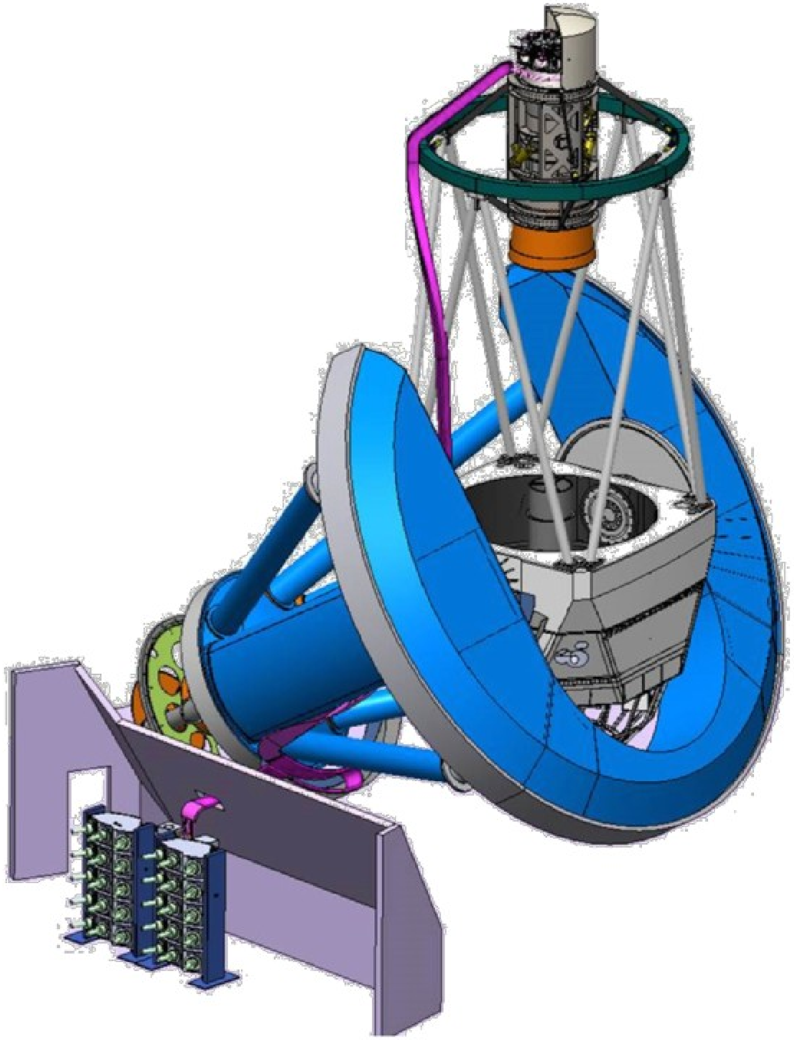


DESI
The Dark Energy Spectroscopic Instrument

Julien Guy (LPNHE/Paris)

Moriond Cosmology, March 2016

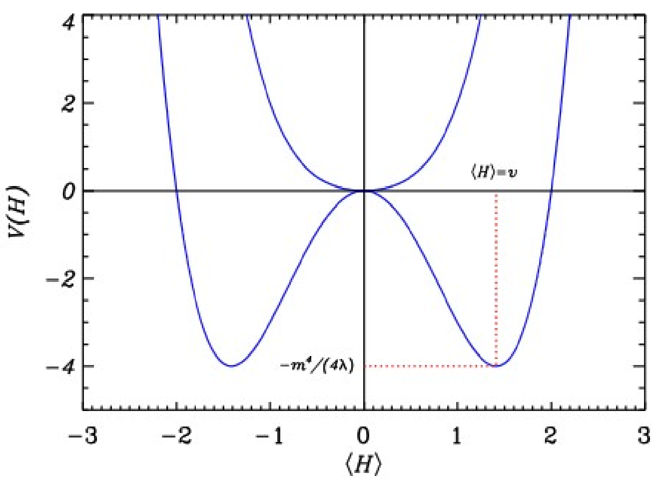
Dark Energy puzzle

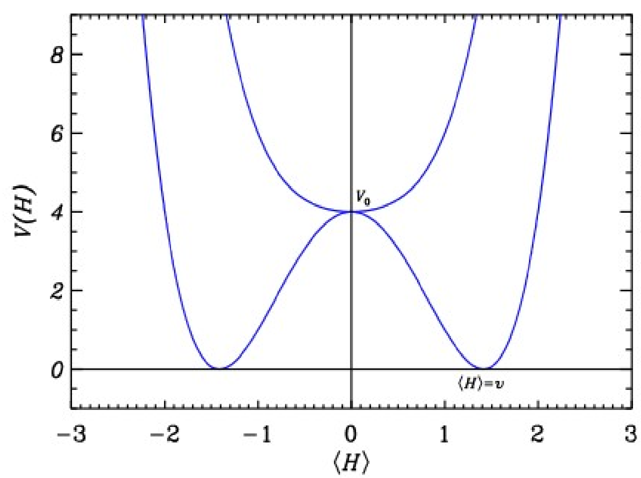
Energy scale : $\Omega_\Lambda \sim 0.7 \rightarrow \rho_\Lambda \sim (10^{-3} eV)^4$

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





$$V(\phi_{\min}) = -\frac{1}{4} m_{\rm H}^2 v^2 = -\frac{\sqrt{2}}{16} \frac{m_{\rm H}^2}{G_{\rm F}^2} \simeq -1.2 \times 10^8 \,\mathrm{GeV}^4$$

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

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

$$10^{-56}!$$

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

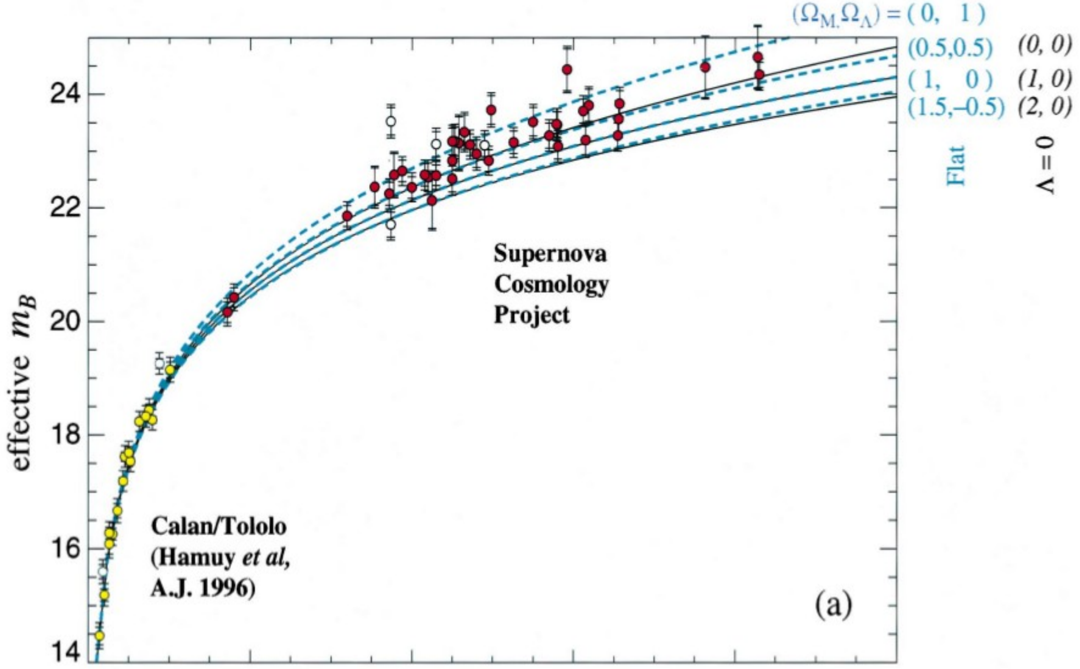
    - its spacial homogeneity : clustering

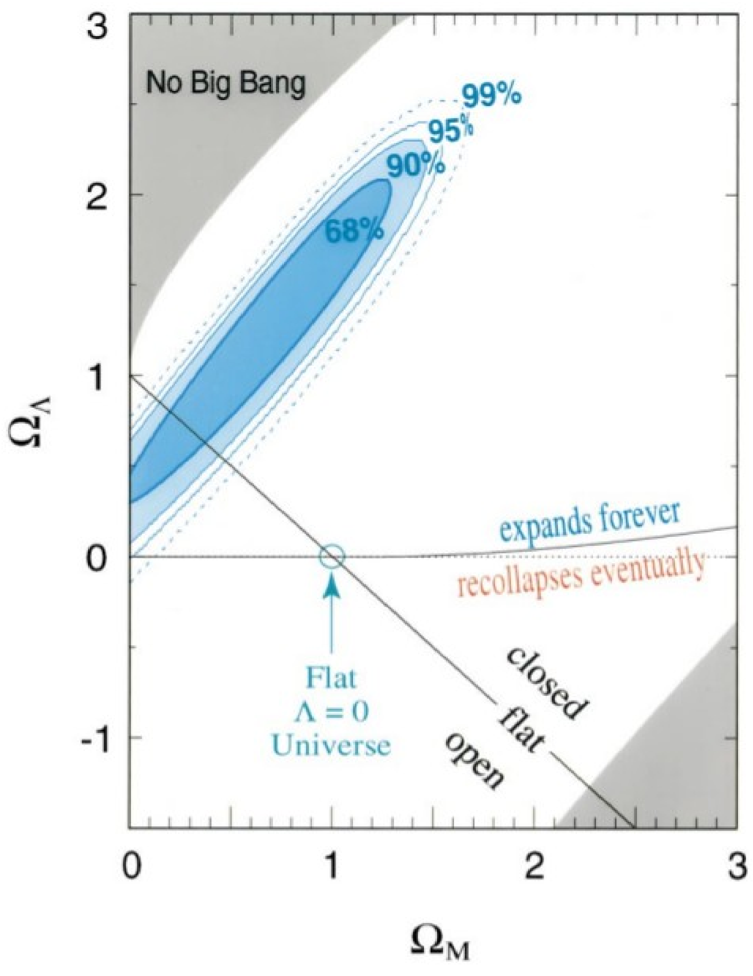
    - across a large redshift range

- 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 with Type Ia supernovae by two teams.

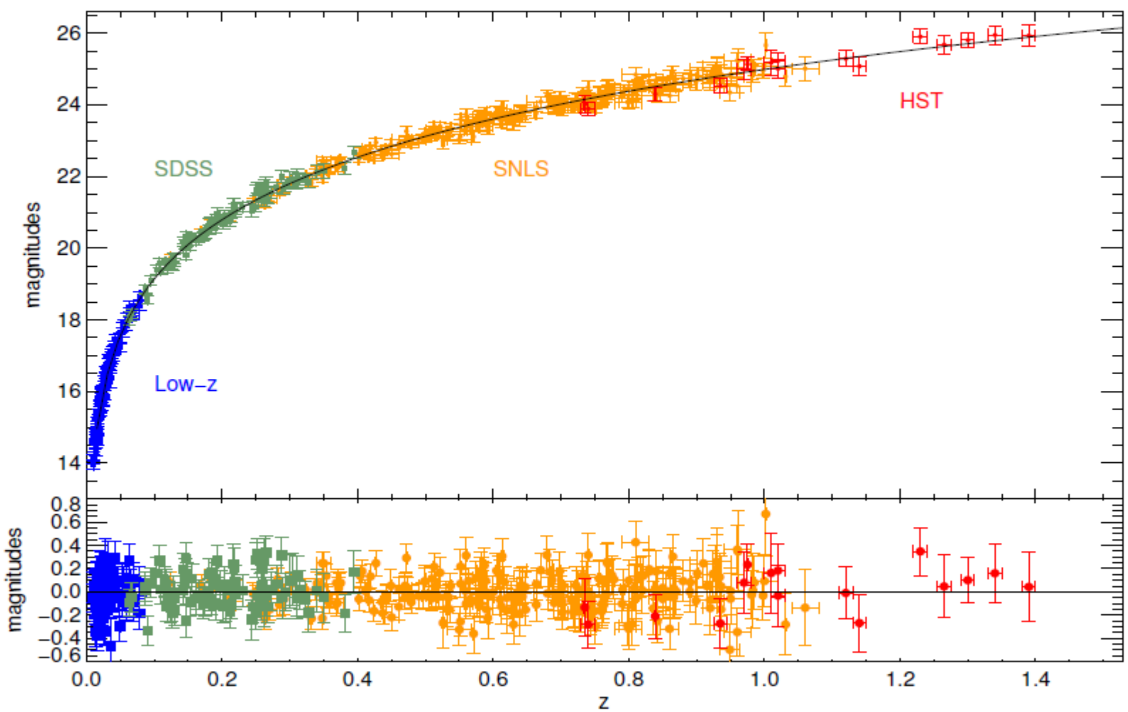


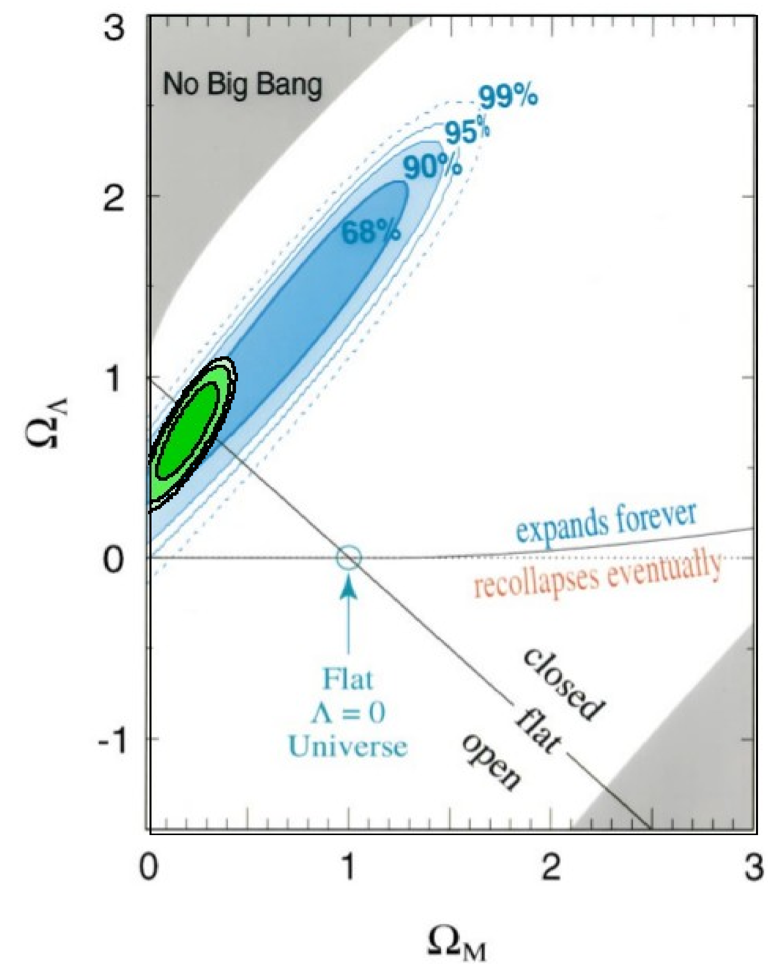


Cosmological signatures of Dark Energy

- The dark energy puzzle started with the discovery of the acceleration of expansion in 1998 with Type Ia supernovae by two teams.

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



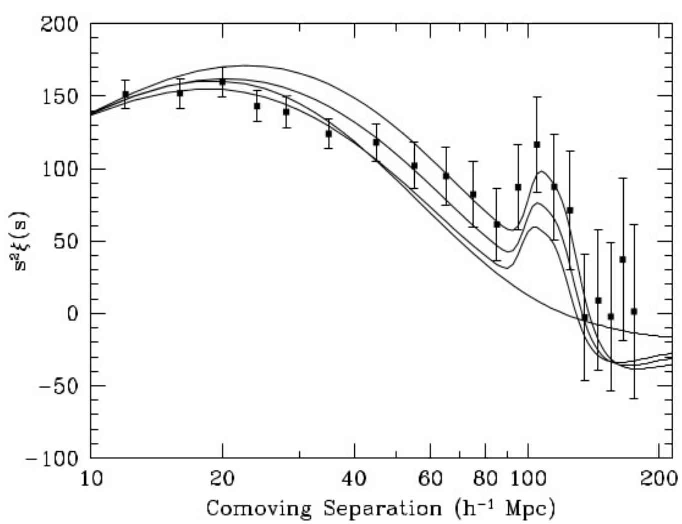


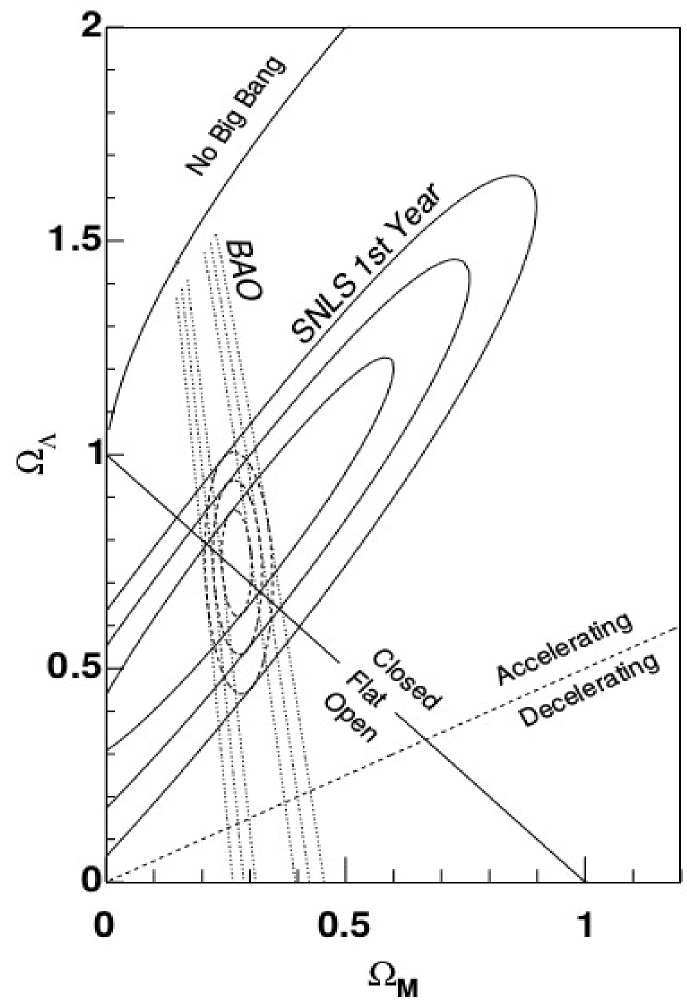
Cosmological signatures of Dark Energy

- The dark energy puzzle started with the discovery of the acceleration of expansion in 1998 with Type Ia supernovae by two teams.

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

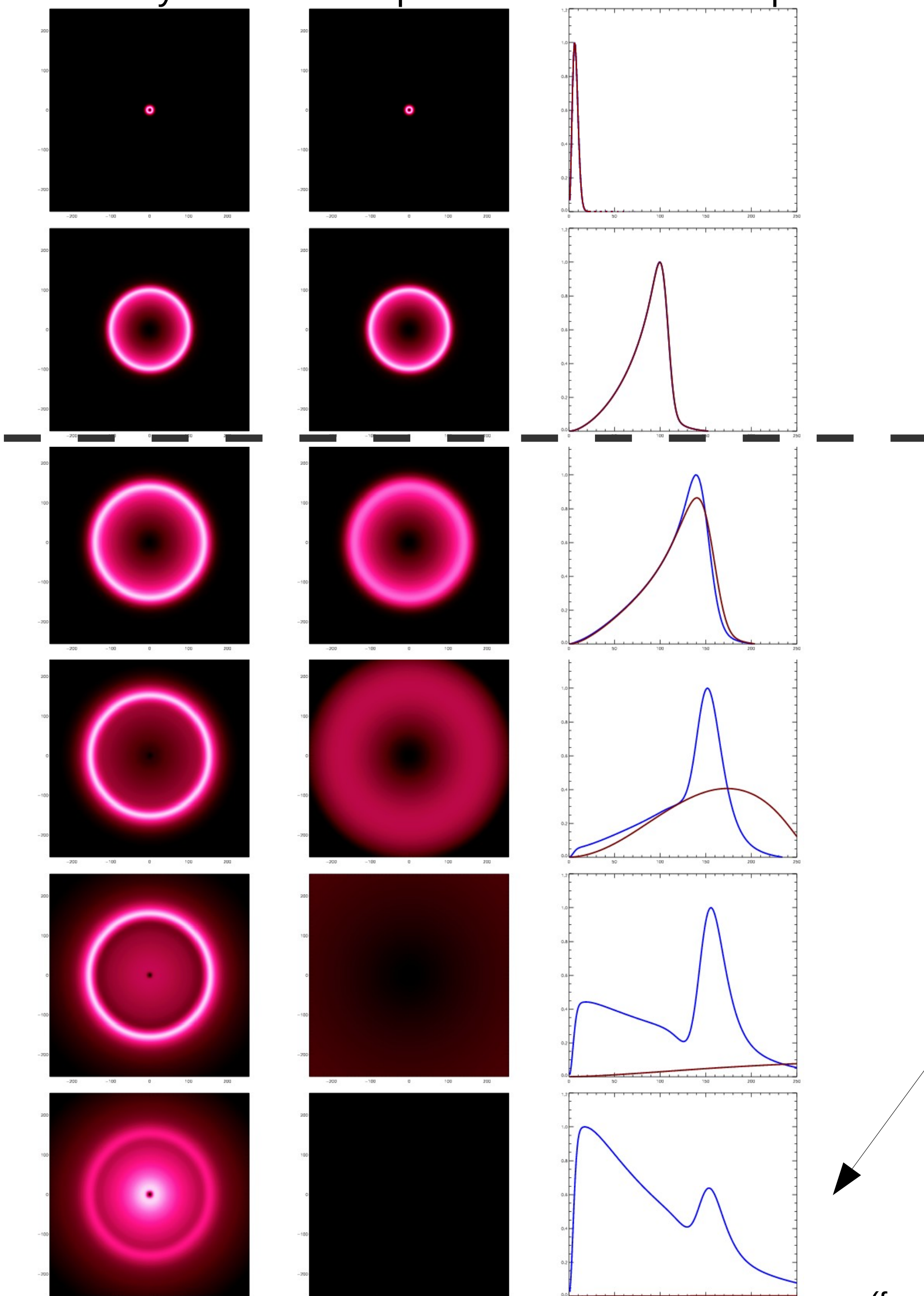
- But the most convincing confirmation was probably the discovery of Baryon Acoustic Oscillations (BAO) with SDSS in 2005 (here combined constraints with SNe, in 2006)



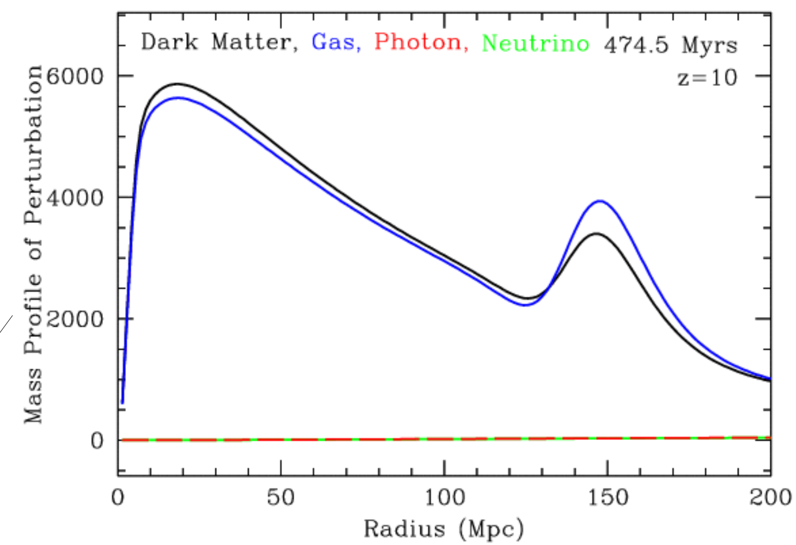


Baryon Acoustic Oscillations (BAO)

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



recombination (p+e -> H)

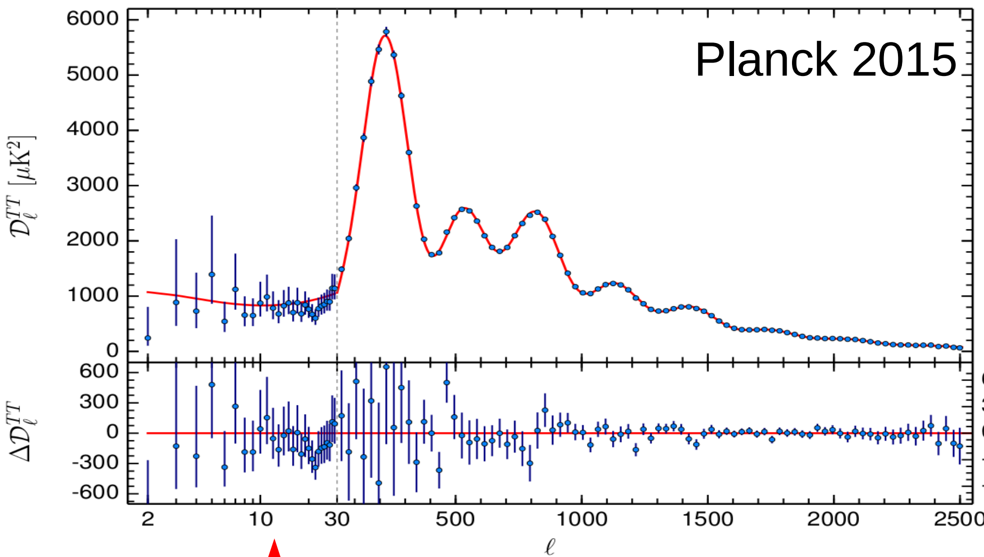


Correlation peak at r~150 Mpc
(in co-mobile coordinates)

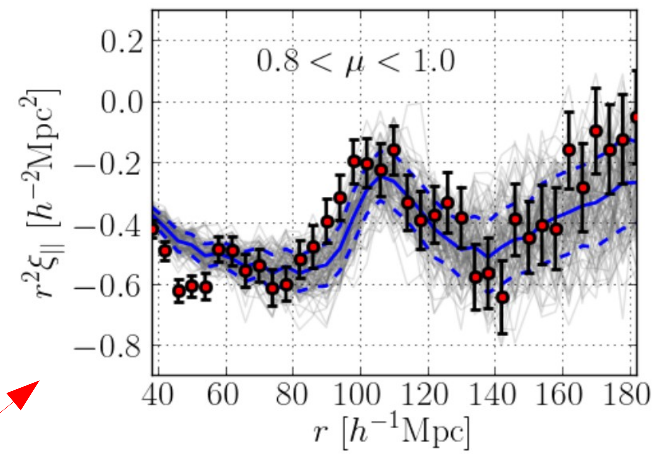
(from M. White, D. Eisenstein)

Baryon Acoustic Oscillations

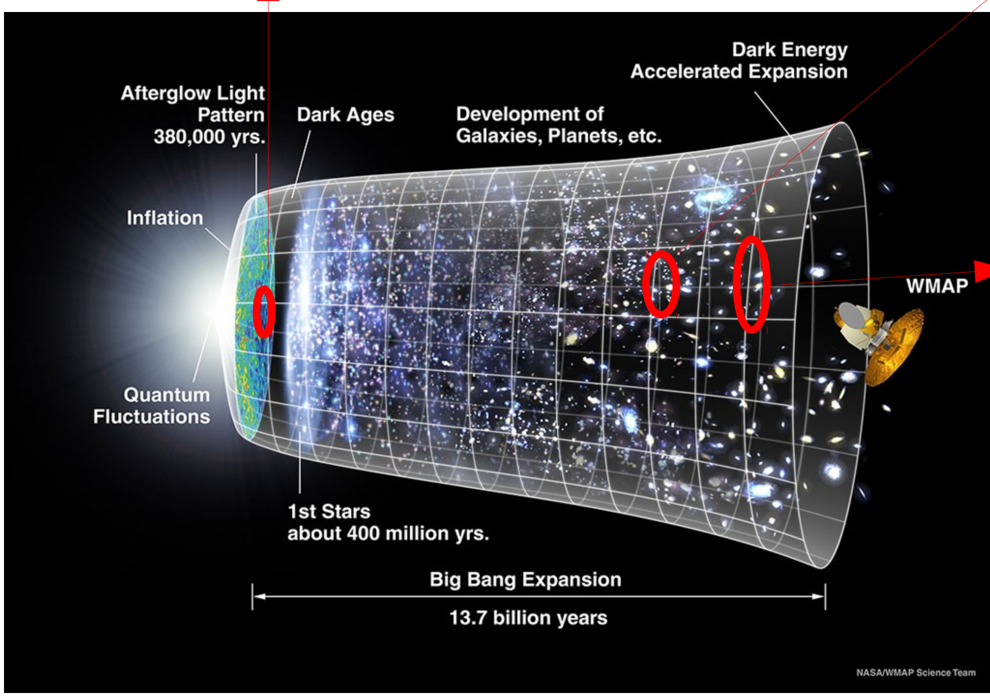
in the CMB at z~1000

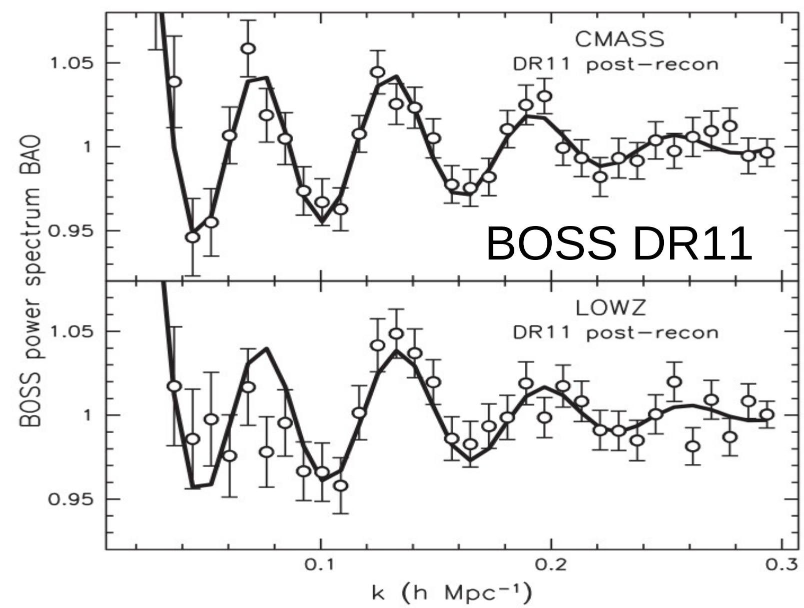


in Lyman-alpha forests at z ~ 2.3



in the galaxy density field





z~0.6

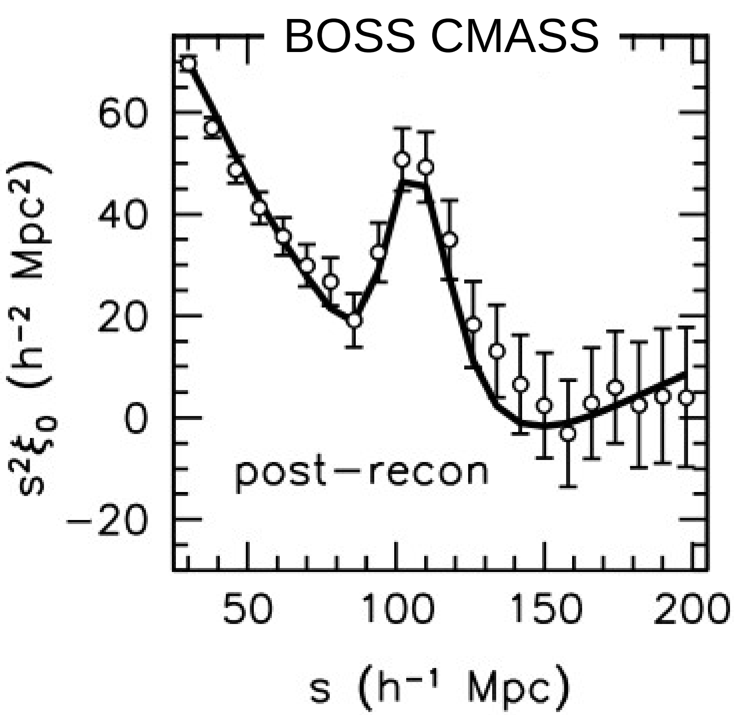
z~0.2

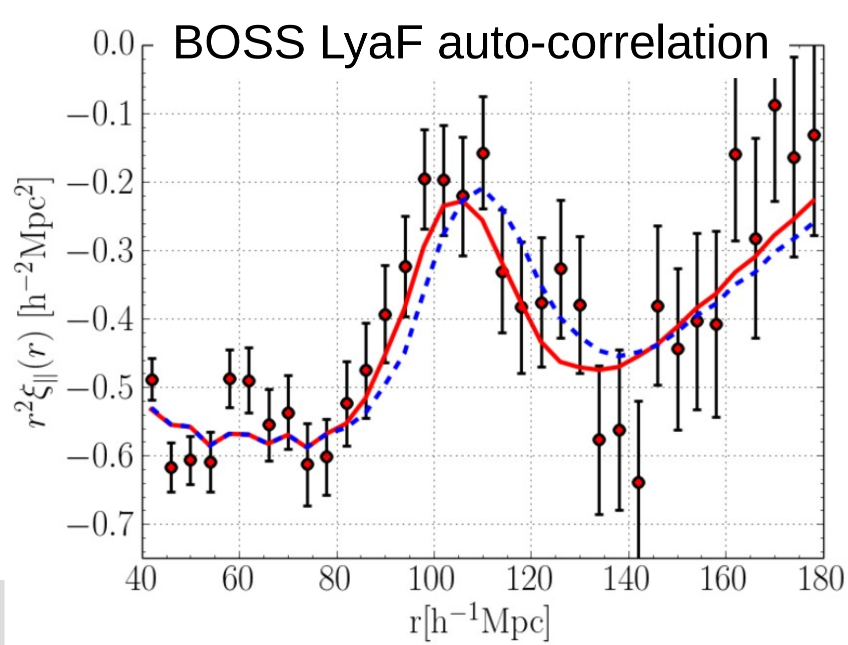
Great success of SDSS3/BOSS (here DR11 results, 90% of the data)

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

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

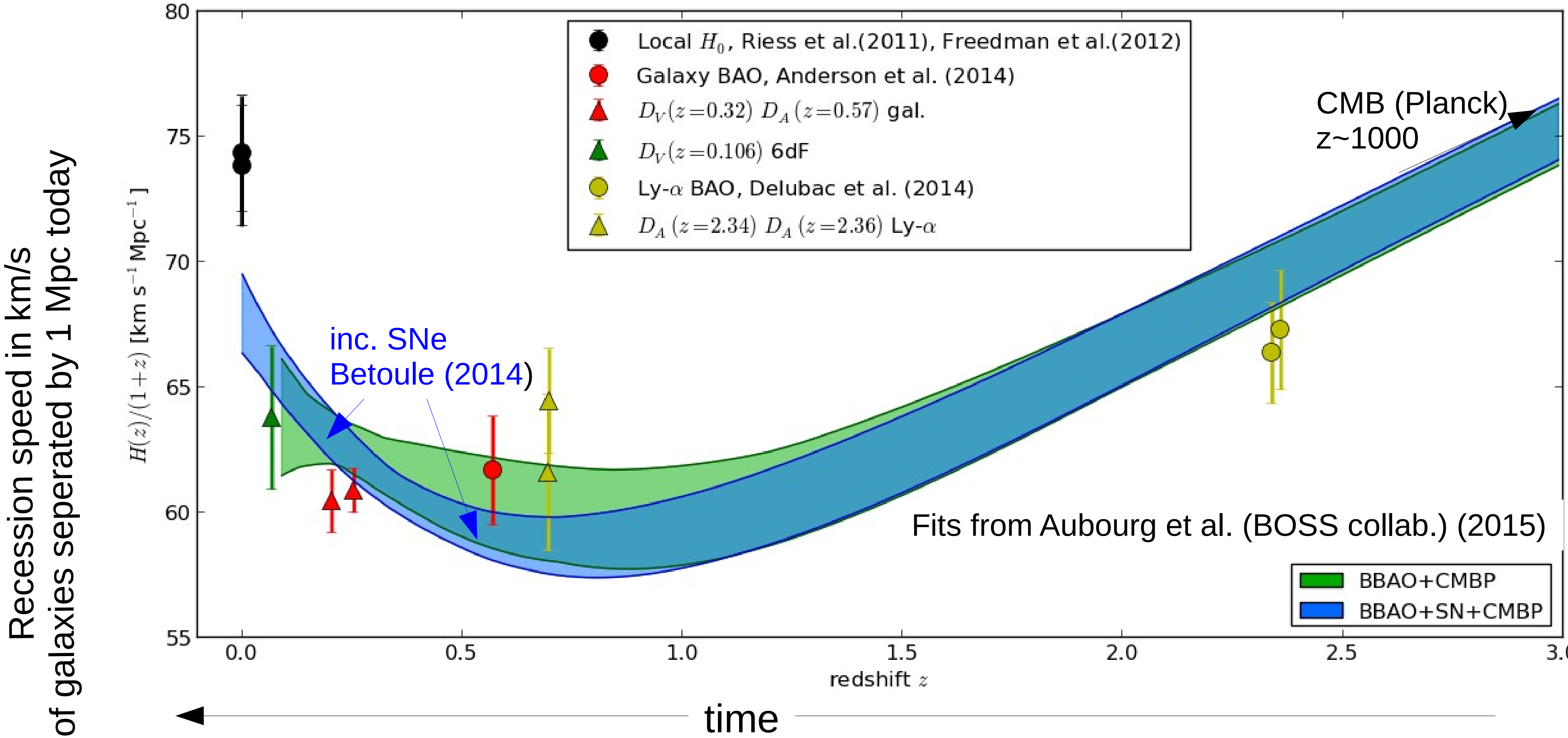
BOSS DR11 sub-sample	z	α_{iso}	$\alpha_\perp$	$\alpha_\parallel$	$corr(\alpha_\perp, \alpha_\parallel)$
BOSS LOWZ sample	0.32	0.020	...	...	....
BOSS CMASS sample	0.57	0.010	0.014	0.035	-0.52
LyaF auto-correlation	2.34	0.021	0.055	0.031	-0.43
LyaF-QSO cross correlation	2.36	0.019	0.037	0.033	-0.39
Combined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





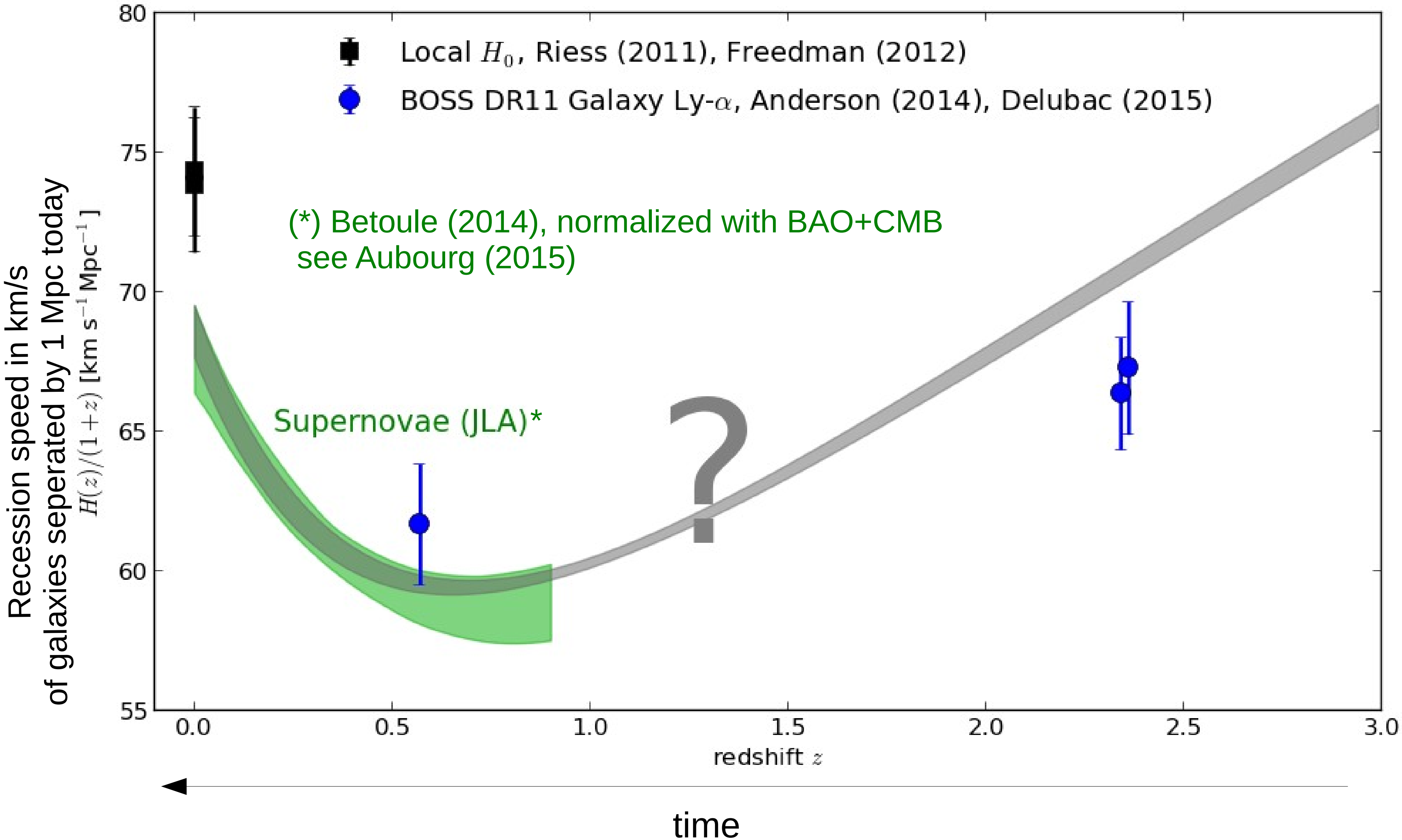
Where do we stand today, with another perspective on the data

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))

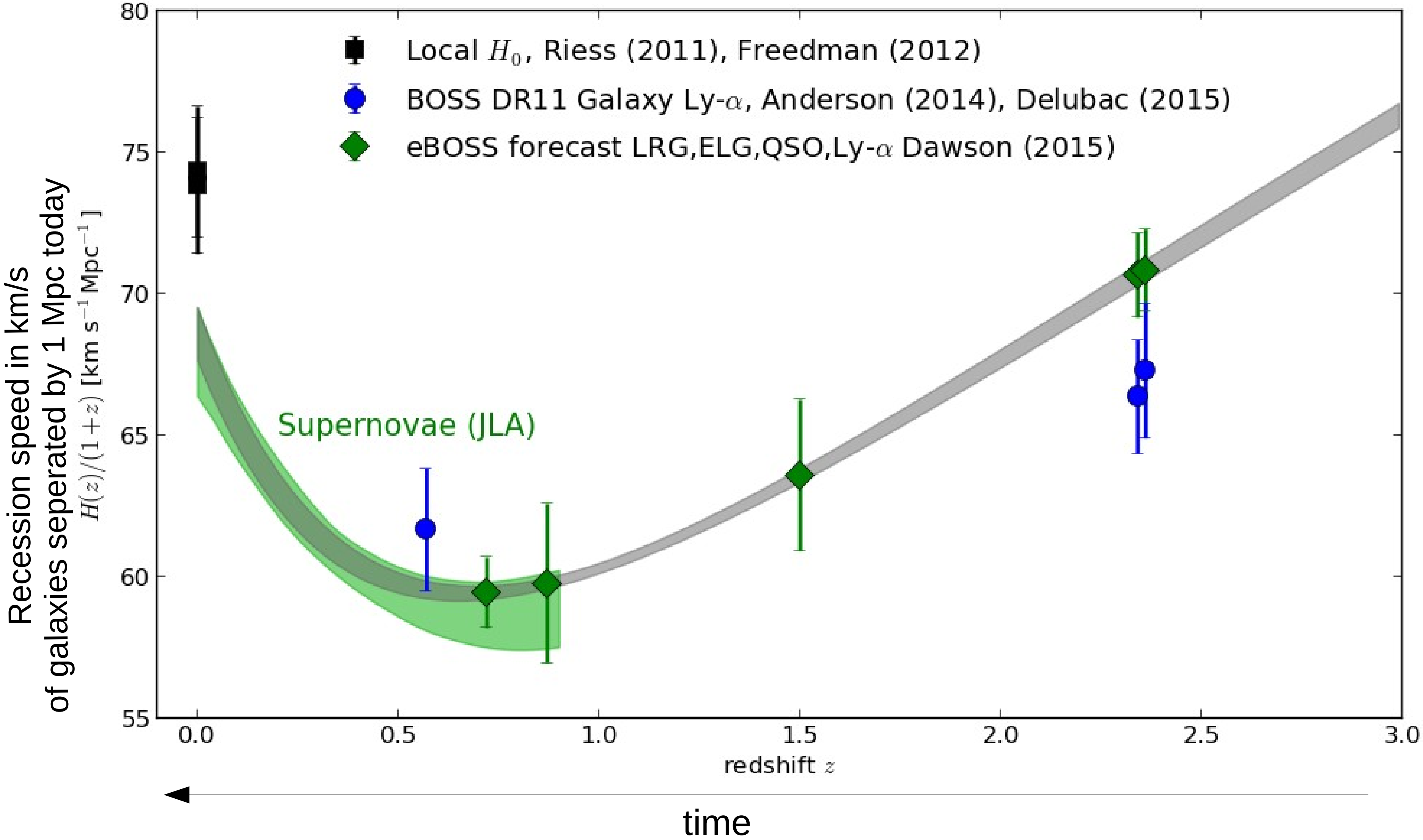


* Confirmation of accelerated of expansion with BAO+CMB discovered with SNe Ia
* Inverse distance ladder measurement of H0
* Test of cosmological model in decelerated expansion with Lyman-alpha forests

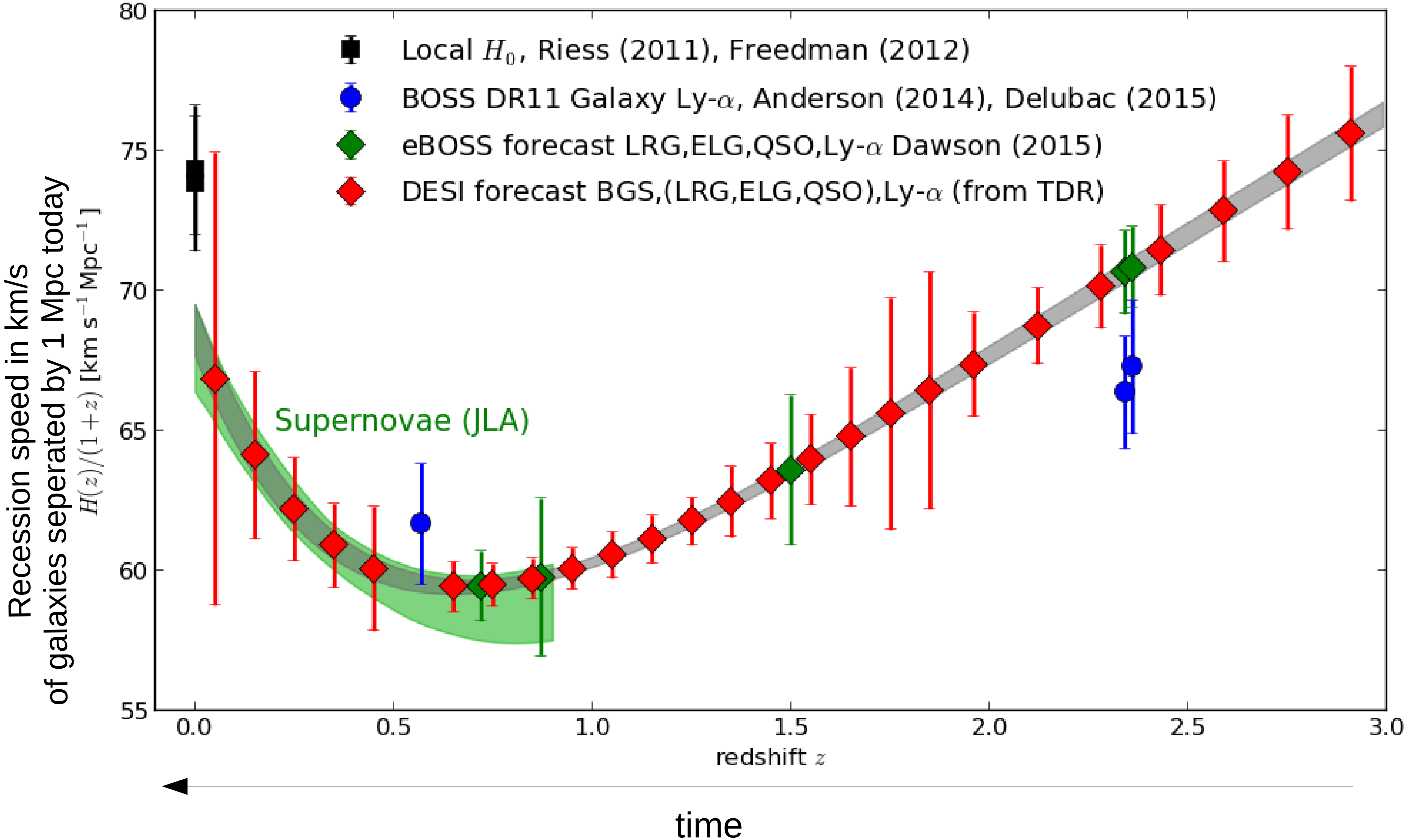
Constraints on H(z)
BOSS



Constraints on H(z)
BOSS+eBOSS

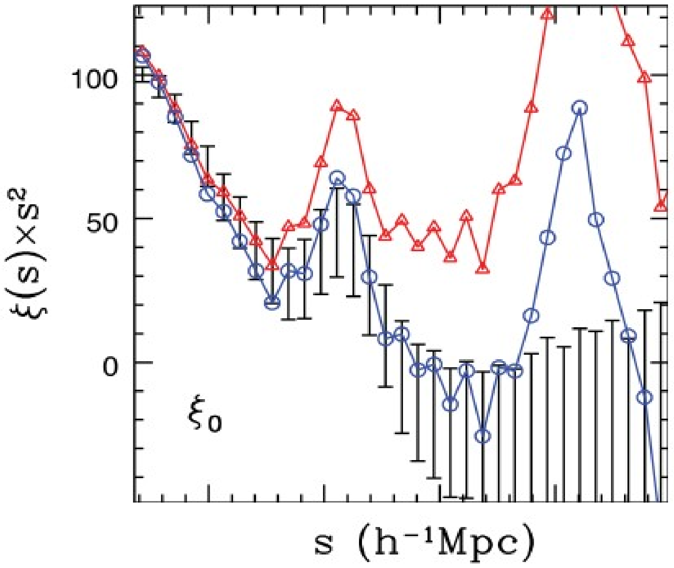


Constraints on H(z)
BOSS+eBOSS+DESI



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

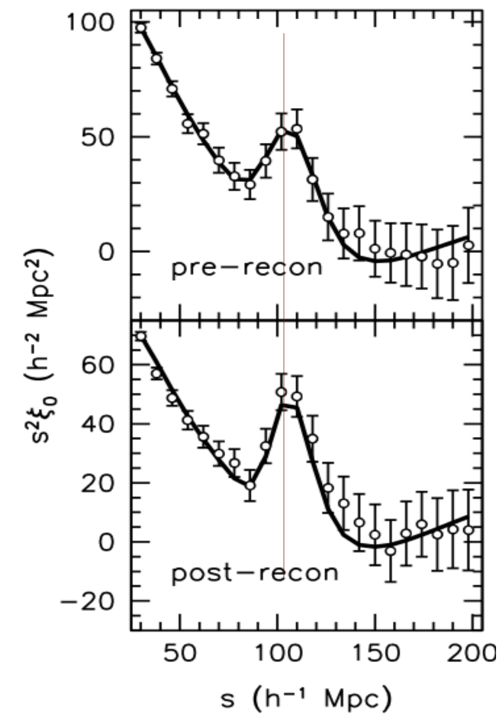
- For galaxies , it's about variations across the sky of :
  - Targeting efficiency
  - Fiber assignment efficiency
  - Redshift efficiency

  - 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
  - uncertainties < 0.5% (DR12 paper in prep.)

The most convincing confirmation of Dark Energy is from BAO because

BAO have low systematic uncertainties



Physical interpretation systematics :

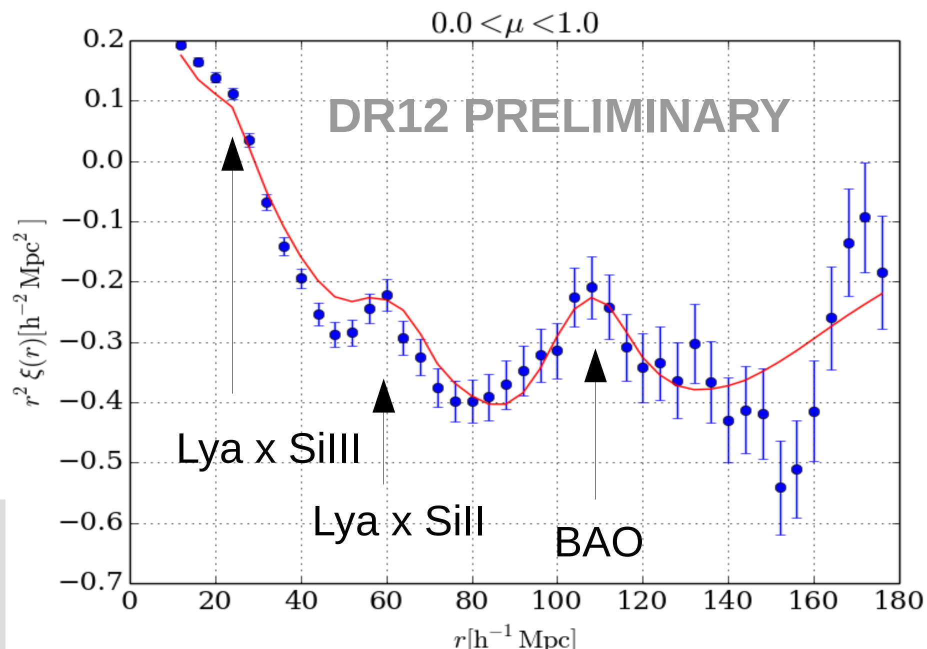
- BAO scale accurately constrained by CMB
  and 1st order perturbation physics
  (we know the successes of Planck)

- 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)

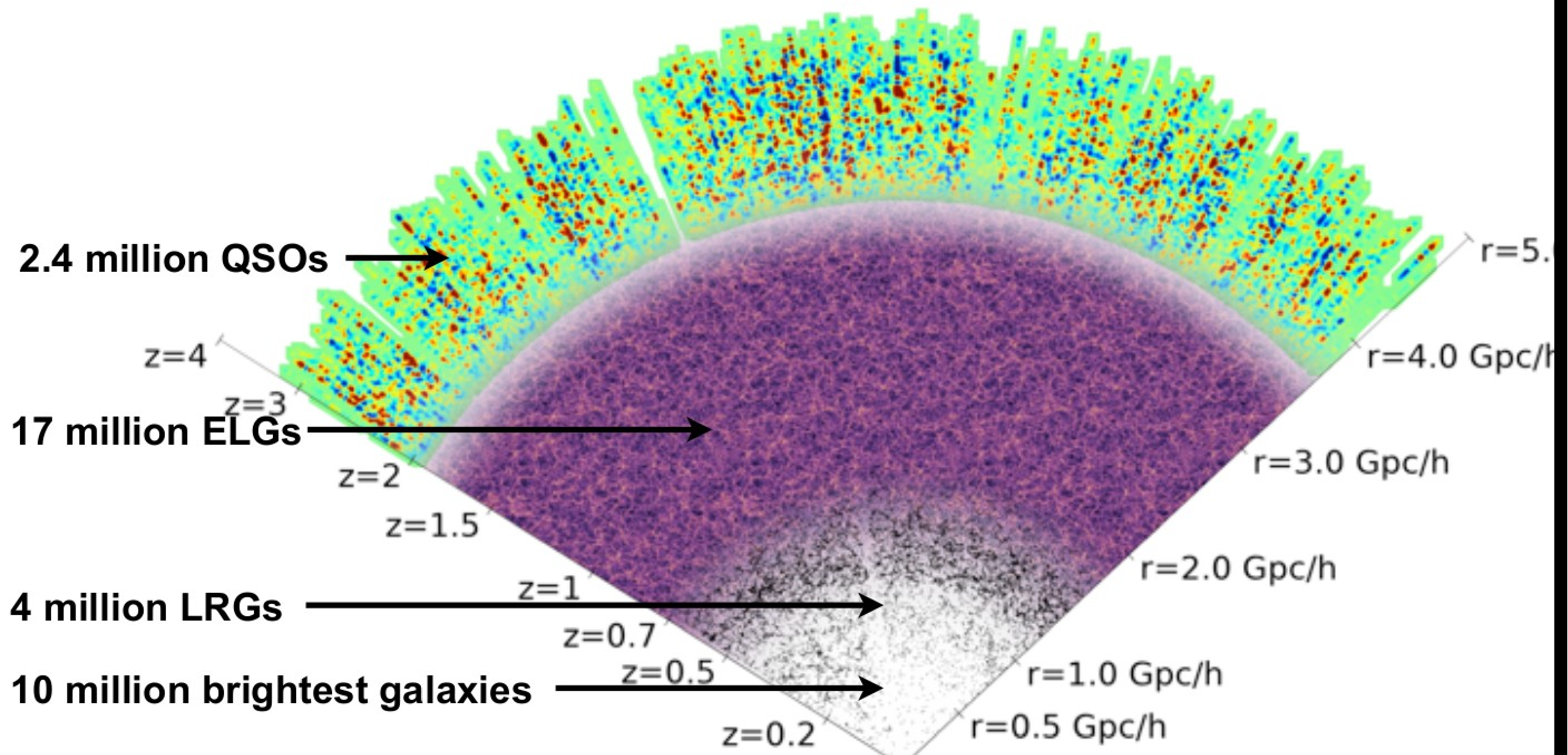
  But : **contamination of the signal** by :
  - other atomic transitions (Si III, Si II),
    and to a lesser extent (SiIV, CIV)
    (visible peaks at 25Mpc/h, 60Mpc/h,
    hidden peak at ~100Mpc/h(!))
  - High column density / damped Lyman-alpha
    systems (Font-Ribera 2012)
  - UV background / ionization fraction fluctuations
    (Gontcho a Gontcho 2014)

  <1% systematic on BAO peak (preliminary)

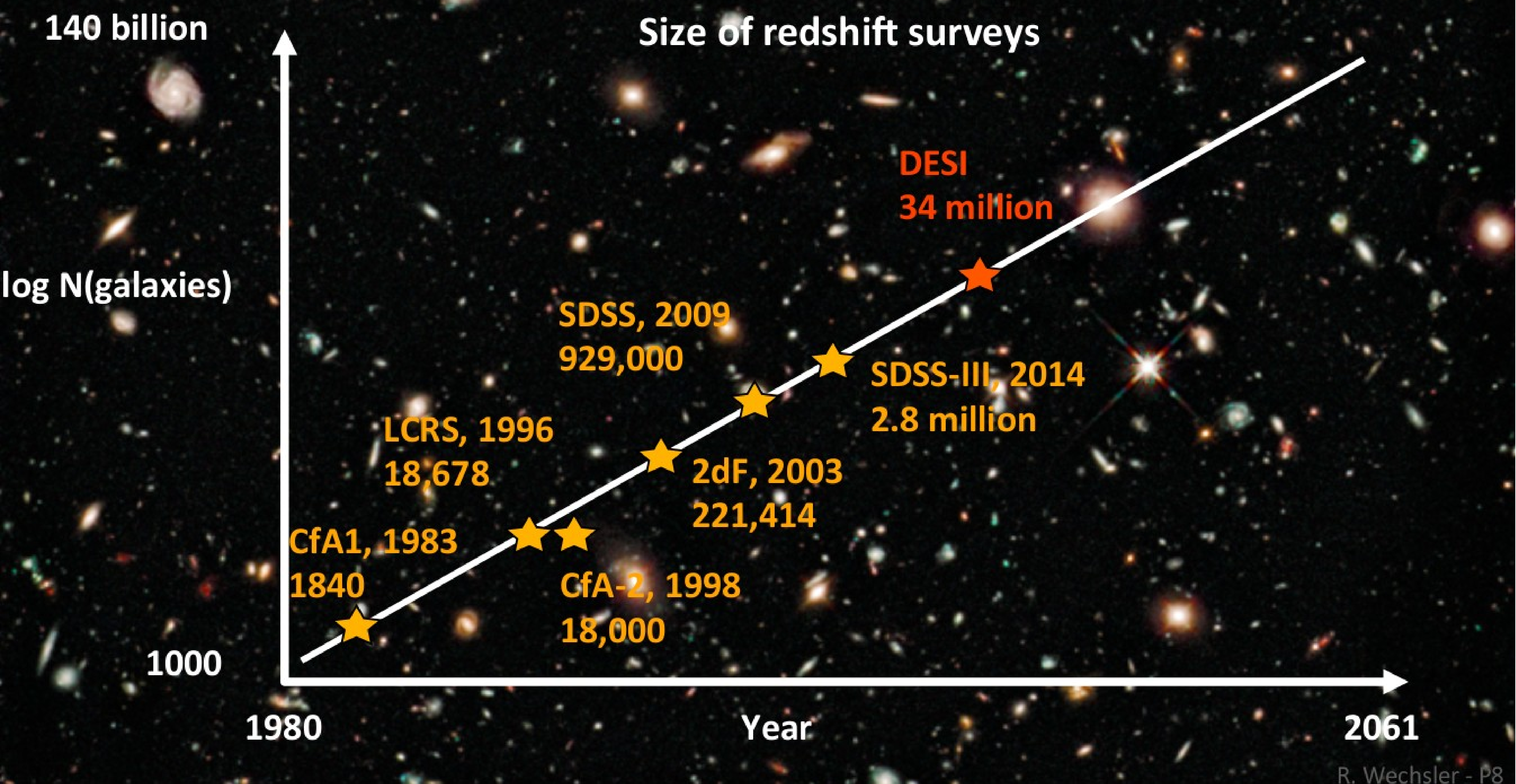


DESI spectroscopic survey 14000 deg2

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

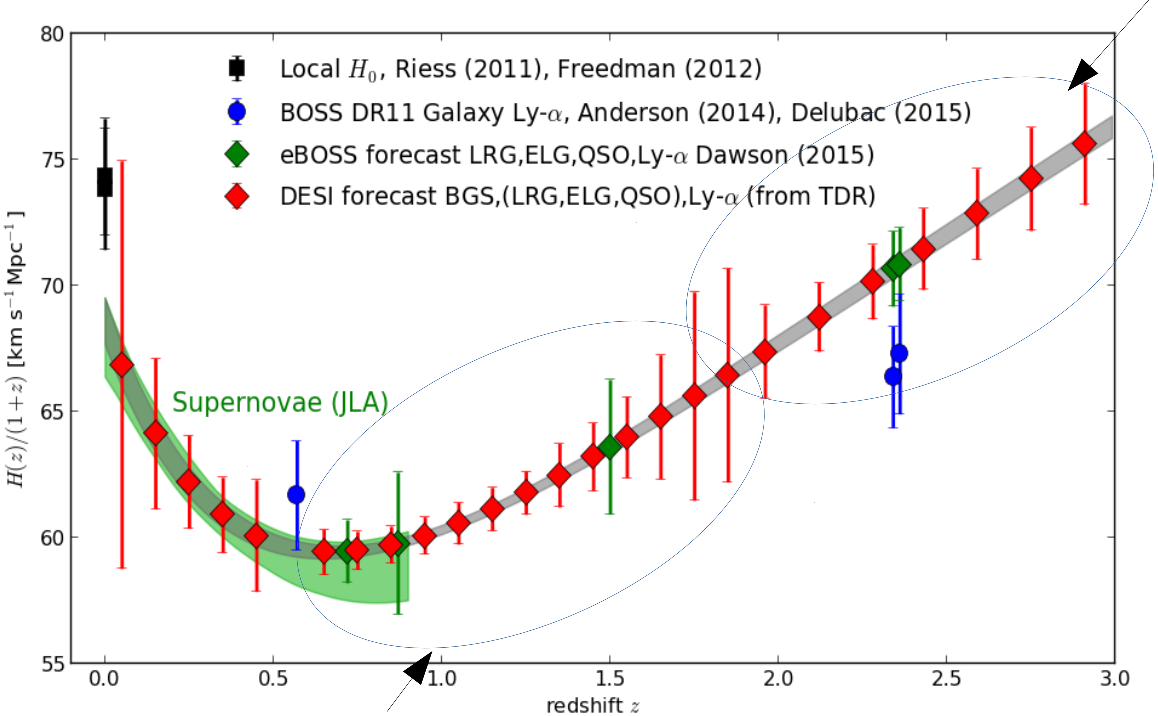


DESI ahead of the curve if completed by 2024



DESI forecast : expansion rate

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



Lyman-alpha (auto-correlation)

z	$\frac{\sigma_{R/s}}{R/s}$ (%)	$\frac{\sigma_{D_A/s}}{D_A/s}$ (%)	$\frac{\sigma_{Hs}}{Hs}$ (%)	$\frac{dN_{QSO}}{dz\ \mathrm{ddeg}^2}$
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

Galaxies (including QSOs)

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}Gpc^3]	$\frac{dN_{ELG}}{dz\ \mathrm{ddeg}^2}$	$\frac{dN_{LRG}}{dz\ \mathrm{ddeg}^2}$	$\frac{dN_{QSO}}{dz\ \mathrm{ddeg}^2}$	$\frac{\sigma_{f\sigma_{0.1}}}{f\sigma_{0.1}}$ %	$\frac{\sigma_{f\sigma_{0.2}}}{f\sigma_{0.2}}$ %
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

DETF Figures of Merit

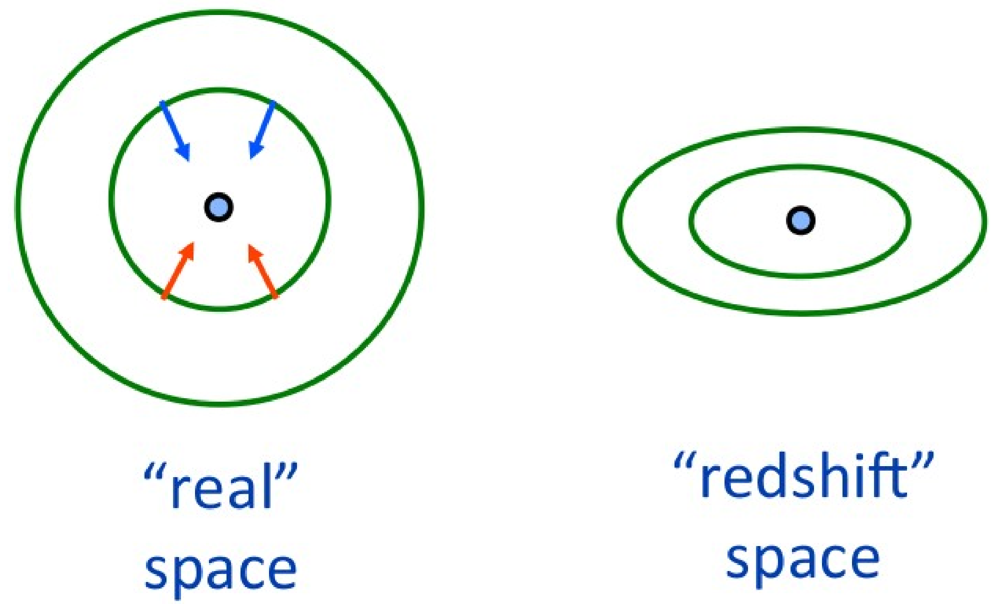
- DESI BAO + Planck CMB meets the Stage IV threshold even for the 9k deg^2 minimal survey: FoM = 121.
  - Stage IV is >10x Stage II, taken to be FoM=11 from Sullivan et al. (2011). Same as LSST review standard.
  - Note that DESI FoM neglects even current SNe and WL/Cluster constraints, whereas the Stage II analysis was CMB+SN+BAO.

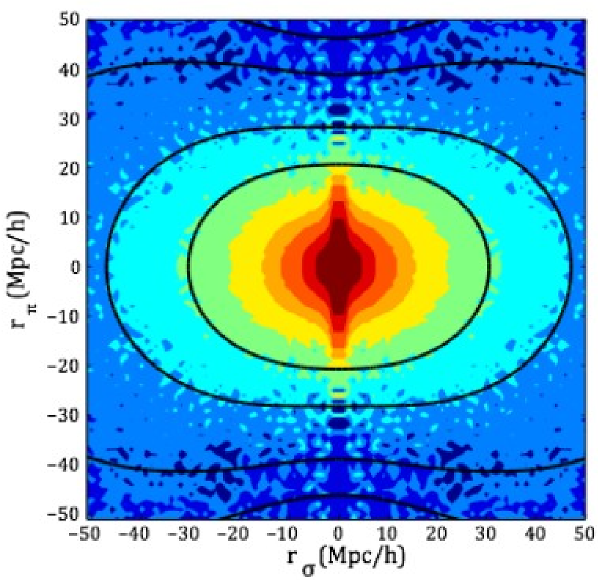
Surveys	FoM	a_p	σ_{w_p}	σ_{Ω_k}
BOSS BAO	37	0.65	0.055	0.0026
DESI 14k galaxy BAO	133	0.69	0.023	0.0013
DESI 14k galaxy and Ly-α forest BAO	169	0.71	0.022	0.0011
DESI 14k BAO + gal. broadband to $k < 0.1\ h\ \mathrm{Mpc}^{-1}$	332	0.74	0.015	0.0009
DESI 14k BAO + gal. broadband to $k < 0.2\ h\ \mathrm{Mpc}^{-1}$	704	0.73	0.011	0.0007

(slide from D. Eisenstein)

Beyond BAO

- There is significantly more information in the galaxy power spectrum than just the information from BAO
  - Growth rate
  - Neutrinos
  - Inflation





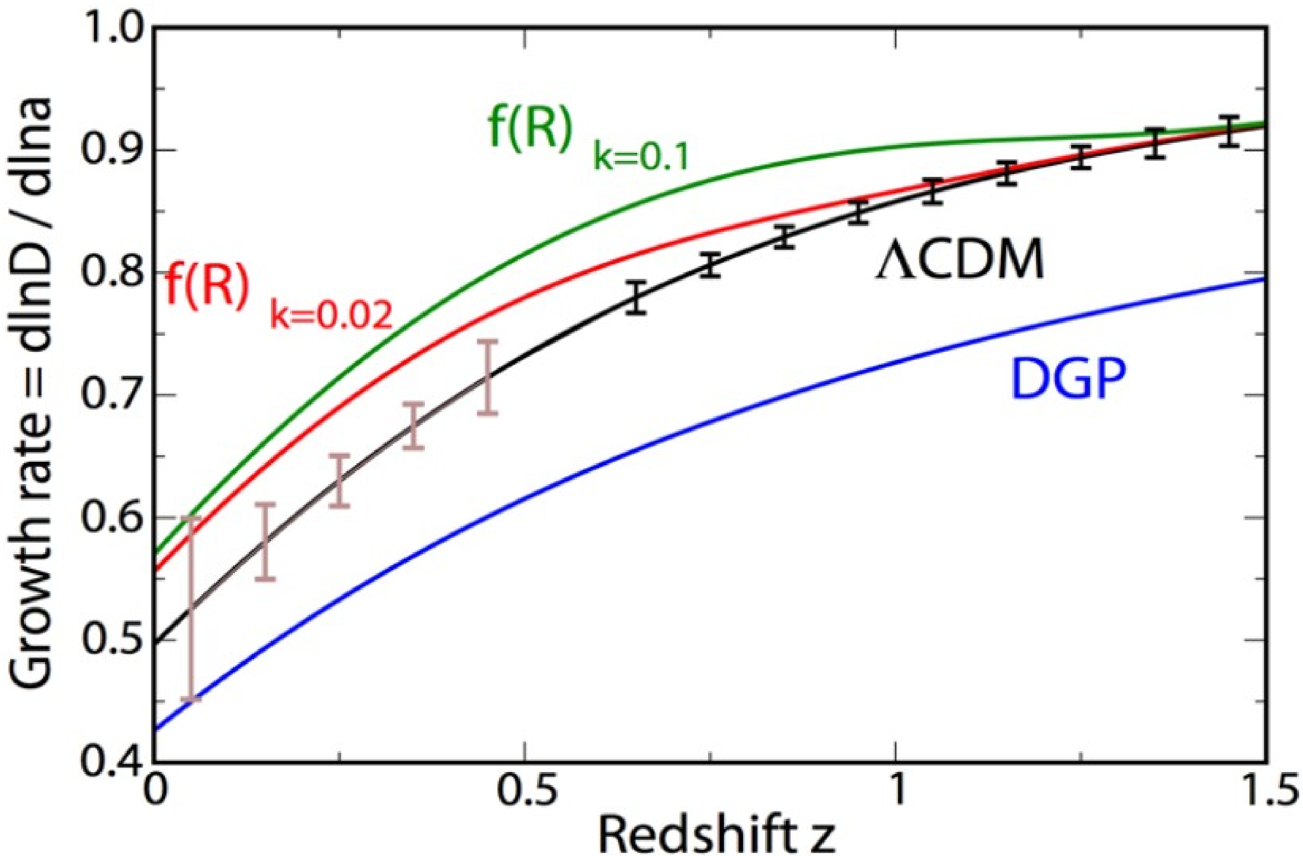
observed redshift space distortions from BOSS

- Anisotropy in the correlation function constrains $f\sigma 8$, where f is the growth rate
- Produces a test of GR
- DESI will measure the growth rate <1% over $0.0 < z < 1.4$

(slide from R. Weschler)

Growth Complements Distance

- Combining distance measurements with growth of structure measurements distinguishes between dark energy and modified gravity as the source of cosmic acceleration.



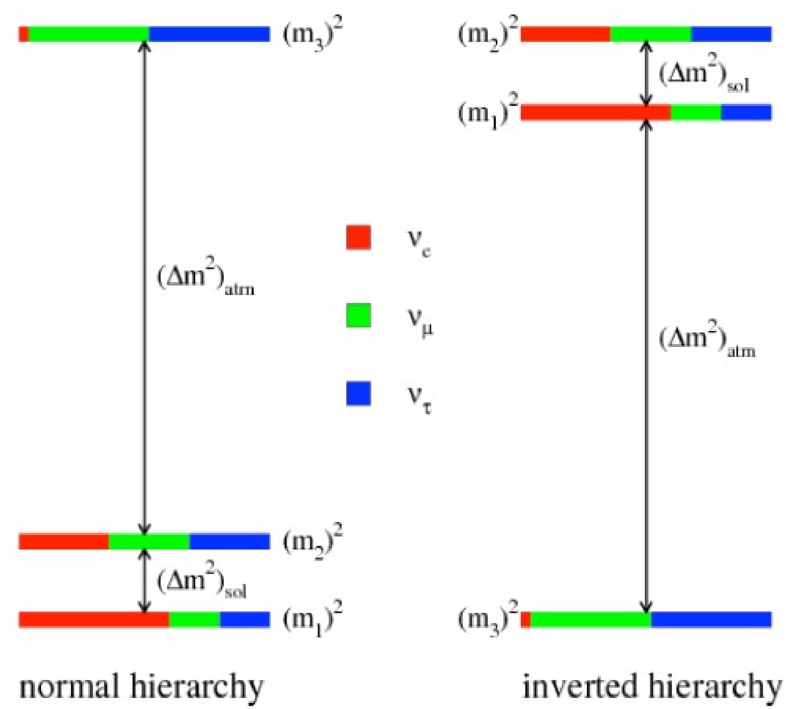
(slide from R. Weschler)

TDR Figure 2.12

DESI measures the total neutrino mass

- Large-scale structure (LSS) is sensitive to neutrino properties
- Massive neutrinos decrease small-scale power at low redshift
  - DESI can measure an error of 0.02 eV in the sum of masses, enough to start to distinguish the normal and inverted hierarchy of mass states
- Extra relativistic species (such as sterile neutrinos) can also be measured with LSS and CMB

Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\max} = 0.1h\,\mathrm{Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\max} = 0.2h\,\mathrm{Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\max} = 0.2$)	0.020	0.062

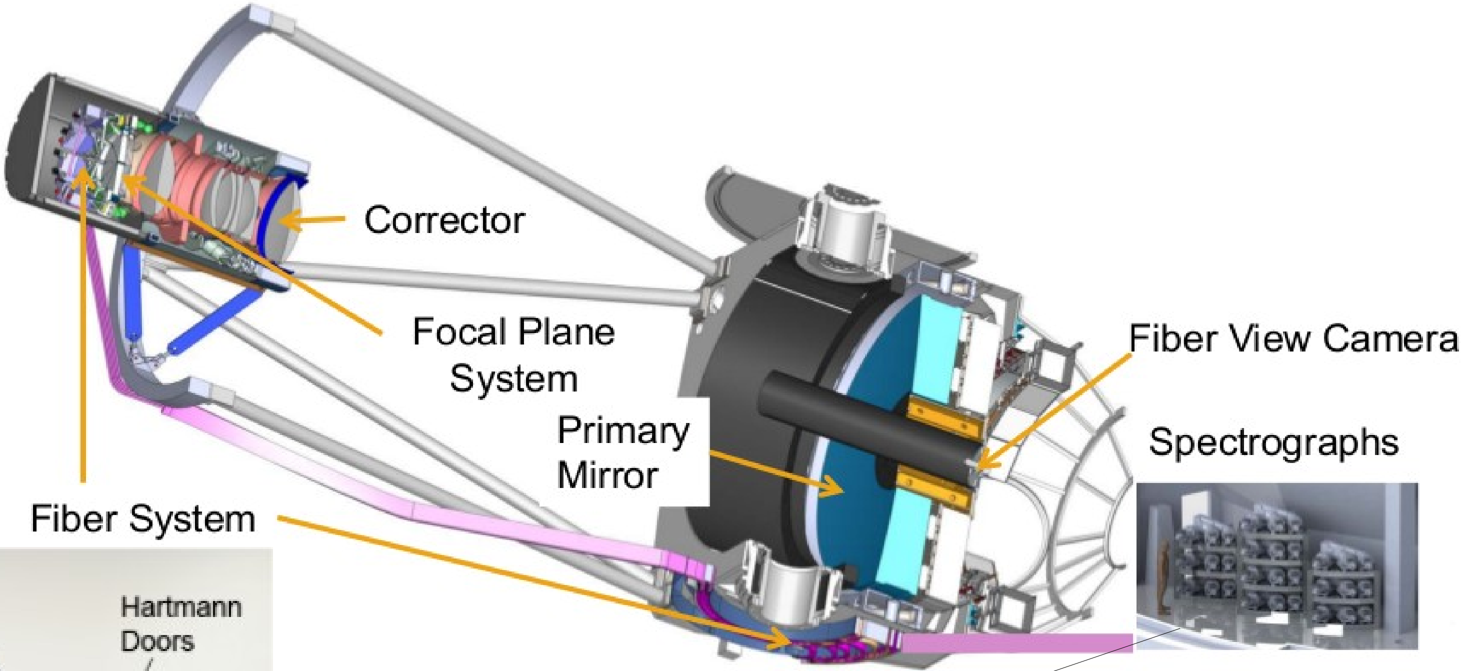


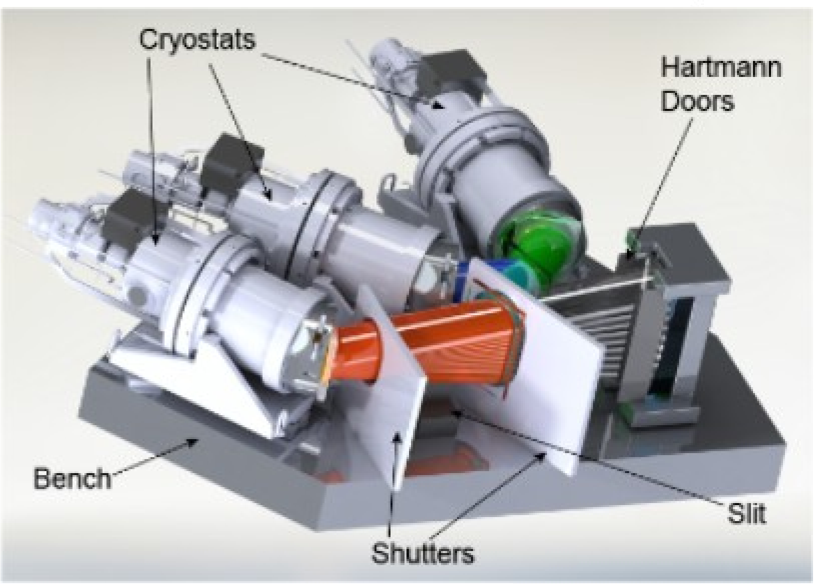
TDR Table 2.11, Figure 2.14

(slide from R. Weschler)

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





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**

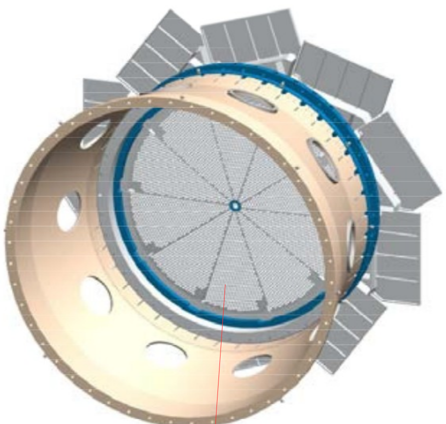
  and 20 times faster for QSOs (no resolution gain)

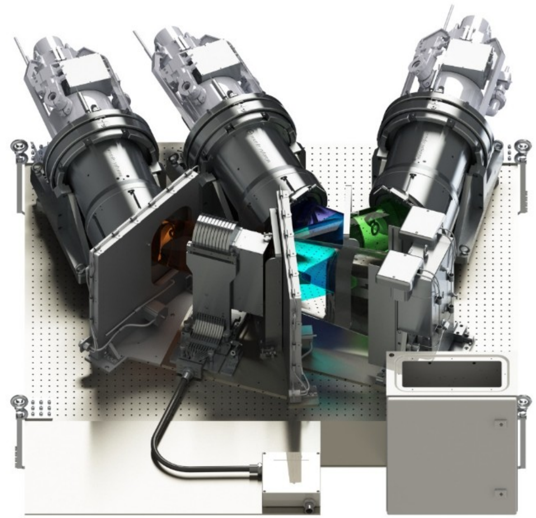
DESI Project Status

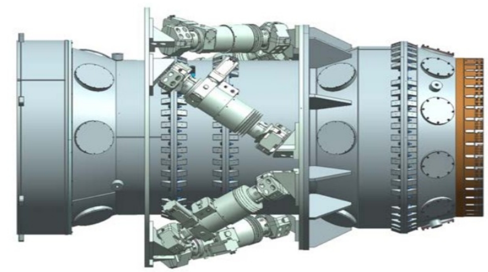
- Funded
- Final Design Review on going, Director's review in April, CD-3 in May 2016
- Commissioning : mid 2019

- Beginning of survey : end 2019

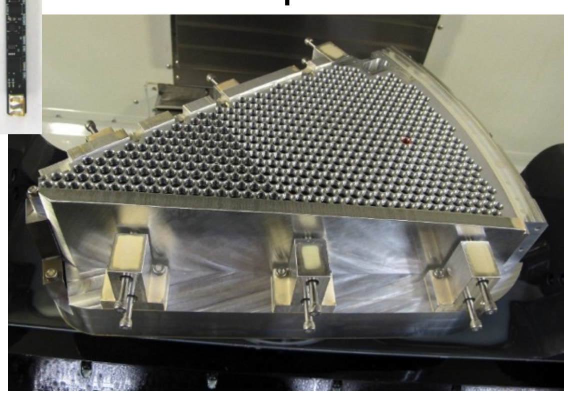
Construction has started ...



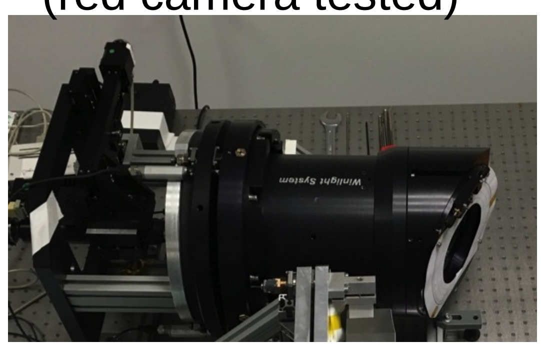




Focal plane

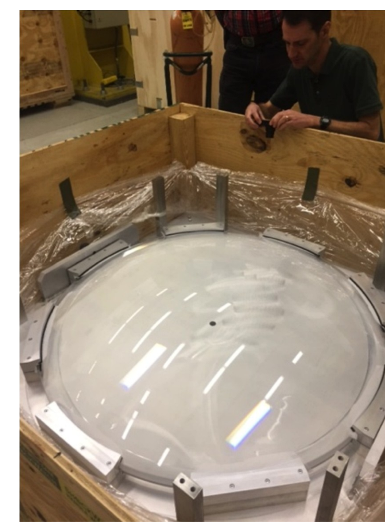


Spectrograph #0
(red camera tested)



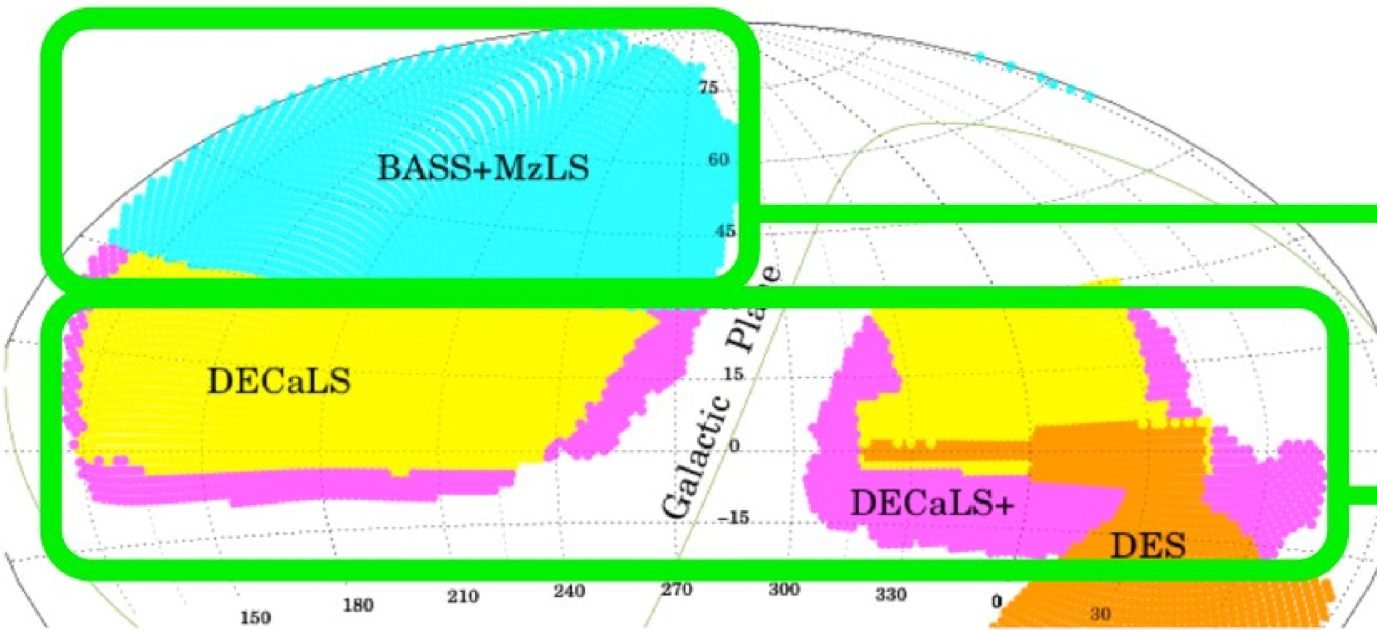
Corrector barrel

Lenses



DESI Imaging

- 14,000 sq. degree footprint defined by low Galactic and atmospheric extinction
- DESI targeting requires new imaging over this area



"North cap":

Accessible from Northern telescopes only

Bok (gr) + Mayall (z)

"Equatorial":

Accessible from Northern or Southern telescopes

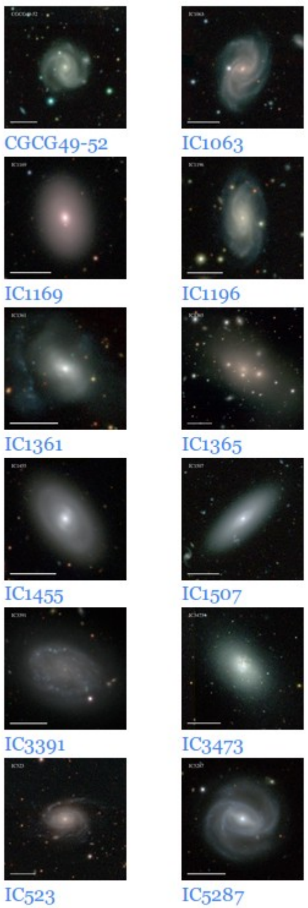
Imaging surveys are on going ...

DECam, including DECALS project started August 2014

(slide from R. Weschler)

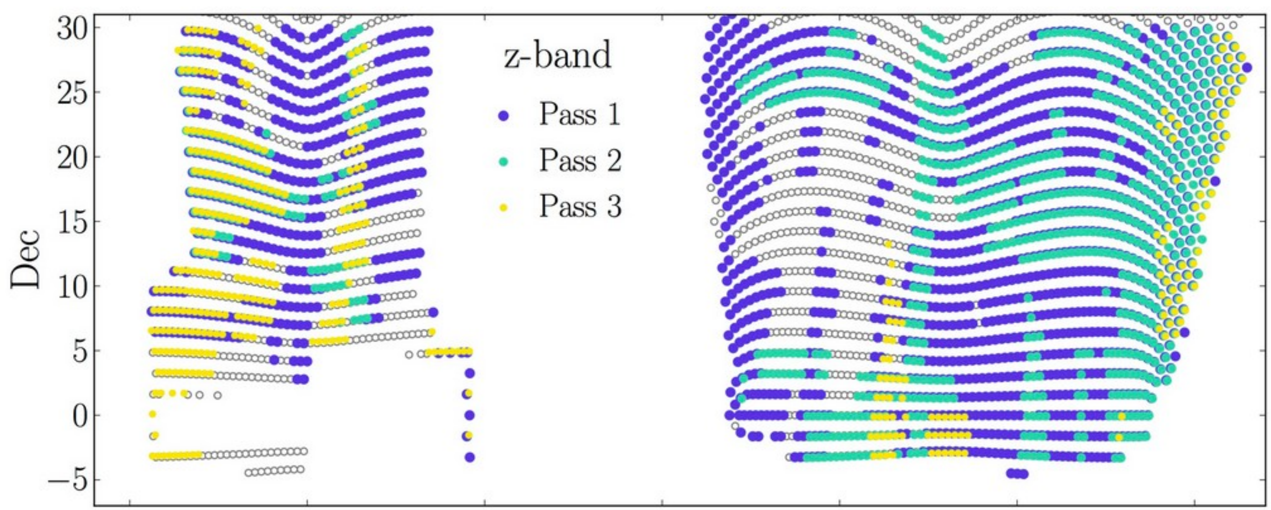
Dark Energy Camera Legacy Survey (DECaLS)

http://legacysurvey.org/decamls/ (data release 2 is public)



With DECam,
6700 deg2 of the SDSS/BOSS extragalactic footprint
in the region -20 deg < dec < +30 deg
depths of g=24.7, r=23.9, and z=23.0 AB mag
(5-sigma point-source)

status of z-band in december 2015



DESI Collaboration

The DESI Collaboration now has ~200 Participants

Project Director M. Levi (LBNL)
Spokespersons D. Eisenstein (Harvard), R. Weschler (SLAC)

USA (ANL, Arizona, BNL, BU, CMU, Cornell, FNAL, Harvard, Irvine, LBNL, LLNL, Michigan, NOAO, OSU, Pennsylvania, Pittsburgh, Siena, SLAC, SMU, UCB, UCSC, Utah, Yale) **Canada** (Toronto) , **China** (NAOC) , **Colombia** (Andes) , **France** (CEA, CPPM, LAM, LPNHE, OHP) , **Korea** (KASI,KIAS) , **Mexico** , **Spain** (Barcelona, Madrid) , **Switzerland** (EPFL, ETHZ) , **UK** (Durham, Portsmouth, UCL)

DESI Collaboration
Working groups

Imaging & targeting
- Mayall Legacy Survey
- BASS Survey
- DECam Legacy Survey
- Image Validation Task Force
- Target Selection

Operations
- Survey Design
- Time Domain Science Committee
- Spectroscopic Pipeline
- Data Distribution Committee

Science working groups
- Galaxy & Quasar Clustering
- Lyman-alpha Forests
- Cosmo Simulation
- Clustering, Clusters & Cross-Correlation
- Bright Galaxy Survey
- Milky Way Survey
- Galaxy & Quasar Physics

Actively working today

on-going imaging surveys & validation,
pilot surveys for targeting,
important activity pipeline, simulations
(detailed and fast),

science planning in 4 phases :
science readiness plan (science WG),
commissioning, science verification,
survey design

(+ huge construction/infrastructure
activity on the project side !)

DESI : the challenges

- actually build the instrument !

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

- data processing : convert ~30 millions observed spectra
  into 3D galaxy catalogs and Lya forests

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

    - efficiency (targeting, fiber assignment, spectroscopic redshift
      and identification) vs target properties
      correlated with their clustering bias

    - spurious signal in the Lya forests

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 experience :

    - QSO clustering
    - ELGs (targeting, clustering)
    - eBOSS faces significant redshift inefficiencies :
      forward modeling of spectroscopic efficiency starting

* Important work ahead of the survey start

  Simulations of everything , data challenges

Conclusion

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

- Baryon Acoustic Oscillations are a key probe of Dark Energy, complementary to supernovae Ia with low systematics

- DESI is a massive spectroscopic survey, first light end of 2019, with very impressive forecasts,

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

So ... exciting times ...