Measuring the Universe with Galaxy Surveys

Luigi Guzzo

Dipartimento di Fisica - Universita' Statale di Milano
INAF & INFN Milano

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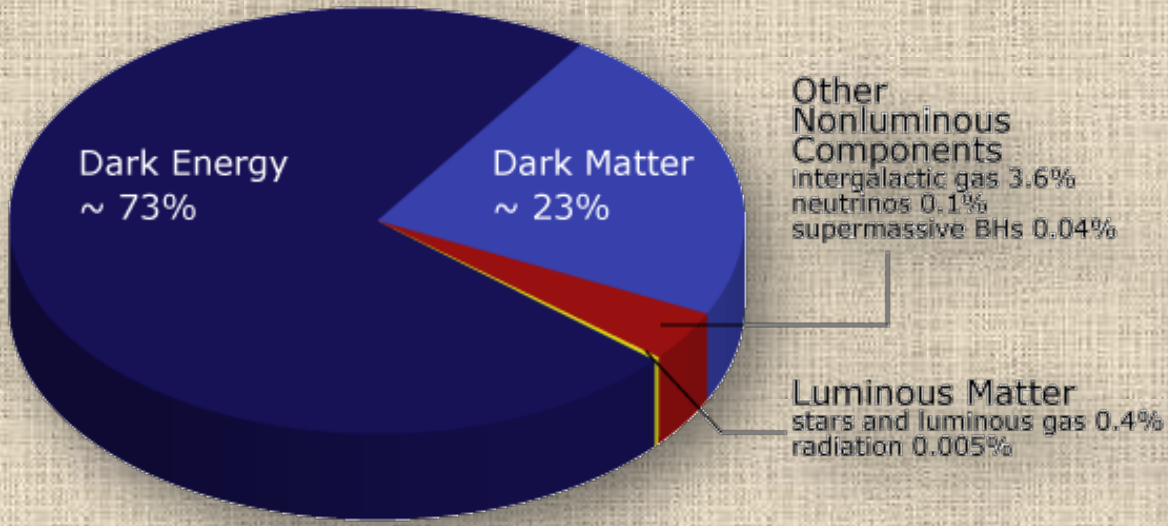
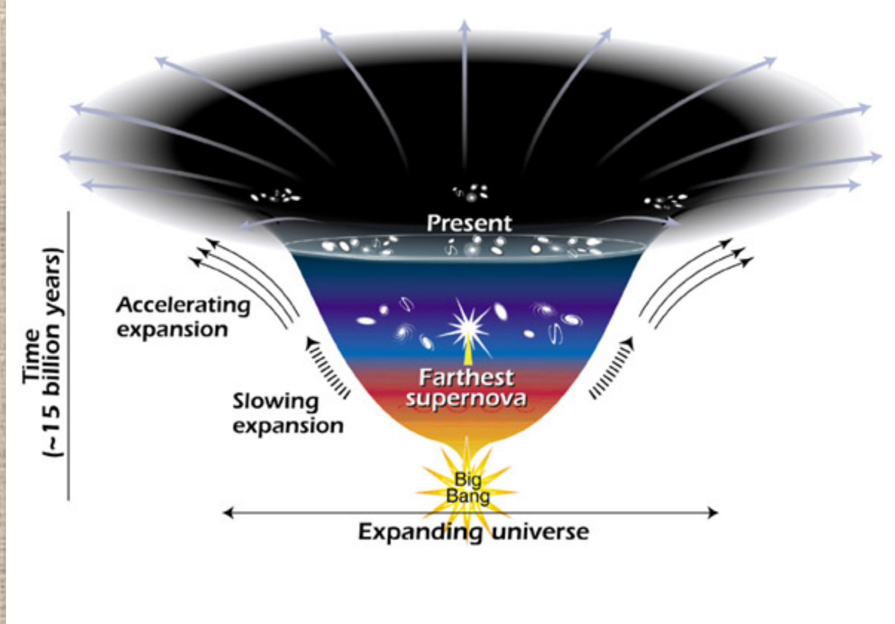
The "cosmic pizza" of the 21st century: but who ordered it?

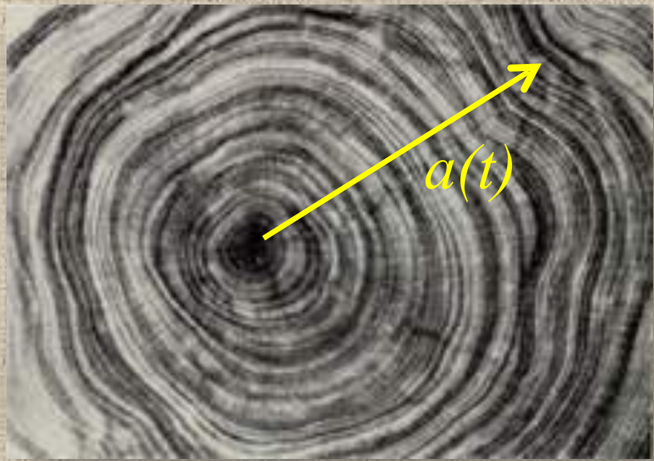




This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers 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…



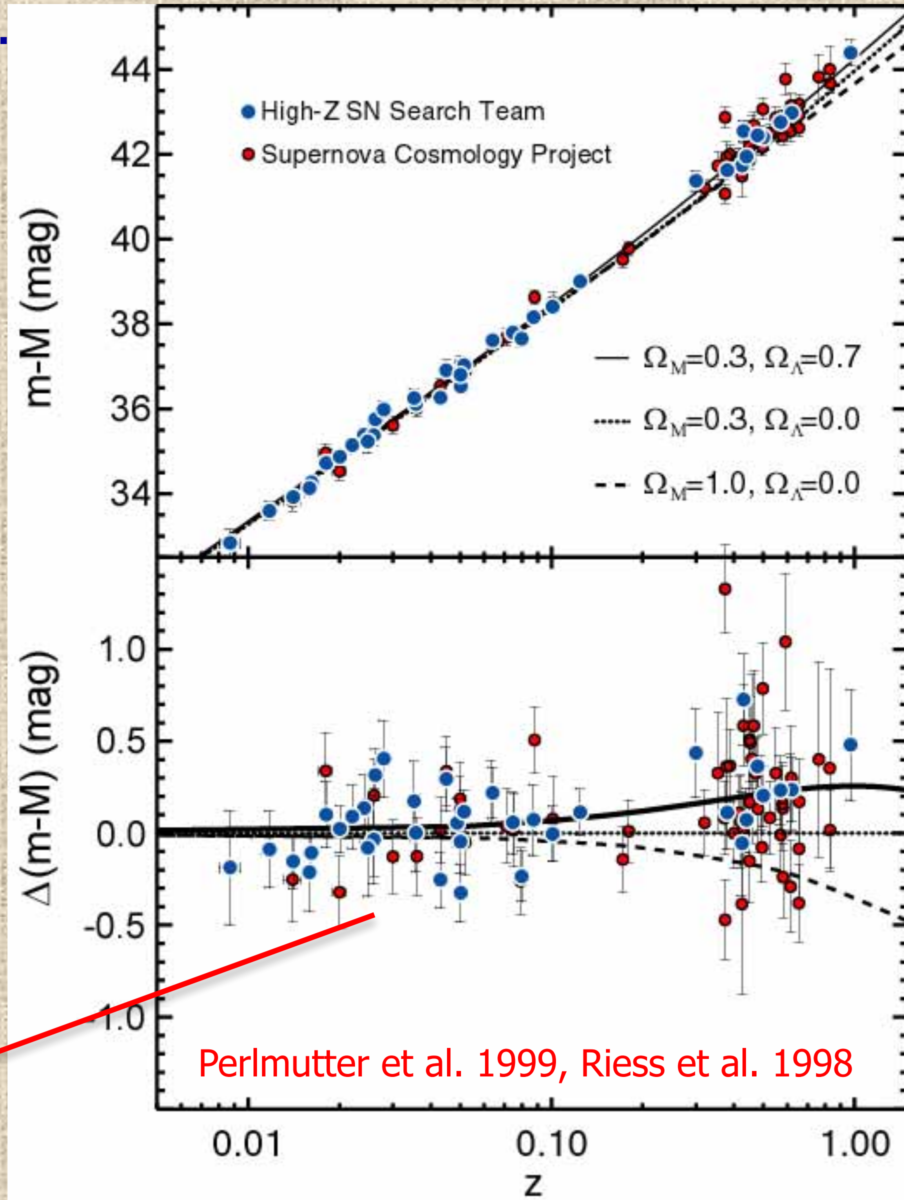
$$H \equiv \frac{\dot{a}}{a}$$

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

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

~0.3 ~0.7

log(Distance d_L)



Perlmutter et al. 1999, Riess et al. 1998

Redshift of spectral lines

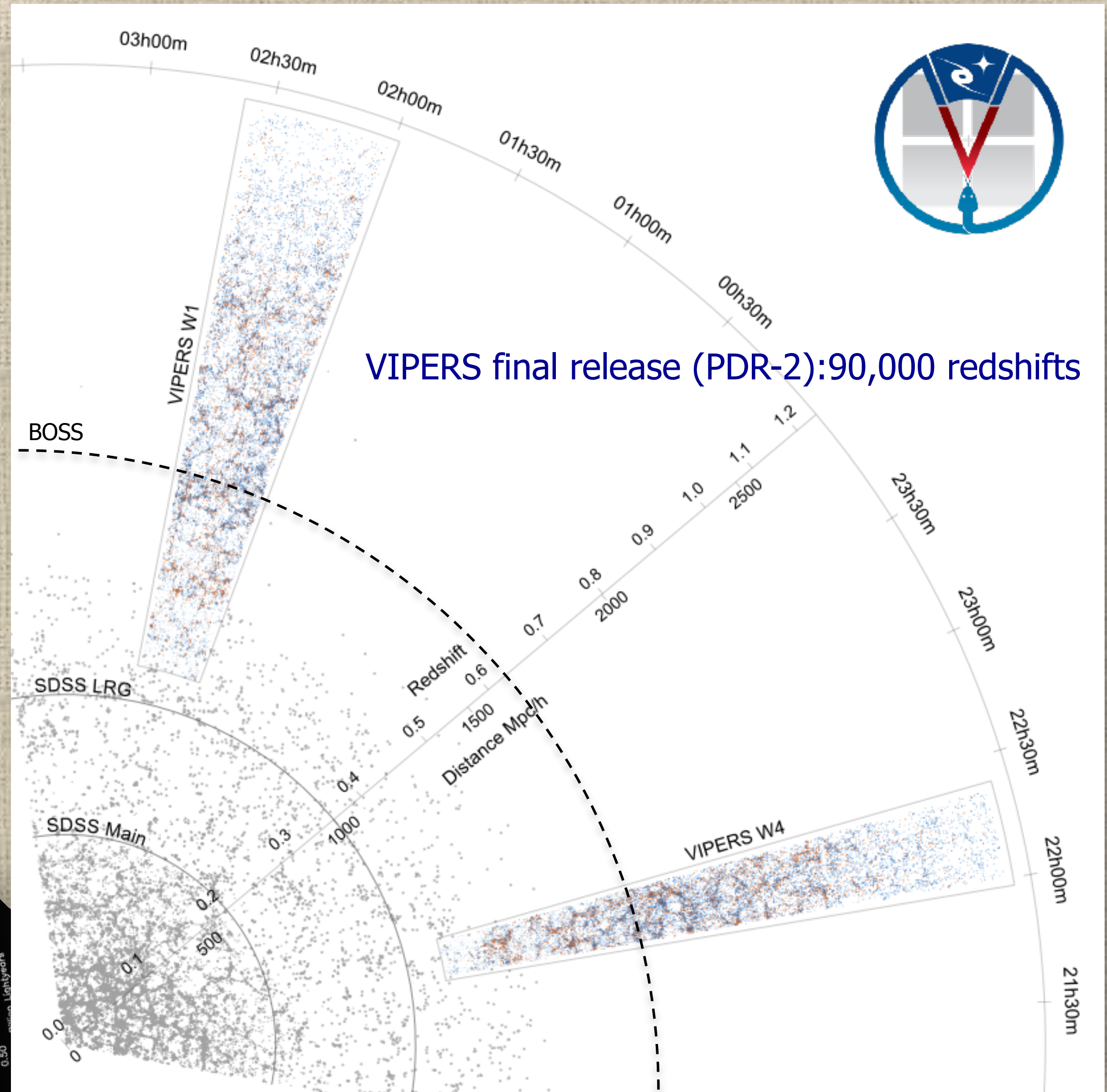
Galaxy redshift surveys: a major pillar of the cosmological model…

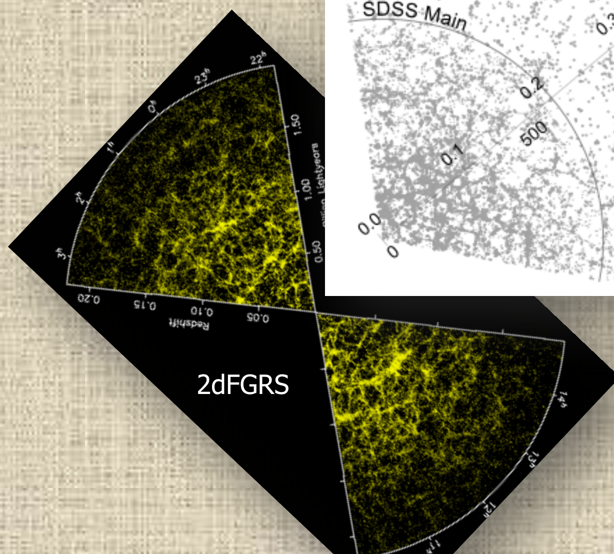
State of the art:

- SDSS-III BOSS (e.g. Alam+ 2016)
- WiggleZ (Blake+ 2014)
- **VIPERS** (Guzzo+2014, Scodeggio+ 2018)
- SDSS-IV eBOSS (Kneib+, ongoing)

Future:

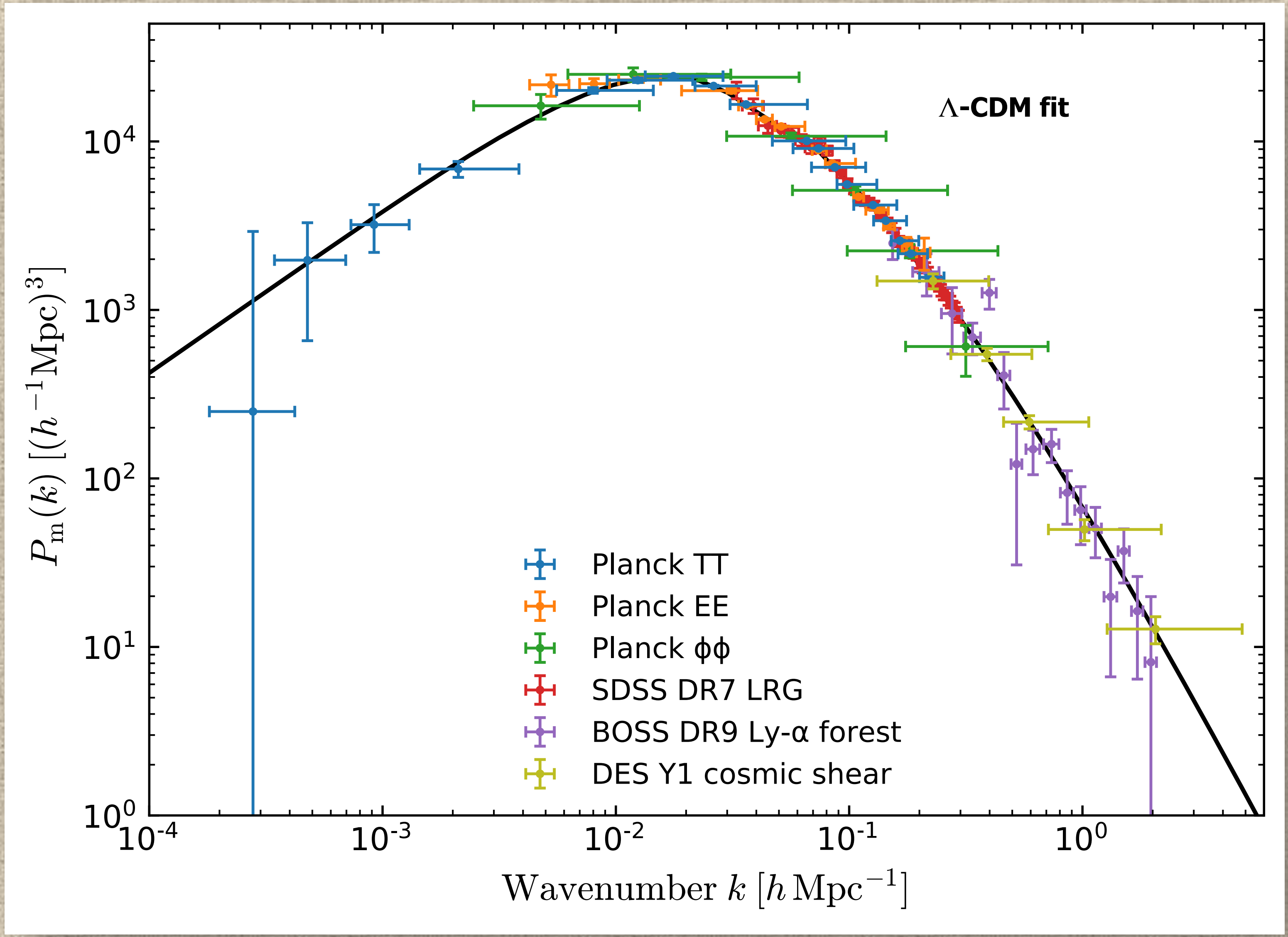
- DESI (2019)
- **Euclid** (2022)





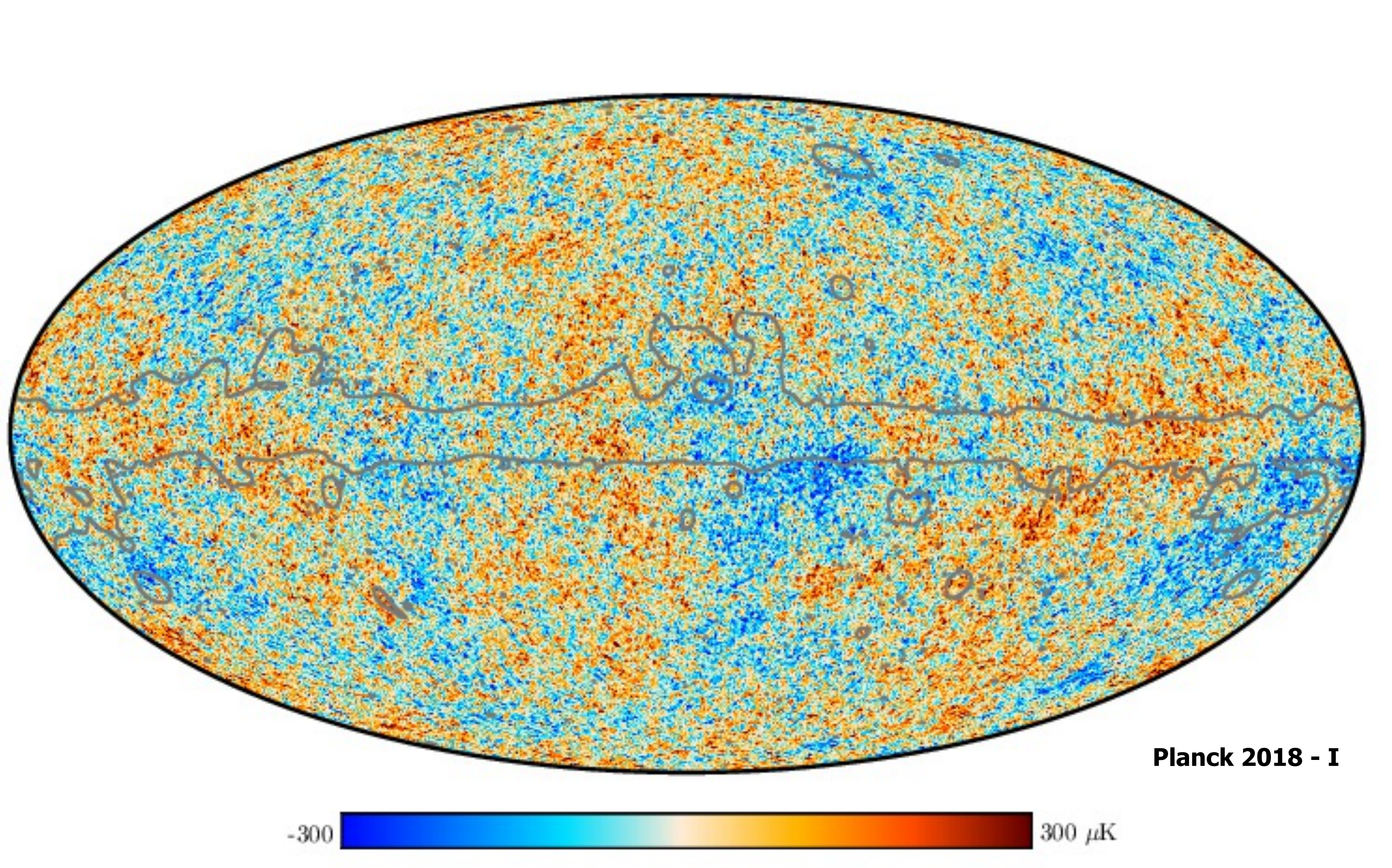
(arXiv 1611.07048)

The power spectrum of inhomogeneities: a direct probe of cosmology



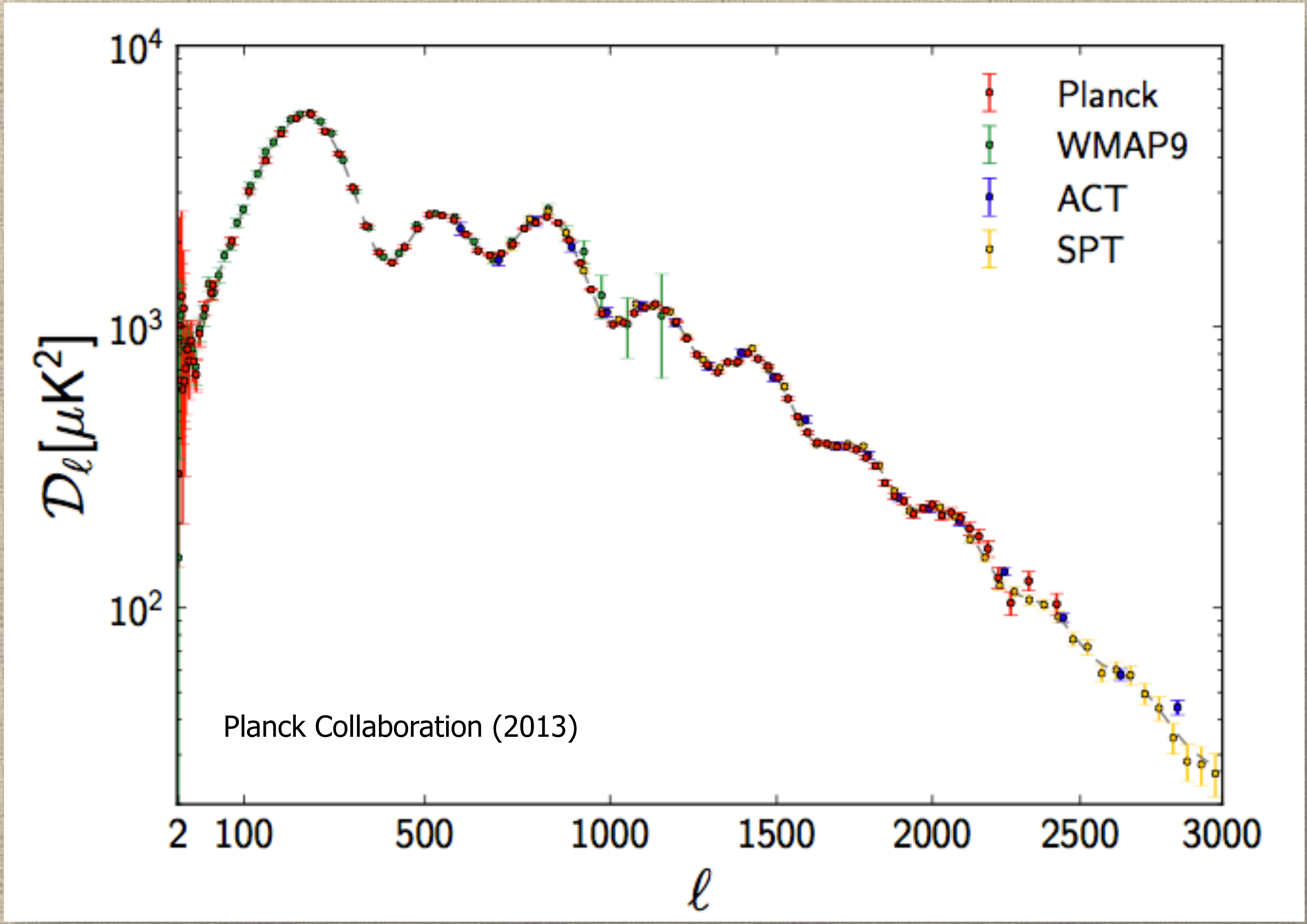
Planck 2018 - I

The second pillar: the Cosmic Microwave Background

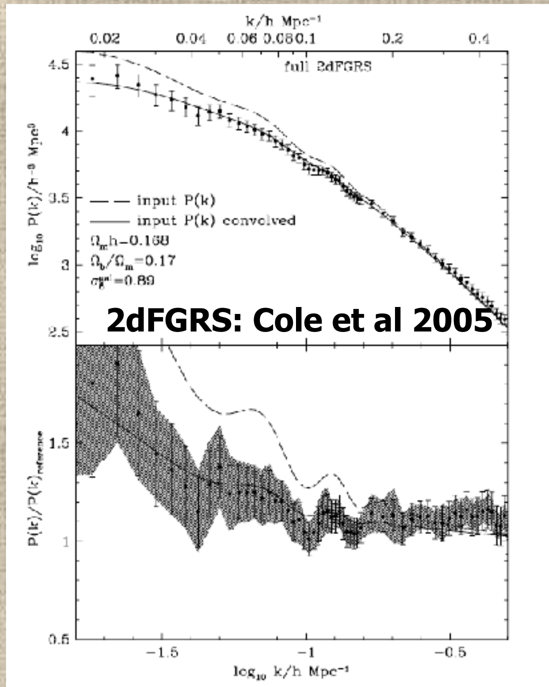


Fluctuations on all scales: however, one characteristic angular scale emerges

Baryonic Acoustic Oscillations in the CMB



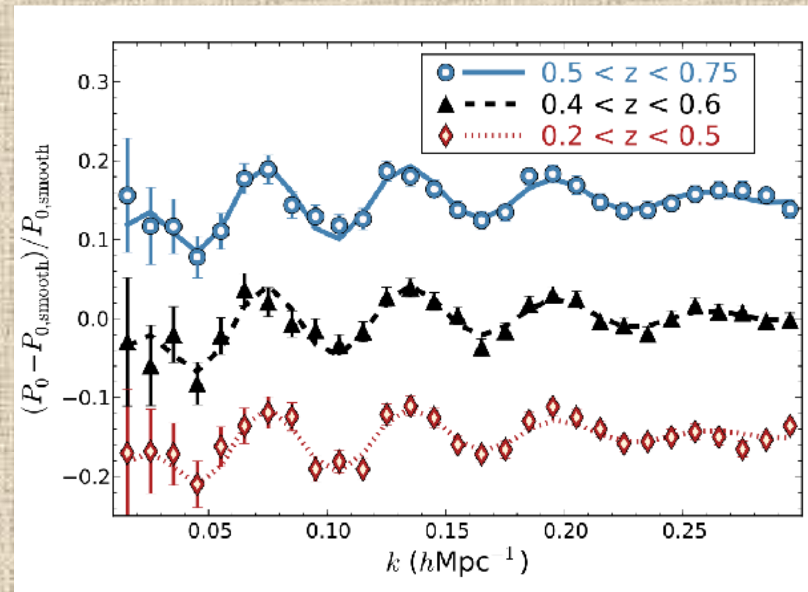
BAO in the galaxy power spectrum: a standard ruler

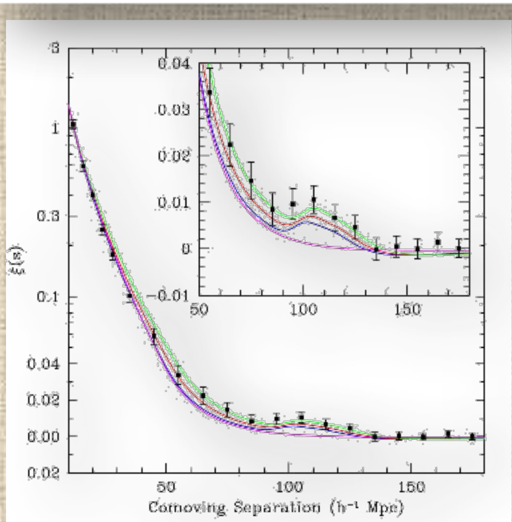


2dFGRS: Cole et al 2005

Fourier Space (wiggles):

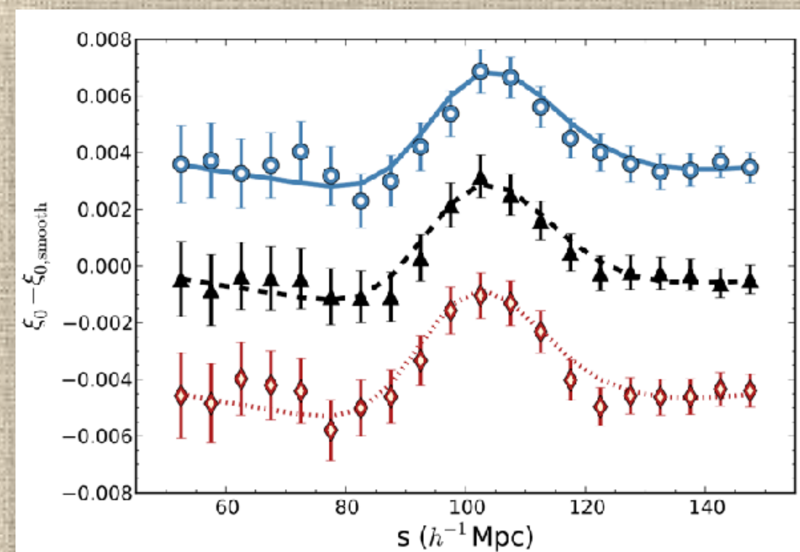
2016: Final measurement from BOSS-DR12





SDSS: Eisenstein et al 2005

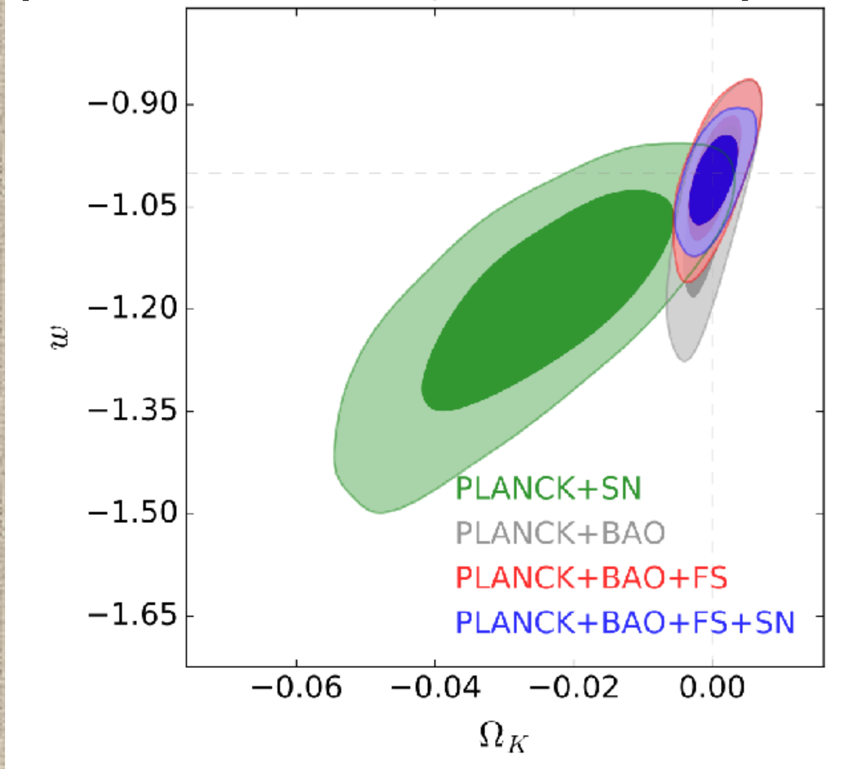
Configuration Space (BAO peak):

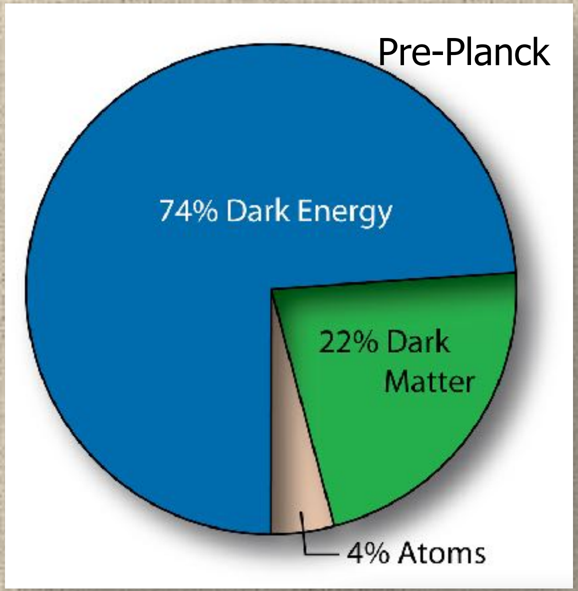


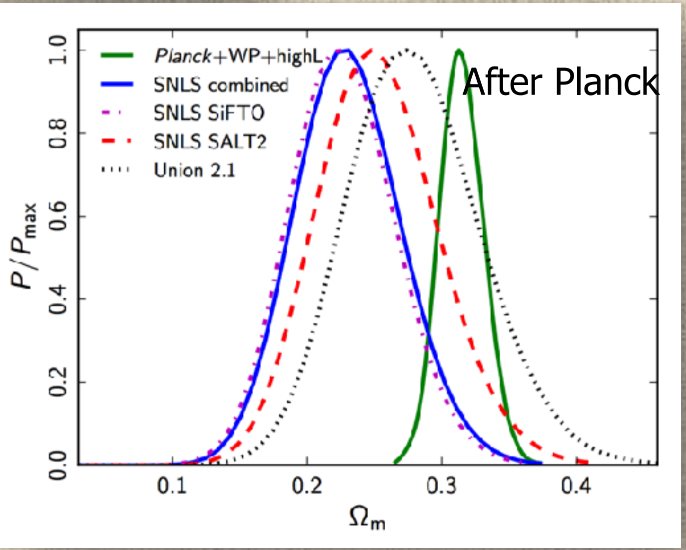
(BOSS Collaboration 2016, arXiv:1607.03155)

Cosmic (quasi) concordance

(BOSS Collaboration 2016, arXiv:1607.03155)







(Planck Collaboration 2013, paper XVI)

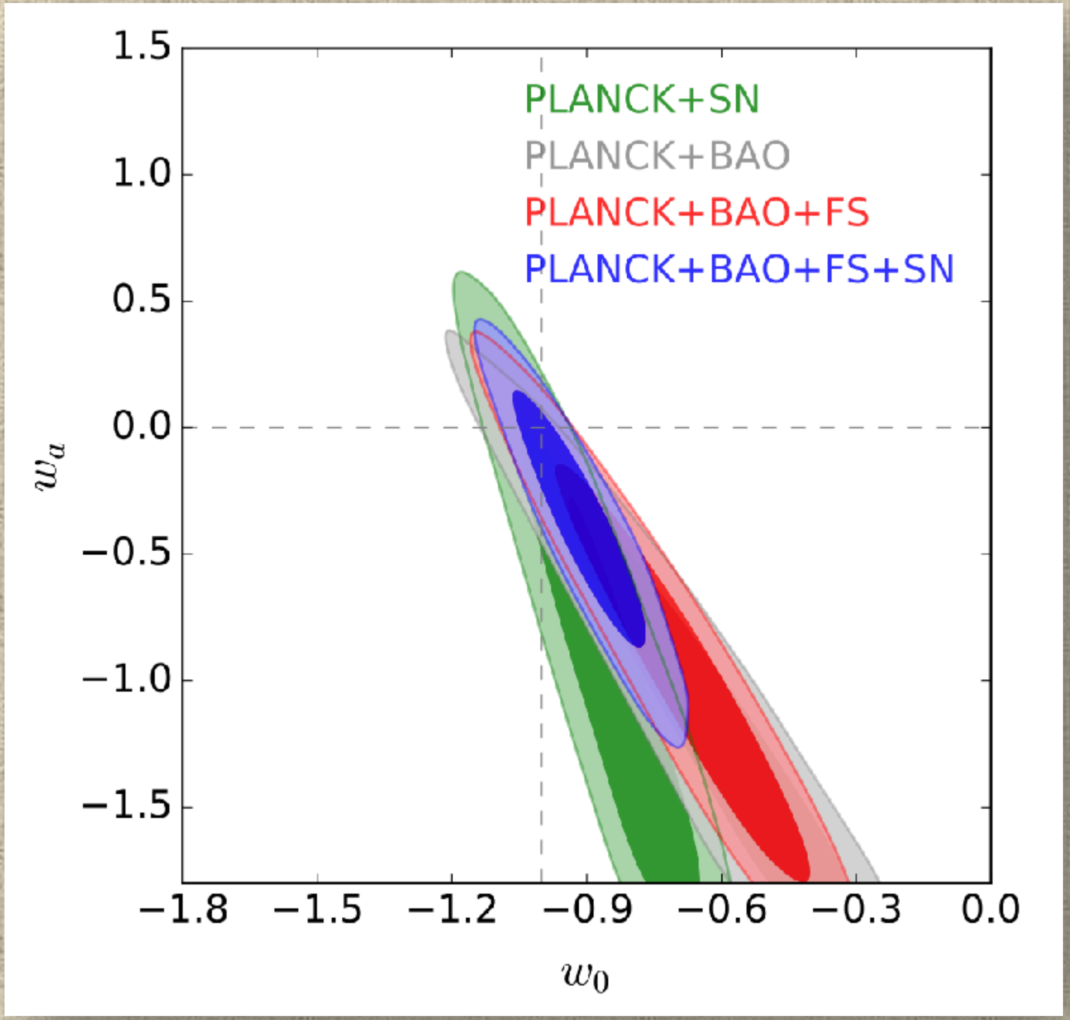
If leaving ***w*** as a free parameter (here with curvature), ***w=-1*** (cosmological constant) remains favoured

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

Parameterizing our ignorance:

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

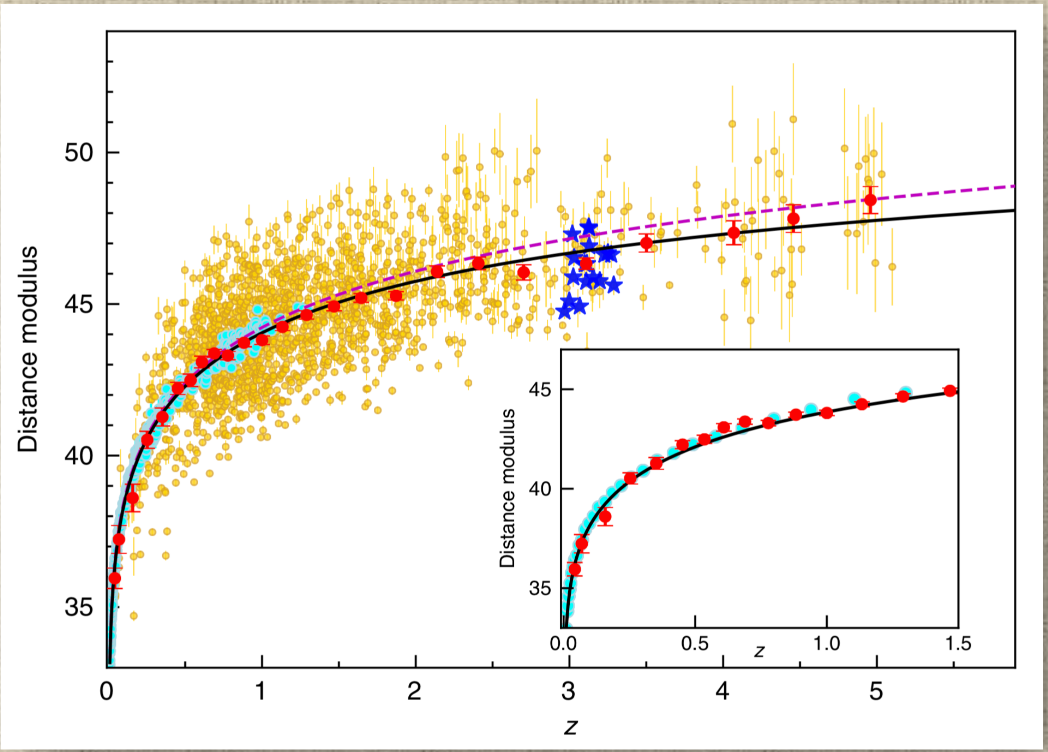
[a = scale factor of the Universe = $(1+z)^{-1}$]

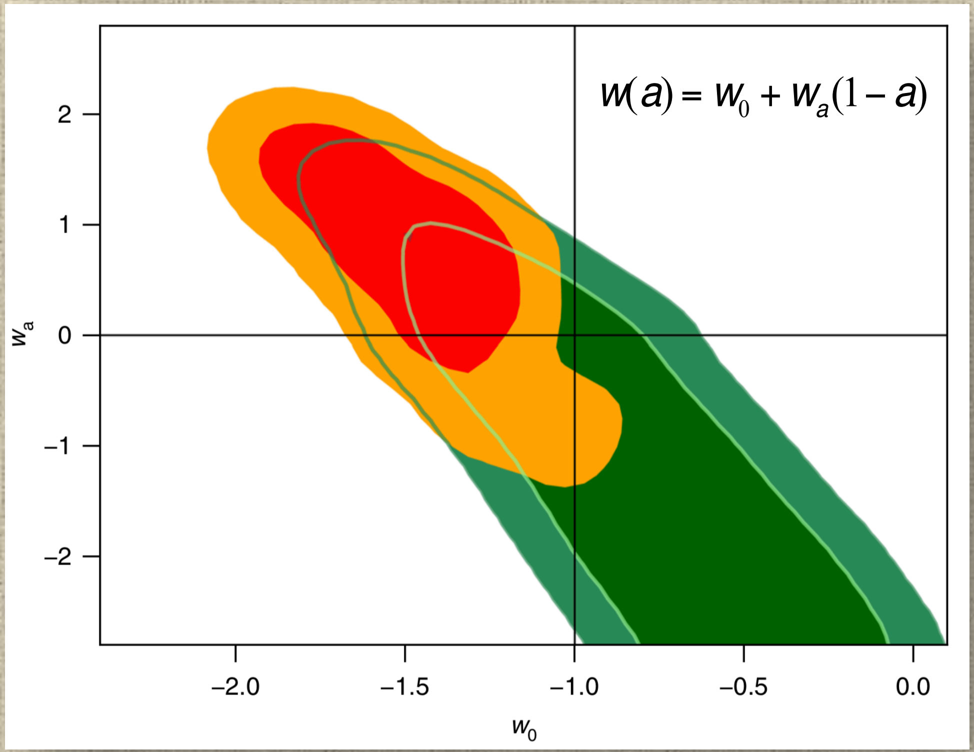


(BOSS Collaboration 2016, arXiv:1607.03155)

Hints for a varying *w(a)* from high-z quasars?

Risaliti & Lusso, 2019, Nature Astronomy





But Λ [or dark energy w(z)] may not be the end of the story…

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

?

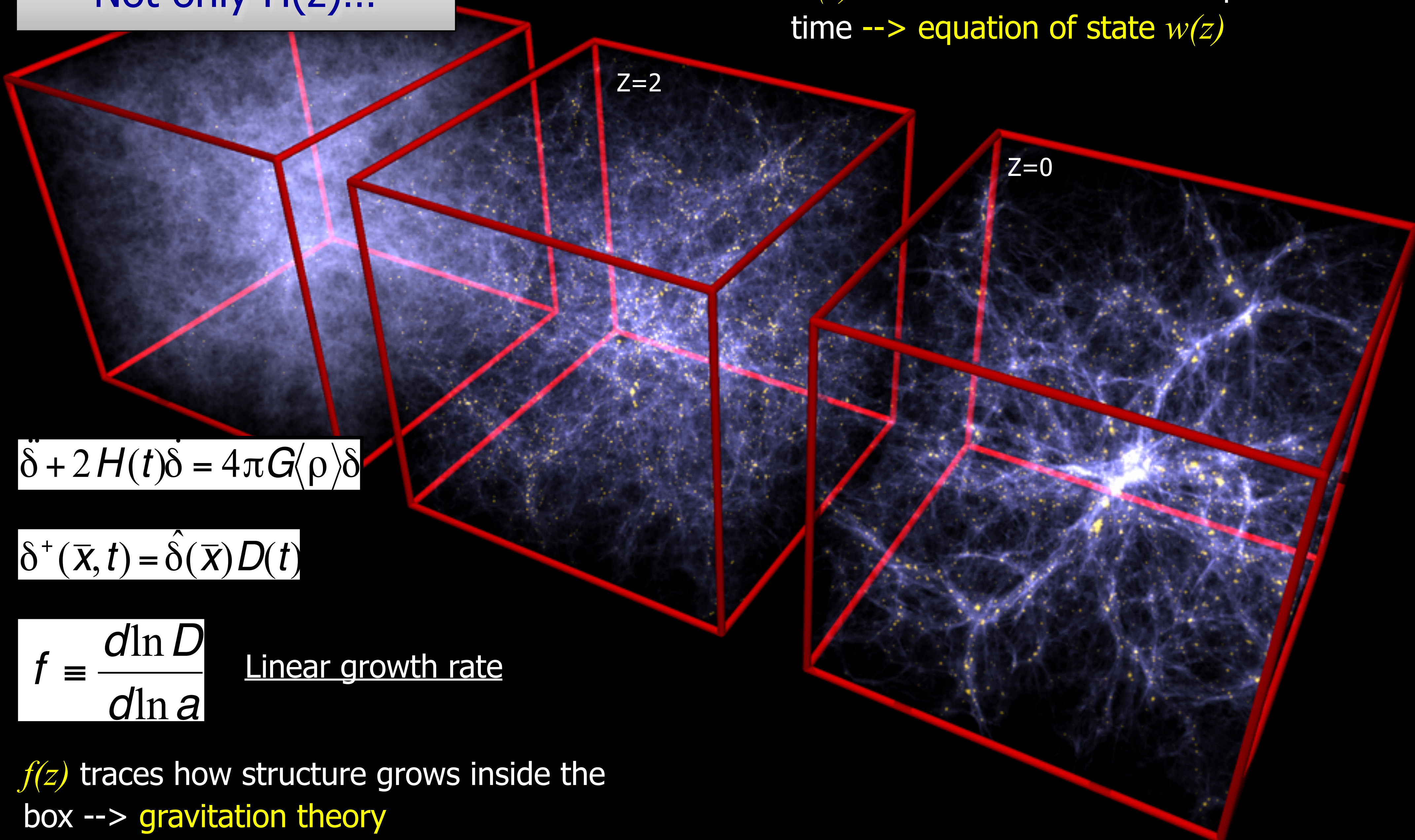
Modify gravity theory [e.g. ***R*** → ***f(R)***]

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)*



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

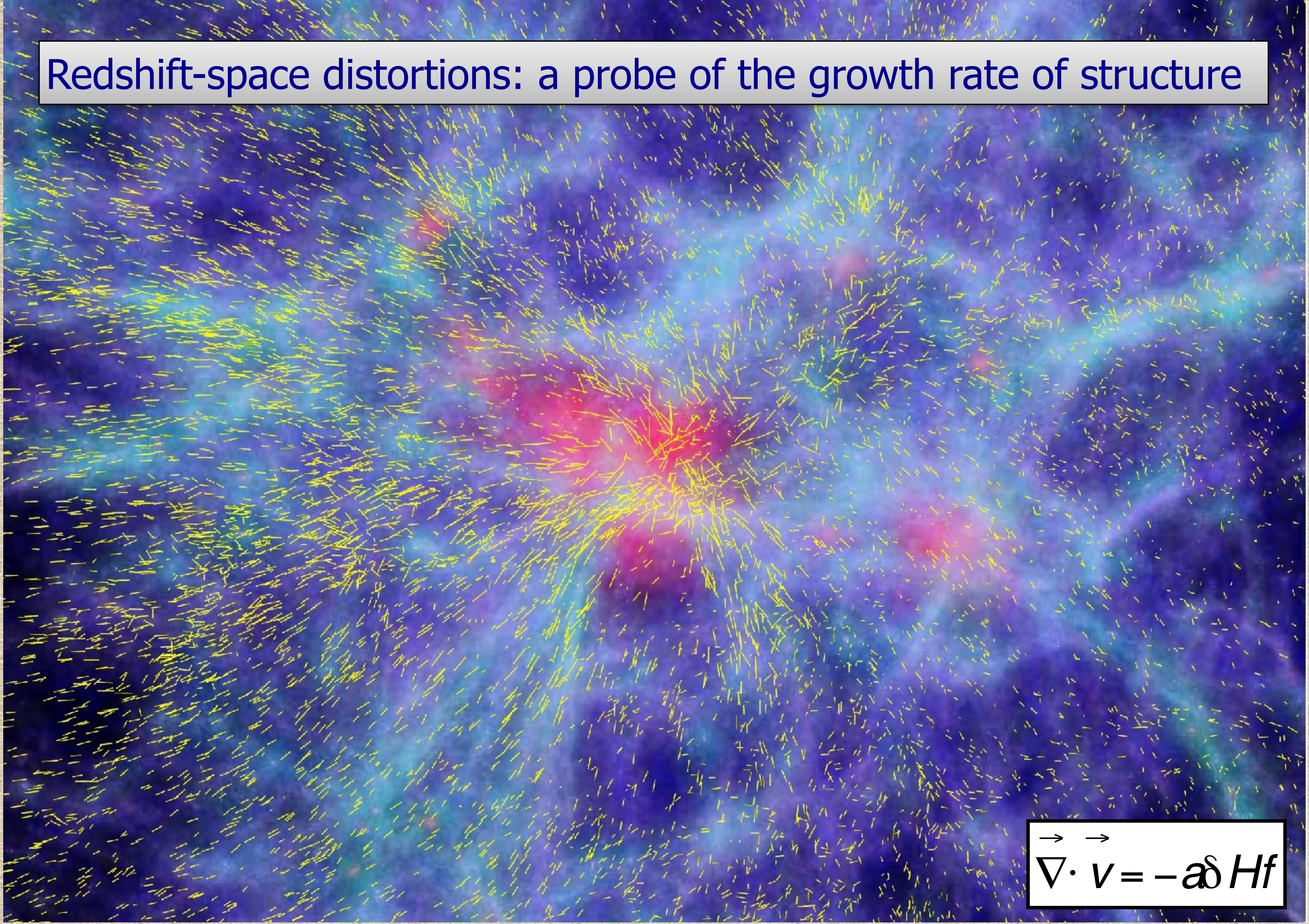
$$\delta^{+}(\bar{x},t) = \hat{\delta}(\bar{x})D(t)$$

$$f \equiv \frac{d\ln D}{d\ln a}$$ Linear growth rate

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

Springel et al.

Redshift-space distortions: a probe of the growth rate of structure

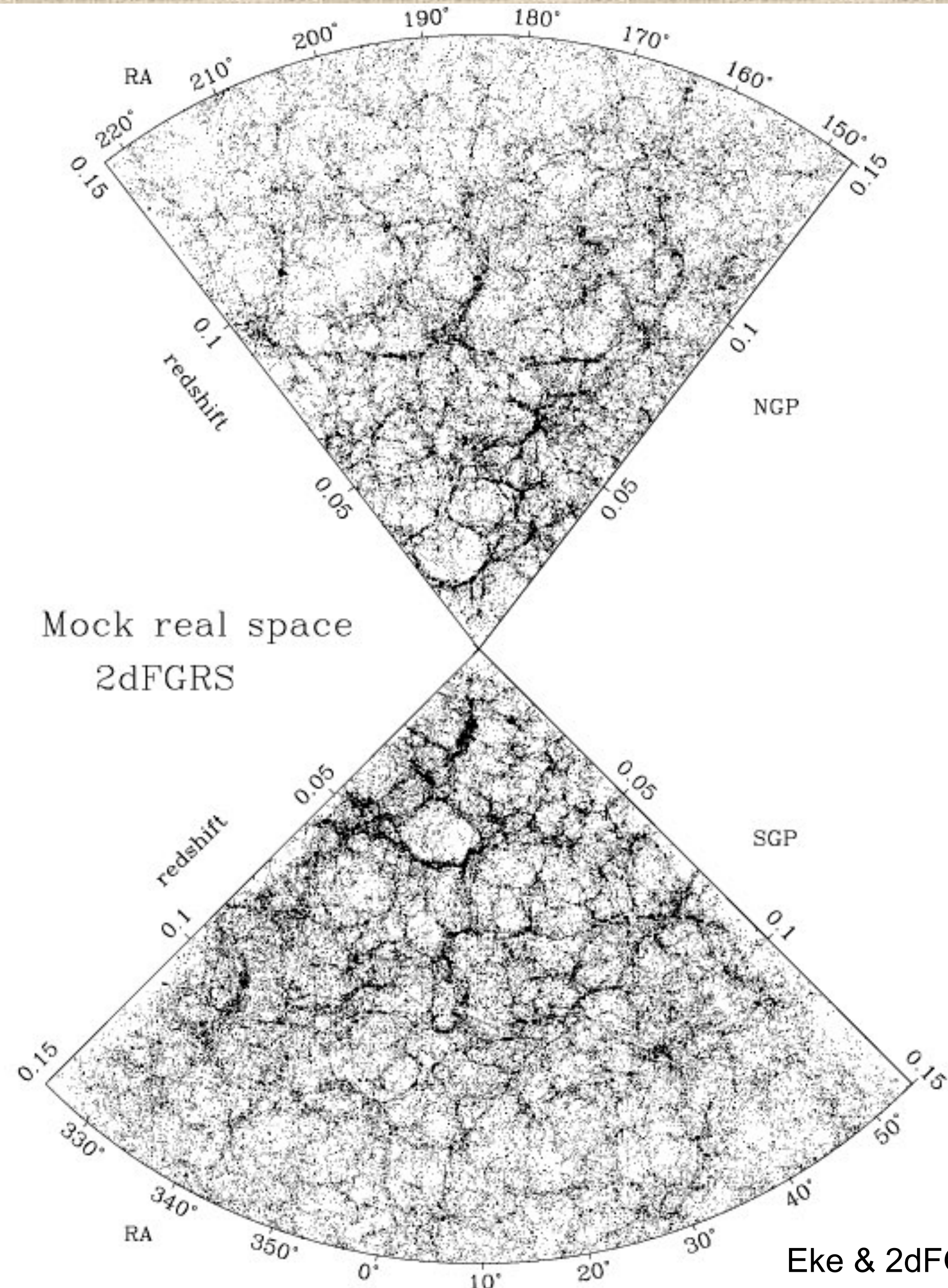


$$\vec{\nabla}\cdot\vec{v} = -a\delta H f$$

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

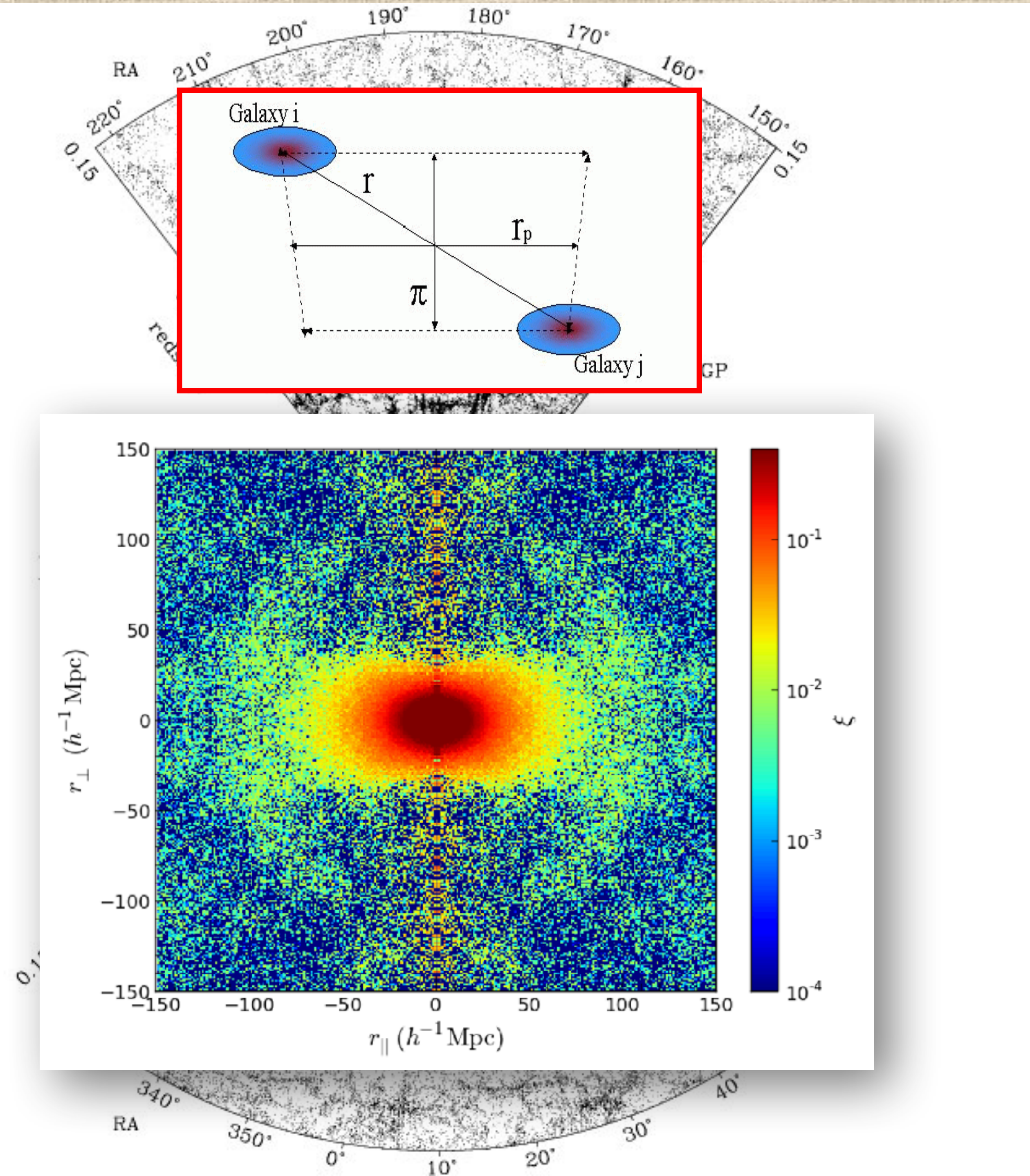
real space

(Kaiser 1987)



Eke & 2dFGRS 2003

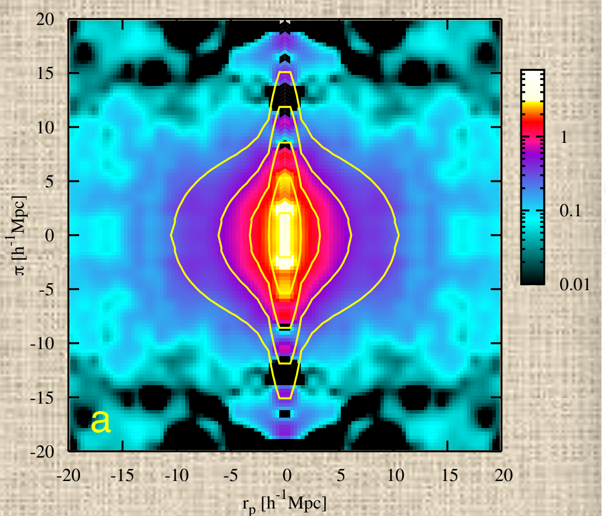
Growth produces peculiar velocities, which manifest themselves in galaxy redshift surveys as redshift-space distortions



redshift space

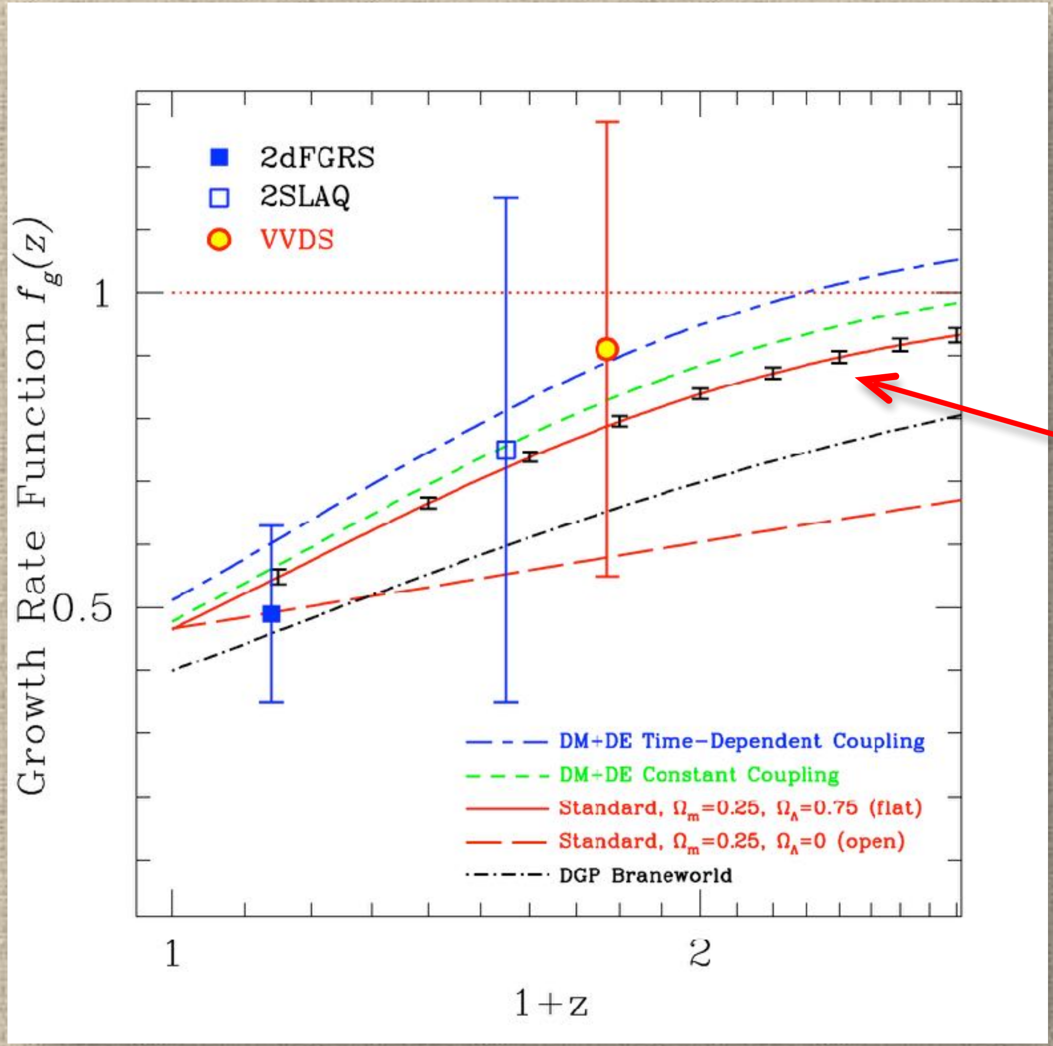
(Kaiser 1987)

Peculiar velocities distort our redshift-space maps: a dark energy test (2008)



VIMOS-VLT Deep Survey proof of concept at z=0.77:

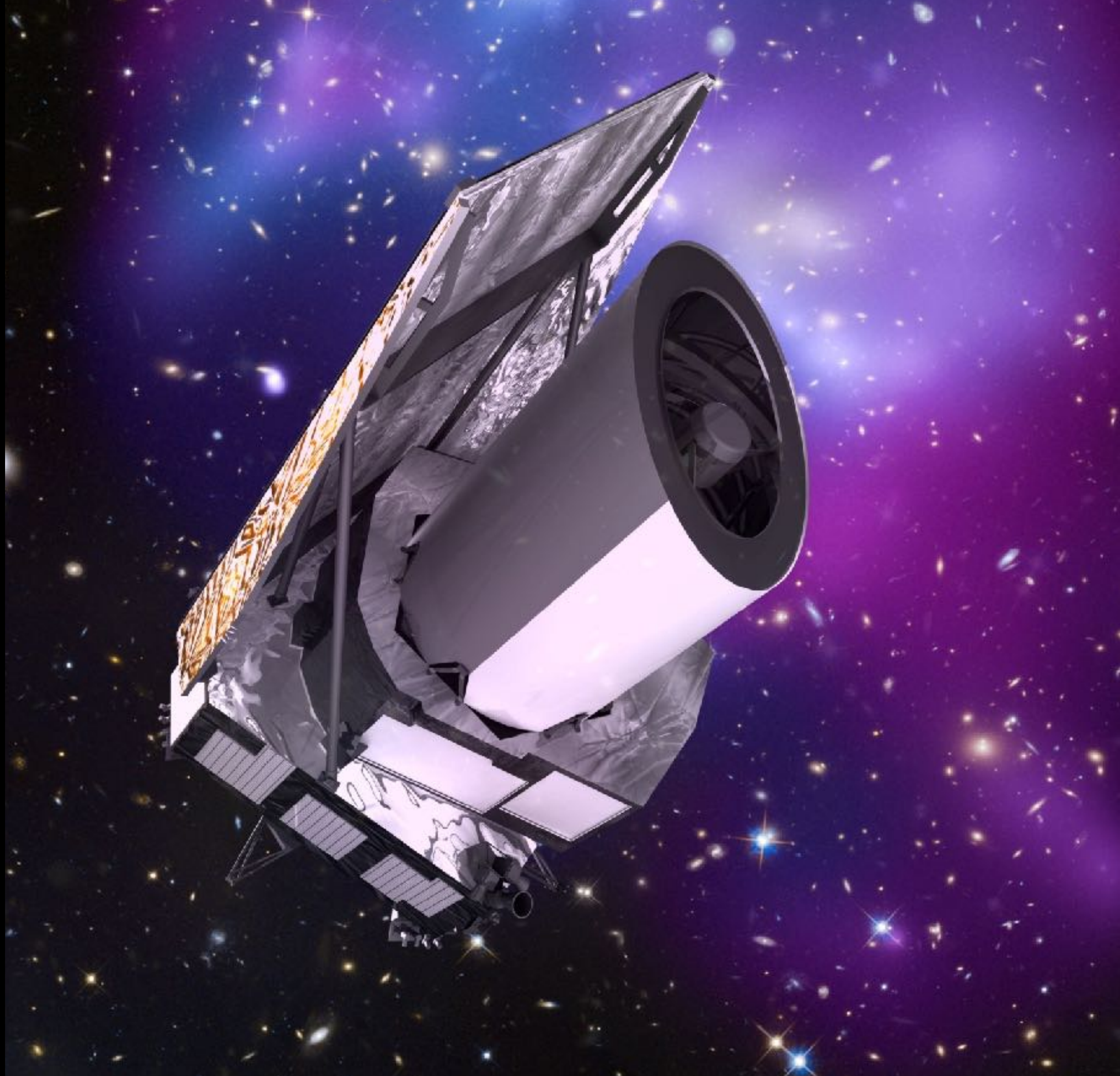
***f*=0.91±0.36**



First forecasts for a Euclid -like mission → ESA 2007 Cosmic Vision proposal

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

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: Y. Mellier (interim: F. Bernardeau)

- 1.2 m telescope
- Visible imaging (1 band)
- Infrared imaging (Y,J,H)
- Infrared slitless spectroscopy
- Launch spring 2022

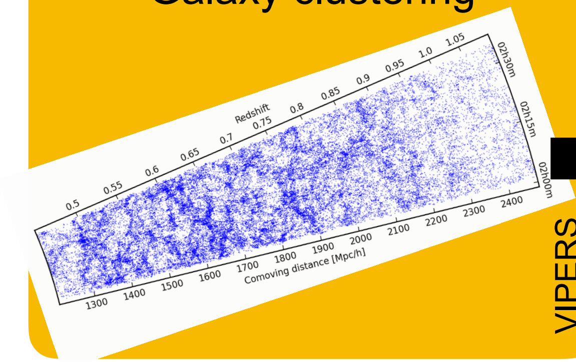
- 15,000 deg^2 survey
- Images for 2x10^9 galaxies
- Spectra for ~5 x 10^7 galaxies (0.9<z<1.8)

Unveiling gravity and dark energy

Φ

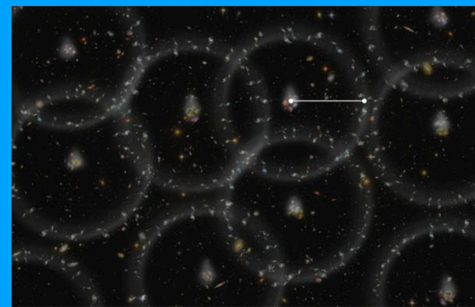
Ψ

Galaxy clustering



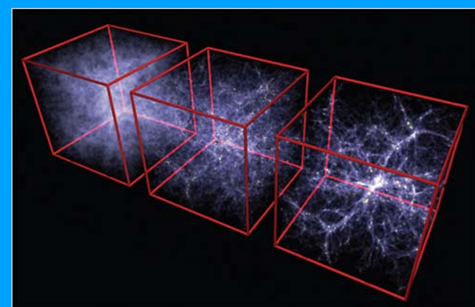
VIPERS

Expansion history



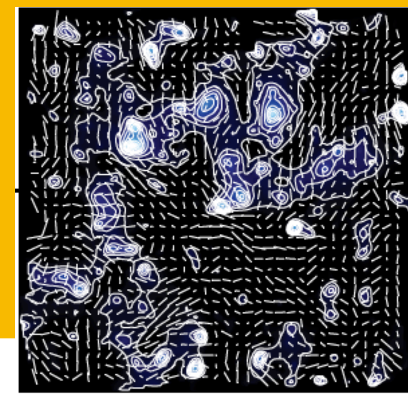
SDSSIII BOSS

Growth of structure



MPA/Millennium

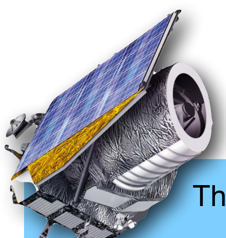
Weak lensing



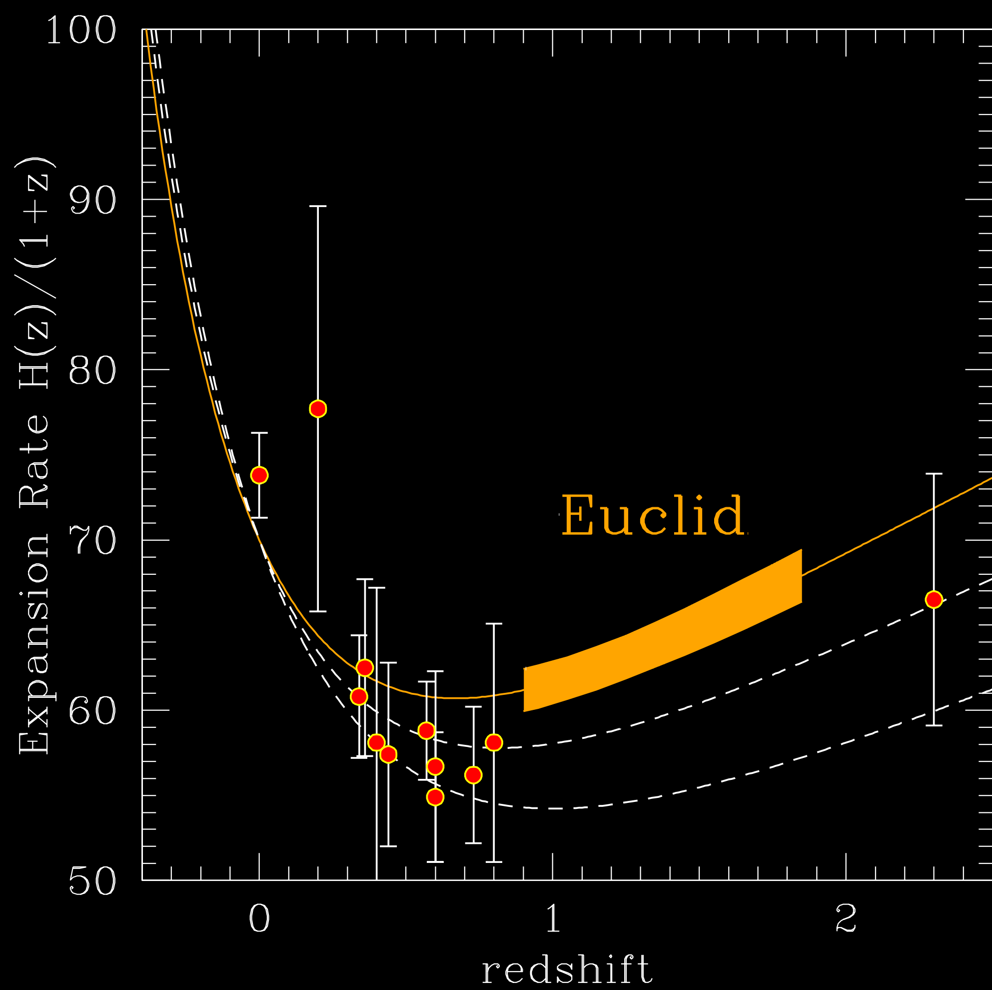
COSMOS

…plus

- Clusters
- CMB cross-correlations
- Strong lensing
- … and more

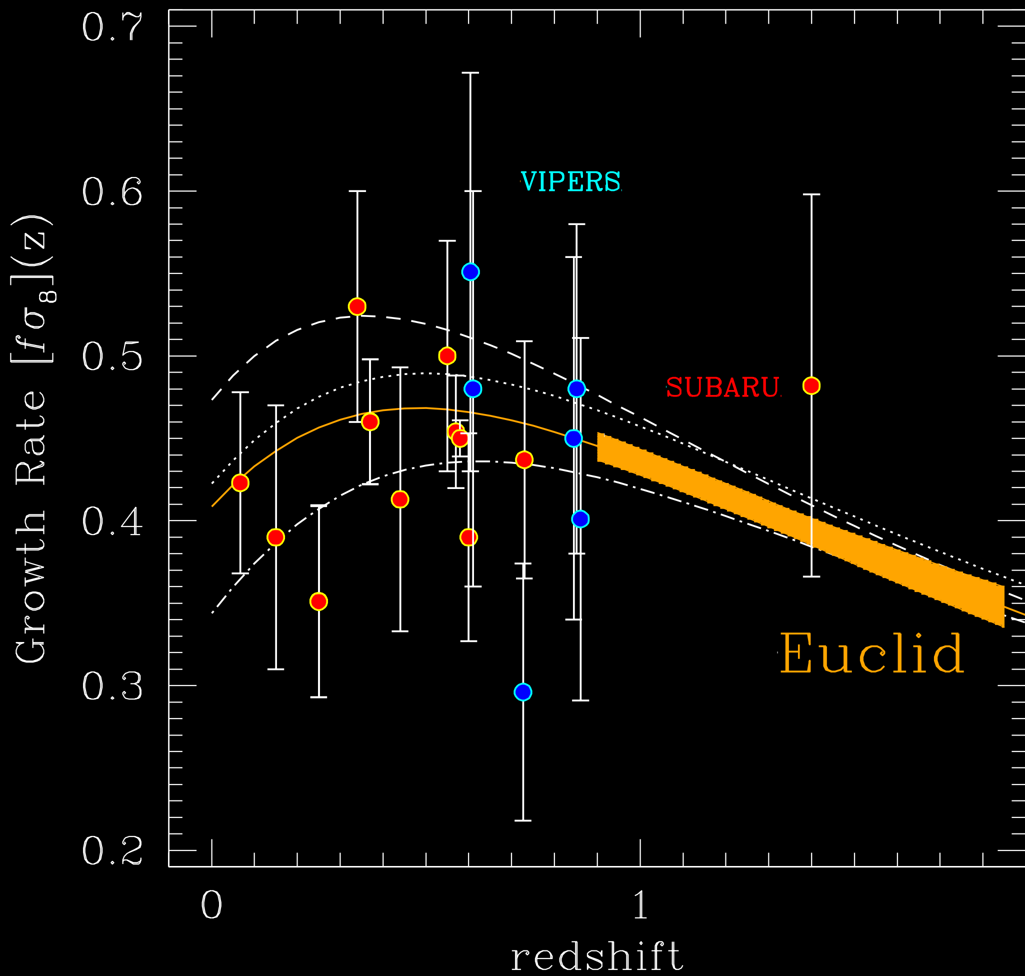


Expansion history from BAO



LG (2017), Euclid forecast based on 2014 Galaxy Clustering WG Interim Review Report

Euclid expectations from RSD

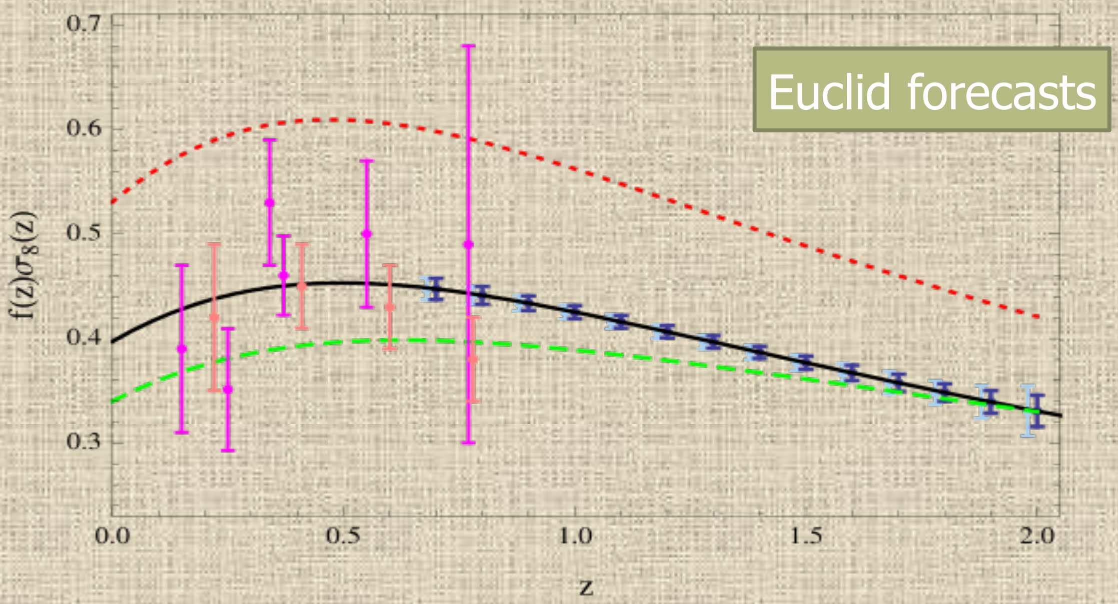


LG (2017), Euclid forecast based on 2014 Galaxy Clustering WG Interim Review Report

Systematic errors in RSD modelling dominate…

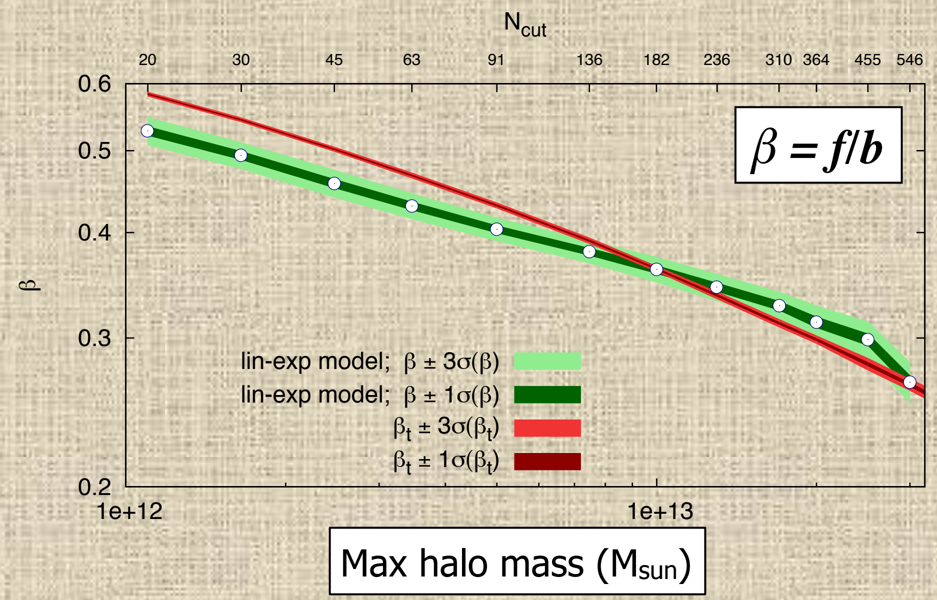
Significant effort over the last 10 years, as to achieve "precision RSD era"

→ EUCLID: aims at 1-3% precision on $f\sigma_8$



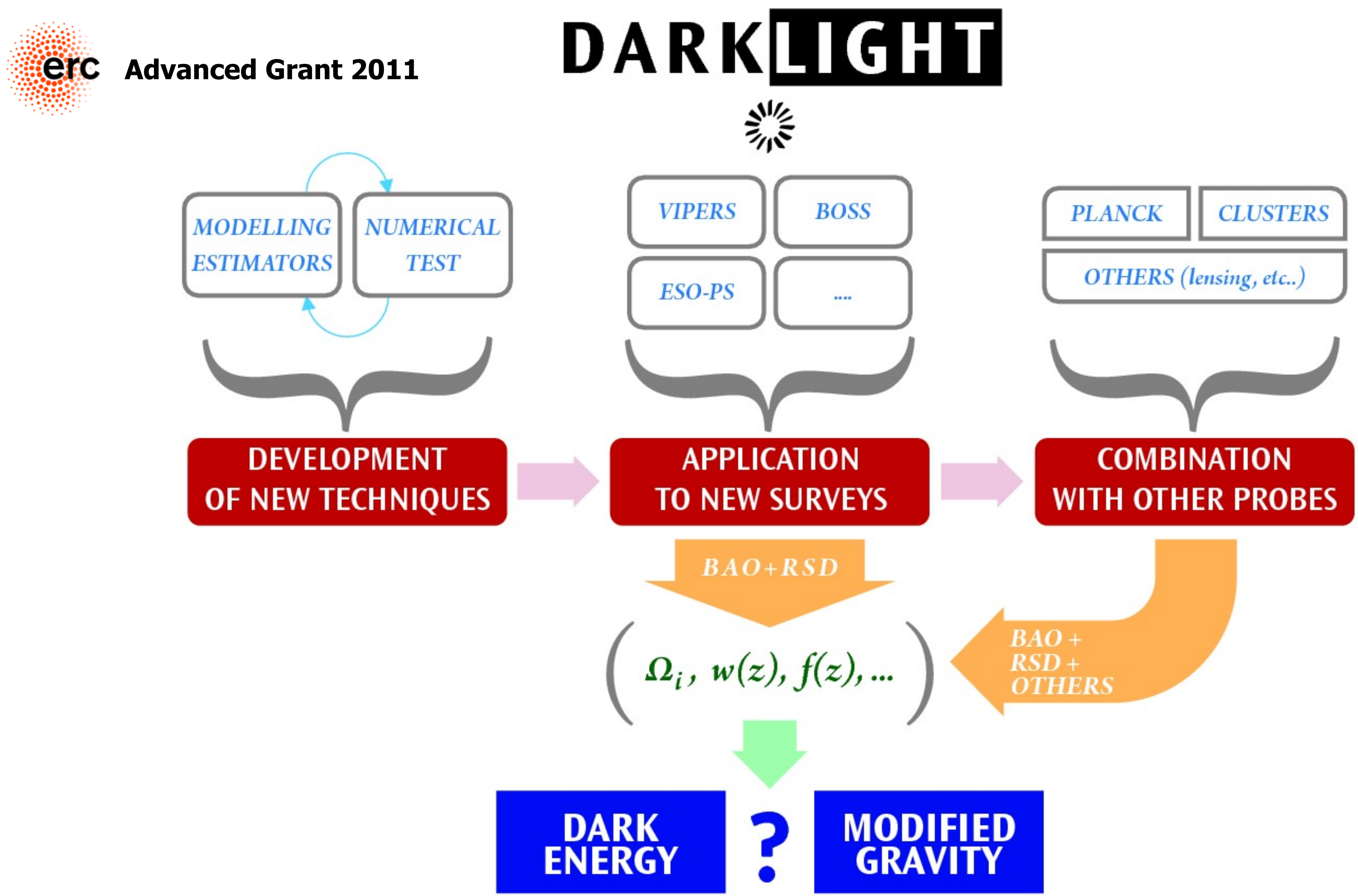
(Majerotto, LG, Samushia et al. 2012)

→ Standard modelling as of 2011: up to 10% systematic error



(Bianchi, LG et al., 2012)

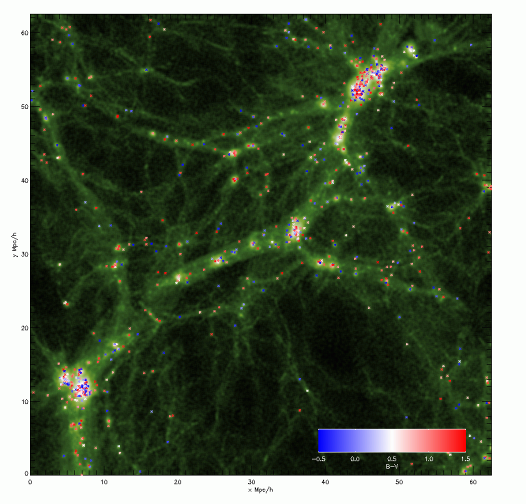
(also: Okumura & Jing, 2011)



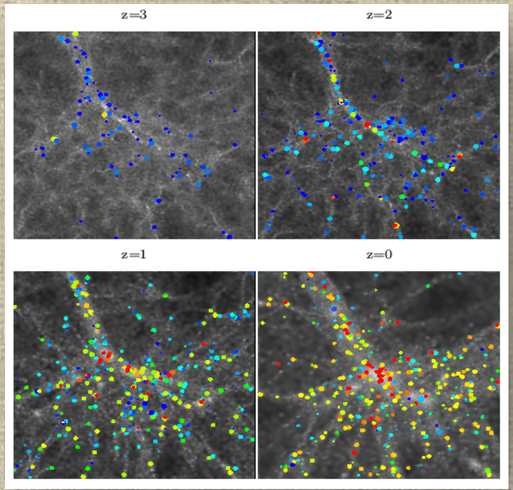
erc
Advanced Grant 2011
DARKLIGHT
MODELLING ESTIMATORS
NUMERICAL TEST
VIPERS
BOSS
ESO-PS
....
PLANCK
CLUSTERS
OTHERS (lensing, etc..)
DEVELOPMENT OF NEW TECHNIQUES
APPLICATION TO NEW SURVEYS
COMBINATION WITH OTHER PROBES
BAO+RSD
BAO + RSD + OTHERS
Ω_i, $w(z)$, $f(z)$, ...
DARK ENERGY
?
MODIFIED GRAVITY

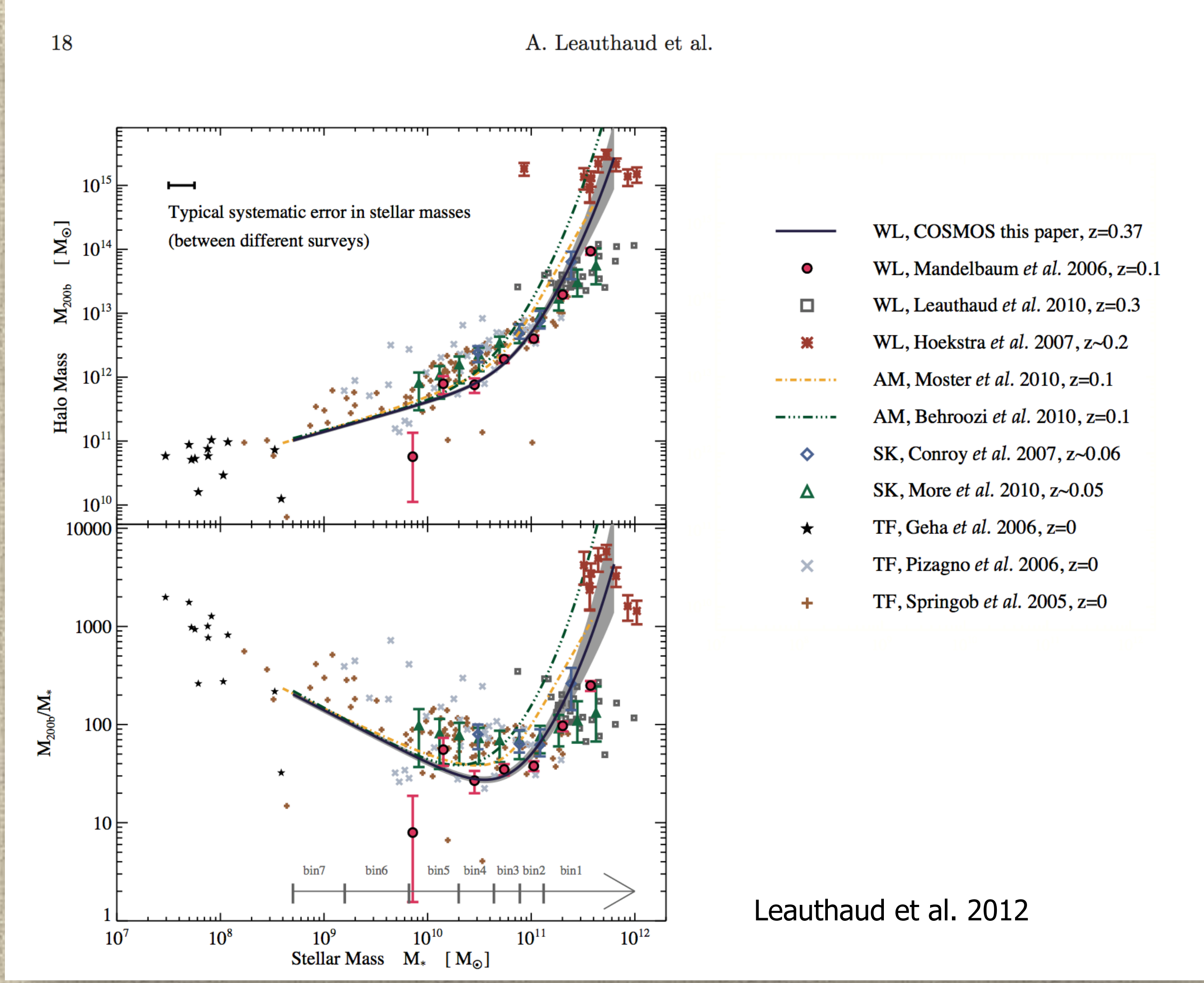
We need to understand galaxies, to do cosmology…

see e.g. Maccio' et al. 2017, MNRAS



Kauffman & Diaferio 1998



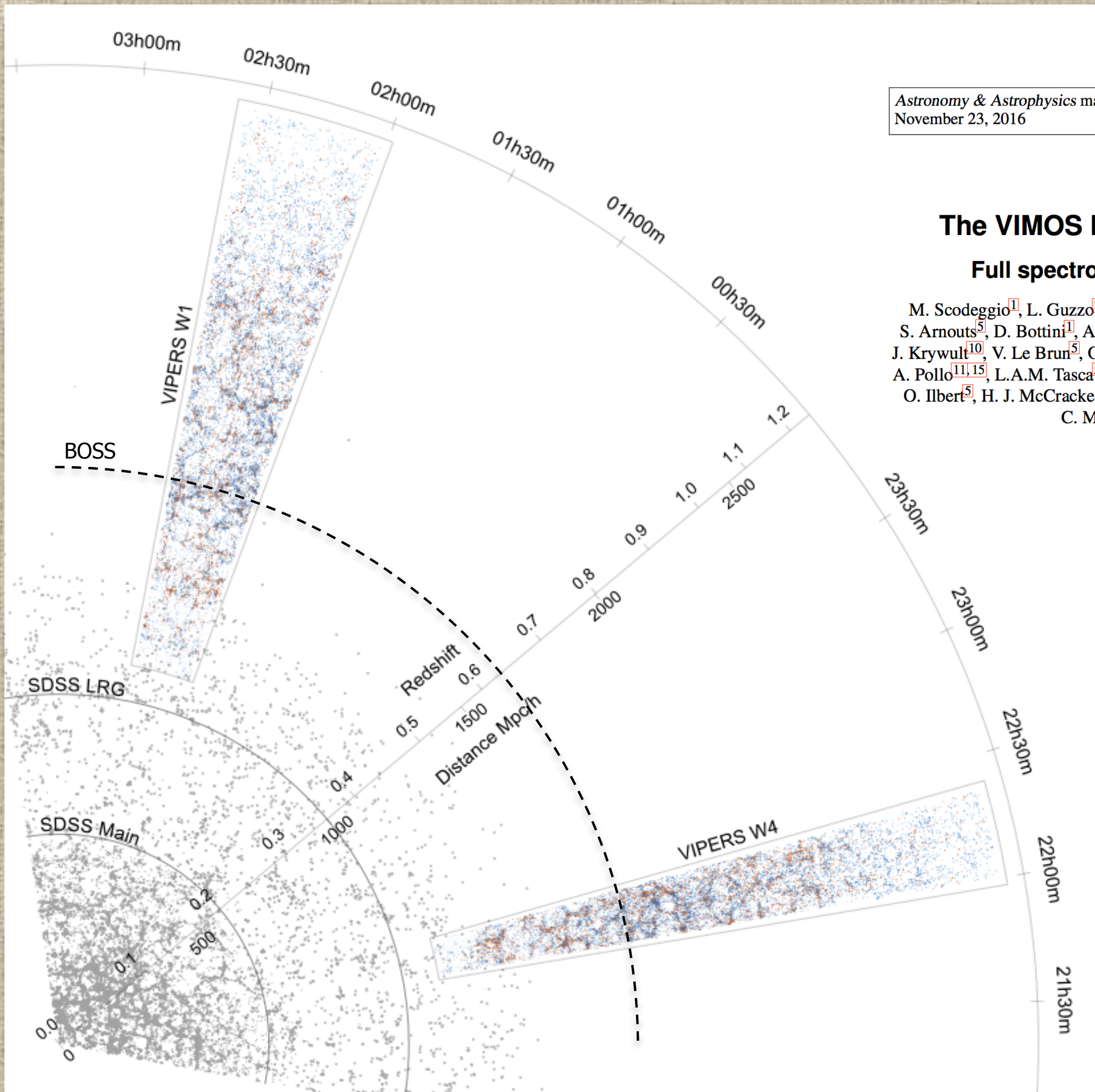


Leauthaud et al. 2012

…improve our data (while waiting for Euclid)


VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

VIPERS brings SDSS-like concept to z~1



Astronomy & Astrophysics manuscript no. scodeggio_PDR2_v2.5
November 23, 2016

The VIMOS Public Extragalactic Redshift Survey (VIPERS)*

Full spectroscopic data and auxiliary information release (PDR-2)

M. Scodeggio[1], L. Guzzo[2,3], B. Garilli[1], B. R. Granett[2,3], M. Bolzonella[4], S. de la Torre[5], U. Abbas[6], C. Adami[5], S. Arnouts[5], D. Bottini[1], A. Cappi[4,7], J. Coupon[8], O. Cucciati[9,4], I. Davidzon[5,4], P. Franzetti[1], A. Fritz[1], A. Iovino[2], J. Krywult[10], V. Le Brun[5], O. Le Fèvre[5], D. Maccagni[1], K. Małek[11], A. Marchetti[1], F. Marulli[9,12,4], M. Polletta[1,13,14], A. Pollo[11,15], L.A.M. Tasca[5], R. Tojeiro[16], D. Vergani[17], A. Zanichelli[18], J. Bel[19], E. Branchini[20,21,22], G. De Lucia[23], O. Ilbert[5], H. J. McCracken[24], T. Moutard[25,5], J. A. Peacock[26], G. Zamorani[4], A. Burden[27], M. Fumana[1], E. Jullo[5], C. Marinoni[19,28], Y. Mellier[24], L. Moscardini[9,12,4], and W. J. Percival[27]

Table 2. The VIPERS PDR-2 spectroscopic sample

Sample	Number
Spectroscopically observed	97,414
— Main survey targets	94,335
— Serendipitous targets	1,478
— AGN candidates (not part of main survey)	1,601
Measured redshifts	**Number**
All measured	91,507
Main survey, all targets	89,022
— galaxies	86,775
— stars	2,247
Flag ≥ 2 main survey, all targets	78,586
Flag ≥ 2 main survey, galaxies	76,552

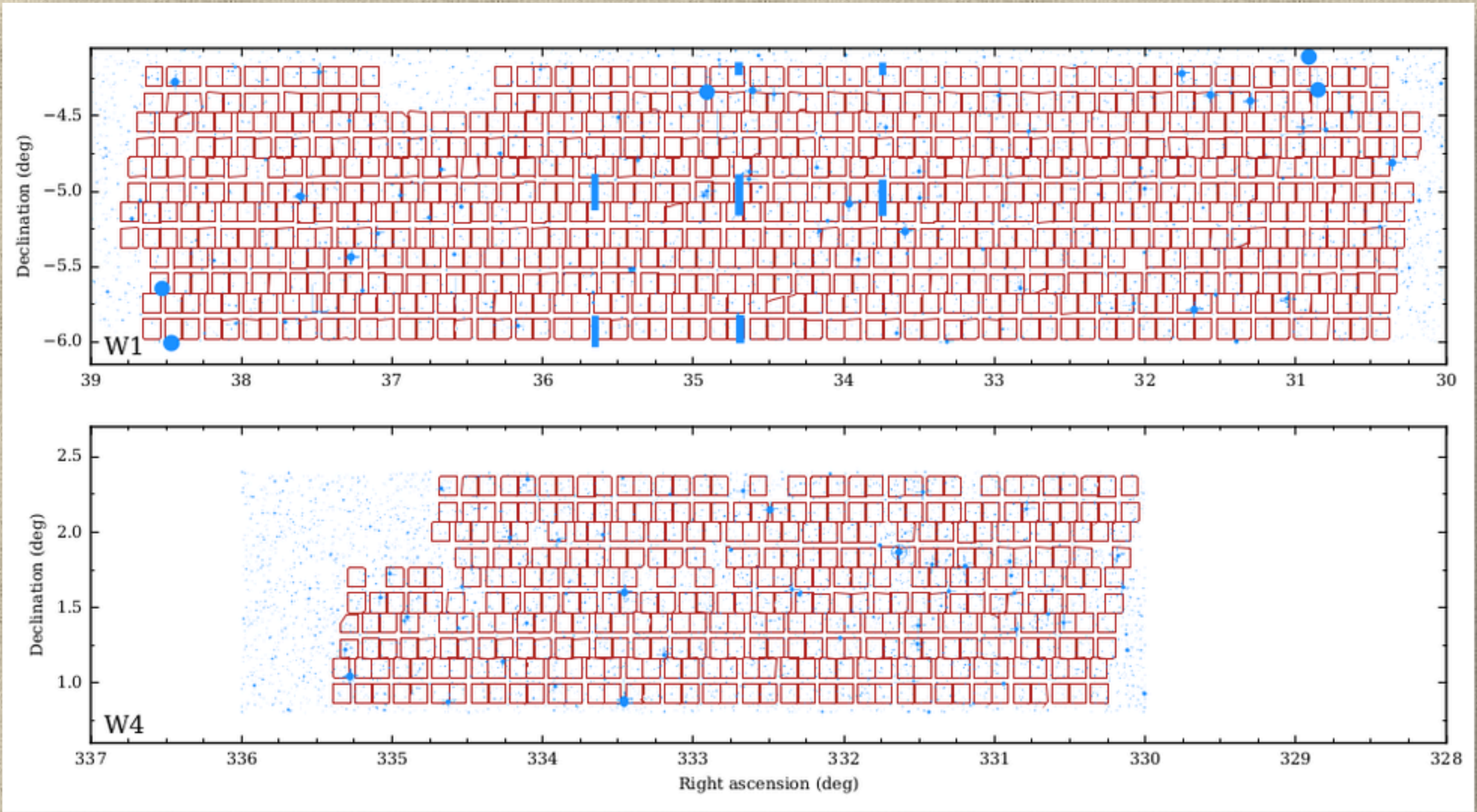
VIMOS @ VLT fills unique niche in density-area observing space

At VIPERS depth: ~100 gal/quadrant →
400/224 gal/arcmin^2 ~ **6000 gal/deg^2**

VIPERS Team

(see http://vipers.inaf.it)

Survey layout and photometric/spectroscopic masks

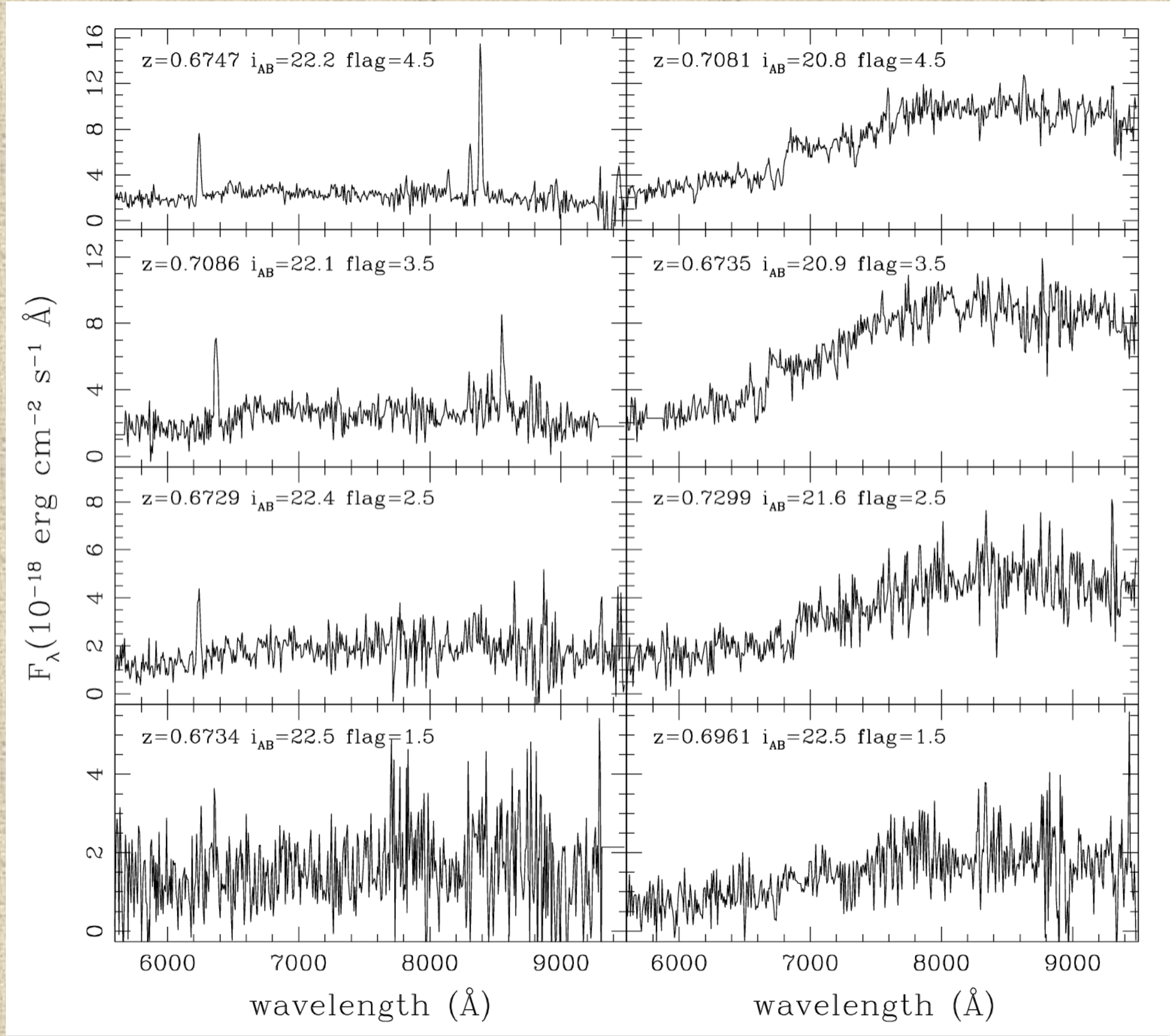


→ This and other ancillary information also released with PDR-2

(mask reconstruction by Ben Granett)

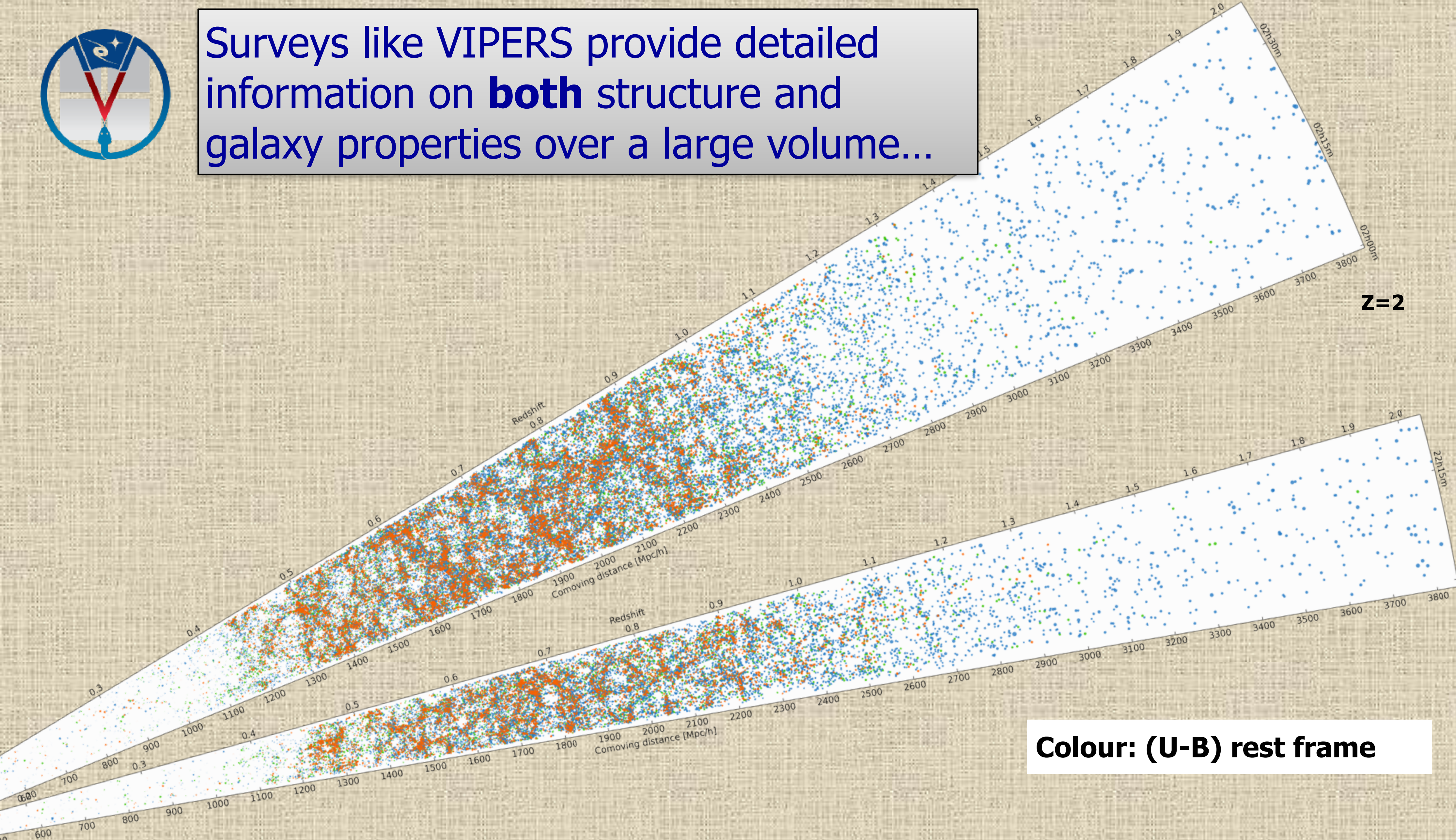
VIPERS spectra

- **R=220 at mid-range**
- **λ= 5500 – 9500 A**
- **σ_z = 0.00054(1+z)**
- **Spectral indices and line fluxes** (e.g. D4000, [OII]3727), available for large fraction of sample



(Scodeggio+ 2018)

Surveys like VIPERS provide detailed information on **both** structure and galaxy properties over a large volume…

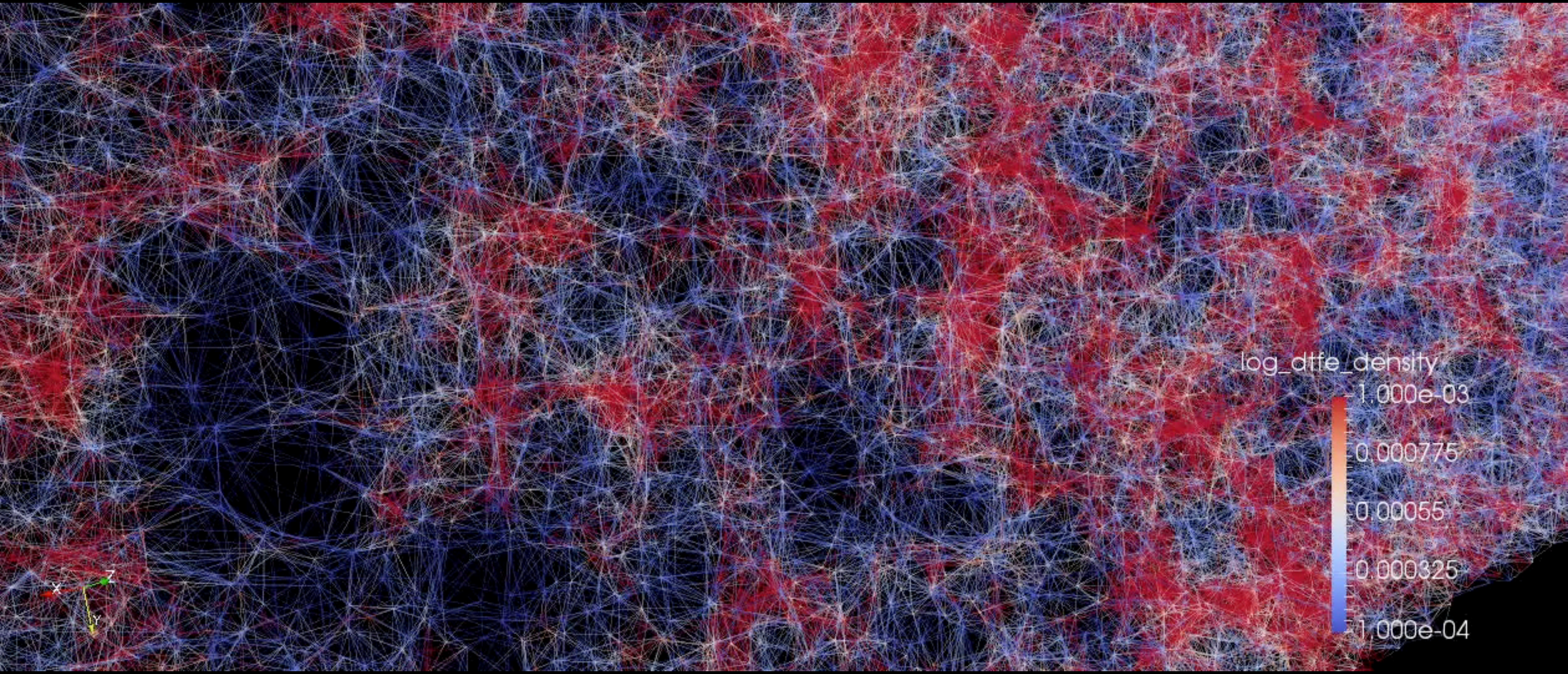


Z=2

Colour: (U-B) rest frame

(artwork by Ben Granett)

VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

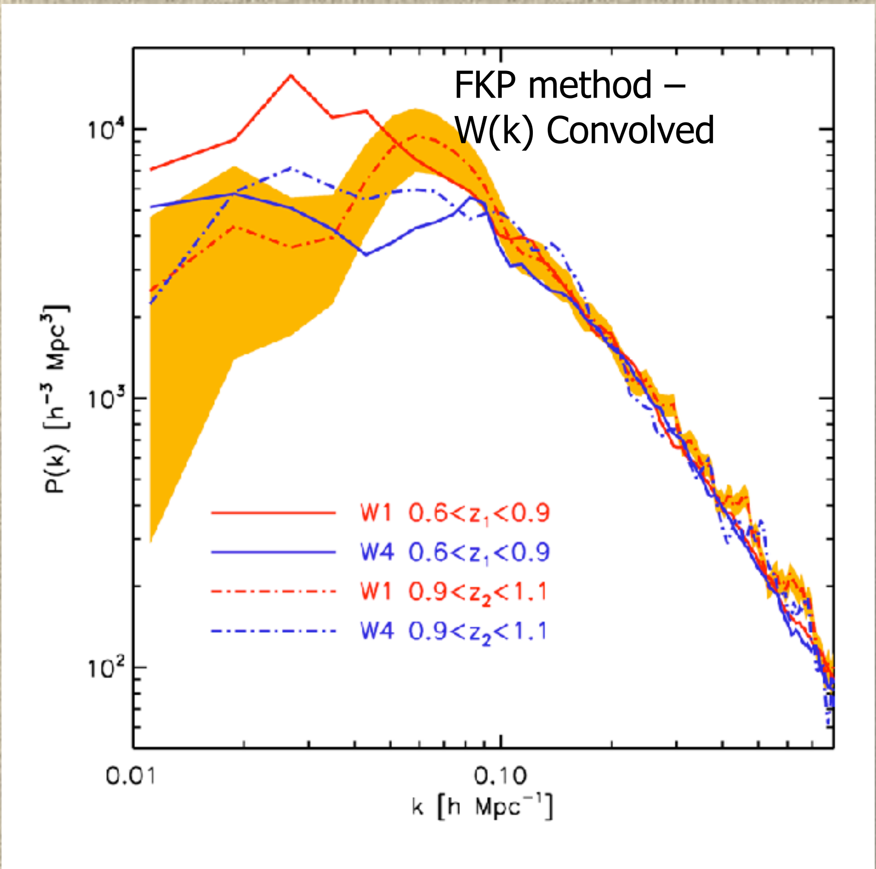


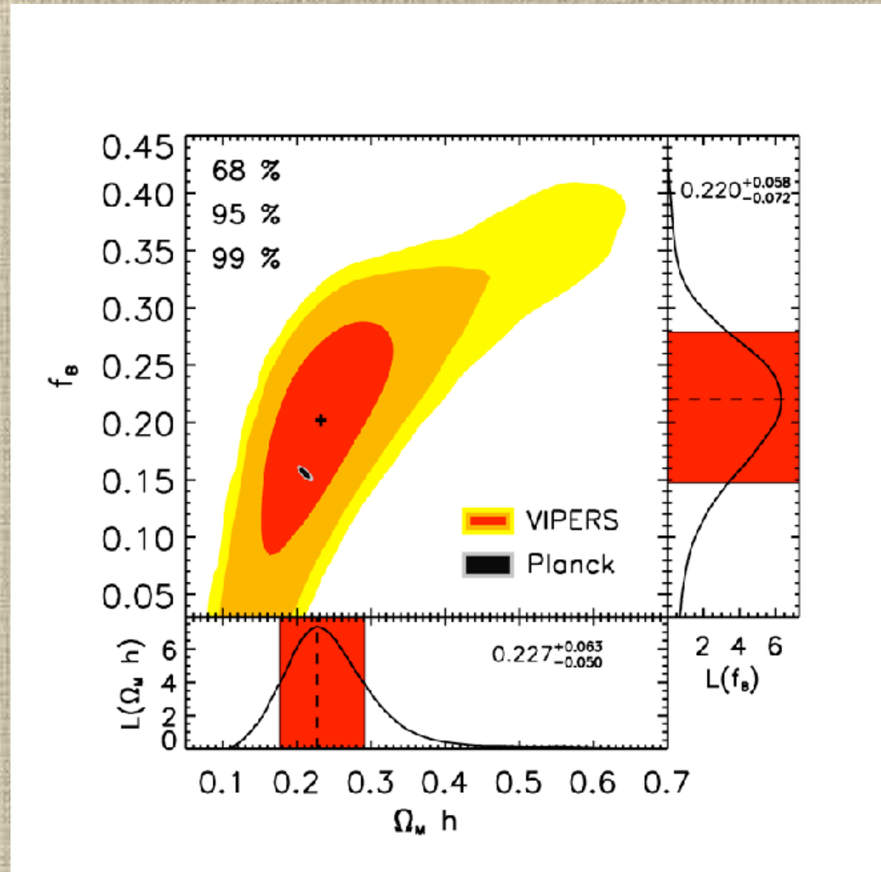
http://vipers.inaf.it

(Movie by N. Malavasi / S. Arnouts& VIPERS collaboration – see 1611.07045)

The power spectrum of the galaxy distribution at z=0.5-1.1

(S. Rota PhD thesis; Rota, Granett+ 2017 (1611.07044)





• Needs careful treatment of window function and nonlinear effects

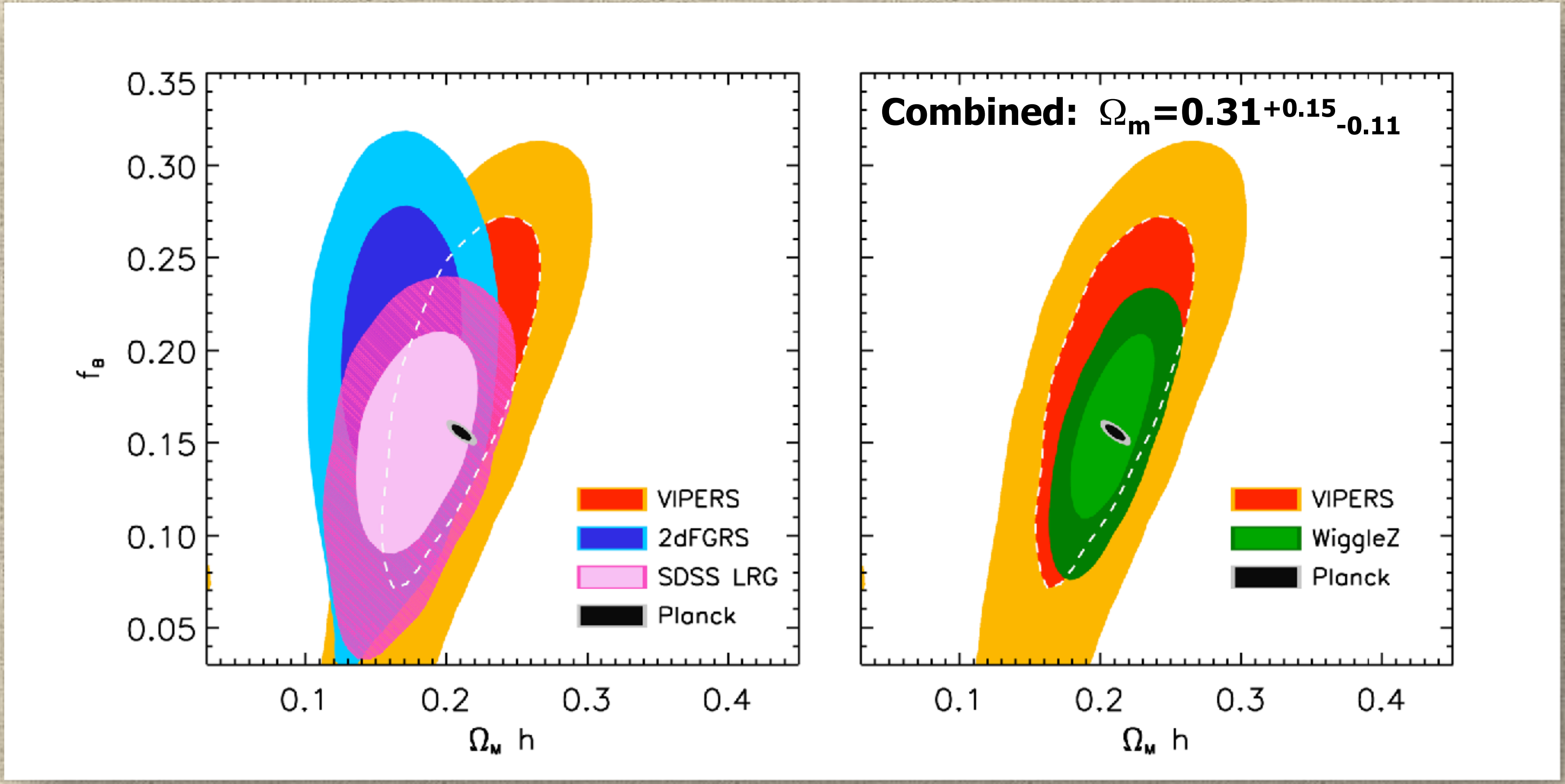
• Joint likelihood of 4 independent estimates: 2 redshift bins in 2 fields (W1 and W4)

erc DARK LIGHT

The power spectrum of the galaxy distribution at z=0.5-1.1

- **Highest redshift at which P(k) measured from galaxy distribution**
- **Consistency test of ΛCMD at about half Hubble time, straddling Planck and local data**

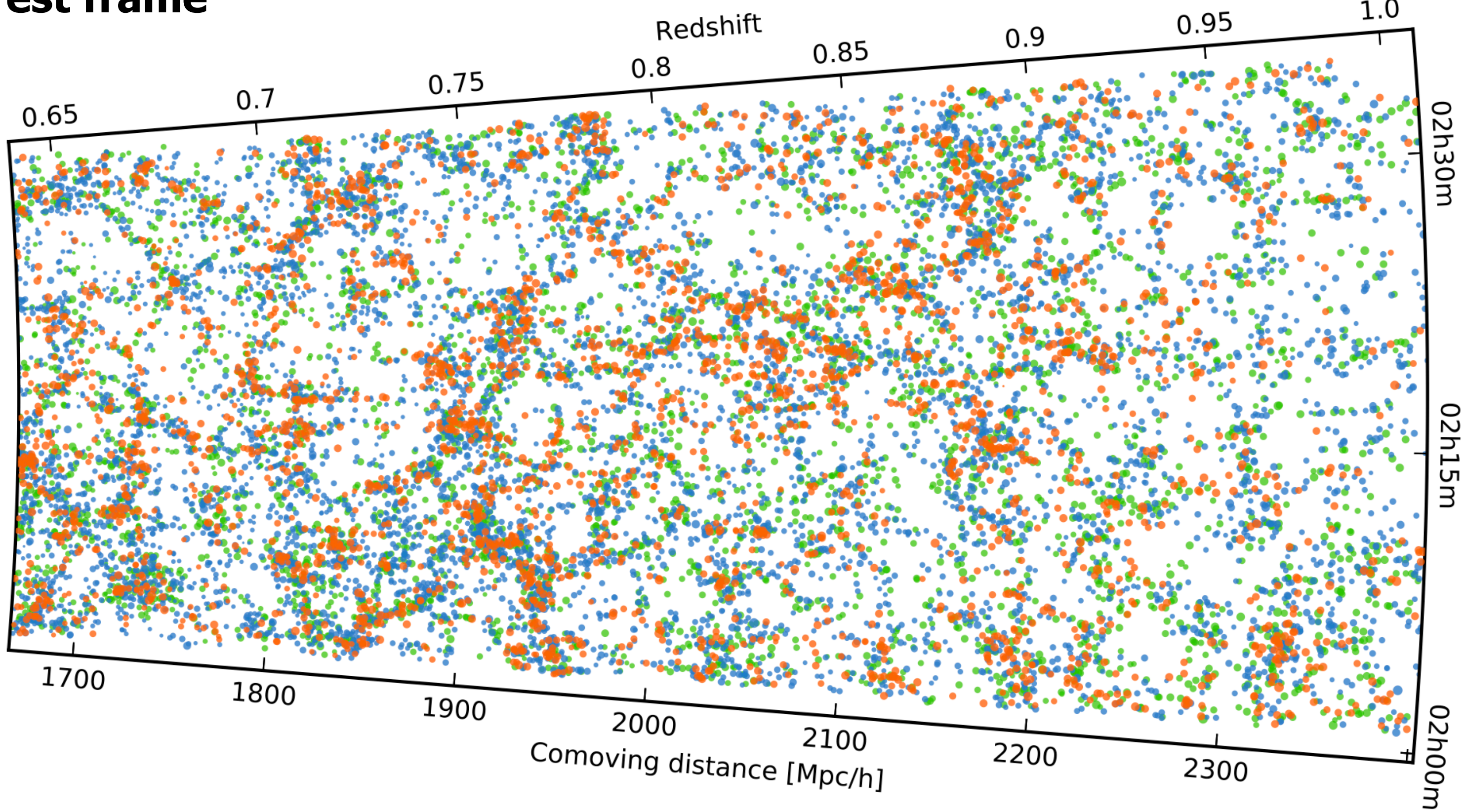
→ Ellipses move towards Planck moving to higher z ?



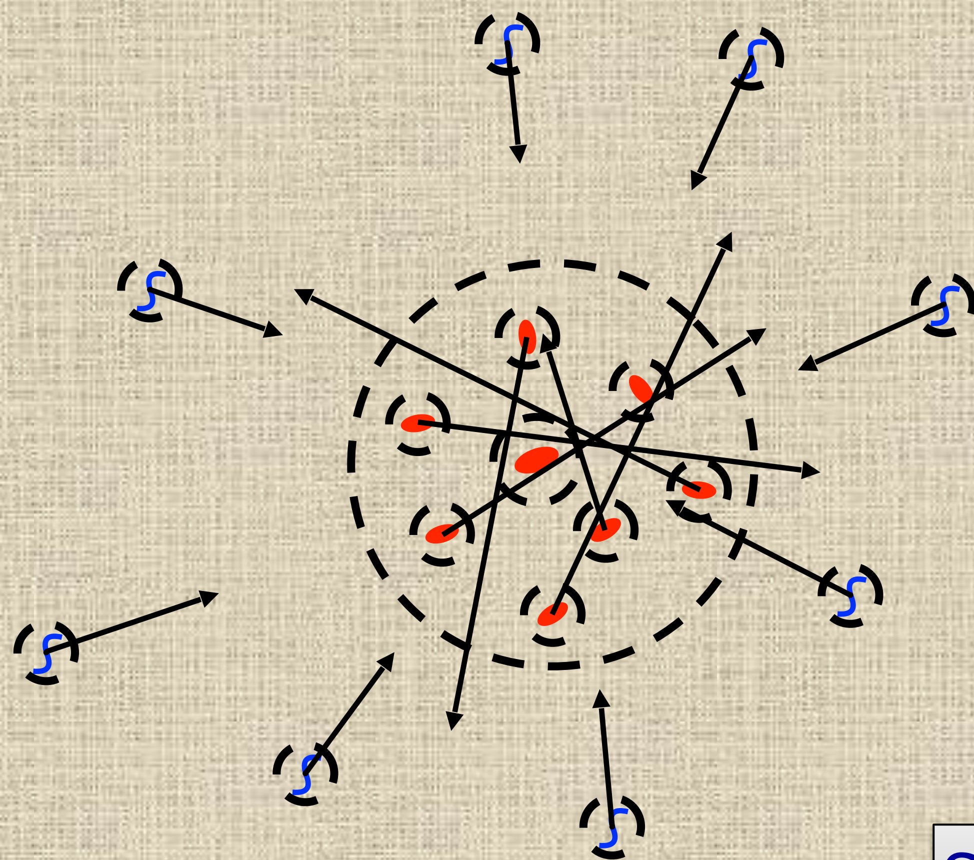
(Rota+ 2017; arXiv:1611.07044)

Broad selection function and detailed galaxy properties

(U-B) rest frame

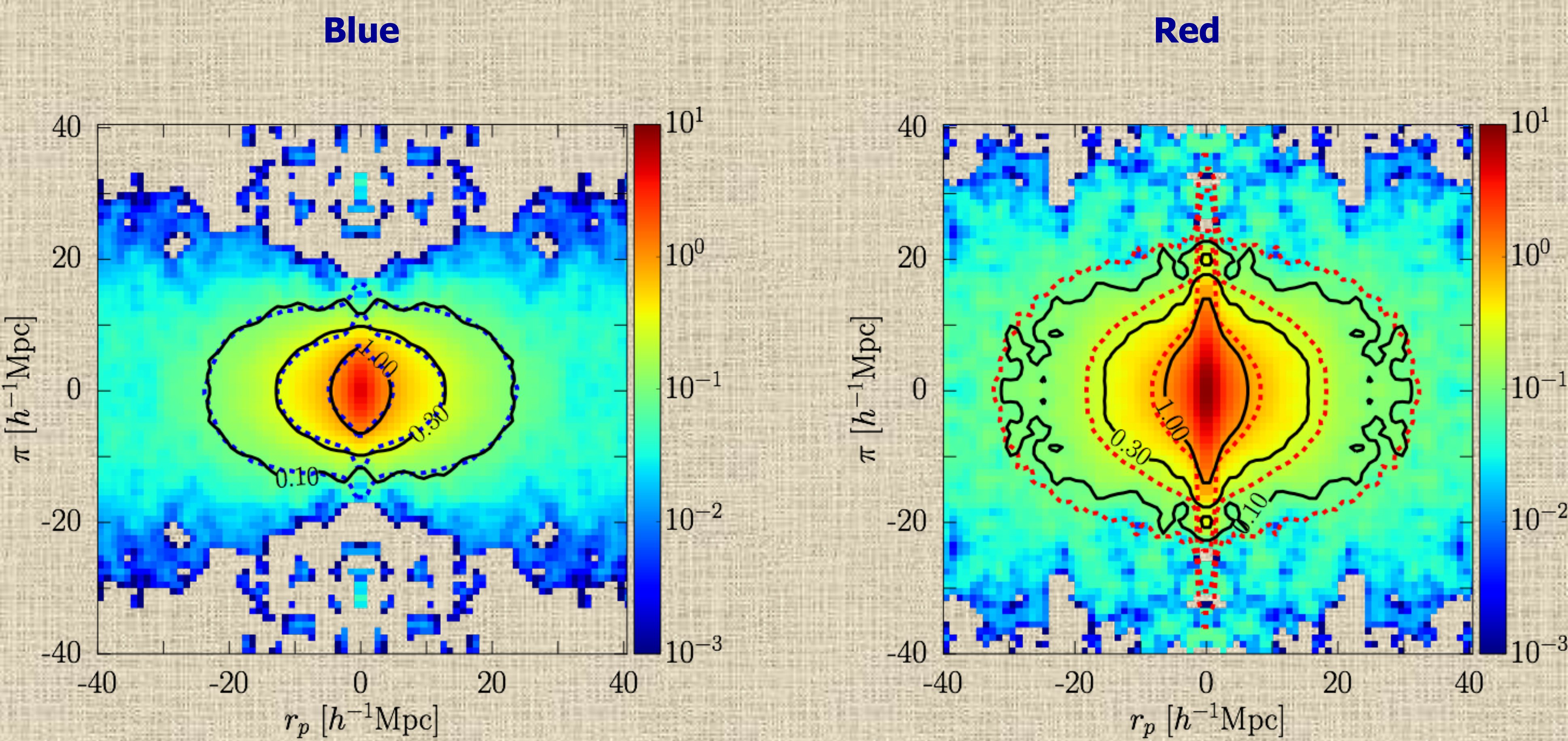


Different galaxies trace the velocity field differently…



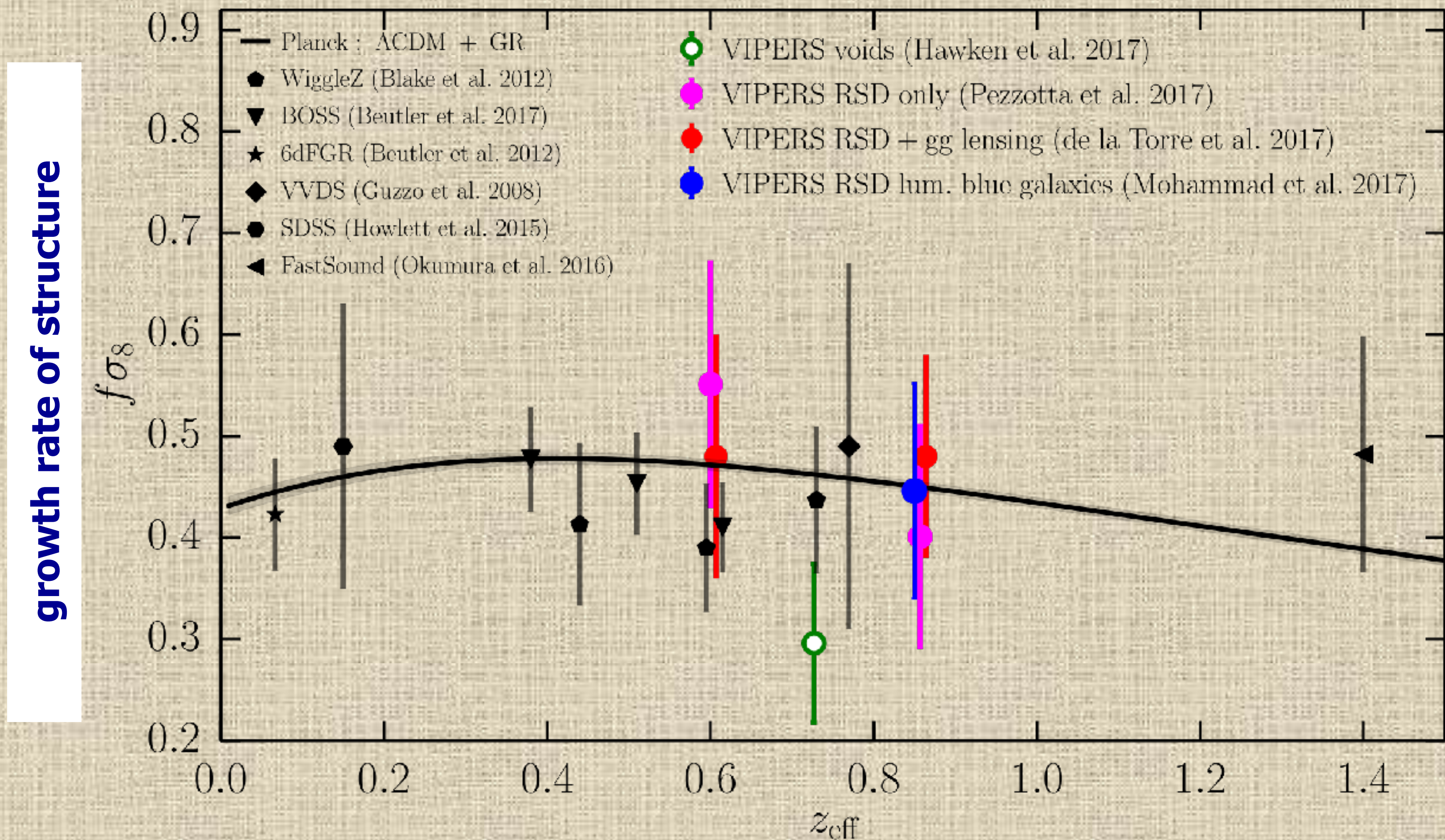
Some may be easier to model…

Redshift-space clustering of blue and red galaxies in VIPERS



(Mohammad+ 2018, arXiv:1708.00026)

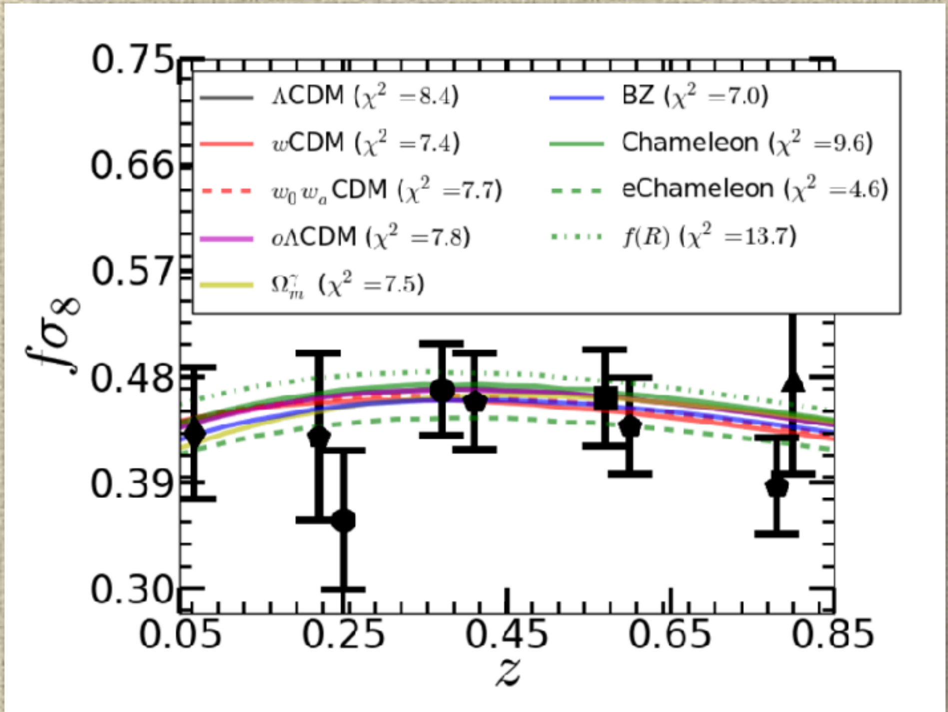
Testing gravity with RSD in VIPERS

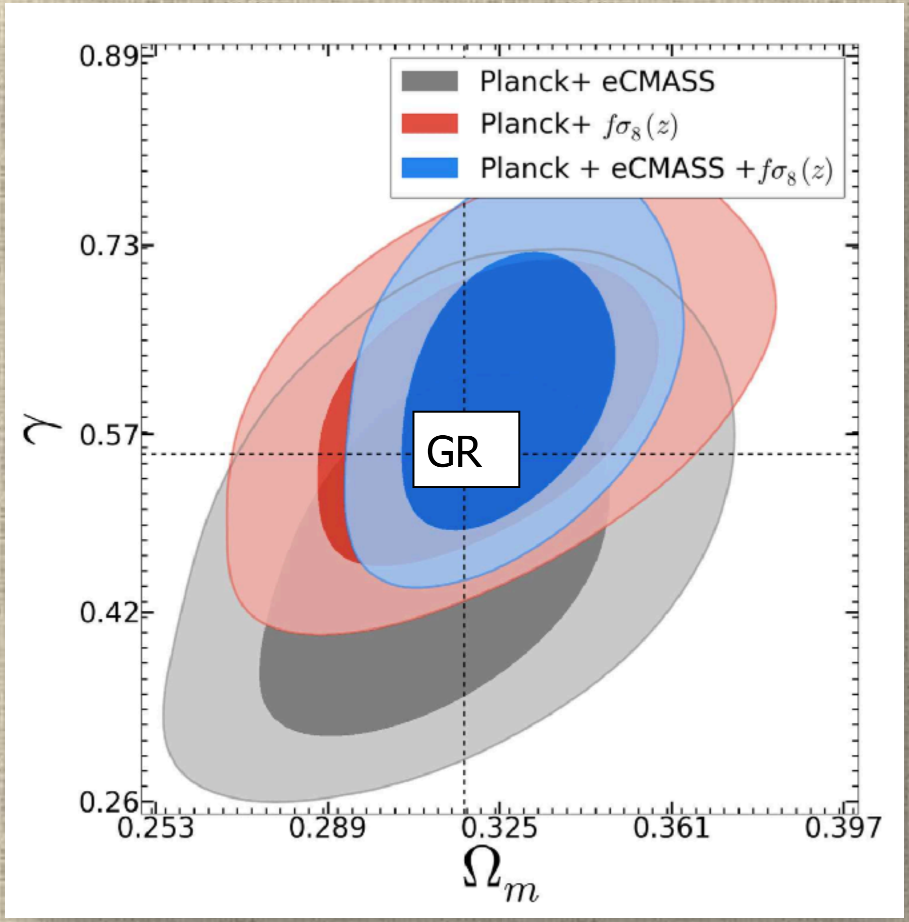


VIPERS PDR-2 (Pezzotta+ 2017; de la Torre+ 2017; Hawken+ 2017; Mohammad+ 2017; Wilson 2018)

Testing gravity with redshift-space distortions

(Alam, Ho & Silvestri 2016)





Forward modelling of survey data: use all available information (e.g. Wiener-filtering)

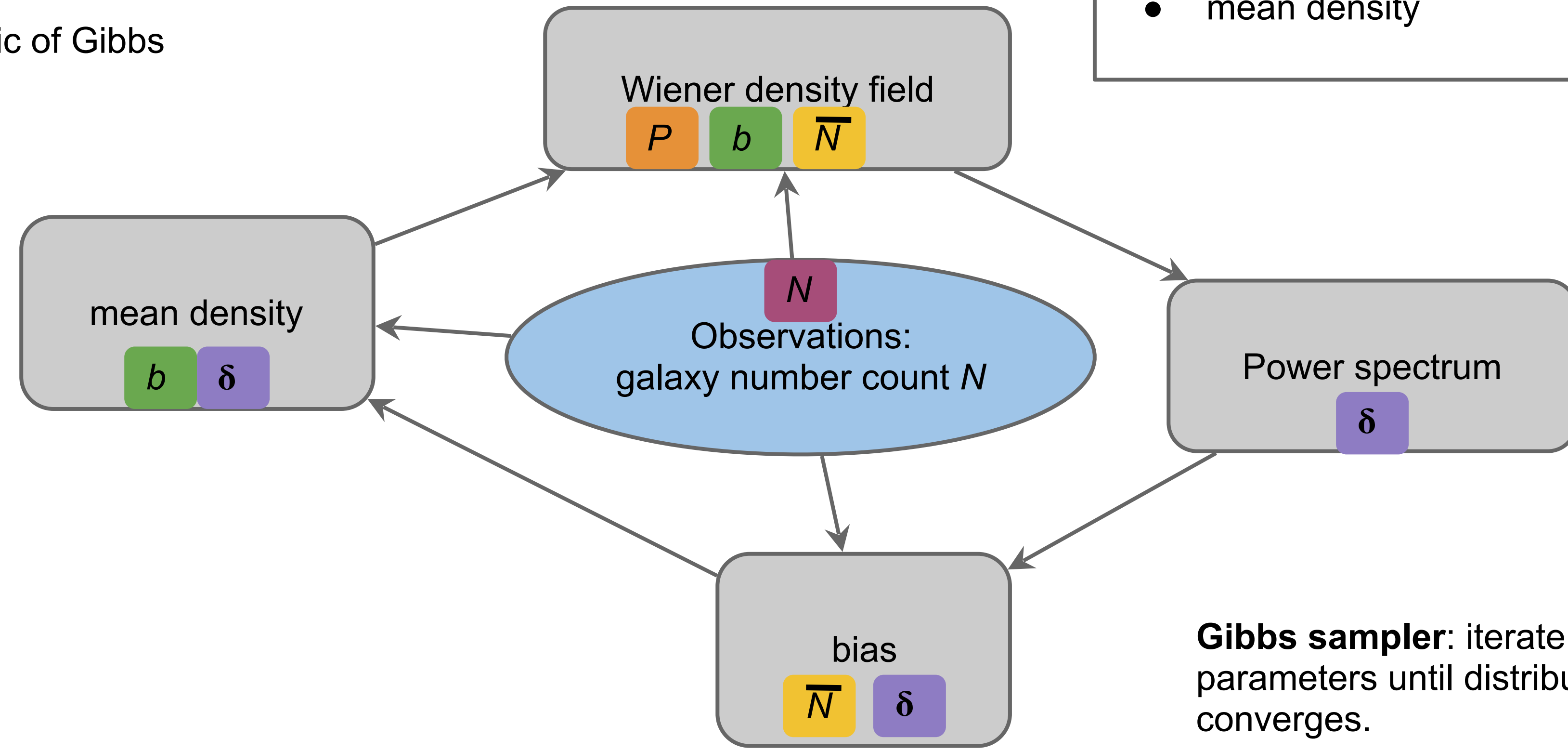
Granett+ 2015 (1505.06337)

- Markov Chain random walk through the parameter space gives the joint posterior probability distribution of the density field and galaxy statistics.

Dependencies

- Wiener density field δ
- Power spectrum P
- bias b
- mean density $\bar{N}$

Schematic of Gibbs sampler:



Gibbs sampler: iterate through parameters until distribution converges.

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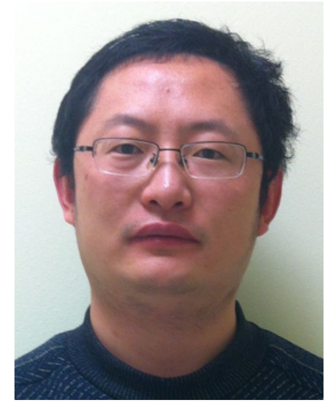
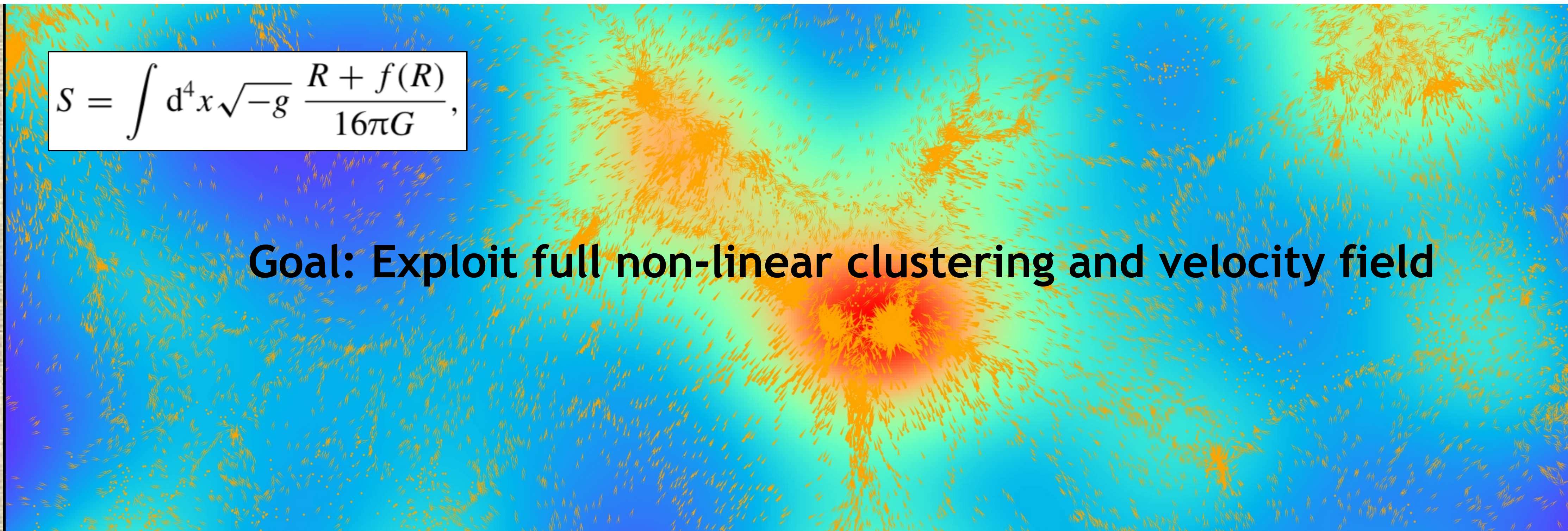
https://doi.org/10.1038/s41550-018-0573-2

No evidence for modifications of gravity from galaxy motions on cosmological scales

Jian-hua He[1*], Luigi Guzzo[2,3,4], Baojiu Li[1] and Carlton M. Baugh[1]



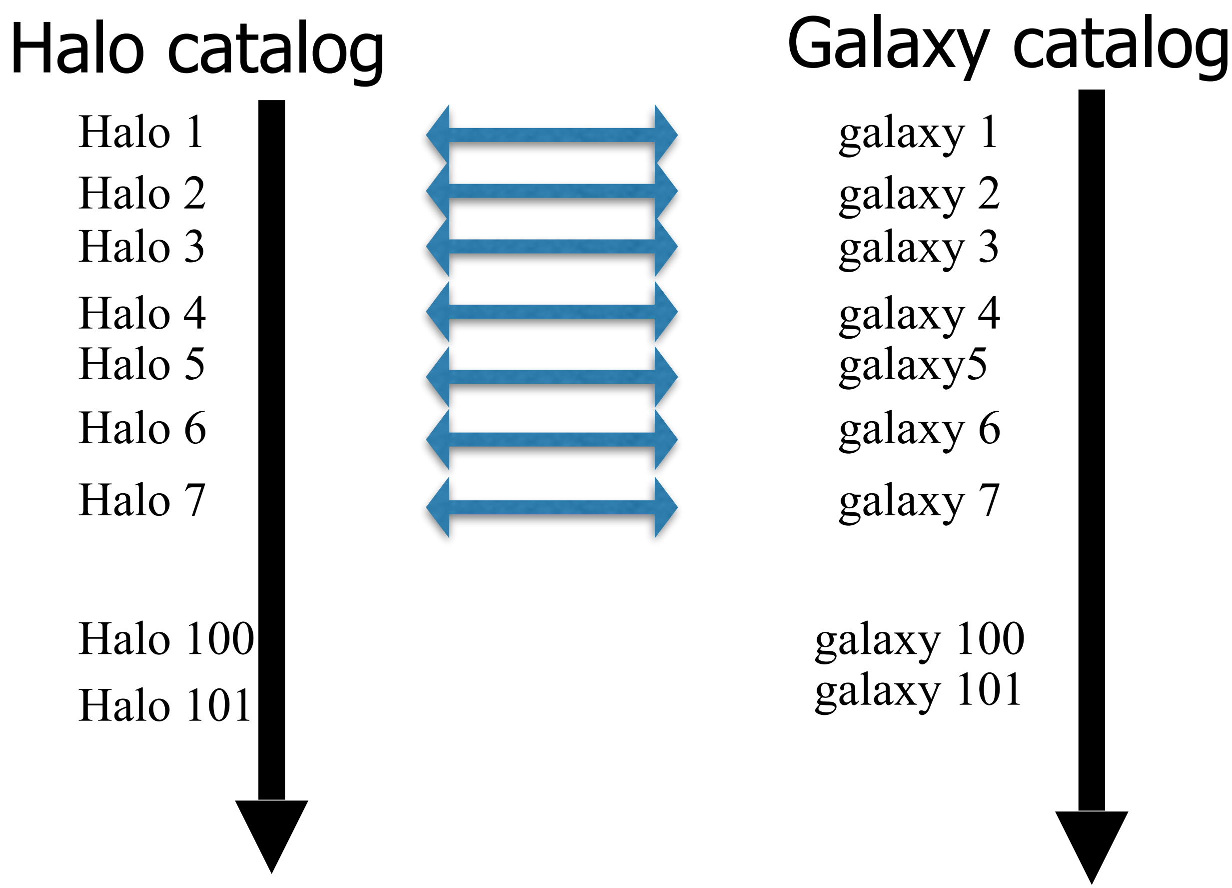


$$S = \int d^4x \sqrt{-g}\, \frac{R + f(R)}{16\pi G},$$

Goal: Exploit full non-linear clustering and velocity field

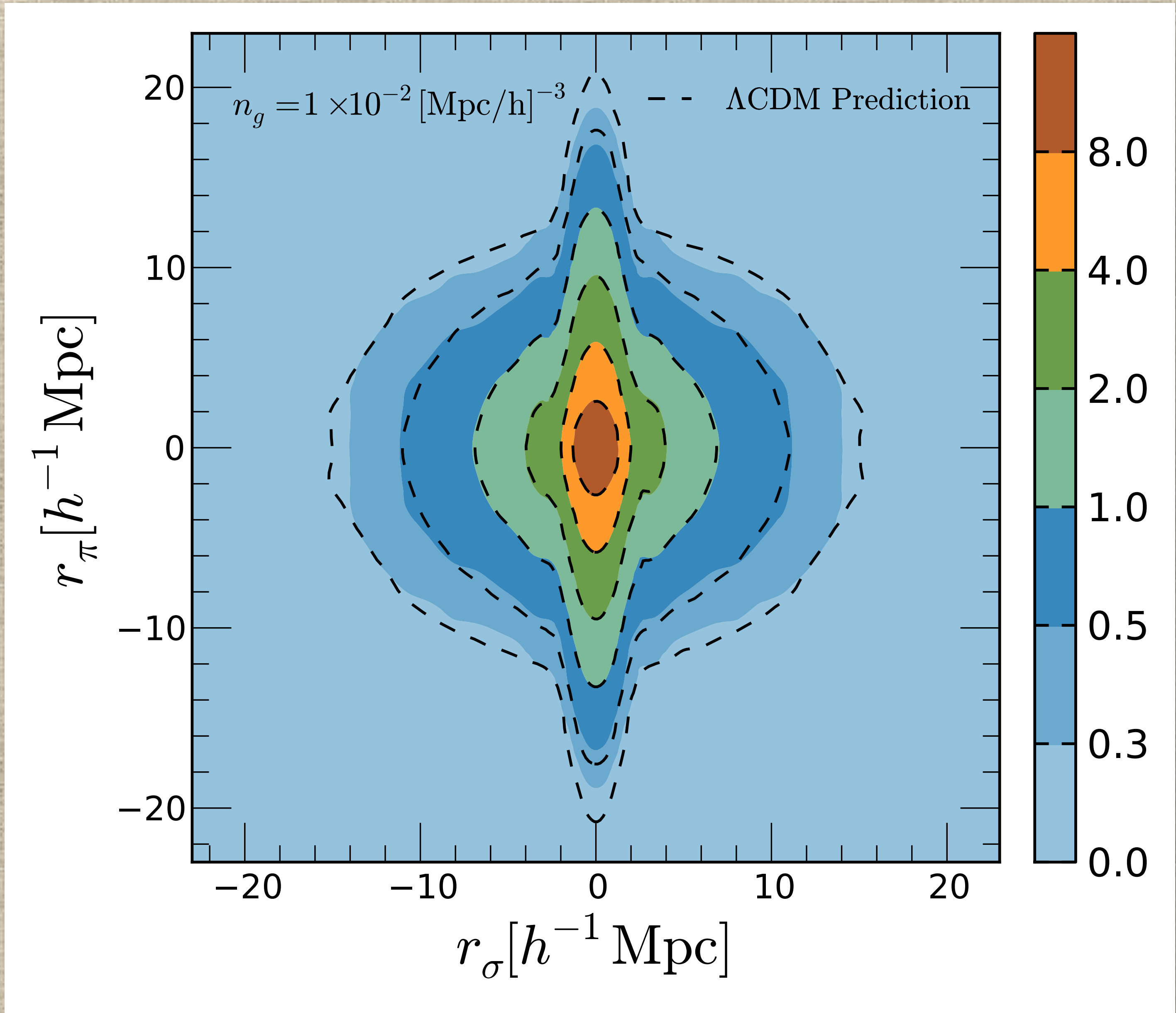
Match a dark matter halo property to a galaxy property
(Sub-Halo Abundance Matching - SHAM)

The paradigm: galaxies form inside dark-matter halos

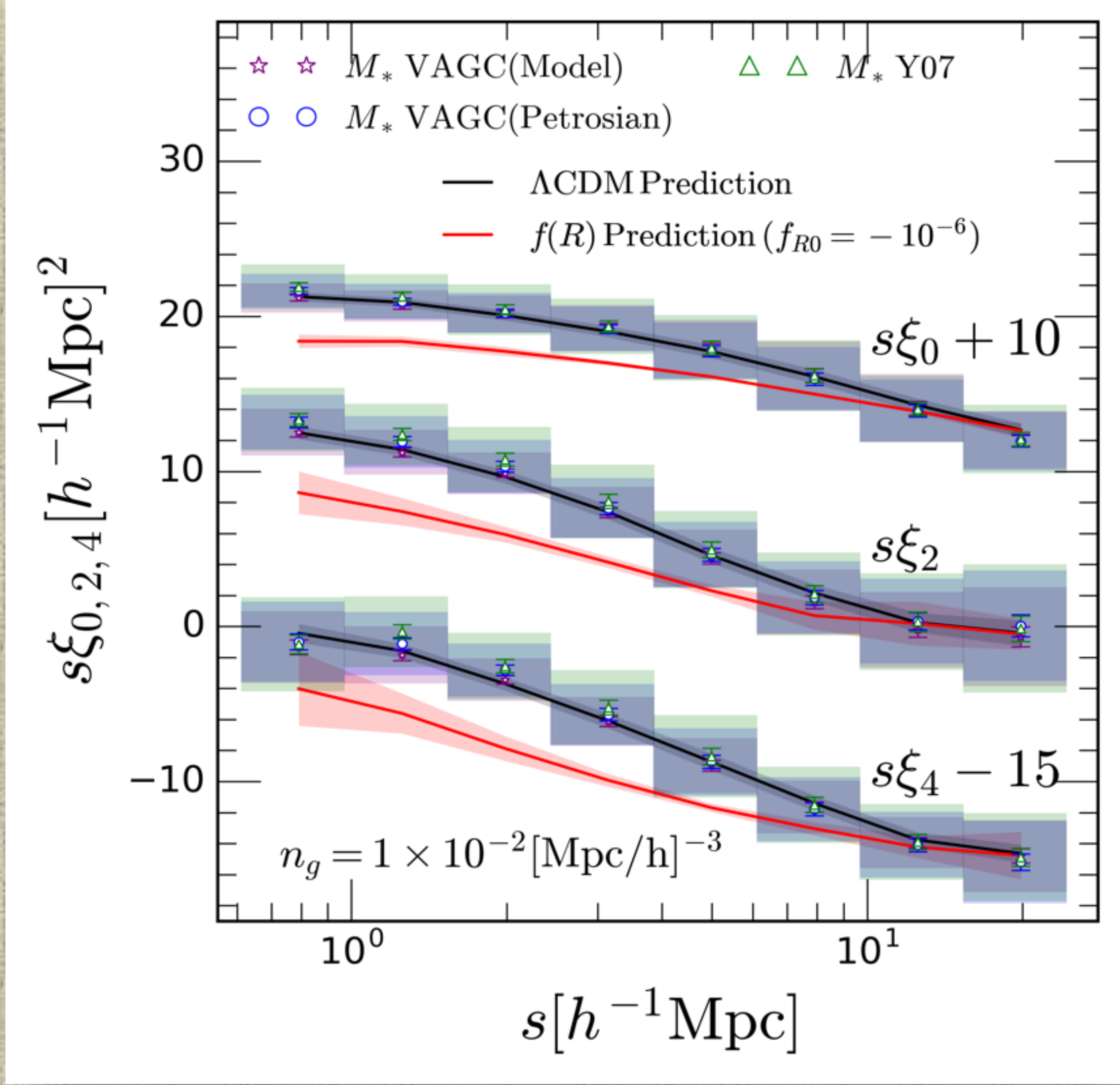


One to one map between (simulated) halos and (observed) galaxies

Results: matching SDSS clustering to ΛCDM



Results: ΛCDM vs f(R)



Summary

- The nature of the dark ingredients of the current standard model of cosmology (**dark energy** and **dark matter**) is surely the central mystery of modern cosmology. Its solution may well require a paradigm shift in our understanding of the Universe (e.g. Boyle+ 1803.08930)
- Dark energy (today revealed as a **cosmological constant Λ**) could either be the ground state of an evolving scalar field, or perhaps evidence of a large-scale failure of General Relativity
- **Galaxy redshift surveys** reconstructing the large-large-scale structure of the Universe have been instrumental to build this very successful model and remain crucial also for the future
- The expansion history can be measured using **Baryonic Acoustic Oscillations** (BAO) as a standard ruler, testing a possible evolution of the equation of state away from $w=-1$
- From the same galaxy maps, the growth rate of structure traced by peculiar velocities probes possible modifications of the gravity theory
- New surveys to measure tens of millions of redshifts out to z=2 are starting soon, as most notably the **ESA Euclid** satellite, which will also map dark matter via **weak gravitational lensing**
- Extracting cosmological information from the data requires careful modelling of nonlinear effects, which can introduce systematic errors that dominate over the tiny statistical ones
- Forward modelling based on numerical simulations allows us in principle to use all scales, provided we understand how to match real galaxies to dark matter simulated halos
- Such matching (SHAM) applied to a standard model GR+ΛCDM simulation (He, LG+ 2018) **reproduces impressively well** galaxy clustering and motions in the data, unlike a simulation based on a mild f(R) modification of GR