Prospects and challenges
of the Dark Energy Spectroscopic
Instrument

Julien Guy

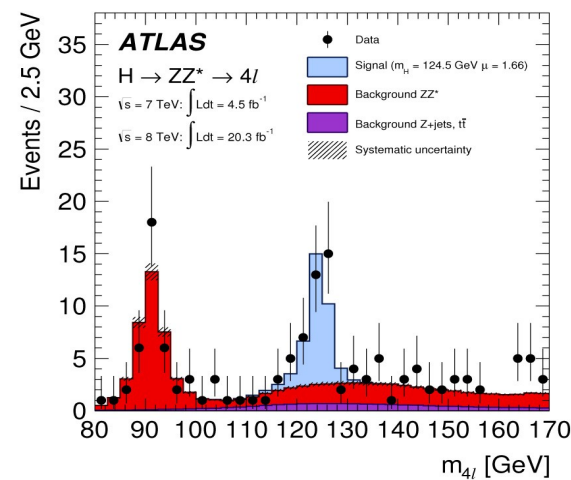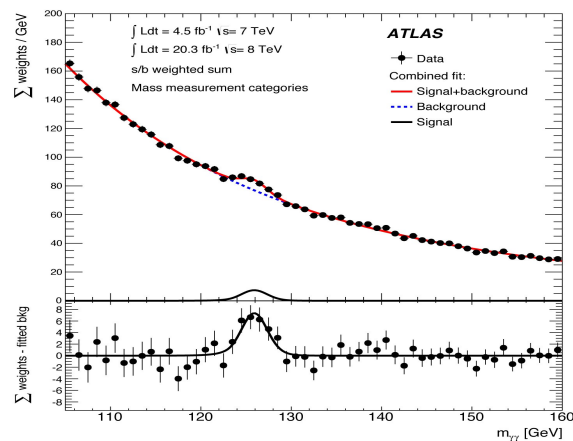LBL RPM Seminar   March 2016

- The Dark Energy puzzle

- Latest results

- DESI forcasts

- DESI projet instrument

- Challenges

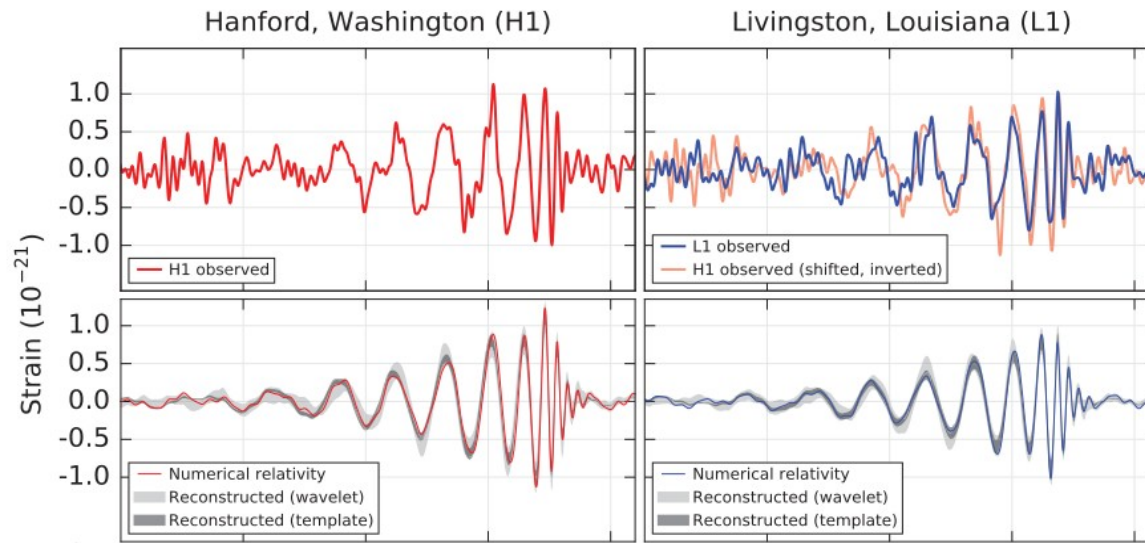# Impressive achievements in physics in the last years

Particle Physics :
- Discovery of Higgs boson at LHC, very precise tests of the standard model

Gravitation :
- Direct measurement of gravitational waves with LIGO
  Renewed success of General Relativity in the strong field regime

**Cosmology brings in
observational evidence for missing blocks:**

- matter/anti-matter asymmetry :
    why no evidence for anti-matter galaxies

- inflation : high energy quantum physics at play
        (or the universe is much older than we think)

- need for dark matter :
    missing elements in the spectrum of stable particles
        (or modified gravity at galaxy/galaxy cluster scale)

- dark energy :
    evidence for a non null but tiny vacuum energy
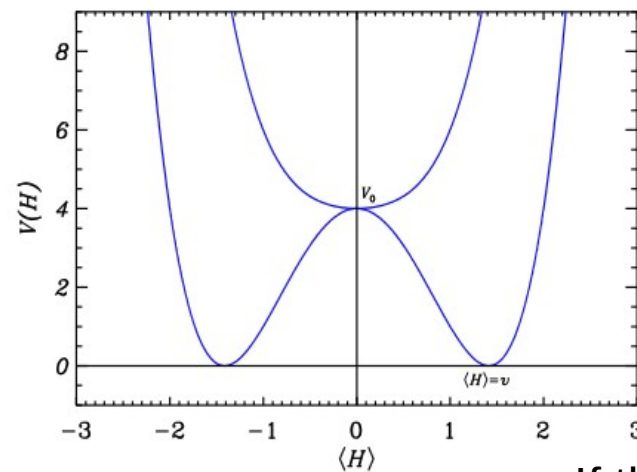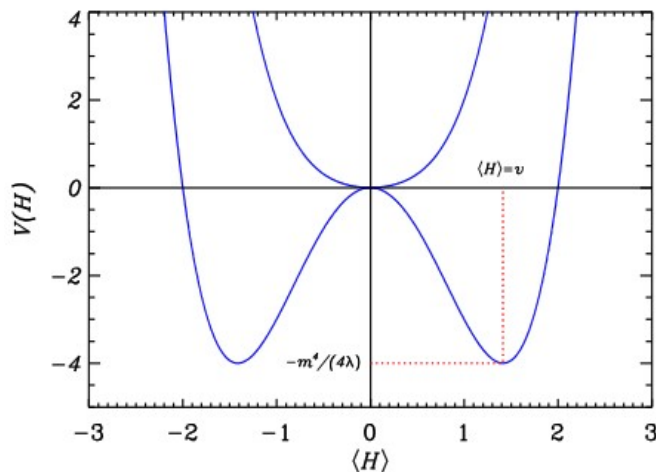   (or just a cosmological constant, but then why?)

Dark Energy puzzle

Energy scale : $\Omega_\Lambda \sim 0.7 \rightarrow \rho_\Lambda \sim \left(10^{-3} eV\right)^4$

when the natural energy scale between quantum physics and gravitation is the Planck mass :

$$m_P = \sqrt{\frac{\bar{h}c}{G}} \rightarrow \rho_P \sim \left(10^{19} GeV\right)^4$$

Also, why wouldn't particle physics fields weight like any other source of energy ?
One example : the Higgs potential

$$V(\phi_{\min}) = -\frac{1}{4}m_H^2 v^2 = -\frac{\sqrt{2}}{16}\frac{m_H^2}{G_F^2} \simeq -1.2 \times 10^8 \text{ GeV}^4$$

If the Higgs field contributes to gravity, a mechanism is needed to tune its potential to :

$$\rho = \dot{Q}^2/2 + V(Q)$$
$$p = \dot{Q}^2/2 - V(Q)$$

$$\rho_{Higgs} \sim \left(10^2 GeV\right)^4$$

$$10^{-56}!$$

Cosmological signatures of Dark Energy

- Dark energy only observed on cosmological scales

- We obviously have to further confirm its observational signature.
  Seen as an extra source of energy we have to test :

     - its time evolution : expansion rate of the universe

     - its spacial homogeneity : clustering

     - across a large redshift range

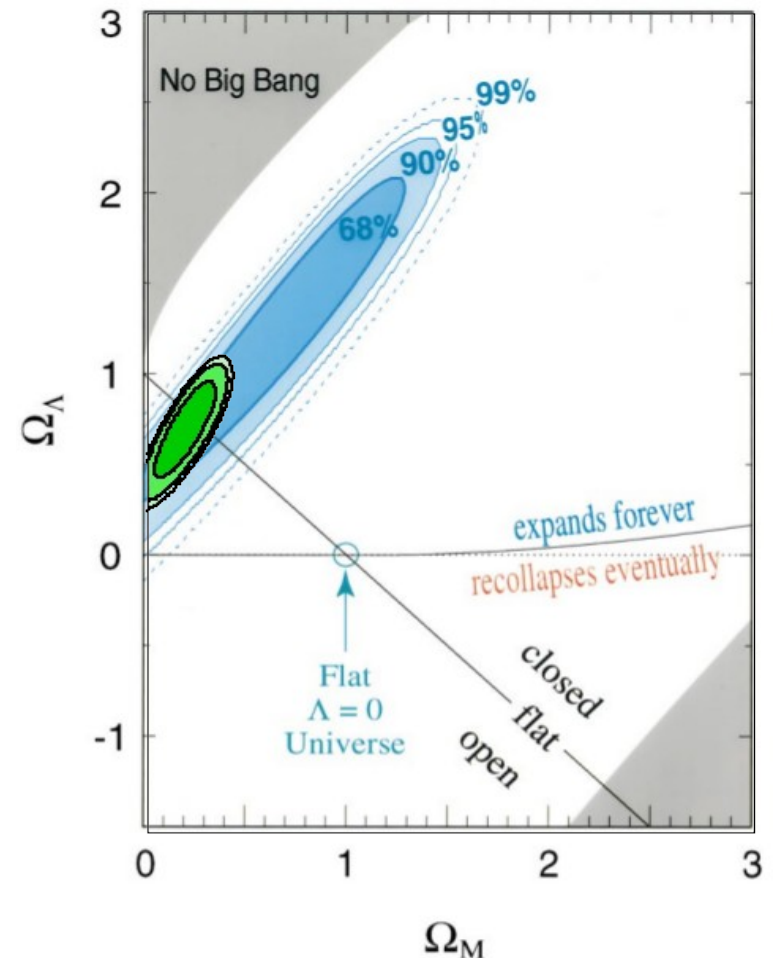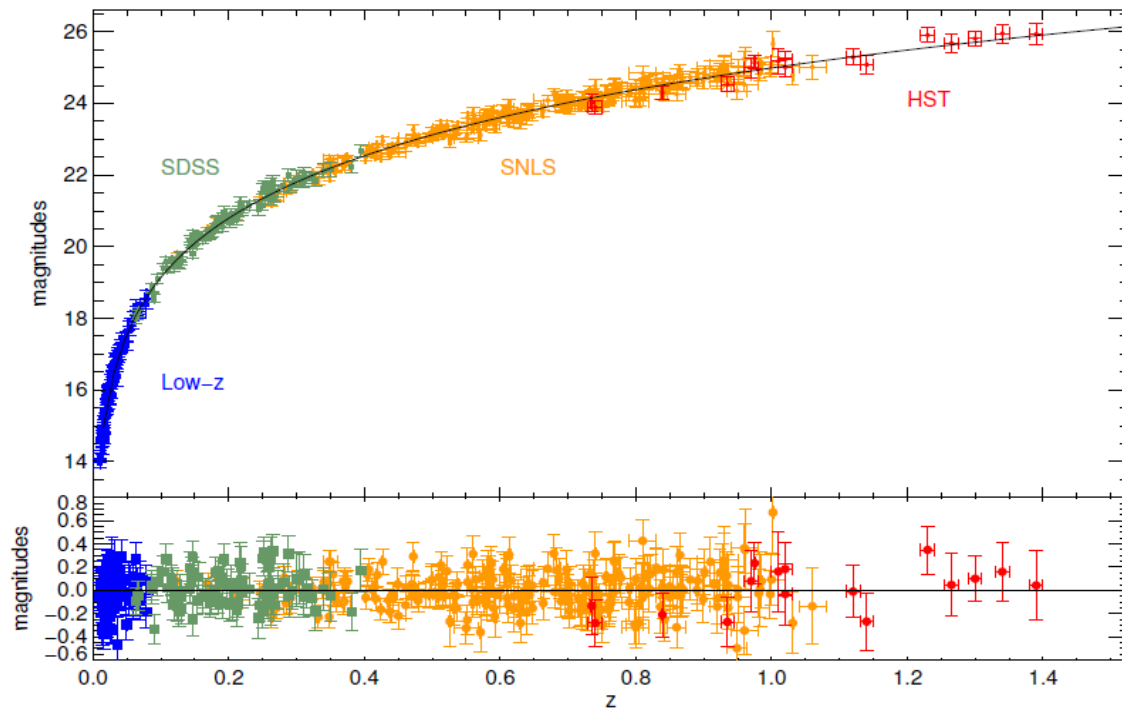- and we might have some surprises ...

Cosmological signatures of Dark Energy

- The dark energy puzzle started with the discovery of the acceleration
of expansion in 1998, in this Lab (and another team), with Type Ia supernovae
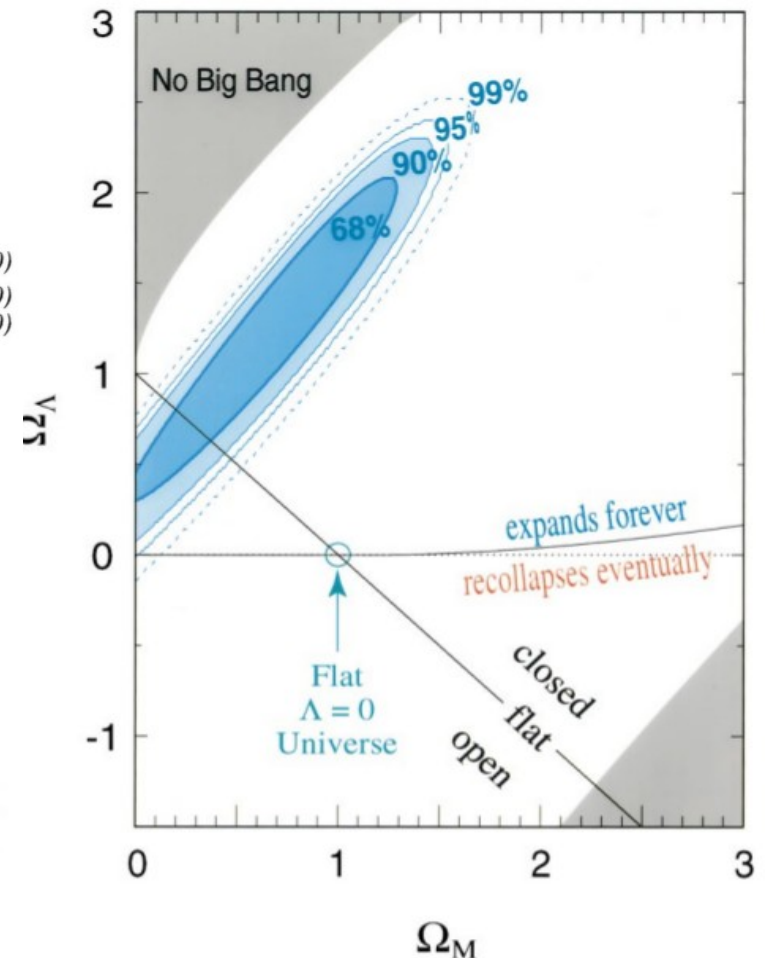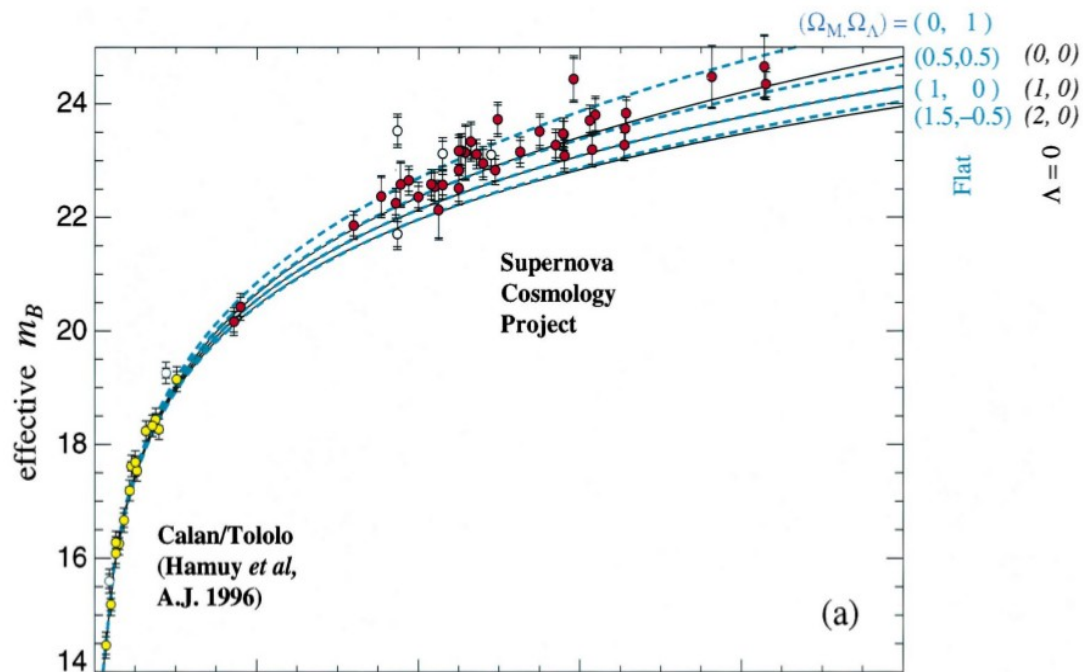
Cosmological signatures of Dark Energy

- The dark energy puzzle emerged with the discovery of the acceleration
of expansion in 1998, in this Lab (and another team), with Type Ia supernovae

- It was confirmed/refined over the years, still with Type Ia supernovae
   (for instance SNLS3, 2010)

Cosmological signatures of Dark Energy

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- Its was confirmed/refined over the years still with Type Ia supernovae
    (for instance SNLS3, 2010)

- But the most convincing confirmation was
    probably the discovery of Baryon Acoustic
    Oscillations (BAO) with SDSS in 2005
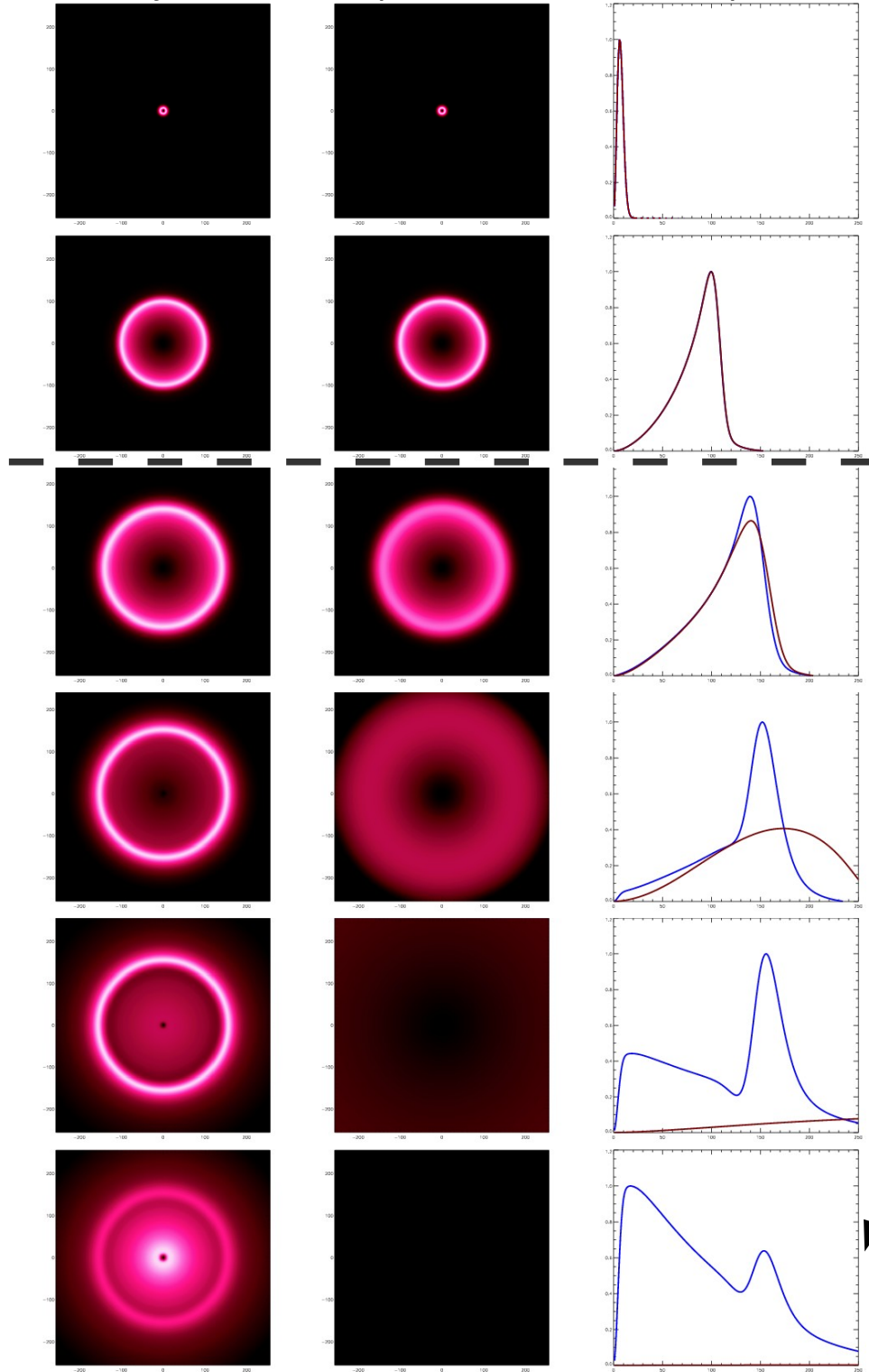   (here combined constraints with SNe, in 2006)
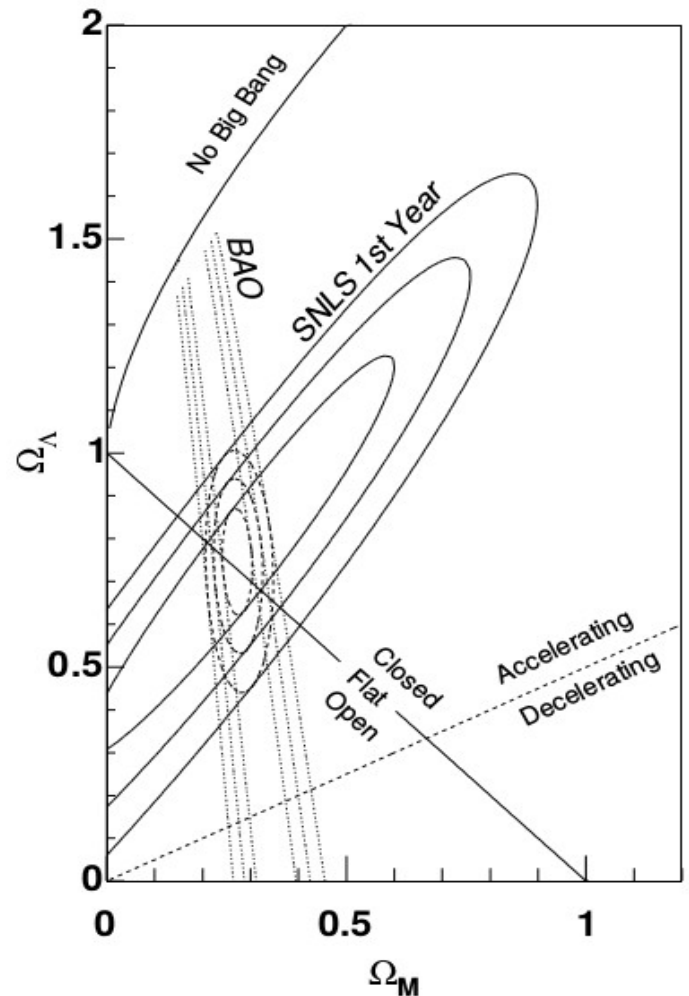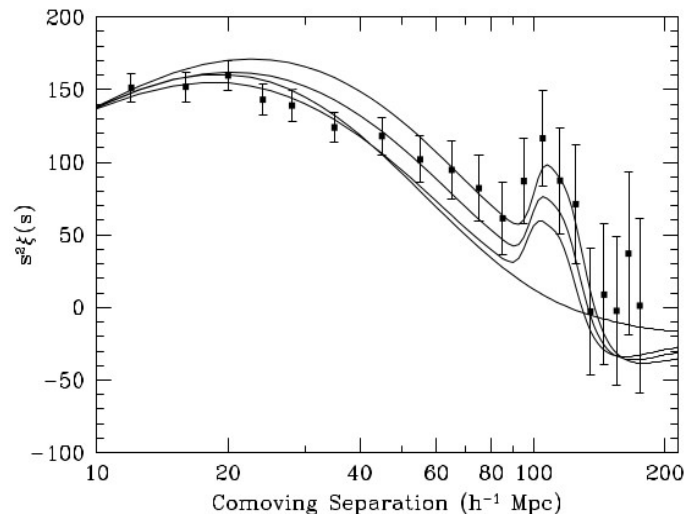
baryons   photons   mass profile
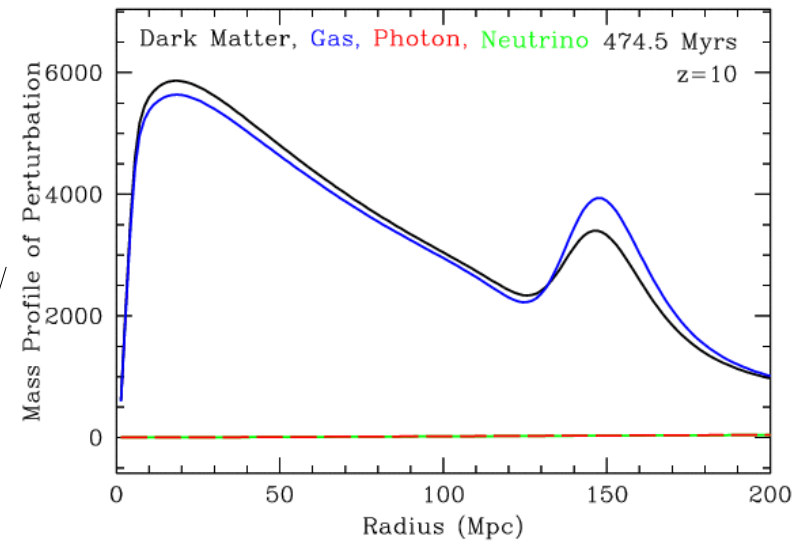
Baryon Acoustic Oscillations (BAO)

- plasma sound wave frozen at recombination
- finite propagation time
- distance = f(sound speed, expansion, recombination time)

recombination (p+e -> H)

Dark Matter, Gas, Photon, Neutrino   474.5 Myrs
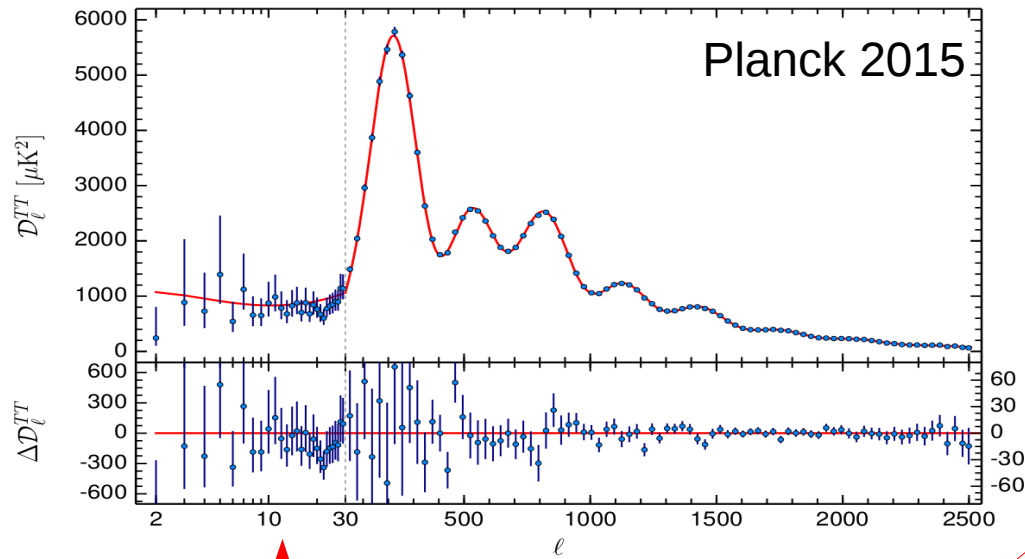z=10

Mass Profile of Perturbation
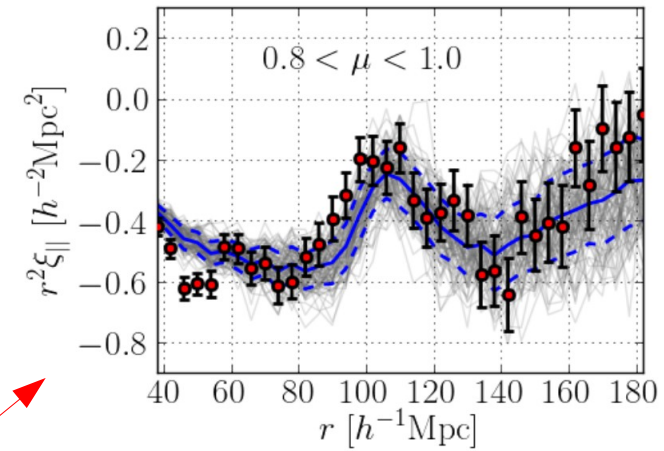
Radius (Mpc)

Correlation peak at r~150 Mpc
(in co-mobile coordinates)

(from M. White, D. Eisenstein)

Baryon Acoustic Oscillations

in the CMB at z~1000

in Lyman-alpha forests at z ~ 2.3

Planck 2015

$0.8 < \mu < 1.0$

in the galaxy density field

z~0.6

BOSS DR11
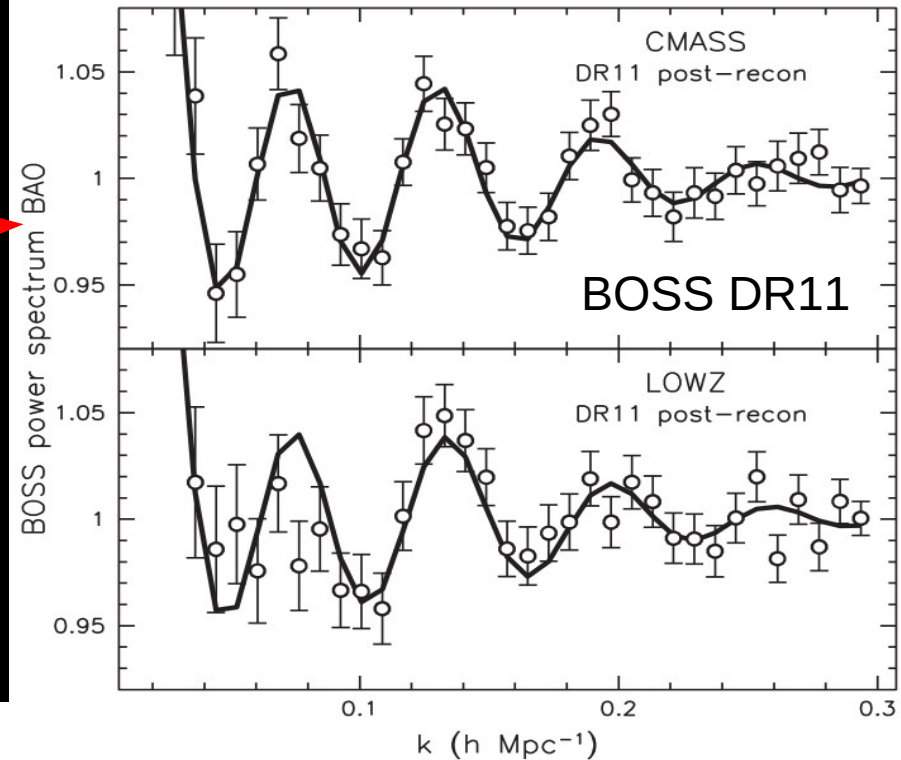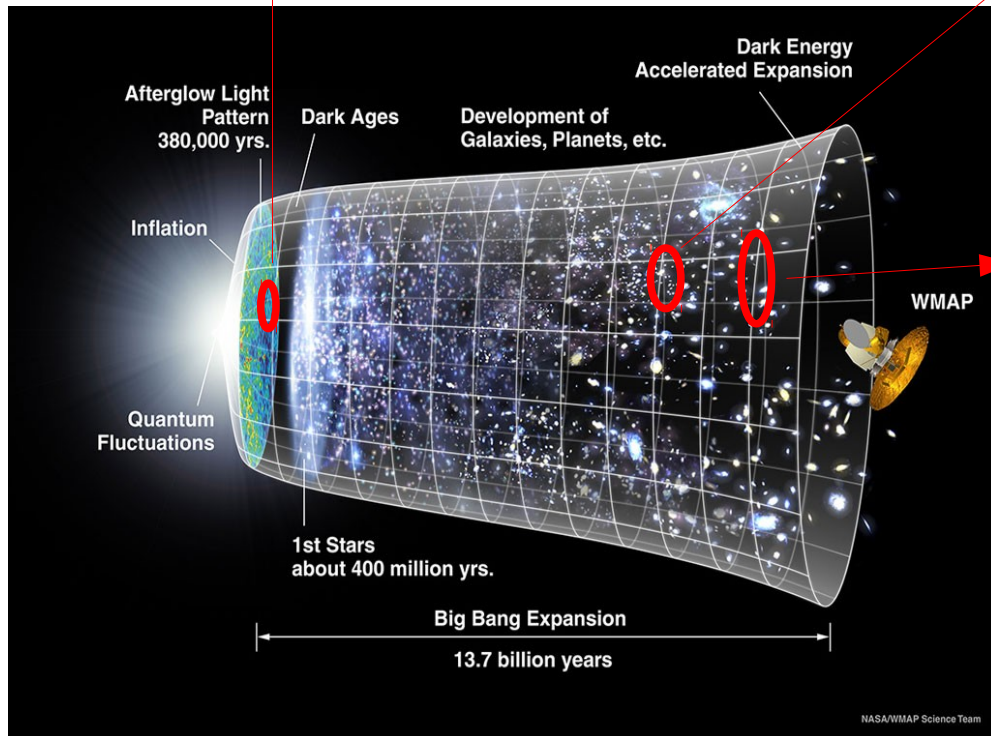
z~0.2

Baryon Acoustic Oscillations

r ~ 150 Mpc : cosmological probe

2 measurement
- angular (transverse)
- redshift (radial)

$$\delta r_{\parallel} = (c/H)\delta z$$

δz

$\delta \Theta$

$$\delta r_{\perp} = (D_a)\delta \Theta$$

$r^2 \xi_{\parallel}(r)$

$\alpha_{\parallel} = 1.026 \pm 0.080$

$r(h^{-1}\,\mathrm{Mpc})$

$r^2 \xi_{\perp}(r)$

× × Data
— Model

$\alpha_{\perp} = 1.020 \pm 0.031$
$\chi^2 = 54.700/66$ dof

$r(h^{-1}\,\mathrm{Mpc})$
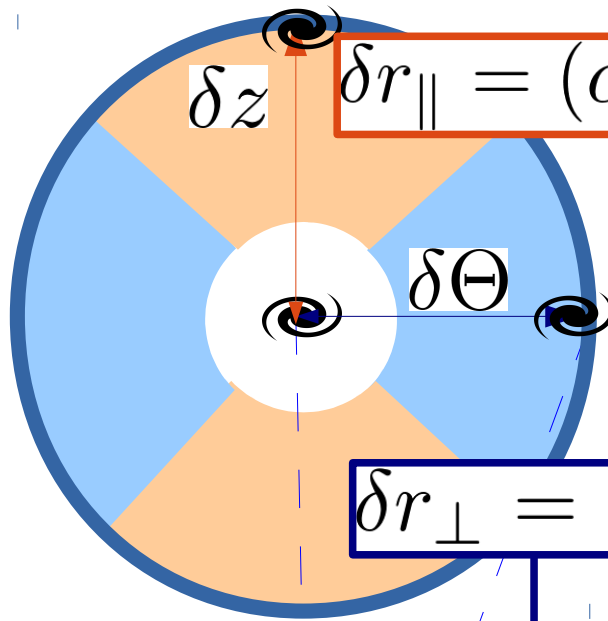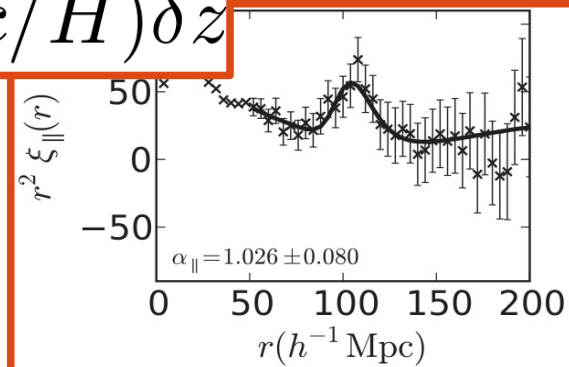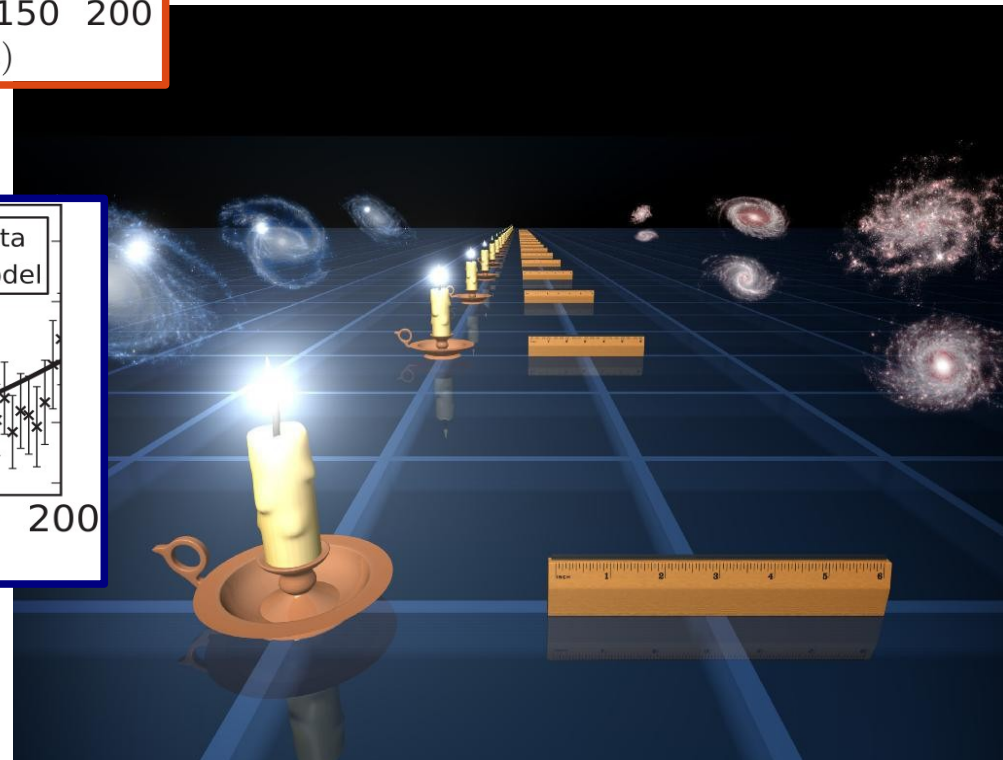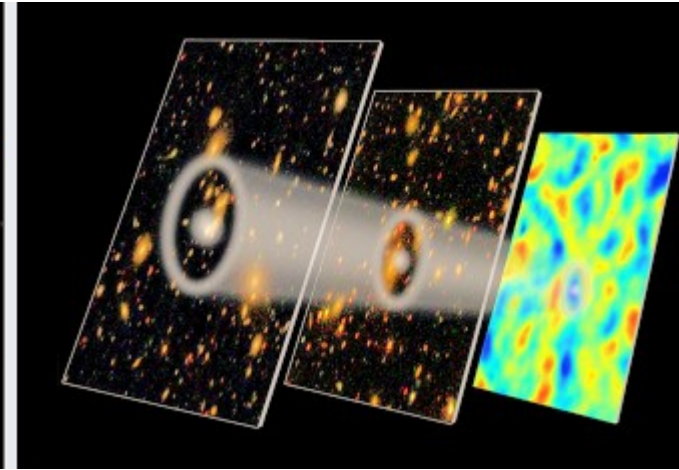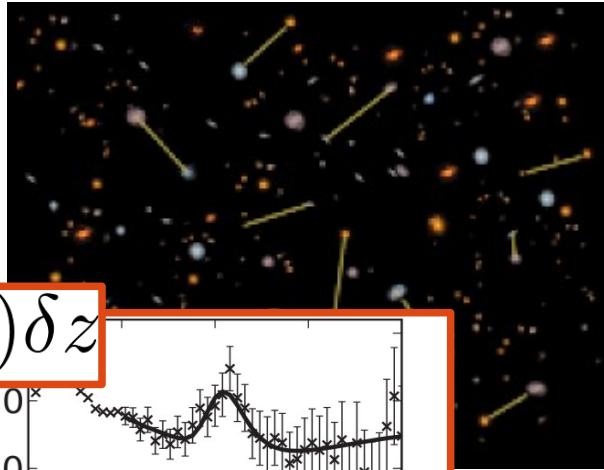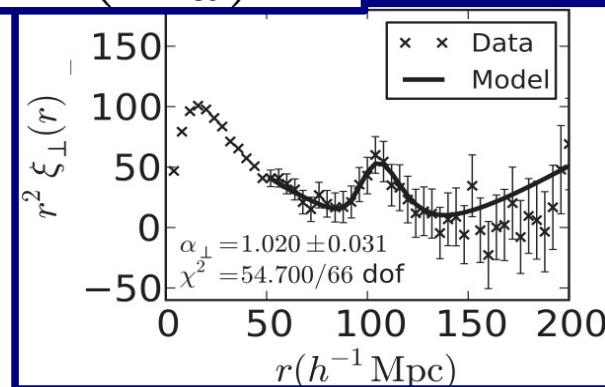
observateur

Lyman-alpha forst
Neutral H Absorption along the line of sight of distant quasars

$$\lambda_{Ly\alpha} = 121 \,\mathrm{nm}$$

$$\lambda_{obs} = (1 + z)\lambda_{Ly\alpha}$$

Flux

$\lambda \rightarrow$

3C 273 $z=0.158$

Intensity

Emitted wavelength, Å

Q1422+2309 $z=3.62$

Intensity

Emitted wavelength, Å
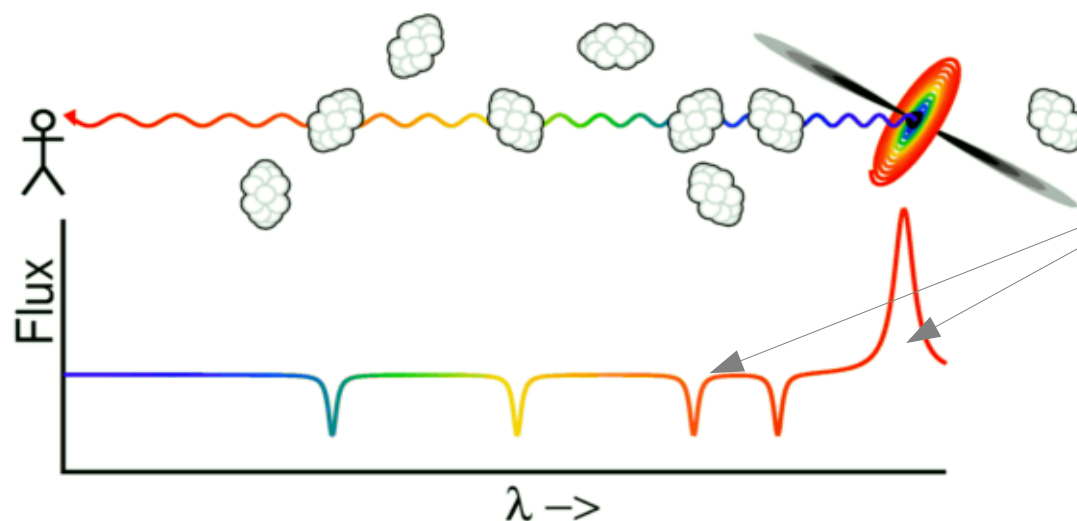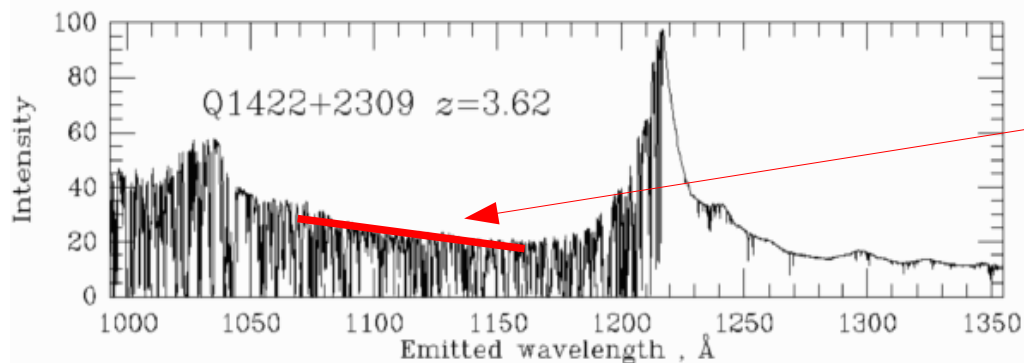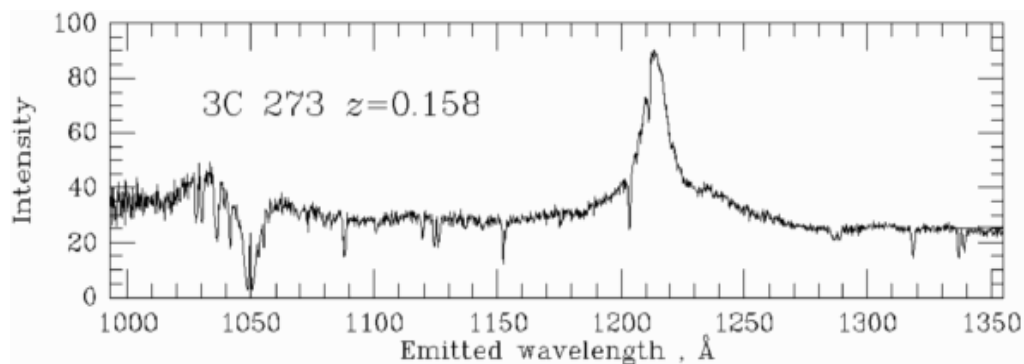
"Flux decrement":

$$F(\lambda) \equiv \frac{f(\lambda)}{Continuum(\lambda)} = e^{-\tau(n_{HI})}$$

$$\delta_F(\lambda) = \frac{F(\lambda)}{\bar{F}(\lambda)} - 1$$

Lyman-alpha auto-correlation function

Delubac et al. 2014
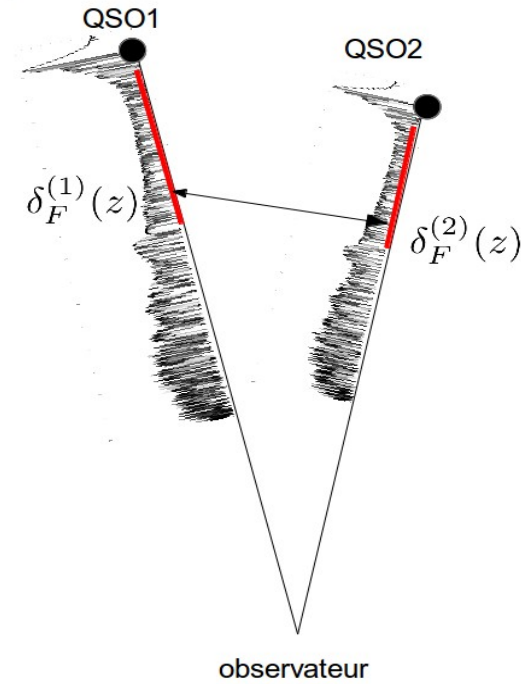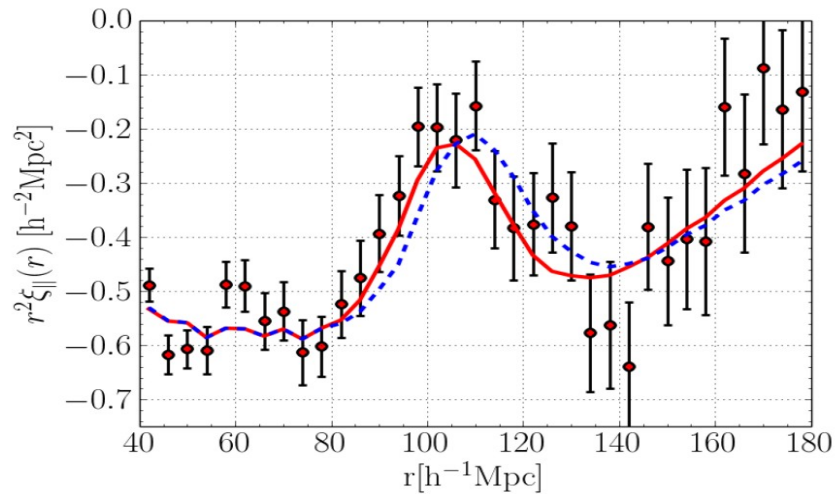
$$\xi(r_{\parallel}, r_{\perp}) = \langle \delta_1 \delta_2 \rangle_{(\Delta r_{1,2} \in r\, bin)}$$
$$(\theta_{12}, z_1, z_2) \to (r_{\perp}, r_{\parallel})$$

QSO Lyman-alpha cross-correlation

Font-Ribera et al 2014
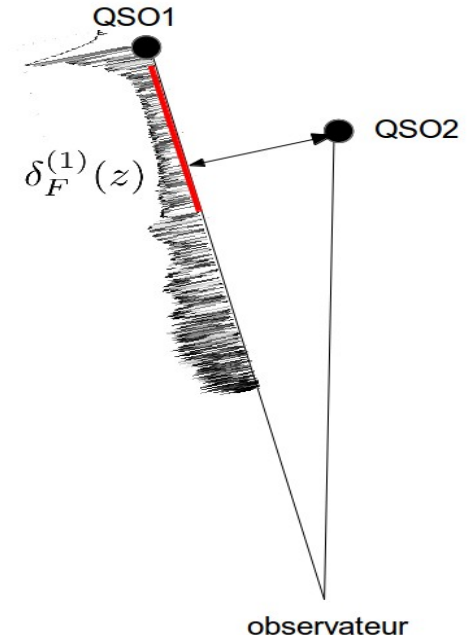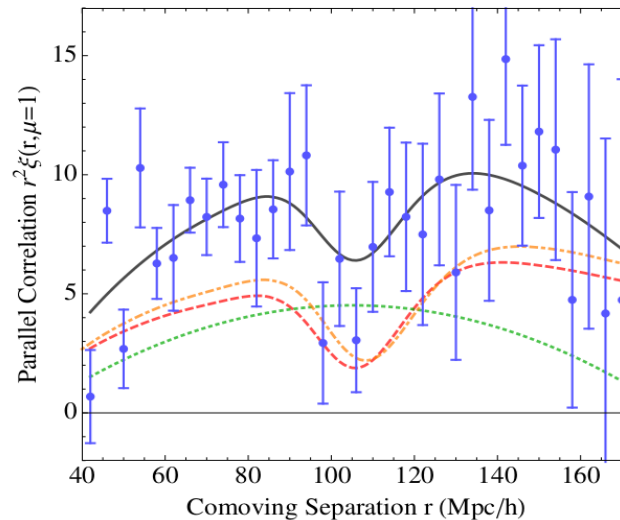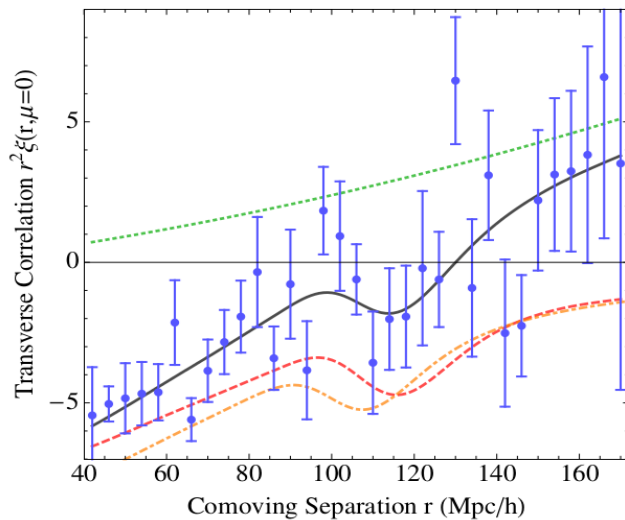
SDSS3/BOSS DR11 results (90% of the data)

$$\alpha_\perp \equiv [D_A/r_d].[r_d/D_A]_{fid}$$
$$\alpha_\parallel \equiv [1/(r_dH)][r_dH]_{fid}$$

statistical uncertainties $\quad (\alpha_{iso} = f(\alpha_\perp, \alpha_\parallel))$

BOSS DR11 sub-sample	z	α_{iso}	$\alpha_\perp$	$\alpha_\parallel$	$corr(\alpha_\perp, \alpha_\parallel)$
BOSS LOWZ sample	0.32	0.020	...	...	....
BOSS CMASS sample	0.57	0.010	0.014	0.035	-0.52
LyaF auto-correlation	2.34	0.021	0.055	0.031	-0.43
LyaF-QSO cross correlation	2.36	0.019	0.037	0.033	-0.39
Combined LyaF	2.34	0.013	0.032	0.022	-0.48
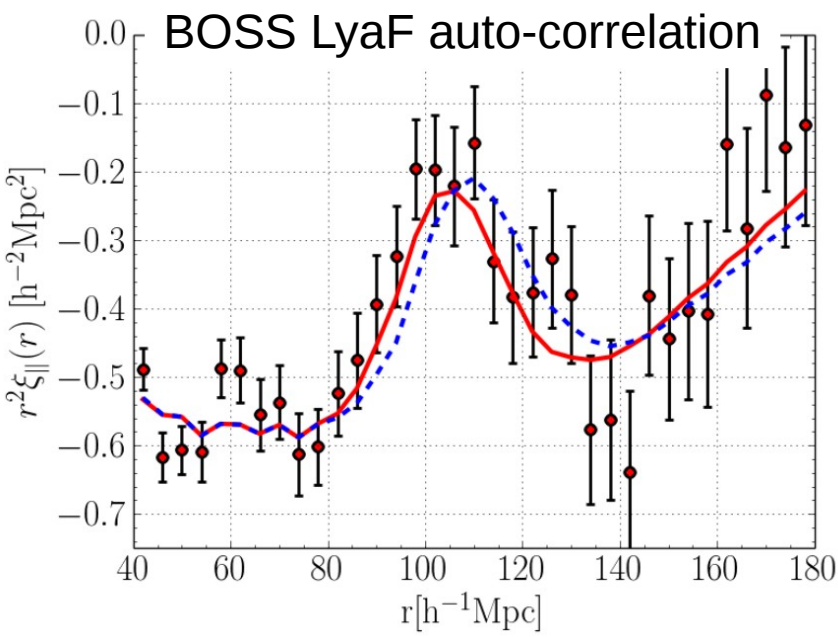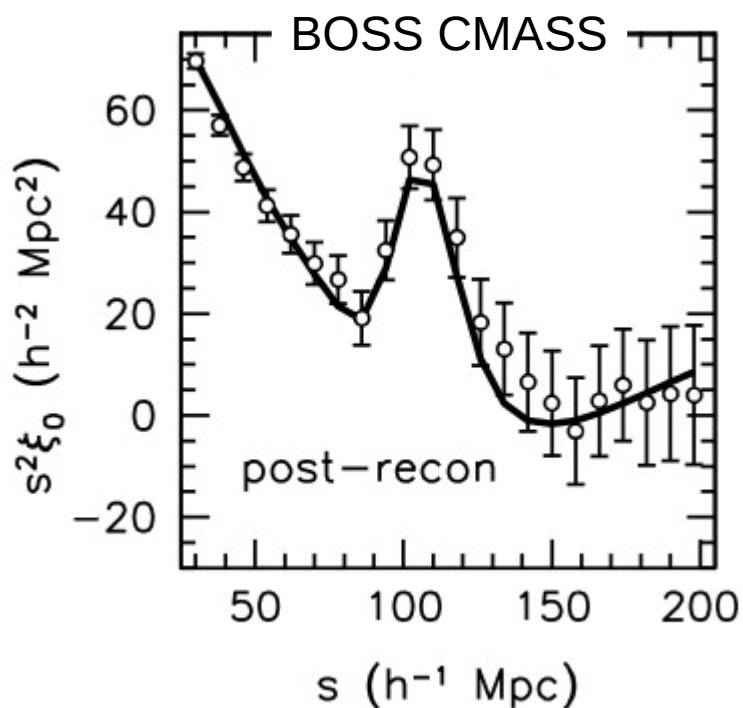
BOSS CMASS

BOSS LyaF auto-correlation

The most convincing confirmation of Dark Energy is from BAO because
BAO have low systematic uncertainties

Instrumental/observation systematics :
Measurement of a correlation peak
in an angular distribution and in redshifts

- For galaxies , it's about variations across the sky of :
    - Targeting efficiency
    - Fiber assignment efficiency (fiber collisions for BOSS,
                                    for close galaxies)
    - Redshift efficiency

    - For BOSS, the associated uncertainty on the BAO peak position is **negligible ~ 0.1%**
        (Ross 2012, Anderson 2012)

- For Lyman-alpha forests :
    - Several sources of correlated intrumental noise in the spectra :
        calibration errors , sky spectrum model noise

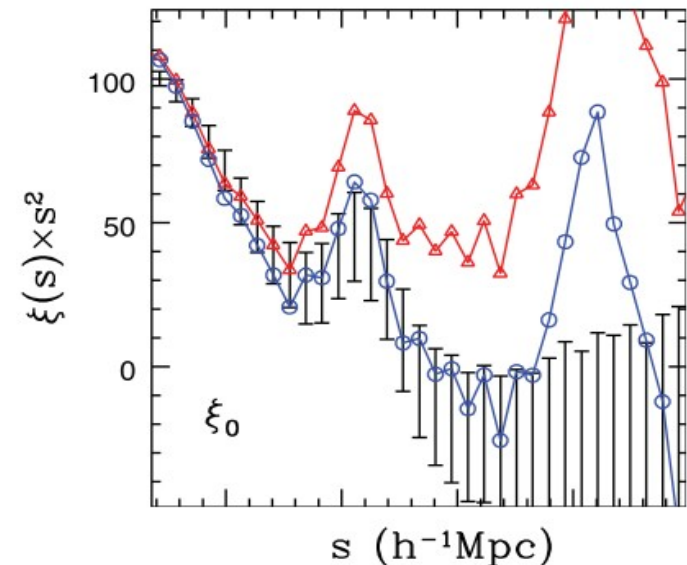|	$\Delta\beta$	$\Delta(1+\beta)\times b$	$\Delta\alpha_{\parallel}$	$\Delta\alpha_{\perp}$
Stat.	± 0.400	± 0.027	± 0.026	± 0.045
Sky model noise	-0.139 ± 0.011	$+0.002 \pm 0.001$	< 0.001	-0.002 ± 0.0003
Sky systematic residuals	$+0.090 \pm 0.191$	$+0.002 \pm 0.009$	-0.005 ± 0.005	$+0.006 \pm 0.008$
Calibration noise	$+0.128 \pm 0.010$	-0.002 ± 0.0004	< 0.001	$+0.002 \pm 0.0003$
Fiber cross-talk	$+0.003$	< 0.001	< 0.001	< 0.001
ISM absorption	-0.036 ± 0.015	$+0.002 \pm 0.001$	< 0.001	< 0.001
Total (with sky residuals)	$+0.047 \pm 0.192$	$+0.004 \pm 0.010$	-0.005 ± 0.005	$+0.006 \pm 0.008$
Total (without sky residuals)	$+-0.043 \pm 0.021$	$+0.002 \pm 0.001$	< 0.001	< 0.001

The most convincing confirmation of Dark Energy is from BAO because

BAO have low systematic uncertainties

Physical interpretation systematics :

- BAO scale accurately constrained by CMB
  and 1st order perturbation physics
  (we know the successes of Planck)

- For galaxies, **weak impact of non-linear clustering**
on the measurement of the peak, here illustrated
with BOSS results before/after "reconstruction".
  0.3% correction to the peak position

- For Lyma-alpha, **negligible non-linear effects on BAO scale**
  (based on hydro simulations, McDonald 2006, Arinvo-i-Prats 2015)

But : **contamination of the signal** by :
- other atomic transitions (Si III, Si II),
  and to a lesser extent (SiIV, CIV)
  (visible peaks at 25Mpc/h, 60Mpc/h,
  hidden peak at ~100Mpc/h(!))
- High column density / damped Lyman-alpha
  systems (Font-Ribera 2012)
- UV background / ionization fraction fluctuations
  (Gontcho a Gontcho 2014)
  <1% systematic on BAO peak (preliminary)
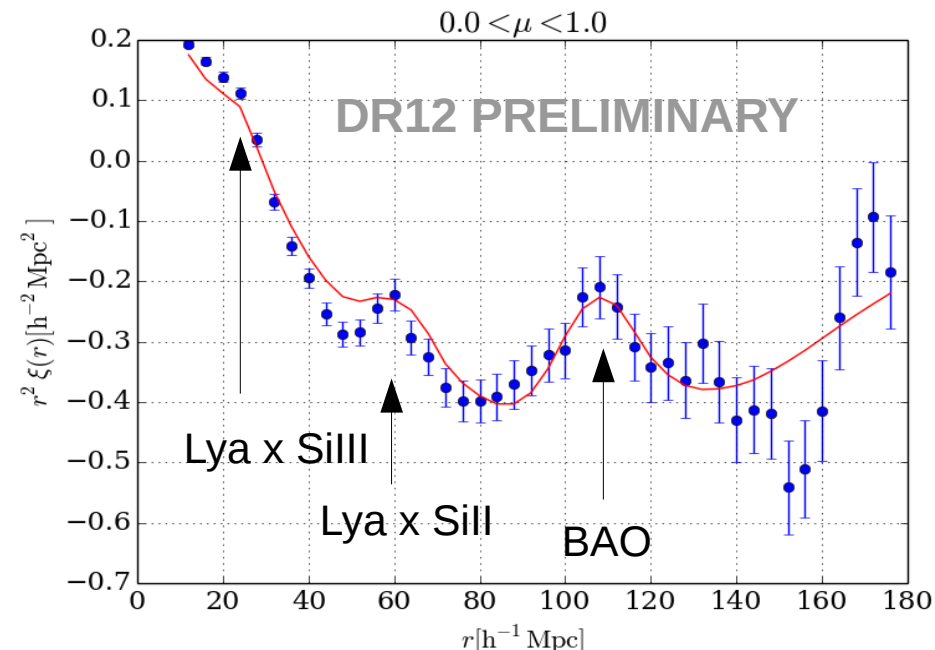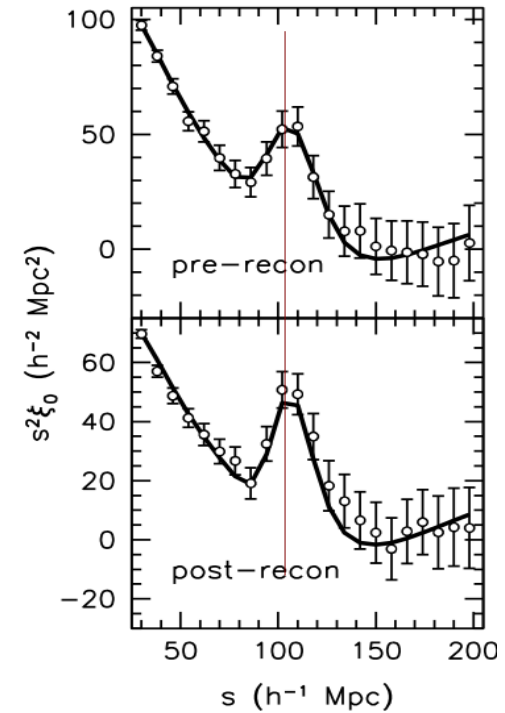
Where do we stand today, with another perspective on the data

Constraints on a model with free $\Omega_m, \Omega_k, w_0, w_a$
BOSS DR11 (90% des données) + SNe (Betoule 2014) + Planck (1st release)
(Da(z) and Dv(z) are graphically represented by an effective measurement of H(z'<z))

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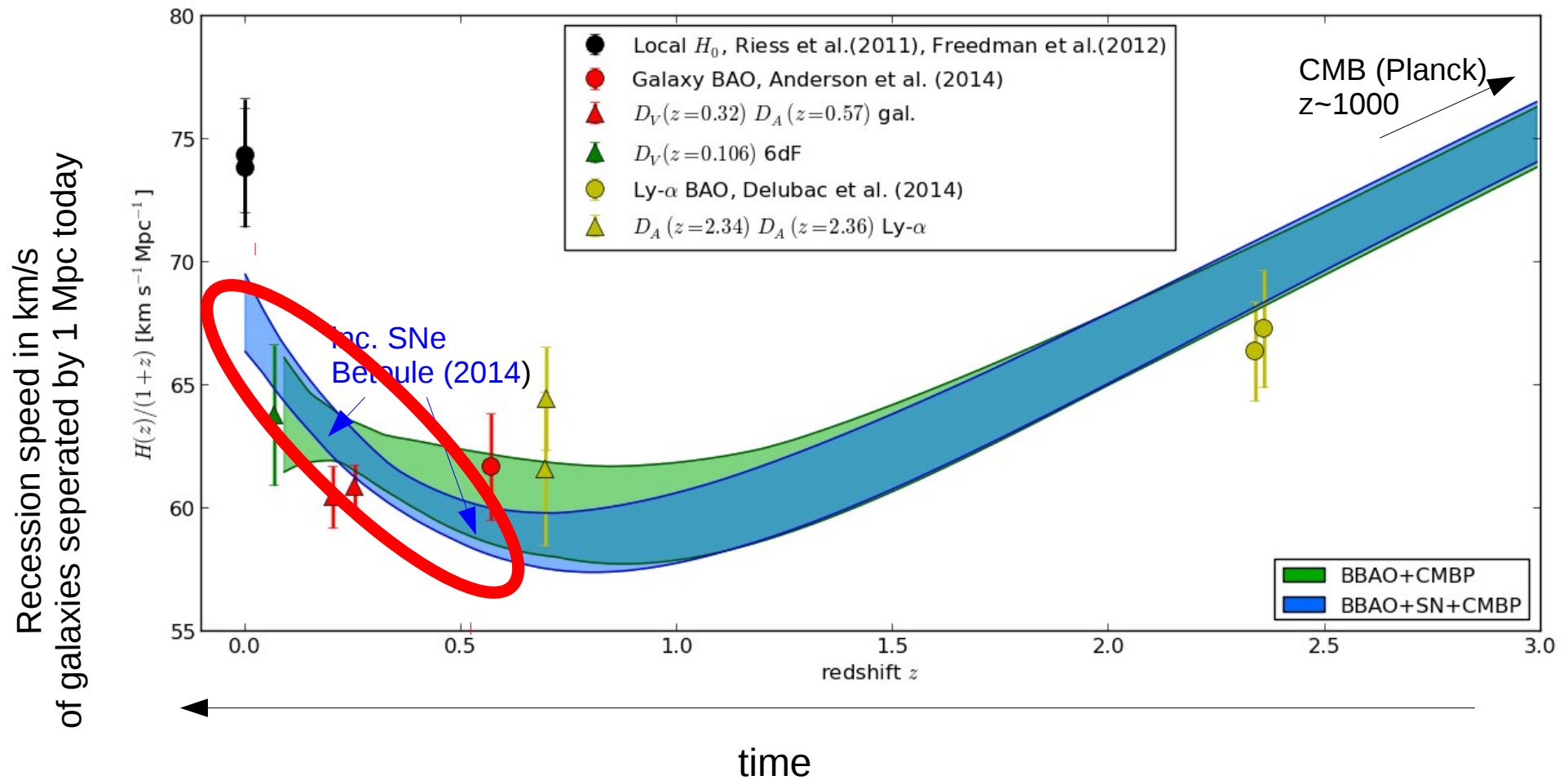
Confirmation of accelerated of expansion with BAO+CMB
discovered with SNe Ia

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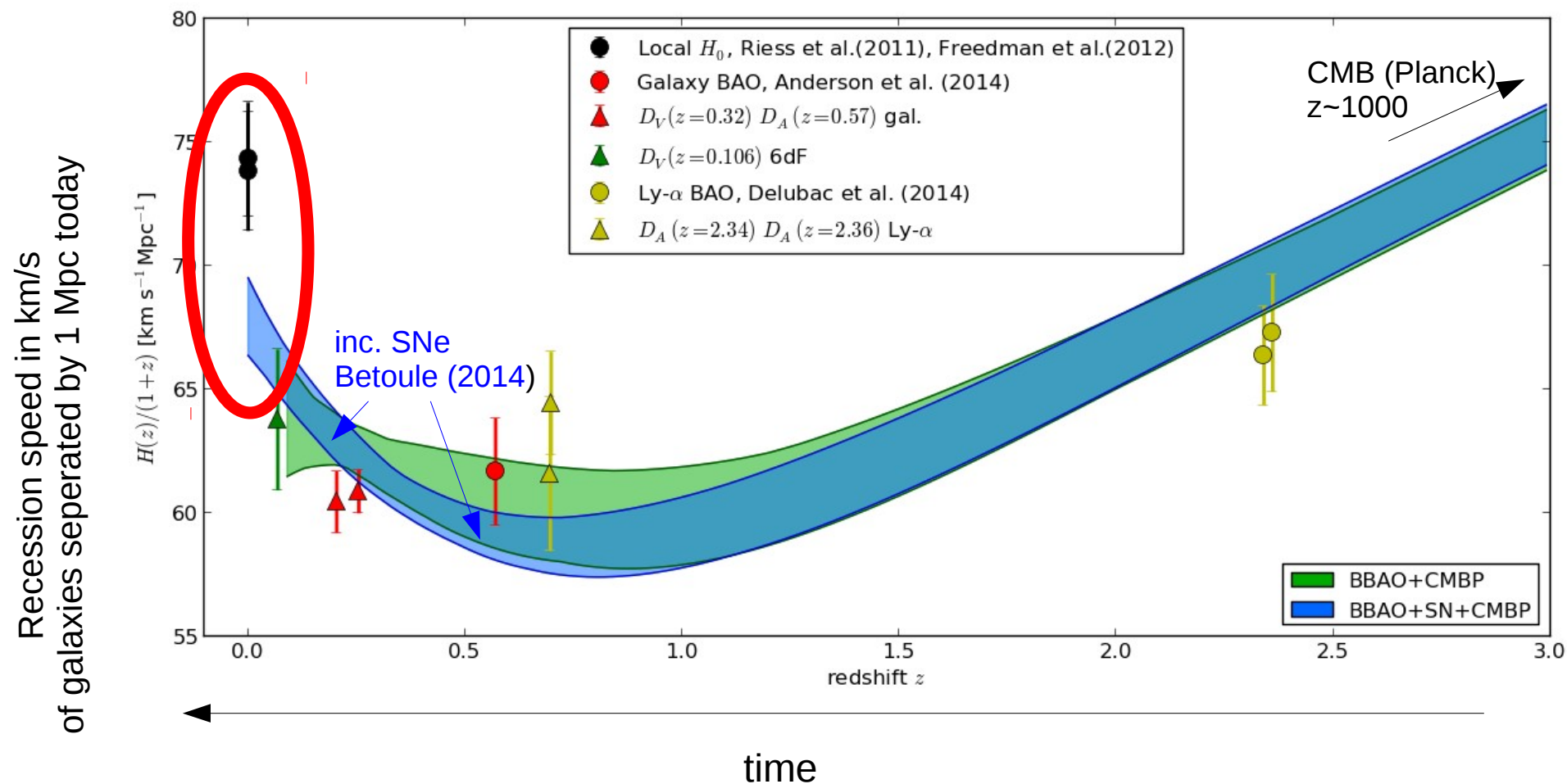
Inverse distance ladder measurement of H0 in tension with
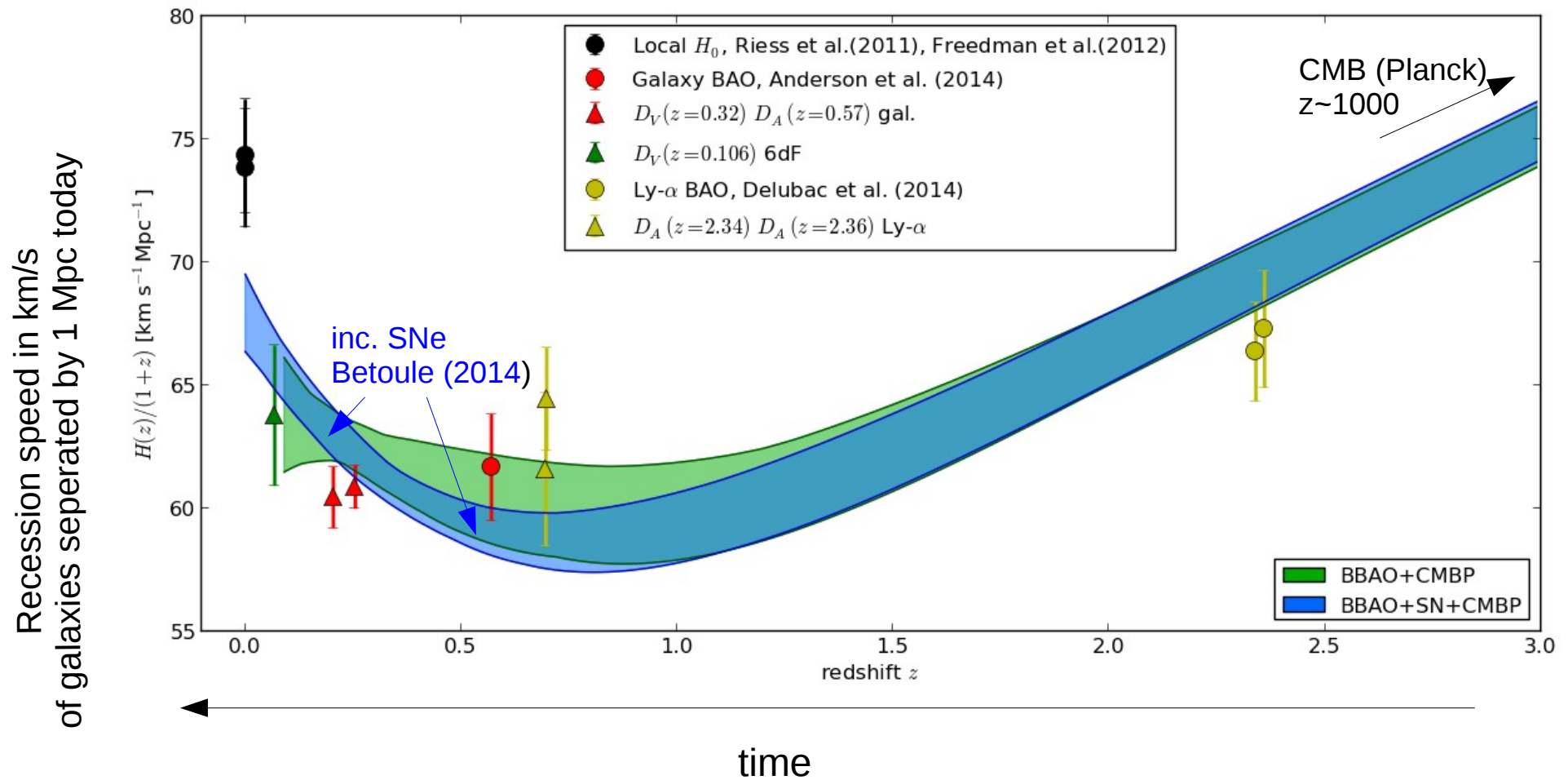standard distance ladder

Where do we stand today, with another perspective on the data

Constraints on a model with free $\Omega_m, \Omega_k, w_0, w_a$
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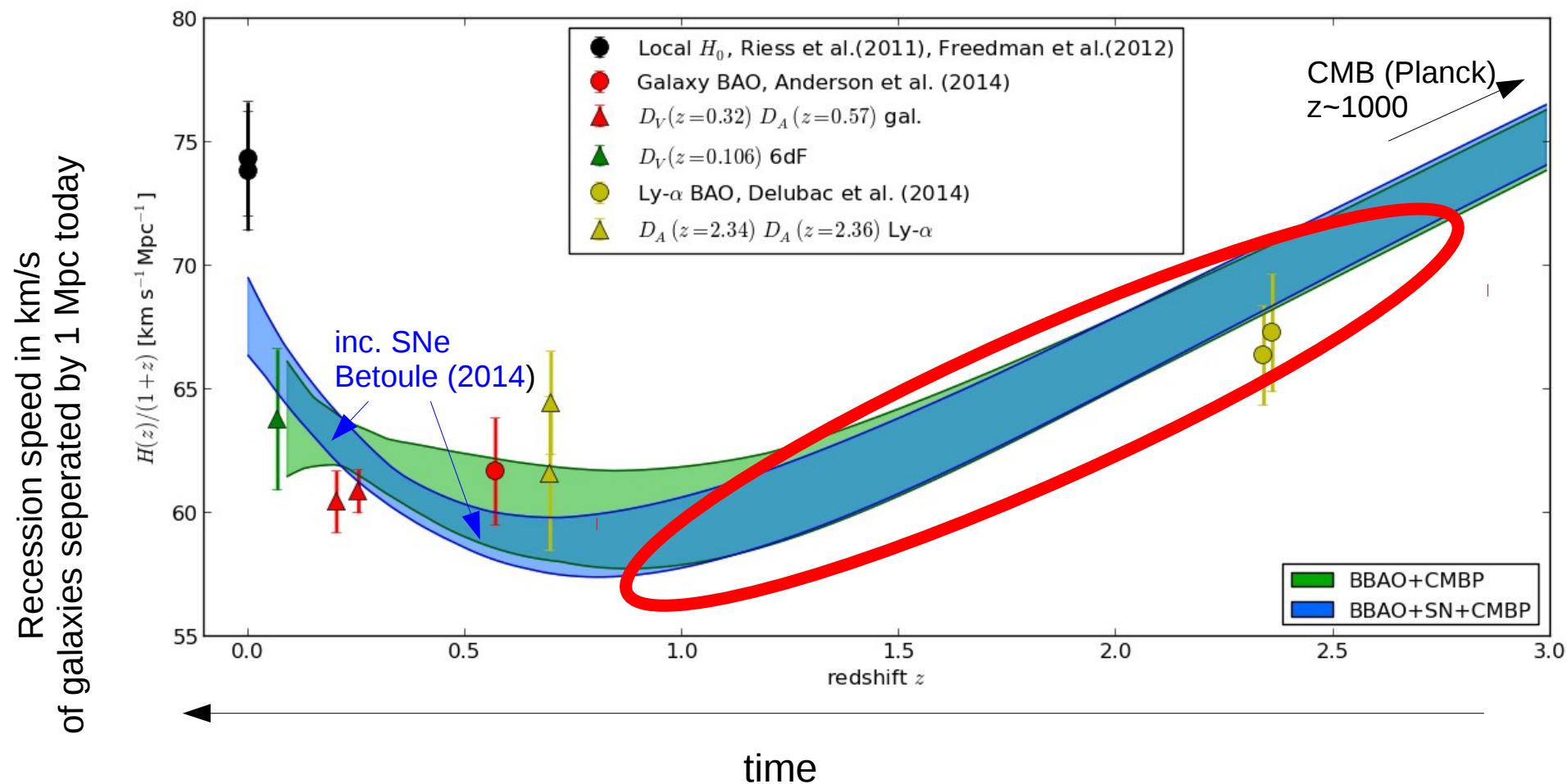
Test of cosmological model in decelerated expansion with Lyman-alpha forests

Constraints on H(z)
BOSS

Legend:
- Local H_0, Riess (2011), Freedman (2012)
- BOSS DR11 Galaxy Ly-α, Anderson (2014), Delubac (2015)

Supernovae (JLA)*

?

y-axis: Recession speed in km/s of galaxies seperated by 1 Mpc today — $H(z)/(1+z)$ [km s^{-1} Mpc^{-1}]

x-axis: redshift z

time
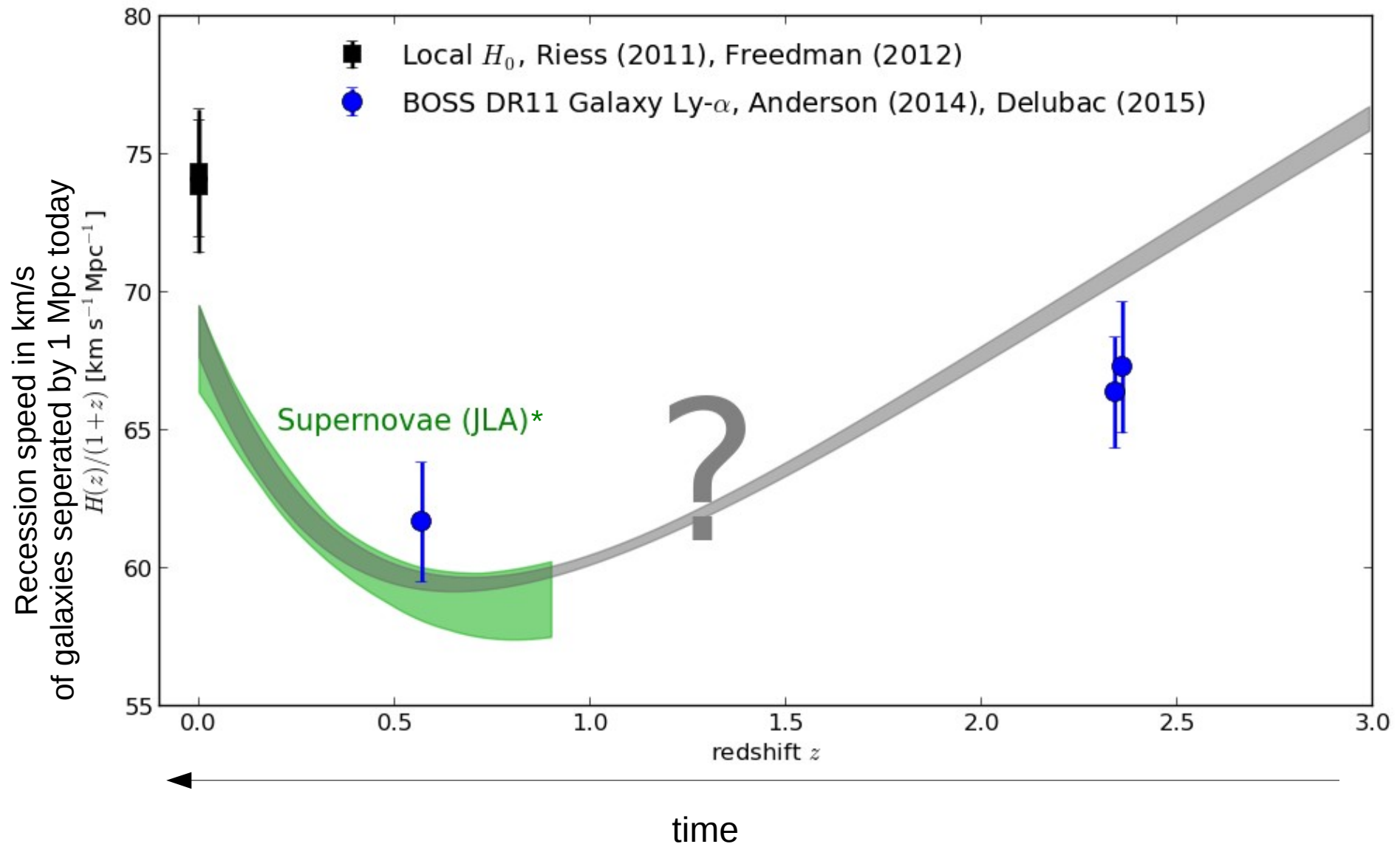
(*) Supernovae JLA, Betoule (2014), normalized with BAO+CMB, see Aubourg (2015)

Constraints on H(z)
BOSS+eBOSS
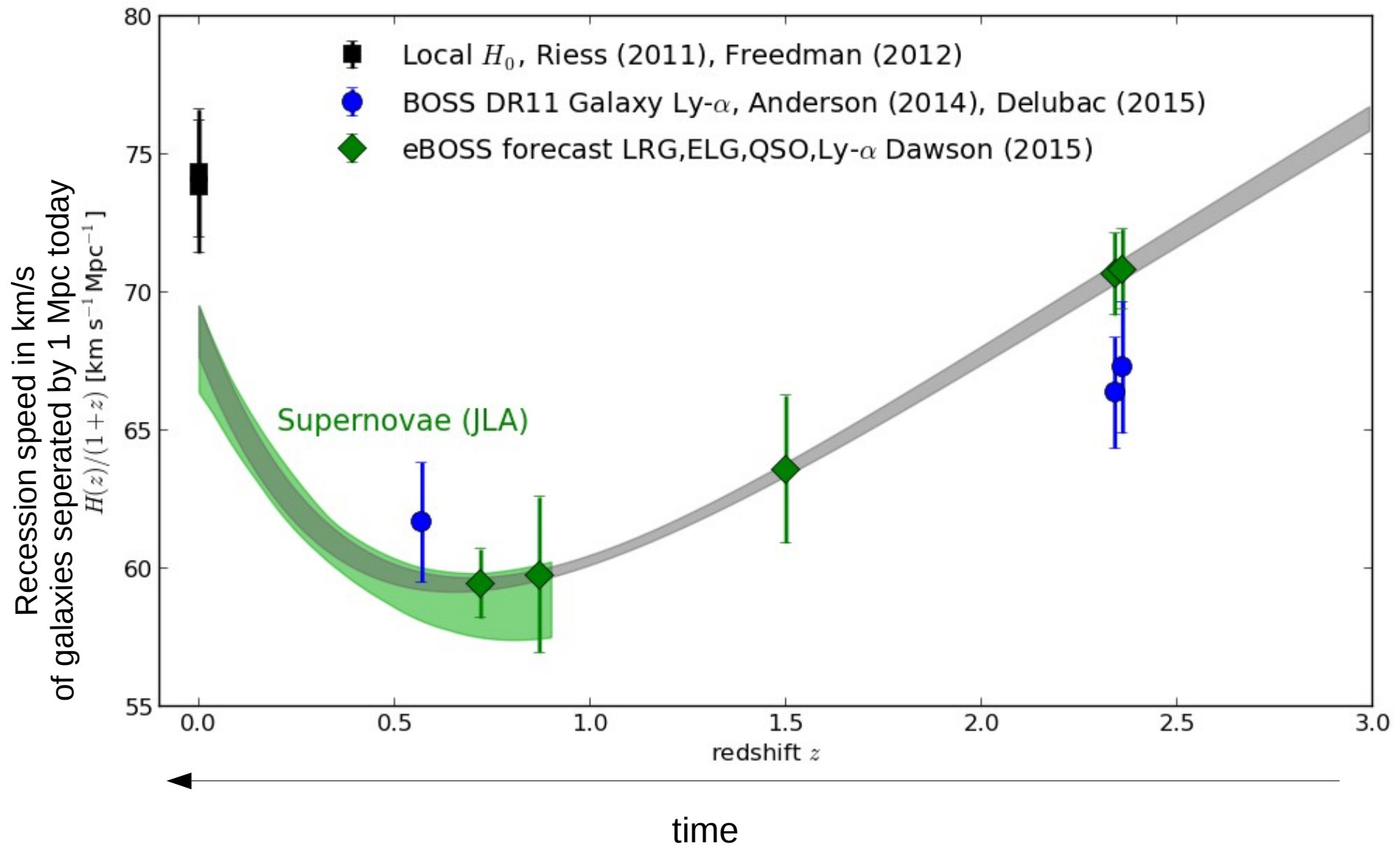
Constraints on H(z)
BOSS+eBOSS+DESI
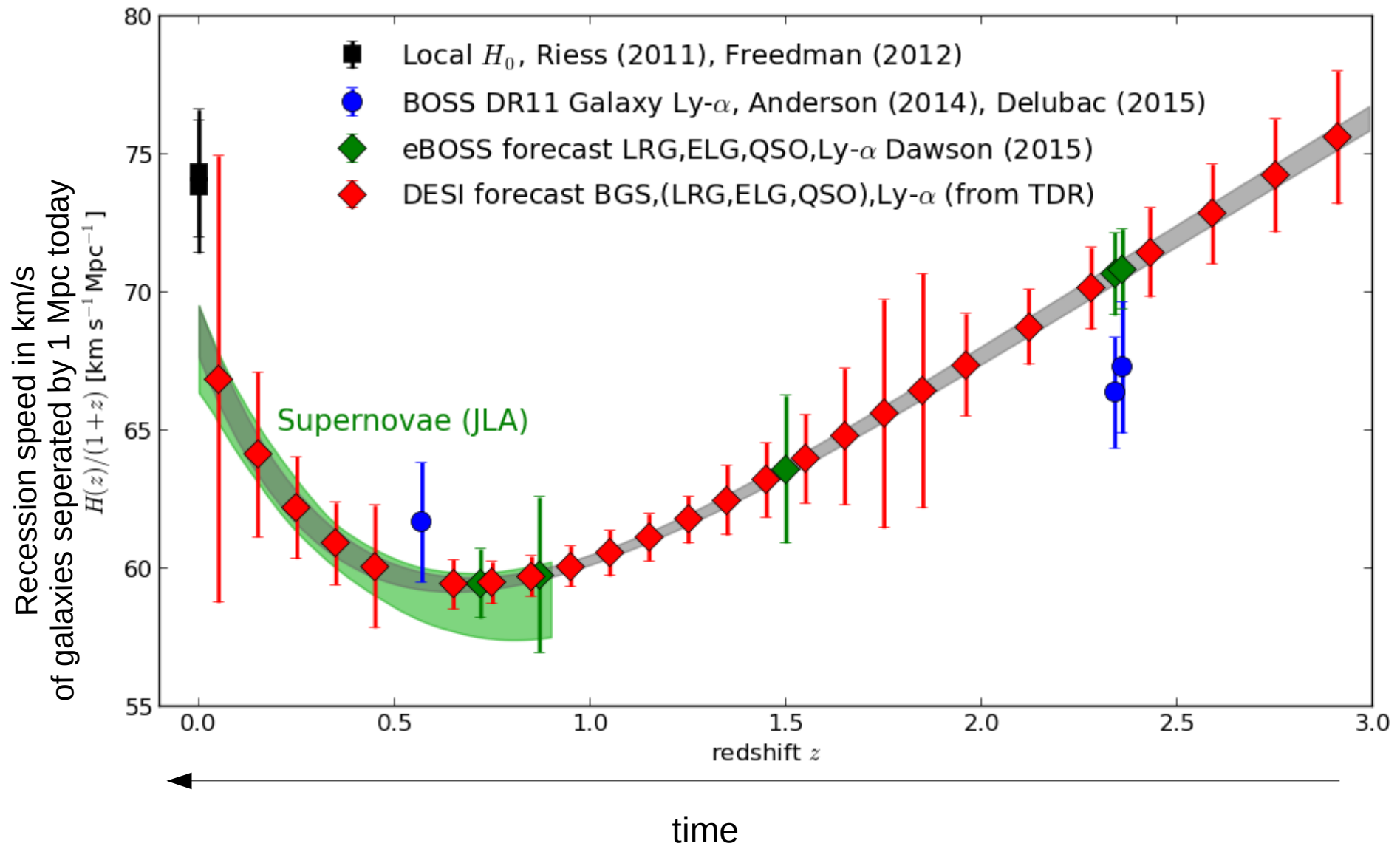
Dark Energy cosmology in the next decade (big projects)

- LSST
- Euclid
- DESI
- WFIRST?

- Supernovae :
    - have no competition so far to measure Dark Energy at z<0.5
    - it's getting harder and harder
        - fantastic requirement on photometric calibration (<~ 0.005 per band)
        - strong evidence for evolution of population with environment

- Lensing :
    - not proven yet (all measurements so far dominated by systematics)
    - need calibration of shear measurement biases
    - need calibration of photo-z
    - need detailed model of matter power spectrum at scales where
            baryonic physics contribute
            (very non-linear, complex radiative transfer / magneto-hydrodynamics)

- Baryon acoustic oscillations :
    - much smaller theoretical systematics
    - much smaller instrumental systematics
    - **need massive spectroscopic survey**

DESI spectroscopic survey 14000 deg2

SDSS ~2h^{-3}Gpc^3 ⟹ BOSS ~6h^{-3}Gpc^3 ⟹ DESI 50h^{-3}Gpc^3

2.4 million QSOs

z=4

z=3

17 million ELGs

z=2

z=1.5

z=1

4 million LRGs

z=0.7

z=0.5

10 million brightest galaxies

z=0.2

r=5.

r=4.0 Gpc/h

r=3.0 Gpc/h

r=2.0 Gpc/h

r=1.0 Gpc/h

r=0.5 Gpc/h
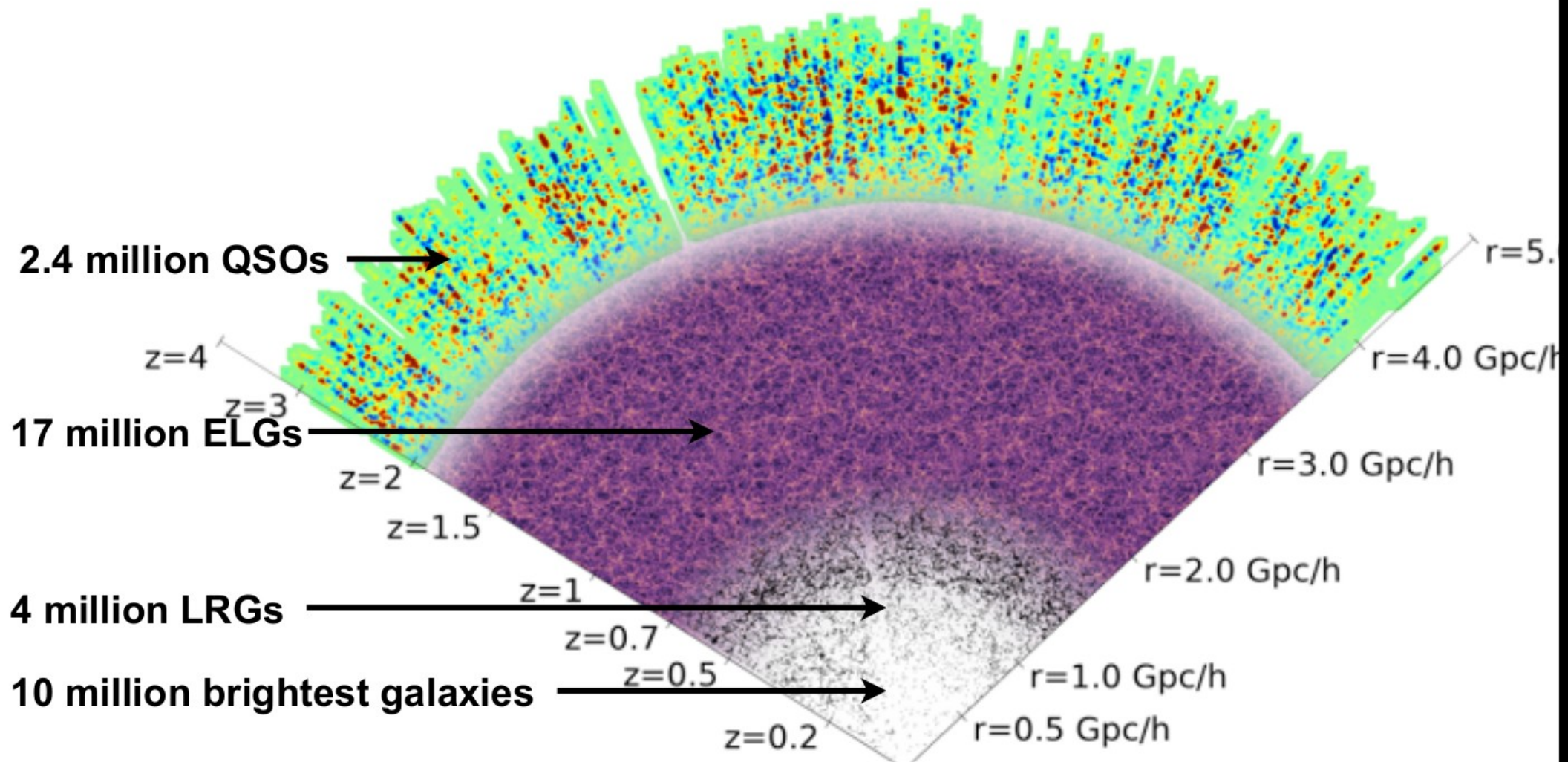
+ imaging survey :
   14000 deg2 in g,r,z at a depth of 24, 23.6, 23.0 mags

DESI forecast
(Technical Design report http://desi.lbl.gov/tdr)

Lyman-alpha (auto-correlation)

Galaxies (including QSOs)
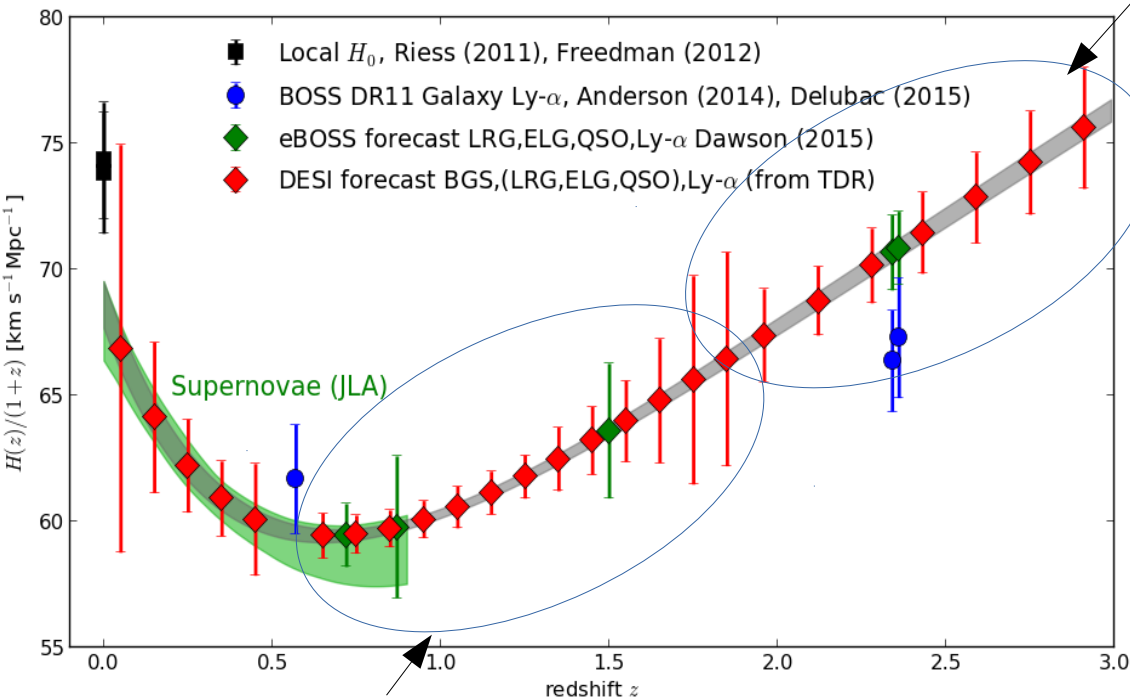
z	$\frac{\sigma_{R/s}}{R/s}$ (%)	$\frac{\sigma_{D_A/s}}{D_A/s}$ (%)	$\frac{\sigma_{Hs}}{Hs}$ (%)	$\frac{dN_{QSO}}{dz\,ddeg^2}$
1.96	1.43	2.69	2.74	82
2.12	1.02	1.95	1.99	69
2.28	1.09	2.18	2.11	53
2.43	1.20	2.46	2.26	43
2.59	1.34	2.86	2.47	37
2.75	1.53	3.40	2.76	31
2.91	1.81	4.21	3.18	26
3.07	2.16	5.29	3.70	21
3.23	2.75	7.10	4.57	16
3.39	3.86	10.46	6.19	13
3.55	5.72	15.91	8.89	9
3.70	-	-	-	7
3.86	-	-	-	5
4.02	-	-	-	3

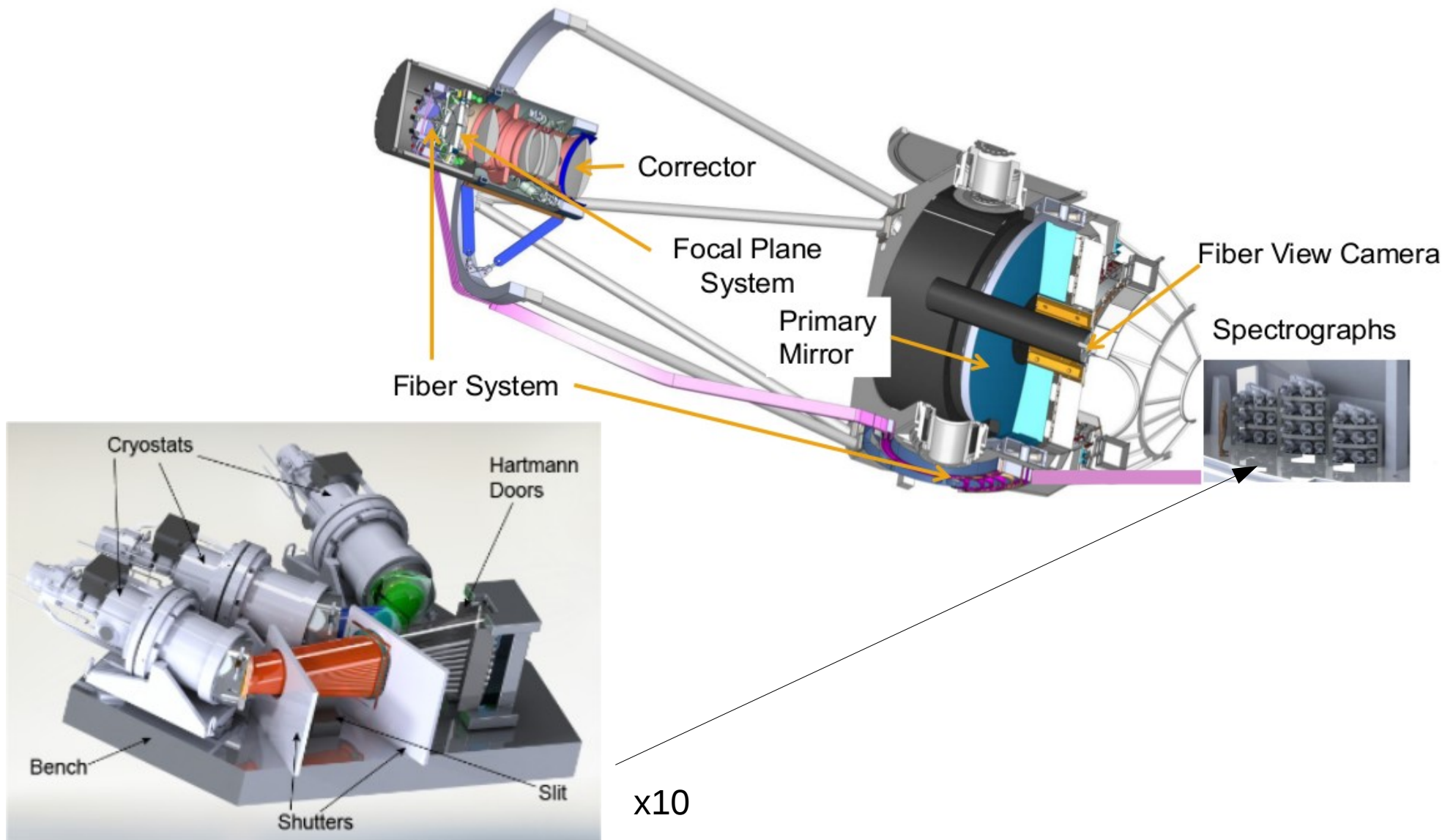| z	$\frac{\sigma_{R/s}}{R/s}$ %	$\frac{\sigma_{D_A/s}}{D_A/s}$ %	$\frac{\sigma_{Hs}}{Hs}$ %	$\bar{n}P_{0.2,0}$	$\bar{n}P_{0.14,0.6}$	V $[h^{-1}\mathrm{Gpc}^3]$	$\frac{dN_{ELG}}{dz\,ddeg^2}$	$\frac{dN_{LRG}}{dz\,ddeg^2}$	$\frac{dN_{QSO}}{dz\,ddeg^2}$	$\frac{\sigma_{f\sigma_{0.1}}}{f\sigma_{0.1}}$ %	$\frac{\sigma_{f\sigma_{0.2}}}{f\sigma_{0.2}}$ %
0.65	0.57	0.82	1.50	2.59	6.23	2.63	309	832	47	3.31	1.57
0.75	0.48	0.69	1.27	3.63	9.25	3.15	2269	986	55	2.10	1.01
0.85	0.47	0.69	1.22	2.33	5.98	3.65	1923	662	61	2.12	1.01
0.95	0.49	0.73	1.22	1.45	3.88	4.10	2094	272	67	2.09	0.99
1.05	0.58	0.89	1.37	0.71	1.95	4.52	1441	51	72	2.23	1.11
1.15	0.60	0.94	1.39	0.58	1.59	4.89	1353	17	76	2.25	1.14
1.25	0.61	0.96	1.39	0.51	1.41	5.22	1337	0	80	2.25	1.16
1.35	0.92	1.50	2.02	0.22	0.61	5.50	523	0	83	2.90	1.73
1.45	0.98	1.59	2.13	0.20	0.53	5.75	466	0	85	3.06	1.87
1.55	1.16	1.90	2.52	0.15	0.40	5.97	329	0	87	3.53	2.27
1.65	1.76	2.88	3.80	0.09	0.22	6.15	126	0	87	5.10	3.61
1.75	2.88	4.64	6.30	0.05	0.12	6.30	0	0	87	8.91	6.81
1.85	2.92	4.71	6.39	0.05	0.12	6.43	0	0	86	9.25	7.07

DESI

- 5000 fibers at the prime focus of the Mayall (3.7m) at Kitt Peak
- 10 spectrographes of 500 fibers with 3 channels (30 CCDs)
    in a temperature controled room

Corrector

Focal Plane System

Primary Mirror

Fiber System

Fiber View Camera

Spectrographs

Cryostats

Hartmann Doors

Bench

Shutters

Slit

x10

DESI vs SDSS/BOSS

- Mirror area x 2.4

- Number of fibers x 5

- Telescope throughput x 1.6

- Resolution x 2.3 at 7000A (for ELGs OII doublet detection, but higher S/N for all lines)

- Fiber positionners instead of drilled plates : more flexibility/science

- Stable spectrographs : smaller sky systematic residuals

- Atmospheric Dispersion Compensator : smaller fiber aperture losses

- DESI can an detect an emission line 3 times fainter than BOSS in the same exposure time

- or detect the same galaxy 9 times faster

- and so **DESI can measure redshifts 45 times faster than BOSS for ELGs**

  and 20 times faster for QSOs (no resolution gain)

DESI : the challenges

- actually build the instrument !

- need targets (DESI is blind without them)
    - massive imaging surveys
    - targeting algorithms

- data processing : convert observations into 3D galaxy catalogs and Lya forests

- optimization of all of this

- understand a lot of things about the instrument and data processing :

    - targeting efficiency/purity vs imaging observational conditions

    - fiber assignment efficiency

    - redshift and spectroscopic identification success rate and errors

    - spurious signal in the Lya forests

    (all as a function of the target properties correlated with their clustering bias)

There is today a huge activity on all those topics in the collaboration

DESI : the challenges (focus on analysis)

* Not starting from scratch

    - BOSS experience :

        - on targeting efficiency (but probably need something better for DESI)
        - fiber assignment : only a problem for close pairs
        - galaxy clustering / Lyman-alpha analysis
        - but no issue with redshift efficiency (>95% efficiency with BOSS)

    - eBOSS facing significant redshift inefficiencies :

        forward modeling of spectroscopic efficiency starting

* Important work ahead of the survey start
    Simulations of everything , data challenges
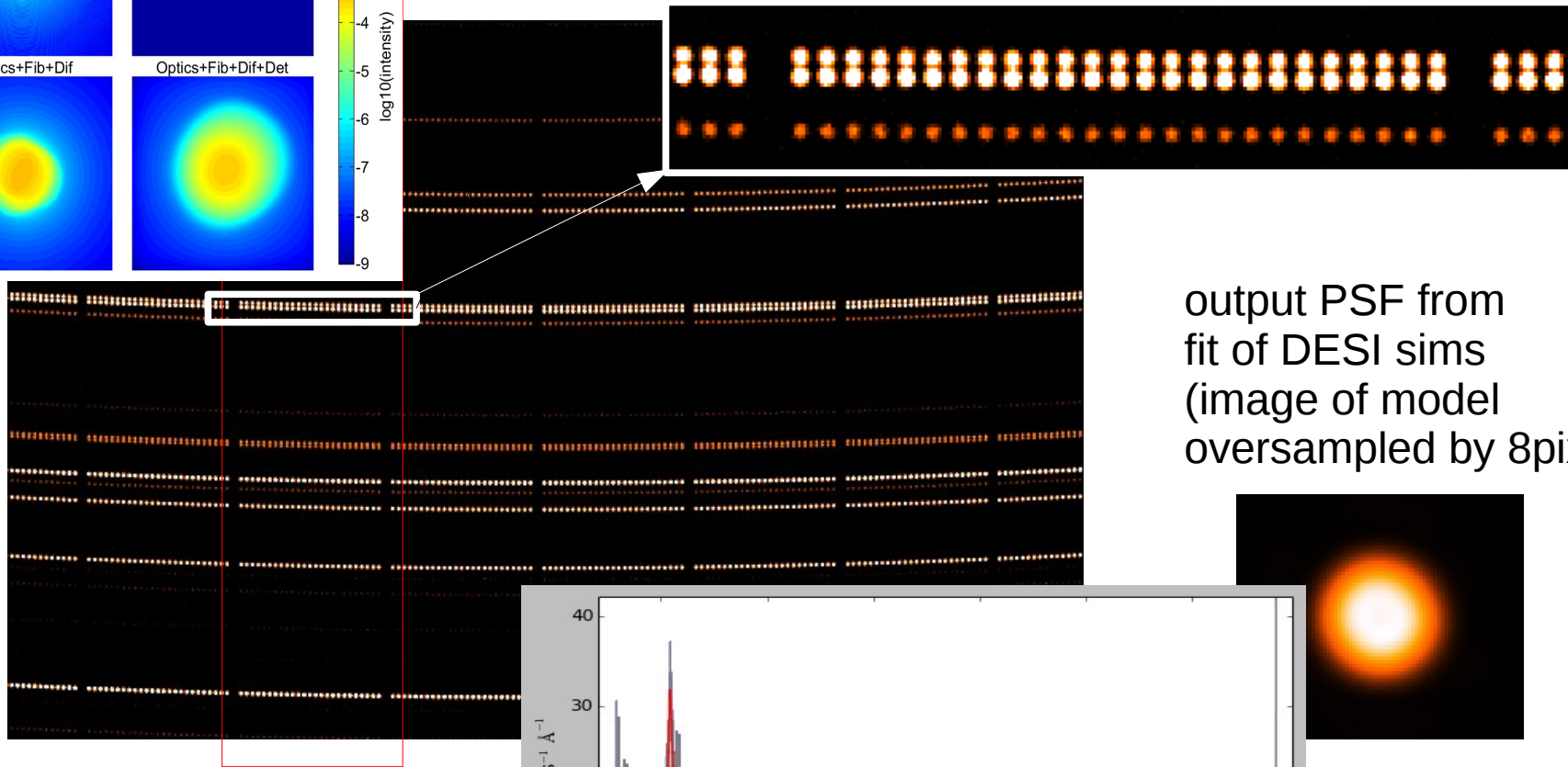
A personal choice of a few examples :
        - data processing with pixel level simulations
        - redshift data challenges
        - redshift fitter used to define hardware requirement
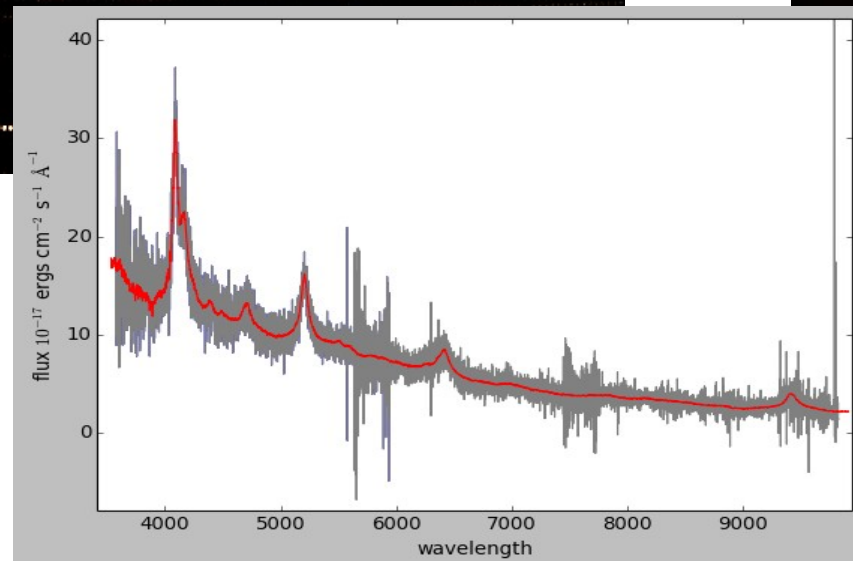   - getting ready for the 1st spectrograph tests

Data processing of CCD image simulations

Optics Diffraction Detector

Optics+Fiber Optics+Fib+Dif Optics+Fib+Dif+Det

log10(intensity)
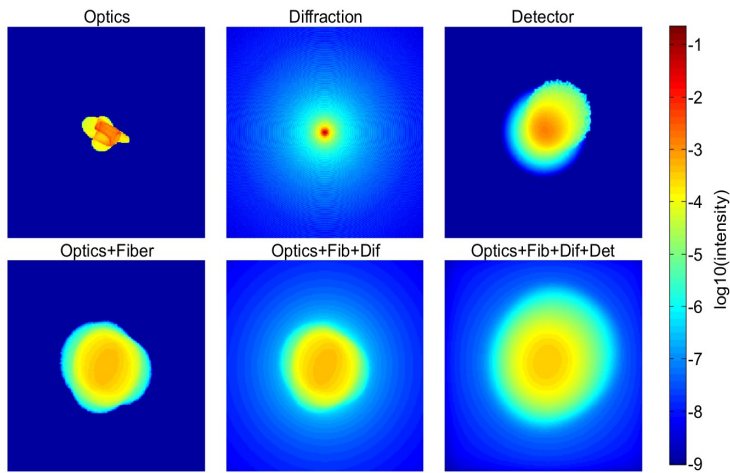
Simulated images accounting for opics/diffraction/detector effects (Jelinsky/Bailey)

output PSF from fit of DESI sims (image of model oversampled by 8pix)

Full pipeline processing gives calibrated spectra + redshifts

flux 10^{-17} ergs cm^{-2} s^{-1} Å^{-1}

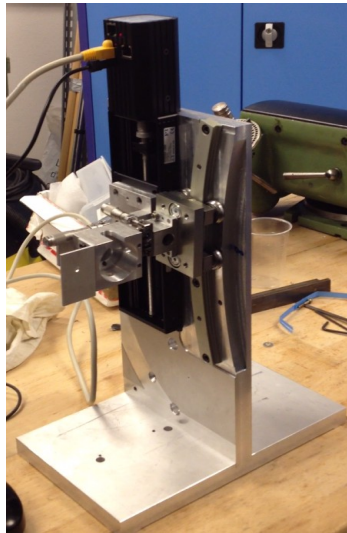wavelength

Simulations will be calibrated with first spectrograph tests this summer

- Tests of wavelength coverage, Resolution (or Point Spread Function), Stability
- Scattered light / second order ...
- Throughput with input light from LEDs calibrated with a calibrated photodiode
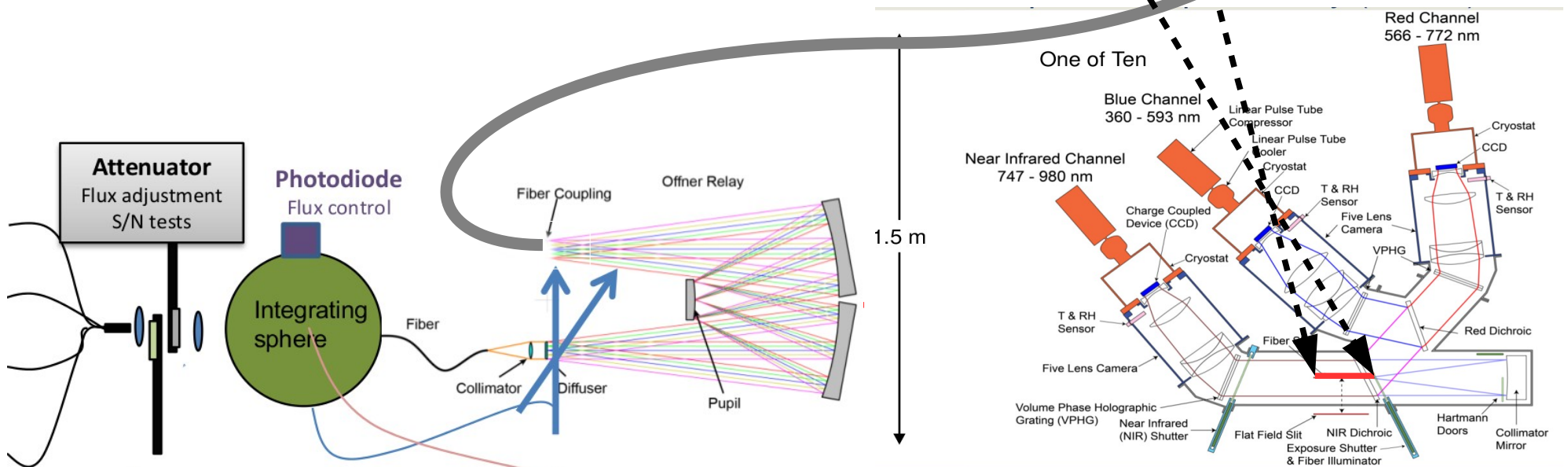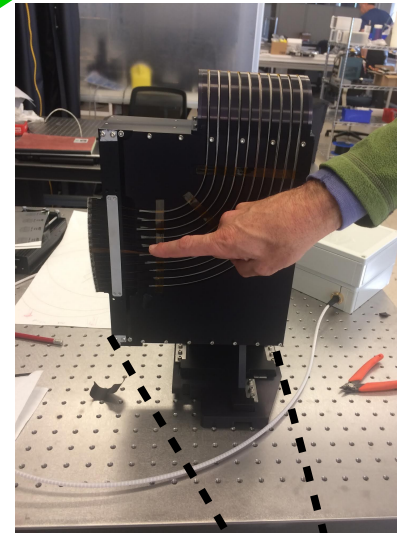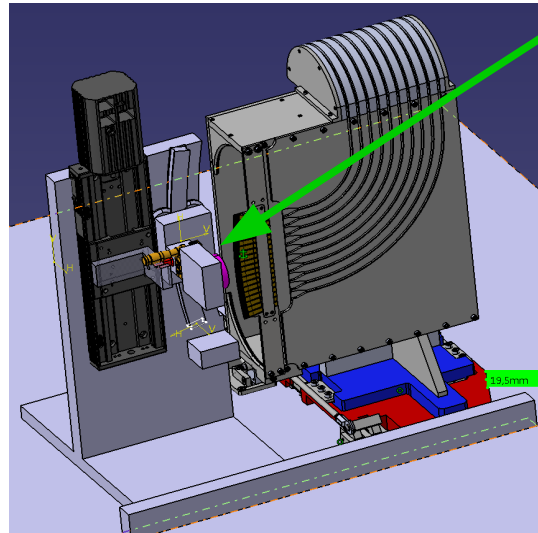
Redshift fitting challenges
Many methods being tested ...

Redshift Measurement and Spectral Classification
for eBOSS Galaxies with the redmonster Software

Timothy A. Hutchinson

Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA

t.hutchinson@utah.edu

and

Redrock

Stephen Bailey & David Schlegel

DESI Data 2016-01-12

https://github.com/sbailey/redrock

zztop redshift fitter

Progress report for ELGs
(zztop tag 0.1.0)

J. Guy and C. Balland

LPNHE, Paris

Bayez
Bayesian redshift estimation for DESI

David Kirkby, Javier Sanchez, Noble Kennamer

DESI Data Telecon
19 January 2016

https://github.com/dkirkby/bayez

DESI-doc-1598

Welcome to MARZ

Redshift fitter need today
- to validate forecasts (FDR)
- define low-level hardware requirements (FDR)
- develop science analysis (how to model redshift efficiency/errors)

One example : DESI calibration system requirements
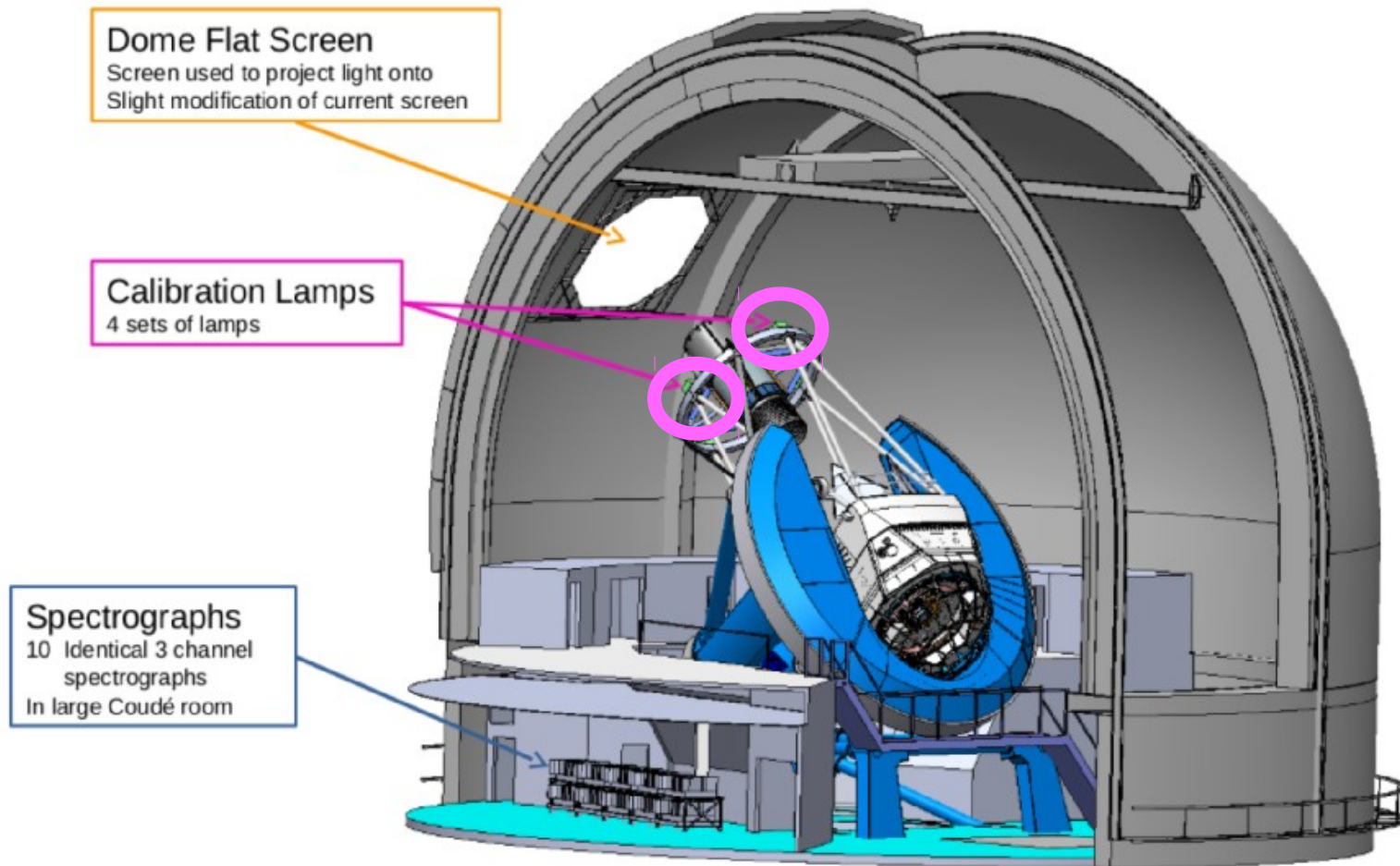Stability of calibration Halogen lamps -> DESI dark energy figure of merit :-)

Figure 9: Overview of the calibration system

Redshift fitter need today
 - to validate forecasts (FDR)
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One example : DESI calibration system requirements
Stability of calibration Halogen lamps -> DESI dark energy figure of merit :-)

Dome Flat Screen
Screen used to project light onto
Slight modification of current screen

Calibration Lamps
4 sets of lamps

Spectrographs
10 Identical 3 channel
spectrographs
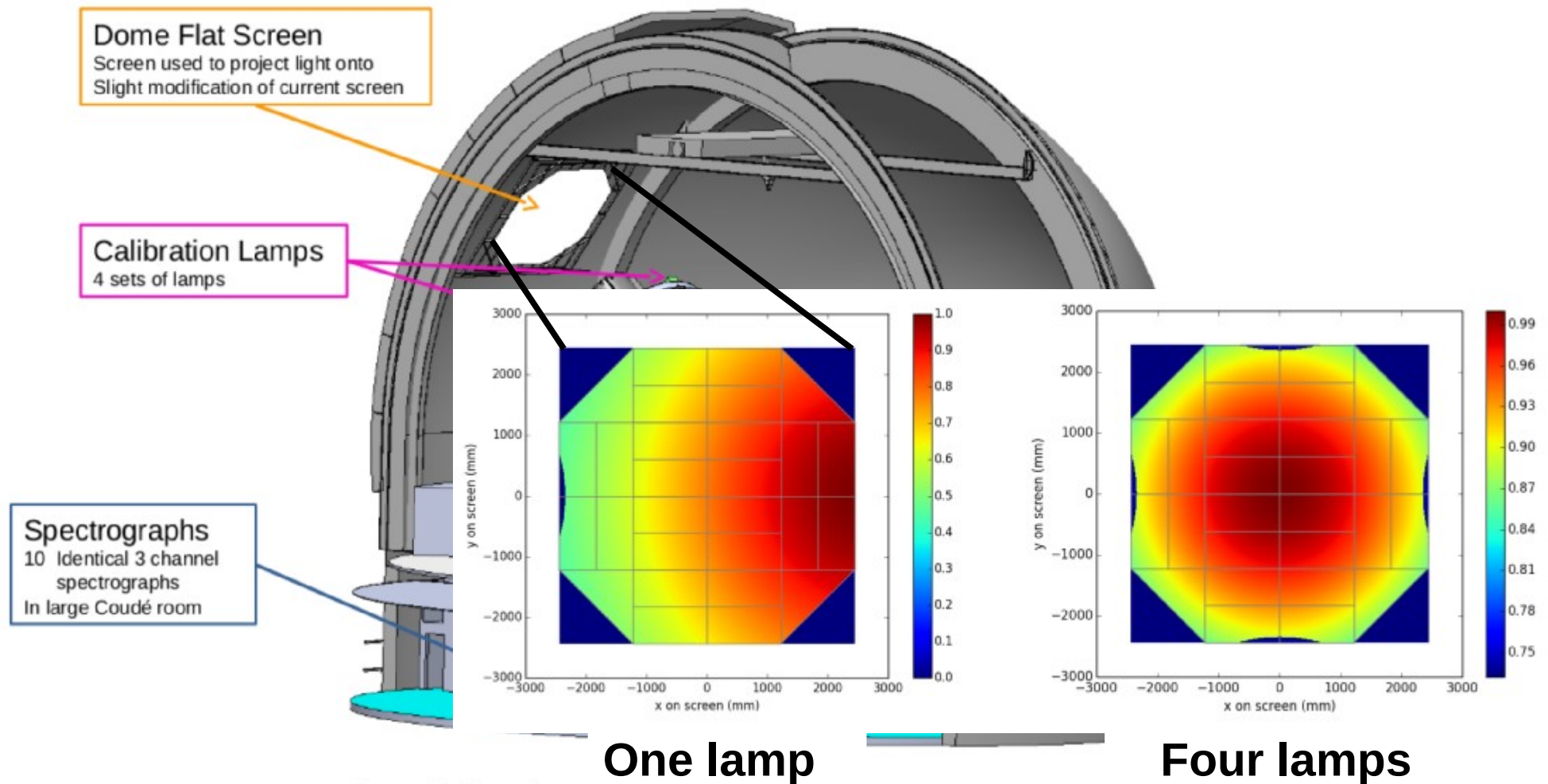In large Coudé room

One lamp **Four lamps**

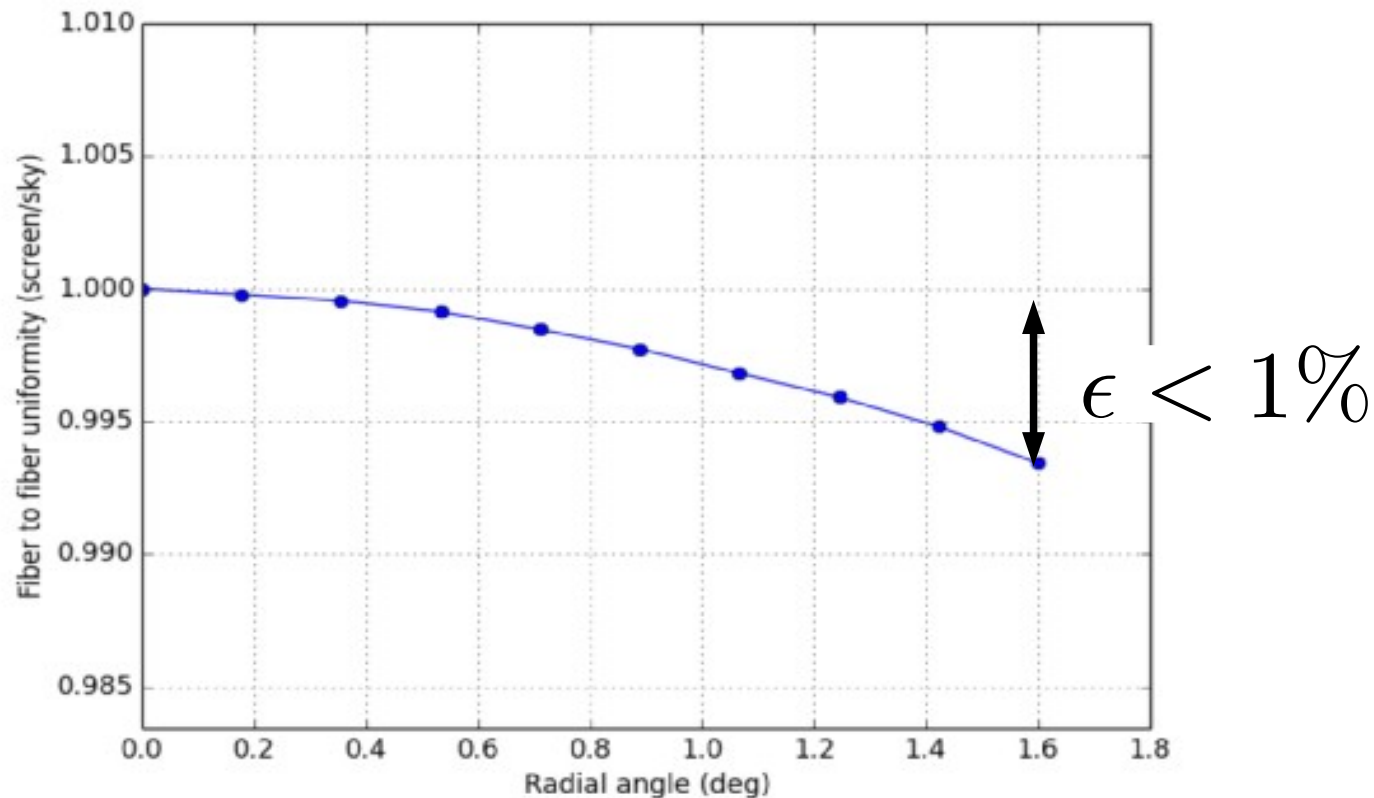Figure 9: Overview of the calibration system

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One example : DESI calibration system requirements
Stability of calibration Halogen lamps -> DESI dark energy figure of merit :-)

With 4 lamps : flat field non-uniformity compared to sky

Redshift fitter need today

- to validate forecasts (FDR)
- define low-level hardware requirements (FDR)
- develop science analysis (how to model redshift efficiency/errors)

One example : DESI calibration system requirements
Stability of calibration Halogen lamps -> DESI dark energy figure of merit :-)

Impact on ELG redshift success rate
compared to requirements and assumptions in TDR/FDR
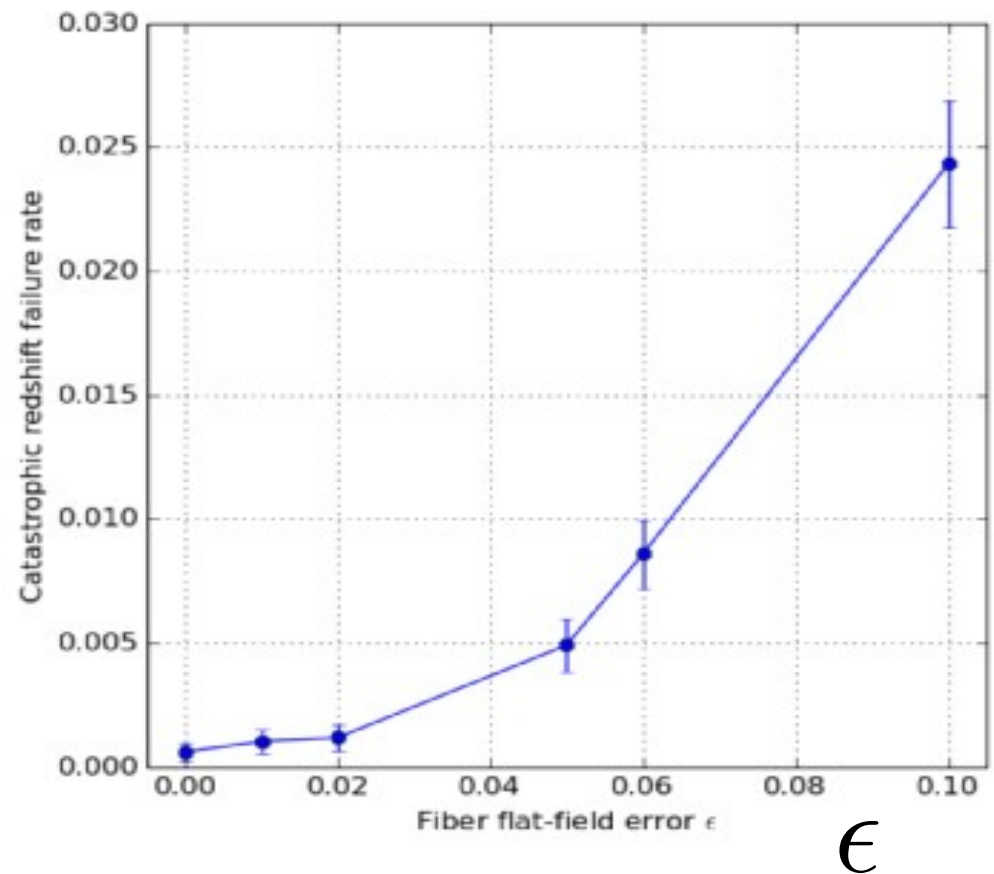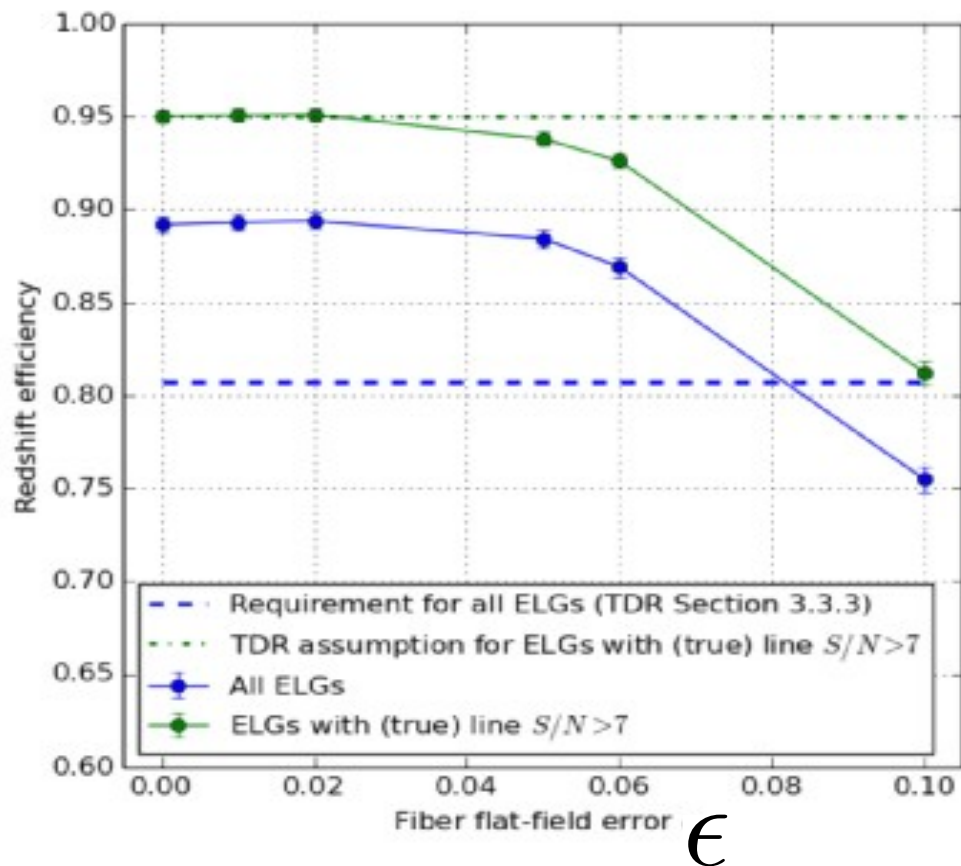
Conclusion

- Dark energy is one of the most important puzzles of fundamental physics

- Baryon Acoustic Oscillations, with low systematics, are complementary to supernovae Ia

- The DESI, a massive spectroscopic survey, has very impressive forecasts,
    and Lyman-alpha forests play an important role at high-z

- A lot of challenges for the preparation of the survey (from hardware to the preparation of the science analyses).

So ... exciting times ...