Cluster Cosmology with Large Photometric Surveys

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Summary

Our Universe's accelerated expansion is *unambiguous* proof of new physics (dark energy or modified gravity).

The growth of large scale structure is a sensitive probe of these physics:

- If GR is correct, the accelerated expansion inhibits structure formation in a deterministic way.
- If GR is not correct, we expect deviations from this prediction.

Need a cosmological probe that can measure the rate of structure formation in the Universe.

Galaxy clusters are the best such probe.

Summary

There is good agreement between cluster cosmology analysis today, but Planck data has opened new questions.

We believe these questions have been resolved, and main outcome is a validation of cosmological work to date.

Future work should decrease statistical and systematic uncertainties, and should make galaxy clusters the most powerful Stage III probe of structure growth.

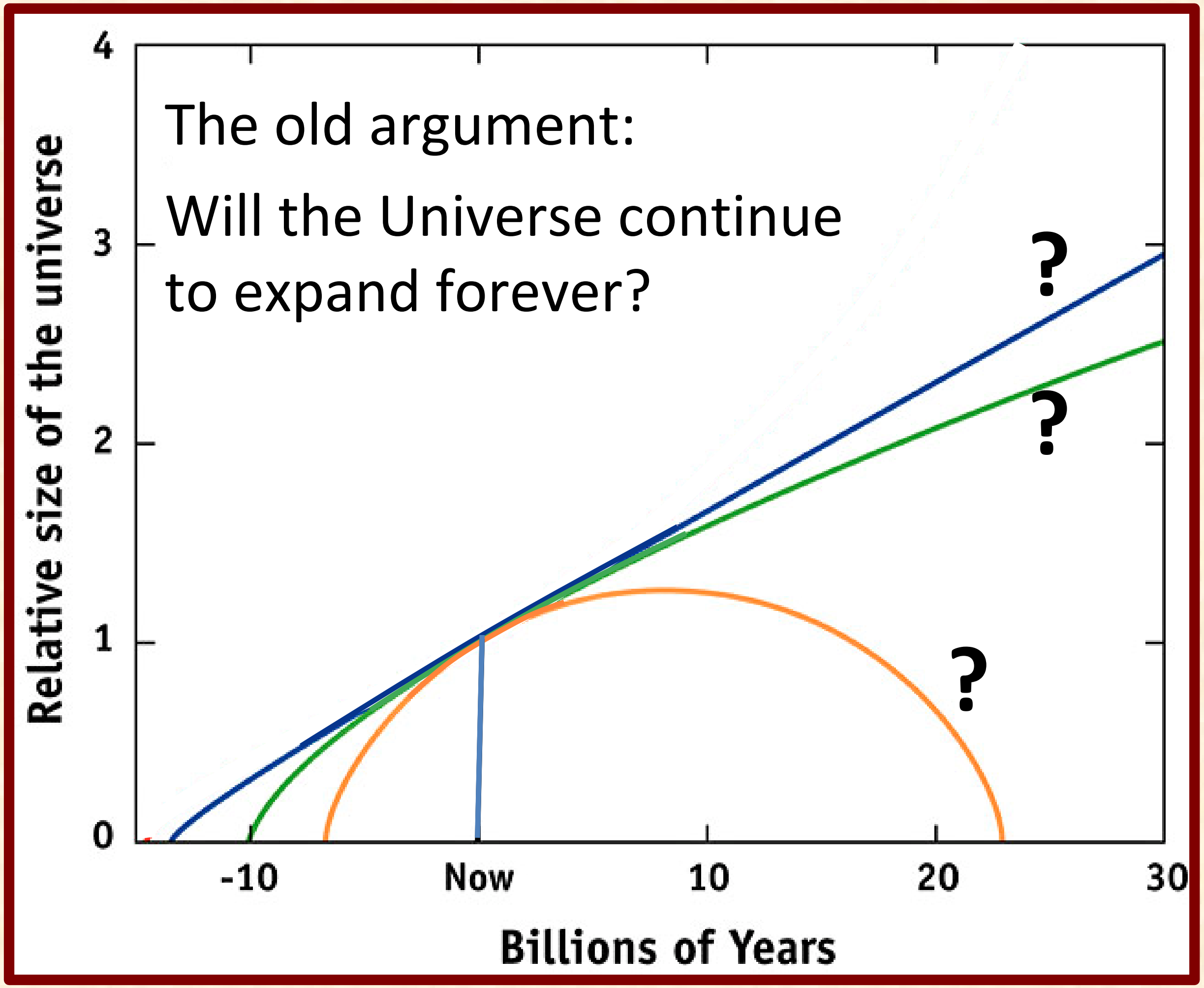
This promise must be demonstrated with a comprehensive simulation tests to lead credence to the results.

The Big Bang Theory in a Nutshell.

Three Things You Need to Know

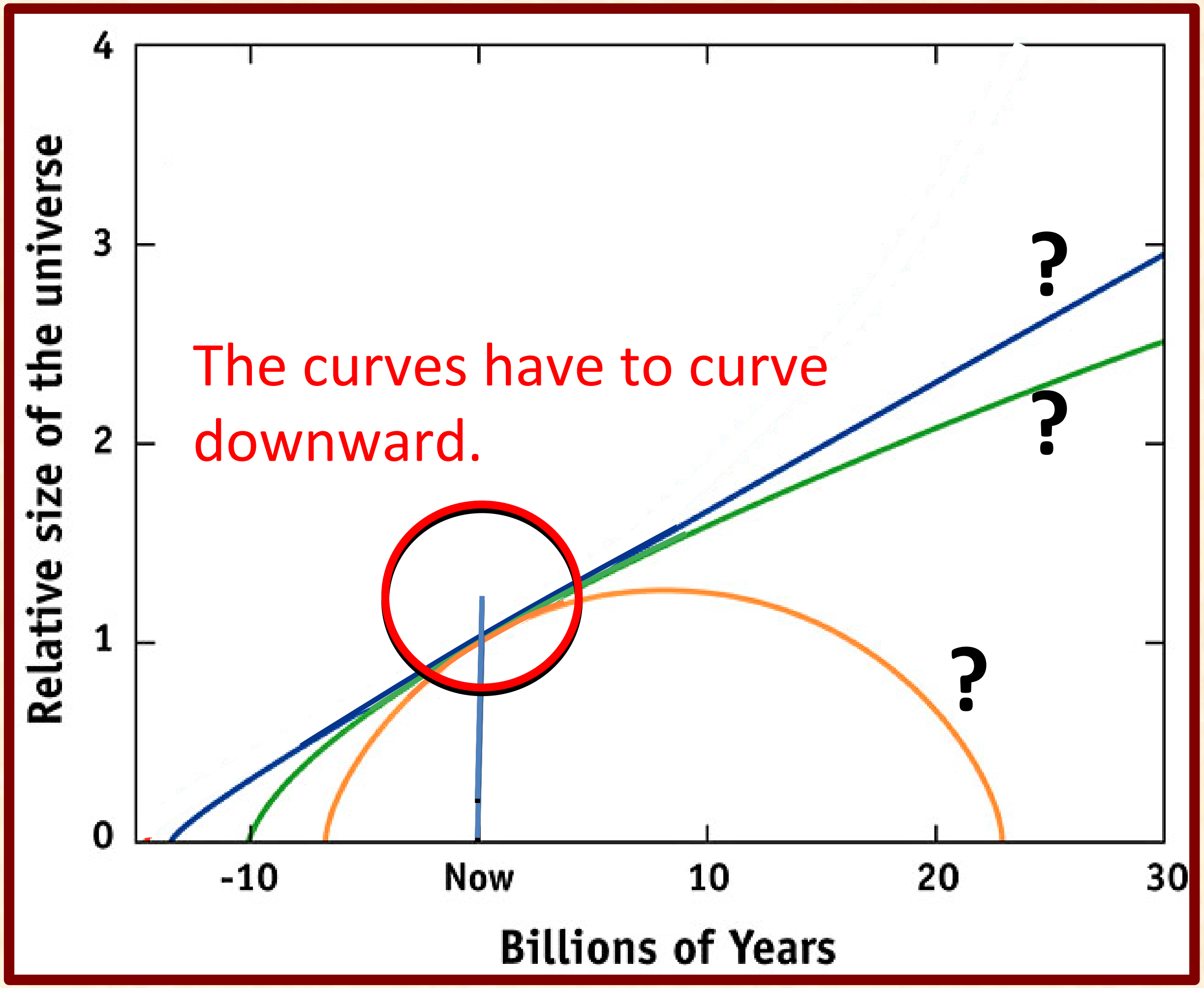
1. The universe is expanding.

The Fate of the Universe



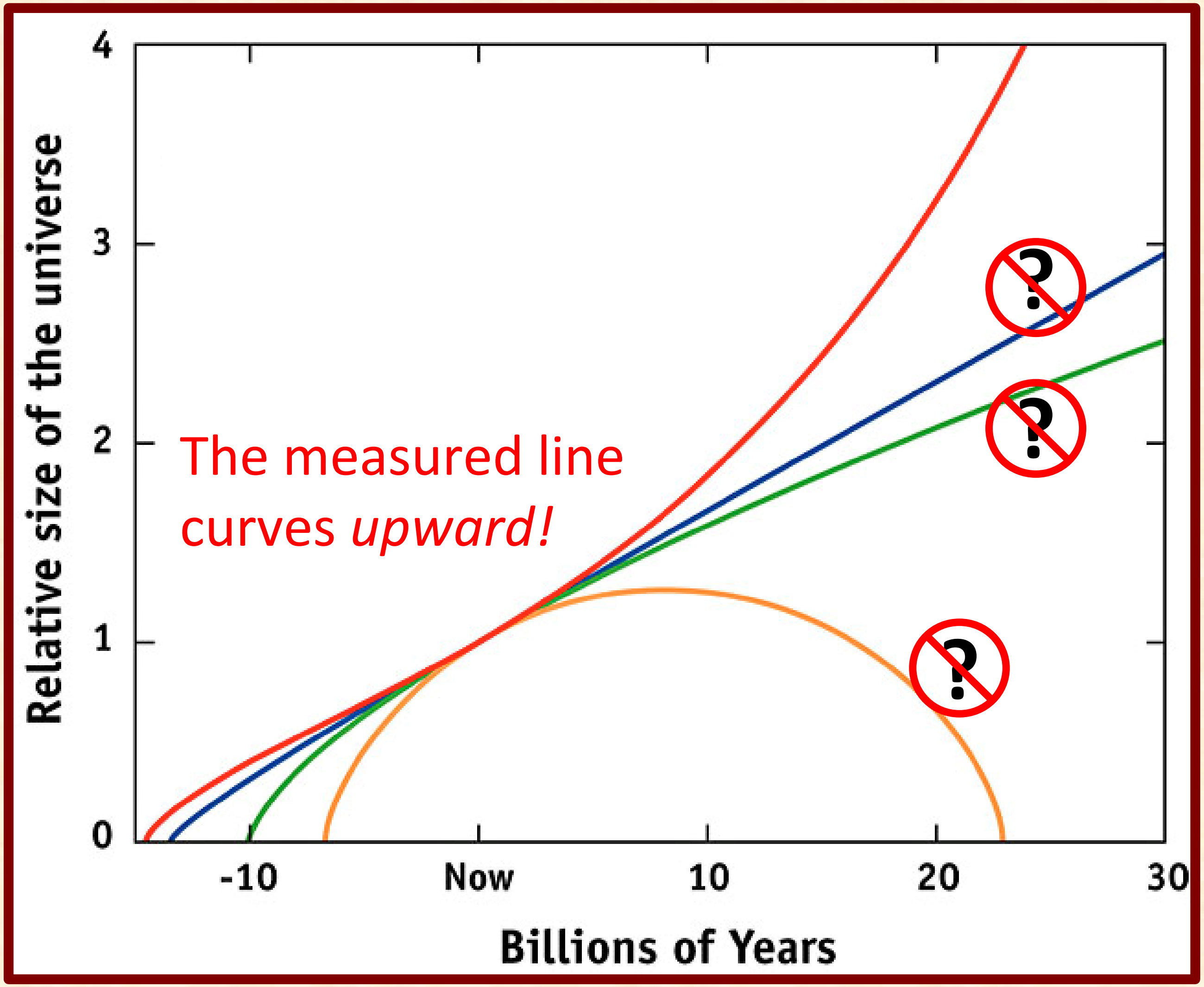
One thing for sure: expansion must slow down.

The Fate of the Universe



One thing for sure: expansion must slow down.

Surprise!



Gravity is *pushing* the expansion along, rather than slowing it down!

How Big of a Surprise is This?

Big enough to come with a free trip to Stockholm.

But *Why* Is it Such a Surprise?

In GR, there is only one way to make the Universe accelerate:

- The Universe contains a new form of energy that has negative pressure.

Alternatively, the accelerated expansion could signal a breakdown of GR on cosmological scales.

Either way, *the accelerated expansion is unequivocal evidence of new physics.*

Three Things You Need to Know

1. **The universe is expanding*, and that expansion is accelerating.***

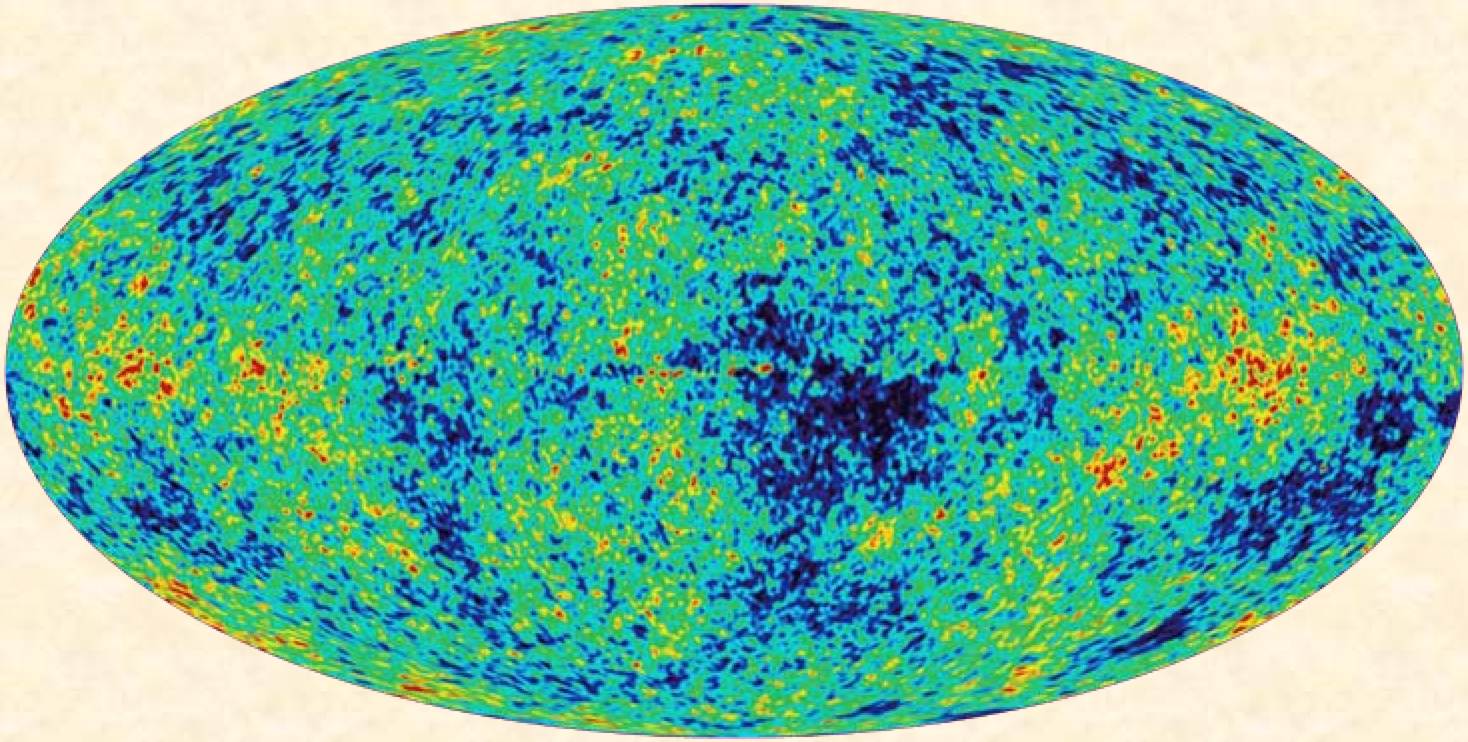
Three Things You Need to Know

1. **The universe is expanding, and that expansion is accelerating.**
2. **Early Universe was very smooth.**

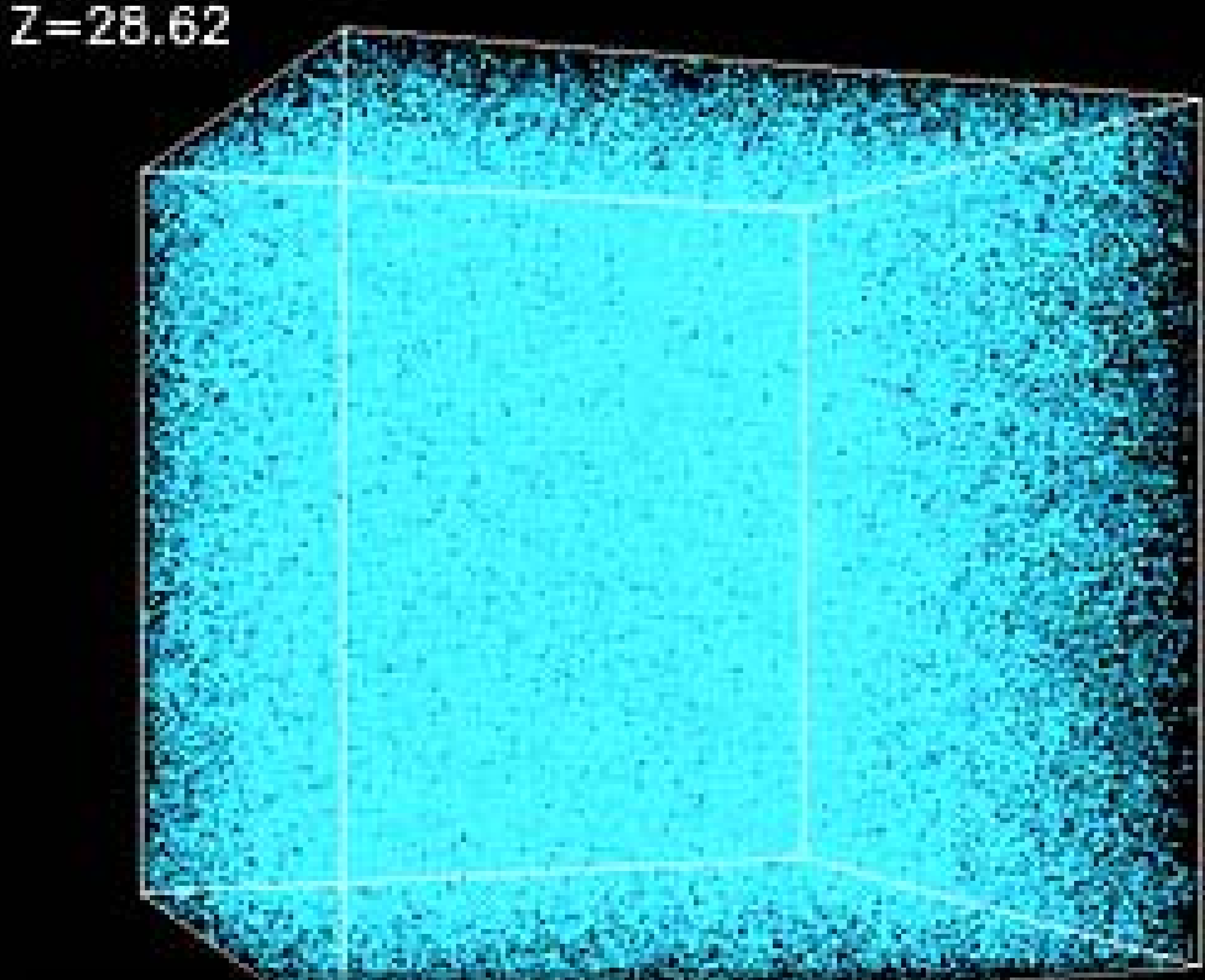
   Gravity clumps matter together to form galaxies.

A Picture of the Early Universe

Early universe was almost perfectly smooth.



But we do see *tiny* (0.001%) perturbations.

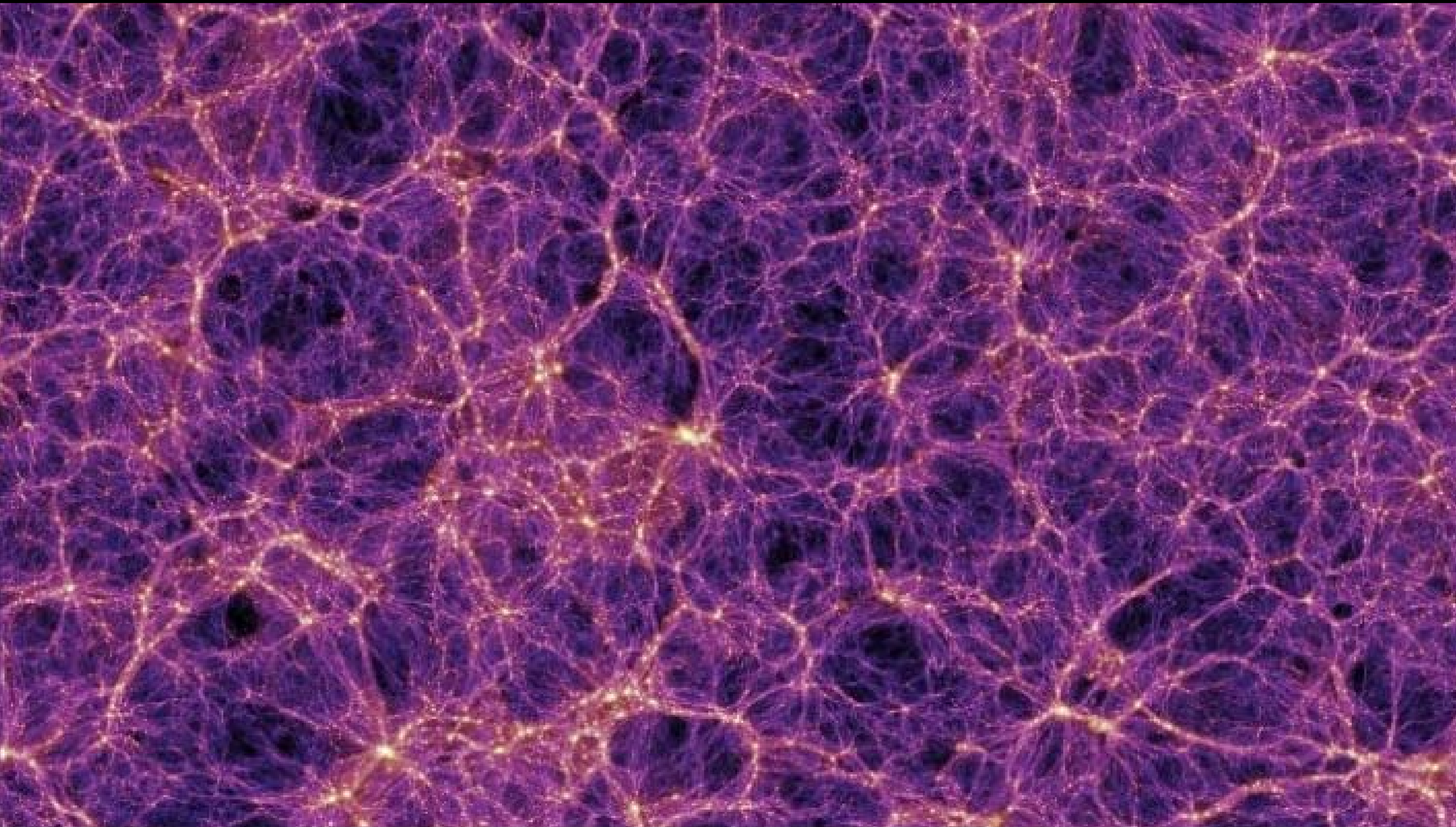


Gravity amplifies the CMB noise into the galaxies we see today

Three Things You Need to Know

1. **The universe is expanding, and that expansion is accelerating.**
2. **Early Universe was very smooth.**
   Gravity clumps matter together to form galaxies.
3. **The accelerating expansion slows down the formation of structure.**

Structure Formation and The Accelerating Universe



Using the Growth of Structure to Test Dark Energy

The expansion of the universe acts as a frictional force:

faster expansion = structure forms more slowly

Assuming we understand gravity,

we can use the measurements Hubble expansion to *predict* growth of large scale structures.

Comparing observations to predictions we can *test* if our understanding of gravity is correct!

How to Measure Growth Rate?

Need to measure the rate at which the Universe's inhomogeneities grow.

Simple!

Pick two time steps separated by a long lever-arm, and measure the amplitude of fluctuations at each time step.
1st time step we already have: CMB.

2nd time step: *how to measure the amplitude of matter fluctuations today?* (σ_8).

Why Is this Difficult?

σ_8 = rms of the density field, smoothed over a sphere of radius 11 Mpc

= Amplitude of matter fluctuations

The problem of galaxy bias:

We need the rms of the *matter* density field.

But- we can only measure the rms of the *galaxy* density field.


We’re trying to tell the mass distribution looks like this…

But this is all we can see!

Need some other method for probing *mass*.

Why Clusters Help

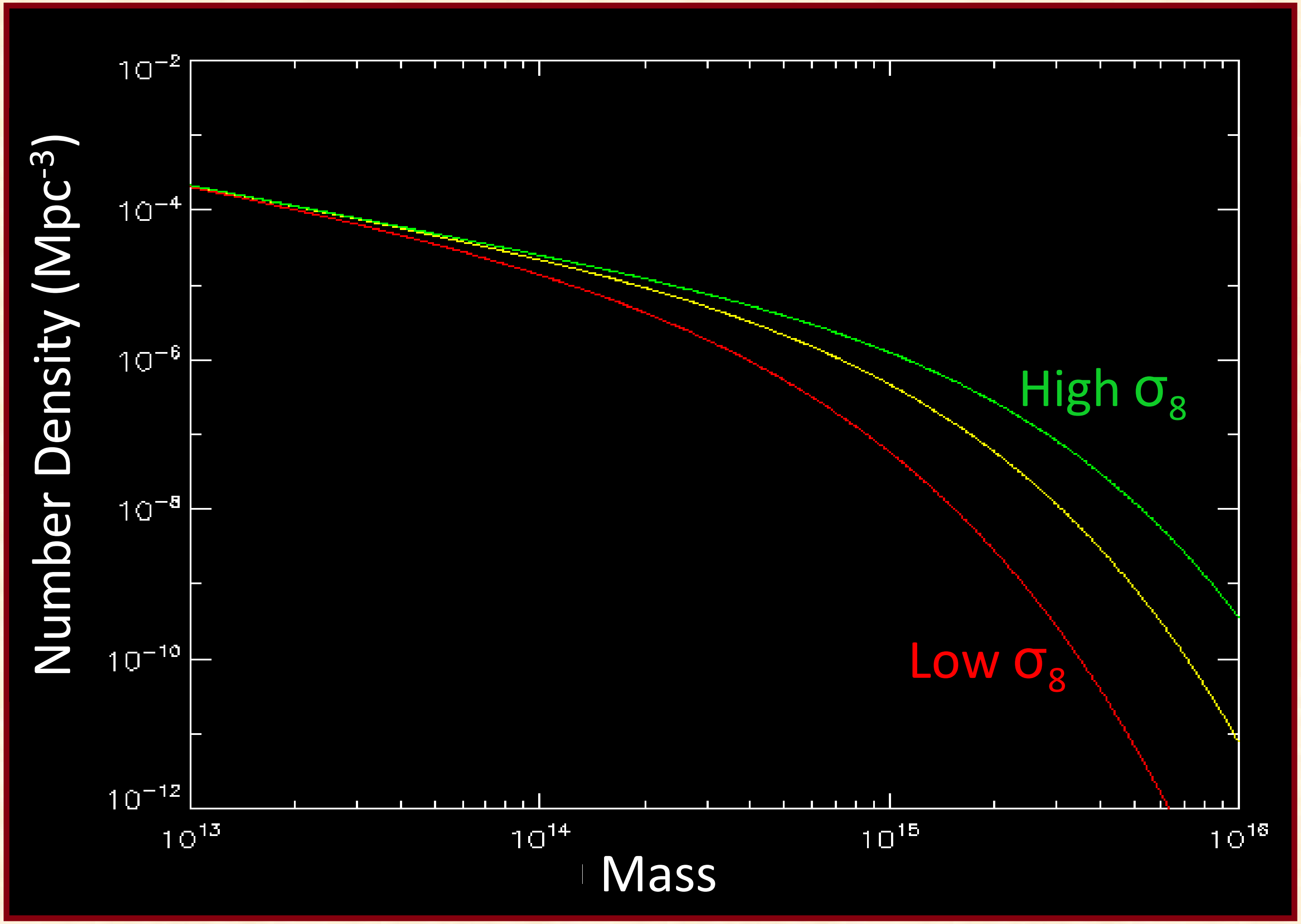
Galaxy clusters form when the gravity of an overdensity overcomes the expansion of the Universe.

Larger fluctuations = larger inhomogeneities

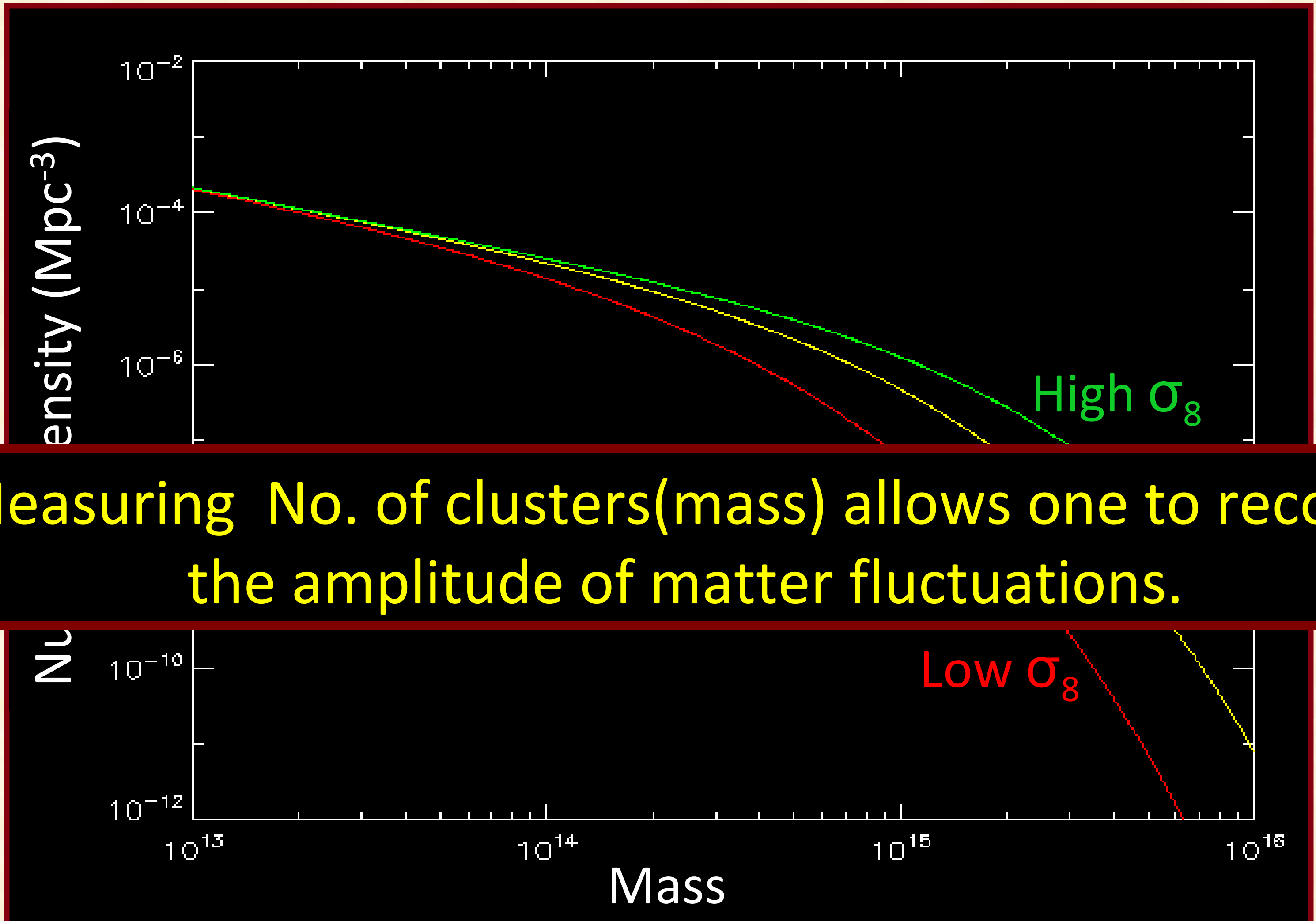
= more, bigger clusters.

The no. of galaxy clusters as a function of *mass* is a sensitive tracer of the amplitude of matter fluctuations.

How Galaxy Clusters Help: A Cartoon Model for Cluster Formation



How Galaxy Clusters Help: A Cartoon Model for Cluster Formation



Measuring No. of clusters(mass) allows one to recover the amplitude of matter fluctuations.

Cosmology with Galaxy Clusters in Two Easy Steps

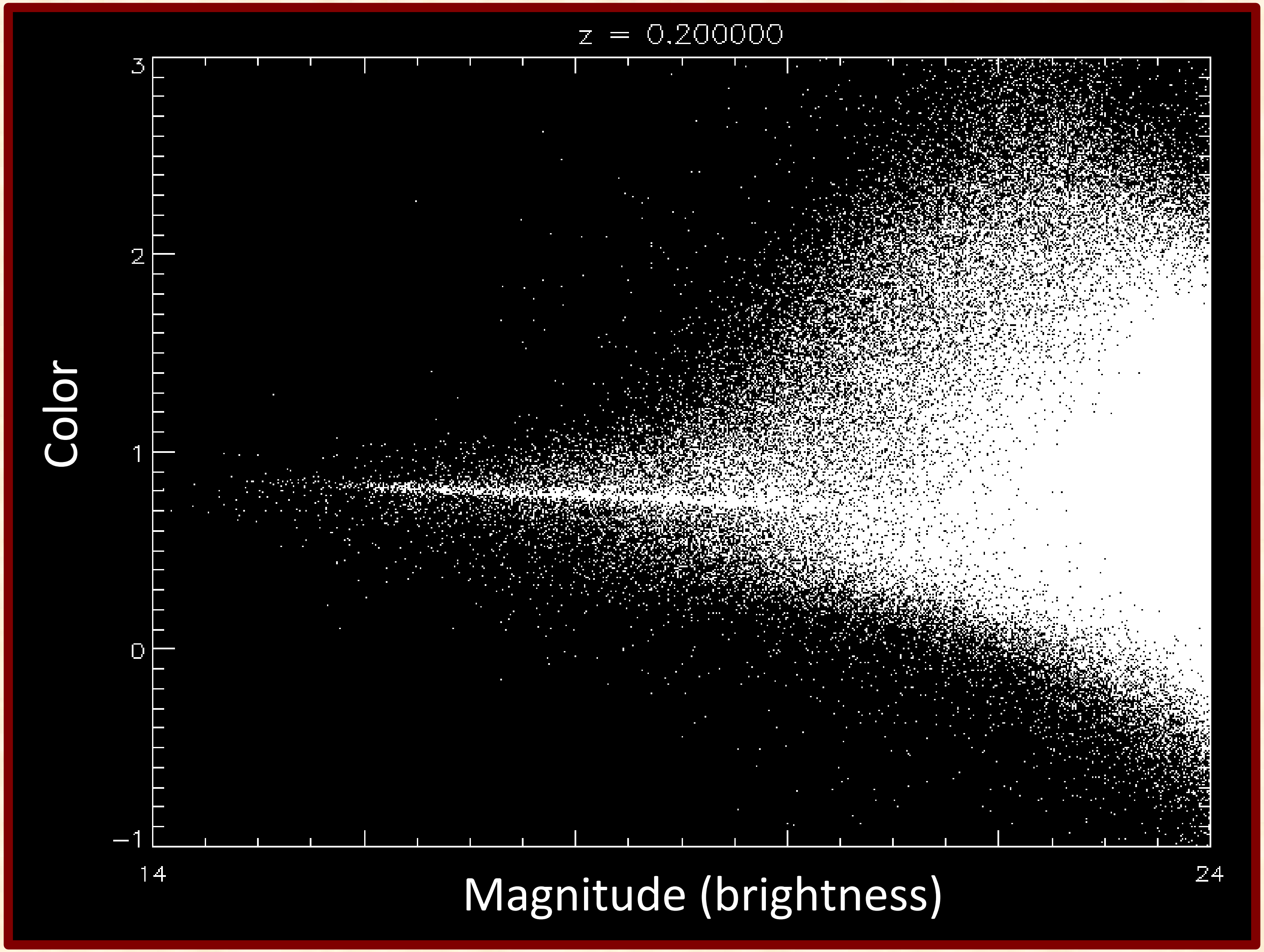
1. Find all galaxy clusters.

    This first part is relatively easy.

Finding Clusters

Look for tight groups of galaxies of the same color.

Cluster Galaxies Have Very Specific Colors



Cosmology with Galaxy Clusters in Two Easy Steps

1. Find all galaxy clusters.

   This first part is relatively easy…

2. Measure the masses of the clusters.

   This part, however…

Two Ways of Measuring Masses

1. Hydrostatic equilibrium.

   Can be used with X-ray/SZ (mm wave) data.

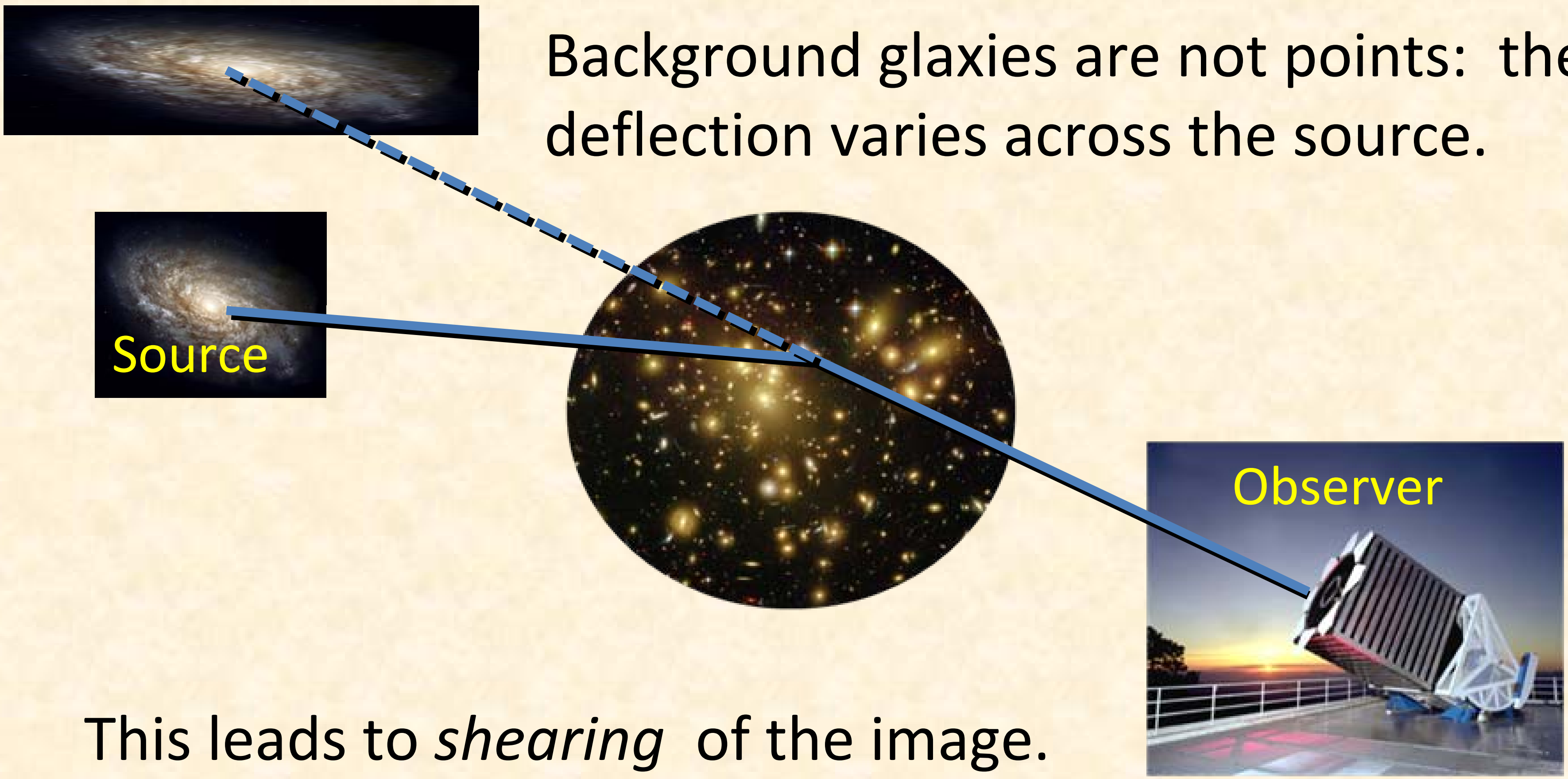
   Assume gravity from cluster mass balances thermal pressure from gas in clusters. Measure pressure (via X-rays or SZ).

2. Weak lensing: method of choice for optical (photometric) surveys.

Weak Lensing

The gravity of a galaxy cluster deflects the photons of background sources that pass near it.

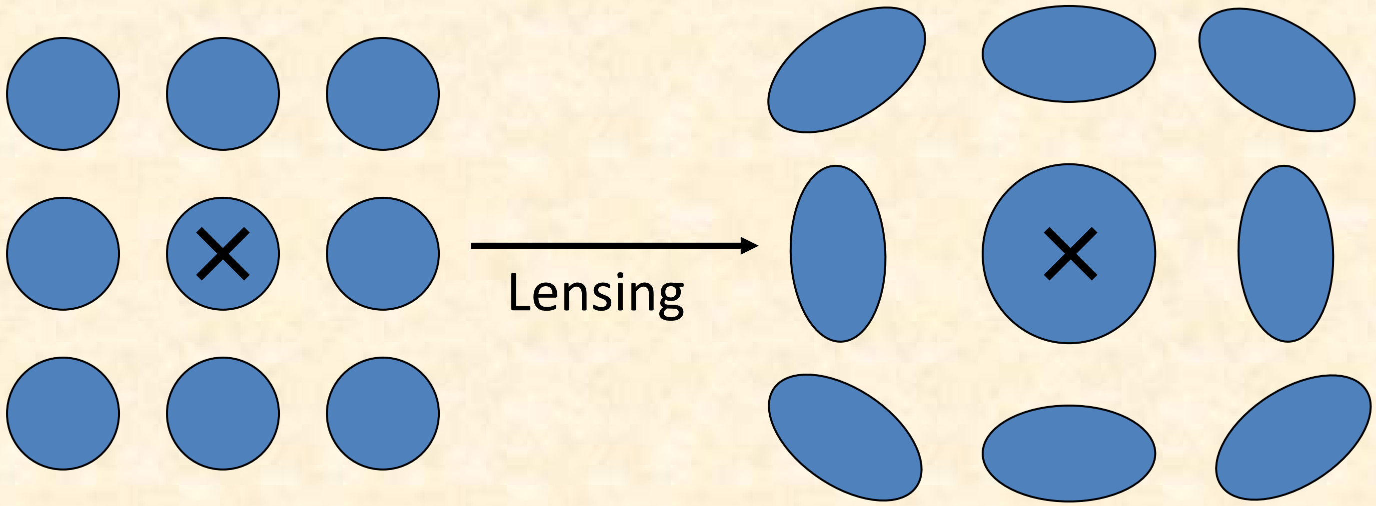
Background glaxies are not points: the deflection varies across the source.



This leads to *shearing* of the image.

Weak Lensing

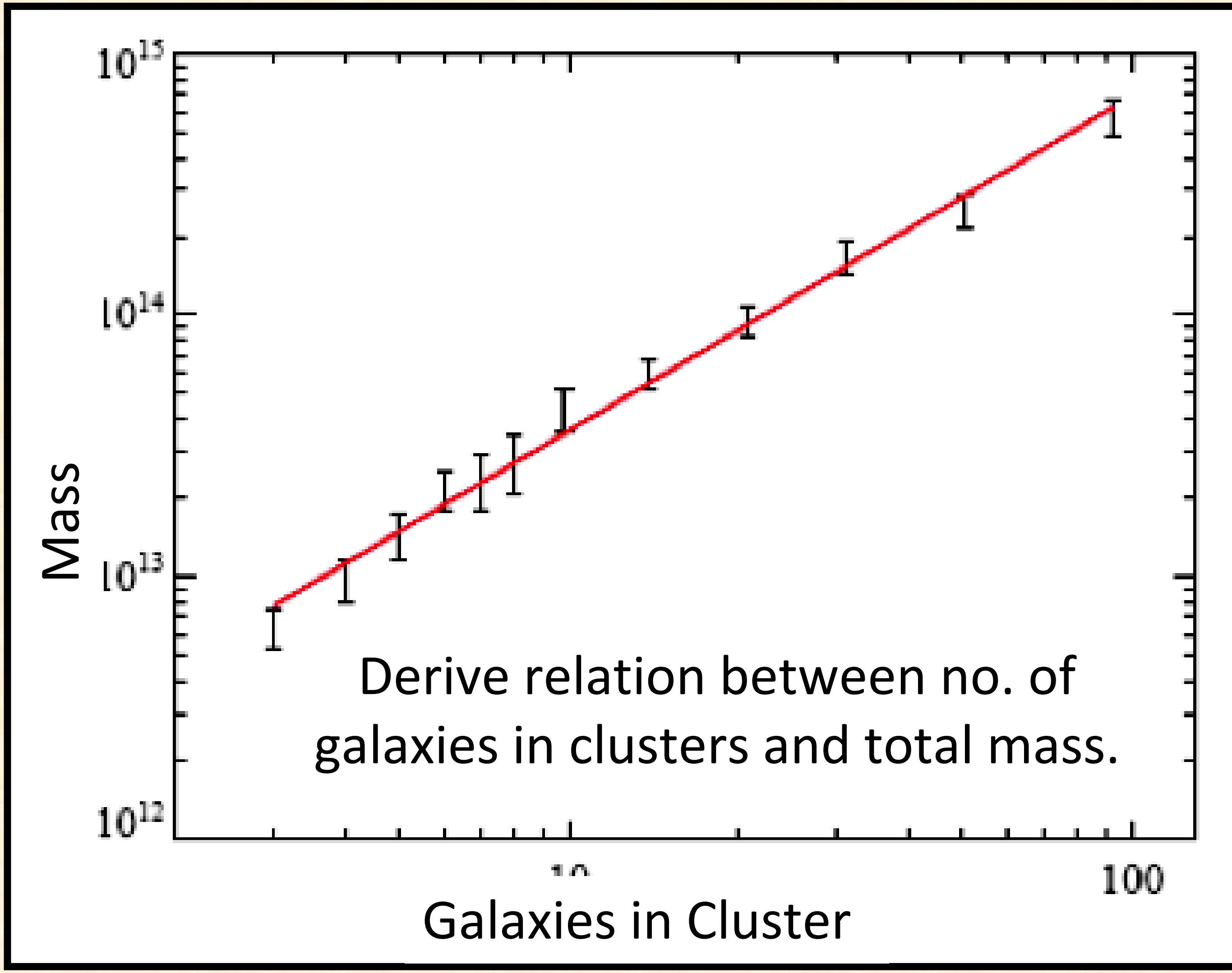
We can detect *shear* statistically:



The mean tangential ellipticity of *background* galaxies around galaxy clusters depends on the cluster mass.

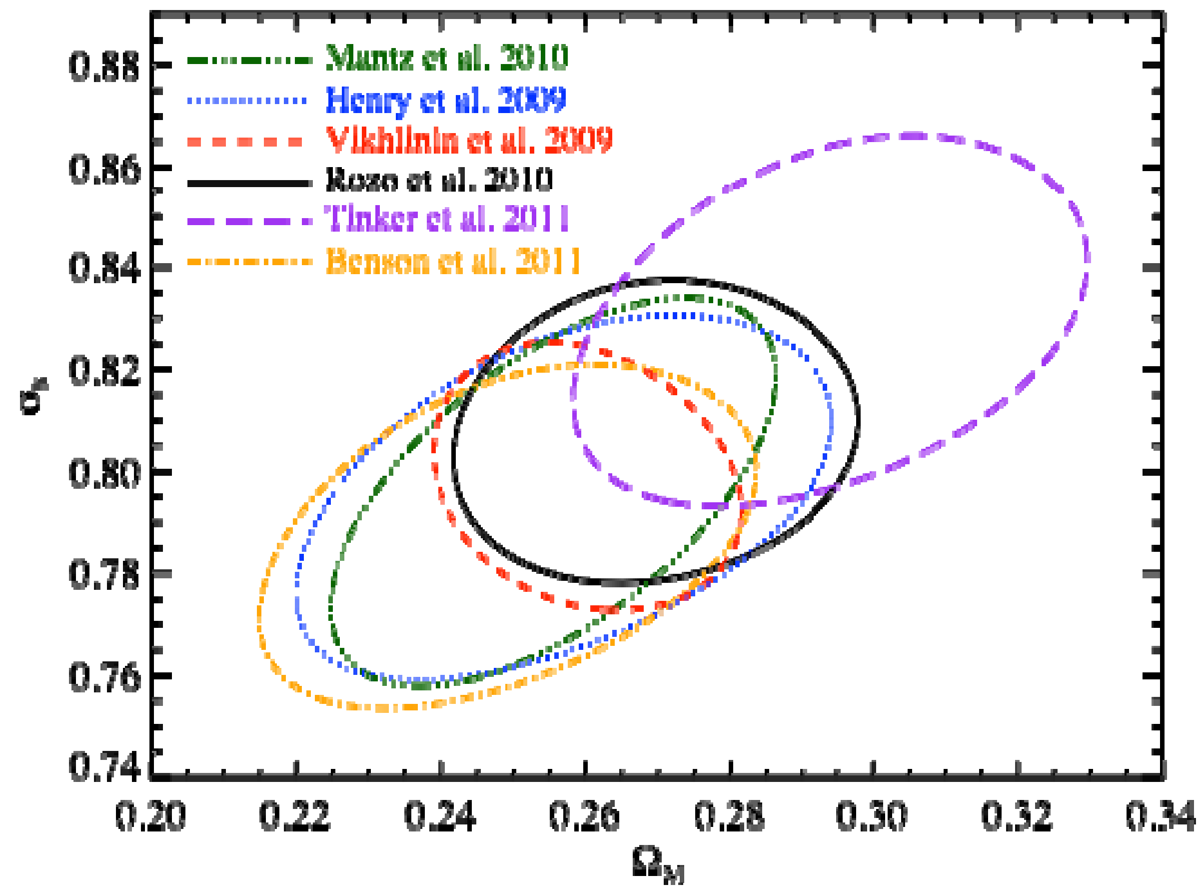
An Extreme Example of Tangential Shear

Weak Lensing: End Result



Put it all together to measure σ_8 and we find…

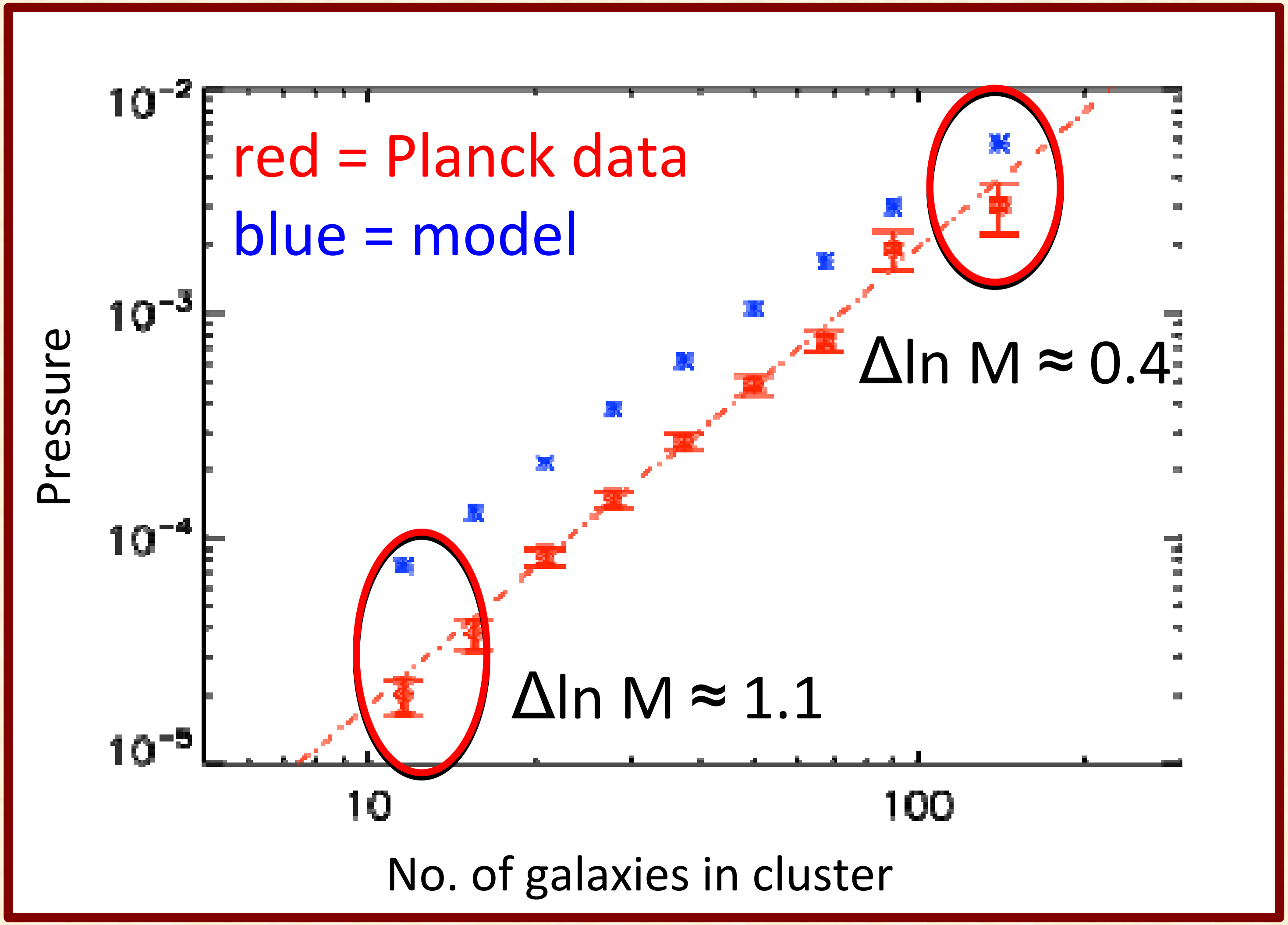
σ_8 Constraints



Results consistent with CMB support LCDM.
Results are consistent with X-rays/SZ!

Victory!

And Then Along Came Jim…



Planck Collaboration et al. 2011

Score Sheet

Optical abundance agrees with X-rays and SZ.

Optical agrees with X-rays on mass.

X-rays agree with SZ on mass.

Optical does ***not*** agree with SZ on mass.

Wait- what?

So what happened?

Warning: work in progress.

Half of the Problem: the Model

$N \xrightarrow{\text{Weak Lensing}} M \xrightarrow{\text{Hydrostatic Eq.}} Y_X \xrightarrow{\text{ICM Modeling}} Y_{SZ}$

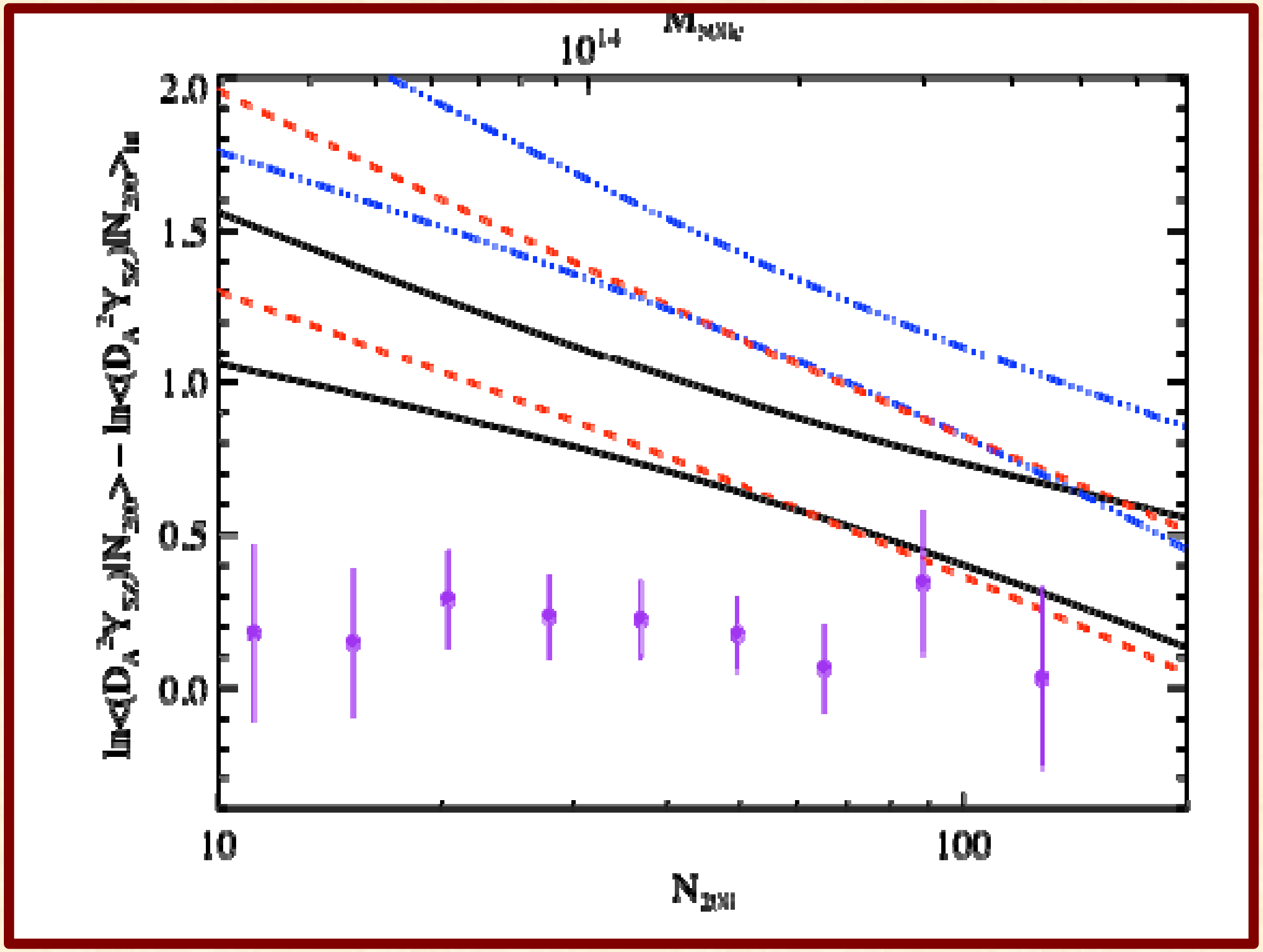
- Y_{SZ} prediction goes through X-rays.
- Different X-ray data sets are not consistent with each other.

Compare three data sets:

- V09 = Vikhlinin et al. 2009
- M10 = Mantz et al. 2010
- P11 = Planck 2011, Arnaud 2010, Pratt 2009.

Does *any* X-ray data set agree with maxBCG?

Nope: But Some Get Closer!



X-ray data used in Planck model appears to be systematically biased.

Another ¼ of the Solution

X-ray masses are hydrostatic masses, i.e.

X-rays *assume* thermal pressure exactly equals the pull of gravity.

This is generically not true: there are (small) non-thermal sources of pressure support.

Simulations predict ~10%-20% bias *from well understood physics*.

10%-20% hydrostatic bias is a *firm* prediction.

The Remaining ¼

After the hydrostatic bias correction, there is still mild tension.

Obvious solution: the optical masses are biased *high*.

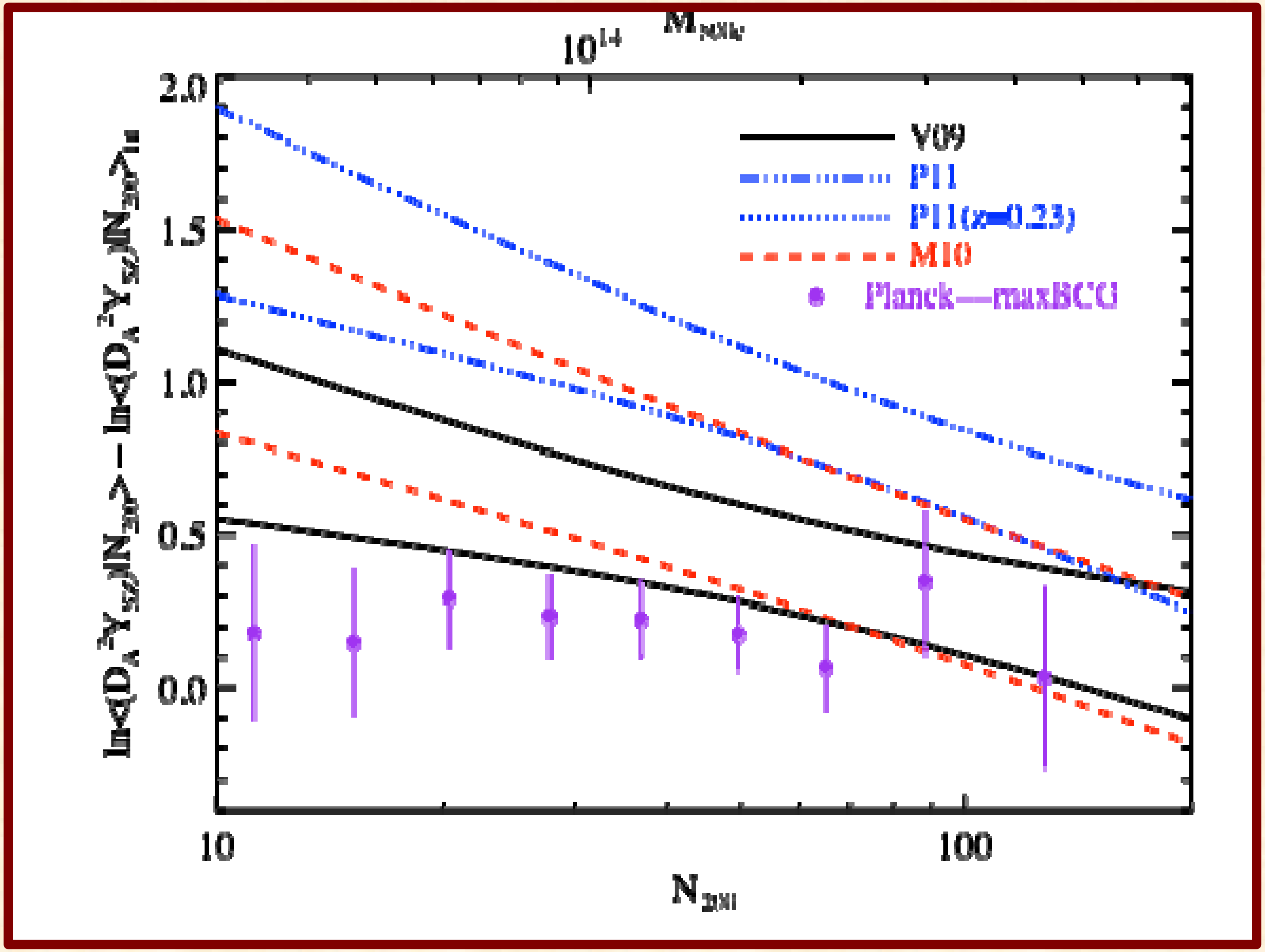
10% correction is enough, and within quoted errors.

Why would the weak lensing masses be biased?

Best guess: photoz's- the source redshifts are slightly off.

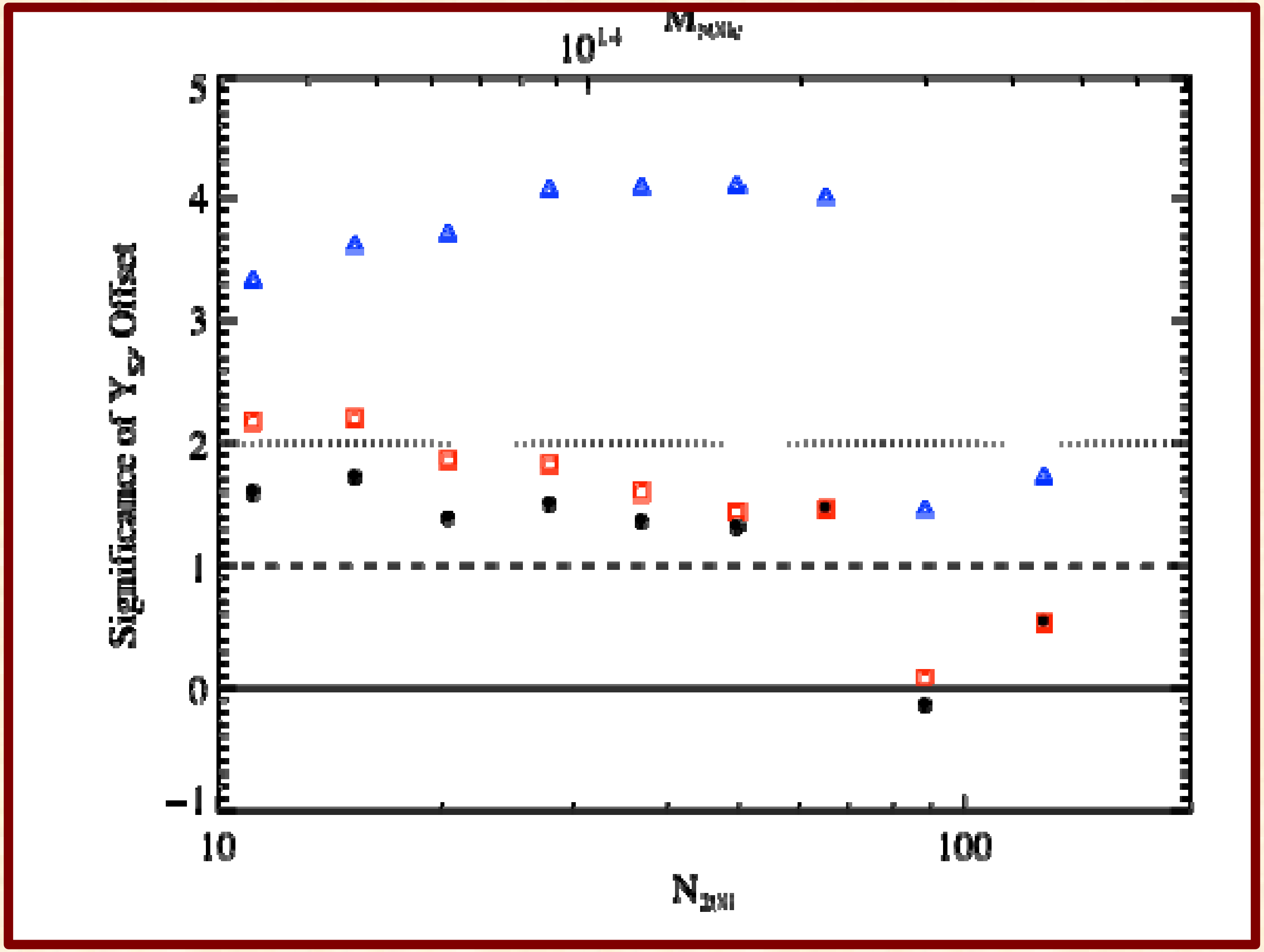
Will be tested in the near future (photoz's have improved).

Y_{SZ}-N With Bias Corrections



Agreement is *much* better.

Significance of Y_{SZ}-N Offset



Proposed solution is statistically acceptable.

Score Sheet

Changes to optical/X-rays are *within allotted systematic uncertainties.*

Optical abundance agrees with X-rays and SZ.

Optical agrees with X-rays on mass.

X-rays agree with SZ on mass.

Optical *does* agree with SZ on mass.

As far as we can tell, *all data is in agreement*.

Victory?

I guess we'll see.

Take Home Messages

• The combination of optical, X-ray, *and* SZ data can detect biases that *any two probes alone do not*.

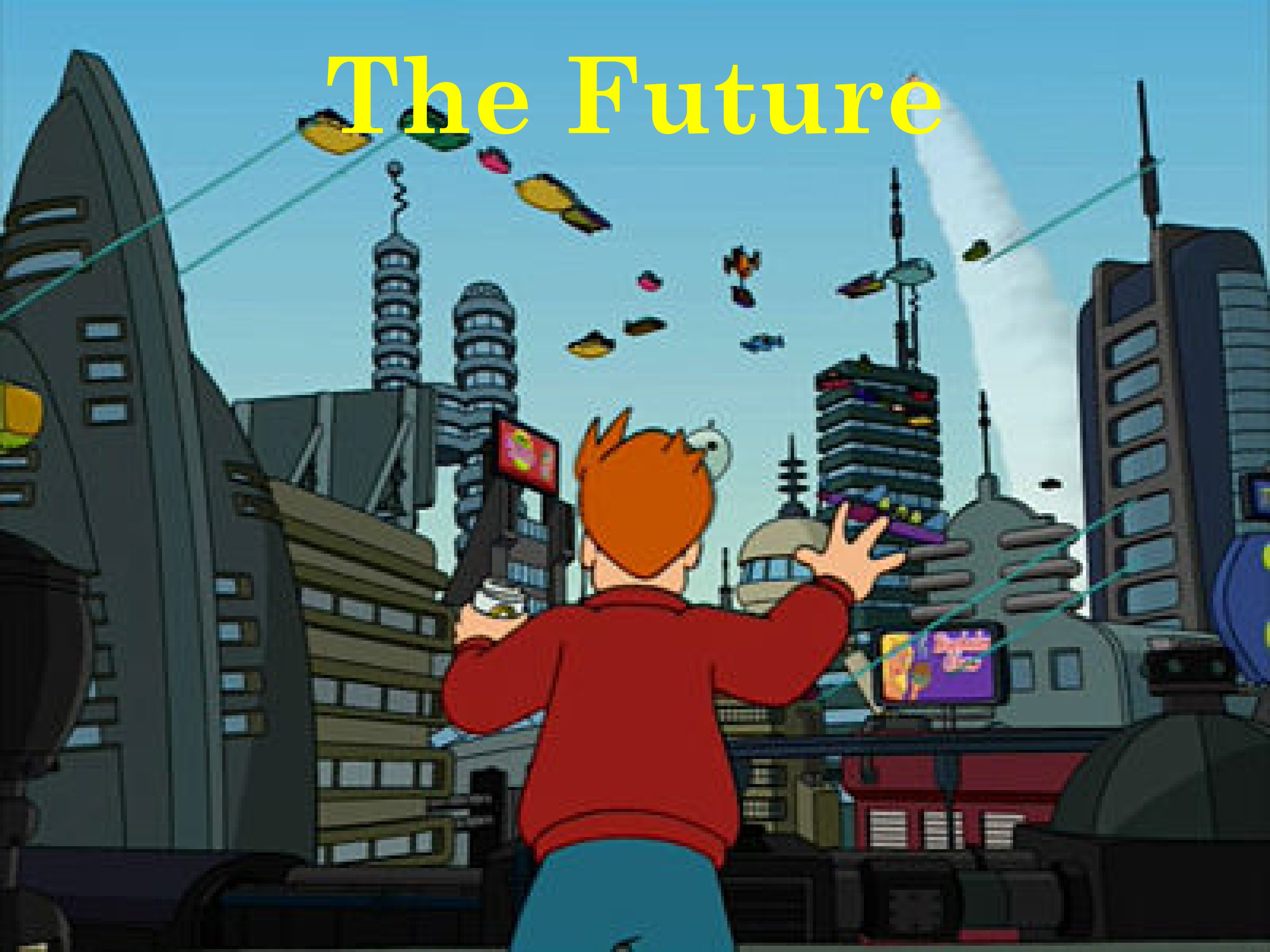
• This tension arises *irrespective of cosmological considerations.*

i.e. it is a powerful systematic probe for cluster cosmology.

• Results are a *validation* of cluster cosmology:

Original agreement is preserved, corrections are within systematic errors, and resolution is an explicit demonstration of self-calibration.

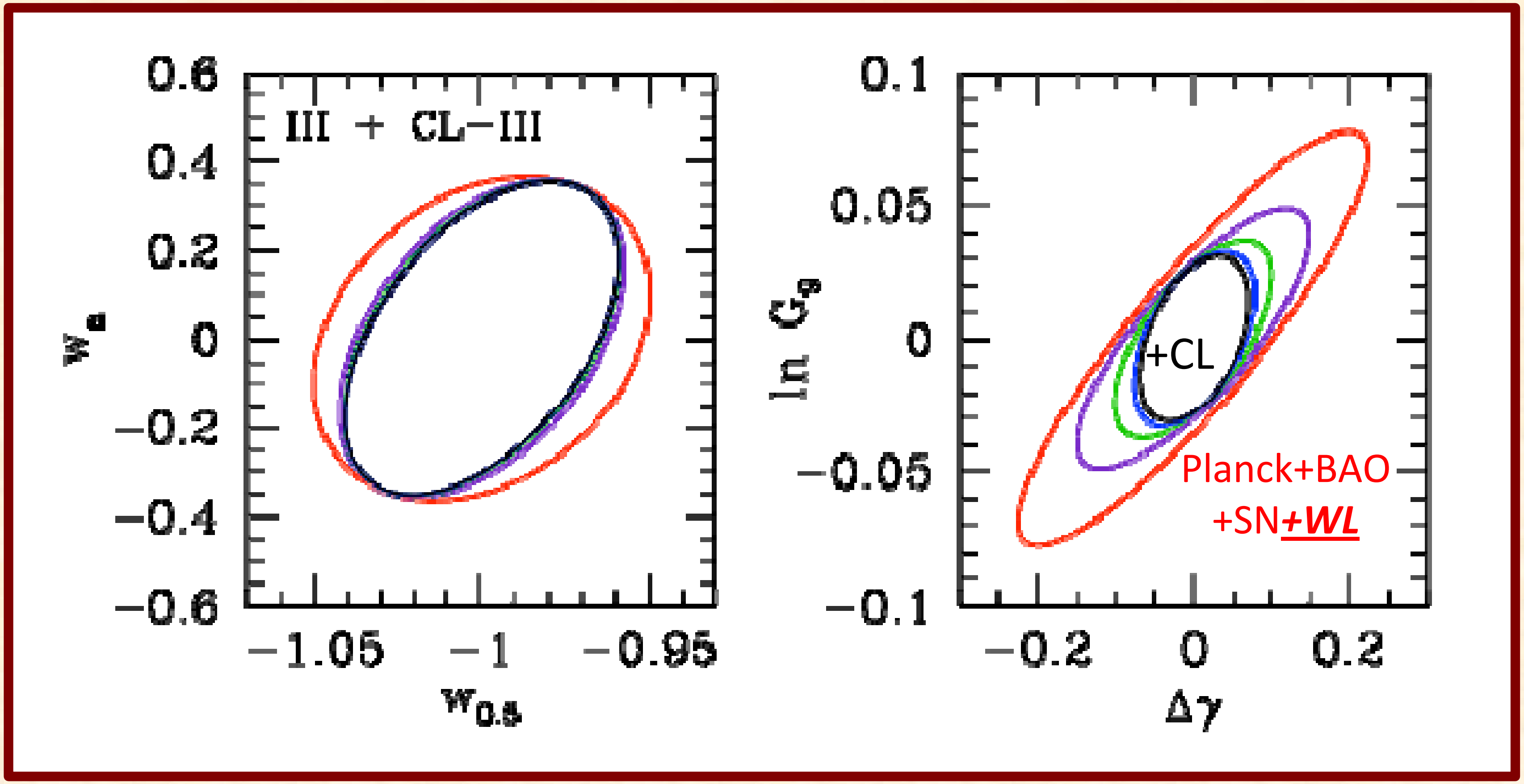
The Future



Do Clusters Even Have a Future in Dark Energy?

Why do clusters when you can do cosmic shear?

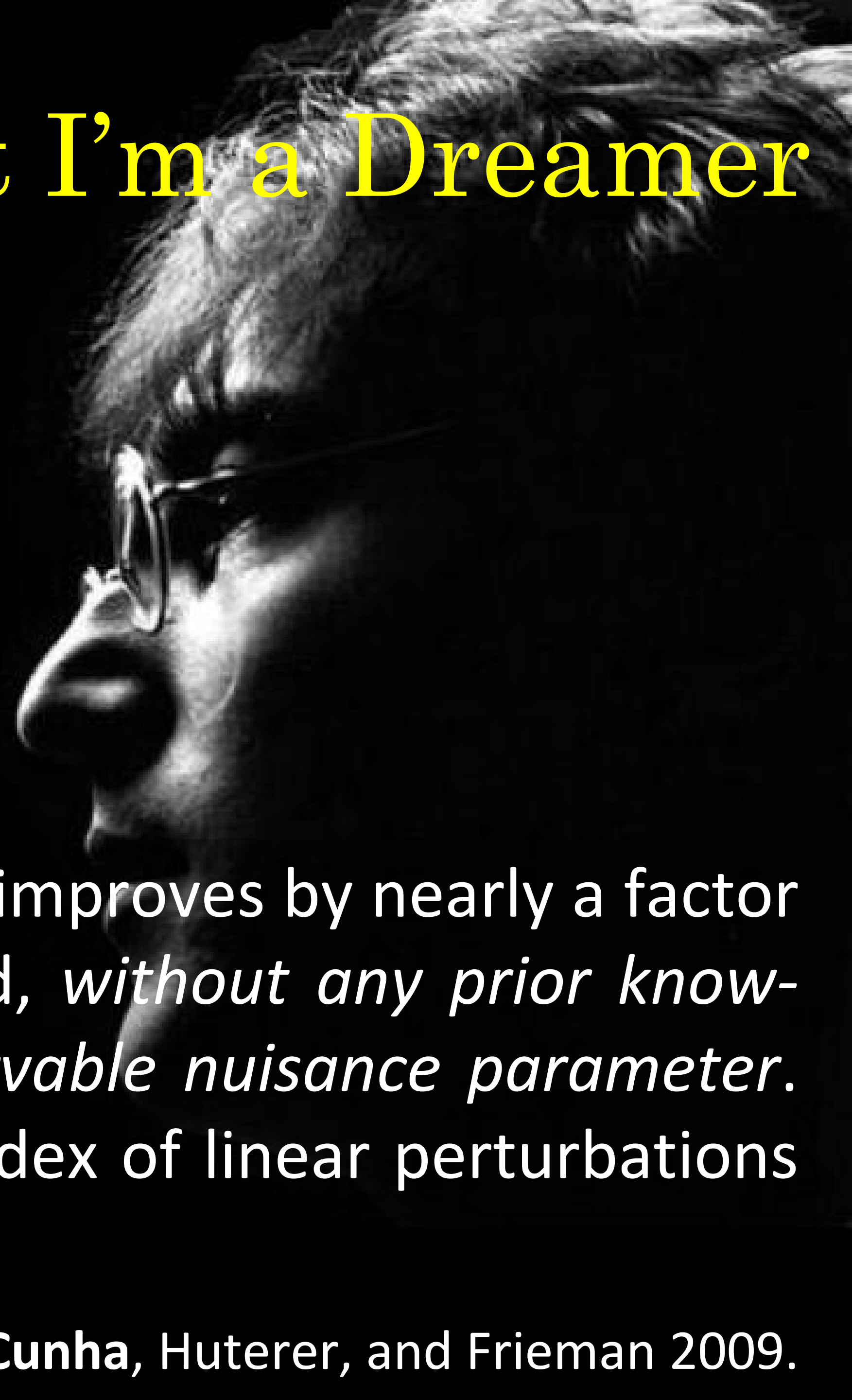
Cosmology at Stage III (next 5-10 years)



Clusters are the best stage III modified gravity probe.

From Weinberg, Mortonson, Eisenstein, Hirata, Riess, and Rozo (2012).

You May Say That I'm a Dreamer



The FoM from BAO, SN, and WL improves by nearly a factor of two when clusters are added, *without any prior knowledge on the cluster mass-observable nuisance parameter*. Measurements of the growth index of linear perturbations γ improve by a factor of several.

Cunha, Huterer, and Frieman 2009.

You May Say That I'm a Dreamer

The resulting [cluster] constraints [marginalized over mis-centering, source redshift, and halo concentration] are in fact quite comparable to those from tomographic cosmic shear *without any marginalization over systematic errors*.

Oguri and Takada 2010.

Do Clusters Even Have a Future in Dark Energy?

YES.

The Dark Energy Survey

DES will map 5000 deg^2, and detect galaxies out to $z=1$.

We can map the growth of large scale structure across half of the history of the Universe.

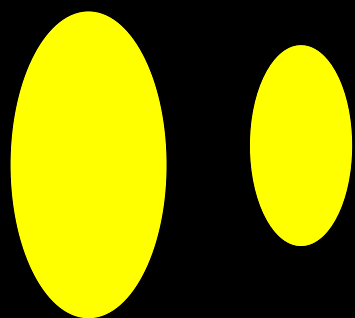
On the sky *this fall*.

The Dark Energy Survey

Bottom line: DES clusters are likely to be the single most powerful probe of large scale structure until the advent of *Euclid*.

Are there any show stoppers?

The Monster in the Dark



Systematics

Systematics

Current constraints are *systematic limited* by the uncertainty in the masses.

However, there are three key points worth emphasizing:

- If our resolution to the Planck-maxBCG problem is correct, then clusters will have had a proven record: *our systematics were properly estimated.*
- For optical galaxy clusters, there are clear solutions to today's limiting problems, namely photoz's and cluster miscentering.
- Even if unresolved, self-calibration is sufficient to match cluster shear *in the absence of systematics.*

Systematics

Bottom line:

There are good reason to believe systematics will go down significantly over the next few years.

But we need to know this for a fact!

Testing the Faith

Only one way to test if everything works as advertised:

Simulate the entire experiment.

- Run N-body simulations with known cosmologies.
- Generate lightcone.
- Populate lightcone with galaxies.
- Perform ray tracing: displace and shear galaxies.
- Run cluster finding algorithms.
- Run weak lensing mass calibration pipeline.
- Retrieve cosmology, and compare with input.

Testing the Faith

This simulation program is not optional.

I expect such a program will be standard for all upcoming photometric surveys (DES, Pan-STARRS, LSST).

DES: ongoing test with 250 deg^2.

Final challenge: 5-10 simulations of 5,000 deg^2

Are we up to the task?

Stay tuned.

Summary

There is good agreement between cluster cosmology analyses today, but Planck data has opened new questions.

We believe these questions have been resolved, and main outcome is a validation of cluster cosmology.

Future work – and the DES in particular – should decrease statistical and systematic uncertainties, and should make galaxy clusters the most powerful Stage III probe of structure growth.

This promise must be demonstrated with a comprehensive simulation tests to lead credence to the results.