Cosmology in the New Era

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Pheno2019

Standard Model of Particle Physics: Predictions for Cosmology

Armed with measurements of the current baryon and radiation density, the SM makes predictions for:

- Expansion History

$$H(a) = H_0(\Omega_B \mathrm{a}^{-3} + \Omega_R \mathrm{a}^{-4} + (1 - \Omega_B)\mathrm{a}^{-2})^{1/2}$$

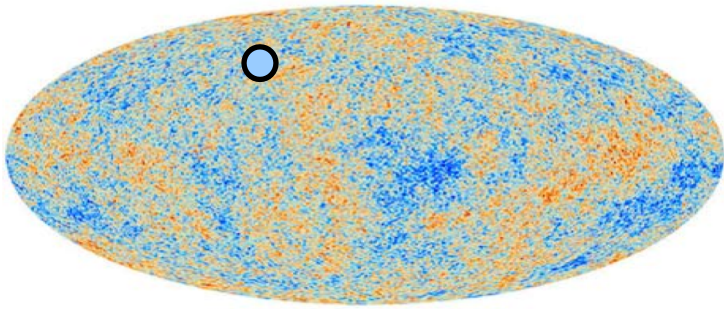
- Epoch of Equality

$$a_{EQ} = \frac{\Omega_R}{\Omega_B}$$

- Growth of Structure

$$\sigma_{8,0} = \sigma_{8,CMB} \frac{D(today)}{D(CMB)}. \qquad D(a)=a$$

What is σ_8 ?



Overdensity $\delta(x) = \dfrac{\rho(x) - \bar{\rho}}{\bar{\rho}}$

Power Spectrum $\left\langle \tilde{\delta}(k)\tilde{\delta}(k') \right\rangle \propto \delta(k + k')P(k)$

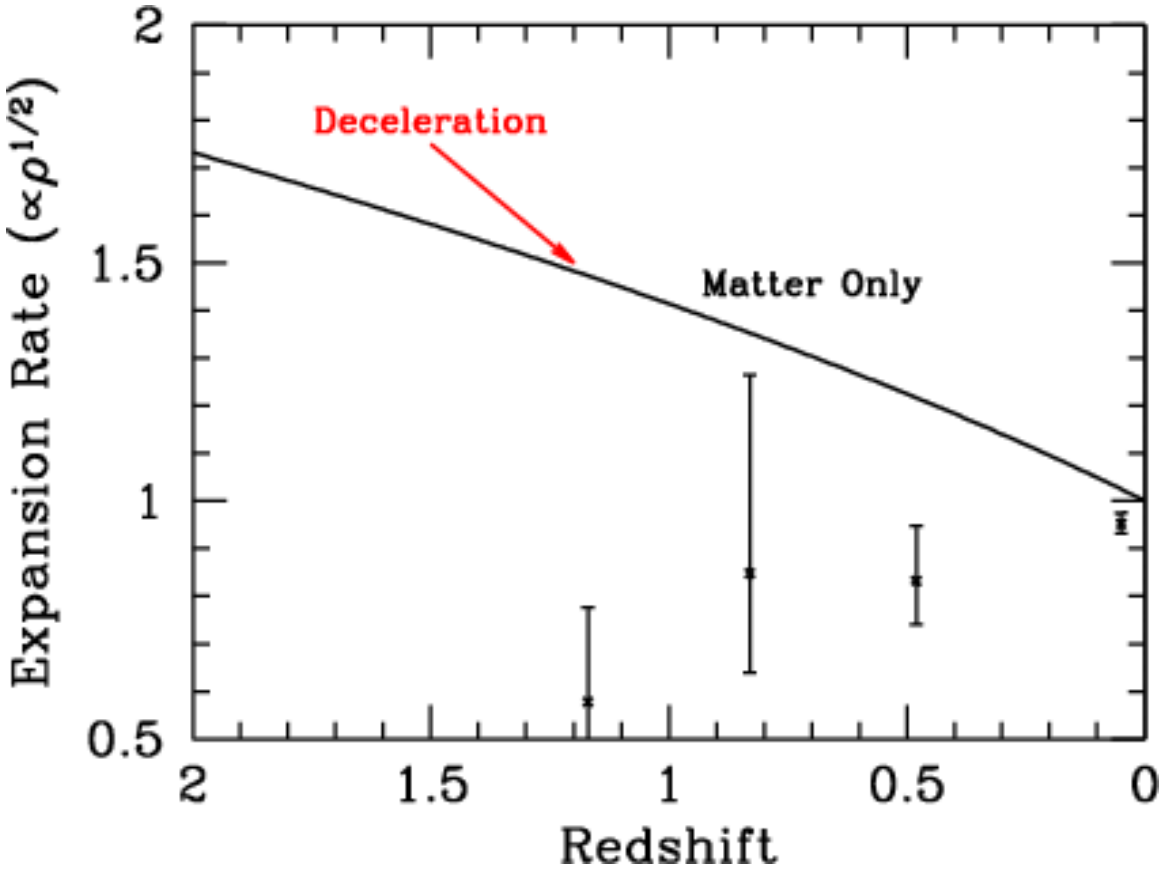
RMS Fluctuations $\sigma_R^2 \equiv \left\langle \delta^2 \right\rangle_R = \int d\ln k \left(\dfrac{k^3 P(k)}{2\pi^2} \right) W_R^2(k)$

σ_8

Choose W_R to be a tophat function
(in real space) with R=8h^{-1}Mpc (37 M light years)

Standard Model of Particle Physics: Predictions for Cosmology

These predictions are wrong



Redshift:
1+z=1/a

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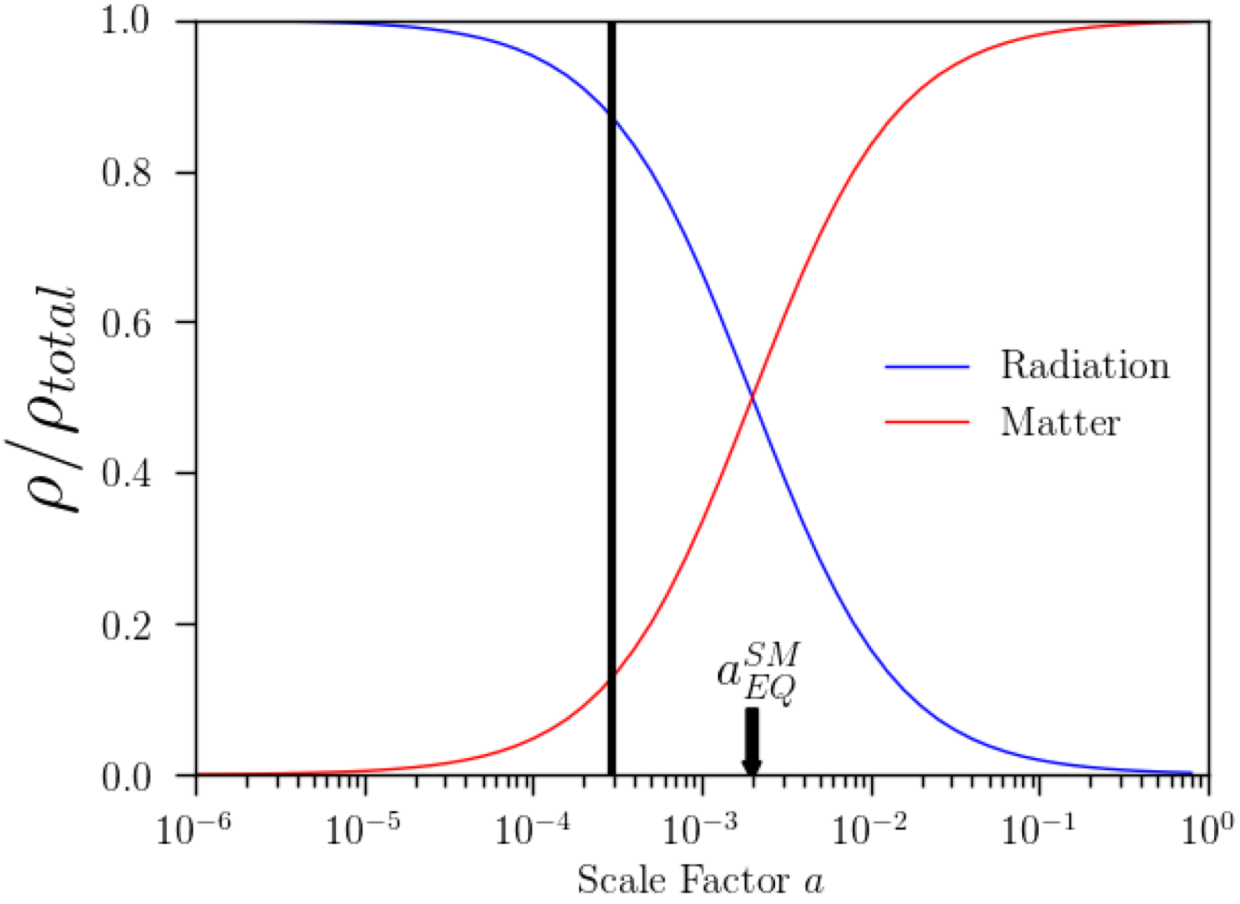

Standard Model of Particle Physics: Predictions for Cosmology

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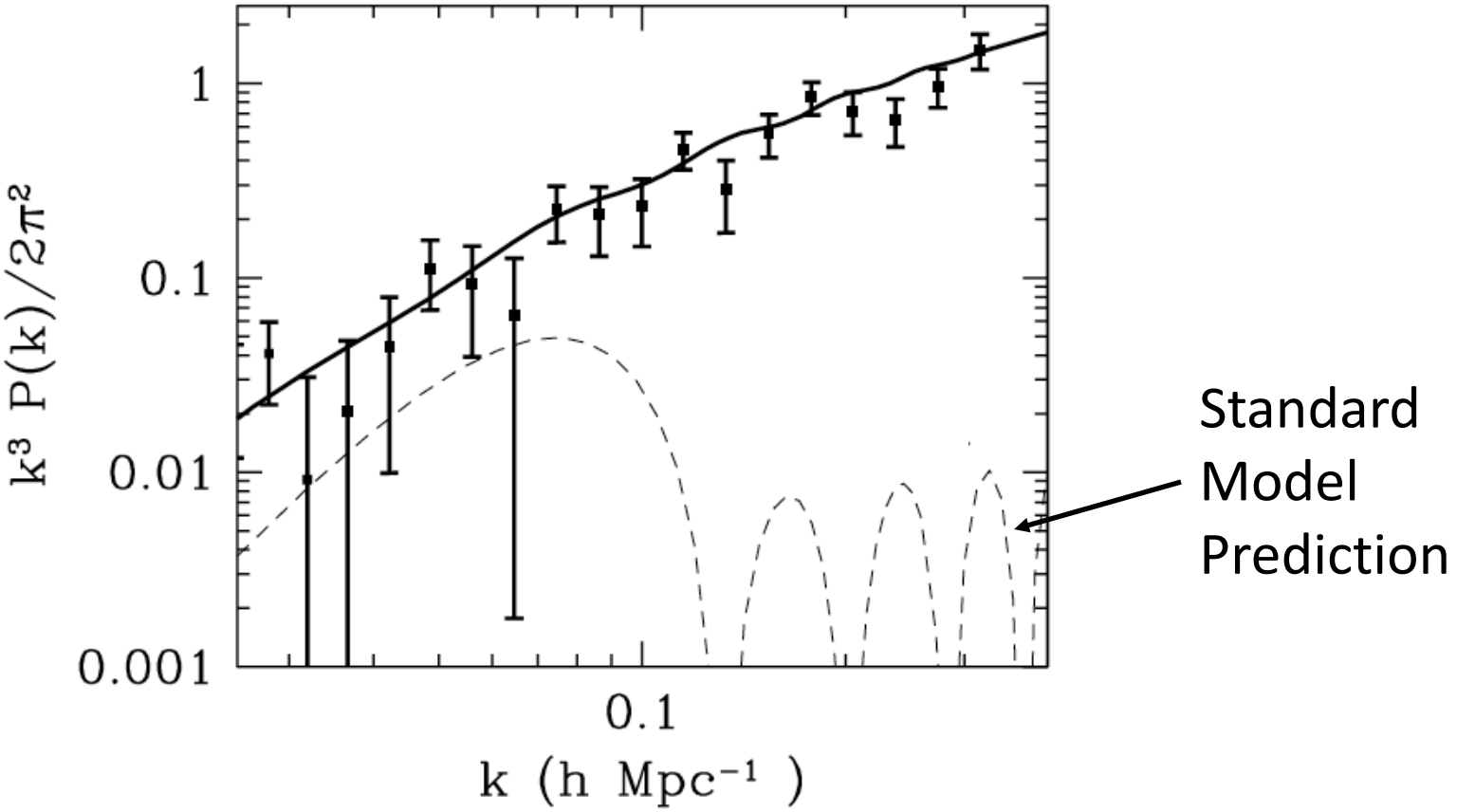
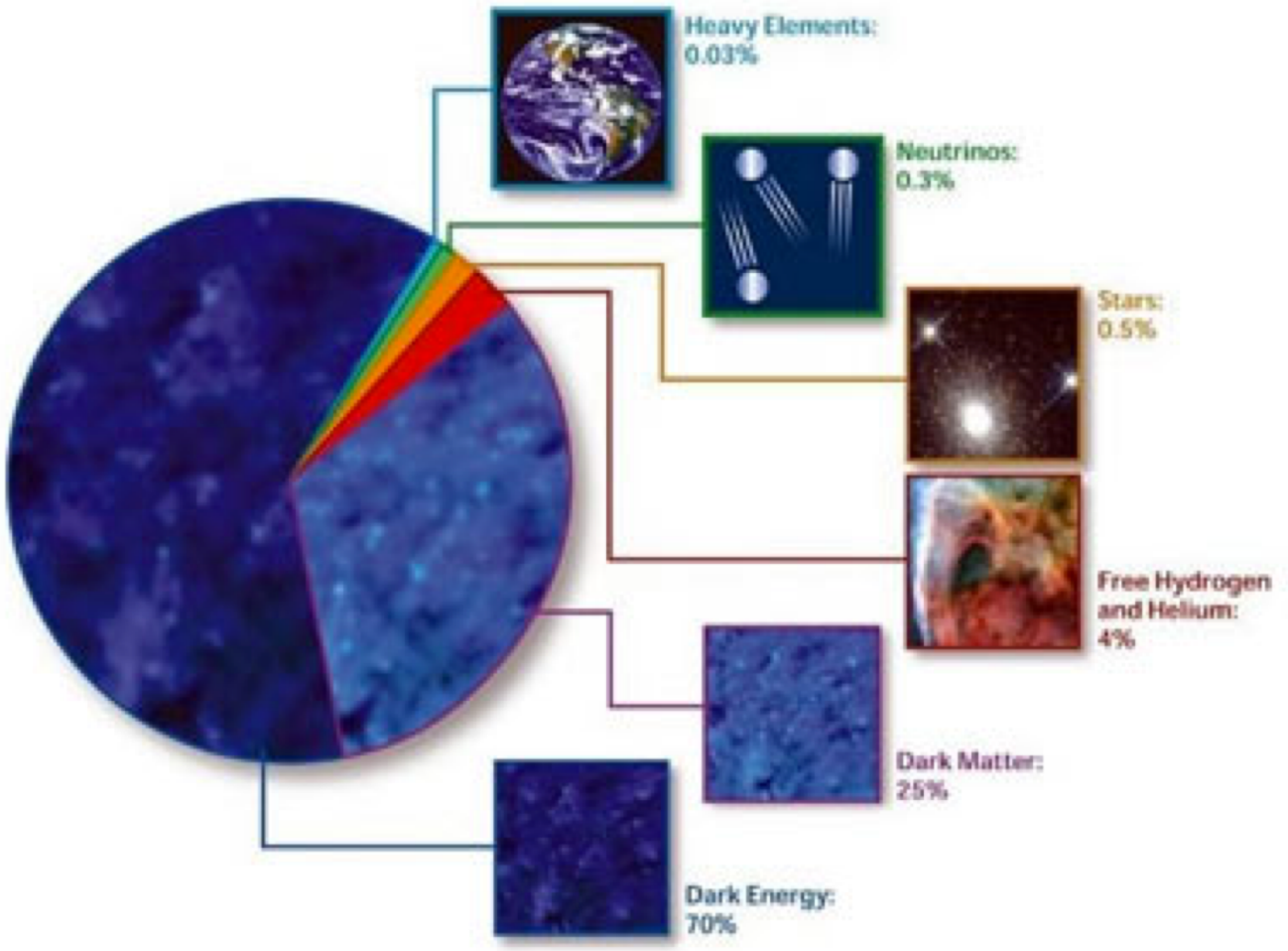
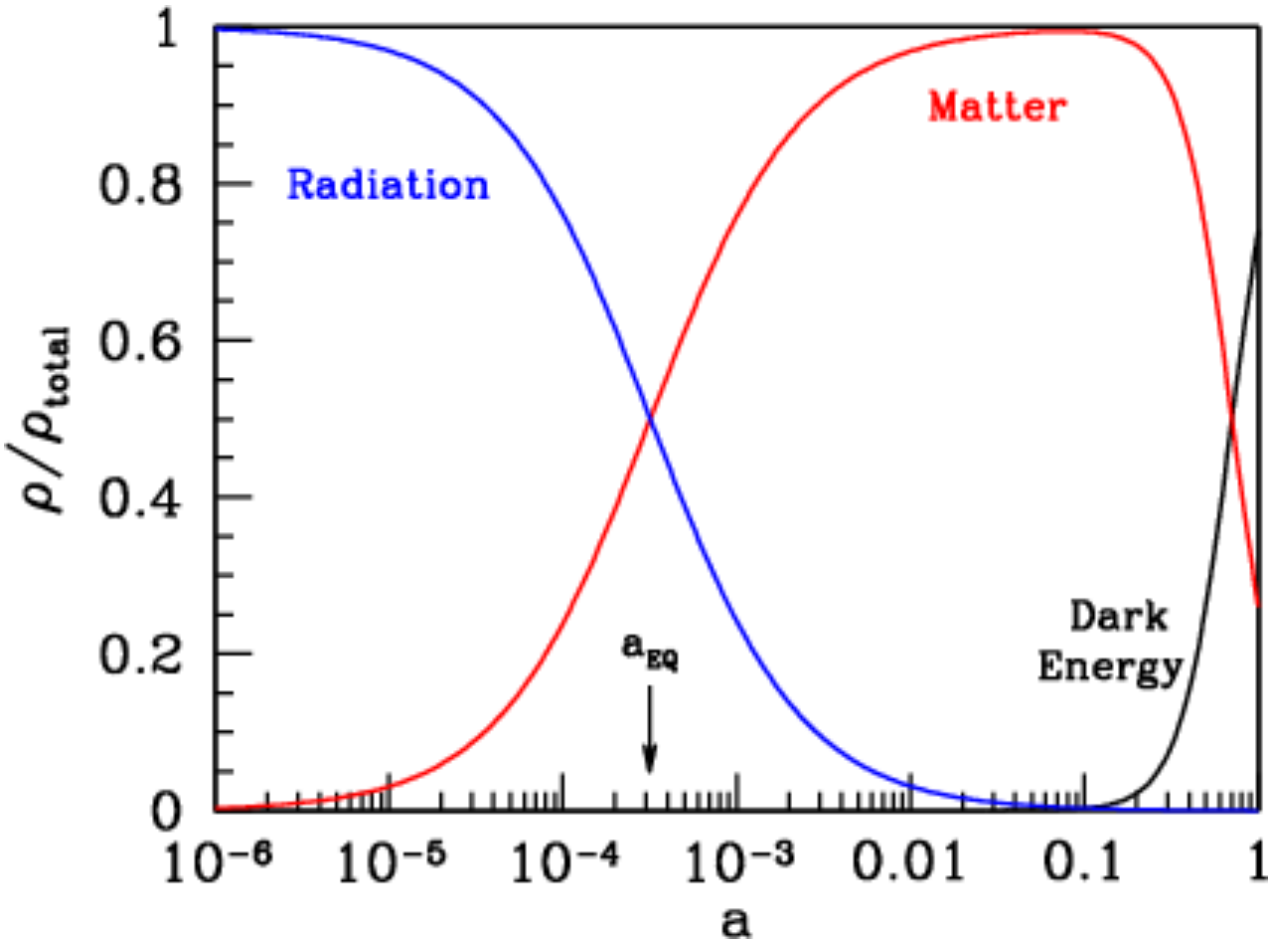


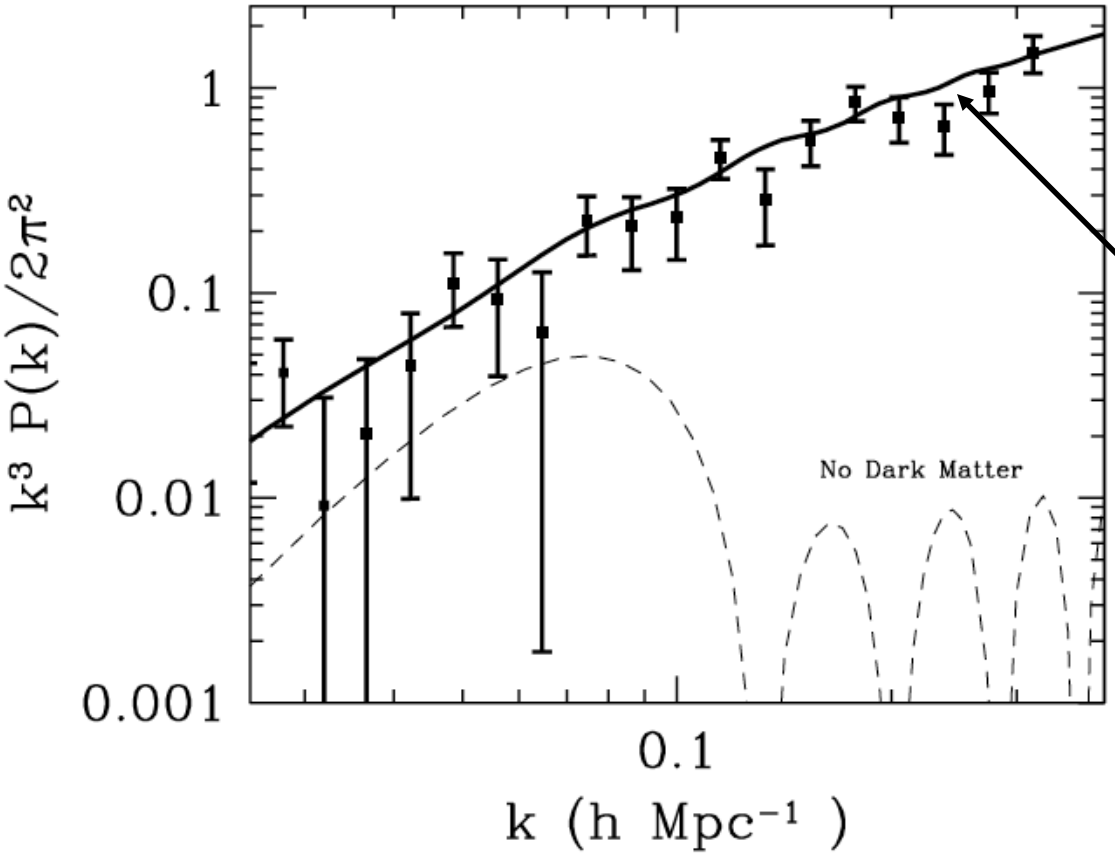
These predictions all fail … leading to "Cosmology in the New Era"



“Cosmology in the New Era” gets the epoch of equality right

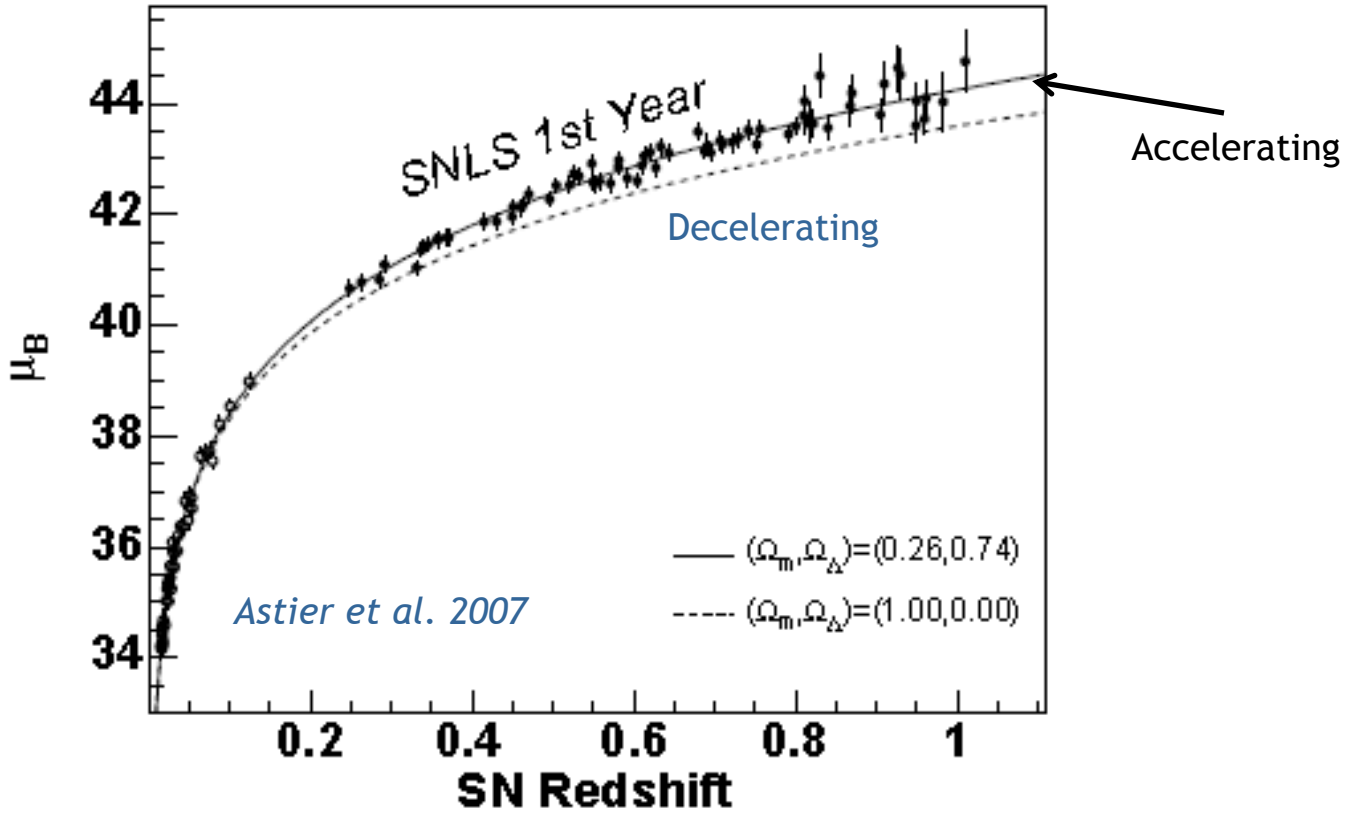


“Cosmology in the New Era” gets the power spectrum right

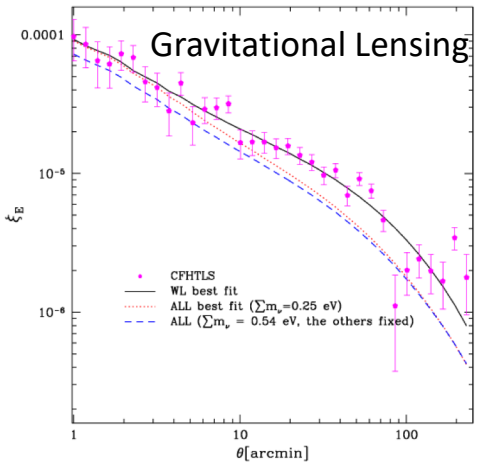


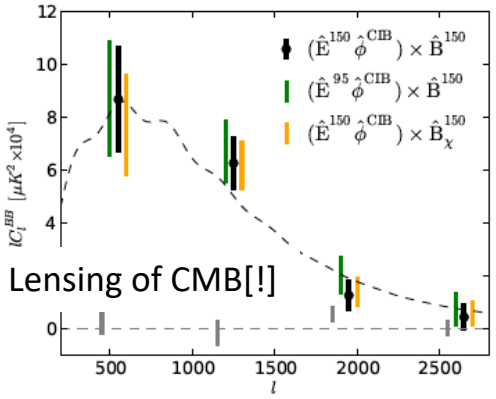
Standard Model of Cosmology

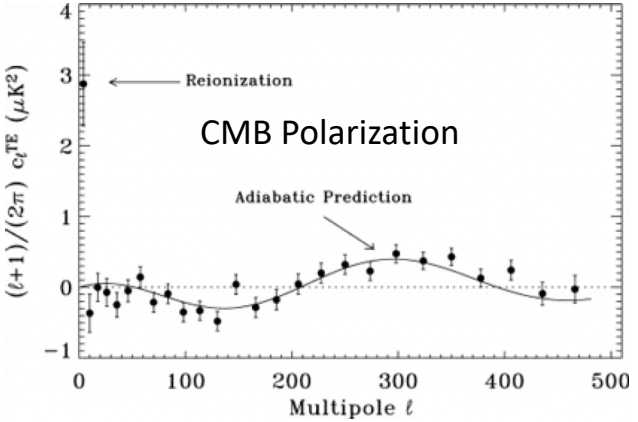
It famously gets the expansion history right

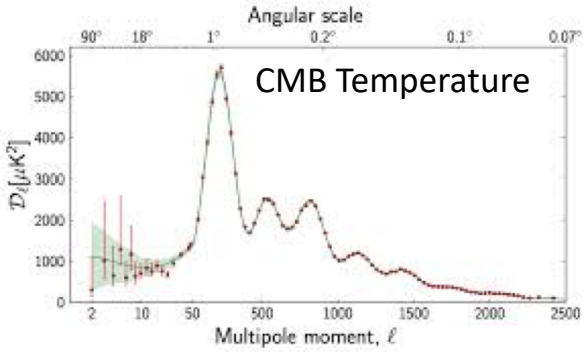


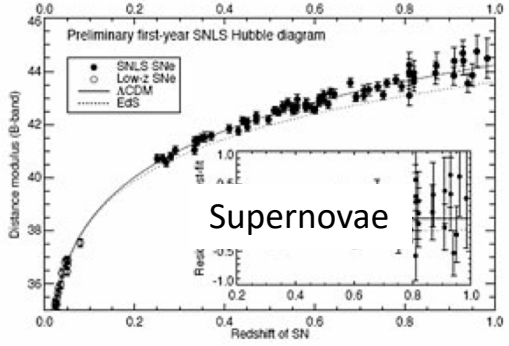
CNE agrees with all data on large scales (the only data for which we can make accurate predictions)

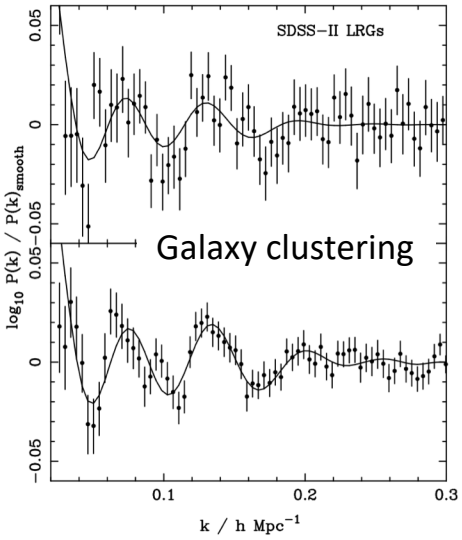




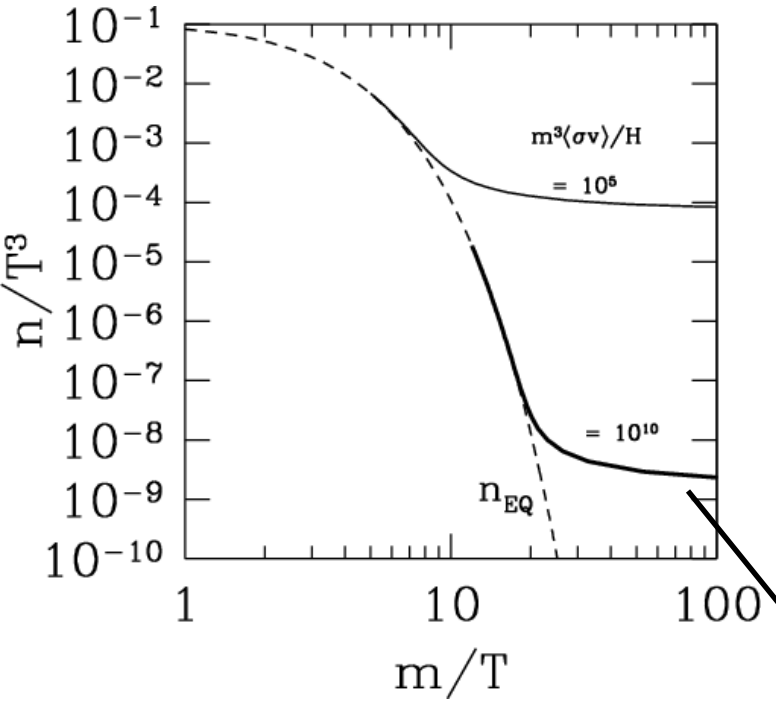






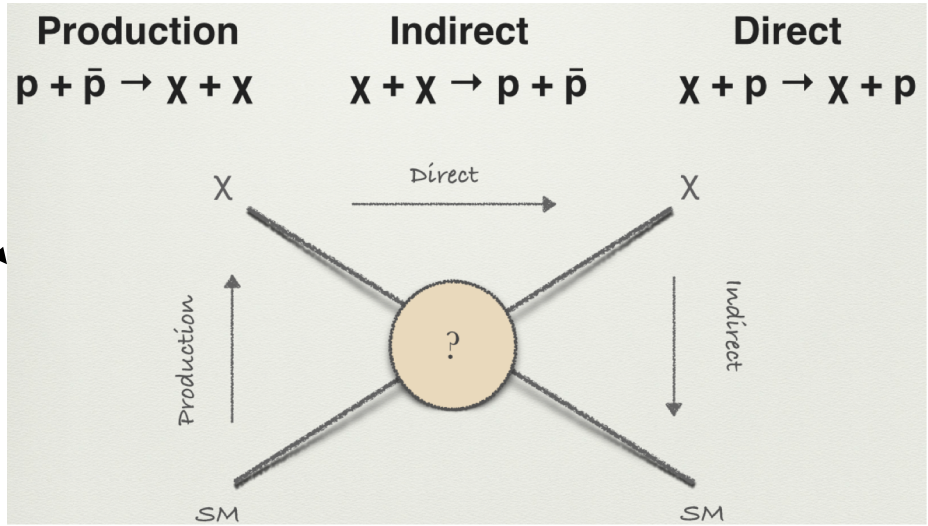


Cosmology in the New Era: Implications for Particle Physics



Determine the identity of the dark matter

Weakly Interacting Massive Particles (WIMPs) led to a well-defined 3-pronged program.



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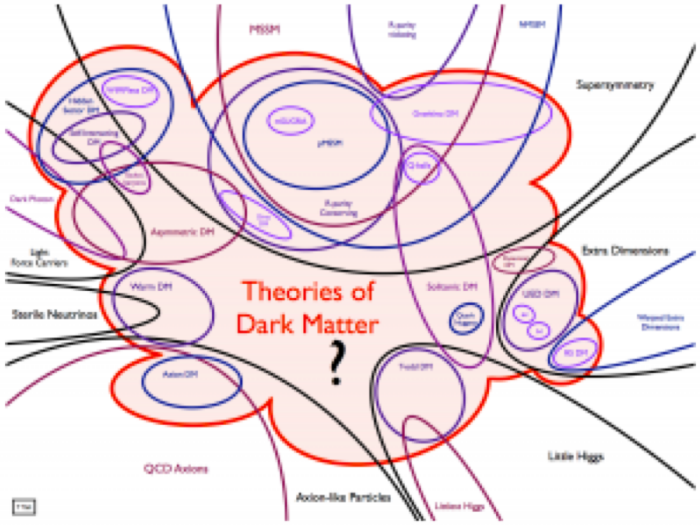
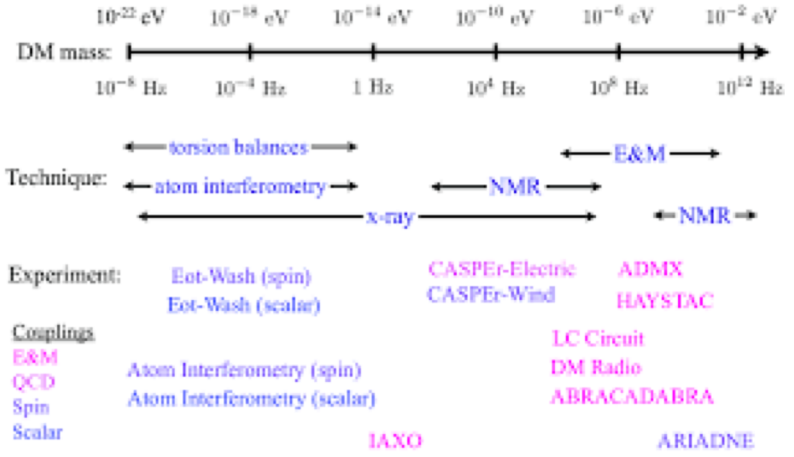


Tim Tait

Determine the identity of the dark matter

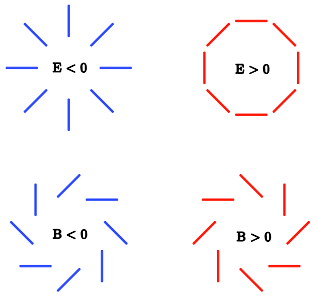


Many new ideas emerging

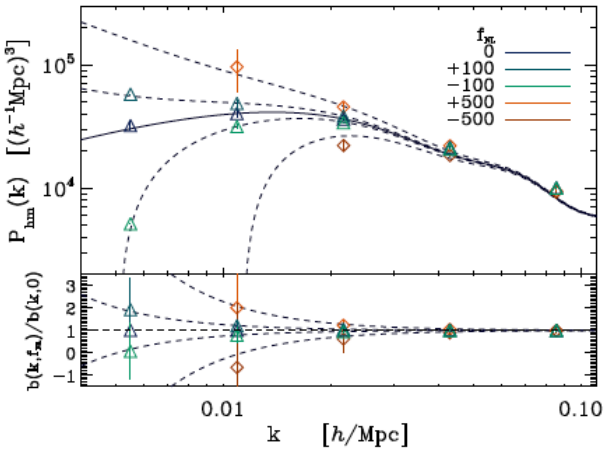
Cosmology in the New Era: Implications for Particle Physics

Determine the origin of the primordial fluctuations (inflation?)

Primordial Gravitational Waves
(Detectors, Delensing, Dust)



Primordial Non-Gaussianity (EFT, 21 cm?)



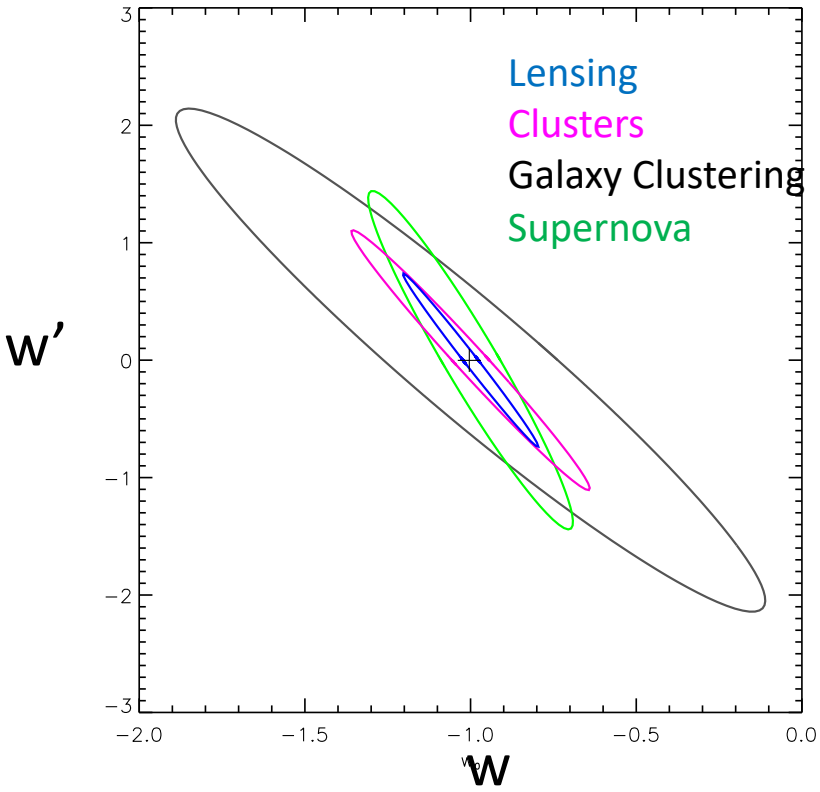
Dalal et al 2007

Running of the Spectrum (?) $\dfrac{\partial \mathrm{n}}{\partial \ln(k)} \propto (n-1)^2$

Cosmology in the New Era: Implications for Particle Physics

Determine the nature of dark energy

$$\rho(a) = \rho_0 \exp\left\{3\int_a^1 \frac{da'}{a'}\left[1 + w(a')\right]\right\}$$

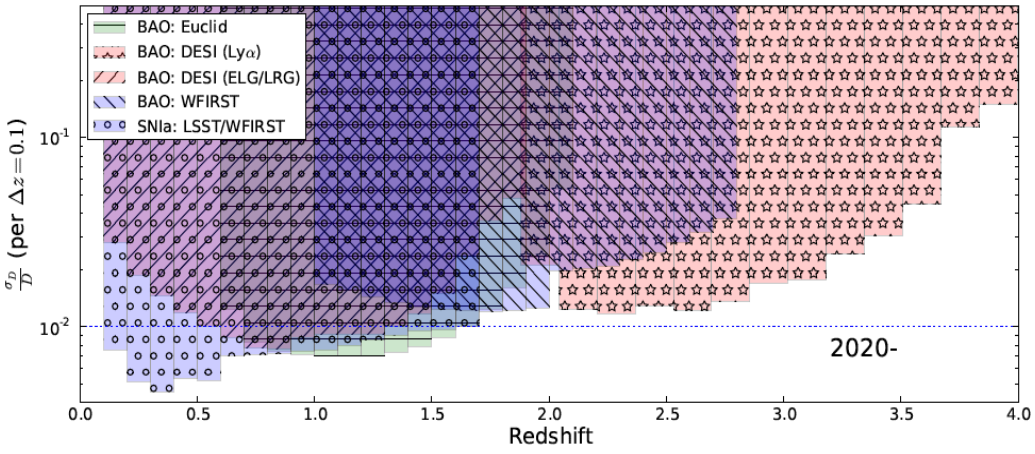


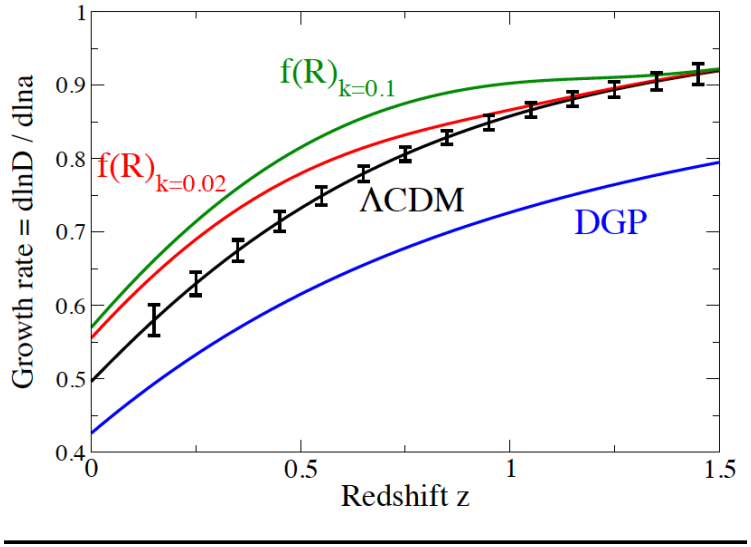
Determine the equation of state of dark energy (w=-1 corresponds to a cosmological constant) →

w=-1 to within ~5%, so …

Cosmology in the New Era: Implications for Particle Physics

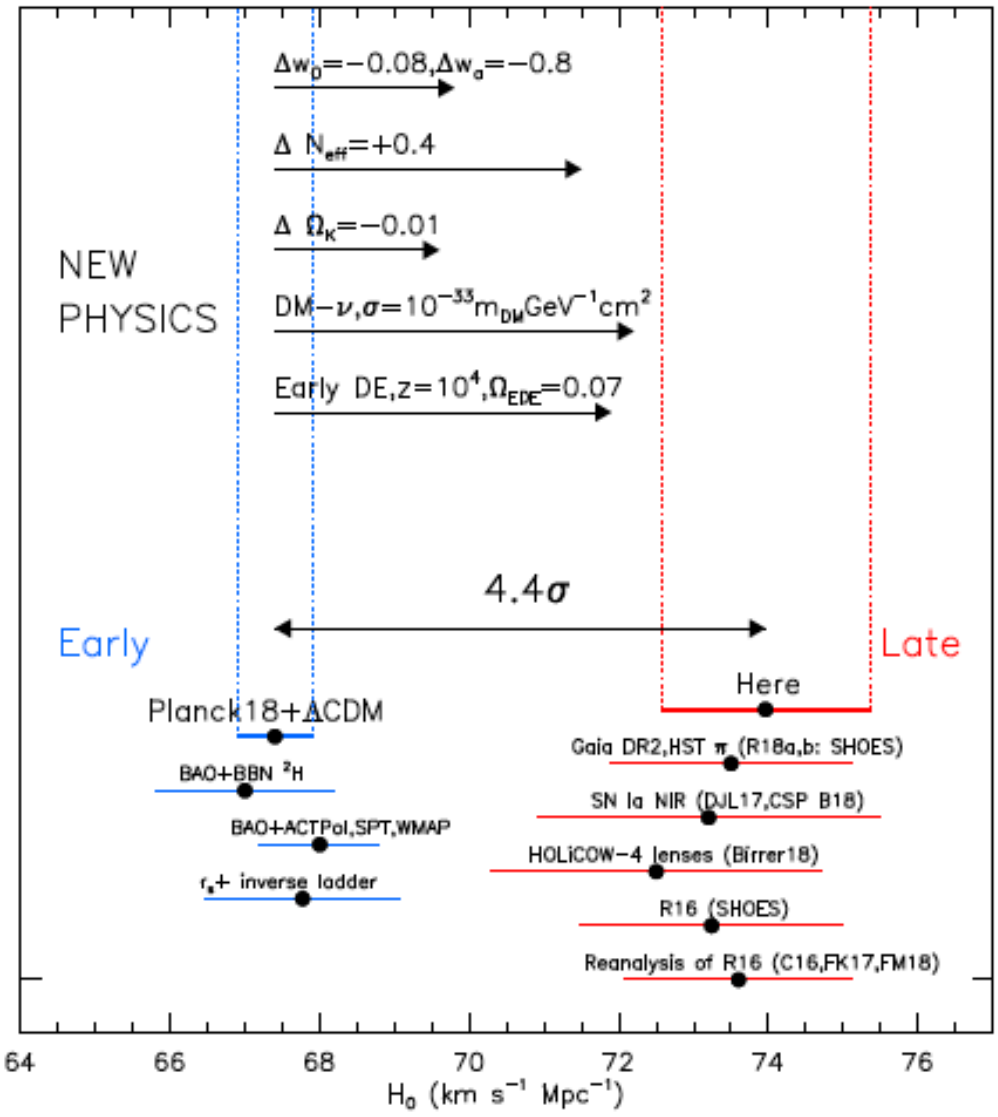
Determine the nature of dark energy → Stress test the Cosmological Constant model





Measure Distances and Growth of Structure

Distance Tests



Riess et al 1903.07603

Growth of Structure Tests

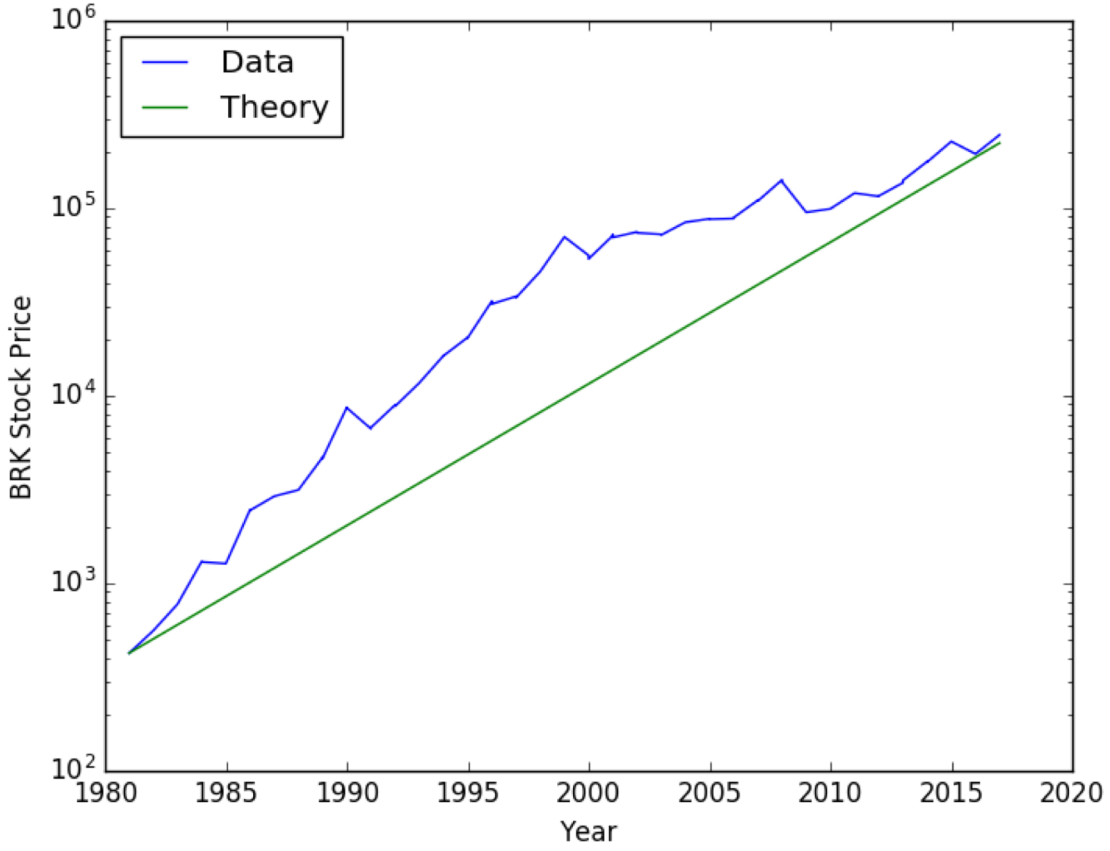
We will focus on two parameters:

- Ω_m The mass density (stars, neutrinos, atoms, dark matter) in units of the ***critical density***
- σ_8 The root mean square of the fluctuations in the mass density smoothed over scales of 8 h^{-1} Mpc ***today***

The parameters are not awe-inspiring (who cares about σ_8***?)*** … but they quantify an amazing testable prediction

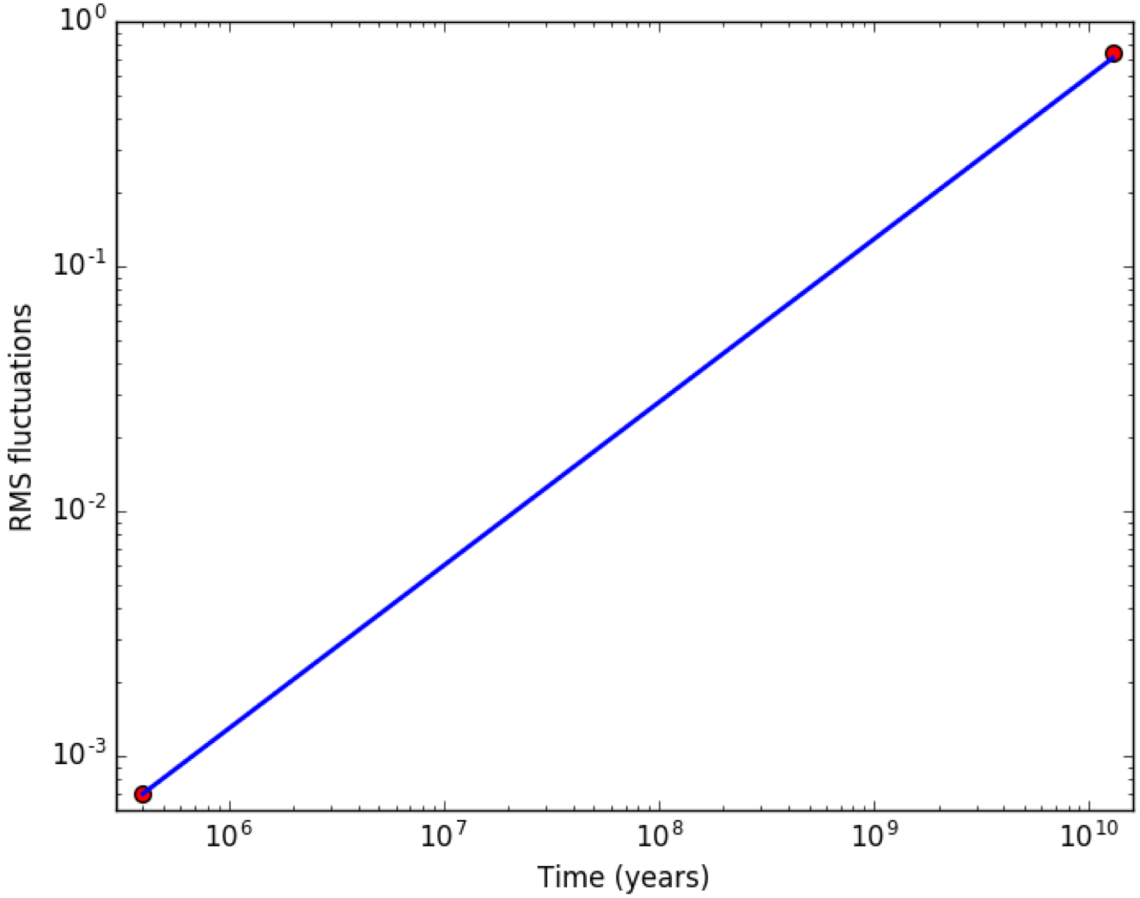
Imagine a similar prediction in the stock market

Your model predicts that the stock price of Berkshire Hathaway will increase by 19% every year. All you need is the 1980 data to predict what the price will be today

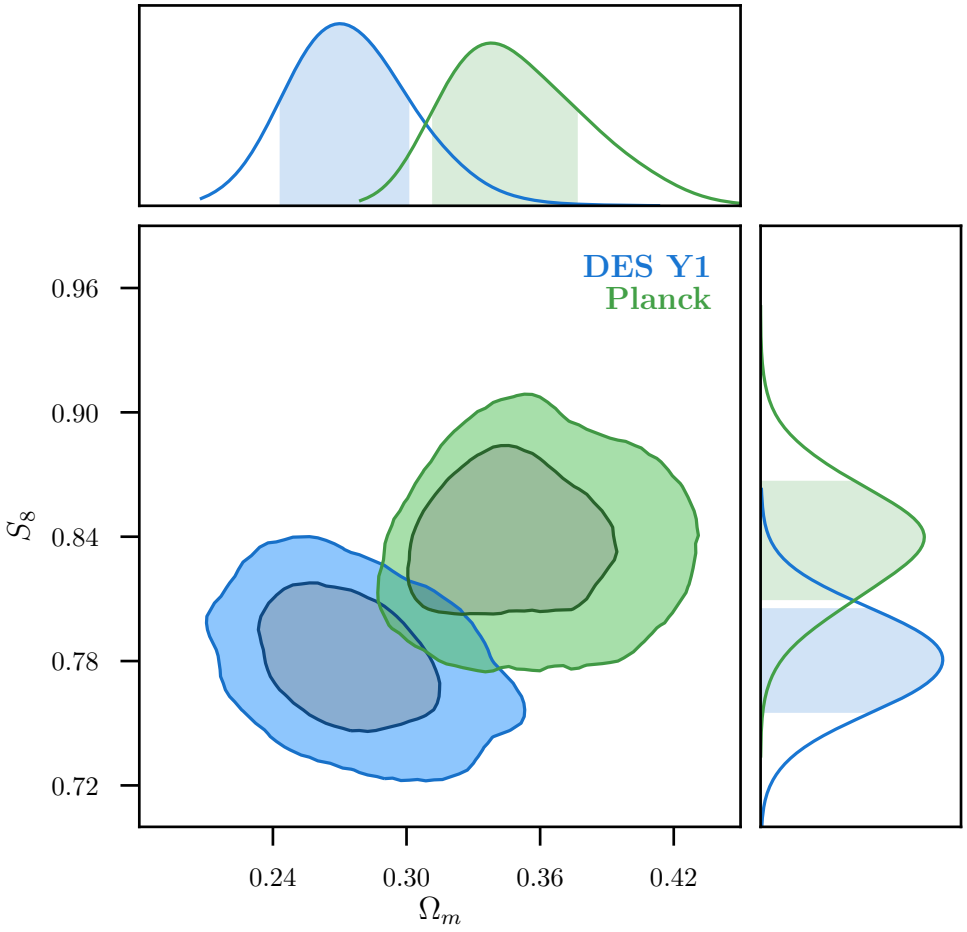


Similarly, the Standard Model, armed with CMB data that provide the initial conditions, makes a zero parameter fit for the RMS fluctuations today

… at the percent level



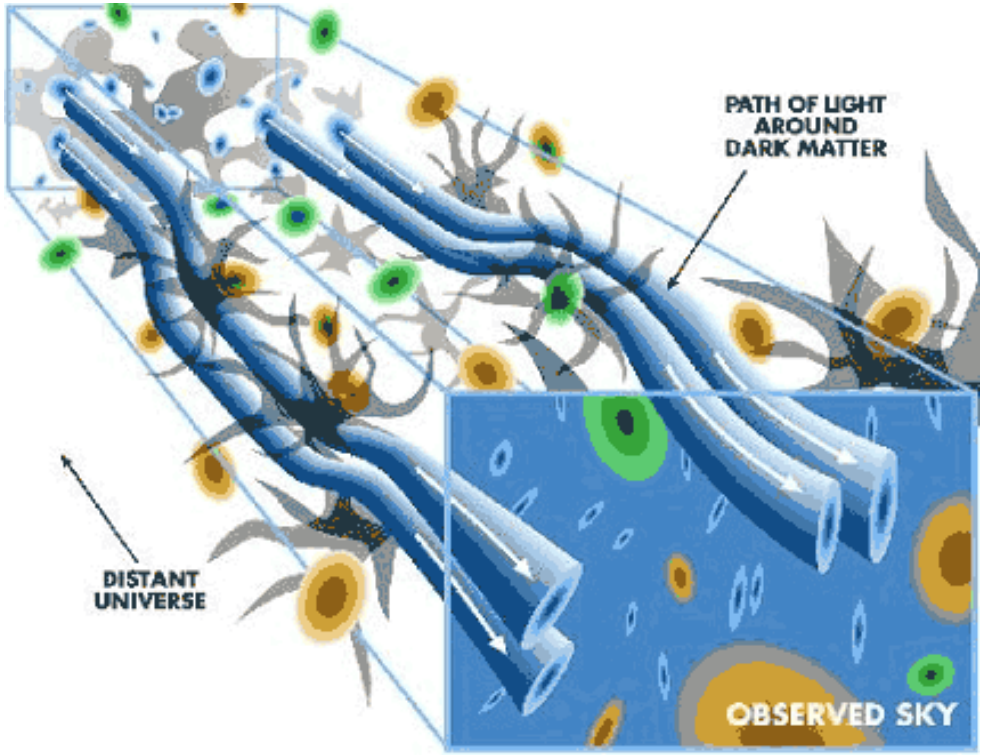
DES Y1 Results: Power a bit lower then the Standard Model predicts

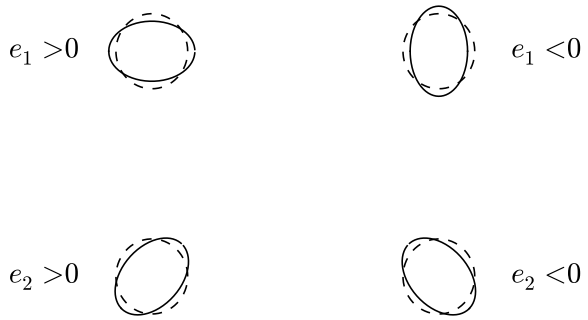


How to measure mass when we see only light?

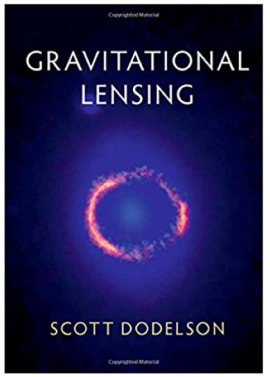
- ***Use Galaxies as tracers***
  Galaxies form in over-dense regions, so an excess of galaxies <-> an excess of mass. But the precise relation between overdensities is governed by a ***bias*** parameter
- ***Measure the shapes of background galaxies***
  Shapes are distorted as the light they emit traverses through the inhomogeneous universe. Infer information about the mass along the line of sight. The distortions are small, much smaller than random variations

Weak Gravitational Lensing: Galaxy Shapes are Distorted by intervening Mass





Measure galaxy shapes → Infer mass integrated along line of sight



</shameless plug>

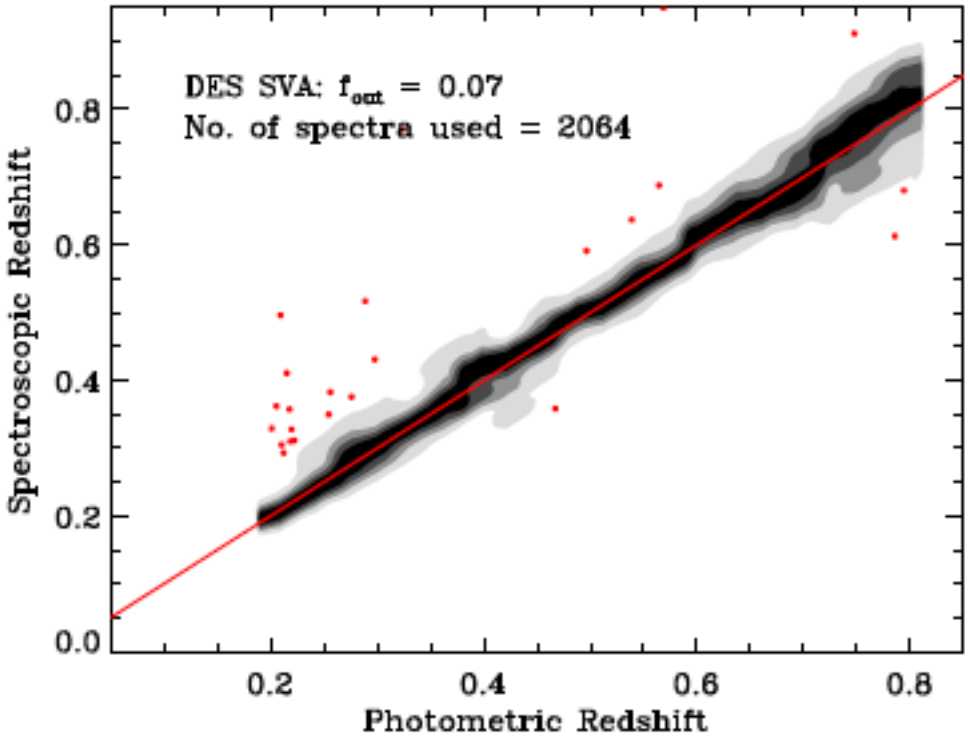
Two fields:
Galaxy over-density $\delta_g(\theta)$
Galaxy ellipticity $e_i(\theta)$

Three 2-point functions:

- Angular correlation function $w(\theta)=<\delta_g\delta_g>$
  measures the clustering of "lens" galaxies
- Galaxy-galaxy lensing $\gamma_t(\theta)=<\delta_g e_i>$
  measures the distortions in "source" galaxies by mass associated with "lens" galaxies
- Shear correlation function $\xi(\theta)=<e_i e_j>$
  measures the correlations between shapes of nearby "source" galaxies due to similar distortions by line-of-sight mass

DES is a Photometric Survey: 2D not 3D

Well-measured redshifts



Rozo et al. 2015

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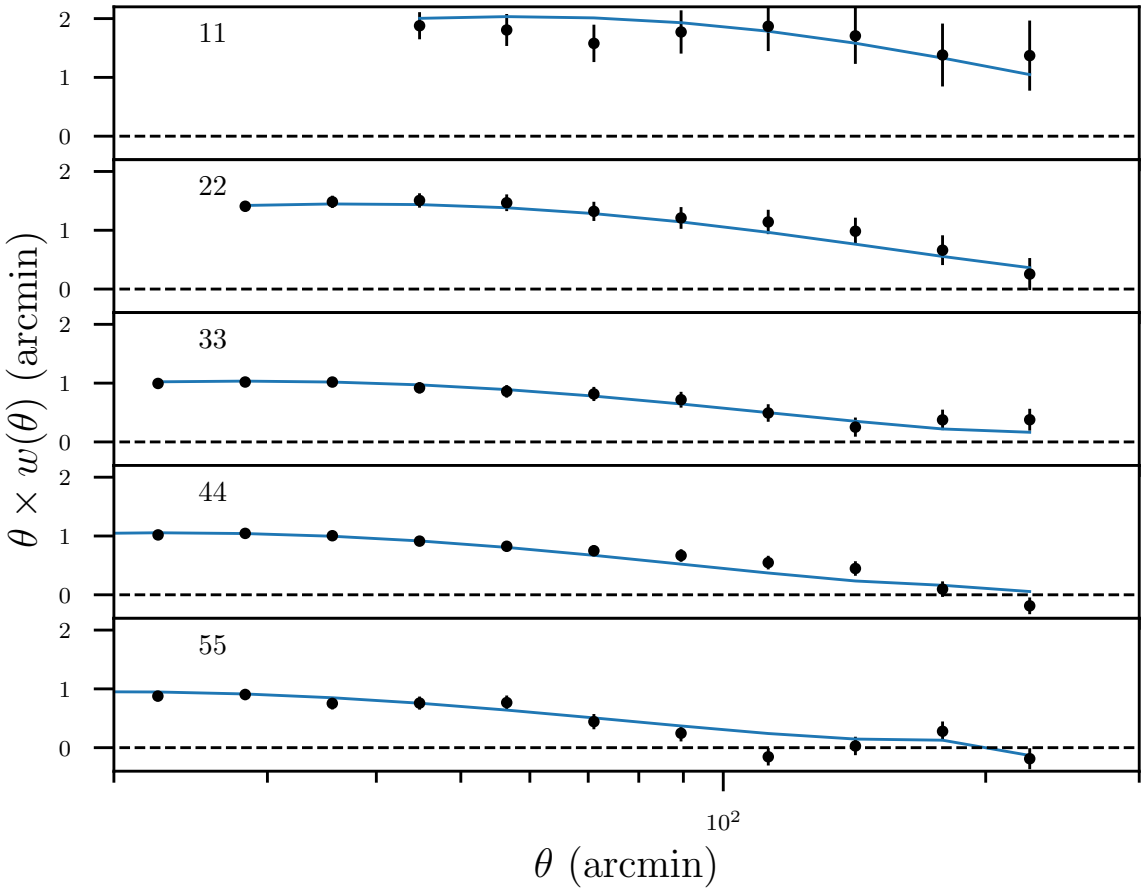
Measure Galaxy Clustering in each of five redshift bins

Blue curve is Standard Model that best fits all the data



DES: Elvin-Poole et al. 2017

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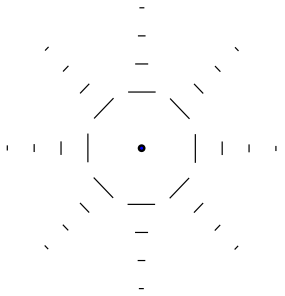
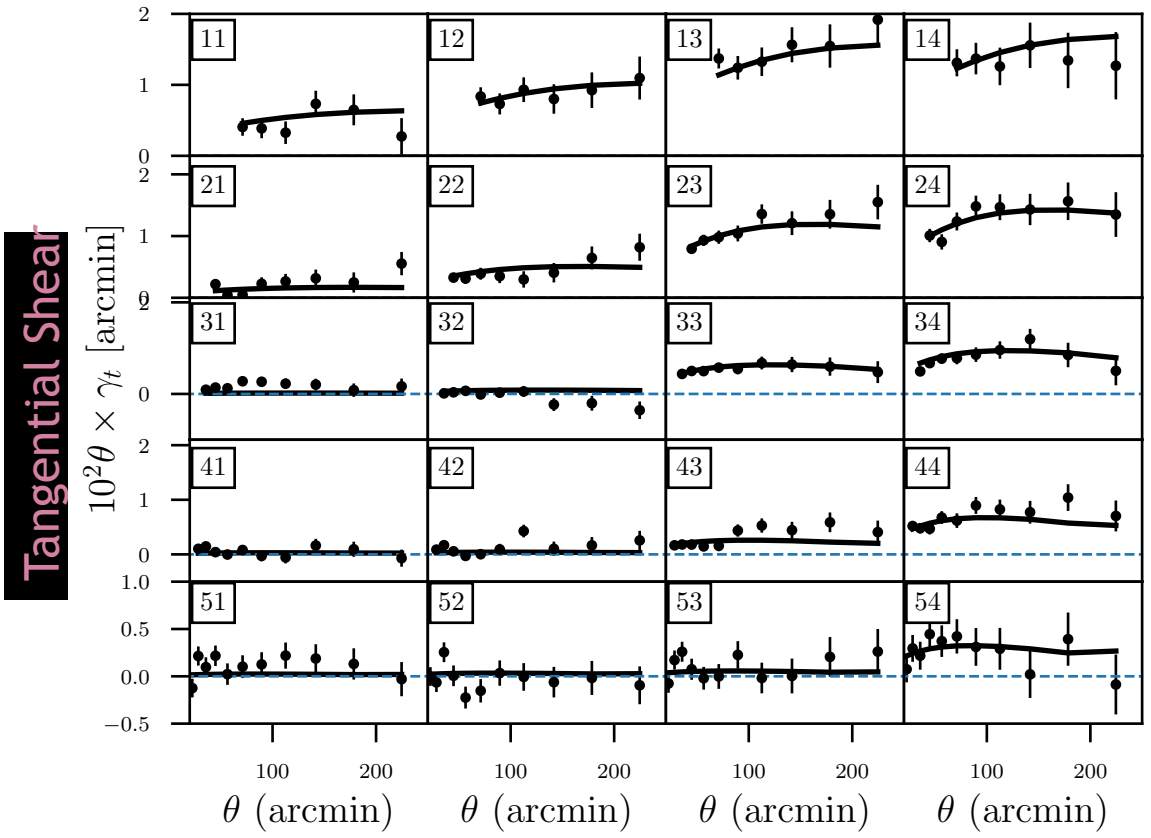
Measure Galaxy-Galaxy Lensing in 4 source bins x 5 lens bins



- Distortions of shapes of background galaxies due to mass associated with foreground galaxies
- Sheds light on *bias*
- Sensitive to shape measurements



DES: Judit Prat, Carles Sanchez et al. 2017

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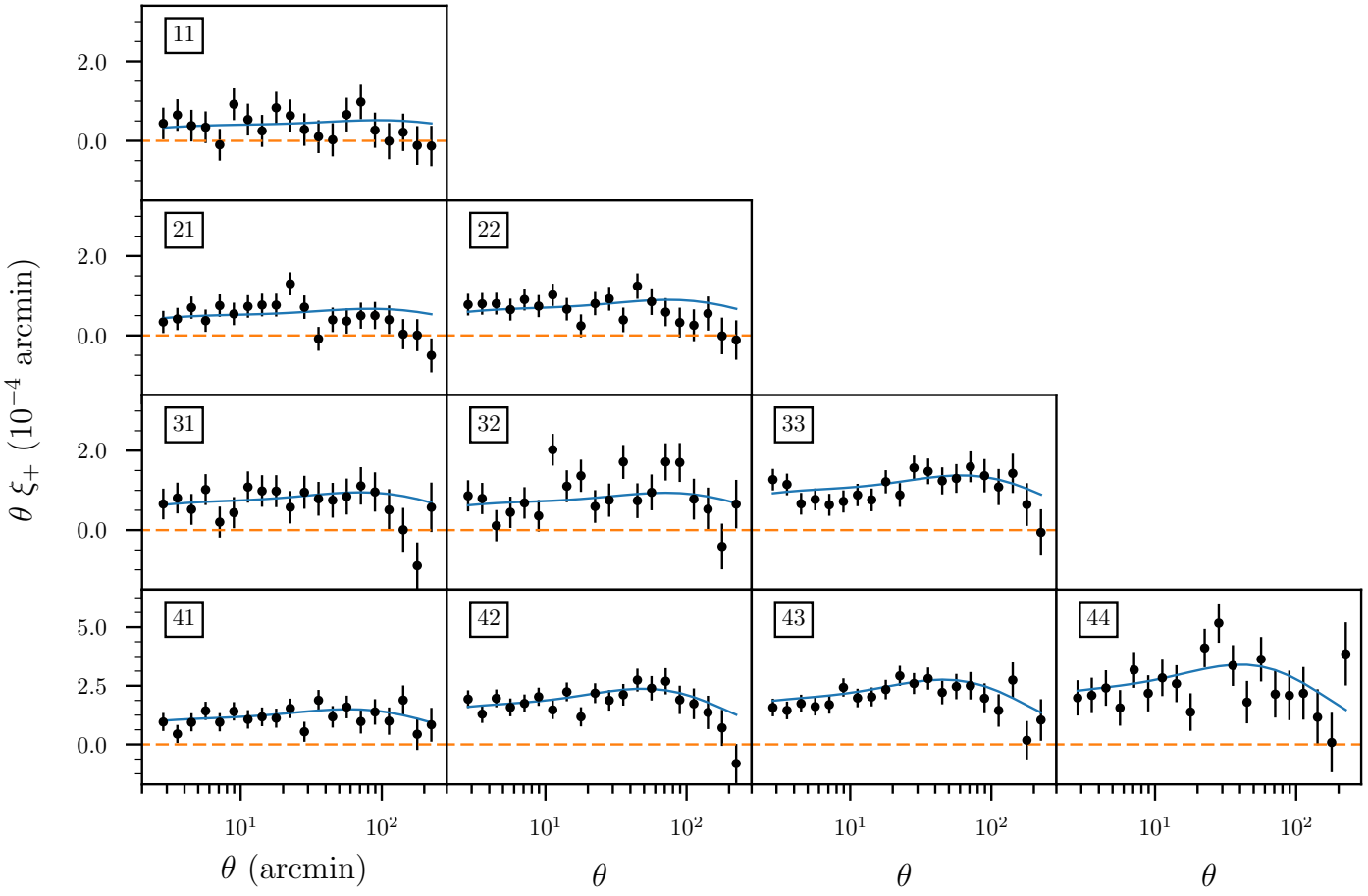
  measures the correlations between shapes of nearby "source" galaxies due to similar distortions by line-of-sight mass

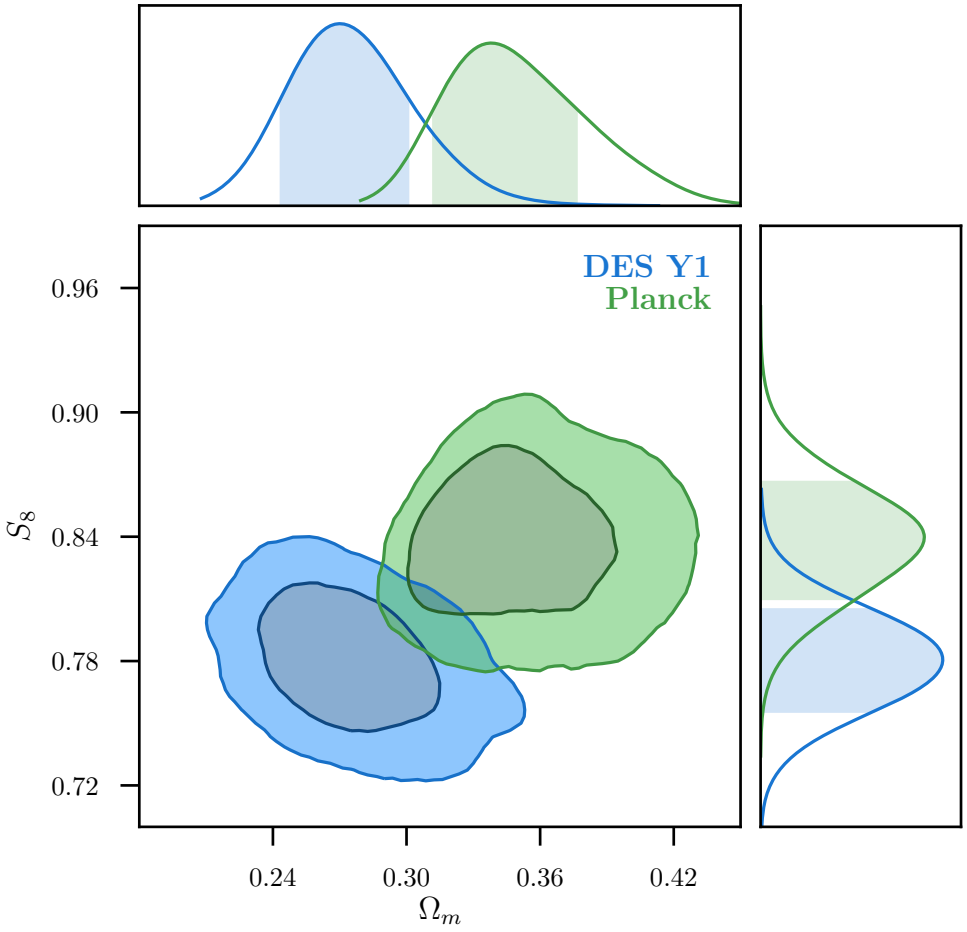
Gravitational Lensing: Shape correlations

- Correlations of shapes of background galaxies due to all mass along the line of sight
- Sensitive to shape measurements
- Independent of bias

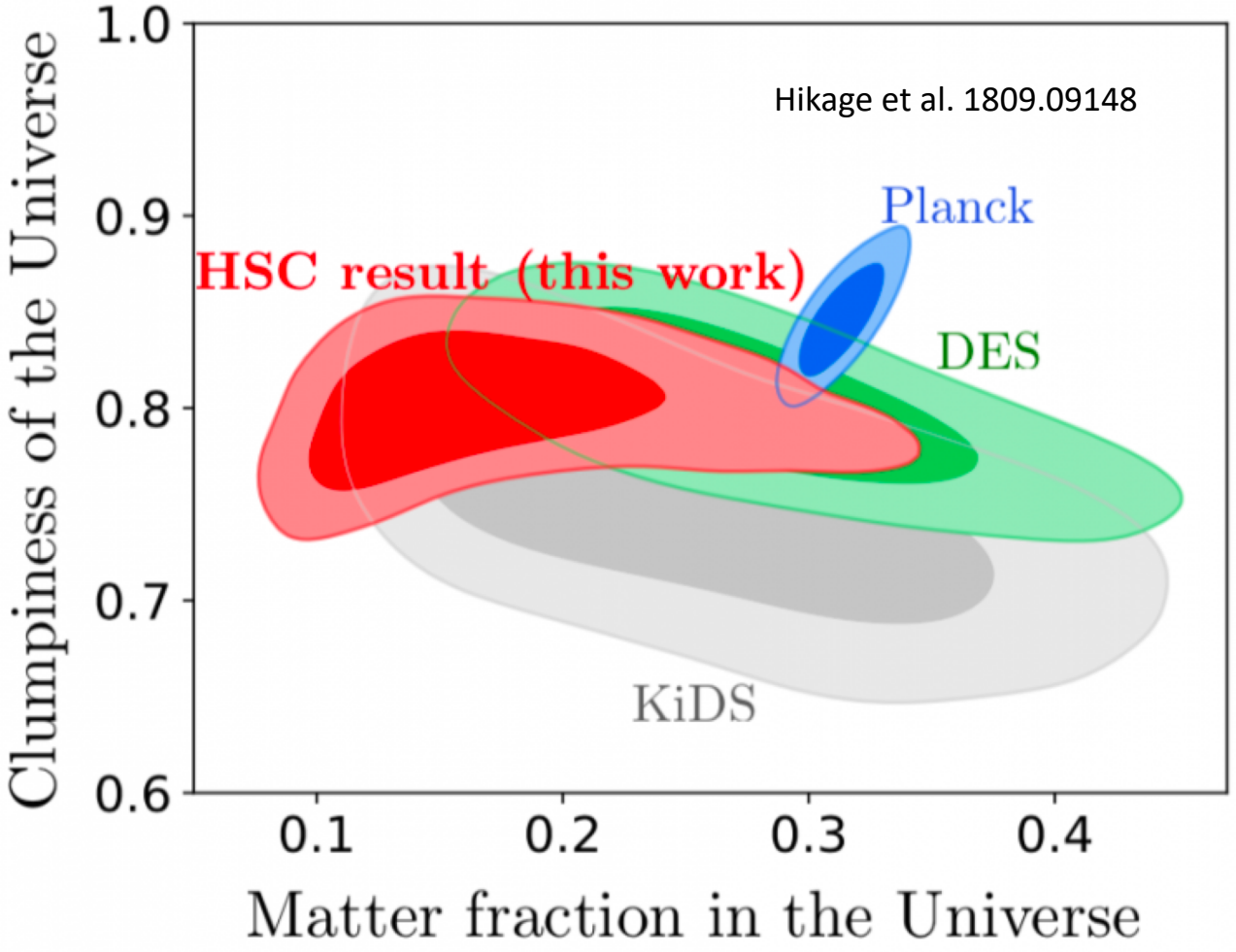


DES: Troxel et al. 2017

DES Y1 Results: Power a bit lower then the Standard Model predicts

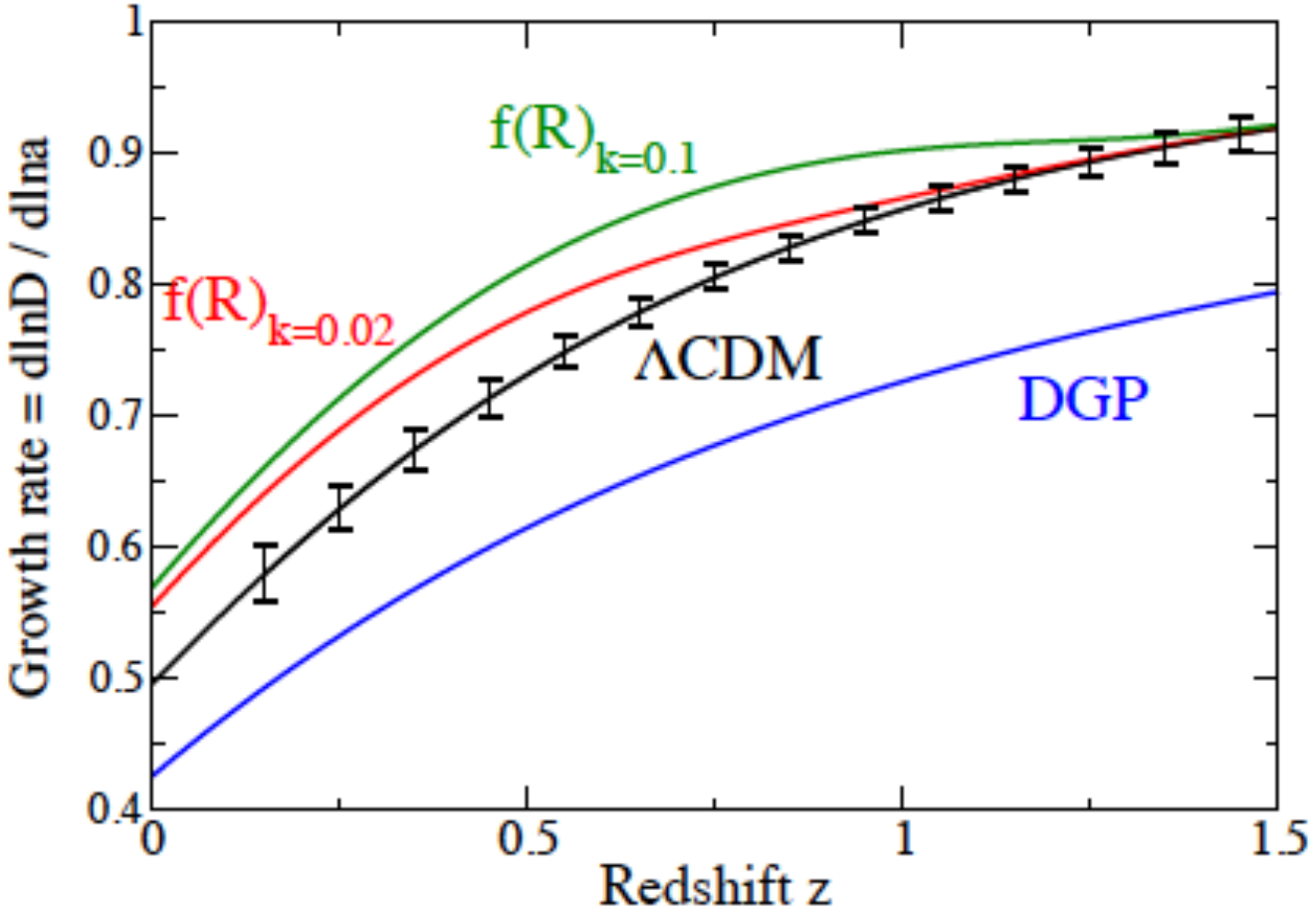


Lensing is Low



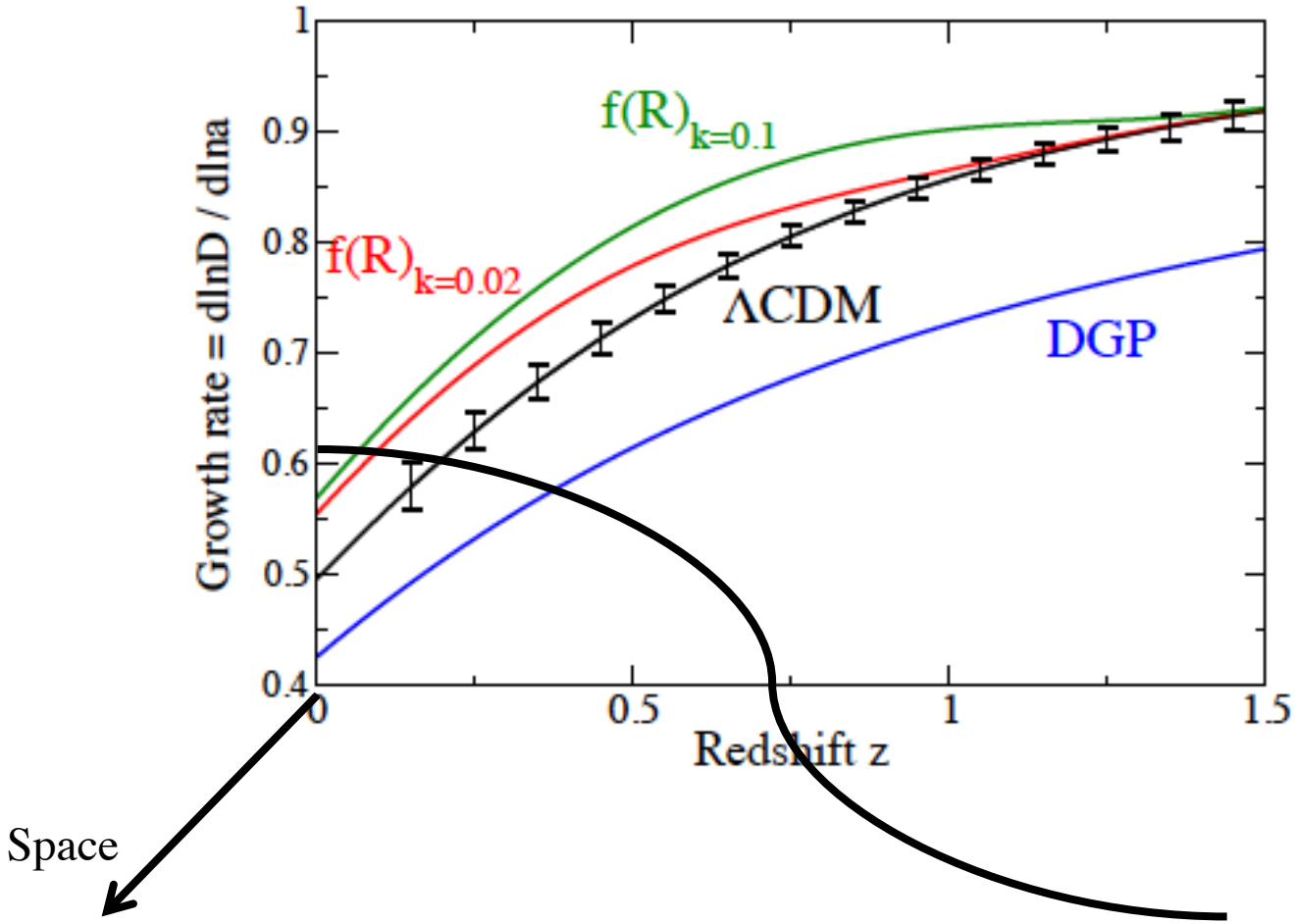
This is only the beginning …

- We have 5 times the data in the can; currently furiously analyzing
- Then comes LSST, Euclid, WFIRST, DESI
- Can measure at many redshifts, not just one



This is only the beginning …

- We have 5 times the data in the can; currently furiously analyzing
- Then comes LSST, Euclid, WFIRST, DESI
- Can measure at many redshifts, not just one
- **Can measure at many scales not just 8 Mpc**



Conclusions

Cosmology **is** in a new era:

- Broaden dark matter searches
- Search for signatures of inflation (B-modes; PNG; running)
- Precision tests of LCDM; there is current tension in both distances and growth. If LCDM fails, the most likely resolution is a new light degree of freedom (quintessence or modified gravity)