Exploiting Weak Gravitational Lensing to Constrain Dark Energy

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Collaborators

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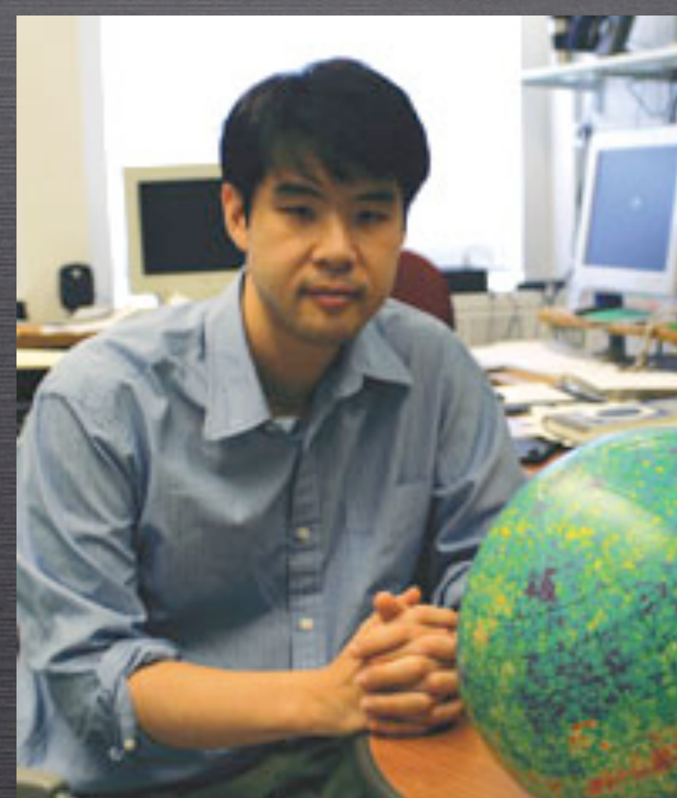


Wayne Hu (U. Chicago)

Based on:

Rudd, ARZ, Kravtsov (2008)

ARZ, Rudd, Hu (2008)

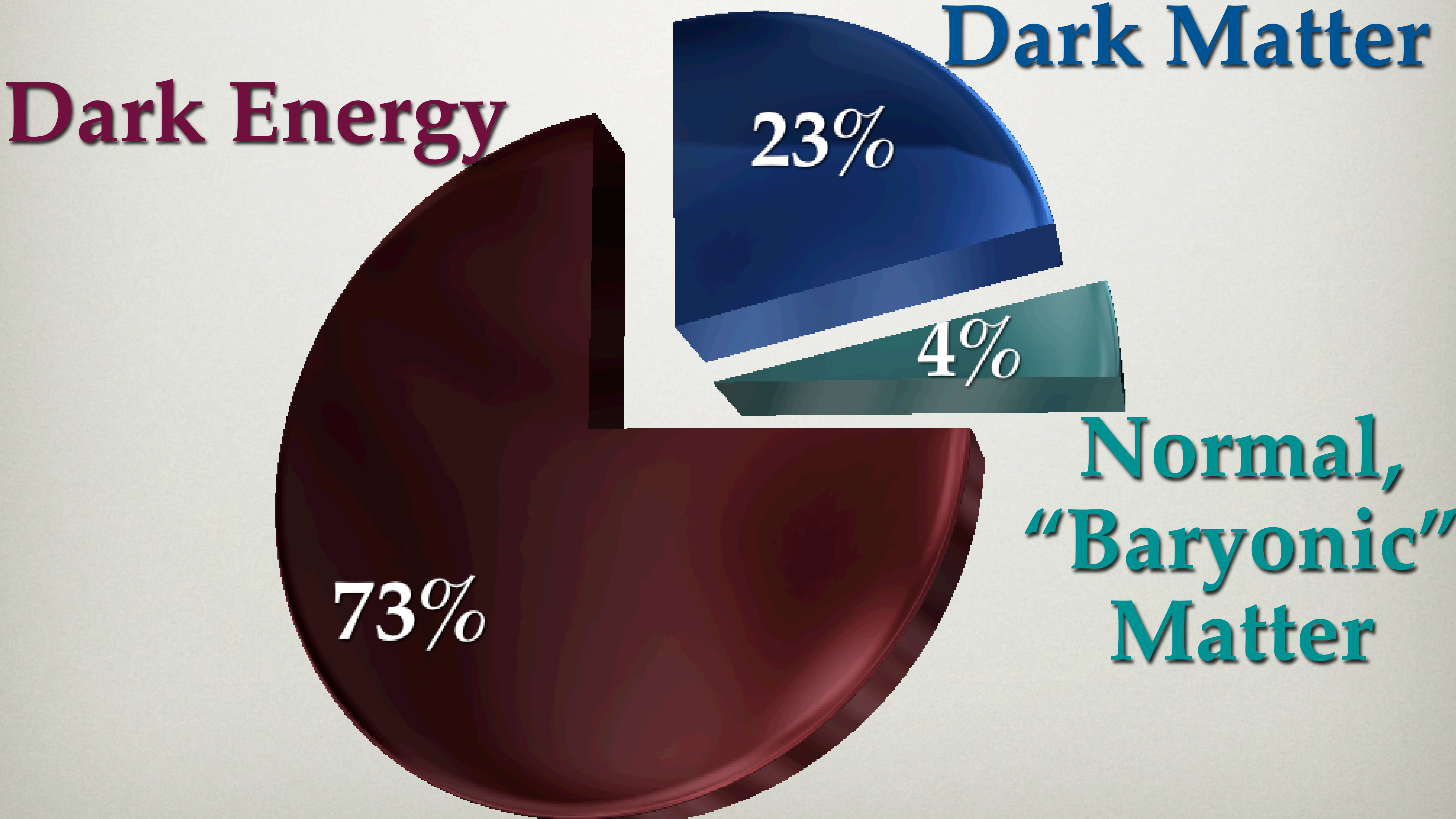
Hearin & ARZ (2009)

Hearin et al. (2010)

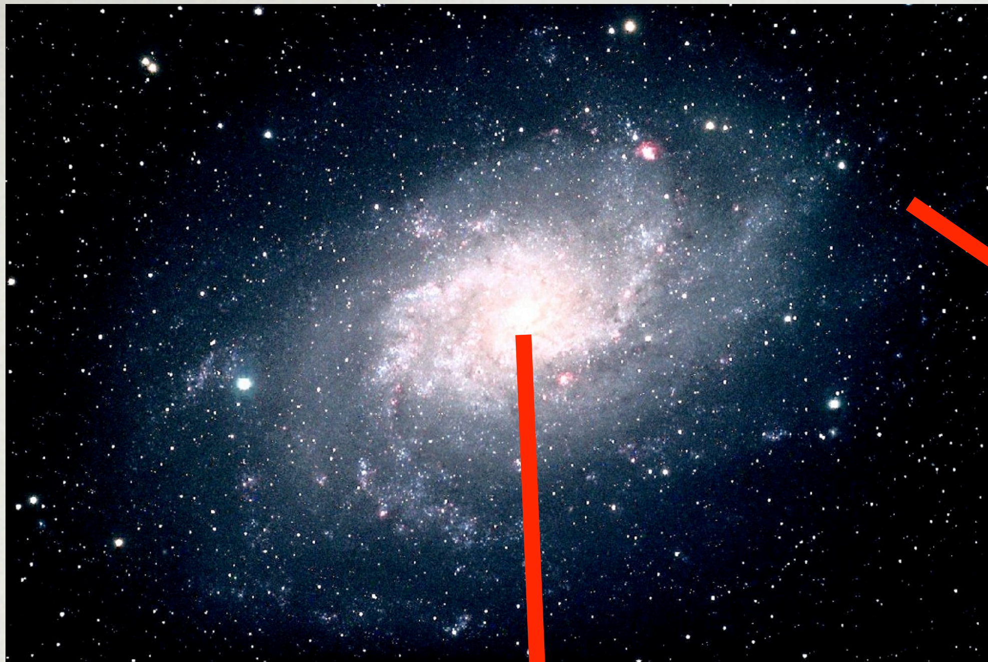
Outline

1. The "Standard Model" of Cosmology and the "Dark Sector"
   1.A. Dark Matter - Brief Mention
   1.B. Dark Energy
2. Gravitational Lensing: A Probe of the Dark Energy
3. The Theoretical Challenge: Galaxy Formation
4. The Future

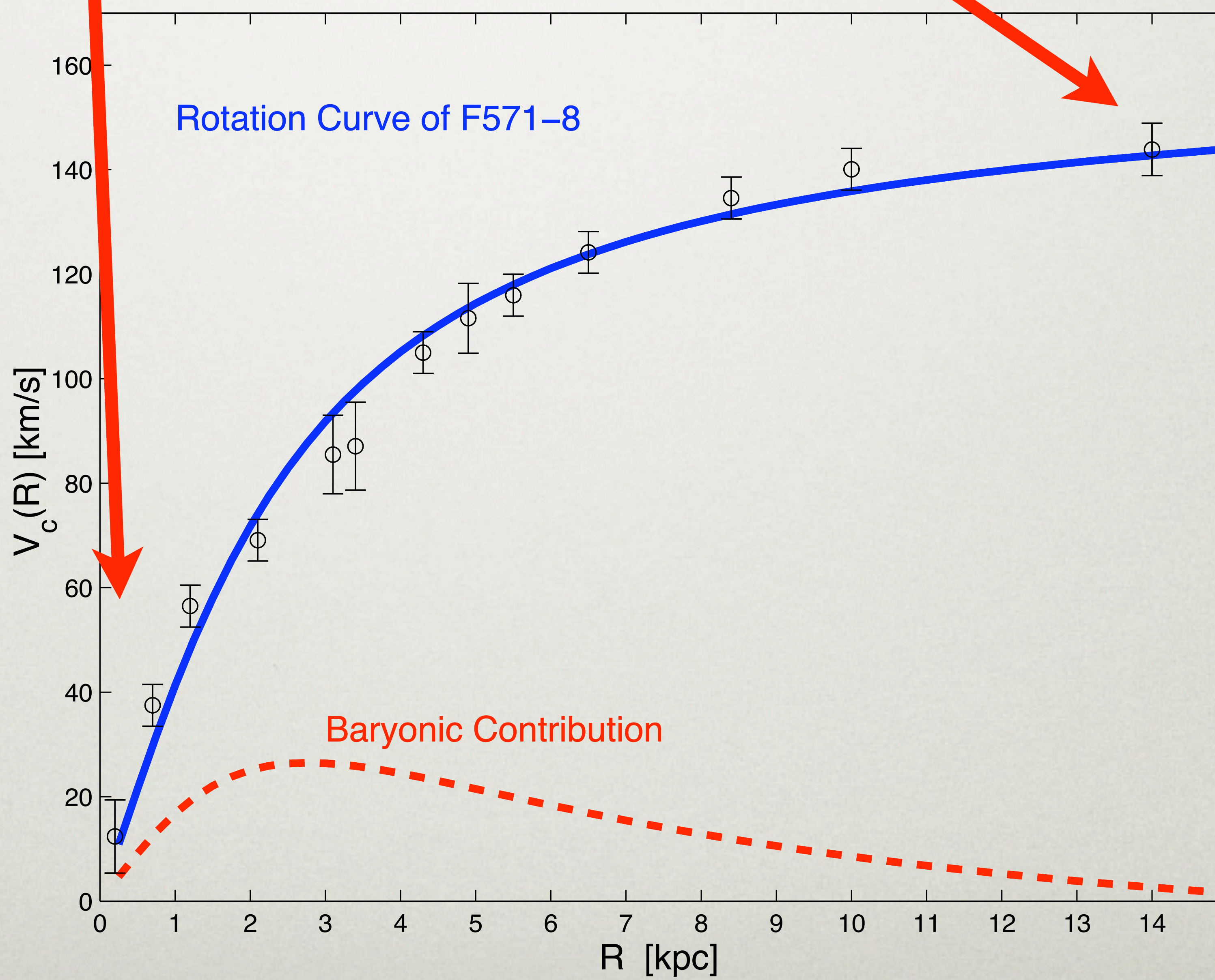
The Current Cosmic Energy Budget



DARK MATTER



Velocities: Observed vs. Expected from Light

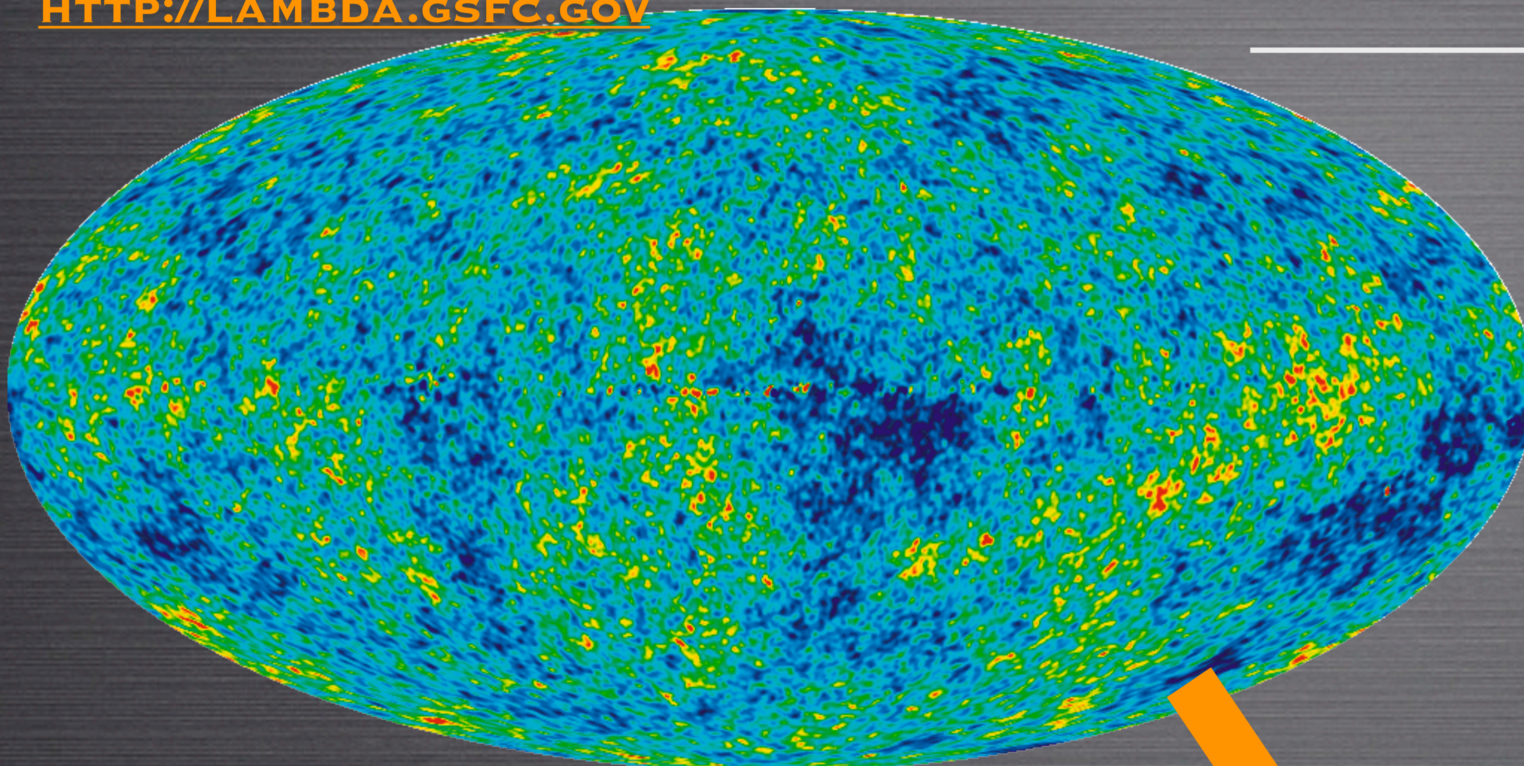


Rotational Velocity

Distance from Galactic Center

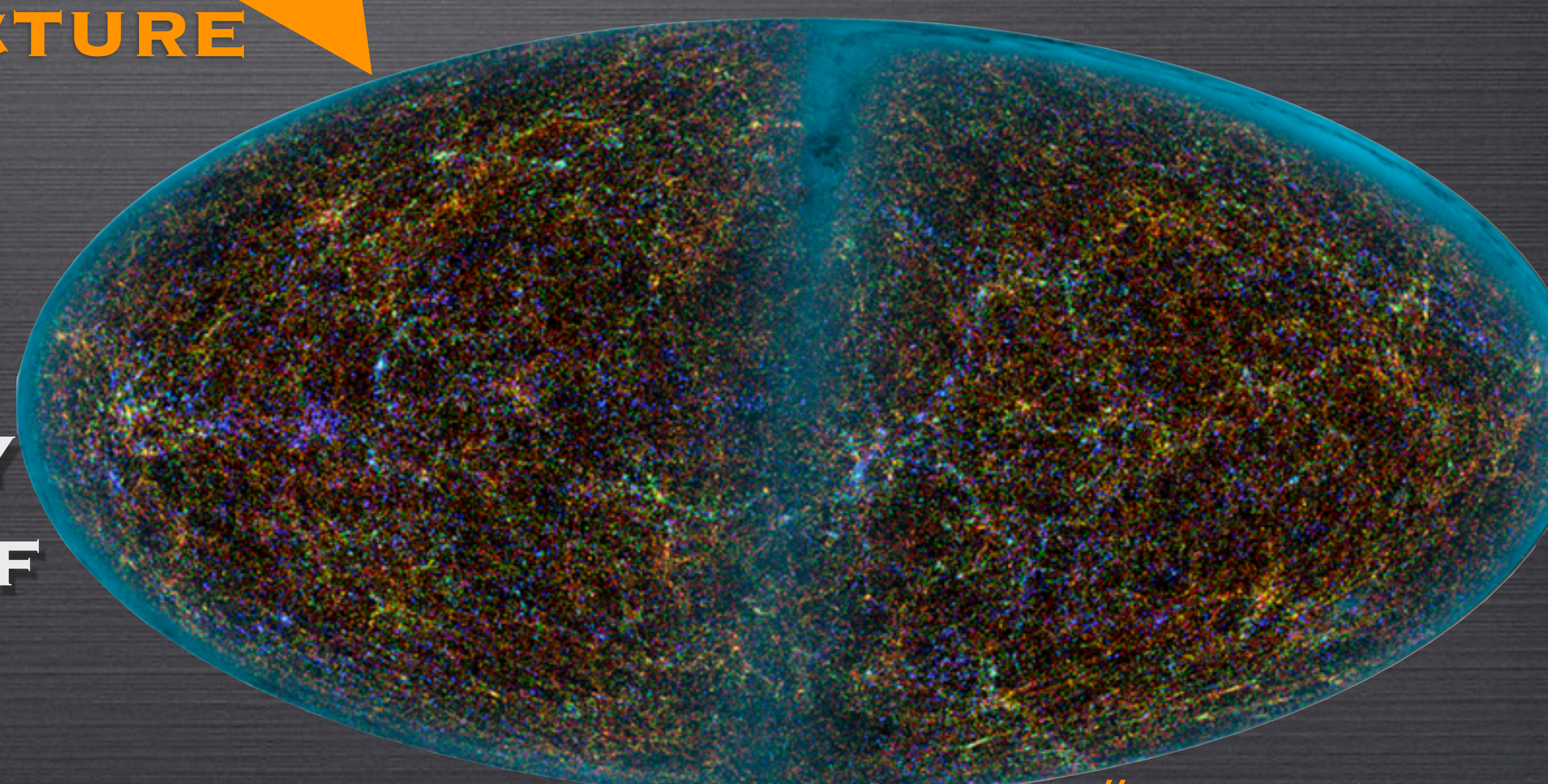
Dark Matter

http://lambda.gsfc.gov



Microwave Background Image of the Universe 13 Billion Years Ago

Necessary to Grow Structure

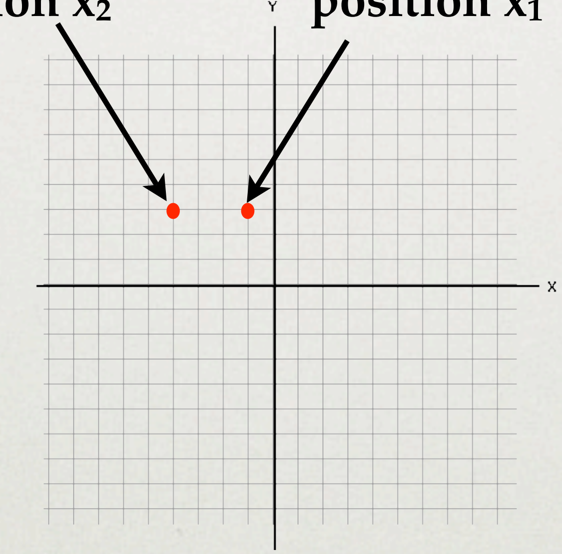


Contemporary Distribution of Galaxies

http://ipac.caltech.edu

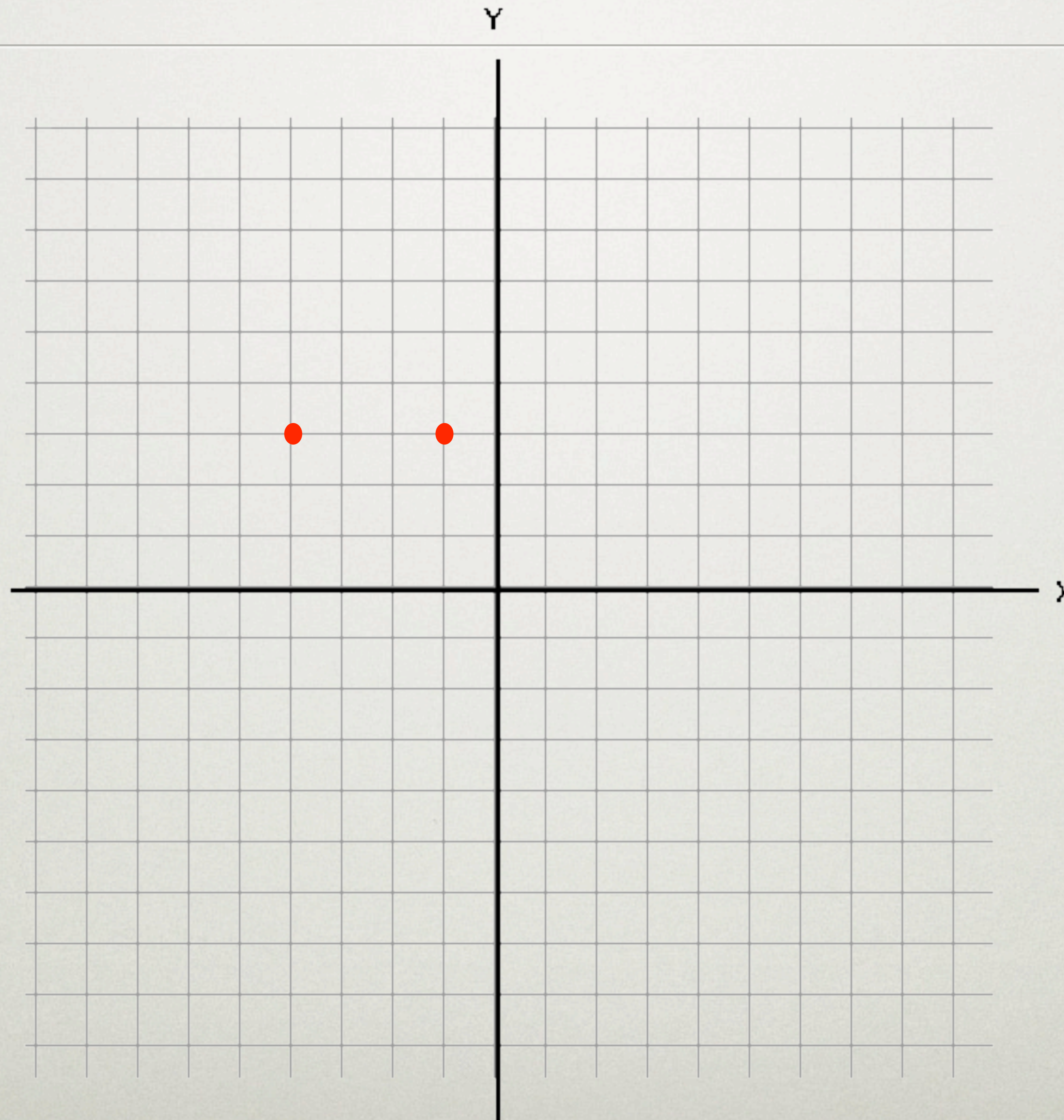
Dark Energy

Cosmic Expansion



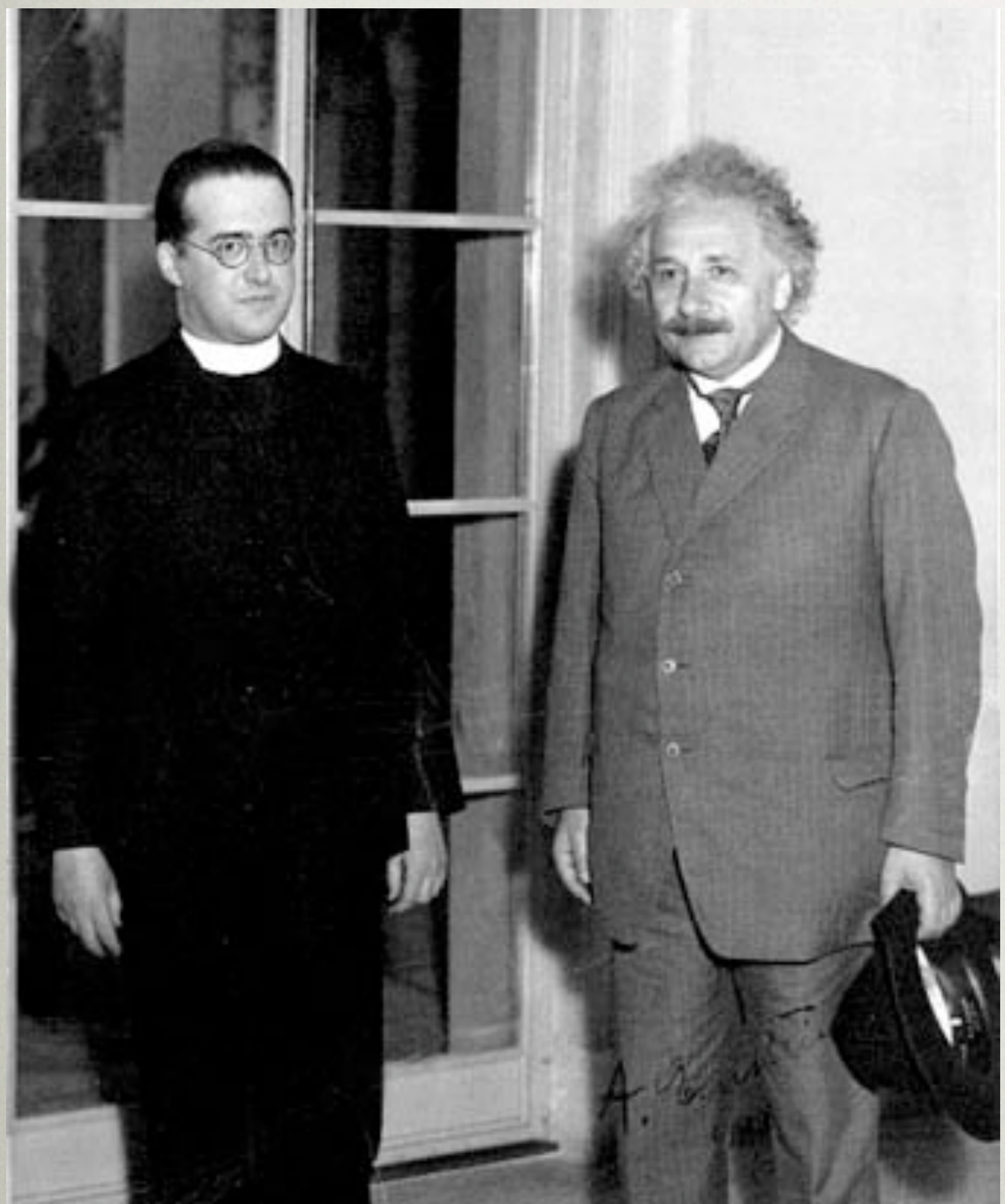
time t_1 : distance is $a_1|x_2 - x_1|$

Cosmic Expansion



$t_2 > t_1$: distance is $a_2 |x2-x1|$

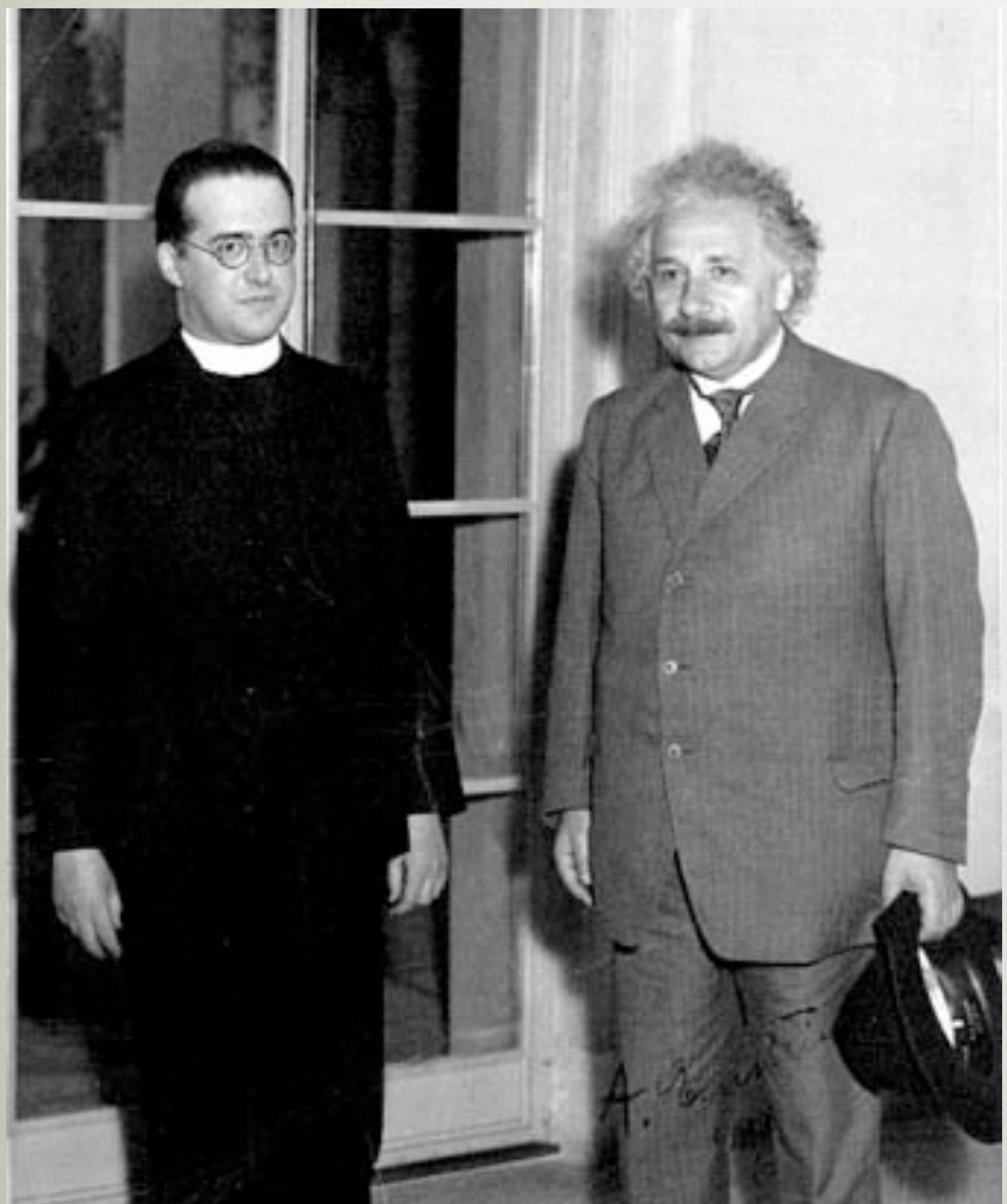
Einstein's Cosmological Constant



Georges
Lemaître

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - 1$$

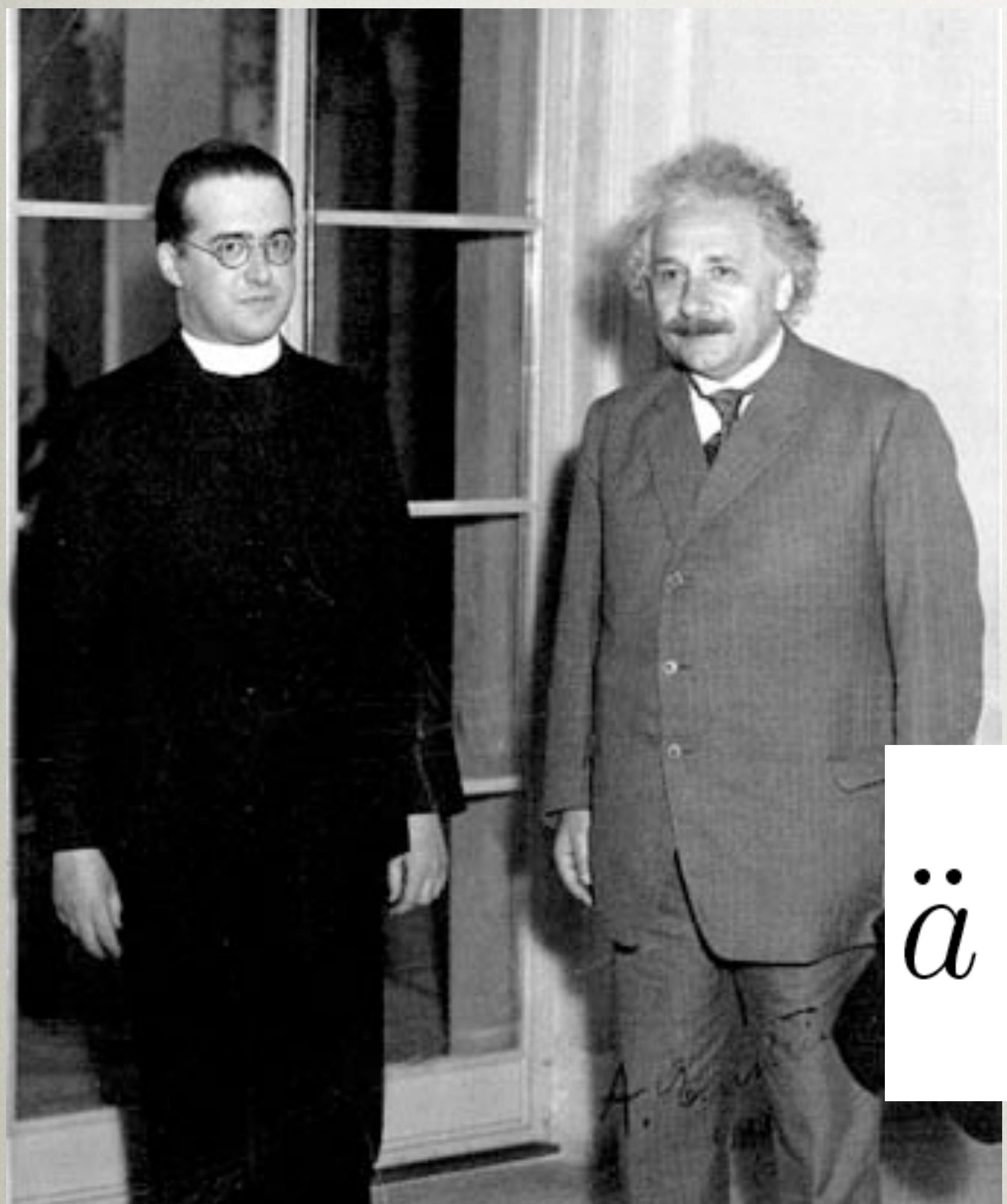
Einstein's Cosmological Constant



Georges
Lemaître

$$\rho = \frac{3}{8\pi G a^2}$$

Einstein's Cosmological Constant

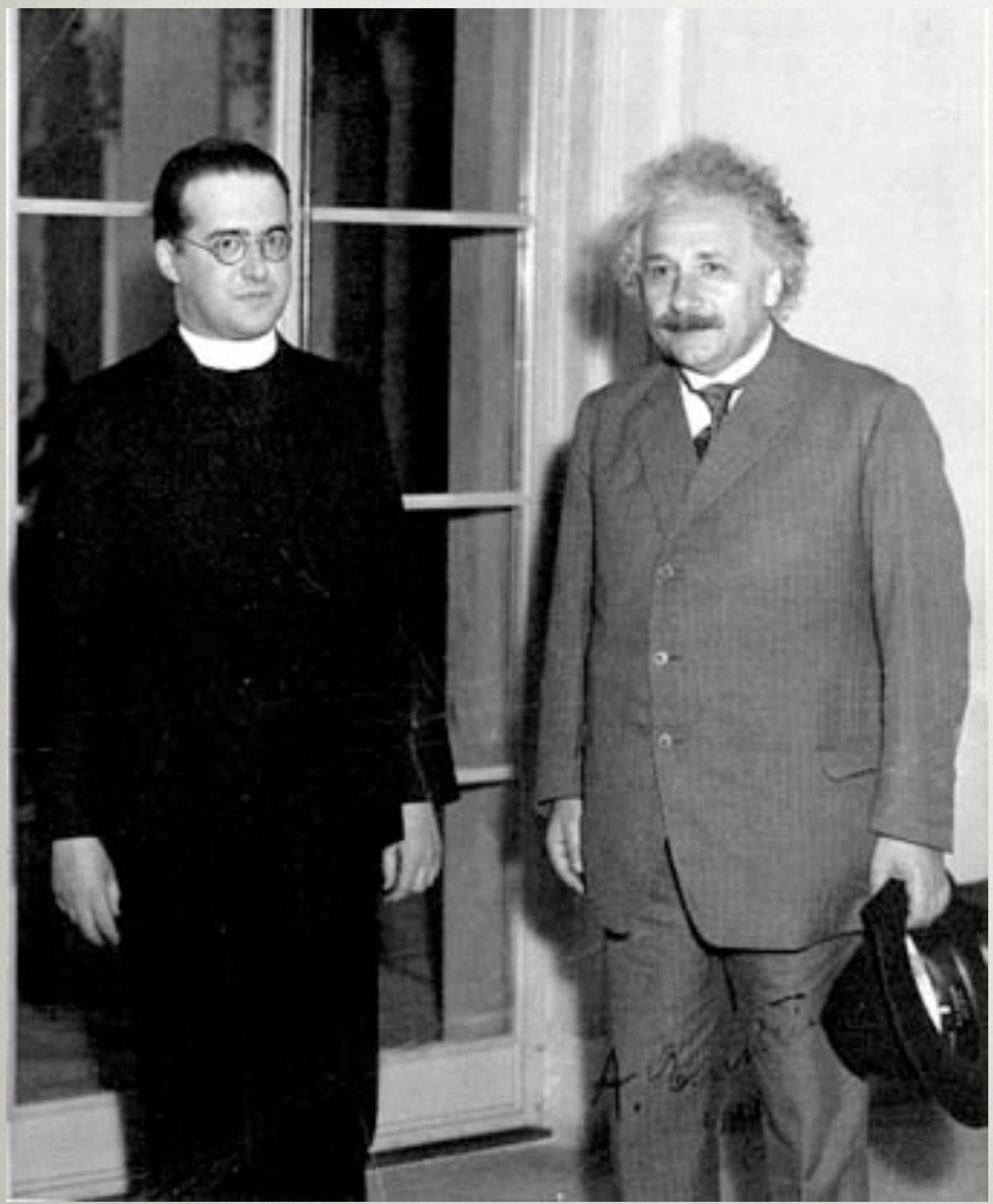


Georges
Lemaître

$$\rho = \frac{3}{8\pi G a^2}$$

$$\ddot{a} = -\frac{4\pi G}{3} a(\rho + 3P)$$

Einstein's Cosmological Constant

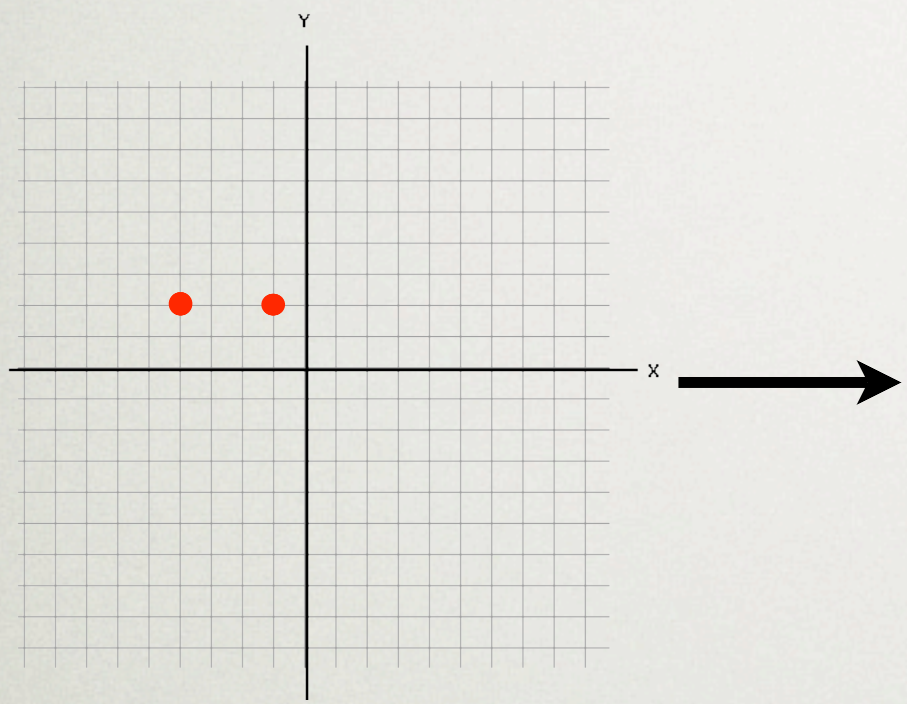


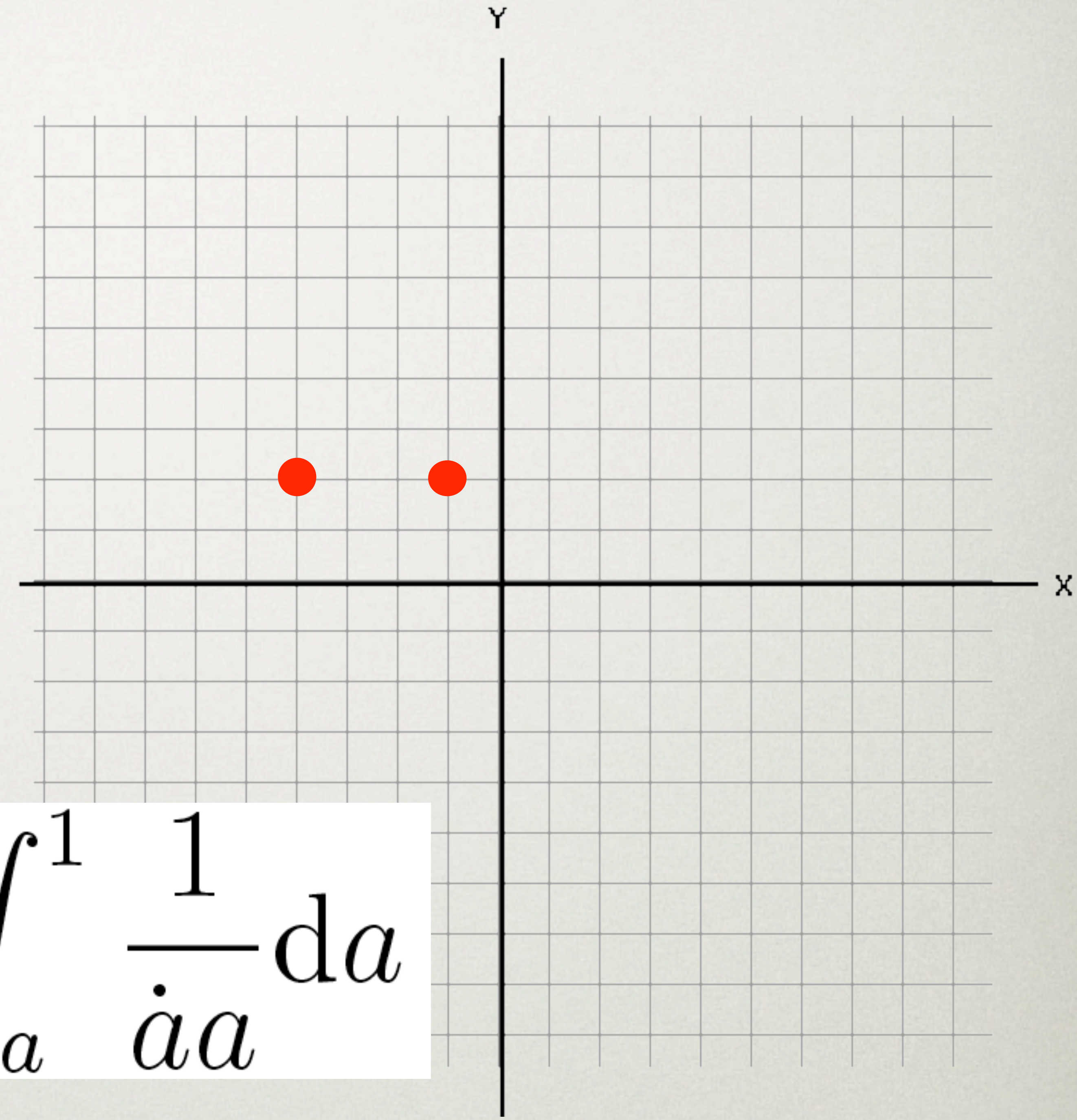
Georges
Lemaître

$$\rho = \frac{3}{8\pi G a^2}$$

$$P = -\frac{\rho}{3}$$

Cosmological Distances

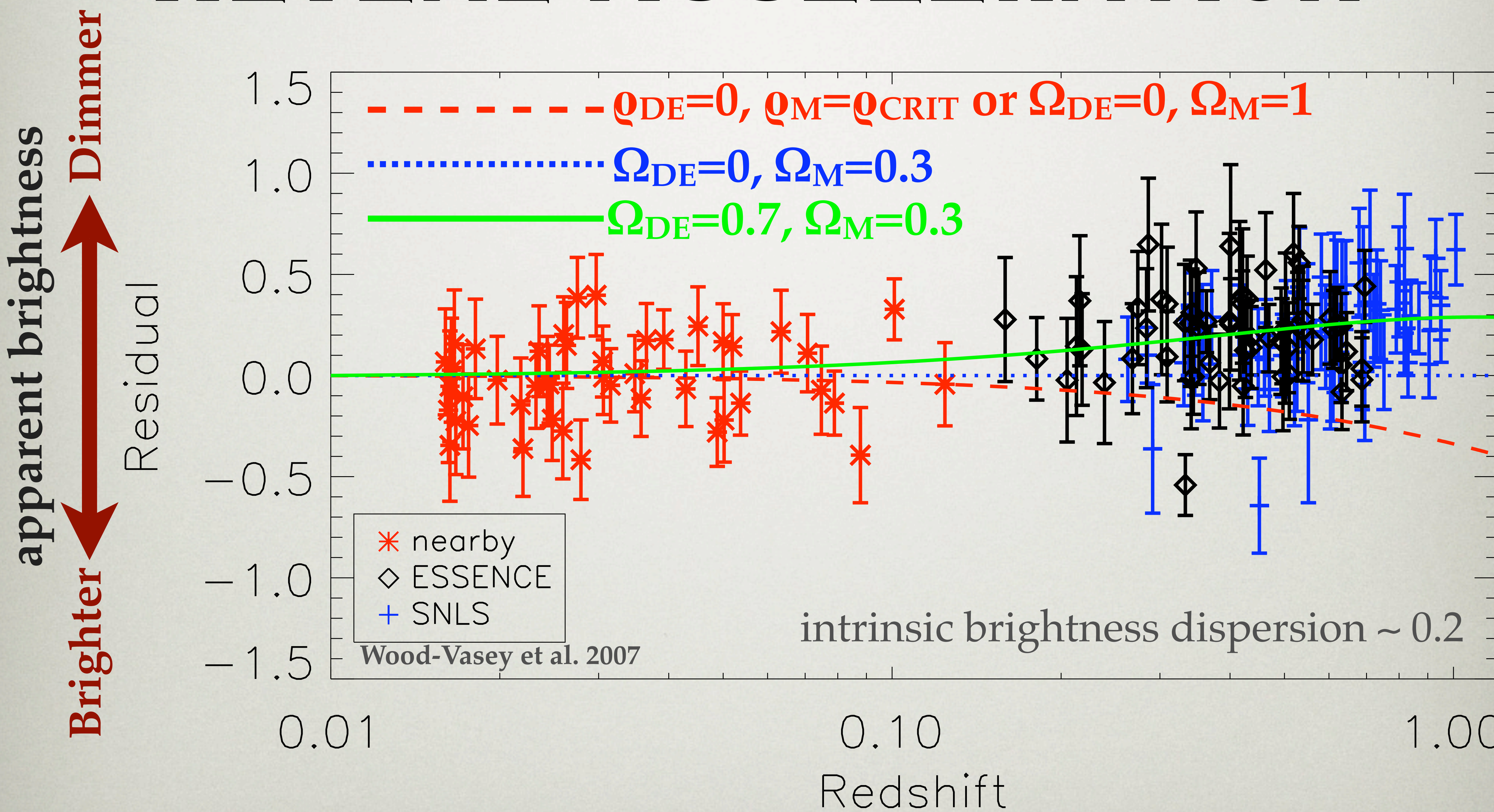




$$\Delta x = \int_t^{t_0} \frac{1}{a} \mathrm{d}t = \int_a^1 \frac{1}{\dot{a}a} \mathrm{d}a$$

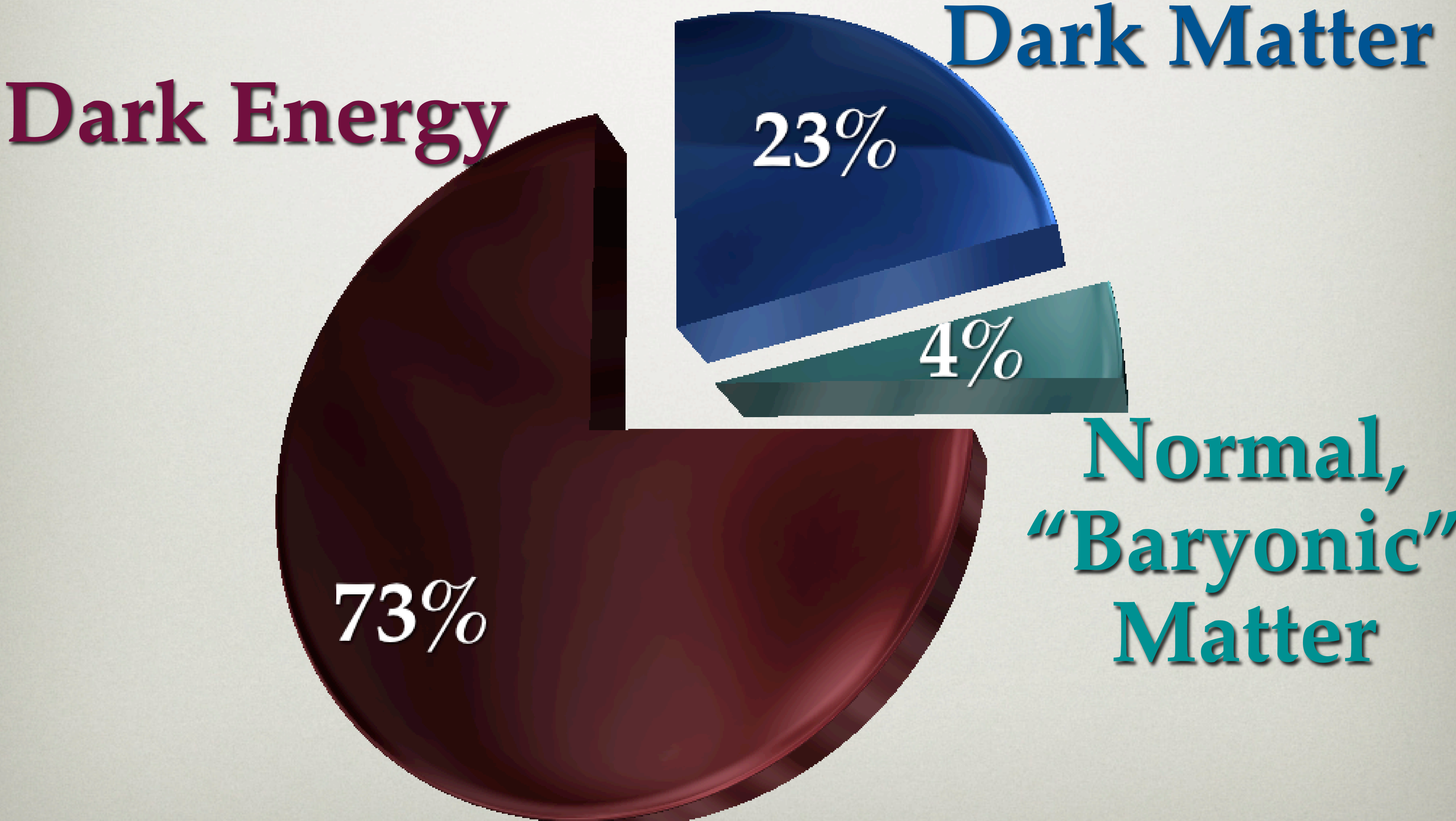
In an <u>accelerating</u> Universe, the distances between objects are <u>greater</u> for a <u>fixed factor of expansion</u>

Supernova Ia Distances Reveal Acceleration



- Ω_{DE}=0 ruled out at 5σ from this data alone

The Current Cosmic Energy Budget

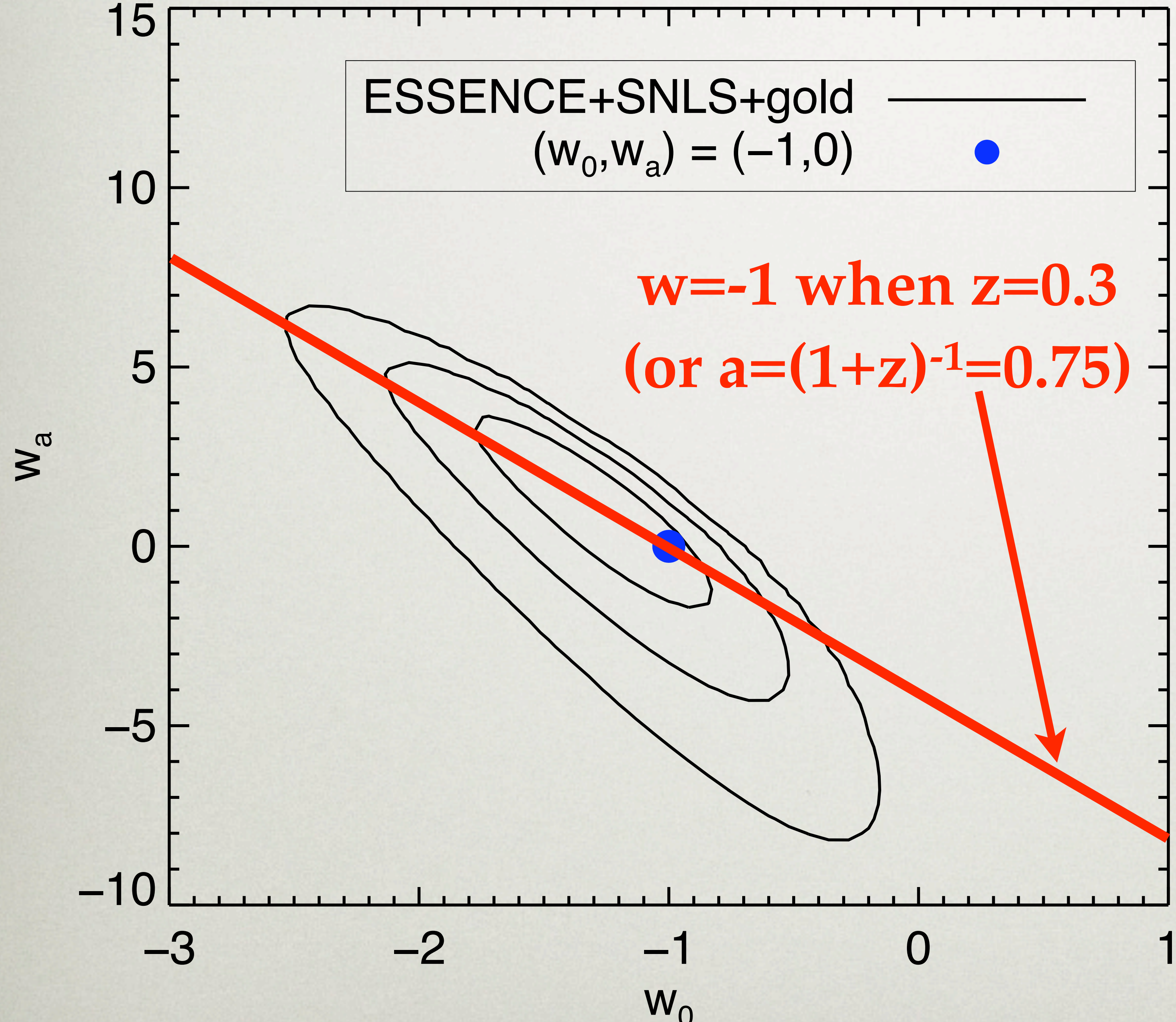


Dark Energy

Dark Energy Phenomenology

- Einstein's cosmological constant or a vacuum energy with $P=-\rho$ are indistinguishable
- For lack of theory, cosmologists benchmark experiments by their ability to measure $w=P/\rho$
- The dark energy density dilutes as $\rho \propto a^{-3(1+w)}$
- Time dependence is usually constrained using a Taylor expansion, $w(a) = w_0 + (1-a)w_a$

Contemporary Dark Energy Constraints

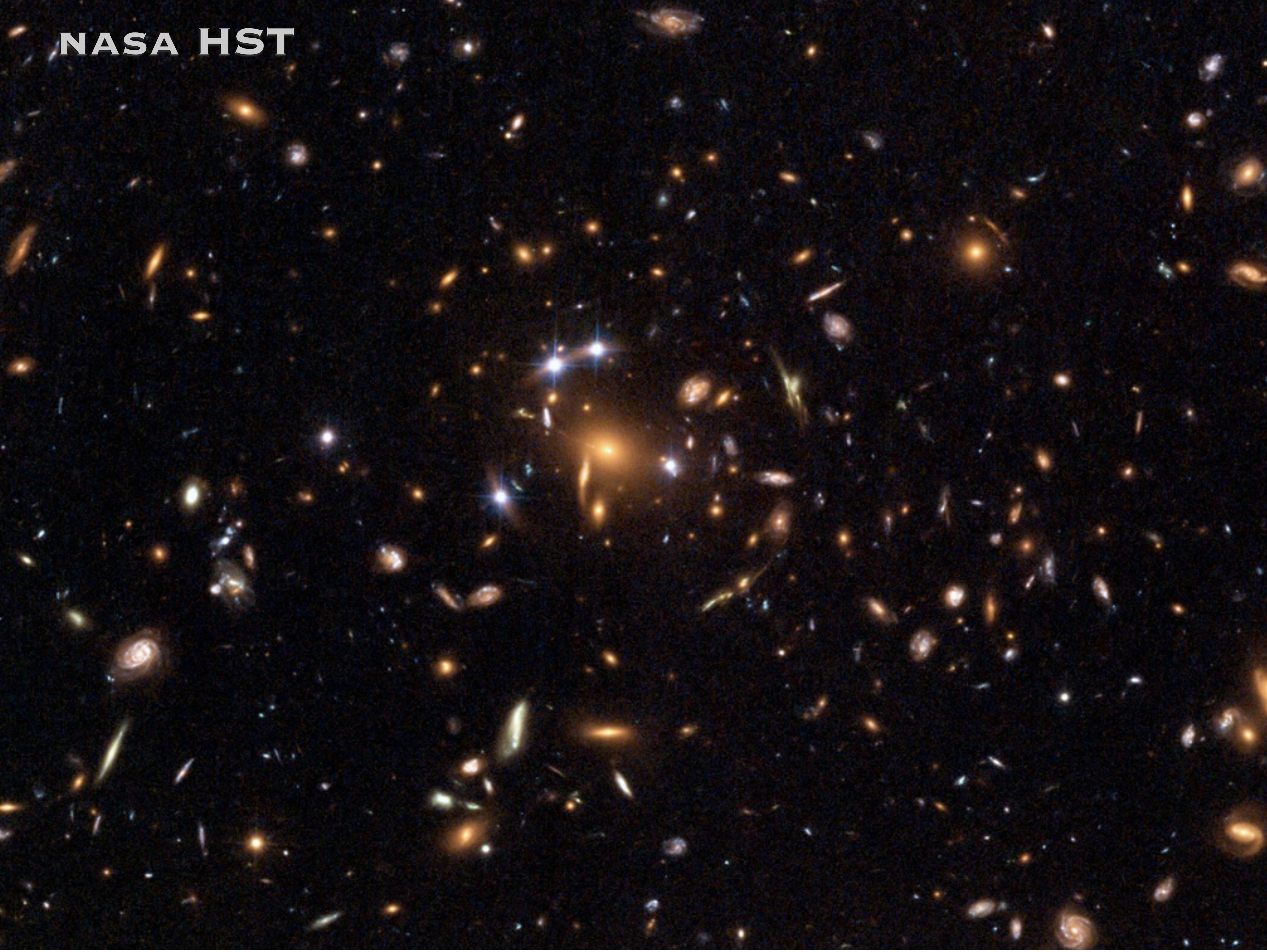


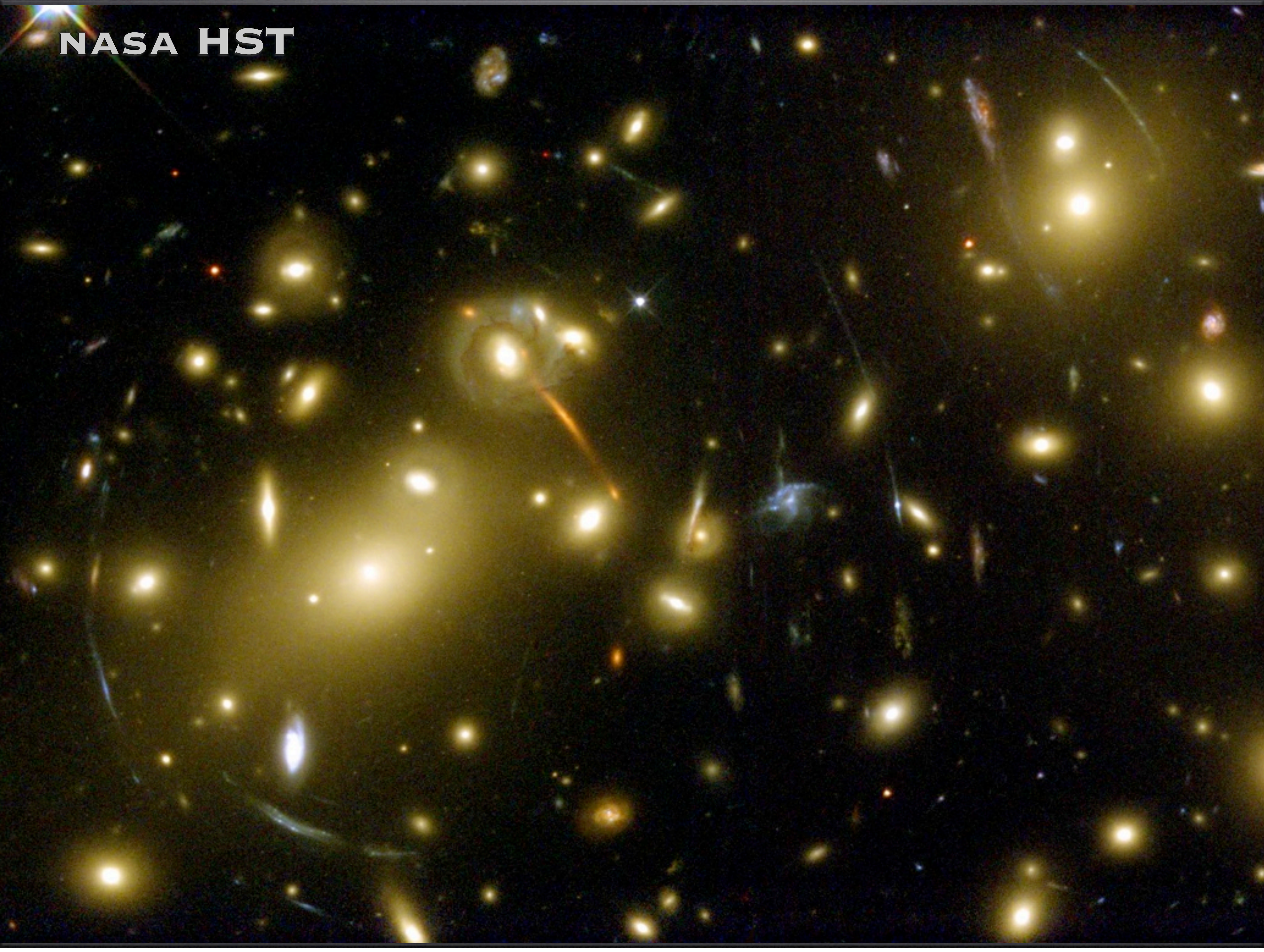
- w is best measured at a "pivot epoch" when $w \equiv w_{piv}$

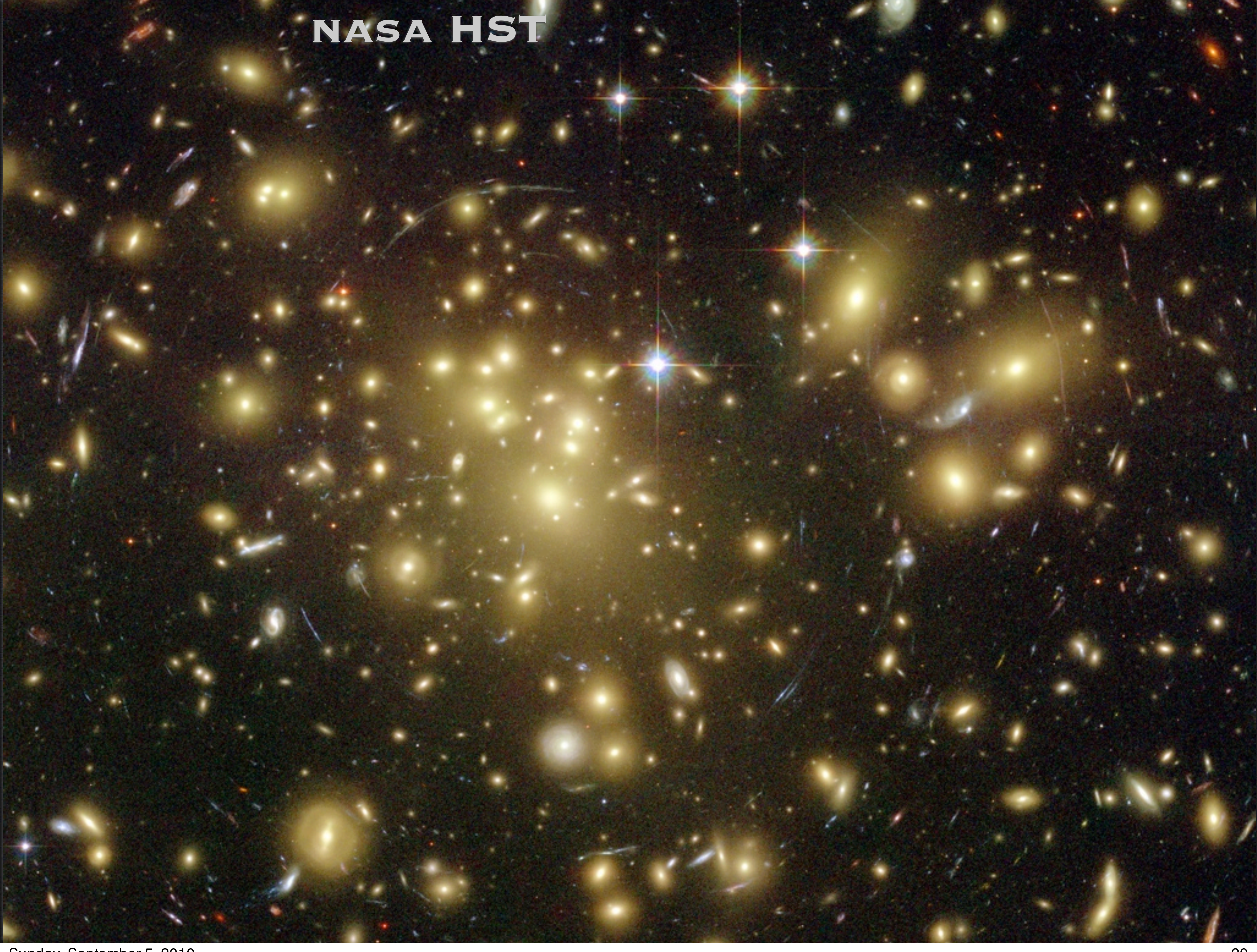
- Best current limit on w=-1 and constant is $\sigma_{piv} \approx 0.15$

Dark Energy: Harder than catching Bin-Laden

Gravitational Lensing


NASA HST


NASA HST


nasa HST

ON THE COSMOLOGICAL DISTORTION EFFECT

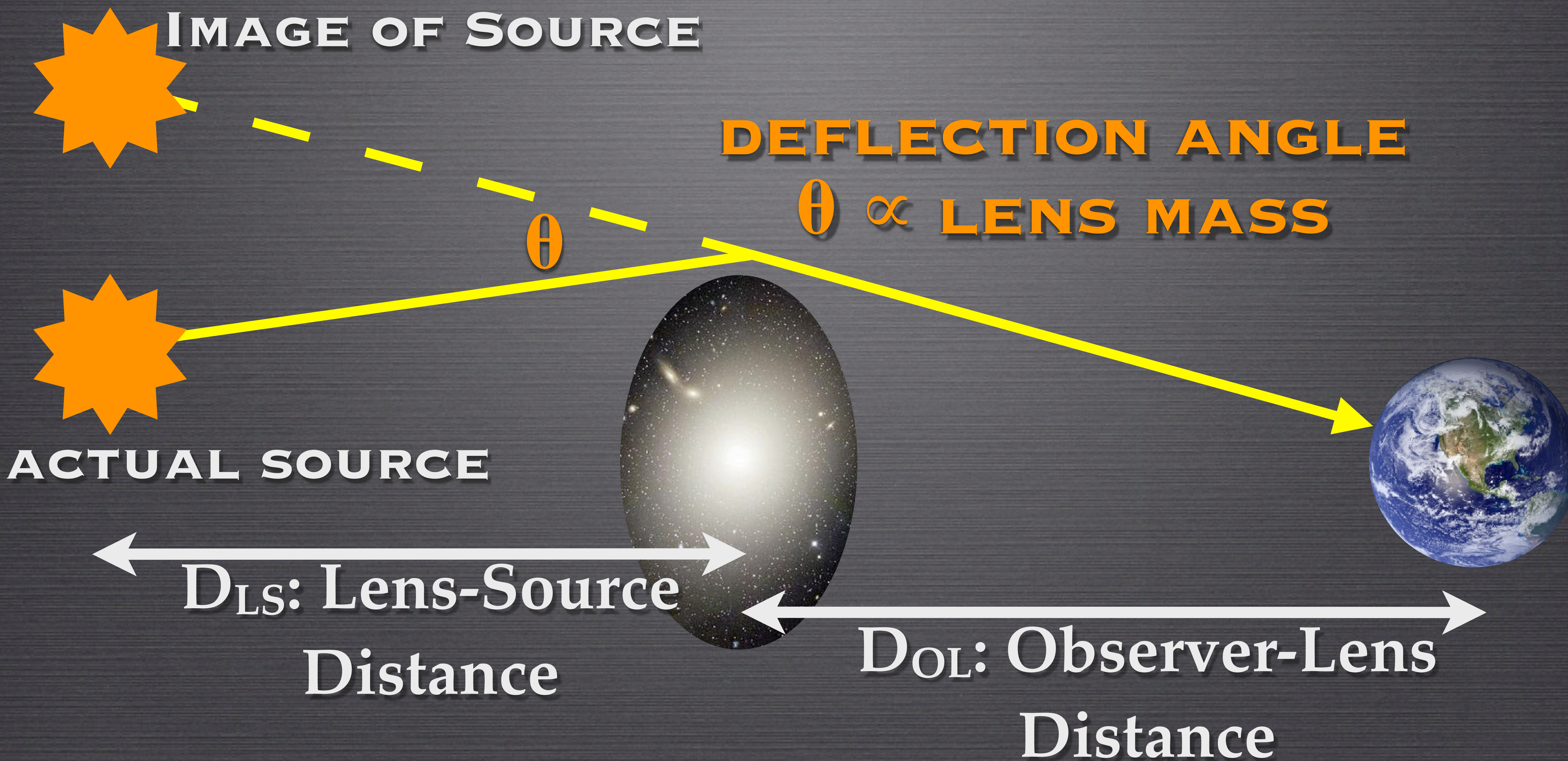
JEROME KRISTIAN
Washburn Observatory, University of Wisconsin

Received August 25, 1966

ABSTRACT

Detailed equations for the effect are given, and an unsuccessful attempt to measure it on 200-inch photographs of clusters of galaxies is described. The results give an upper limit of 2×10^{-18} yr^{-2} for all components of the incident magnetic-type gravitational field and 0.6×10^{-18} yr^{-2} for at least some of them. These numbers are not very stringent tests of the Friedmann and steady-state models, but seem to be about the best that can be done with this kind of measurement.

A Gravitational Lens



Amount of Shear ~ Mass × D_{LS} D_{OL}/D_{OS}

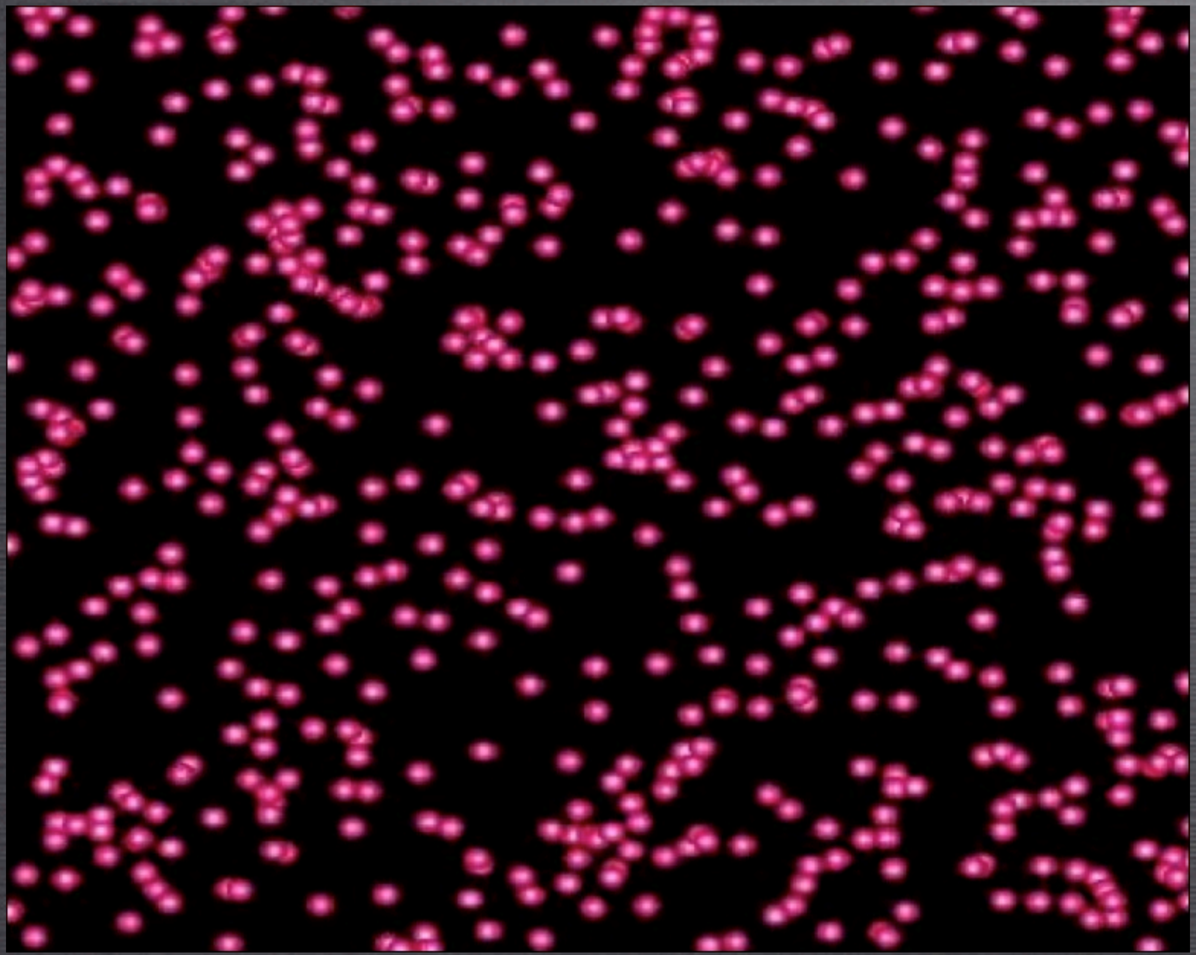
Lensing Shear

Lensing Shear

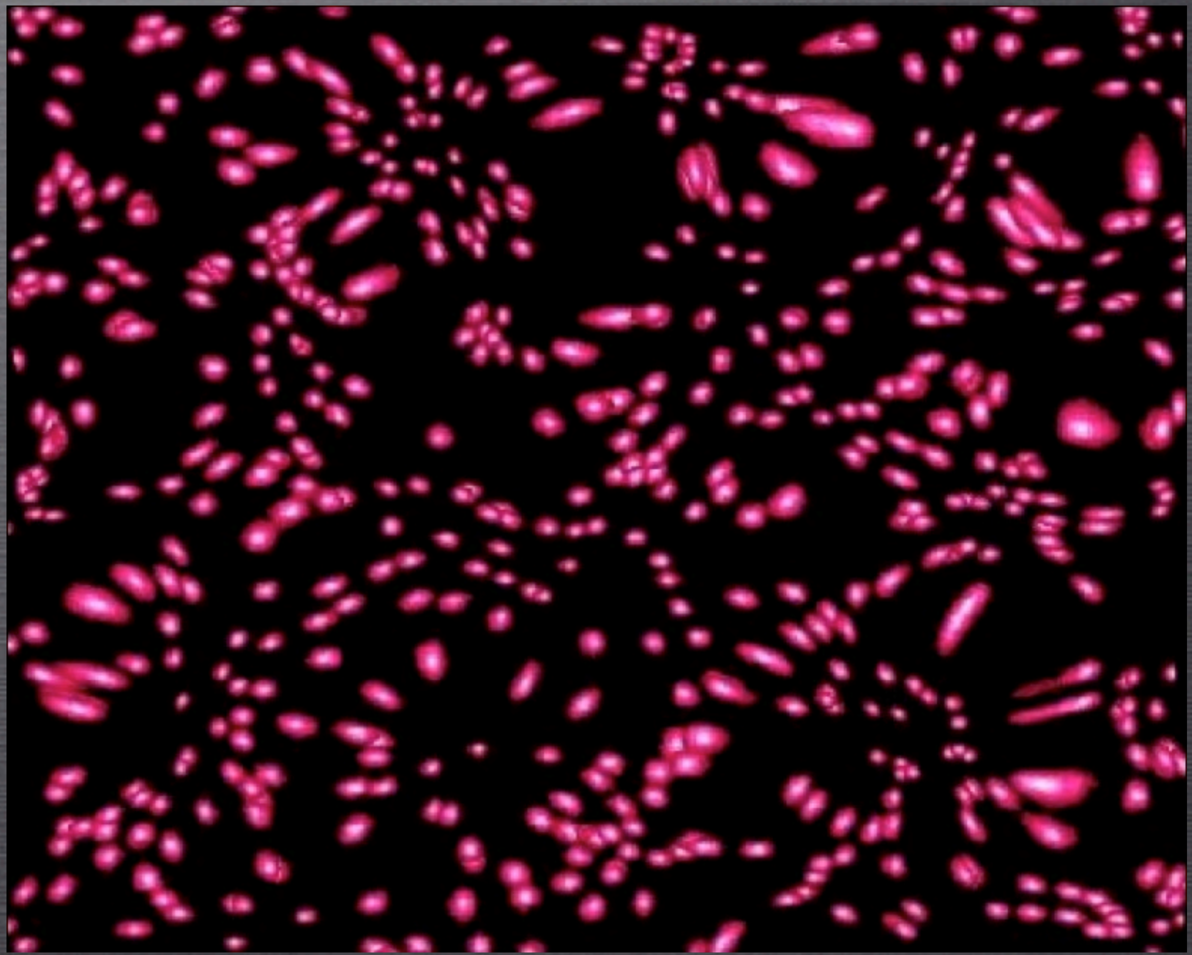
Weak Lensing

Weak Lensing Shear

http://aether.lbl.gov/Weak_Lensing



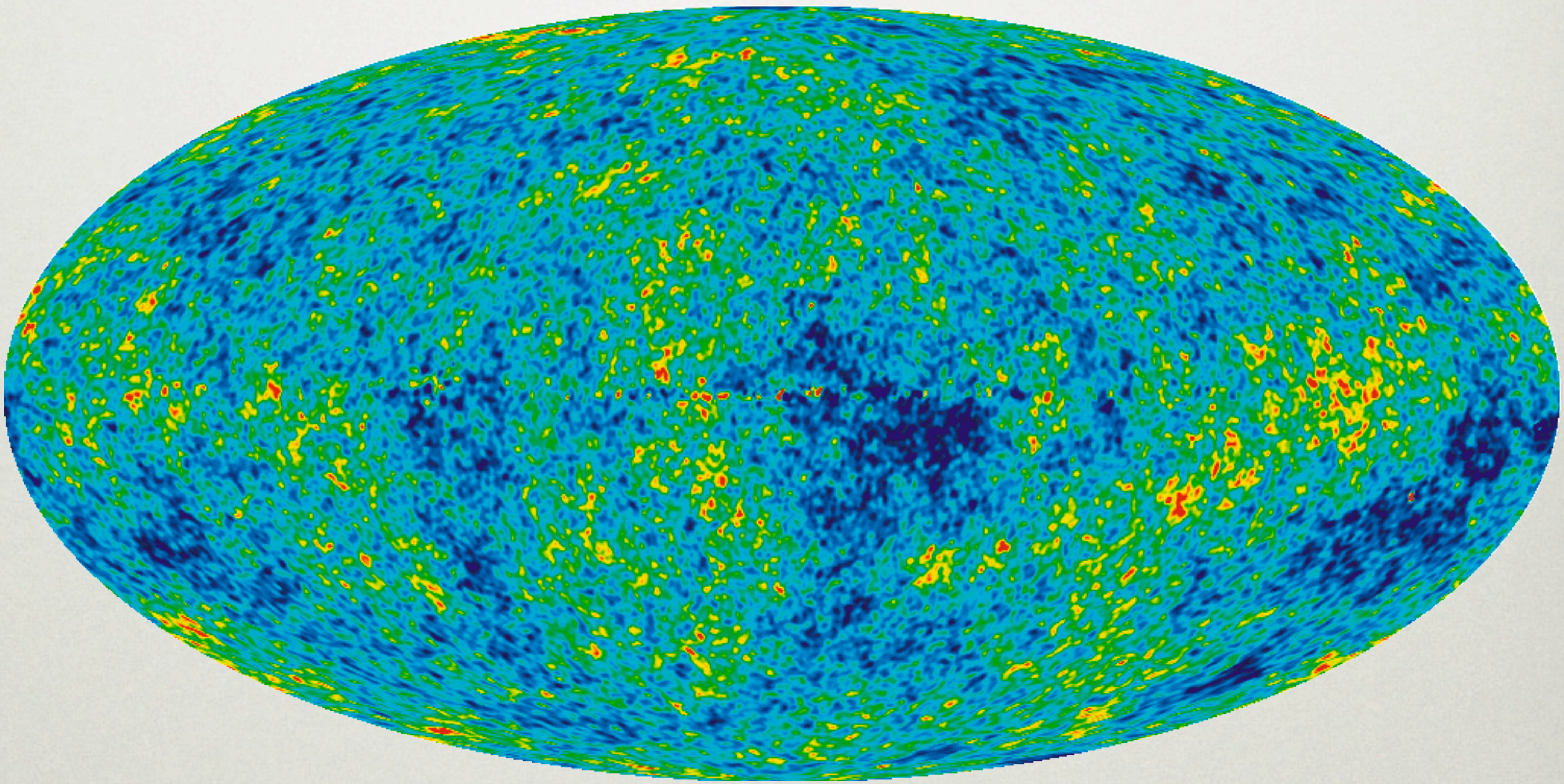
Unlensed, "Spherical Galaxies"



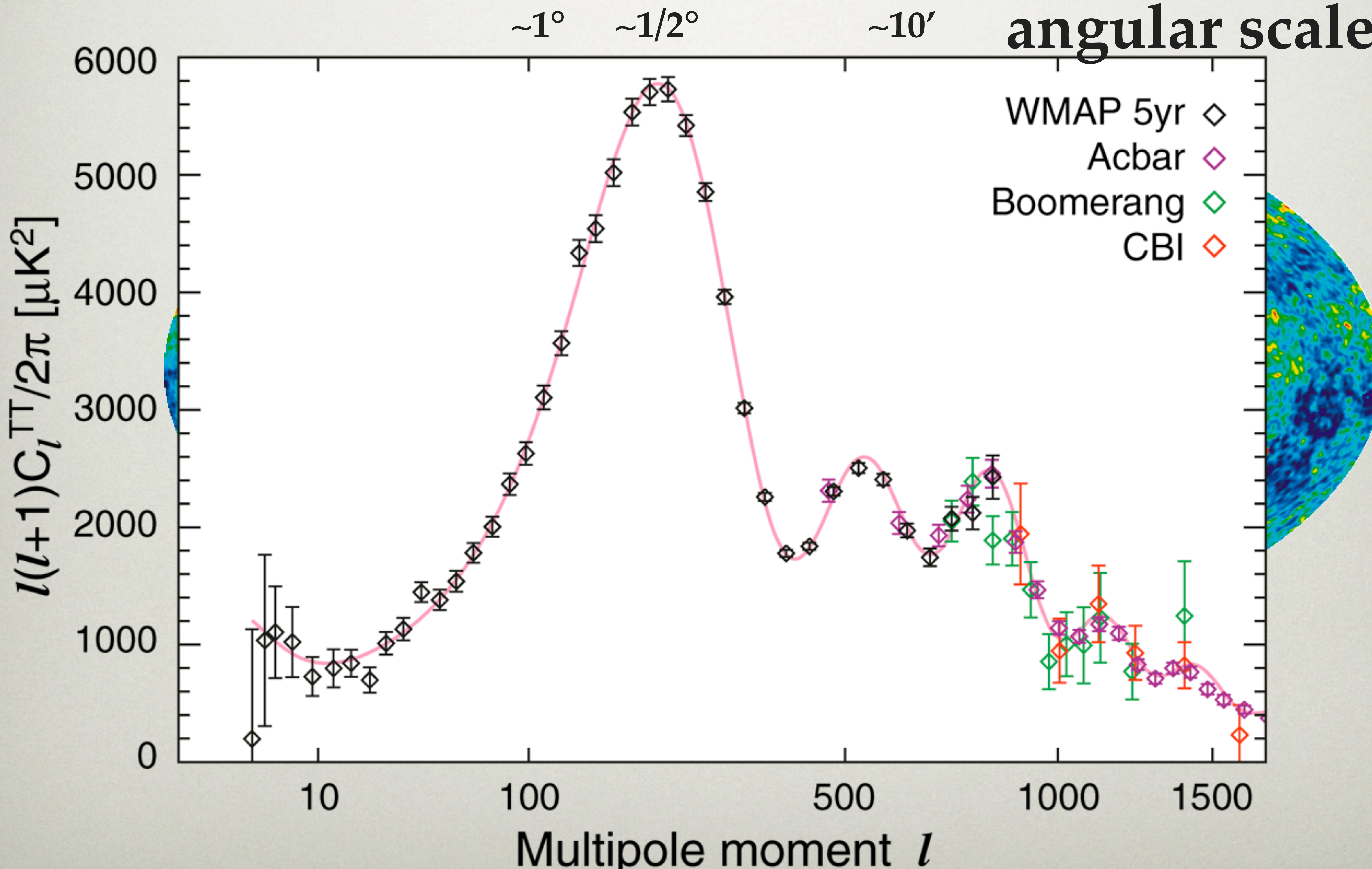
lensed Galaxies


Find that distortion here...

An Analogy: CMB Power Temperature SpectruM

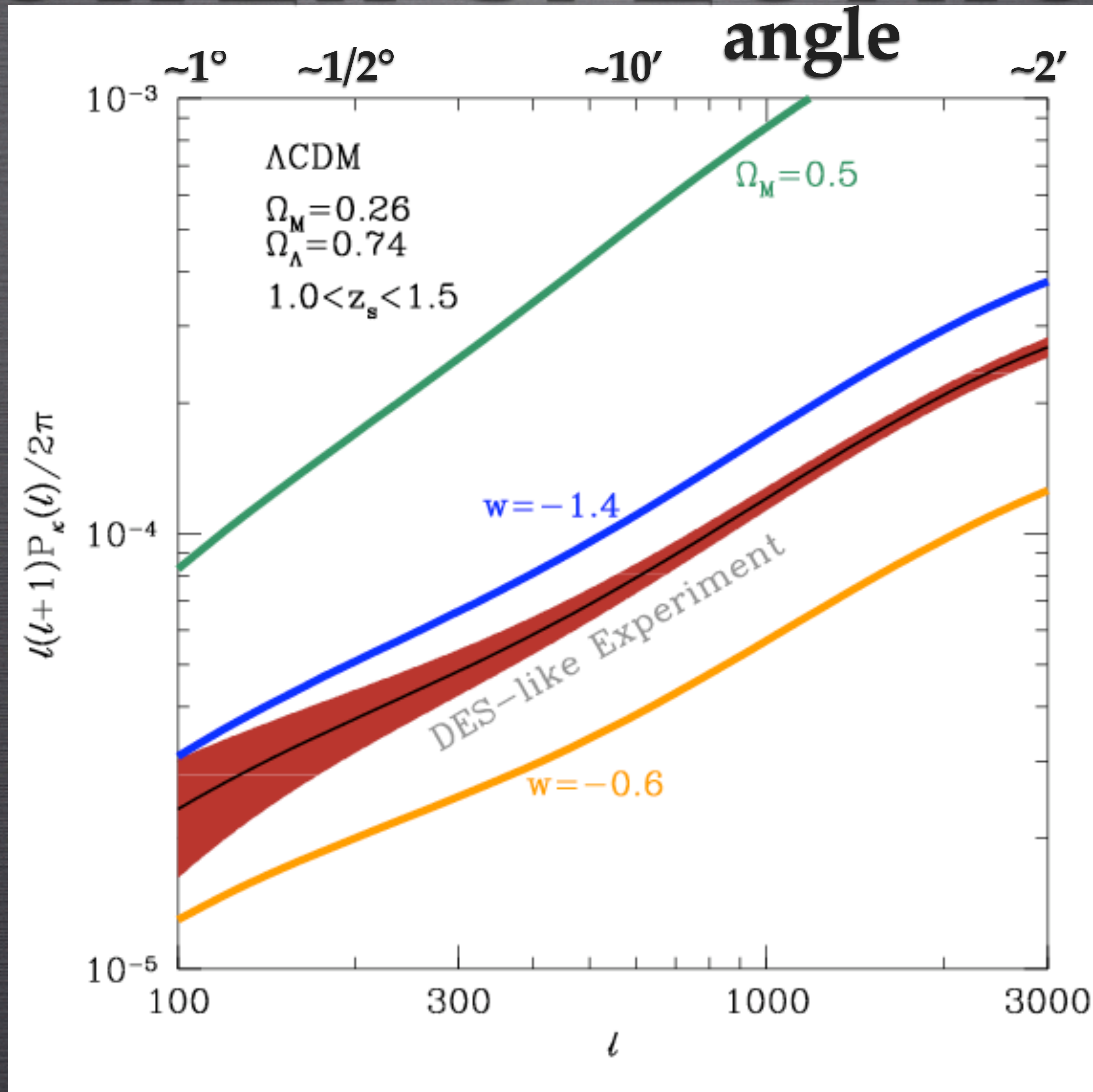


An Analogy: CMB Power Temperature SpectruM



Lensing Shear Power spectrum

Lensing Power Spectrum

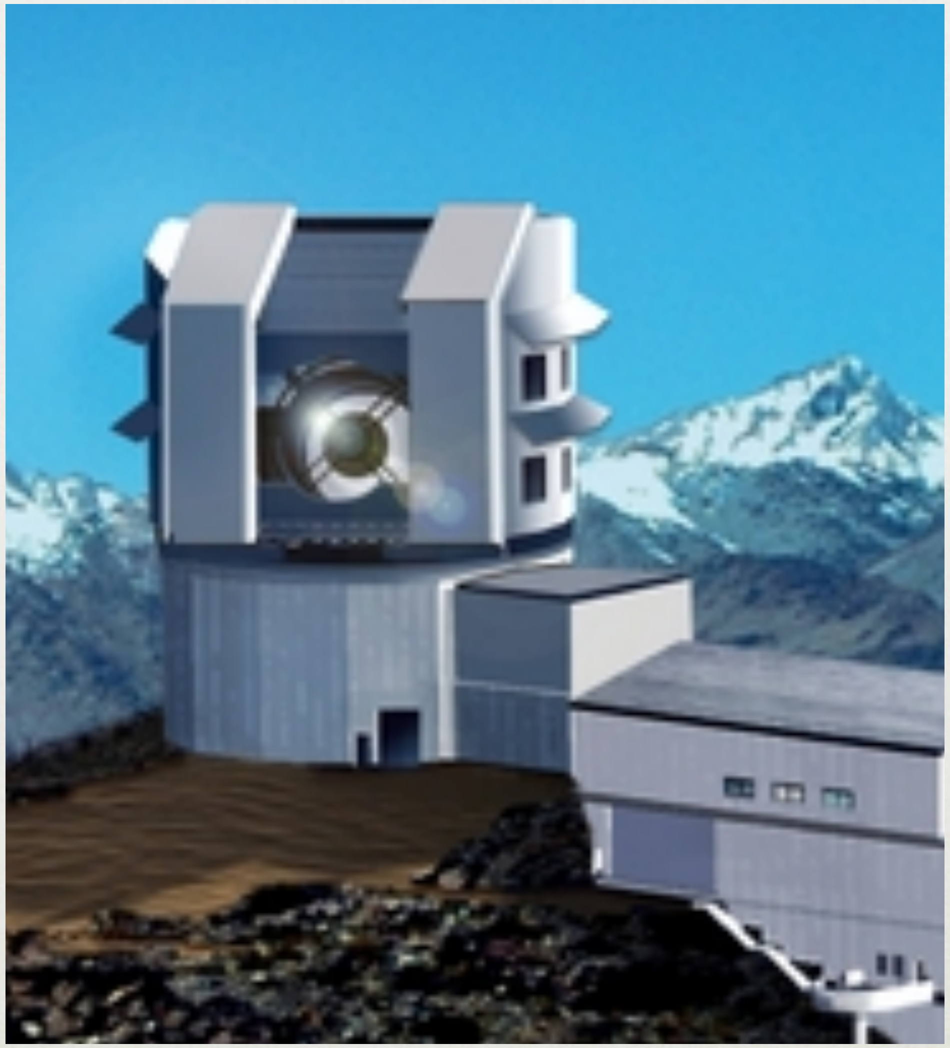


Multipole Moment

Next Generation Experiments

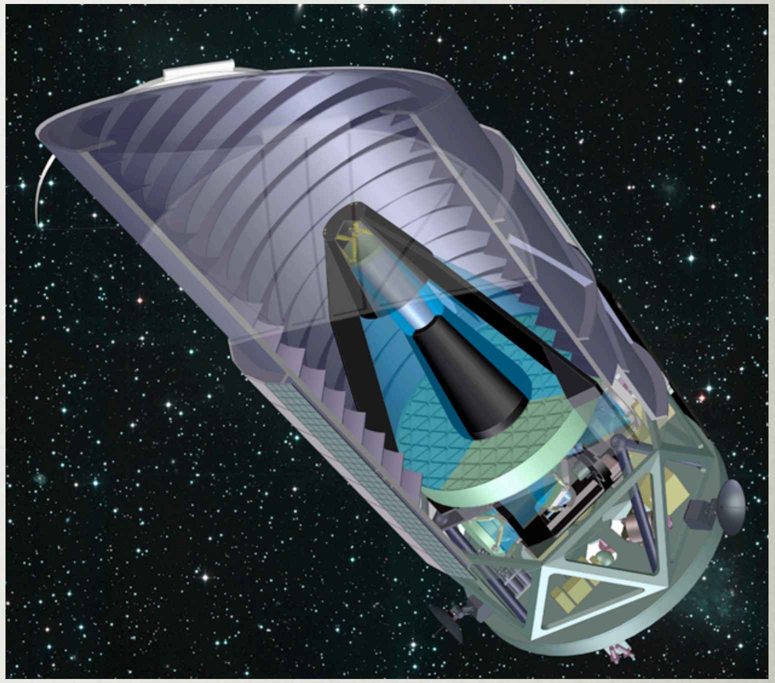
Dark Energy Survey (DES)

First Light ~2011,
First Results ~2013



Large Synoptic Survey Telescope (LSST)

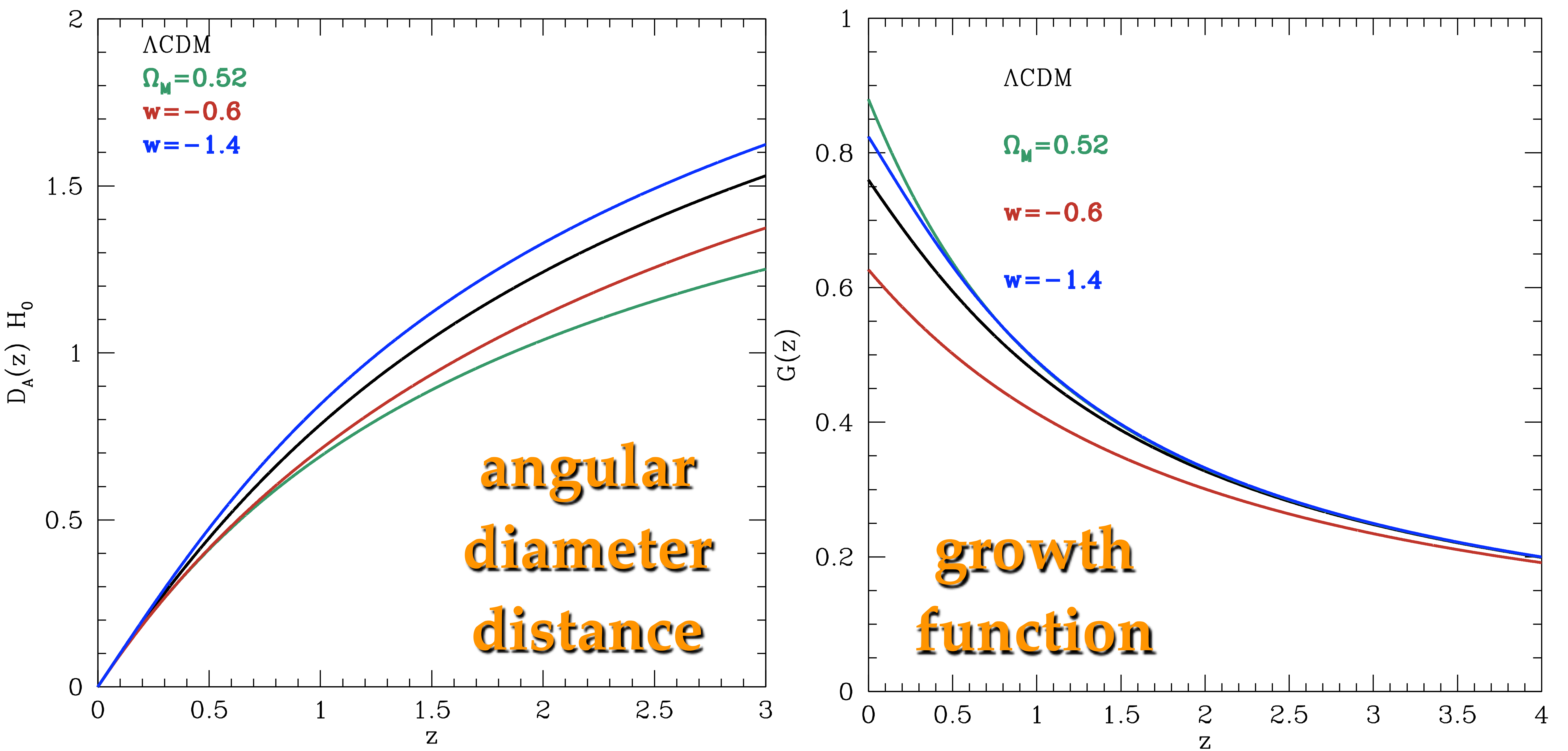
First Light ~2015,
First Results ~2017



Joint Dark Energy Mission
JDEM/SNAP

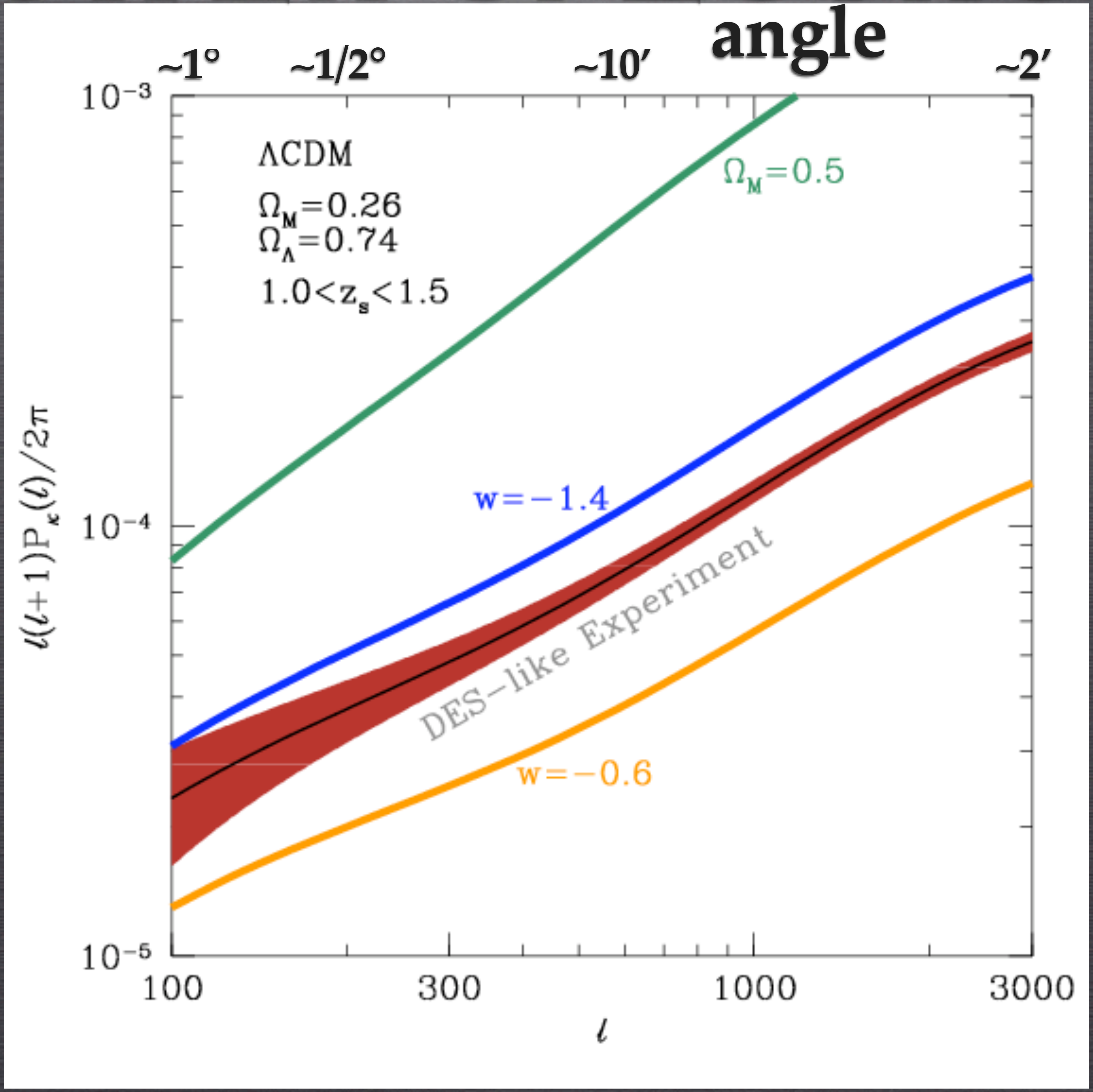
> 2019 ?

Weak Lensing Constraints on DE



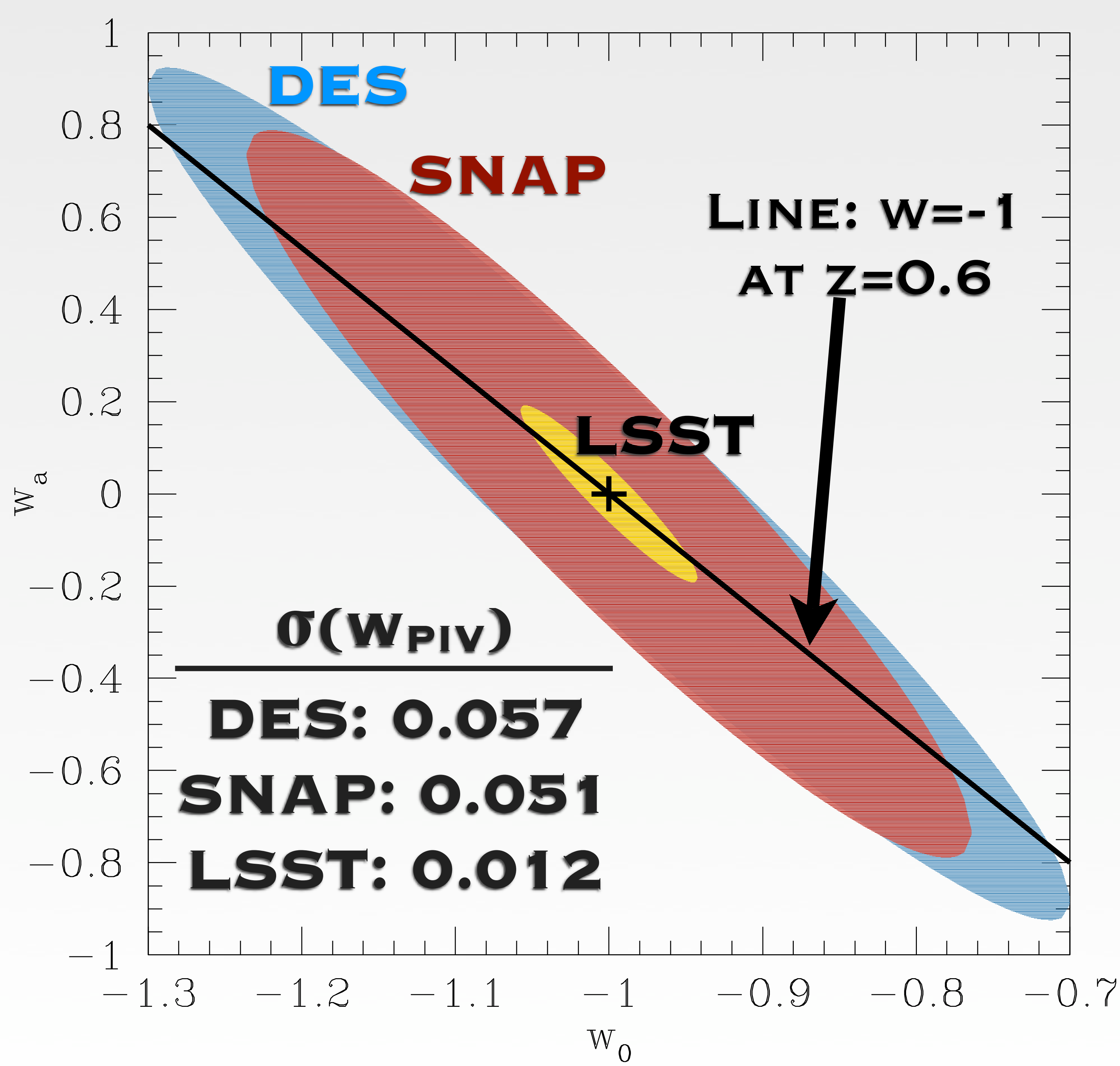
Lensing Shear Power spectrum

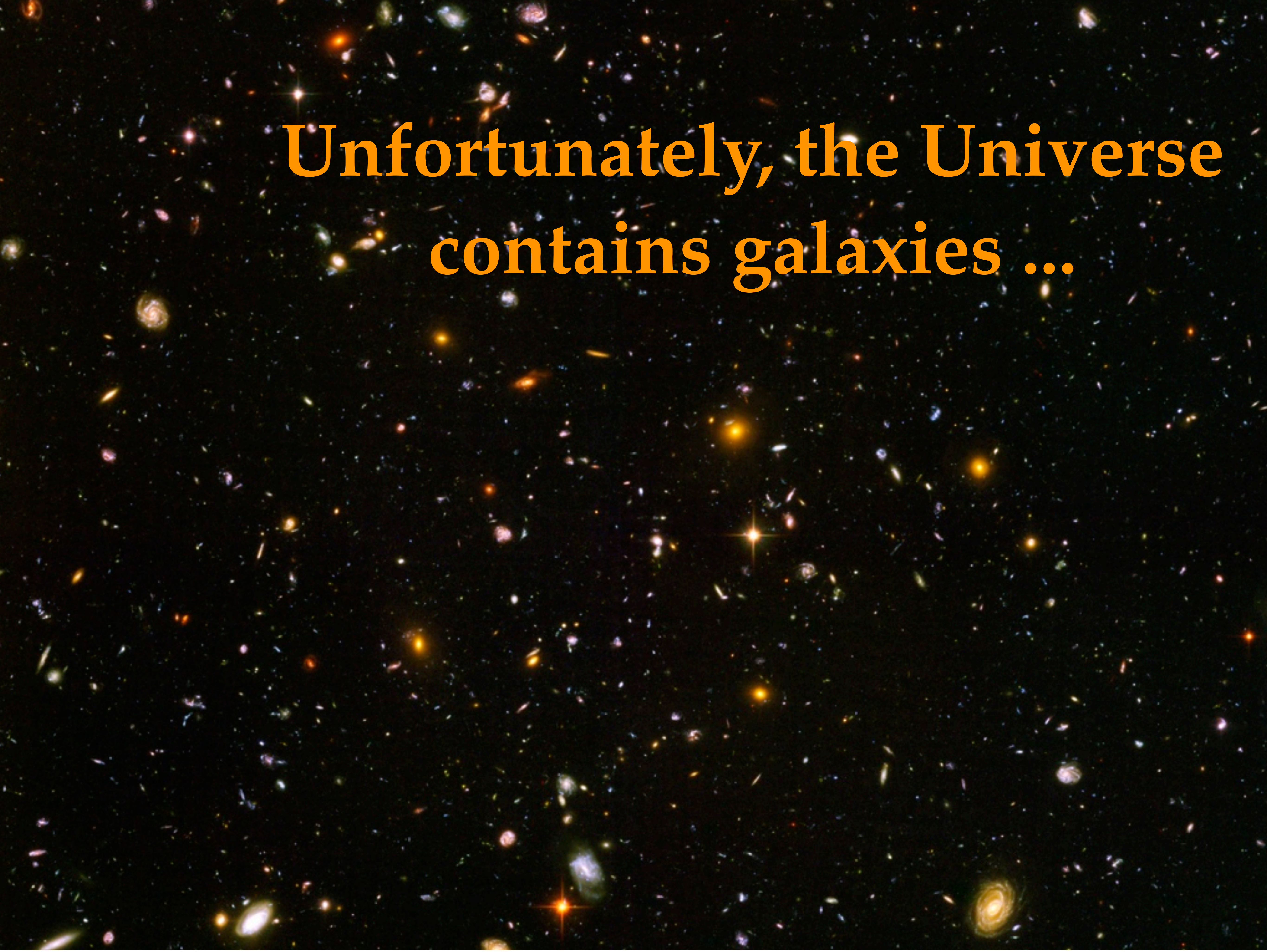
Lensing Power Spectrum



Multipole Moment

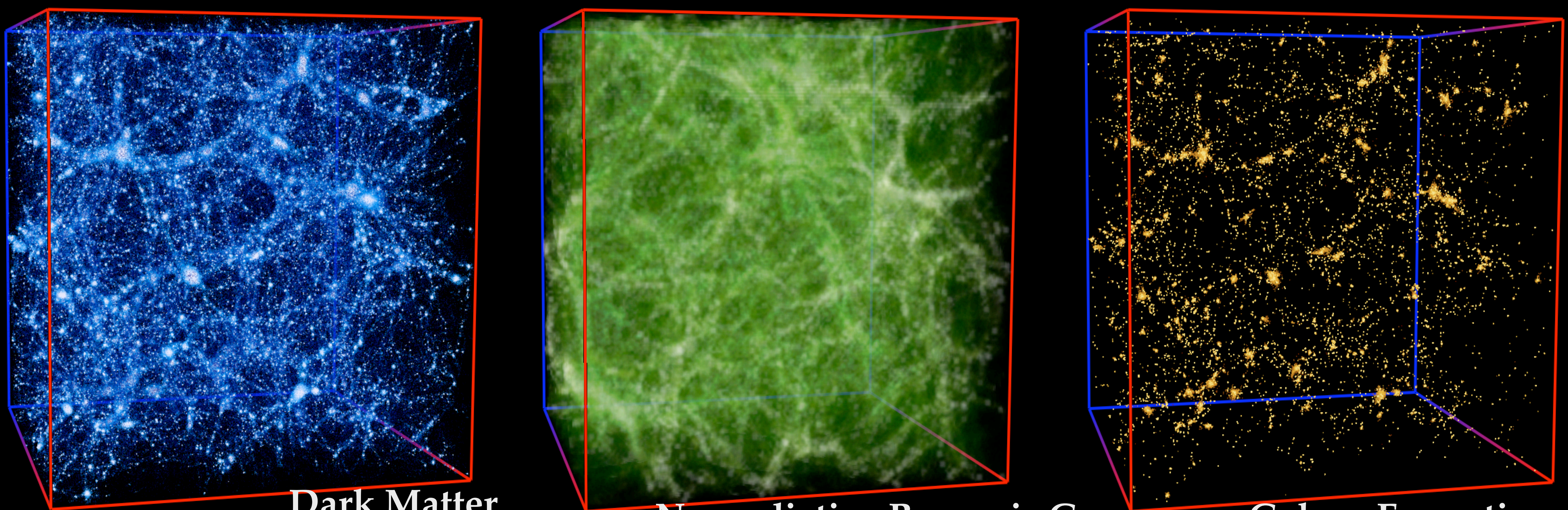
Dark Energy Constraints




Unfortunately, the Universe
contains galaxies ...

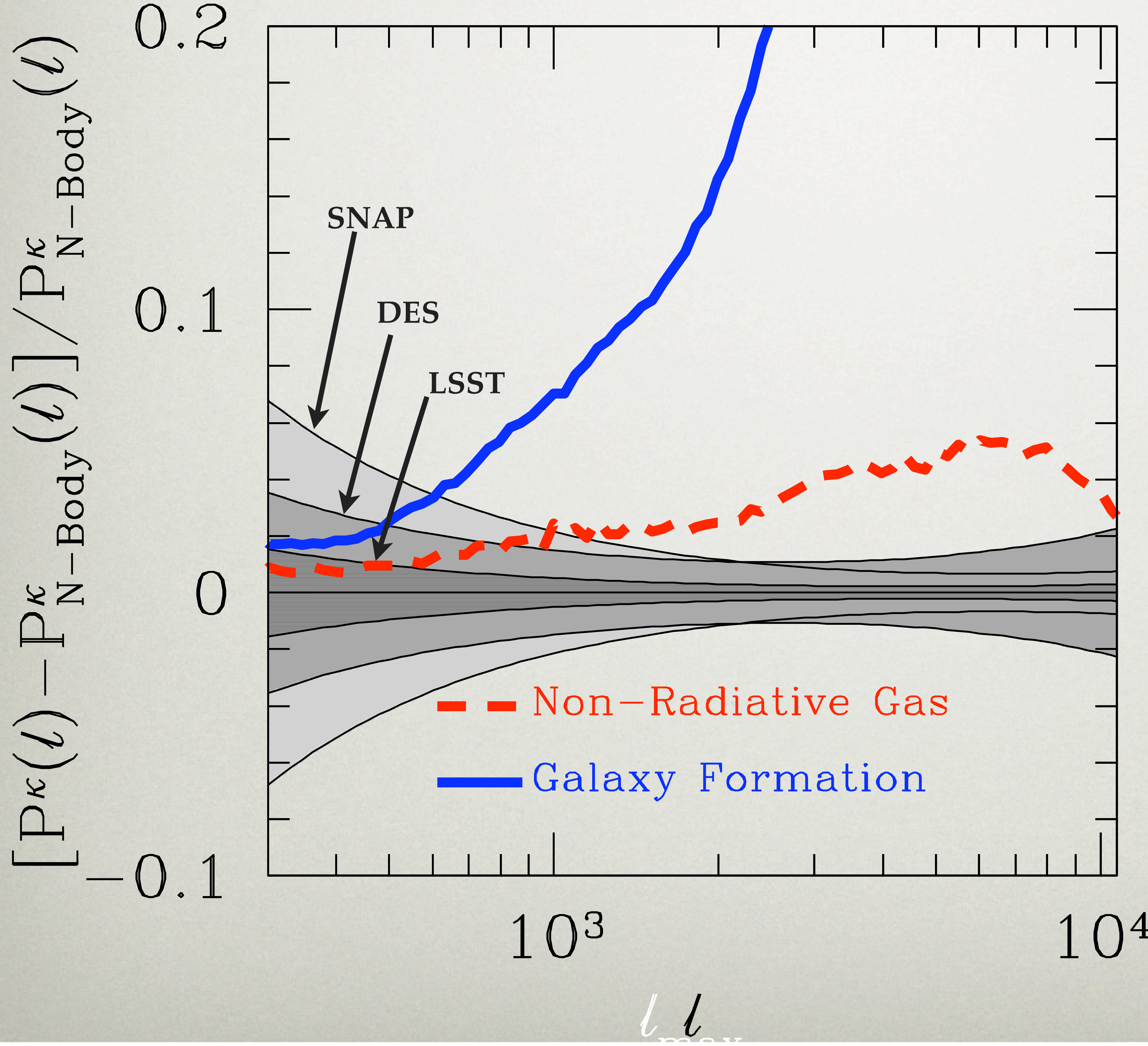
The Difficulty: Modeling Galaxy Formation

Simulations from Identical Initial Conditions



Rudd, AZ, & Kravtsov 2008

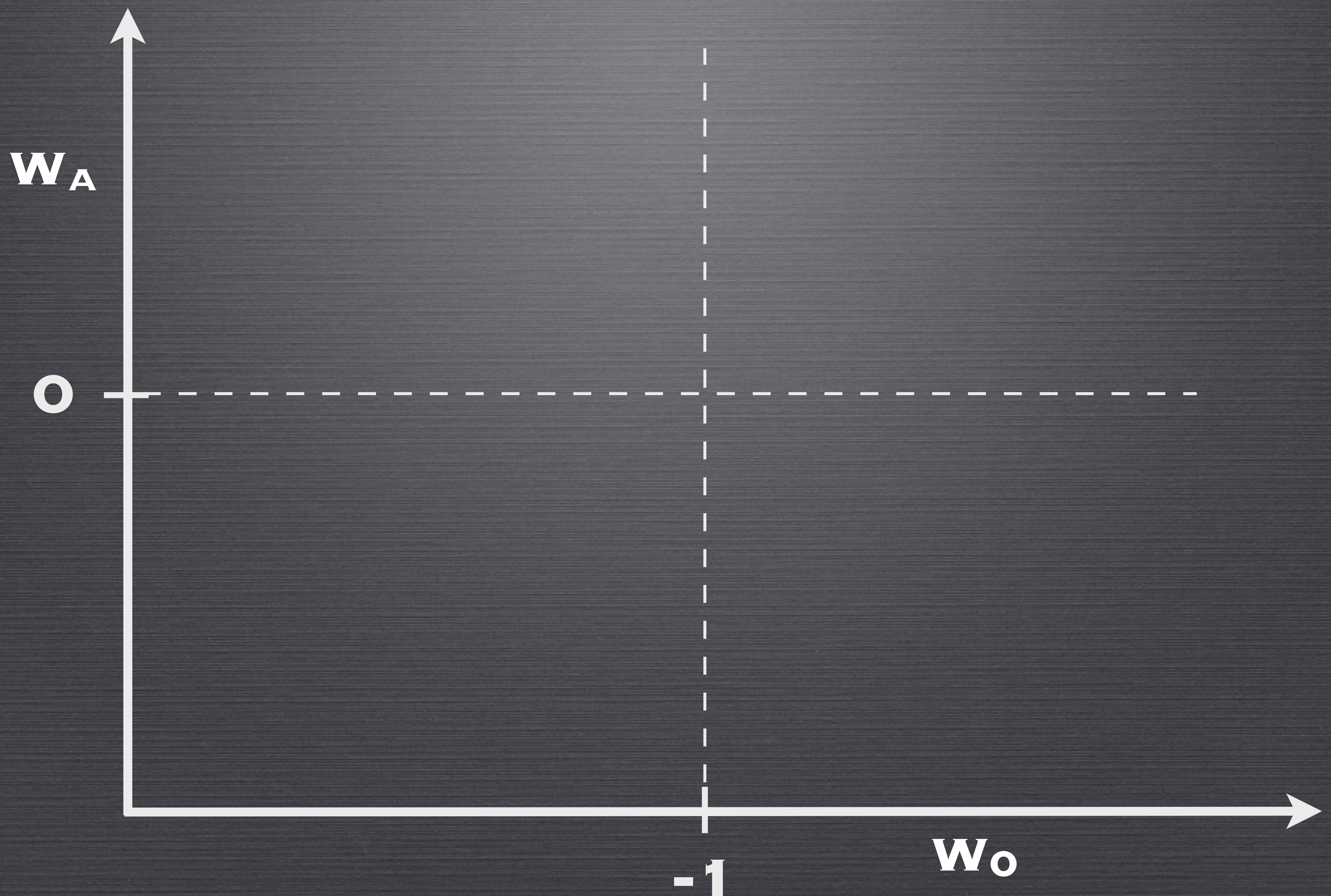
How Galaxies Affect Shear Spectra



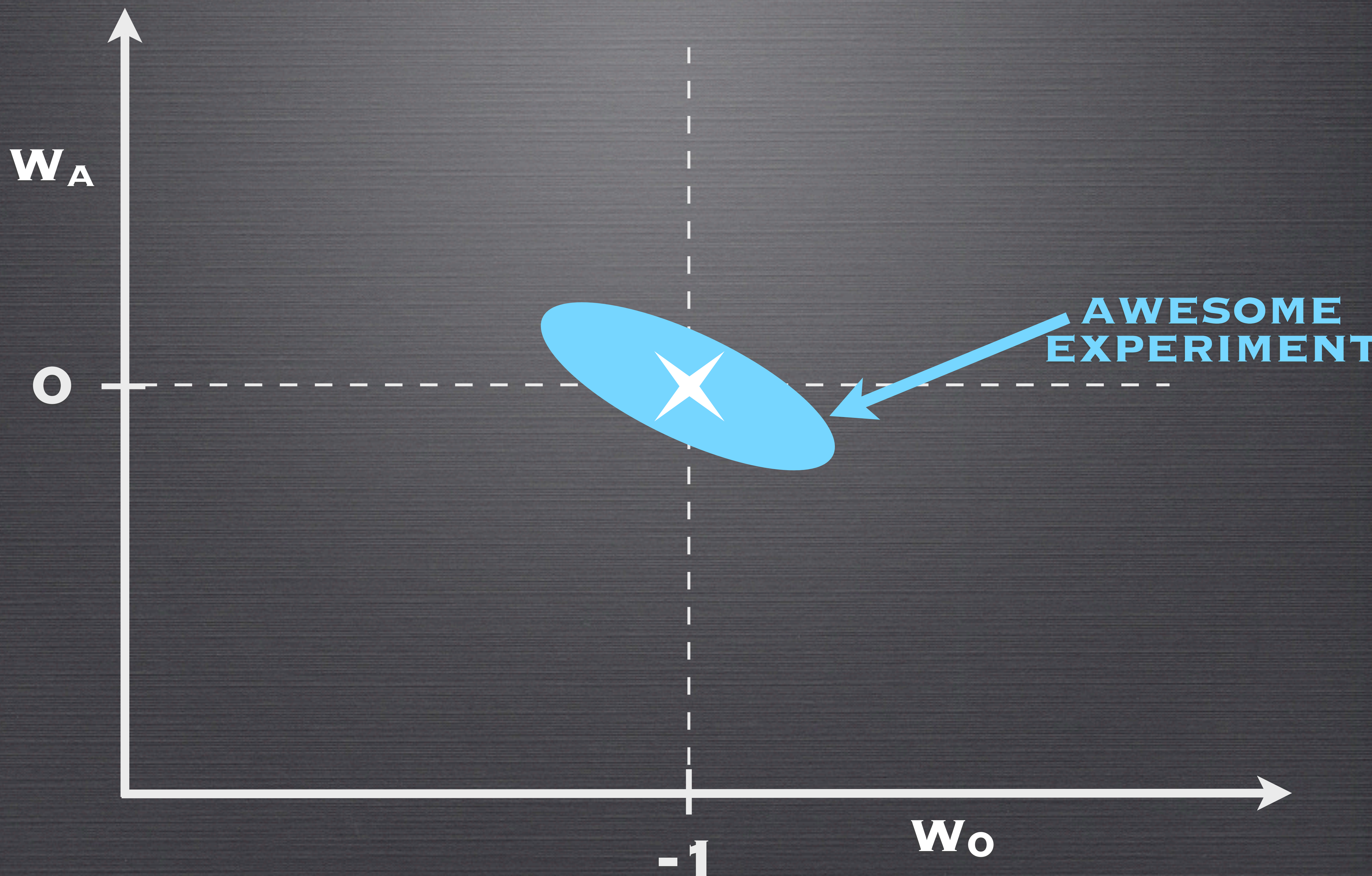
- Can lead to ~6σ "bias" in inferred cosmological parameters (w_0,w_a)!
- How can we test dark energy or our theory of gravity?

How Does This Affect the Dark Energy Program?

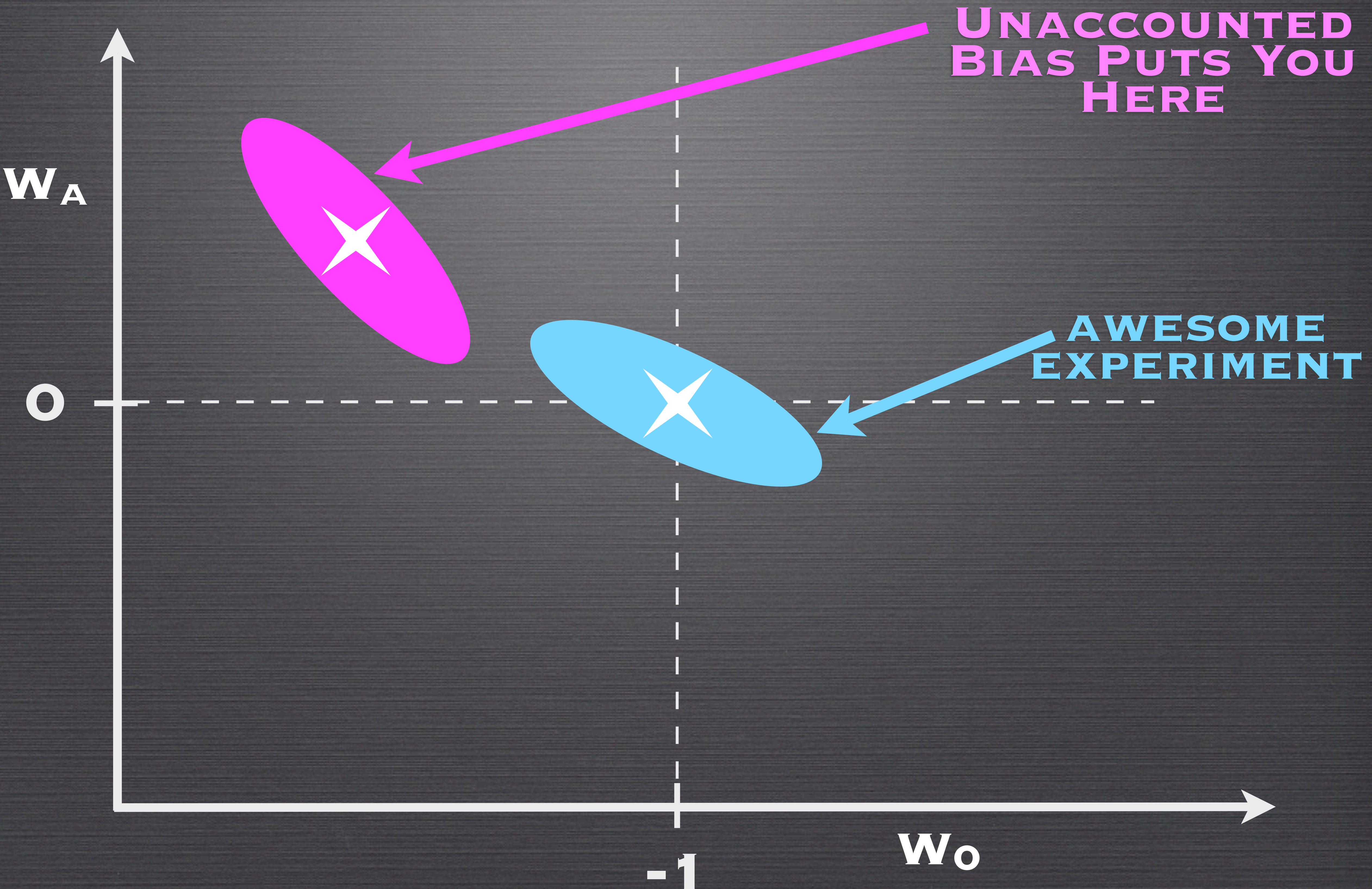
Biases



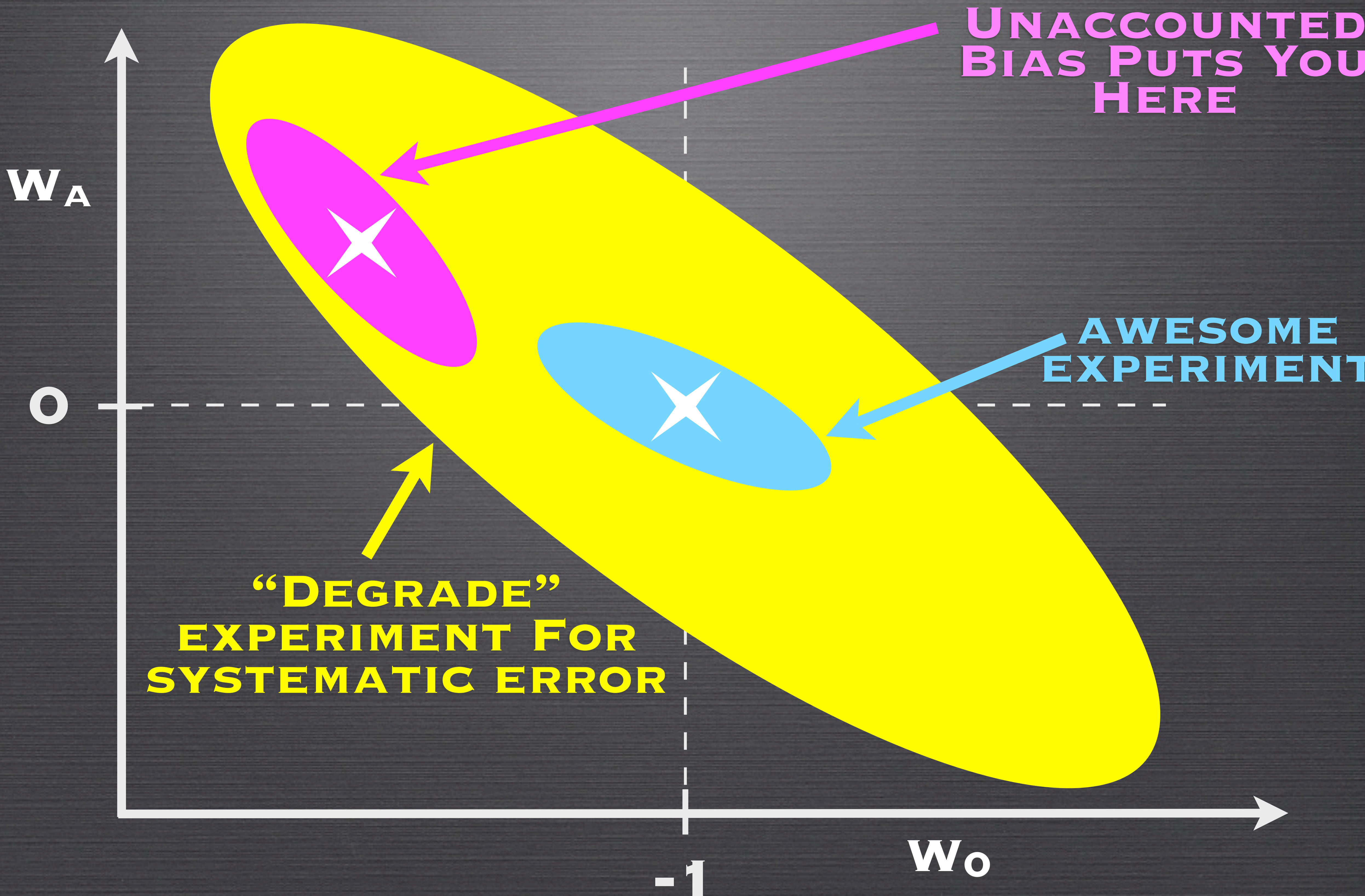
Biases



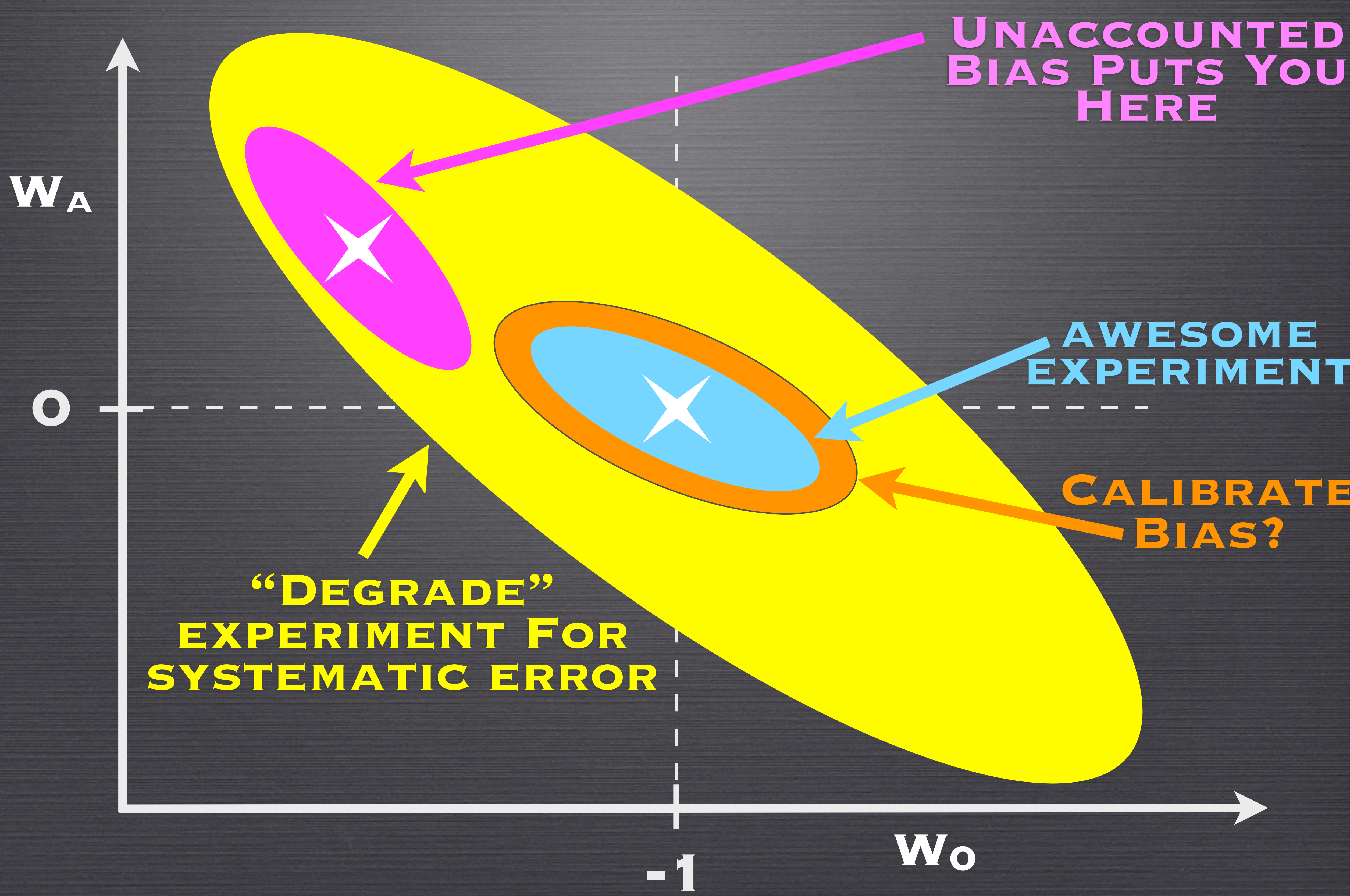
Biases



Biases

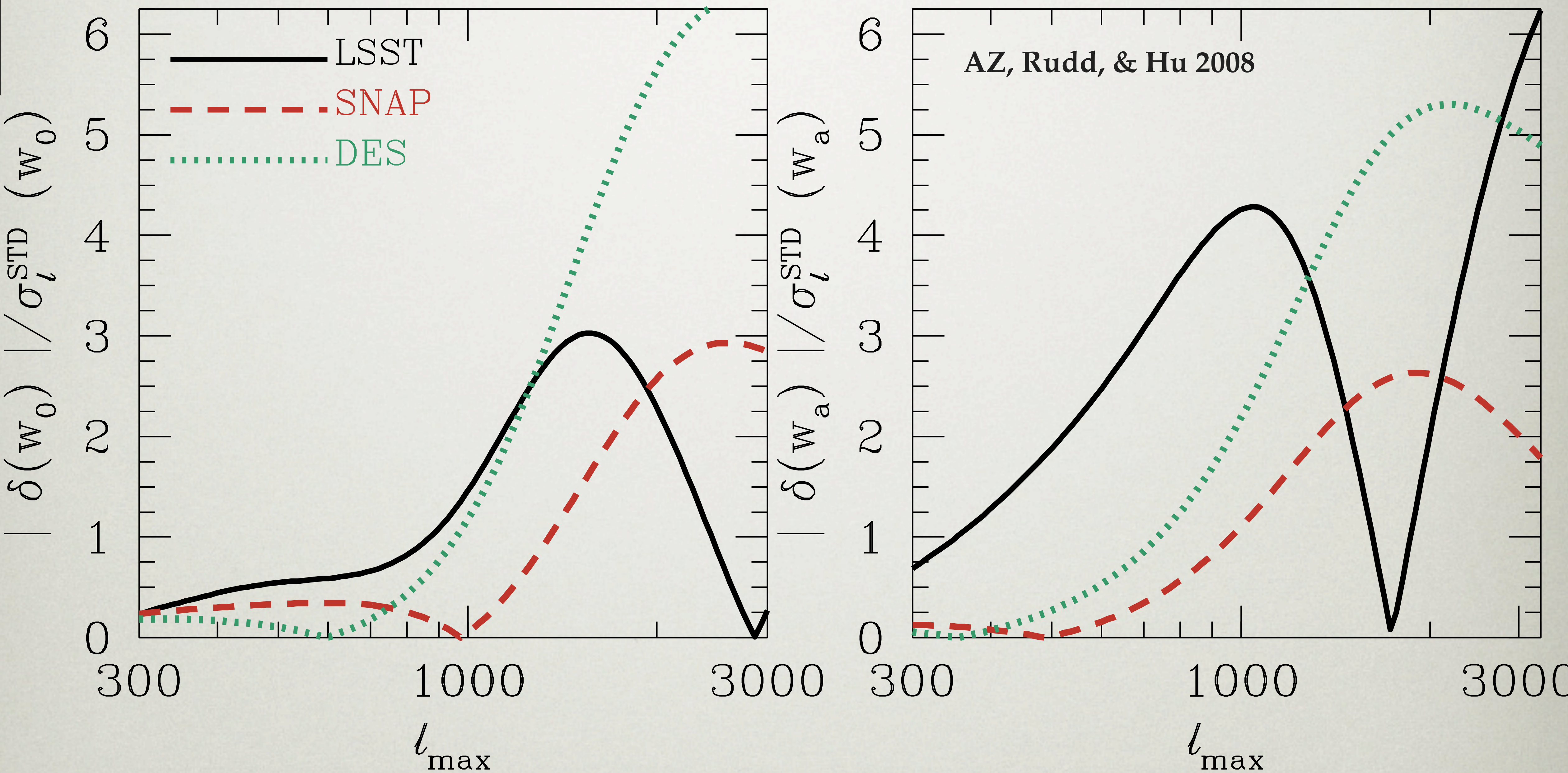

Unaccounted Bias Puts You Here
awesome experiment
"Degrade" experiment For systematic error
w_A
0
-1
w_0

Biases


Unaccounted Bias Puts You Here
w_A
0
Awesome experiment
Calibrate Bias?
"Degrade" experiment For systematic error
-1
w_0

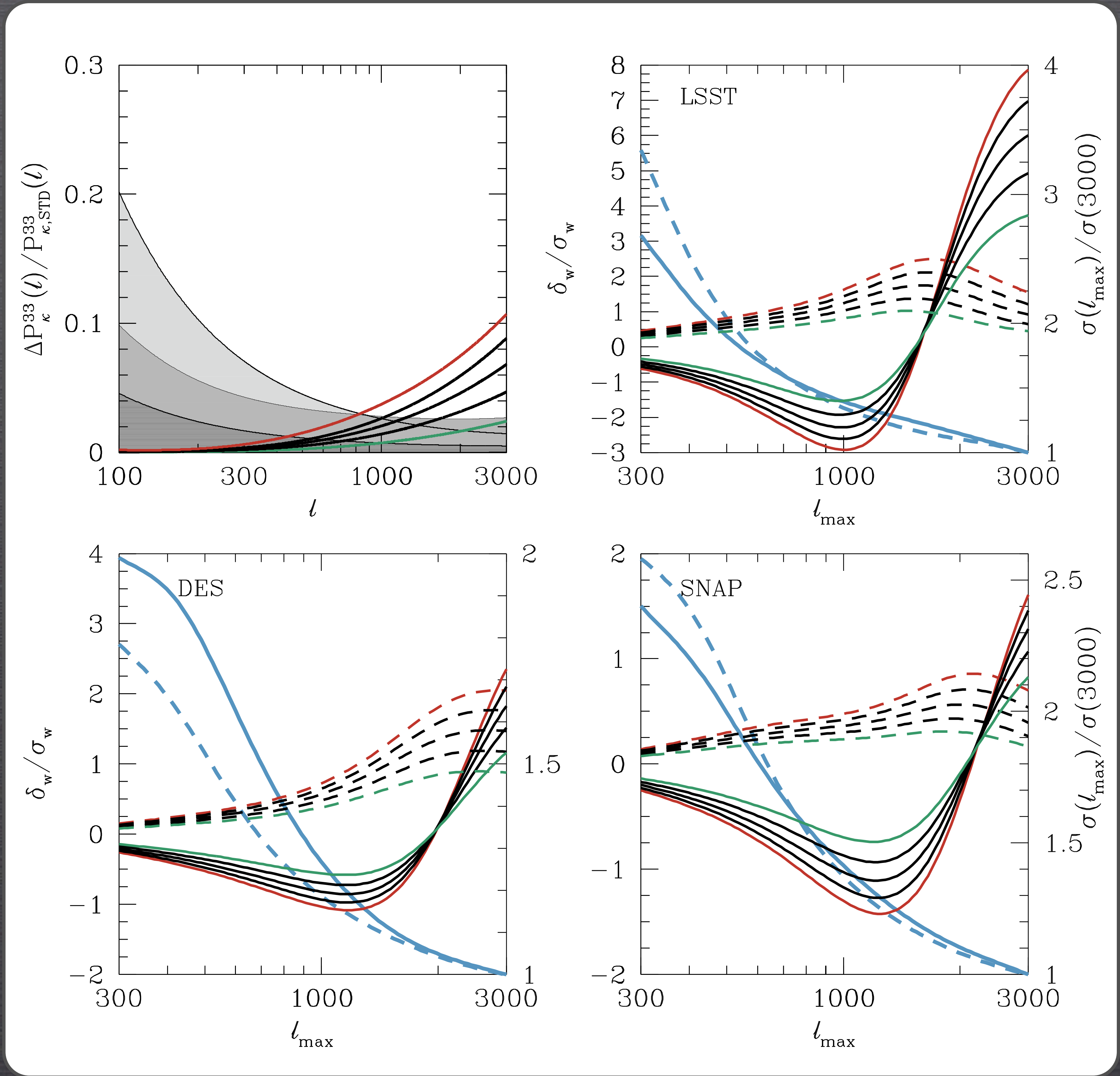
Parameter Biases

Parameter Bias Relative to Statistical Uncertainty



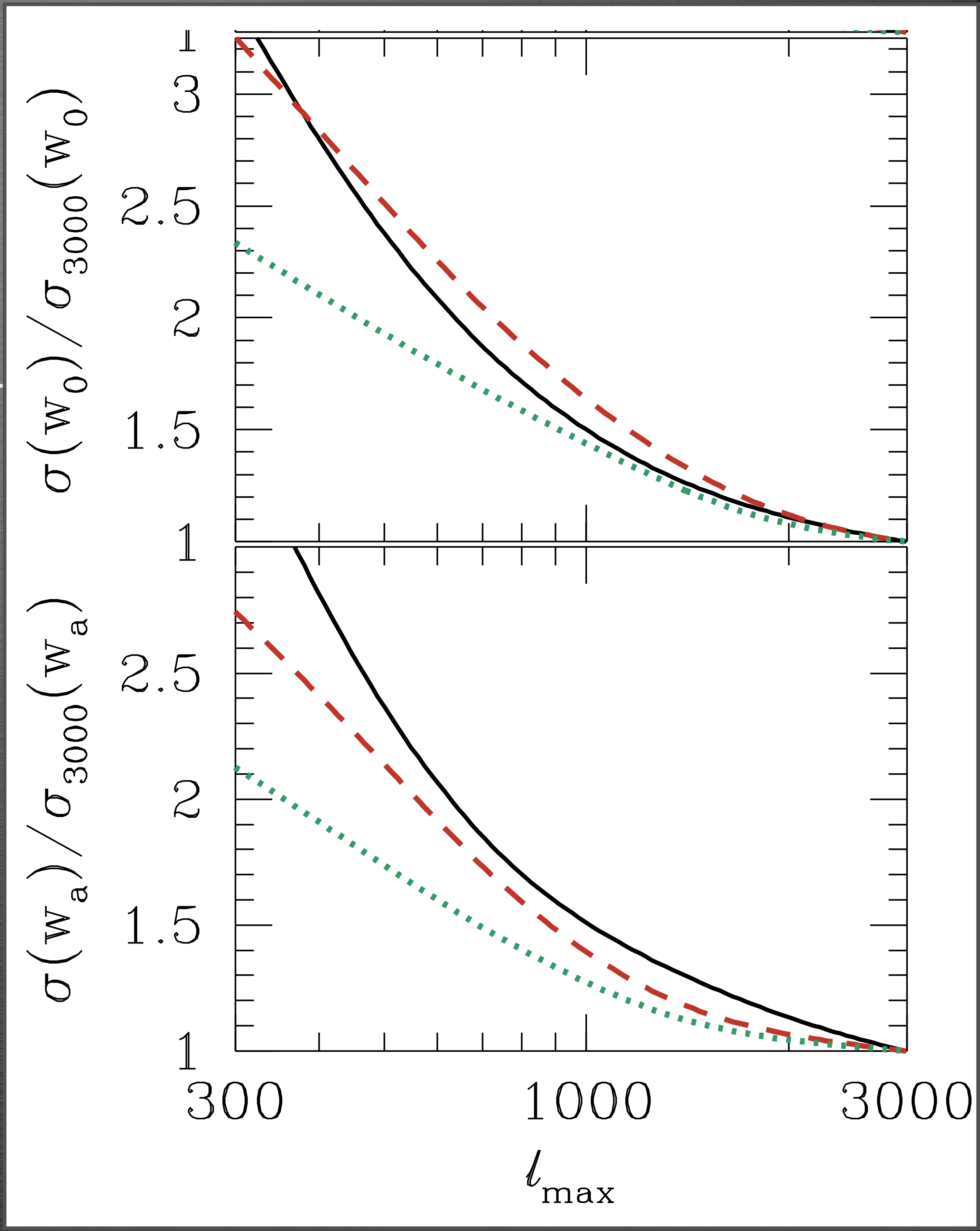
Maximum Multipole
Under Consideration

Testing Gravity

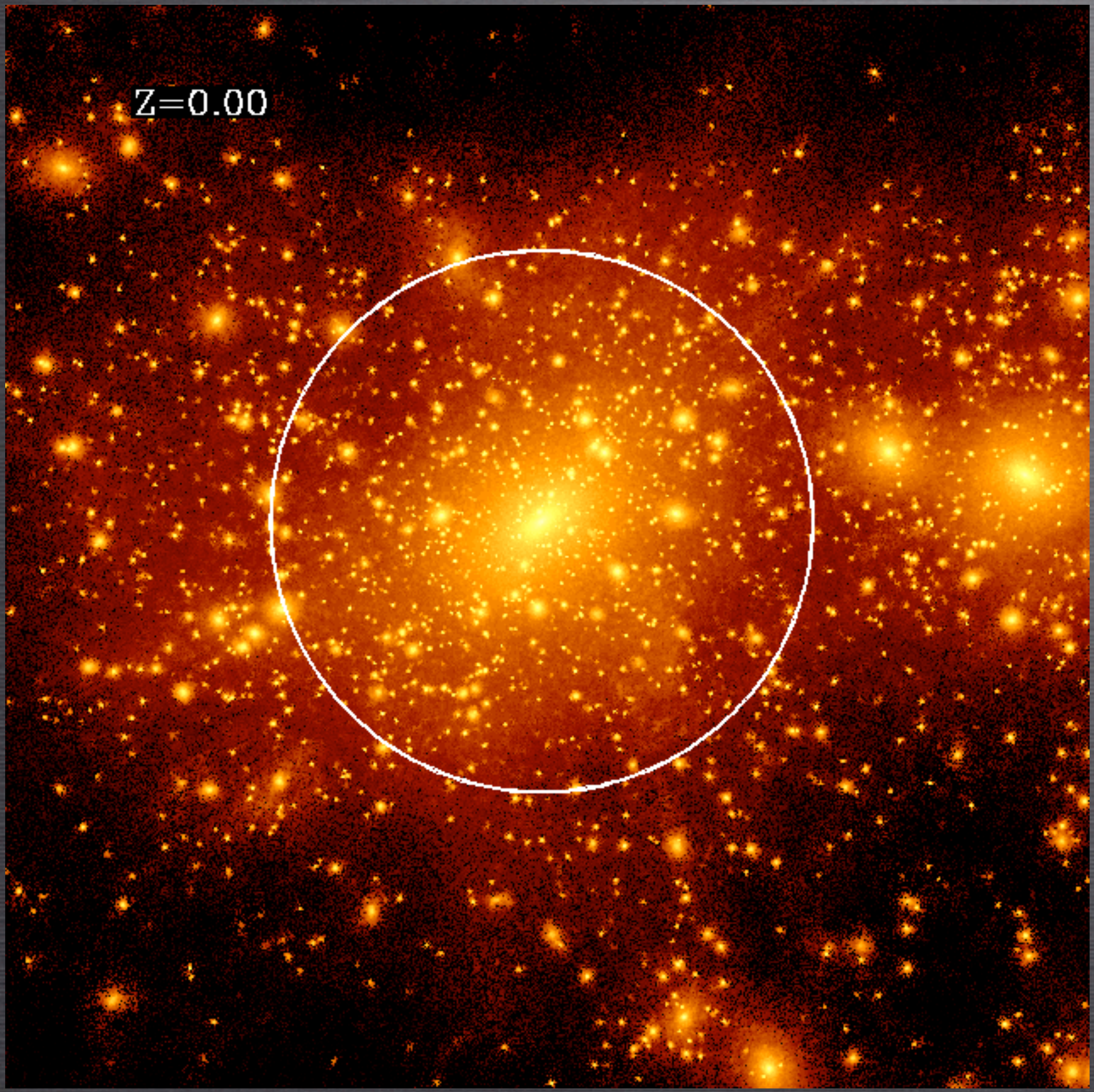


Excise Small Scales?

- AT RIGHT: Scaling of statistical errors with maximum multipole exploited
- Excising nonlinear information to mitigate bias expands statistical errors by a factor of ~2-4



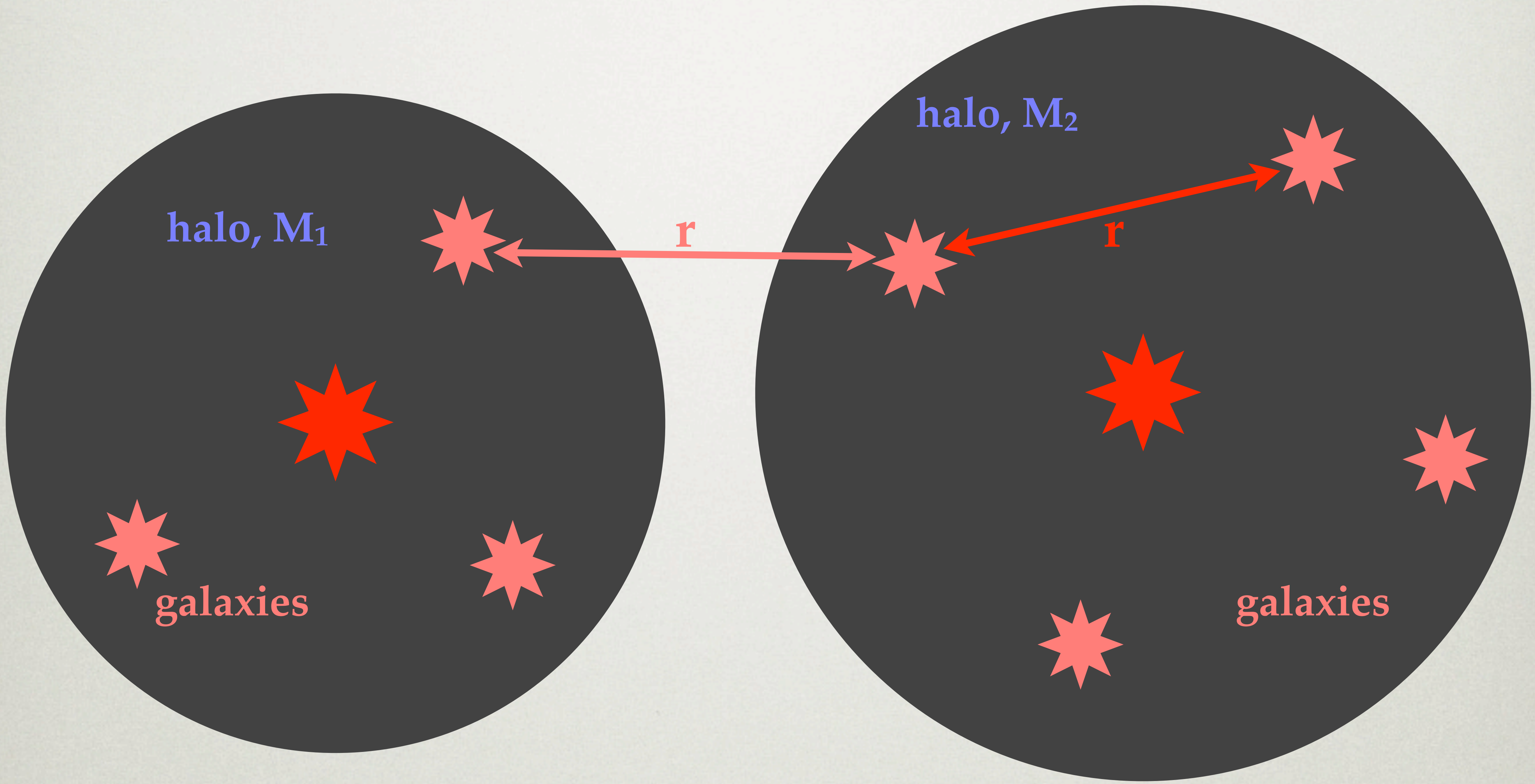
Dark Matter Halos



- Halos are Nonlinear building blocks of structure defined to have average densities of a few hundred times the mean within their virial radii

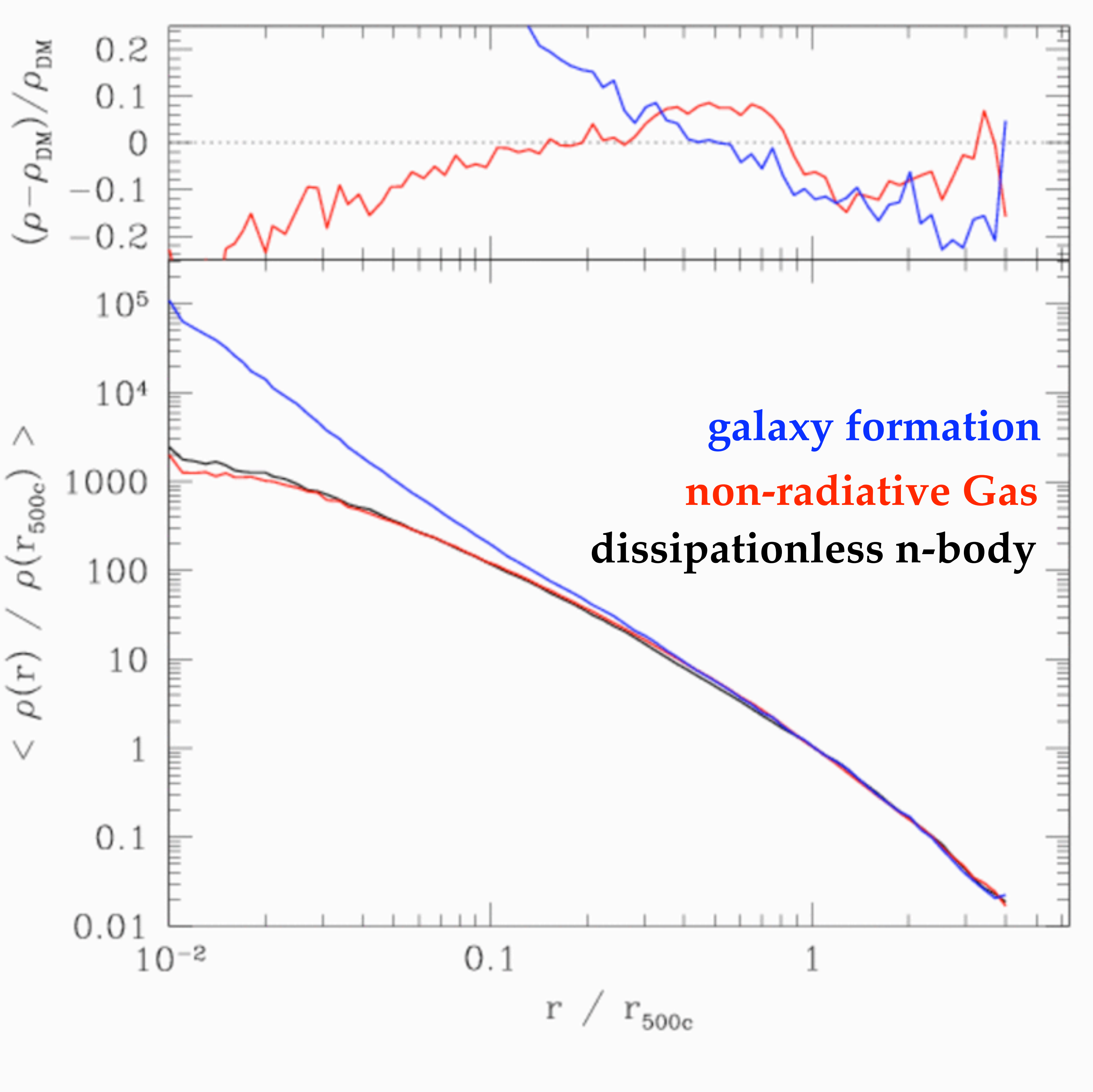
- $\rho_{NFW} \propto (c\ R/R_{vir})^{-1}(1+c\ R/R_{vir})^{-2}$
- "c" is dimensionless Halo "concentration Parameter"

The Halo Model



- Compute correlation statistics using halos as the fundamental unit of structure

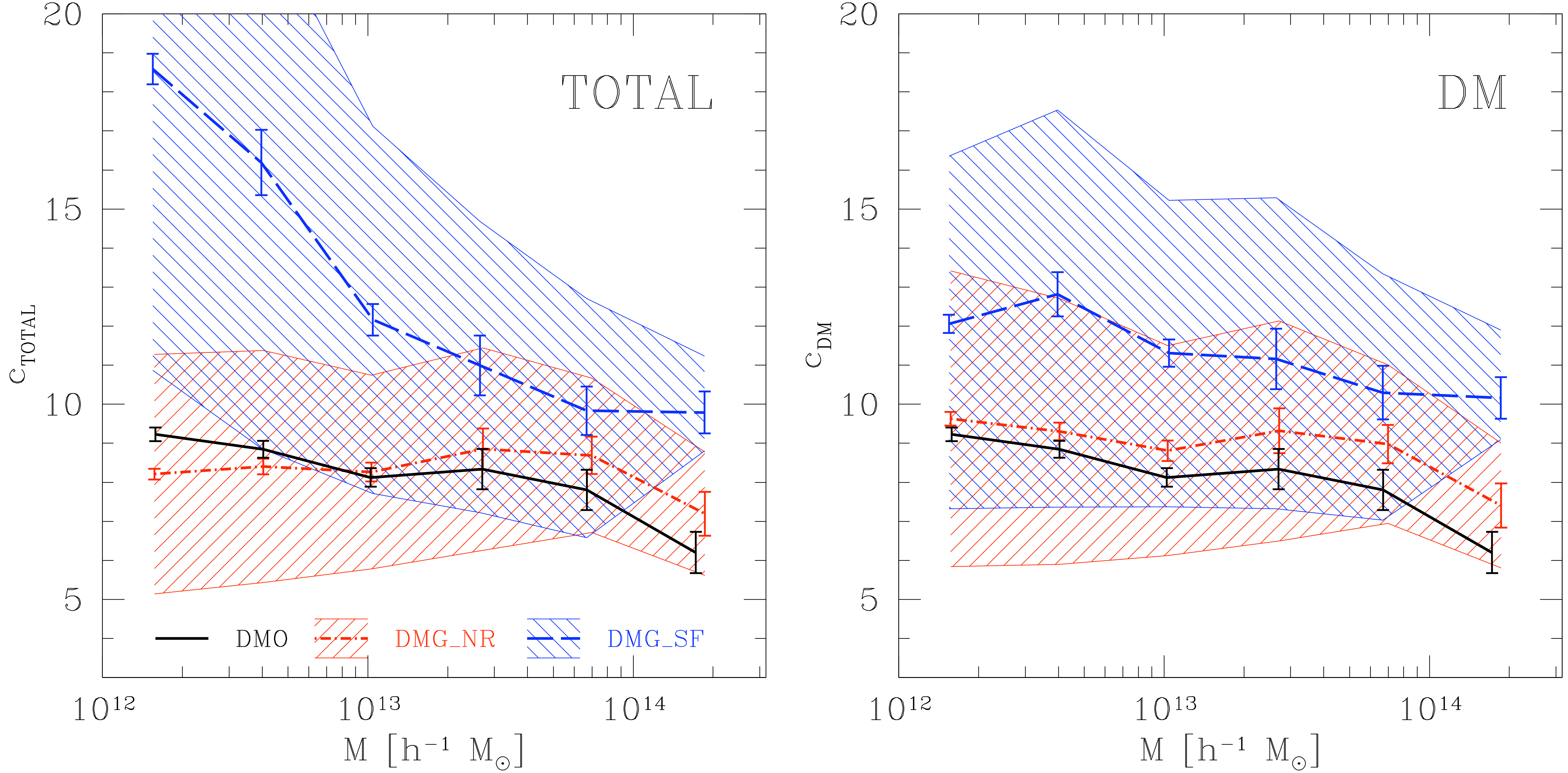
Halos with Galaxies



Modify Halo structure, account for contraction, compute lensing spectra

Halos in baryonic simulations look like NFW halos with modified concentrations

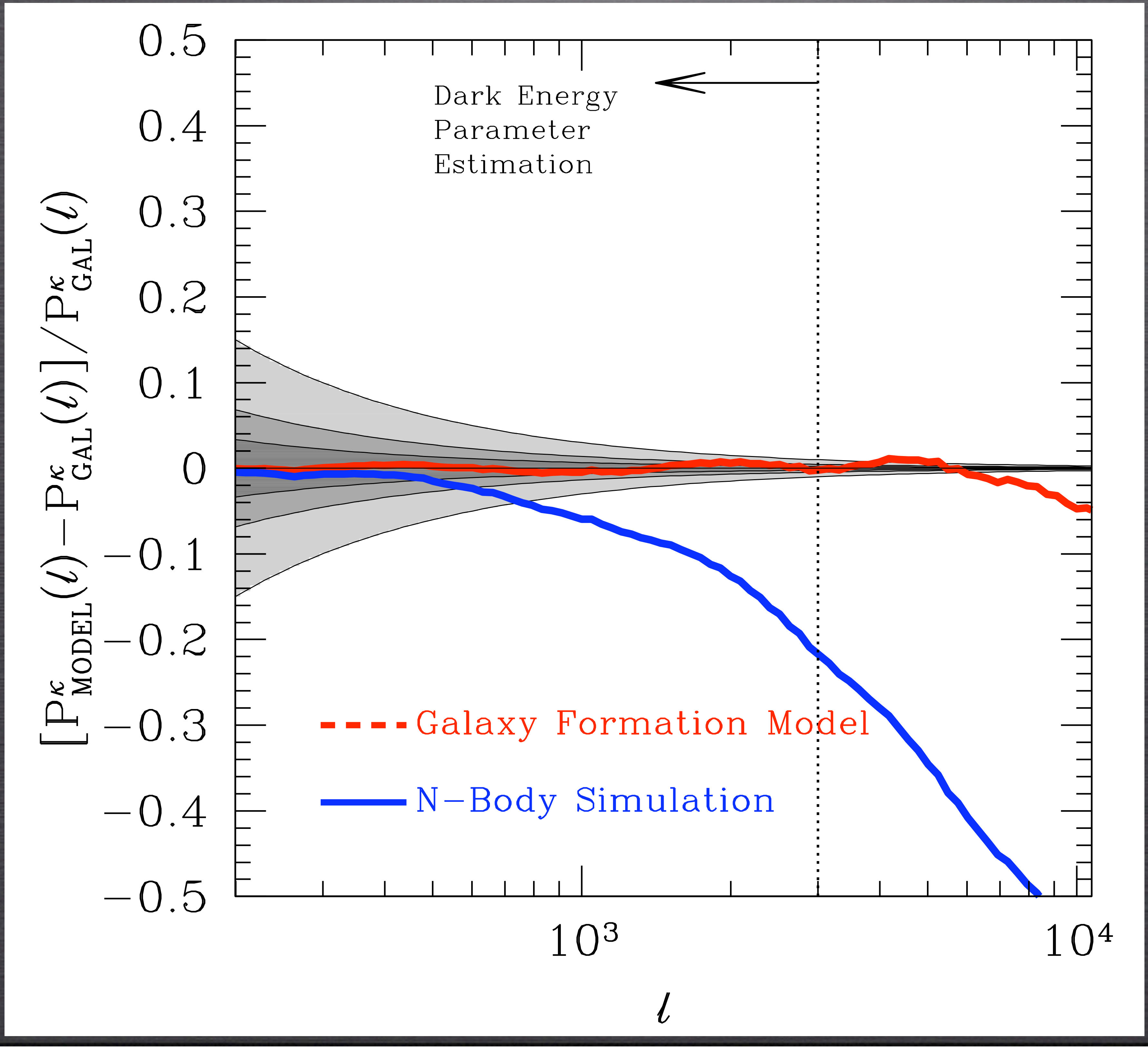
Halos with Galaxies



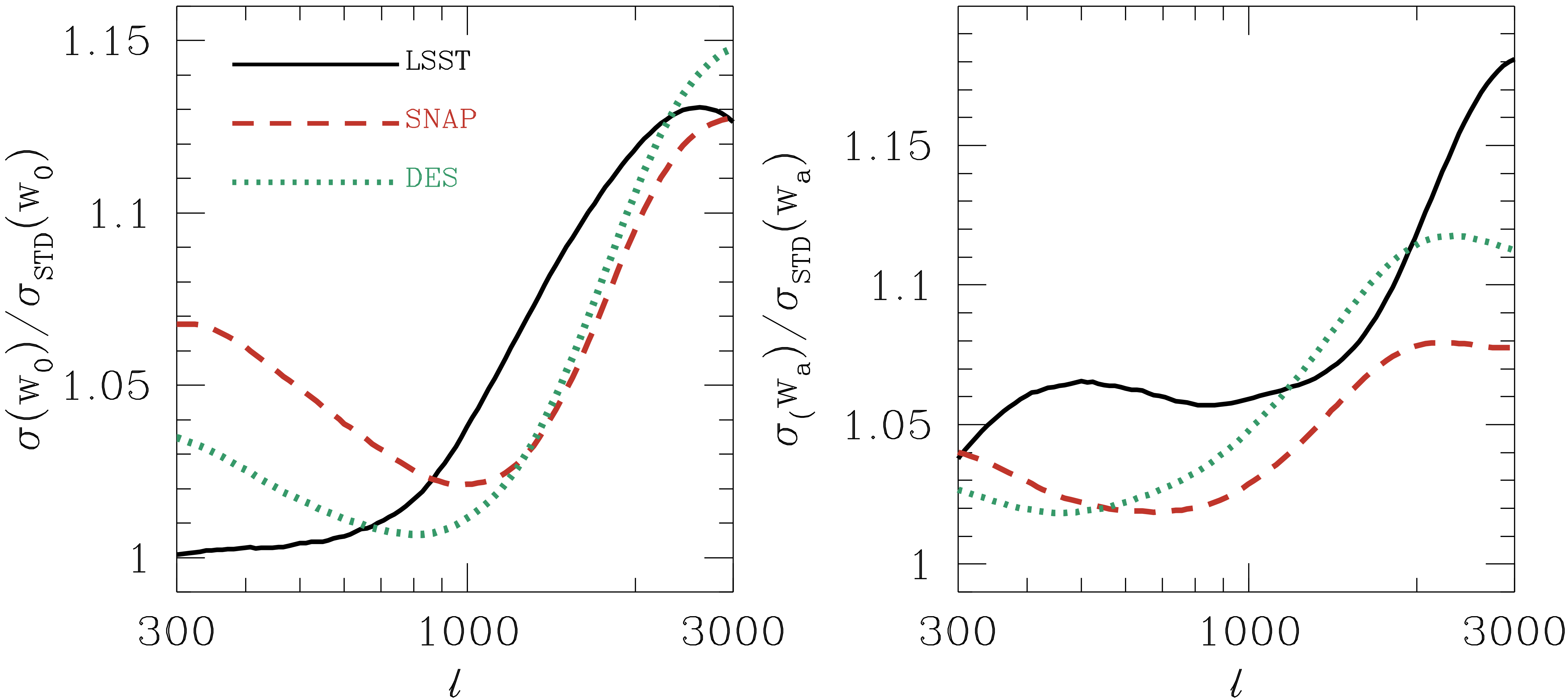
- Modified Halo Concentration Relation Relative to the Standard N-Body Result

Spectrum Model with Contracted Halos

residual with respect to galaxy formation simulation

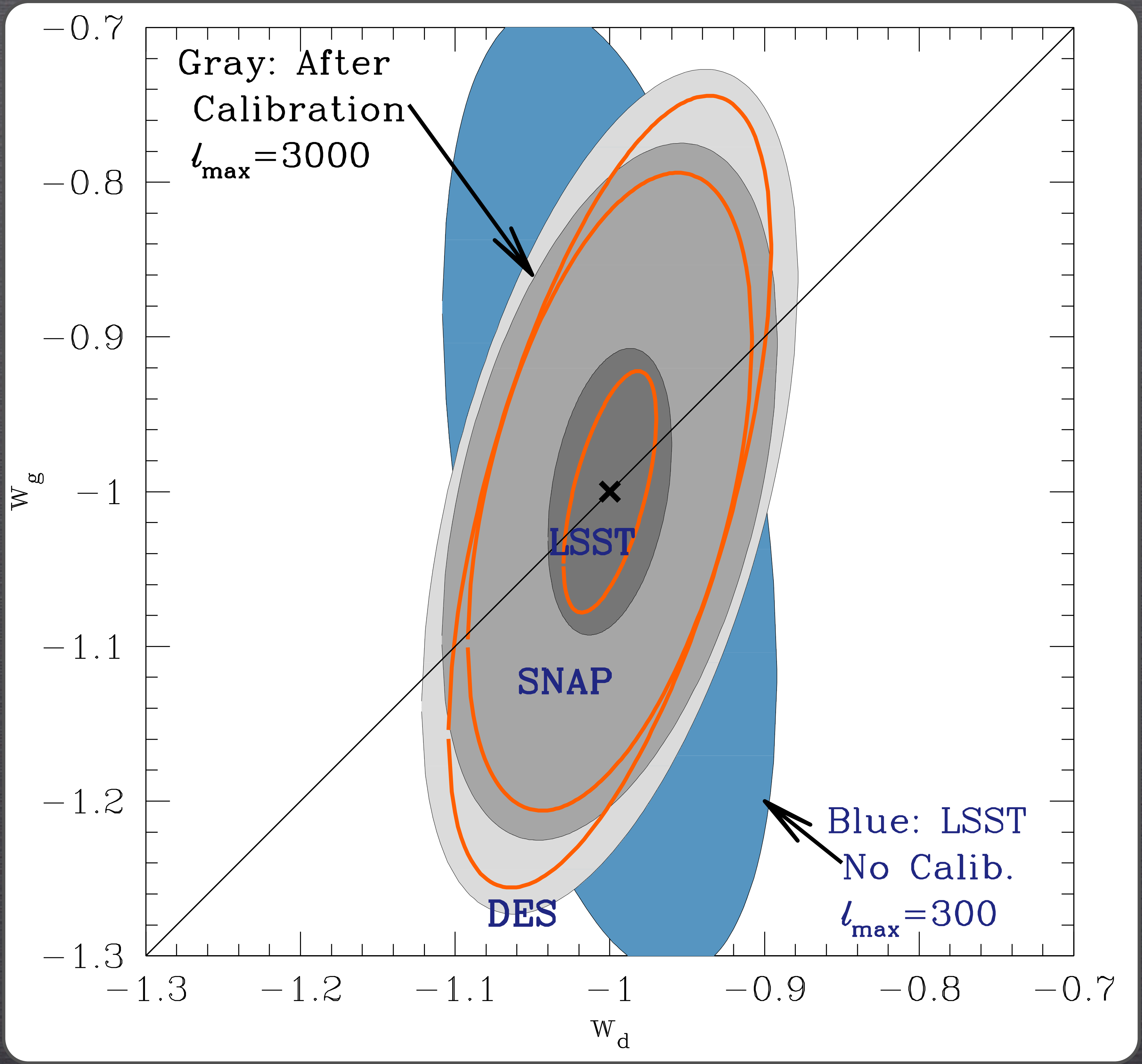


Dark Energy Constraints

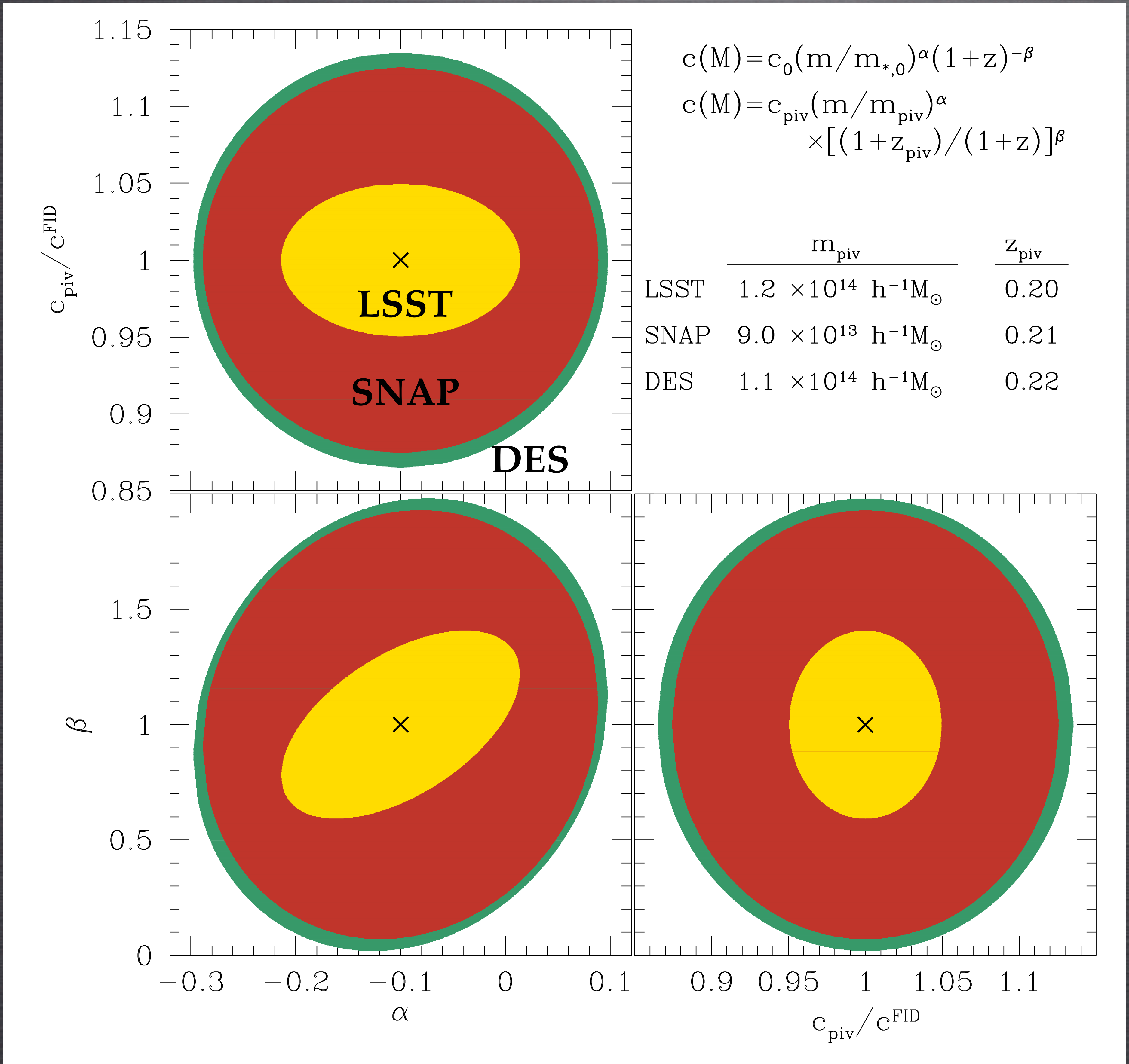


- **Calibration is both feasible and profitable, recall 300% degradation from excising small scales**
- **Biases < 10% of statistical errors with simple model**

Testing Gravity



Halo Structure



	m_{piv}	z_{piv}
LSST	1.2×10^{14} $h^{-1}M_\odot$	0.20
SNAP	9.0×10^{13} $h^{-1}M_\odot$	0.21
DES	1.1×10^{14} $h^{-1}M_\odot$	0.22

- "Galaxy formation" parameters constrained at interesting levels

Shear Tomography

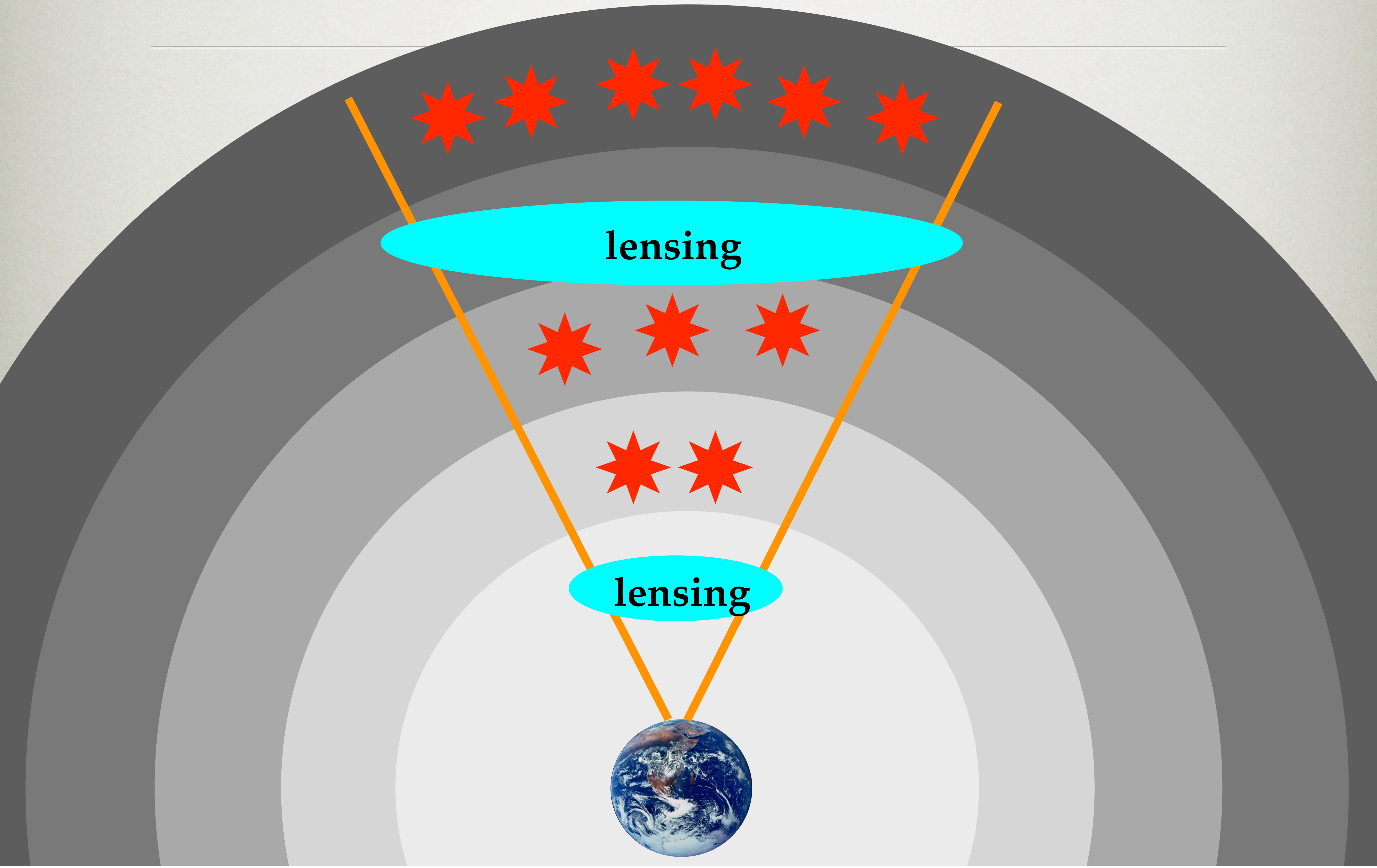
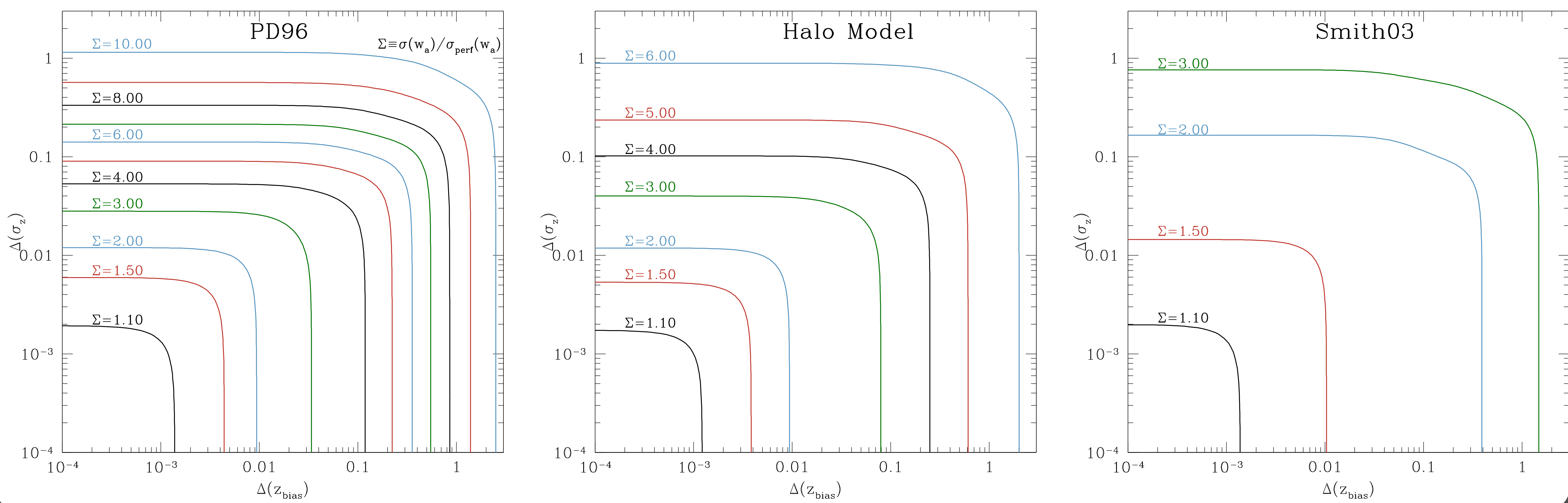


Photo-Z & NL Structure



- Treatment of nonlinear structure influences the goals and approaches of forthcoming experiments

The Future

1. Develop a better understanding of nonlinear cosmological structure growth, including:
   1.1. Galaxy Formation Processes
   1.2. Energy injection by Supernovae & Active Galaxies ...
2. A Simulation program is necessary **(and underway)** and will broaden the scope of future missions
3. We may soon have unprecedented constraints on **both dark energy and galaxy formation**