

Title: Resolving the Mystery of Dark Matter - EinsteinPlus Keynote Session

Date: Jul 20, 2007 10:40 AM

URL: <http://pirsa.org/07070011>

Abstract: For more than 70 years, astronomers have had the uneasy suspicion that there was more to the universe than met the eye - much, much more. In the past five years, this suspicion has become a certainty. We now know for sure that normal matter and normal radiation account for only 4% of the density of the universe. One of the two biggest components, dark matter, may be finally be identified by new experiments coming on line next year. I'll summarise the long quest to identify dark matter and our prospects for finally achieving this goal in the next two years.



RESOLVING THE MYSTERY OF
DARK MATTER

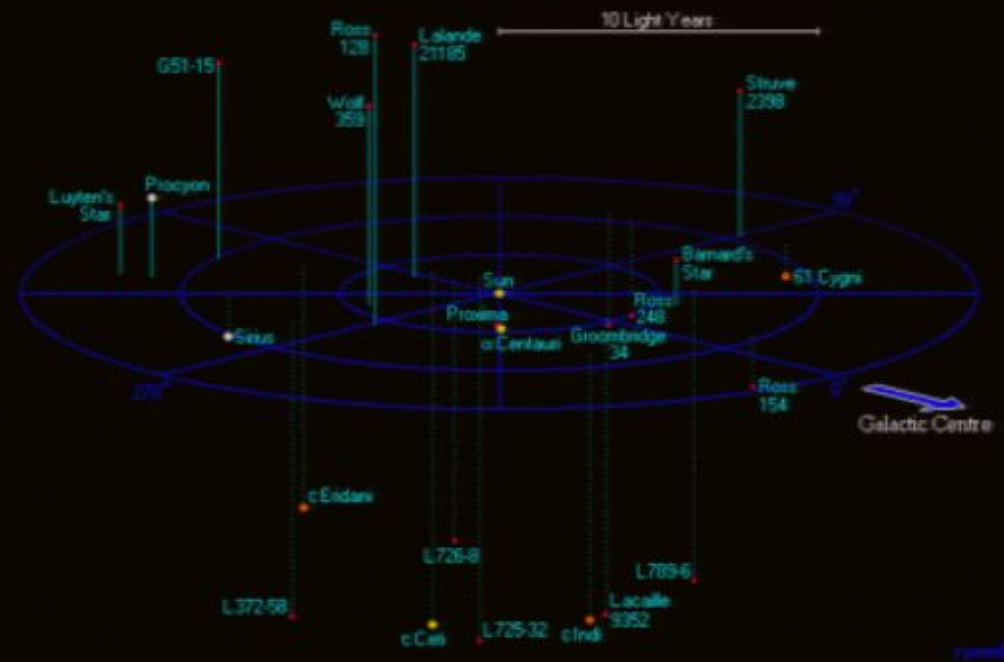
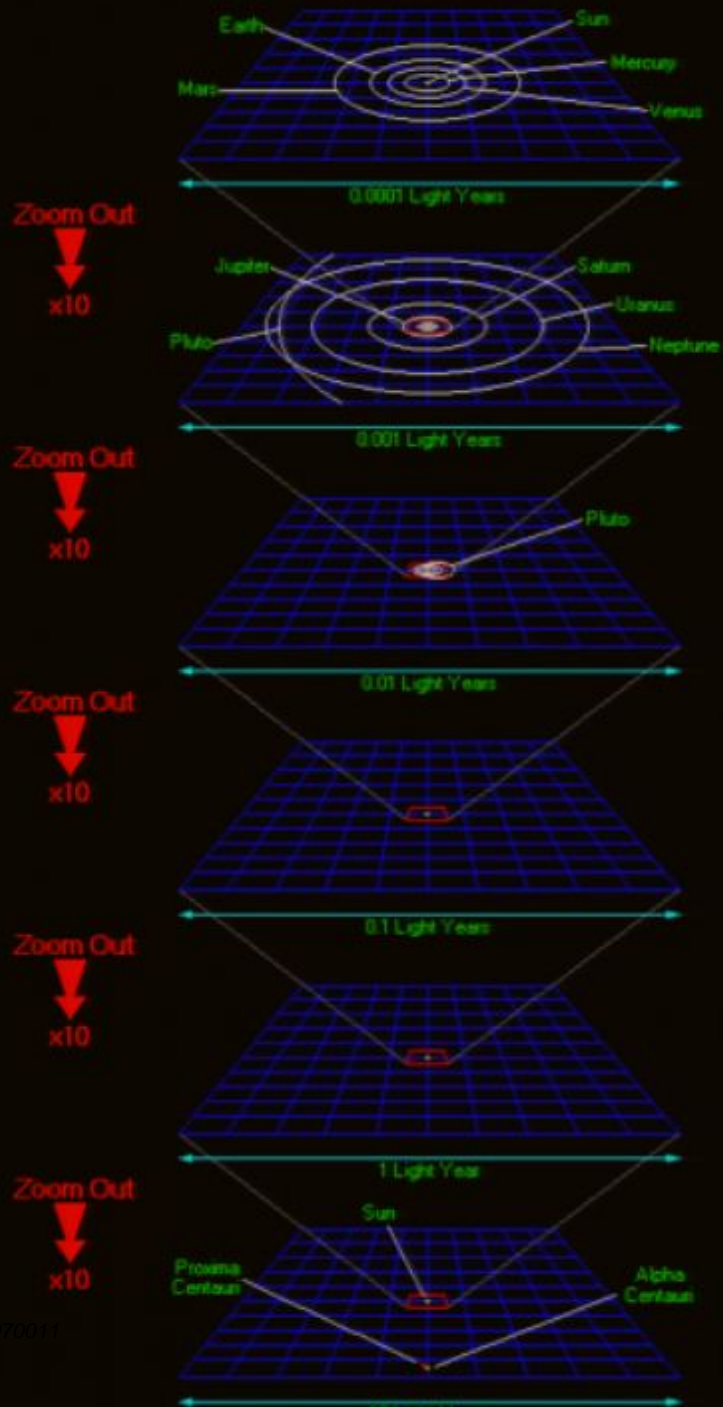
James Taylor
Department of Physics and Astronomy
University of Waterloo

Outline

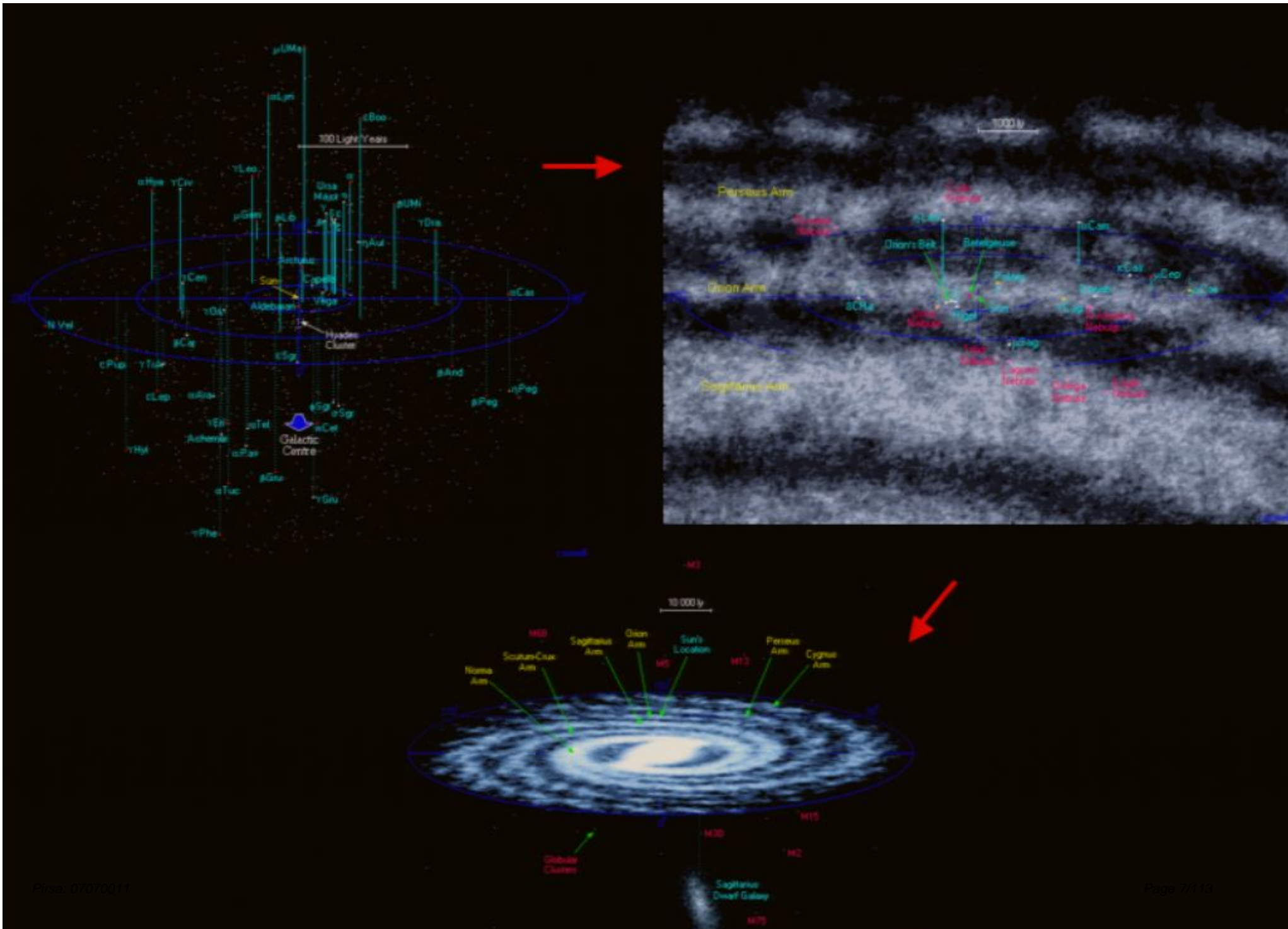
- 1 The Universe Around Us
- 2 The Evidence for Dark Matter
- 3 A slight digression: The Cold Dark Matter Universe
- 4 A complete digression: Dark Matter on 'Small' Scales
- 5 Resolving the Mystery of Dark Matter:
Prospects for the (Near) Future

I: The Universe Around Us

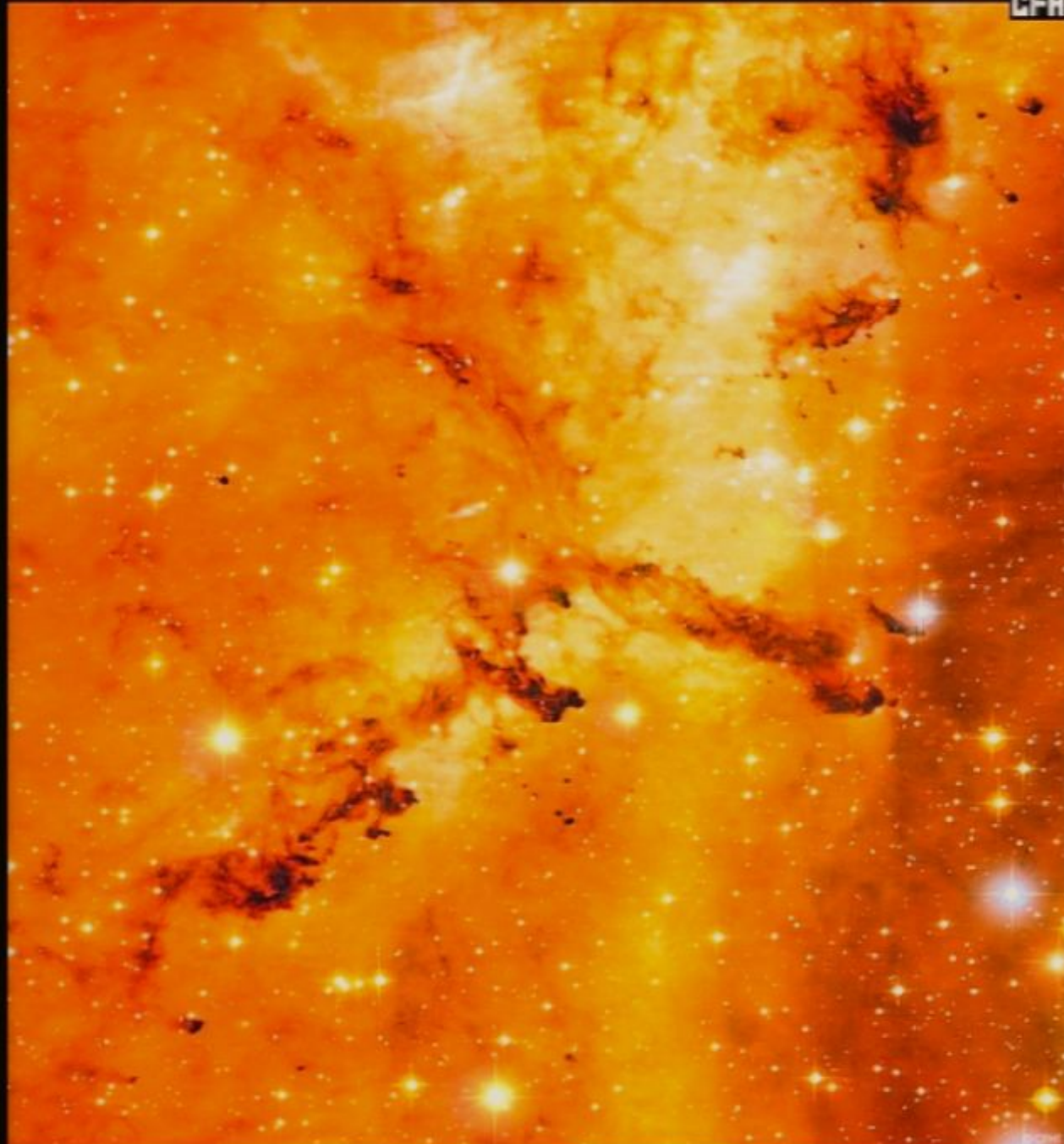




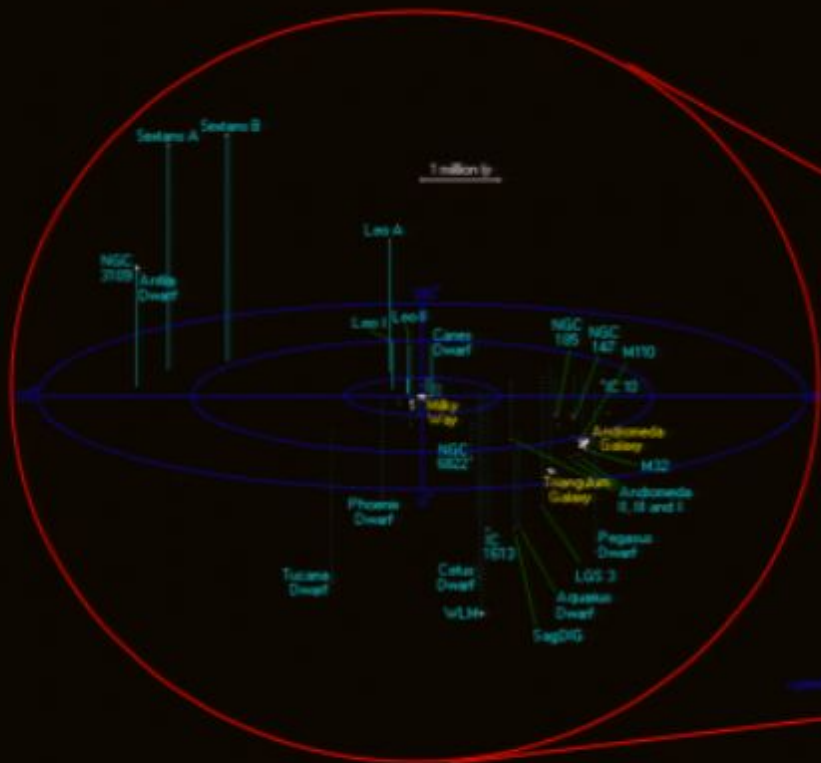
Images from Richard Powell's
<http://www.atlasoftheuniverse.com>



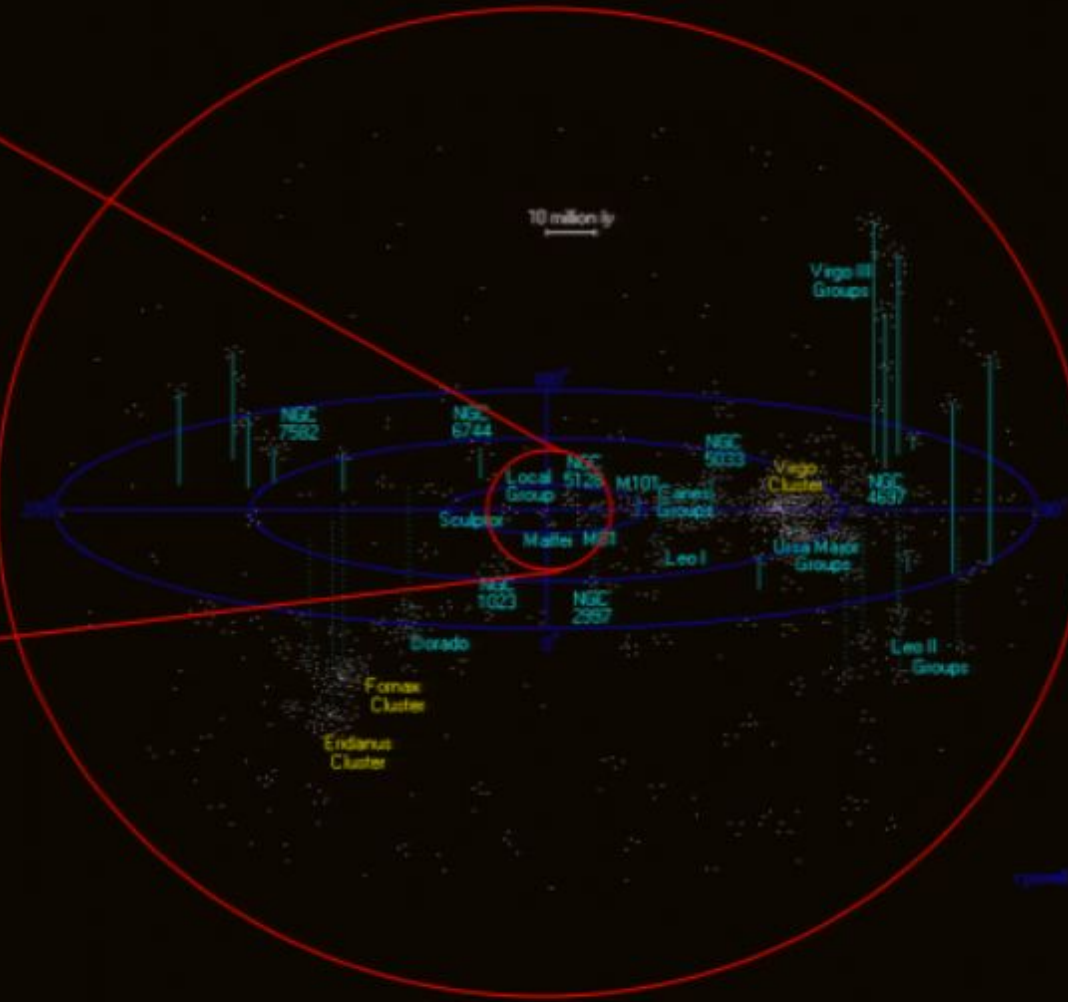




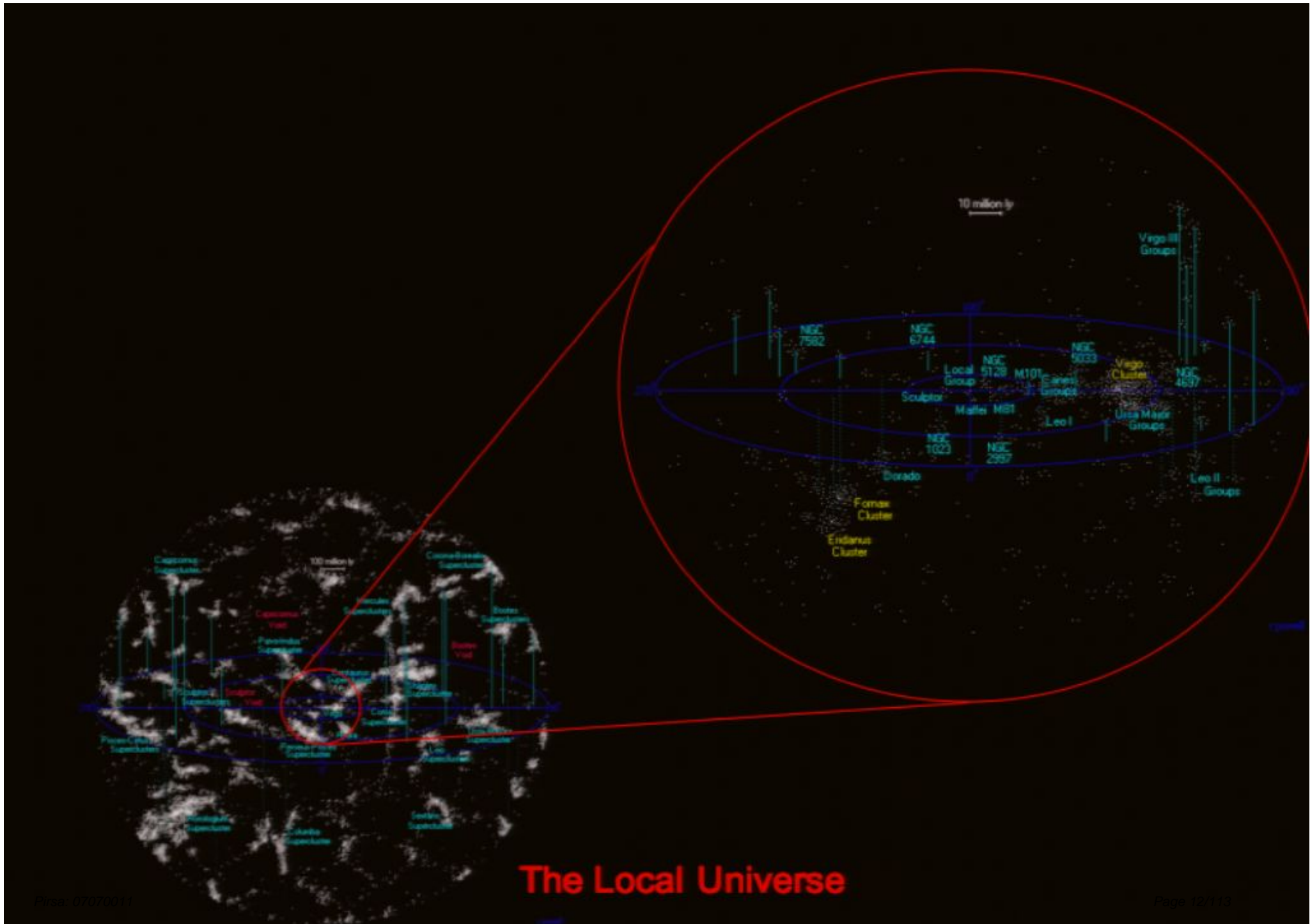




The "Local Group"



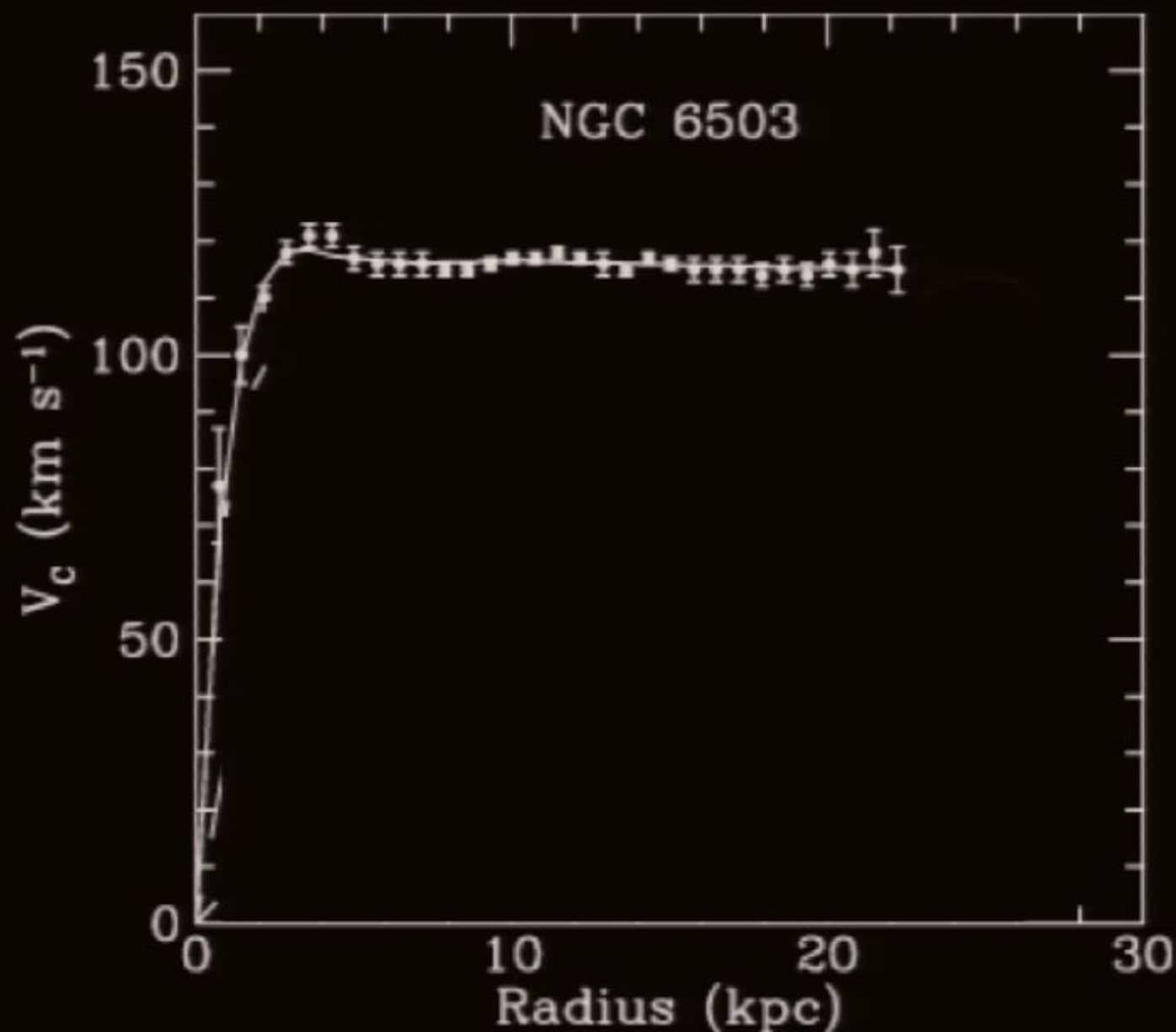
The Local Volume



The Local Universe

2: The Evidence for Dark Matter

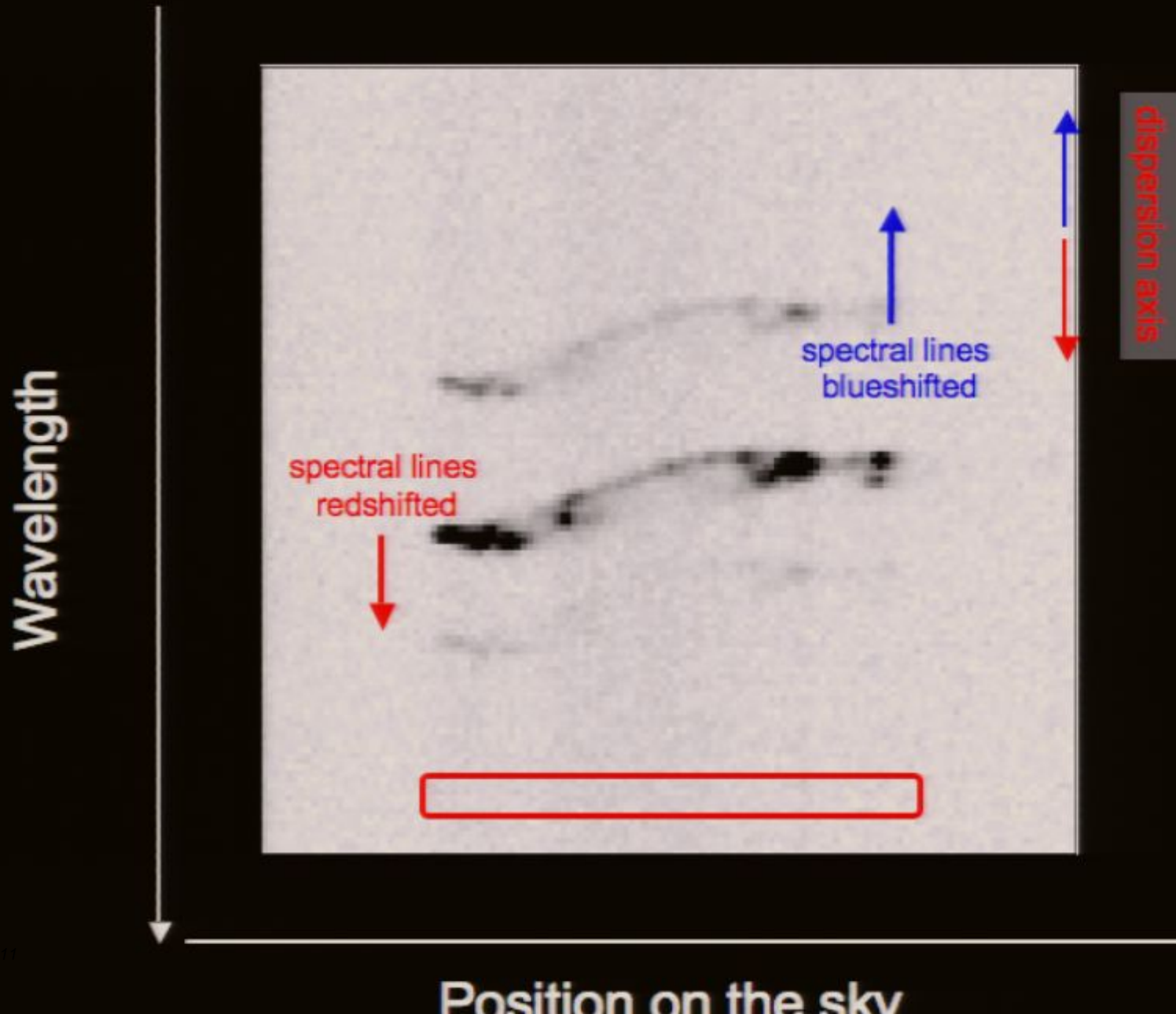
A Galactic Rotation Curve (NGC 6503 - cf. Kamionkowski et al. 2002)



Spiral Galaxy NGC 4414



Rotation Curves from Spectral Line Profiles



Physics of rotation curves:

Consider a gas cloud of mass m moving with circular velocity v_c :

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Equilibrium gives equation for the rotation curve:

$$v_c = [GM(<r)/r]^{1/2}$$

1970s: mounting evidence for dark matter from galaxy rotation curves



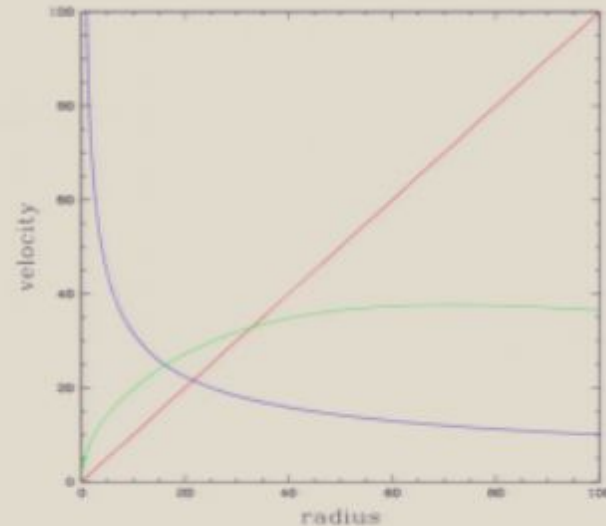
Vera Rubin (1928-)

Centrifugal force:
 $V_c^2 = GM(<r)/r$

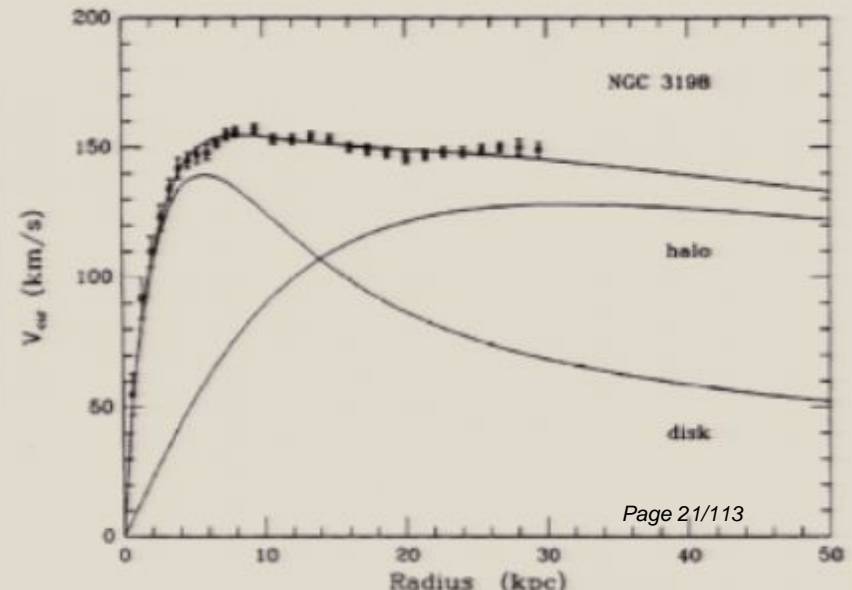
$$M(<r) = M_0$$

$$M(<r) \sim r^3$$

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- First woman to be allowed to observe at Mt. Palomar (in 1965)
- In 1970s, measured flat rotation curves in the outer parts of spiral galaxies, implying large masses
- Result widely hailed as wrong
- Subsequently the first woman to win the gold medal of the Royal Astronomical society since Caroline Herschel in 1828



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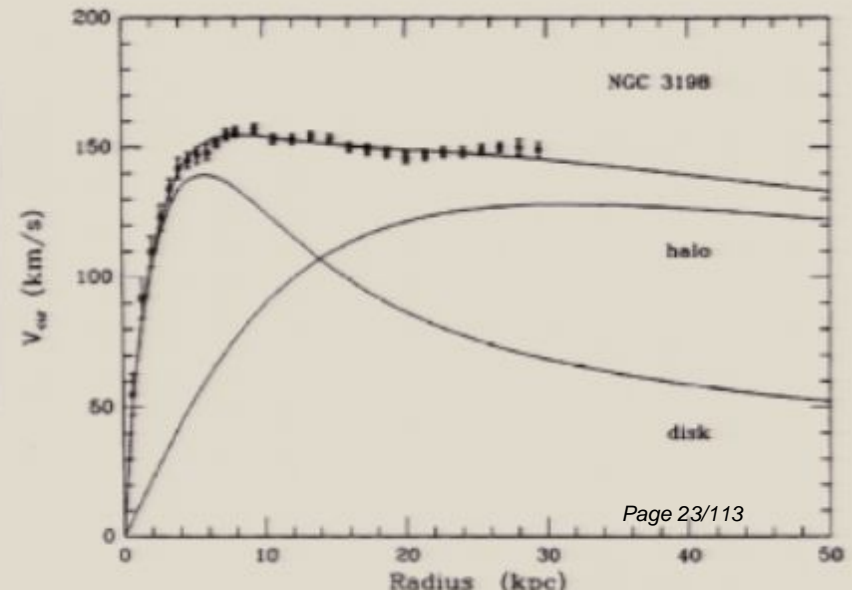
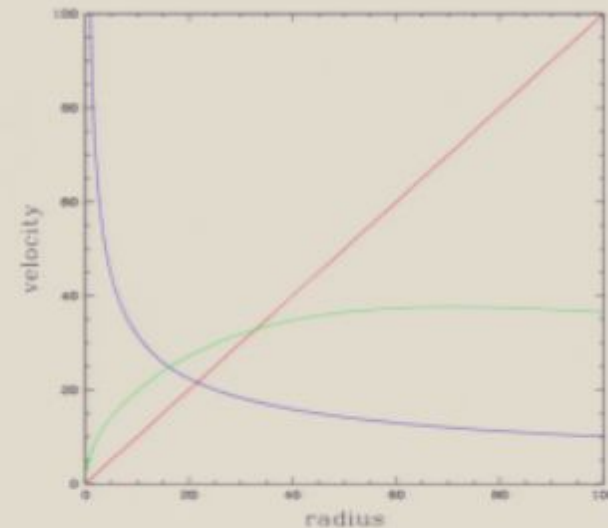
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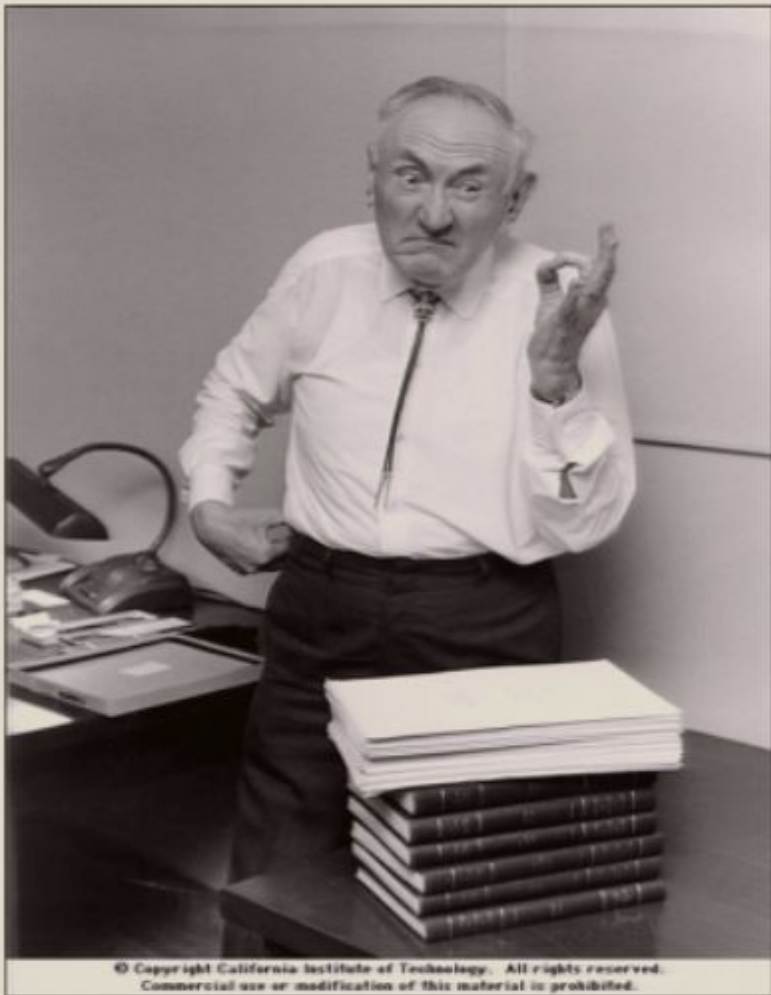
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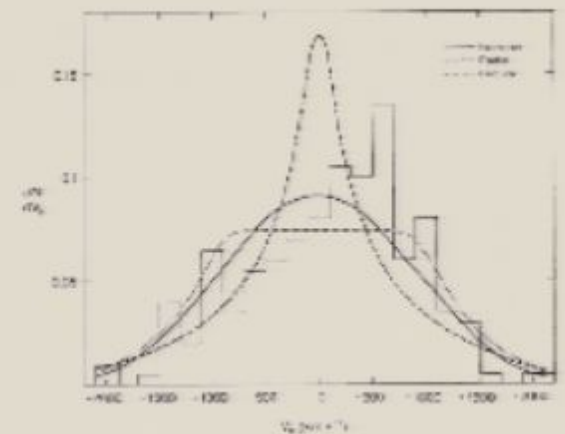


1933: The first indication that something out there is missing



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Fritz Zwicky (1898-1974)

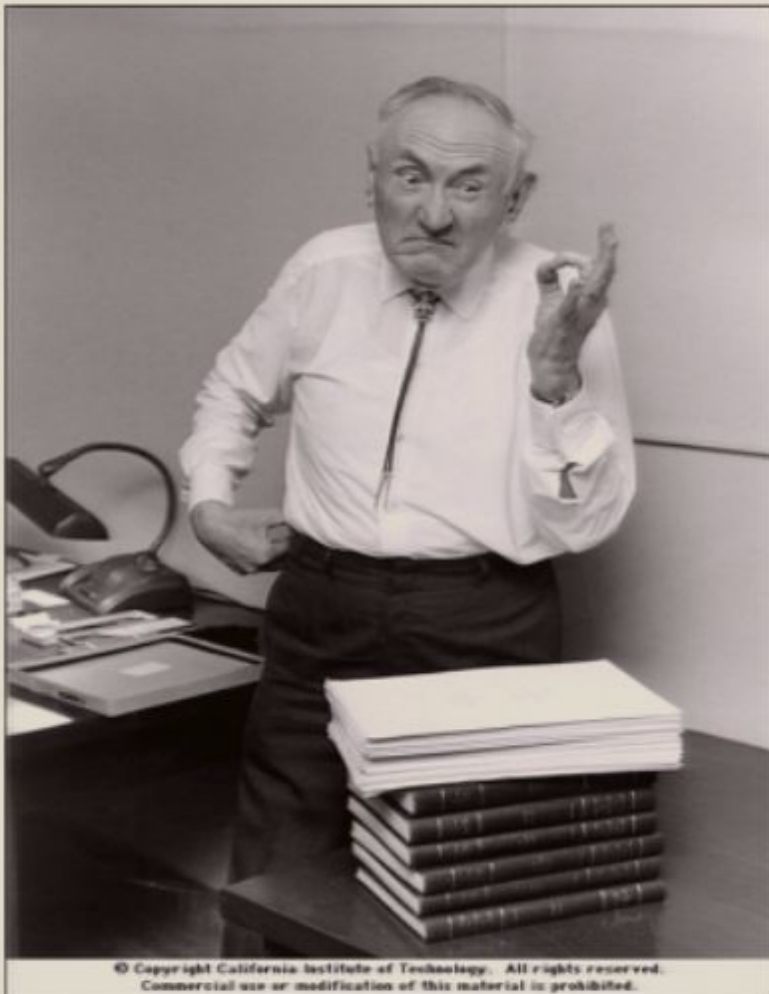


The virial theorem:

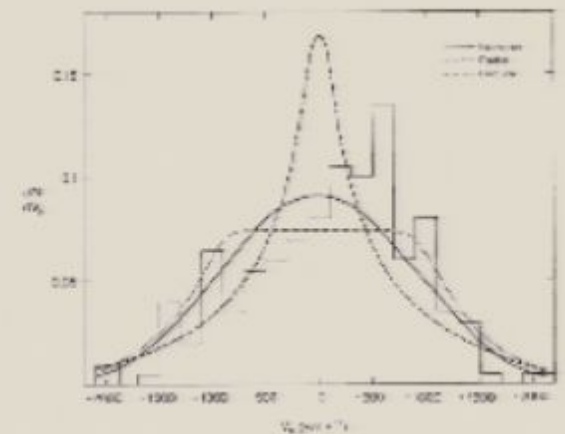
$$\langle T \rangle = -\langle U \rangle / 2$$

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1933: The first indication that something out there is missing



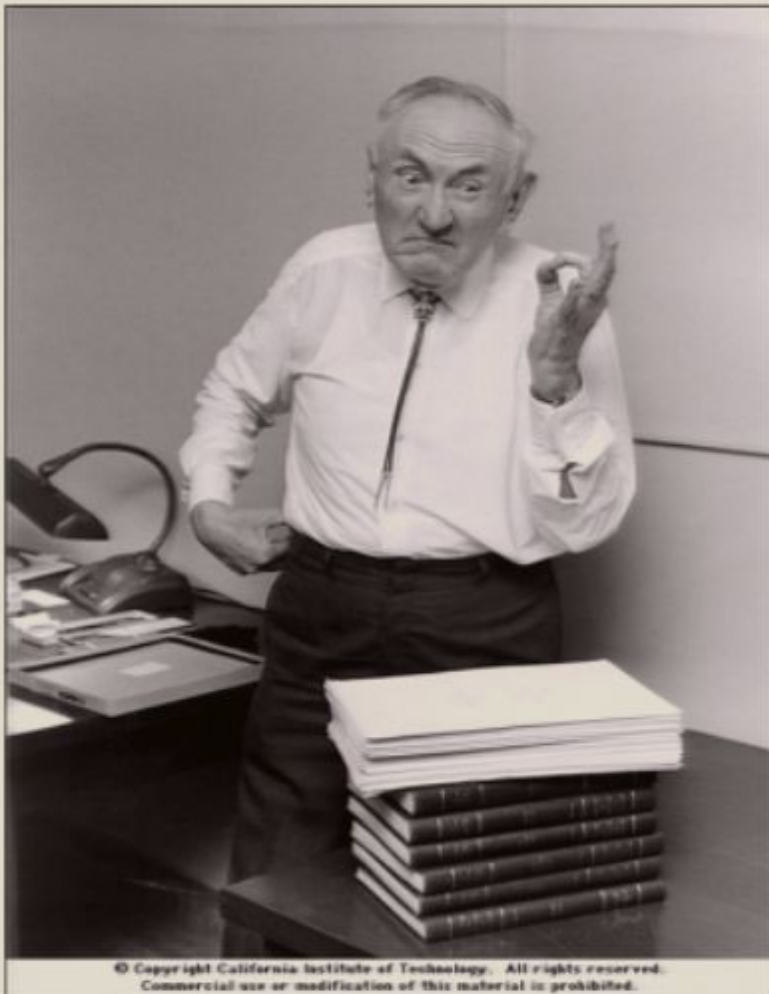
- Irascible
- Swiss
- Physicist
- Doubled the number of known supernovae



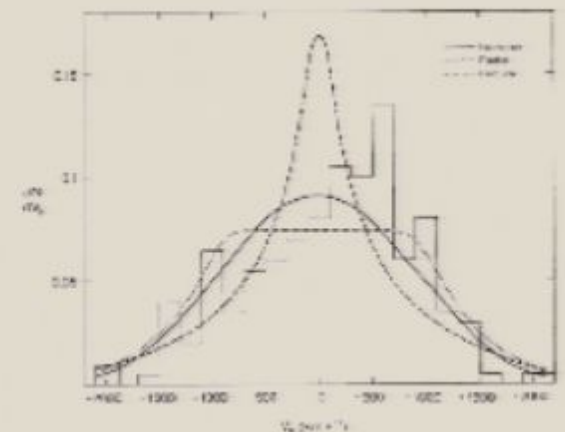
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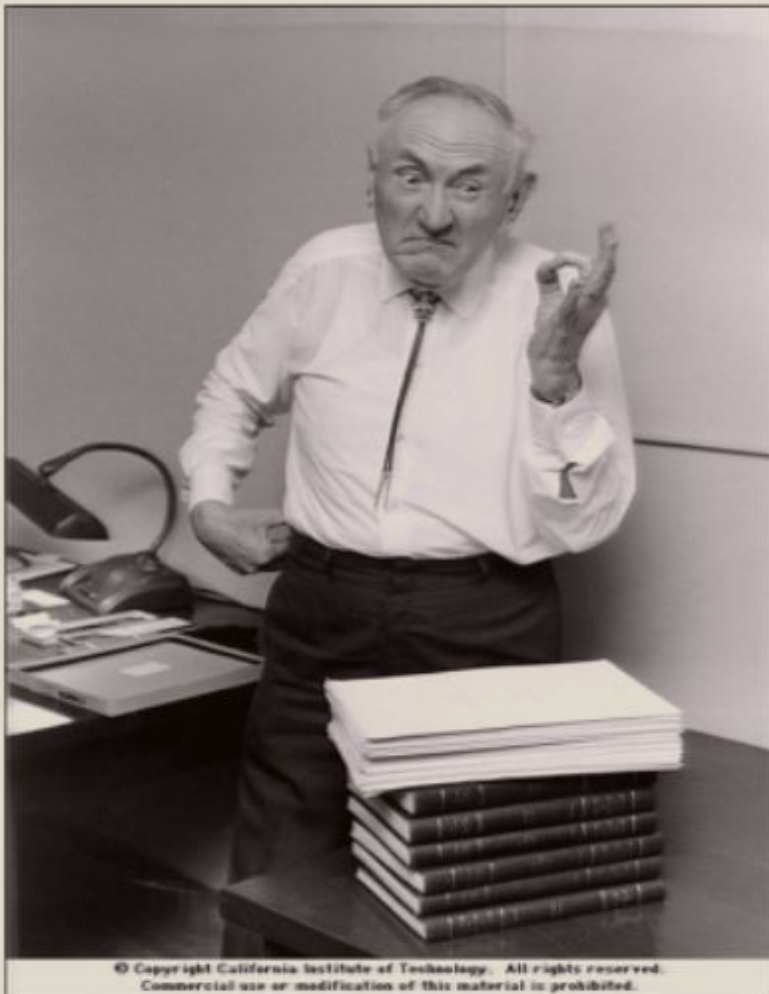
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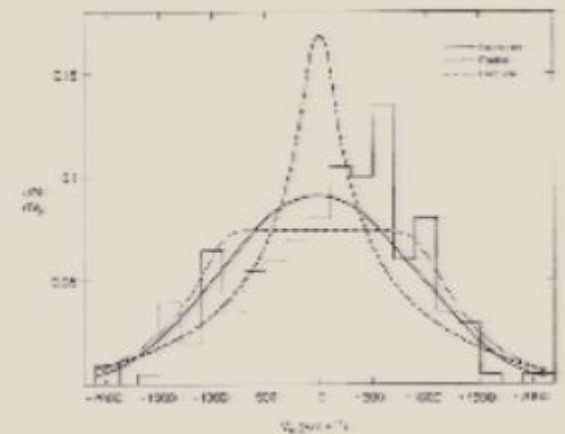
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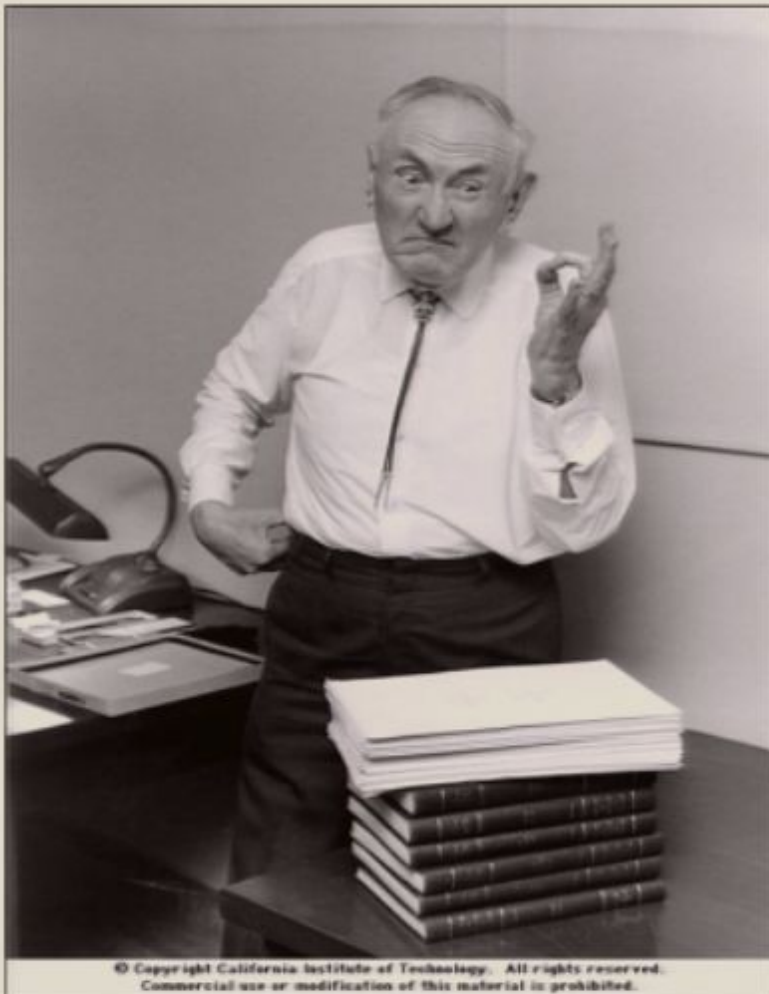
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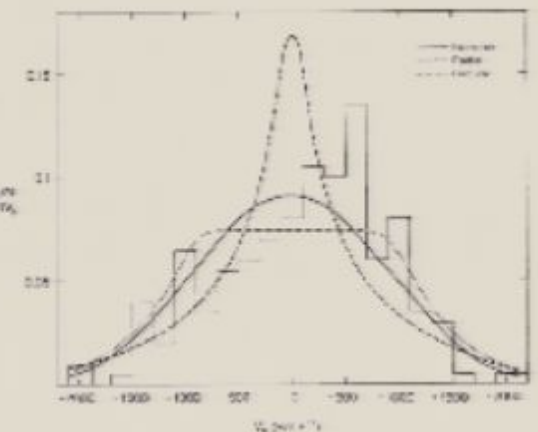
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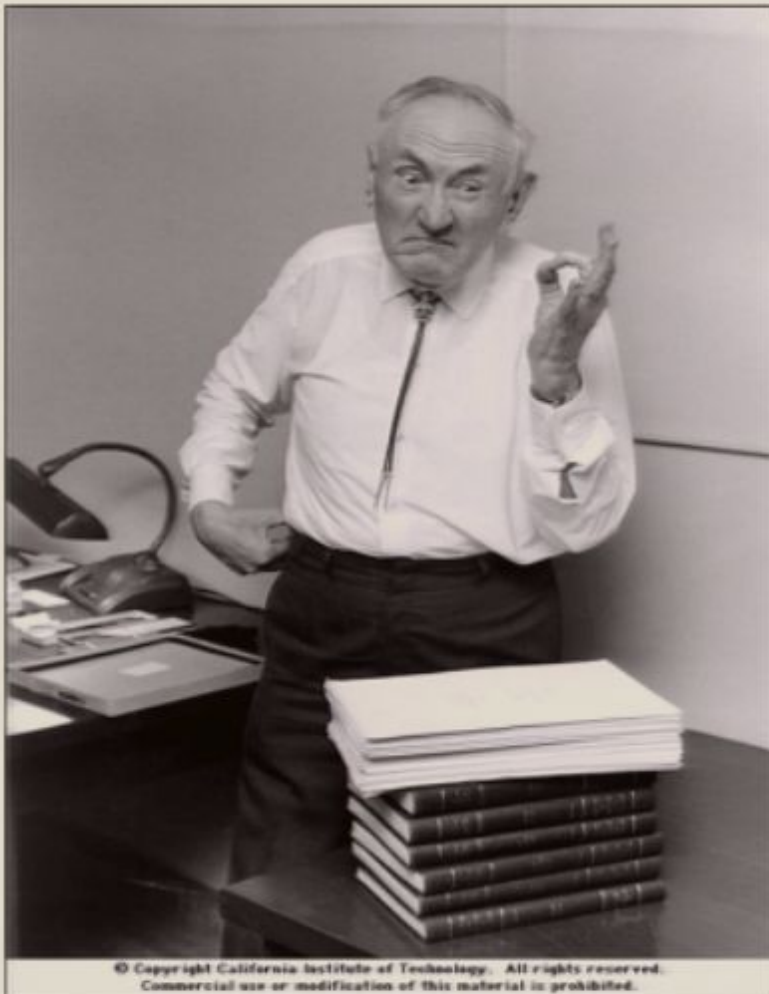
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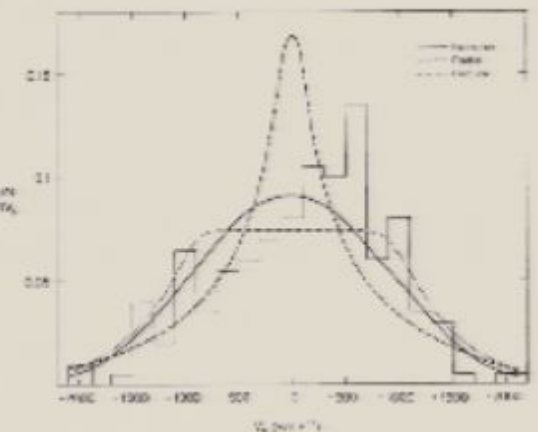


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- Suggested this light deficit was due to "dark matter"

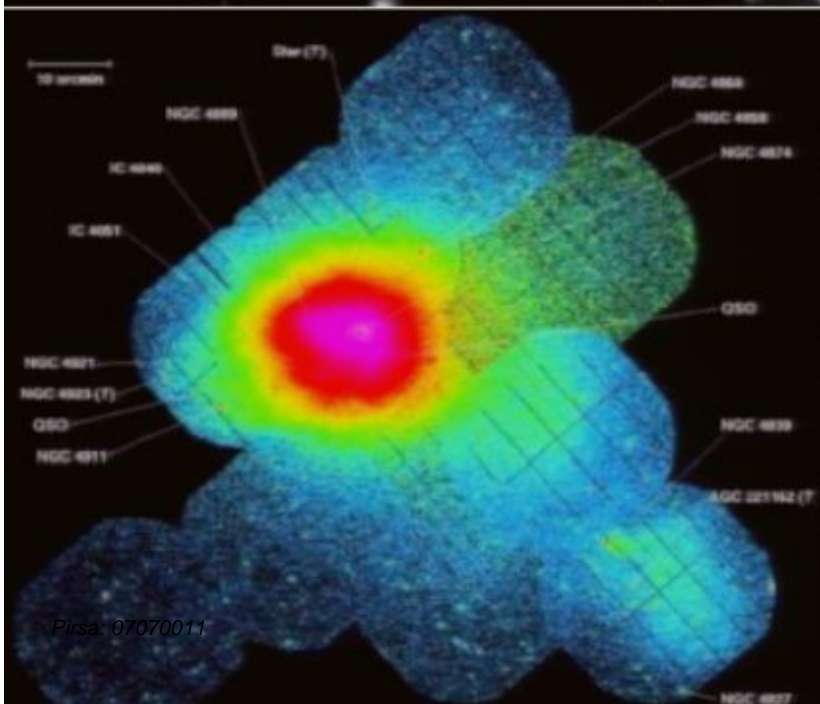


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The Coma Cluster in Optical light and X-rays

XMM X-ray image



N.B. Gravitational Lensing

Gravitational Lens in Galaxy Cluster Abell 1689  HUBBLESTIE.org

2006: The bullet cluster - a smoking gun?



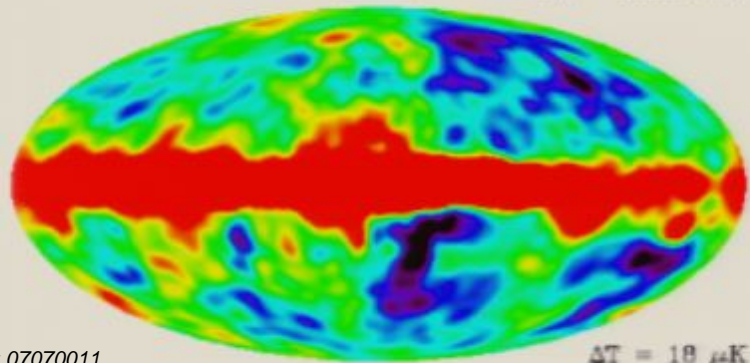
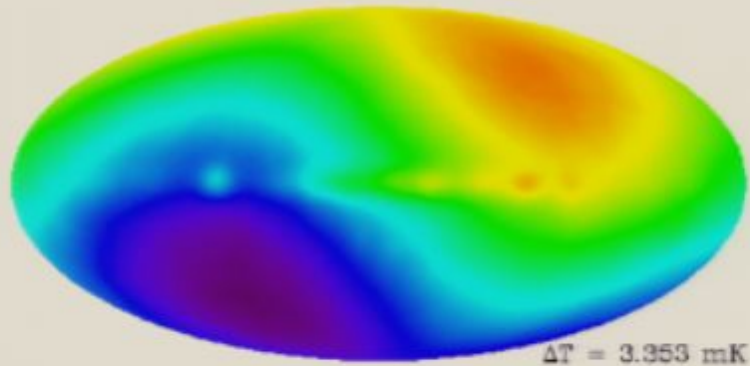








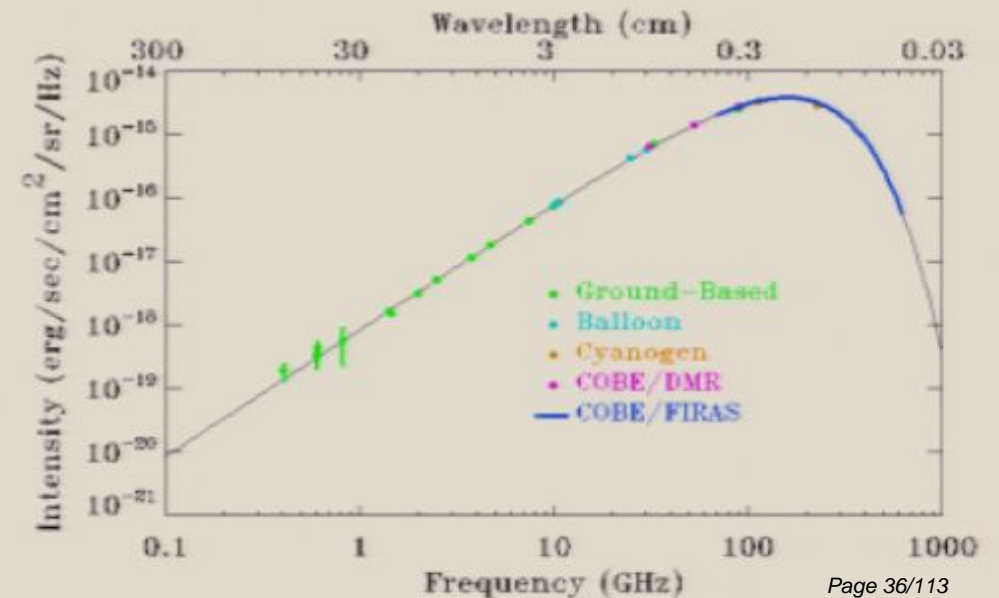
2006: Nobel Prize for COBE



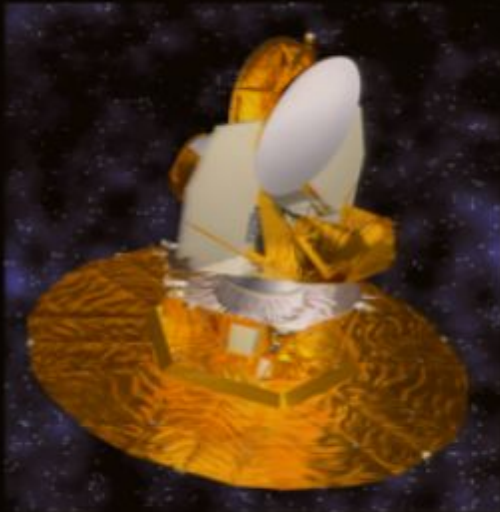
COBE: 1989 launch

John C. Mather: The Blackbody Spectrum

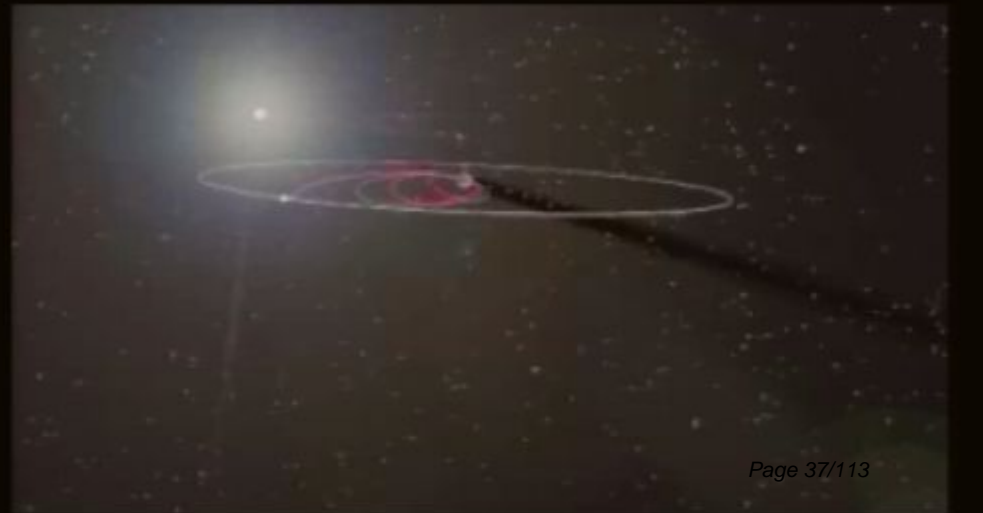
George F. Smoot: Spatial Anisotropies



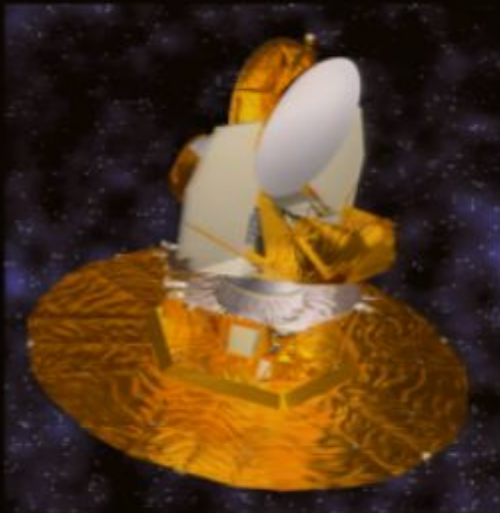
2003-2006: Dark matter confirmed on the largest scales



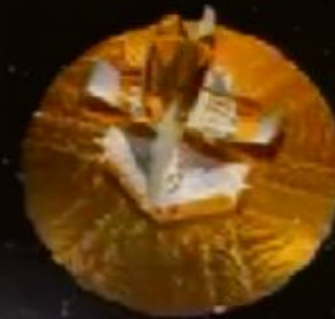
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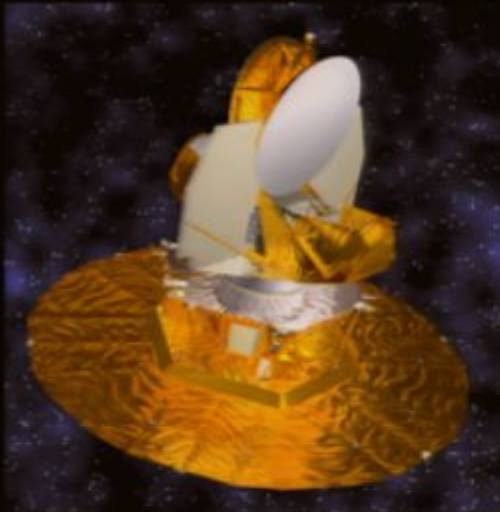
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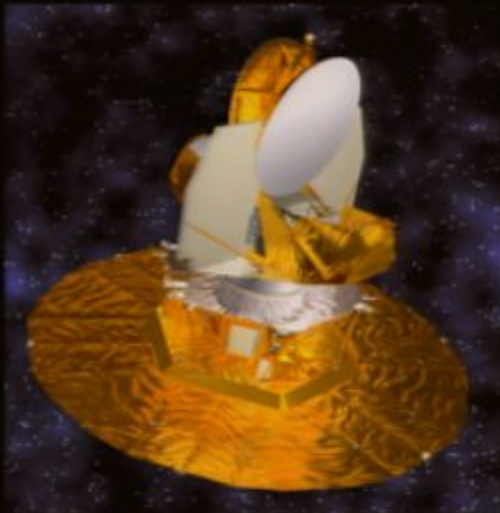
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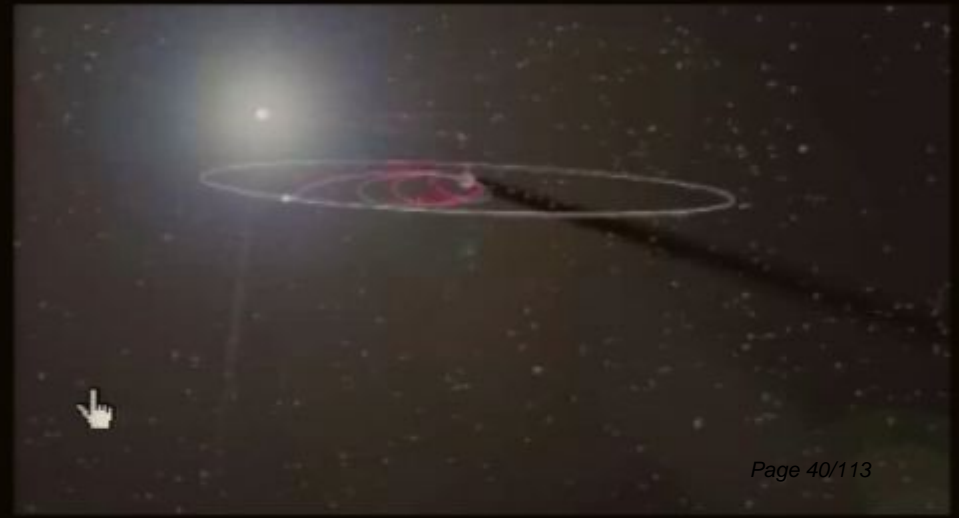
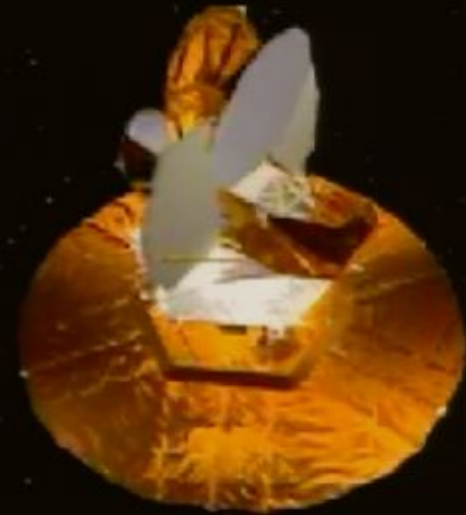
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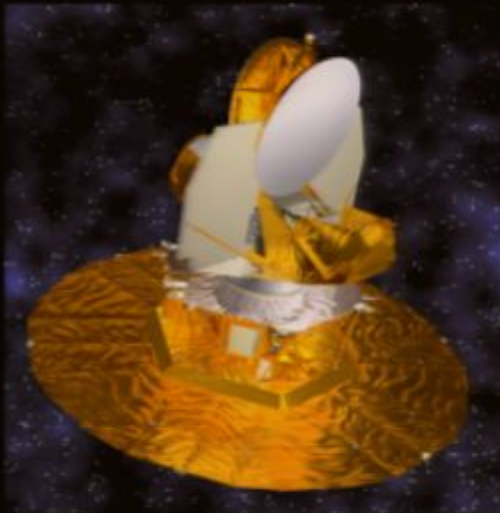
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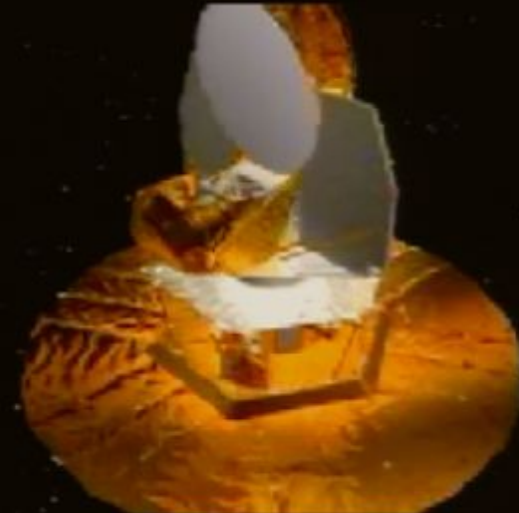
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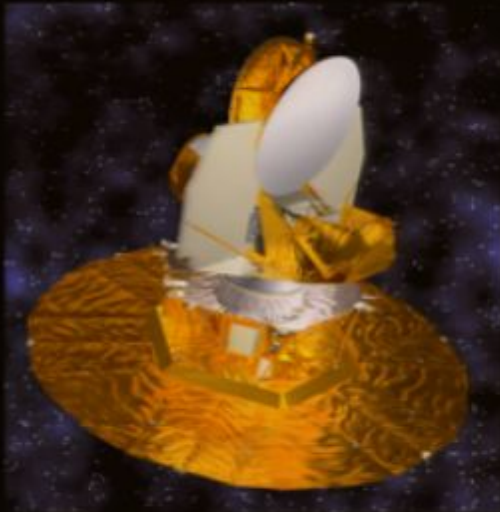
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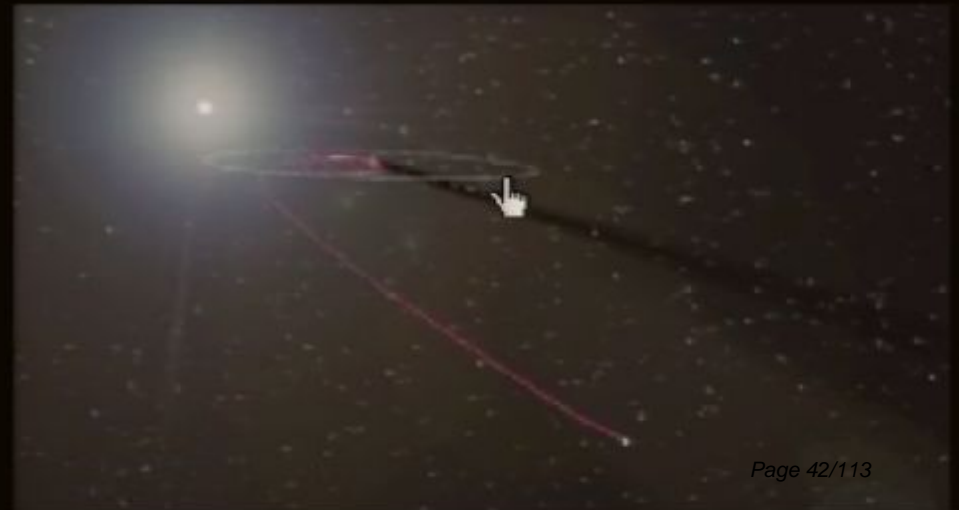
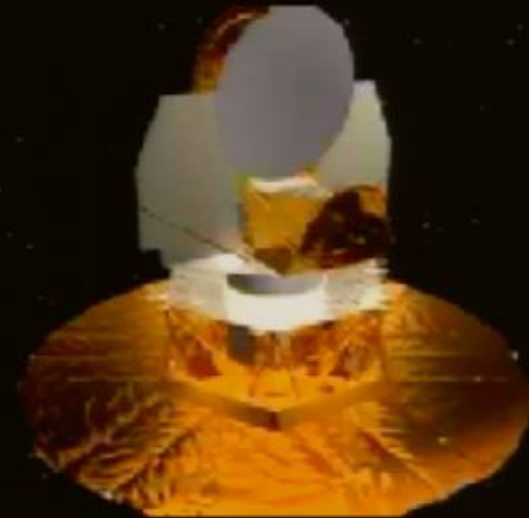
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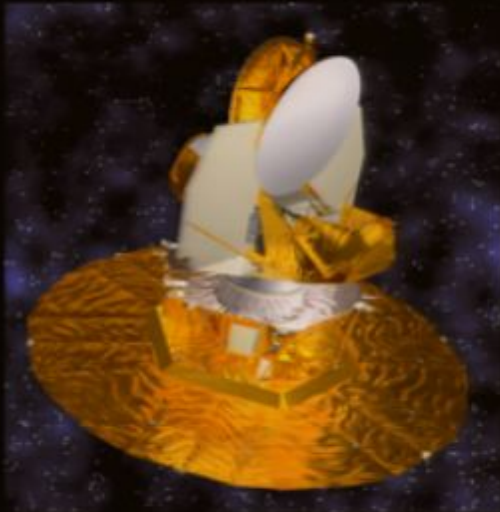
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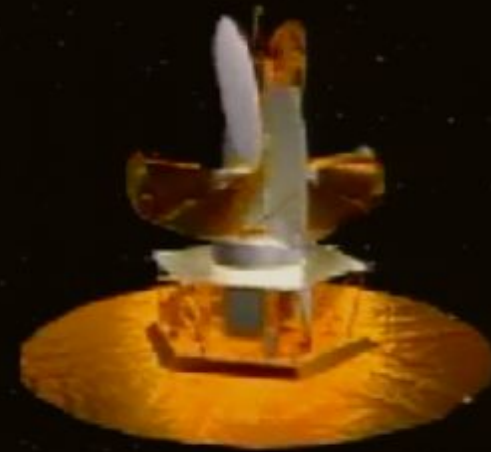
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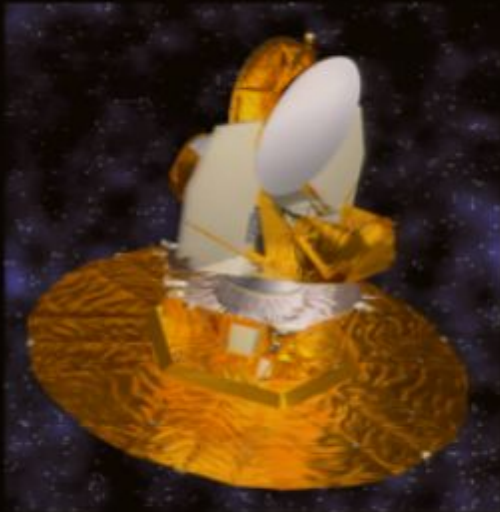
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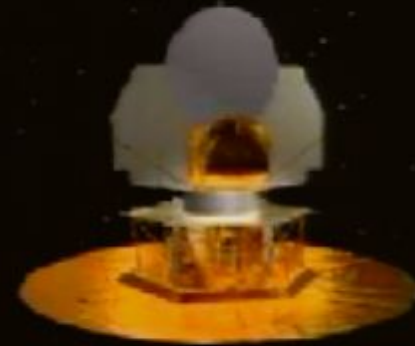
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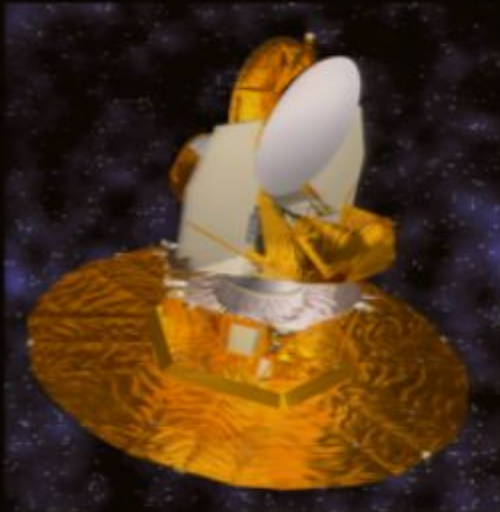
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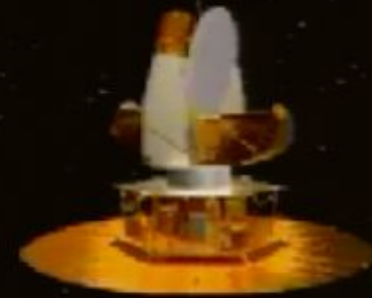
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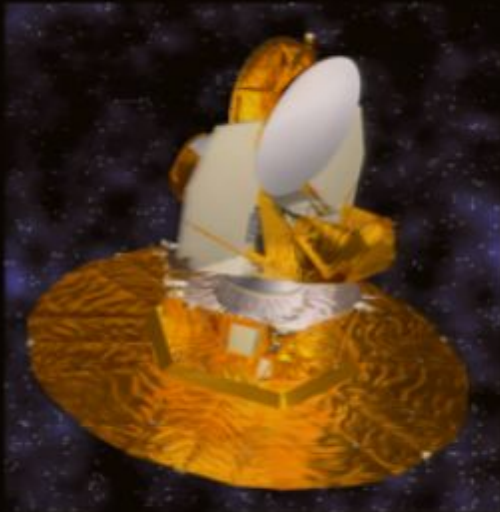
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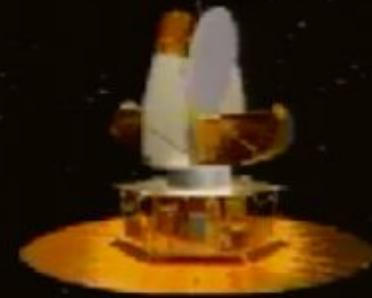
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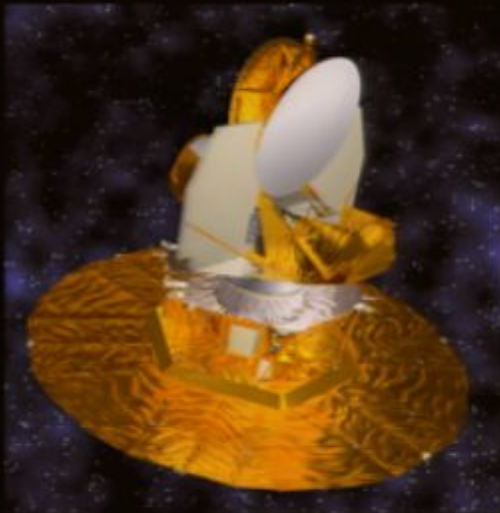
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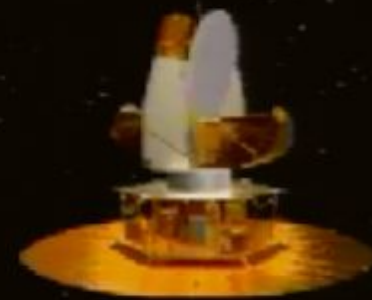
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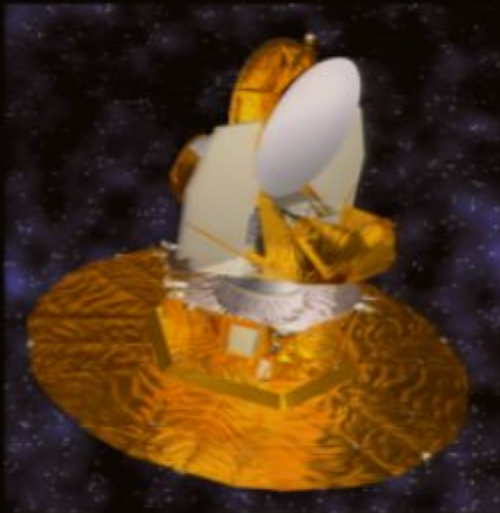
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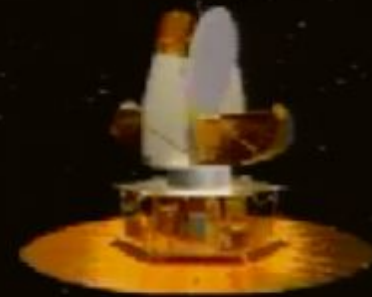
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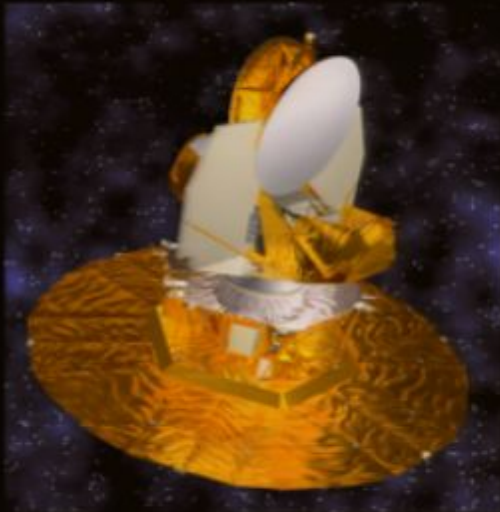
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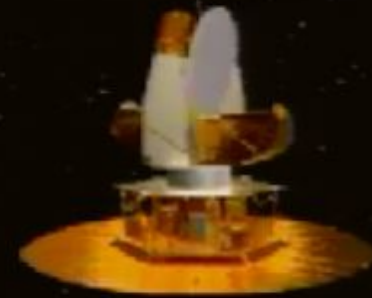
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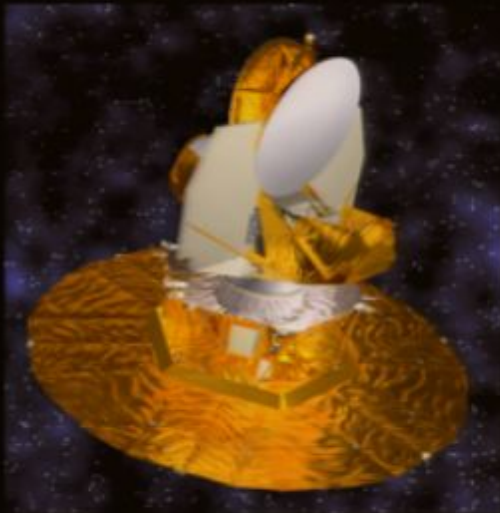
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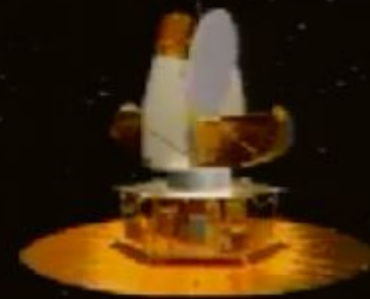
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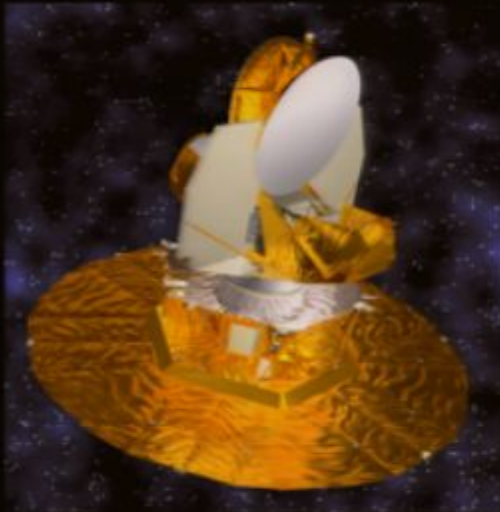
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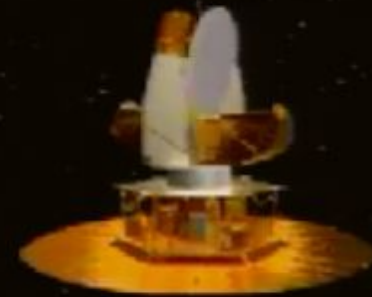
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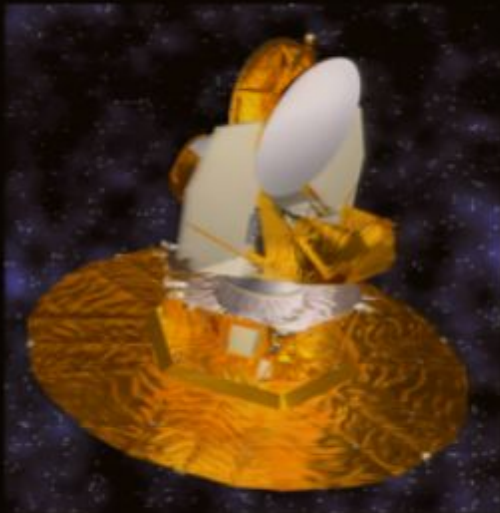
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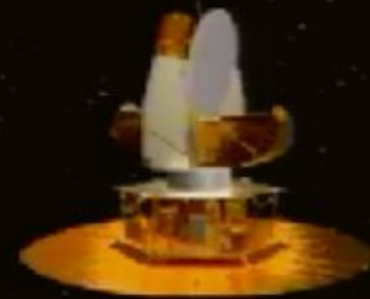
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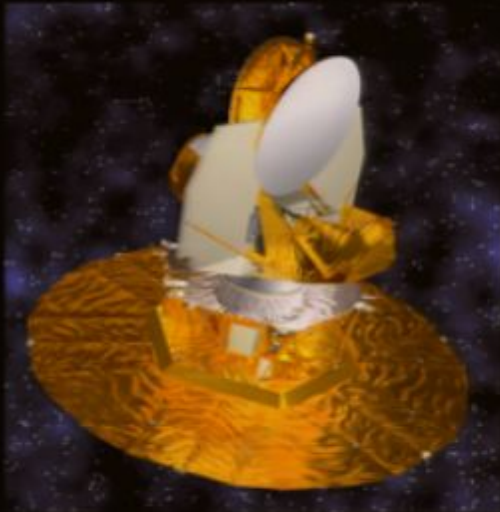
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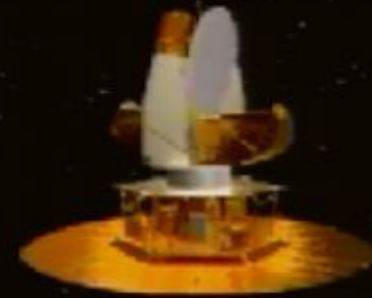
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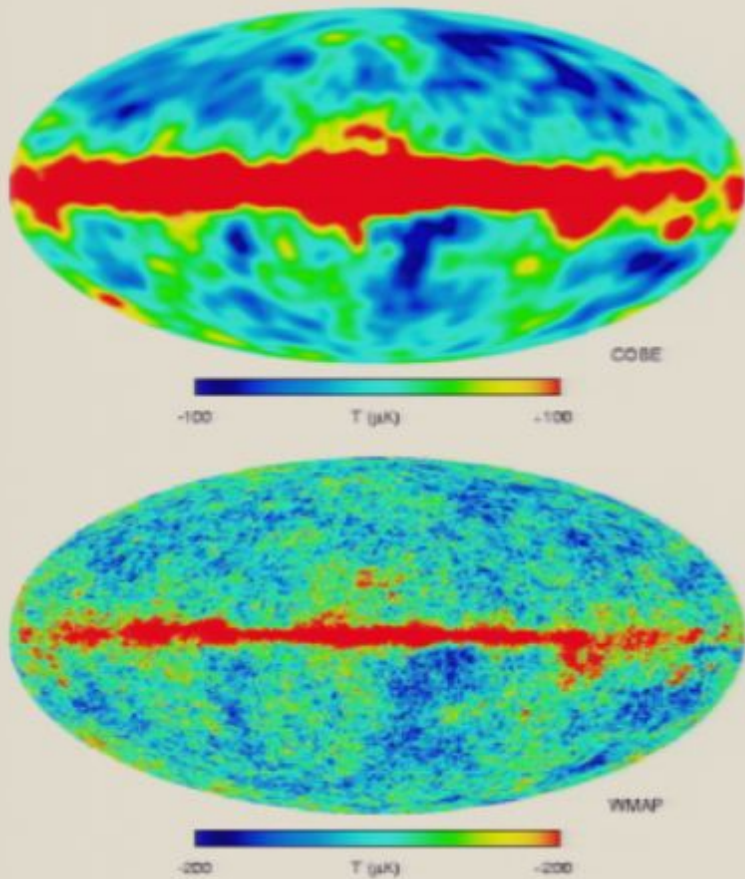
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Peaks in angular power spectrum from acoustic oscillations in photon-baryon-dark matter fluid

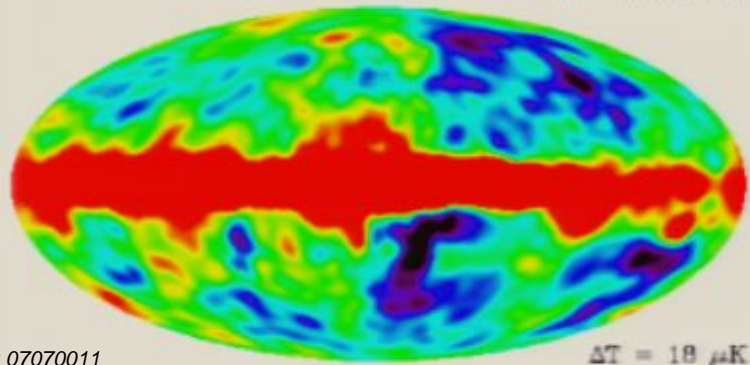
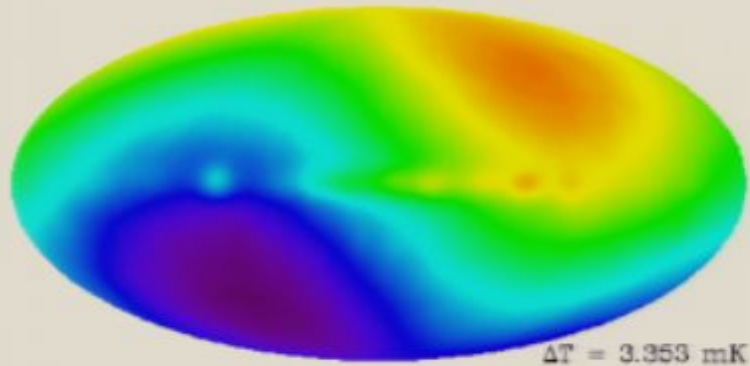
Height and shape of peaks depends on equation of state (e.g. sound speed)

Simple test of overall energy content of the universe at $z=1000$

Fig. 7.— A comparison of the COBE 90 GHz map (Bennett et al. 1996) with the WMAP WMAP map. The WMAP map has 50 times finer resolution than the COBE map.



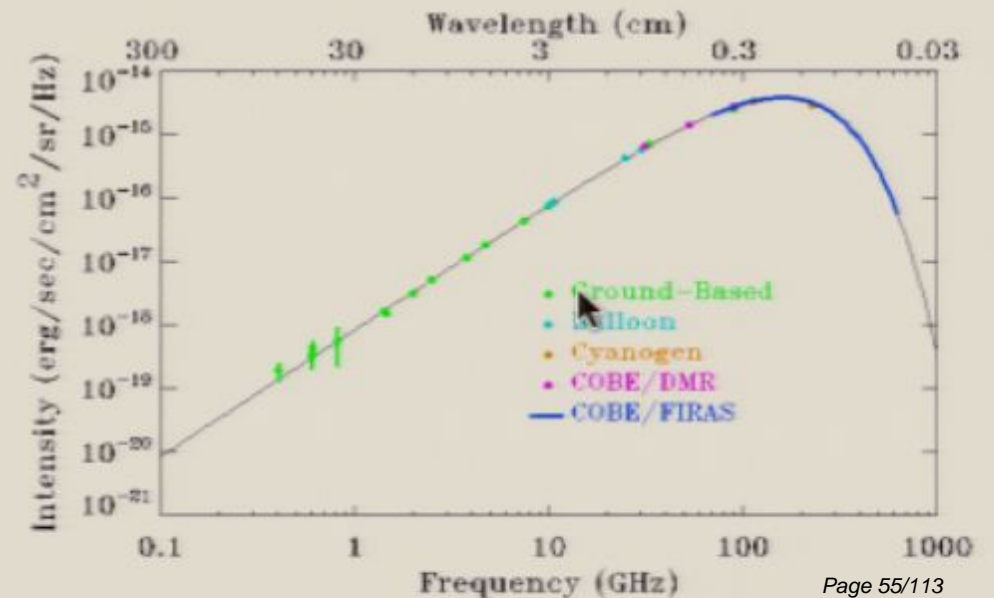
2006: Nobel Prize for COBE



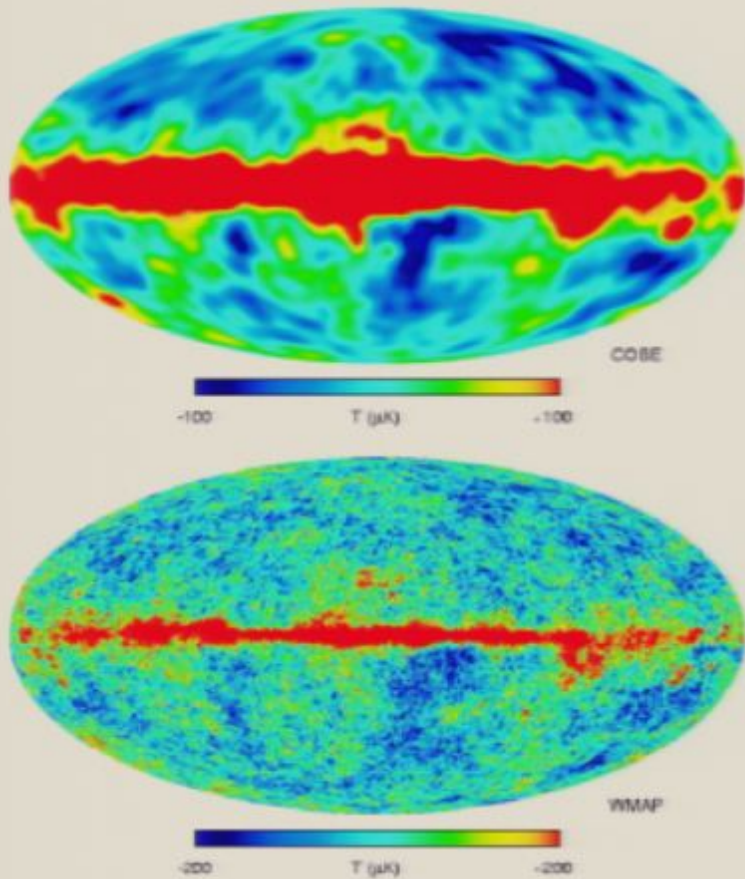
COBE: 1989 launch

John C. Mather: The Blackbody Spectrum

George F. Smoot: Spatial Anisotropies



2003-2006: Dark matter confirmed on the largest scales



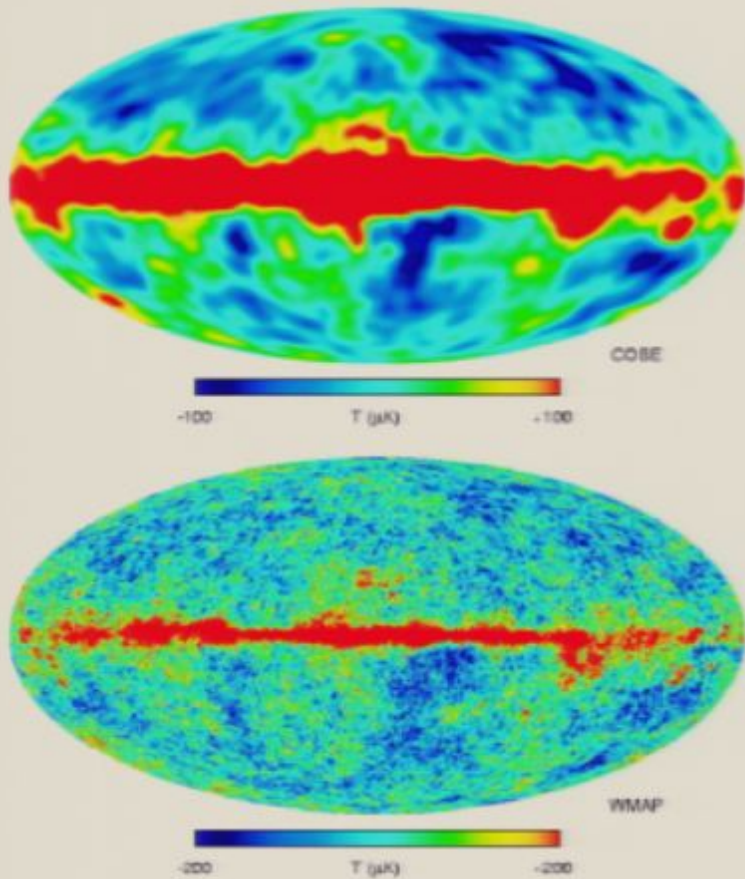
Peaks in angular power spectrum from acoustic oscillations in photon-baryon-dark matter fluid

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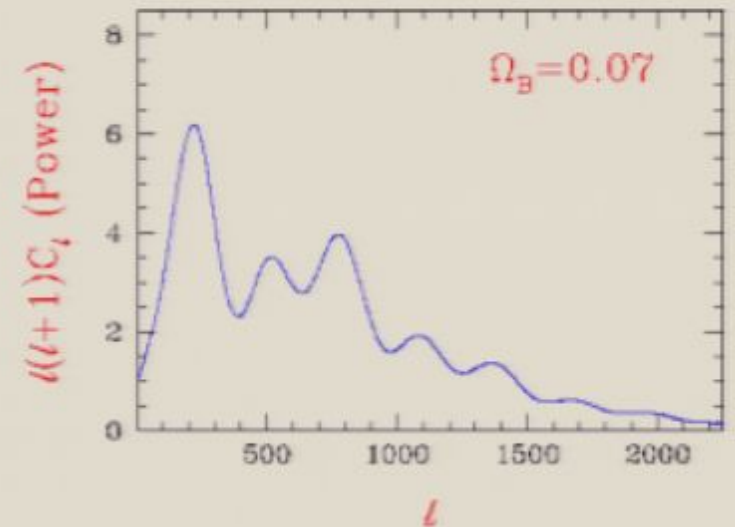
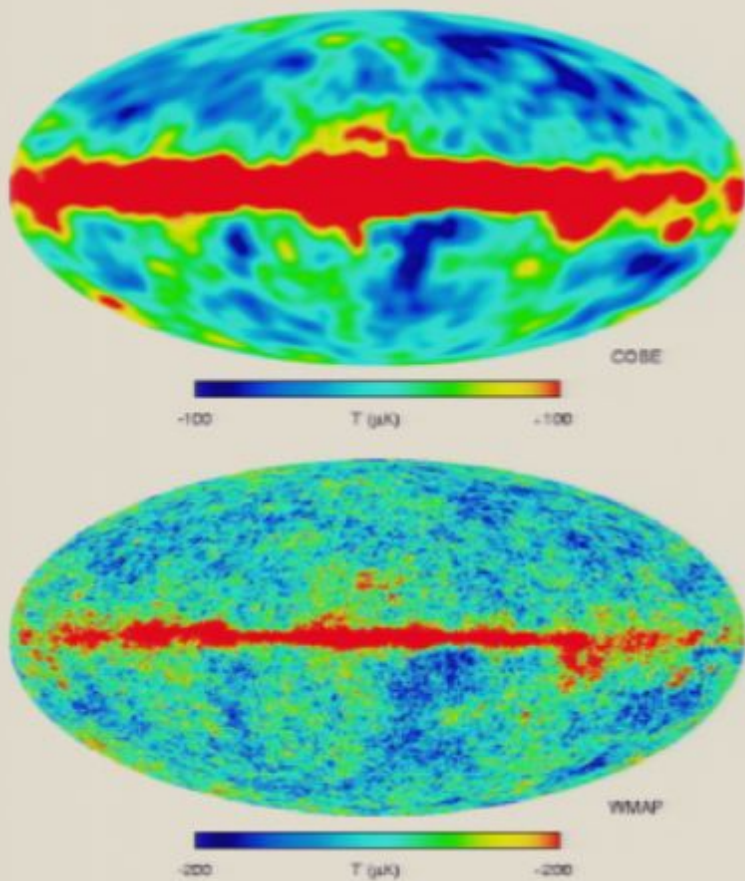


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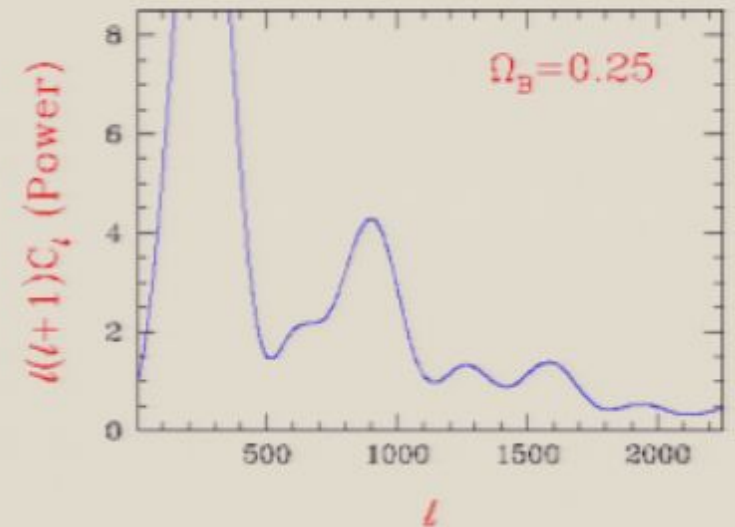
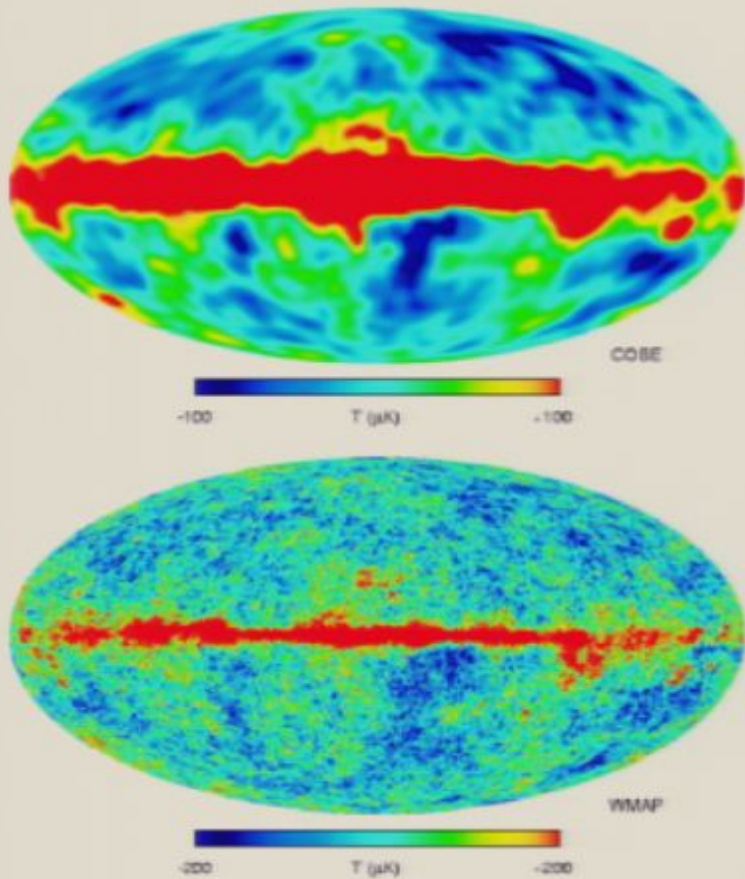


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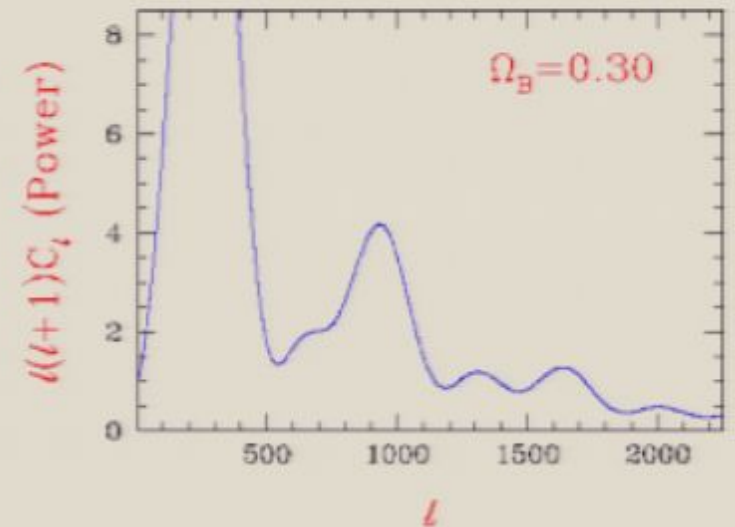
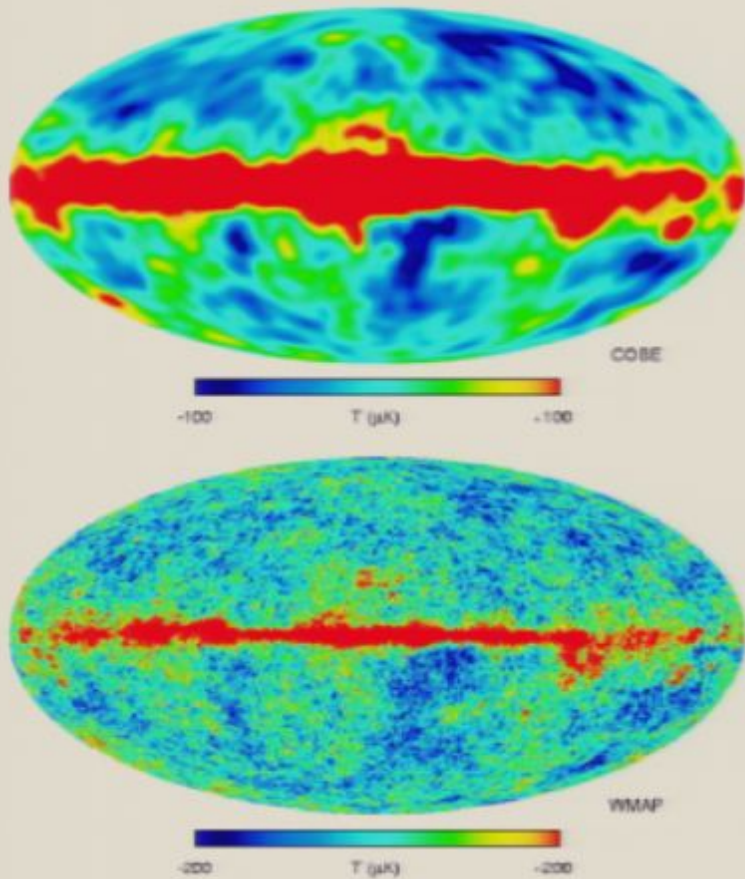


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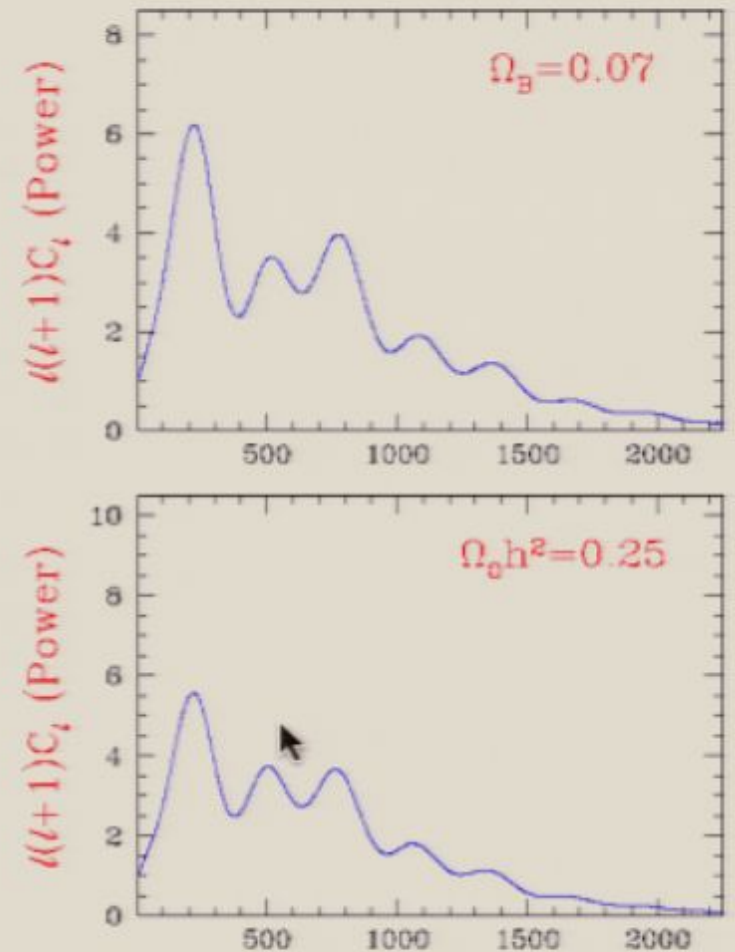
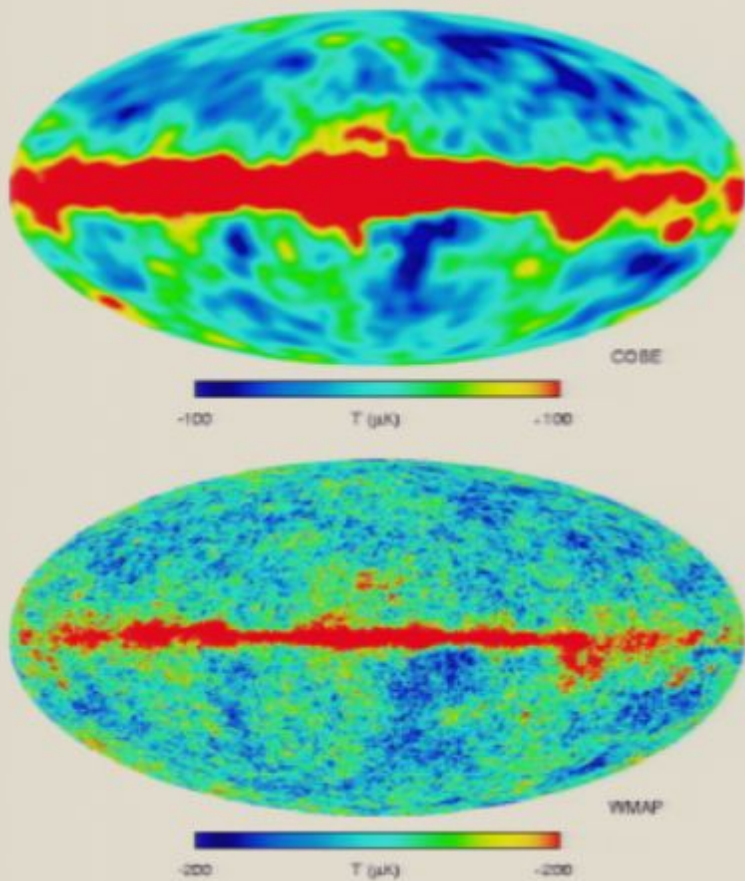


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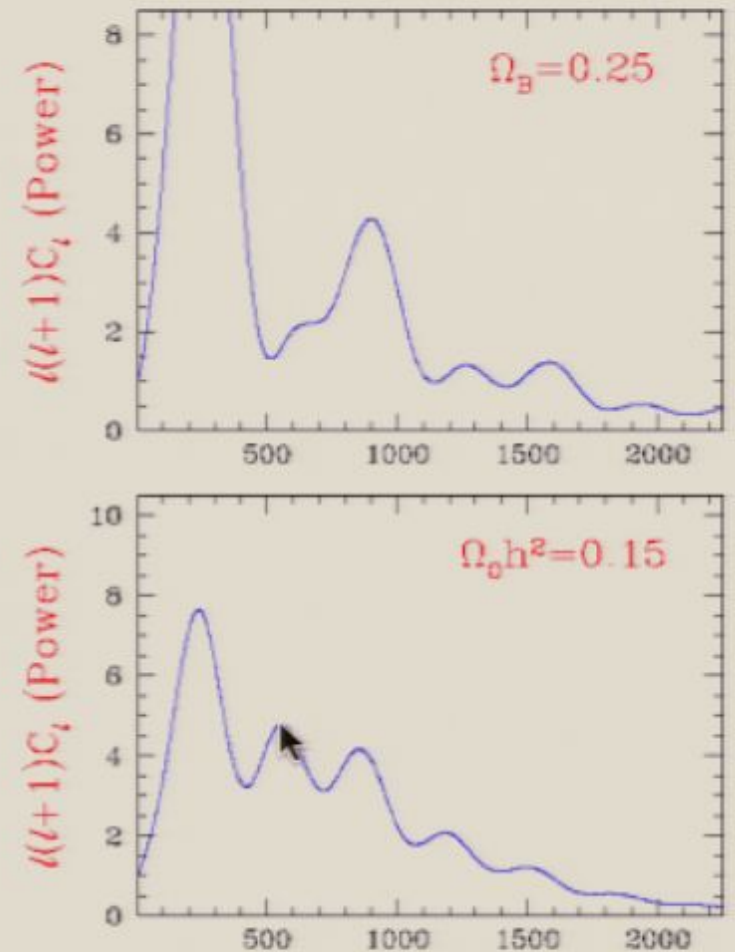
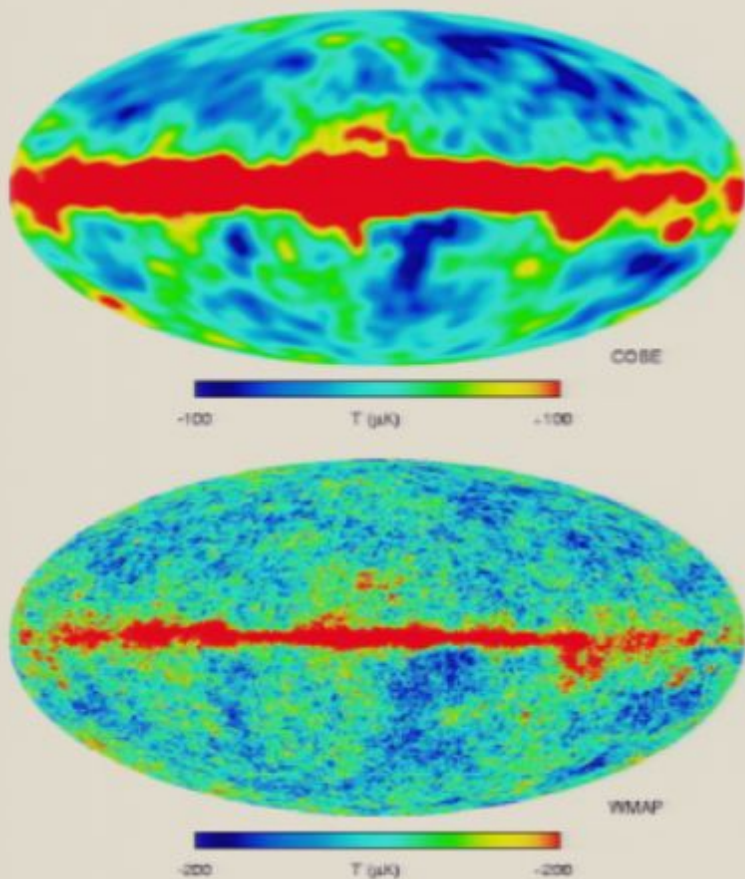


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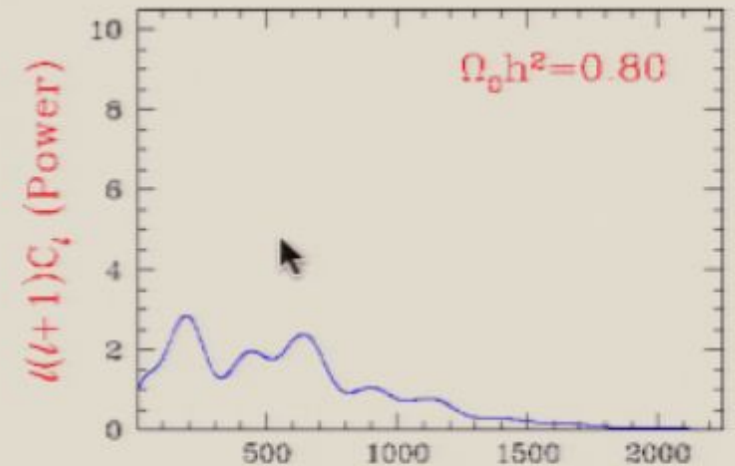
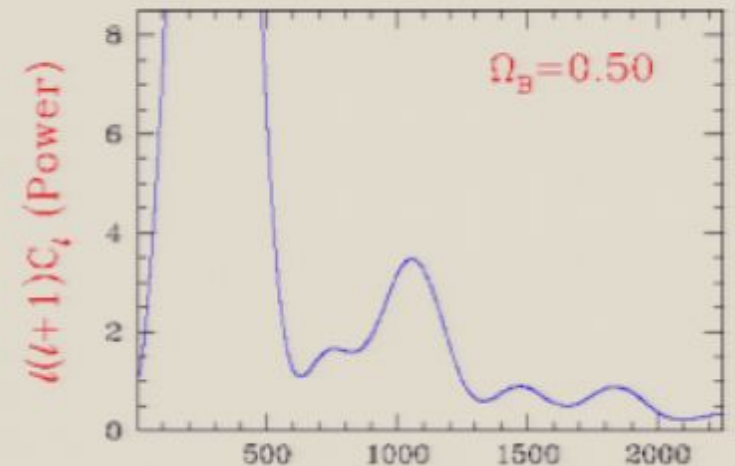
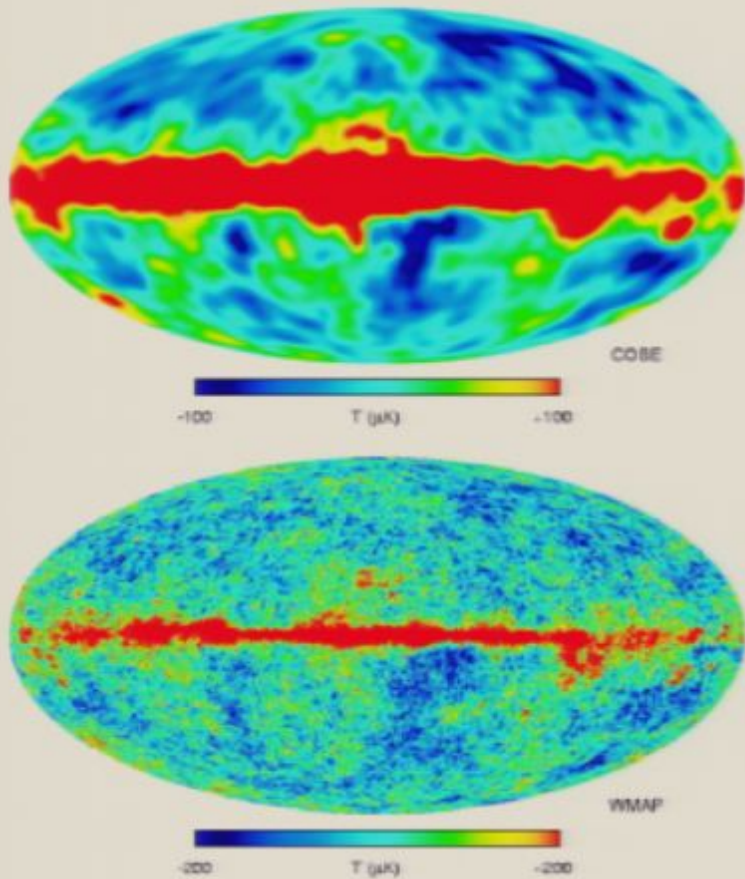


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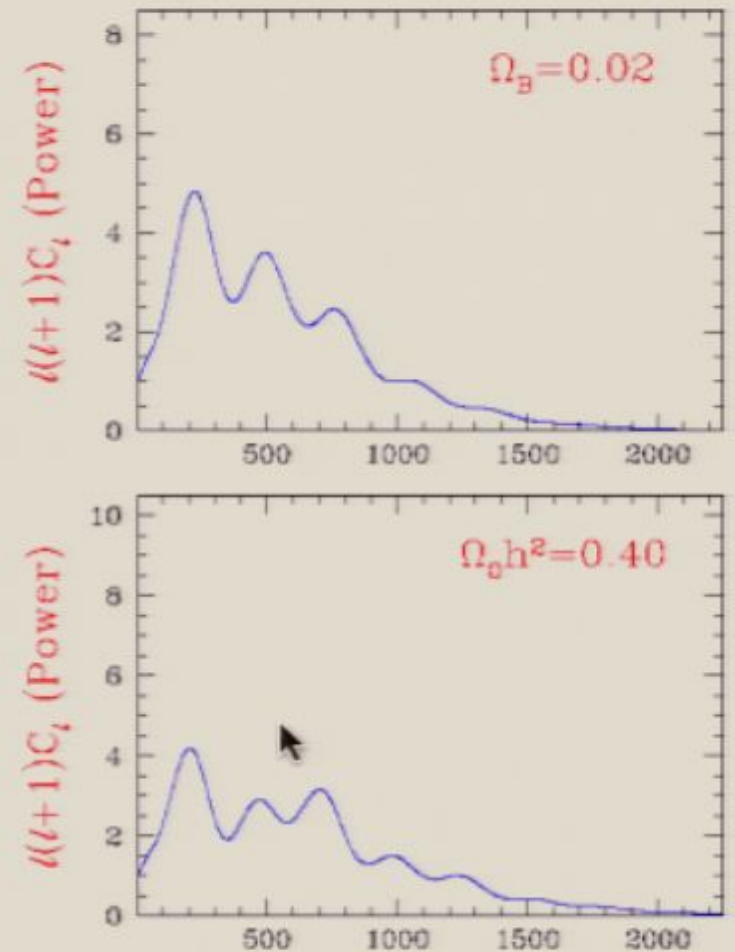
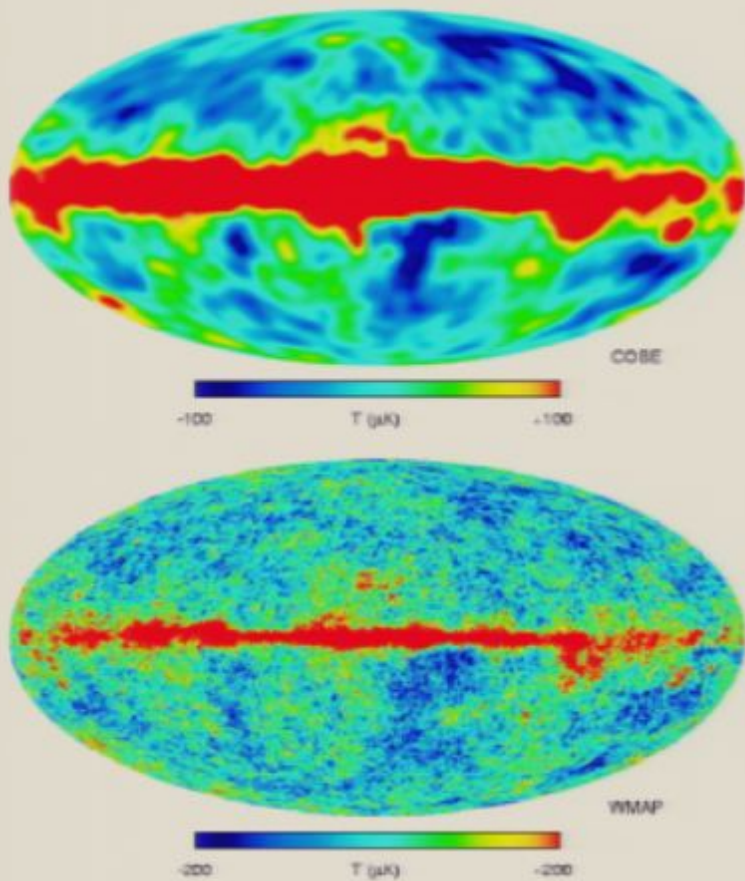


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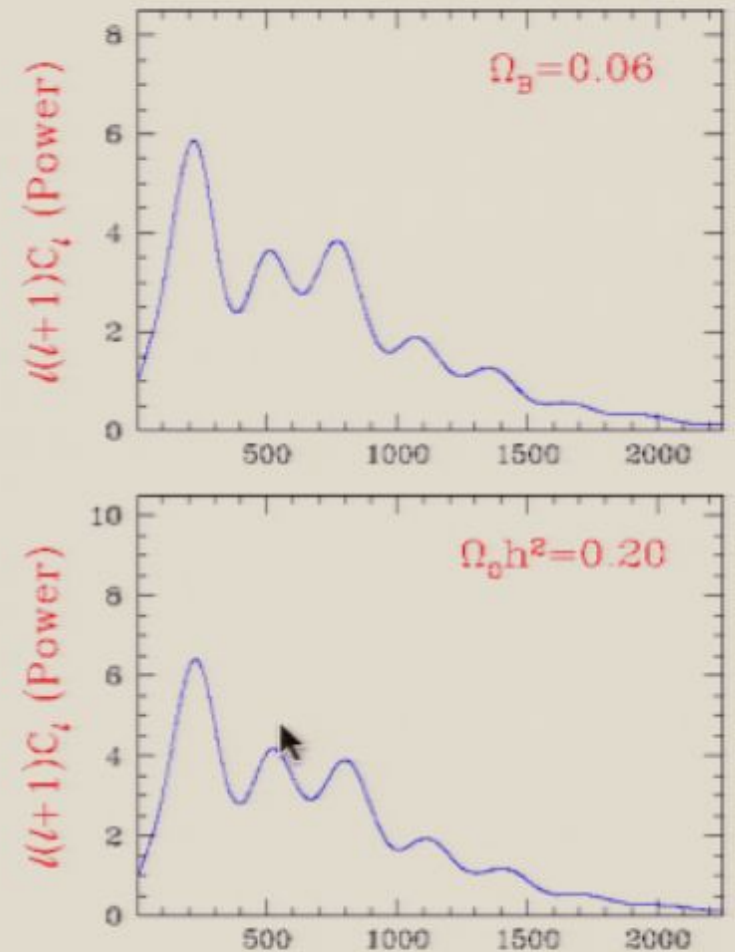
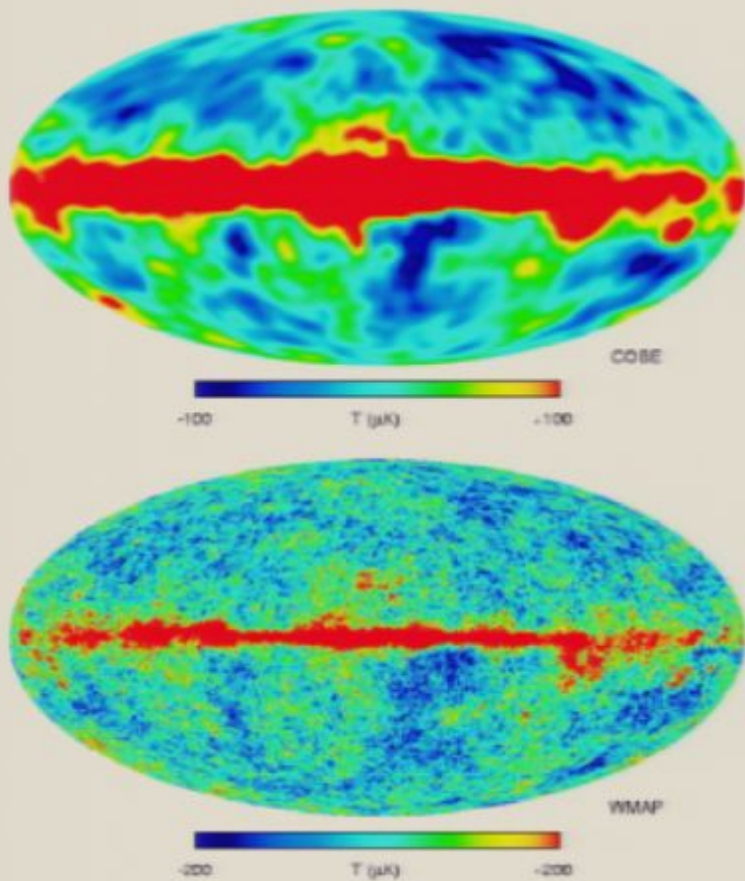


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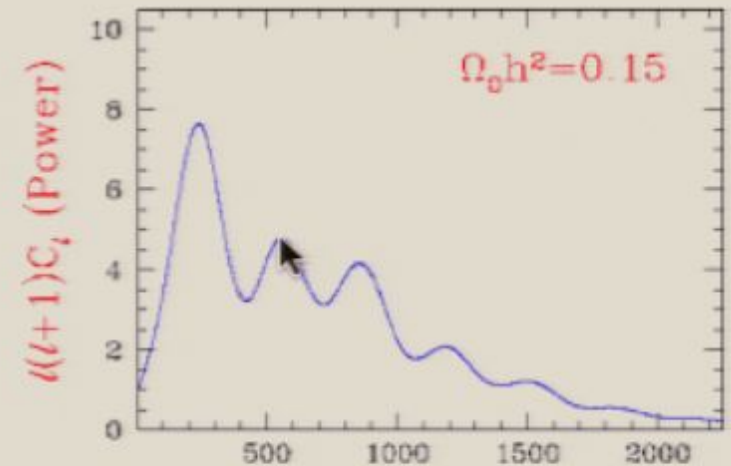
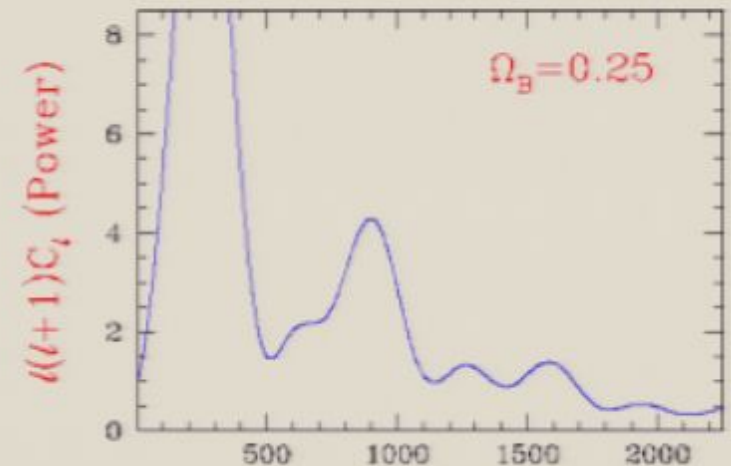
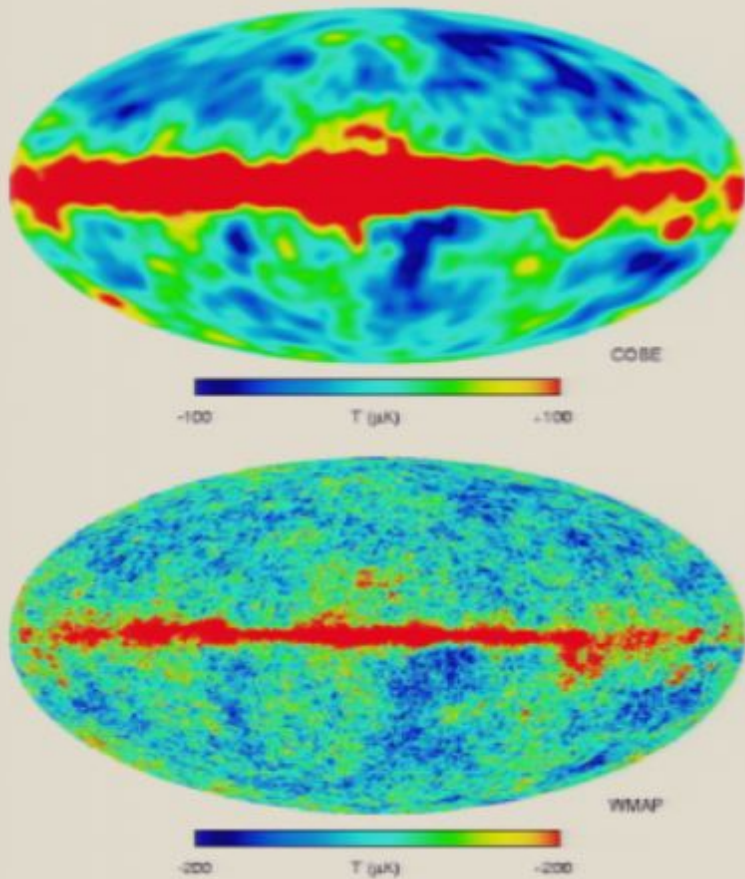


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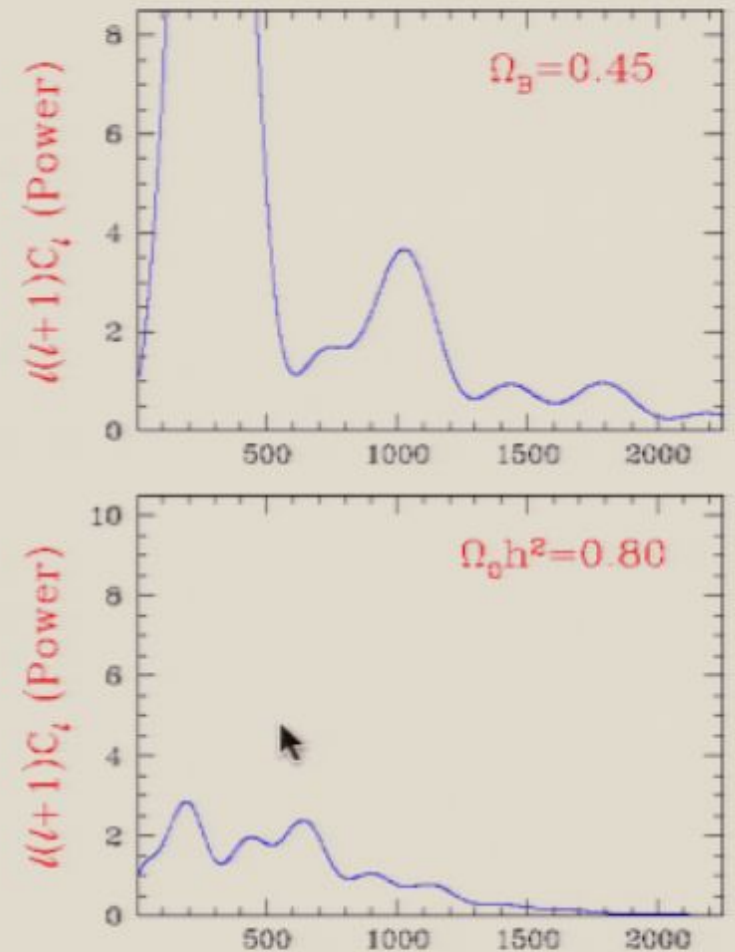
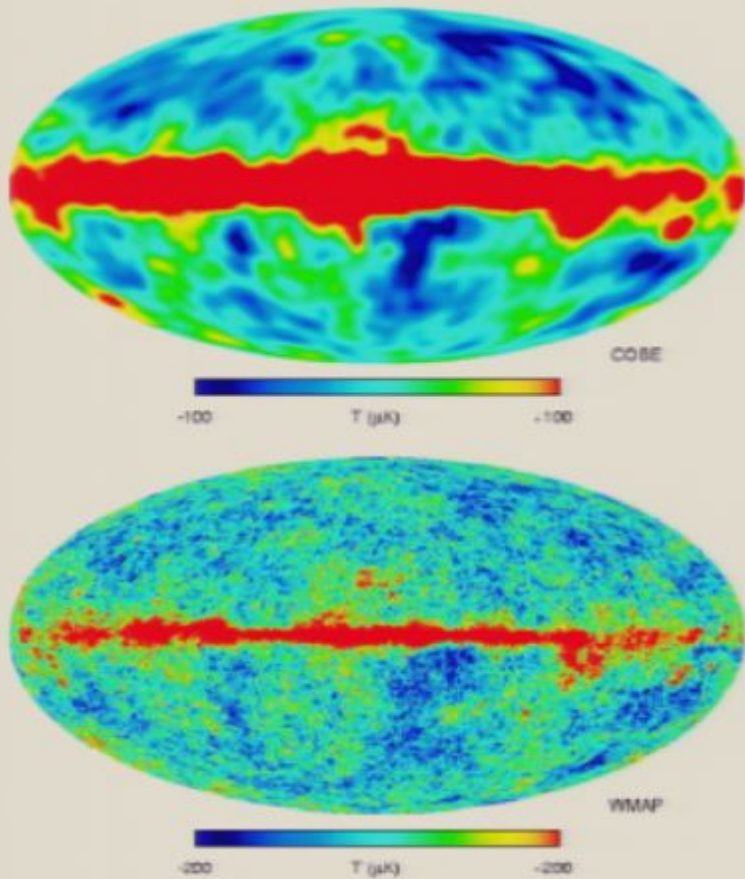


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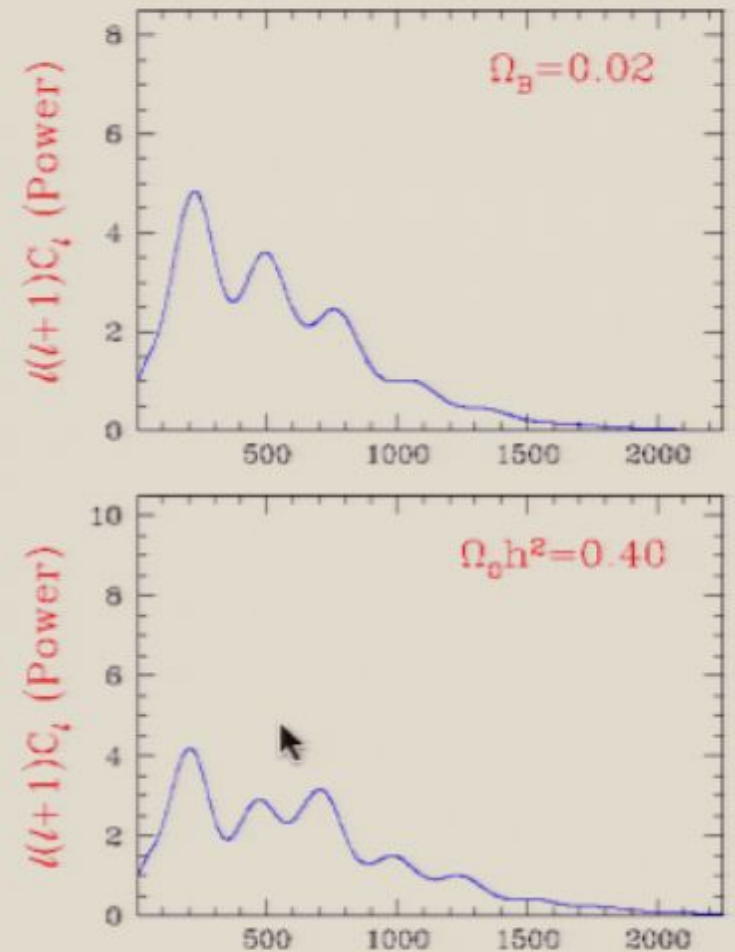
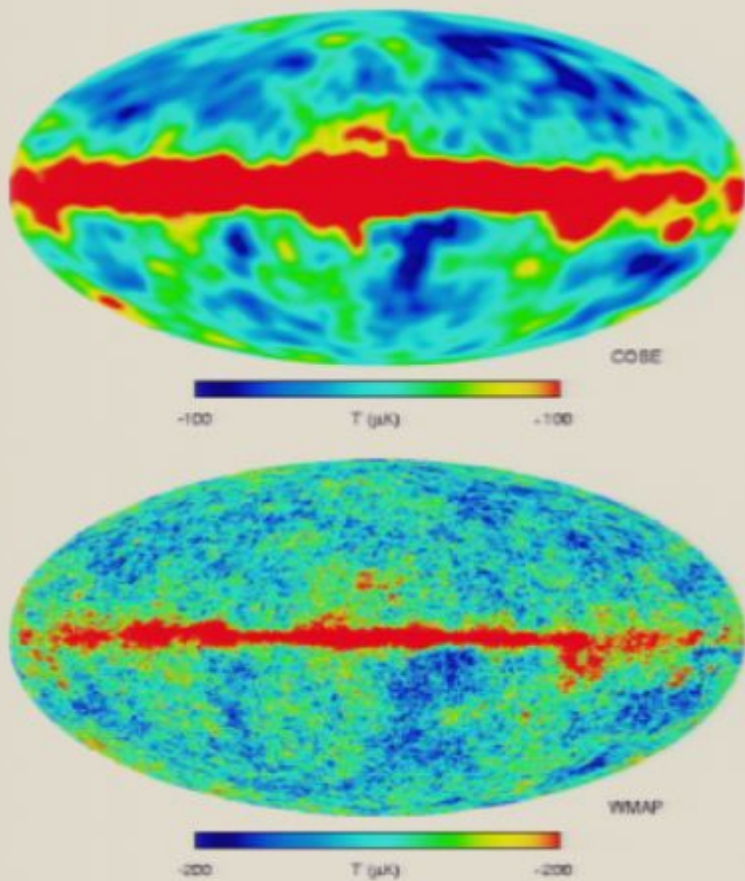


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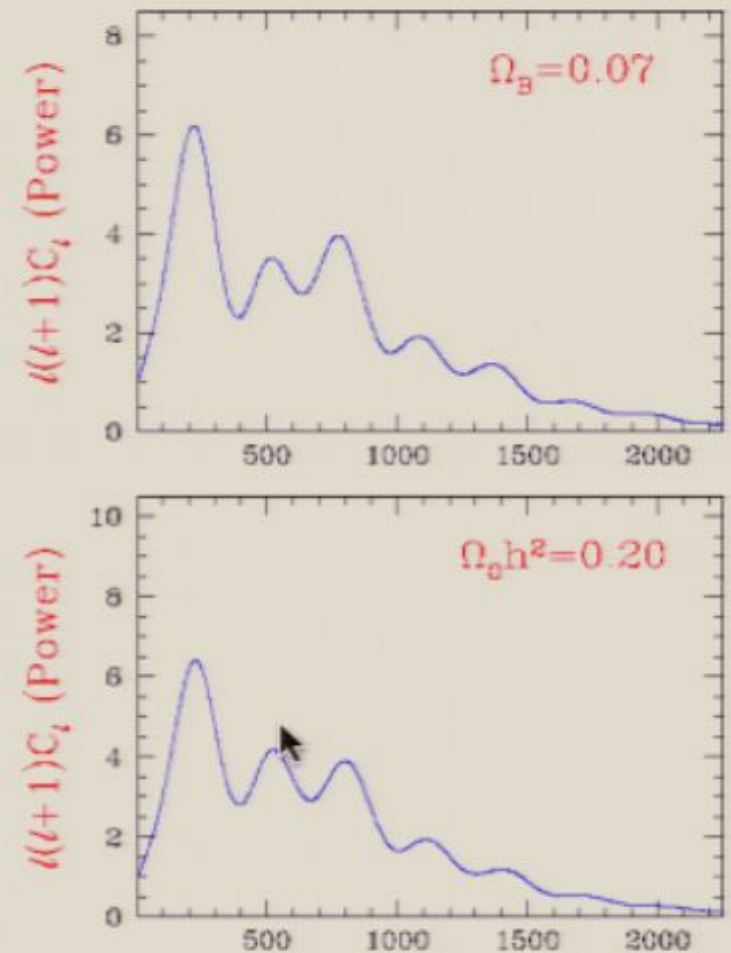
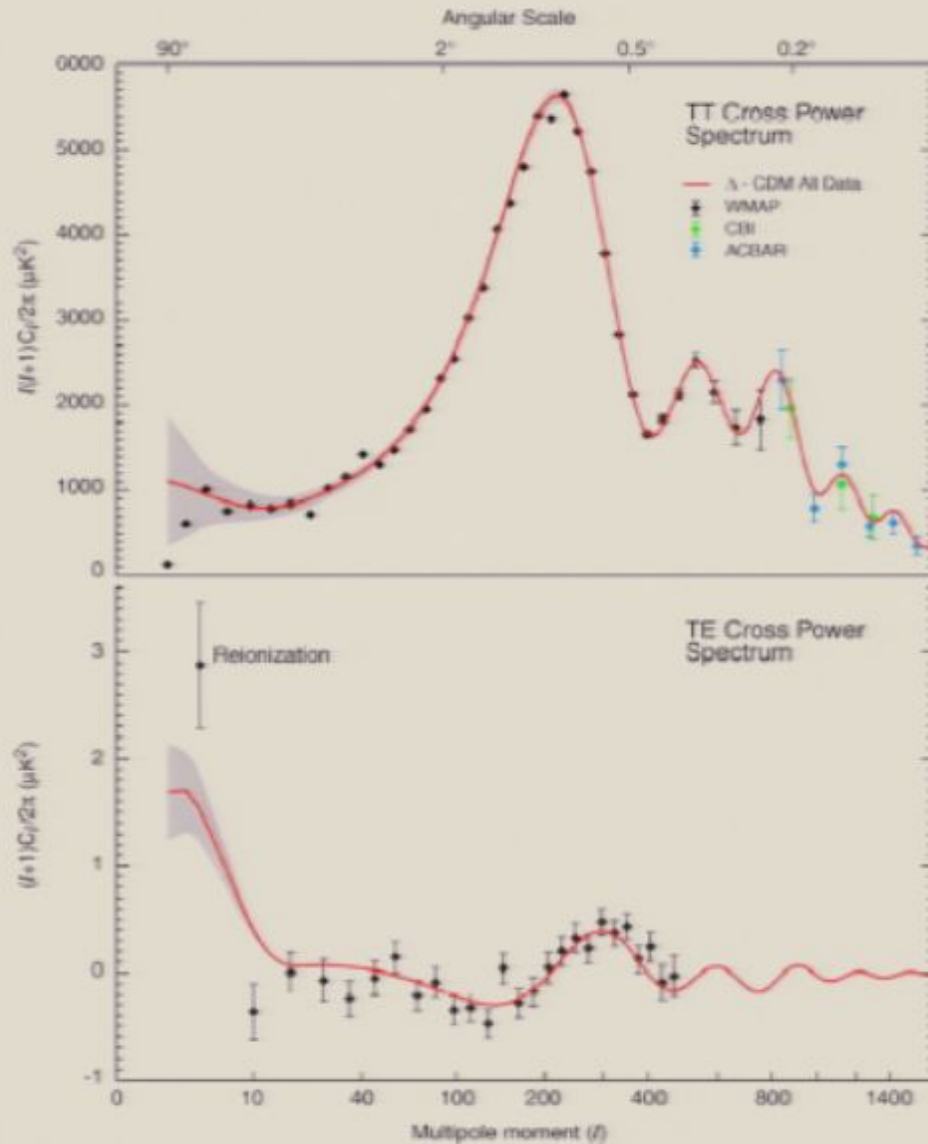


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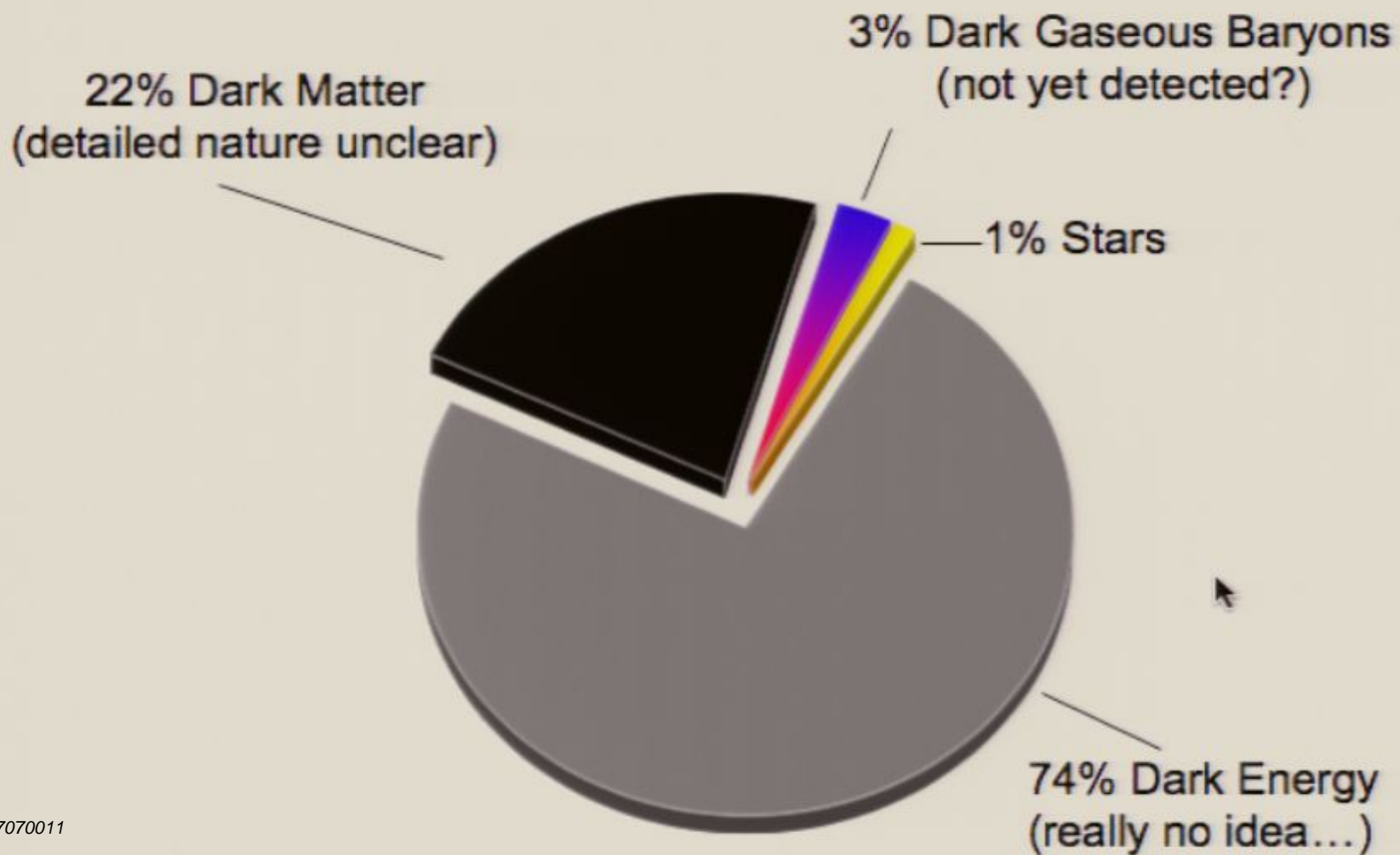
Matter density:
 $0.135h^{-2} \pm 0.009$

Baryon density:
 $0.0224h^{-2} \pm 0.0009$

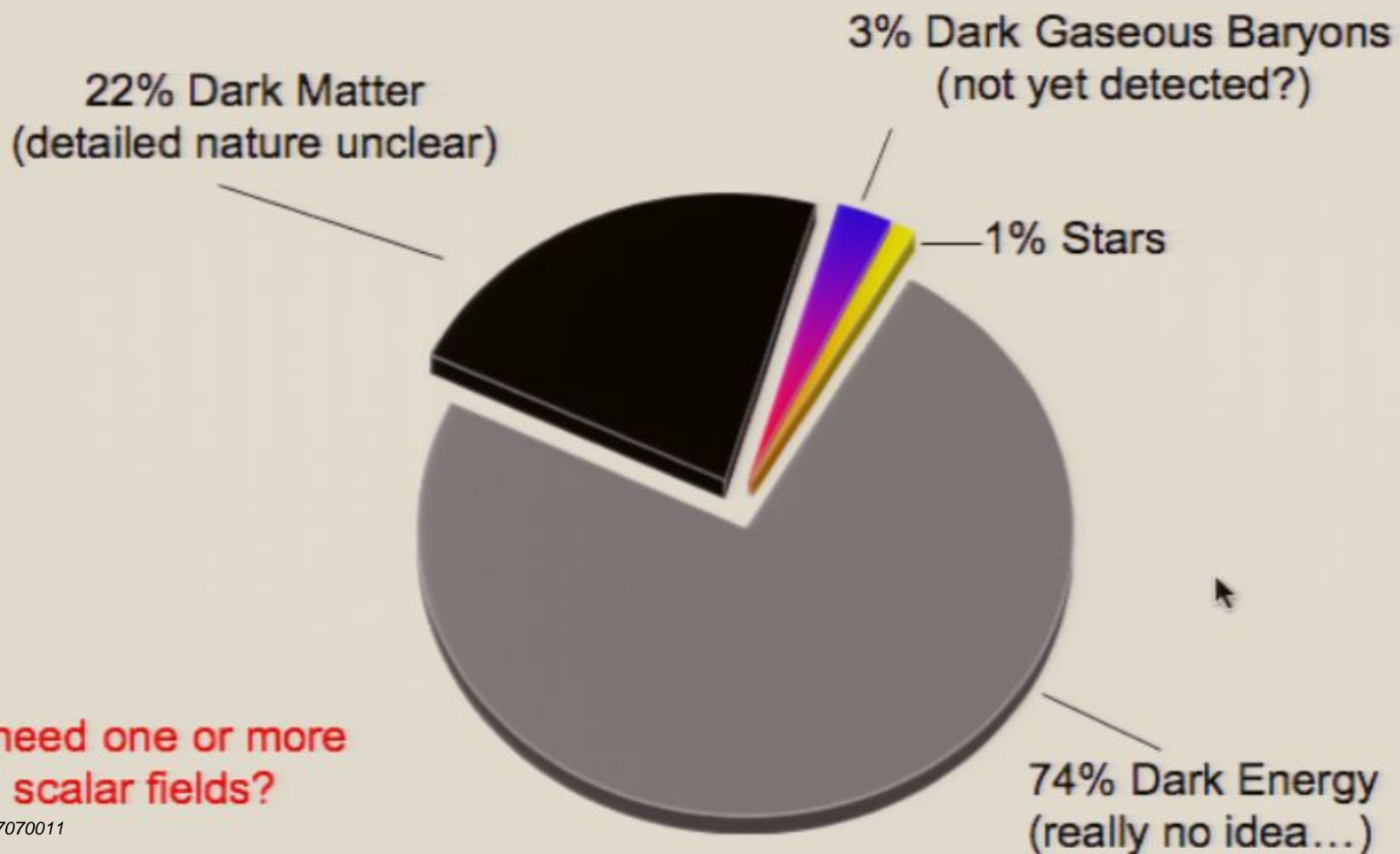
(in units of the critical density for recollapse)

Summary:

The Composition of the Universe (fourth quarter 2006)

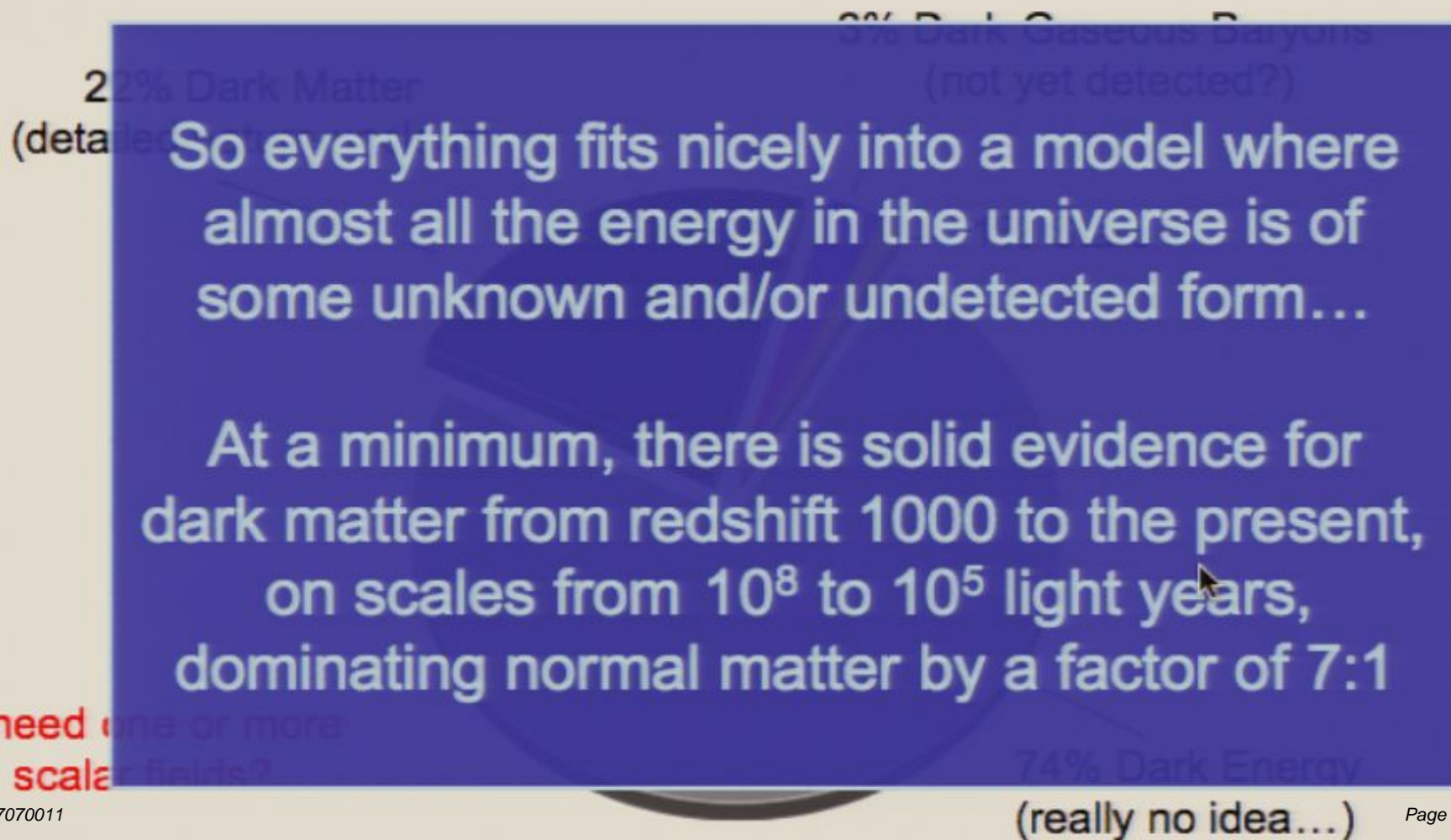


Summary:
The Composition of the Universe (fourth quarter 2006)



Summary:

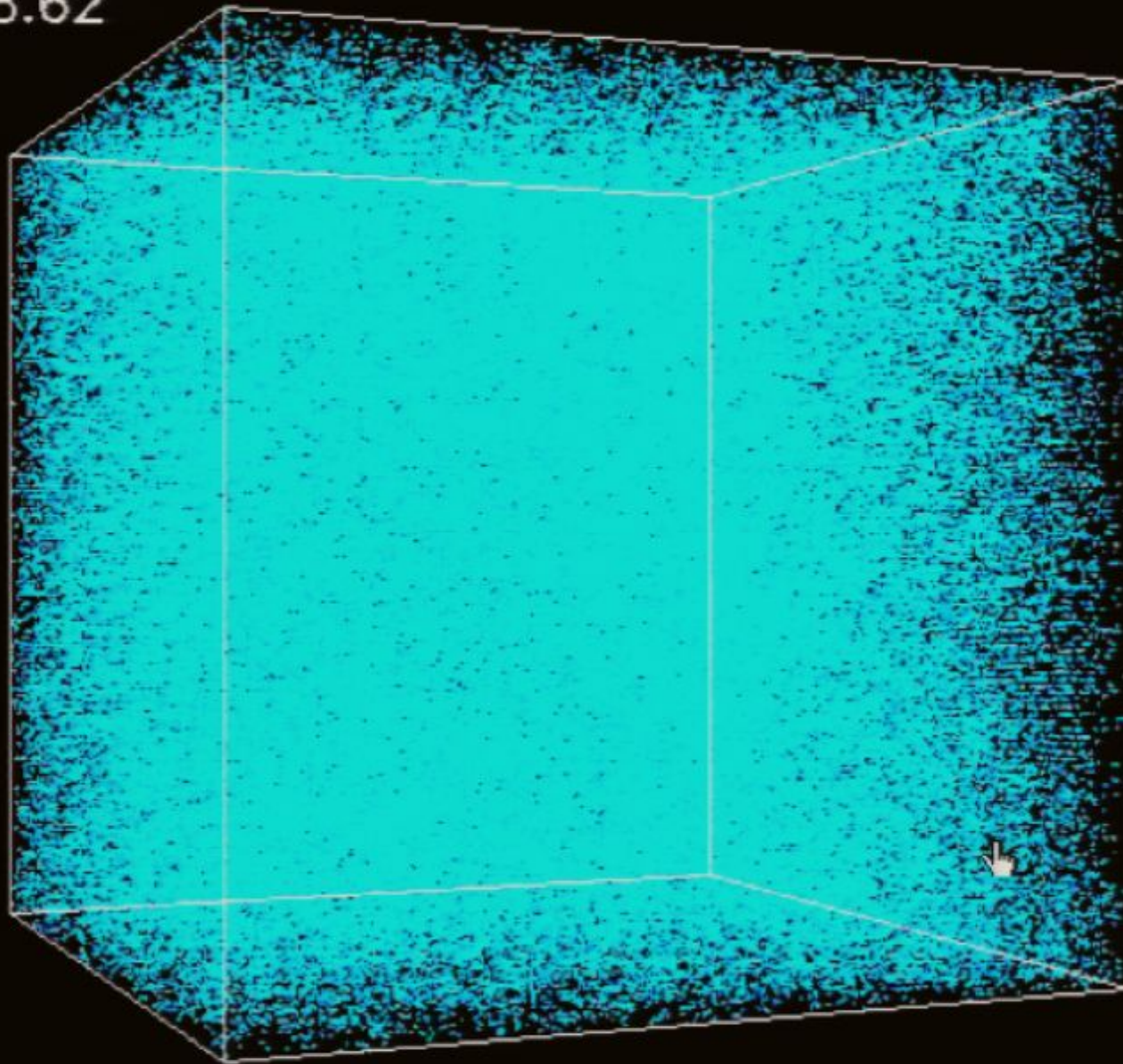
The Composition of the Universe (fourth quarter 2006)



3: A slight digression: The Cold Dark Matter Universe

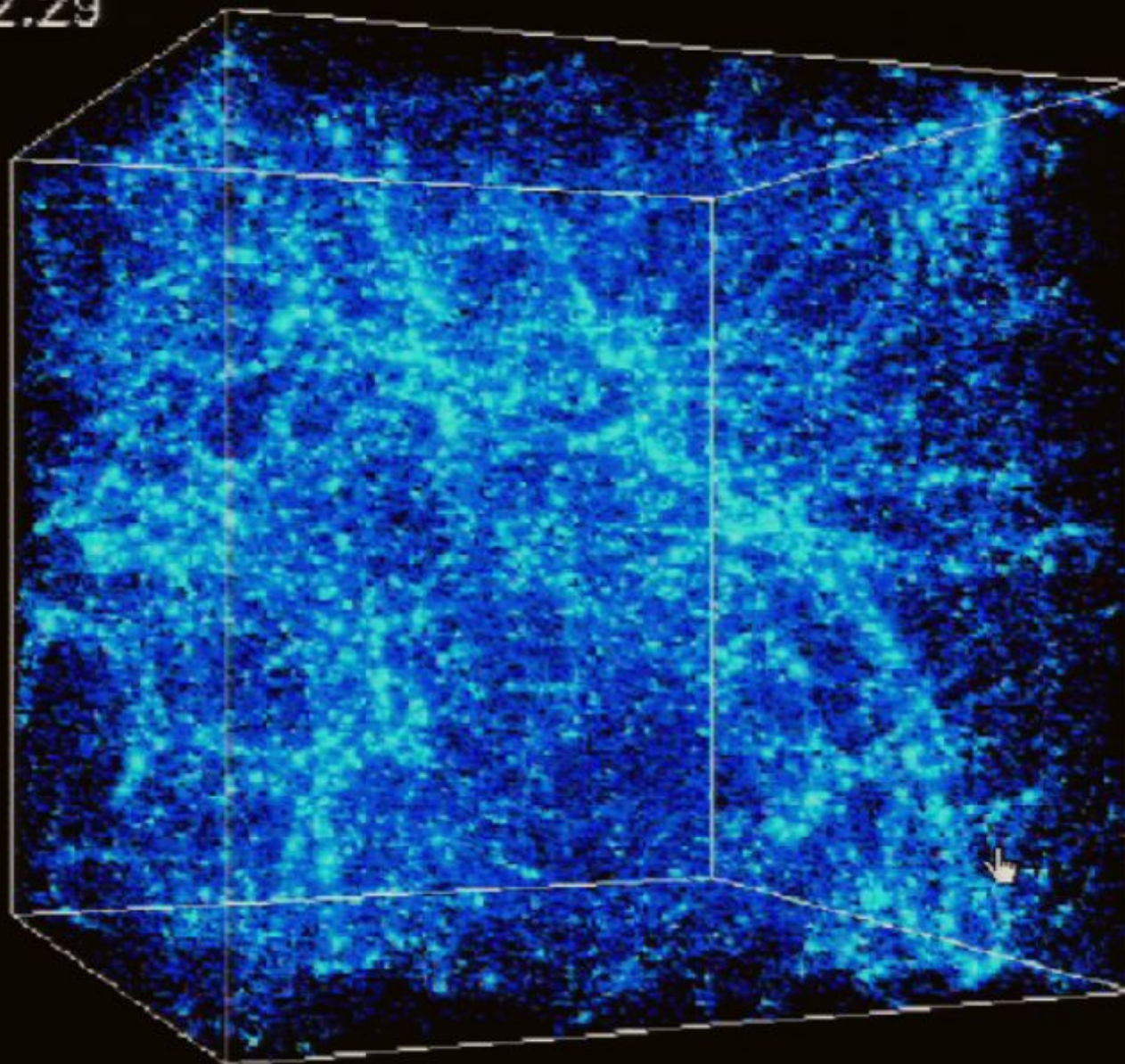


Z=28.62

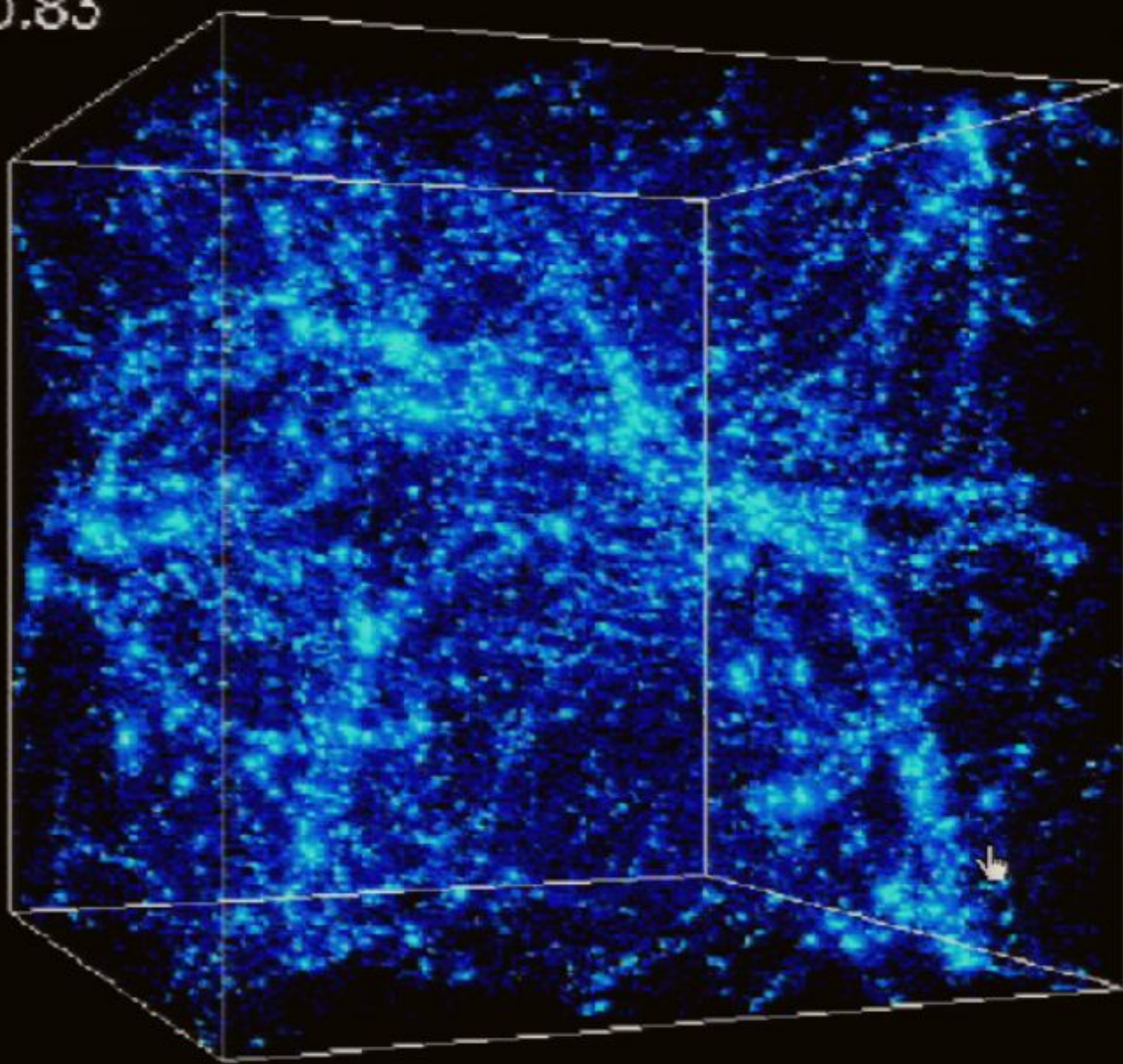


Andrei Kravtsov Page 5 of 13

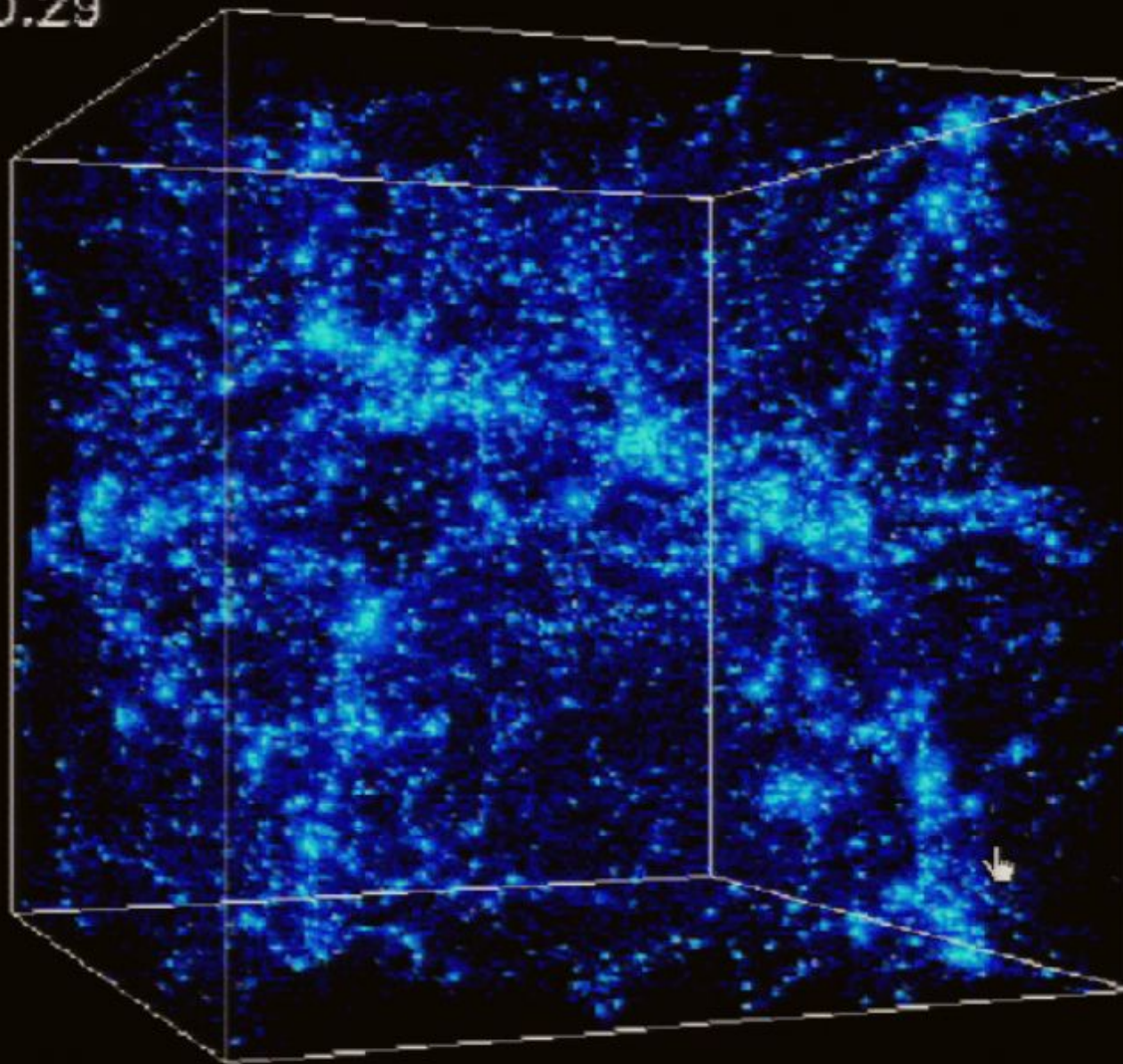
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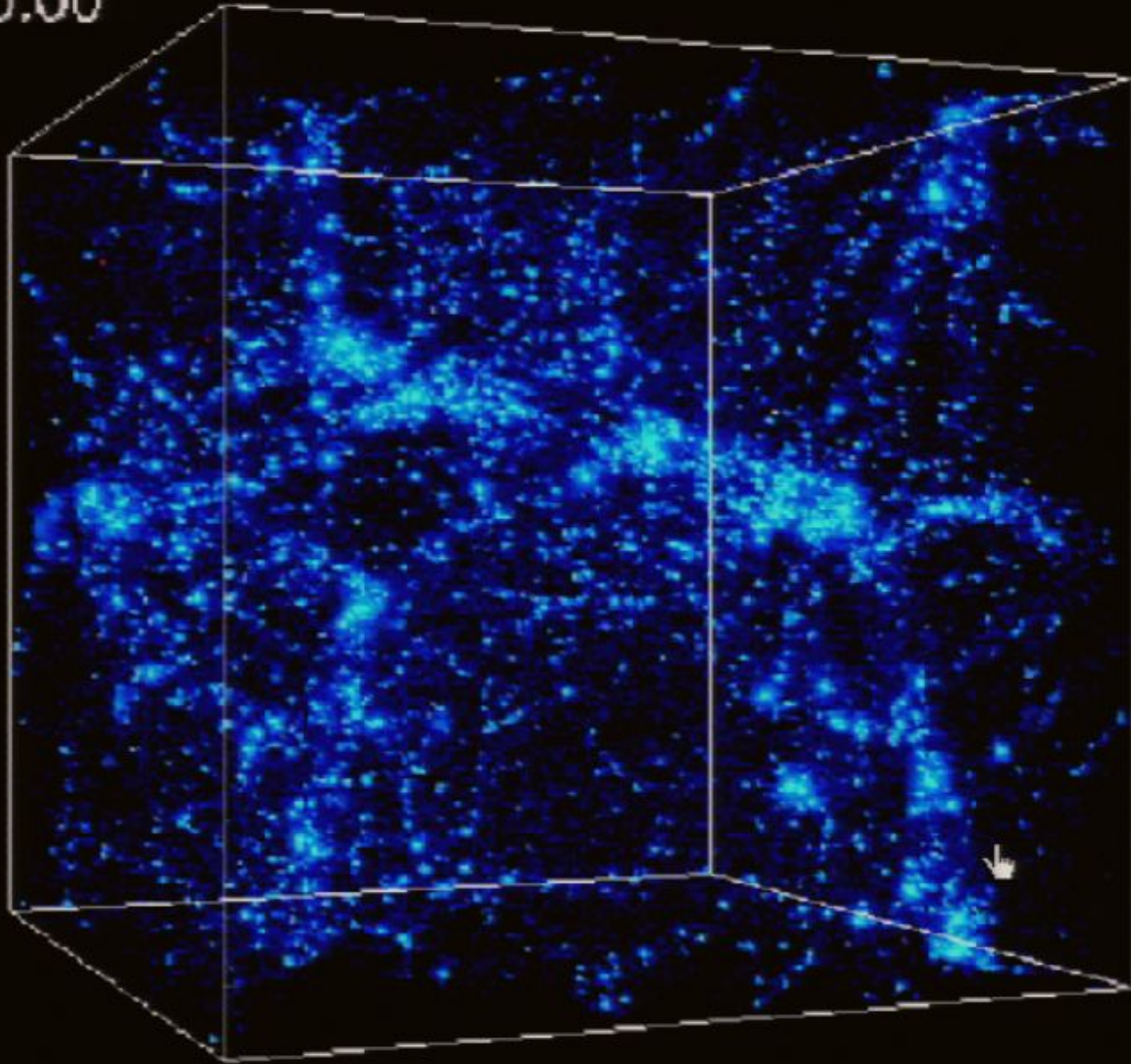
$Z = 0.83$



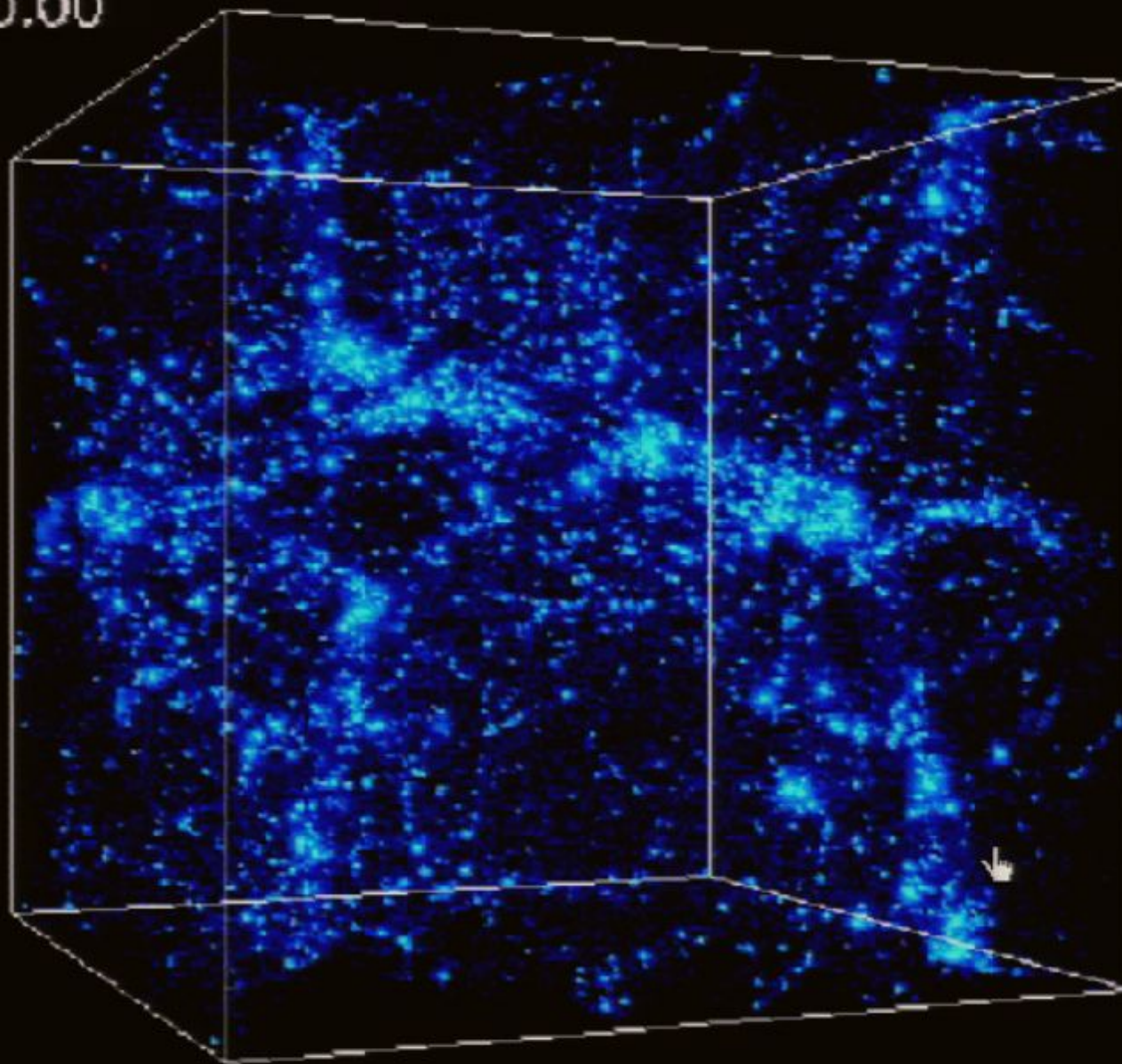
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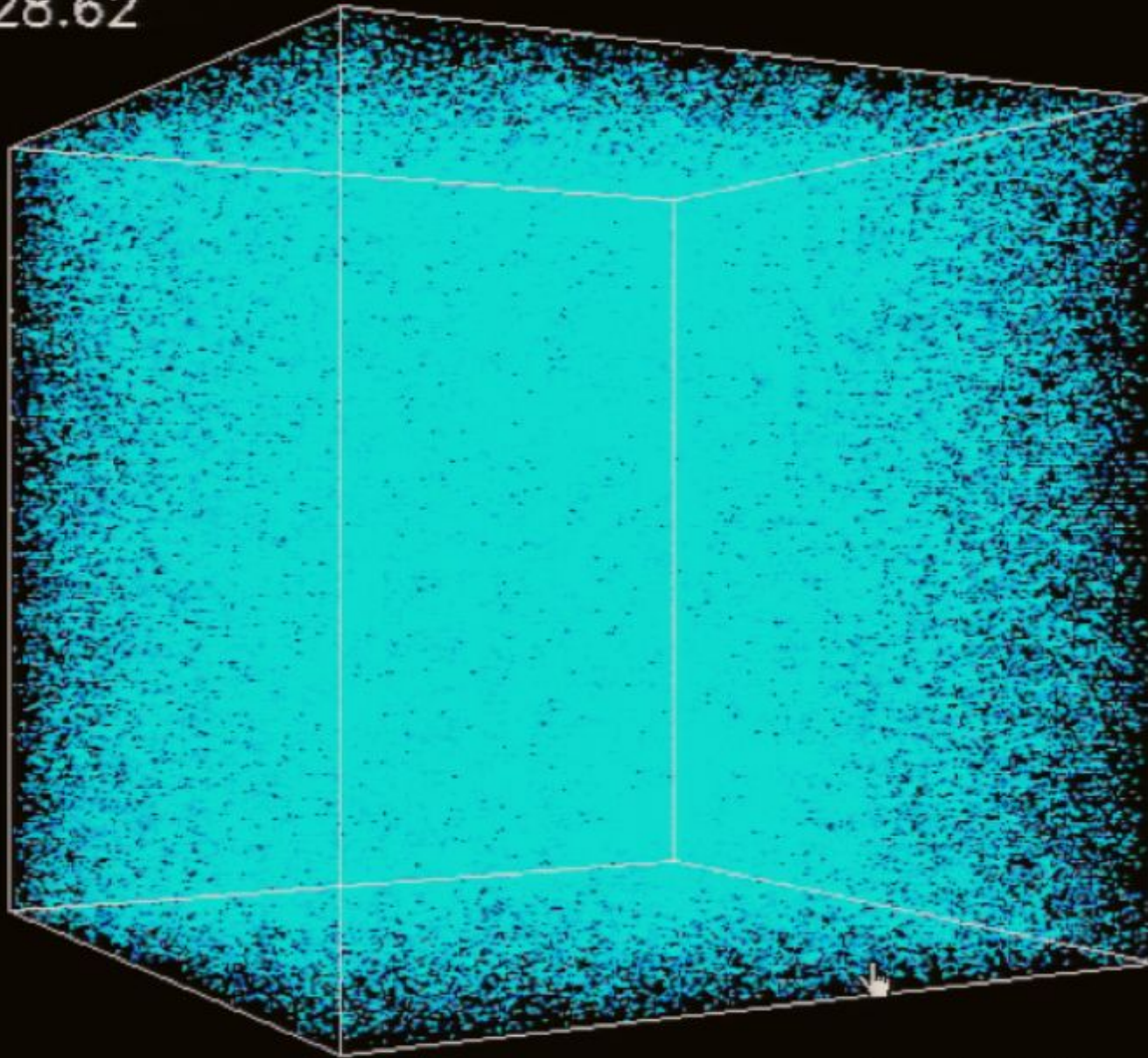
Z= 0.00



$Z = 0.00$



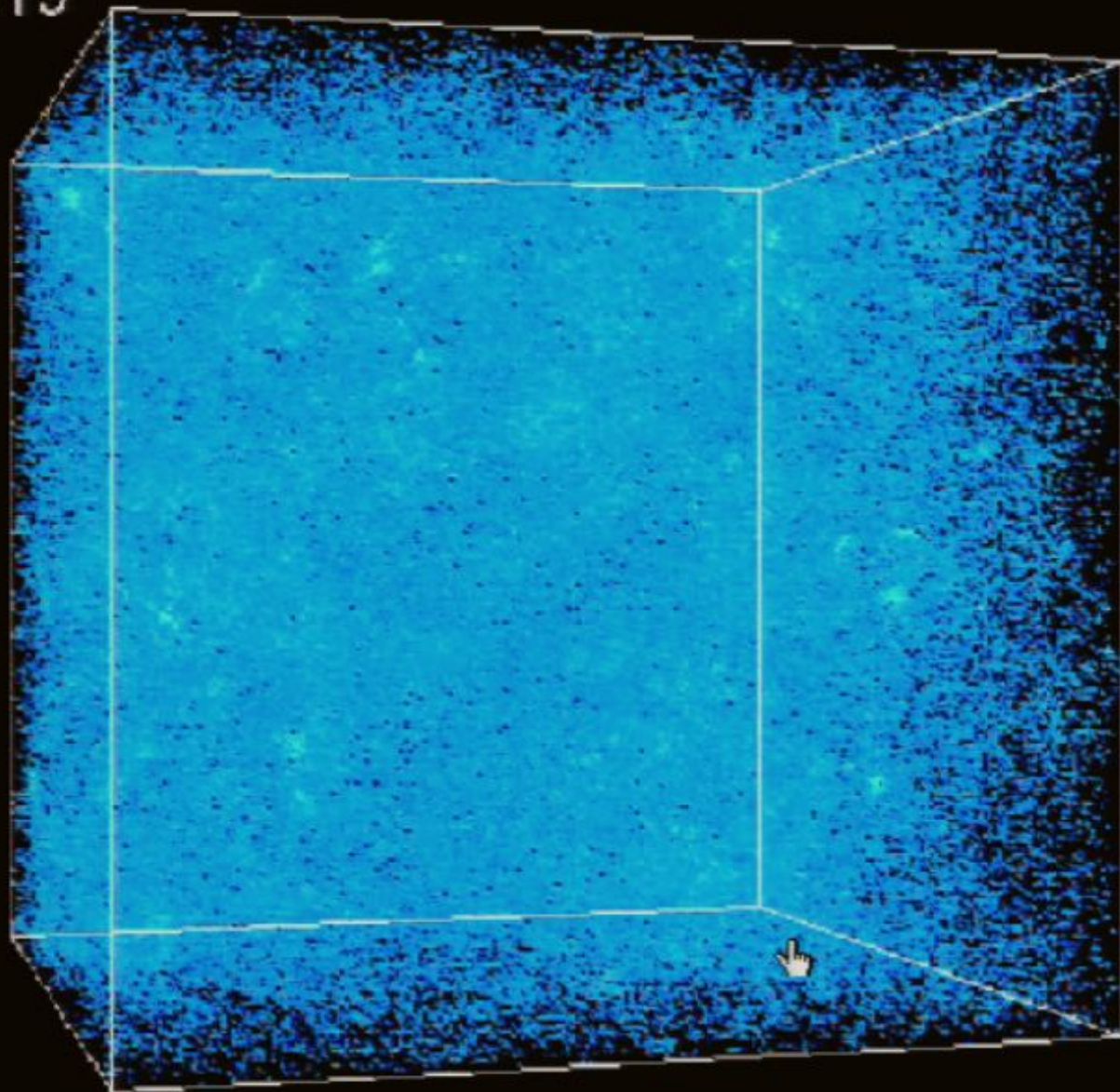
$Z=28.62$



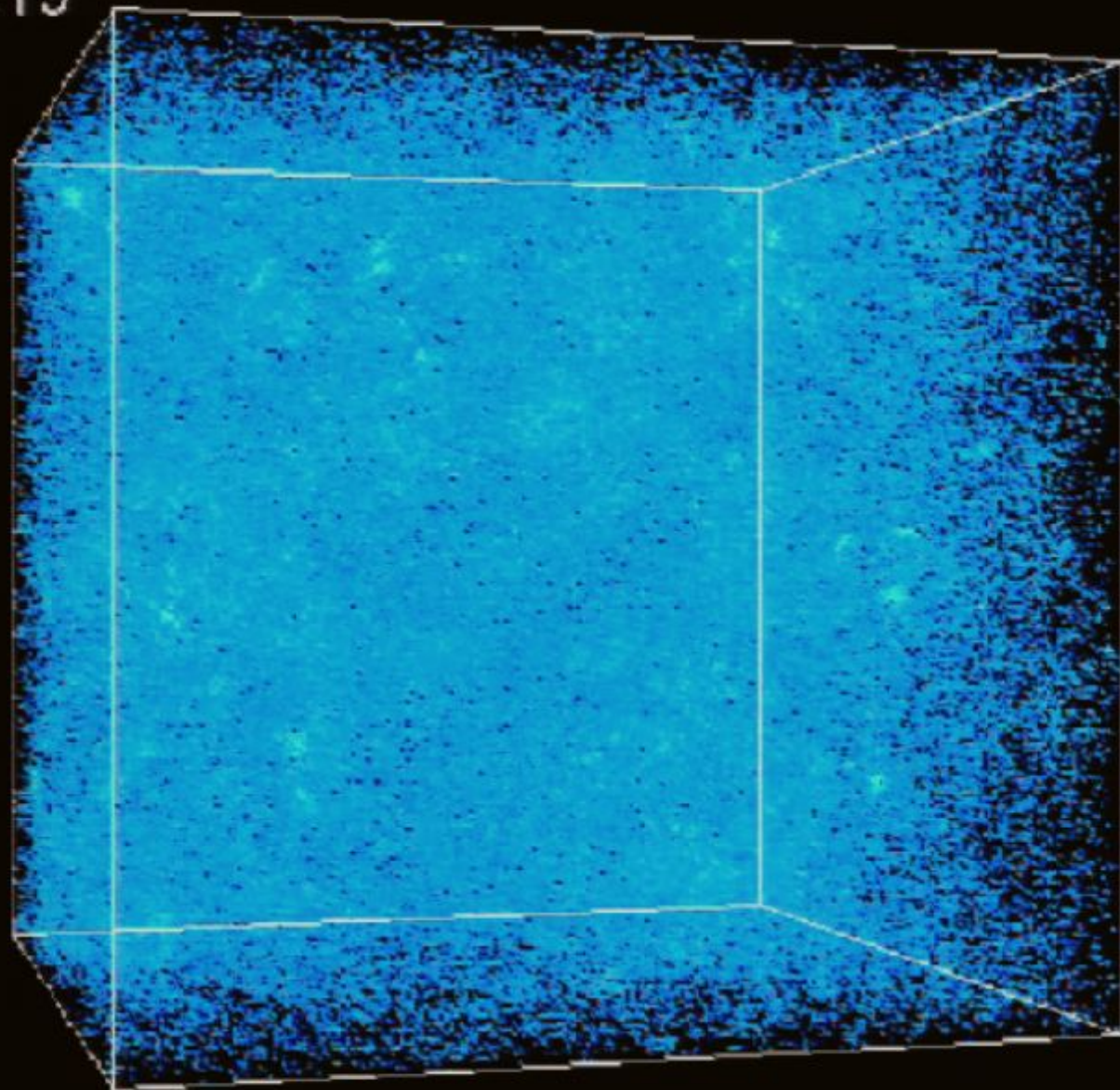
Andrei Kravtsov

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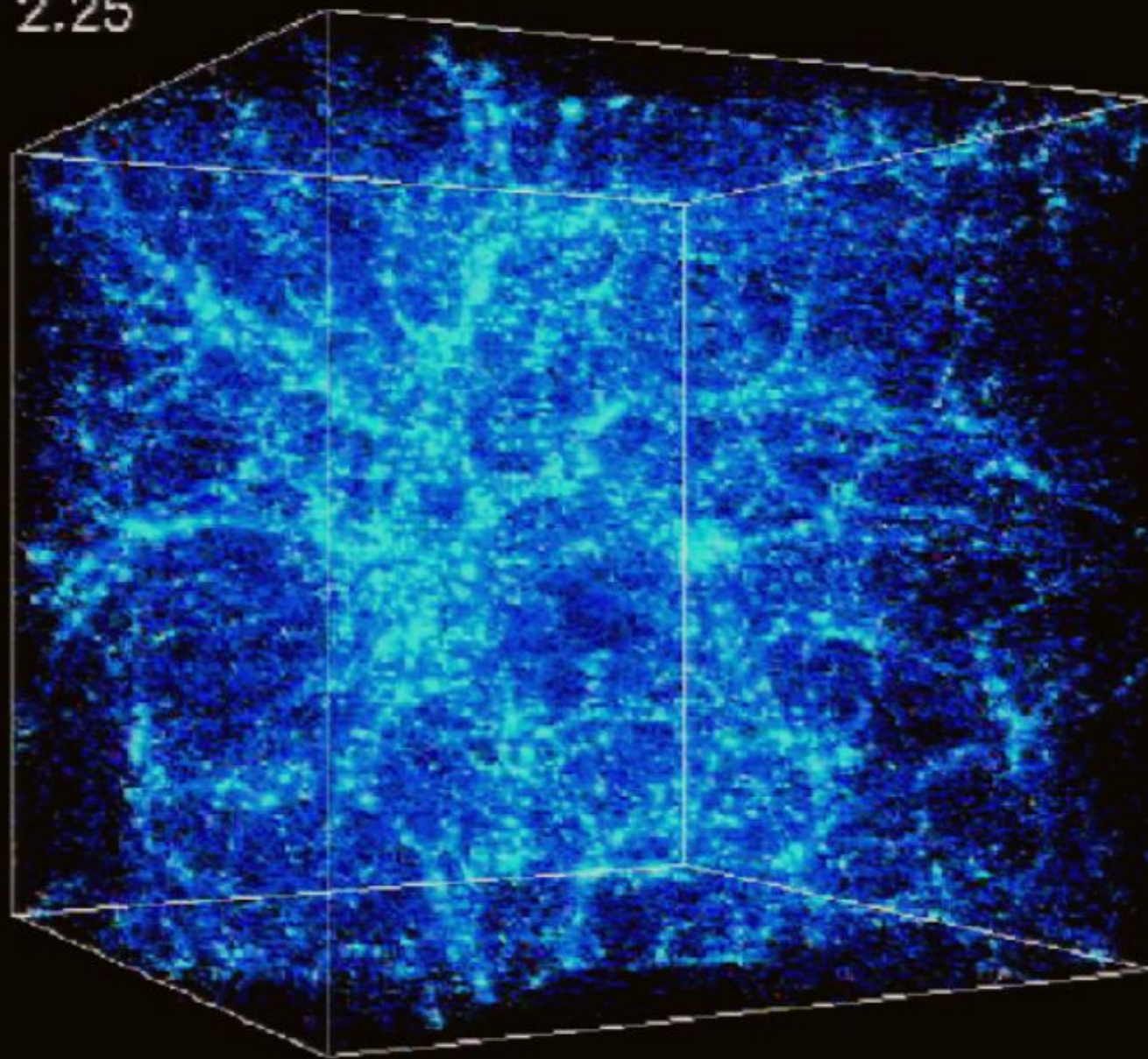
Z=12.19



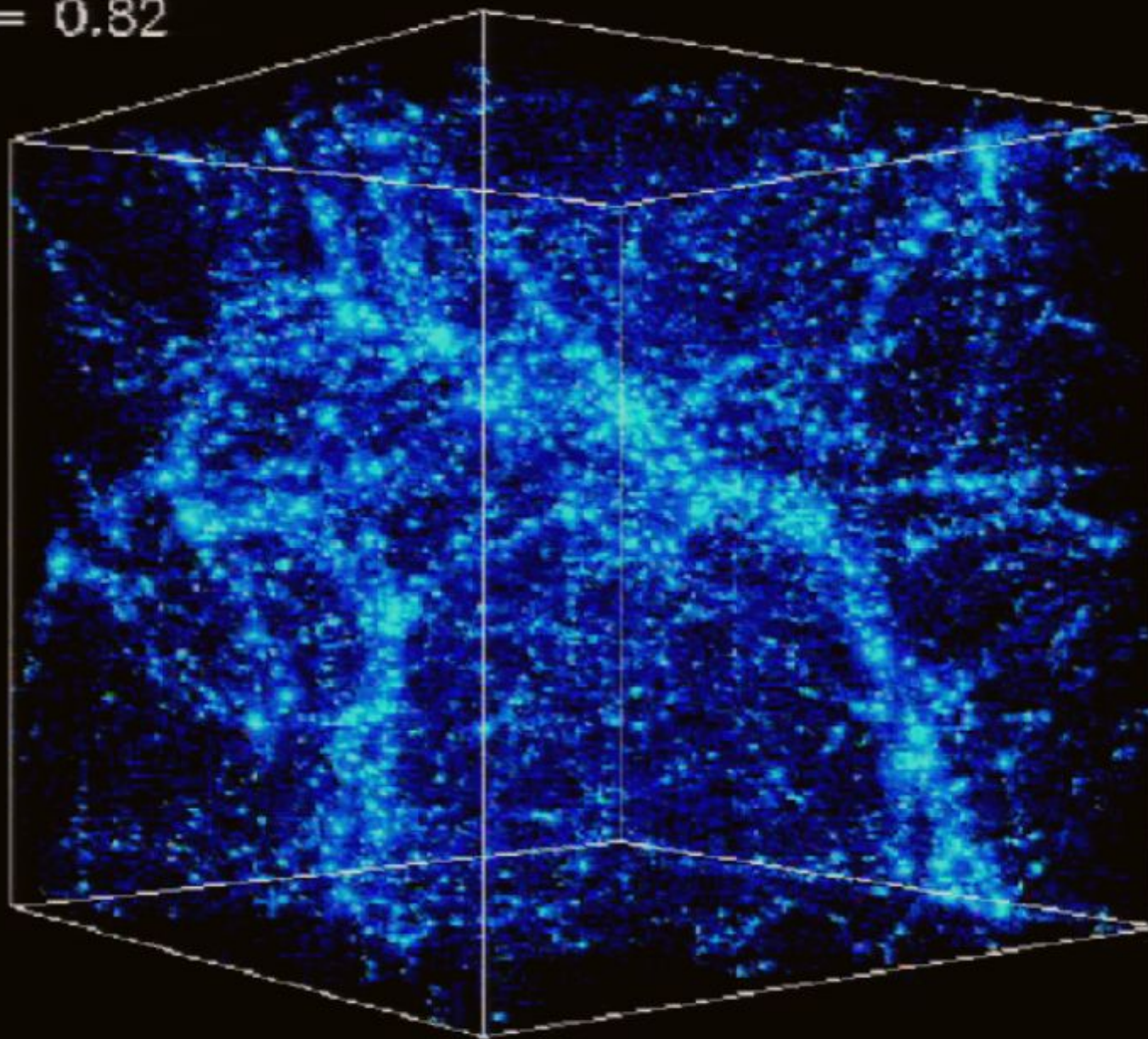
Z=12.19



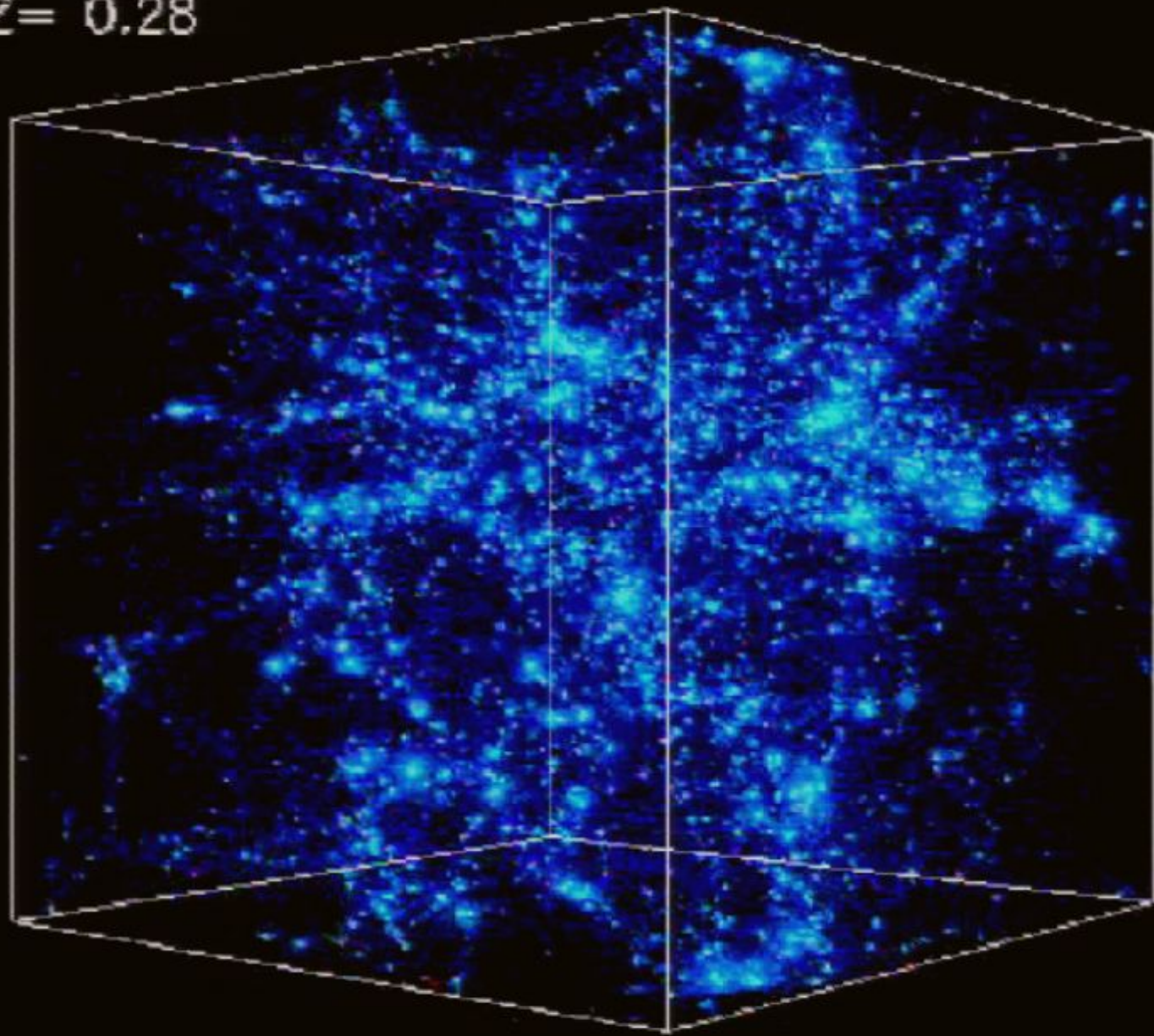
$z = 2.25$



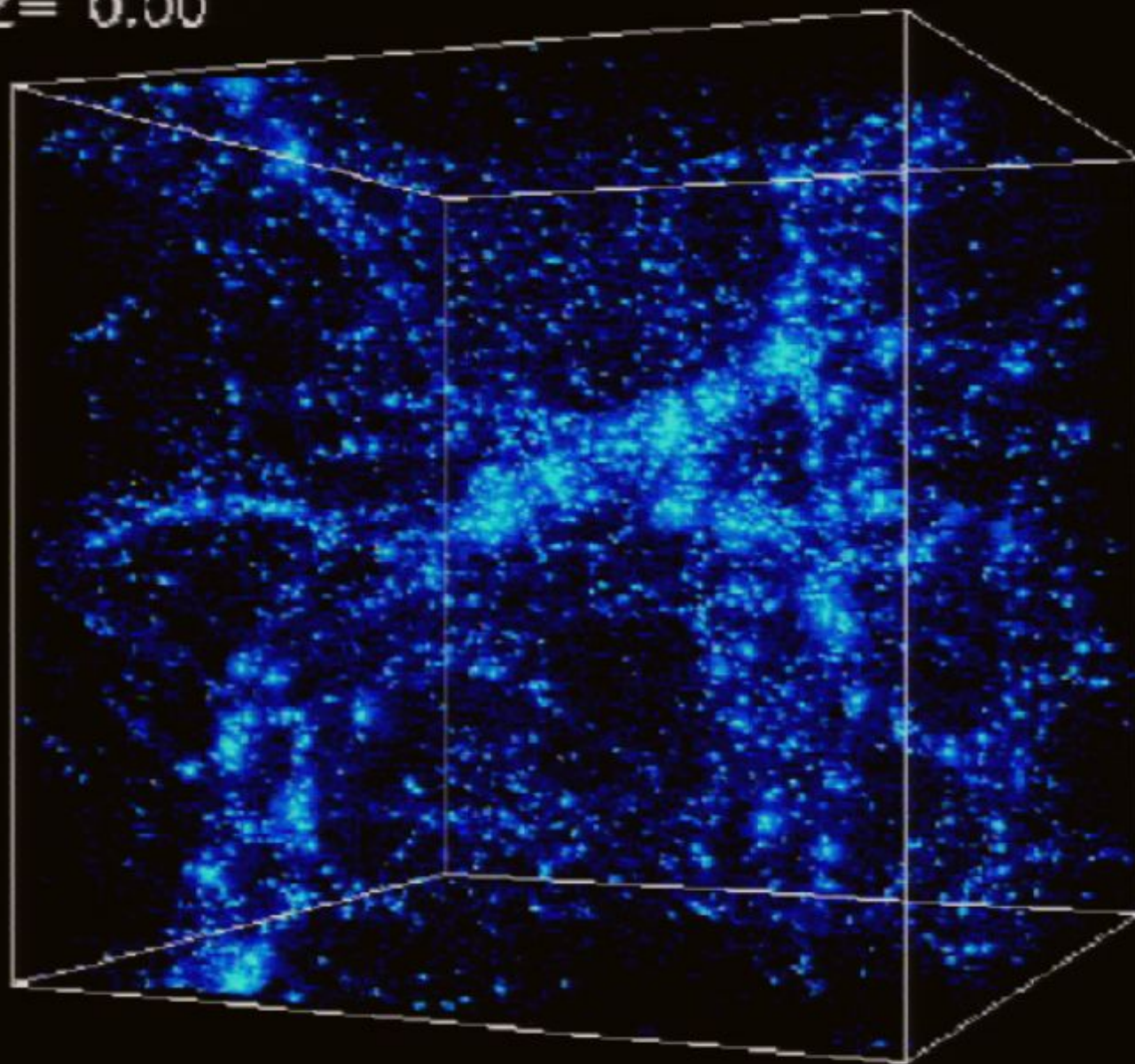
$z = 0.82$



$z = 0.28$



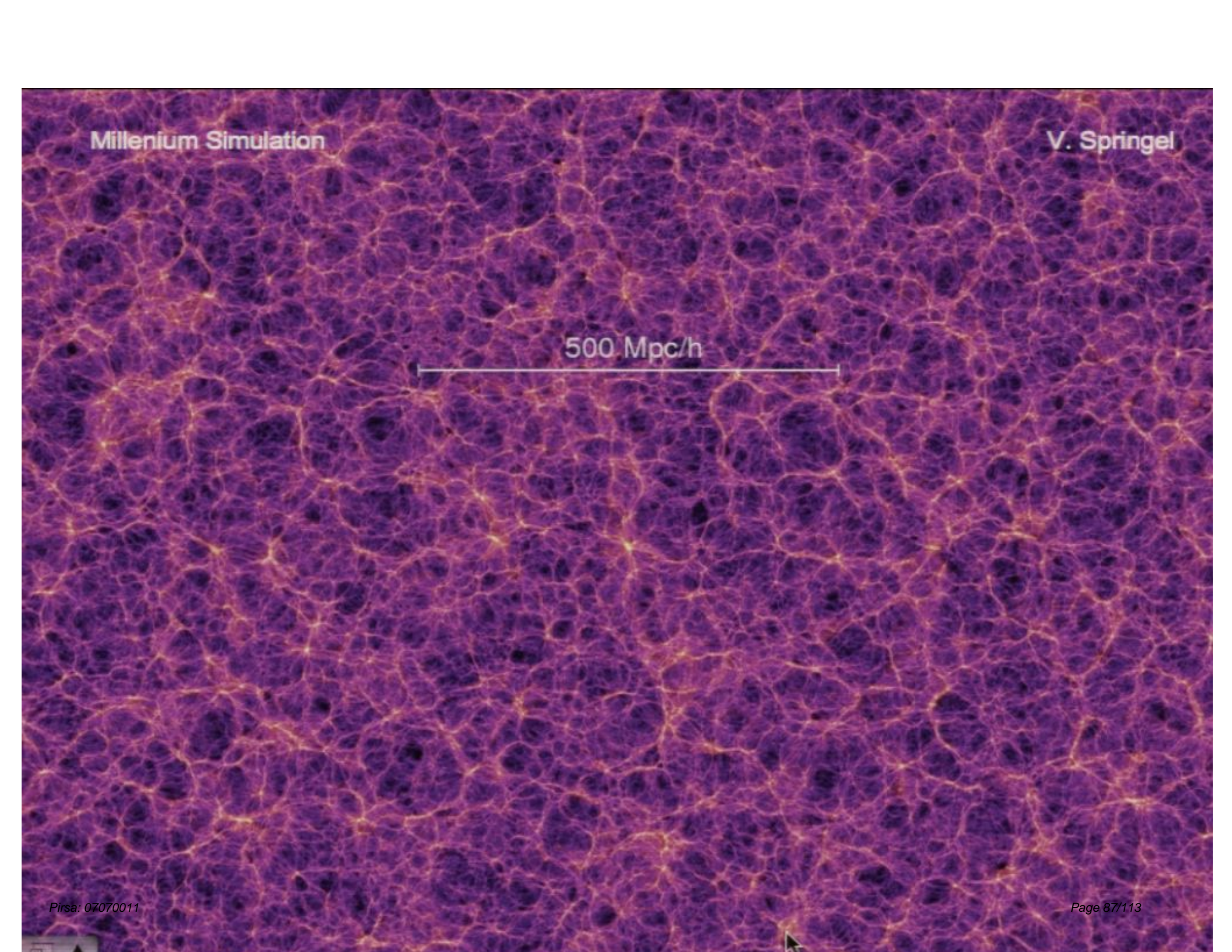
$Z = 0.00$

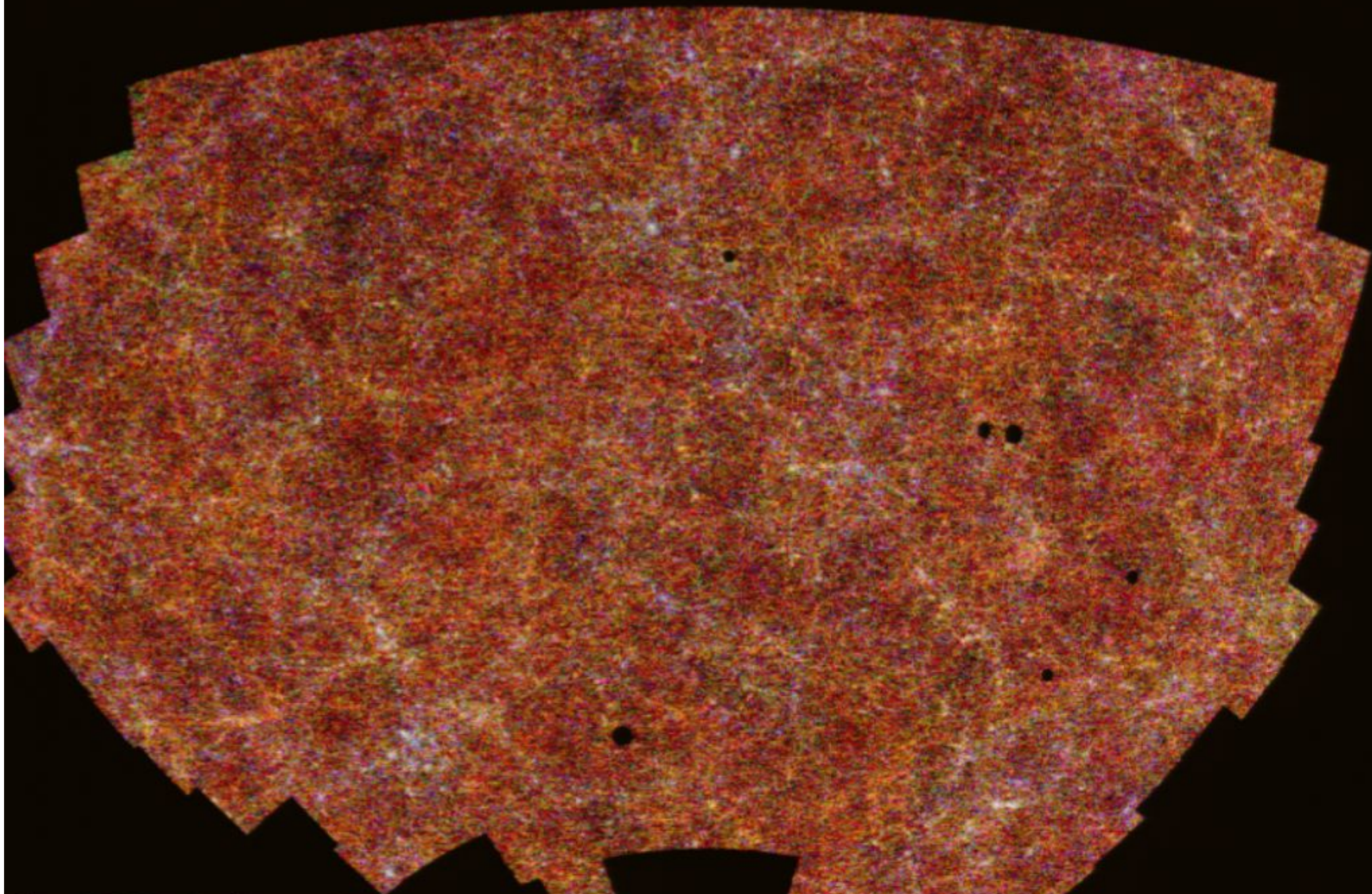


Millenium Simulation

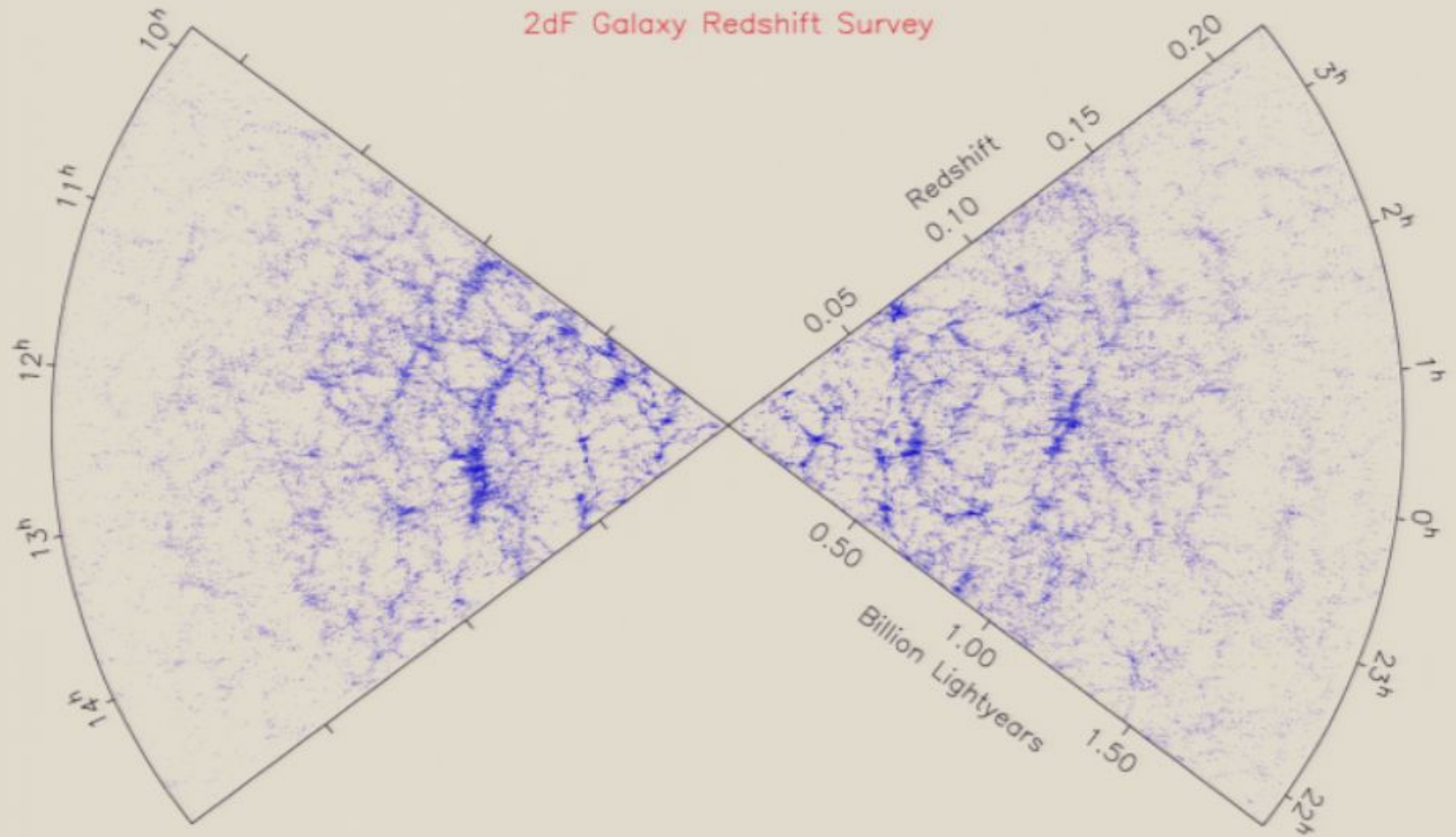
V. Springel

500 Mpc/h





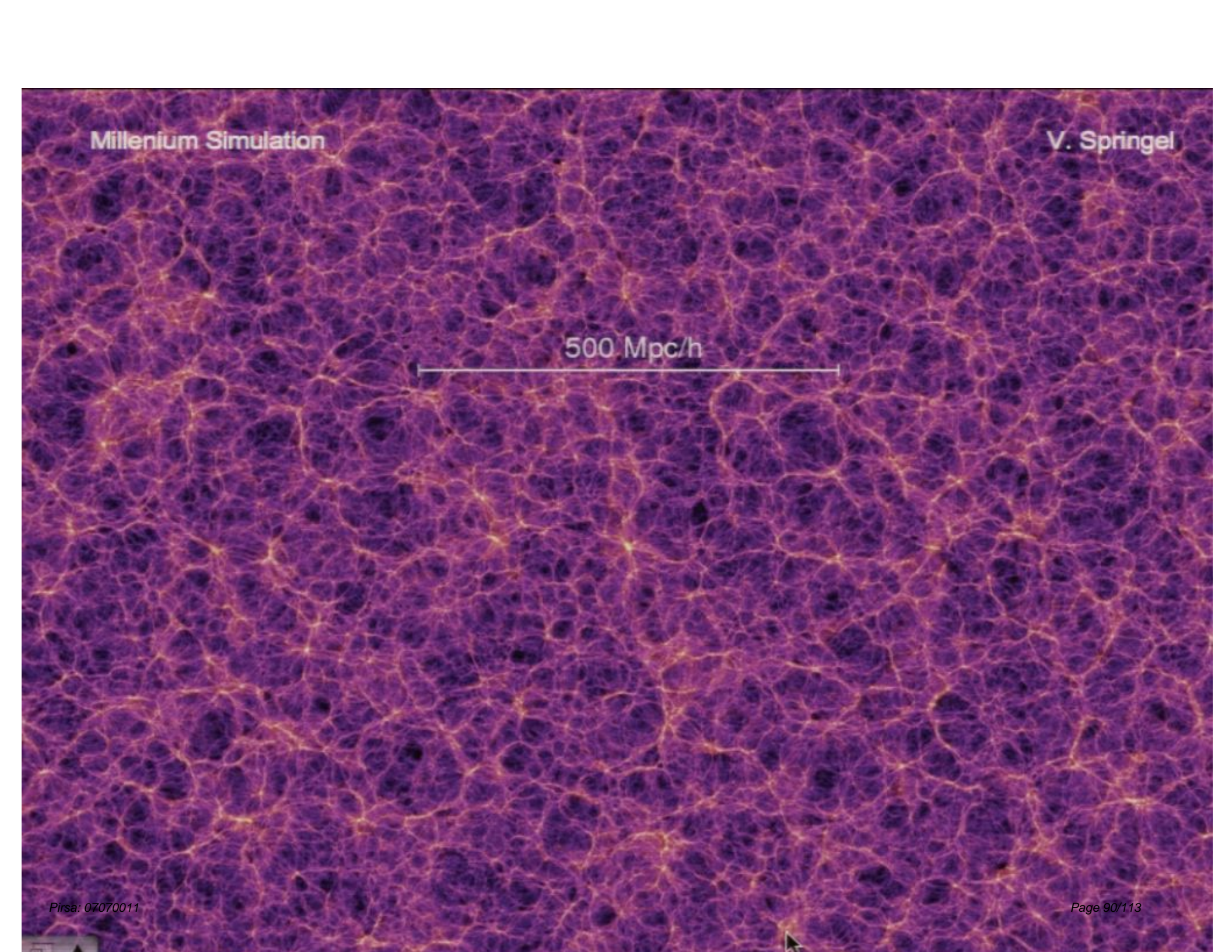
A plausible match to reality?



Millenium Simulation

V. Springel

500 Mpc/h



Millenium Simulation

V. Springel

31.25 Mpc/h

Millenium Simulation

V. Springel

31.25 Mpc/h



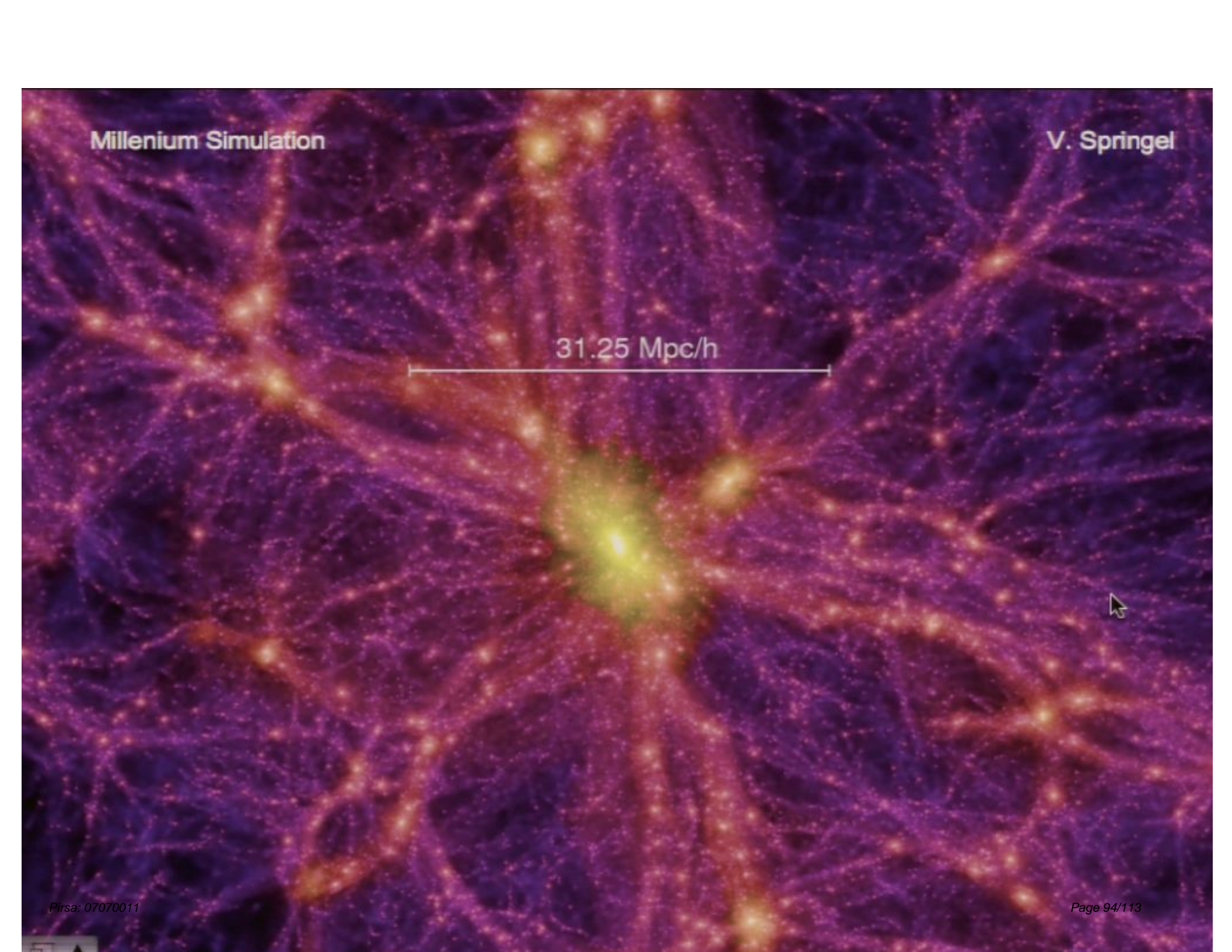
31.25 Mpc/h



Millenium Simulation

V. Springel

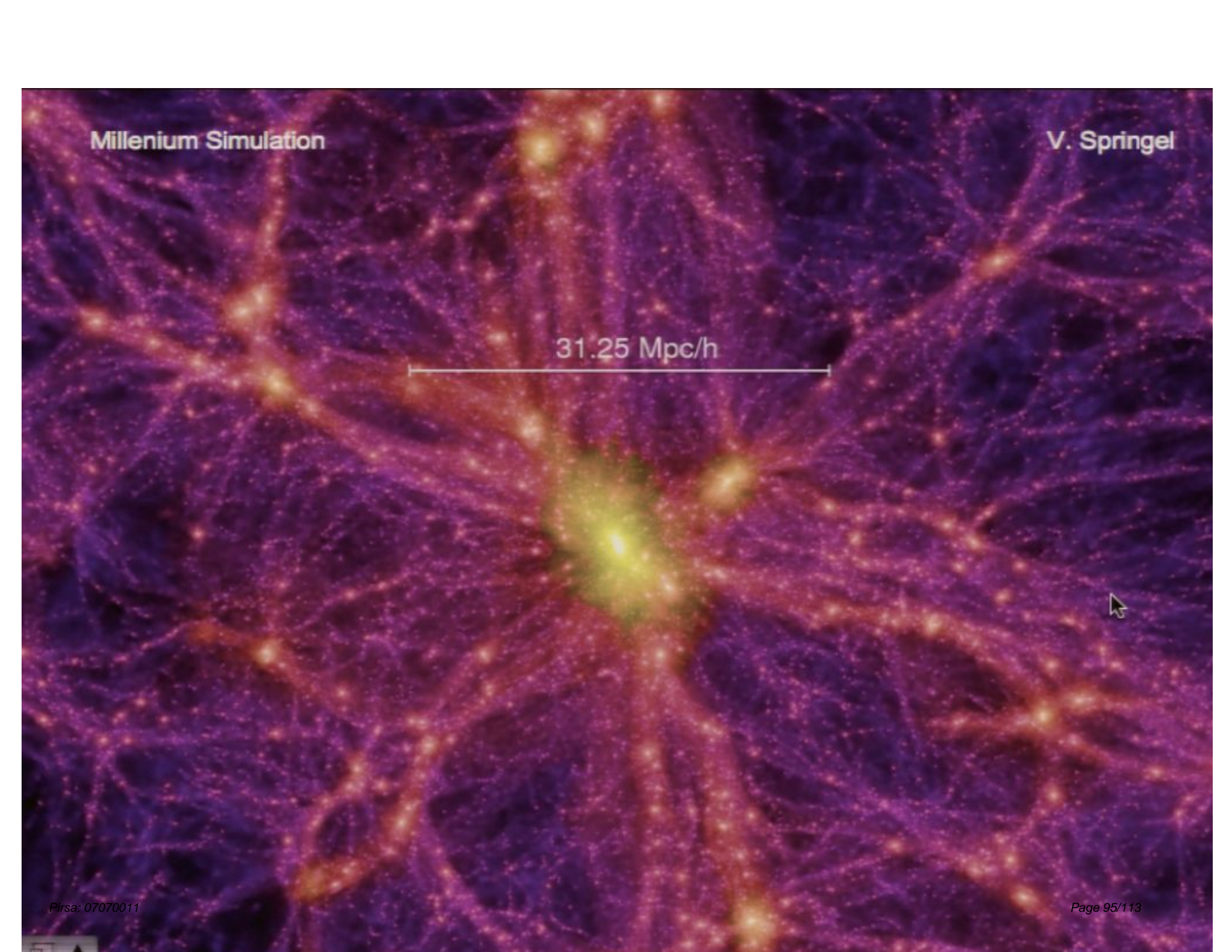
31.25 Mpc/h



Millenium Simulation

V. Springel

31.25 Mpc/h



4: A complete digression: Predictions on 'Small' Scales

(Diemand et al. 2005)

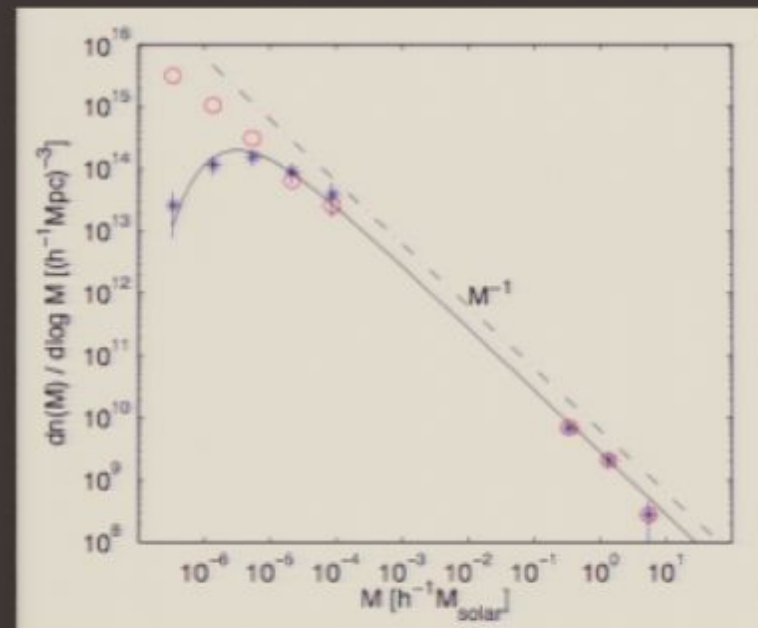
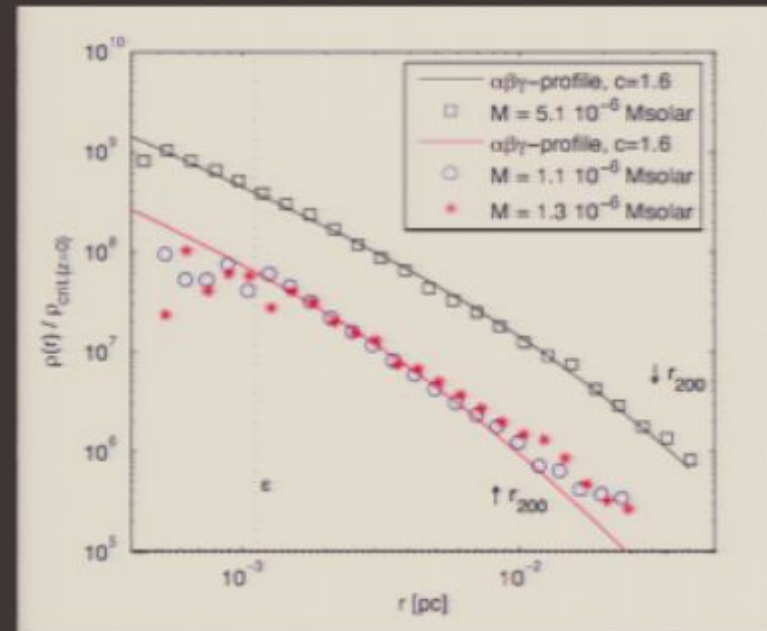
Based on the properties of the smallest dark matter halos, our galaxy should be full of these lumps.

- 10^{15} microhalos in total, or $500/\text{pc}^3$ locally, the nearest being within $\sim 0.15\text{pc}$ away

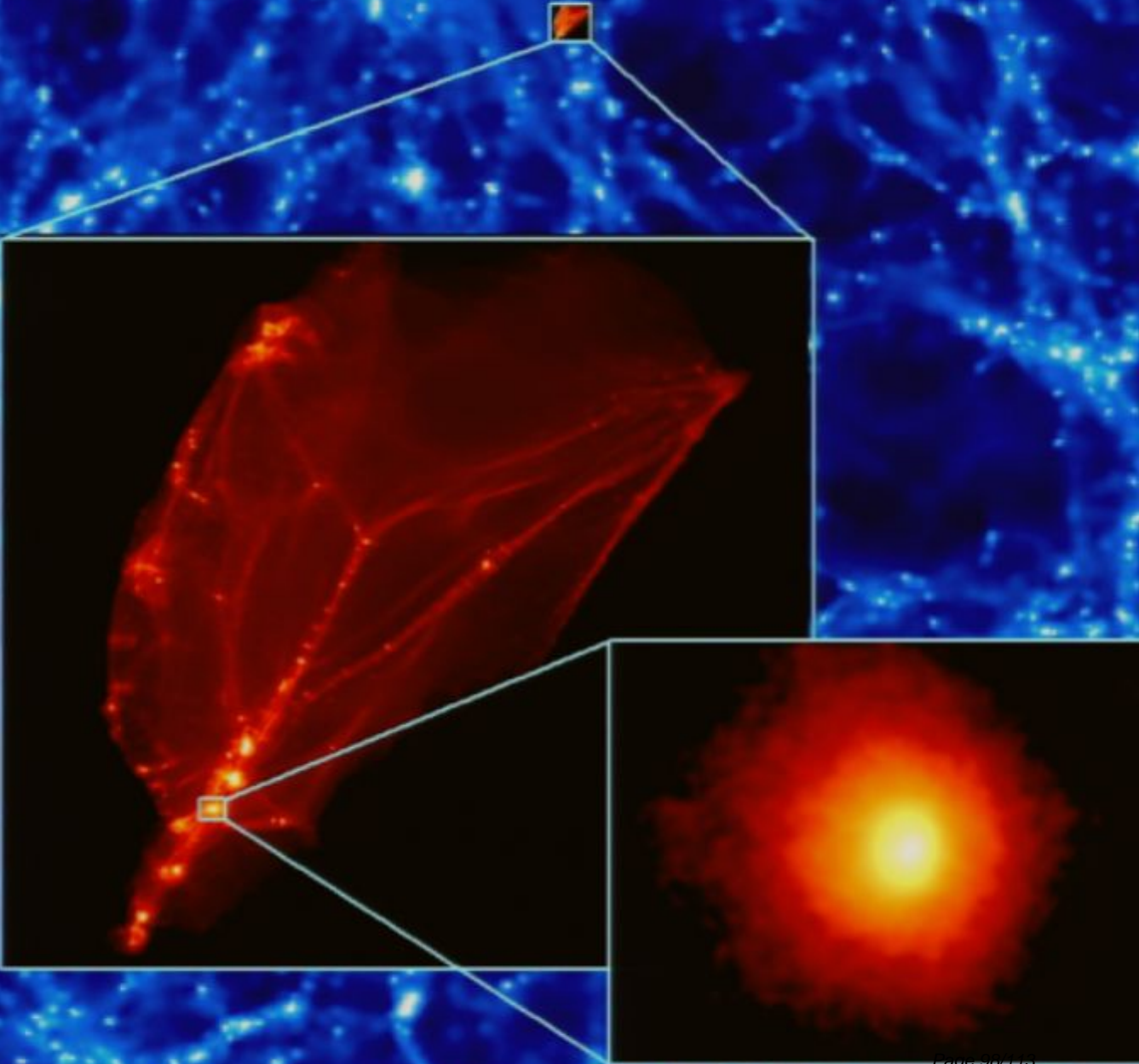
Further implications for direct and indirect detection :

These objects move through solar system in ~ 100 years, once every 10,000 years

Motion on sky ~ 1 arcmin/yr



Djemand et al. (2005)



(Diemand et al. 2005)

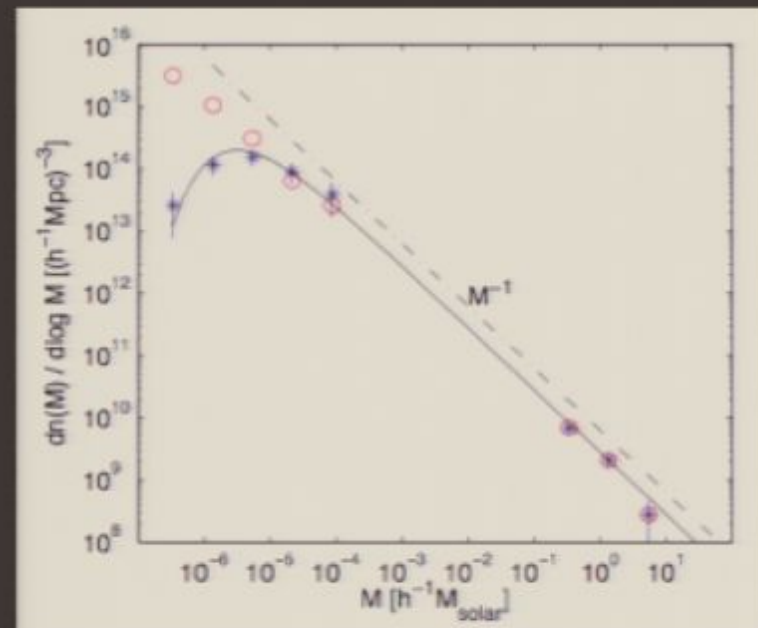
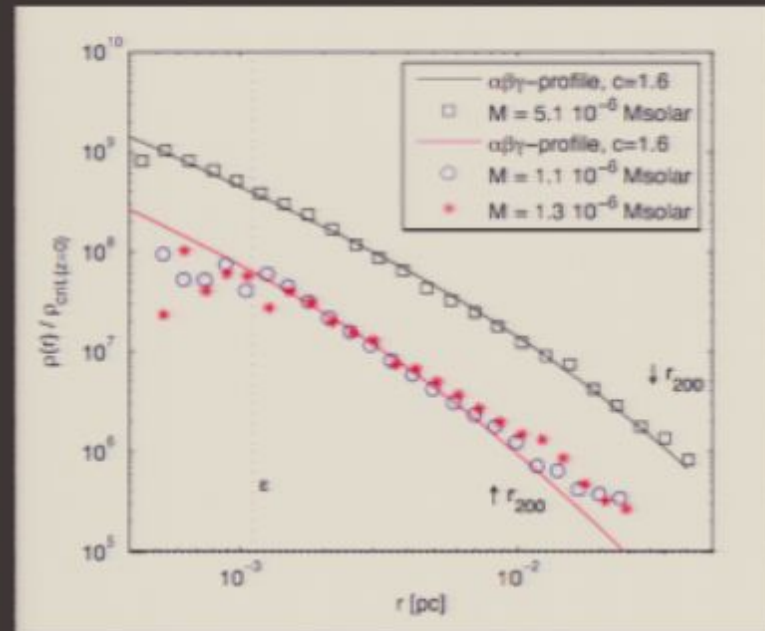
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The problem with this:

Typical microhalo has a density of $10^{-6} M_{\odot}/(0.01\text{pc})^3 \sim 1M_{\odot}/\text{pc}^3$

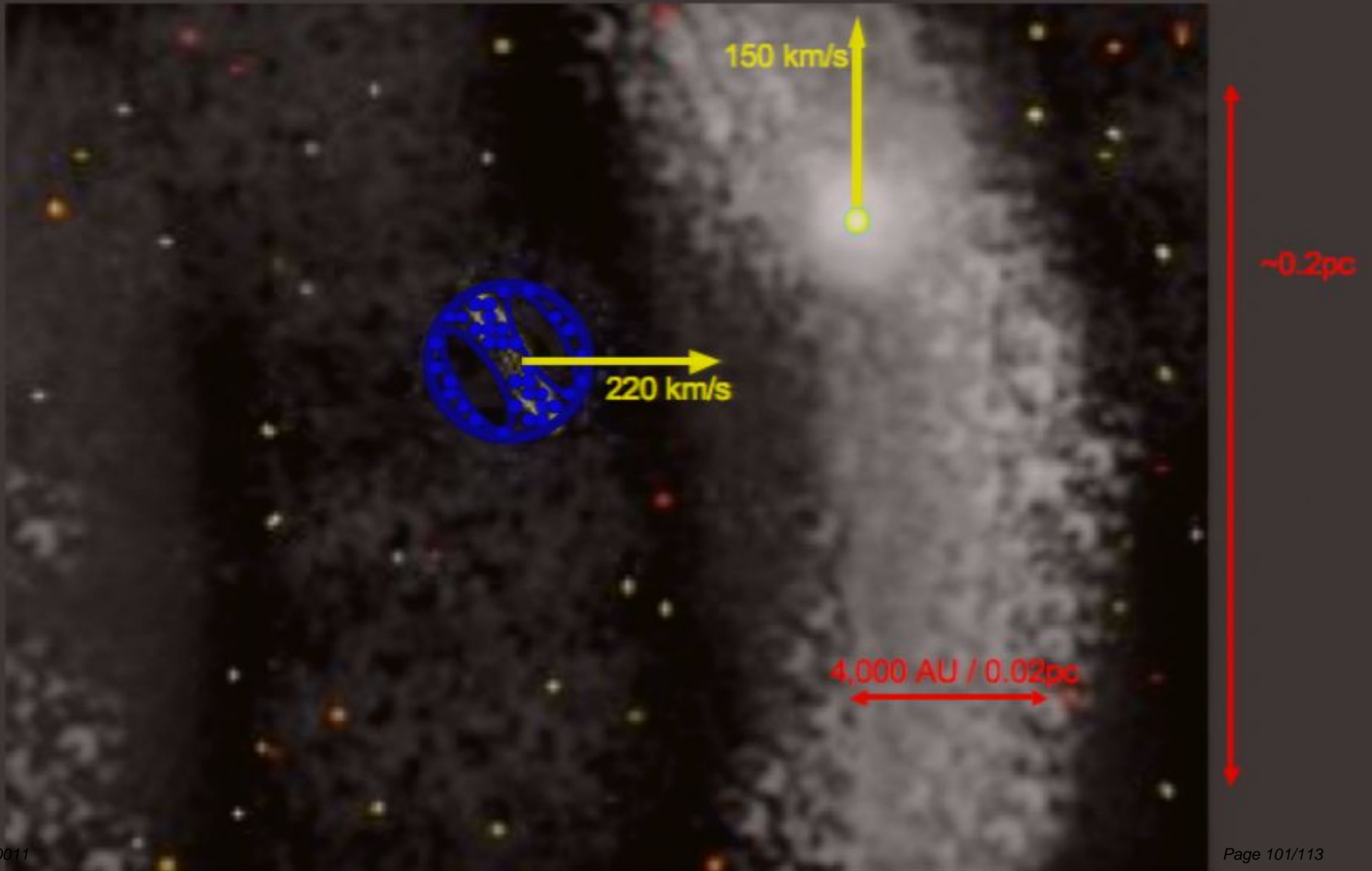
This is ~ 10 times the local DM density (so microhalo survives halo formation), but corresponds to a restoring force less than the tidal field of the solar system within 1 pc.

Thus, encounters with $1 M_{\odot}$ stars at $b < 1$ pc will cause mass loss and/or disruption

These encounters should be common, since $\Sigma_d \sim 40\text{-}50 M_{\odot} \text{pc}^{-2}$ in the disk

Thus the "graininess" of the local distribution of normal matter will shred small microhalos into microstreams.

Structure of the local solar environment:



So What is Dark Matter?

What about normal, non-stellar objects?

would need to be **massive, compact** objects, (e.g. black holes, white dwarfs, planets) distributed in a **halo** around each galaxy ⇒ **MACHOS**

try detecting them via gravitational lensing?

⇒ giant **microlensing** experiments
over the past decade rule
out most of dark matter being
in this form



Experiments to detect dark matter

CDM particle \Rightarrow decay products

“direct detection”
(accelerator) production

“indirect detection”
e.g. photons

neutrinos

positrons

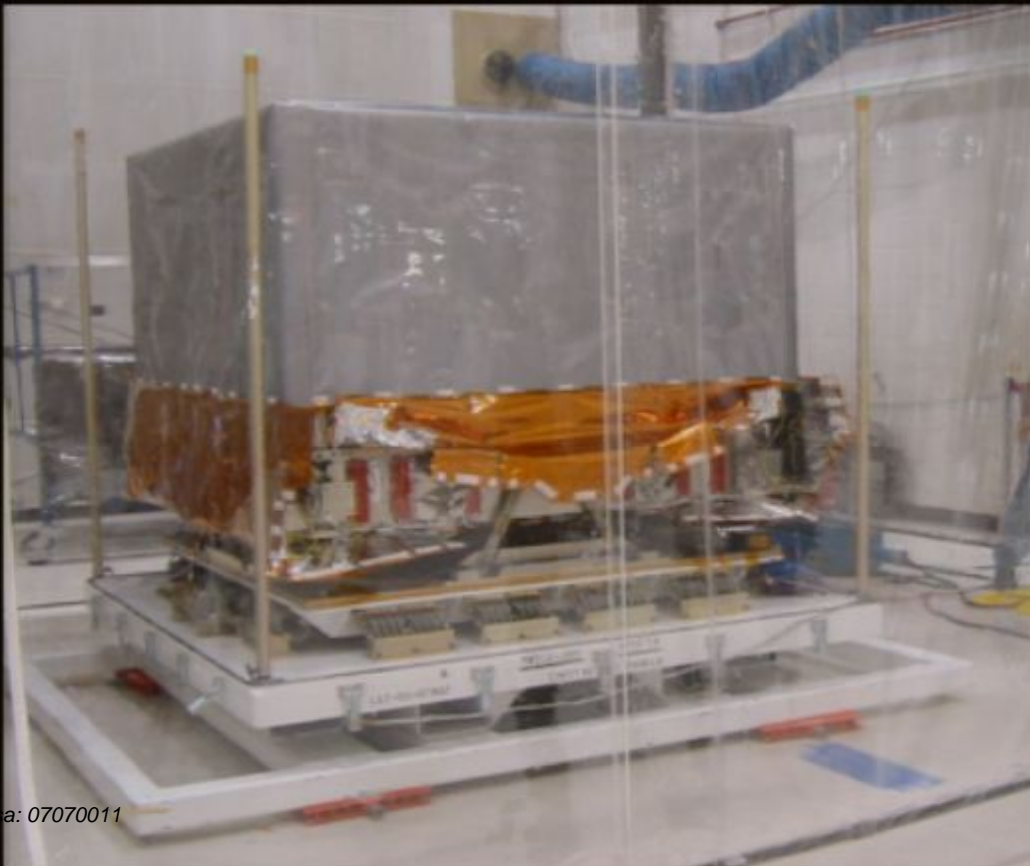
Experiments to detect dark matter

GLAST: Gamma-ray telescope (~ 100 MeV – several GeV)

- scheduled launch currently January 31st 2008

(well, at least “no earlier than...”)

- could see signal from dark matter annihilation in our Galaxy?



Experiments to detect particle dark matter

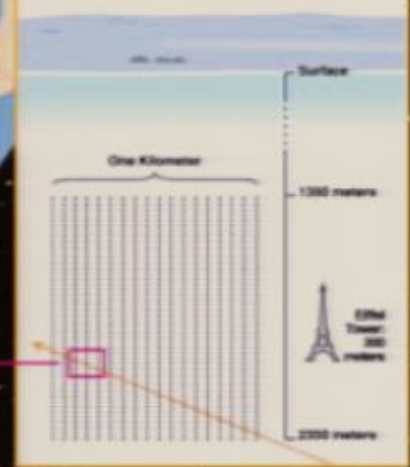
AMANDA/IceCube: experiments under the Antarctic ice cap to detect energetic neutrinos, some of which may come from decays of dark matter particles



'Ice Cube' Neutrino Detector Array

Buried a mile deep in the Antarctic ice, the Ice Cube Neutrino Detector Array promises a new kind of astronomy. When completed, Ice Cube will occupy a cubic kilometer of deep ice, transforming the polar ice cap into a detector capable of sampling the high-energy neutrinos that emanate from some of the most distant and violent phenomena in the cosmos - colliding black holes, galaxies with super-violet cores and mysterious gamma-ray bursts. Like ghostly messengers, high-energy neutrinos traverse huge distances, passing through stars, planets, magnetic fields and entire galaxies without stopping a beat.

To distinguish neutrinos from a background of cosmic-ray muons, the Earth is used as a filter, with only neutrinos able to pass through the planet unchecked.



A trail of Cherenkov light is created when a neutrino, on very rare occasions, crashes head-on into another particle such as a proton or neutron. From the wreckage of these collisions emerges a muon which creates a feeble trail of blue light on a path identical to that of the originating neutrino, allowing scientists to follow it back to a point of origin.

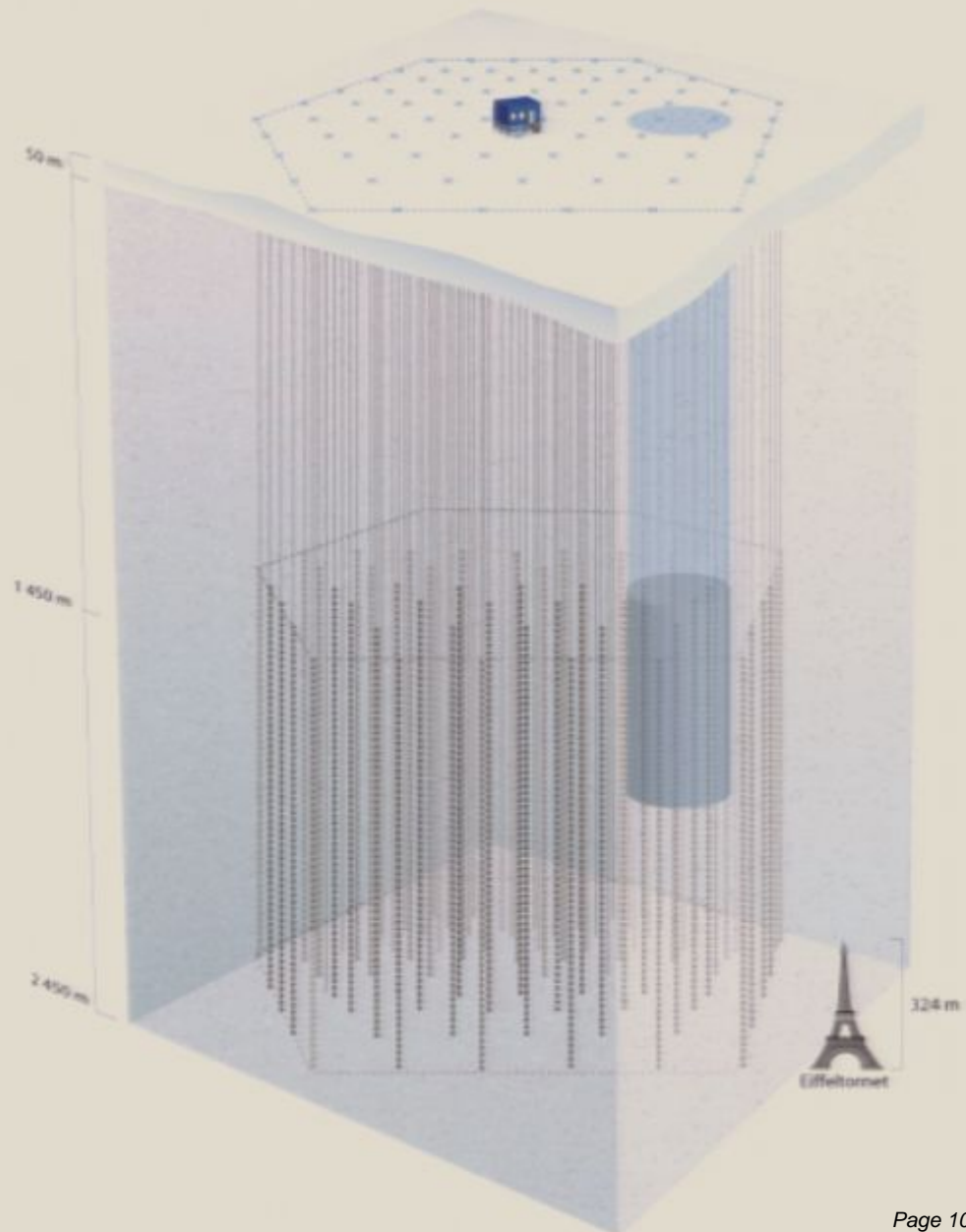
Slightly larger than a basketball, the optical sensors at the heart of Ice Cube are arranged on hundreds of electrical and fiber-optic cables. Deployed deep in the ice like beads on a necklace, the sensors work like light tubes in reverse. They can capture light - even the faint and fleeting Cherenkov light traced by muons -



convert it to electricity, amplify it and turn it into an optical signal that is sent to the surface where it can be stored, read and interpreted.

IceCube

A giant transparent detector for catching flashes from passing neutrinos



Experiments to detect particle dark matter

AMANDA/IceCube: experiments under the Antarctic ice cap to detect energetic neutrinos, some of which may come from decays of dark matter particles



'Ice Cube' Neutrino Detector Array

Buried a mile deep in the Antarctic ice, the Ice Cube Neutrino Detector Array promises a new kind of astronomy. When completed, Ice Cube will occupy a cubic kilometer of deep ice, transforming the polar ice cap into a detector capable of sampling the high-energy neutrinos that emanate from some of the most distant and violent phenomena in the cosmos - colliding black holes, galaxies with super violent cores and mysterious gamma ray bursts. Like ghostly messengers, high-energy neutrinos traverse huge distances, passing through stars, planets, magnetic fields and entire galaxies without skipping a beat.



A trail of Cherenkov light is created when a neutrino, on very rare occasions, crashes head-on into another particle such as a proton or neutron. From the wreckage of those collisions emerges a muon which creates a fleeting trail of blue light on a path identical to that of the originating neutrino, allowing scientists to follow it back to a point of origin.

To distinguish neutrinos from a background of cosmic ray muons, the Earth is used as a filter, with only neutrinos able to pass through the planet unchecked.

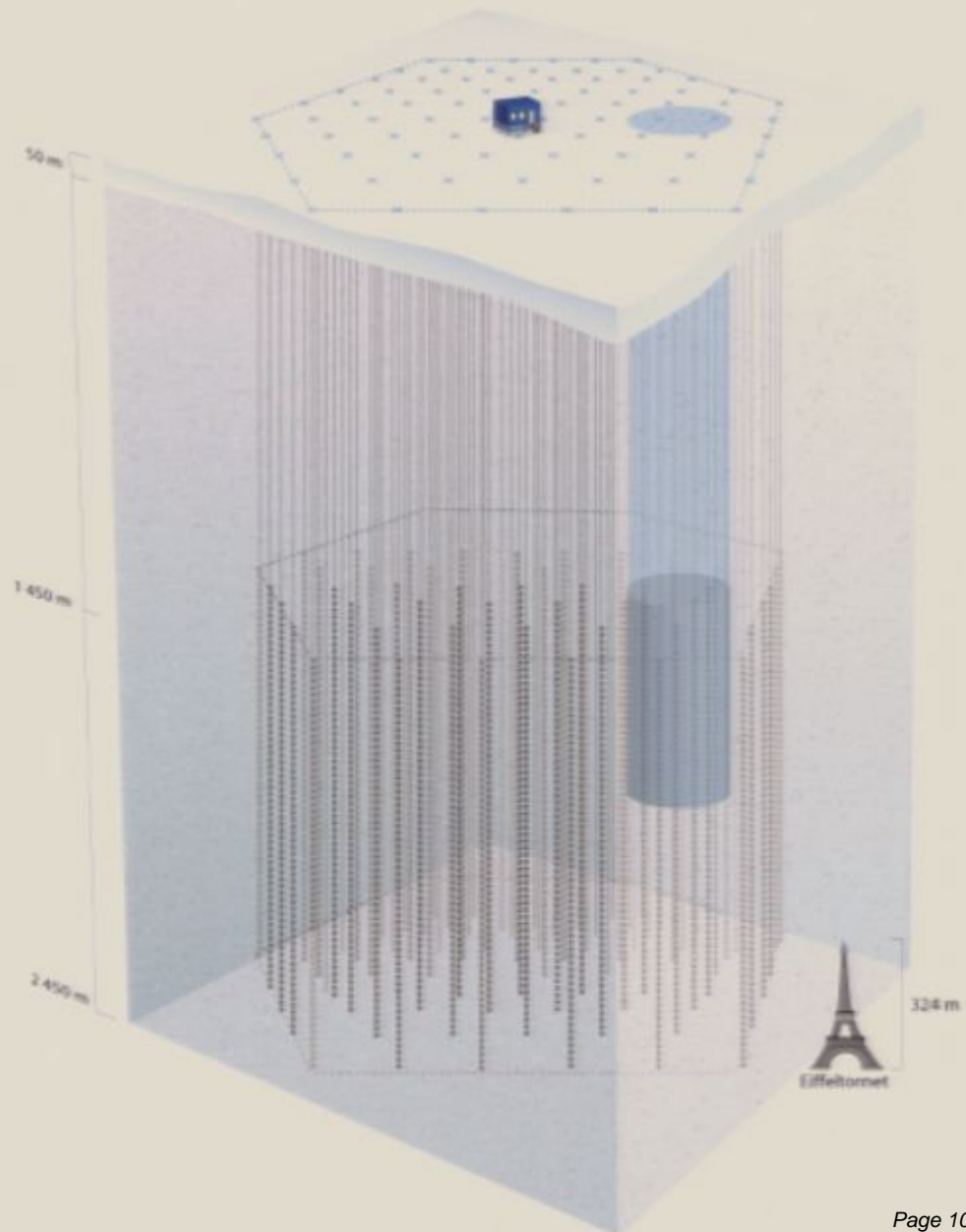


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Experiments to detect dark matter

Direct detection experiments seek to identify collisions between normal particles and dark matter particles in the lab

e.g. Canadian centre for dark matter experiments SNOLab, on the site of the Sudbury Neutrino Observatory



The Large Hadron Collider (LHC) at CERN



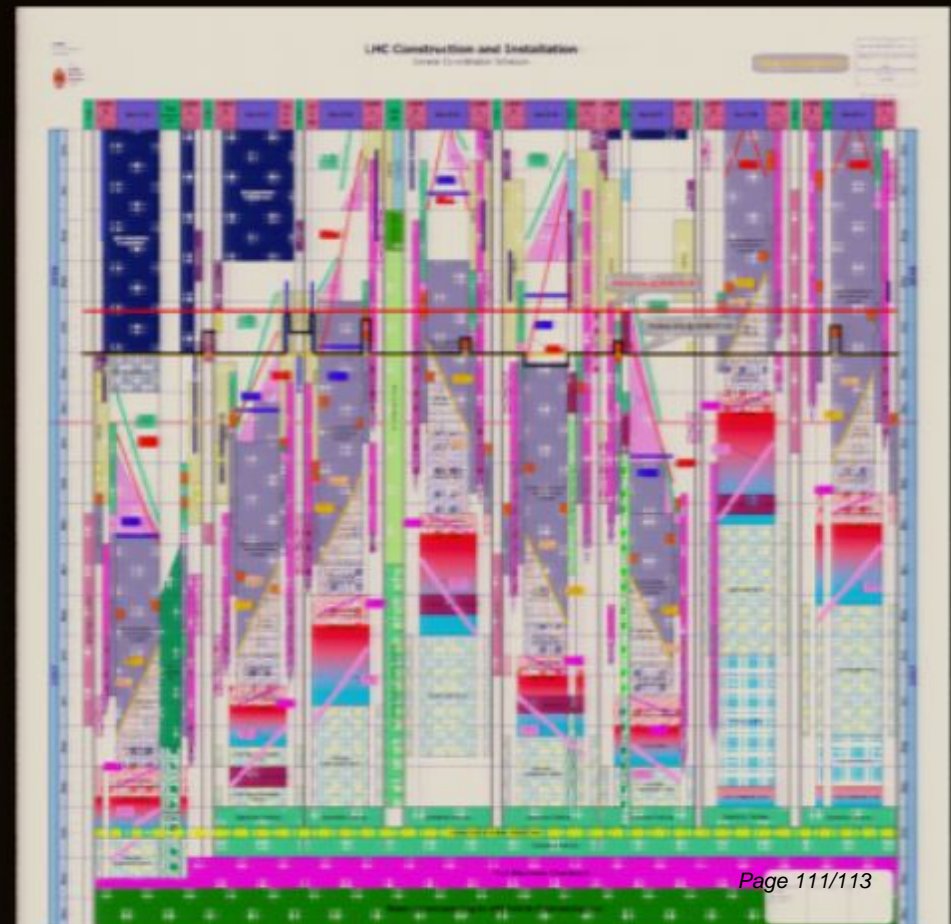
Experiments to detect dark matter

The Large Hadron Collider (LHC) at CERN:

The worlds next large particle accelerator, set to take science data next year (first runs now scheduled for May 2008)

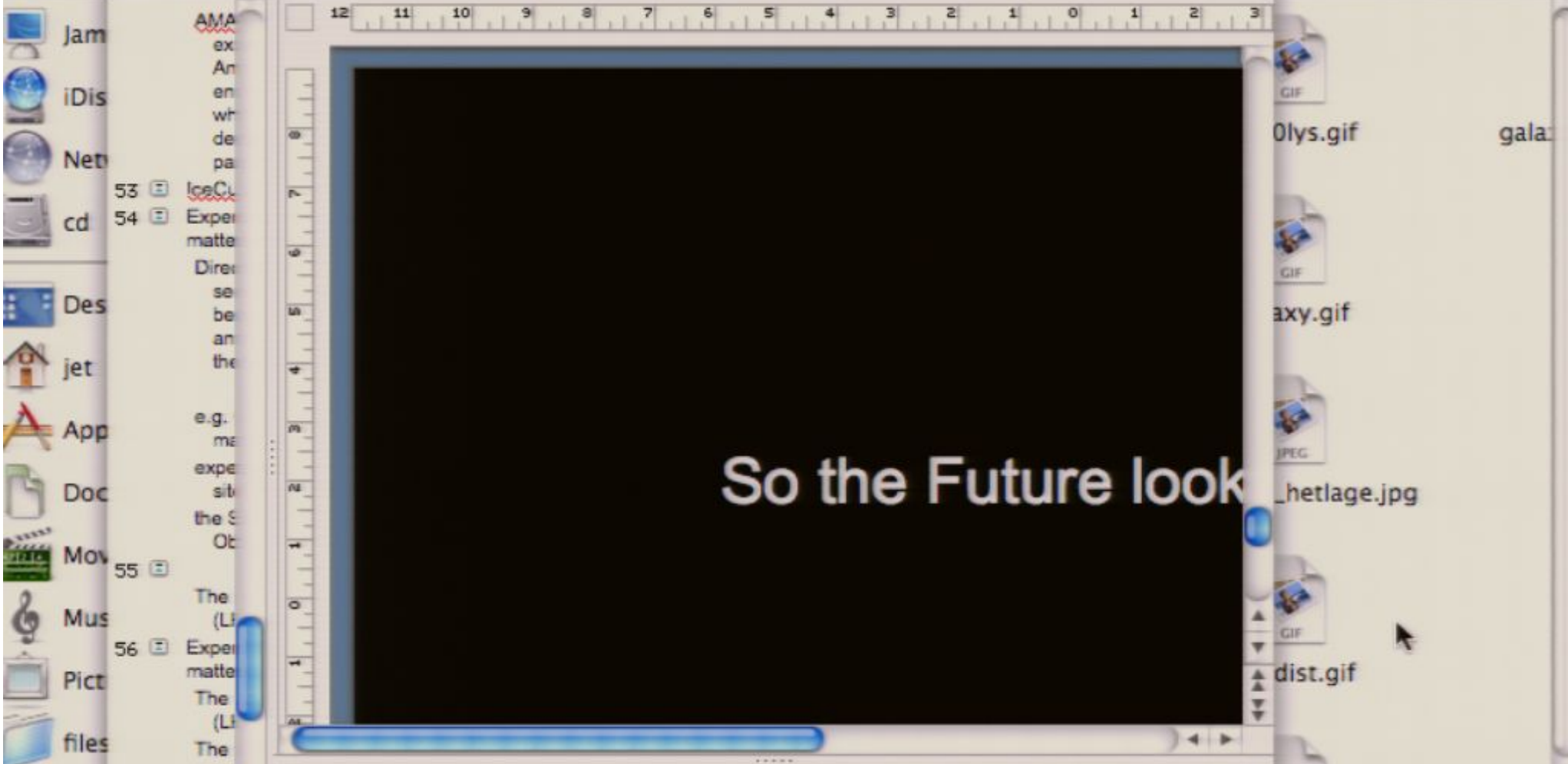


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So the Future looks dark!



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