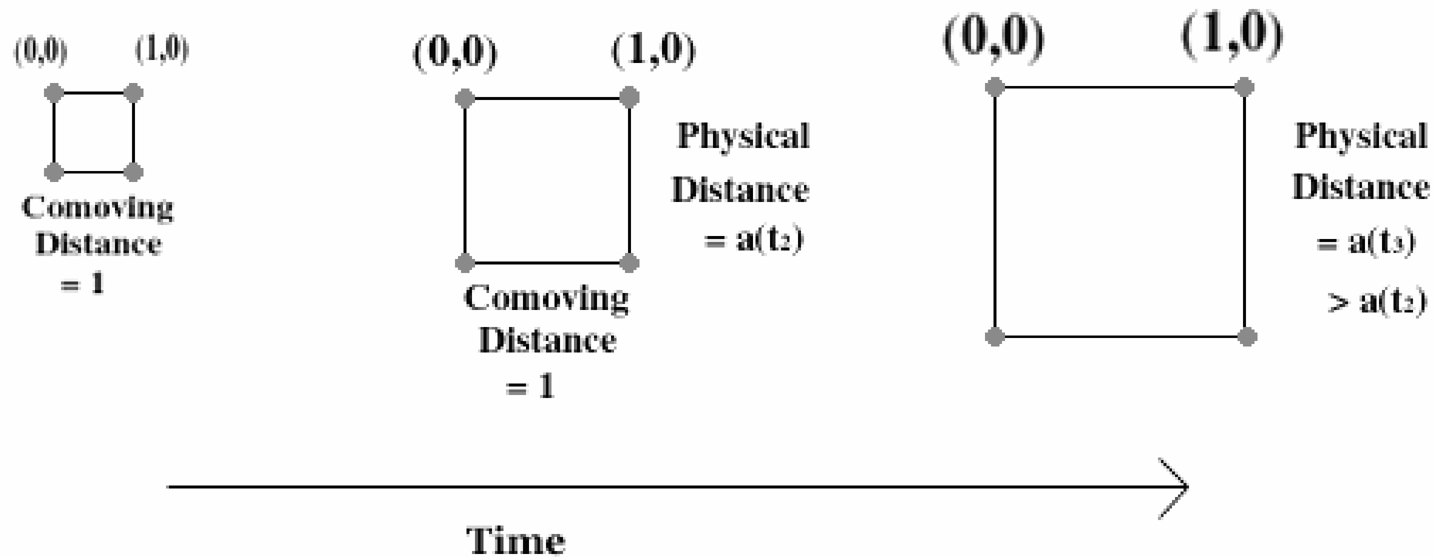
Astro/Cosmo Window on the Standard Model

Standard Model of Particle Physics: Predictions for Cosmology
Standard Model of Cosmology: Implications for Particle Physics
Precision Tests of the Standard Model

Scott Dodelson
Carnegie Mellon University
August 2, 2018

Scale Factor *a* quantifies expansion



The scale factor *a(t)* is the key function in the Friedmann-Robertson-Walker metric

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2 \right)$$

Apply Einstein's Equations to this metric to determine the expansion history

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho}$$

and find that the energy density of a substance scales as

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

with $w = P/\rho$

Scaling with Expansion

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

with $w = P/\rho$

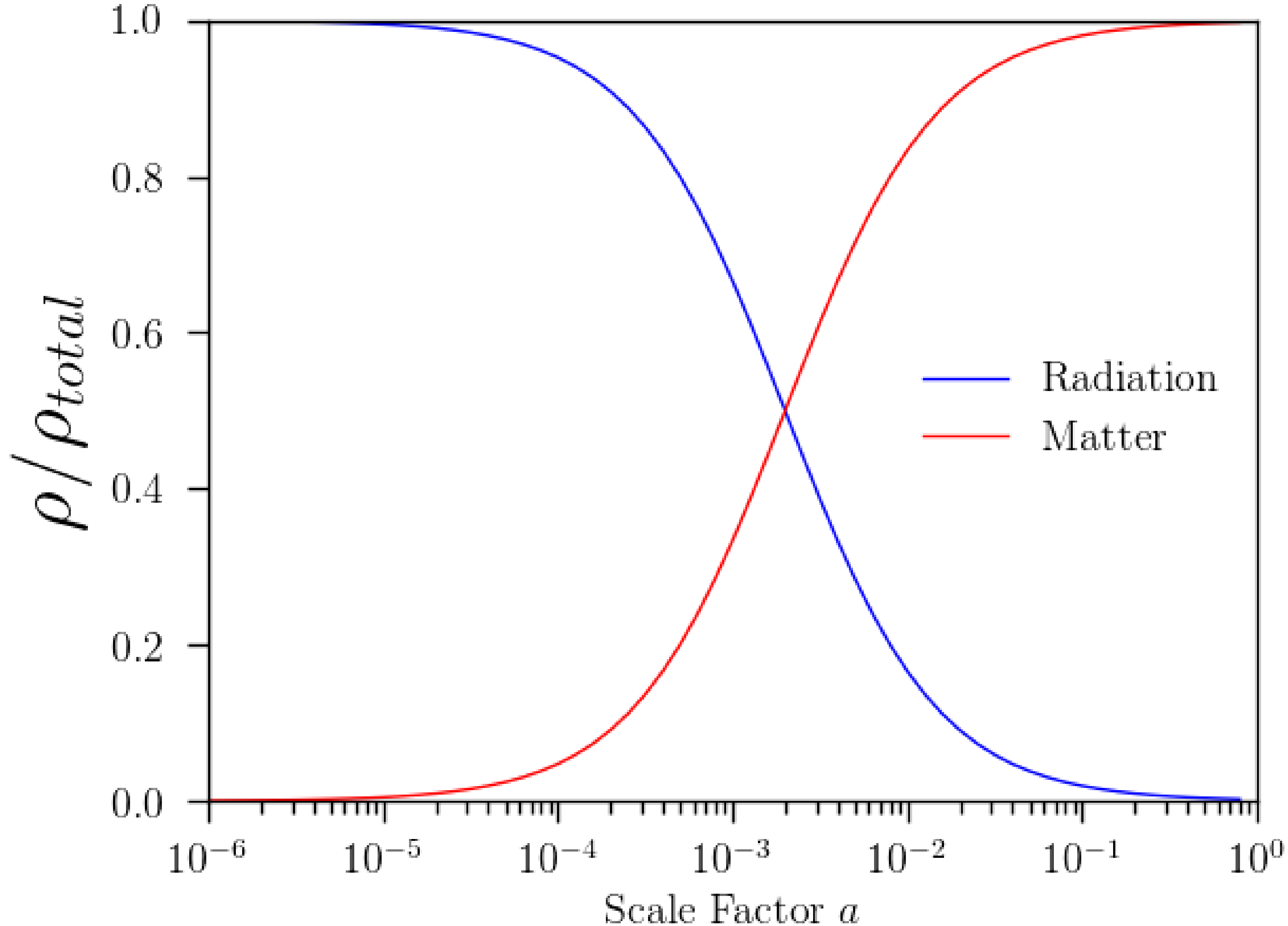
- Protons: $w=T/m<<1 \rightarrow \rho \propto a^{-3}$
- Photons: $w=1/3 \rightarrow \rho \propto a^{-4}$

Note: this also means that T $\propto a^{-1}$. The universe used to be much hotter and denser

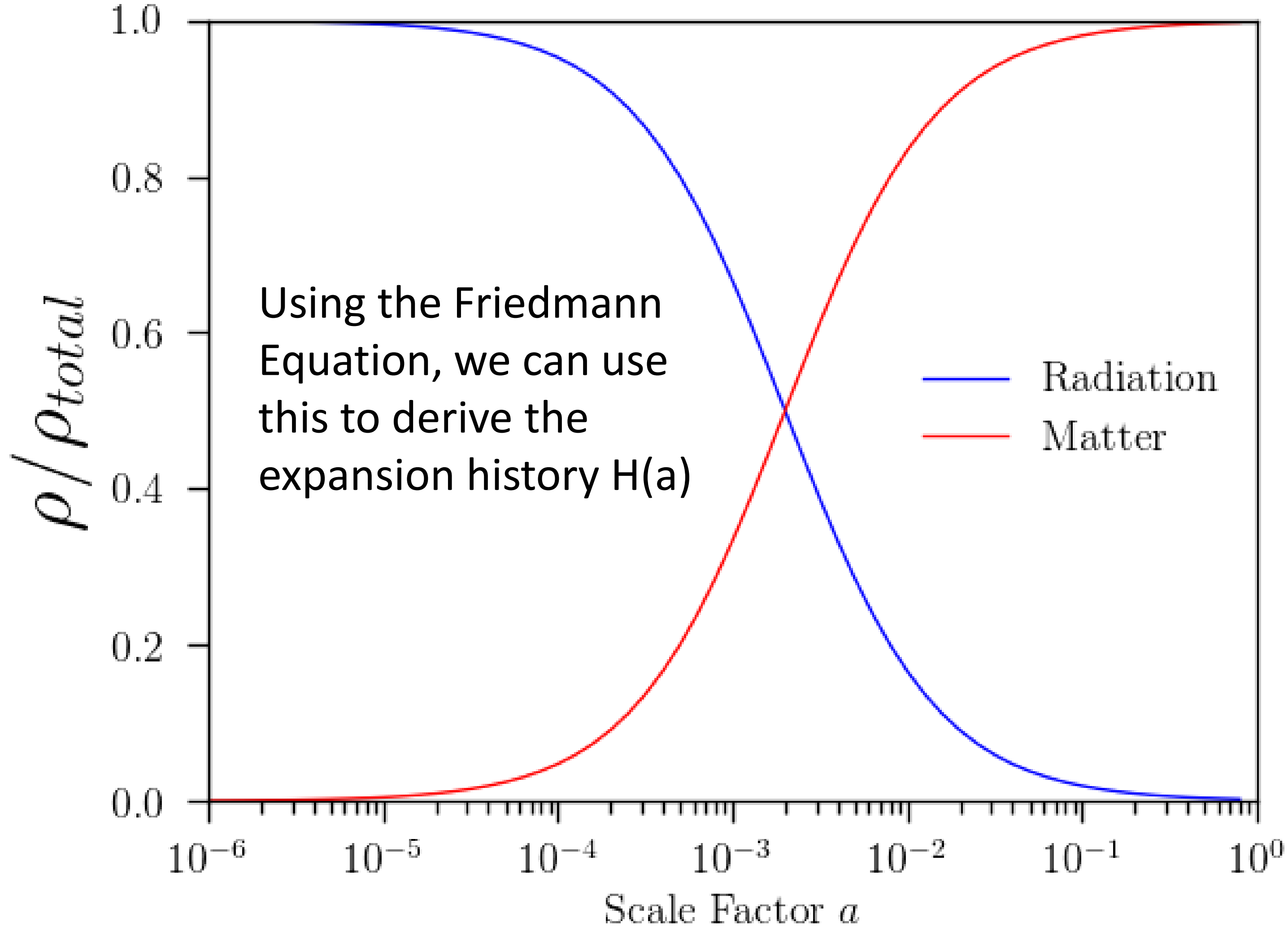
What else?

- Massive unstable particles (neutrons, Higgs, pions, muons, etc.) decay at early times
- Trace amounts of D and He are produced when the universe was much hotter and denser
- Neutrinos were produced and remain today
- The universe is neutral so the number of electrons is equal to the number of protons
- No anti-matter (small excess so all anti-matter annihilated away at early times)

Very Simple Thermal History

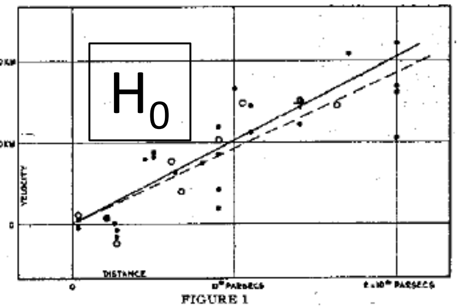


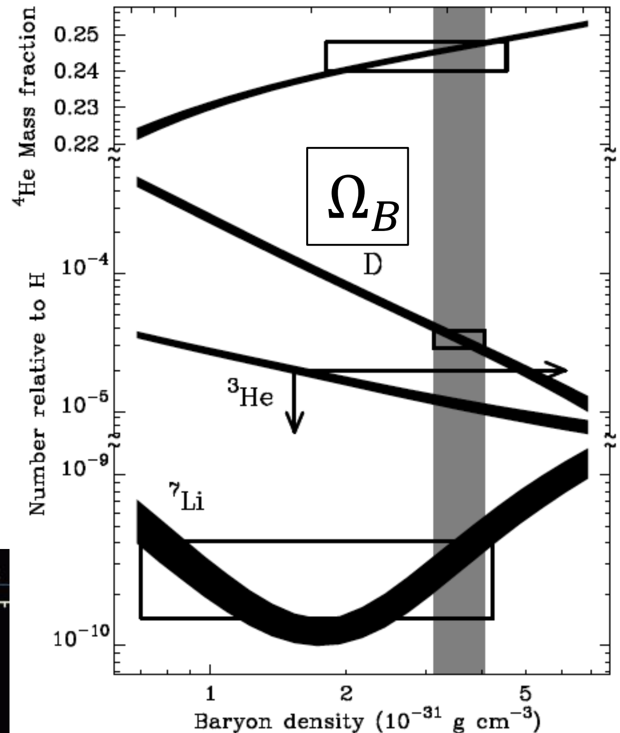
Very Simple Thermal History



Using the Friedmann Equation, we can use this to derive the expansion history H(a)

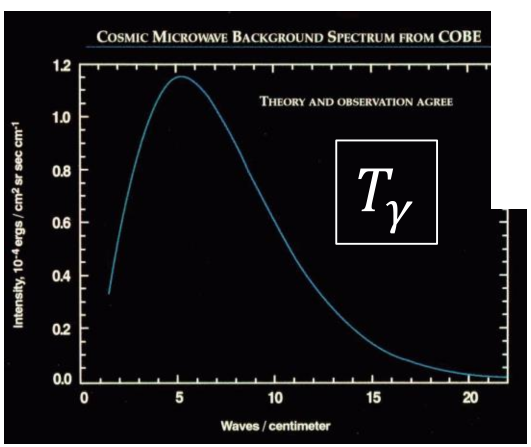
Standard Model of Particle Physics: Predictions for Cosmology

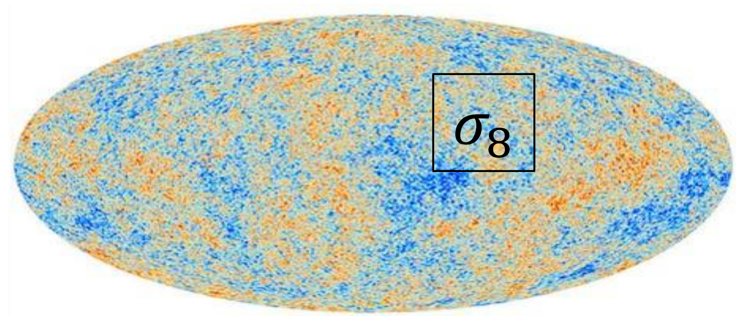




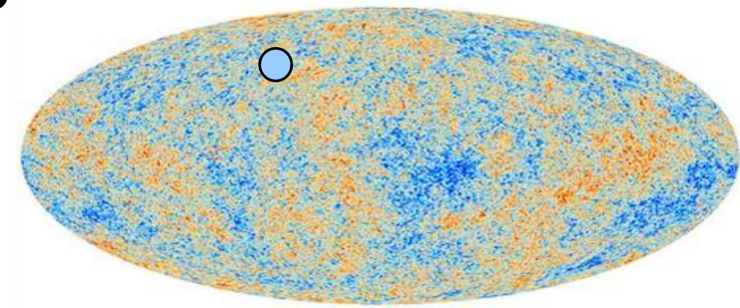
Free Parameters:

- Expansion Rate Today H_0
- Photon Temperature
- Baryon Density (in some units) Ω_B
- Fluctuation Amplitude





What is σ_8?



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

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

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

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

Armed with these measurements, 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

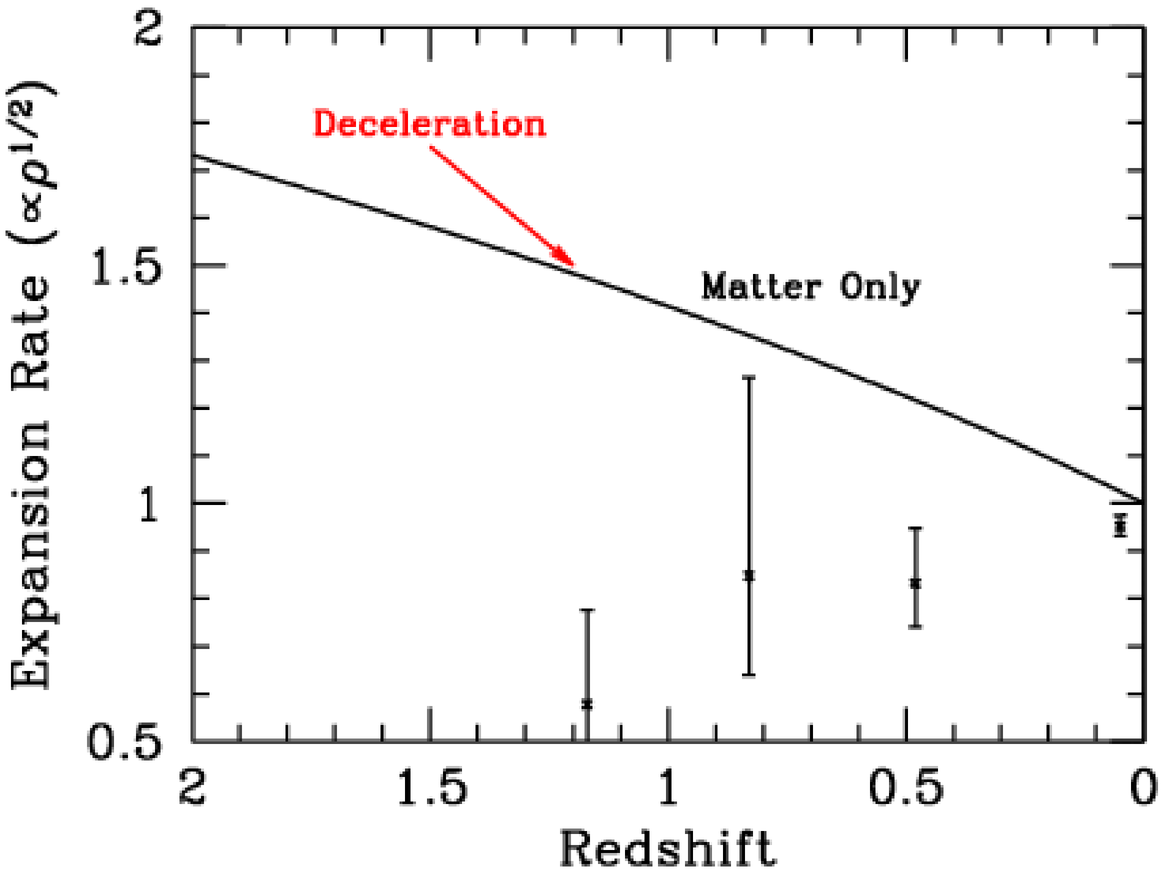
$$a_{EQ} = \frac{\Omega_R}{\Omega_B}$$

- Growth of Structure

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

Standard Model of Particle Physics: Predictions for Cosmology

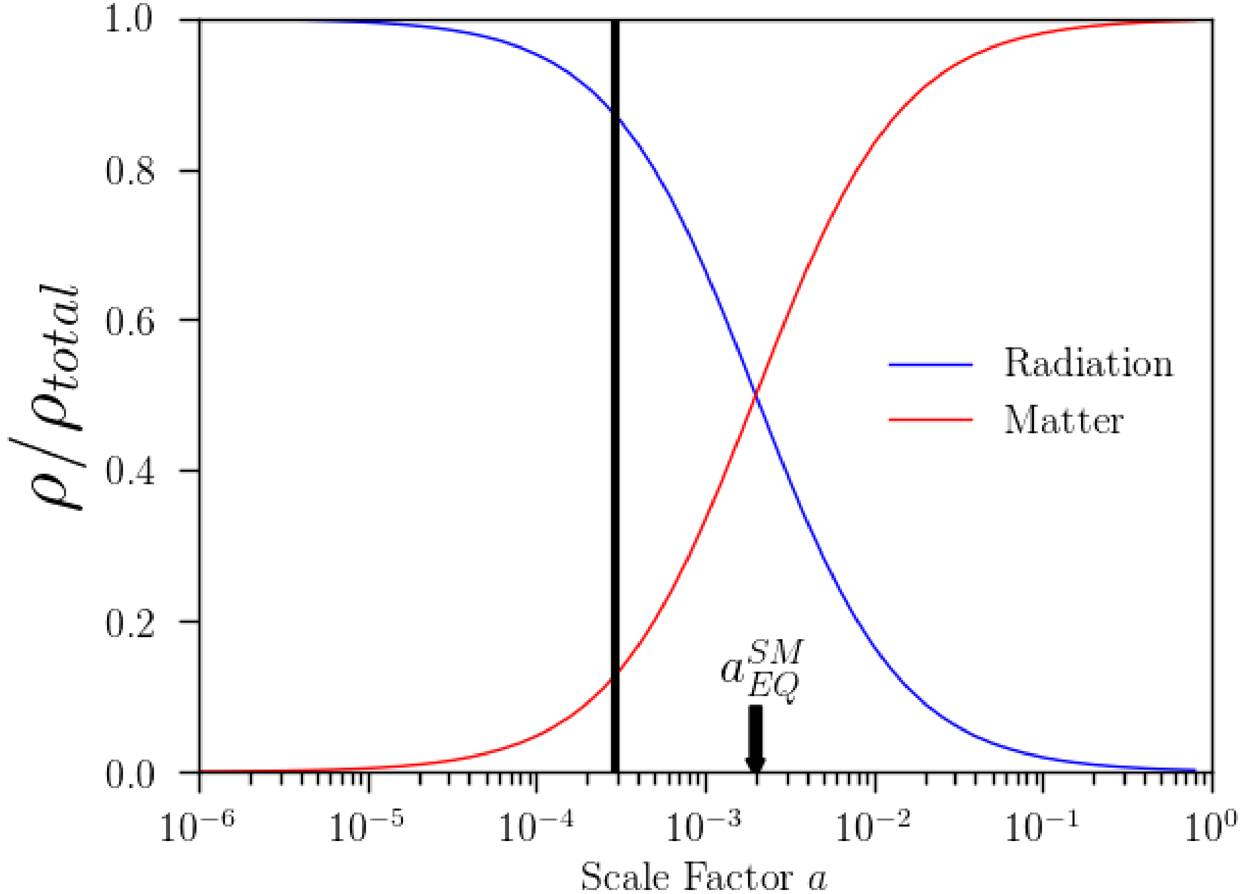
These predictions are wrong



Redshift:
1+z=1/a

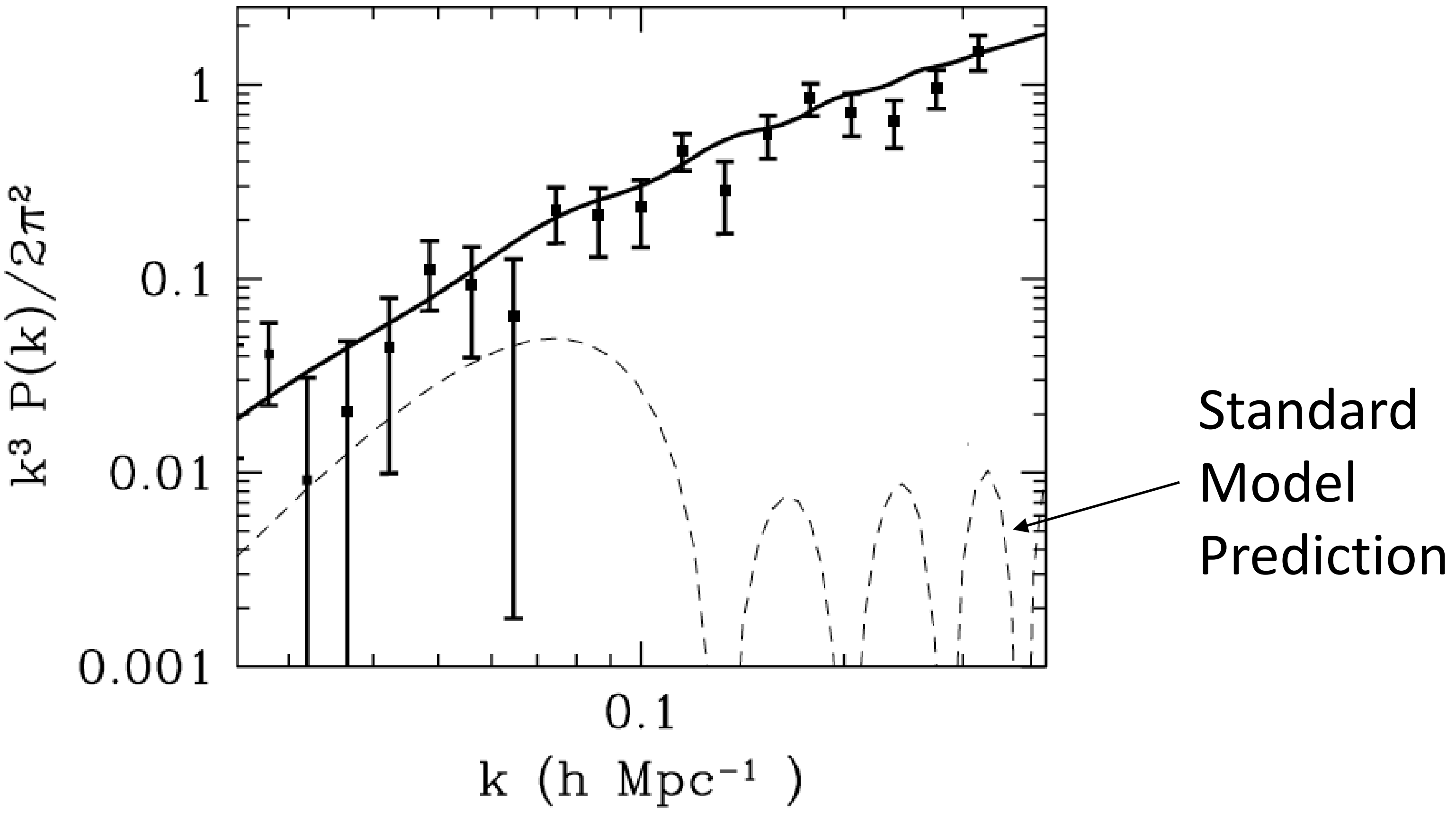
Standard Model of Particle Physics: Predictions for Cosmology

These predictions are wrong

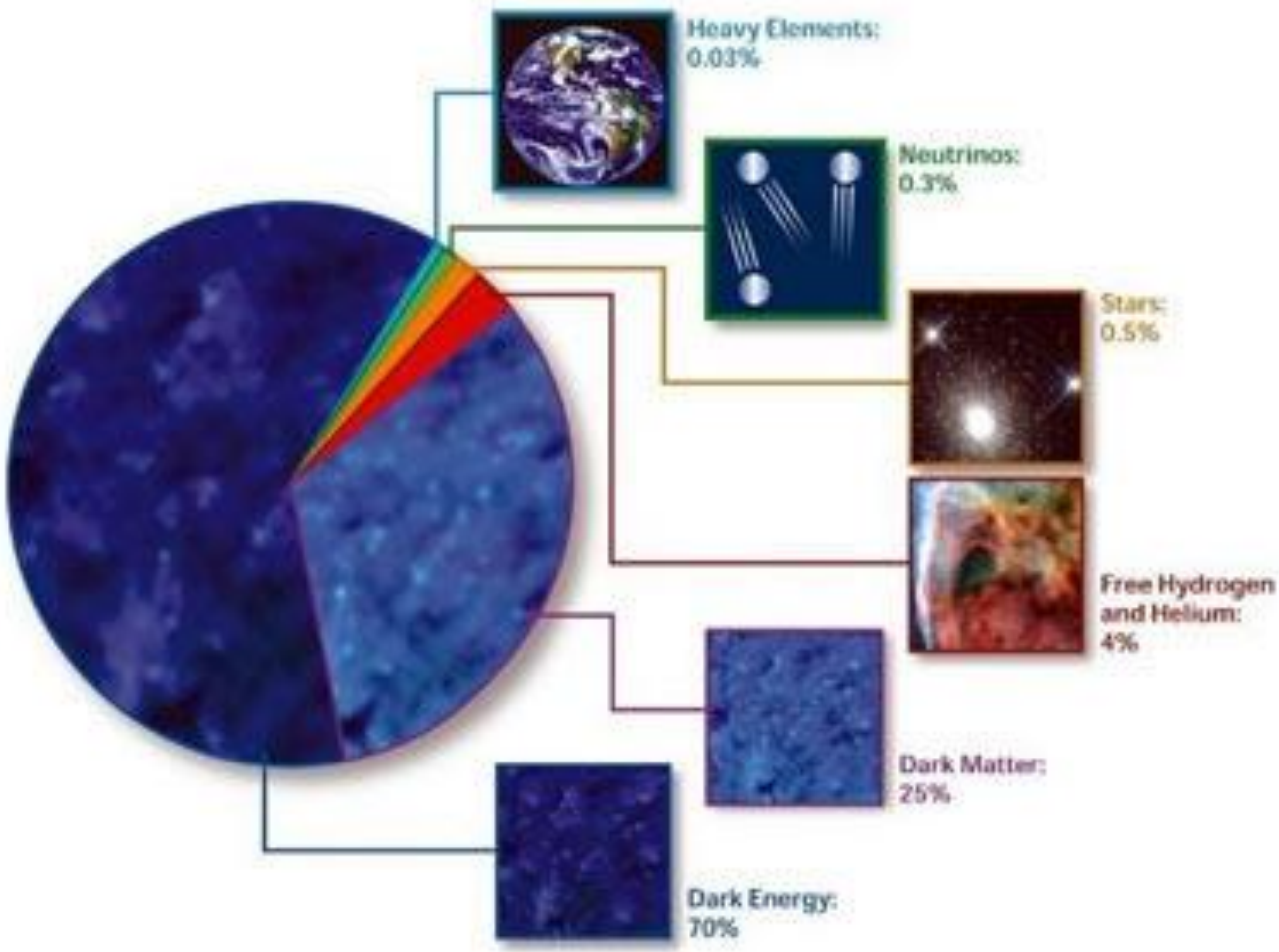


Standard Model of Particle Physics: Predictions for Cosmology

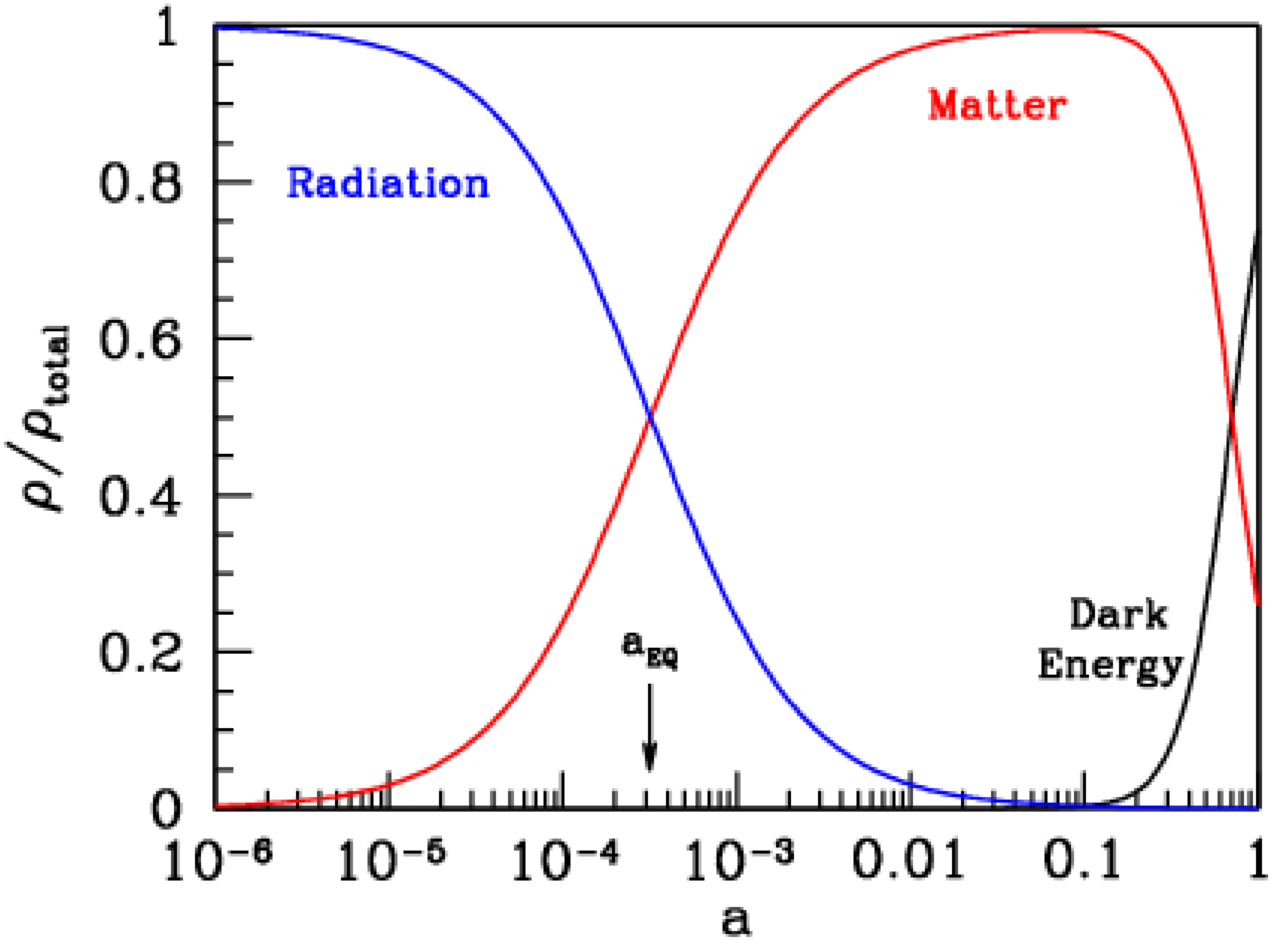
These predictions are wrong



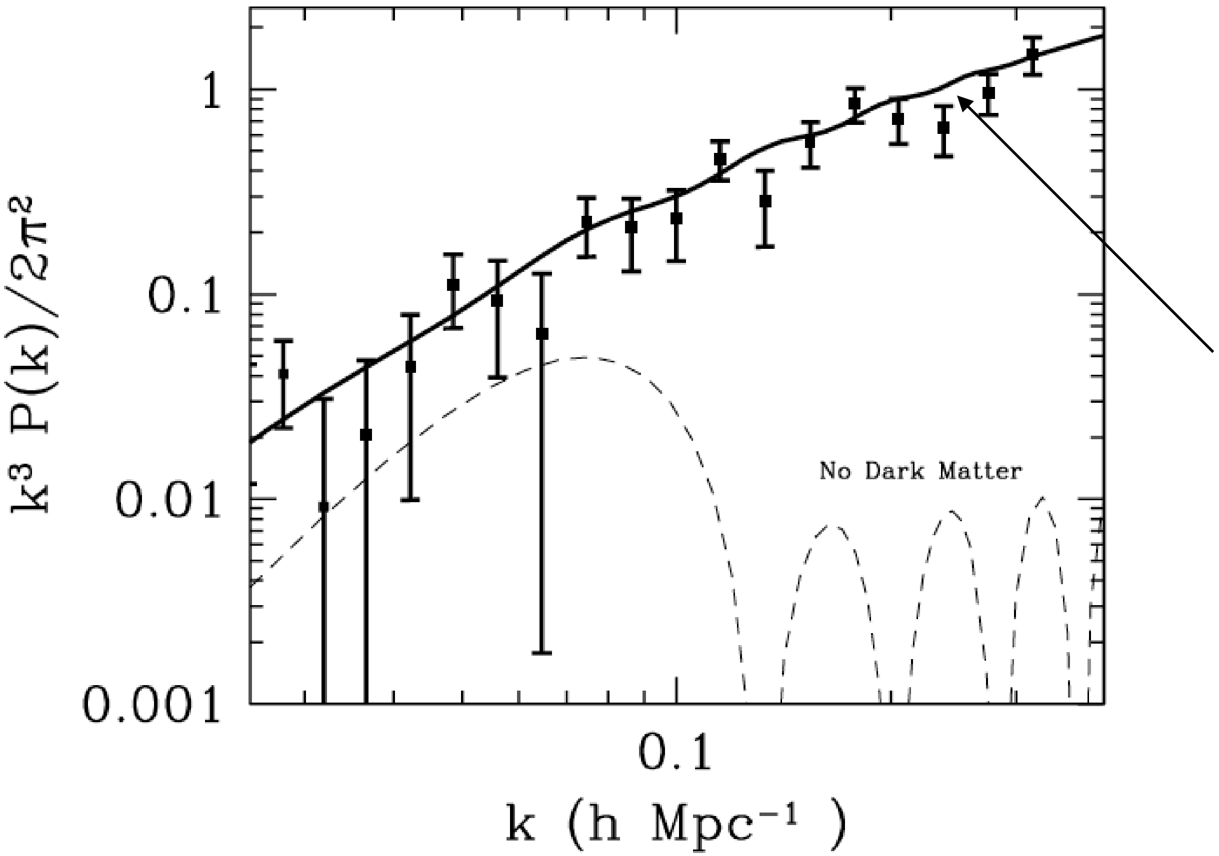
These predictions all fail … leading to a new Standard Model of Cosmology



SM of Cosmology gets the epoch of equality right

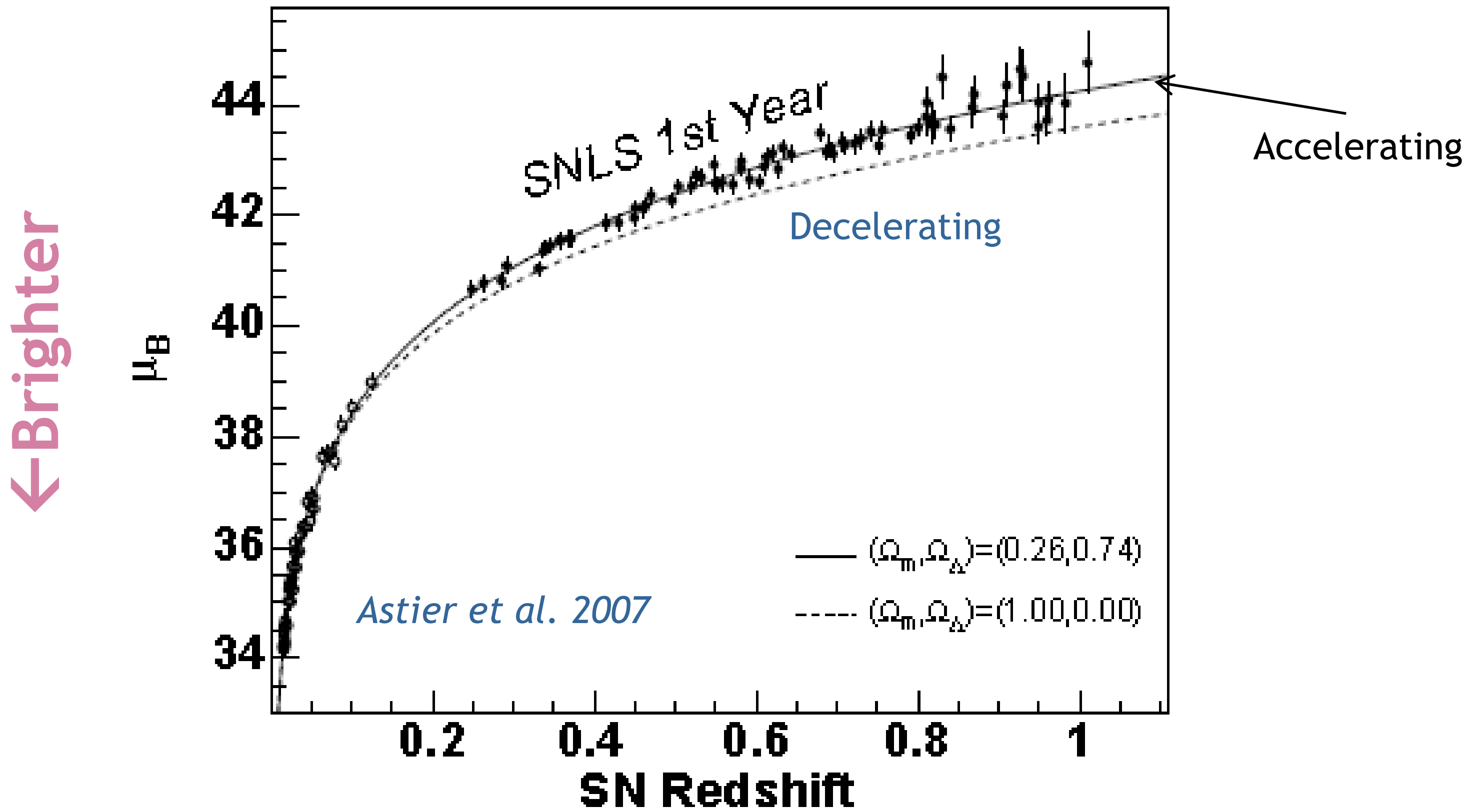


SM of Cosmology gets the power spectrum right

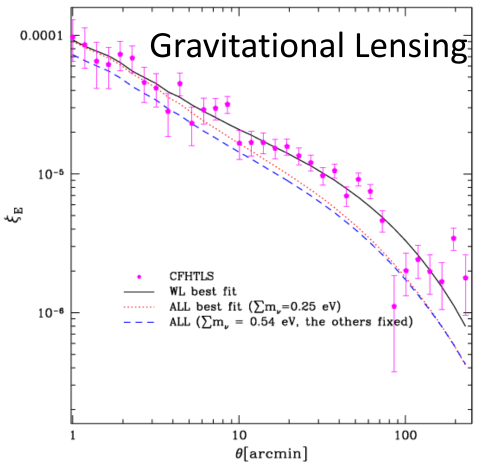


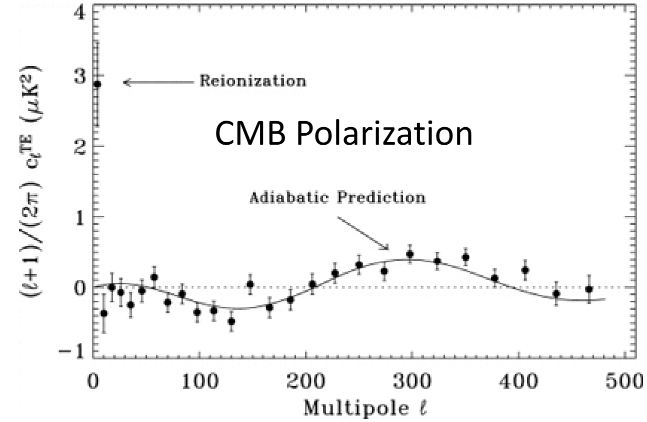
Standard Model of Cosmology

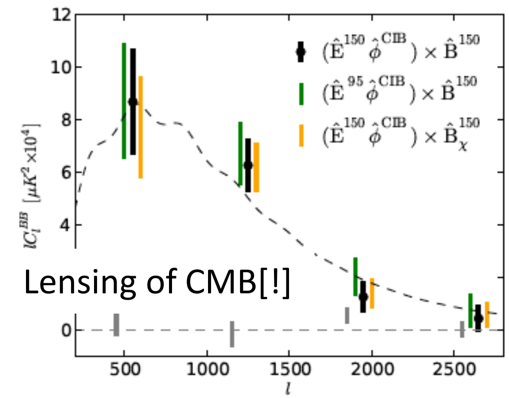
It famously gets the expansion history right

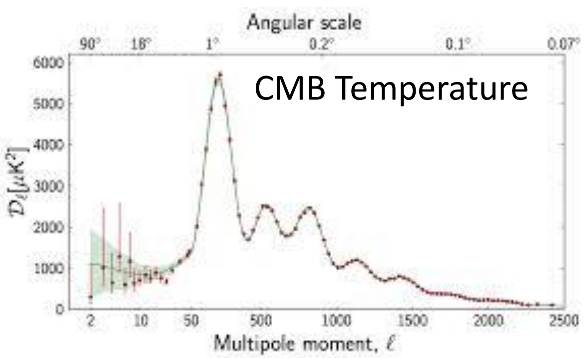


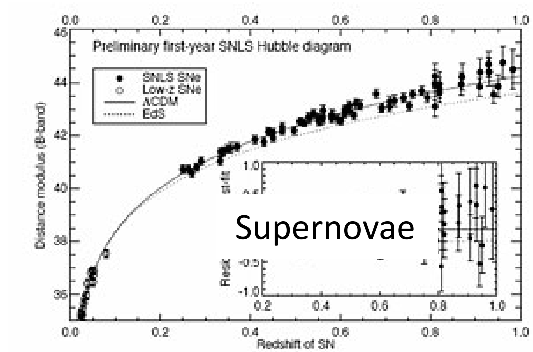
SM of Cosmology agrees with all data on large scales (the only data for which we can make accurate predictions)

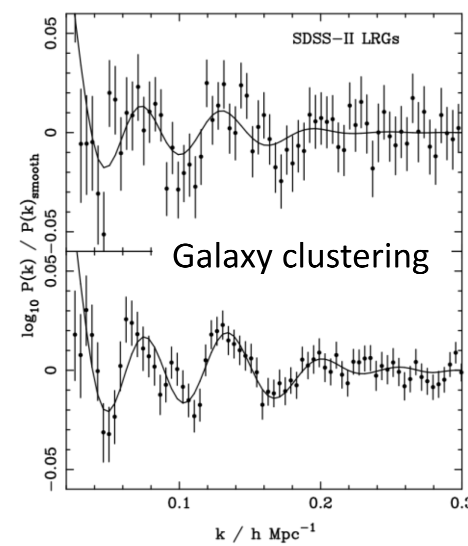




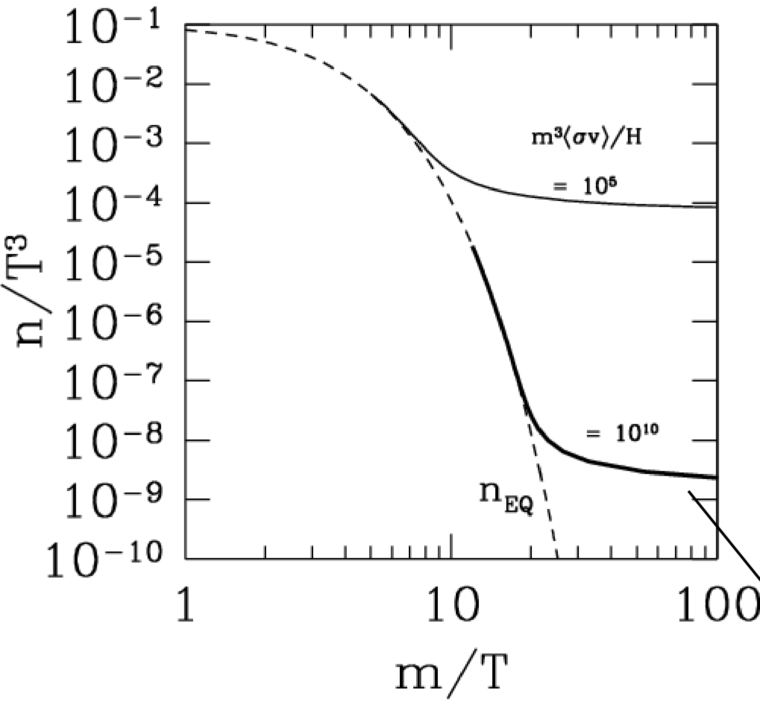






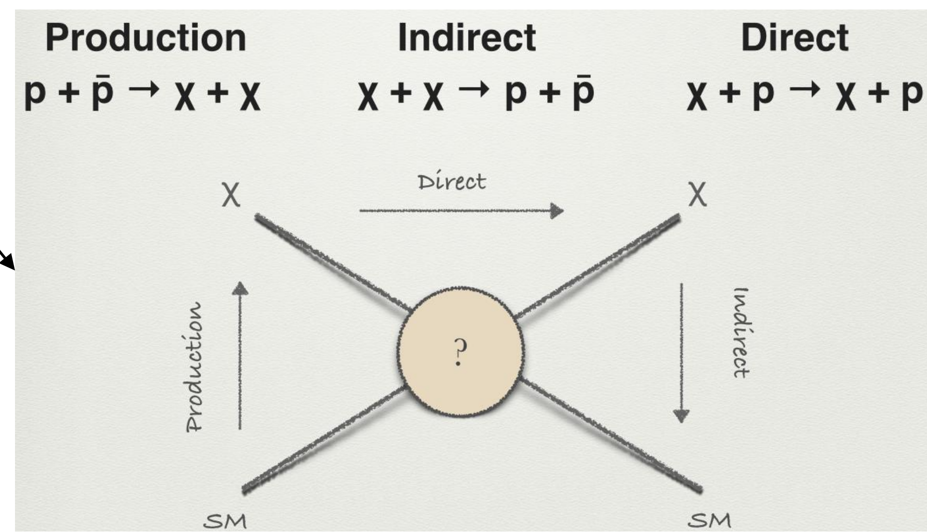


Standard Model of Cosmology: Implications for Particle Physics

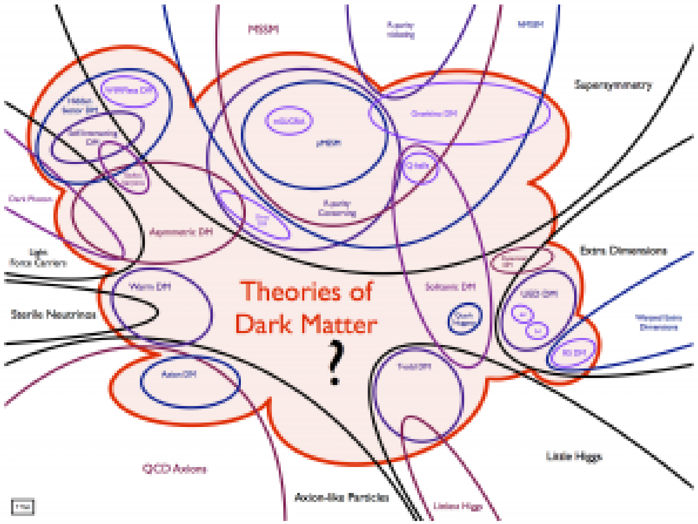


Determine the identity of the dark matter

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



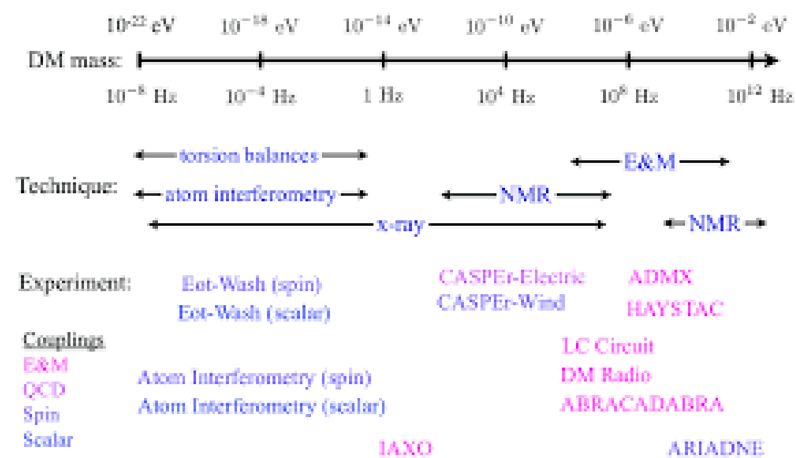
Standard Model of Cosmology: Implications for Particle Physics



Tim Tait

Determine the identity of the dark matter

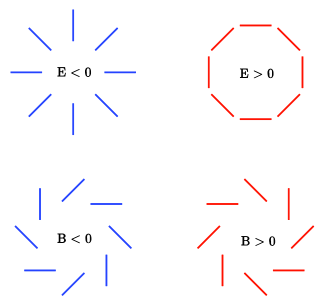
Many new ideas emerging



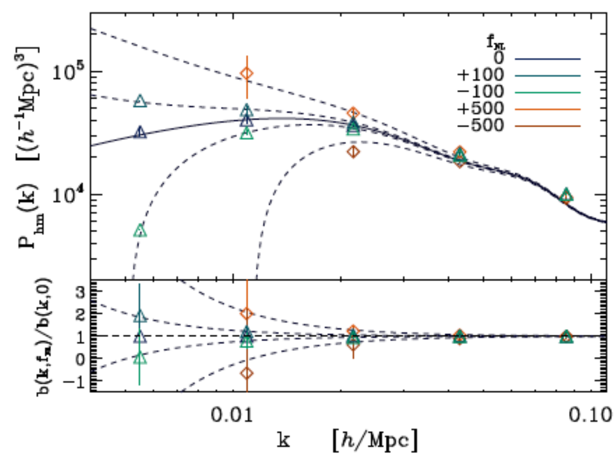
Standard Model of Cosmology: Implications for Particle Physics

Determine the origin of the primordial fluctuations (inflation?)

Primordial Gravitational Waves
(Detectors, Delensing, Dust)



Primordial Non-Gaussianity (EFT, 21 cm?)



Dalal et al 2007

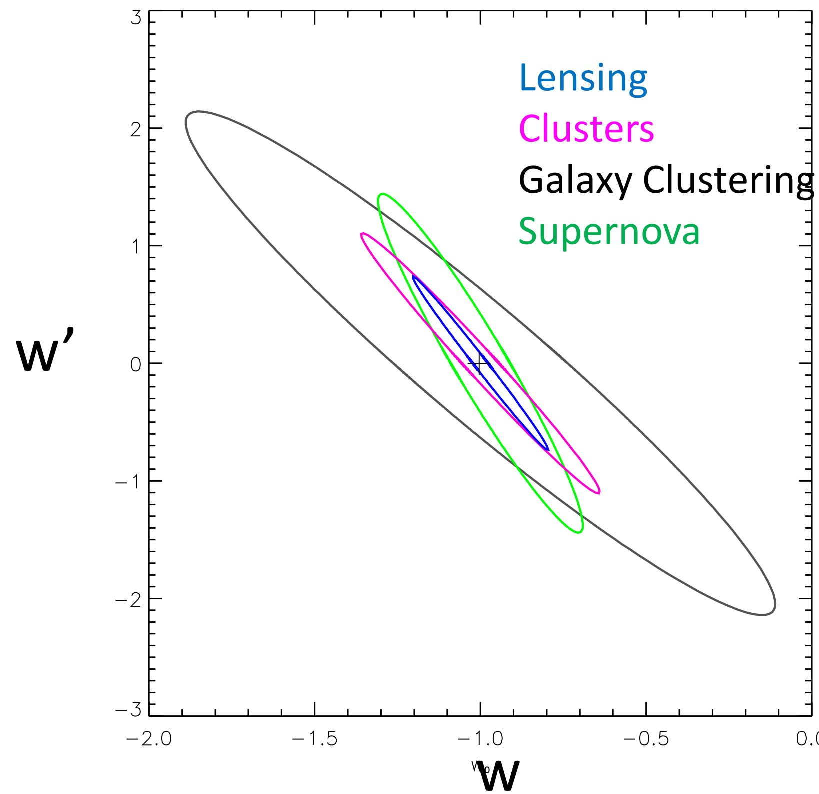
Running of the Spectrum (?) $$\frac{\partial \mathrm{n}}{\partial \ln(k)} \propto (n-1)^2$$

Standard Model of Cosmology: Implications for Particle Physics

Determine the nature of dark energy

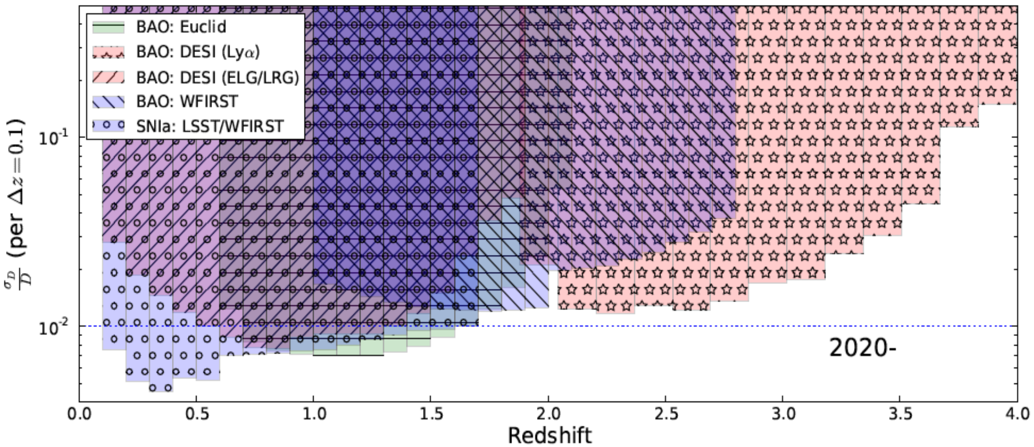
$$\rho(a) = \rho_0 \exp\left\{ 3\int_a^1 \frac{da'}{a'} \left[1 + w(a')\right] \right\}$$

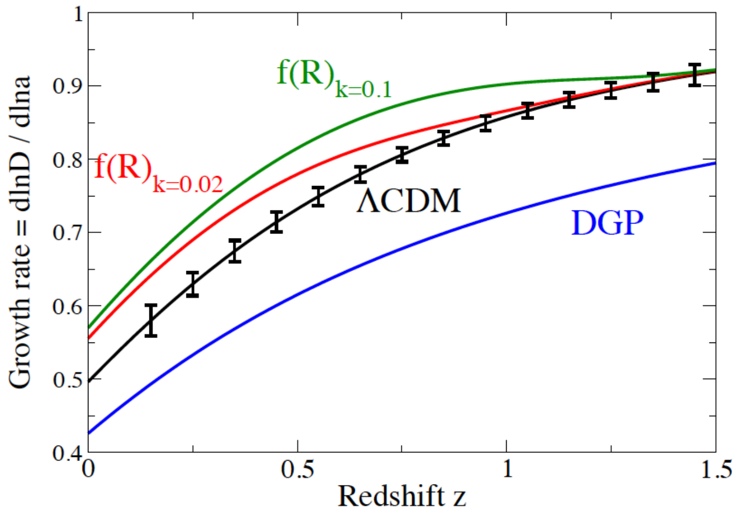
Determine the equation of state of dark energy (w=-1 corresponds to a cosmological constant)



Standard Model of Cosmology: Implications for Particle Physics

Determine the nature of dark energy → the mechanism driving the current epoch of acceleration

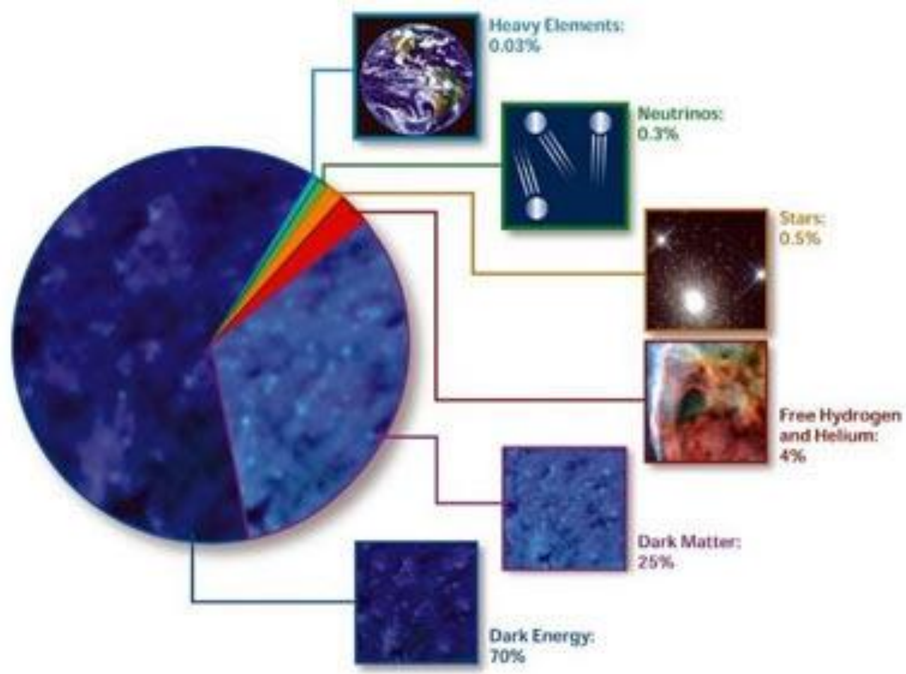




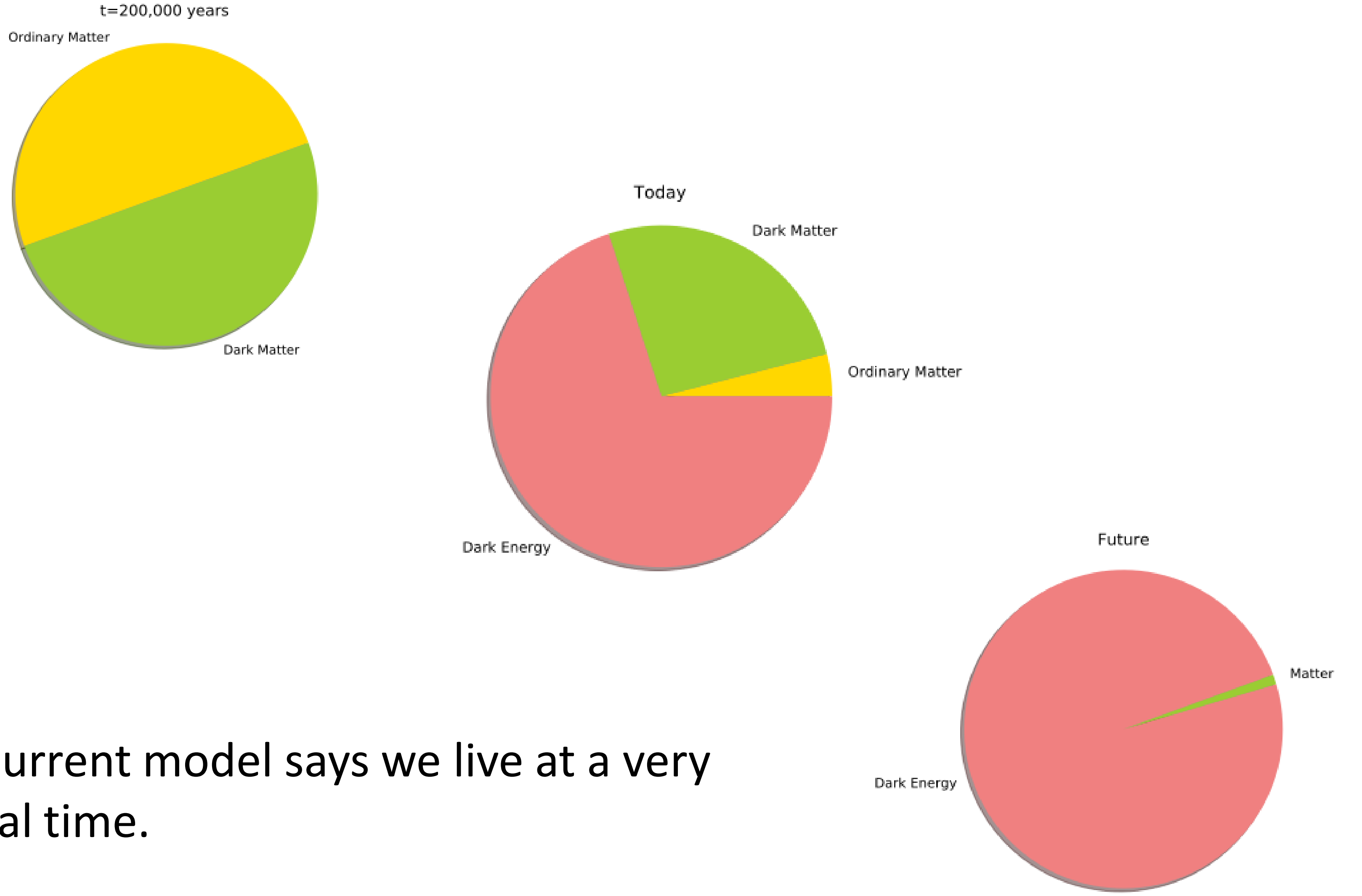
Measure Distances and Growth of Structure: Cosmological constant, quintessence, modified gravity, etc.

Precision Tests of the Standard Model (of Cosmology): ΛCDM

Why search for cracks in the Standard Model of Cosmology?

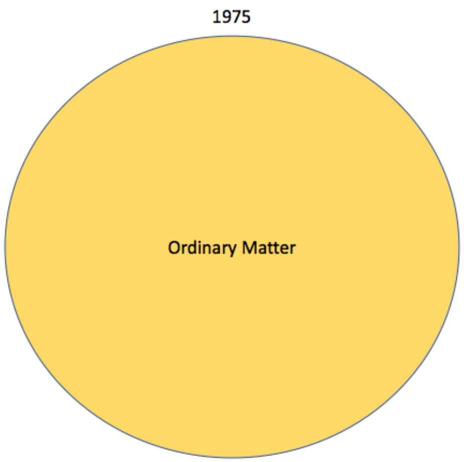


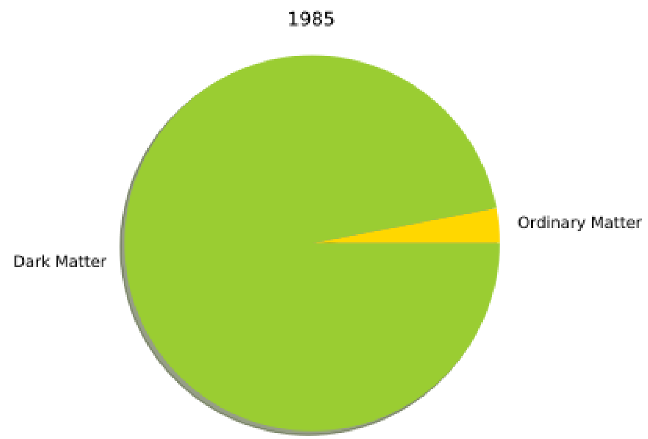
The Dark Sector: Evolution in Time

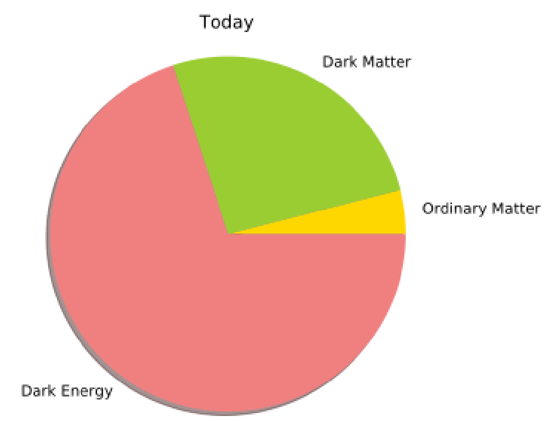


The current model says we live at a very special time.

The Dark Sector: Evolution in Time, Take 2

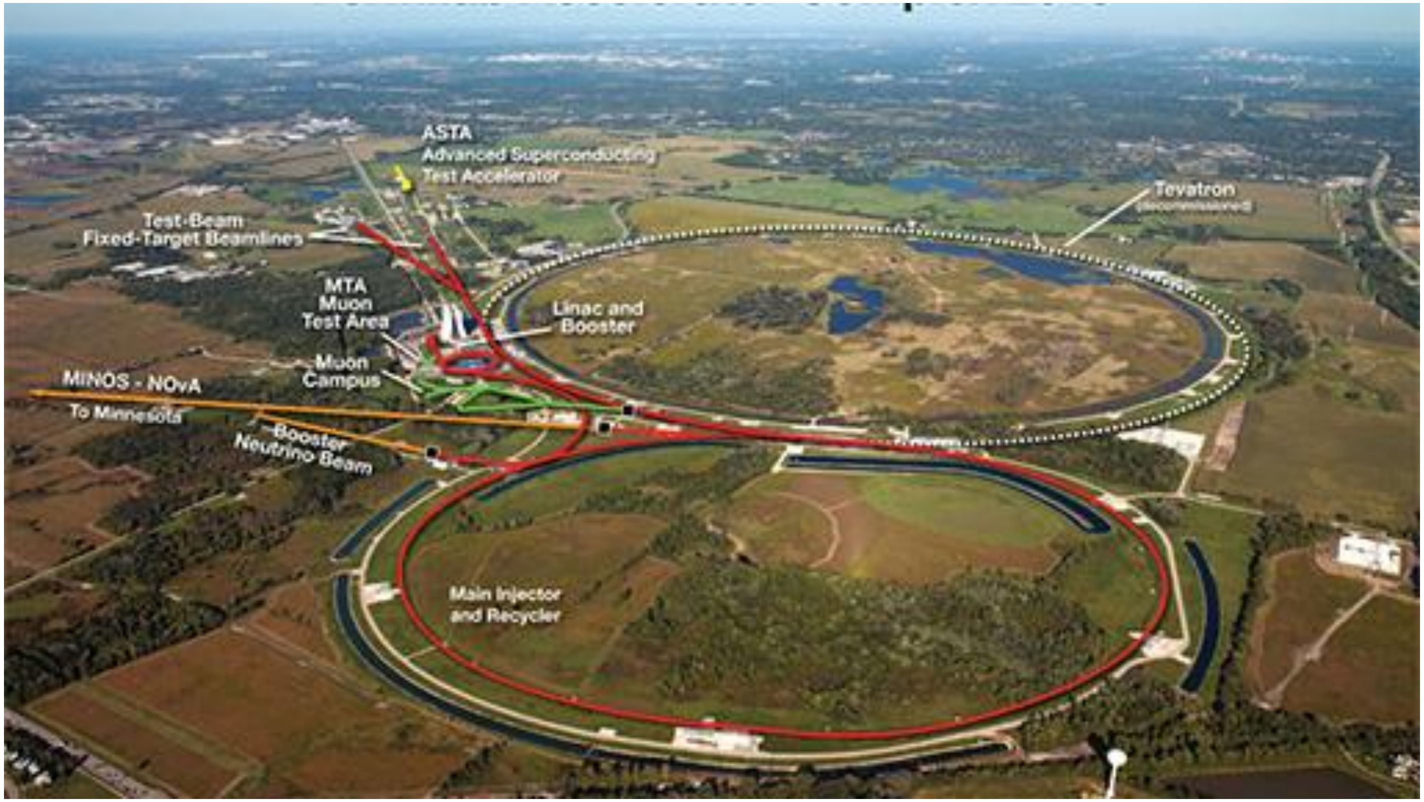




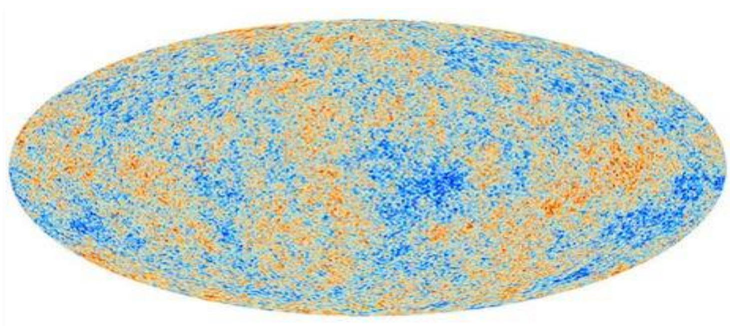


Those who claim we now know the answer may well be wrong

Also, as **you** know, High Energy Physicists have searched for “new physics” Beyond the Standard Model for decades with no success; is it plausible for astronomers/cosmologists to invoke hypothetical substances to make our model work?

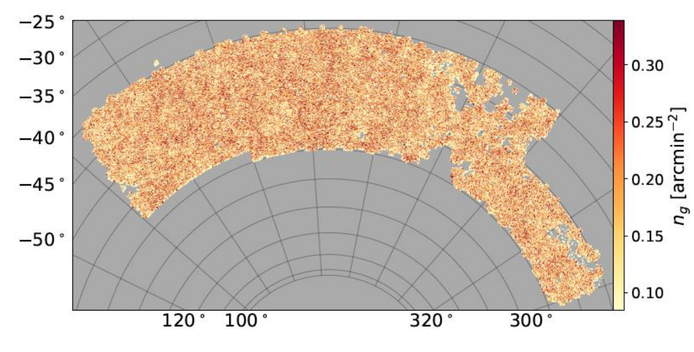


The Standard Model explains how we evolved from early to late times



UNIFORM TO ONE
PART IN 10,000

VERY NONLINEAR



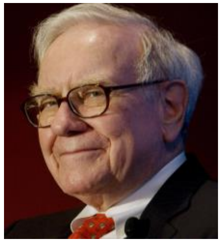
Precision Tests of the Standard Model (of Cosmology)

We will focus on two parameters:

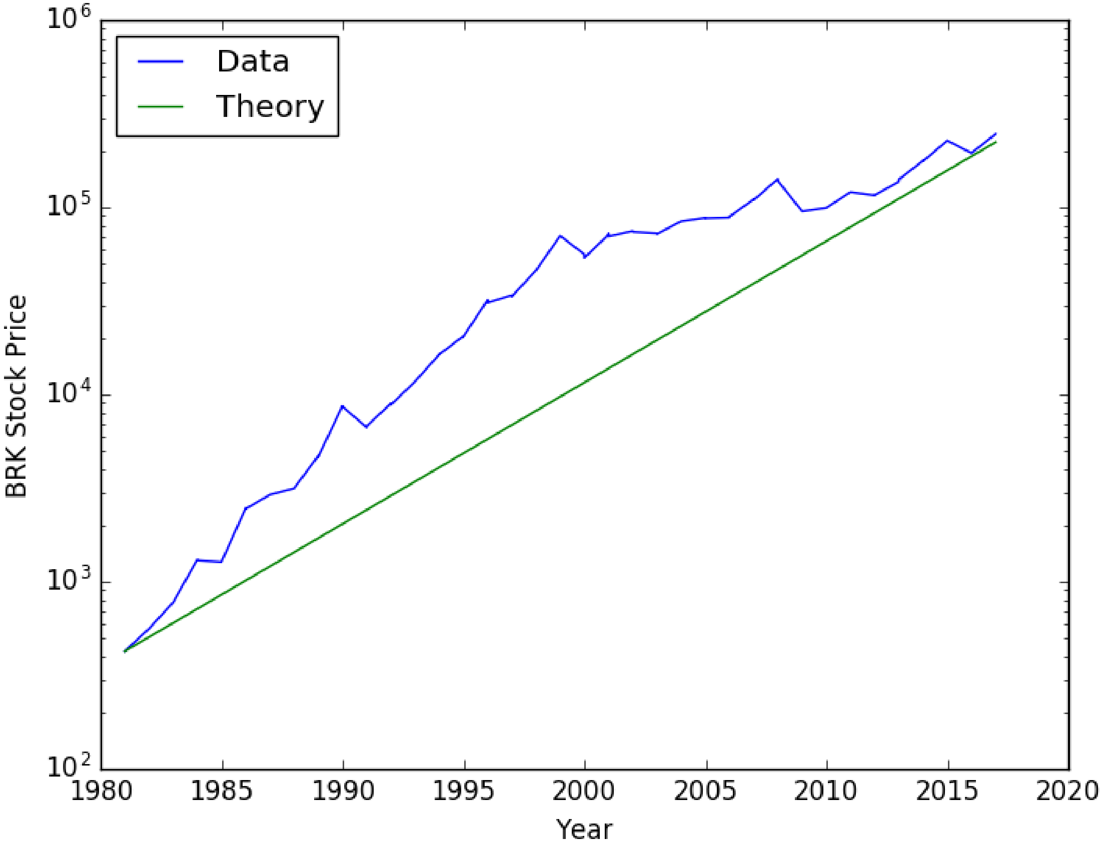
- ***Ω_m*** The mass density (stars, neutrinos, atoms, dark matter) in units of the ***critical density***
- ***σ_8*** The root mean square of the fluctuations in the mass density smoothed over scales of 8 h^{-1} Mpc ***today***

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

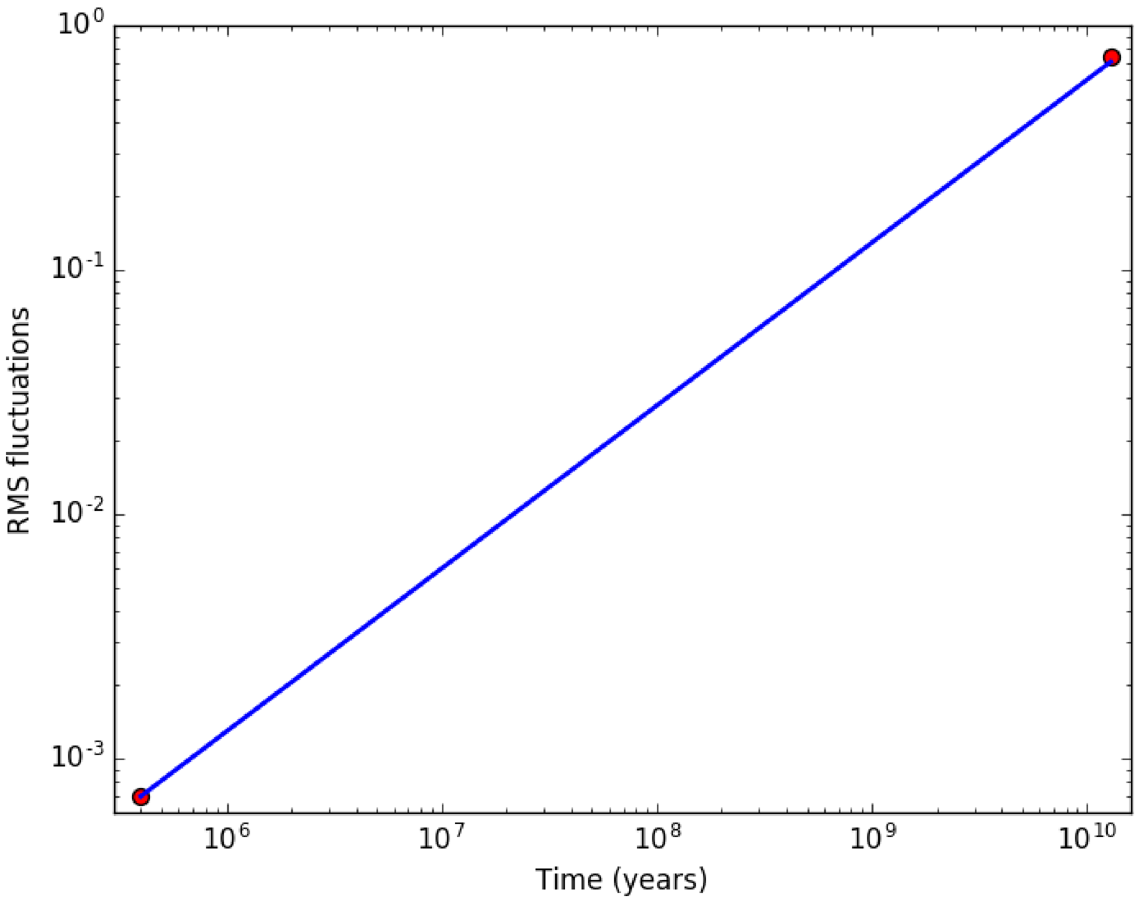
Imagine a similar prediction in the stock market



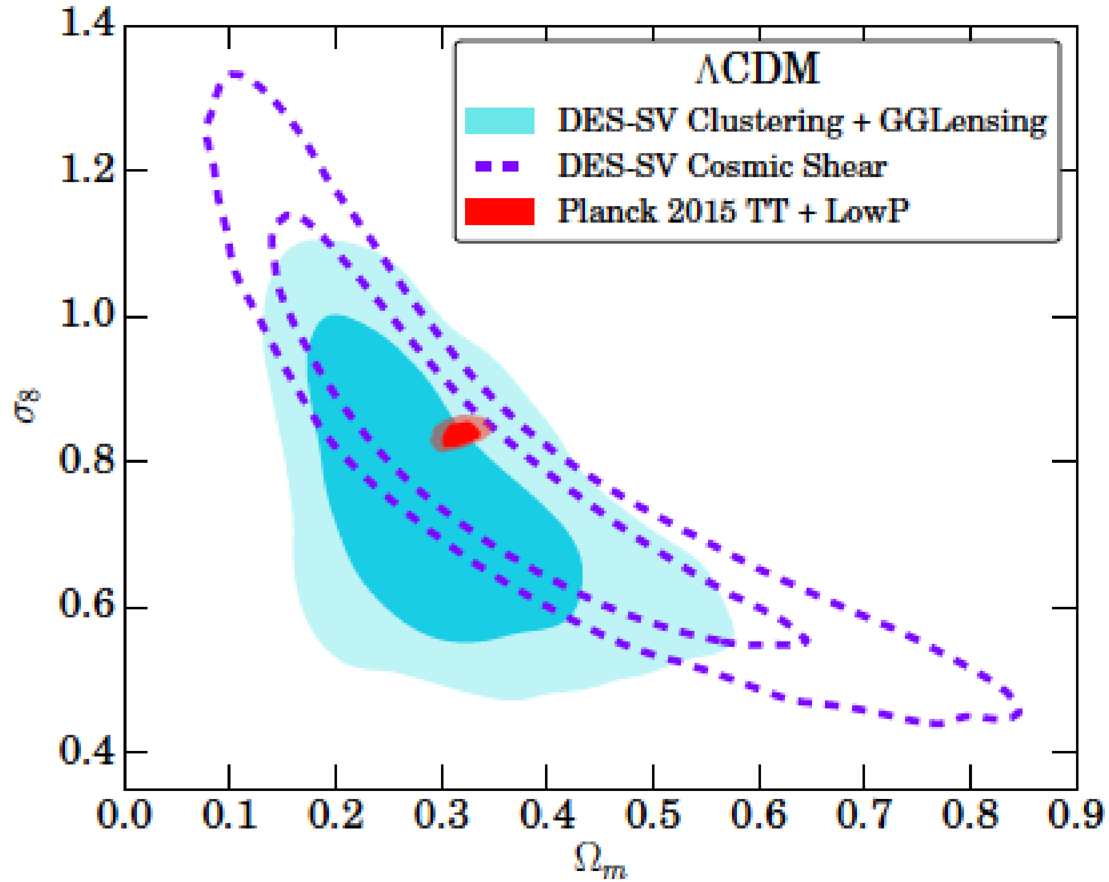
Your model predicts that the stock price of Berkshire Hathaway will increase by 19% every year. All you need is the 1980 data to predict what the price will be in 2017



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

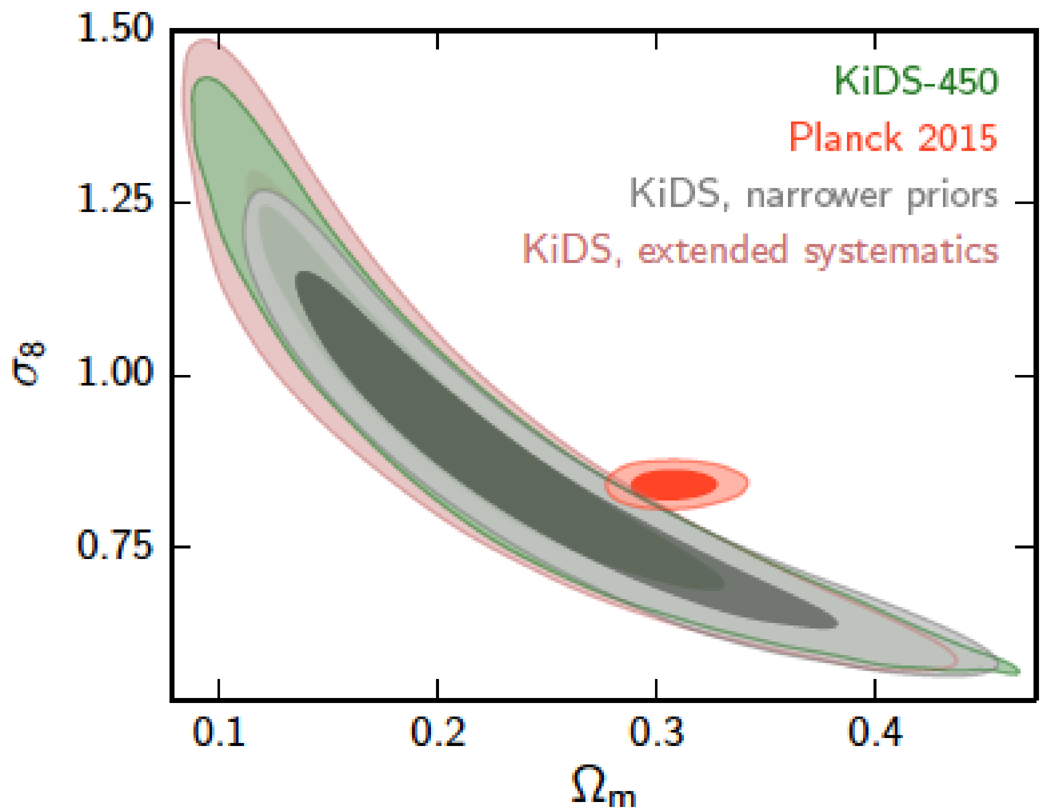


Measure these parameters with the CMB (very early times) and Optical Surveys (much later times) to test the (zero parameter) growth of structure predictions



Moral: Much easier to extract parameters from the (linear) CMB. Think hadron colliders vs. lepton colliders

More recent experiments have reported tension



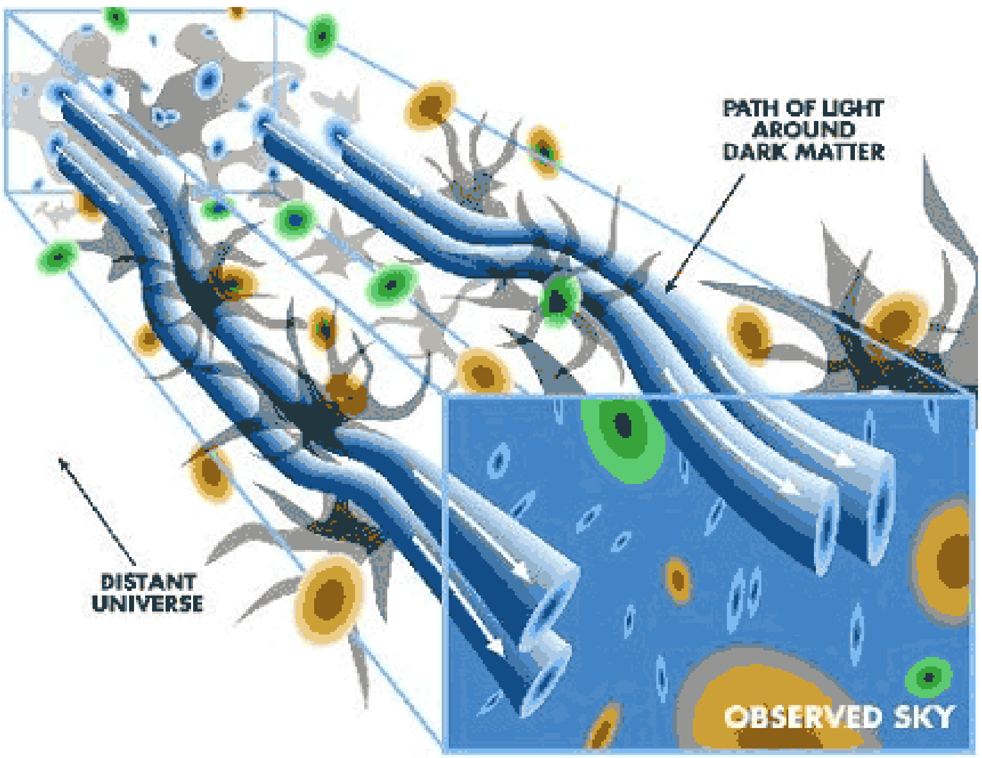
Dark Energy Survey

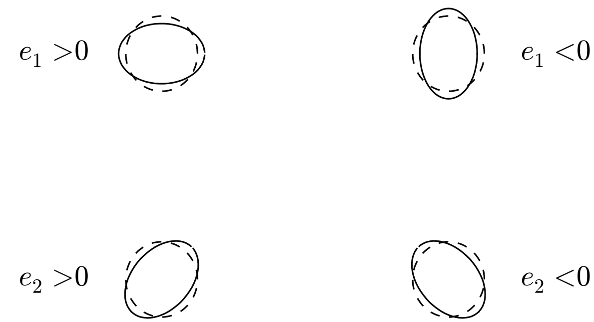
- 570 Megapixel camera built at Fermilab for the Blanco 4m telescope in Chile
- Full Survey 2013-18 ***(Y1 2013-4)***
  - 5000 sq. deg. (**1300**)
  - 5 Bands
  - ~24th magnitude (**23rd**)
  - Sub-arcsec seeing

How to measure mass when we see only light?

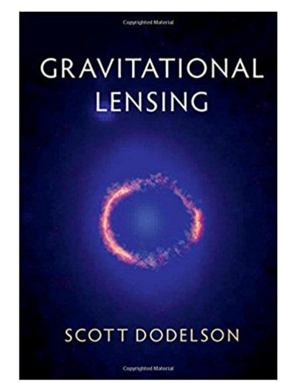
- ***<u>Use Galaxies as tracers</u>***
  Galaxies form in over-dense regions, so an excess of galaxies <-> an excess of mass. But the precise relation between overdensities is governed by a ***bias*** parameter
- ***<u>Measure the shapes of background galaxies</u>***
  Shapes are distorted as the light 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>

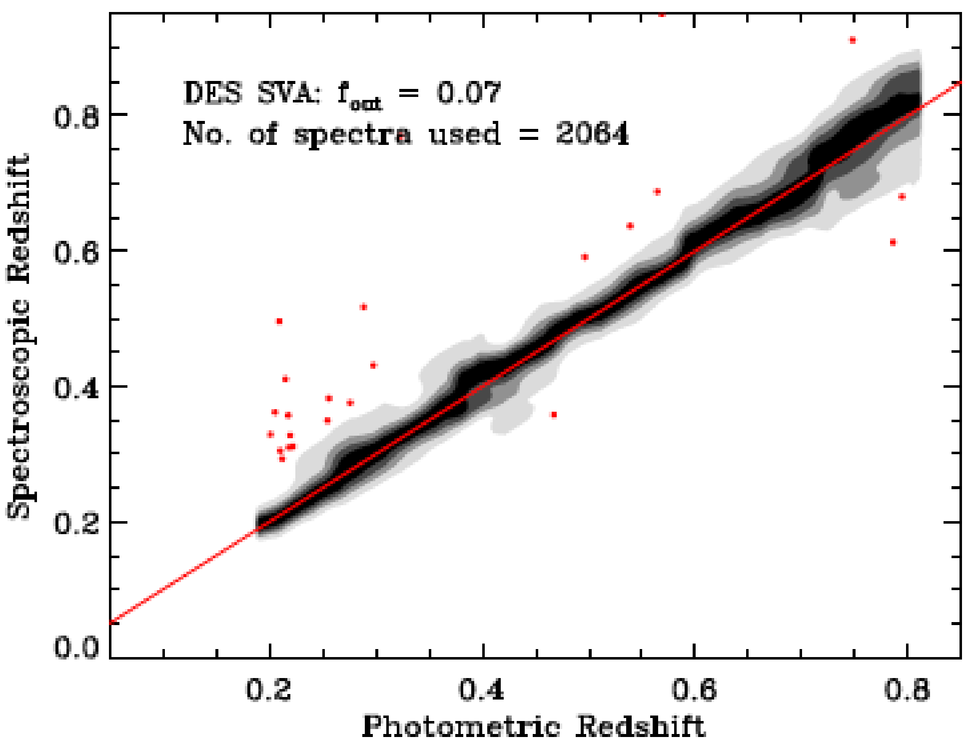
Two fields:
Galaxy over-density $\delta_g(\theta)$
Galaxy ellipticity $e_i(\theta)$

Three 2-point functions:

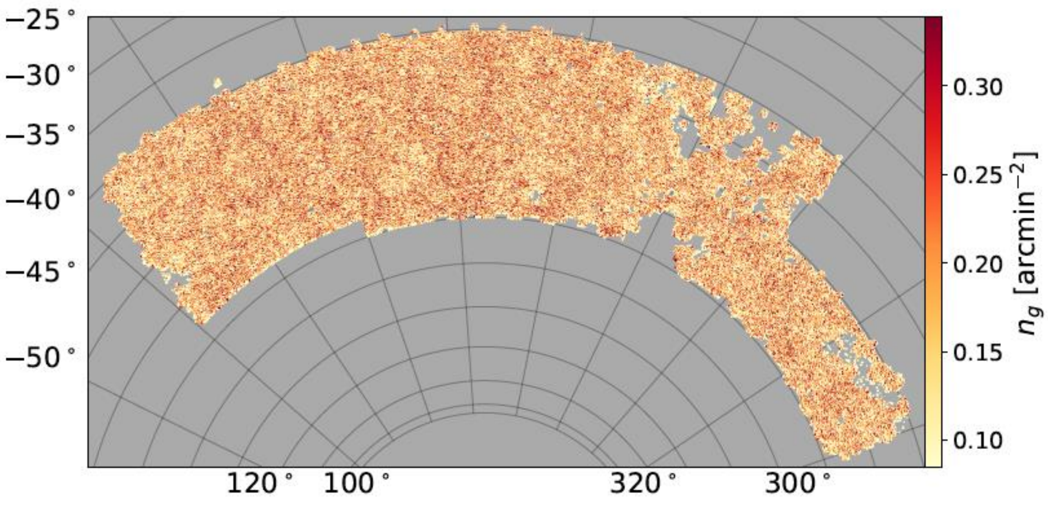
- Angular correlation function $w(\theta)=<\delta_g\delta_g>$ measures the clustering of "lens" galaxies
- Galaxy-galaxy lensing $\gamma_t(\theta)=<\delta_g e_i>$ measures the distortions in "source" galaxies by mass associated with "lens" galaxies
- Shear correlation function $\xi(\theta)=<e_i e_j>$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

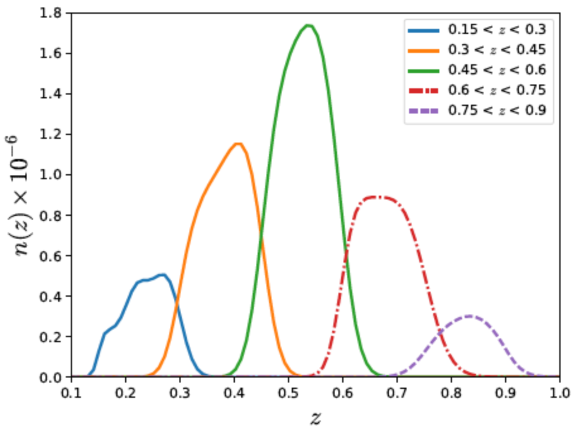
DES is a Photometric Survey: 2D not 3D

Well-measured redshifts



660,000 redMaGiC galaxies are the “lenses”, divided into 5 tomographic bins





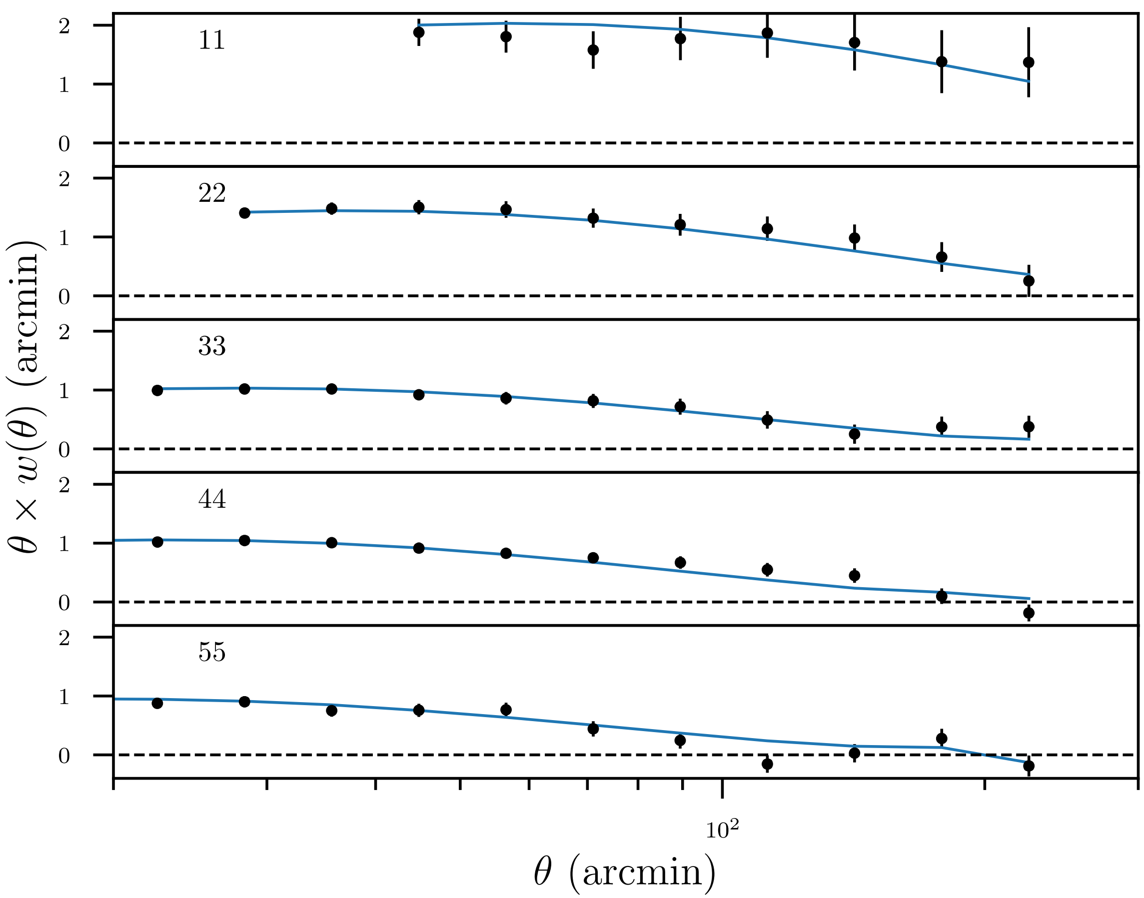
Two fields:
Galaxy over-density $\delta_g(\theta)$
Galaxy ellipticity $e_i(\theta)$

Three 2-point functions:

- ***Angular correlation function $w(\vartheta)$=<$\delta_g\delta_g$> 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

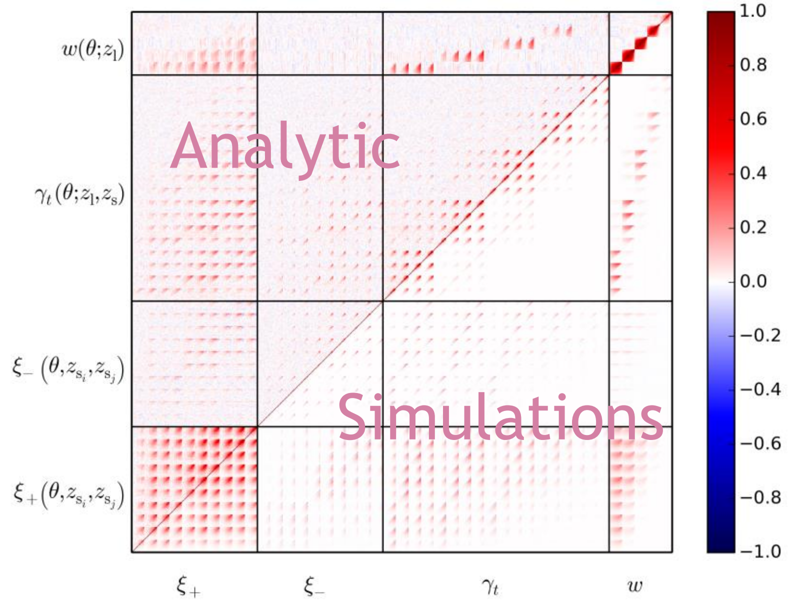
Measure redMaGiC Galaxy Clustering in each of five redshift bins

Blue curve is Standard Model that best fits all the data



Theoretical Challenges

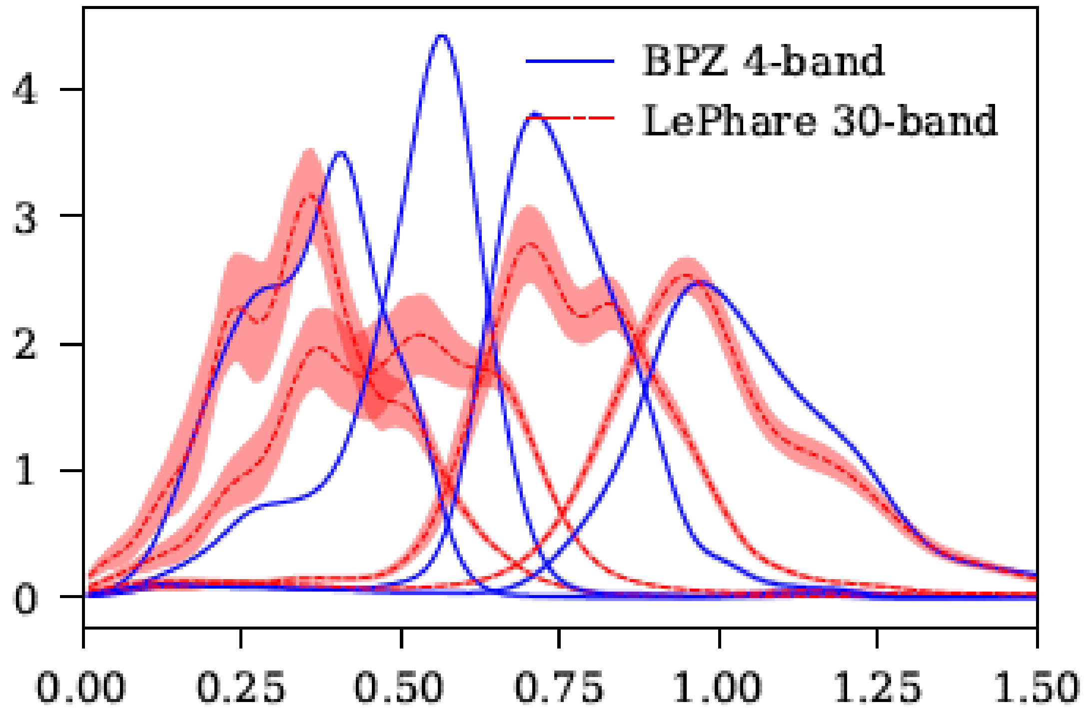
- Large scale (linear) predictions accurate at sub-percent level
- Small scale predictions: nonlinear gravity; relation between matter and galaxies; effects of baryons
- Covariance matrix



Elisabeth Krause et al. 1706.09359

Redshift distributions of *source* galaxies

Allow the mean for the BPZ photo-z to be a free parameter and fit using COSMOS redshifts and clustering

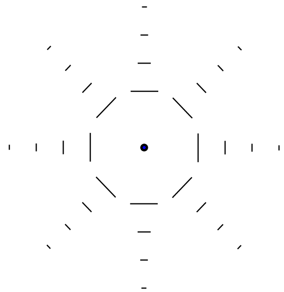


Two fields:
Galaxy over-density $\delta_g(\theta)$
Galaxy ellipticity $e_i(\theta)$

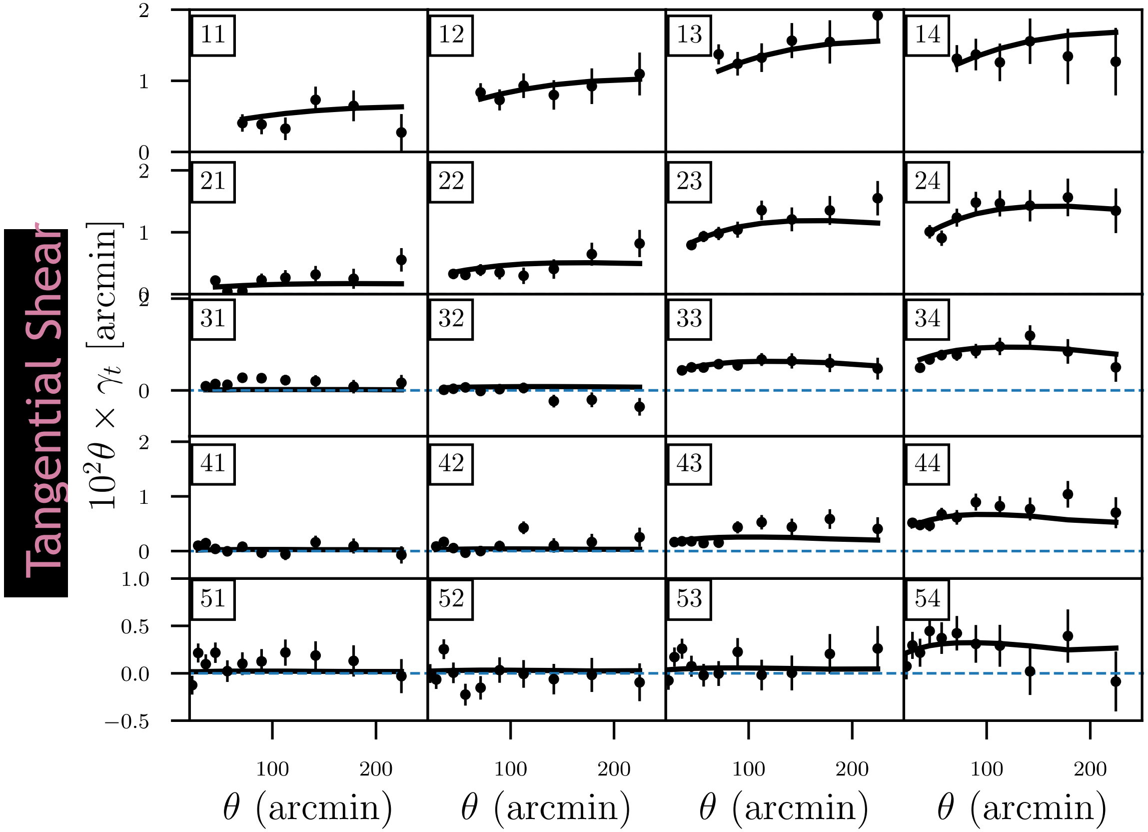
Three 2-point functions:

- Angular correlation function $w(\theta)=<\delta_g\delta_g>$ measures the clustering of "lens" galaxies
- ***Galaxy-galaxy lensing $\gamma_t(\vartheta)=<\delta_g e_i>$ 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

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

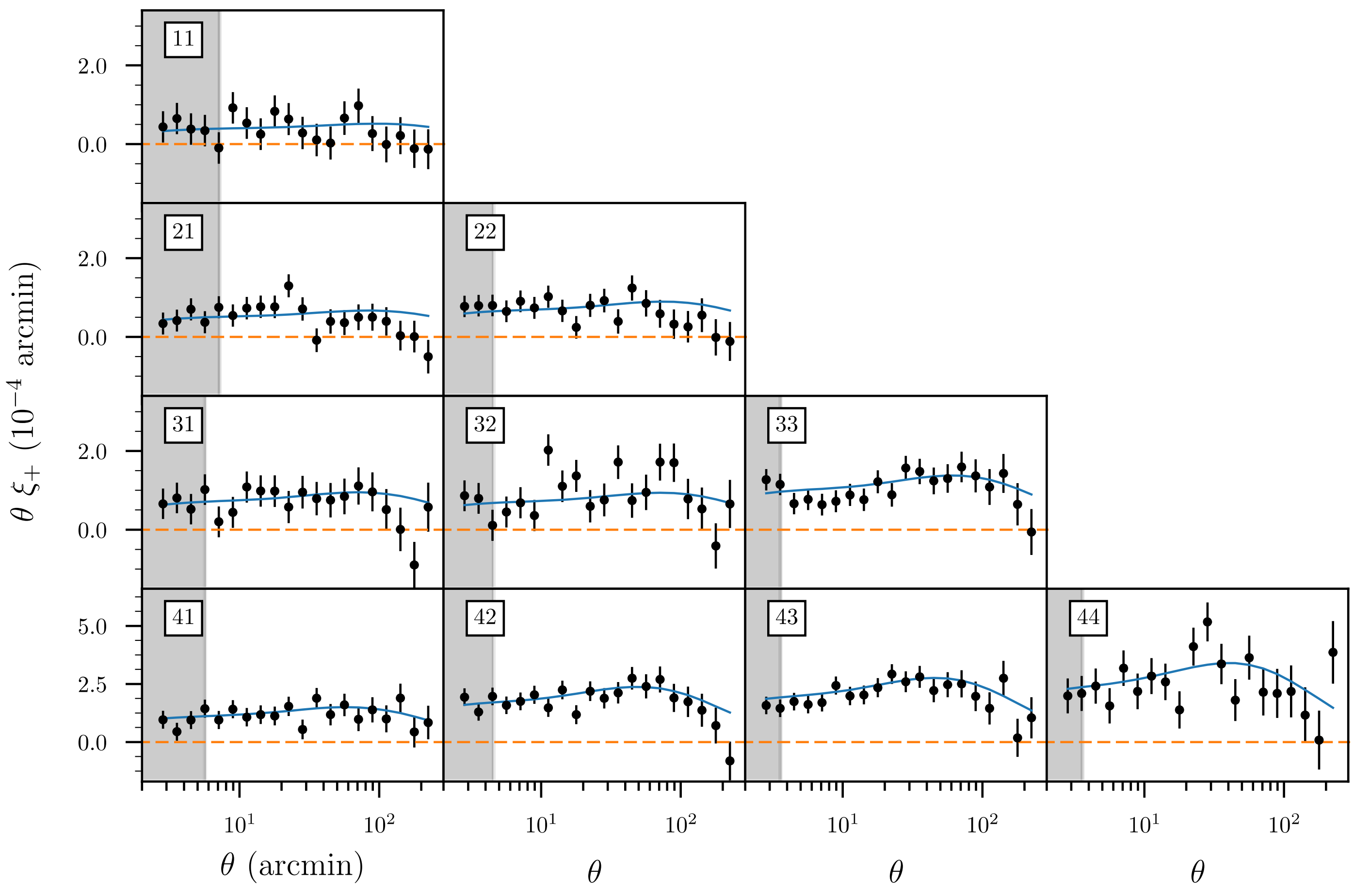
Two fields:
Galaxy over-density $\delta_g(\theta)$
Galaxy ellipticity $e_i(\theta)$

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 $\xi(\vartheta)=<e_i e_j>$ measures the correlations between shapes of nearby “source” galaxies due to similar distortions by line-of-sight mass***

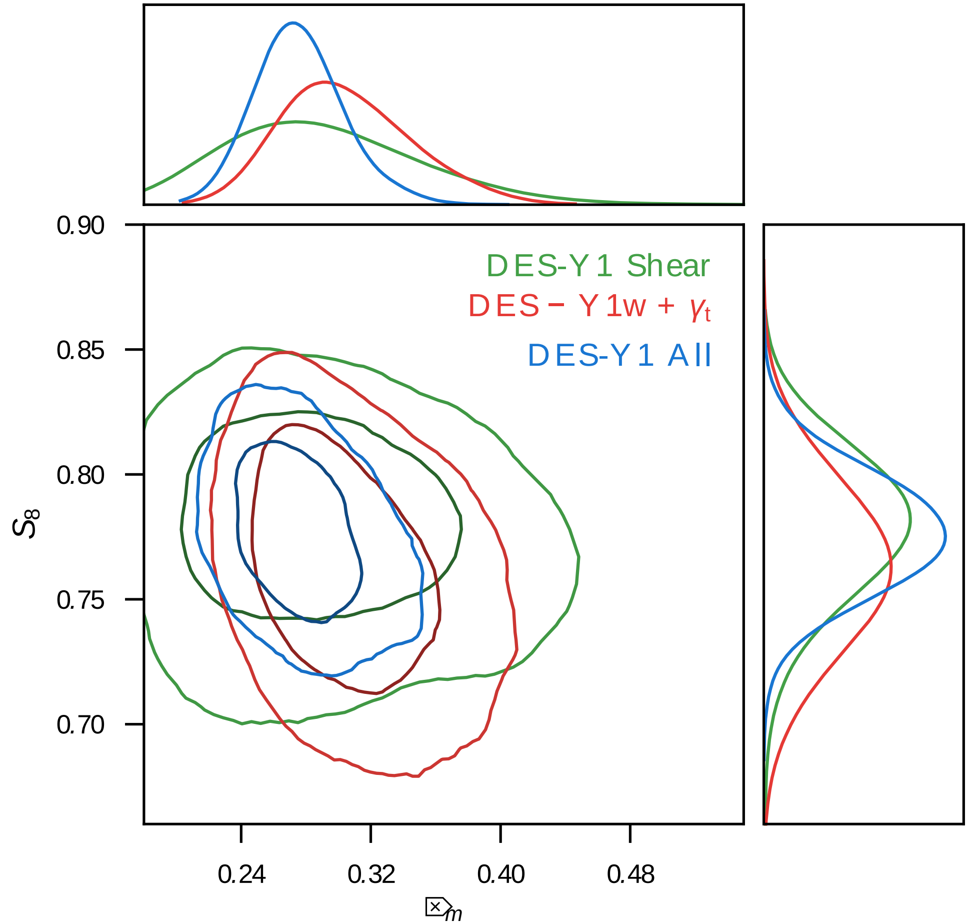
Gravitational Lensing: Shape correlations

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

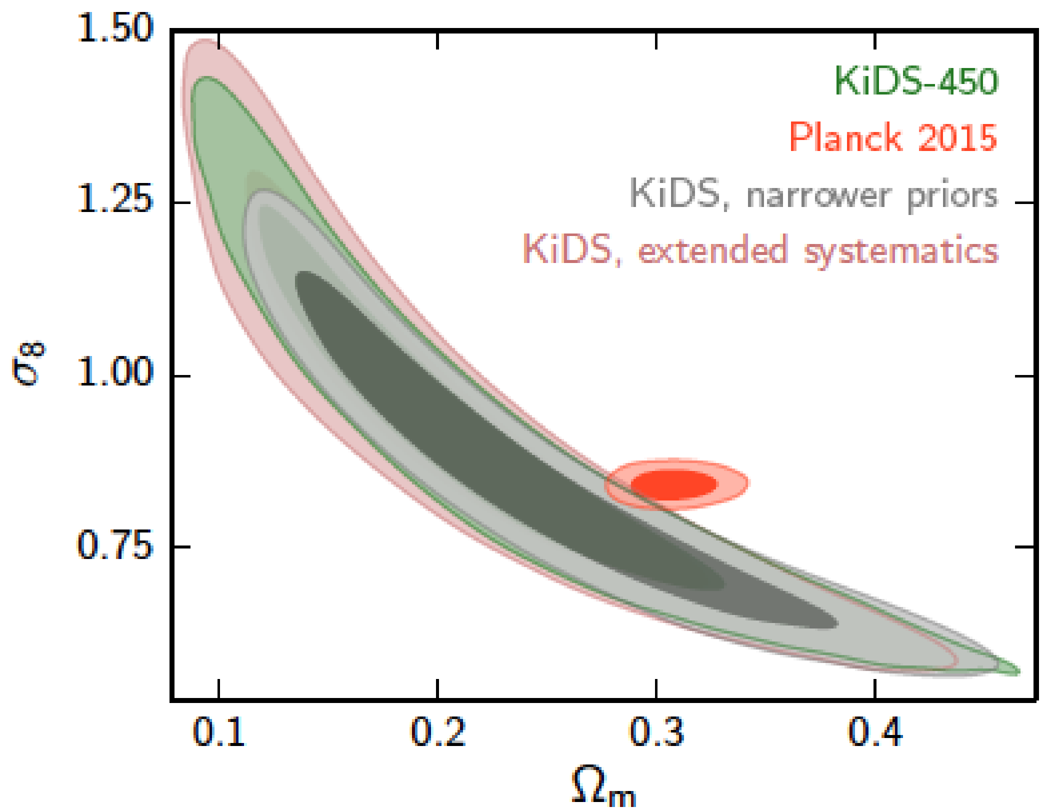


DES: Troxel et al. 2017

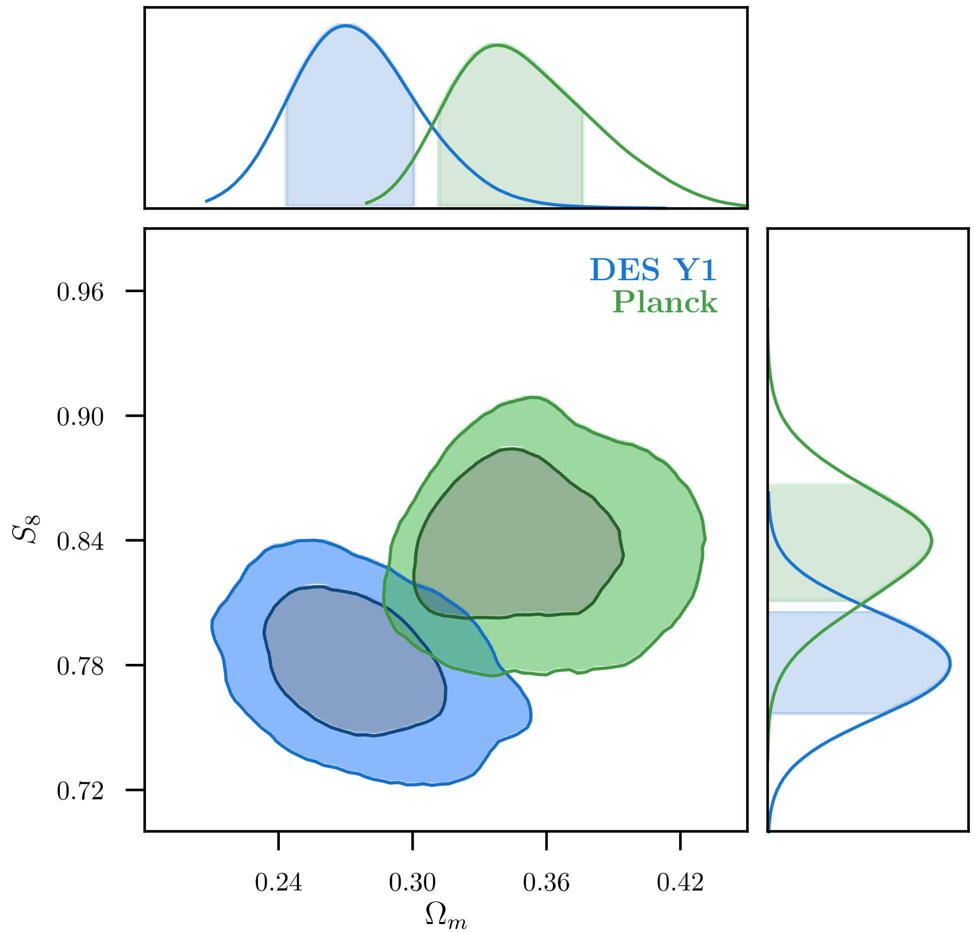
We generate results from (galaxy clustering + galaxy-galaxy lensing) and (cosmic shear)



Recall the previous state-of-the art

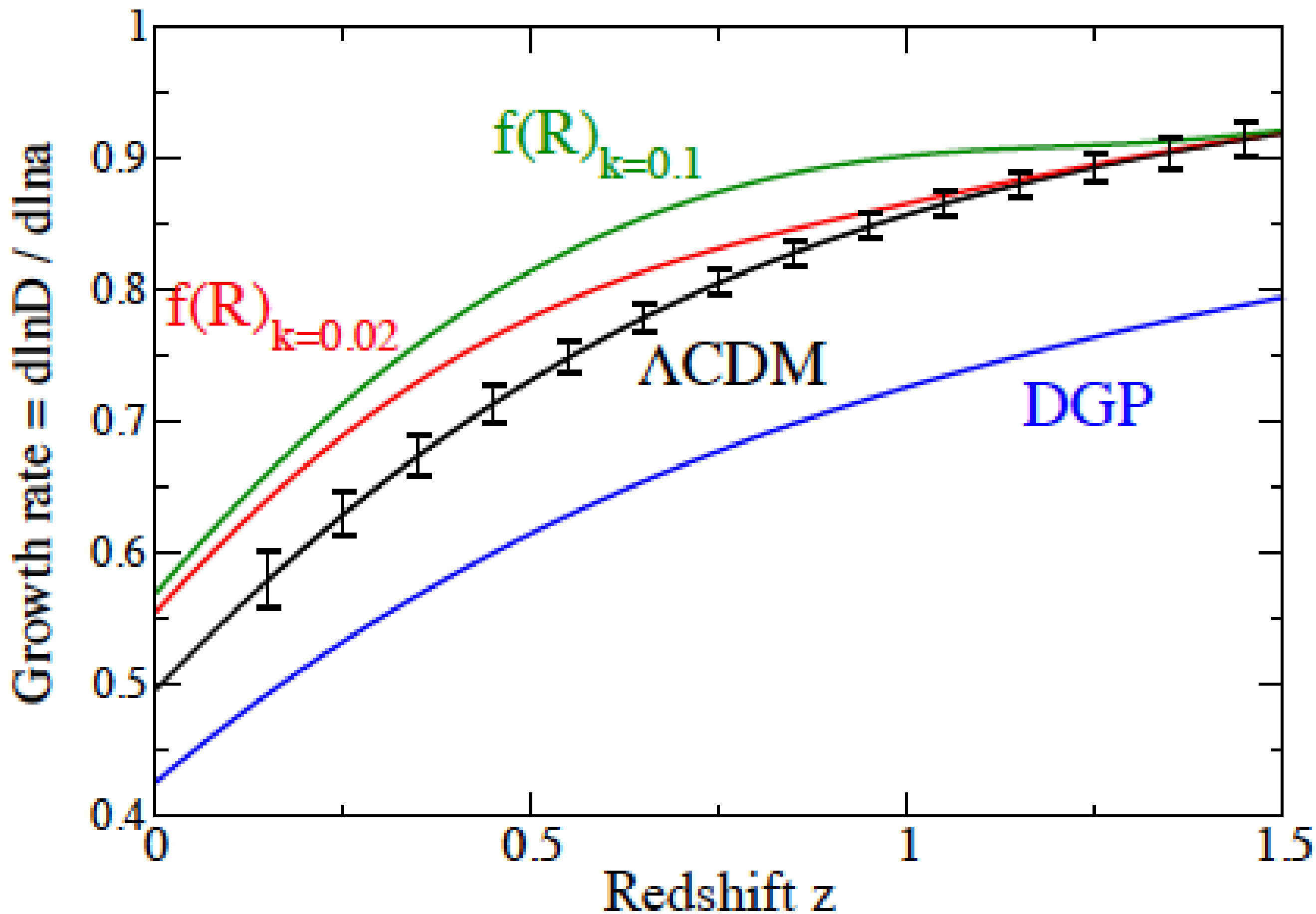


DES Y1 Results: Power a bit lower then the Standard Model predicts



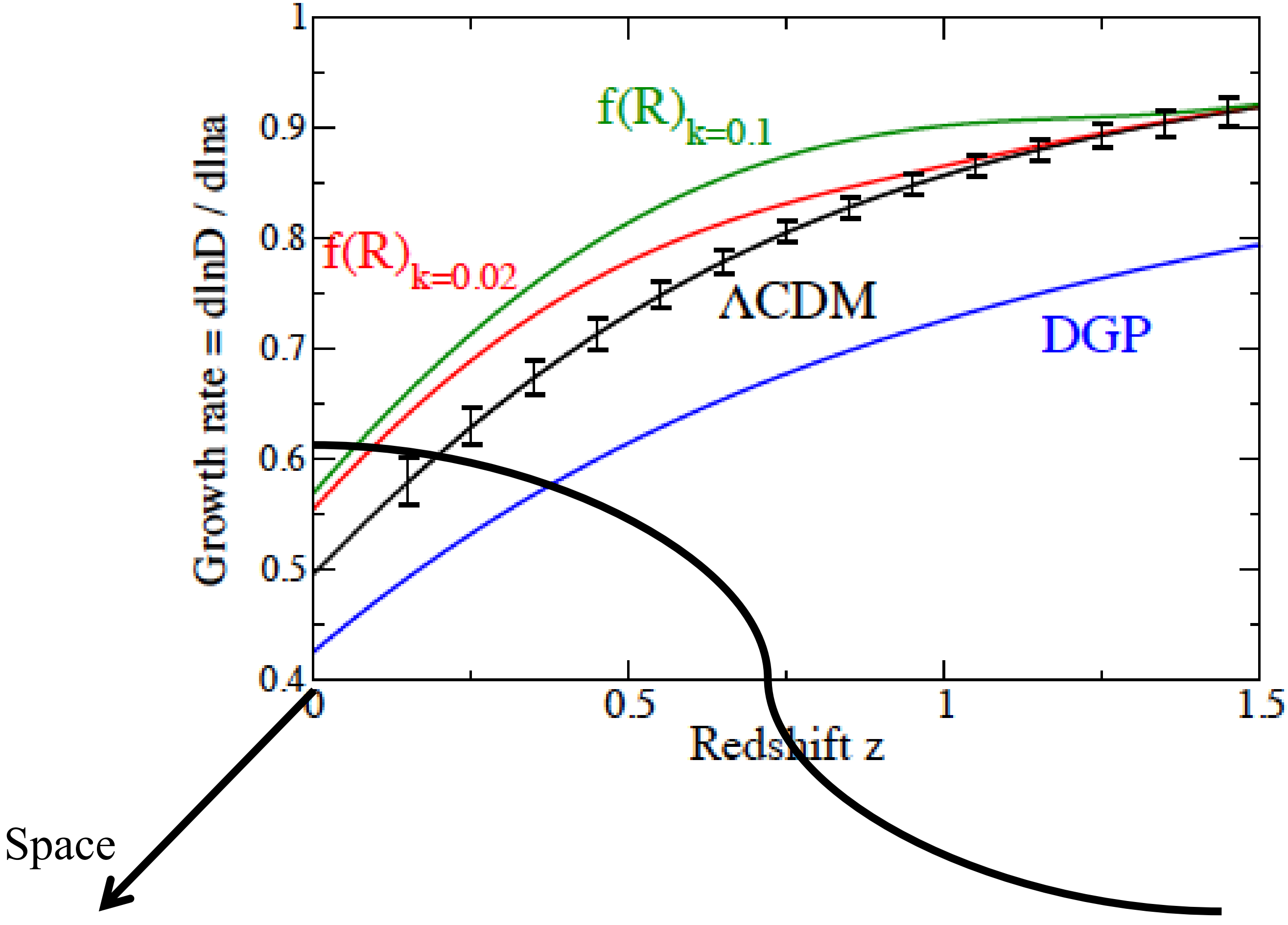
This is only the beginning …

- 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

On these two parameters, cosmic surveys using clustering measurements have now attained constraining power comparable to the cosmic microwave background. It is hard to overstate the significance of this development.

Conclusions

- On these two parameters, cosmic surveys using clustering measurements have now attained constraining power comparable to the cosmic microwave background. It is hard to overstate the significance of this development.
- The constraints on Ω_m from the CMB stem from the impact of the matter density on the relative heights of the acoustic peaks in the cosmic plasma when the universe was only 400,000 years old and from the distance between us today and the last scattering surface. The CMB constraints on S_8 are an expression of both the very small RMS fluctuations in the density at that early time and the model's prediction for how rapidly they would grow over billions of years due to gravitational instability. The measurements themselves are of course in microwave bands and probe the universe when it was extraordinarily smooth.

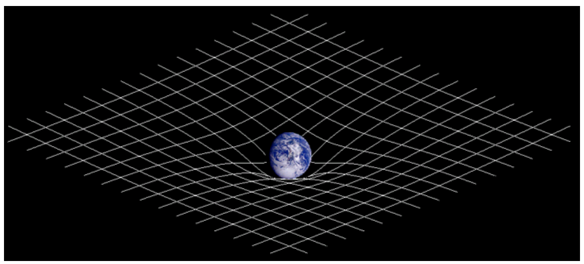
Conclusions

- The constraints on Ω_m from the CMB stem from the impact of the matter density on the relative heights of the acoustic peaks in the cosmic plasma when the universe was only 400,000 years old and from the distance between us today and the last scattering surface. The CMB constraints on the S_8 are an expression of both the very small RMS fluctuations in the density at that early time and the model's prediction for how rapidly they would grow over billions of years due to gravitational instability. The measurements themselves are of course in microwave bands and probe the universe when it was extraordinarily smooth.
- DES is different in every way: it probes in optical bands billions of years later when the universe had evolved to be extraordinarily inhomogeneous. Instead of using the radiation as a tracer, DES uses galaxies and shear. It is truly extraordinary that a simple model makes predictions for these vastly different sets of experiments.

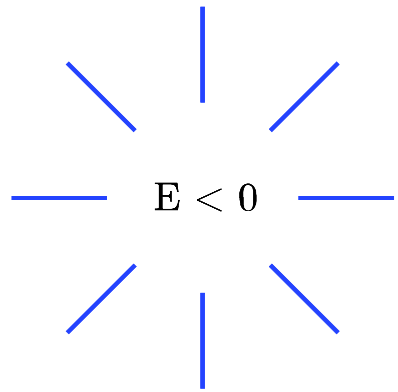
Conclusions

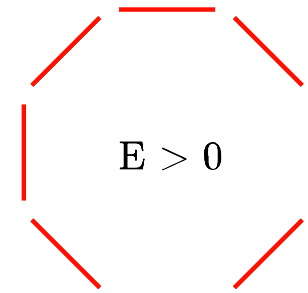
- How well they agree remains an open question (which we have begun exploring with Year 3 data) but the very fact that they can be compared and that, now for the first time, optical surveys obtain constraints as tight as the CMB on at least some parameters **heralds a new era in cosmology**.

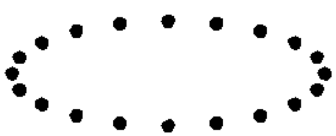
CMB Polarization decomposed into E- and B- modes



Density perturbations produce only E-modes







Gravity waves produce E- and B- modes