



Jet Propulsion Laboratory
California Institute of Technology

Gravitational Lensing and the Dark Side of the Universe

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Outline

- What is Cosmology?: The Big Bang
- What is the Universe made of?
 - Dark Energy and Dark Matter
- Gravitational Lensing
 - Measurements
- Current and Future Experiments
 - The role of JPL
- Conclusions

Cosmology

Cosmology is the scientific study of the universe as a whole

- What is the origin of the Universe?
- How old is the Universe?
- What are the components of the Universe?
- What is the fate of the Universe?

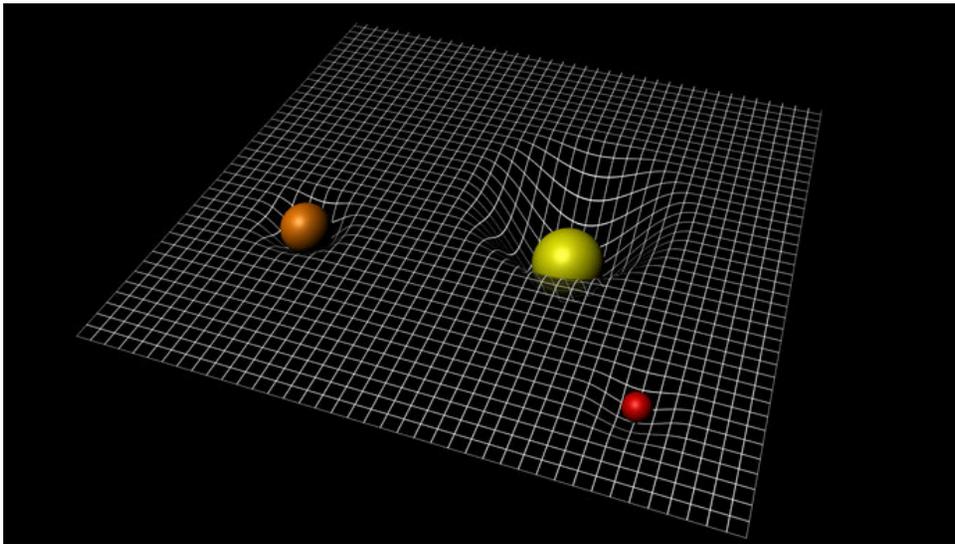


Credit: <https://en.wikipedia.org/wiki/File:Universum.jpg>

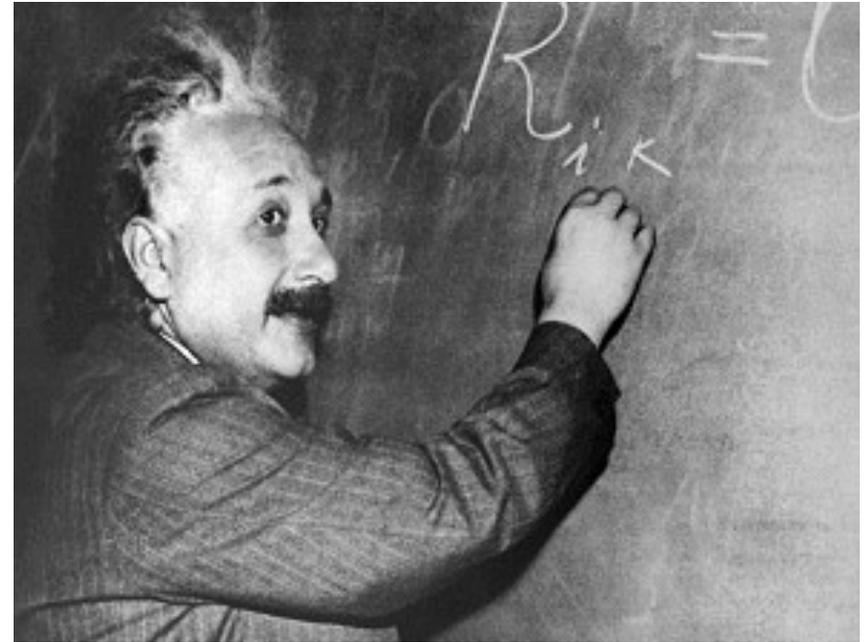
The Big Bang Theory: theoretical foundations

- **General Relativity:** Albert Einstein, 1916

Gravity is conceived as a distortion of space and time itself.



Credit: ESA-C.Carreau

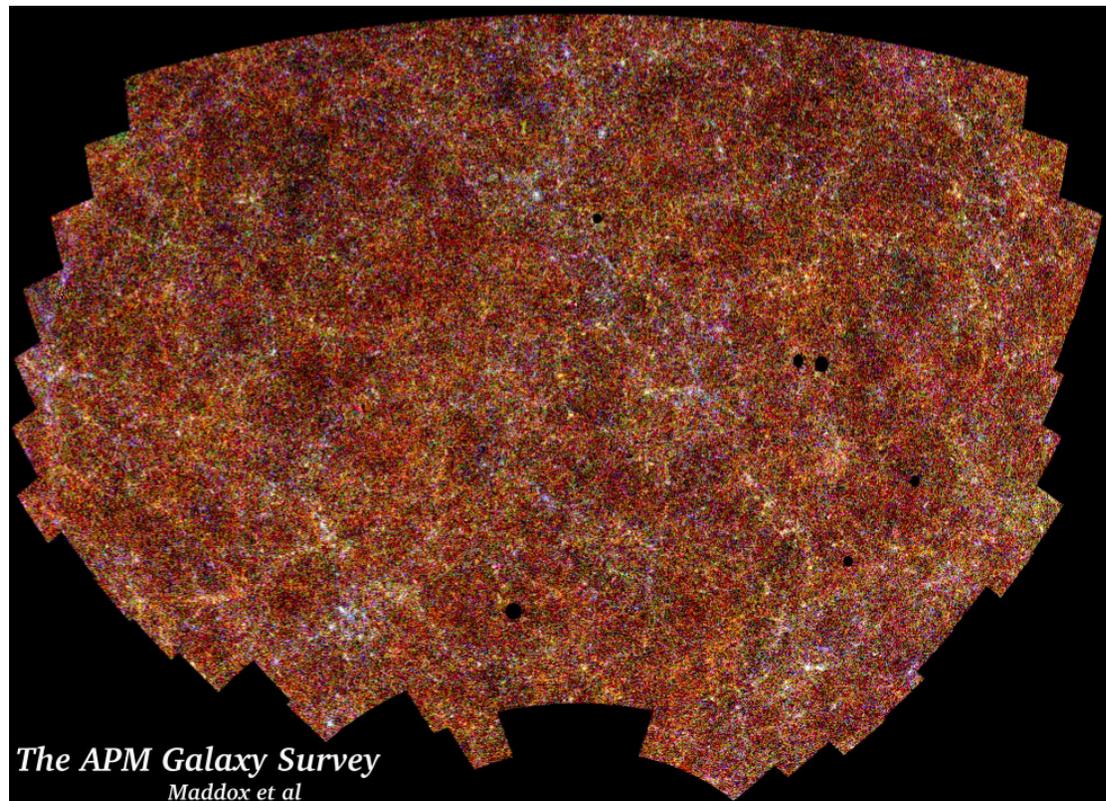


Credit: https://map.gsfc.nasa.gov/universe/bb_theory.html

"Matter tells space how to curve, and space tells matter how to move." J. Wheeler

The Big Bang Theory: theoretical foundations

- **The Cosmological Principle:** on the largest scales, the Universe appears roughly the same everywhere and in every direction.

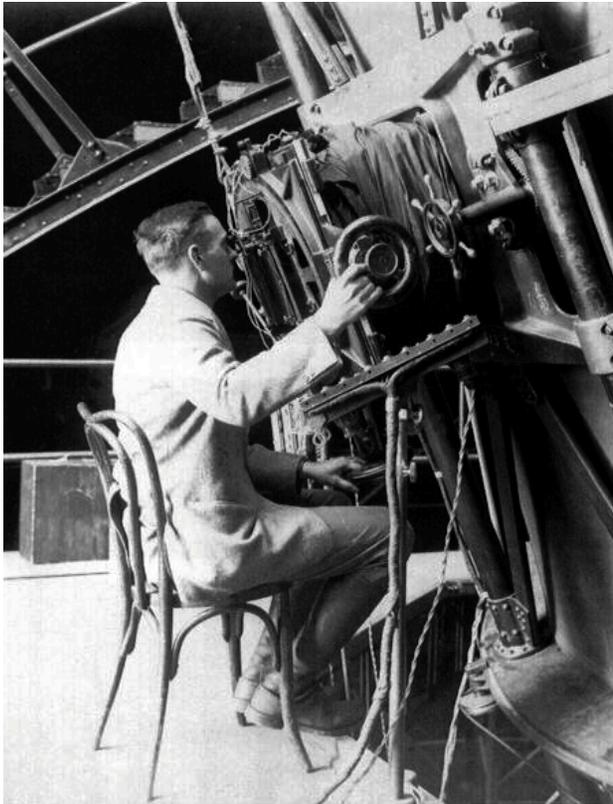


*The APM Galaxy Survey
Maddox et al*

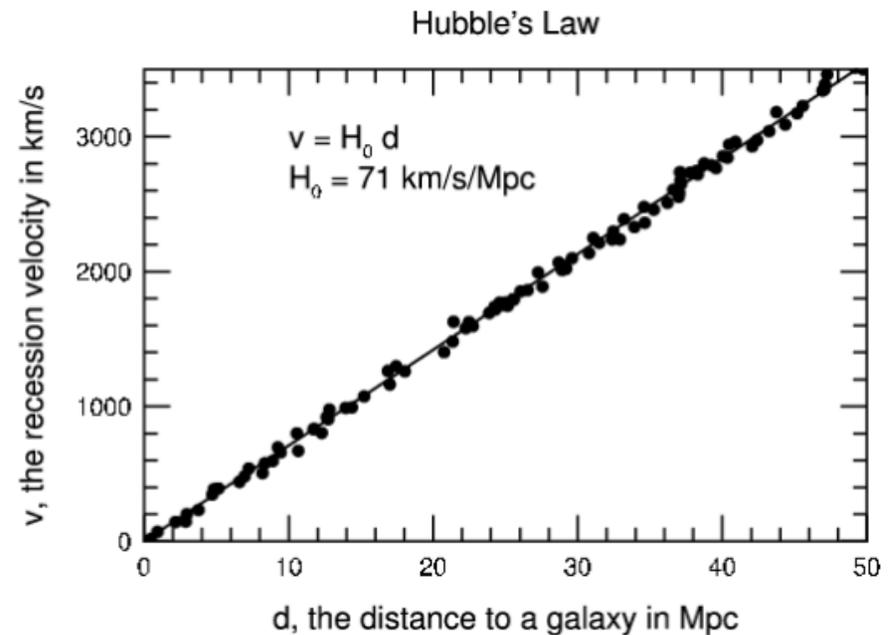
https://map.gsfc.nasa.gov/universe/bb_theory.html

Observational Evidence of The Big Bang Theory

- **The Expansion of the Universe: Edwin Hubble at Mount Wilson, 1929**



Credit: Huntington Library

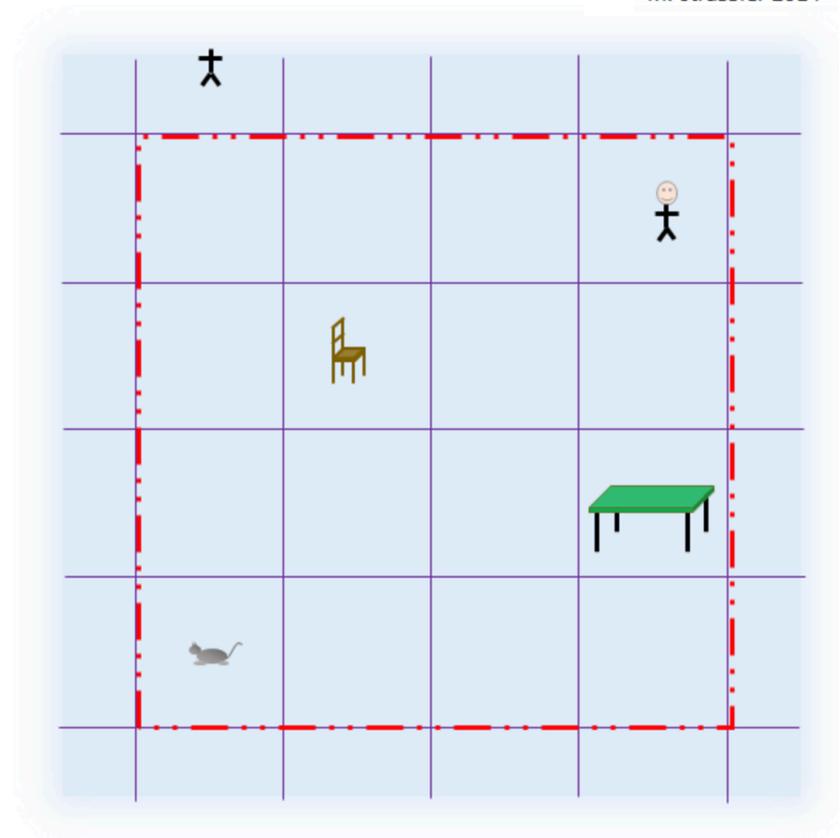
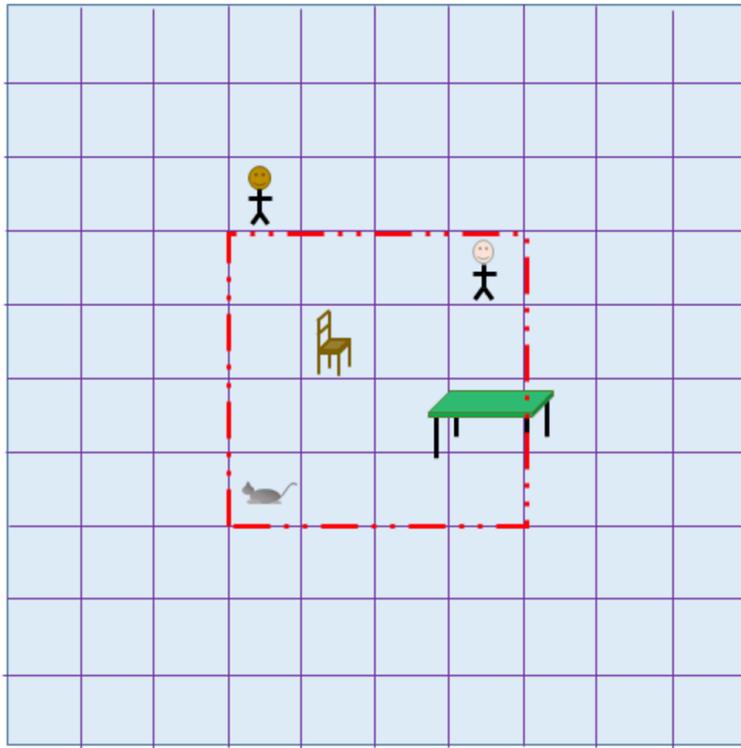


Credit: <http://firedrake.bu.edu/CC105/2007/hubble.htm>

Observational Evidence of The Bing Bang Theory

Expansion *Of* Space

M. Strassler 2014



Credit: <https://profmattstrassler.com/>

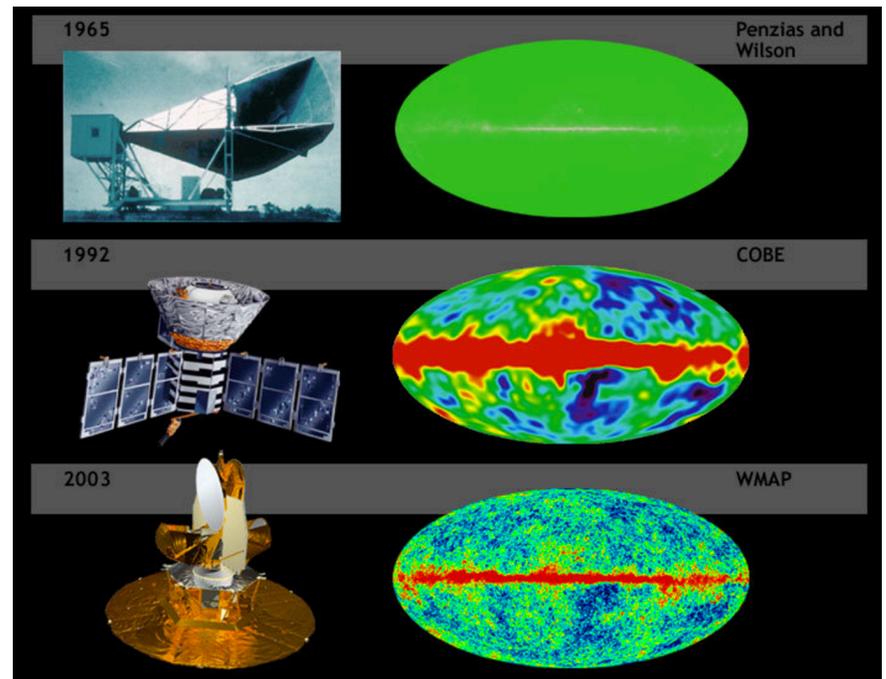
Observational Evidence of The Big Bang Theory

- **The Cosmic Microwave Background**

The Big Bang theory predicts that the early universe was a very hot place and that as it expands, the gas within it cools. Therefore, the universe should be filled with radiation that is the remnant heat left over from the Big Bang.



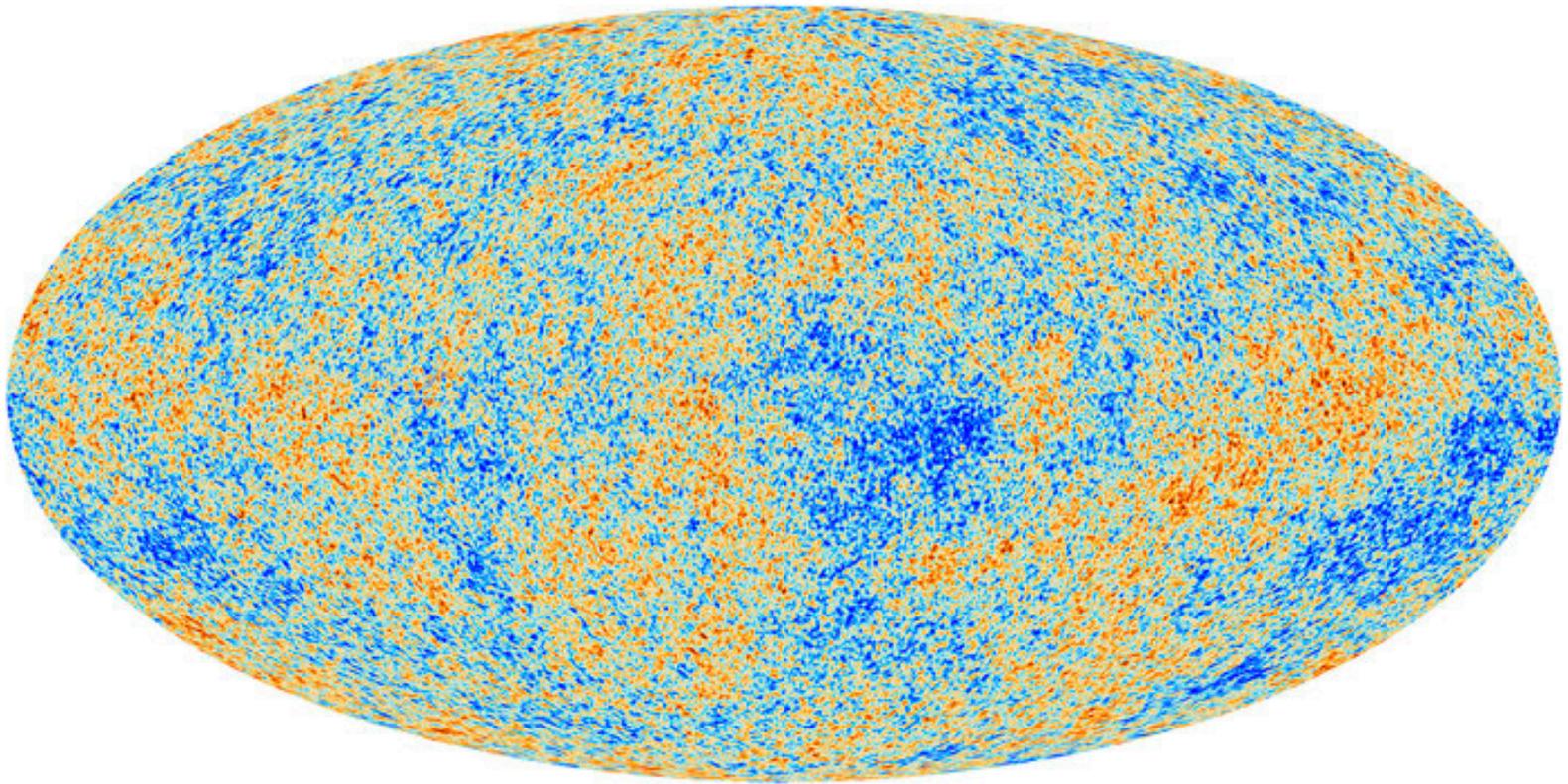
Arno Penzias and Robert Wilson, 1964
Credit: Bell Labs



Credit: https://map.gsfc.nasa.gov/m_ig/030644/030644.html

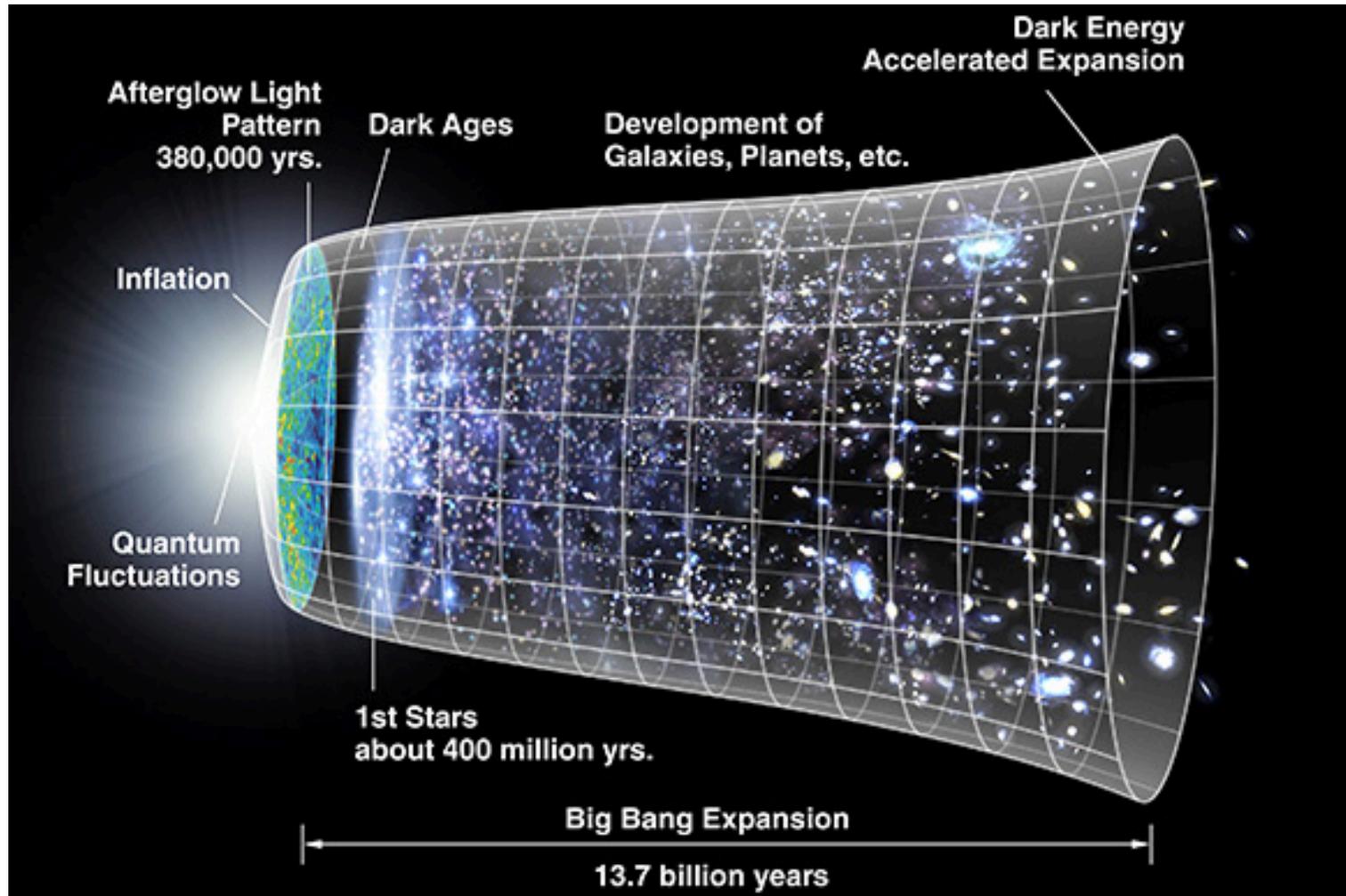
Observational Evidence of The Big Bang Theory

PLANCK CMB



Credit: ESA and the Planck Collaboration

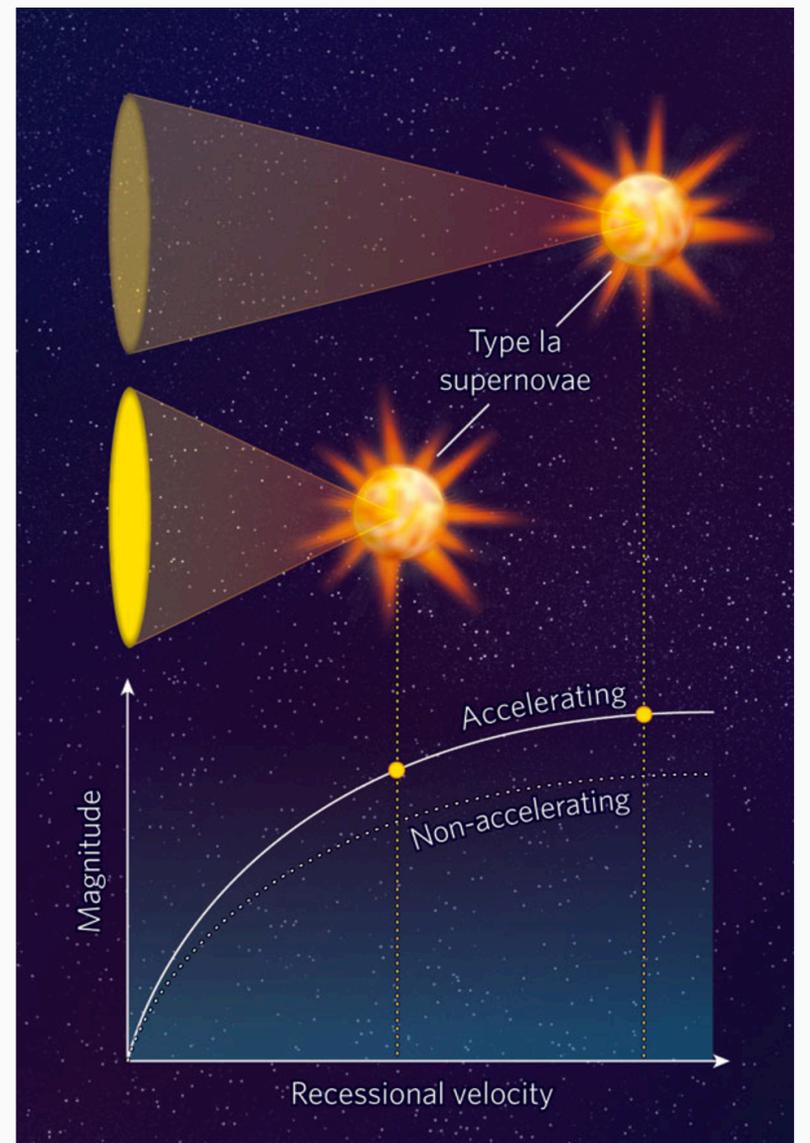
Observational Evidence of The Big Bang Theory



Credit: NASA/WMAP Science Team

Accelerated Expansion of the Universe

- It was expected that the expansion should be slowing down due to the gravity
- In 1998, two independent teams set up to measure how the universe was slowing down.
- To everyone's surprise, they found the opposite.
- They did so by using a special type of exploding star that always has the same **intrinsic** brightness after exploding (i.e., a "standard candle").
- The dimmer the object seems to be, the higher the value of its magnitude and the farther away it is.



Credit: R. Caldwell, M. Kamionkowski, Nature 458, 587-589 (2009)

Dark Energy



Credit: Nobel Foundation



Photo: Lawrence Berkeley National Lab

Saul Perlmutter



Photo: Belinda Pratten, Australian National University

Brian P. Schmidt



Photo: Scanpix/AFP

Adam G. Riess

The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

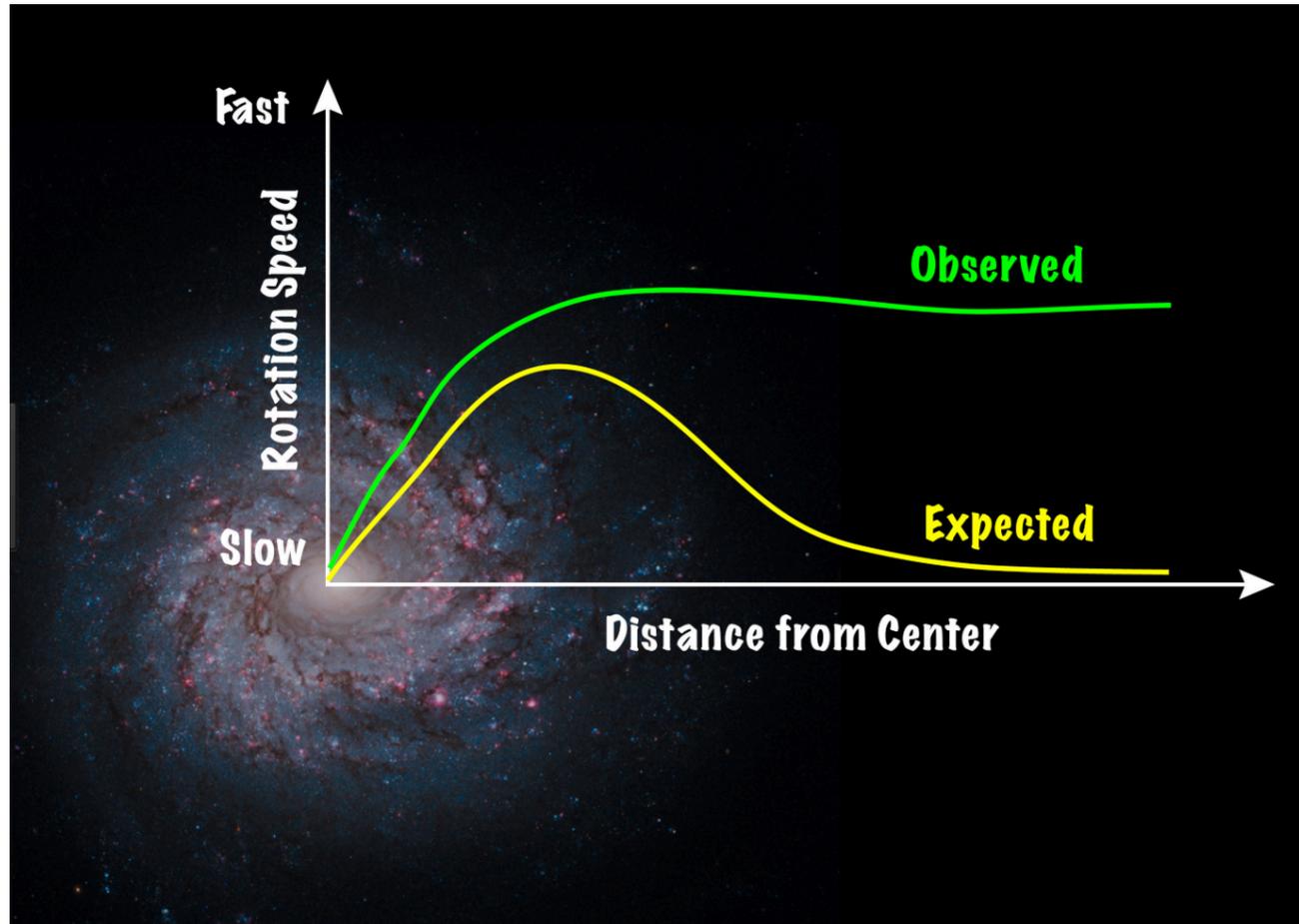
Credit: <http://asymptotia.com/2011/10/04/the-2011-nobel-prize-in-physics/>

Is it the energy of the vacuum? The cosmological constant with opposite sign?

Do we need to modify **General Relativity** on large scales?

Dark Matter

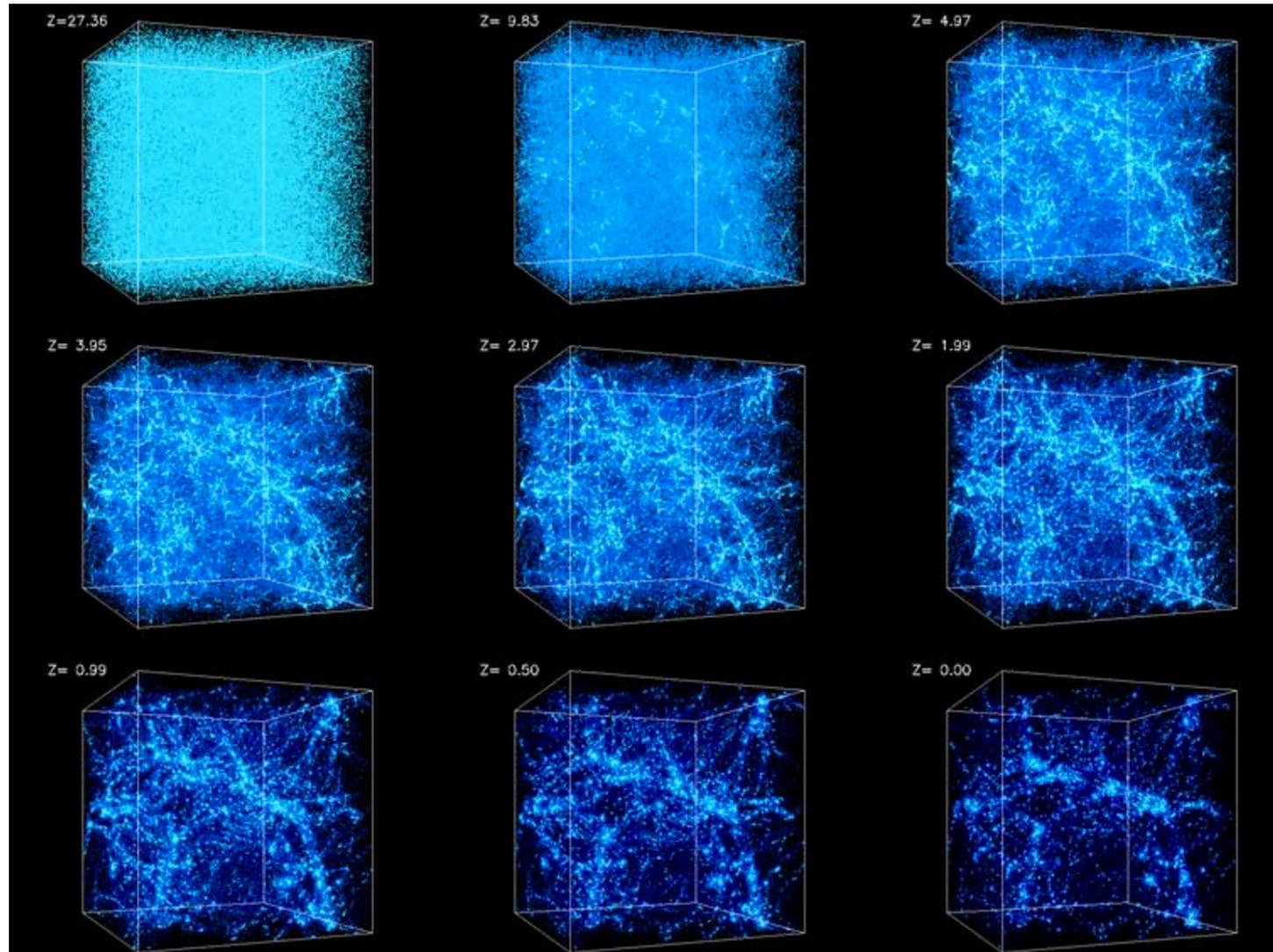
The manner in which the stars' velocities vary with radius reflects the distribution of mass in a galaxy.



Credit: <https://writescience.files.wordpress.com/2015/05/galaxyrotationcurve.jpg>

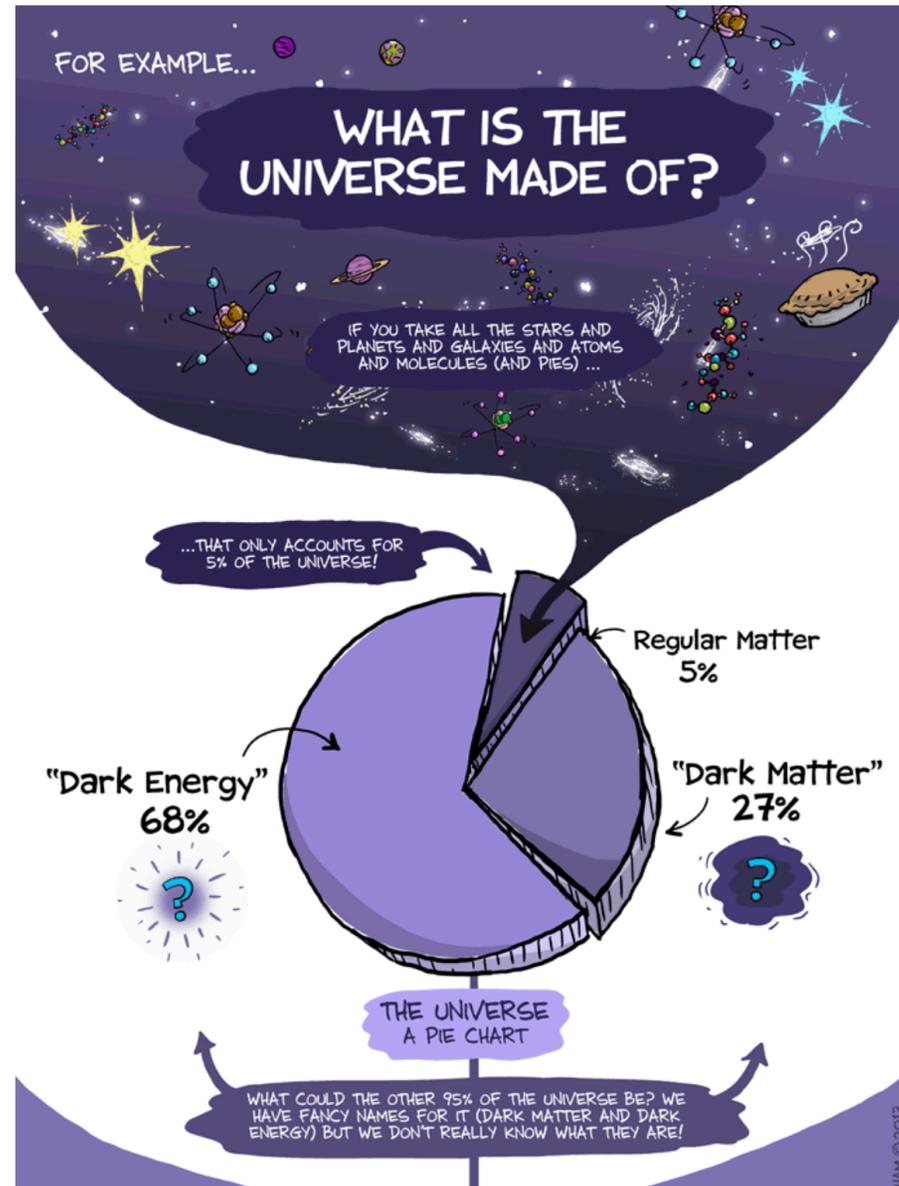
A flat rotation curve implies that the mass continues to increase linearly with radius. Therefore, the rotation curves of galaxies present strong evidence for dark matter

Dark Matter



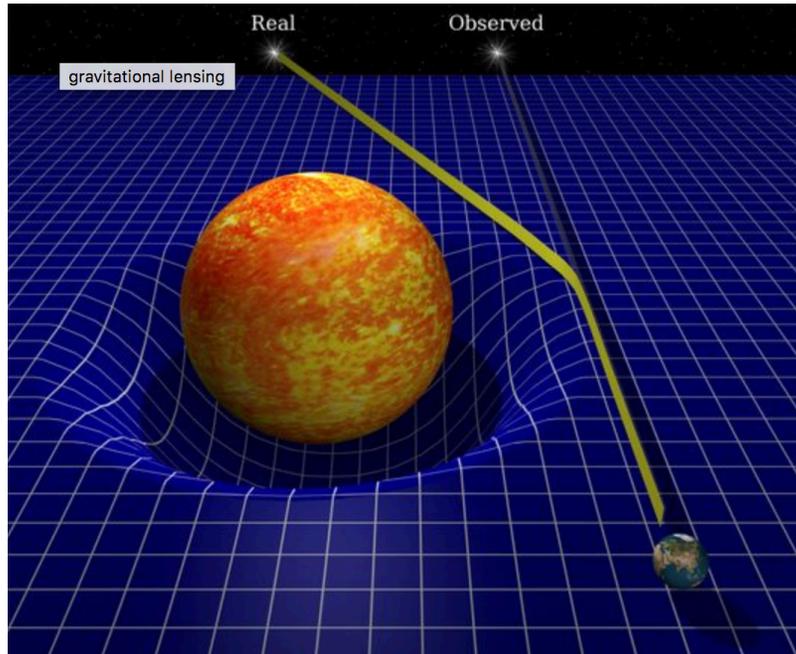
Credit: <http://astro.wku.edu/astr106/structure/filaments.html>

The Composition of the Universe

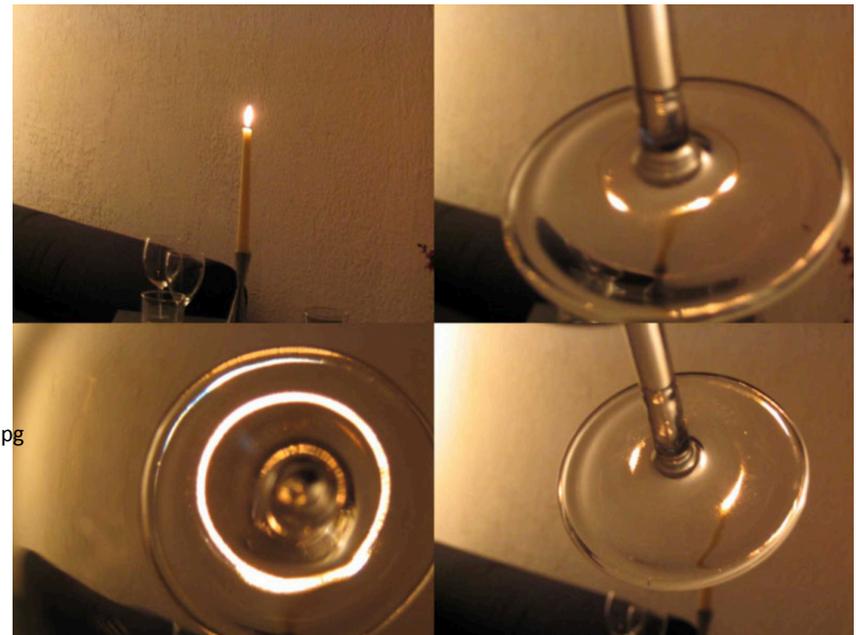


Credit: Jorge Cham

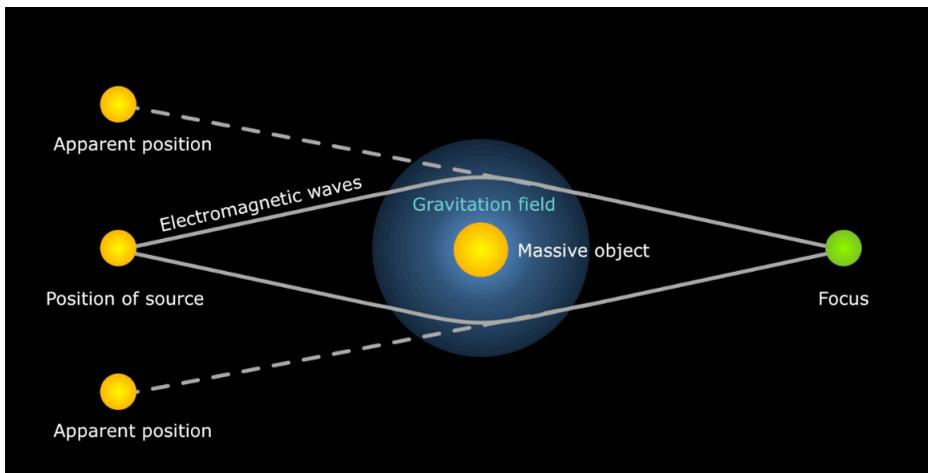
Gravitational Lensing



Credit: <https://s-media-cache-ak0.pinimg.com/736x/a3/ee/21/a3ee21dddb457afed66d8c2362e2f552.jpg>

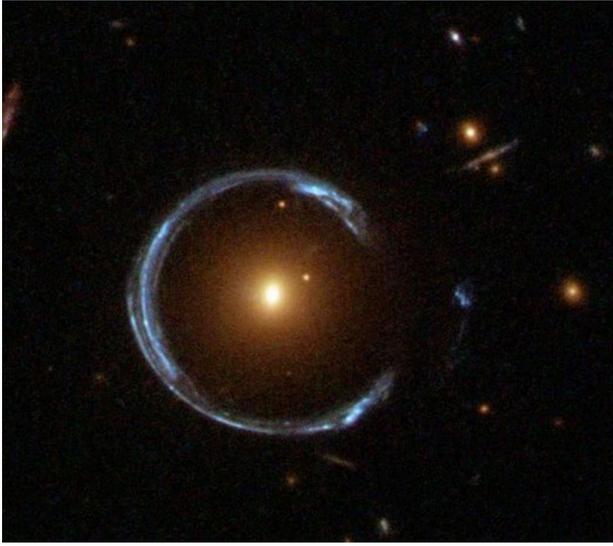


Credit: http://kipac.stanford.edu/kipac/research/gravitational_lensing

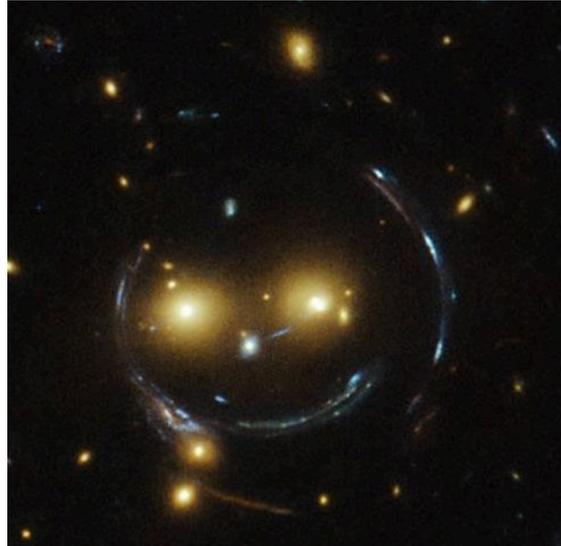


Credit: <http://topyaps.com/wp-content/uploads/2016/06/gravitational-lens-1024x533.jpg>

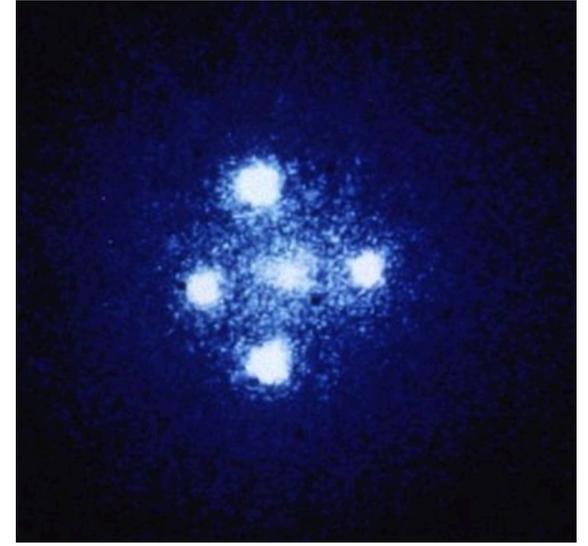
Gravitational Lensing



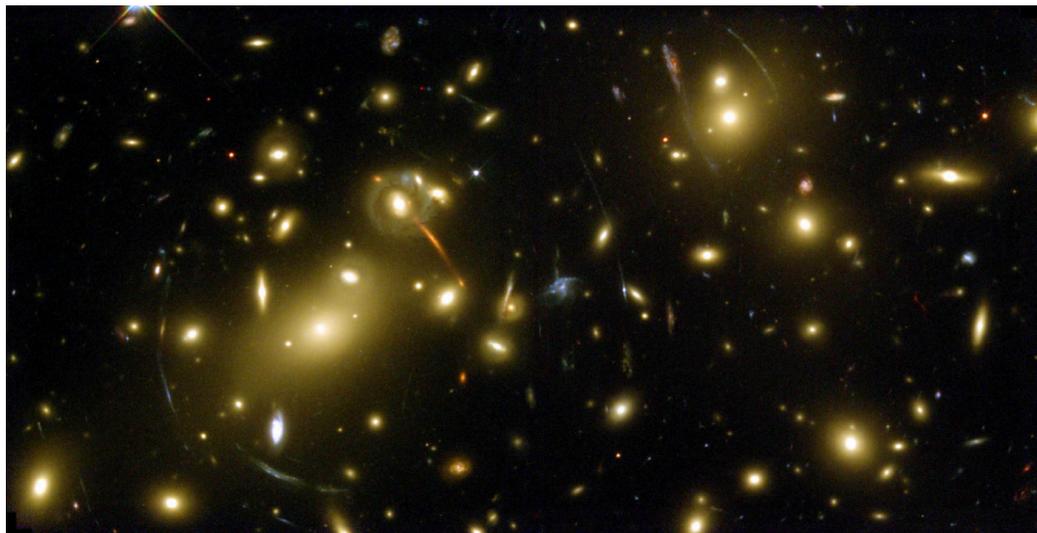
Credit: https://upload.wikimedia.org/wikipedia/commons/1/11/A_Horseshoe_Einstein_Ring_from_Hubble.JPG



<https://cdn.spacetelescope.org/archives/images/wallpaper5/potw1506a.jpg>



https://upload.wikimedia.org/wikipedia/commons/thumb/c/c8/Einstein_cross.jpg/300px-Einstein_cross.jpg



Credit: http://www.roe.ac.uk/~heyman/website_images/abell2218.jpg

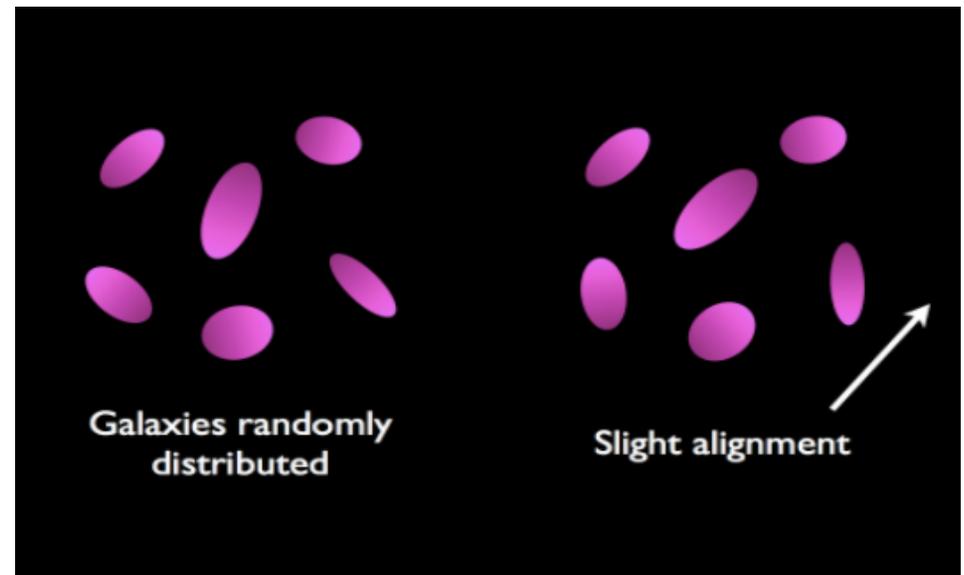
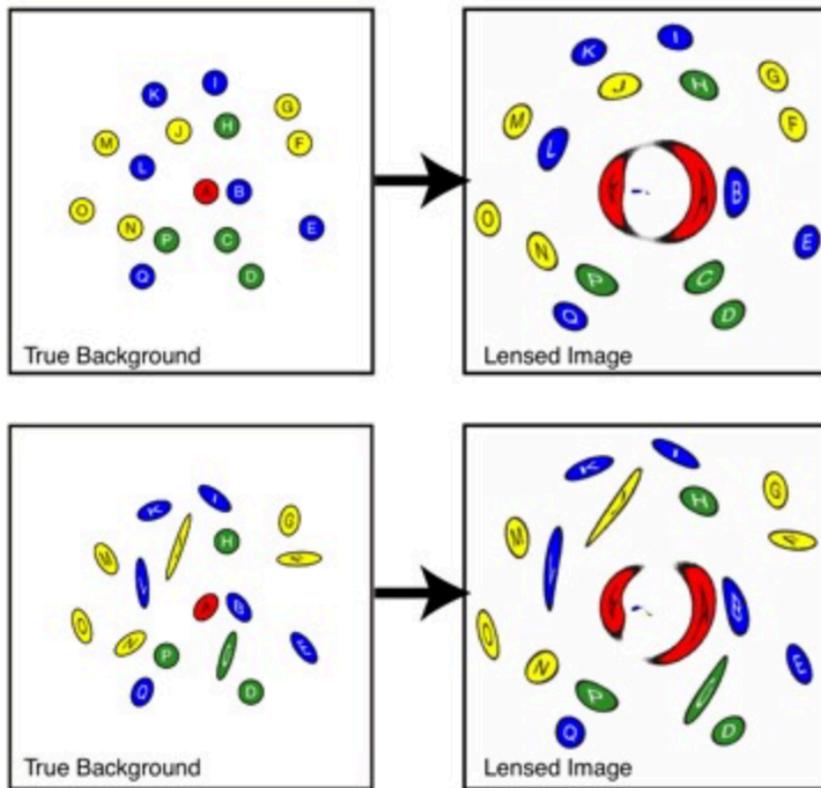
Visualizing dark matter with gravitational lensing



Credit: <http://jesserogerson.com/wp-content/uploads/2013/08/bulletclusterAPOD.jpg>

Weak Gravitational Lensing

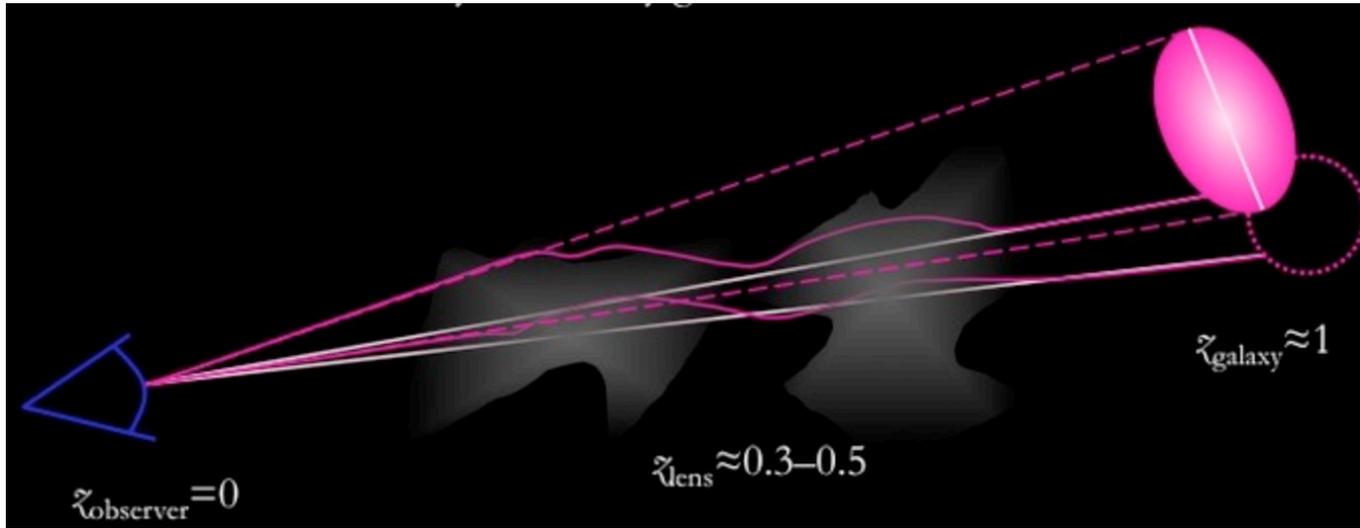
Strong lensing is not common. Requires special conditions.
Much more common: [weak gravitational lensing](#).



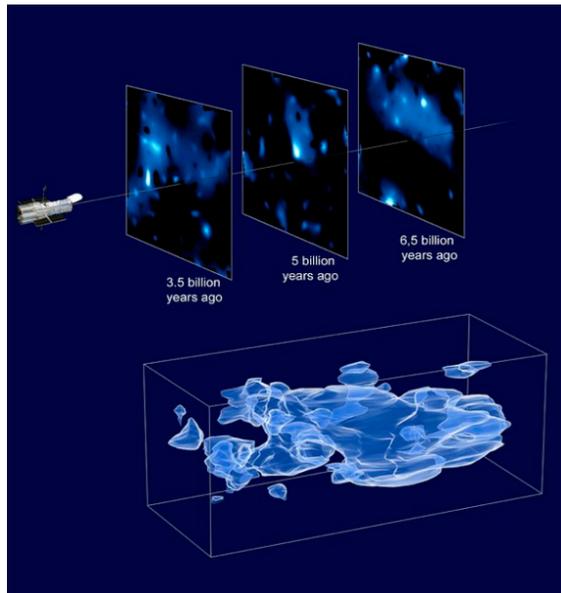
Credit: [http://www.roe.ac.uk/~heymans/website_images/weak_lensing_schematic.020\(1\).jpg](http://www.roe.ac.uk/~heymans/website_images/weak_lensing_schematic.020(1).jpg)

Credit: <http://www.jyi.org/issue/development-of-charged-coupled-devices-for-precision-cosmology-and-the-supernova-acceleration-probe-satellite/>

Mapping Dark Matter with weak gravitational Lensing



Credit: <http://www.euclid.caltech.edu/system/pages/images/33/page/weaklensing-1.jpg?1429912665>

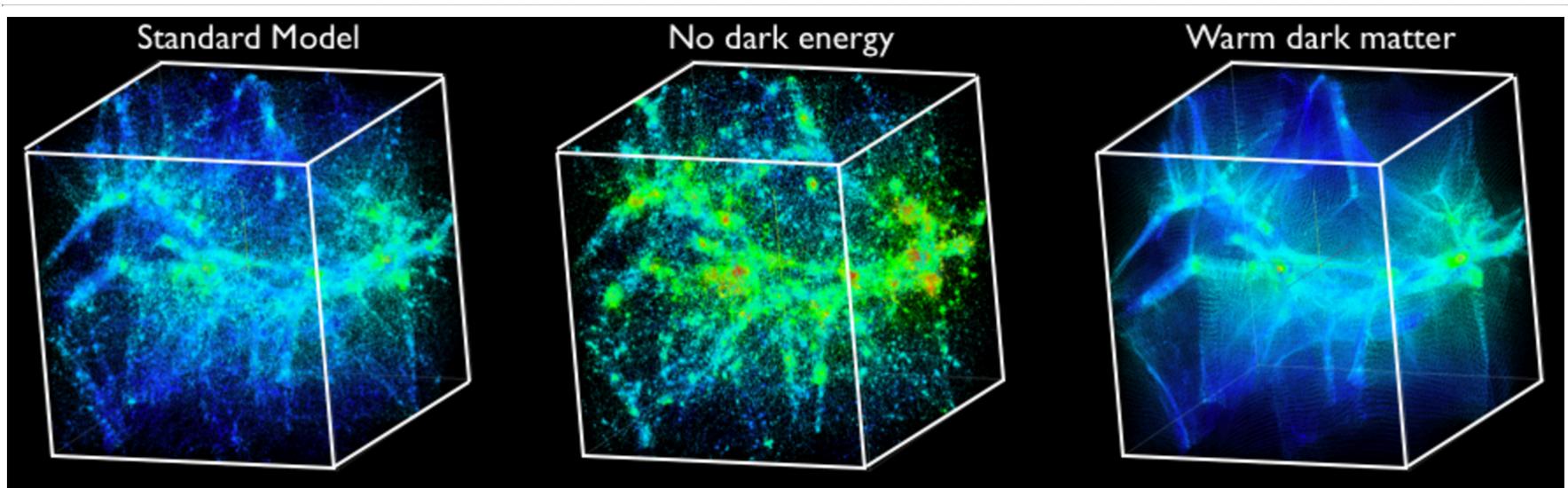


3D DM map using data from ground-based telescopes (Canada-Hawaii-France Telescope, Subaru, Very Large Telescope) and Hubble Space Telescope data.

Credit: http://scienceblogs.com/startswithabang/files/2011/04/Euclid_weak_lensing.jpeg

Comparison with simulations

The relative densities of dark matter and dark energy affect the rate of growth of structure in the Universe.

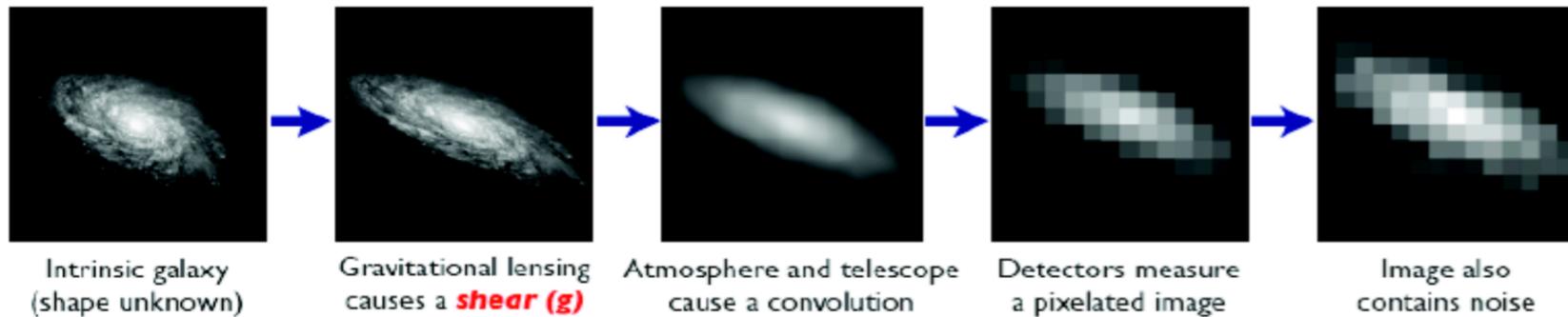


Credit: <http://newatlas.com/roadrunner-universe/13229/>

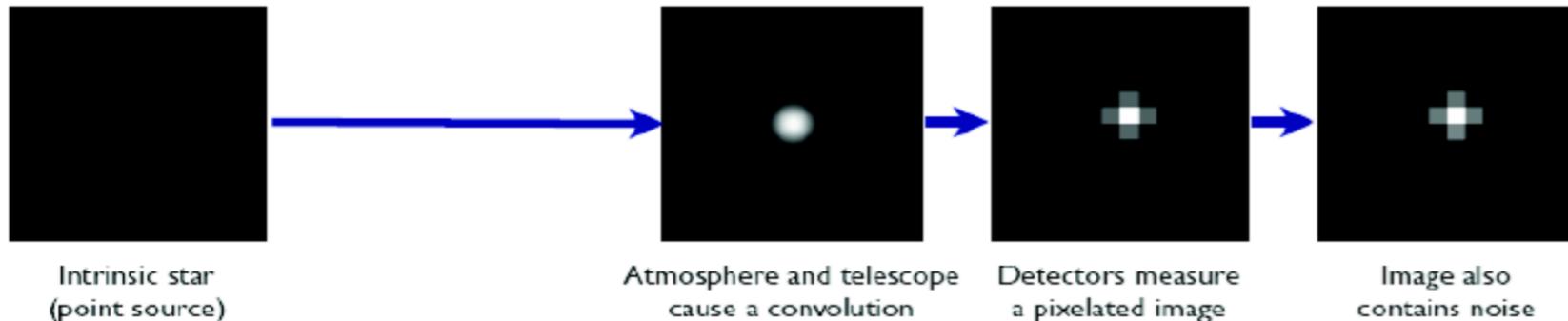
Measuring Weak Gravitational Lensing

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:



Stars: Point sources to star images:



Measuring Weak Gravitational Lensing

Weak Lensing “...is likely to be the most powerful individual technique, and also the most powerful component in a multi-technique program...” to learn about Dark Energy if systematic errors can be controlled. [Dark Energy Task Force Report, Albrecht et al 2006.](#)

There are multiple sources of systematic errors when measuring the weak lensing signal. For example:

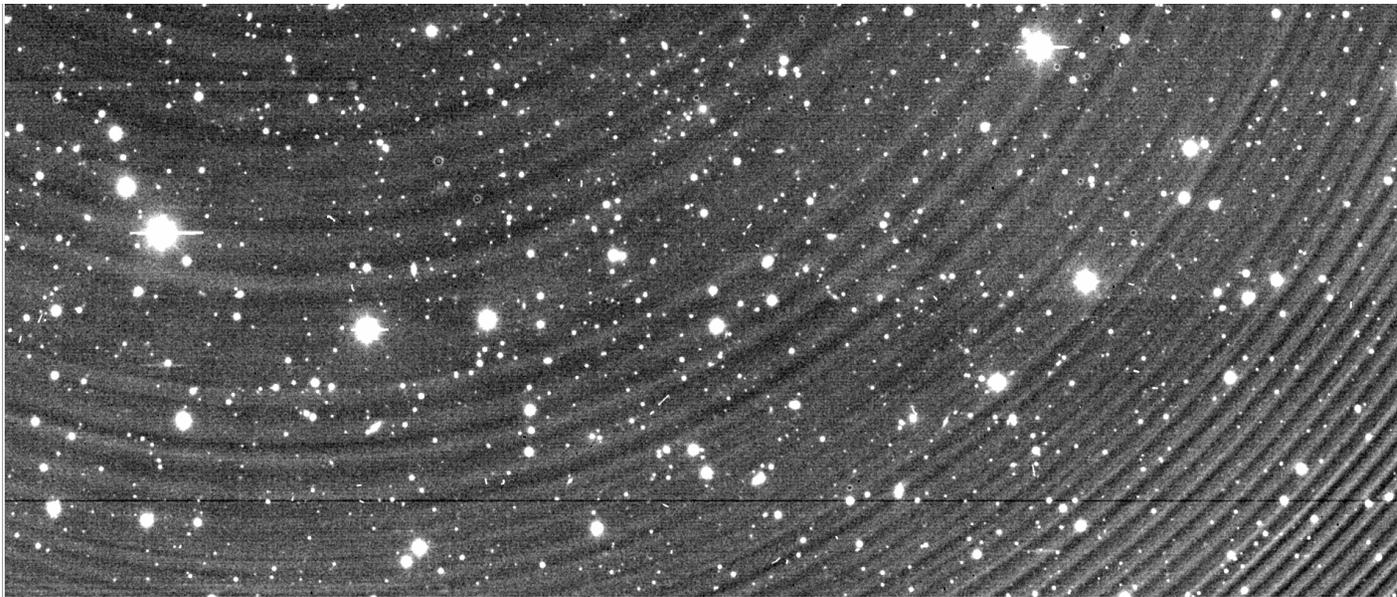
- Determination of the amplitude of the signal
- **Measurement of the projected shape of galaxies**
- Atmospheric variations
- Telescope optics
- **Detectors**
- Theoretical models, simulations, and statistical analyses.

Systematics: instrumental signatures

On-Sky Measurements of the Transverse Electric Fields' Effects in the Dark Energy Camera CCDs

A. A. PLAZAS,¹ G. M. BERNSTEIN,² AND E. S. SHELDON¹

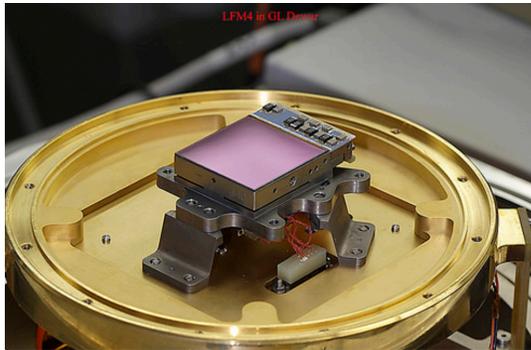
Received 2014 March 24; accepted 2014 June 06; published 2014 July 21



The “ripples” could stretch galaxies in a way that resembles the coherent pattern induced by weak lensing.

Systematics: Precision Projector Laboratory

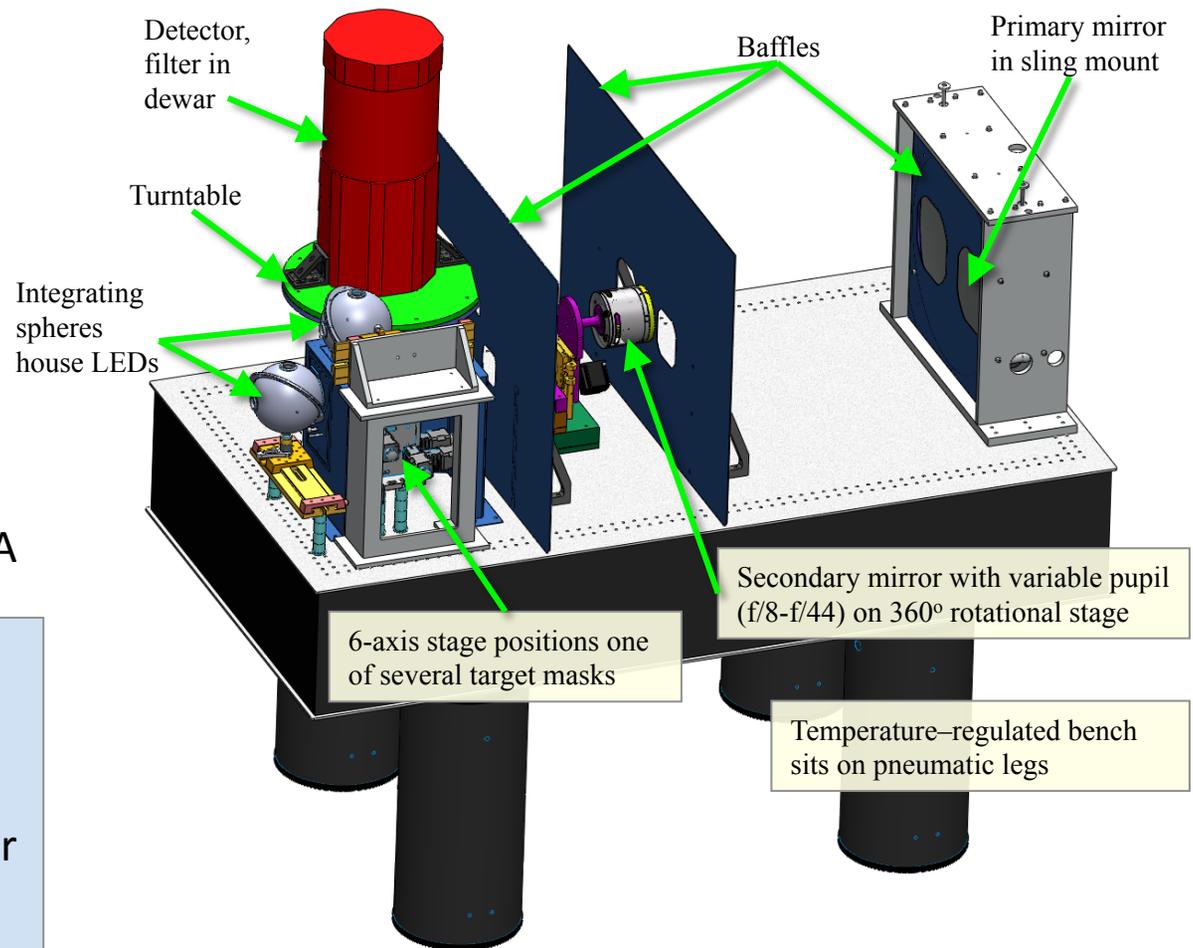
- Image of an illuminated mask (emulated scene) is focused onto the detector



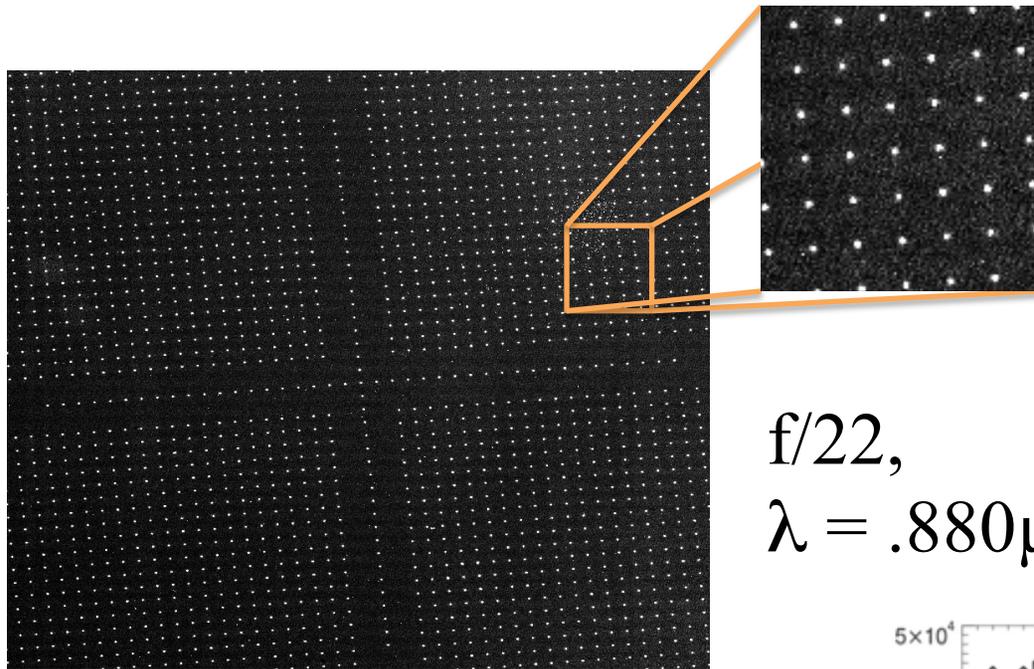
Credit: University of Arizona/NASA

- PSF can be varied by changing $f/\#$ or LEDs
- Errors can be isolated by rotating mask, pupil or dewar
- Masks can emulate stars, galaxies or spectra

Offner relay system



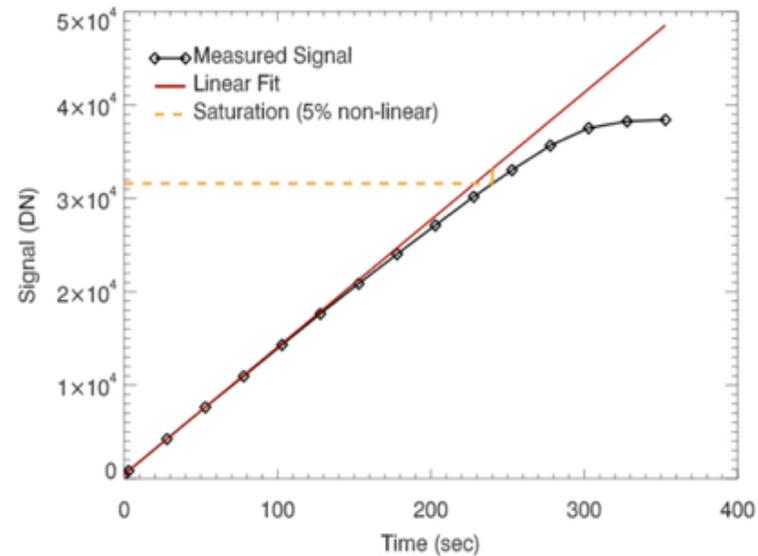
Systematics: Precision Projector Laboratory



Grid of $3\mu\text{m}$
pinhole spots
(emulated stars)
onto the detector

$f/22,$
 $\lambda = .880\mu\text{m}$

↑
Spots



Systematics: instrumental signatures

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doi:10.1088/1538-3873/128/968/104001



The Effect of Detector Nonlinearity on *WFIRST* PSF Profiles for Weak Gravitational Lensing Measurements

A. A. Plazas¹, C. Shapiro^{1,2}, A. Kannawadi³, R. Mandelbaum³, J. Rhodes^{1,2,4}, and R. Smith²

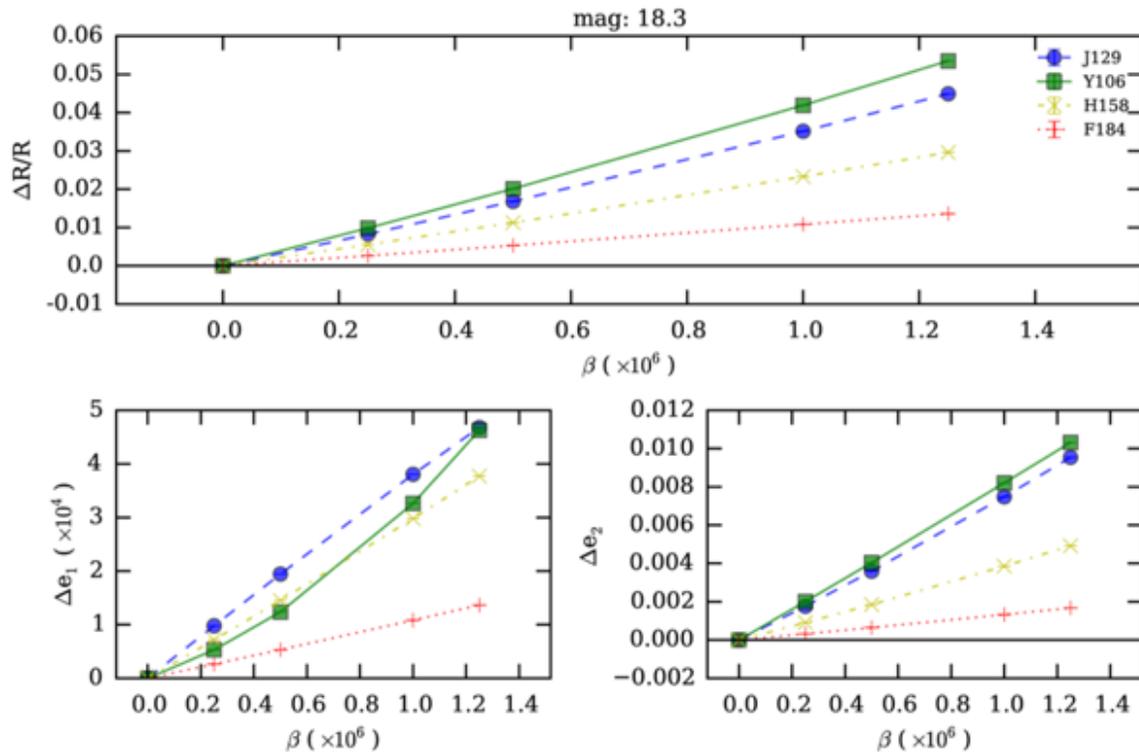
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- We find that NL induces errors in PSF size and shape larger to what is tolerable by accurate WL measurements.

The Dark Sector Group at JPL

- Researchers from different groups at JPL/IPAC/Caltech with common interests in **dark matter and dark energy science**.

Origin of the Universe (3268): People

 Olivier Dore Group Supervisor Read More >>	 James Bock Read More >>
 Philip Bull Read More >>	 Brendan Crill Read More >>
 Curt Cutler Read More >>	 Tim Eifler Read More >>
 Jerome Gleyzes Read More >>	 Krzysztof M. Gorski Read More >>
 Brandon Hensley Read More >>	 Sergi Hildebrandt Rafels Read More >>
 Eric Huff Read More >>	 Michael Janssen Read More >>
 Daniel Lenz Read More >>	 Steven Levin Juno Project Scientist Read More >>
 Cheng Li Read More >>	 Hironao Miyatake Read More >>
 Hien Nguyen Read More >>	 Andres A Plazas Malagon Read More >>
 Graca Rocha Read More >>	 Michael Seiffert Read More >>
 Paolo Serra NASA Senior Postdoctoral Fellow Read More >>	

Structure of the Universe (3266): People

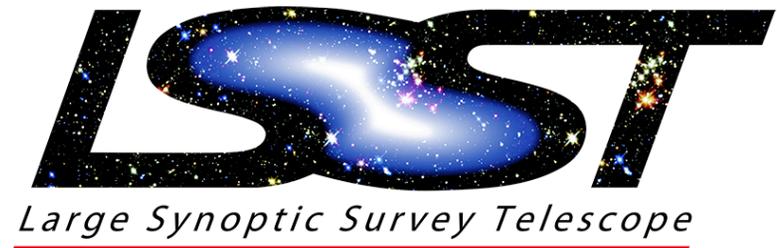
 Alina Kiessling Read More >>	 Tzu-Ching Chang Read More >>
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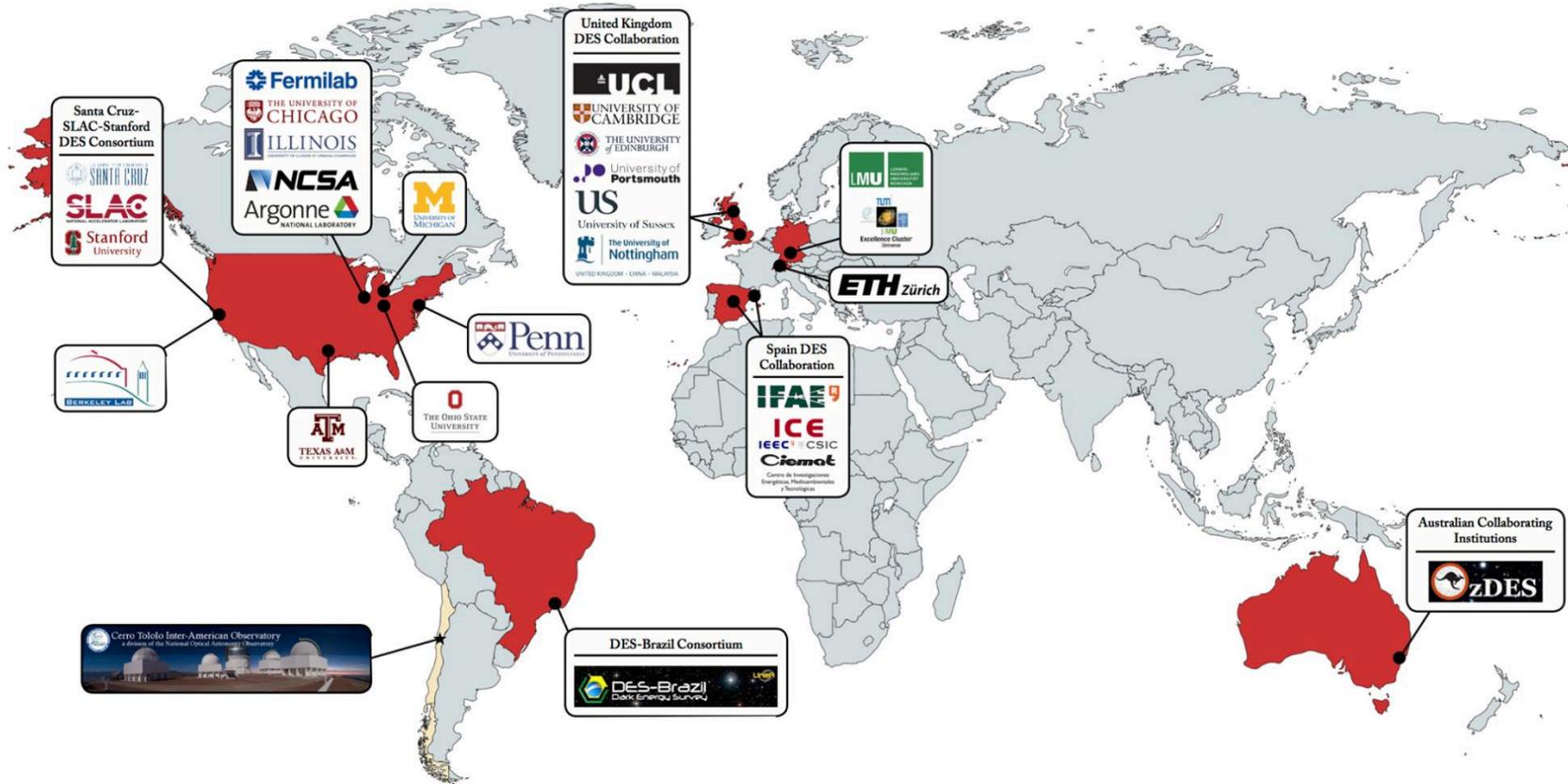
Caltech

Projects



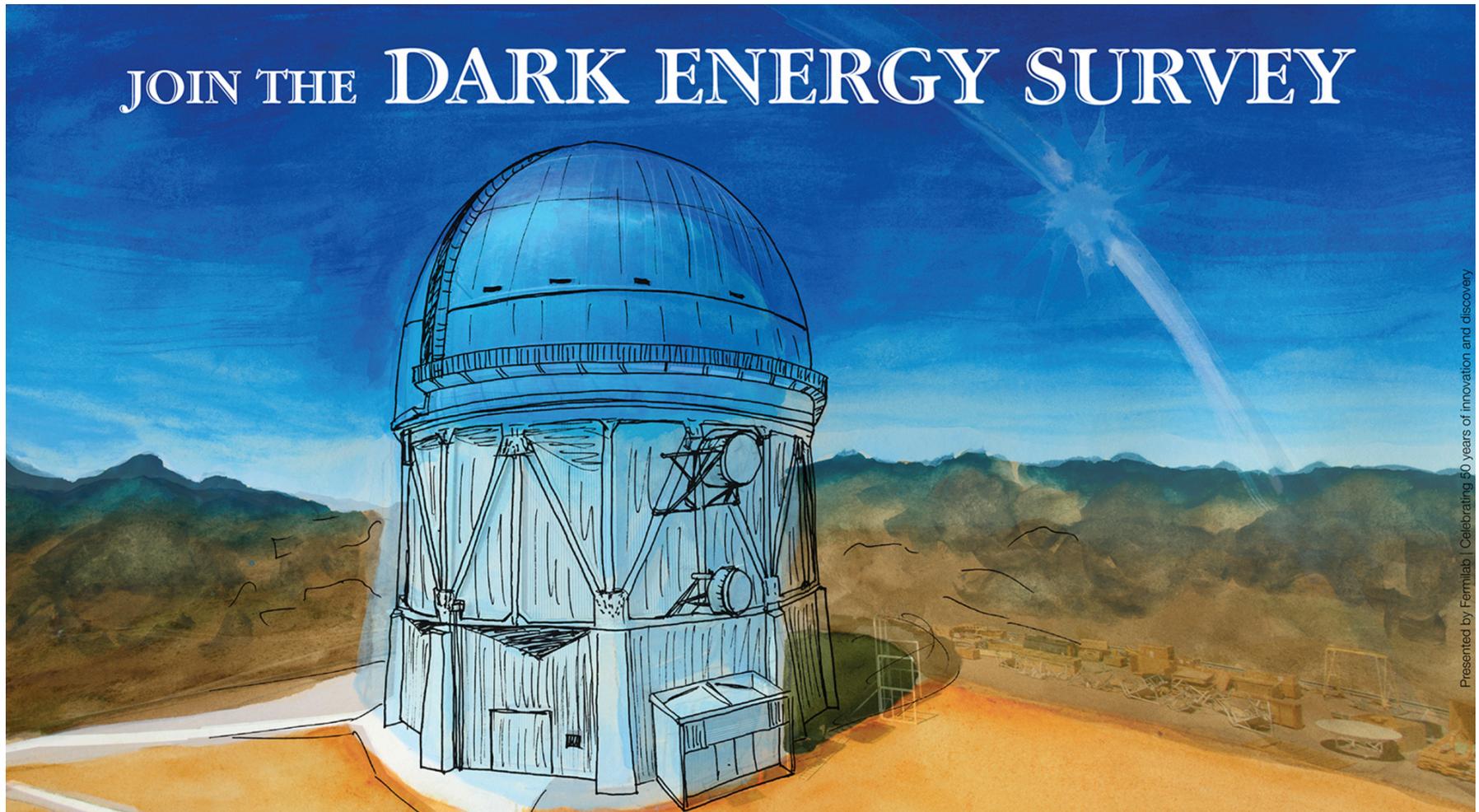
The Dark Energy Survey

The Dark Energy Survey Collaboration



Credit: The Dark Energy Survey Collaboration

The Dark Energy Survey



Credit: http://news.fnal.gov/wp-content/uploads/2017/06/50.Decampstr-FNL.MED_.jpg

The Dark Energy Survey

Victor Blanco 4m telescope at Cerro Tololo Inter-American Observatory



Credit (images 1,2, and 4): <https://www.darkenergysurvey.org/>

The Dark Energy Camera

- 570 Mega pixels, 62 CCD
- 3 sq. deg. field of view

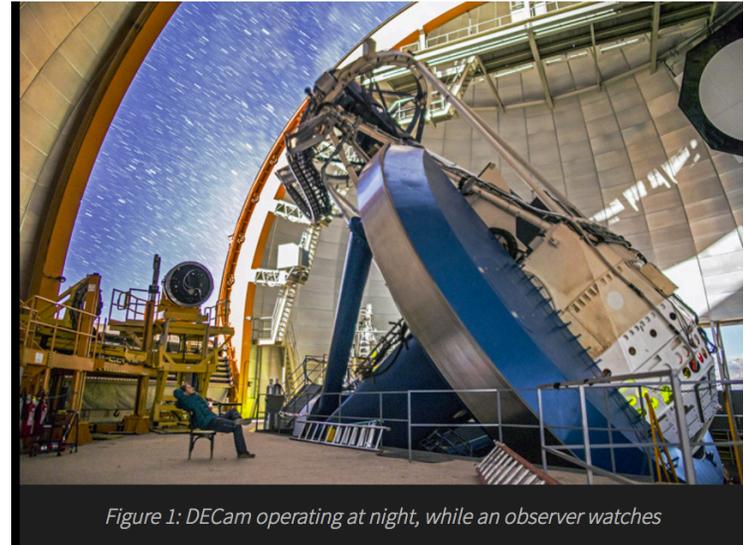
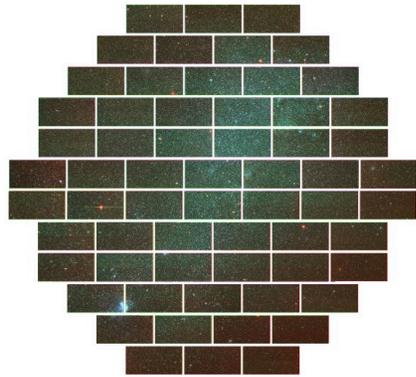
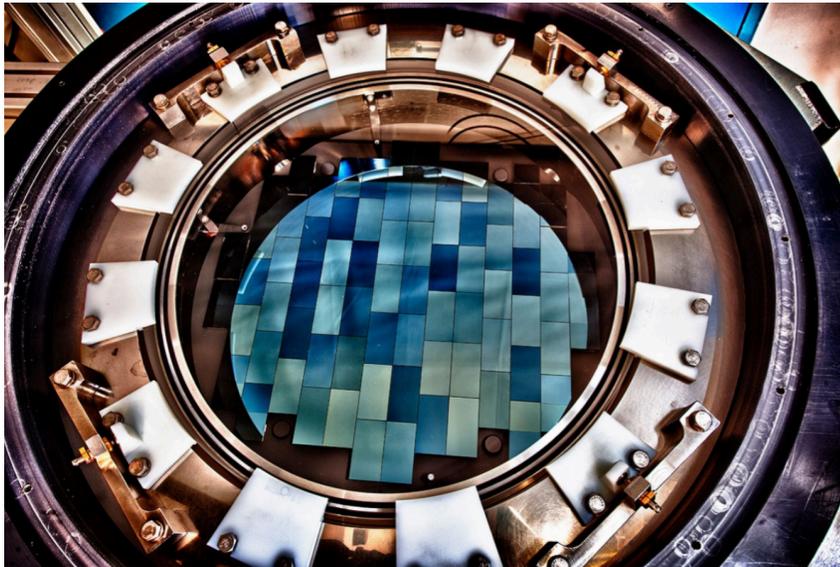


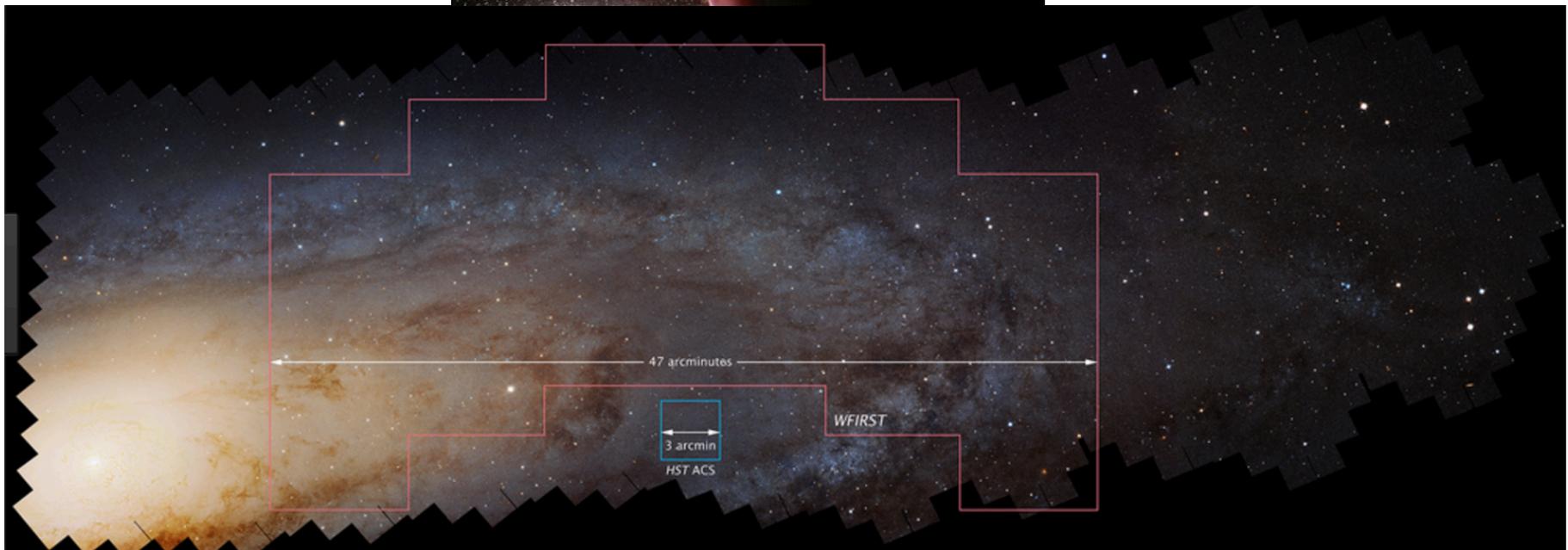
Figure 1: DECam operating at night, while an observer watches



Credit (all images except bottom right): <https://www.darkenergysurvey.org/the-des-project/instrument/>

WFIRST: Wide Field Infrared Survey Telescope

NASA observatory to answer questions in exoplanet detection and dark energy science.



Credit (both images): <http://newsletter.stsci.edu/wfirst-starts-mission-formation-phase/>

Thanks!

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The Composition of the Universe

