Princeton'66 San Francisco Lunch
September 25, 2019

# State of the Universe Report

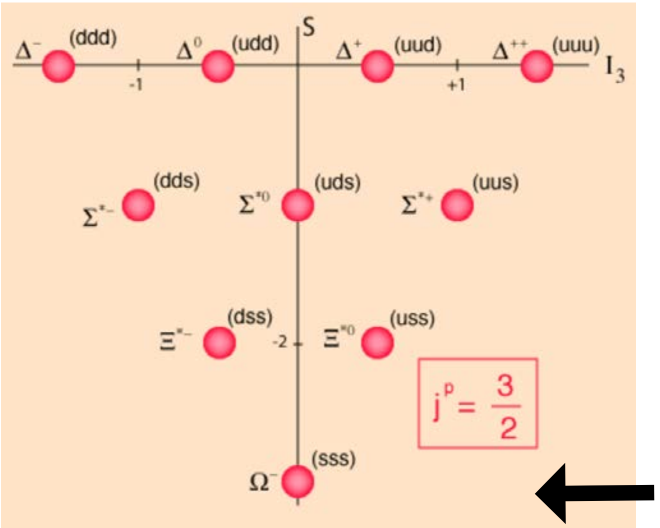

**Joel Primack '66**

Distinguished Professor of Physics Emeritus, UCSC

President, Sigma Xi, the Scientific Research Honor Society

Chair, Forum on Physics and Society

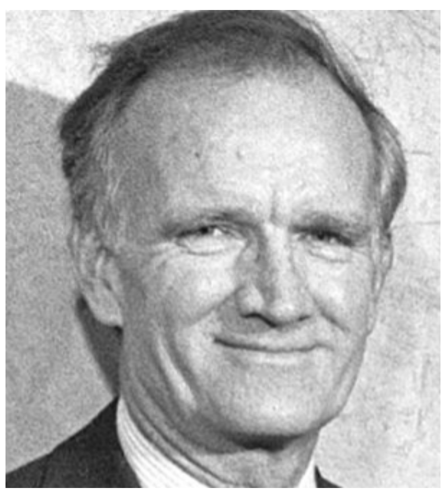
# KEY PHYSICS DISCOVERIES WHILE WE WERE UNDERGRADUATES




← $\Omega^-$

## $\Omega^-$ discovery in 1964

**leads to the quark model and the "Standard Model" of particle physics**



## CP violation discovery in 1964

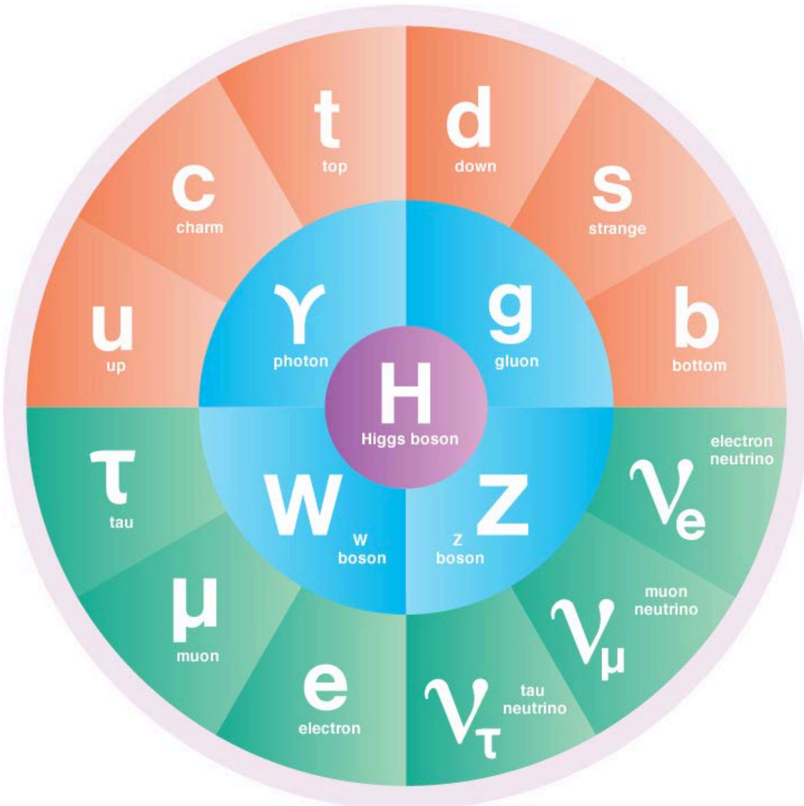
**by James Cronin and Princeton's Val Fitch**

**explained matter-antimatter asymmetry (a billion+1 quarks annihilate a billion antiquarks in the early universe — we are made of the remnants)**

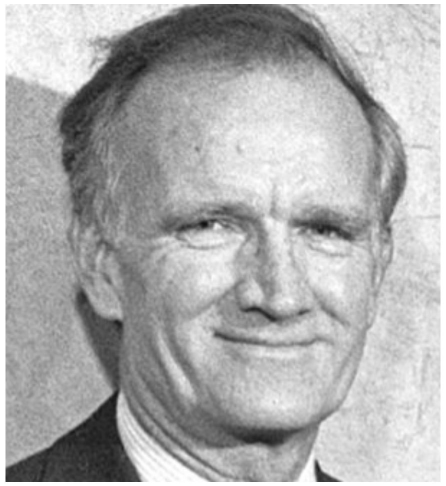
## Cosmic Background Radiation discovery in 1965

**by Princeton's Robert Dicke and others led to acceptance of the Big Bang**

# KEY PHYSICS DISCOVERIES WHILE WE WERE UNDERGRADUATES

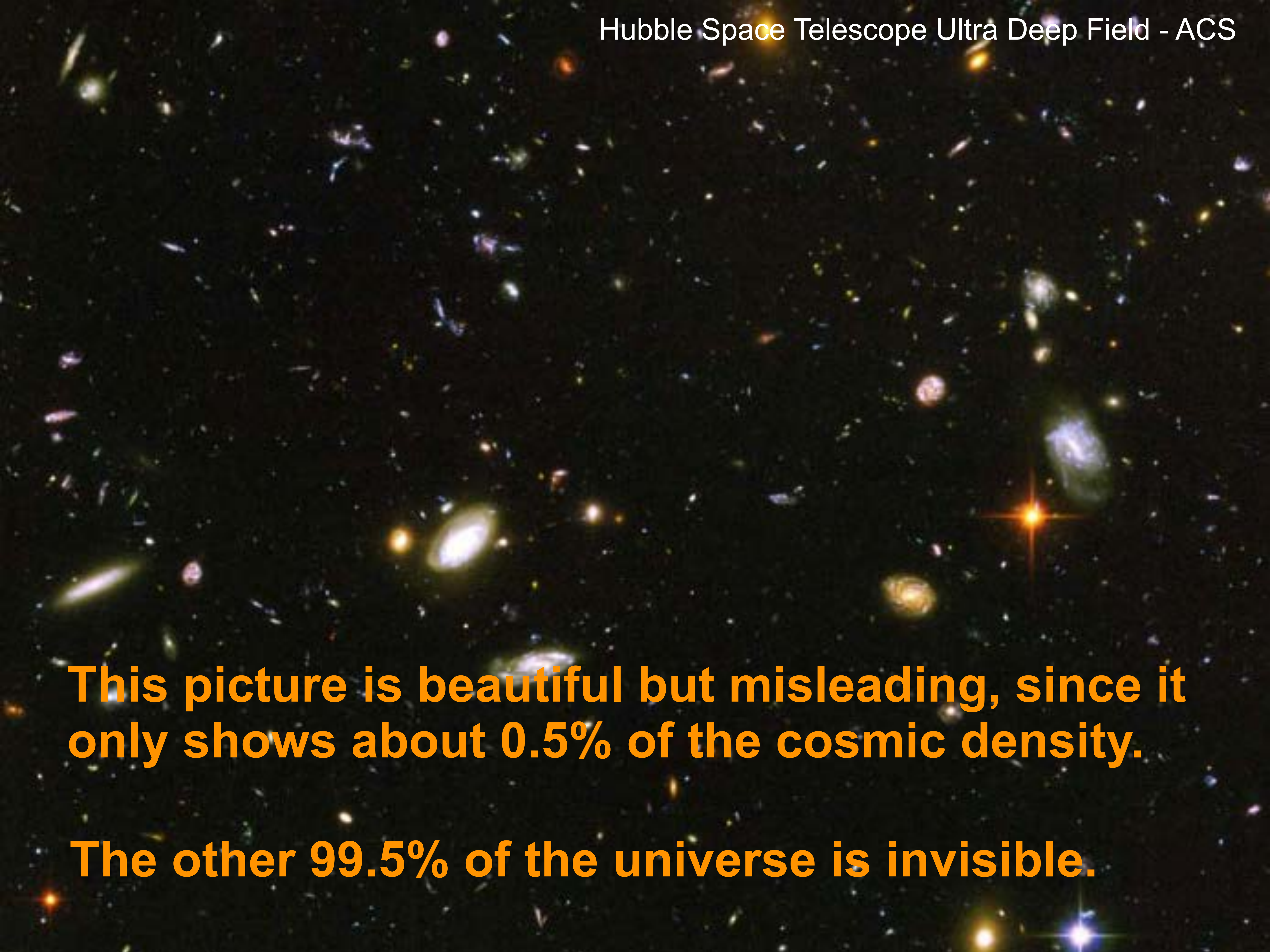



**$\Omega^-$ discovery in 1964**
**leads to the quark model and the "Standard Model" of particle physics**
**— which I worked on in 1967-80**



**CP violation discovery in 1964**
**by James Cronin and Princeton's Val Fitch**
**— which provided part of the input to my 1972 calculation of the charmed quark mass with Ben Lee and Princeton's Sam Treiman**

**Cosmic Background Radiation discovery in 1965**
**by Princeton's Robert Dicke and others**
**led to acceptance of the Big Bang**
**— which I worked on starting in 1979**




**This picture is beautiful but misleading, since it only shows about 0.5% of the cosmic density.**

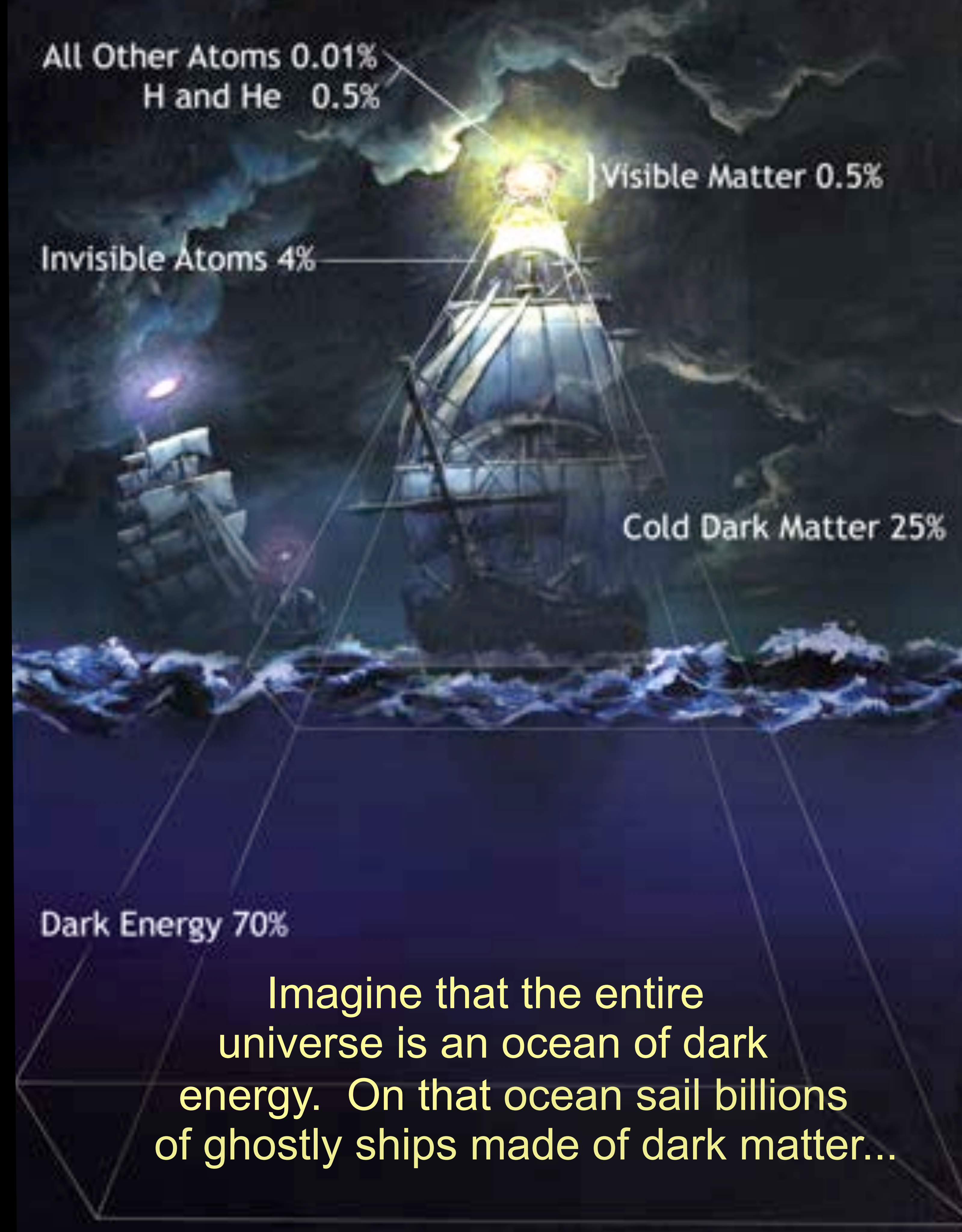
**The other 99.5% of the universe is invisible.**

# Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean




Matter and Energy Content of the Universe

ΛCDM

Double Dark Theory

# DISCOVERING THE INVISIBLE UNIVERSE

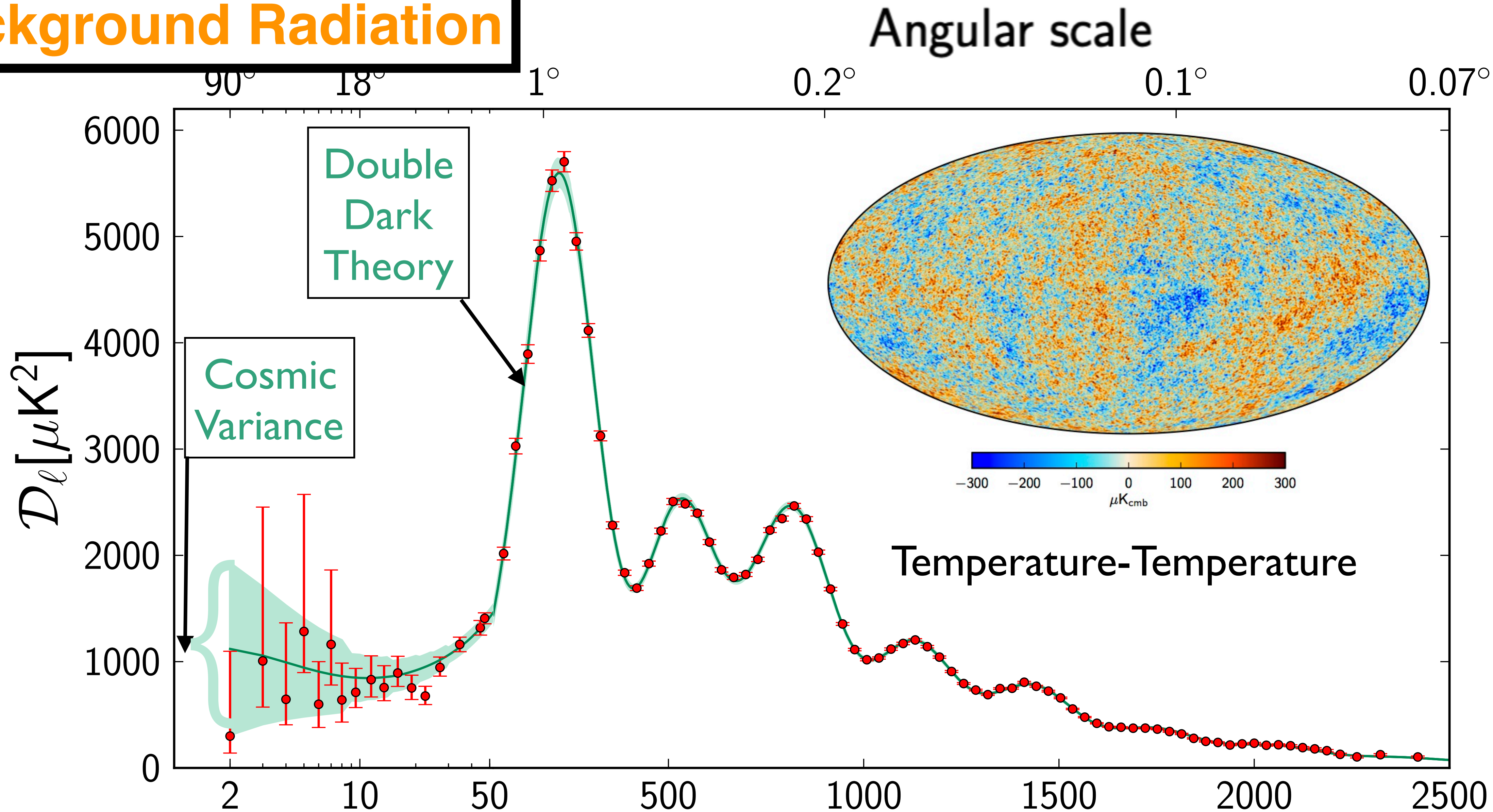
## Joel Primack

Although the first evidence for dark matter was discovered in the 1930s, it was not until about 1980 that astronomers became convinced that most of the mass holding galaxies and clusters of galaxies together is invisible. For two decades, alternative theories were proposed and attacked. By 2000 the ΛCDM “Double Dark” standard cosmological model was accepted: dark energy Λ plus Cold Dark Matter − non-atomic matter different from that which makes up the stars, planets, and us − together make up 95% of the cosmic density. ΛCDM correctly predicts the cosmic background radiation and the large-scale distribution of galaxies. The challenge now is to understand the underlying physics of the dark matter and the dark energy, and how they result in the universe of galaxies that we observe.

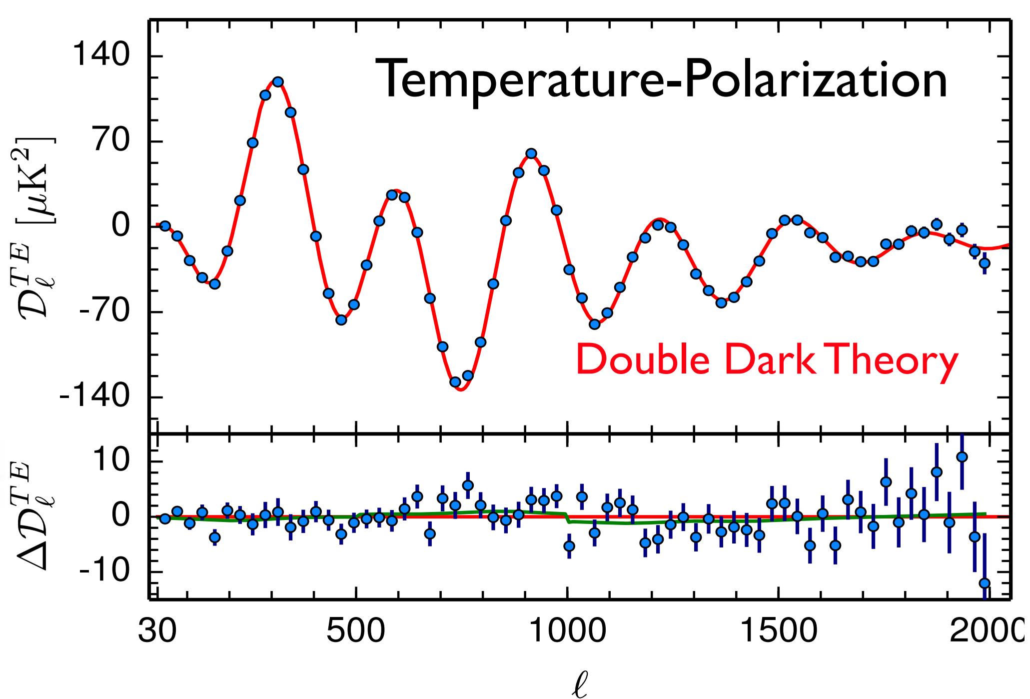
# Cosmic Background Radiation

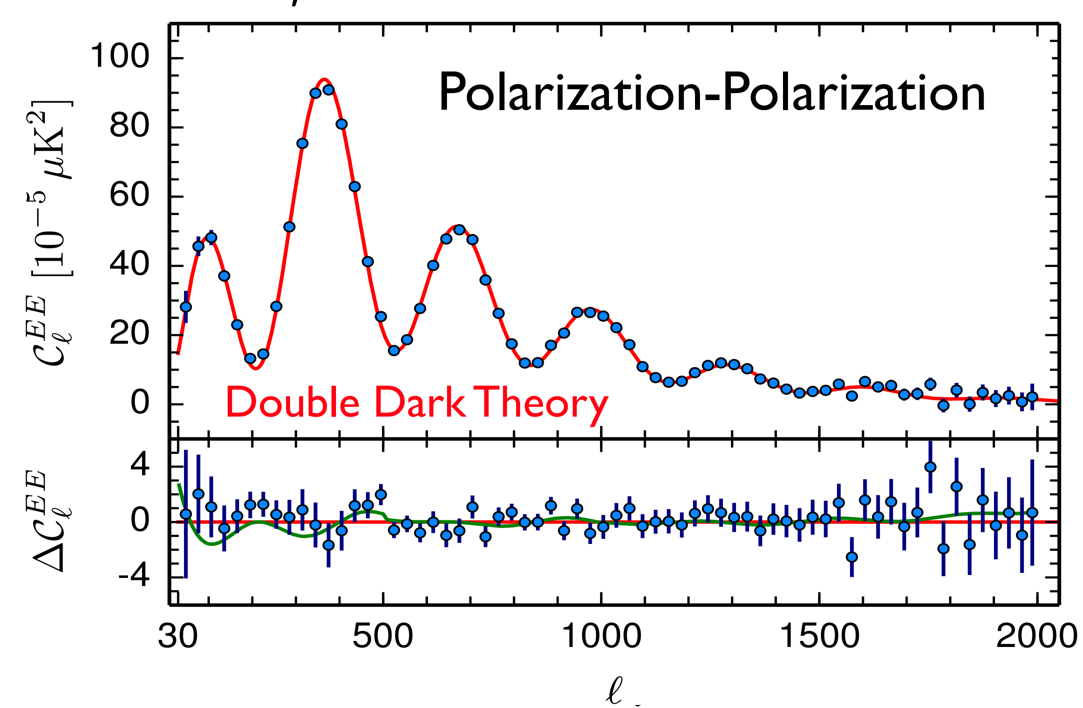
European Space Agency PLANCK Satellite Data

Released February 9, 2015

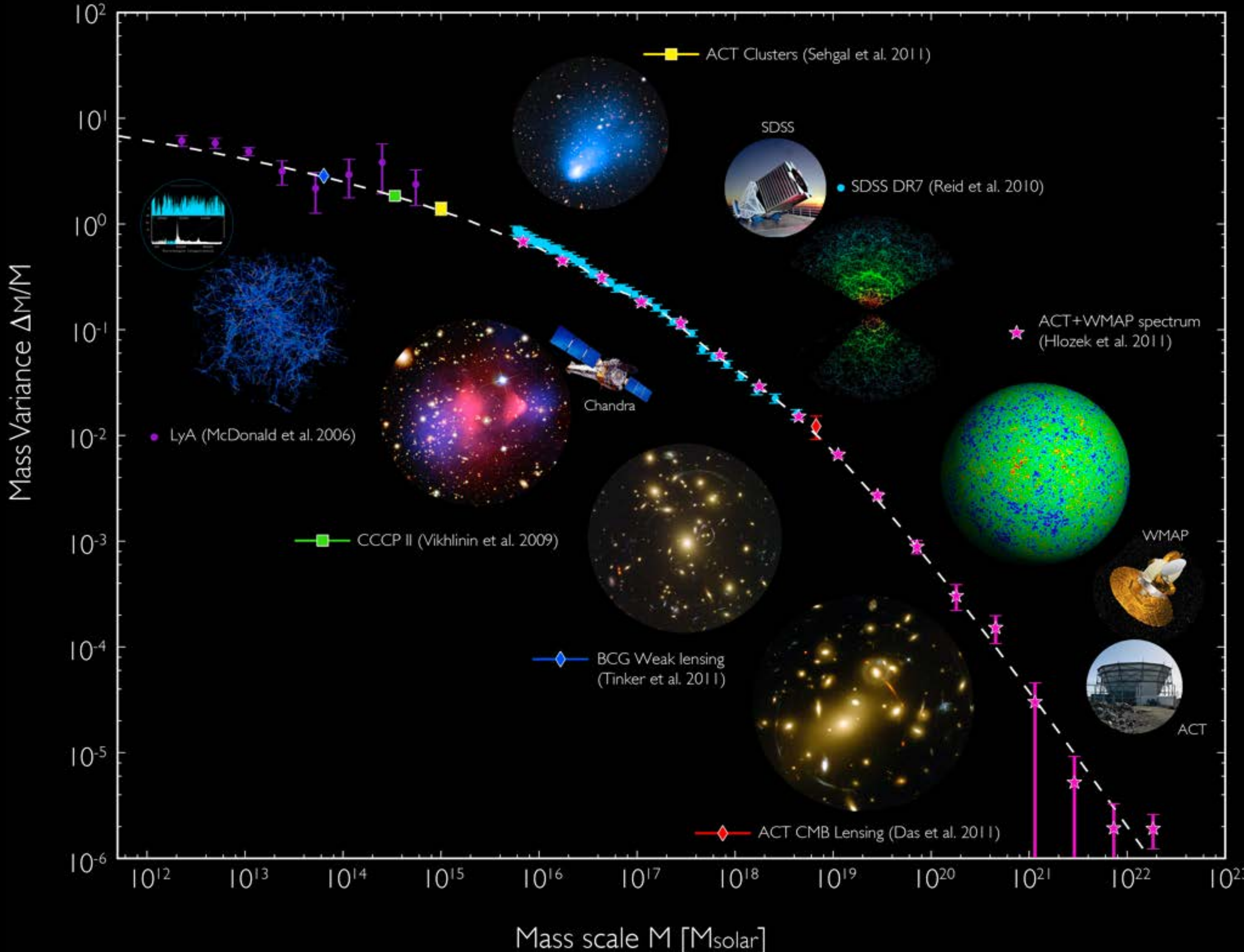


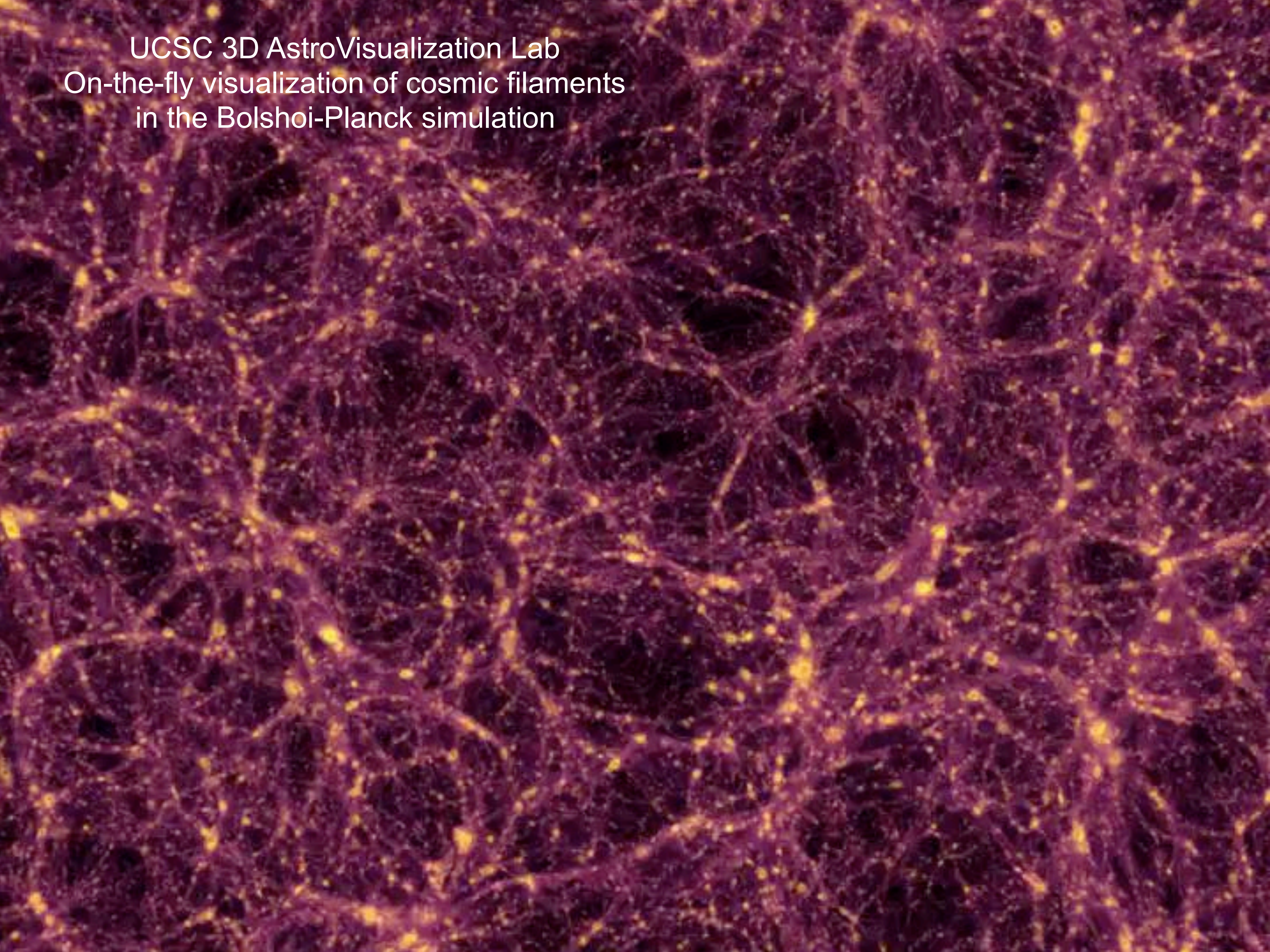

**Agrees with Double Dark Theory!**



# Matter Distribution Agrees with Double Dark Theory!




UCSC 3D AstroVisualization Lab
On-the-fly visualization of cosmic filaments
in the Bolshoi-Planck simulation


# Cosmology and Astrophysics

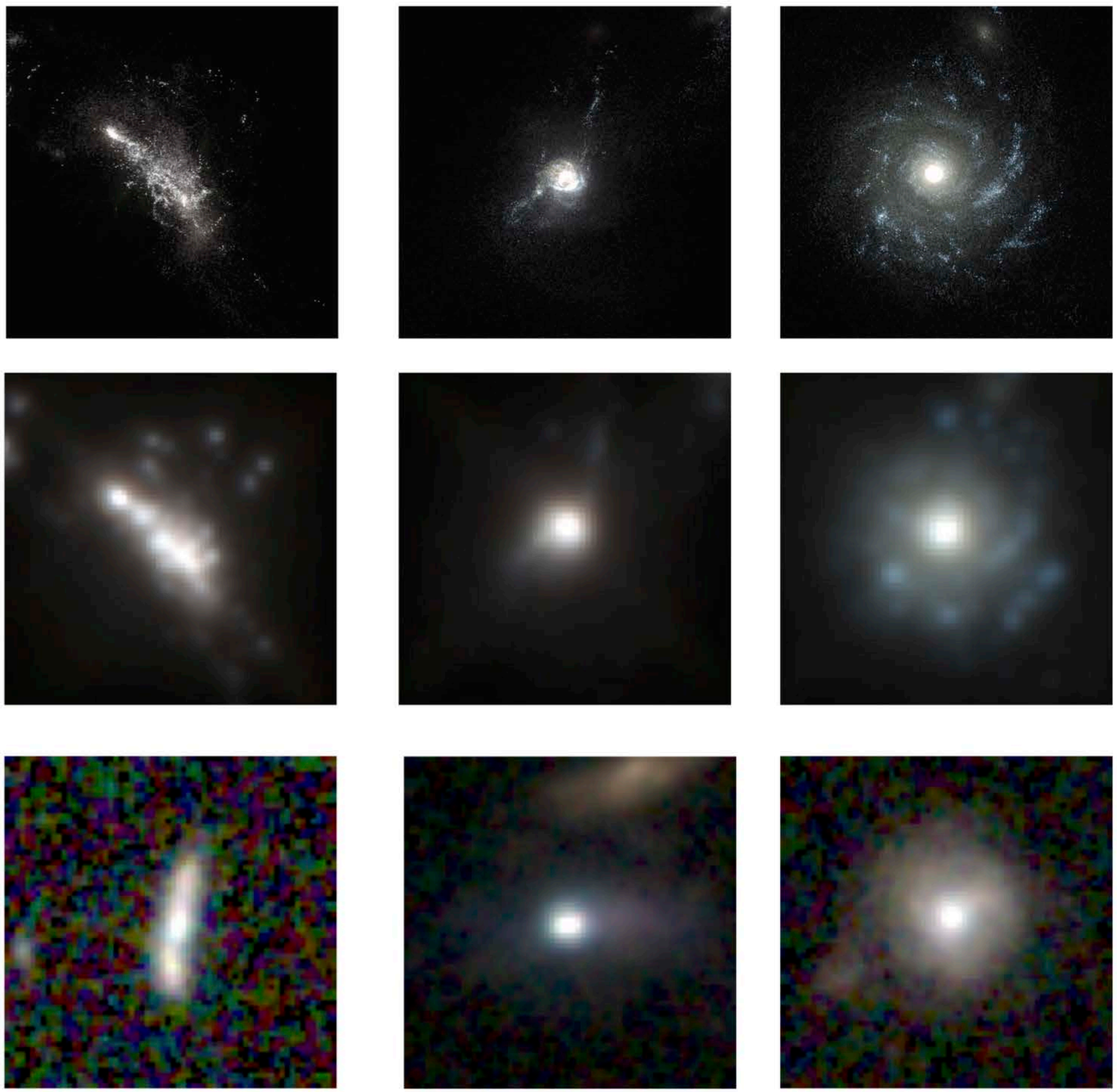
## Joel Primack current research

- Bolshoi - best cosmological simulations using the latest cosmological parameters.
- Largest suite of high-resolution zoom-in hydrodynamic galaxy simulations compared with observations by CANDELS, the largest-ever Hubble Space Telescope project.
- Dust absorption and re-radiation of starlight in simulated galaxies using my group's Sunrise code to make realistic galaxy images from our simulations.
- Explain observed galaxy clumps, compaction, "pickle galaxies". New methods for comparison of simulated galaxies with observations, including deep learning.
- Co-leading the Assembling Galaxies of Resolved Anatomy (AGORA) international collaboration to run and compare high-resolution galaxy simulations.
- Calculating and measuring all the light in the universe using gamma rays.

# Face Recognition for Galaxies

**Simulations Agree with Hubble Space Telescope Observations**

| Pre-BN | BN | Post-BN |
|---|---|---|
| Pre-Blue-Nugget-Stage | Blue-Nugget-Stage | Post-Blue-Nugget-Stage |



VELA Simulation High-Res Images

VELA Simulation HST-Res Images

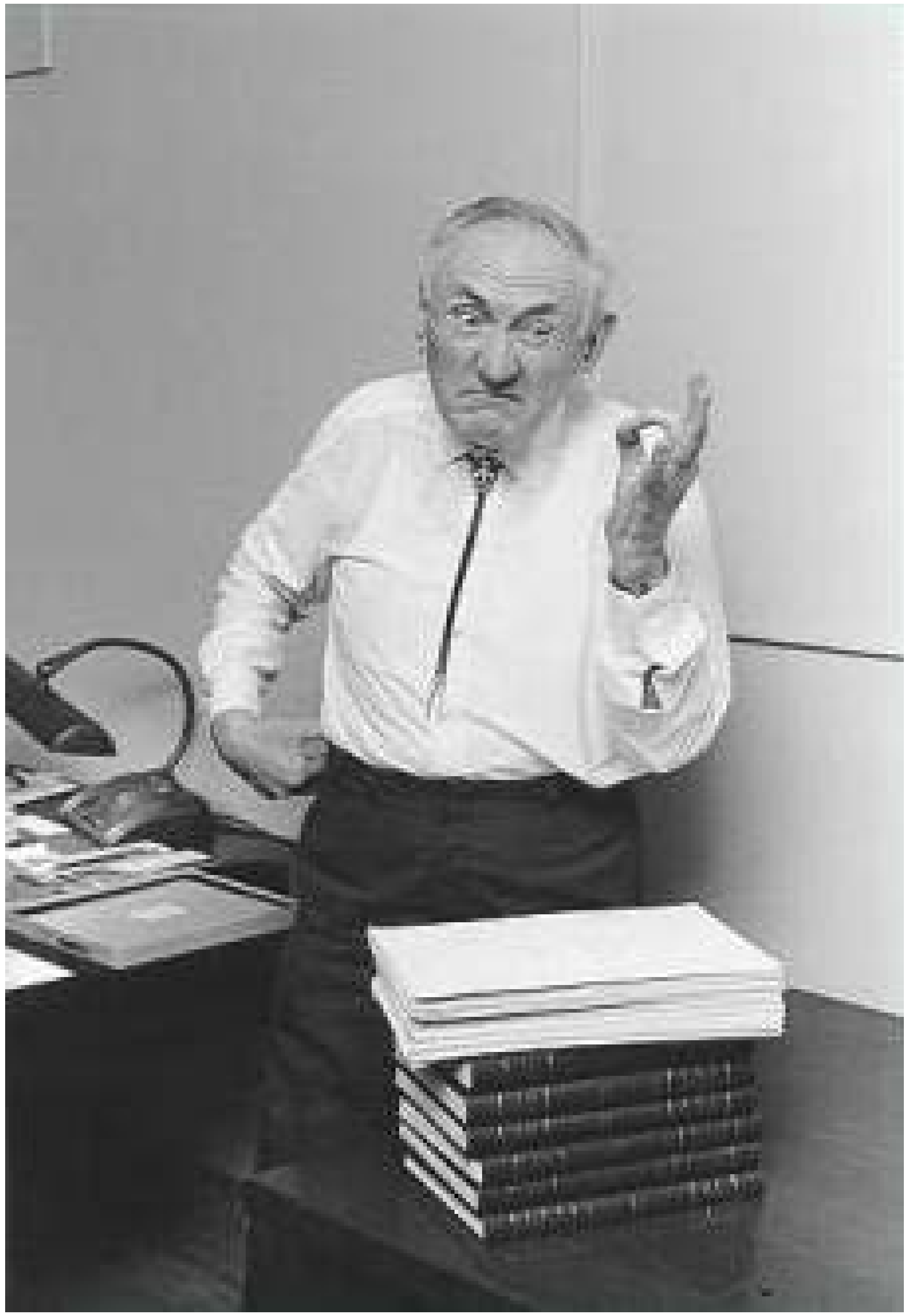
Real HST Images

# SUMMARY

- We now know the cosmic recipe. Most of the universe is invisible stuff called "nonbaryonic dark matter" (25%) and "dark energy" (70%). Everything that we can see makes up only about 0.5% of the cosmic density, and invisible atoms about 4.5%. The earth and its inhabitants are made of the rarest stuff of all: elements made in stars (0.01%).
- The ΛCDM Dark Energy + Cold Dark Matter Double Dark theory based on this recipe appears to be able to account for all the large scale features of the observable universe, including the details of the heat radiation of the Big Bang and the large scale distribution and masses of galaxies.
- Constantly improving data are repeatedly testing this theory. The main ingredients have been checked several different ways.
- We still don't know what the dark matter and dark energy are, nor really understand how galaxies form and evolve within dark matter halos. There's lots more work for us to do!

THANKS!

# Galaxy Clusters Are Mostly Dark Matter



Fritz Zwicky

## ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY 1937 ApJ 86, 217

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

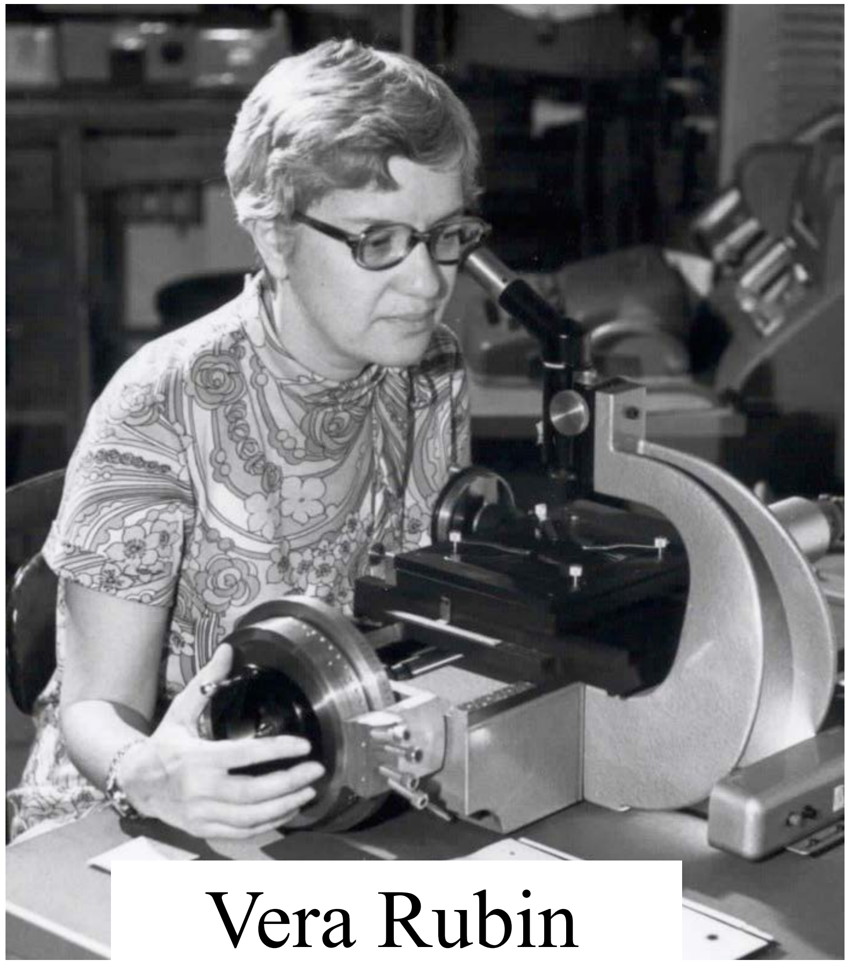
$$\overline{M} > 9 \times 10^{43}\ \mathrm{gr} = 4.5 \times 10^{10}\ M_{\odot}\ . \tag{36}$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about $8.5 \times 10^7$ suns. According to (36), the conversion factor $\gamma$ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\text{Mass/Light} = \gamma = 500\ , \tag{37}$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system.

**This article also proposed measuring the masses of galaxies by gravitational lensing.**


Vera Rubin

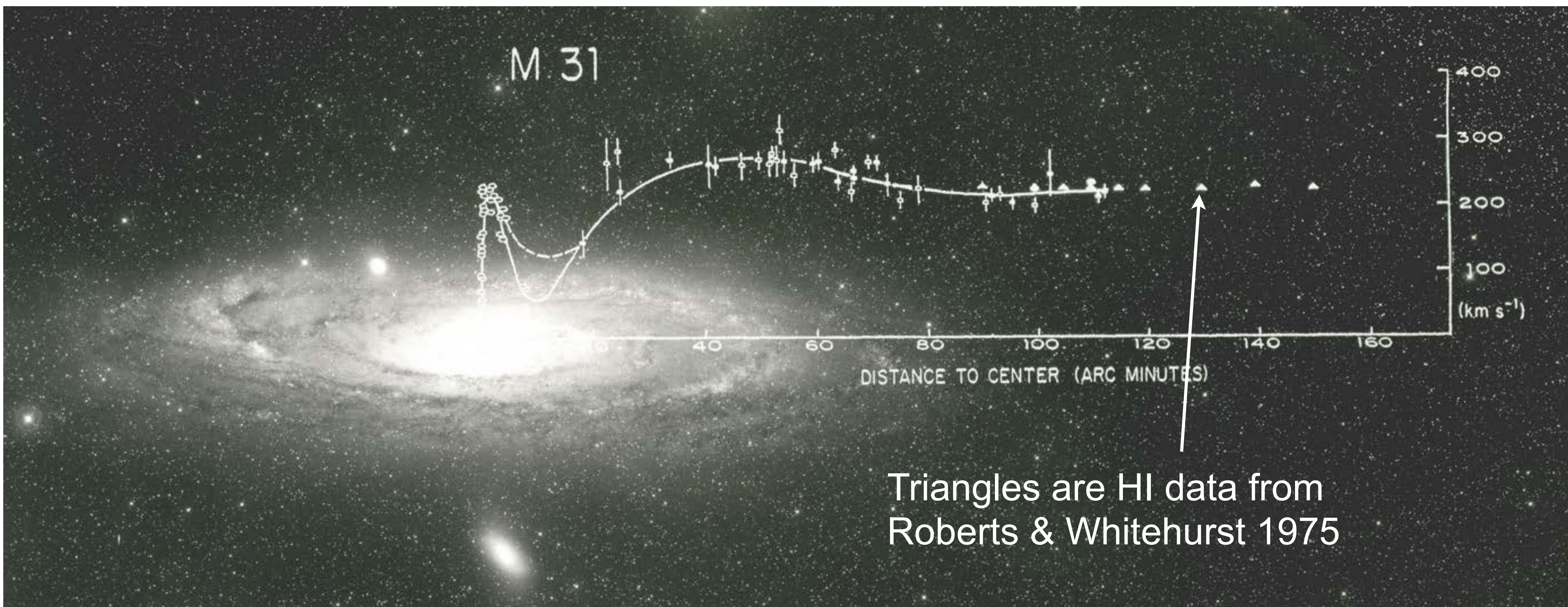
# Flat Rotation Curves imply that

## Galaxies Are Mostly Dark Matter

1970 ApJ 159, 379

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

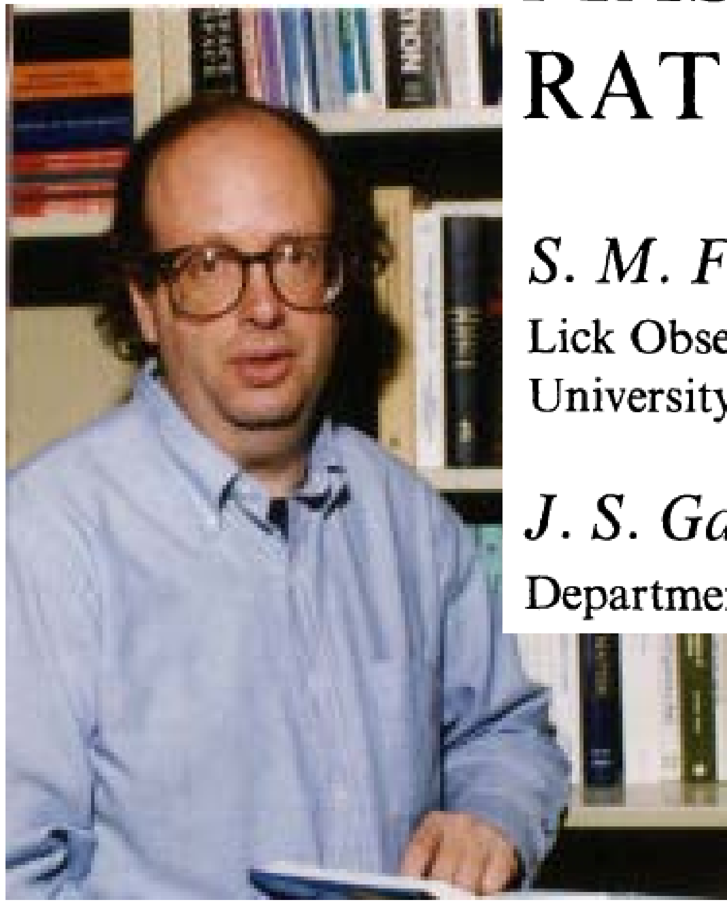


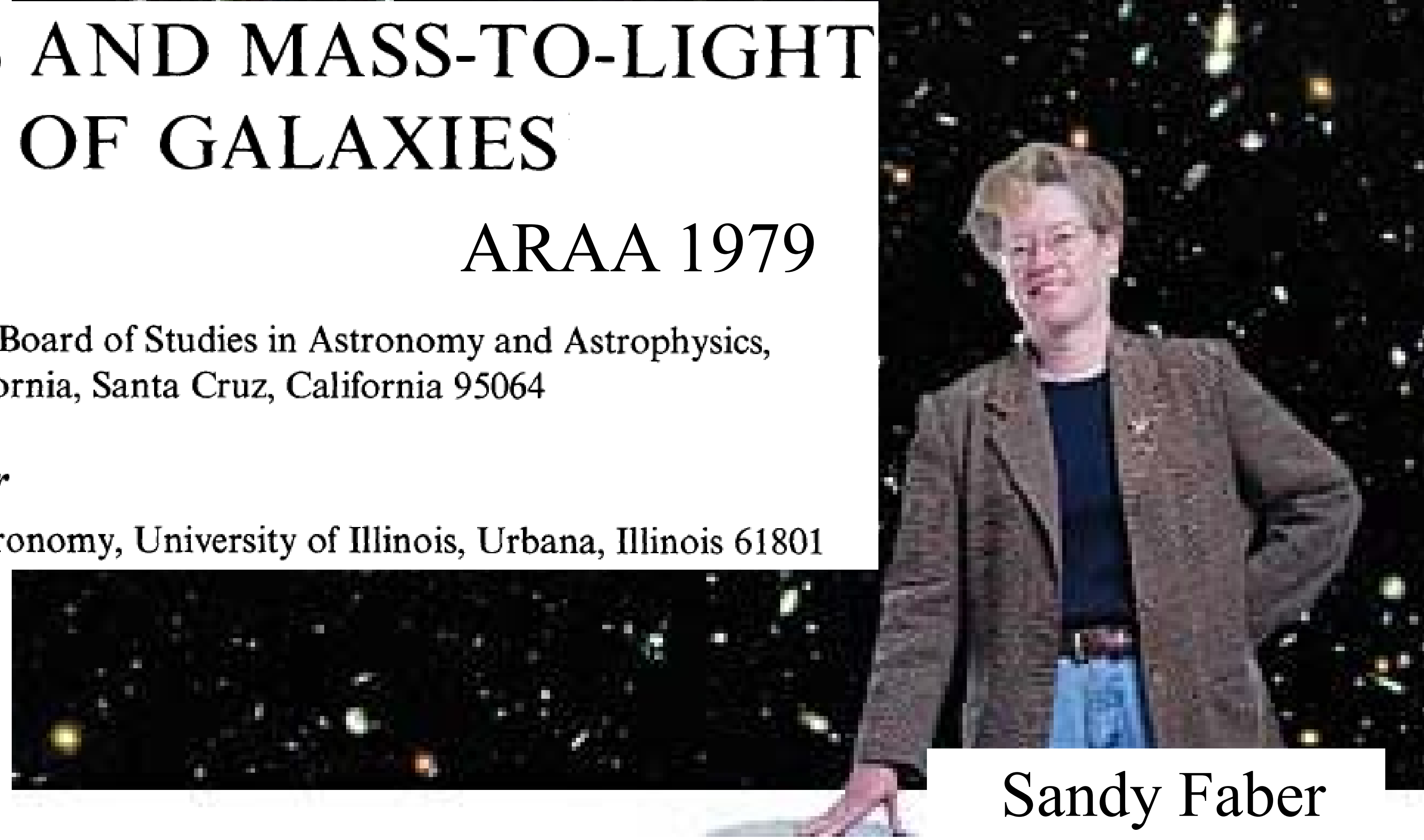
# MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES

ARAA 1979

*S. M. Faber*
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

*J. S. Gallagher*
Department of Astronomy, University of Illinois, Urbana, Illinois 61801





Sandy Faber

After reviewing all the evidence, it is our opinion that the case for invisible mass in the Universe is very strong and getting stronger. Particularly encouraging is the fact that the mass-to-light ratio for binaries agrees so well with that for small groups. Furthermore, our detailed knowledge of the mass distribution of the Milky Way and Local Group is reassuringly consistent with the mean properties of galaxies and groups elsewhere. In sum, although such questions as observational errors and membership probabilities are not yet completely resolved, we think it likely that the discovery of invisible matter will endure as one of the major conclusions of modern astronomy.

Weakly Interacting Massive Particles

**WIMP Dark Matter**

1982 PRL 48, 224

# Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies

Heinz Pagels
*The Rockefeller University, New York, New York 10021*

and

Joel R. Primack
*Physics Department, University of California, Santa Cruz, California 95064*
(Received 17 August 1981)

If one assumes a spontaneously broken local supersymmetry, big-bang cosmology implies that the universe is filled with a gravitino ($g_{3/2}$) gas—possibly its dominant constituent. From the observational bound on the cosmological mass density it follows that $m_{g_{3/2}} \lesssim 1$ keV. Correspondingly, the supersymmetry breaking parameter $F$ satisfies $\sqrt{F} \lesssim 2\times 10^3$ TeV, requiring new supersymmetric physics in the teraelectronvolt energy region. An exact sum rule is derived and used to estimate the threshold and cross section for the production of the new states.

# Galaxy formation by dissipationless particles heavier than neutrinos

1982 Nature 299, 37

**George R. Blumenthal*, Heinz Pagels†**
**& Joel R. Primack‡**

**Warm Dark Matter**

* Lick Observatory, Board of Studies in Astronomy and Astrophysics, ‡ Board of Studies in Physics, University of California, Santa Cruz, California 95064, USA
† The Rockefeller University, New York, New York 10021, USA

**In a baryon dominated universe, there is no scale length corresponding to the masses of galaxies. If neutrinos with mass <50 eV dominate the present mass density of the universe, then their Jeans mass $M_{J\nu} \sim 10^{16} M_\odot$, which resembles supercluster rather than galactic masses. Neutral particles that interact much more weakly than neutrinos would decouple much earlier, have a smaller number density today, and consequently could have a mass >50 eV without exceeding the observational mass density limit. A candidate particle is the gravitino, the spin 3/2 supersymmetric partner of the graviton, which has been shown[1] to have a mass ≤1 keV if stable[2]. The Jeans mass for a 1-keV noninteracting particle is $\sim 10^{12} M_\odot$, about the mass of a typical spiral galaxy including the nonluminous halo. We suggest here that the gravitino dominated universe can produce galaxies by gravitational instability while avoiding several observational difficulties associated with the neutrino dominated universe.**

**Cold Dark Matter**



# Formation of galaxies and large-scale structure with cold dark matter

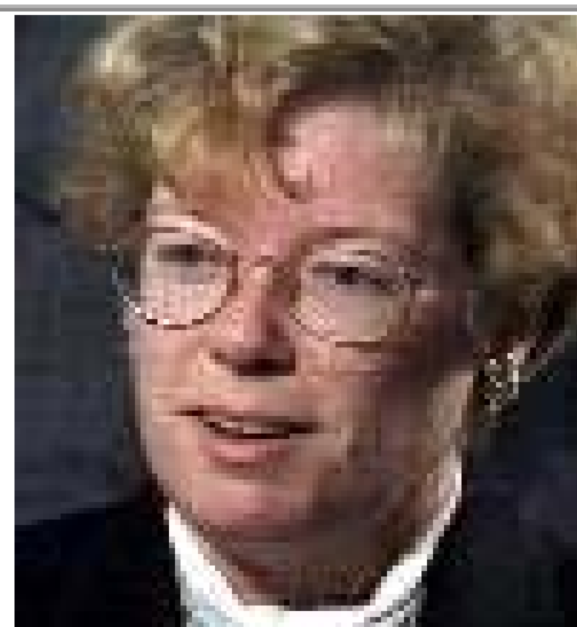
**George R. Blumenthal* & S. M. Faber***

* Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA

**Joel R. Primack†§ & Martin J. Rees‡§**

† Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA
‡ Institute of Theoretical Physics, University of California, Santa Barbara, California 93106, USA

*The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich* ($|\delta_k|^2 \propto k$) *spectrum of primordial fluctuations.*



*Ann. Rev. Nucl. Part. Sci. 1988. 38: 751–807*


# DETECTION OF COSMIC DARK MATTER

*Joel R. Primack and David Seckel*

Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, California 95064

*Bernard Sadoulet*

Physics Department, University of California, Berkeley, California 94720

CONTENTS

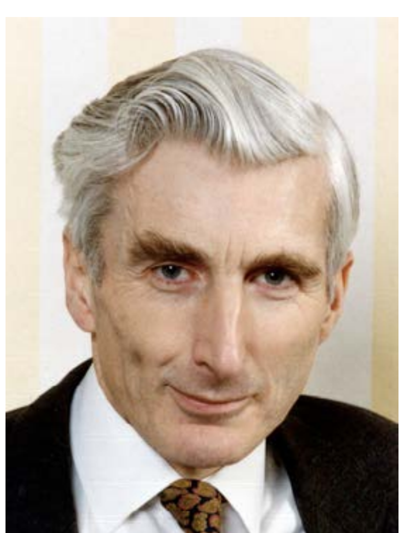


*Mon. Not. R. astr. Soc.* (1991) **251,** 128–136

# Dynamical effects of the cosmological constant

**Ofer Lahav, Per B. Lilje, Joel R. Primack, and Martin J. Rees**

**Dark Energy**



**SUMMARY**

The possibility of measuring the density parameter $\Omega_0$ and the cosmological constant $\lambda_0 \equiv \Lambda/(3H_0^2)$ using dynamical tests is explored in linear and non-linear theory. In linear theory we find that the rate of growth of the perturbations at the present epoch is approximated by $f(z=0) \approx \Omega_0^{0.6} + \frac{1}{70}\lambda_0(1+\frac{1}{2}\Omega_0)$. Therefore, dynamical tests such as infall around clusters and dipoles at the present epoch do not distinguish well between universes with and without a cosmological constant. At higher redshifts, the perturbations also depend mainly on the matter density at a particular epoch, $f(z) \approx \Omega^{0.6}(z)$, which has a strong dependence on $\lambda_0$ at $z \approx 0.5$–$2.0$. Therefore, information on both parameters can be obtained by looking at clustering at different redshifts. In practice, however, the other observables also depend on the cosmology, and in some cases conspire to give a weak dependence on $\lambda_0$. By using the non-linear spherical infall model for a family of Cold Dark Matter (CDM) power-spectra we also find that dynamics at $z=0$ does not tell much about $\lambda_0$. At higher redshifts there is unfortunately another conspiracy between conventional observables, which hides information about $\lambda_0$. The final radius of a virialized cluster (relative to the turn-around radius) is approximated by $R_f/R_{ta} \approx (1-\eta/2)/(2-\eta/2)$, where $\eta$ is the ratio of $\Lambda$ to the density at turn-around. Therefore a repulsive $\Lambda$ gives a smaller final radius than a vanishing $\Lambda$.

**Accelerating Expansion Discovered in 1998**

# Joel Primack RECENT PhD STUDENTS

**Rachel Somerville** (PhD 1997) Jerusalem (postdoc) – Cambridge (postdoc) – Michigan (Asst. Prof.) – MPI Astronomy Heidelberg (Prof.) – STScI/Johns Hopkins – Rutgers (Prof.) – CCA (Galaxy Group Leader)
**Michael Gross** (PhD 1997) Goddard (postdoc) – UCSC (staff) – NASA Ames (staff)
**James Bullock** (PhD 1999) Ohio State (postdoc) – Harvard (Hubble Fellow) – UC Irvine (Professor, Dean)
**Ari Maller** (PhD 1999) Jerusalem – U Mass Amherst (postdoc) – CityTech CUNY (Assoc. Prof.)
**Risa Wechsler** (PhD 2001) Michigan – Chicago (Hubble Fellow) – Stanford U (Prof., KIPAC Director)
**T. J. Cox** (PhD 2004) Harvard (postdoc, Keck Fellow) – Carnegie Observatories (postdoc) – Data Scientist at Voxer, San Francisco – Data Scientist at Apple, Cupertino
**Patrik Jonsson** (PhD 2004) UCSC (postdoc) – Harvard CfA (staff) – SpaceX senior programmer
**Brandon Allgood** (PhD 2005) – Numerate, Inc. (co-founder)
**Matt Covington** (PhD 2008) – analytic understanding of galaxy mergers, semi-analytic models of galaxy formation – U Minn (postdoc) – U Arkansas (Assoc. Prof. geophysics)
**Greg Novak** (PhD 2008) – running and comparing galaxy merger simulations with observations – Princeton (postdoc) – Inst Astrophysique Paris (postdoc) – Data Scientist at Stitch Fix, San Francisco
**Christy Pierce** (PhD 2009) – AGN in galaxy mergers – Georgia Tech (postdoc) – teaching
**Rudy Gilmore** (PhD 2009) – WIMP properties and annihilation; extragalactic background light and gamma ray absorption – SISSA, Trieste, Italy (postdoc), Data Scientist at TrueCar, L.A.
**Alberto Dominguez** (PhD 2011) – UCR (postdoc) - Clemson U (postdoc) - Madrid (Juan de la Cierva postdoc, Ramon y Cajal Fellow, Assistant Prof. Complutense University)
**Lauren Porter** (PhD 2013) – semi-analytic models vs. observations - Data Scientist at Groupon; Facebook
**Chris Moody** – analysis of high-resolution galaxy simulations: galaxy morphology transformations (PhD 2014) – Data Scientist at Square, San Francisco; Senior Data Scientist at Stitch Fix, San Francisco
**Christoph Lee** – (PhD 2019) galaxy-halo connection; deep learning for stellar clumps in galaxies

# Joel Primack CURRENT PhD STUDENTS

**David Reiman** – artificial intelligence for astrophysics: de-blending, image enhancement, galaxy environment
**Viraj Pandya** – prolate galaxy alignments; semi-analytic models for galaxies
**Clayton Strawn** – circumgalactic medium: simulations vs. observations
**James Kakos** – distant galaxy environments from photometric plus spectroscopic redshifts

# THANKS!