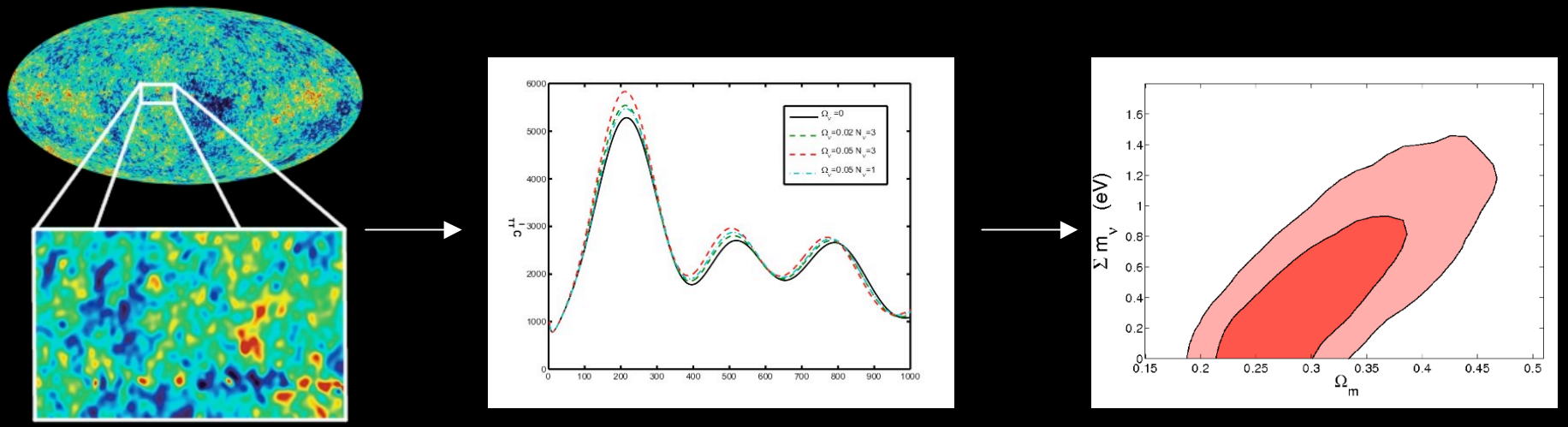
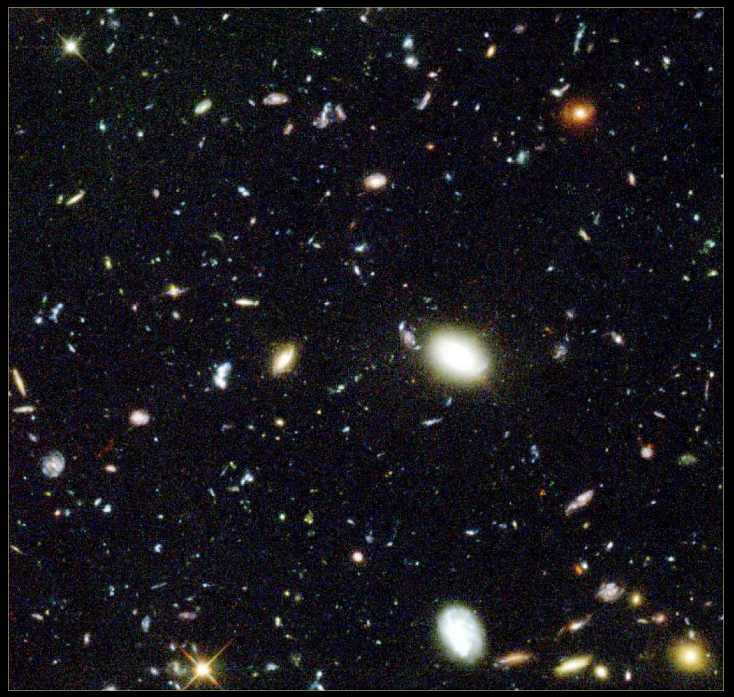
Weighing Neutrinos with Cosmology

"What *exactly* are they doing…?"



arXiv:0911.5291 - *PRL*

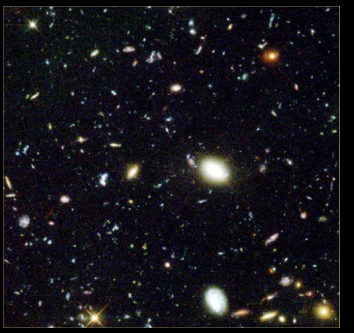
Outline



1. 'The Cosmological Model'
2. Neutrino signatures in the model
3. Probes of the Model
   - Cosmic Microwave Background
   - Galaxy Surveys
   - Supernovae and Baryon Oscillations
4. Current/Previous work: Thomas, Abdalla & Lahav: [arXiv:0911.5291] - *PRL*
5. For the Future…?

Determining the neutrino mass is important because:

OR - *"things to put in funding applications…."*



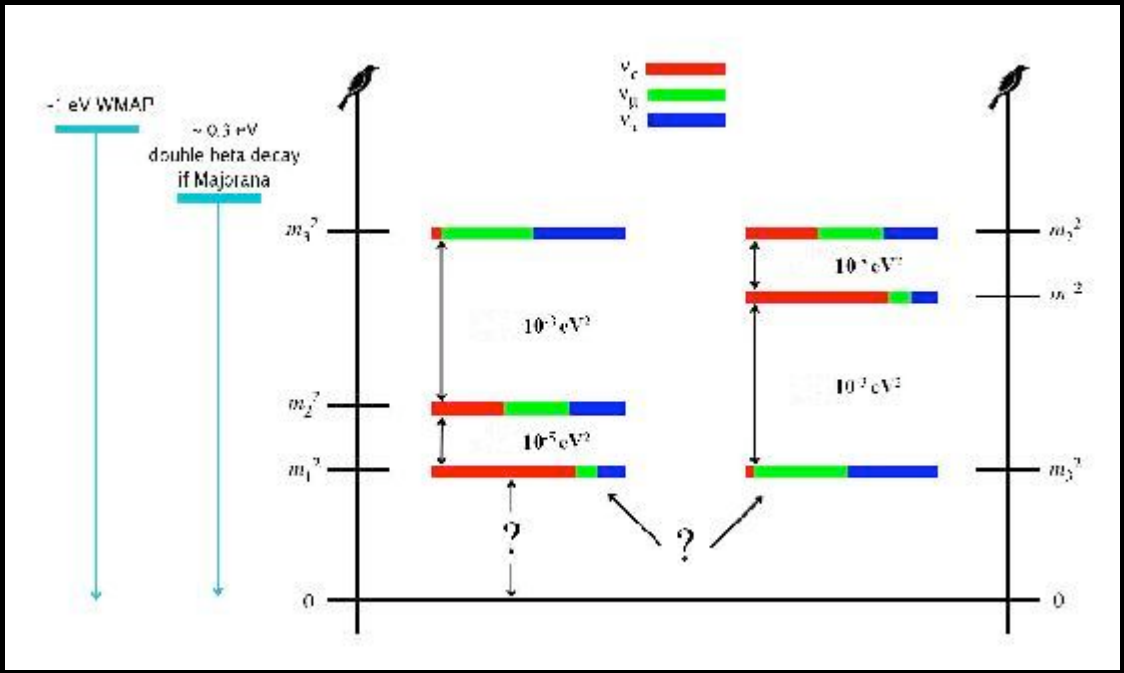
1. Neutrinos' mass has a significant impact on cosmological measurements
2. Incorrect neutrino mass will bias cutting edge science: dark energy
3. Particle physics - cosmology comparison: unique check on all cosmology!

- -

- Extension to the standard model and intrinsic nature etc.
- (Neutrinos: 3 Nobel Prizes over the last quarter of a century or so!!)

Neutrino oscillations indicate they have mass!

A cosmologist's understanding..



But not on the absolute scale of mass…

For example…

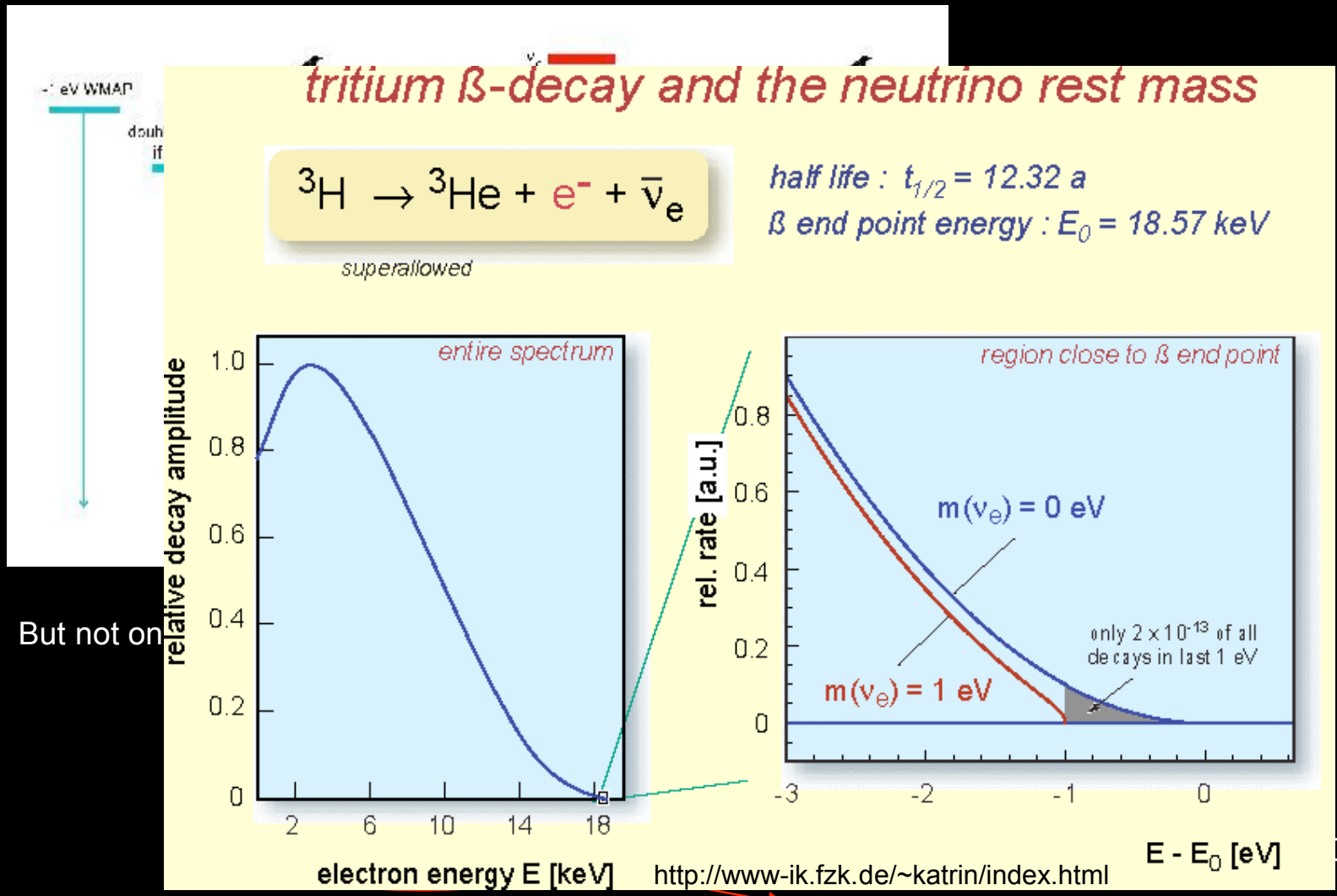
- Beta-decay kinematics → KATRIN
- Neutrinoless double beta-decay → nemo
- Cosmology! → ST, Abdalla, Lahav (2009)

Age of precision Cosmology →

Not just interesting
An integral part of the *cosmological model…*

Neutrino oscillations indicate they have mass!

A cosmologist's understanding..



But not on

09)

http://www-ik.fzk.de/~katrin/index.html

Not just interesting

Age of precision Cosmology

An integral part of the *cosmological model…*

What is Cosmology?

- Study of the Universe on the largest scales
- Asks: What is the Origin, evolution and fate of the Universe?

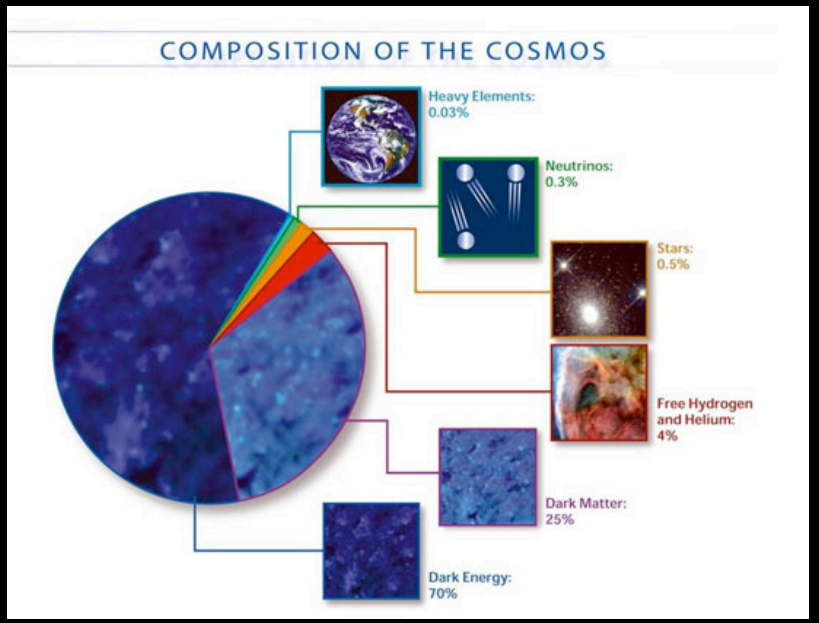
- Take a census of the Universe's contents

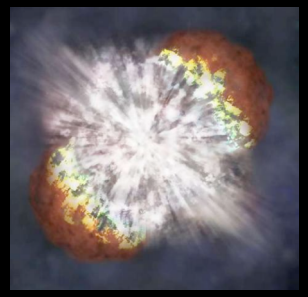
"In science there is only physics; all the rest is stamp collecting", Rutherford

BUT:

Interesting contents!

Themes intimately related

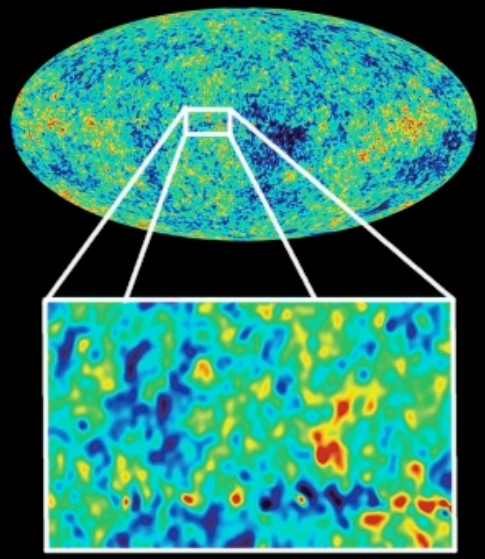




Famously, supernovae indicated Dark Energy

Probe of distance and expansion: The smooth Universe

E.g., Perlmutter et al. (1999)



Cosmology

Combination of probes, data and surveys

Probes of anisotropy: The clumpy Universe!

APM survey: *Efstathiou et al. (1990)*

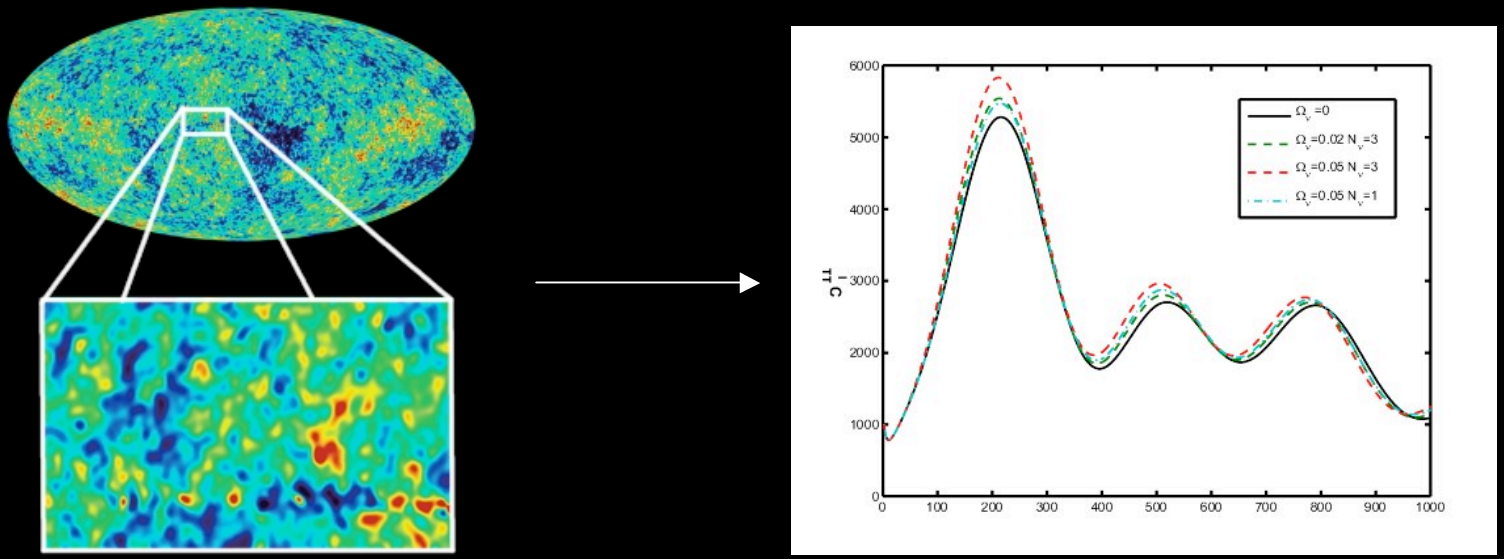
The Cosmological Model

Does NOT predict the *exact* location of a galaxy or structure in the sky

Does predict the *statistical* distribution of galaxies or structures in the sky

The *statistic* is the 'Power Spectrum'

The power spectrum tells us how much some field varies on different scales

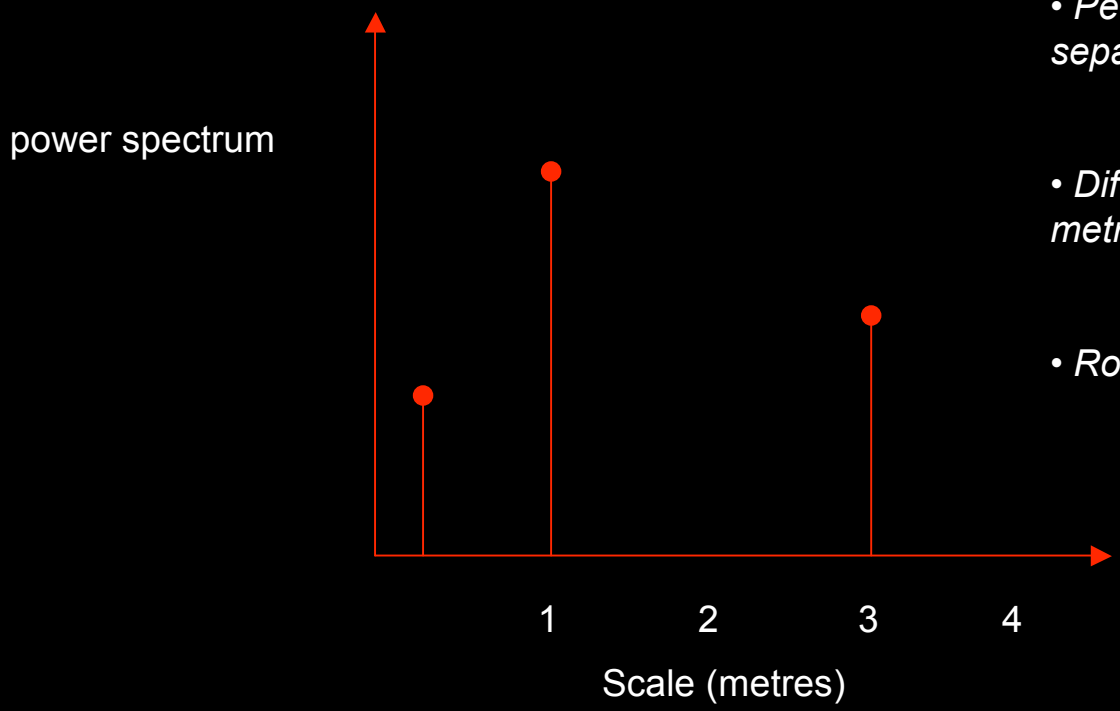


Parameters go into the cosmological model - detailing physical quantities (e.g. neutrinos or dark energy) - that change the power spectrum -> compare to data

The Power Spectrum

"Variance of the underlying statistic as a function of scale"

Power spectrum of people at a party

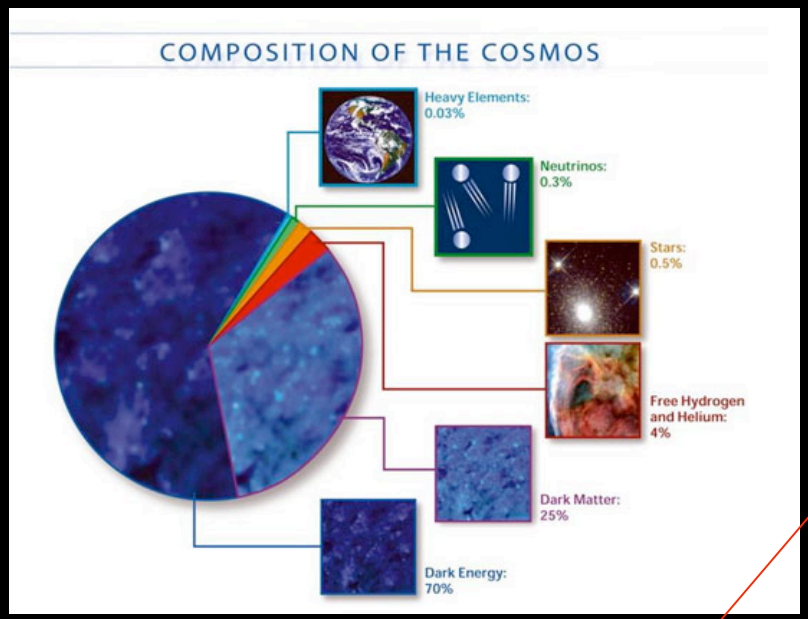


- *People cluster into speaking groups - separated by ~ metre*
- *Different groups separated by several metres*
- *Romantically involved might be closer…*

Neutrino

Signatures in the Model

• Suppress the *growth of matter structure* and cosmological perturbations



Neutrinos have large thermal velocities and Free-stream out of over-densities/inhomogeneities thus suppressing the clustering of matter and galaxies

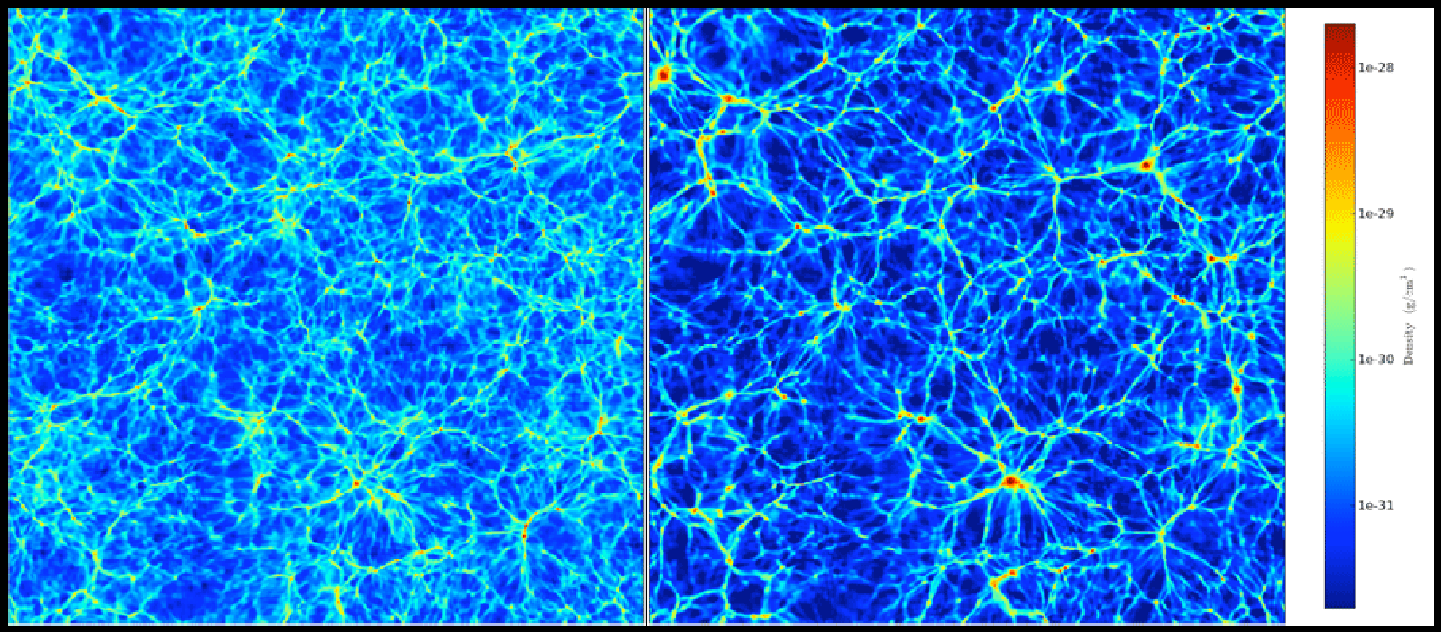
$$\Omega_\nu = \frac{3}{11}\frac{m_\nu N_\nu n_\gamma}{\rho_c} = \frac{m_\nu N_\nu}{94 h^2 eV}$$

Neutrino

Signatures in the Model

- Suppress the *growth of matter structure* and cosmological perturbations

Dark Matter N-body simulations

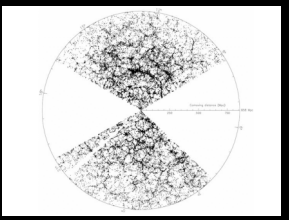


0 eV Neutrinos *1 eV Neutrinos*

Which we see in the power spectrum…

Neutrino

Signatures in the Model



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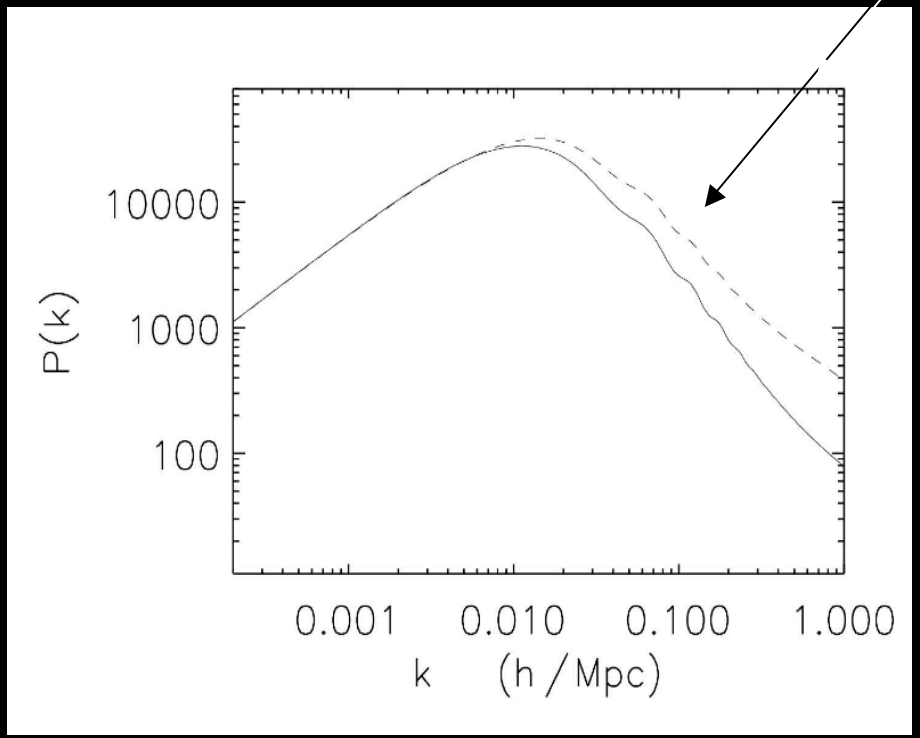
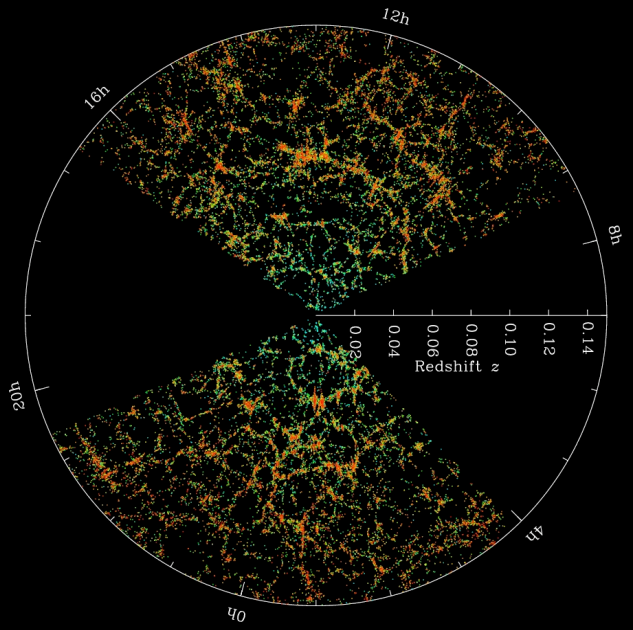




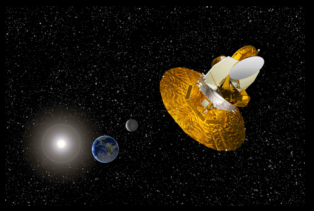
Smaller Scales →

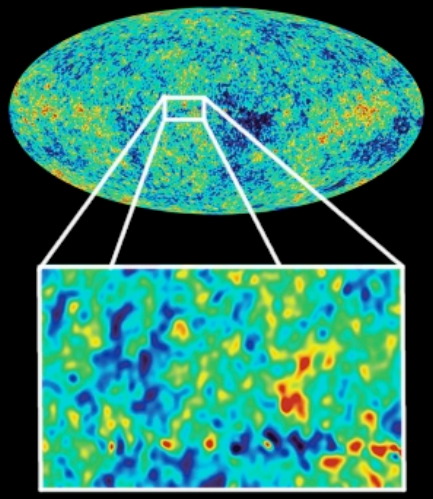
Galaxy tracers = Galaxy Survey

Probes of Cosmology

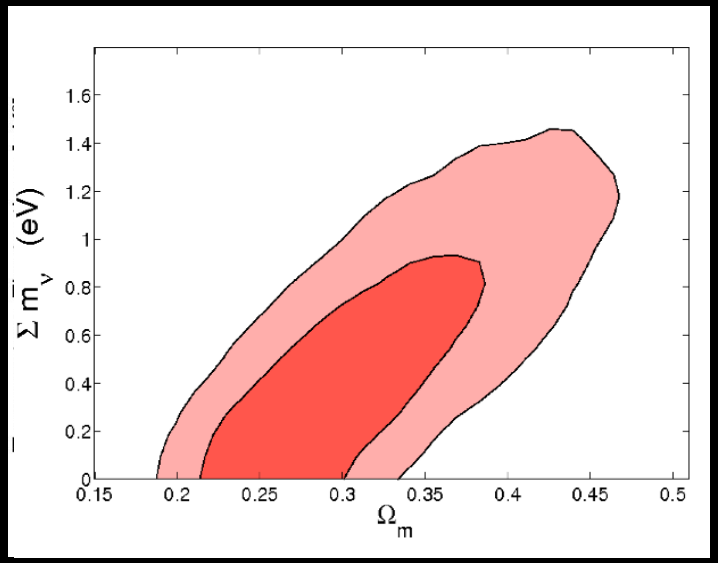
Cosmic Microwave Background (CMB)

E.g. WMAP and Planck





Model Data Constraint



WMAP 5 year (CMB) : < 1.3 eV (95% CL)

Komatsu et al. [arXiv:0803.0547]

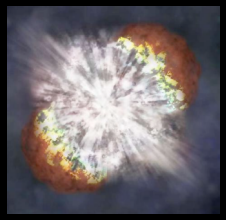
Thomas et al. [arXiv:0911.5291]

Parameter degeneracy - constrain matter component
=> better neutrino determination

Probes of Cosmology

Supernovae (SN)

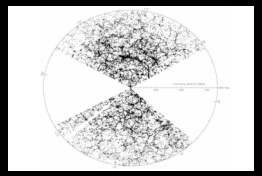
E.g. Supernova Legacy Survey



Standard candle allows one to measure the expansion history

This is sensitive to matter content of the Universe

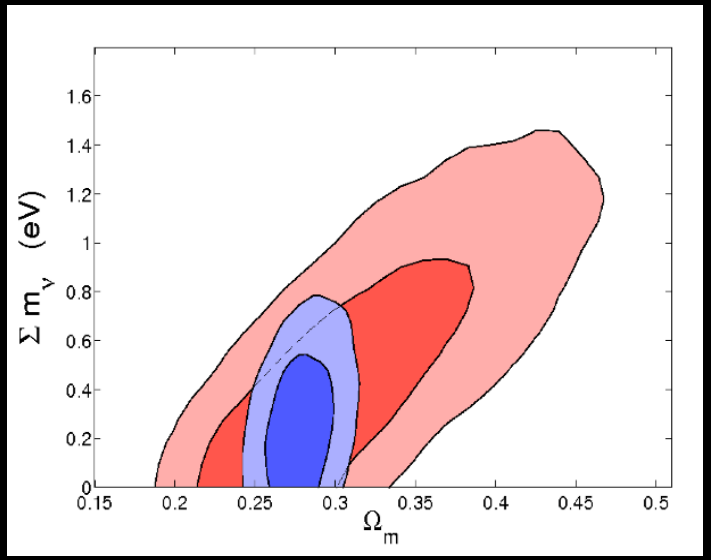
Baryon Acoustic Oscillations (BAOs)



Primordial CMB photon-baryon oscillations are imprinted onto late-time matter power spectrum: BAO

Standard ruler allows one to measure the expansion history

This is sensitive to matter content of the Universe



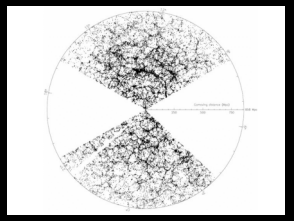
CMB + SN + BAO : < 0.69 eV (95% CL)

Thomas et al. [arXiv:0911.5291]

Probes of Cosmology

+ Galaxy Clustering!

Sloan Digital Sky Survey (SDSS)



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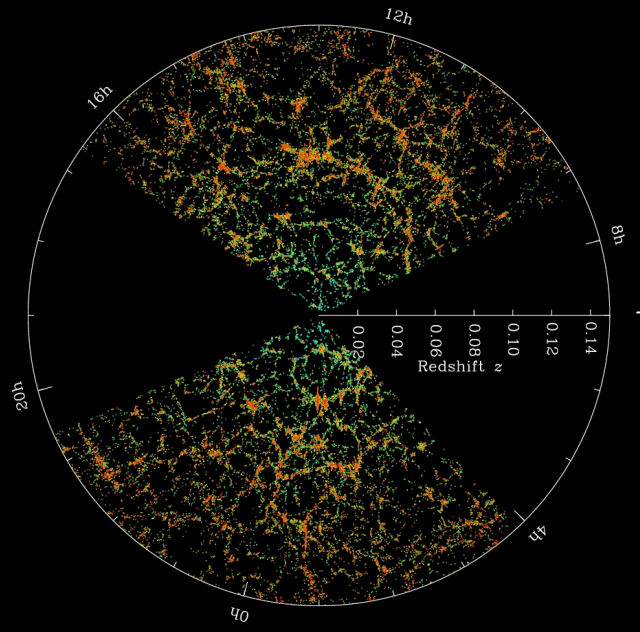

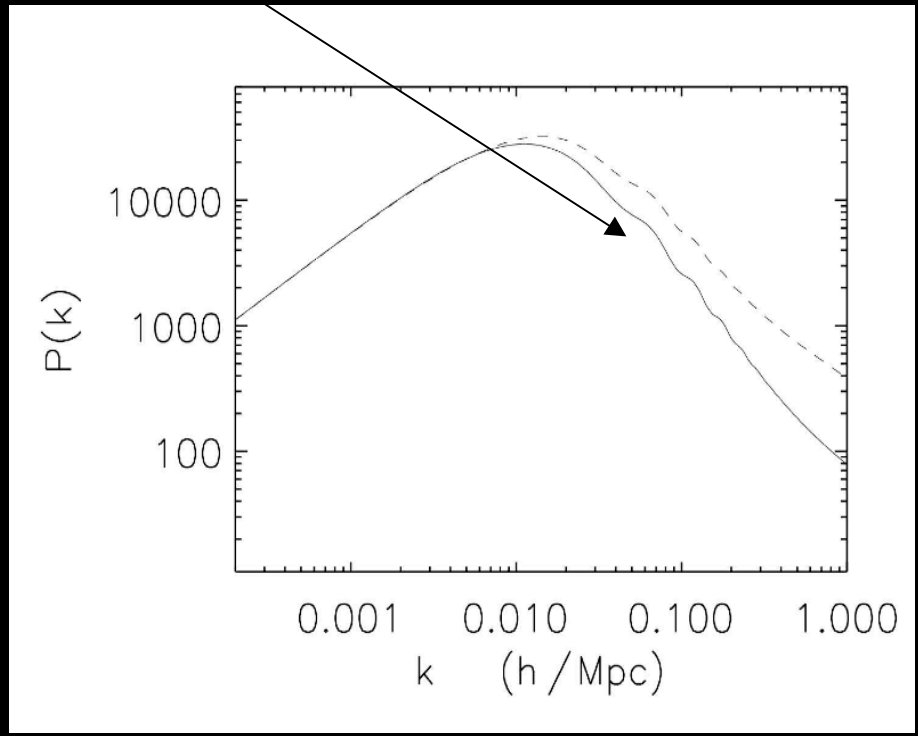

Smaller Scales ⟶

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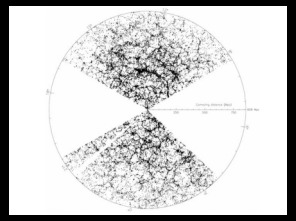
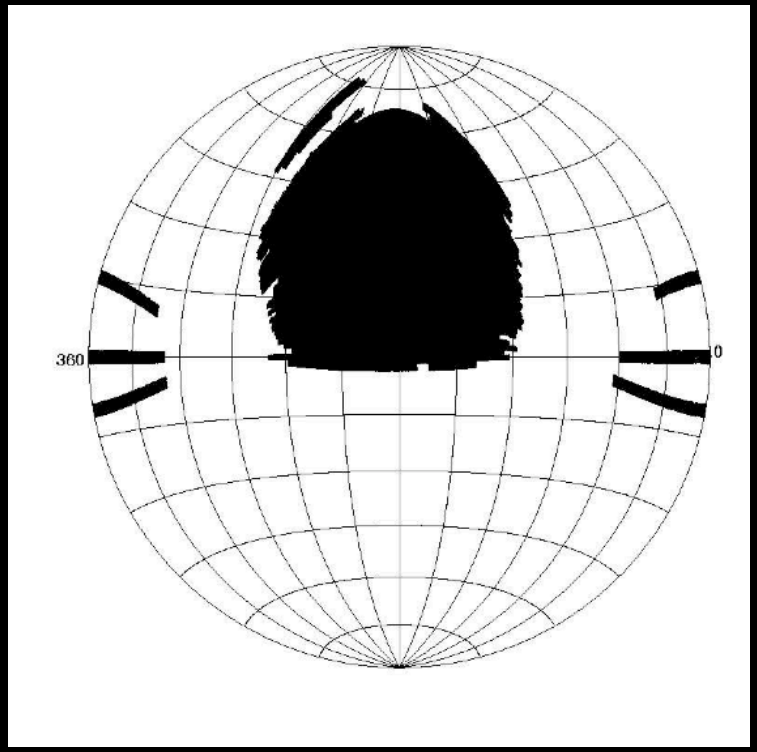


Luminous Red Galaxies (LRGs)



Thomas, Abdalla & Lahav - MNRAS (2010)

MegaZ: Largest galaxy survey

723,556 LRGs

7,746 square degrees

- Luminous - can map out over Universe
- Accurate redshift/distance information

$0.45 < z < 0.65$

Four redshift bins

Probes of Cosmology

+ Galaxy Clustering!

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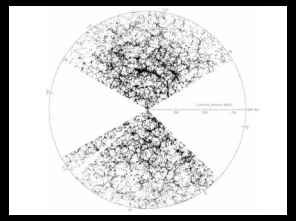

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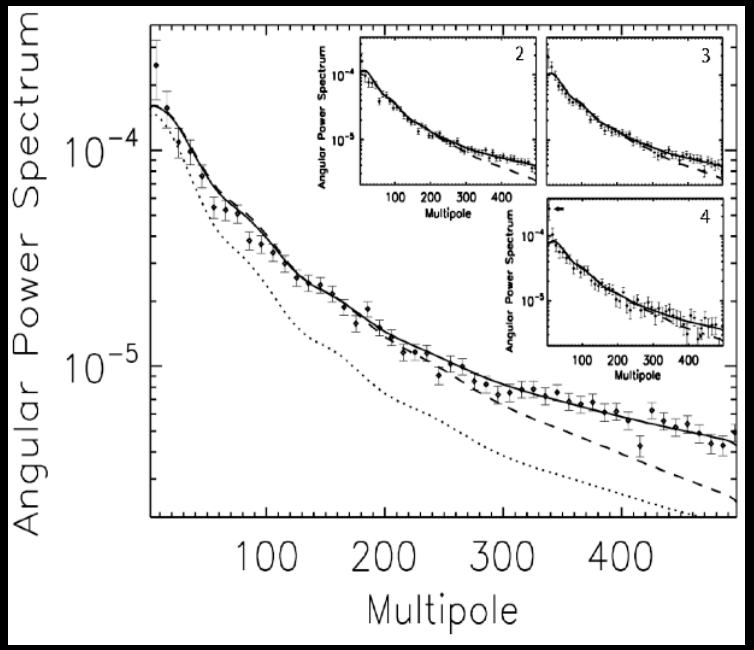
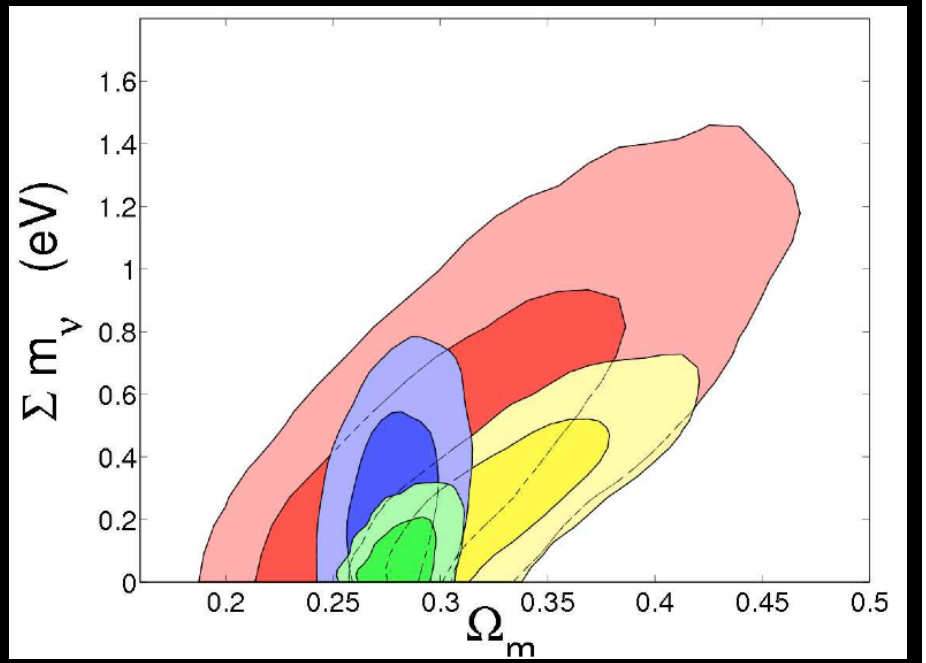




12 Parameters:

$$\Omega_b h^2;\Omega_c h^2;\Omega_\Lambda;\tau;n_s;\ln(10^{10}A_s);\sum m_\upsilon;A_{SZ};b_1;b_2;b_3;b_4$$

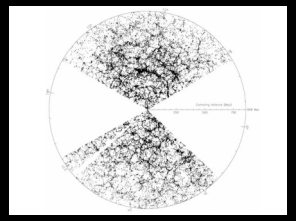
CMB + SN + BAO + SDSS LRGs + HST: < 0.28 eV (95% CL)

Thomas et al. [arXiv:0911.5291]

Probes of Cosmology

+ Galaxy Clustering!

Sloan Digital Sky Survey (SDSS)



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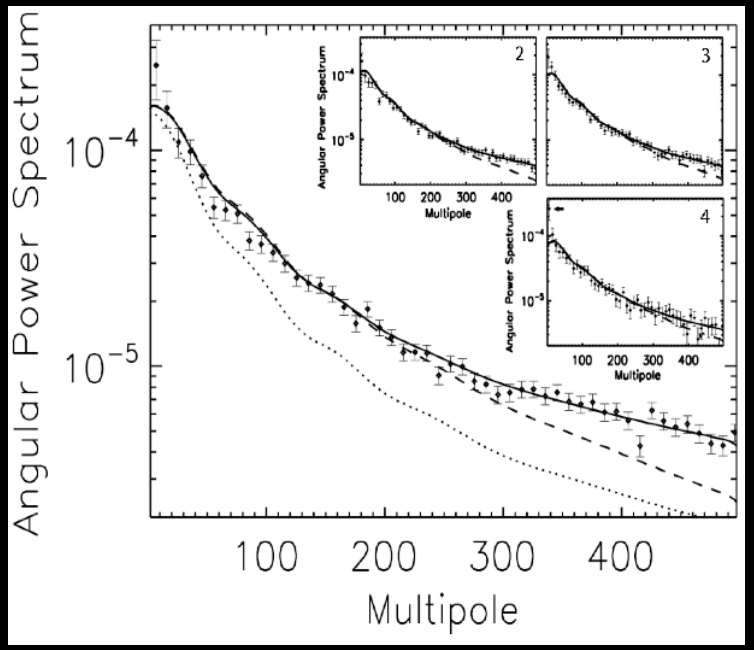

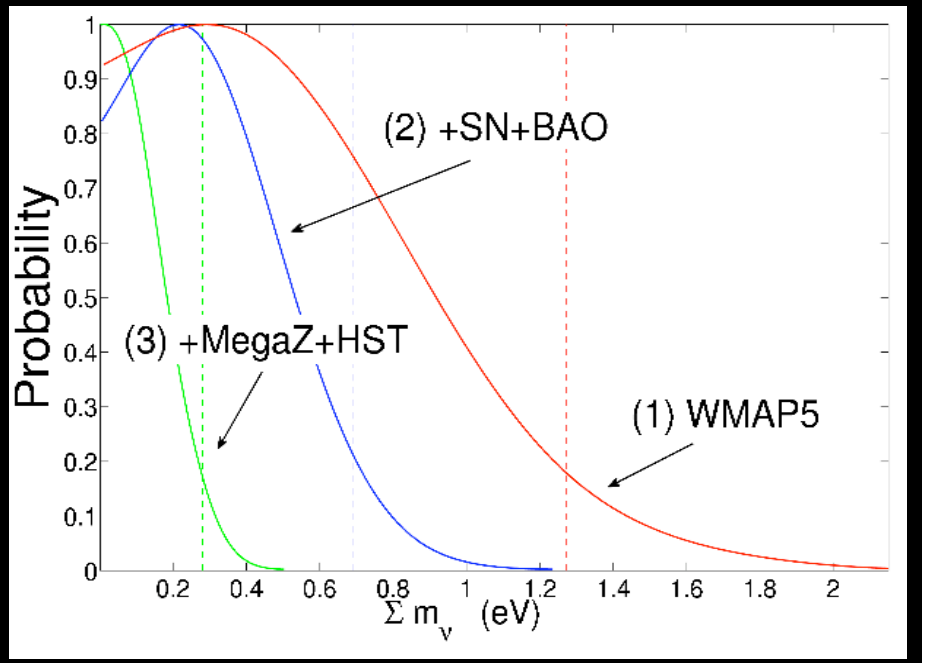

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Statistics in Cosmology Bayes

$$P(X,Y) = P(Y|X) \times P(X)$$

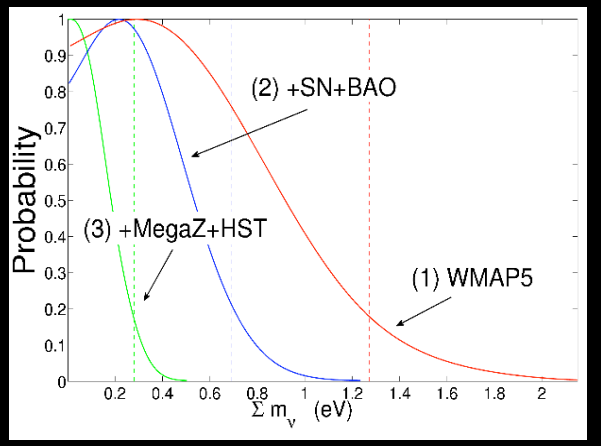
$$P(X,Y) + P(X,\bar{Y}) = P(Y|X) \times P(X) + P(\bar{Y}|X) \times P(X)$$

$$P(X,Y) + P(X,\bar{Y}) = [P(Y|X) + P(\bar{Y}|X)] \times P(X)$$

$$P(X,Y) + P(X,\bar{Y}) = P(X)$$

$$\sum_{i=1}^{N} P(X,Y_i) = P(X) \qquad \int P(X,Y)dY = P(X)$$

- Marginalised over the other parameters
- Limit is irrespective of the other parameters
- Limit accounts for uncertainty in other parameters



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Cosmology and Neutrinos

Komatsu et al. [arXiv:0803.0547]	< 0.67 eV	(CMB+SN+BAO)
Tereno et al. [arXiv:0810.0555]	< 0.54 eV	(CMB+SN+BAO+WL)
Ichiki, Takada & Takahashi [arXiv:0810.4921]	< 0.54 eV	(CMB+SN+BAO+WL)
Seljak et al. [arXiv:0604335]	< 0.17 eV	(+ Lyman Alpha…)

Systematics - e.g. winds?

Thomas, Abdalla & Lahav [0911.5291]	0.28 eV	CMB + SN + BAO + SDSS LRGs +HST

Cosmology is starting to predict that experiments such as KATRIN will not detect anything

UNIQUE opportunity for consistency check!!!!!

Systematics

We have seen that ‘precision’ cosmology is sensitive to the neutrino mass and that we are in the process of making very good constraints

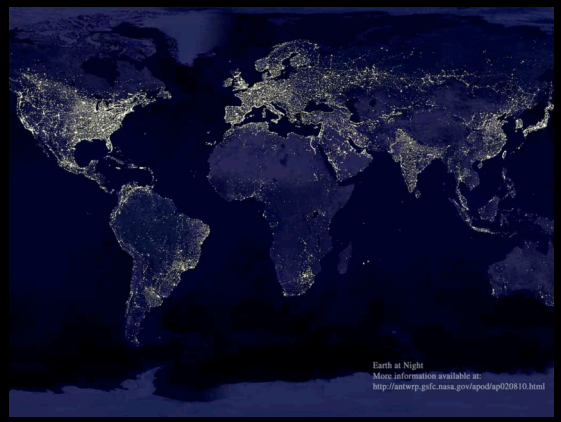
However

Although we want tighter neutrino constraints
We also want trustworthy neutrino constraints.

Galaxy Bias

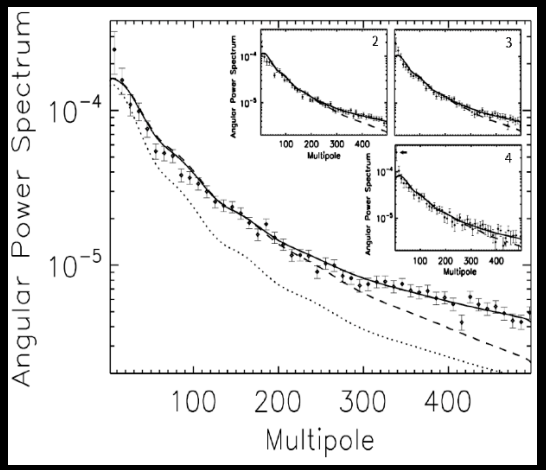
Model underlying matter power spectrum but measure the galaxy power spectrum

How are they related?



Non-linearities

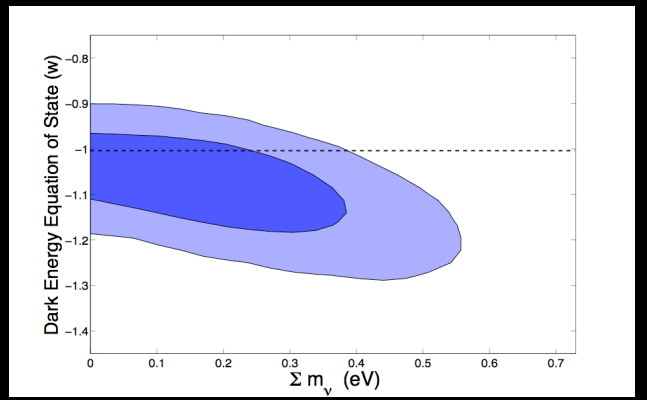
Bias result or lose data

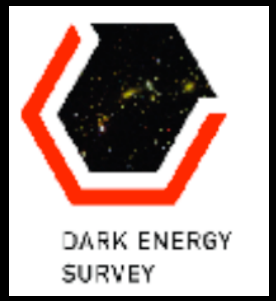


L_max = 300 =>	0.28 eV
L_max = 200 =>	0.34 eV

Parameter Degeneracies

Degeneracy with w increases error bar





The Dark Energy Survey (DES)

http://www.darkenergysurvey.org

Blanco 4m Telescope - Cerro Tololo Inter-American Observatory (CTIO)

5000 sq. deg around the southern galactic cap

525 nights: Oct - Feb (2011-2016)

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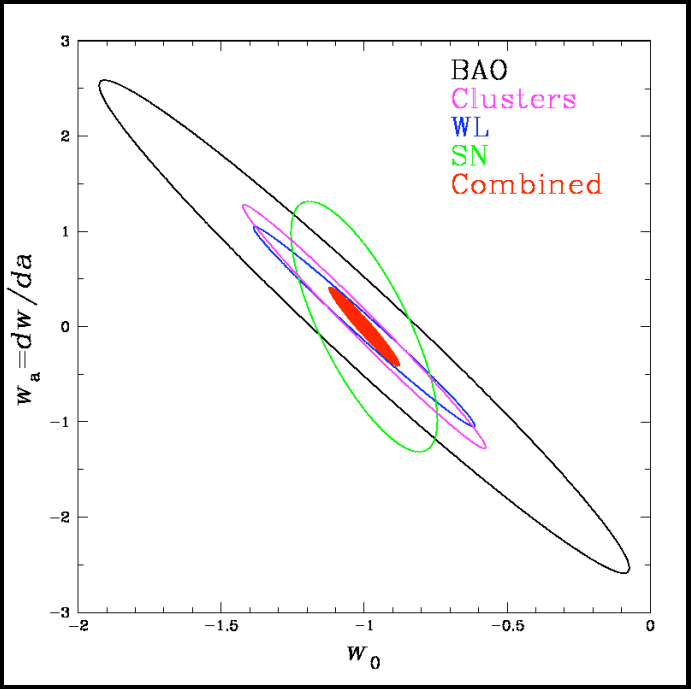


Measure Dark Energy with 4 main techniques:

1. Clusters
2. Galaxy Clustering
3. Weak Lensing
4. Supernovae

Also give exquisite information on:

Neutrino masses, gravity etc.…

In the Future… The Dark Energy Survey (DES) http://www.darkenergysurvey.org

- *300 million galaxies*
- *UCL central involvement*
- *Data taking October 2011*

Forecast for Galaxy Clustering + Planck: < 0.12 eV

E.g. Lahav, Kiakotou, Abdalla and Blake - arXiv: 0910.4714

- Plus other future surveys will start to impinge on hierarchy
- *Unique consistency test for cosmology - are we doing it right?*

Summary

- Cosmology is a sensitive neutrino experiment! (Funded billions of years ago!)
- Massive neutrinos *suppress* the growth of structure
- Probes such as galaxy clustering are sensitive to this growth
- It is an integral part of cosmological model and parameter space
- Have a complete complementary constraint (sub eV region)

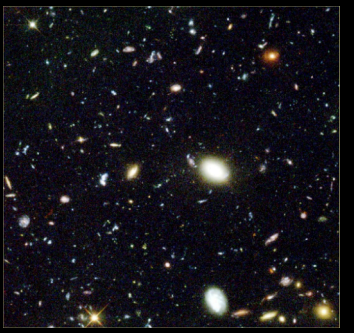
Having produced data for a tighter constraint

- The Future: Constraints with more and improved data
- The Future: Understanding systematics!!!!

Tighter neutrino constraint. Trustworthy neutrino constraint.

Determining the neutrino mass is important because:

OR - *"things to put in funding applications…."*



1. Neutrinos' mass has a significant impact on cosmological measurements
2. Incorrect neutrino mass will bias cutting edge science: dark energy
3. Particle physics - cosmology comparison: unique check on all cosmology!

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- Extension to the standard model and intrinsic nature etc.
- (Neutrinos: 3 Nobel Prizes over the last quarter of a century or so!!)

Related and Further Reading

Cosmology and Neutrinos

ST, Abdalla & Lahav [arXiv:0911.5291]

Komatsu et al. [arXiv:0803.0547]

Elgaroy and Lahav [arXiv:0606007]

Seljak et al. [arXiv:0604335]

Agarwal & Feldman [arxiv:0812.3149]

Galaxy Clustering

ST, Abdalla & Lahav [arxiv:1011.2448]

ST, Abdalla & Lahav [arxiv:1012.2272]

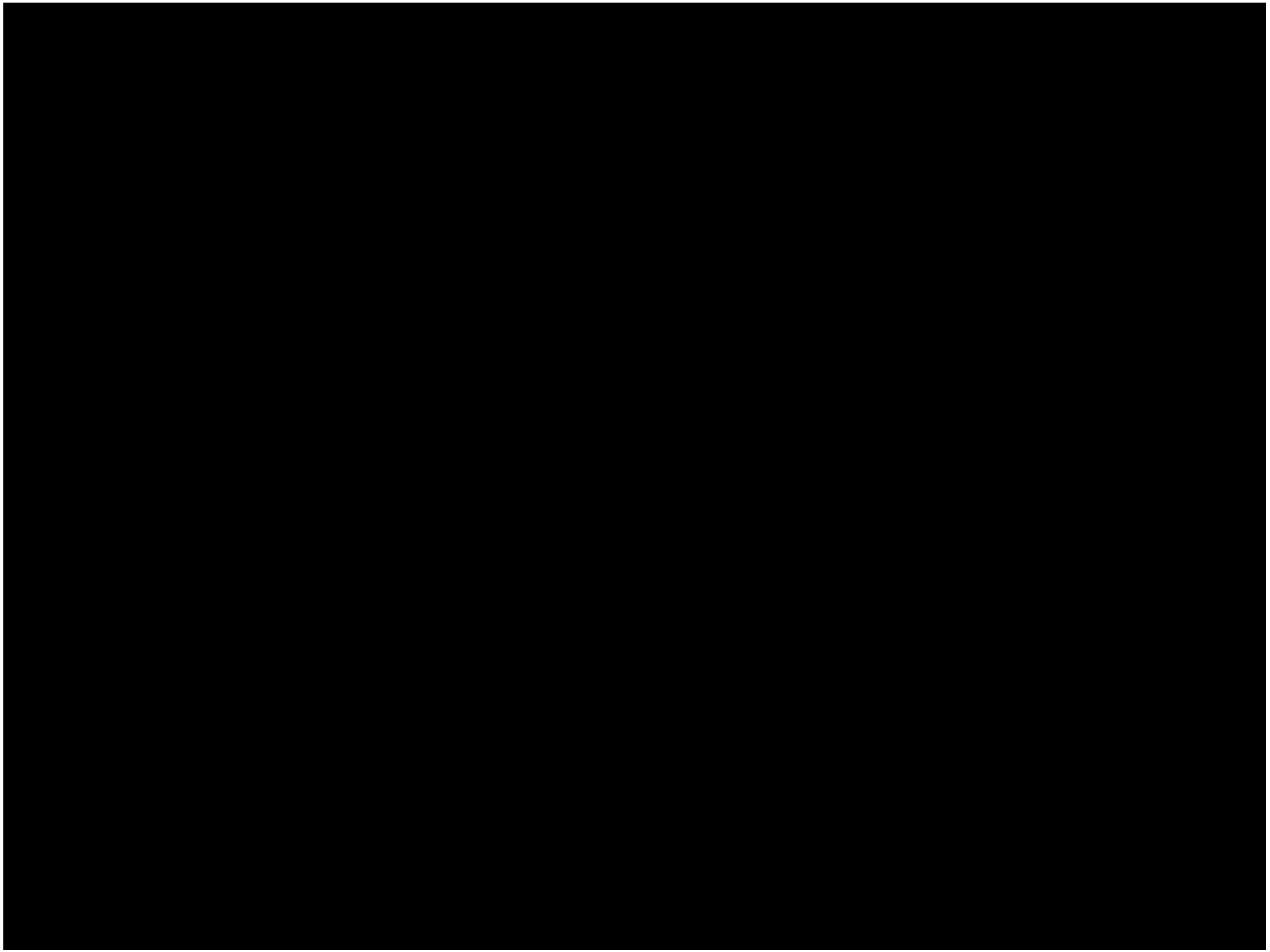
Neutrino Experiments

MINOS

NEMO

KATRIN

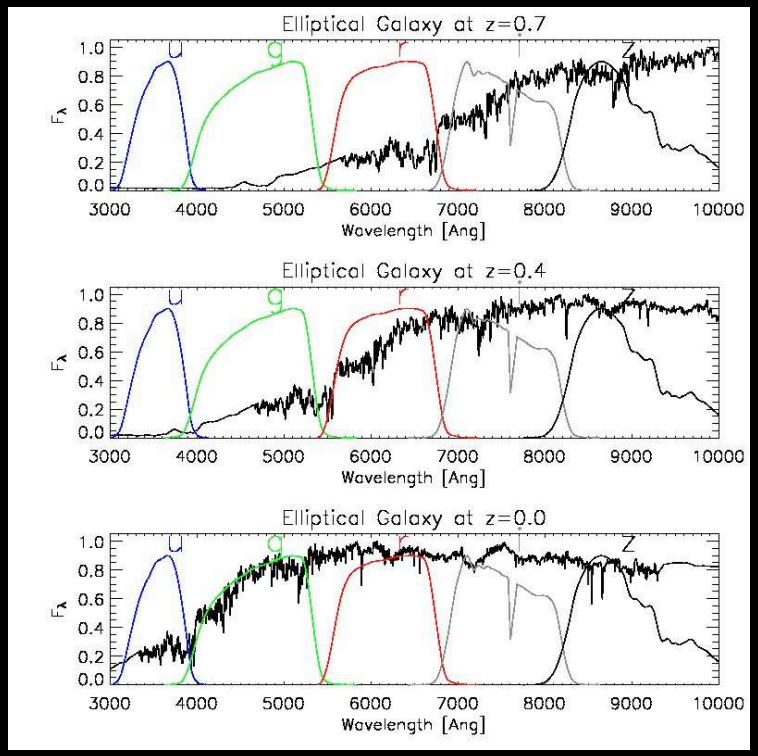
Contact: sat@star.ucl.ac.uk



The Photometric Redshift

"photo-z"

Observe the flux through broad filters



Padmanabhan et al. 2007

- Template — For example:
  - # SDSS
  - # Le Phare
- Empirical — Use training set
  - # Polynomial Fitting
  - # Neural Network

ANNz - Collister & Lahav (2004)