So What’s The Fuzz All About?

Planck allows us to constrain cosmological parameters in several ways:

• CMB primaries
• Galaxy clusters

The problem: *if we assume vanilla LCDM,*

The cosmology from CMB primaries (pXVI) are in tension with the cosmology from clusters (pXX).

Tension can be eased if neutrinos are massive.
How Seriously Should You Take this Tension?

My answer: not very.

Why?

The cluster cosmology results are *very* sensitive to our ability to calibrate cluster masses.

There is strong evidence of systematics in the mass calibration used by Planck.

In fact, this was all known a priori.
Cluster Cosmology
Using Large Scale Structure to Test GR/Dark Energy

Early universe was almost perfectly smooth.

But we do see tiny (0.001%) perturbations.
Structure Growth is Sensitive to Cosmological Parameters

Low matter density  High matter density
Basic Plan of Attack

- Measure initial conditions (CMB).
- Measure expansion history (e.g. SN and/or BAO).
- Predict amount of structure today ($\sigma_8$).
- Measure structure today ($\sigma_8$), and compare to prediction.

This is where clusters come in.

$\sigma_8 = \text{rms of the density field, smoothed over a sphere of radius 11 Mpc}$

i.e. $\sigma_8$ measures “clumpiness”.
Why Measuring $\sigma_8$ is Hard

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

More structure = more massive halos

Count halos as a function of mass to infer $\sigma_8$. 
The Key Point

More massive clusters = more structure = higher $\sigma_8$

The abundance we observe is fixed;

The key moving part is the cluster mass.

Cluster mass goes up, $\sigma_8$ goes up.

It’s all about the masses!
Neutrinos and $\sigma_8$

Given initial conditions from the CMB, massive neutrinos result in reduced structure.
Clusters measure the x-axis - **but remember the key point!**
Neutrinos and Clusters

Low mass clusters.

Rozo et al. 2013.
Neutrinos and Clusters

High mass clusters.
Cluster Cosmology in 3 Easy Steps

1. Find all galaxy clusters.
   This part is comparatively “easy.”

2. Measure cluster masses
   This part is hard.
Two Ways of Measuring Masses

• X-rays (this is what Planck used).
  • flux \( \sim \rho^2 \): measure gas density
  • spectrum measures temperature.
  • **Assume hydrostatic equilibrium**, get masses.

• Weak gravitational lensing.
Weak Lensing

The gravity of a galaxy cluster bends the light of galaxies behind it.

Differential deflection across source shears the image.
We can detect *shear* statistically:

The mean tangential ellipticity of *background* galaxies around galaxy clusters depends on the cluster mass.
Cluster Cosmology in 3 Easy Steps

1. Find all galaxy clusters. This part is comparatively “easy.”
2. Measure cluster masses. This part is very hard.
3. Infer $\sigma_8$ from cluster counts and learn about neutrinos!
Planck Results

\[ \sigma_8 \text{ is lower } \rightarrow \text{ explain with neutrinos} \]
Planck Results

Planck XX

CMB

Can only be reconciled if the clusters are 45% *more massive* than what Planck originally thought!

Clusters (+ BAO)

$\sigma_8$ is lower -> explain with neutrinos

Planck Results
But are Planck cluster masses trustworthy?
A Brief History of Planck Masses
Is There Good Evidence in Favor of the Planck Masses?
Evidence for Planck Masses

Measure $L_X$-M relation
Measure $Y_{SZ}$-M relation

→ Predict $Y_{SZ}$-$L_X$ relation

It works!
Evidence for Planck Masses

Measure $L_X$-M relation
Measure $Y_{SZ}$-M relation

→ Predict $Y_{SZ}$-$L_X$ relation

“The excellent agreement argues that the SZ and X-ray calibrations we have used are fundamentally sound.”

It works!
But-
A Puzzle: Optical Doesn’t Fit!

Planck Collaboration 2011

red = Planck data
blue = model
model = optical+X-ray

Optical requires X-ray masses to be biased low by 40%.
How to Reconcile?

Possibilities:

• Optical masses/predictions could be wrong.
• X-ray masses/predictions could be wrong.

Answer: both!  
(Rozo et al. 2012 a,b,c,d).
Where Do Planck Masses Come From?

Calibration of $Y_{SZ}$-$M$ in 3 steps:

1- Calibrate $Y_X$-$M$ using **hydrostatic masses**.
2- Calibrate $Y_{SZ}$-$Y_X$ (ask me after)
3- Combine to get $Y_{SZ}$-$M$ (ask me after)

There is evidence of problems in all 3 steps!
X-Ray Masses

2 key systematics:
- hydrostatic bias
- measurement systematics (e.g. detector calibration)

Hydrostatic bias:
• Simulation values are range from 10%-30%.
• Cosmology analysis assumes 20% ± 0% (!)
• Inconsistent with treatment in Planck 2011.

Bottom line: need ~20% ± 10% correction
Comparing X-rays to X-rays

10\%-15\% systematic differences seen in $T_X, Y_X$. 

Factor of 2
average difference

Rozo et al. 2012
Comparing X-rays to X-rays

XMM calibration cluster masses are ~10%-20% lower than Chandra observations.

Chandra Calibration is itself uncertain at ~10%.

Suggests 15% ± 15% correction to Planck masses.


10%-15% systematic differences seen in $T_X$, $Y_X$. 
Optical Masses

• Raw measurements seem very robust:
  - 3 independent shear measurements
  - 1 quasar magnification
  - 1 galaxy magnification measurement
  - 1 CMB lensing measurement

  These are *all* consistent with each other.

• Interpretation is subtle!
  - Mass and optical richness are *correlated*.
  - Introduces a ~10% bias.

Net Result

Planck mass calibration should be increased by 35%±20%.
Optical calibration should be reduced by 10%±10%.

These 2 effects reconcile optical+X-ray+SZ data!
But What About This?
Important Point: Solution Must be Consistent with *All* Data.

Any solution must simultaneously fit:

- Abundance data (Optical *and* X-ray)
- WL data
- L$_X$ data
- Y$_{SZ}$ data (Integrated pressure)

In R12, we show our scaling relations fit all available data.
This is *strong evidence* that Planck masses are biased.

In fact- we predicted the tension between Planck and CMB primaries! (Rozo et al. 2013).
GABRIEL GARCIA MARQUEZ

Chronicle of a Death Foretold
Are Our Masses Consistent with Planck?

We don’t have the Planck selection functions. But-

We can assume Planck cosmology, and infer cluster masses from abundance.

How do these CMB-inferred masses compare to our?
Mass Comparison

Low masses

High masses

Units: \( D_A^2 Y_{sz} \): \( 10^{-6} \) Mpc\(^2\)
M: \( 6 \times 10^{14} \) \( M_\odot \)

“Tension” is between 1\( \sigma \)-1.5\( \sigma \)
Lessons and Conclusions

1. There is significant constraining power in multi-wavelength observations of galaxy cluster.

2. Planck (+BAO) clearly favors a high – but plausible - cluster mass calibration.

At this time, there is no tension between clusters and CMB for a flat LCDM cosmology. i.e. no evidence for massive neutrinos.
But?

There are other lines of evidence that prefer a lower matter density and/or $\sigma_8$, e.g.:

- Cosmic shear from CFHTLens
- Growth measurements from RSD
- $gg$ lensing+clustering.

How solid are these lines of evidence?

I don’t know.
One more thing...
Cluster Cosmology in 3 Easy Steps

1. Find all galaxy clusters.
   This part is comparatively “easy.”
redMaPPer

SDSS DR8 redMaPPer footprint

What is redMaPPer?

redmapper is a photometric cluster finding algorithm.

The key outputs of a cluster finder:

• Location of the cluster: redshift
• Some estimate of size: richness = # of galaxies.
  (Relating between size and mass is calibrated with WL)

So how does redmapper do at these things?
Performance Tests in DR8
Excellent Photozs

Typical photoz error at low redshift: $\sigma_z/(1+z) \approx 0.006$

$\Delta z$ of 0.003 = 1000 km/s
Well Understood Photozs

\[ \frac{z_{\text{spec}} - z_{\text{photo}}}{\sigma_z} \]
Inferred scatter in mass
≈ 20%
Low Scatter Mass Proxy

\[ M_{\text{gas}} (10^{14} M_\odot) \]

Inferred scatter in mass
\[ \approx 20\% \]
Low Scatter Mass Proxy

\[ M_{\text{gas}} \left(10^{14} M_\odot\right) \]

~1% bad photometry.
Low Scatter Mass Proxy

~1% outlier rate.
Low Scatter is Unique to redMaPPer

Rozo and Rykoff 2013

redMaPPer
20% scatter

Next best thing
(Wen et al. 2012)
33% scatter
We Can Test redMaPPer with Planck and Vice Versa

245 clusters in common between Planck and SDSS RM.
100% of Planck cluster clusters in SDSS region, z<0.6.

Rozo et al. 2014
Comparison to Planck Clusters

Inferred scatter in mass ≈ 21%
(200+ clusters)
Comparison to Planck Clusters

Inferred scatter in mass ≈ 21%
(200+ clusters)

bad redshifts in Planck.
We Can Test redMaPPer with Planck and Vice Versa

245 clusters in common between Planck and SDSS RM.
100% of Planck cluster clusters in SDSS region, z<0.6.

Clusters establish a tight scaling relation.

Identified 3 failures in redMaPPer (1.2% failure rate).
Identified 36 redshift failures in Planck (14.7% rate).

Also: 5 projection effects
17 new high z candidates (z>0.6)

Rozo et al. 2014
Cool Projection!
Completeness and Purity

Completeness:
100% of all Planck and ACT clusters in SDSS found.
100% (90%) of all $L_X > 10^{44}$ ergs/s ($10^{43}$ ergs/s) clusters found.

Purity:
100% of all rich, low redshift clusters detected in X-rays.
(X-ray detection is only limited by depth in RASS).
Purity

Non X-ray detection rate consistent with RASS flux limit.

Matching to ROSAT Bright and Faint Source Catalogs.
Summary

At this time, there is no tension between clusters and CMB for a flat LCDM cosmology.