What we know about the Universe Today

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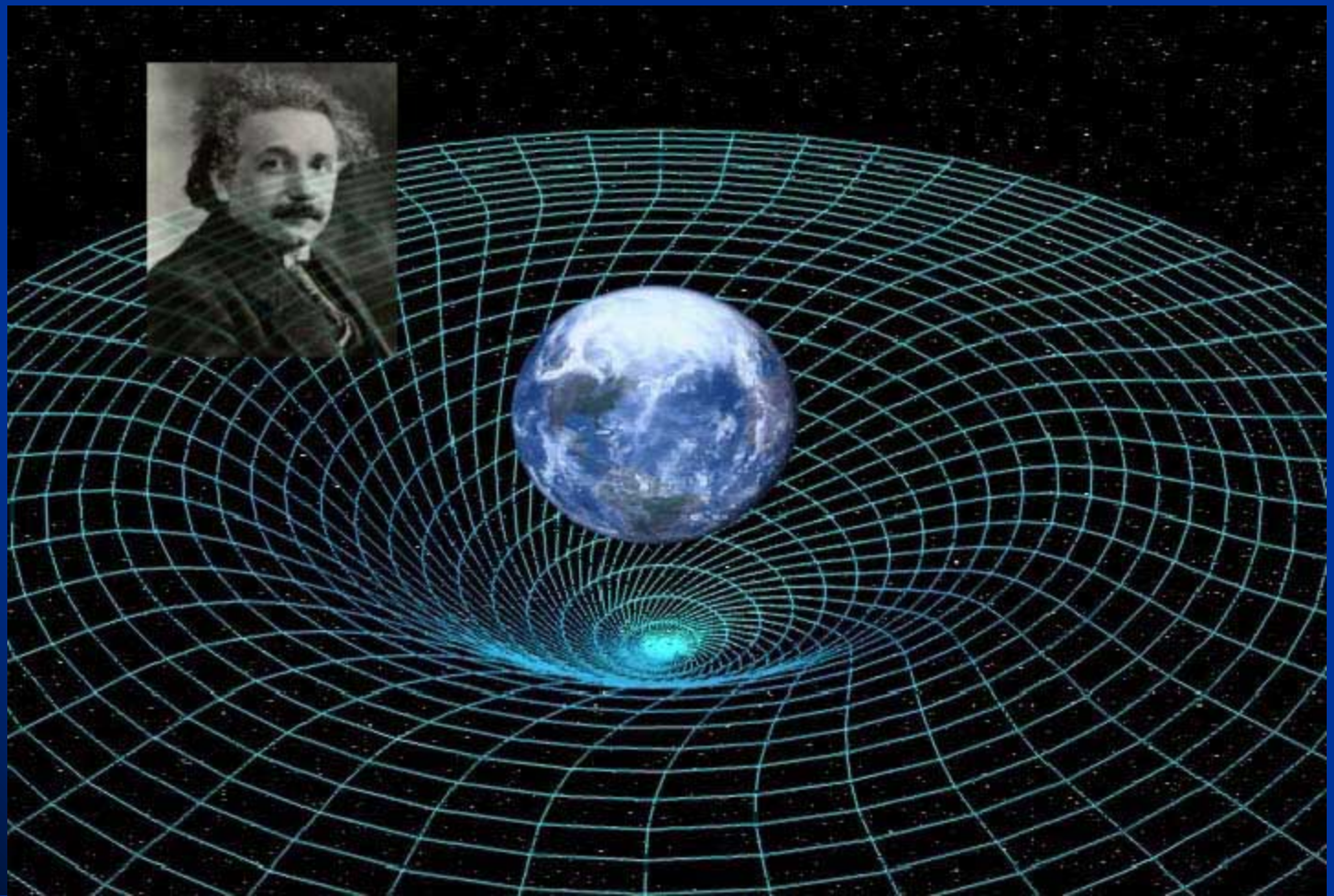
Origins of Modern Cosmology

- A scientific approach to the shape and evolution of the Universe date to the brilliant insights of Einstein's General Relativity in 1915.
- Friedmann, Robertson, Walker, Lemaitre (1920's) applied Einstein's theory to the universe as a whole.
- Several possible solutions to the equations existed: expanding, contracting, or static.
- Einstein preferred the extra symmetry of a static Universe. Idea of small universe is consistent with static universe. He postulated that it looks the same (on the average) at all times.

Geometry is Determined by Matter Content

Warping of Spacetime:



General Relativity: Einstein's Field Equations (1915)

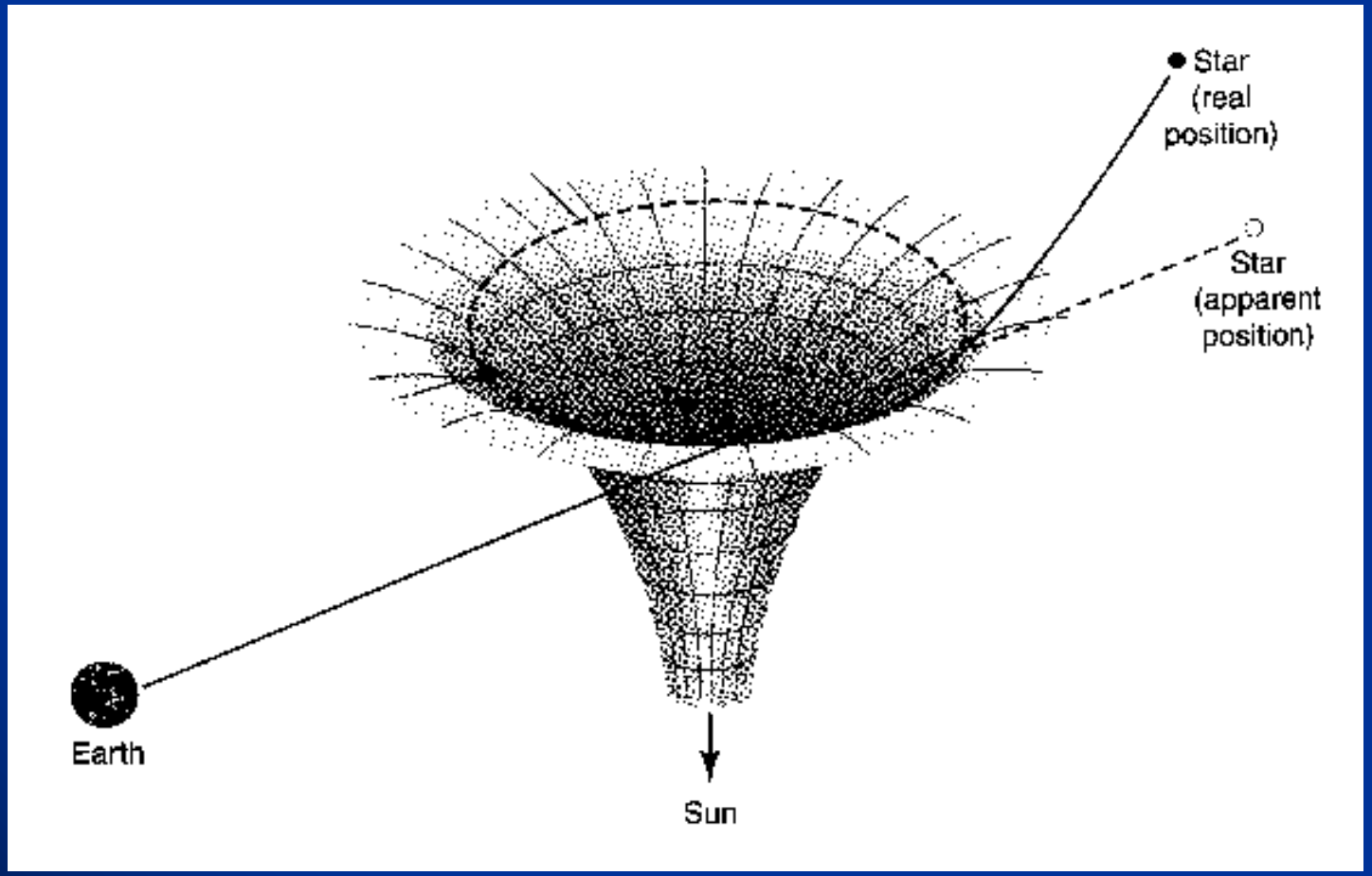
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

Relates geometry (left hand side of equation)

to

matter/energy content (right hand side of equation)

Matter Bends Light: Gravitational Lensing



REVOLUTION IN SCIENCE.

NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was difference of opinion as to whether science had to face merely a new and unexplained fact, or to reckon with a theory that would completely revolutionize the accepted fundamentals of physics.

SIR FRANK DYSON, the Astronomer Royal, described the work of the expeditions sent respectively to Sobral in North Brazil and the island of Principe, off the West Coast of Africa. At each of these places, if the weather were propitious on the day of the eclipse, it would be possible to take during totality a set of photographs of the obscured sun and of a number of bright stars which happened to be in its immediate vicinity. The desired object was to ascertain whether the light from these stars, as it passed the sun, came as directly towards us as if the sun were not there, or if there was a deflection due to its presence, and if the latter proved to be the case, what the amount of the deflection was. If deflection did occur, the stars would appear on the photographic plates at a measurable distance from their theoretical positions. He explained in detail the apparatus that had been employed, the corrections that had to be made for various disturbing factors, and the methods by which comparison between the theoretical and the observed positions had been made. He convinced the meeting that the results were definite and conclusive. Deflection did take place, and the measurements showed that the extent of the deflection was in close accord with the theoretical degree predicted by Einstein, as opposed to half that degree, the amount that would follow from the principles of Newton. It is interesting to recall that Sir Oliver Lodge, speaking at the Royal Institution last February, had also ventured on a prediction. He doubted if deflection would be observed, but was confident that if it did take place, it would follow the law of Newton and not that of Einstein.

DR. CROMMELIN and PROFESSOR EDDINGTON, two of the actual observers, followed the Astronomer-Royal, and gave interesting accounts of their work, in every way confirming the general conclusions that had been enunciated.

"MOMENTOUS PRONOUNCEMENT."

So far the matter was clear, but when the discussion began, it was plain that the scientific interest centred more in the theoretical bearings of the results than in the results themselves. Even the President of the Royal Society, in stating that they had just listened to "one of the most momentous, if not the most momentous, pronouncements of human thought," had to confess that no one had yet succeeded in stating in clear language what the theory of Einstein really was. It was accepted, however, that Einstein, on the basis of his theory, had made three predictions. The first, as to the motion of the planet Mercury, had been verified. The second, as to the existence and the degree of deflection of light as it passed the sphere of influence of the sun, had now been verified. As to the third, which depended on spectroscopic observations there was still uncertainty. But he was confident that the Einstein theory must now be reckoned with, and that our conceptions of the fabric of the universe must be fundamentally altered

At this stage Sir Oliver Lodge, whose contribution to the discussion had been eagerly expected, left the meeting.

Subsequent speakers joined in congratulating the observers, and agreed in accepting their results. More than one, however, including Professor Newall, of Cambridge, hesitated as to the full extent of the inferences that had been drawn and suggested that the phenomena might be due to an unknown solar atmosphere further in its extent than had been supposed and with unknown properties. No speaker succeeded in giving a clear non-mathematical statement of the theoretical question.

SPACE "WARPED."

Put in the most general way it may be described as follows: the Newtonian principles assume that space is invariable, that, for instance, the three angles of a triangle always equal, and must equal, two right angles. But these principles really rest on the observation that the angles of a triangle do equal two right angles, and that a circle is really circular. But there are certain physical facts that seem to throw doubt on the universality of these observations, and suggest that space may acquire a twist or warp in certain circumstances, as, for instance, under the influence of gravitation, a dislocation in itself slight and applying to the instruments of measurement as well as to the things measured. The Einstein doctrine is that the qualities of space, hitherto believed absolute, are relative to their circumstances. He drew the inference from his theory that in certain cases actual measurement of light would show the effects of the warping in a degree that could be predicted and calculated. His predictions in two of three cases have now been verified, but the question remains open as to whether the verifications prove the theory from which the predictions were deduced.

Deflection of Light by the Sun

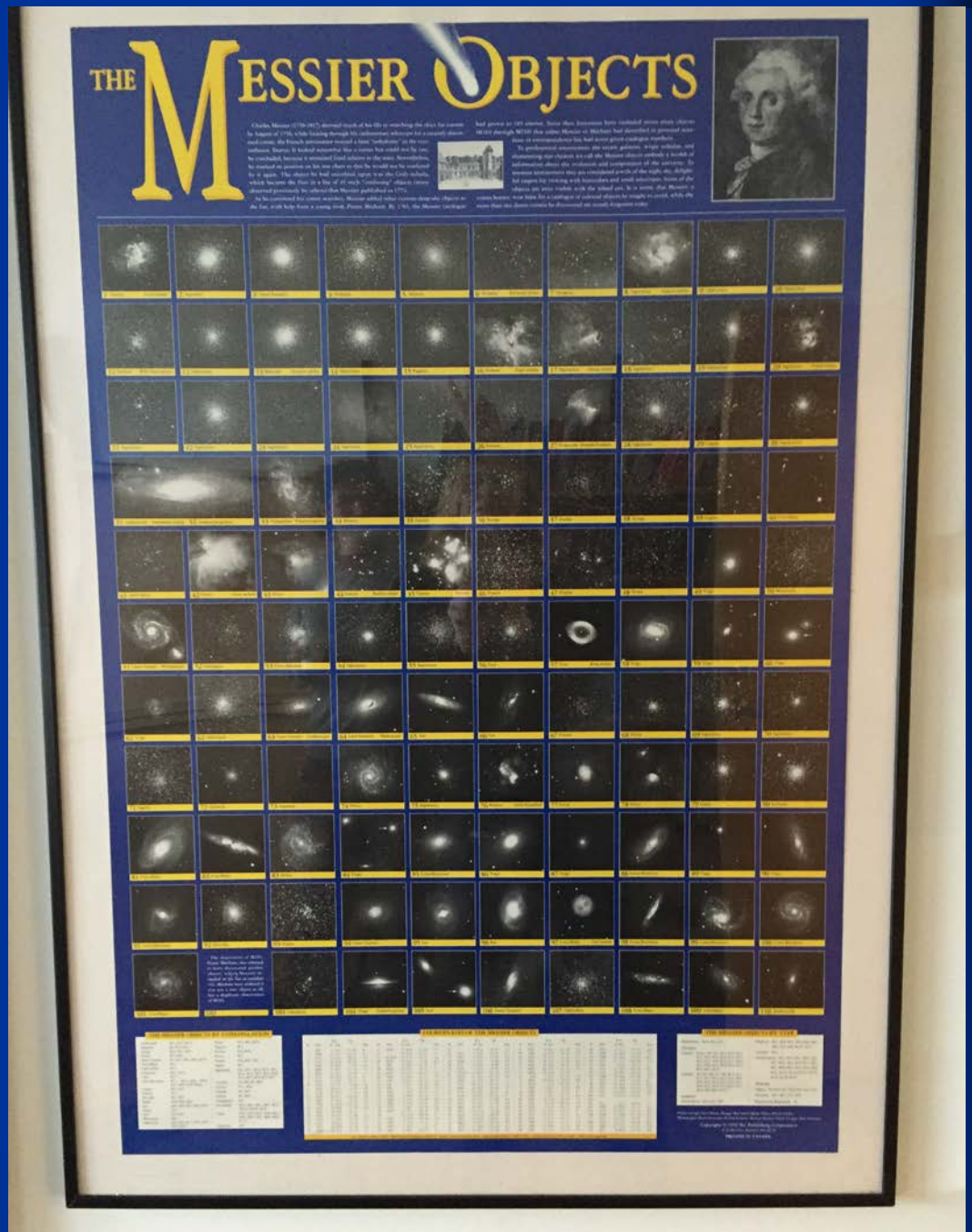
London Times 1919

One Hundred Years Ago

- At the time of Einstein's theoretical breakthroughs in relativity circa 1915
- Astronomy was primitive
- Scientists thought that all bright objects in the sky were nearby stars contained inside the Milky Way
- Are there 'island universes' (galaxies), or is everything contained in the Milky Way? Is the universe 10,000 light years in size?
- Messier (first catalogue of galaxies and clusters) thought these 'nebulae' were a nuisance in the way of his studies of comets

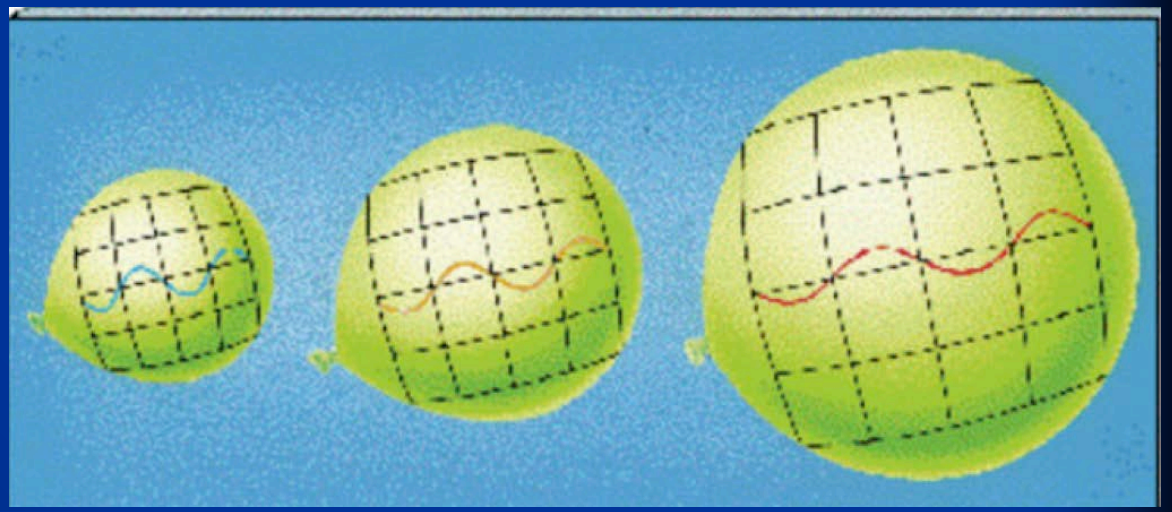
- In the 1700s Charles Messier comet hunter, catalogued nebulae frustrating him

These are now the Messier Catalogue of galaxies!
M31 is Andromeda Galaxy, the nearby giant to the Milky Way



Hubble Expansion in 1929

- Edwin Hubble using the Mt. Wilson Observatory above Pasadena made astronishing discoveries.
- He proved that other galaxies exist beyond our own.
- He observed light from galaxies at various distances away from Earth. The light waves are stretched, or redshifted, by the time they gets to us. The reason is the expansion of space.
- THE UNIVERSE
- IS EXPANDING!!!

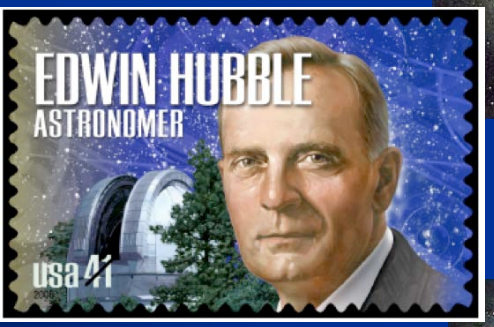


- Einstein

abandoned

the static Universe

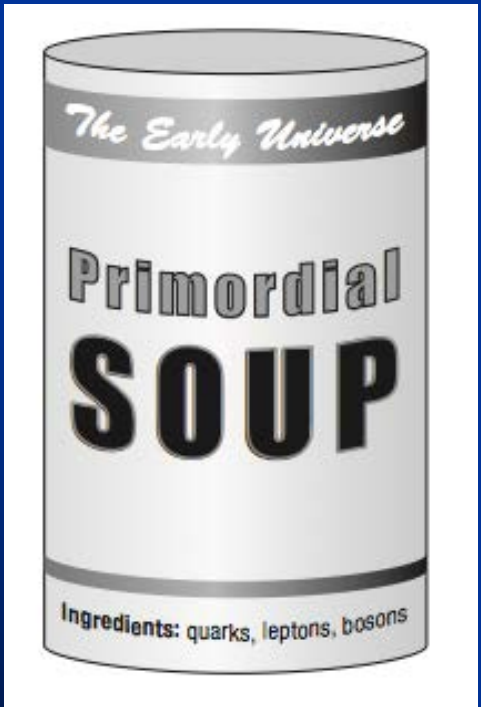
Galaxies are moving apart from one another.
The Universe is expanding.

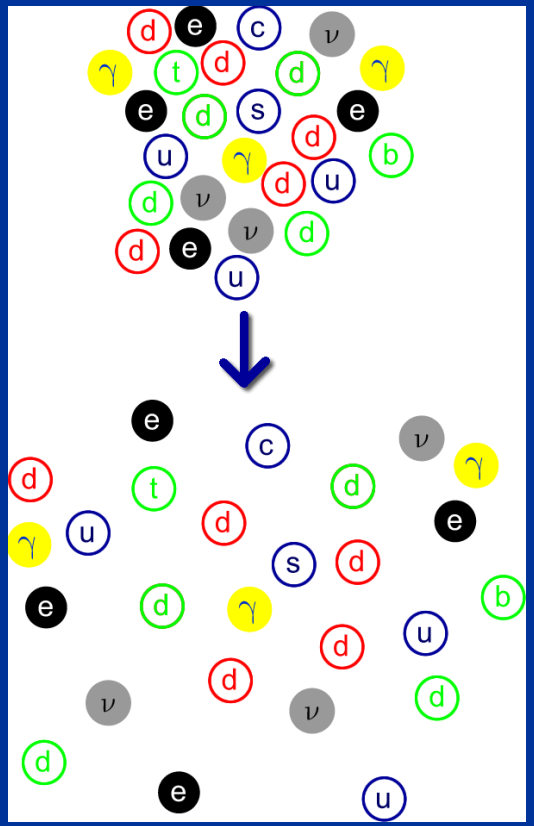


(1929)

THE BIG BANG

14 BILLION
YEARS AGO

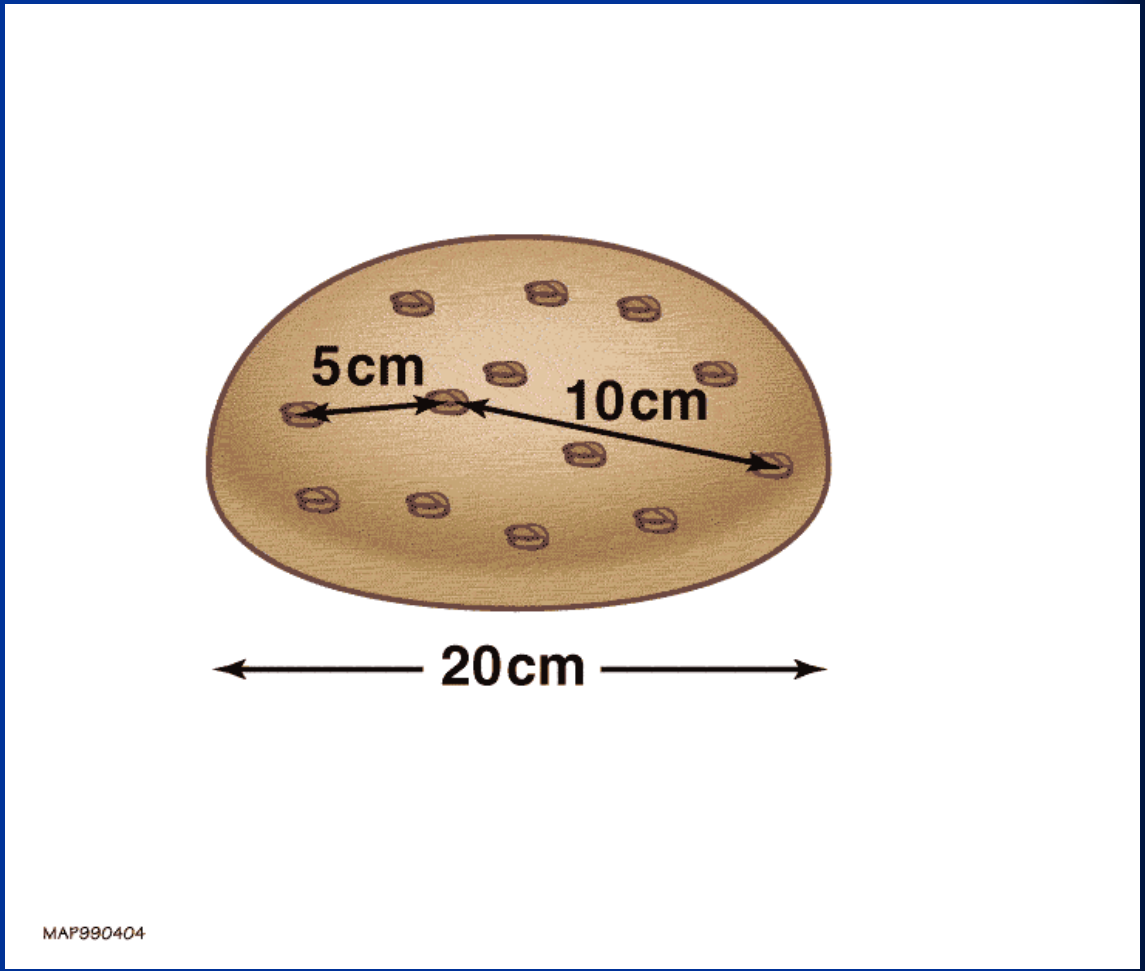




The Universe started out hot;
It is cooling and expanding.

Raisin Bread Model of the Universe

- As the loaf rises, raisins move steadily apart from one another, with the loaf maintaining the same configuration.



As we look backwards in time:

- All points in infinite universe getting closer and closer

  --- yet universe can still be infinite all the way back!

Eventually, the density at each point is so great we lose description (maybe string theory?)

Big Bang at every point in the universe.

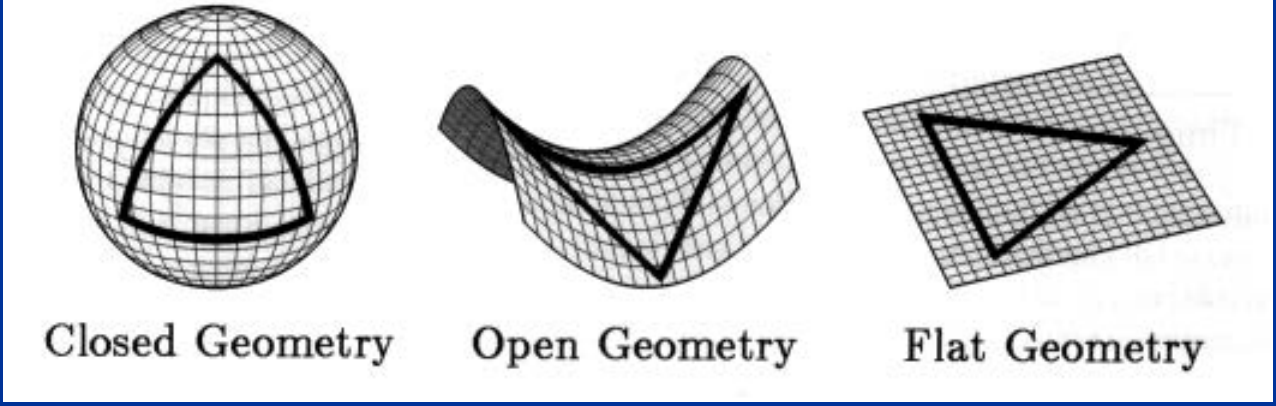
Big Bang happens everywhere at once (not at a single point)







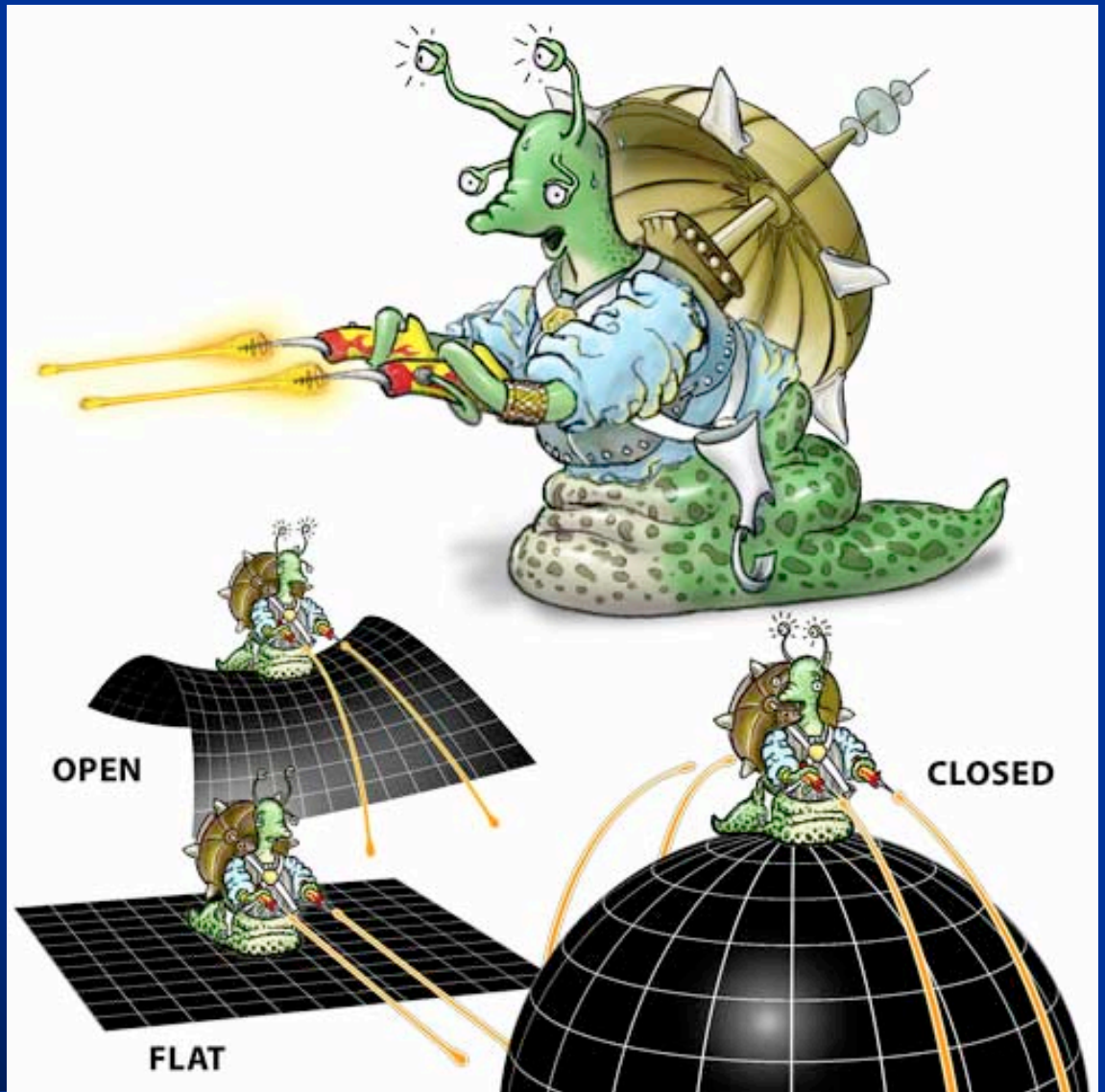
Geometry of the Universe



1930: Three possible geometries for the universe

2000: The geometry of the universe is FLAT!!!!!!

Geometry of the Universe



ENORMOUS PROGRESS OVER THE LAST CENTURY

At the turn of the Millenium, recent experiments answered BIG QUESTIONS:

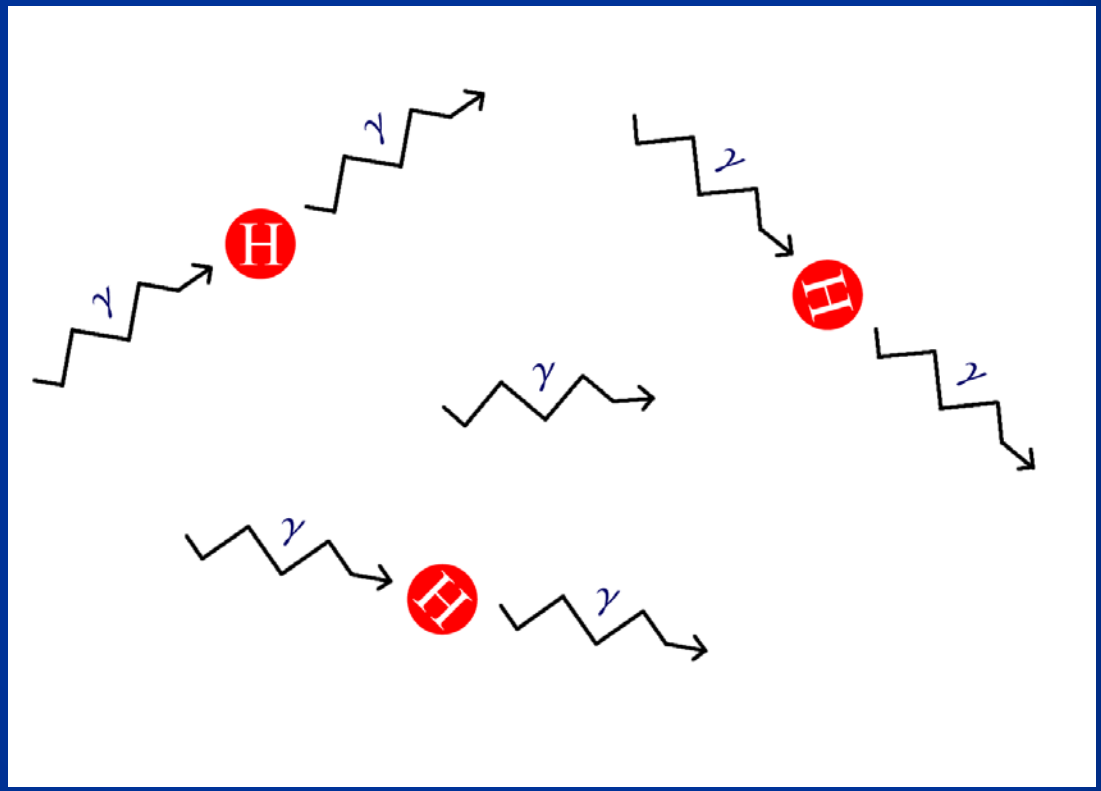
- We know the geometry of the universe
- We know the energy density of the universe
- We understand the physics all the way to the edge of the observable universe (the horizon)
- BUT many questions remain: what is the universe made of (dark matter and dark energy)? How did it begin? How will it end?

GEOMETRY AND TOTAL CONTENT OF THE UNIVERSE HAVE BEEN DISCOVERED

- Cosmic Microwave Background: Left over light from the hot early Universe.
- Powerful probe of the early Universe and of cosmological parameters.
- CMB Experiments determined that the universe has a FLAT geometry, and determined the total amount of matter/energy density in the universe.

Last Scattering

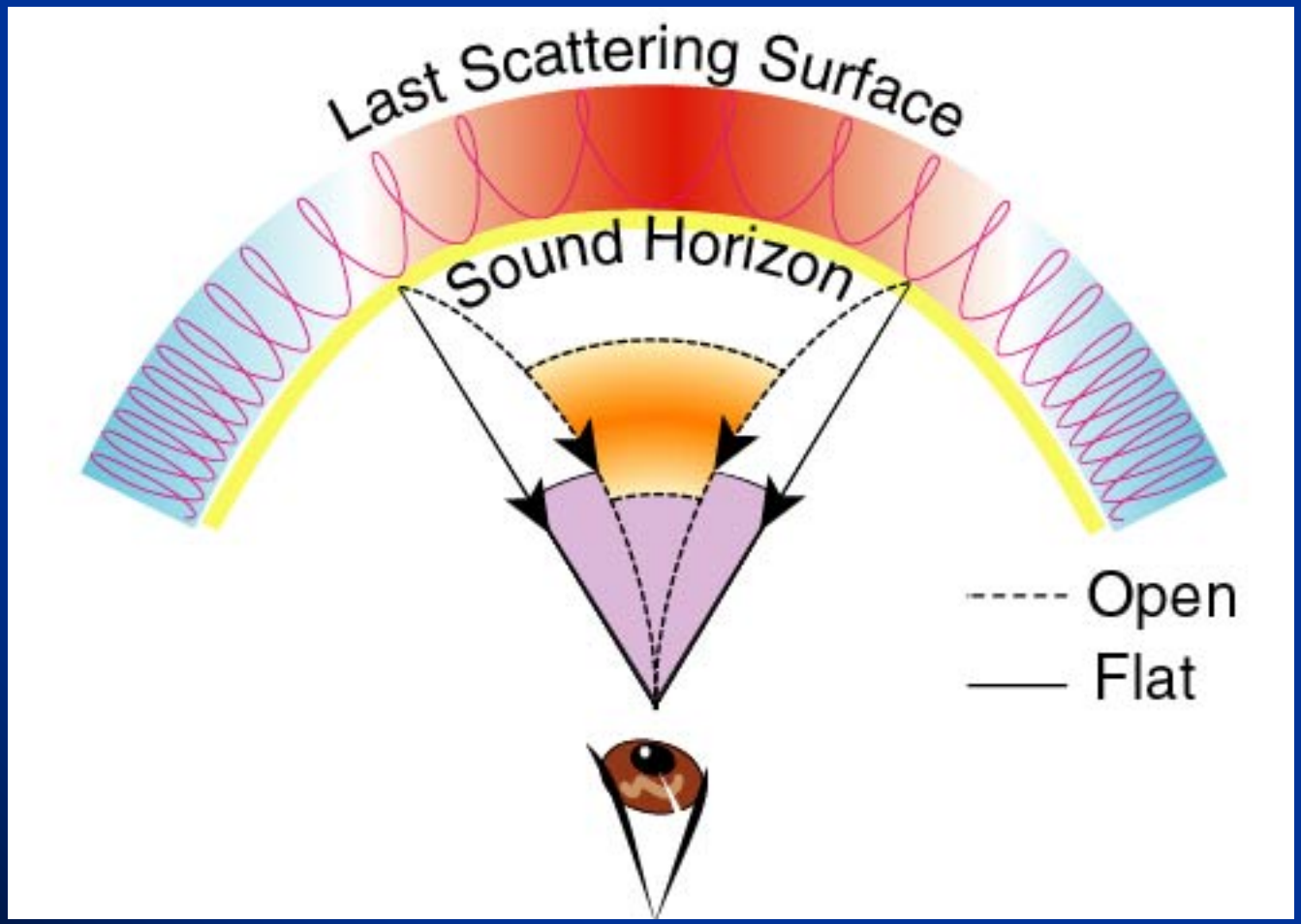
- When the universe is 380,000 years old, at a temperature of 3000K, the photons (light particles) scatter one last time. After that, the electrons are gone (into hydrogen atoms) so that the photons are free to travel all the way to the present universe.



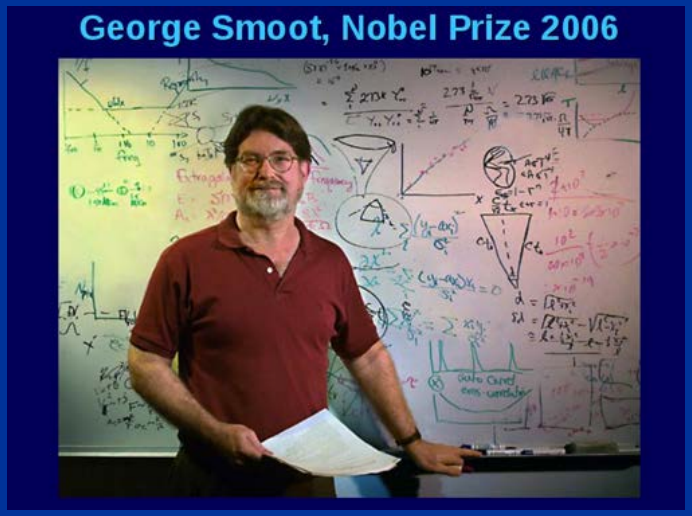
Photons no longer interact.
Universe becomes transparent

Due to rapid interactions, Photons develop Planck spectrum

How can Microwave Background tell us about geometry?



2006 Nobel Prize in Physics

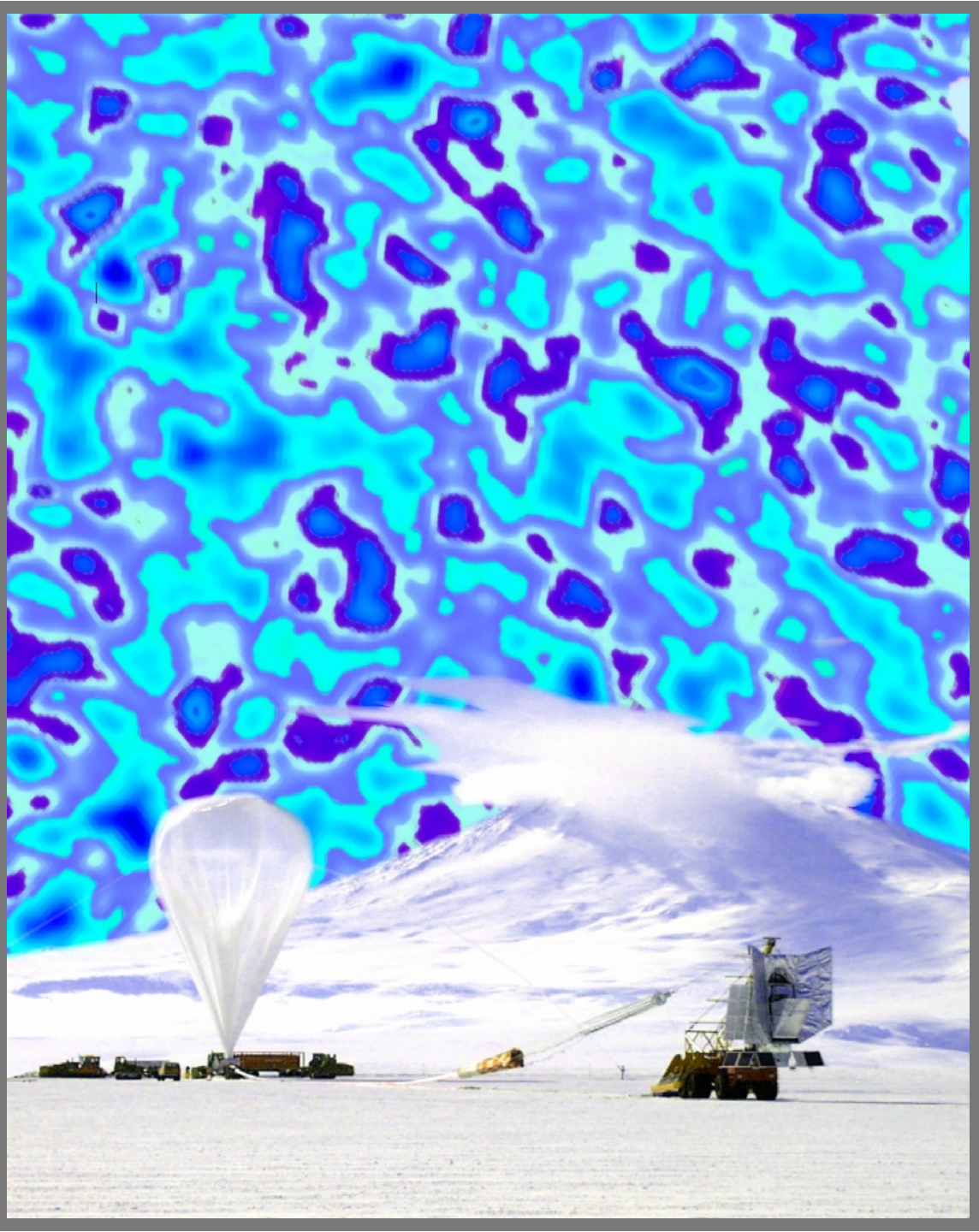


- *To John Mather and George Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."*

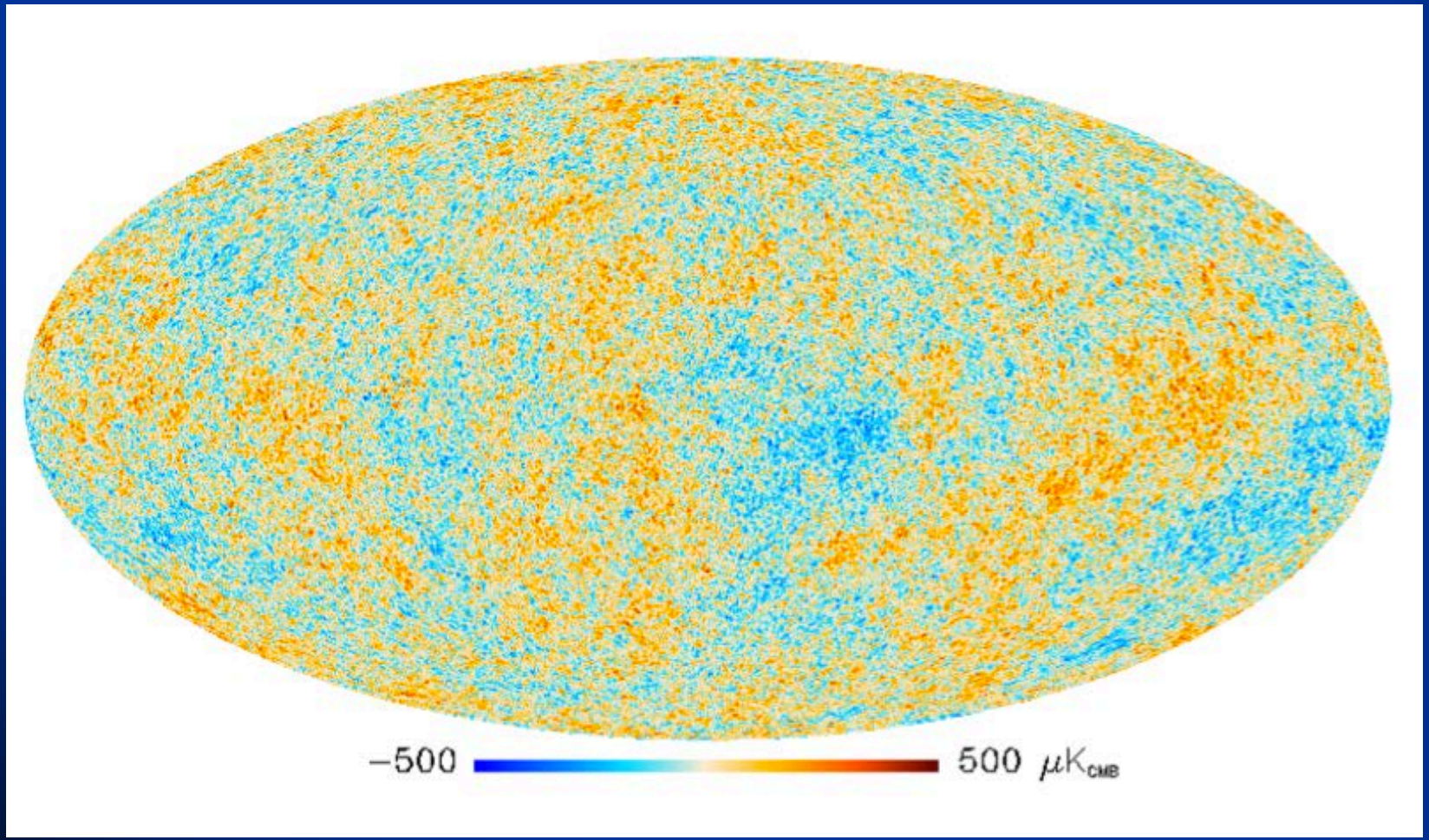
The Doppler Peak

- Acoustic oscillations in the photon/atom fluid are imprinted at last scattering. We expect a peak in the microwave background at the sound horizon (distance sound could travel in the age of the universe).
- If the universe is flat, the peak is at one degree.
- If the universe is a saddle, the peak is at less than one degree.
- First discovery of Doppler peak: TOCO 1999, BOOMERANG 2000, WMAP satellite, PLANCK

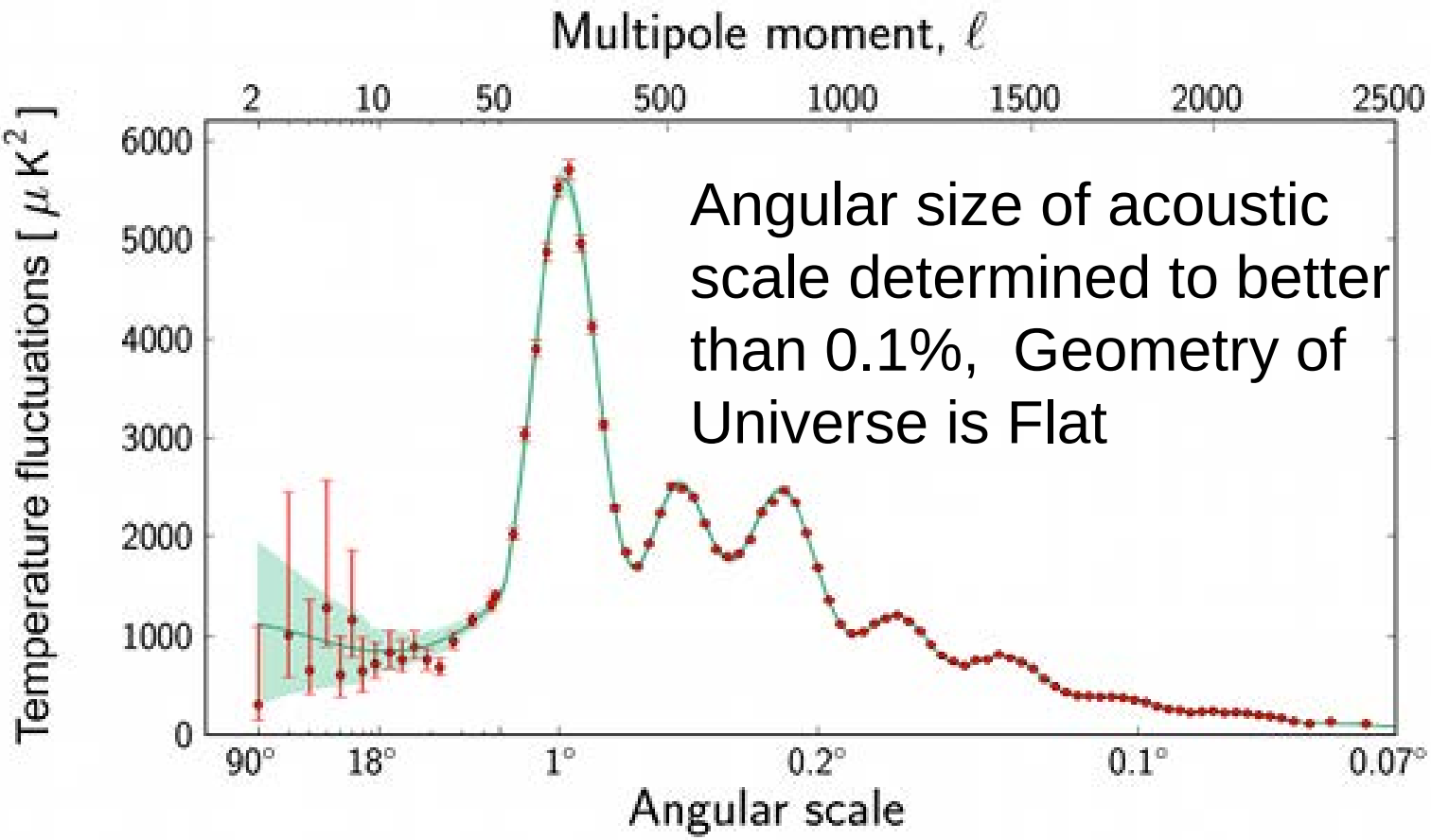
BOOMERANG SKY



The Universe according to ESA's Planck Space Telescope, March 2013



Planck Data



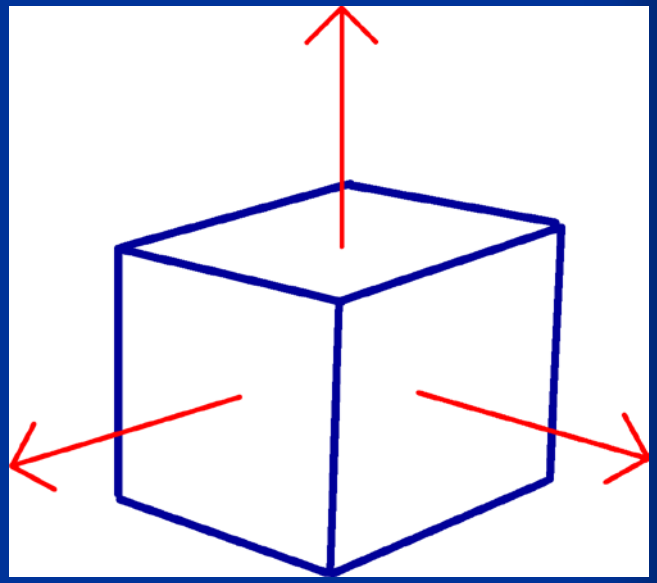
Seven acoustic peaks

Universe has Flat Geometry

- Universe is NOT two-dimensional.
- Goes out to infinity in all three directions:

Shortest distance between two points is a straight line.

No curvature required, no weird geometry.



Einstein's relativity connects the geometry with the total mass/energy content

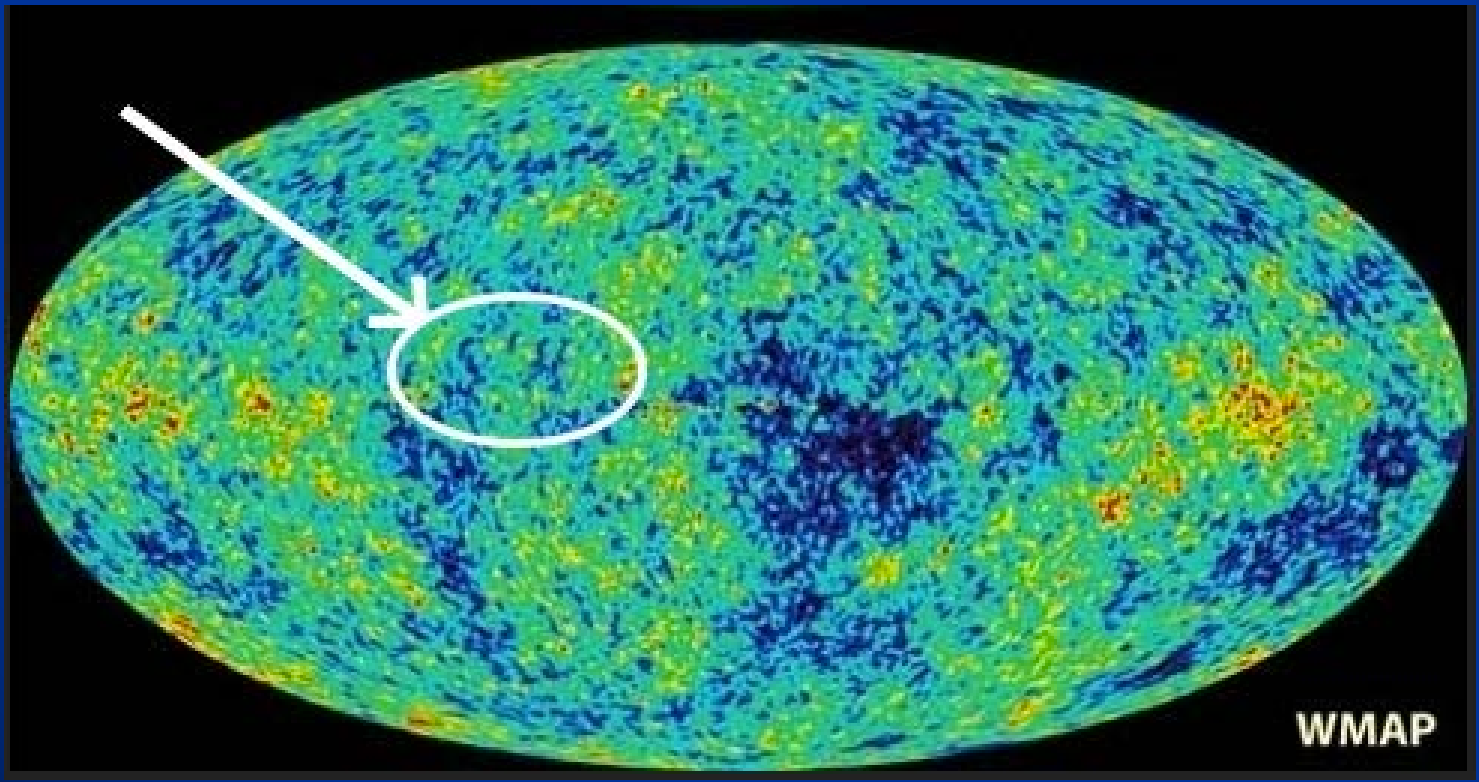
- The energy density of the universe is

$$\rho = \rho_c = 10^{-29}\ \mathrm{gm/cm}^3$$

(compare to water on Earth, which has 1 gm/cm^3)

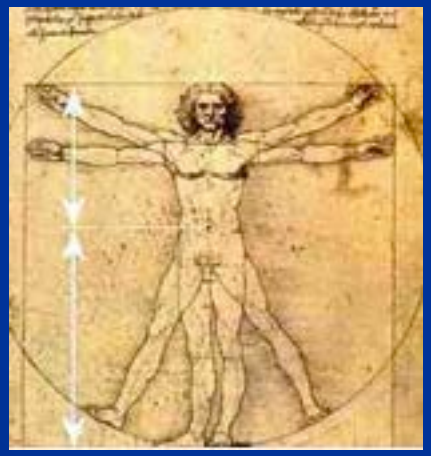
This is the density of "outer space" (as I tried to explain to Queen Silvia)

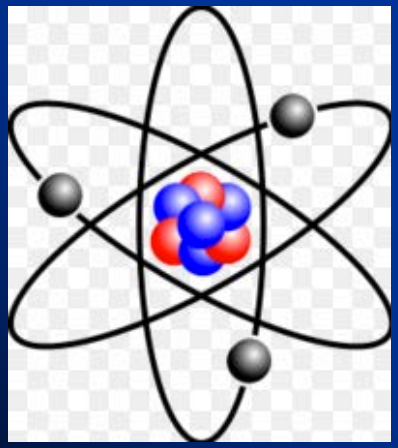
SH initials in WMAP satellite data



What is the Universe made of?
The answer is very SURPRISING!

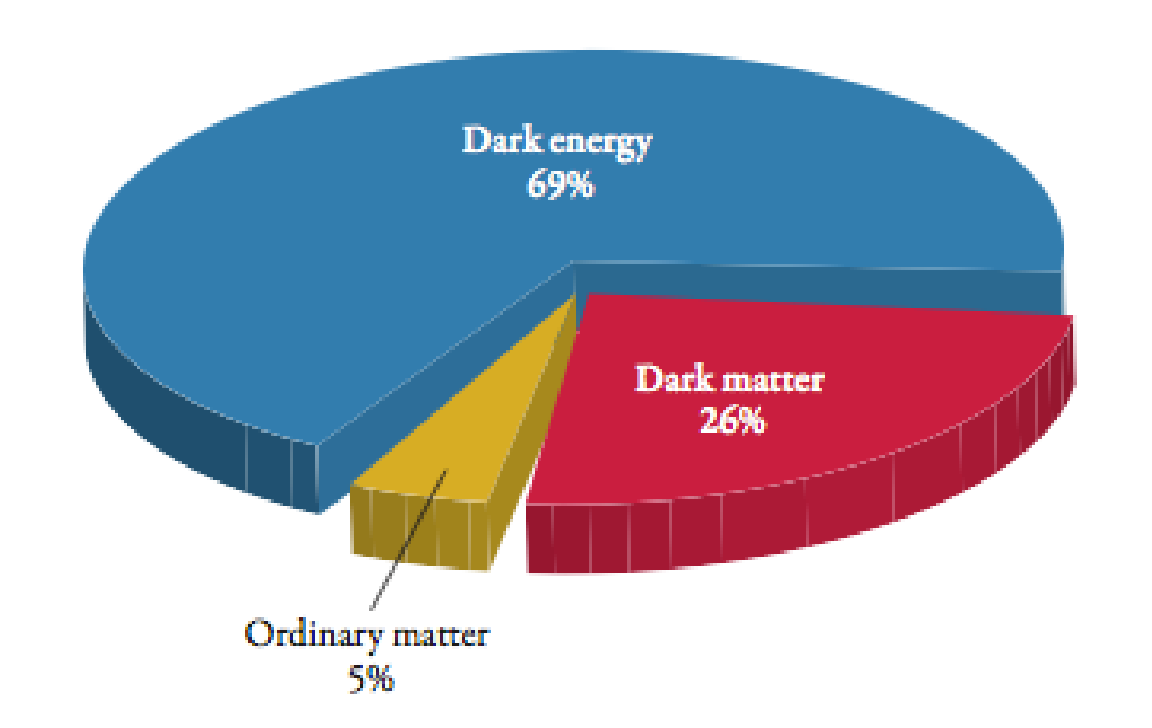
All the objects of our daily experience:





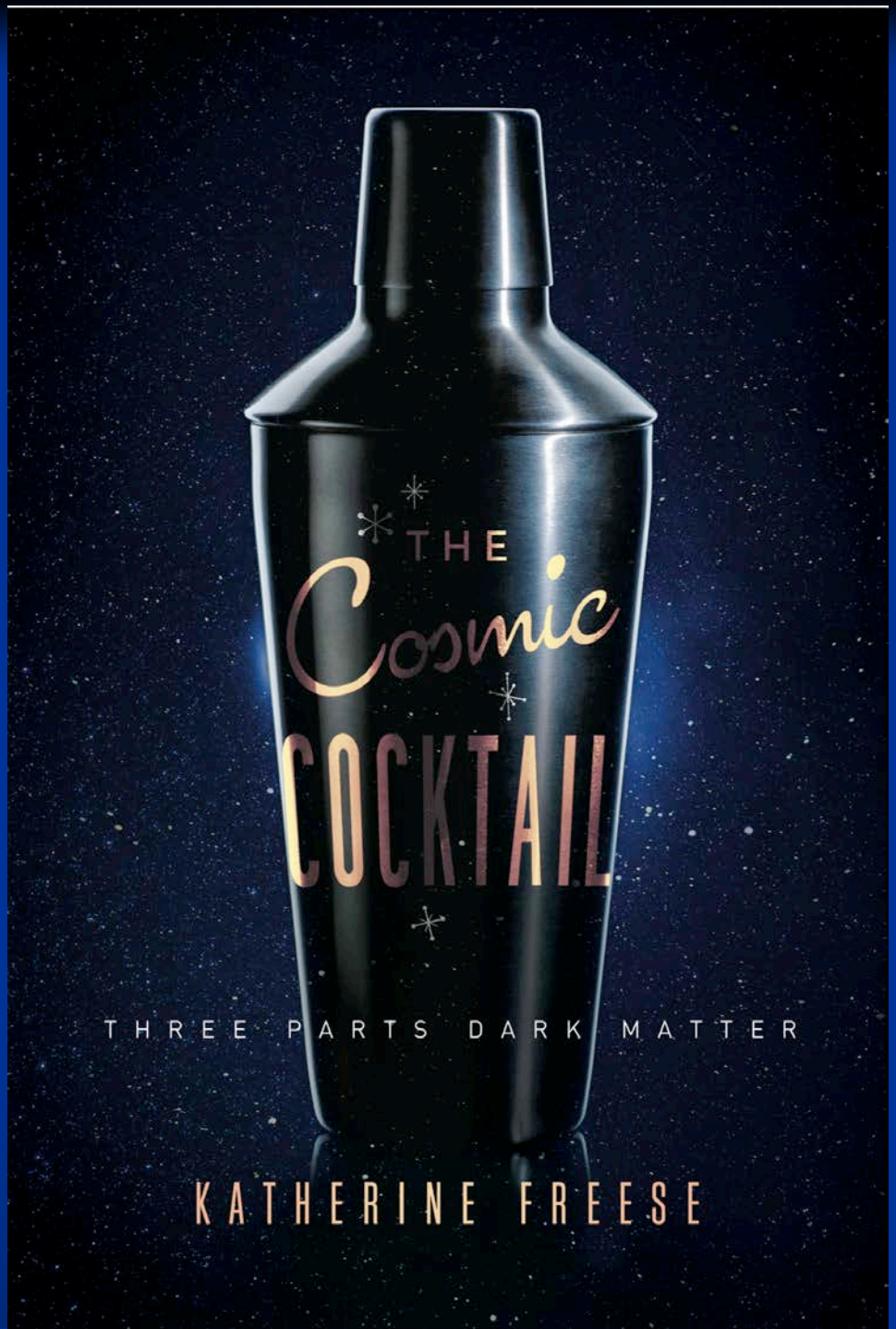
ALL ADD UP TO ONLY 5% OF THE UNIVERSE!

Pie Chart of The Universe



Less than 5% ordinary matter.

What is the dark matter? What is the dark energy?


THE
Cosmic
COCKTAIL
THREE PARTS DARK MATTER
KATHERINE FREESE

The Cosmic Cocktail: A Recipe for the Cosmos

3 oz. dark matter

7 oz. dark energy

1/2 oz. hydrogen and helium gas

3 thousandth oz. other chemical elements

5 hundredth oz. stars

5 hundredth oz. neutrinos

5 ten-thousandth oz. cosmic microwave background light

1 millionth oz. supermassive black holes

Shaken, not stirred.

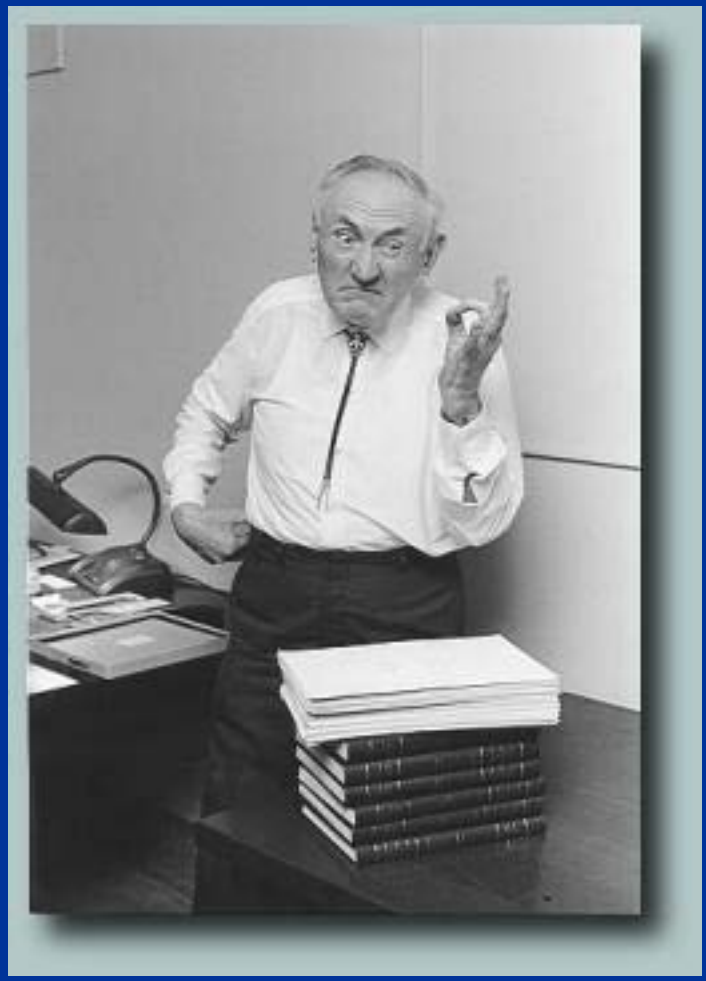
Secret ingredient: dark matter

Fritz Zwicky in 1933

Galaxies in the Coma cluster were moving too rapidly.

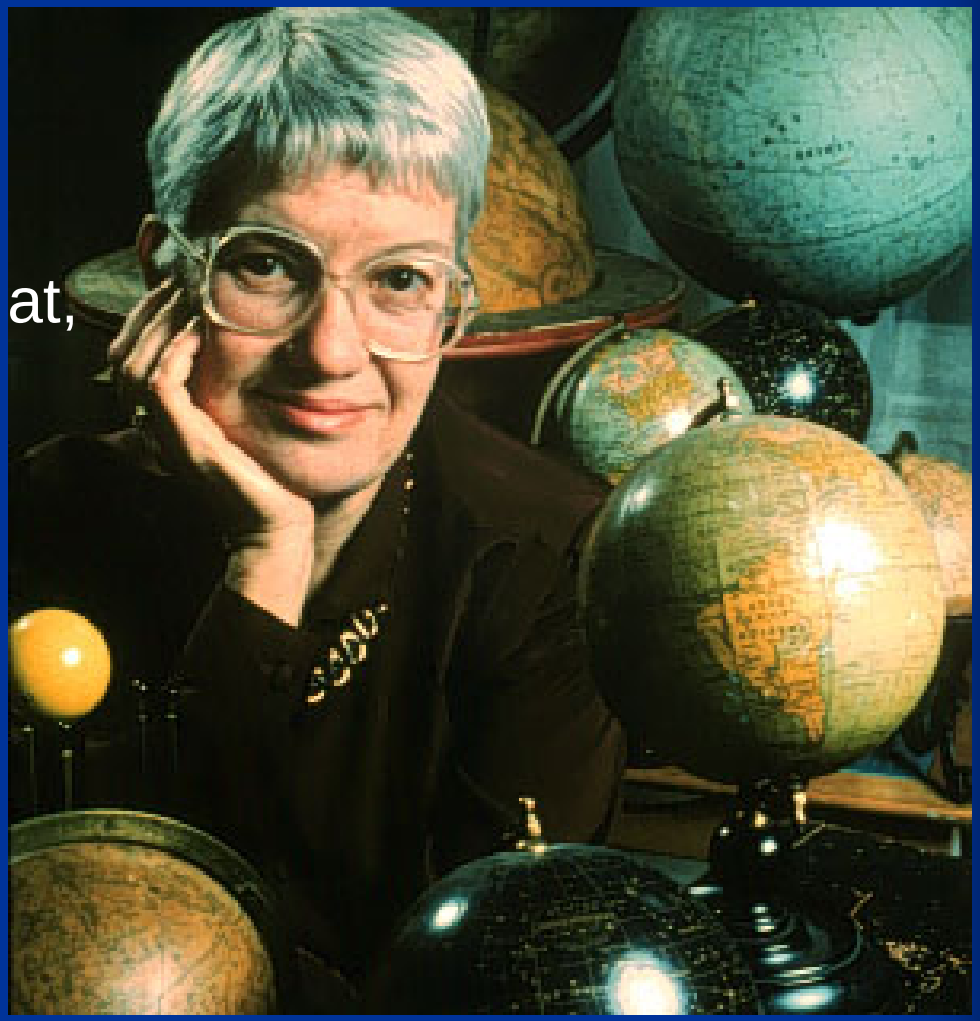
He proposed "Dunkle Materie" as the explanation.

THE BEGINNING OF THE DARK MATTER PROBLEM



Vera Rubin in 1970s

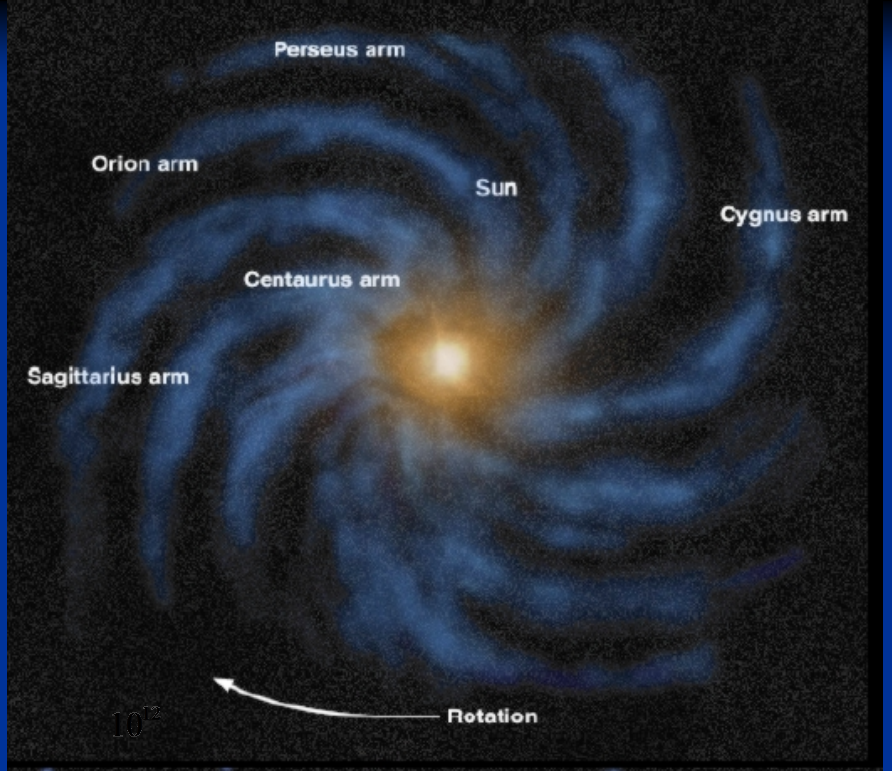
Found dark matter in all galaxies she looked at, and the scientific community became convinced that dark matter must exist.

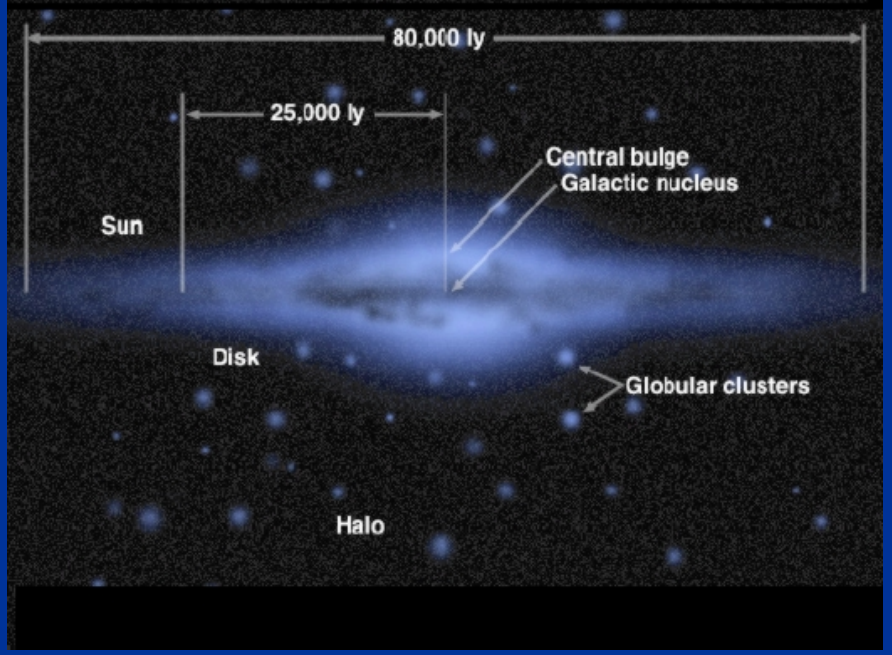


Our Galaxy: The Milky Way

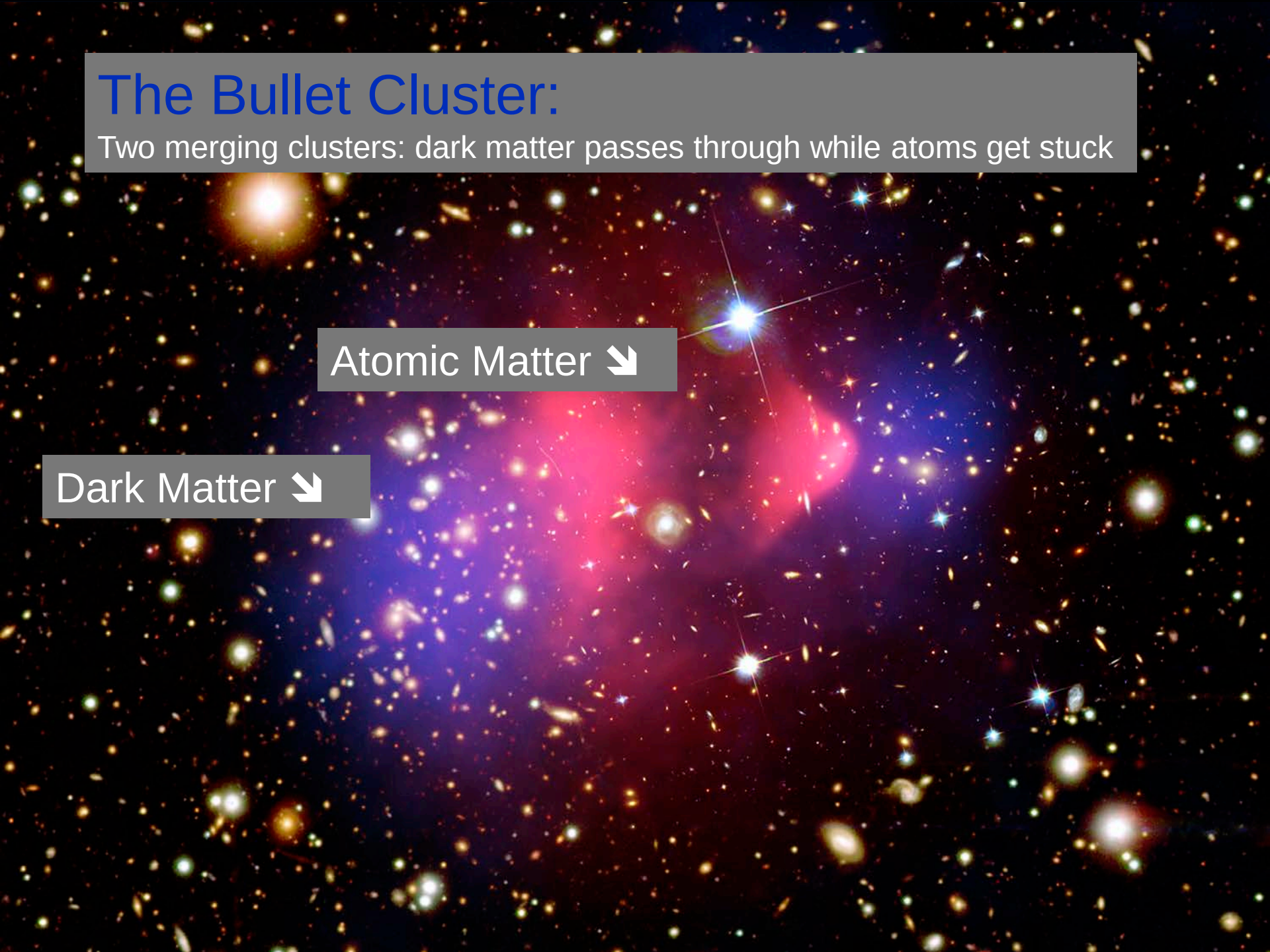
The mass of the galaxy:

10^{12} solar masses





Galaxies have Dark Matter Haloes

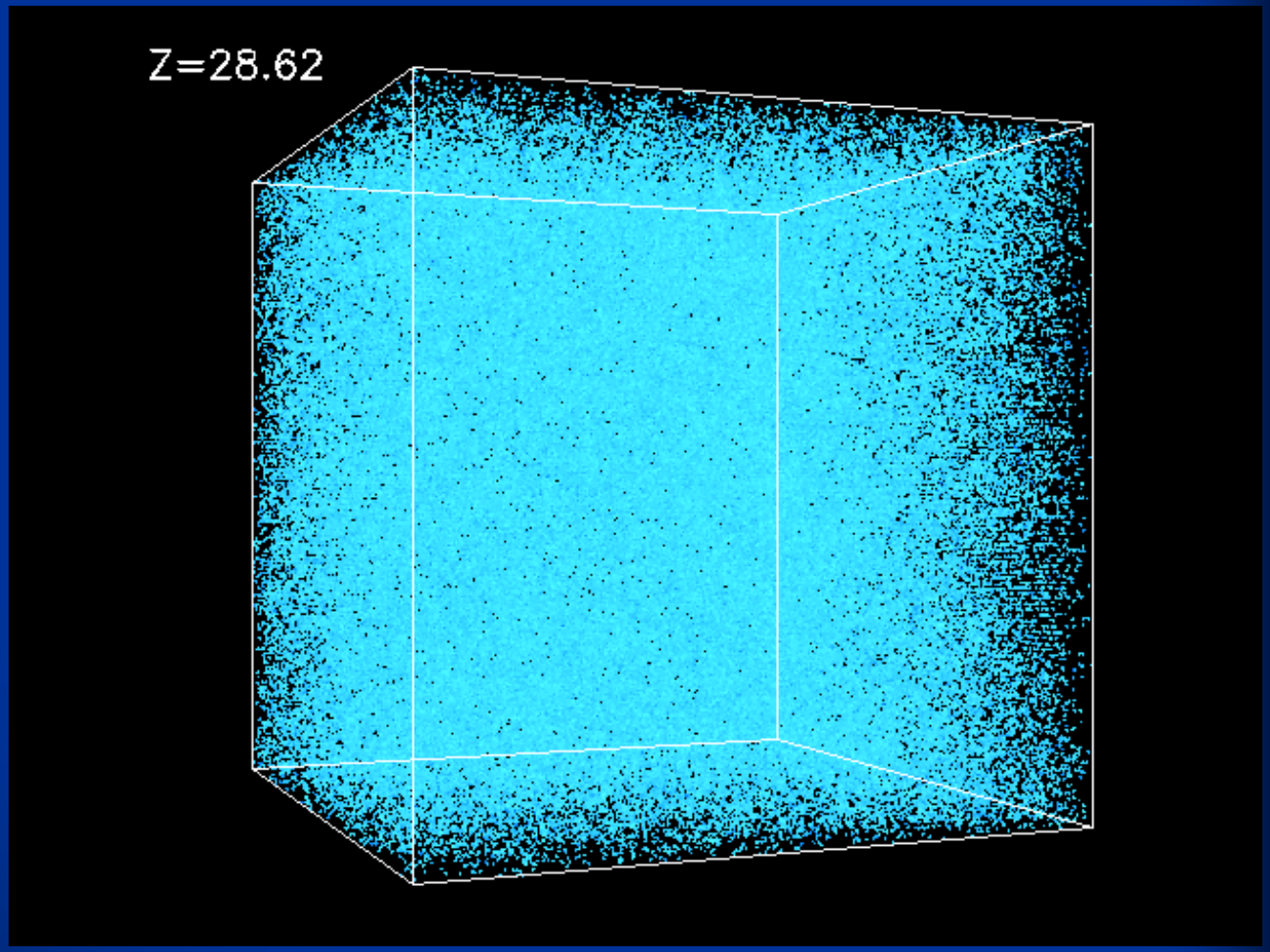

The Bullet Cluster:
Two merging clusters: dark matter passes through while atoms get stuck
Atomic Matter ↘
Dark Matter ↘

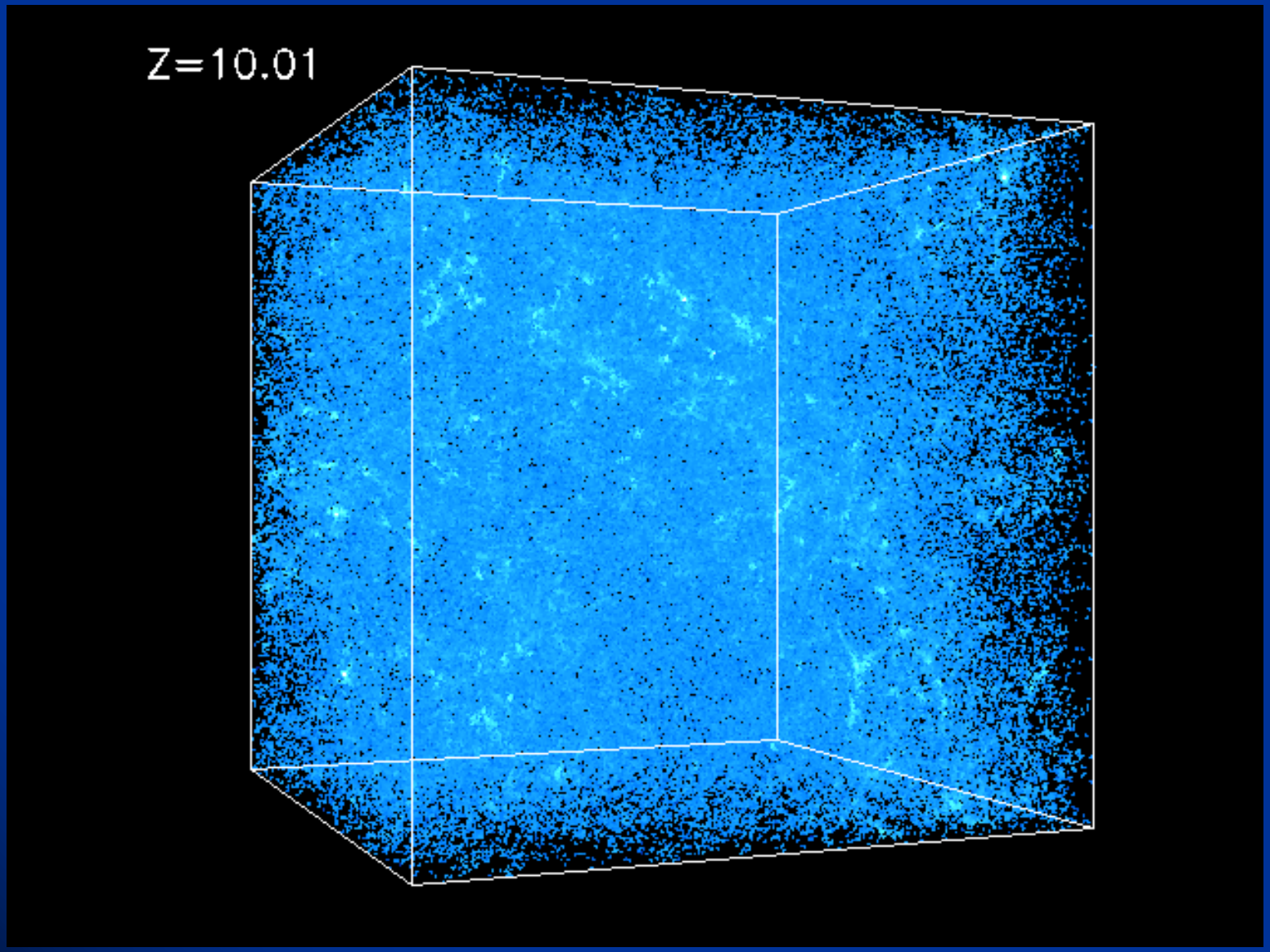
Evidence for Dark Matter: Formation of Structure, Computer Simulations

Initial conditions from inflation

Dark Matter particles come together to make galaxies, clusters, and larger scale structures

Computer simulations with dark matter match the data

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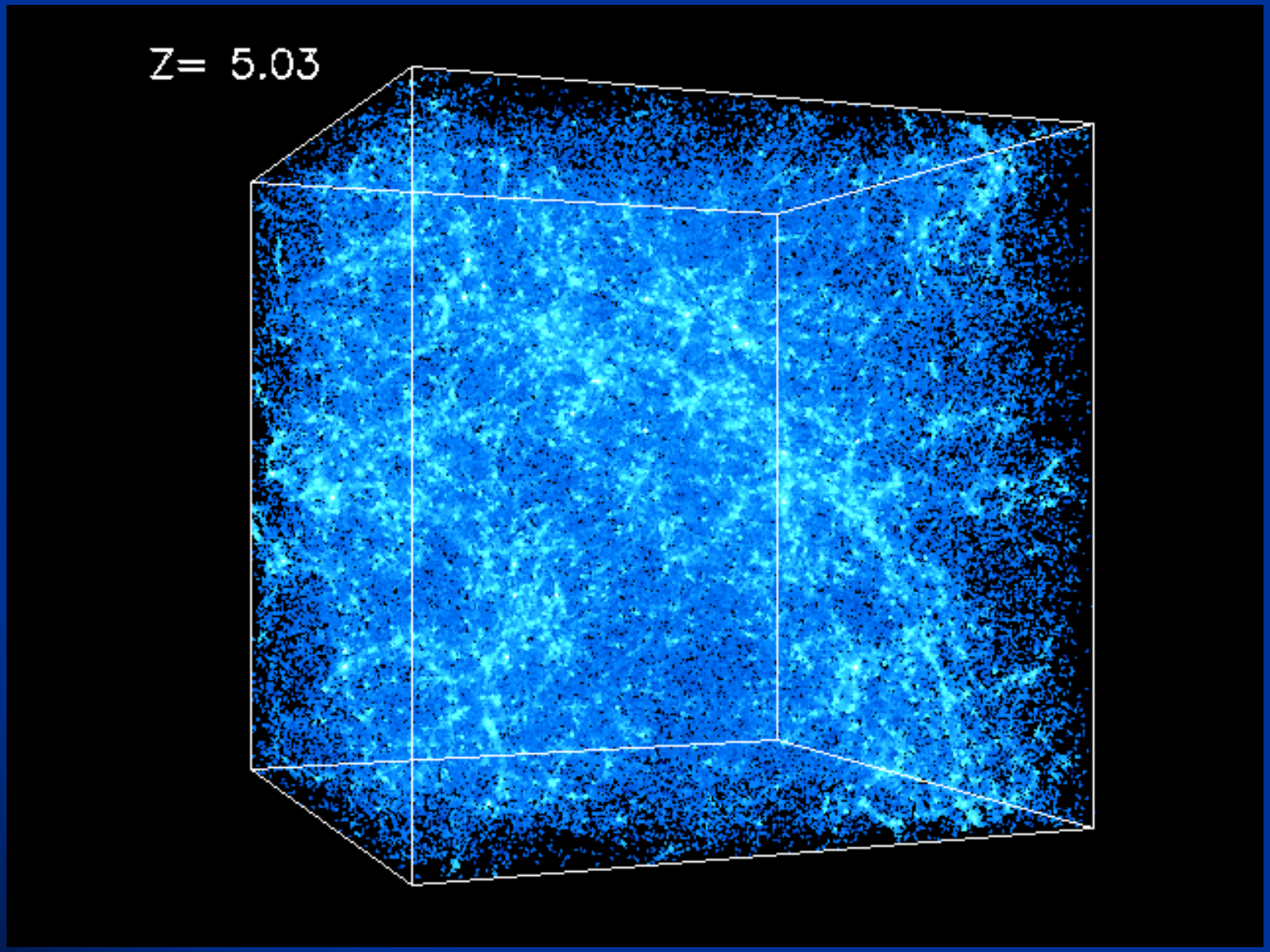
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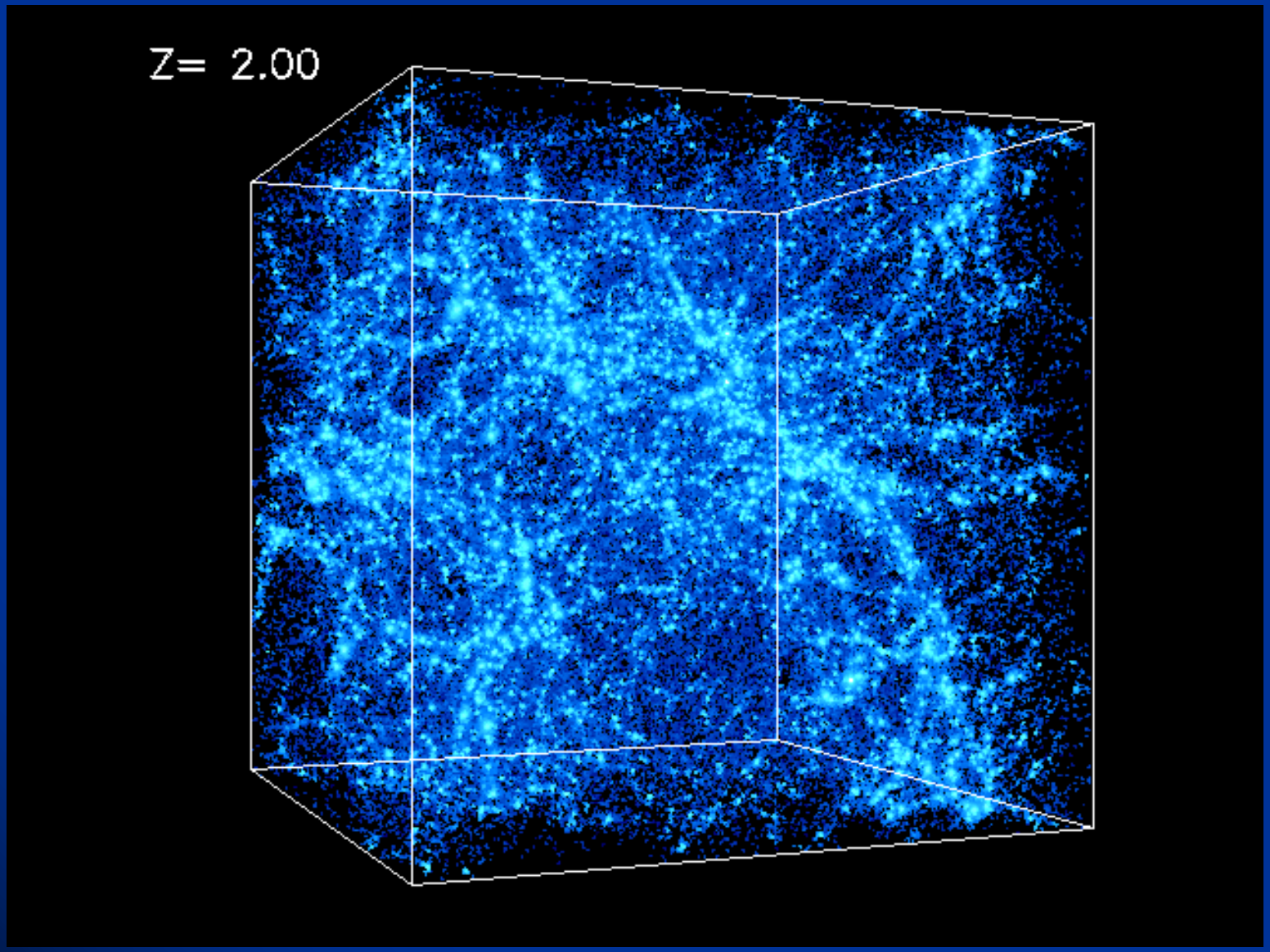
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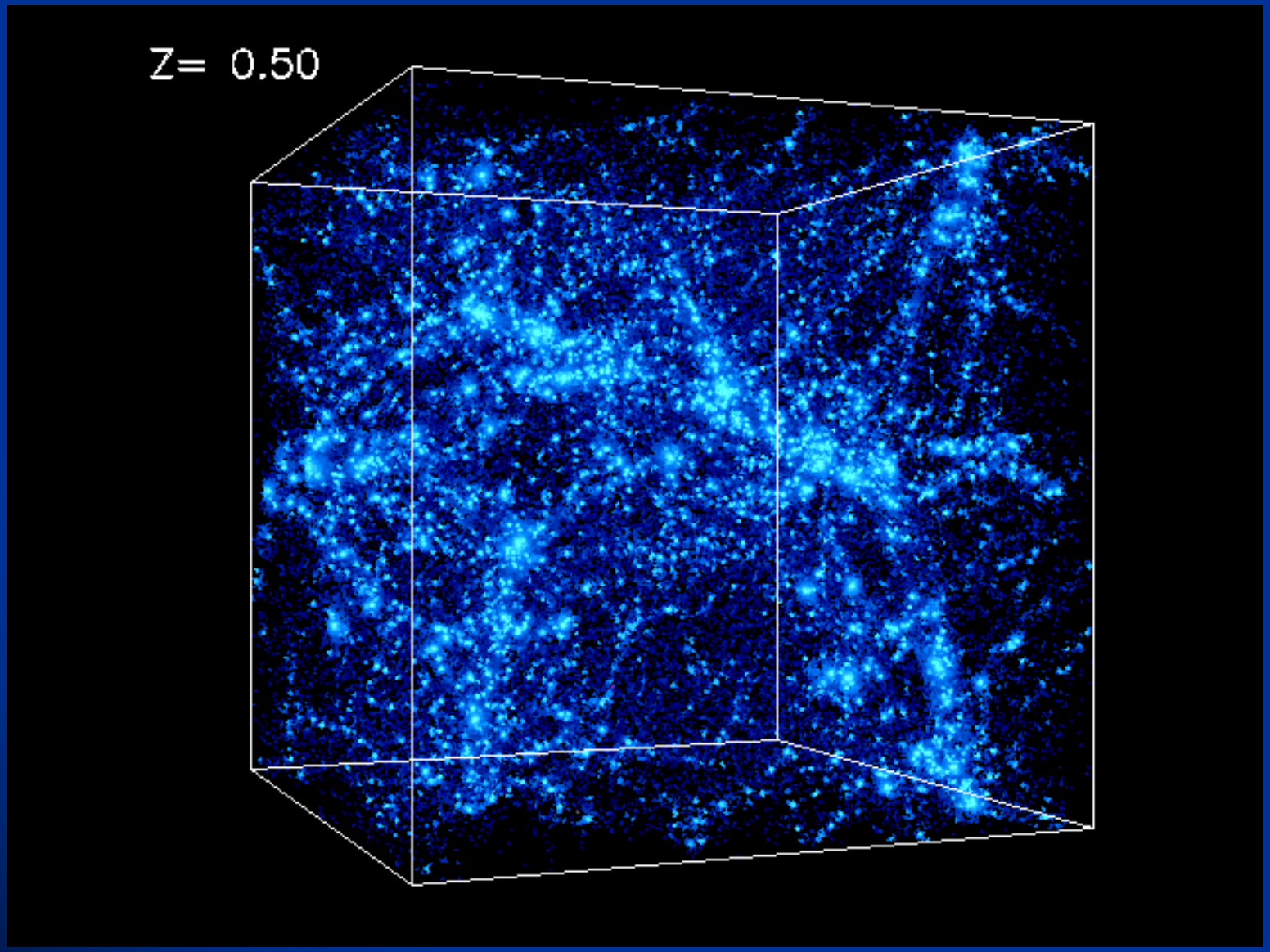
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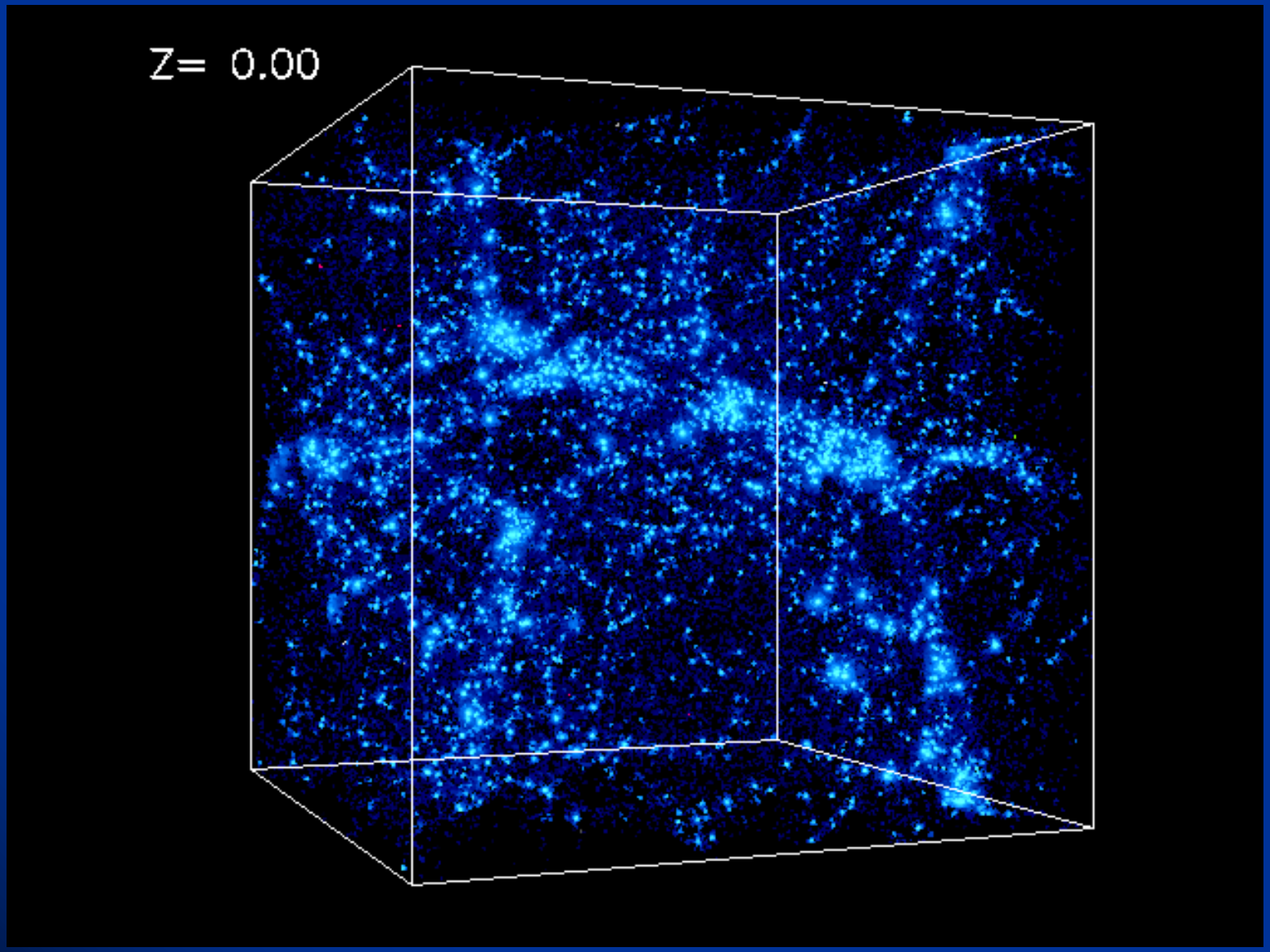

Z= 0.00

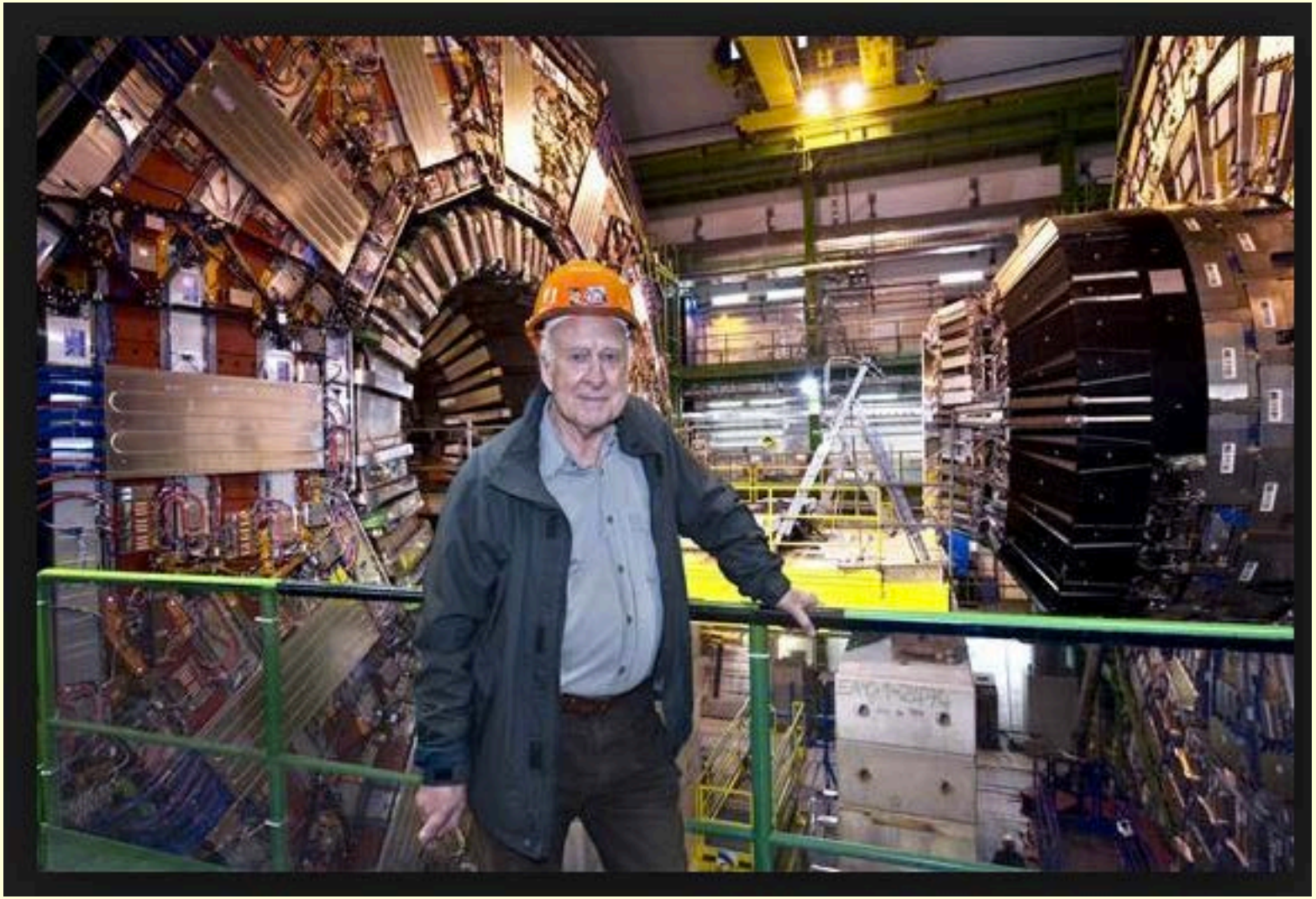
The best bet for the Dark Matter Particle: WIMPs

- Weakly Interacting Massive Particles
- Billions pass through your body every second
- No strong nuclear forces
- No electromagnetic forces
- Yes, they feel gravity
- Of the four fundamental forces, the other possibility is weak interactions (also responsible for radioactivity)
- Weigh 1 to 10,000 times protons

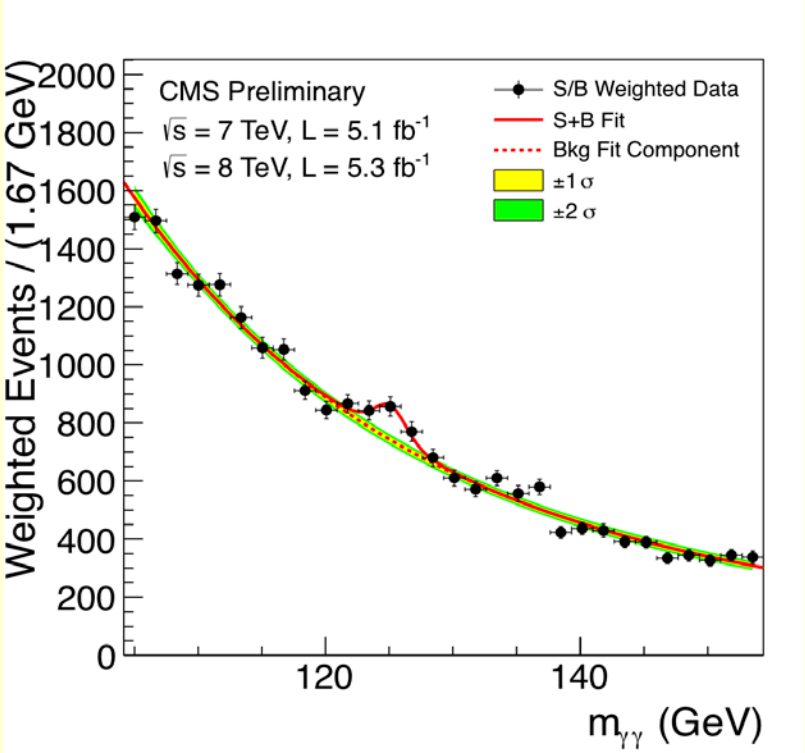
(i) FIRST WAY TO SEARCH FOR WIMPS

Fabiola Gianotti, spokesperson of ATLAS detector
Now Director General of CERN

Peter Higgs and CMS detector

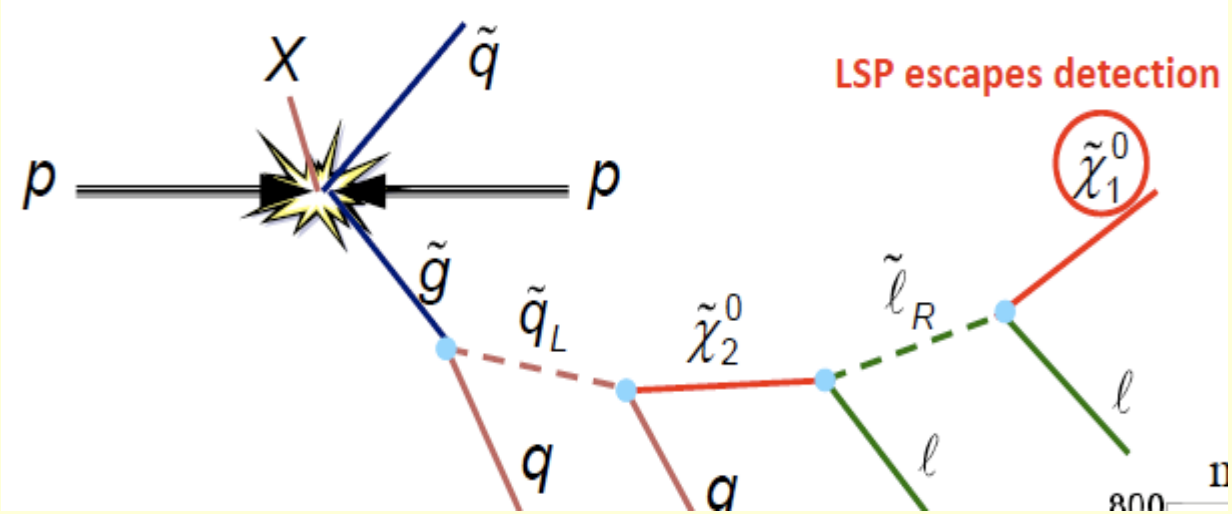


LHC's first success
Discovery of Higgs boson
weighing 125 GeV



Second major goal of LHC: search for SUSY and dark matter

- Two signatures: Missing energy plus jets



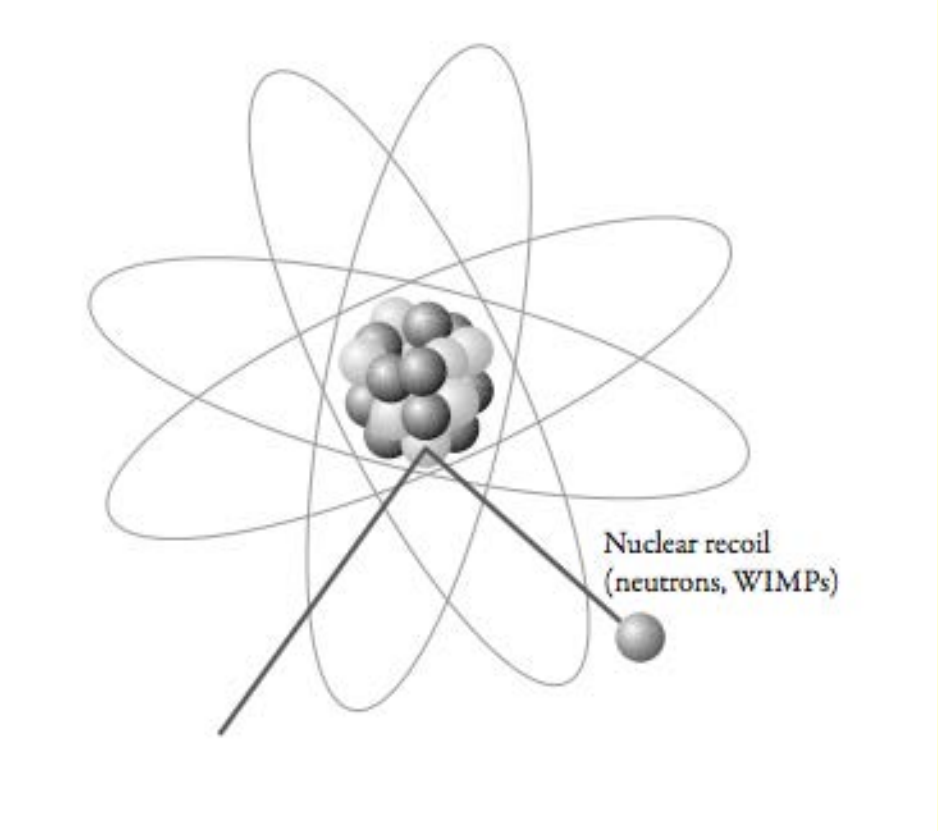
- Nothing seen yet: particle masses pushed to higher masses

(ii) SECOND WAY TO SEARCH FOR WIMPS

DIRECT DETECTION
Laboratory EXPERIMENTS

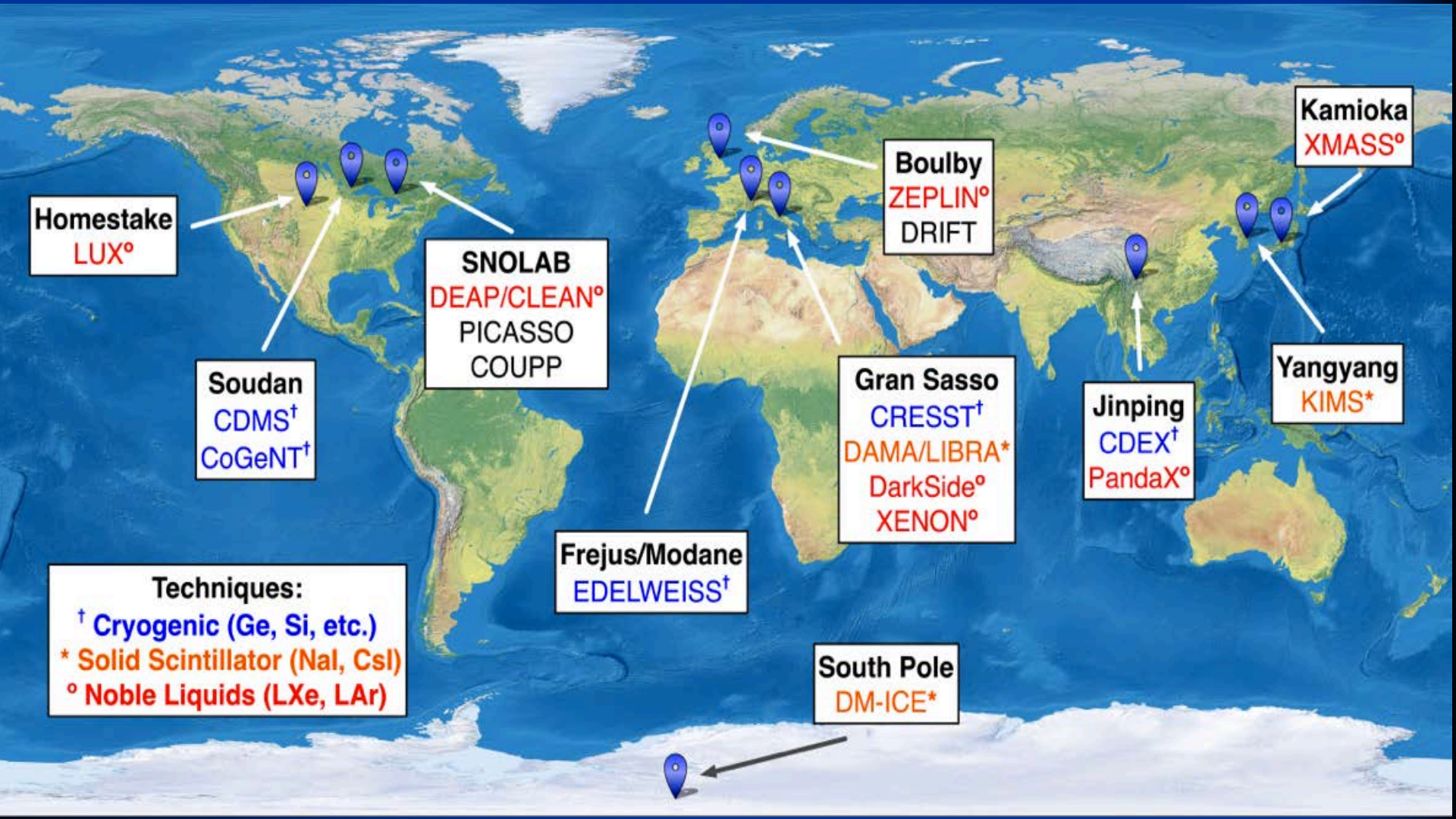
DIRECT DETECTION OF WIMP DARK MATTER

A WIMP in the Galaxy travels through our detectors. It hits a nucleus, and deposits a tiny amount of energy. The nucleus recoils, and we detect this energy deposit.



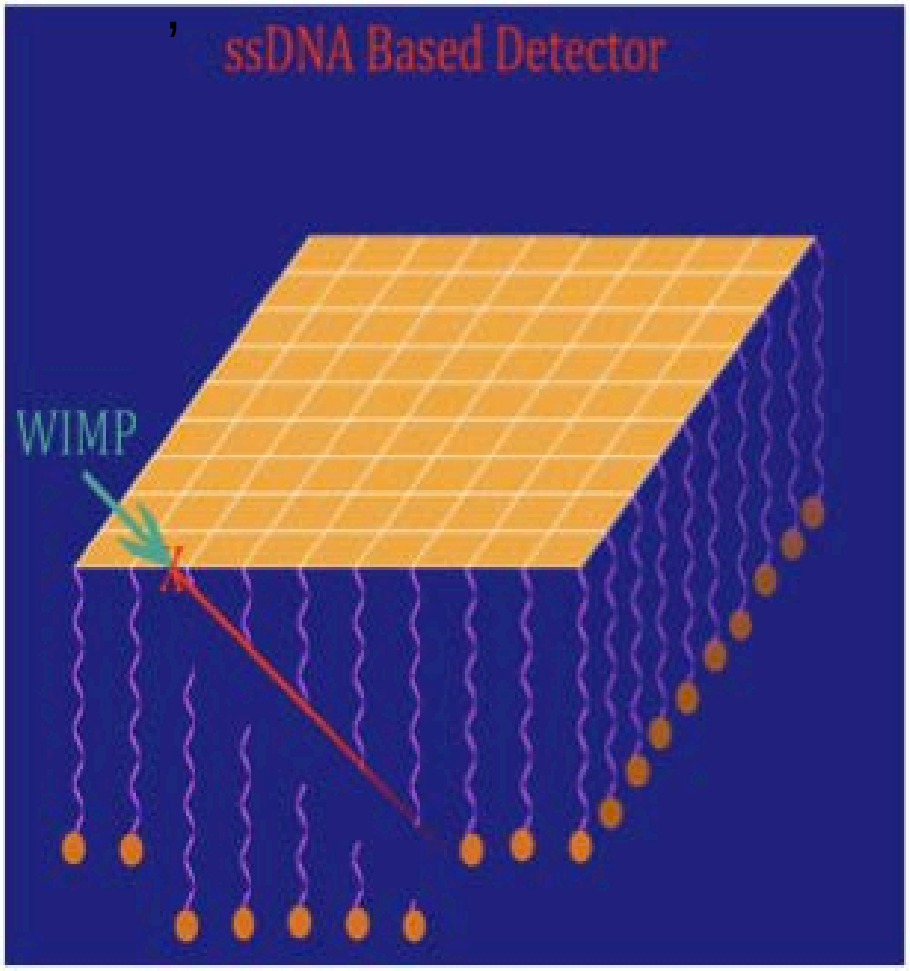
Expected Rate: less than one count/kg/day!

UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DNA Tracker: nanometer resolution!

- 1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known



BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

Drukier, Freese, Spergel, Lopez, Cantor, Church, Sano

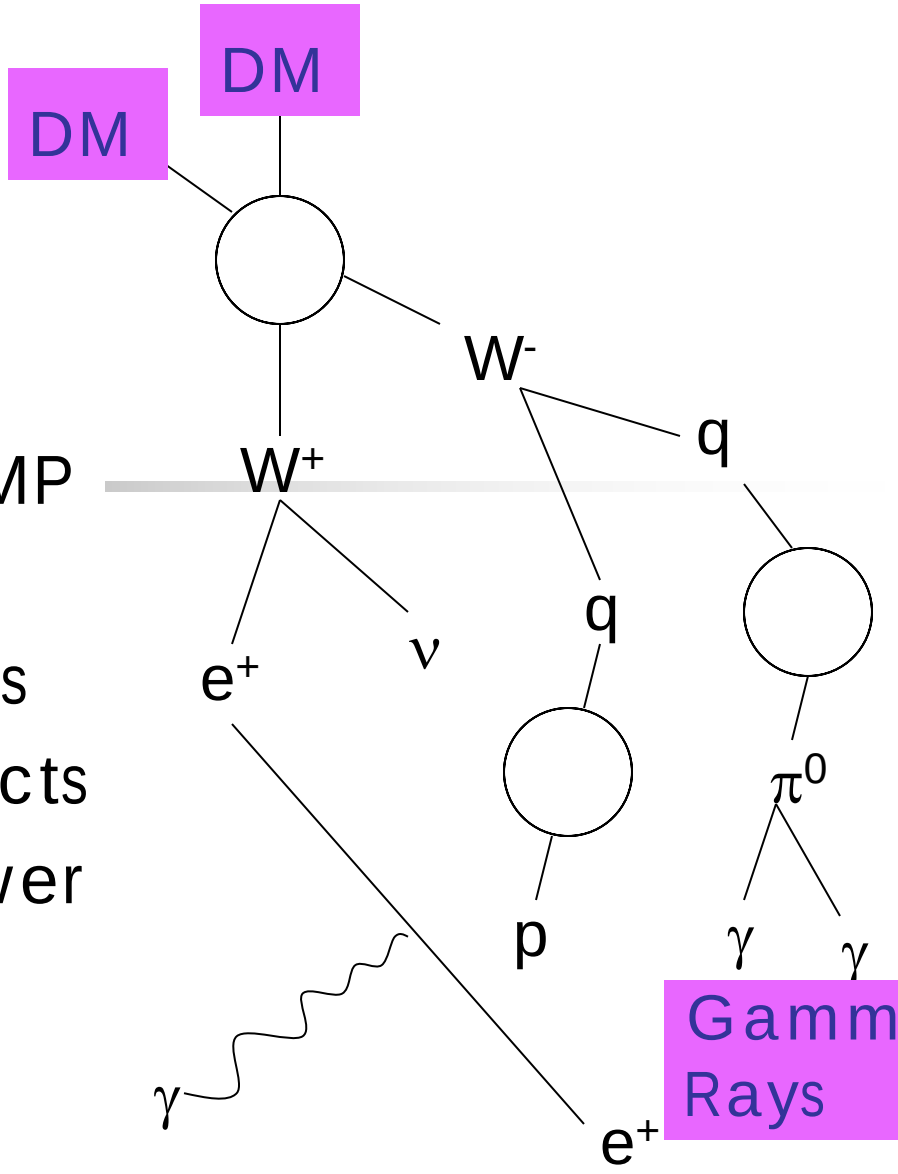
(iii) THIRD WAY TO SEARCH FOR WIMPS

INDIRECT DETECTION: searching for astrophysical WIMP annihilation products

WIMP Annihilation

Many WIMPs are their own antiparticles, annihilate among themselves:

- 1) Early Universe gives WIMP miracle
- 2) Indirect Detection expts look for annihilation products
- 3) Same process can power Stars (dark stars)

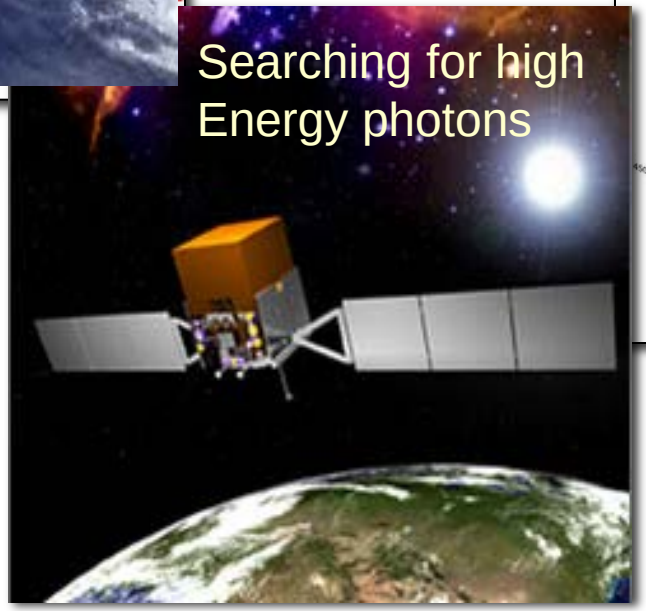


New Indirect Detection Results

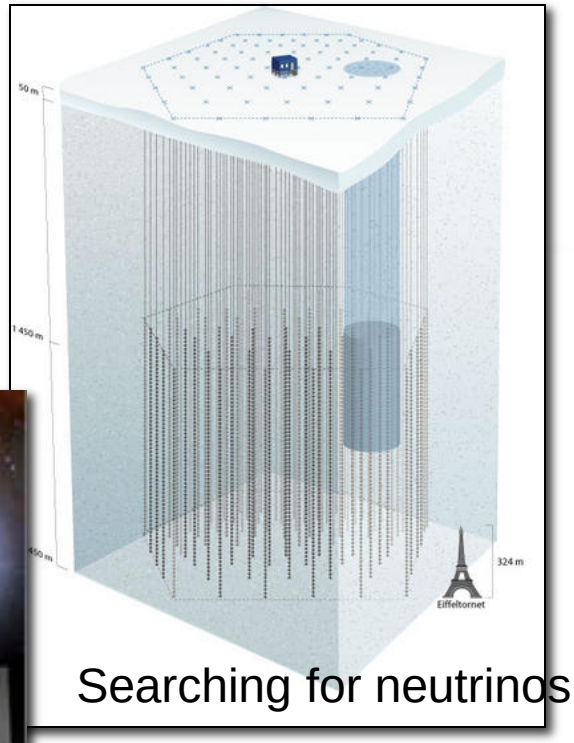
AMS aboard the ISS

Found
excess e+
Is it from WIMPS?
Probably not.

FERMI



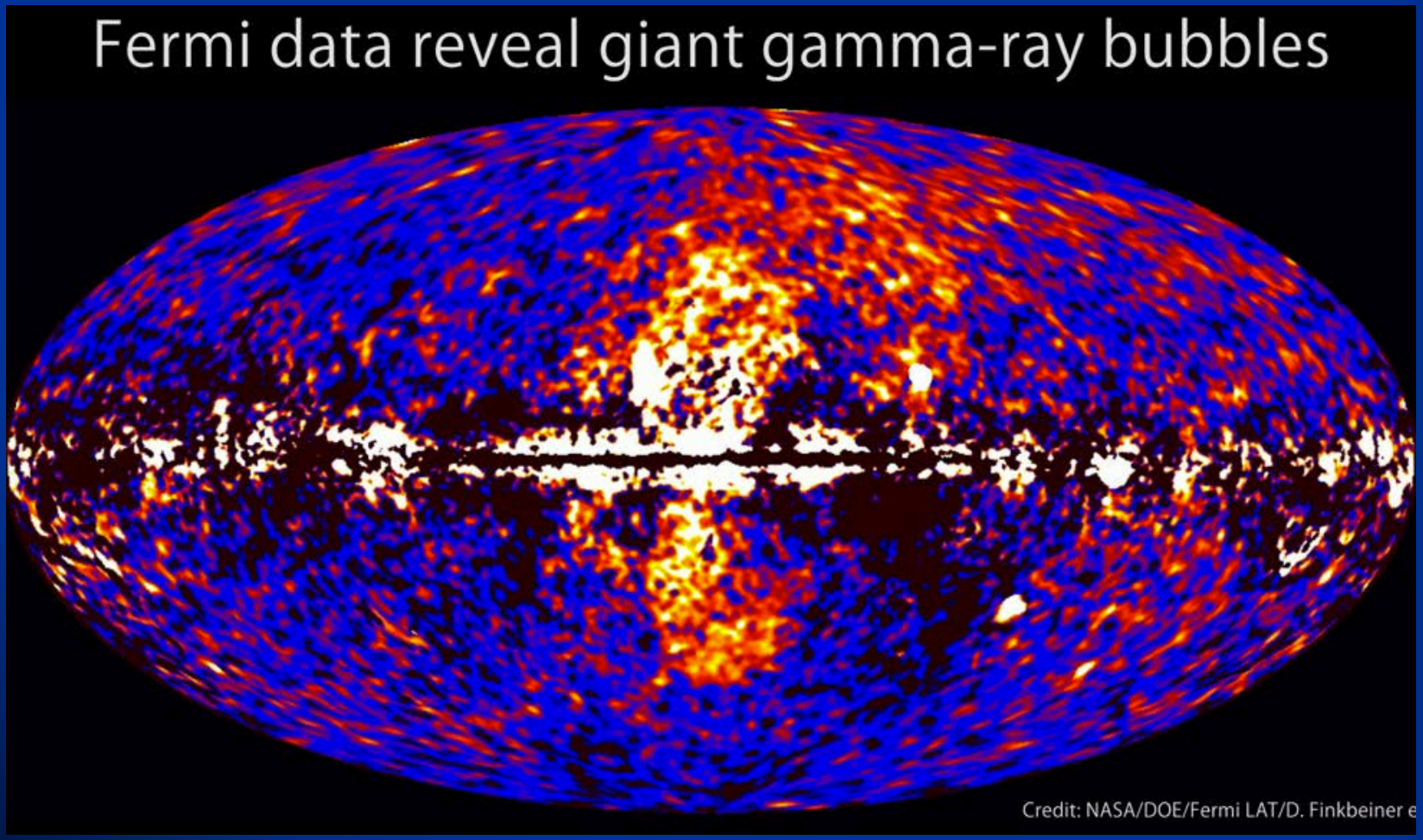
IceCube/DeepCore



Searching for neutrinos

THE FERMI SATELLITE: SEARCHING FOR GAMMA-RAYS, E.G. FROM DM ANNIHILATION

Fermi data reveal giant gamma-ray bubbles



Fermi/LAT gamma-ray excess

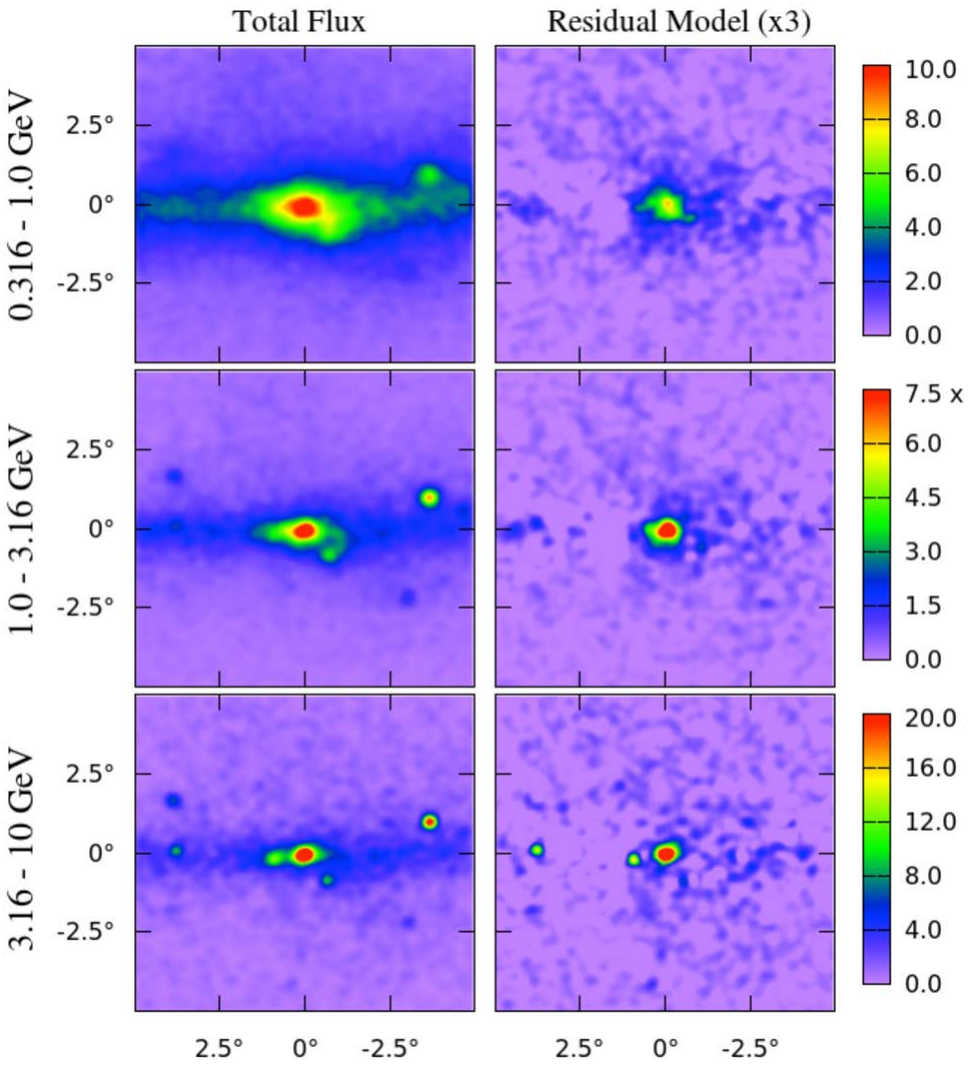
Bergstrom

Goodenough & Hooper (2009)

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer (2014)

Towards galactic center:

- Model and subtract astrophysical sources
- Excess remains
- Spectrum consistent with DM (30 GeV, $\chi\chi \rightarrow$ b-bbar)

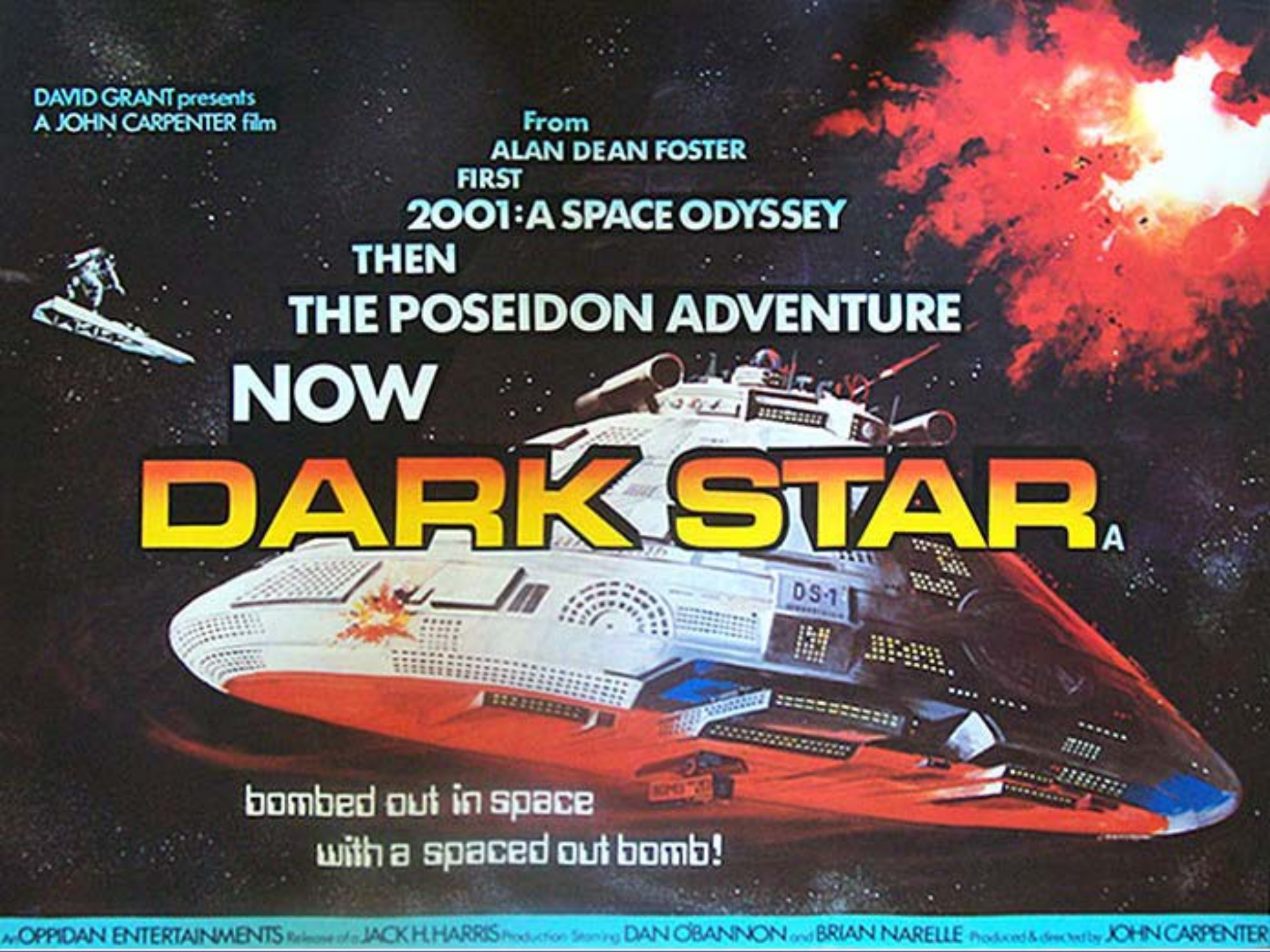


Possible evidence for WIMP detection already now:

- Direct Detection:
  DAMA annual modulation
  (but XENON, LUX)
- Indirect Detection:
  FERMI gamma ray excess near galactic center
- Theorists are looking for models in which some of these results are consistent with one another (given an interpretation in terms of WIMPs)

(iv) FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can power the first stars

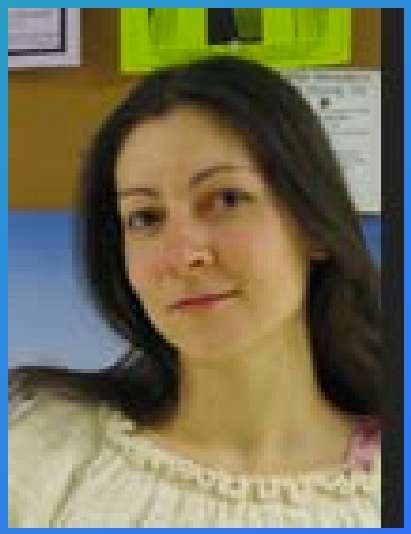

DAVID GRANT presents
A JOHN CARPENTER film
From
ALAN DEAN FOSTER
FIRST
2001: A SPACE ODYSSEY
THEN
THE POSEIDON ADVENTURE
NOW
DARK STAR
A
DS-1
bombed out in space
with a spaced out bomb!
An OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN O'BANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

Collaborators

Doug Spolyar

Paolo Gondolo

Pearl Sandick



Tanja Rindler-Daller

Peter Bodenheimer

Dark Stars

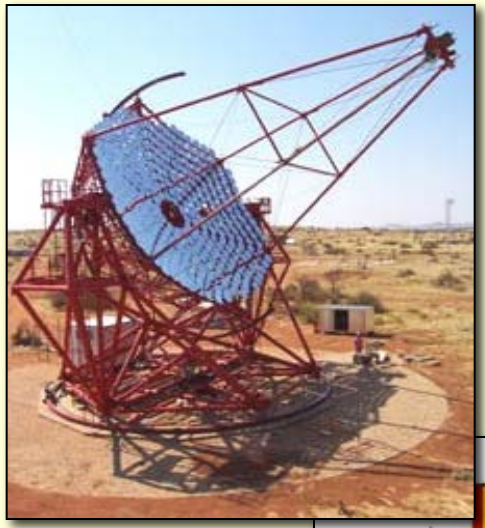
The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion (even though the dark matter constitutes less than 0.1% of the mass of the star).

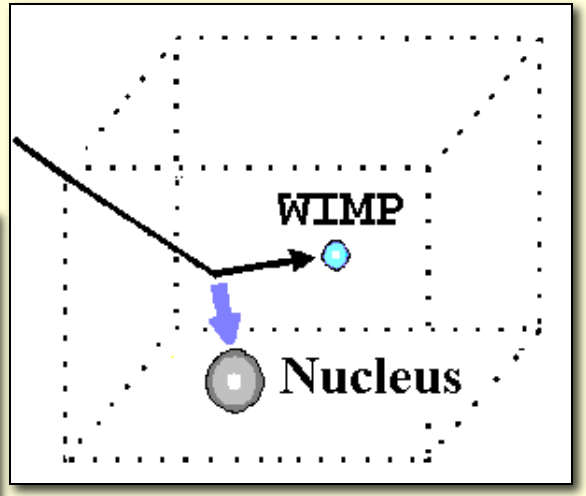
- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: thousands to millions of solar masses. Supermassive DS are very bright (millions to hundred billion solar luminosities) and can be seen in JWST or even HST
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: is this the origin of supermassive black holes?

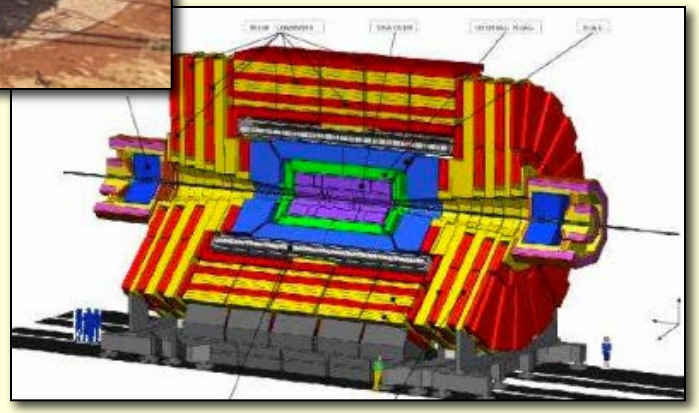
WIMP Hunting: Good chance of detection this decade

- **Direct Detection**
- **Indirect Detection**
- **Collider Searches**

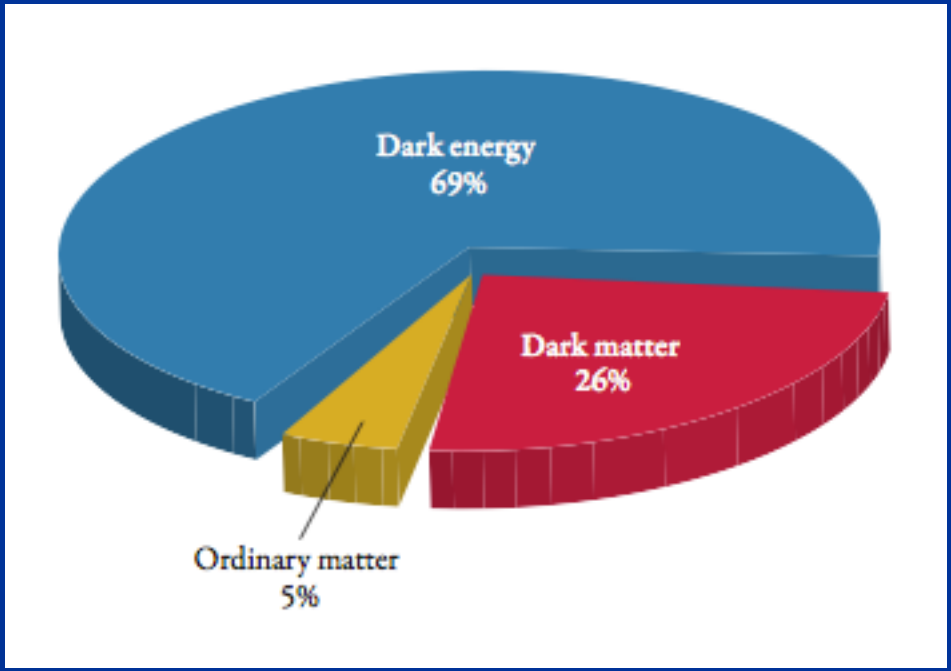
Looking for Dark Stars







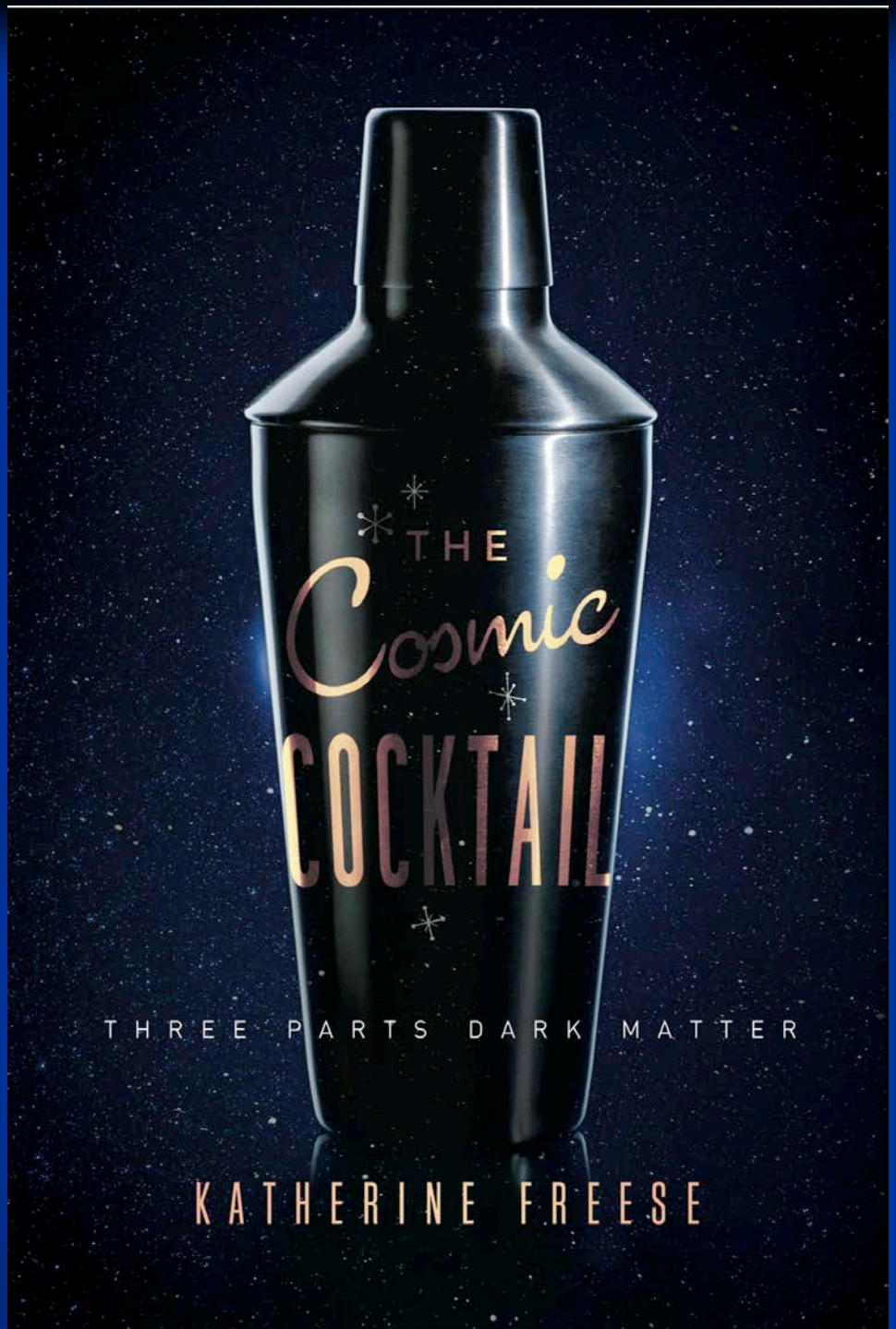
PIE CHART OF THE UNIVERSE



The panel on “The Dark Side of the Universe” at the World Science Festival in NY in June 2011

The three women representing Dark Matter are, from the right, Katherine Freese, Elena Aprile, and Glennys Farrar. Continuing to the left are three men representing Dark Energy: Michael Turner, Saul Perlmutter and Brian Greene (co-host of the Festival).

“Dark matter is attractive, while dark energy is repulsive!”


THE
Cosmic
COCKTAIL
THREE PARTS DARK MATTER
KATHERINE FREESE