Cosmic acceleration: new results and perspectives from galaxy surveys

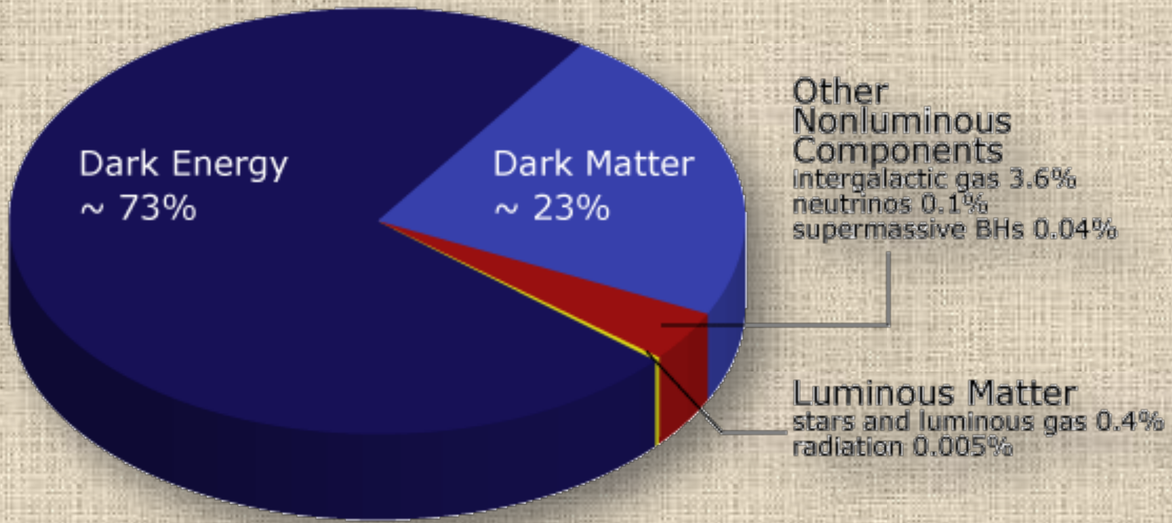
Luigi Guzzo

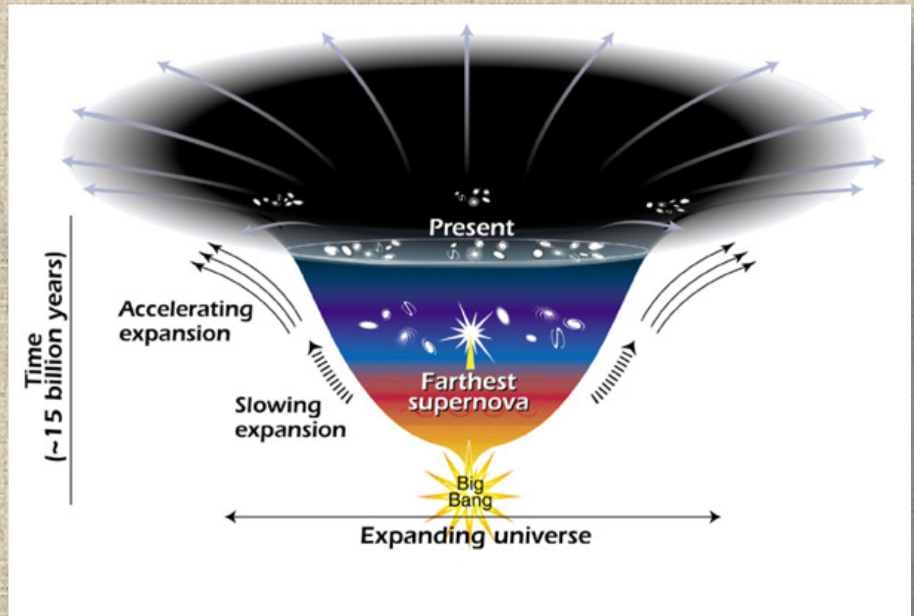
Dipartimento di Fisica - Universita' Statale di Milano

& National Institute of Astrophysics (INAF)

Work presented here has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration, under grant agreement no 291521

The "cosmic pizza" of the 21st century: but who ordered it?



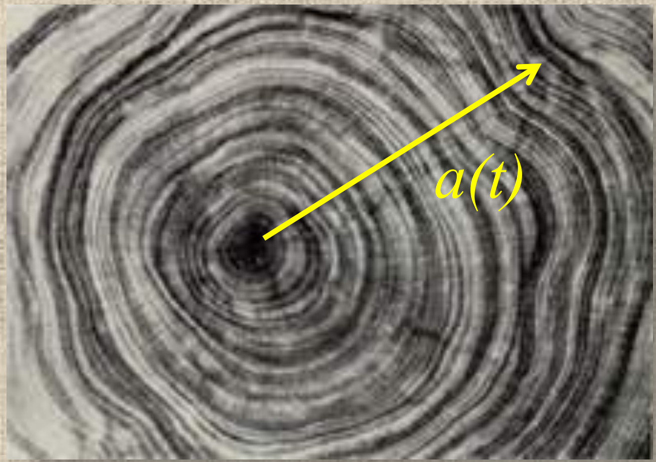


This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.



2011 Nobel Prize

All starts (again) with a "Hubble diagram", which, using Type Ia supernovae (1998), gives a surprising indication…



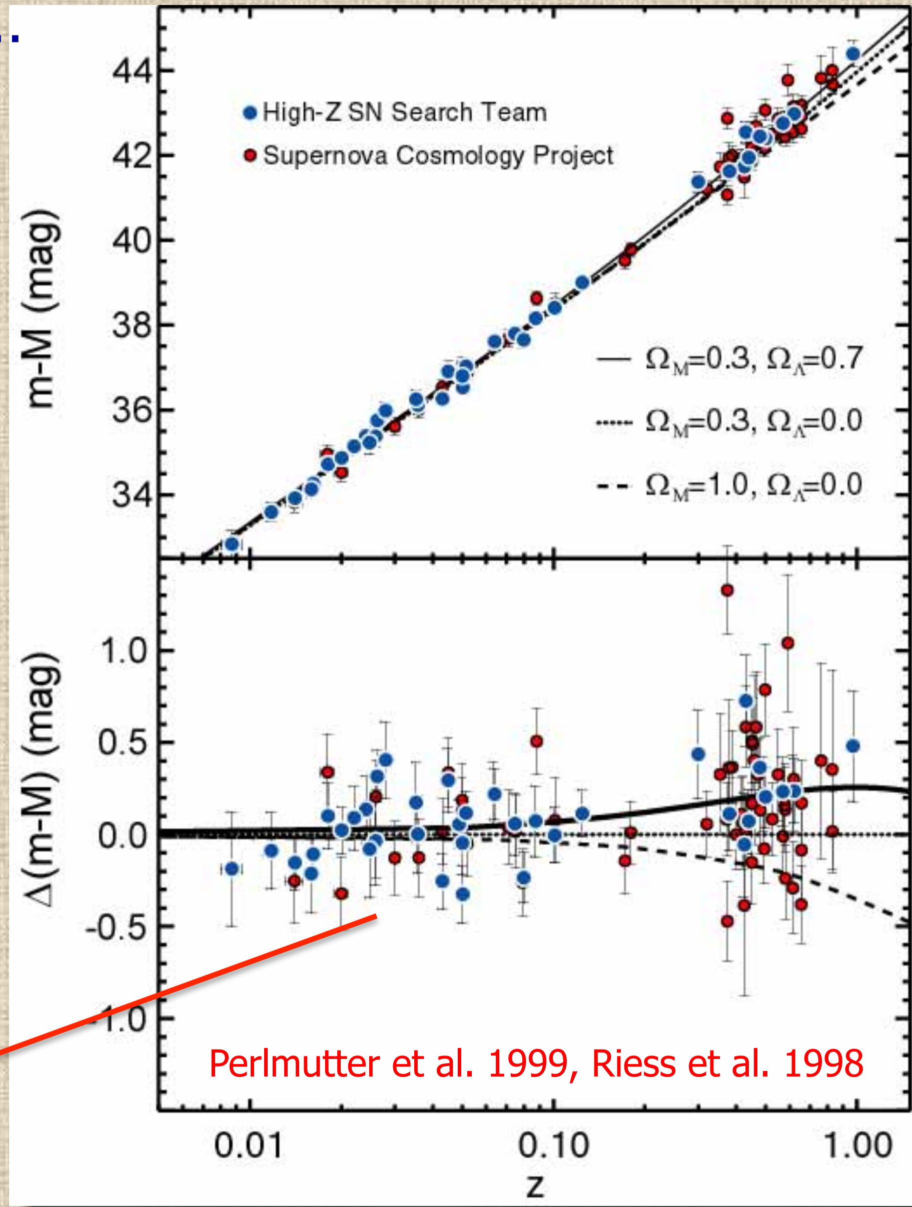
$$H \equiv \frac{\dot{a}}{a}$$

$$\boxed{d_L = (1+z)\int_0^z \frac{dz'}{H(z',\Omega_m,\Omega_\Lambda)}}$$

$$\boxed{H^2(z) = H_0^2\{\Omega_m(1+z)^3 + \Omega_\Lambda\}}$$

~0.3 ~0.7

$\log(Distance\ d_L)$



Perlmutter et al. 1999, Riess et al. 1998

Redshift of spectral lines

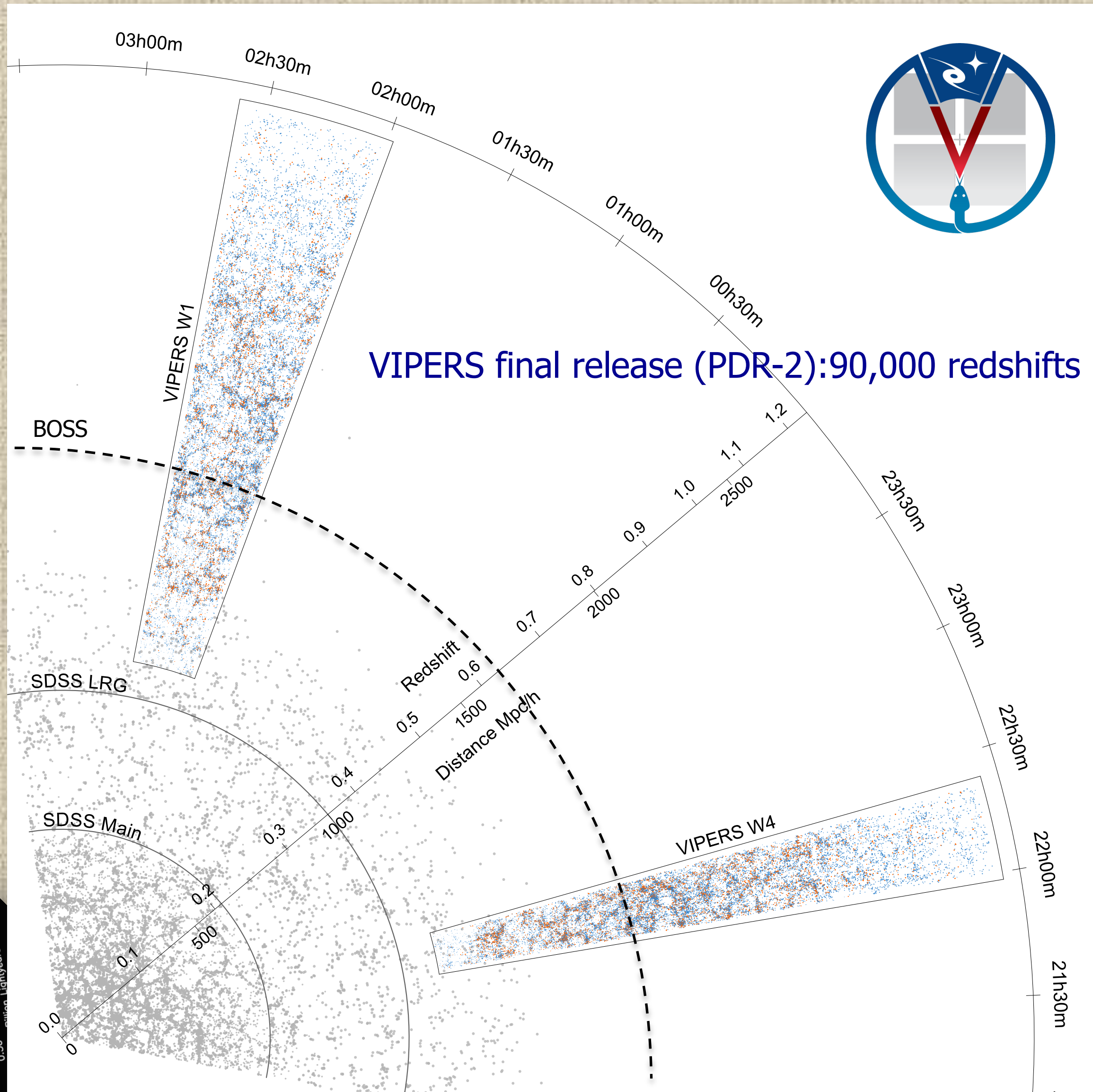
Galaxy redshift surveys: a major pillar of the cosmological model…

State of the art:

- SDSS-III BOSS (e.g. Alam+ 2016)
- WiggleZ (Blake+ 2014)
- **VIPERS** (Guzzo+2014, Scodeggio+ 2017)

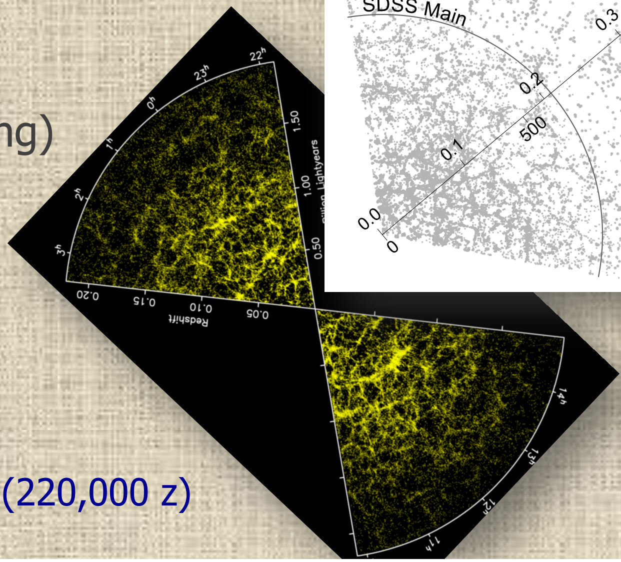
Future:

- SDSS-IV eBOSS (ongoing)
- DESI (2019-)
- **Euclid** (2020+)



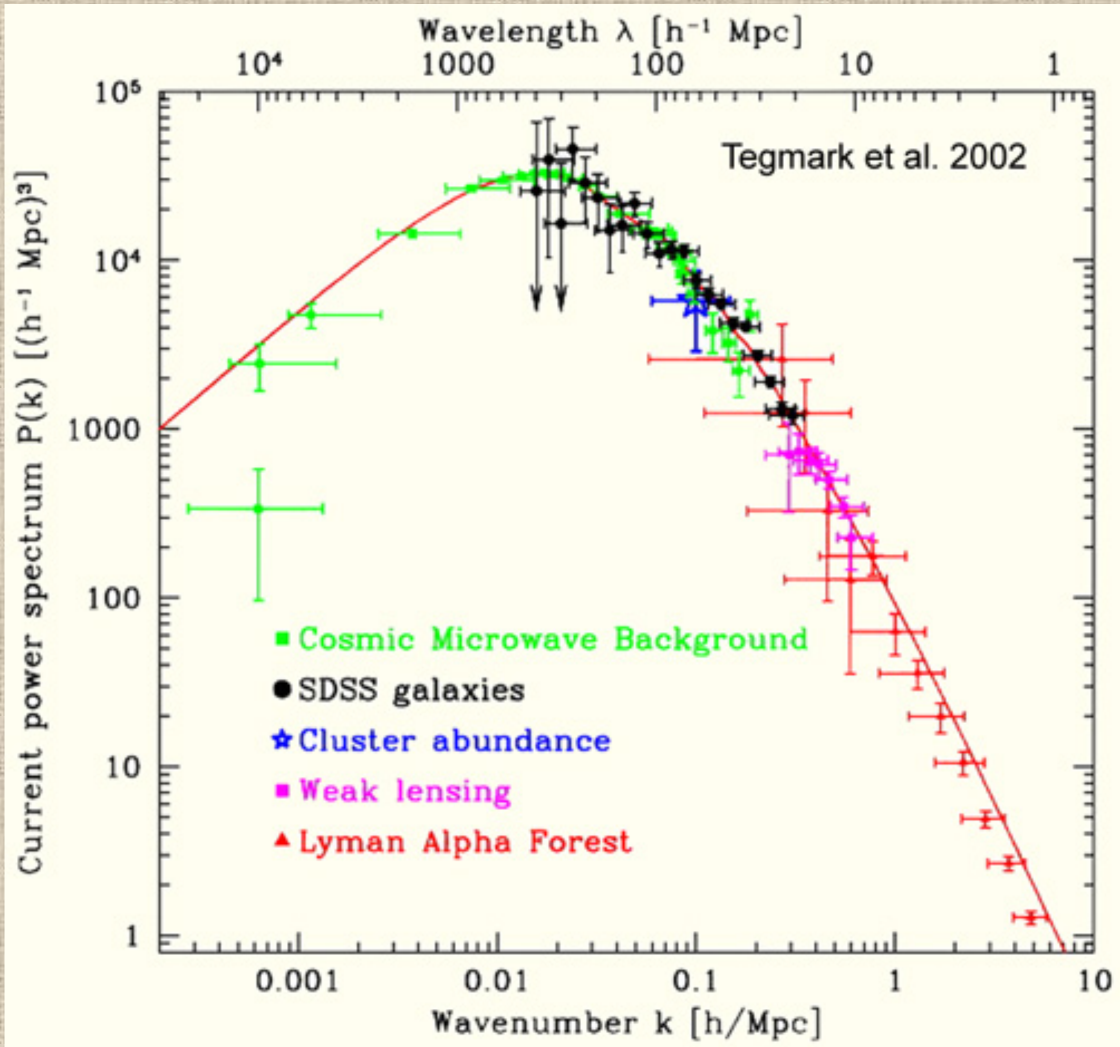
VIPERS final release (PDR-2):90,000 redshifts

(arXiv 1611.07048)

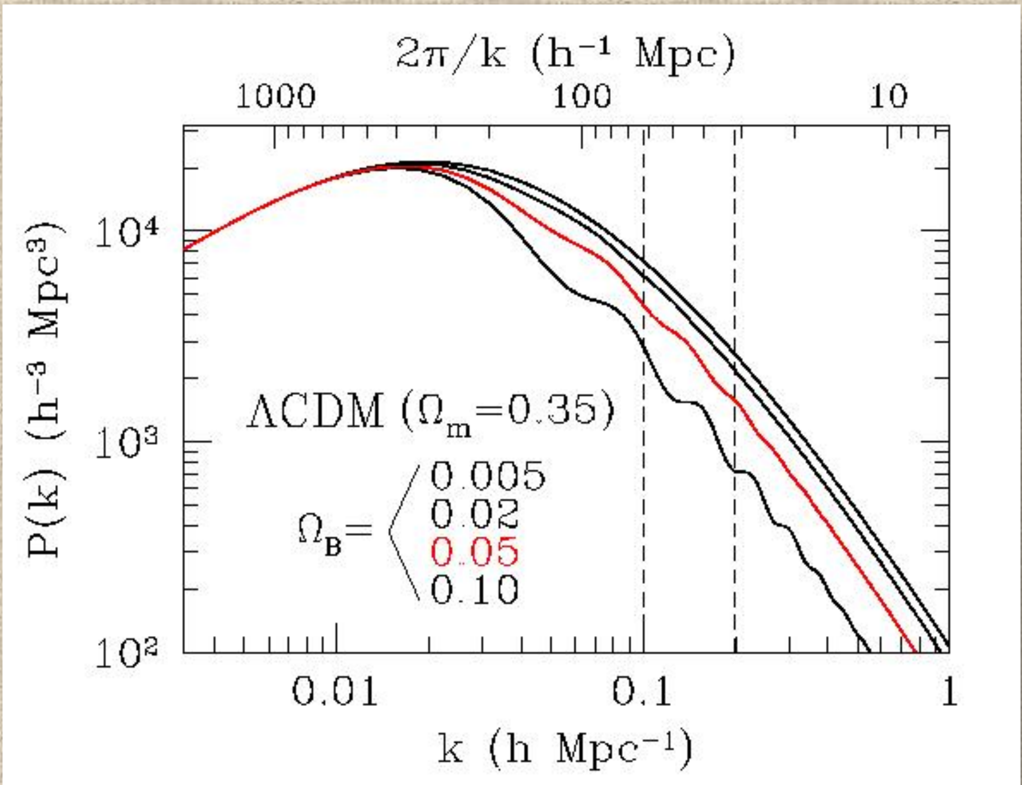


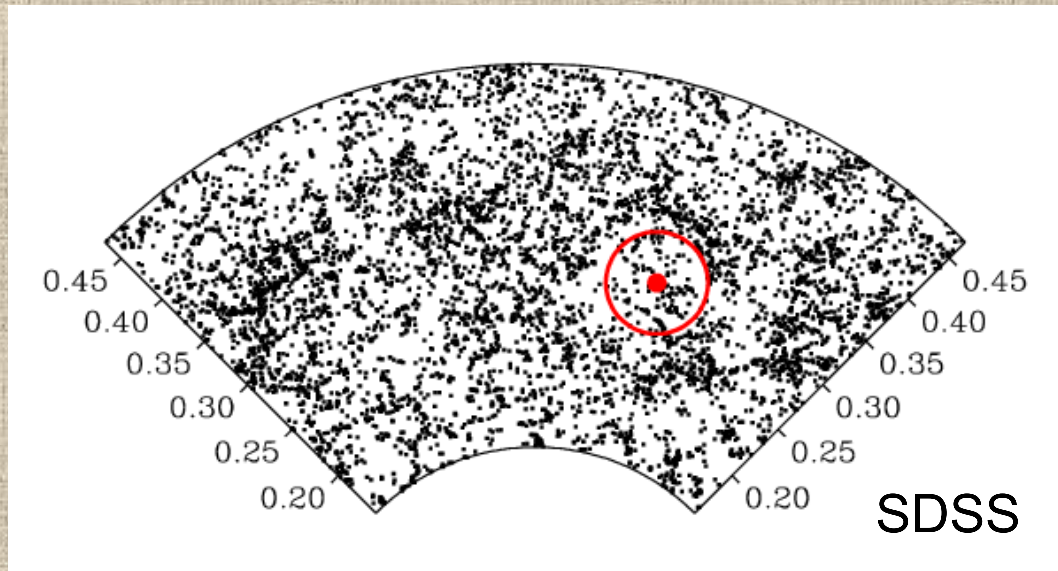
2dFGRS (220,000 z)

The clustering power spectrum: a probe of the underlying cosmology



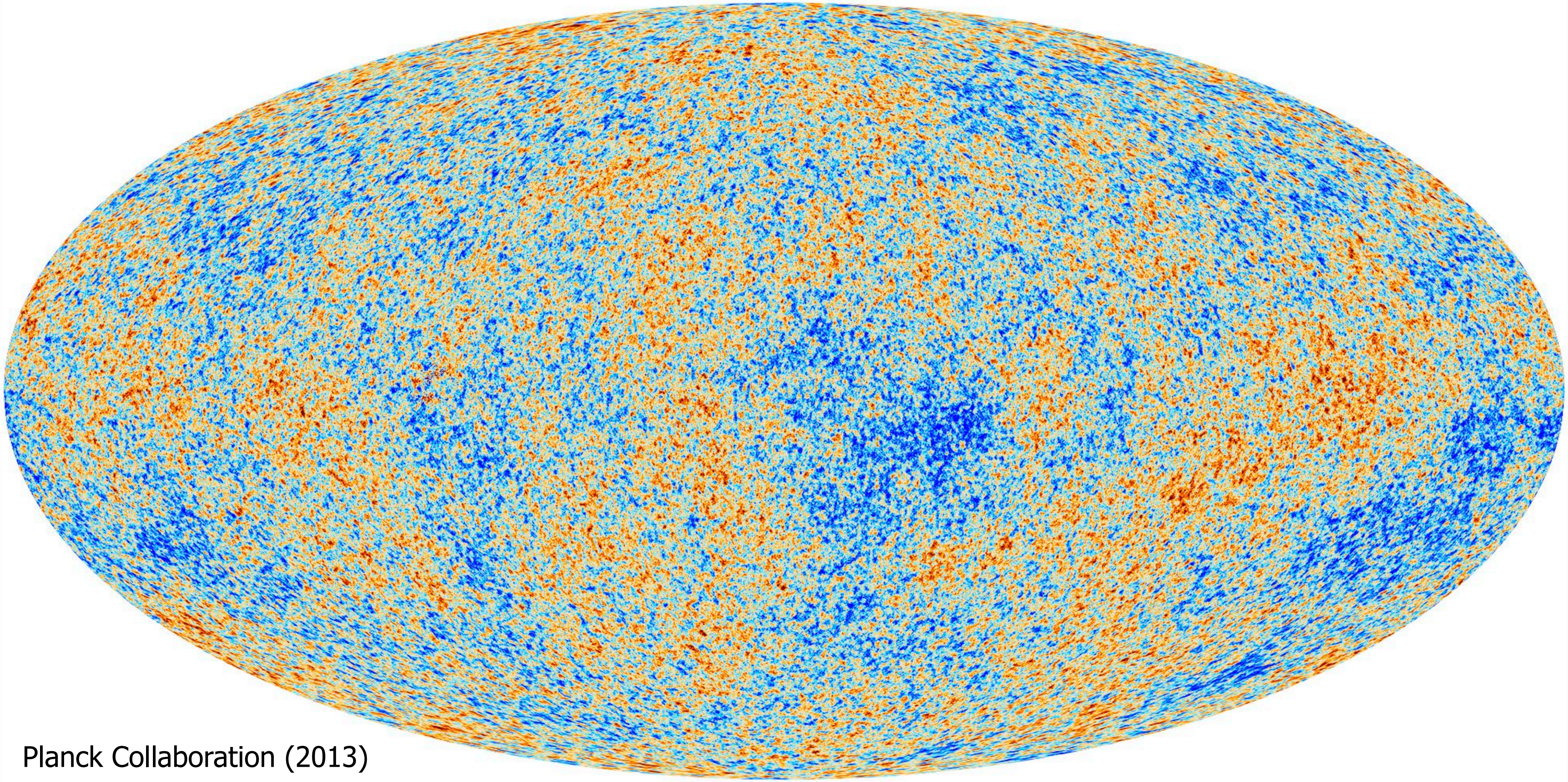
Baryonic Acoustic Oscillations: a standard ruler to measure H(z)





D. Eisenstein 2007

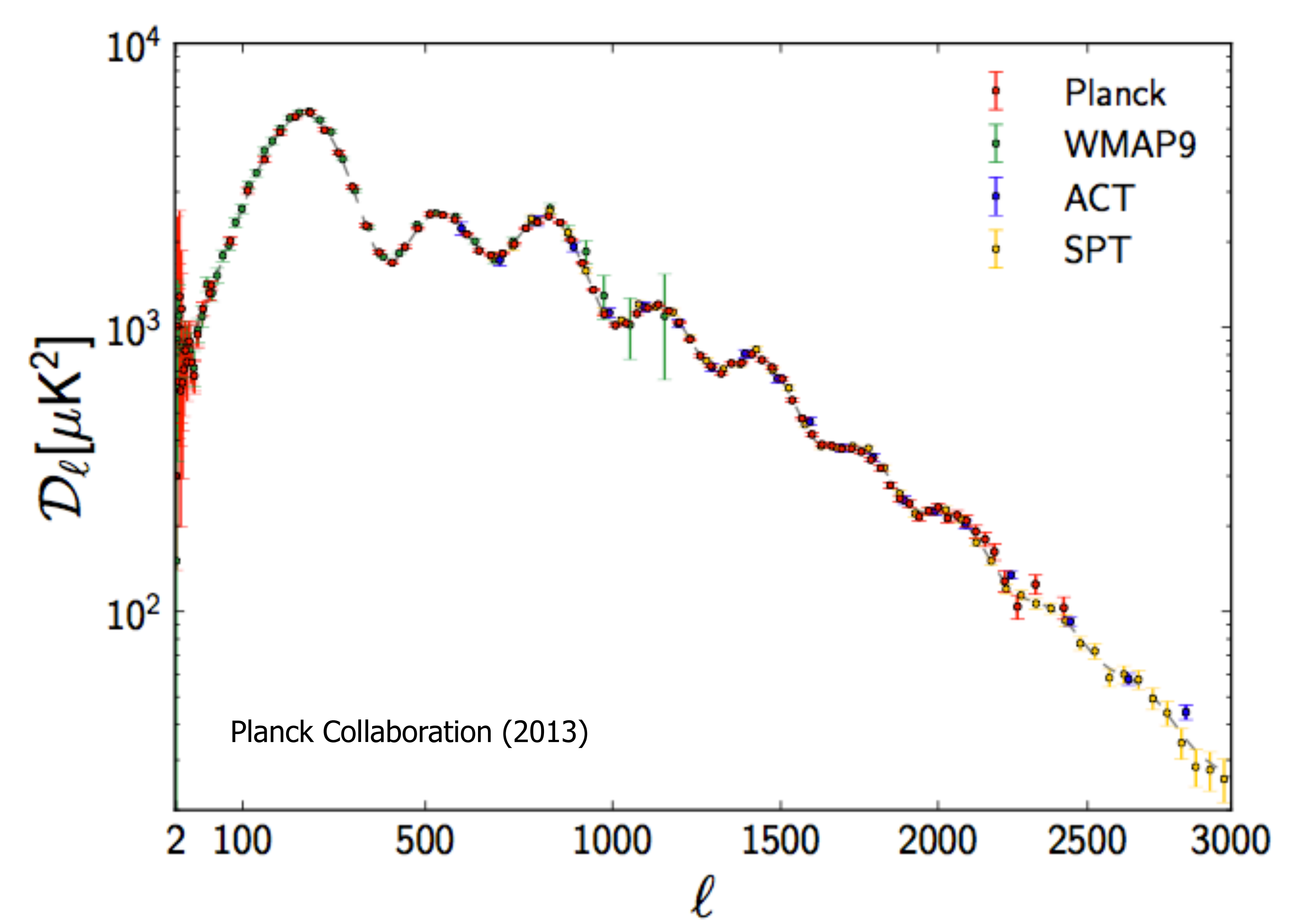
Inhomogeneities in the Cosmic Microwave Background



Planck Collaboration (2013)

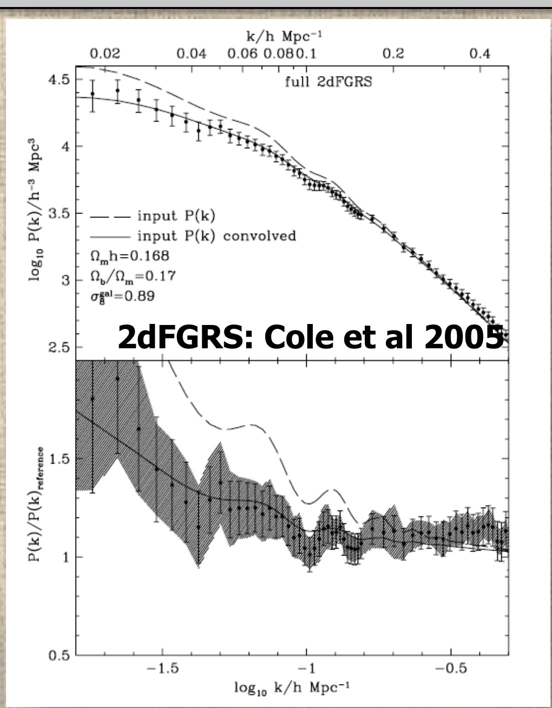
Fluctuations on all scales: however, one characteristic angular scale emerges

Baryonic Acoustic Oscillations in the CMB

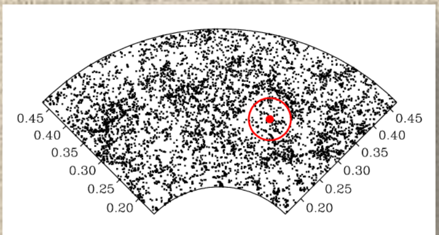


BAO in galaxy redshift surveys: first detected in 2005

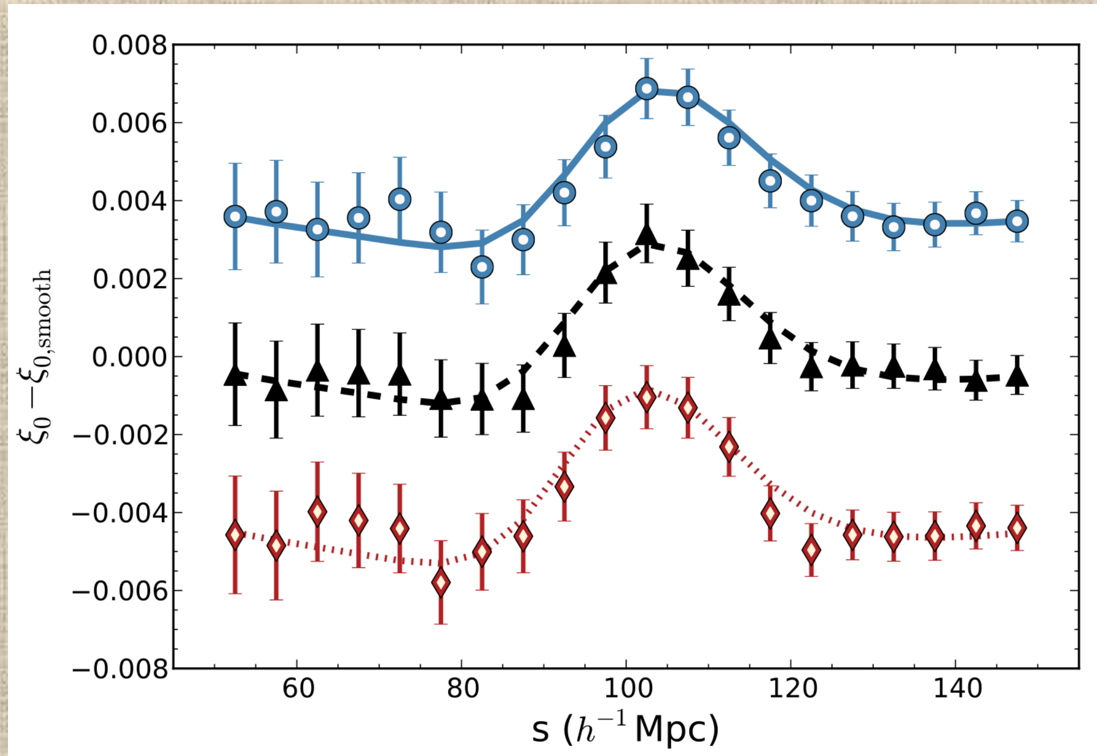
Fourier Space (wiggles):



2dFGRS: Cole et al 2005

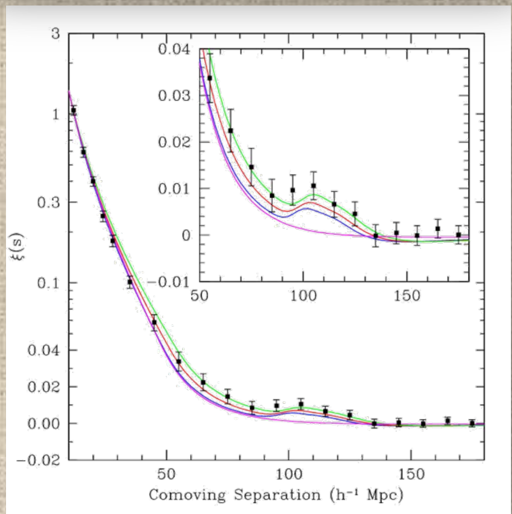


2016: Final measurement from BOSS-DR12



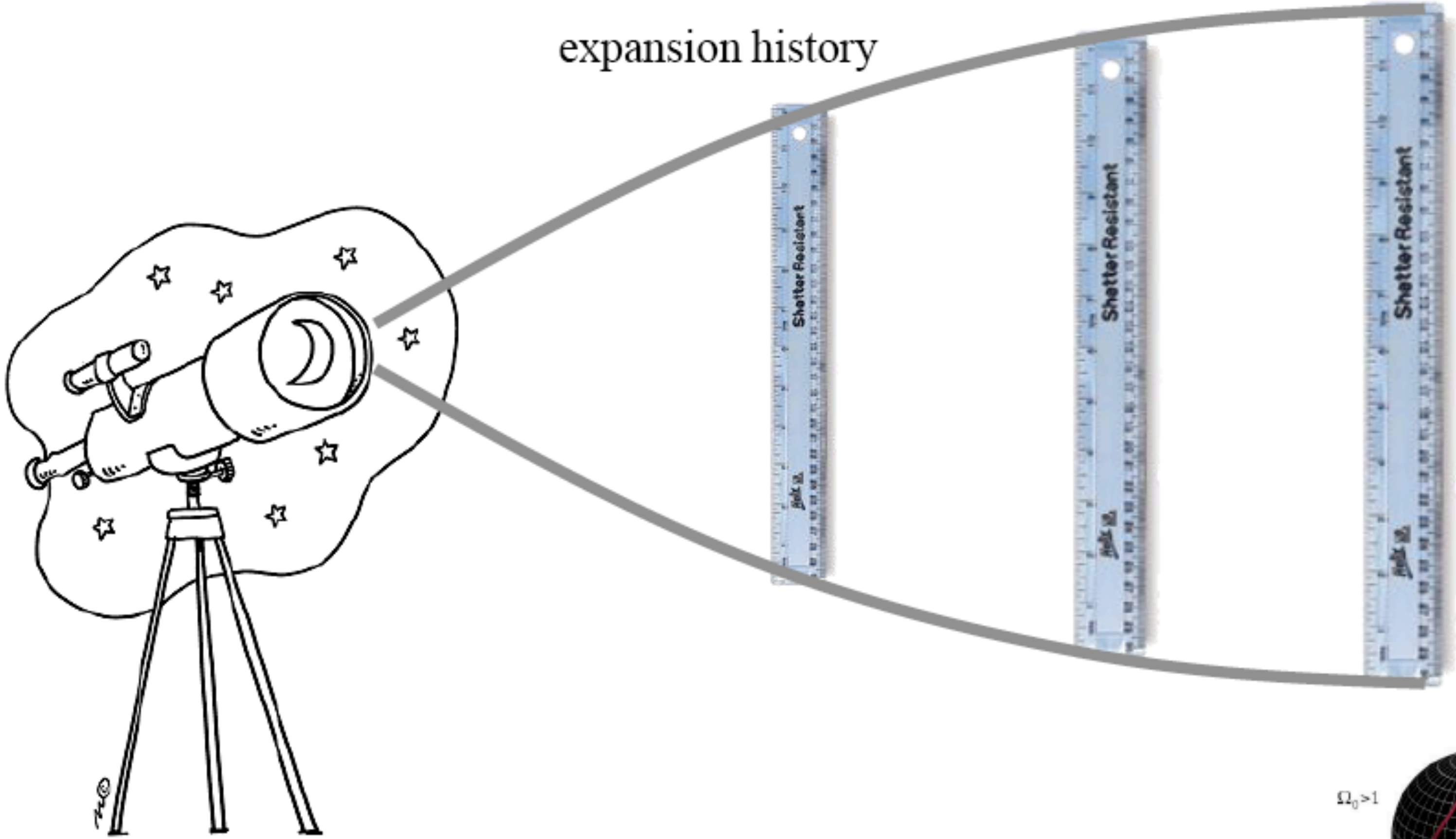
(BOSS Collaboration 2016, arXiv:1607.03155)

Configuration Space (BAO peak):

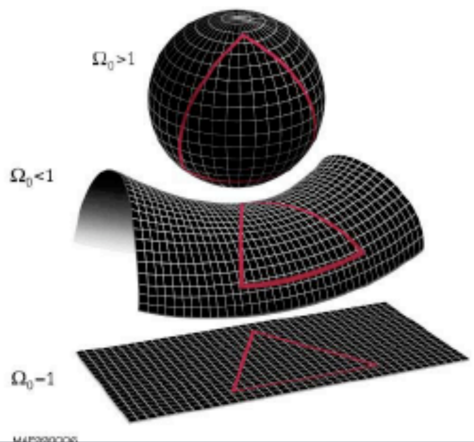


SDSS: Eisenstein et al 2005

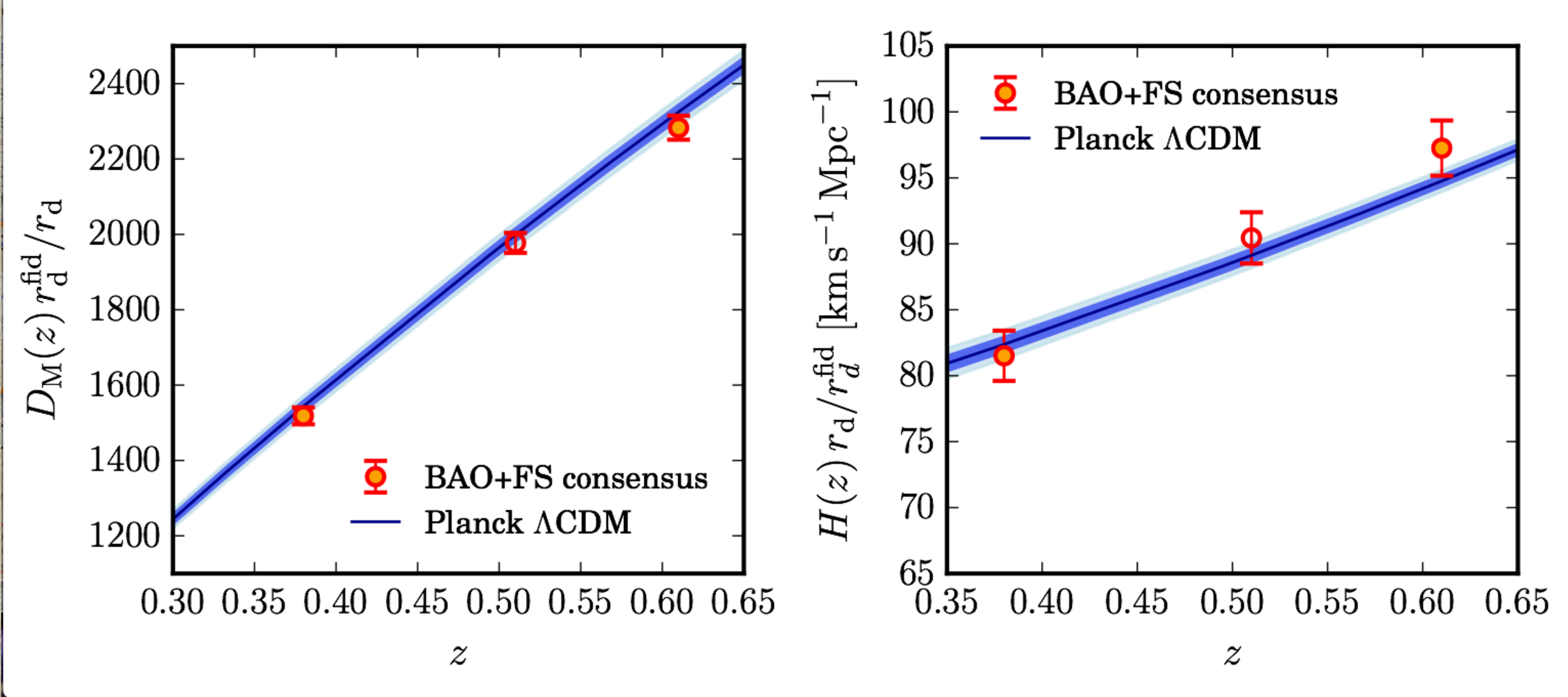
Baryonic Acoustic Oscillations: measure H(z) from redshift surveys



Give $D_A(z)$ and $H(z)$

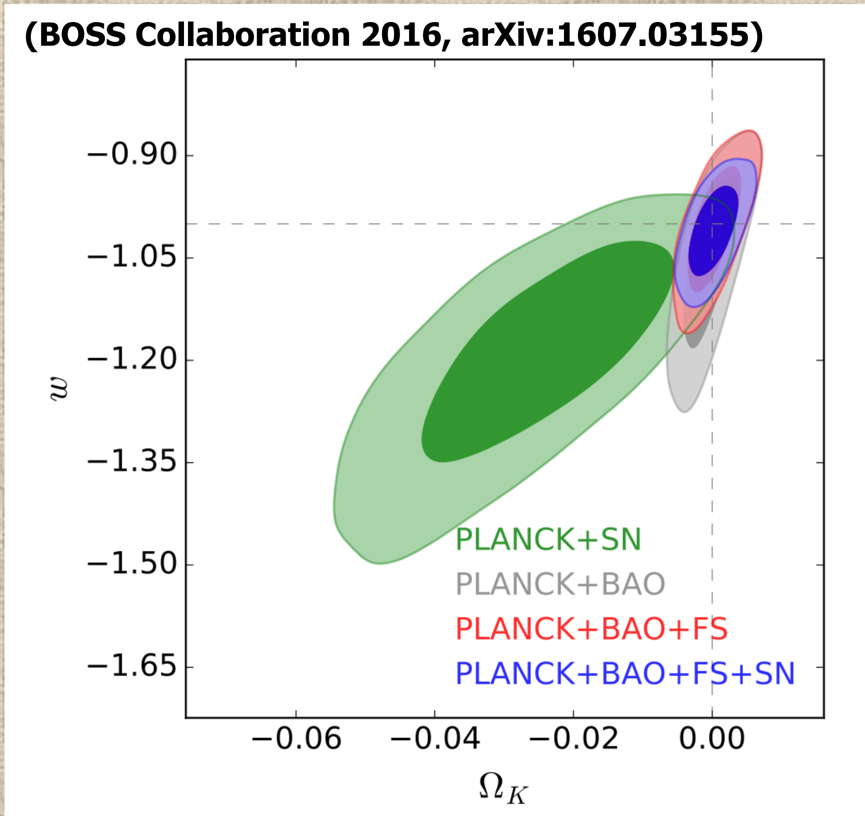


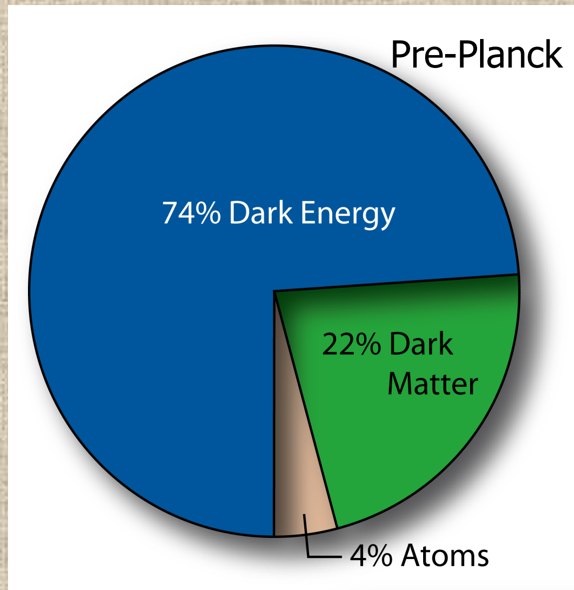
Probe expansion history with BAO

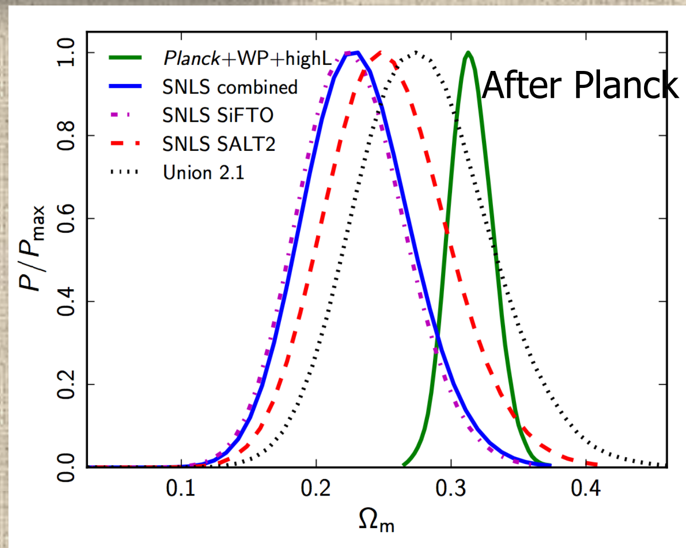


(BOSS Collaboration 2016)

Cosmic (quasi) concordance







(Planck Collaboration 2013, paper XVI)

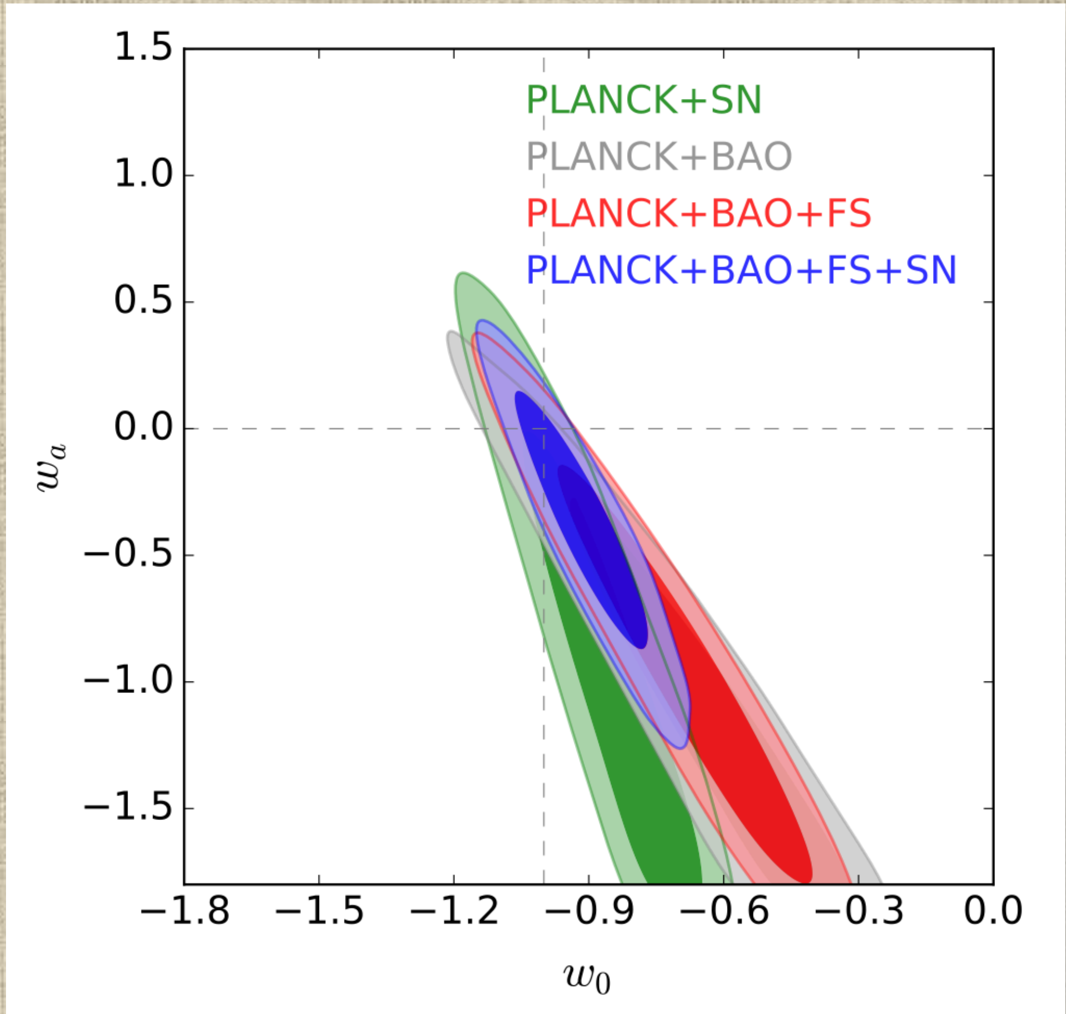
If leaving ***w*** as a free parameter (here with curvature), ***w=-1*** (cosmological constant) remains favoured

Λ is too small and fine-tuned: an evolving equation of state $w(a)$?

Parameterizing our ignorance:

$$w(a) = w_0 + w_a(1-a)$$

[a = scale factor of the Universe = $(1+z)^{-1}$]



(BOSS Collaboration 2016, arXiv:1607.03155)

But Lambda [or dark energy w(z)] is not the end of the story…

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

?

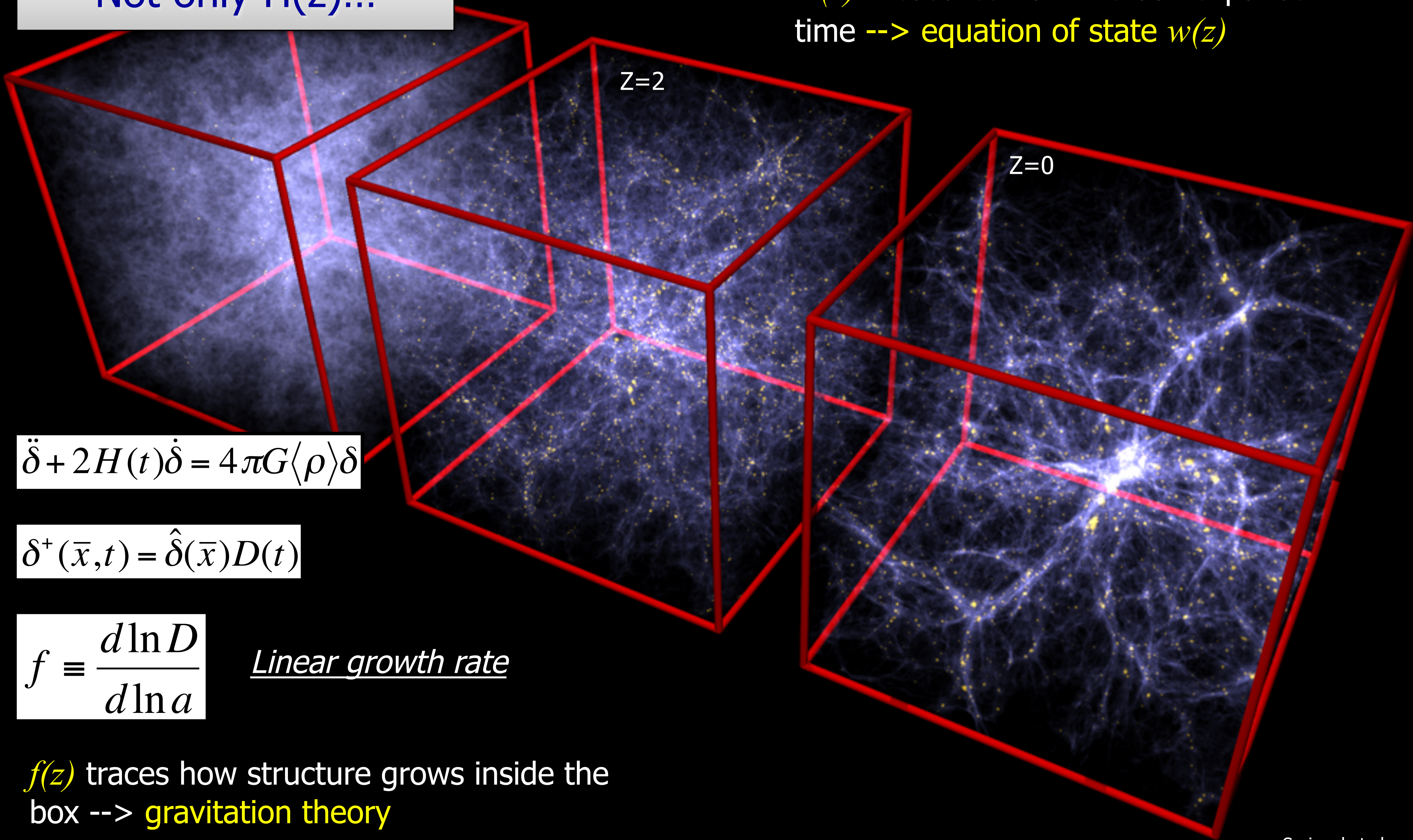
Modify gravity theory [e.g. $R \rightarrow f(R)$]

Add dark energy

"…the Force be with you"

Not only H(z)…

H(z) measures how the box expands with time --> equation of state *w(z)*



$$\ddot{\delta} + 2H(t)\dot{\delta} = 4\pi G\langle\rho\rangle\delta$$

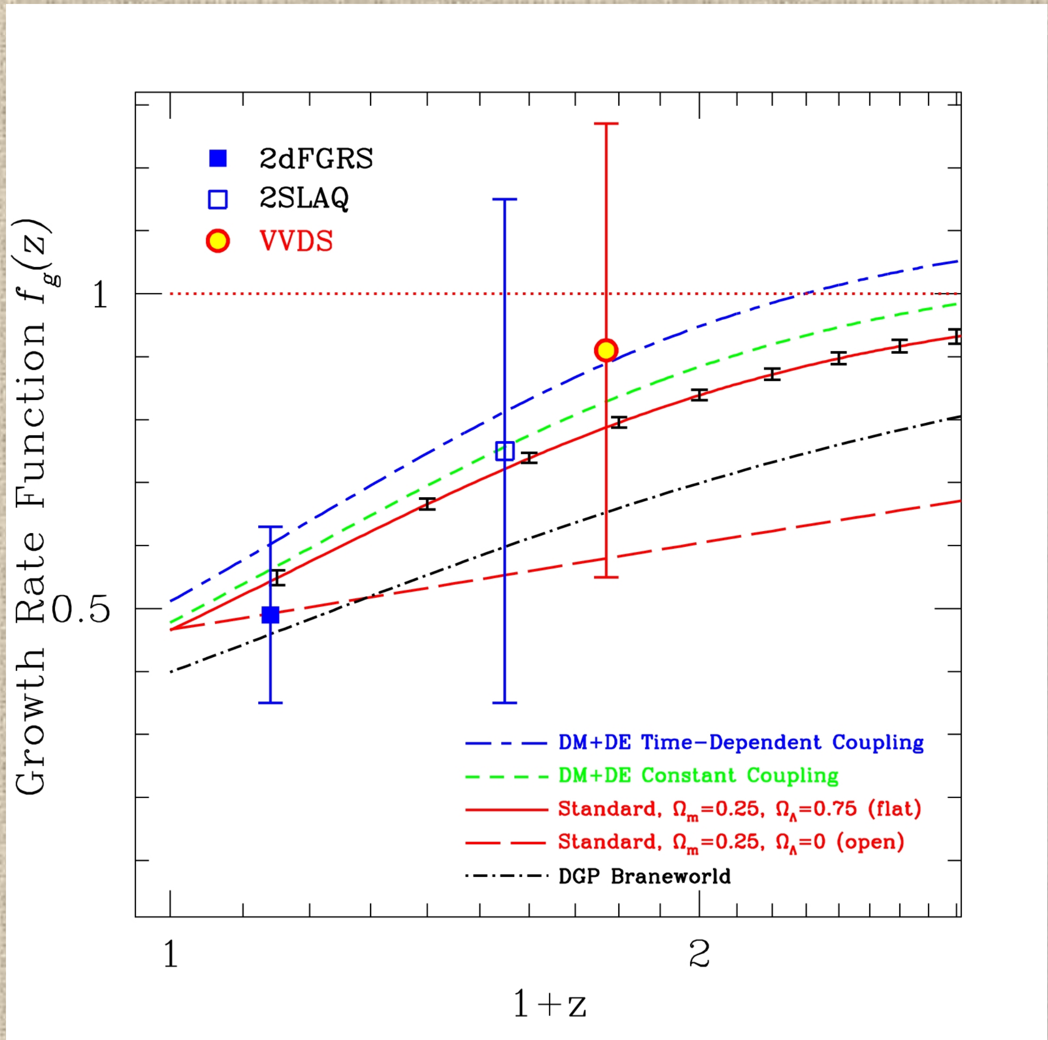
$$\delta^{+}(\bar{x},t) = \hat{\delta}(\bar{x})D(t)$$

$$f \equiv \frac{d\ln D}{d\ln a}$$

<u>*Linear growth rate*</u>

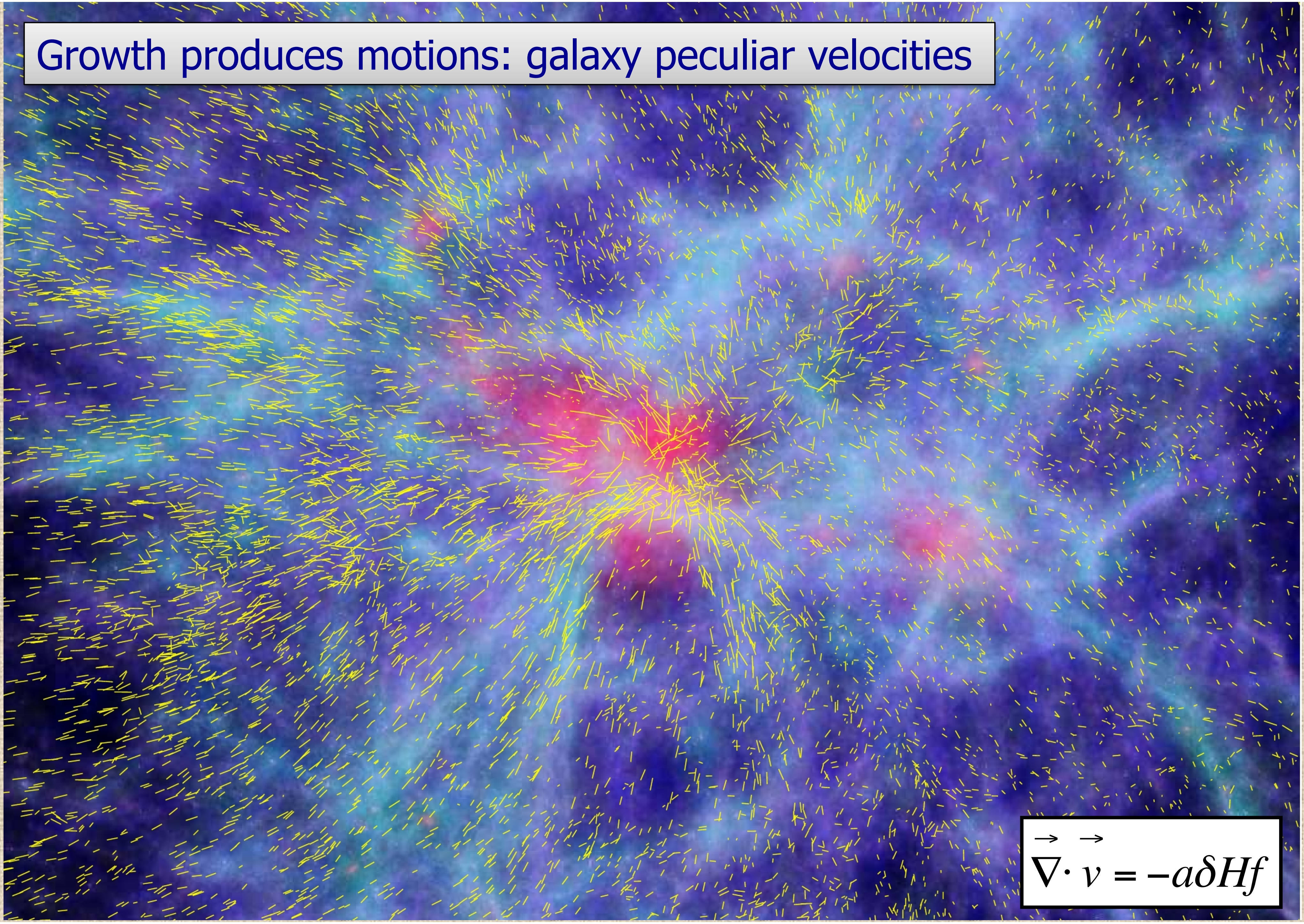
f(z) traces how structure grows inside the box --> gravitation theory

Growth rate of structure probes modified gravity



Guzzo et al., Nature 451, 541 (2008)

Growth produces motions: galaxy peculiar velocities

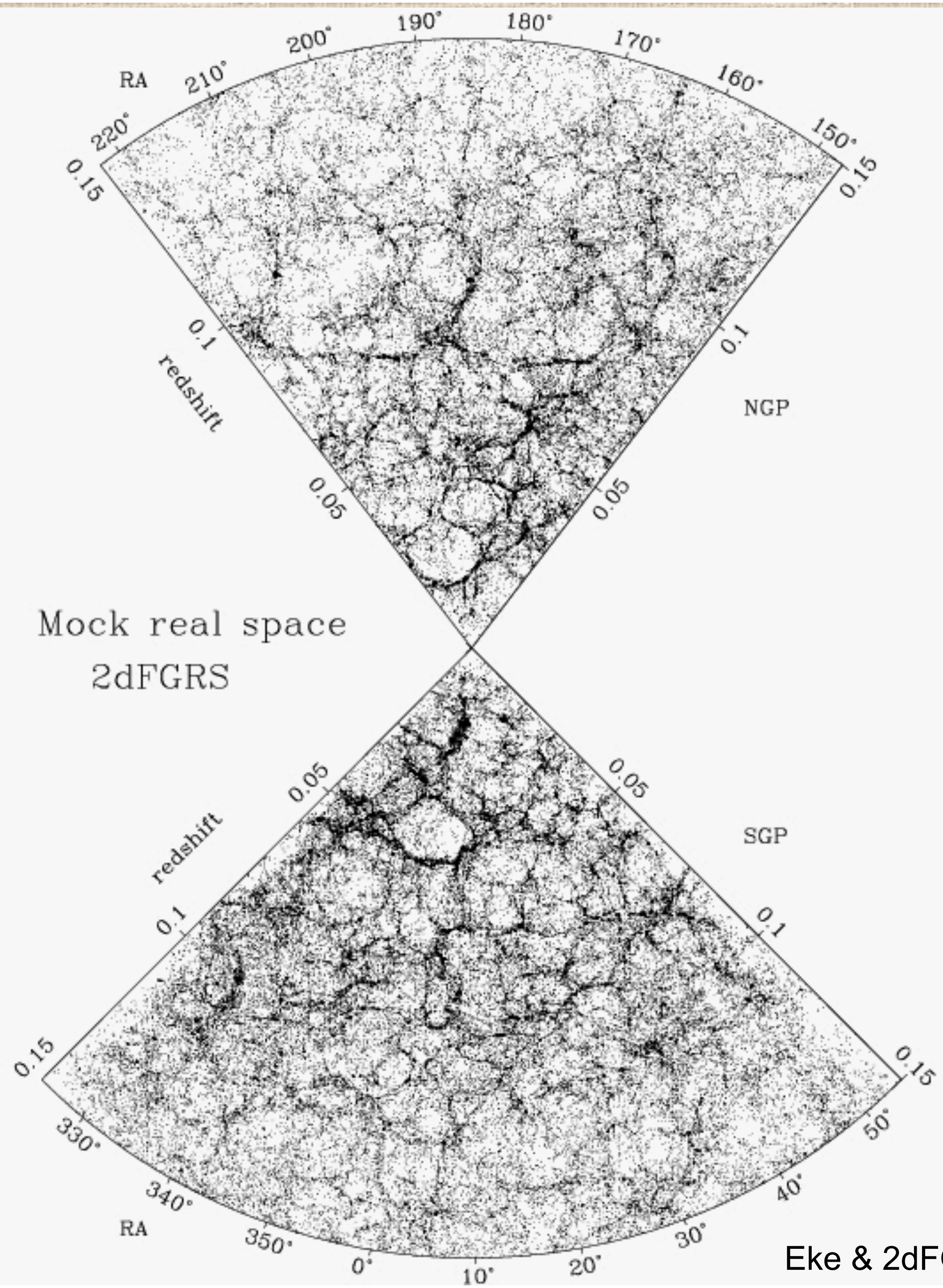


$$\vec{\nabla} \cdot \vec{v} = -a\delta H f$$

Growth produces peculiar velocities, which manifest themselves in galaxy redshift surveys as *redshift-space distortions*

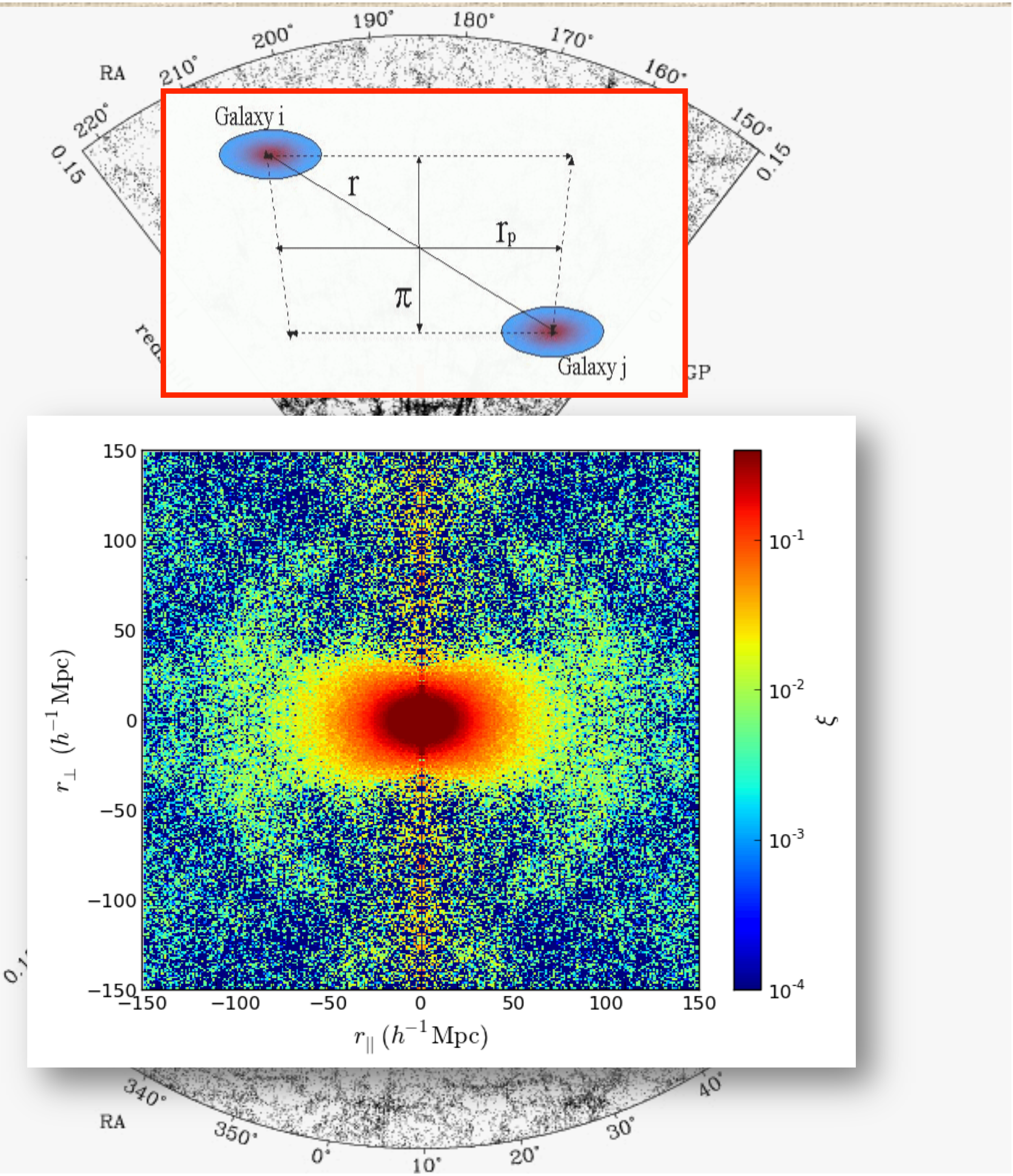
real space

(Kaiser 1987)



Eke & 2dFGRS 2003

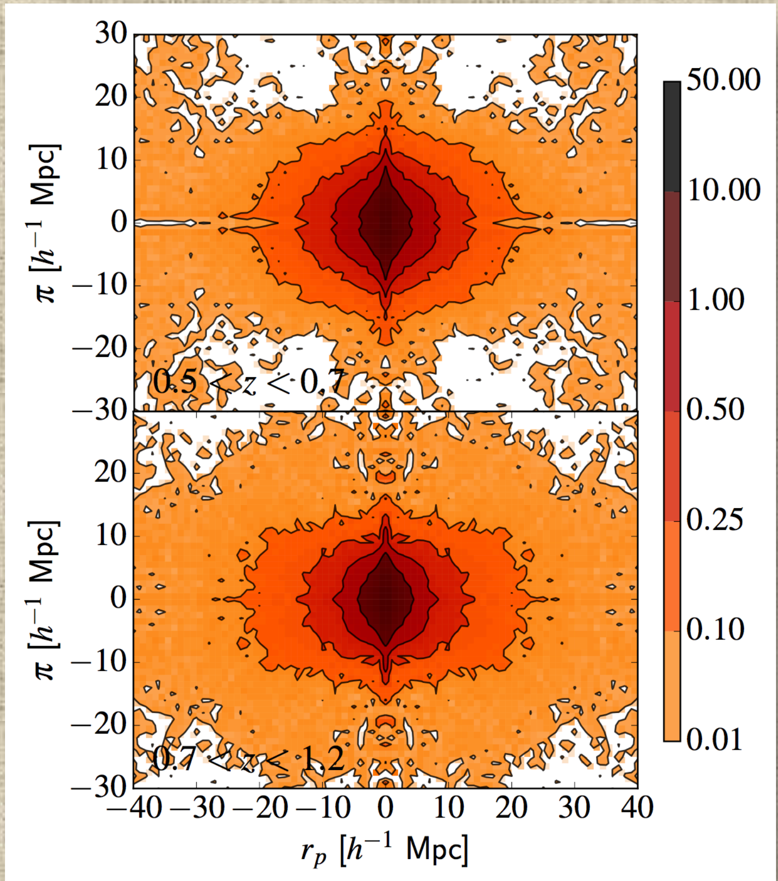
Growth produces peculiar velocities, which manifest themselves in galaxy redshift surveys as *redshift-space distortions*

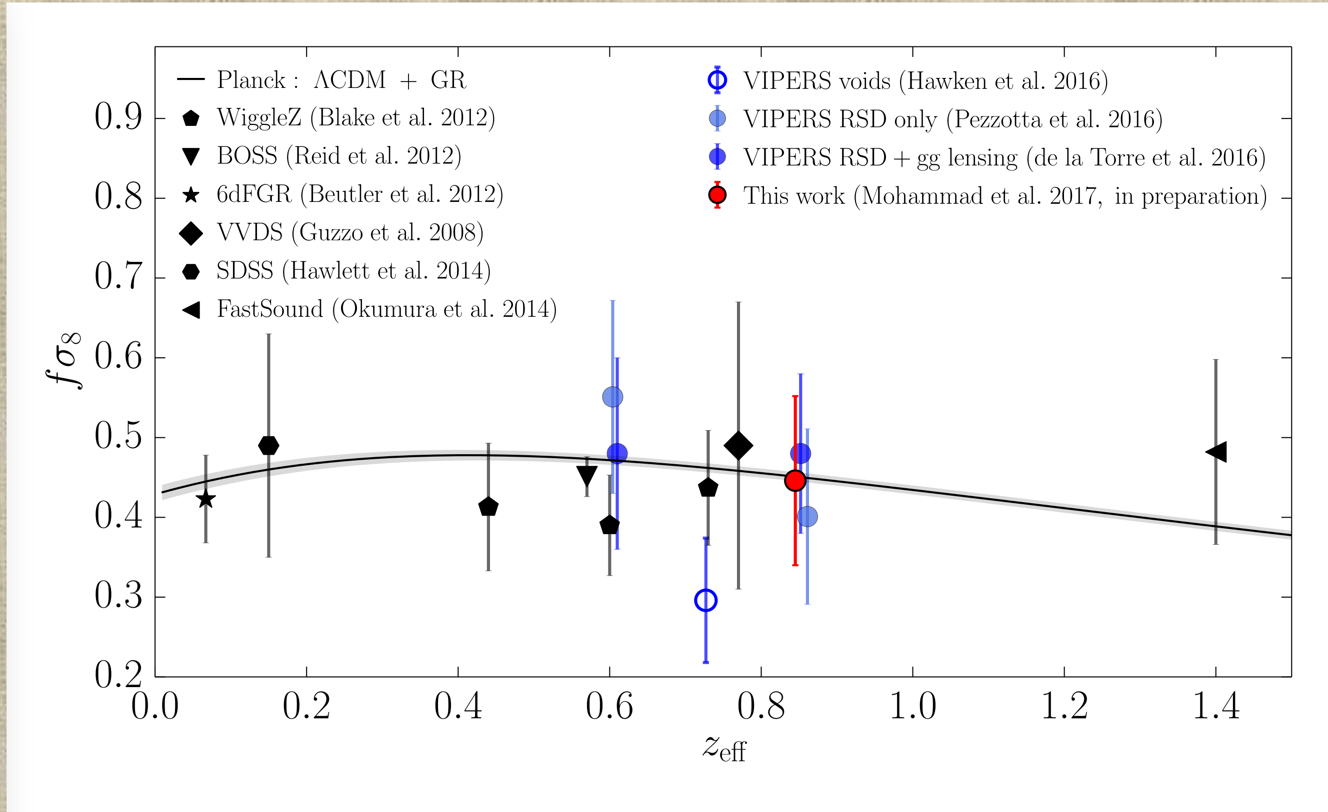


redshift space

(Kaiser 1987)

Testing gravity with redshift-space distortions

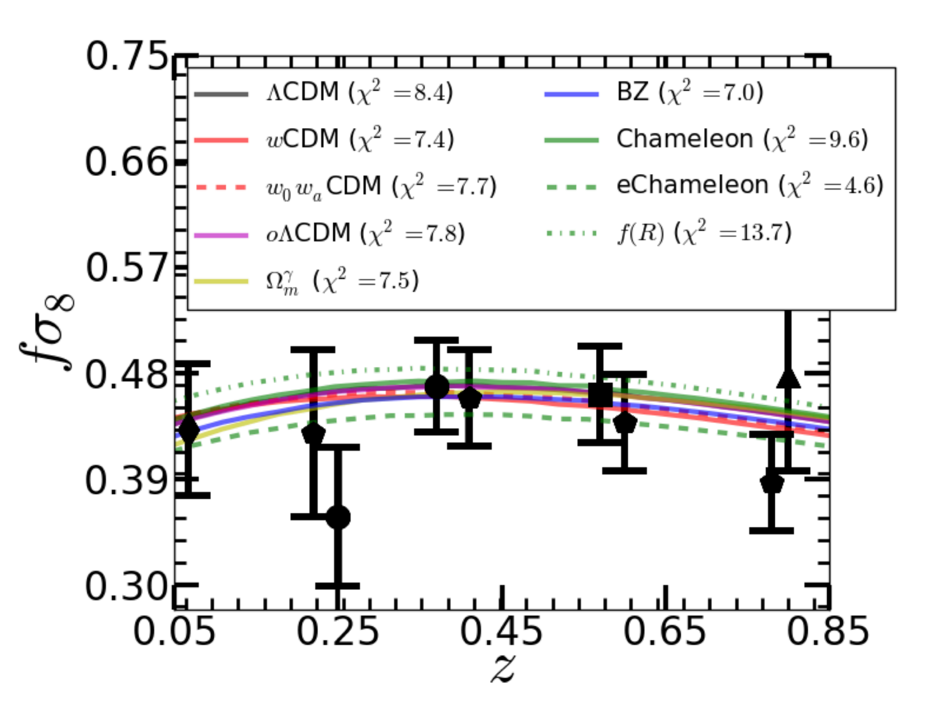


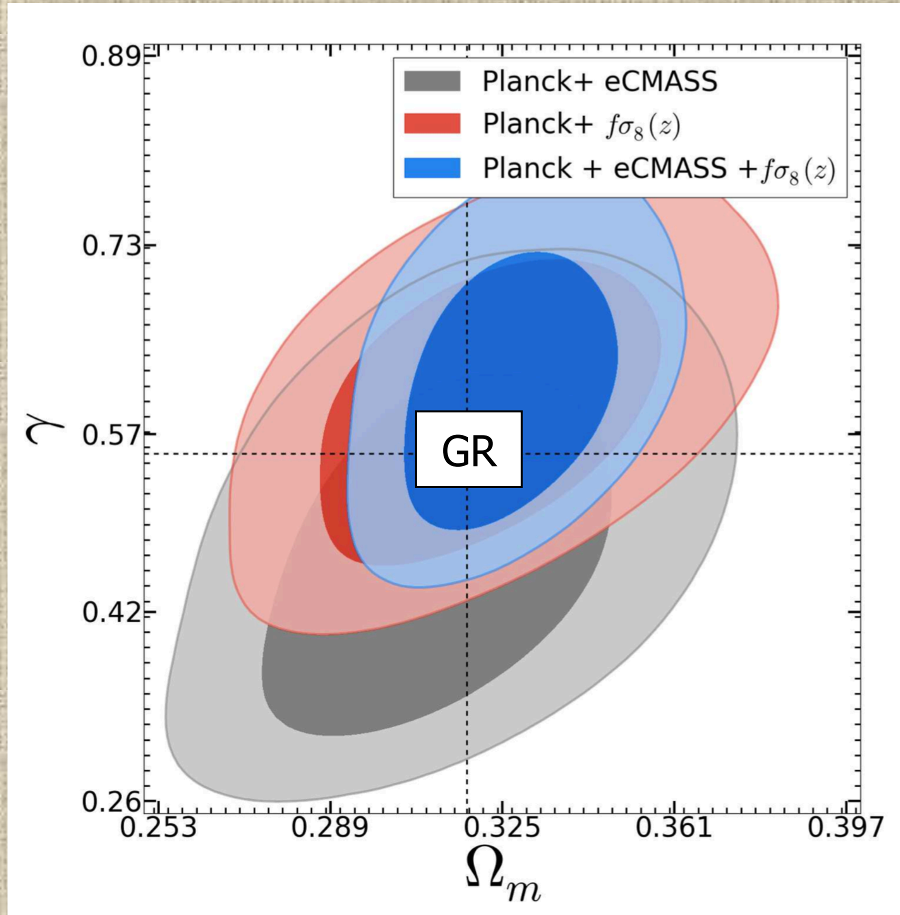


VIPERS PDR-2 (Pezzotta+ 2017; de la Torre+ 2017; Hawken+ 2017; Mohammad+ 2017; Wilson 2017)

Testing gravity with redshift-space distortions

(Alam, Ho & Silvestri 2016)





Galaxy clustering: a primary probe to answer the high-level questions…

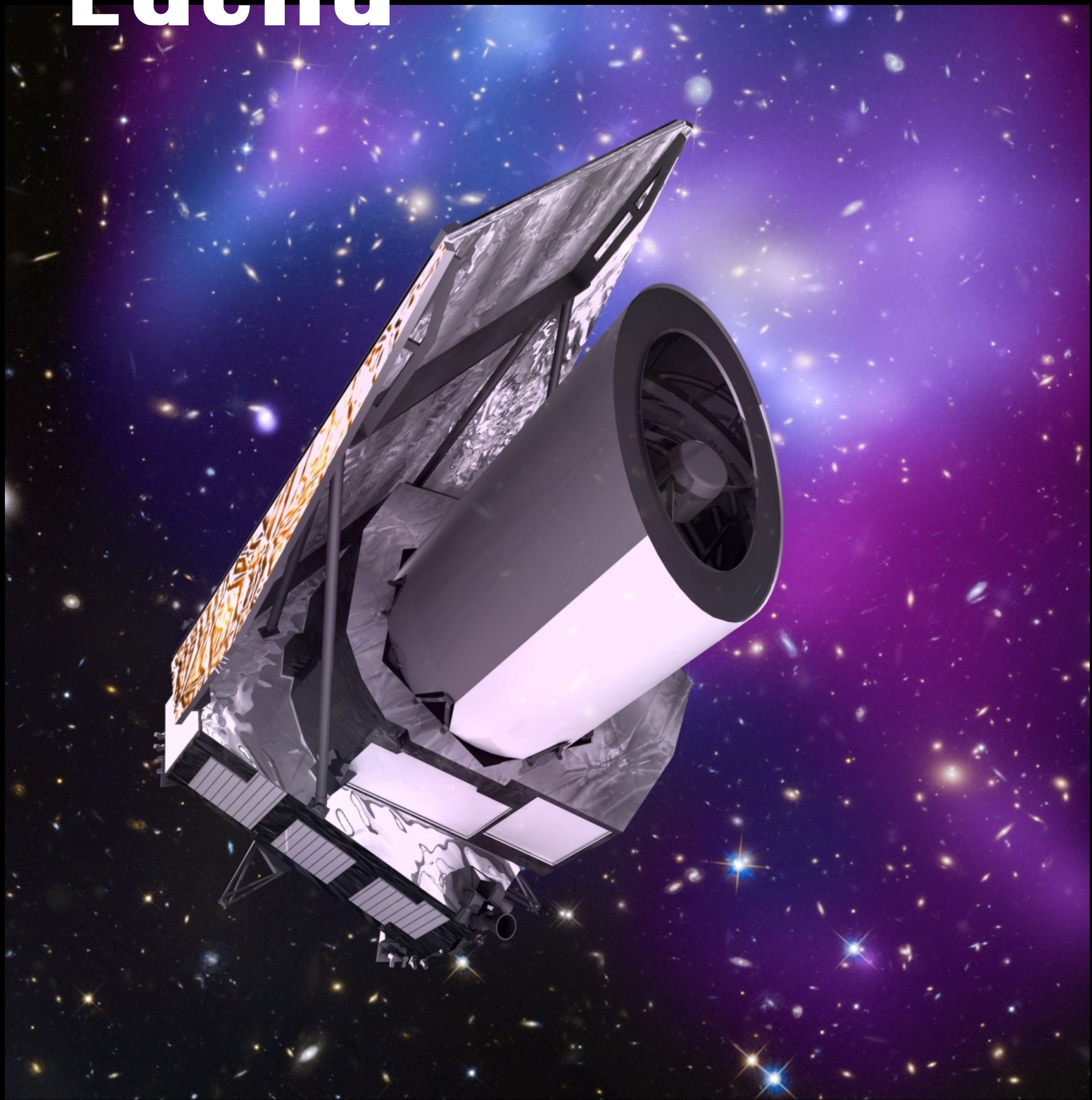
- Nature of Dark Matter ?
- Nature of Dark Energy ?
- Behaviour of gravity at the largest scales (did Einstein have final word)?
- Physics of the initial conditions (inflation) ?
- Neutrino mass ?

Implications for physics

→ the Standard Model of cosmology (ΛCDM)

→ the Standard Model of particle physics

Euclid



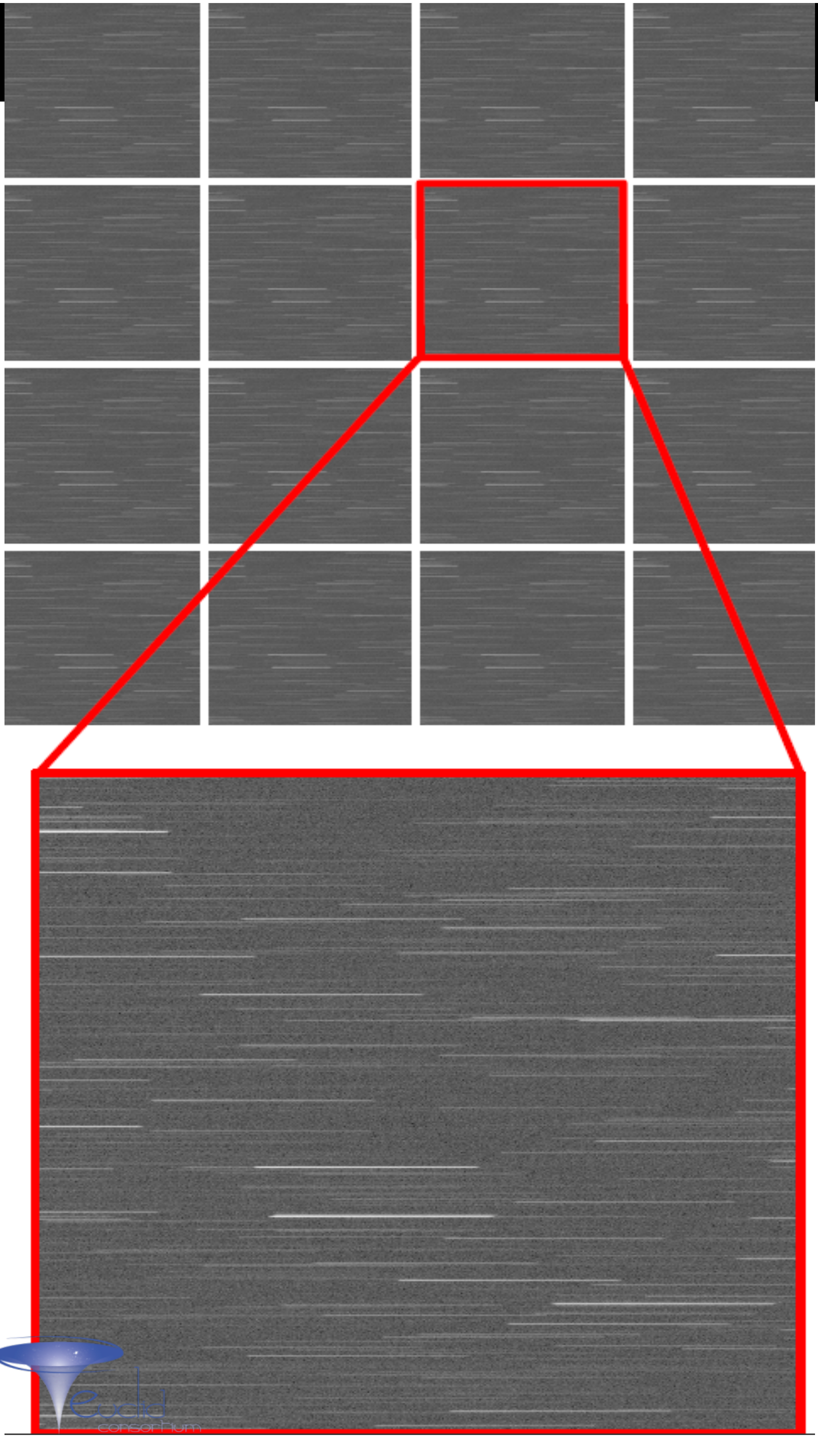
- An ESA mission with extra contribution by national agencies (France & Italy among main contributors as lead countries of parent DUNE +SPACE projects)

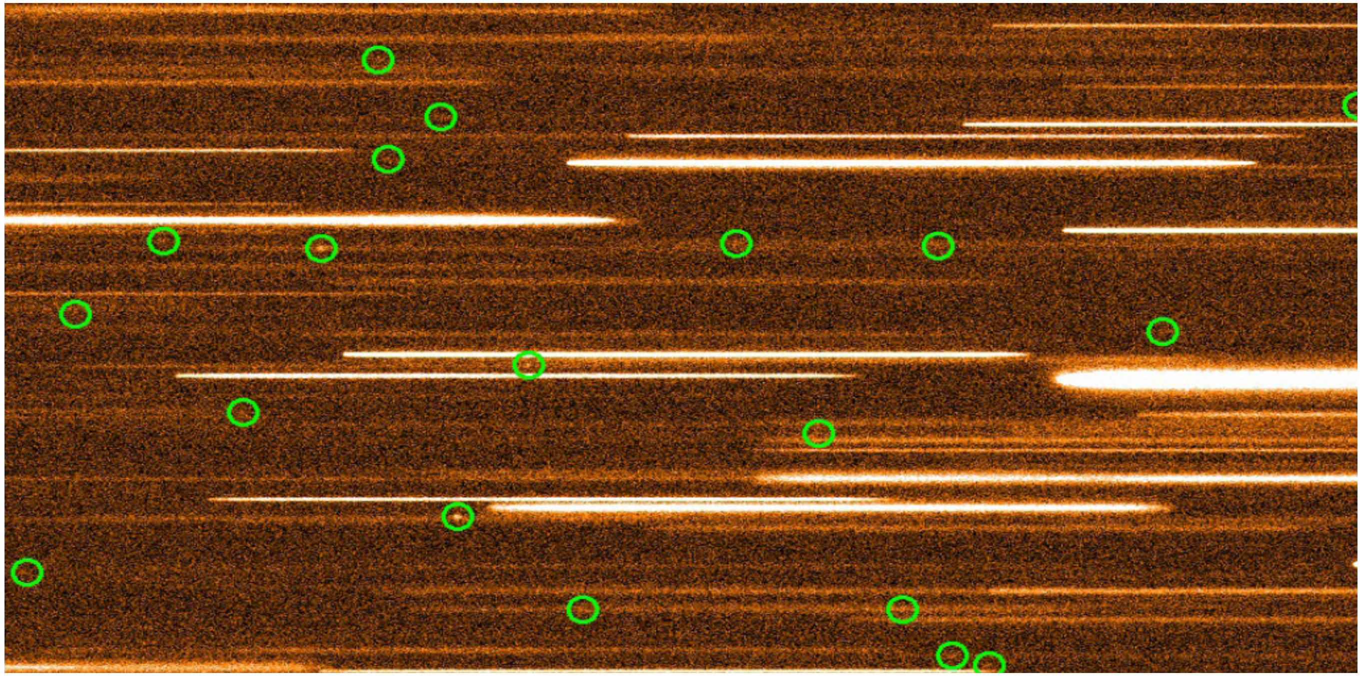
- Euclid Consortium Lead: Yannick Mellier (IAP)

- 1.2 m telescope
- Visible imaging (1 band)
- Infrared imaging (Y,J,H)
- Infrared slitless spectroscopy
- Launch 2020

- 15,000 deg^2 survey
- Images for 2×10^9 galaxies
- Spectra for ~5×10^7 galaxies ($0.9<z<1.8$)

Euclid NISP spectroscopy simulations (2015)

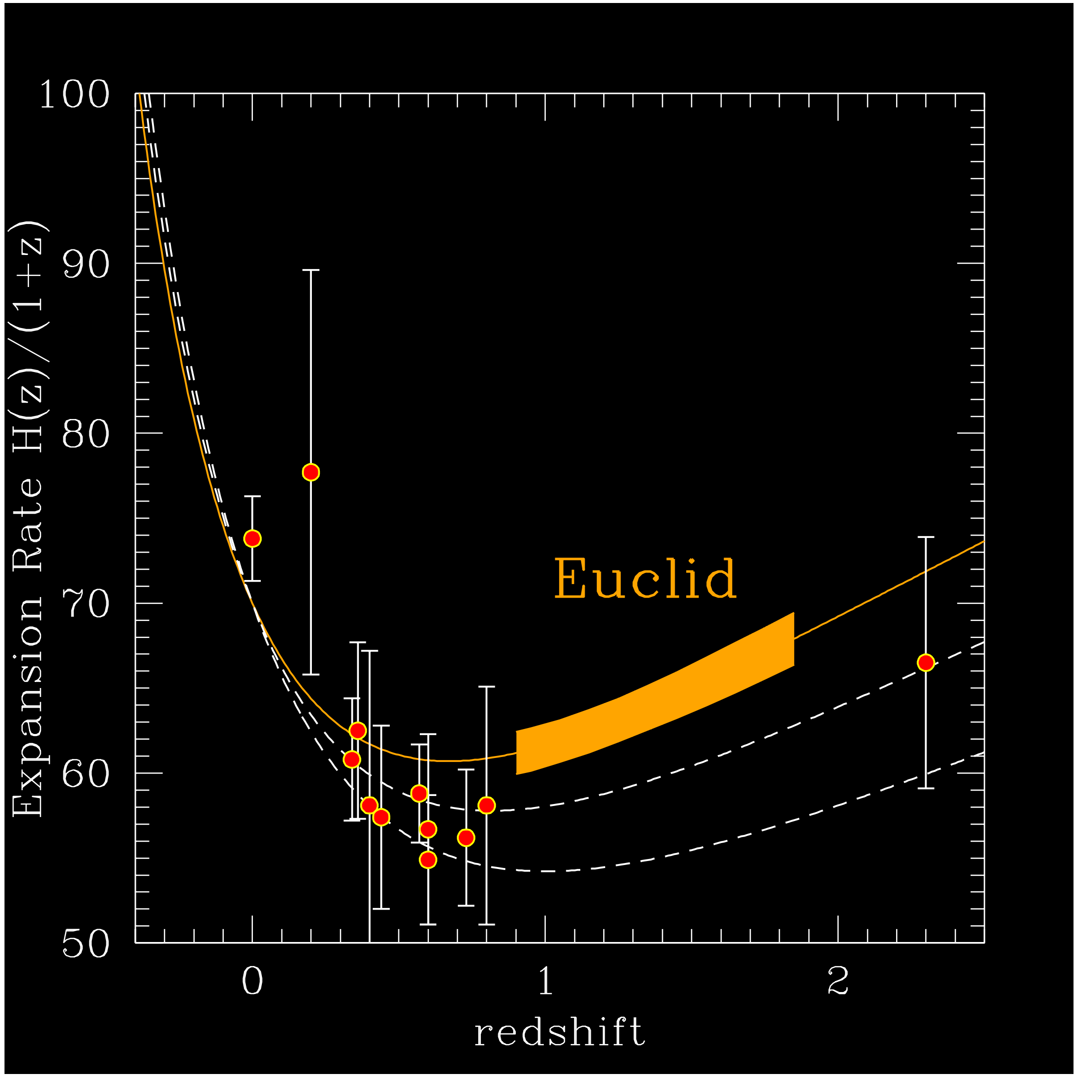




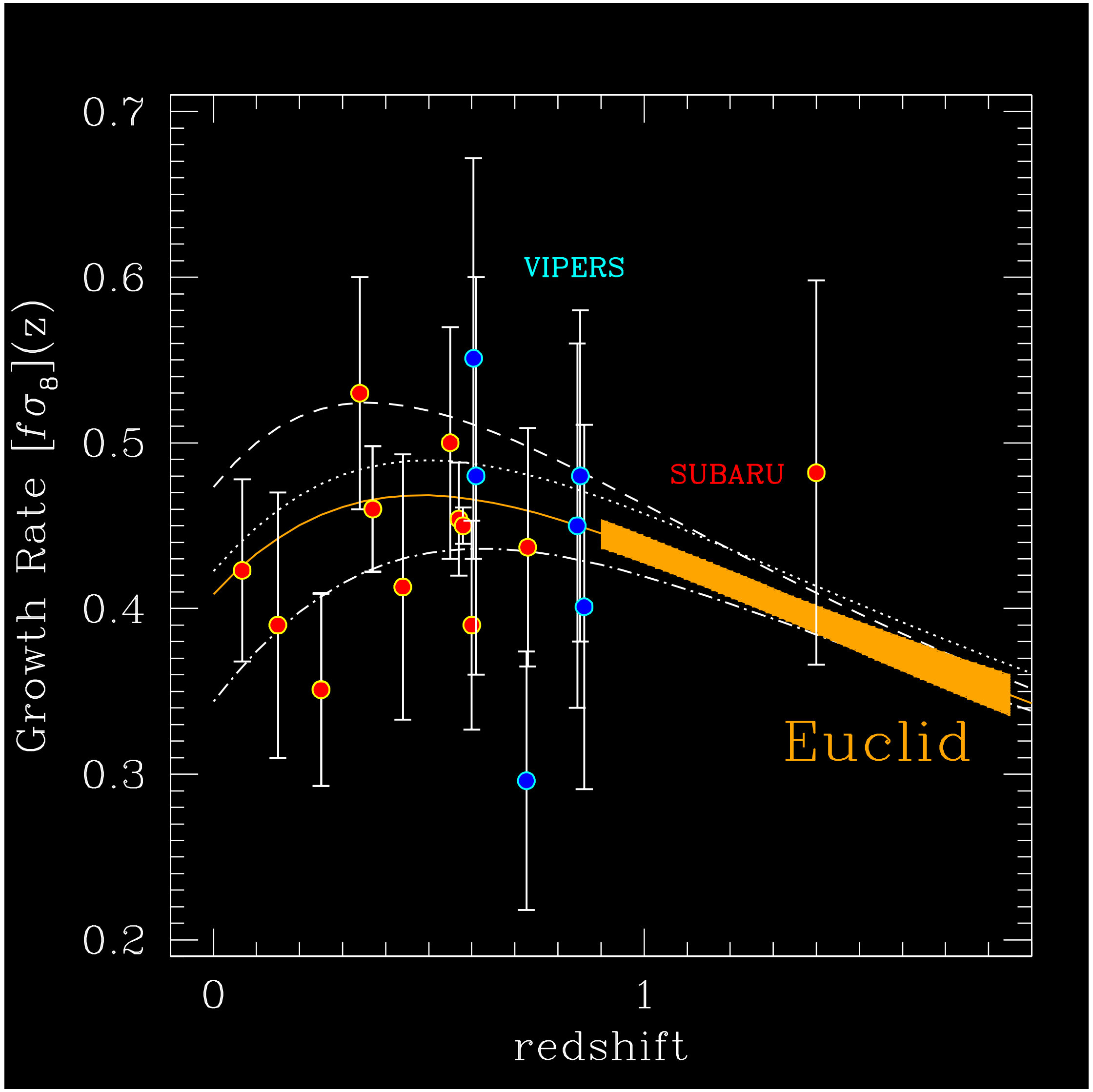
Sims by P. Franzetti, B. Garilli, A. Ealet, N. Fourmanoit & J. Zoubian

Expansion history H(z) from BAO to ~1% precision

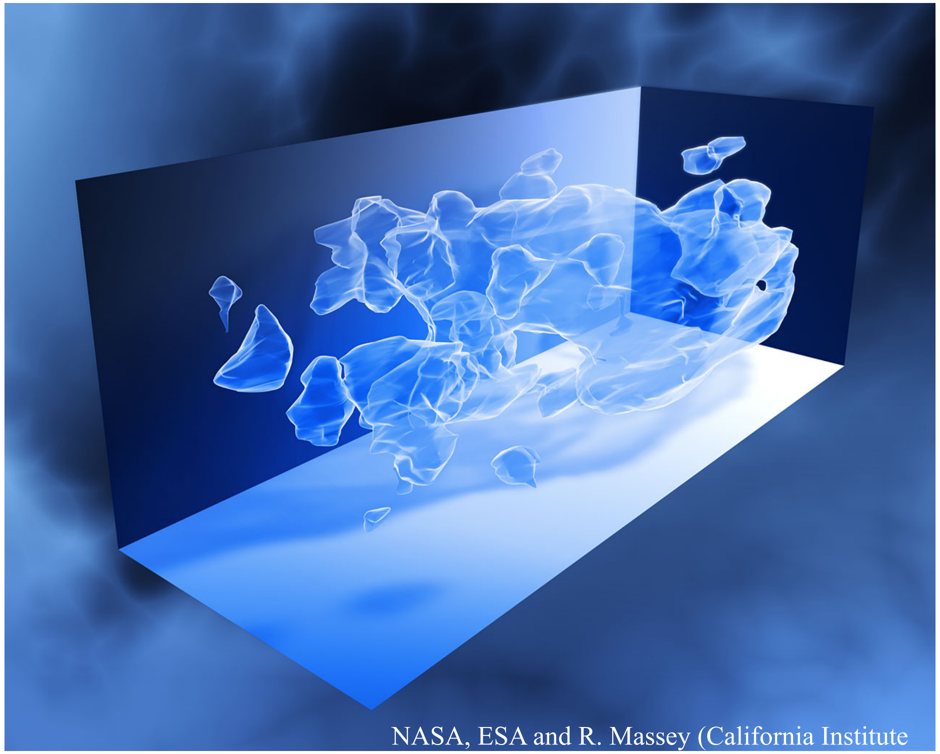
Euclid Consortium

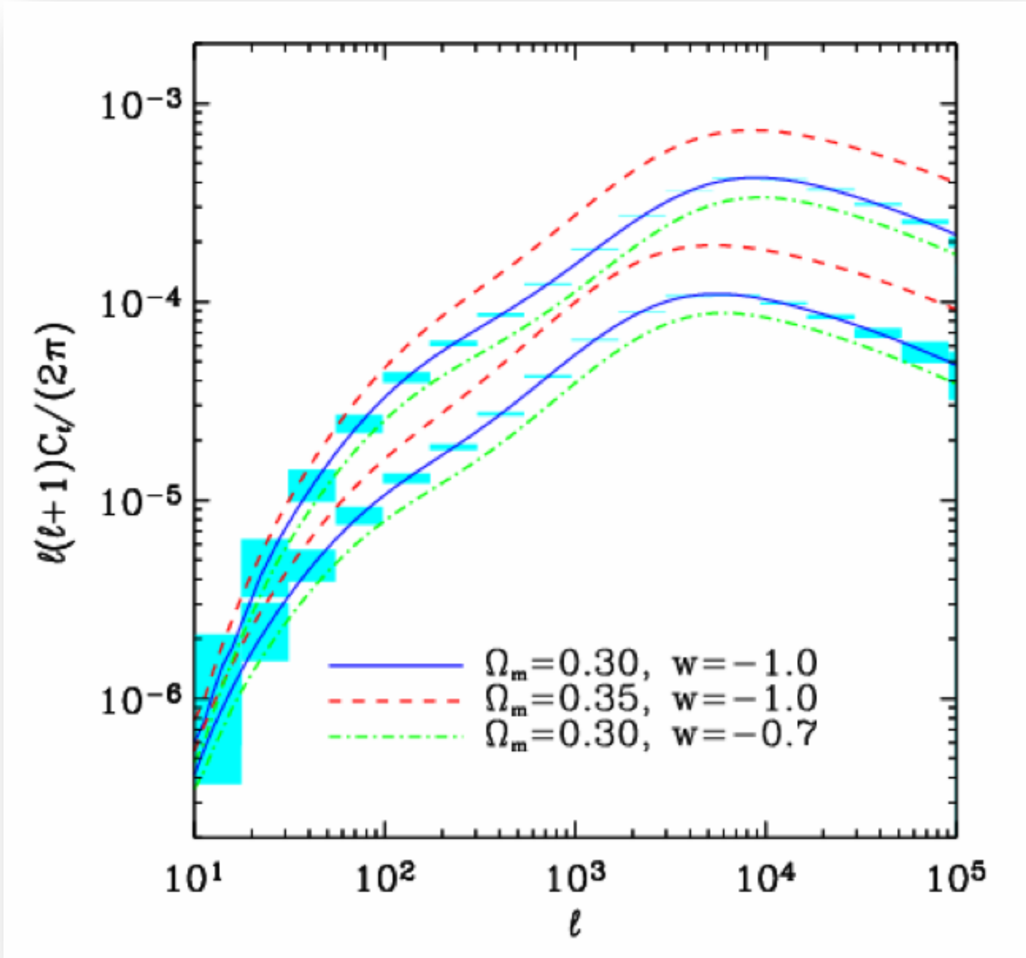


Growth rate from RSD to ~1% precision



Weak gravitational lensing: cosmic tomography

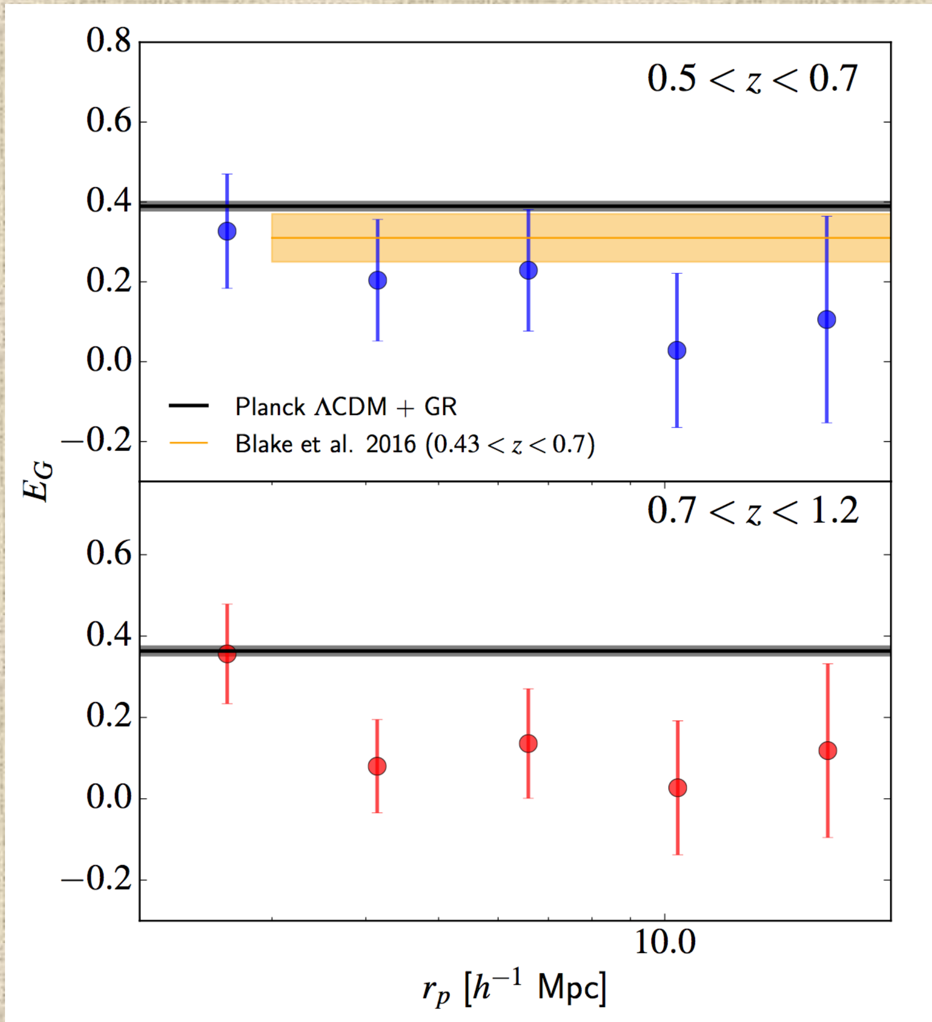




- Weak Lensing can directly map the dark matter distribution in 3D

Combining galaxy clustering and weak lensing

- Test for modified gravity combining CFHTLens imaging with VIPERS final data release PDR-2 (de la Torre + VIPERS Team 2017): **Slip parameter**

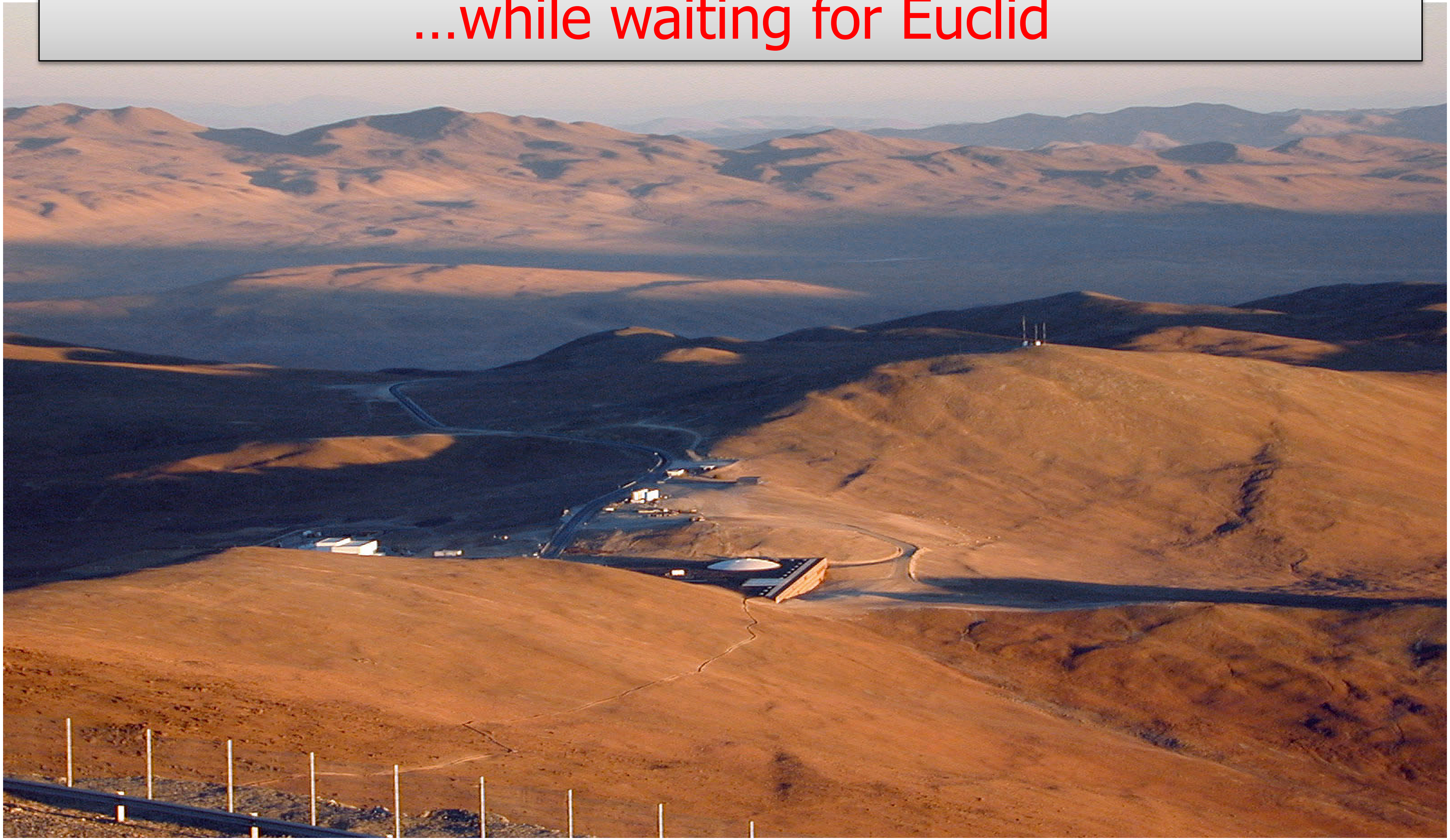


Complementarity of galaxy clustering and weak gravitational lensing: control systematic effects

(proof of concept for Euclid)

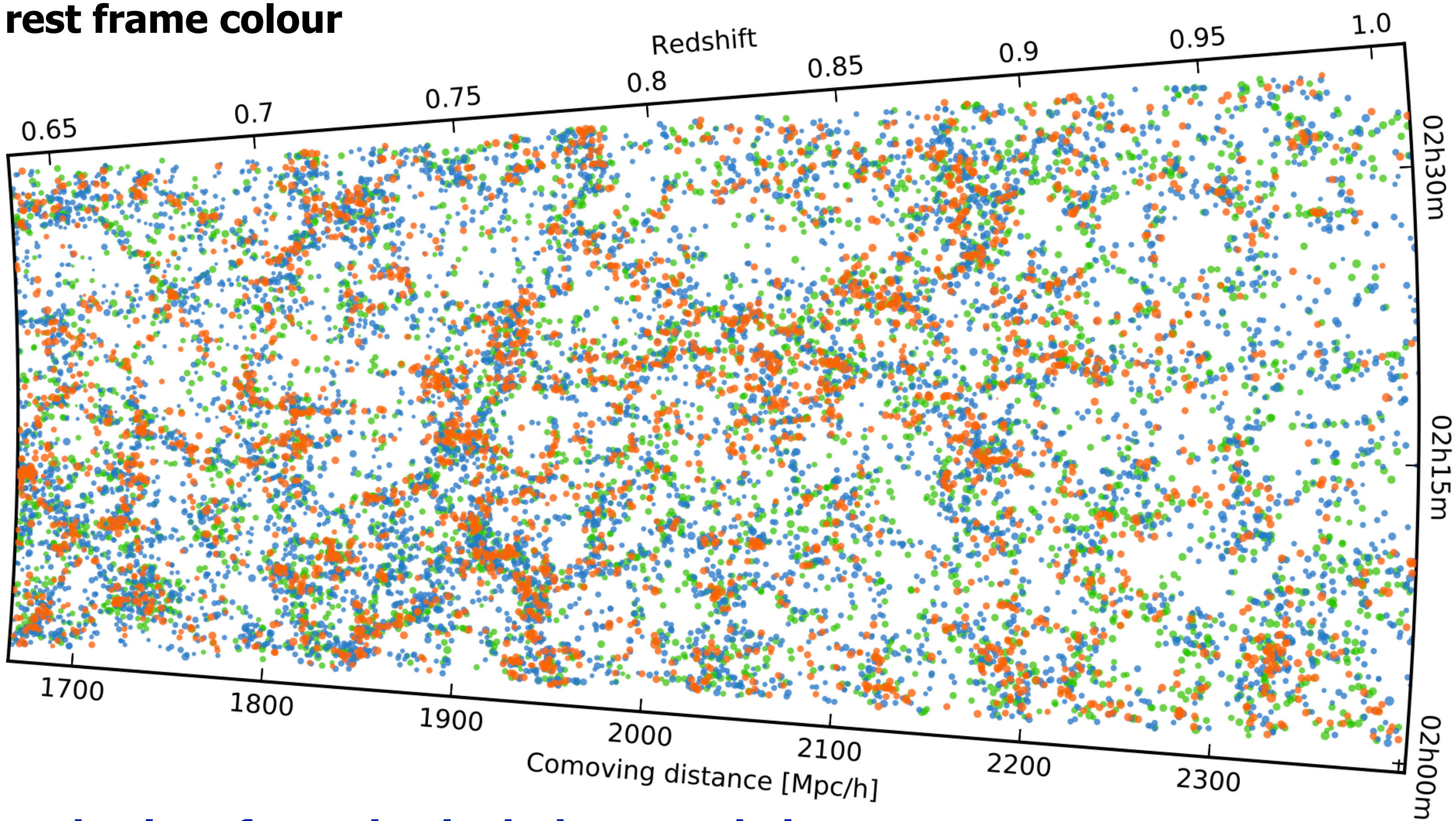
(see also Zhang et al. 2007; Reyes et al. 2009)

…while waiting for Euclid



Improve modelling and understanding of galaxies…

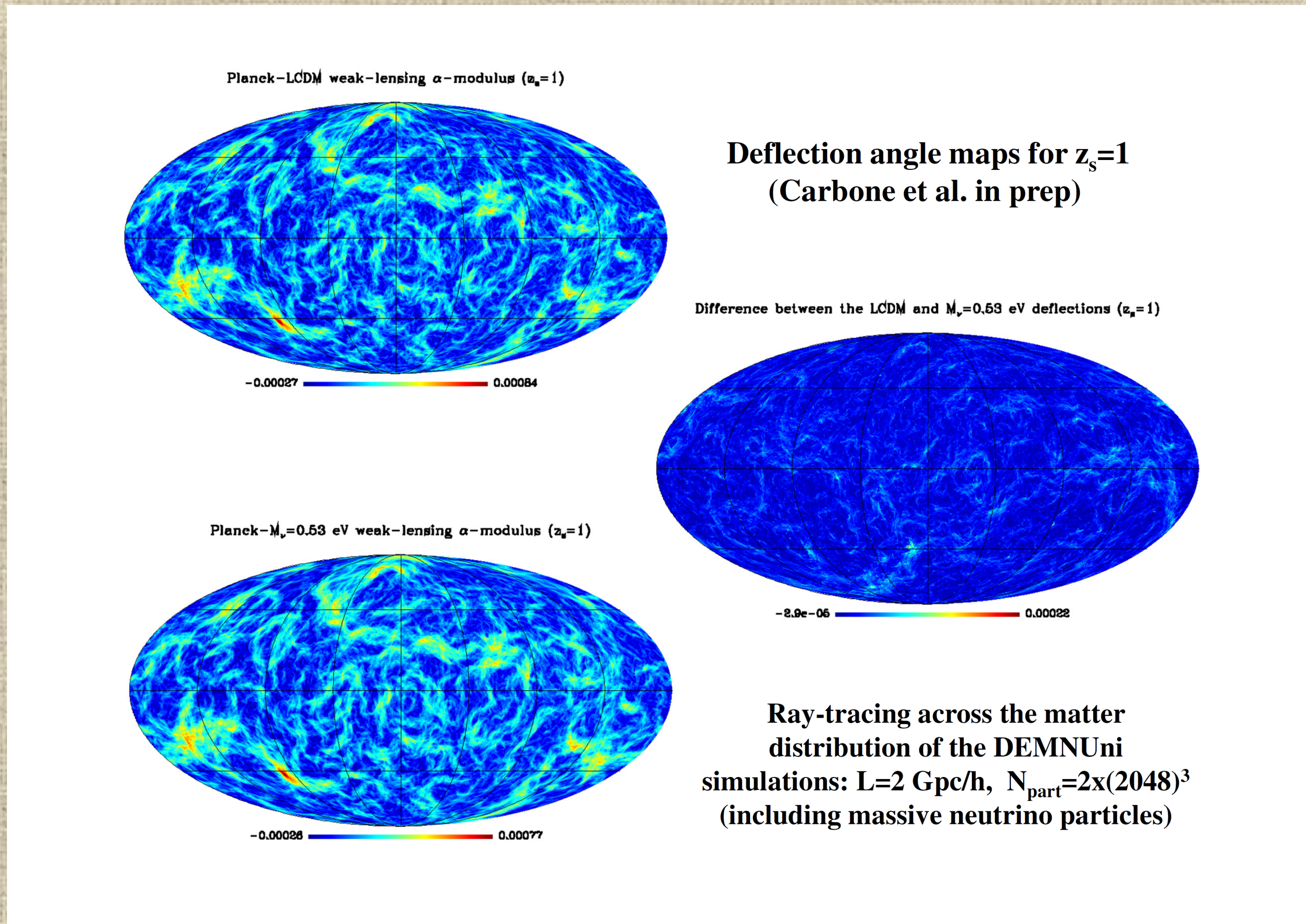
VIPERS galaxies encoded using (U-B) rest frame colour



- **Understand galaxy formation in dark matter halos**
- **Understand *galaxy bias:* use galaxies properly to precisely infer cosmological parameters**

Account for all existing components: neutrinos!

Carbone et al., DEMNUni simulations, largest existing n-body simulations including massive neutrino component (Carbone et al. 2016).
Need particular care in setting initial conditions (Zennaro+ arXiv:1605.05283)



The name of the game

A brilliant future ahead for cosmology with galaxy surveys: by 2030 we'll have >50 million redshifts measured, over huge volumes down to z=2 (Euclid, DESI, but also SKA, etc). <u>This makes systematic errors the real limit</u>

OBSERVATIONAL BIASES

- e.g. Low SNR slitless spectra (Euclid): confusion, completeness, purity → all these can be position dependent on the sky!
- Observational mask, uneven exposures, etc
- **Do not plan galaxy surveys just for cosmology! Leave door open for new techniques (e.g. voids, requiring high sampling), or selection of optimal sub-samples of galaxies**

MODELLING

- How do my galaxy tracers sample the dark-matter distribution? DM-baryon connection (**bias)**
- We like it linear, however reality is **non-linear** if we want to maximise signal
- We work in **redshift space**: we have turned this to our advantage, yet need to keep improving RSD models (e.g. de la Torre & Guzzo 2012, Bianchi et al. 2014, 2016)
- **Modelling is easier if we choose the right galaxy population (Mohammad+ 2017)**
- We are working at 1% precision. Need to include all ingredients → **neutrinos!** (e.g. Carbone+ 2017)