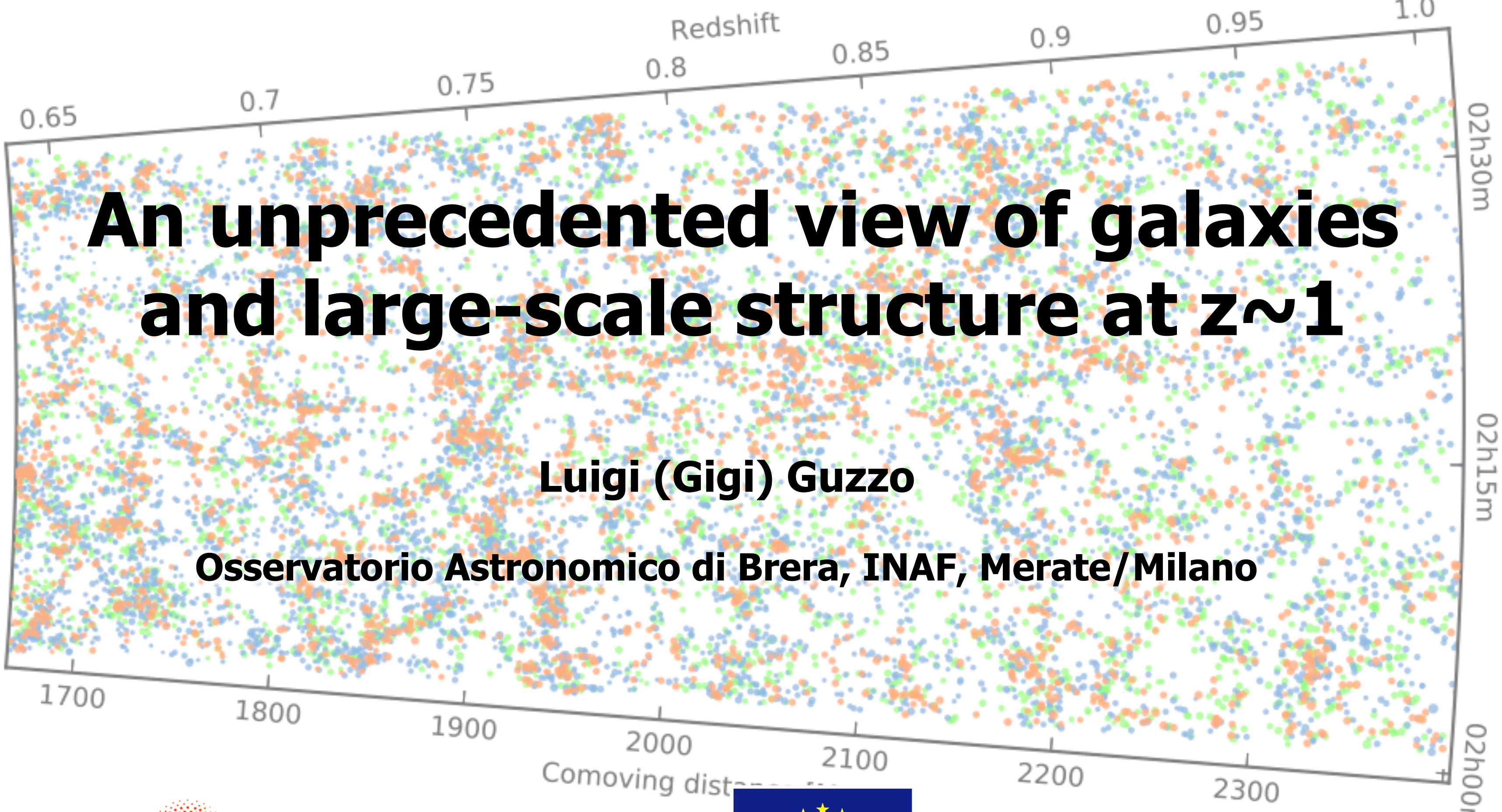
VIPERS

VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

An unprecedented view of galaxies and large-scale structure at z~1



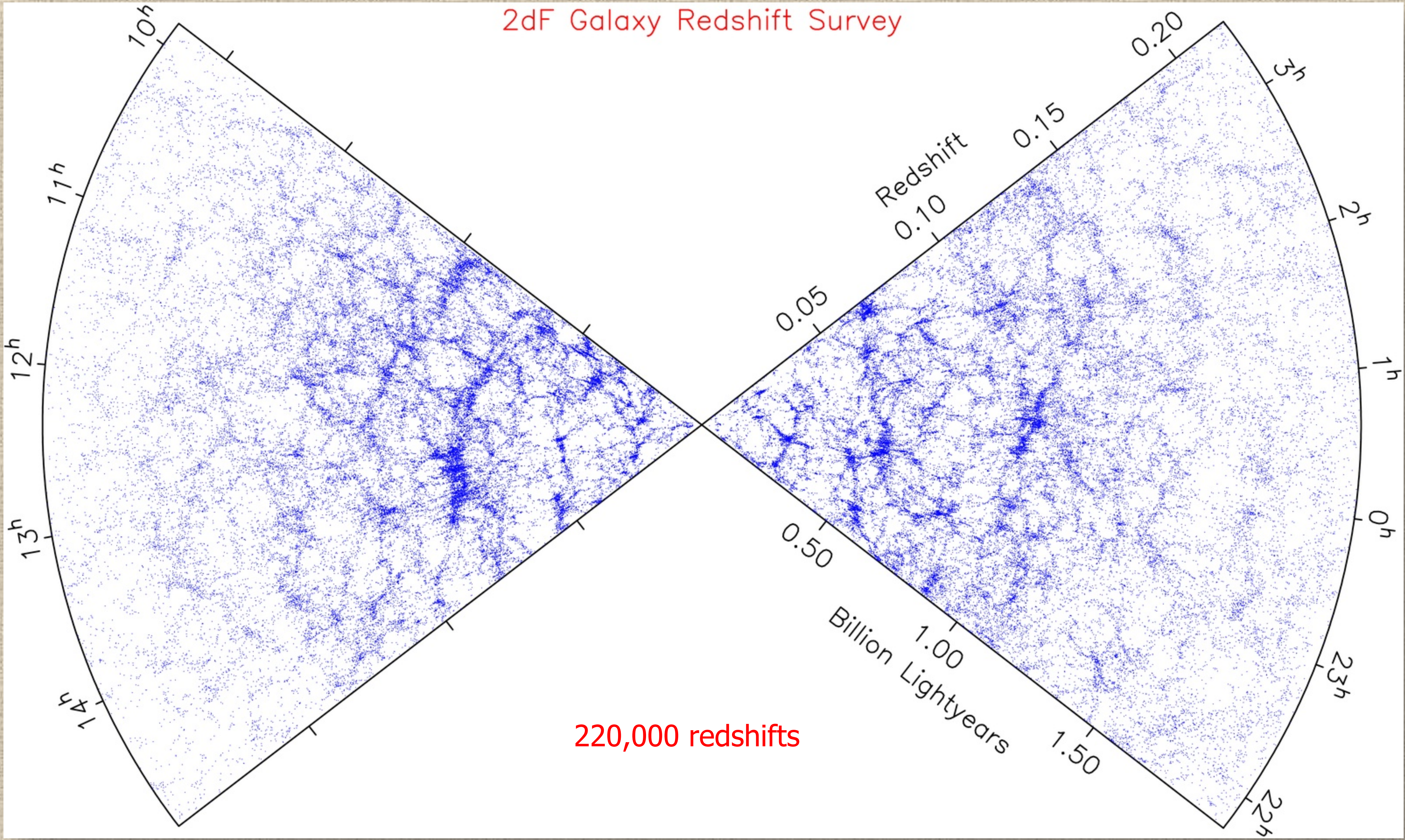
Luigi (Gigi) Guzzo

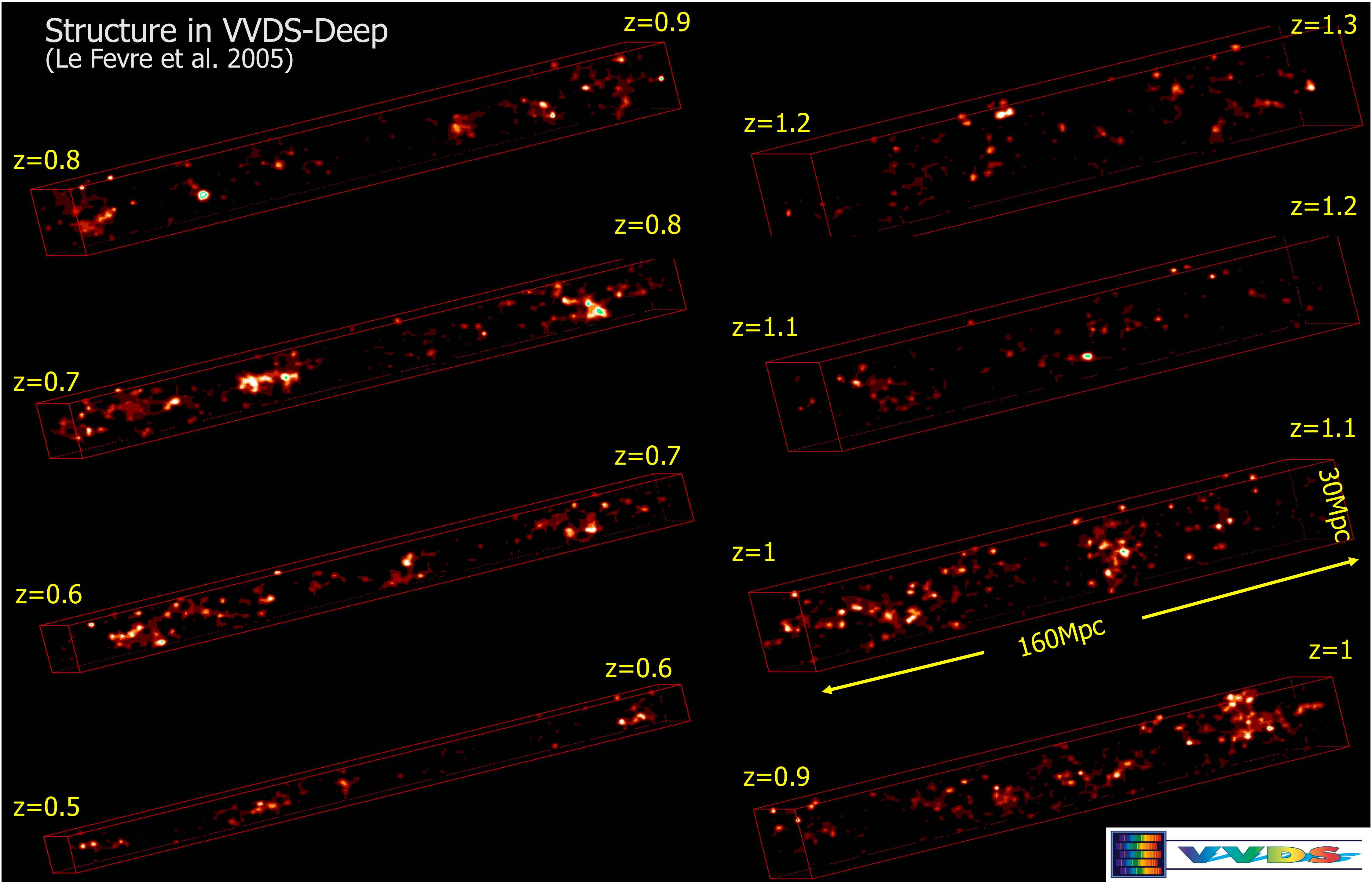
Osservatorio Astronomico di Brera, INAF, Merate/Milano

erc DARK LIGHT

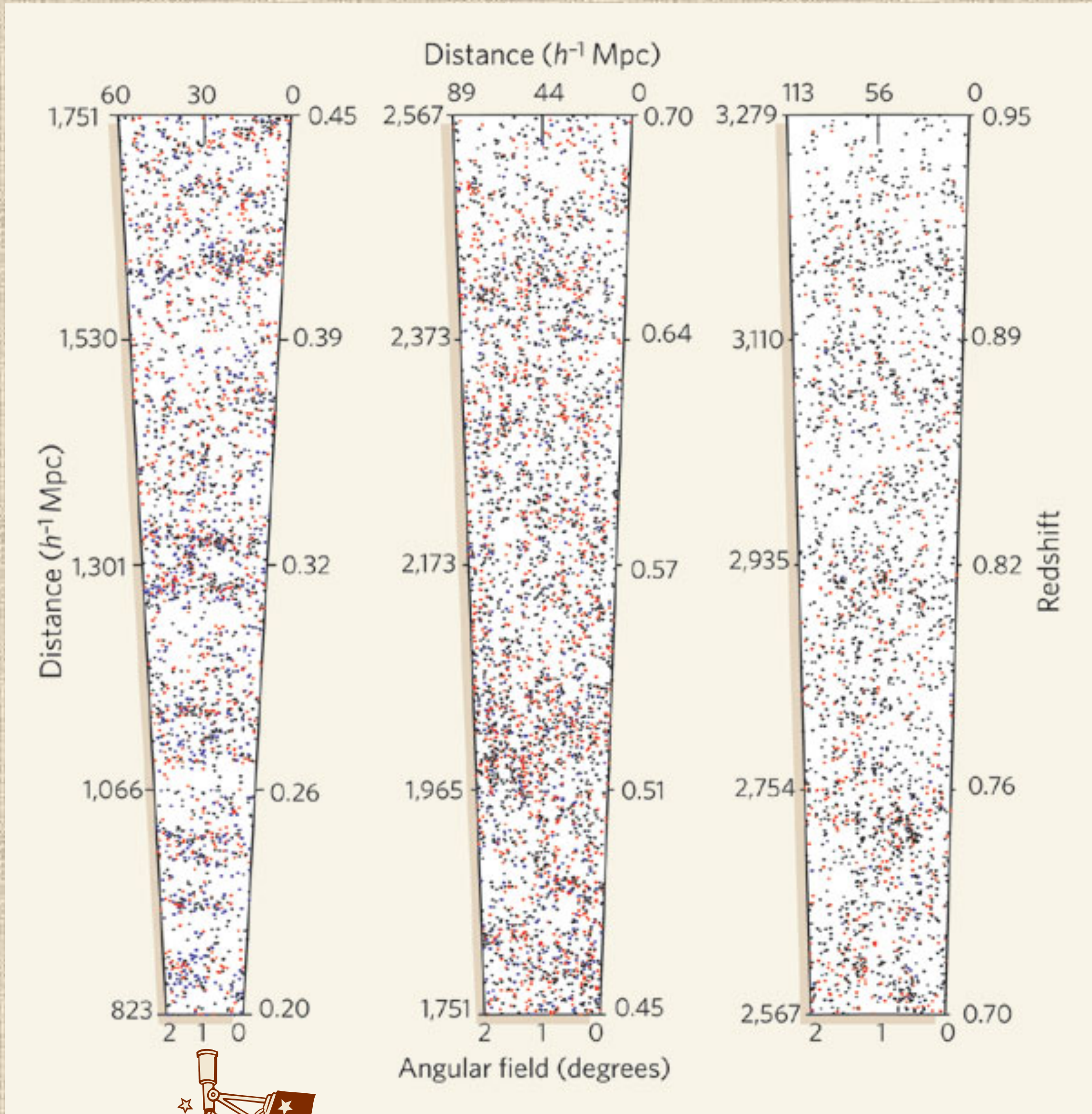
Projects presented here have received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration, under grant agreement no 291521

Large-scale structure at z<0.2

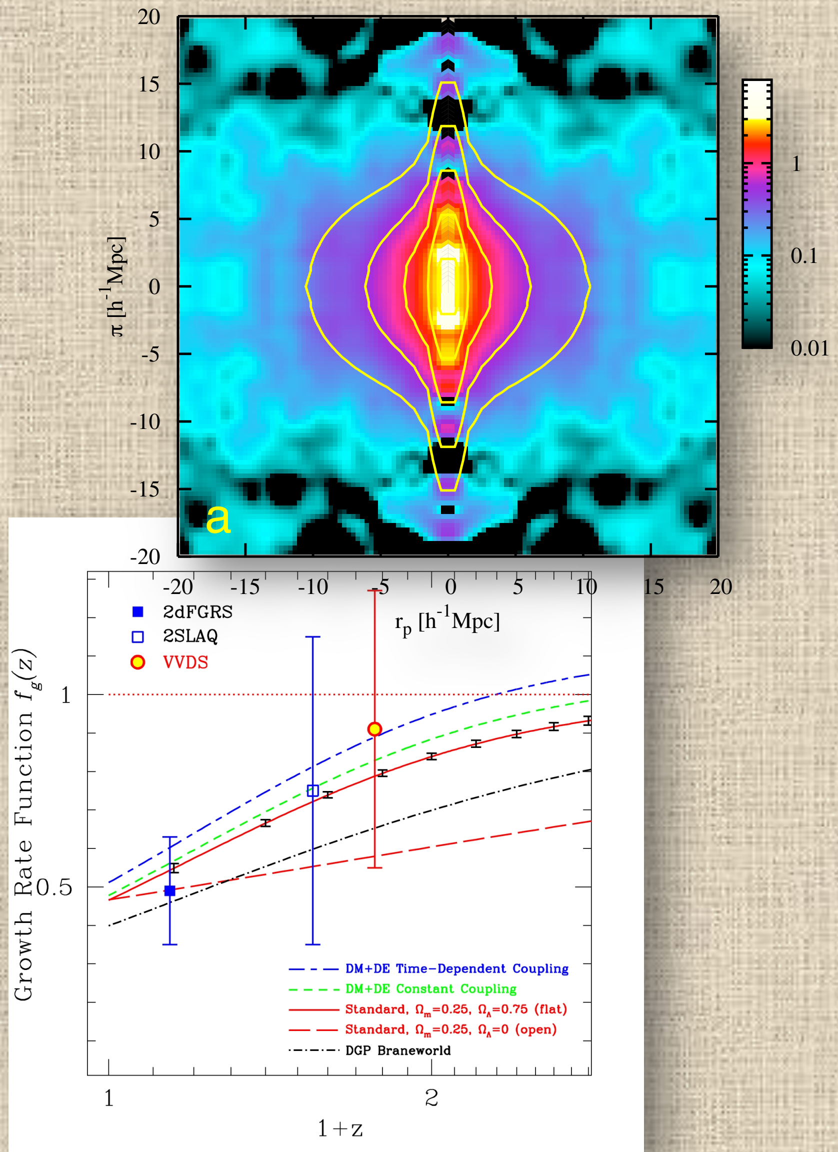



Structure in VVDS-Deep
(Le Fevre et al. 2005)
z=0.9
z=0.8
z=0.8
z=0.7
z=0.7
z=0.6
z=0.6
z=0.5
z=1.3
z=1.2
z=1.2
z=1.1
z=1.1
z=1
z=1
z=0.9
30Mpc
160Mpc
VVDS

VVDS-Wide F22 field: 4 deg^2, 10,000 redshifts to z~1.2

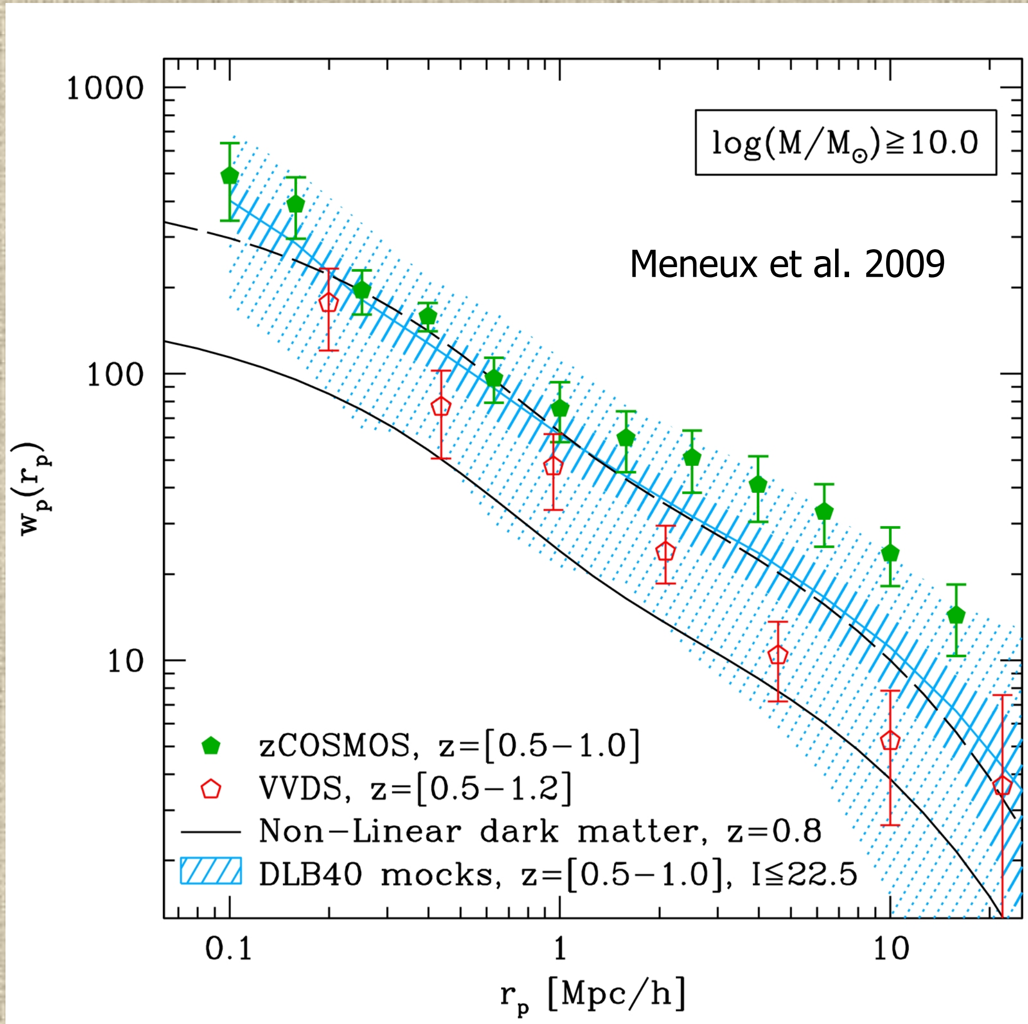


(Garilli et al. 2008, A&A 486, 683)



The renaissance of **Redshift-Space Distortions**
(Guzzo et al. 2008, Nature 451, 541)

Still small volumes: strong sample variance



→ 2-point clustering: **zCOSMOS vs VVDS-Wide F22** at <z>~0.8

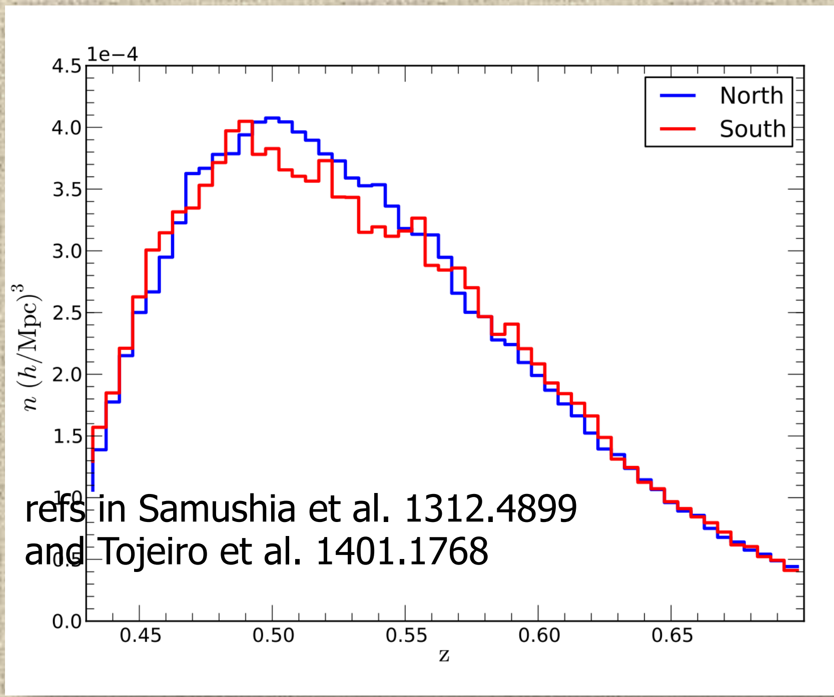
→ Excess clustering expected in a hierarchical scenario if density PDF is biased (here due to excess of high-density regions in zCOSMOS at these redshifts)

De la Torre, LG & zCOSMOS Collaboration, 2010, MNRAS, 409, 867

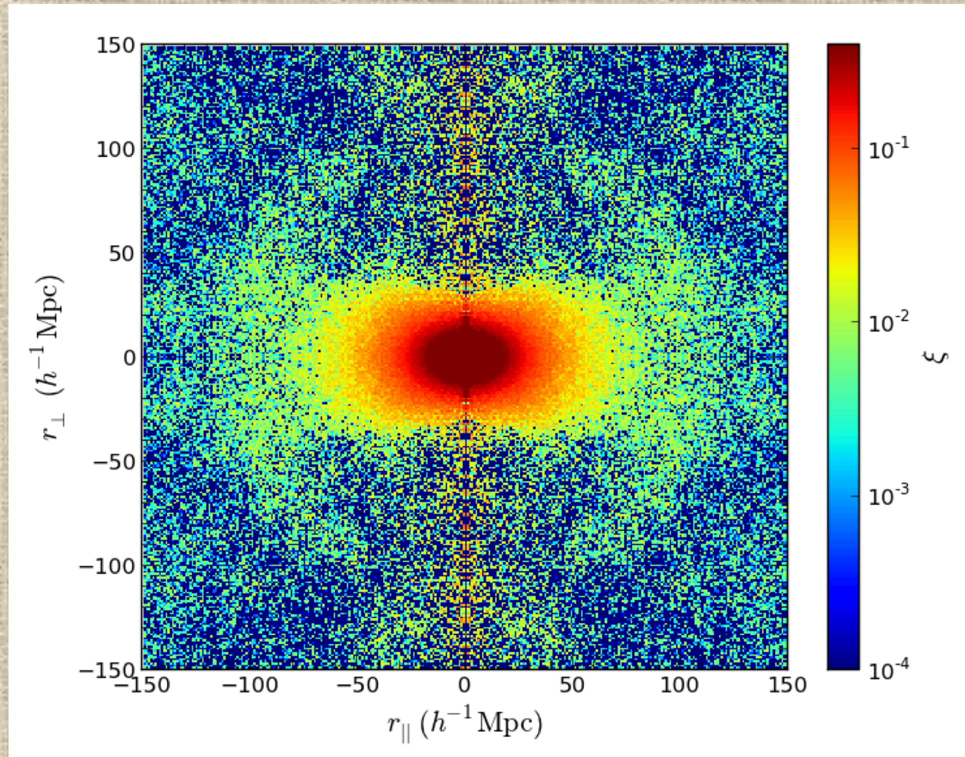
Sparsely sample larger volumes (at z~0.5-0.8) using "special" galaxies

e.g. BOSS:

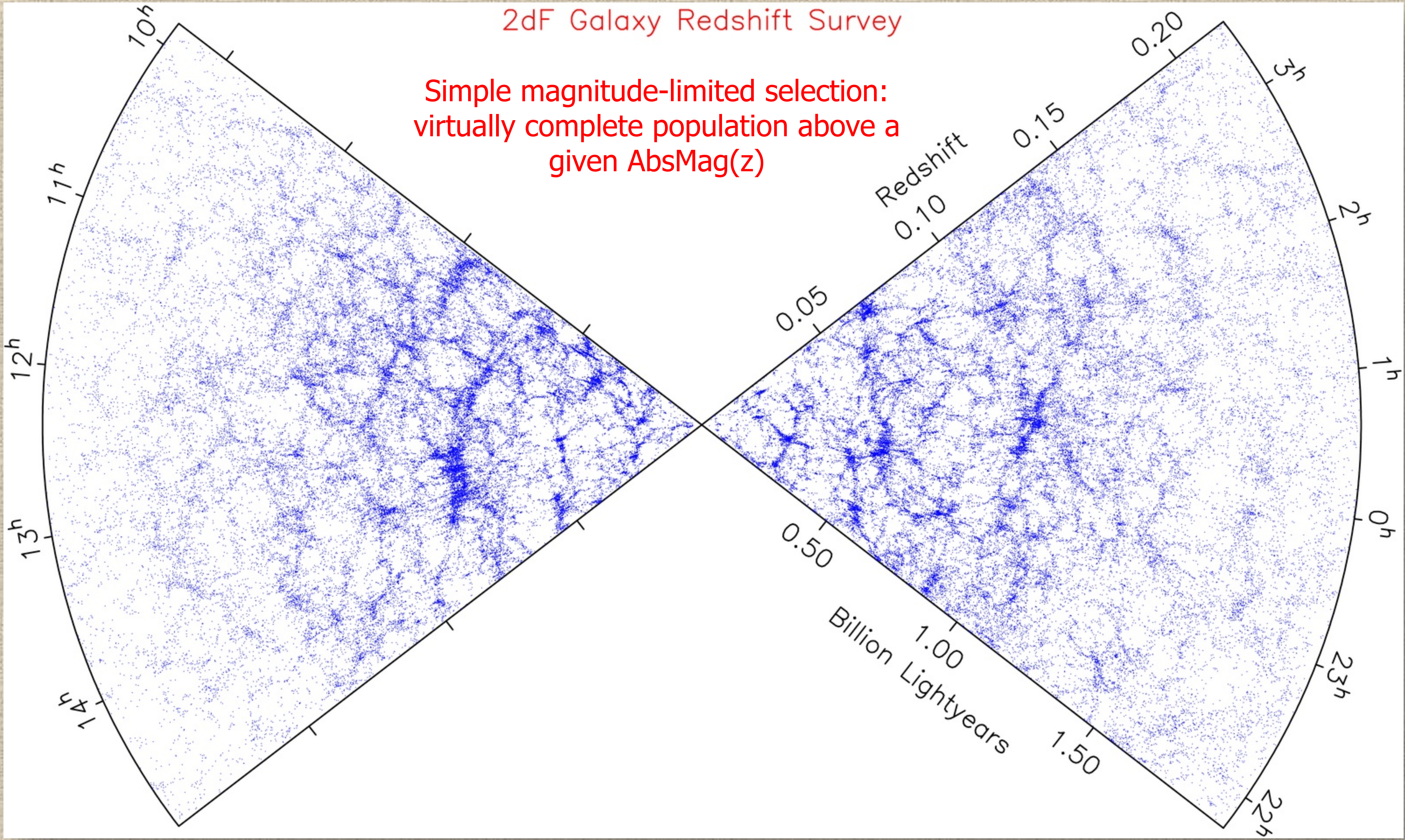
- "CMASS" LRG-like col-col selection, **"loosely selecting constant mass galaxies"**
- Area=8500 deg^2 , **Volume~6 h^{-3} Gpc**, Ngal = 690,000
- **Low-density tracers (a few 10^{-4} h Mpc^{-3})**
- Optimized for **BAO**, not for P(k) shape information (selection function)
- Excellent (a posteriori) for **Redshift Space Distortions** thanks to huge volume
- (other example is **Wigglez** @ AAT – Blake et al.)



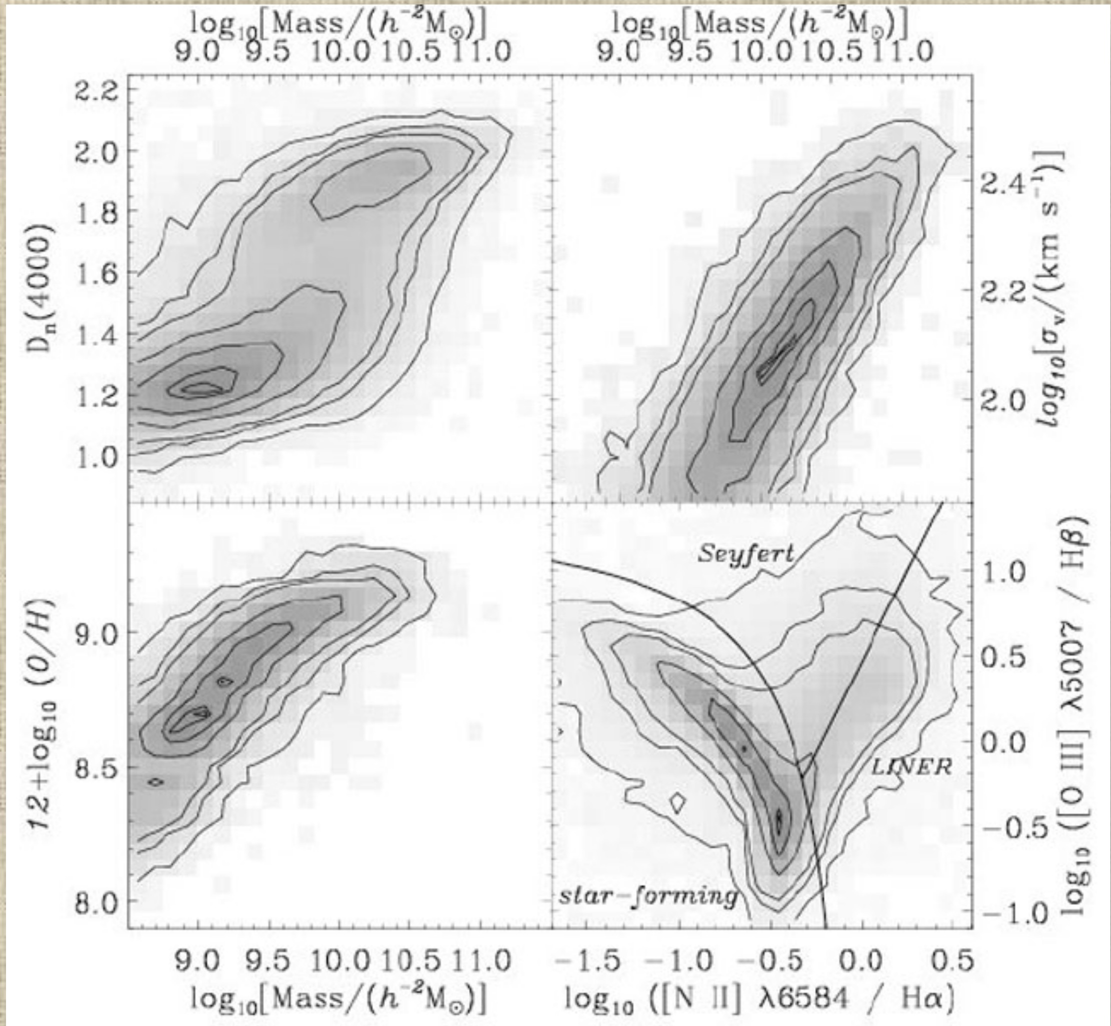
refs in Samushia et al. 1312.4899
and Tojeiro et al. 1401.1768



…however, rather special galaxies, if compared to 2dFGRS or SDSS…

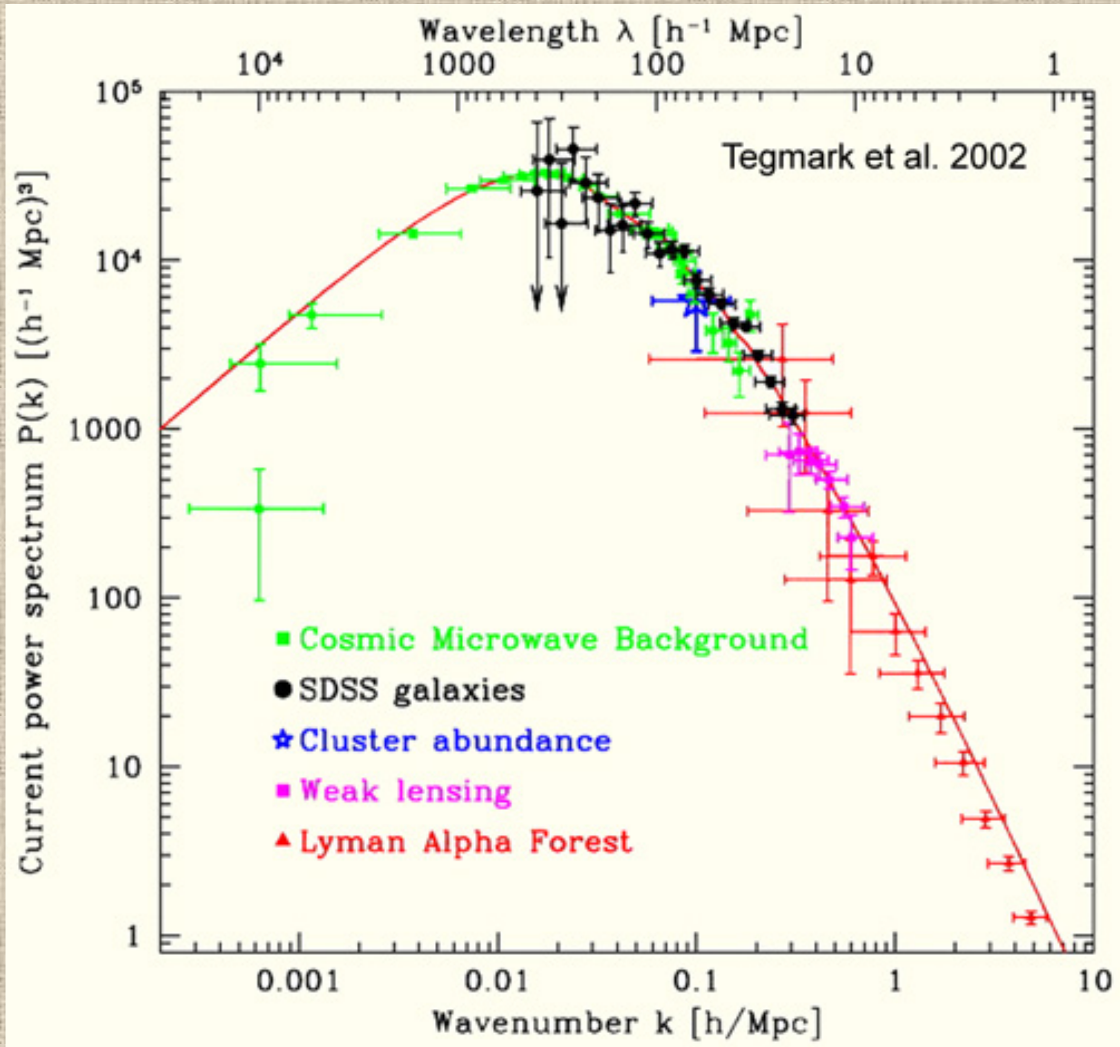


…which also boosted our understanding of the galaxy population…



- SDSS: statistical distribution of galaxy properties for ~10^6 galaxies

We need to understand galaxies, to do cosmology…

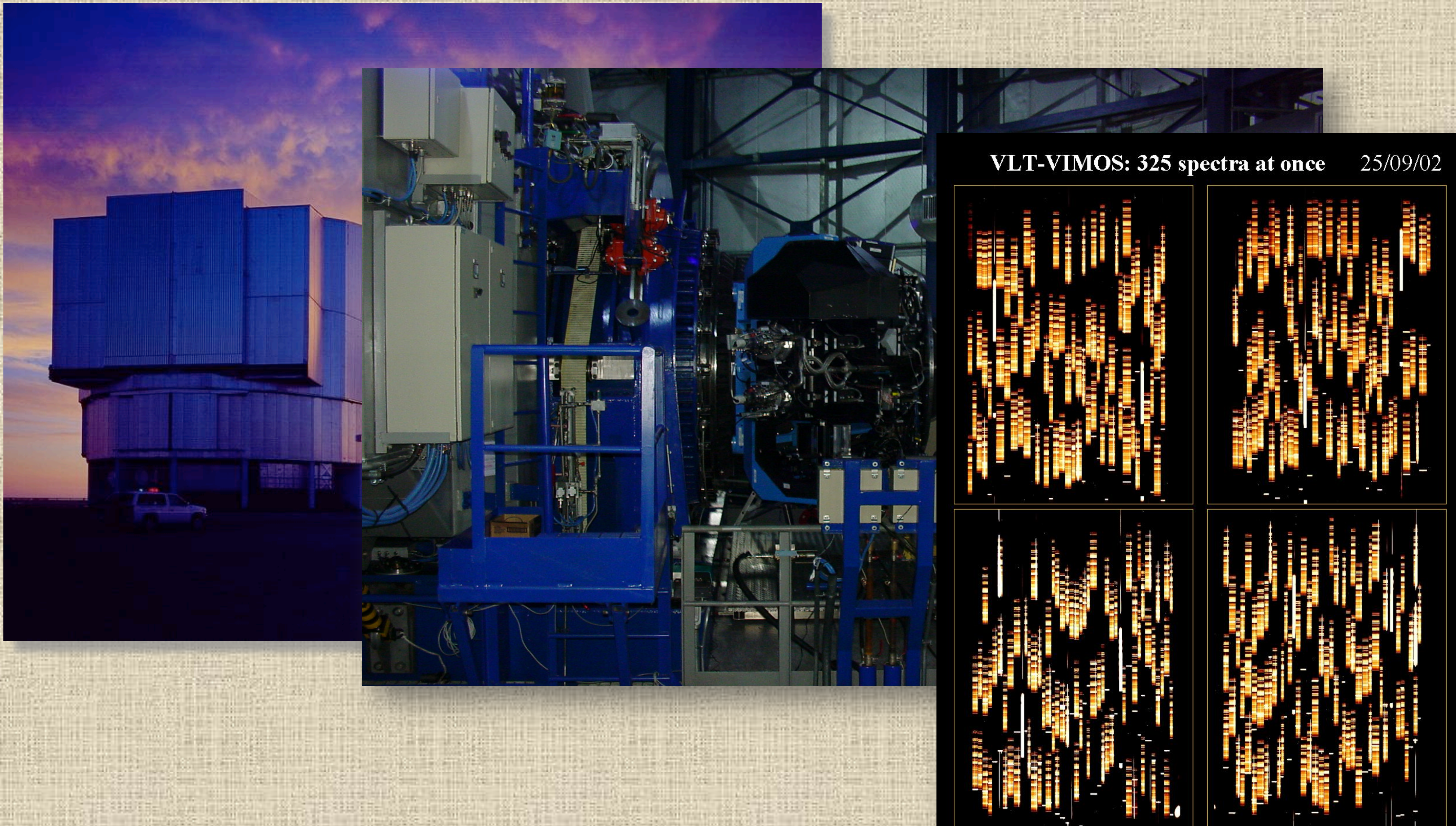


→ Aim at reaching, at z>0.5, **both** volume and sampling (in density and galaxy types) comparable to 2dFGRS and SDSS…

VIPERS

VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

VIMOS @ VLT fills unique niche in density-area space



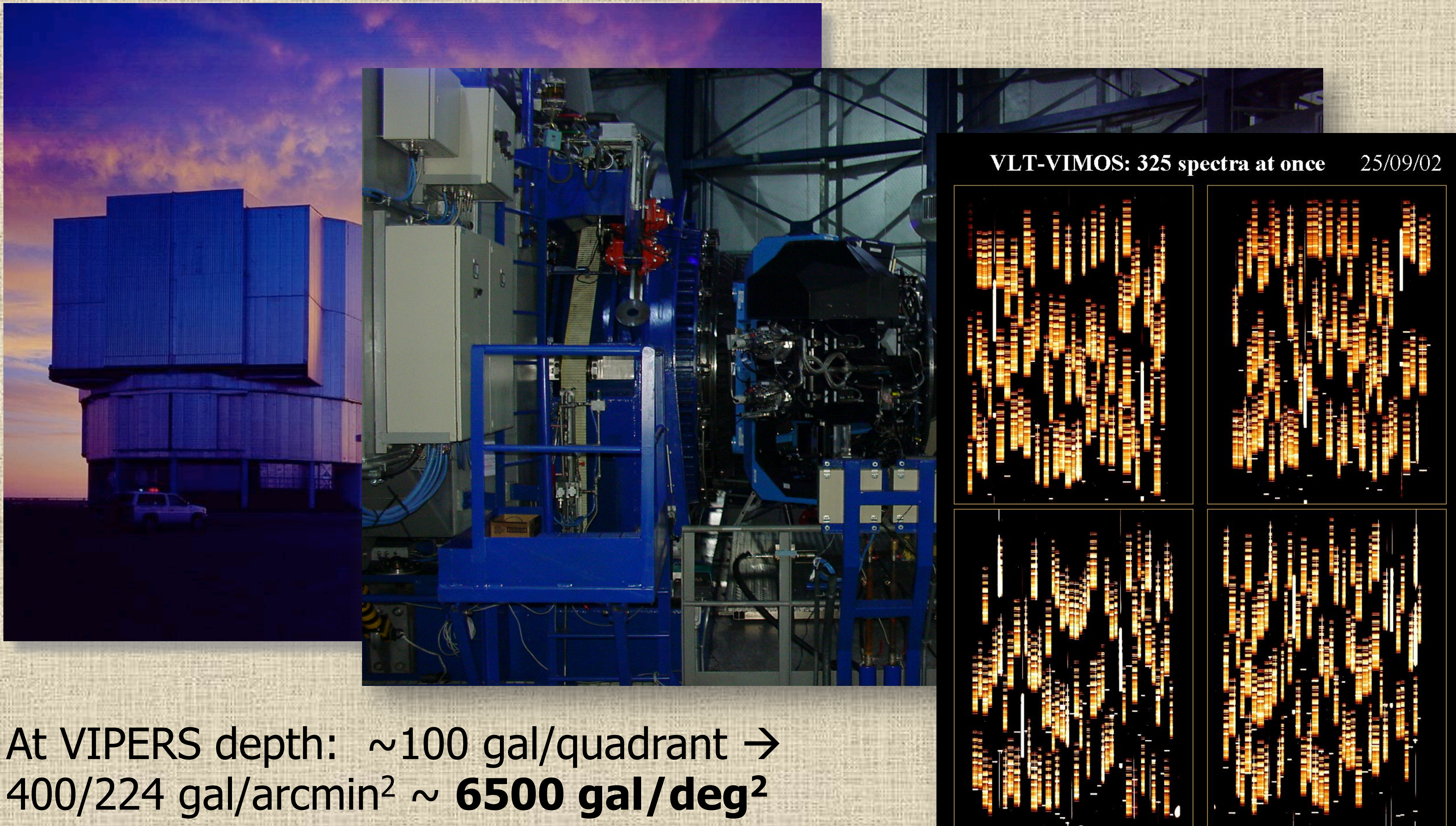
VIPERS headline science goals

- **Growth rate from redshift-space distortions at z~1**
- **Clustering at z~1 with precision comparable to z~0:**
  - Evolution of $\xi(r)$ and $P(k)$ (Ω_m, Ω_b at z~1)
  - Dependence on galaxy properties
  - Galaxy-DM relations (HOD modeling)
- **Evolution and non-linearity of galaxy biasing**
- **Evolution of galaxy colors and environmental effects**
- **Bright/massive/rare galaxies at z~1 and evolution of the galaxy luminosity and stellar mass functions**
- **Combined clustering / weak-lensing** (cosmology, photo-z calibr., CFHTLenS match)
- **Groups, Clusters…**
- **Multi-wavelength** SED information (SWIRE, XMM-XXL, UDS, VIDEO,…)

VIPERS strategy

- **Want volume and density comparable to a survey like 2dFGRS, but at z=[0.5-1]:** cosmology driven, but with broader legacy return
- **Means Vol~5 x 10^7 h^{-3} Mpc^3, ~100,000 redshifts, close to full sampling**
- Implies **I_{AB}<22.5, ~24 deg^2**
- Improve sampling within redshift range of interest through **z>0.5 robust color-color pre-selection** (+star-galaxy separation), with also better match to **VIMOS** multiplexing: **>40% sampling**
- **CFHTLS Wide** (W1 and W4 fields, ~16 + 8 deg^2) provides accurate multi-band photometry to support this
- VIMOS LR Red grism, **45 min exposure**
- 288 pointings, **440.5 VLT hours (~55 night-equivalent)**

VIMOS @ VLT fills unique niche in density-area space

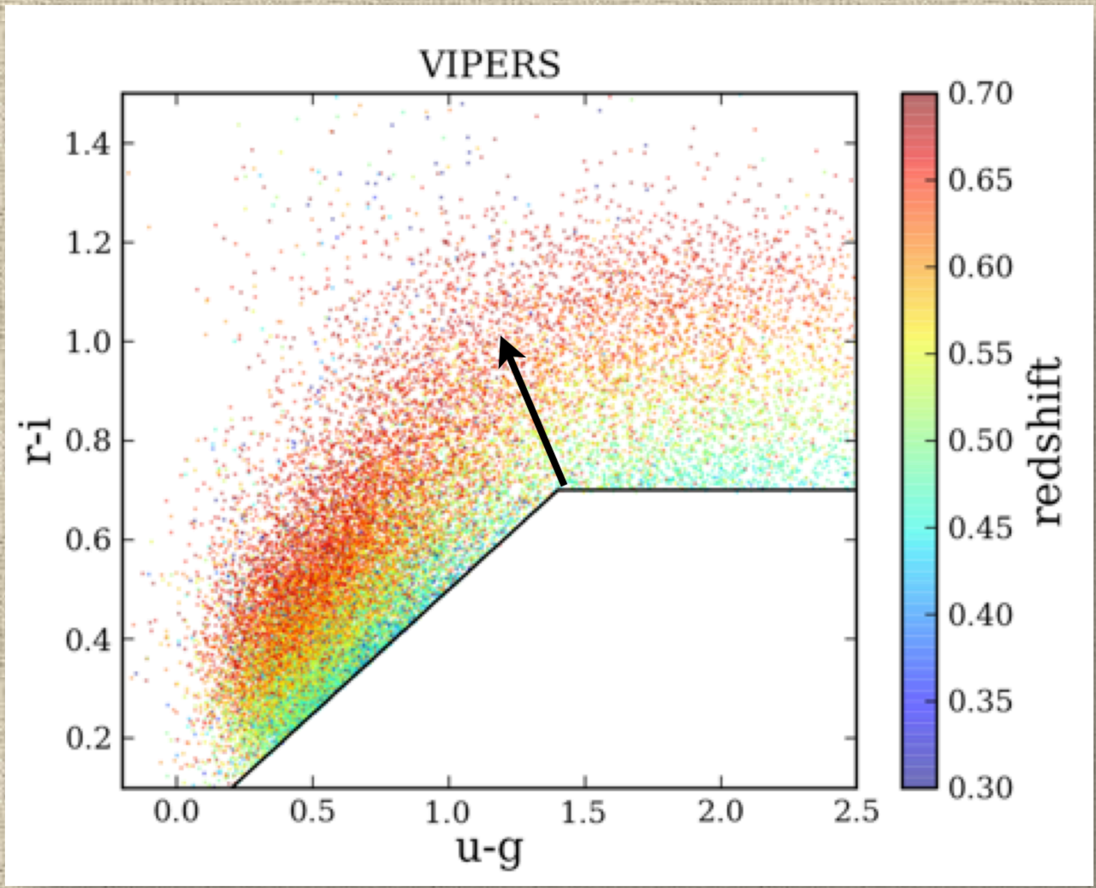


At VIPERS depth: ~100 gal/quadrant →
400/224 gal/arcmin^2 ~ **6500 gal/deg^2**

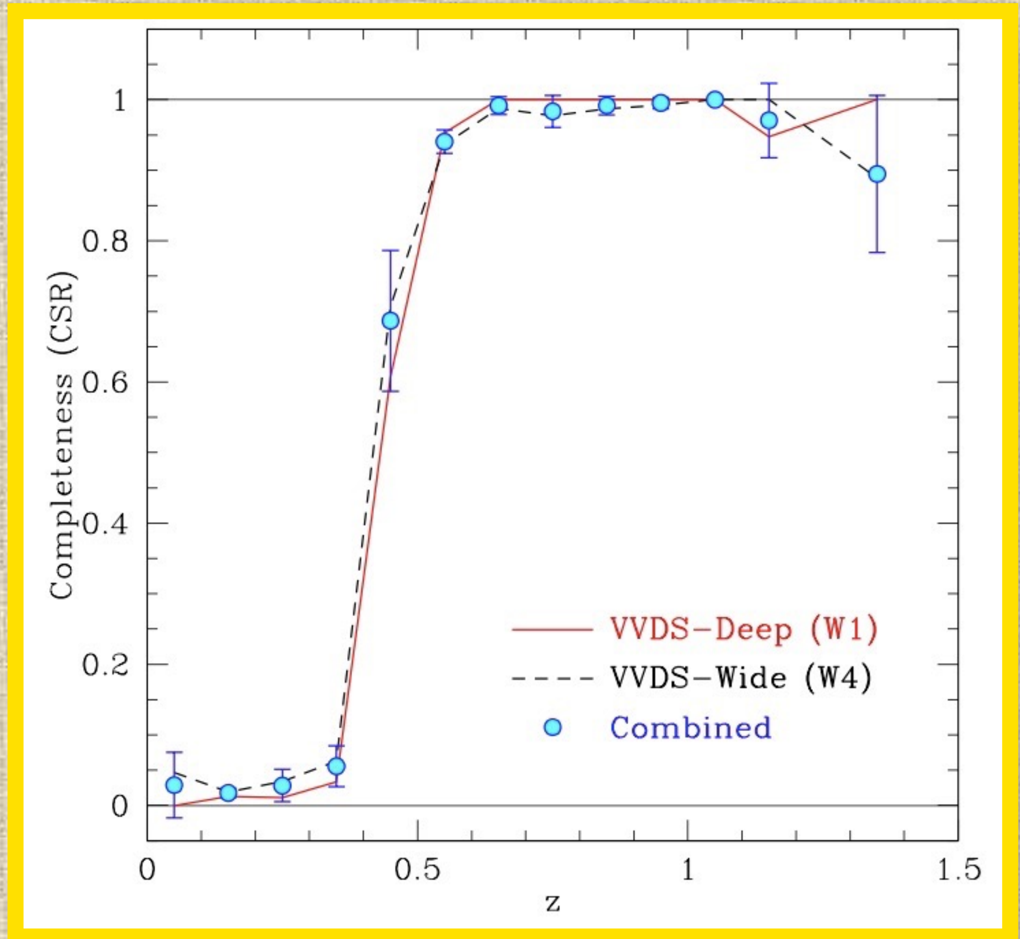
VIPERS Team

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

VIPERS Colour-Colour selection: measure galaxies only where we need them, i.e. z>0.5 (calibrated using VVDS)

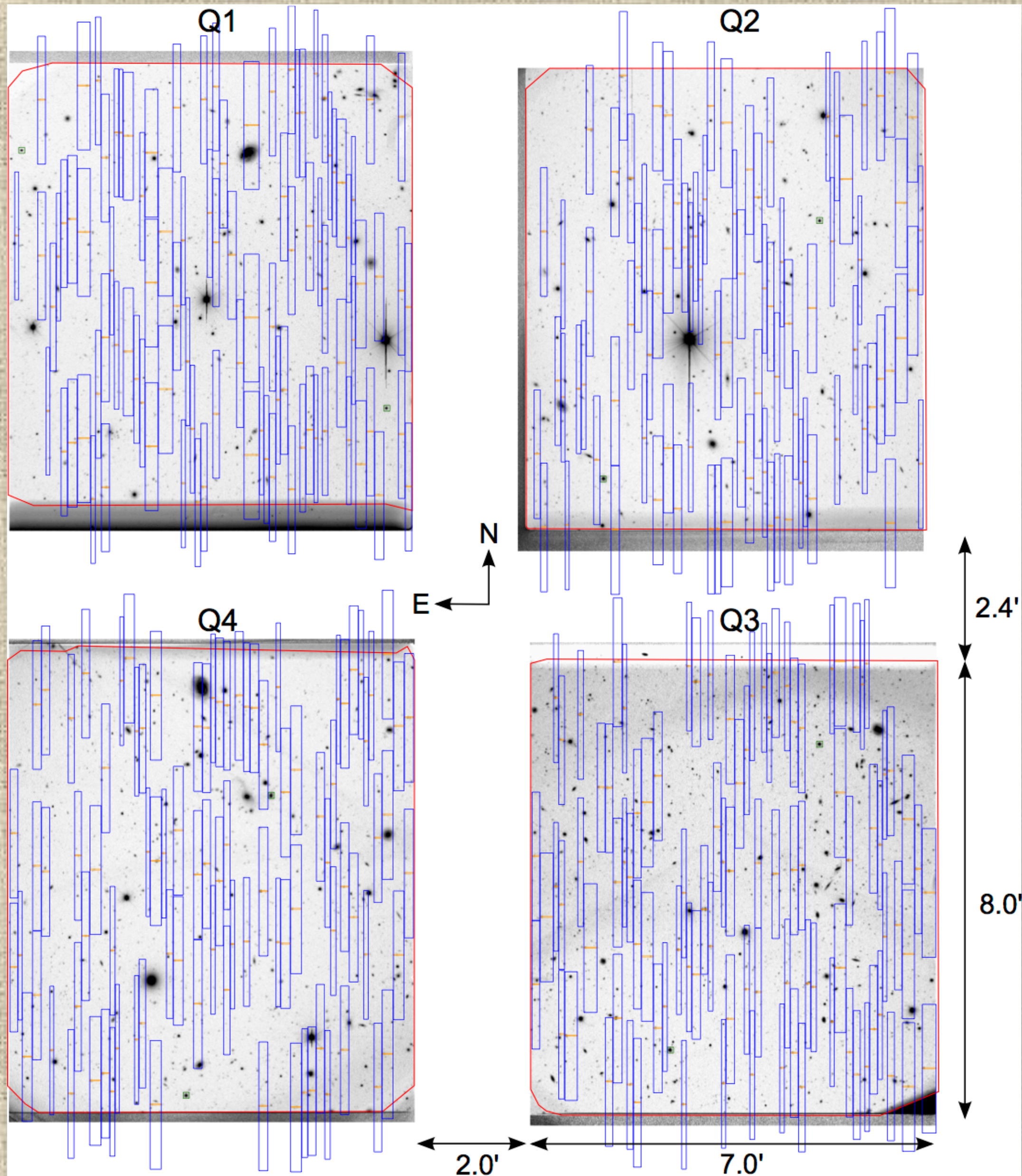


DEEP-2 like, but using 4 photometric bands

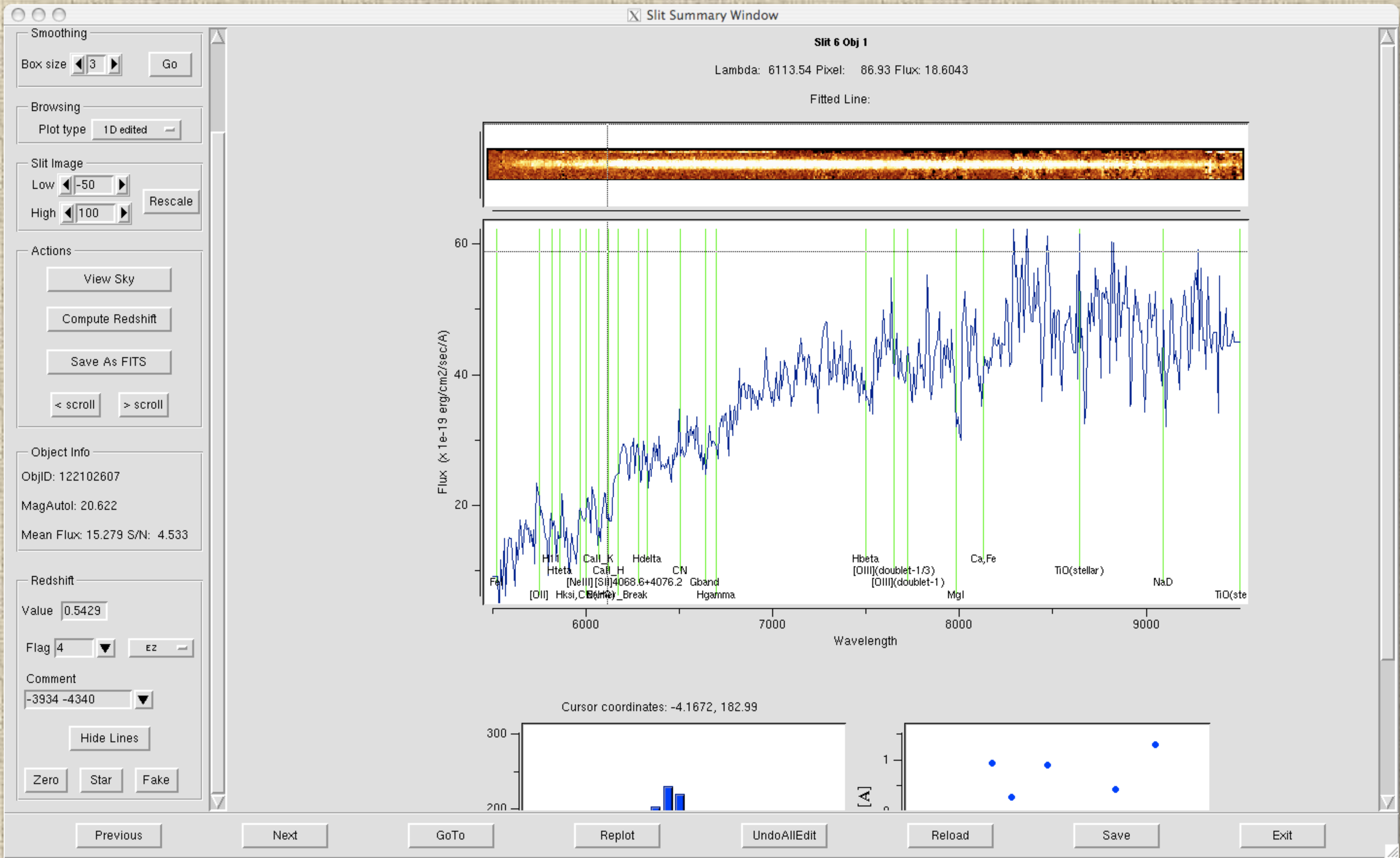


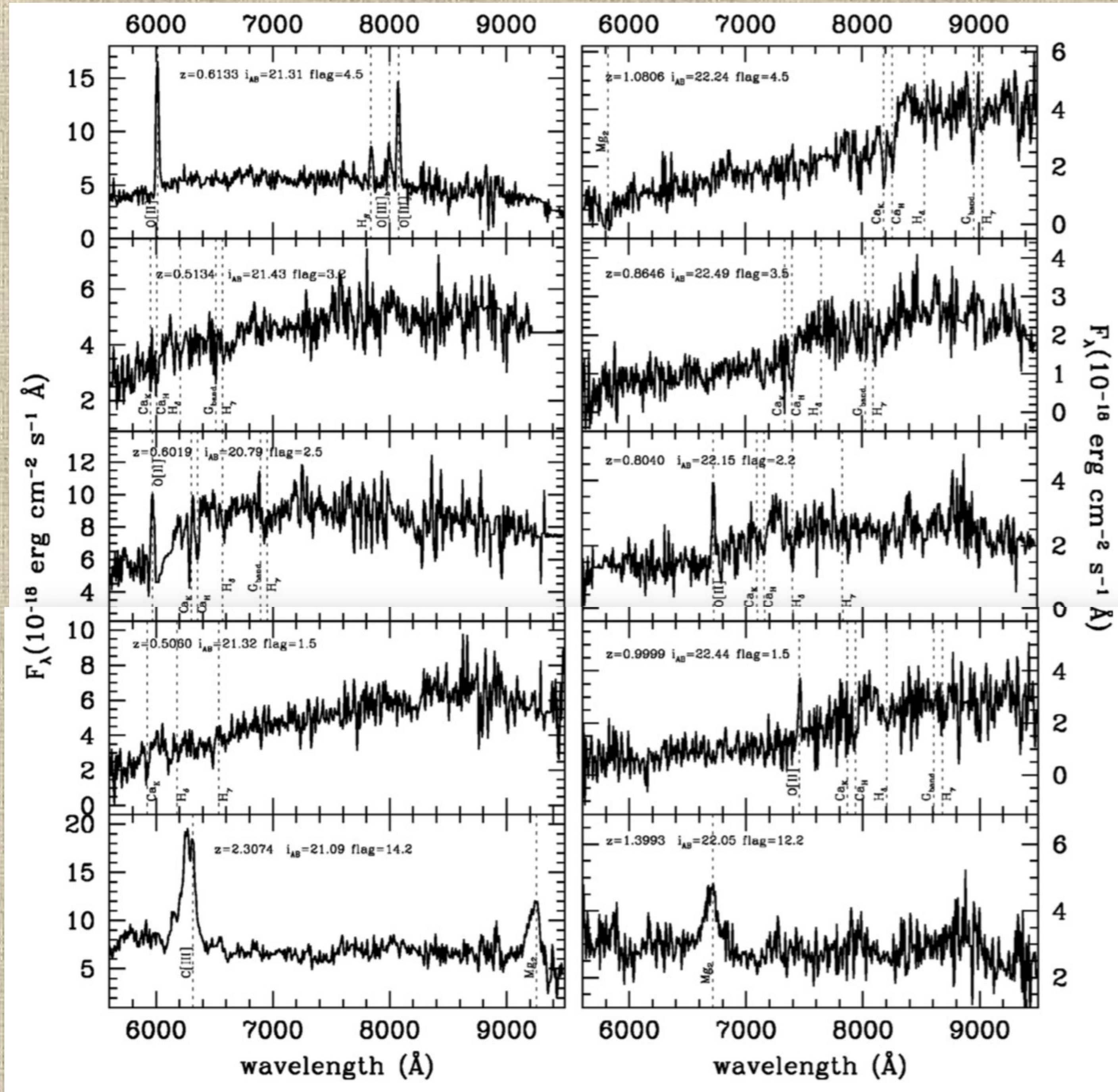
VIPERS single-shot footprint on the sky

- **On average, 360 spectra observed per VIMOS pointing, given VIPERS target sample surface density and clustering**
- **VIPERS strategy yields mean spatial density $\langle n \rangle \sim 10^{-2}\ h^3\ \mathrm{Mpc}^{-3}$ within the range of interest**

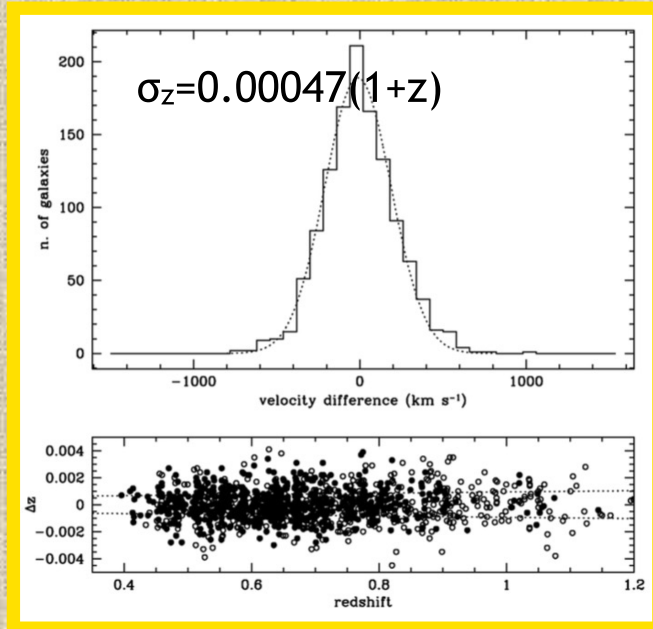


1. Automatic spectral extraction/calibration + redshift measurement: ***EasyLife*** pipeline running at INAF- IASF Milano (Garilli et al. 2012, PASP, 124)
2. Redshift review and validation: ***VIPGI*** (Scodeggio et al. 2005, PASP, 117) ***&*** ***EZ*** (Garilli et al. 2010, PASP, 122)



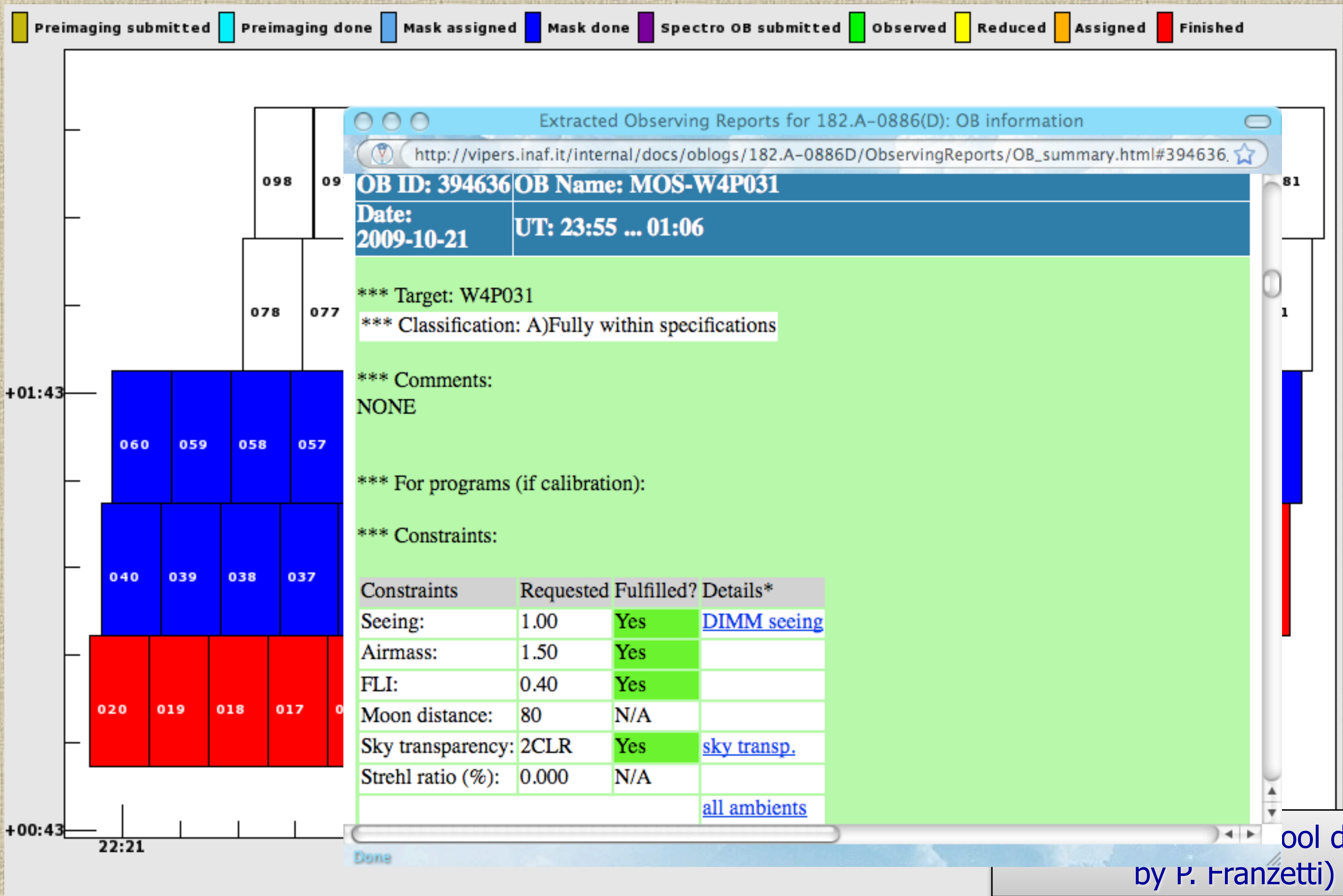


z=0.6133 i_AB=21.31 flag=4.5
z=1.0806 i_AB=22.24 flag=4.5
z=0.5134 i_AB=21.43 flag=3.2
z=0.8646 i_AB=22.49 flag=3.5
z=0.6019 i_AB=20.79 flag=2.5
z=0.8040 i_AB=22.15 flag=2.2
z=0.5060 i_AB=21.32 flag=1.5
z=0.9999 i_AB=22.44 flag=1.5
z=2.3074 i_AB=21.09 flag=14.2
z=1.3993 i_AB=22.05 flag=12.2
F_λ(10^-18 erg cm^-2 s^-1 Å)
wavelength (Å)



σz=0.00047(1+z)
n. of galaxies
velocity difference (km s⁻¹)
Δz
redshift

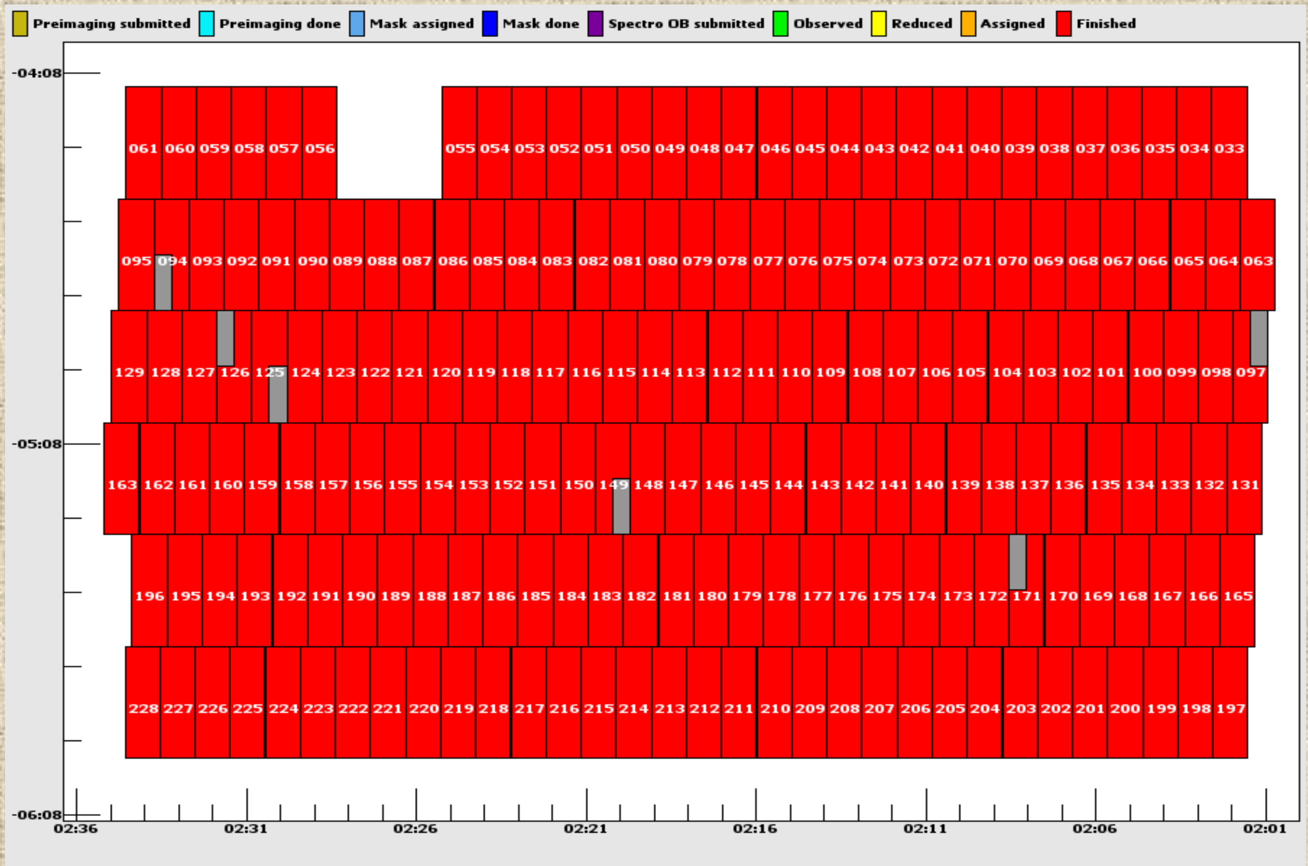
Fully automated web-based archive



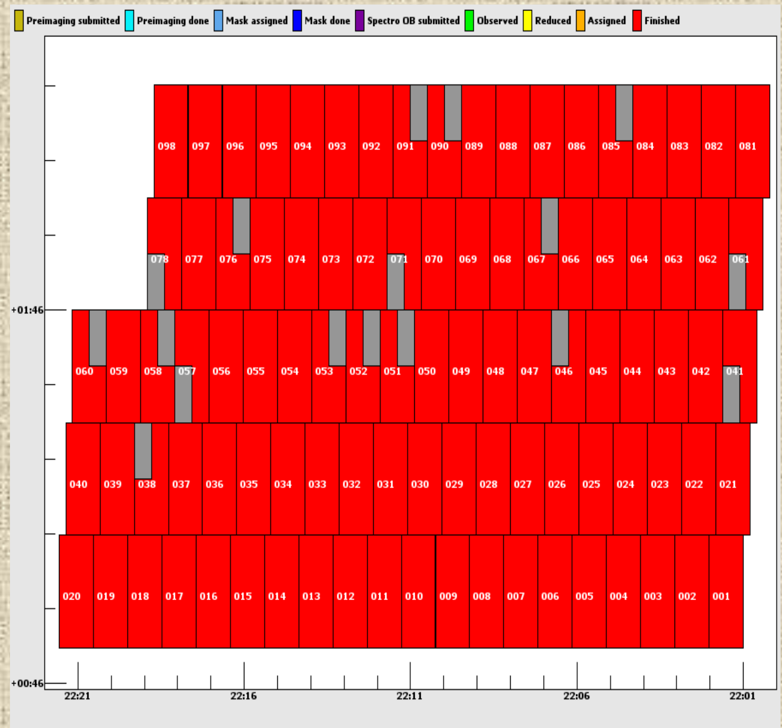
(…ool developed by P. Franzetti)

Sky coverage today: VIPERS is finished!

W1



W4



VIPERS Status and milestones

- **Survey completed in Jan 2015; all data reduced and validated by May: internal final (V7.0) release made available to team**

SURVEY STATUS AS OF 14/05/2015

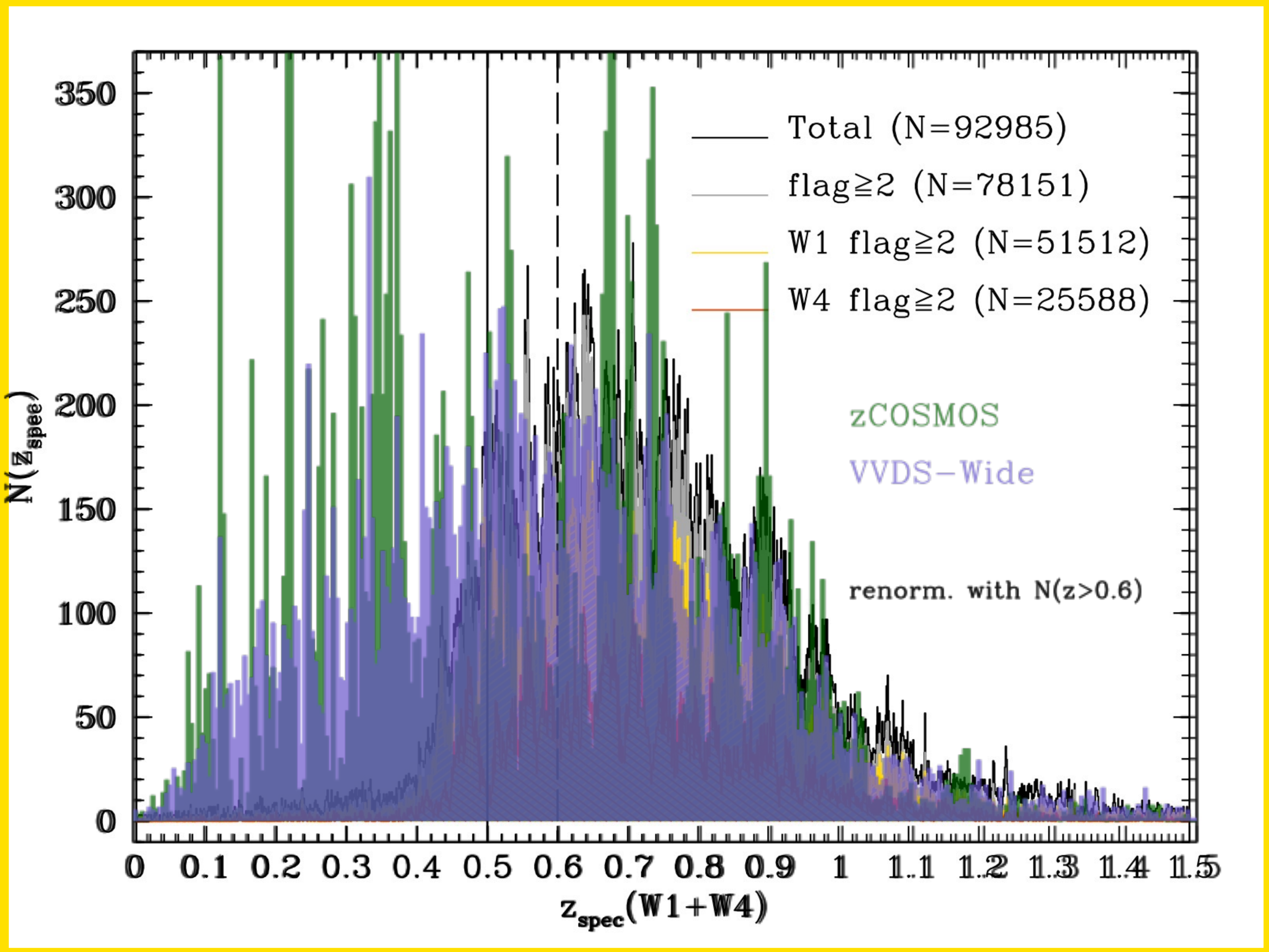
EFFECTIVE TARGETS	MEASURED REDSHIFTS	STELLAR CONTAMINATION	COVERED AREA
93252	88901	2265 (2.5 %)	100.0 %

EFFECTIVE TARGETS (ET) are all the primary targeted objects with the exclusion of the ones flagged as -10 (undetected). MEASURED REDSHIFTS (MR) are the fraction of ET for which a redshift has been measured. STELLAR CONTAMINATION are the MR objects which have been identified as stars.

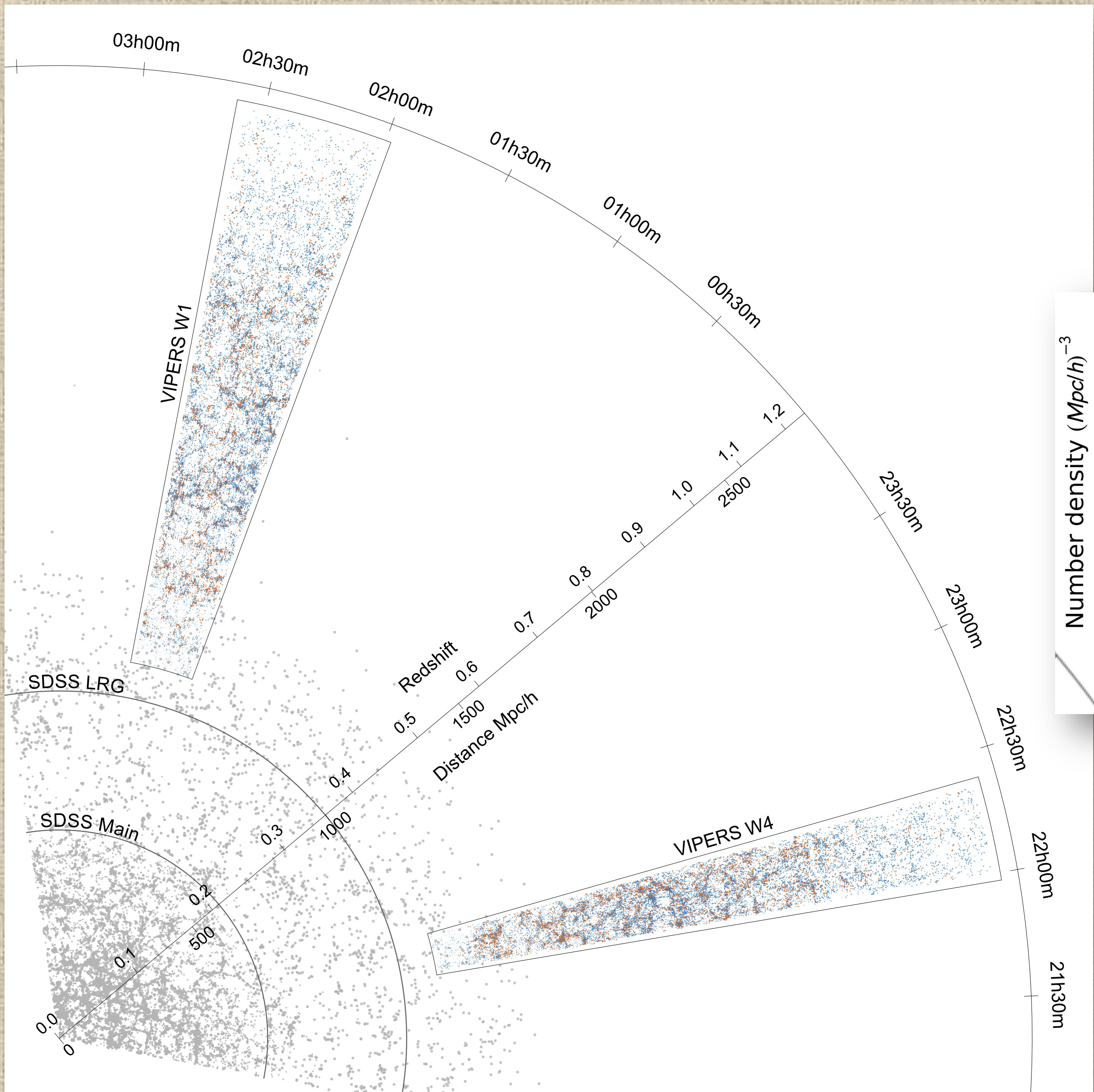
- **2/3 of survey (~55,000 redshifts) public since October 2013 (released 6 months after very first “wave” of scientific results)**

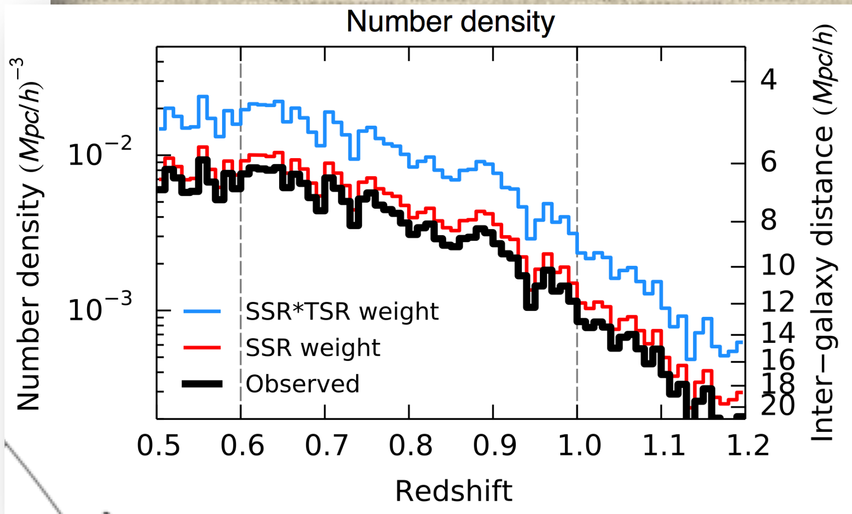
- **Scientific analyses on final sample ongoing, public release foreseen for summer/fall 2016**

Final VIPERS vs previous smaller-area probes (all i_{AB}<22.5)

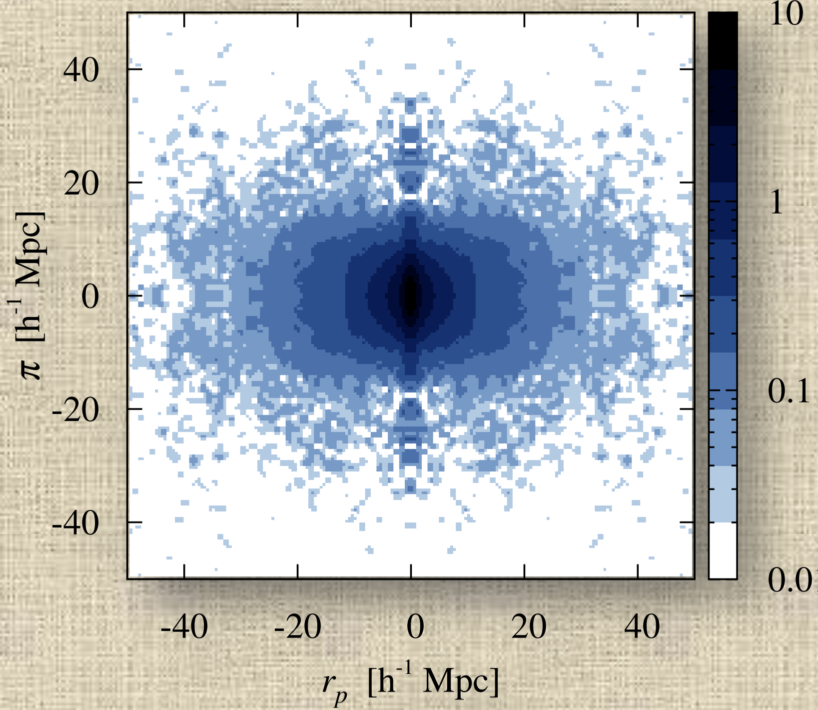


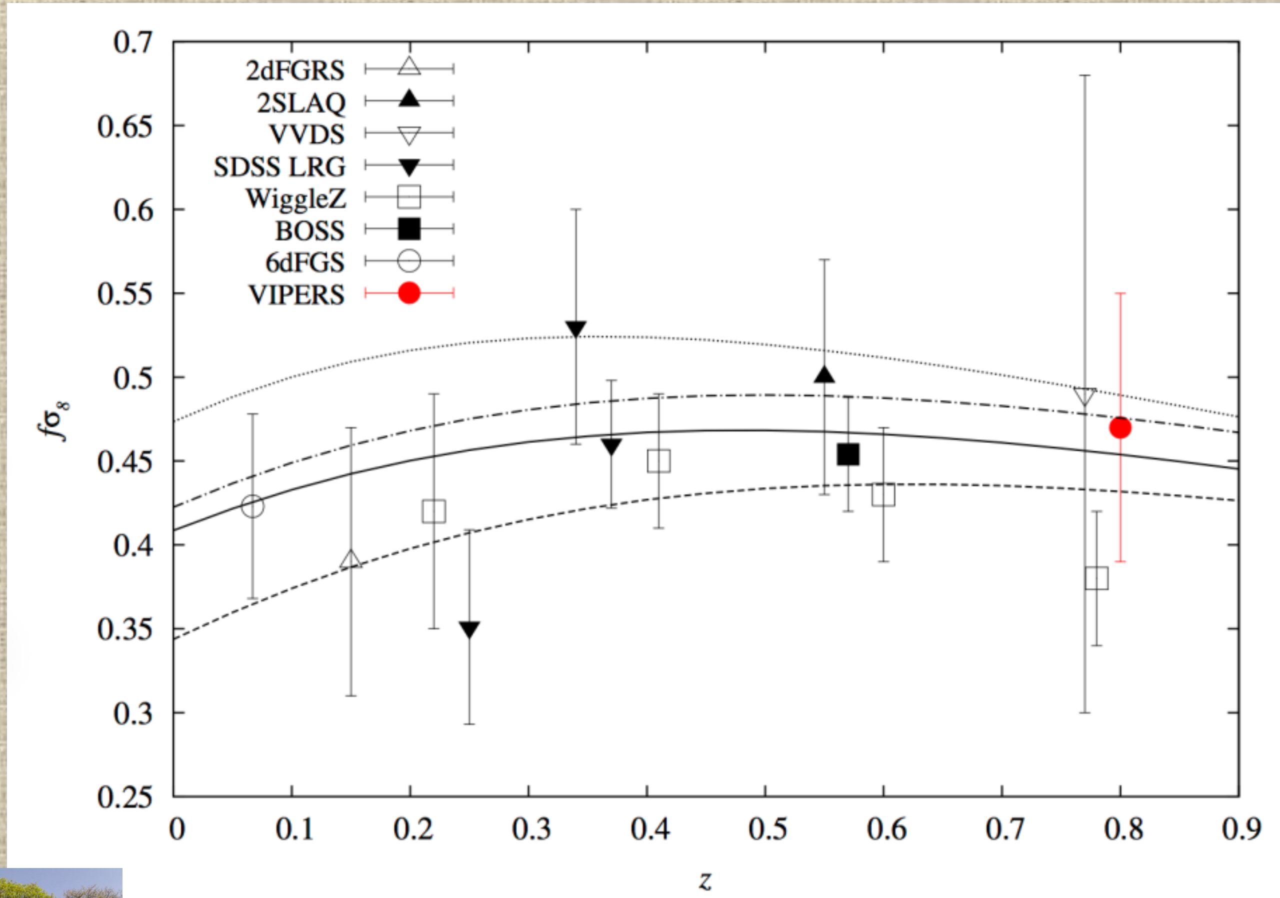
(Comparison by M. Bolzonella)


03h00m
02h30m
02h00m
01h30m
01h00m
00h30m
23h30m
23h00m
22h30m
22h00m
21h30m
VIPERS W1
VIPERS W4
SDSS LRG
SDSS Main
Redshift
Distance Mpc/h
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
0
500
1000
1500
2000
2500

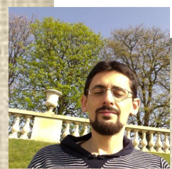

Number density
Number density (Mpc/h)^−3
Inter−galaxy distance (Mpc/h)
10^−2
10^−3
4
6
8
10
12
14
16
18
20
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Redshift
SSR*TSR weight
SSR weight
Observed

Redshift-space clustering and growth rate of structure from the PDR-1



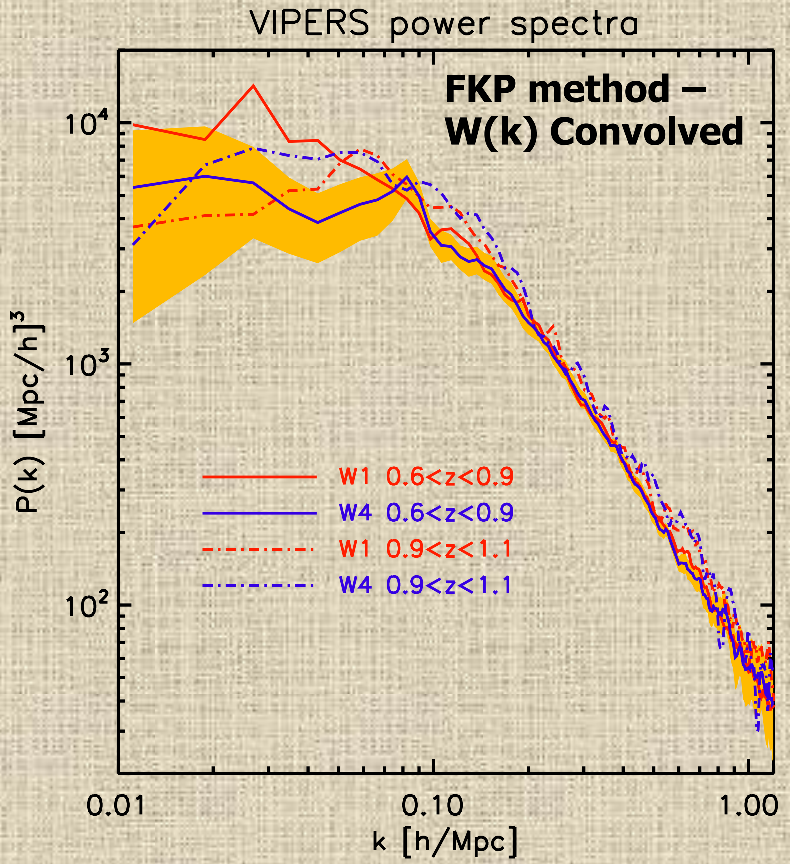


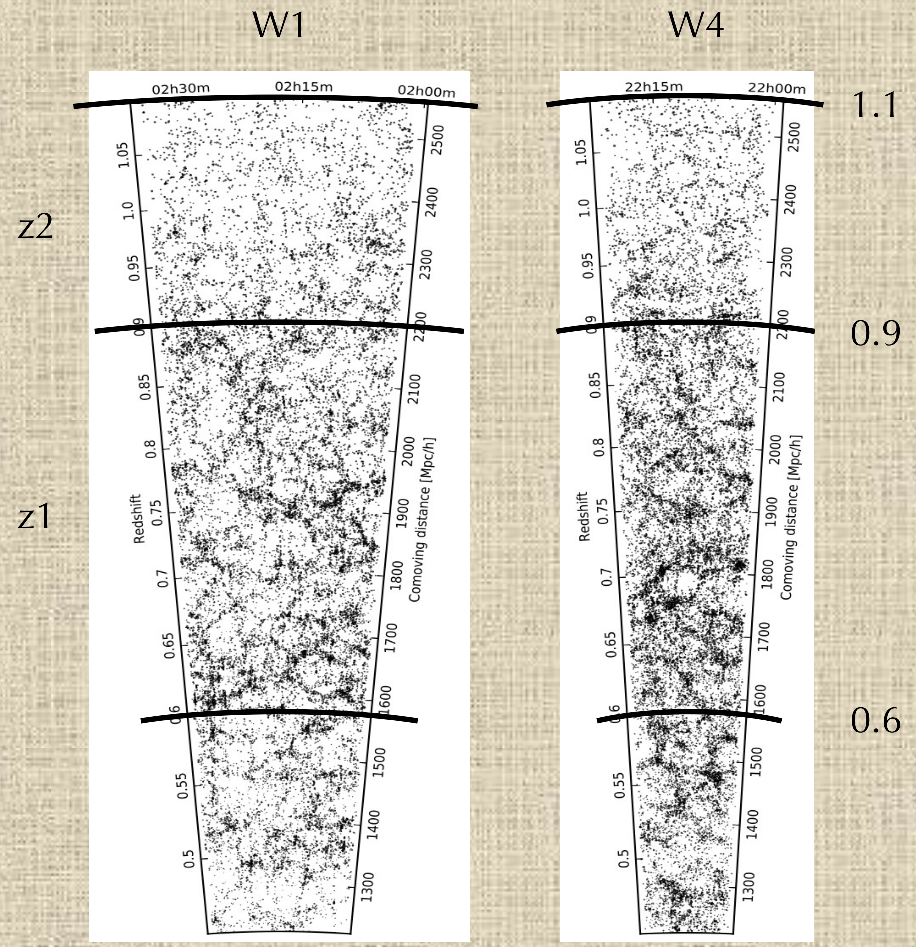
VIPERS: $f\sigma_8(z=0.8) = 0.47\pm0.08$



De la Torre et al. 2013

The power spectrum of the galaxy distribution at z=0.5-1.1 from VIPERS (S. Rota PhD work)



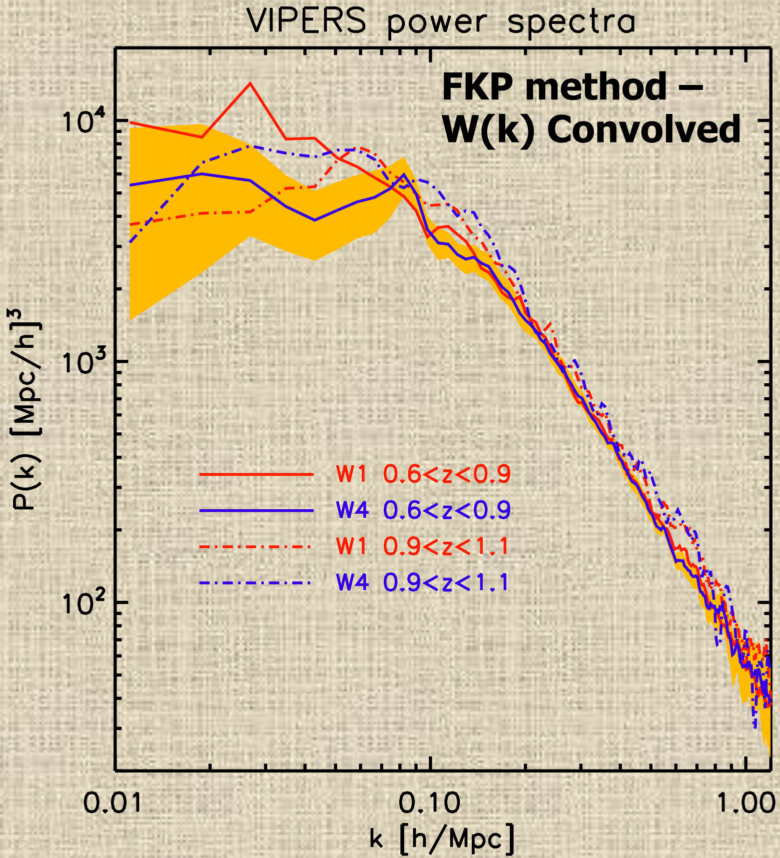


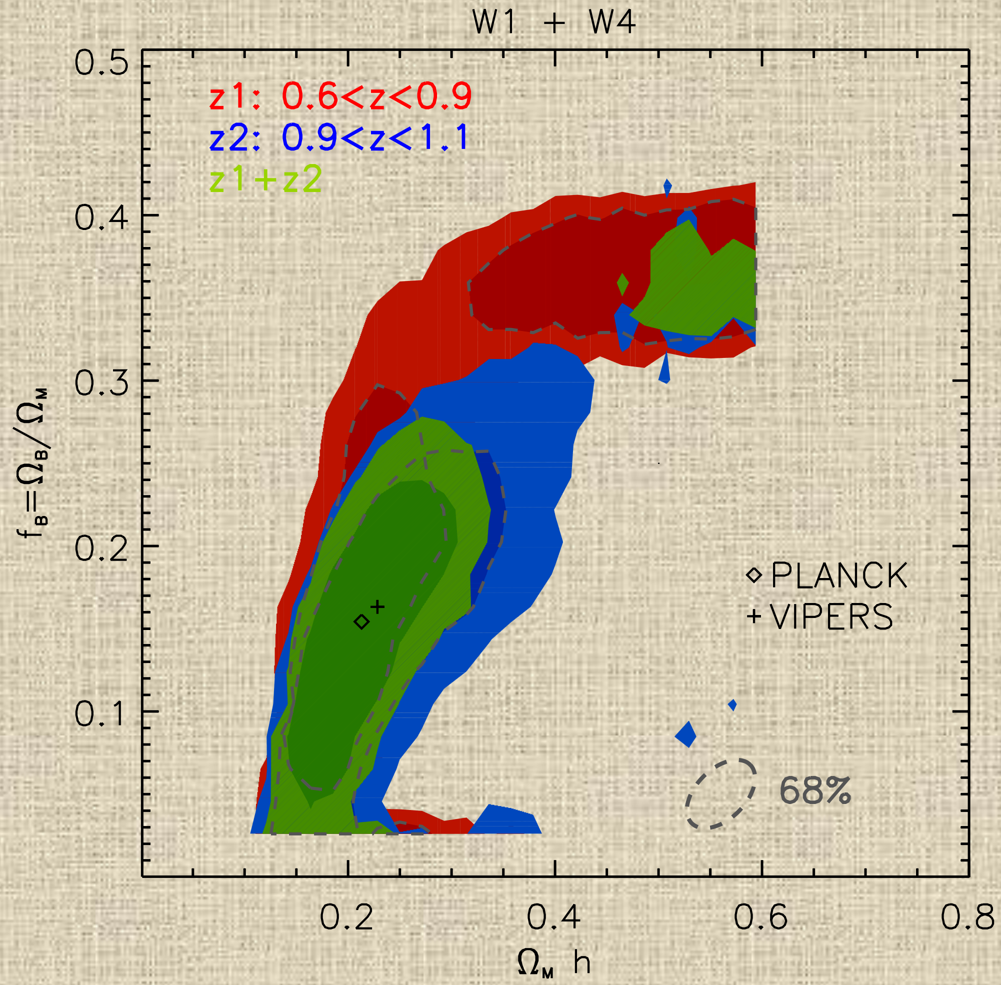
- Very careful treatment of window function

(Rota, Bel, Granett, LG & VIPERS Team, in preparation)

- 4 independent estimates: 2 z bins in 2 independent fields (W1 and W4)

The power spectrum of the galaxy distribution at z=0.5-1.1 from VIPERS (S. Rota PhD work)



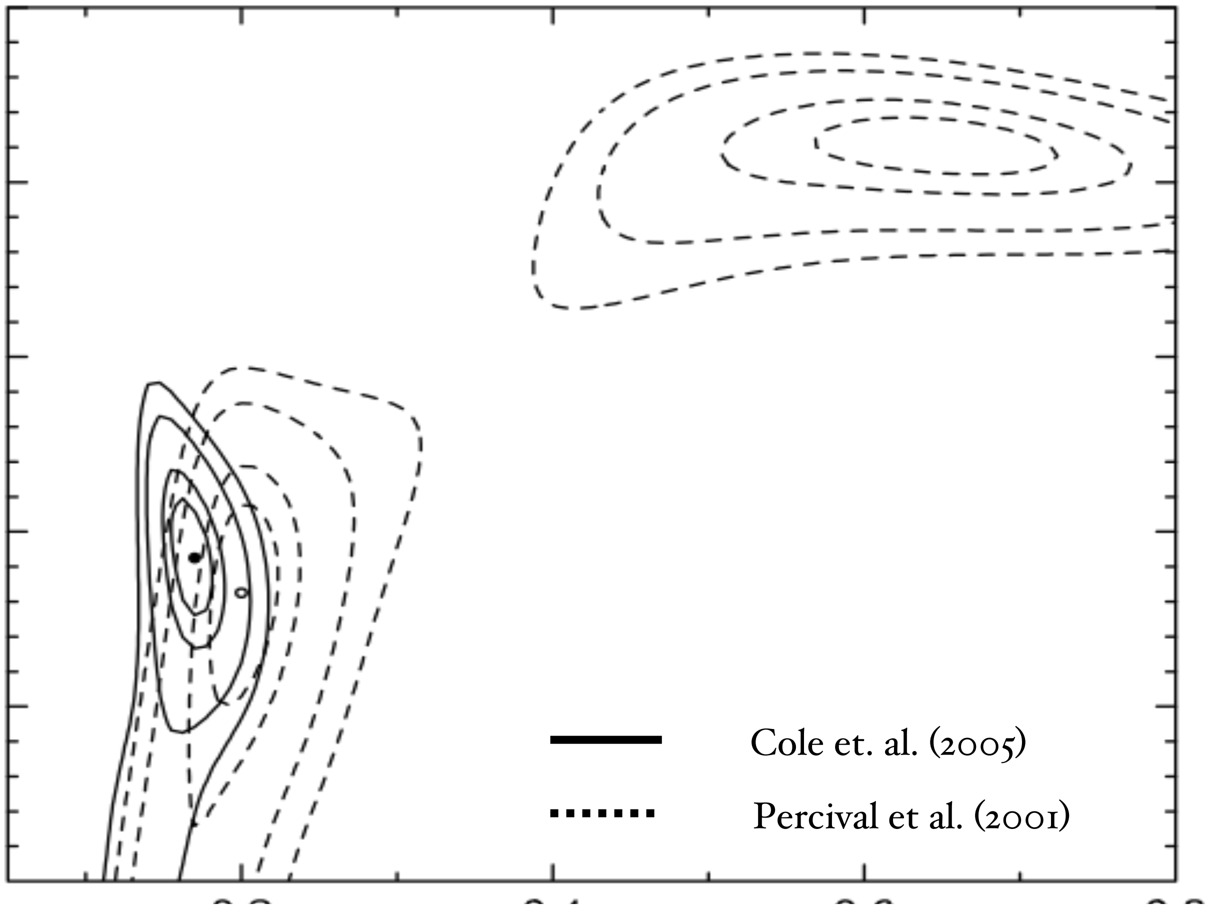


- Very careful treatment of window function

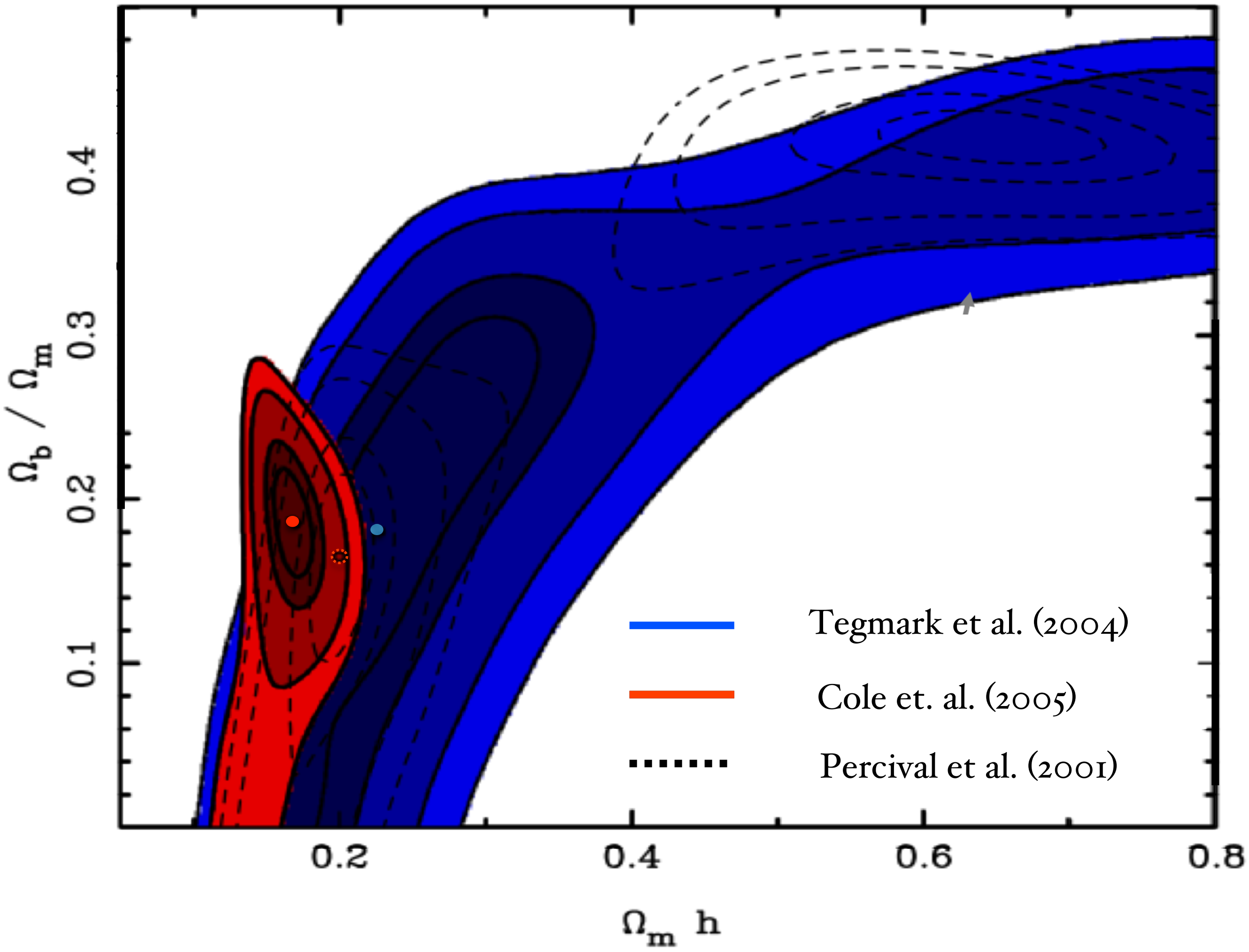
(Rota, Bel, Granett, LG & VIPERS Team, to be submitted)

- 4 independent estimates: 2 z bins in 2 independent fields (W1 and W4)

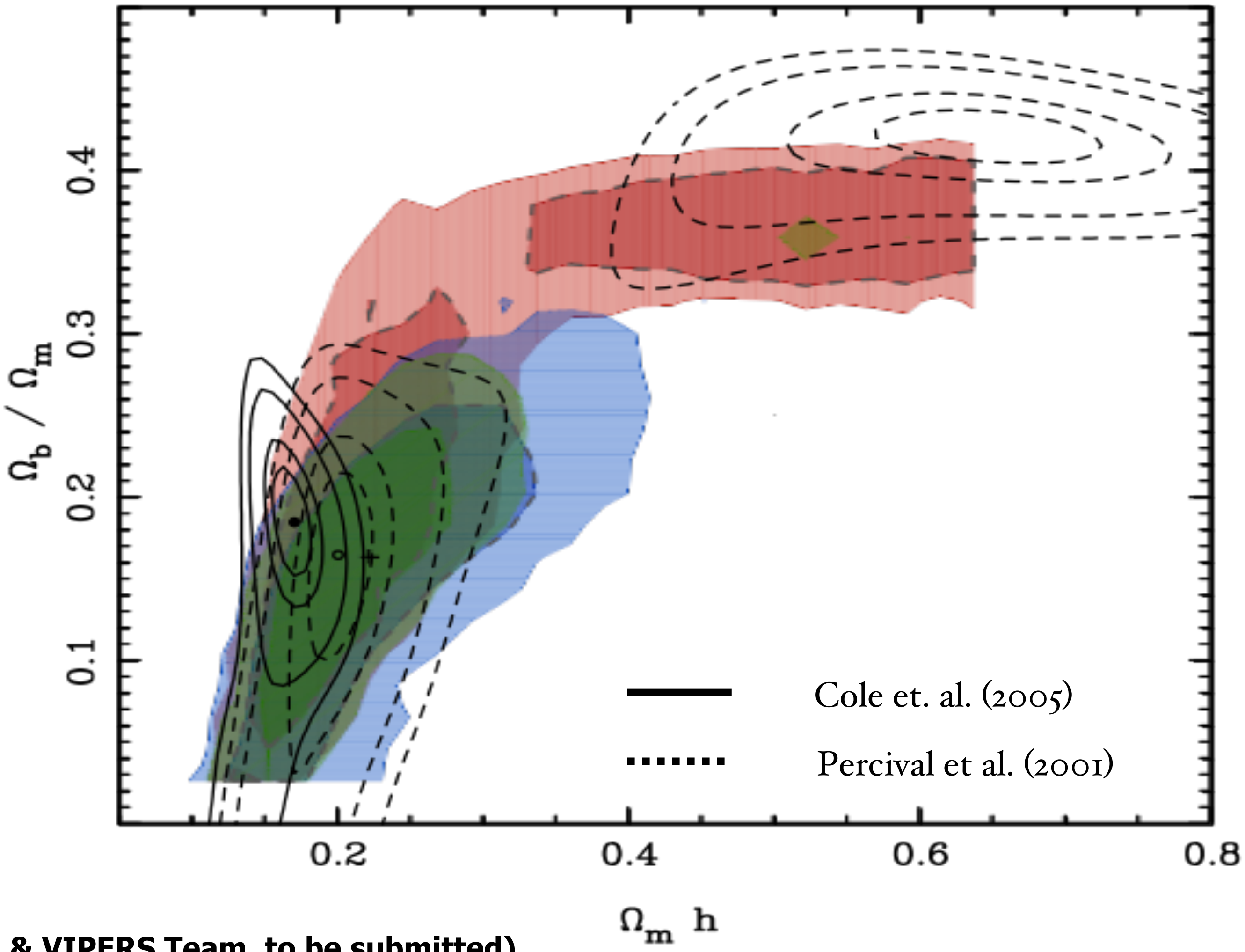
Comparison to z~0, 2dFGRS



Comparison to z~0, 2dFGRS vs SDSS



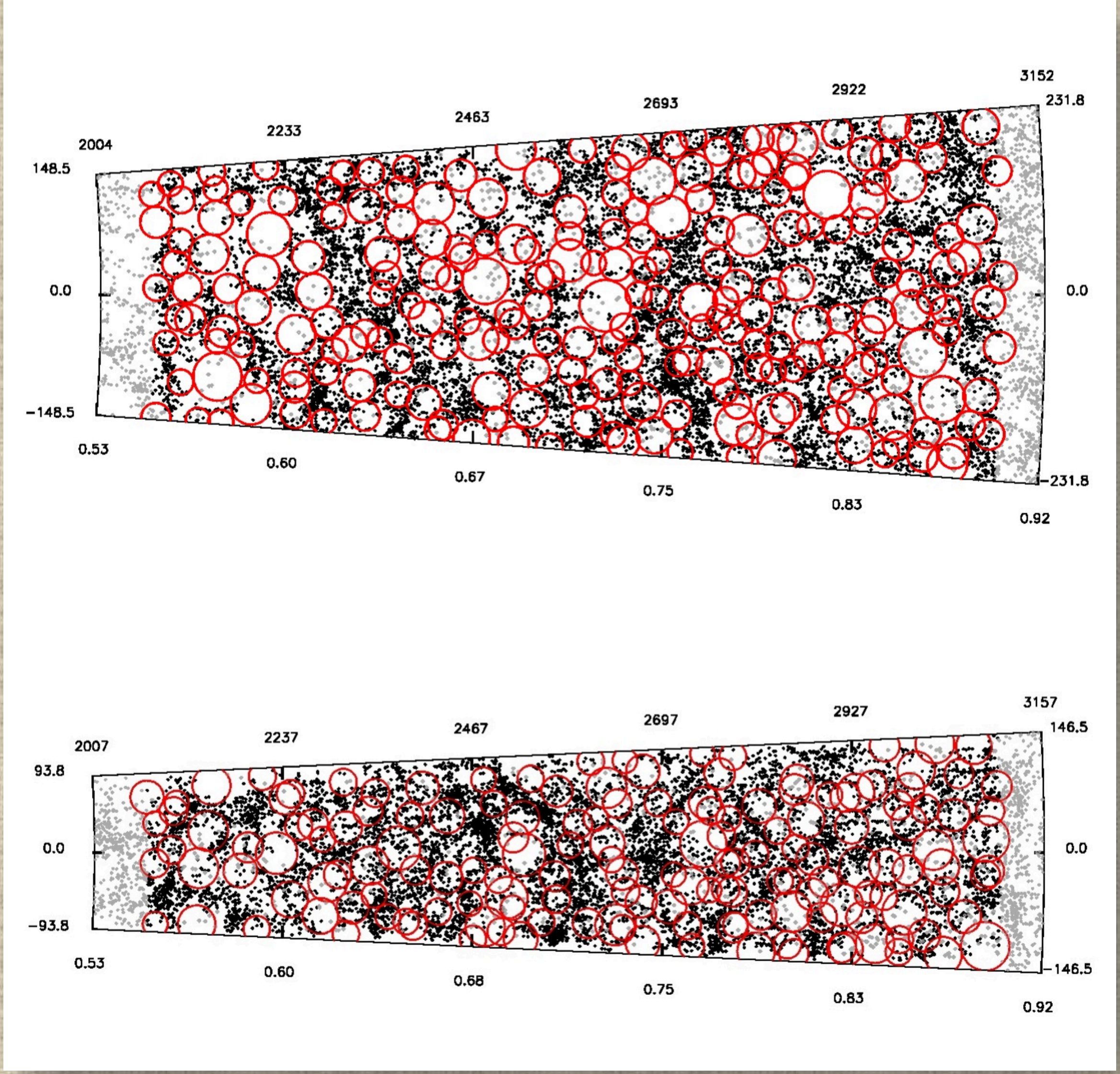
Comparison to z~0, VIPERS vs 2dFGRS



(Rota, Bel, Granett, LG & VIPERS Team, to be submitted)

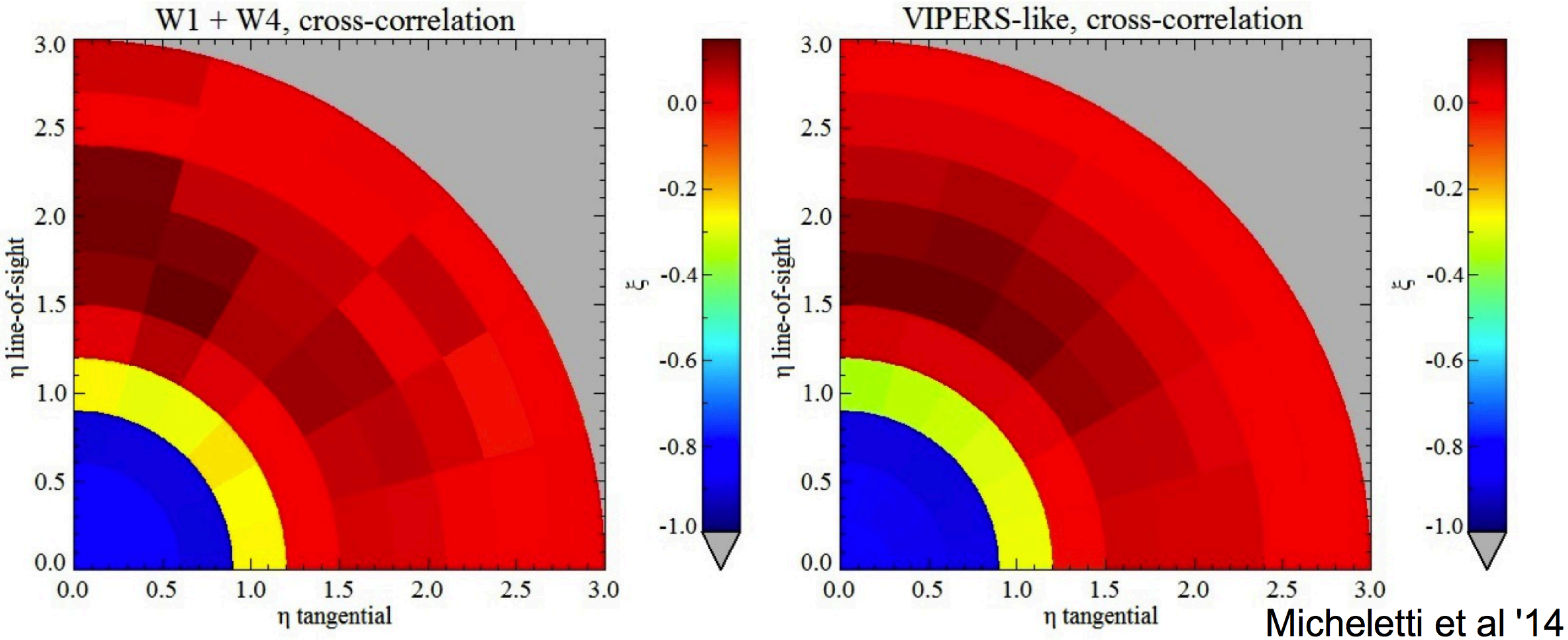
Identify new cosmological probes: cosmic voids at z~1

Micheletti, Iovino, Hawken, Granett & VIPERS team, 2014



Growth rate from galaxy outflows from cosmic voids at z~1

The void-galaxy cross correlation function



Micheletti et al '14

A. Hawken et al., in preparation

→ First quantitative measurement of growth rate of structure from outflows (see also Hamaus et al. 2014)
→ Optimal with highly-sampled surveys like VIPERS (or GAMA)

Combining imaging and spectroscopy: bypass galaxy bias and probe the two potentials of metric perturbations

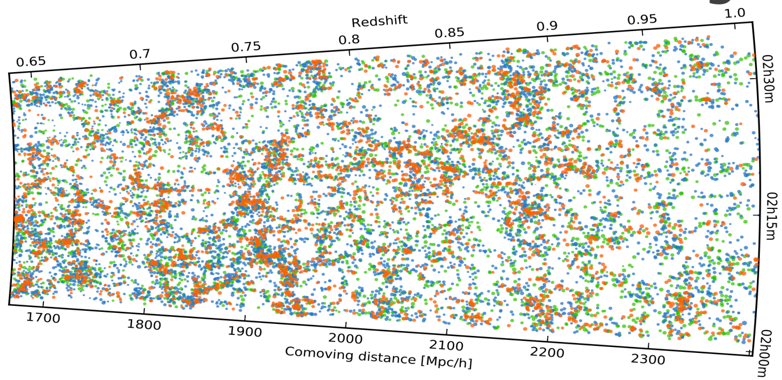
$$ds^2 = -a^2(\tau)\left[(1+2\Psi)\,d\tau^2 - (1-2\Phi)\,d\vec{x}^2\right]$$

Φ : governs motion of matter

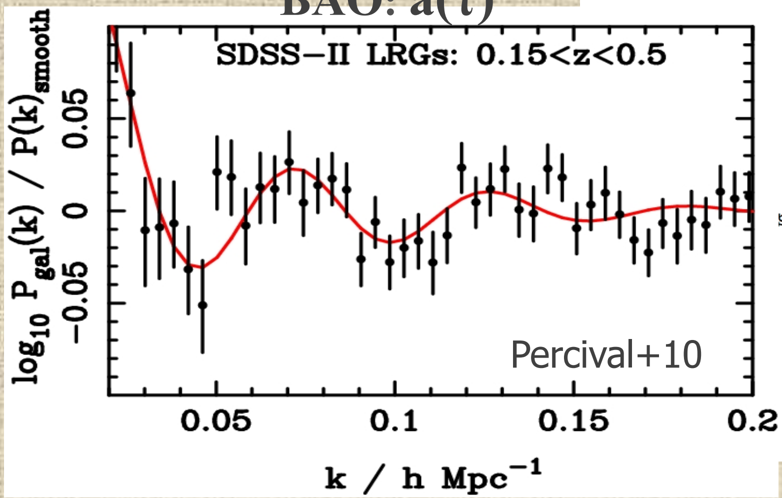
Ψ : governs motion of light

$\Phi = \Psi$ for GR

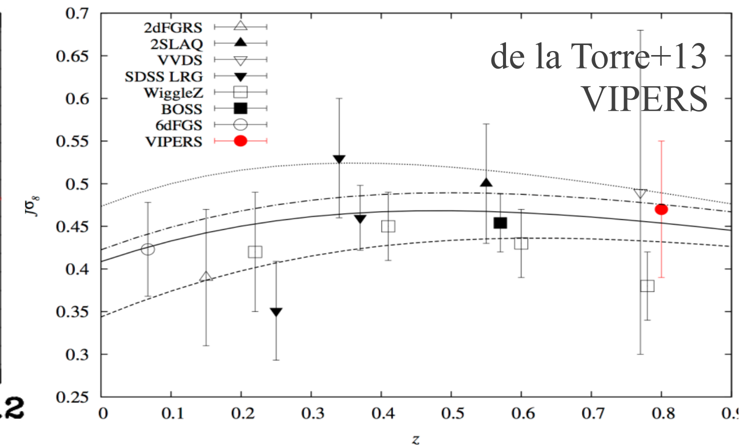
(Not with VIPERS)



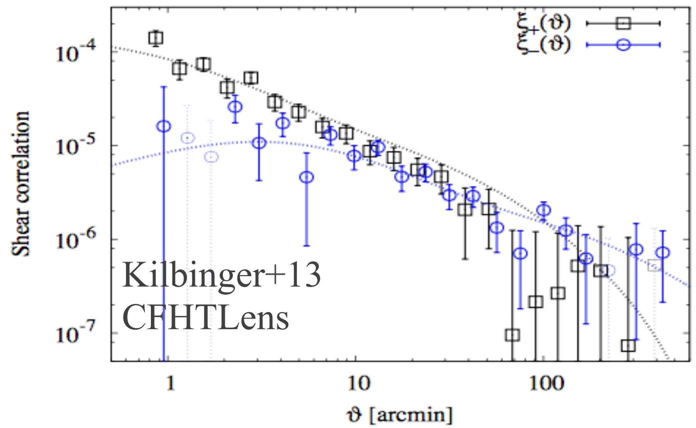
BAO: $a(\tau)$



RSD: Φ

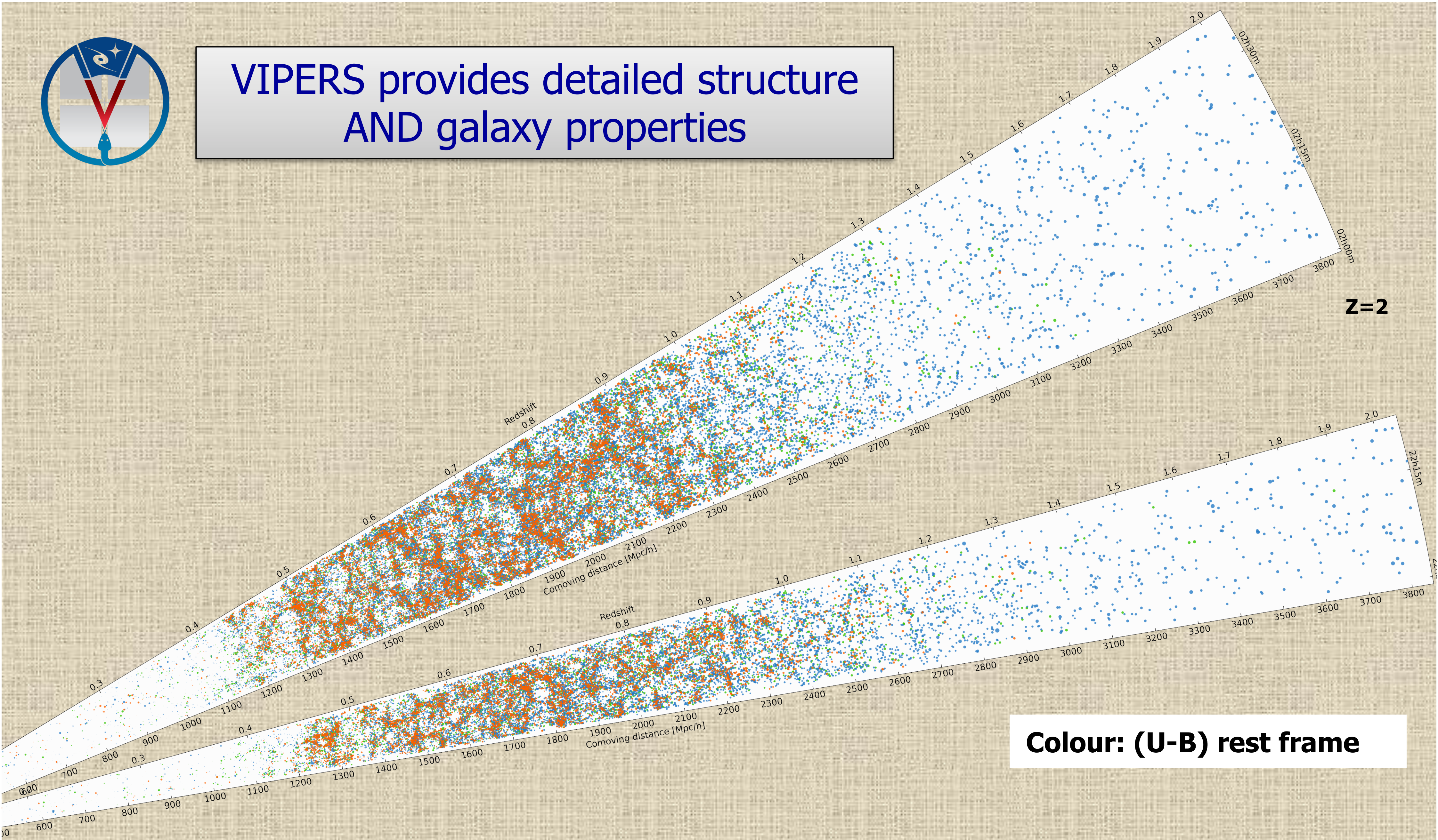


Cosmic shear: $\Phi + \Psi$



De la Torre, Jullo & VIPERS Team, in preparation

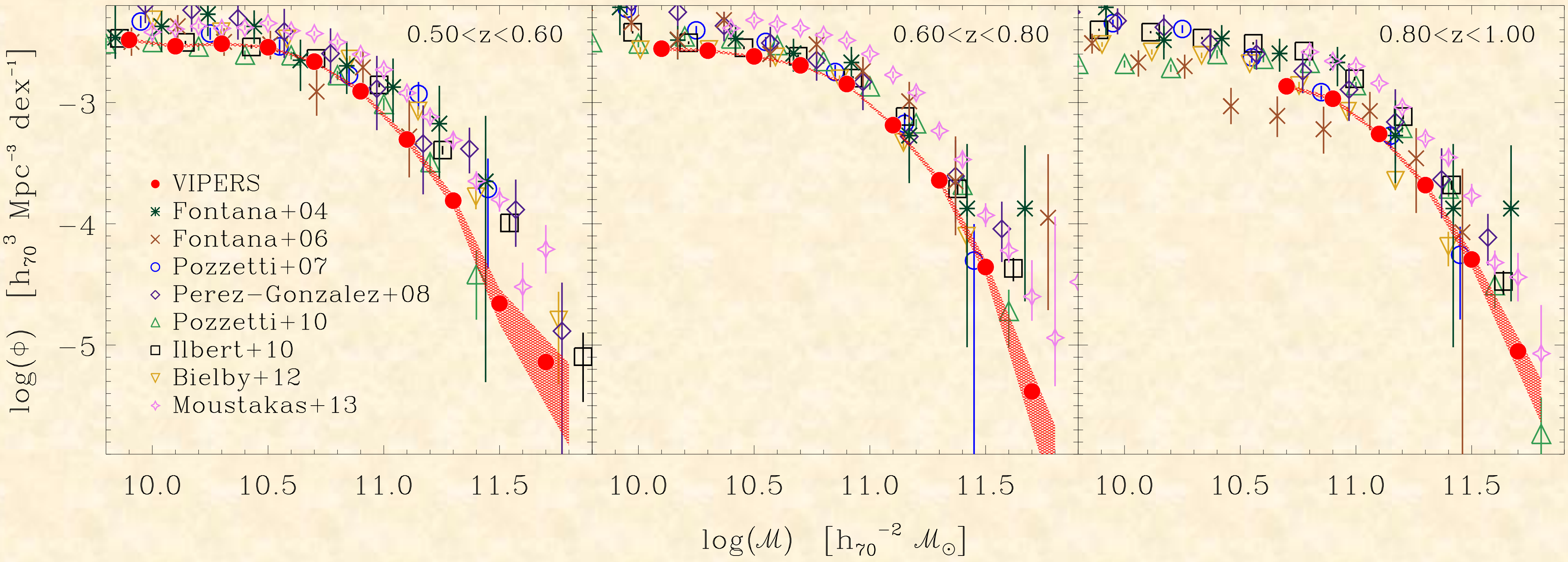
VIPERS provides detailed structure AND galaxy properties



Colour: (U-B) rest frame

(Artwork by Ben Granett)

Galaxy Stellar Mass Function



MOST PRECISE EXISTING MEASUREMENT OF THE NUMBER DENSITY OF MASSIVE GALAXIES AT Z~1

I. Davidzon, Bolzonella et al. 2013, A&A, 558, 23

II. Fritz et al. (CM diagram + LF), 2014, A&A, 563, 92

Wiener-filter reconstruction of the density field

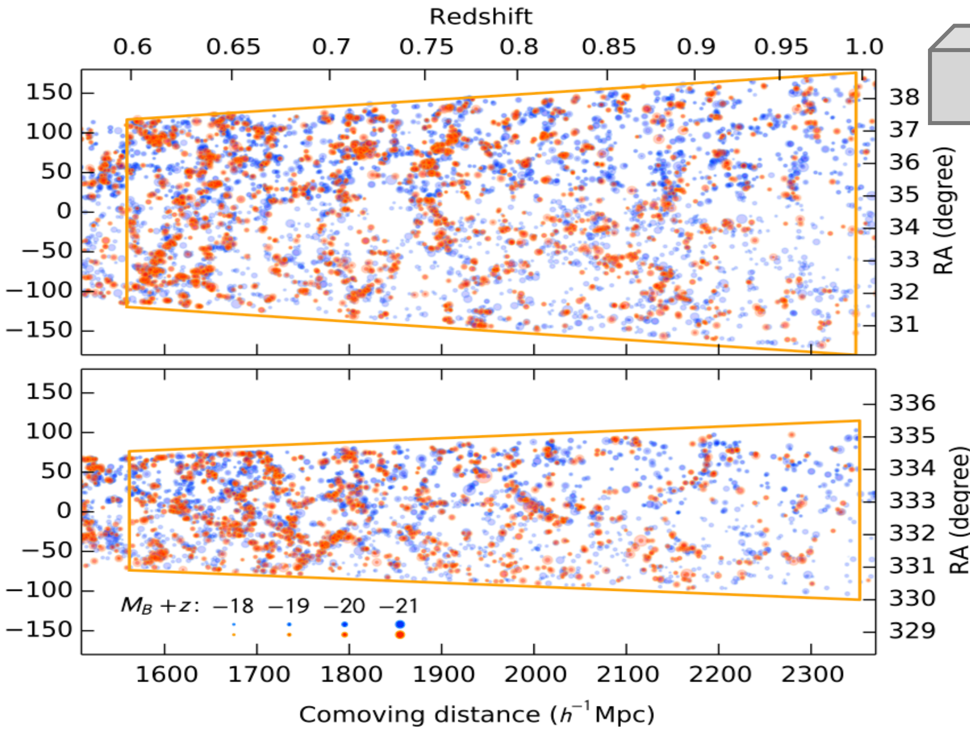
(slides by Ben Granett)

Bayesian technique to exploit all available information, self-consistently

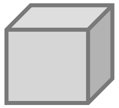
- Galaxies of different luminosity and colour trace an underlying density field (*in redshift space*) with a linear bias
- The density field is characterised in Fourier space by a power spectrum.
- Take Gaussian prior on delta and Gaussian likelihood (Wiener filter)

Box is filled with a Gaussian random field correlated with VIPERS structures

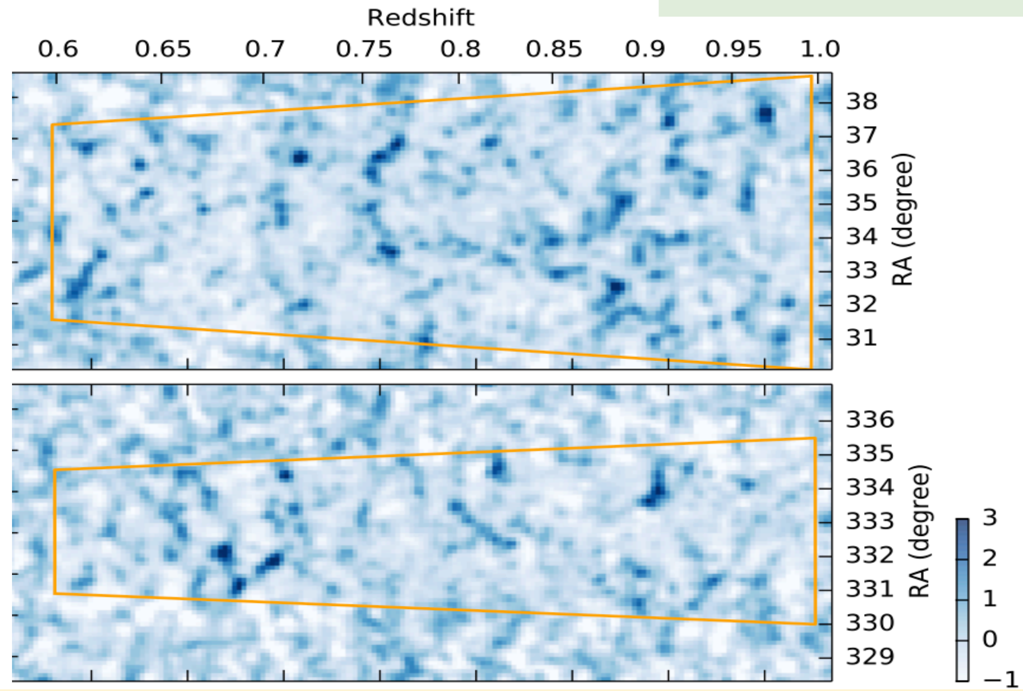
Galaxies



5 Mpc/h cells



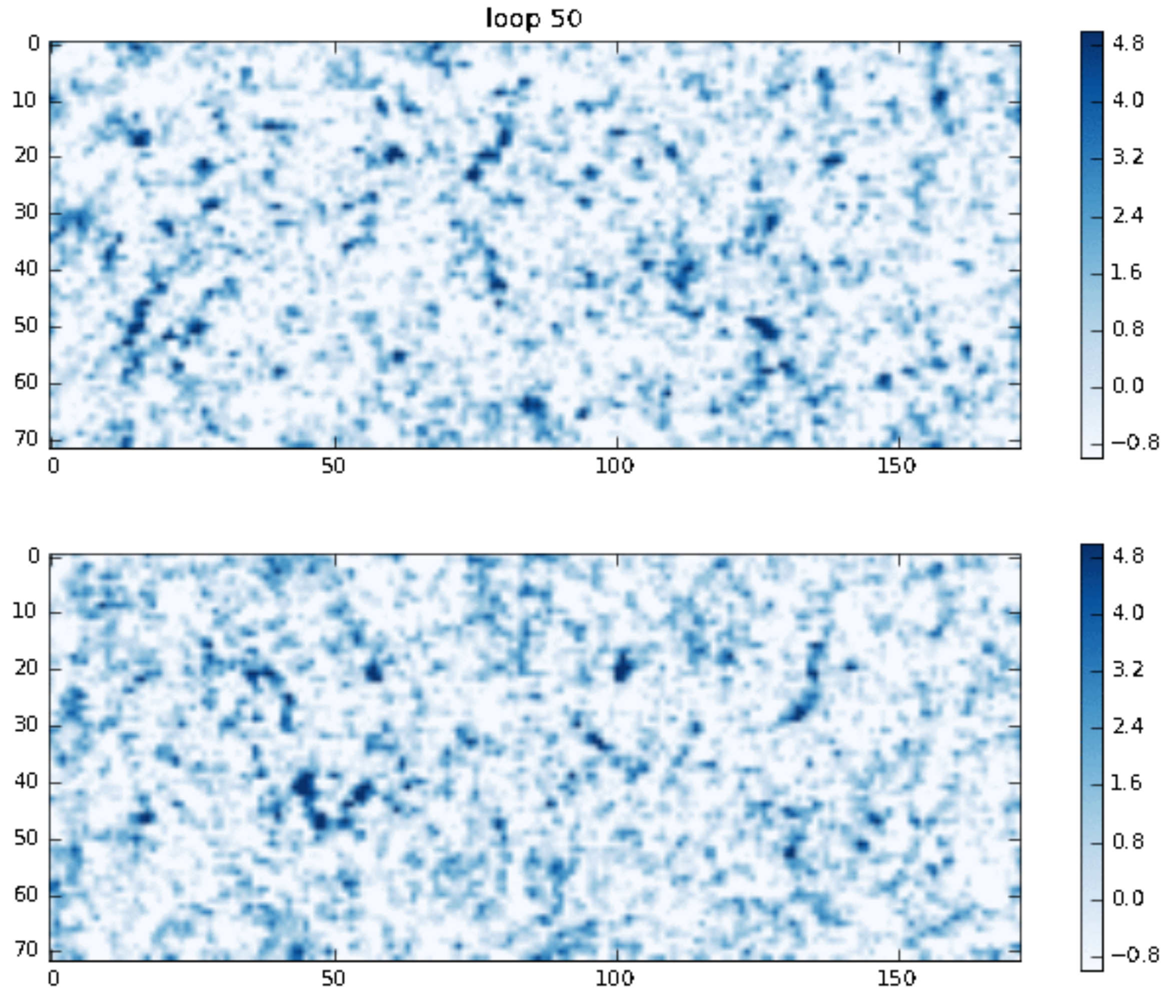
Wiener density field



Granett, Branchini, LG & VIPERS team, 2015, in press (arxiv:1505.06337)

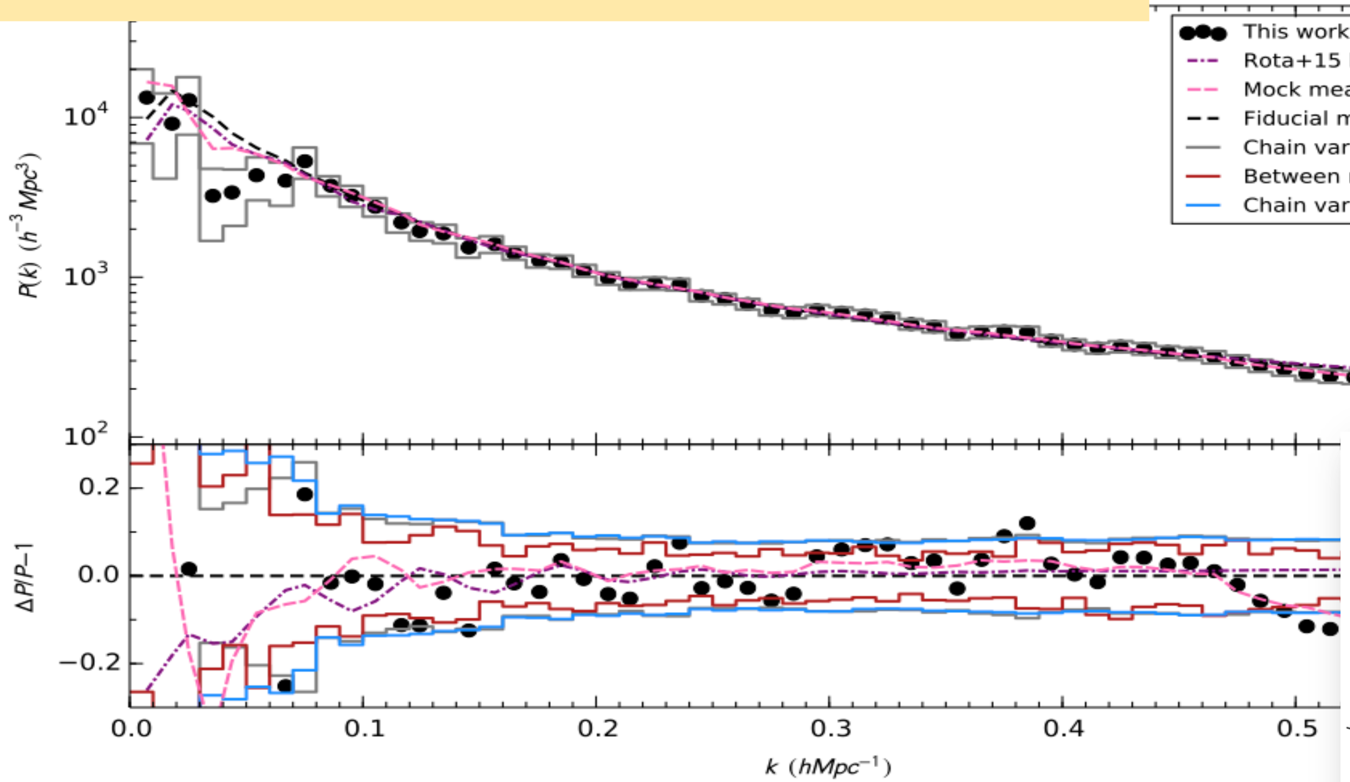
The Wiener density field estimator combines galaxy subsamples with bias weights (Cai+11)

Wiener-filter reconstruction of the density field



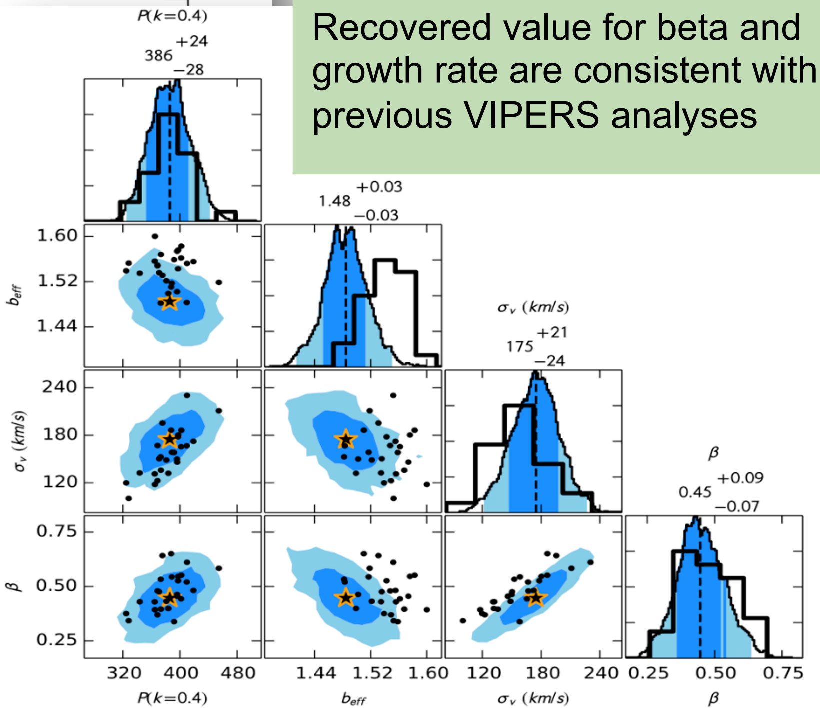
Results of Bayesian analysis: (1) Power spectrum and RSD parameters

Plots compare constraints from 26 mocks and data



Granett+VIPERS team (2015)
http://arxiv.org/abs/1505.06337

Recovered value for beta and growth rate are consistent with previous VIPERS analyses



Other self-consistent outputs:
(2) Galaxy bias and its colour dependence
(3) Number density and luminosity function

→ All can be compared to previous direct estimates

VIPERS: papers over past ~2 years

- Marchetti et al. 2013: *The VIMOS Public Extragalactic Redshift Survey (VIPERS): spectral classification through principal component analysis*
- Małek et al. 2013: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). A support vector machine classification of galaxies, stars, and AGNs*
- Marulli et al. 2013: *The VIMOS Public Extragalactic Redshift Survey (VIPERS) . Luminosity and stellar mass dependence of galaxy clustering at $0.5 < z < 1.1$*
- de la Torre et al. 2013: *The VIMOS Public Extragalactic Redshift Survey (VIPERS) . Galaxy clustering and redshift-space distortions at $z \simeq 0.8$ in the first data release*
- Davidzon et al. 2013: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). A precise measurement of the galaxy stellar mass function and the abundance of massive galaxies at redshifts $0.5 < z < 1.3$*
- Guzzo et al. 2014: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). An unprecedented view of galaxies and large-scale structure at $0.5 < z < 1.2$*
- Garilli et al. 2014: *The VIMOS Public Extragalactic Survey (VIPERS). First Data Release of 57 204 spectroscopic measurements*
- Bel et al. 2014: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). Ω_{m0} from the galaxy clustering ratio measured at $z \sim 1$*
- Fritz et al. 2014: *The VIMOS Public Extragalactic Redshift Survey (VIPERS):. A quiescent formation of massive red-sequence galaxies over the past 9 Gyr*
- Cucciati et al. 2014: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). Never mind the gaps: comparing techniques to restore homogeneous sky coverage*
- Micheletti et al. 2014: *The VIMOS Public Extragalactic Redshift Survey. Searching for cosmic voids*
- Coupon et al. 2015: *The galaxy-halo connection from a joint lensing, clustering and abundance analysis in the CFHTLenS/VIPERS field*
- Cappi et al. 2015: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). Hierarchical scaling and biasing*
- Di Porto et al. 2015: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). Measuring nonlinear galaxy bias at z~0.8*
- Bel et al. 2015: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). Recovering the count-in-cell PDF*
- Granett et al. 2015: *The VIMOS Public Extragalactic Redshift Survey (VIPERS). Reconstruction of the redshift-space galaxy density field*

Summary

- VIPERS is finished and delivered as expected (or even better)
- Nearly fully automatic data reduction, redshift measurement and SQL database
- It exploited VIMOS capabilities for LSS studies, filling a specific niche at z~1: volume $6 \times 10^7\ h^{-3}\ Mpc^3$, sampling > 40%
- Measuring clustering and growth at 0.5<z<1, to precision (and accuracy) comparable to local state-of-the-art surveys: f(z), P(k), high-order correlations and new statistics (voids) at z~1 ongoing with full sample
- Measurements of galaxy properties and evolution in the **full context of their hosting environment** (luminosities, colours, stellar masses) and with **complete population statistics**
- Large set of ancillary data (GALEX, WIRCAM, VISTA, XMM) → **independent check of systematics from photo-z samples** (e.g. Moutard et al. 2016)
- **2/3 of full survey (~55,000 redshifts) public since Oct 2013, six months after first science release: a public survey "de facto". Final data release in 2016**

Lessons learned

- **Initial effort pays back**
  - Early careful planning of areas, field locations, pointing grid coordinates, time scales…
  - Accurate target sample selection and “cleaning” (correction of CFHT-LS tile-to-tile zero-point variations, star-galaxy separation, colour-colour selection, etc.)
  - Constant monitoring of data quality (e.g. CCD update saga…)
  - The reward is that VIPERS final numbers match all initial predictions very well (e.g. colour completeness is great, stellar contamination is very low)

Lessons learned

- **Cumulative team expertise;** data reduction infrastructure and experience accumulated with VVDS and zCOSMOS reached exquisite level with VIPERS, as e.g.:
  - Full control of data structure/properties/history, survey progress and team communications from centralized web site: decide steps, assign fields for mask preparation, validation or other operations with just one click
  - Fully automatic data reduction and redshift measurement, with monitored quality control
  - Internal SQL database same as public database: data go public in one click when we so decide
- **Do it public:** release your data soon and get feedback (and reward) from the community