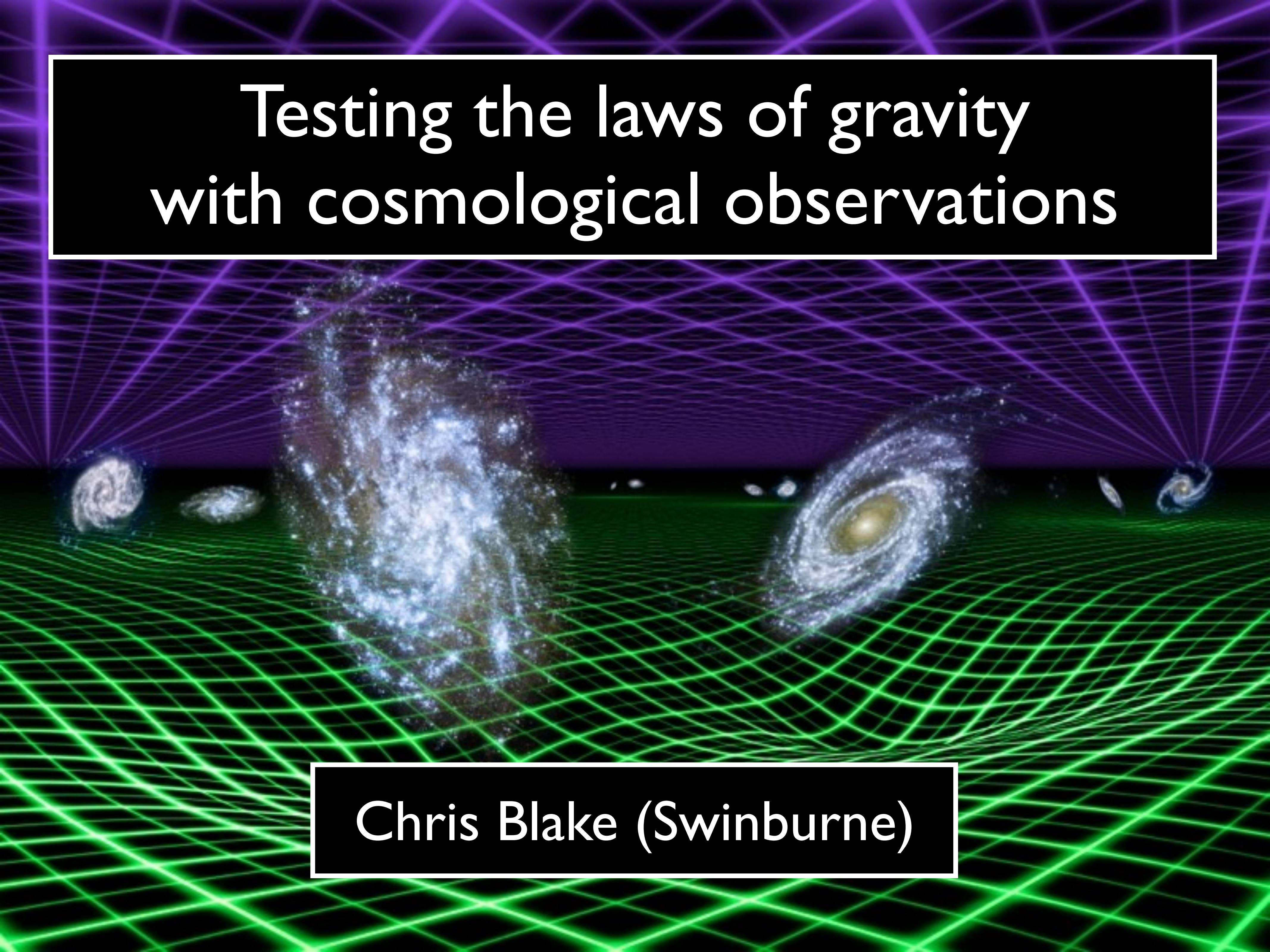
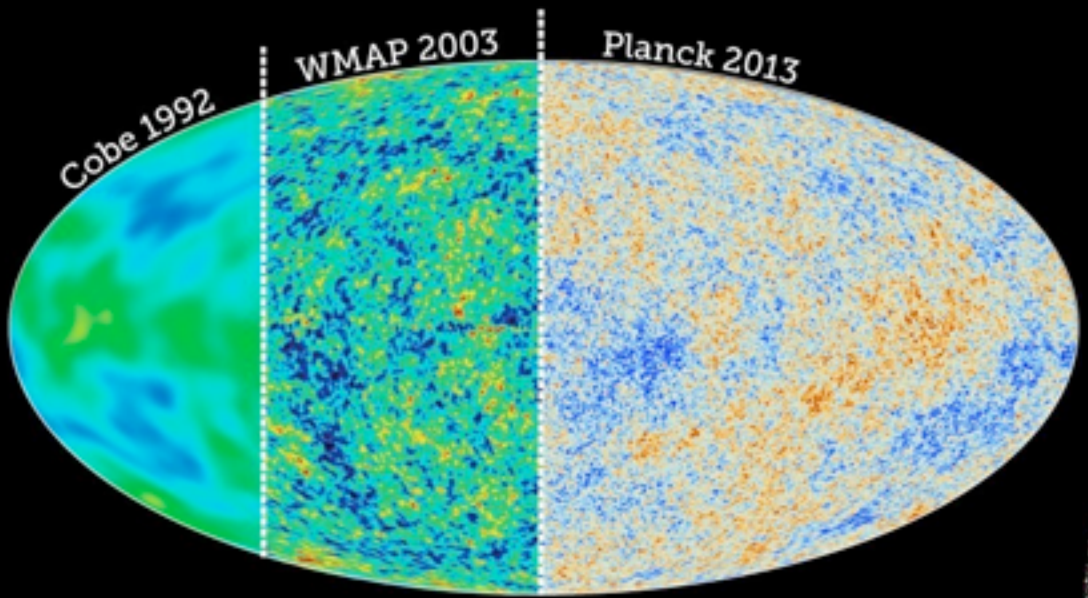
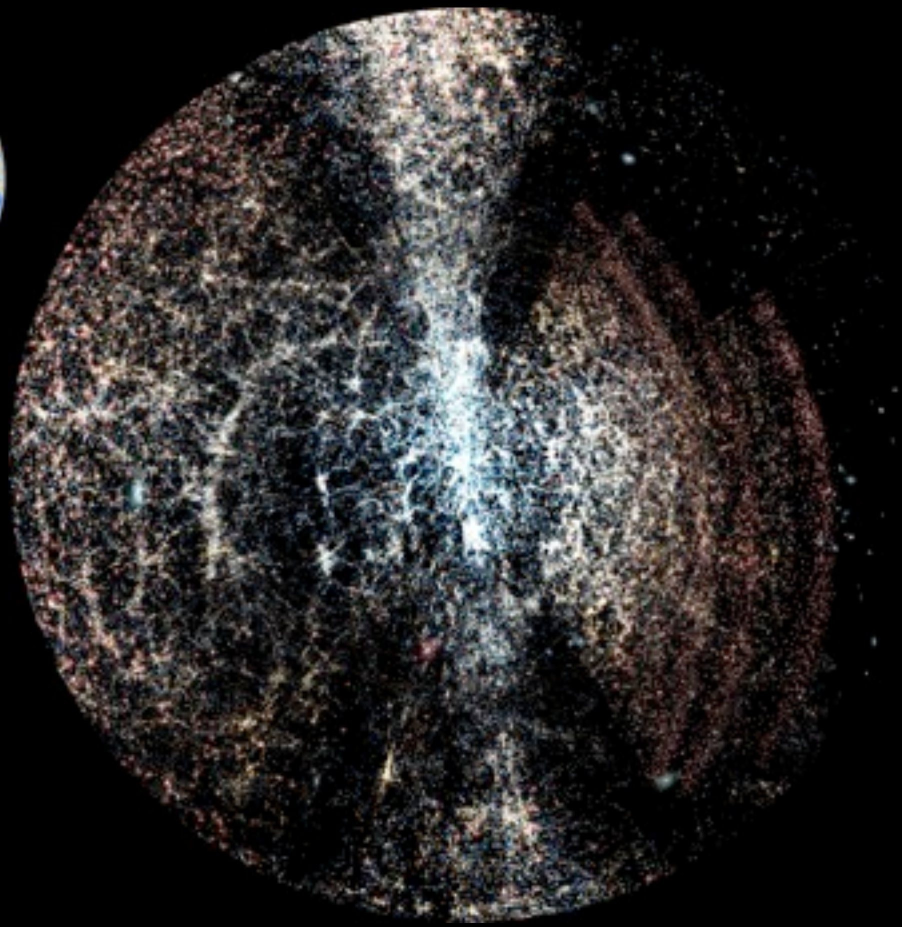


Testing the laws of gravity with cosmological observations

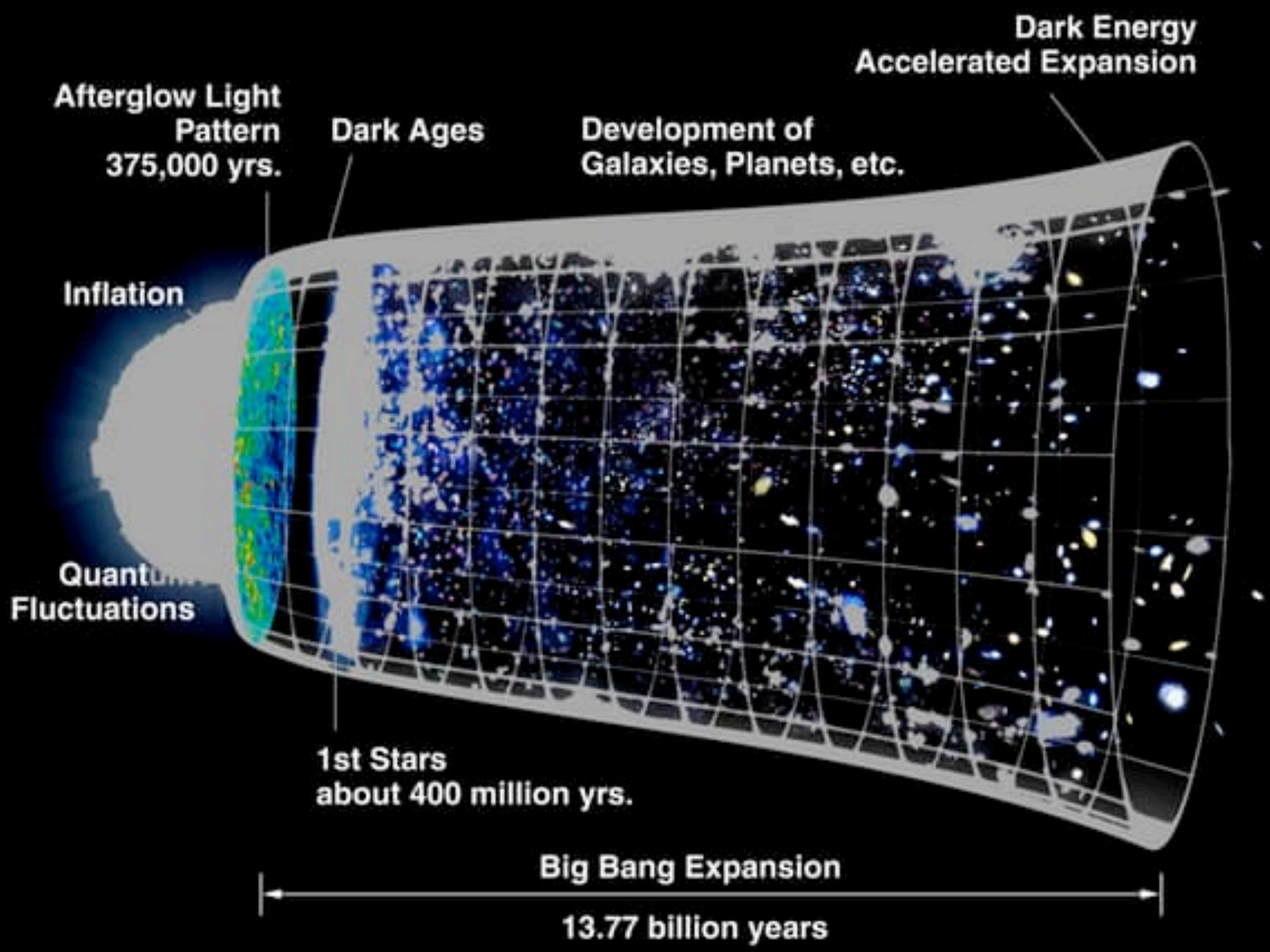
Chris Blake (Swinburne)

- The science of cosmology has been transformed by a remarkable growth in data over the past ~20 years

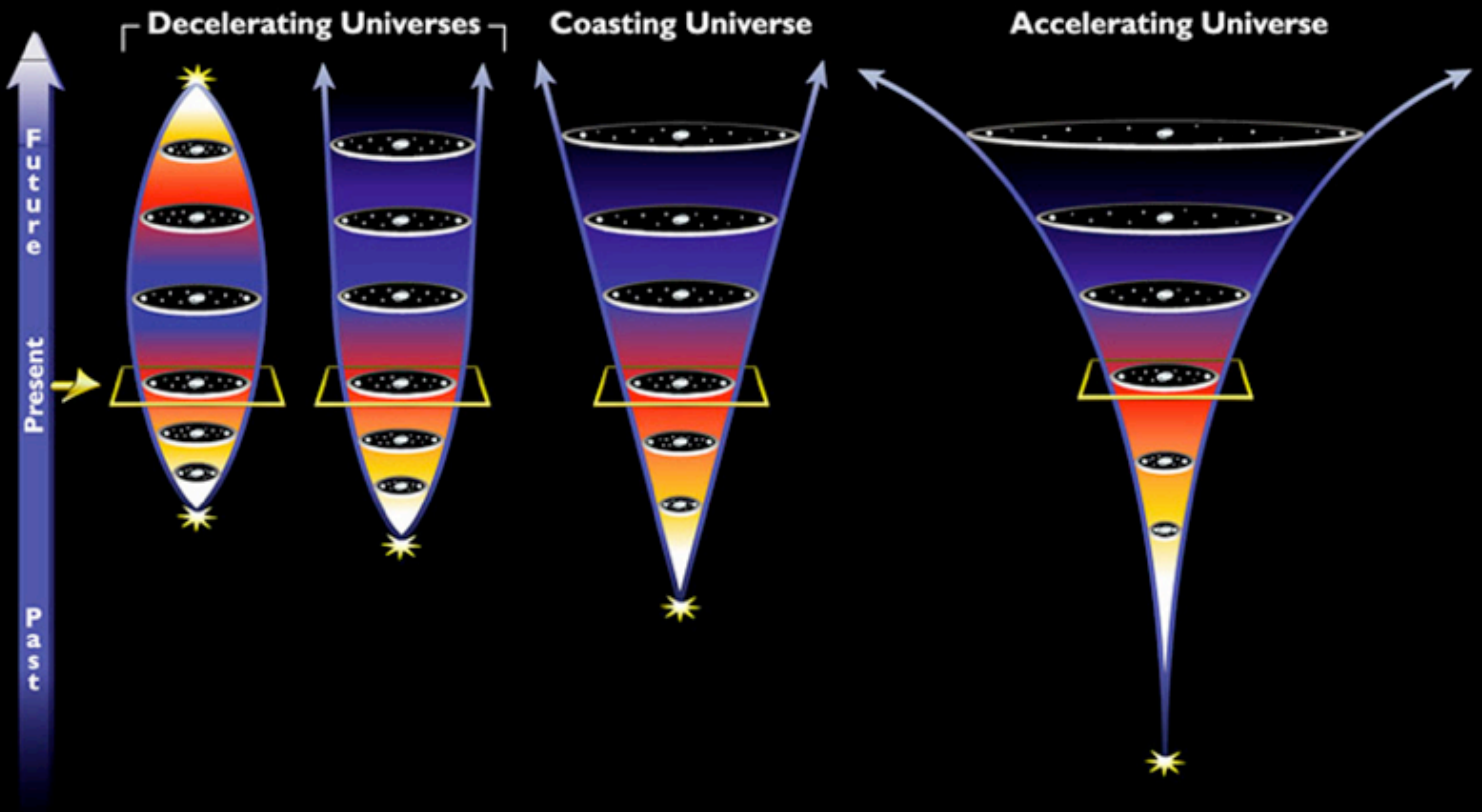




- Cosmologists have used these observations to build a detailed model of the history of the Universe



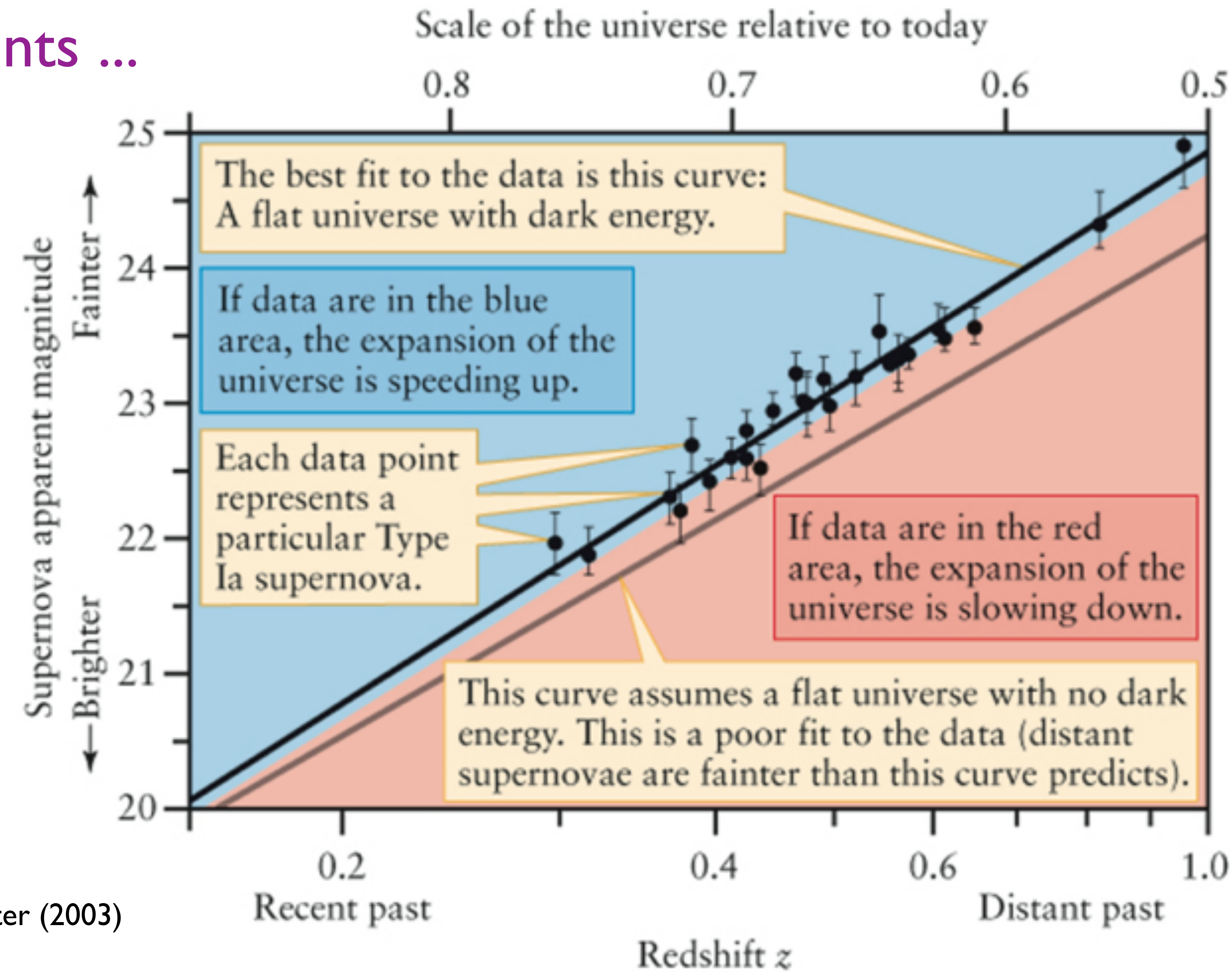
- The most startling discovery is that the cosmic expansion seems to be accelerating!



- This is the "dark energy problem" : the attempt to understand the physics of cosmic acceleration, and its implications

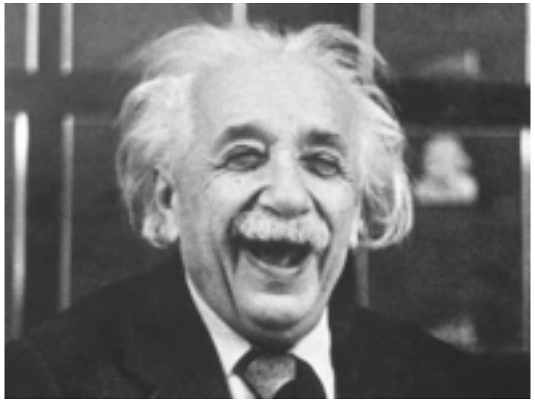
The cosmic expansion is accelerating!

Early hints ...

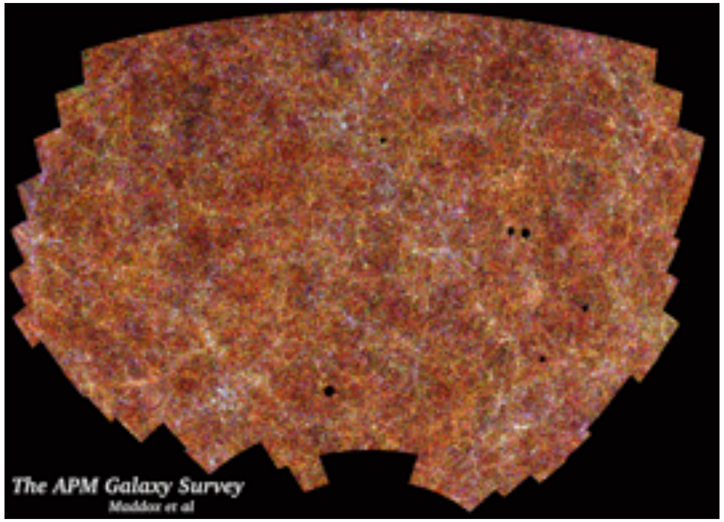


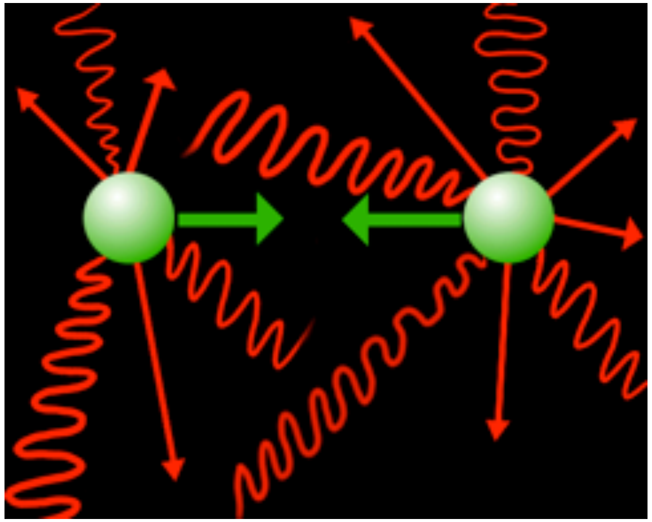
Credit: Perlmutter (2003)

The cosmic expansion is accelerating!



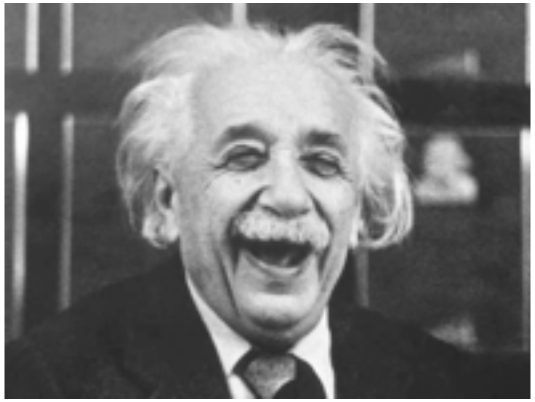
$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$$





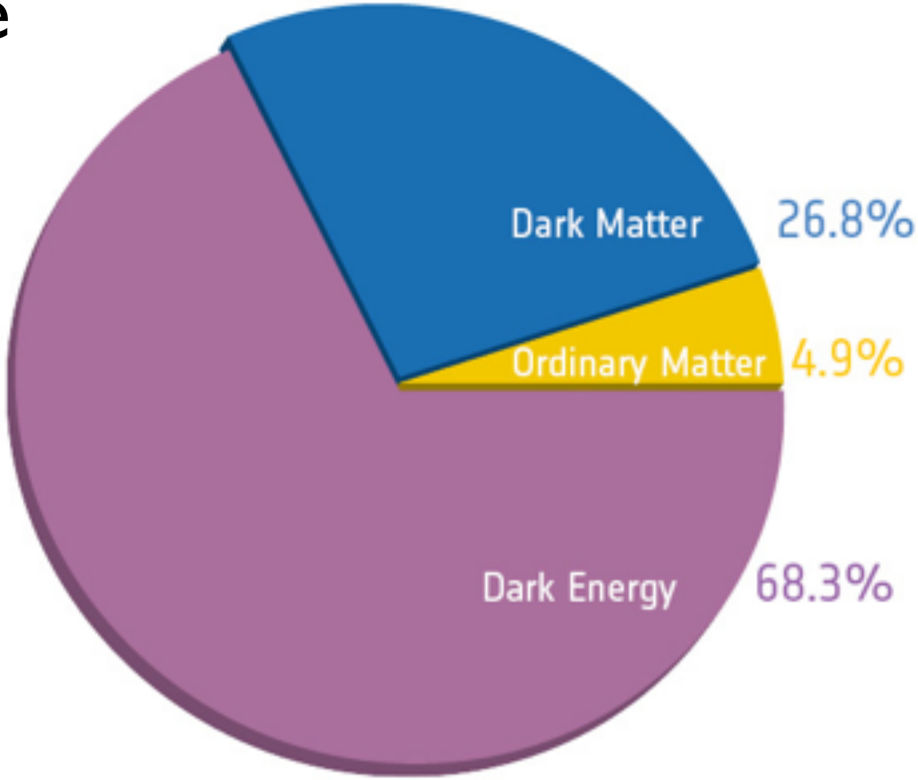
- The accelerating cosmic expansion cannot be produced by applying General Relativity to a homogeneous and isotropic Universe containing matter and radiation

The cosmic expansion is accelerating!



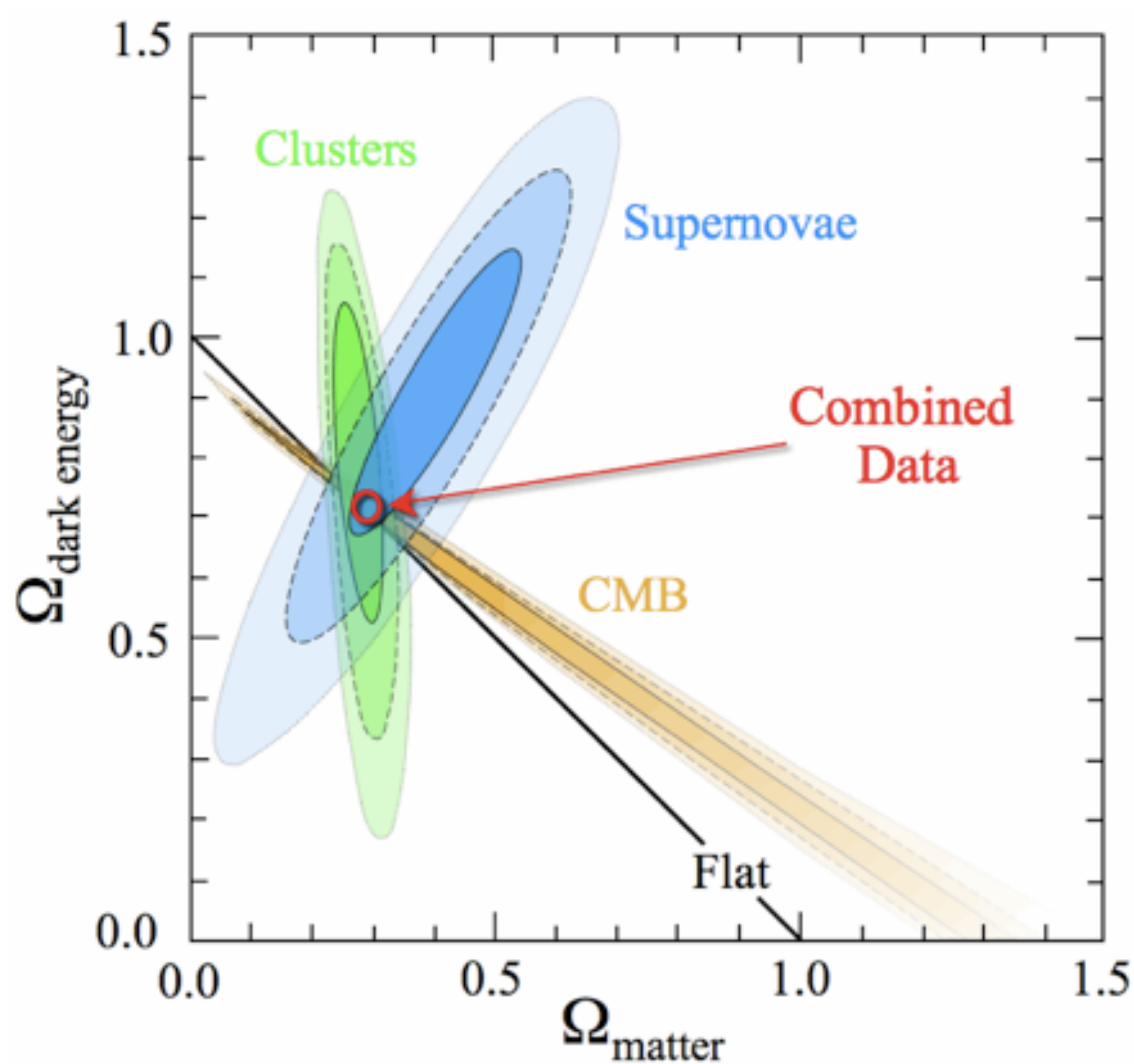
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

- Accelerating expansion can be produced by adding a cosmological constant term
- A wide range of data is consistent with a Universe where the current energy density is ~70% cosmological constant and ~30% matter



The cosmic expansion is accelerating!

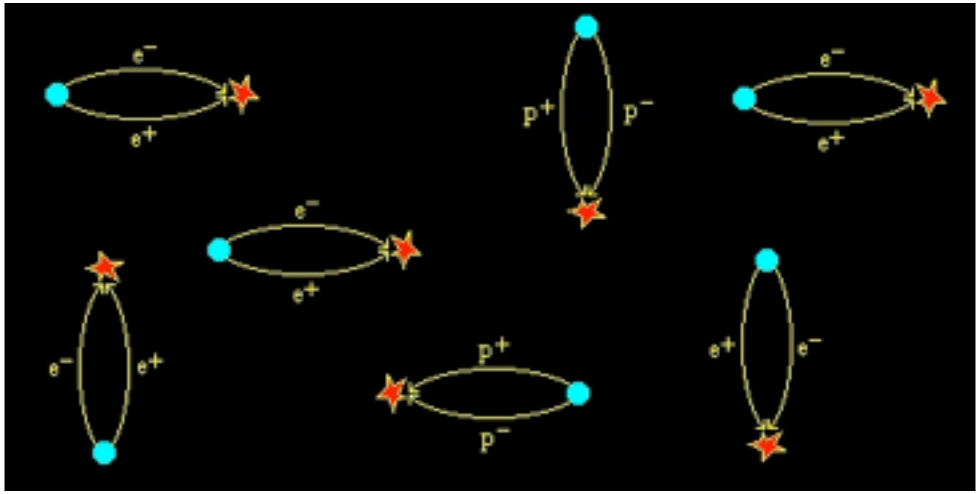
- This is the concordance "Lambda CDM" cosmology!



Credit: Kowalski et al. (2008)

Why is this a problem?

$$\Lambda_{\rm obs} \sim \left(10^{-30}\, M_{\rm Pl}\right)^4$$

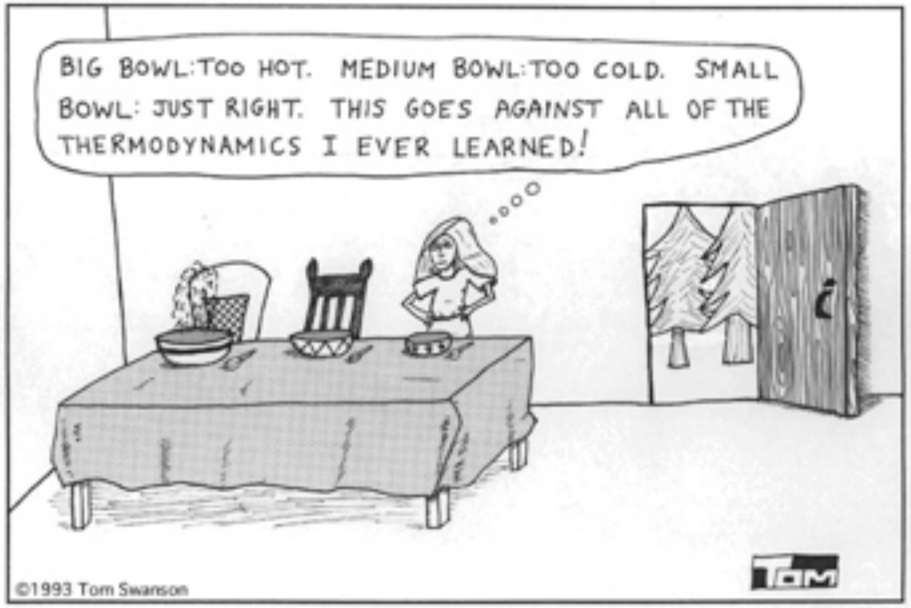


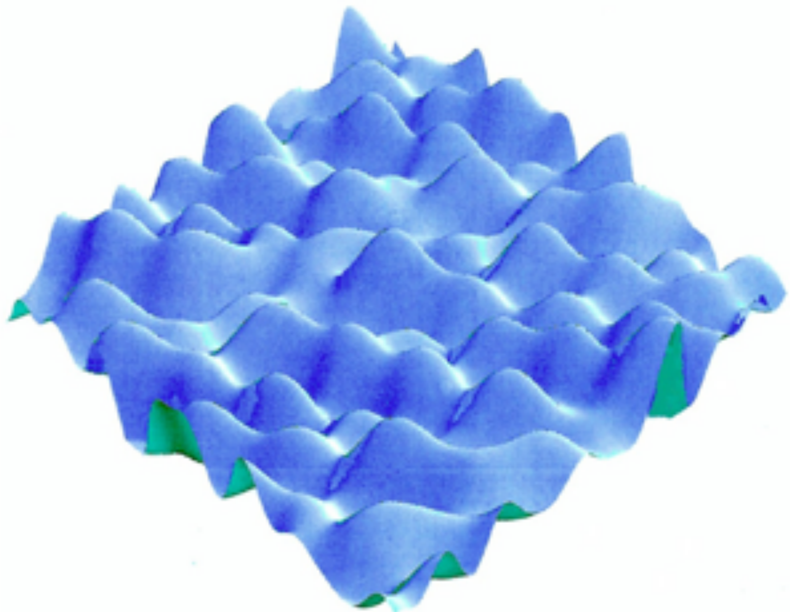
- Why is the energy density in the cosmological constant "unnaturally low"? [many tens of orders lower than expected from quantum mechanical processes involving standard particles]

- Why are the energy densities in cosmological constant and matter roughly equal today? ["coincidence problem"]

- Is the cosmological constant a sign of new physics?

Anthropic principle!





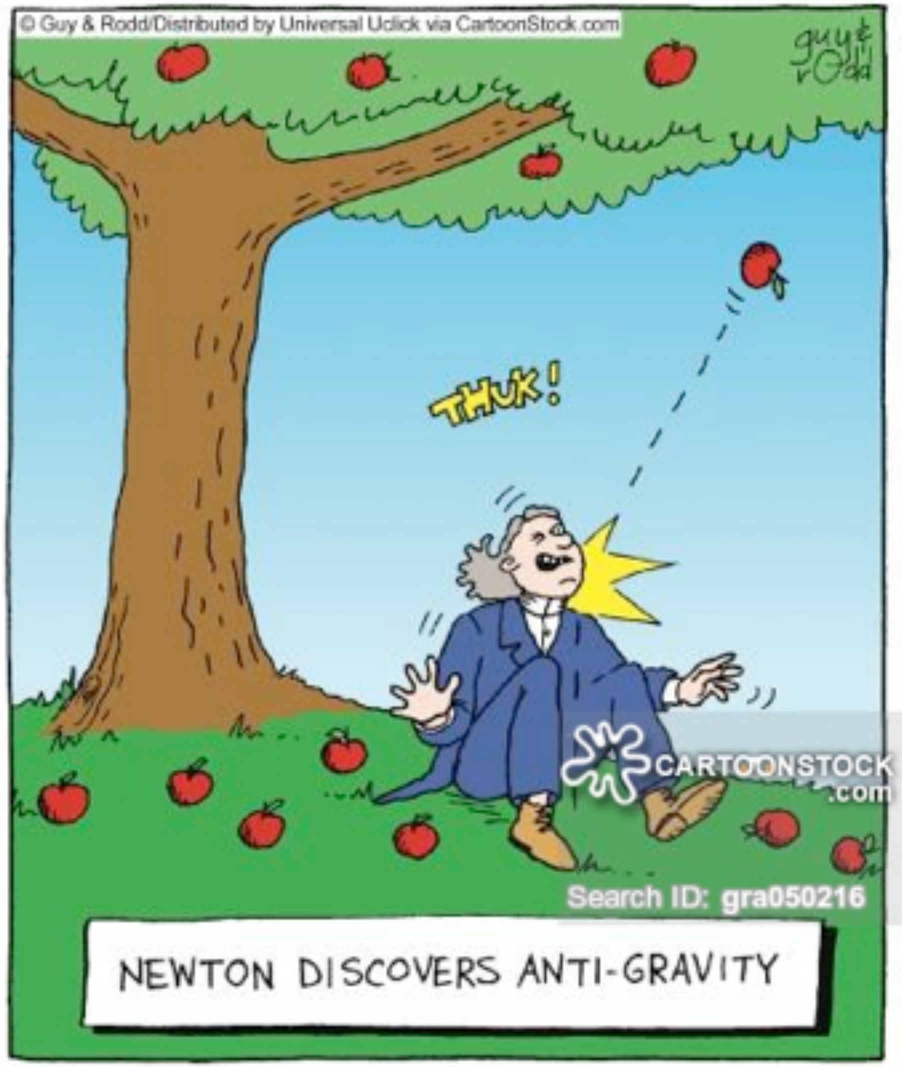
- If the cosmological constant were significantly larger, cosmic structure could not grow and life may not arise
- Perhaps our particular Universe is selected from a wide distribution ("string theory landscape") ...
- Let's not abandon the search for other explanations!

Other explanations ...

Let's not worry about cosmological constant and seek another solution!

- "Accelerating expansion cannot be produced applying GR to a homogeneous/isotropic Universe containing matter and radiation"
- Modify General Relativity? [e.g. Einstein-Hilbert action]
- Allow for effects of inhomogeneity? [very hard!]
- Add extra "source" [e.g. dynamical scalar field]

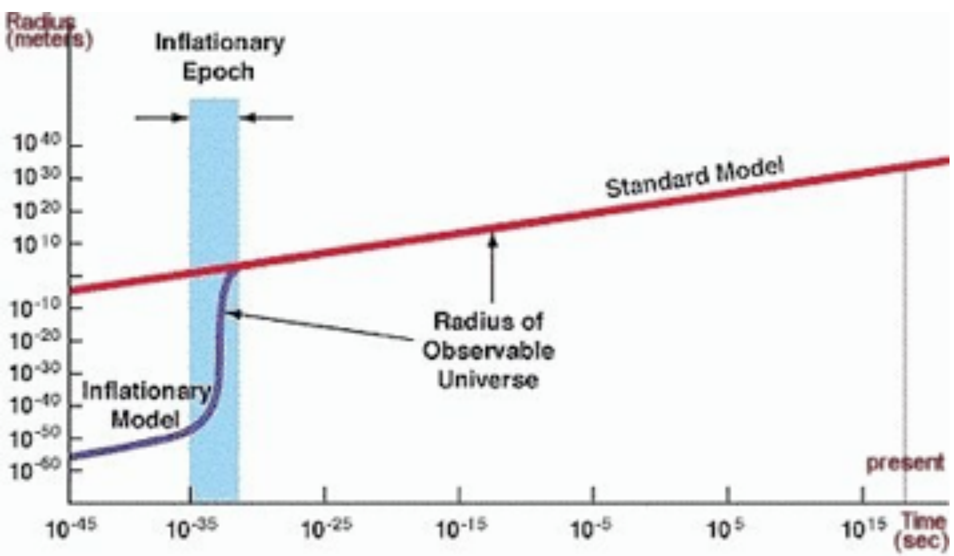
What does it mean to "modify gravity"?

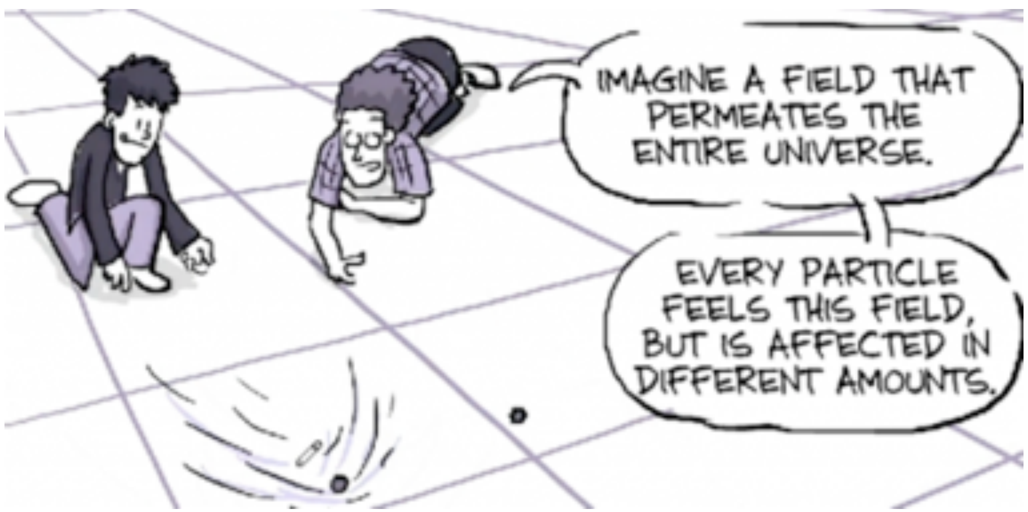


- Add some kind of "fifth force" [... to the four we already have]
- But we have extremely accurate laboratory and solar system tests of General Relativity!
- Add a "screening mechanism" which allows the fifth force to vary with environment

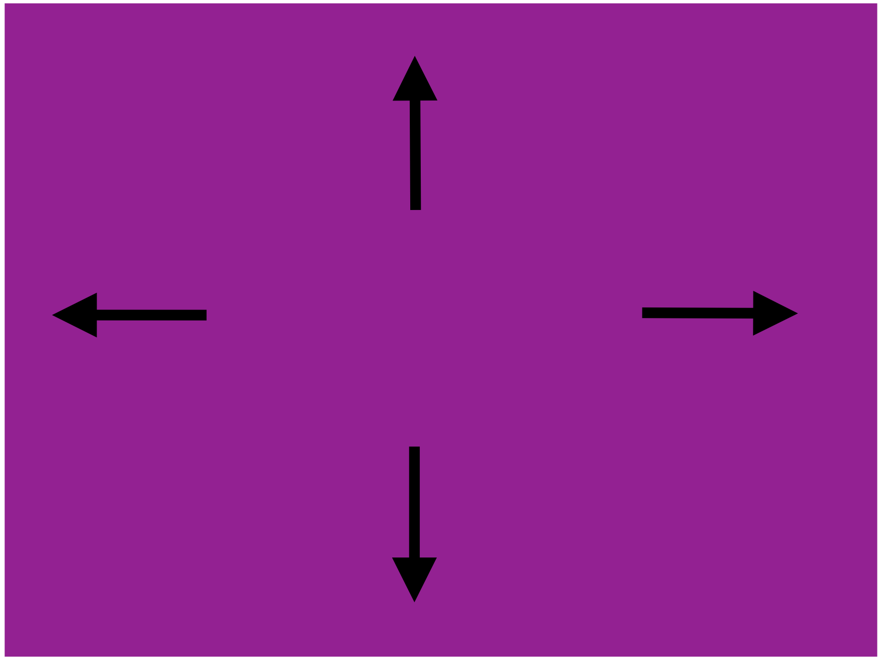
Adding an extra source term?

- Perhaps the cosmological constant is a dynamical scalar field ("quintessence") which relaxes to its present-day value through some mechanism
- Other scalar fields are known (inflation? Higgs?)
- Tracking matter could resolve coincidence problem

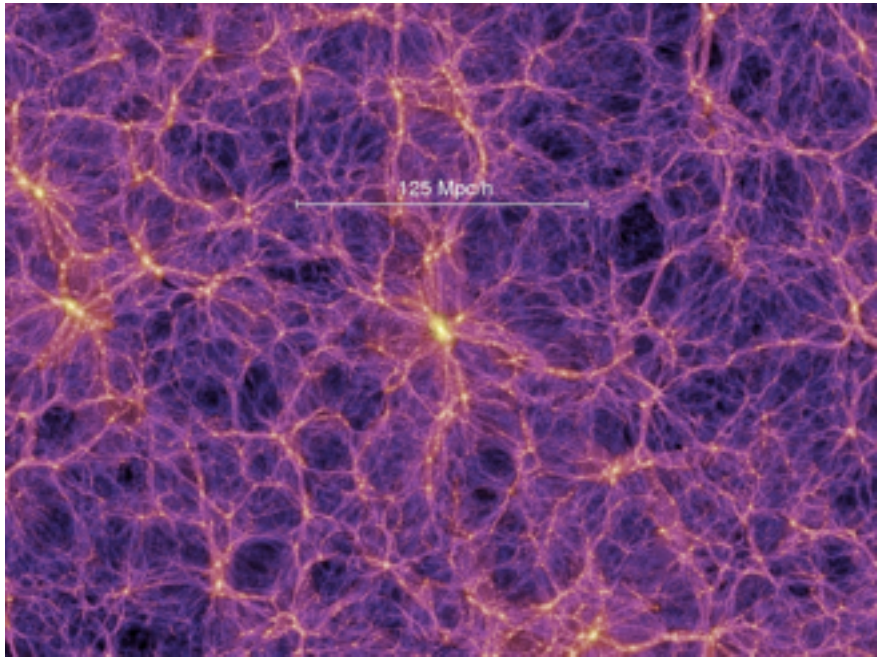




What observations can cosmologists make?



Expansion of the homogeneous Universe



Growth of perturbations within the expanding background

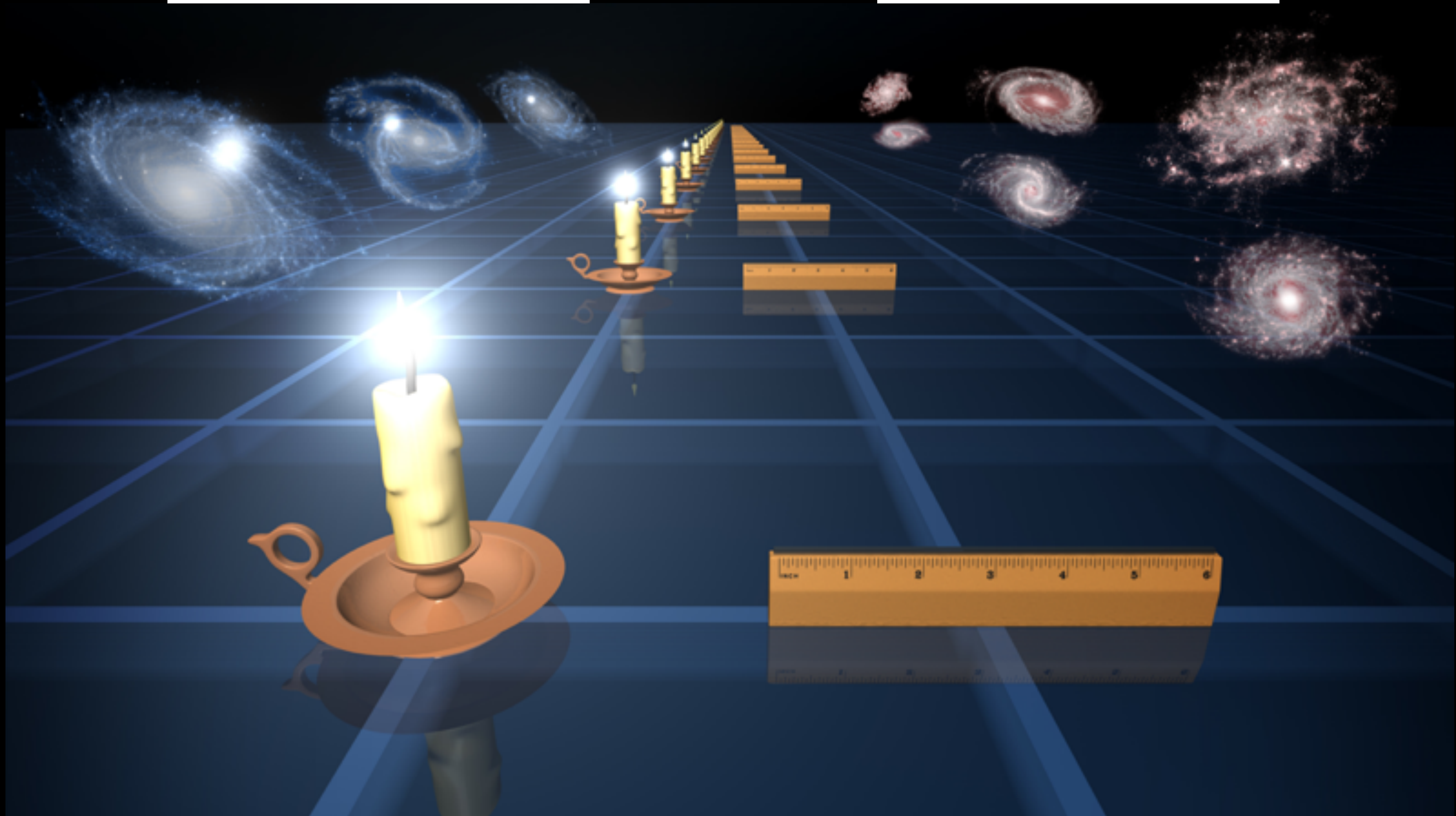
Expansion of the homogeneous Universe

- Cosmic expansion is described by the scale factor $a(t)$ which is related to the redshift z of light, $a = 1/(1+z)$
- The Friedmann equation relates the scale factor to the matter/energy contents of the Universe
- The "distance" to a given redshift is computed from the metric and depends on the matter/energy contents
- Cosmologists can measure distance by using standard candles or standard rulers

Expansion of the homogeneous Universe

Standard candles

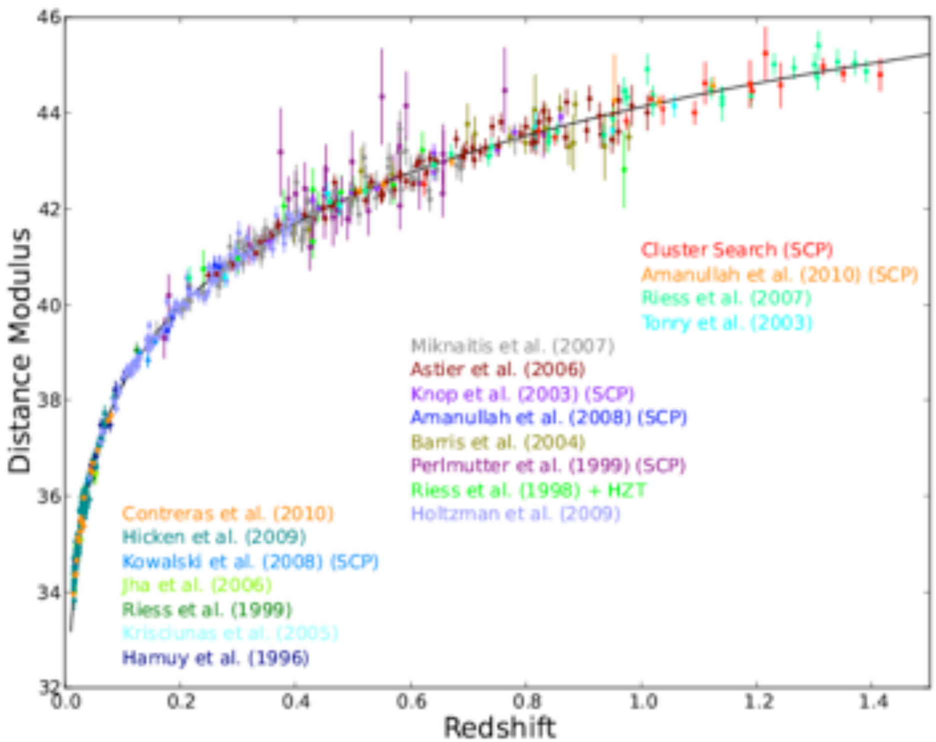
Standard rulers



Expansion of the homogeneous Universe

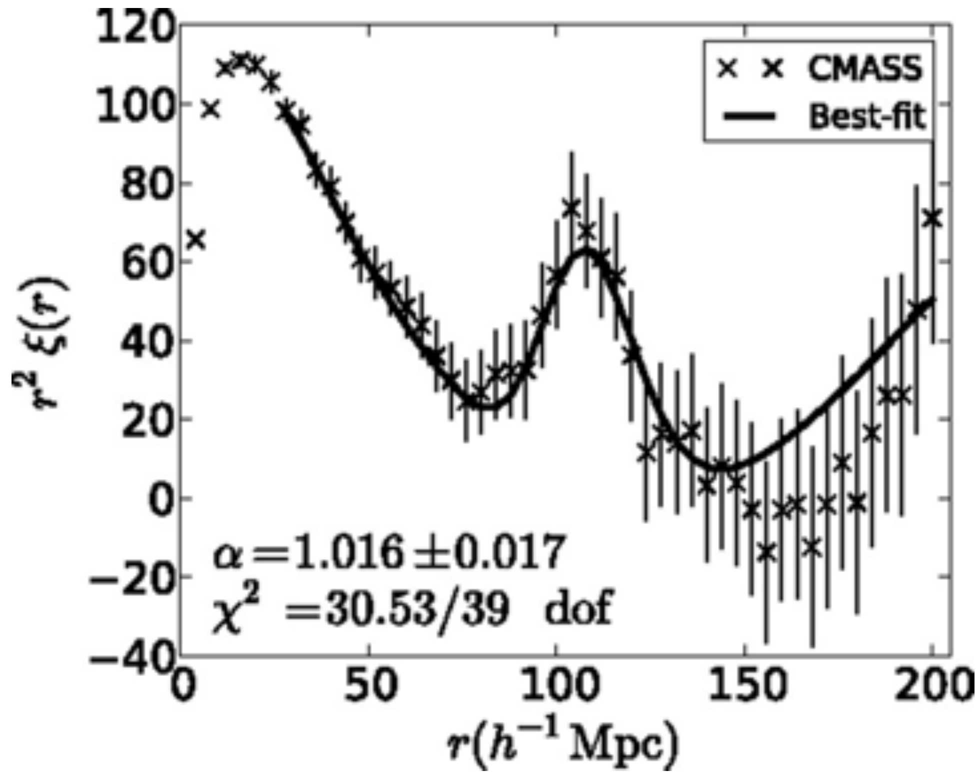
Standard candles

Credit : Amanullah et al. (2010)



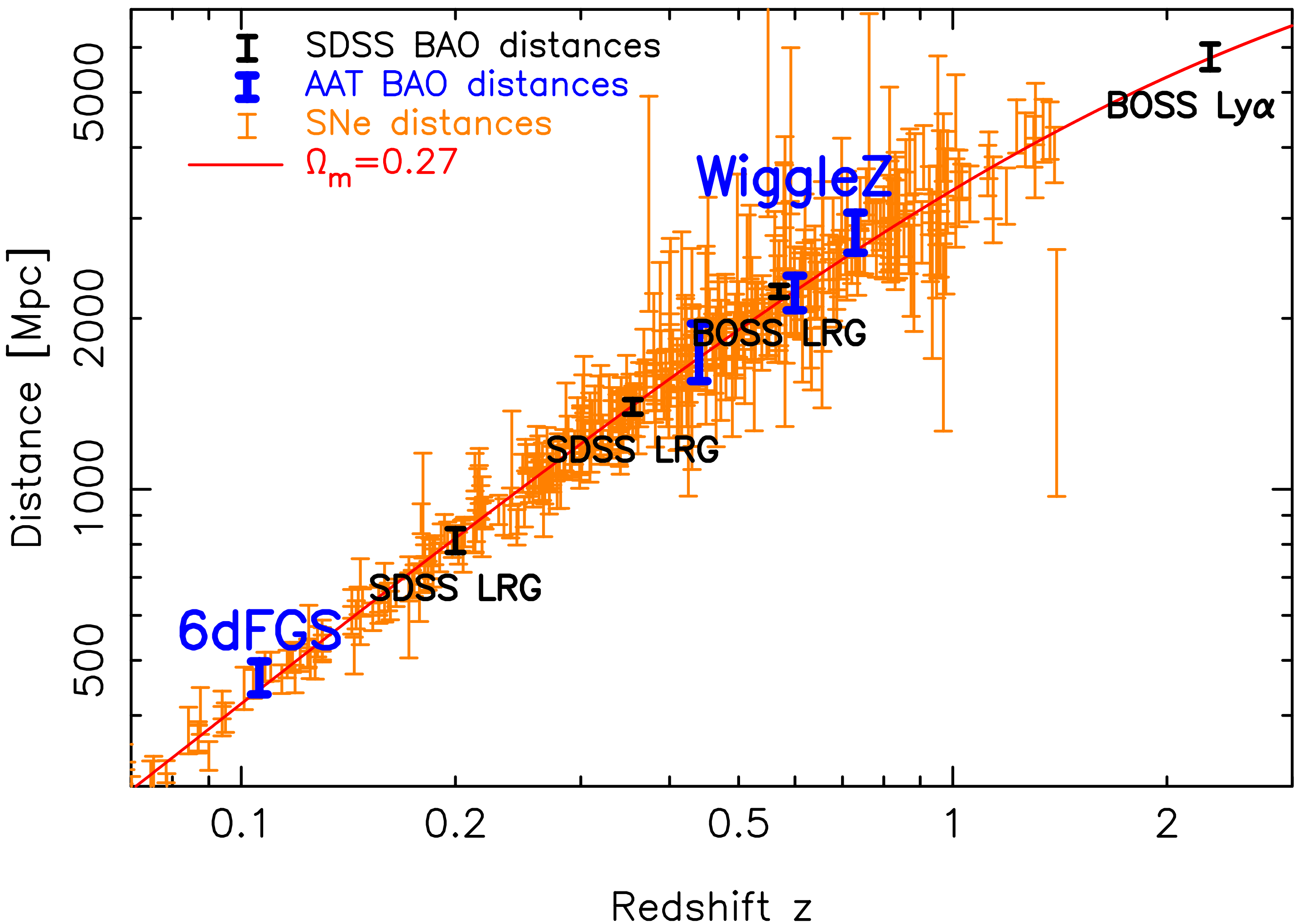
Standard rulers

Credit : Anderson et al. (2013)



- The cosmic expansion history over the last ~7 billion years has been measured with ~1% accuracy

Expansion of the homogeneous Universe



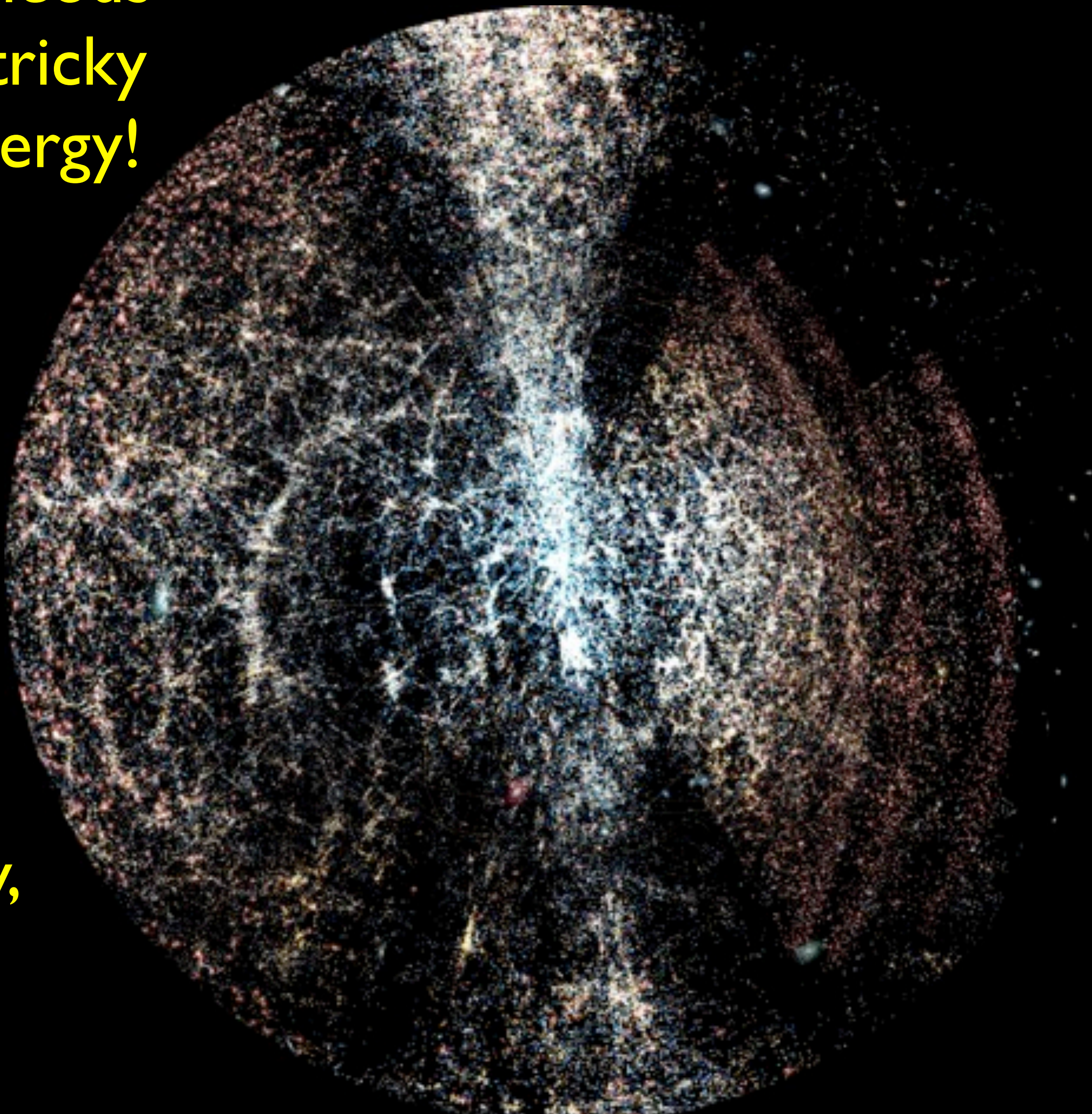
- The cosmic expansion history over the last ~7 billion years has been measured with ~1% accuracy

Growth of perturbations

In a perfectly homogeneous Universe, it would be tricky to understand dark energy!

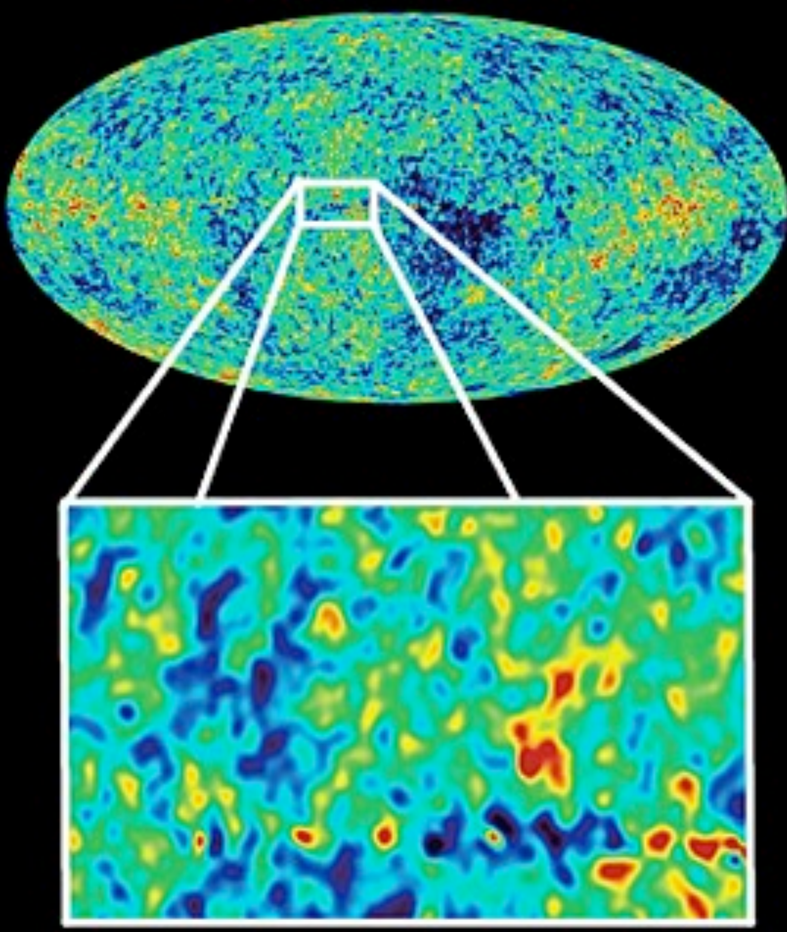
There are a rich variety of observable signatures in the clumpy Universe!

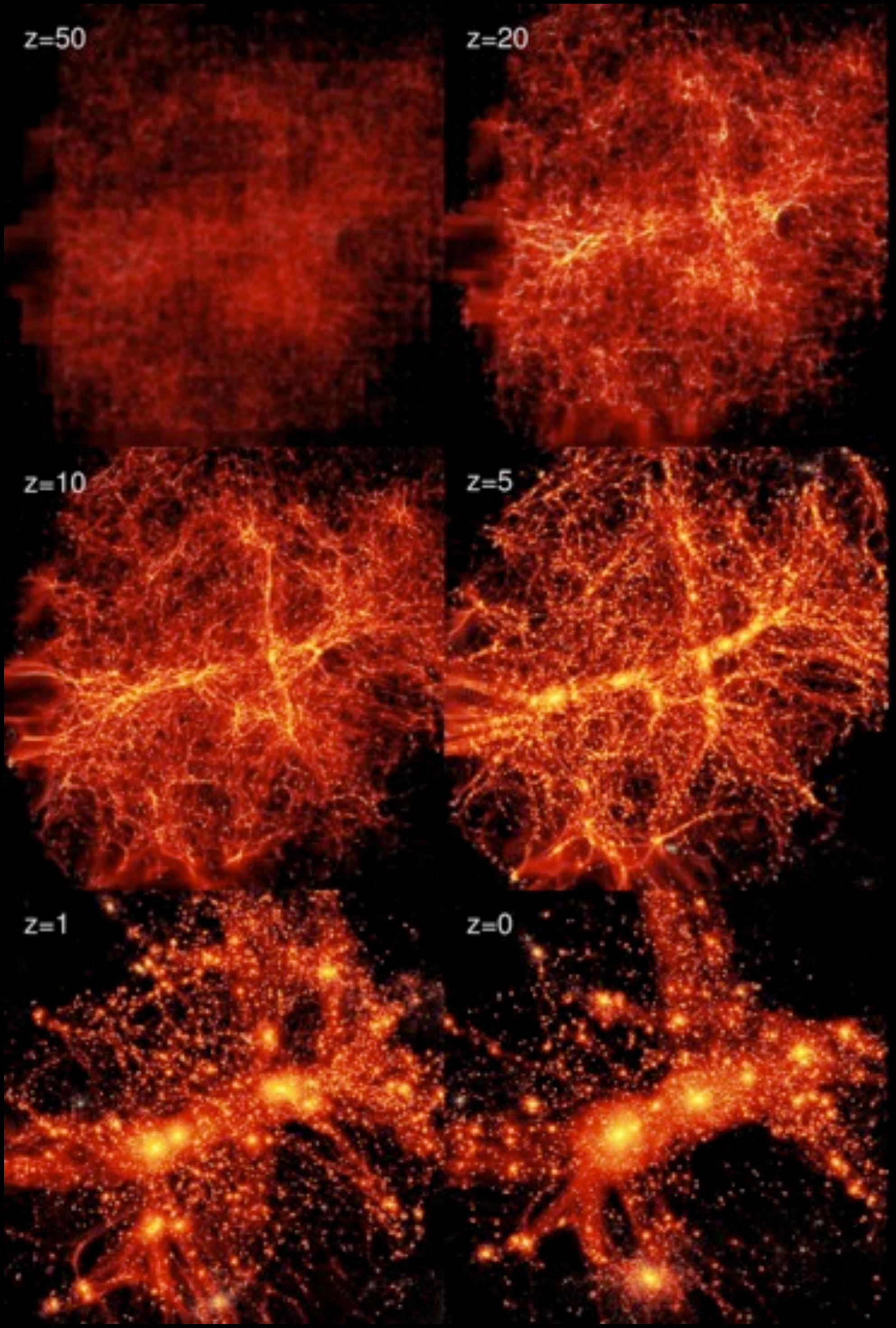
These have not been measured as accurately, and are crucial for distinguishing physics



Growth of perturbations

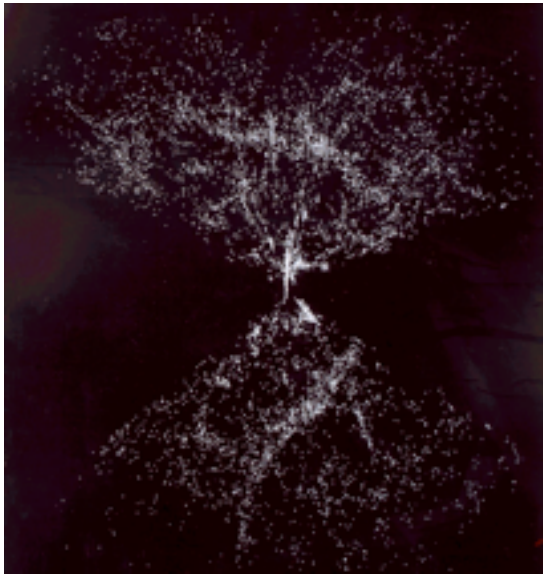
Measure these perturbations as a function of redshift (z) and scale (Fourier mode k)

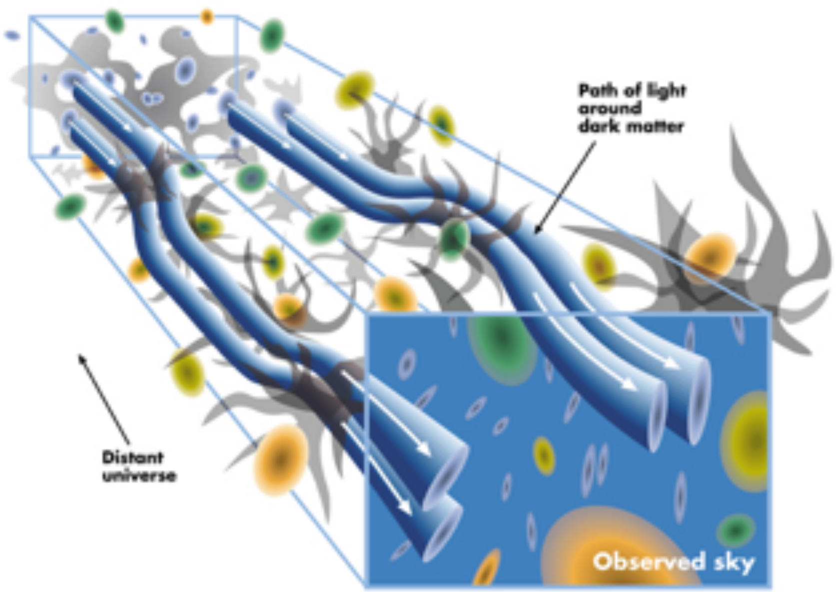


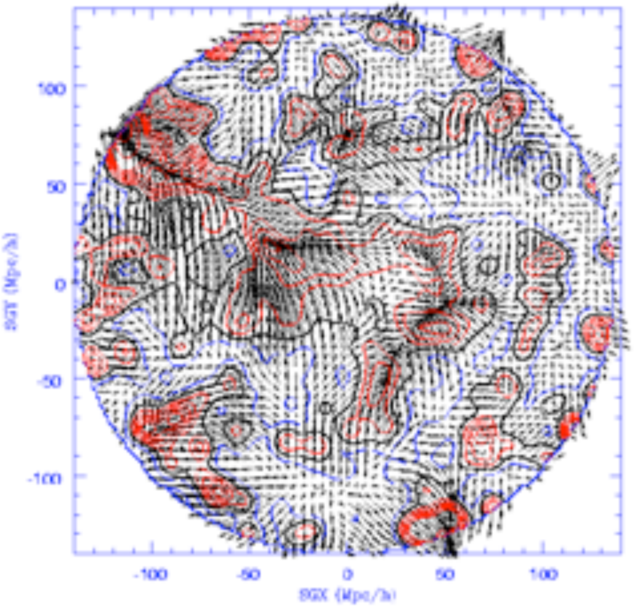


Growth of perturbations

- Clustering of galaxies [measured using a galaxy redshift survey]
- Velocities of objects [measured through the additional Doppler shift in the cosmological redshift]
- Gravitational lensing of light [measured through the correlated shapes of background galaxies as their light passes through structure]
- Abundance/properties of structures e.g. clusters/voids







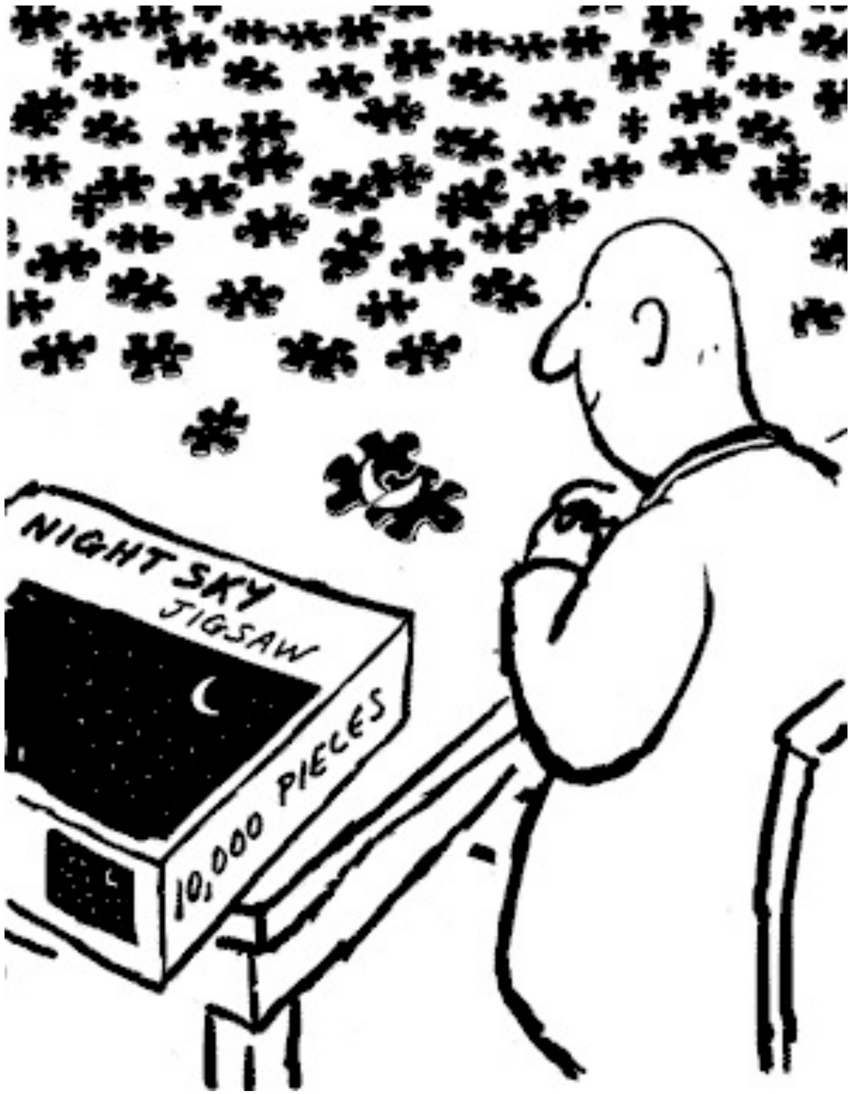
Lensing and clustering : complementarity

- Sensitive to theories of gravity in complementary ways
- General perturbations to spacetime metric:

$$ds^2 = [1+2\psi(x,t)]\,dt^2 - a^2(t)\,[1-2\phi(x,t)]\,dx^2$$

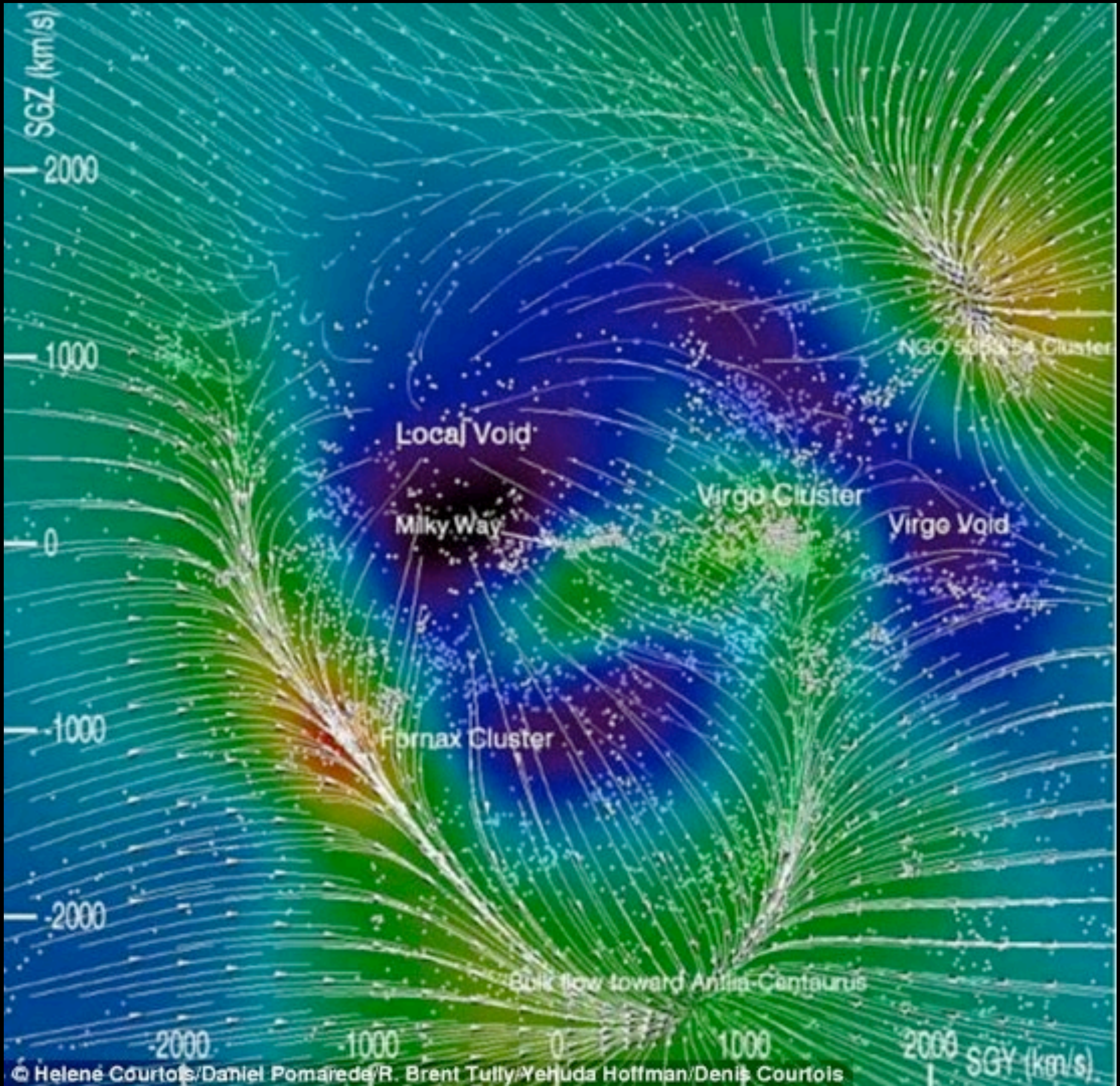
- (ψ, ϕ) are metric gravitational potentials, identical in General Relativity but can differ in general theories
- Relativistic particles (e.g. light rays for lensing) collect equal contributions and are sensitive to $(\psi + \phi)$
- Non-relativistic particles (e.g. galaxies infalling into clusters) experience the Newtonian potential ψ

What approaches are possible?



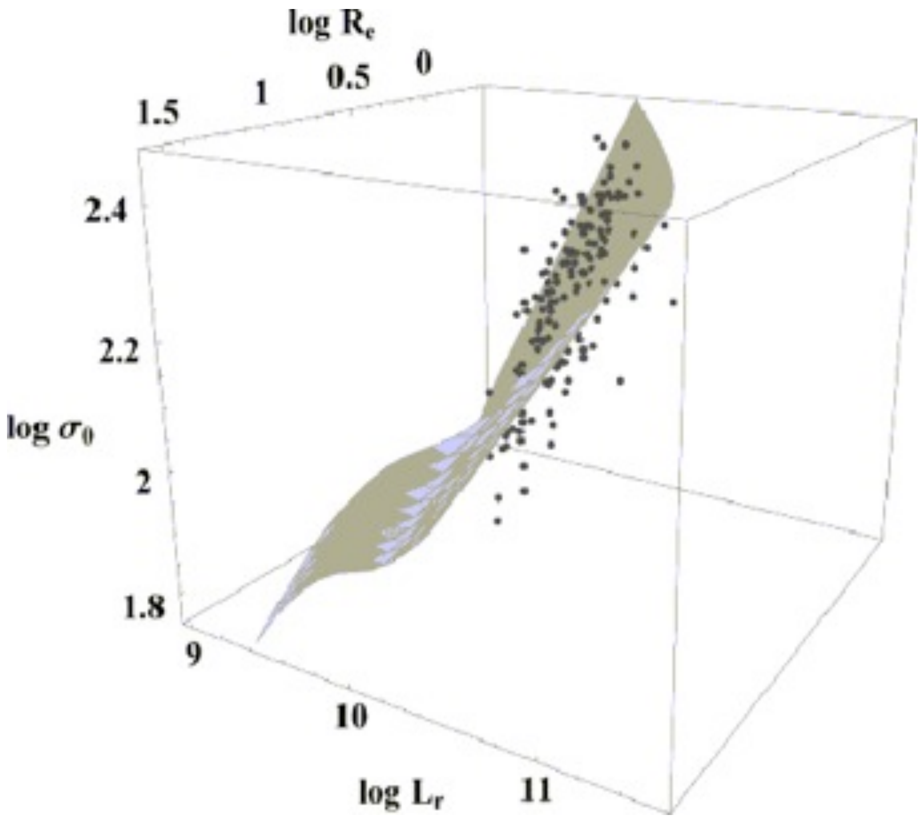
- Measure an observable, is it consistent with the prediction of the LambdaCDM model?
- Parametrize deviations from GR, and seek to place constraints on those deviations
- Target particularly important signatures of new physics, e.g. difference in metric potentials

Is an observable consistent : galaxy velocities



Measuring velocities of individual galaxies

- Simultaneous measurements of distance D and redshift z
- Use standard candle (supernovae, fundamental plane, ...)

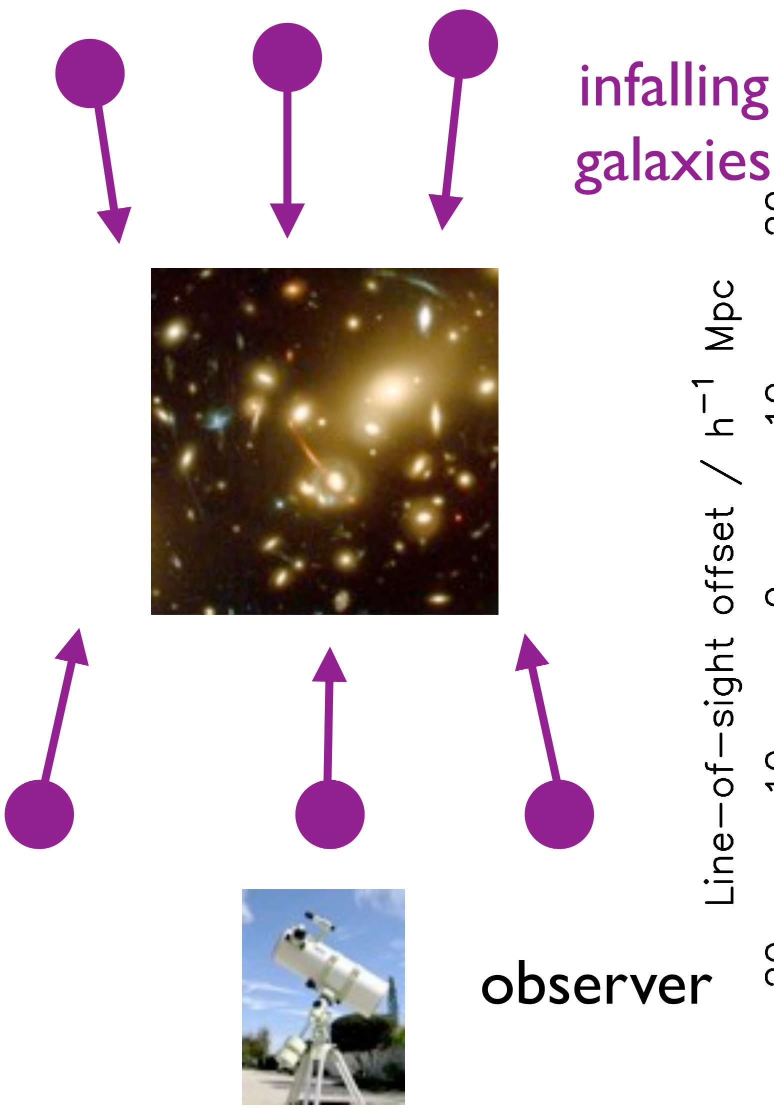


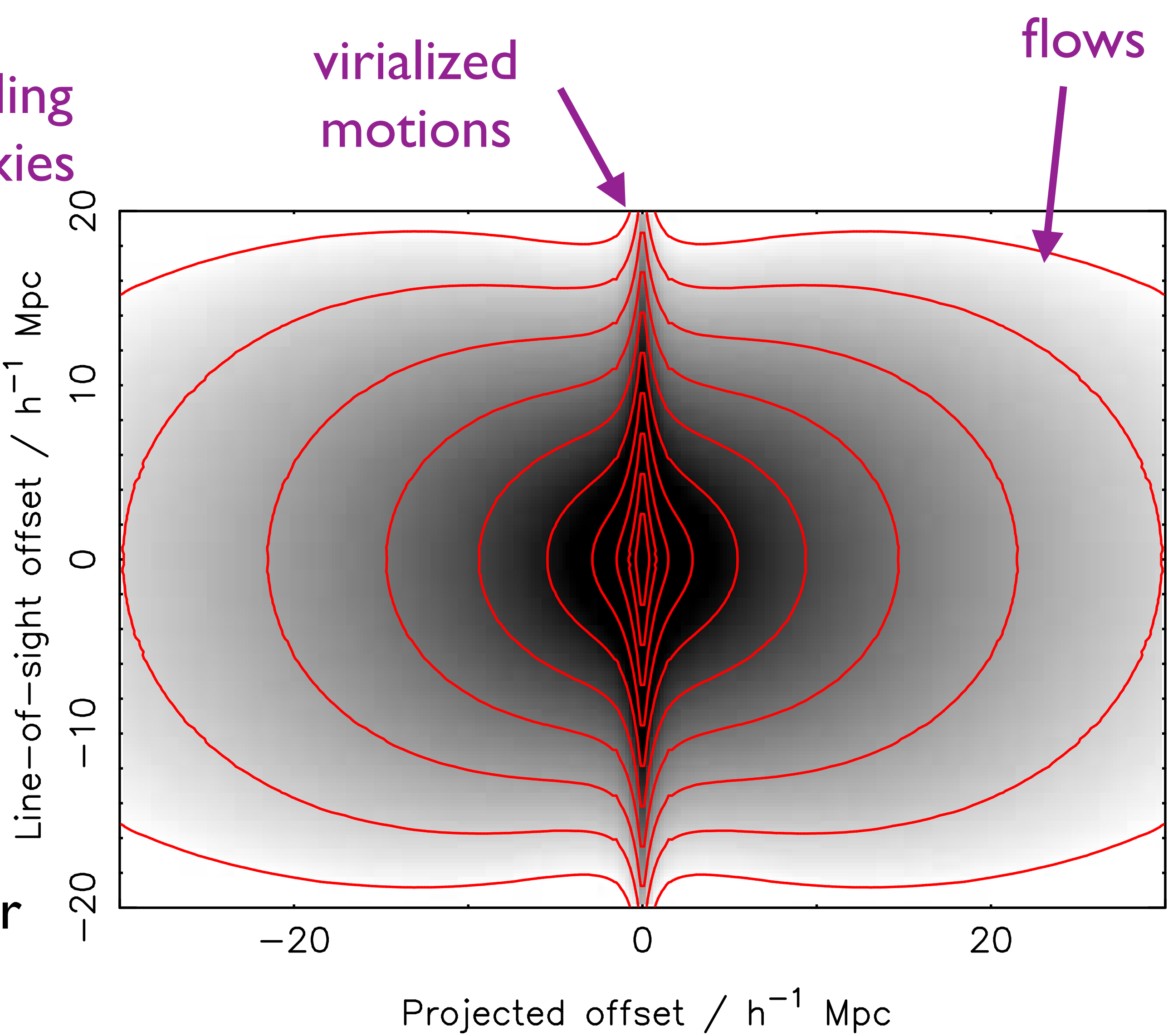
$$v_{\text{peculiar}} = c\,z - H_0\,D$$

[Small print :
this equation is not exact!]

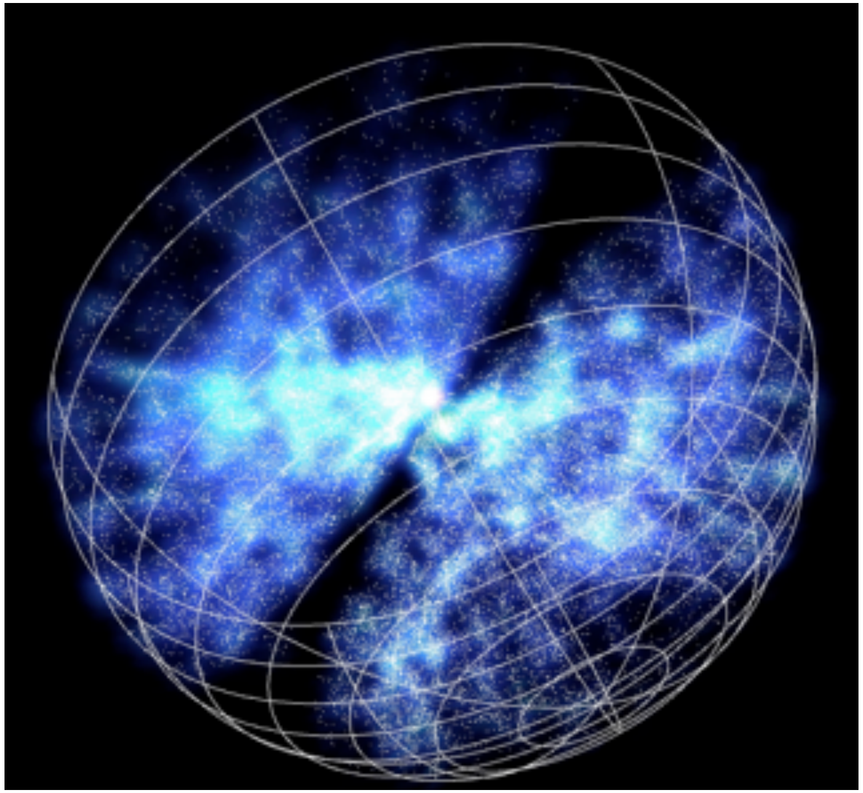
Measuring correlated galaxy velocities

- Even without velocity measurements, can detect via redshift-space distortion in galaxy redshift surveys





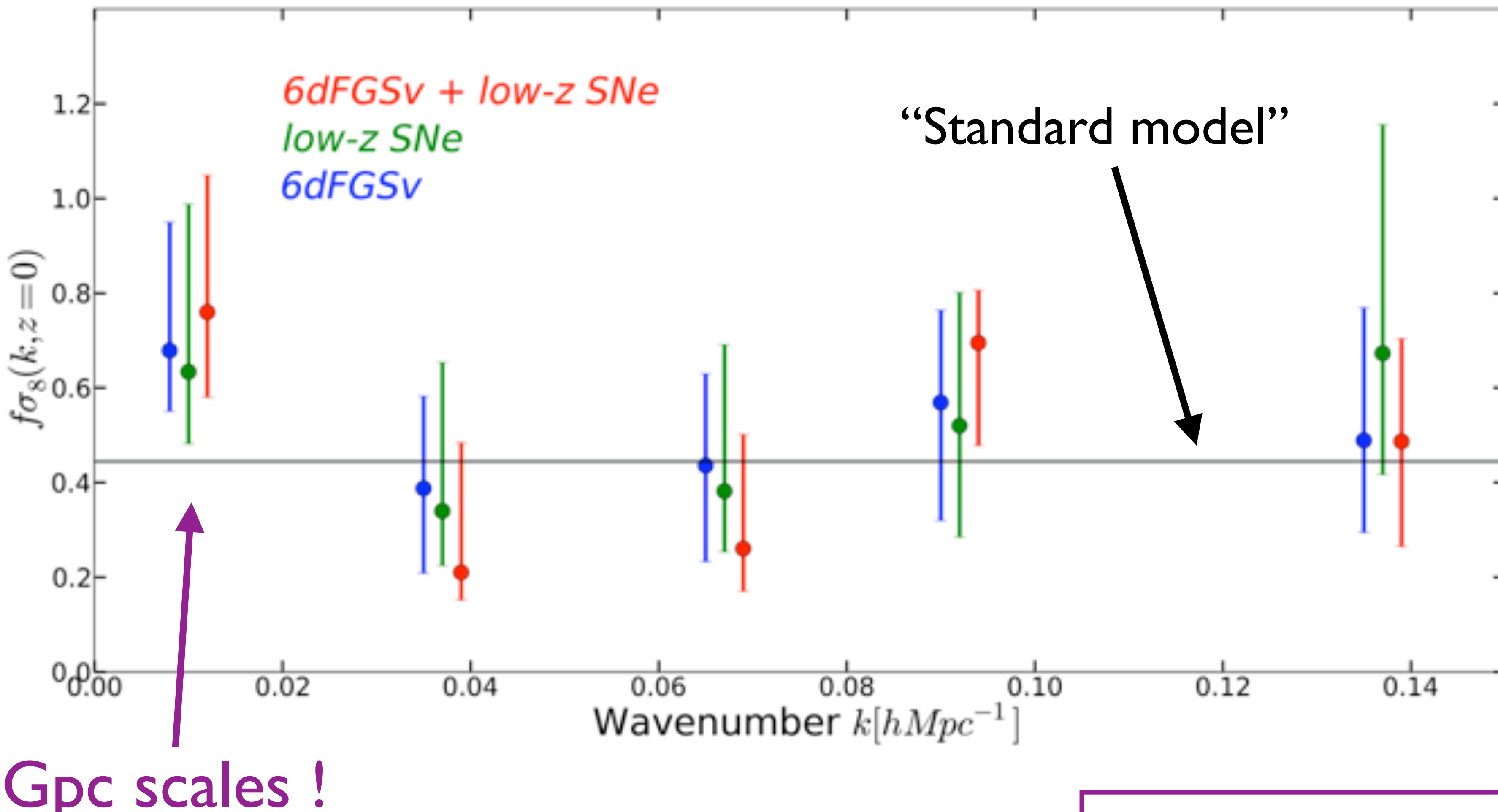
Is an observable consistent : galaxy velocities



- A galaxy's standard-candle distance and redshift determines its velocity
- The velocity is linked to the matter density by gravity, via the growth rate of structure
- We measure the velocity power spectrum of 9,000 standard-candle galaxies from the 6dF Galaxy Survey
- Credit to Andrew Johnson!

Is an observable consistent : galaxy velocities

- Here is our result : consistency with the prediction with particular sensitivity to large scales



arXiv : 1404.3799

Parametrized deviations : G_{matter} and G_{light}

- Use these data to test for deviations from GR using a phenomenological model

$$\boxed{\begin{aligned} \nabla^2\psi &= 4\pi G_N a^2 \bar{\rho}_m \Delta_m \\ \nabla^2(\phi+\psi) &= 8\pi G_N a^2 \bar{\rho}_m \Delta_m \end{aligned}}$$

Parametrized deviations : G_{matter} and G_{light}

- Use these data to test for deviations from GR using a phenomenological model

$$\boxed{\begin{aligned} \nabla^2\psi &= 4\pi G_N a^2 \bar{\rho}_m \Delta_m \times G_{\rm matter} \\ \nabla^2(\phi+\psi) &= 8\pi G_N a^2 \bar{\rho}_m \Delta_m \times G_{\rm light}\ . \end{aligned}}$$

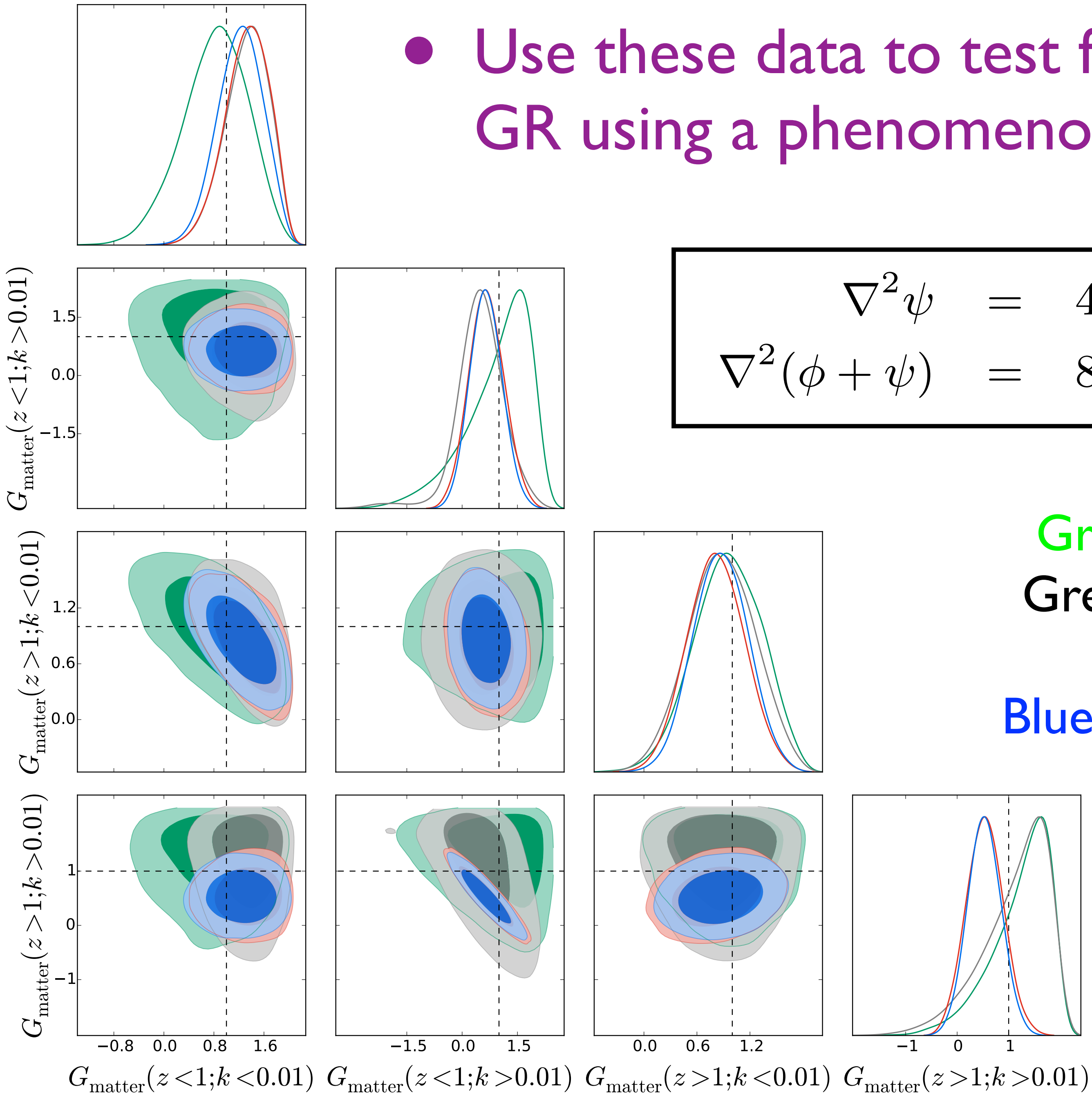
Parametrized deviations : G_{matter} and G_{light}

- Use these data to test for deviations from GR using a phenomenological model

$$
\boxed{\begin{aligned}
\nabla^2\psi &= 4\pi G_N a^2 \bar{\rho}_m \Delta_m \times G_{\rm matter} \\
\nabla^2(\phi+\psi) &= 8\pi G_N a^2 \bar{\rho}_m \Delta_m \times G_{\rm light} \; .
\end{aligned}}
$$

$G_{matter}(k,z)$ and $G_{light}(k,z)$ in two bins of k and z (8 parameters)

Parametrized deviations : G_{matter} and G_{light}



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Green : CMB+BAO+SNe

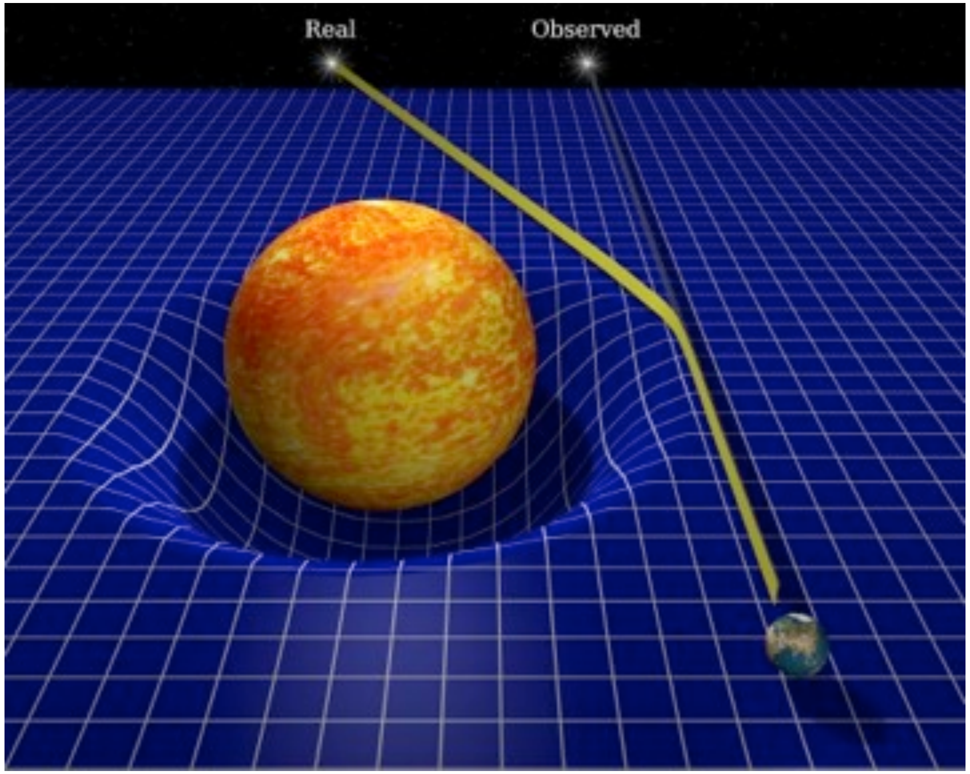
Grey : + peculiar velocities

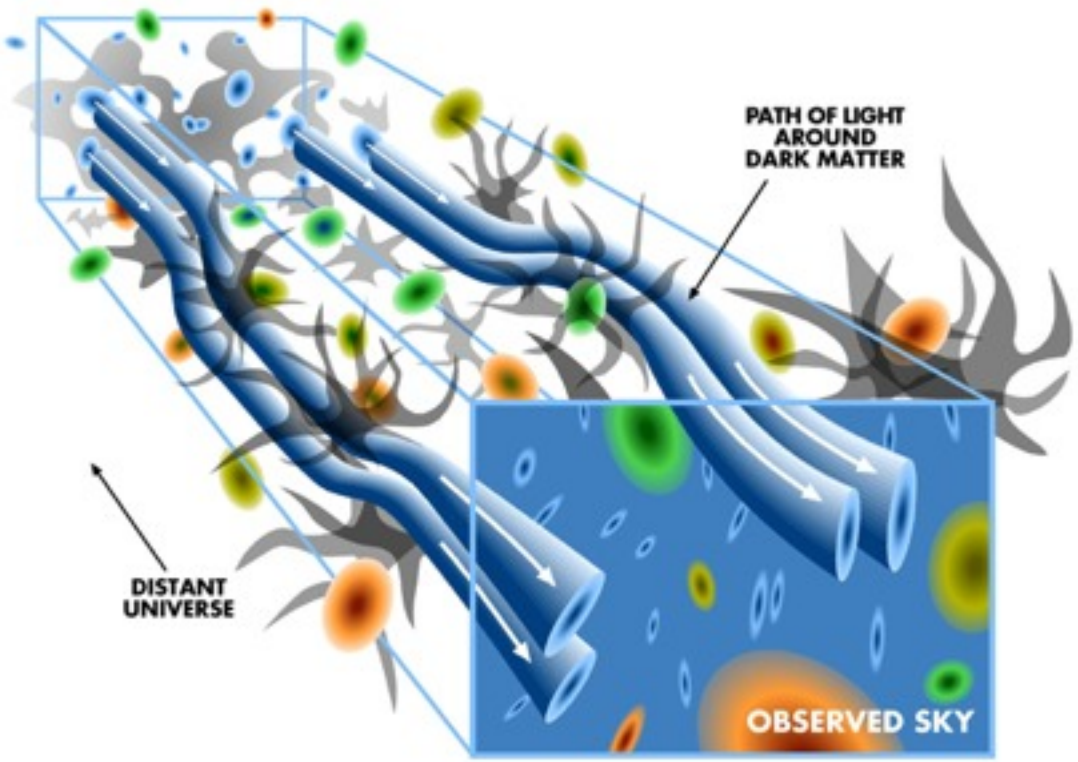
Red : + RSD

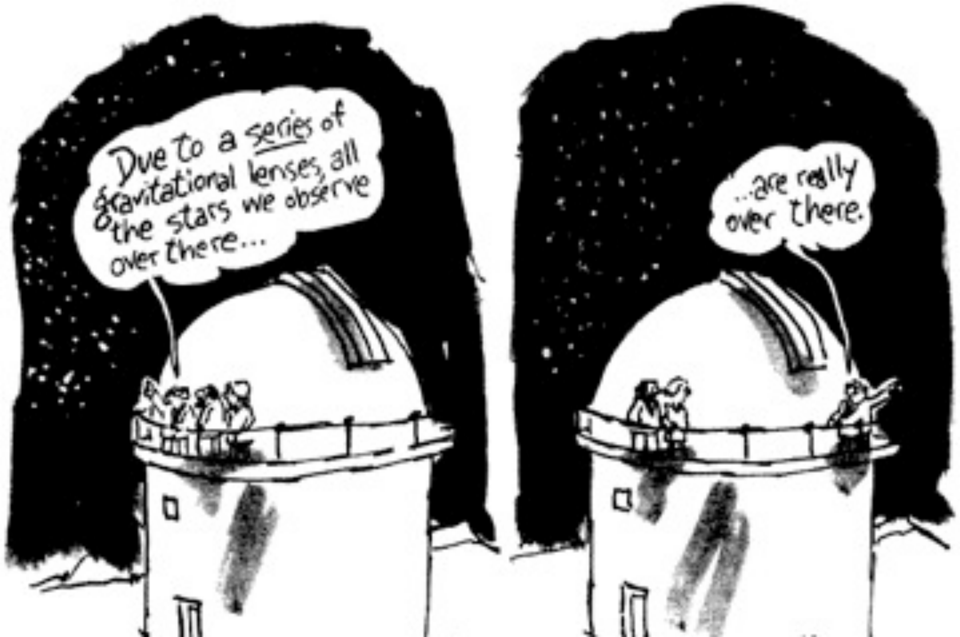
Blue : + CMB X-correlations

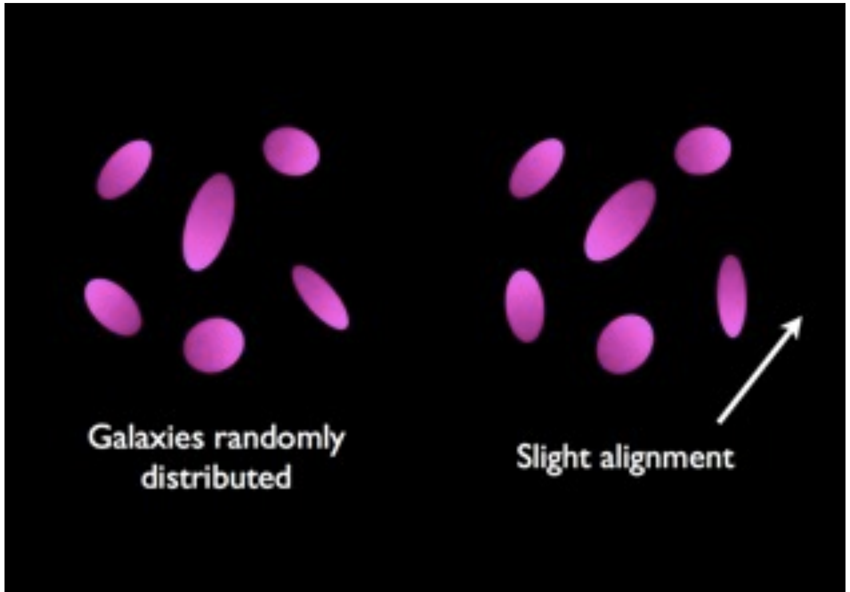
arXiv : 1504.06885

Gravitational lensing



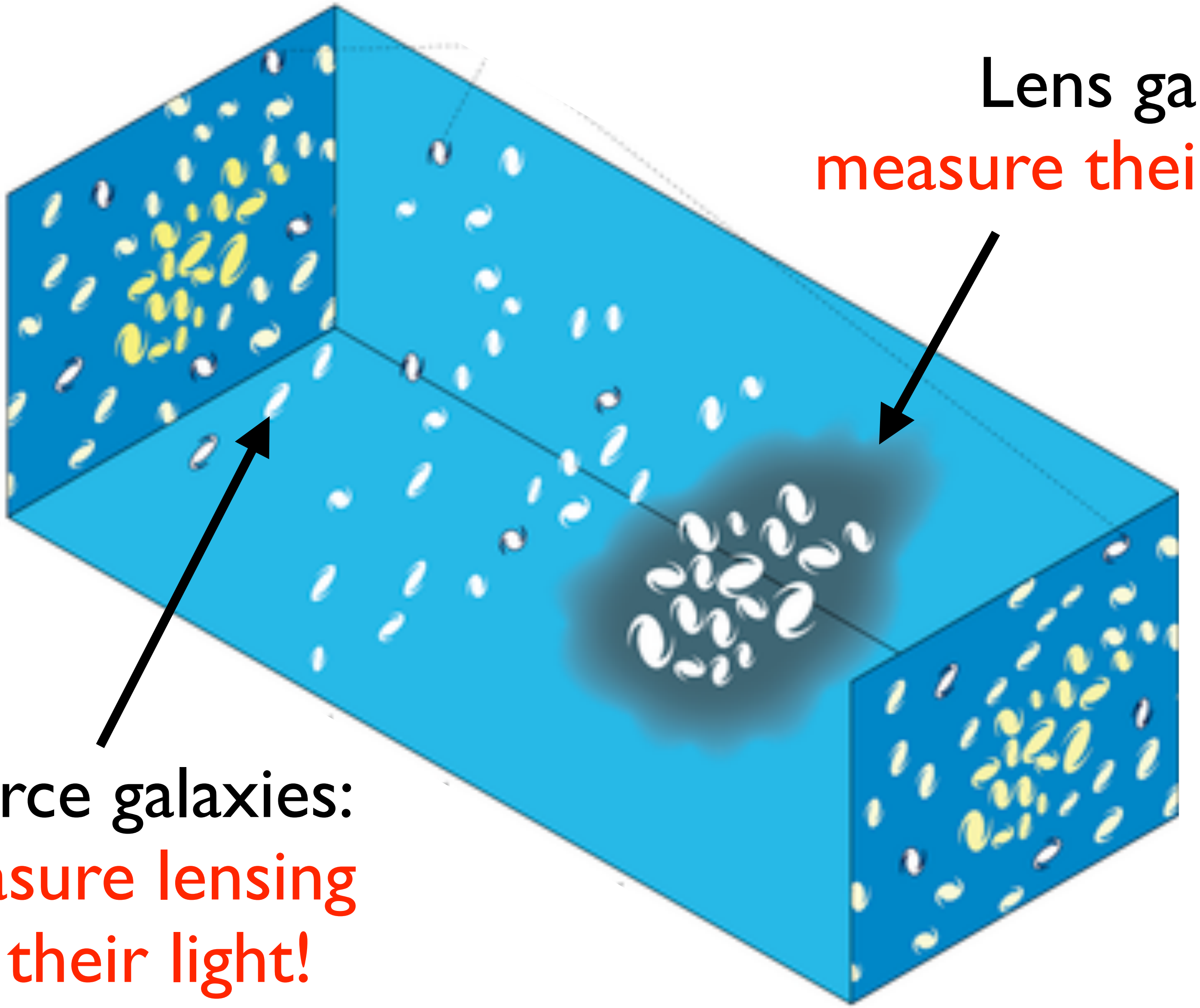






Targetted test : lensing vs. dynamics

- What is the gravity generated by the density field?



Lens galaxies:
measure their velocities!

Source galaxies:
measure lensing
of their light!

Targetted test : lensing vs. dynamics

- Measure cross-correlations between source shapes from CFHTLenS / RCSLenS (to r ~ 25) and lenses from WiggleZ / BOSS (covering $0.15 < z < 0.7$)

- Total overlap area ~ 500 deg^2

- Shape measurements using "lensfit" give shape density of 14 arcmin^{-2} [CFHTLenS] and 6 arcmin^{-2} [RCSLenS]

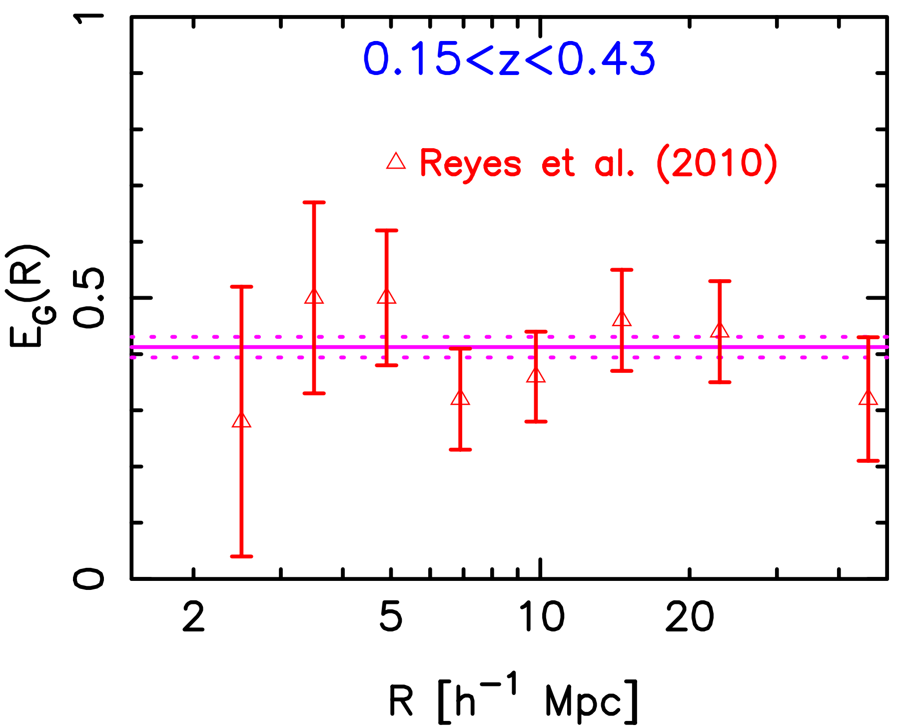
- Source photometric redshift catalogue using BPZ

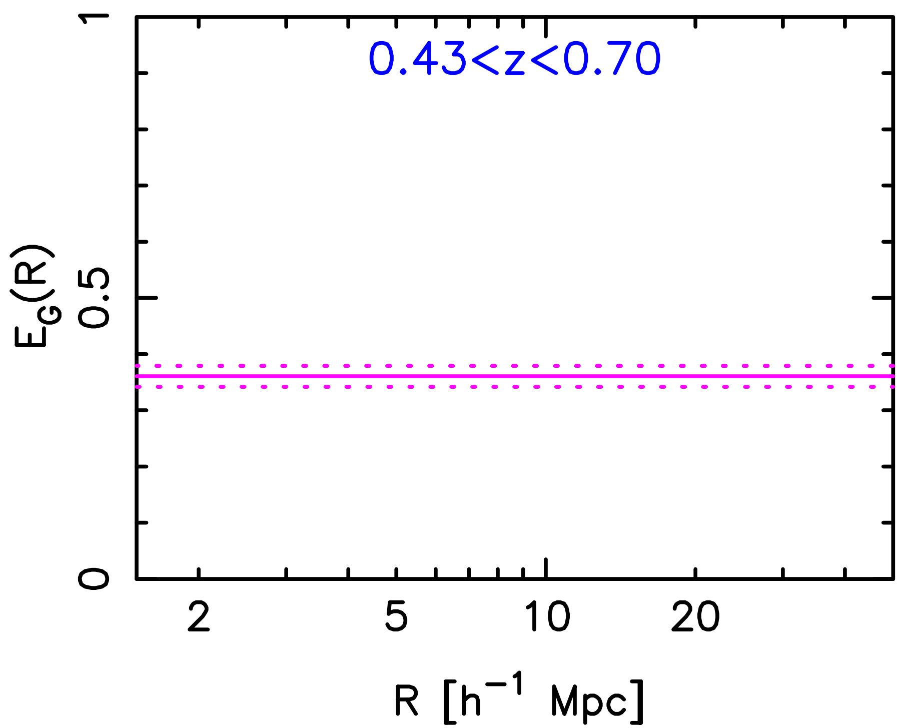
- Battery of systematic tests of shear measurements, results blinded

Targetted test : lensing vs. dynamics

$$\text{Measurement [scale]} = \frac{\text{Amplitude of lensing [scale]}}{\text{Amplitude of velocities [scale]}} \qquad E_G(R) = \frac{1}{\beta}\frac{\Upsilon_{gm}(R, R_0)}{\Upsilon_{gg}(R, R_0)}$$

$$\text{Prediction} = \frac{\text{Matter density}}{\text{Cosmic growth rate}} \qquad E_G = \Omega_m / f$$





Targetted test : lensing vs. dynamics

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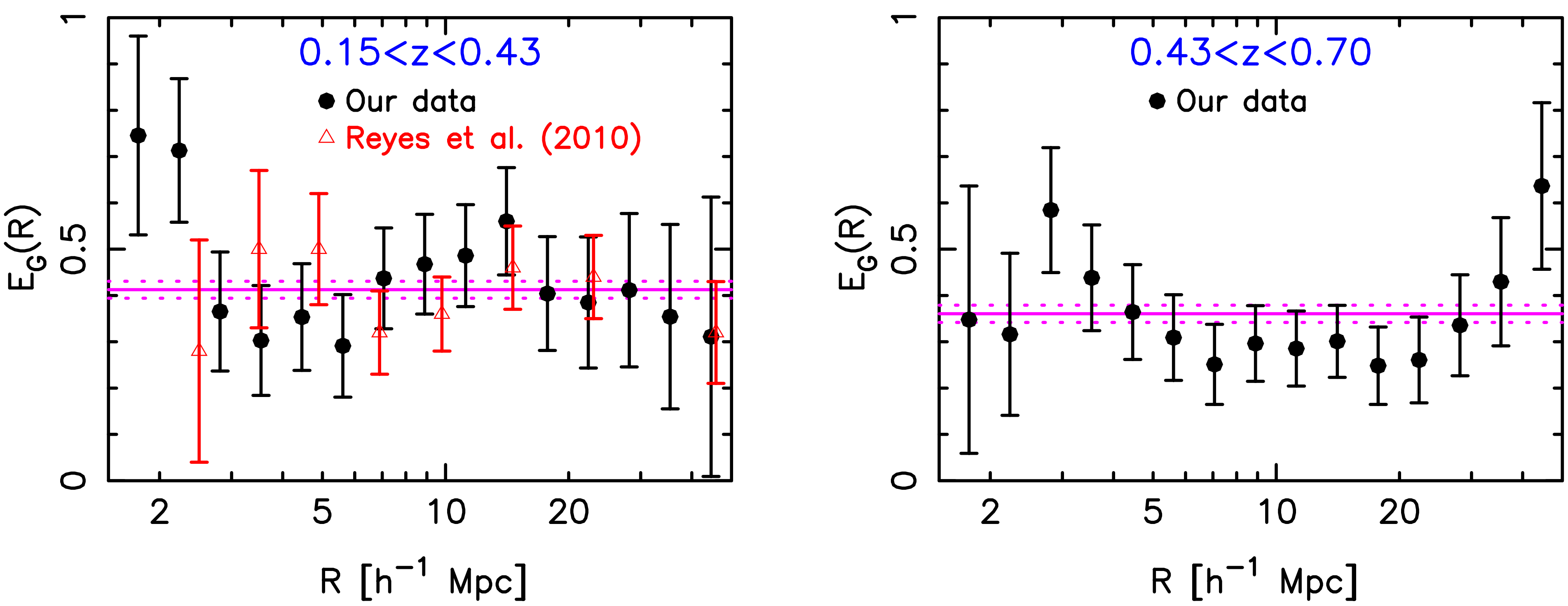
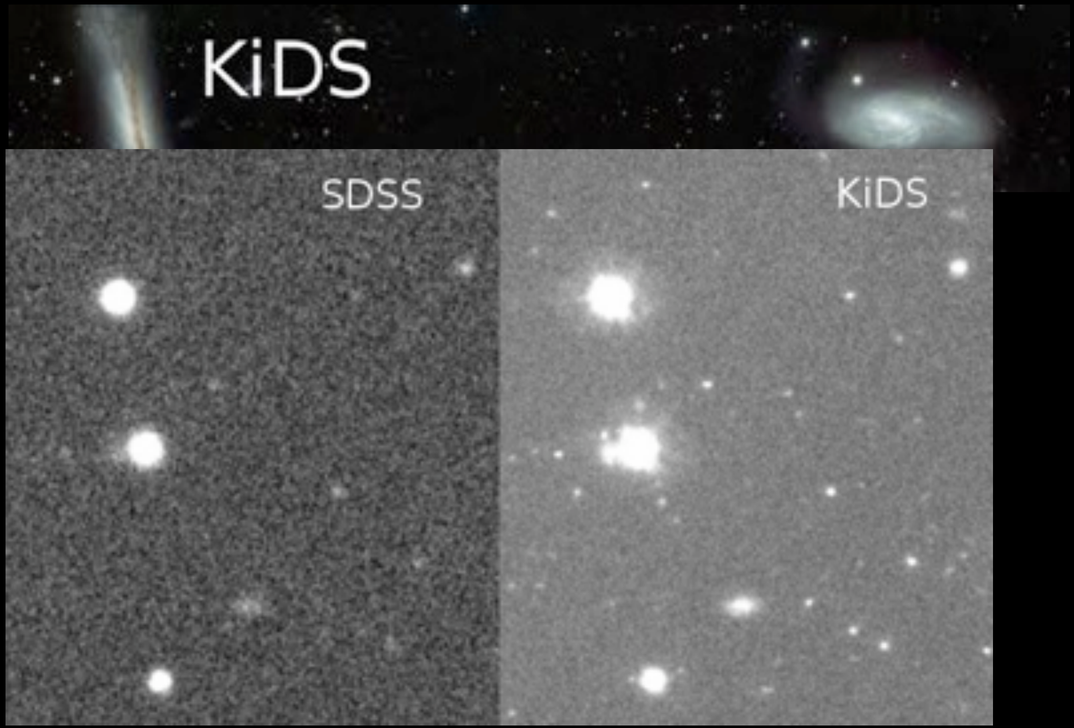


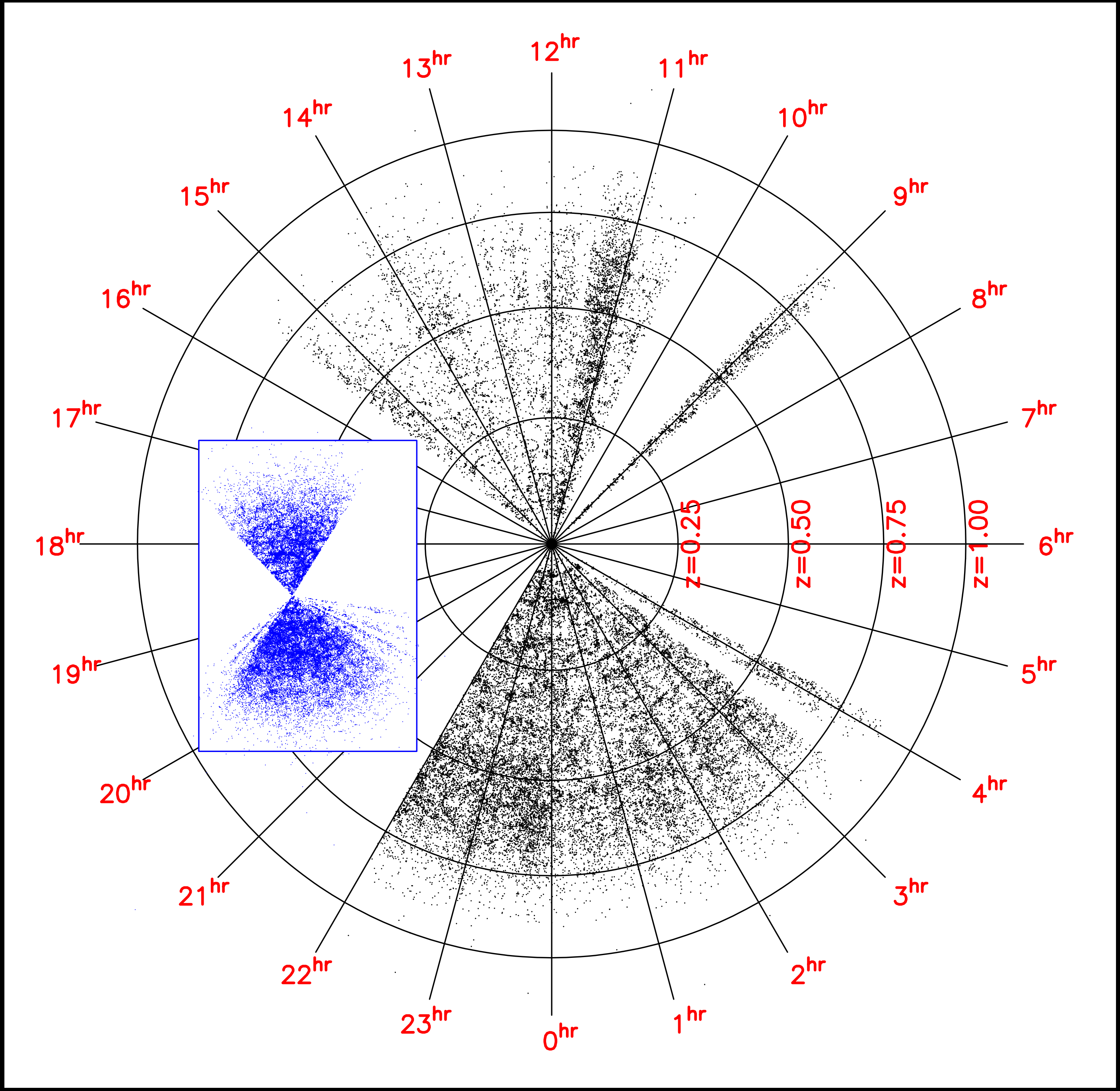
arXiv : 1507.03086

2-degree Field Lensing Survey (2dFLenS)



- 50 AAT nights used for spectroscopic follow-up of southern lensing surveys such as KiDS and DES
- Galaxy lens sample (~50,000) to test gravity by cross-correlating weak lensing and galaxy velocities
- Photo-z calibration samples (direct / cross-correlation)

2dF Lensing Survey (2dFLenS)



Outlook

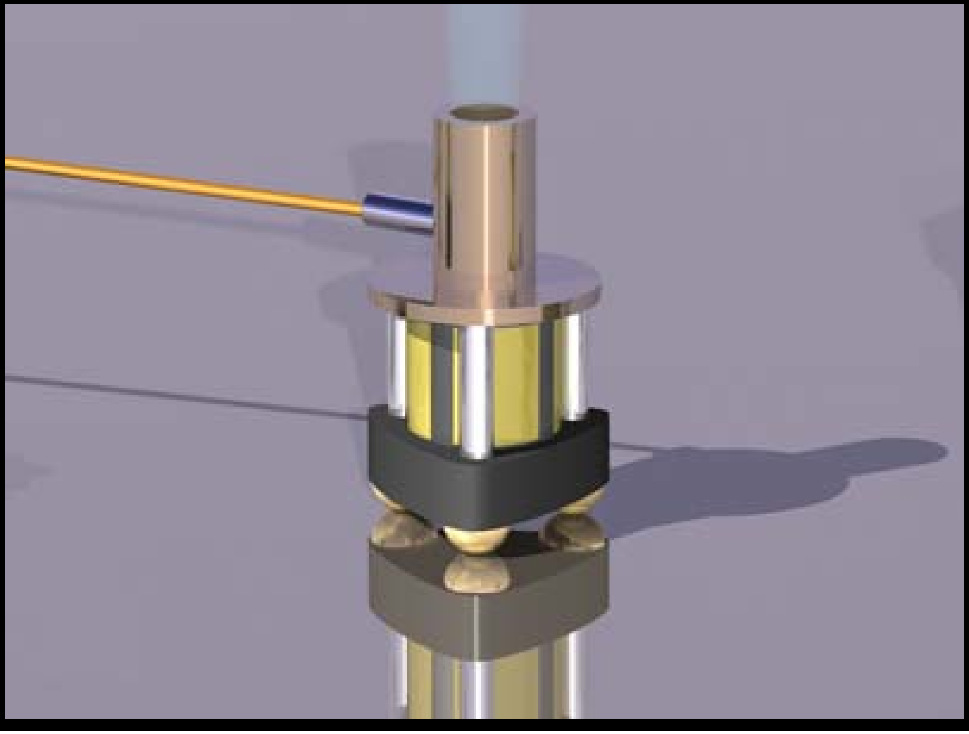
- Cosmological datasets will grow by further orders of magnitude over the next few years (DES, HSC, KiDS, LSST, Taipan, DESI, 4MOST, PFS, Euclid, WFIRST, SKA)

- These data will be a goldmine for advances in cosmology, astrophysics and statistical methods

- "Predictable" science goals include measuring neutrino mass, testing if expansion is matter-dominated at high-z, constraining deviations from GR across scales/redshifts

- "Unpredictable" science goals include observing a signature of modified gravity! (e.g., in a targetted test)

Taipan Galaxy Survey



- Local Universe survey of ~1M galaxy redshifts ($z < 0.3$) and ~100,000 velocities ($z < 0.1$) starting this year
- 1% measurement of H_0 through baryon acoustic peak
- Perform new tests of General Relativity using combined analyses of the density and velocity fields

Challenges

- Observational probes are all systematics-limited such that progress is now very difficult
- Sociology is changing (large collaborations...)
- Specialization means that bridging observations and theory is harder than ever
- No guarantee that we will ever understand the physics of cosmic acceleration!