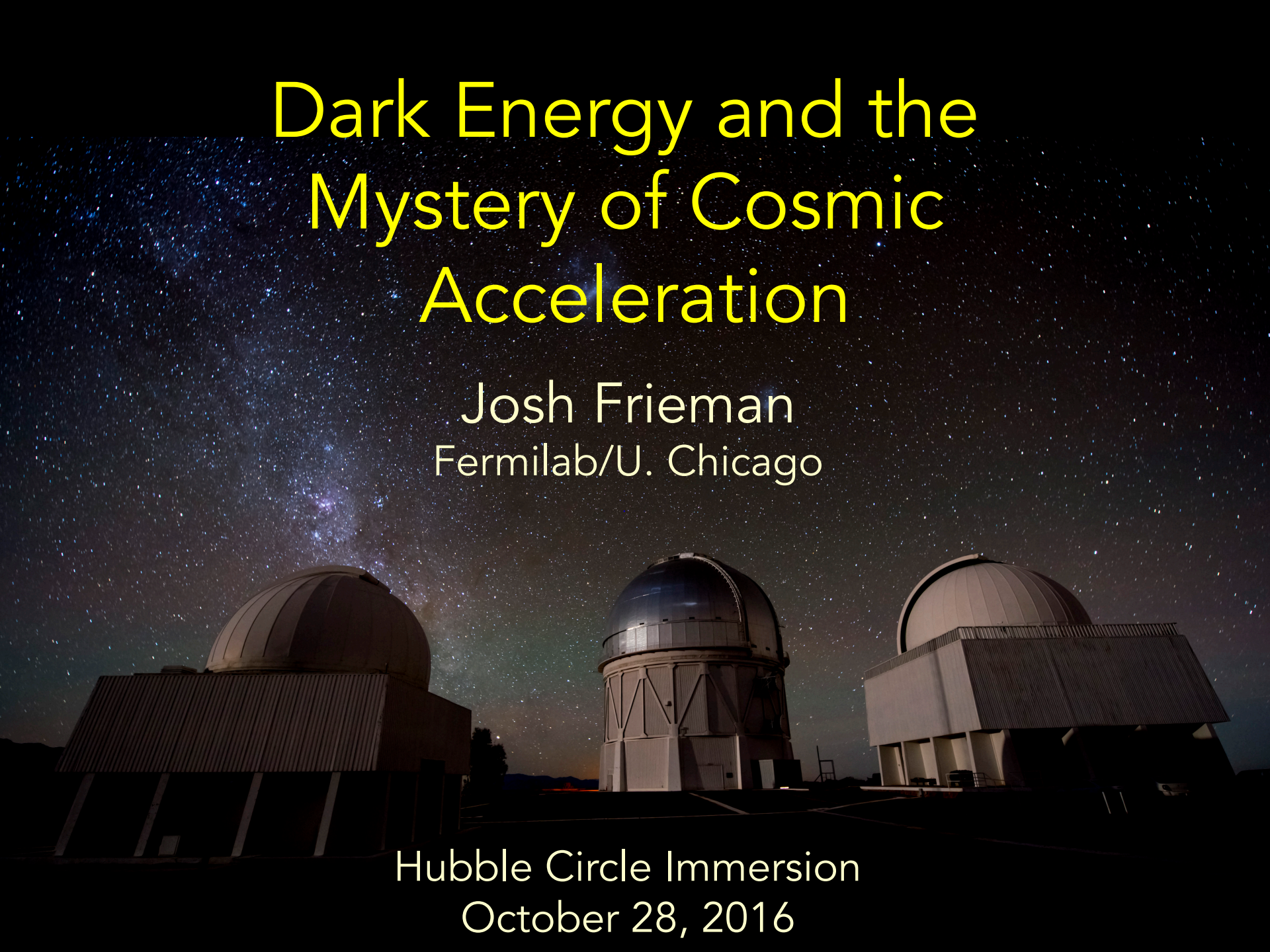
Dark Energy and the Mystery of Cosmic Acceleration

Josh Frieman
Fermilab/U. Chicago



Hubble Circle Immersion
October 28, 2016

Galaxies visible with the naked eye in the Southern hemisphere

Galaxies: ~60,000 light-years across, contain ~10 billion stars

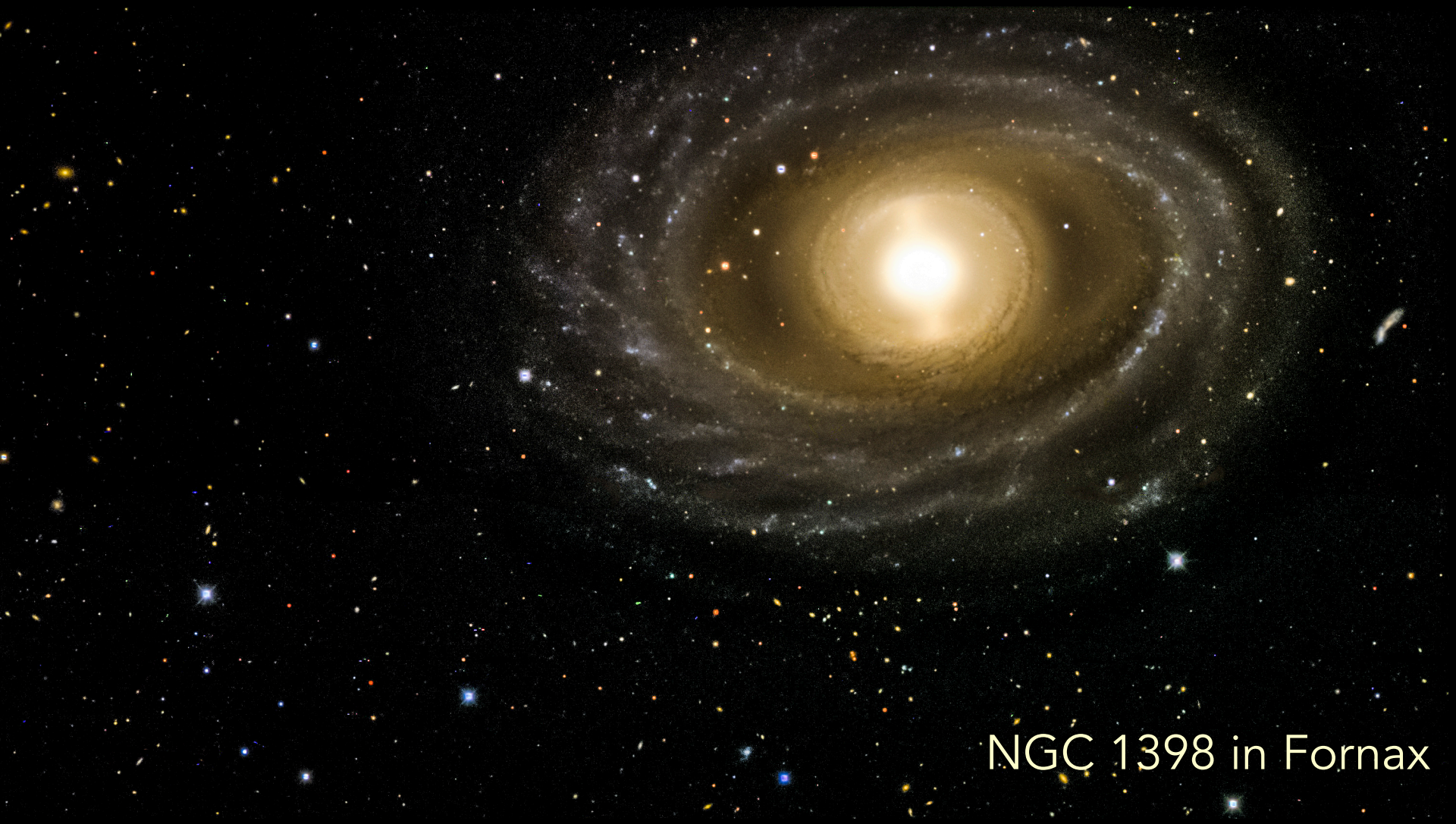


Image taken with the Dark Energy Camera

Vera Rubin
(1970's)

Galaxy M33

Dark Matter (V. Rubin)

- The stars in a galaxy like M33 are moving around faster than we can explain.
- The gravity of something *that we can't see* must be keeping the stars from flying off into space: Dark Matter
- Galaxies are mostly made of dark matter: stars are like sprinkles on dark matter ice cream.
- We know dark matter is there because it exerts gravitational pull on the stars we can see in galaxies.

Evidence for Dark Matter from Weak Lensing by Galaxies

- Measure the shapes of a large sample of distant `background' galaxies, the images of which are very weakly distorted by the gravity of the Dark Matter of a foreground population of galaxies

- This method probes the *average* mass of a population of galaxies.

Lensing results:

Luminous Galaxies are surrounded by Extended, Massive Halos of Dark Matter

December 14, 1999

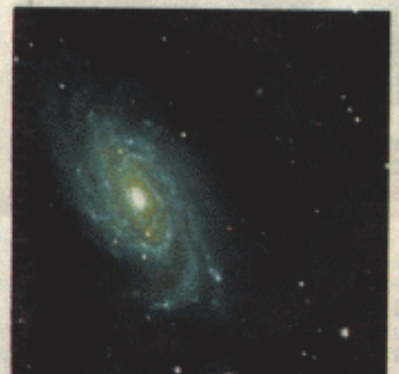
Science Ti

The New York Time

Galaxies' Vastness Surprises Scientists

By JAMES GLANZ

Using a technique akin to overlaying thousands of faint X-ray images to create one sharp picture, astronomers have discovered that typical galaxies may be twice as large and contain twice as much mass as suggested by previous measurements. The new observations, which have emerged from a five-year census of the heavens called the Sloan Digital Sky Survey, indicate that an average galaxy extends invisibly for well over a million light-years into space and weighs the equivalent of at



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A portrait of a woman far different from the cavewoman stereotype is emerging from these Stone Age Venuses: above is Venus of Willendorf in Austria; at right, the back and front views of Venus of Kostenki in Russia; far right, Venus of Lespugue, with prominent buttocks and a "grass" skirt, in southwest France.

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Bu
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By NATALIE ANGIER

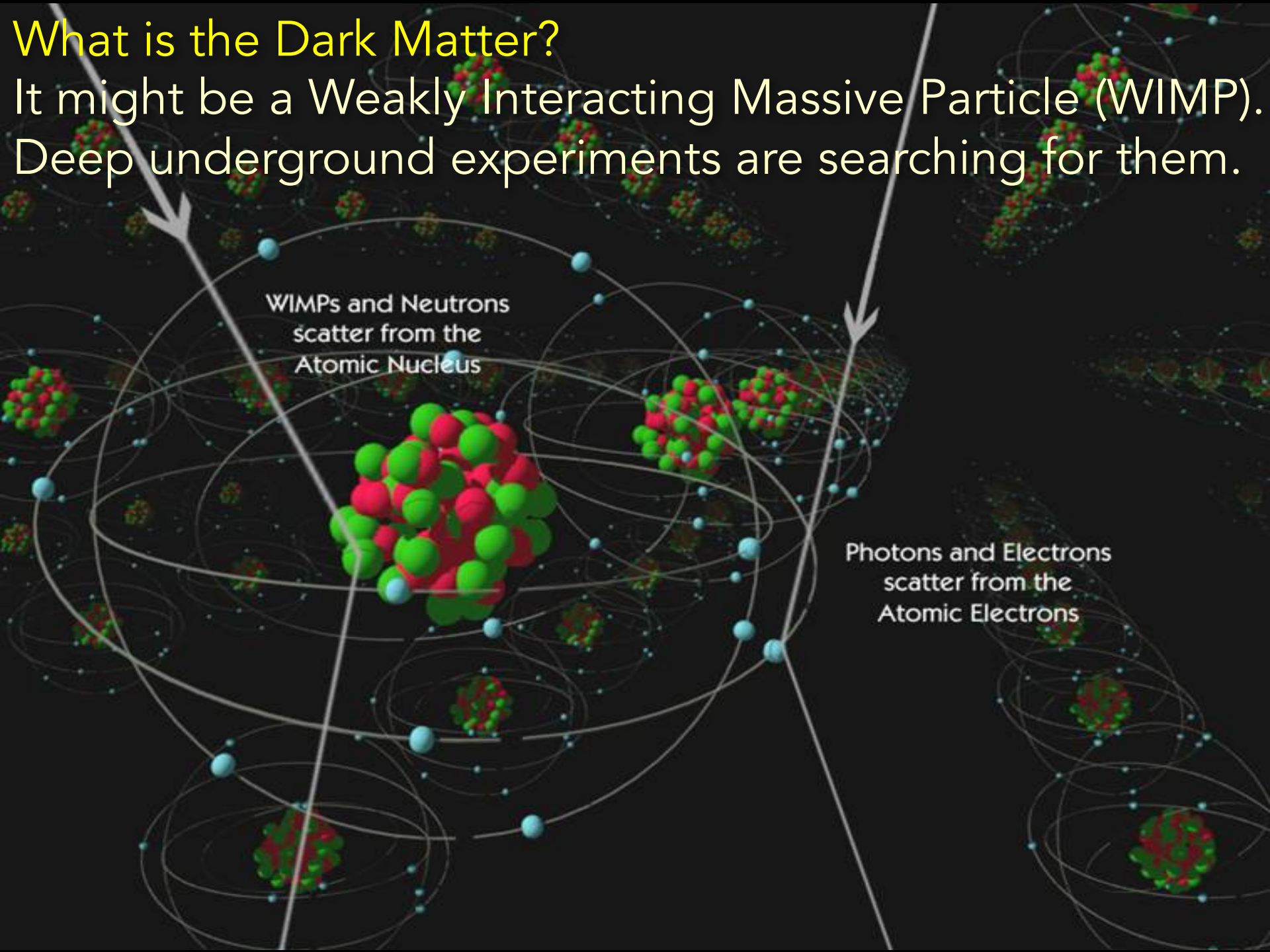
Ah, the poor Stone Age woman of our kitschy imagination. When she isn't getting bonked over the head with a club and

Dark Matter

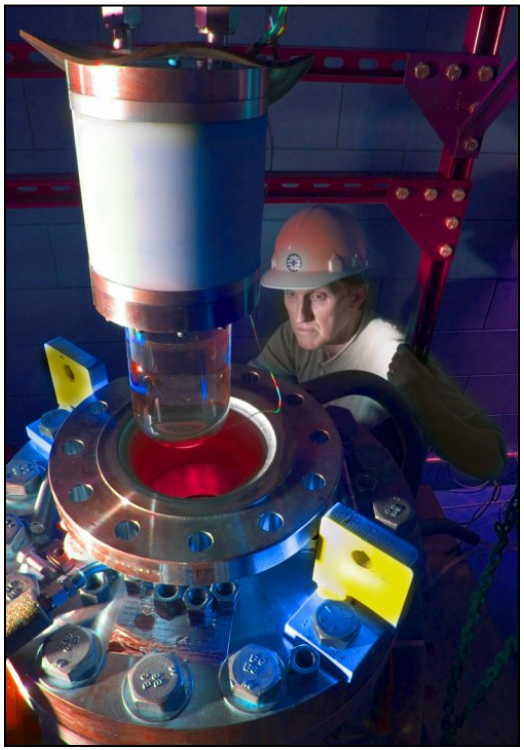
- Is dark matter made of atoms?
  - Very faint stars, planets, and other things made of atoms can't do it: there aren't enough atoms in the Universe to account for all the dark matter we infer in galaxies.
  - Dark matter must be made of something other than atoms: likely a new kind of elementary particle that we've never seen before.

What is the Dark Matter?

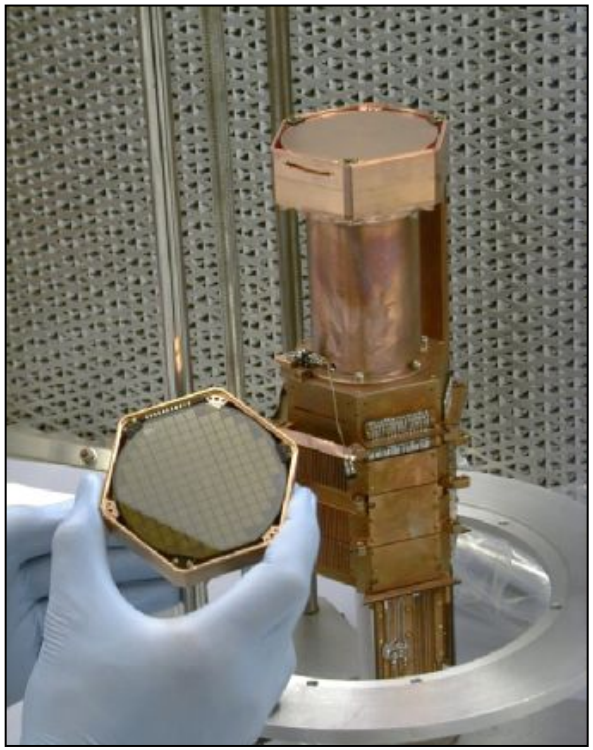
It might be a Weakly Interacting Massive Particle (WIMP).
Deep underground experiments are searching for them.



COUPP



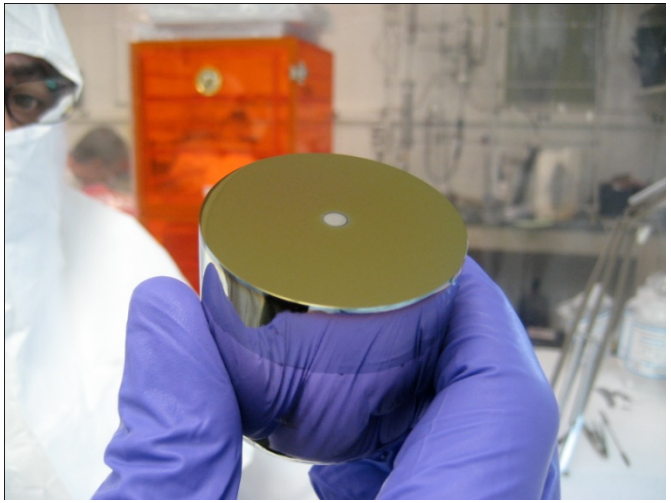
CDMS



XENON

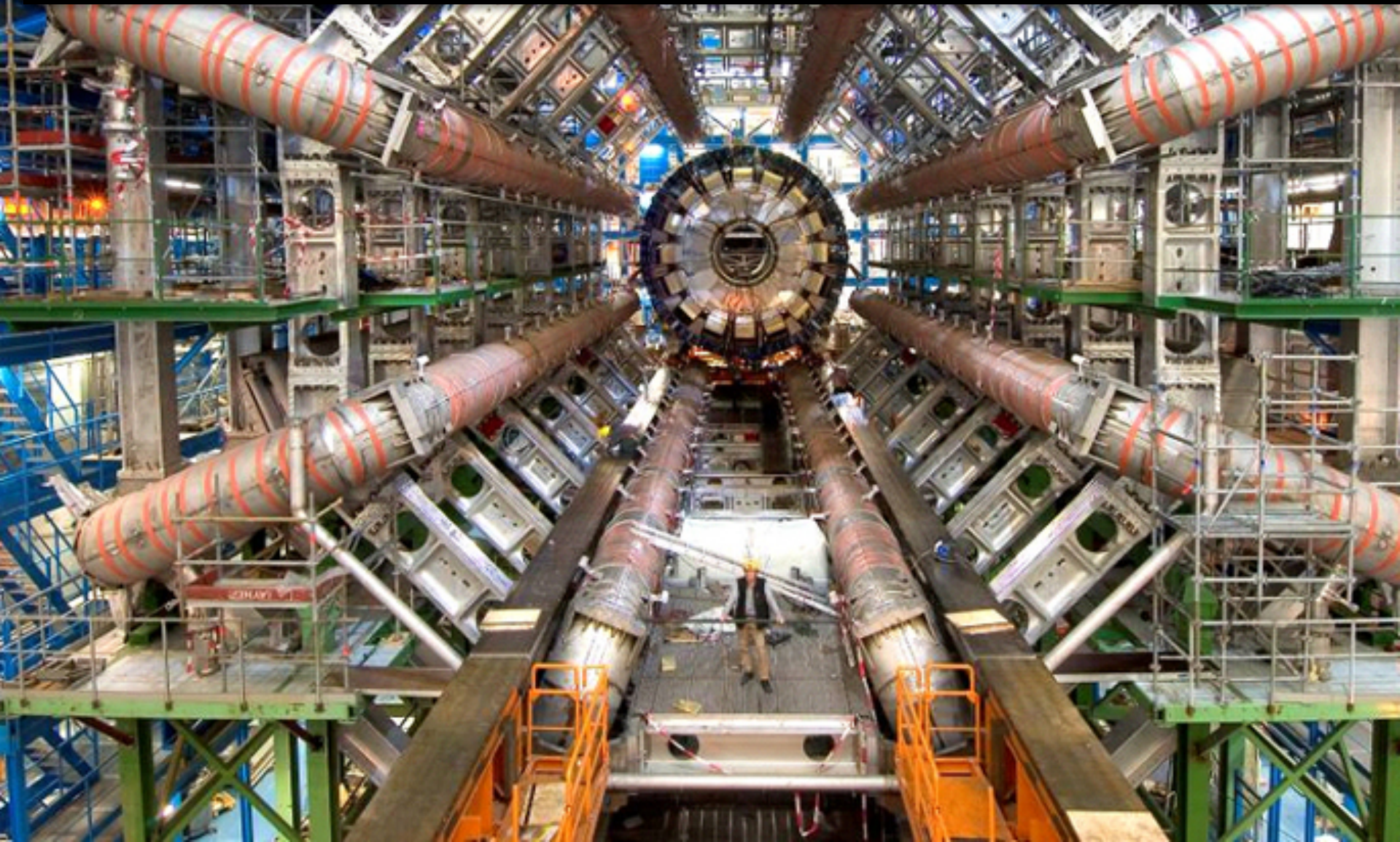
Experiments searching for Dark Matter particles

CoGeNT



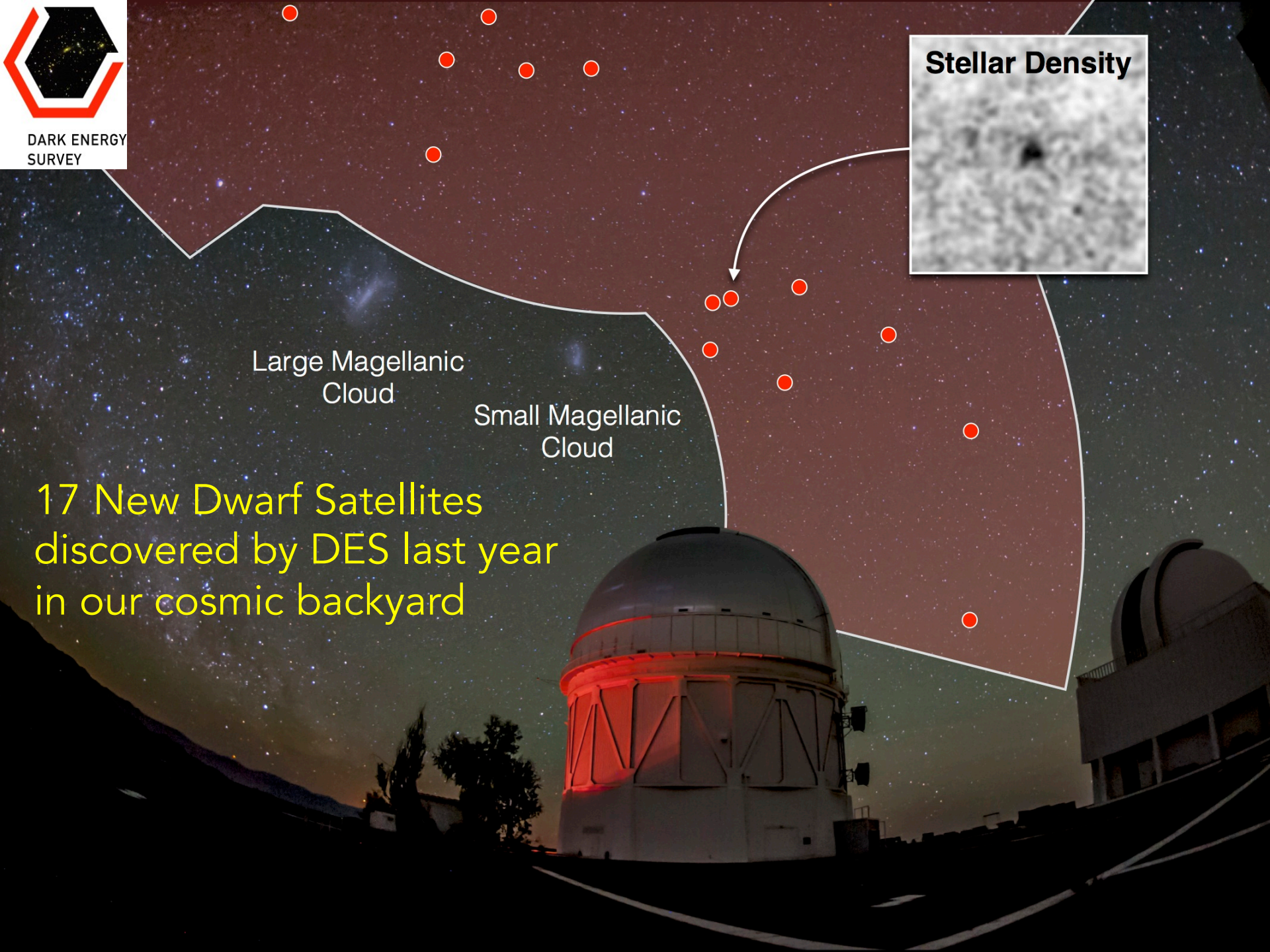
DAMA/LIBRA

WIMPs might also be produced at the
Large Hadron Collider now operating in Switzerland,
where the Higgs Boson was discovered in 2012.



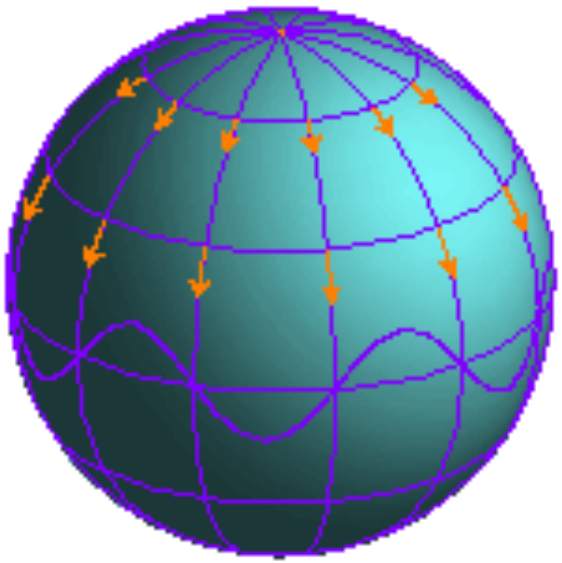
Dark Matter Annihilation

- A third method to discover WIMPs would be annihilation of WIMP particles and anti-particles at the center of the Milky Way or in nearby dwarf galaxies.
- WIMP/anti-WIMP annihilation would produce intense beams of gamma rays observable with NASA's Fermi gamma-ray satellite.
- Last year, we discovered 17 new nearby dwarf galaxies and worked with Fermi to hunt for dark matter in them.


DARK ENERGY SURVEY
Stellar Density
Large Magellanic Cloud
Small Magellanic Cloud
17 New Dwarf Satellites discovered by DES last year in our cosmic backyard

The Expanding Universe

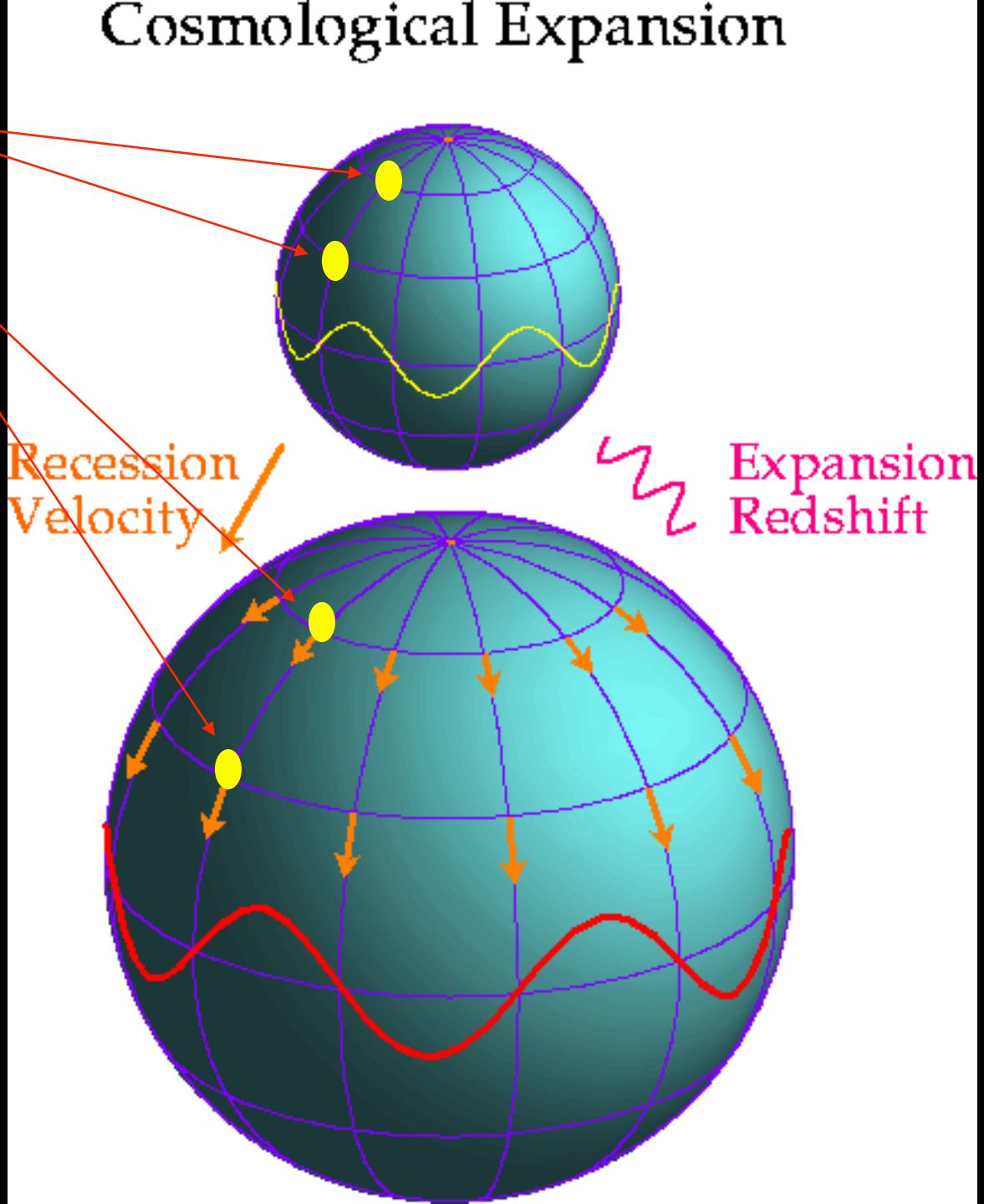
Run it backward: expansion started in a Big Bang 13.8 billion years ago



The distance *between* galaxies increases with time

A galaxy 100 Million light years away is moving away from us at 2000 miles per second.

Galaxies are not expanding: they are bound together by the gravity of dark matter.



Edwin Hubble
(1889-1953)
U Chicago grad

Proved that Spiral nebulae are galaxies outside the Milky Way

Discovered the Expanding Universe

Catalogued galaxies

University of Chicago 1909 National Champions

Does the expansion of the Universe change over time?

Does the expansion of the Universe change over time?

Gravity:

Milky Way is tugging on all the receding galaxies

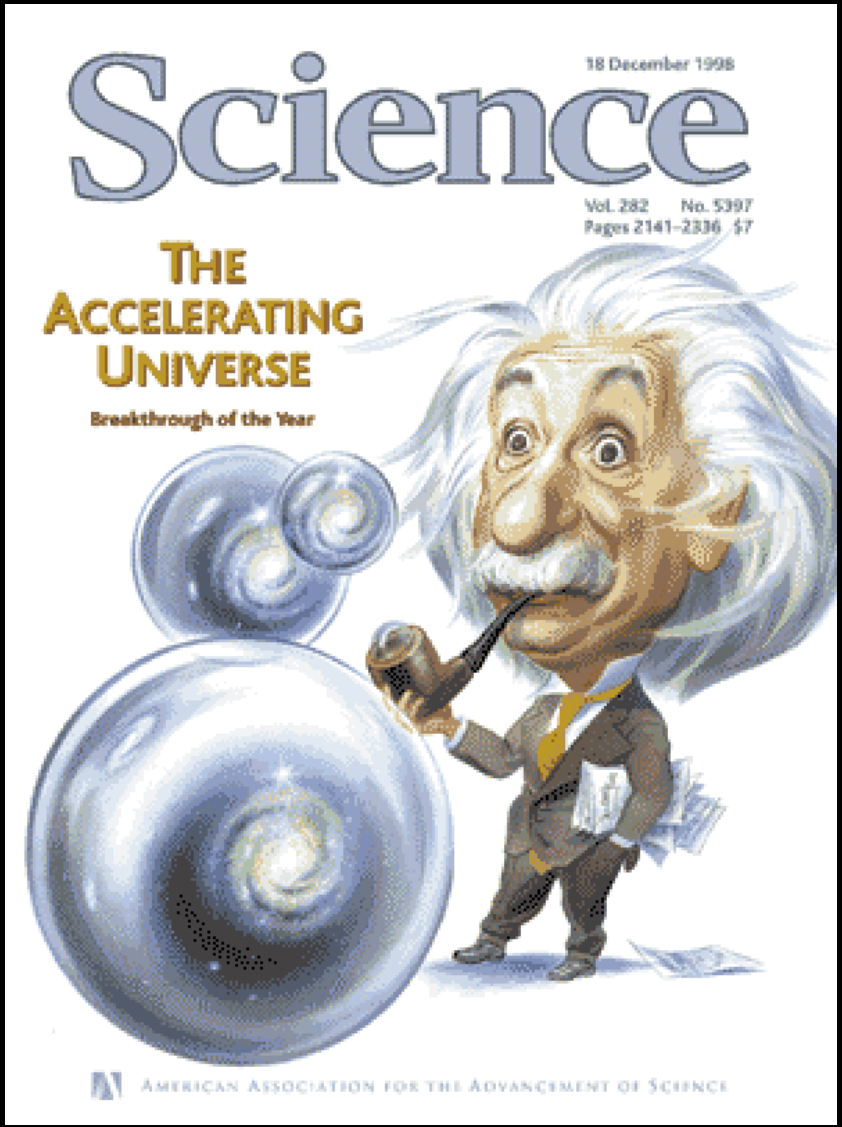
↓

they should slow down over time

The Expansion is Speeding Up

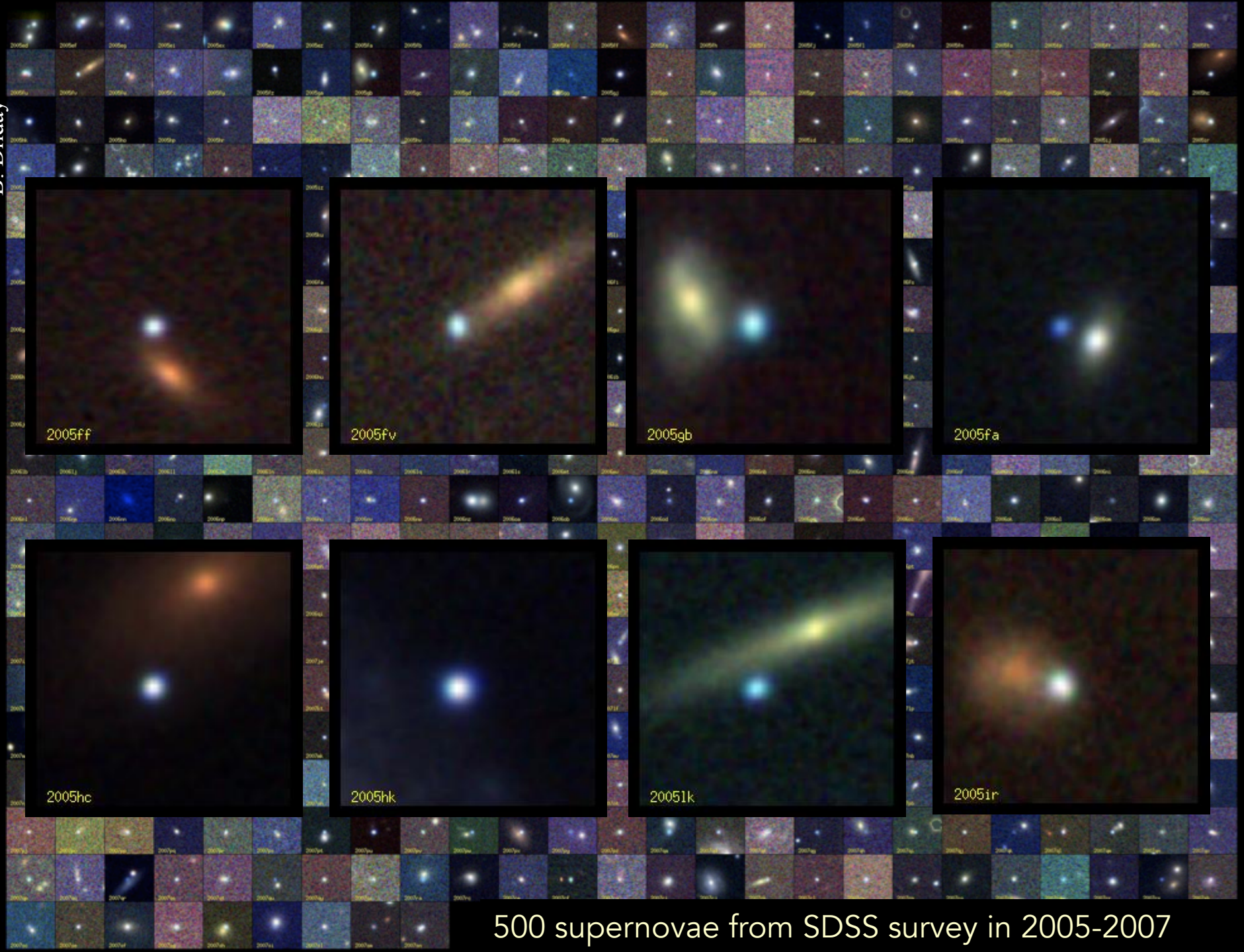
Discovered in 1998 by 2 teams of astronomers.

Nobel Prize in 2011 for this discovery.



Supernova: an exploding star. The brightness of distant supernovae showed that expansion is speeding up.

B. Dilday



500 supernovae from SDSS survey in 2005-2007

Type Ia Supernovae: Exploding White Dwarfs

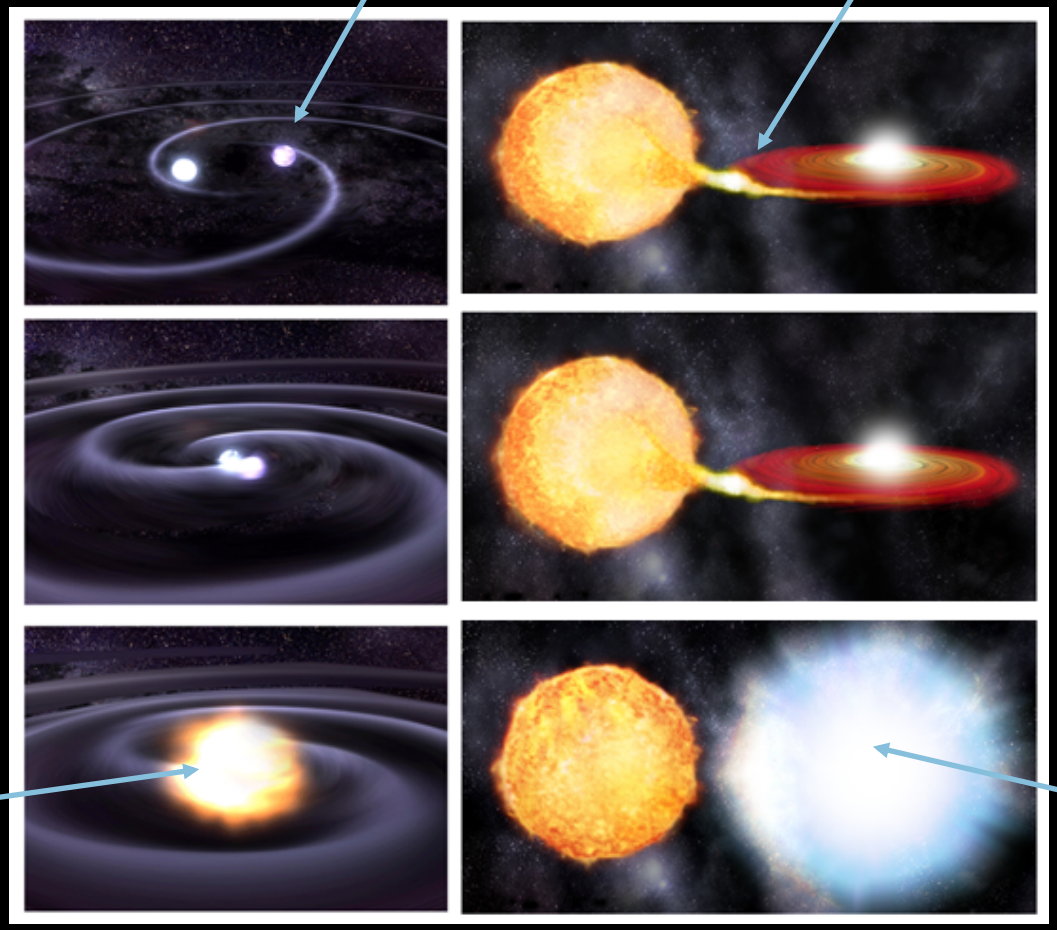
Nearly standard candle (uniform luminosity)

Carbon/Oxygen core of dead star

accretion from companion star

Colliding White Dwarf Model

Accreting White Dwarf Model



losing orbital energy via gravitational waves

Chandrasekhar mass (~1.4 M_{Sun})

thermonuclear explosion: runaway Carbon burning

10 billion times brighter than the Sun: as bright as an entire galaxy of stars

Why is this a mystery?

When you throw a ball straight up in the air, imagine it first slows down but then, instead of falling back to Earth, it starts speeding up and rockets out of the atmosphere.

That's what the Universe appears to be doing.

What causes Cosmic Speed-up?

Two possibilities:

1. The Universe is filled with stuff that gives rise to `anti-gravity'. We now call this

   Dark Energy

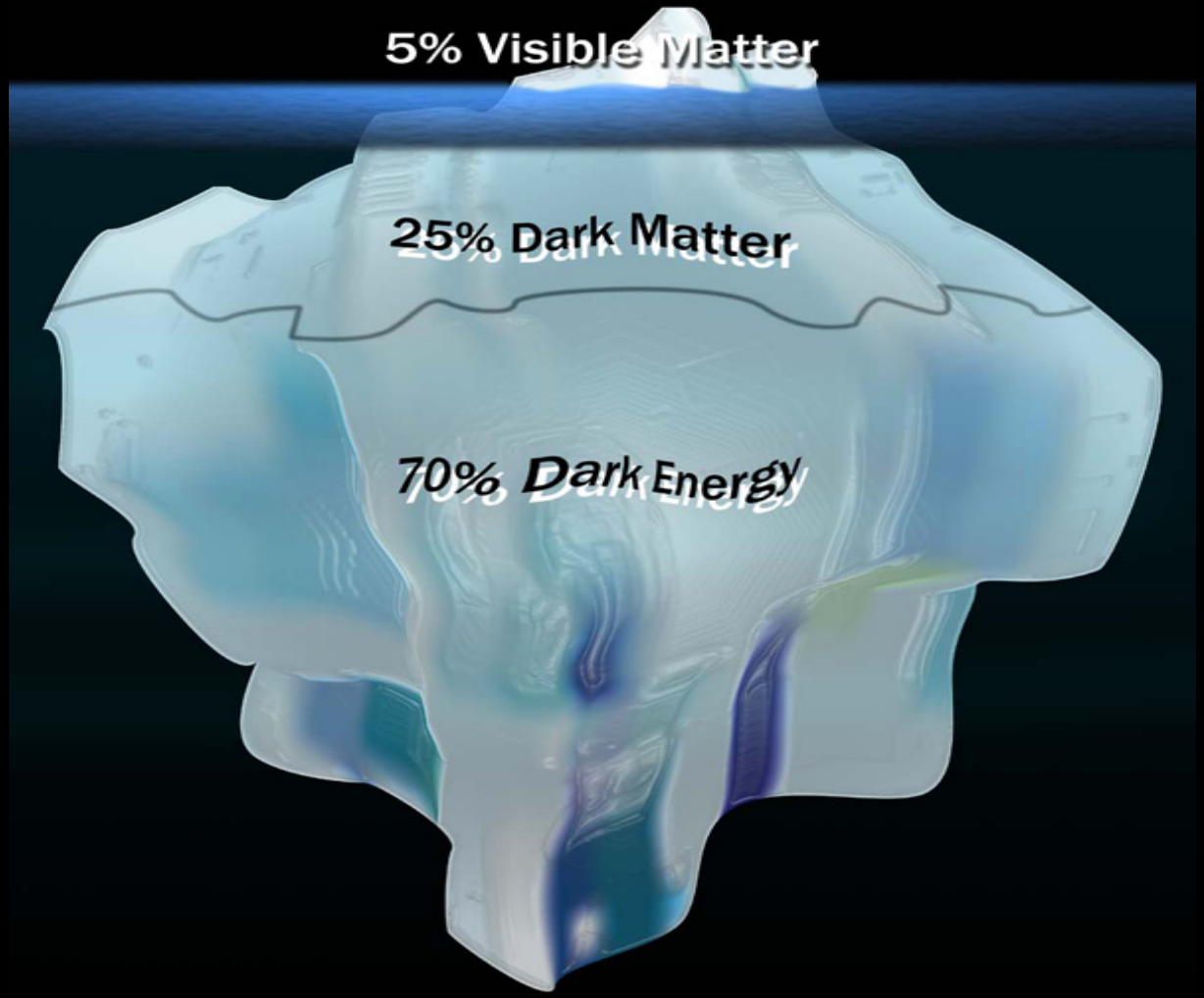
2. Our understanding of gravity—Einstein's Theory of General Relativity—-is wrong.

95% of the Universe is Dark

Ordinary Matter: atoms

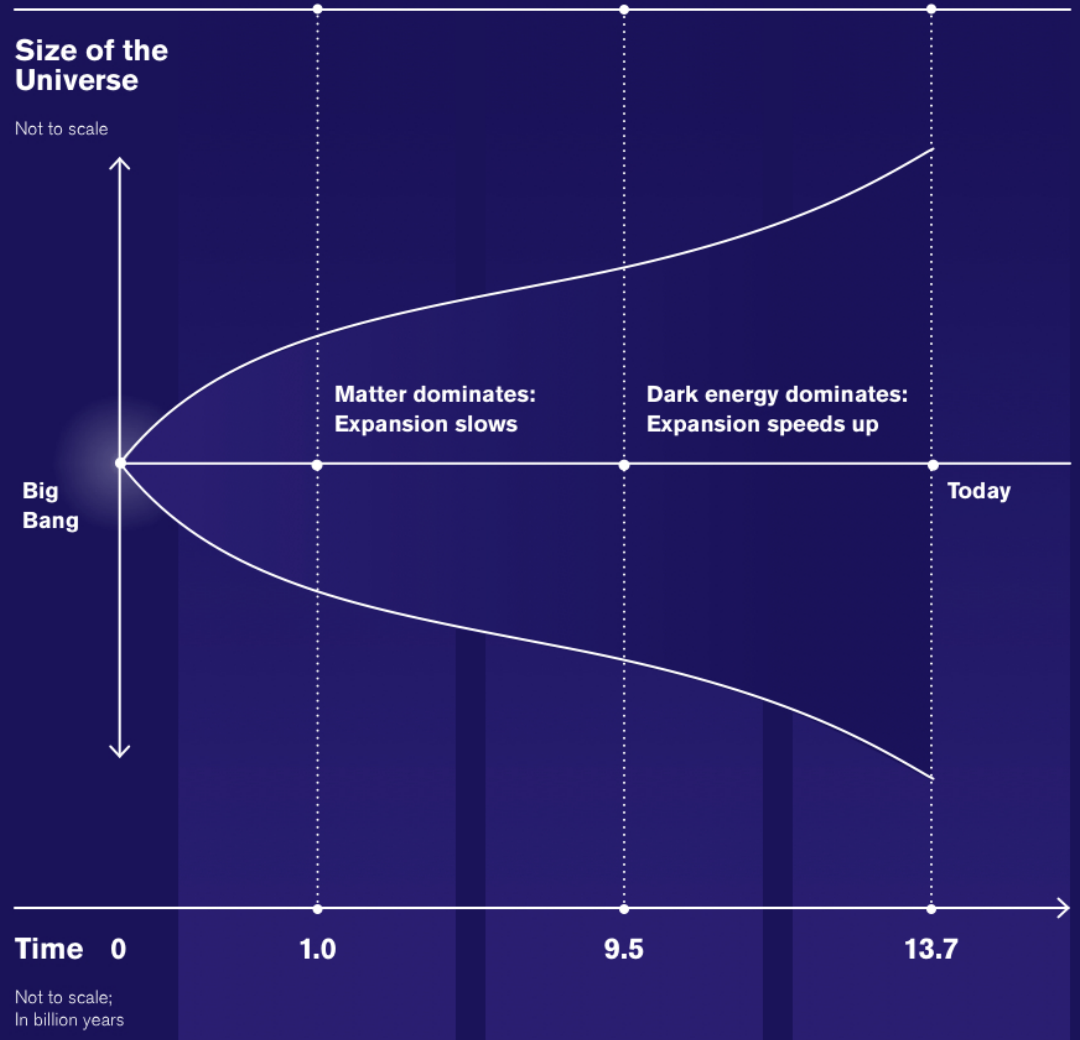
Dark Matter: holds galaxies together, helps them form

Dark Energy: `gravitationally repulsive' stuff that speeds up cosmic expansion

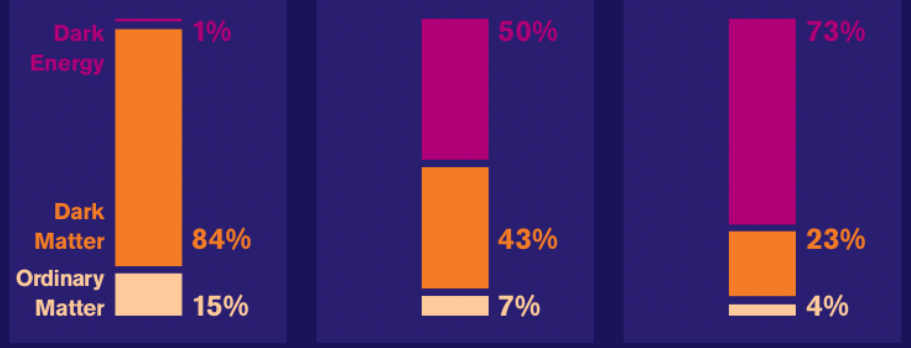


Size of the Universe

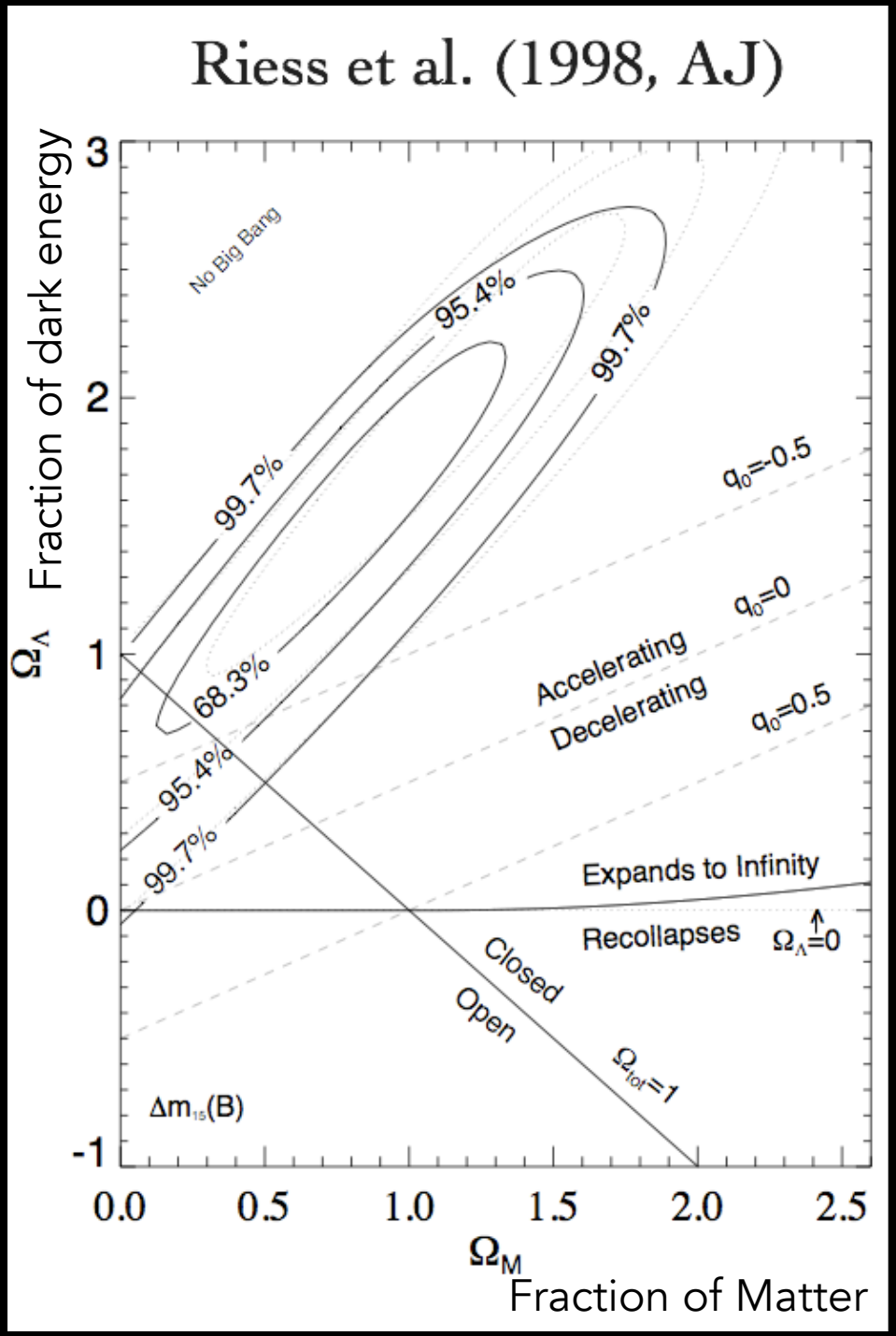
Not to scale



Energy and Matter Content

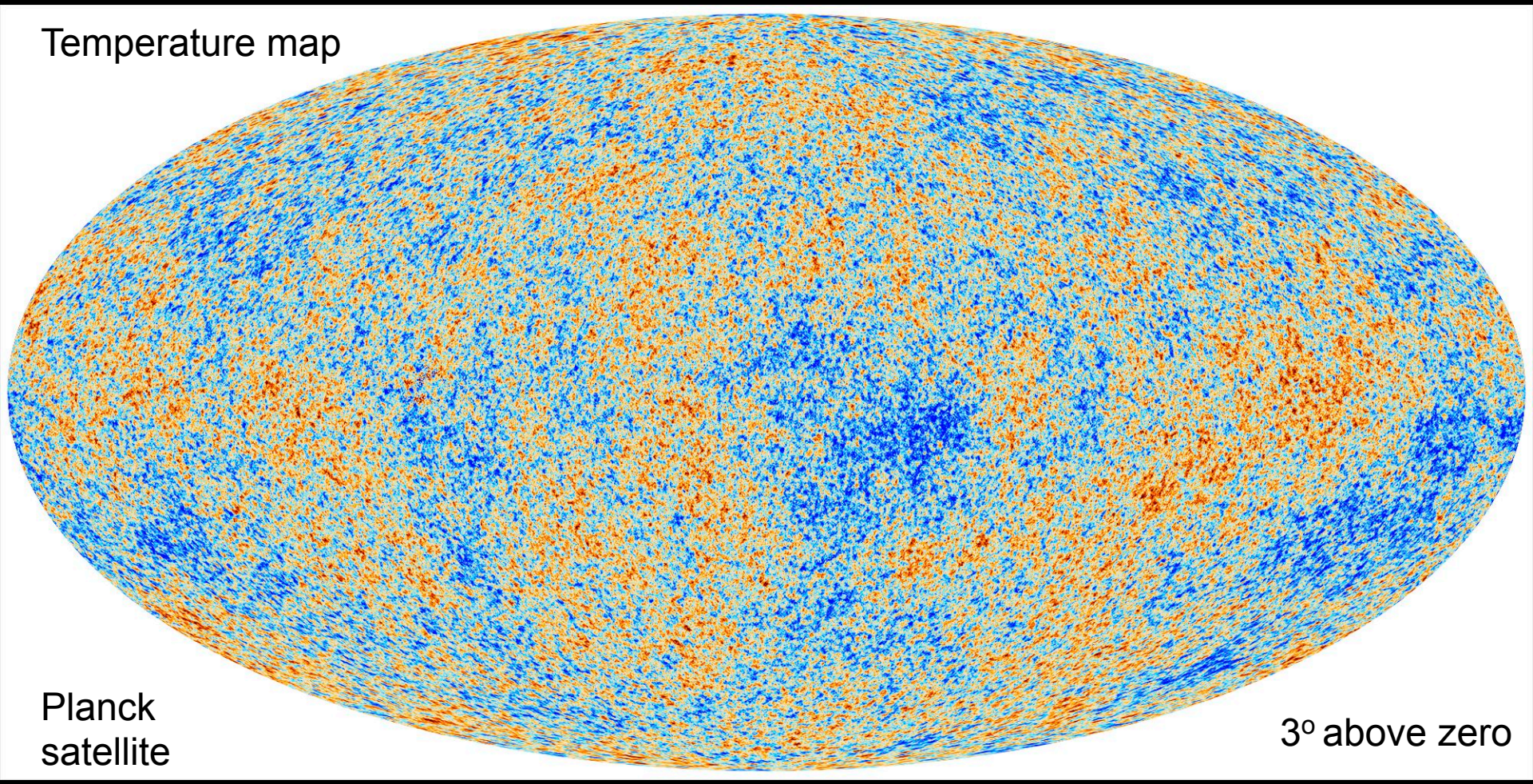


Discovery of Cosmic Acceleration



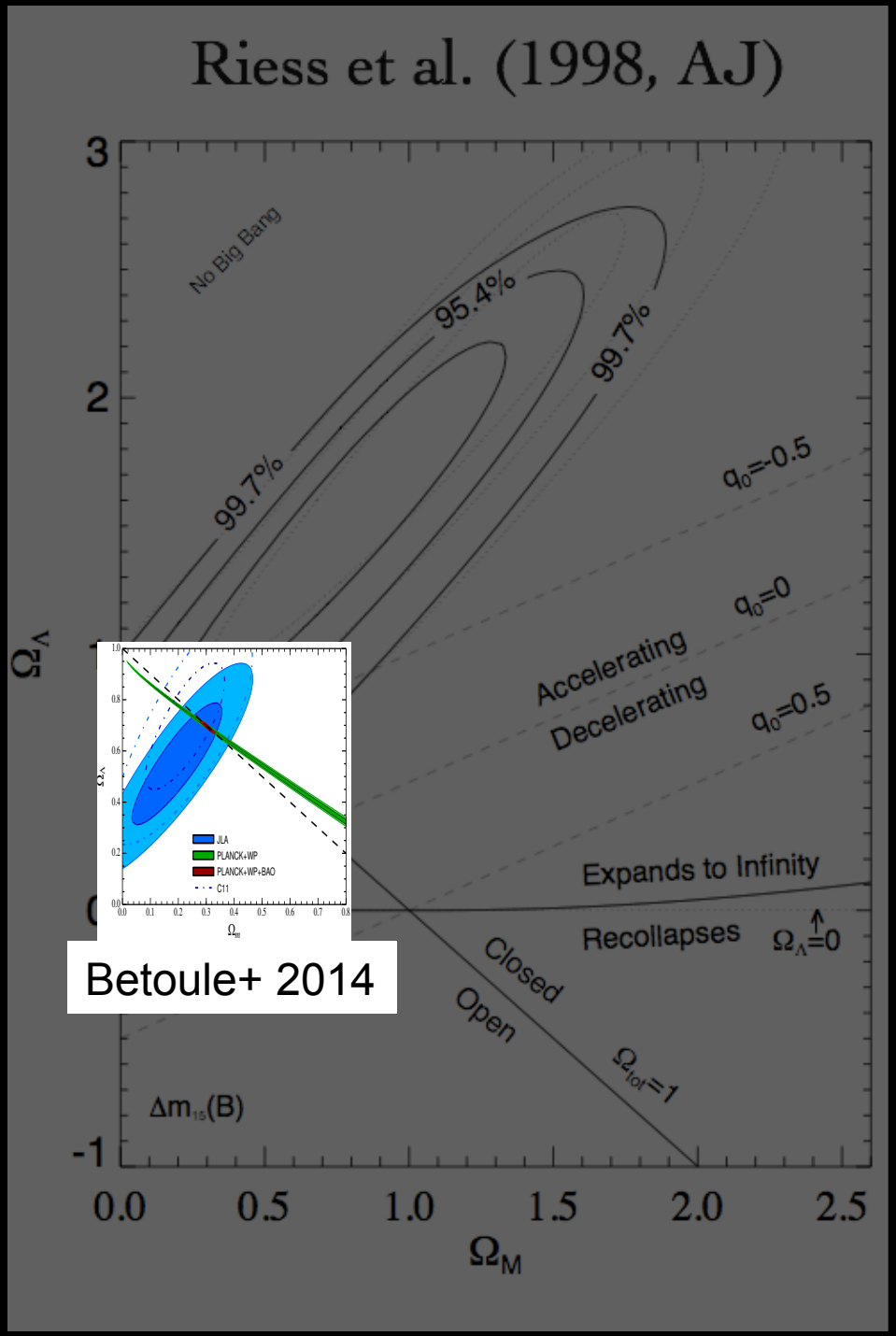
Supernovae

Cosmic Microwave Background Radiation



Snapshot of the Universe when it was 380,000 years old (and had a temperature of a few thousand degrees)

Progress over the last 18 years: evidence for acceleration more robust



Betoule+ 2014

Supernovae

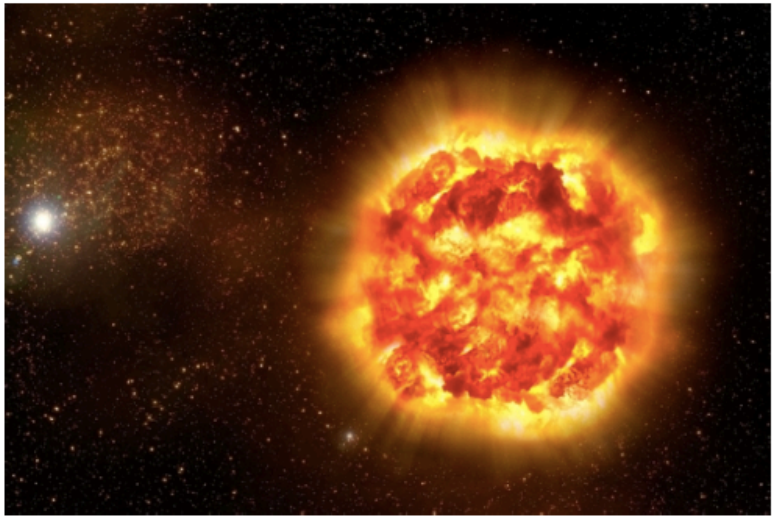
Cosmic Microwave Background (Planck satellite)

CMB+Large-scale structure

No, Astronomers Haven't Decided Dark Energy Is Nonexistent

You might have read otherwise in some headlines lately, but don't be misled

By Dan Scolnic, Adam G. Riess on October 26, 2016



What is Dark Energy?

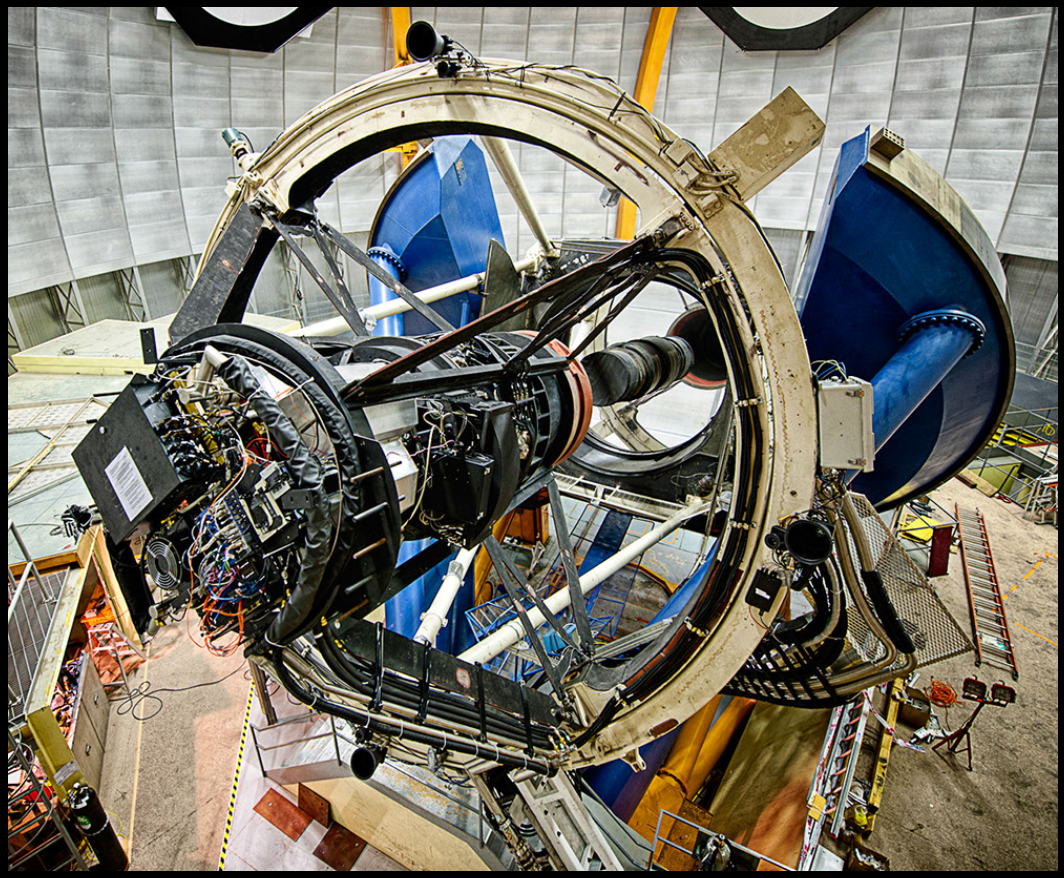
- We don't know: a component with negative pressure.
- Most conservative hypothesis is that it's the energy of empty space: the vacuum.
- Quantum theory predicts vacuum energy per unit volume should be infinite. Major embarrassment for theoretical physics.
- Other ideas (e.g., the energy of a much, much lighter cousin of the Higgs boson) even more speculative.

Why is Dark Energy important?

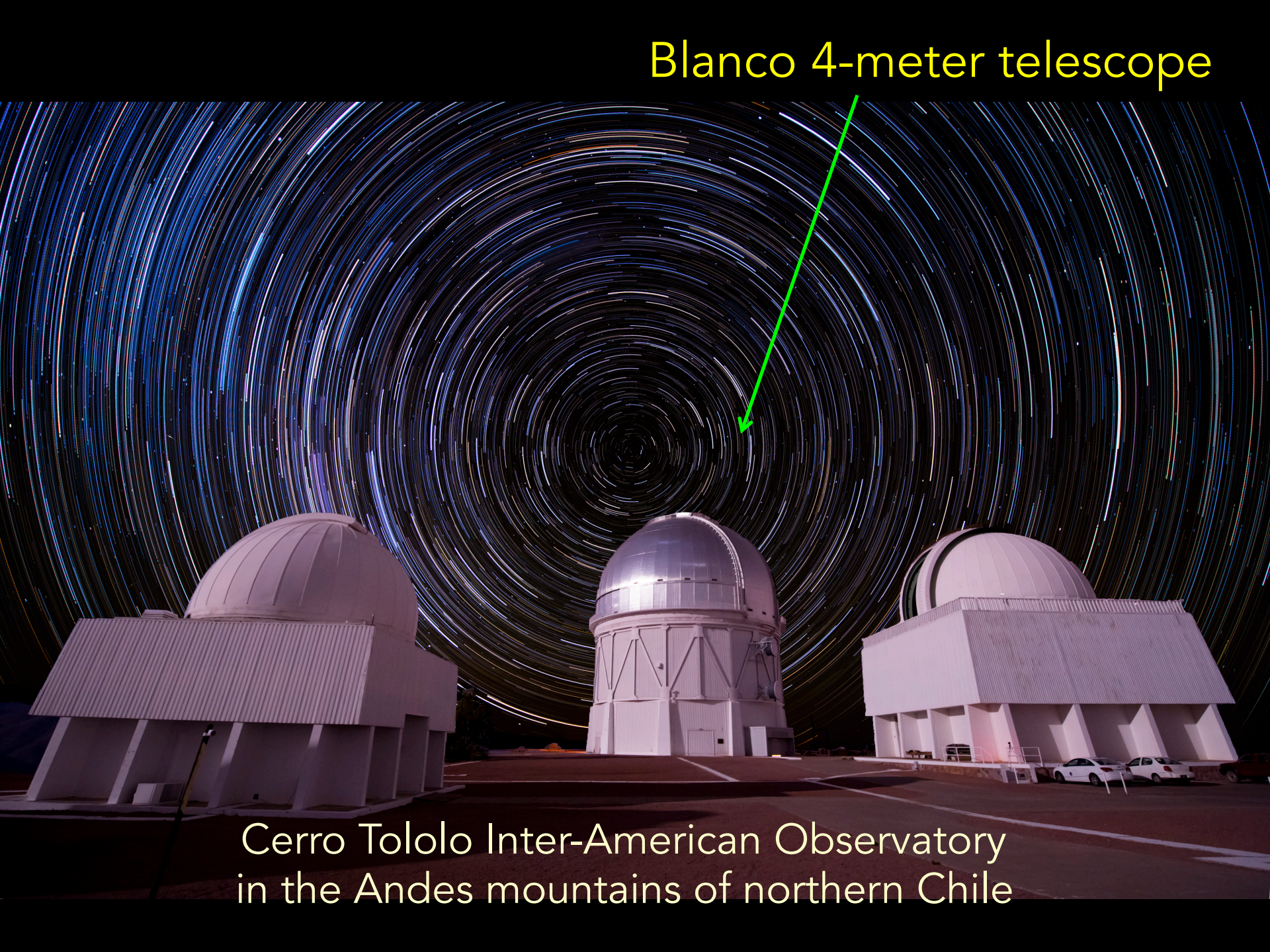
- Nature of Dark Energy will determine the future evolution of the Universe (but its effects on Earth or in our galaxy are now extremely tiny).
- It's 70% of the Universe now and will be more dominant in future.
- Mapping the Universe can give us clues to what Dark Energy is.

The Dark Energy Survey

- Probe Dark Energy and the origin of Cosmic Acceleration:
  - History of cosmic expansion
  - History of growth of structure
- Two multicolor surveys:
  300 Million galaxies, 1/8 sky
  3000 supernovae
- Five-year Survey started Aug. 31, 2013



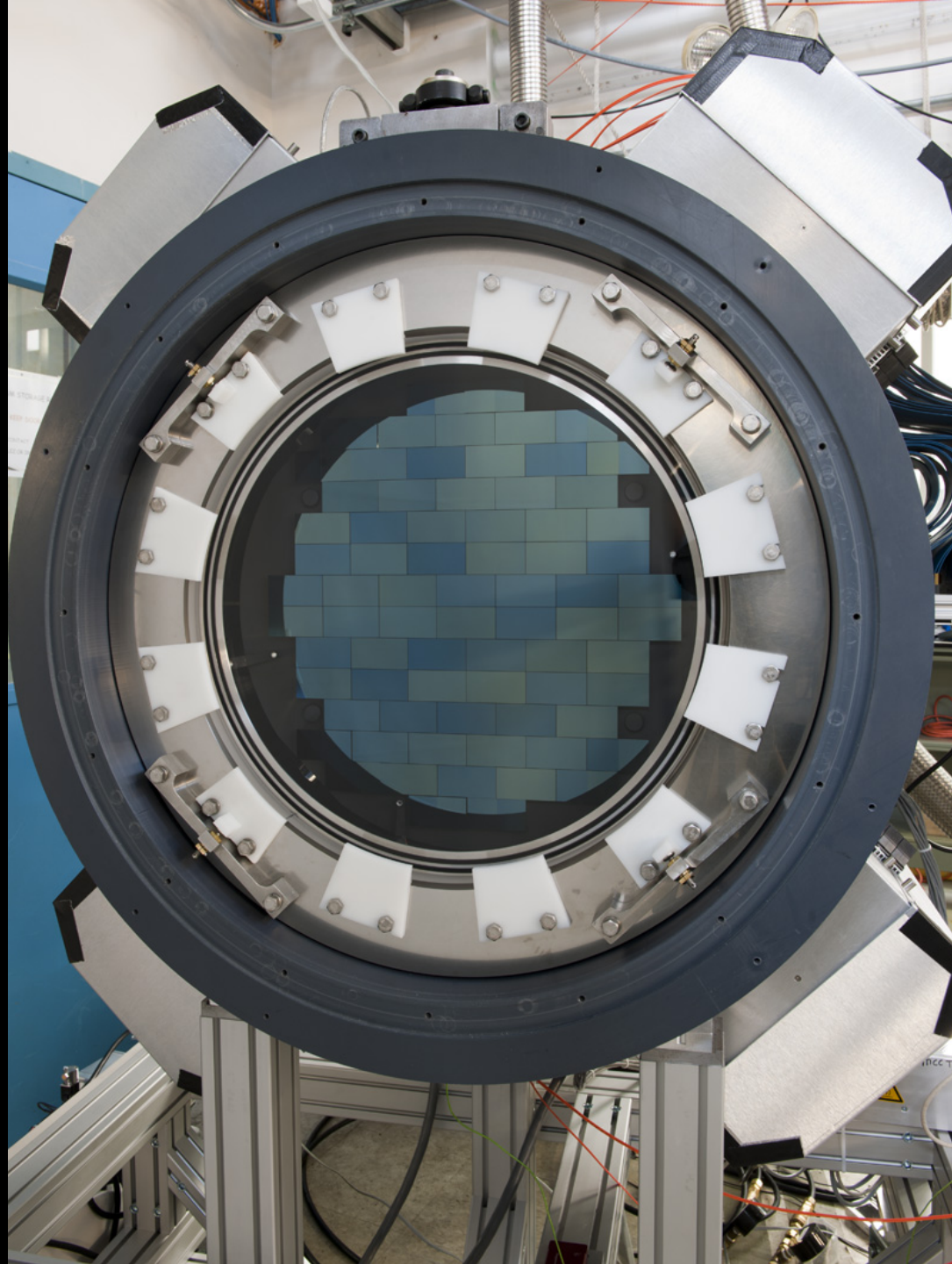
www.darkenergysurvey.org


Blanco 4-meter telescope
Cerro Tololo Inter-American Observatory
in the Andes mountains of northern Chile

570-Million pixel Dark Energy Camera

Built at Fermilab

Installed on the Blanco telescope in 2012

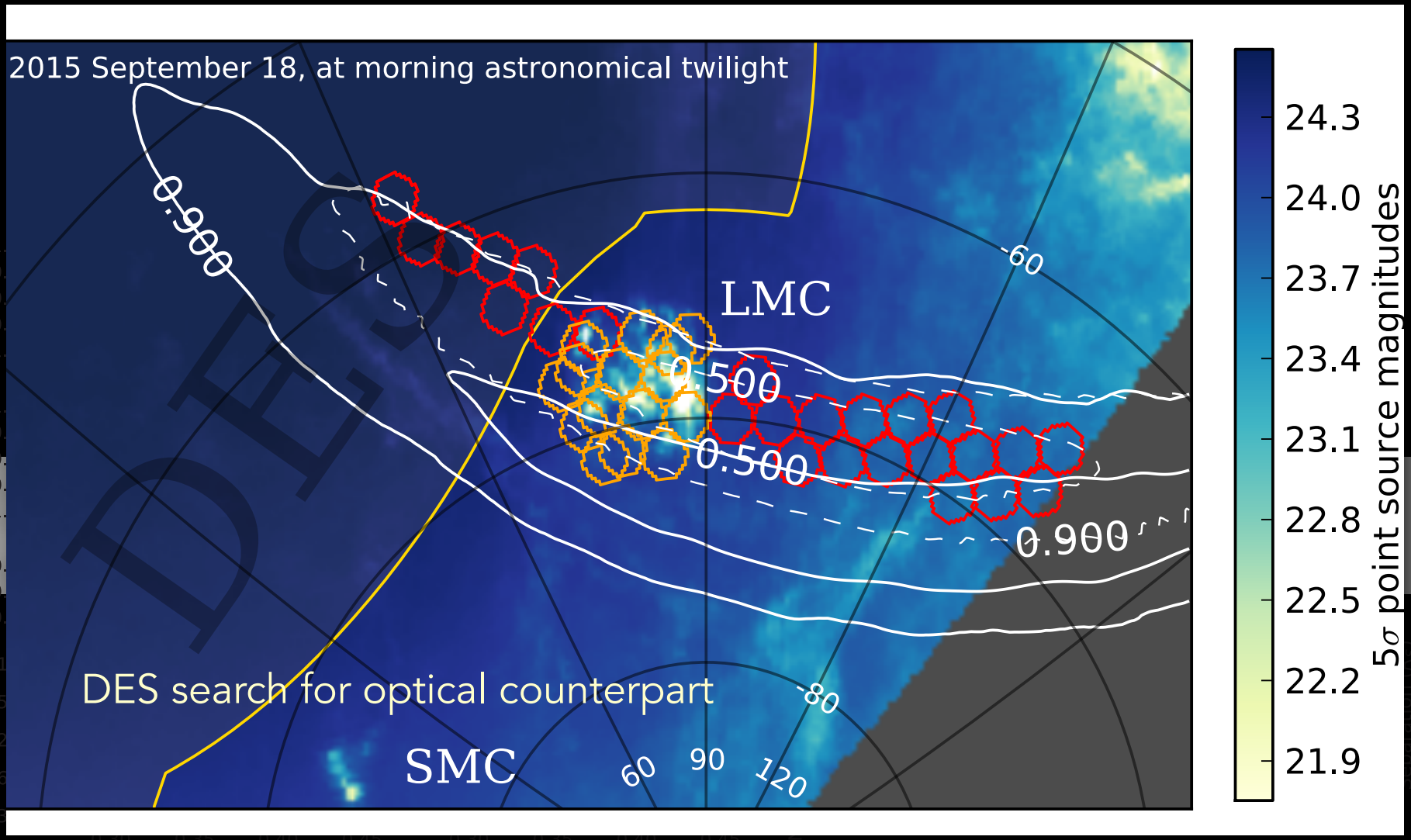


NGC 1512 at 38 million light-years

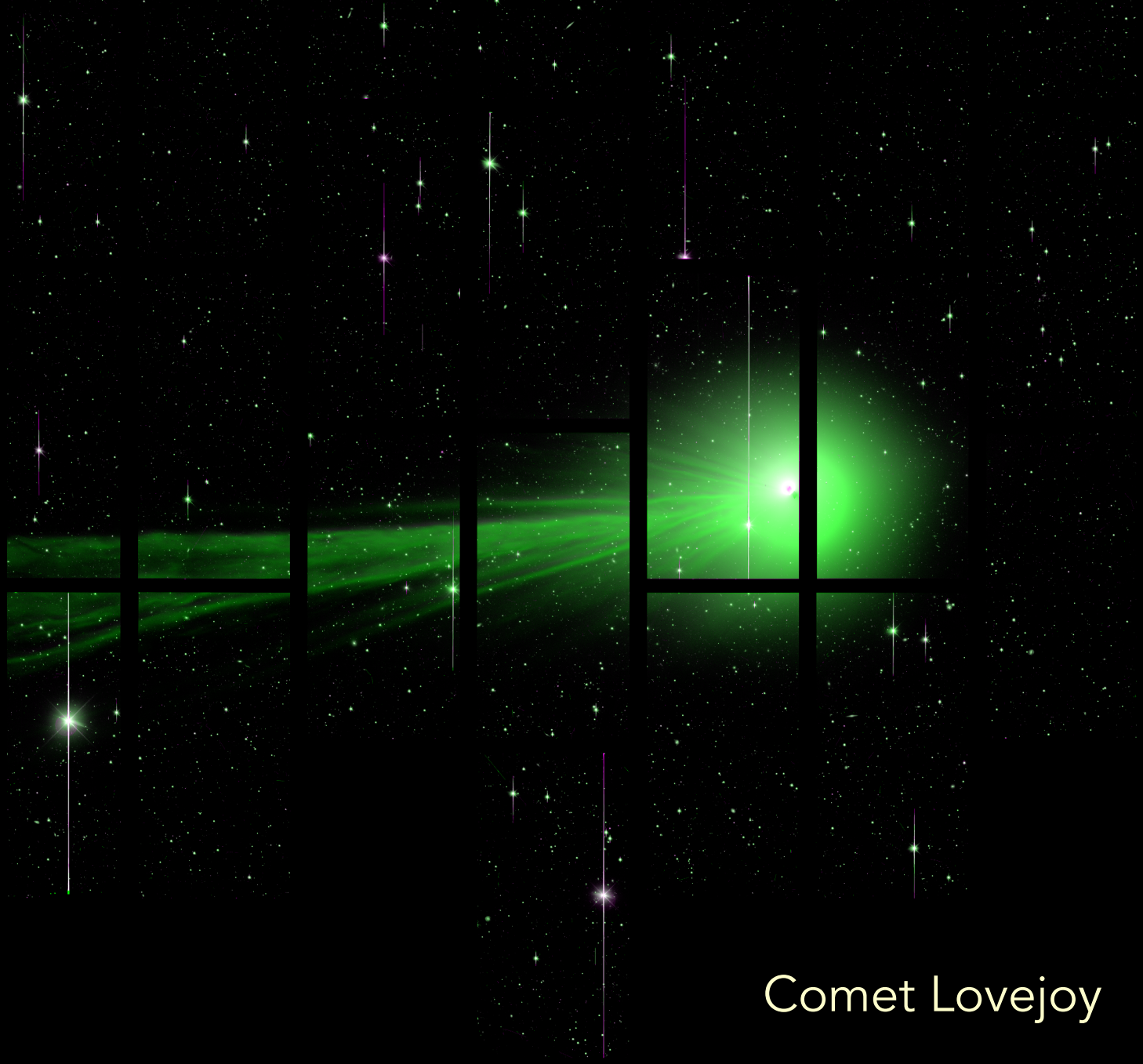
DARK ENERGY SURVEY

Cluster of Galaxies

Discovery of Gravitational Waves by LIGO

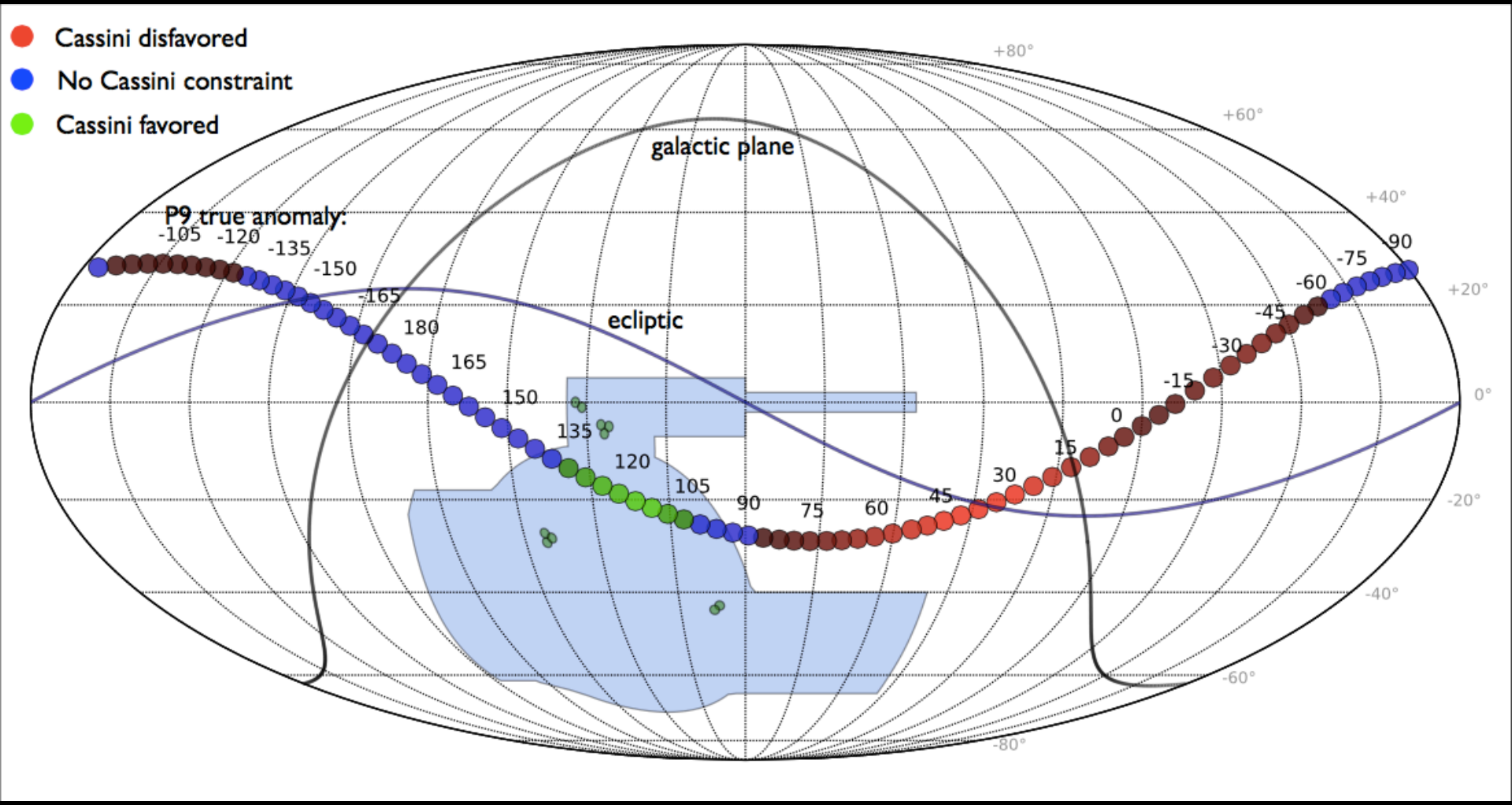



Orion nebula



Comet Lovejoy

Planet 9 Likely Orbit



Summary

- The Universe is:
  - 13.8 billion years old
  - 95% dark (25% dark matter, 70% dark energy)
  - filled with galaxies that are mostly dark matter
  - expanding from a Big Bang
  - speeding up, likely due to Dark Energy
- With the Dark Energy Survey, we are embarked on a 5-year journey to address this mystery and learn more about the evolution of the cosmos.