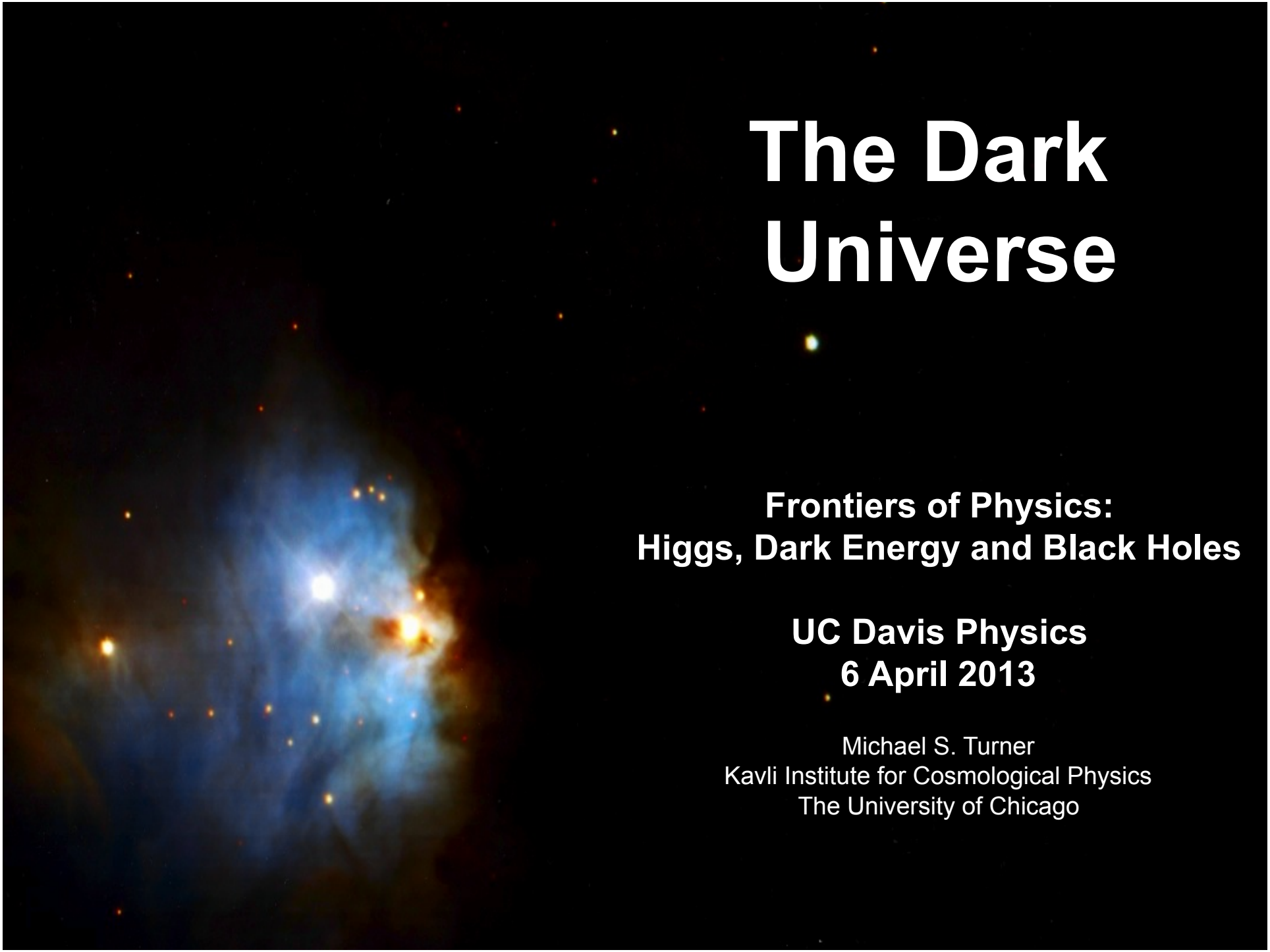


The Dark Universe

Frontiers of Physics:
Higgs, Dark Energy and Black Holes

UC Davis Physics
6 April 2013

Michael S. Turner
Kavli Institute for Cosmological Physics
The University of Chicago

DON'T LET THE BRIGHT LIGHTS FOOL YOU

THE DARK SIDE CONTROLS THE UNIVERSE

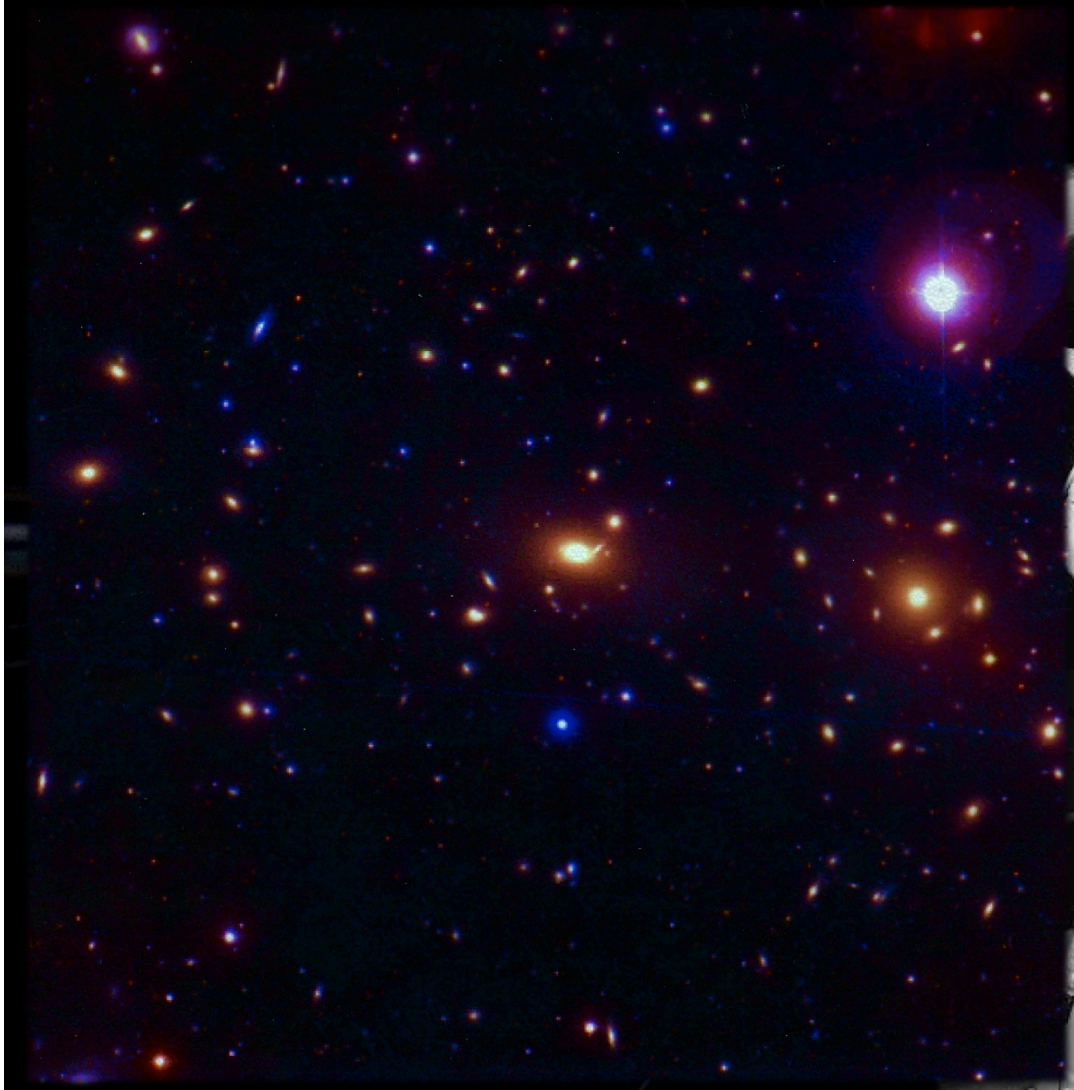
OUR UNIVERSE

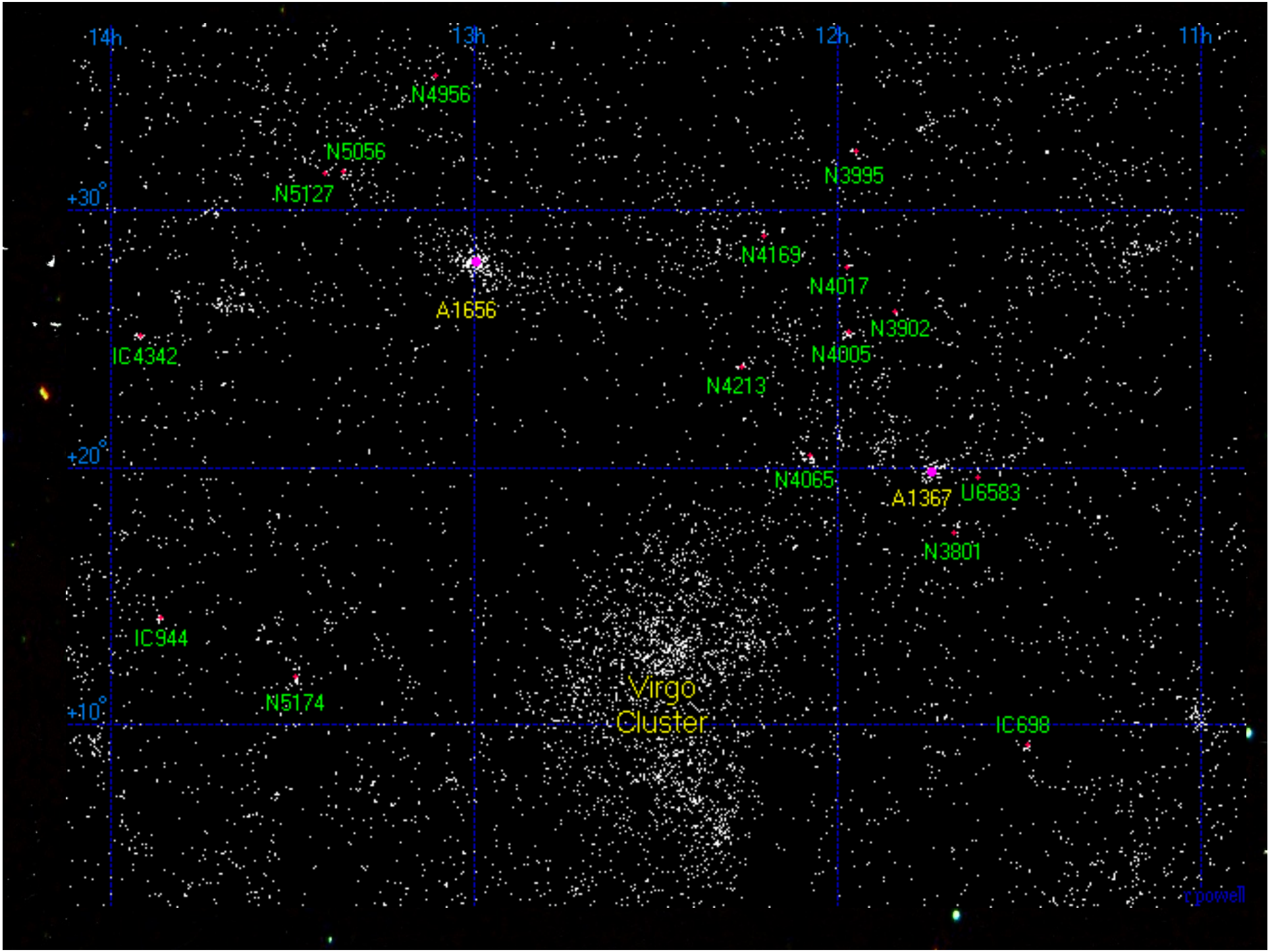
- STARS: 0.5%
- DARK MATTER: 33%
- DARK ENERGY: 66%

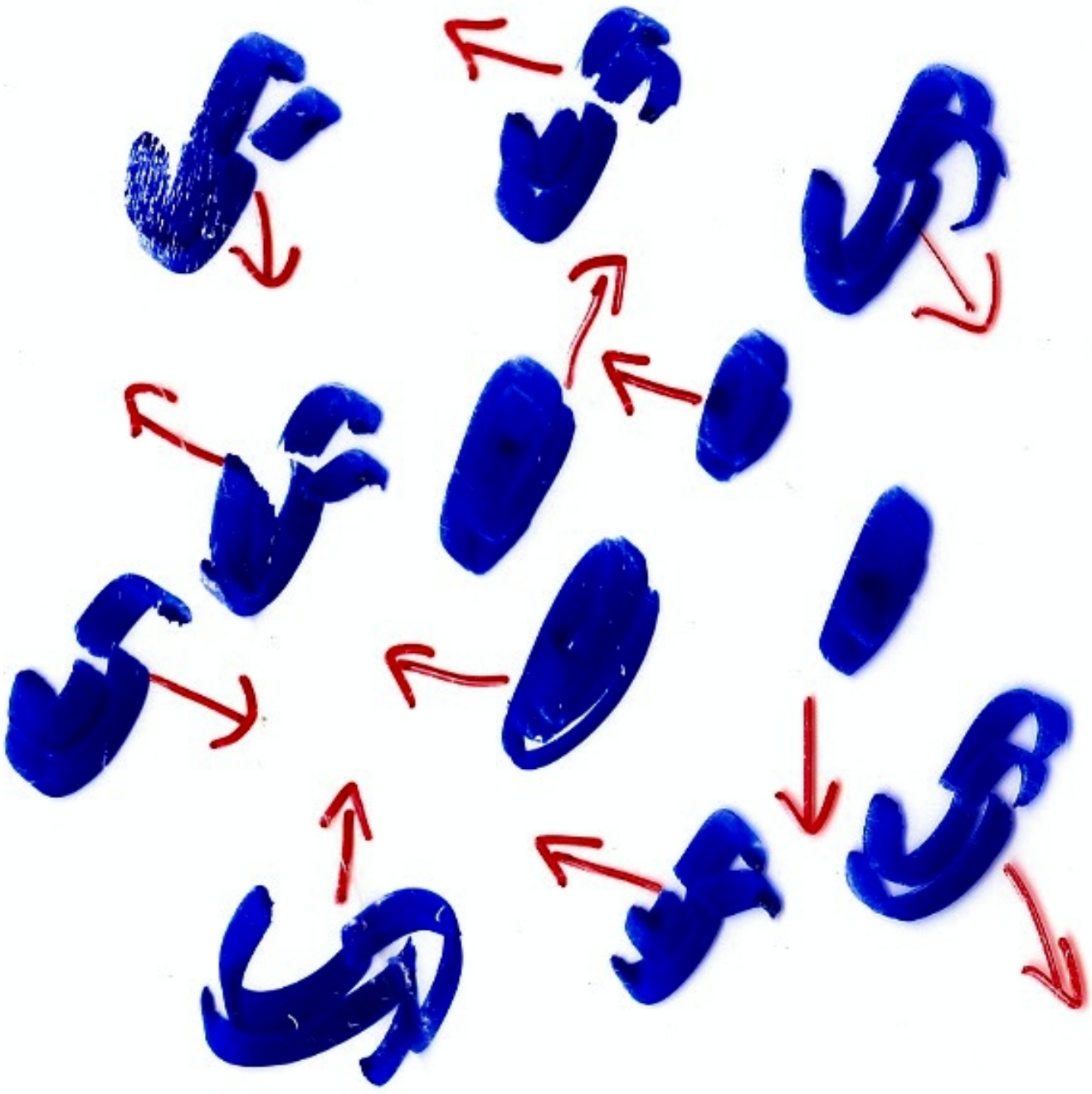
DARK MATTER HOLDS IT TOGETHER

DARK ENERGY DETERMINES ITS DESTINY

1935: Zwicky, Coma and Dark Matter

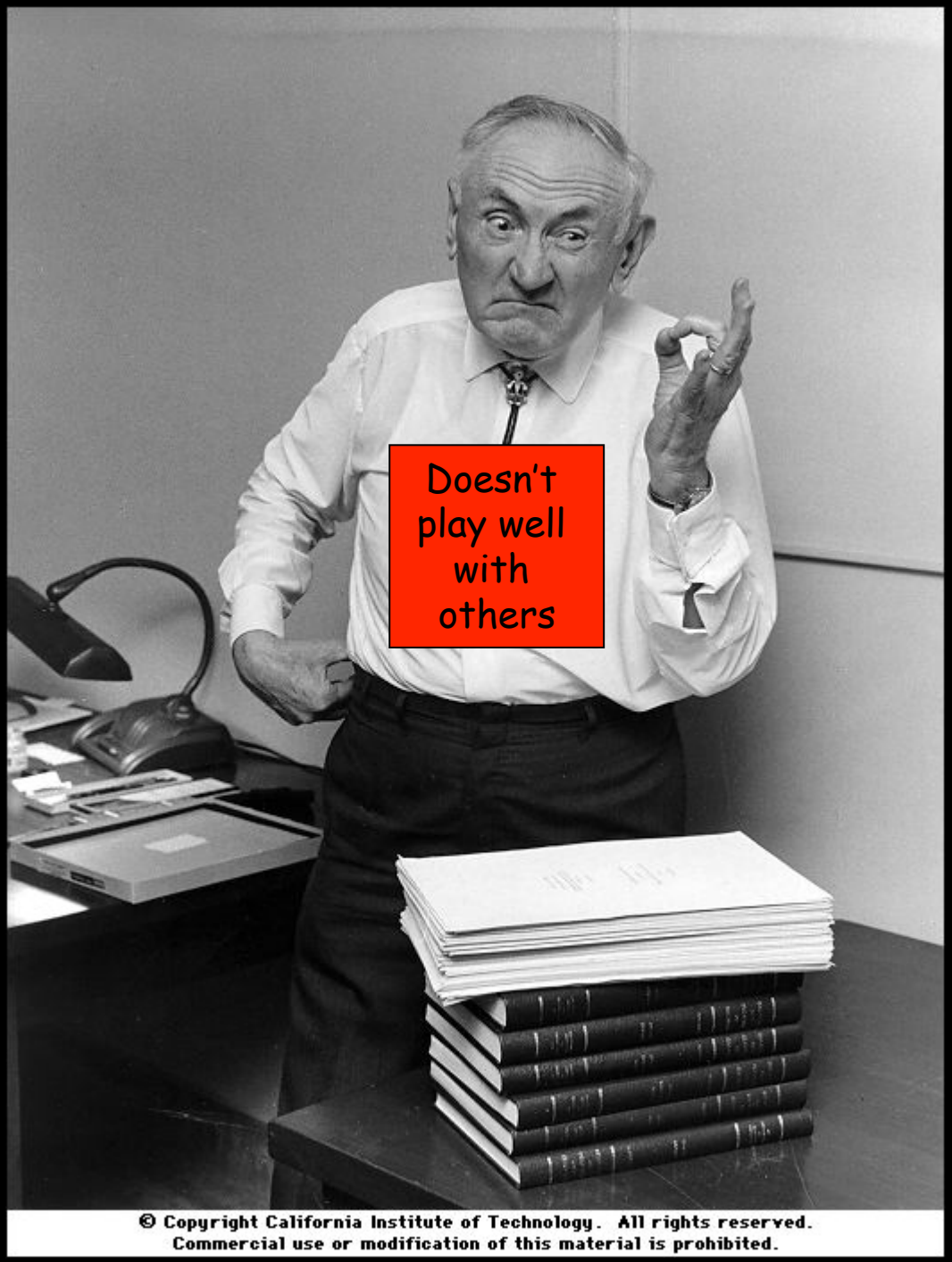



14h
13h
12h
11h
+30°
+20°
+10°
N4956
N5056
N5127
N3995
N4169
N4017
A1656
N3902
IC4342
N4005
N4213
N4065
A1367
U6583
N3801
IC944
N5174
Virgo
Cluster
IC698
rpowell



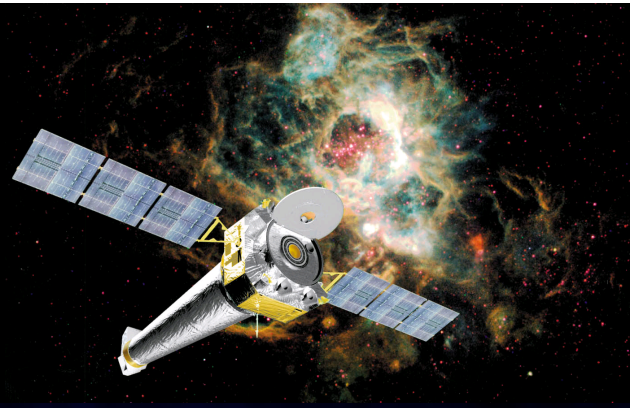
The Gravity of the Stars is not Enough to Hold Clusters Together

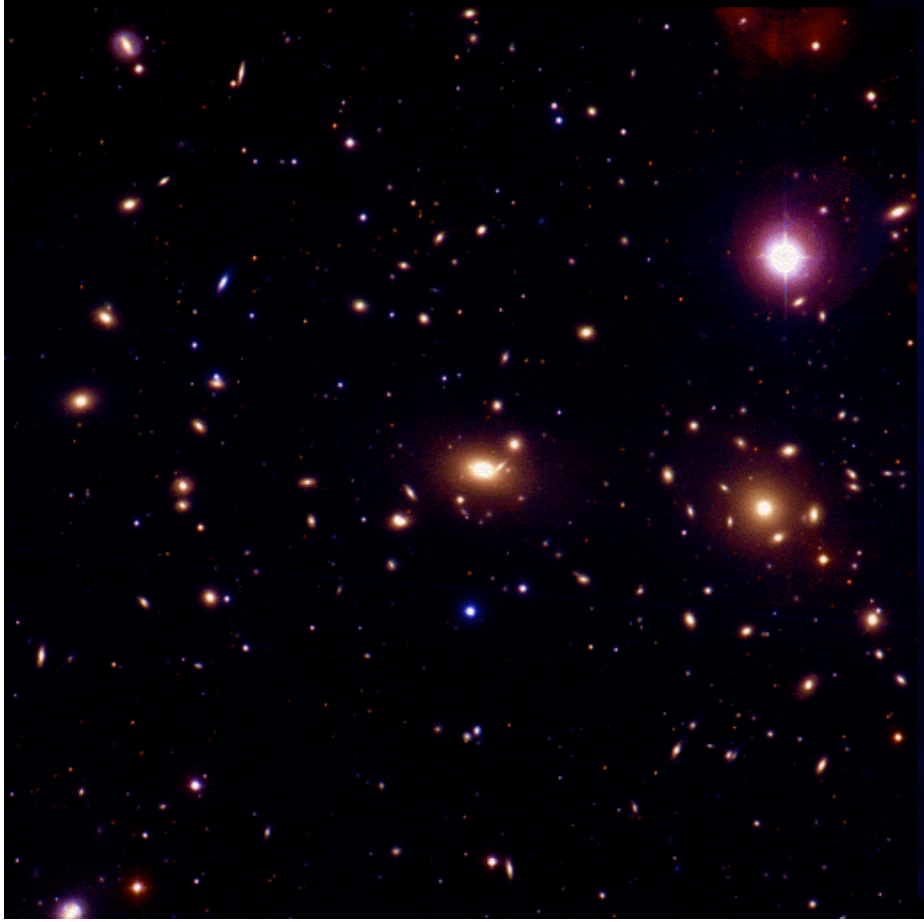
Zwicky: Clusters Must be Held Together by the Gravity of Unseen "Dark Matter"

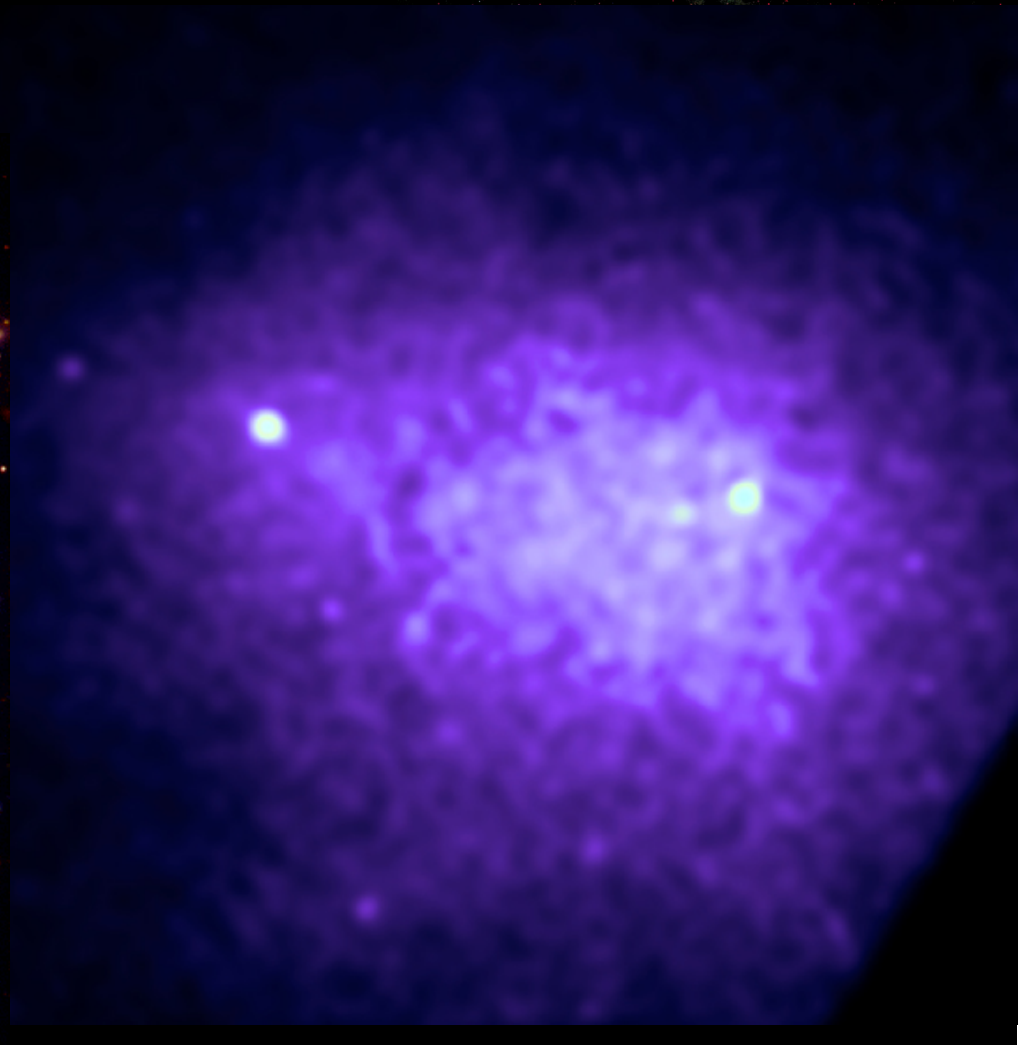


© Copyright California Institute of Technology. All rights reserved.
Commercial use or modification of this material is prohibited.

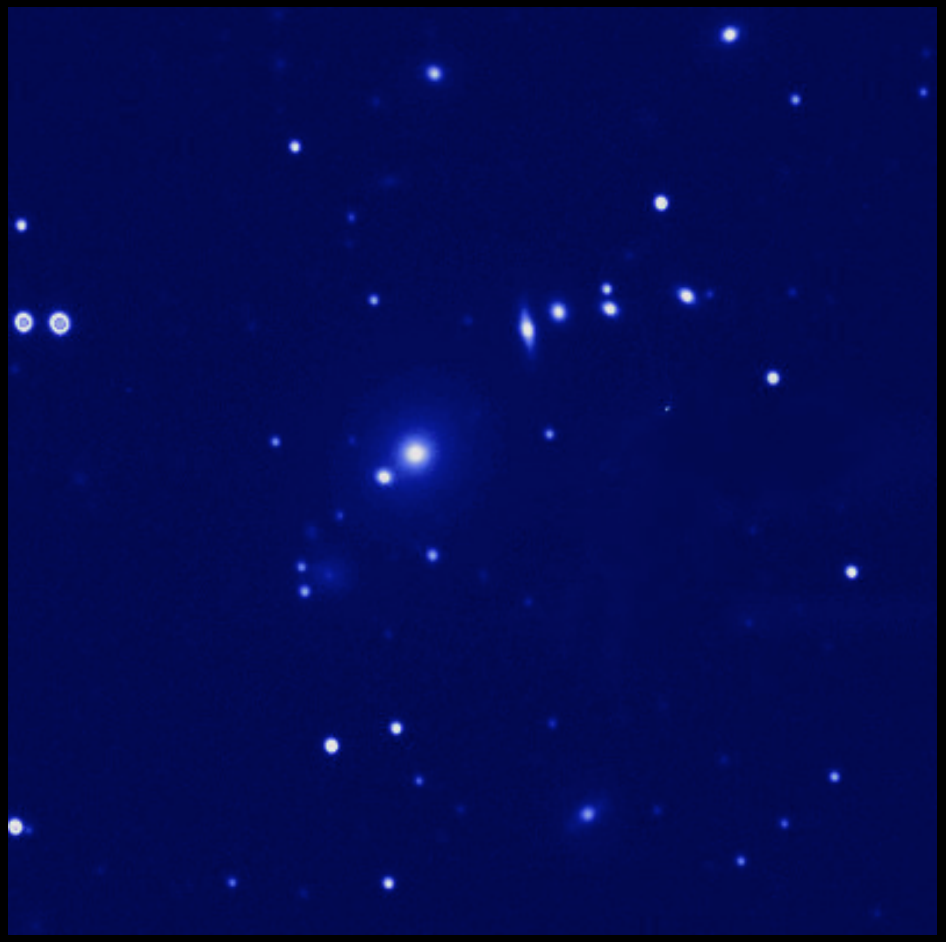
COMA in X-Ray

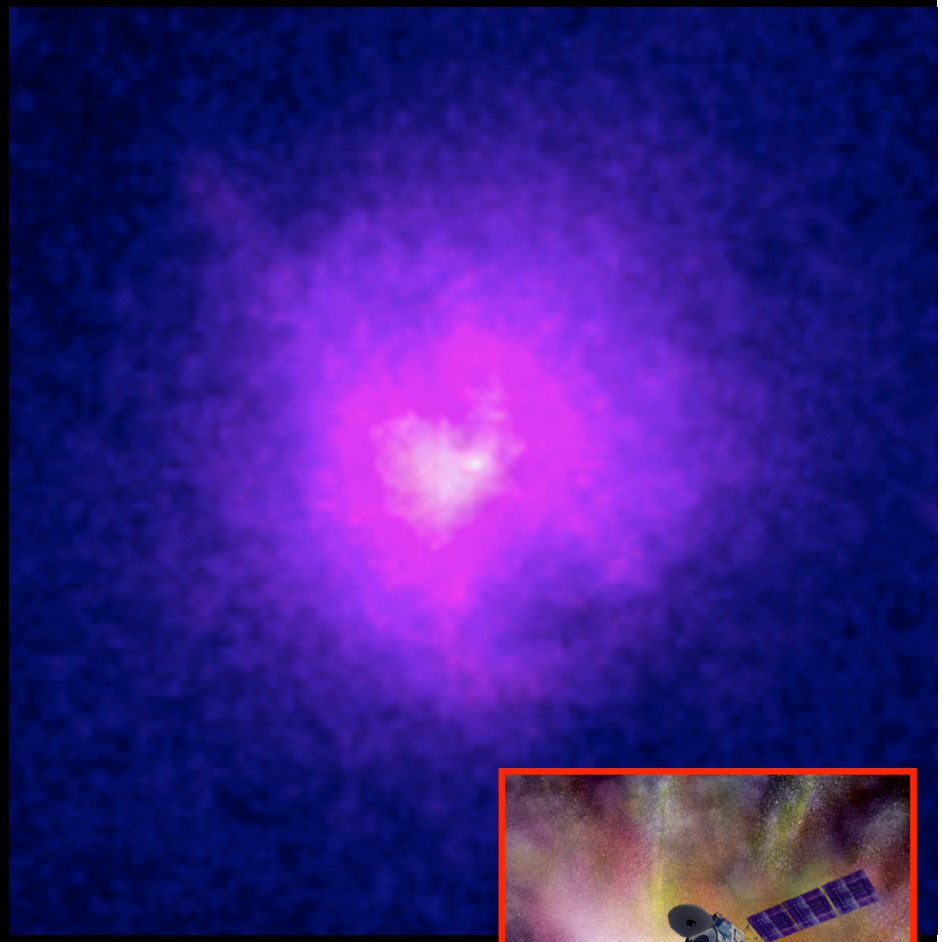


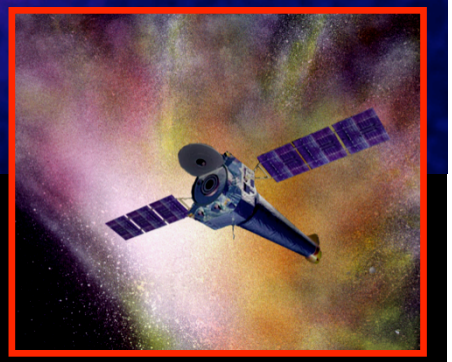




More than Meets the Eye





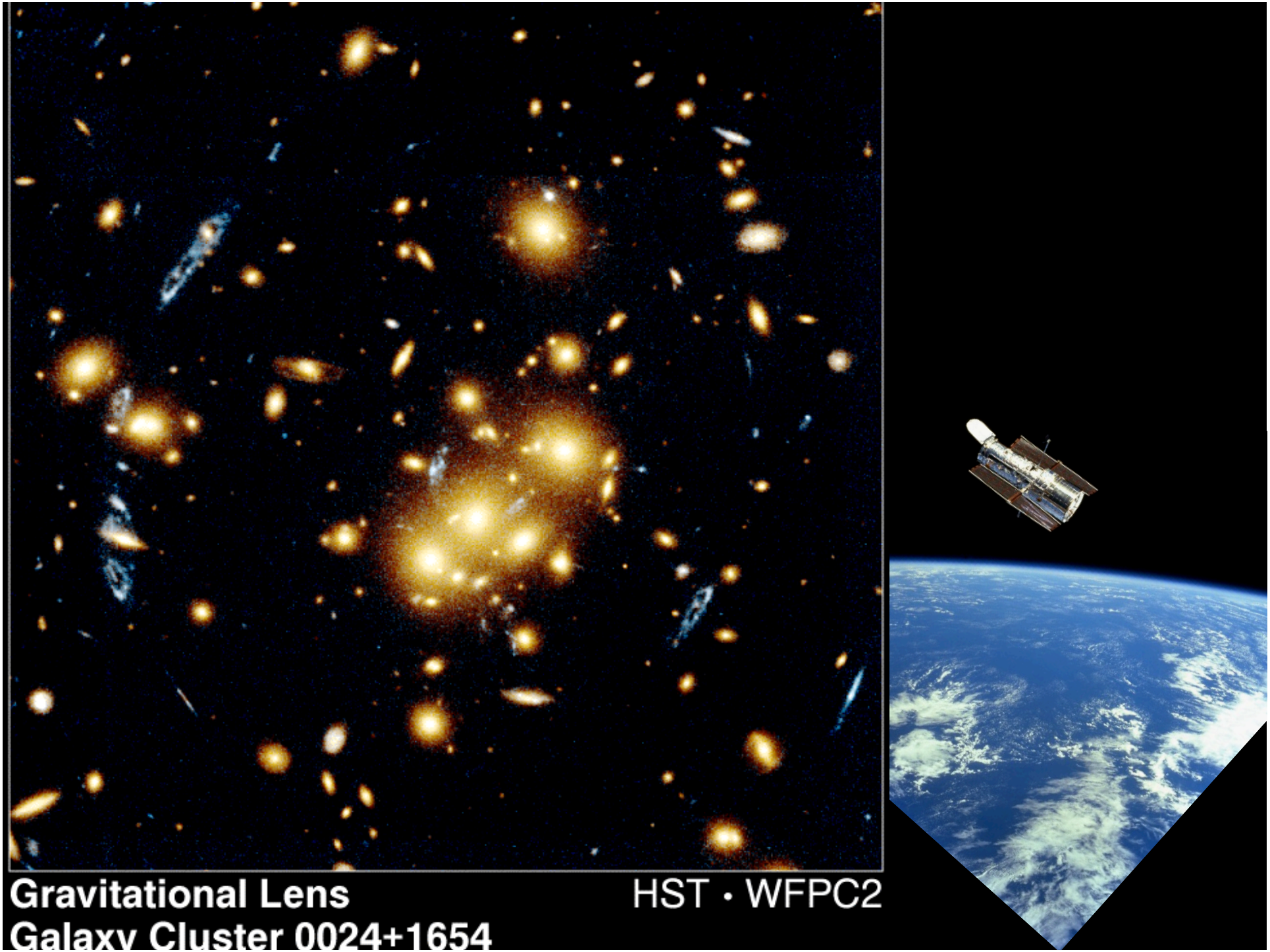


… but not enough to account for the dark matter

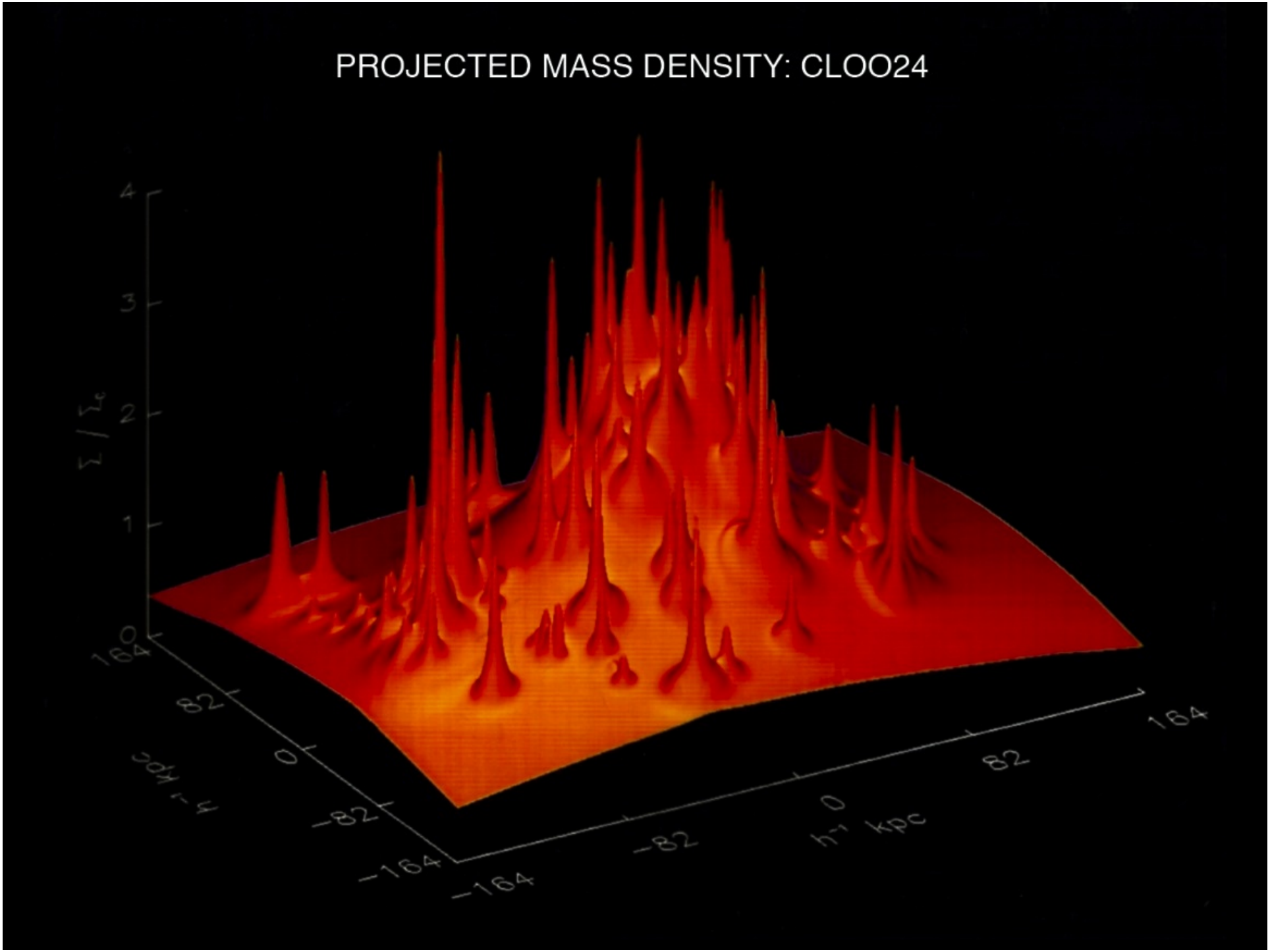
Lots of Hot, X-ray Gas

Accounts for Most of the Atoms in Clusters

… But a Factor of 6 Short of Accounting for the Dark Matter


Gravitational Lens
Galaxy Cluster 0024+1654
HST • WFPC2

PROJECTED MASS DENSITY: CLOO24



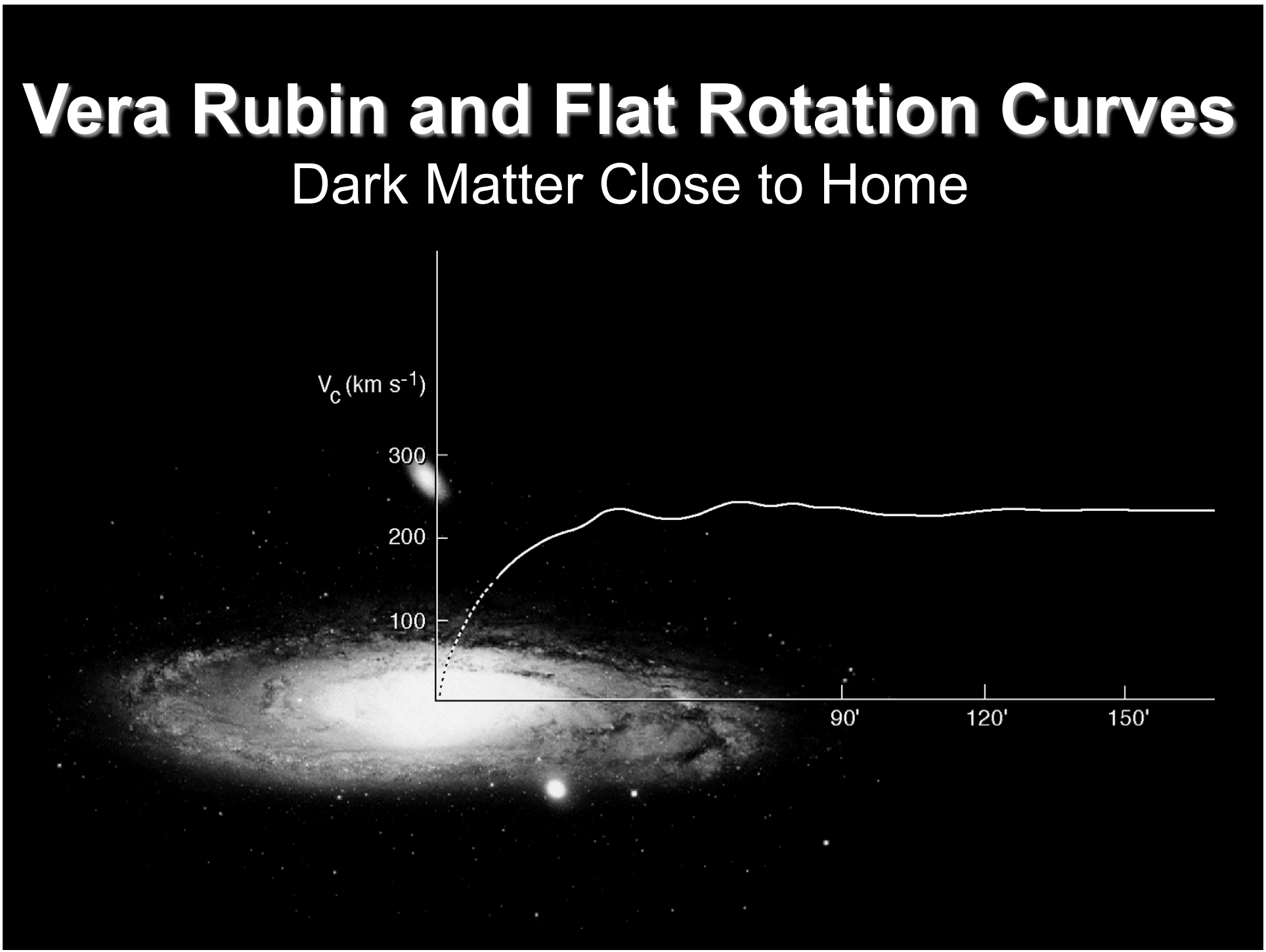
The Bullet Cluster

DARK MATTER

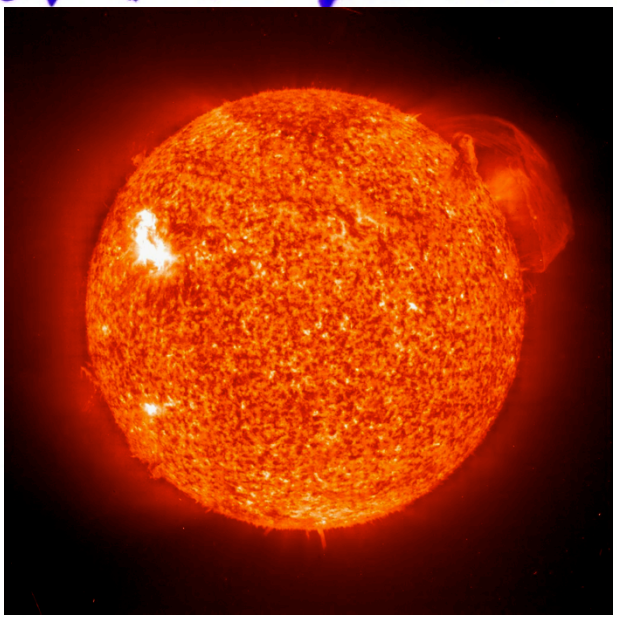
Most of the universe can't even be bothered to interact with you.

Vera Rubin and Flat Rotation Curves

Dark Matter Close to Home



ROTATION CURVE FOR SOLAR SYSTEM



ORBITAL SPEED

50 km/s

40 km/s

30 km/s

20 km/s

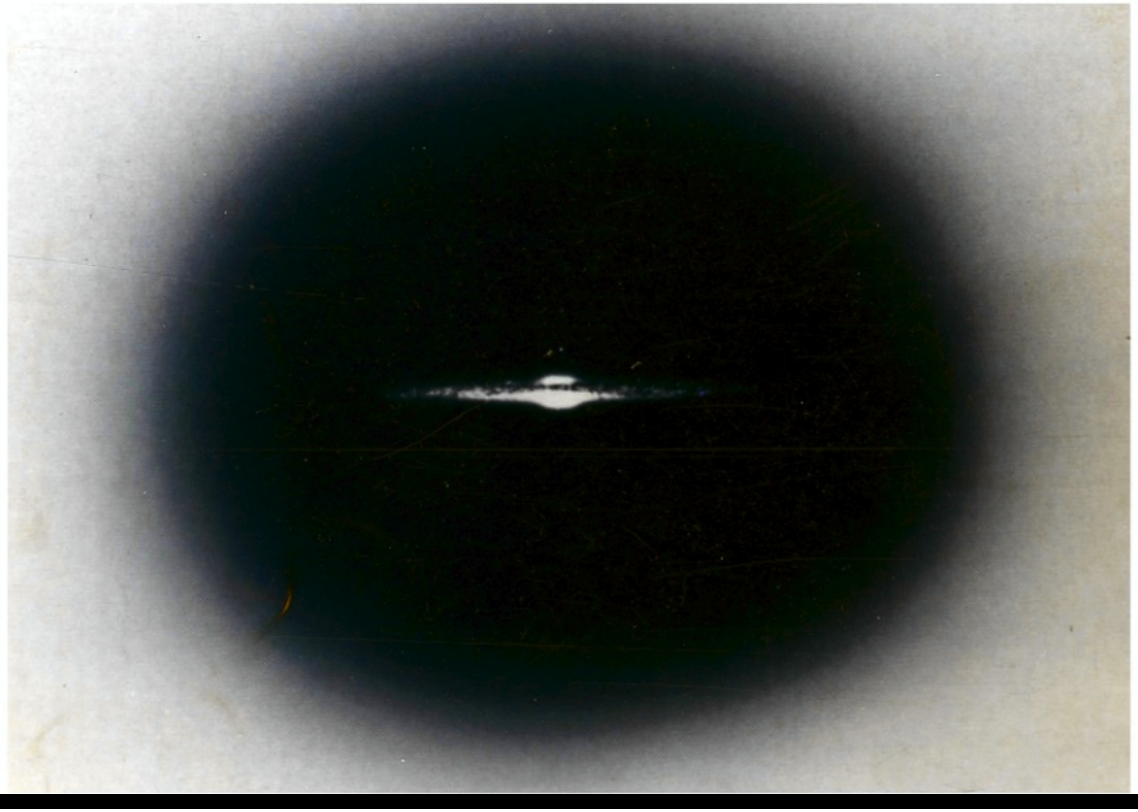
10 km/s

10AU 20AU 30AU 40AU

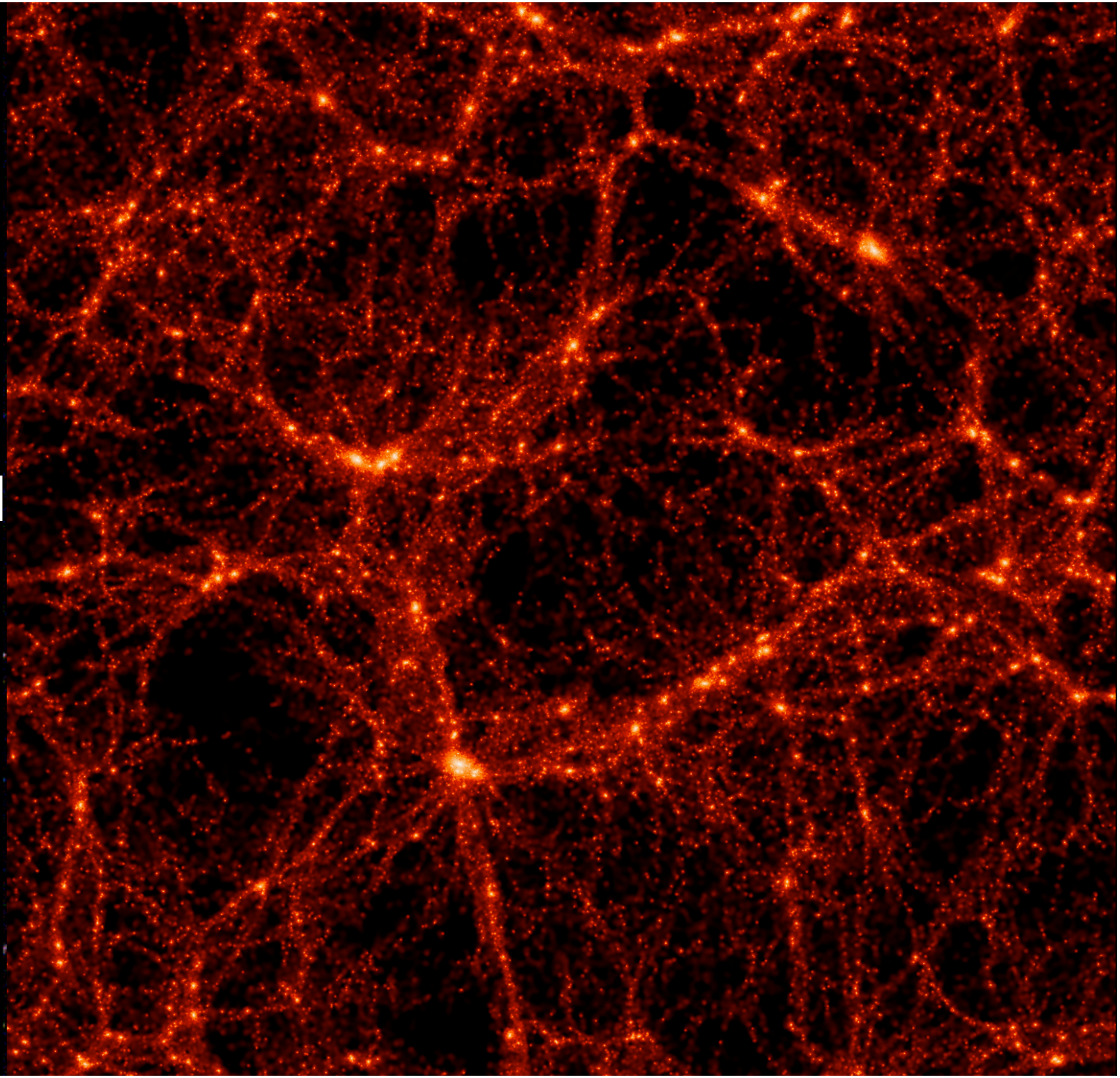
DISTANCE

AU = 90 MILLION MILES km/s = 2200 MPH

LOTS OF DARK MATTER-RIGHT HERE!



Cosmic Web of Dark Matter Decorated by Stars



So What is It?

- Black Holes? no
- White Dwarfs? no
- Green House Gas? no
- Dust? no
- None of the above!

NOT ENOUGH ORDINARY MATTER

4% OF CRITICAL

TO ACCOUNT FOR

THE AMOUNT OF DARK MATTER

33% OF CRITICAL

DARK MATTER IS A NEW FORM OF MATTER!

"COLD DARK MATTER"

Particles left over from the Quark Soup phase of cosmic evolution

ORDINARY MATTER: FROM QUARKS TO US

INFLATION
BARYOGENESIS

10^{-5} SEC

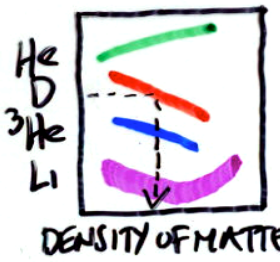
TRANSITION FROM
QUARKS → NEUTRONS, PROTONS

100 SEC

BBN

$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Omega_B = 0.04 \pm 0.002$



BIG-BANG
NUCLEOSYNTHESIS
Formation of H, D,
He, He-3, Li

FORMATION OF ATOMS

COSMIC MICROWAVE
BACKGROUND

400,000 YRS

QSO LIGHT

1 BILLION YRS
FIRST QUASARS

CMB

CMB

RATIO OF FIRST-TO-
SECOND PEAKS: 2/1

$\Omega_B = 0.045 \pm 0.008$

INTERGALACTIC GAS

ABSORPTION OF
QUASAR LIGHT
BY HYDROGEN

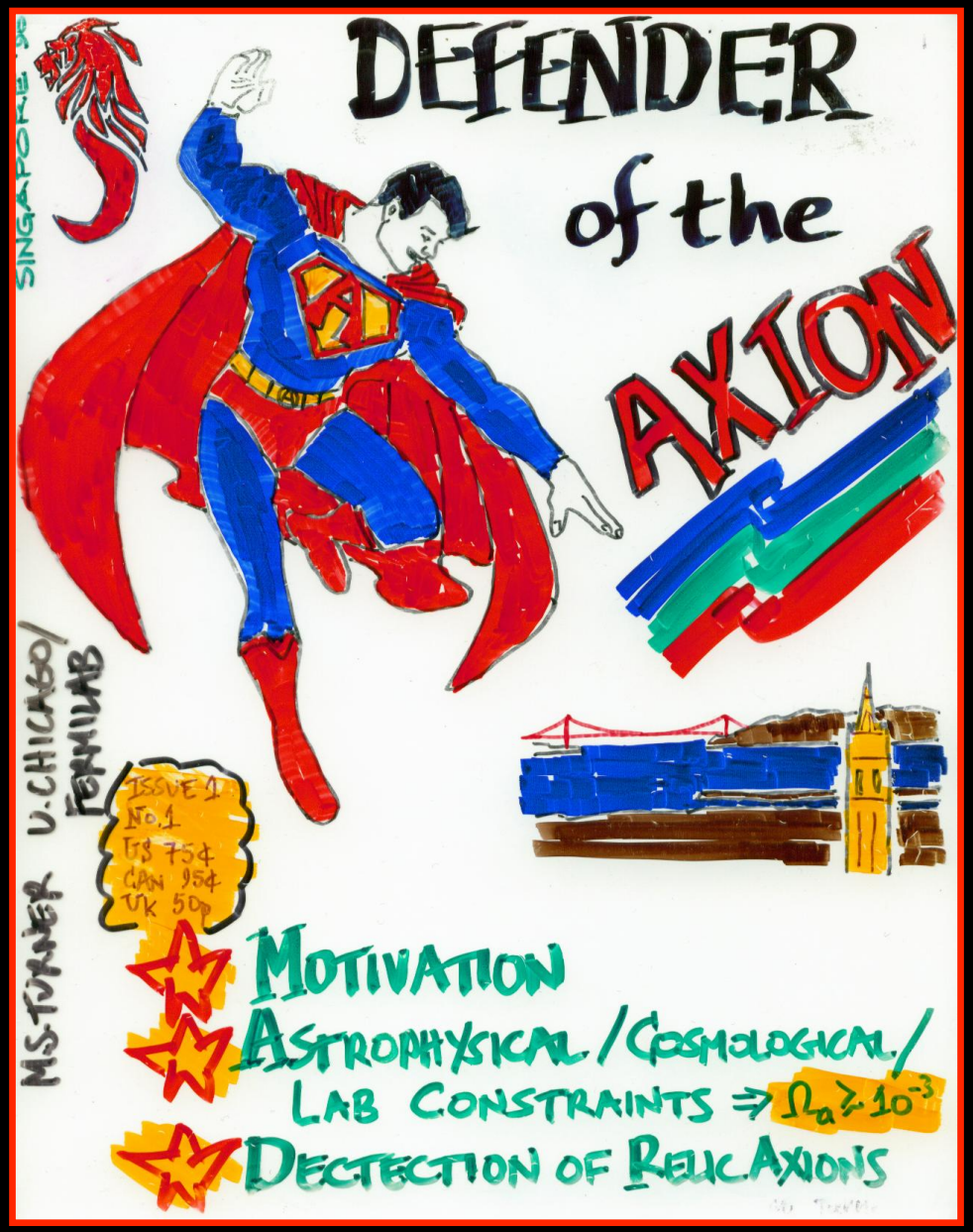
$\Omega_B \geq 0.04$

HERE & NOW
14 Billion YRS
stars, gas,
dust, ...

MOOSE DIAGRAM of DARK MATTER CANDIDATES

MBT '90

The Axion is My Favorite!



… and we now know that neutrinos are a (small) part of the dark matter (few tenths of a percent)

Its time to indentify the rest!

In the sky, on the ground and underground

HIGGS BOSON

H

ory

DARK MATTER

?

DARK MATTER is the name given to material in the Universe

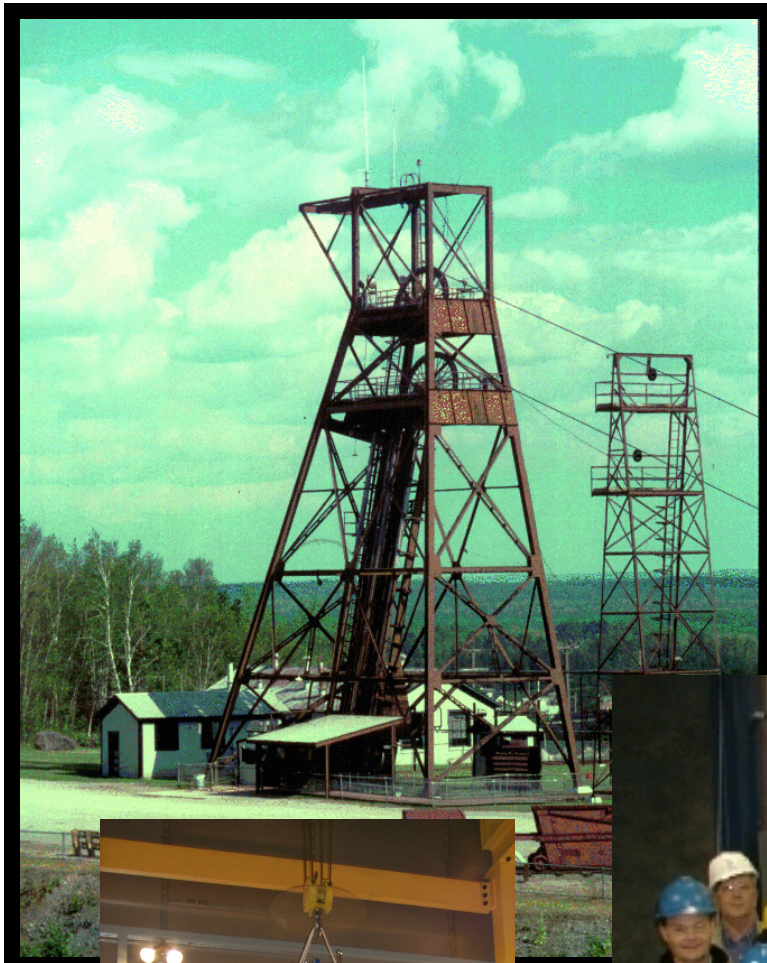
LIGHT

LIGHT

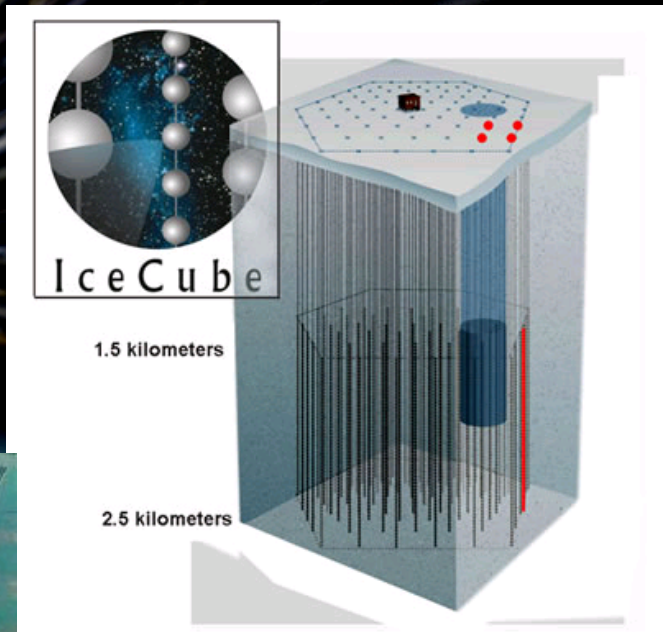
GLUON PHOTON NEUTRINO T GLUON PHOTON
NEUTRON DOWN QUARK TAU NEUTRON DOWN
NEUTRINO MUON UP QUARK NEUTRINO MUO
ARK PROTON NEUTRON DOWN QUARK TAU GLU
RK TAU NEUTRINO MUON UP QUARK PROTON N
ON ELECTRON UP QUARK DOWN QUARK TAU NEU

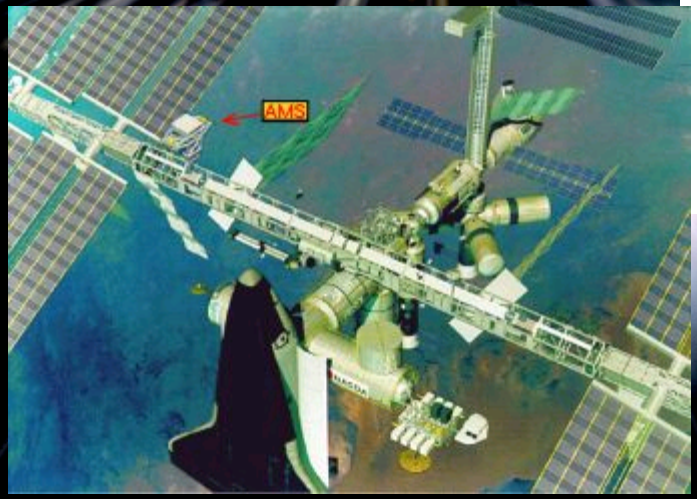
The PARTIC The PARTICLE ZOO

Soudan Mine, MN
Dark Matter Search

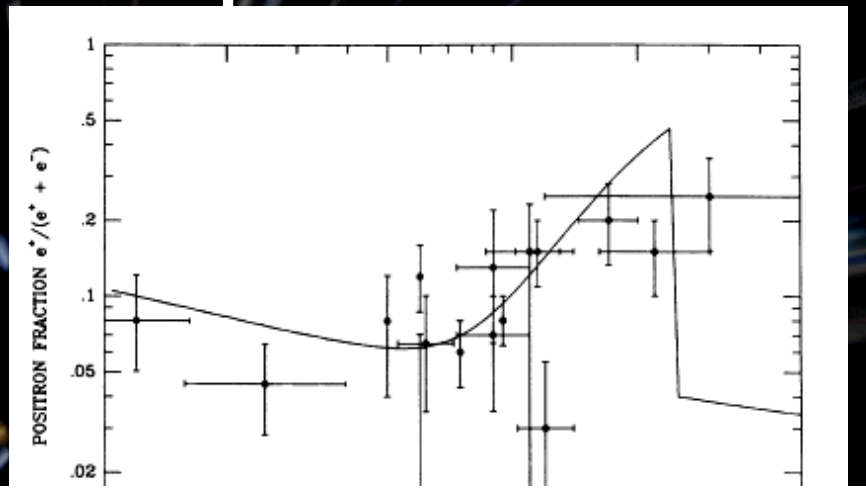


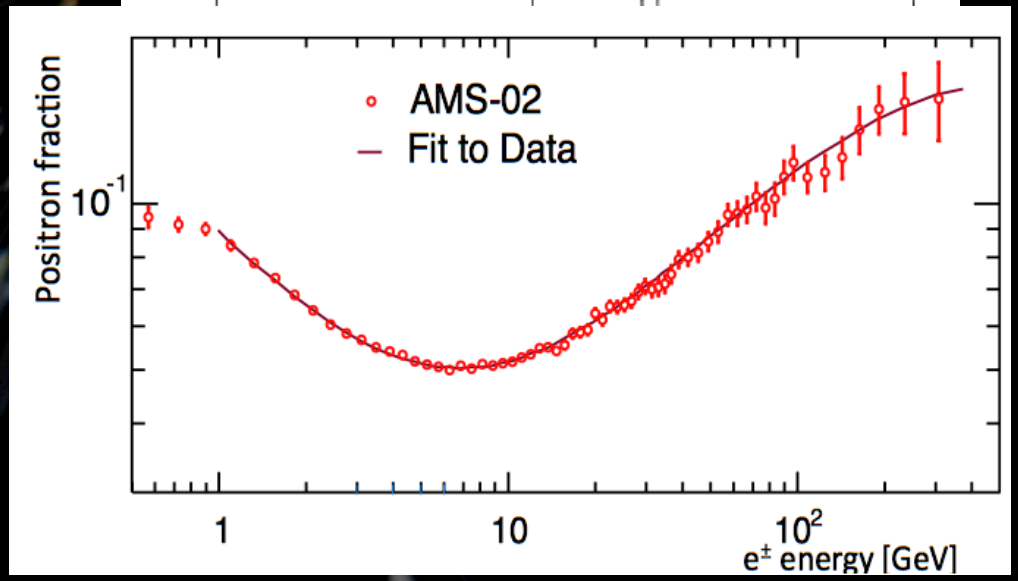
Dark Matter annihilating in our halo produces positrons, neutrinos and gamma rays





AMS: Dark Matter annihilating into electrons and positrons?





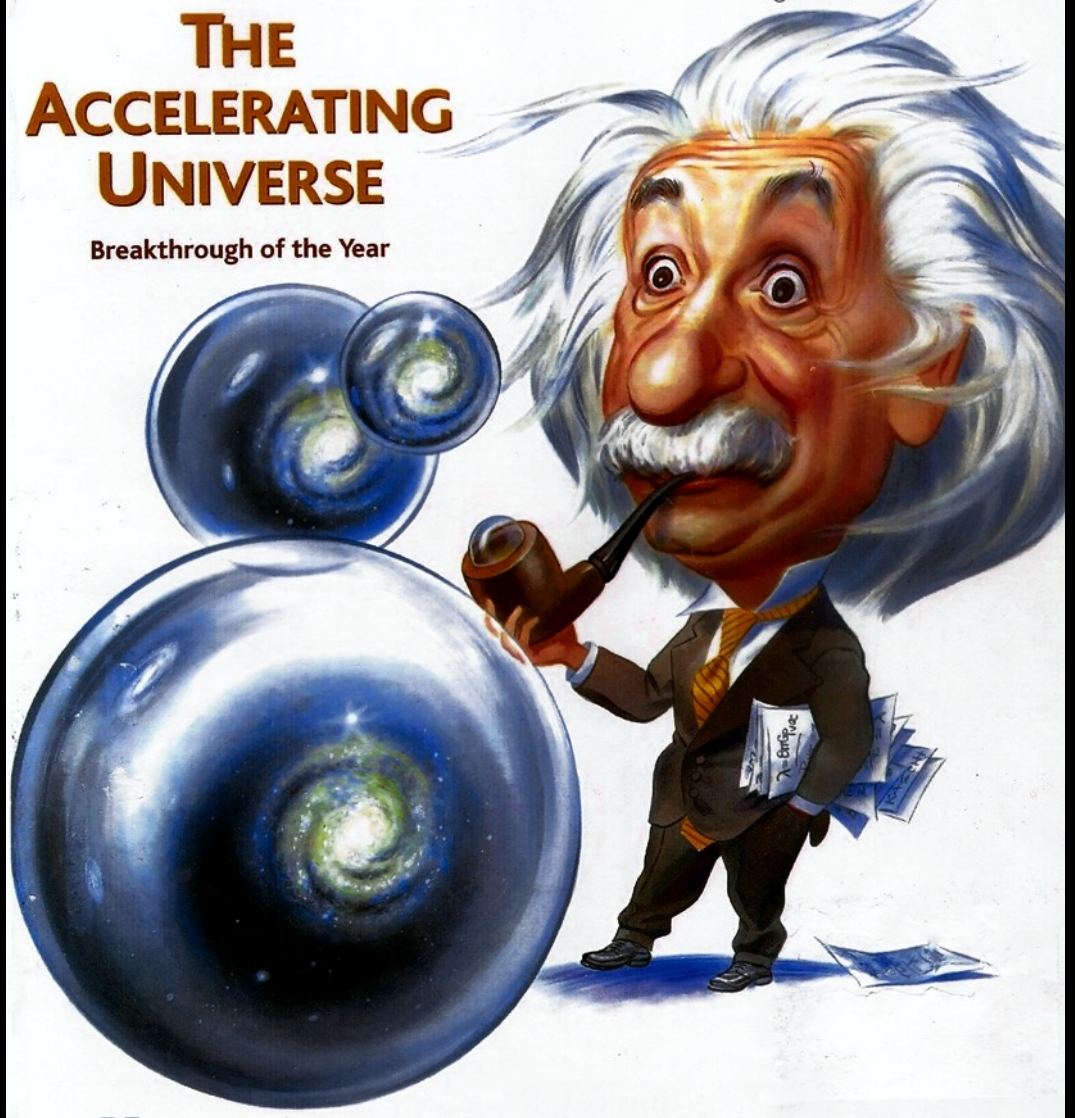
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

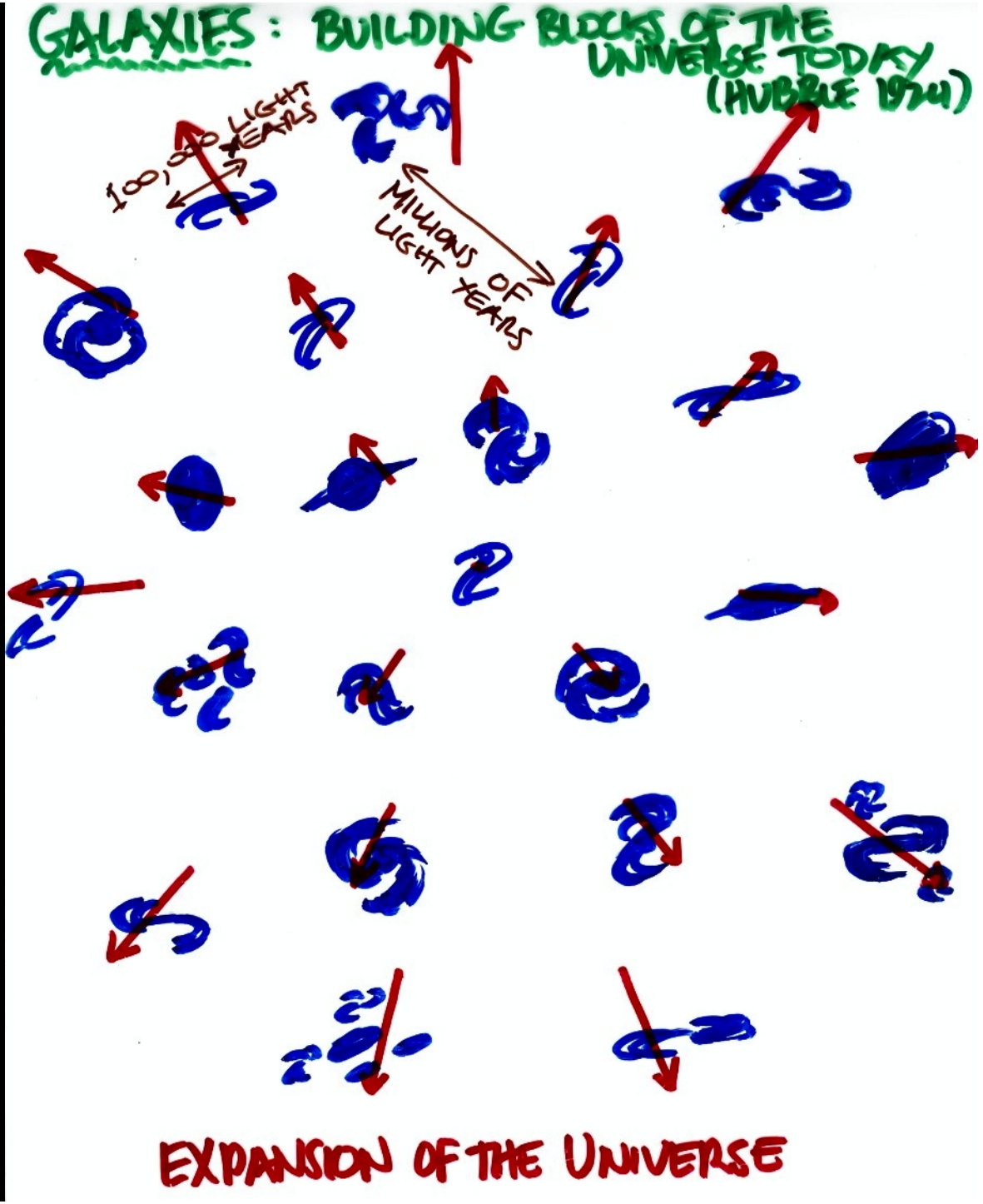
Discovery!

Hi z Supernova Team

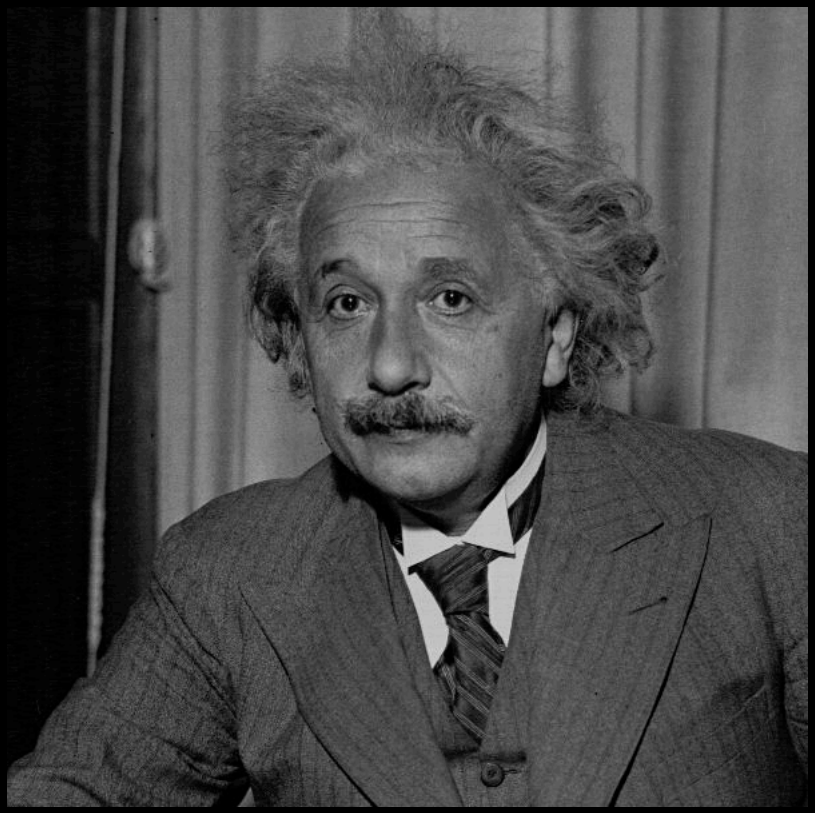
Supernova Cosmology Project

The Universe is expanding and had a beginning

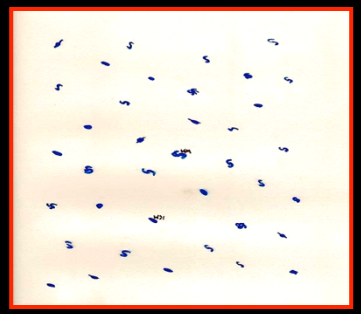
… Hubble, 1929

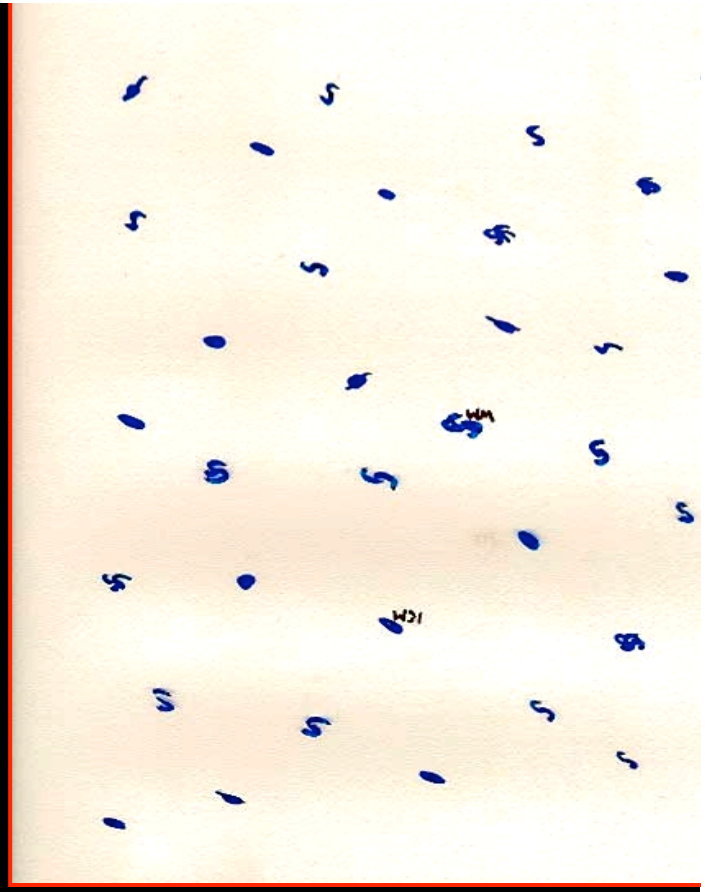


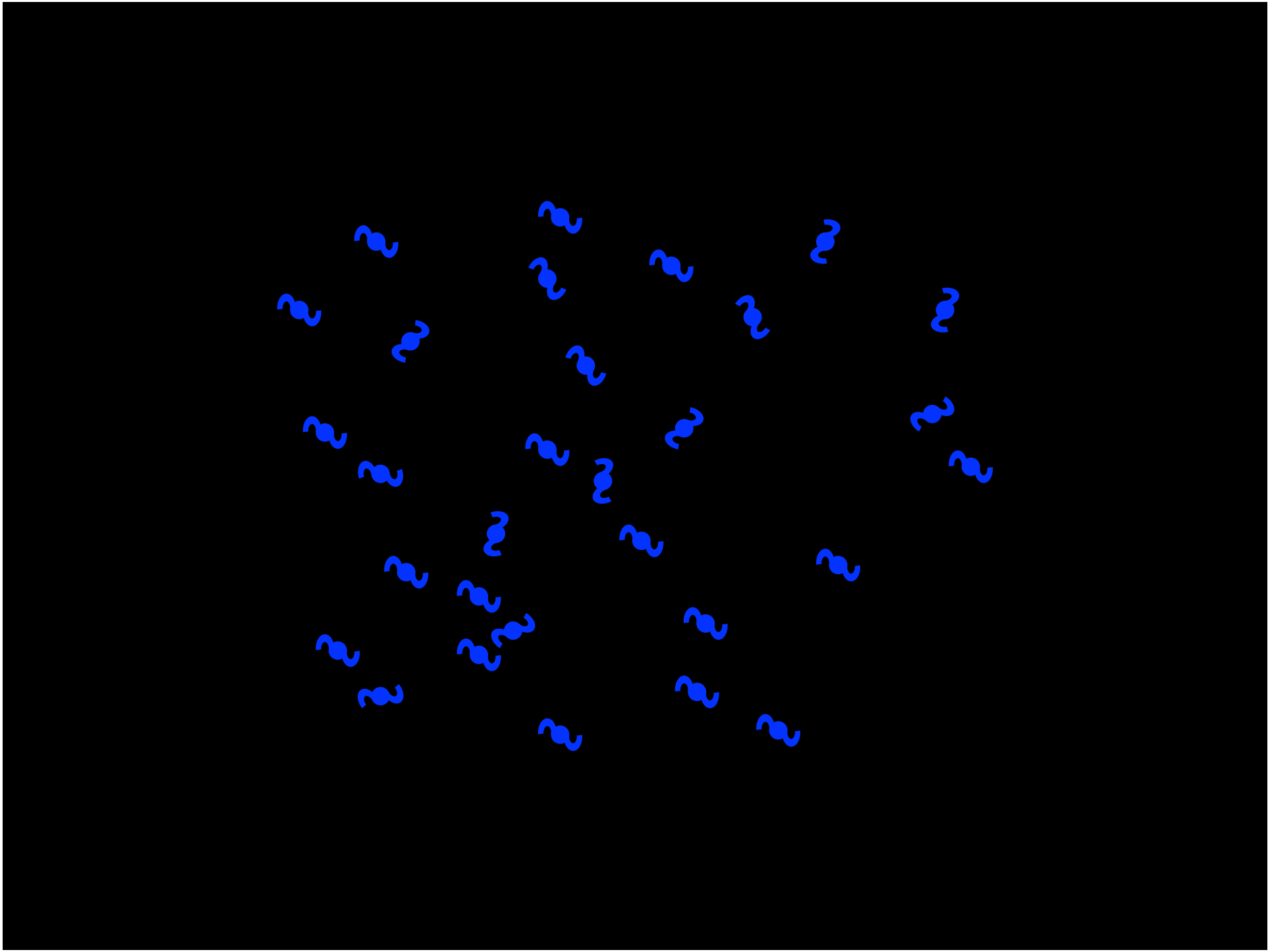
Not an explosion into space but An Explosion of Space (galaxies carried along)

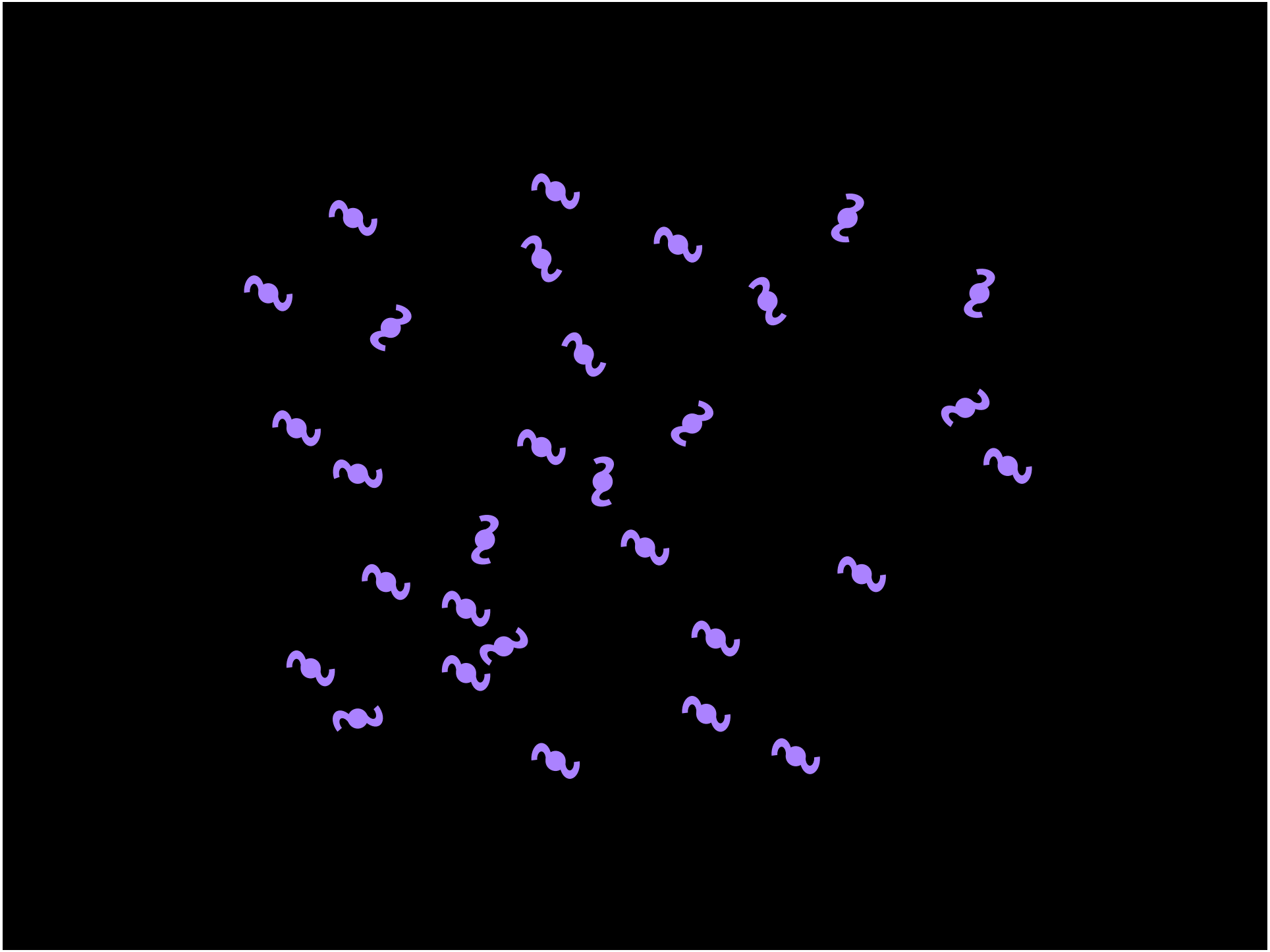


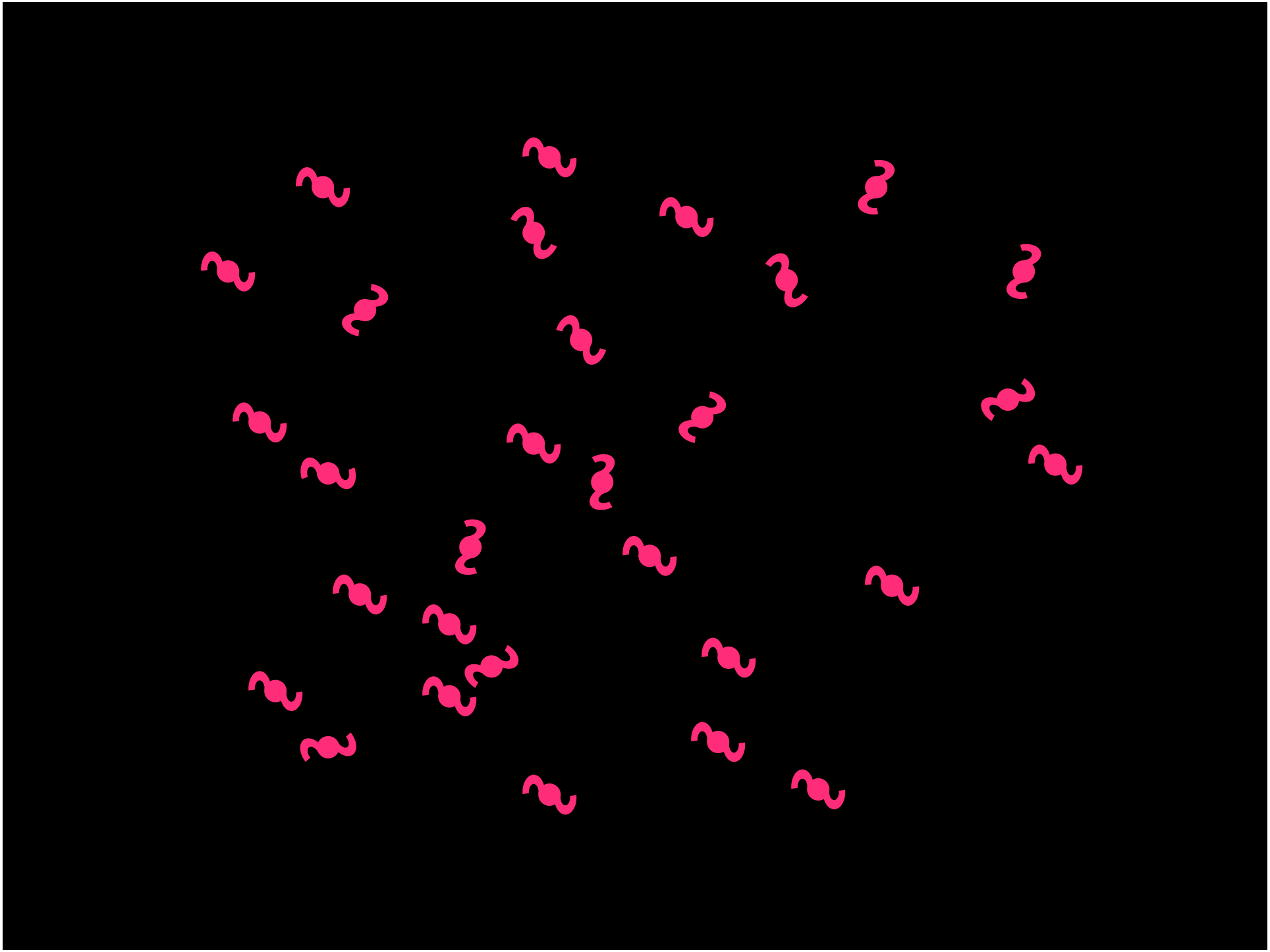
Time warps, space stretches and God plays dice!

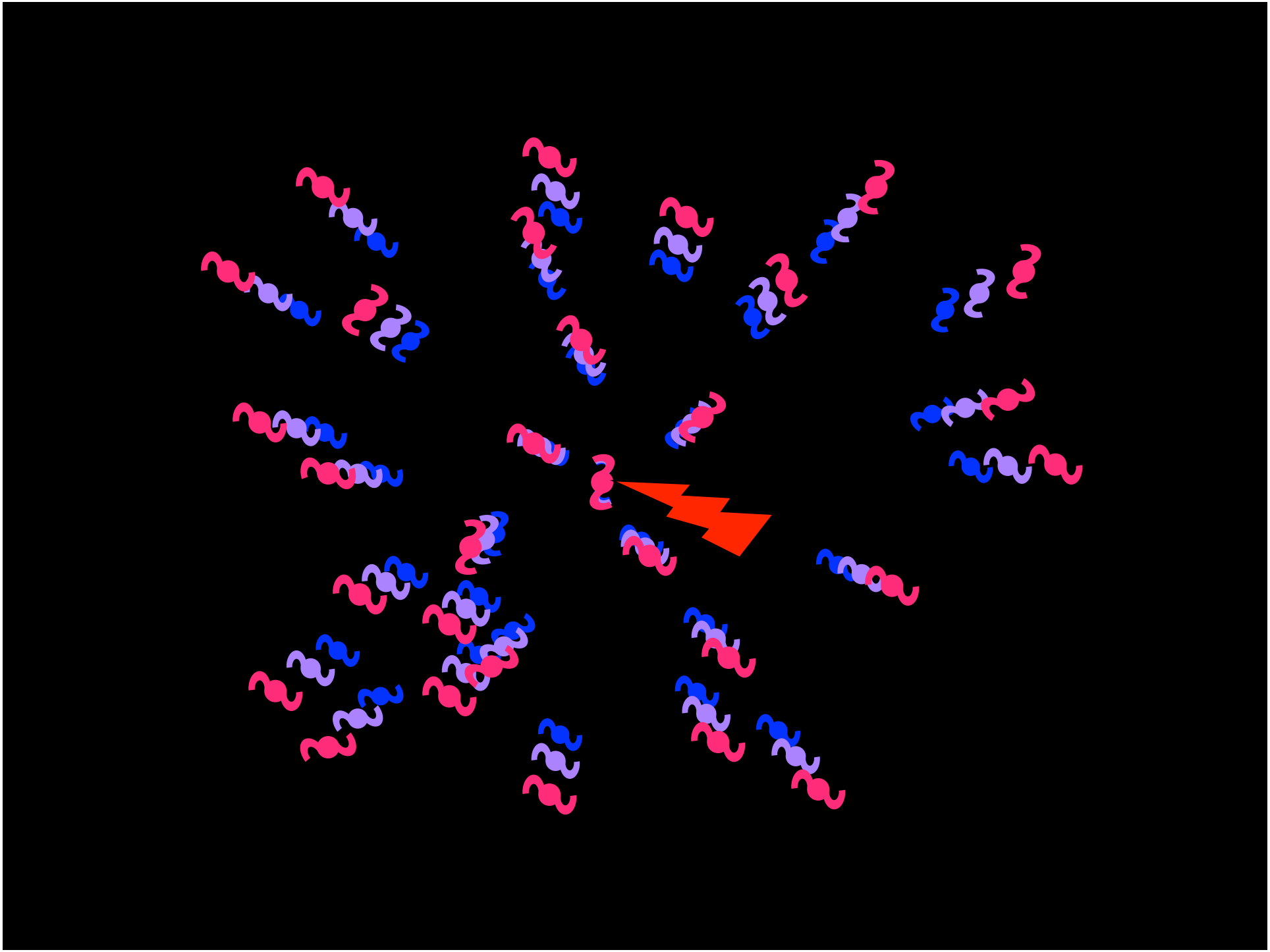


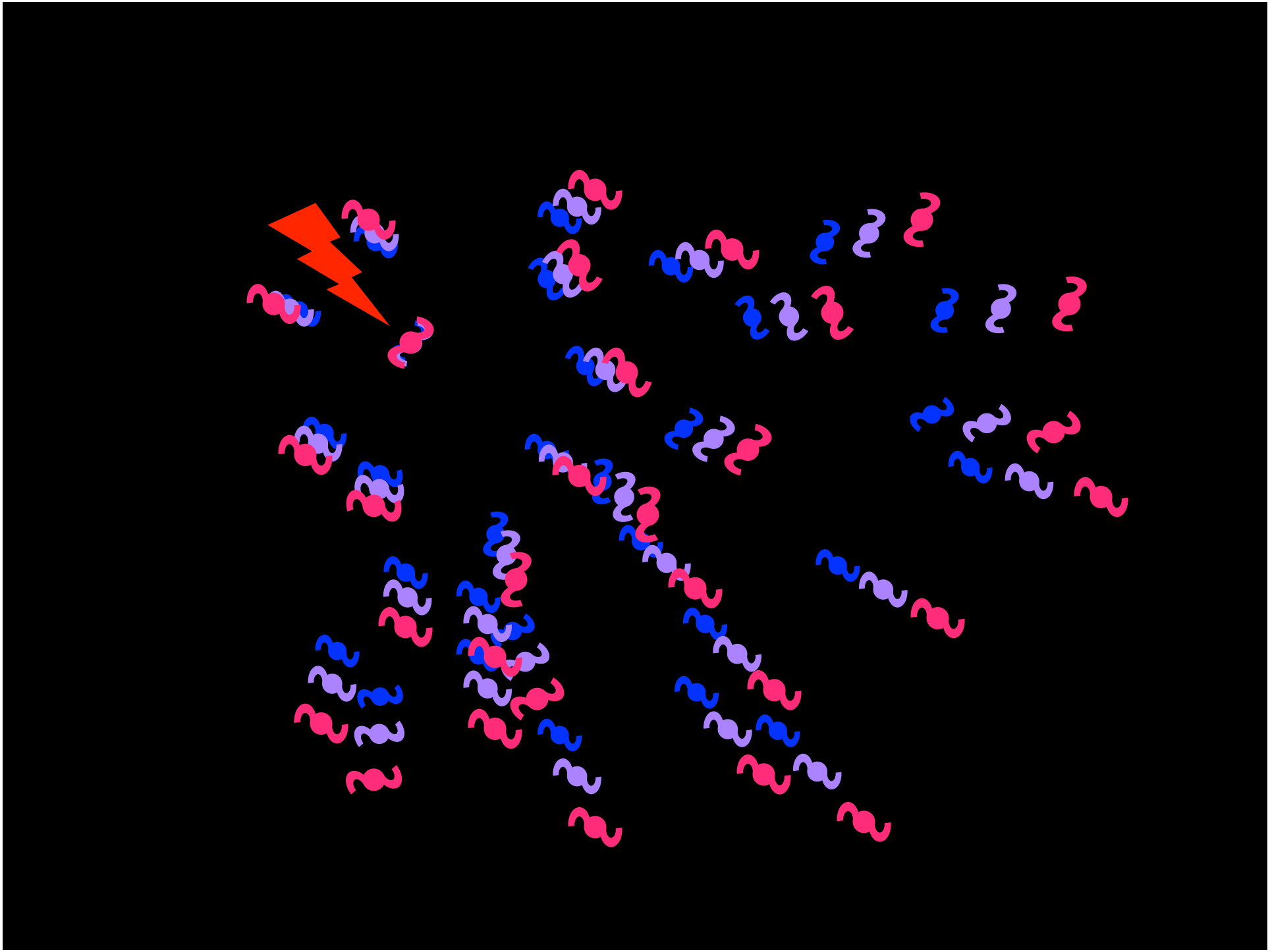


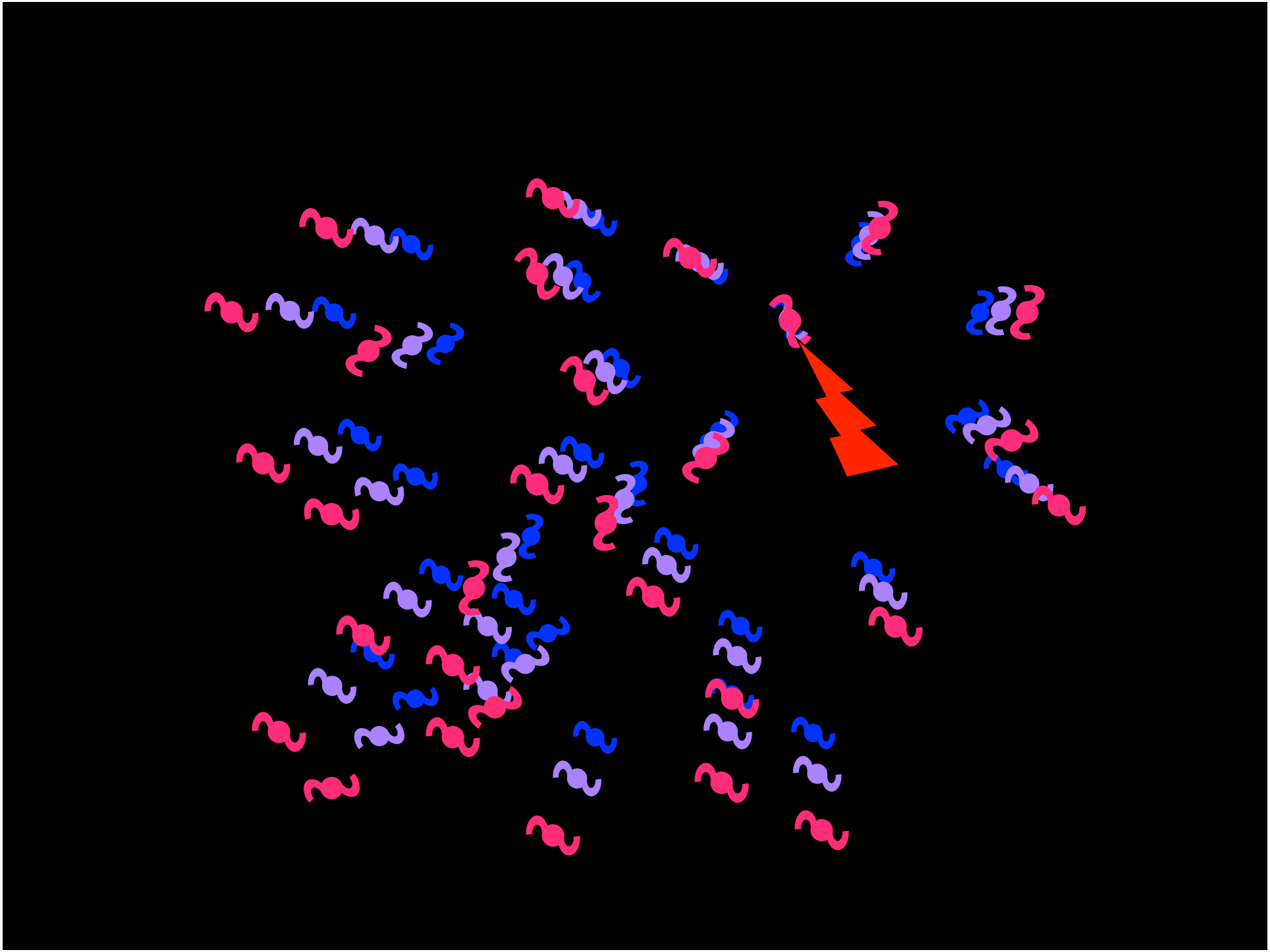




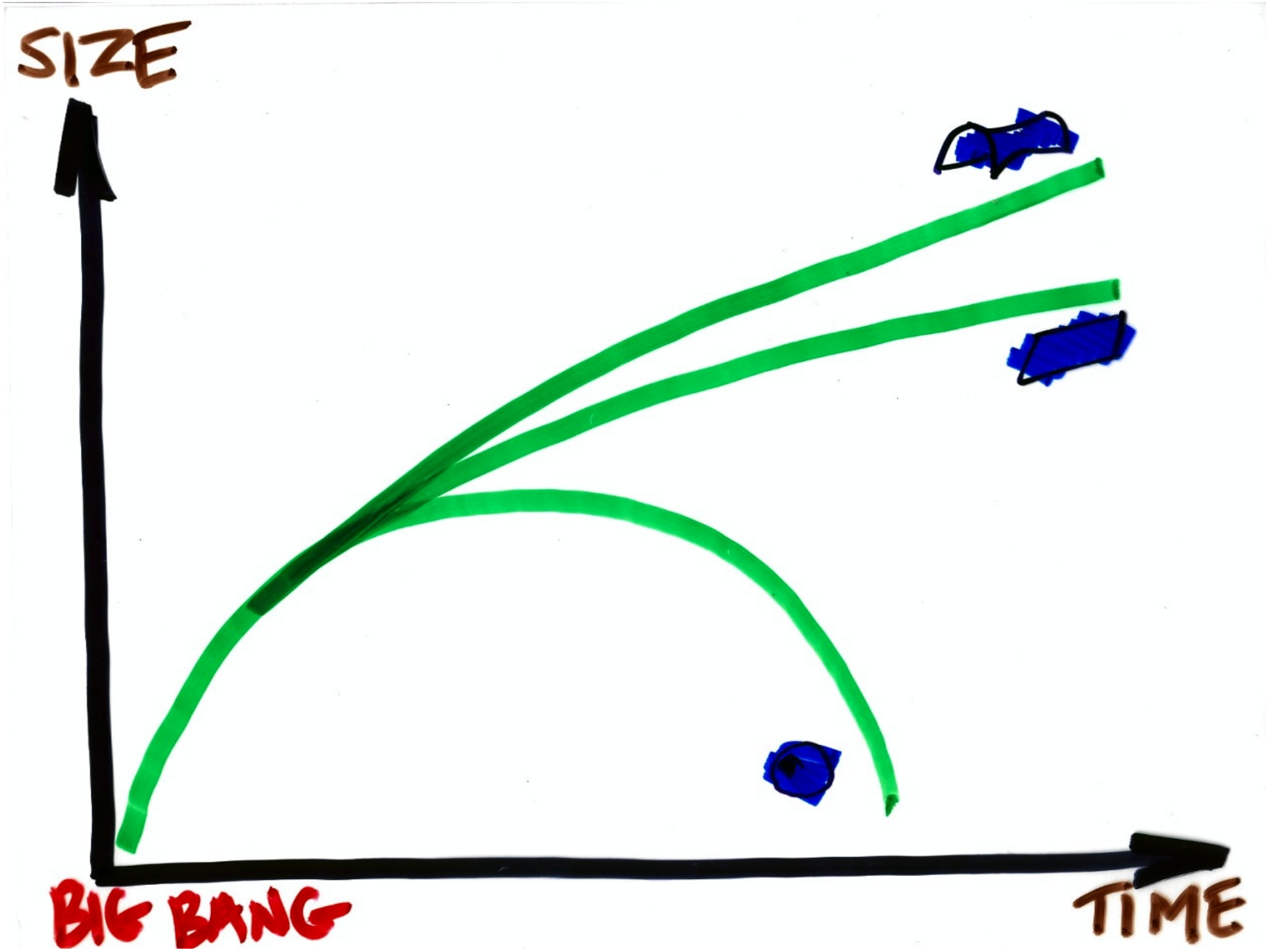




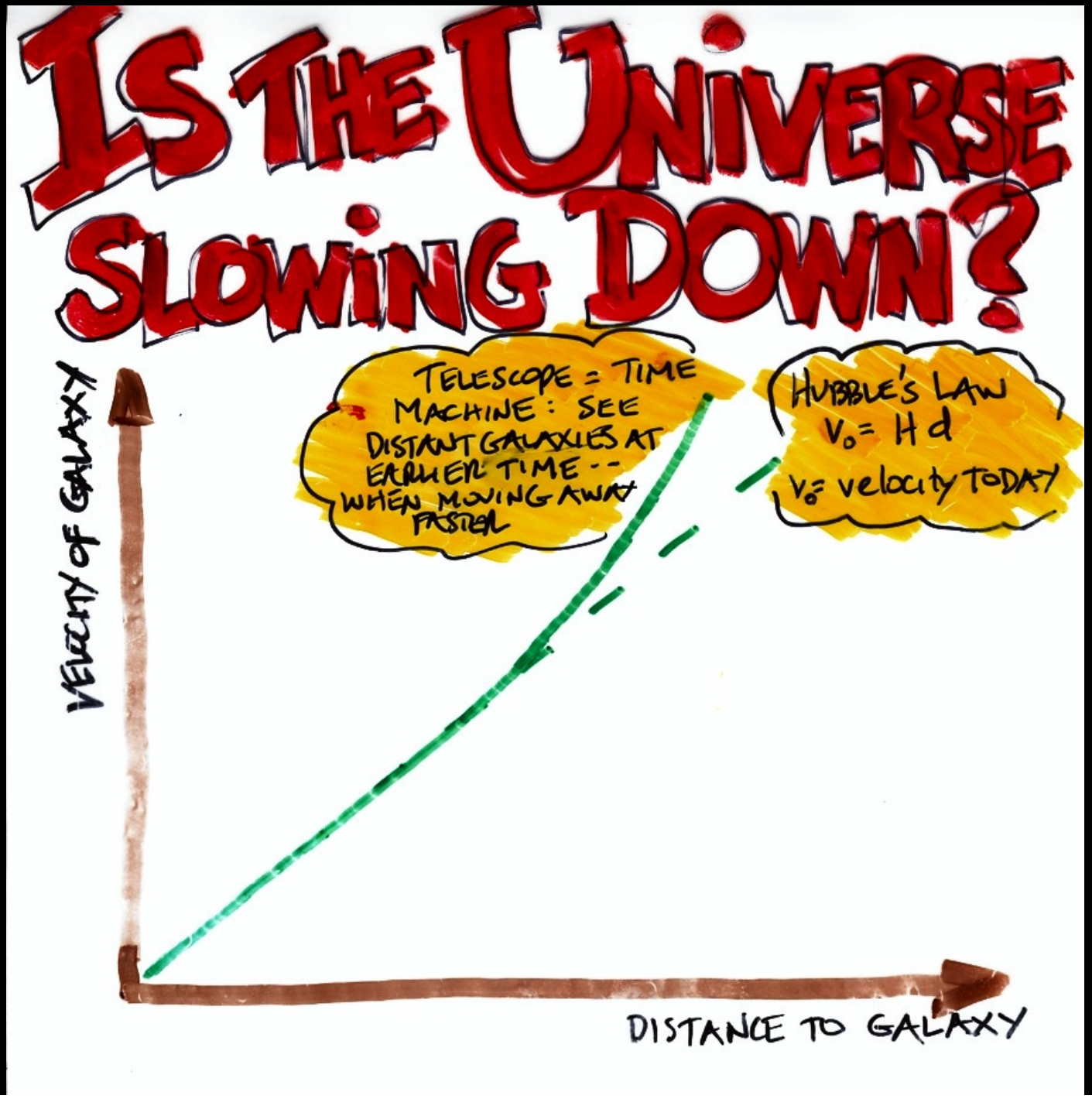




No Center
Different Perspectives
One Scale Factor


SIZE
BIG BANG
TIME

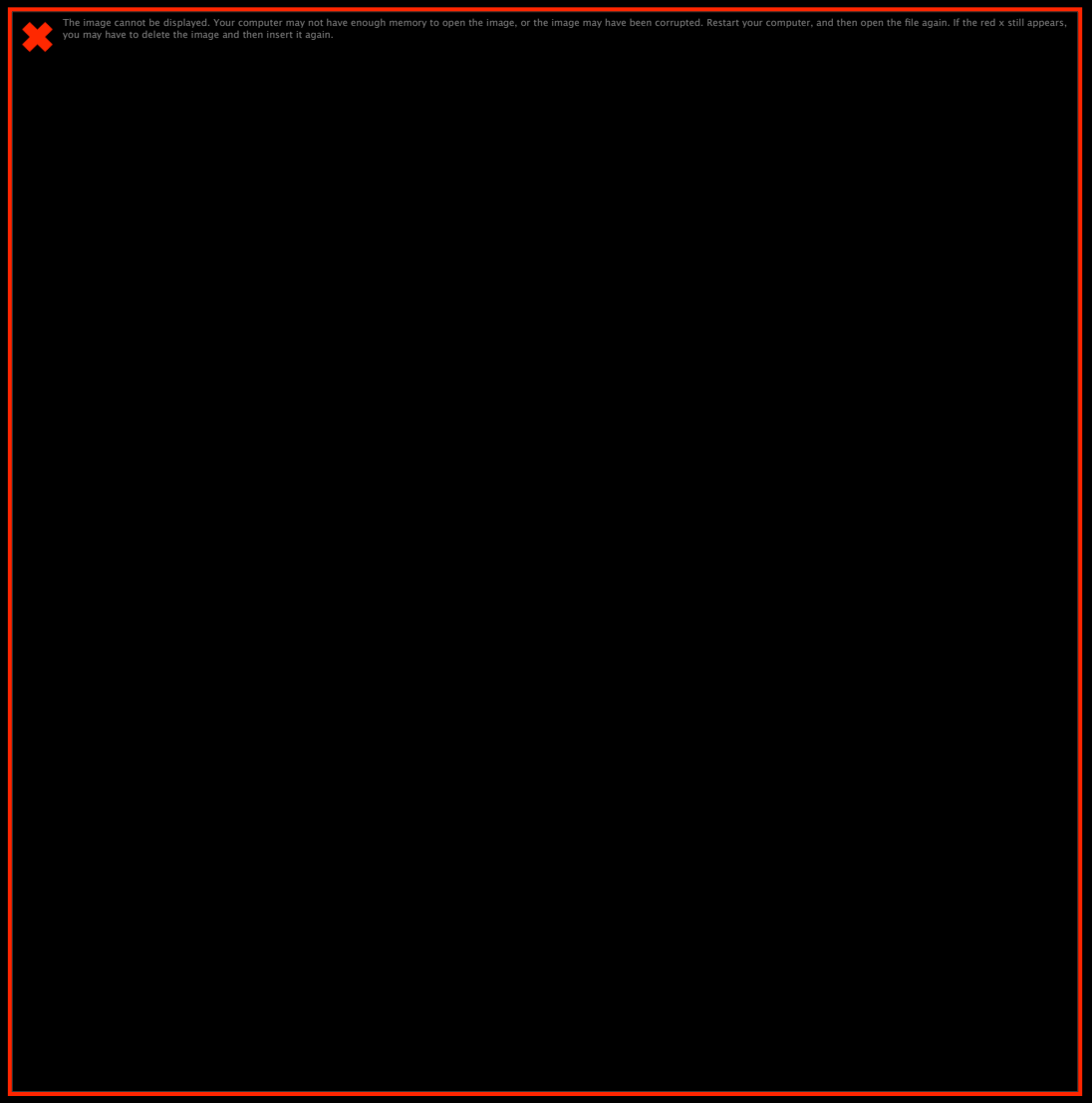
Is the Universe Slowing Down?

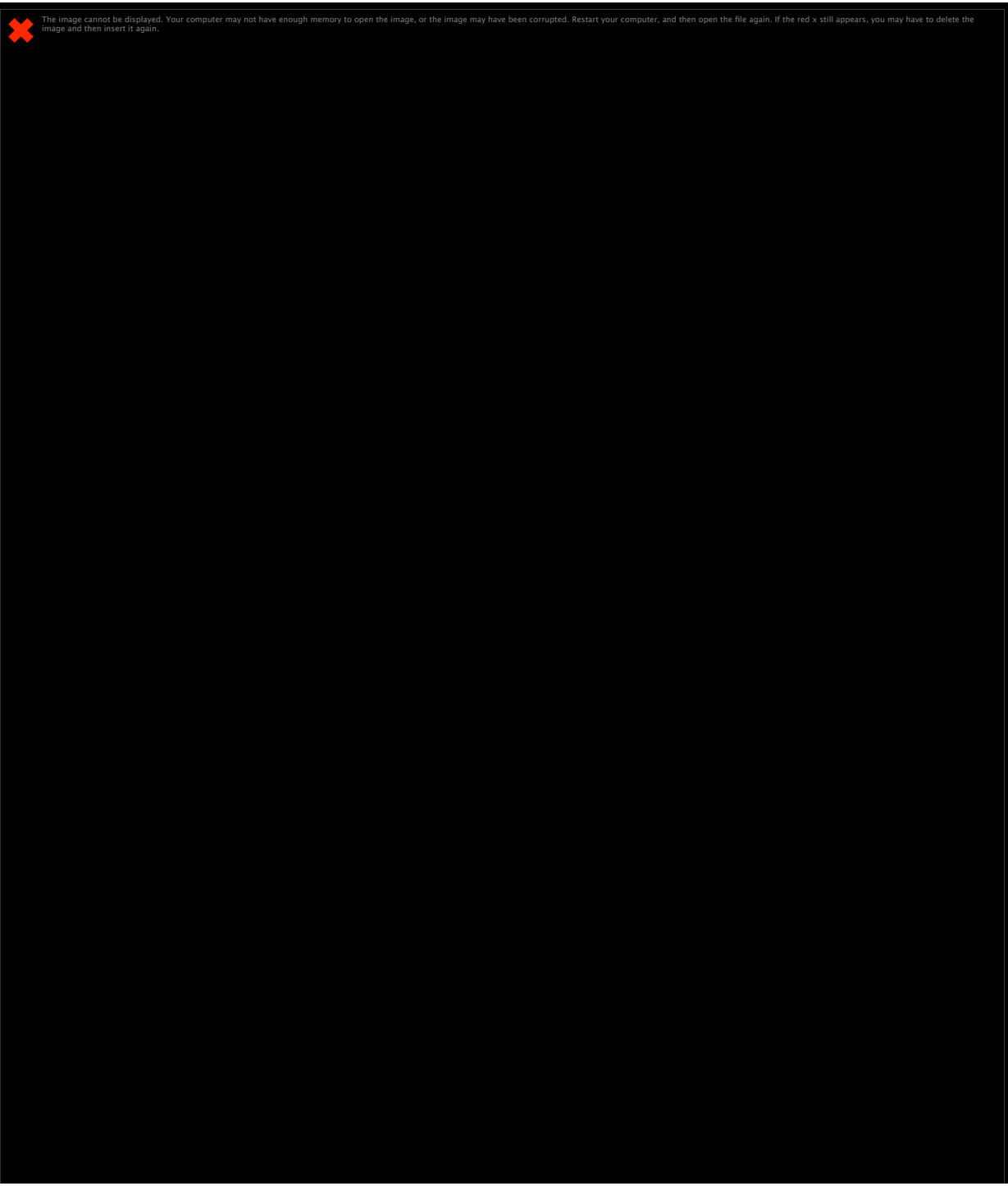


Standard Candle To Measure Cosmic Distances

Type Ia Supernova:

1.4 Solar Mass Thermonuclear Bomb – Rare, But Easy to See Across The Cosmos and




The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

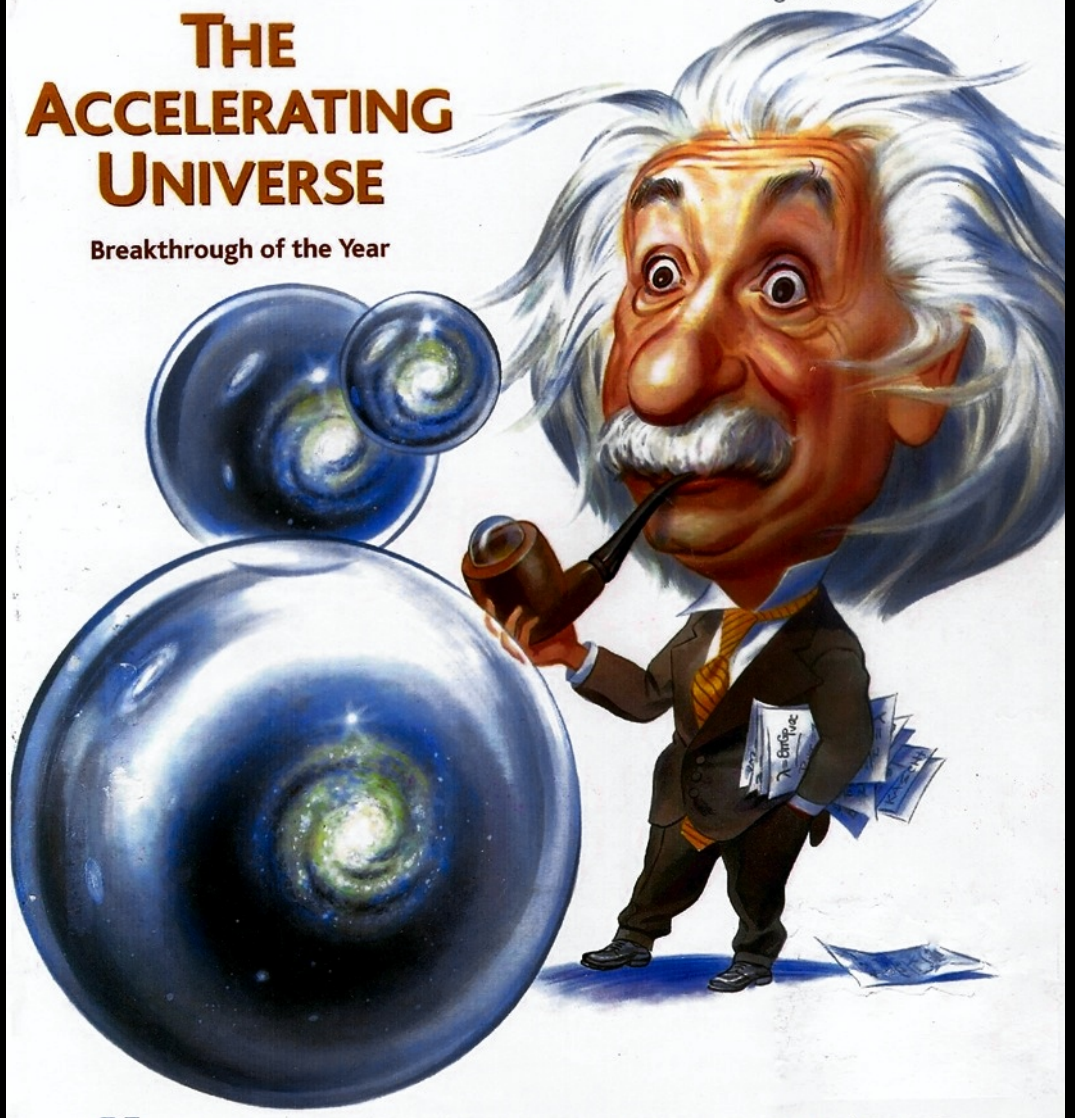
18 December 1998

Science

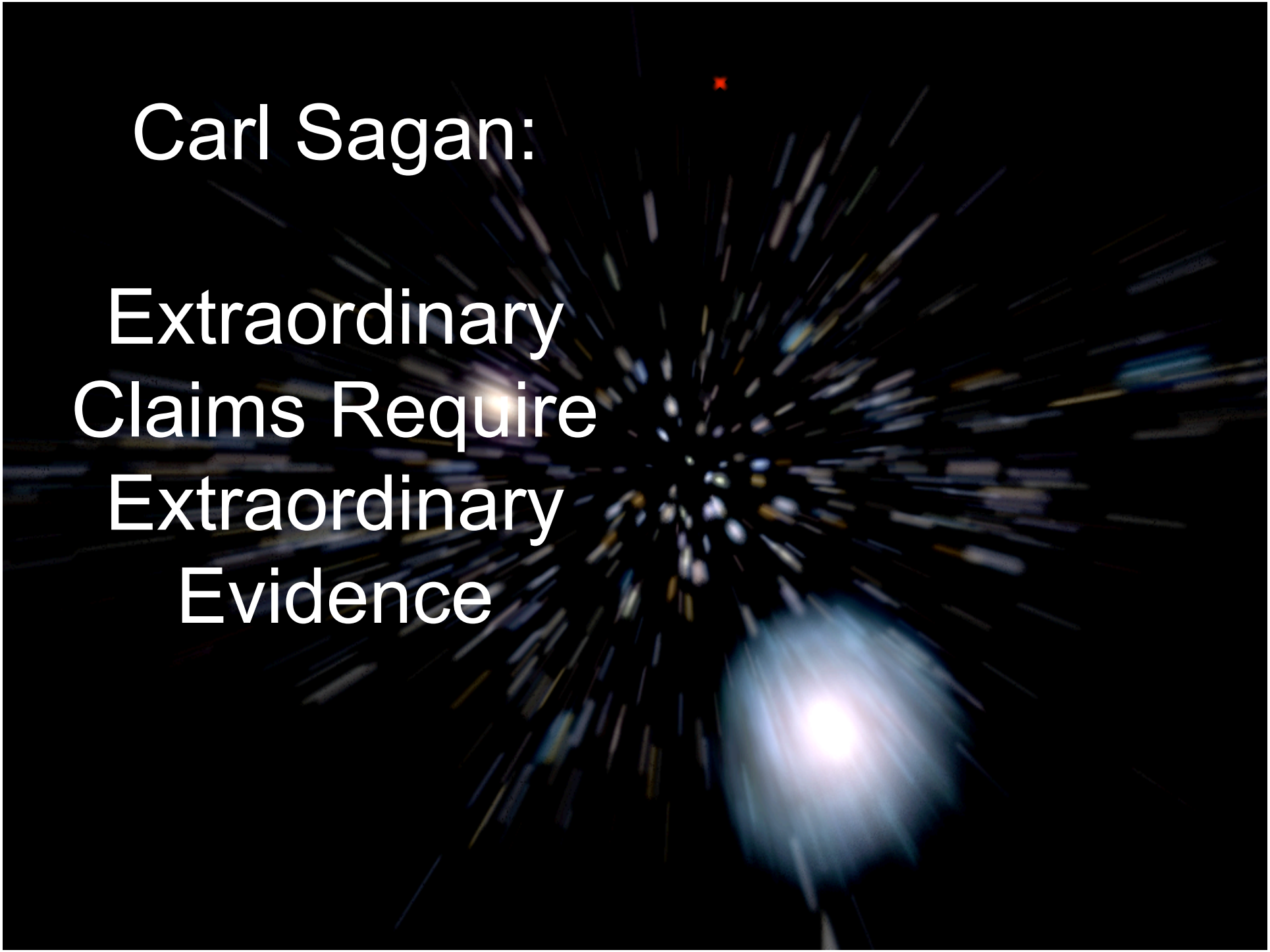
Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

Breakthrough of the Year

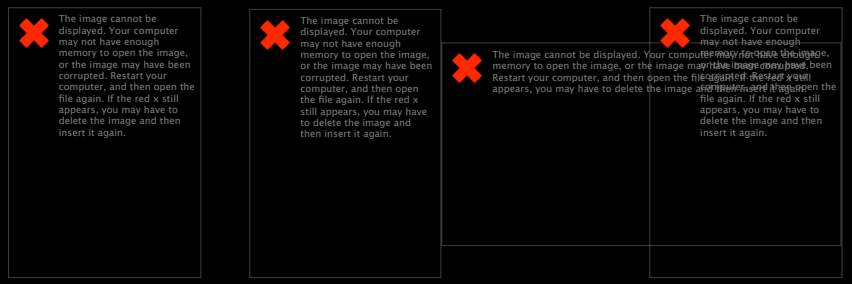


AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE


Carl Sagan:
Extraordinary Claims Require Extraordinary Evidence

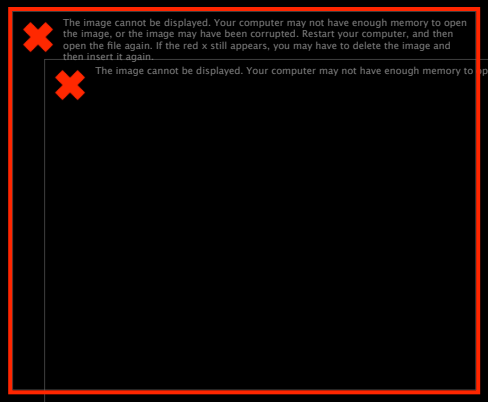
The evidence for cosmic acceleration has gotten stronger

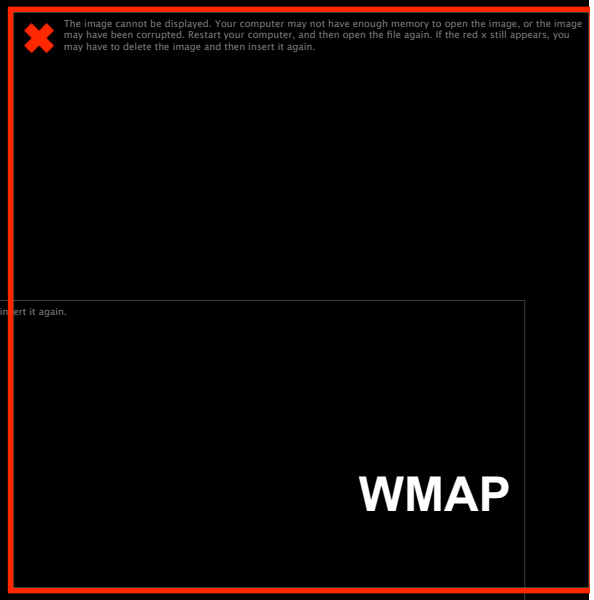
… no doubt that the expansion of the Universe is speeding up

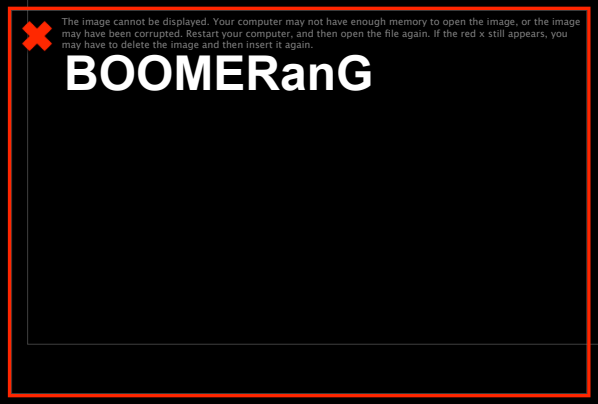


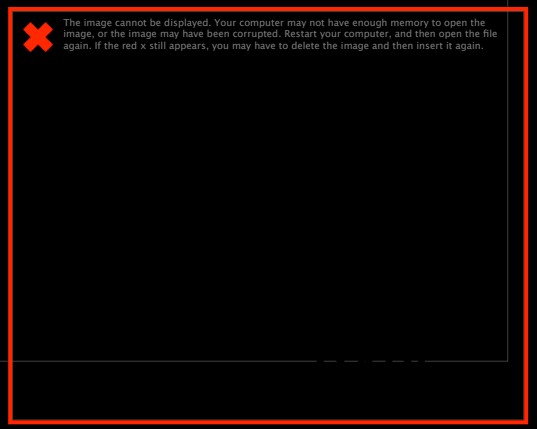
2011: Certified by Stockholm!

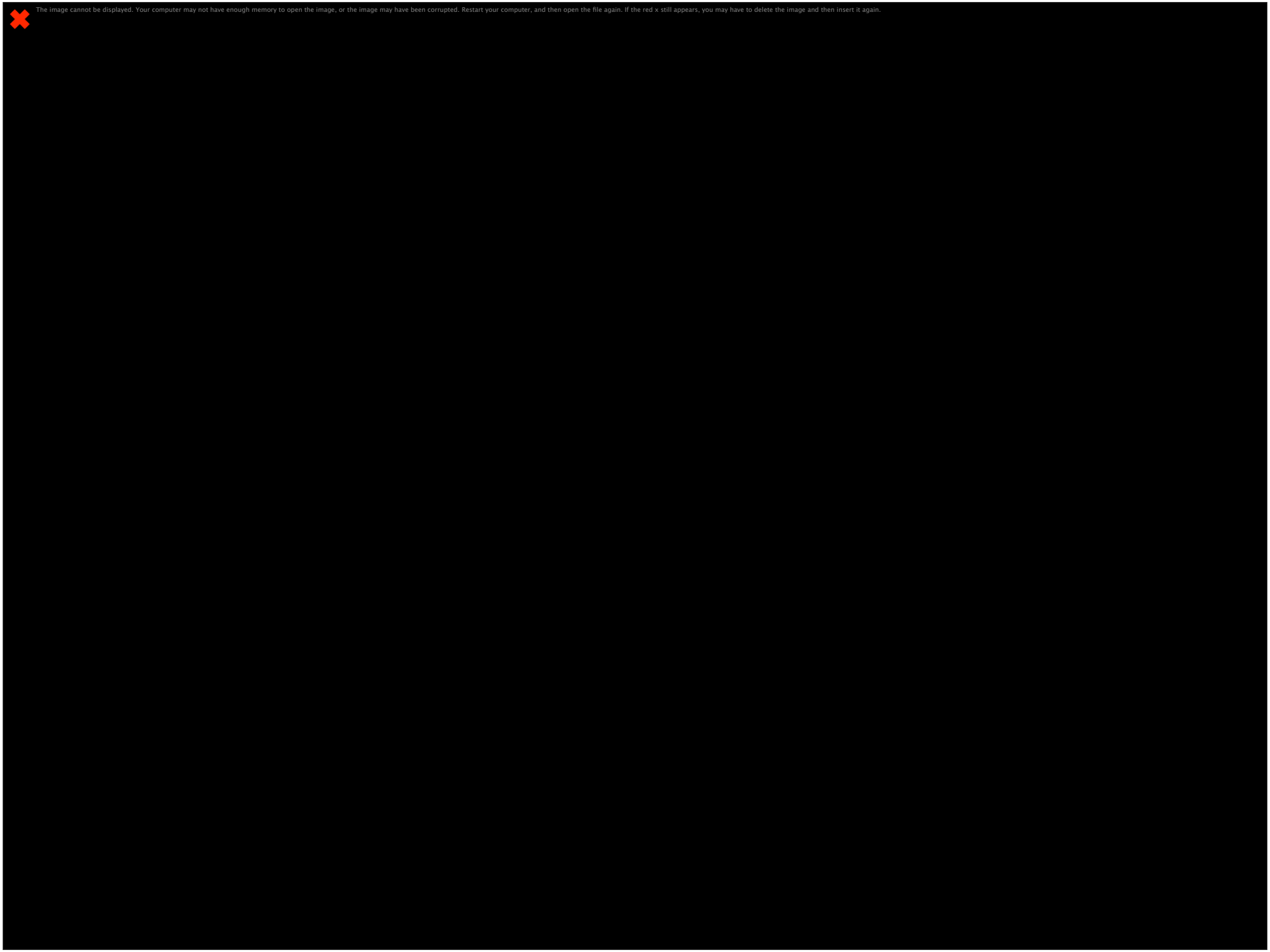
Cosmic Microwave Background: Independent Line of Evidence










The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

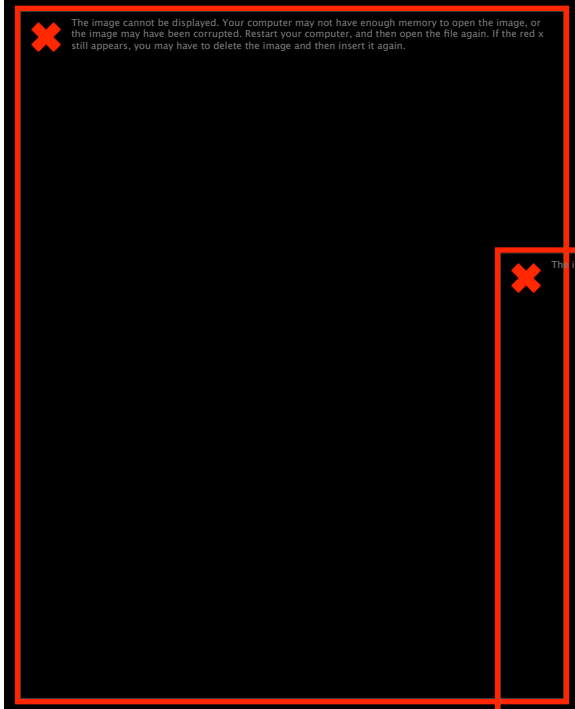
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Accounting only works with dark energy:

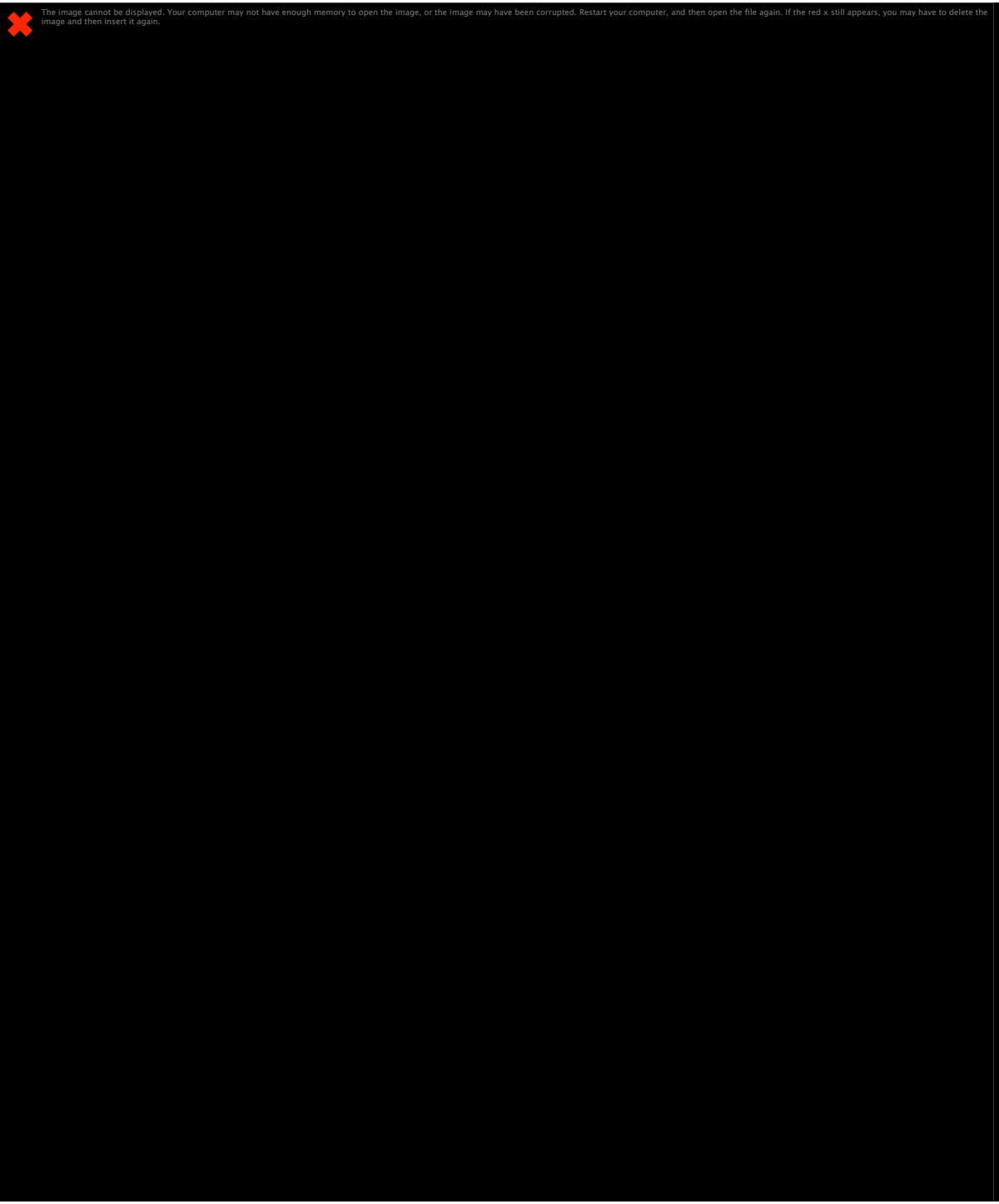
4% + 25% +70% (DE) = 100% (flat)

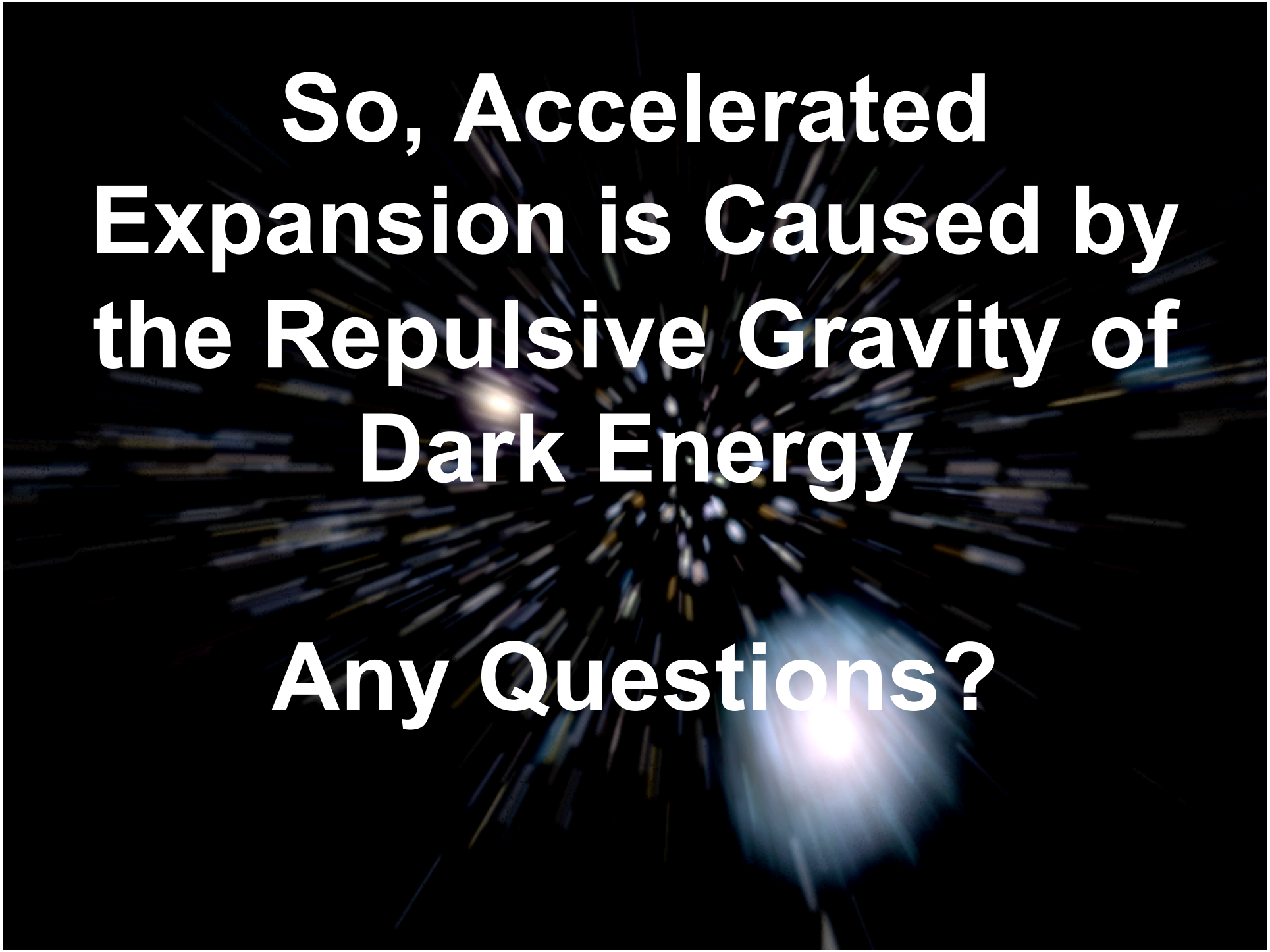
Our Universe

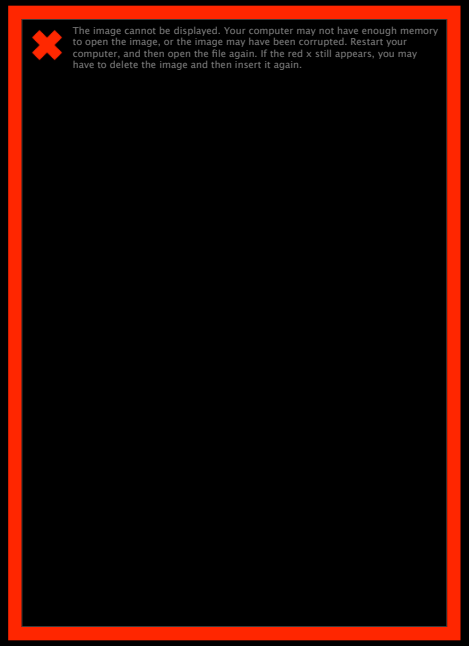
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

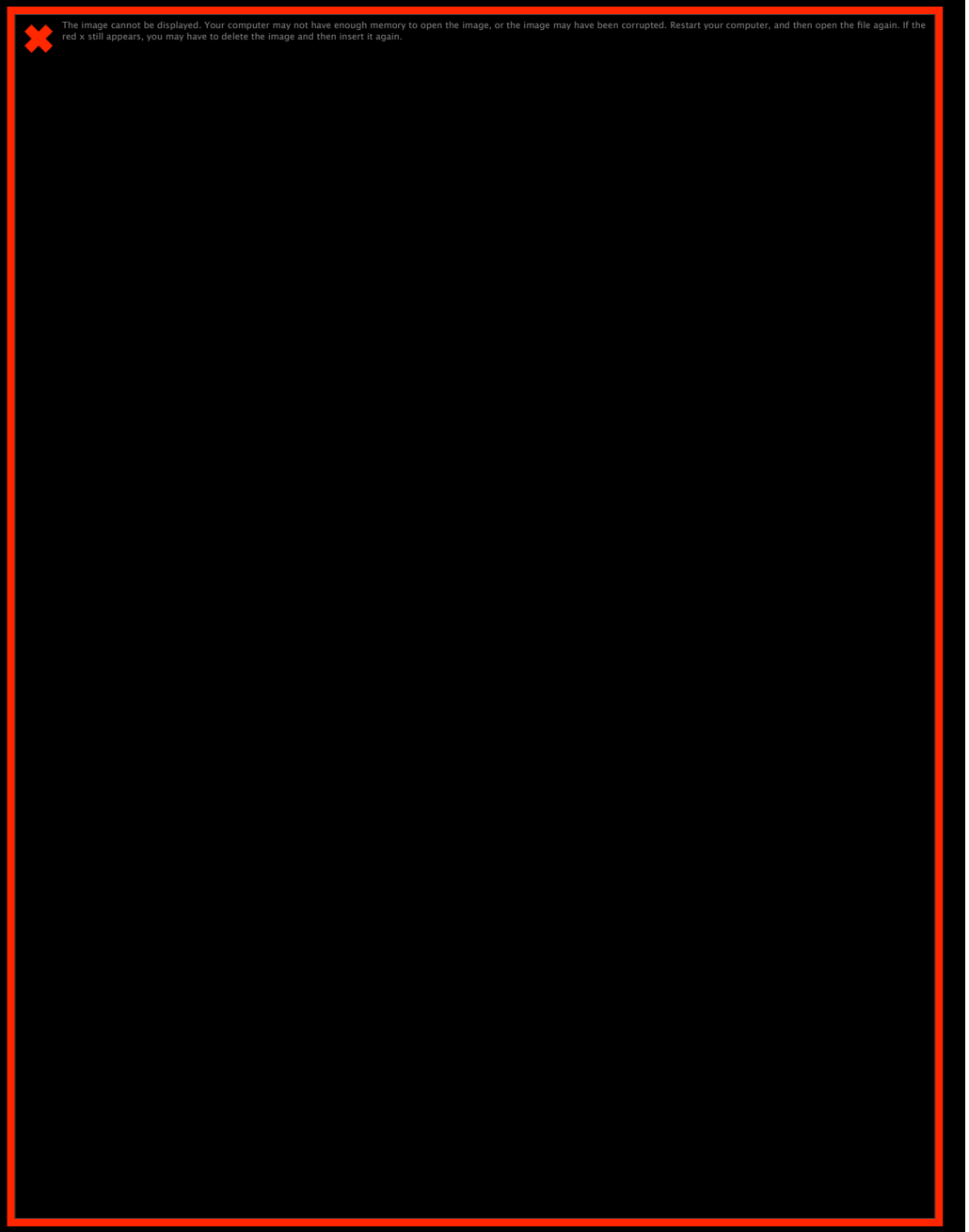

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.


So, Accelerated Expansion is Caused by the Repulsive Gravity of Dark Energy
Any Questions?



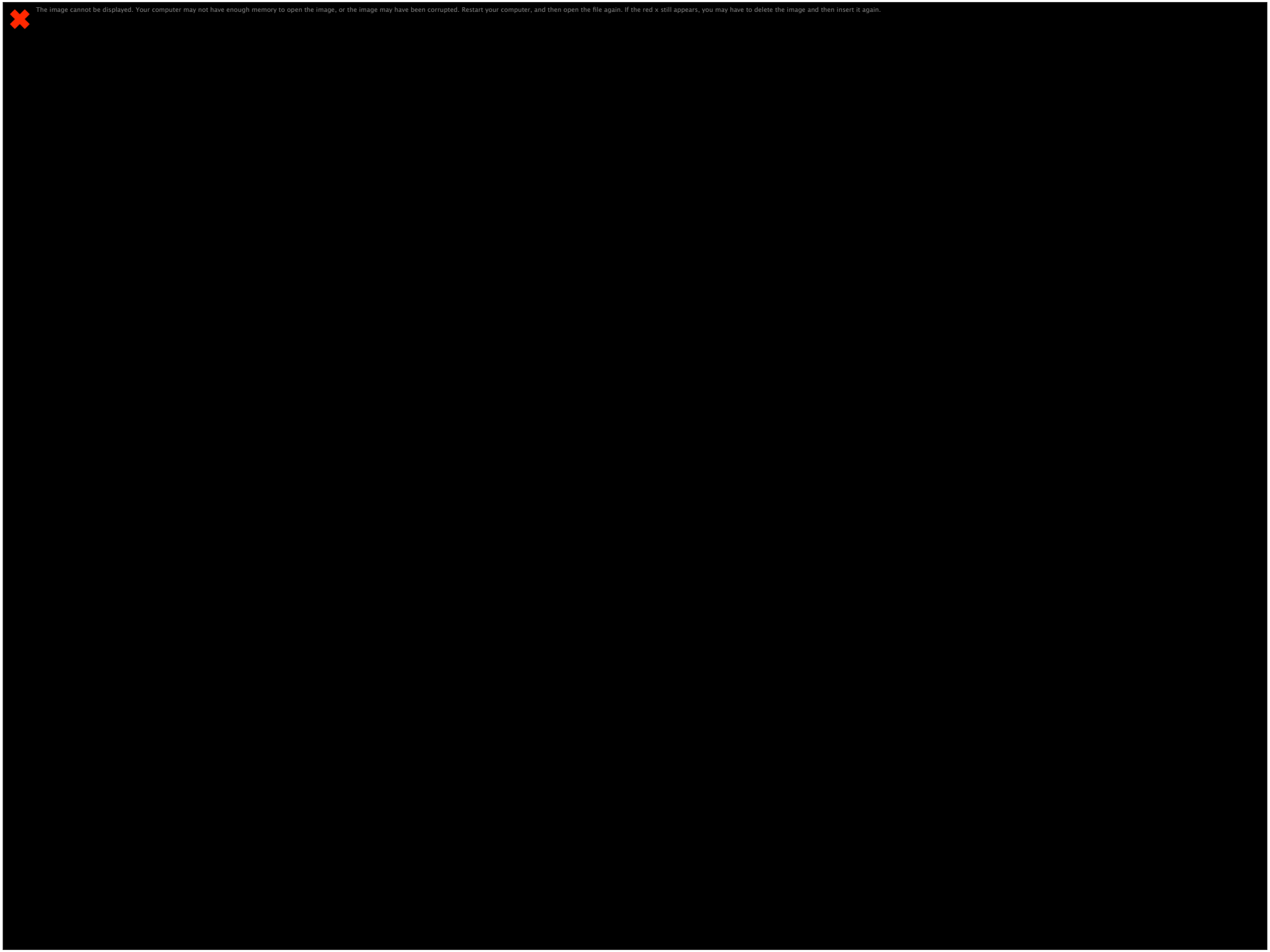


May 1998
Birth of Funny Energy
But, Focus Groups
Didn't Like Name

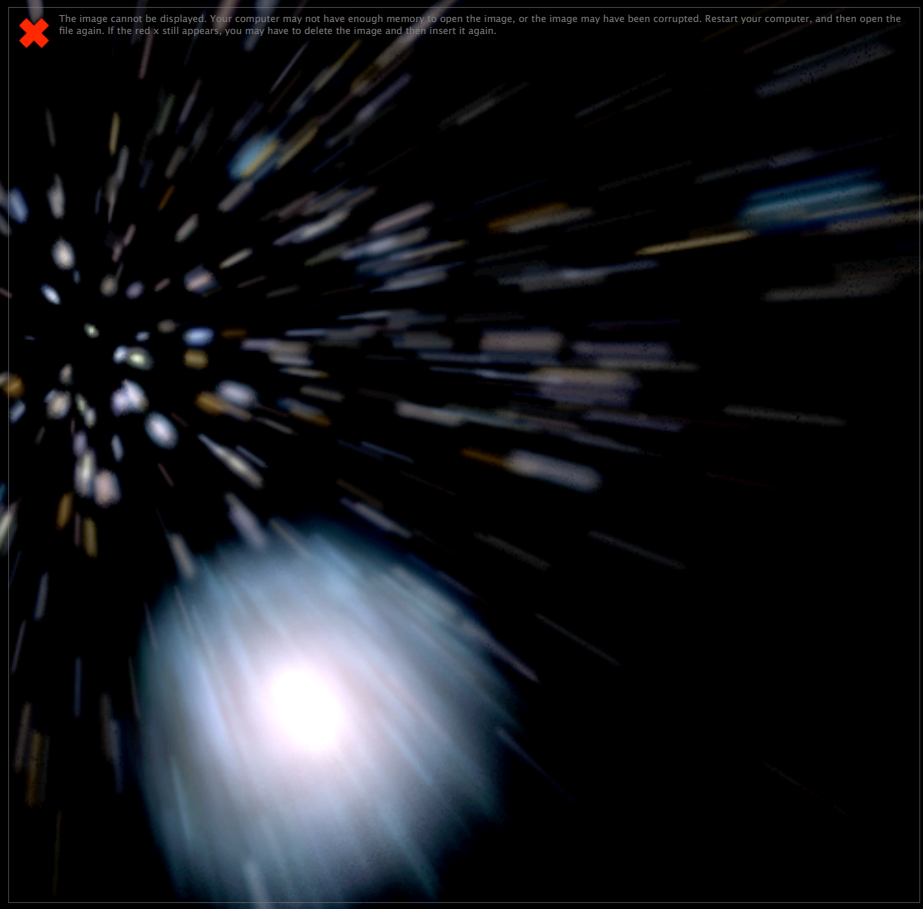
August 1998

Birth of Dark Energy

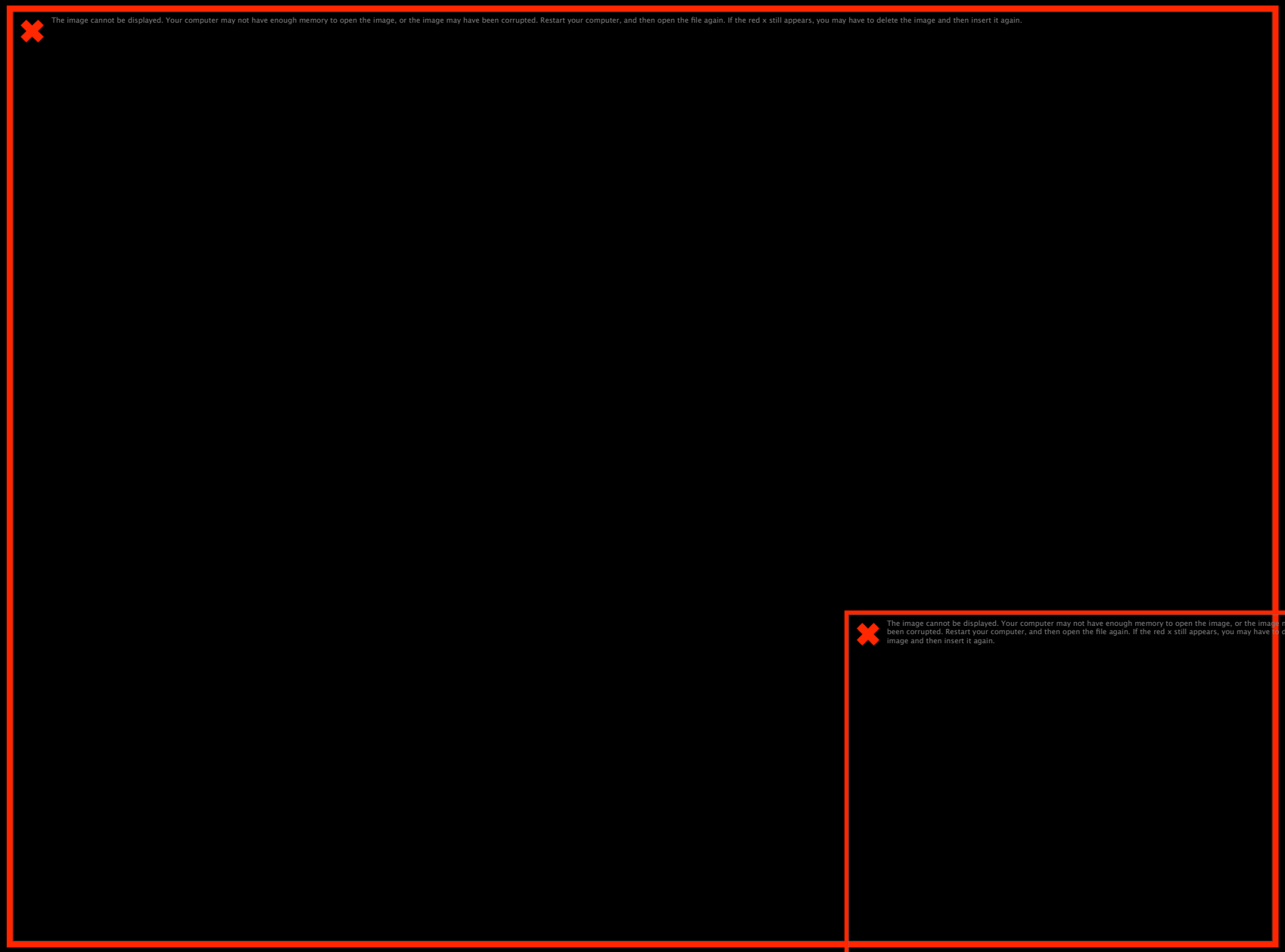
Third Stromlo Symposium
astro-ph/9811454


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

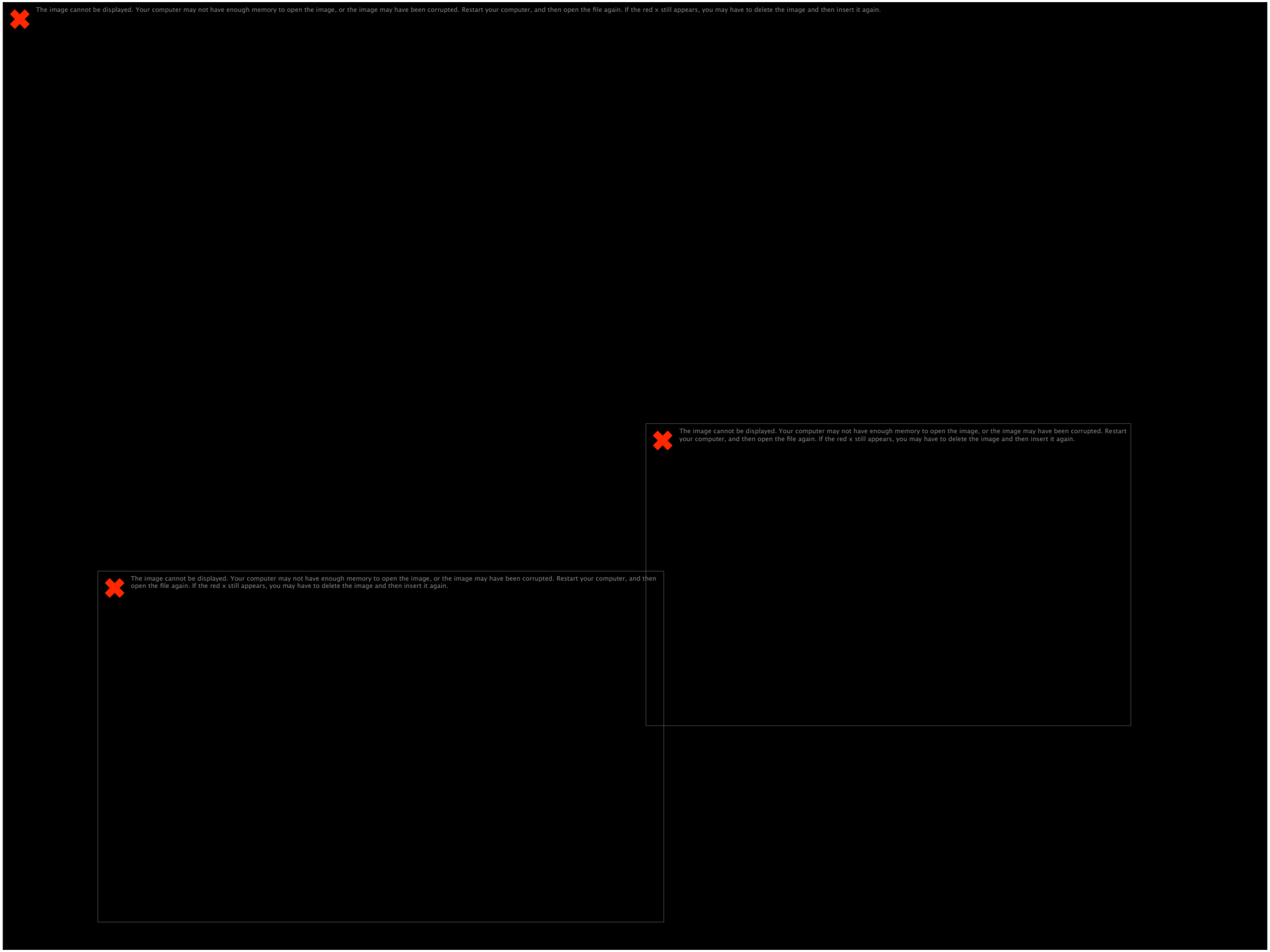
The Cosmic Landscape of Superstring Theory



- M-theory → 10^{500} vacua
- $\varrho_{vac} \sim O(m_{Pl}^4) \pm O(m_{Pl}^4)$
- Universe has a multiverse structure & we were lucky (narcissistic principle)
- Testable??
- Extravagant solution!



@ Joe Turner, Age 6

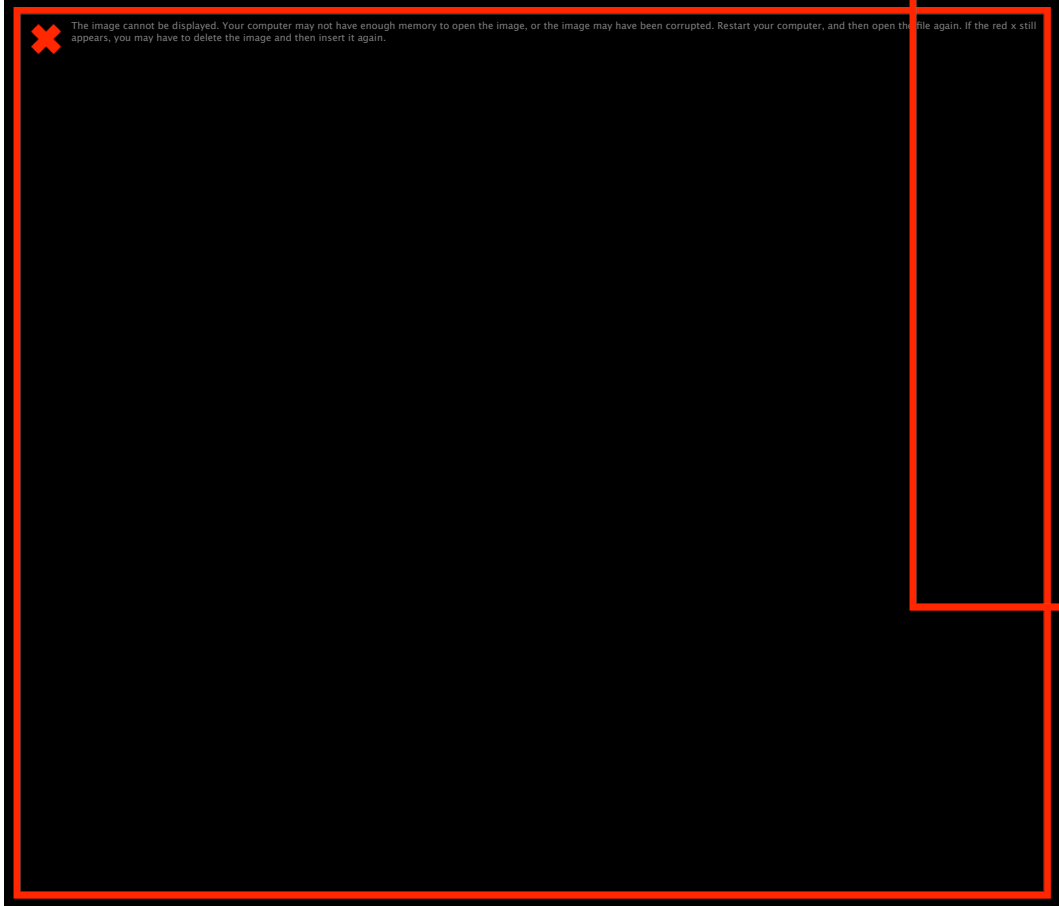

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

nnot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

From Here to Eternity

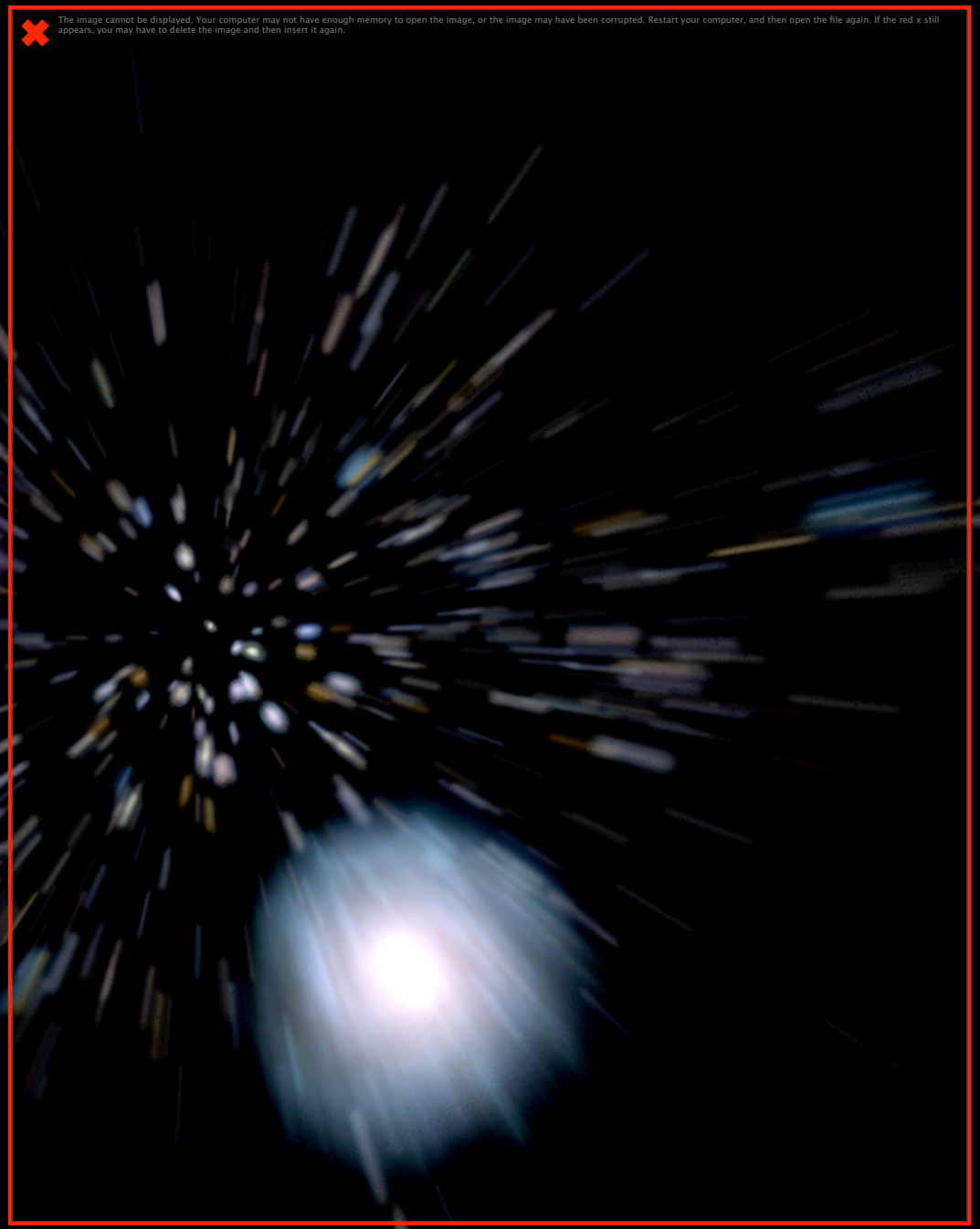
In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!



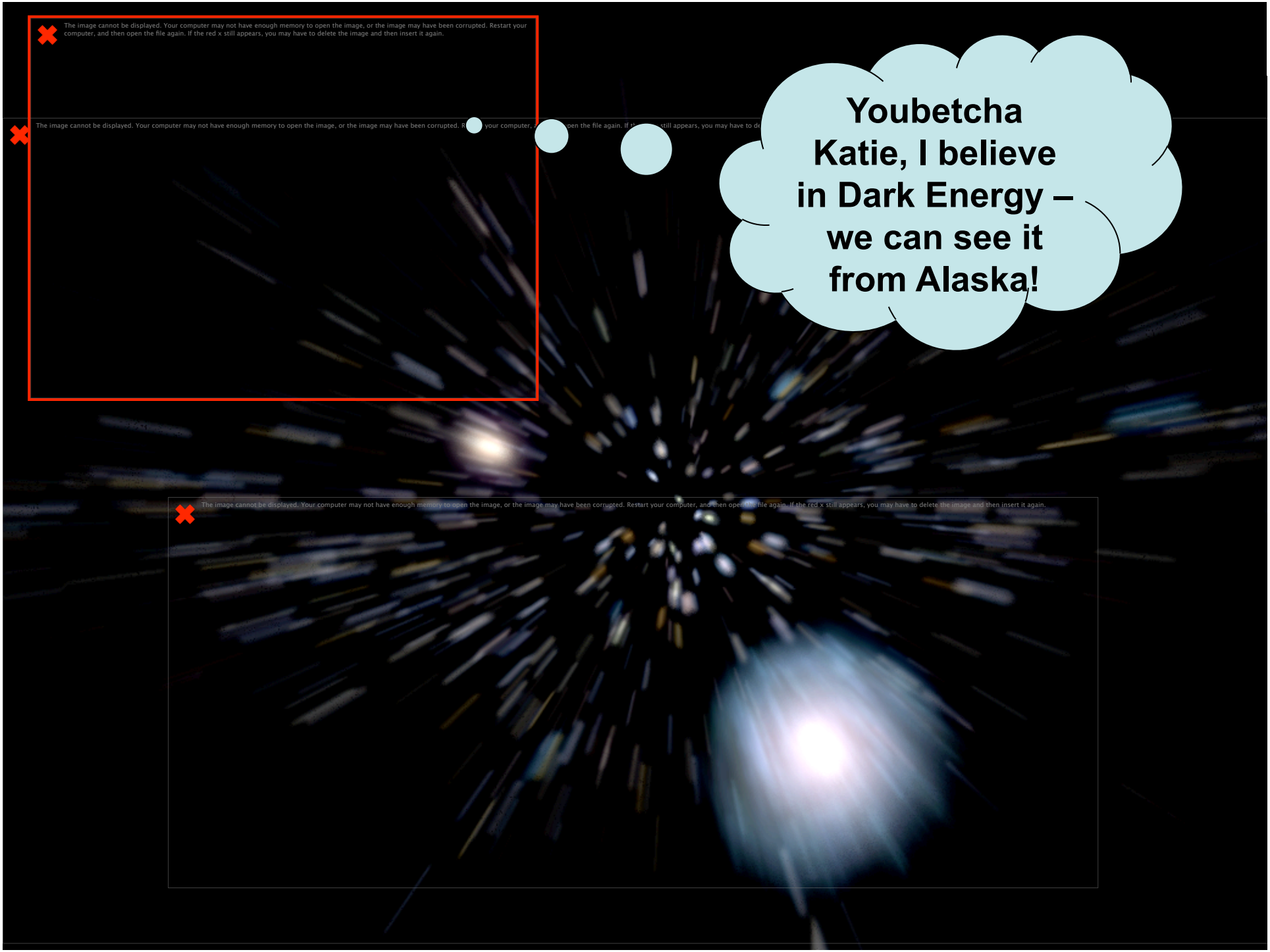
Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

Important

At the very least, we can now say that the formation of our Universe was the battle between the two dark titans



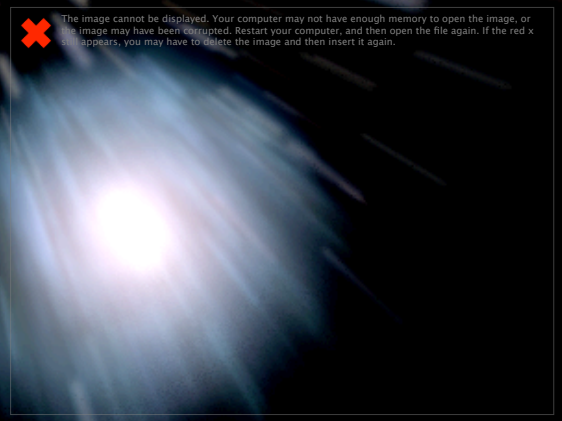
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

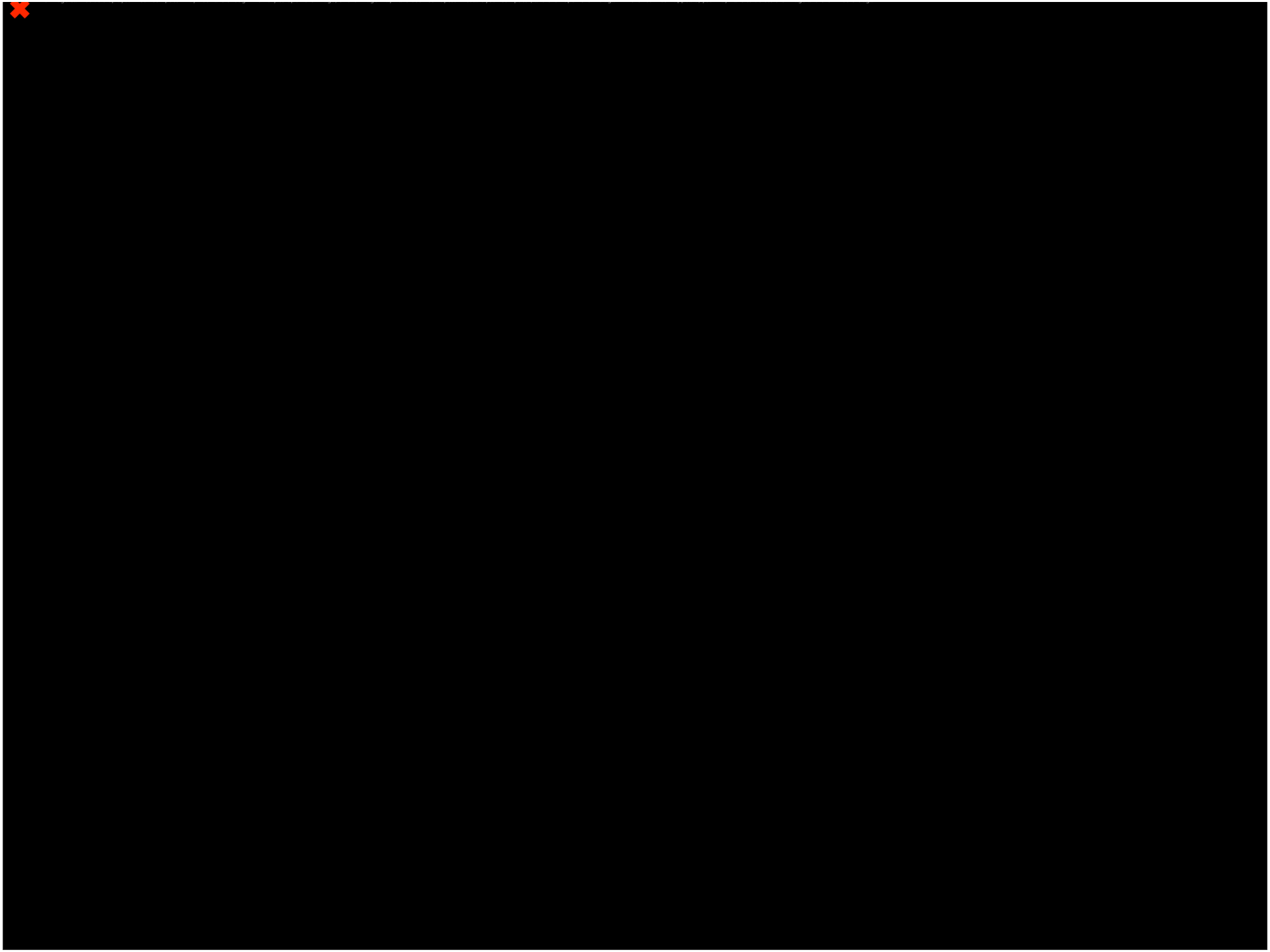

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.
Youbetcha Katie, I believe in Dark Energy – we can see it from Alaska!

3 Epochs
3 dimensionless ratios

- $1 + z_{DE} = [\Omega_{DE}/\Omega_M]^{1/3} \approx 1.37$
- $1 + z_M = \Omega_M/\Omega_R \approx 3300$
- NB: $1 + z_{DEC} \approx 1100 \sim [13.6\ eV/3\ K]/\ln(1/\eta)$

- $\Omega_{CDM}/\Omega_B \approx 7$
- $\Omega_B/\Omega_v \sim 40$
- $(1 + z_M)/(1 + z_{DEC}) \sim 3$





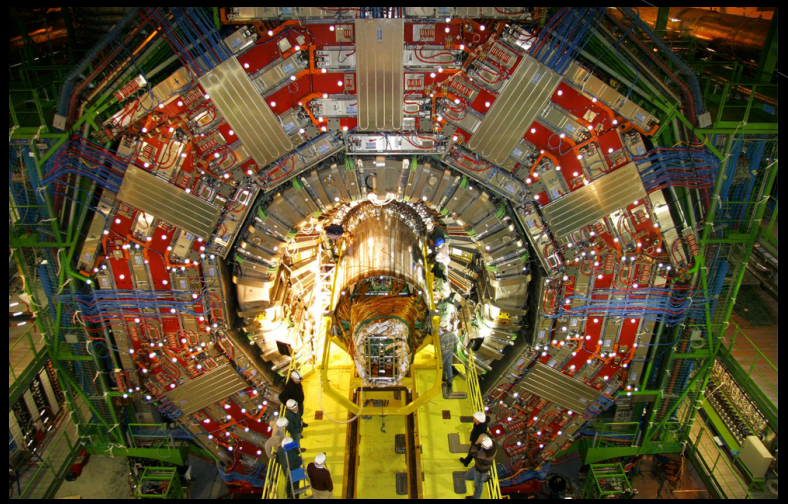
Probes of Dark Energy: Telescopes and Accelerators

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

SNAP/JDEM: Probing Dark Energy by Measuring the Past Expansion Rate

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

LSST: Probe Dark Energy by Measuring the Evolution of Structure in the Universe



LHC: Probing Dark Energy by Searching for SuperSymmetry

The Dark Side of the Universe

Stuff of the Universe

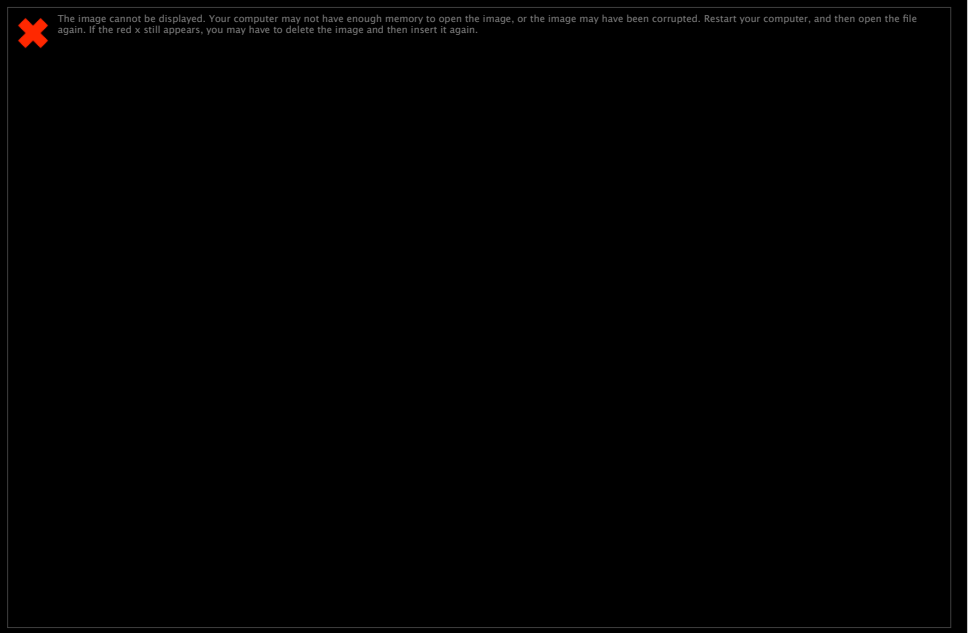
Stars: 0.5%

Hot Atoms: 4.0%

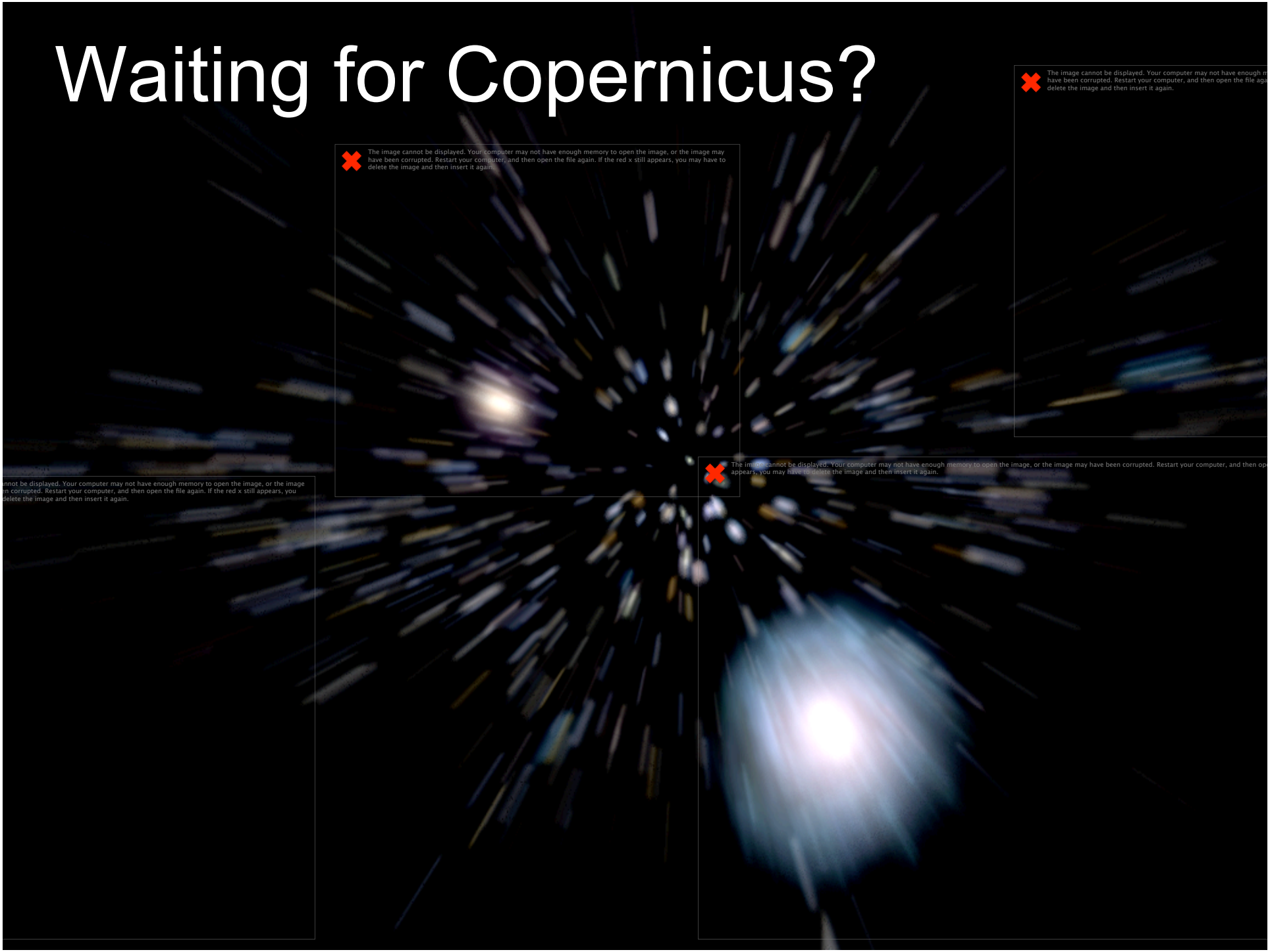
Dark Matter: 24%

(Neutrinos: few 0.1%)

Dark Energy: 71%



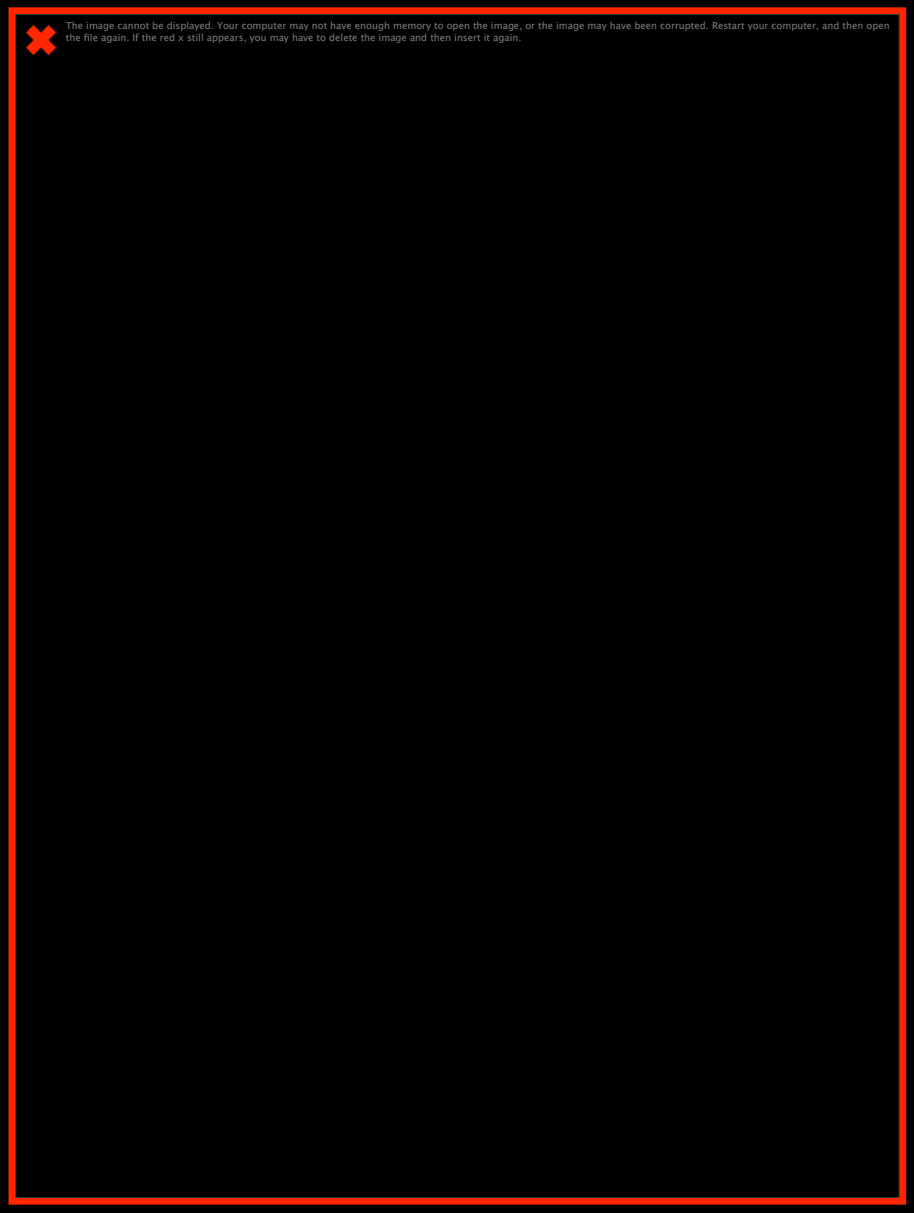
Waiting for Copernicus?

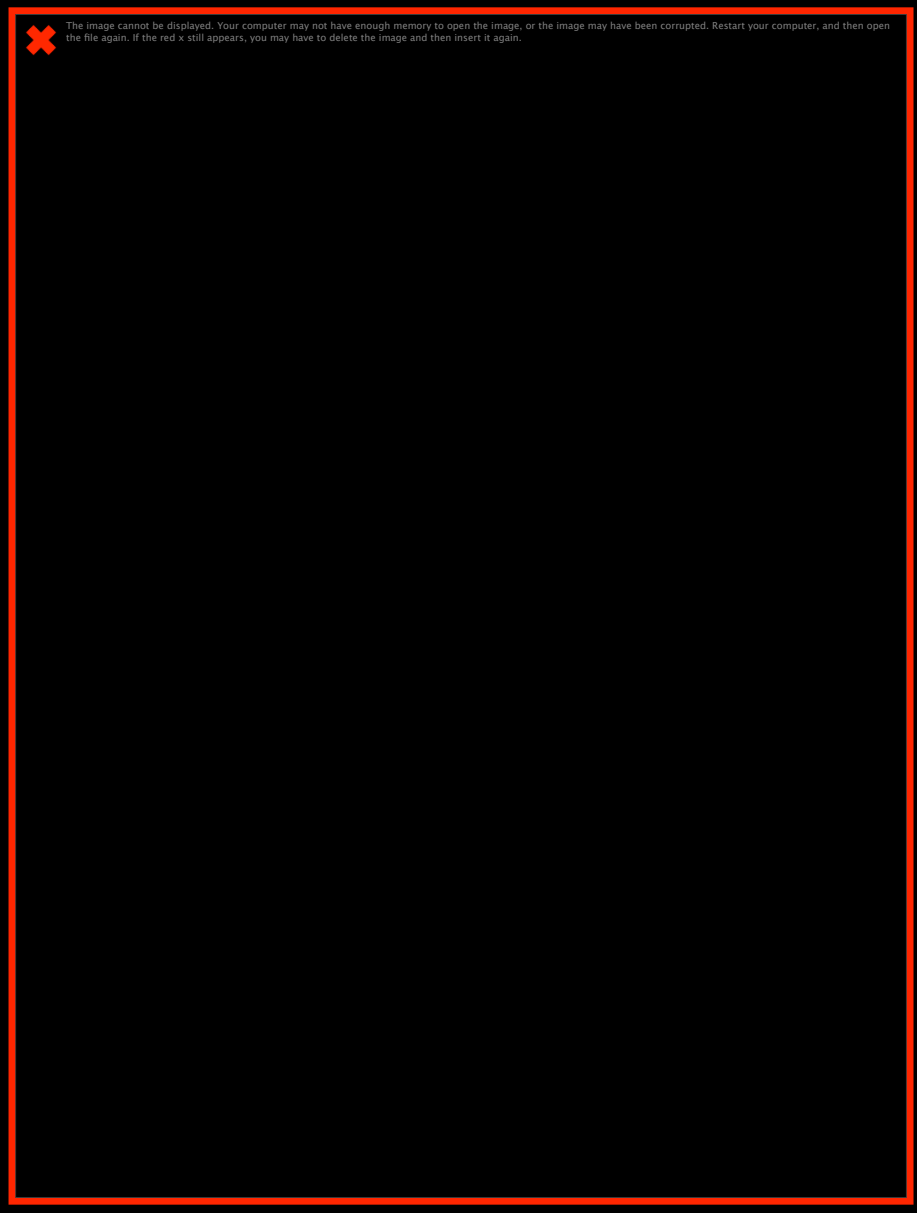


Big Questions!

e image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

… for the next generation of scientists to answer


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.