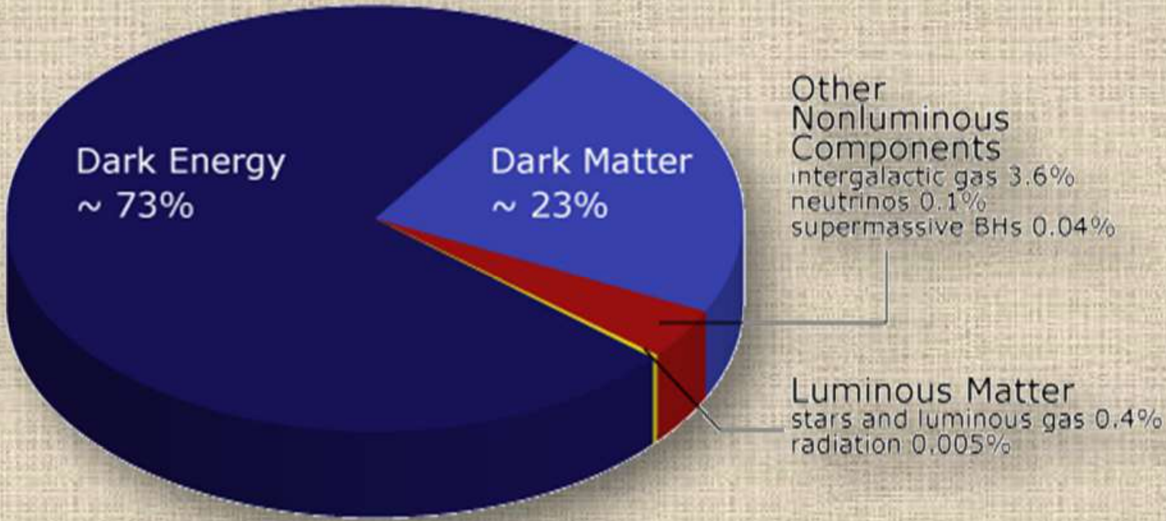
Illuminating Dark Energy with the Next Generation of Cosmological Redshift Surveys

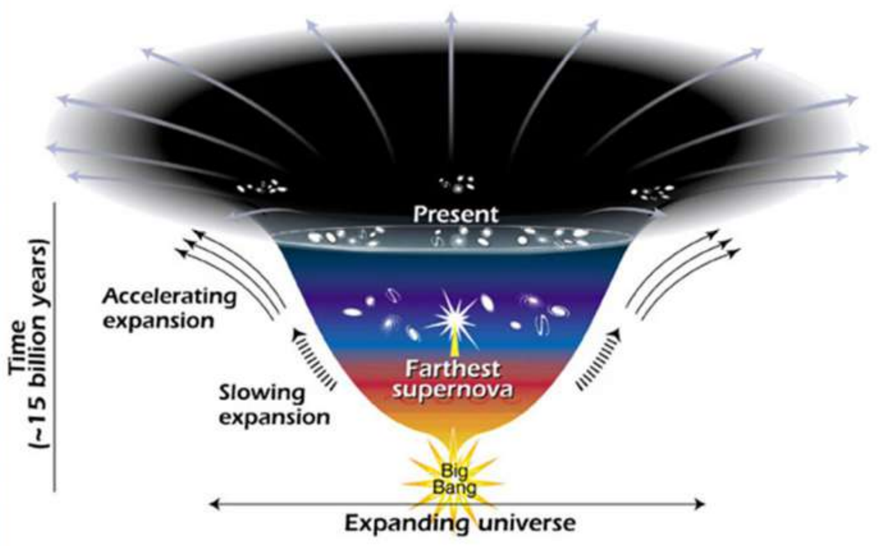
Carmelita Carbone

on behalf of Luigi Guzzo and the Darklight group
(B. Granett, A. Hawken, F. Mohammad, M. Zennaro, et al.)

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 soup" of the 21st century: but who ordered it?

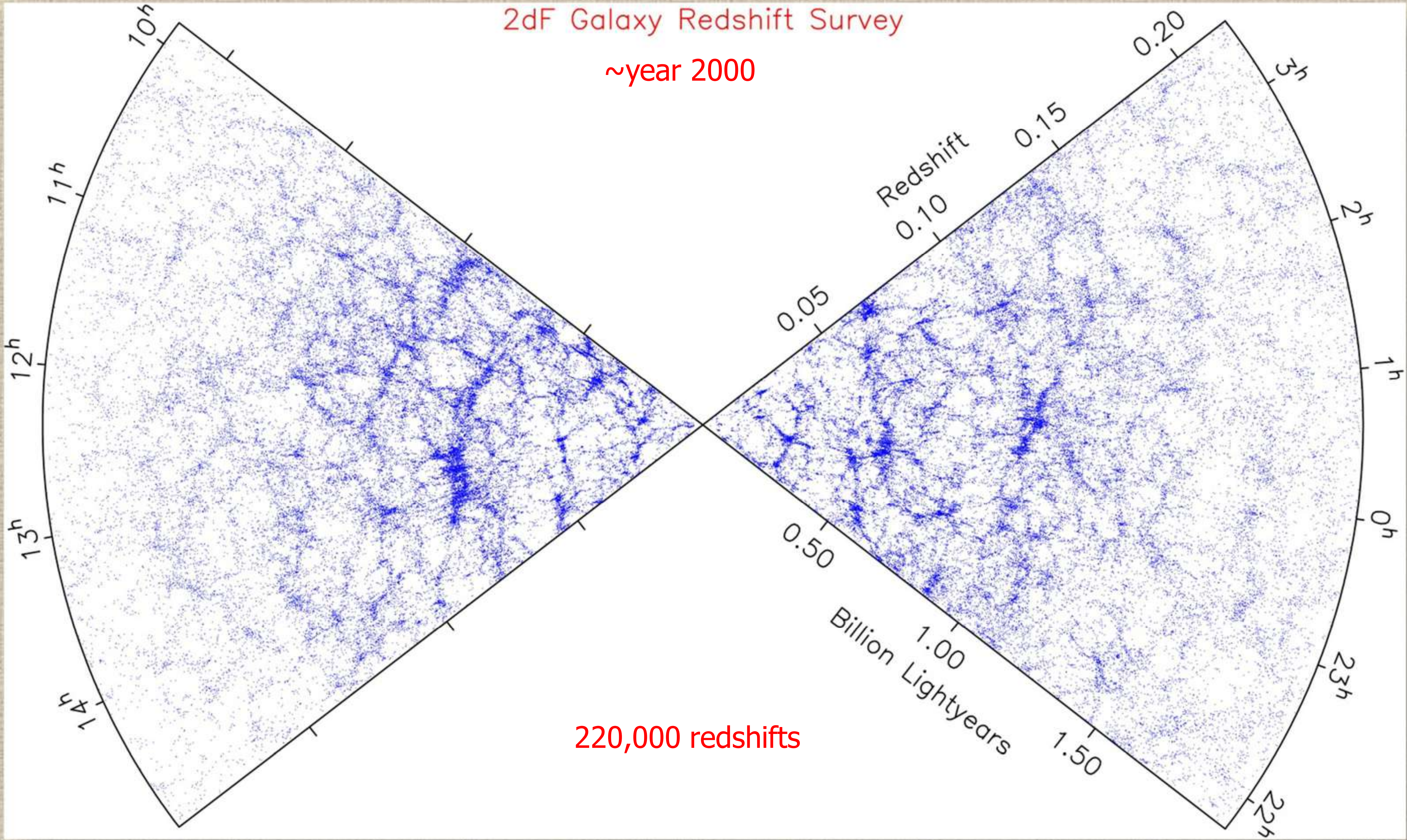




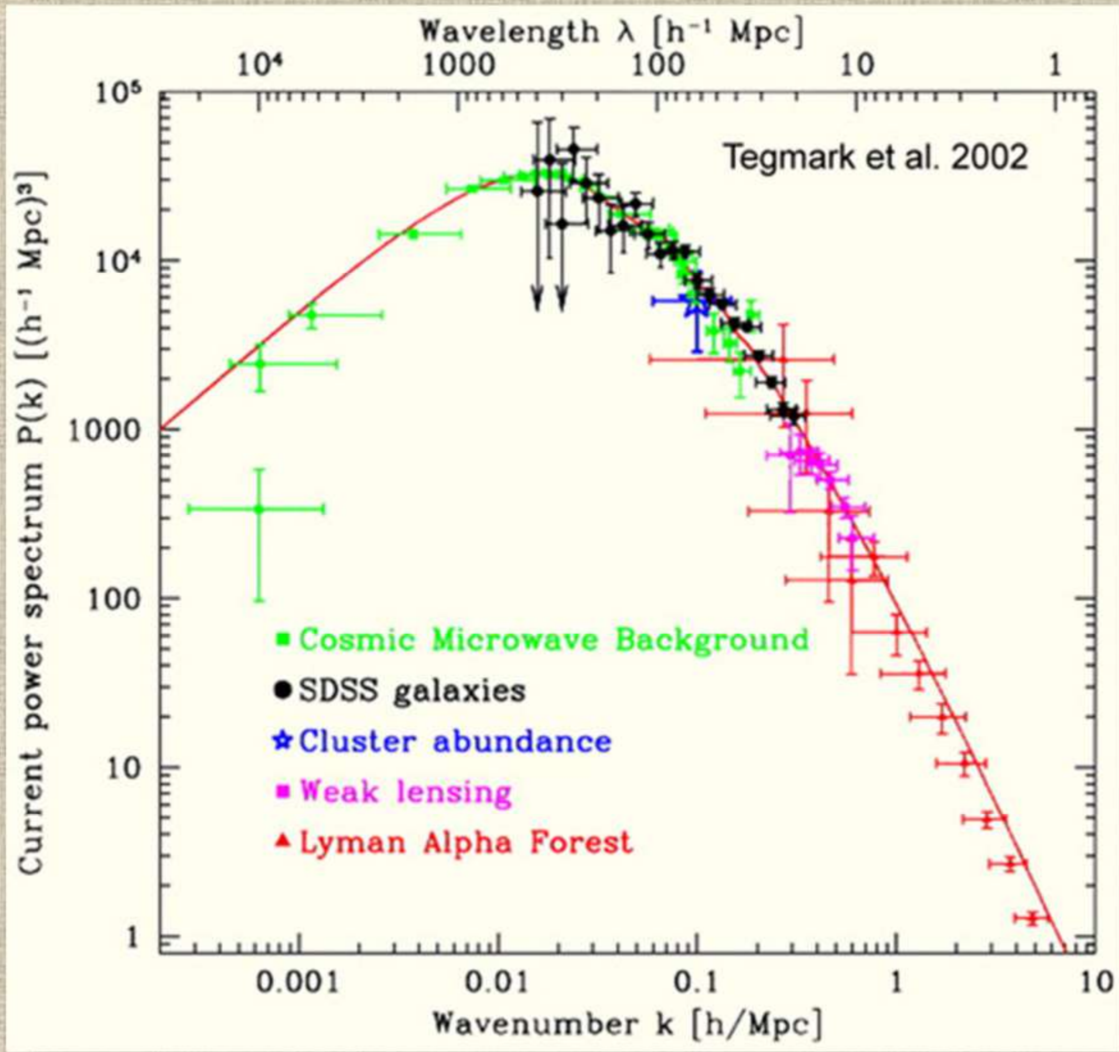
This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers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

2011 Nobel Prize

Cosmic large-scale structure: a pillar of the standard model

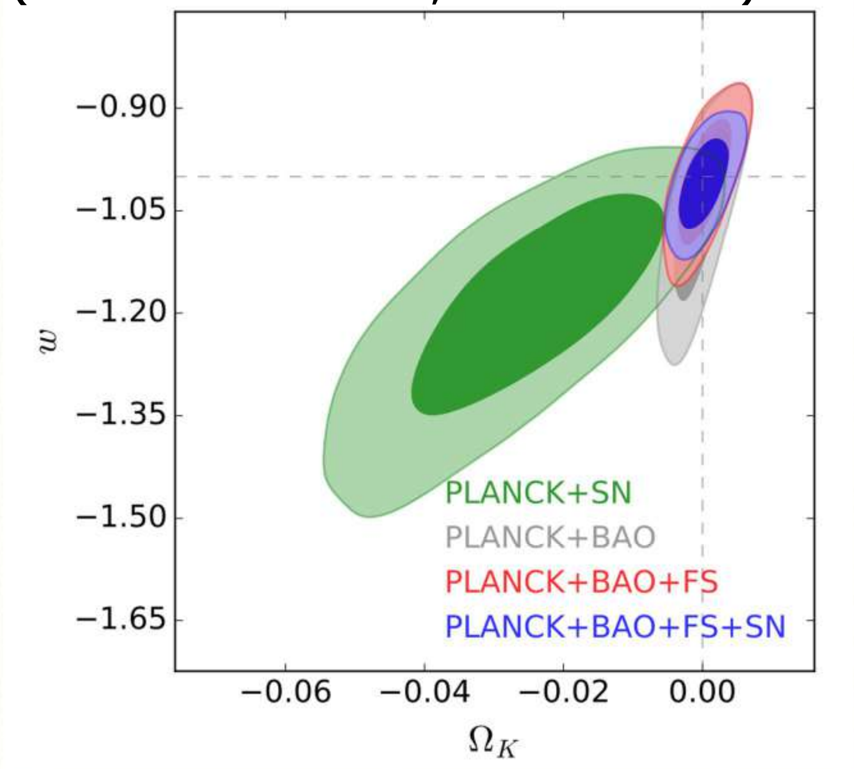


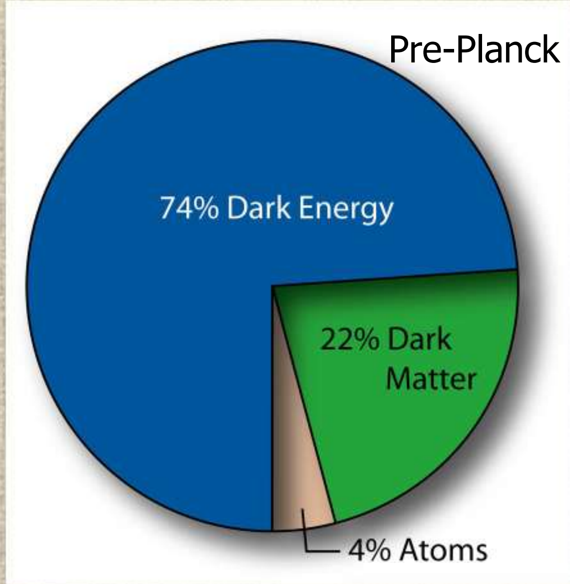
The clustering power spectrum: scale-dependence of inhomogeneities

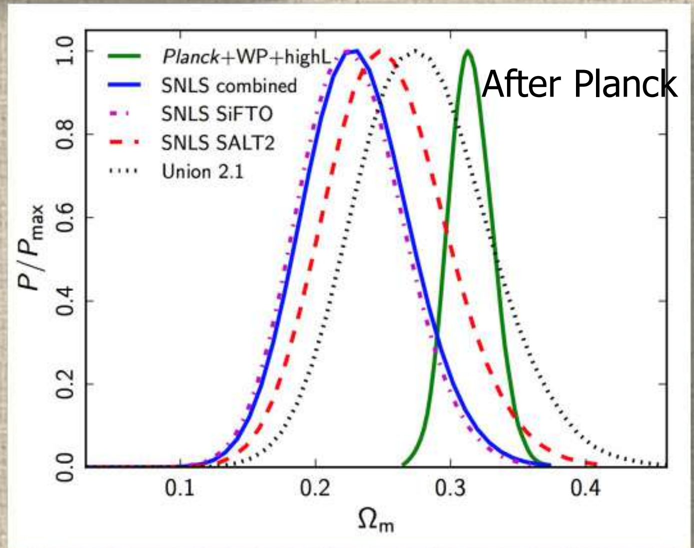


Cosmic (quasi) concordance: a model dominated by Λ (vacuum energy?)

(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 $w(a)$?

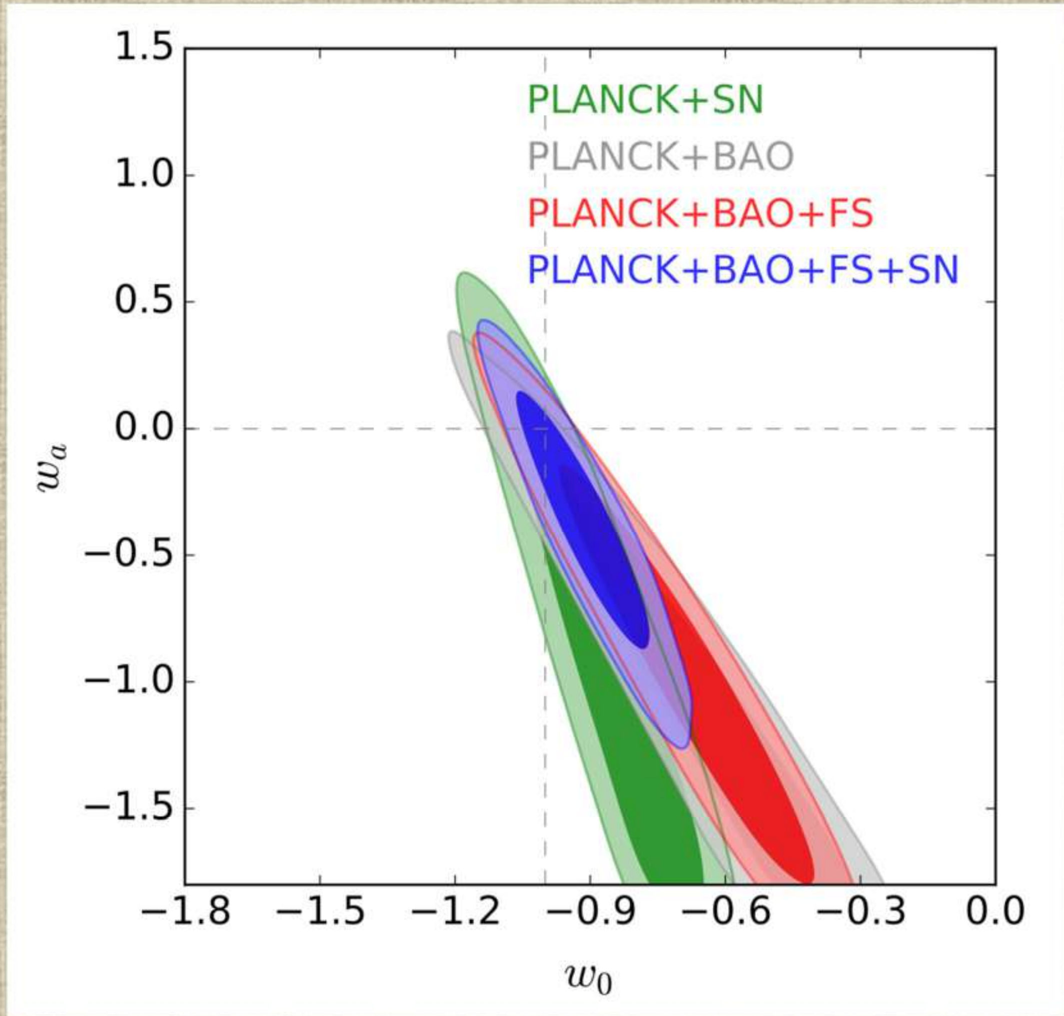
Parameterizing our ignorance:

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

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

A Figure of Merit for dark energy experiments (DETF – Albrecht et al. 2006):

$$\mathrm{FoM} = 1/(\Delta w_0 \times \Delta w_a)$$



(BOSS Collaboration 2016, arXiv:1607.03155)

But, is the cosmological constant (or dark energy) the end of the story?

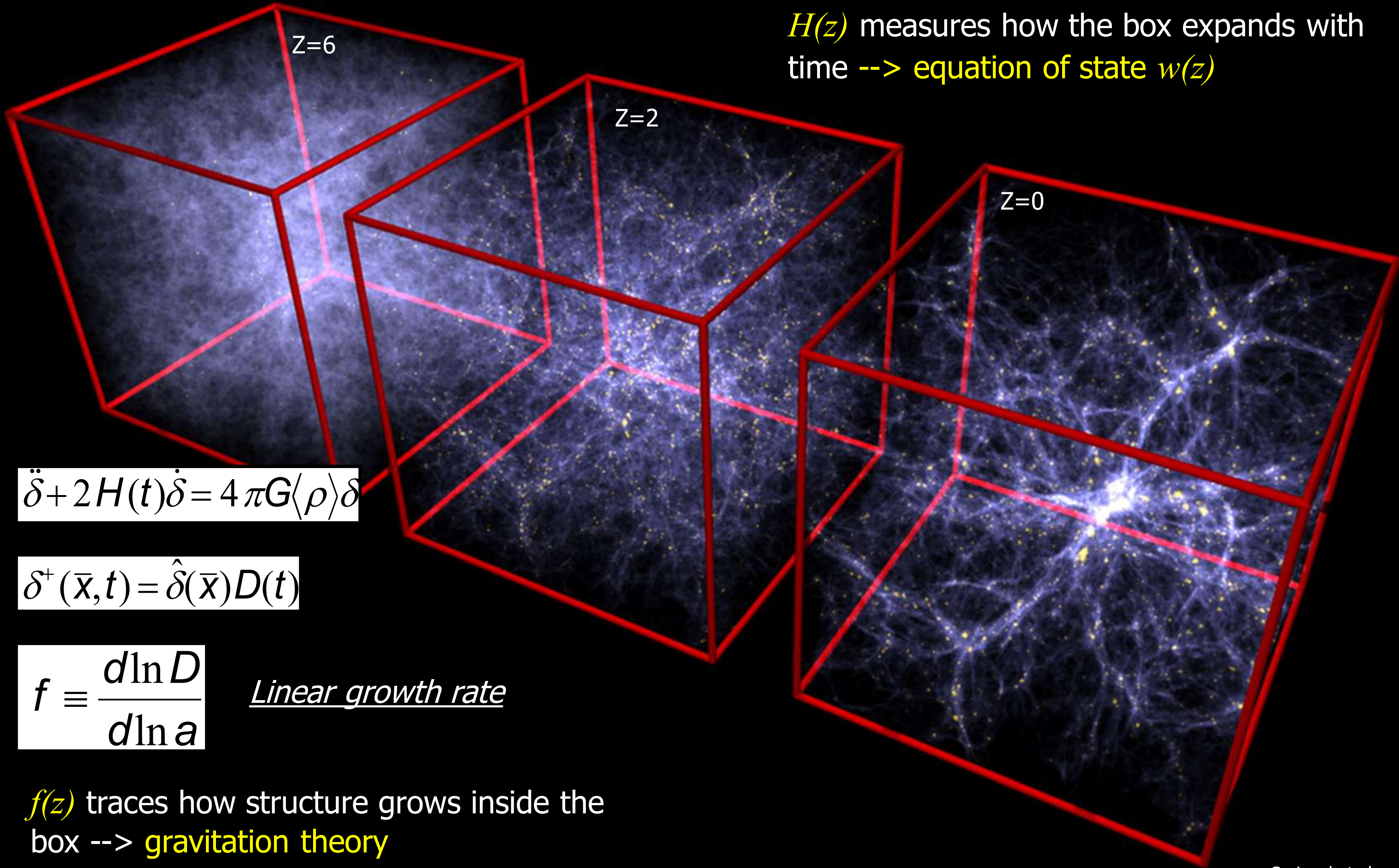
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

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

Add dark energy

"…the Force be with you"

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



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

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

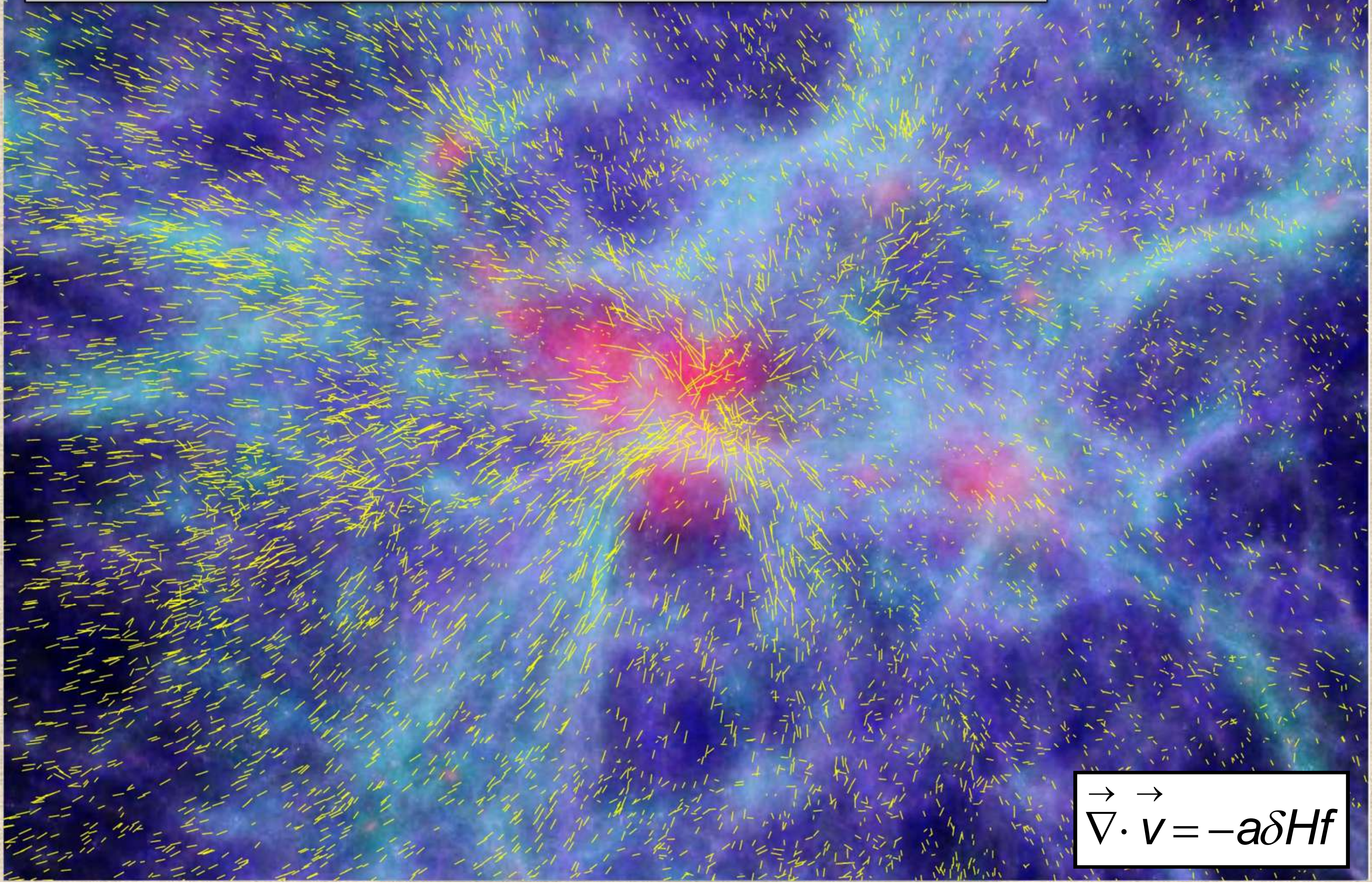
$$f \equiv \frac{d\ln D}{d\ln a}$$

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

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

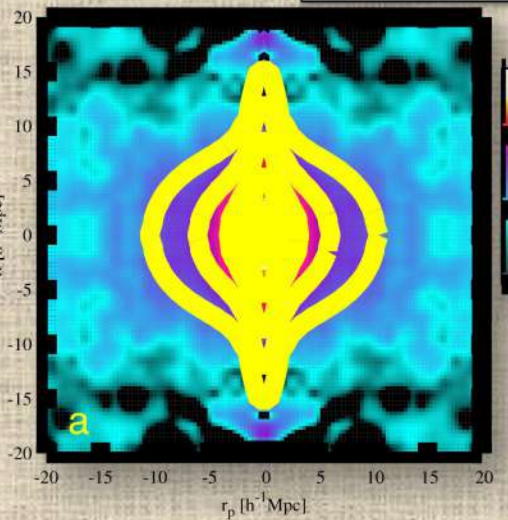
Springel et al.

Growth produces motions: galaxy peculiar velocities



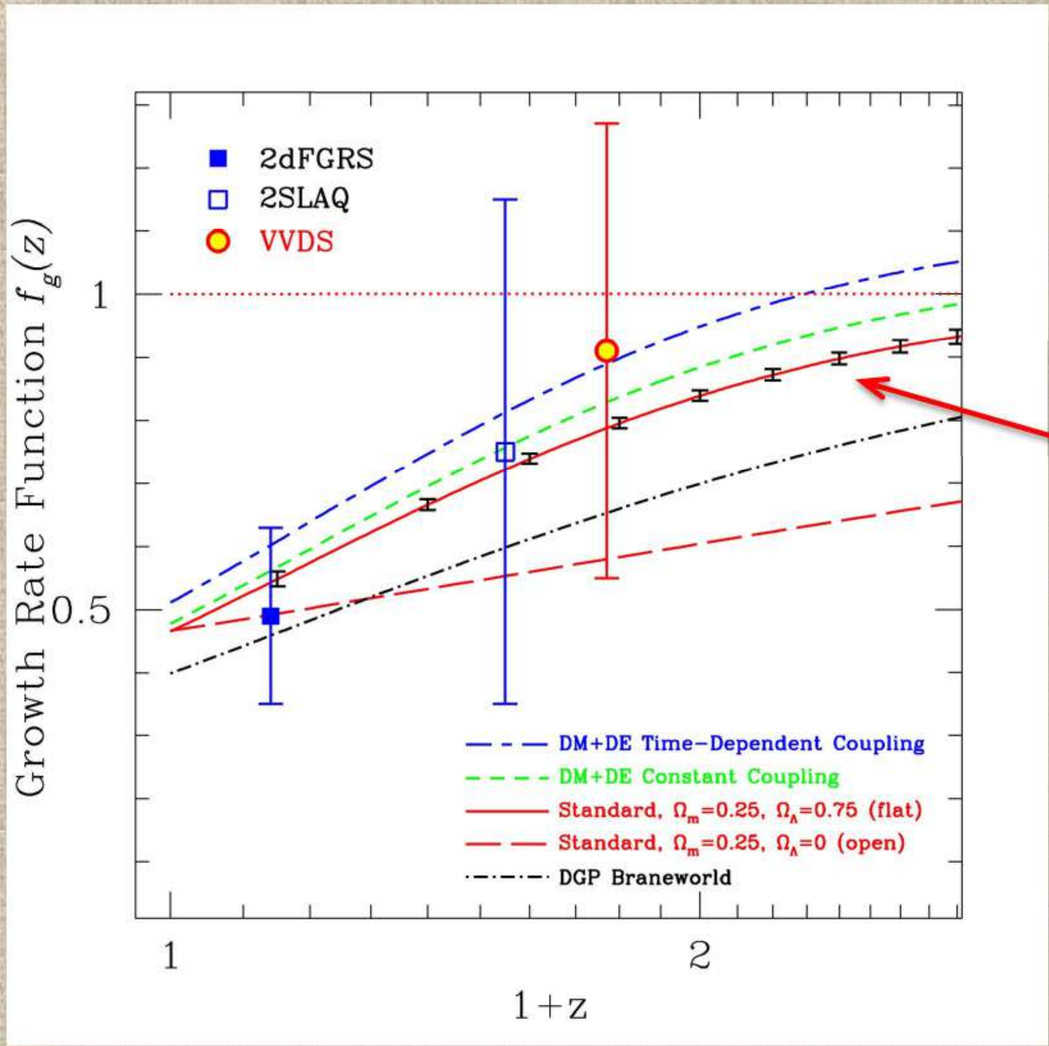
$$\vec{\nabla} \cdot \vec{v} = -a\delta H f$$

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**

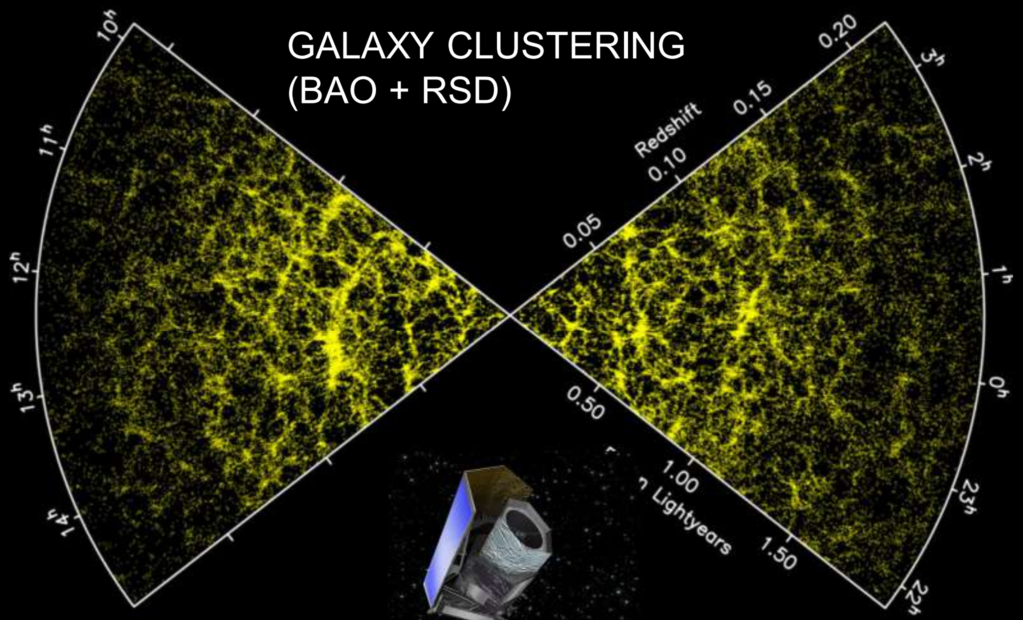


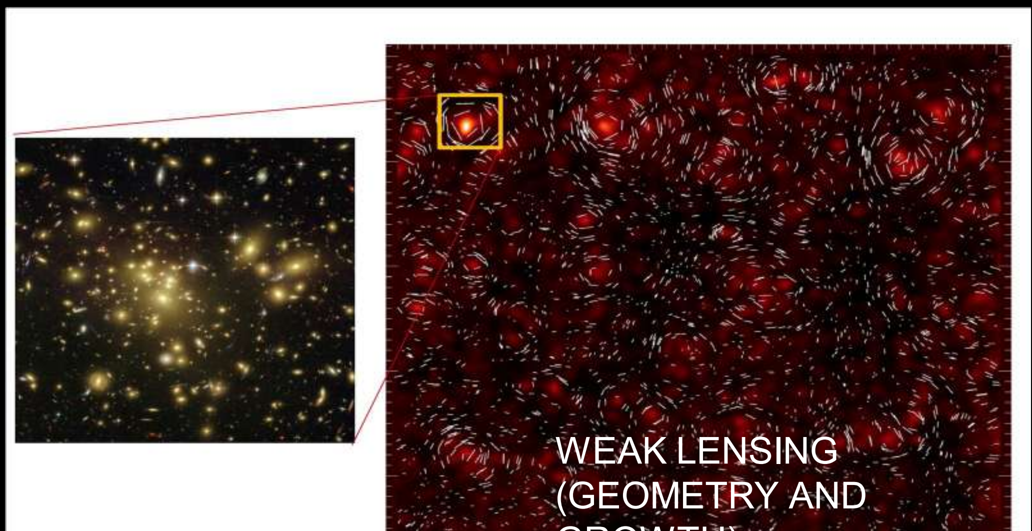
First forecasts for a Euclid -like mission → ESA 2007 Cosmic Vision proposal

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

Euclid

GALAXY CLUSTERING
(BAO + RSD)





WEAK LENSING
(GEOMETRY AND
GROWTH)

OBJECTIVES:

- Build a map of dark and luminous matter over 1/3 of the sky and to z~2
- Unveil the nature of dark matter
- Solve the mystery of dark energy (cosmic acceleration)
- Use multiple probes → max control over systematic errors

UniMI strongly involved (see poster):

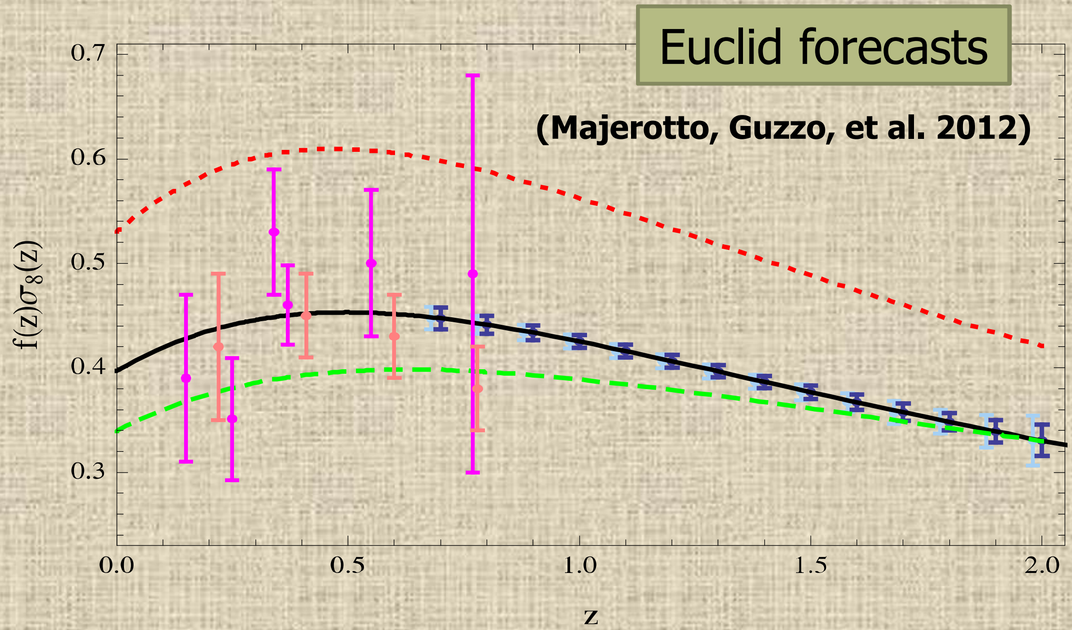
- Science coordination and developemnt
- Ground segment (SDC)

The Euclid "Red Book"
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983#

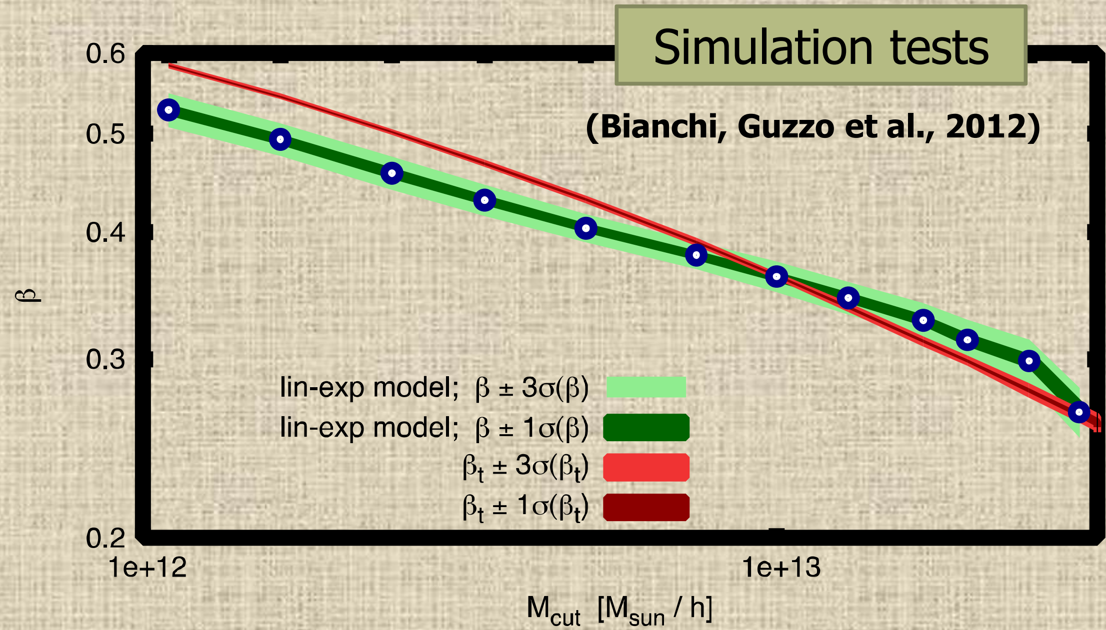
Systematic errors on RSD become the main source of concern…

The situation in 2012: need to improve modelling to enter *"precision RSD era"*

→ EUCLID: expected 1-3% precision



→ Standard RSD modelling: up to 10% systematic error



→ **2017: Milan group currently leading current Euclid GC Fisher forecast code comparison (C. Carbone)** erc DARK LIGHT

European Research Council

ERC Advanced Grant 2011
Research proposal (Part B1)

Illuminating Dark Energy with the Next Generation of Cosmological Redshift Surveys

DARKLIGHT

- Principal Investigator: **Luigi Guzzo**
- Hosting Institution: **INAF – Osservatorio di Brera**
- Project duration: **60 months**

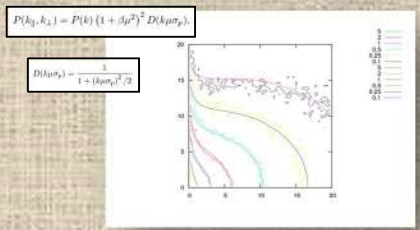
Galaxy redshift surveys have been central in establishing the current successful cosmological model. Reconstructing the large-scale distribution of galaxies in space and time, they provide us with a unique probe of the basic constituents of the Universe, their evolution and the background fundamental physics. A new generation of even larger surveys is planned for the starting decade, with the aim of solving the remaining mysteries of the standard model using high-precision measurements of galaxy clustering. These entail the nature of the "dark sector" and in particular the origin of the accelerated cosmic expansion. While data accumulation already started, the needed analysis capabilities to reach the required percent levels in both accuracy and precision are not ready yet.

I propose to establish a focused research group to develop these capabilities and optimally analyze the new data. New techniques as redshift-space distortions and well-known but still debated probes as galaxy clusters will be refined to a new level. They will be combined with more established methods as baryonic acoustic oscillations and with external data as CMB anisotropies. Performances will be validated on mock samples from large numerical simulations and then applied to state-of-the-art data with enhanced control over systematic errors to obtain the best achievable measurements.

These new, coherently developed capabilities will be decisive in enabling ongoing and future surveys to address and solve the key open problems in cosmology: What is the nature of dark energy? Is it produced by an evolving scalar field? Or does it rather require a modification of the laws of gravity? How does it relate to dark matter? The answer to these questions may well revolutionize our view of physics.

Also including:

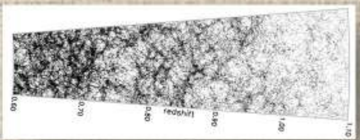
- P. Dell'Arme (Project Assistant)
- E. Sefusatti (INAF staff: theory of clustering)
- Jian-Hua He (ASI fellow: theory, modif. gravity)



WP1

IMPROVE MODELS AND ESTIMATORS OF COSMOLOGICAL PARAMETERS FROM GALAXY CLUSTERING AND REDSHIFT-SPACE DISTORTIONS

J. Bel, A. Hawken, F. Mohammad (PhD), D. Bianchi (PhD UniMI), M. Chiesa (PhD UniMI)



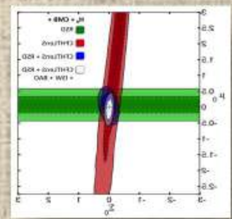
NUMERICAL SIMULATIONS AND MOCK SURVEYS

C. Carbone, J. Koda

WP2

TESTS AND VALIDATION ON MOCK SAMPLES

B. Granett, A. Pezzotta (PhD)



WP6

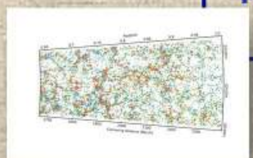
IMPACT OF (SO FAR) NEGLECTED COMPONENTS: MASSIVE NEUTRINOS

C. Carbone, M. Zennaro (PhD UniMI)

WP3

APPLICATION TO REDSHIFT SURVEY DATA (VIPERS, etc.)

B. Granett, A. Hawken, F. Mohammad, S. Rota (PhD), A. Marchetti (PhD)



WP5

WP4

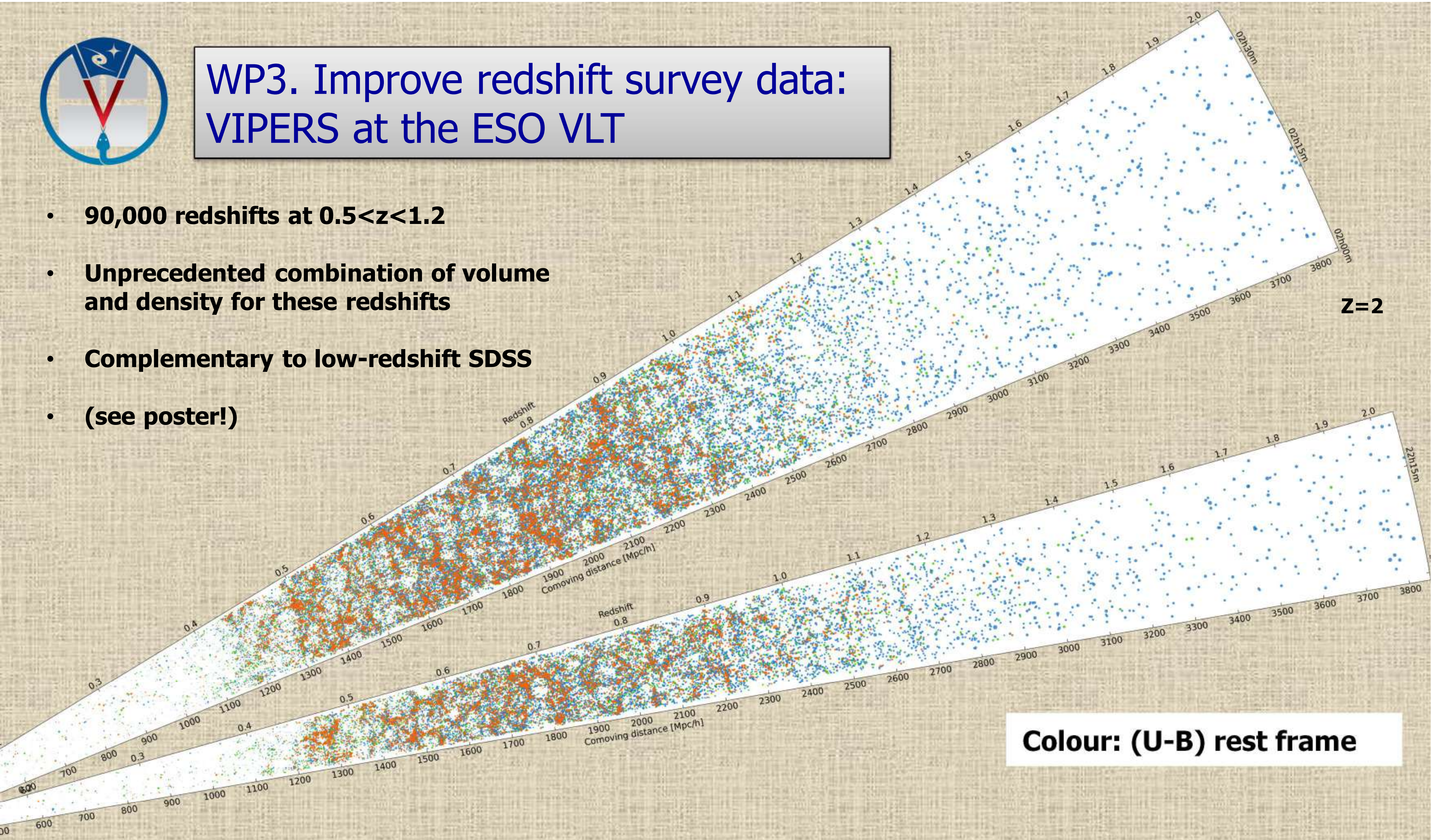
COMBINATION WITH OTHER COSMOLOGICAL PROBES (Lensing, CMB, Voids…)

C. Carbone, B. Granett (CMB ISW), J. Dossett

COSMOLOGICAL PARAMETERS

WP3. Improve redshift survey data: VIPERS at the ESO VLT

- **90,000 redshifts at 0.5<z<1.2**
- **Unprecedented combination of volume and density for these redshifts**
- **Complementary to low-redshift SDSS**
- **(see poster!)**



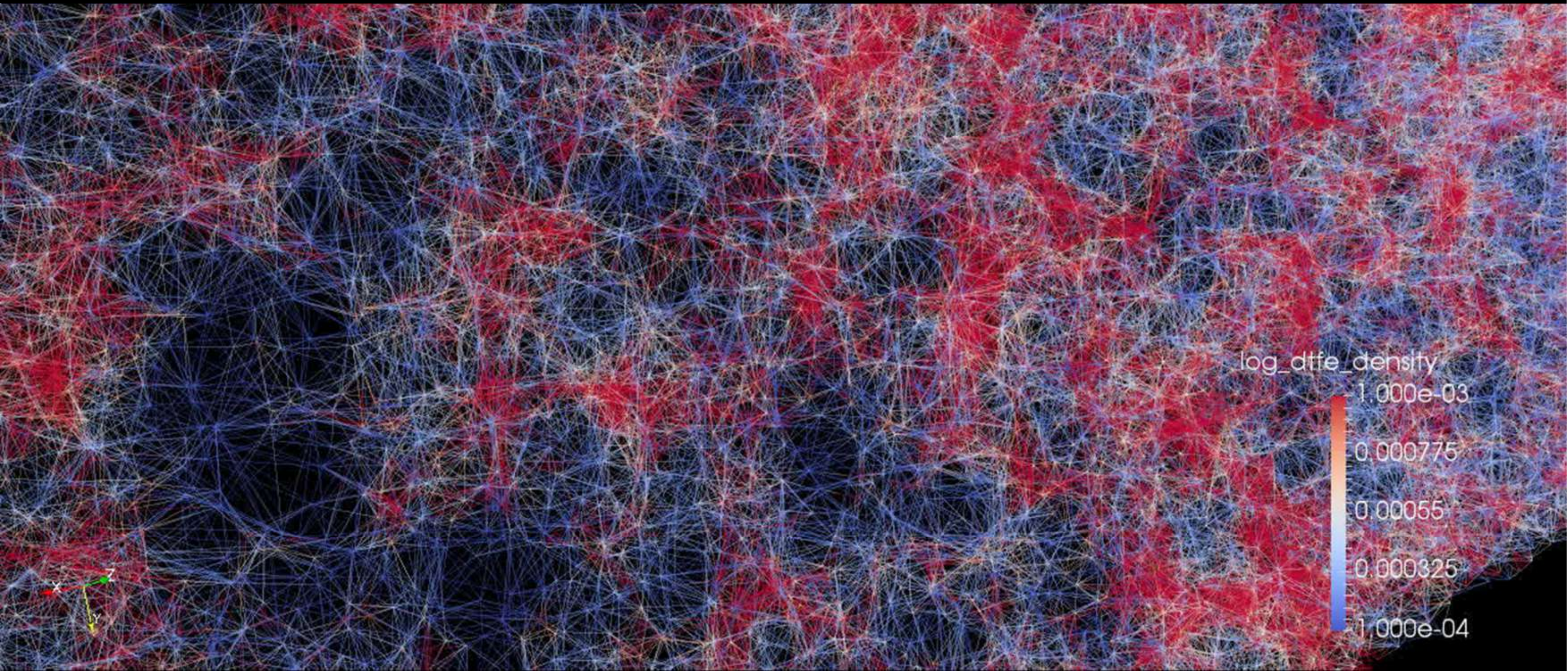
Z=2

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)

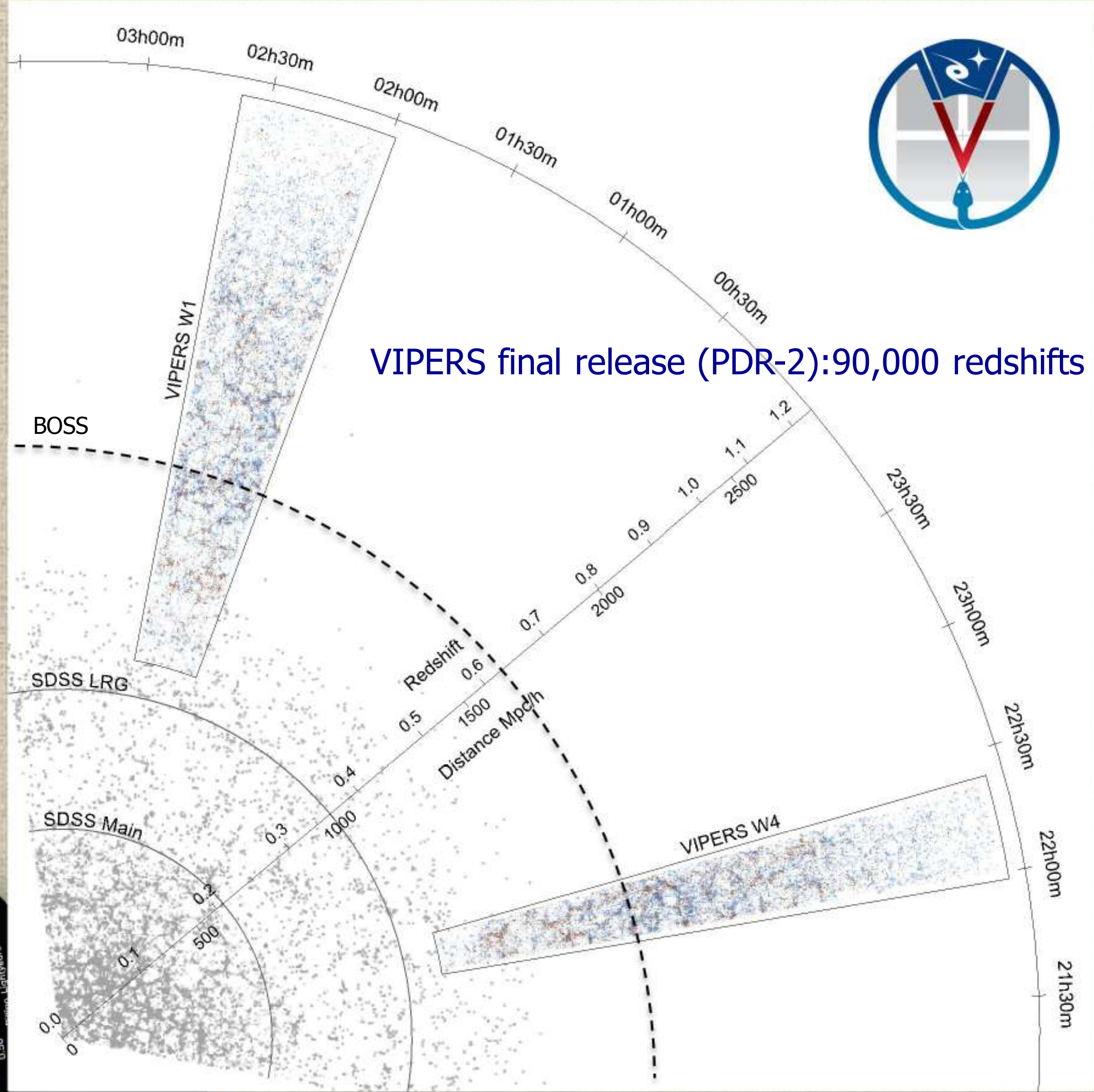
VIPERS fills unique niche in the current scenario of galaxy surveys:

State of the art:

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

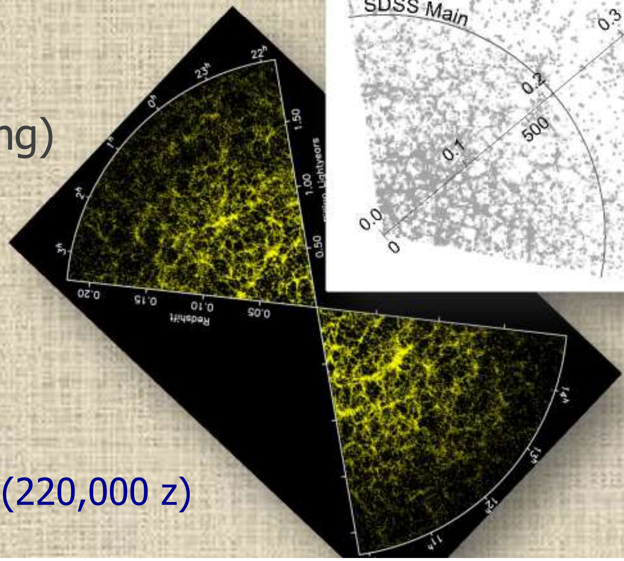
Future:

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



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

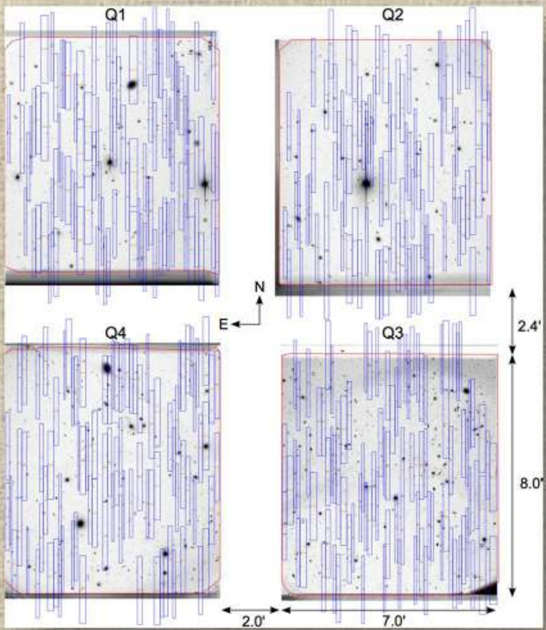
(arXiv 1611.07048)

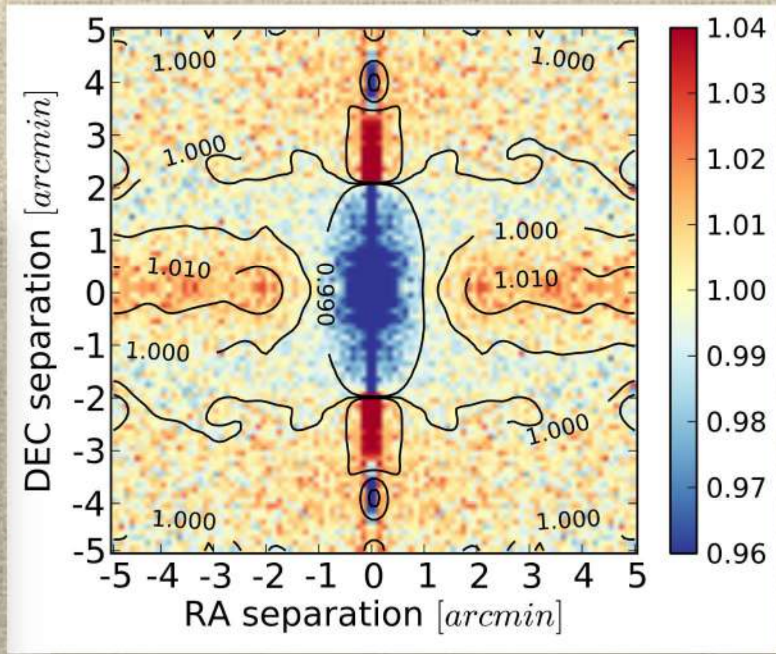


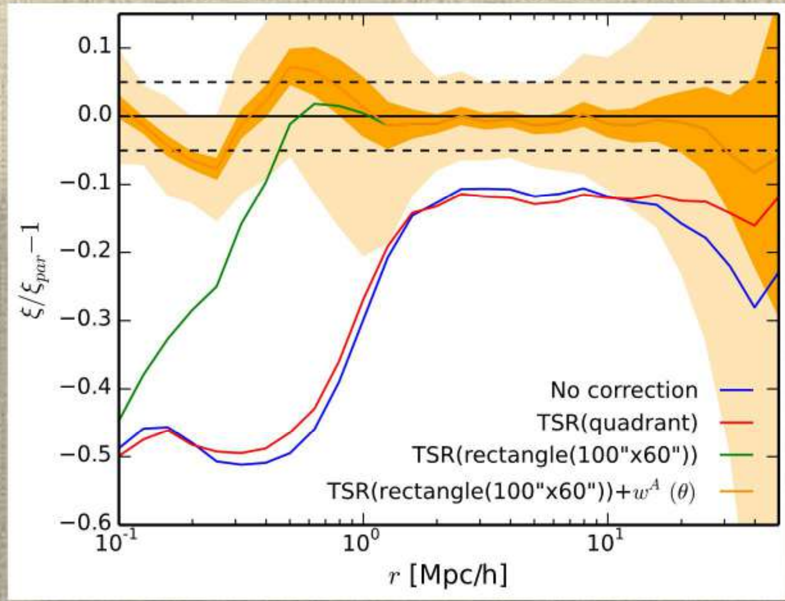
2dFGRS (220,000 z)

WP1: Minimize observational effects (not obvious at 1% level!)

E.g. detailed correction of masking effects in the VIPERS data on the estimate of two-point correlations (A. Pezzotta PhD work)



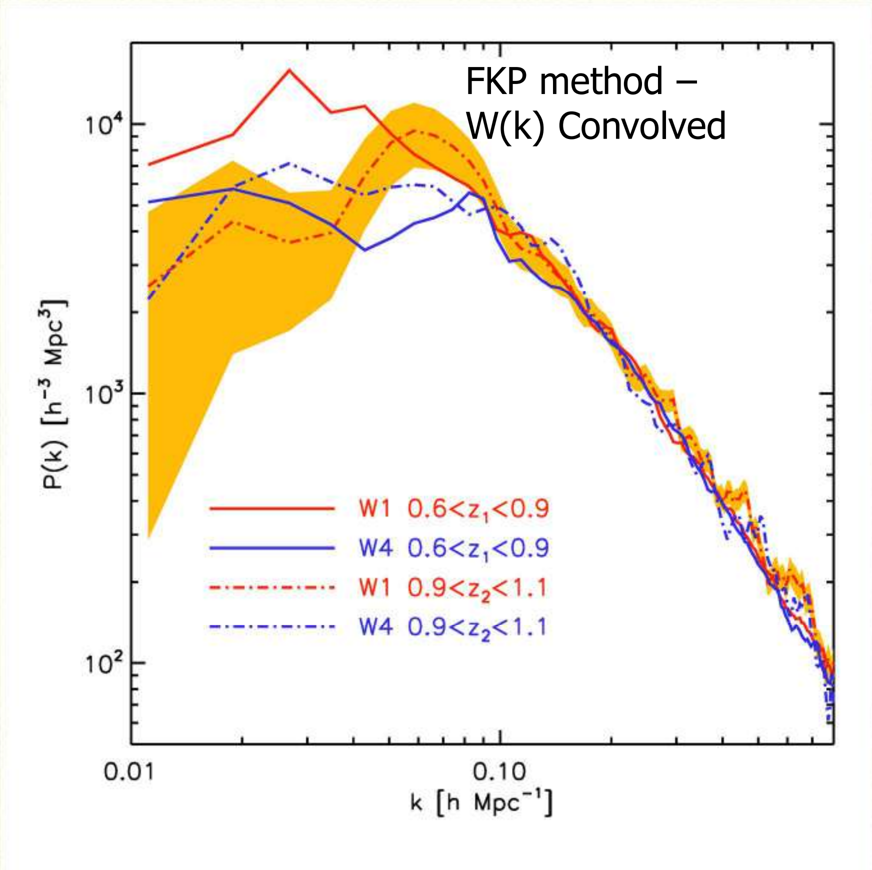


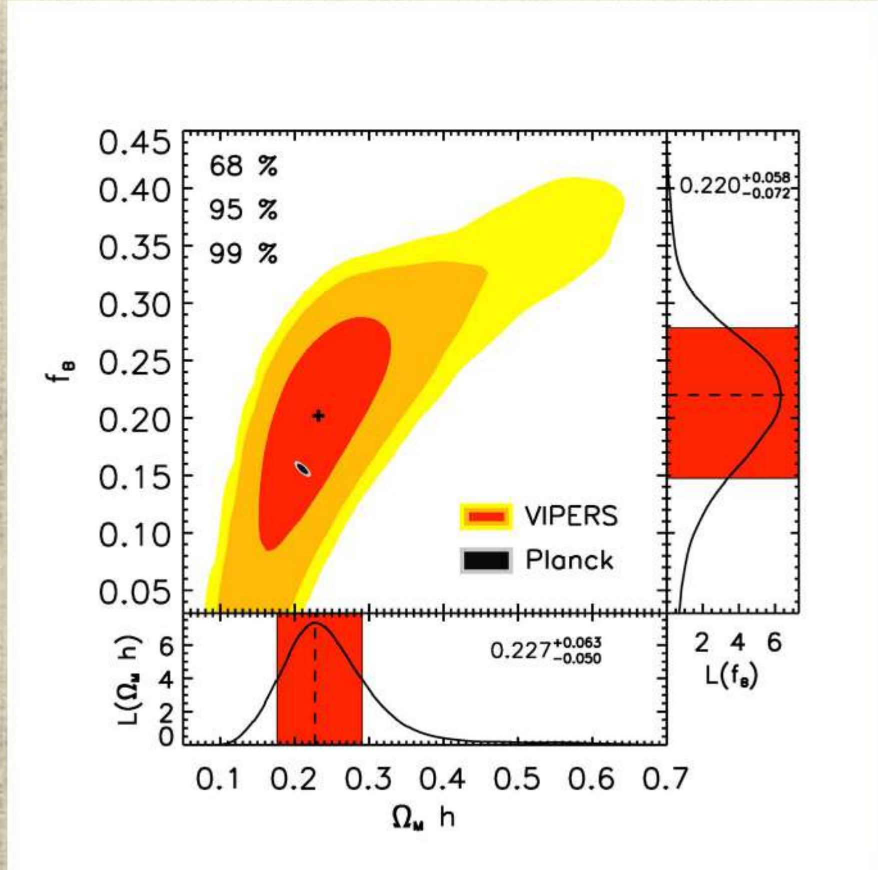


→ **This will be very relevant for Euclid slitless spectroscopic mode**

WP3: the power spectrum of the galaxy distribution at z=0.5-1.1

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



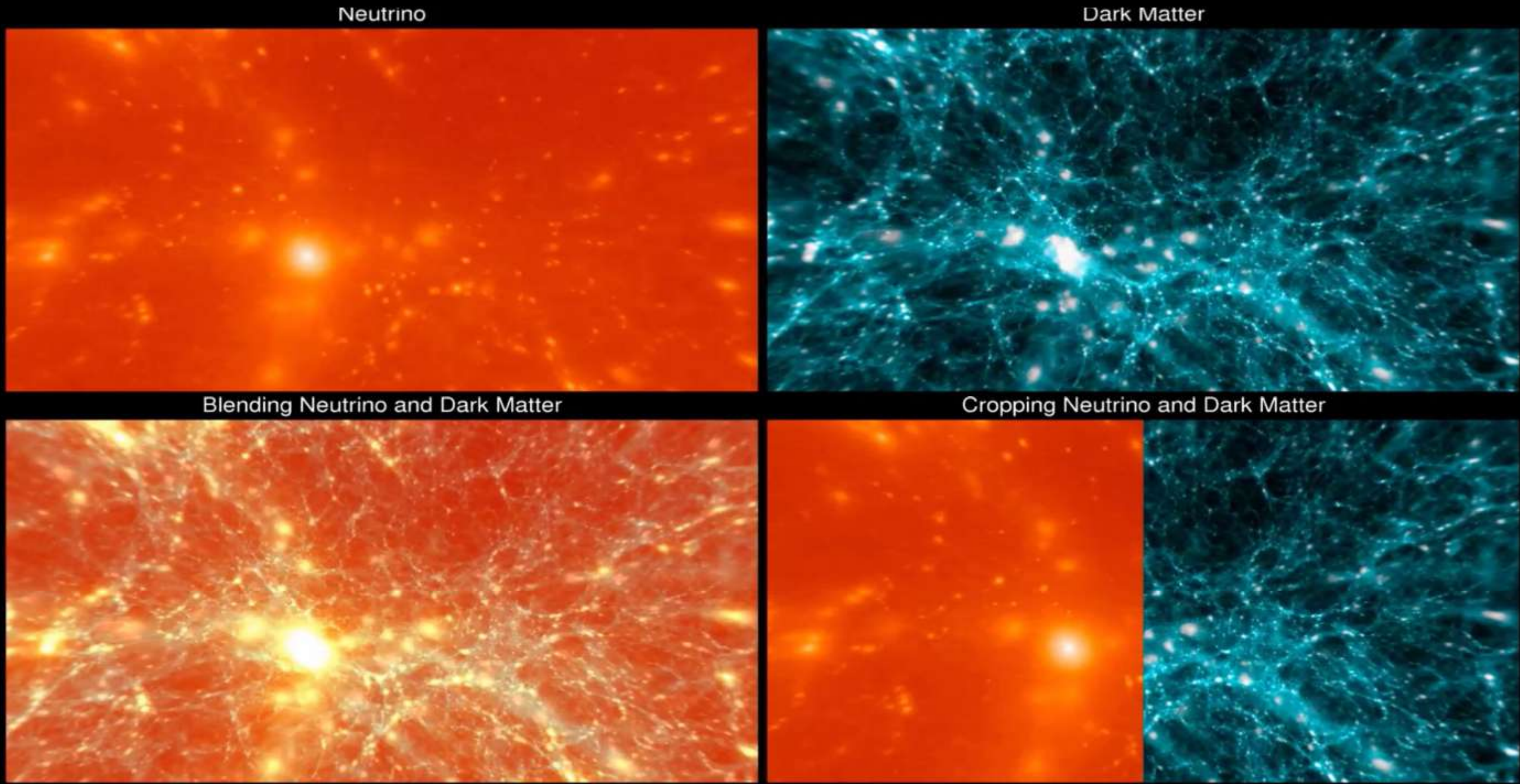


- Very careful tests of window function and nonlinear effects (use algorithms from WP1)

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

WP6: this is where we will see the impact of massive neutrinos…

CDM/ν clustering in high resolution simulations
(2400 times smaller than DEMNUni)



Courtesy of F. Villaescusa-Navarro

L=150 Mpc/h $N_{cdm}=512^3$ $N_{\nu}=1024^3$ $M_{\nu}=1$ eV

The Dark Energy and Massive Neutrino Universe simulations (DEMNUni)

(PI: Carmelita Carbone)

1. DEMNUni-I: 5M cpu-hr on Fermi Tier-0 @CINECA (**COMPLETED**)

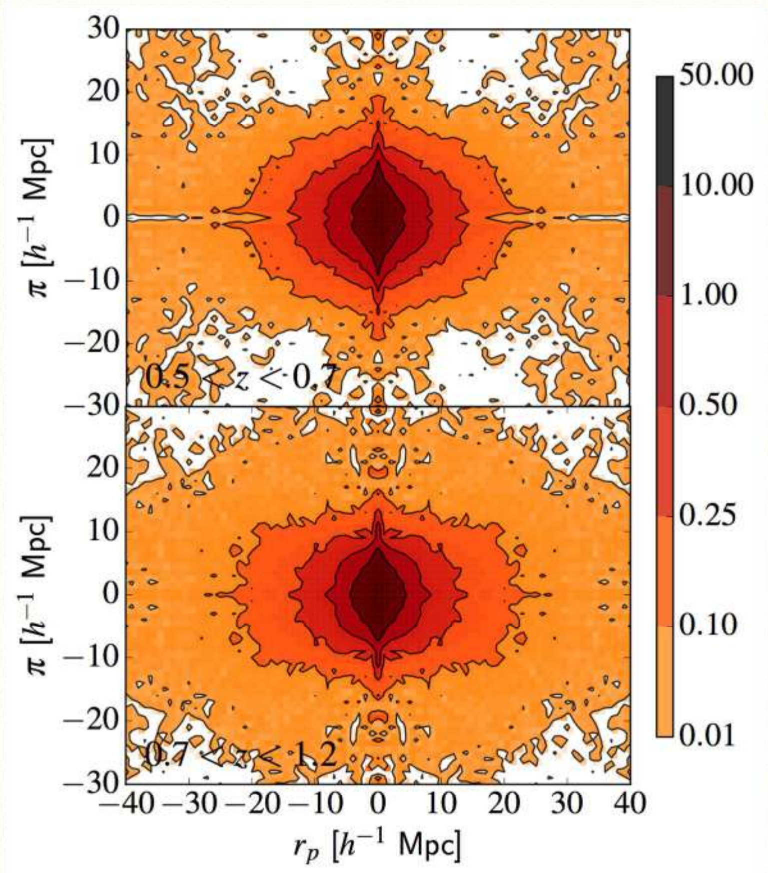
2. DEMNUni-II: 8M cpu-hr on Fermi Tier-0 @CINECA (**COMPLETED**)

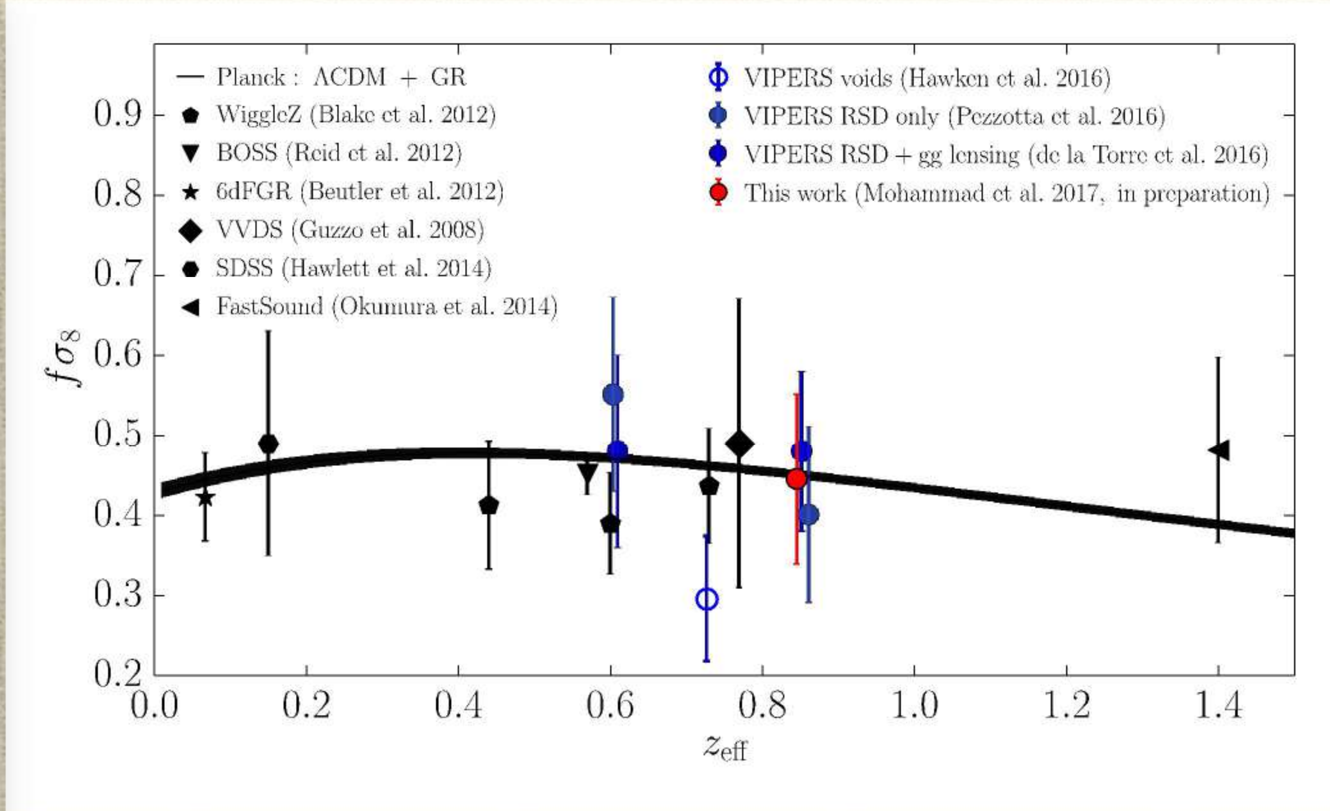
14 cosmological simulations with volume: $(2\ \mathrm{Gpc}/h)^3$ and N_{part}: 2×2048^3 (CDM+ν)
baseline Planck cosmology +
M_ν=0, 0.17, 0.3, 0.53 eV & (M_ν, w_0, w_a)=(0÷0.16,-0.9,±0.3),(0÷0.16,-1.1,±0.3)

3. DEMNUni-Covariances: 3M cpu-hr on Marconi Tier-0 @CINECA (**STARTED**)

→ 300 cosmological simulations with V=1 $(\mathrm{Gpc}/h)^3$ and $N_{part}=2 \times 1024^3$ (CDM+ν)

WP3: Testing gravity with VIPERS & Darklight tools

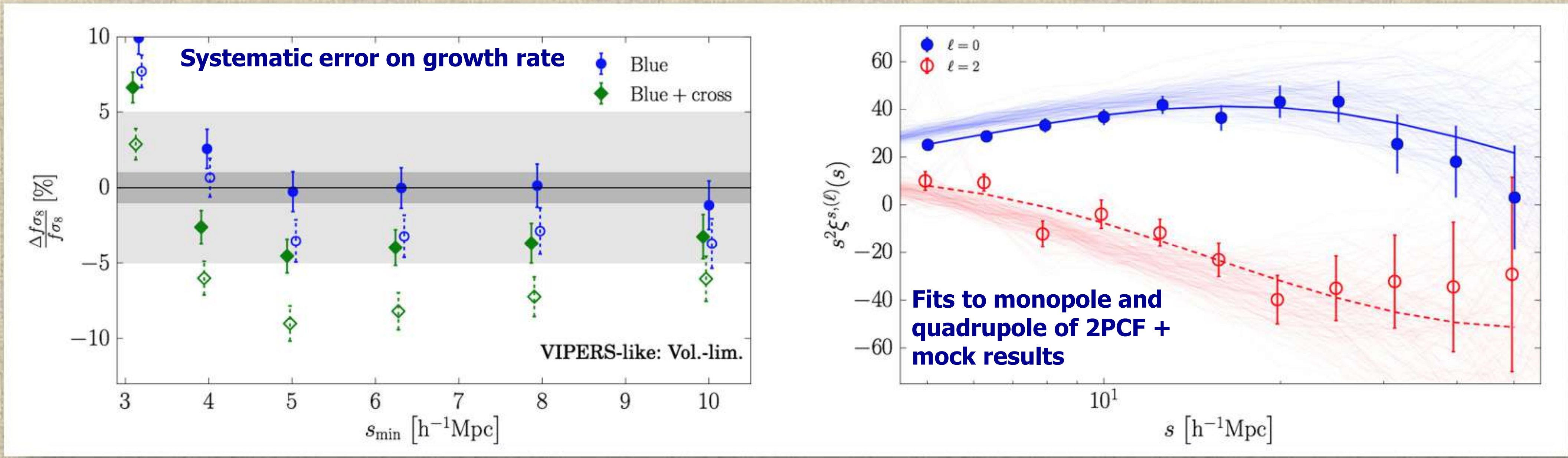




VIPERS PDR-2 (Pezzotta+ 2017; de la Torre+ 2017; Hawken+ 2017; Mohammad+ 2017; Wilson 2017)

For example, improved modelling using optimised tracers (WP1)

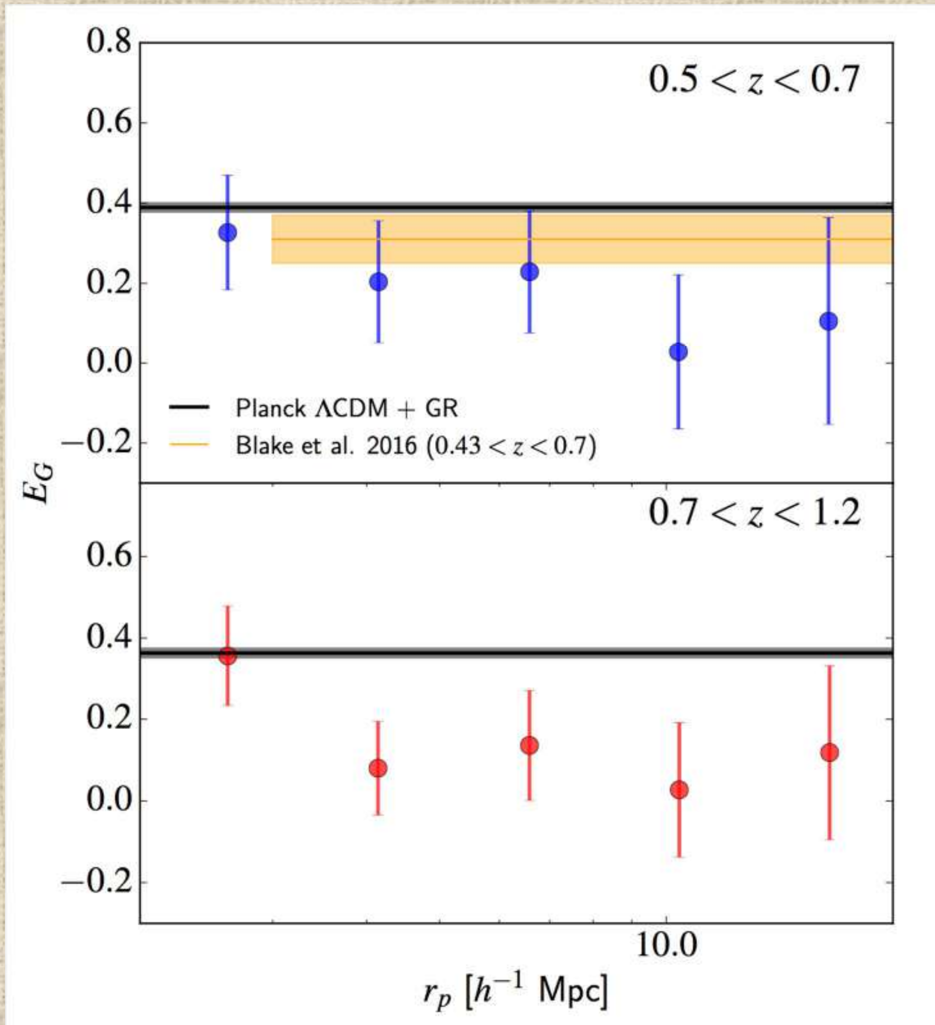
(Mohammad, Granett, Guzzo+ VIPERS, to be submitted to A&A)



→ Luminous blue galaxies are better tracers of the linear component of the velocity field → allow simpler, more robust modelling

WP5: Combine galaxy clustering and weak lensing

- **Test for modified gravity** combining CFHTLens imaging with VIPERS (de la Torre + 2017): **slip parameter (solid line gives GR prediction)**



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

(proof of concept for Euclid)

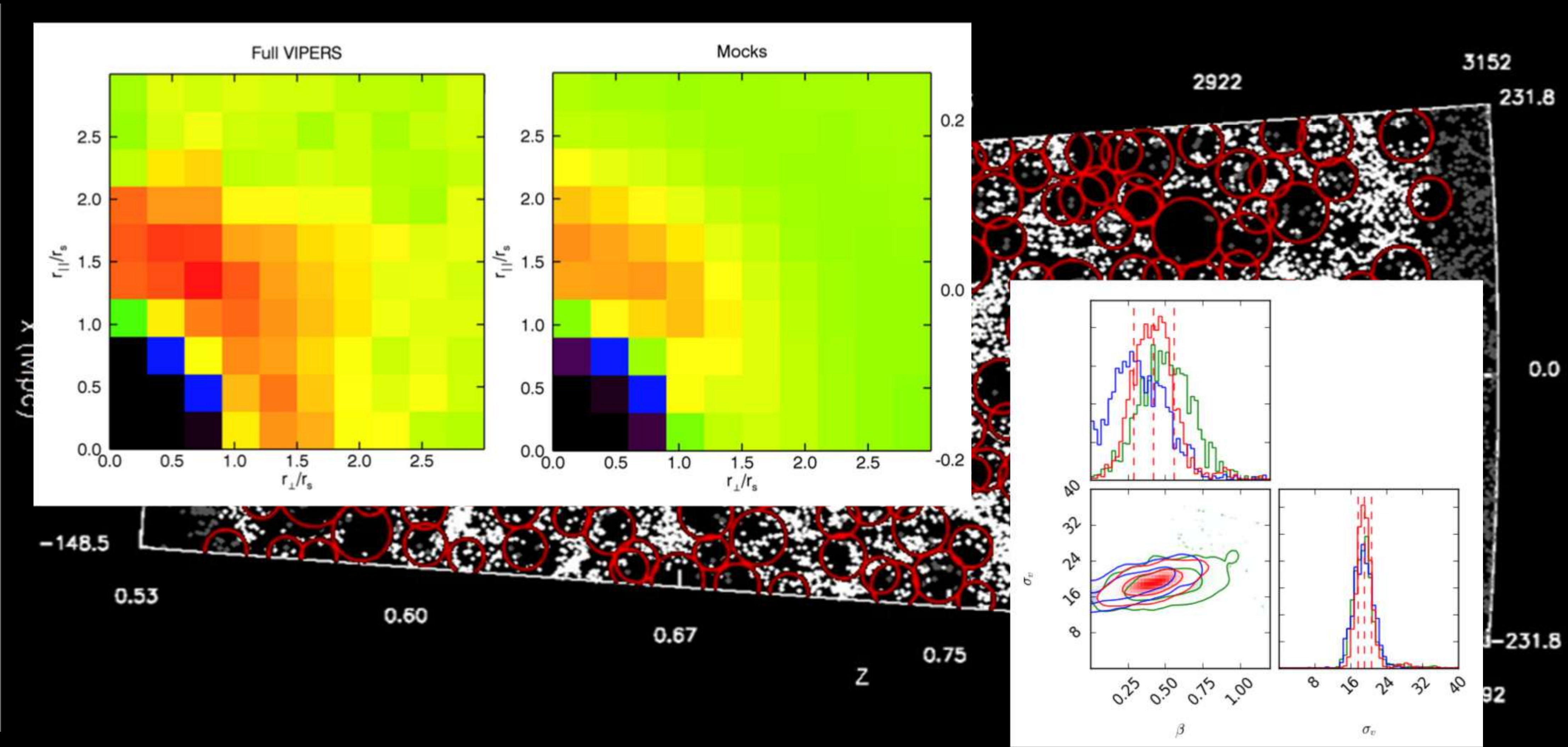
$$E_G = \frac{\nabla^2(\Psi(r) - \Phi(r))}{3H_o^2 a^{-1}\theta}$$

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

erc DARK LIGHT

WP5: new cosmological probes, cosmic voids

Hawken+ 1611.07046, A&A in press



Summary

- **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). This makes systematic errors the real limit**
- **To this end, Darklight built new ways to model and optimise the data, supporting the construction of new observational data sets (VIPERS), theoretical tools and simulations**
- **VIPERS represents the state of the art for redshift surveys of the z~1 Universe: more results on galaxy evolution not reported here (e.g. Haines+ 2017; Gargiulo+ 2017)**
- **Darklight pioneered use of new techniques to measure redshift distortions (Bianchi et al. 2014, 2016; Pezzotta+ 2017; Mohammad+ 2017), together with new probes of large-scale structure (cosmic voids – Hawken et al. 2017)**
- **Darklight is leading current numerical studies of structure evolution in the presence of massive neutrinos, a component that cannot be ignored anymore, if we are aiming at 1% precision (Carbone et al. 2017)**
- **In the spirit of ERC grants, Darklight built a legacy that projected most of its former members into leading positions in European research, as in particular in the Euclid project, the next generation cosmological mission of ESA**

"ILLUMINATING DARK ENERGY WITH THE NEXT GENERATION OF COSMOLOGICAL REDSHIFT SURVEYS"

http://darklight.fisica.unimi.it/

EXTRA SLIDES