DESI
The Dark Energy Spectroscopic Instrument

Julien Guy (LPNHE/Paris)
Moriond Cosmology, March 2016
Dark Energy puzzle

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

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

\[
m_P = \sqrt{\frac{\hbar c}{G}} \rightarrow \rho_P \sim (10^{19} \text{GeV})^4
\]

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

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

\[
\rho_{\text{Higgs}} \sim (10^2 \text{GeV})^4
\]

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

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- 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)

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

(from M. White, D. Eisenstein)
Baryon Acoustic Oscillations in the CMB at $z \sim 1000$

Planck 2015

$\Delta P_T / P_T$

in Lyman-alpha forests at $z \sim 2.3$

in the galaxy density field

Afterglow Light Pattern 360,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy

Accelerated Expansion

Inflation

Quantum Fluctuations

1st Stars about 400 million yrs.

Big Bang Expansion

13.7 billion years

BOSS DR11

$z \sim 0.6$

$z \sim 0.2$

Dark Energy Spectroscopic Instrument

Moriond 2016, J.Guy LPNHE/Paris
Great success of SDSS3/BOSS (here DR11 results, 90% of the data)

\[
\alpha_\perp \equiv \left[ \frac{D_A}{r_d} \right] \left[ \frac{r_d}{D_A} \right]_{fid} \\
\alpha_\parallel \equiv \left[ \frac{1}{(r_d H)} \right] \left[ r_d H \right]_{fid}
\]

<table>
<thead>
<tr>
<th>BOSS DR11 sub-sample</th>
<th>(z)</th>
<th>(\alpha_{iso})</th>
<th>(\alpha_\perp)</th>
<th>(\alpha_\parallel)</th>
<th>(corr(\alpha_\perp, \alpha_\parallel))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOSS LOWZ sample</td>
<td>0.32</td>
<td>0.020</td>
<td>...</td>
<td>...</td>
<td>......</td>
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<td>BOSS CMASS sample</td>
<td>0.57</td>
<td>0.010</td>
<td>0.014</td>
<td>0.035</td>
<td>-0.52</td>
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<tr>
<td>LyaF auto-correlation</td>
<td>2.34</td>
<td>0.021</td>
<td>0.055</td>
<td>0.031</td>
<td>-0.43</td>
</tr>
<tr>
<td>LyaF-QSO cross correlation</td>
<td>2.36</td>
<td>0.019</td>
<td>0.037</td>
<td>0.033</td>
<td>-0.39</td>
</tr>
<tr>
<td>Combined LyaF</td>
<td>2.34</td>
<td>0.013</td>
<td>0.032</td>
<td>0.022</td>
<td>-0.48</td>
</tr>
</tbody>
</table>
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 $H_0$
* Test of cosmological model in decelerated expansion with Lyman-alpha forests
Constraints on H(z)

**BOSS**


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

Supernovae (JLA)*
Constraints on $H(z)$

**BOSS+eBOSS**

![Graph showing constraints on $H(z)$](image)

- **Local $H_0$, Riess (2011), Freedman (2012)**
- **BOSS DR11 Galaxy Ly-α, Anderson (2014), Delubac (2015)**
- **eBOSS forecast LRG,ELG,QSO,Ly-α Dawson (2015)**

**Recession speed in km/s of galaxies separated by 1 Mpc today $H(z)/(1+z)$ [km s$^{-1}$ Mpc$^{-1}$]**

- **Supernovae (JLA)**

**Time**

---

Dark Energy Spectroscopic Instrument

Moriond 2016, J.Guy LPNHE/Paris
Constraints on H(z)

BOSS+eBOSS+DESI

Recession speed in km/s of galaxies separated by 1 Mpc today

$H(z)/(1+z)$ [km s$^{-1}$ Mpc$^{-1}$]

redshift $z$

time

Supernovae (JLA)

Local $H_0$, Riess (2011), Freedman (2012)


eBOSS forecast LRG,ELG,QSO,Ly-α Dawson (2015)

DESI forecast BGS,(LRG,ELG,QSO),Ly-α (from TDR)
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 instrumental 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 Lya-alpha, **negligible non-linear effects on BAO scale** (based on hydro simulations, McDonald 2006, Arinyo-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 $\sim 2h^{-3}\text{Gpc}^3 \rightarrow$ BOSS $\sim 6h^{-3}\text{Gpc}^3 \rightarrow$ DESI $50h^{-3}\text{Gpc}^3$

2.4 million QSOs
17 million ELGs
4 million LRGs
10 million brightest galaxies
DESI ahead of the curve if completed by 2024

Size of redshift surveys

140 billion

log \( N(\text{galaxies}) \)

1980

1996

CfA1, 1983
18,400

LCRS, 1996
18,678

SDSS, 2009
929,000

2dF, 2003
221,414

CfA-2, 1998
18,000

DESI
34 million

2014

SDSS-III, 2014
2.8 million

2061

R. Wechsler - P8
DESI forecast: expansion rate
(Technical Design report http://desi.lbl.gov/tdr)

Galaxies (including QSOs)

<table>
<thead>
<tr>
<th>$z$</th>
<th>$\sigma_R/\sigma_R$</th>
<th>$\sigma_D/\sigma_A$</th>
<th>$\sigma_H/\sigma_H$</th>
<th>$n_{P_{0.2}}$</th>
<th>$n_{P_{0.4}}$</th>
<th>$V$</th>
<th>$dN_{E&amp;G}/dz/d\text{ddeg}^2$</th>
<th>$dN_{L&amp;G}/dz/d\text{ddeg}^2$</th>
<th>$dN_{QSO}/dz/d\text{ddeg}^2$</th>
<th>$\sigma_{f_{P0.1}}$</th>
<th>$\sigma_{f_{P0.2}}$</th>
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<td>6.23</td>
<td>2.63</td>
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<td>832</td>
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<td>0.75</td>
<td>0.48</td>
<td>0.69</td>
<td>1.27</td>
<td>3.63</td>
<td>9.25</td>
<td>3.15</td>
<td>2269</td>
<td>986</td>
<td>55</td>
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<td>0.85</td>
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<td>662</td>
<td>61</td>
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<td>0.95</td>
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<td>1.65</td>
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<td>1.75</td>
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<td>4.64</td>
<td>6.30</td>
<td>0.05</td>
<td>0.12</td>
<td>6.30</td>
<td>0</td>
<td>0</td>
<td>87</td>
<td>8.91</td>
<td>6.81</td>
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<tr>
<td>1.85</td>
<td>2.92</td>
<td>4.71</td>
<td>6.39</td>
<td>0.05</td>
<td>0.12</td>
<td>6.43</td>
<td>0</td>
<td>0</td>
<td>86</td>
<td>9.25</td>
<td>7.07</td>
</tr>
</tbody>
</table>

Lyman-alpha (auto-correlation)
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.

<table>
<thead>
<tr>
<th>Surveys</th>
<th>FoM</th>
<th>$a_p$</th>
<th>$\sigma_{w\beta}$</th>
<th>$\sigma_{\Omega_k}$</th>
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</thead>
<tbody>
<tr>
<td>BOSS BAO</td>
<td>37</td>
<td>0.65</td>
<td>0.055</td>
<td>0.0026</td>
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<tr>
<td>DESI 14k galaxy BAO</td>
<td>133</td>
<td>0.69</td>
<td>0.023</td>
<td>0.0013</td>
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<tr>
<td>DESI 14k galaxy and Ly-\alpha forest BAO</td>
<td>169</td>
<td>0.71</td>
<td>0.022</td>
<td>0.0011</td>
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<tr>
<td>DESI 14k BAO + gal. broadband to $k &lt; 0.1 \ h \ Mpc^{-1}$</td>
<td>332</td>
<td>0.74</td>
<td>0.015</td>
<td>0.0009</td>
</tr>
<tr>
<td>DESI 14k BAO + gal. broadband to $k &lt; 0.2 \ h \ Mpc^{-1}$</td>
<td>704</td>
<td>0.73</td>
<td>0.011</td>
<td>0.0007</td>
</tr>
</tbody>
</table>

(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

- 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 $0.0 < z < 1.4$

(observed redshift space) distortions from BOSS

“real” space

“redshift” space
Growth Complements Distance

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

<table>
<thead>
<tr>
<th>Data</th>
<th>$\sigma \Sigma m_\nu$ [eV]</th>
<th>$\sigma N_{\nu,\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck</td>
<td>0.56</td>
<td>0.19</td>
</tr>
<tr>
<td>Planck + BAO</td>
<td>0.087</td>
<td>0.18</td>
</tr>
<tr>
<td>Gal ($k_{\text{max}} = 0.1h\text{ Mpc}^{-1}$)</td>
<td>0.030</td>
<td>0.13</td>
</tr>
<tr>
<td>Gal ($k_{\text{max}} = 0.2h\text{ Mpc}^{-1}$)</td>
<td>0.021</td>
<td>0.083</td>
</tr>
<tr>
<td>Ly-(\alpha) forest</td>
<td>0.041</td>
<td>0.11</td>
</tr>
<tr>
<td>Ly-(\alpha) forest + Gal ($k_{\text{max}} = 0.2$)</td>
<td>0.020</td>
<td>0.062</td>
</tr>
</tbody>
</table>

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
DESI vs SDSS/BOSS

- Mirror area x 2.4
- Number of fibers x 5
- Telescope throughput x 1.6
- Resolution x 2.3 at 7000Å (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 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

Imaging surveys are on going ...

“North cap”:
Accessible from Northern telescopes only
Bok (gr) + Mayall (z)

“Equatorial”:
Accessible from Northern or Southern telescopes

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

**Operations**
- Survey Design
- Time Domain Science Committee
- Spectroscopic Pipeline
- Data Distribution Committee
  
  science planning in 4 phases:
  science readiness plan (science WG), commissioning, science verification, survey design

**Science working groups**
- Galaxy & Quasar Clustering
- Lyman-alpha Forests
- Cosmo Simulation
- Clustering, Clusters & Cross-Correlation
- Bright Galaxy Survey
- Milky Way Survey
- Galaxy & Quasar Physics
  
  (+ huge construction/infrastructure activity on the project side !)

Dark Energy Spectroscopic Instrument

Moriond 2016, J.Guy LPNHE/Paris
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 ...