The Mystery of Dark Matter

Katherine Freese

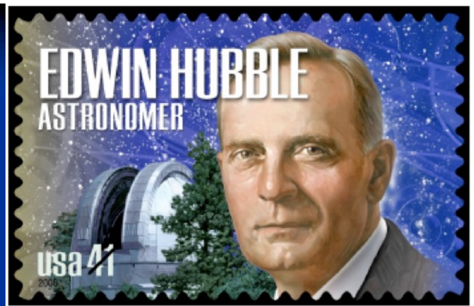
- Director, Weinberg Institute for Theoretical Physics, Jeff & Gail Kodosky Chair,
- Prof of Physics, University of Texas, Austin
- Guest Professor, Stockholm University

- Director Emerita, Nordita (Nordic Institute for Theoretical Physics, in Stockholm)

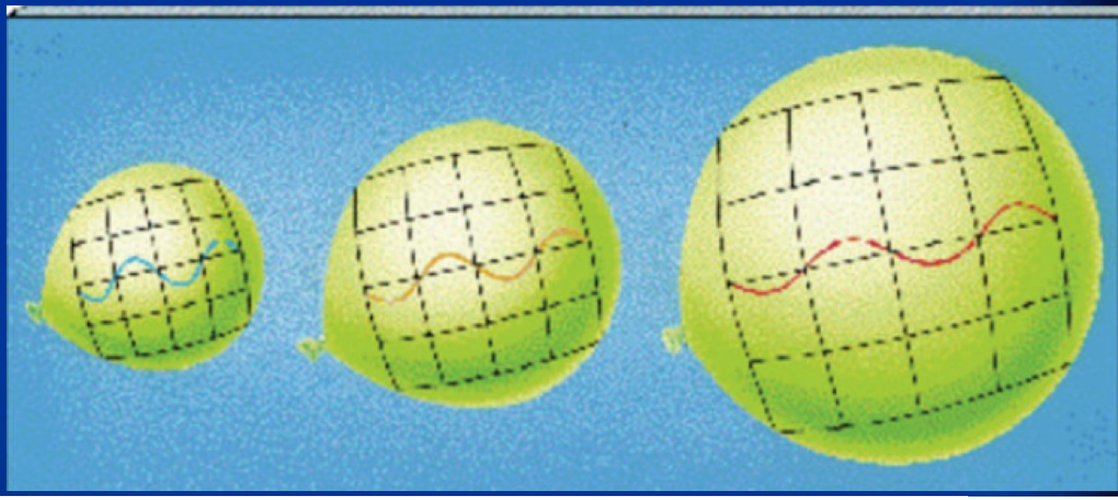
Origins of Modern Cosmology

- 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.

Hubble Expansion in 1929

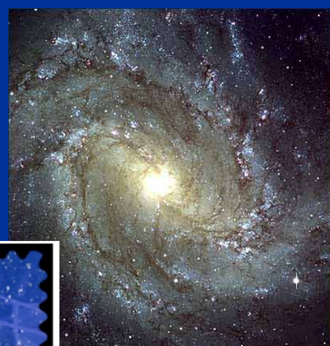


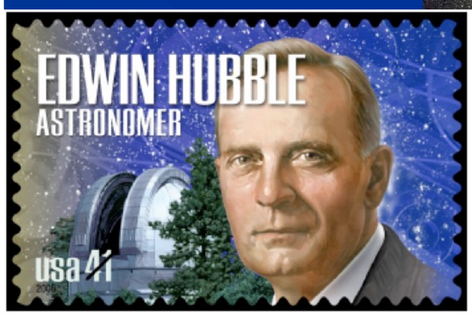
- Edwin Hubble using the Mt. Wilson Observatory above Pasadena made astronishing discoveries.
- He proved that other galaxies exist beyond our own.
- He observed light from galaxies at various distances away from Earth. The light waves are stretched, or redshifted, by the time they gets to us. The reason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

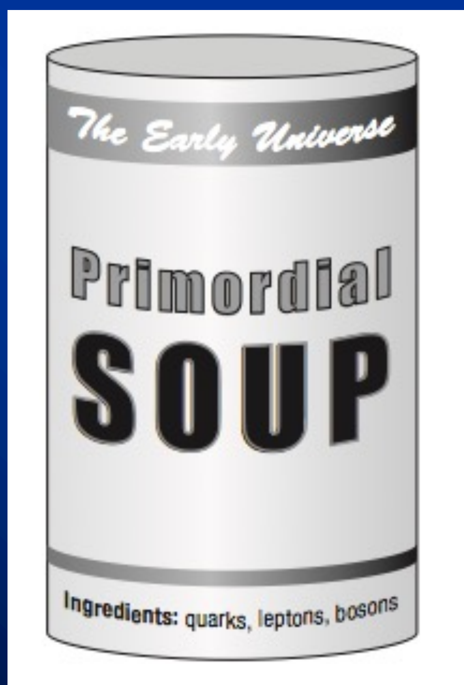


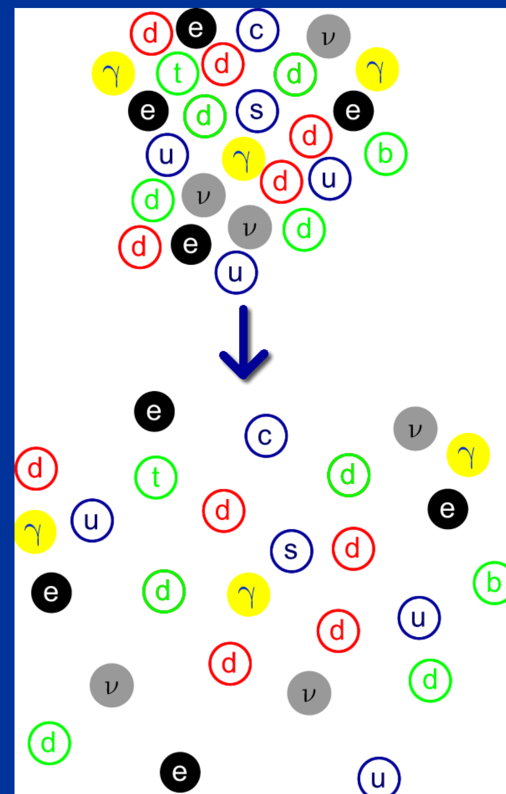


(1929)

THE BIG BANG

14 BILLION
YEARS AGO

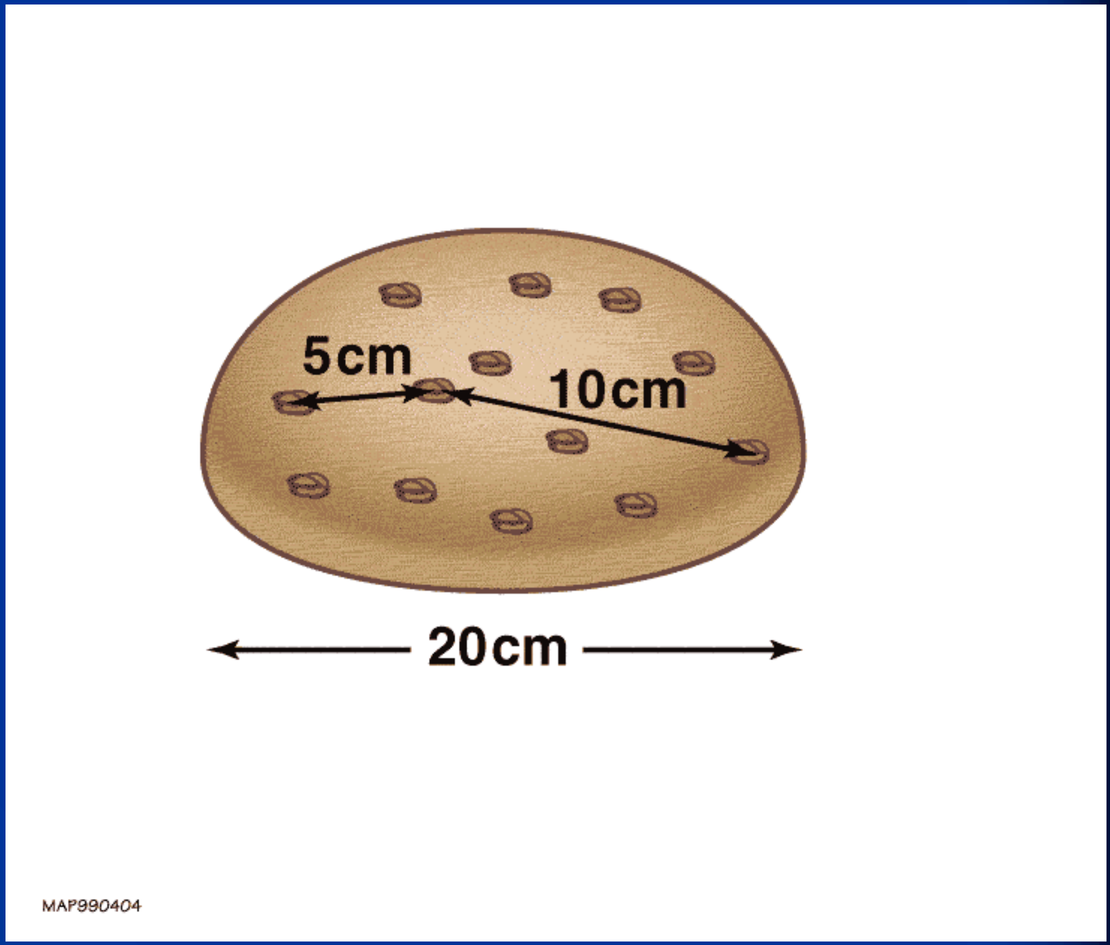




The Universe started out hot;
It is cooling and expanding.

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.

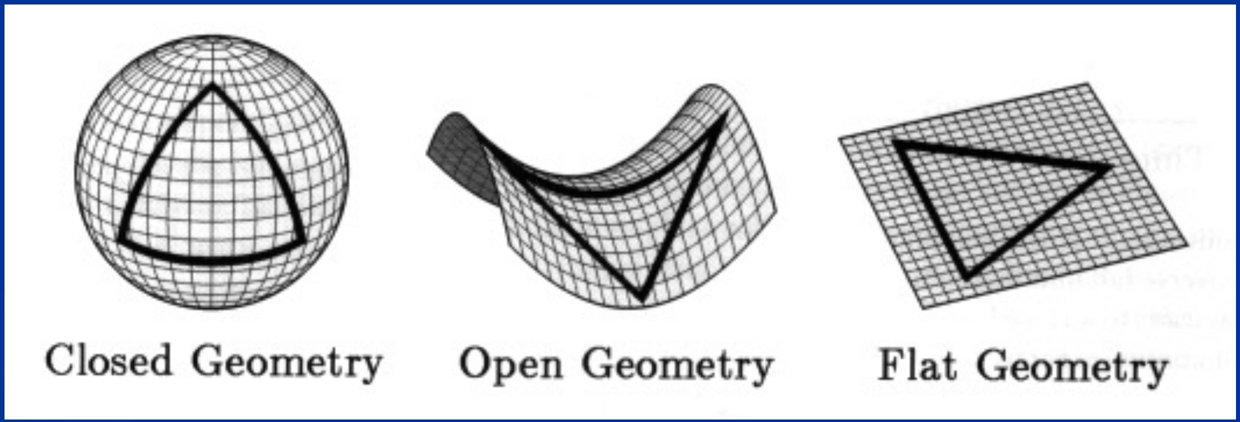
Big Bang happens everywhere at once (not at a single point)

Where do we stand in Cosmology?

- Big questions answered at the turn of the millenium:
- What is the geometry of the Universe?
- What is the total mass/energy content of the Universe?
- How old is the Universe?
- Primordial density perturbations lead to growth of structure

- BUT other big questions remain:
- How did the Universe begin?
- What is the Universe made of? Dark matter, dark energy.

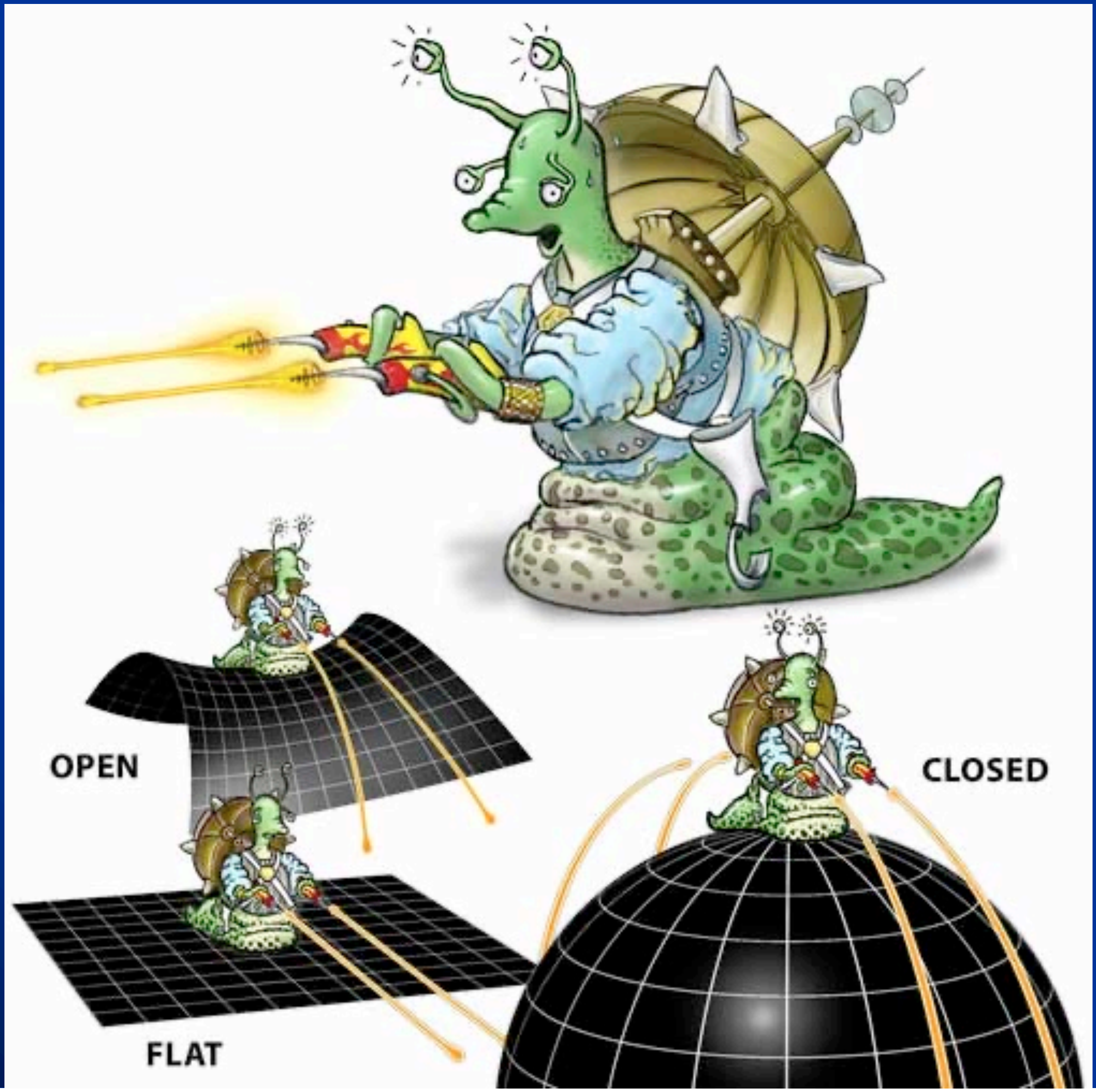
Geometry of the Universe



1930: Three possible geometries for the universe

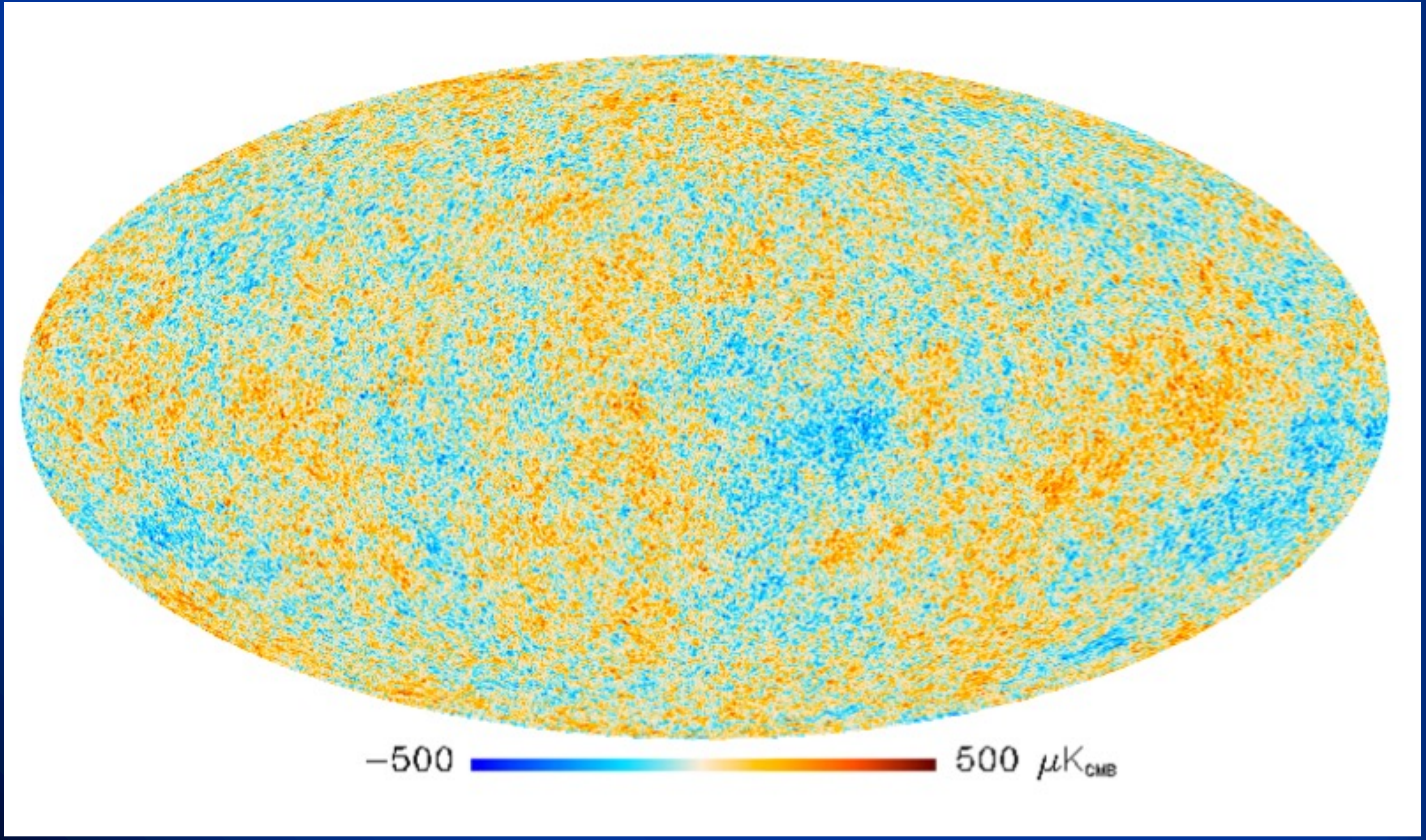
2000: The geometry of the universe is FLAT!!!!!!

Geometry of the Universe



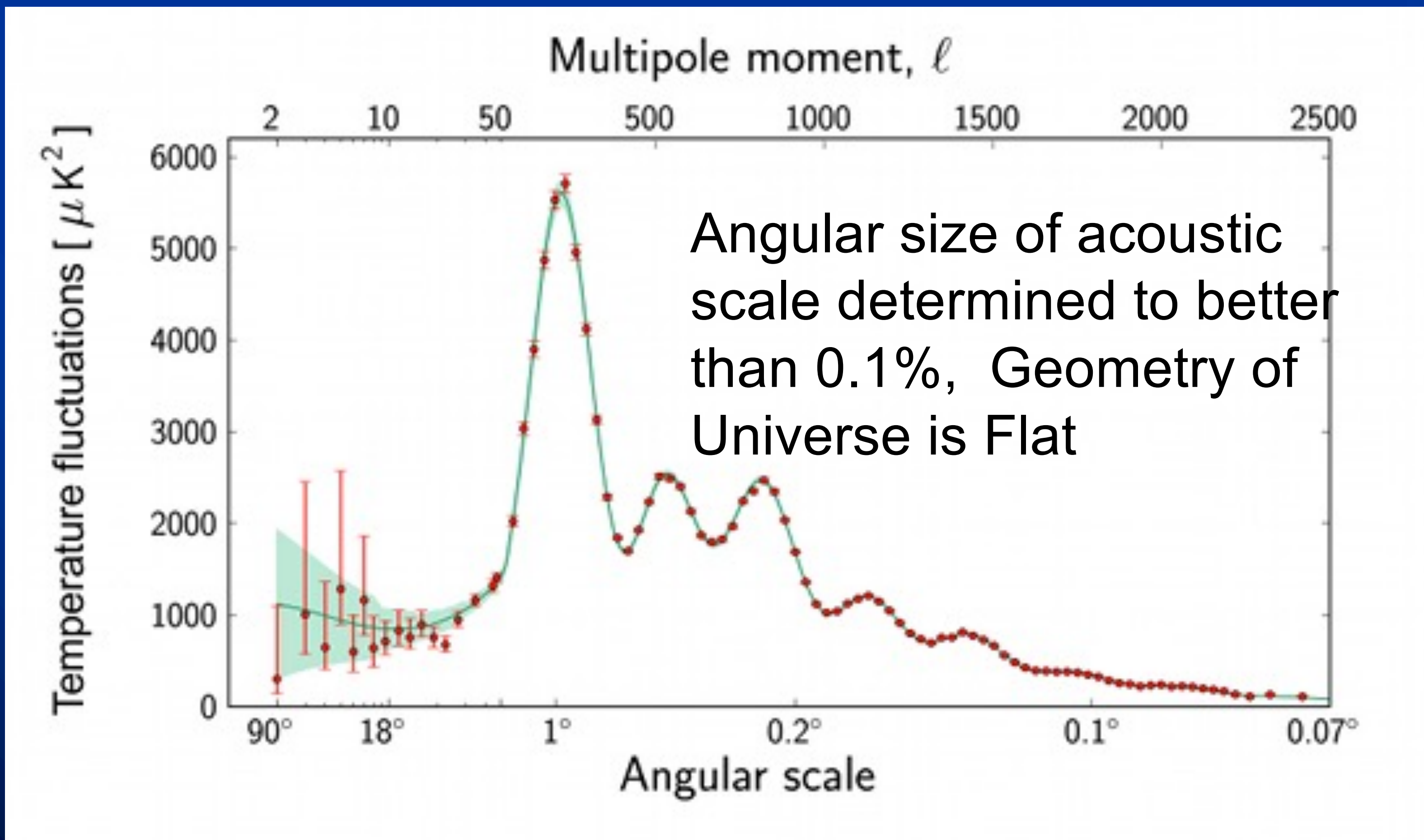
The Universe according to ESA's Planck Space Telescope:

the Cosmic Microwave Background (light leftover from the hot early epoch of the universe)



Planck Data

If light moves in straight lines, then we expect a peak at 1 degree



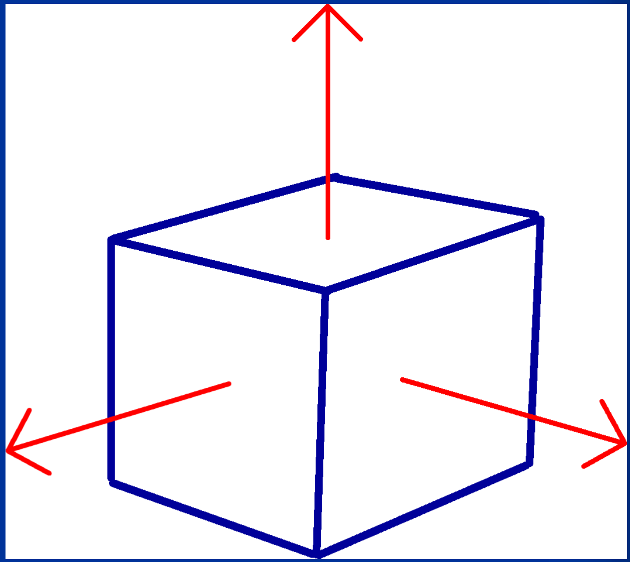
2000: The geometry of the universe is FLAT!

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.



General Relativity: Einstein’s Field Equations (1915)

Curvature of space

Distribution of mass/energy

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Some constants

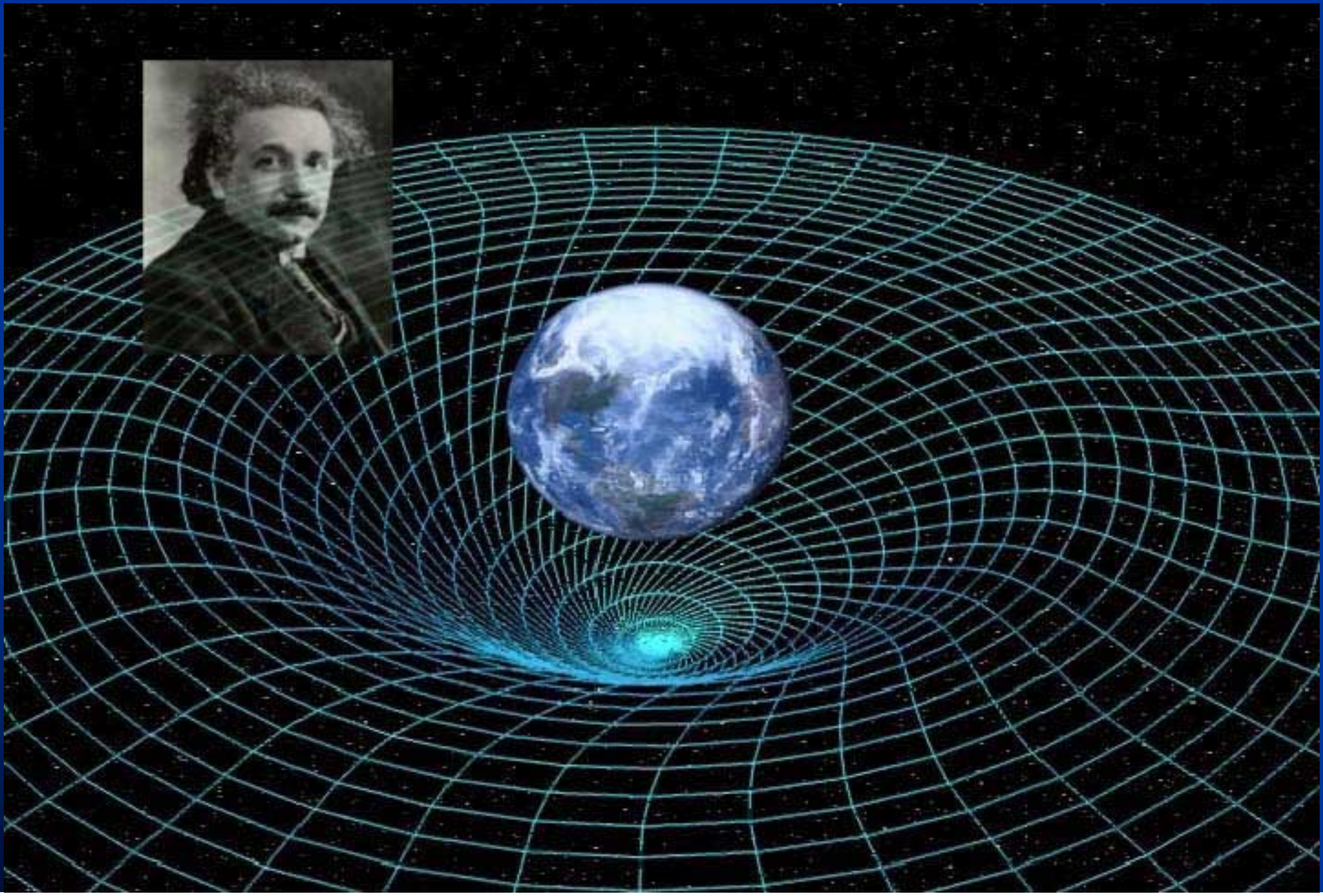
Relates geometry (left hand side of equation)

to

matter/energy content (right hand side of equation)

Geometry is Determined by Matter Content

Warping of Spacetime:



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

- The energy density of the universe is

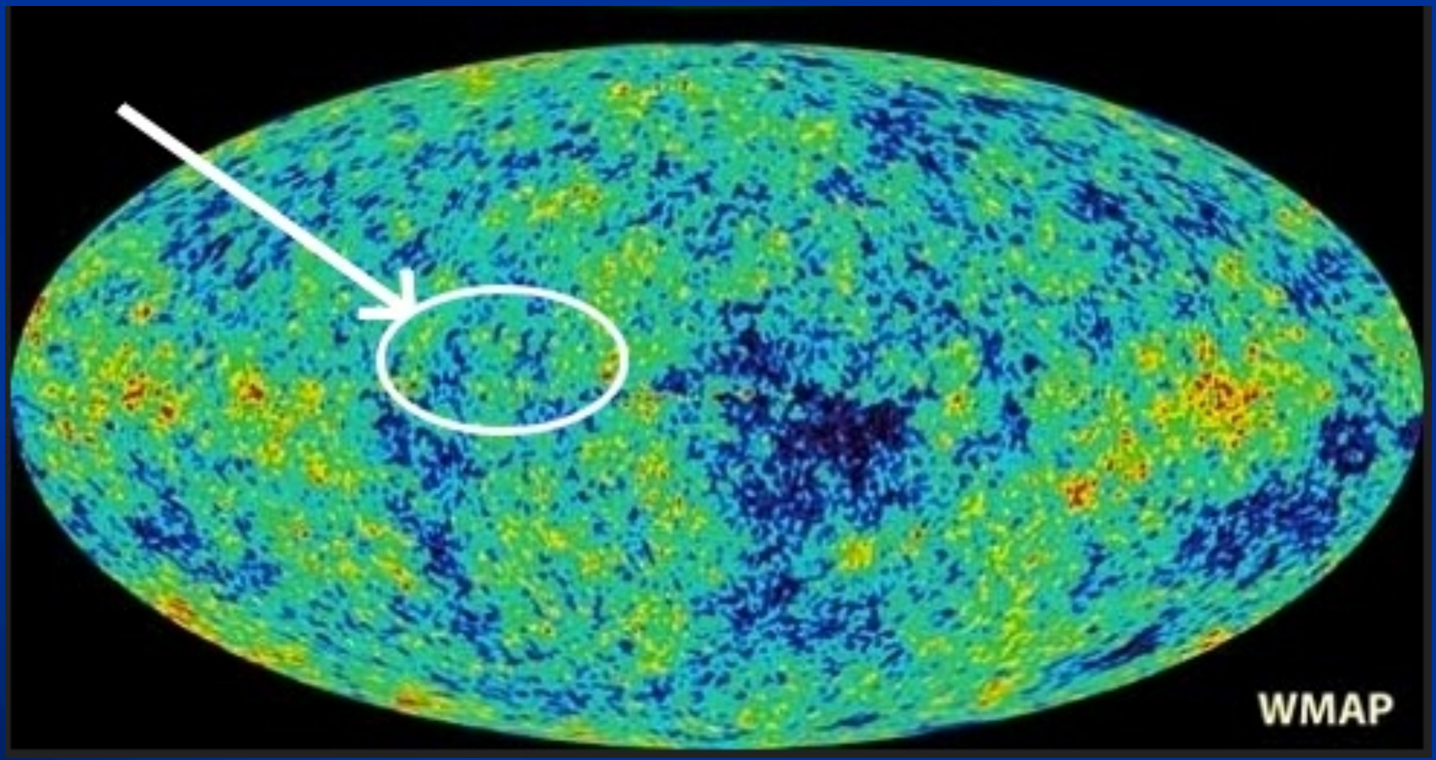
$$\rho = \rho_c = 10^{-29} \text{ gm/cm}^3$$

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

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

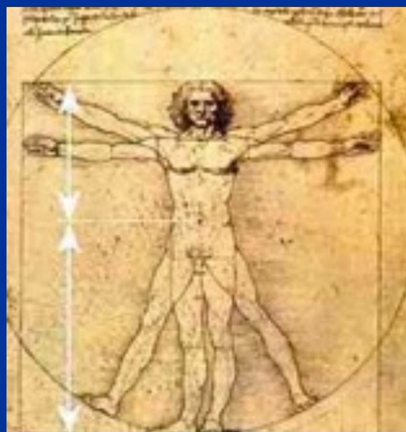
- BIG QUESTION: WHAT IS IT?

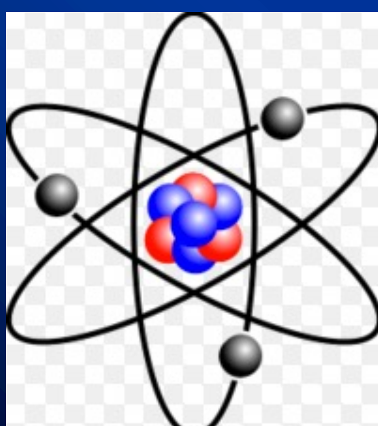
SH initials in WMAP satellite data

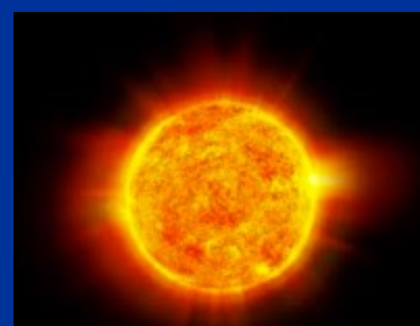


What is the Universe made of?
The answer is very SURPRISING!

All the objects of our daily experience:

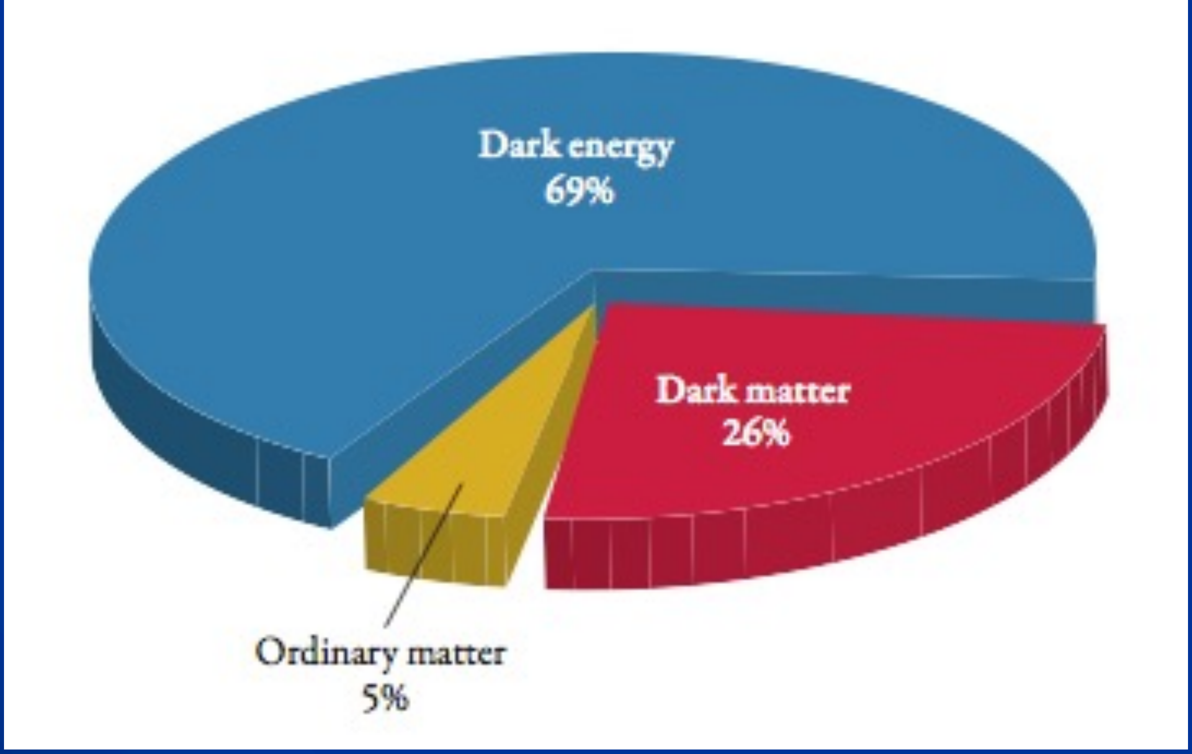





ALL ADD UP TO ONLY 5% OF THE UNIVERSE!

PIE PICTURE OF THE UNIVERSE



Less than 5% ordinary matter.

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

The Cosmic Cocktail Recipe

3 oz. dark matter
7 oz. dark energy
1/2 oz. hydrogen and helium gas
3 thousandths oz. other chemical elements
5 hundredths oz. stars
5 hundredths oz. neutrinos
5 ten-thousandths oz. cosmic microwave background light
1 millionth oz. supermassive black holes

Shaken, not stirred.
Secret ingredient: dark matter

The Dark Matter Problem is 90 years old: Dates back to Knut Lundmark in 1930 and Fritz Zwicky in 1933

Knut Lundmark

Knut Lundmark as student in 1908

Galaxies in the Coma cluster were moving too rapidly.

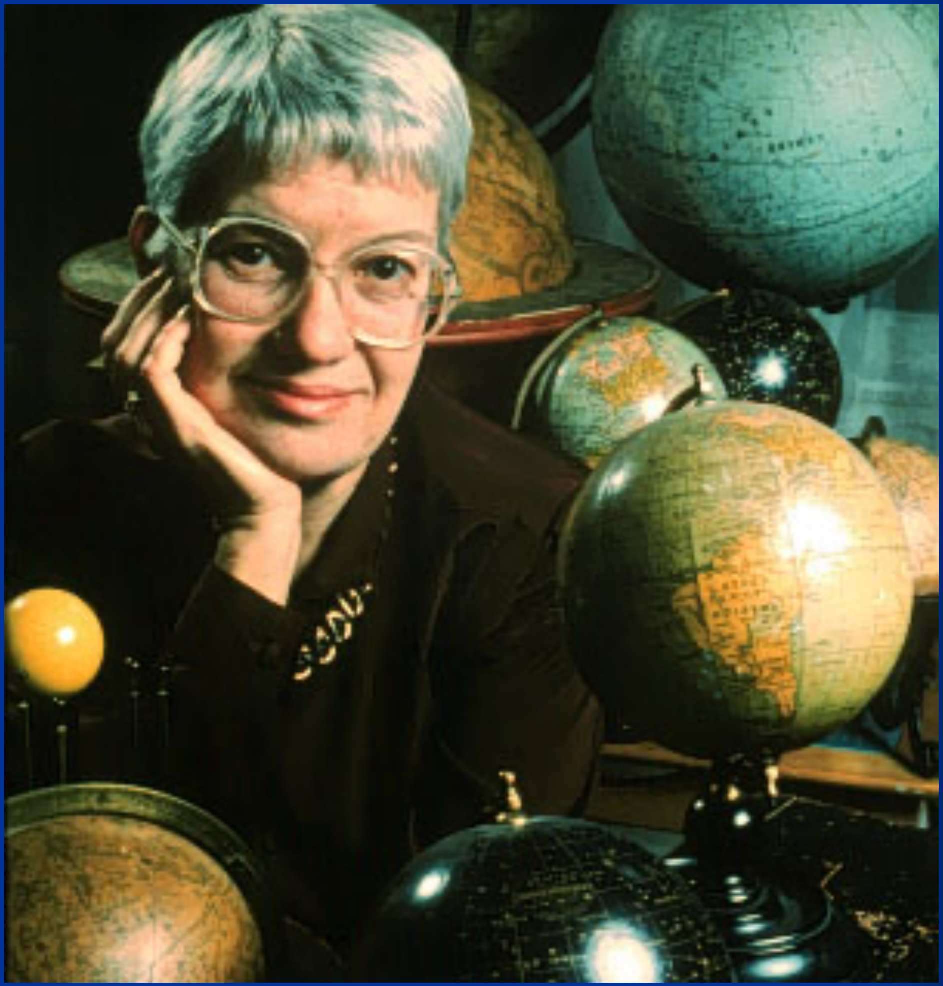
Proposed Dunkle Materie as the explanation.

It’s not stars, it doesn’t shine.
It’s DARK.

Vera Rubin and Kent Ford in 1970s

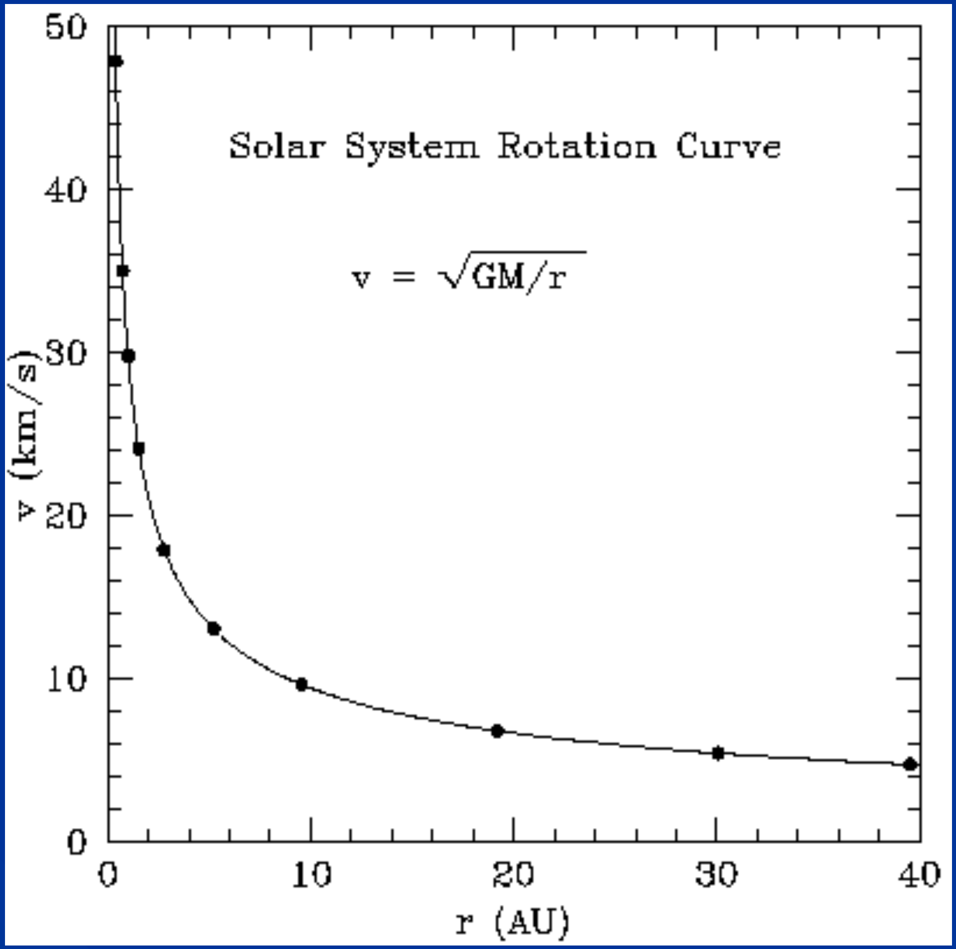
Studied rotation curves of galaxies, and found that they are all FLAT.

This work led to scientific consensus that the DM problem is ubiquitous.



Analogy: Solar System Rotation Curve

Average Speeds
of the Planets



As you move out from the Sun, speeds of the planets drop.

If Sun were more massive, planets would move faster

SHOWS THE IDEA (This slide has nothing to do with proving DARK MATTER exists)

Tyco Brahe (1546-1601)

Lost his nose in a duel, and wore a gold and silver replacement.

Studied planetary orbits.

Died of a burst bladder at a dinner with the king.

Now let's get back to Dark Matter:

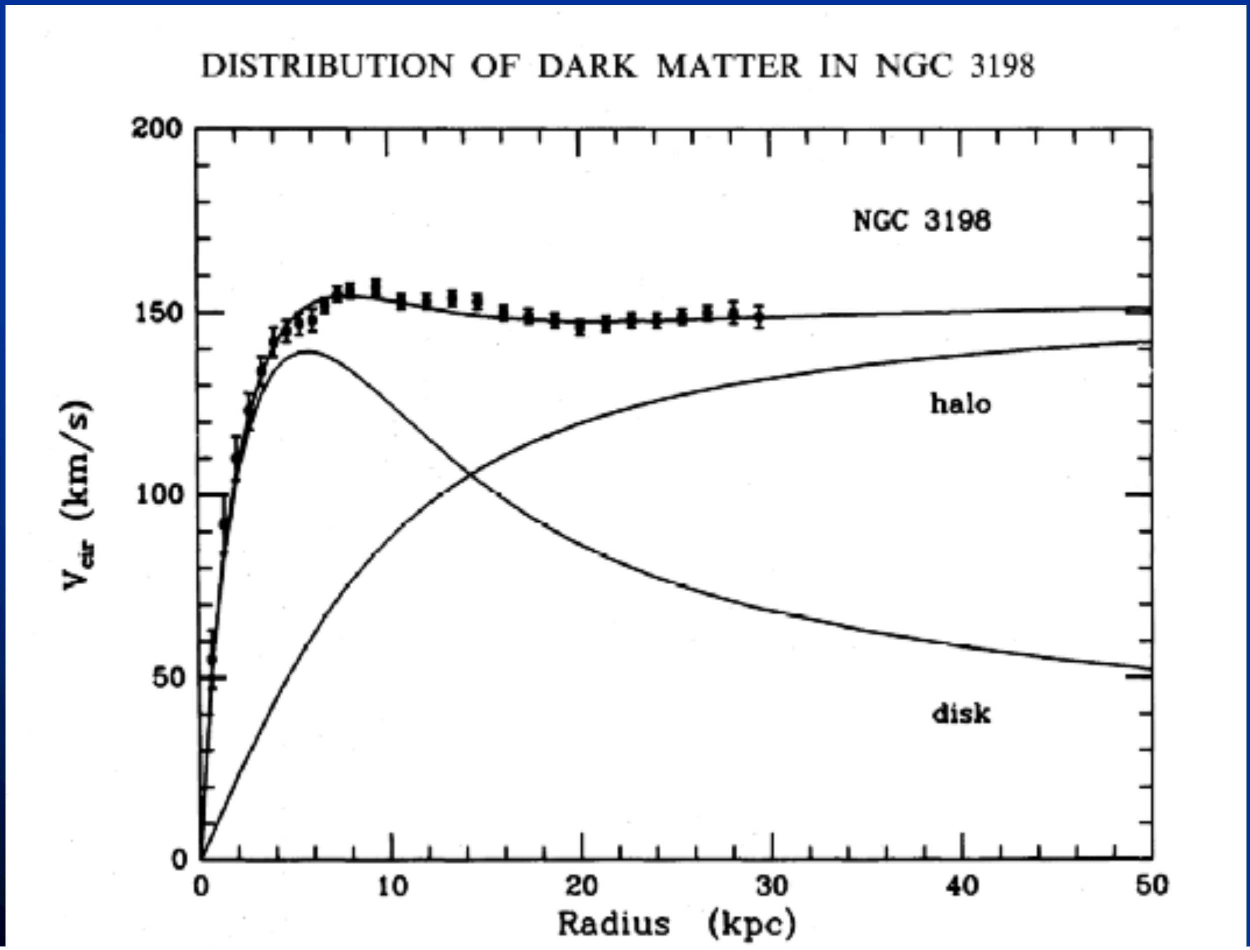
Rotation Curves of Galaxies

Orbit of a star in a Galaxy: speed is Determined by Mass. Larger mass causes faster orbits.

$$\frac{GM(r)m}{r^2} = \frac{mv^2}{r}$$

95% of the matter in galaxies is unknown dark matter

- Rotation Curves of Galaxies:



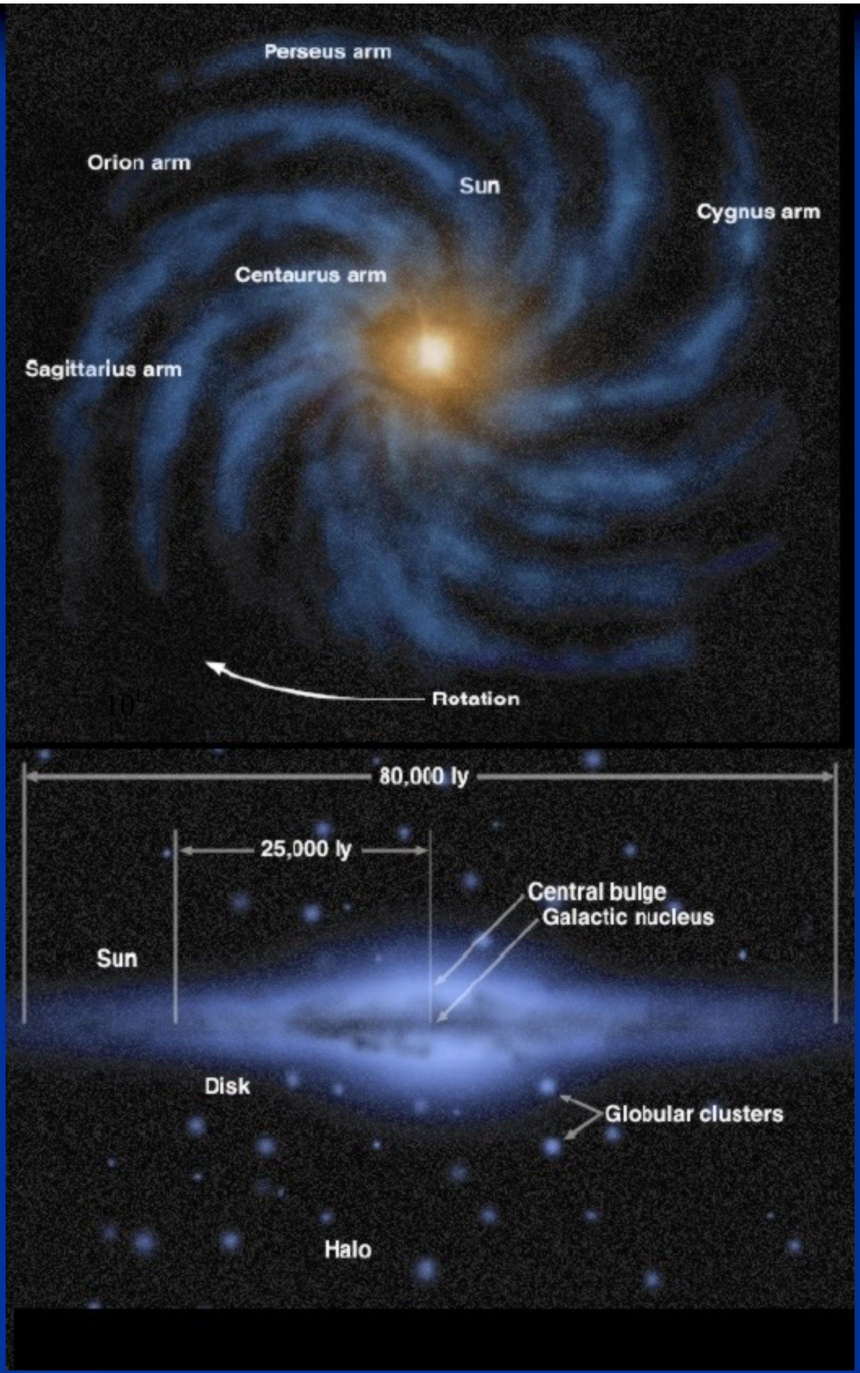
OBSERVED:
FLAT ROTATION
CURVE

EXPECTED
FROM STARS

Our Galaxy: The Milky Way

The mass of the galaxy:

10^{12} solar masses

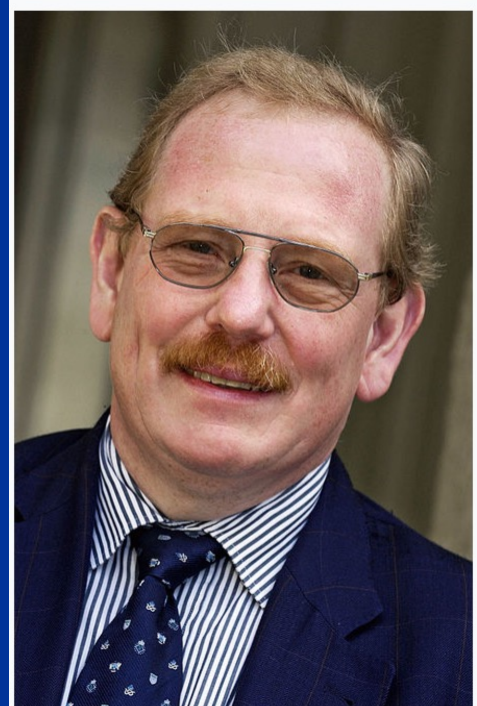


2020 Nobel Prize in Physics

(half) for the discovery of the supermassive black hole at the center of our Milky Way Galaxy

Andrea M. Ghez

Reinhard Genzel



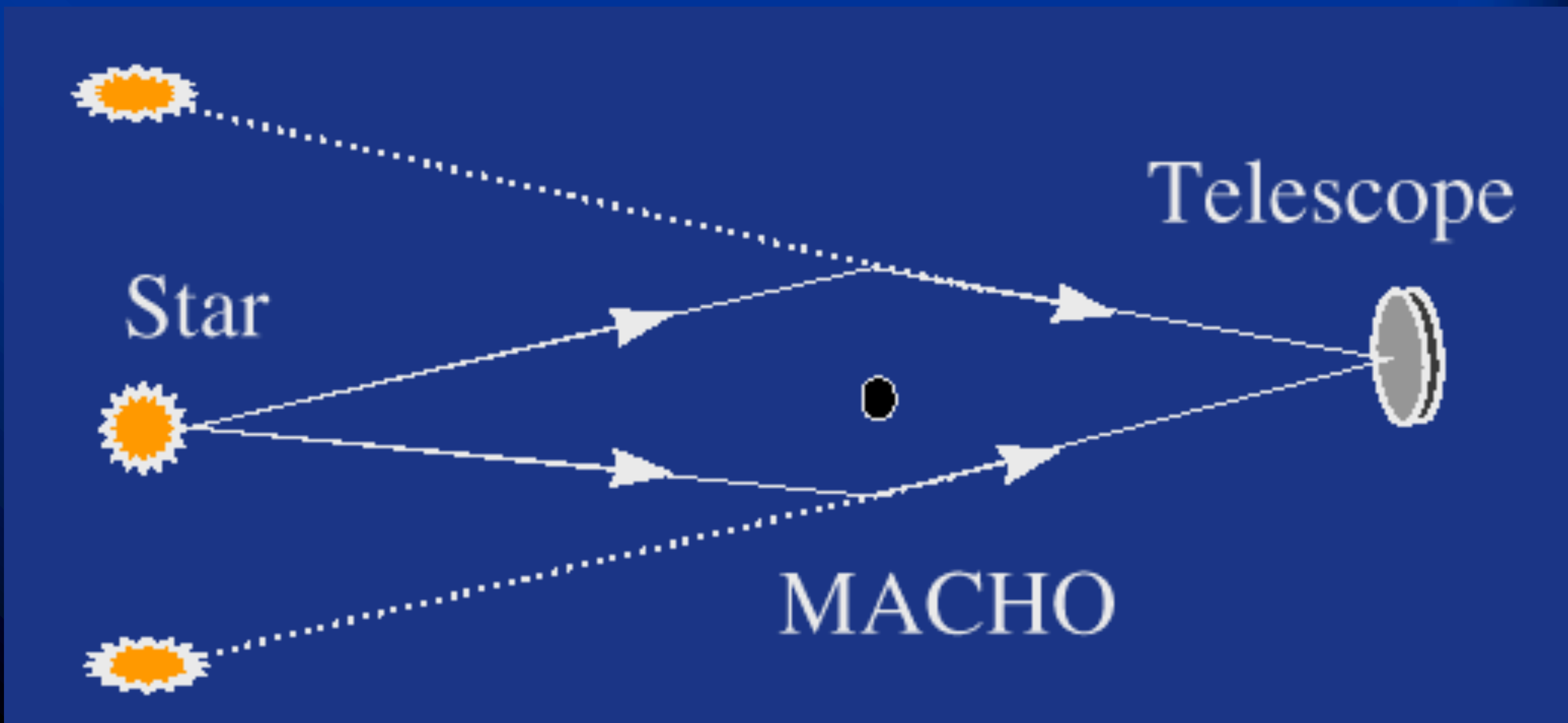
The BH weighs 4 million Suns

SUPERMASSIVE BLACK HOLES are NOT the DARK MATTER

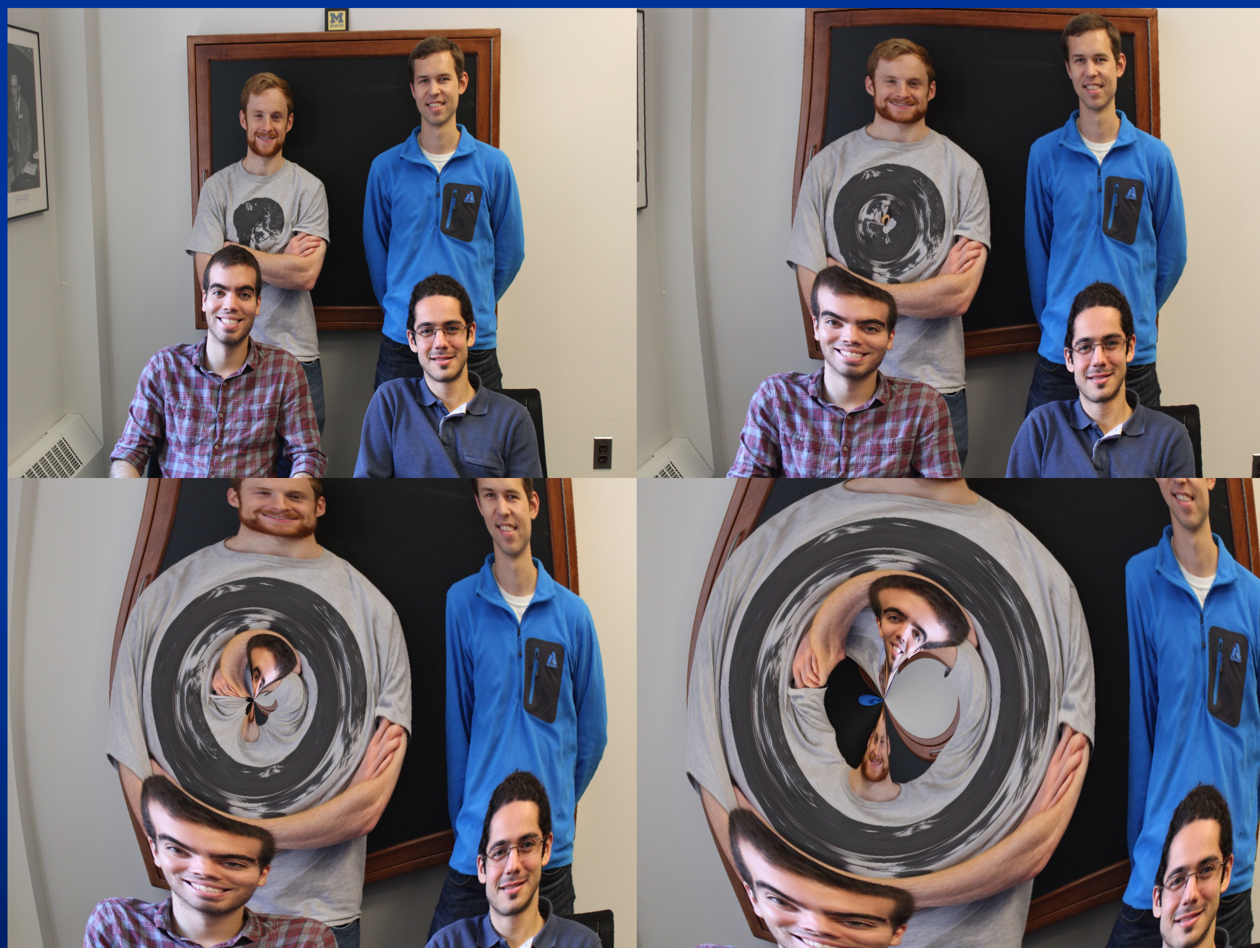
Every galaxy has one at the center, but they make up only a tiny fraction of the Universe as a whole

Galaxies have Dark Matter Haloes

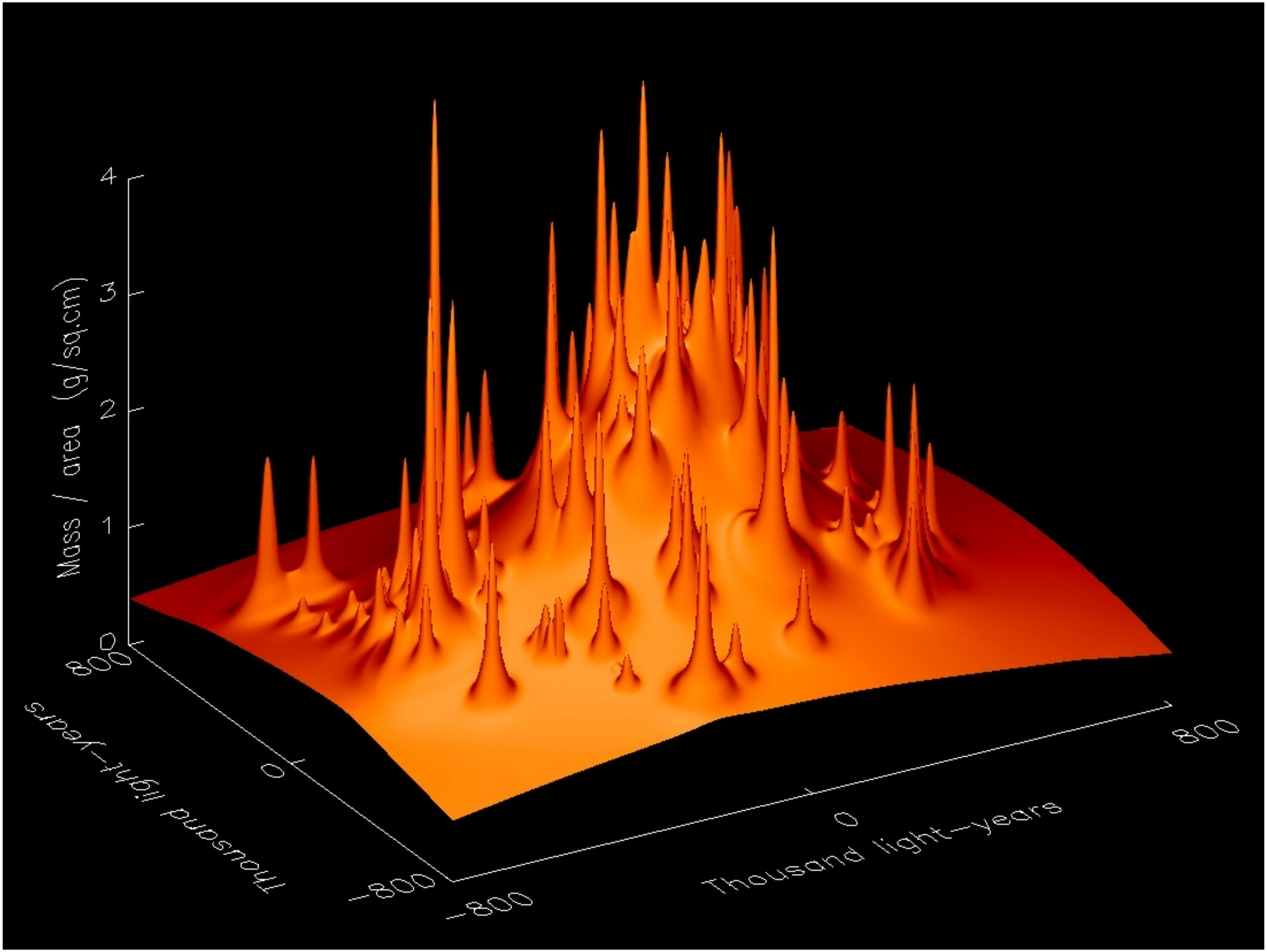
Einstein's Lensing: Another way to detect dark matter: it makes light bend



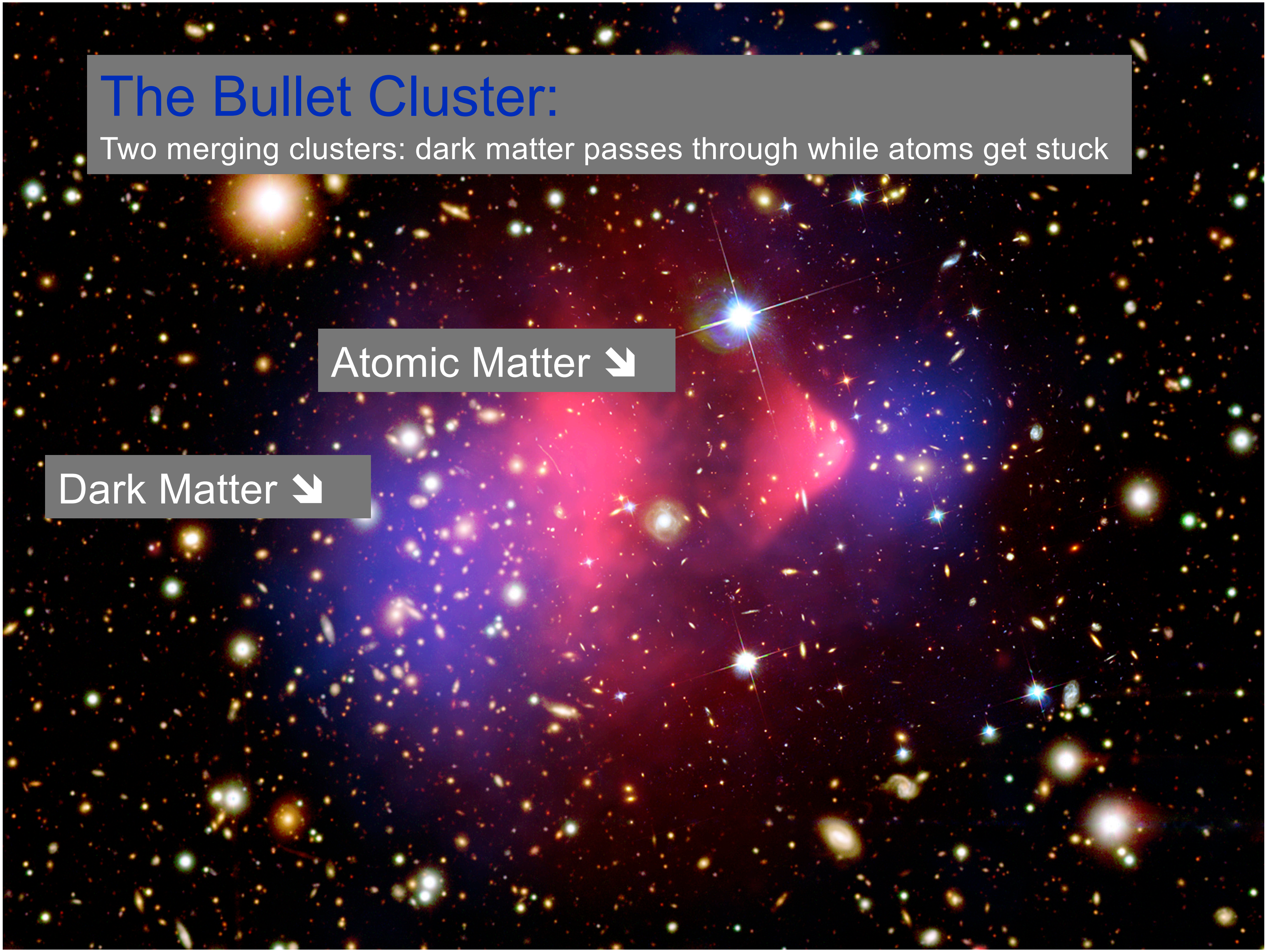
Lensing of students



Strong lensing by dark matter



Mass / area (g/sq.cm)
0
1
2
3
4
800
0
−800
Thousand light−years
−800
0
800
Thousand light−years

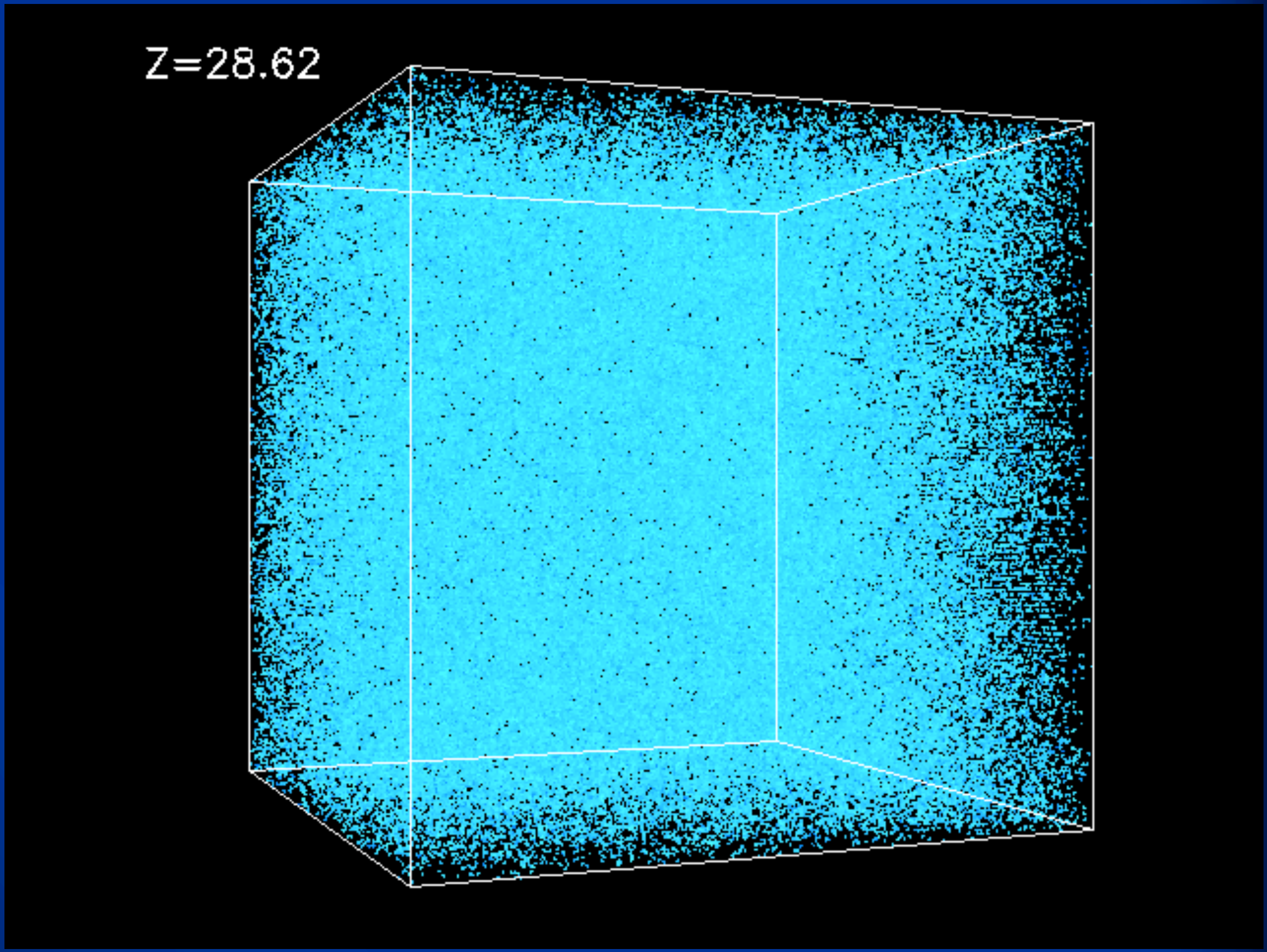

The Bullet Cluster:
Two merging clusters: dark matter passes through while atoms get stuck
Atomic Matter ➘
Dark Matter ➘

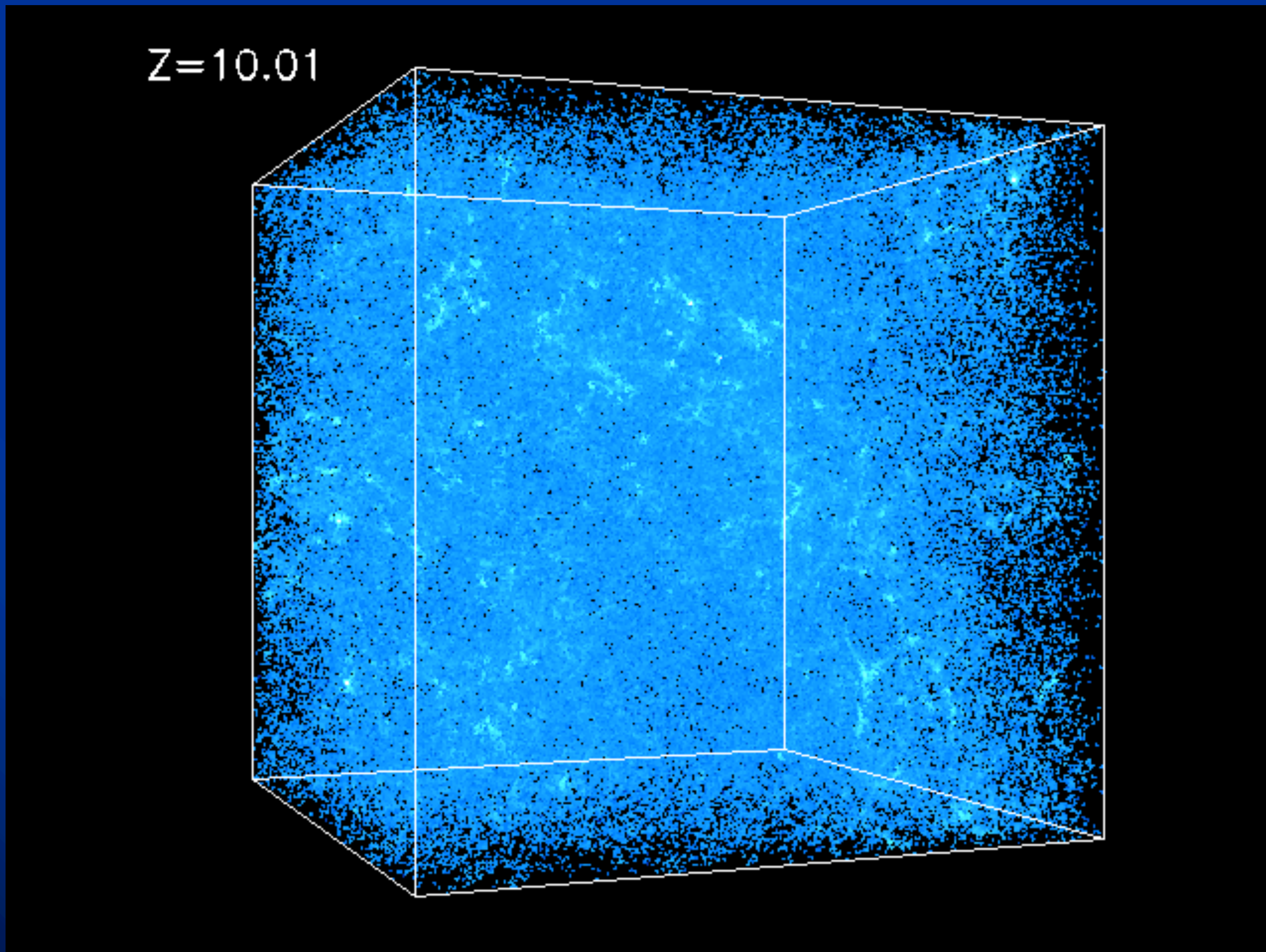
Evidence for Dark Matter: Formation of Structure, Computer Simulations

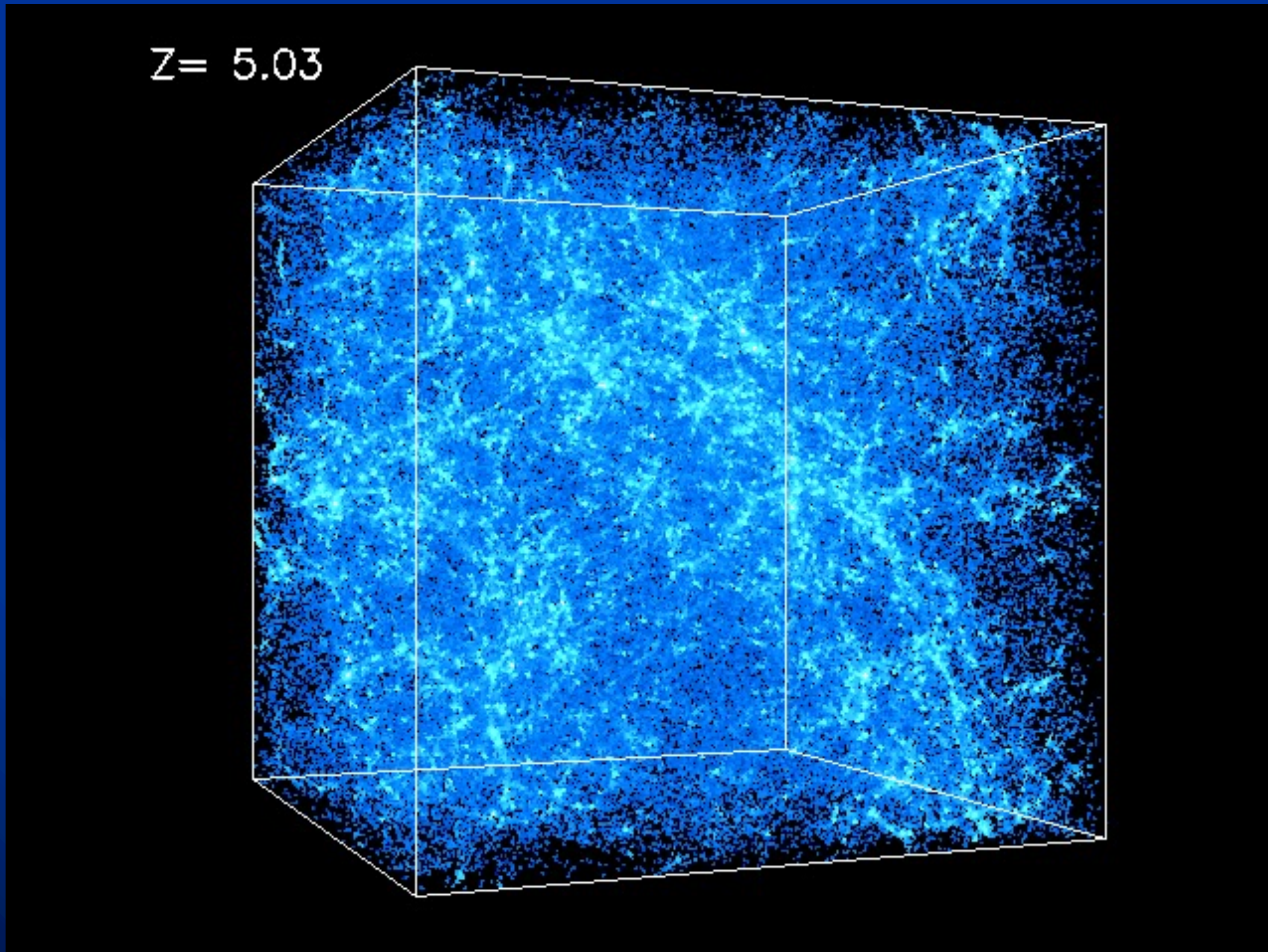
Initial conditions from inflation

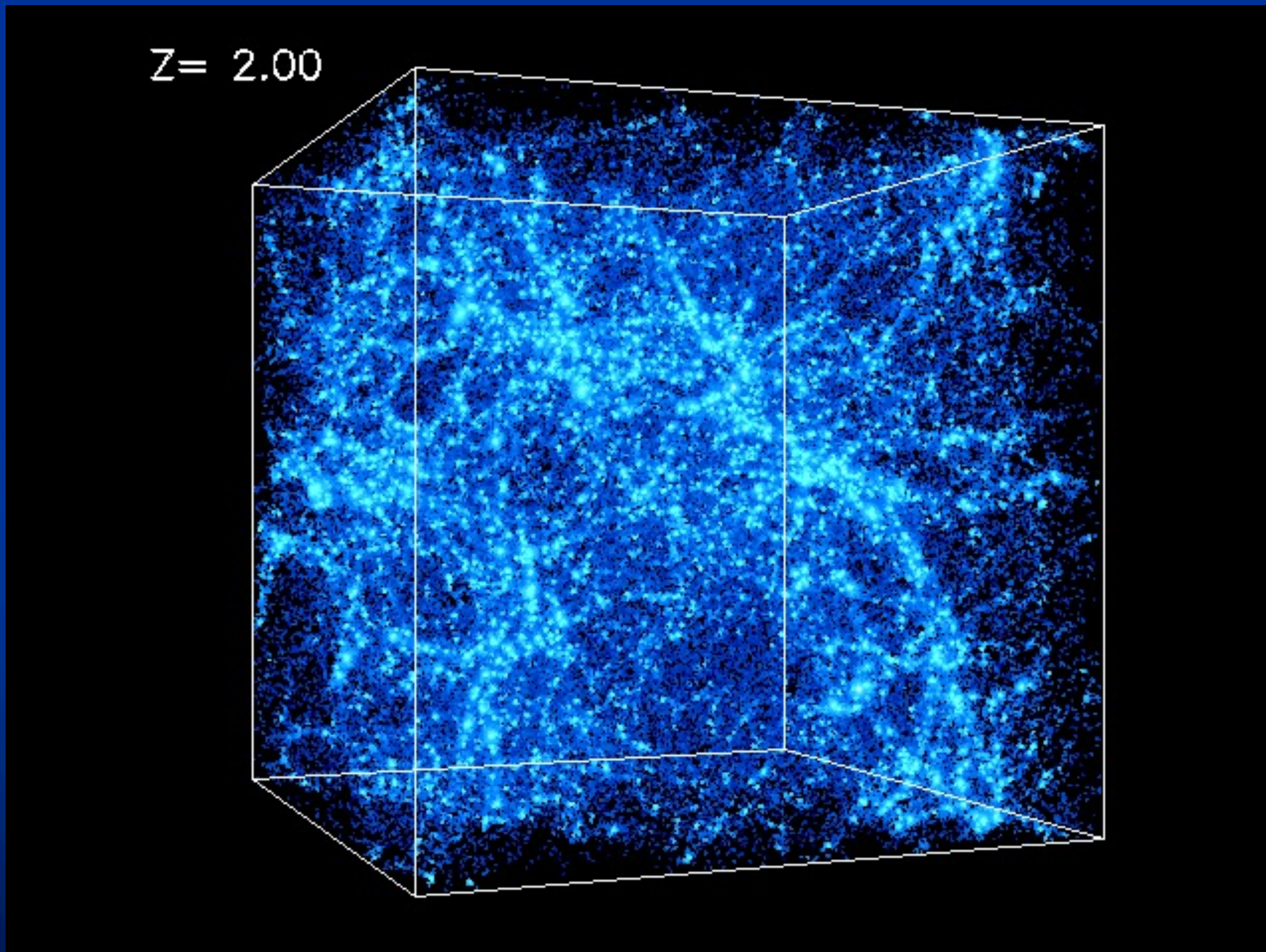
Dark Matter particles come together to make galaxies, clusters, and larger scale structures

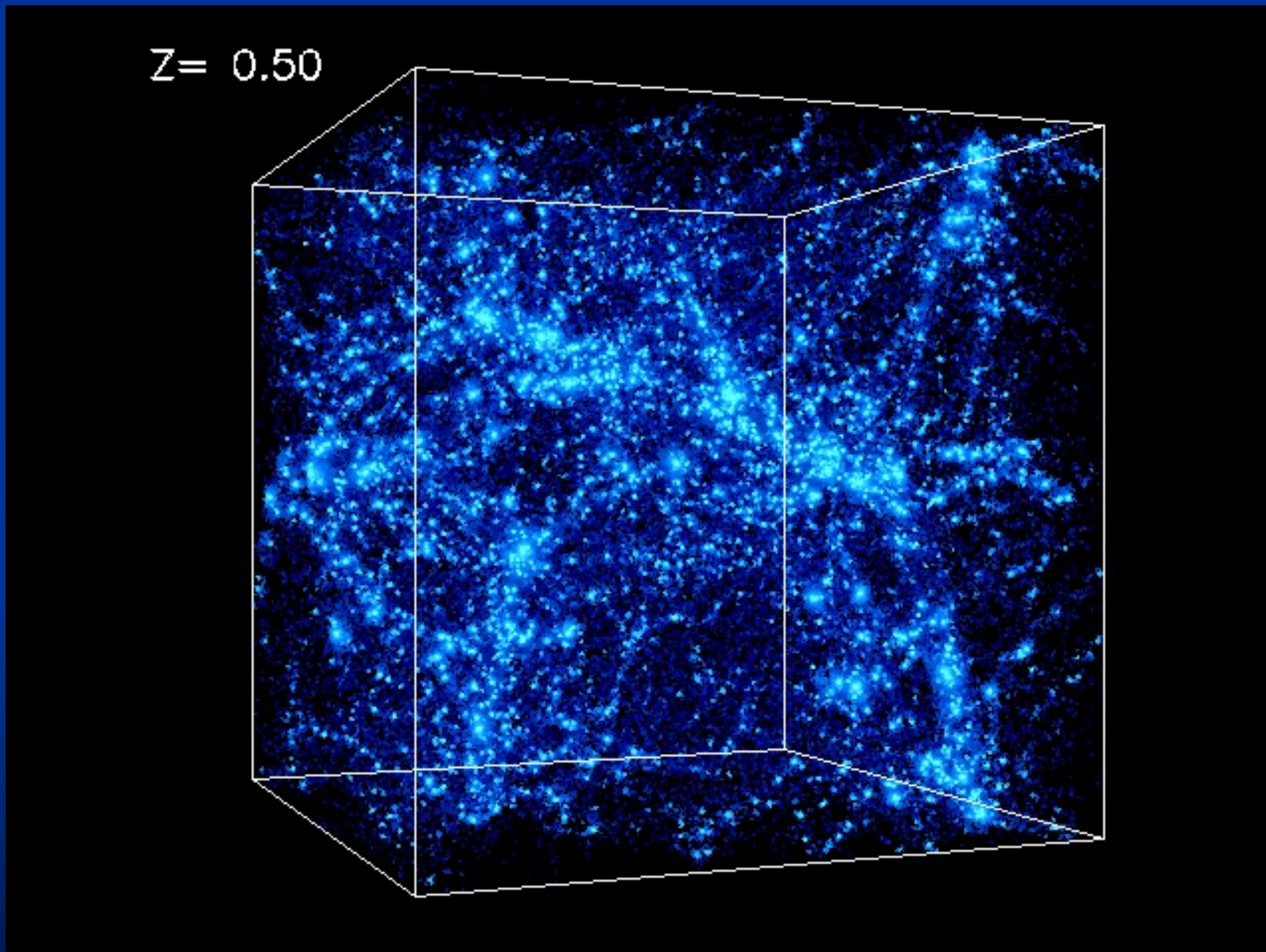
Computer simulations with dark matter match the data

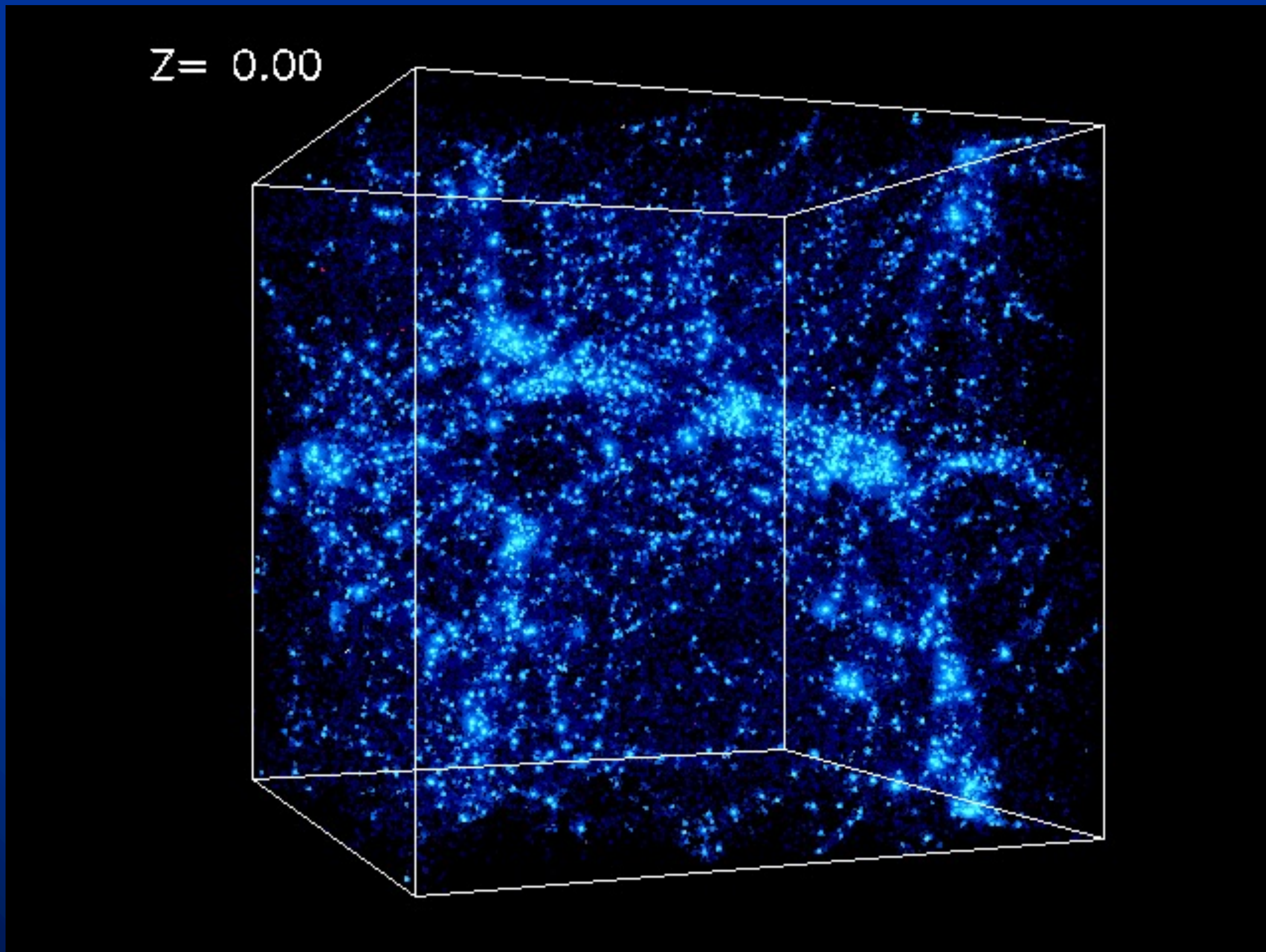



Z=10.01


Z= 5.03


Z= 2.00


Z= 0.50

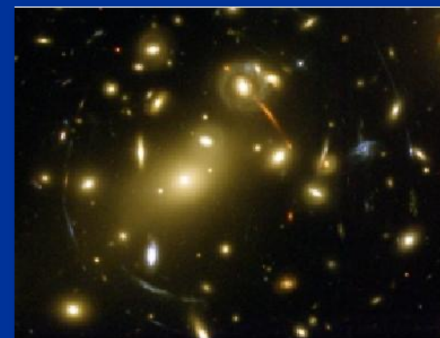

Z= 0.00

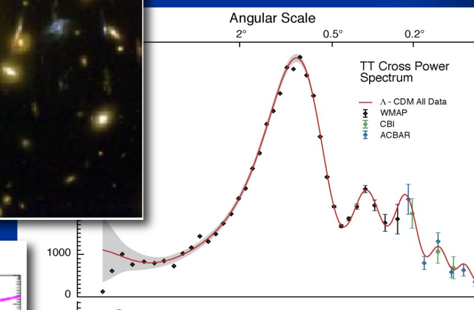
Evidence for Dark Matter Redux

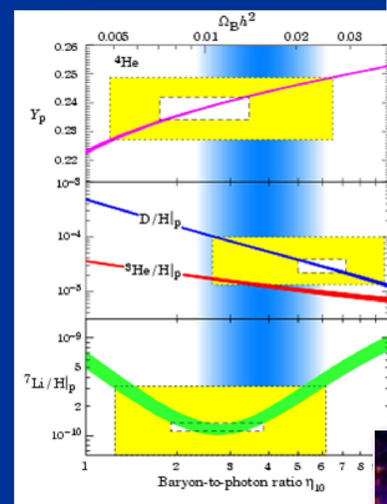
- There exists a wide variety of independent indications that dark matter exists

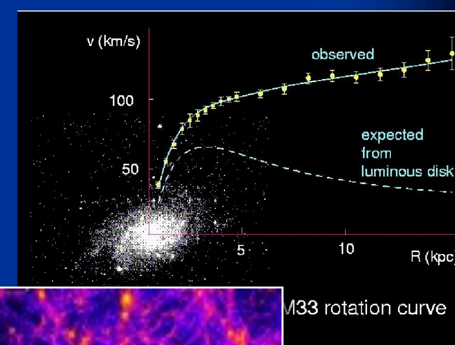
- Each of these observations infer dark matter’ s presence through its gravitational influence

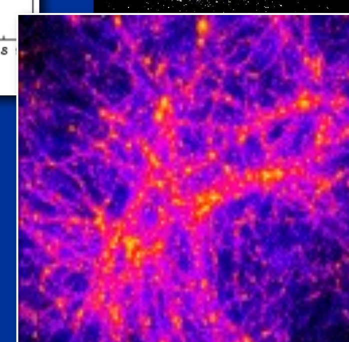
- Still no observations of dark matter’ s non-gravitational interactions. We still don’ t know what it is



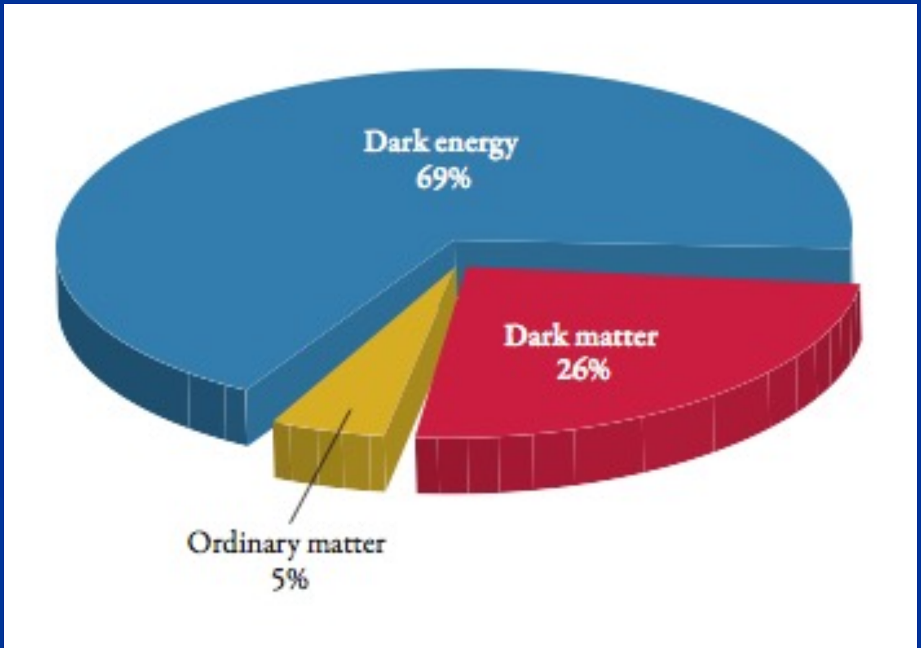








PIE CHART OF THE UNIVERSE



WHAT ARE THE PIECES OF THE PIE???

WHAT IS THE DARK MATTER?

The Dark Matter is NOT

- Diffuse Hot Gas (would produce x-rays)
- Cool Neutral Hydrogen (see in quasar absorption lines)
- Small lumps or snowballs of hydrogen (would evaporate)
- Rocks or Dust (high metallicity)

  (Hegyi and Olive 1986)
- Small stars, planetary objects, white dwarfs or neutron stars (Fields, Freese, and Graff 1990s)

2) What is the Dark Matter? Candidates:

- Cold Dark Matter candidates w/ strong theoretical motivation:
- WIMPs (SUSY or extra dimensions)
- Axions (exist automatically in solution to strong CP problem)
- ---
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Primordial black holes
- Asymmetric Dark Matter
- Light Dark Matter, Fuzzy DM
- Self Interacting Dark Matter
- Q-balls
- WIMPzillas

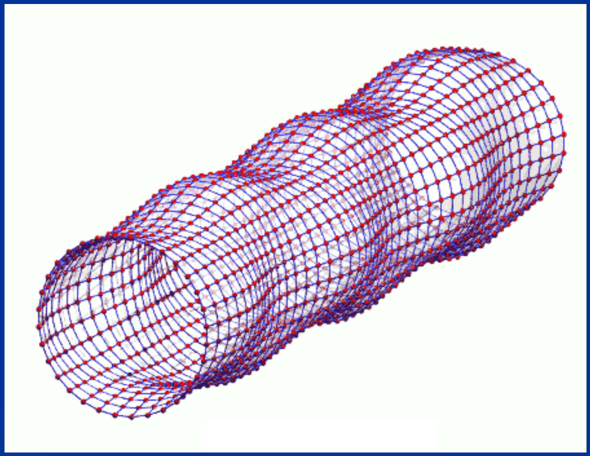
Florian Kuhnel
Primordial
Black Holes

Primordial Black Holes as Dark Matter?

- Primordial: they would have been born in the Universe's first fractions of a second, when fluctuations in the density led to small regions having enough mass to collapse in on themselves.
- One possibility: they formed at the transition in the early Universe when free quarks became bound together into protons, neutrons, etc. Pressure drop led to black holes.
- Resurgence of interest as possible explanation of gravitational waves seen in LIGO detector in 2016 due to merging black holes as massive as 30 suns.
- There could be millions of these between us and the center of the Milky Way.

Gravitational Waves

- Gravitational waves alternately stretch and squeeze space-time both vertically and horizontally as they propagate.



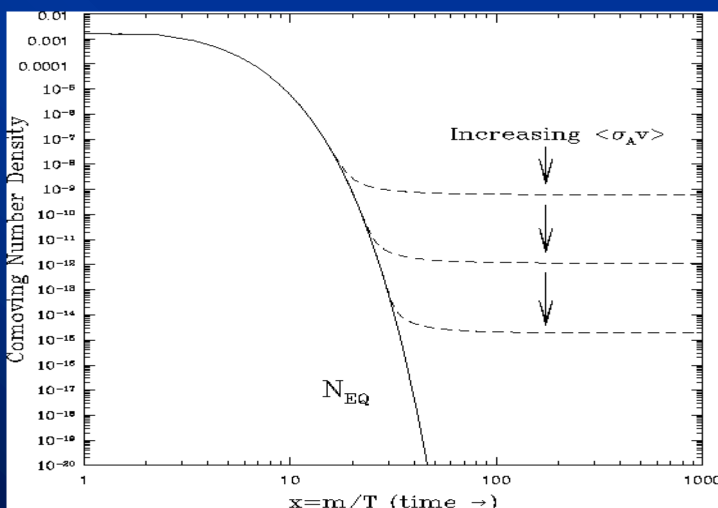
Detection of Gravitational Waves by LIGO

Two arms, 4km each, length of one increases while the other decreases – by a fraction of the size of a proton -- when gravitational waves come by that stretch the spacetime differently in perpendicular directions

2017 Nobel Prize to Barish, Thorne, and Weiss

Best motivated Dark matter candidates: cosmologists don't need to "invent" new particles

- Weakly Interacting Massive Particles (WIMPS). e.g.,neutralinos



- Axions

$m_a \sim 10^{-(3\text{-}6)}$ eV

arise in Peccei-Quinn solution to strong-CP problem

(Weinberg; Wilczek; Dine, Fischler, Srednicki; Zhitnitskii)

Axions

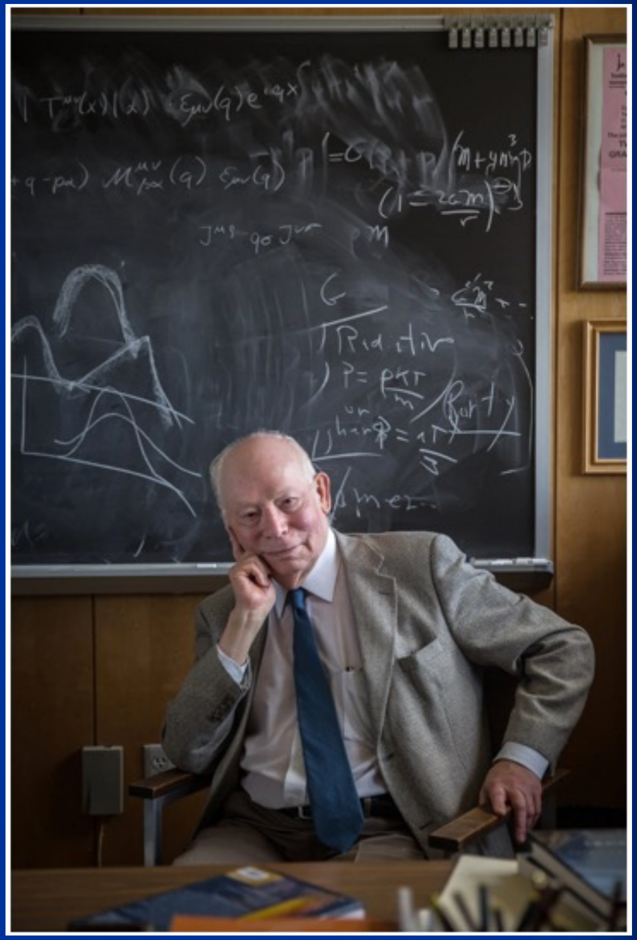
- Axions automatically exist in a proposed solution to the strong CP problem in the theory of strong interaction. They are very light, weighing a trillionth as much as protons; yet they are slow-moving. Axions are among the top candidates for dark matter.

Steven Weinberg

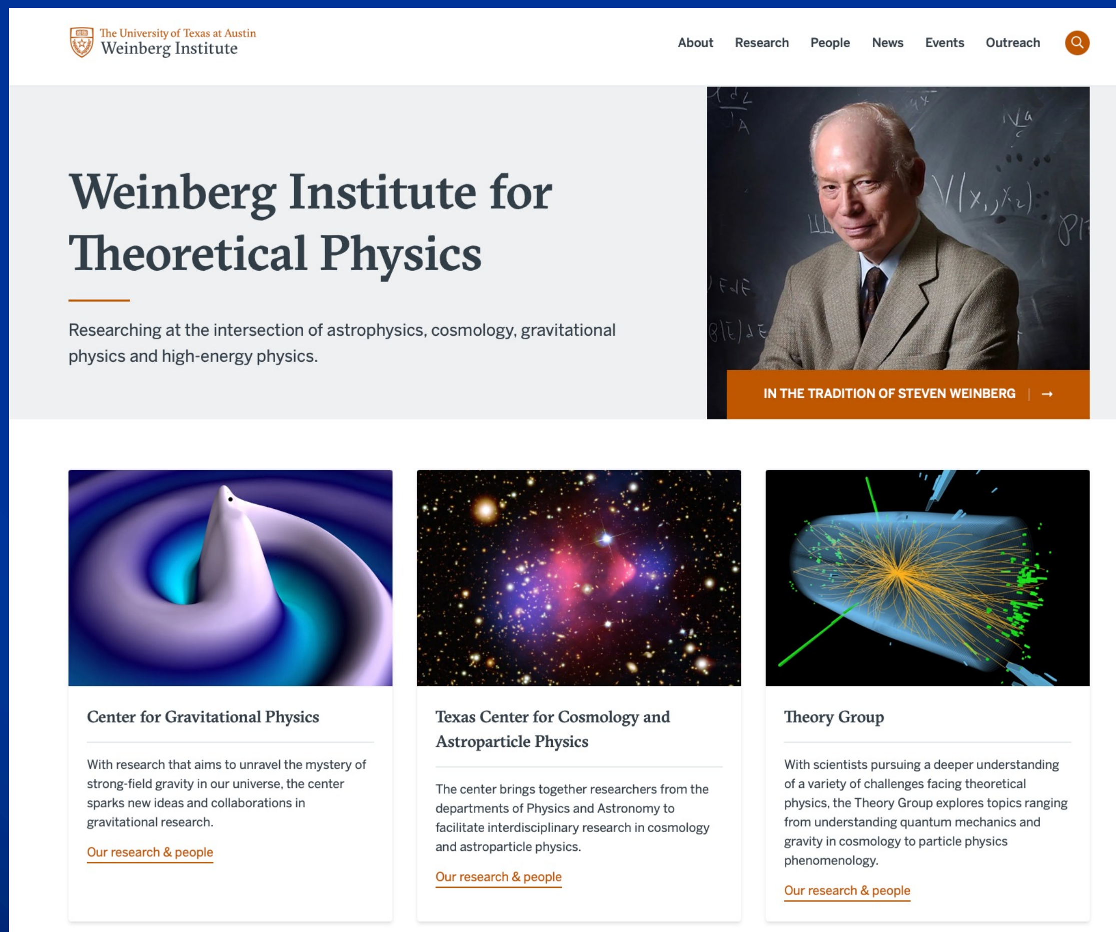
Frank Wilczek

Steven Weinberg, 1933- July 23, 2021

- Driver of some of the most groundbreaking ideas of the last half century. One of the most important thinkers on the planet and a wonderful human being.
- Foundational work creating the Standard Model of Particle Physics.
- We will miss him terribly at University of Texas --
- A major loss for us and for the world!



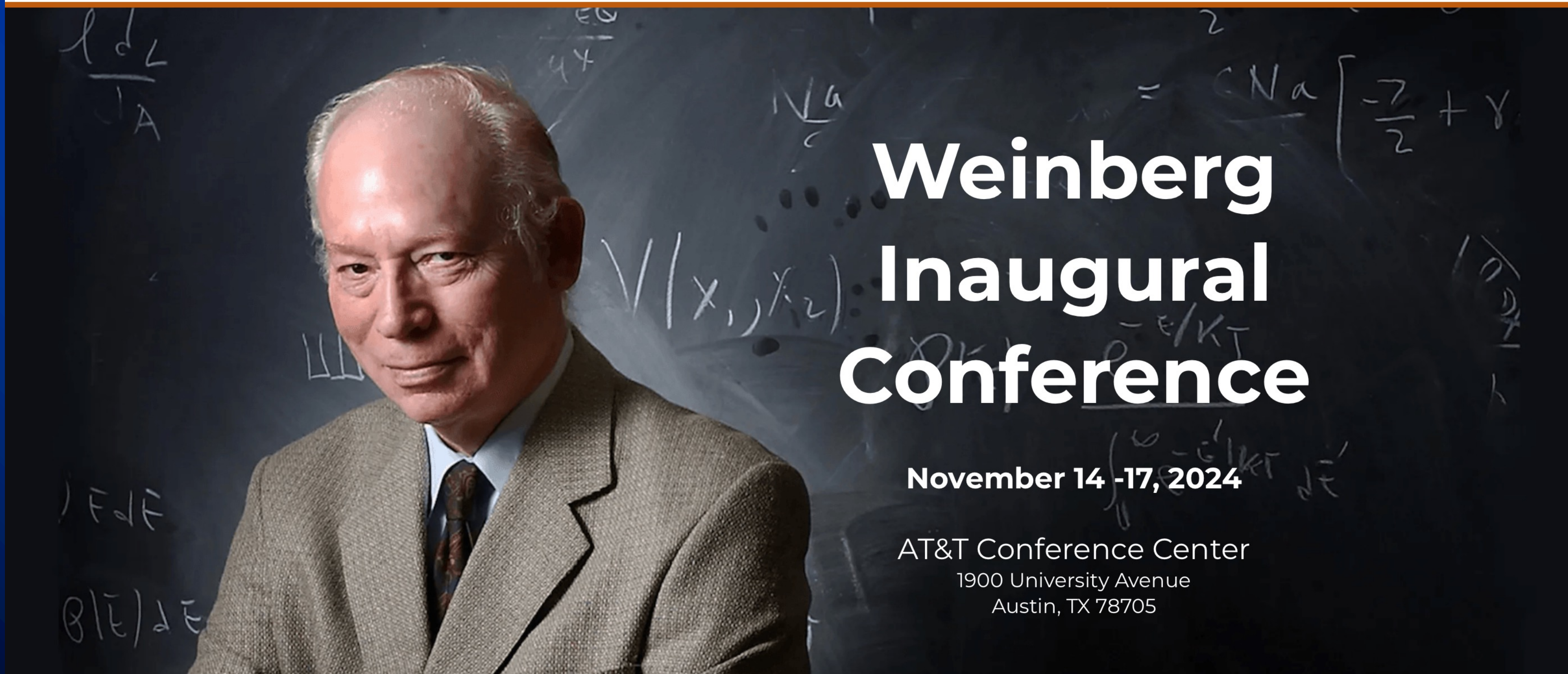
Weinberg Institute for Theoretical Physics at UT Austin



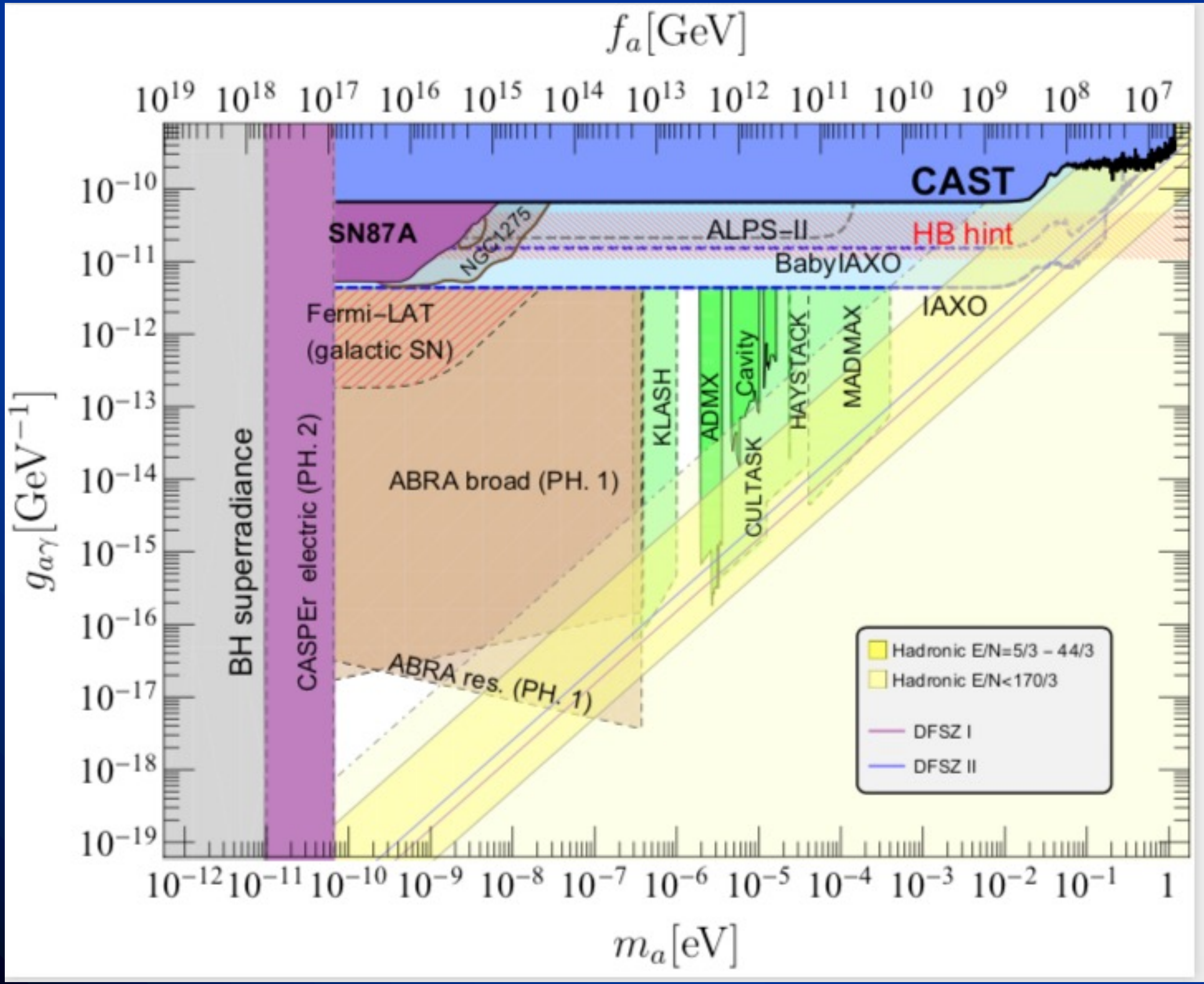
TEXAS
The University of Texas at Austin

Summary Weinberg's Legacy Travel Information Accommodations
Scientific Program Social Activities Attendees Organizing Committee

Register Now



Very active area: Searches for Axions and Axion Like Particles



From review by Luca Visinelli

Among the top candidates for Dark Matter Particles: WIMPs

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

Two reasons we favor WIMPs: First, the numbers come out right!

Weakly Interacting Massive Particles Many are their own antipartners. Annihilation rate in the early universe determines the density today.

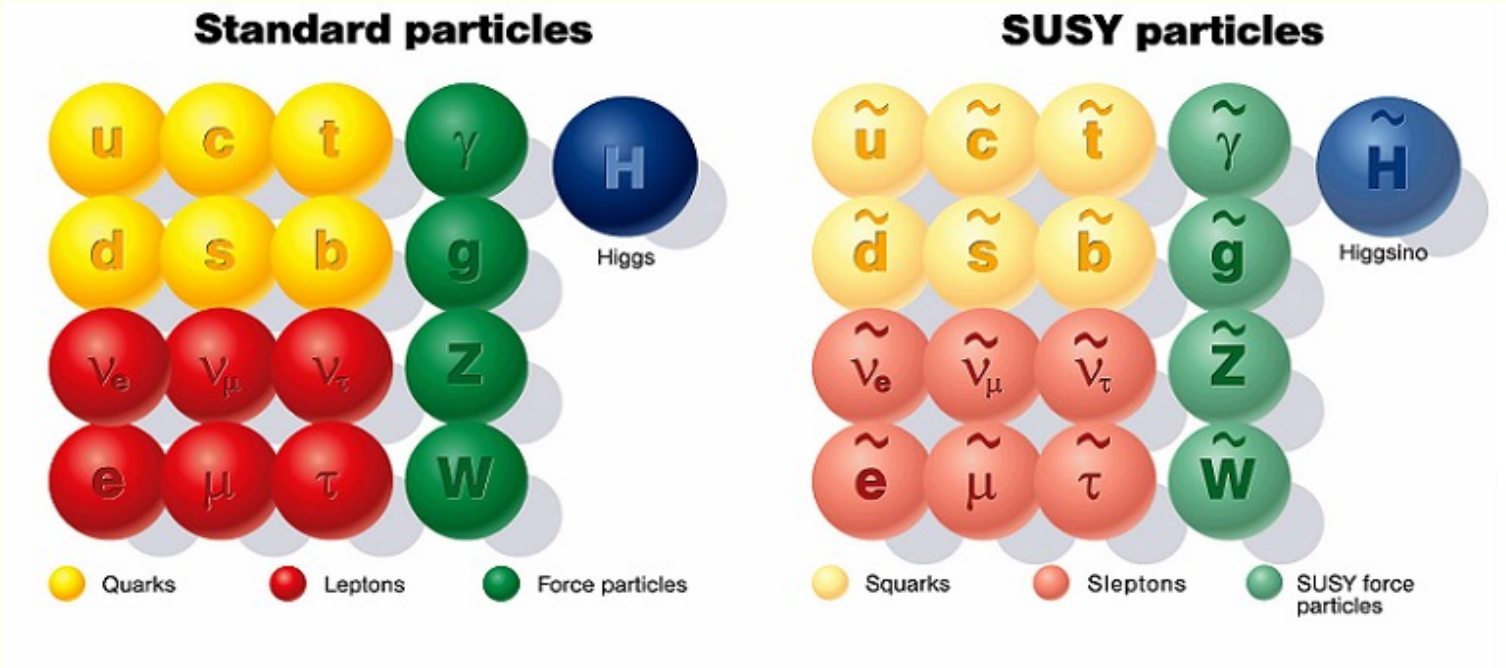
$$\Omega_\chi h^2 = \frac{3\times10^{-27}\ cm^3/\mathrm{sec}}{<\sigma v>_{ann}}$$

This is the mass fraction of WIMPs today, and gives the right answer if the dark matter is weakly interacting

WIMP mass:
Their possible weights vary between
1- 10,000 times as much as protons

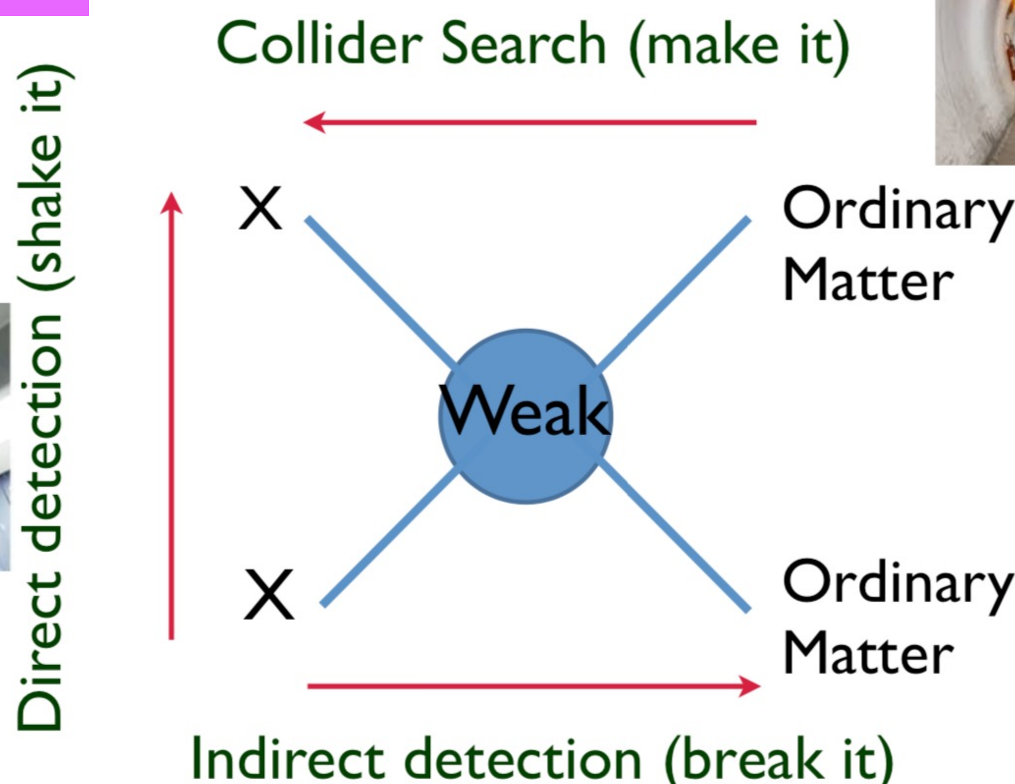
Another reason we favor WIMPS: in particle theories, eg supersymmetry

- Every particle we know has a partner

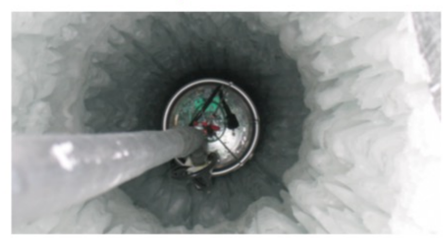


- The lightest supersymmetric particle may be the dark matter.

THREE PRONGED APPROACH TO WIMP DETECTION



FOURTH PRONG: DARK STARS

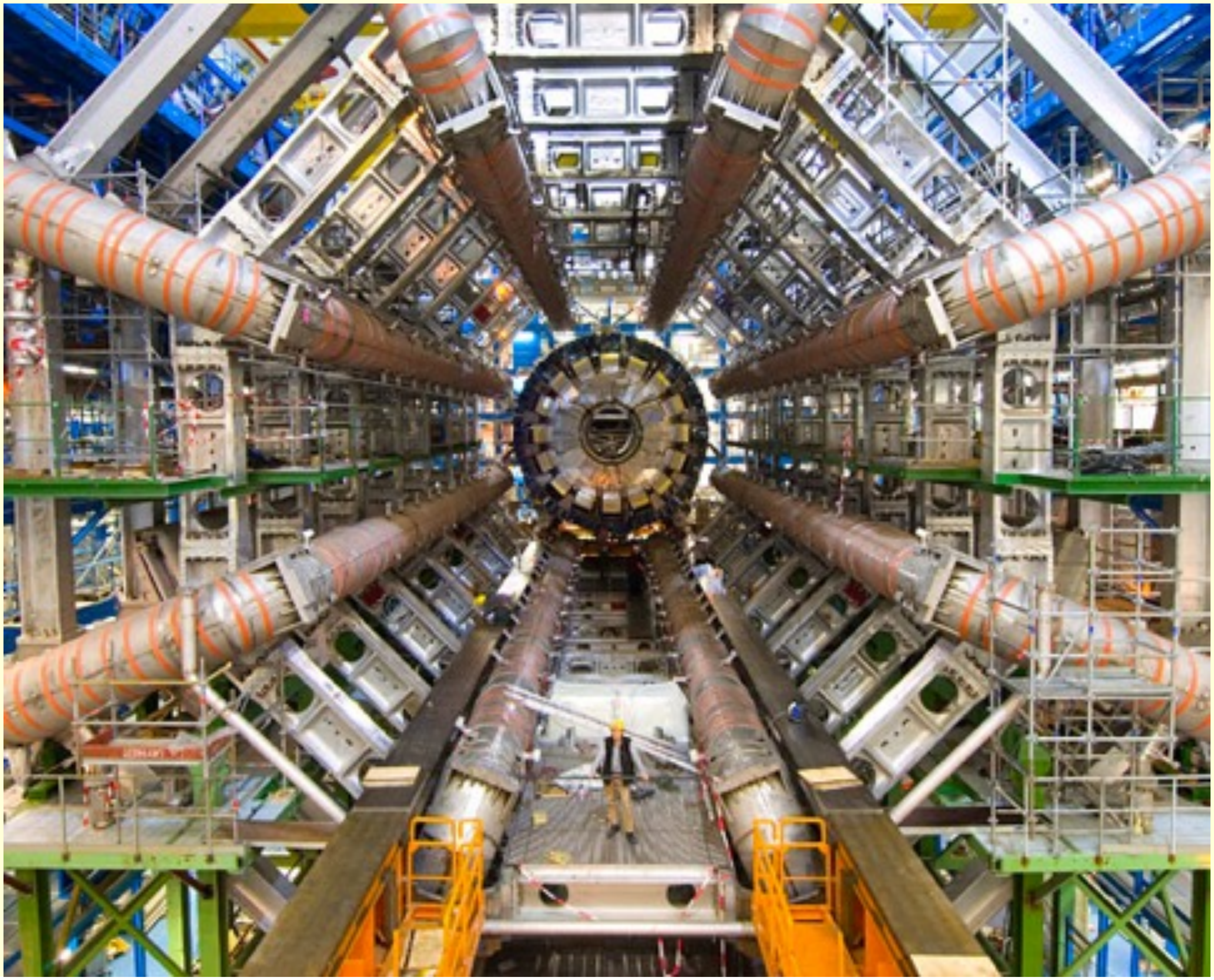


FIRST WAY TO SEARCH FOR WIMPS

Ring that is 17 miles around.
Two proton beams traveling underground in opposite directions collide at the locations of the detectors

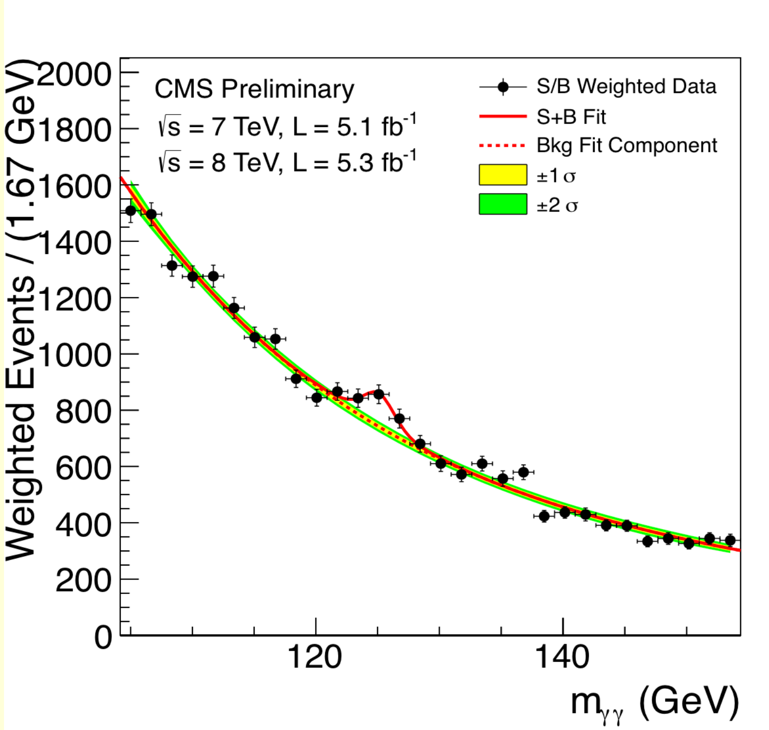
ATLAS detector:
Fabiola Gianotti, spokesperson for Higgs searches
now Director General at CERN

ATLAS Detector at CERN



Peter Higgs and CMS detector

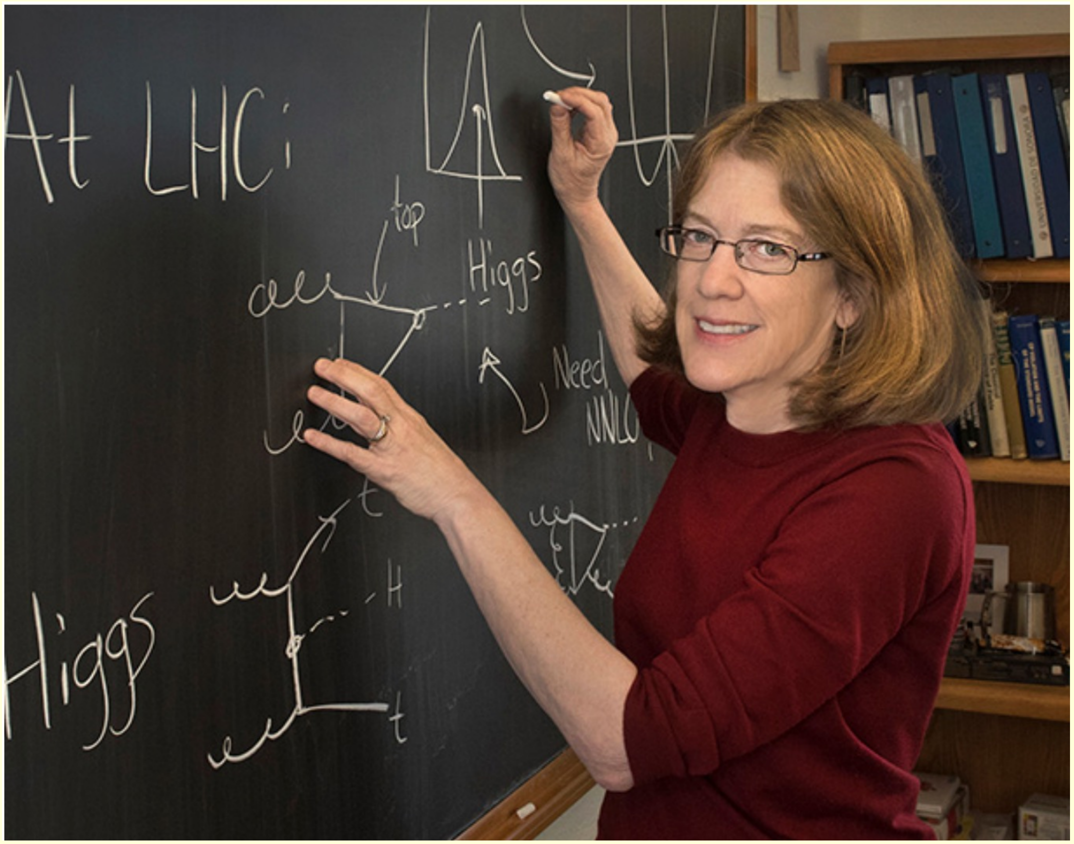
LHC's first success
Discovery of Higgs boson
weighing 125 GeV



Key role of Higgs: imparts mass to other particles

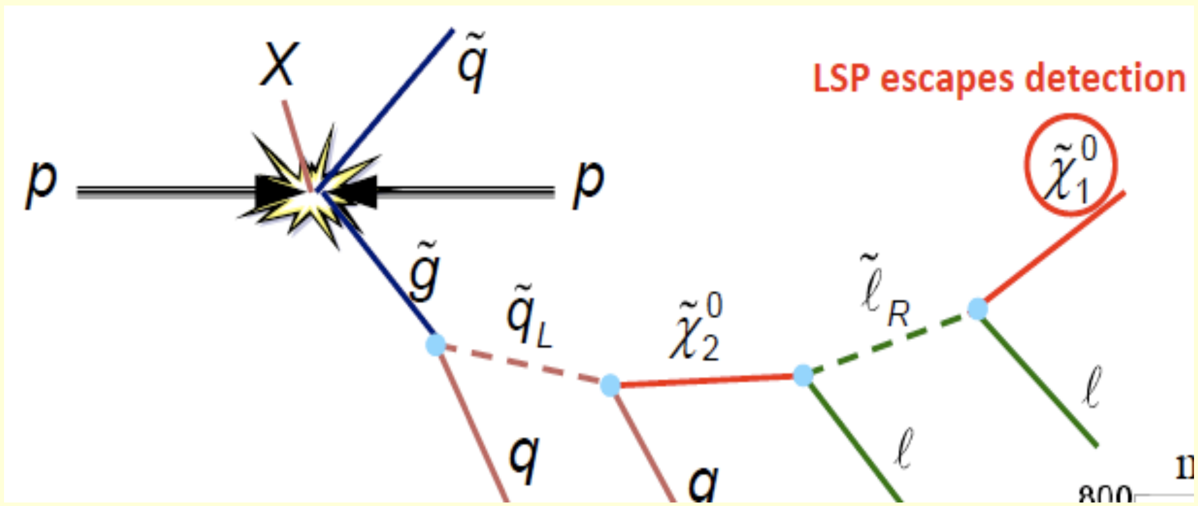
Brookhaven’s Sally Dawson

is known for her work on the Higgs



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

- Two signatures: Missing energy plus jets



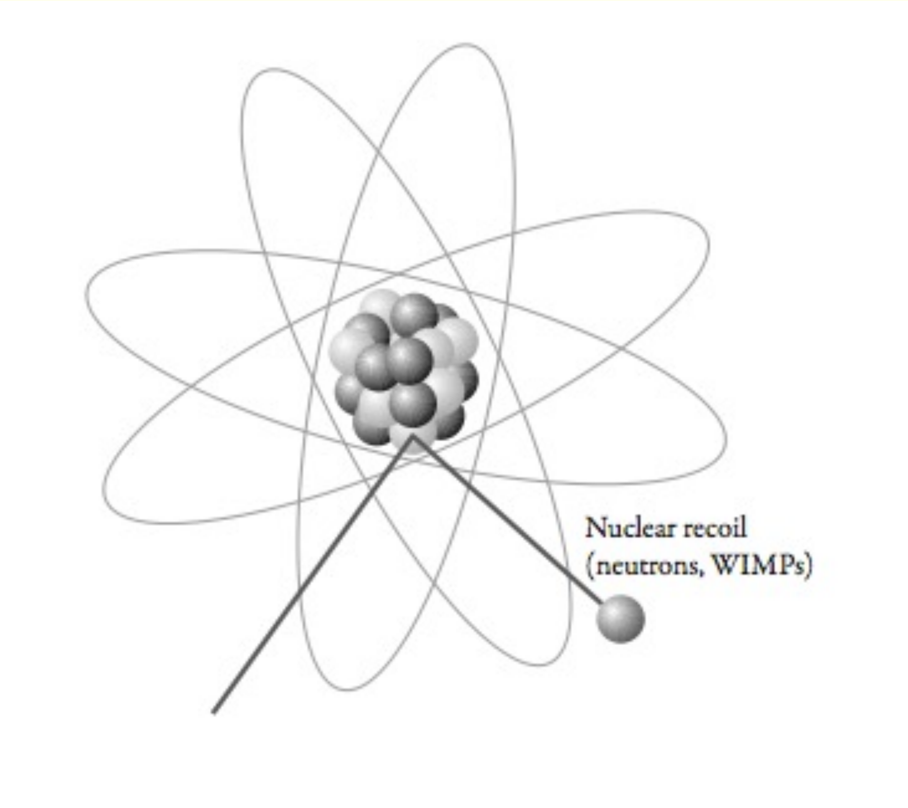
- Nothing seen yet: particle masses pushed to higher masses

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!

How did I get into Cosmology and studies of Dark Matter?

PhD Advisor at Univ of Chicago, David Schramm

Drukier, Freese, & Spergel (1986)

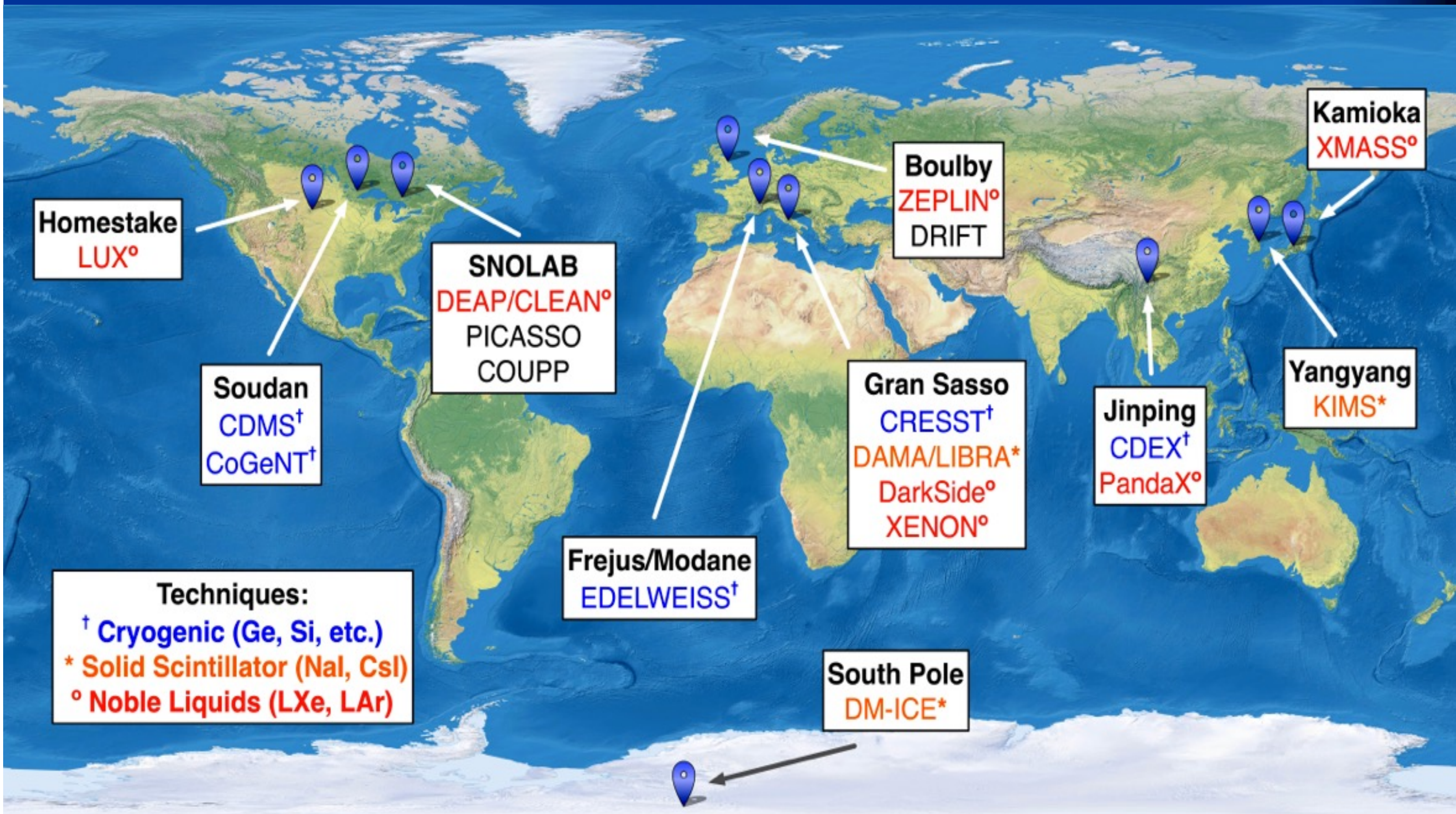
We studied the WIMPs in the Galaxy and the particle physics of the interactions to compute expected count rates, and we proposed annual modulation to identify a WIMP signal

WIMP detectors must be in underground laboratories

Need to shield from Cosmic Rays

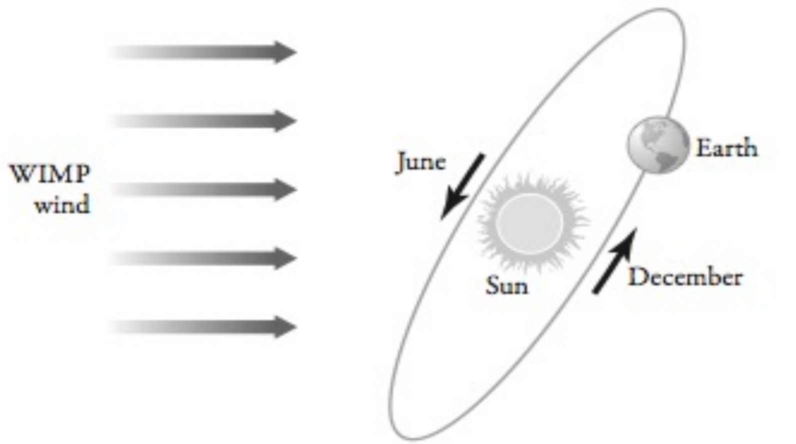
XENON experiment in Gran Sasso Tunnel

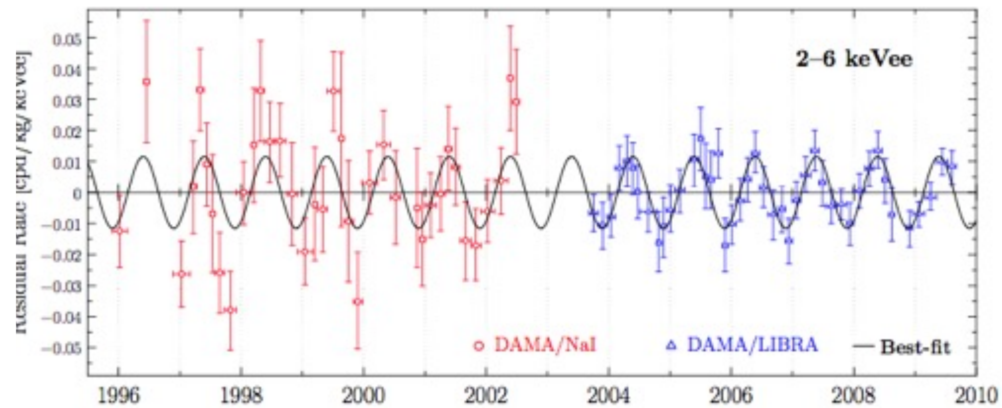
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DAMA annual modulation

Drukier, Freese, and Spergel (1986);
Freese, Frieman, and Gould (1988)





NaI crystals in Gran Sasso Tunnel under the Apennine Mountains near Rome.

Data do show modulation at 14 sigma. Peak in June, minimum in December (as predicted). Are these WIMPs??

Two Issues with DAMA

- 1. The experimenters won't release their data to the public

- 2. Comparison to other experiments:

Other experiments don't confirm their results

(see no signal)

But comparison is difficult because

experiments are made of different

detector materials

"I' m a Spaniard caught between two Italian women"

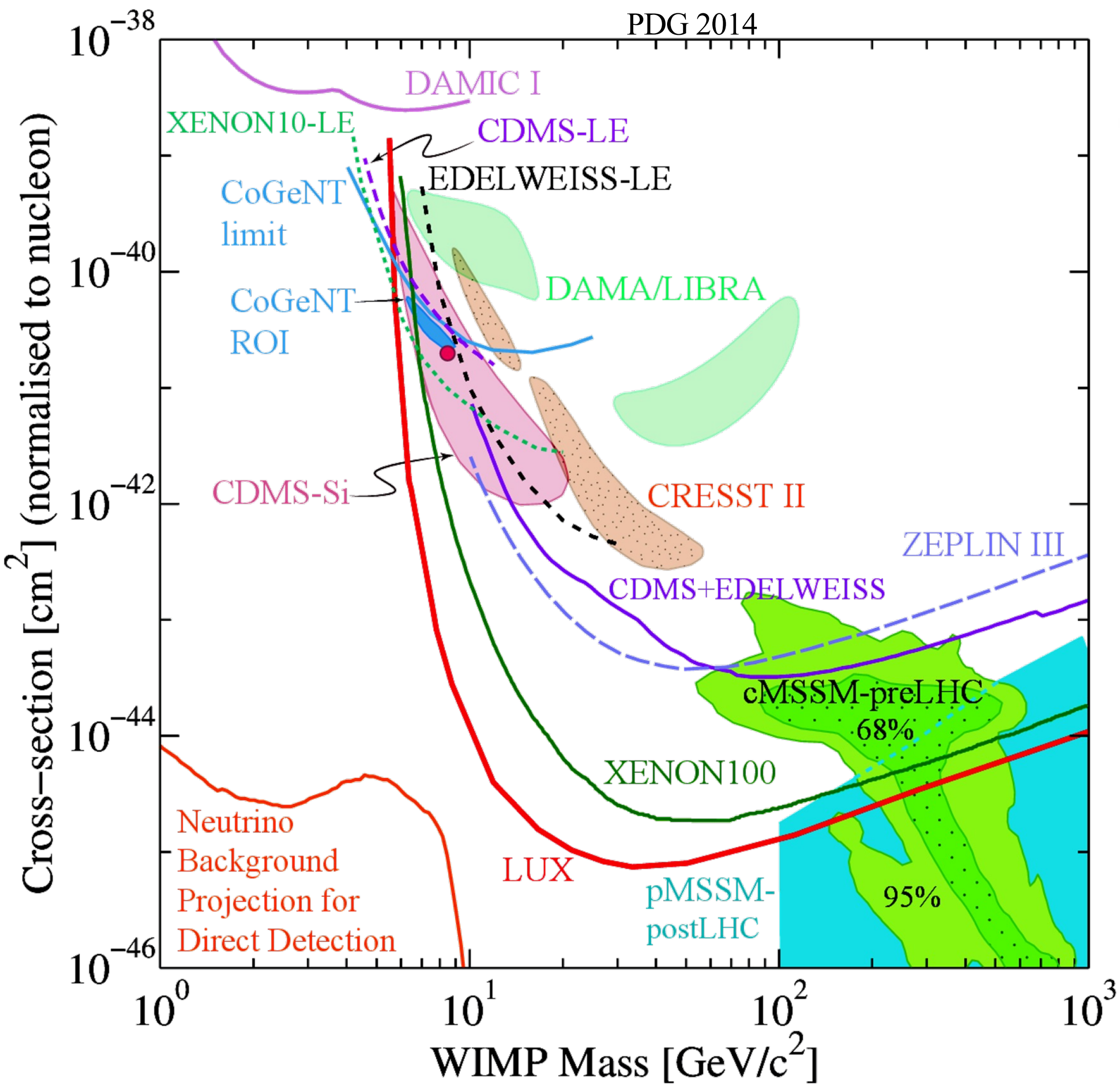
Rita Bernabei, DAMA

Juan Collar, COGENT

Elena Aprile, XENON

Bounds on Spin Independent WIMPs

Events in detector



BUT:

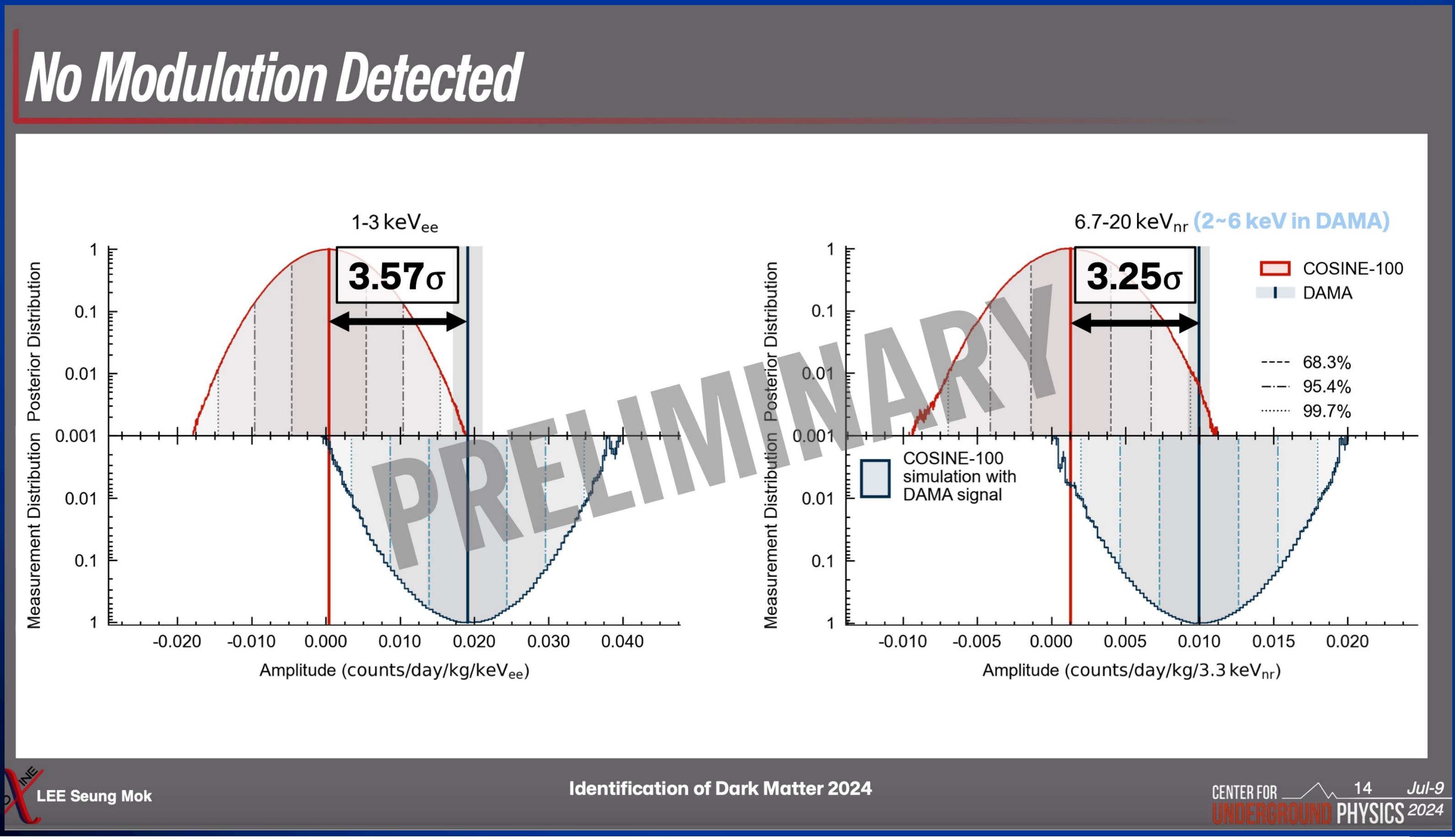
--- it's hard to compare results from different detector materials

--- can we trust results near threshold?

To test DAMA

- Unexplained signal still there after 13 years
- Other groups are now using the same material: NaI crystals
- COSINE-100 has new results
- NO MODULATION: ``does not confirm" DAMA in terms of dark matter interpretation
- SABRE
- ANAIS also has new results, no modulation
- COSINUS
- DAMA, the only expt with signal isn't confirmed

Talk at International Dark Matter meeting in l'Aquila last summer: Cosine-100 disagrees with DAMA at 99% statistical confidence



Paleodetectors

WIMPs leave tracks in ancient minerals from 10km below the surface of the Earth.

Collecting tracks for 500 Myr.

Backgrounds: Ur-238 decay and fission
Take advantage of nanotools: can identify nanometer tracks in 3D

Baum, Drukier, Freese, Gorski, Stengel arXiv:1806.05991

Pat Stengel

Sebastian Baum

Digging for dark matter

Despite making up most of the universe, we still haven't detected dark matter. A clue could lie buried in ancient rocks, says physicist **Sebastian Baum**

MOST of our universe is missing. Observations of the smallest galaxies to structures spanning the entire universe show that ordinary matter – the stuff that makes up you, me and everything we see in the cosmos around us – accounts for only one-fifth of all matter. The remaining 80 per cent is a mystery.
After decades trying to hunt down this

article in
New Scientist

New Research Direction with many ongoing experimental efforts worldwide

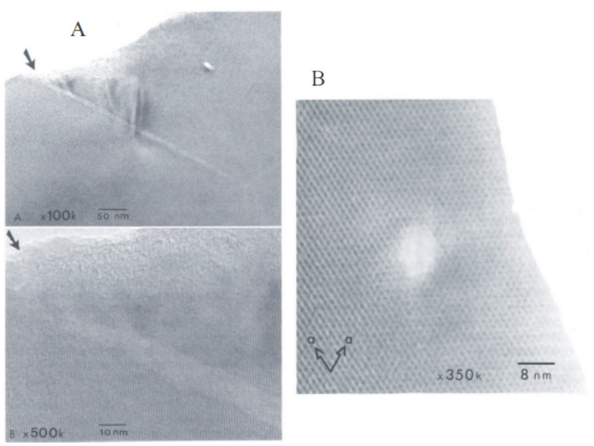


Figure 1: TEM-images of latent fission-tracks in apatite. *Left (A)*: Images taken parallel to the flight trajectory (light grey). *Right (B)*: Image taken perpendicular to the flight trajectory. Core of a fission-track is visible in the central part of the image. Figure taken from Ref. [90].

e.g. Color Centers:
Vacancies in crystal lattice,
e pairs fill in, get excited and fluoresce,
the crystal changes color

Biannual Conferences
Trieste 2022
Wash DC 2024

Useful for many things:
- Dark matter
- Neutrinos from Supernovae
- Cosmic Ray neutrinos
- Monitoring Nuclear Reactors

Paleodetector Experimental Efforts have received funding!

- 1) Josh Spitz at Univ of Michigan got 1.5M from the Moore Foundation to study neutrinos from cosmic rays
- 2) We got an NSF grant for 3.5M led by Patrick Huber at VA Tech together with international collaboration (Europe, Japan)

UCLA DARK MATTER MEETING

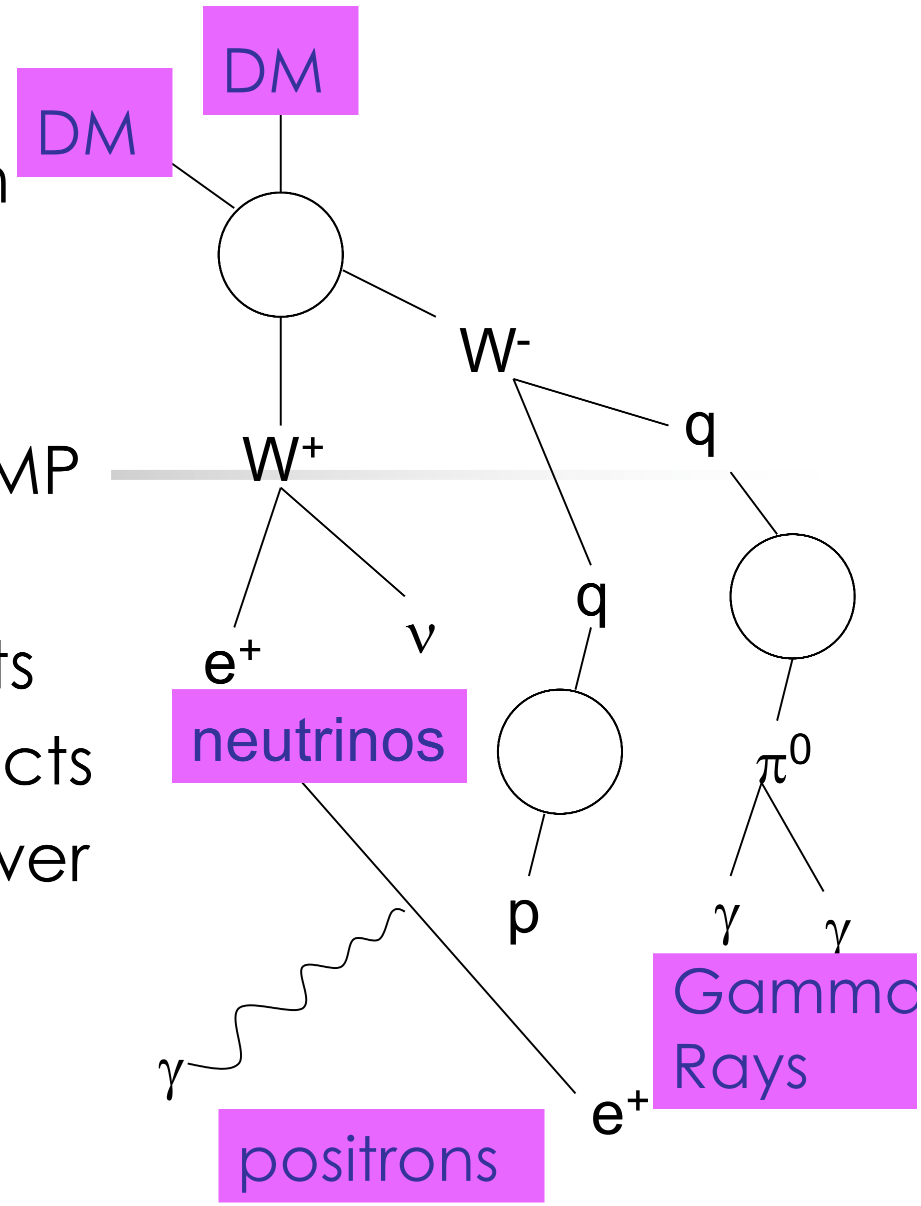
THIRD WAY TO SEARCH FOR WIMPS

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)

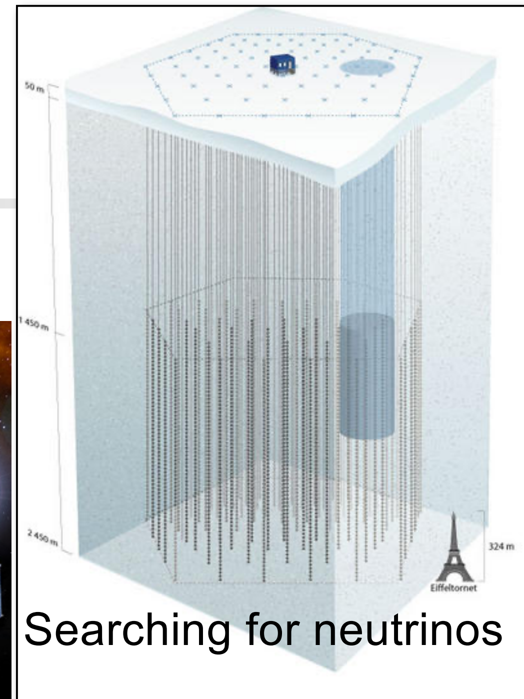


Indirect Detection: looking for DM annihilation signals

AMS aboard the International Space Station

Found excess e+

IceCube
At the South Pole



FERMI

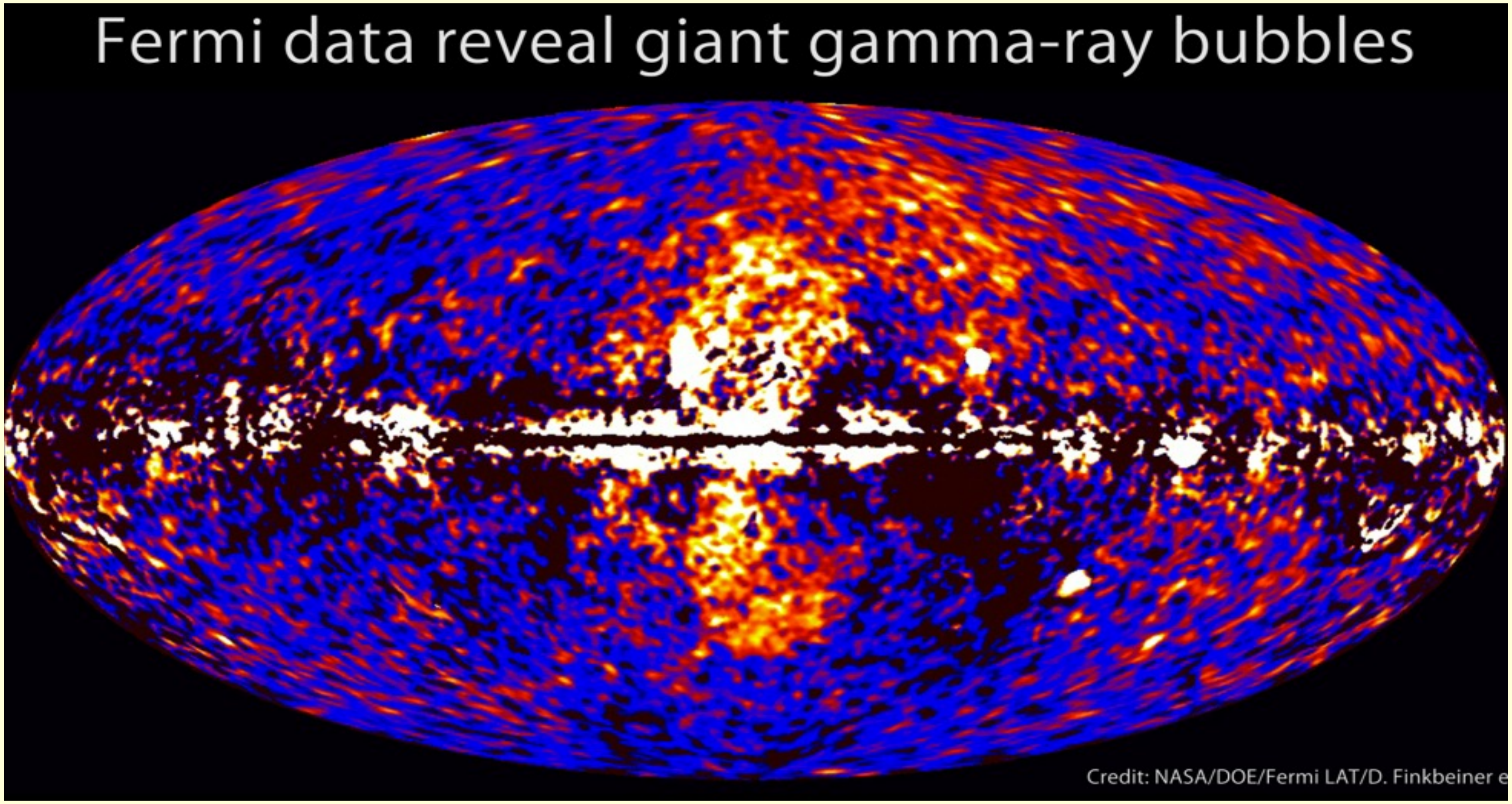
INDIRECT DETECTION: HIGH ENERGY PHOTONS (GAMMA-RAYS)

Are they from DM annihilation?

THE FERMI SATELLITE

Stony Brooks' Neelima Sehgal

The gamma ray sky

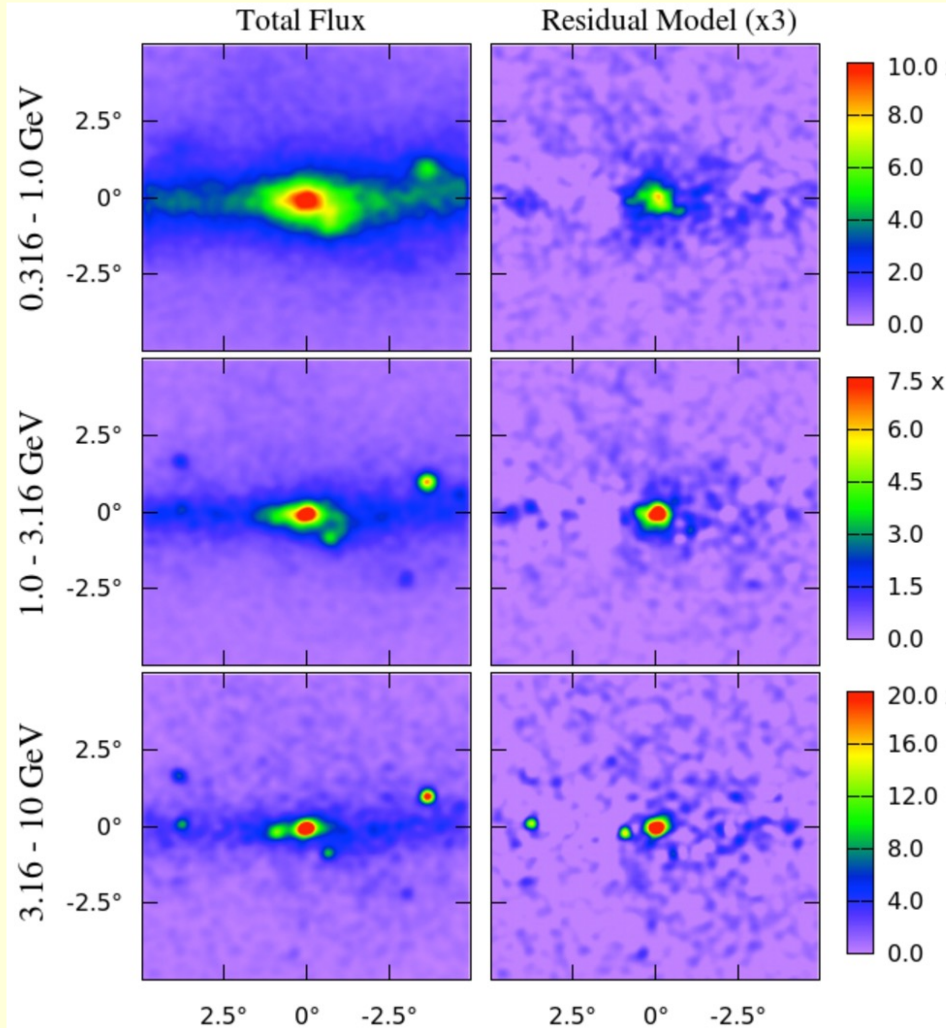


Excess from Galactic Center could be from Dark Matter annihilation

Unexplained light coming from the Galactic Center: could it be a discovery of Dark Matter?

Towards galactic center:

- Model and subtract astrophysical sources
- Excess remains
- Consistent with DM (50 GeV)
- BUT it could be astrophysical point sources. Status unclear.
- (Hooper and Goodenough)
- Interesting Hint of Detection!

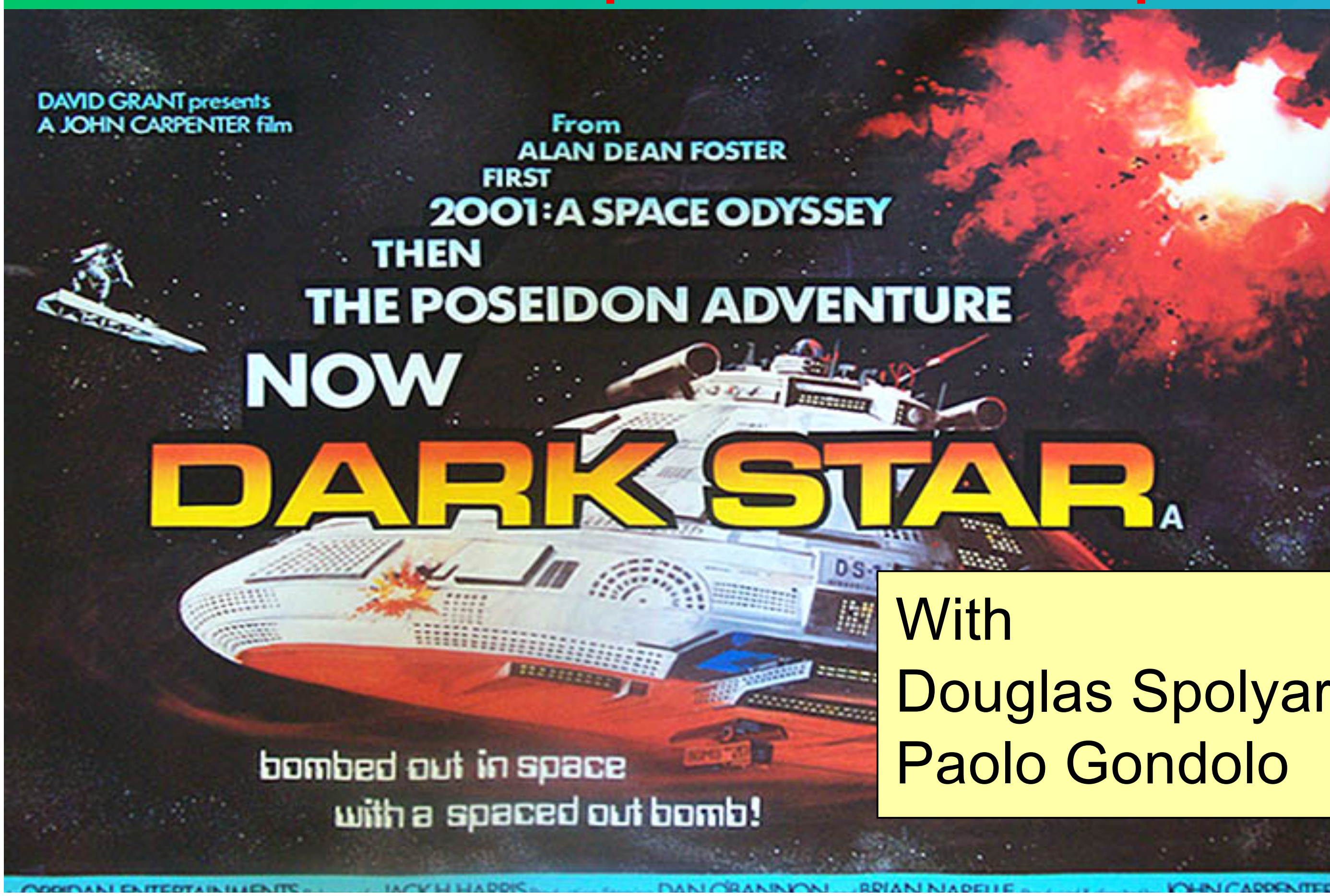


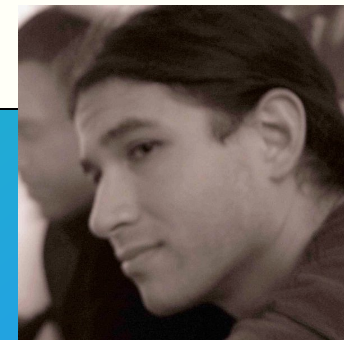
FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can power the first stars

Fourth Way: Find Dark Stars (hydrogen stars powered by dark matter) in James Webb Space Telescope, sequel to Hubble Space Telescope

W Doug Spolyar, P. Gondolo





With
Douglas Spolyar,
Paolo Gondolo

Dark Stars

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion. Dark stars are made almost entirely of hyrdogen and helium, with dark matter constituting 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: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to a billion times as bright as the Sun. **These may have been seen in James Webb Space Telescope.**
- 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?**

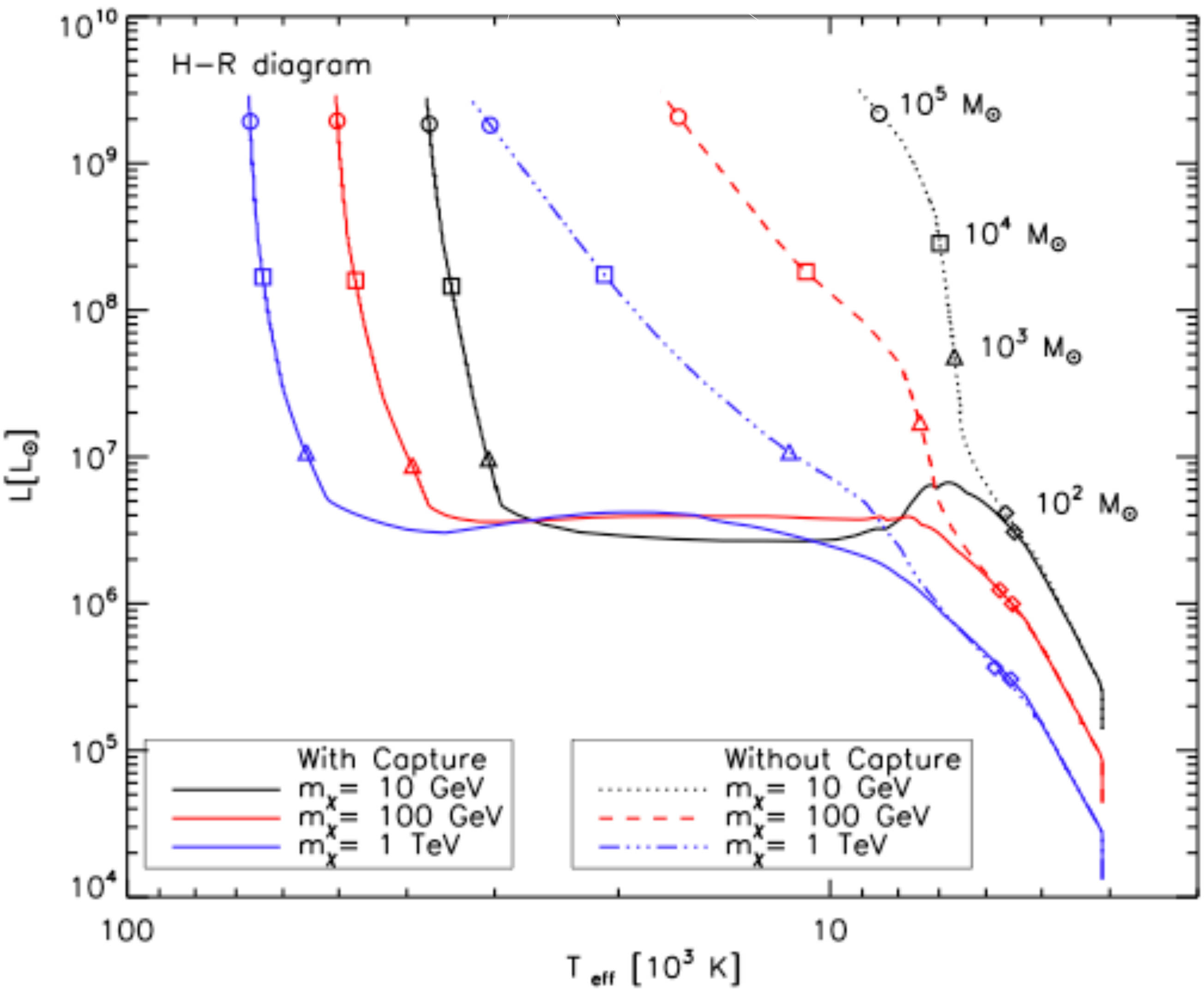
Basic Picture

- The first stars form 200 million years after the Big Bang in the centers of protogalaxies --- right in the DM rich center.
- As a gas cloud cools and collapses en route to star formation, the cloud pulls in more DM gravitationally.
- DM annihilation products typically include e+/e- and photons. These collide with hydrogen, are trapped inside the cloud, and heat it up.
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms; the cloud can no longer continue to cool and collapse. A Dark Star is born, powered by DM.

DS Properties

- We find that DS are big puffy objects:
  - Massive: can grow to ten million times the mass of the Sun --- $10^7 M_\odot$
  - Enormous Radii: 10 a.u. (radius of Earth's orbit around Sun)
  - Very Bright: up to ten billion times as bright as the Sun --- $10^{10} L_\odot$
  - Cool: 10,000 K vs. 100,000 K plus
  - Long lived: more than 10^6 years, even till today?.
    - Not blowing off hot material that prevents further accretion

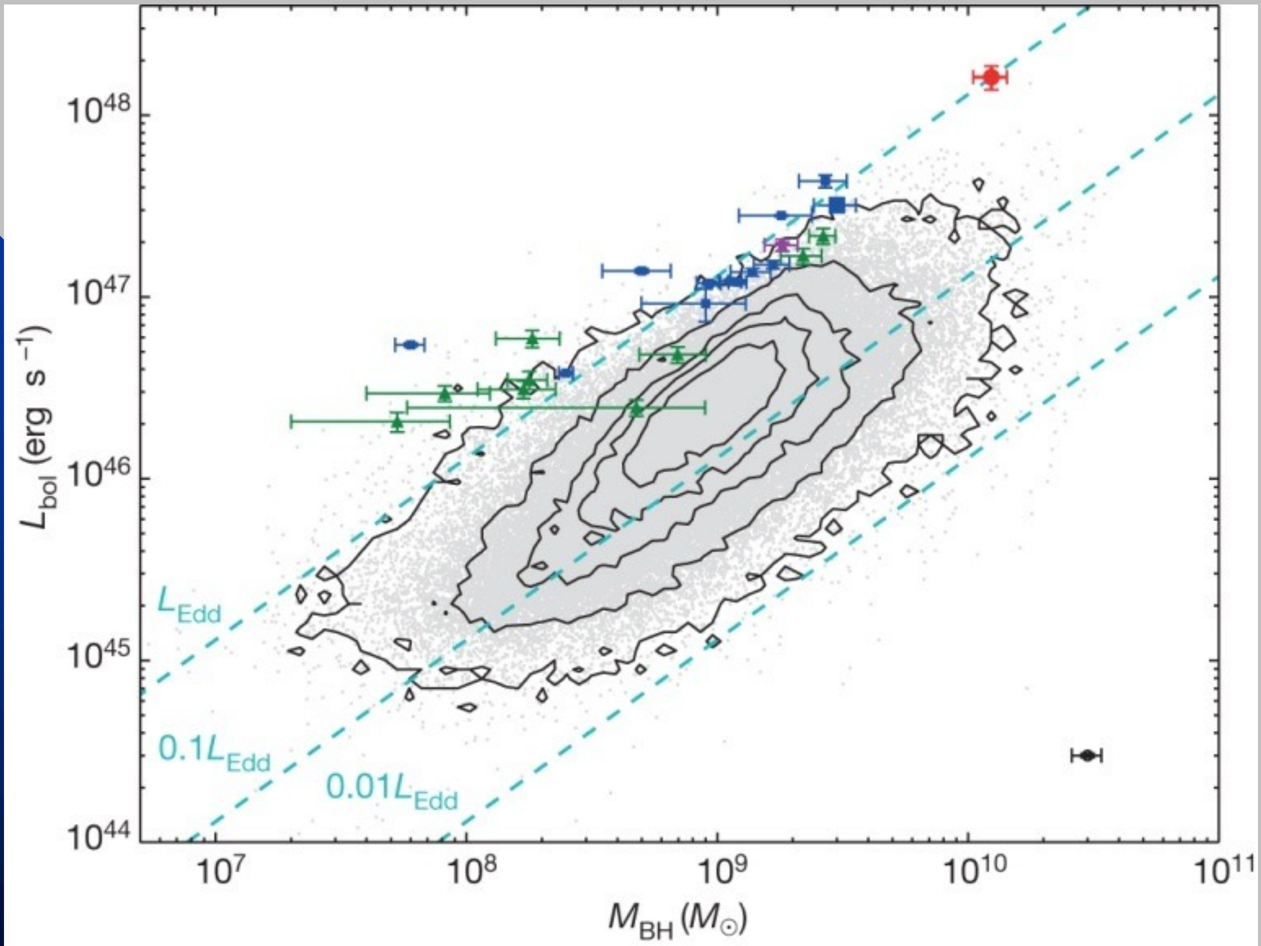
Building up the Mass: a Dark Star starts with the mass of the Sun,
Some keep growing up to a million times the mass of the Sun and a billion times as bright!



Helps Solve the BIG BLACK HOLE PROBLEM!

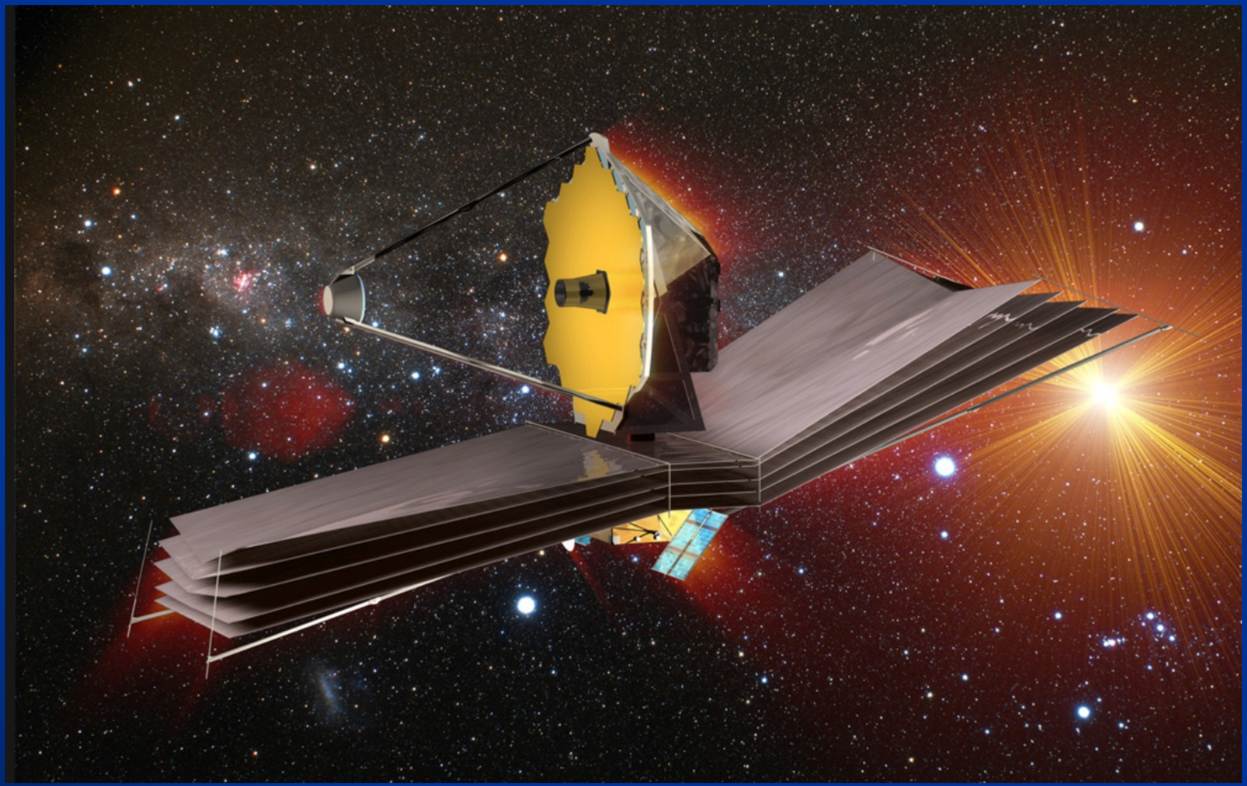
After the Dark Stars die, they collapse to million solar mass black holes which can merge together to make the otherwise unexplained very early giant black holes.

Challenging to form 10^{10} M⦿ Supermassive Black Holes



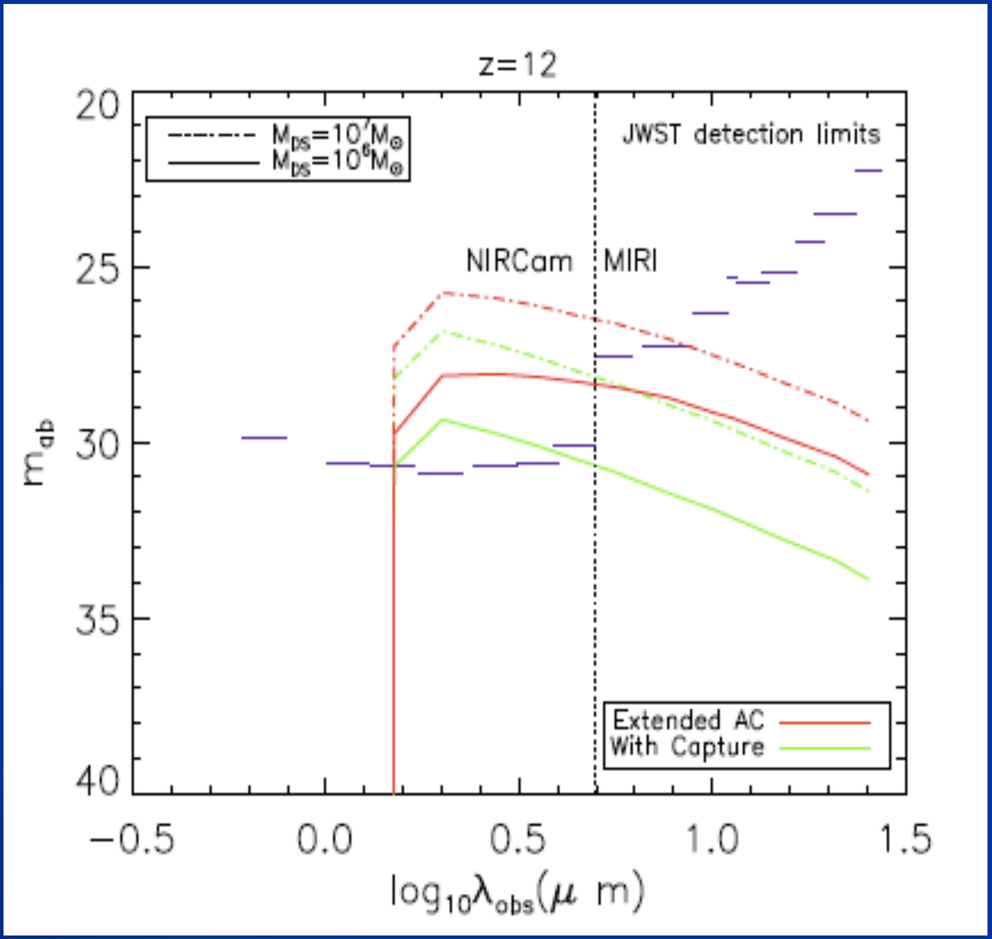
nature

Observing Dark Stars with James Webb Space Telescope



One supermassive dark star would be as bright as an entire early galaxy of stars. Observable in JWST!

Dark Stars in JWST

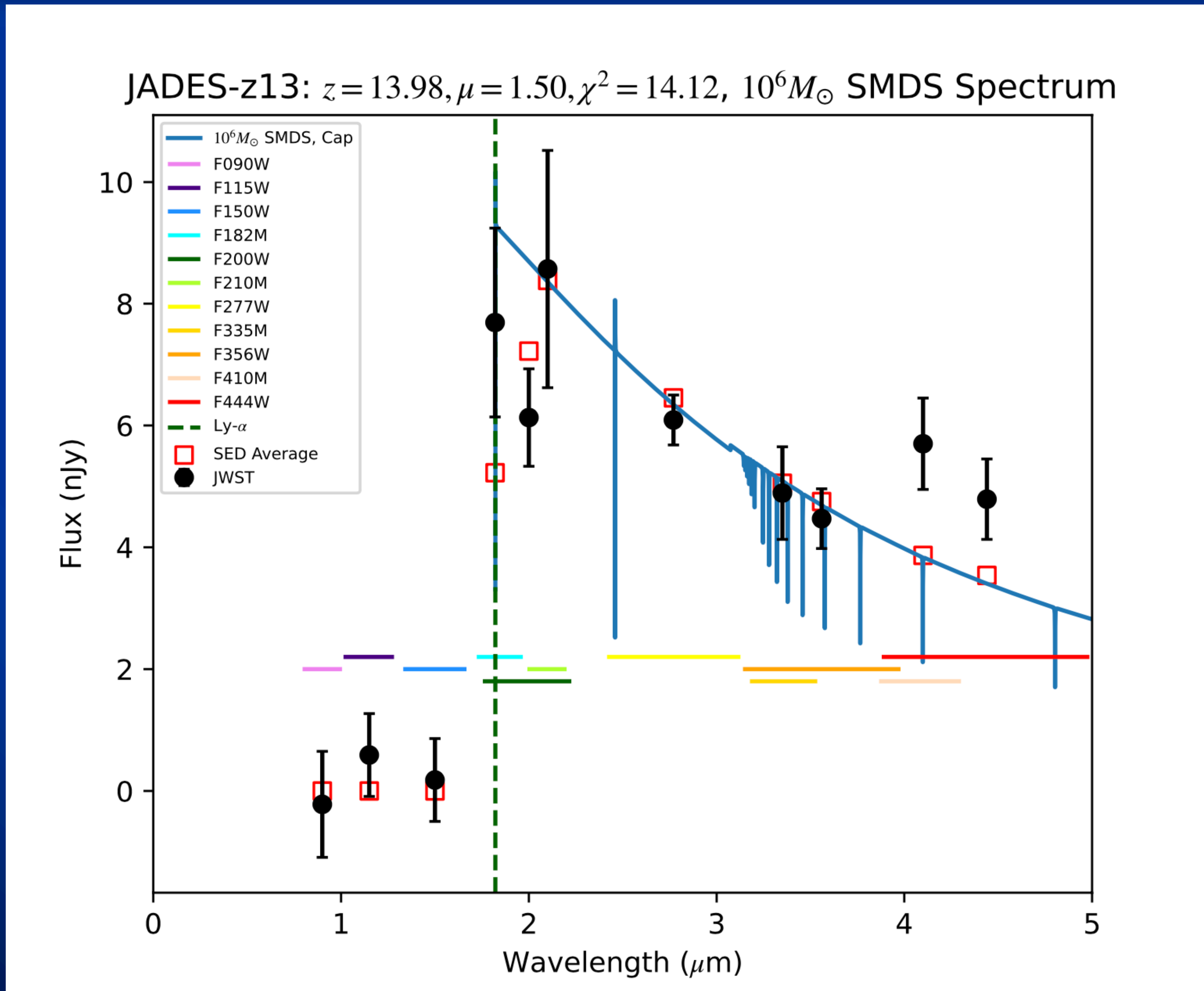


Of 5 objects in JWST data with spectra: 2 could be Dark Stars!

Criteria to be Supermassive Dark Star candidates vs. early galaxies:

- 1) Point object (SMDS) vs. extended object (galaxy)
- 2) DS spectra match data (the right amount of light in different wavelength bands)
- 3) Dark stars are only made of hydrogen and helium from the Big Bang; galaxies have many other elements like carbon, nitrogen, etc.
- 4) Smoking gun for Dark Stars:

  HeII1640 absorption line


JADES-z13: $z = 13.98, \mu = 1.50, \chi^2 = 14.12,\ 10^6 M_\odot$ SMDS Spectrum
$10^6 M_\odot$ SMDS, Cap
F090W
F115W
F150W
F182M
F200W
F210M
F277W
F335M
F356W
F410M
F444W
Ly-α
SED Average
JWST
Flux (nJy)
Wavelength (μm)
0
2
4
6
8
10
0
1
2
3
4
5

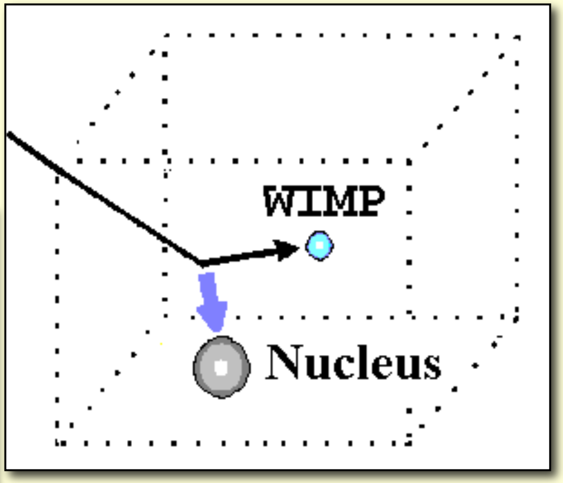
The Bottom Line

- JWST found ~ 700 bright objects from the early Universe. They assumed these are "galaxy candidates"
- Too many galaxies for the standard model of cosmology.
- Are some of them Dark Stars?

One Dark Star can be as bright as an entire galaxy of early stars

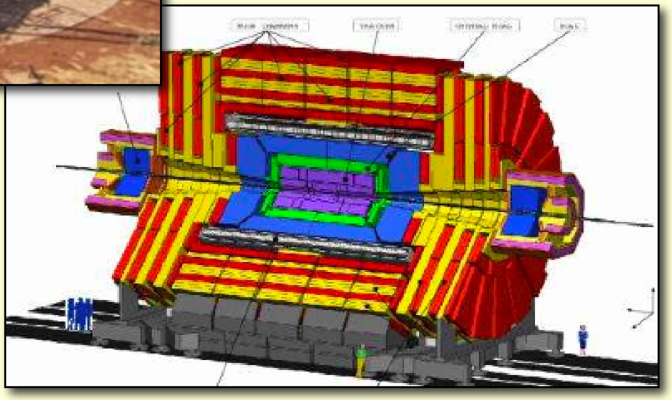
- OUR RESULTS: Two of the five hi-z JWST objects w published spectra are consistent with Dark Stars.

WIMP Hunting: Good chance of detection this decade



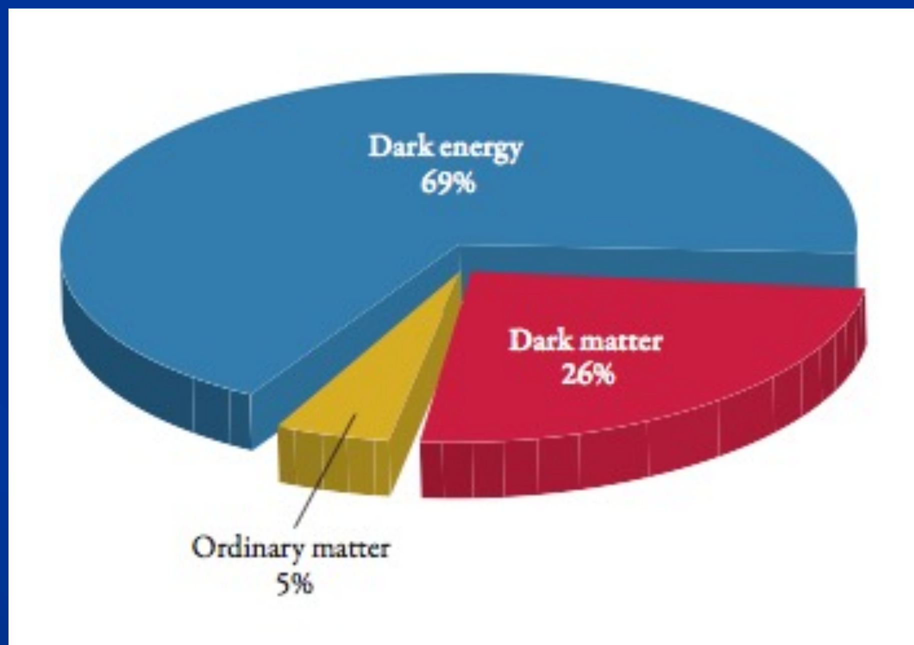
- Direct Detection

- Indirect Detection
- Collider Searches

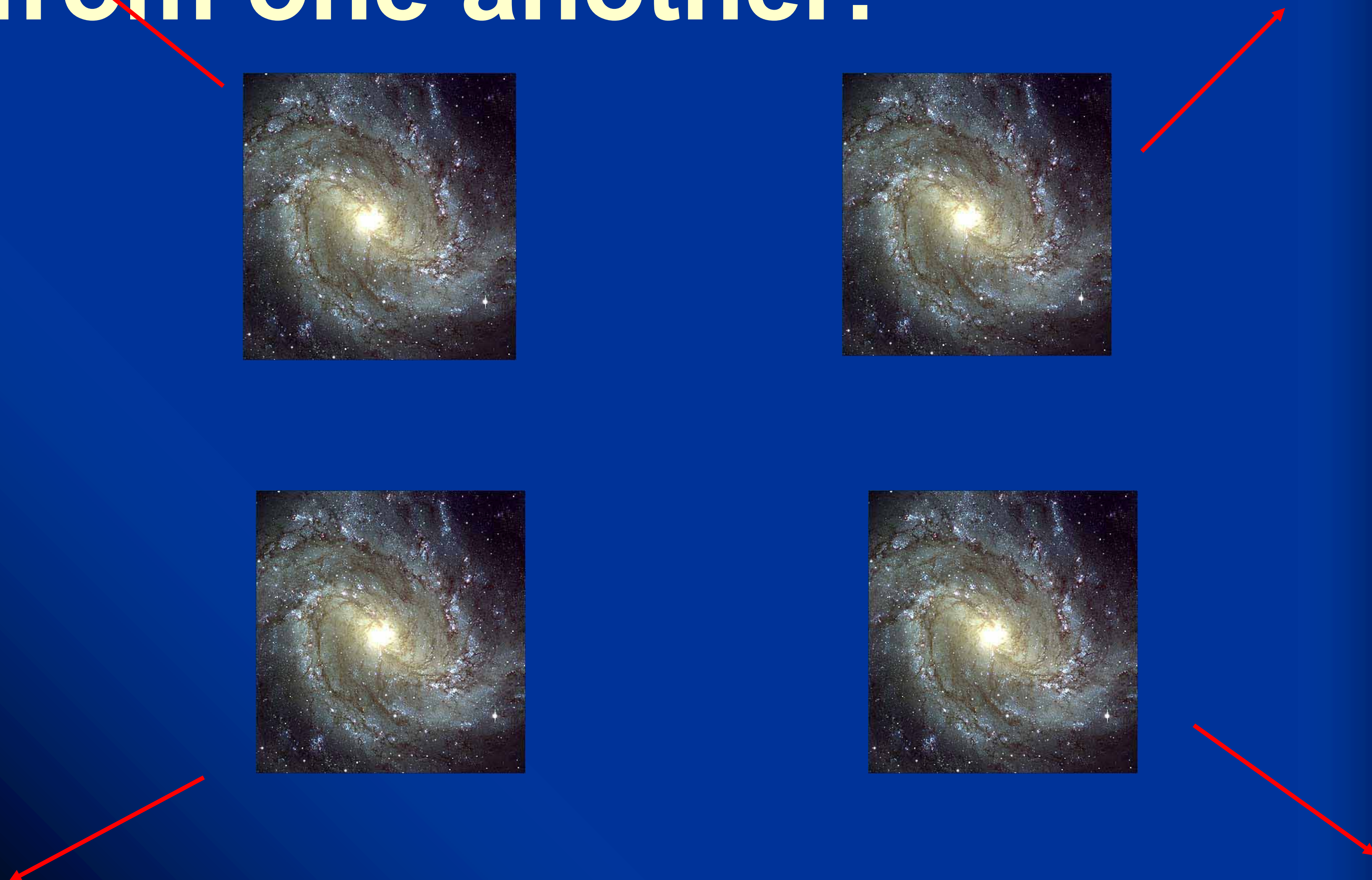


Looking for Dark Stars

Even stranger: Dark Energy



DARK ENERGY: Galaxies are accelerating apart from one another!



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 Recipe

3 oz. dark matter
7 oz. dark energy
1/2 oz. hydrogen and helium gas
3 thousandths oz. other chemical elements
5 hundredths oz. stars
5 hundredths oz. neutrinos
5 ten-thousandths oz. cosmic microwave background light
1 millionth oz. supermassive black holes

Shaken, not stirred.
Secret ingredient: dark matter

THE END and extra slides

At Nobel Prize dinner and ball 2017

Fuzzy Dark Matter (UltraLight Axion)

- Particle masses are around 10^-32 times that of a proton. So light they act more like waves than particles.

- At scales larger than galaxies the dark matter acts like cold dark matter, while below the scale quantum pressure from the uncertainty principle suppresses the smaller structure formation so that it can resolve the small scale crisis of the conventional cold dark matter model.

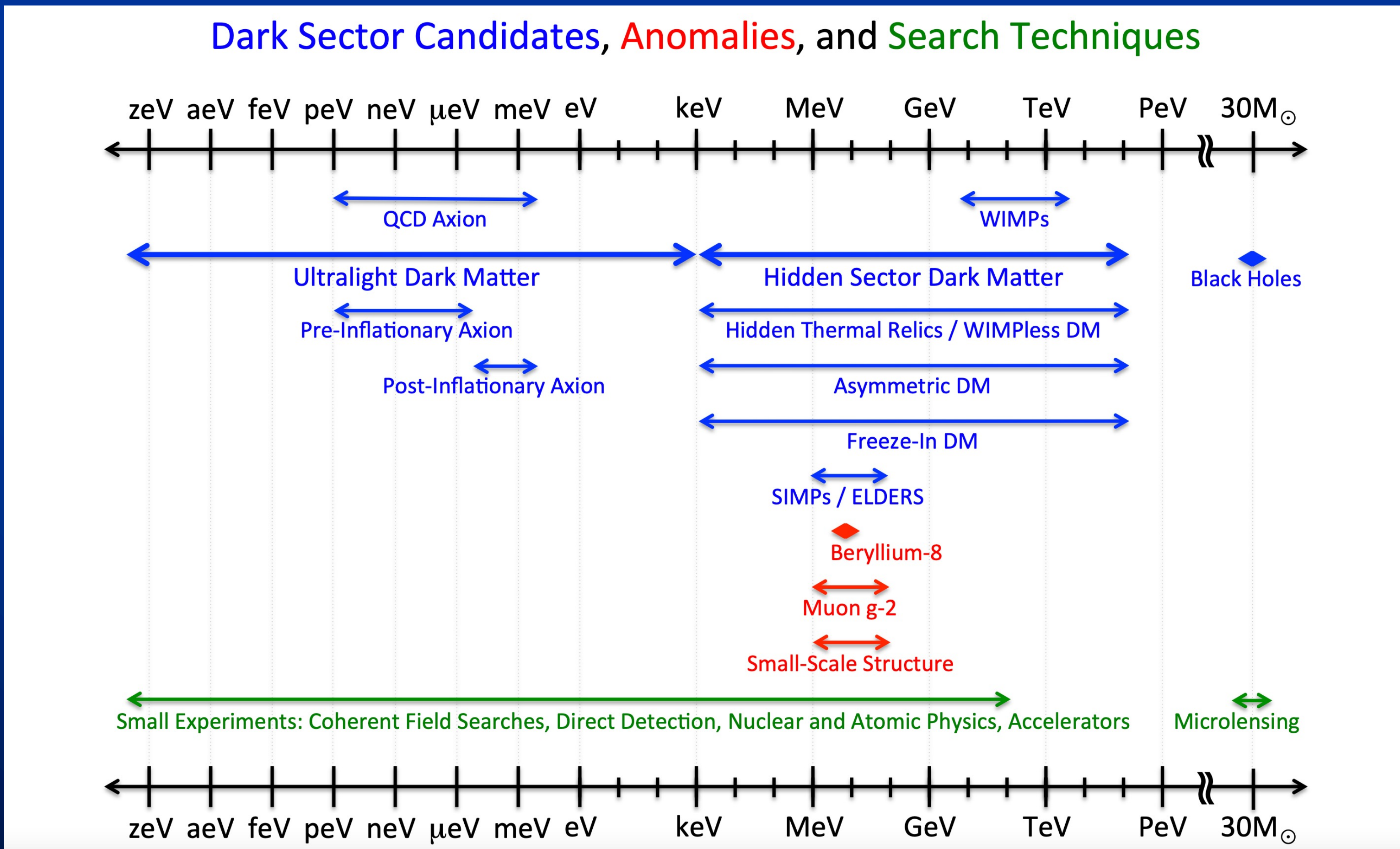
Fuzzy Dark Matter (ultralight axion)

Particle masses are around 10^-32 times that of a proton.
So light they act more like waves than particles.

Fuzzy DM. Another possibility is DM as an ultralight scalar field. For particles of mass m and velocity v, the corresponding de Broglie wavelength is

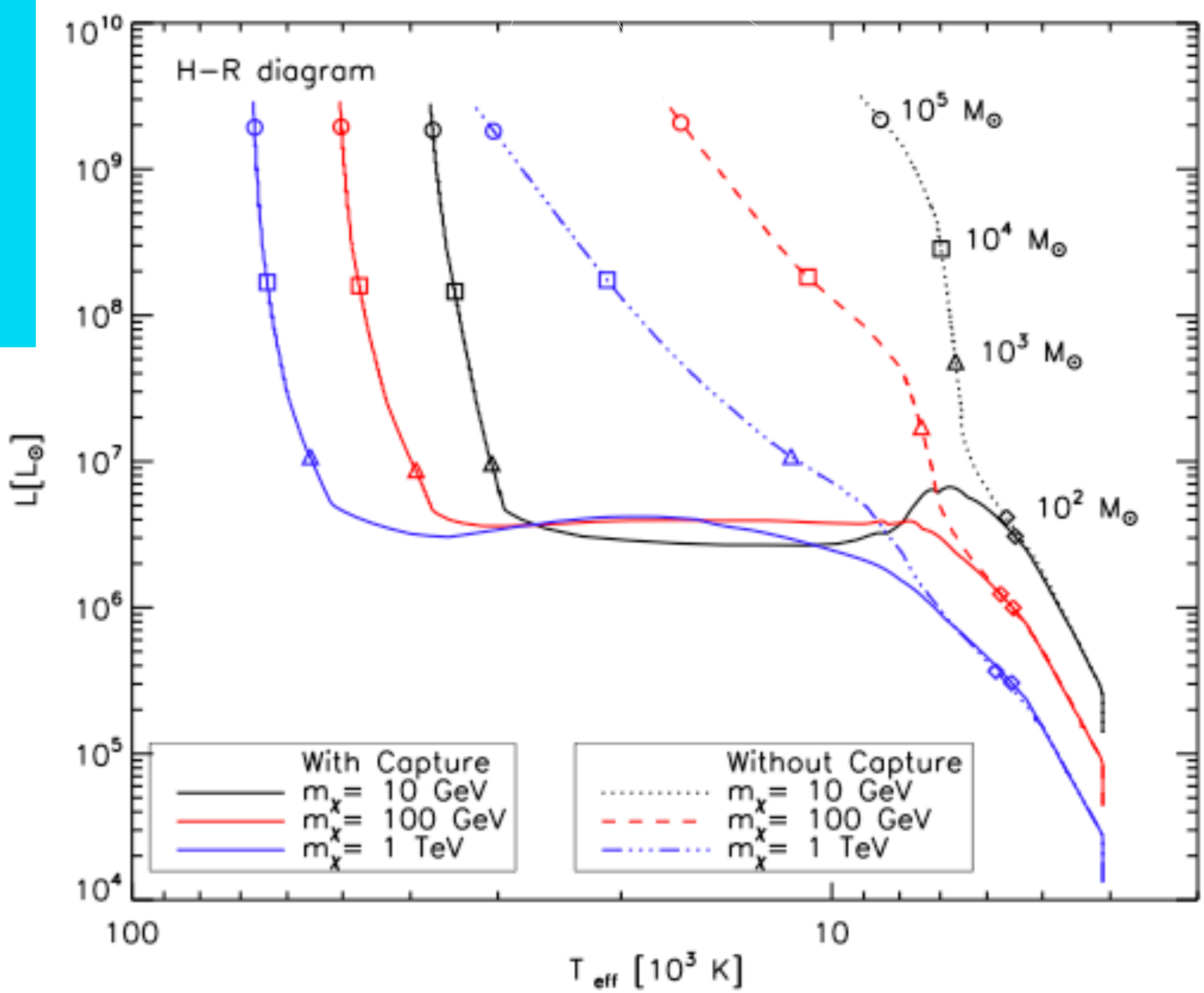
$$\lambda_{\mathrm{dB}} \approx 600\ \mathrm{pc}\left(\frac{10^{-23}\ \mathrm{eV}}{m}\right)\left(\frac{10^{-3}}{v}\right). \tag{2}$$

The wave nature of the DM stabilizes it from collapse on scales of λ_{dB}, smoothing out inhomogeneities on smaller scales and thereby suppressing structure [230]. For DM within the Galaxy, the scalar field behaves classically. Its pressure oscillates with an angular frequency $\omega \approx 2m$ and induces oscillations in the gravitational potential [231]. DM masses of $m \sim 10^{-23}$ eV are particularly interesting, since the oscillation frequency $f \sim 5 \times 10^{-8}(m/10^{-22}\ \mathrm{eV})$ Hz is in the sensitivity range of PTAs. Current limits constrains the ultralight DM density to be below $6\ \mathrm{GeV/cm^3}$ for masses $m \lesssim 10^{-23}$ eV [232].


Dark Sector Candidates, Anomalies, and Search Techniques
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS
Beryllium-8
Muon g-2
Small-Scale Structure
Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
Microlensing
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙

Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

Assuming all of the baryons can accrete in a 10^6 $M_\odot$ halo



DS in JWST

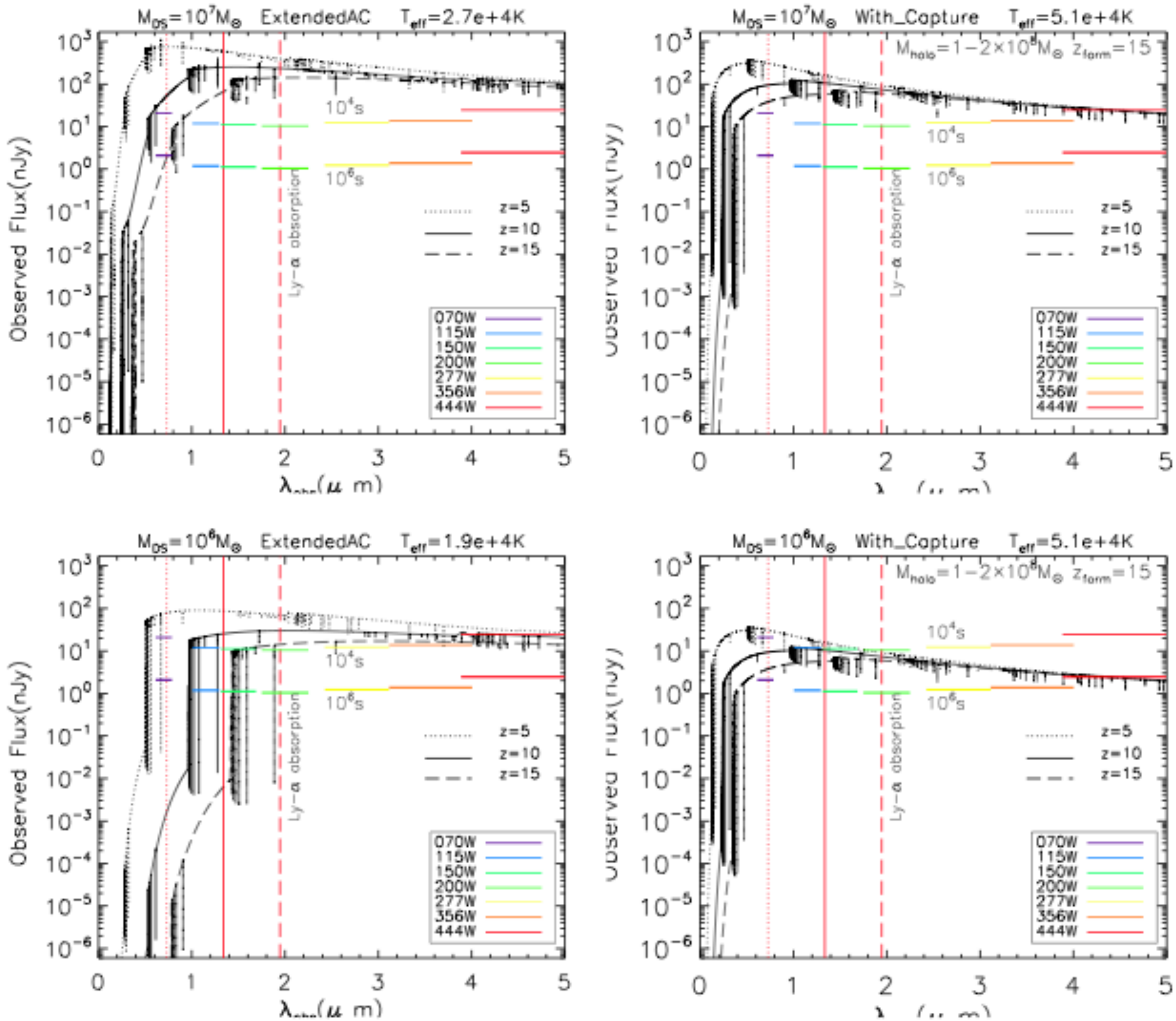


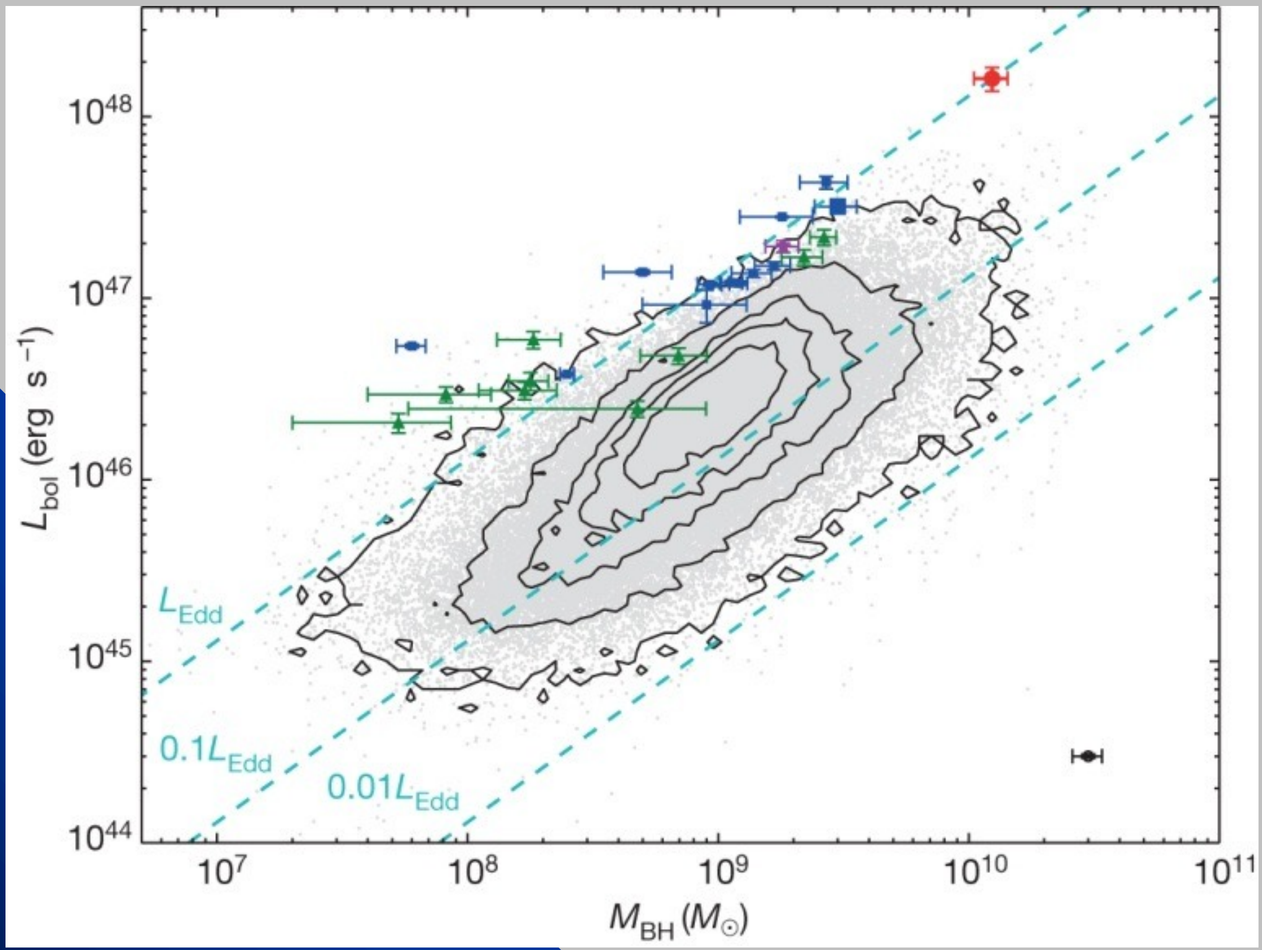
Figure 7. Spectra for supermassive DSs formed at $z_{\rm form} = 15$ (formation redshift)

What happens next? BIG BLACK HOLES

- Star reaches $T=10^7$K, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
- (I) in centers of galaxies
- (ii) billion solar mass BH at z=6 (Fan, Jiang)
- (iii) intermediate mass BH

SupperMassive Black holes from Dark Stars

Very Massive progenitor Million Solar Masses at z=6
No other way to form supermassive BH this early



X-B Wu *et al. Nature* **518**, 512-515 (2015) doi:10.1038/nature14241

nature

An 800 million solar mass black hole in a significantly neutral universe at redshift 7.5

Eduardo Bañados[1,*], Bram P. Venemans[2], Chiara Mazzucchelli[2], Emanuele P. Farina[2], Fabian Walter[2], Feige Wang[3,4], Roberto Decarli[2,5], Daniel Stern[6], Xiaohui Fan[7], Fred Davies[8], Joseph F. Hennawi[8], Rob Simcoe[9], Monica L. Turner[9,10], Hans-Walter Rix[2], Jinyi Yang[3,4], Daniel D. Kelson[1], Gwen Rudie[1], and Jan Martin Winters[11]

[1]The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
[2]Max Planck Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany
[3]Department of Astronomy, School of Physics, Peking University, Beijing 100871, China
[4]Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
[5]INAF – Osservatorio Astronomico di Bologna, via Gobetti 93/3, 40129, Bologna, Italy
[6]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[7]Steward Observatory, The University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721–0065, USA
[8]Department of Physics, Broida Hall, University of California, Santa Barbara, CA 93106–9530, USA
[9]MIT-Kavli Center for Astrophysics and Space Research, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA
[10]Las Cumbres Observatory, 6740 Cortona Dr, Goleta, CA 93117, USA
[11]Institut de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, 38406 Saint Martin d'Hères, France
[*]ebanados@carnegiescience.edu

ABSTRACT

Quasars are the most luminous non-transient objects known, and as such, they enable unparalleled studies of the universe at the earliest cosmic epochs. However, despite extensive efforts from the astronomical community, the quasar ULAS J1120+0641 at $z = 7.09$ (hereafter J1120+0641) has remained as the only one known at $z > 7$ for more than half a decade[1]. Here we report observations of the quasar ULAS J134208.10+092838.61 (hereafter J1342+0928) at a redshift of $z = 7.54$. This quasar has a bolometric luminosity of $4 \times 10^{13} L_{\odot}$ and a black hole mass of $8 \times 10^{8} M_{\odot}$. The existence of this supermassive black hole when the universe was only 690 Myr old, i.e., just 5% its current age, reinforces early black hole growth models that allow black holes with initial masses $\gtrsim 10^{4} M_{\odot}$[2,3] or episodic hyper-Eddington accretion[4,5]. We see strong evidence of the quasar's Lyα emission line being absorbed by a Gunn-Peterson damping wing from the intergalactic medium, as would be expected if the intergalactic hydrogen surrounding J1342+0928 is significantly neutral. We derive a significant neutral fraction, although the exact value depends on the modeling. However, even in our most conservative analysis we find $\bar{x}_{HI} > 0.33$ ($\bar{x}_{HI} > 0.11$) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.