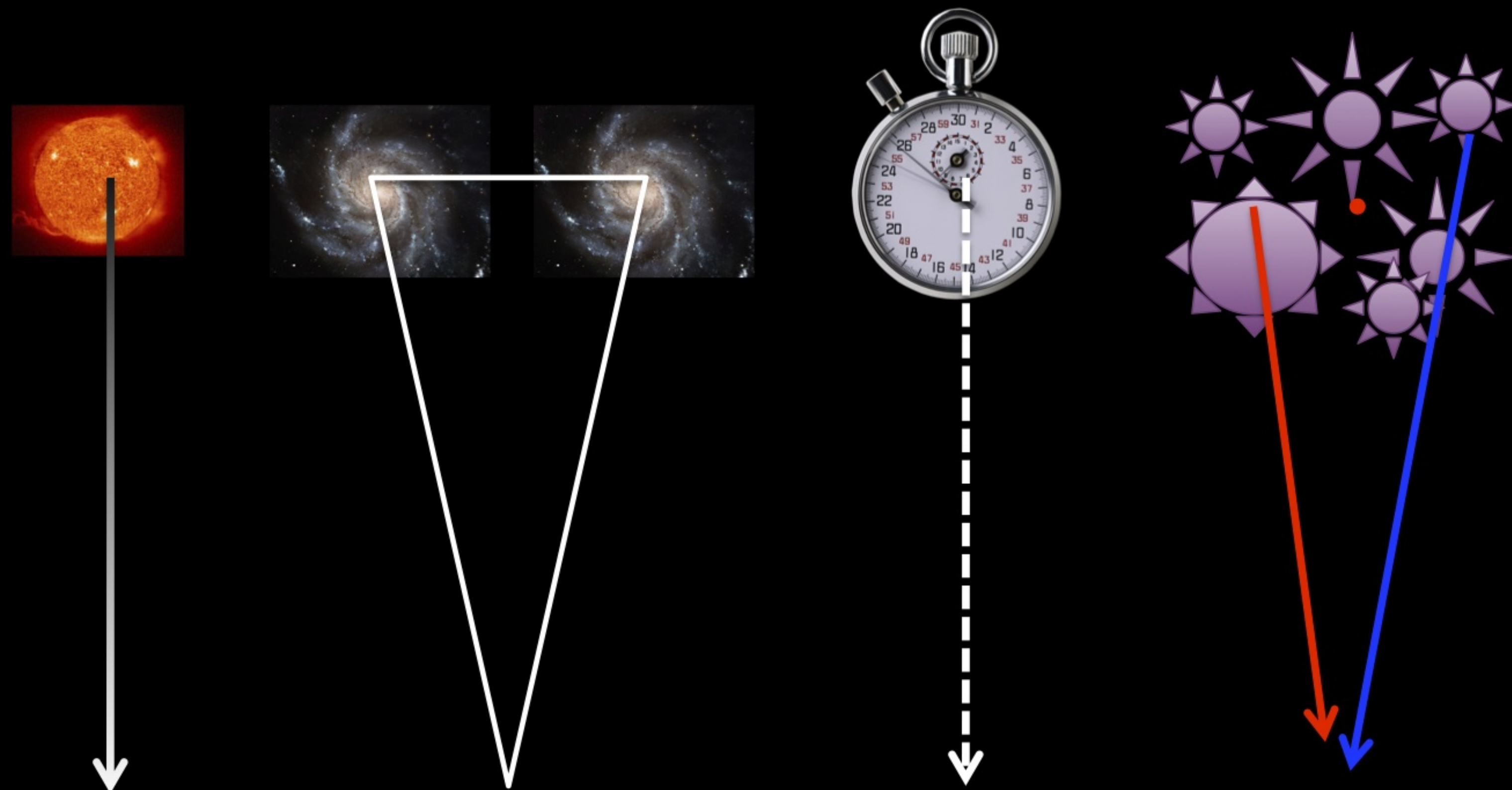
Title: Cosmological insight into fundamental physics

Date: Dec 01, 2010 10:10 AM

URL: http://pirsa.org/10120050

Abstract: Tamara Davis
The last decade of astrophysics has shown more than ever before that cosmology can teach us about the nuts-and-bolts of basic physics. This has been driven by the discovery of the accelerating universe (dark energy) --- the theories being proposed to explain dark energy often invoke new physics such as brane-worlds arising from fledgling models of quantum-gravity. It has become evident that the large timescales and spatial-scales probed by cosmology allow us to learn about fundamental physics in a way inaccessible to any earth-bound experiment.

This talk will review my work as part of the ESSENCE and SDSS supernova surveys, and the WiggleZ Baryon Acoustic Oscillation survey, to test new fundamental physics. I'll present the latest data and discuss how the cosmological constraints will be improved in the future with more data, different types of data, and improved analysis techniques.



Cosmological insight into fundamental physics
Candles, rulers, clocks, and co-motion

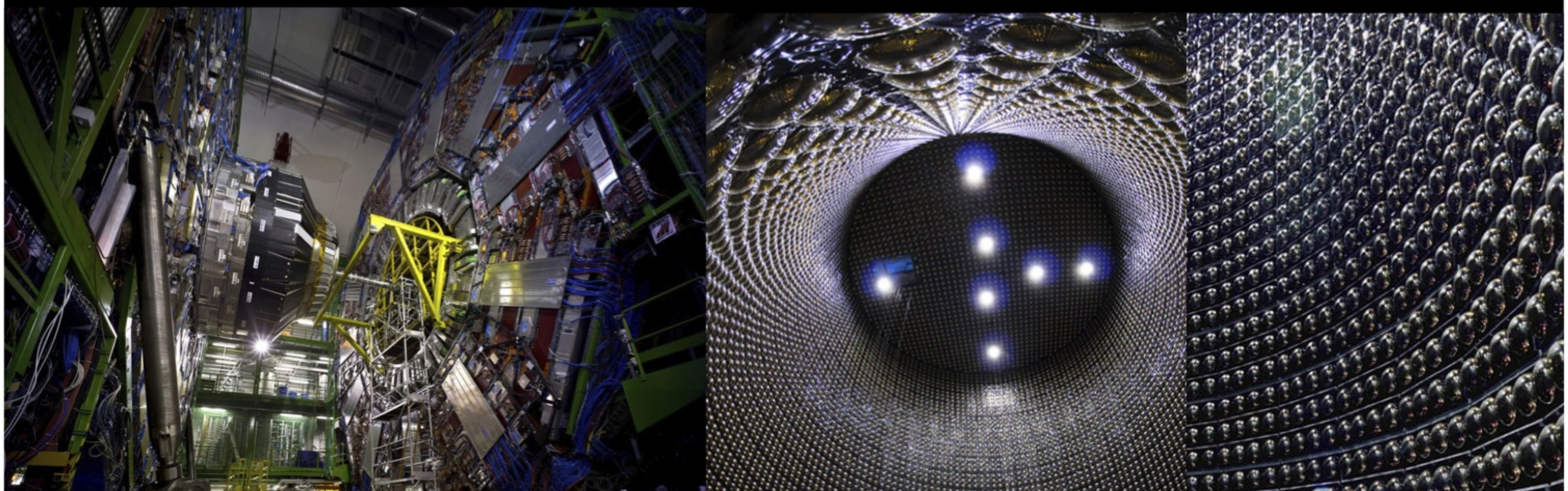
Tamara Davis, David Parkinson, and Signe Riemer-Sorensen

University of Queensland Astrophysics

PIAF Workshop, Dec 2010

Cosmology constrains fundamental physics

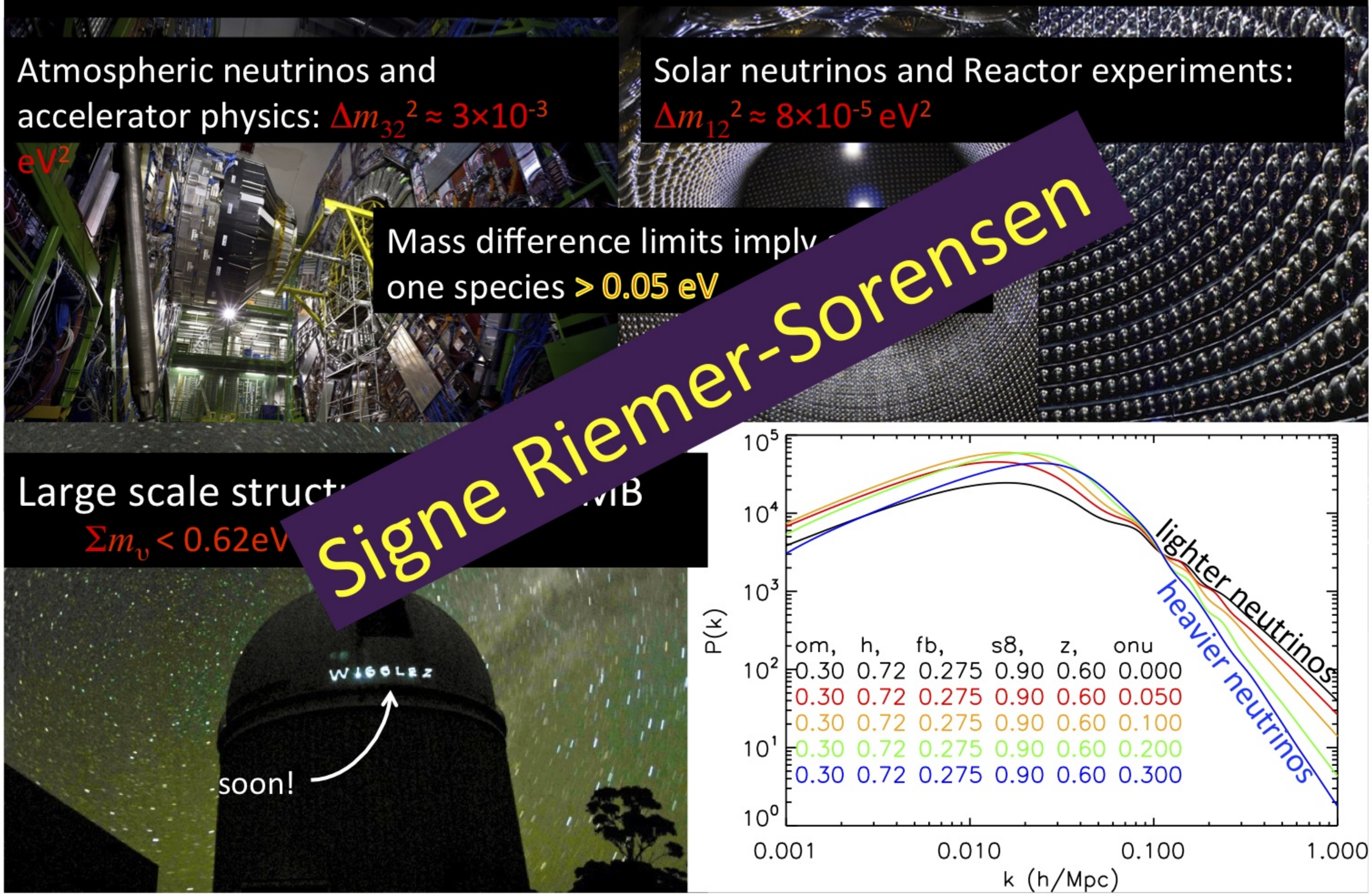
- Billions is being spent each year on experiments to test physics at the highest energies and smallest scales possible



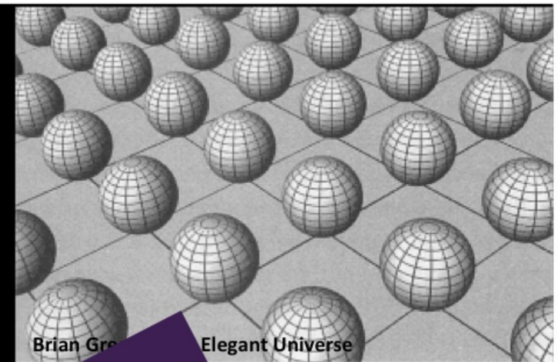
But the Universe routinely does experiments on time and energy scales beyond what we can ever hope to achieve on (or near) Earth

Dark matter; Dark Energy; Standard model of particle physics
New theories of fundamental physics (brane worlds, string theory….)
Possible variations in the constants of nature??

One example: neutrino mass



New theoretical models to explain dark matter/energy



Dvali-Gabadadze-Porrati (DGP)

Brane related model in which gravity leaks out into extra dimensions, with [illegible] characteristic scale r_c

$$\frac{H^2}{[illegible]} [illegible] \frac{[illegible]}{a^3} + \Omega_{r_c} + \sqrt{\Omega_{r_c}}\Bigg)^2$$

David Parkinson

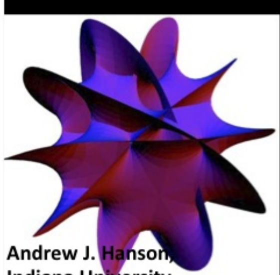
Cardassian Expansion

Variation on gener[illegible] [illegible]ich self-interacting d[illegible] [illegible]d cause acceler[illegible] [illegible]k *energy*

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3}\left[1 + \frac{(\Omega_m^{-q} - 1)}{a^{3q(n-1)}}\right]^{1/q}$$

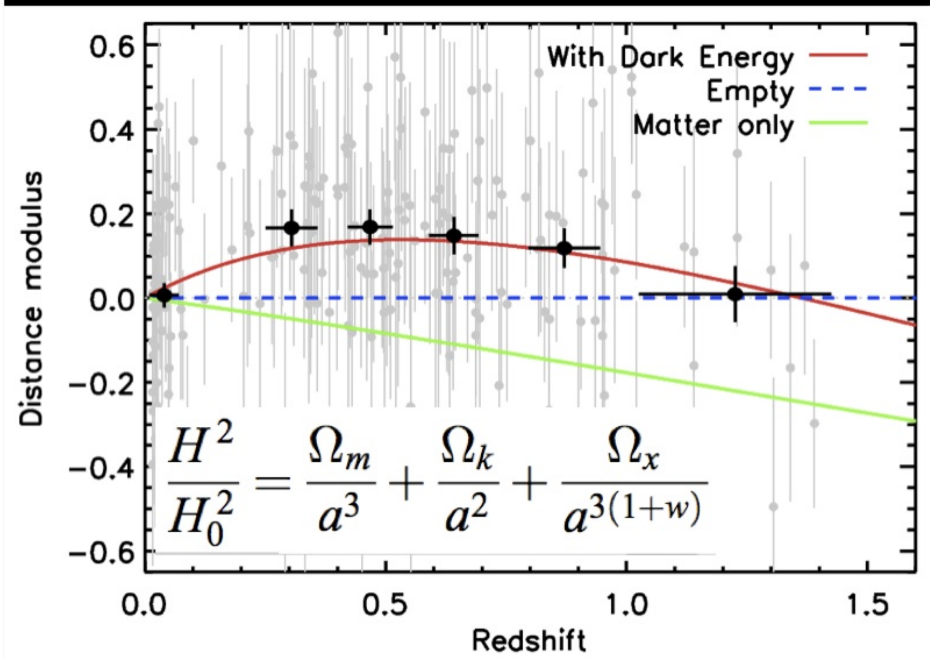
Chaplyg[illegible]

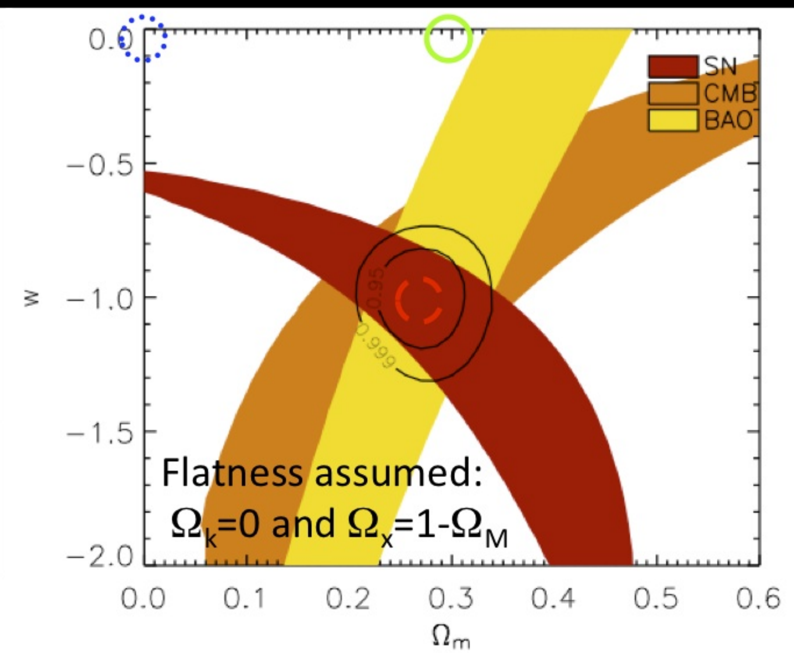
invoke[illegible] background fluid with peculiar properties that could unify *dark matter* and *dark energy* (branes again)



$$\frac{H^2}{H_0^2} = \frac{\Omega_k}{a^2} + (1-\Omega_k)\left[A + \frac{(1-A)}{a^{3(1+\alpha)}}\right]^{1/(1+\alpha)}$$

Standard Candles: e.g. supernovae

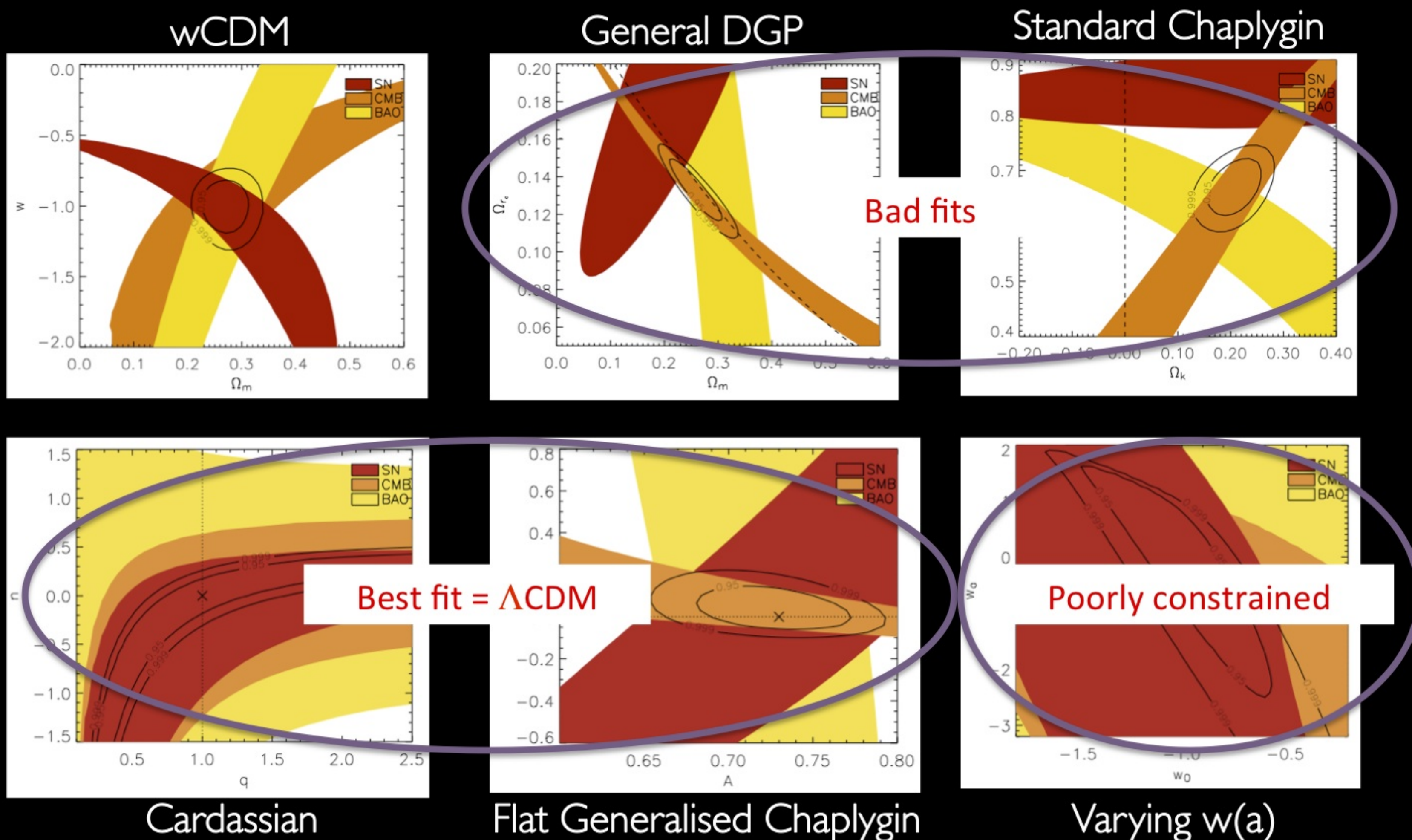




Detects: Distance vs redshift (recession velocity)
Used to measure: Acceleration or Deceleration of the universe
Conclusion: Universe is **accelerating**
Inference: Either General Relativity needs revision,
or there's something with anti-gravity properties out there
-> vacuum energy?; beyond standard model physics??

Existing fits show three distinct classes

(Plots from Davis et al. 2007, ESSENCE)

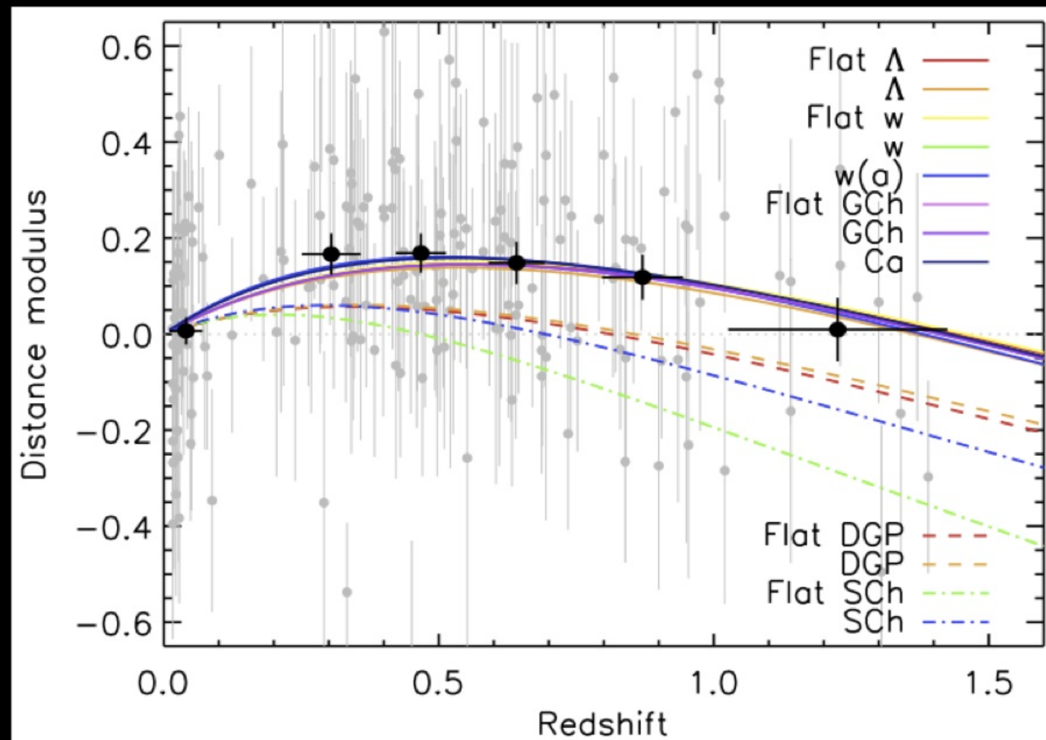


Degeneracy

(Plot from Davis et al. 2007, ESSENCE)

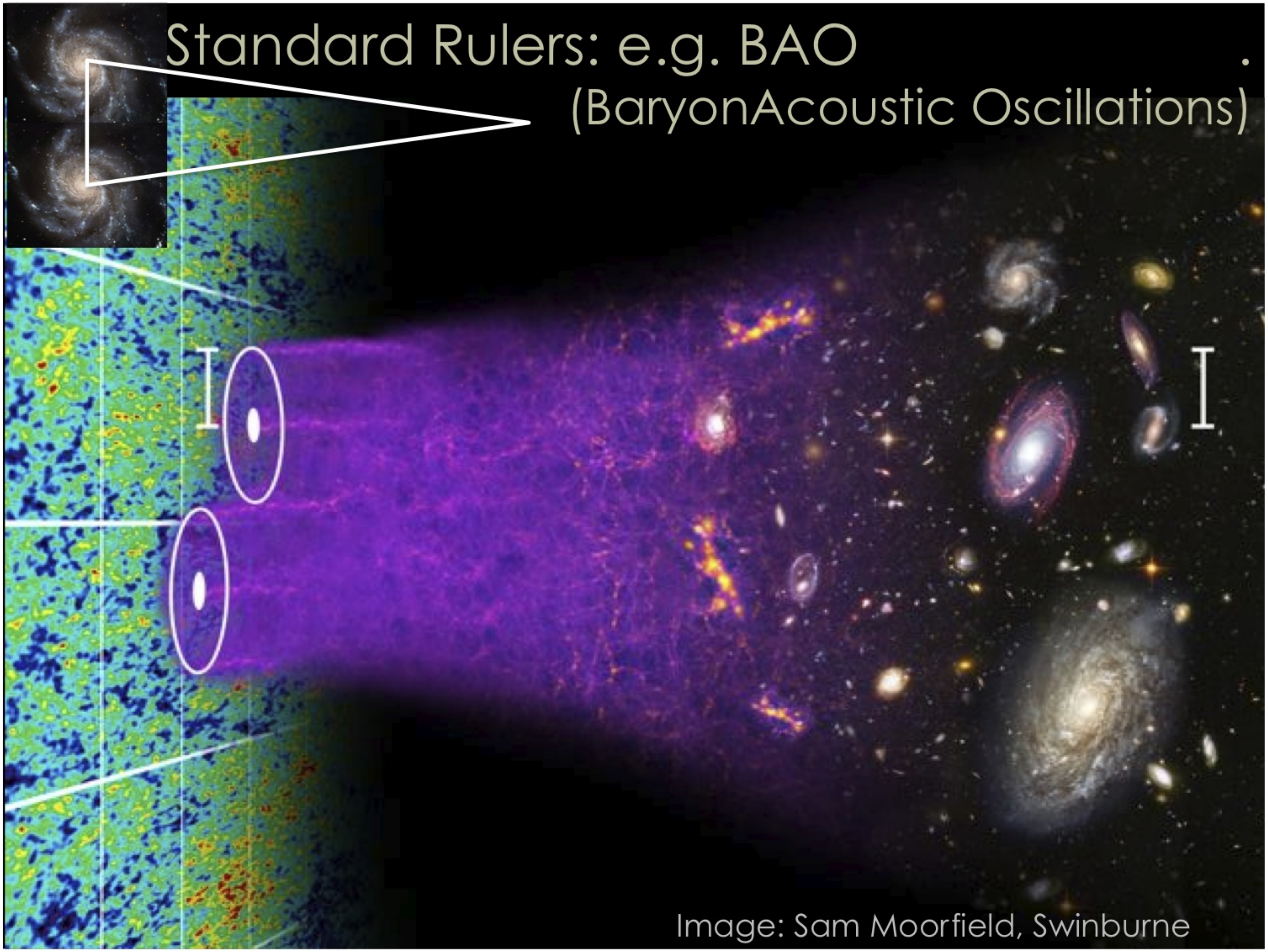
Every model that fitted the data could mimic our standard ΛCDM model behaviour

The best fit parameters always included ΛCDM



Measurements of the expansion *cannot IN PRINCIPLE* distinguish between some models, even in the limit of perfect data.

We need other *types* of tests.

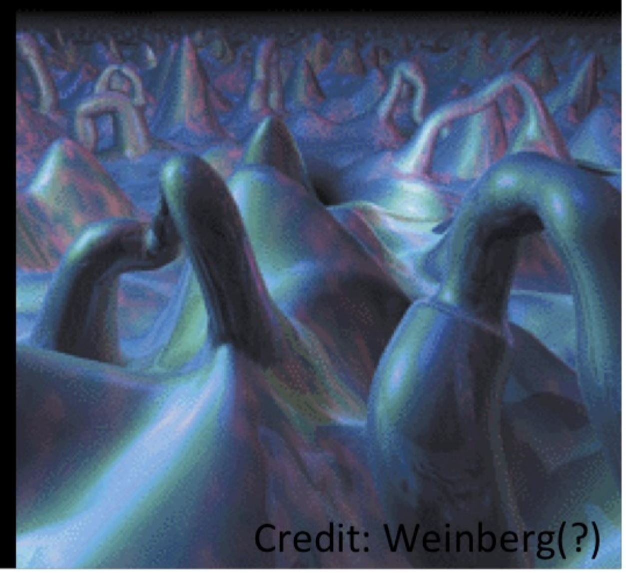

Standard Rulers: e.g. BAO
(BaryonAcoustic Oscillations)
Image: Sam Moorfield, Swinburne

Fluctuations and structure

- Quantum fluctuations are the seeds of structure
  - Heisenberg's uncertainty principle guarantees density inhomogeneities in the early universe (because positions are indeterminate)
  - Same on all scales (scale invariant)
- Quantum fluctuations produce real fluctuations when virtual particle pairs find themselves separated by more than a Hubble distance (to annihilate they have to travel >c)

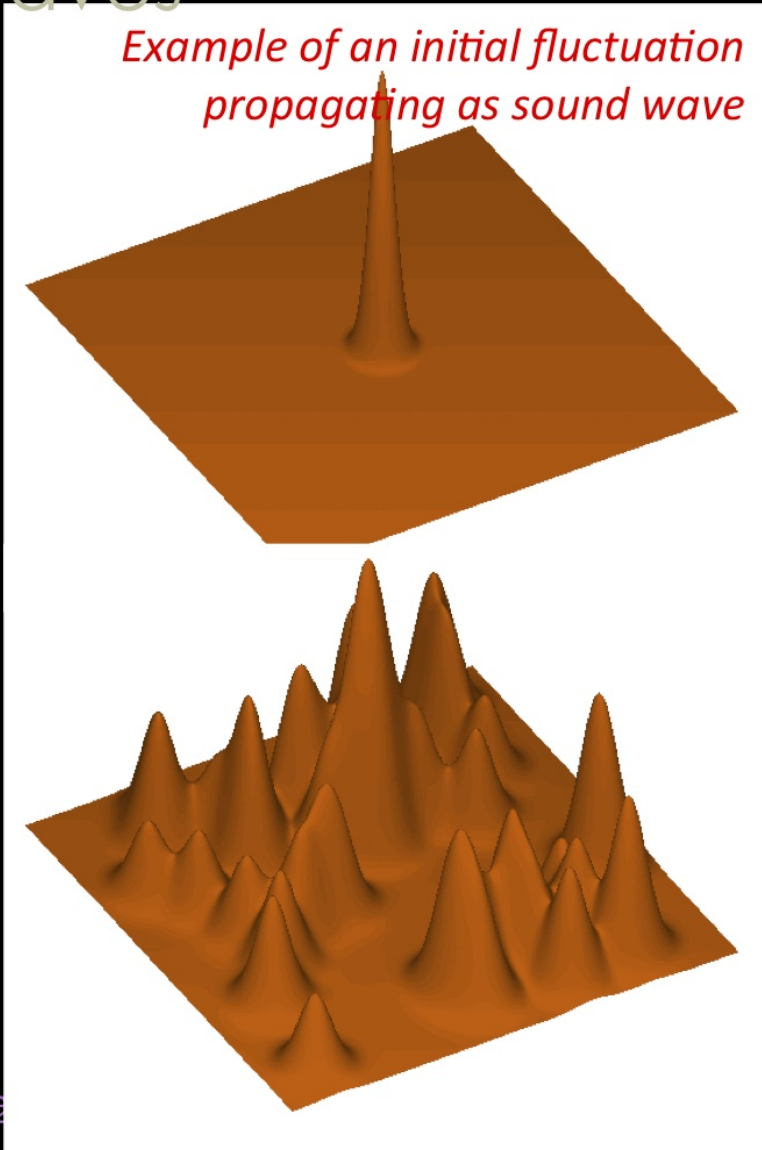
$$\Delta t \leq \hbar / \Delta E$$

- Incurs an energy debt paid for by the expansion
- What is it that drives the inflation and has the energy to repay this debt?



Density Fluctuations initially evolve as sound waves

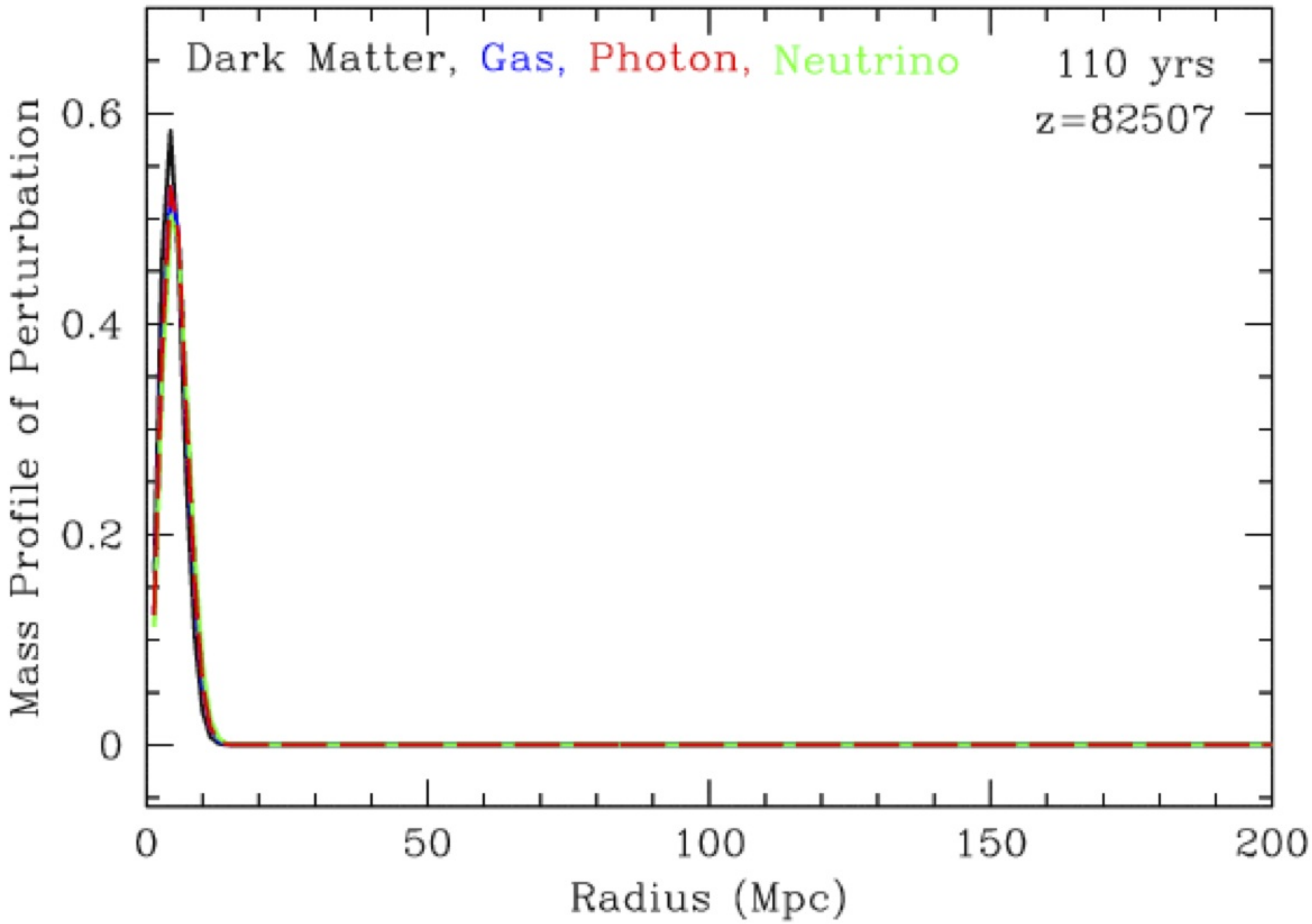
- Once fluctuations becomes sub-horizon, but before recombination
  - Experience **acoustic oscillations**
  - Sound waves travel at nearly light speed ($c/\sqrt{3}$), leave imprint on CMB
- Smaller fluctuations did not survive
  - Photons leaked out of small regions, damping structure
  - Minimum mass to survive was about an elliptical cD galaxy or small galaxy cluster ($8\times10^{13}\,M_\odot$)



Animation credit=Dan Eisenstein
http://cmb.as.arizona.edu/~eisenste/acousticpea

Formation of acoustic peak

- http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html



University of Queensland: Tamara Davis, Michael Drinkwater, Signe Riemer-Sorensen, David Parkinson

Swinburne: Chris Blake, Carlos Contreras, Felipe Marin, Warrick Couch, Darren Croton, Karl Glazebrook, Tornado Li, Greg Poole, Emily Wisniowksi

AAO: Sarah Brough, Matthew Colless, Mike Pracy, Rob Sharp

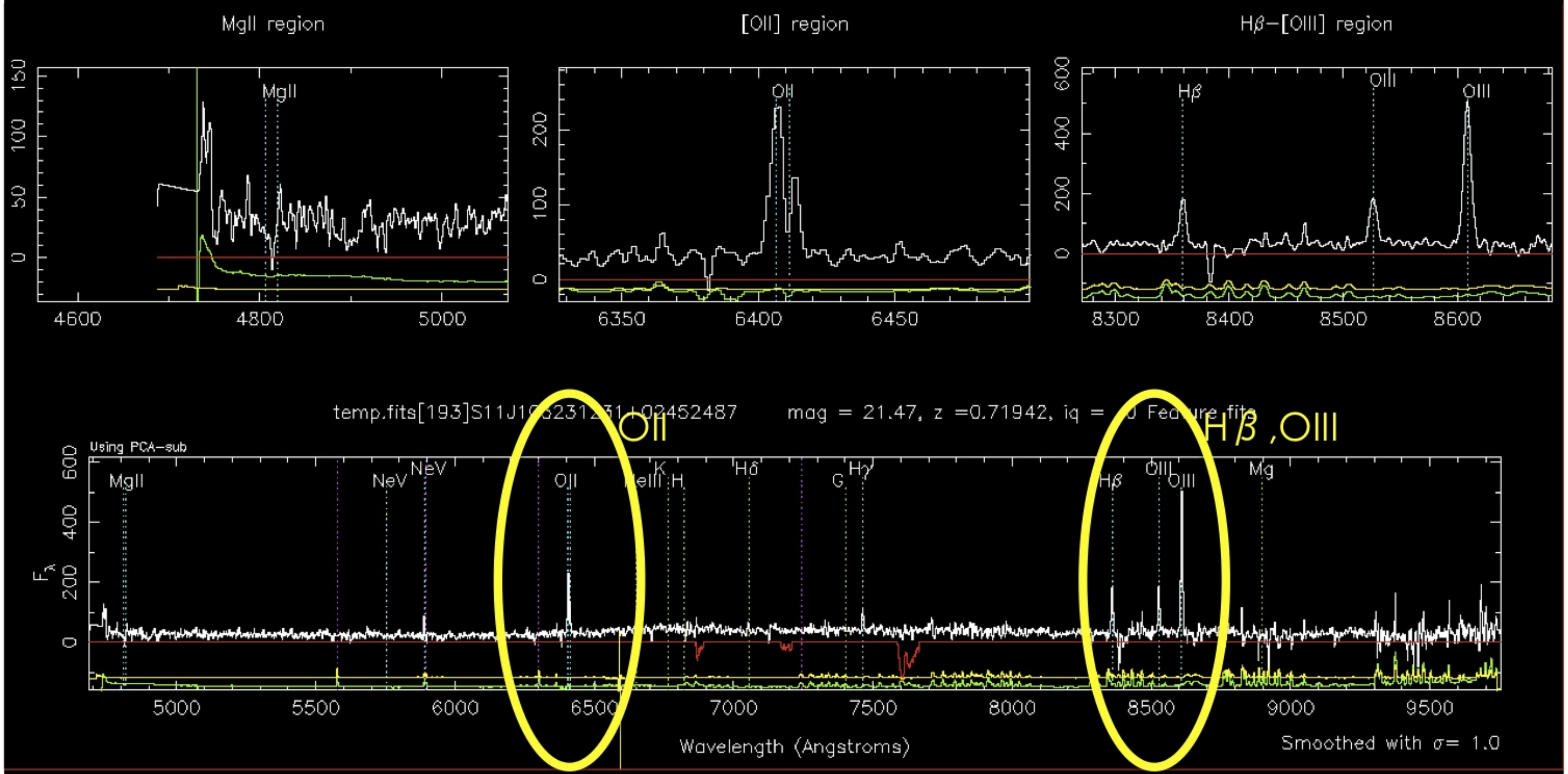
Scott Croom (U.Syd), Ben Jelliffe (U.Syd), David Woods (UBC), Kevin Pimbblet (Monash), Russell Jurek (ATNF)

Galex Team: Karl Forster, Barry Madore, Chris Martin, Ted Wyder

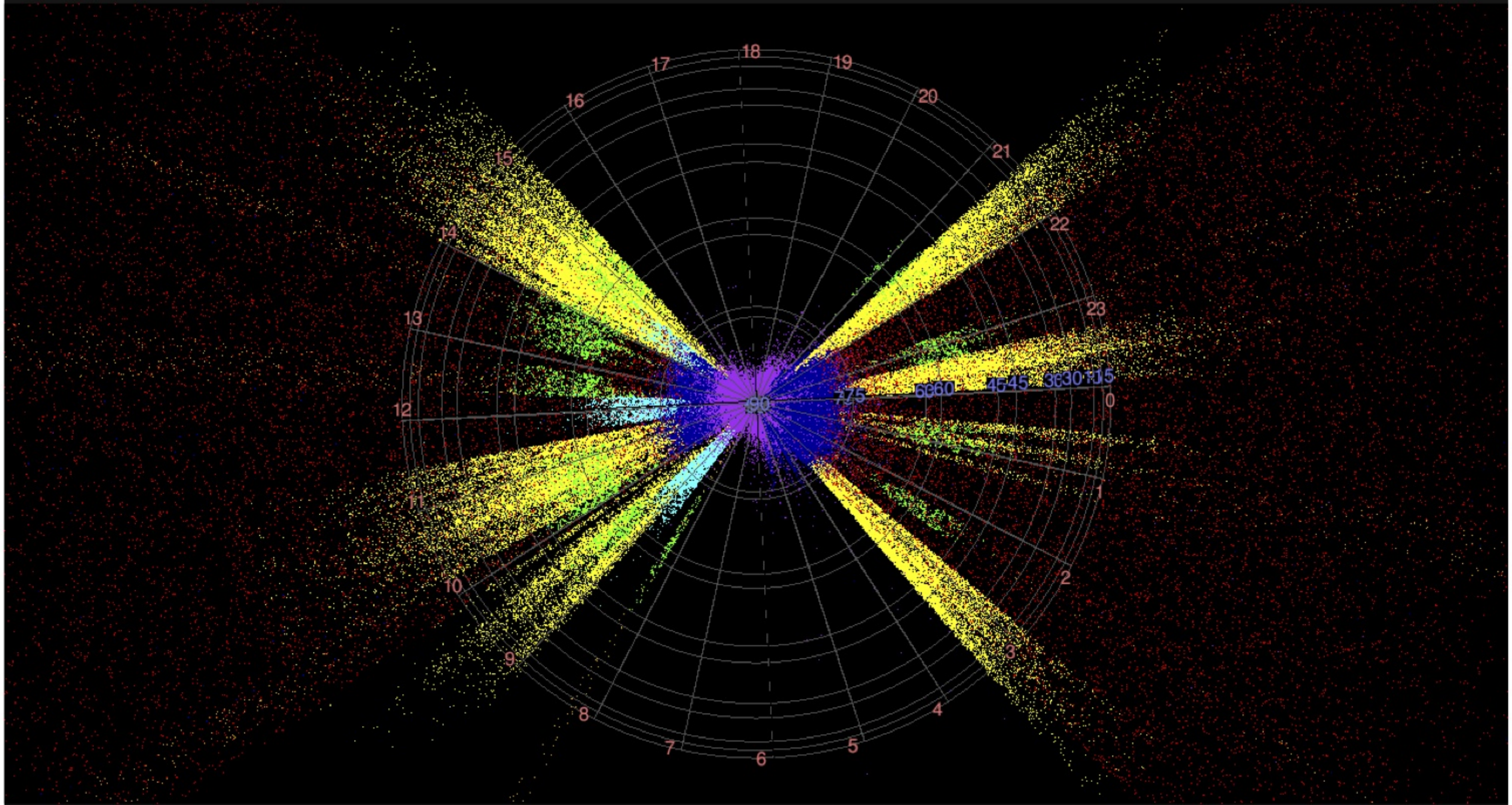
RCS2 Team: David Gilbank, Mike Gladders, Howard Yee

Associate, Berian James (DARK)

Example spectrum of galaxy at z = 0.72 (light emitted 5Gyr ago)

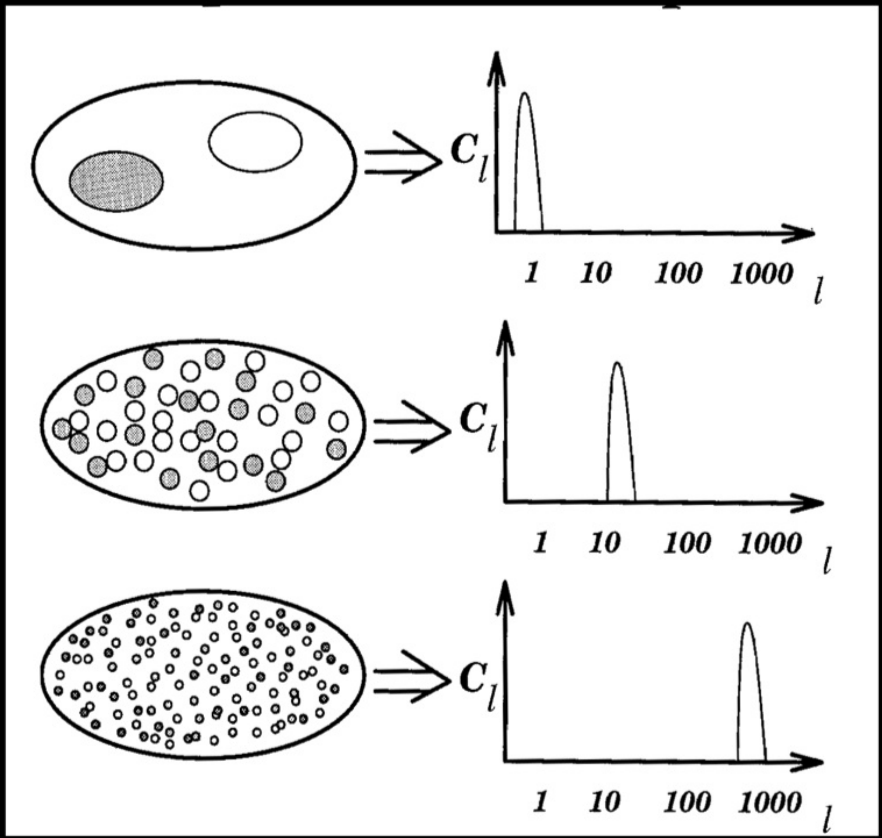


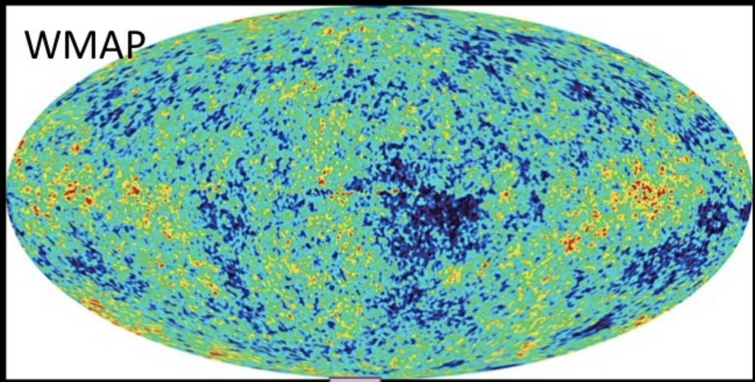
AAT and UKST redshift surveys

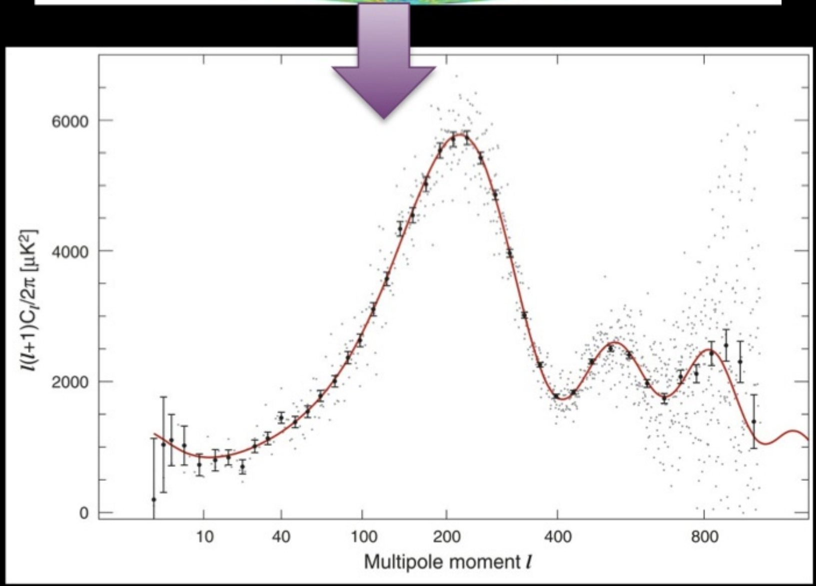


6dFGS (purple), 2dFGRS (blue), MGC (navy), GAMA (cyan), 2SLAQ-LRG (green), WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at z=1.

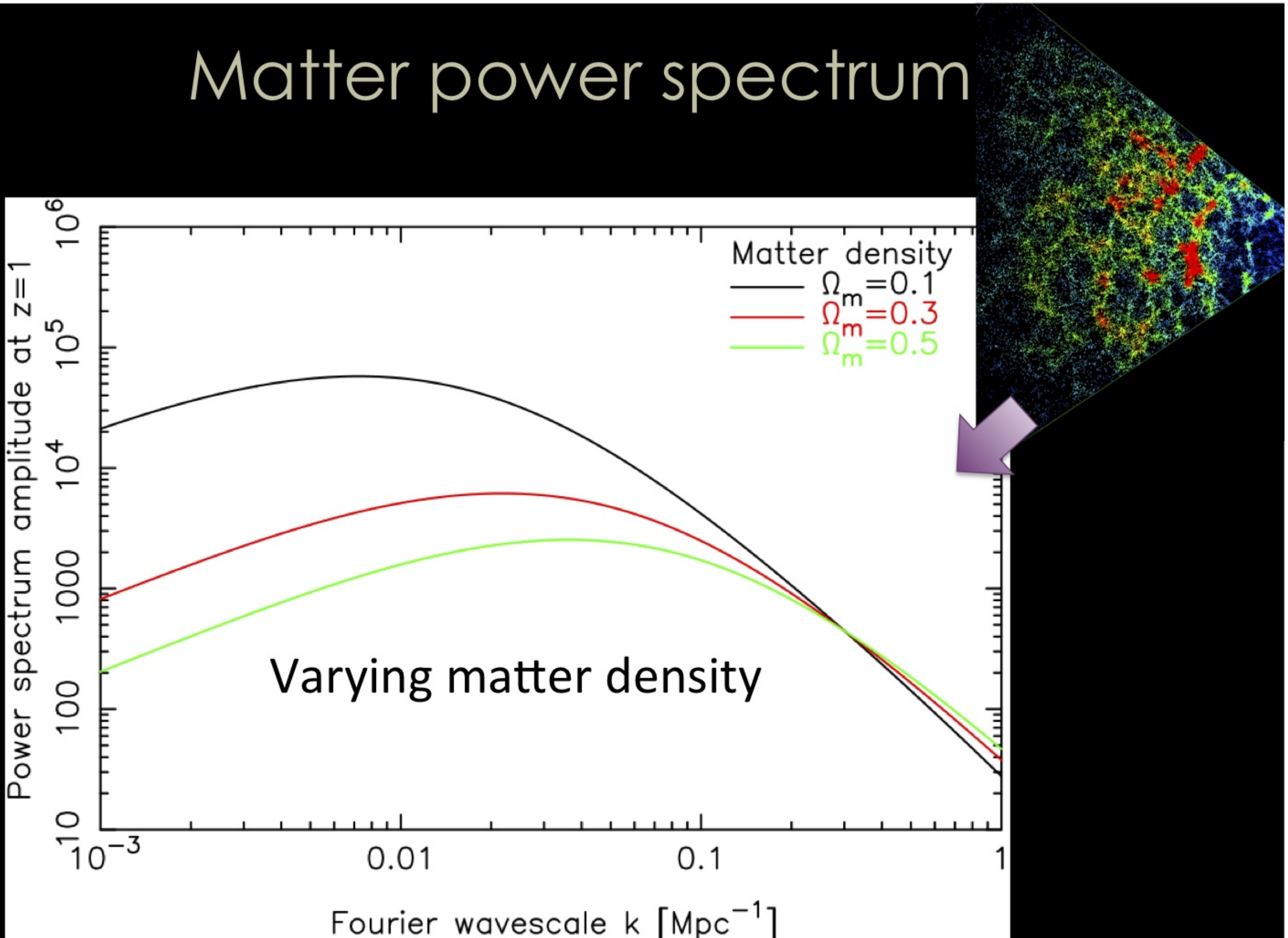
Quantifying structure: power spectrum



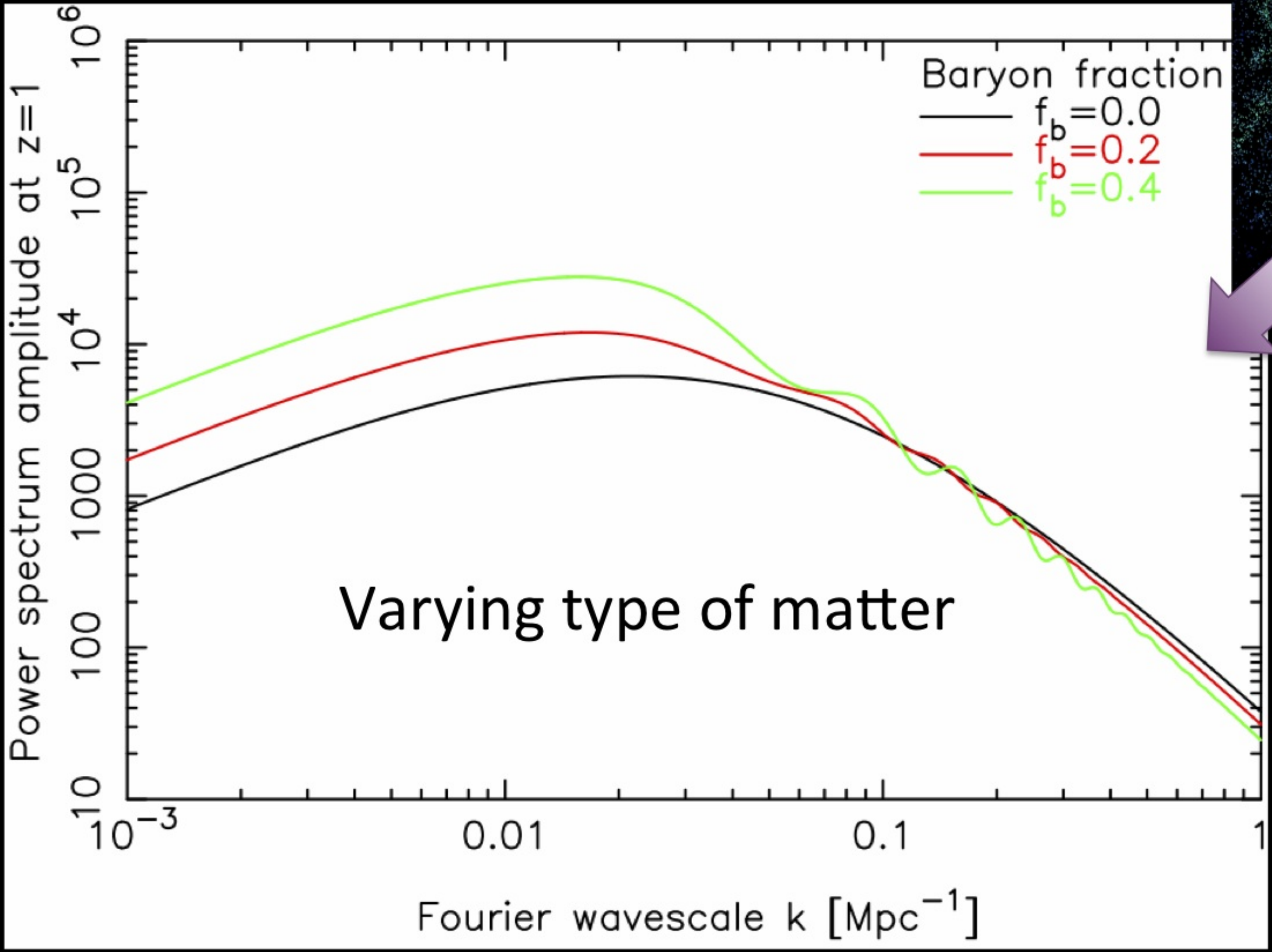


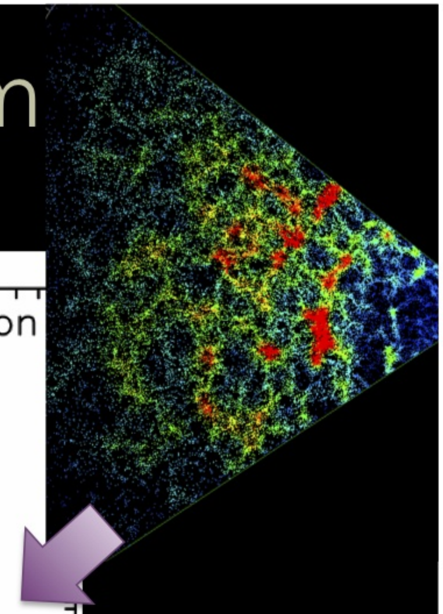


Matter power spectrum

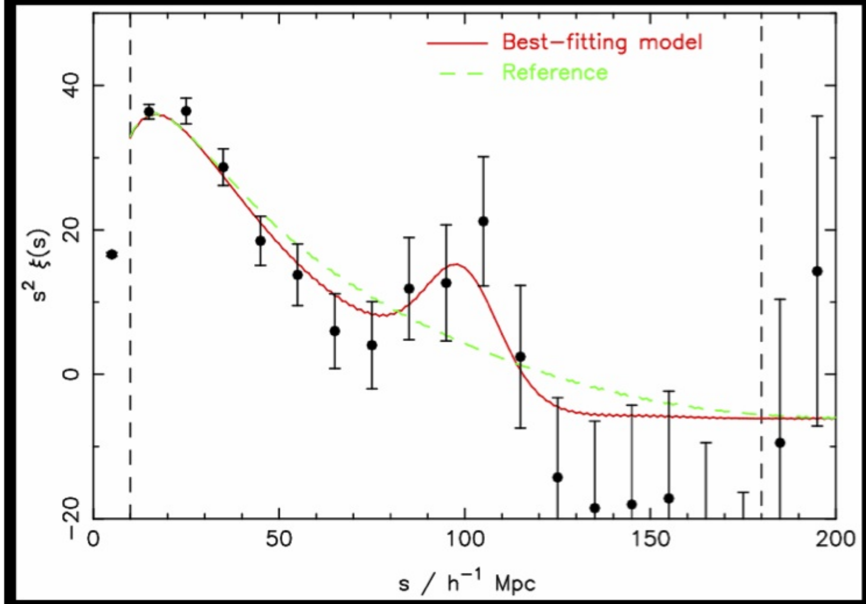


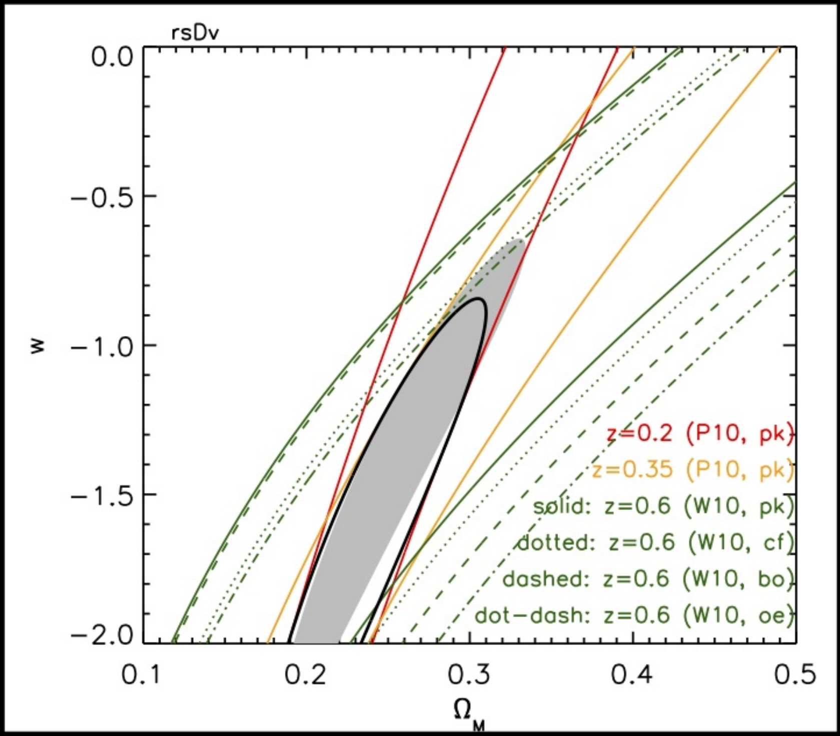
Matter power spectrum



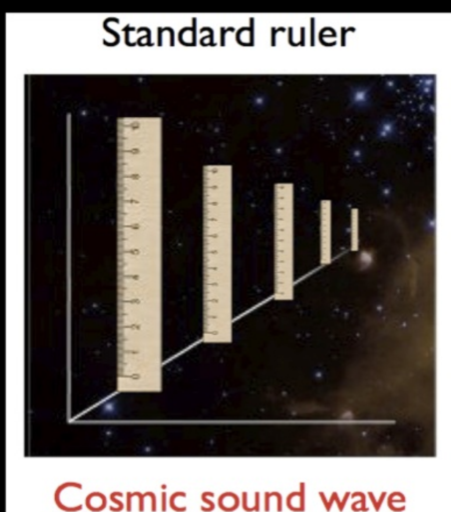


WiggleZ detects the BAO peak!!



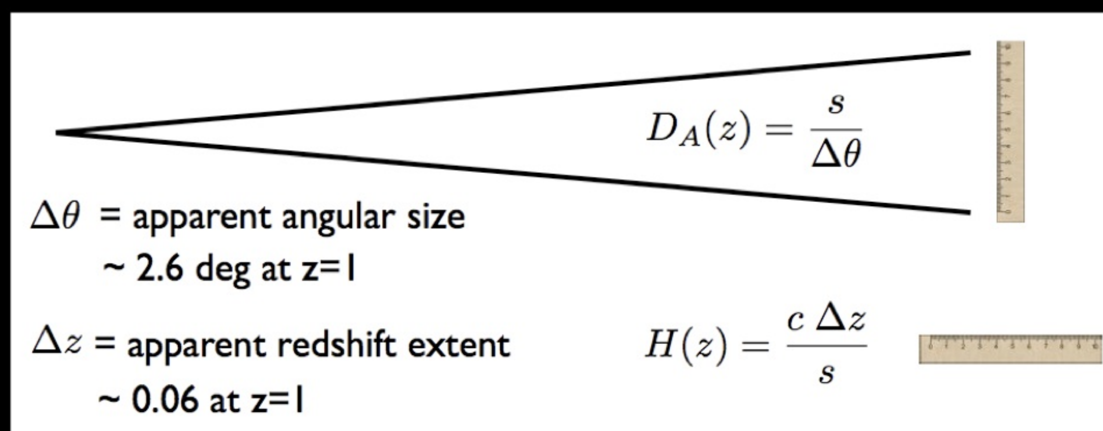


Other TYPES of tests: A standard ruler in 3D



- SNe = radial
- CMB = tangential info (surface of sphere)

- BAO can be applied radially to give H(z) AND tangentially to give $D_A(z)$



Commotion: Redshift-space distortions

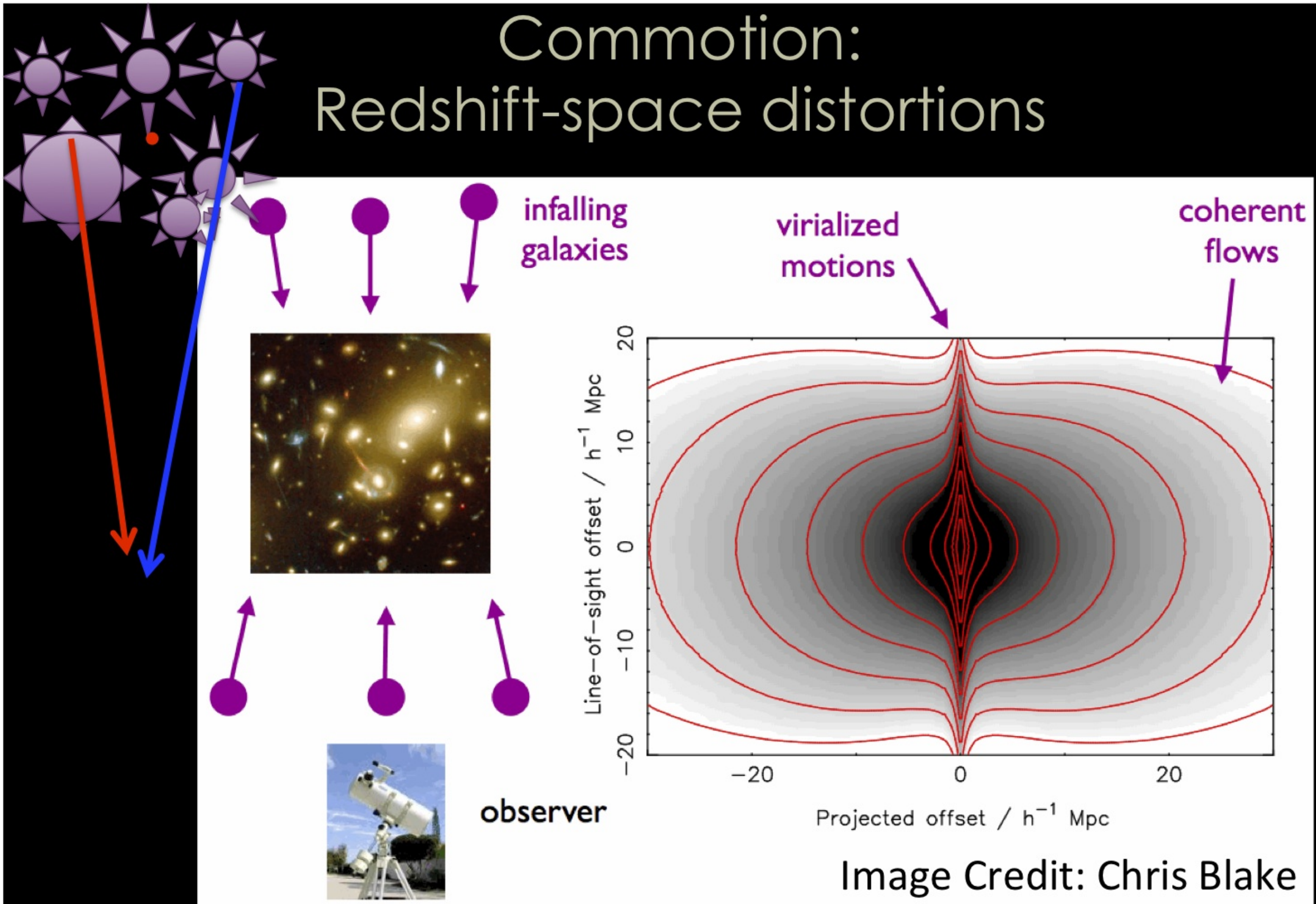
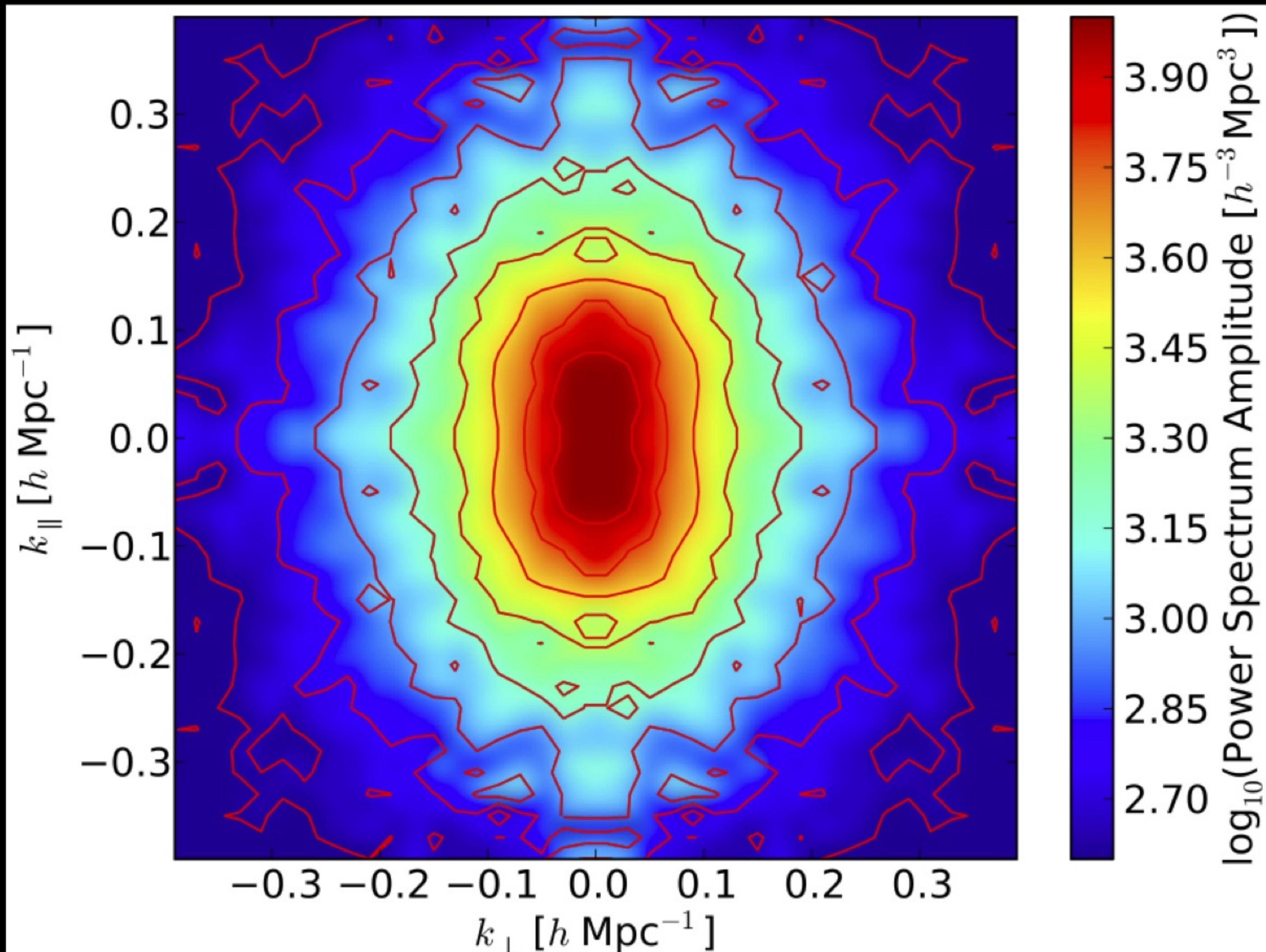


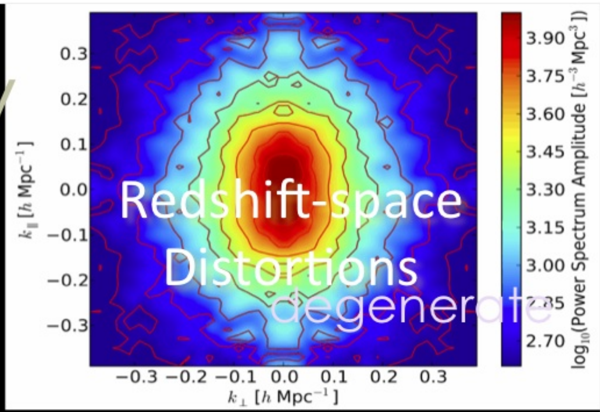
Image Credit: Chris Blake

Redshift space distortions

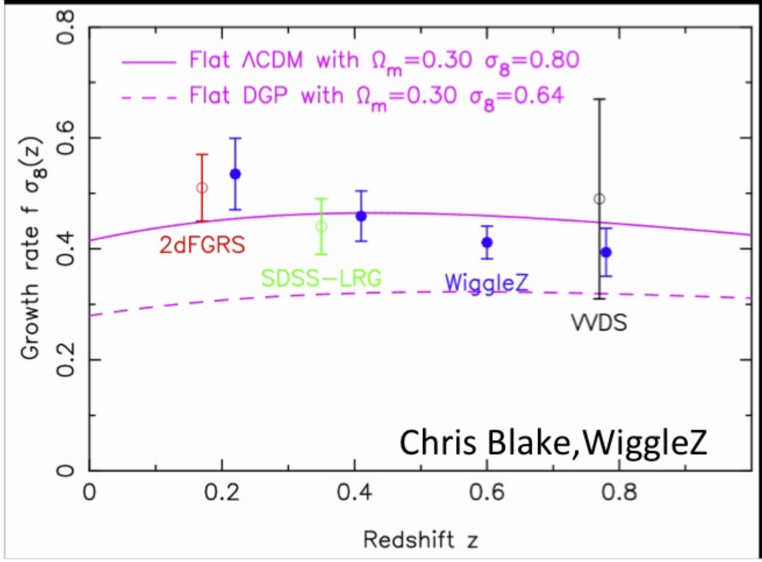


Distinguishing dark energy

Tests of structure growth in the universe can distinguish between models that are degenerate to geometric tests



- Density distributions…. power spectra / correlation functions
- Velocity distributions…. bulk flows / velocity moments
- Growth…. redshift space distortions



One area where Australian facilities have a competitive advantage now (or soon)

Statistical:

WiggleZ	250,000 Galaxies (z-space dist.)

With distances:

6dF :	10,000 Galaxies (Fund. Plane)
SkyMapper:	1,000 SNe Ia (Std Candle)
ASKAP:	30,000 Galaxies (Tully Fisher)

Testing Theories of Gravity

Tamara Davis, David Parkinson, and Signe Riemer-Sorensen
University of Queensland Astrophysics
PIAF Workshop, Dec 2010

Gravity

- General relativity is a "scale-invariant" theory
  - A scaling of distance, time and energy leaves the equations unchanged
- It appears to break down on scales much larger than the solar system, requiring some 'dark' fluids

$$G_{\mu\nu} - \kappa T_{\mu\nu}^{light} = \kappa T_{\mu\nu}^{dark}$$

- Instead of Dark Energy, maybe the law of gravity is wrong
  - c.f. perihelion of Mercury – Vulcan vs. Einstein
- But new theories must match Earth/Solar system tests – require "cross-over" scale when new physics takes over

New Theories

- *f(R)* – replace Ricci scalar in Einstein-Hilbert action with more complex function, *f*
  - Length scale corresponds to "Compton wavelength" of theory, B
- DGP (Davli-Gabadaze-Porrati) – gravity leaks away into higher dimension
  - Length scale set by Hubble scale
- Massive gravity/Cascading gravity – graviton has a mass associated with it
  - Length scale set by actual Compton wavelength – graviton behaves as massless particle below and massive above
- Others – scalar-tensor, Galileon cosmology, *f(G)*, Emergent gravity etc

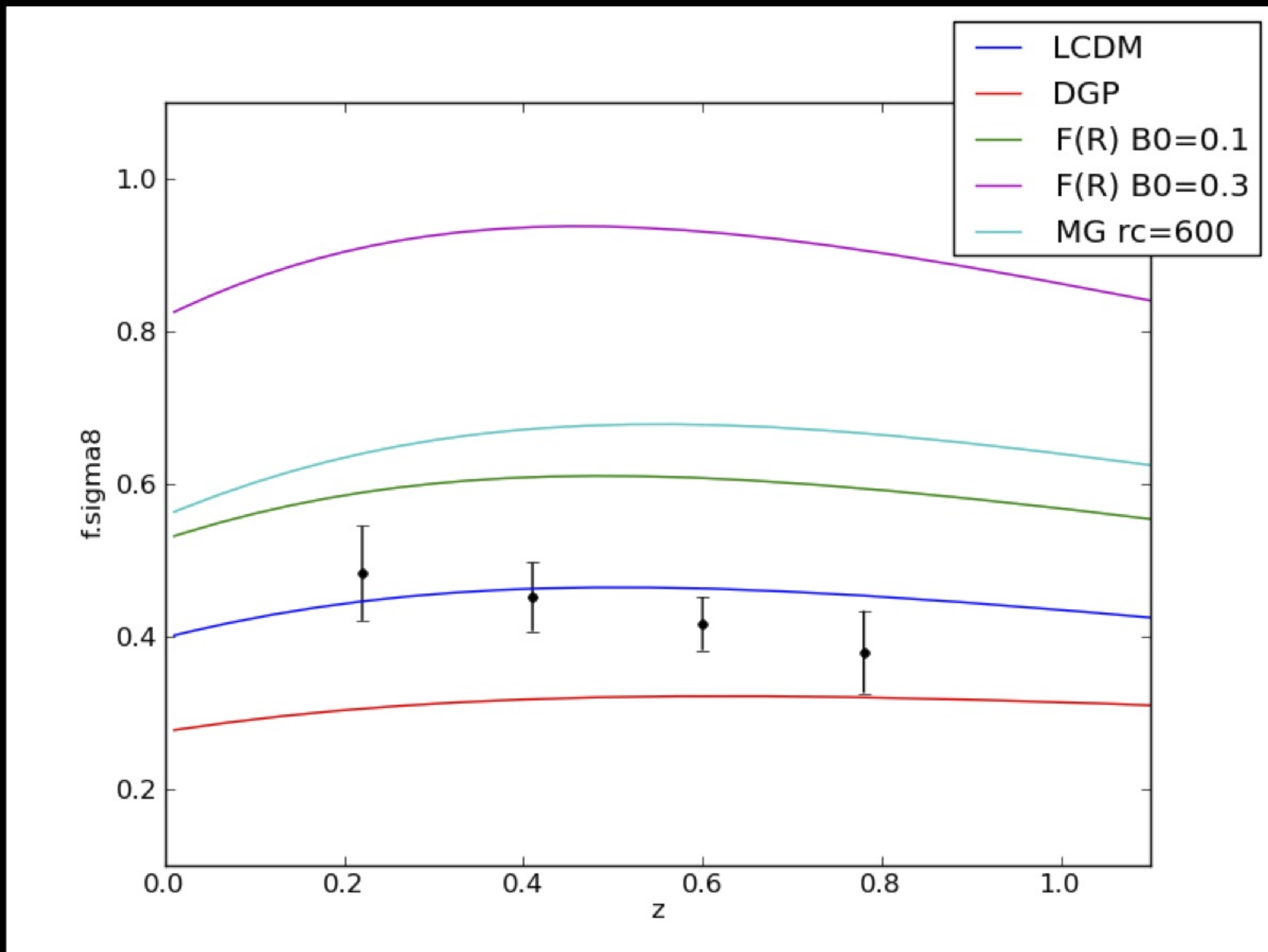
Testing gravity through Structure Formation

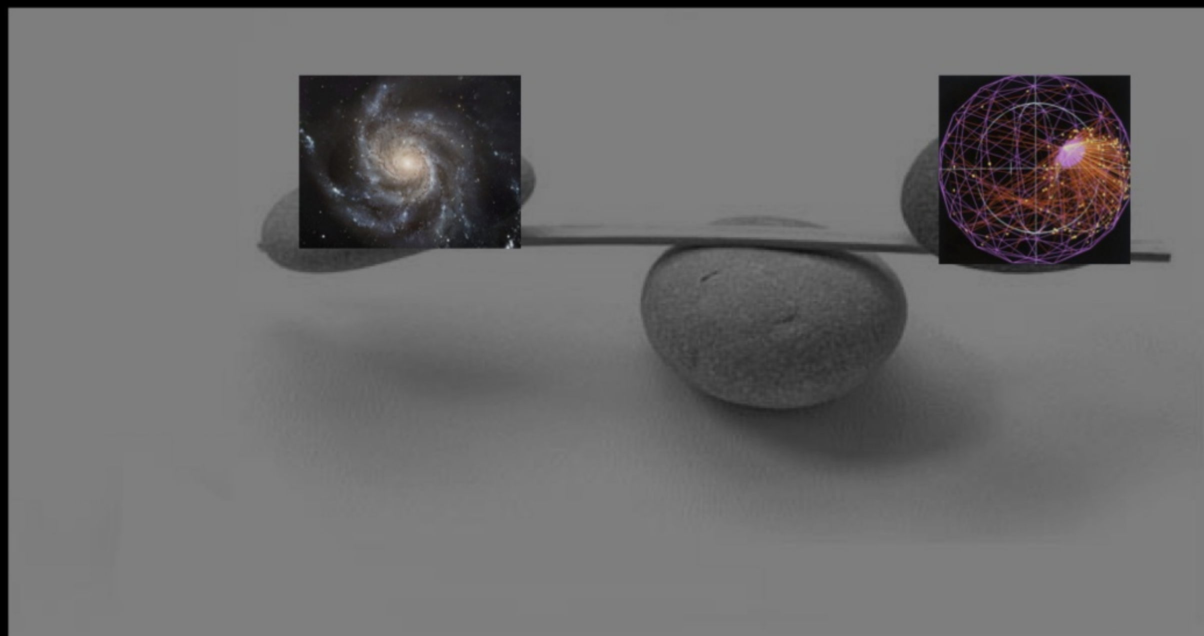
- How do we test gravity on Earth – watching particles fall towards each other
- Structure forms in the universe under gravity
  - Small perturbations in matter density (δ) grow by attracting and accumulating material
- The rate of growth on large scales (linear physics) is set by the theory of gravity
- We find rate of growth is a power law of the density of matter

$$\frac{d\ln\delta}{d\ln a} = f = \Omega_M^{\gamma}$$

- Different theories predict different values of the growth index

Predictions & Measurements



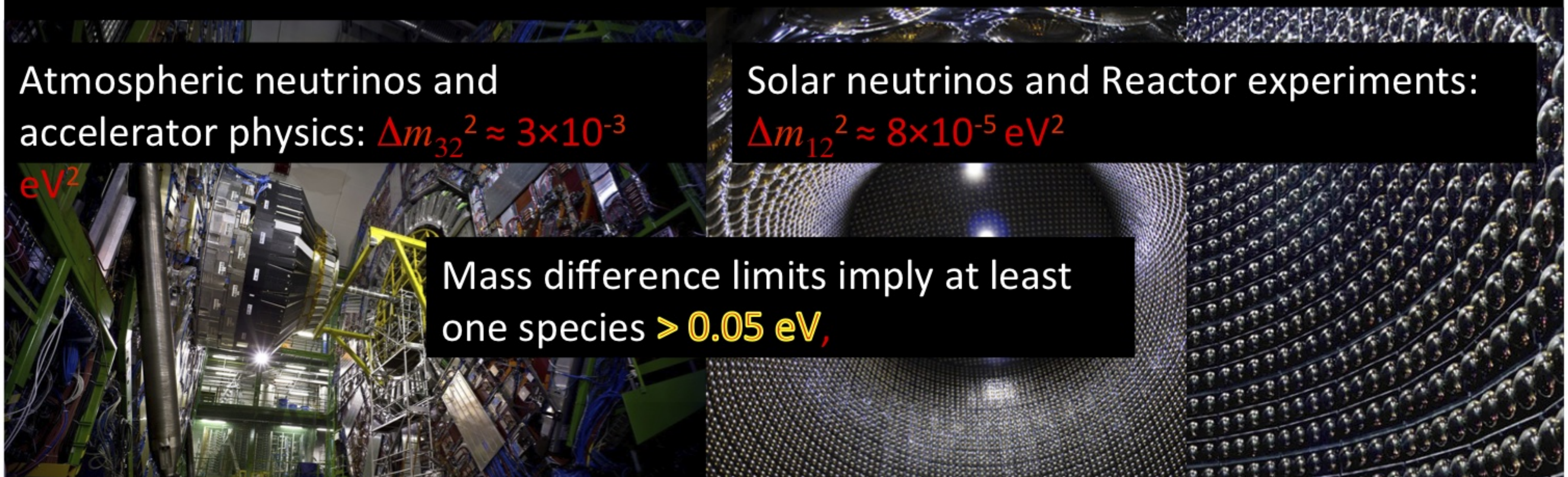


Cosmological particle physics

Tamara Davis, David Parkinson, and Signe Riemer-Sorensen
University of Queensland Astrophysics

PIAF Workshop, Dec 2010

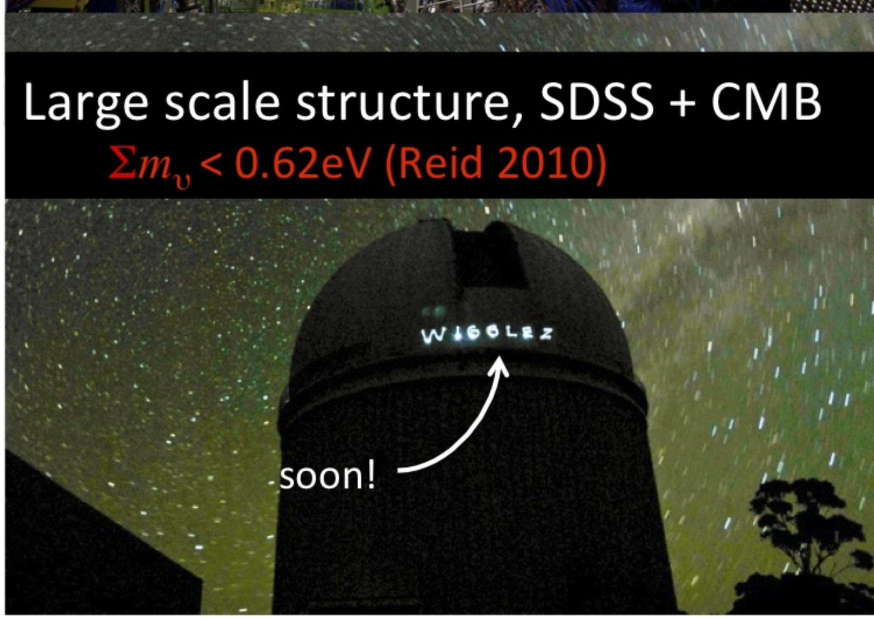
One example: neutrino mass



Atmospheric neutrinos and accelerator physics: $\Delta m_{32}^2 \approx 3\times10^{-3}$ eV^2

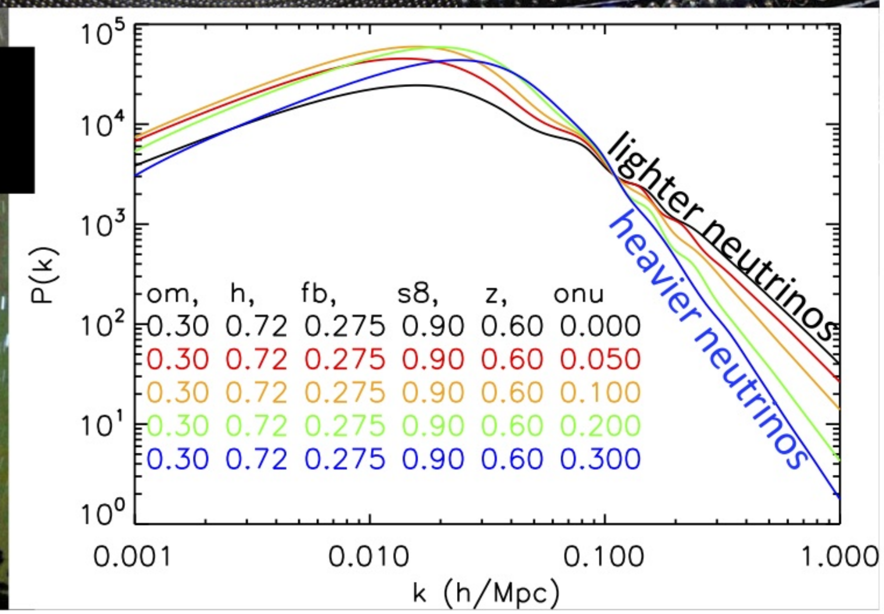
Solar neutrinos and Reactor experiments: $\Delta m_{12}^2 \approx 8\times10^{-5}$ eV^2

Mass difference limits imply at least one species > 0.05 eV,



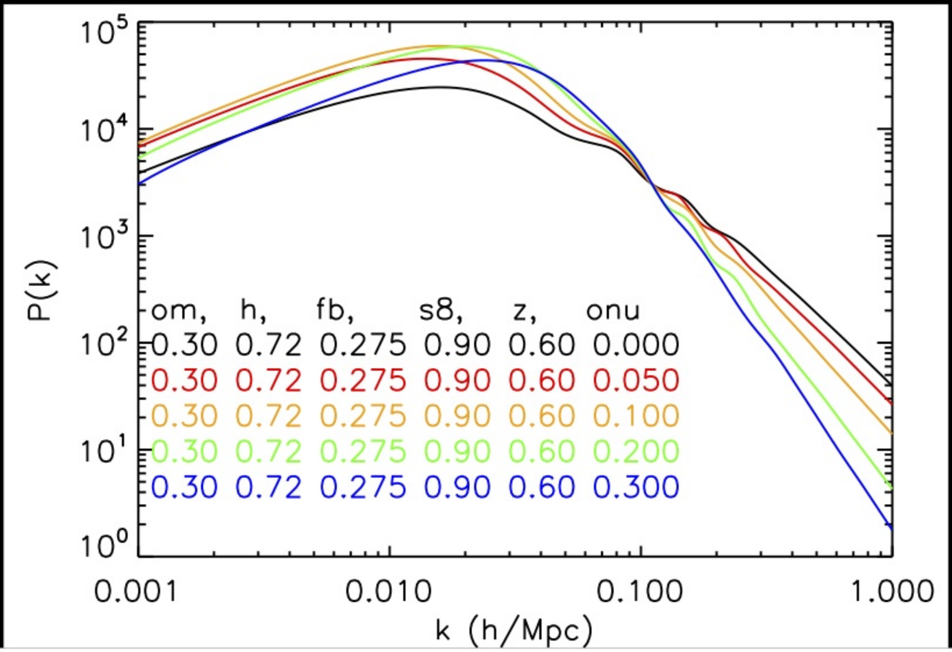
Large scale structure, SDSS + CMB

$\Sigma m_\nu < 0.62$eV (Reid 2010)

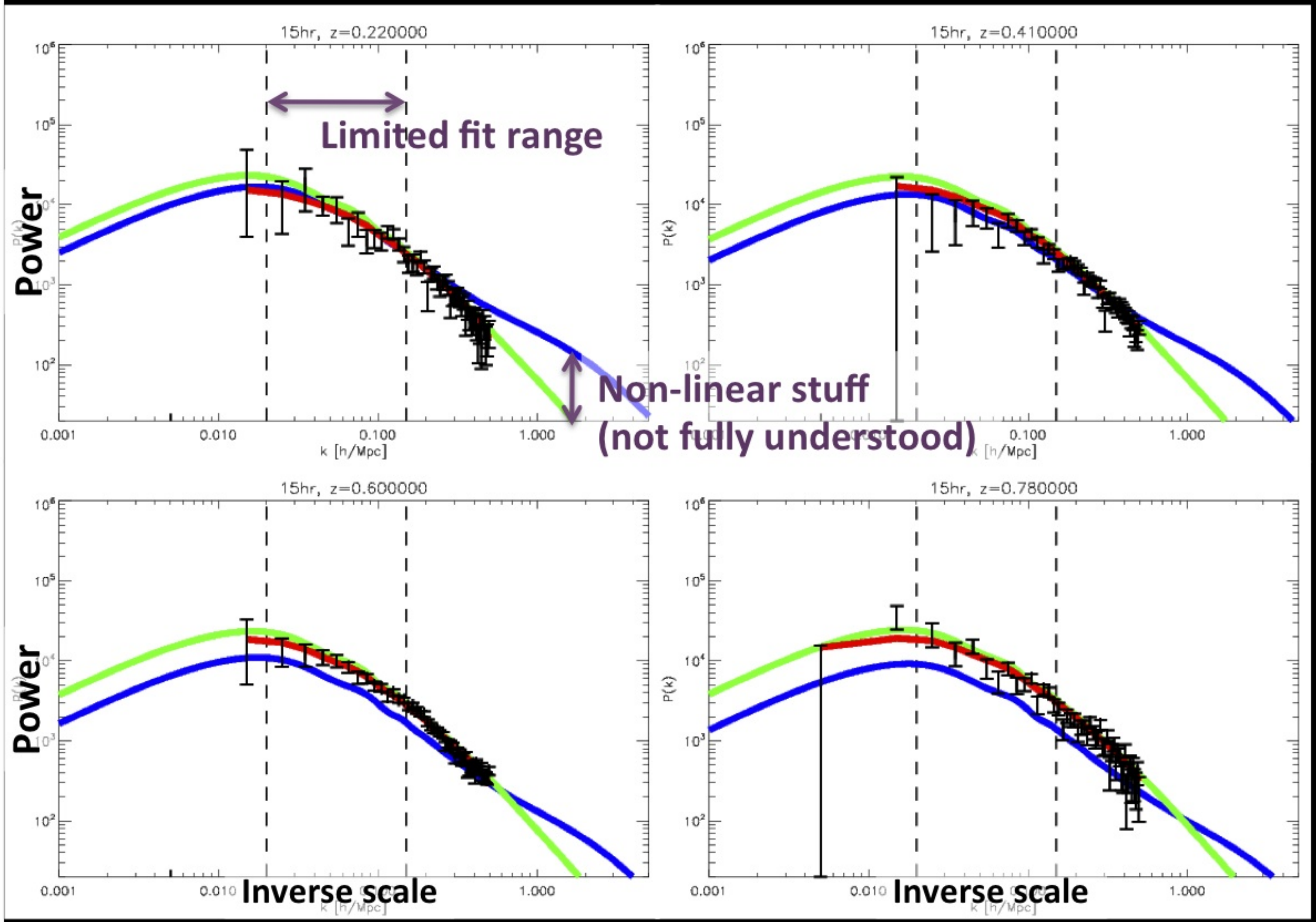


Massive neutrinos alter structure

- Neutrinos *suppress structure formation* on small scales by free-streaming out of initial density perturbations.
- The free streaming length is lower for higher neutrino masses, since velocities decay
  - Heavy neutrinos =strong suppression over short range
  - Light neutrinos = weak suppression over long range



WiggleZ (+WMAP)



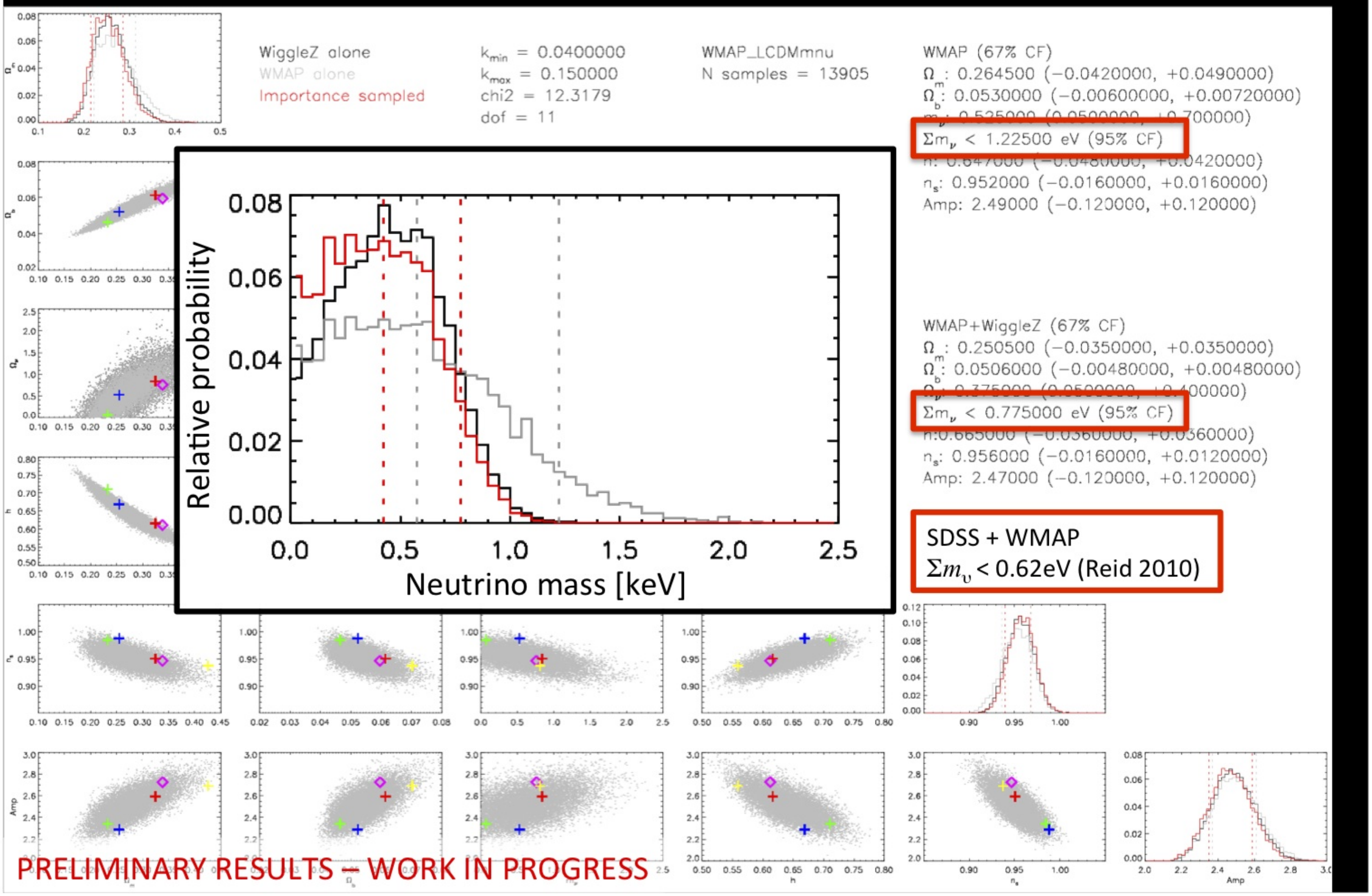
Predicted from structure formation

Corrected for bias and redshift space distortions

Corrected for observational effects

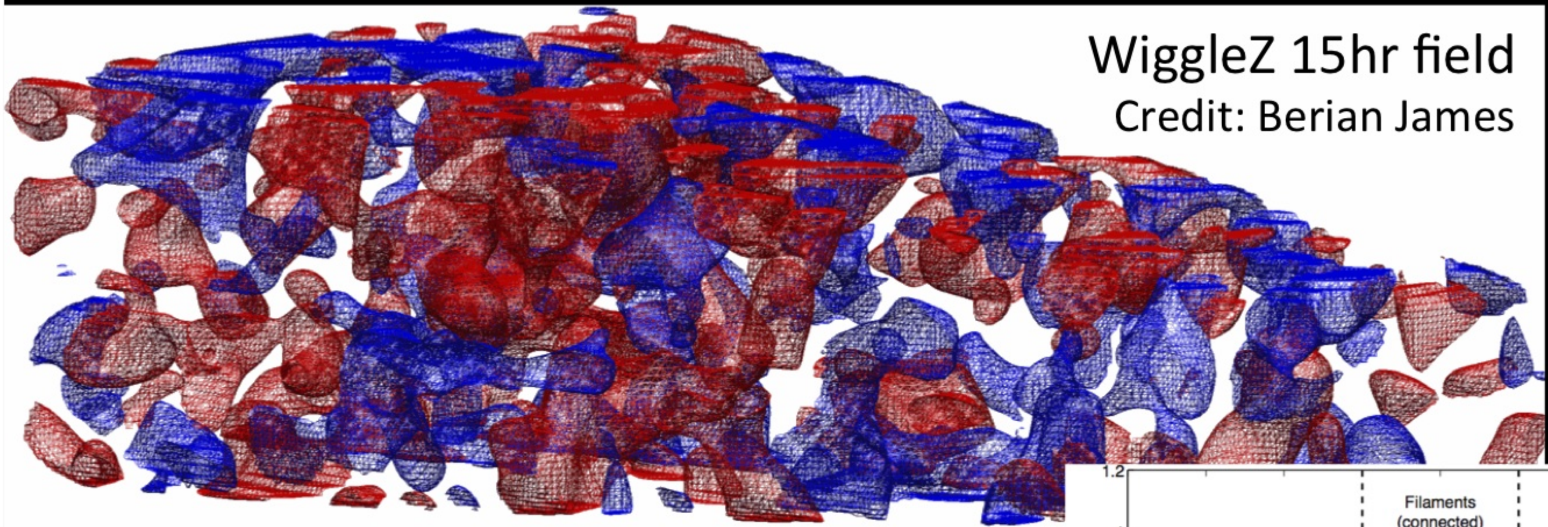
PRELIMINARY RESULTS – WORK IN PROGRESS

Results



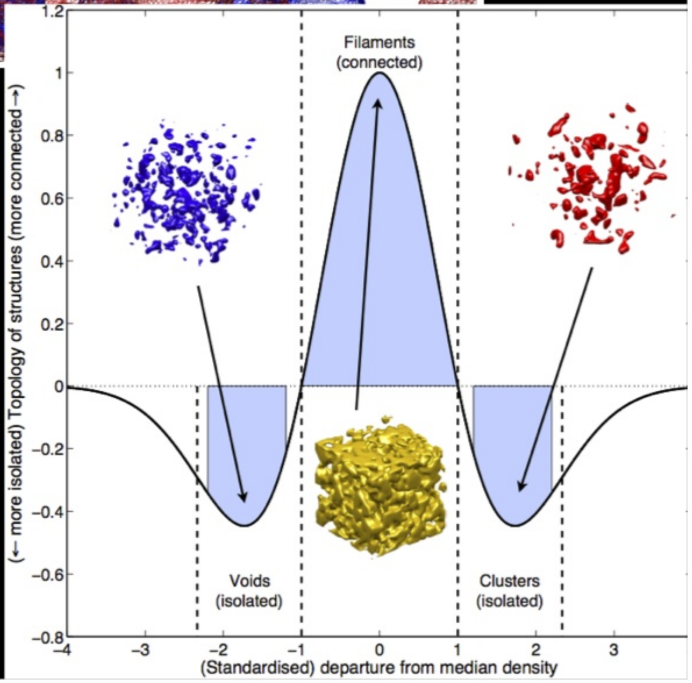
WiggleZ alone
WMAP alone
Importance sampled
k_min = 0.0400000
k_max = 0.150000
chi2 = 12.3179
dof = 11
WMAP_LCDMmnu
N samples = 13905
WMAP (67% CF)
Ω_m: 0.264500 (−0.0420000, +0.0490000)
Ω_b: 0.0530000 (−0.00600000, +0.00720000)
Σm_ν < 1.22500 eV (95% CF)
n_s: 0.952000 (−0.0160000, +0.0160000)
Amp: 2.49000 (−0.120000, +0.120000)
WMAP+WiggleZ (67% CF)
Ω_m: 0.250500 (−0.0350000, +0.0350000)
Ω_b: 0.0506000 (−0.00480000, +0.00480000)
Σm_ν < 0.775000 eV (95% CF)
n_s: 0.956000 (−0.0160000, +0.0120000)
Amp: 2.47000 (−0.120000, +0.120000)
SDSS + WMAP
Σm_υ < 0.62eV (Reid 2010)
Relative probability
Neutrino mass [keV]
PRELIMINARY RESULTS – WORK IN PROGRESS

Topology, genus, and gaussianity



Highest and Lowest density regions (each 10% by volume).

The genus statistic measures the topology of structure and is sensitive to non-gaussianity
(key to understanding inflation)



Standard Clocks: e.g. Supernovae

- We measured time dilation caused by the expansion of the universe by timing supernova explosions

nature Vol 454|14 August 2008

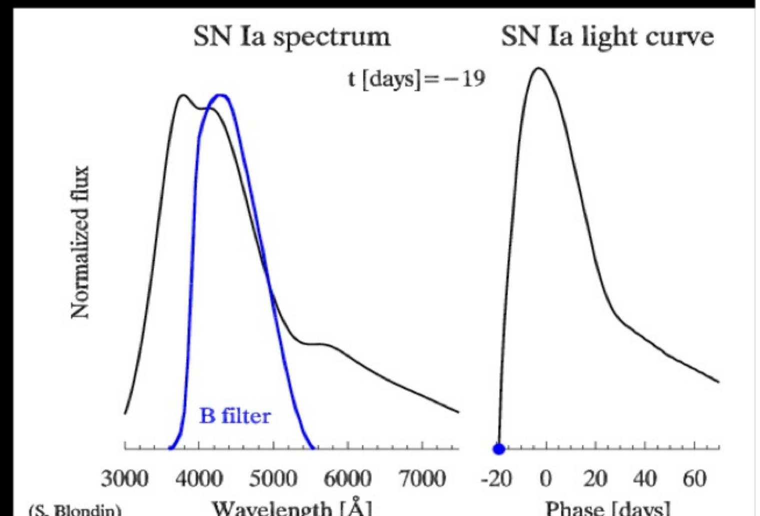
RESEARCH HIGHLIGHTS

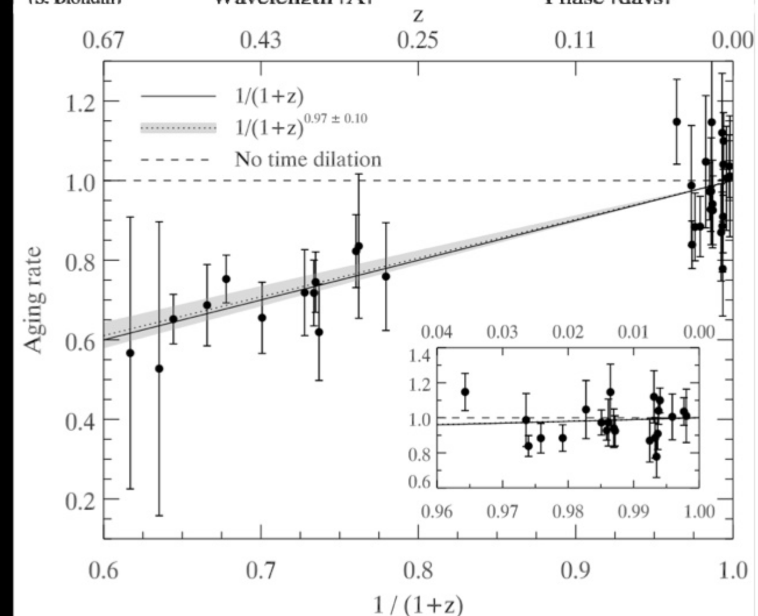
ASTROPHYSICS

Slow-motion supernovae

Astrophys. J. **682,** 724–736 (2008)

A survey of exploding stars shows that the farther away they are, the slower they seem to blow apart, as predicted on the basis of general relativity. The supernovae studied are known as type 1a supernovae, and are important for gauging the strength of dark energy — a mysterious force that seems to be pushing the Universe apart. These findings

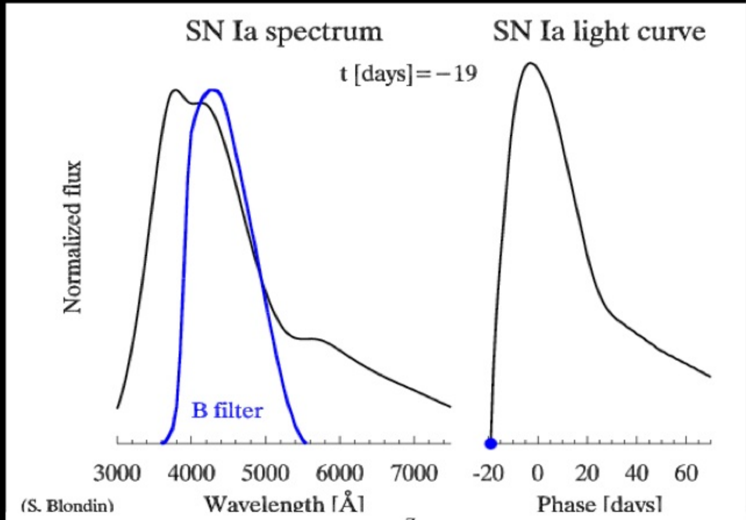


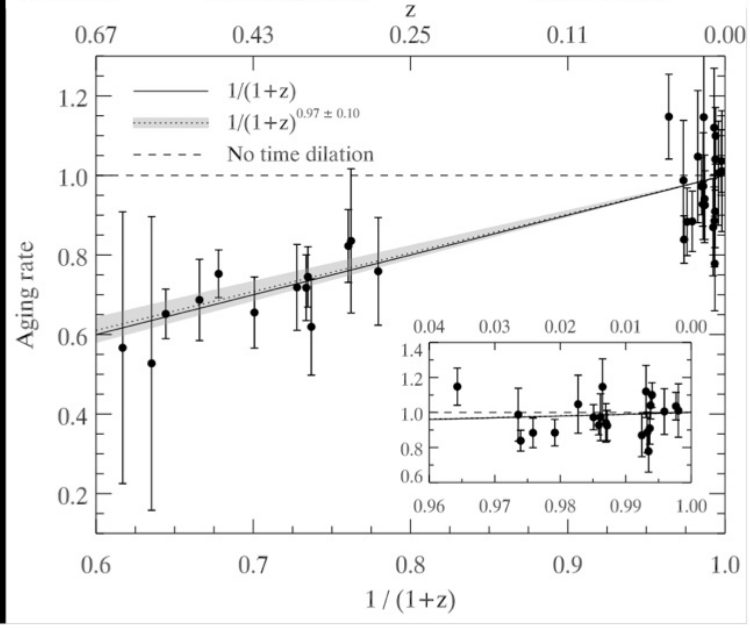



!!! SHOCKING NEWS !!!
ASTROPHYSICICISTS CONFIRM
EXPANSION OF UNIVERSE

Standard Clocks: e.g. Supernovae

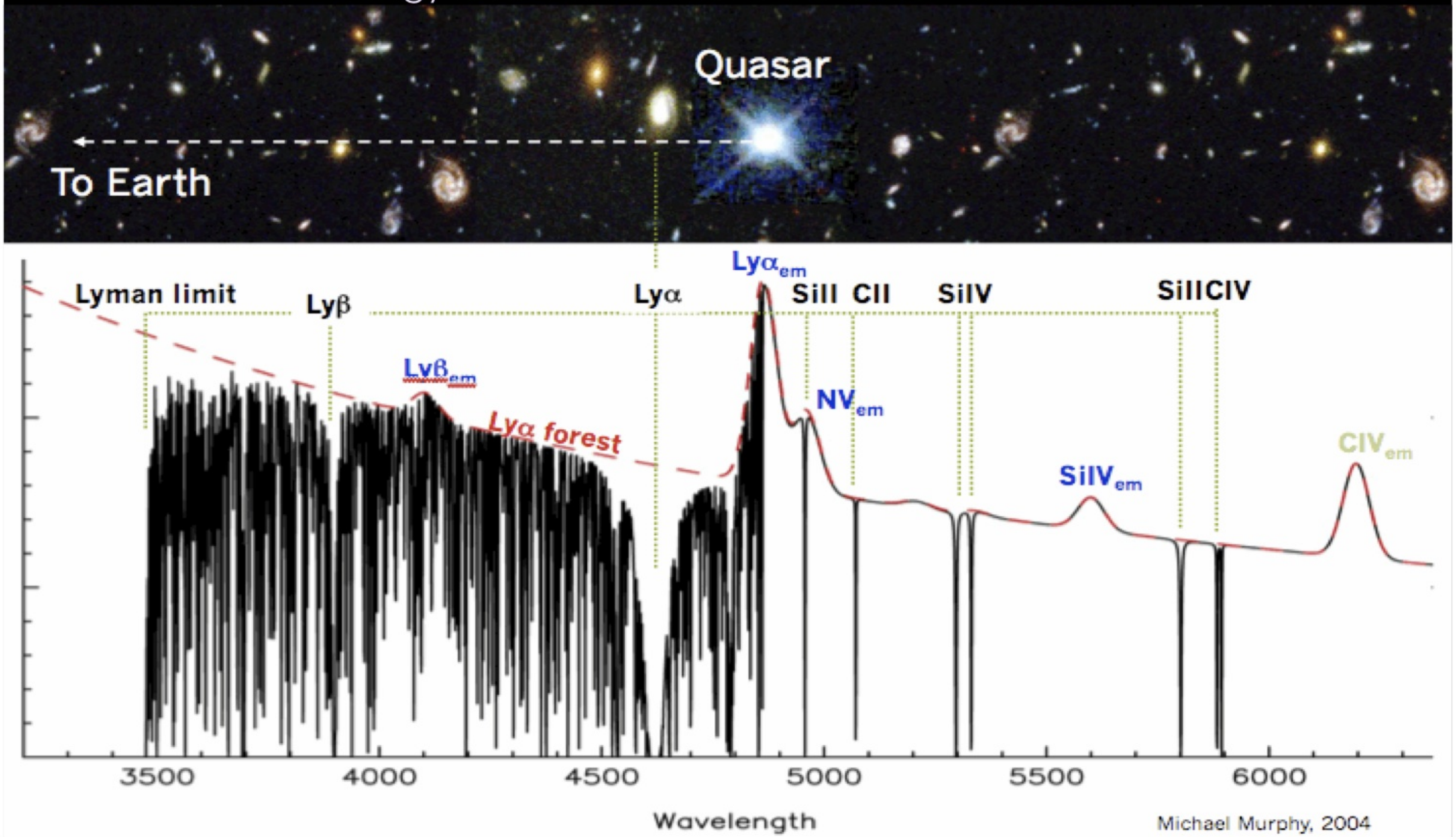
- We measured time dilation caused by the expansion of the universe by timing supernova explosions
- Many other applications of time-delay measurements
  - Particularly of double images of gravitational lensed sources





Little rulers…. do the constants vary?

- The fine structure constant determines the energy levels seen in spectra
- Are those energy levels the same in the distant universe?



Conclusions

- Astrophysics has a wealth of information we can harvest.
- Our tools include: standard candles, rulers, clocks, and motion and with them we are trying to answer…

- What are the fundamental rules that govern our universe?
  - Is general relativity the correct theory of gravity?
  - If so, what form does the dark energy take?
  - What is dark matter?
  - What are the parameters of the standard model of particle physics.
  - Do the constants of nature vary?
- What initiated the expansion?
  - Test predictions of inflation
- How did galaxies form and how do they evolve?
  - Test structure formation and galaxy evolution