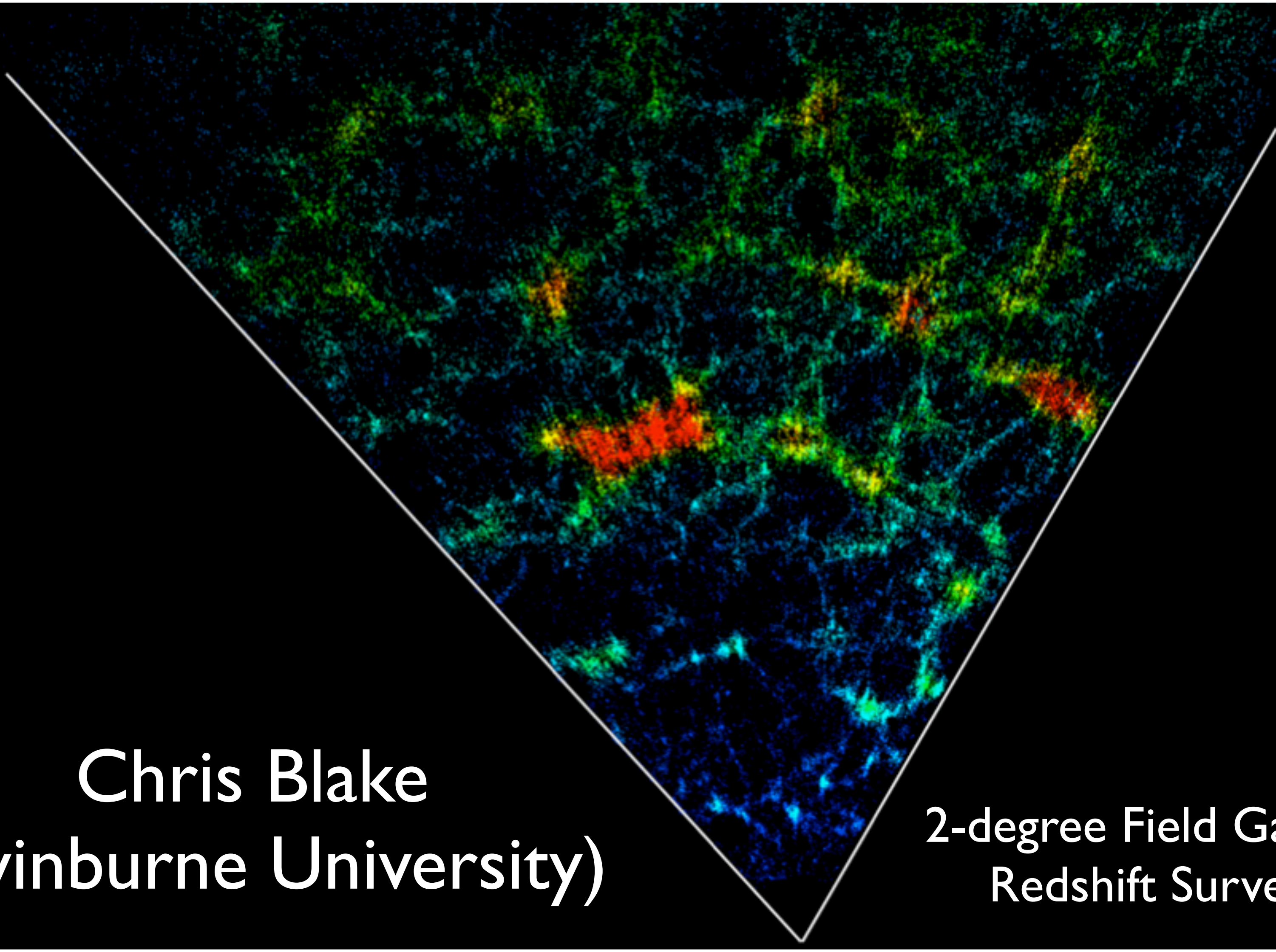
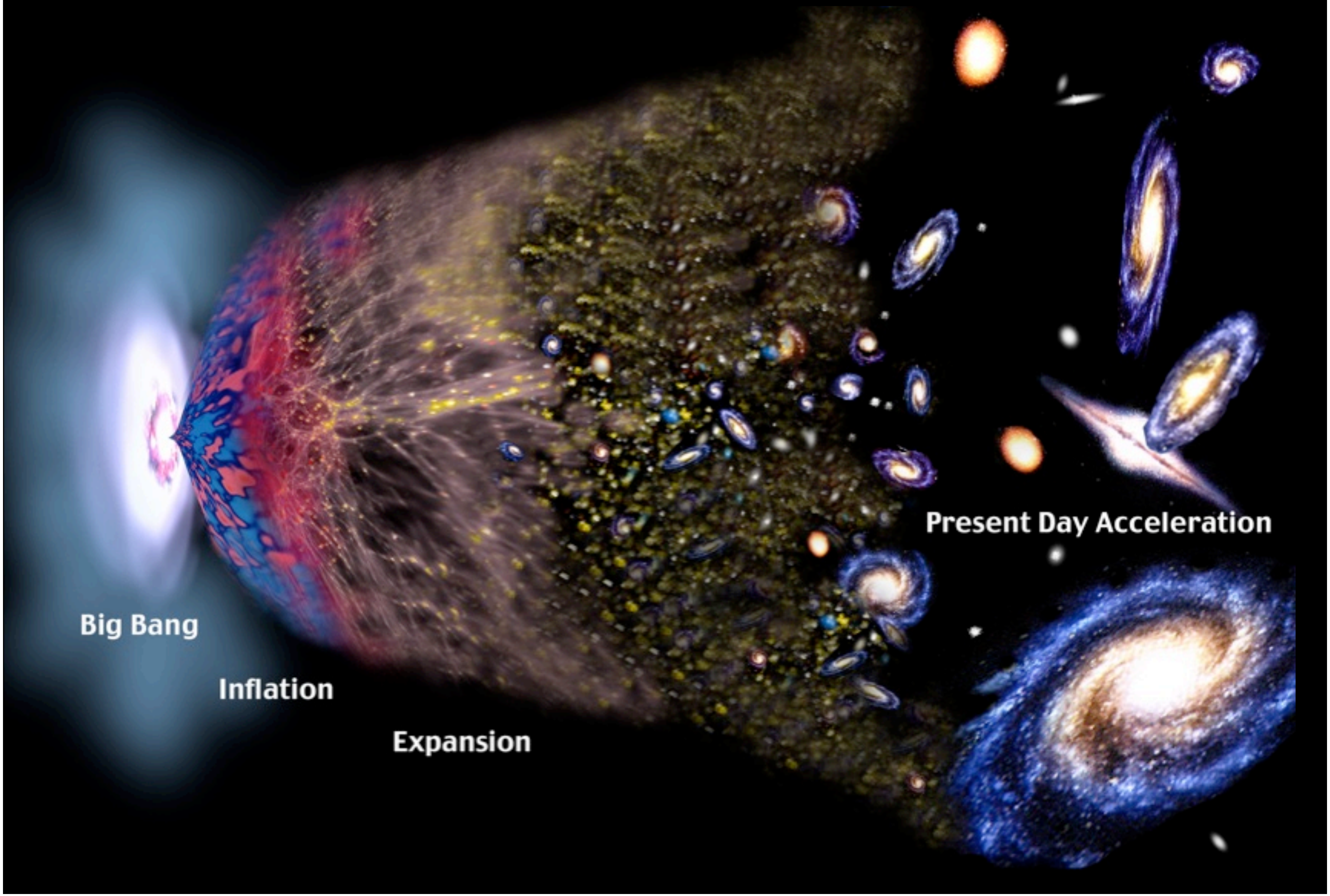
What does the galaxy distribution tell us about the Universe?



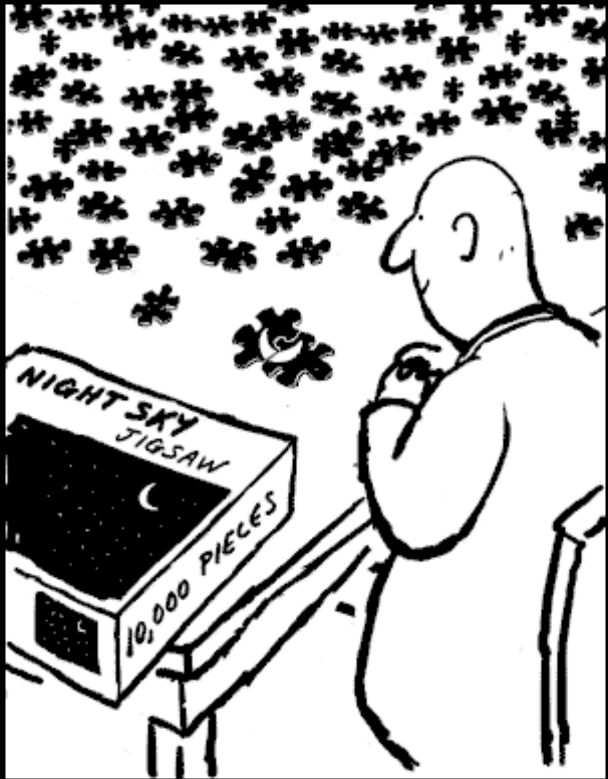
2-degree Field Galaxy Redshift Survey

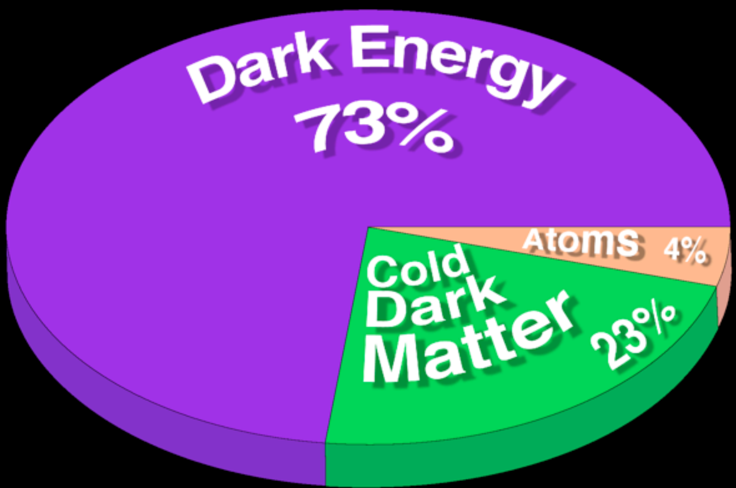
Chris Blake
(Swinburne University)

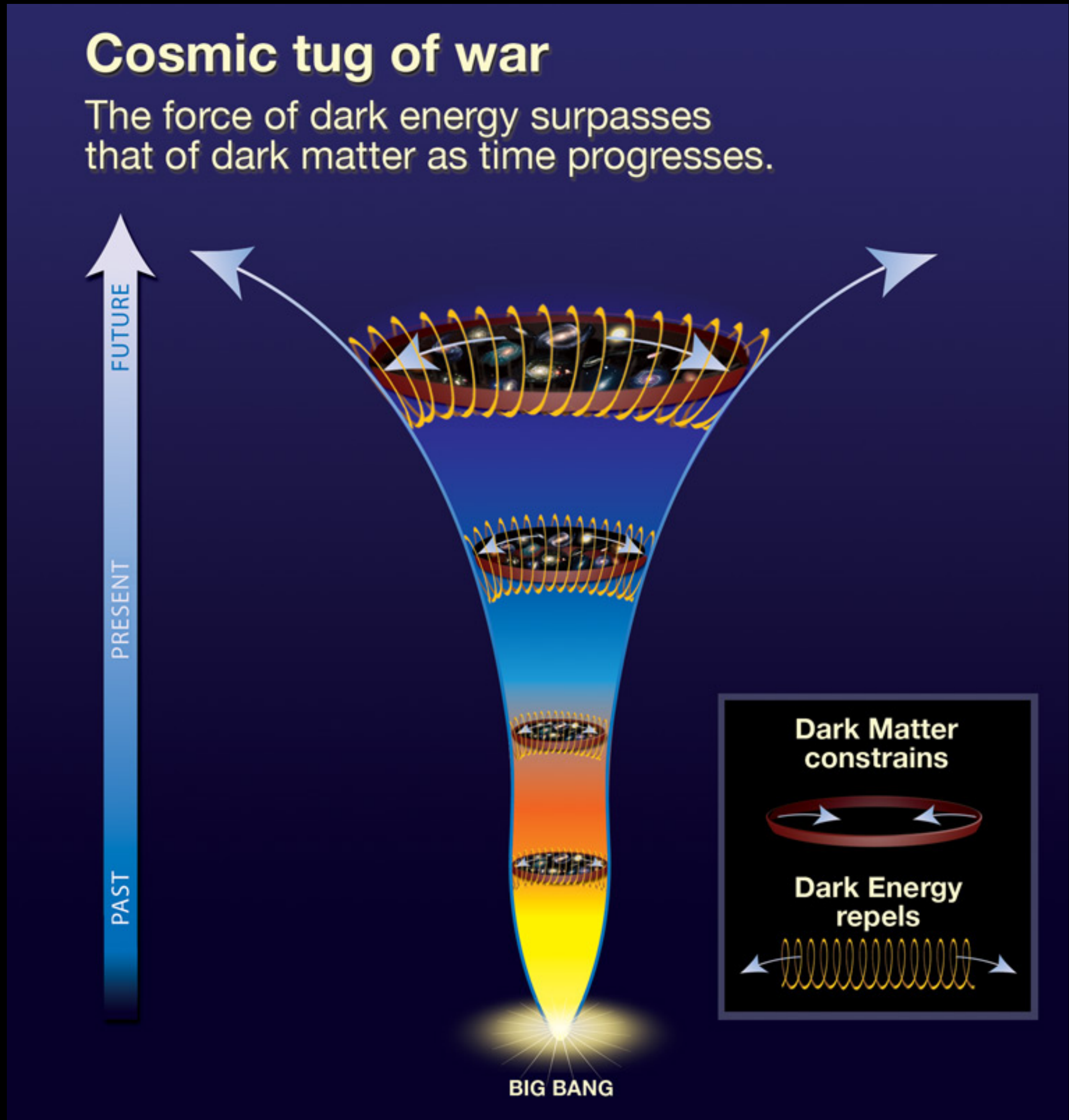
Our current model of cosmology



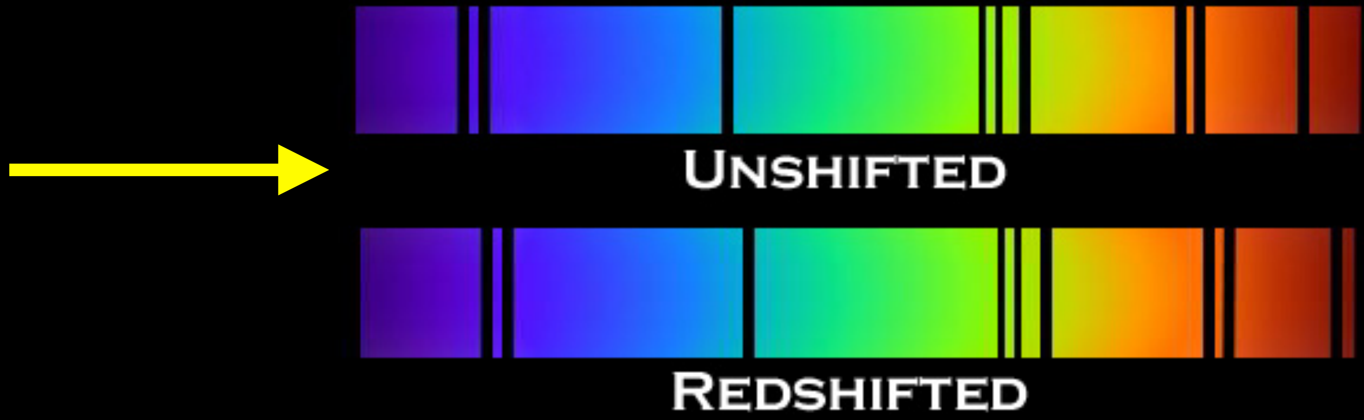
Our current model of cosmology

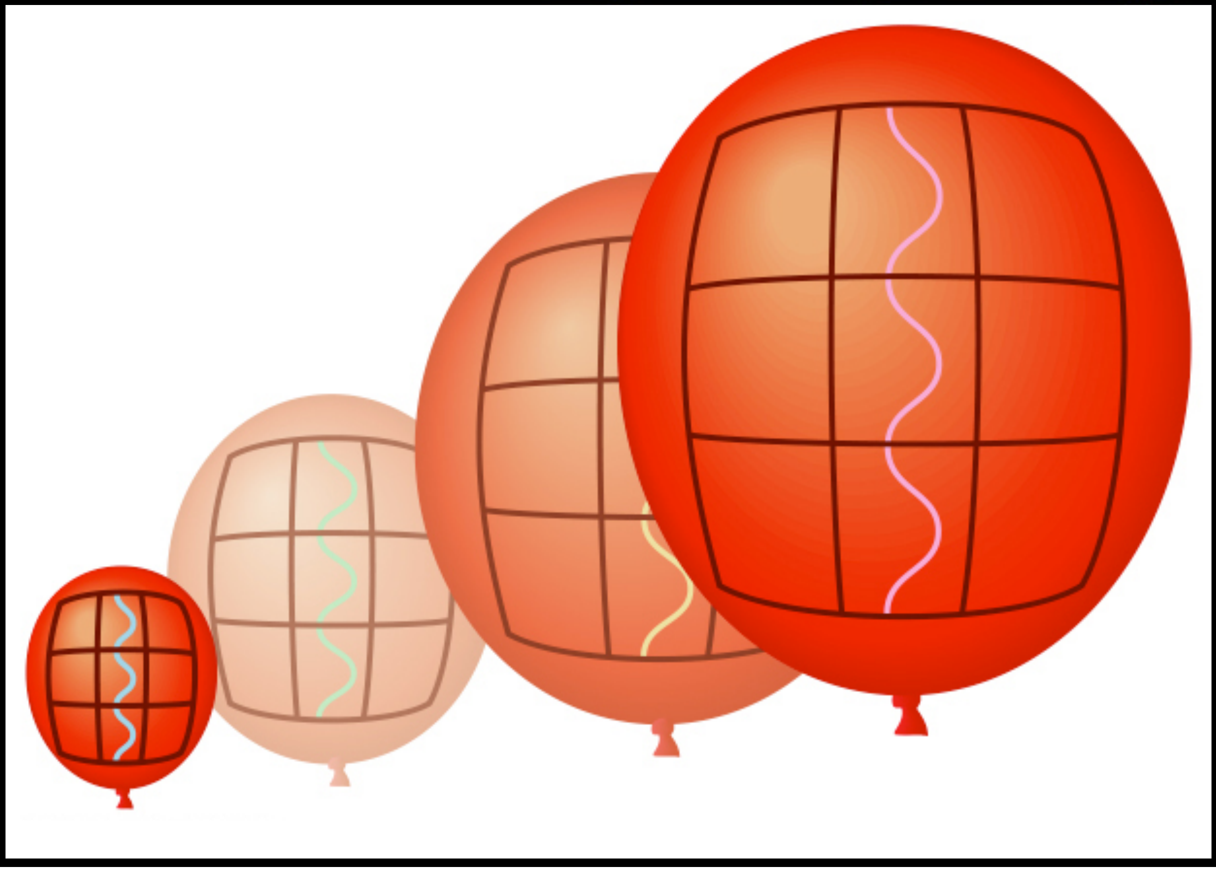






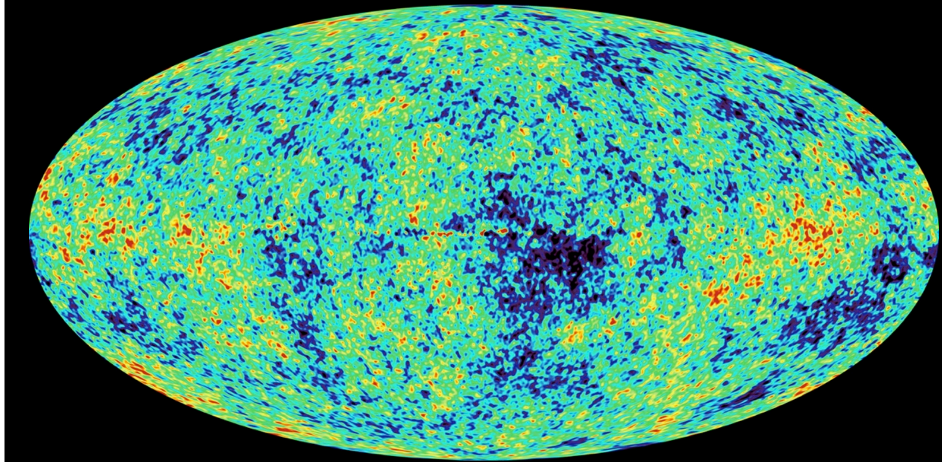
Cosmological redshift



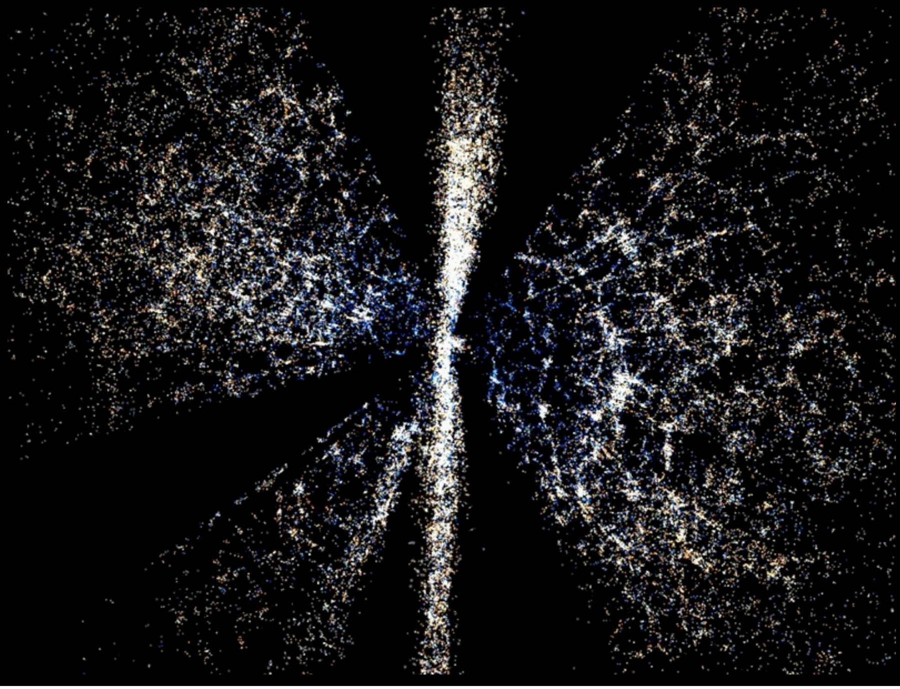


Cosmologist's tools

Cosmic microwave background



Galaxy surveys

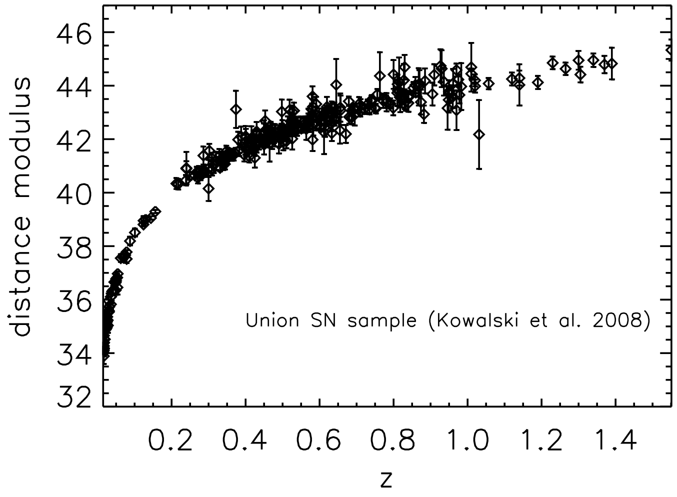


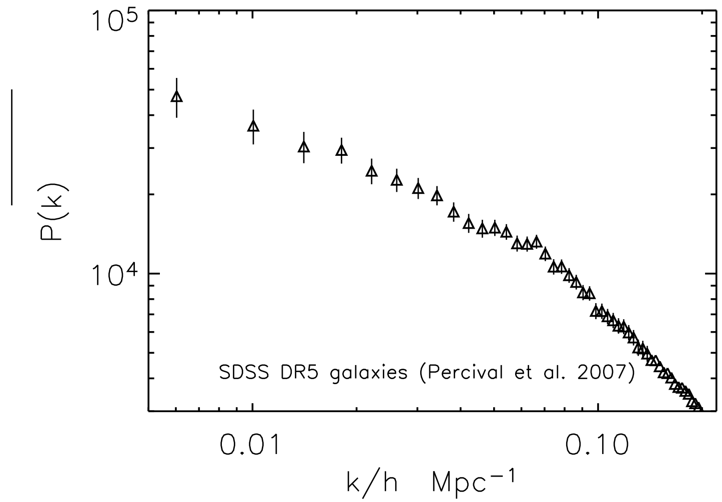
Supernovae

The link between cosmology and eResearch

- Cosmology is now a data-driven science dominated by a series of "big experiments"
- Advanced computer simulations of the Universe are needed for end-to-end testing of analysis pipelines and determining measurement errors
- Sophisticated statistical tools and algorithms are required for answering questions

The need for statistics!



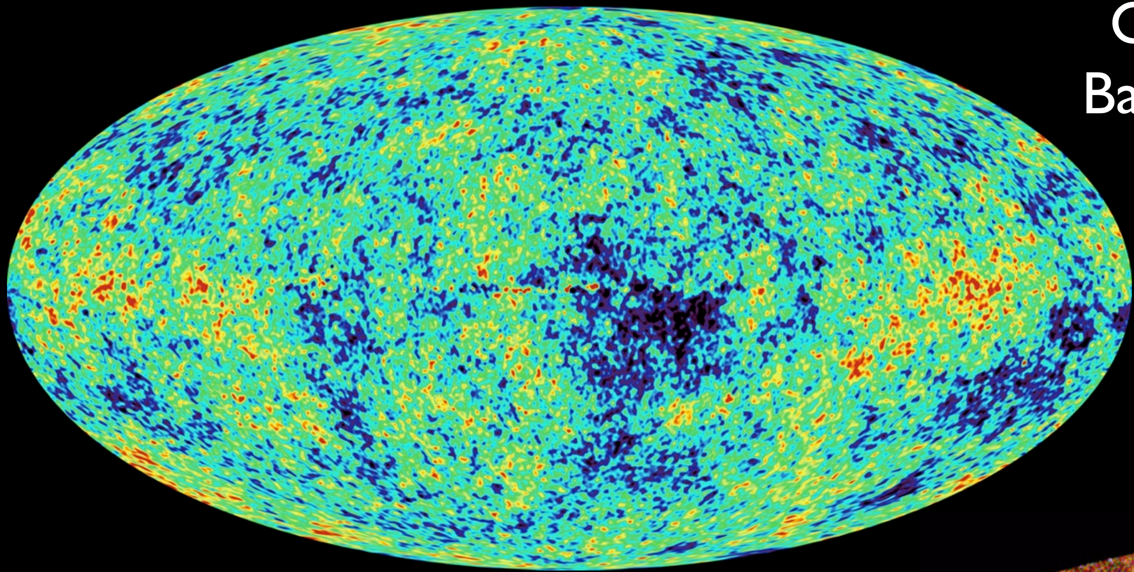


- Cosmological model predictions are inherently statistical
- We live in an era of "precision cosmology" which demands robust statistical methods
- Systematic errors must also be quantified
- We are typically doing one of : hypothesis testing, parameter estimation, model selection or forecasting

Typical questions asked by a cosmologist

- Is the Universe homogeneous and isotropic? [hypothesis testing]
- Are the initial conditions of the Universe consistent with Gaussian fluctuations? [hypothesis testing]
- What is the value of the cosmic expansion rate today? [parameter estimation]
- Are the properties of dark energy constant over the age of the Universe, or do they evolve? [model selection]
- How well will Planck satellite measurements determine the gravitational wave background? [forecasting]

The cosmological principle

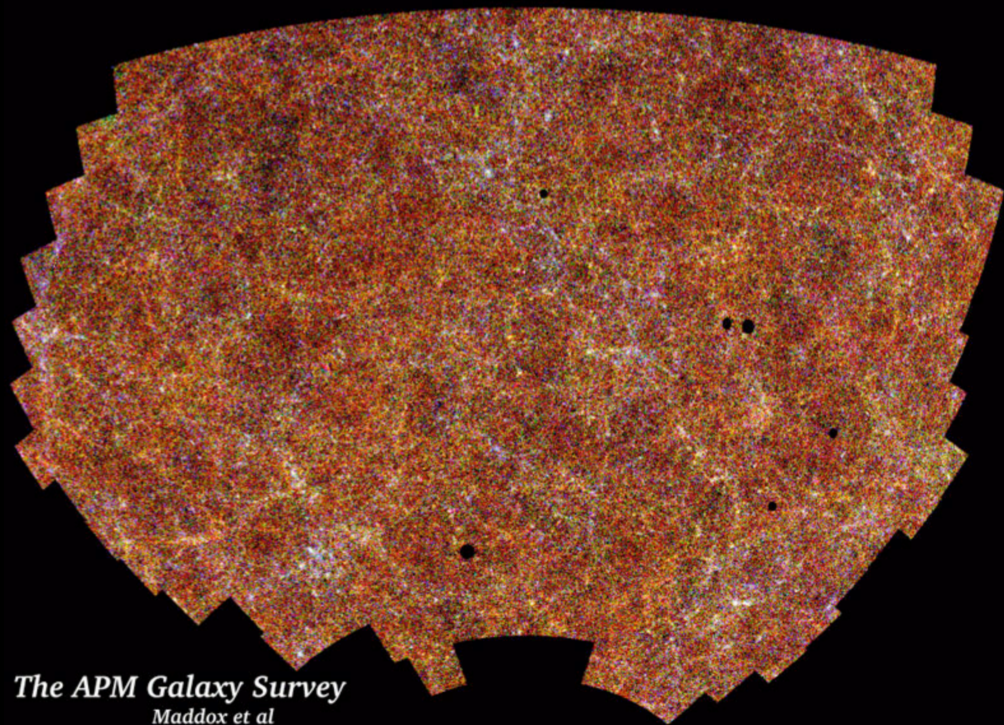


Cosmic Microwave Background radiation (WMAP)

Ripples are 1 part in 100,000

Homogeneity and isotropy

Galaxy distribution on the sky (APM survey)

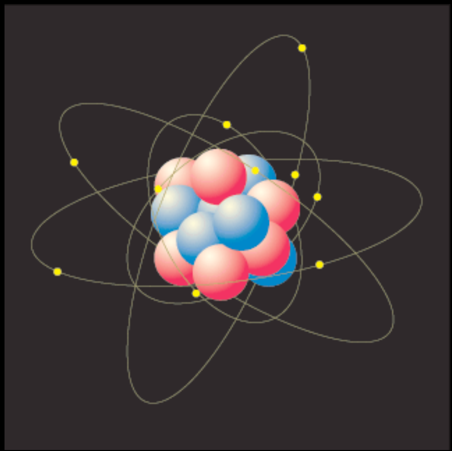


How do we model the Universe?

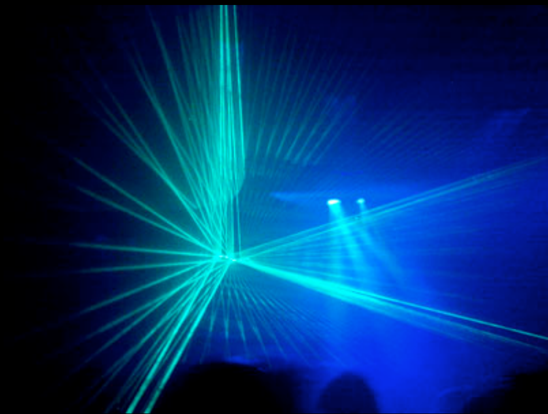
$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \langle\rho\rangle}{\langle\rho\rangle}$$

- Assume we have observed a fair sample of the Universe
- Assume the Universe is homogeneous and isotropic
- Assume the density is a Gaussian random field [theoretical motivation from inflation, analytic tools]
- All information is encoded in the 2-point statistics (power spectrum or correlation function)
- Real-world issues : higher-order statistics, determination of errors, survey "selection function", galaxy "bias"

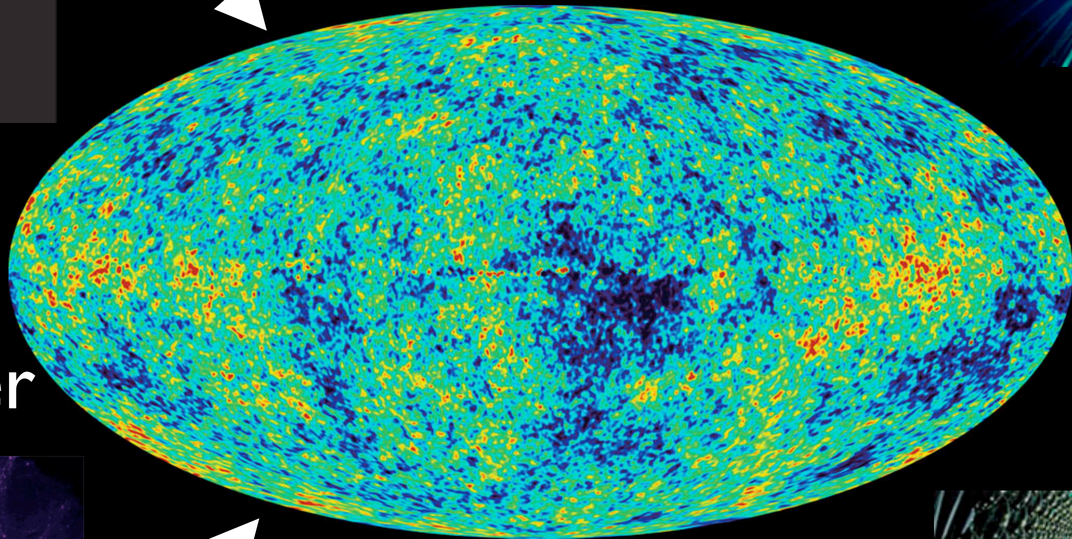
How do we model the Universe?



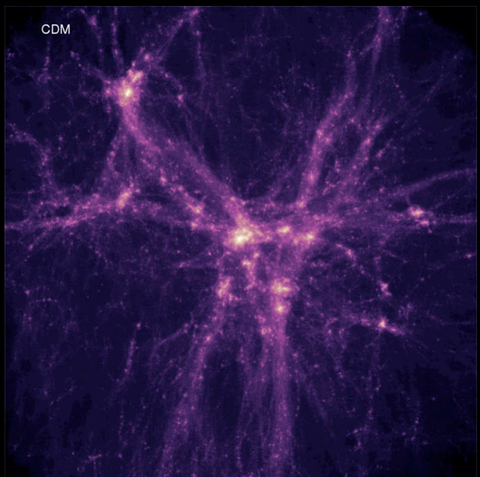
Atoms



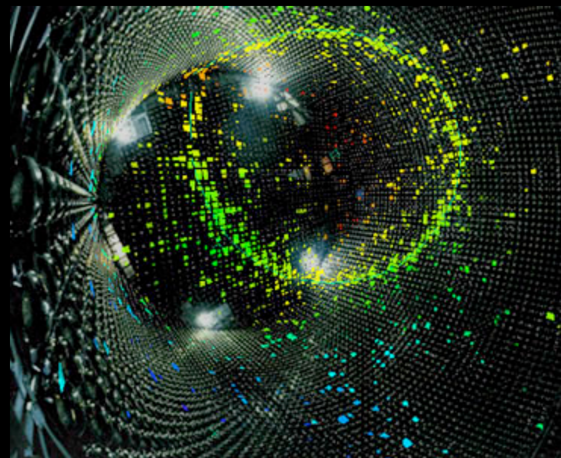
Radiation



Dark matter



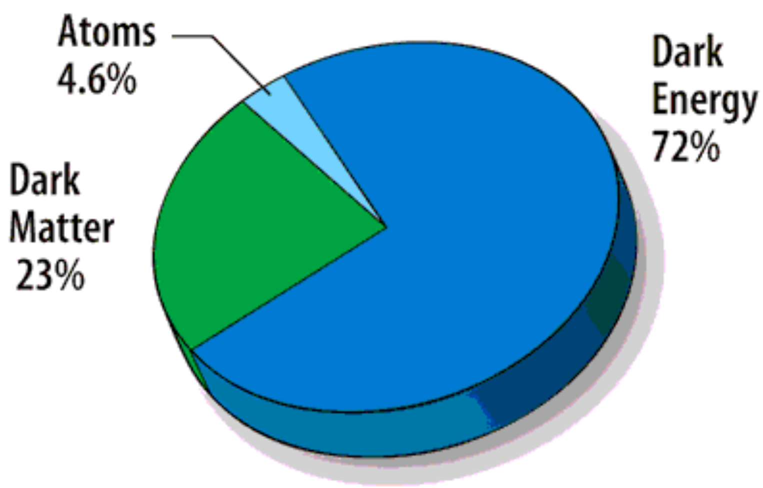
Neutrinos



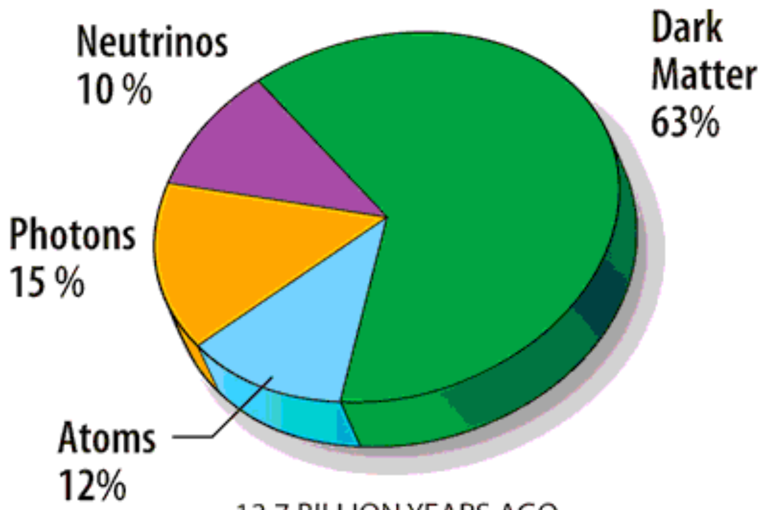
We can solve
these equations
exactly and predict
2-point statistics !

Dark energy : what do we know?

- Dark energy smoothly fills space with a roughly constant energy density
- Dark energy dominates the Universe today but is insignificant at high redshift
- Dark energy propels the cosmos into a phase of accelerating expansion



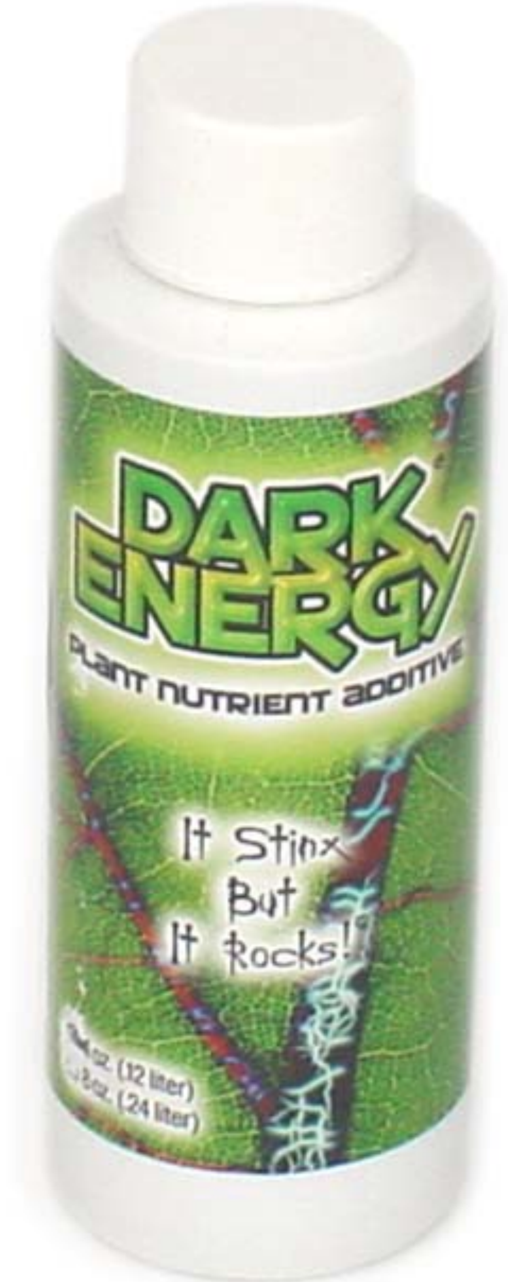
TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

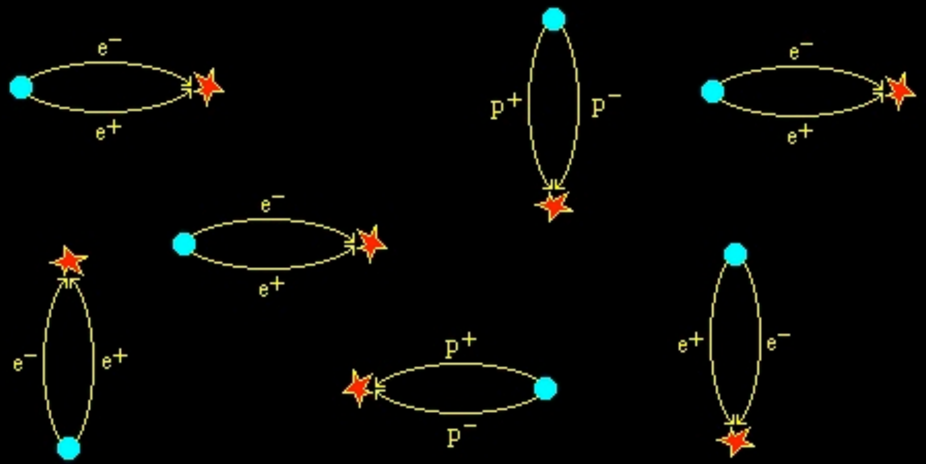
Dark energy : what don't we know?

- Physically, is it a manifestation of gravity or matter-energy?
- Why now? - why does dark energy become important billions of years after the Big Bang?
- If dark energy is vacuum energy, how can we explain its magnitude?
- How are our observations of dark energy affected by inhomogeneity?



Dark energy : is it a cosmological constant?

A cosmological constant matches the data so far, but its amplitude is inexplicable

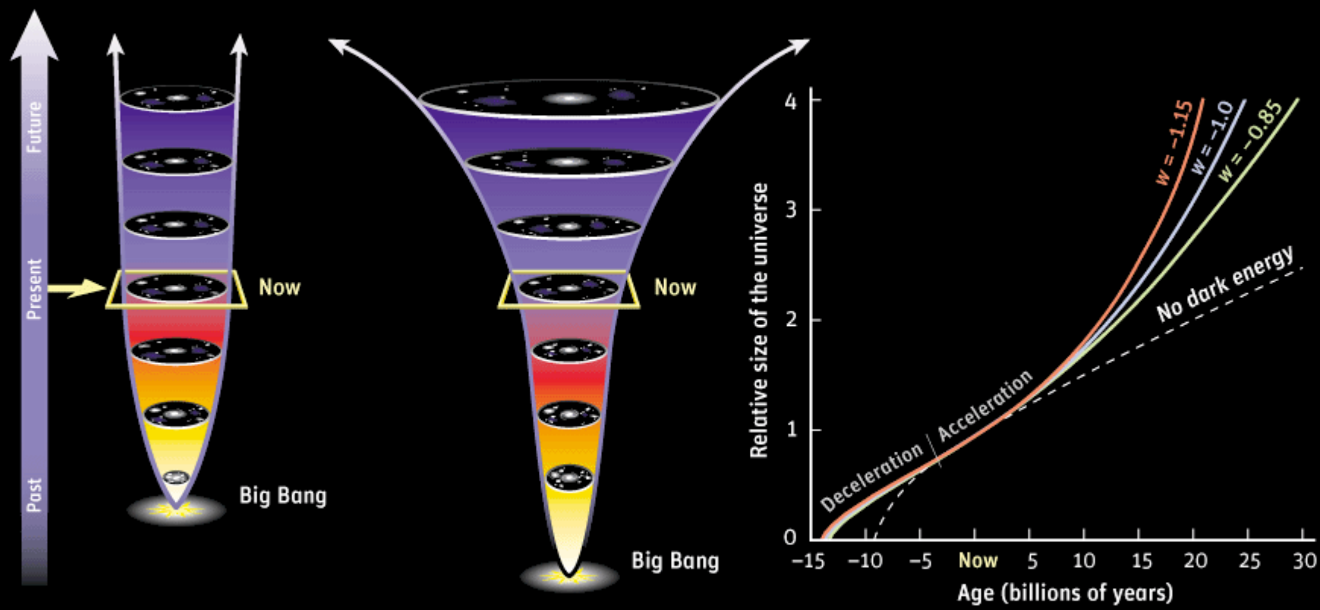


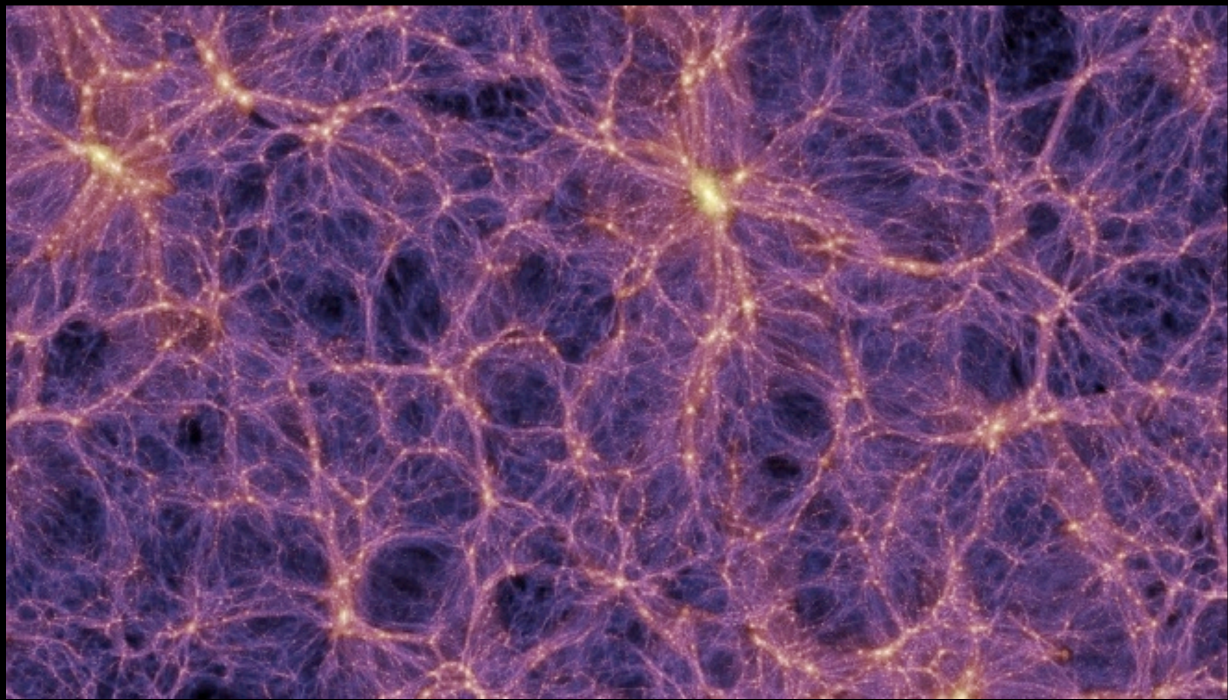
Dark energy : determining its nature

Cosmic expansion history

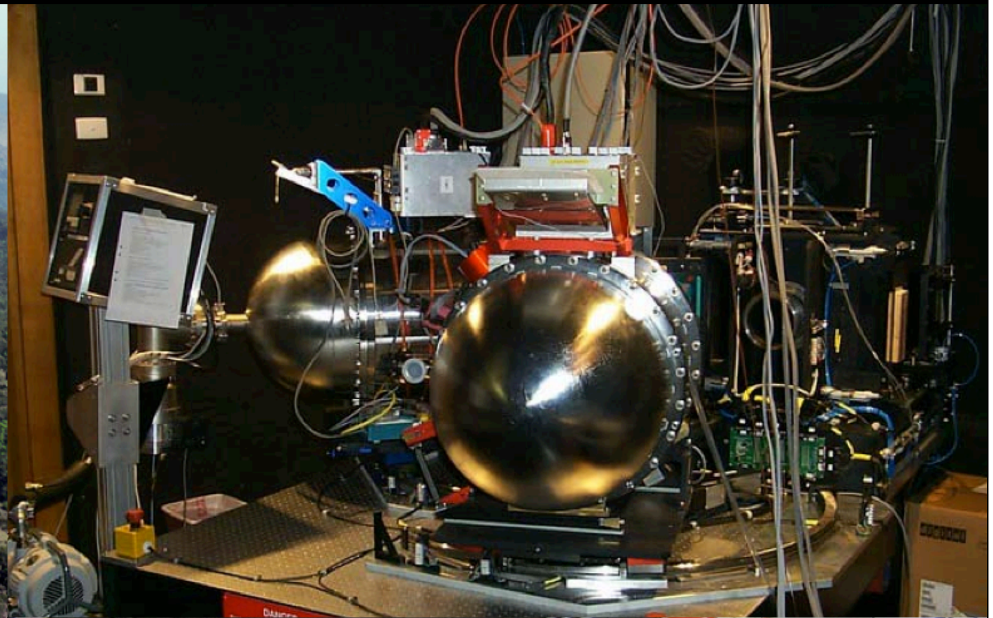
↕

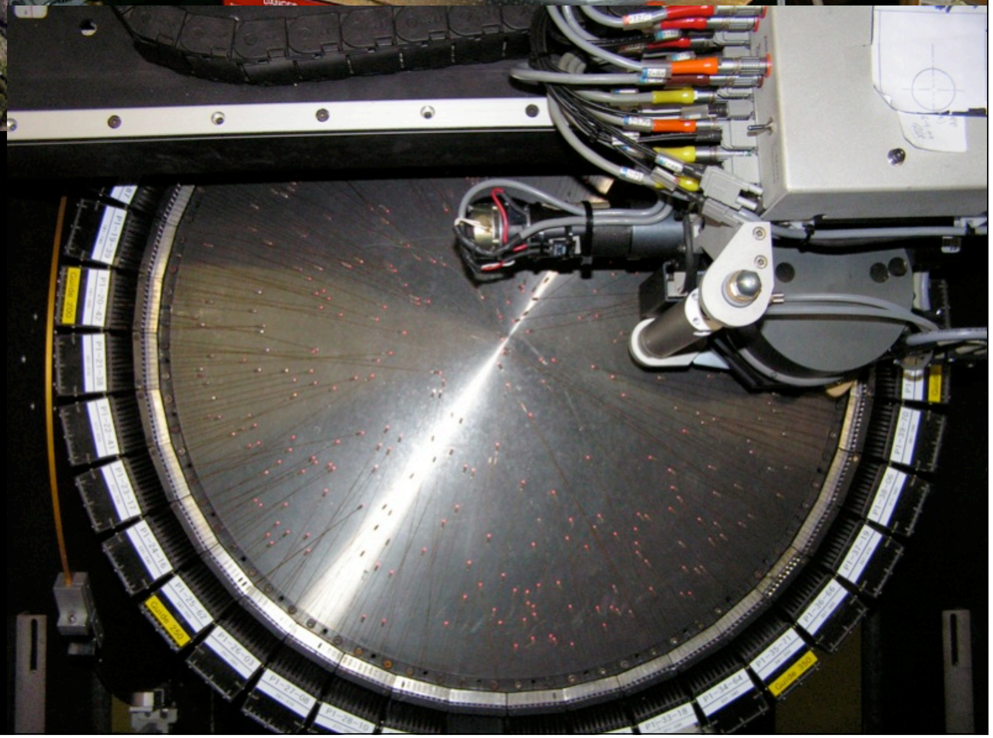
Cosmic growth history





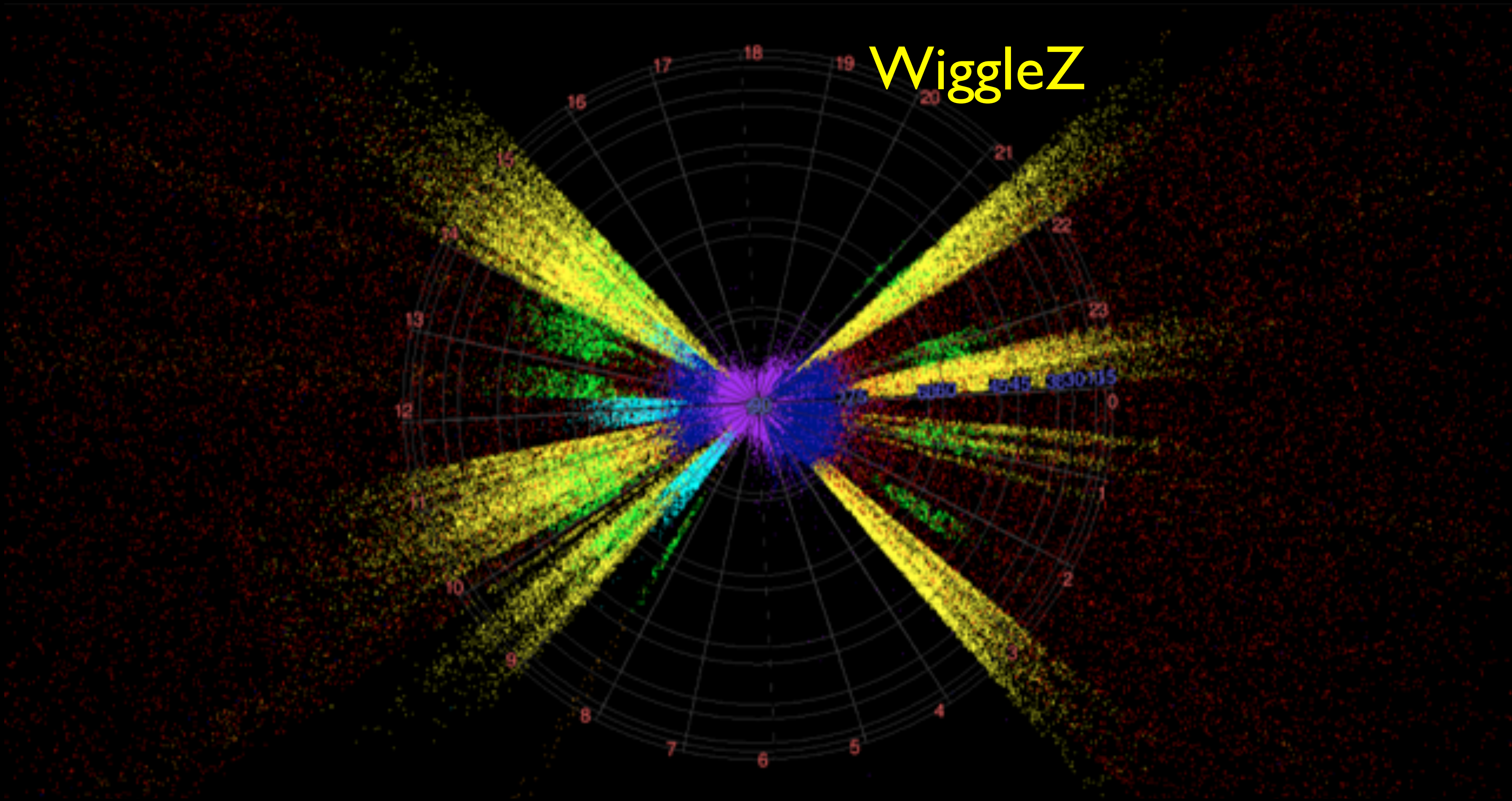
The WiggleZ Dark Energy Survey





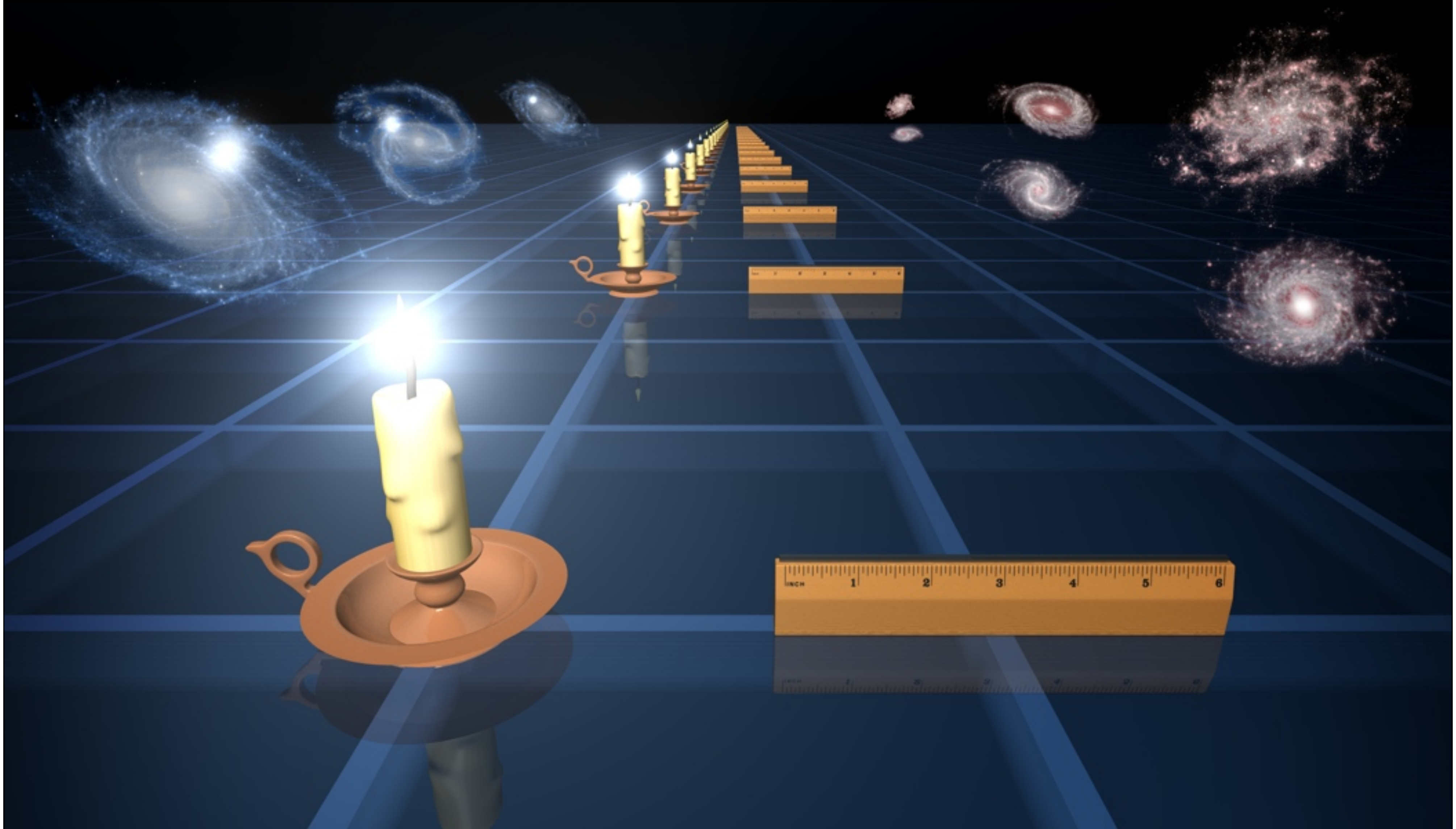
- 1000 sq deg , 0.2 < z < 1.0
- 200,000 redshifts
- blue star-forming galaxies
- Aug 2006 - Jan 2011

The WiggleZ Dark Energy Survey

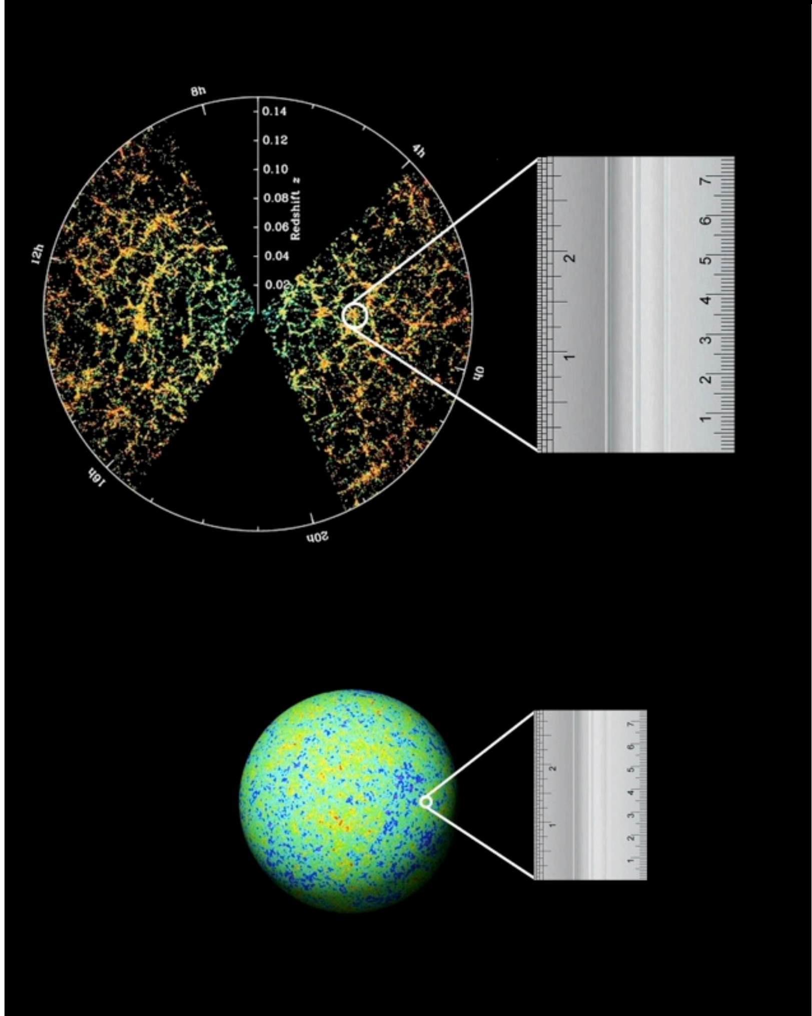


Southern sky surveys [image courtesy of Simon Driver]

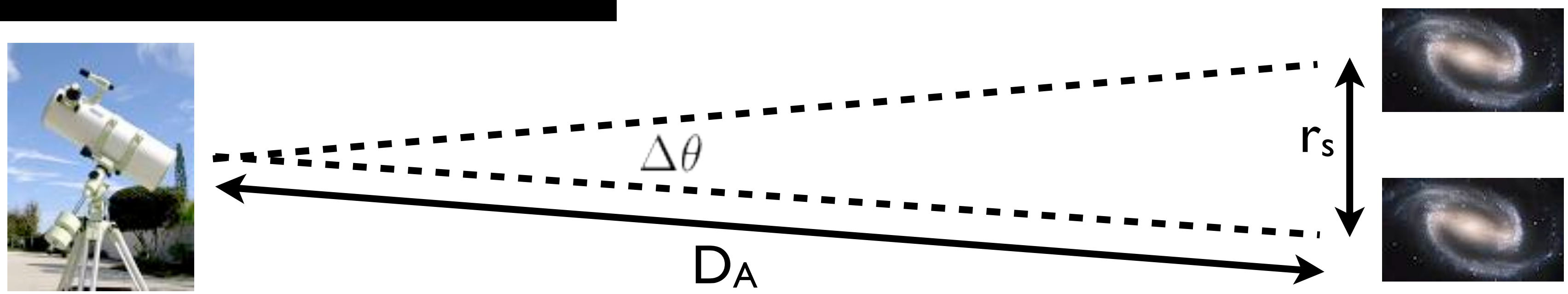
Standard candles and rulers



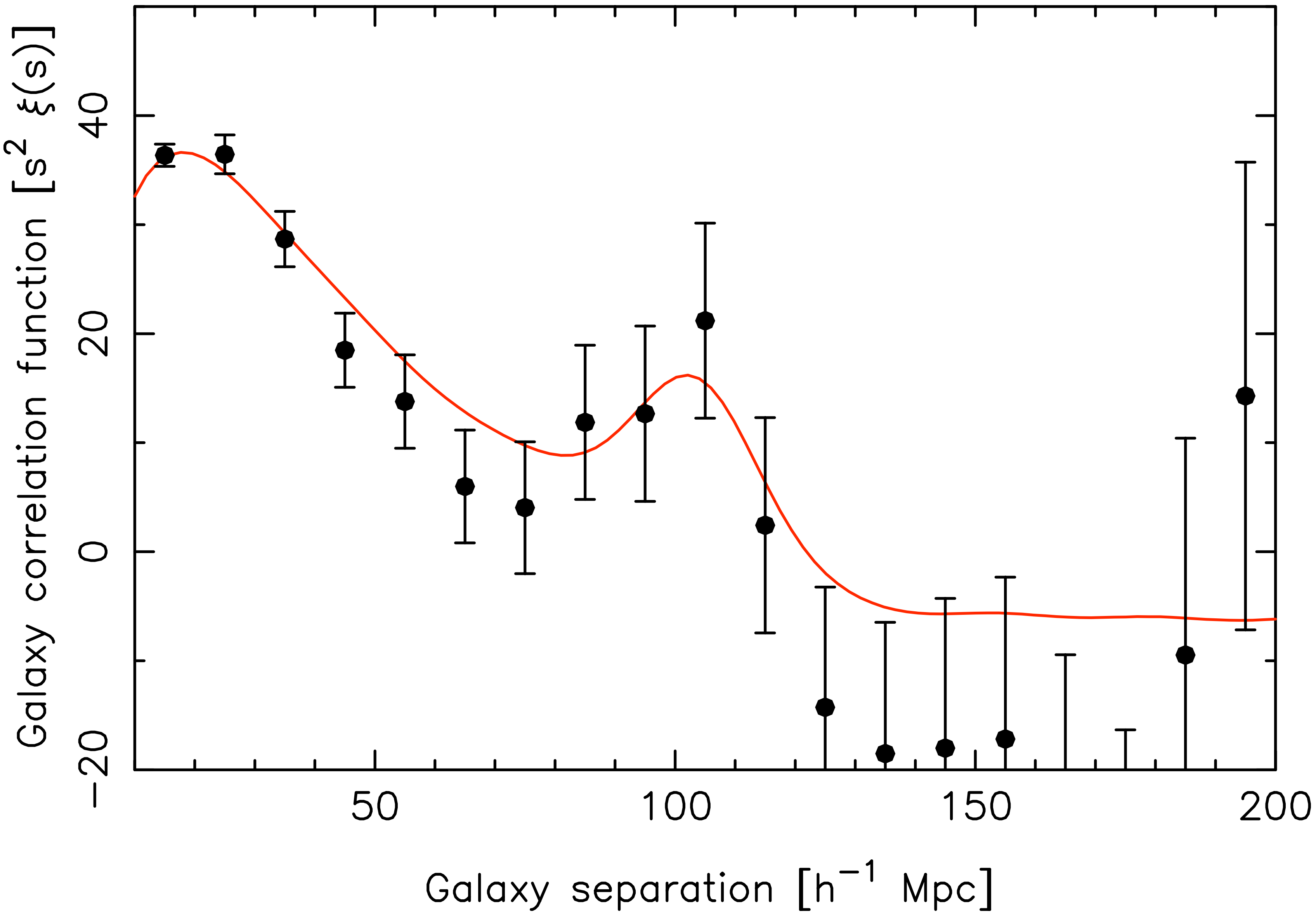
Standard ruler : baryon acoustic peak



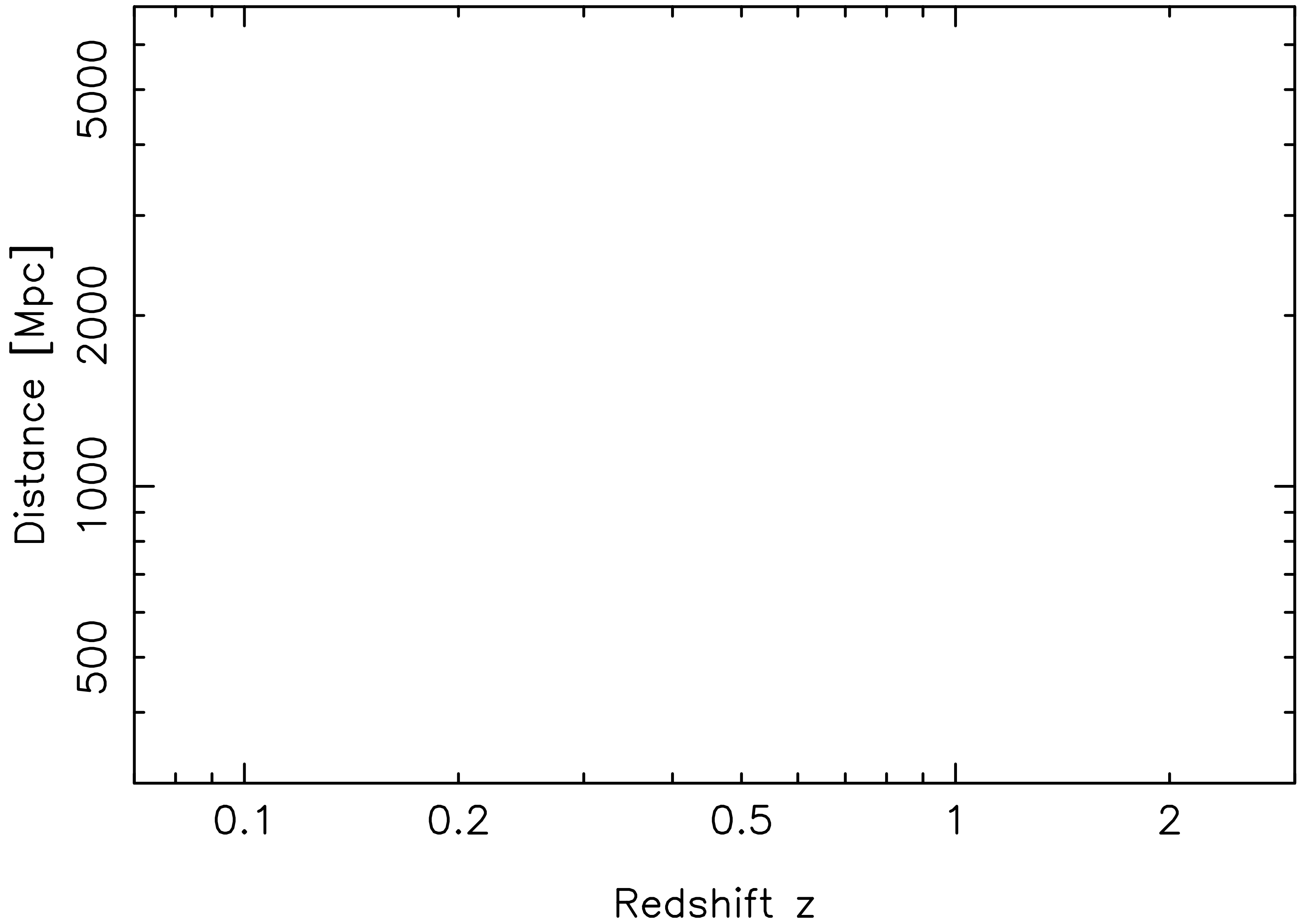
- Preferred co-moving separation of 105 Mpc between clumps imprinted at recombination
- We observe a preferred angular separation between galaxies at some redshift
- Allows distance determination by simple geometry



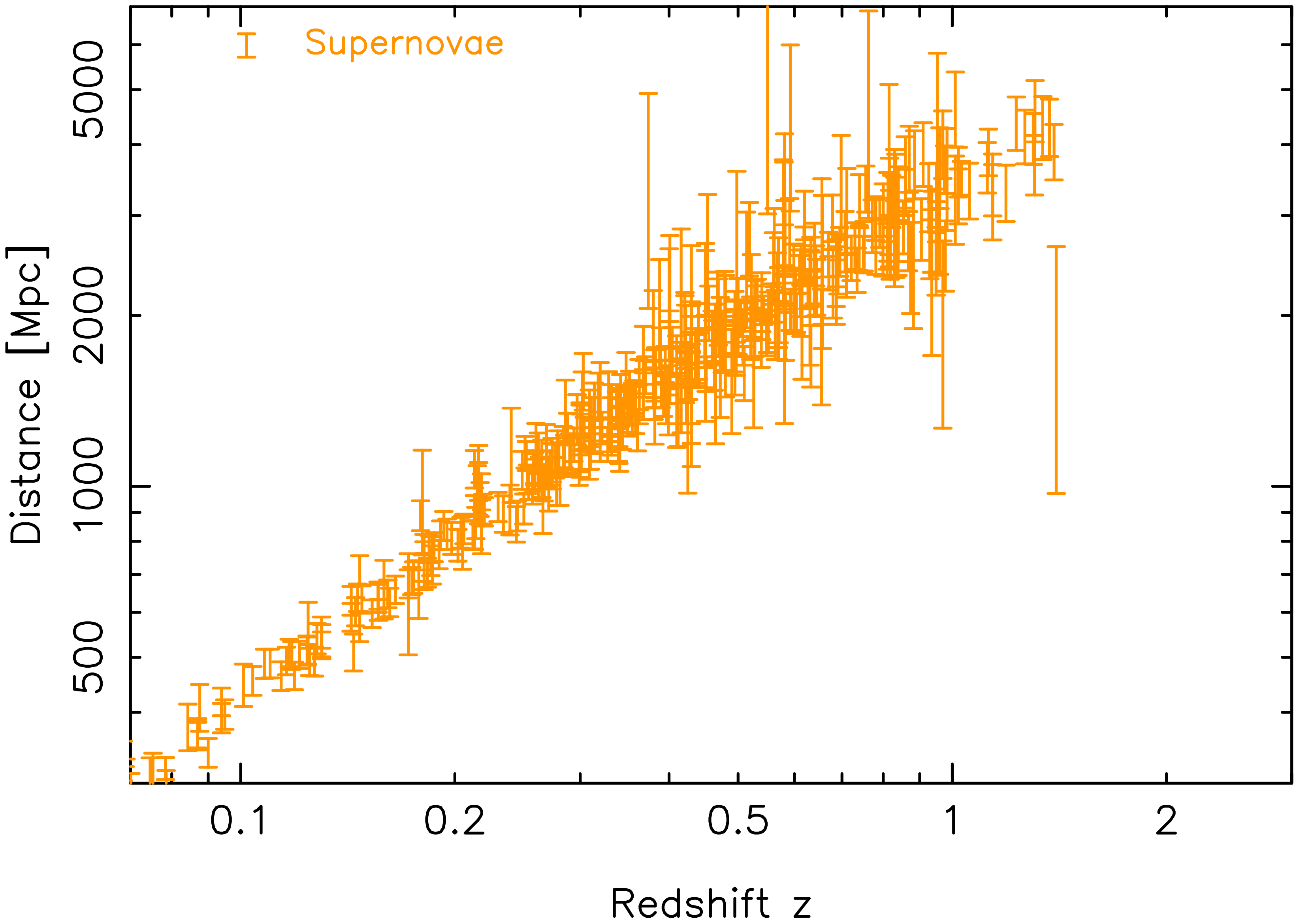
The baryon acoustic peak in WiggleZ



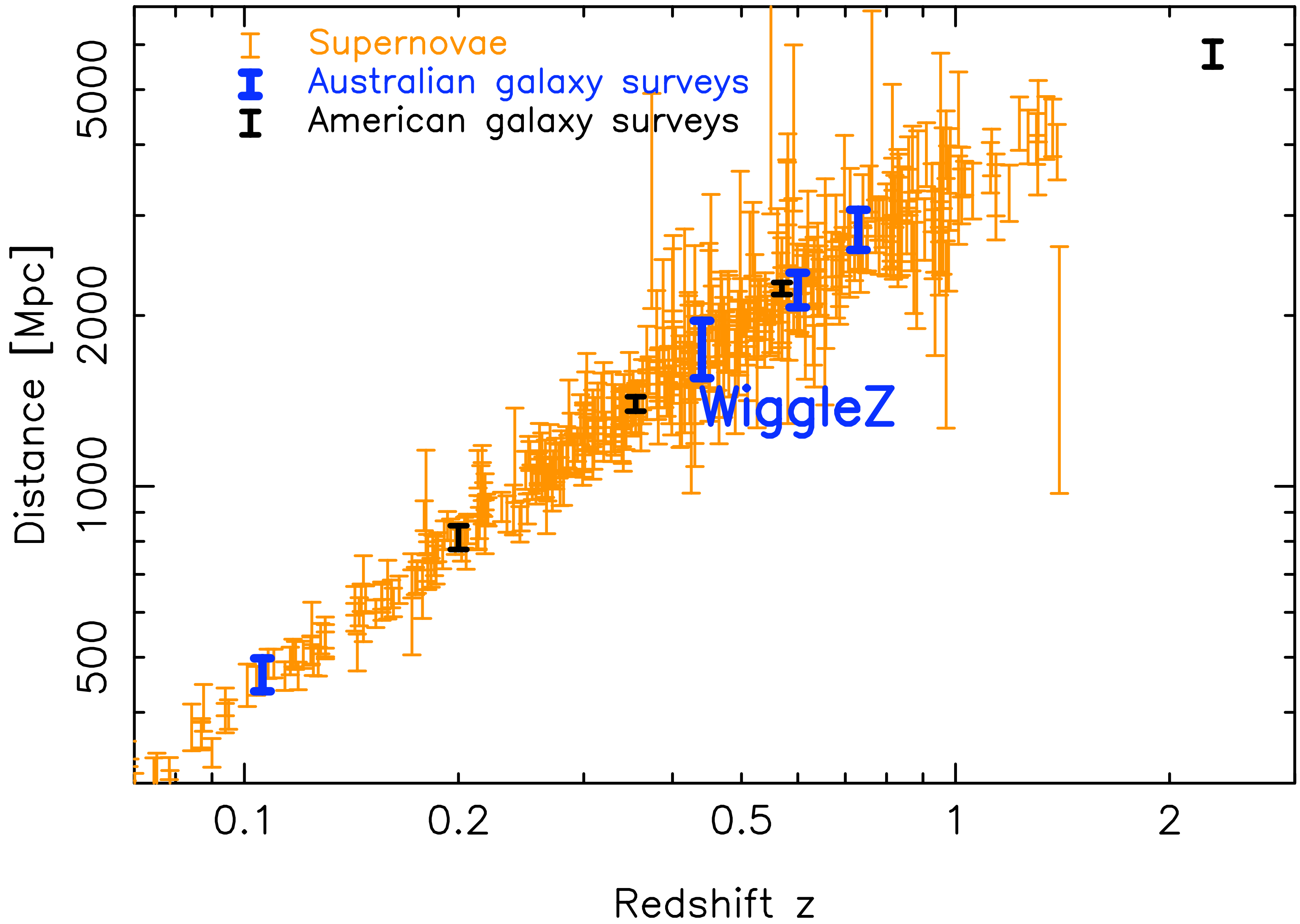
Hubble diagram



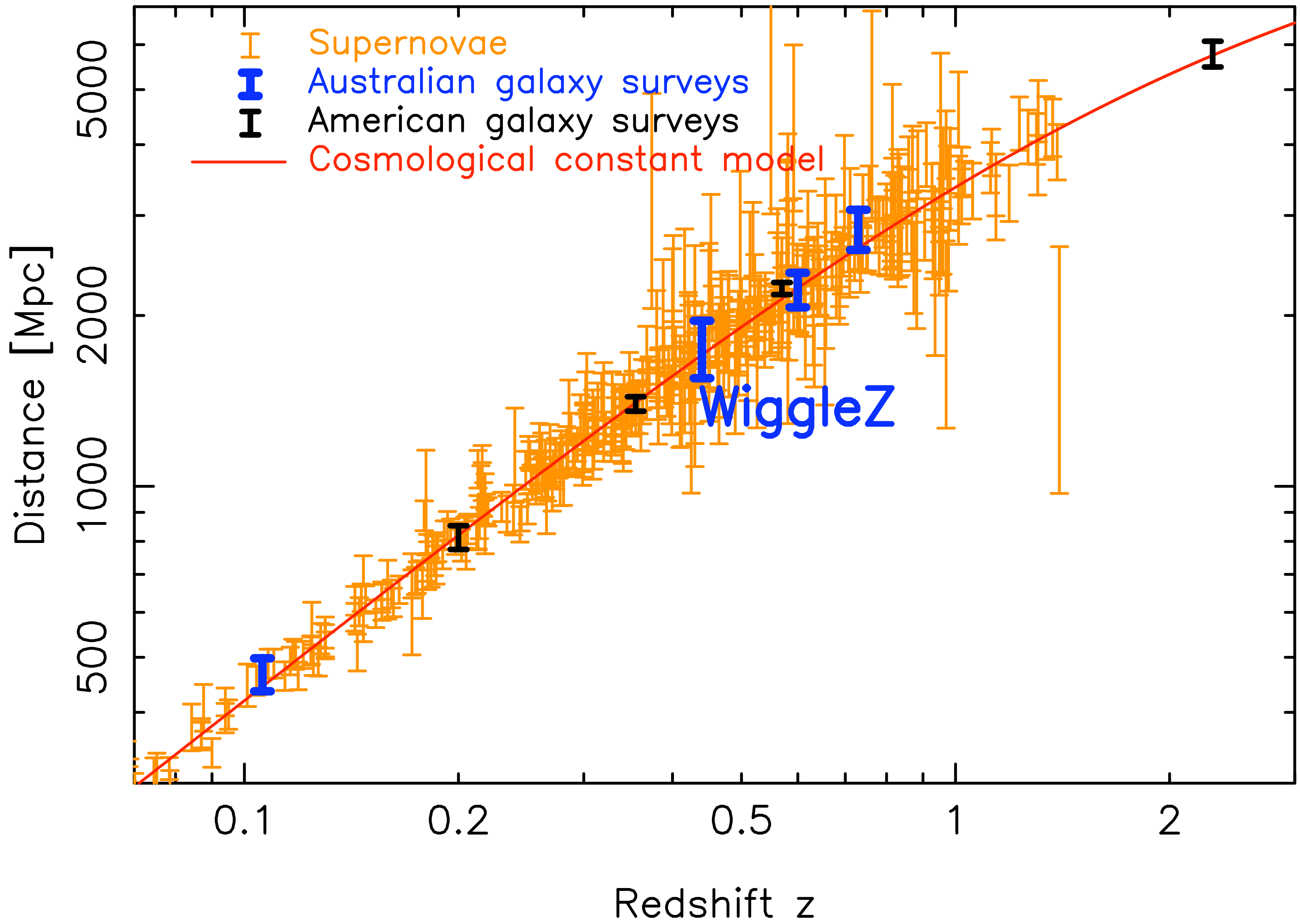
Hubble diagram



Hubble diagram



Hubble diagram



Dark energy : the "w" parameter

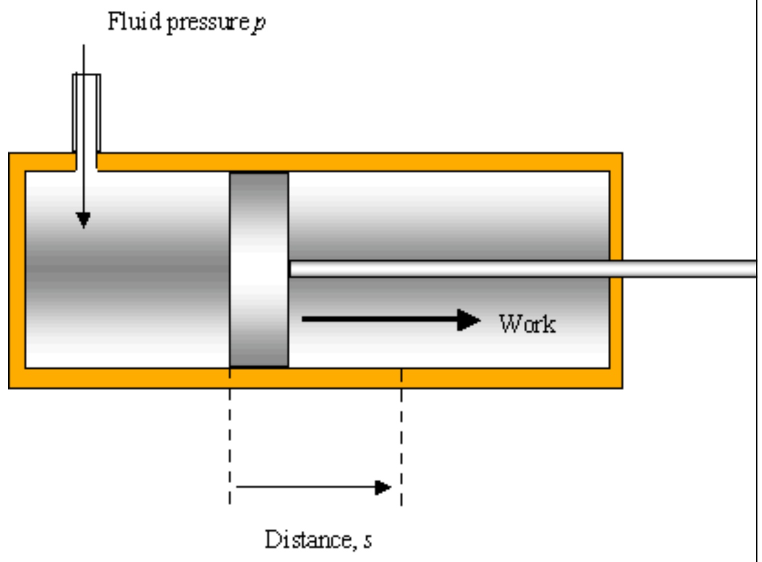
Key values ...

Matter : $w = 0$

Radiation : $w = 1/3$

Cosmological constant : $w = -1$

Accelerating fluid : $w < -1/3$



Physics of dark energy ...

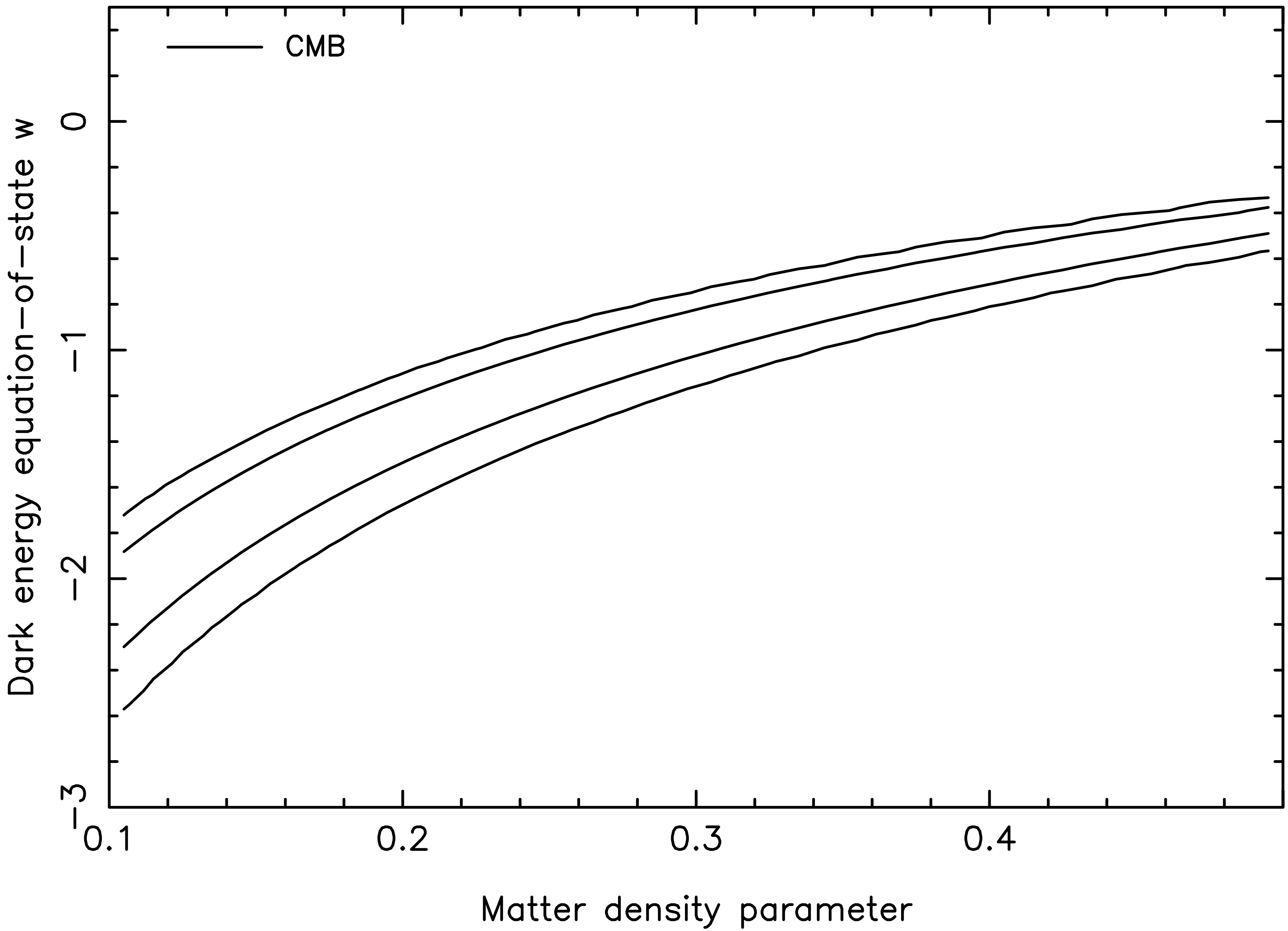
Equation of state : $P = w\,\rho$

Conservation of energy : $dE = d(\rho\, a^3) = -p\, d(a^3)$

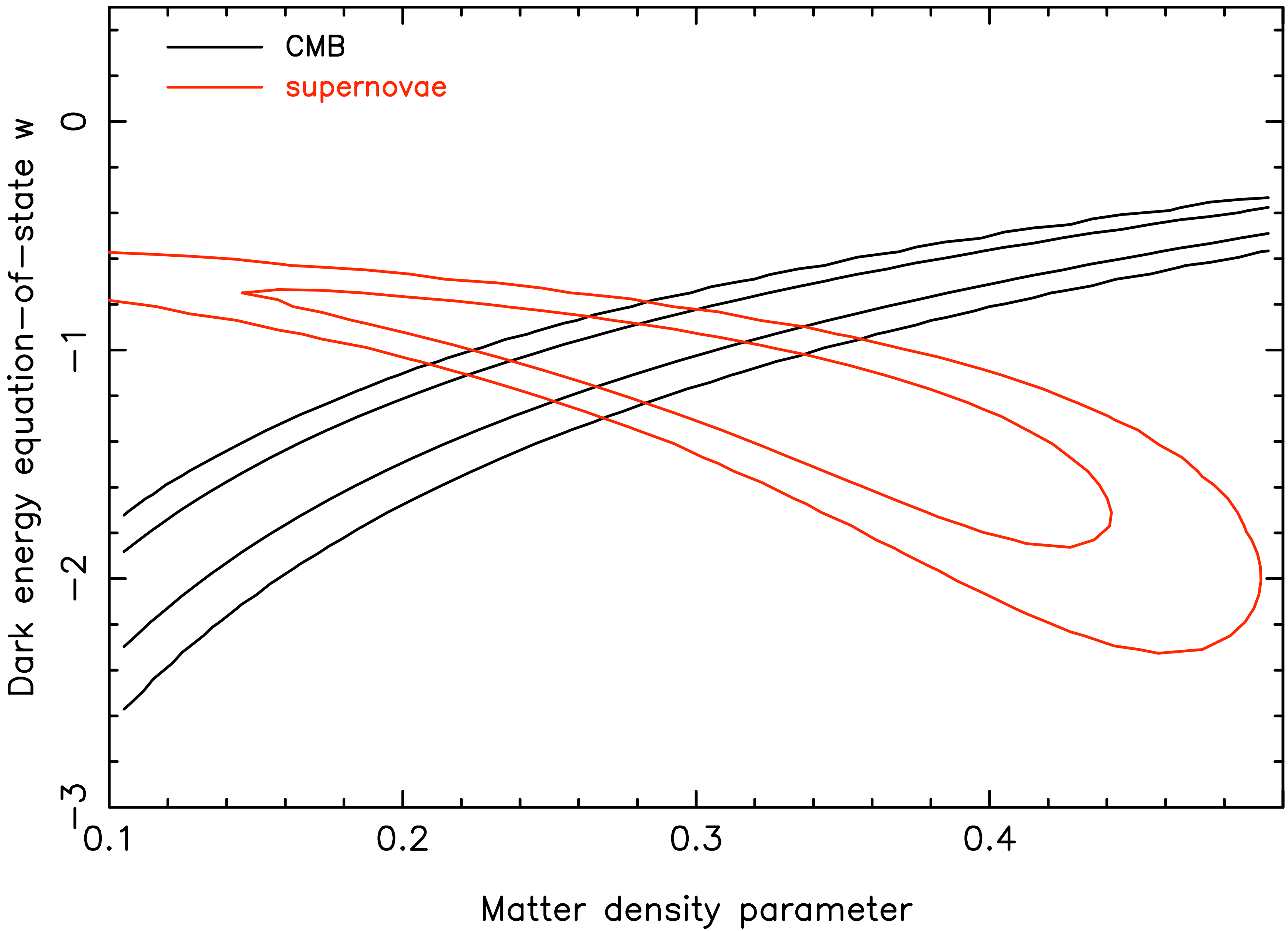
Re-arranging : $\rho \propto a^{-3(1+w)}$

Friedmann equation : $da/dt \propto a^{-(1+3w)/2}$

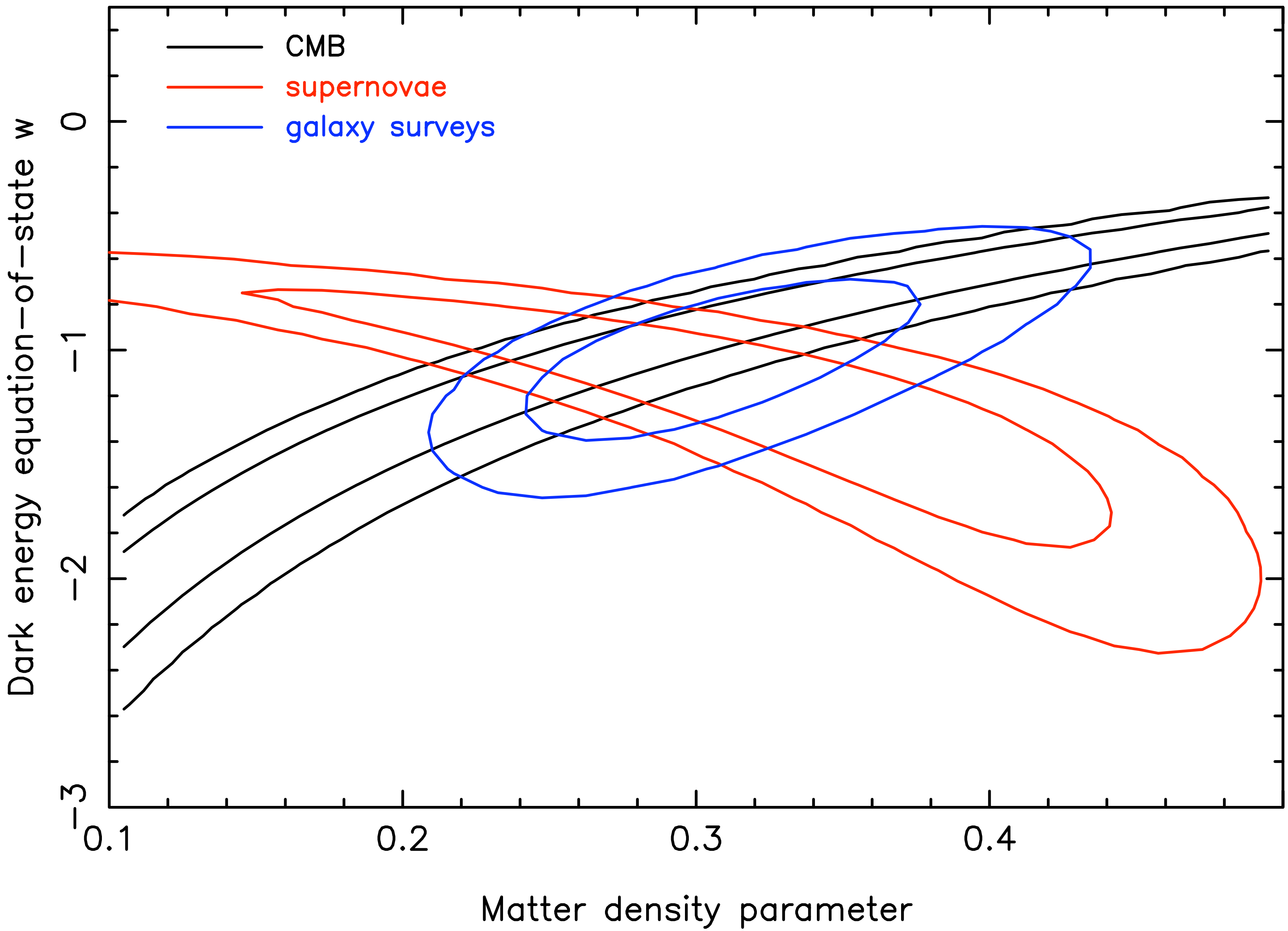
Cosmological parameter fits



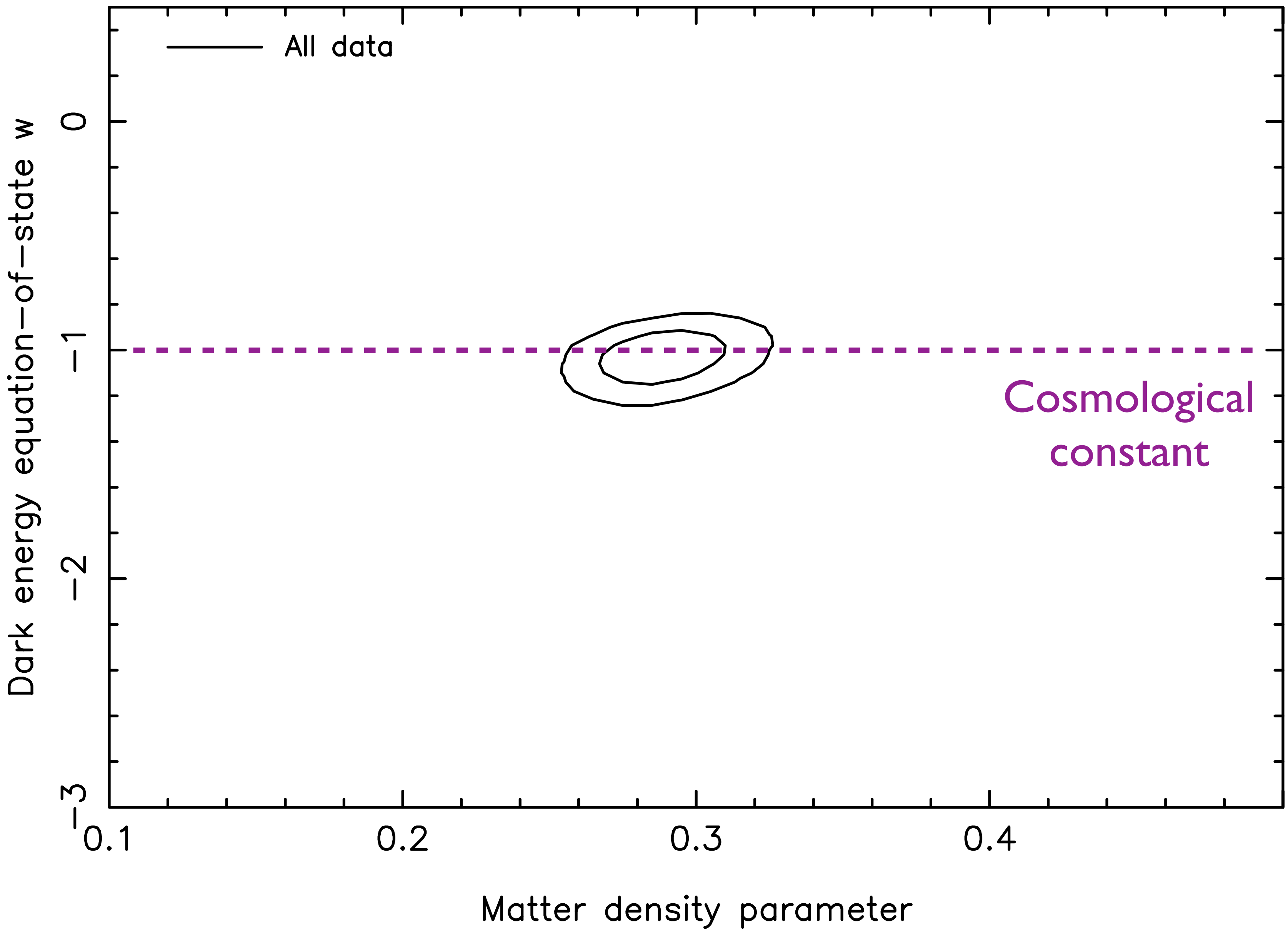
Cosmological parameter fits



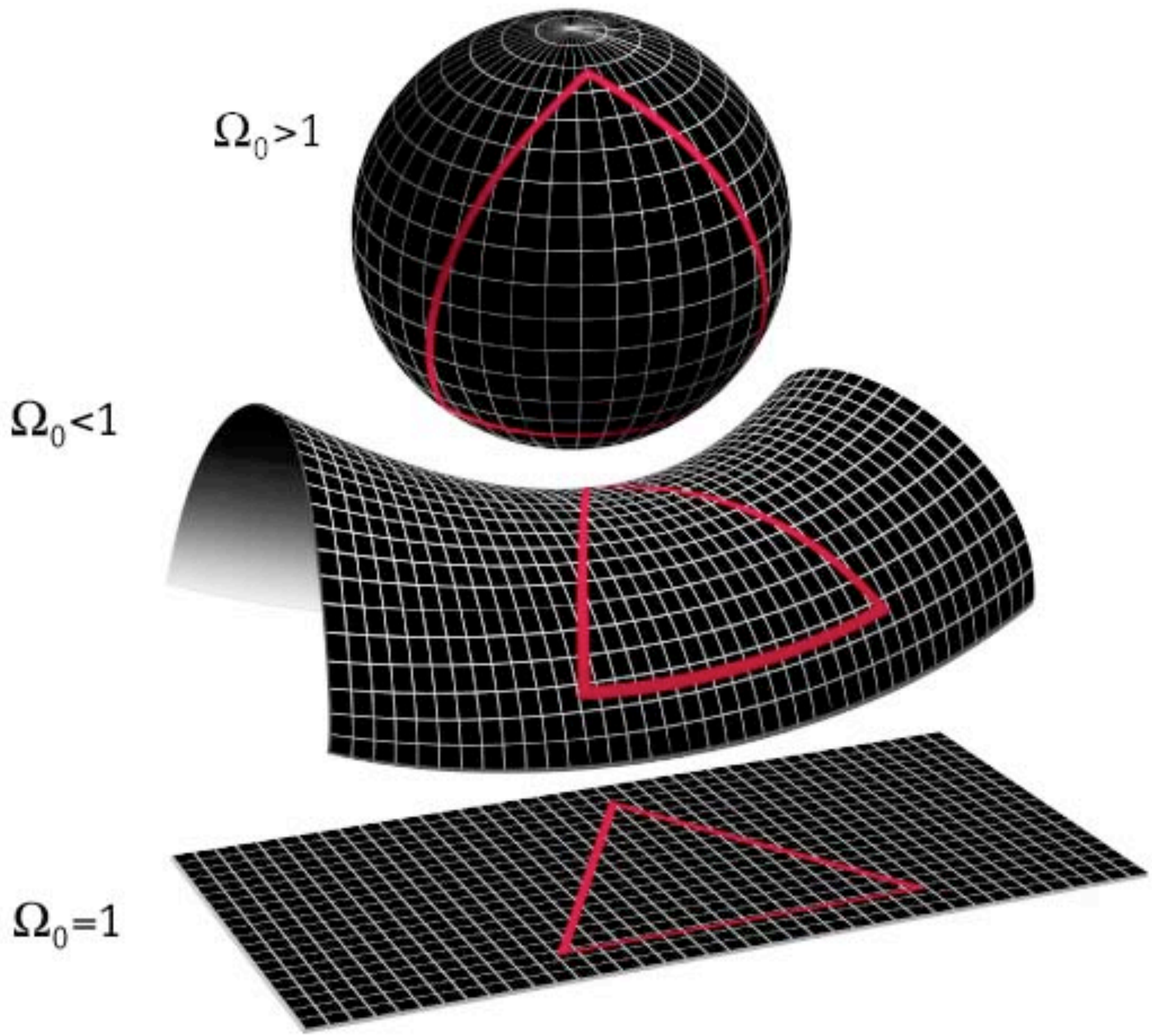
Cosmological parameter fits



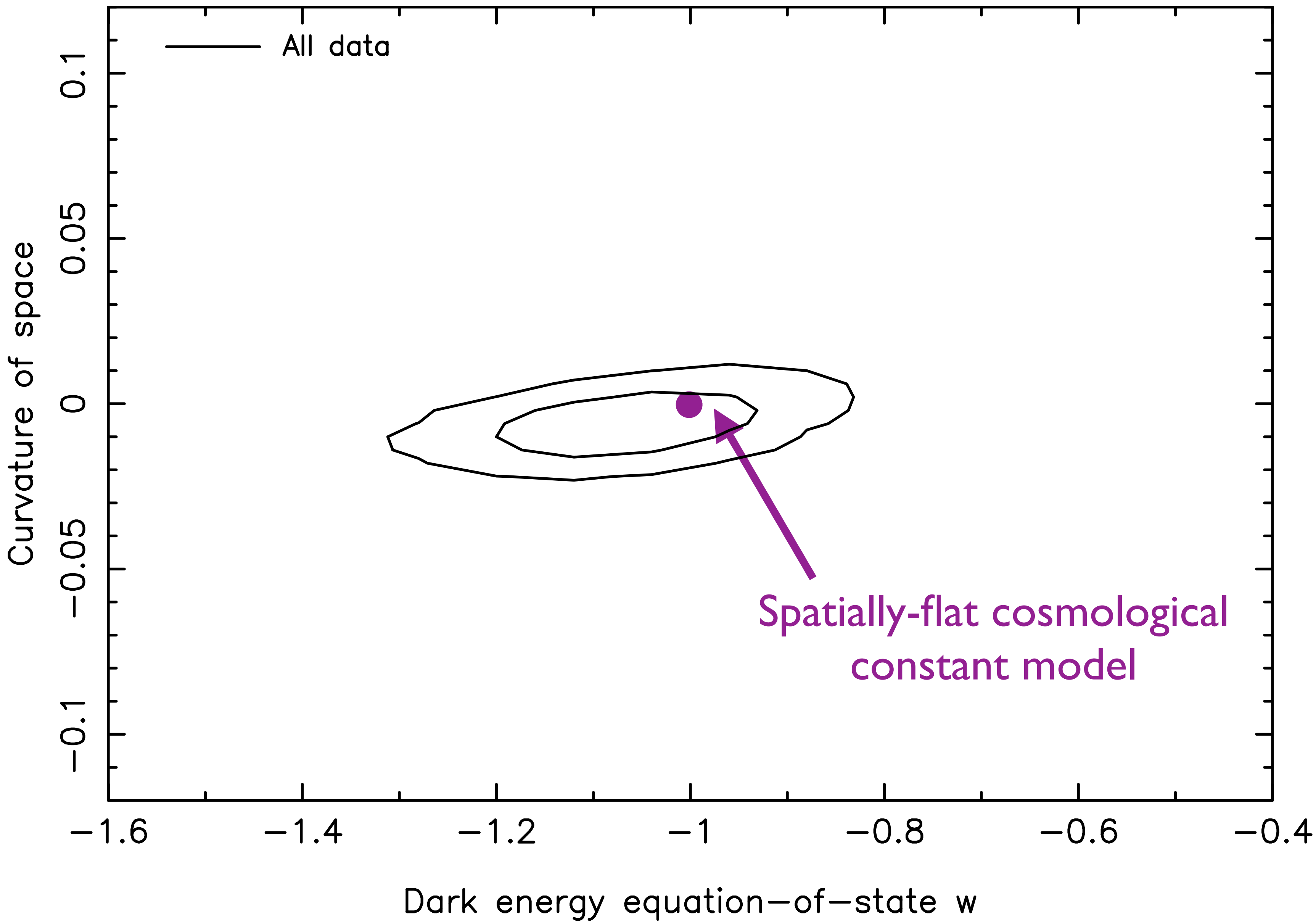
Cosmological parameter fits



Cosmological parameter fits



Cosmological parameter fits



The physics of dark energy

- Einstein equations relate gravity/geometry to matter/energy. Is dark energy a form of matter:

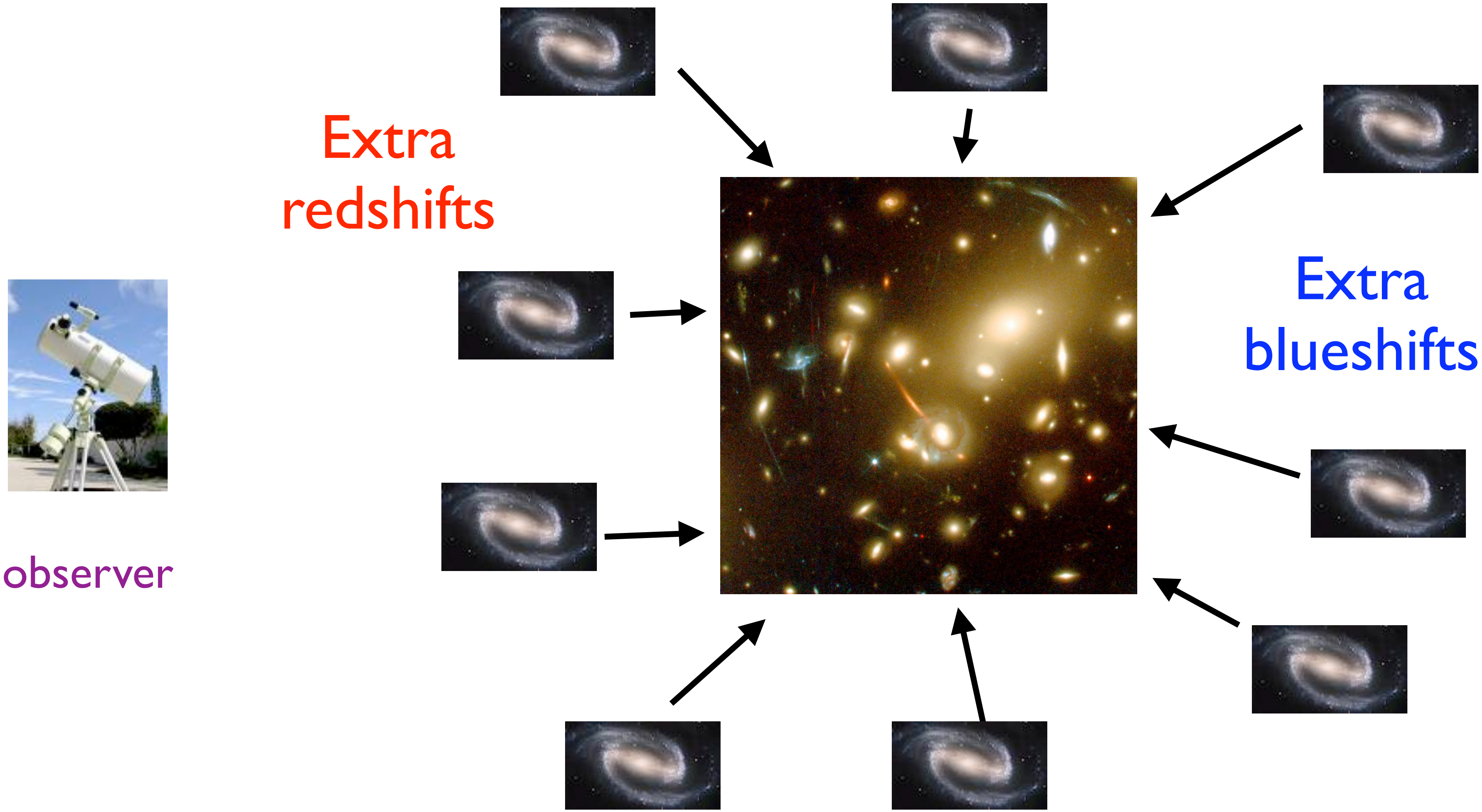
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu} - g_{\mu\nu}\Lambda$$

- Or is it gravity:

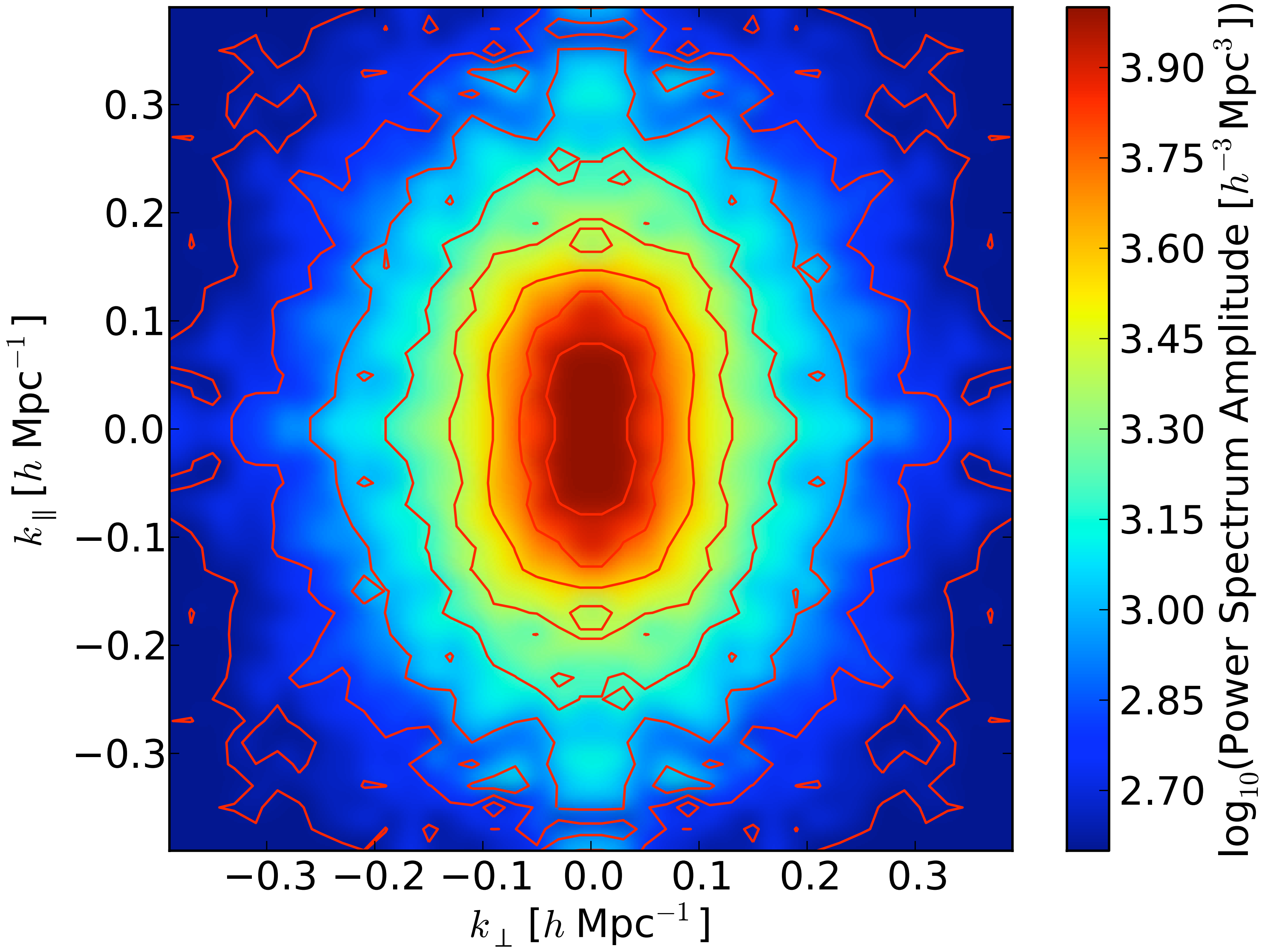
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- We cannot distinguish between these cases if we only measure the distance-redshift relation. Galaxy surveys provide extra information through growth of structure

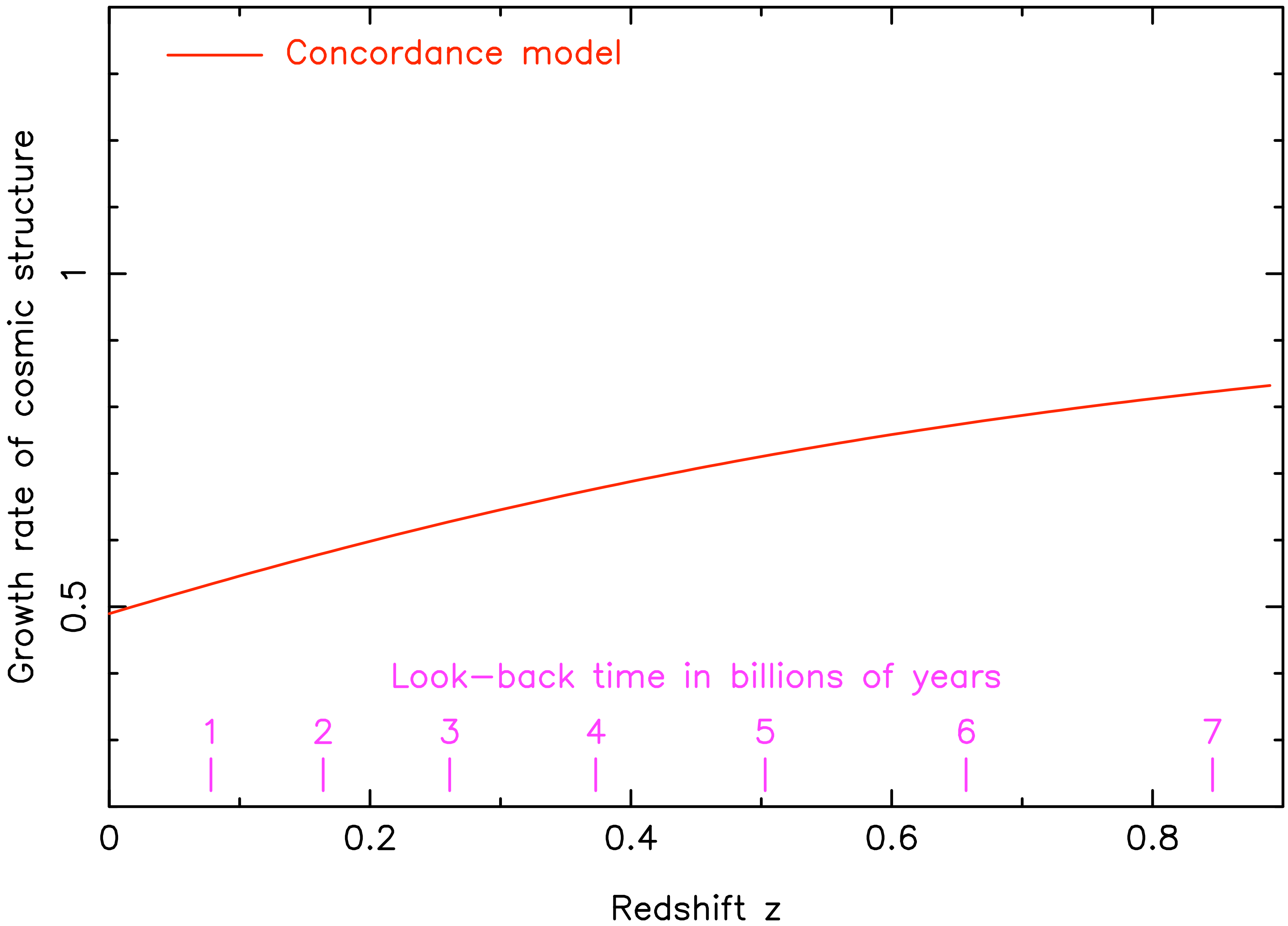
Galaxy flows



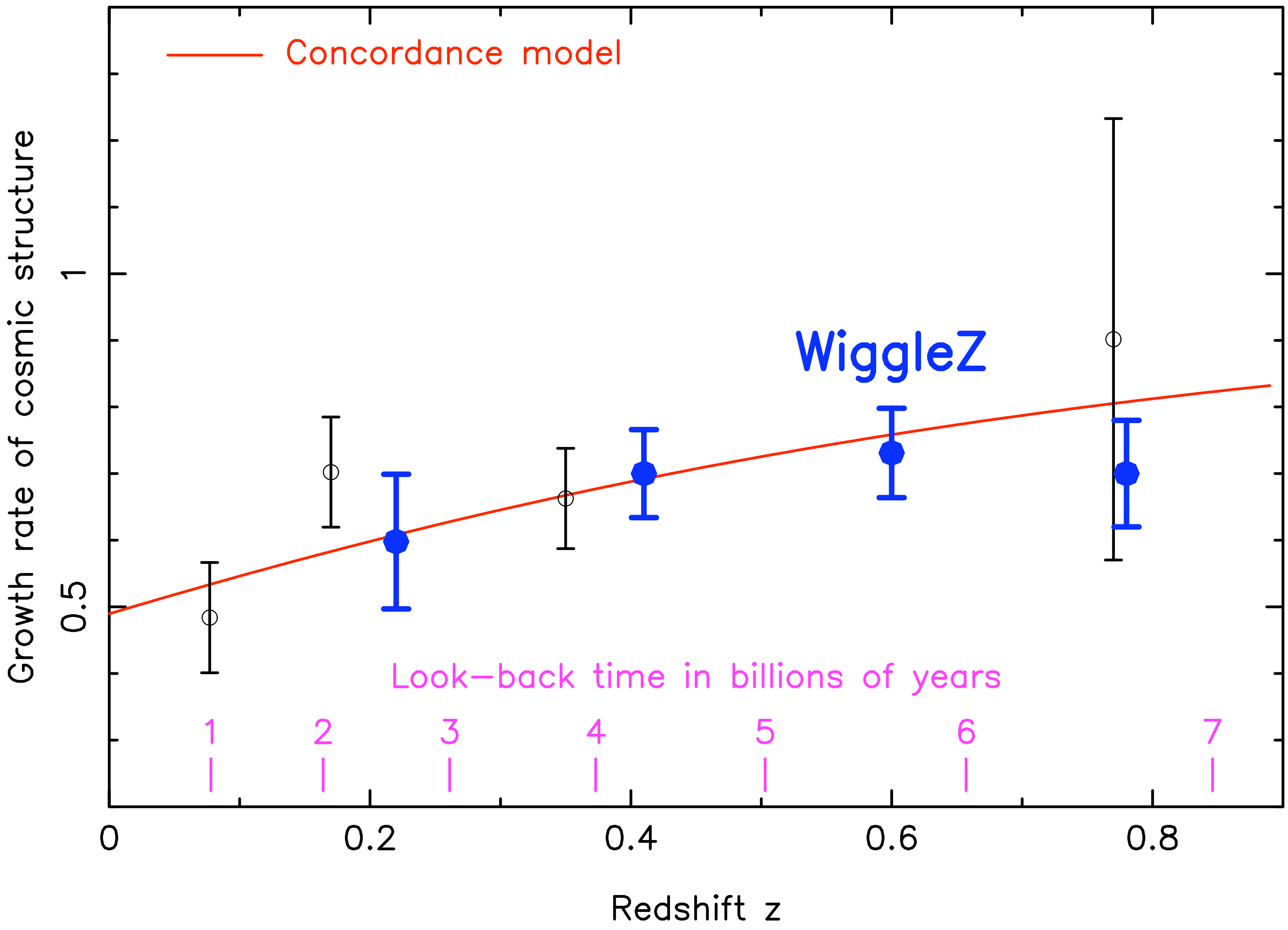
Galaxy flows in WiggleZ



Growth rate measurements from WiggleZ



Growth rate measurements from WiggleZ



Summary of results from WiggleZ

- Large galaxy surveys offer a powerful means to test the cosmological model
- Baryon acoustic oscillations measure cosmic distances to z=0.8 and provide cross-check with supernovae
- Galaxy flows provide accurate measurement of growth of structure to high redshift
- General Relativity + cosmological constant models have been tested in a new way and remain a good fit
- If dark energy behaves as Lambda, what is its physics?

Thank you!