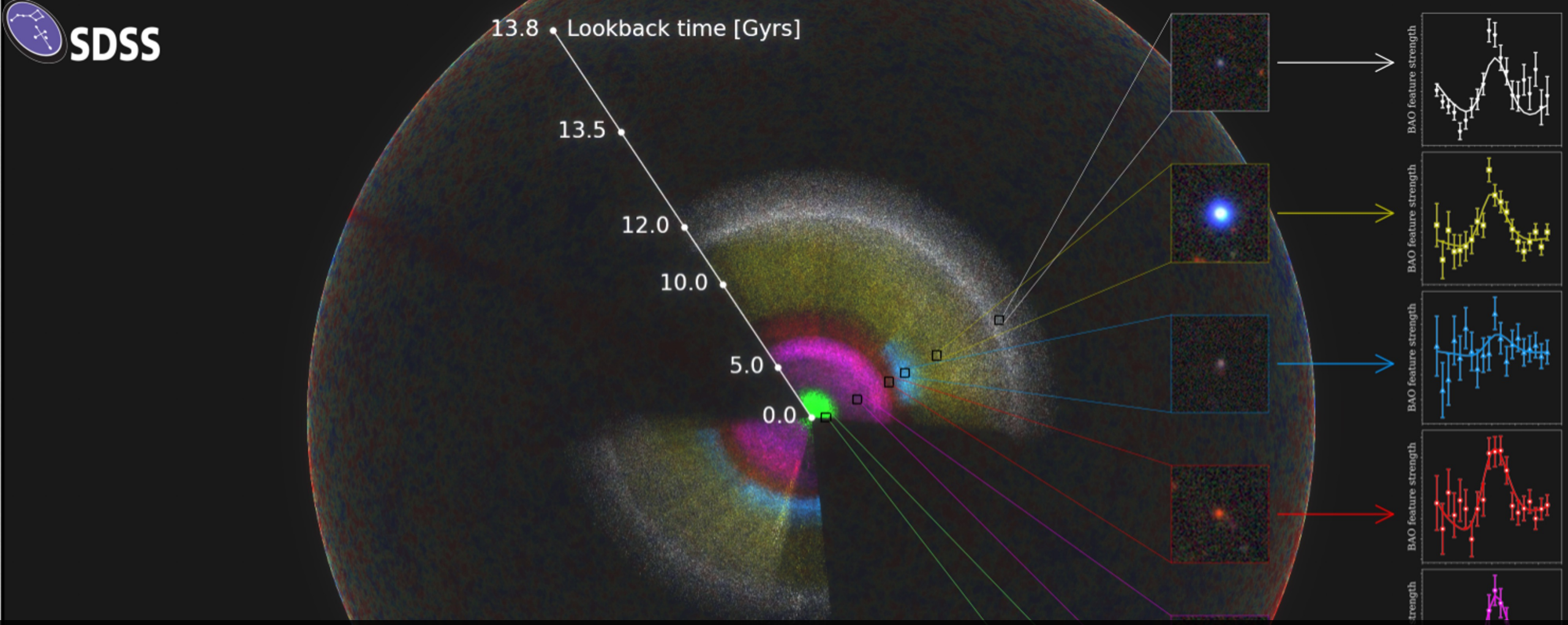


Cosmological implications of large galaxy surveys

Texas 2023

Gong-Bo Zhao

National Astronomical Observatories, CAS

Dec 15, 2023

Multiple cosmological probes

CMB

Multiple cosmological probes

CMB

Multiple cosmological probes

CMB

SNe

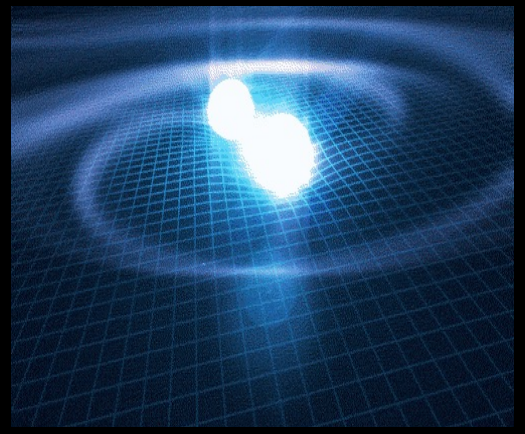
Multiple cosmological probes

CMB

SNe

Multiple cosmological probes

CMB



Gravitational waves

SNe

Multiple cosmological probes

CMB

Gravitational waves

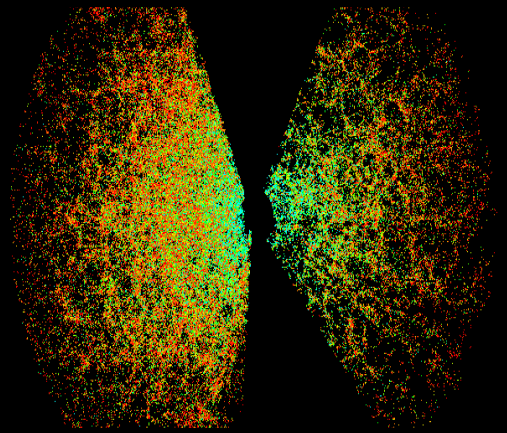
SNe

Multiple cosmological probes

CMB

Gravitational waves

SNe



LSS

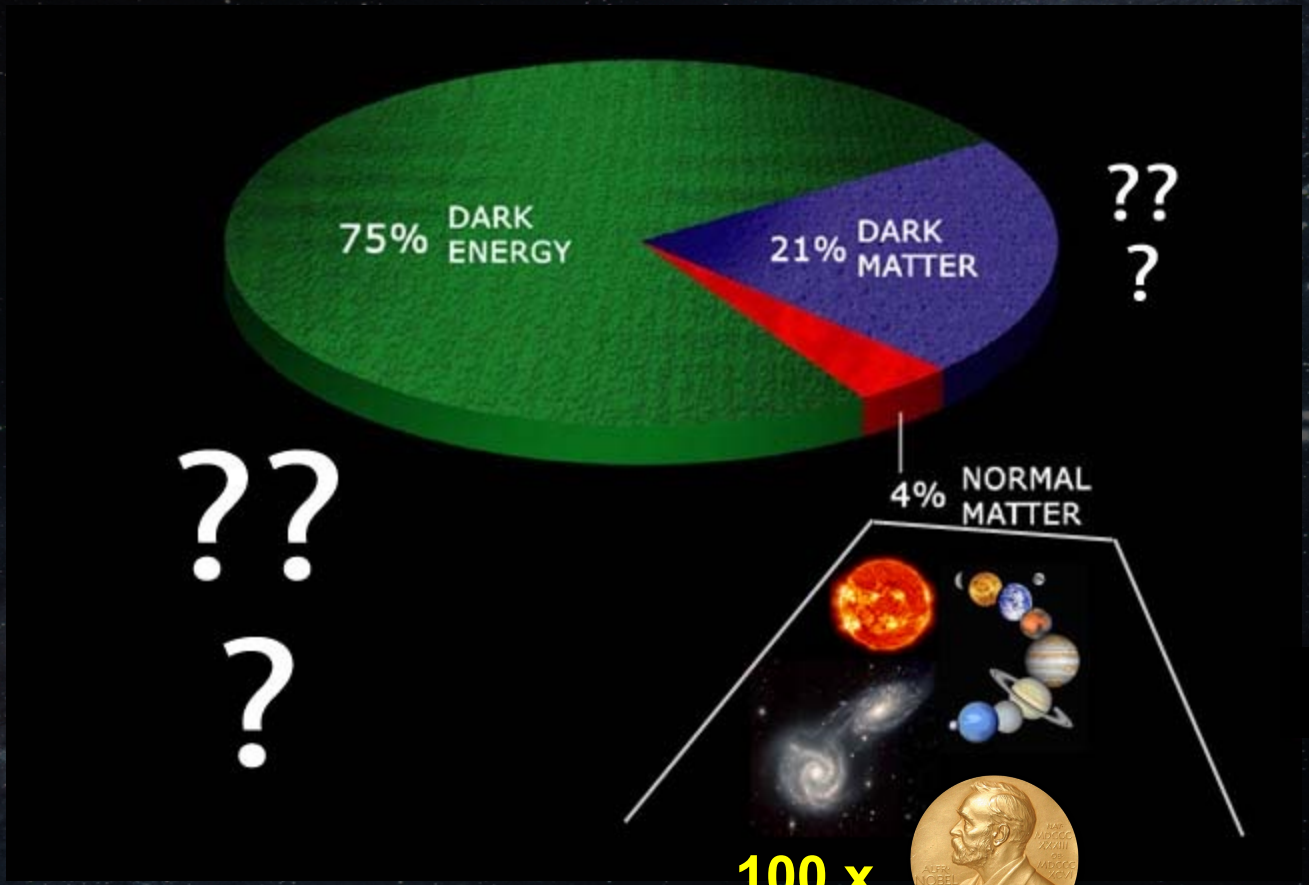
Multiple cosmological probes

CMB

Gravitational waves

SNe

LSS

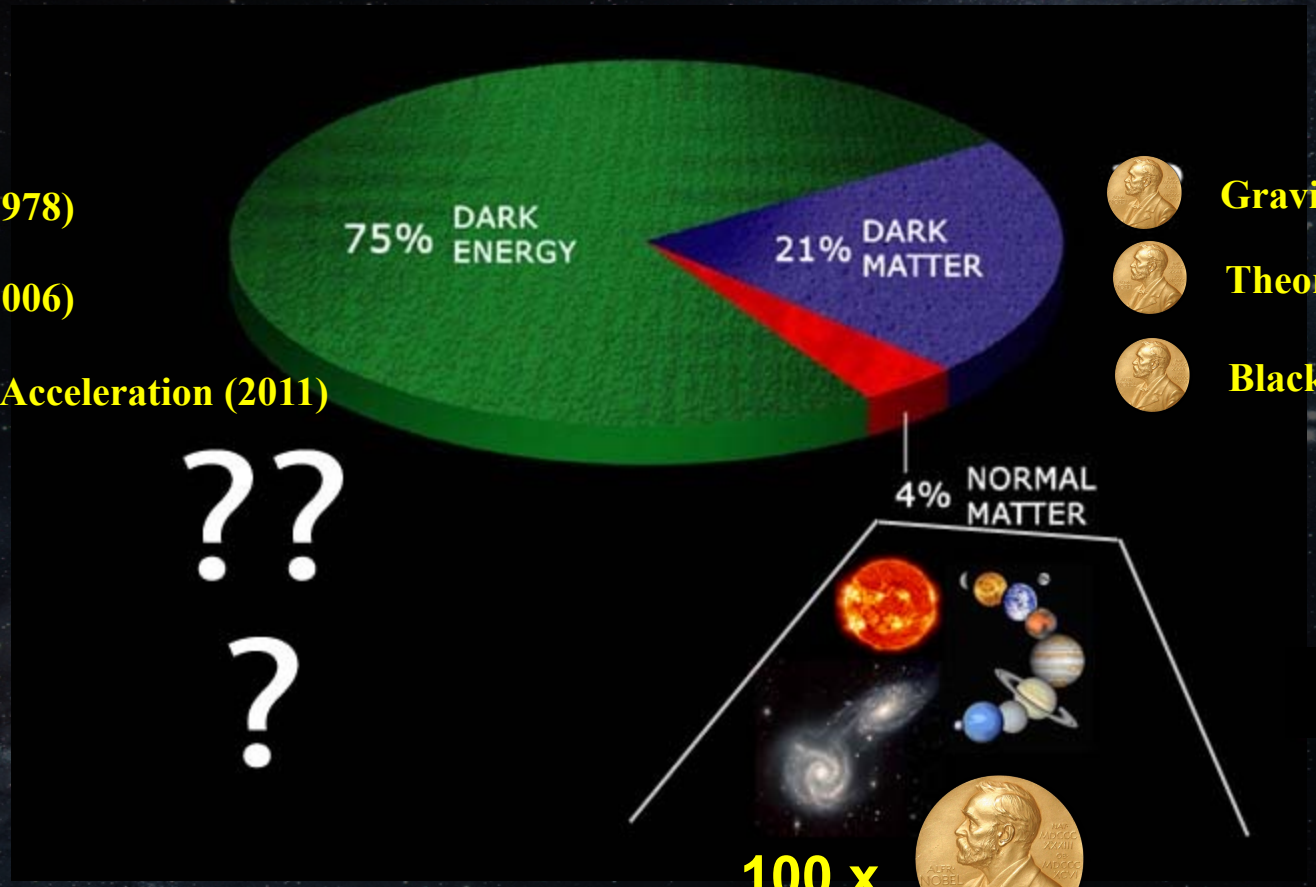


100 x

CMB (1978)

CMB (2006)

Cosmic Acceleration (2011)

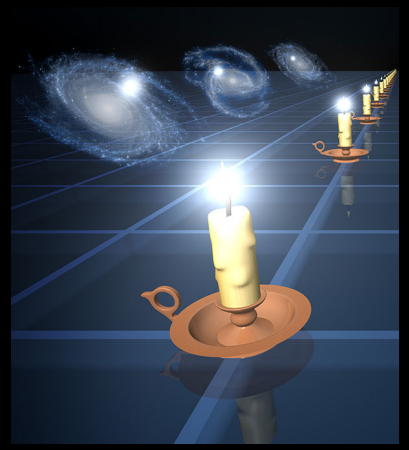


Gravitational waves (2017)

Theoretical cosmology (2019)

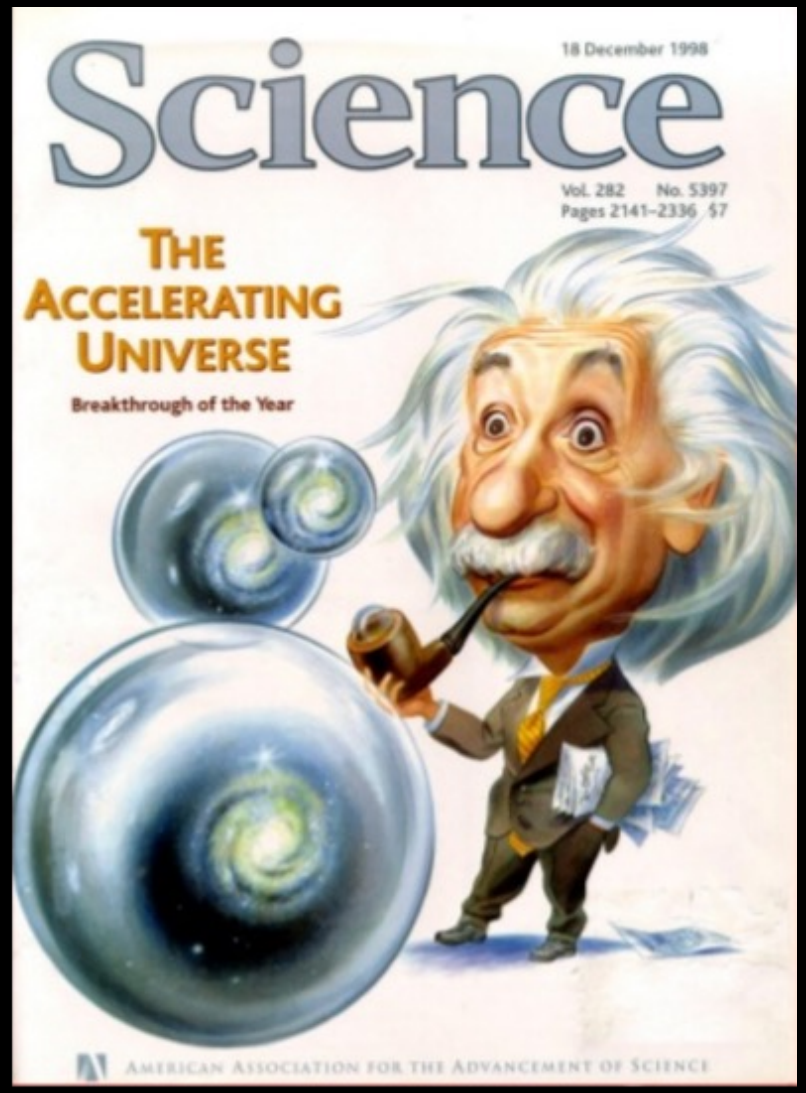
Black holes (2020)

100 x



The accelerating Universe!

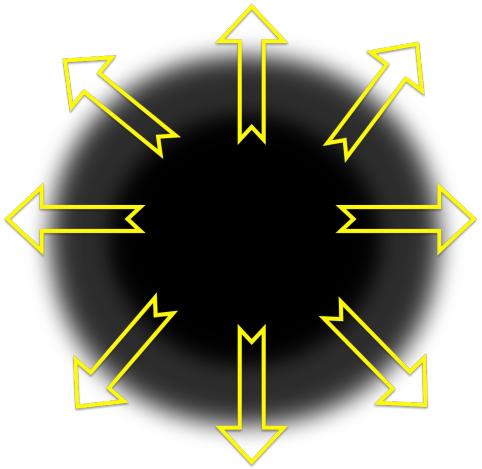
2011



The expansion of the Universe can **accelerate** if

In GR, to add new 'repulsive matter', which contributes 70% total energy

To modify General Relativity



Dark Energy

$$G_{\mu\nu} = 8\pi G \tilde{T}_{\mu\nu}$$

Modified Gravity

$$\tilde{G}_{\mu\nu} = 8\pi G T_{\mu\nu}$$

The expansion of the Universe can **accelerate** if

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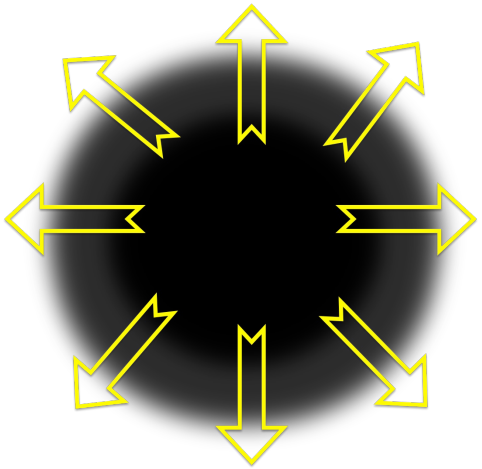


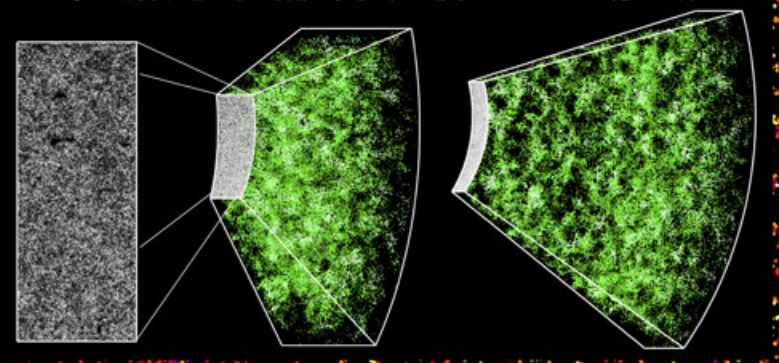
Dark Energy

$$G_{\mu\nu} = 8\pi G \tilde{T}_{\mu\nu}$$

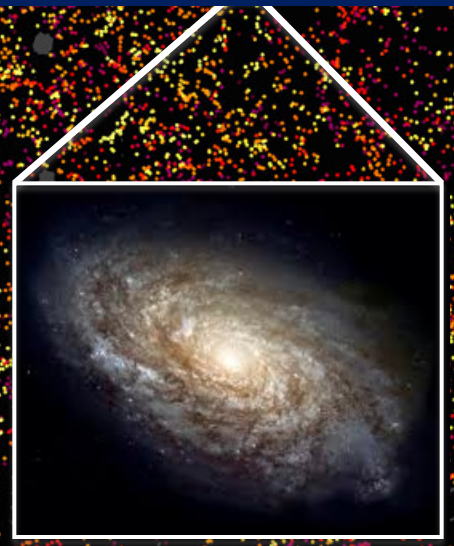
Modified Gravity

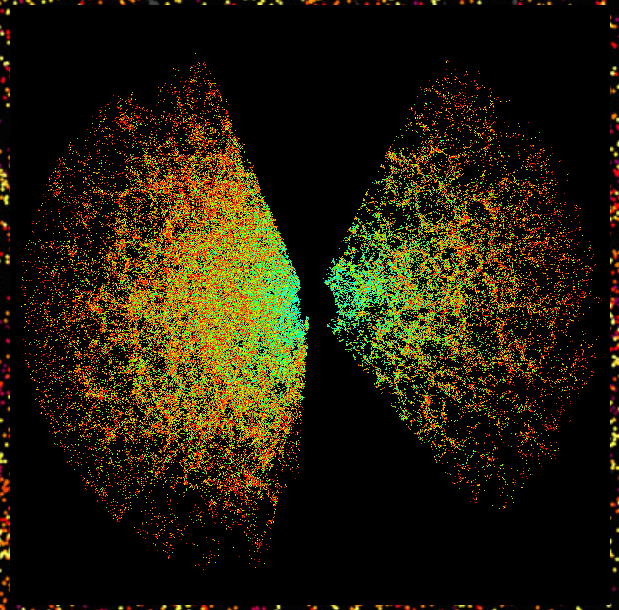
$$\tilde{G}_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Galaxy surveys can break the dark degeneracy!



Massive redshift surveys as a key cosmological probe

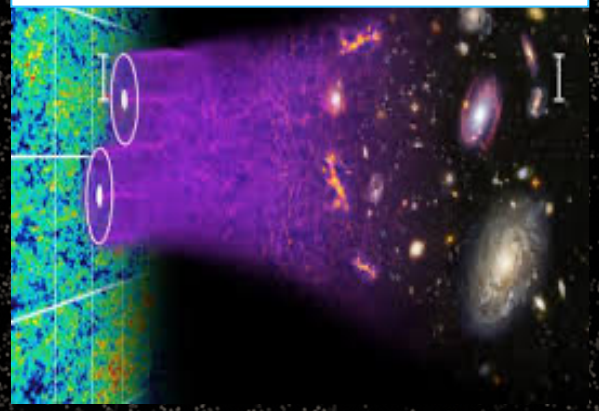


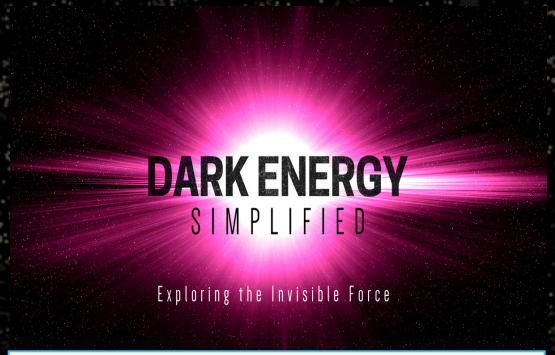


BOSS
SDSS III

Large z-surveys : a key probe of the Universe

BAO

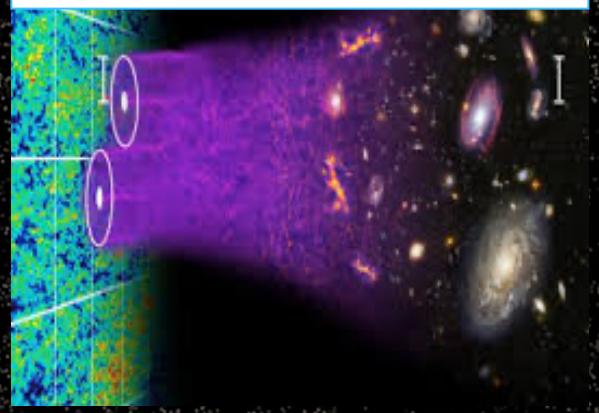




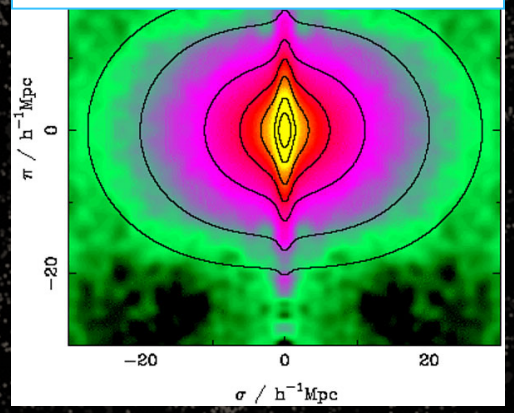
Dark Energy

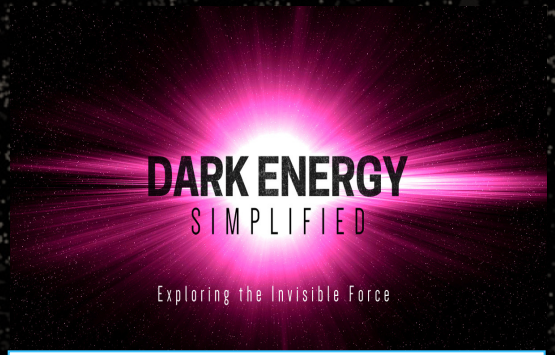
Large z-surveys : a key probe of the Universe

BAO



RSD



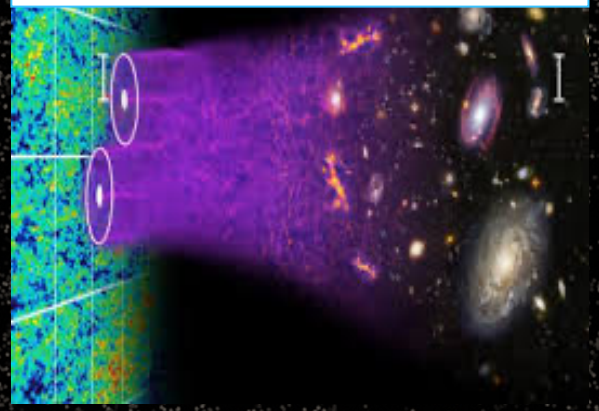


Dark Energy

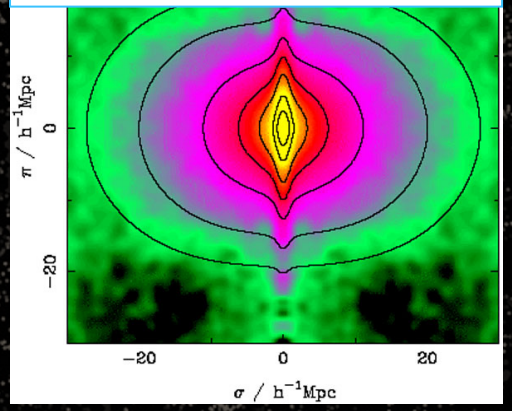
Modified Gravity

Large z-surveys : a key probe of the Universe

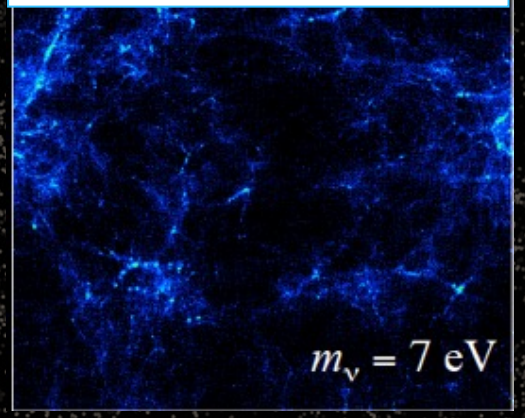
BAO

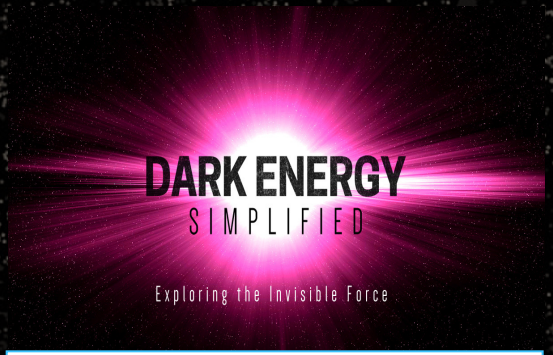


RSD



Free-streaming





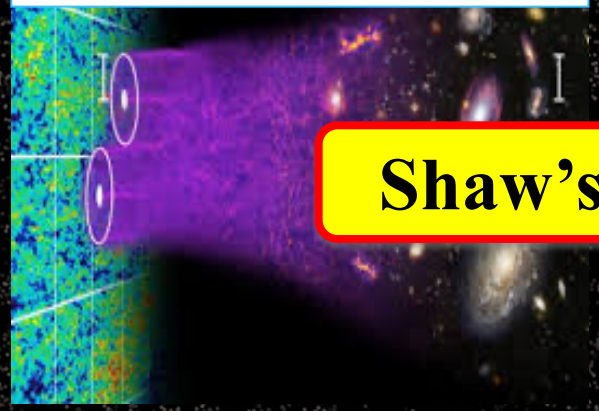
Dark Energy

Modified Gravity

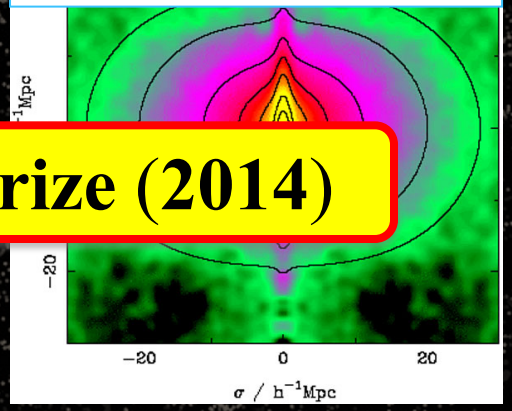
Neutrino masses

Large z-surveys : a key probe of the Universe

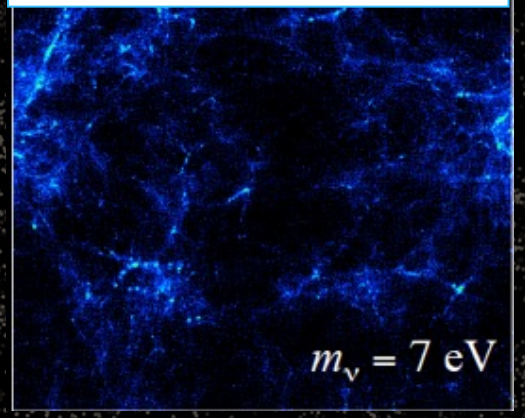
BAO



RSD

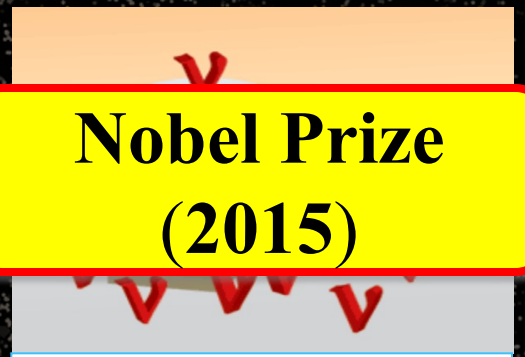


Free-streaming



Shaw's prize (2014)

Nobel Prize (2011)

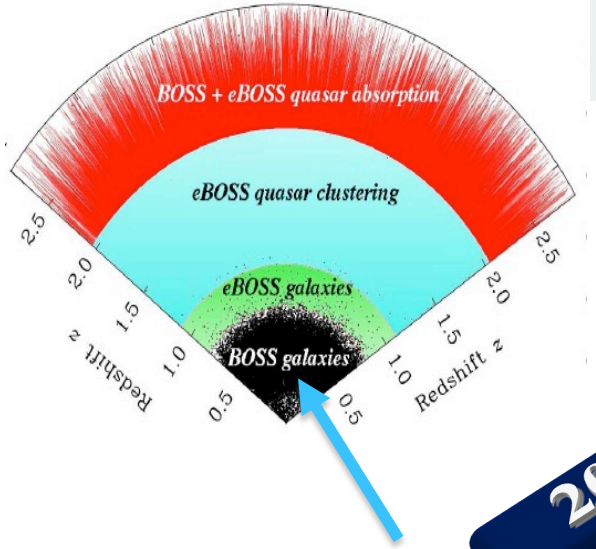


Nobel Prize (2015)

Dark Energy

Modified Gravity

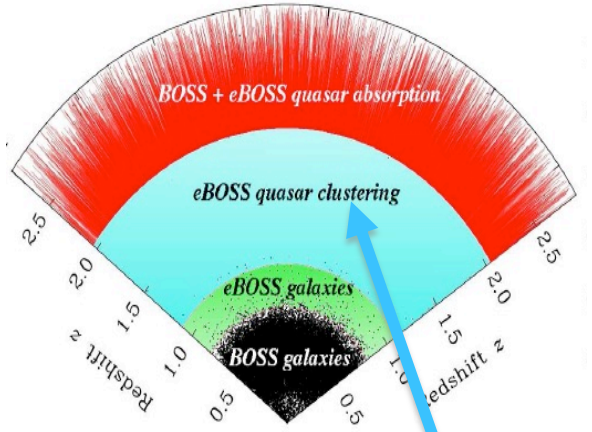
Neutrino masses



New Mexico
2.5m

2009 2014 2020 2021 2022

SDSS-III
Baryon Oscillation Spectroscopic Survey (BOSS) (z<0.6)
1.6M LRGs
The largest in the past decade



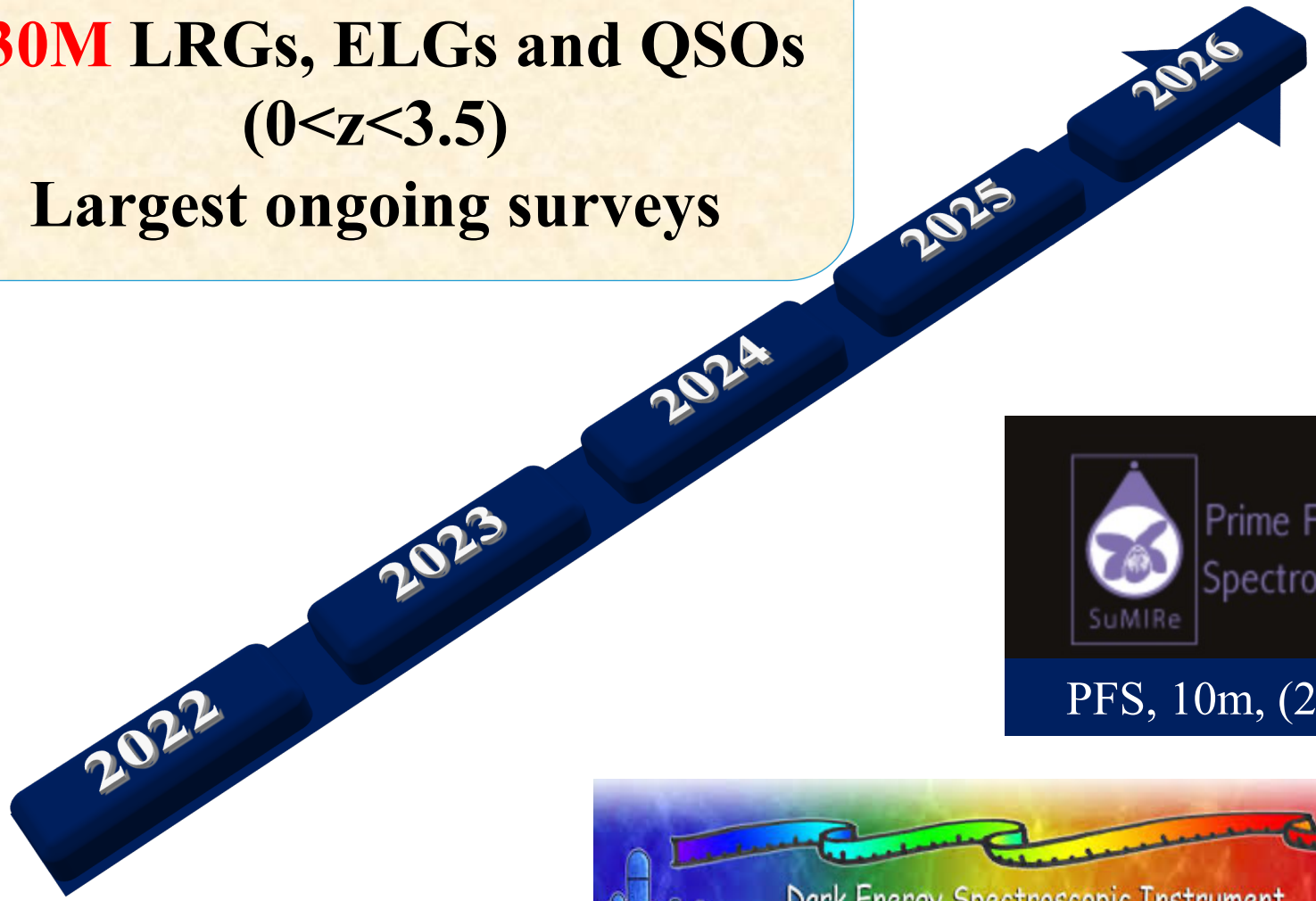
2009 2014 2020 2021 2022

SDSS-IV
extended BOSS (eBOSS)
1M LRGs, ELGs and QSOs
(0.6<z<3.5)
The largest in the
past 5 years

DESI & PFS

>30M LRGs, ELGs and QSOs (0<z<3.5)

Largest ongoing surveys

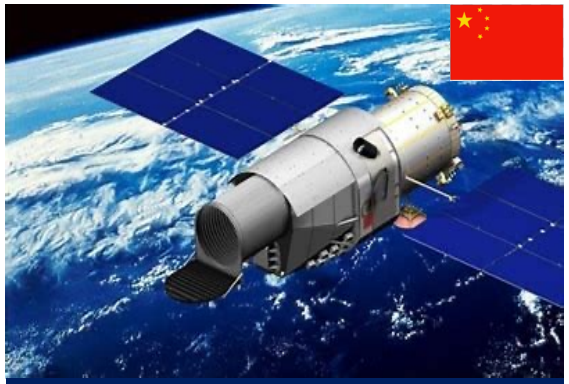


Prime Focus Spectrograph
SuMIRe

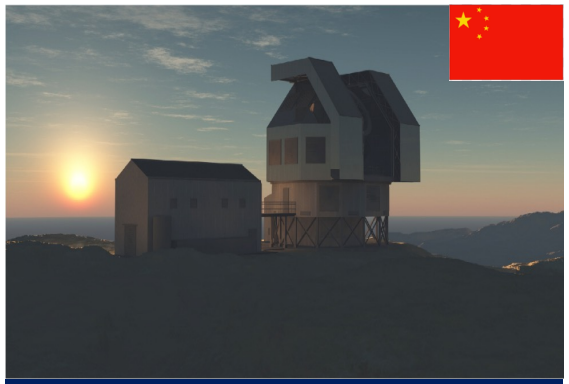
PFS, 10m, (2024-)

Dark Energy Spectroscopic Instrument

DESI, 4m, (2020-)

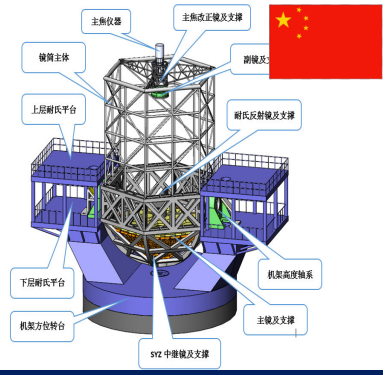


CSST, 2m in space

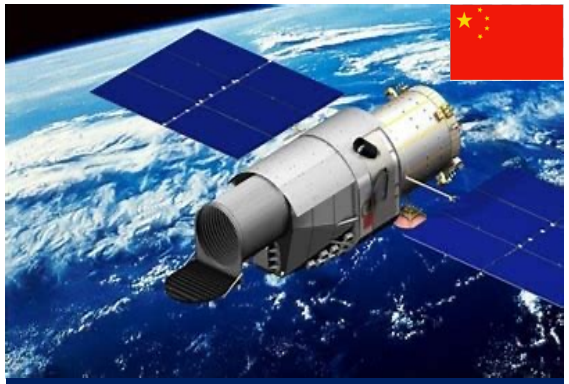


MUST, 6.5m

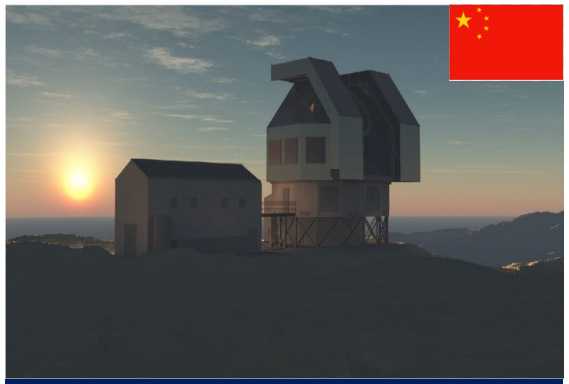
LAMOST-II, 4+m



LOT, 12m

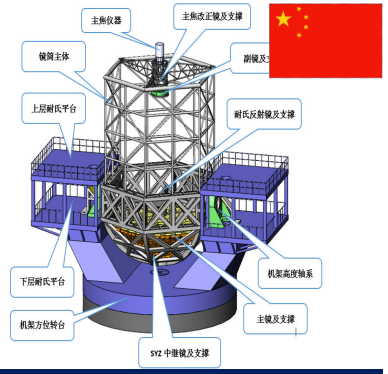


CSST, 2m in space

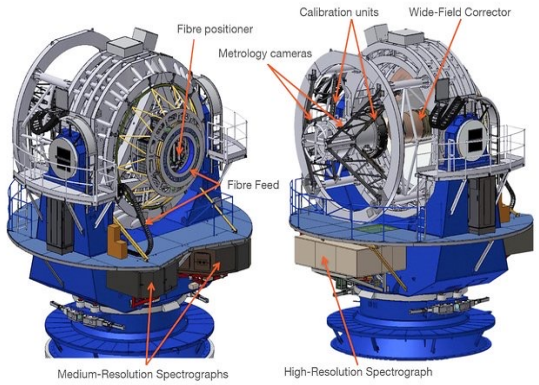


MUST, 6.5m

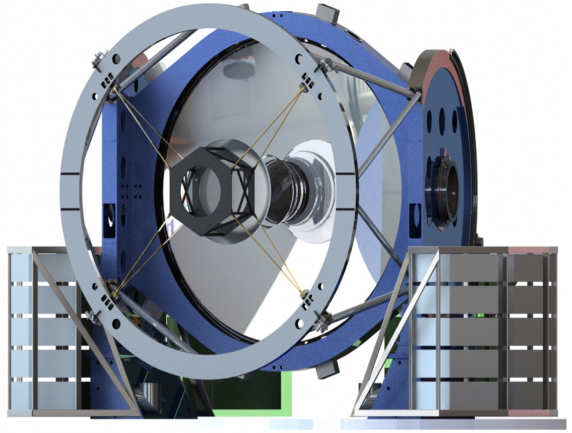
LAMOST-II, 4+m



LOT, 12m

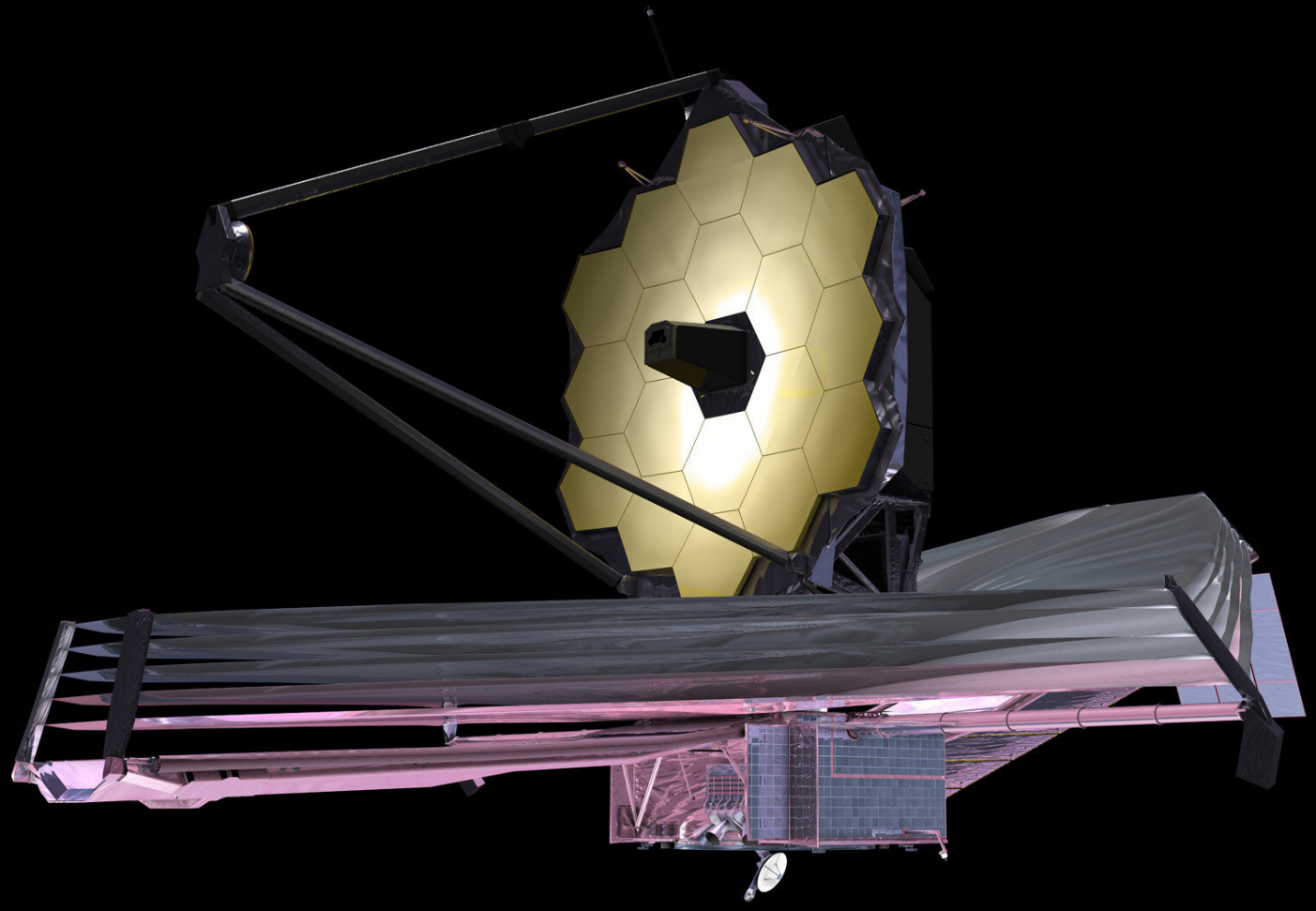


4MOST, 4m



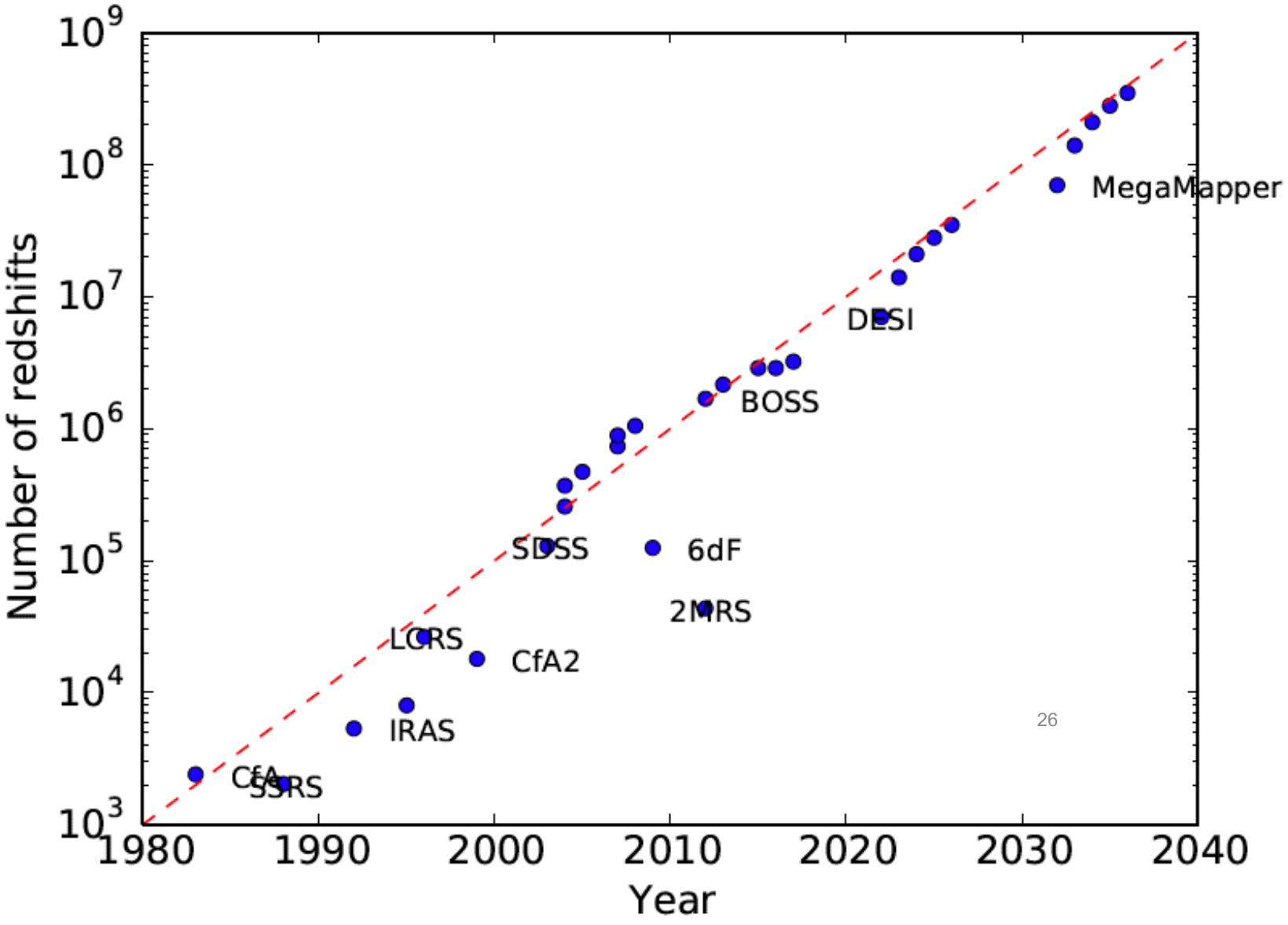
MegaMapper, 6.5m

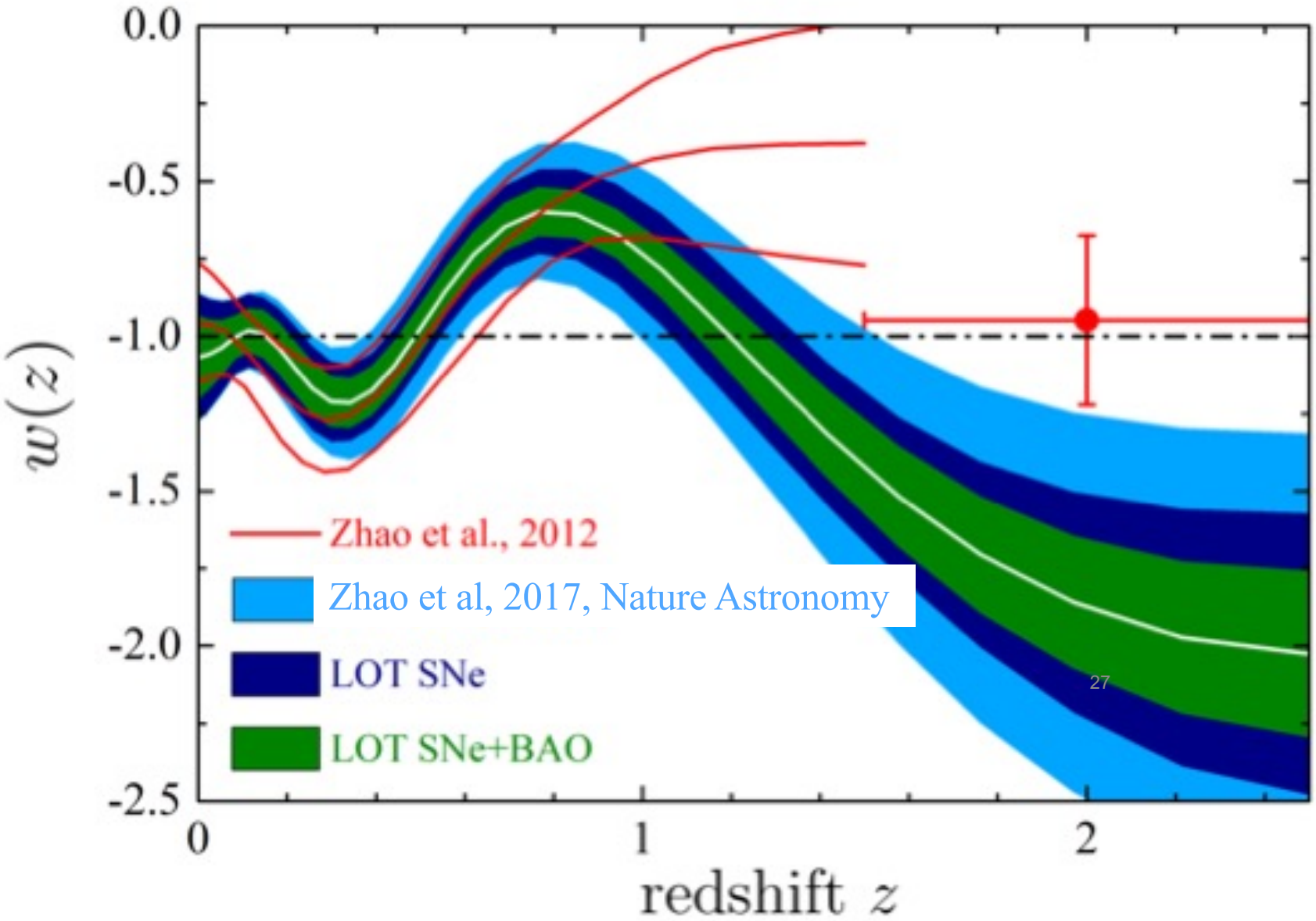
MSE, 10m

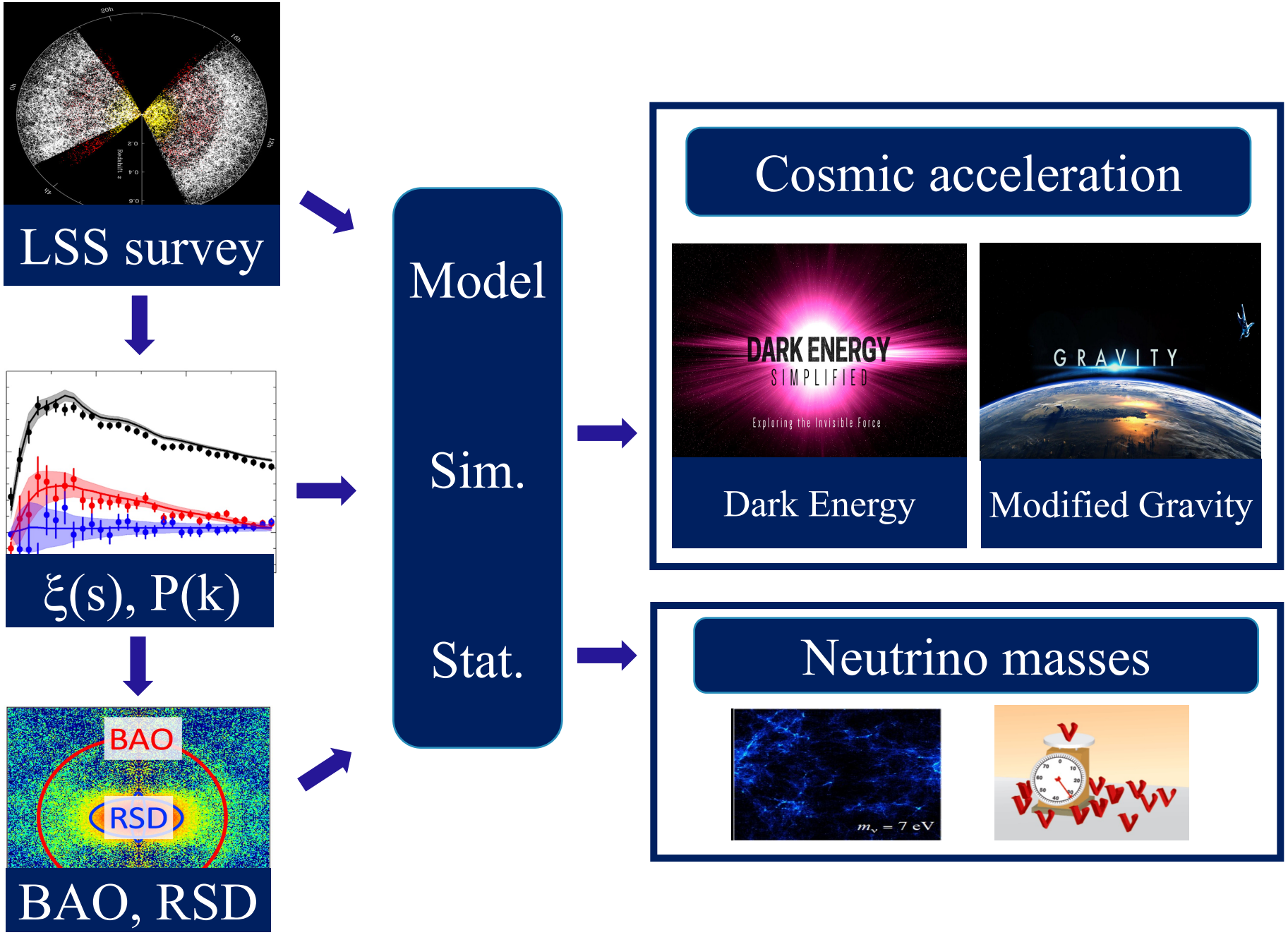


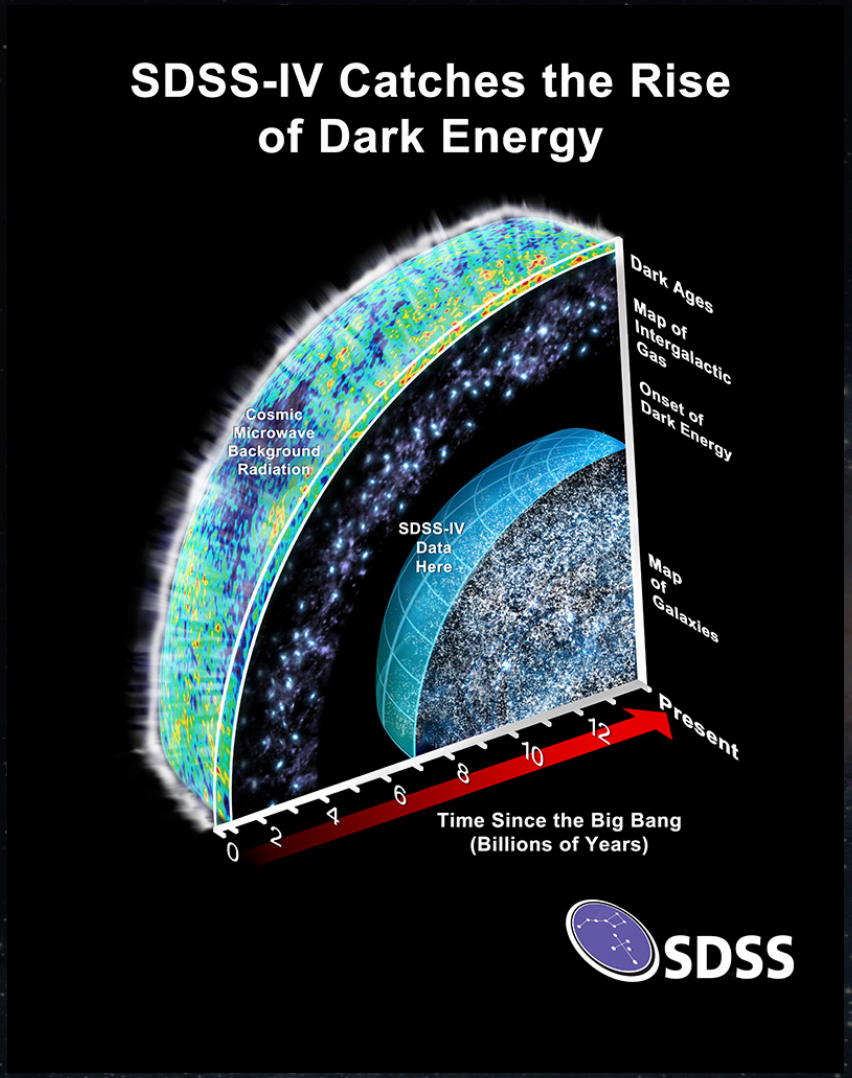
280 m at L2!!

arXiv: 2010.06064

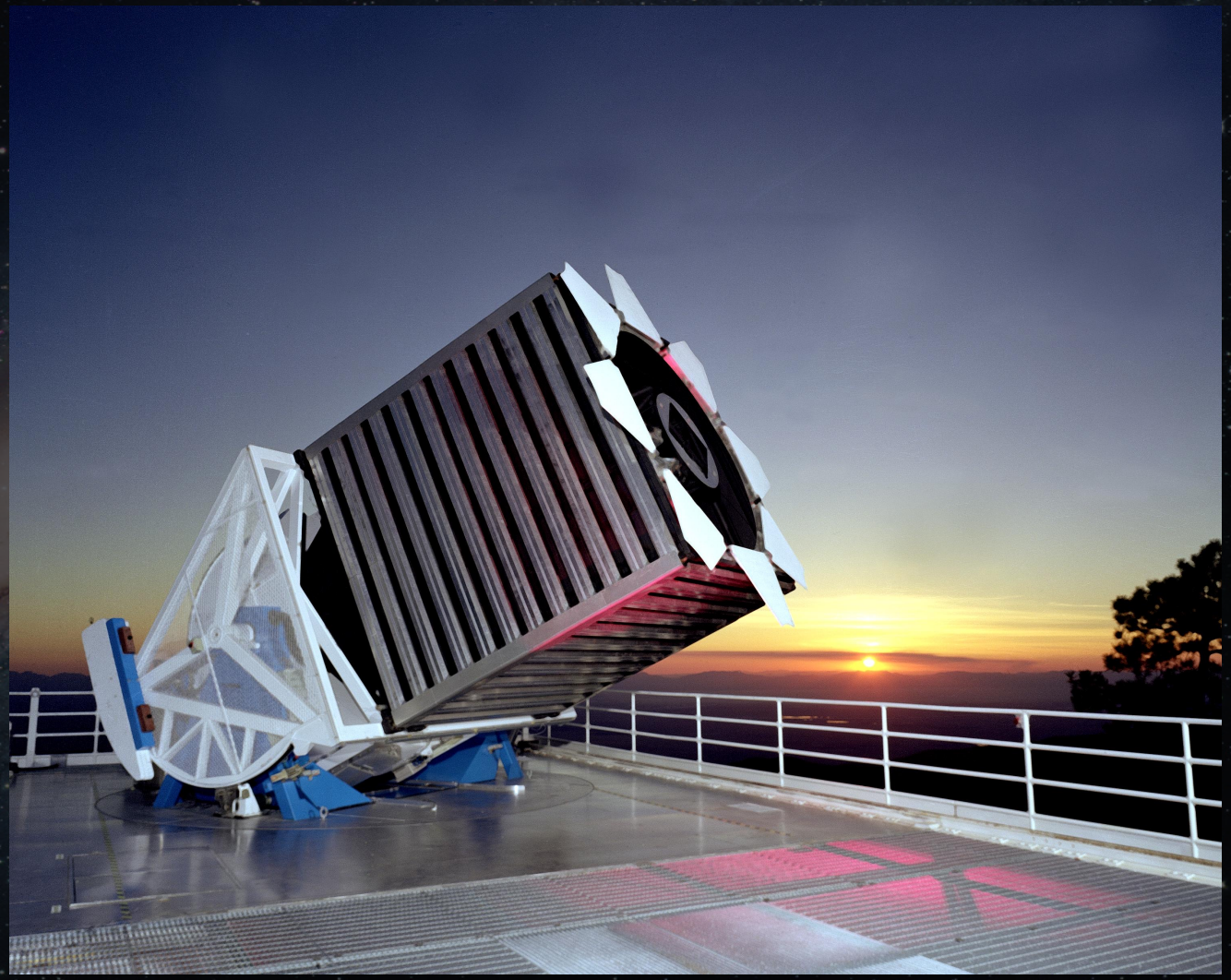

Number of redshifts
Year
10^9
10^8
10^7
10^6
10^5
10^4
10^3
1980
1990
2000
2010
2020
2030
2040
MegaMapper
DESI
BOSS
SDSS
6dF
2MRS
LCRS
CfA2
IRAS
CfA
SSRS


0.0
-0.5
-1.0
-1.5
-2.0
-2.5
$w(z)$
0
1
2
redshift z
Zhao et al., 2012
Zhao et al, 2017, Nature Astronomy
LOT SNe
LOT SNe+BAO


LSS survey
ξ(s), P(k)
BAO
RSD
BAO, RSD
Model
Sim.
Stat.
Cosmic acceleration
DARK ENERGY
SIMPLIFIED
Exploring the Invisible Force
Dark Energy
GRAVITY
Modified Gravity
Neutrino masses
$m_\nu = 7$ eV



eBOSS (2014-2020)



2.5 m SDSS telescope @ New Mexico

Latest result released on July 20, 2020 in 20+ papers

SDSS

Data Surveys Instruments Collaboration Science

Search www

No need to Mind the Gap: Astrophysicists fill in 11 billion years of our universe's expansion history

July 19, 2020

The Sloan Digital Sky Survey (SDSS) released today a comprehensive analysis of the largest three-dimensional map of the Universe ever created, filling in the most significant gaps in our possible exploration of its history.

sdss.org

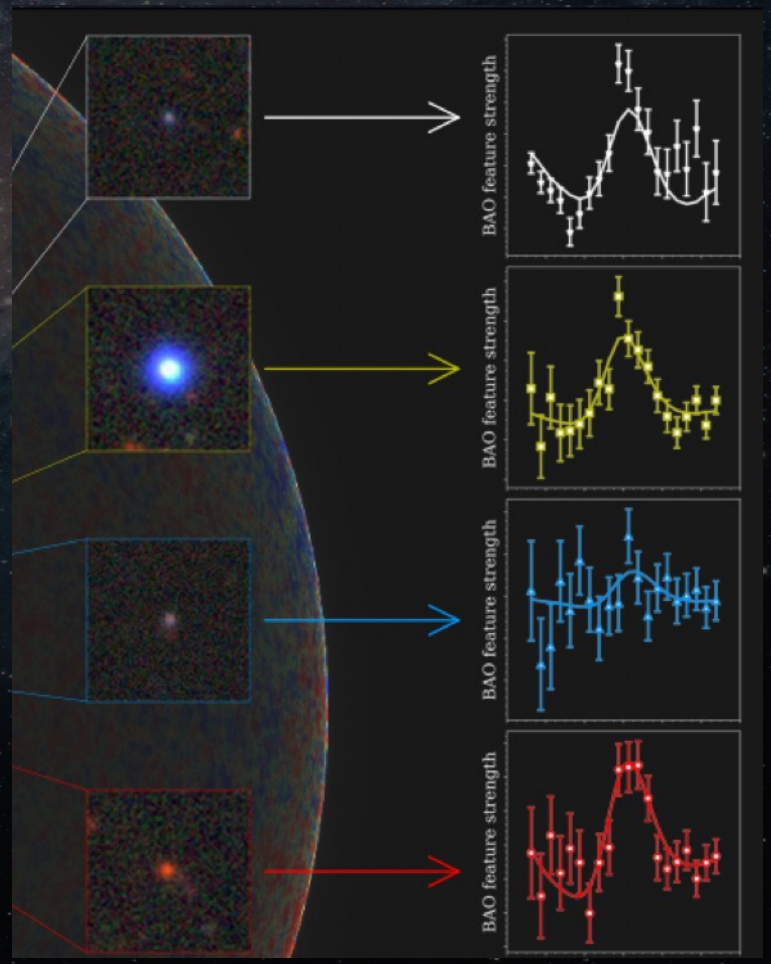
eBOSS tracers

Lyman-a forest

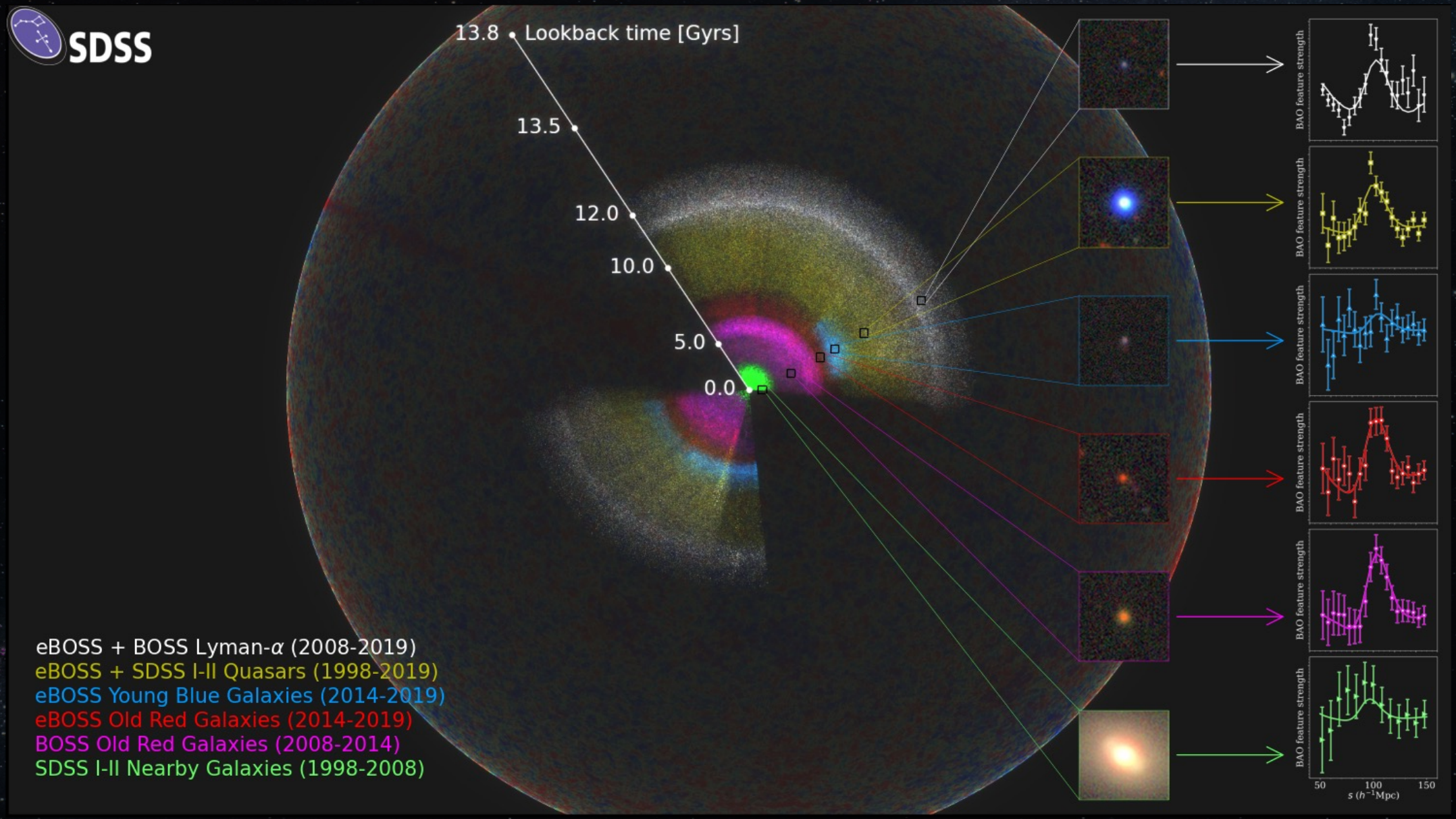
Clustering quasars

Emission Line Galaxies (ELGs)

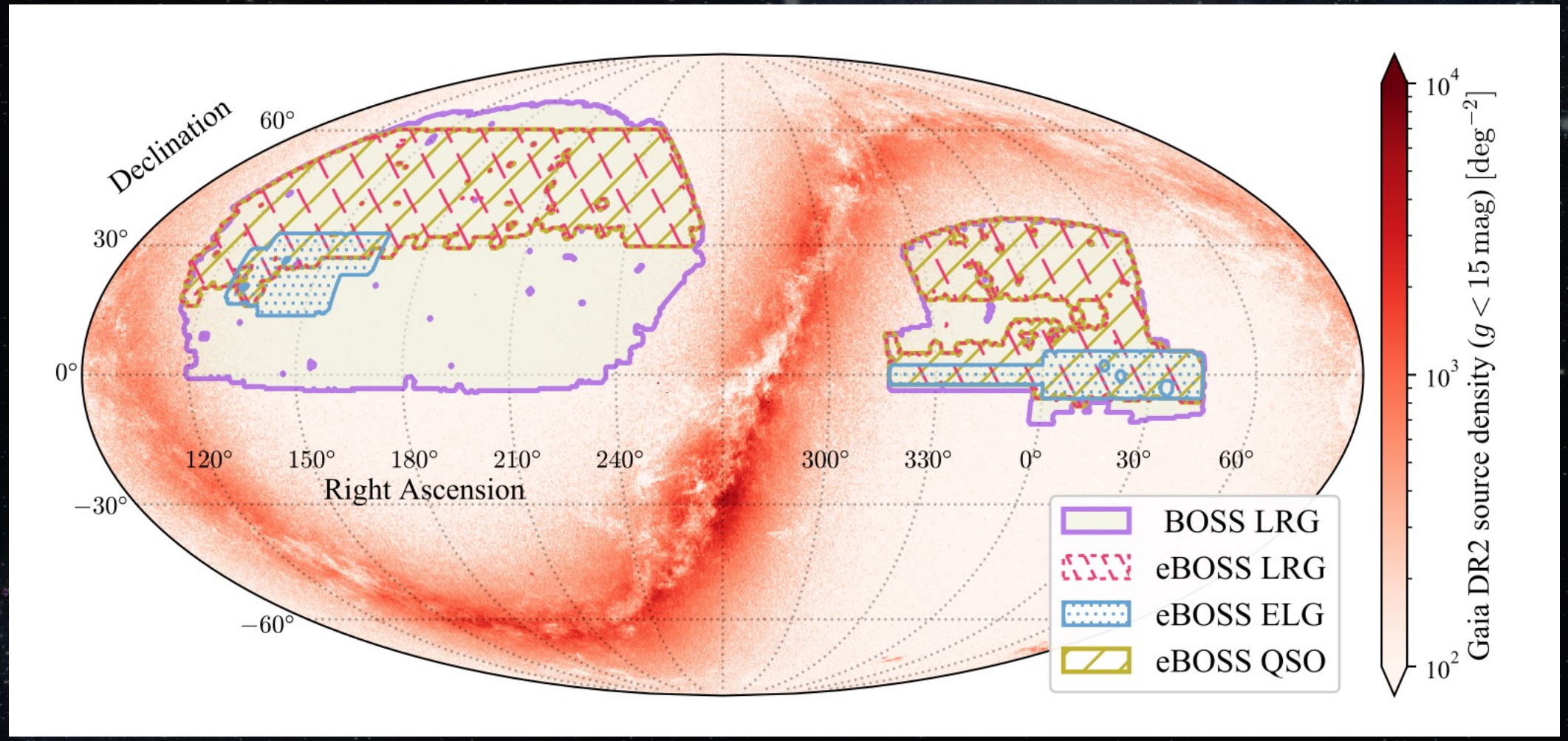
Luminous Red Galaxies (LRGs)



- ELG (k-space): De Mattia et al, 2007.09008
- ELG (s-space): Tamone et al, 2007.09009
- LRG (k-space): Gil-Marin et al, 2007.08994
- LRG (s-space): Bautista et al, 2007.08993
- ELG x LRG (k-space): G-B. Zhao et al, 2007.09011
- ELG x LRG (s-space): Y. Wang et al, 2007.09010
- QSO (k-space): Neveux et al, 2007.08999
- QSO (s-space): Hou et al, 2007.08998
- LyA BAO (s-space): du Mas des Bourboux et al, 2007.08995
- Cosmological implications: Alam et al, 2007.08991
- Mocks, Catalog papers


SDSS
13.8
Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)
BAO feature strength
50
100
150
s (h⁻¹Mpc)

eBOSS footprint



C. Zhao+, 2020

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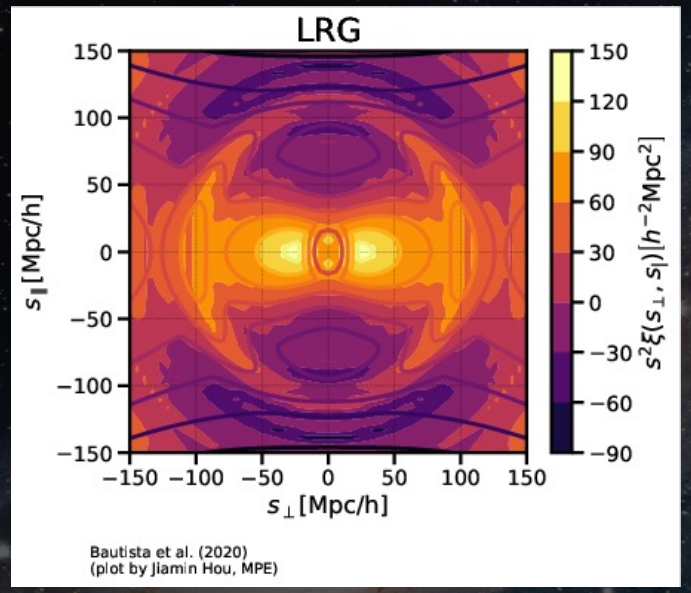
Luminous Red Galaxies (LRGs)

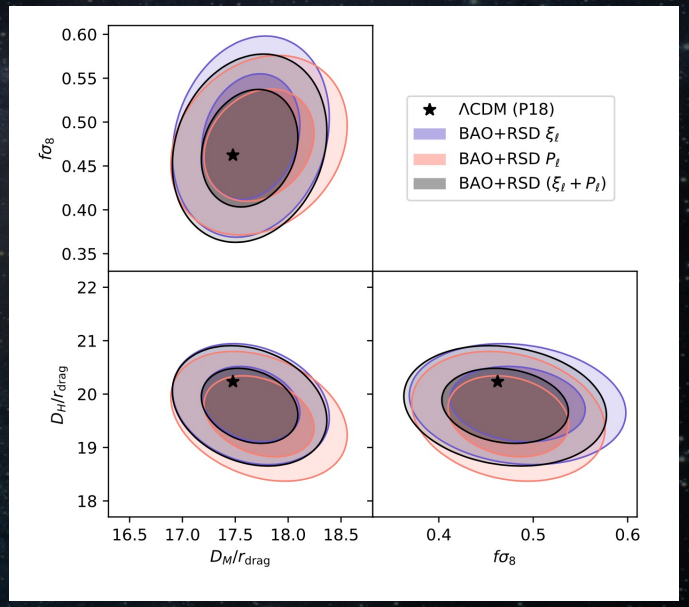
$0.6 < z < 1.0$, $z_{eff} = 0.77$

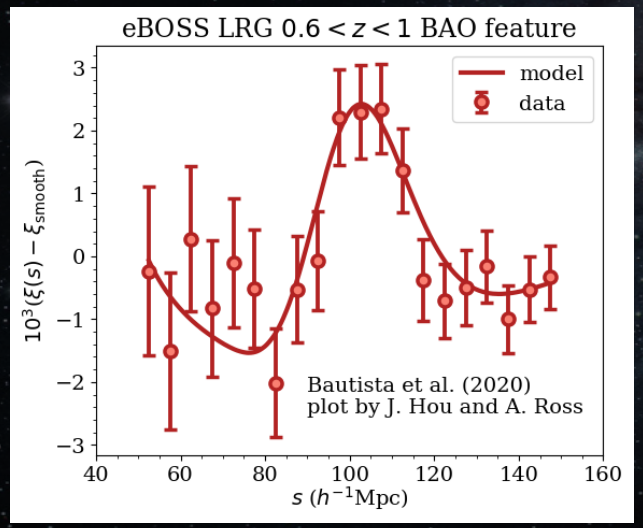
~9500 deg^2

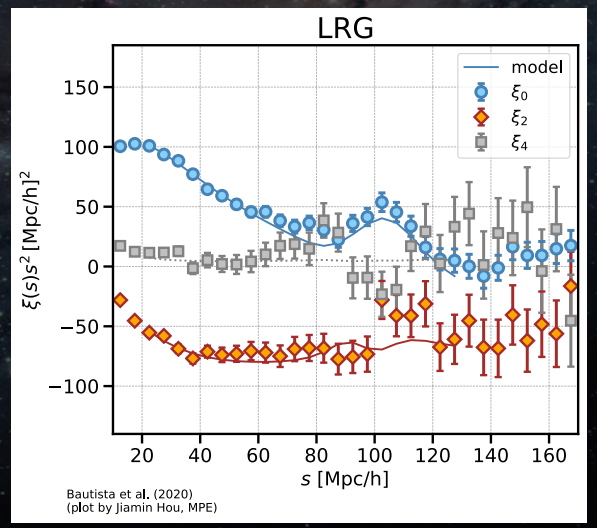
~400 K spectra

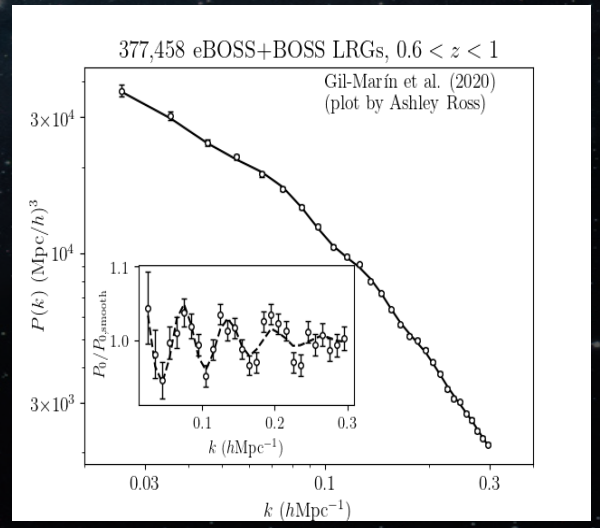
Bautista+, 2020; Gil-Marin+, 2020

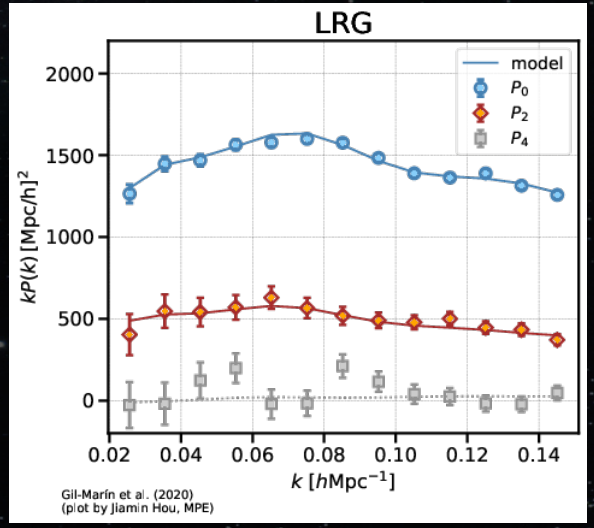












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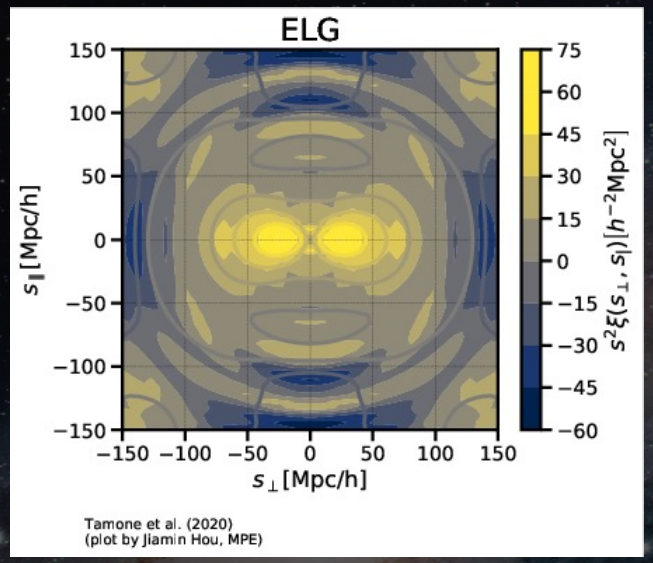
Emission line Galaxies (ELGs)

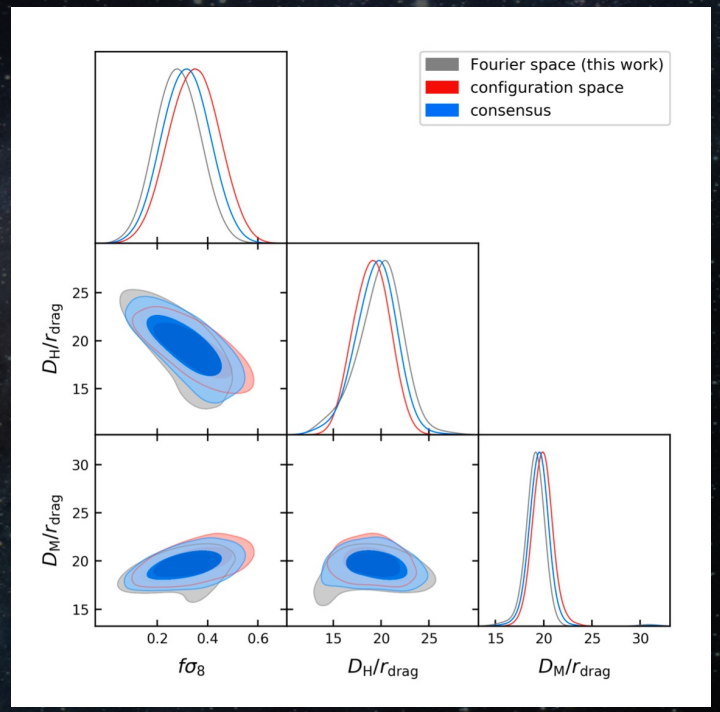
$0.6 < z < 1.1$, $z_{eff} = 0.845$

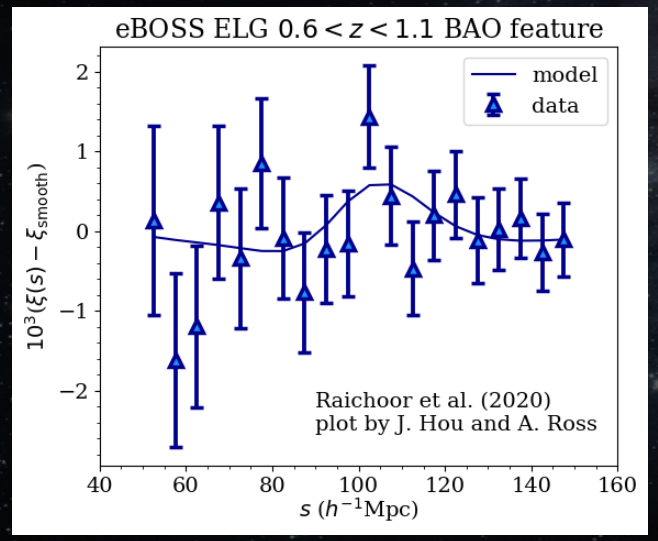
~730 deg²

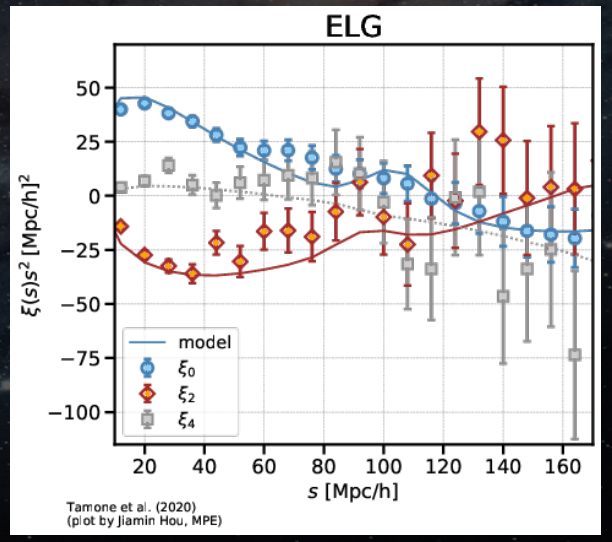
~170 K spectra

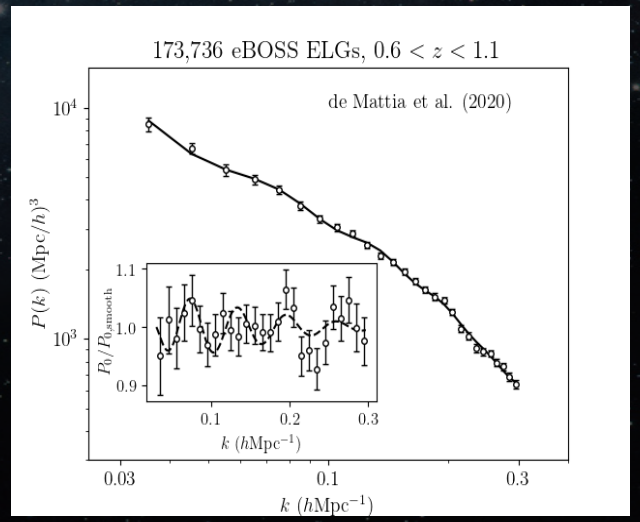
de Mattia+, 2020; Tamone+, 2020

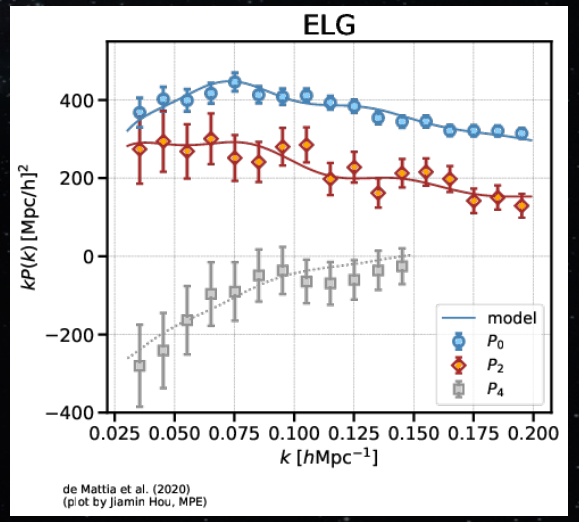












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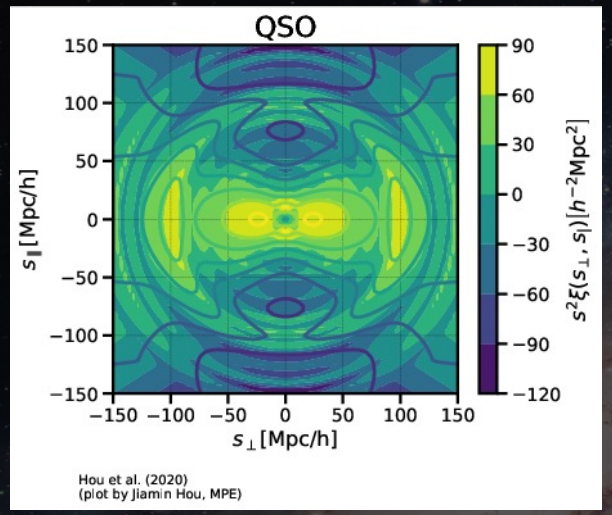
Clustering quasars (QSOs)

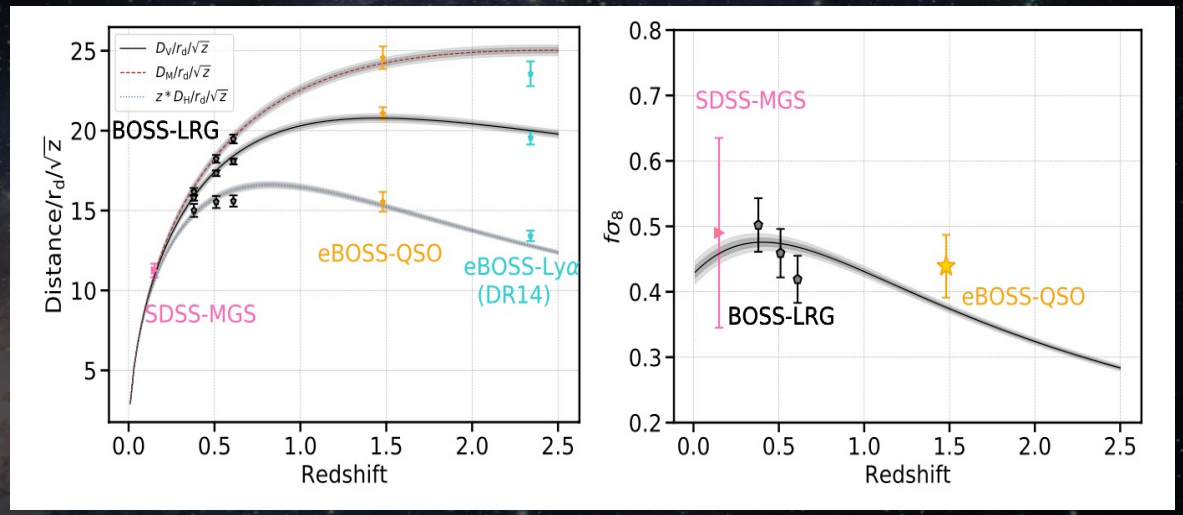
$0.8 < z < 2.2$, $z_{eff} = 1.48$

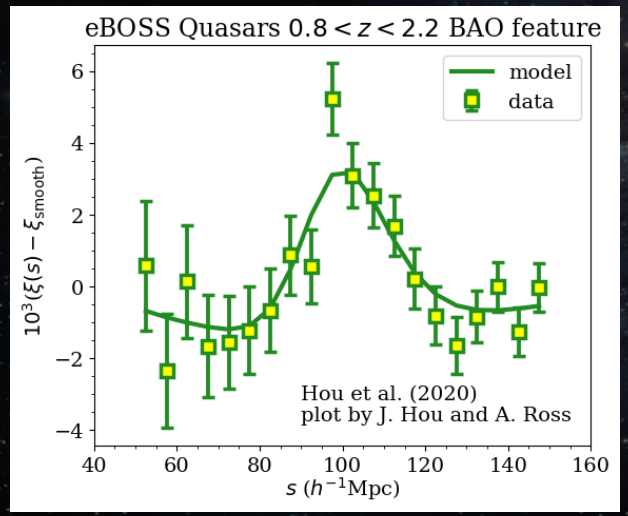
~4700 deg^2

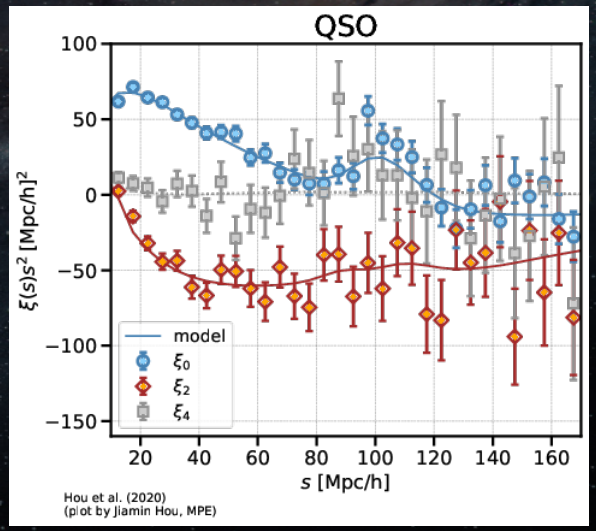
~340 K spectra

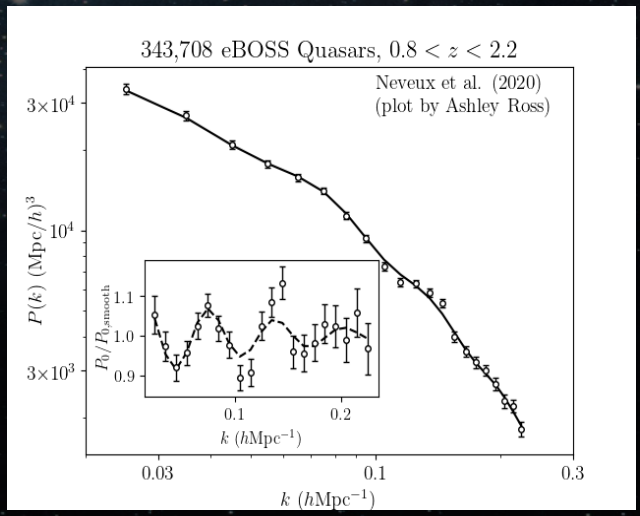
Hou+, 2020; Neveux+, 2020

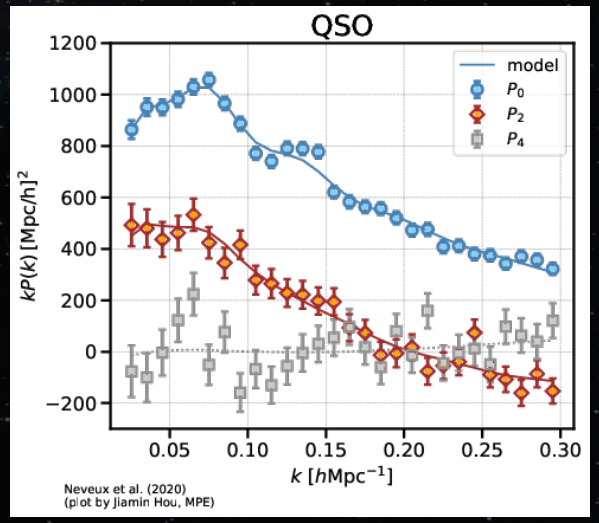




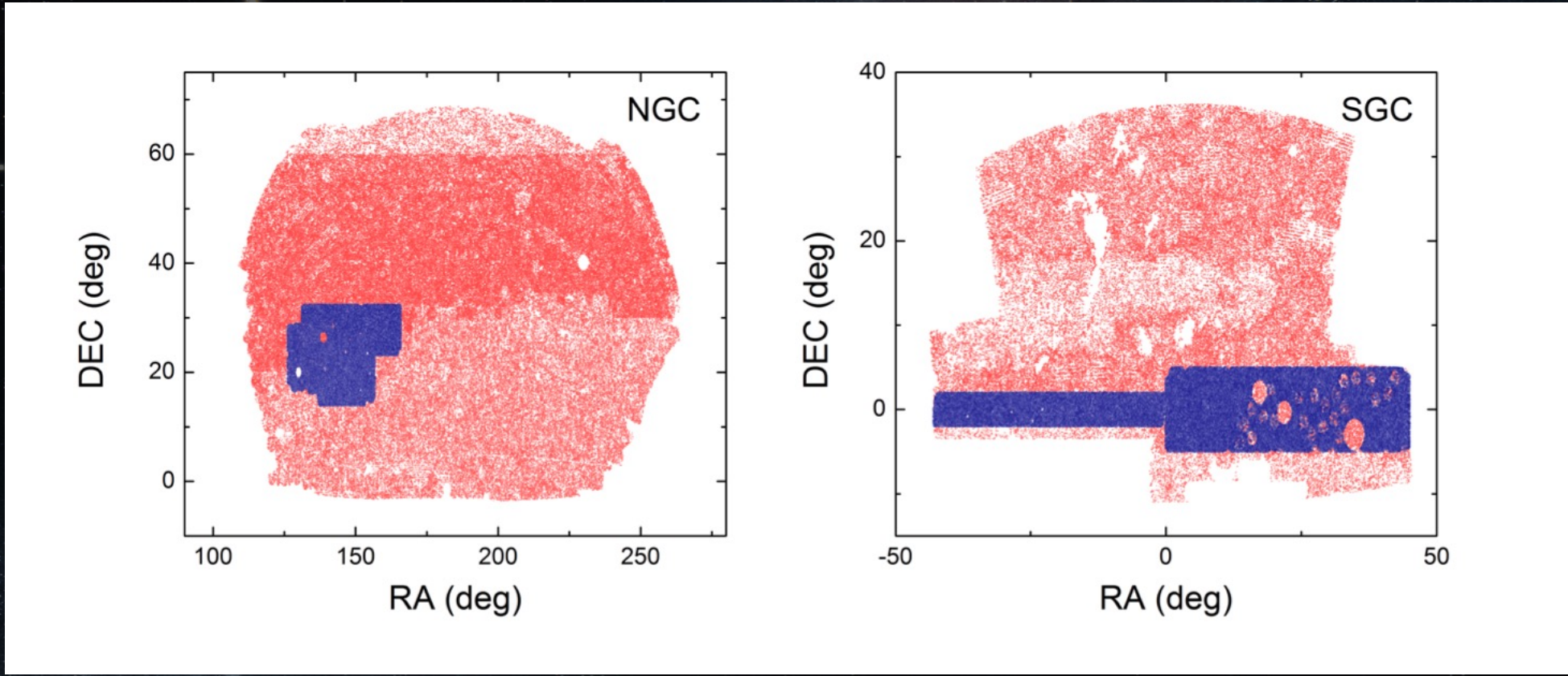






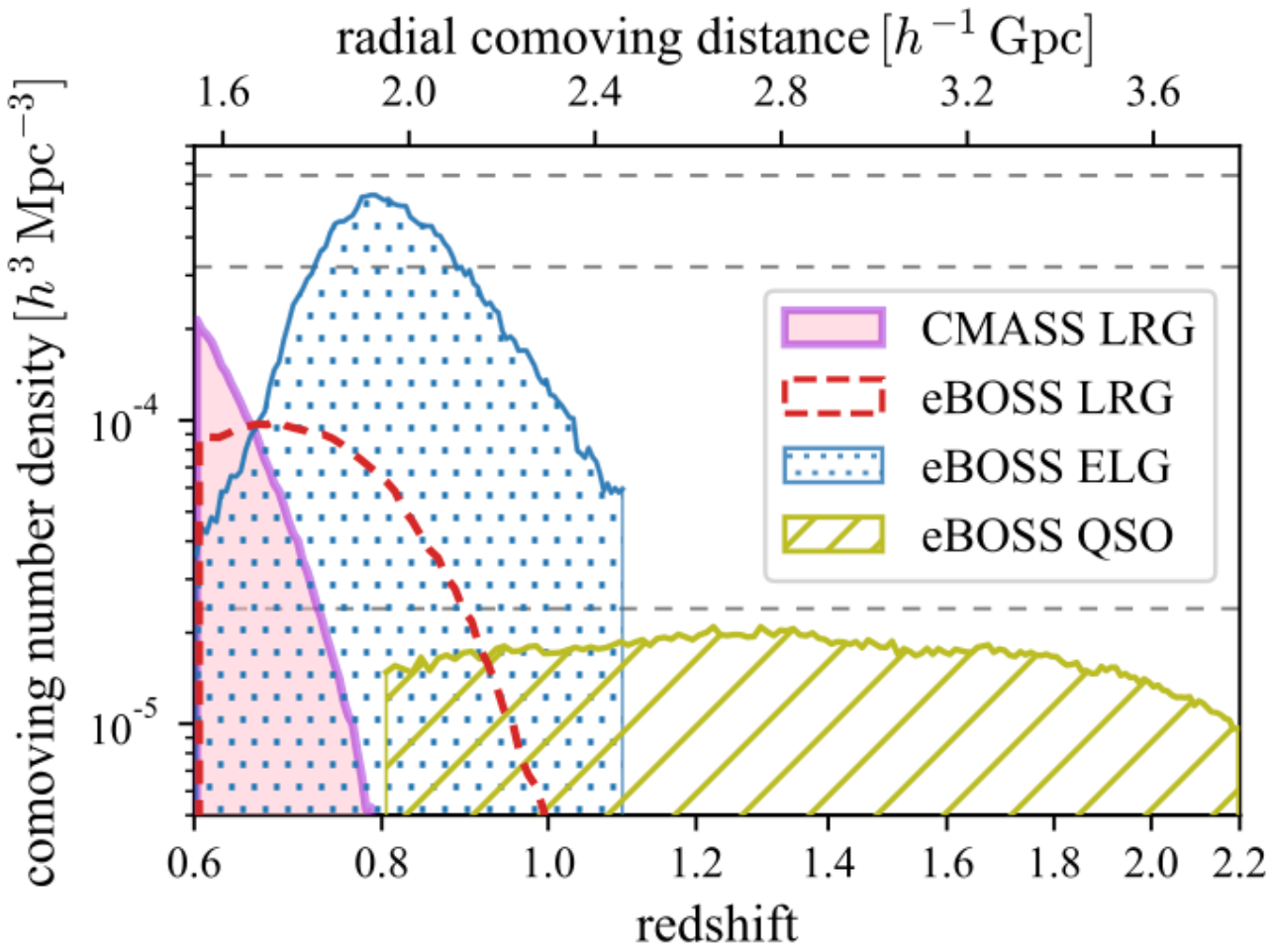


Angular overlap



GBZ+, 2020

Radial overlap



Why cross-correlation is cool?

- It can remove the cosmic variance, thus reduce the statistical uncertainty!

1-tracer: $\delta_{g1} = (b_1 + f\mu^2)\delta + \epsilon_1 = f\left(\beta^{-1} + \mu^2\right)\delta + \epsilon_1$

$C = 2\langle\delta_{g1}^2\rangle$ $\frac{\sigma_\beta^2}{\beta^2} = \frac{(1+\beta)^2}{\beta^2}$

2-tracers: $\delta_{g1} = f\left(\beta^{-1} + \mu^2\right)\delta + \epsilon_1$ $\delta_{g2} = f\left(\alpha\beta^{-1} + \mu^2\right)\delta + \epsilon_2$

$$C \equiv \begin{bmatrix} \langle\delta_{g1}^2\rangle & \langle\delta_{g1}\delta_{g2}\rangle \\ \langle\delta_{g2}\delta_{g1}\rangle & \langle\delta_{g2}^2\rangle \end{bmatrix} = \frac{P_{\theta\theta}}{2}\begin{bmatrix} \left(\beta^{-1}+\mu^2\right)^2 & \left(\beta^{-1}+\mu^2\right)\left(\alpha\beta^{-1}+\mu^2\right) \\ \left(\beta^{-1}+\mu^2\right)\left(\alpha\beta^{-1}+\mu^2\right) & \left(\alpha\beta^{-1}+\mu^2\right)^2 \end{bmatrix} + \frac{N}{2}$$

$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{\alpha\beta^{-1}+\mu^2}{\beta^{-1}+\mu^2}.$$

McDonald & Seljak 2008; Seljak 2009

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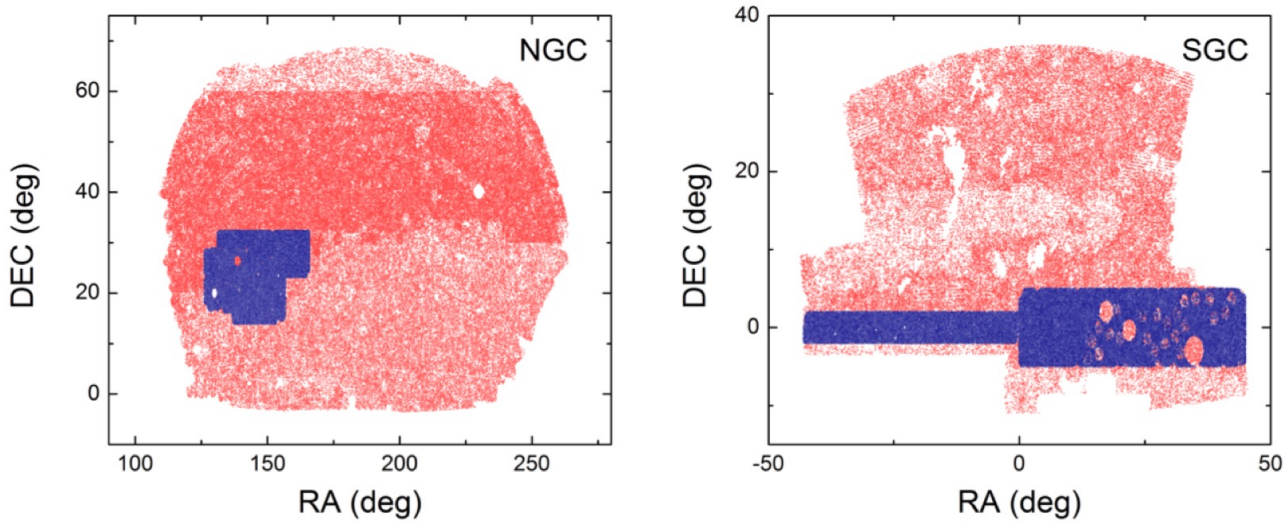
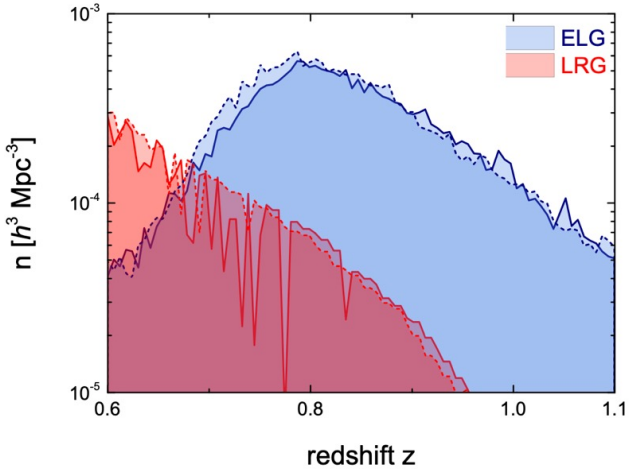
$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{\alpha\beta^{-1}+\mu^2}{\beta^{-1}+\mu^2}.$$

McDonald & Seljak 2008; Seljak 2009

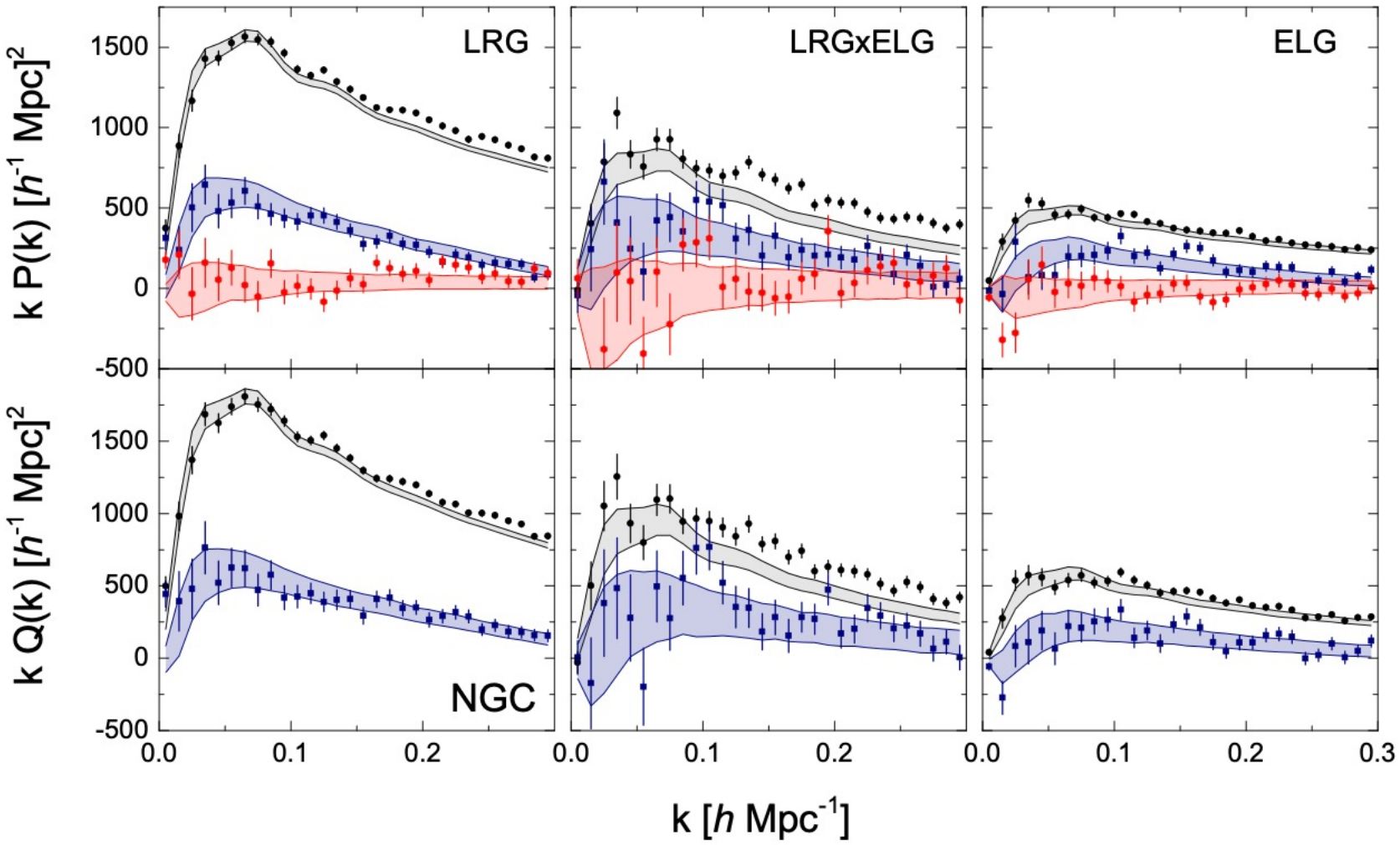
- It can reduce the systematics, as the photometry used for observing different tracers are usually uncorrelated!



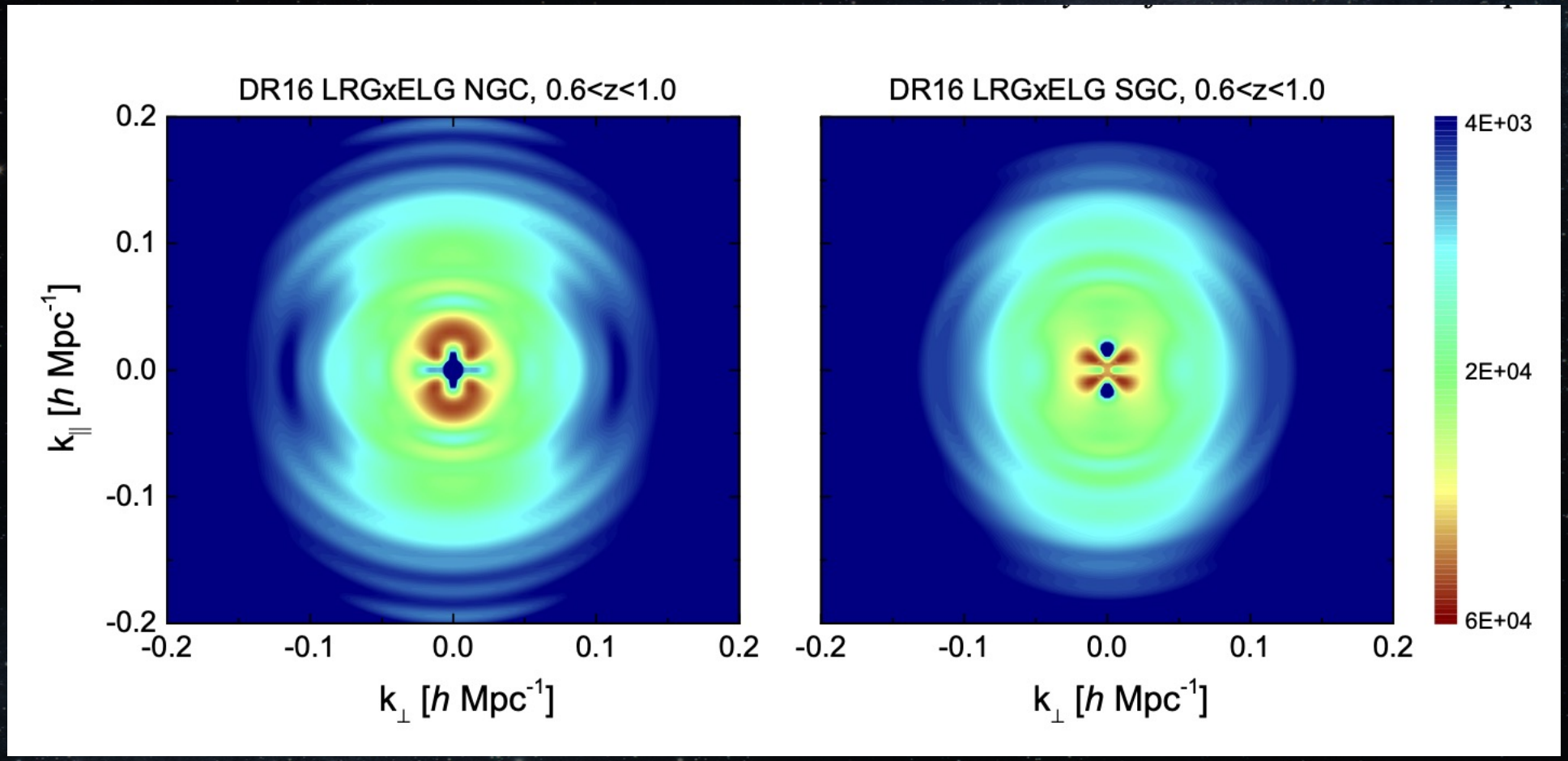


Decent overlap between
eBOSS DR16
LRGs and ELGs
in AREA ~ 800 deg^2
and in REDSHIFT [0.6,1.0]

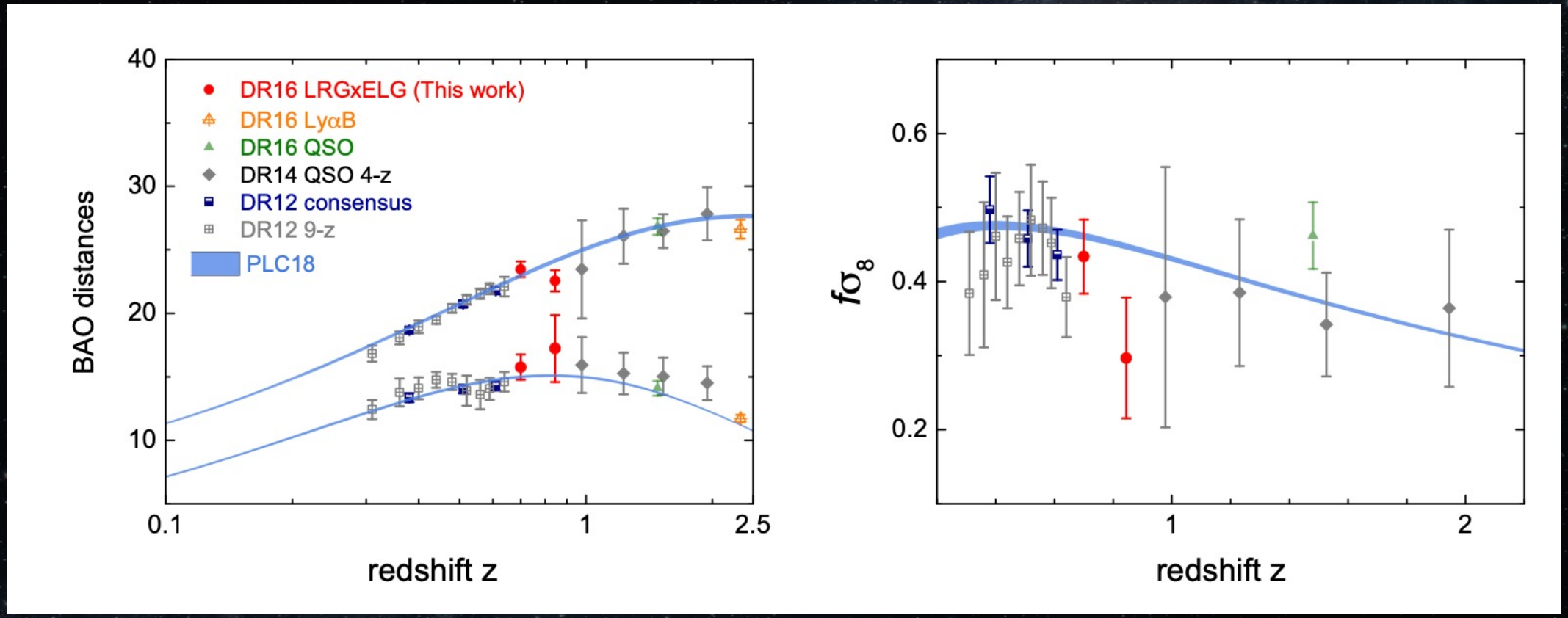
Zhao, Wang et al, (eBOSS), 2007.09011 (k-space)
Wang, **Zhao** et al, (eBOSS), 2007.09010 (s-space)


LRG
LRGxELG
ELG
NGC
k P(k) [h^-1 Mpc]^2
k Q(k) [h^-1 Mpc]^2
k [h Mpc^-1]
1500
1000
500
0
-500
0.0
0.1
0.2
0.3

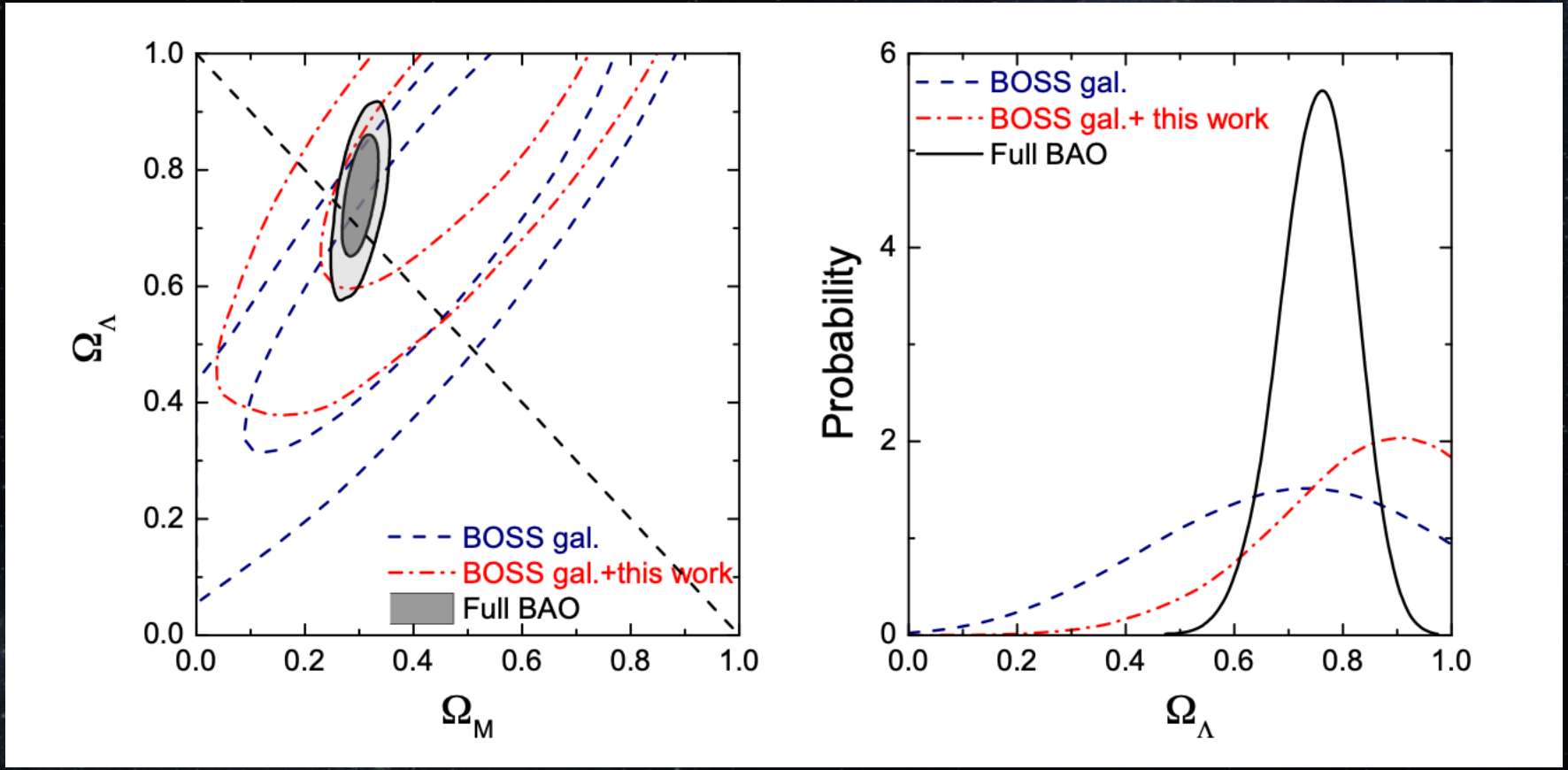
GBZ+, 2020


DR16 LRGxELG NGC, 0.6<z<1.0
DR16 LRGxELG SGC, 0.6<z<1.0
0.2
0.1
0.0
-0.1
-0.2
$k_{\parallel}$ [h Mpc^{-1}]
-0.2
-0.1
0.0
0.1
0.2
$k_{\perp}$ [h Mpc^{-1}]
4E+03
2E+04
6E+04

GBZ+, 2020

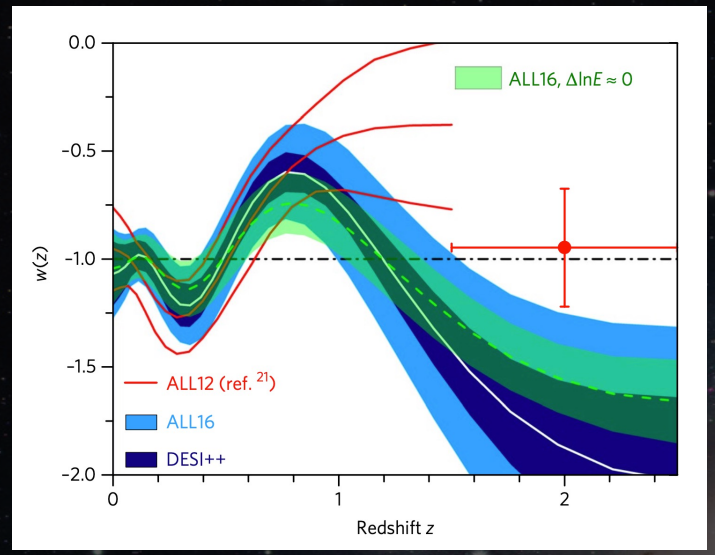

DR16 LRGxELG (This work)
DR16 LyαB
DR16 QSO
DR14 QSO 4-z
DR12 consensus
DR12 9-z
PLC18
BAO distances
40
30
20
10
0.1
1
2.5
redshift z
$f\sigma_8$
0.6
0.4
0.2
1
2
redshift z

GBZ+, 2020

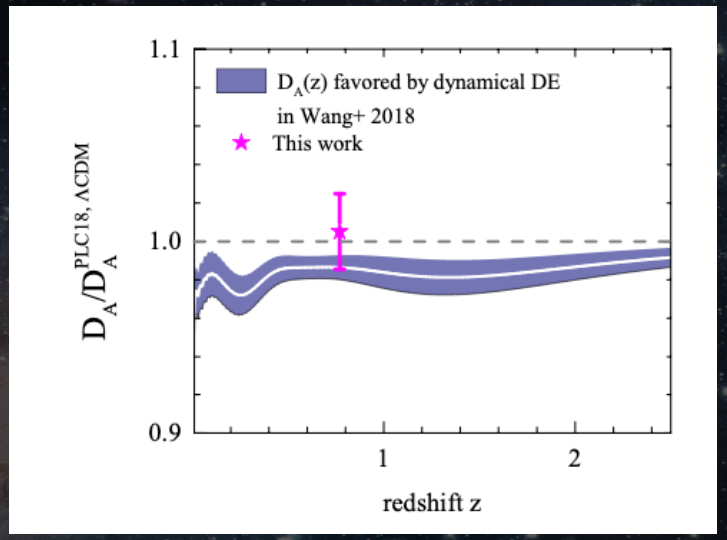


A 11σ detection of $\Omega_\Lambda > 0$

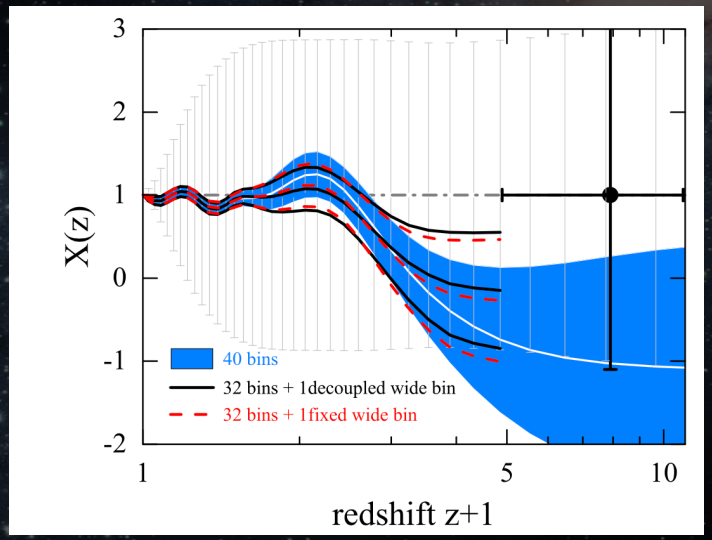
Zhao, Wang et al, (eBOSS), 2007.09011



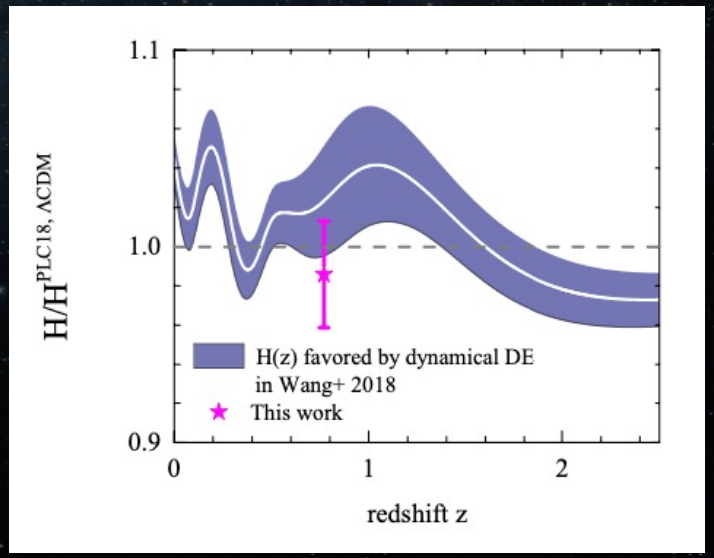
GBZ+, 2017, Nature Astronomy



Wang+, 2020

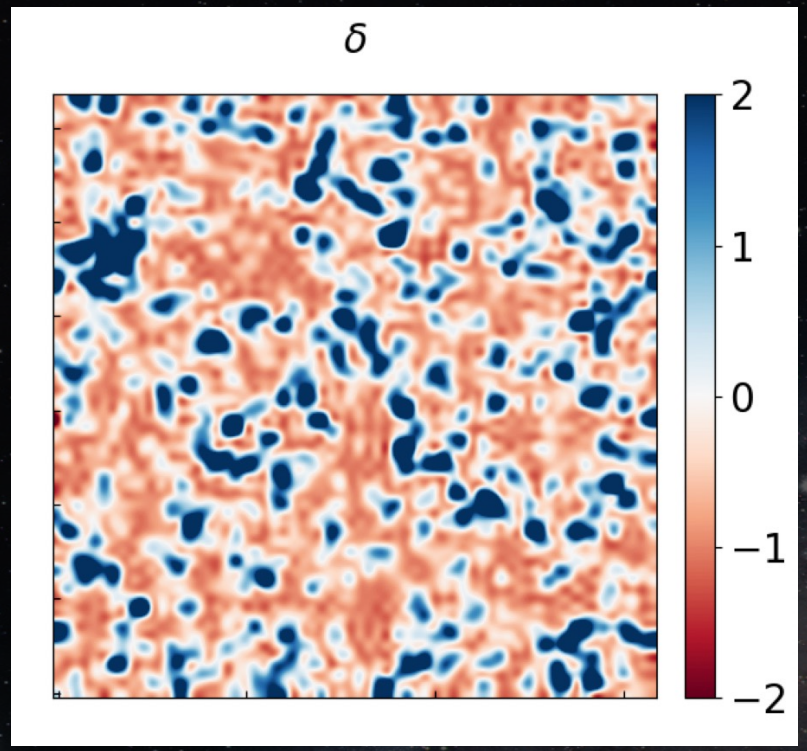


Wang+, 2018, ApJL

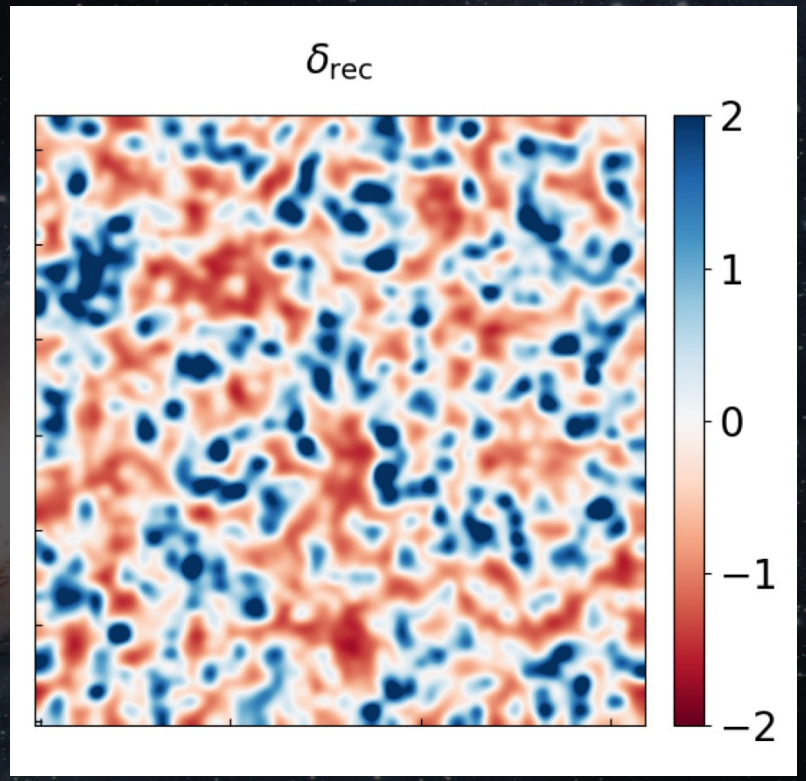


Wang+, 2020

A new method to extract high-order information from 2-pt



phase info.



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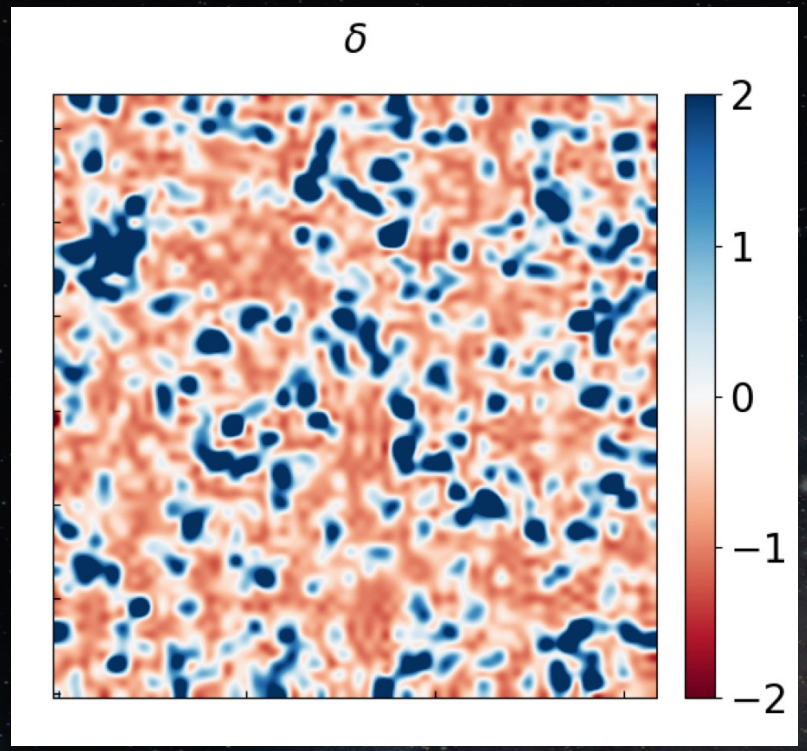
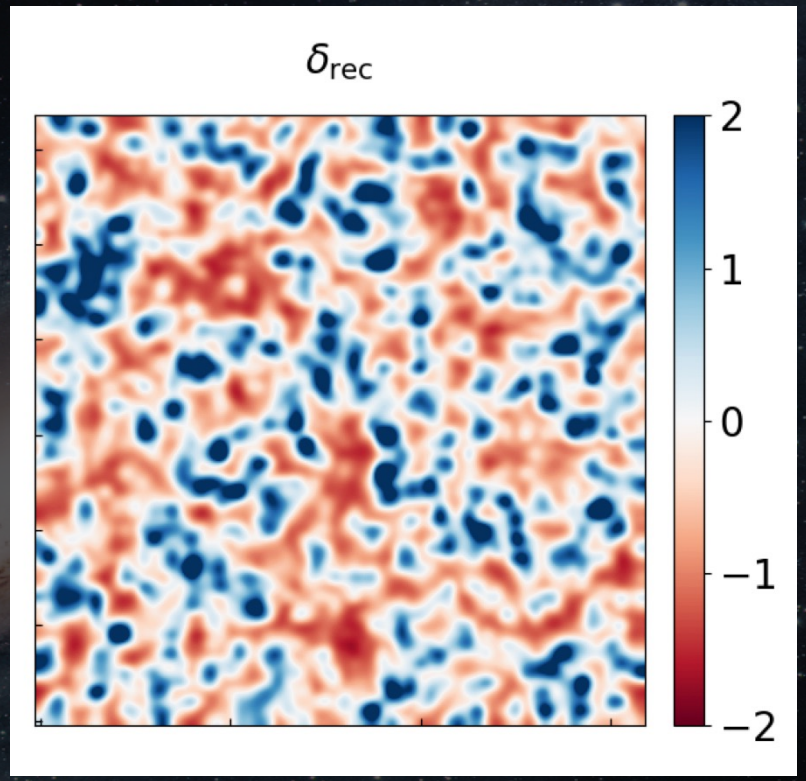


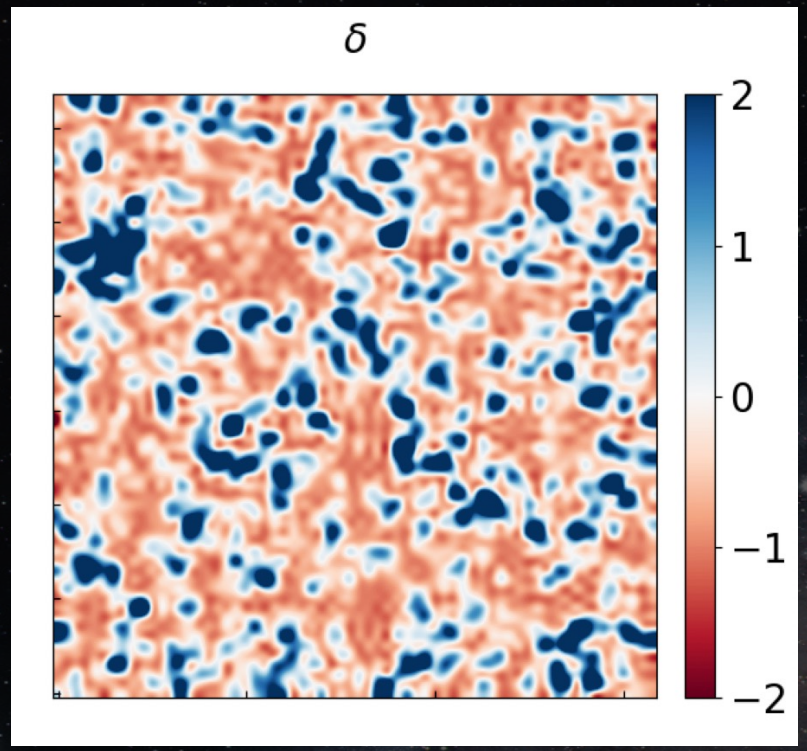
phase info.



$P_{\rm pre}$

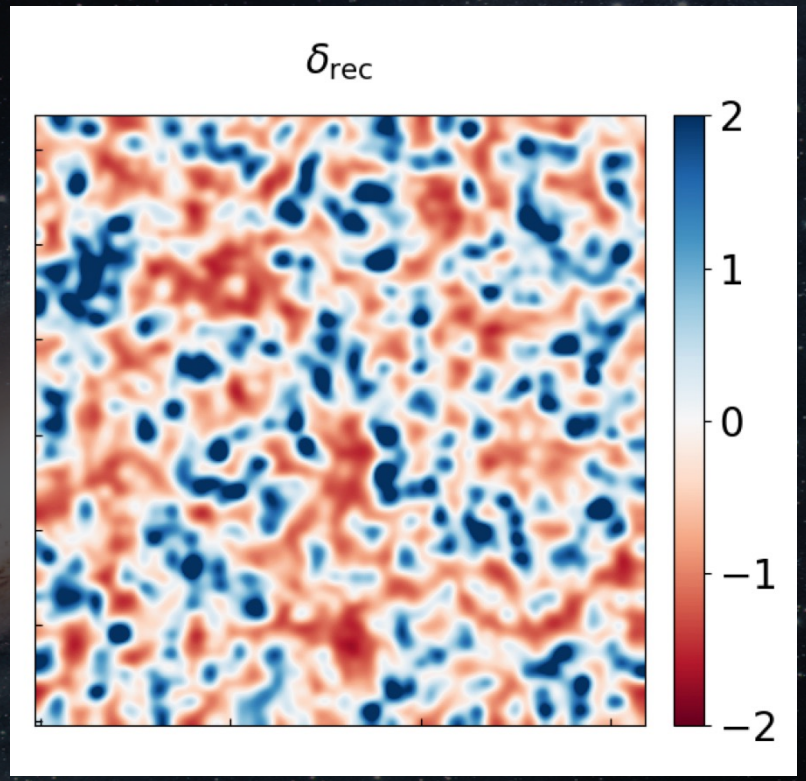
$P_{\rm post}$

A new method to extract high-order information from 2-pt



phase info.

X



$P_{\rm cross}$

$P_{\rm pre}$

$P_{\rm post}$

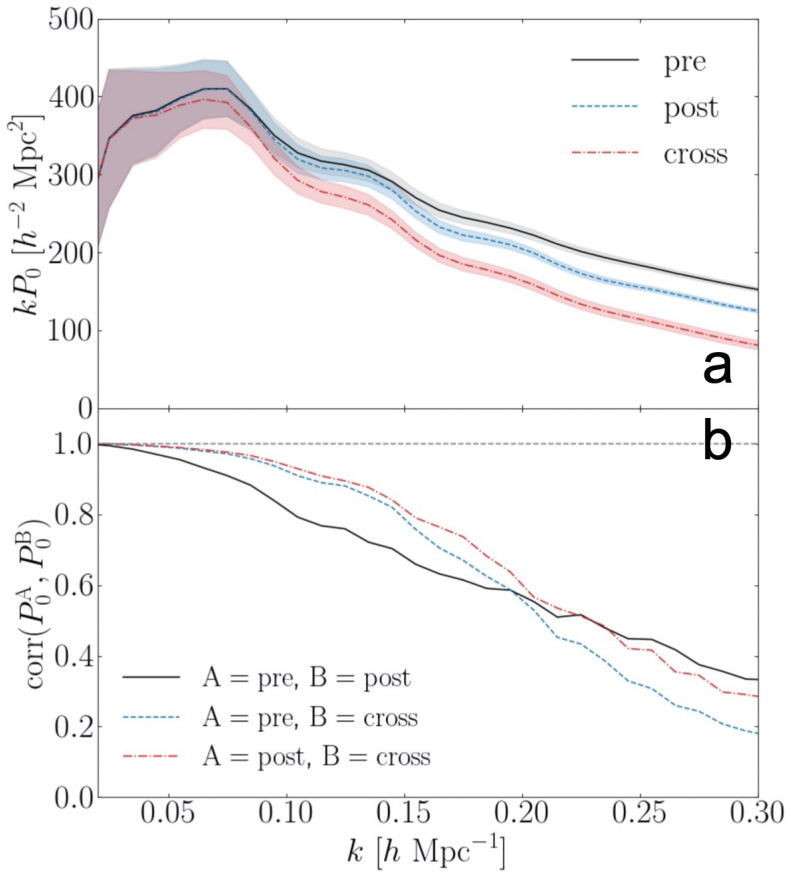
Information content for the Euler reconstruction

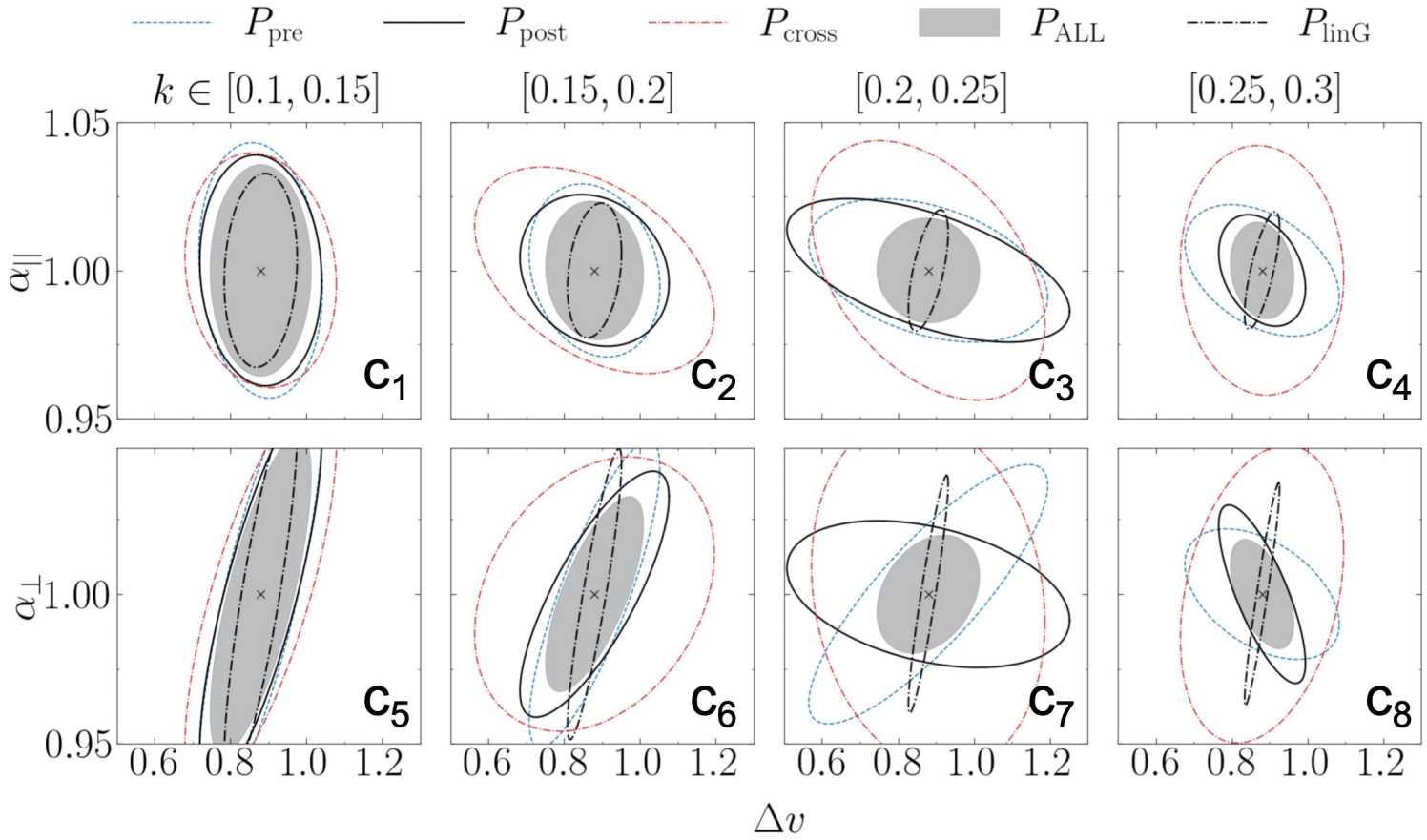
$$\delta^{\rm rec}_{\rm EGS}(\mathbf{x}) = \delta(\mathbf{x},\eta) - \underbrace{\mathbf{s}(\mathbf{x},\eta)\cdot\nabla\delta(\mathbf{x},\eta)}_{\text{shift}} - \underbrace{\delta(\mathbf{x},\eta)\delta_R(\mathbf{x},\eta)}_{\text{growth}},$$

$$\hat{P}_{\delta^{\rm rec}_{\rm EGS},\delta^{\rm rec}_{\rm EGS}}(k) = \underbrace{\hat{P}_{\delta,\delta}(k)}_{\text{2pt}} \underbrace{-2\hat{P}_{\delta^2,\delta}(k) - 2\hat{P}_{\mathbf{s}\cdot\nabla\delta,\delta}(k)}_{\text{3pt}} + \underbrace{\hat{P}_{\delta^2,\delta^2}(k) + \hat{P}_{\mathbf{s}\cdot\nabla\delta,\mathbf{s}\cdot\nabla\delta}(k) + 2\hat{P}_{\mathbf{s}\cdot\nabla\delta,\delta^2}(k)}_{\text{4pt}},$$

Schmittfull et al, 2015

A demonstration using **4000** high-res N-body simulations at z=1.02





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Analysis on other cosmological parameters on Quijote galaxy mocks (Molino)

Yuting Wang, GBZ*, et al, **arXiv: 2202.05248**

MOCK GALAXY catalogs

(Hahn2020)

QUIJOTE Simulations

- ❑ 1Gpc^3
- ❑ realizations
- ❑ cosmologies

5-paras. HOD model

(Zheng2007)

- @ z=0
- Covmat: 15,000 mocks (z-RSD)
- Derivatives : 2, 500 mocks (x-, y-, z-RSD)

$M_\nu^{+++} = 0.4$					
$M_\nu^{++} = 0.2$					
$M_\nu^{+} = 0.1$	$\Omega_m^{+} = 0.3275$	$\Omega_b^{+} = 0.051$	$h^{+} = 0.6911$	$n_s^{+} = 0.9824$	$\sigma_8^{+} = 0.849$
$M_\nu = 0.0\text{eV}$	$\Omega_m = 0.3175$	$\Omega_b = 0.049$	$h = 0.6711$	$n_s = 0.9624$	$\sigma_8 = 0.834$
	$\Omega_m^{-} = 0.3075$	$\Omega_b^{-} = 0.047$	$h^{-} = 0.6511$	$n_s^{-} = 0.9424$	$\sigma_8^{-} = 0.819$

$M_{\rm min}^{+} = 13.7$	$\sigma_{\log M}^{+} = 0.22$	$\log M_0^{+} = 14.2$	$\alpha^{+} = 1.3$	$\log M_1^{+} = 14.2$
$M_{\rm min} = 13.65$	$\sigma_{\log M} = 0.2$	$\log M_0 = 14$	$\alpha = 1.1$	$\log M_1 = 14$
$M_{\rm min}^{-} = 13.6$	$\sigma_{\log M}^{-} = 0.18$	$\log M_0^{+} = 13.8$	$\alpha^{-} = 0.9$	$\log M_1^{-} = 13.8$

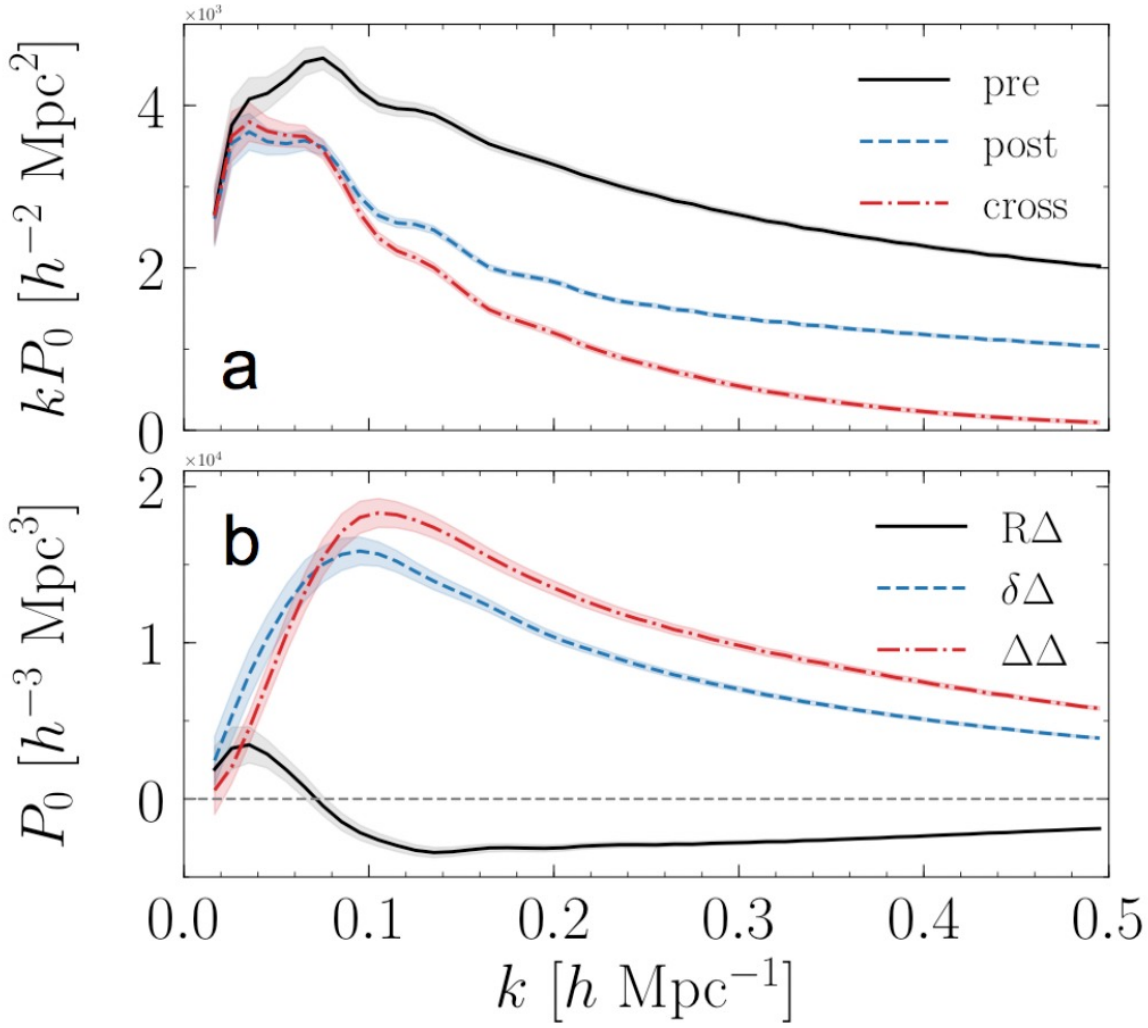
mean central galaxy occupation

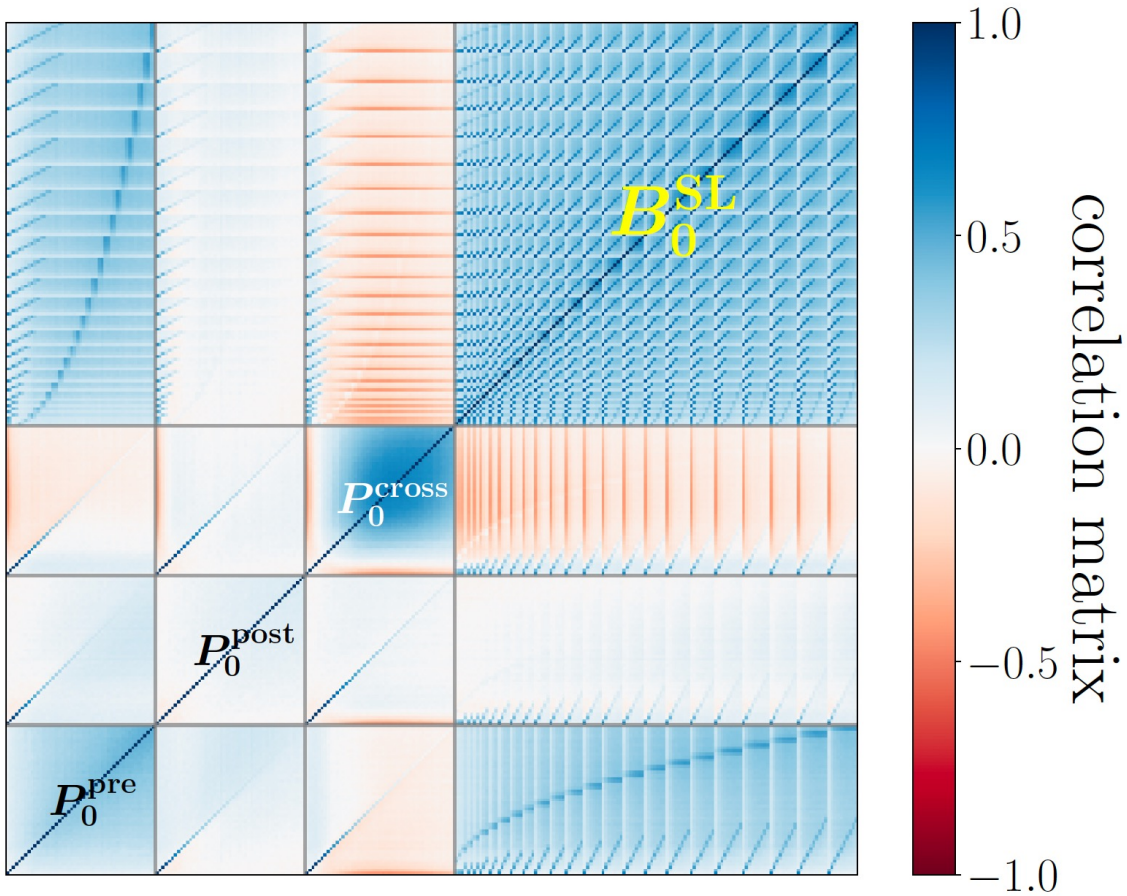
$$\langle N_{\rm cen}\rangle = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M_h - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

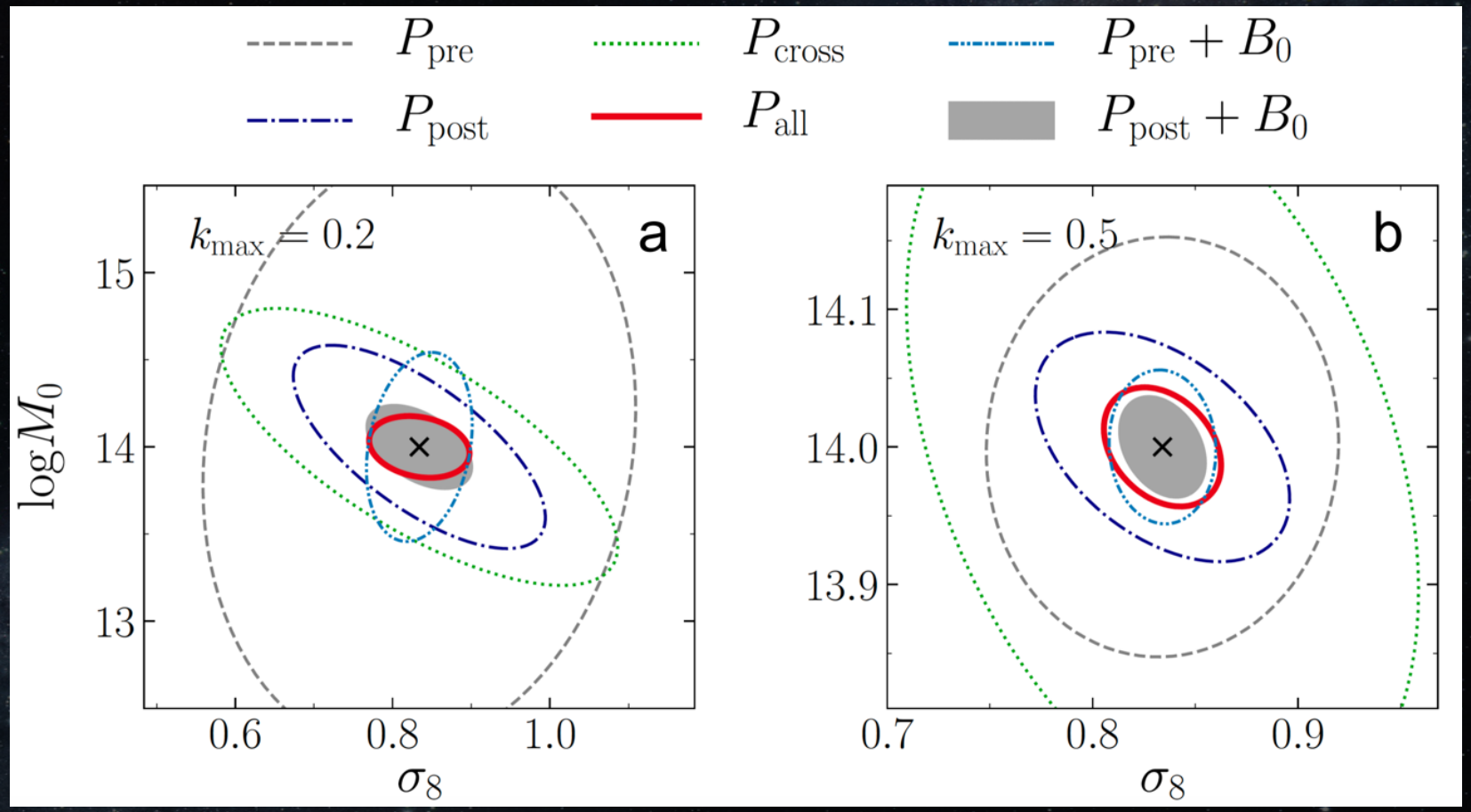
mean satellite galaxy occupation

$$\langle N_{\rm sat}\rangle = \langle N_{\rm cen}\rangle \left(\frac{M_h - M_0}{M_1}\right)^{\alpha}.$$

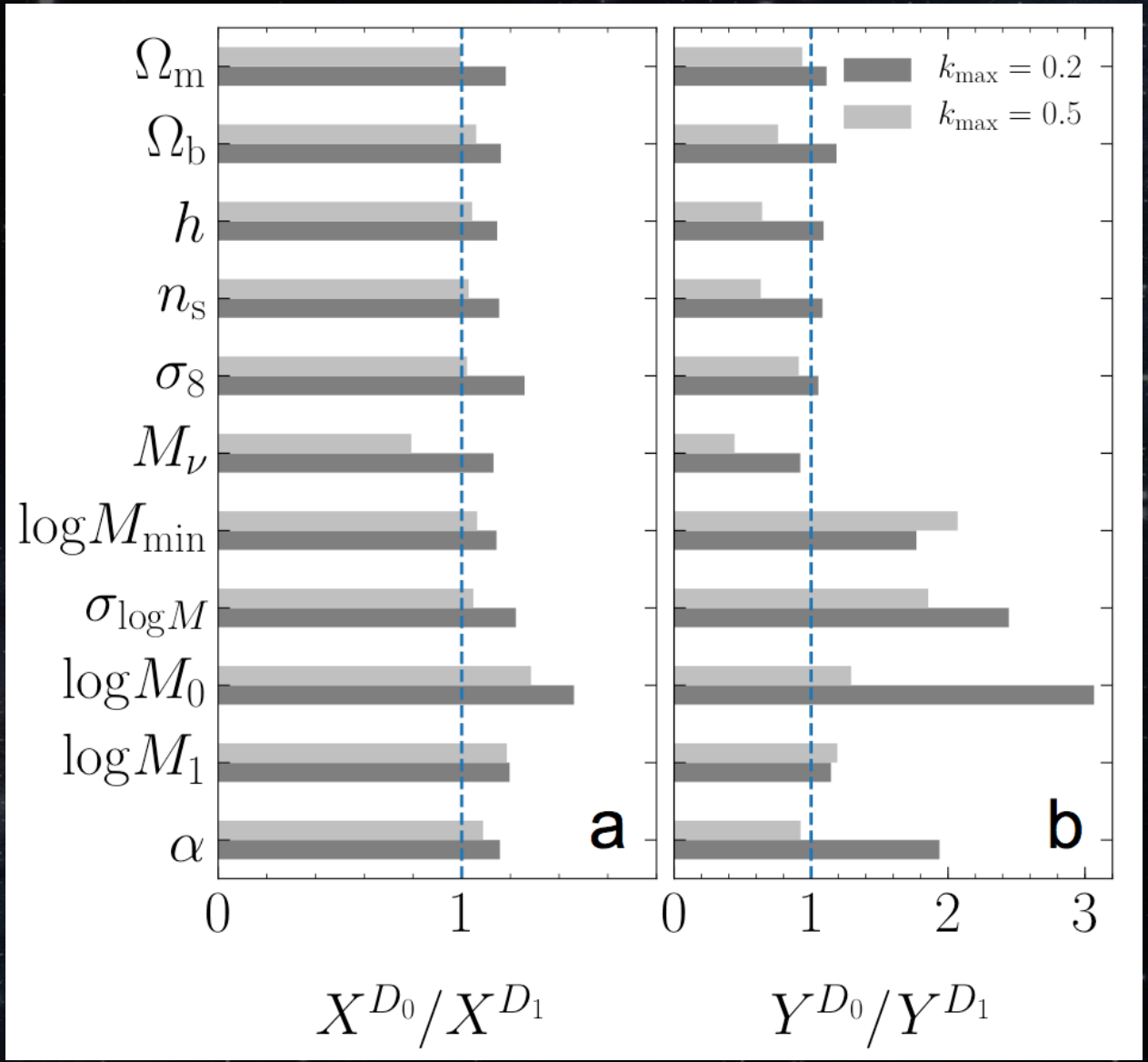
A further demonstration using **15000** realistic Molino galaxy mocks at z = 0



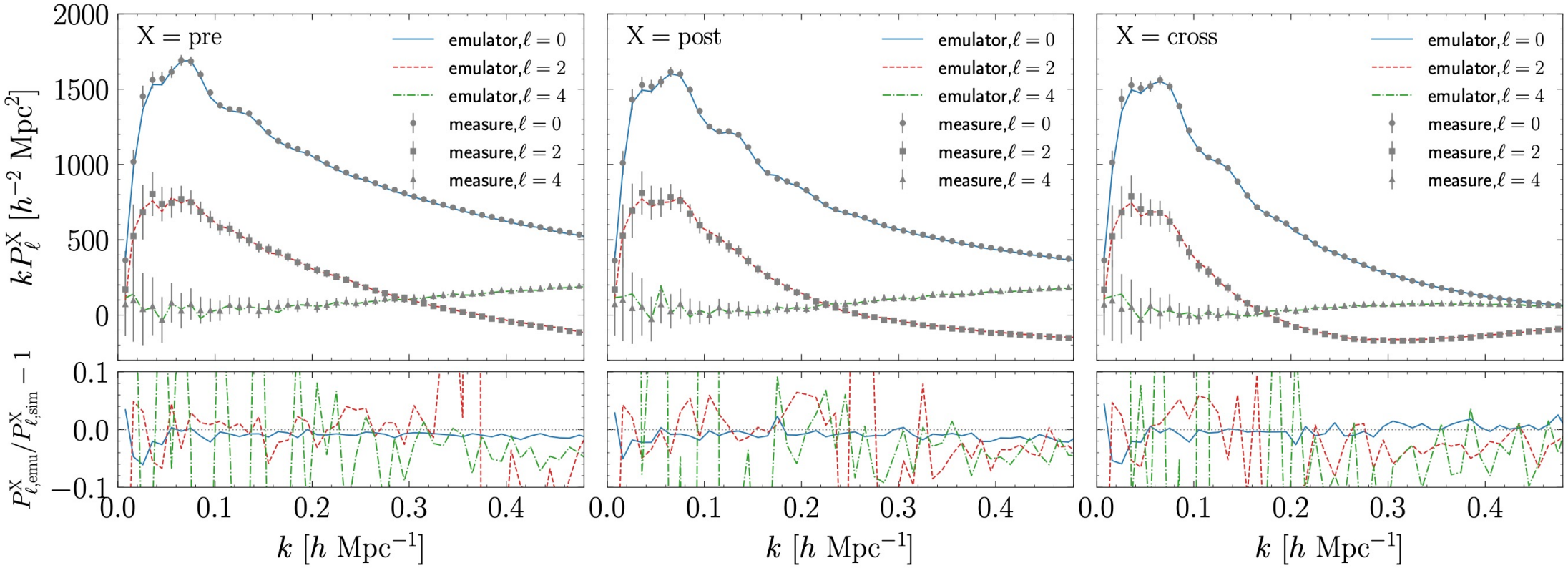




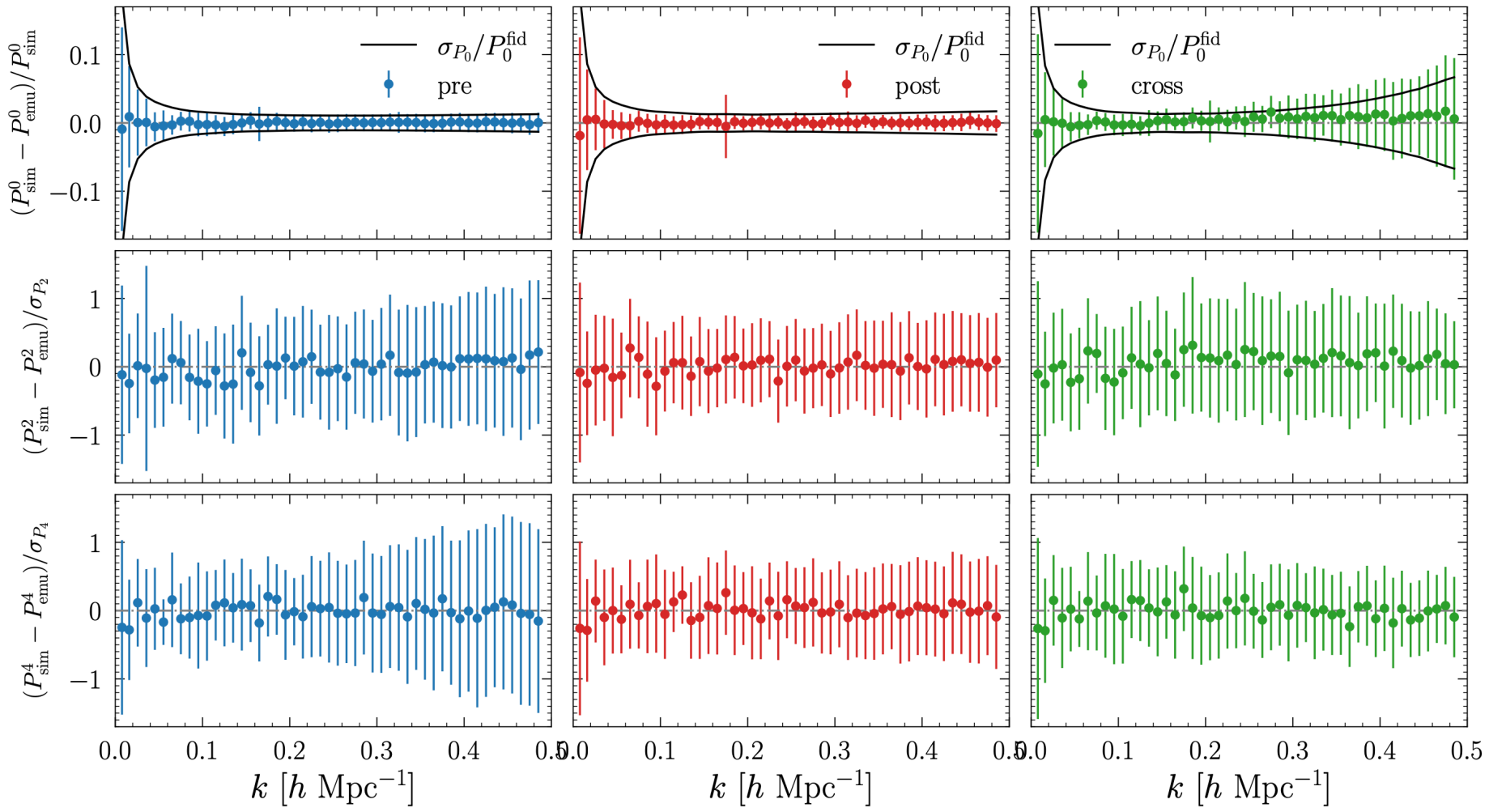
Yuting Wang, GBZ*, et al, **arXiv: 2202.05248**



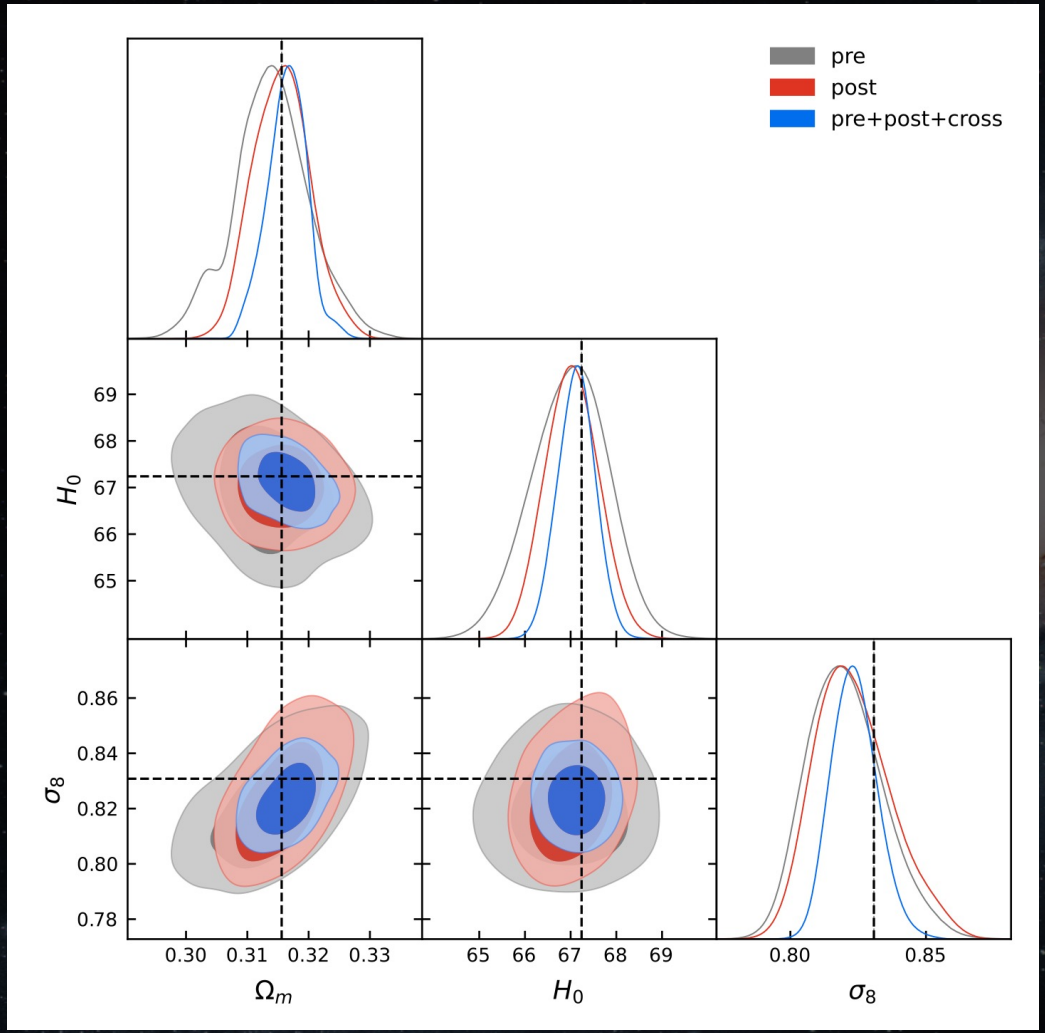
Yuting Wang, GBZ*, et al, **arXiv: 2202.05248**

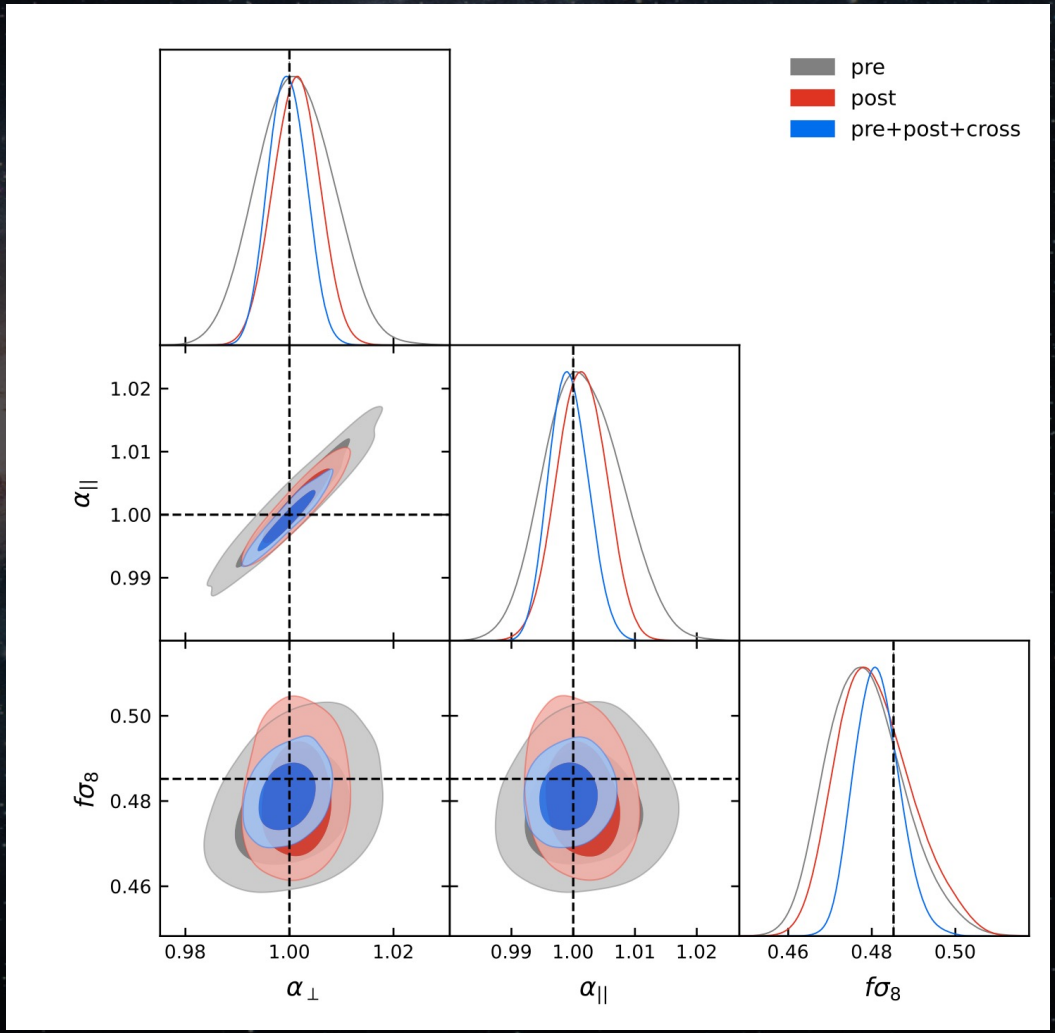


Yuting Wang, …, GBZ*, et al, 2311.05848



Yuting Wang, …, GBZ*, et al, 2311.05848





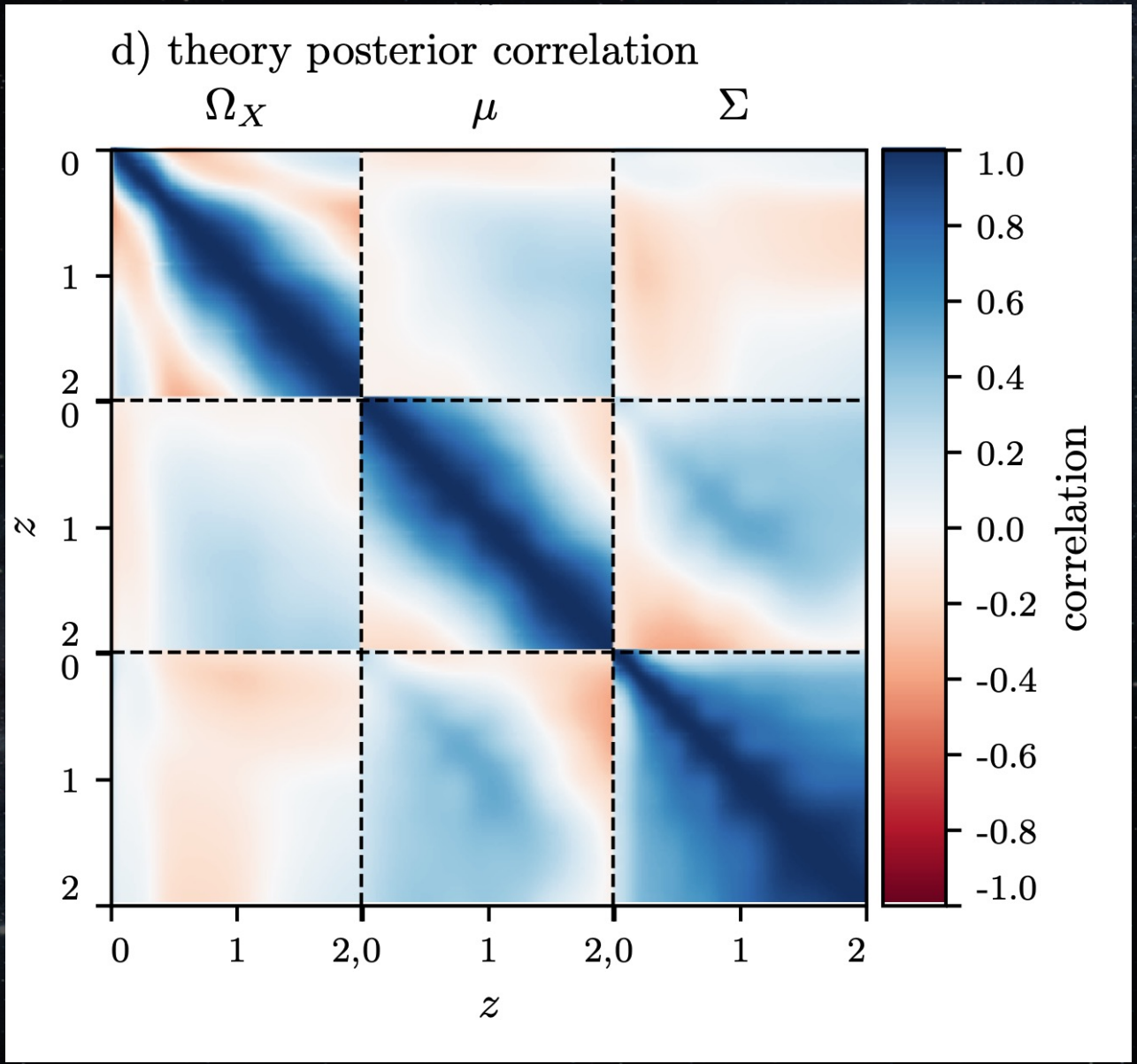
Yuting Wang, …, GBZ*, et al, 2311.05848

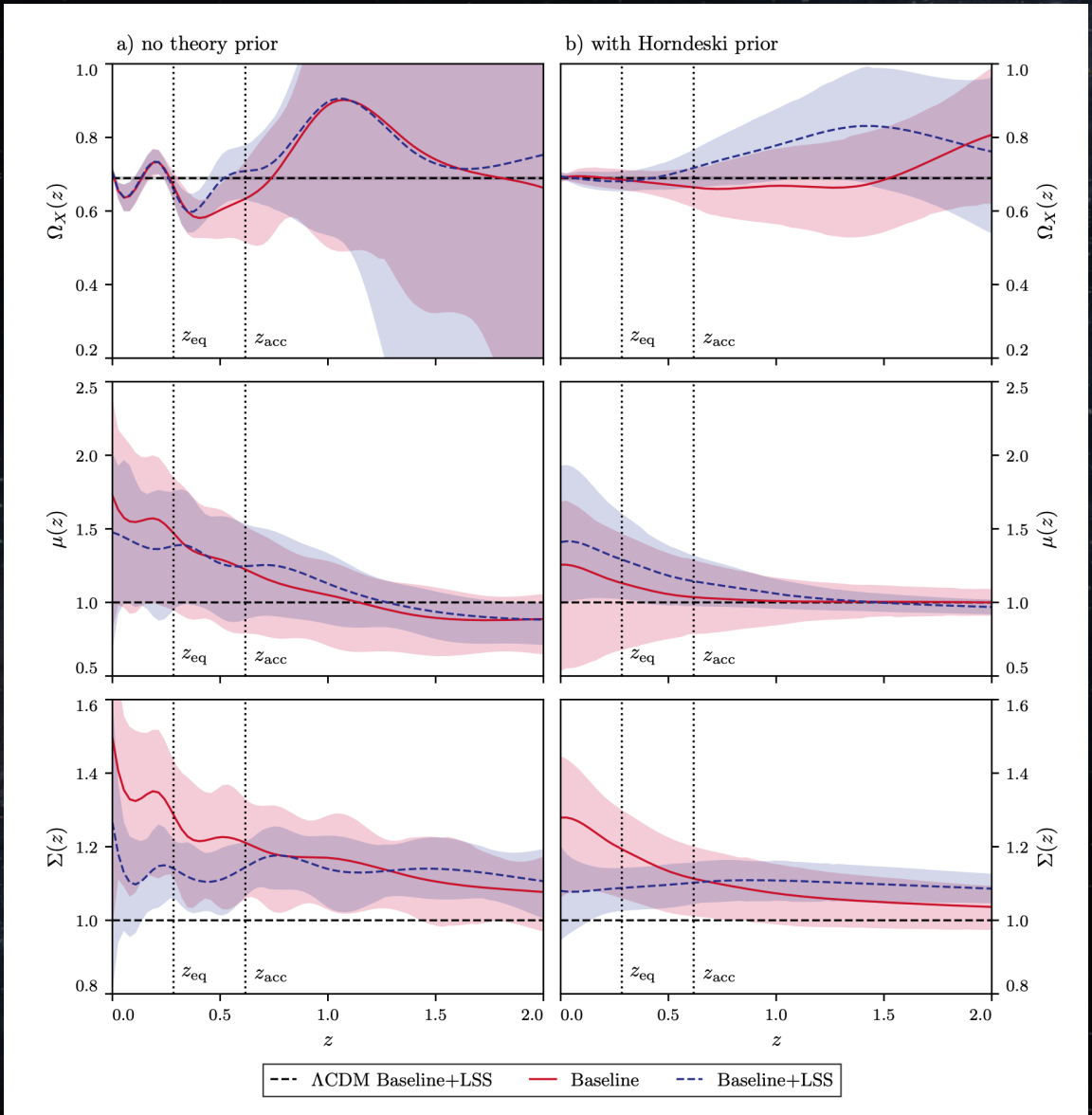
A first reconstruction of dark gravity using observations

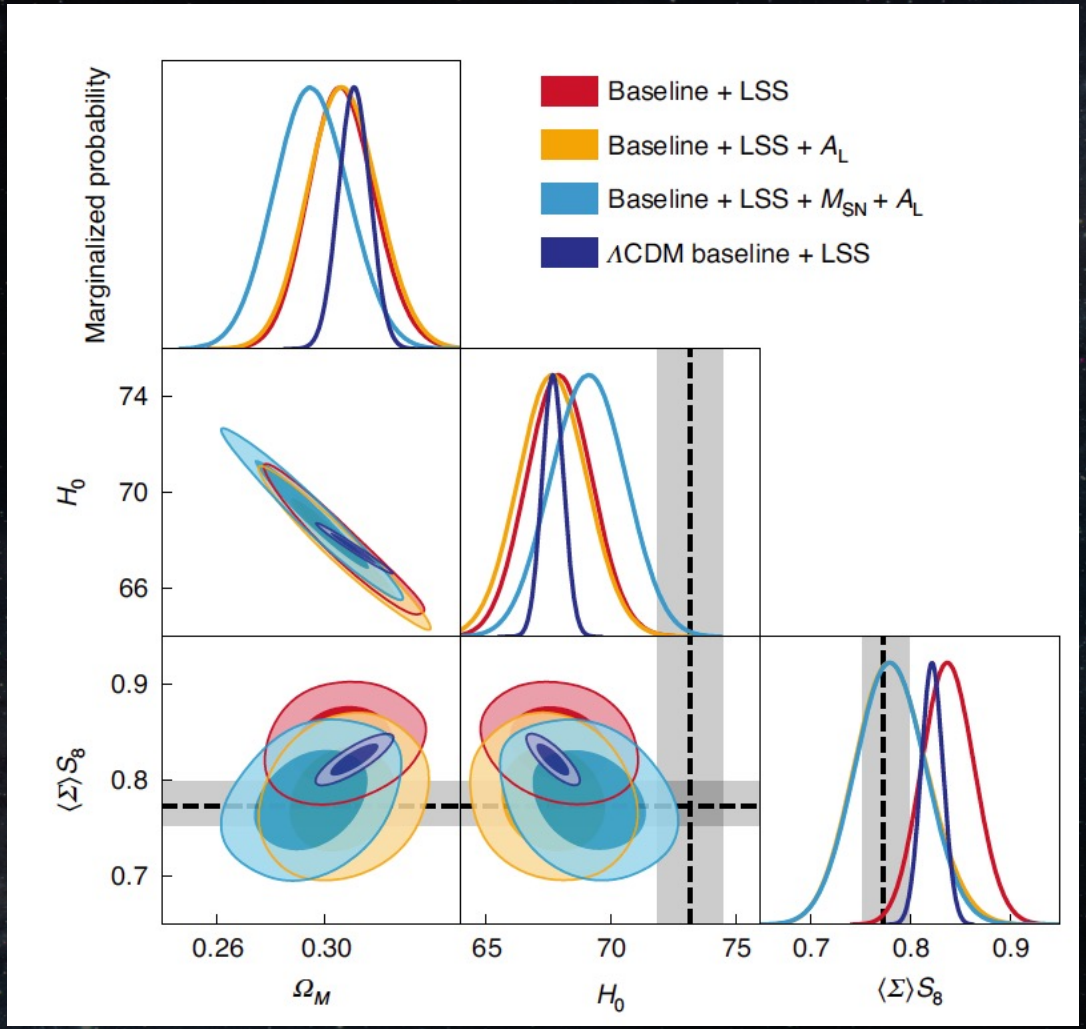
$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)d\mathbf{x}^2 \ ,$$

$$k^2\psi = -4\pi G\mu(a,k)a^2\left[\rho\Delta + 3(\rho+P)\sigma\right] \ ,$$
$$k^2(\phi+\psi) = -4\pi G\Sigma(a,k)a^2\left[2\rho\Delta + 3(\rho+P)\sigma\right]$$

$$\frac{H^2}{H_0^2} = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_{\rm X}(z)\,,$$


d) theory posterior correlation
Ω_X
μ
Σ
0
1
2
0
1
2
0
1
2
z
0
1
2,0
1
2,0
1
2
z
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
correlation

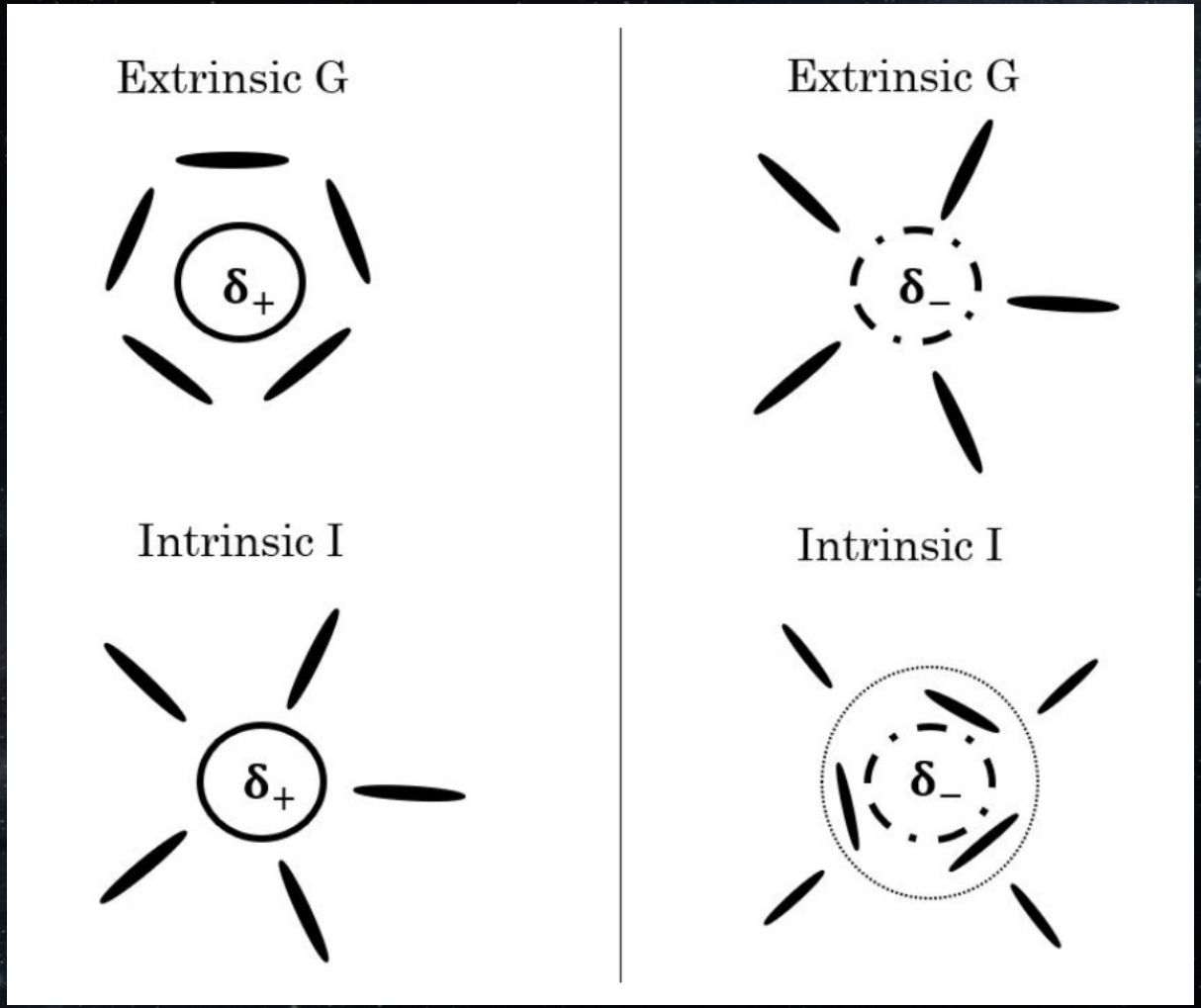

a) no theory prior
b) with Horndeski prior
$\Omega_X(z)$
$\mu(z)$
$\Sigma(z)$
$z_{\rm eq}$
$z_{\rm acc}$
z
ΛCDM Baseline+LSS
Baseline
Baseline+LSS



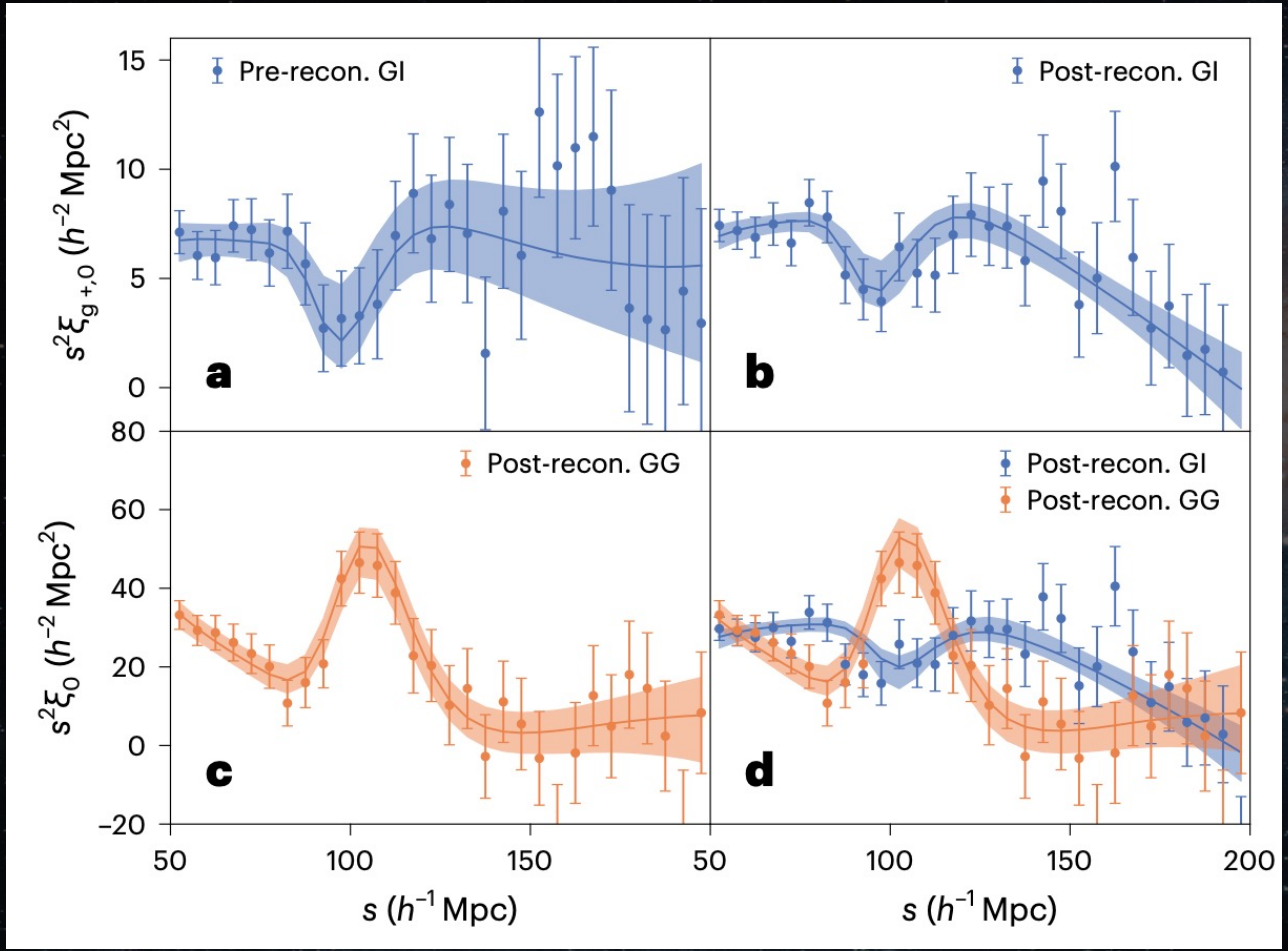
Pogosian (PIFI B), …, GBZ, et al

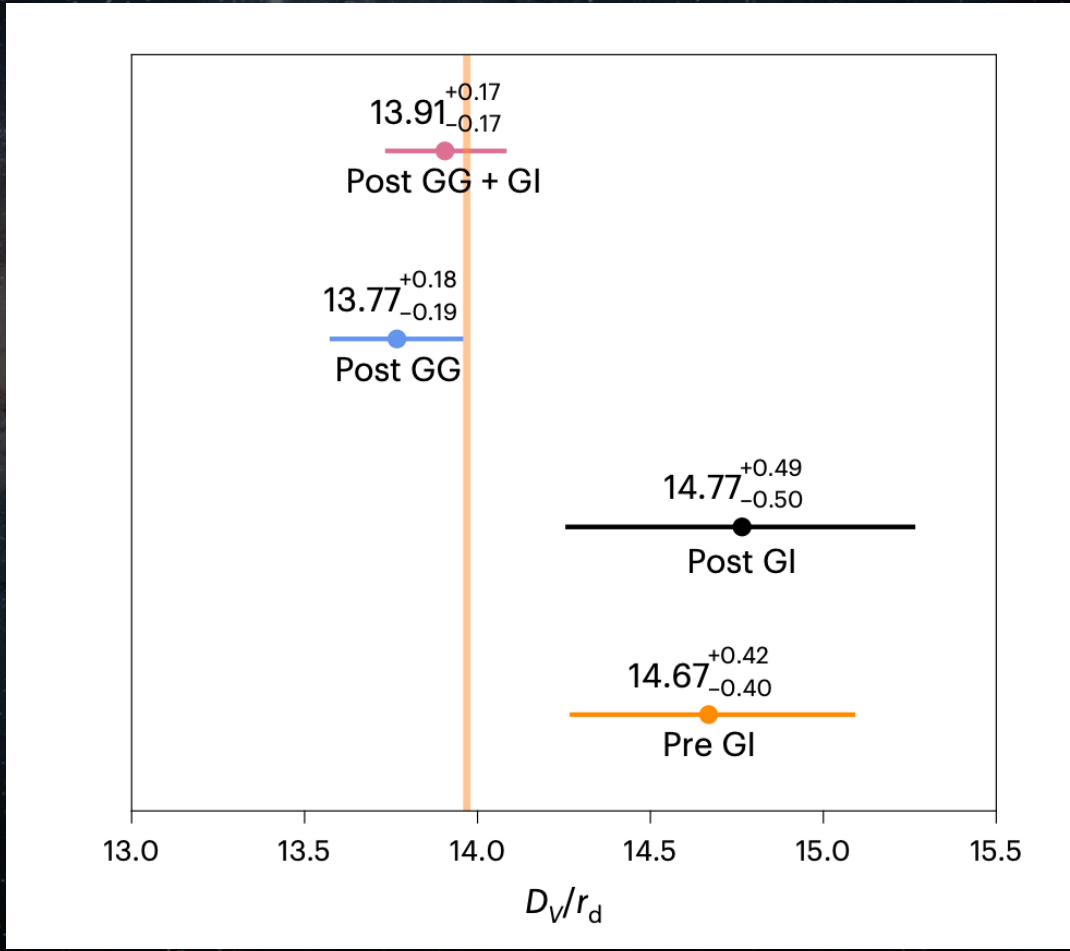
Nature Astronomy, 2022

A first detection of BAO from galaxy-ellipticity correlations



d'Assignies D. et al. 2021





Xu, Jing, GBZ et al, Nature Astronomy (2023)

Summary

- eBOSS completed successfully with ~1M spectra covering $0.6<z<3$;
- A multi-tracer analysis was performed for LRGs and ELGs, and a RSD signal is detected at 4 σ in the cross-power spectrum;
- A standard ΛCDM model seems fine with data, but extended models (dynamical DE, modified gravity, neutrinos, etc) are worth exploring in more depth.