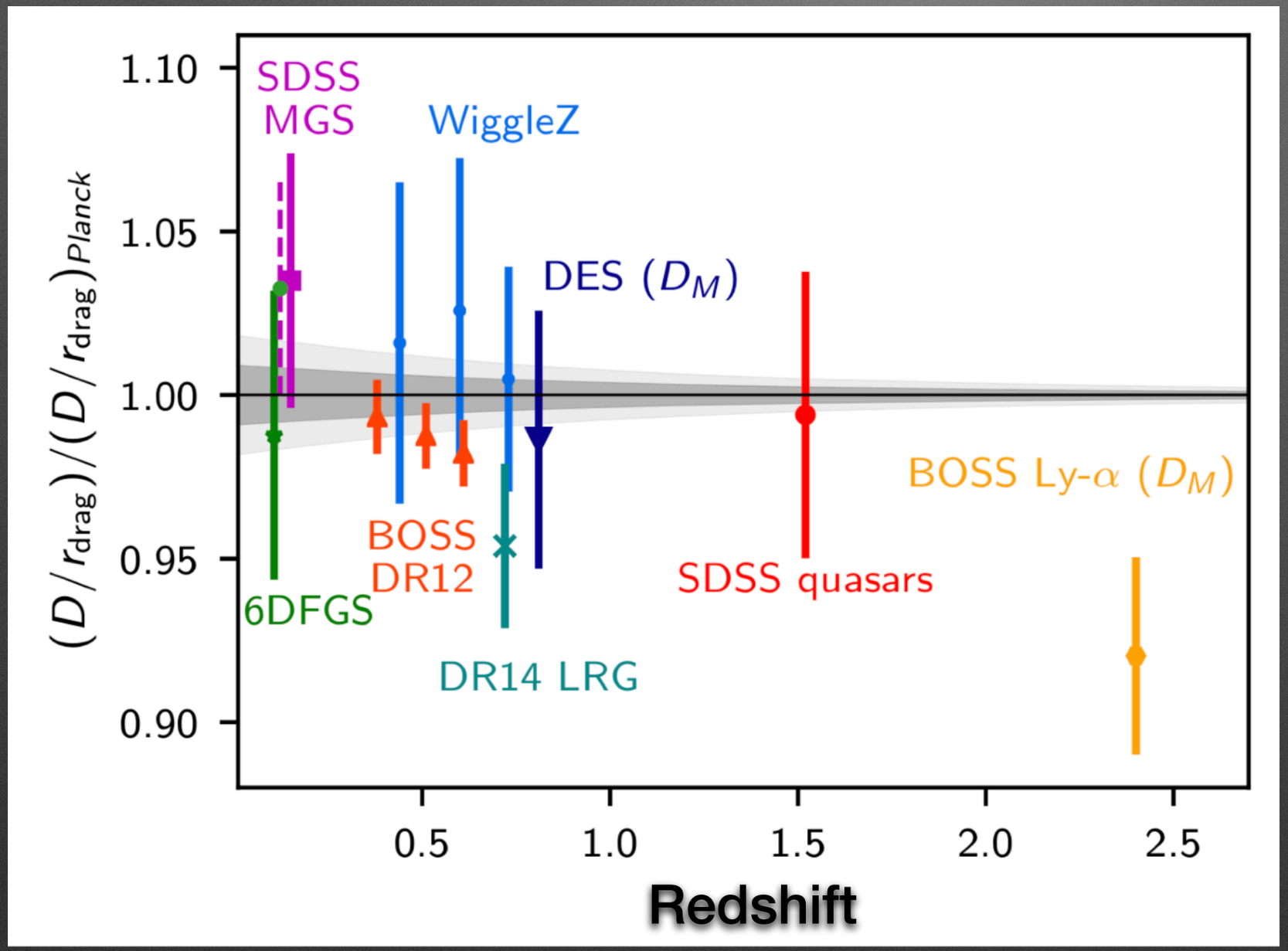
O legado cosmológico do Sloan Digital Sky Survey

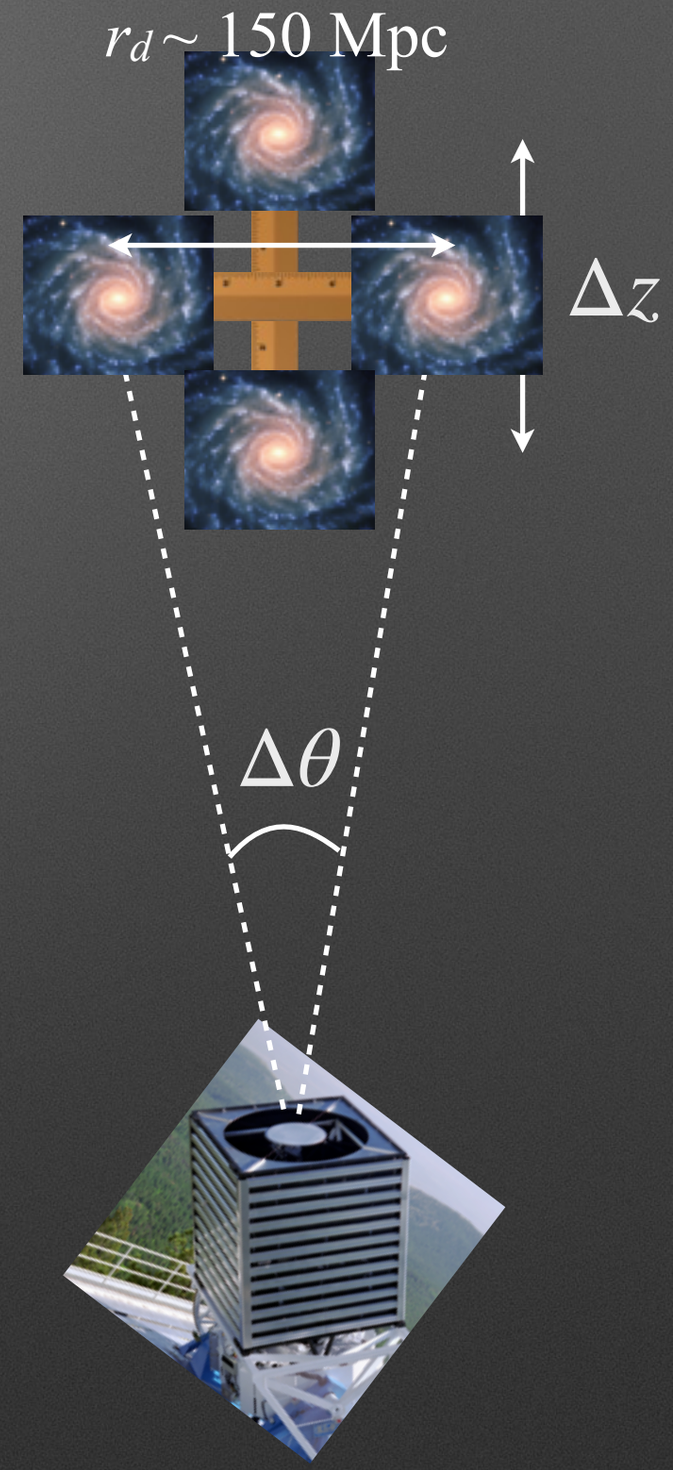
Julian Bautista
Institute of Cosmology and Gravitation - University of Portsmouth, UK

LIneA Webinar
31 Outubro de 2019

- Medindo a história cósmica com o Sloan
- Medidas com eBOSS DR14
- DESI

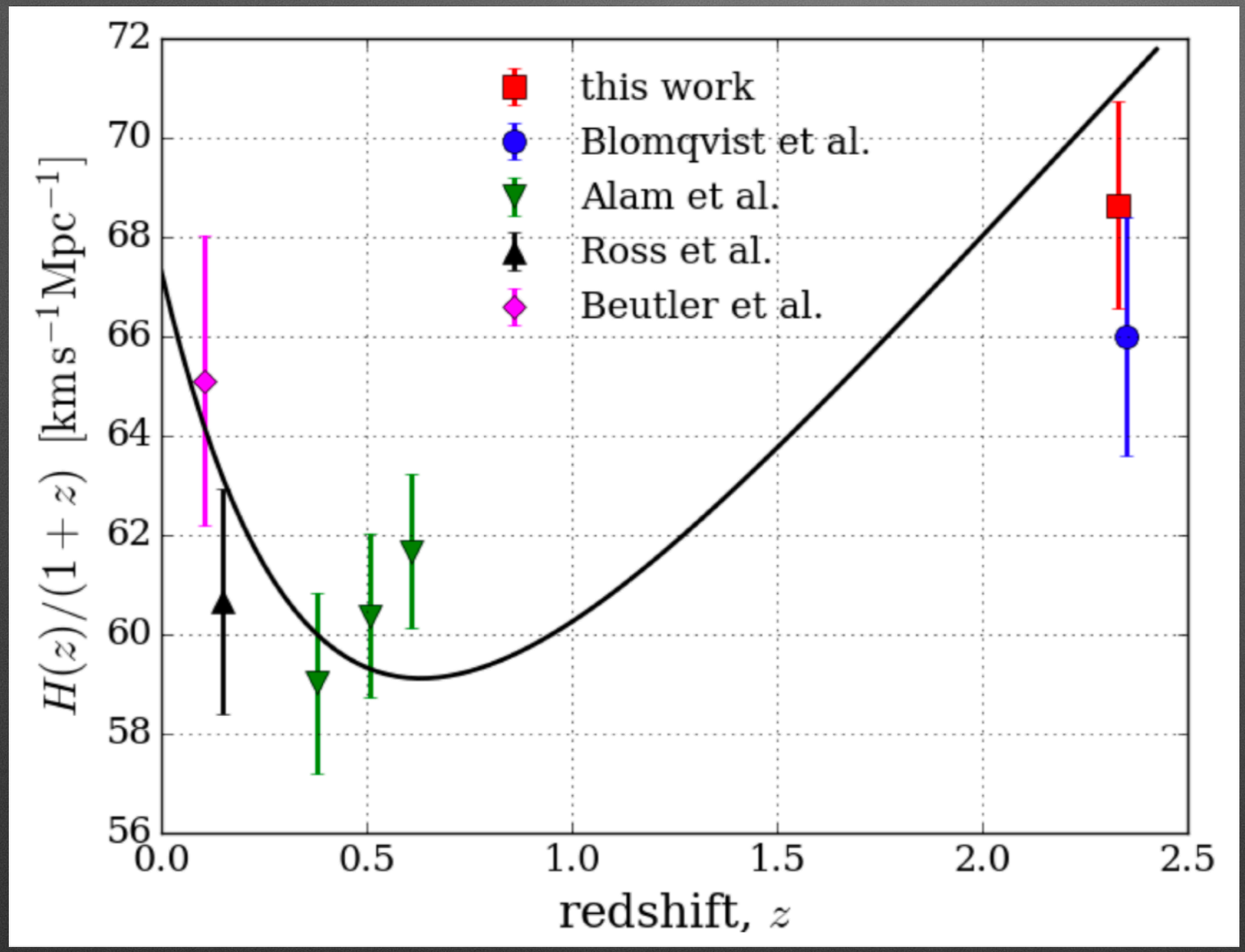
Ângulo medido / Ângulo previsto por um modelo

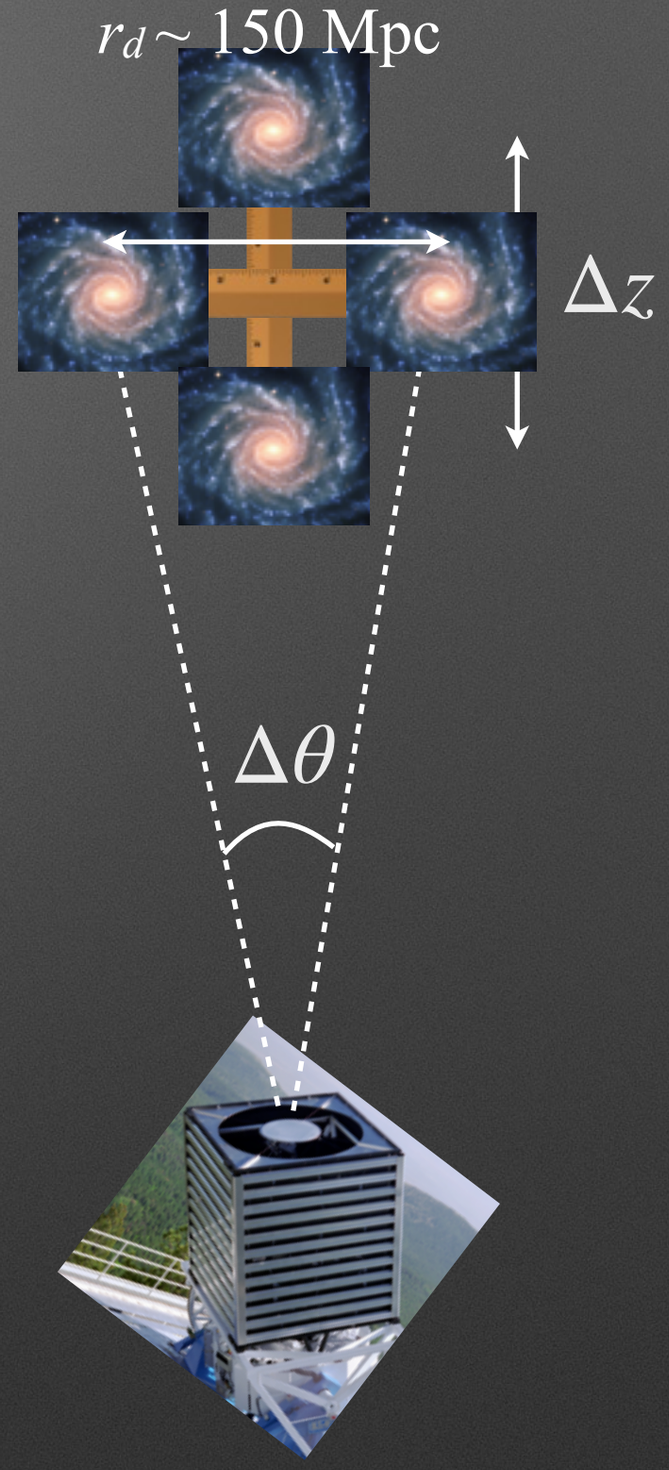




Planck Collaboration 2018 Paper VI

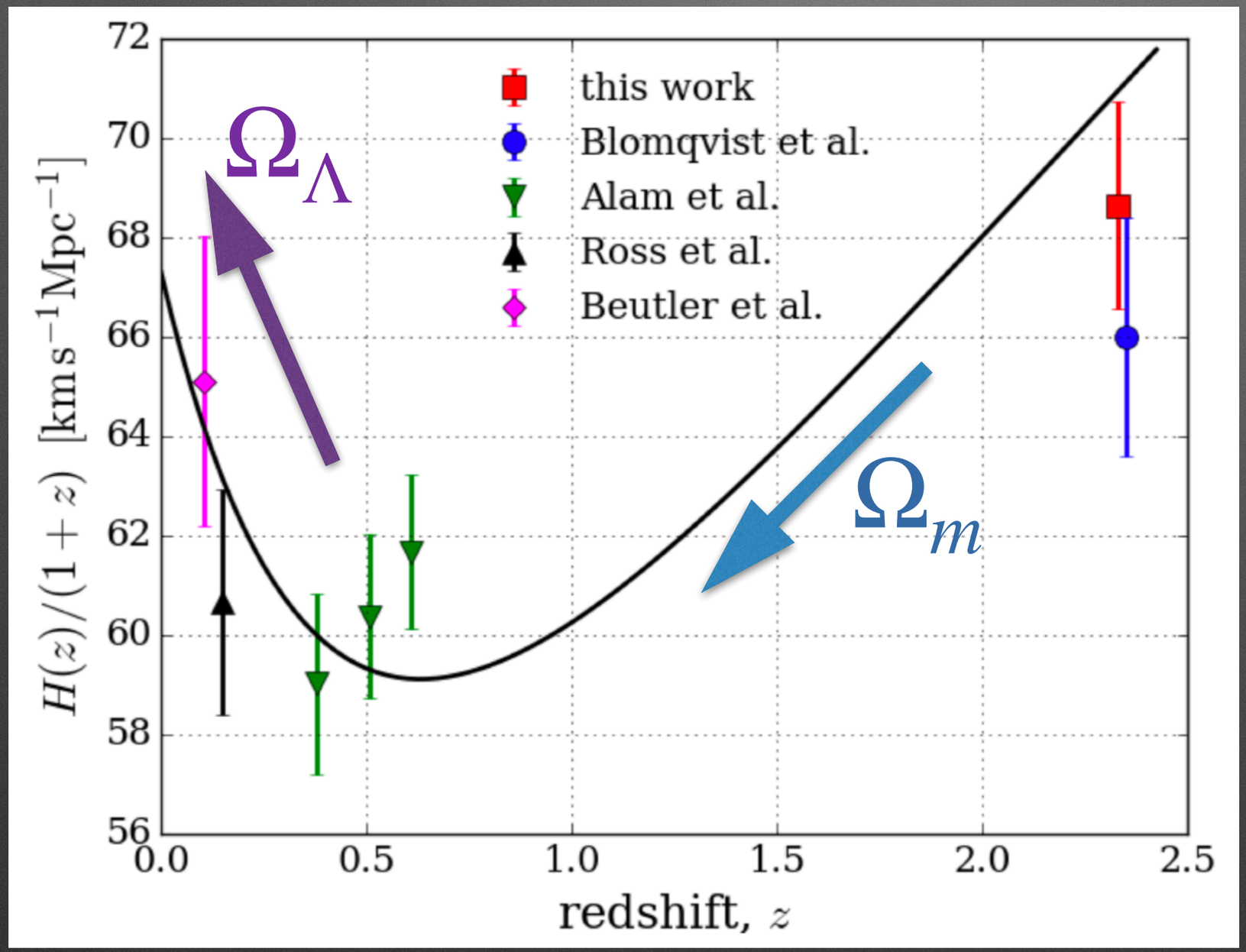
"Velocidade de expansão"

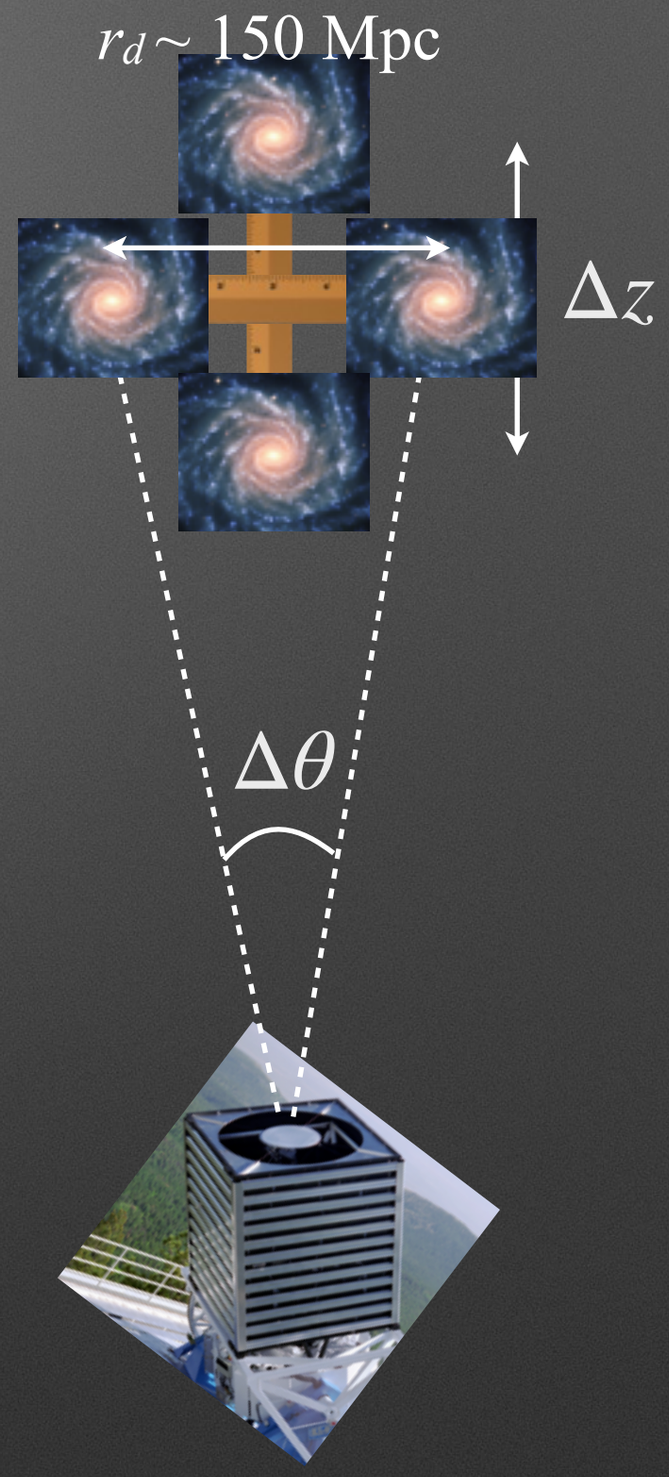




de Sainte Agathe et al. 2019
Blomqvist et al. 2019

"Velocidade de expansão"

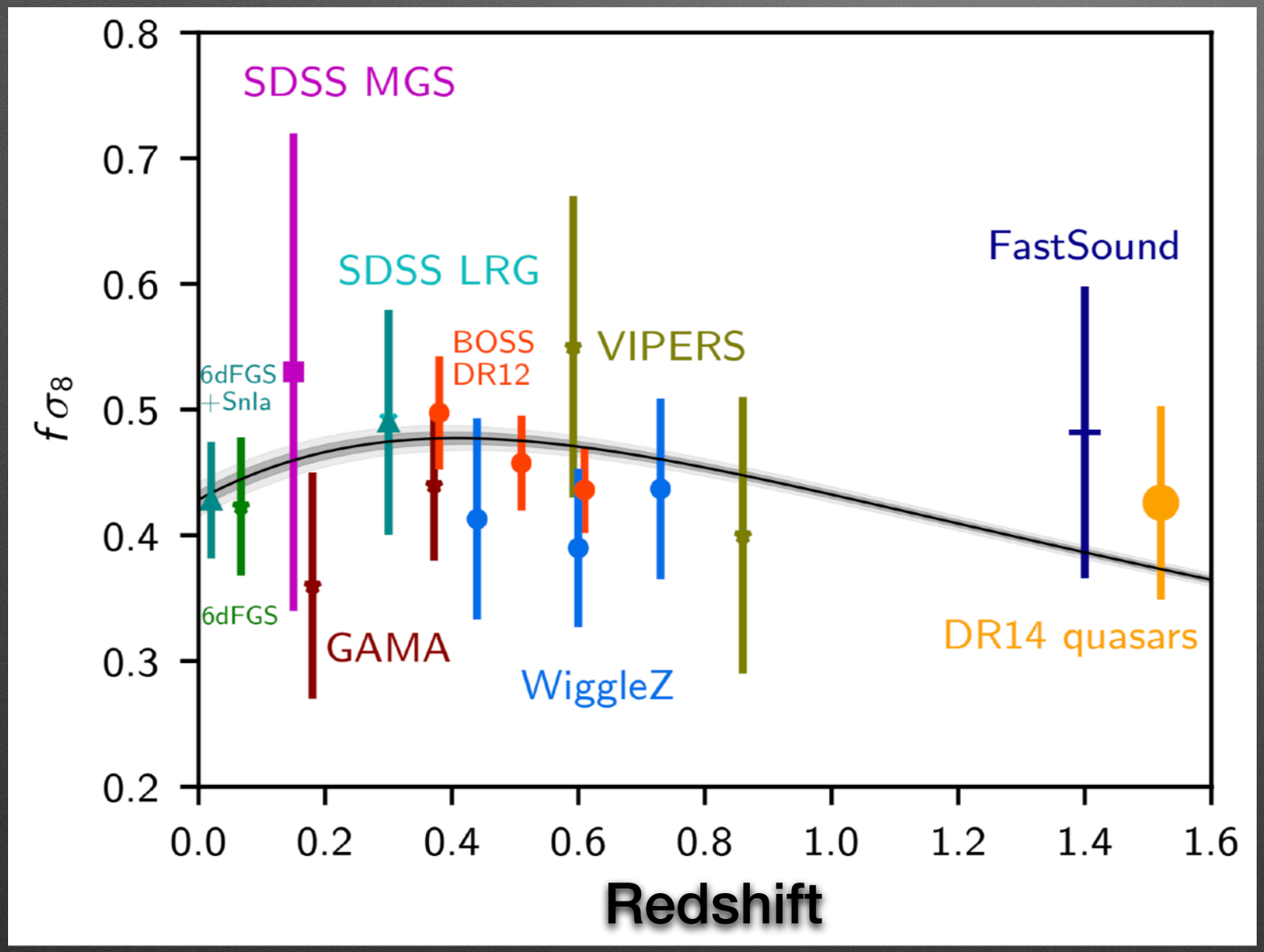




$$H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3 + \ldots}$$

de Sainte Agathe et al. 2019
Blomqvist et al. 2019

"Taxa de crescimento das estruturas"



Dinâmica das estruturas

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_M\delta = 0$$

$$\delta(z) = D(z)\delta(z=0)$$

$$f(z) = \frac{d\ln D}{d\ln a}$$

Em LCDM:

$$f(z) \sim \Omega_m^{\gamma}(z)$$

Planck Collaboration 2018 Paper VI

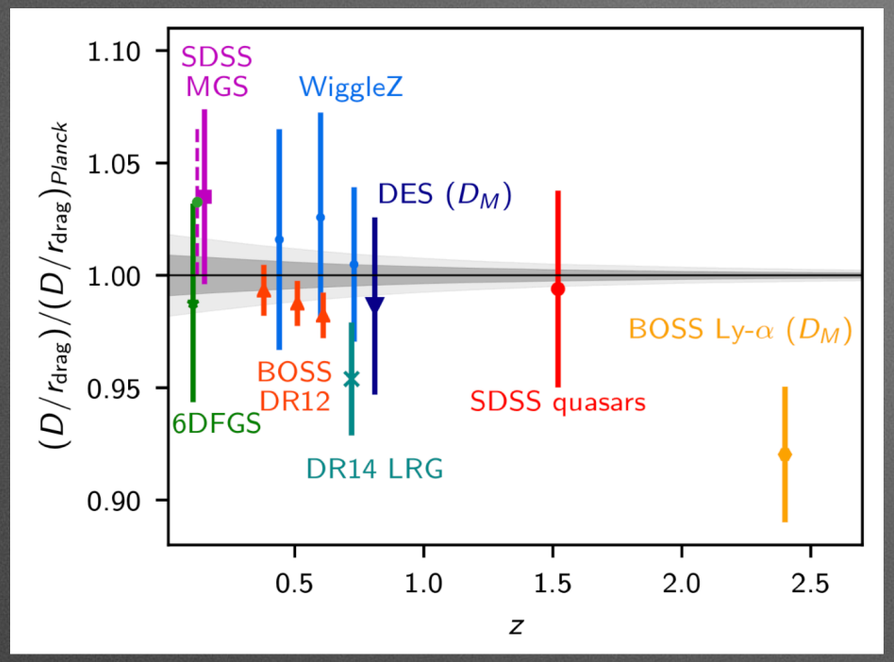
Medidas cosmológicas com estruturas

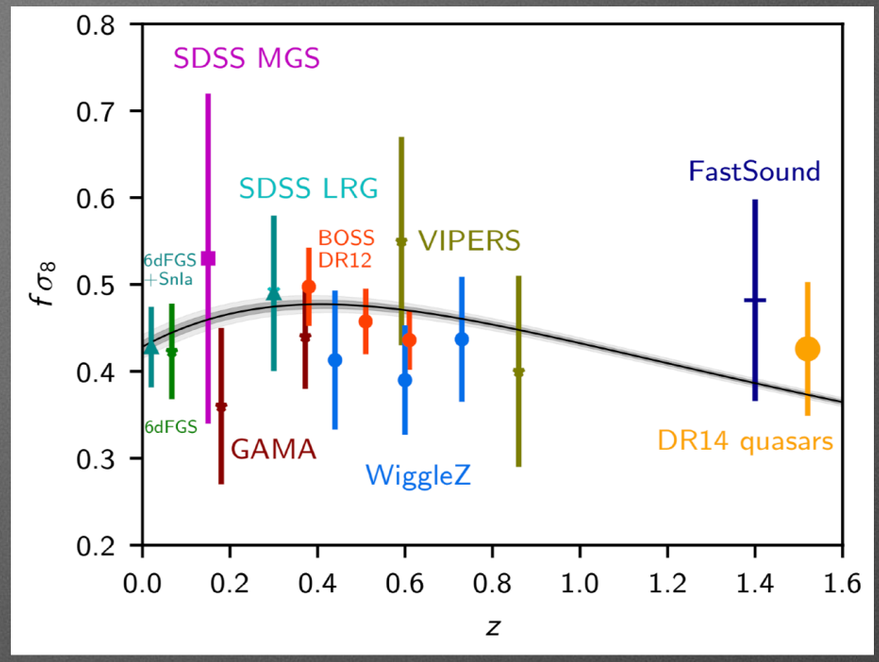
- Distâncias angulares → BAO
- Taxa de expansão
- Taxa de crescimento das estruturas → RSD

Baryon Acoustic Oscillations

Redshift-Space Distortions

Contribuição do SDSS





SDSS MGS
SDSS LRG
BOSS DR12
DR14 LRG
SDSS quasars
DR14 quasars
BOSS Ly-alpha

SDSS

História cósmica em
0.1 < z < 3.5 !

Baryon Acoustic Oscillations

HISTORY OF THE UNIVERSE

Dark energy accelerated expansion

Structure formation

Cosmic Microwave Background radiation is visible

Accelerators

RHIC & LHC heavy ions

LHC protons

High-energy cosmic rays

Size of visible universe

TODAY

Inflation

Big Bang

Plasma primordial

POSSIBLE DARK MATTER RELICS

NUCLEOSYNTHESIS

$t = 10^{-36}$ s
$E = 10^{16}$ GeV

$t = 10^{-10}$ s
$E = 10^{2}$ GeV

$t = 10^{-4}$ s
$E = 10^{-1}$ GeV

$t = 10^{2}$ s
$E = 10^{-4}$ GeV

$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Key

quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

The concept for the above figure originated in a 1986 paper by Michael Turner.

Supported by DOE

HISTORY OF THE UNIVERSE

Dark energy accelerated expansion

Structure formation

Cosmic Microwave Background radiation is visible

RHIC & LHC heavy ions

Accelerators

LHC protons

High-energy cosmic rays

Size of visible universe

TODAY

Inflation

Big Bang

Plasma primordial

$t = 10^{-36}$ s
$E = 10^{16}$ GeV

$t = 10^{-10}$ s
$E = 10^{2}$ GeV

$t = 10^{-4}$ s
$E = 10^{-1}$ GeV

$t = 10^{2}$ s
$E = 10^{-4}$ GeV

$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

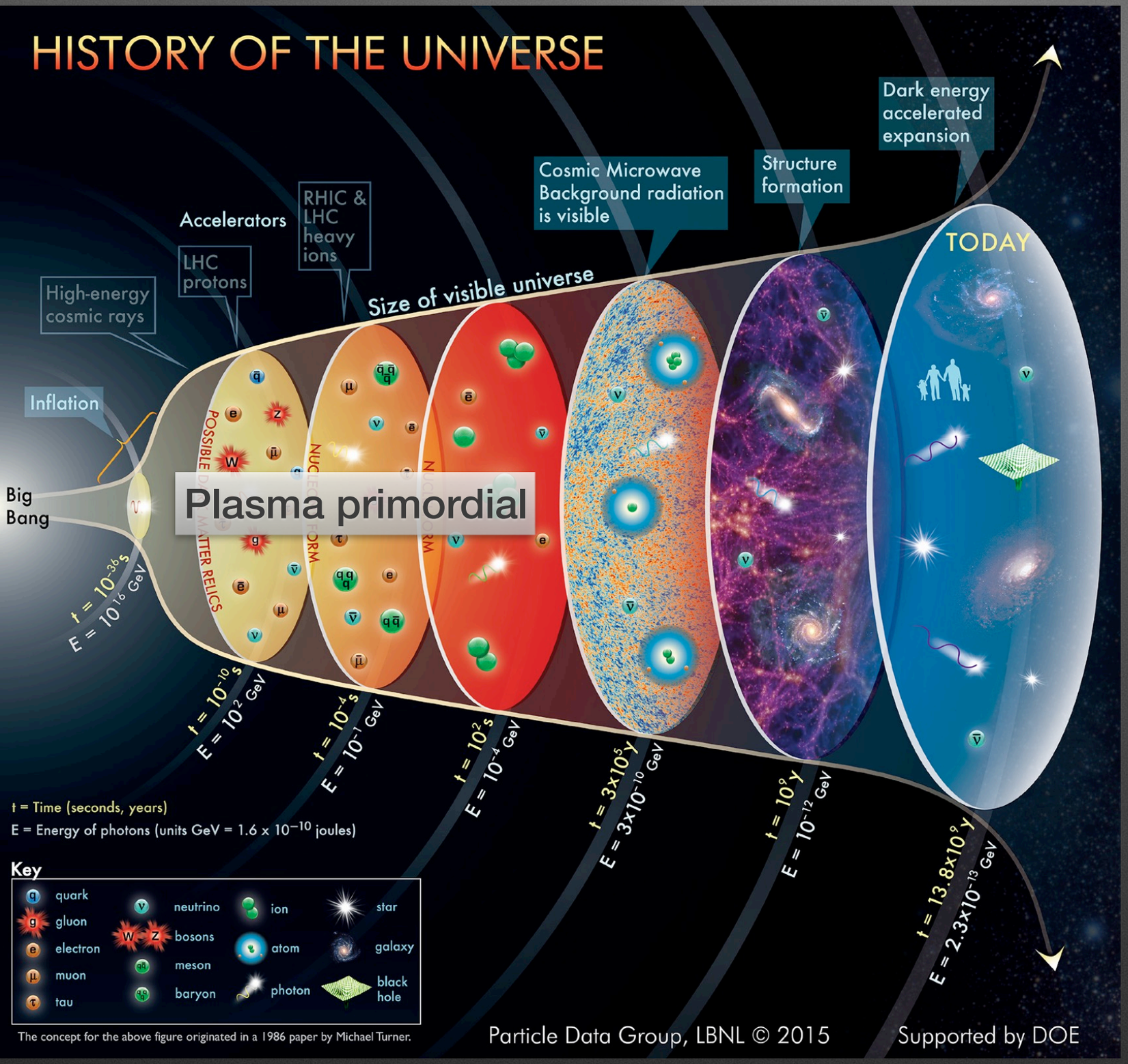
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

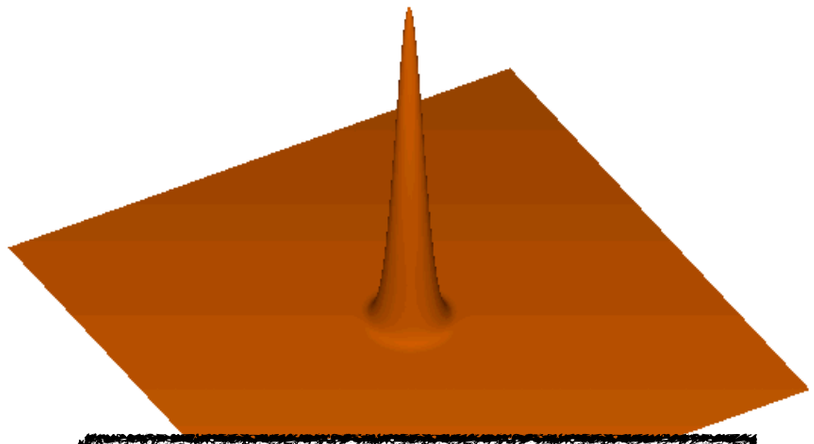
Key

quark, gluon, electron, muon, tau, neutrino, bosons, meson, baryon, ion, atom, photon, star, galaxy, black hole

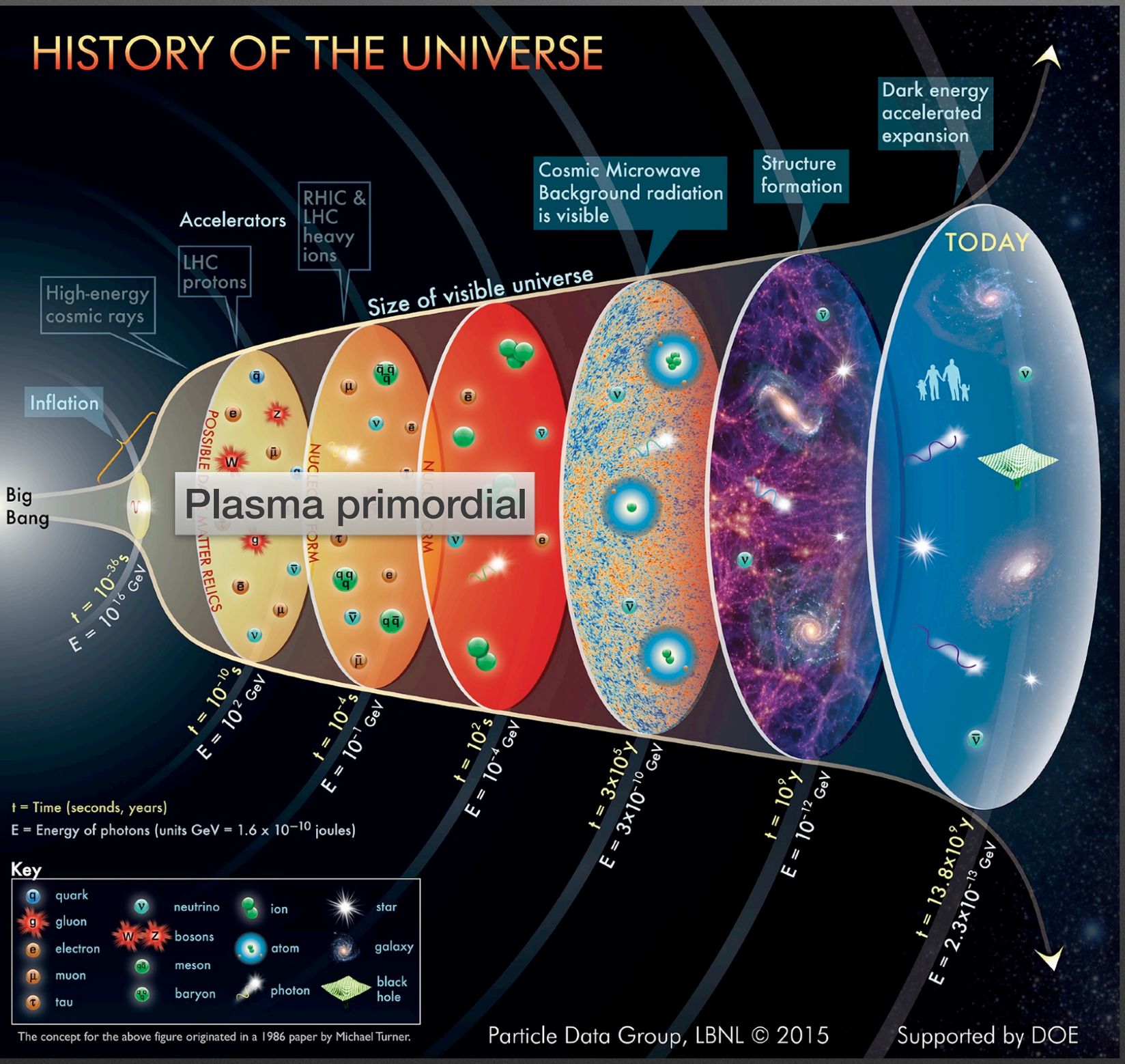
The concept for the above figure originated in a 1986 paper by Michael Turner.

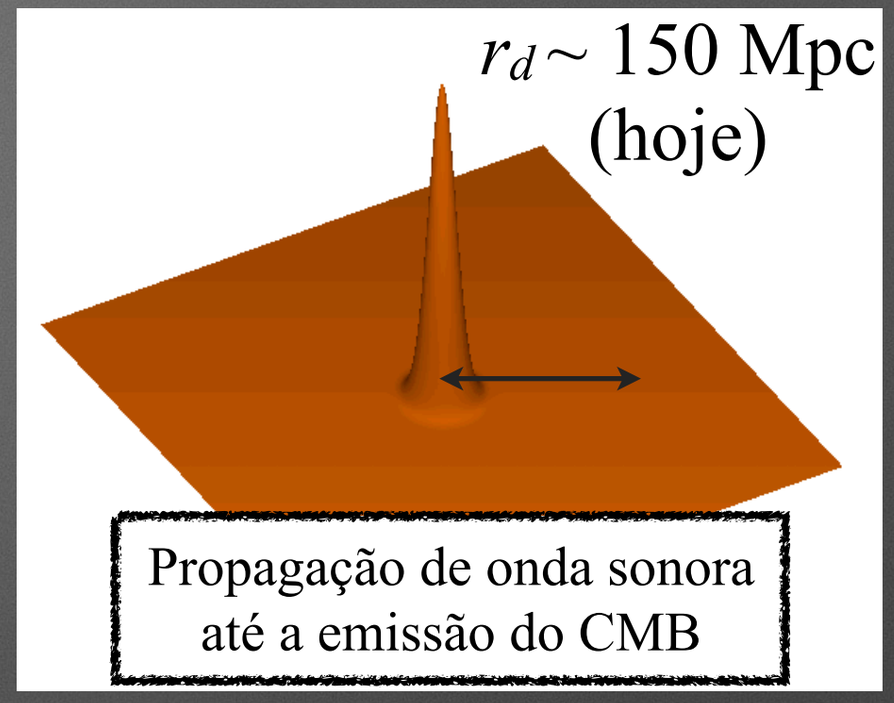
Supported by DOE

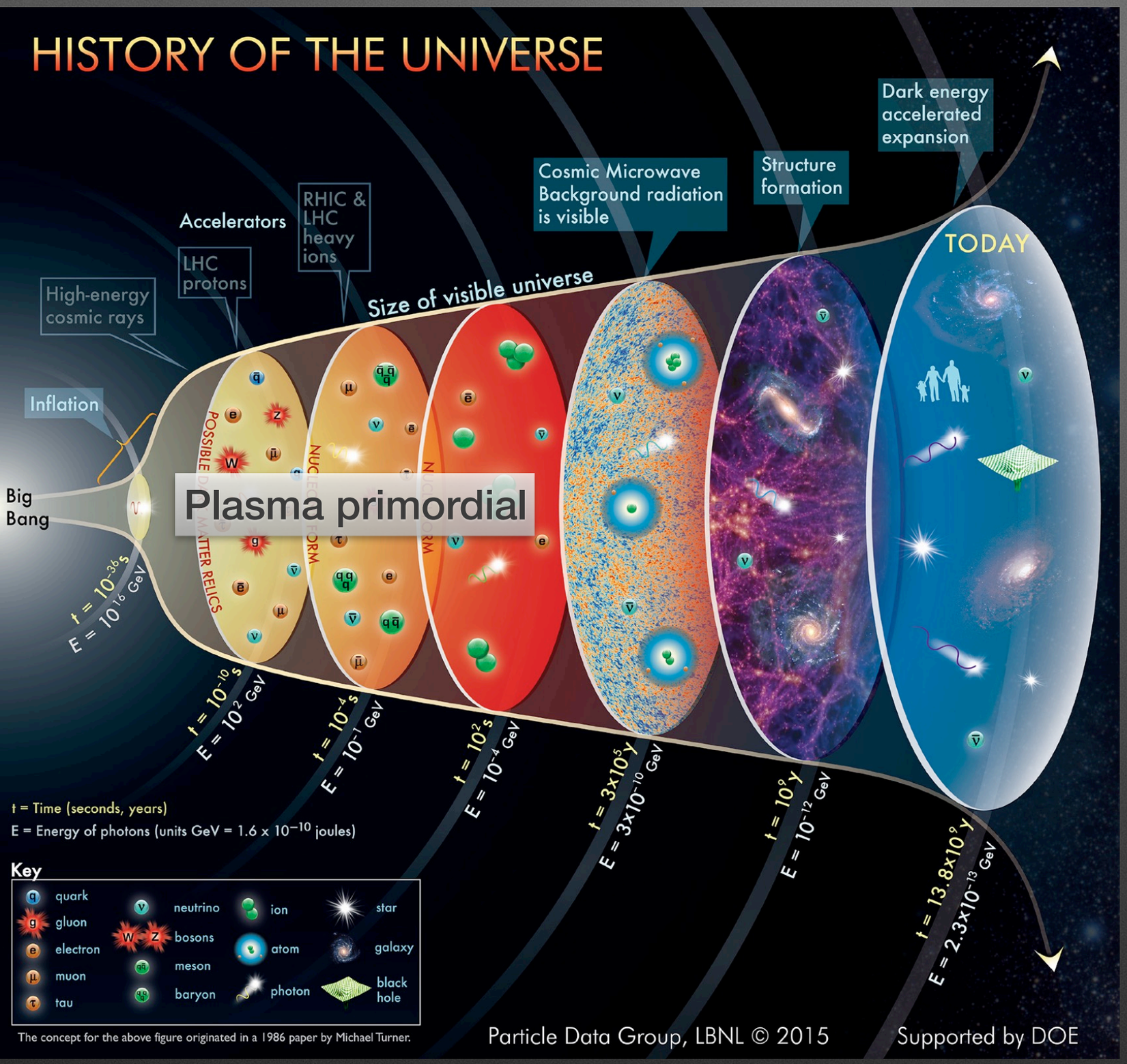




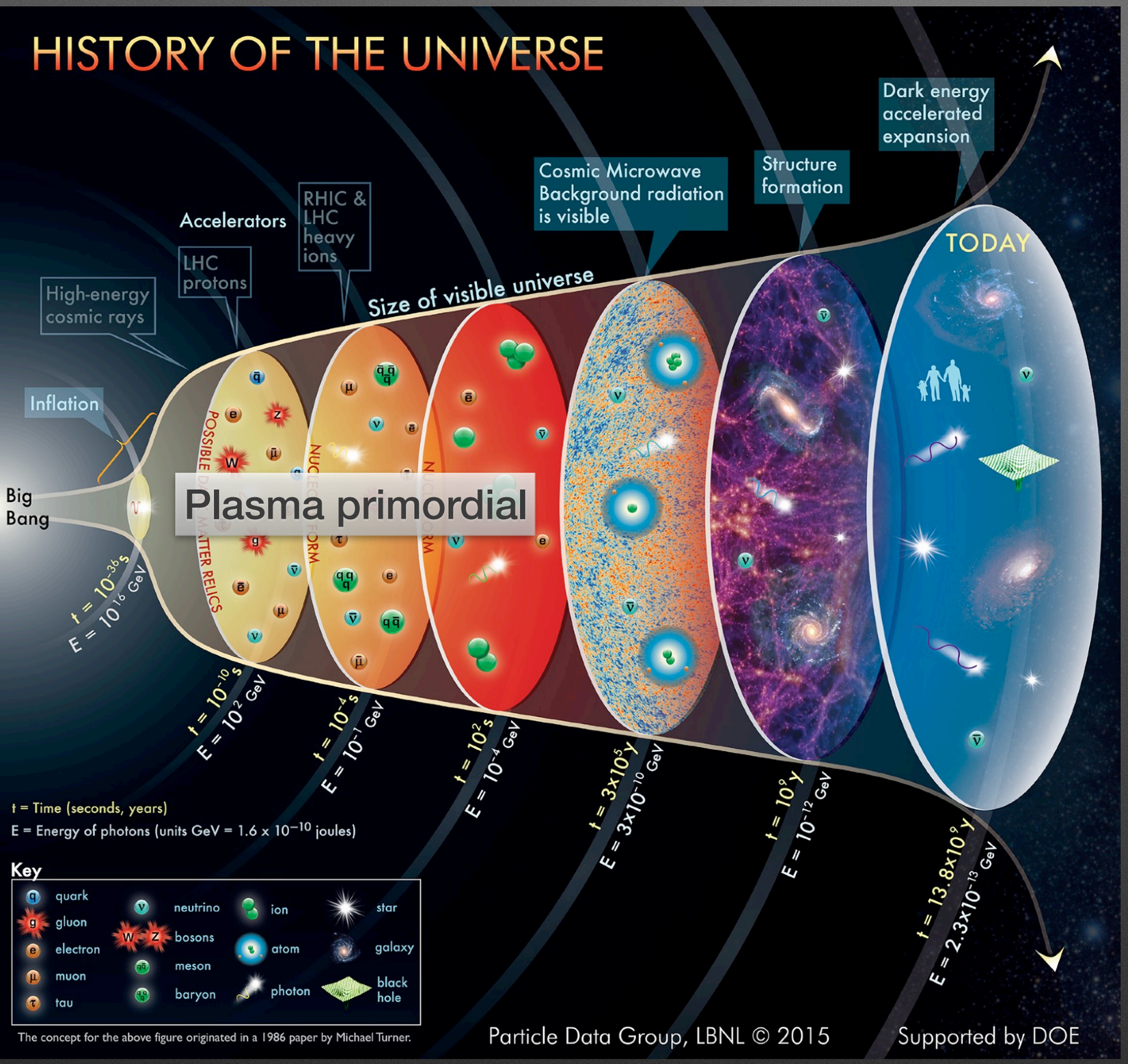
Propagação de onda sonora até a emissão do CMB

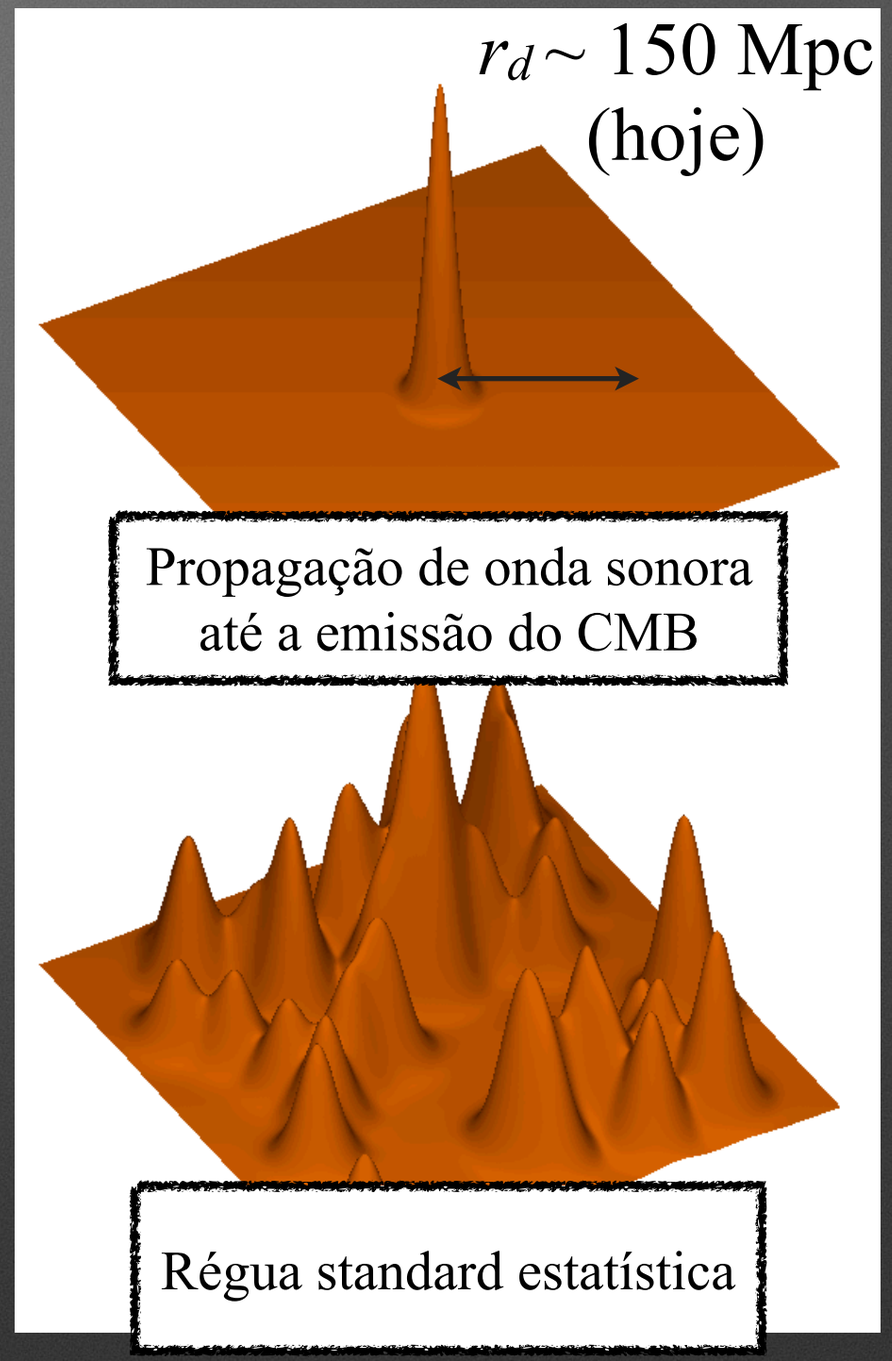

HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
Plasma primordial
POSSIBLE DARK MATTER RELICS
NUCLEOSYNTHESIS
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE


$r_d \sim 150$ Mpc
(hoje)
Propagação de onda sonora
até a emissão do CMB


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
Plasma primordial
POSSIBLE DARK MATTER RELICS
NUCLEOSYNTHESIS
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE


$r_d \sim 150$ Mpc
(hoje)
Propagação de onda sonora
até a emissão do CMB


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
Plasma primordial
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE


$r_d \sim 150$ Mpc
(hoje)
Propagação de onda sonora até a emissão do CMB
Régua standard estatística

BAO

A origem da régua standard

Função de correlação do contraste de densidade

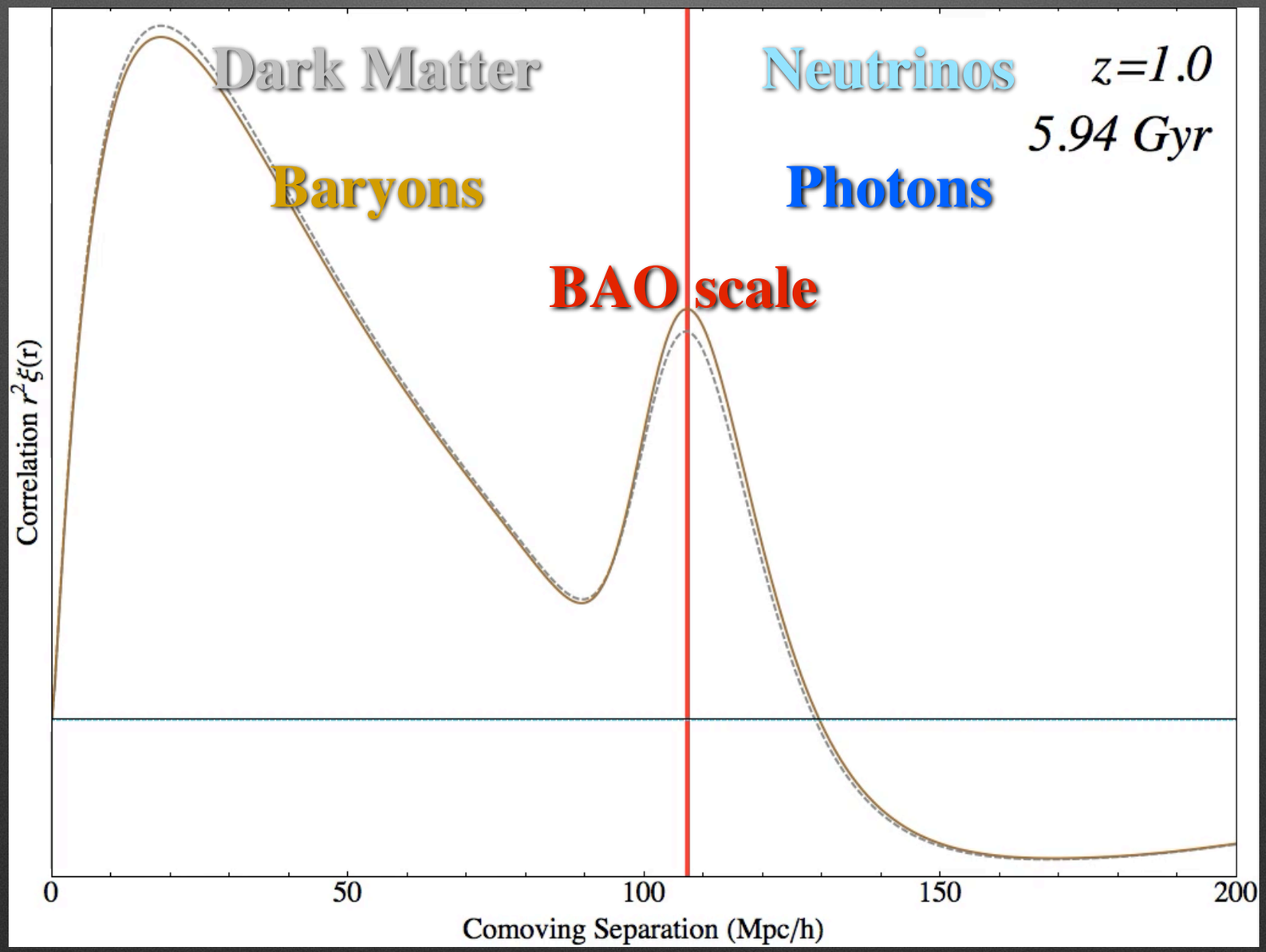
$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle$$

BAO

A origem da régua standard

Função de correlação do contraste de densidade

$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle$$



(by David Kirkby)

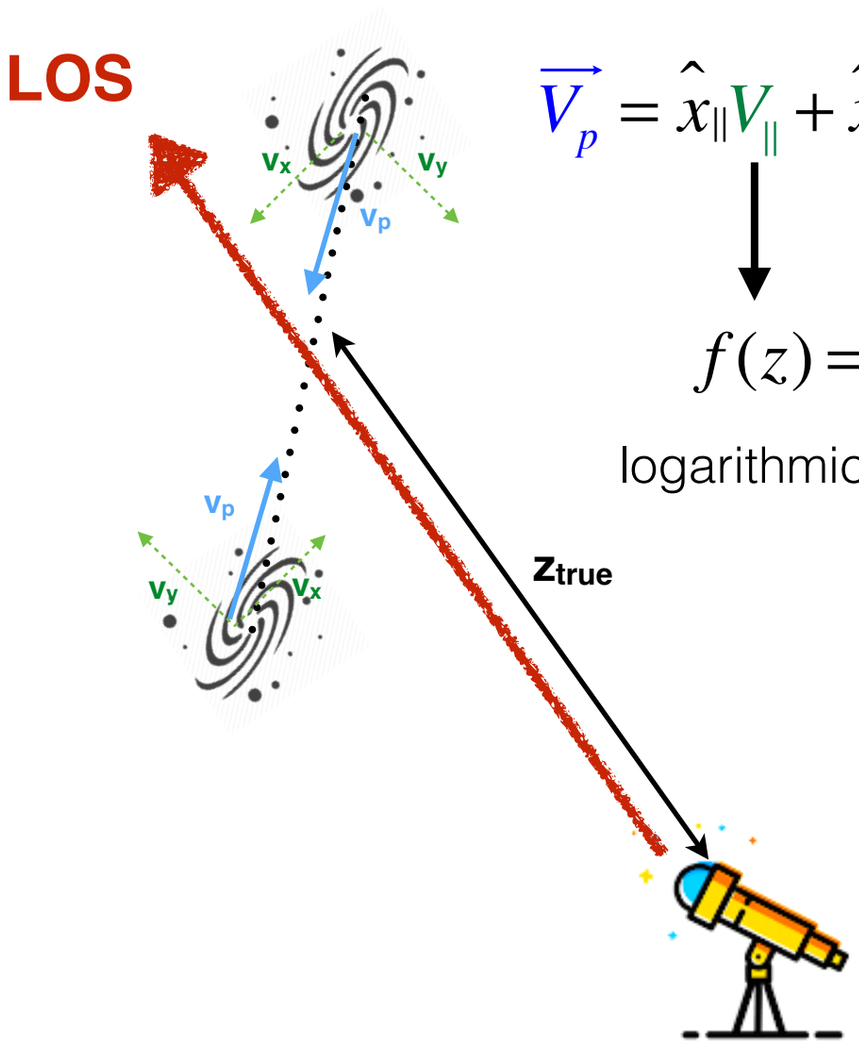
BAO

A origem da régua standard

(sdss3.org)

Redshift-Space Distortions

Redshift-Space Distortions



not detected

$$\overrightarrow{V_p} = \hat{x}_{\parallel} V_{\parallel} + \hat{x}_{\perp} V_{\perp}$$

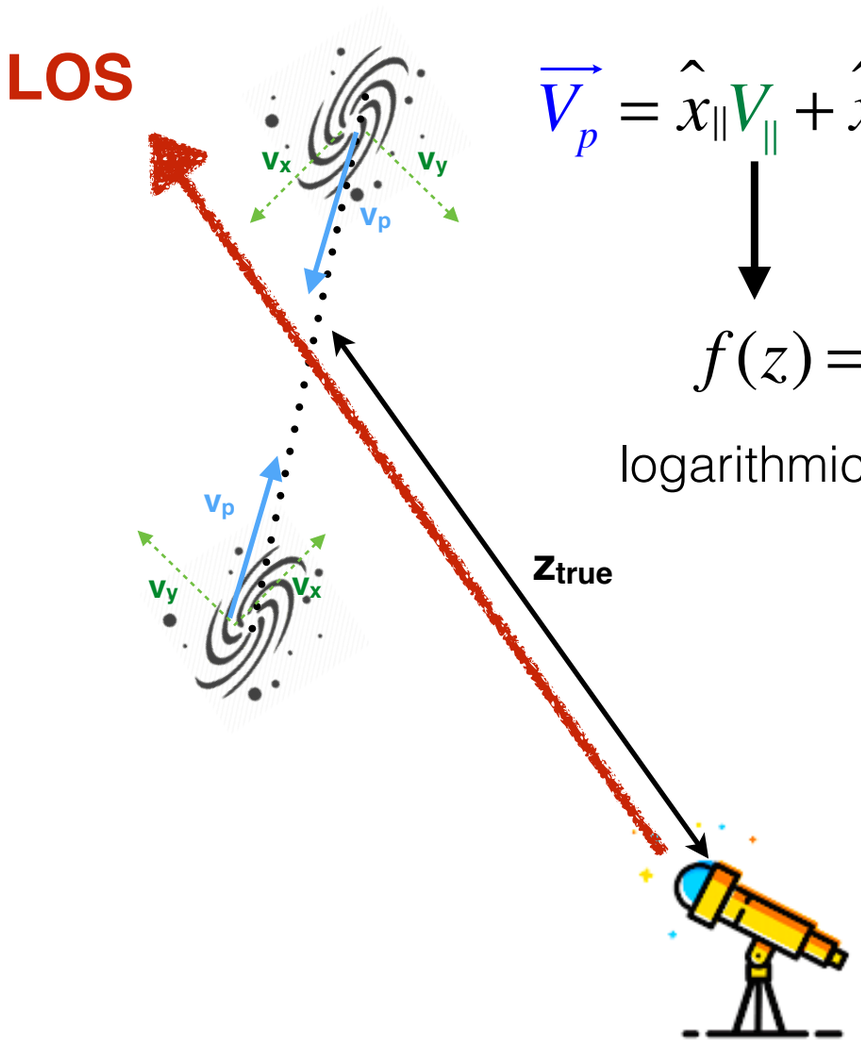
$$f(z) = \Omega_m(z)^{\gamma}$$

logarithmic growth of structure

$$z_{obs} = z_{true} \oplus z_{pec} \equiv \left[(1 + z_{true}) \times (1 + z_{pec}) \right] - 1$$

1. Expansão do Universo (Hubble flow)
2. Velocidades peculiares causadas pelo crescimento de estruturas

Redshift-Space Distortions

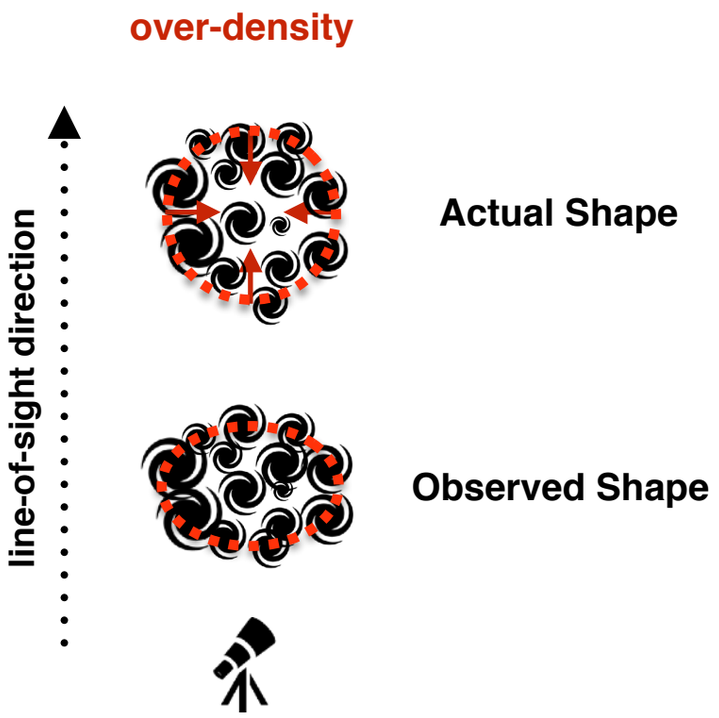


not detected

$$\overrightarrow{V_p} = \hat{x}_{\parallel} V_{\parallel} + \hat{x}_{\perp} V_{\perp}$$

$$f(z) = \Omega_m(z)^{\gamma}$$

logarithmic growth of structure



$$z_{obs} = z_{true} \oplus z_{pec} \equiv \left[(1 + z_{true}) \times (1 + z_{pec}) \right] - 1$$

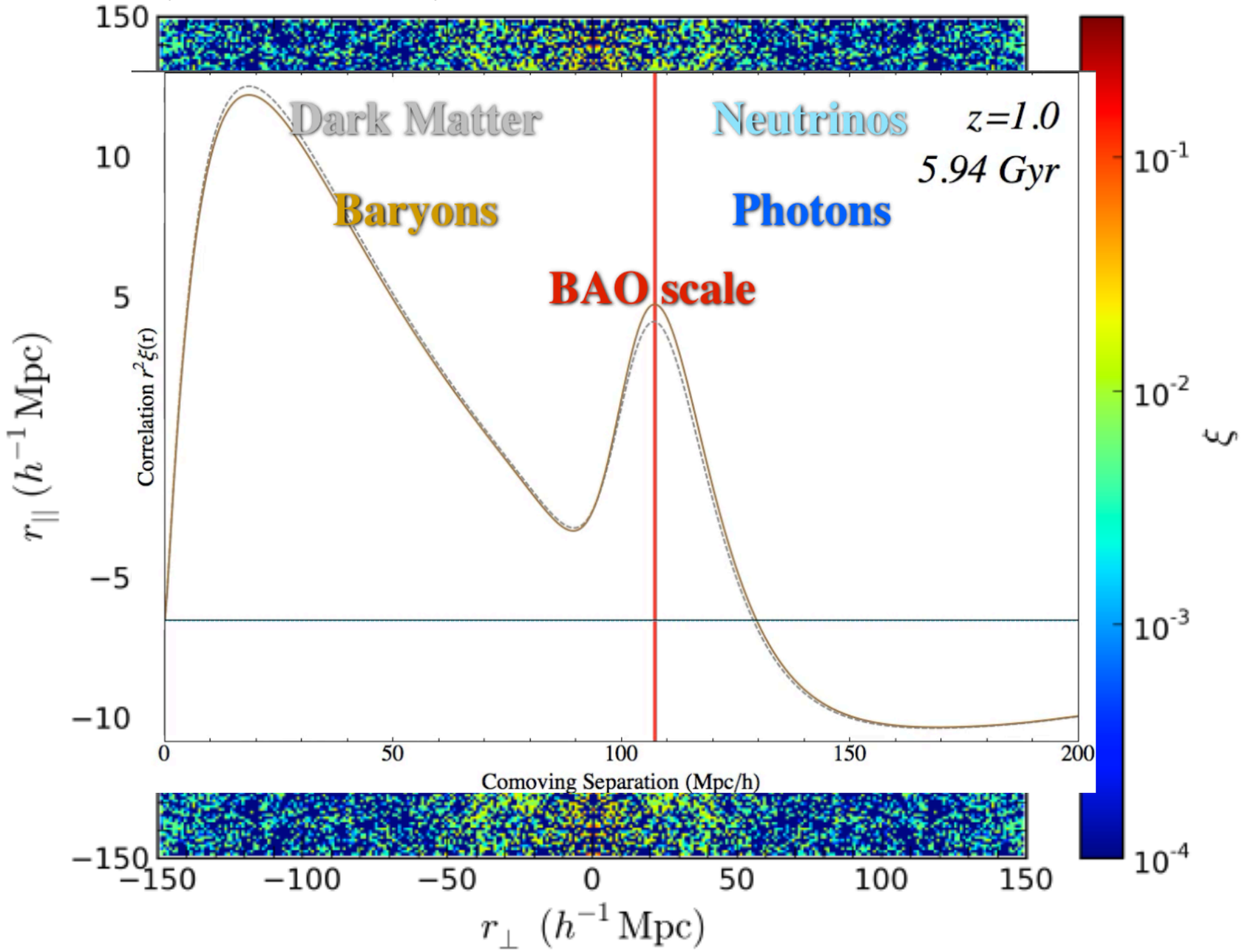
1. Expansão do Universo (Hubble flow)
2. Velocidades peculiares causadas pelo crescimento de estruturas

Ao converter redshift em distância, as separações são modificadas e os aglomerados não são mais isotrópicos

Redshift-Space Distortions

Função de correlação de galáxias

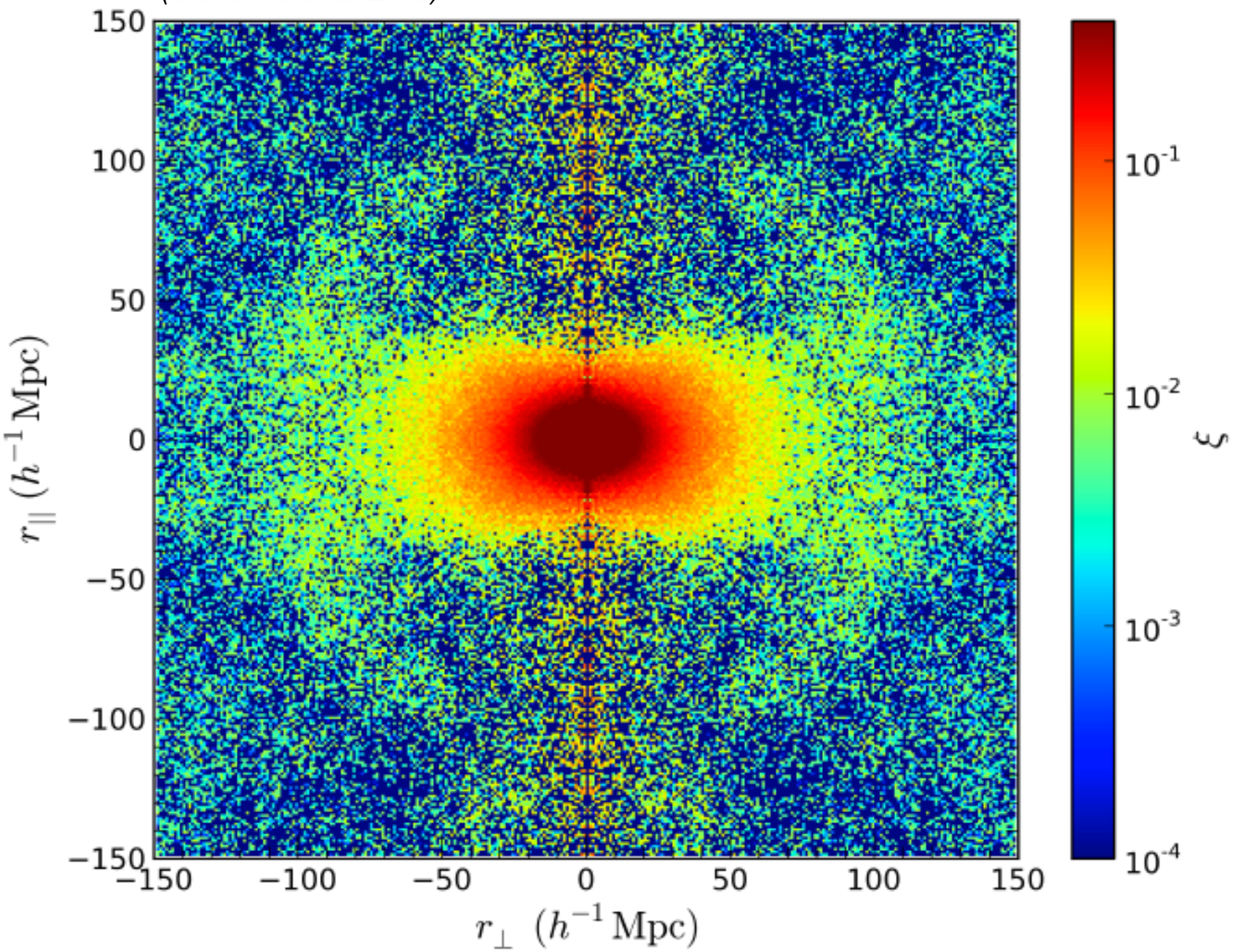
(Samushia et al. 2013)



Redshift-Space Distortions

Função de correlação de galáxias

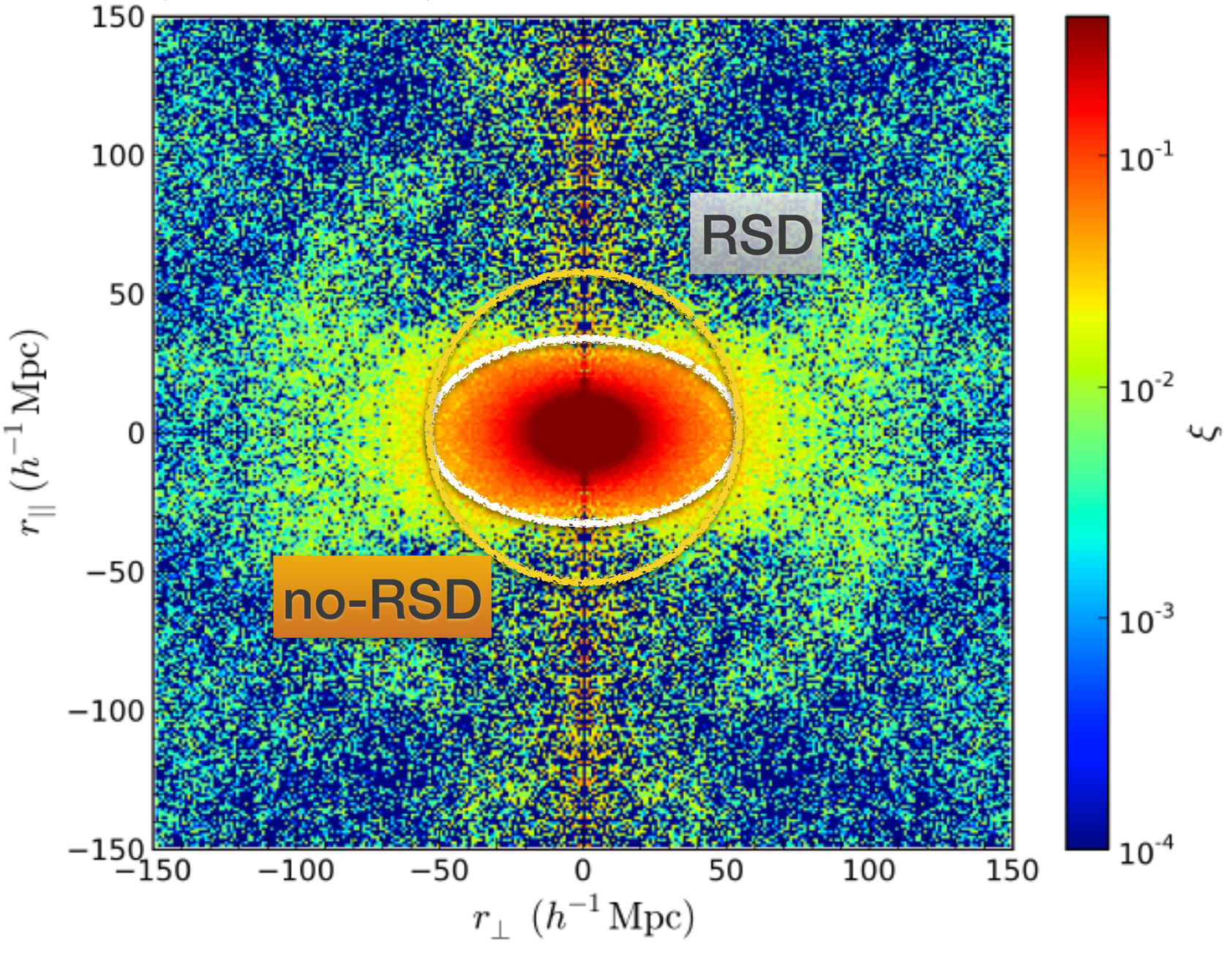
(Samushia et al. 2013)



Redshift-Space Distortions

Função de correlação de galáxias

(Samushia et al. 2013)



Redshift-Space Distortions

Espectro de potências da matéria

$$P(\vec{k}) \leftrightarrow \xi(\vec{x})$$

$$P_g^{(s)}(k,\mu) = \left[b + f\mu^2 \right]^2 P_m(k) \longrightarrow f(z) = \frac{d \ln D}{d \ln a}$$

Kaiser 1987

Como medir as estruturas do Universo?

Como medir as estruturas do Universo?

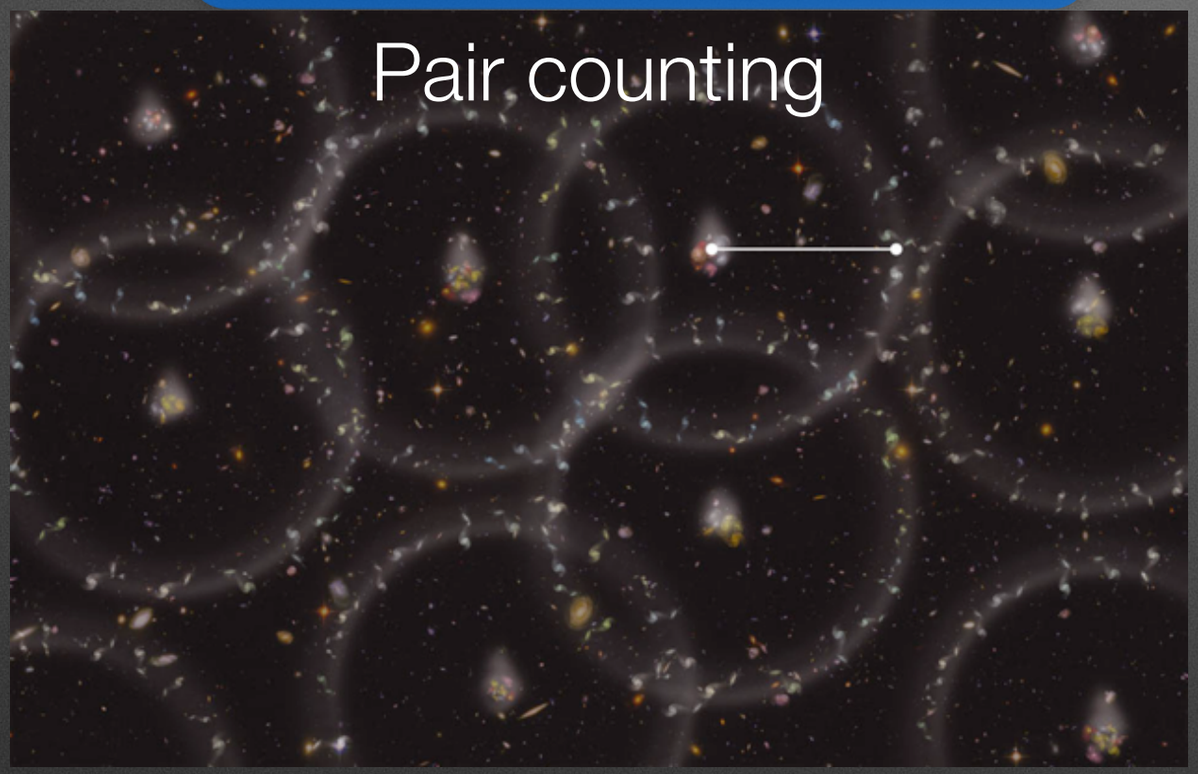
Galaxies or Quasars

Trace dense regions $\delta \gg 200$

Como medir as estruturas do Universo?

Galaxies or Quasars

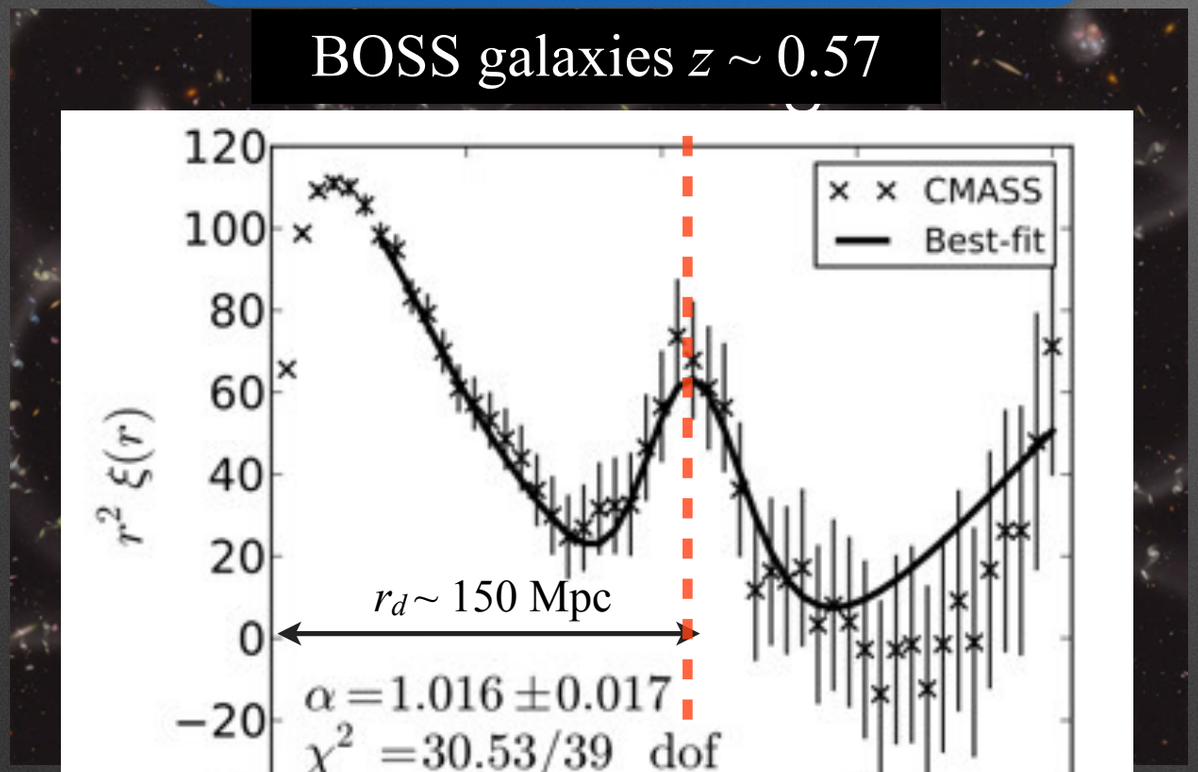
Trace dense regions $\delta \gg 200$



Como medir as estruturas do Universo?

Galaxies or Quasars

Trace dense regions $\delta \gg 200$



(Anderson et al. 2012)

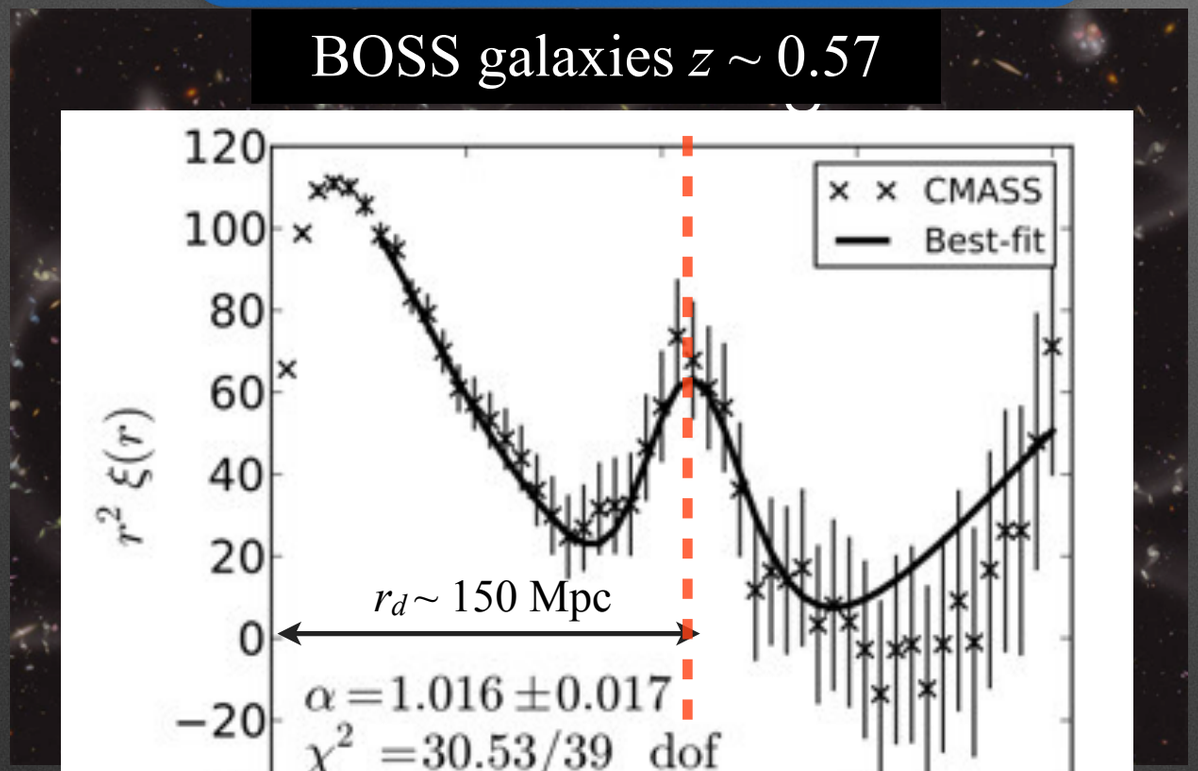
Como medir as estruturas do Universo?

Galaxies or Quasars

Trace dense regions $\delta \gg 200$

Lyman-α Forest

Small over-densities $\delta \approx 1$



(Anderson et al. 2012)

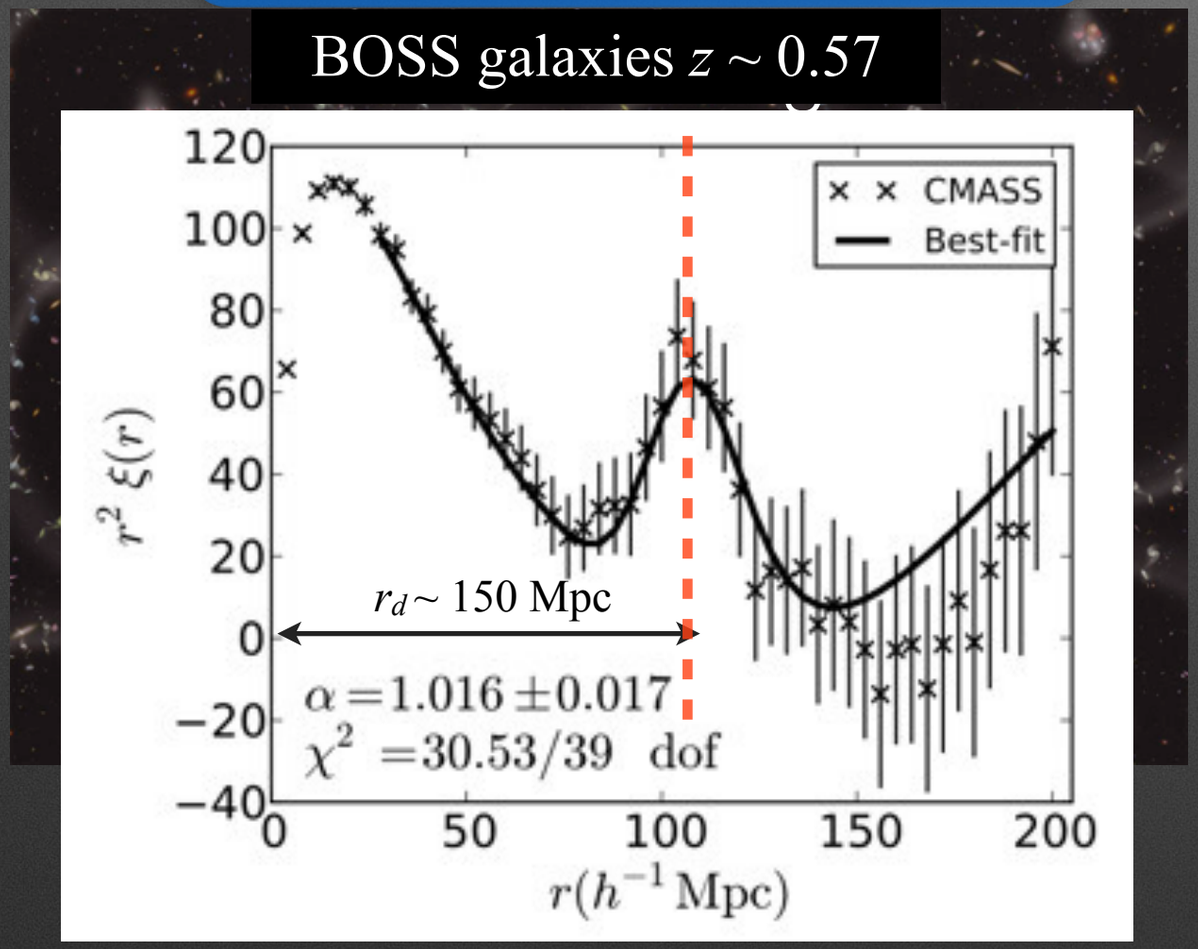
Como medir as estruturas do Universo?

Galaxies or Quasars

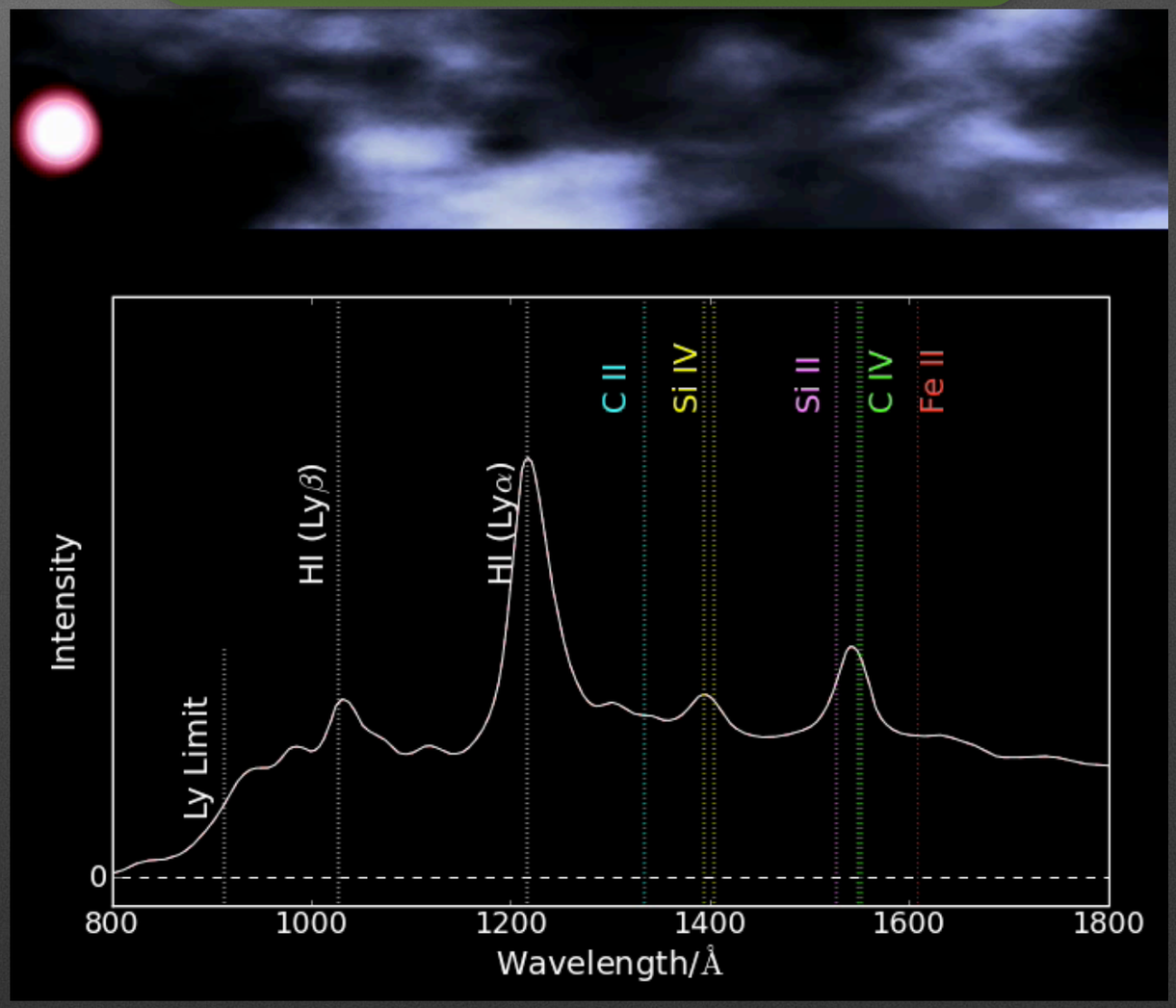
Trace dense regions $\delta \gg 200$

Lyman-α Forest

Small over-densities $\delta \approx 1$



(Anderson et al. 2012)



Como medir as estruturas do Universo?

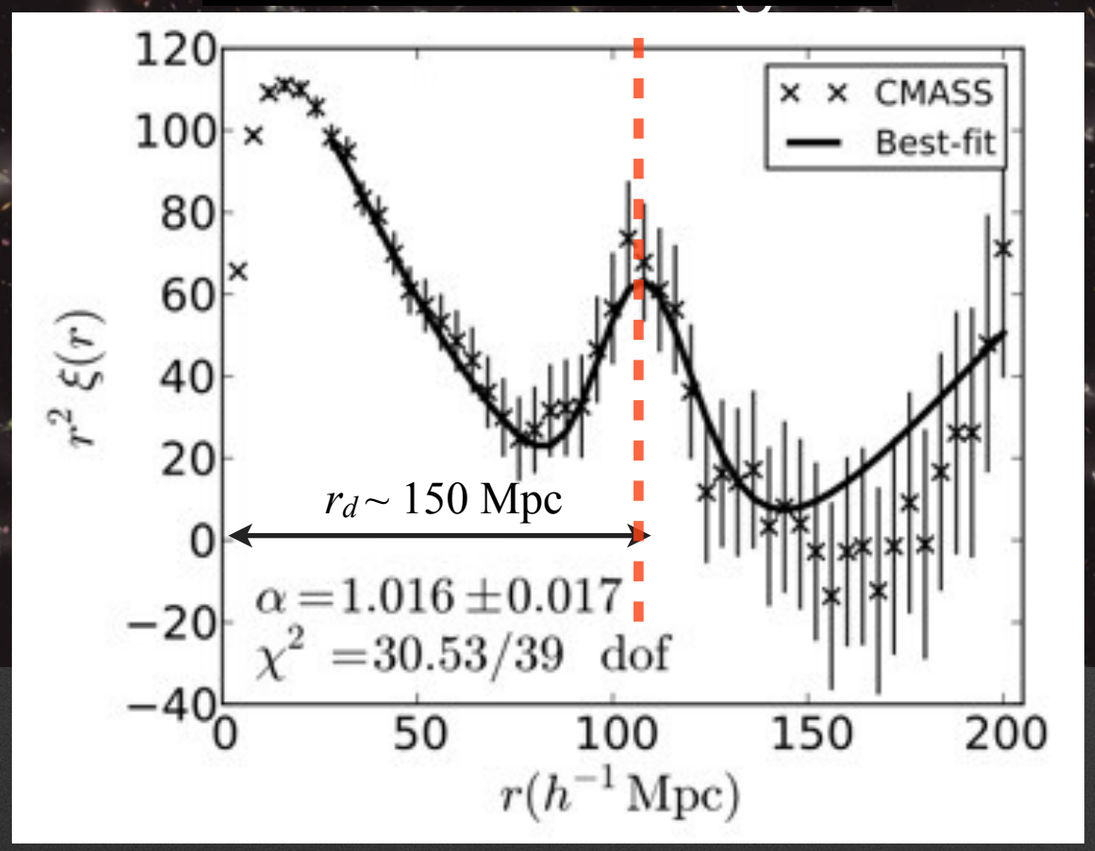
Galaxies or Quasars

Trace dense regions $\delta \gg 200$

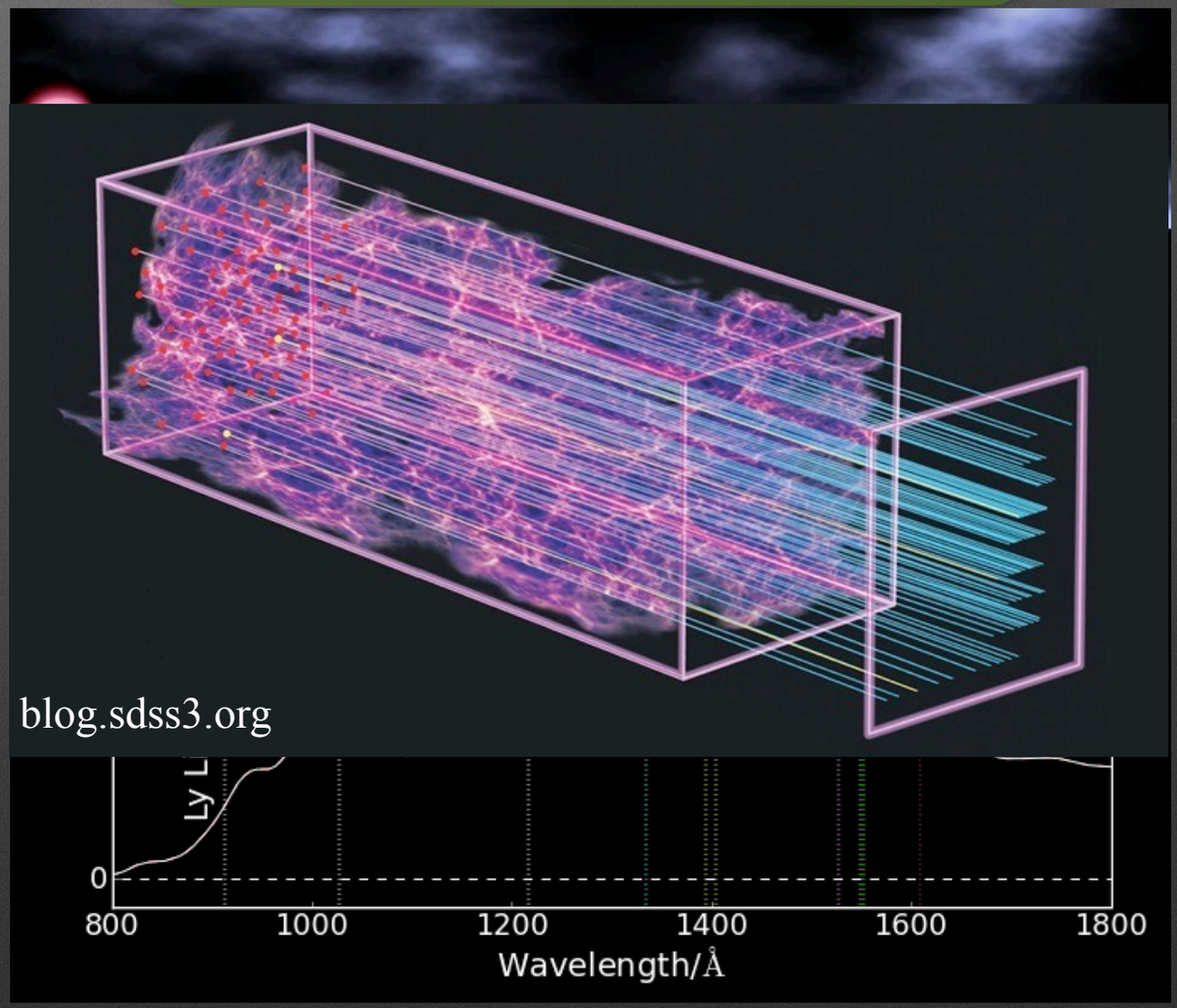
Lyman-α Forest

Small over-densities $\delta \approx 1$

BOSS galaxies $z \sim 0.57$



(Anderson et al. 2012)



(e)BOSS

(extended) Baryon Oscillation Spectroscopic Survey

Apache Point Observatory, New Mexico, USA

(e)BOSS

(extended) Baryon Oscillation Spectroscopic Survey

Apache Point Observatory, New Mexico, USA

(e)BOSS

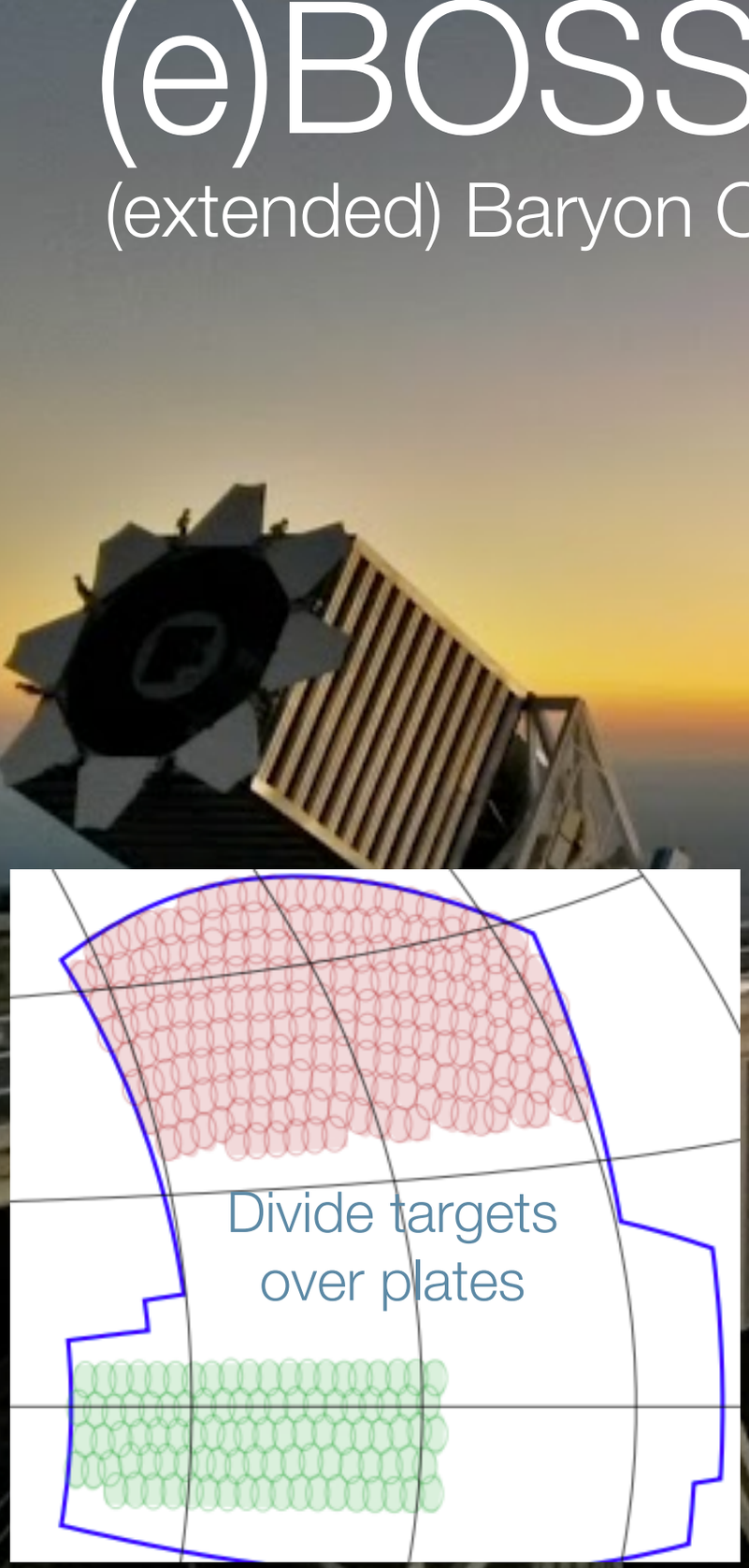
(extended) Baryon Oscillation Spectroscopic Survey

Apache Point Observatory, New Mexico, USA

(e)BOSS

(extended) Baryon Oscillation Spectroscopic Survey

Select galaxies and quasars from photometry

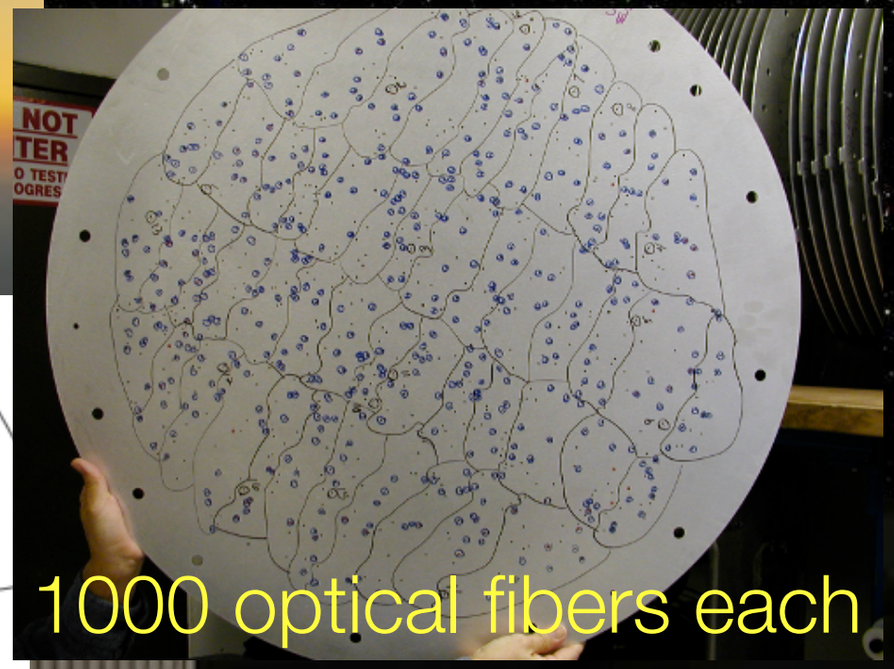


Apache Point Observatory, New Mexico, USA

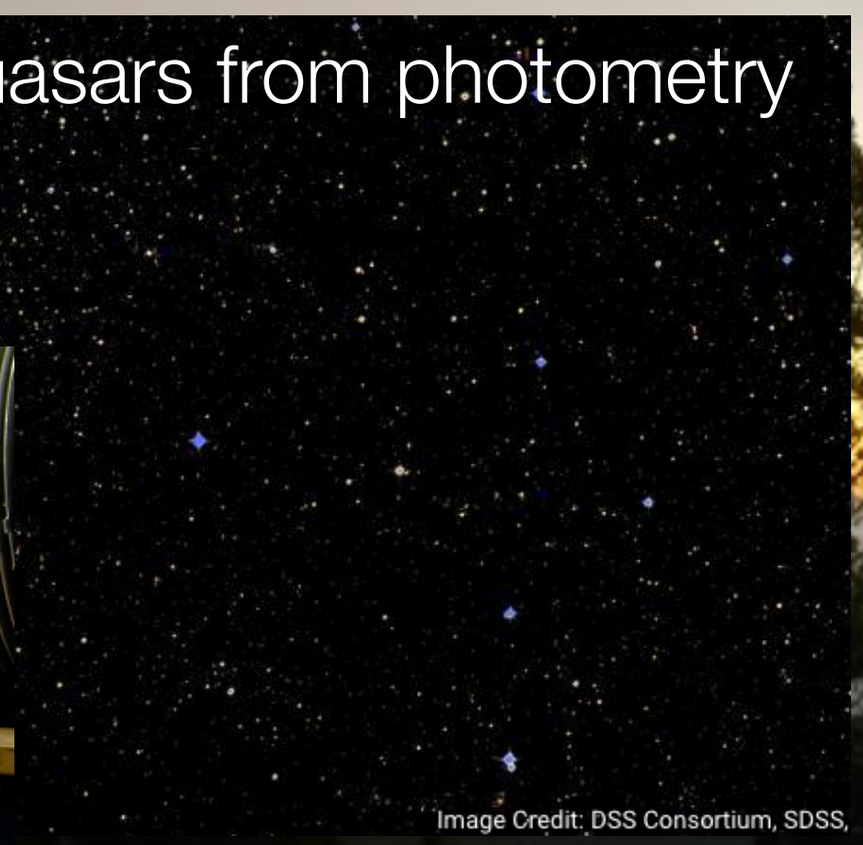
(e)BOSS

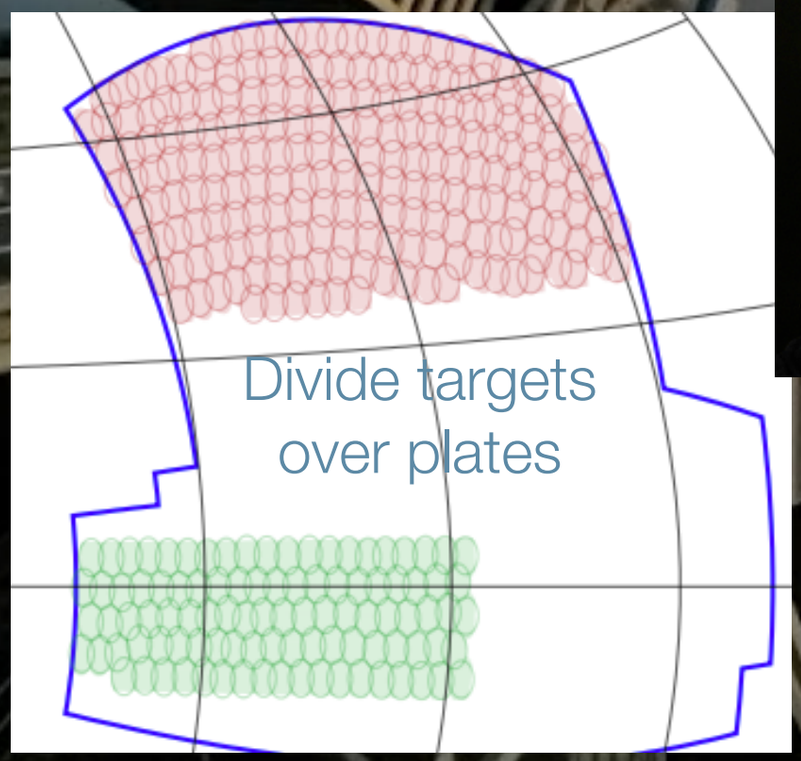
(extended) Baryon Oscillation Spectroscopic Survey

Select galaxies and quasars from photometry



1000 optical fibers each

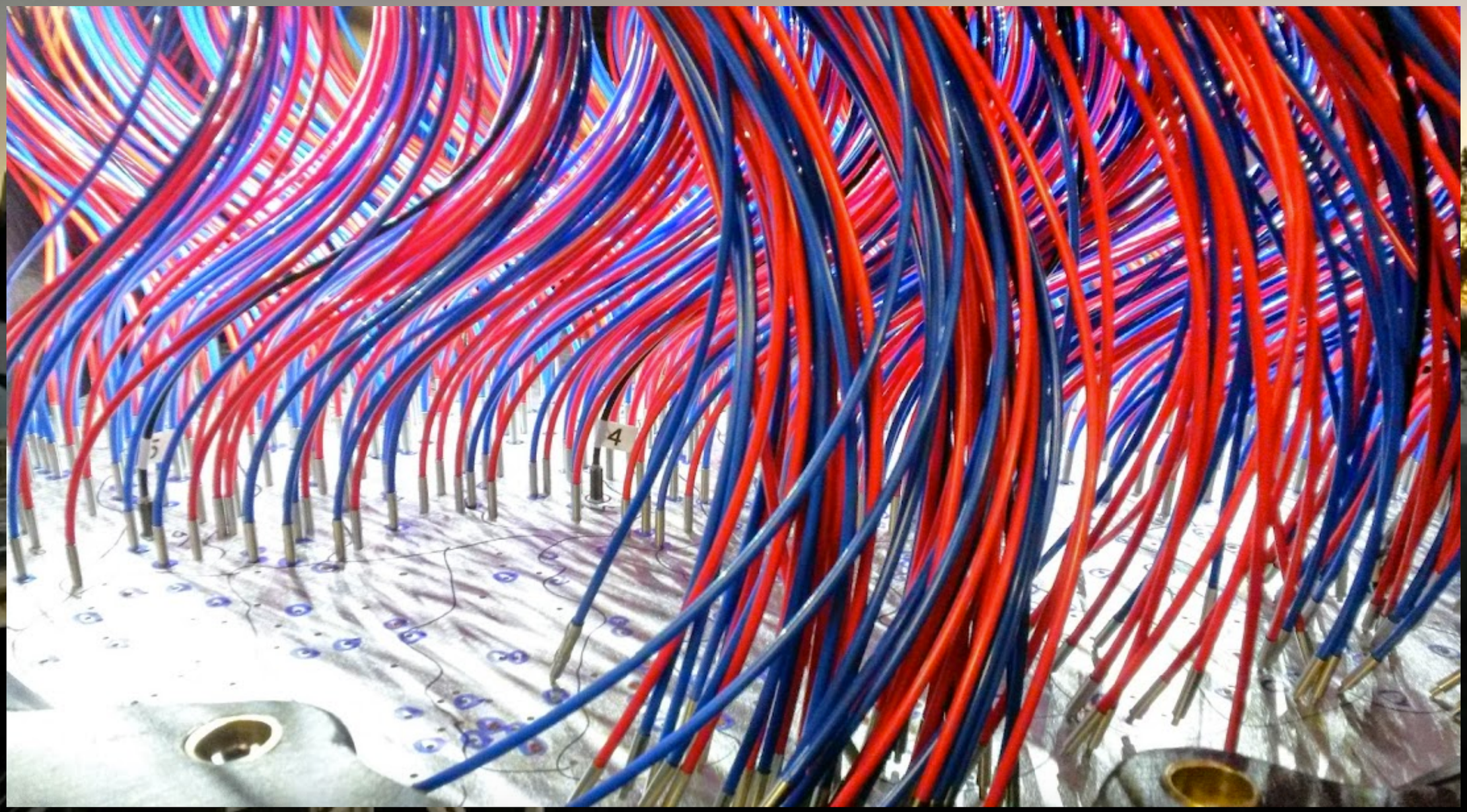




Apache Point Observatory, New Mexico, USA

(e)BOSS

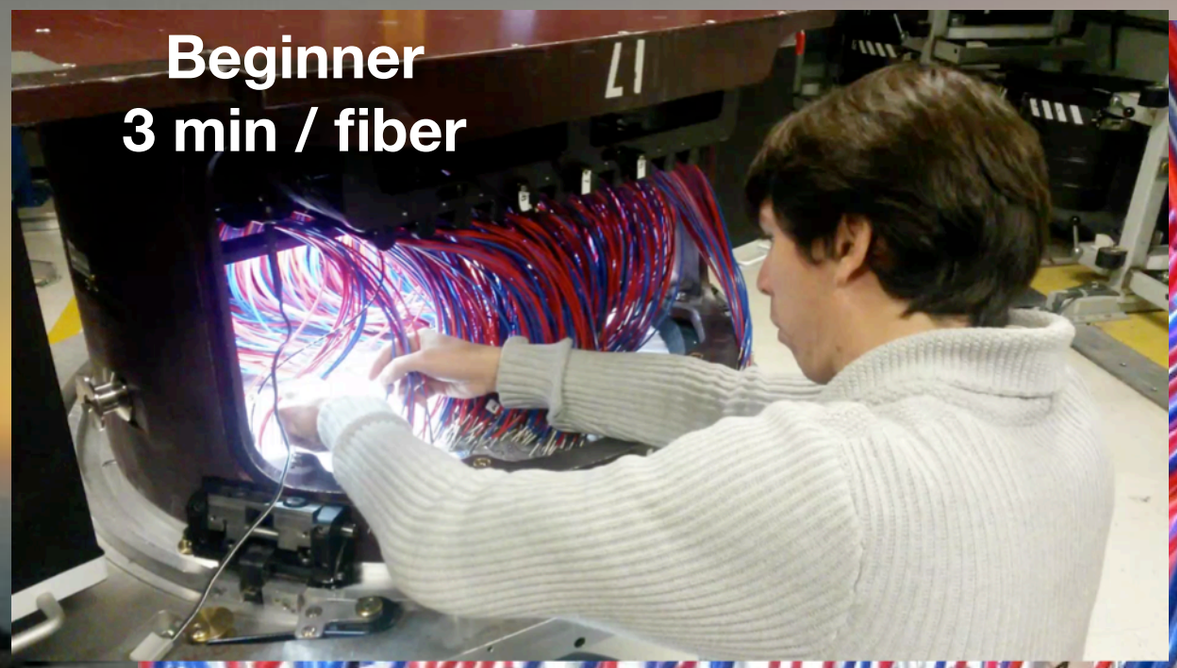
(extended) Baryon Oscillation Spectroscopic Survey

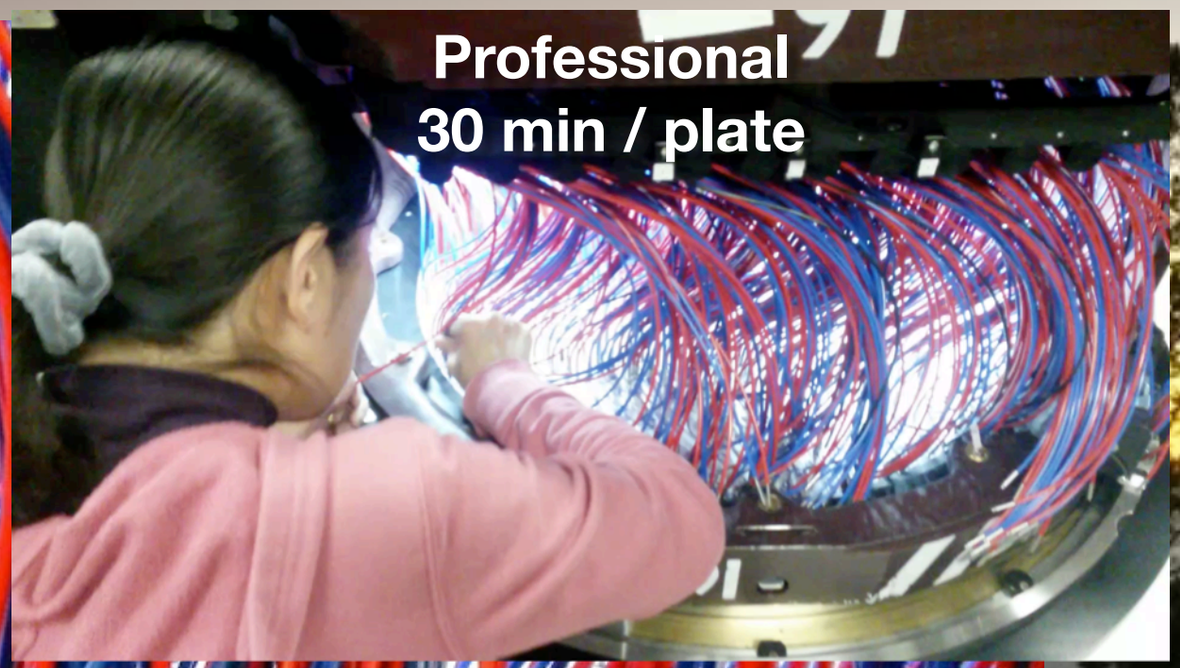


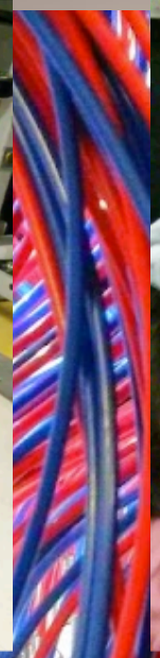
Apache Point Observatory, New Mexico, USA

(e)BOSS

(extended) Baryon Oscillation Spectroscopic Survey



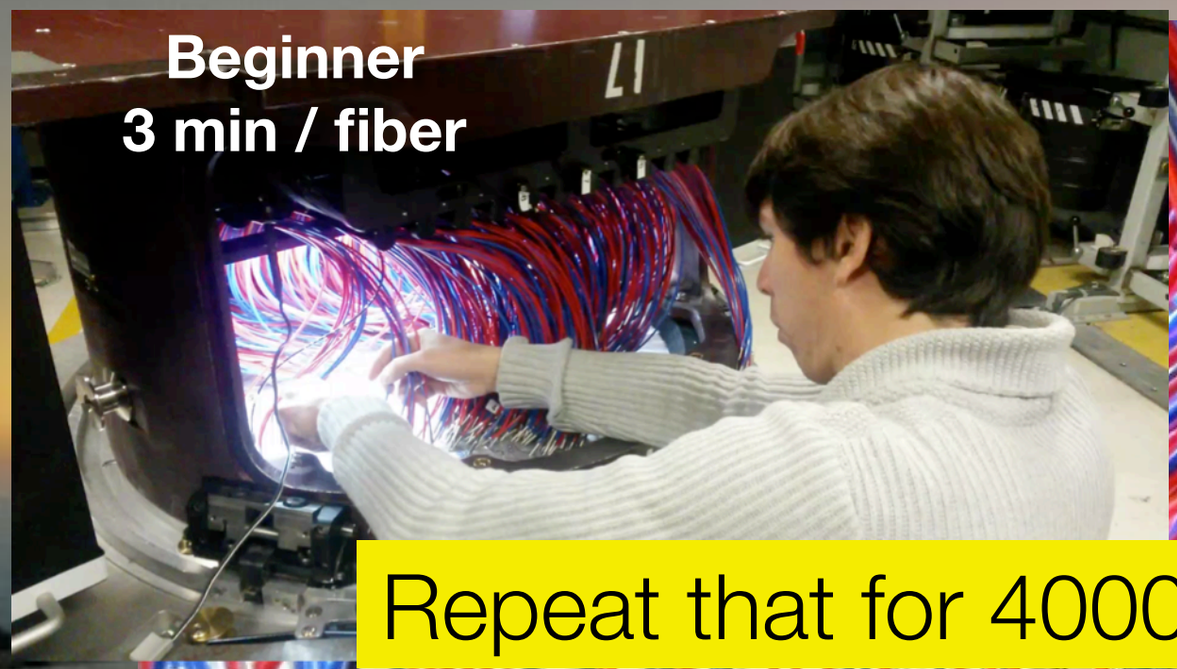


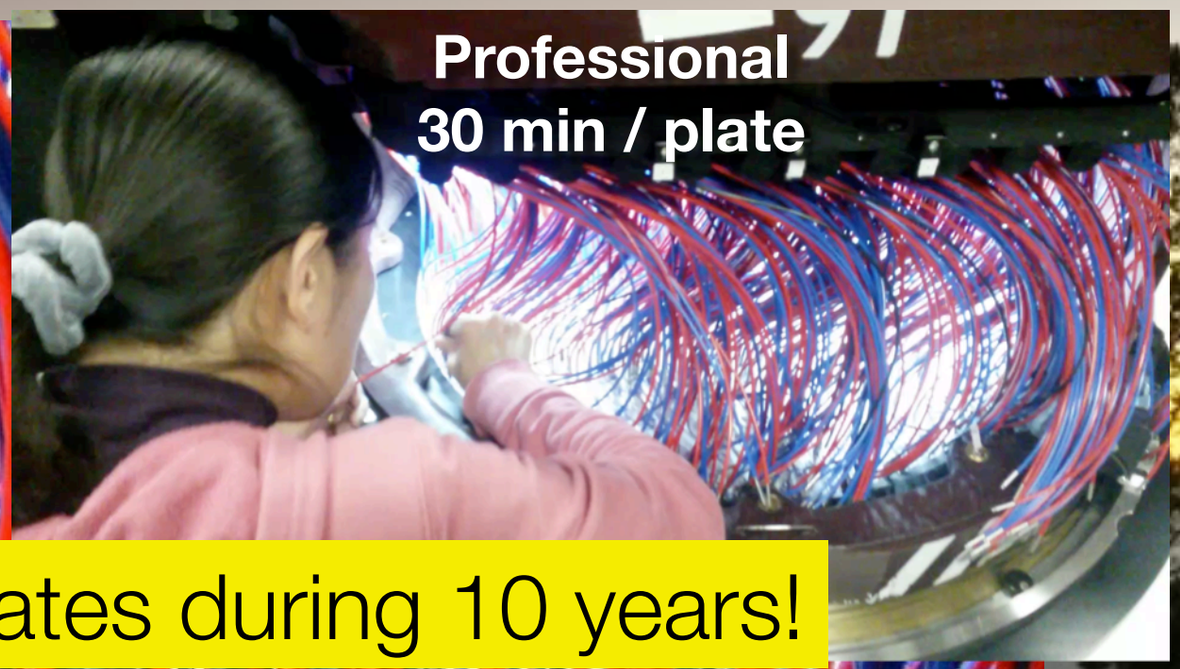


Apache Point Observatory, New Mexico, USA

(e)BOSS

(extended) Baryon Oscillation Spectroscopic Survey



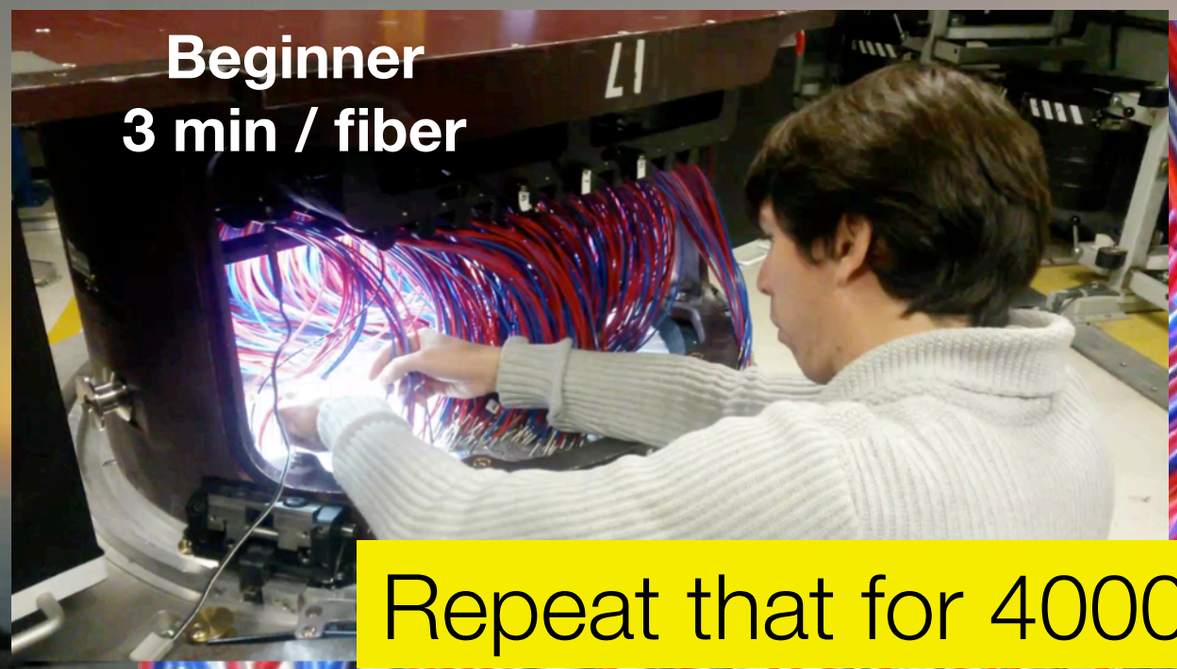


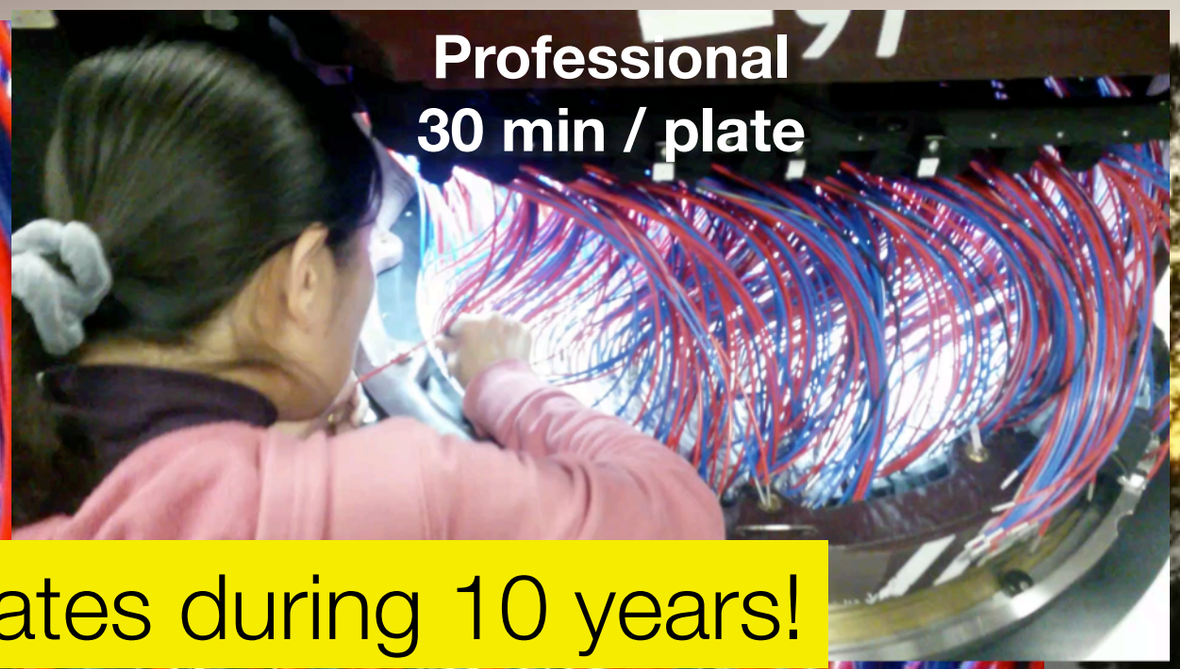
Repeat that for 4000 plates during 10 years!

Apache Point Observatory, New Mexico, USA

(e)BOSS

(extended) Baryon Oscillation Spectroscopic Survey





Repeat that for 4000 plates during 10 years!

More than 2 million galaxies observed

Apache Point Observatory, New Mexico, USA

(e)BOSS

(extended) Baryon Oscillation Spectroscopic Survey

Repeat that for 4000 plates during 10 years!

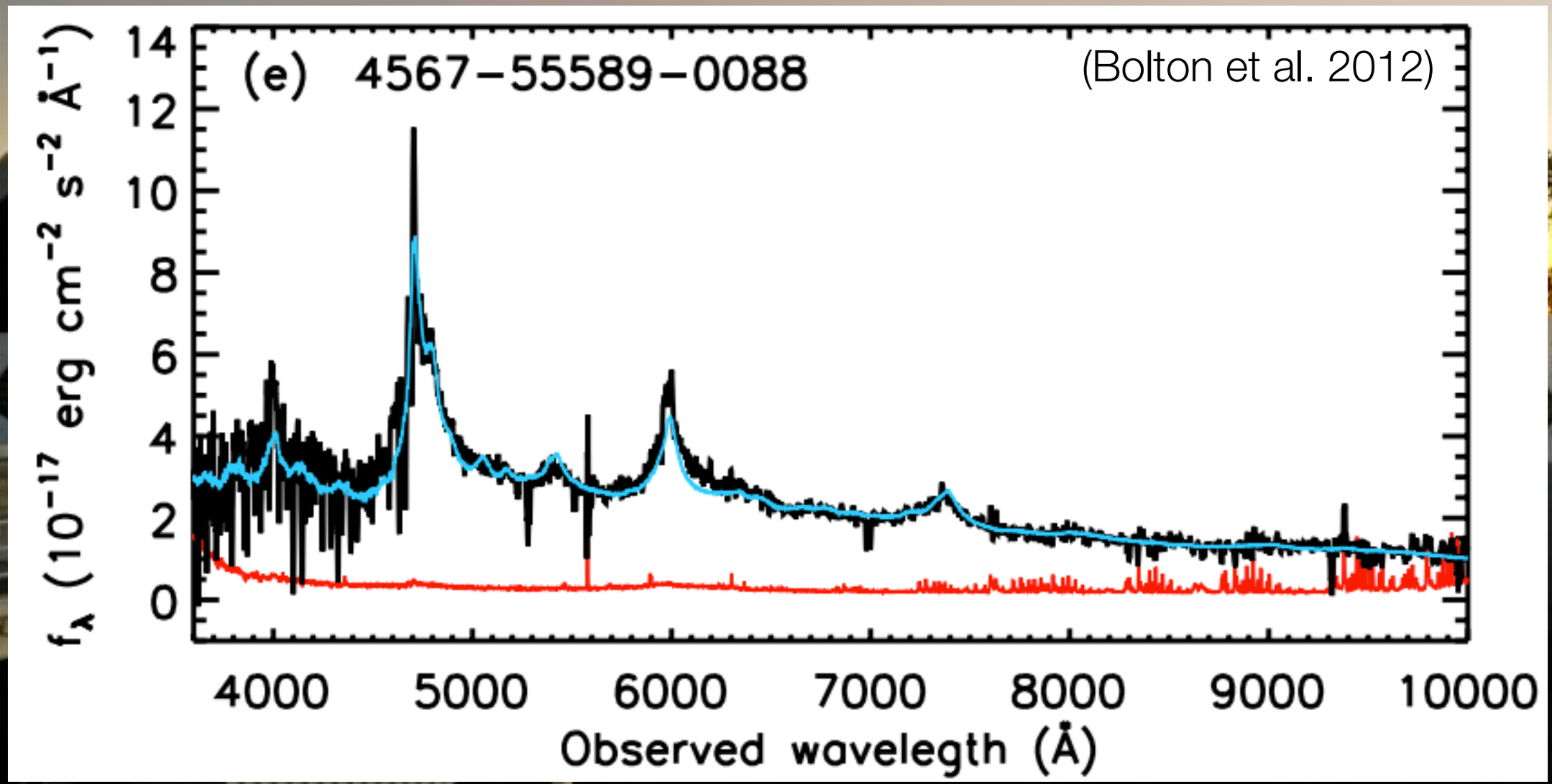
More than 2 million galaxies observed

More than 800 000 quasars observed

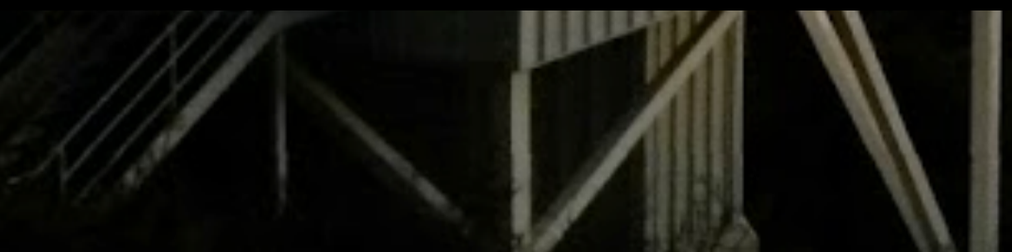
Apache Point Observatory, New Mexico, USA

(e)BOSS

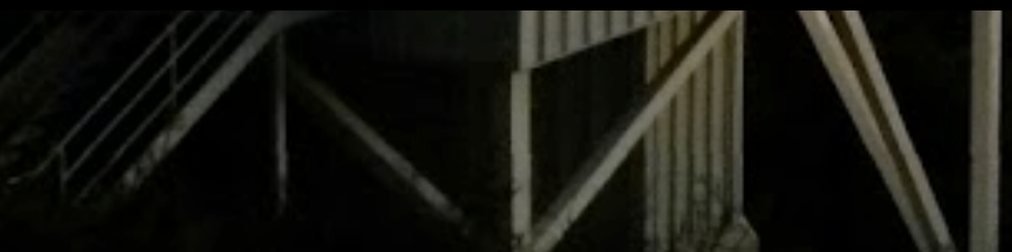
(extended) Baryon Oscillation Spectroscopic Survey



Apache Point Observatory, New Mexico, USA



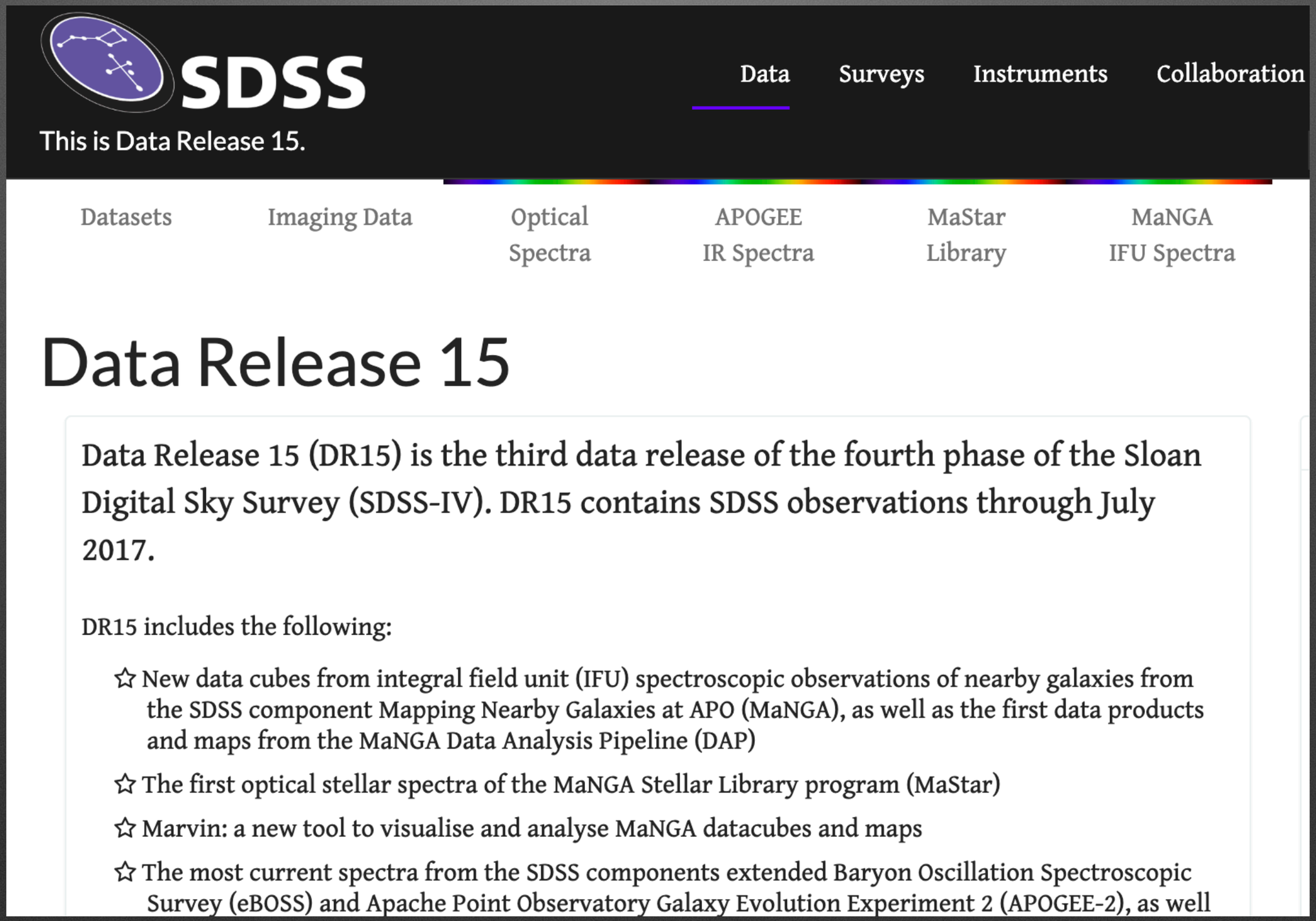
Apache Point Observatory, New Mexico, USA



Apache Point Observatory, New Mexico, USA

Últimos resultados publicados pelo eBOSS

Data Release 15
sdss.org



Últimos dados públicos do eBOSS: DR14

Resultados do eBOSS DR14

Bautista et al. 2018 - BAO com LRGs
Icaza et al. 2019 - BAO e RSD com LRGs

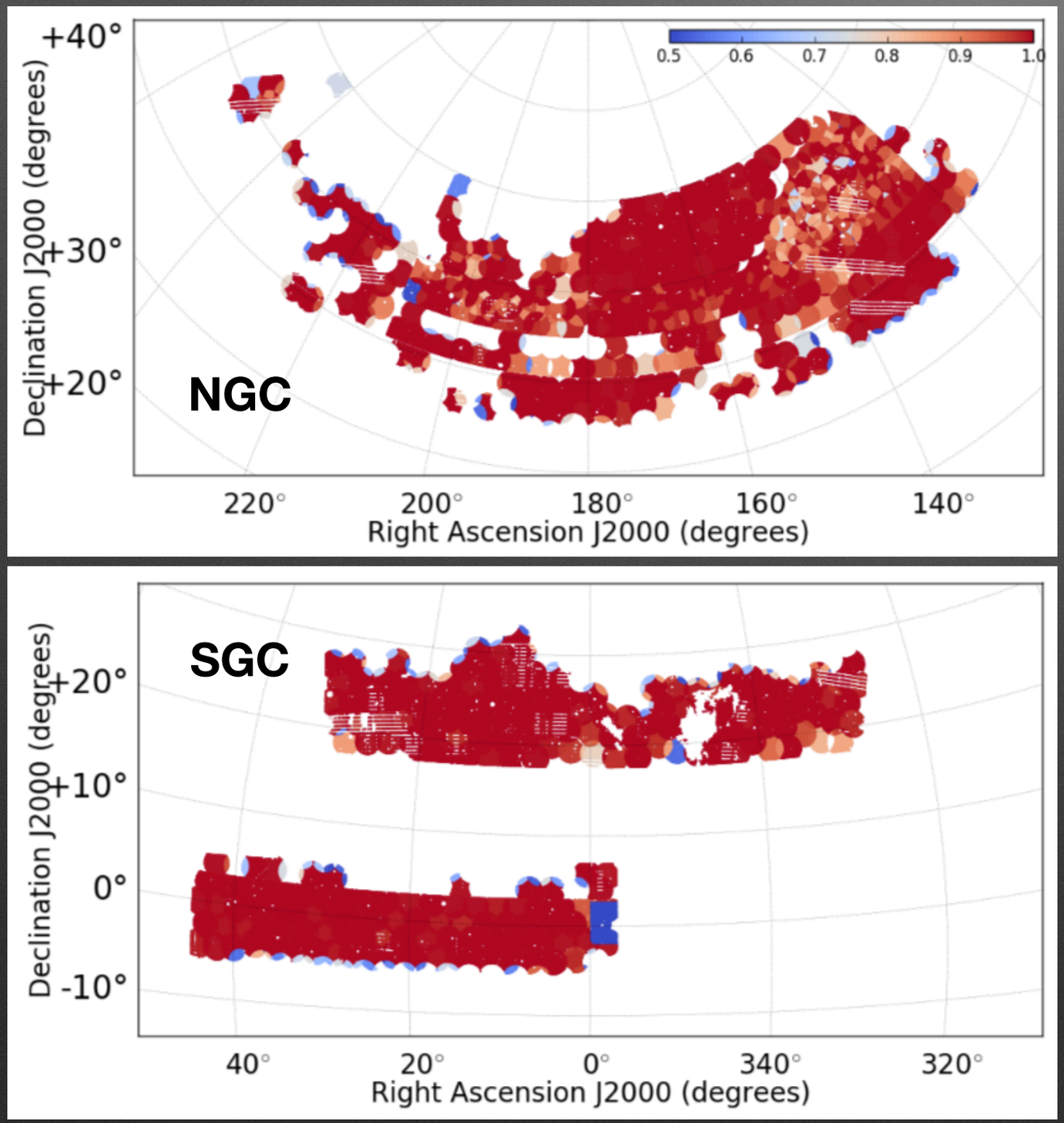
Ata et al. 2018 - BAO com QSO
Gil-Marín et al. 2018 - BAO e RSD com QSOs (Fourier)
Zarrouk et al. 2018 - BAO e RSD com QSOs (Config)
Hou et al. 2018 - BAO e RSD com QSOs (Config)

Wang et al. 2018 - BAO com QSOs e z-weights (Fourier)
Zhao et al. 2018 - Tomografia com QSOs e z-weights

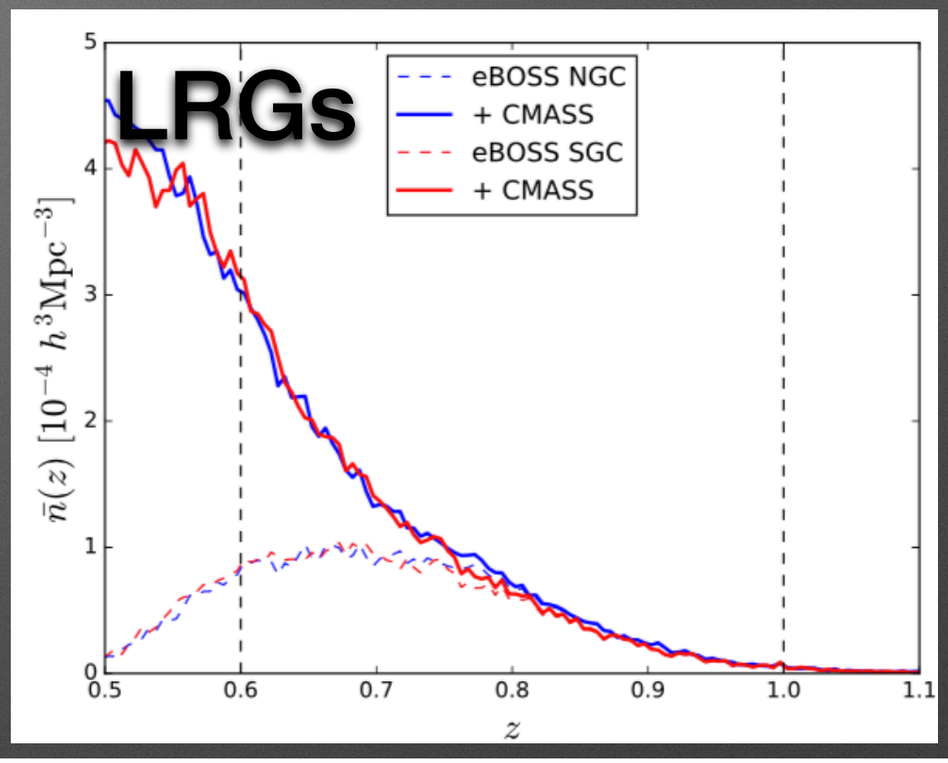
de Sainte Agathe et al. 2019 - BAO com Lya forest (auto)
Blomqvist et al. 2019 - BAO com Lya-QSO (cross)
Chabanier et al. 2019 - Power-spectrum 1D com Lya forest

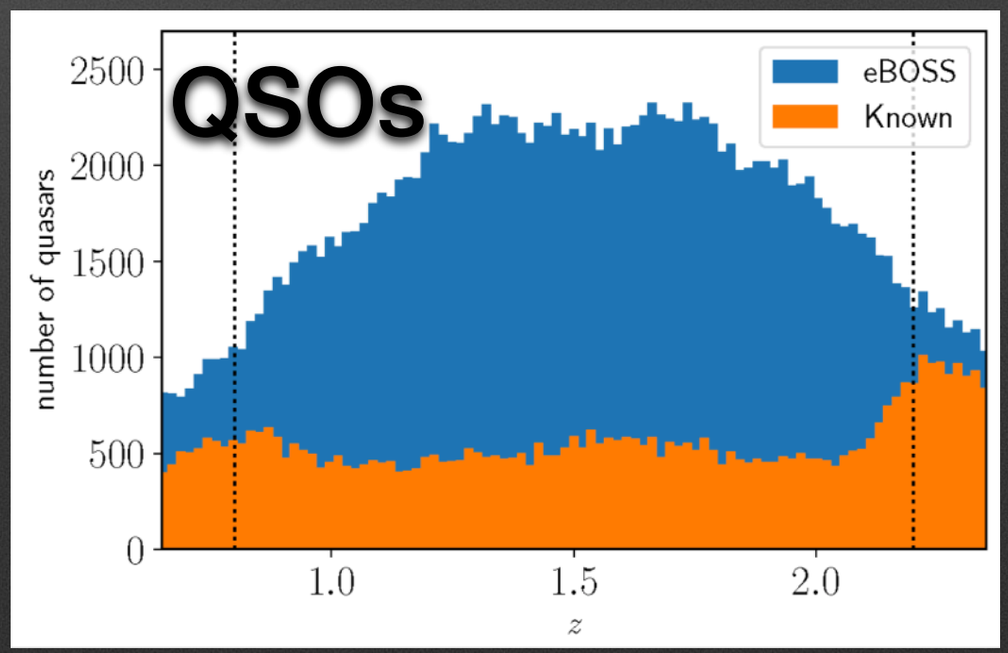
Hawken et al. 2019 - RSD com vazios cósmicos

eBOSS DR14



Redshift distribution

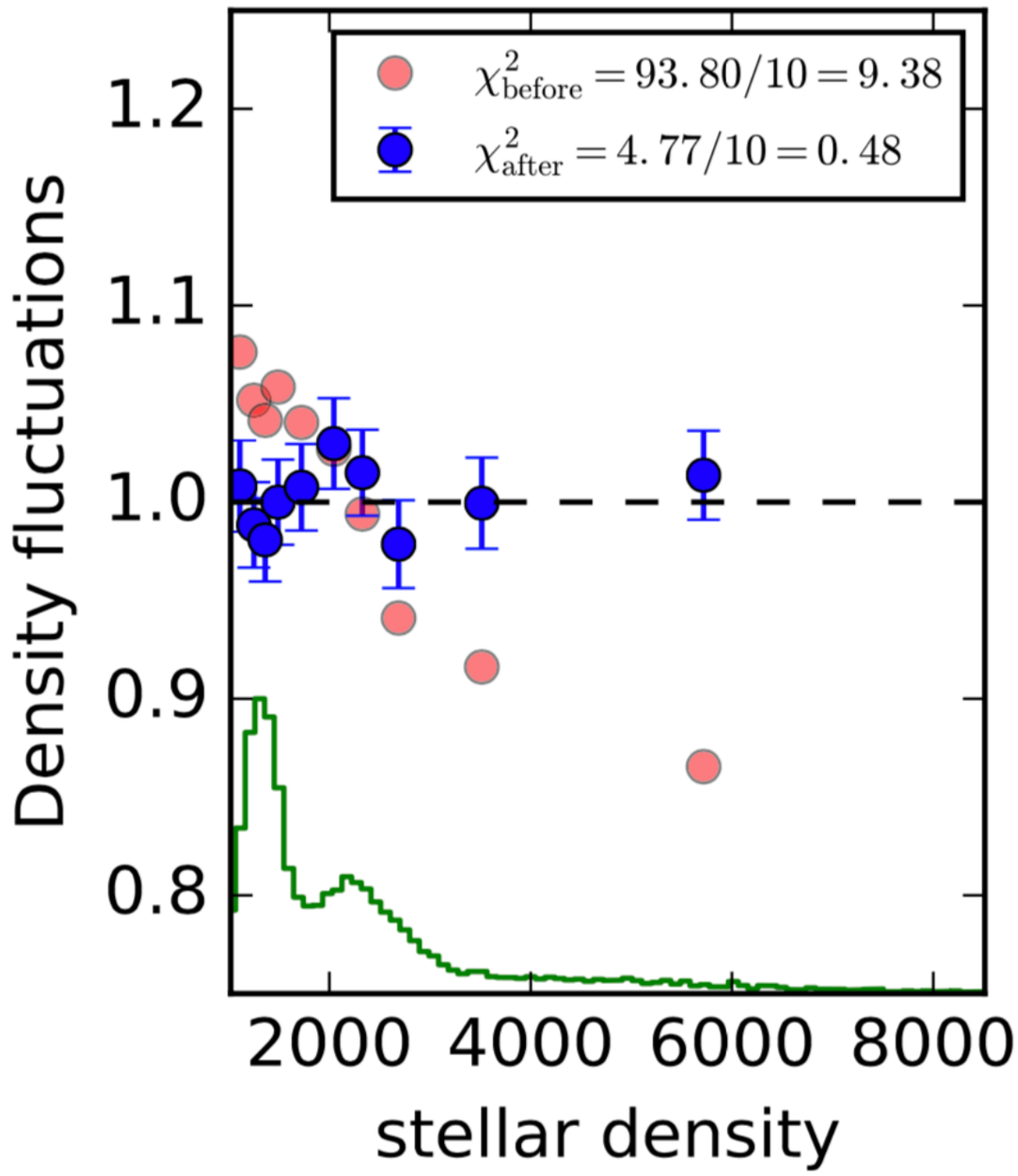




Efeitos sistemáticos

- completude de fibras
- flutuações fotométricas
- falhas na obtenção dos redshifts
- colisões de fibras ópticas

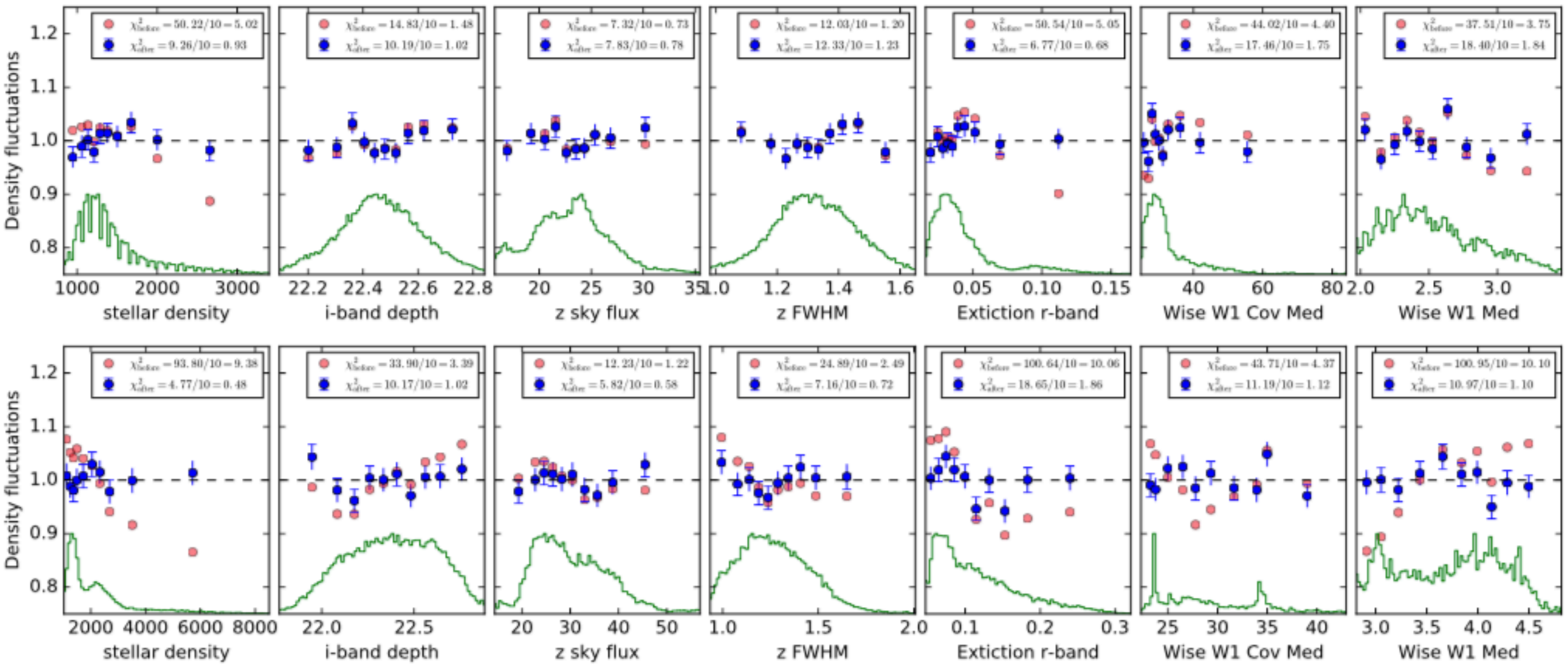
Correcting for fluctuations caused by photometry (Ross et al. 2016, Prakash et al. 2016)



red = before

blue = after

Correcting for fluctuations caused by photometry (Ross et al. 2016, Prakash et al. 2016)

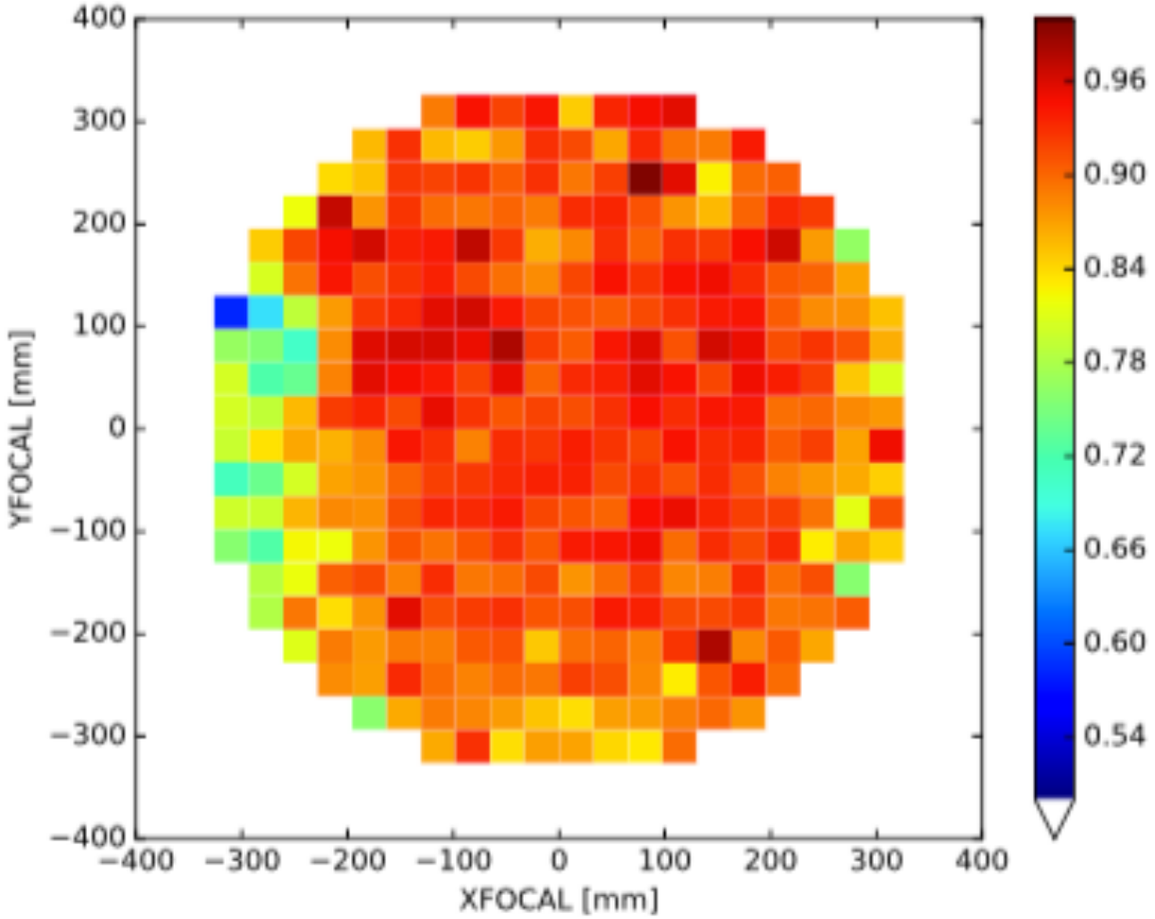


red = before

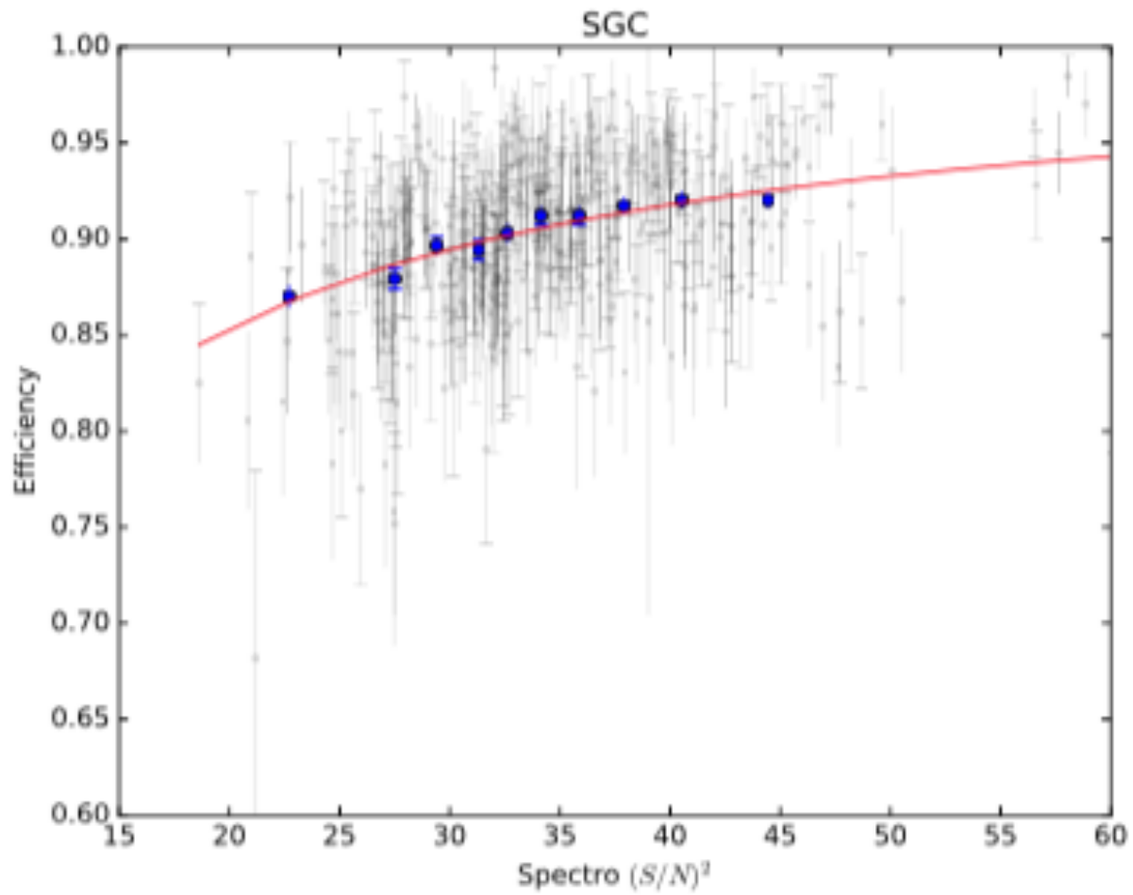
blue = after

Correcting for fluctuations caused by ‘redshift failures’
(failure to obtain redshift from spectrum)

dependency with focal plane



dependency with spectral S/N

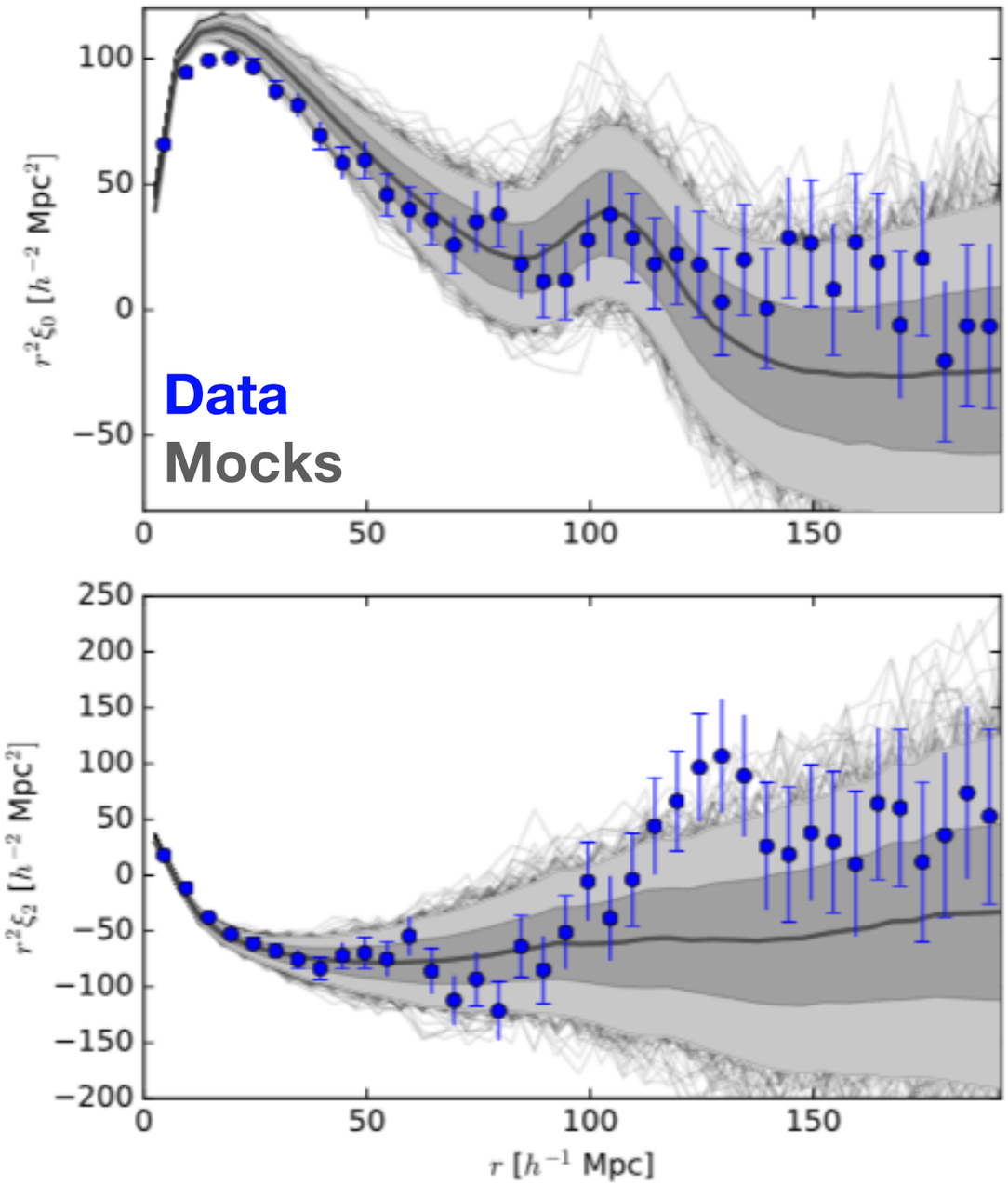


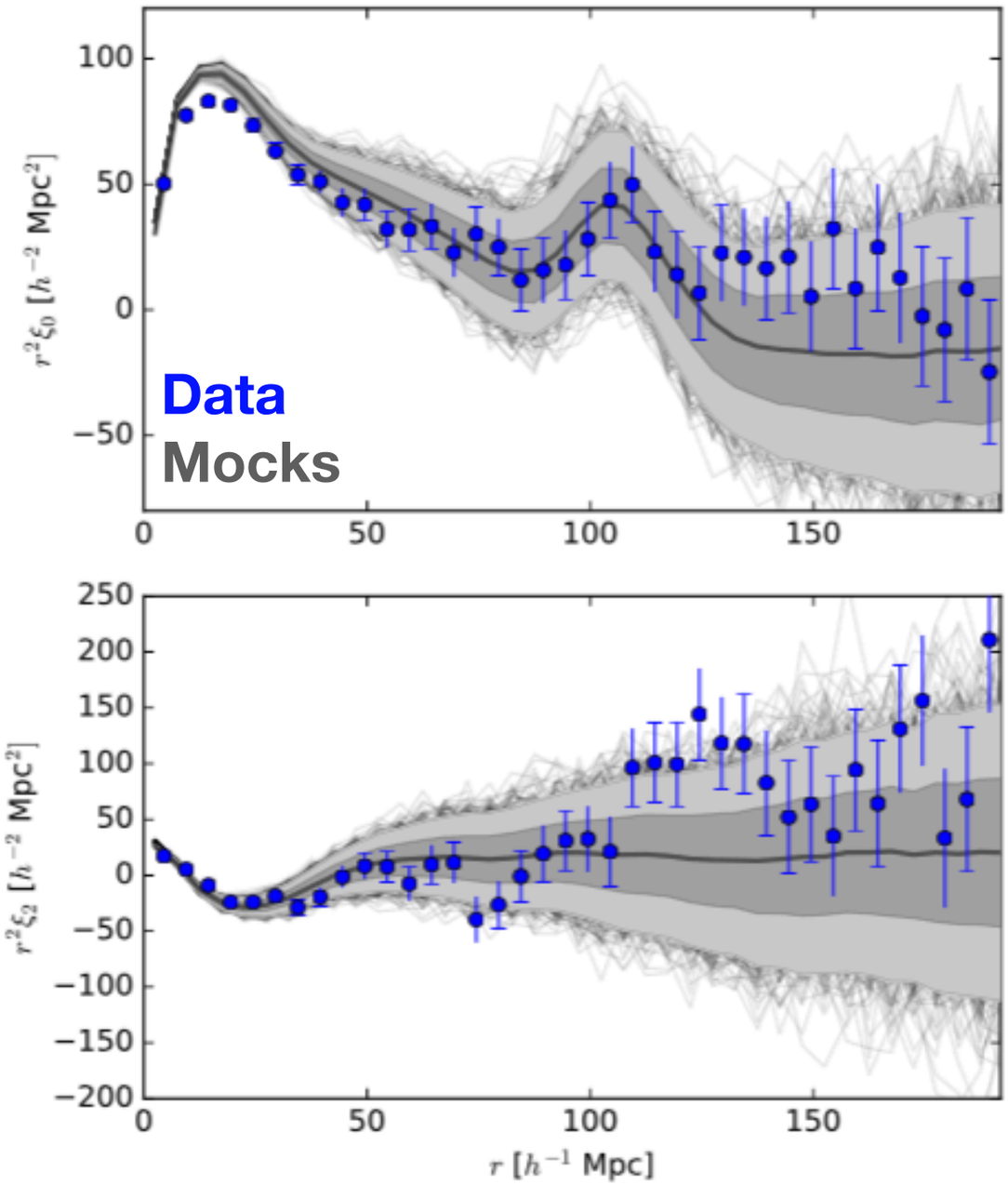
All corrections performed by sub-sampling of the random catalog

Simulações aproximadas para matriz de covariança

Pre-reconstruction | **Post-reconstruction**

Monopole





Quadrupole

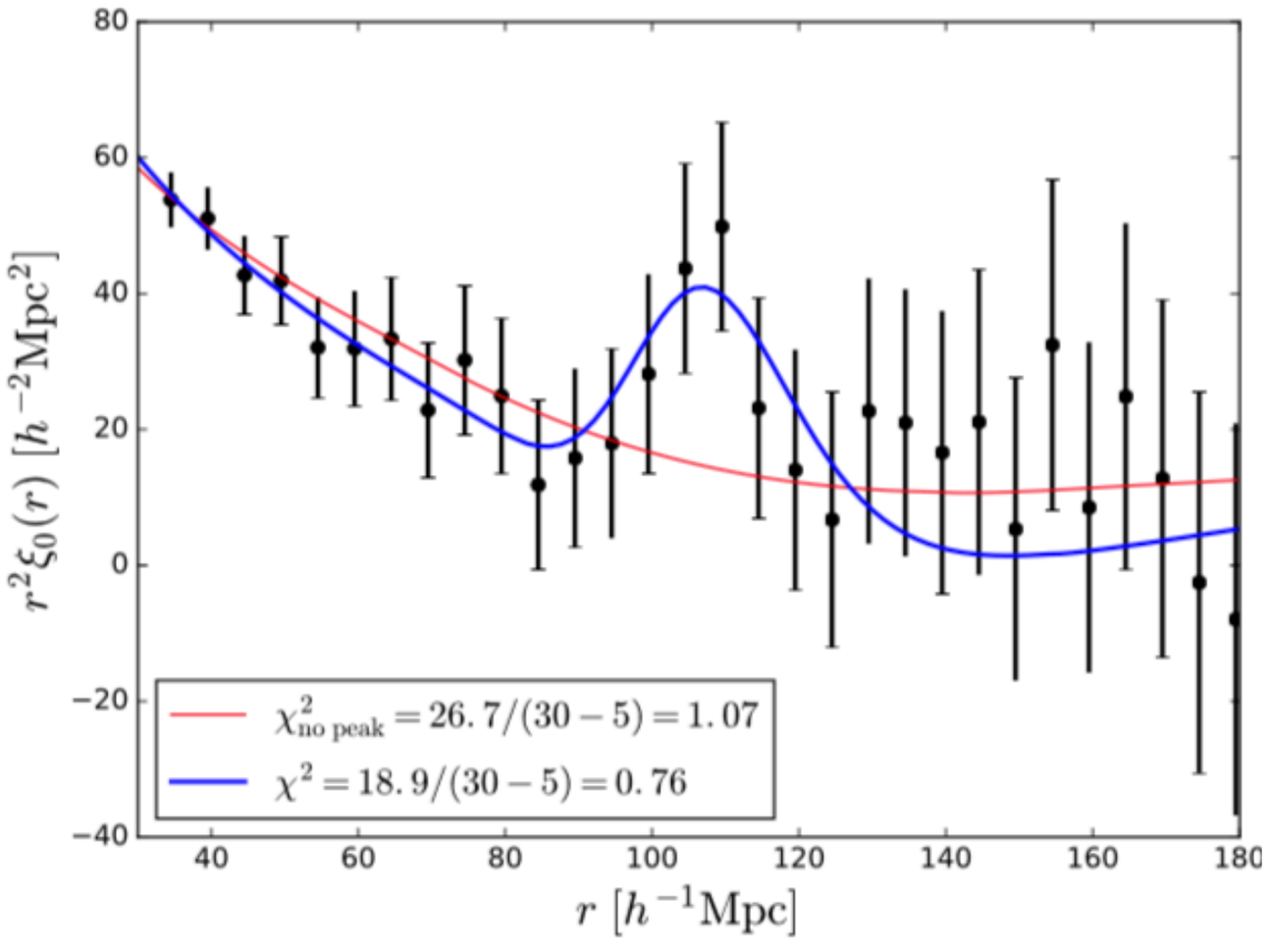
1000 mock catalogs using Quick Particle Mesh technique (White et al. 2013, Zhai et al. 2016)

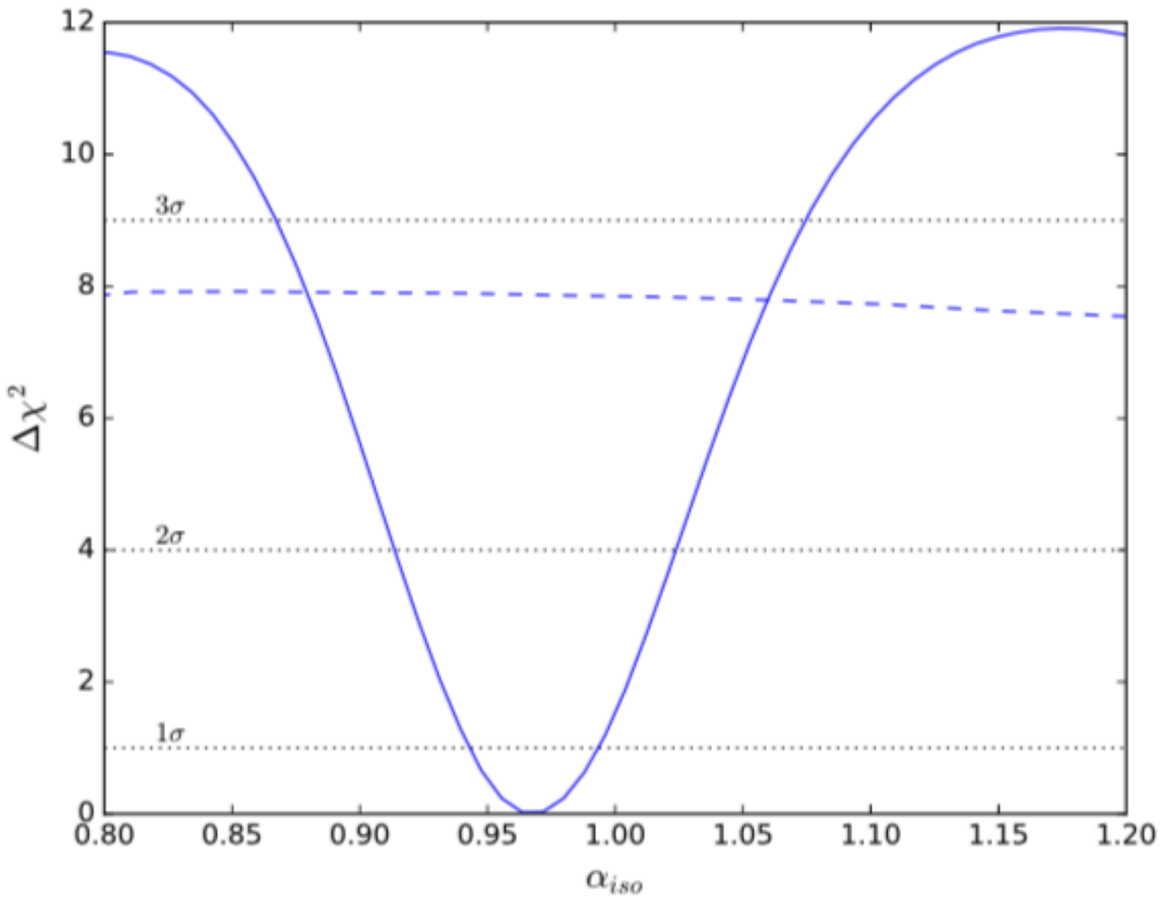
BAO with LRGs (z=0.72)

(Bautista et al. 2018)

Isotropic BAO fit

$$D_V(z = 0.72) = 2377^{+61}_{-59}(r_d/r_{d,\mathrm{fid}})\ \mathrm{Mpc}$$





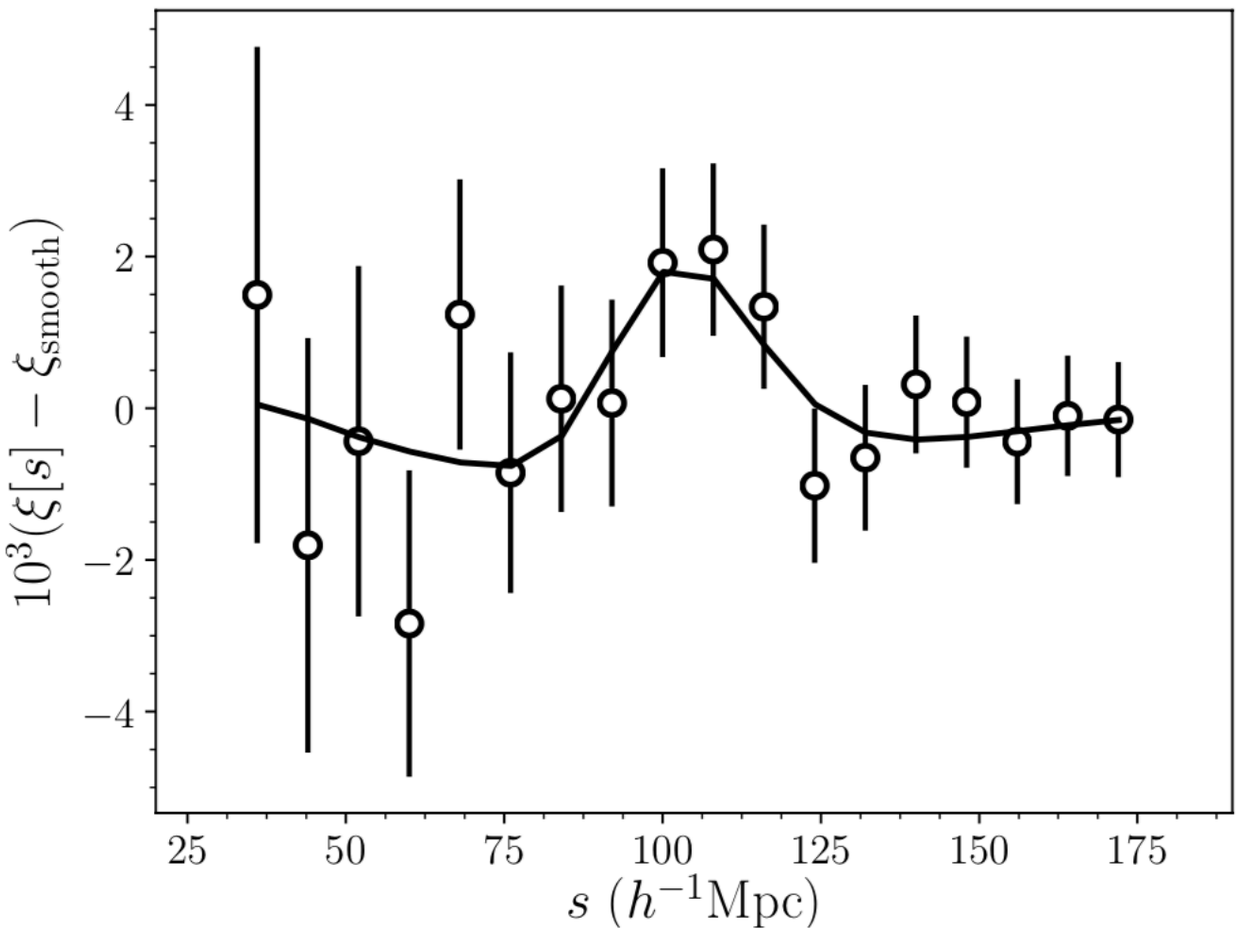
Sample not large enough yet for anisotropic constraints

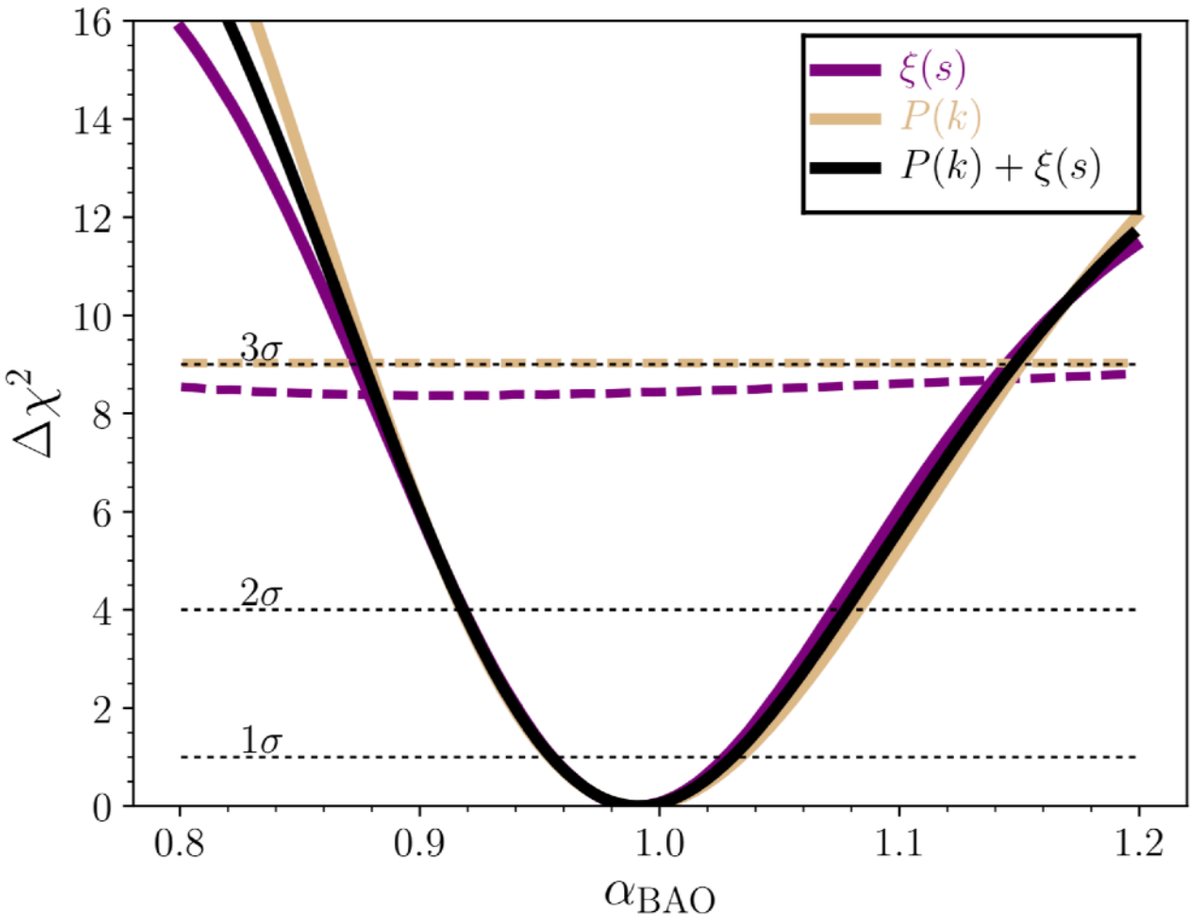
BAO with QSOs (z=1.5)

(Ata et al. 2018)

Isotropic BAO fit

$$D_V(z = 1.52) = 3843 \pm 147\,(r_{\rm d}/r_{\rm d,fid})\ {\rm Mpc}$$



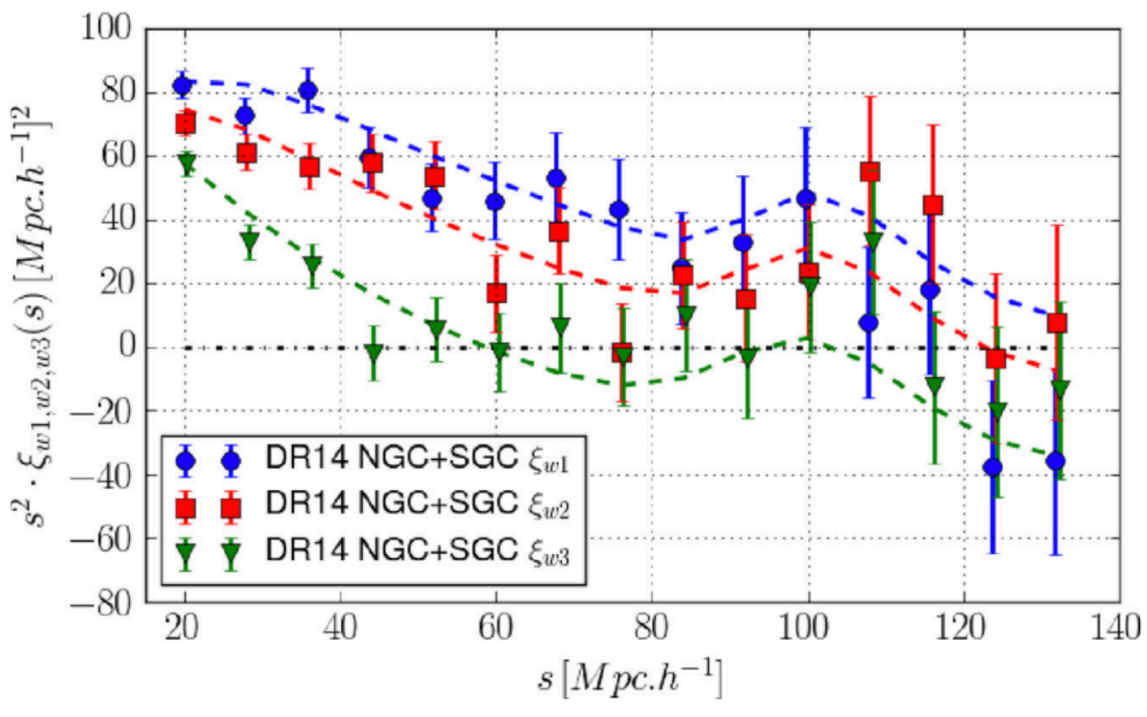


RSD with QSOs (z=1.5)

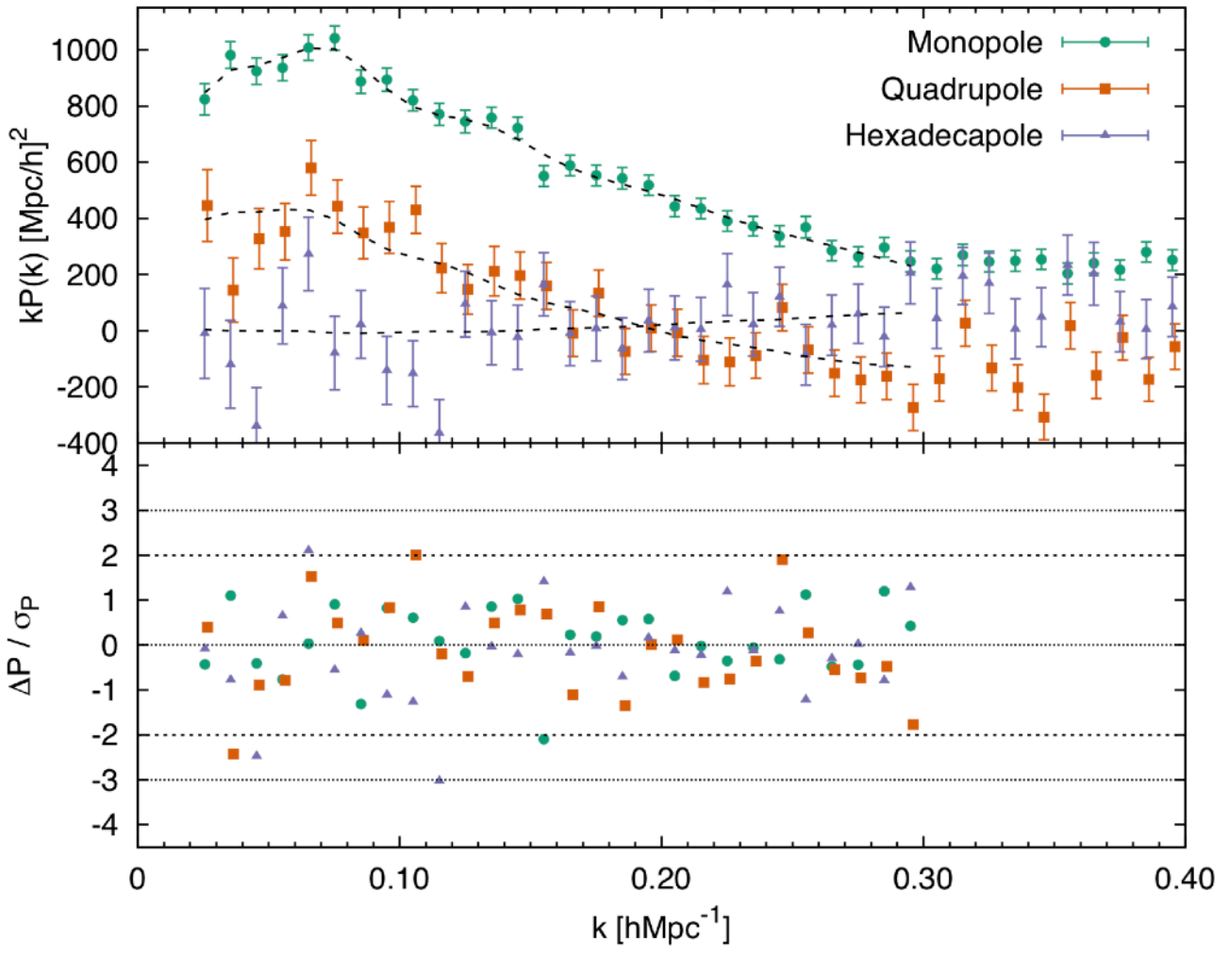
(Gil-Marín et al. 2018, Hou et al. 2018, Zarrouk et al. 2018)

- Comoving Lagrangian Perturbation Theory (Matsubara 2009)
- Eulerian Eulerian non-linear bias model (McDonald & Roy 2009)

Config. space

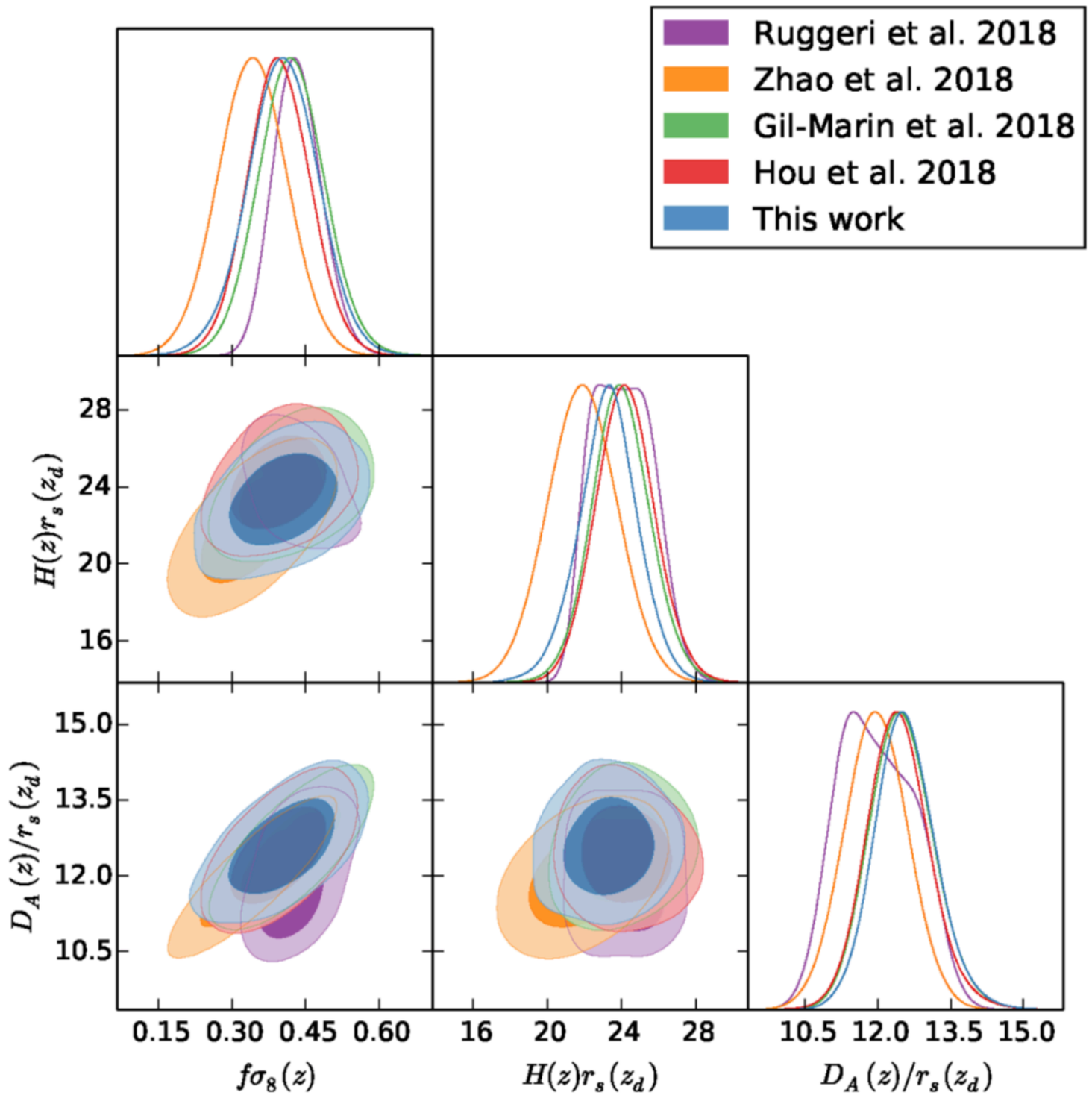


Fourier space



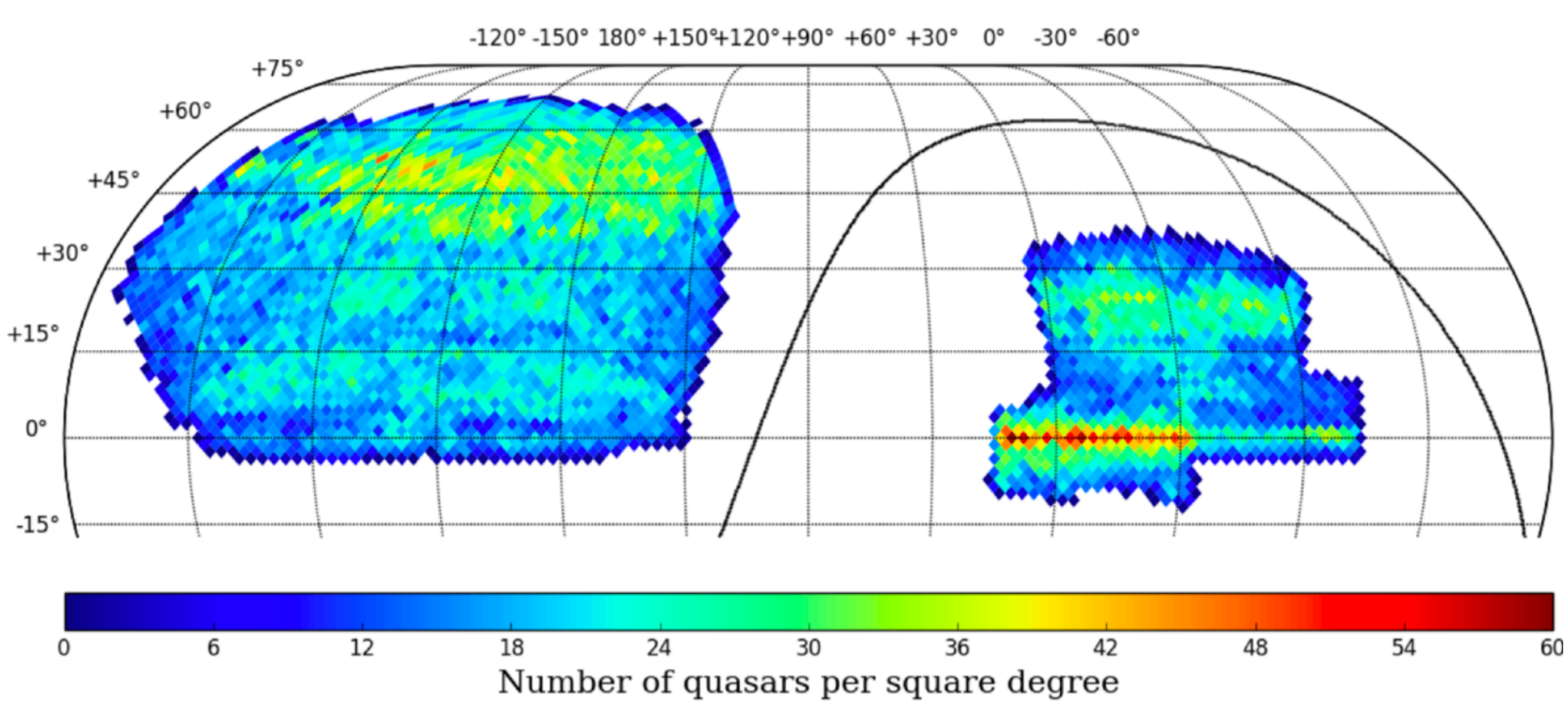
RSD with QSOs (z=1.5)

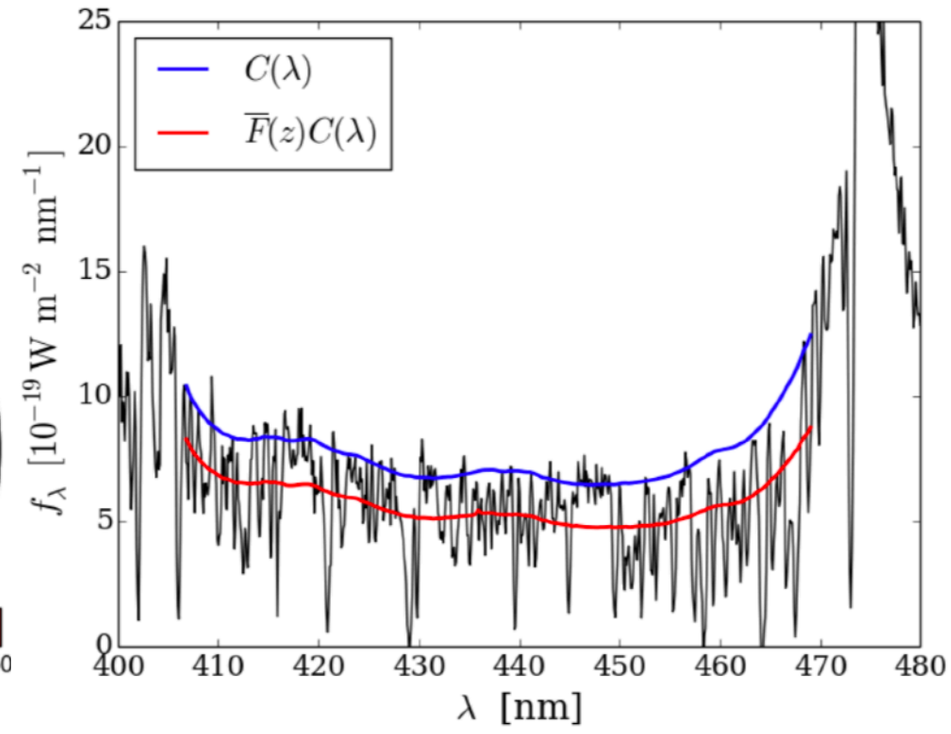
(Gil-Marín et al. 2018, Hou et al. 2018, Zarrouk et al. 2018)

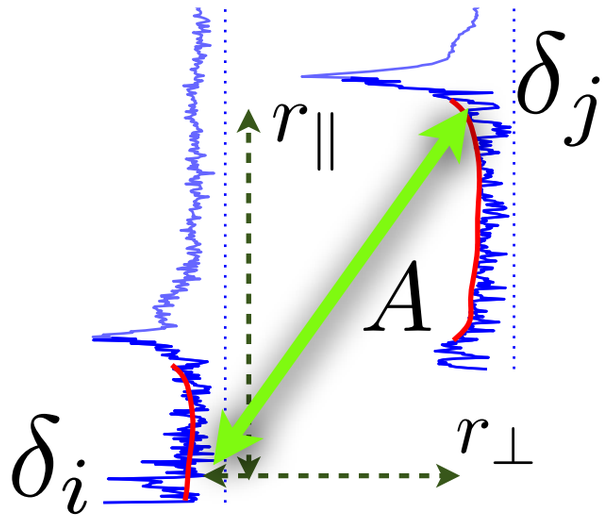


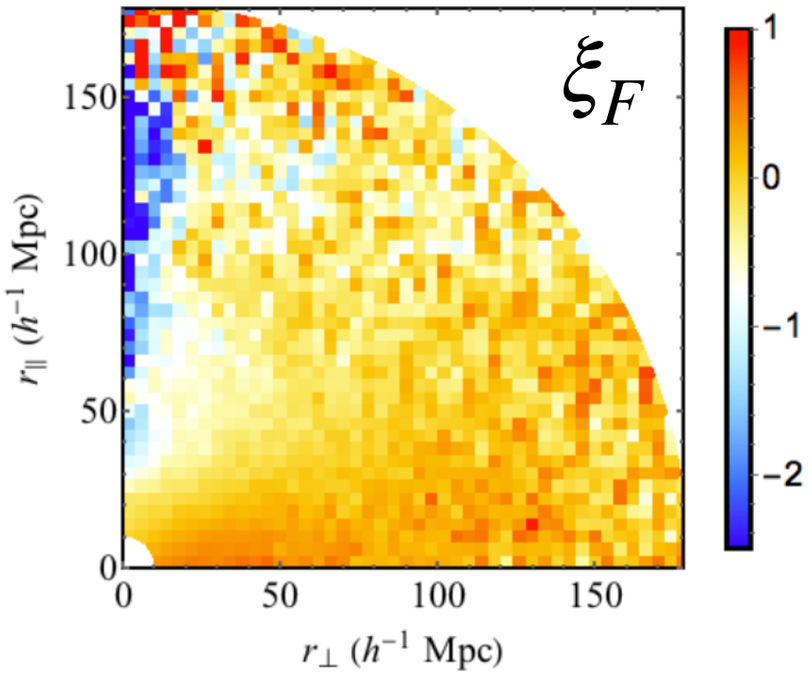
BAO with forests a z > 2.0

(Sainte Agathe et al. 2019, Blomqvist et al. 2019)









List of tests on systematic tests

Astrophysical systematics

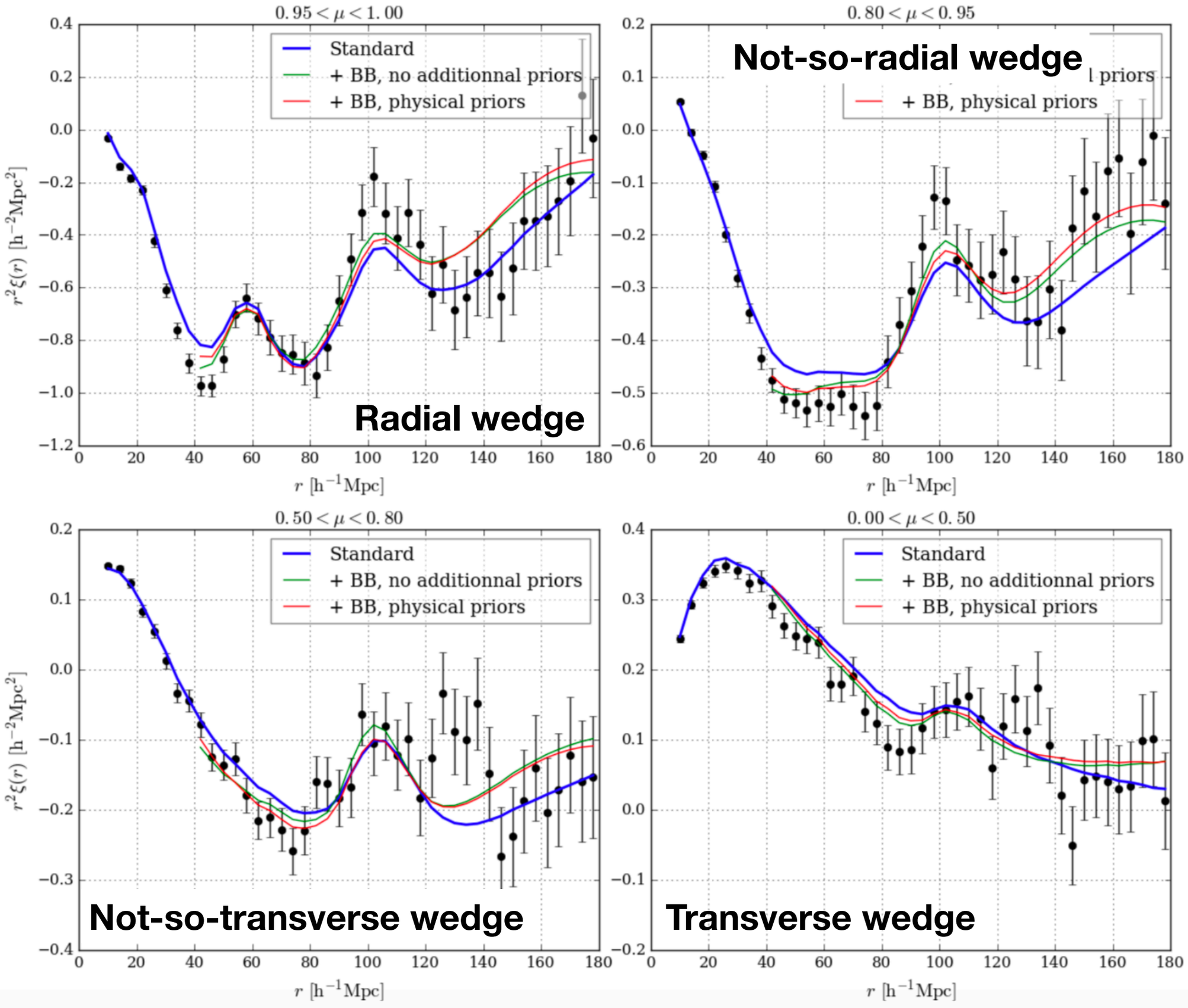
- contamination by **metals**: Si, C
- contamination by **DLAs**, or BALs
- contamination by galactic absorption
- effect of UV background fluctuations
- effect of continuum fitting

Instrumental systematics

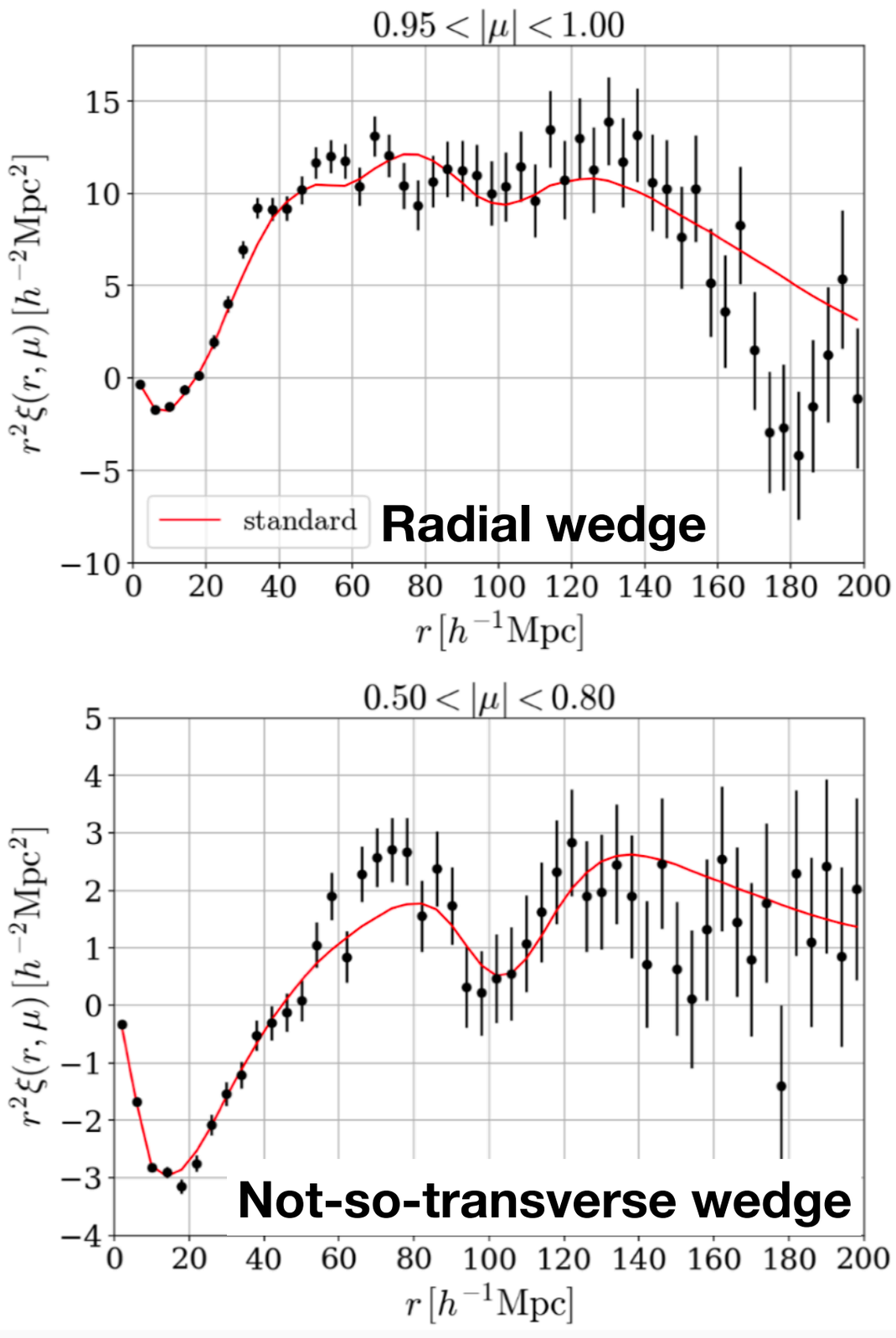
- impact of flux calibration
- impact of sky residuals
- impact of fiber cross-talk
- impact of extraction

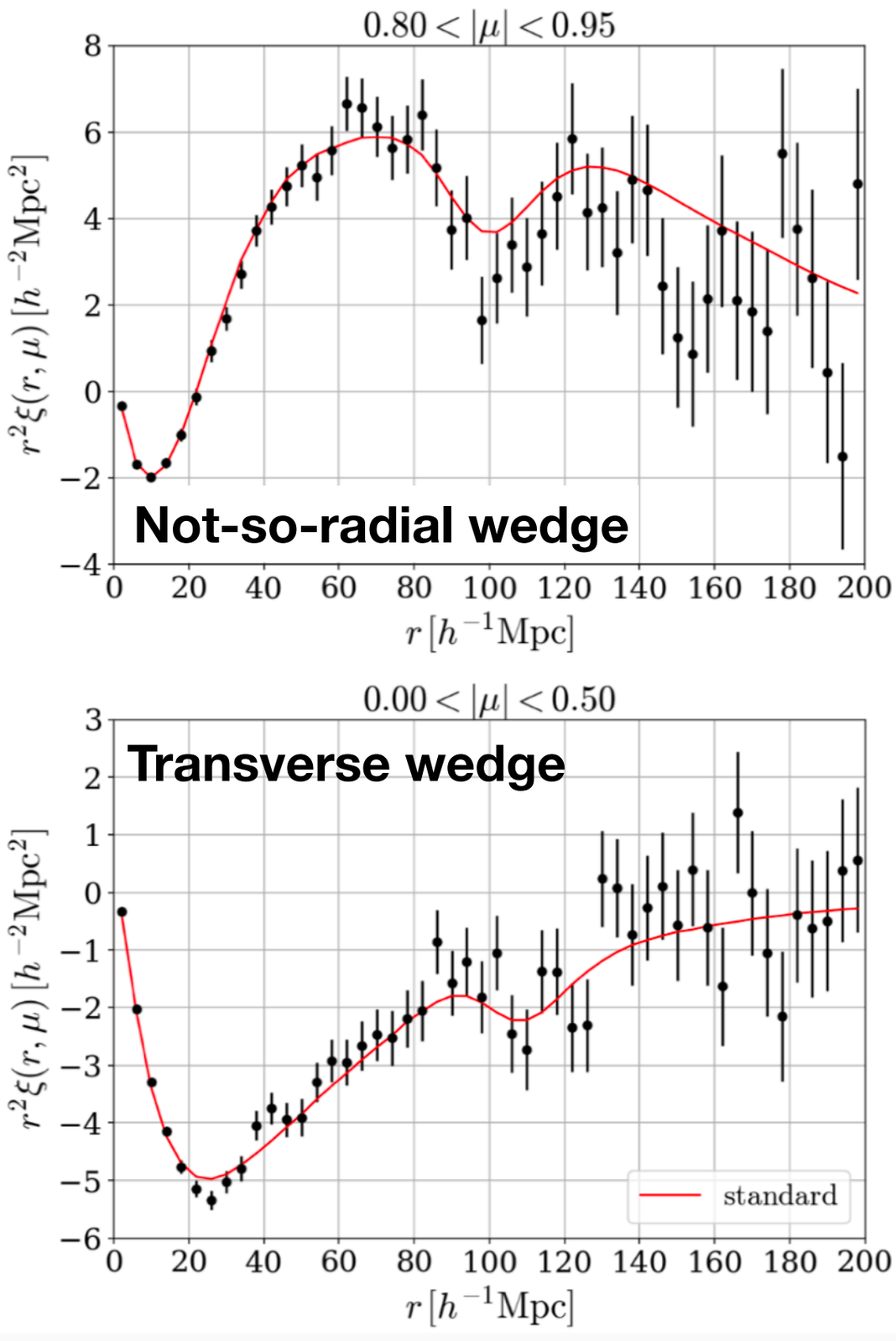
All tests were performed on data and mock catalogs

Auto-correlation (de Sainte Agathe et al. 2019)

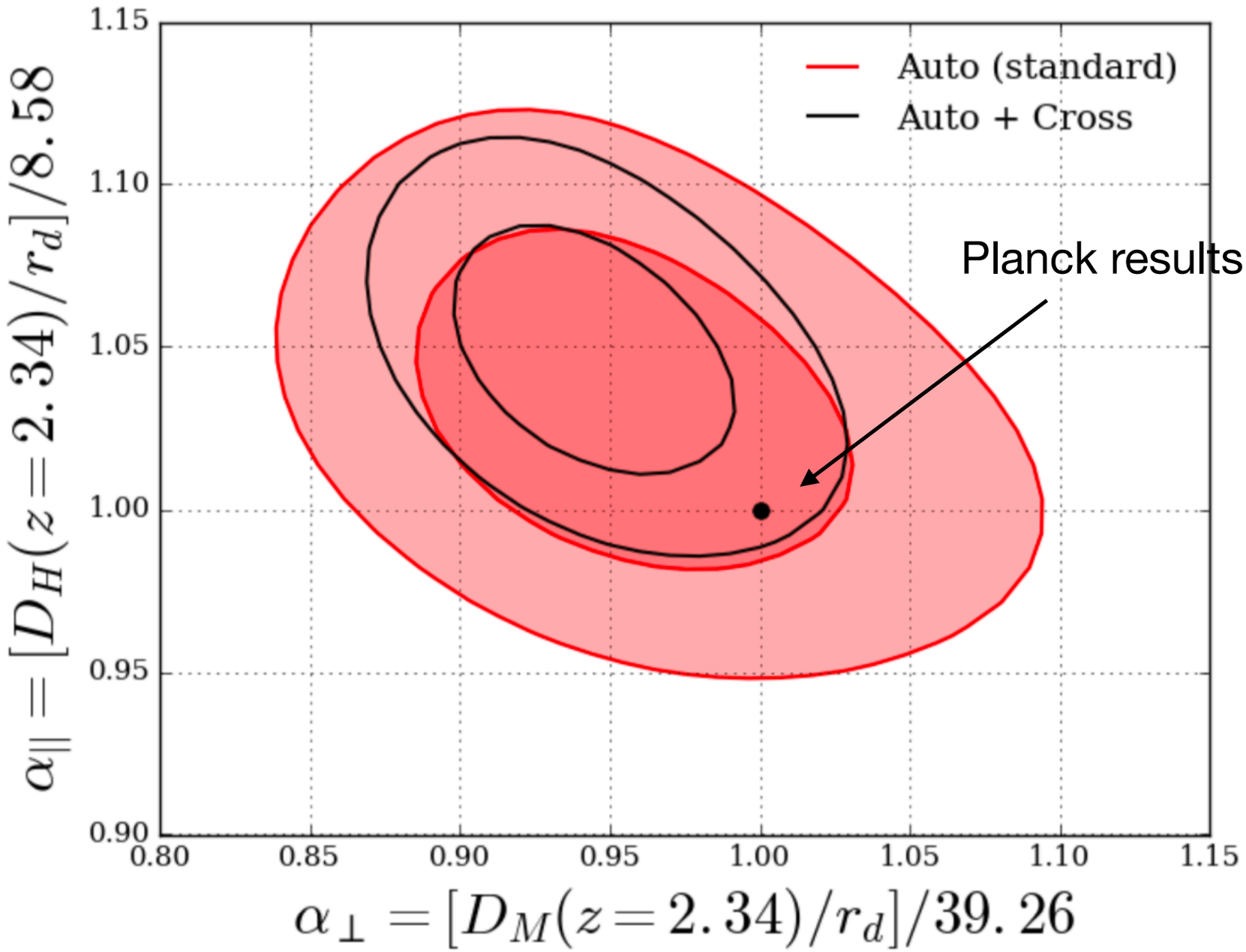


Cross-correlation with QSOs (Blomqvist et al. 2019)

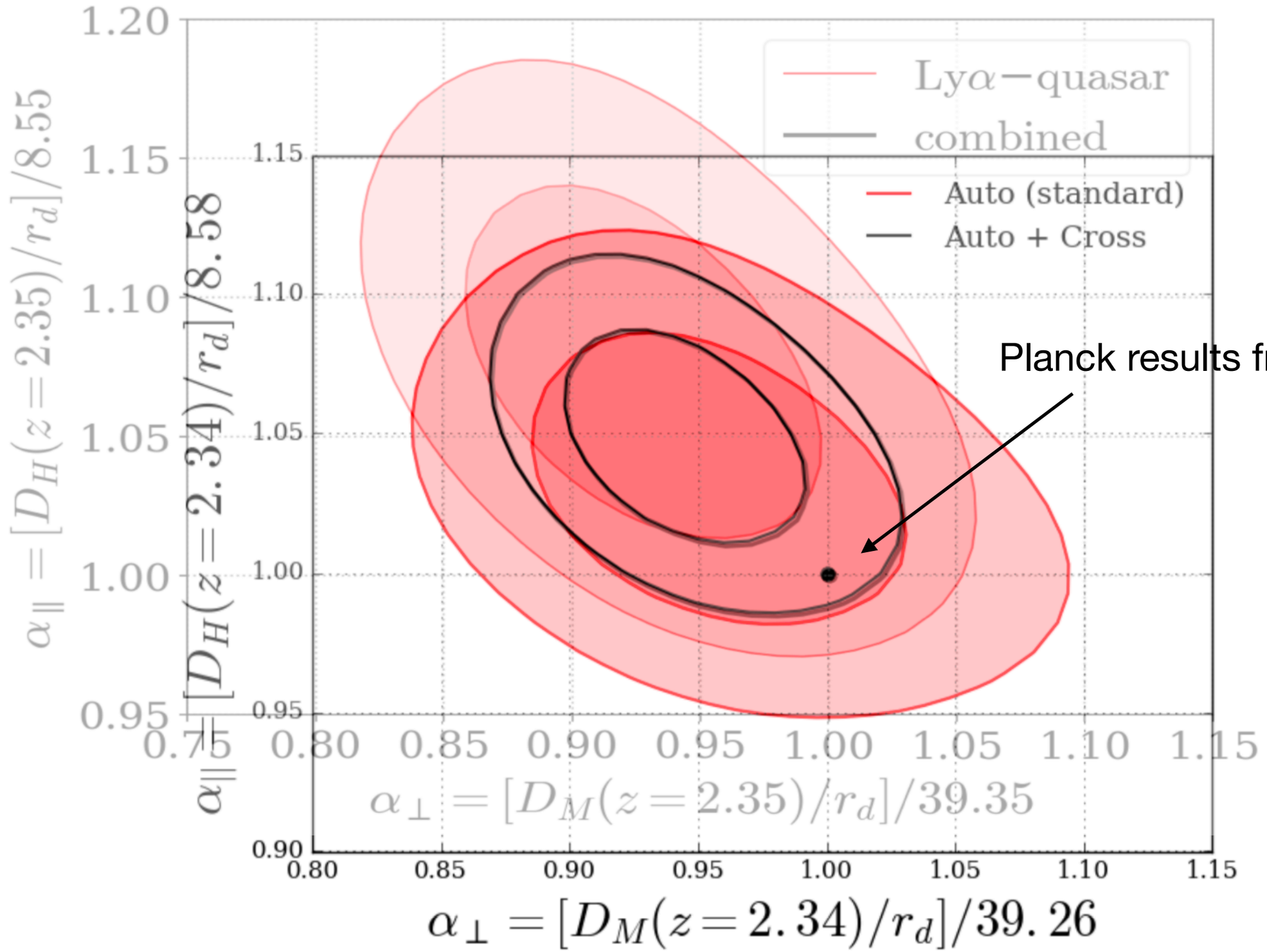




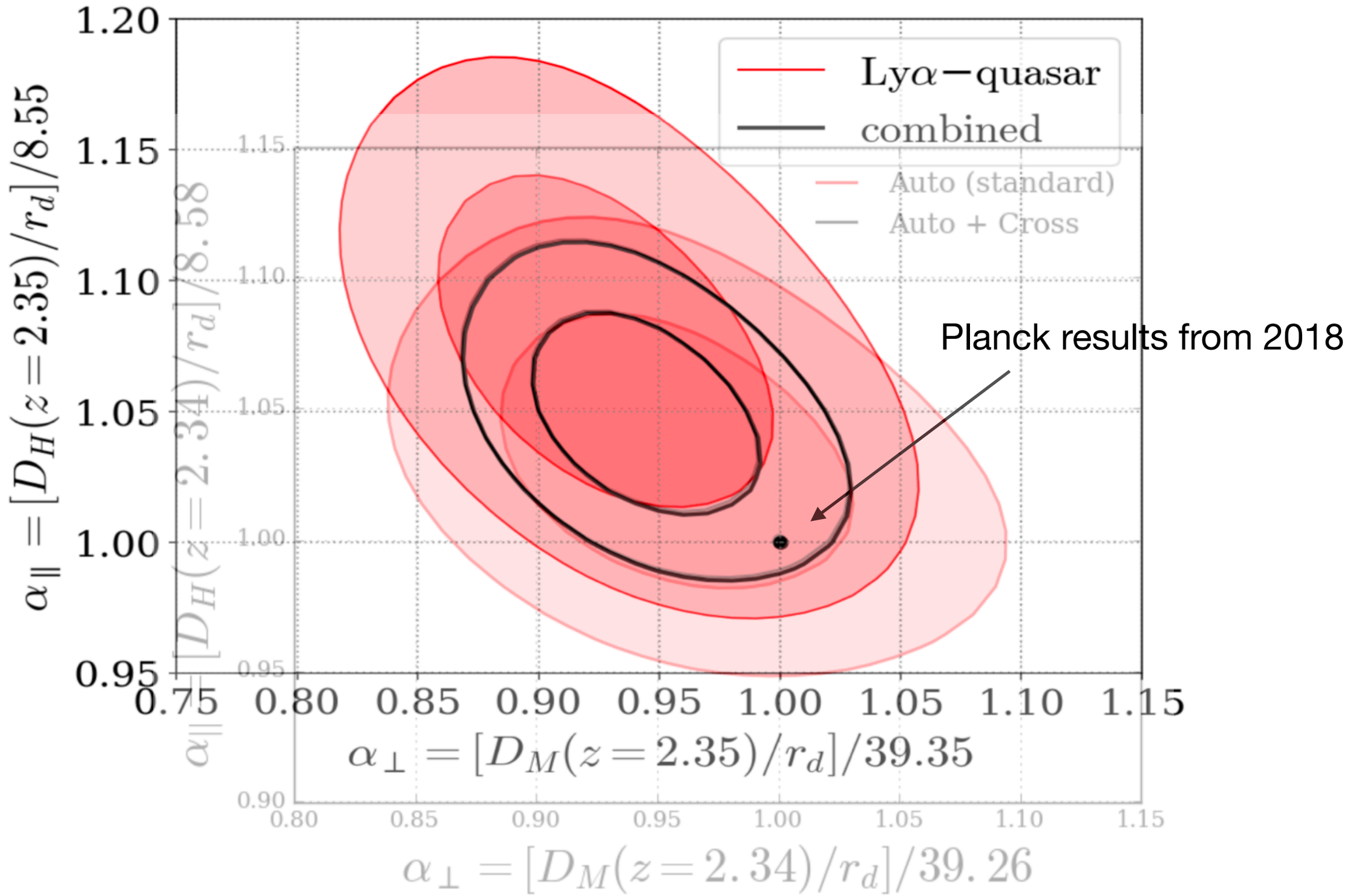
Auto-correlation BAO constraints



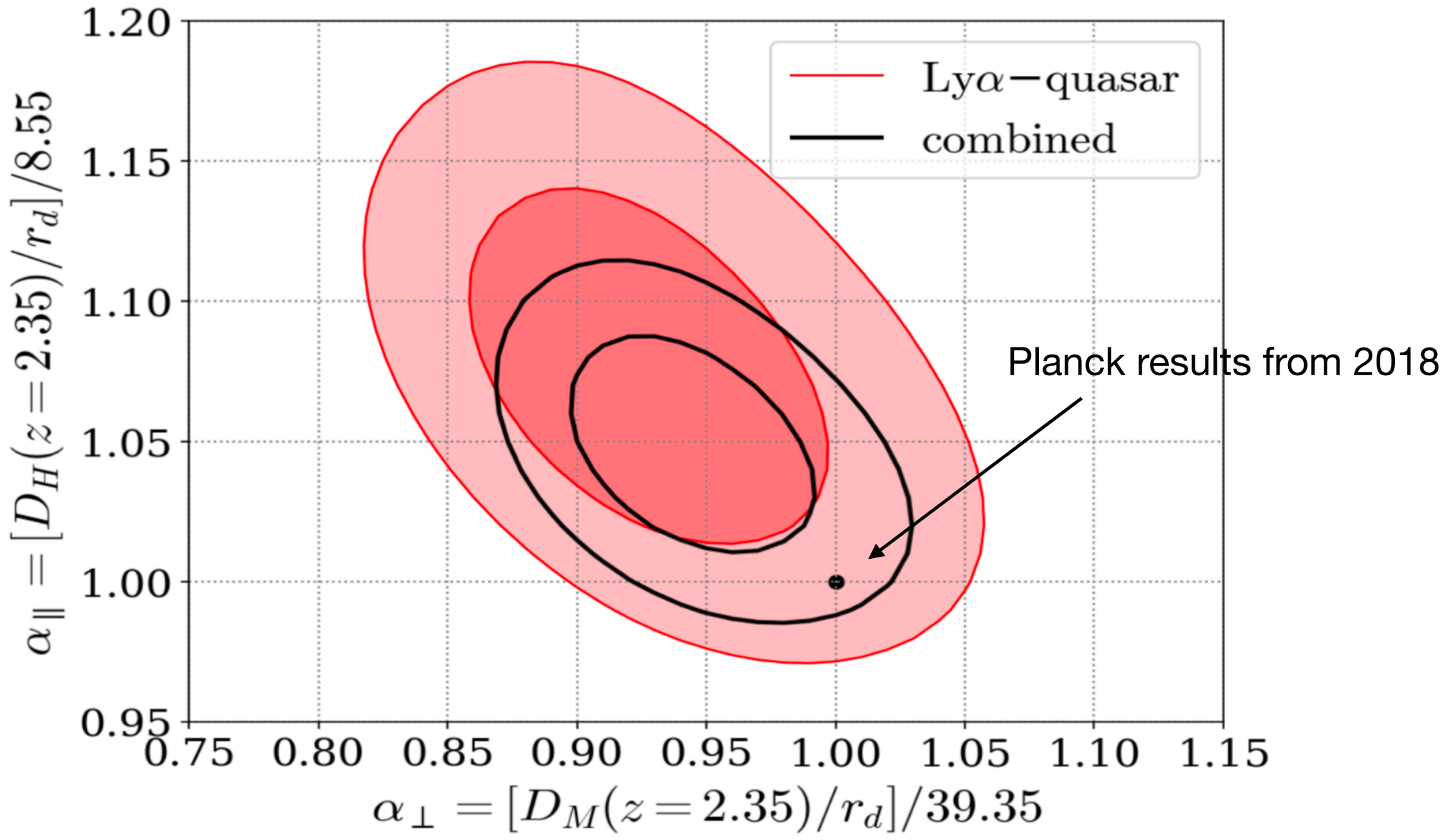
Auto-correlation BAO constraints



Auto-correlation BAO constraints

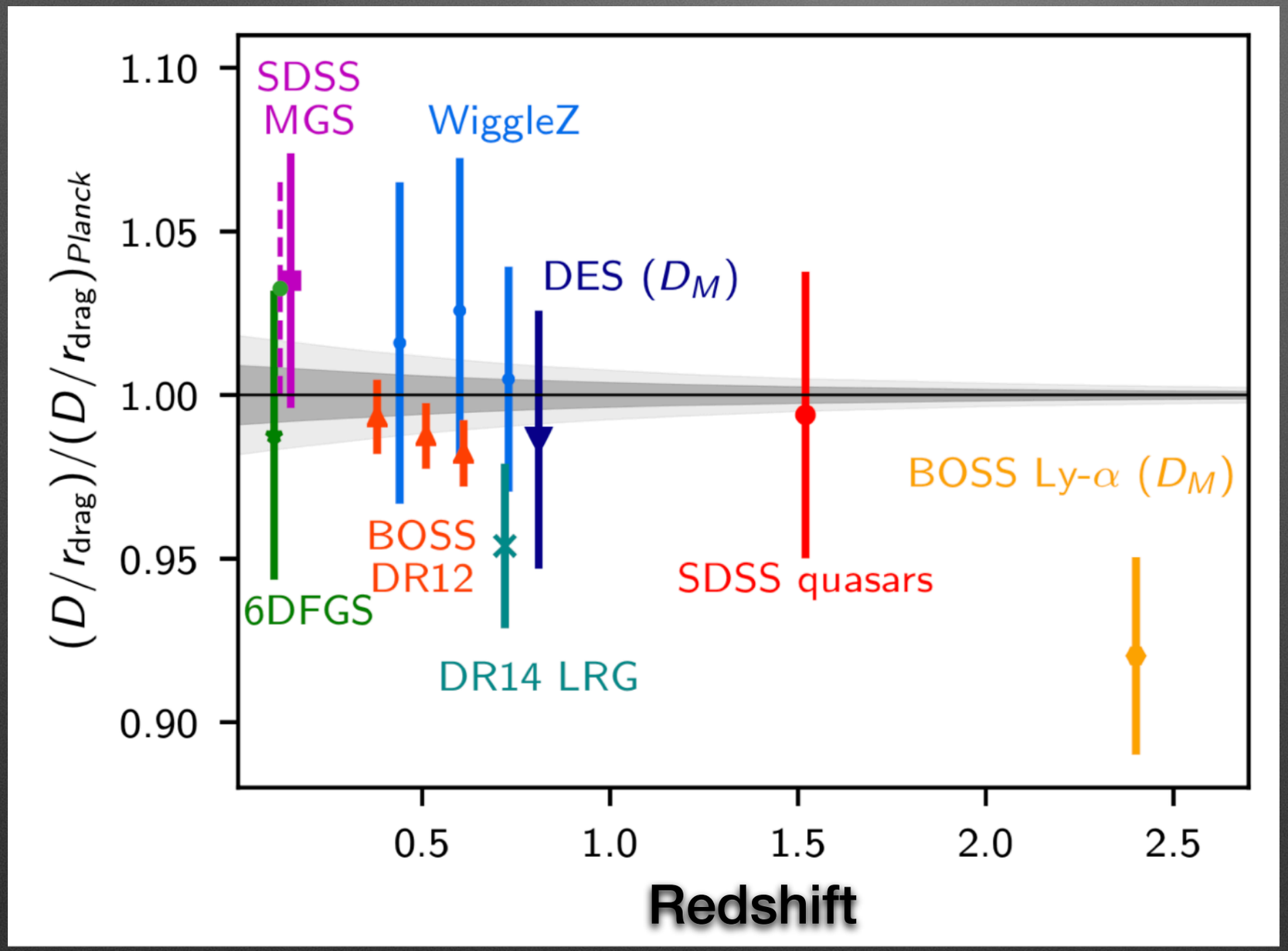


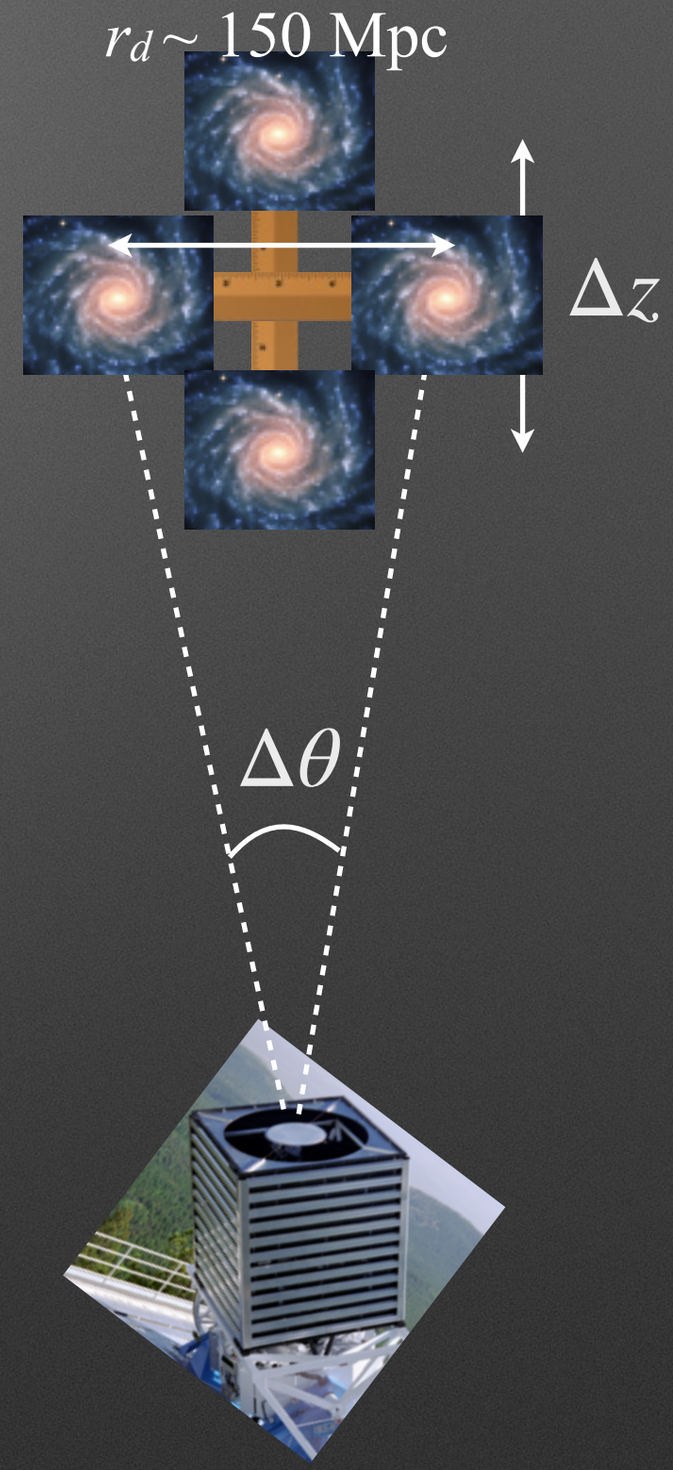
Cross-correlation BAO constraints



Tension with Planck reduced from 2.3 sigma to 1.7 sigma

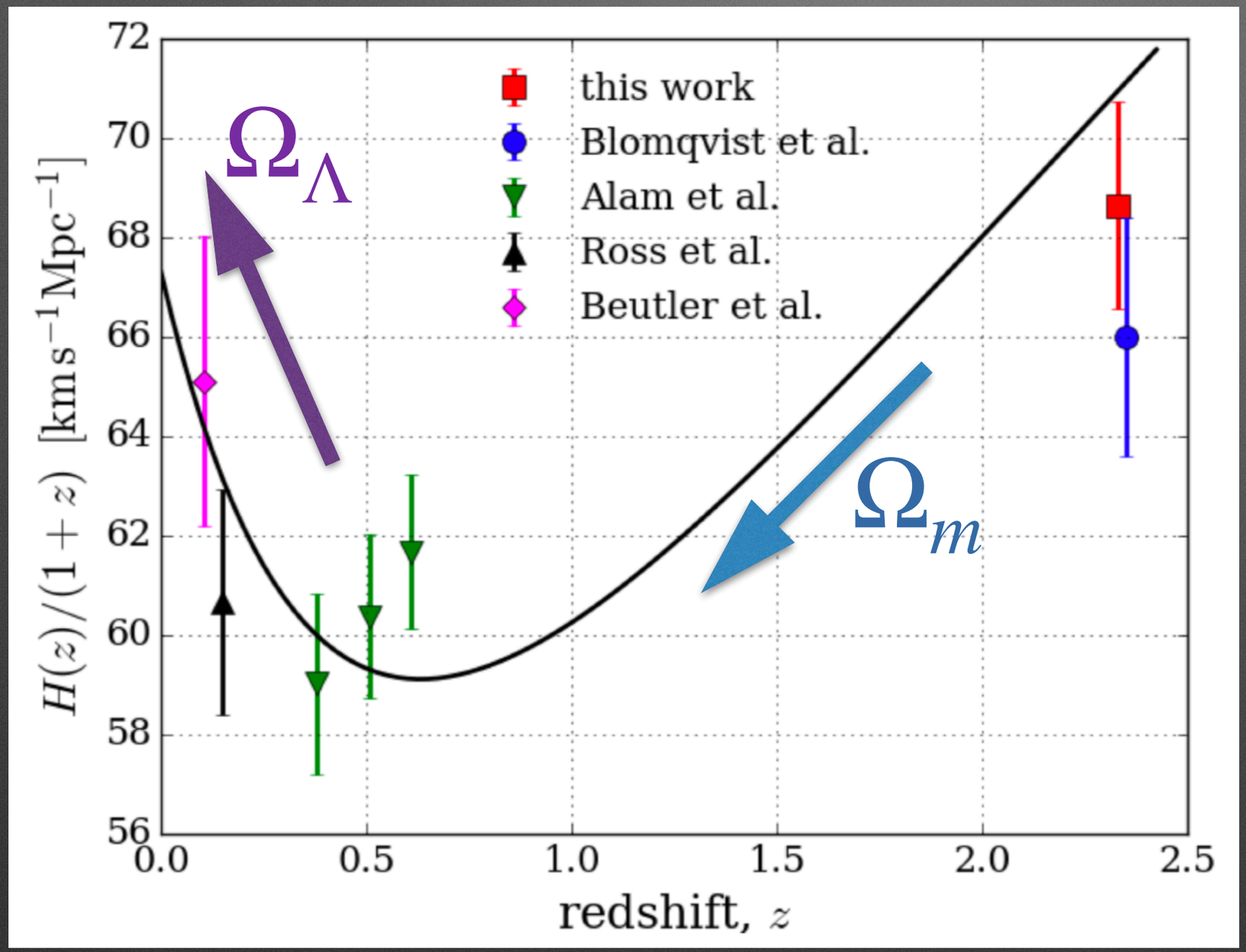
Ângulo medido / Ângulo previsto por um modelo

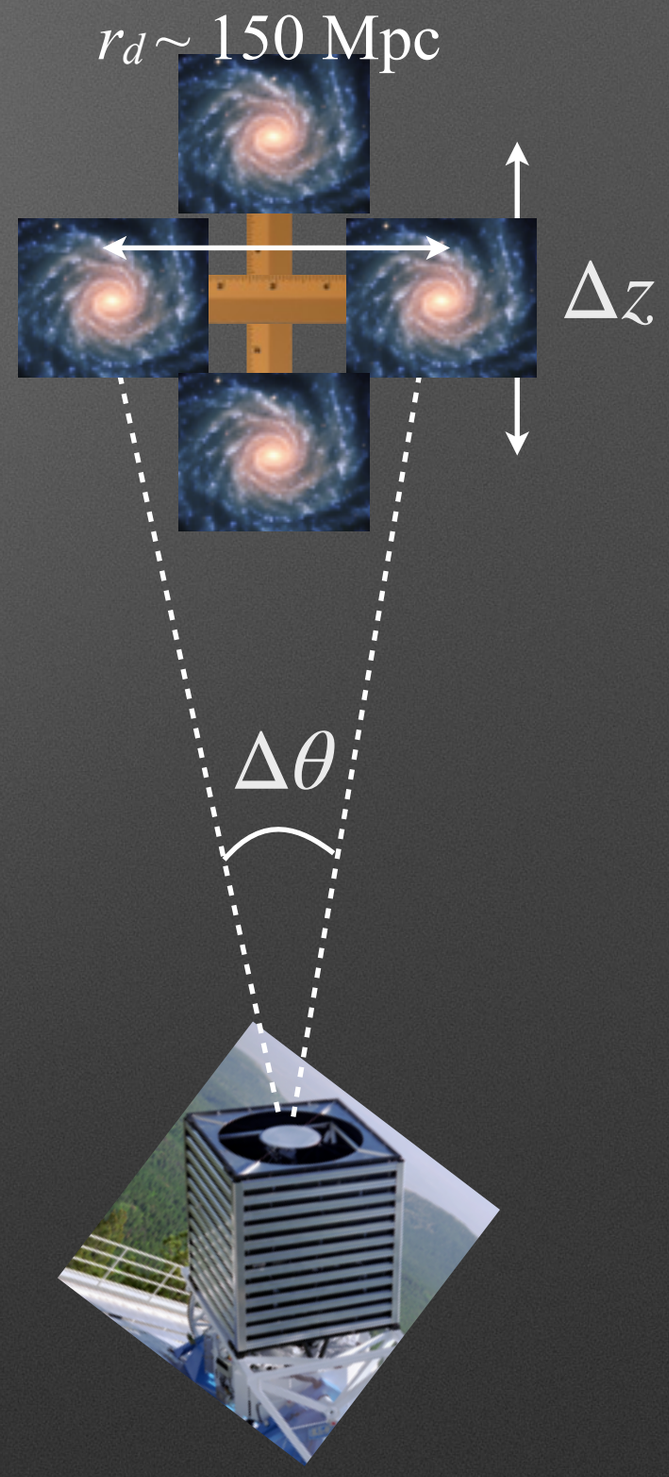




Planck Collaboration 2018 Paper VI

"Velocidade de expansão"

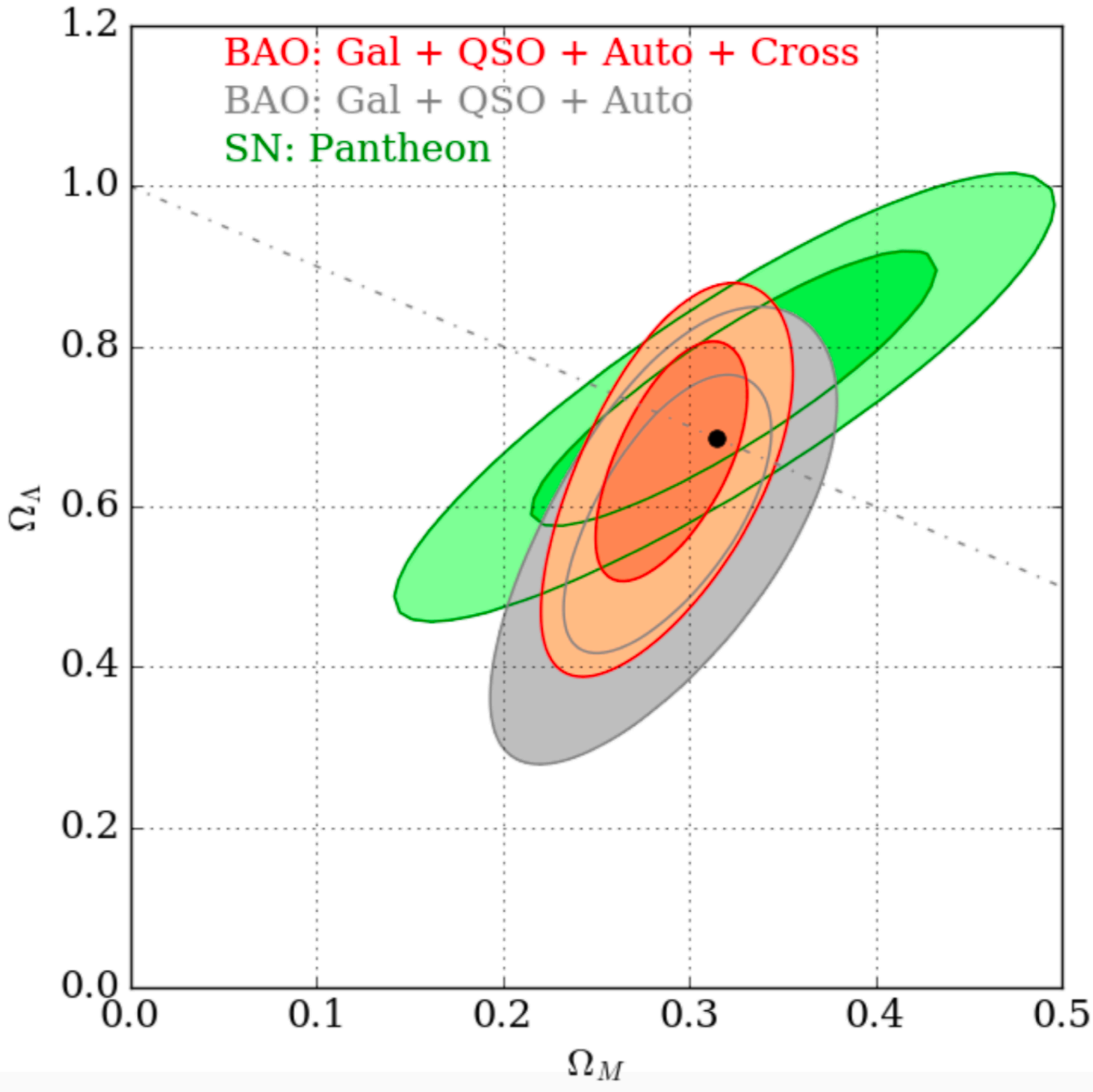




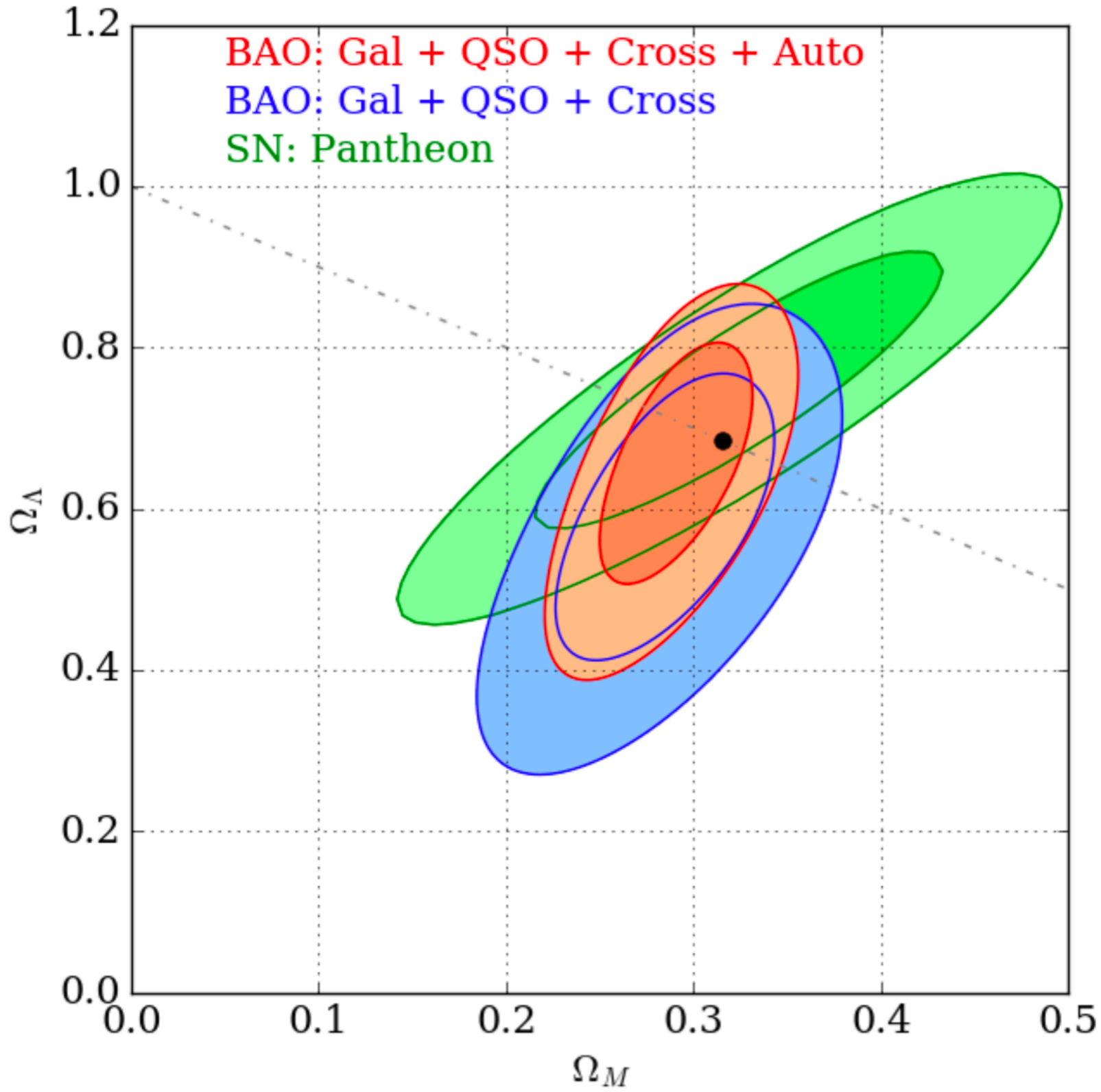
$$H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3 + \ldots}$$

de Sainte Agathe et al. 2019
Blomqvist et al. 2019

Energia escura com BAO



Energia escura com BAO



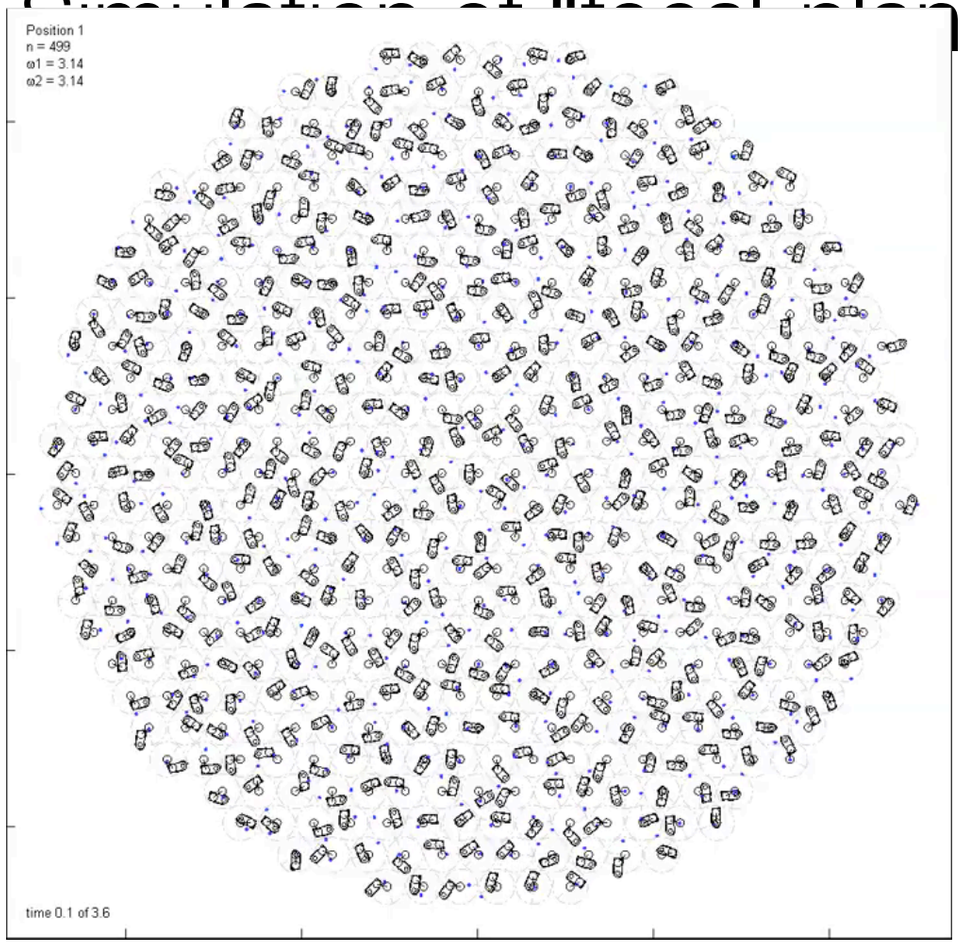
DESI

Dark Energy Spectroscopic Survey
commissioning started last week!

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

Fiber positioner

Simulation of "focal plane"

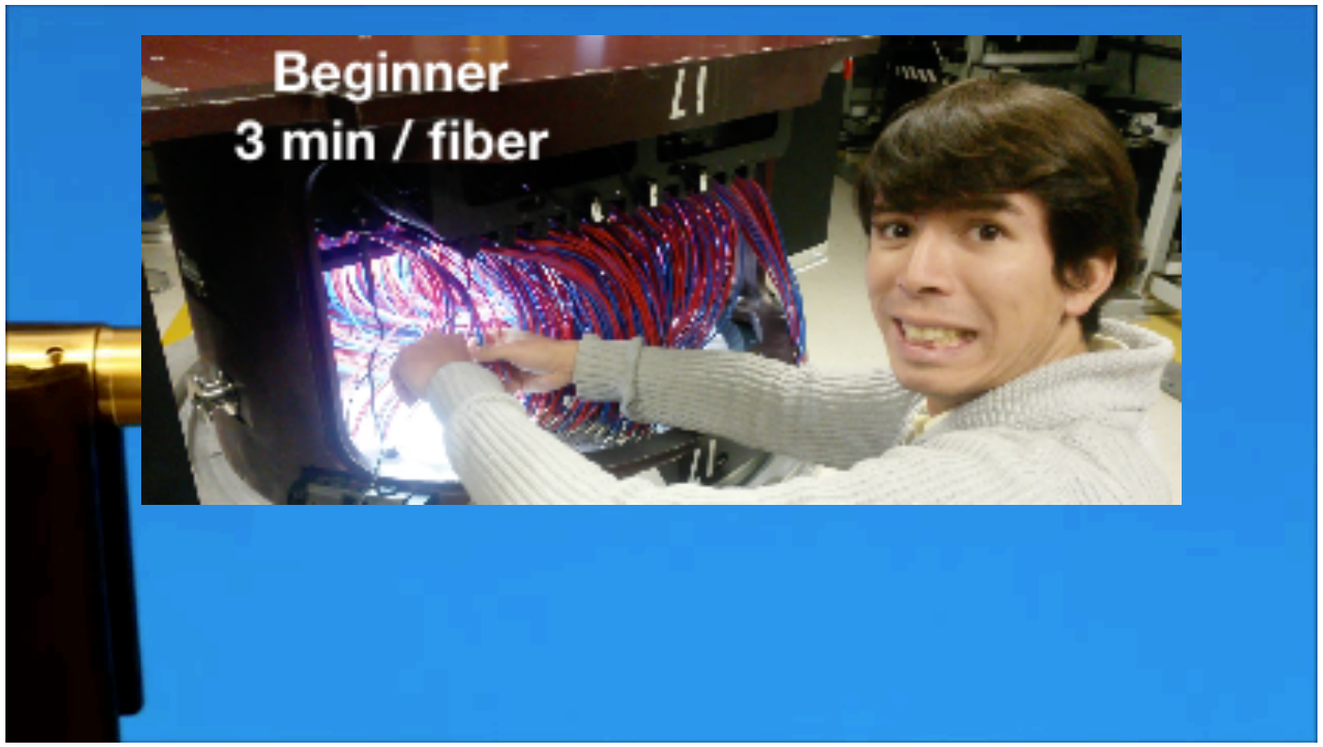


DESI

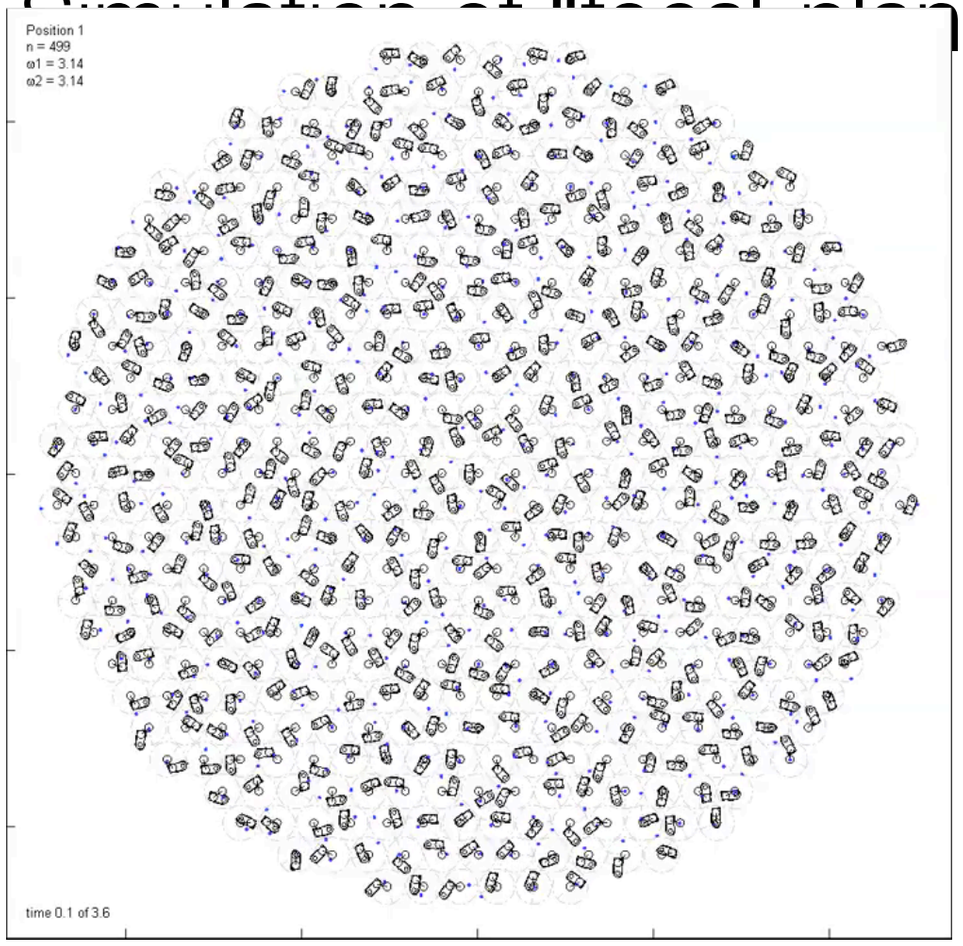
Dark Energy Spectroscopic Survey
commissioning started last week!

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

Fiber positioner



Simulation of "focal plane"



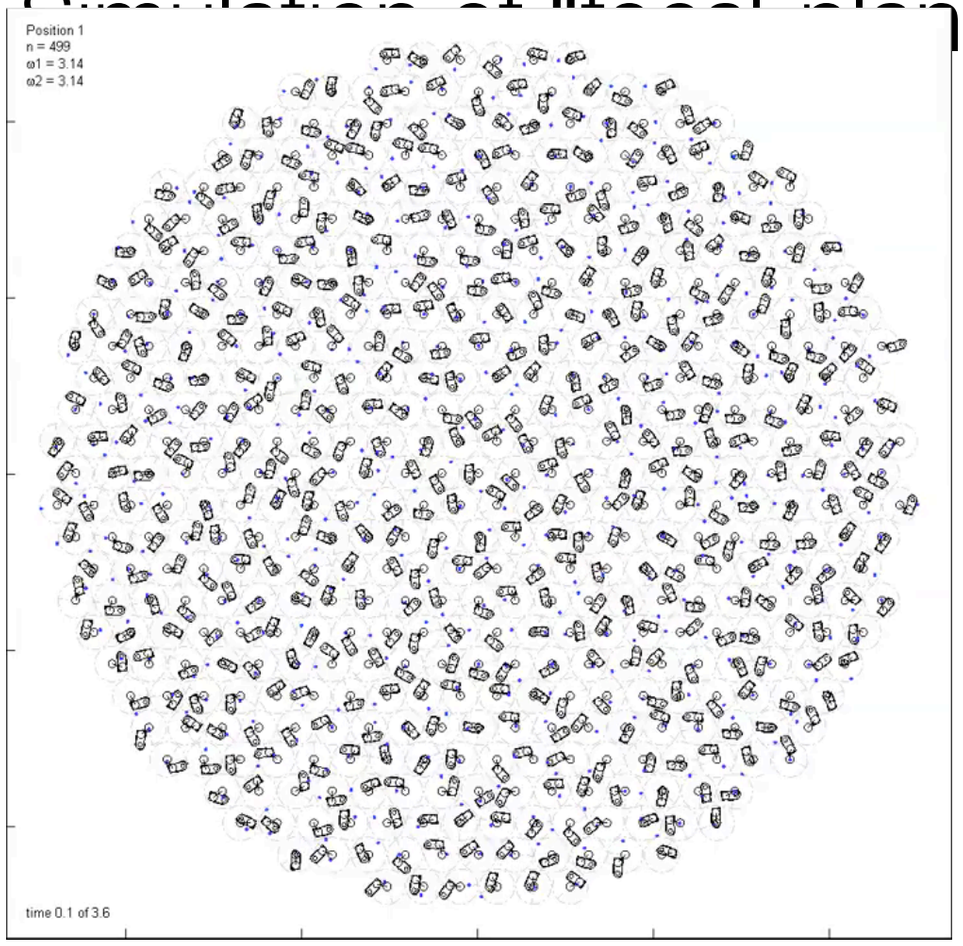
DESI

Dark Energy Spectroscopic Survey
commissioning started last week!

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

Fiber positioner

Simulation of "focal plane"



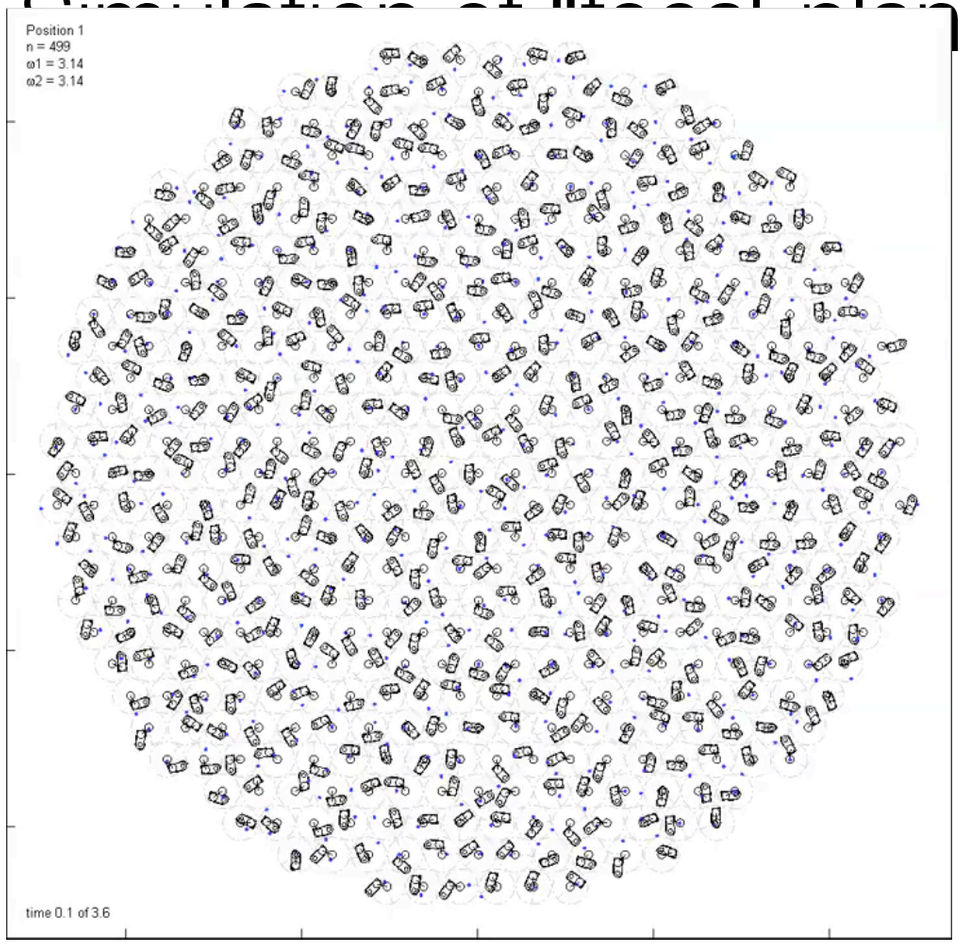
DESI

Dark Energy Spectroscopic Survey
commissioning started last week!

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

Fiber positioner

Simulation of "focal plane"



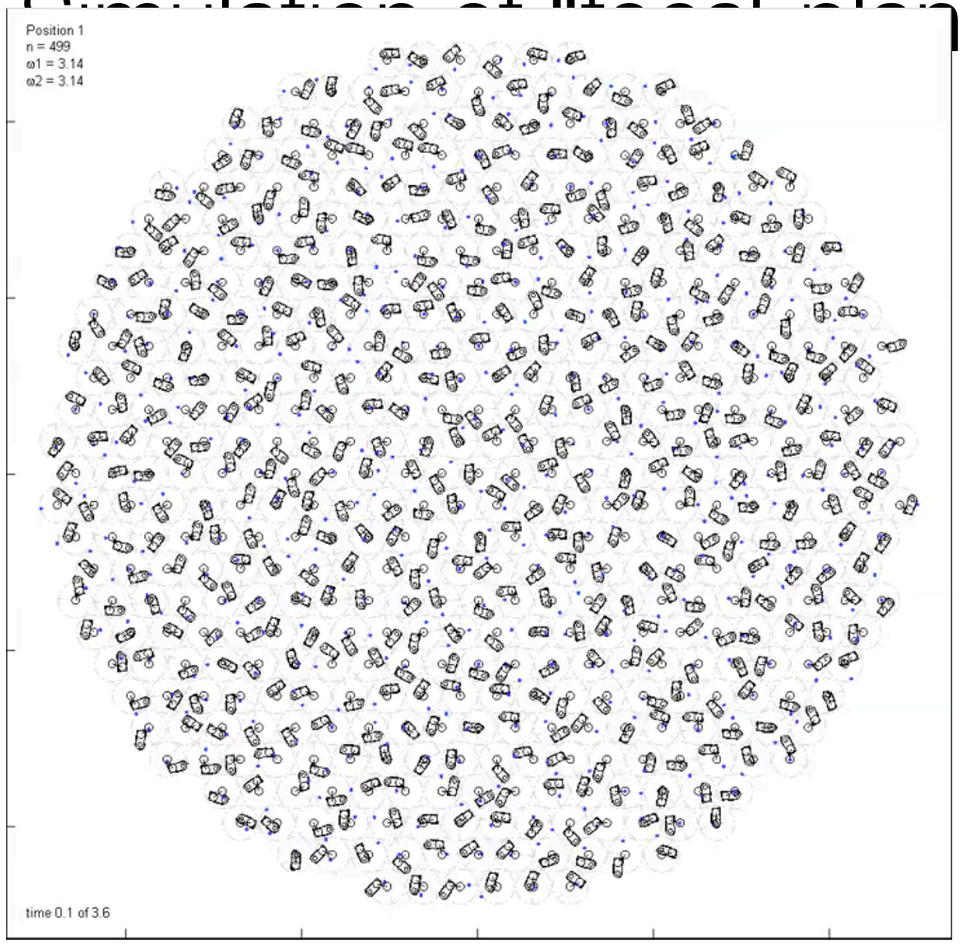
DESI

Dark Energy Spectroscopic Survey
commissioning started last week!

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

Fiber positioner

Simulation of "focal plane"

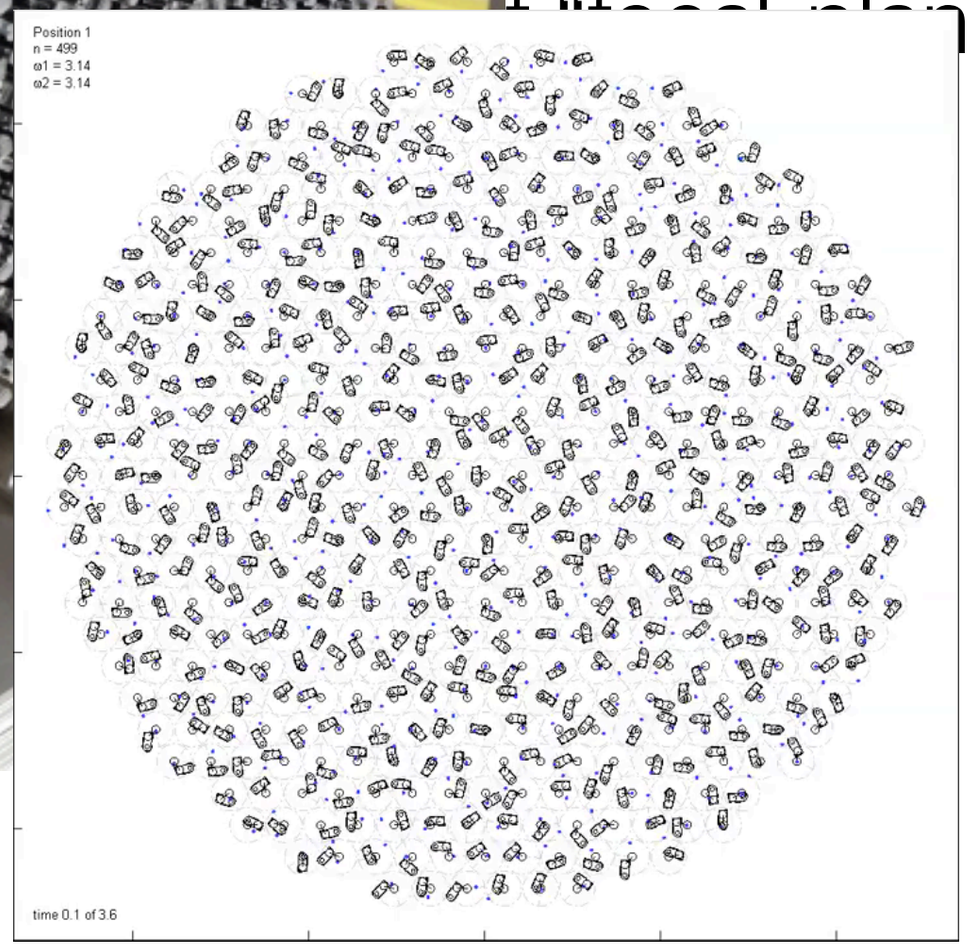


DESI

Dark Energy Spectroscopic Survey

commissioning started last week!

Fiber [illegible] of “focal plane”



DESI

Dark Energy Spectroscopic Survey

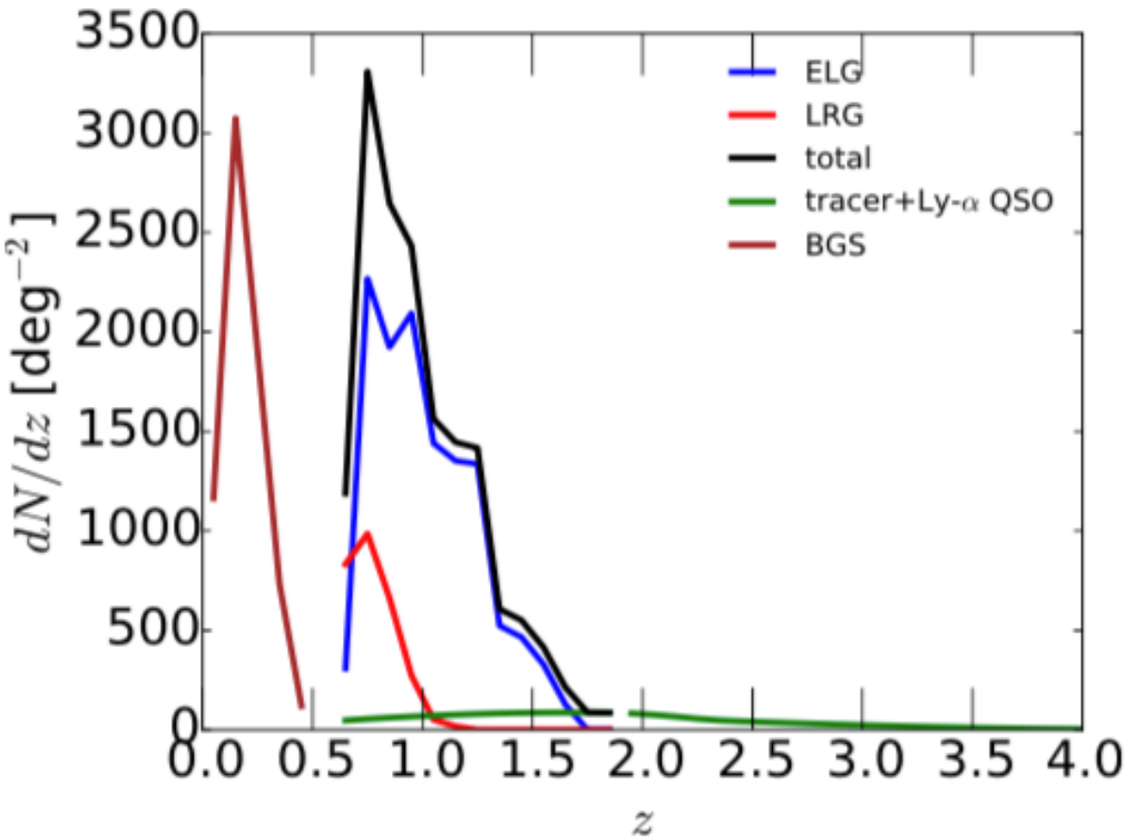
2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

DESI

Dark Energy Spectroscopic Survey

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

Mostly ELGs, LRGs and QSOs

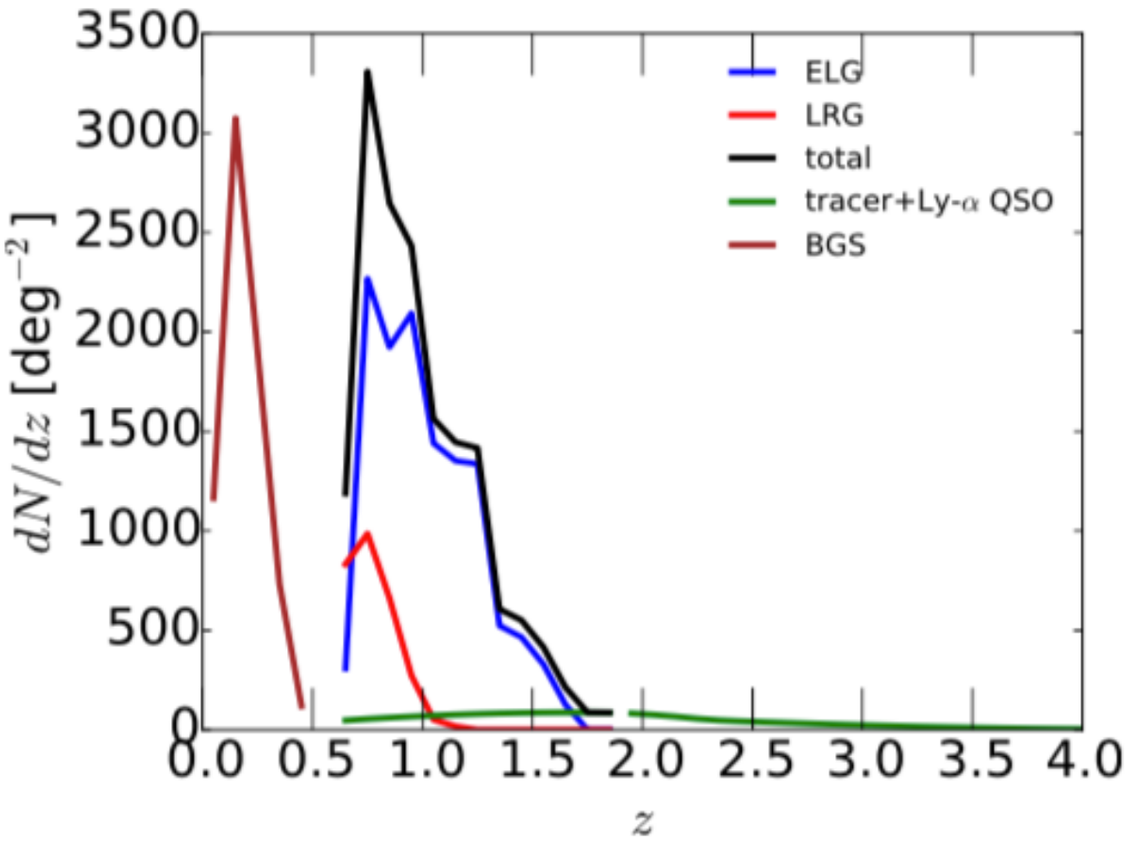


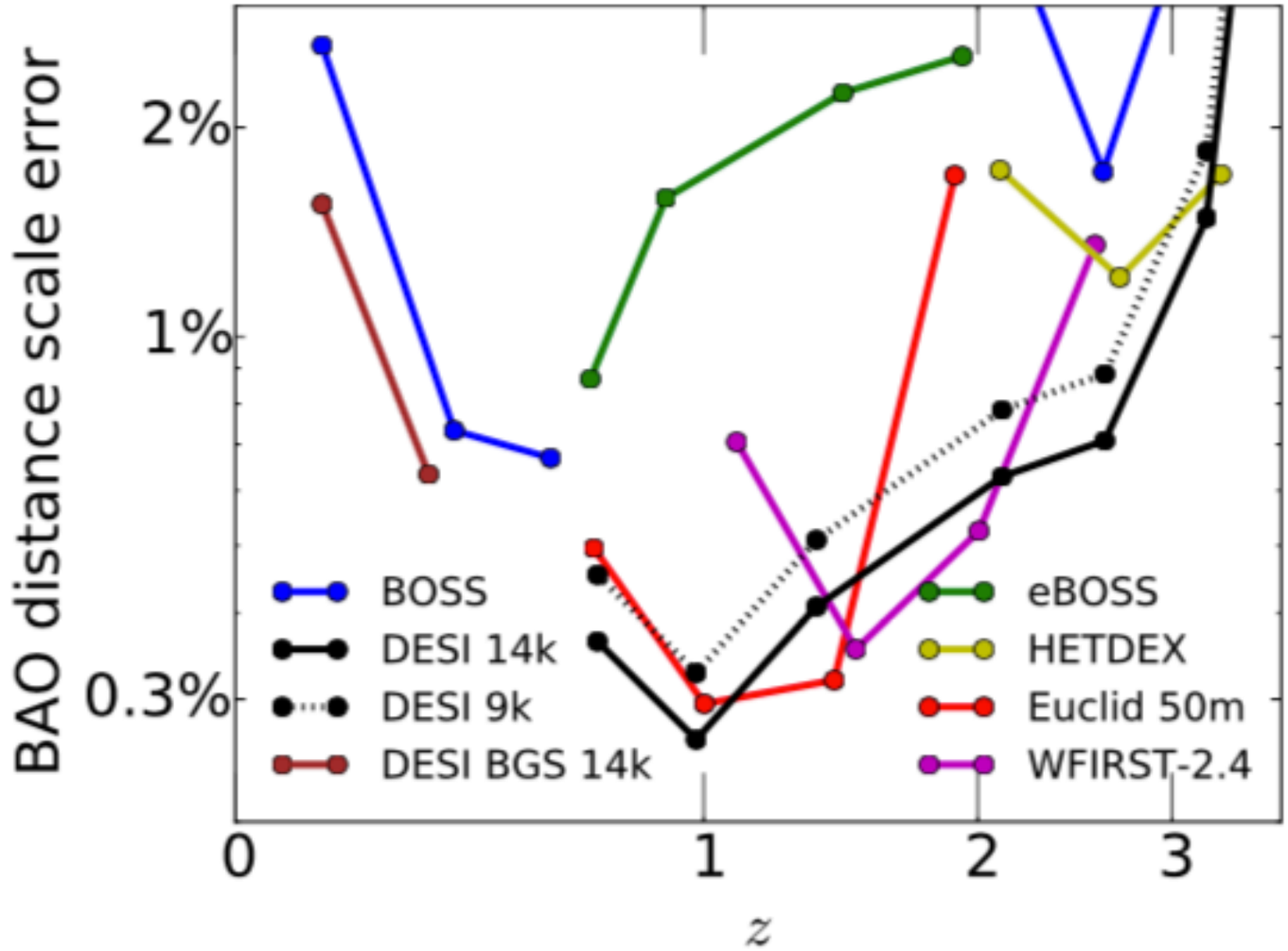
DESI

Dark Energy Spectroscopic Survey

2.5 meters -> 4.0 meters
7500 deg^2 -> 14000 deg^2
1000 fibers -> 5000 fibers
fibers plugged by human -> fibers plugged by robot
similar final spectral S/N

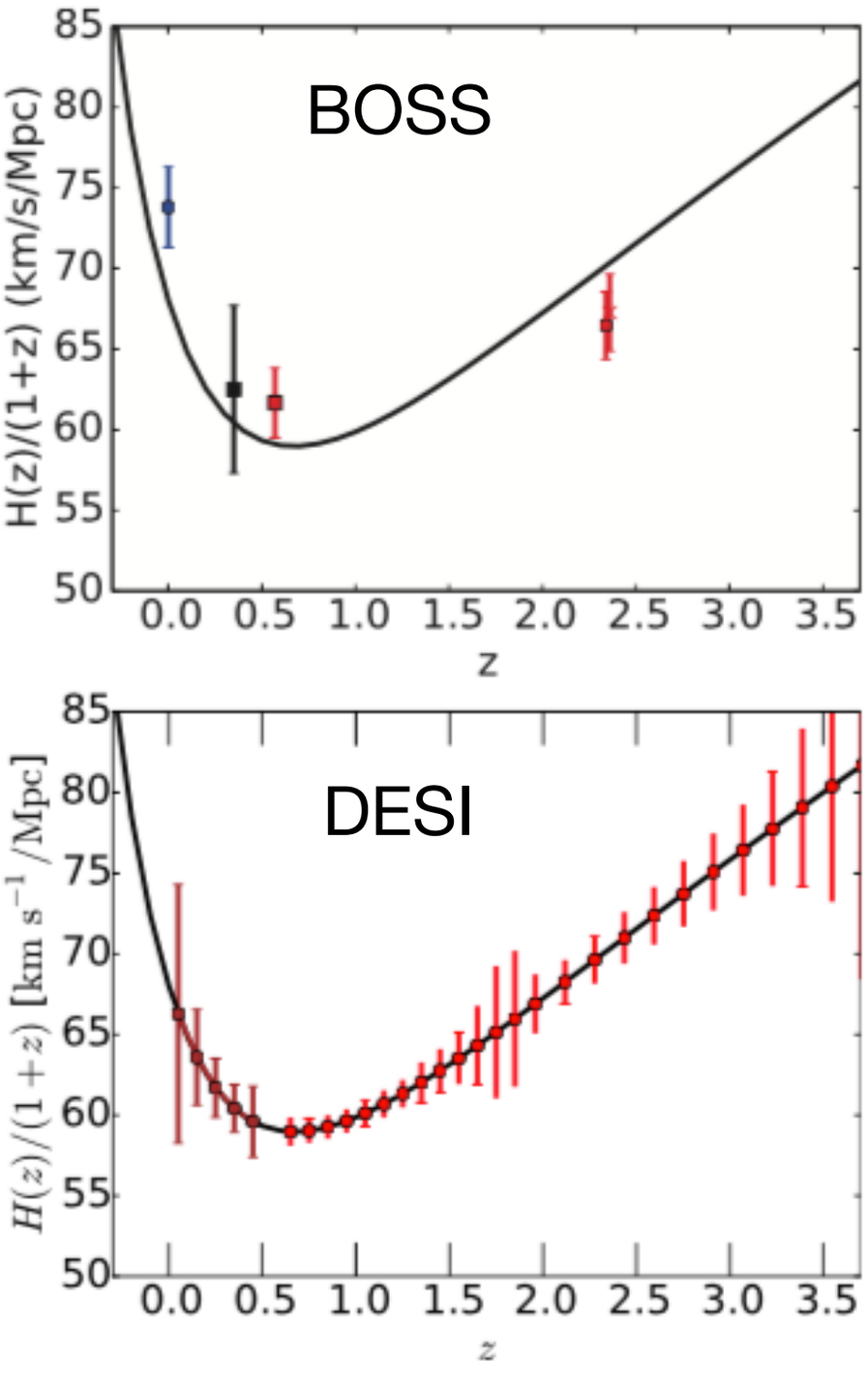
Mostly ELGs, LRGs and QSOs





DESI

Dark Energy Spectroscopic Survey



2.5 meters -> 4.0 meters
'500 deg² -> 14000 deg²
000 fibers -> 5000 fibers
l by human -> fibers plugged by robot
similar final spectral S/N

)s

qso

5 4.0

Conclusões

- Sloan has made the largest map of the universe in 3D
- Com medidas das estruturas, SDSS em 20 anos conseguiu as melhores observações da história cósmica de $0.1 < z < 3$
- Vínculos de modelos de energia escura mais fortes com BAO e RSD
- DESI começou semana passada e vai melhorar medidas de expansão e taxa de crescimento de mais de uma ordem de grandeza, e quem sabe, a massa total dos neutrinos