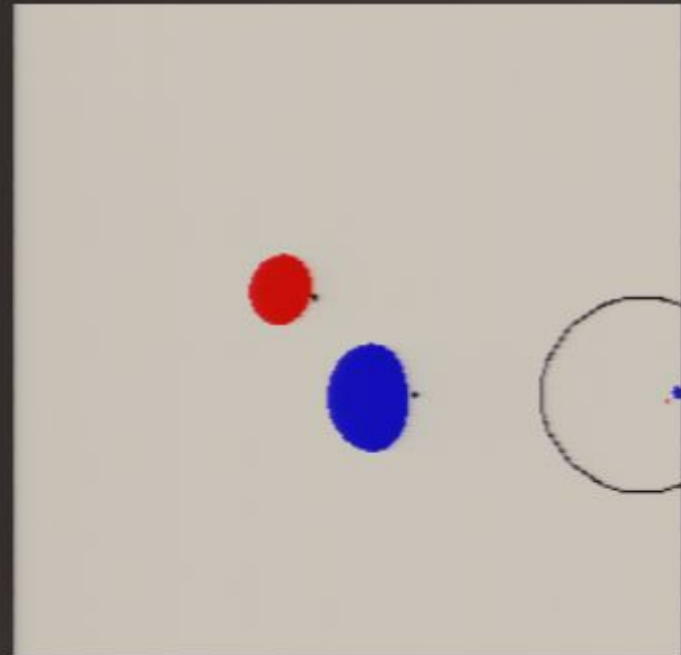
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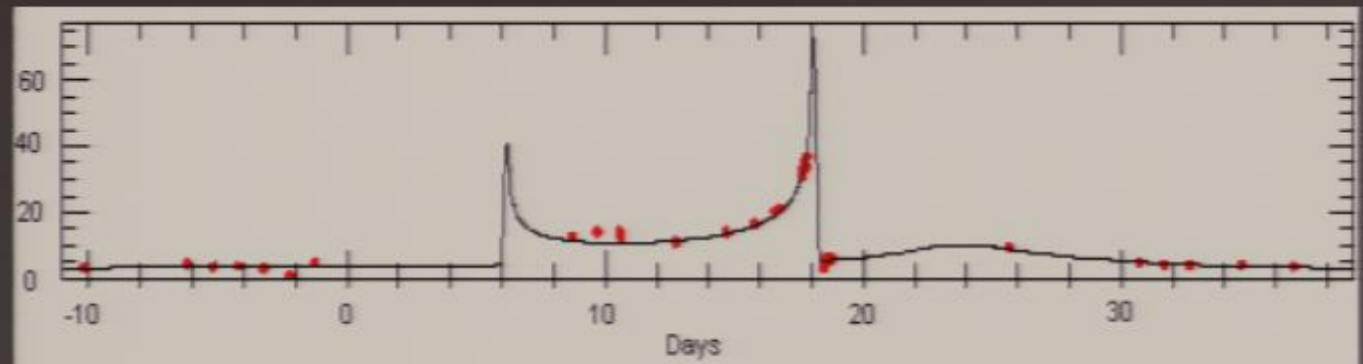
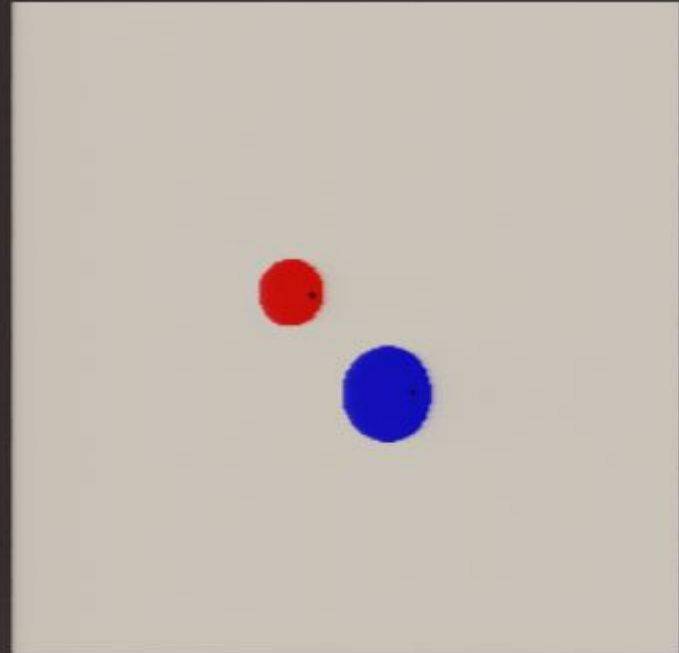
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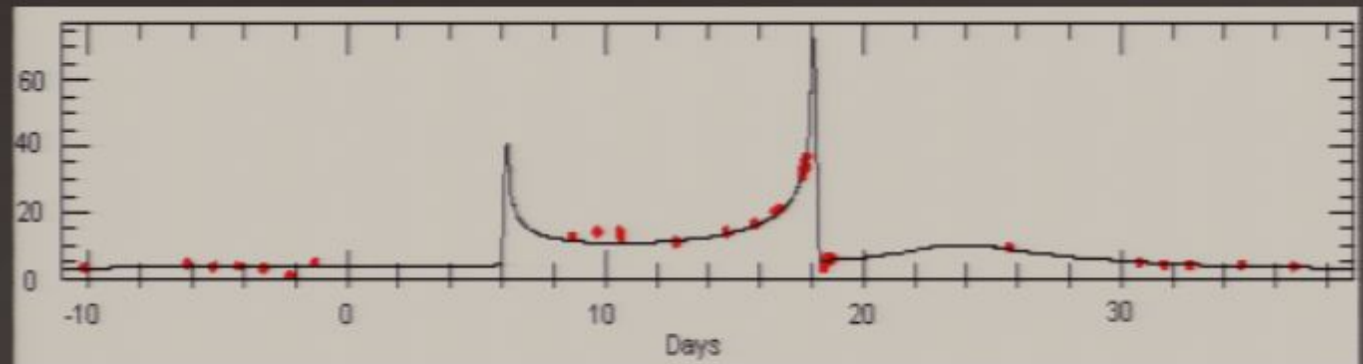
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What is the Dark Matter?

- 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.

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 Energy

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



Dark energy is what causes the expansion of space which causes this light

69

Evidence for Dark Energy

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

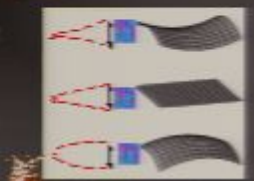


Size of the CMB fluctuation depends on the geometry of space the light travels

70

Evidence for Dark Energy

- Brightness of very distant supernovae
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Size of the CMB fluctuation depends on the geometry of space the light travels

71

Evidence for Dark Energy

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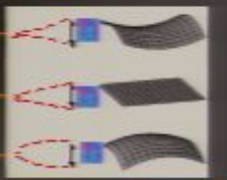


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72

Evidence for Dark Energy

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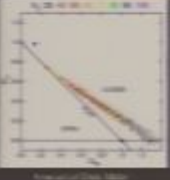


Size of the CMB fluctuation depends on the geometry of space the light travels

73

Evidence for Dark Energy

- Brightness of very distant supernovae
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Measurements of CMB fluctuations are consistent with an accelerated expansion rate H_0

74

Evidence for Dark Energy

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

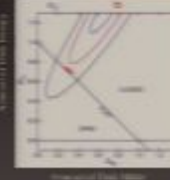


Measured H_0 with CMB fluctuations agrees a lot better

75

Evidence for Dark Energy

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




Dark Energy required to explain CMB fluctuations with observational acceleration regime

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Evidence for Dark Energy

- Brightness of very distant supernovae
- Flatness of the universe



Concordance Cosmology



Concordance Cosmology



Outline

- The Hot Big Bang
 - Evidence for a Hot Expanding Universe
 - Dark Matter and Dark Energy
- Contact With Fundamental Physics
 - Dark Matter
 - Dark Energy

Evidence for Dark Matter

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

Temperature fluctuations in the CMB associated to sound waves in the ionized medium after the CMB was emitted.

The amplitude of these waves depends on the gravitational potential of all the matter present at the time.

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Evidence for Dark Matter

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

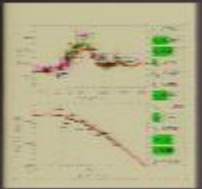


Dark Matter Matter

58

Evidence for Dark Matter

- Mass in galaxies
- Mass in clusters of galaxies
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Dark Matter Matter

59

Evidence for Dark Matter

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

Massive dark matter clumps that form galaxies can only exist collapsing matter in form galaxies after matter dominates the energy density.

The small density fluctuations visible in the CMB are small to become galaxies if not dark matter structures.

60

Evidence for Dark Matter

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



61

Evidence for Dark Energy

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

62

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 expansion.

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

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Evidence for Dark Energy

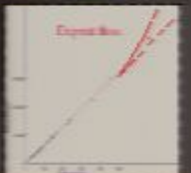
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Evidence for Dark Energy

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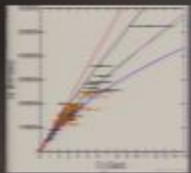


Expansion rate

Expansion rate should be decreasing.

Evidence for Dark Energy

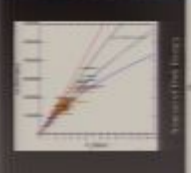
- Brightness of very distant supernovae
- Flatness of the universe as a whole



Expansion rate

Evidence for Dark Energy

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



Expansion rate

Evidence for Dark Energy

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



Small temperature variations in the ionized medium in the CMB.

Outlook

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

Albert Einstein



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.

...with thanks to Sam Watterson

