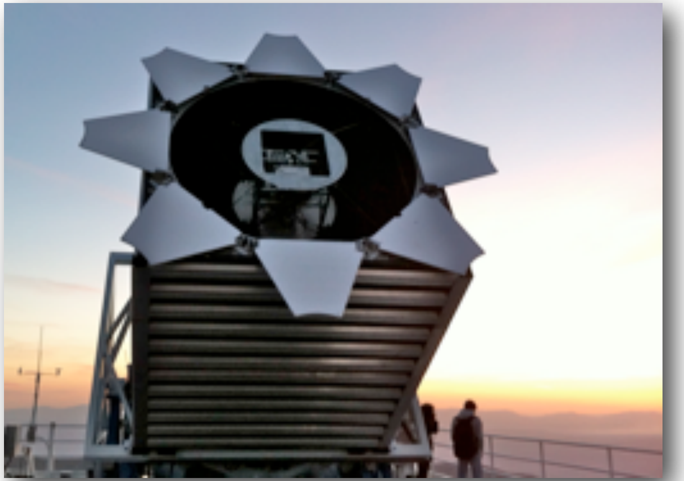


# Emission Line Galaxies as BAO tracers

# ... and a few words on eBOSS

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

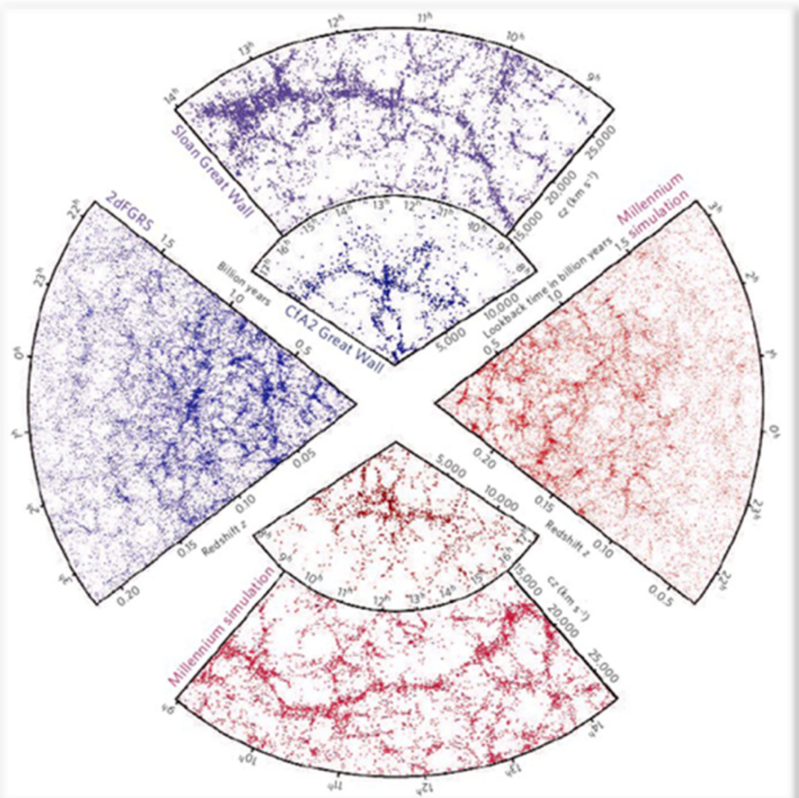
European Research Council
Established by the European Commission

Jean-Paul KNEIB (EPFL/LAM)
**Johan Comparat**, Eric Jullo (LAM)
+ eBOSS collaboration

# Outline

- Motivation
- Emission Line Galaxies Properties
- ELG SDSS-III/BOSS survey(s)
- ELG VLT-FORS-2 survey
- SEQUELS
- eBOSS
- Conclusion & Future prospects

# 'Redshift-meters'




- **Hubble (1930):** expanding Universe
- **CfA Redshift Survey (1985):** first large scale structures (wall, filaments)
- **2dF (~2000):** 1500 sqdeg
- **SDSS (~2002):** 5700 sqdeg
- **VVDS/DEEP2 (~2004):** deep Universe ~1 sqdeg
- **WiggleZ (2011)**: 800 sqdeg (BAO)
- **VIPERS (2012):** 25 sqdeg (RSD)
- **SDSS-III/BOSS (2014)**: 10,000 sqdeg BAO/LSS
- **e-BOSS (2014-2020):** BAO/LSS: 7,500 sqdeg w/ LRG+QSO & 1,500 sqdeg of ELGs
- **DESI** (2018) mostly ELGs
- **PFS** (2018) mostly ELGs
- **4MOST** (2020)
- **Euclid** (2020) ELGs

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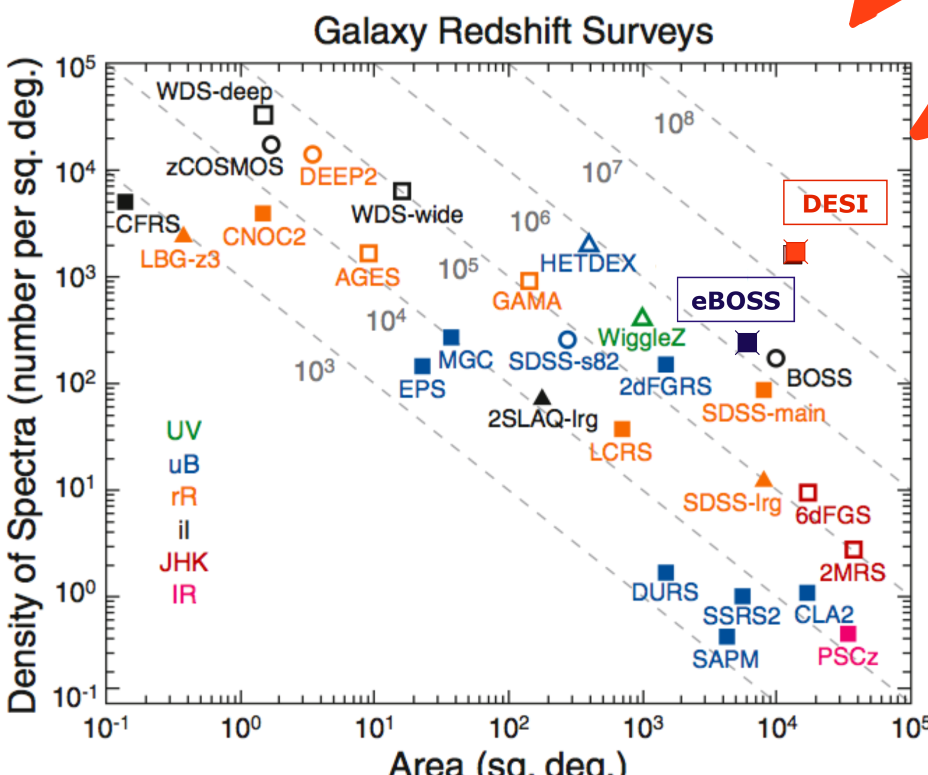


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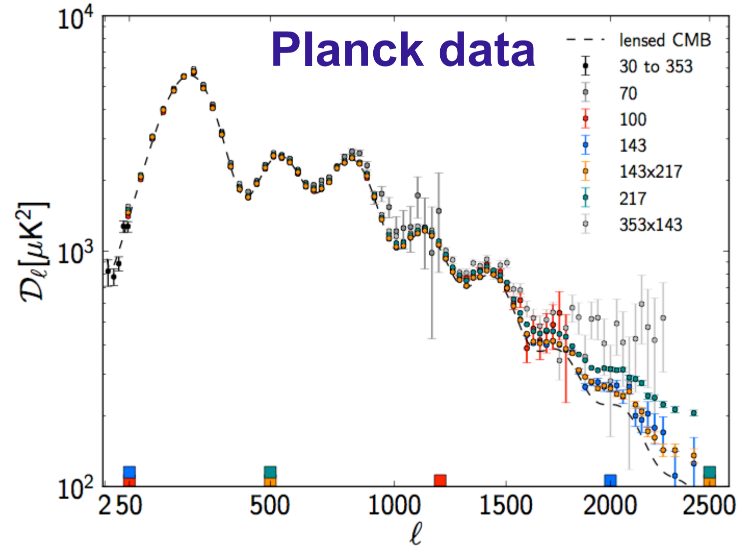
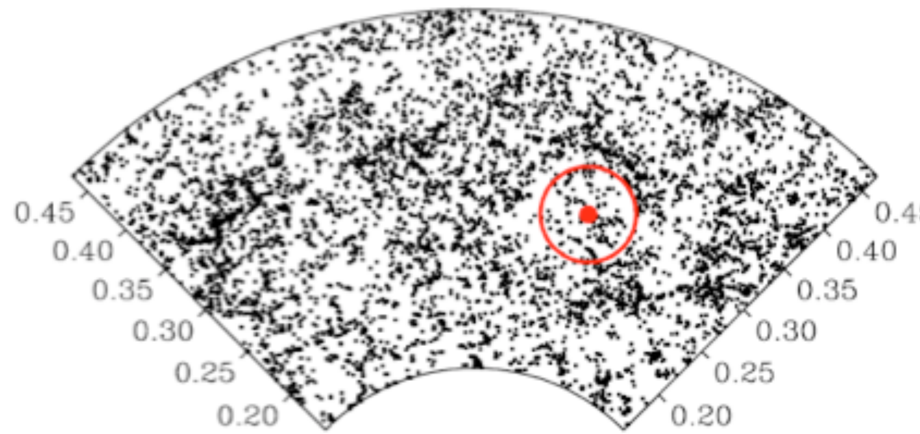
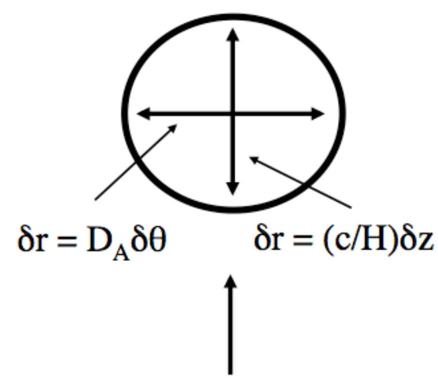
- **Euclid** (2020) ELGs

# Baryonic Acoustic Oscillation (BAO)

- Early Universe: each initial overdensity is an overpressure that launches a spherical sound wave
- Seen in the CMB
- Sound waves stalls at ~150 Mpc at recombination
- Seed galaxy formation with a preferred separation at BAO scale (local overdensity)
- **BAO measurement yields H(z) and $D_A$(z) relation**

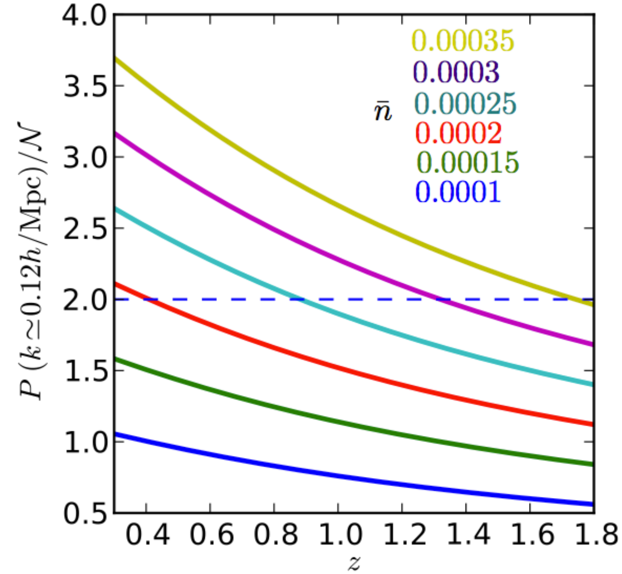


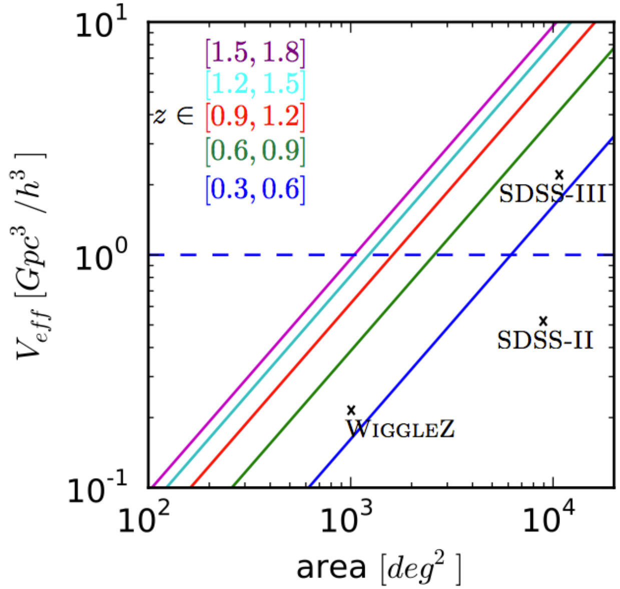



# BAO survey strategy

- BAO scale is big! few degrees scale => very wide field survey (ultimately as much sky as possible)
- Number density of tracers should increase with redshift to keep shot noise small (also helps for reconstruction)
- High bias tracers are more valuable
- **Aim to measure BAO for various redshift bins.**




High number density of sources required to beat shot noise statistics




**~5% BAO**

Large survey area to beat cosmic variance, and lead to accurate

# BAO survey opens up numerous science opportunity at smaller (but also even larger) scales

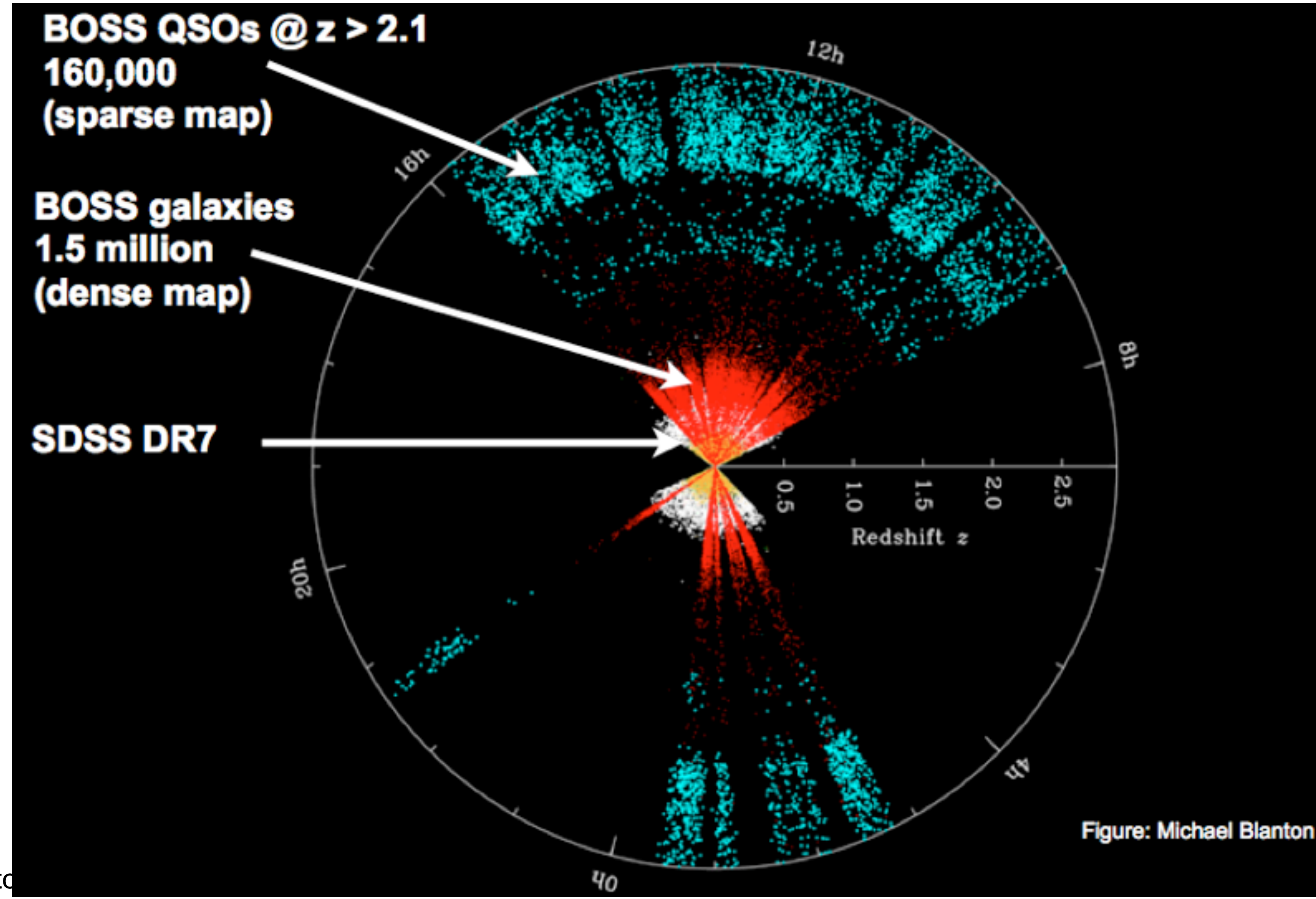
Wide Field Galaxy/QSO Redshift Survey allow to:

- Probe Universe Expansion (distance-redshift relation)
- Probe Universe Geometry (flat Universe?)
- Probe General Relativity (valid on large scales?)
- Probe Dark Energy (nature? equation of state?)
- Probe Neutrino Physics (number of species, mass limit?)
- Probe Early Universe (non-Gaussianity?)
- **Physics of the tracers** (Galaxy and Quasars)
- Study of extreme/rare objects
- and also Lensing ... (strong lenses and calibration for WL)

# SDSS-III/BOSS
# Baryon Oscillation Spectroscopic Survey

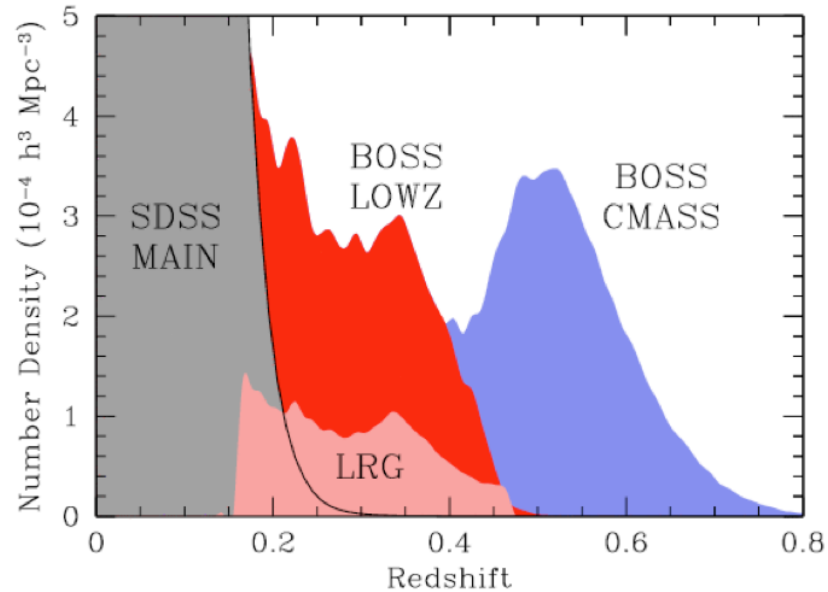
**Key Project uses most capable BAO instrument in the world**

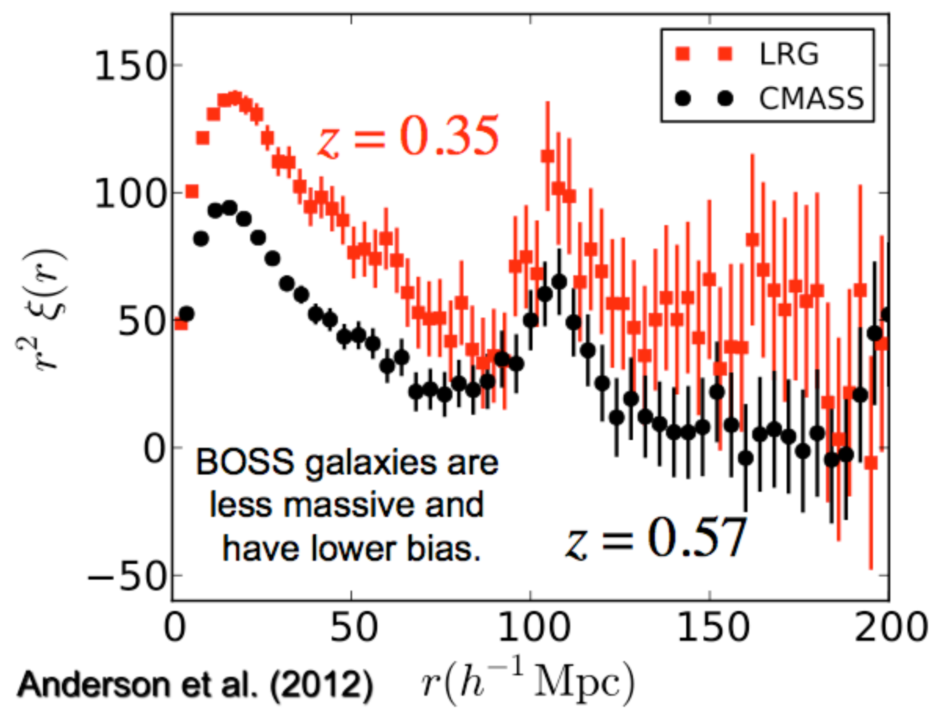
# BOSS Main Surveys



# BAO Measurement with Galaxies

- BOSS is targeting 1.5 million galaxies over 0.2<z<0.6 over 10,000 sqdeg
- survey now 90% complete
- Very clear detection of the acoustic peak
- Distance measured to z=0.57 to 1.7% precision

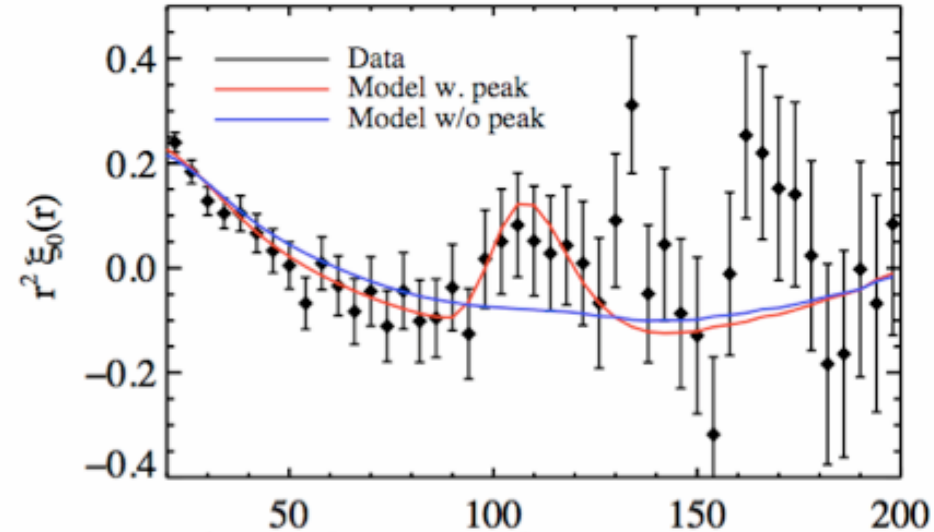


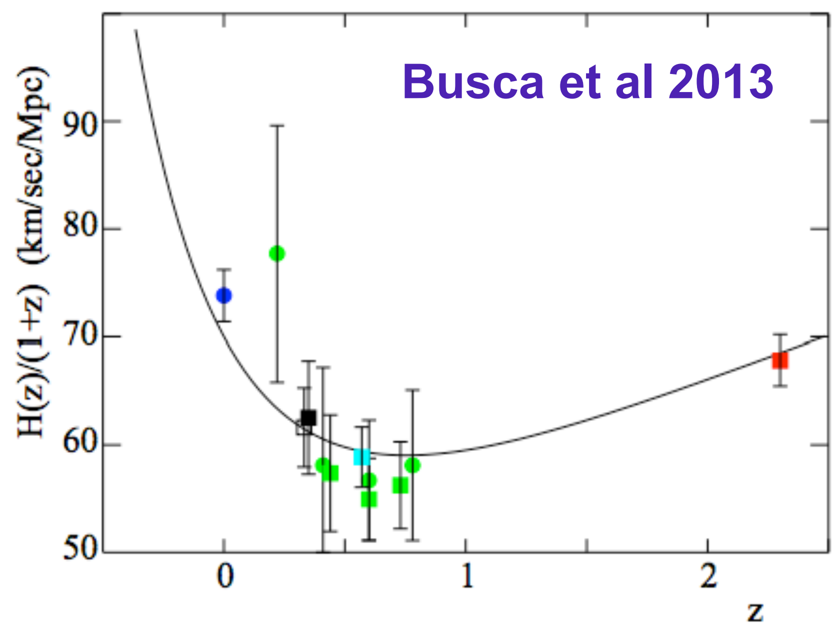

Anderson et al. (2012)

# BAO Measurement in the Ly-alpha Forest

- BOSS is targeting 160,000 quasars with 2.1<z<3.5
- Very clear detection of the acoustic peak using 48,000 quasars (Busca et al 2013)
- H(z) measured at z=2.3 to better than 4% precision
- Detection of cosmic deceleration from z=2.3 to z=0.6



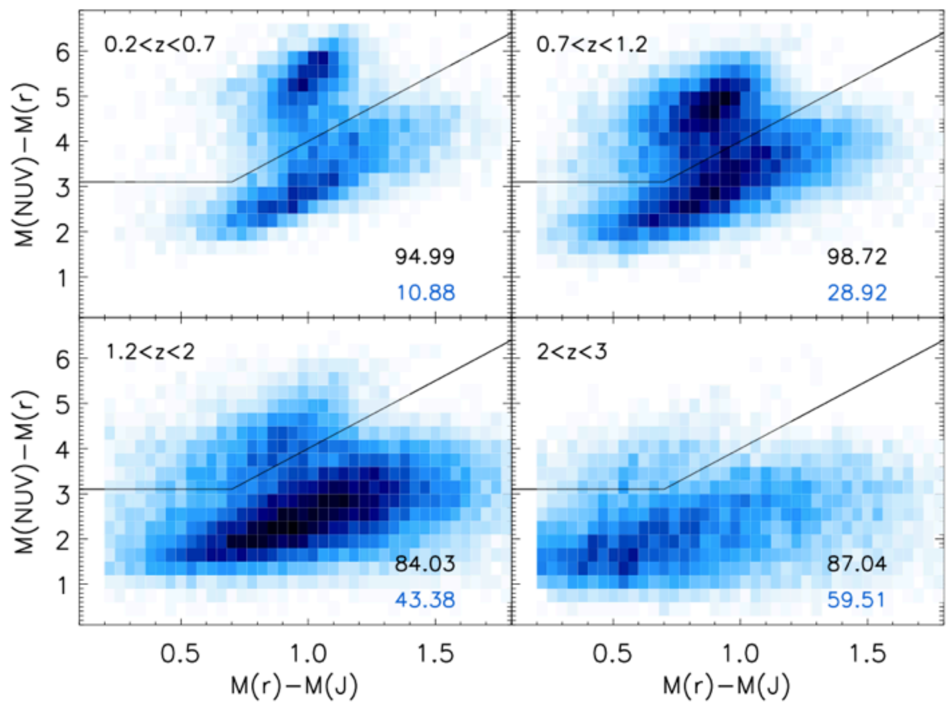

Busca et al (2013)



# Future BAO Surveys

# Galaxy evolution - COSMOS field study

- COSMOS field is a ~1.5 sqdeg area with deep multi-wavelength dataset, allowing representative study of galaxy evolution
- Useful laboratory to study galaxy evolution
- Recent study as a function of stellar mass thanks to ultra-deep K-band data (UltraVista project) **Ilbert et al 2013**
- Follow-up on redshift evolution of quiescent and star-forming galaxies




Restframe color selection of quiescent vs. star-forming galaxies

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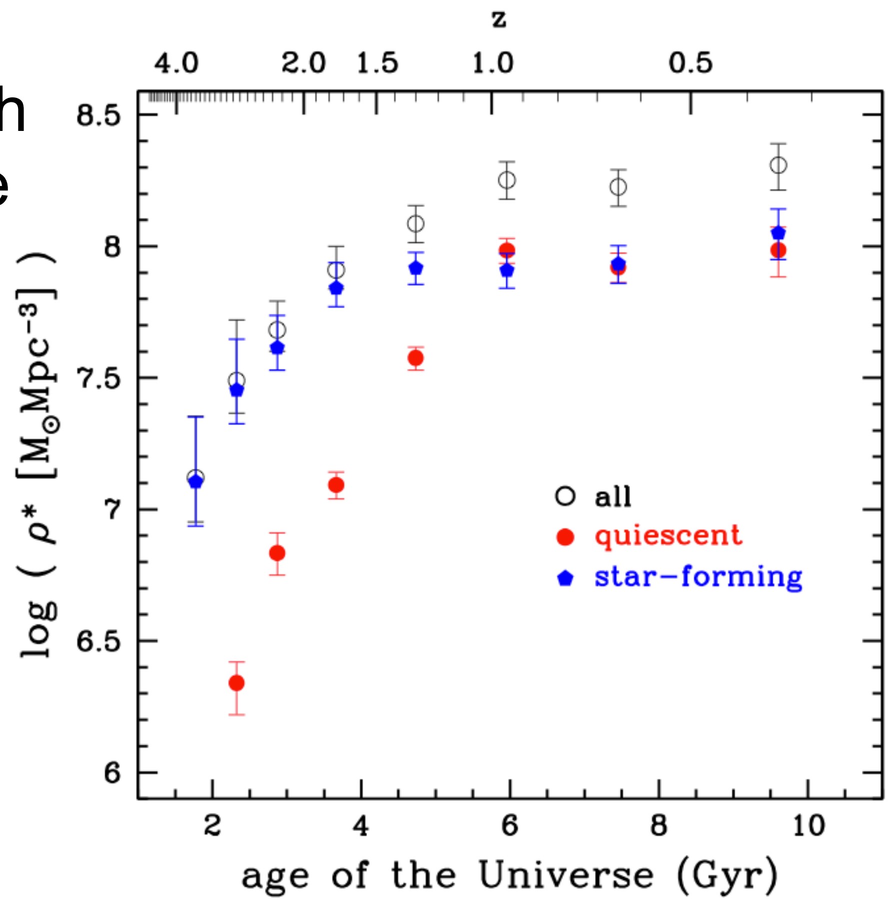
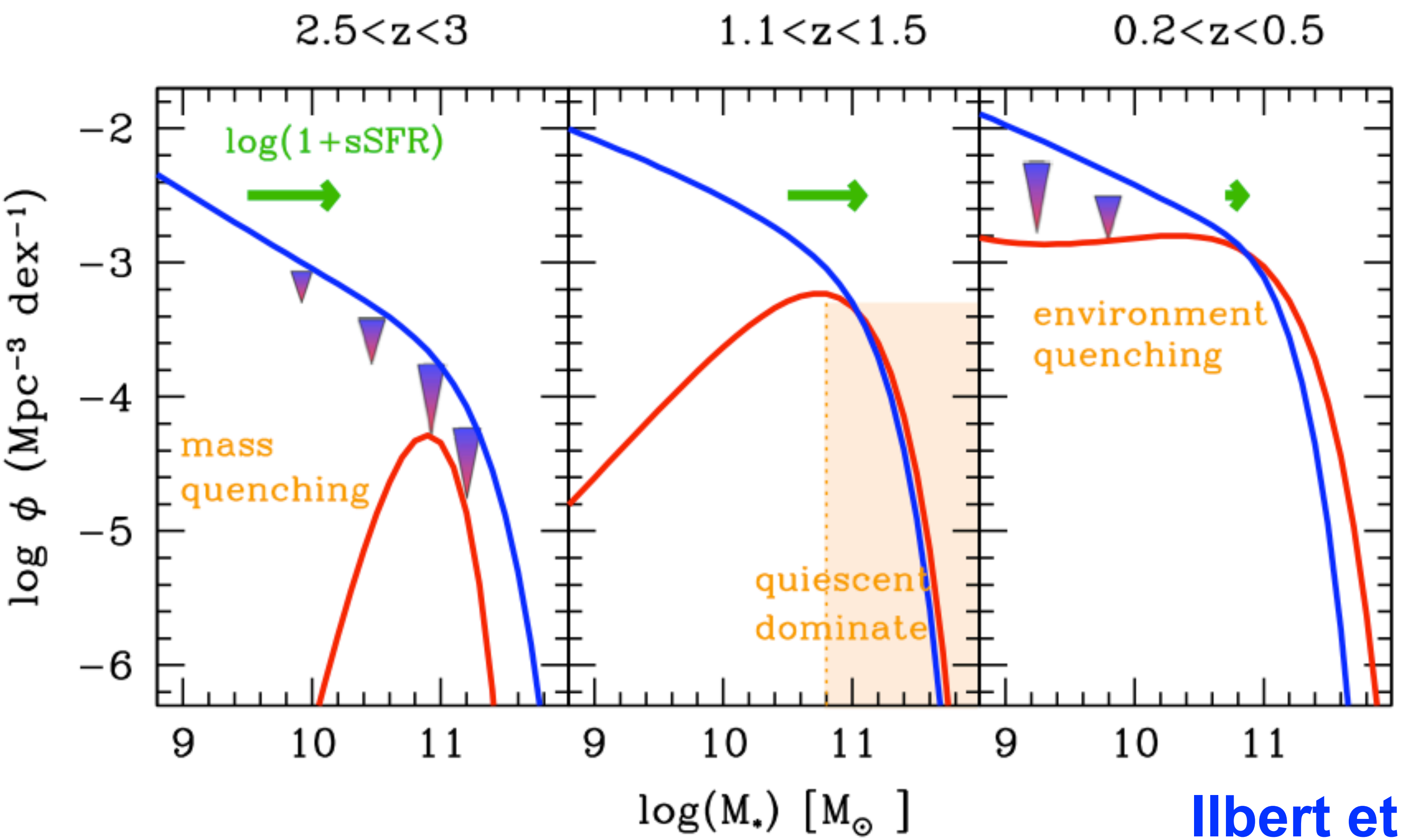



Stellar density evolution of quiescent vs. star-forming galaxies

# Galaxy evolution - COSMOS field study

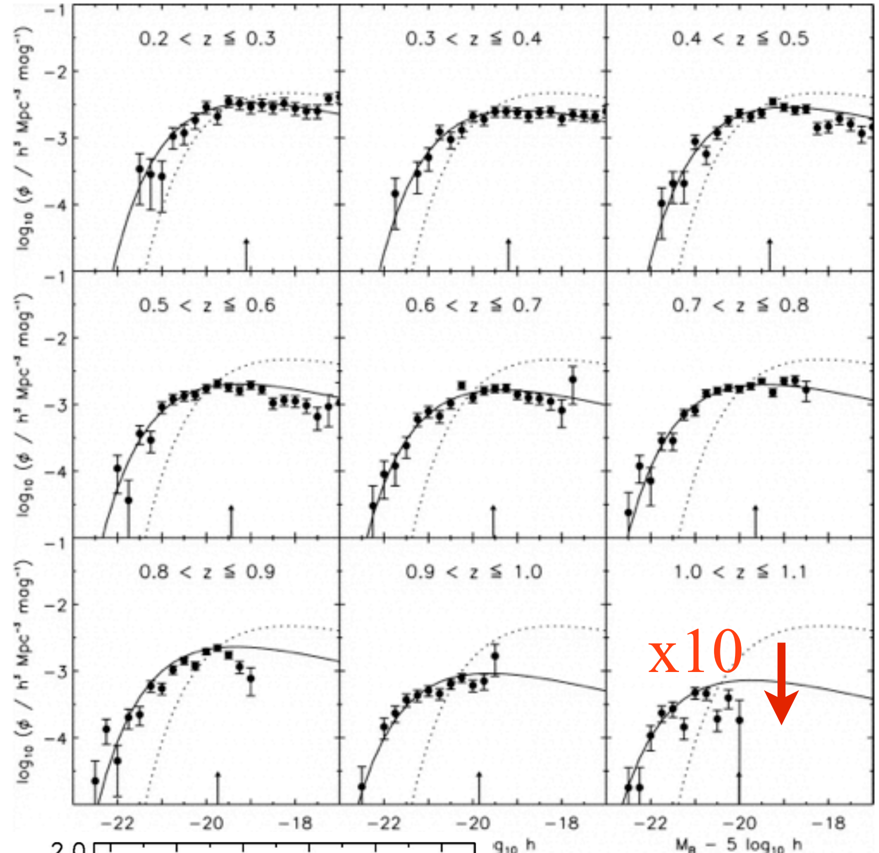


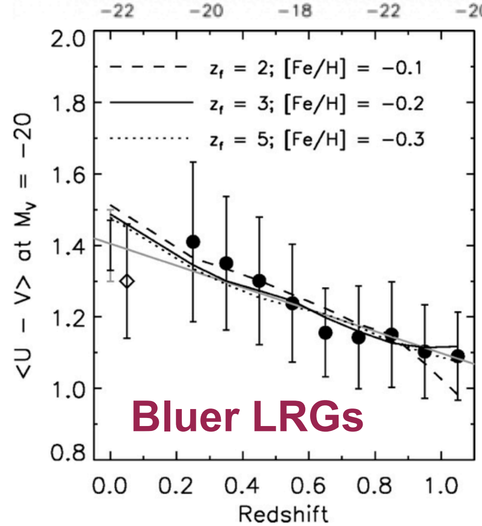

**Ilbert et al 2013**

Mass function evolution of quiescent and star-forming galaxies
Effect of stellar mass assembly and SFquenching

# Which tracers for BAO? LRGs ?

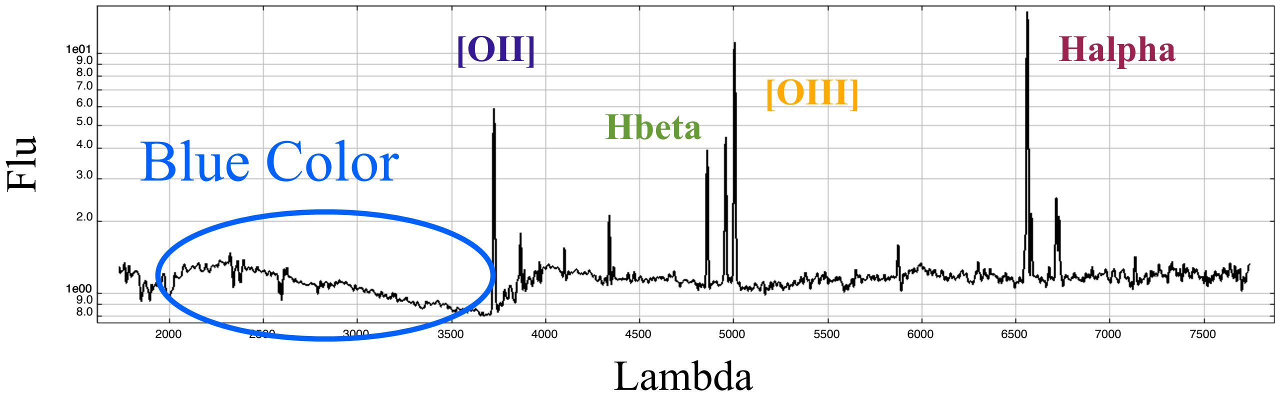
- LRG are good tracers of galaxy over-density.
- However:
  - redshift measurement relies on continuum measurement **(SDSS limit i<20, z<~0.7)**
  - LRG number density is decreasing with redshift (at least x10 in covolume density)
  - they are becoming bluer at higher redshift (0.5mag decrease at z~1)
- **But new selection technique using WISE infrared data to find LRG up to z~1 (see eBOSS discussion)**

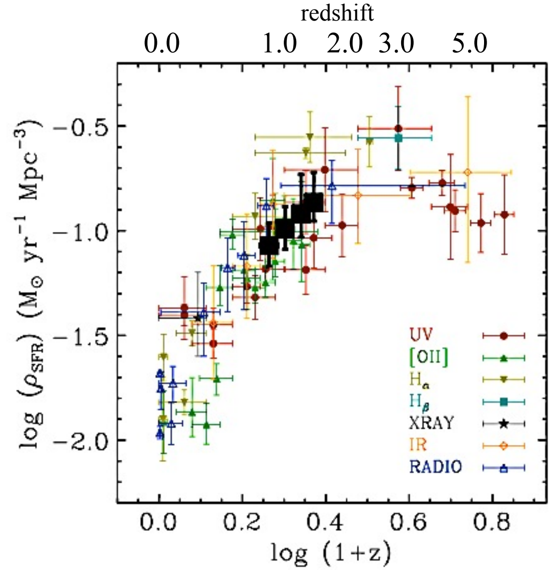



Bell et al 2004 (GEMS)

# Probing new tracers: why ELGs?




- *Number of ELGs with strong lines increase with redshift as the star formation density increases to z~2.*
- Redshift measurement relies on emission lines => can push ~2 mag deeper than continuum redshift measurement.
- ELGs have been the focus of previous surveys (DEEP2, VVDS, WiggleZ).
- Unique targets for cosmological surveys: [OII] can be detected from the ground at: 0.6<z<1.7
- At R>3500 can resolve the [OII] doublet (unique identification)

# ELG target selection

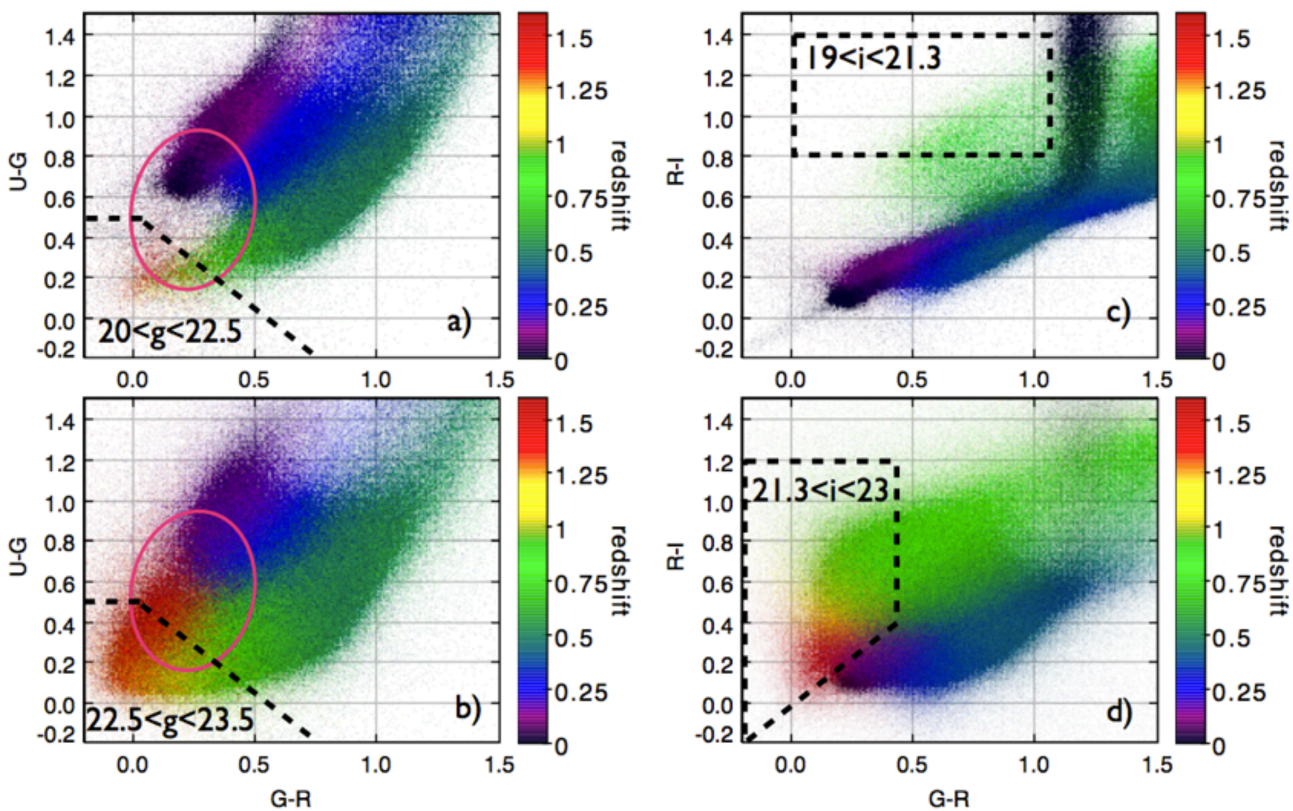
**2011: BOSS Ancillary project looking for high luminosity [OII] emitters**

- 880 ELGs with *ugr* selection, [0.6<z<1.7]
- 900 ELGs with *gri* selection, [0.6<z<1.1]
- ~70% z-efficiency in both selections

*ugr* *gri*

Bright Selection

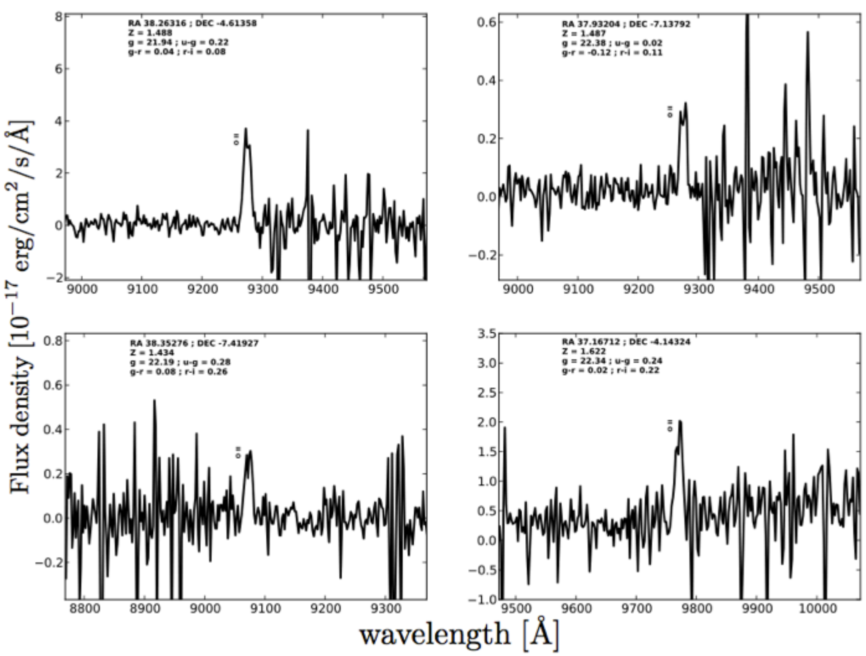
Faint Selection

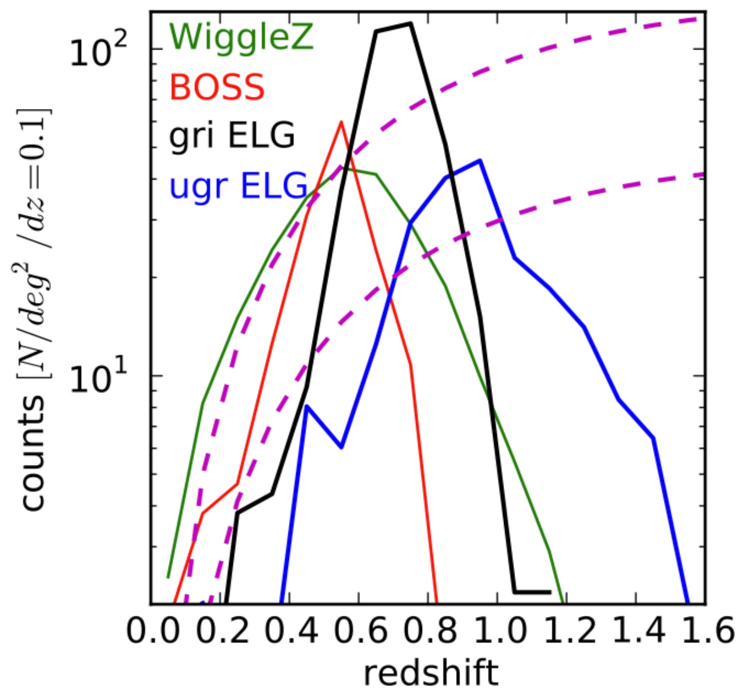



**Comparat et al 2013a**

# ELG target selection

- High-z measurement and N(z)
- Redshift efficiency is linked to photometry quality (60% and 75% for SDSS and CFHT)

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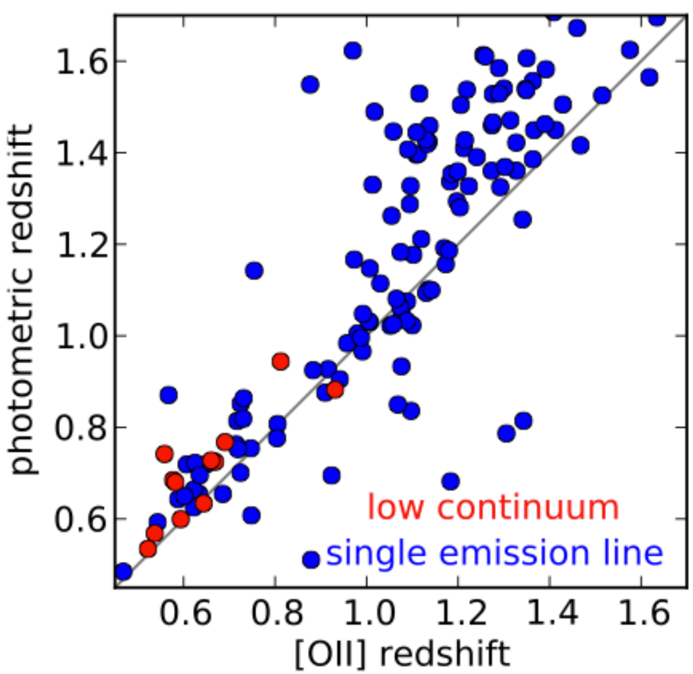
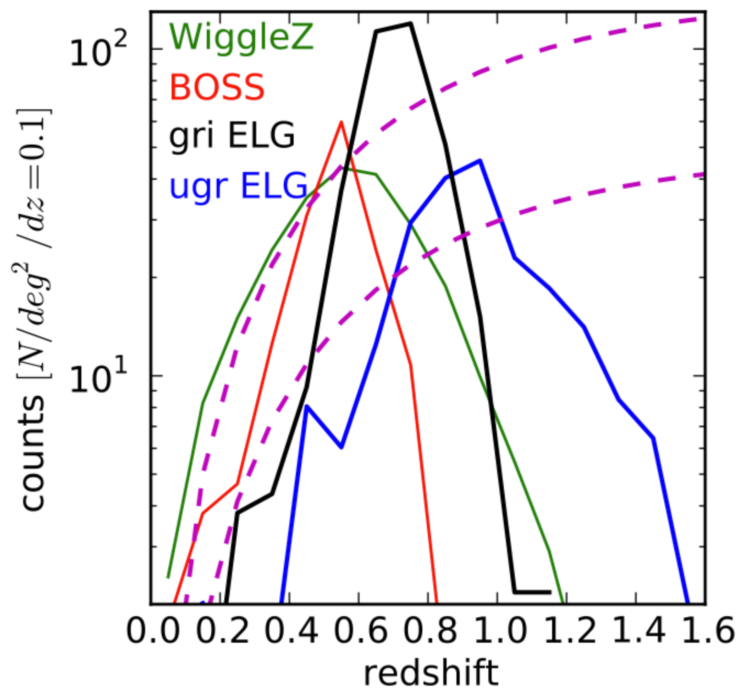
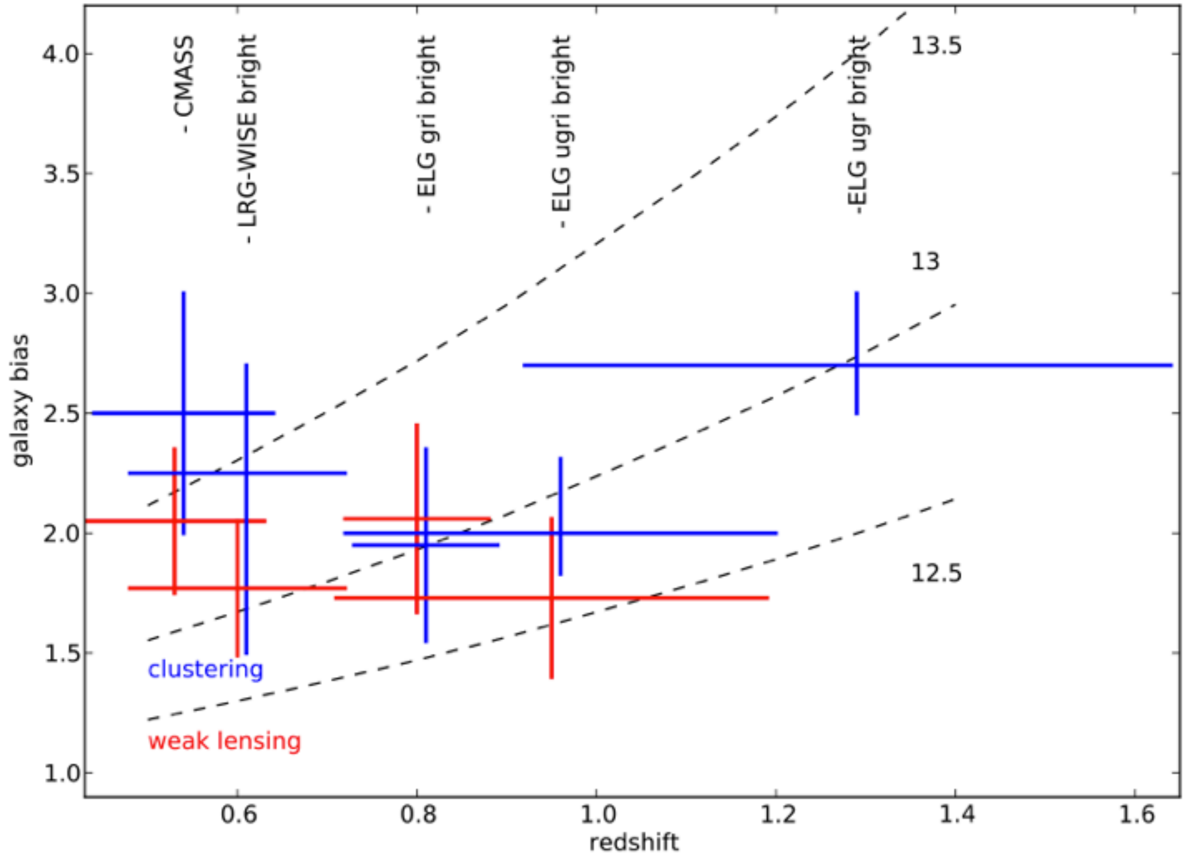



Comparat et al 2013a

# Bias measurements with clustering and weak lensing

- color selected galaxies in CFHT-LS
- bias from CFHT-LS weak lensing data
- bias from clustering analysis of photometric samples



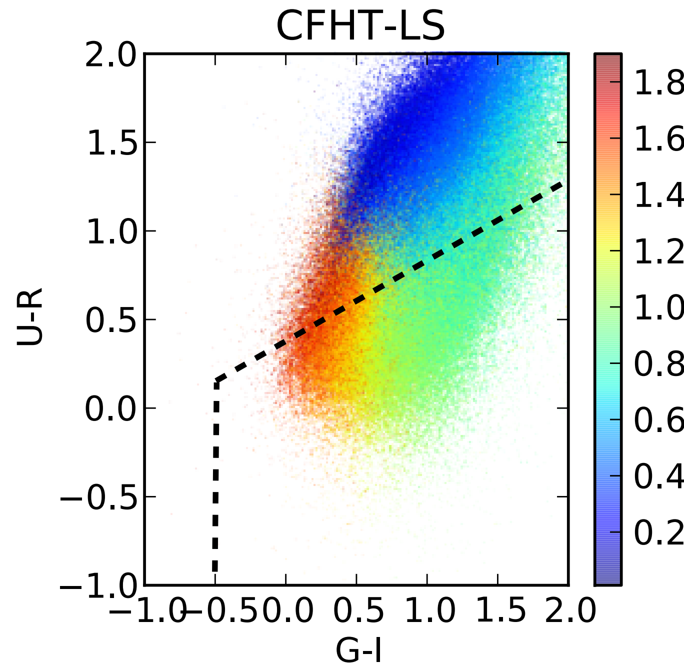

Comparat et al 2013b

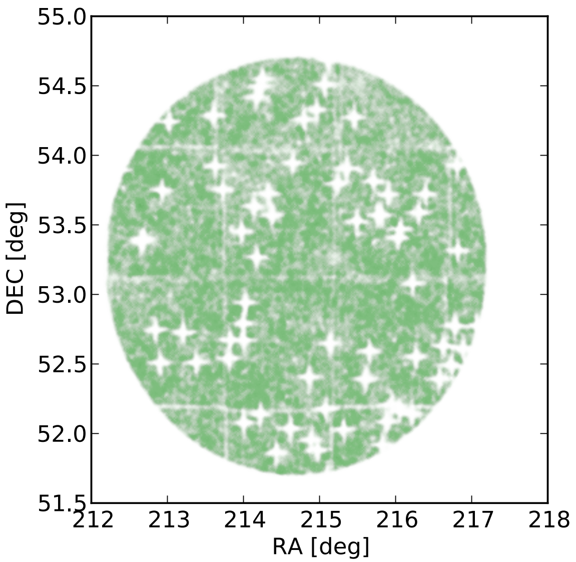
# Further ELG target selection

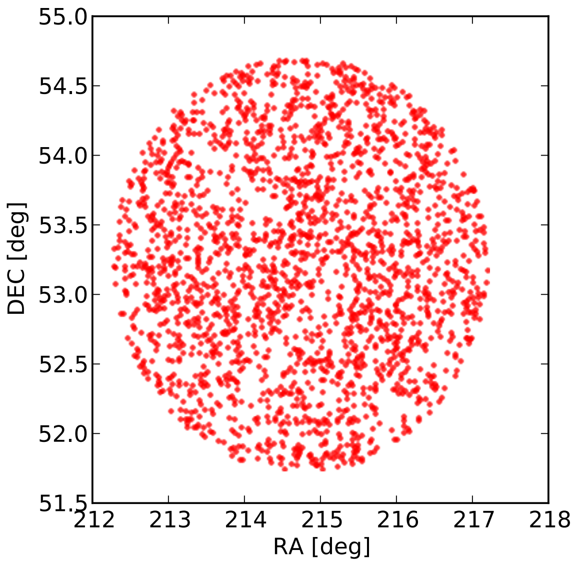
- We have conducted 2 further experiments (during 2012-2013) in order to:
  - ✦explore alternative/more-efficient color selection: *ugri* using CFHT-LS photometry and the BOSS spectrograph [similar to eBOSS strategy]
  - ✦validate the [OII] luminosity function for luminous and z>~1.3 galaxies using the VLT/FORS-2 spectrograph [similar to DESI/PFS strategy]

# New BOSS Ancillary ELG Project

- 3 dedicated plates for 2300 spectra (out of 3800 targets [535 $deg^{-2}$]),
- observed April 2013
- CFHT-W3 field; 20<g<22.8
- stars removed (SED fit)

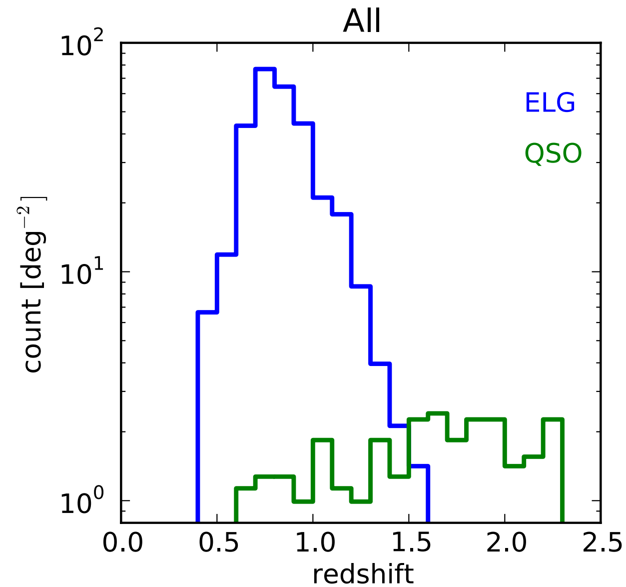


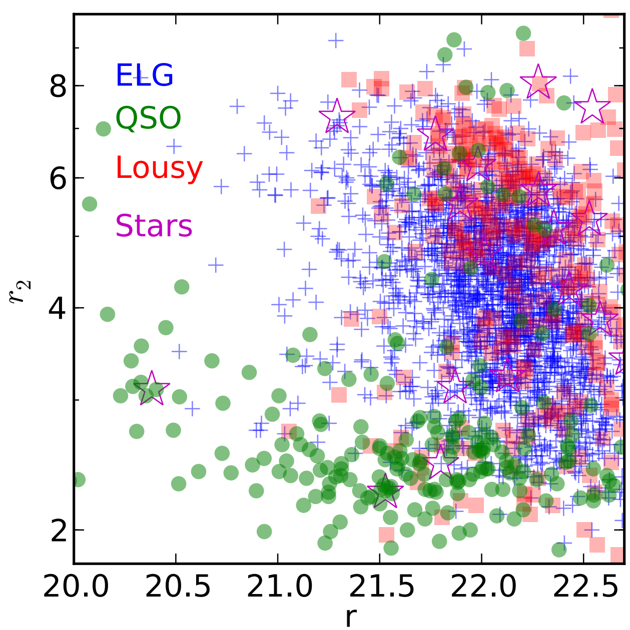



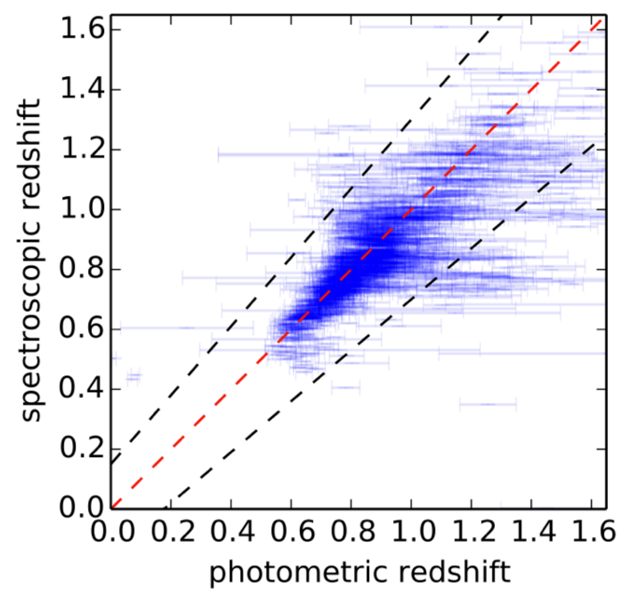
# New BOSS Ancillary ELG Project

- Improved BOSS pipeline
- 89% redshift success rate
- 82% ELG, 6% QSO, 1% stars
- 11% bad data




CFHT-LS photo-z predict higher-z



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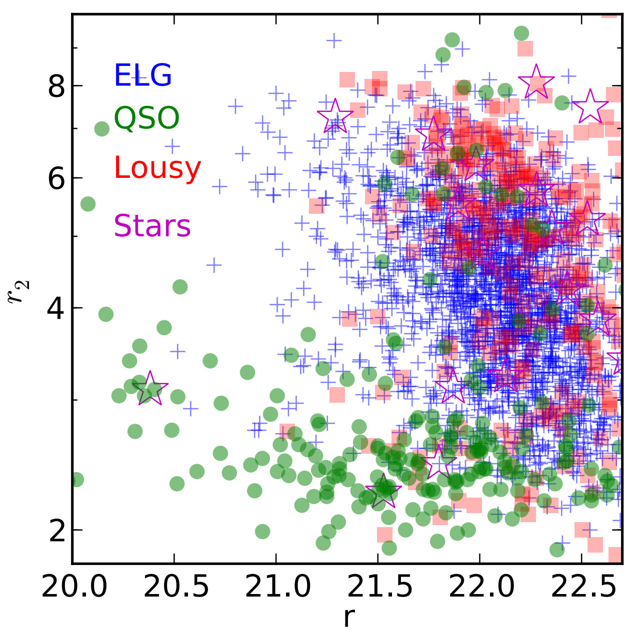
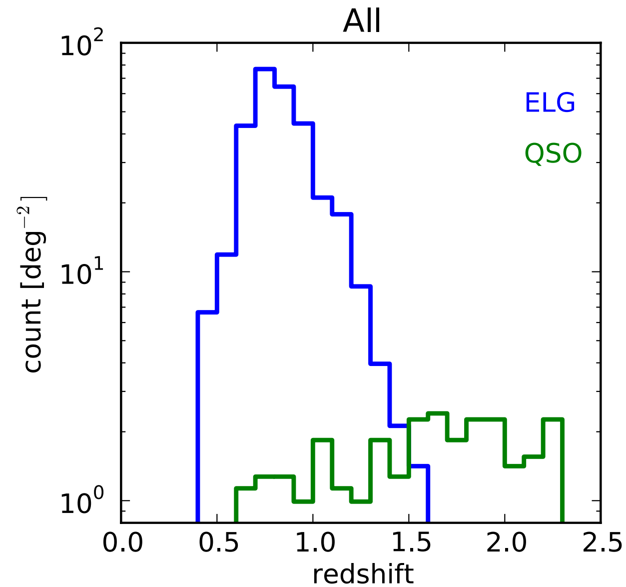
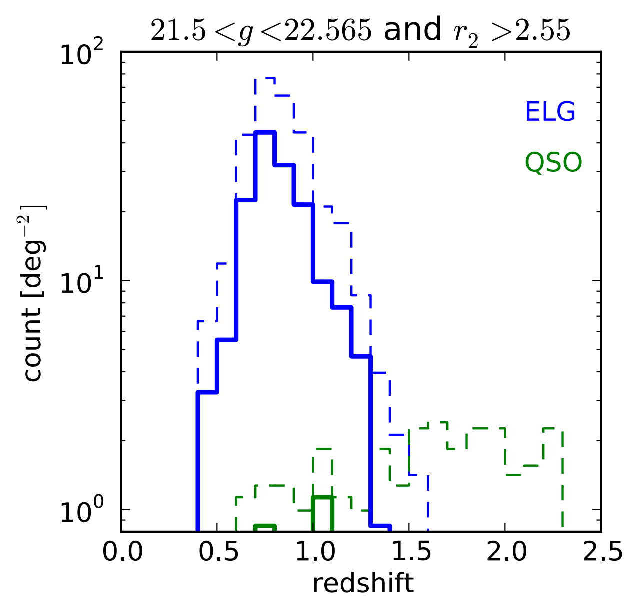
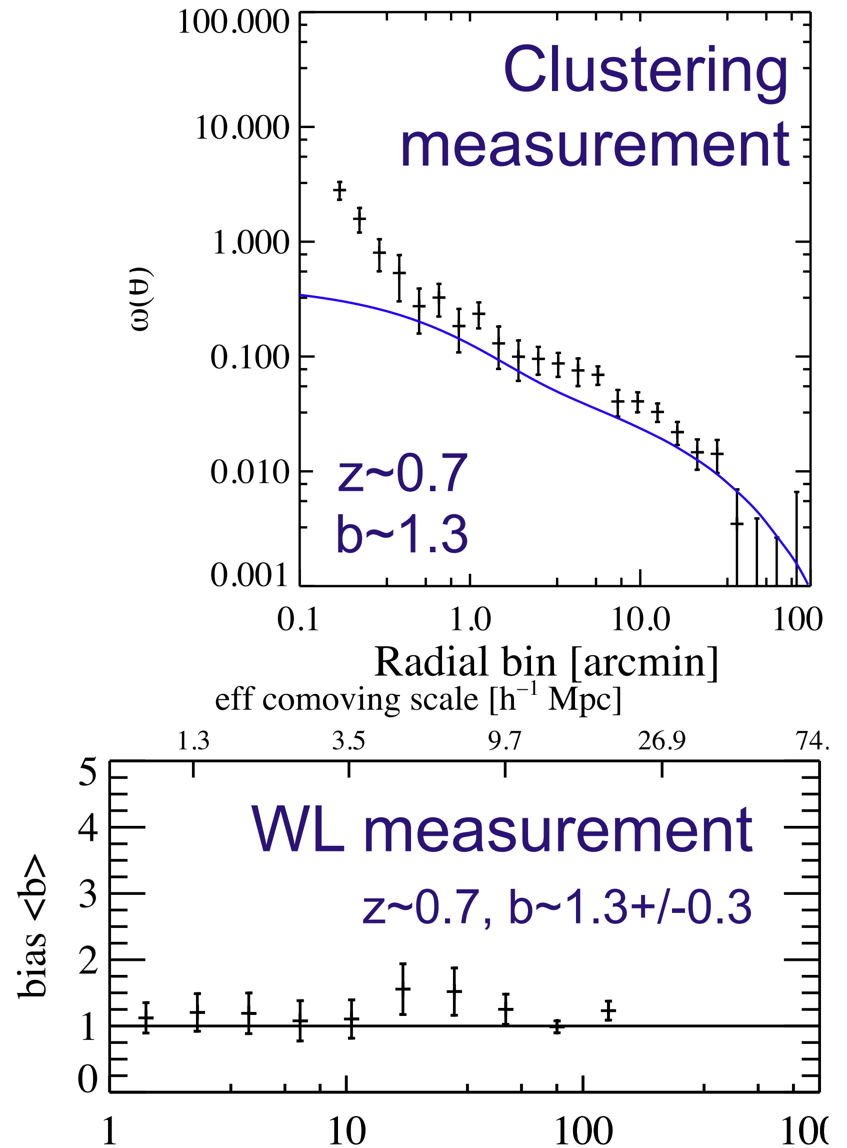


# New BOSS Ancillary ELG Project

- Measuring bias using clustering and WL analysis in the new *ugri* selected W3 ELG sample
- low-z sample (z~0.7): b~1.3
- high-z sample (z~0.9): b~1.7
- clustering & WL in agreement

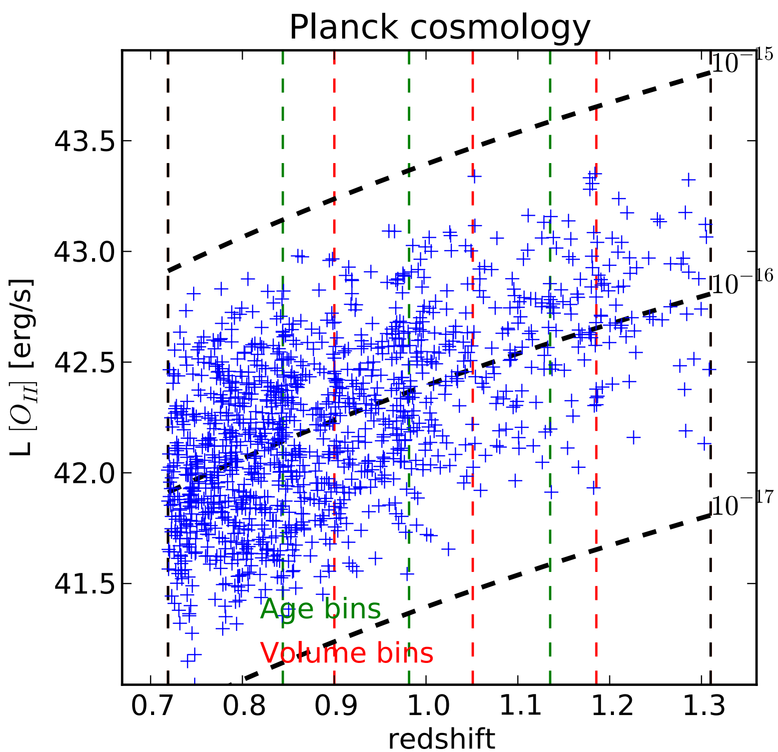


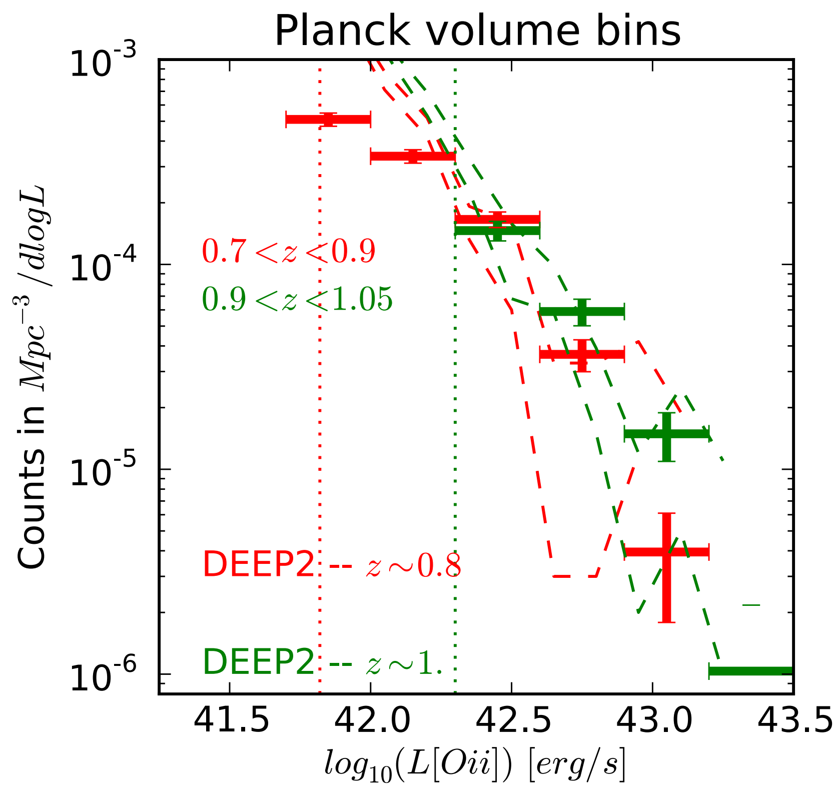

*Comparat et al 2013c*

# BOSS Ancillary ELG Project

*Comparat et al 2014*

- [OII]-luminosity vs. redshift
- Luminosity function, extend DEEP2 [OII] LF at higher [OII] luminosity

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# BOSS Ancillary ELG Project

*Comparat et al 2014*

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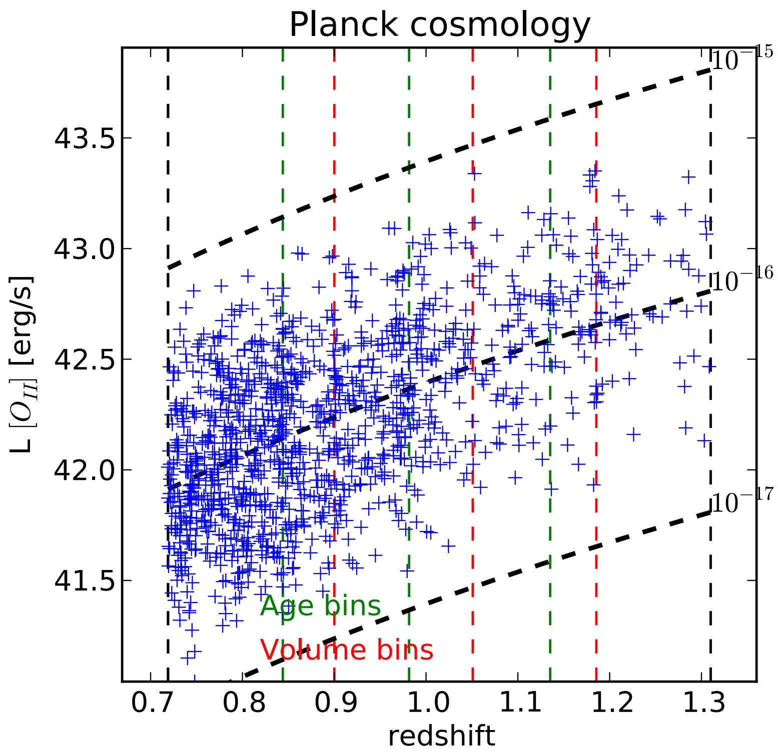
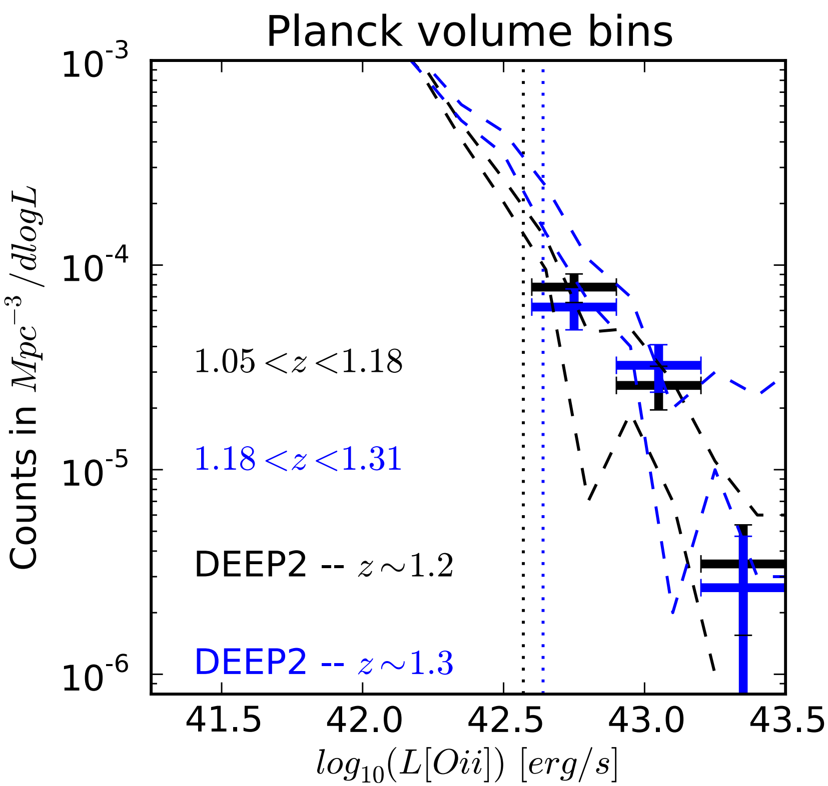
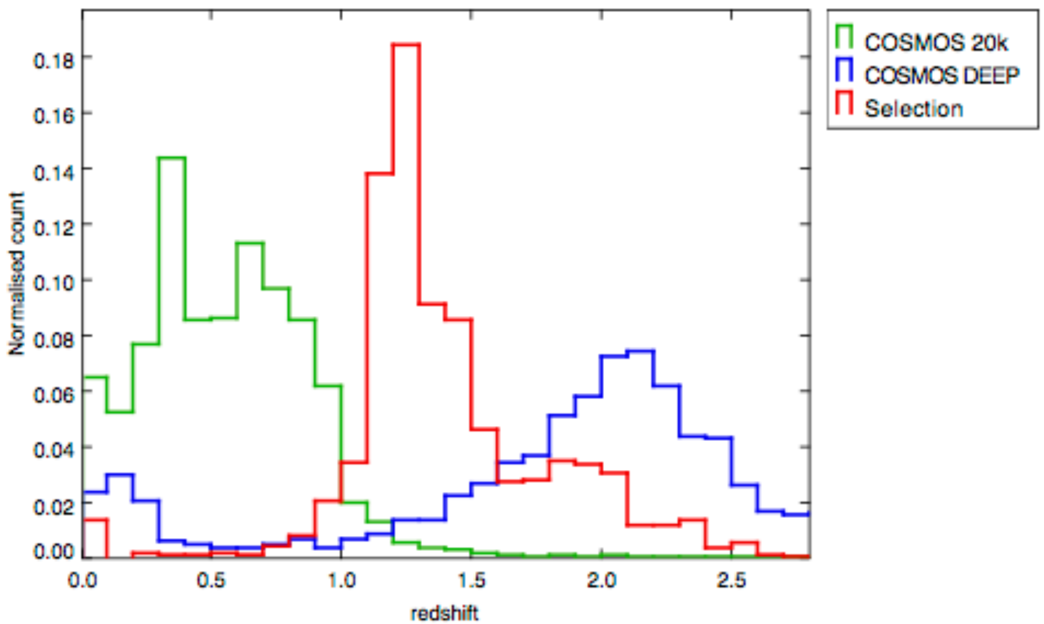


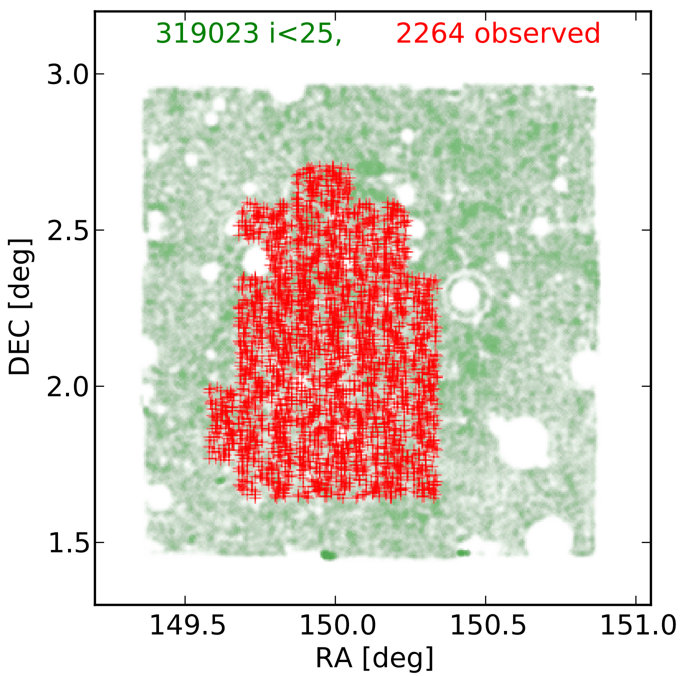



# Testing the ELG strategy with VLT/FORS-2 project

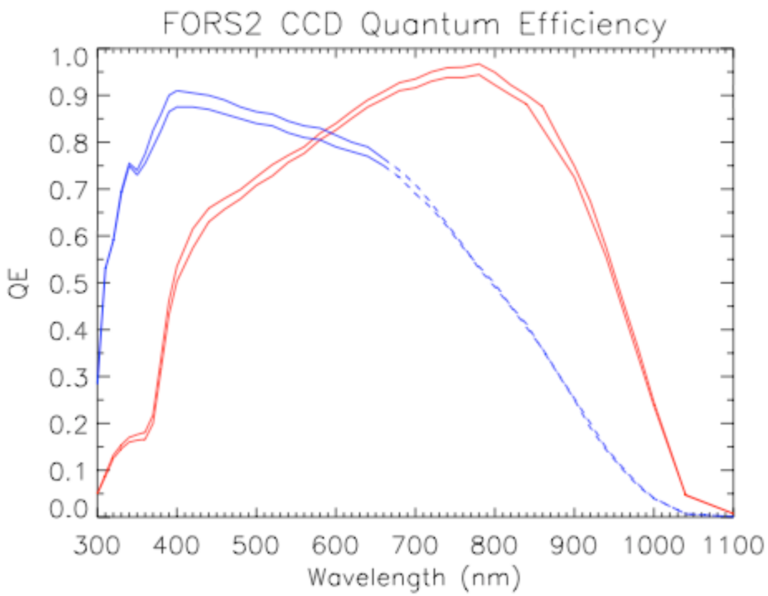
- Observation conducted during Winter 2012 and 2013:
  - VLT / FORS2 observation targeting ~950 ELGs (g<24, from 3000 deg$^{-2}$) over 0.65 deg$^2$ with 0.9<phot-z<1.6 in the COSMOS field, following a ***griz*** selection
  - probe the [OII] luminosity function of DESI-like selected galaxies, validating the requirement of DESI sensitivity limit

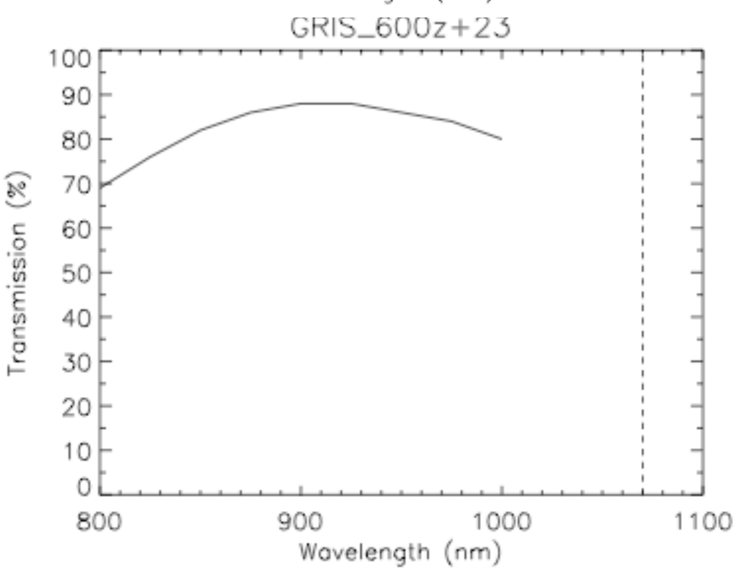
*Comparat et al 2014*



# FORS-2 Set-up



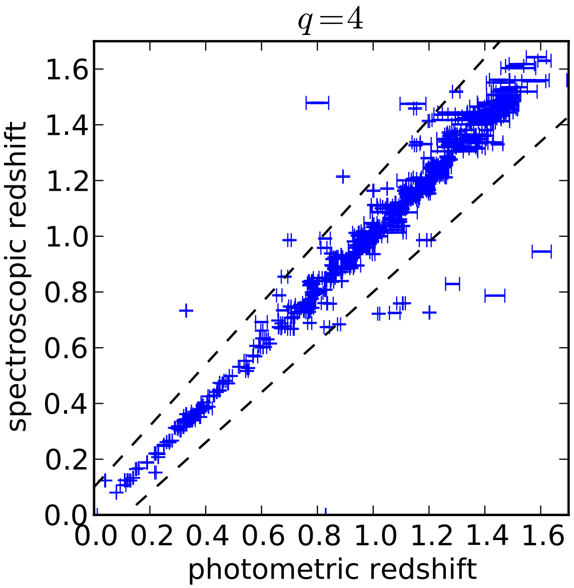

*Comparat et al 2014*

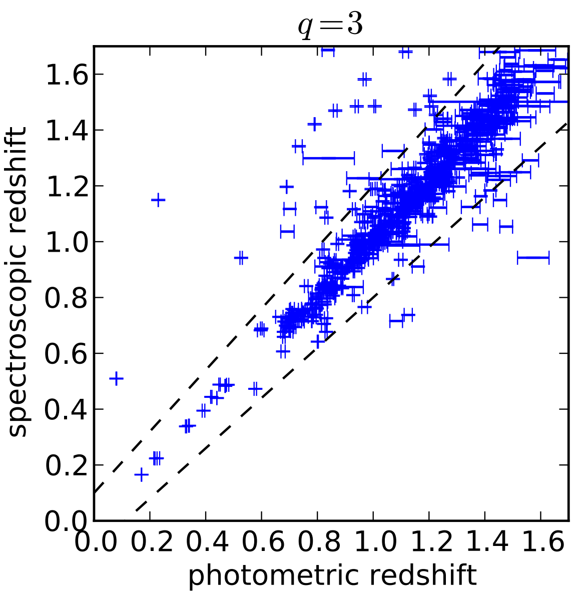
- FORS-2 - red detector
- Multi-slit (~40 slit per mask)
- Holographic grism, dispersion of 0.8A/pixel
- Throughput: 25% at 8500 Angstrom, 10% at 9700 Angstrom (much worse than DESI !!)
- Short exposure 310 sec.
- But 450 sec of overheads!

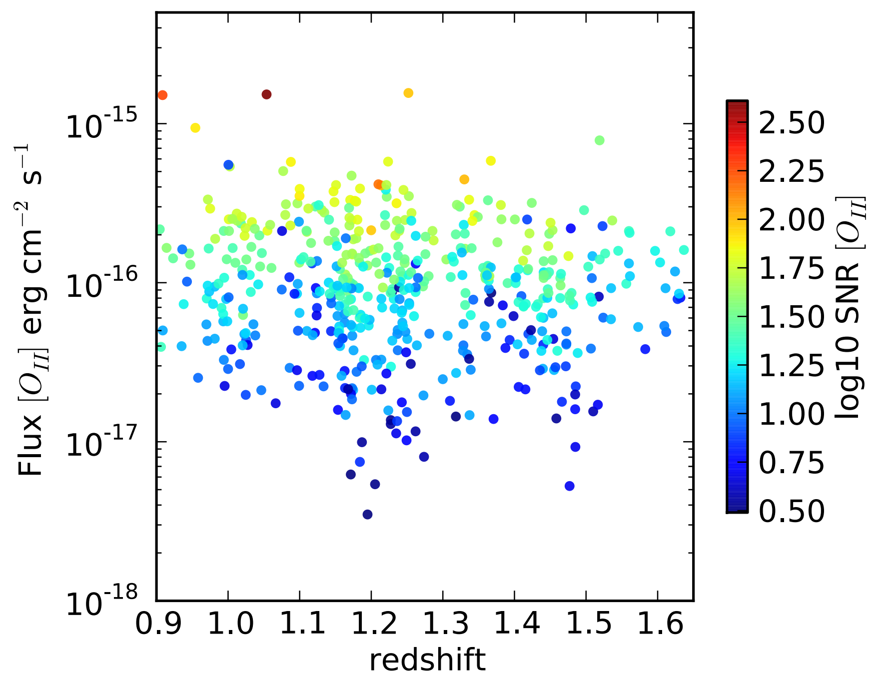
# FORS-2 Results

*Comparat et al 2014*

- 800 out of 950 targets (75%) have a high-quality redshift identification with 0.9<z<1.6
- good agreement with COSMOS photo-z



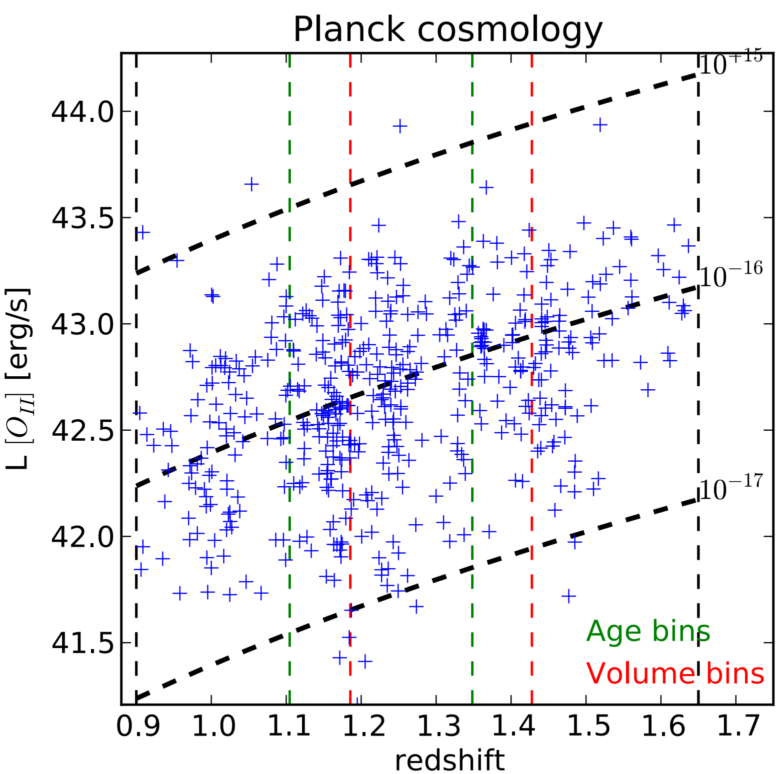



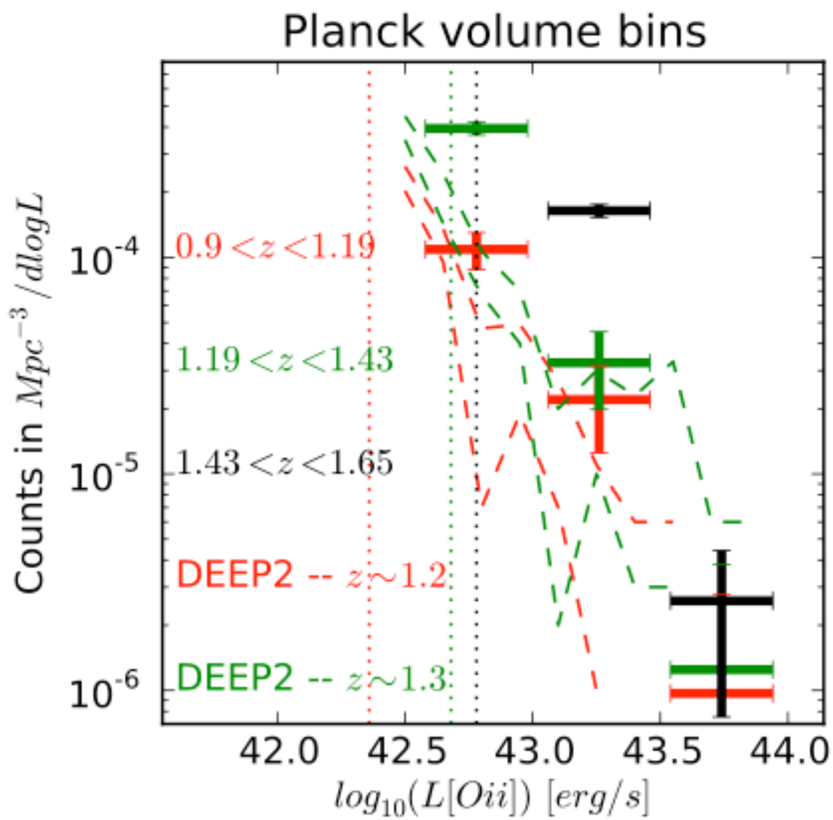

Return

# FORS-2 ELG Project, LF results

*Comparat et al 2014*

- [OII]-luminosity vs. redshift
- Preliminary Luminosity function (extend DEEP2 measurement to higher -z, increased volume density)

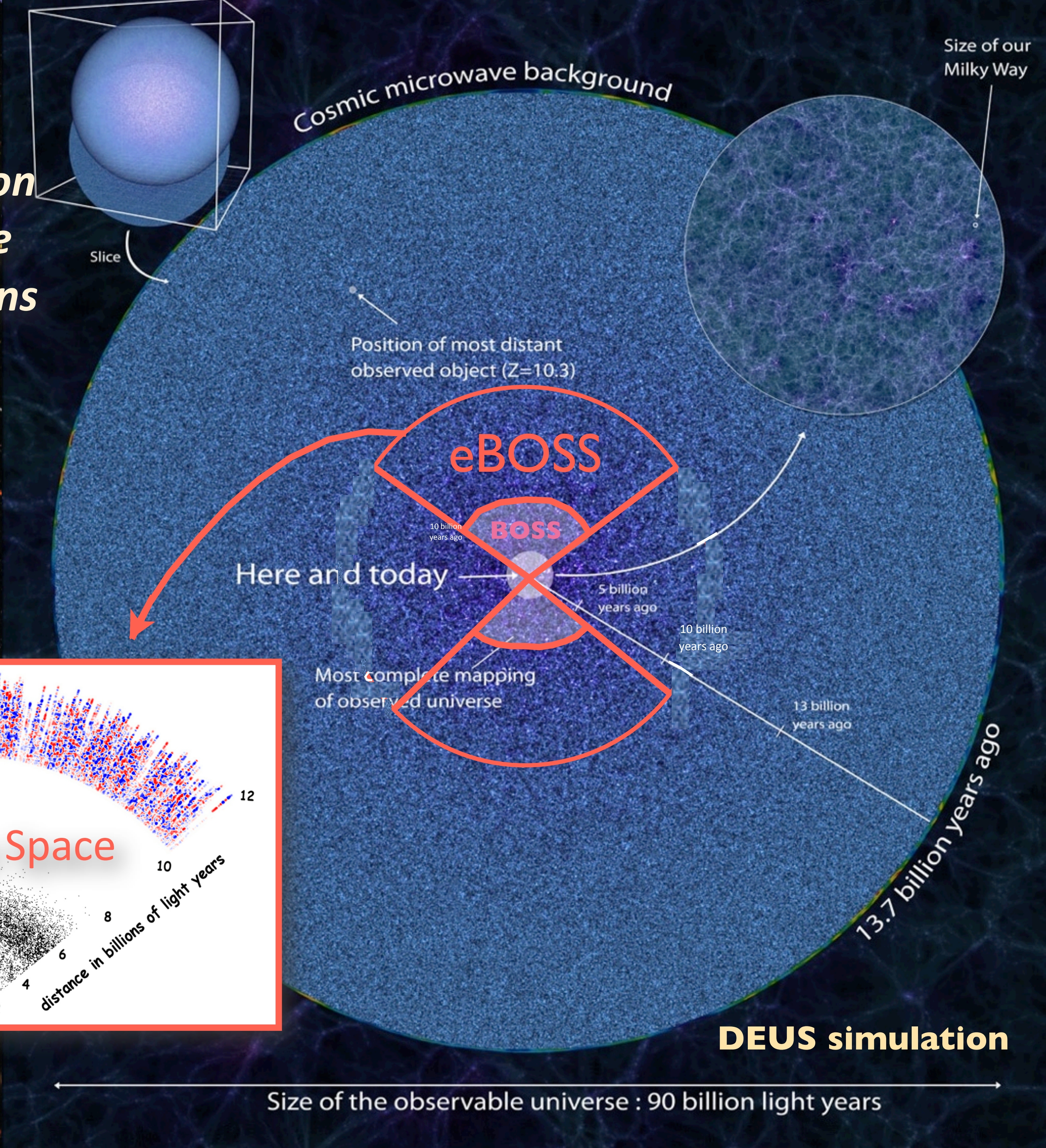


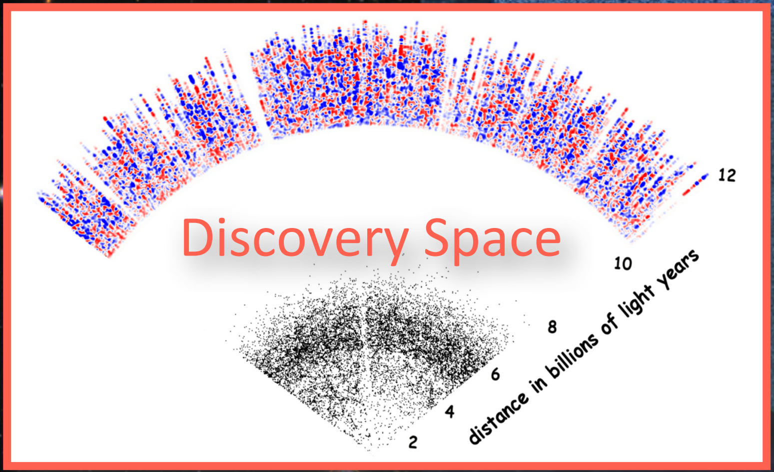



# eBOSS

# eBOSS:

## *Measuring the Expansion History of the Universe between 7 and 11 billions of light years with ~1 million Quasars, ~1/2 million LRGs ~1/4 million of ELGs [2014-2020]*

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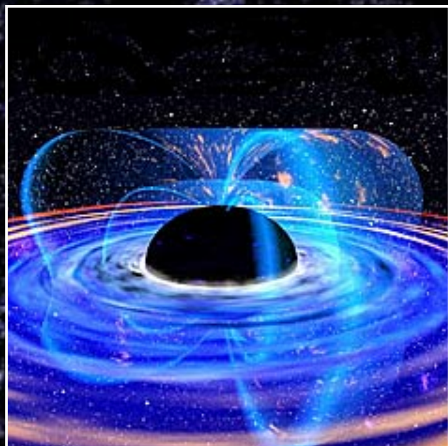
Gas that falls into a black hole settles into a so-called accretion disk. Friction and magnetic fields in the disk cause the gas to heat and emit UV and X-ray light.



# eBOSS:

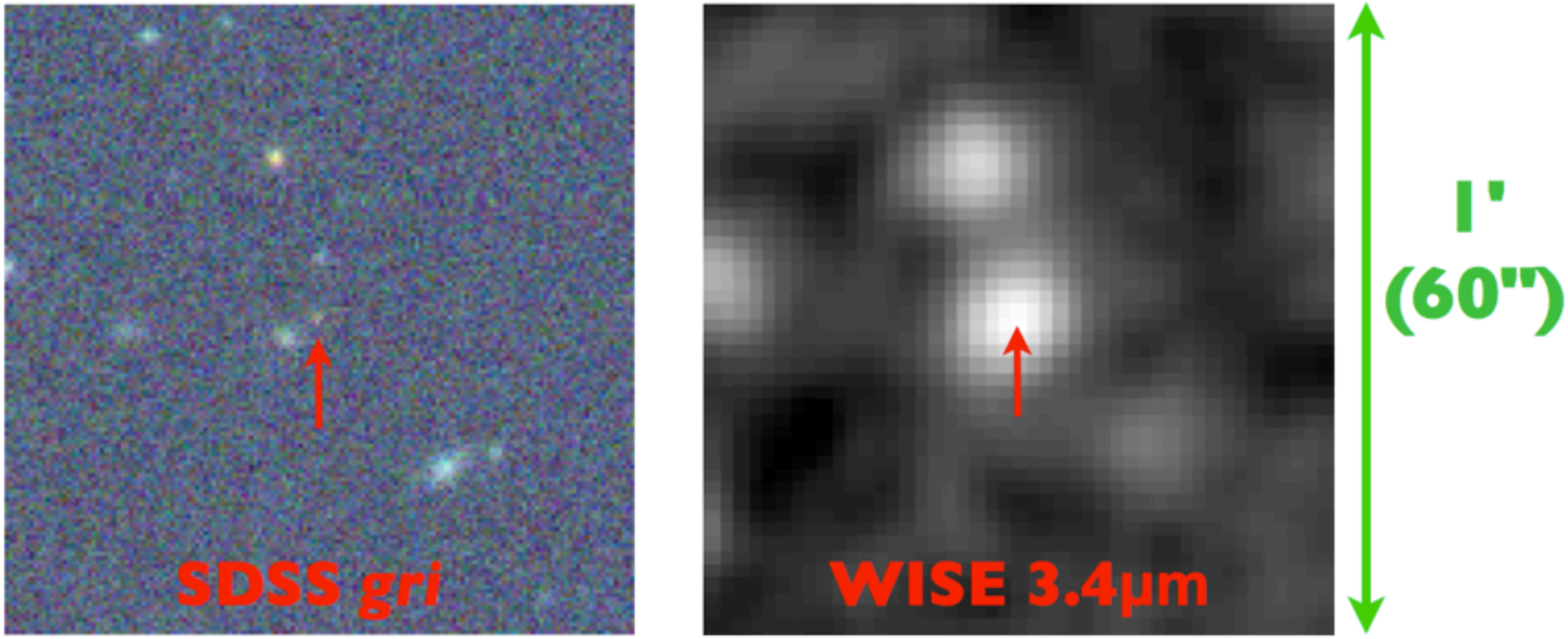
## *Measuring the Distribution of <u>MILLION Quasars</u> using different detection techniques (UV excess, variability, WISE, X-ray) over 7,500 sq.deg. !!!*

eROSITA

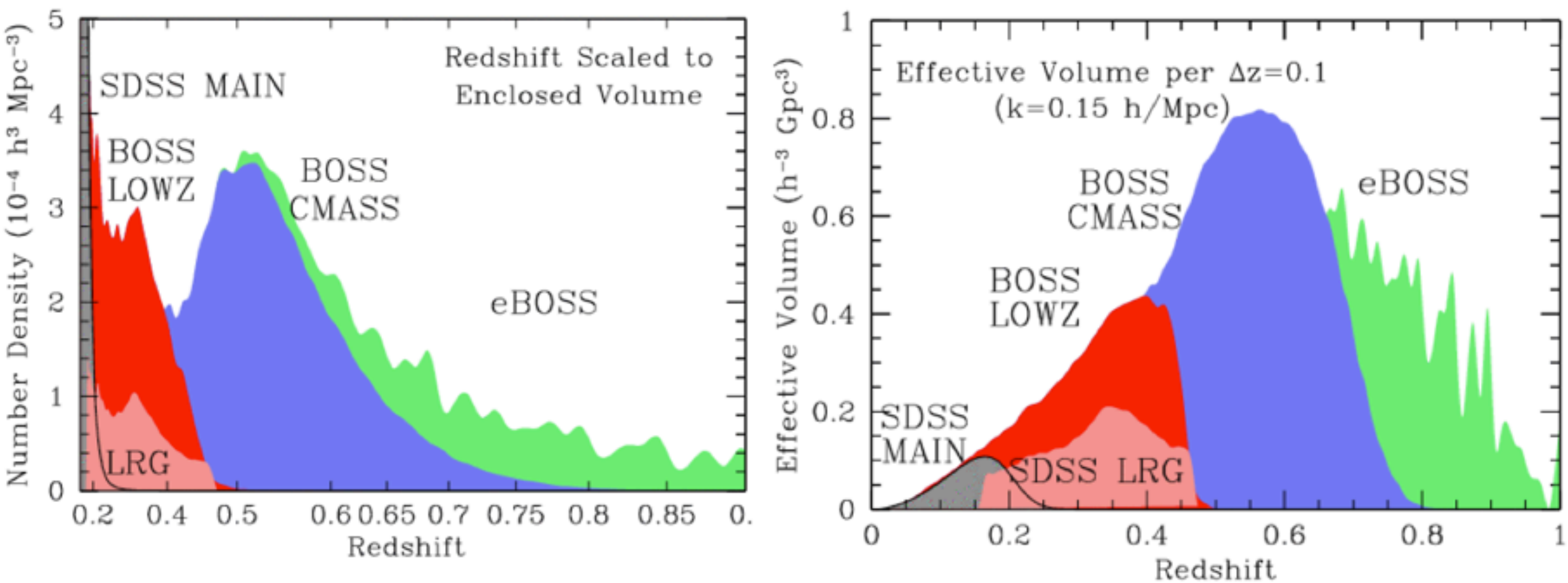
eBOSS

# LRGs selection with the WISE survey

- **Bolometric SED of LRGs peaks at restframe 1.6 microns**
- **Example: z=1.0 LRG from DEEP2**
  - **At SDSS 5σ limit in r & i**
  - **Easily detected by 40cm WISE telescope at 3.4 microns**

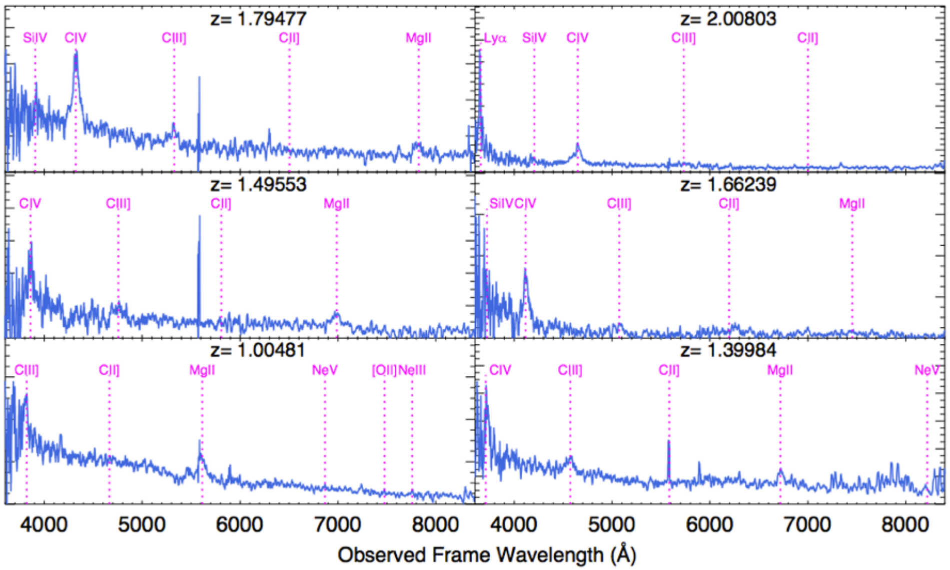


# eBOSS LRG forecast




- **eBOSS brings high-$z$ LRG BAO errors from 2.2% at $z$=0.69 (BOSS) to 1.3-1.4% at $z$=0.76**
- **In combination with eBOSS ELGs (even without cross-correlations), yields better distance constraints at 0.65<$z$<0.9 than CMASS at 0.43<$z$<0.65, sub-1% errors**

# Probing new tracers: Quasars

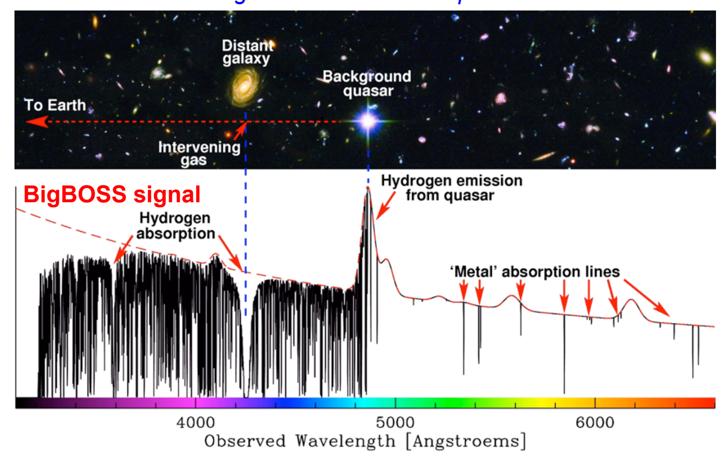



QSOs at z < 2.2 will be observed once → "tracer QSOs"

QSOs at z > 2.2 will be observed 5X for high S/N for "Lyman-alpha forest"

*Map of hydrogen gas along line-of-sight skewers*

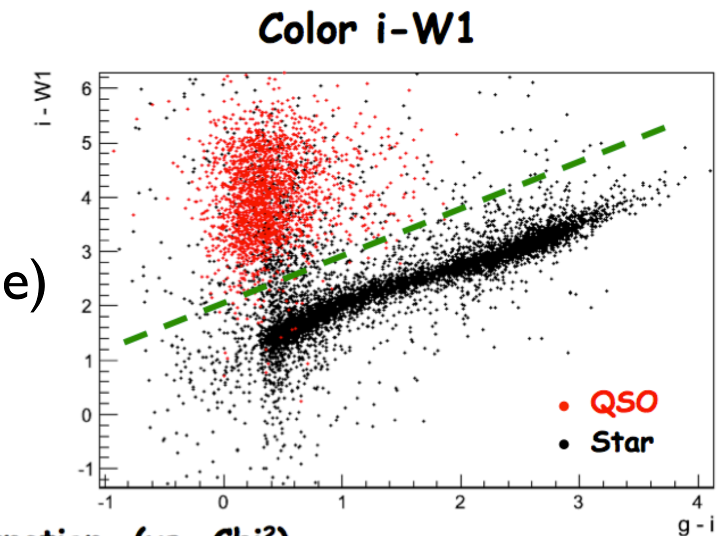
*BOSS validating their use as 3-D maps for BAO*



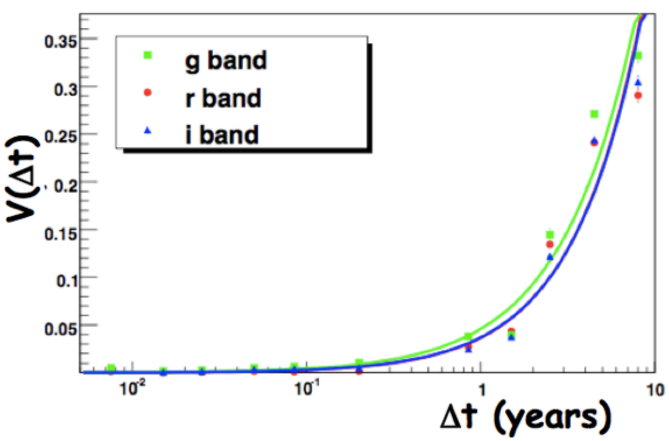

- *Quasar redshift are easy to measure, quasar number density peaks at z~2.*
- ***Quasars are highly biased sources.***
- Redshift measurement relies on emission lines
- UV excess quasar selection is very effective (XDQSOz algorithm of Bovy et al)
- include other quasar selection (WISE, variability, eROSITA ...)

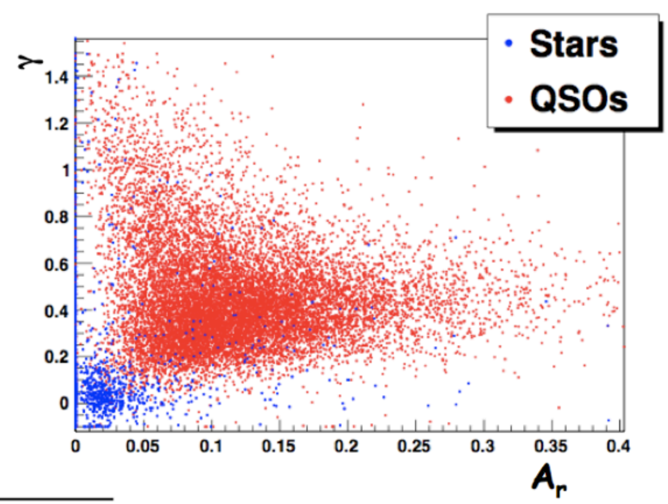
# Advanced techniques for quasars selection

- using mid-infared WISE data
- using quasar variability: using PTF multi-epoch photometry (Palanque-Delabrouille)




**- More sophisticated selection: structure function (vs. Chi²)**




$$V(\Delta t_{ij}) = \left|\Delta m_{ij}\right| - \sqrt{\sigma_i^2 + \sigma_j^2} = A(\Delta t)^{\gamma}$$

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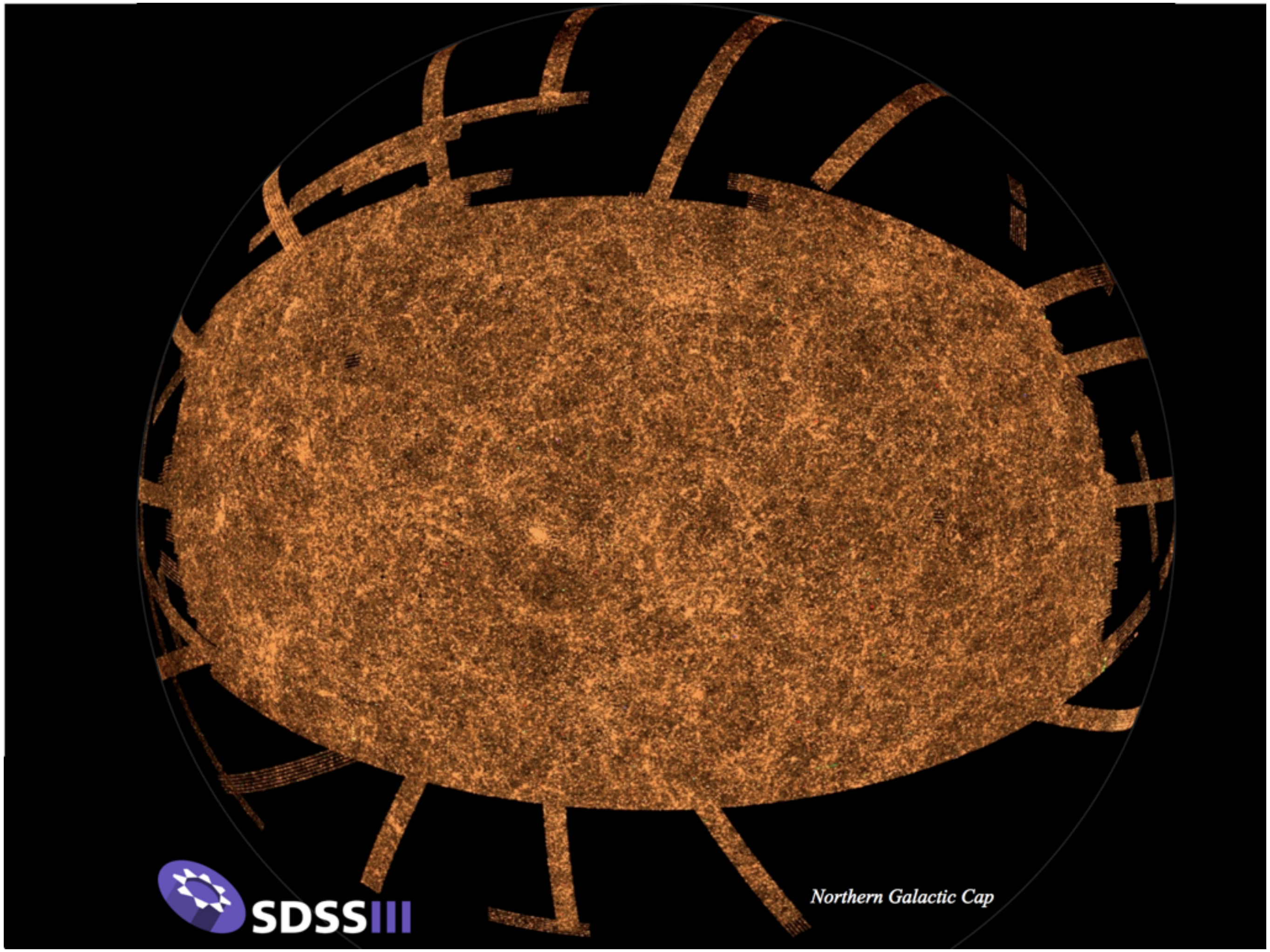
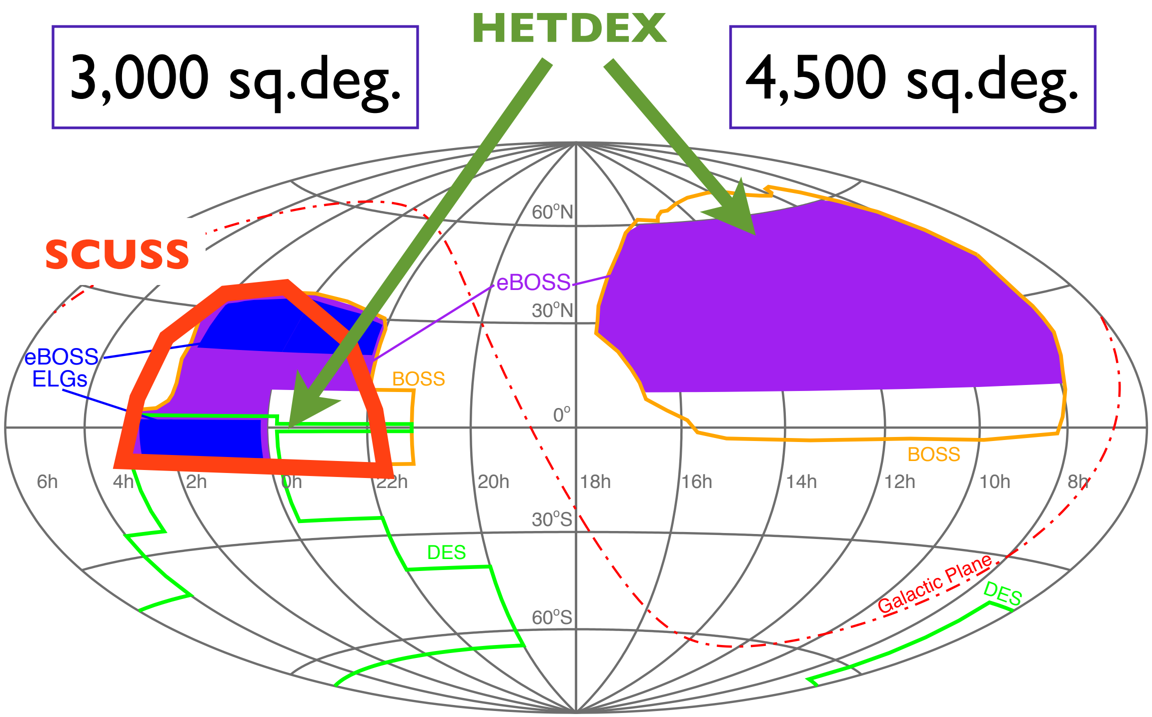
# eBOSS footprint & Survey Plan



# eBOSS footprint

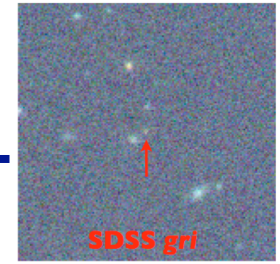


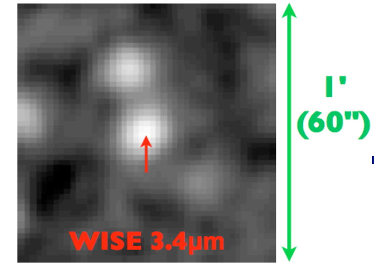

1.6 million science fibers !

Footprint depends on:

- SDSS-IV time share between projects
- DES coverage (500 sq.deg overlap)
- SCUSS U-band survey on SGC
- eROSITA (German Sky)

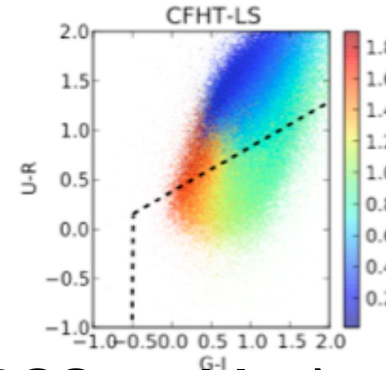
# eBOSS Targets






**1. 375k (60 deg$^{-2}$) Luminous Red Galaxies**

- Selected at 0.6< z <0.8 with SDSS+WISE
- Efficient BAO tracers due to large bias




**2. 270k (180 deg$^{-2}$) Emission Line Galaxies (ELGs)**

- Selected at 0.6<z<1, when star formation rates were high with SDSS+U-band or DES+U-band

**3. 750k (105 deg$^{-2}$) "Core" QSOs (1 million including SDSS archive)**

- Target ***all*** we can, most 1 < *z* < 2.15 with SDSS+U-band+WISE

**4. 150k (30 deg$^{-2}$) Lyman-alpha QSOs (z > 2.15)**

- 3-D density map from Ly-a forest, selected from variability (PTF/PS1)

**5. ~30k TDSS**

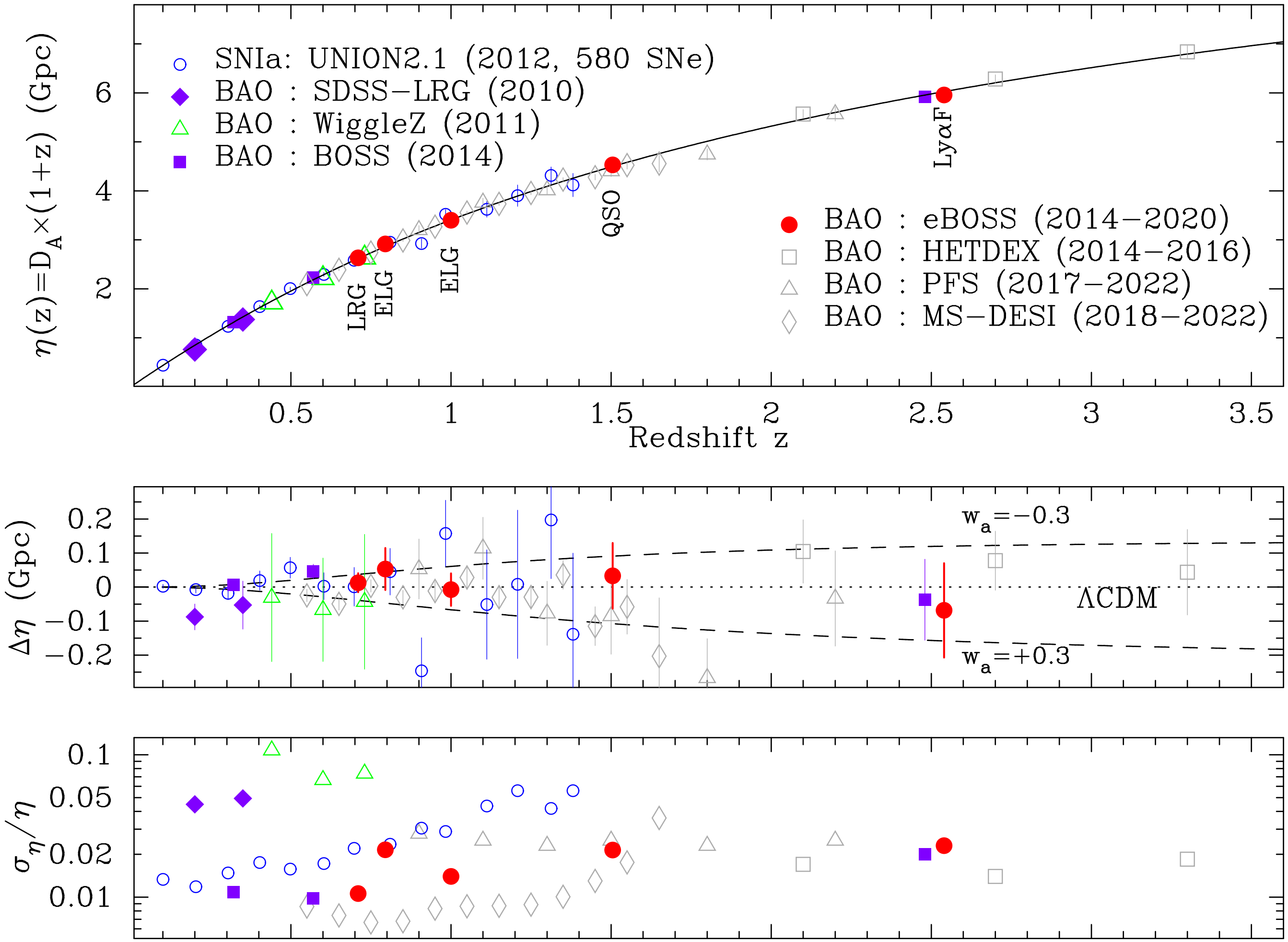
- variability objects from PannSTARRS-1 (3PI data)

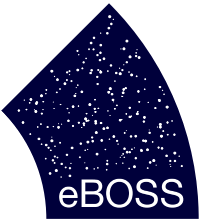
**6. ~30k eROSITA sources (mainly AGN and a few cluster members)**

**ELG sample over 1500 deg$^2$; LRGs & QSOs over 7500 deg$^2$**

# Science: Hubble Diagram Forecast

With 4 classes of target **eBOSS** will deliver *first high precision measurements* in the epochs when DE emerged as the dominant component of the Universe.

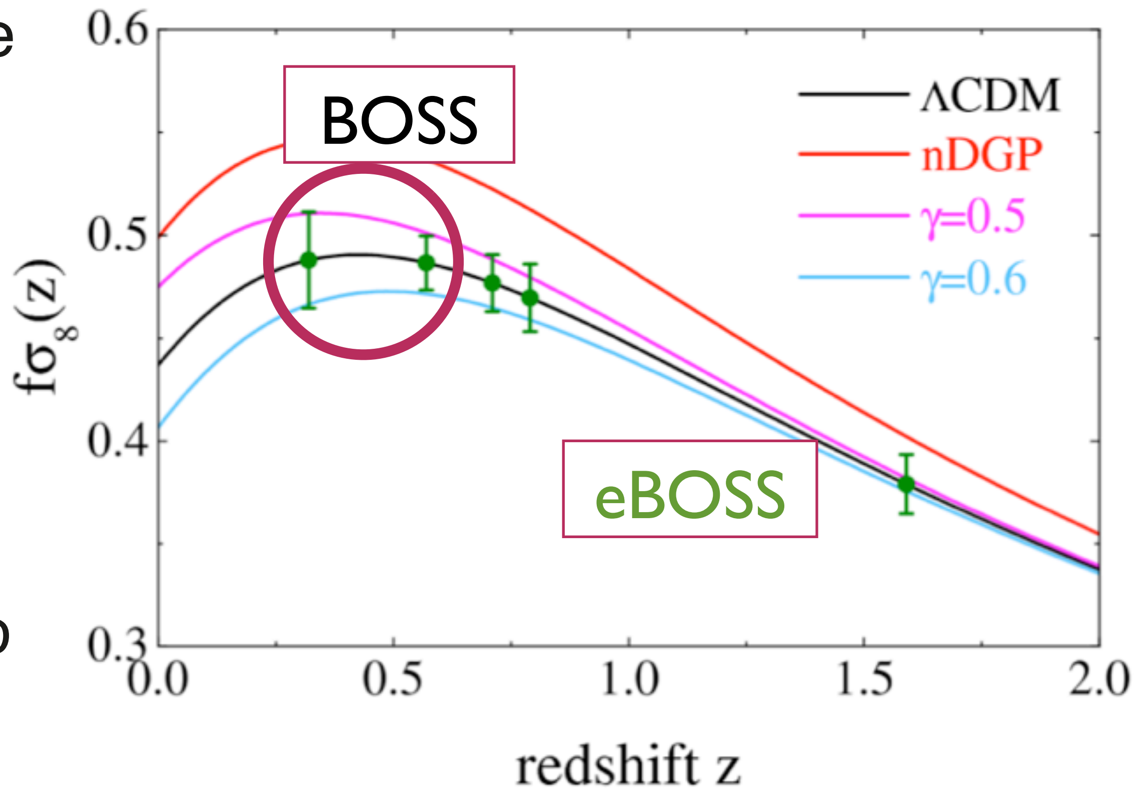


# Science: RSD

- redshift-space distortions (RSD) measure the anisotropy of the clustering on intermediate scale => growth rate
- RSD provide tests of General Relativity on cosmological scales - complementary to BAO tracer.
- Motivation to compare to WL in DES/HSC-eBOSS overlap

**eBOSS Forecast ~5%**



# eBOSS Forecast

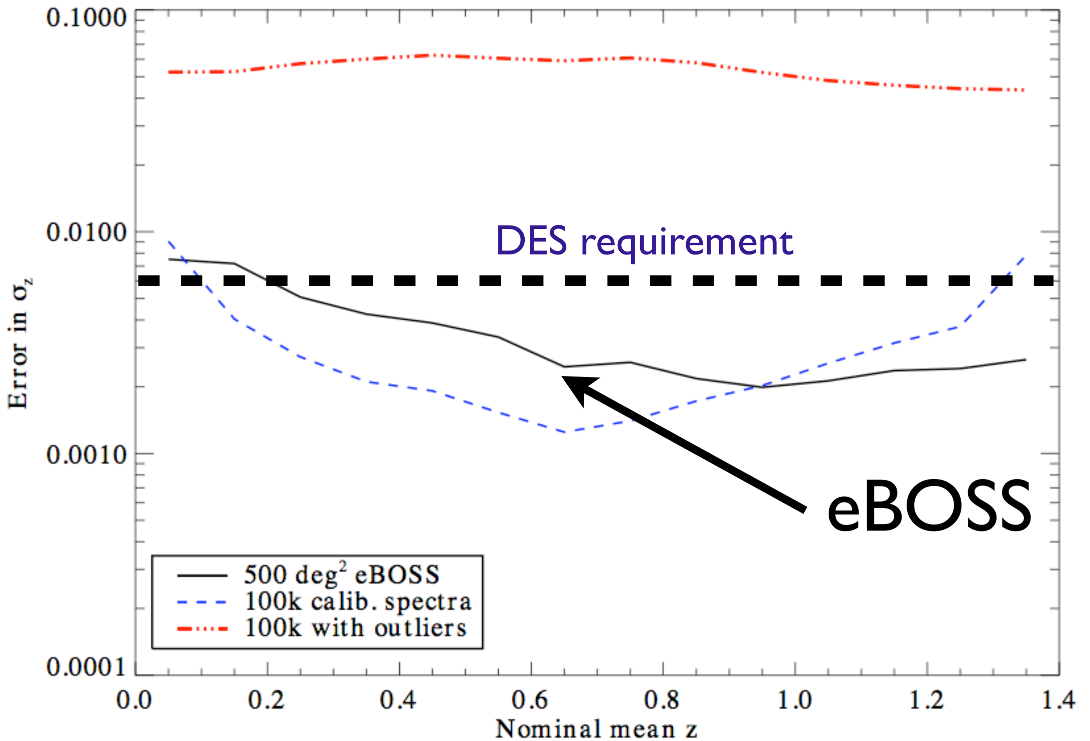
- Assume Planck CMB measurements, 5% H0 constraint, and the BAO measurements from the complete BOSS galaxy sample => **1-2% accuracy over 0.7<z<2.5**
- **BAO DETF FoM increase by a factor of ~2.2 from BOSS to eBOSS**
- RSD improvement will also be a factor ~2 better

| Galaxies | Redshifts | Target sky density | Total area | Target success | Number of good redshifts | Distance precision | Effective volume |
|---|---|---|---|---|---|---|---|
| LRG | $0.7<z<0.9$ | 60deg$^{-2}$ | 7500deg$^{2}$ | 95% | 430k | 0.8% | 4.7 Gpc$^{3}$ |
| ELG | $0.6<z<1.0$ | 180deg$^{-2}$ | 1500deg$^{2}$ | 80% | 216k | 2.0% | 2.3 Gpc$^{3}$ |
| QSO | $0.9<z<2.3$<br>all | 105deg$^{-2}$ | 7500deg$^{2}$ | 70%<br>90% | 525k<br>700k | 1.5% | 6.6 Gpc$^{3}$ |
| Lya QSO | $z>2.15$ | 5+22deg$^{-2}$ | 5000deg$^{2}$ | 30% | 64k<br>(+revisit) | - | - |

eBOSS

# Science: DES synergy

- DES will cover 5000 $deg^2$ of southern sky, @4m Blanco. It will provide imaging of 300 million galaxies in the grizY filters (=>WL)
- ~500 $deg^2$ overlap with eBOSS
- Synergy by "Cross-Correlations" of imaging and spectroscopic surveys for cosmological constraints (BAO+RSD+WL)
- *eBOSS should play a critical role allowing high-precision calibration of photo-z.*




Comparison of traditional spectroscopic calibration technique and cross-correlation technique for photo-z calibration needed for accurate WL measurement.

# Science: Cross-Correlations

- Benefiting from **many target class**, wide redshift range, and **growing number of large scale surveys**
- **eBOSS science will include MANY cross-correlation opportunities**
  - using eBOSS data (LRG-ELG, LRG-QSO, ELG-QSO, CMASS-QSO, QSO absorbers-Galaxies ...)
  - using other dataset: U-band, WISE, PLanck, eROSITA, DES, HSC, HETDEX ...

eBOSS

# SEQUELS
# starting eBOSS now!

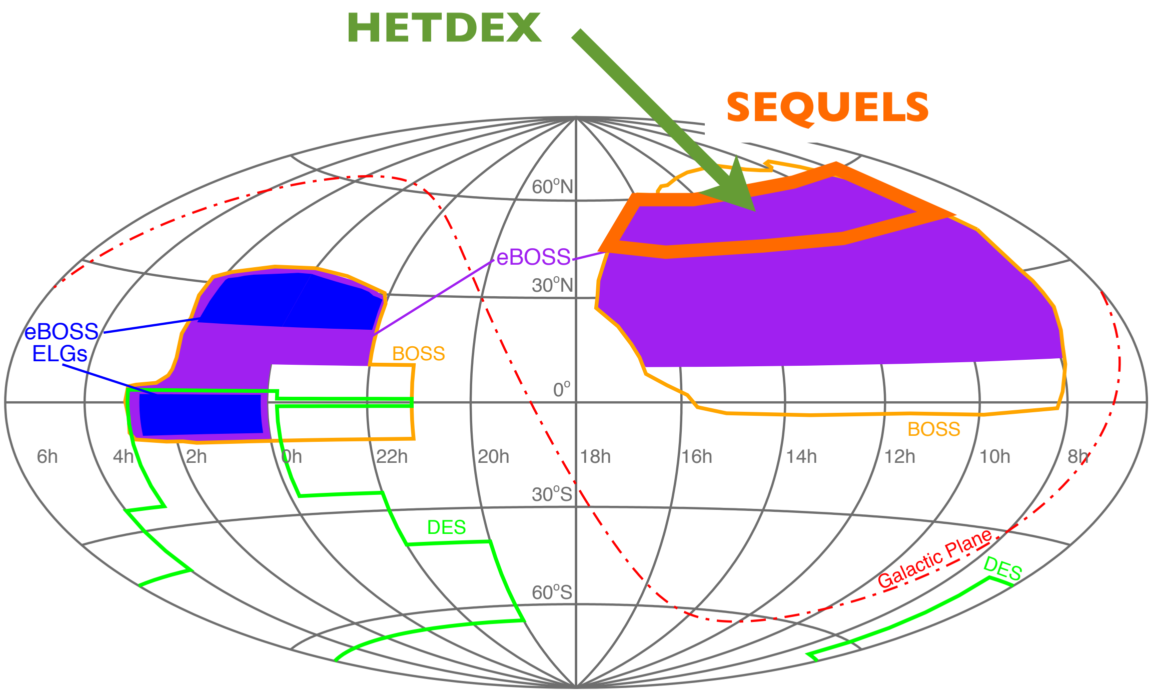
# SEQUELS Project

- Motivation: early start on eBOSS science providing first cosmology results
  - BOSS collisioned fibers => BOSS systematics
  - LRG (SDSS+WISE) => BAO with photo-z of WISE-LRG
  - QSO (SDSS+WISE, +PTF variability selected) => selection test + first clustering measurement
  - PTF SNe => SNIa anchor at low-z
  - TDSS & SPIDERS (AGN+cluster) science
- ELG ugri color selection validation with SCUSS U-band data.

# SEQUELS plates

- 120 plates covering on average 4 sq.deg./plate (instead of 5.5 sq.deg. for eBOSS) focusing on the LRG+QSO samples =>500 sq.deg (equivalent to 1/3 of a year of eBOSS observation).
- 10 special plates on ELG: 29 sqdeg of SGC combining SCUSS+SDSS ugri ELG selection

# SEQUELS footprint




- eBOSS starts early with SEQUELS!
- starts from the Northern part +60 to +45 deg
    - allowing flexibility in scheduling
    - not covering German eROSITA footprint

eBOSS

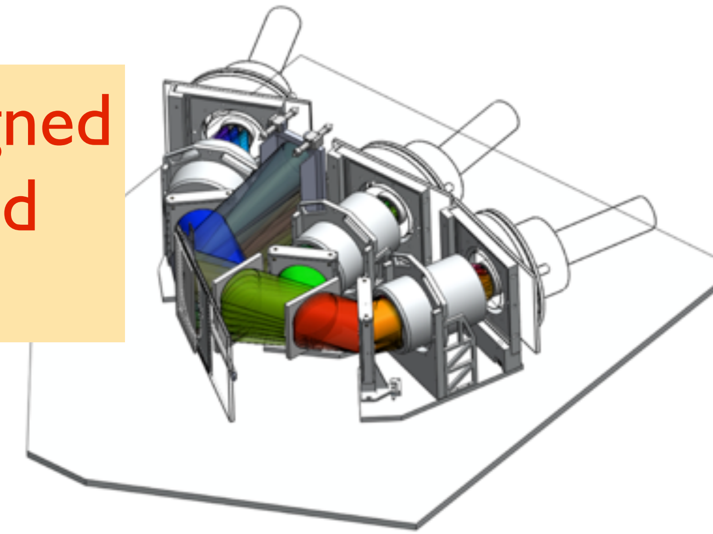
# 3rd Spectrograph

# 3rd spectrograph ?

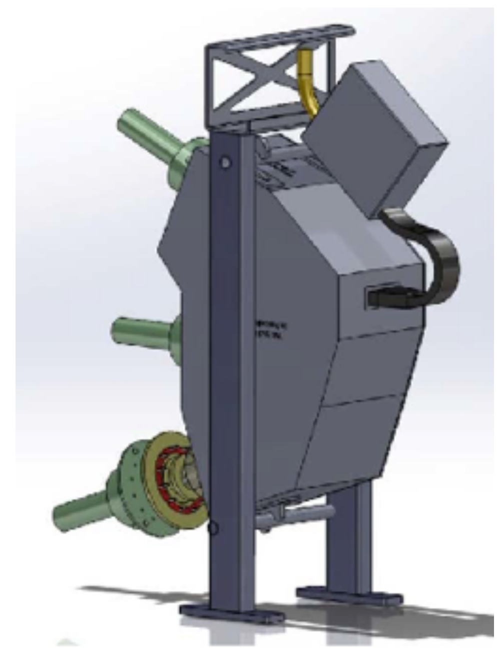
- Why a 3rd spectrograph?
  - eBOSS scope was cut down from original proposal by at least 1/3
  - allow faster survey in view of early start of future projects: DESI and PFS
  - enhance science of ELG
- Spectrograph opportunity:
  - DESI unit #1: could arrive in summer 2015, may not stay long, but already funded. Need funding for fiber links.
- 3rd spectro not part of the baseline (extra funds required!)

# 3rd spectrograph

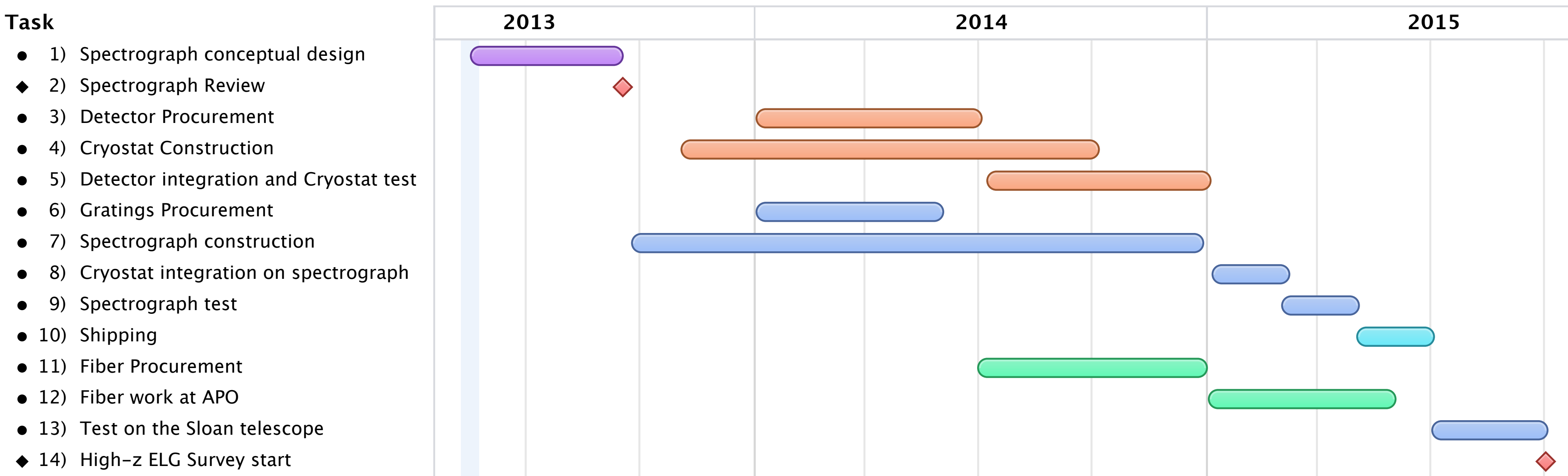
**Oct 2013: Contract signed with Winlight to build the first unit**



- eBOSS
  - 3rd Spectrograph Christophe Yèche
    - Spectrograph
      - Detector (LBL)
      - Cryostat (CEA)
      - Grating
      - Spectrograph
      - Test & Shipping
    - Fiber System
      - cartridge
      - Fiber run
      - Connectors
      - Testing
      - Plugging
    - Commissioning



# 3rd spectro schedule




**Installation at APO:** June-August 2015

**Commissioning of 3$^{rd}$ Arm :** September-November 2015 :

- Official target selection prepared with 2 spectrographs
- Parallel ELG survey with 3$^{rd}$ spectrograph (no impact on eBOSS main survey)

| Galaxies | Redshifts | Sky Density | Total Area | Target Success | Distance Precision |
|---|---|---|---|---|---|
| Hiz ELG | 0.8<z<1.4 | 90 deg$^{-2}$ | 7500 deg$^{2}$ | 80% | 1.4 % |

*Proposal Submitted to Swiss Science National Foundation*

# Conclusion

- BAO is a robust distance-redshift measurement technique
- BAO surveys provide science opportunities for numerous studies: LSS, but also physics of tracers
- **As BAO survey probes deeper in redshift we need to target new tracers - moving from LRGs to ELGs (and QSOs)**
- **eBOSS is the next SDSS Cosmological survey:** will start in January 2014 probing the untouched window $0.6<z<2.2$ *using new tracers*: Quasars and ELGs
- **Future experiments (DES, PFS, ...)** will explore the same redshift range but with larger number densities (BAO will likely then be limited by systematics ... more physics to learn?)

THANKS