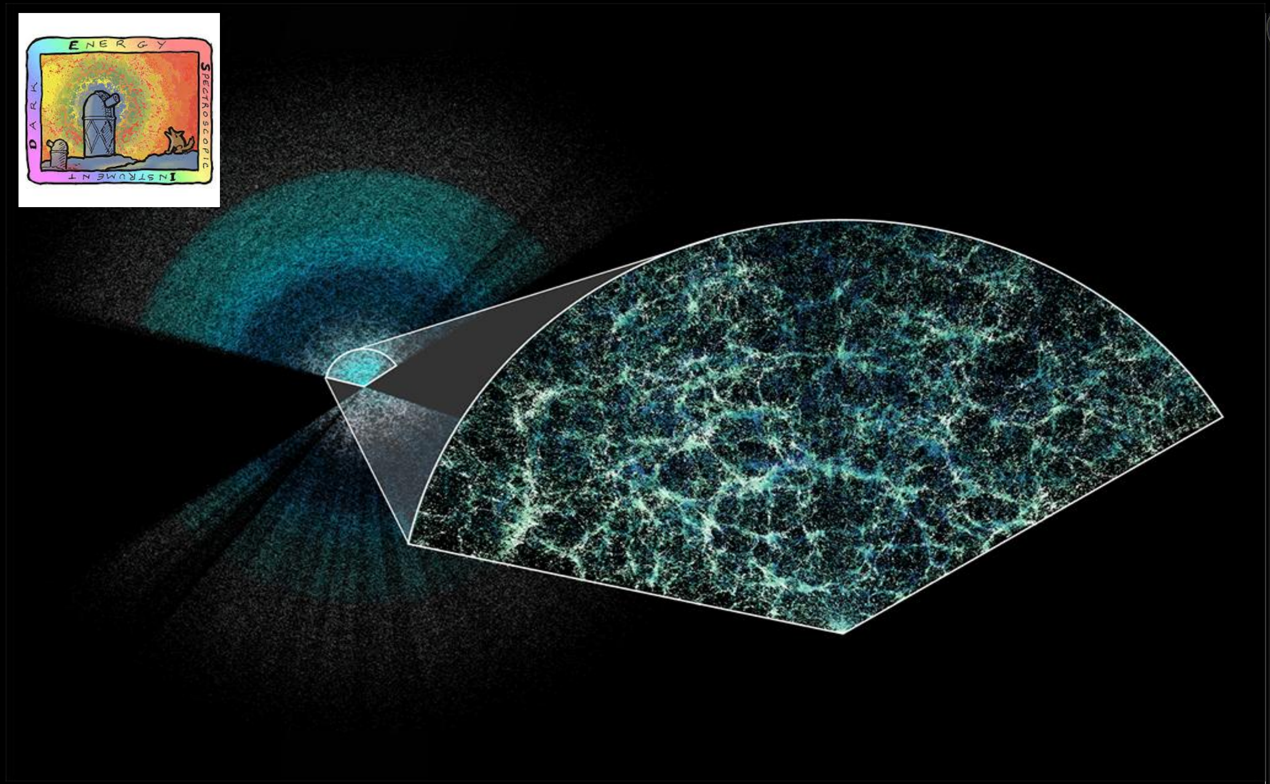
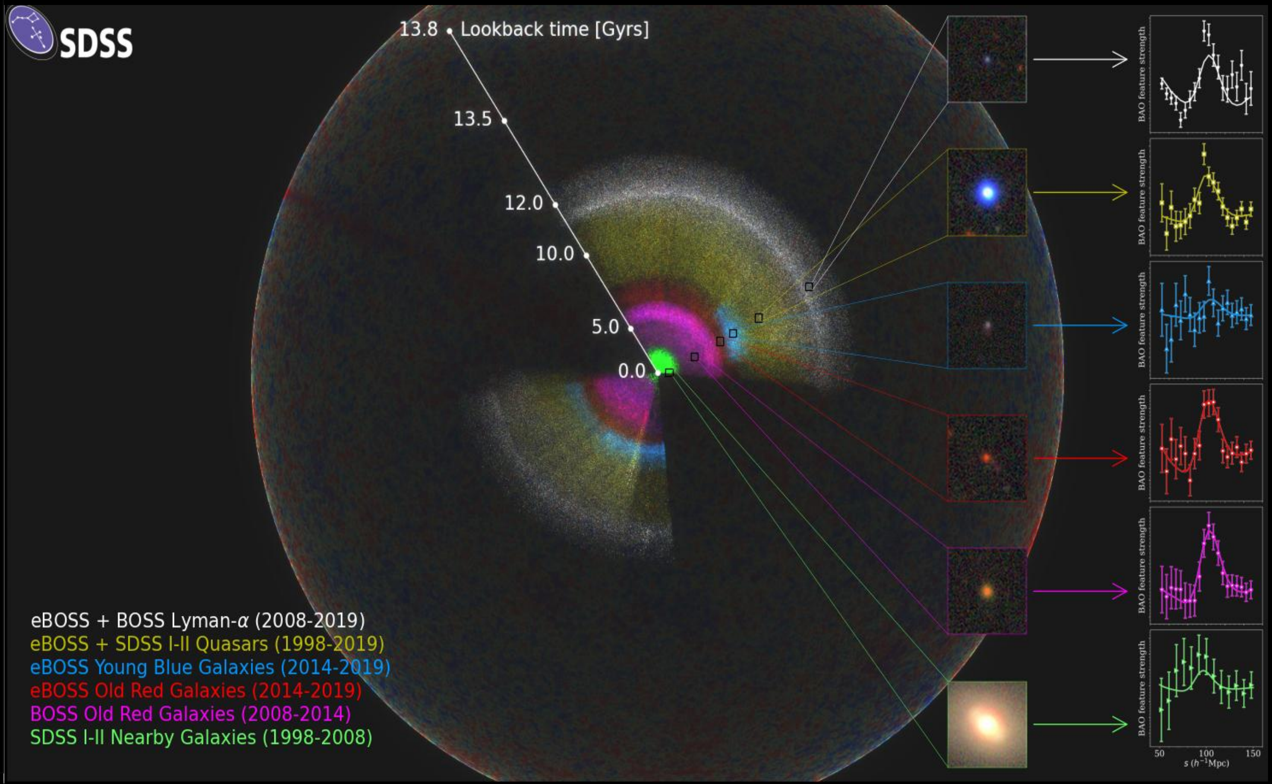




Cosmological implications of massive galaxy surveys

Gong-Bo Zhao

National Astronomical Observatories, CAS

July 18, 2025

Multiple cosmological probes

CMB

Multiple cosmological probes

CMB

Multiple cosmological probes

CMB

SNe

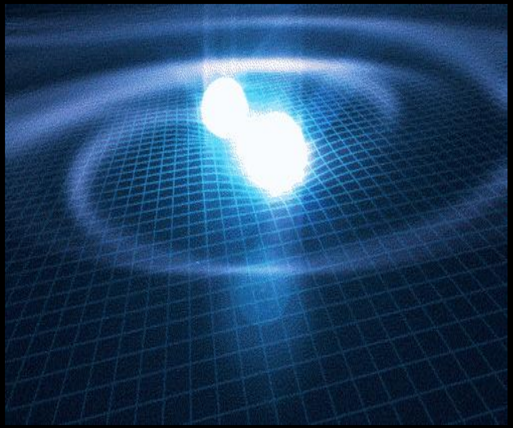
Multiple cosmological probes

CMB

SNe

Multiple cosmological probes

CMB



Gravitational waves

SNe

Multiple cosmological probes

CMB

Gravitational waves

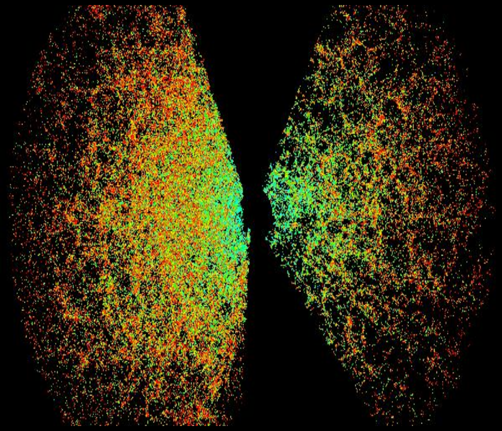
SNe

Multiple cosmological probes

CMB

Gravitational waves

SNe



LSS

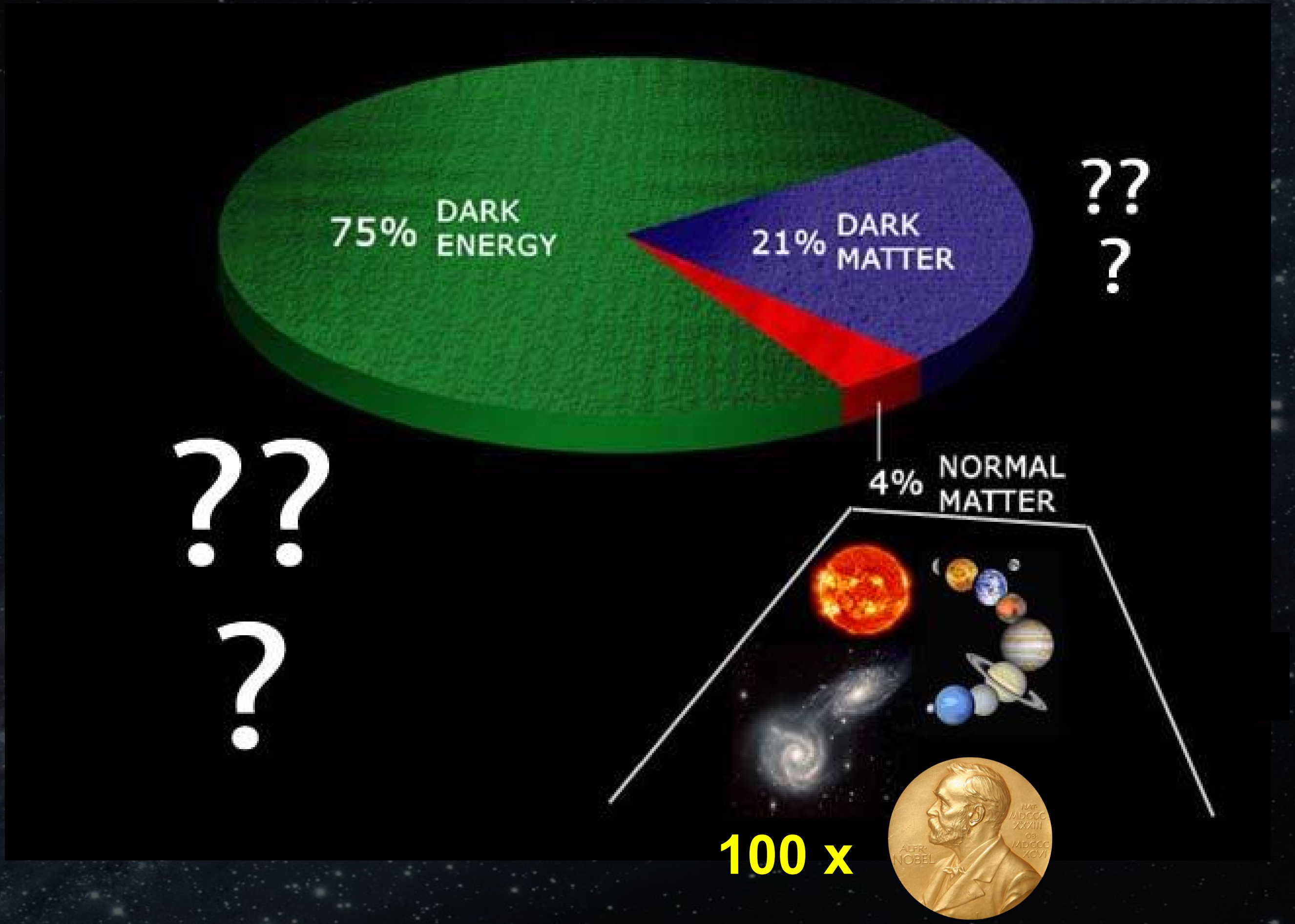
Multiple cosmological probes

CMB

Gravitational waves

SNe

LSS


75% DARK ENERGY
21% DARK MATTER
4% NORMAL MATTER
??
?
??
?
100 x

CMB (1978)

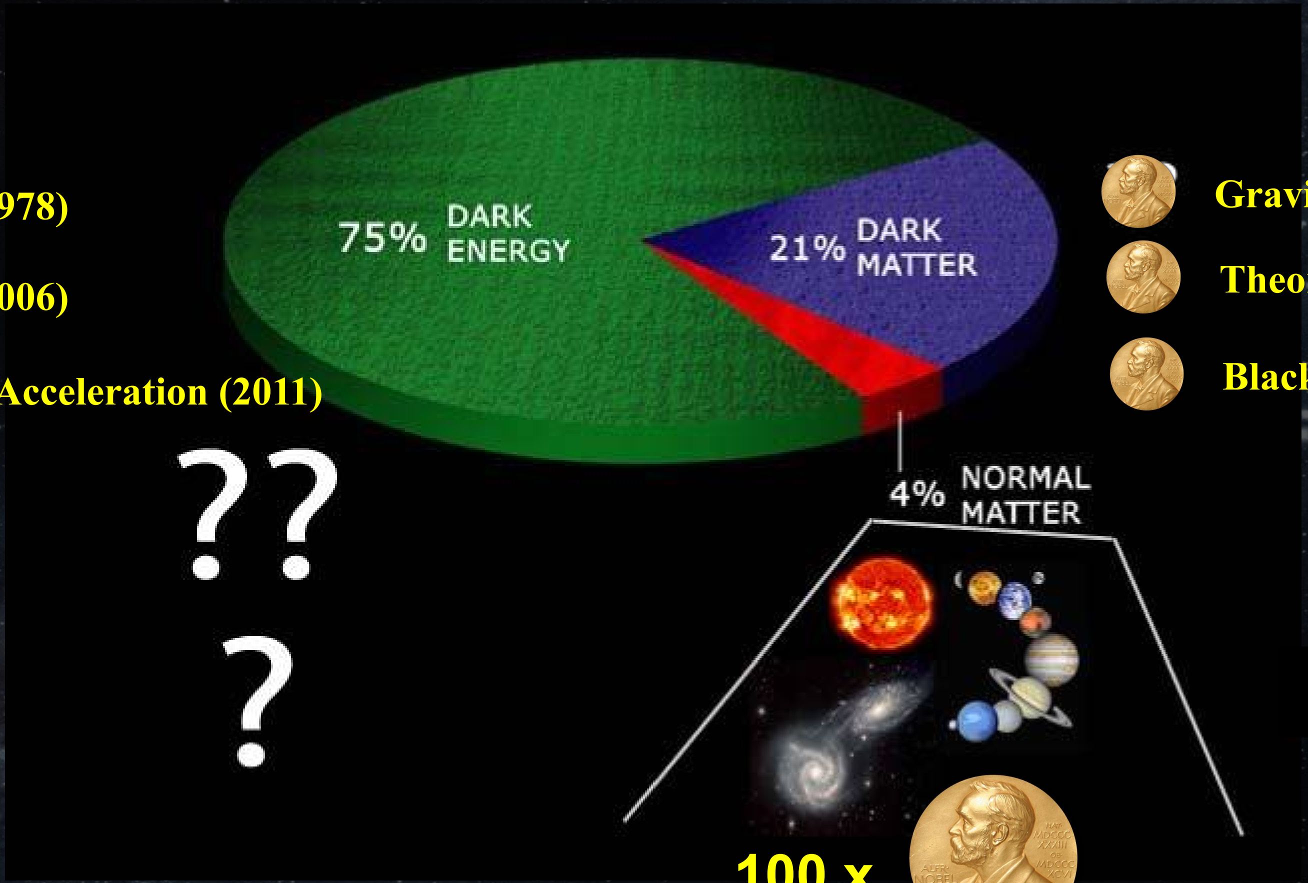
CMB (2006)

Cosmic Acceleration (2011)

Gravitational waves (2017)

Theoretical cosmology (2019)

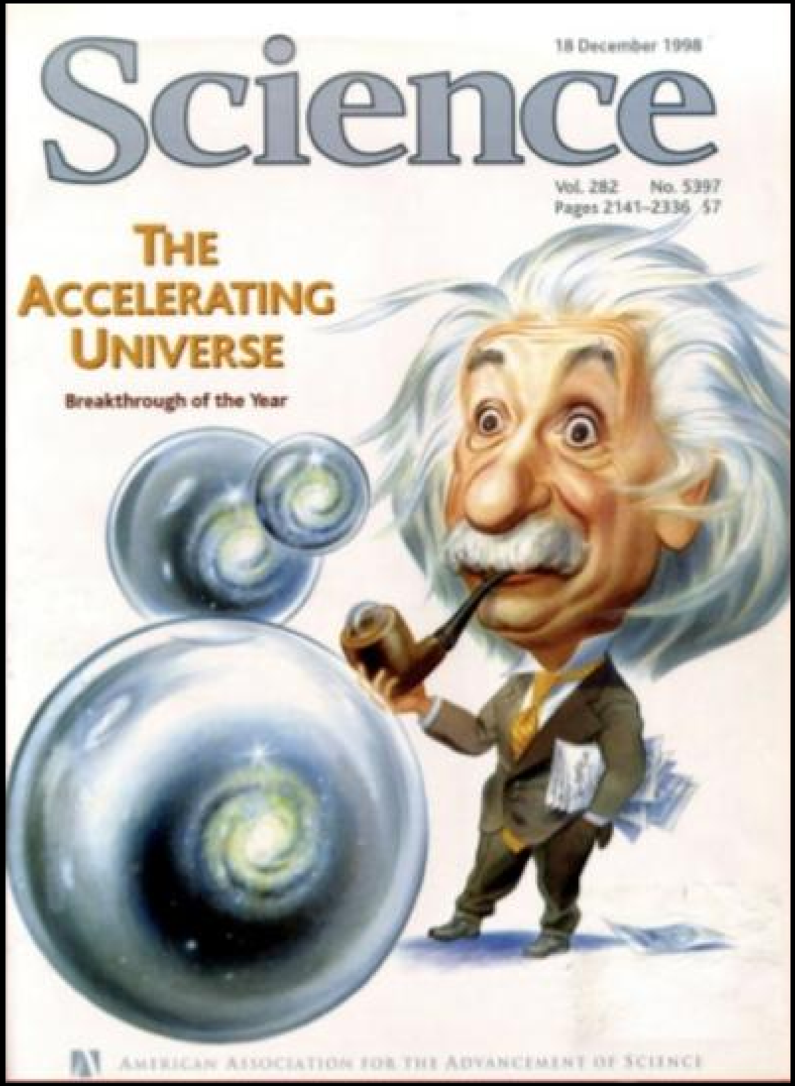
Black holes (2020)



100 x

The accelerating Universe!

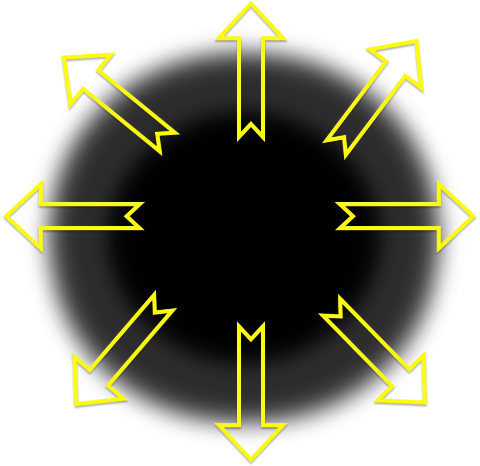
2011



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

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

Modified Gravity

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

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

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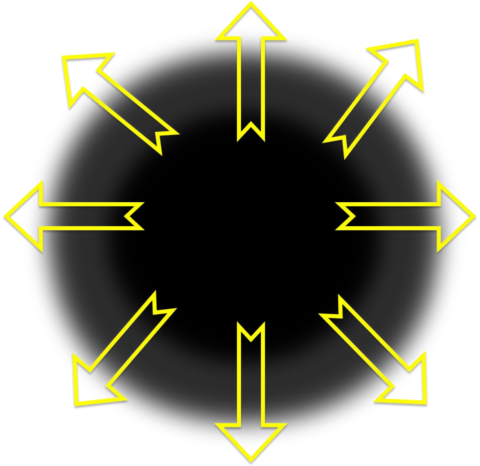


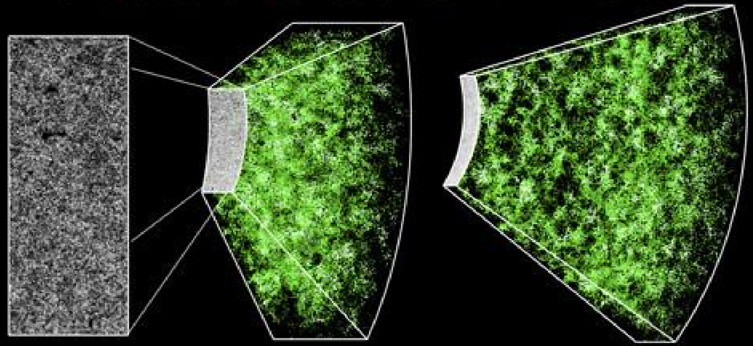
Dark Energy

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

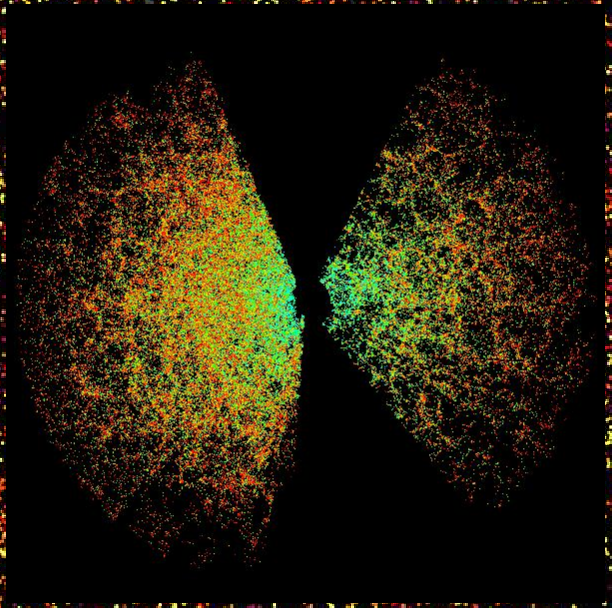
Modified Gravity

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

Galaxy surveys can break the dark degeneracy!



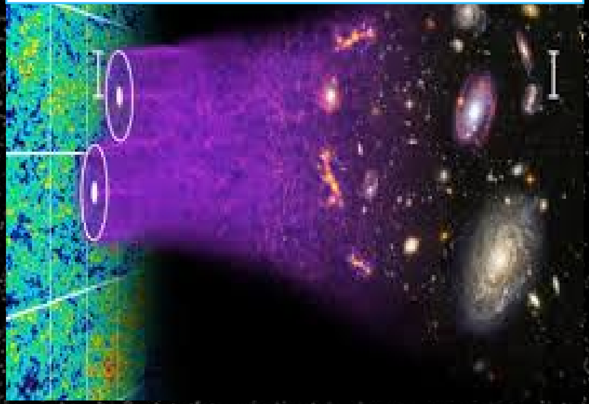
Massive redshift surveys as a key cosmological probe

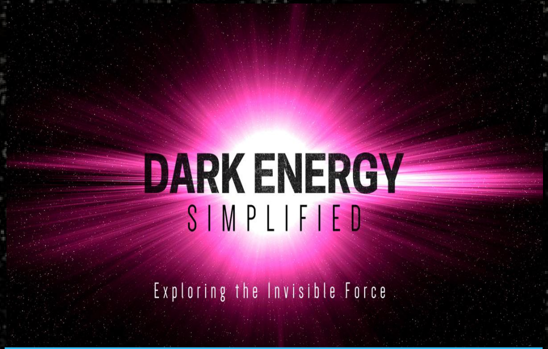


BOSS
SDSS III

Large z-surveys : a key probe of the Universe

BAO

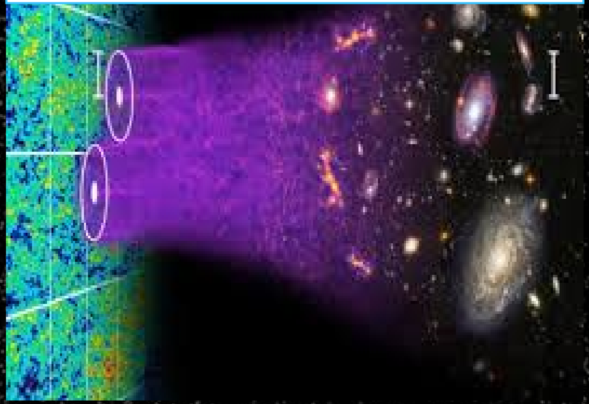




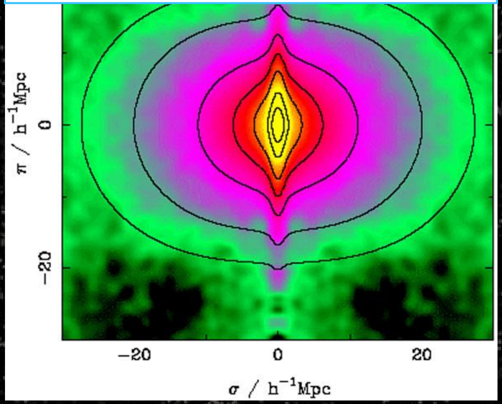
Dark Energy

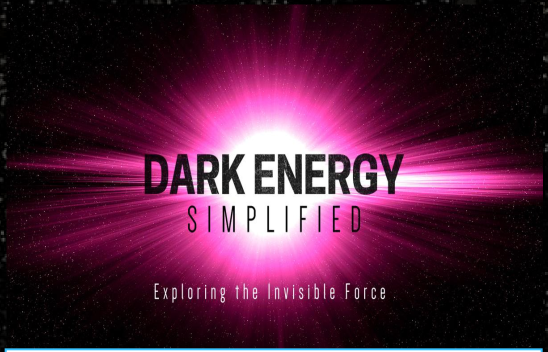
Large z-surveys : a key probe of the Universe

BAO



RSD



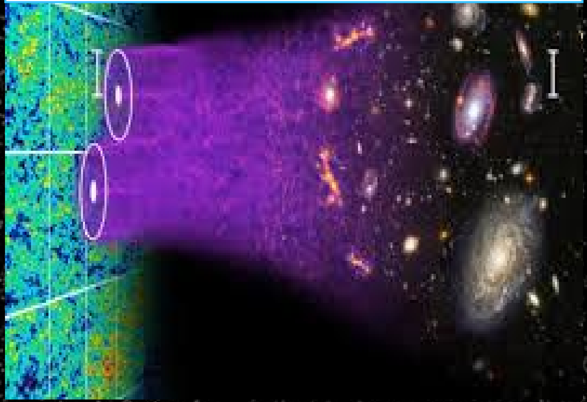


Dark Energy

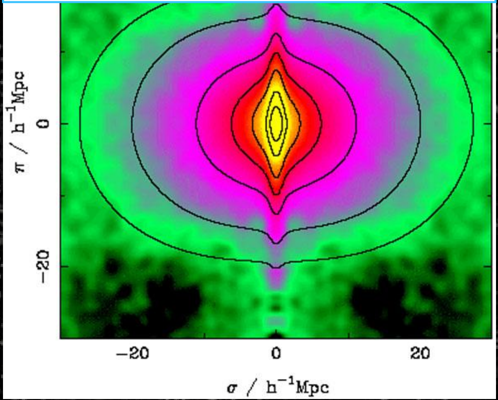
Modified Gravity

Large z-surveys : a key probe of the Universe

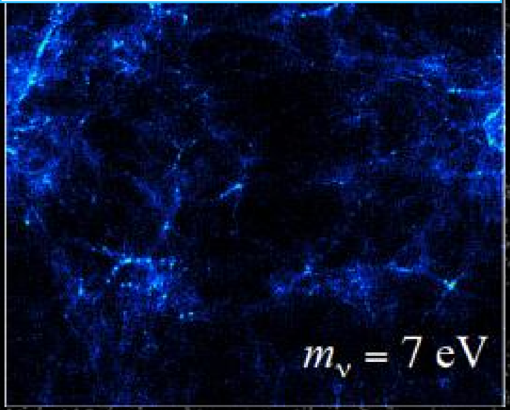
BAO

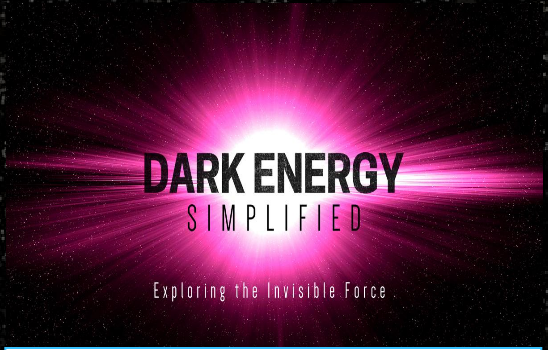


RSD



Free-streaming





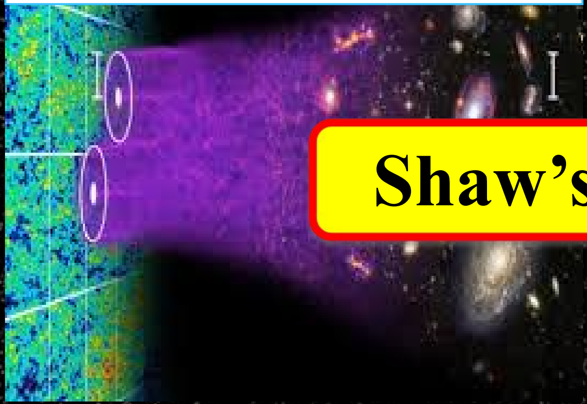
Dark Energy

Modified Gravity

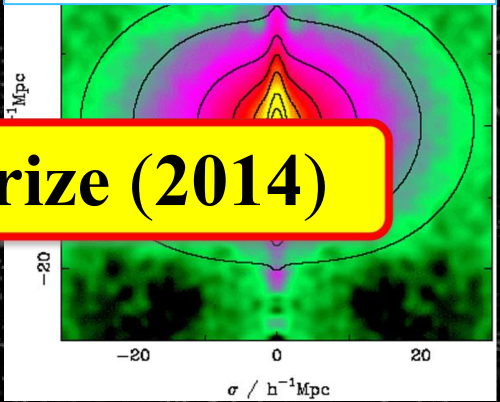
Neutrino masses

Large z-surveys : a key probe of the Universe

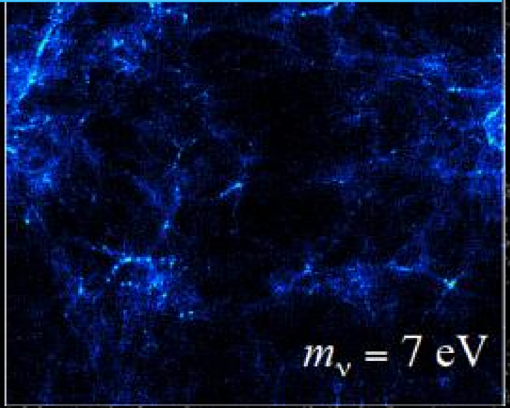
BAO



RSD

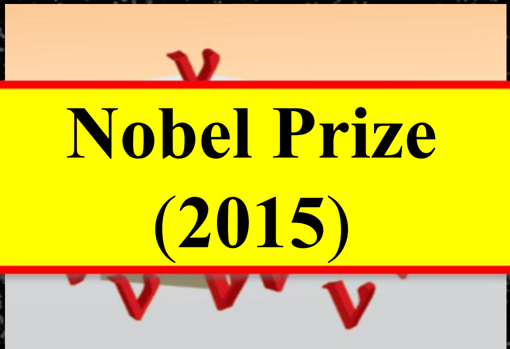


Free-streaming



Shaw's prize (2014)

Nobel Prize (2011)

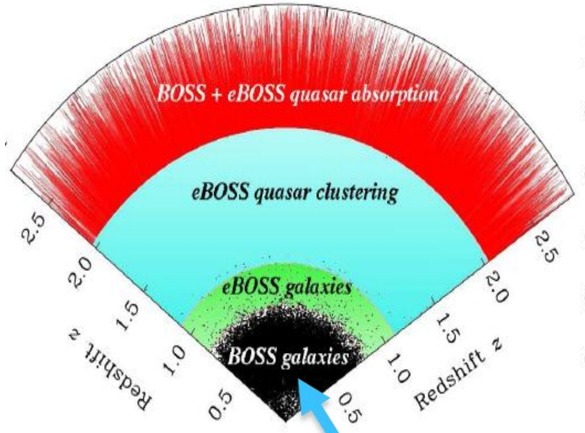


Nobel Prize (2015)

Dark Energy

Modified Gravity

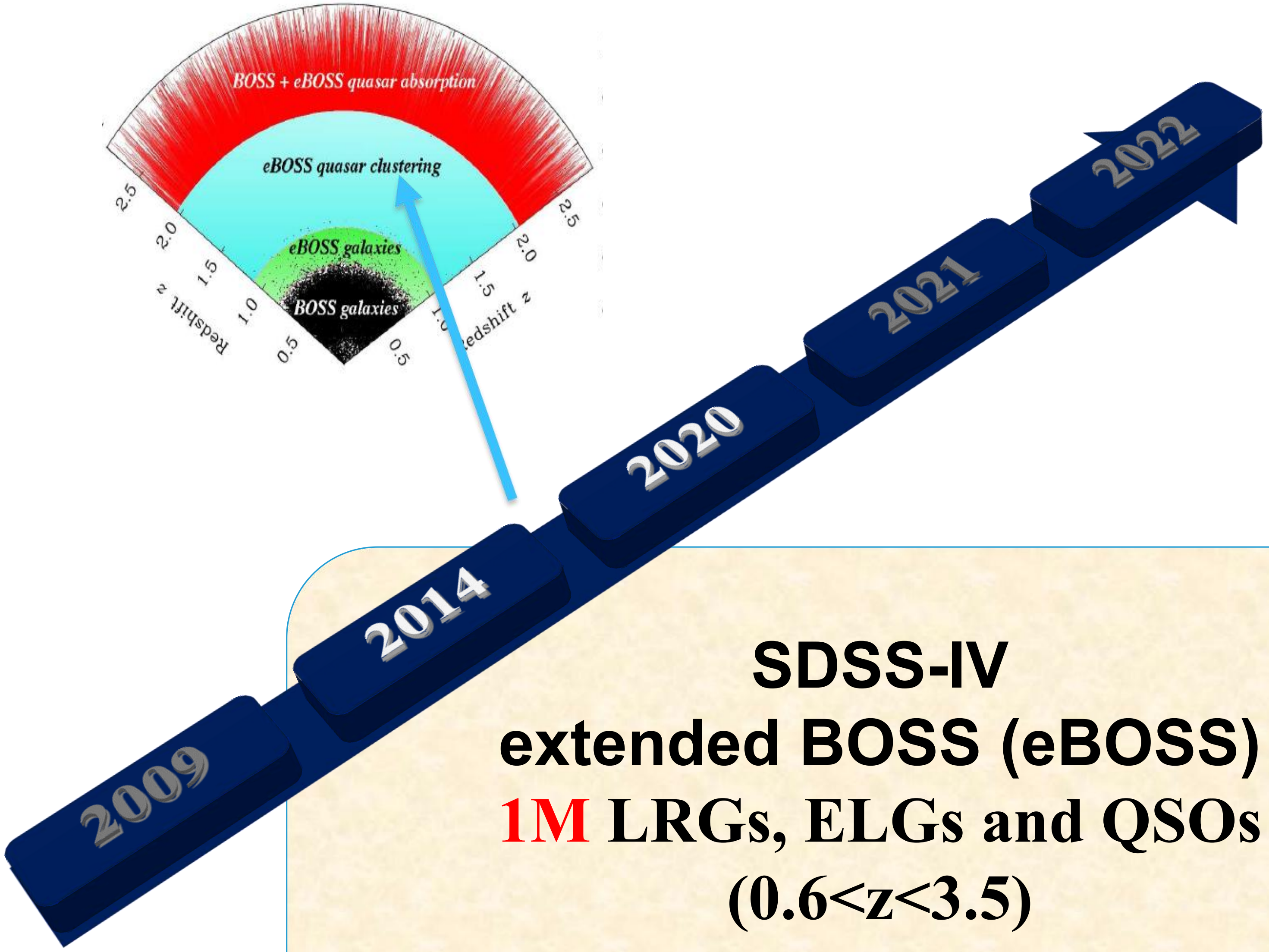
Neutrino masses



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 last decade



SDSS-IV

extended BOSS (eBOSS)

1M LRGs, ELGs and QSOs

(0.6<z<3.5)

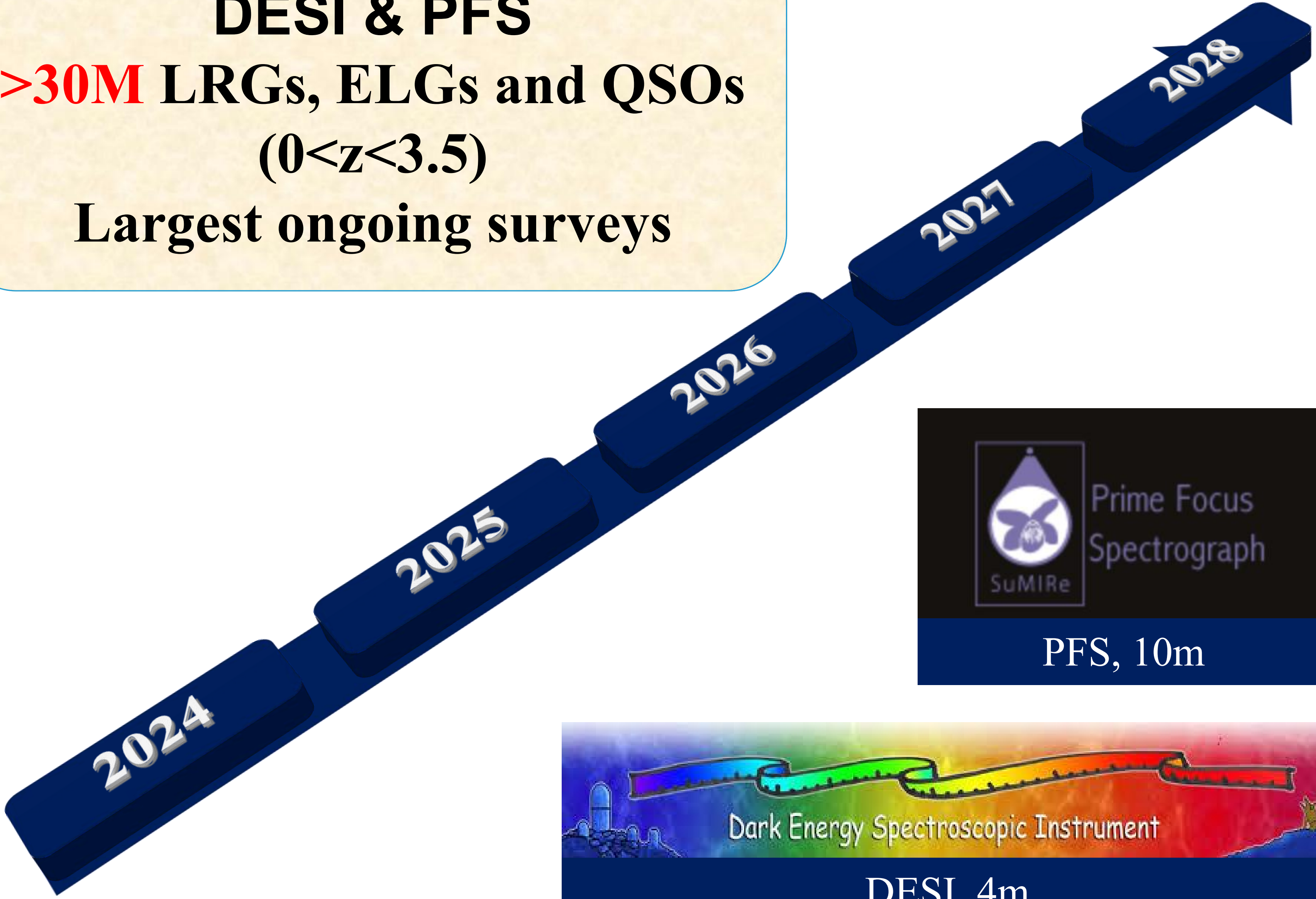
The largest in the past 5 years

DESI & PFS

>30M LRGs, ELGs and QSOs

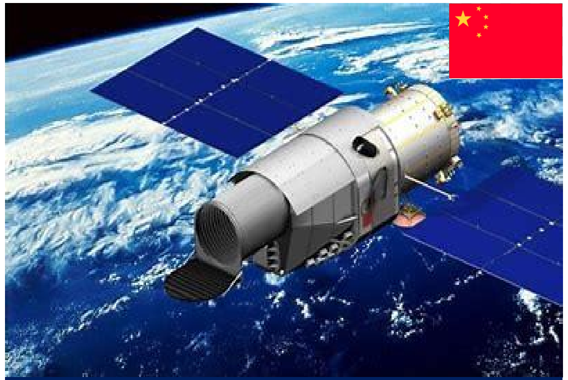
(0<z<3.5)

Largest ongoing surveys

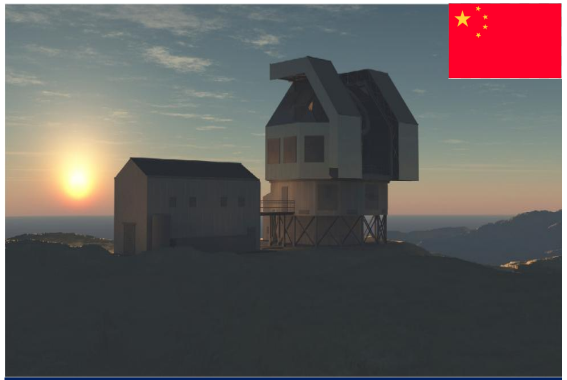


PFS, 10m

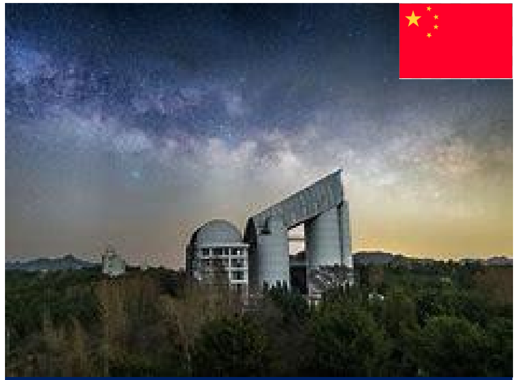
DESI, 4m



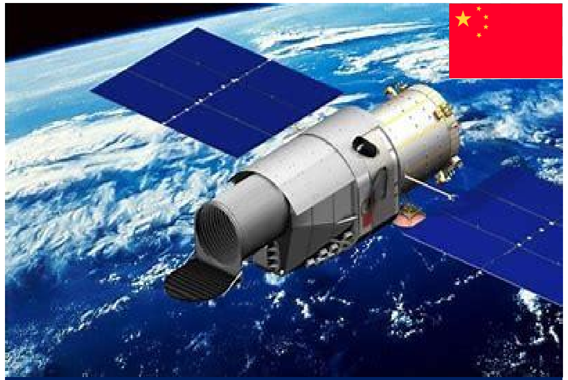
CSST, 2m in space



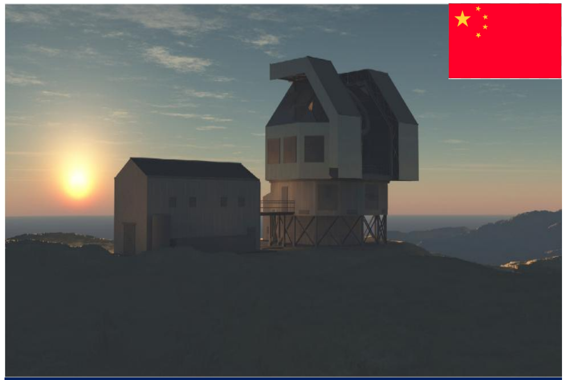
MUST, 6.5m



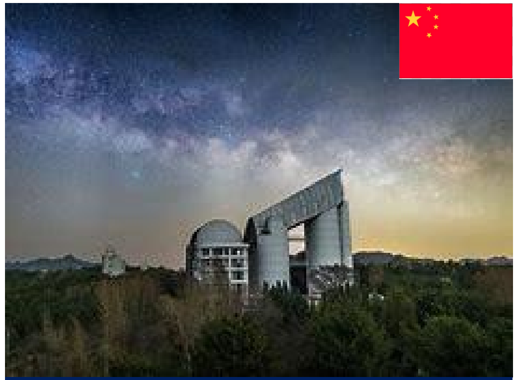
ESST, 10+m



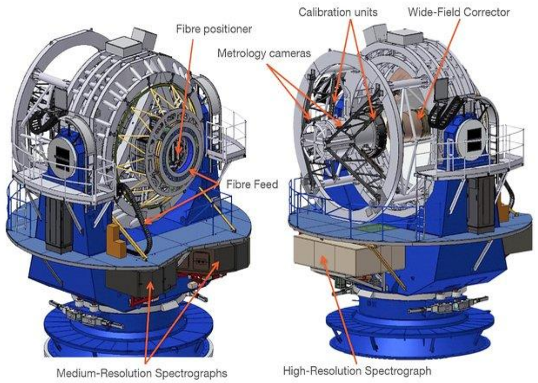
CSST, 2m in space



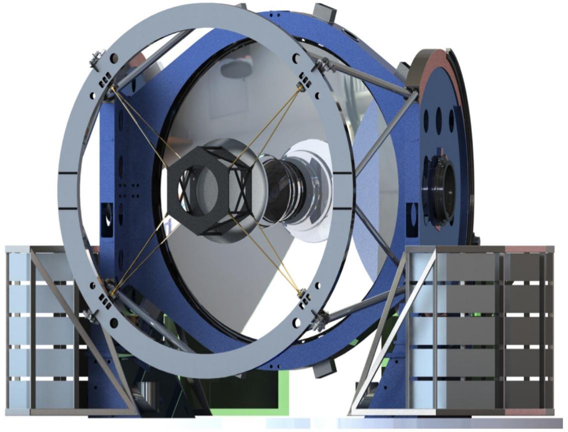
MUST, 6.5m



ESST, 10+m

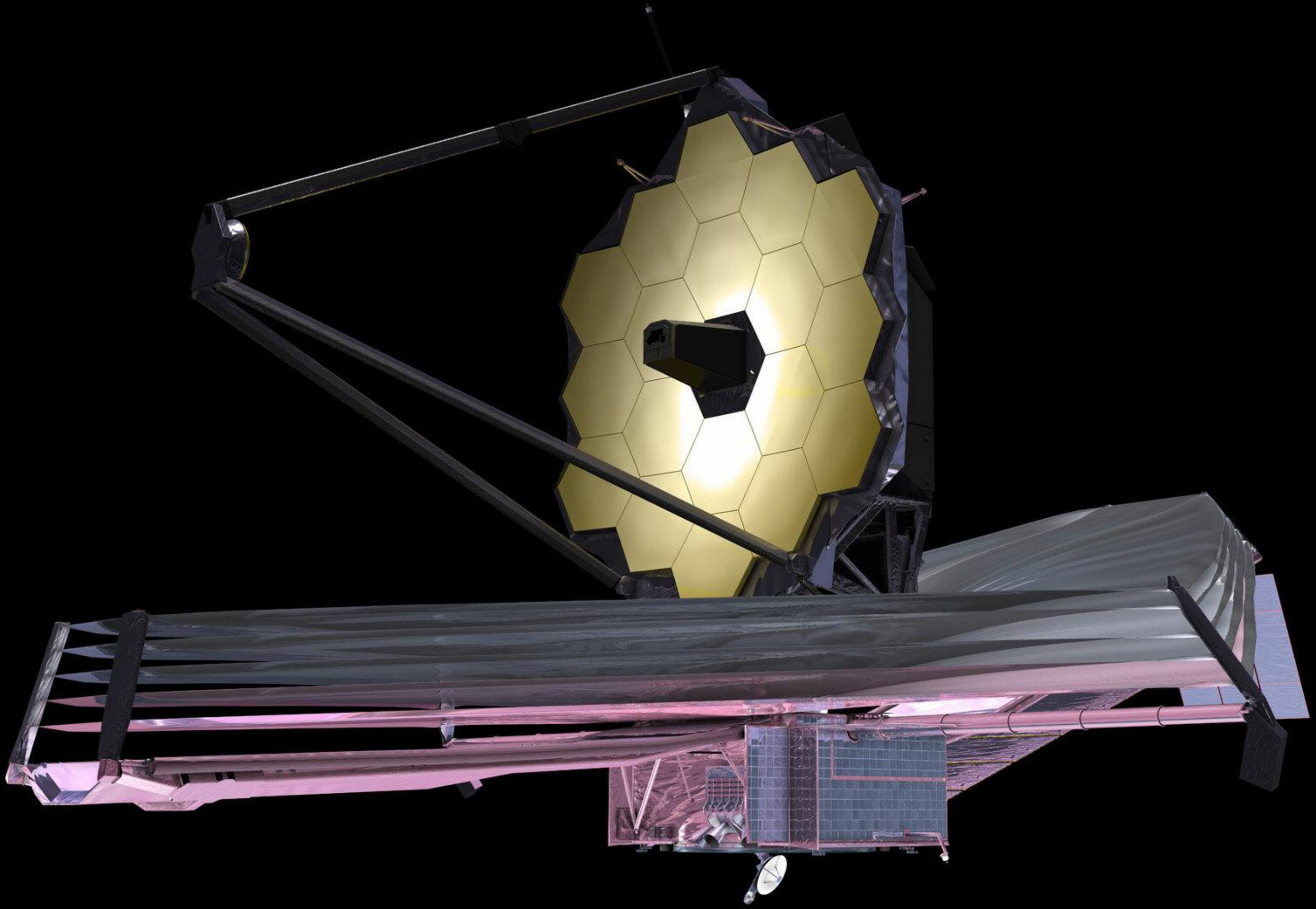


4MOST, 4m



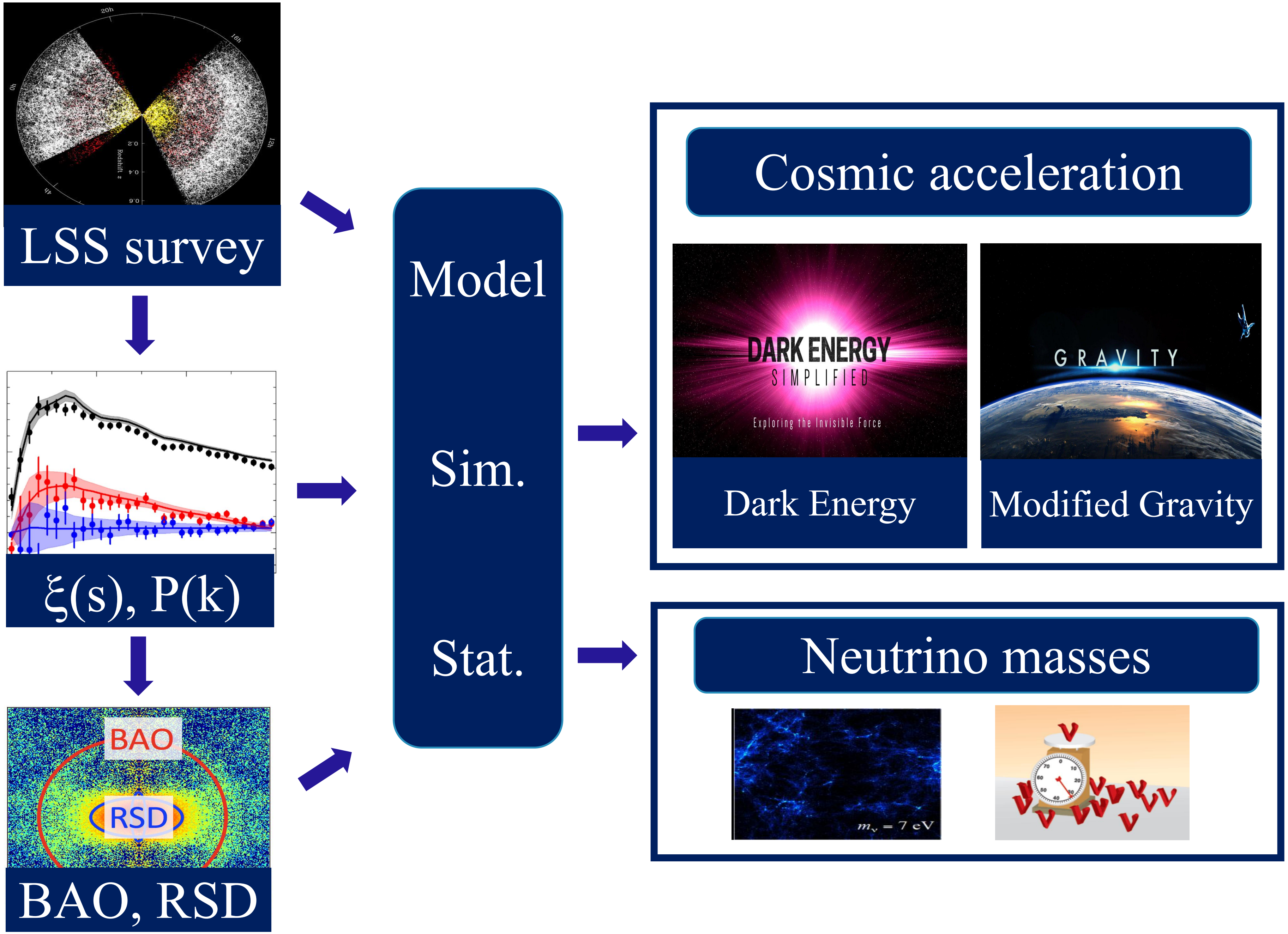
MegaMapper, 6.5m

WST, 10+m



280 m at L2!!

arXiv: 2010.06064



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

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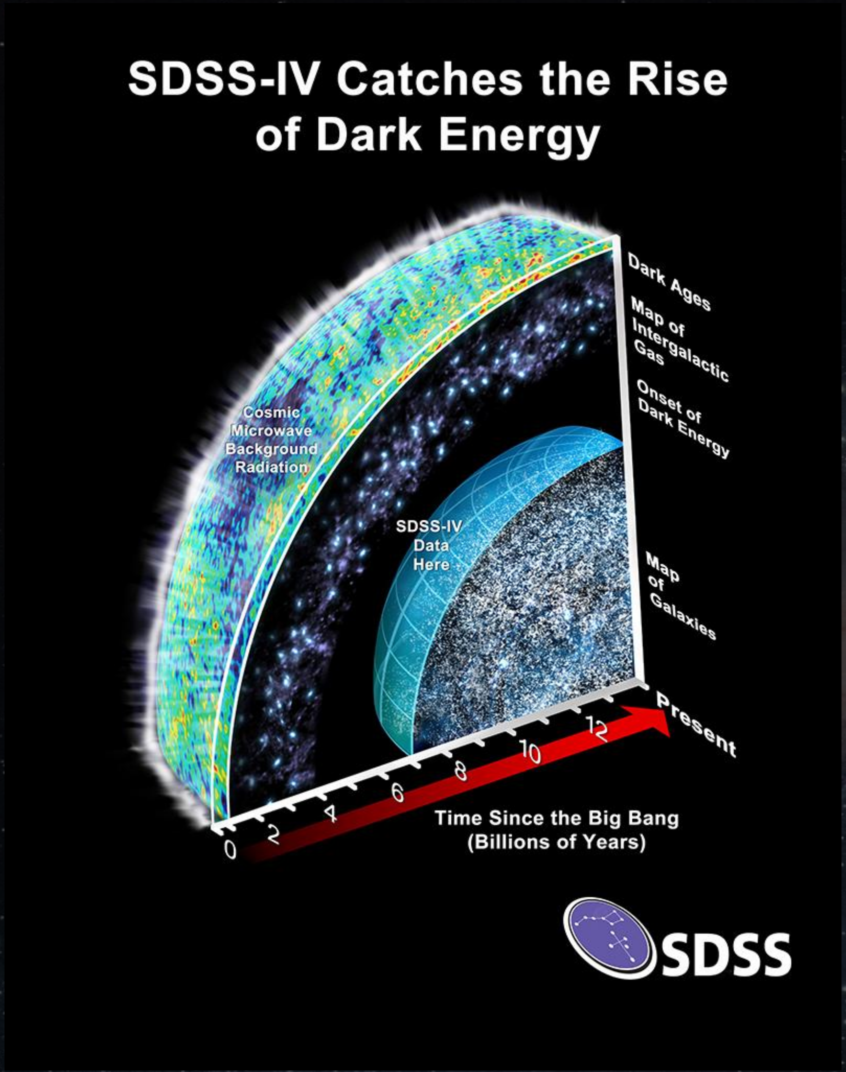

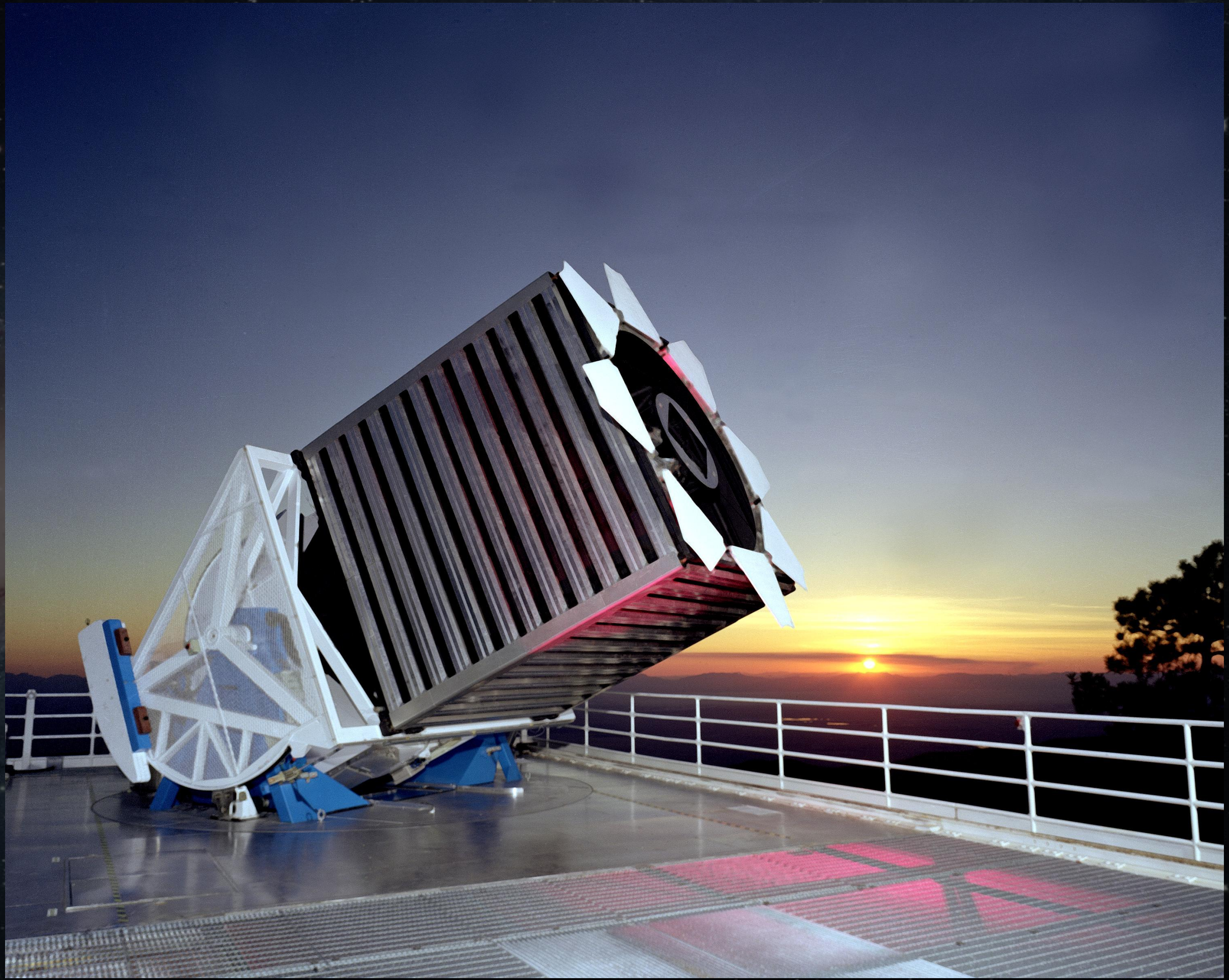

eBOSS (2014-2020)

2.5 m SDSS telescope @ New Mexico

eBOSS 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.

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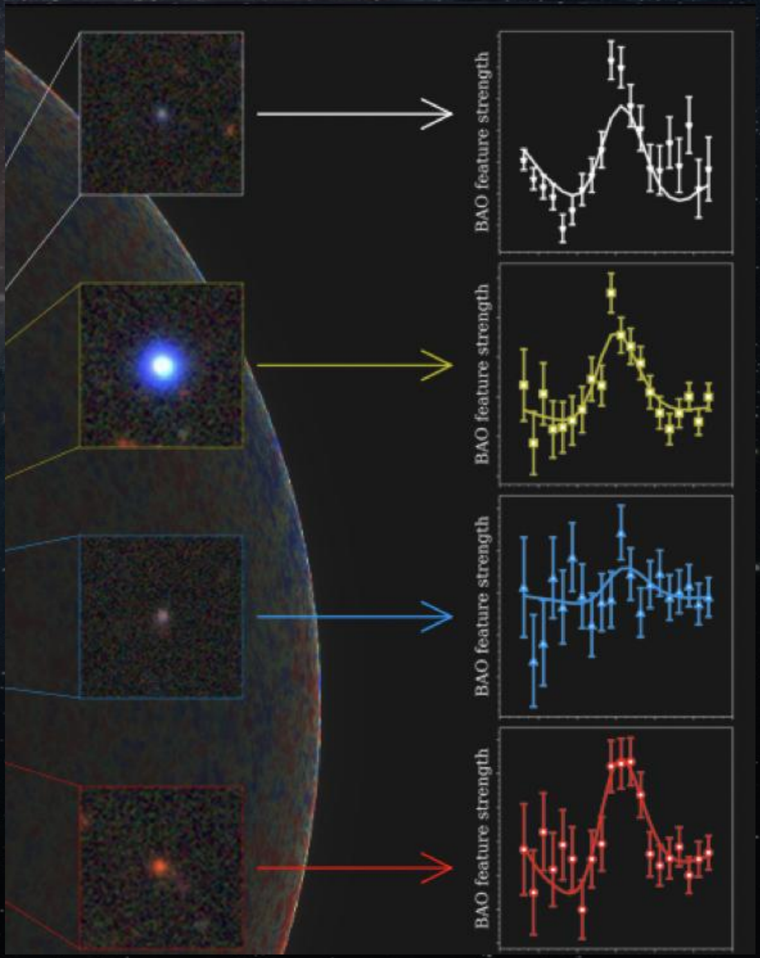
eBOSS tracers

Lyman-a forest

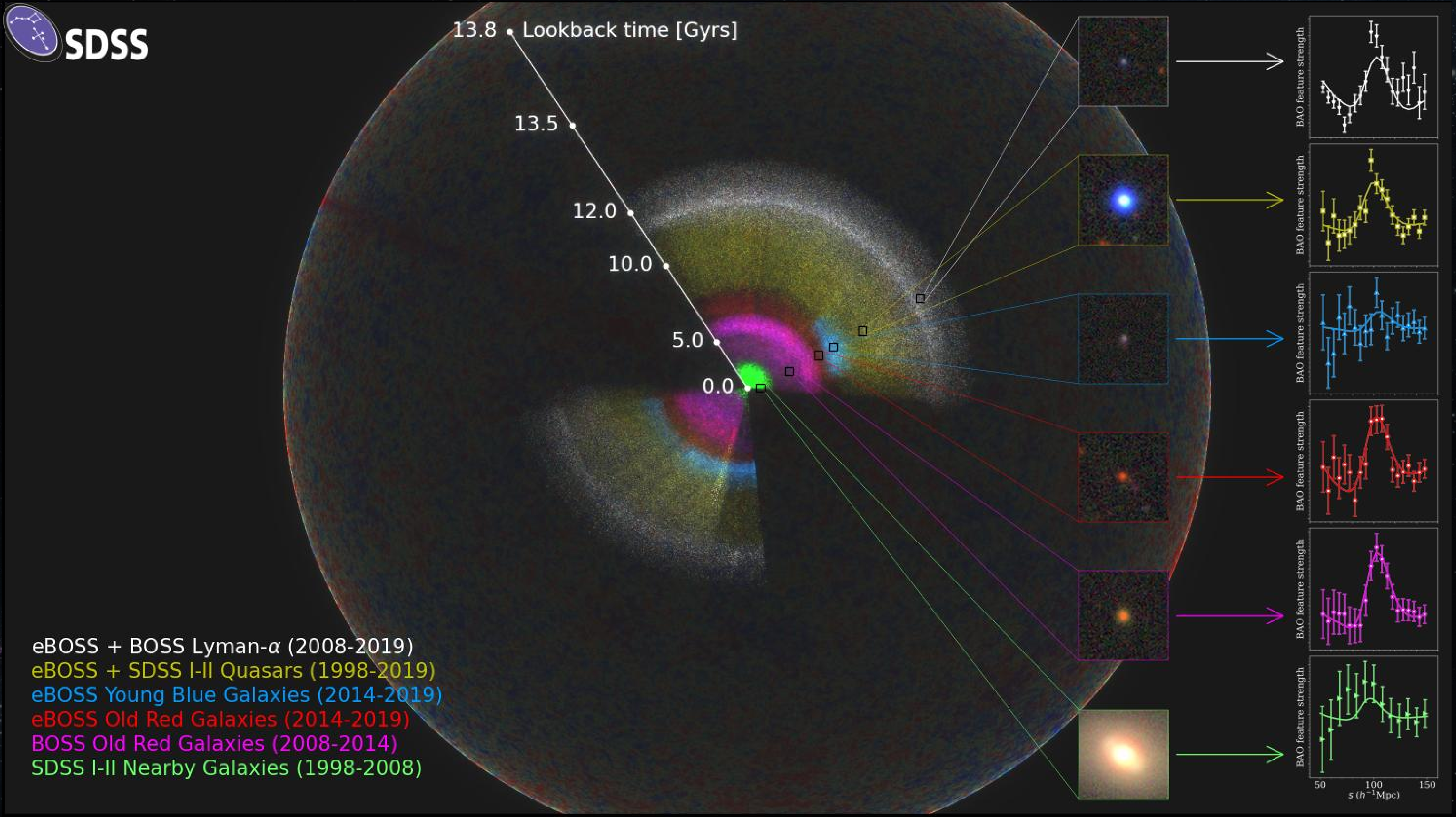
Clustering quasars

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
BAO feature strength
50
100
150
s (h^{-1}Mpc)
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)

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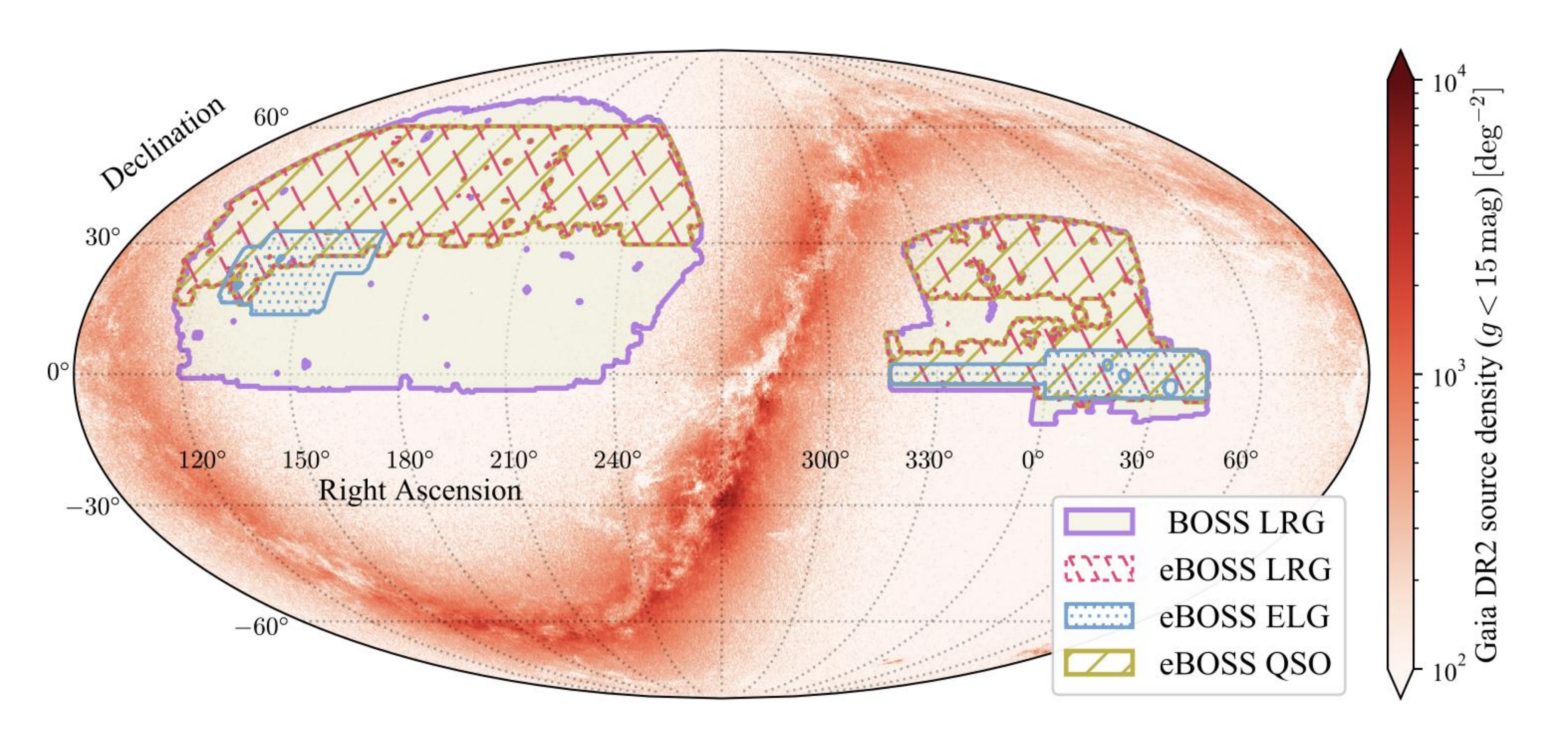
eBOSS footprint



C. Zhao+, 2020

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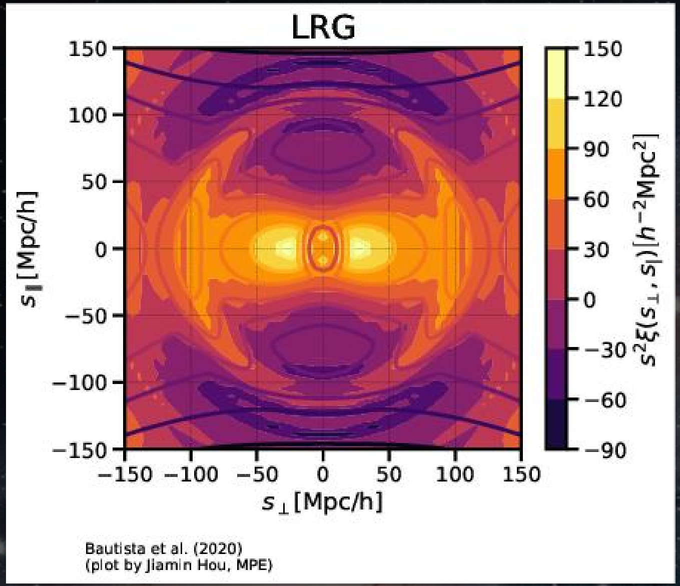
Luminous Red Galaxies (LRGs)

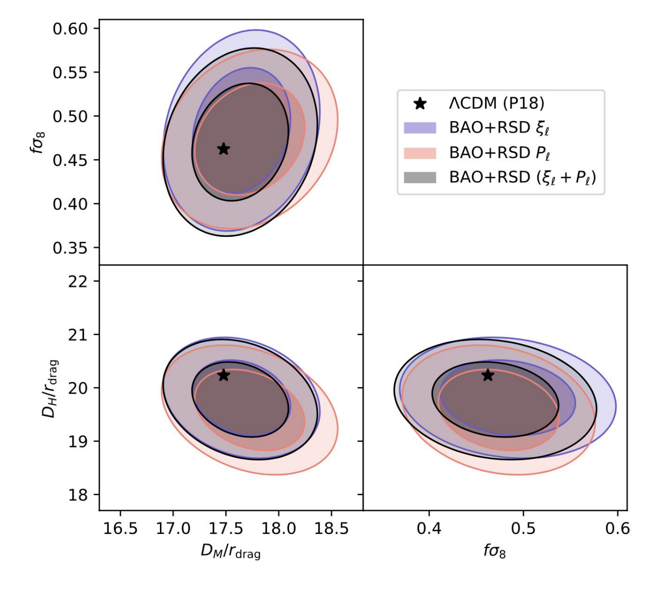
$0.6 < z < 1.0$, $z_{eff} = 0.77$

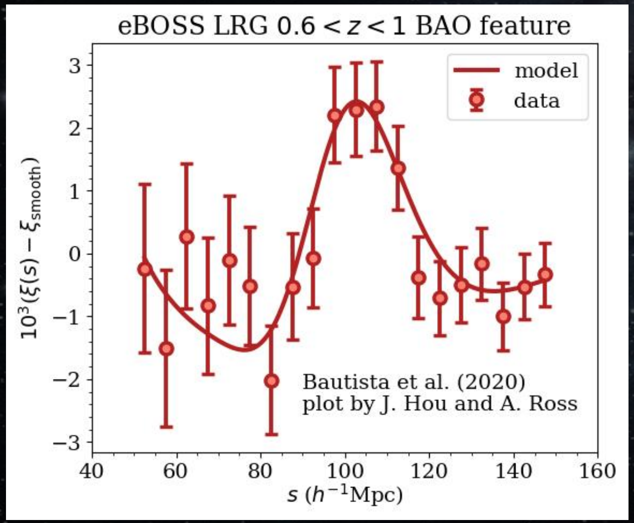
~9500 deg^2

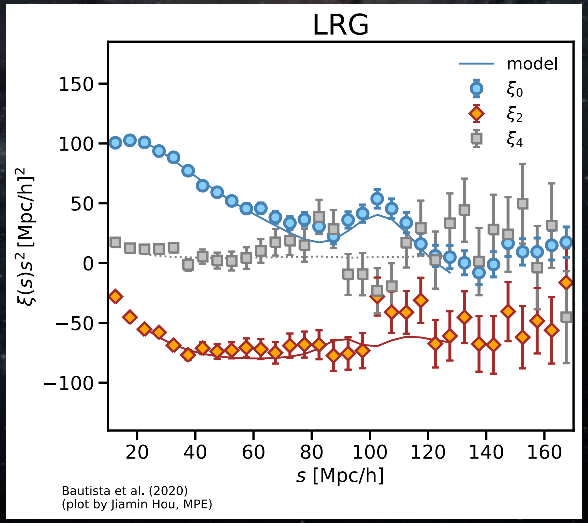
~400 K spectra

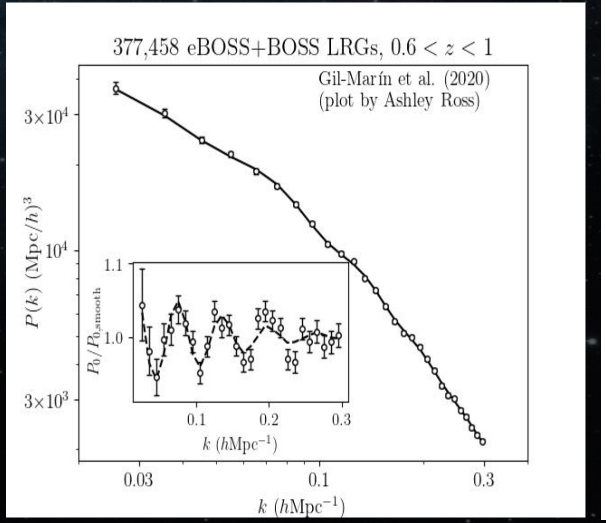
Bautista+, 2020; Gil-Marin+, 2020

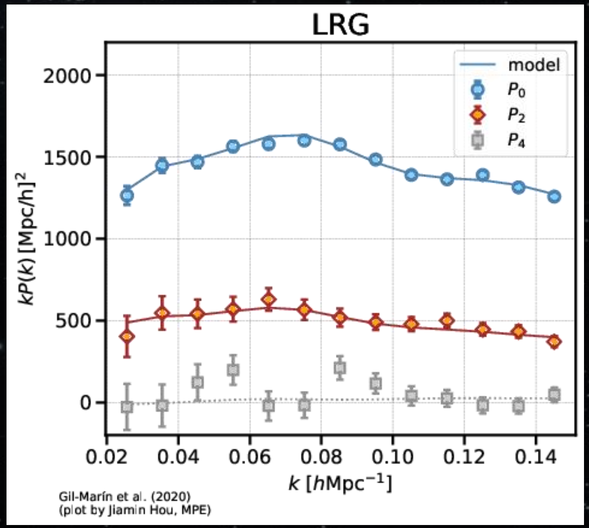












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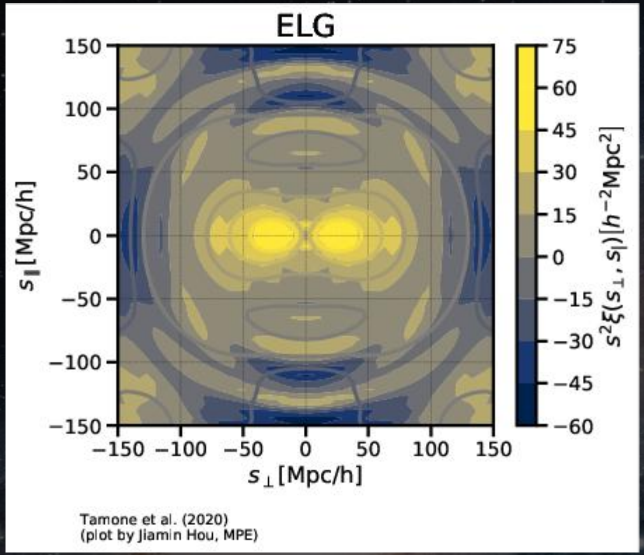
Emission line Galaxies (ELGs)

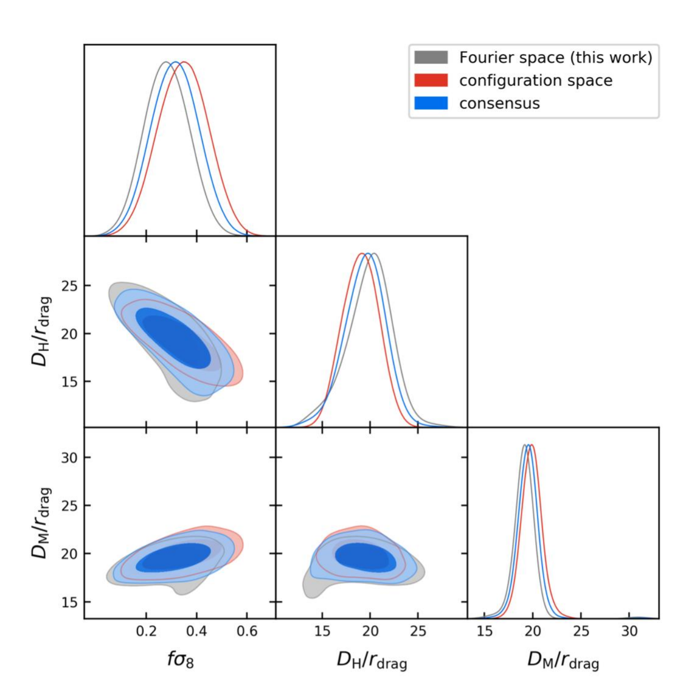
$0.6 < z < 1.1$, $z_{eff} = 0.845$

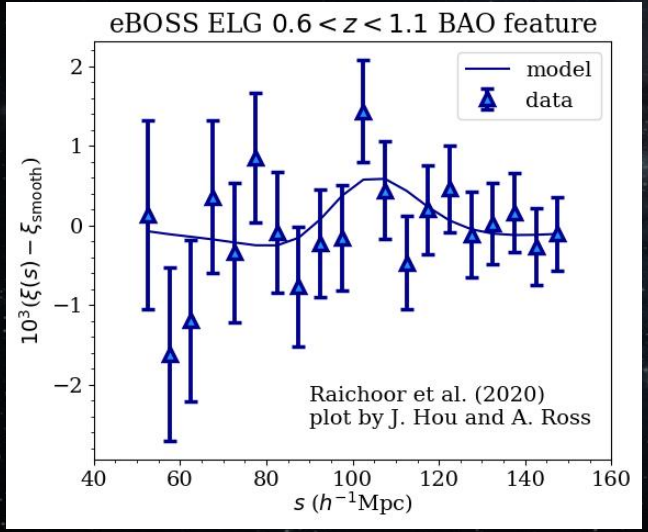
~730 deg²

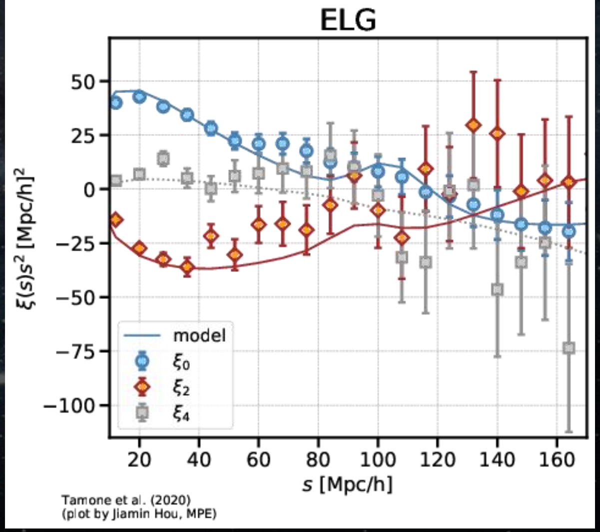
~170 K spectra

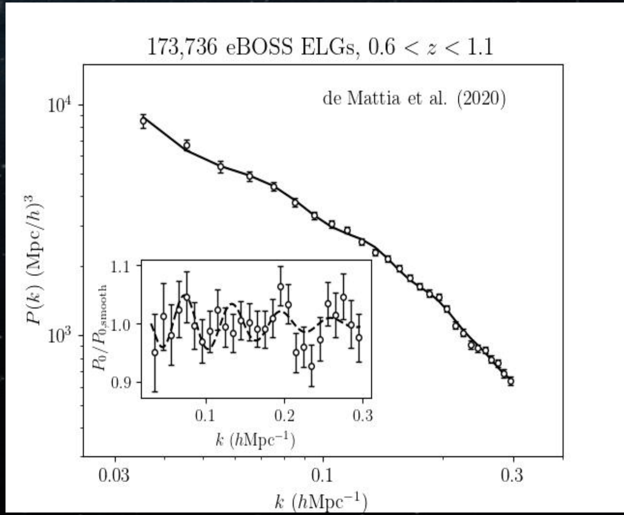
de Mattia+, 2020; Tamone+, 2020

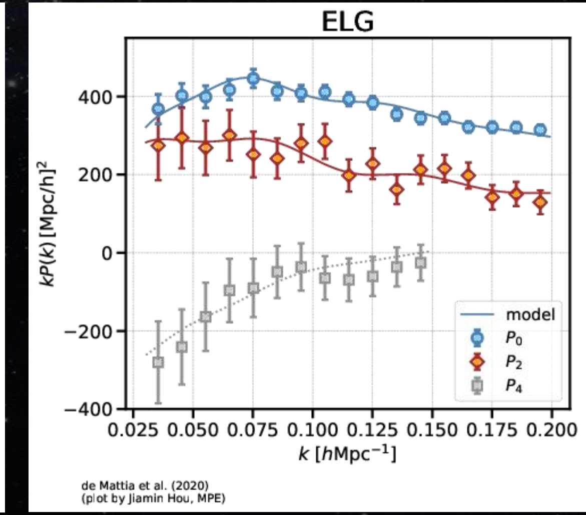












NAOC 中国科学院国家天文台
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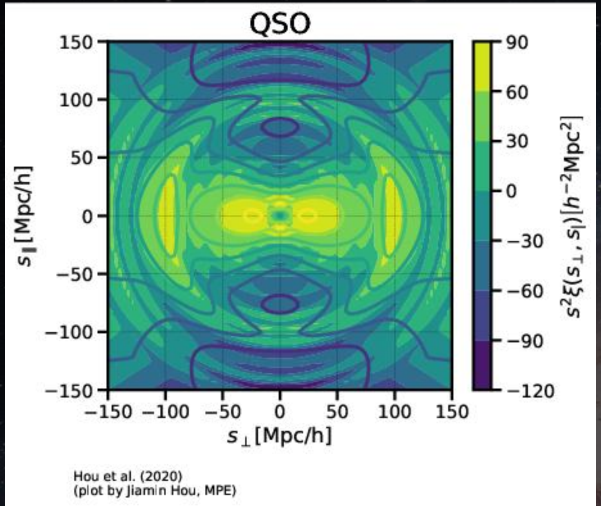
Clustering quasars (QSOs)

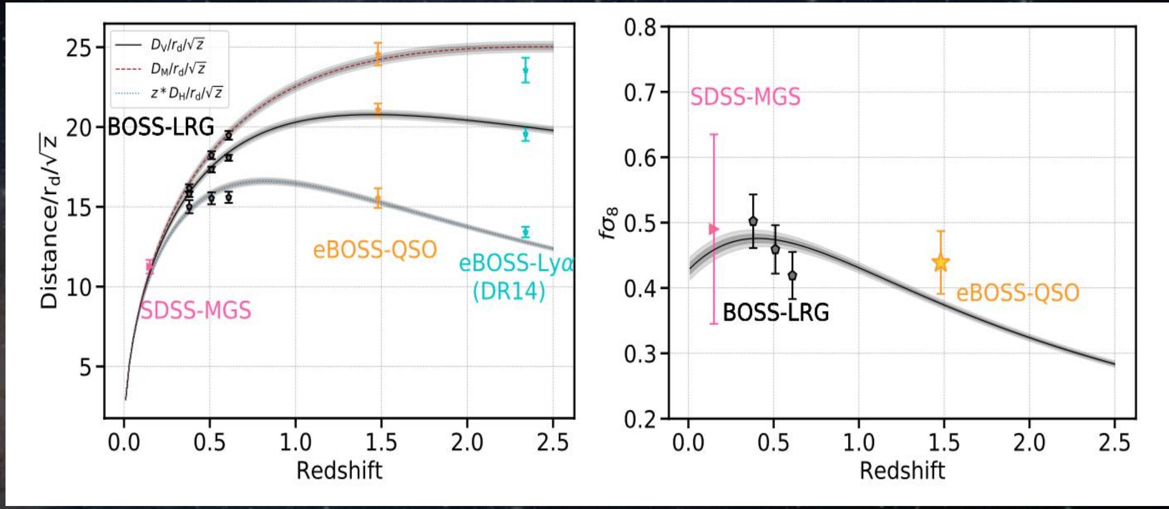
$0.8 < z < 2.2$, $z_{eff} = 1.48$

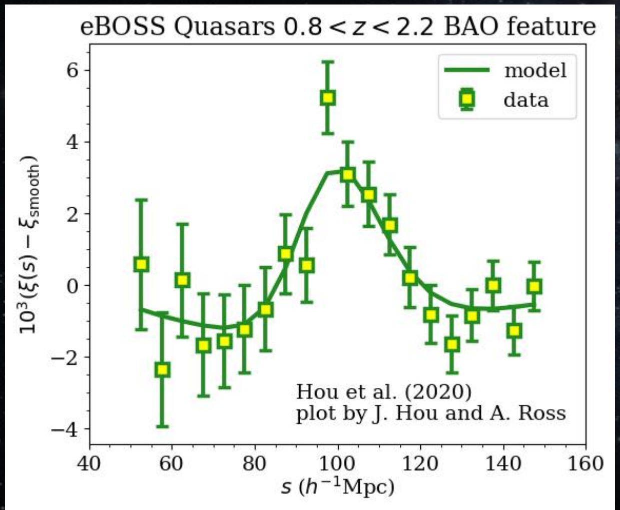
~4700 deg²

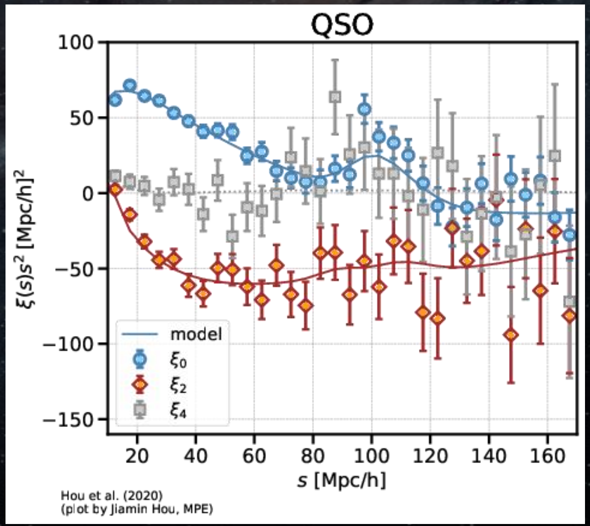
~340 K spectra

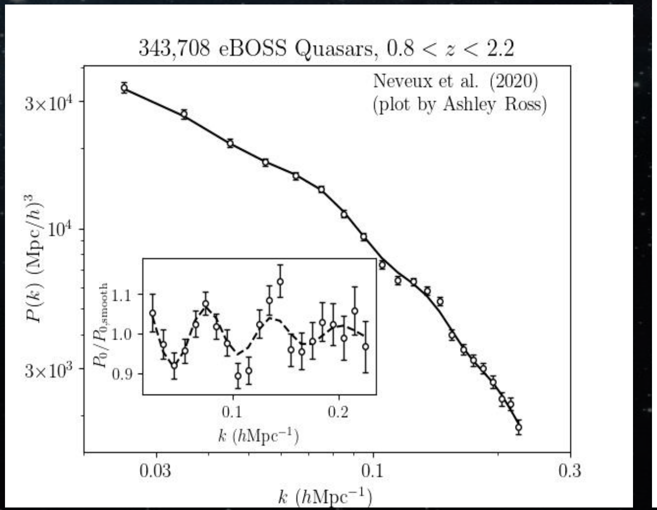
Hou+, 2020; Neveux+, 2020

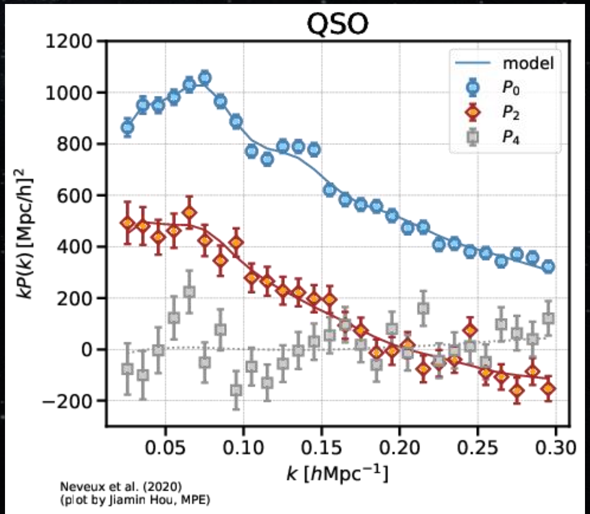












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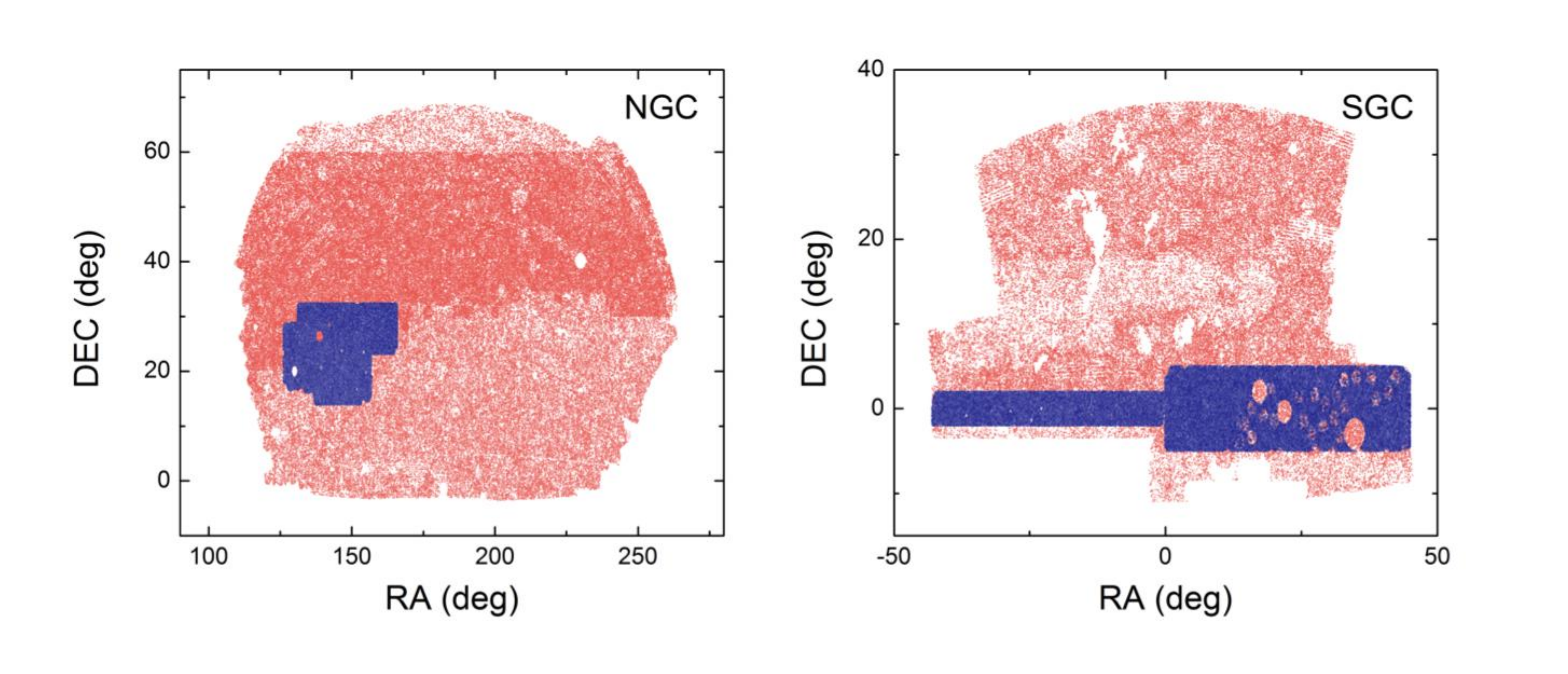
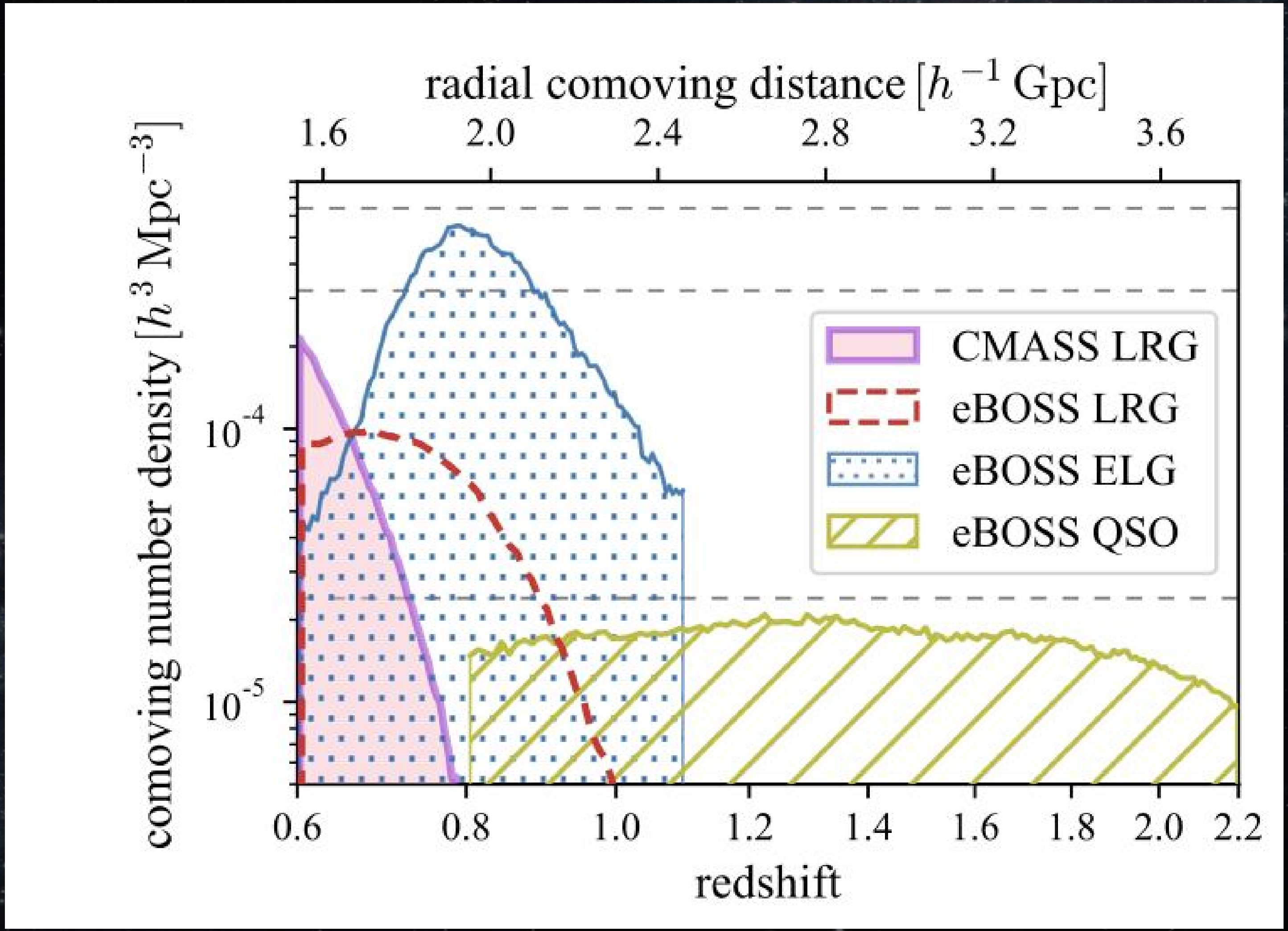
Angular overlap



GBZ+, 2020

Radial overlap



Why cross-correlation is cool?

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

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

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

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

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

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

McDonald & Seljak 2008; Seljak 2009

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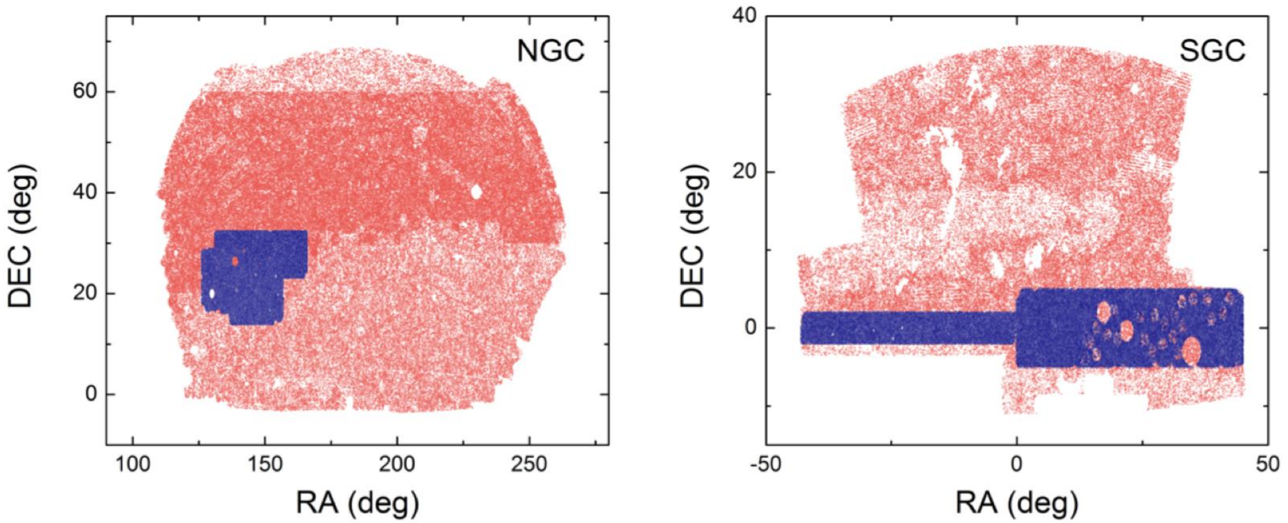
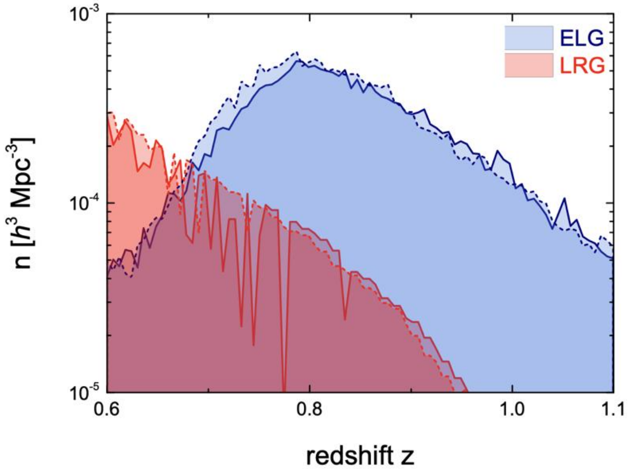
$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{\alpha\beta^{-1}+\mu^2}{\beta^{-1}+\mu^2}.$$

McDonald & Seljak 2008; Seljak 2009

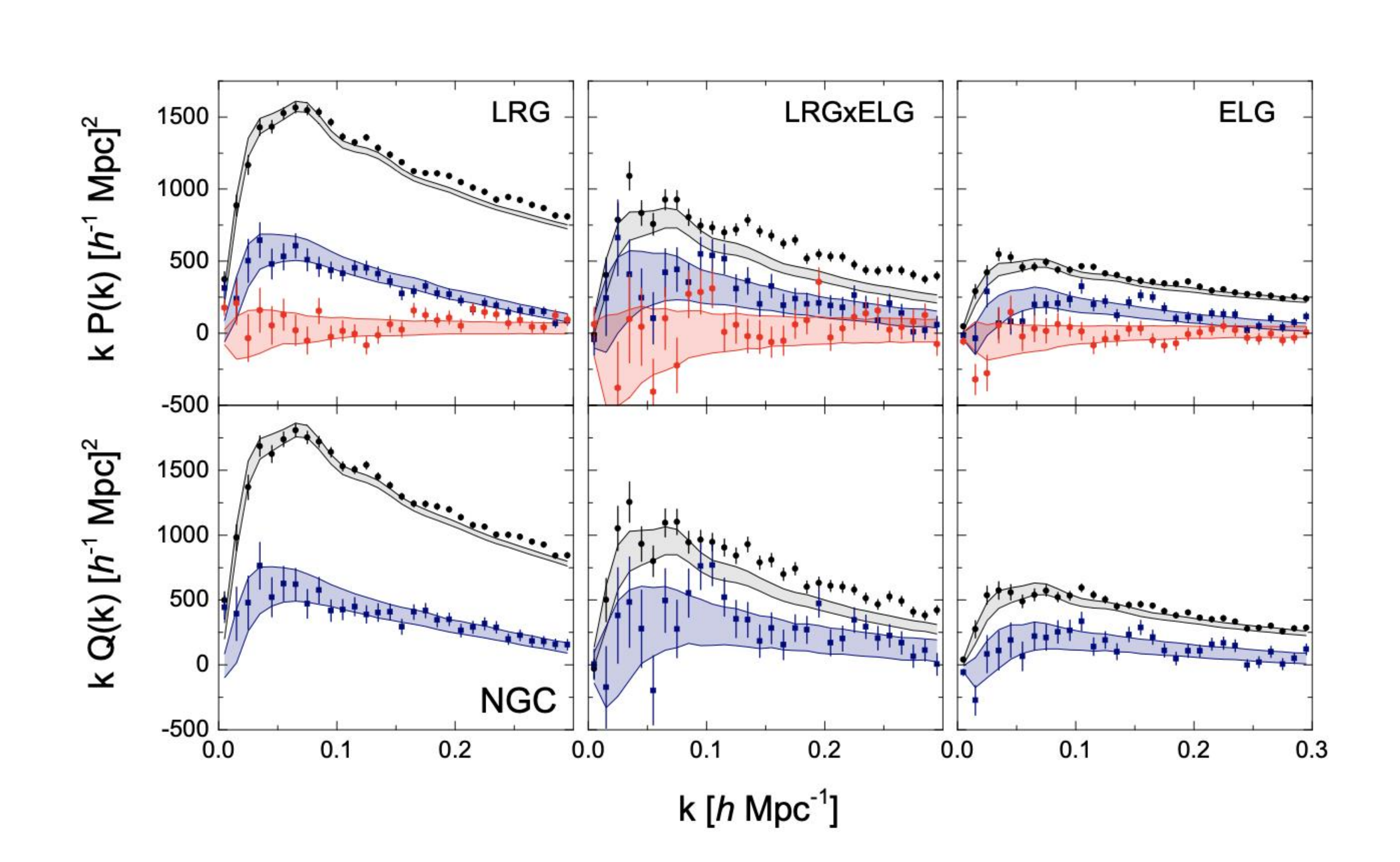
- It can reduce the systematics, as the photometry used for observing different tracers are usually uncorrelated!



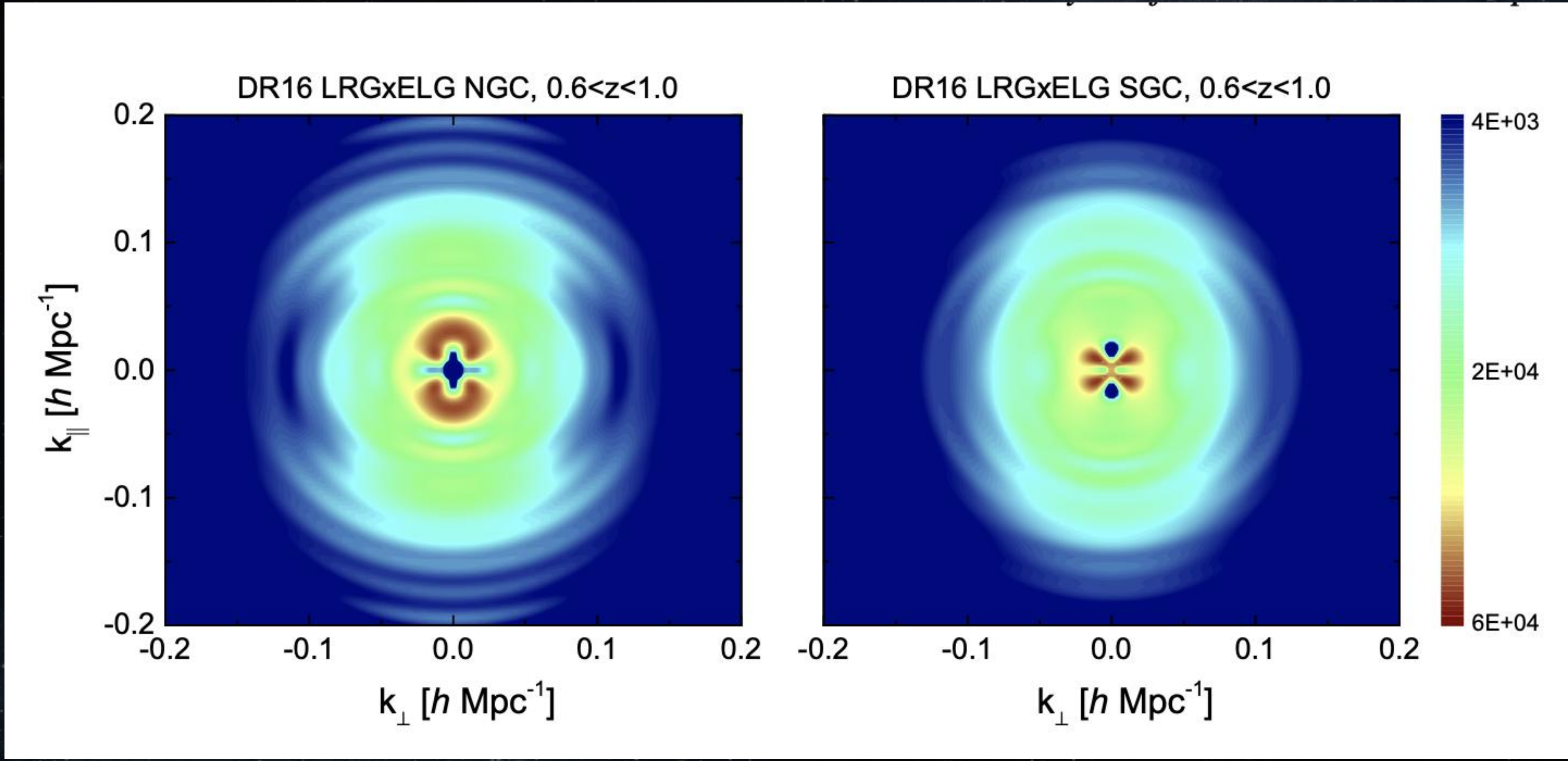


Decent overlap between
eBOSS DR16
LRGs and ELGs
in AREA ~ 800 deg^2
and in REDSHIFT [0.6,1.0]

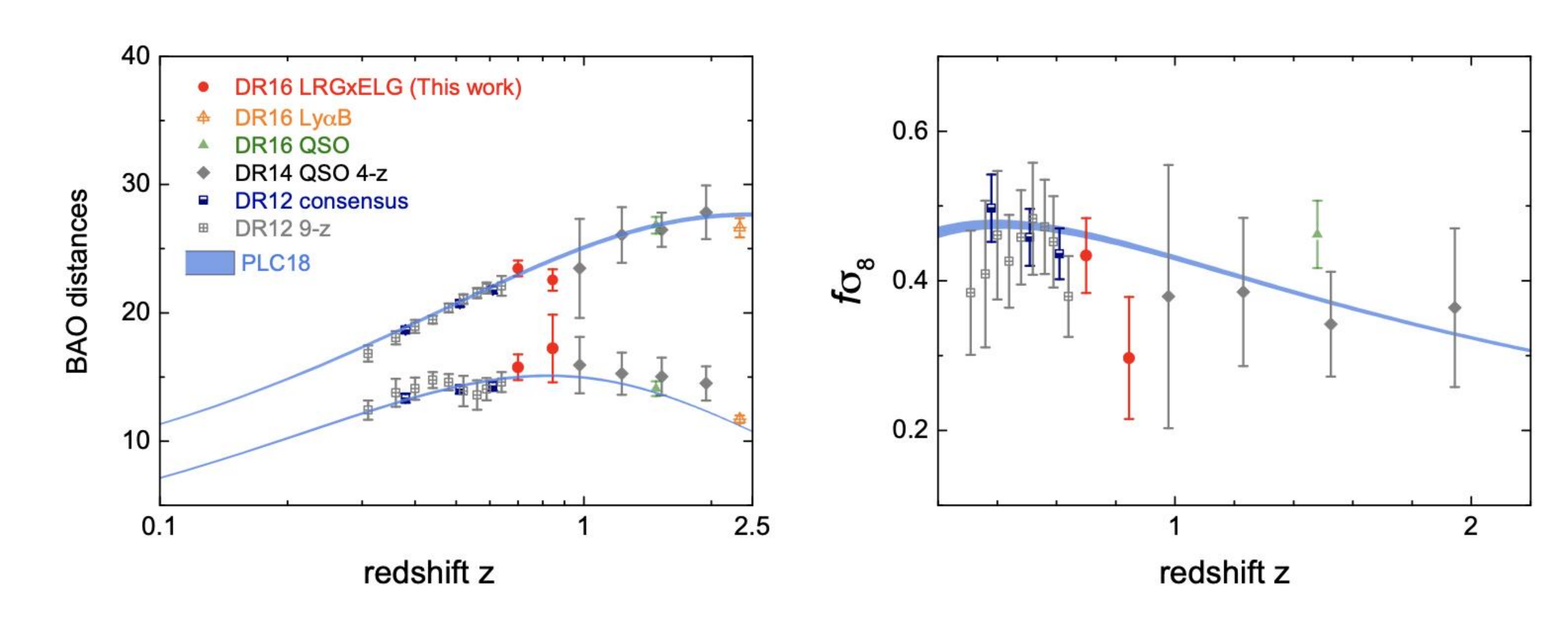
Zhao, Wang et al, (eBOSS), 2007.09011 (k-space)
Wang, **Zhao** et al, (eBOSS), 2007.09010 (s-space)


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

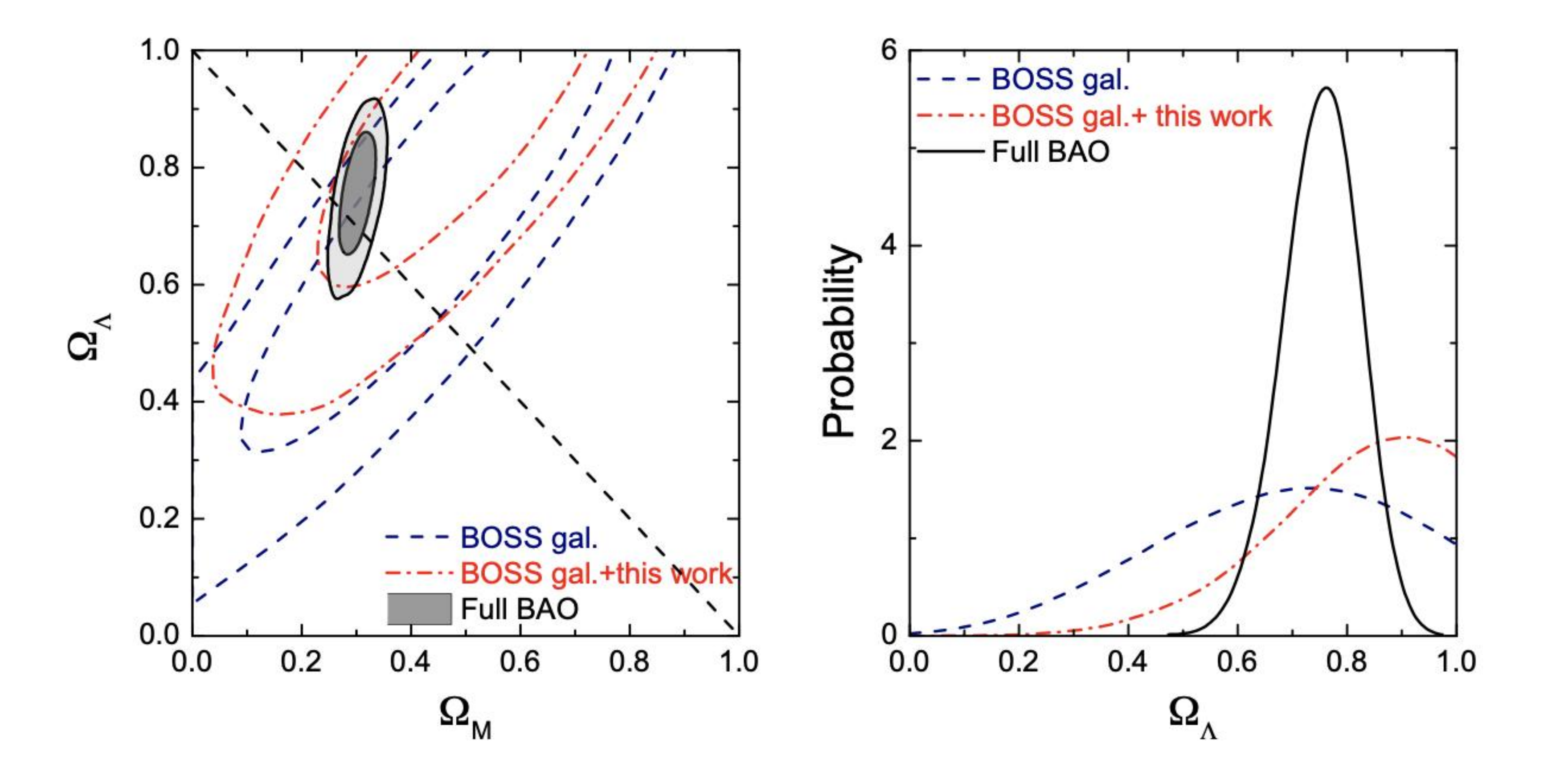
GBZ+, 2020


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|| [h Mpc-1]
k⊥ [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
redshift z
0.1
1
2.5
10
20
30
40
fσ8
0.2
0.4
0.6
2

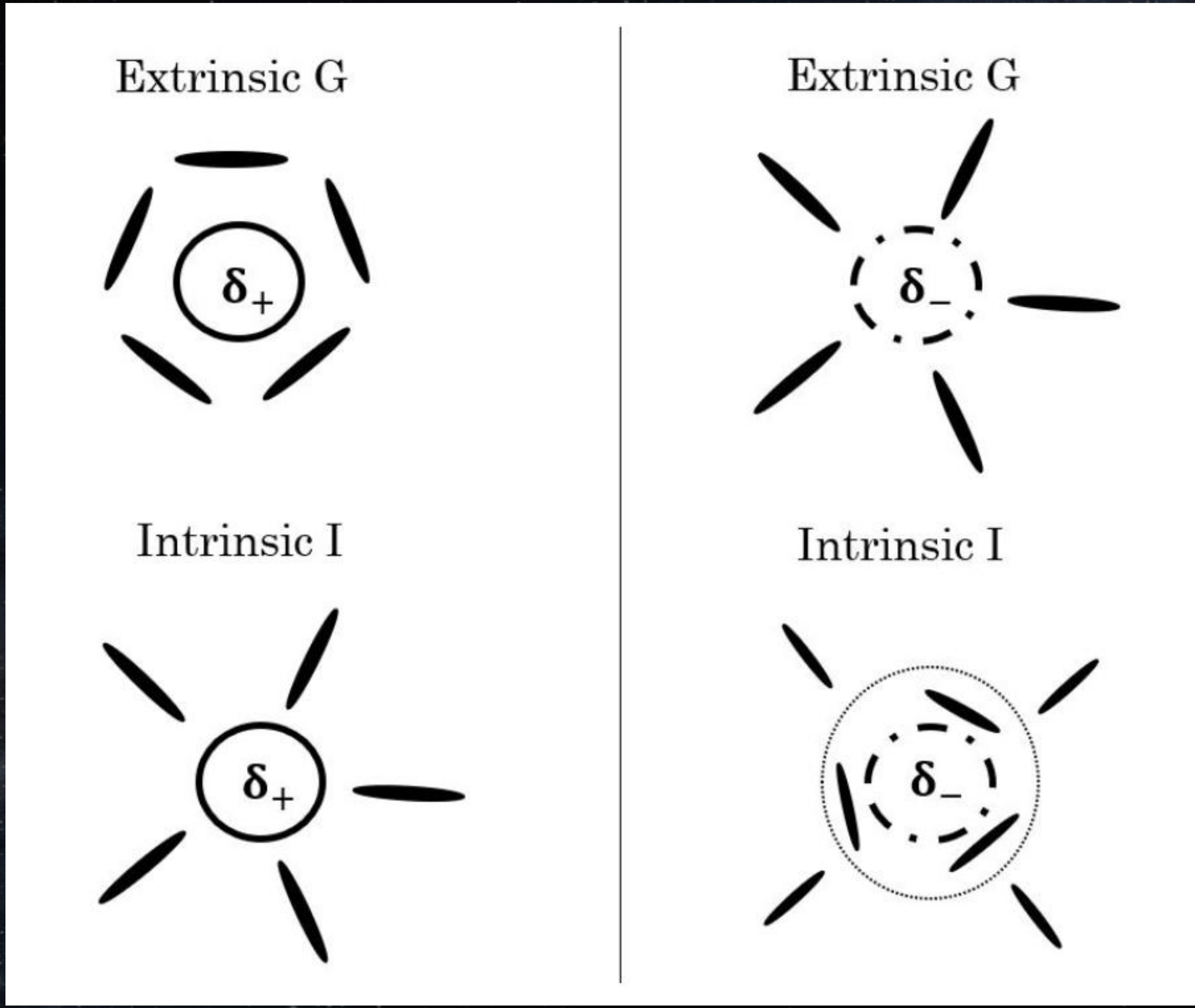
GBZ+, 2020



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

Zhao, Wang et al, (eBOSS), 2007.09011

A first detection of BAO from galaxy-ellipticity correlations



d’Assignies D. et al. 2021

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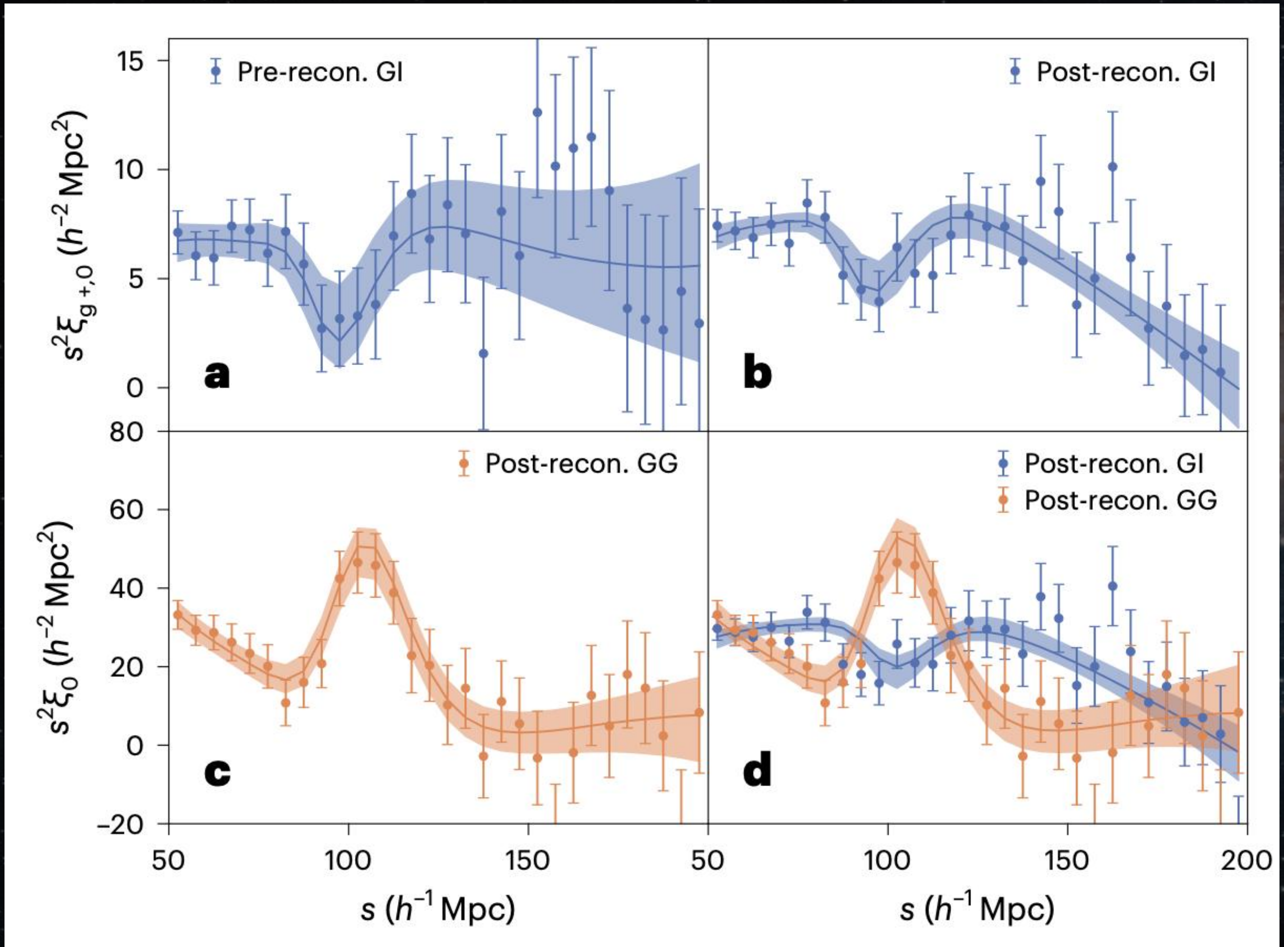
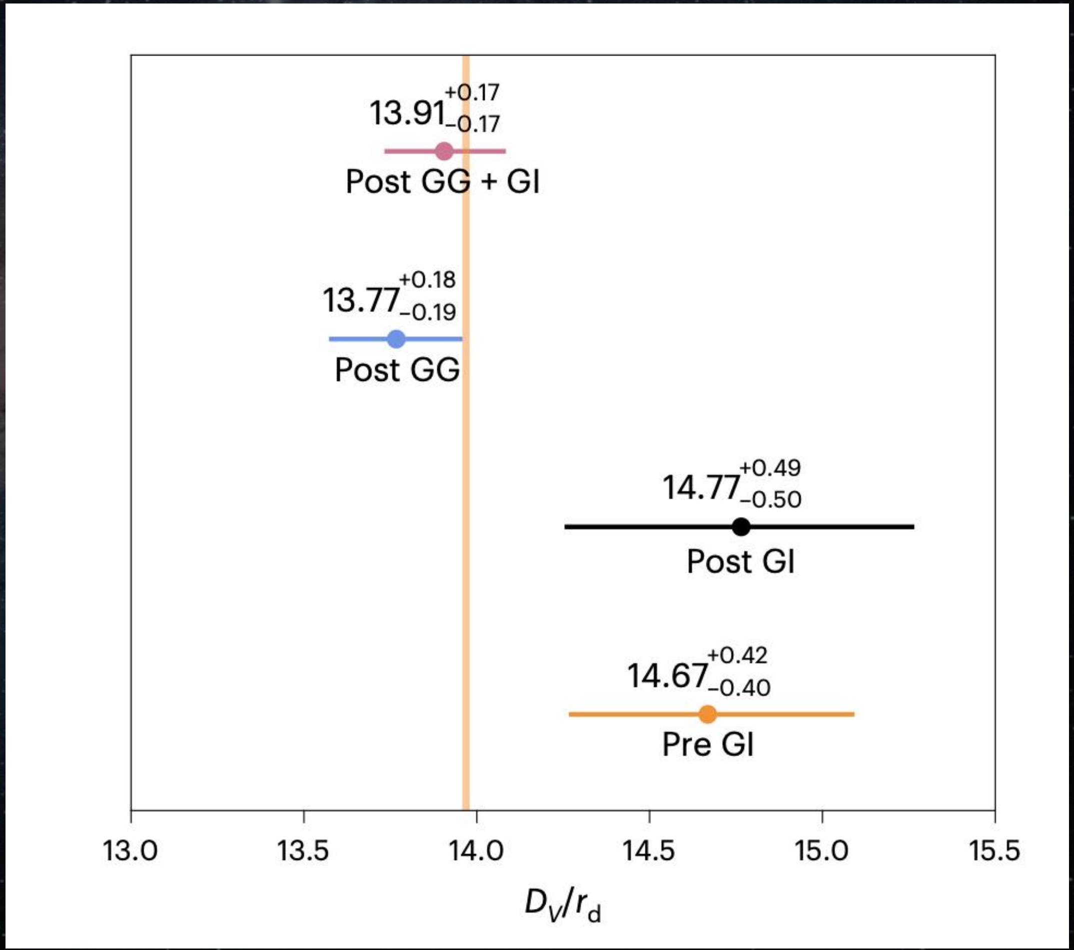
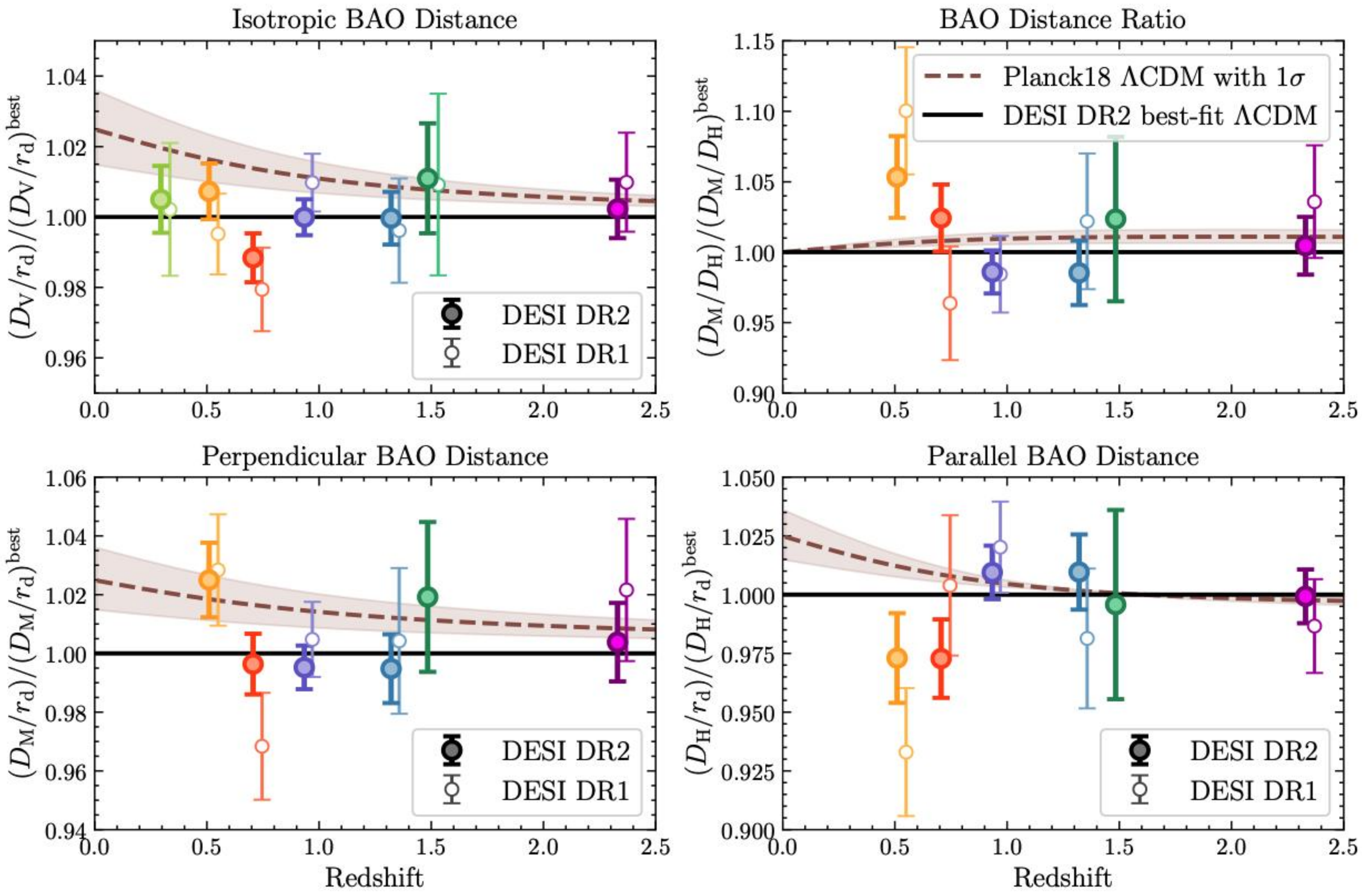




Xu, Jing, GBZ et al, Nature Astronomy (2023)

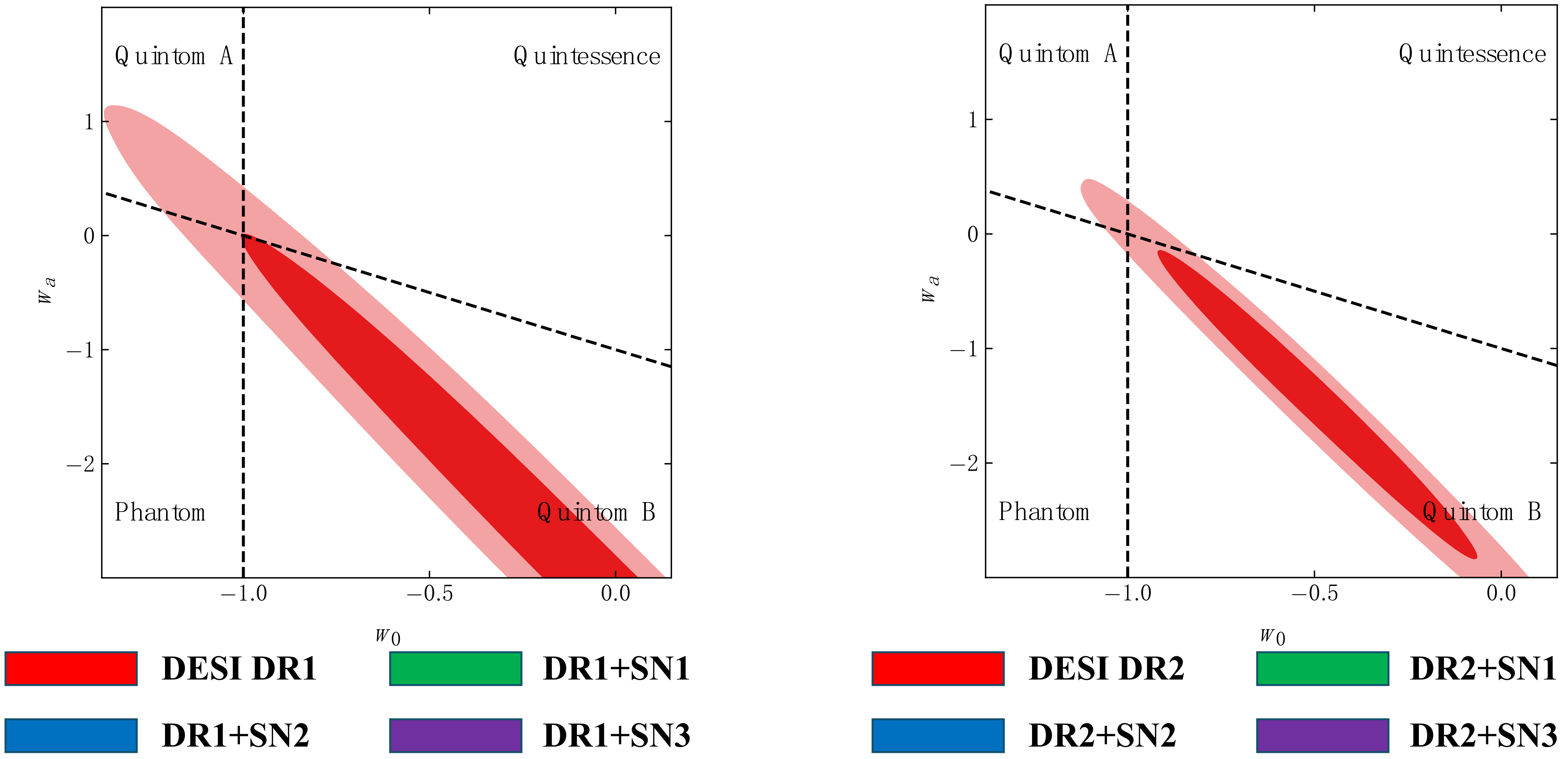
A study of dynamical dark gravity using DESI



DESI paper: 2503.14738

A study of dynamical dark gravity using DESI

$$w(a) = w_0 + w_a(1-a)$$



Two ways to study dynamics of dark energy

- Indirect: get features of w(z) directly from distance measurements

✓ : cheap; no data combination needed

✗ : no w(z) derived

Two ways to study dynamics of dark energy

- **Indirect: get features of w(z) directly from distance measurements**

✓: cheap; no data combination needed

✗: no w(z) derived

- **Direct: reconstruct w(z) from observations**

✓: show w(z) with details

✗: expensive; usually requires datasets to be combined

Probing dynamical DE from distance measurements

(Gu et al, 2404.06303; Wang et al, 2404.06310)

$$\frac{D_\mathrm{A}(z)}{D_{\mathrm{A,fid}}(z)} = \alpha_0 \left(1 + \alpha_1 x + \frac{1}{2}\alpha_2 x^2 + \frac{1}{6}\alpha_3 x^3 + \frac{1}{24}\alpha_4 x^4\right)$$

(Zhu et al, 2015)

$$\frac{H_\mathrm{fid}(z)}{H(z)} = \alpha_0 \left[1 + \alpha_1 + (2\alpha_1 + \alpha_2)x + \left(\frac{3}{2}\alpha_2 + \frac{1}{2}\alpha_3\right)x^2 + \left(\frac{2}{3}\alpha_3 + \frac{1}{6}\alpha_4\right)x^3 + \frac{5}{24}\alpha_4 x^4\right]$$

$$1 + x \equiv D_{\mathrm{A,fid}}(z)/D_{\mathrm{A,fid}}(z_\star)$$

$$S(a) \equiv A\ H^2(a)a^3 = B\ X(a)a^3 + C$$

$$A = r_{\mathrm{d}}^2,\ B = AH_0^2(1-\Omega_{\mathrm{M}}),\ C = AH_0^2\Omega_{\mathrm{M}} \quad X(a) \equiv \rho_{\mathrm{DE}}(a)/\rho_{\mathrm{DE}}(1)$$

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$$S_0(a) \equiv a^3 - \frac{3\,[S(a)-S(1)]}{S'(1)} = a^3 + \frac{X(a)a^3-1}{w(1)} \xrightarrow{\Lambda} 1$$

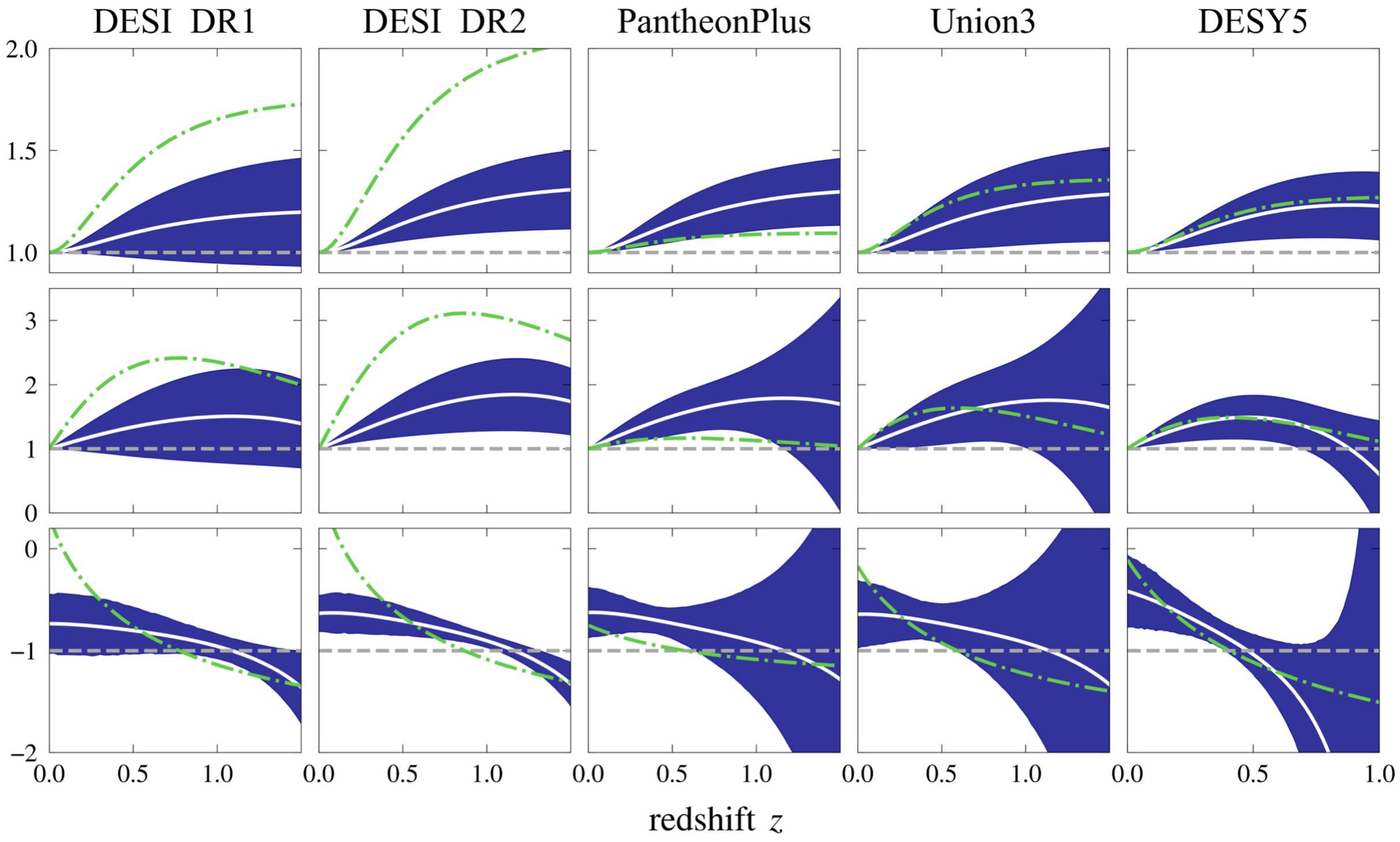
$$S_1(a) \equiv \frac{1}{a^3}\frac{S'(a)}{S'(1)} = \frac{P_{\rm DE}(a)}{P_{\rm DE}(1)} \xrightarrow{\Lambda} 1,$$

$$S_2(a) \equiv -\frac{S''(a)}{3S'(a)} = w(a) - \frac{w'(a)}{3w(a)} \xrightarrow{\Lambda} -1,$$

$$a^3 + \frac{X(a)a^3 - 1}{w(1)}$$

$$\frac{P_{\mathrm{DE}}(a)}{P_{\mathrm{DE}}(1)}$$

$$w(a) - \frac{w'(a)}{3w(a)}$$



Gu, Wang, Wang, GBZ, et al [DESI collaboration], 2504.06118, to appear in **Nature Astronomy**

Reconstructing the evolution history of dark energy

Crittenden, Pogosian, GBZ (CPZ, JCAP 2009)
Crittenden, GBZ, Pogosian, Samushia, Zhang (JCAP 2012)

$$\xi_w(|a-a'|) \equiv \langle [w(a) - w^{\rm fid}(a)][w(a') - w^{\rm fid}(a')] \rangle$$

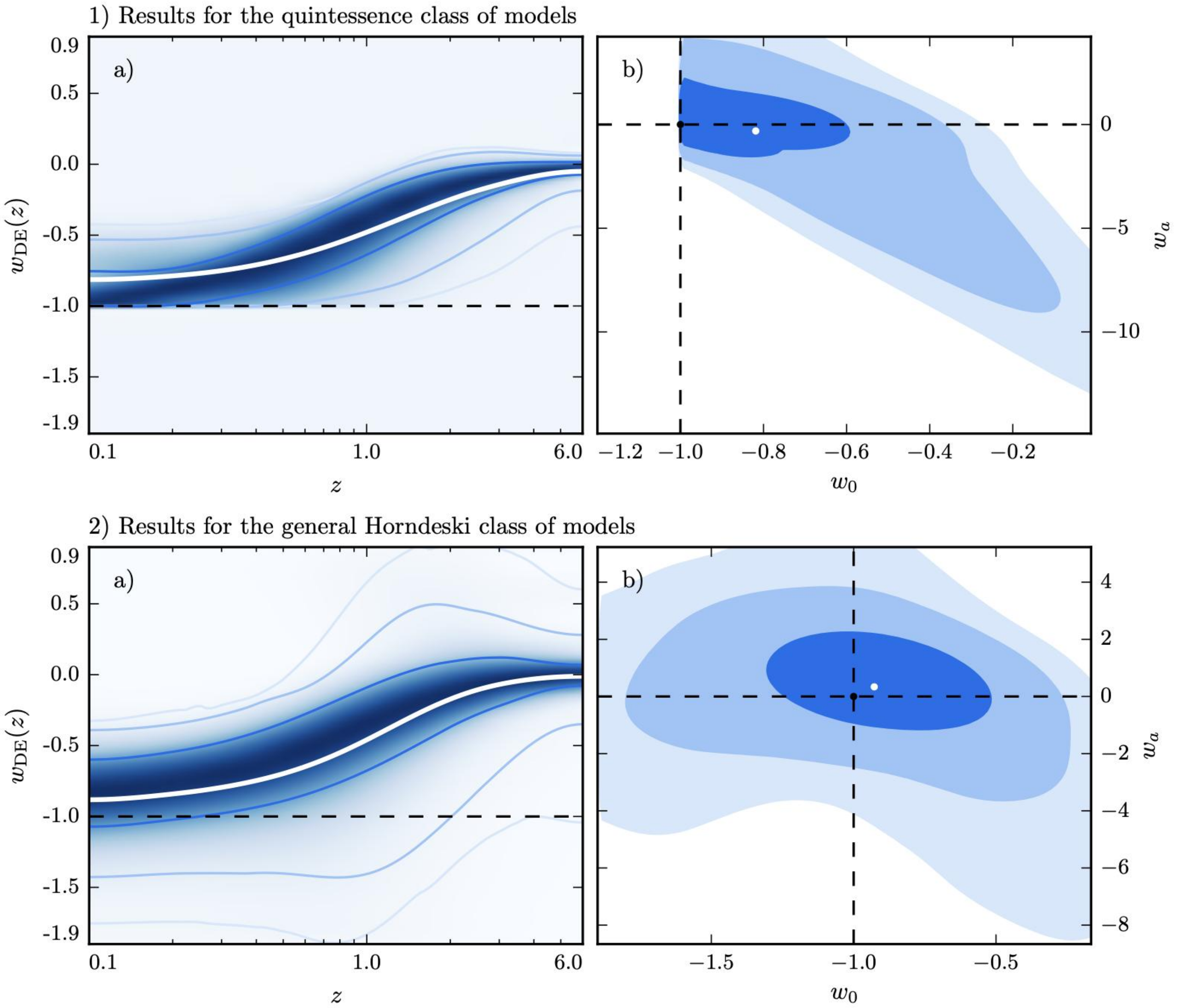
$$w_i = \frac{1}{\Delta} \int_{a_i}^{a_i+\Delta} da\, w(a)$$

$$C_{ij} \equiv \langle \delta w_i \delta w_j \rangle = \frac{1}{\Delta^2} \int_{a_i}^{a_i+\Delta} da \int_{a_j}^{a_j+\Delta} da' \xi_w(|a-a'|)$$

$$\chi^2_{\rm prior} = -2 \ln \mathcal{P}_{\rm prior} = (\mathbf{w} - \mathbf{w}^{\rm fid})^T \mathbf{C}^{-1} (\mathbf{w} - \mathbf{w}^{\rm fid})$$

Theory-motivated correlated prior on w(z) (Raveri et al, 1703.05297)

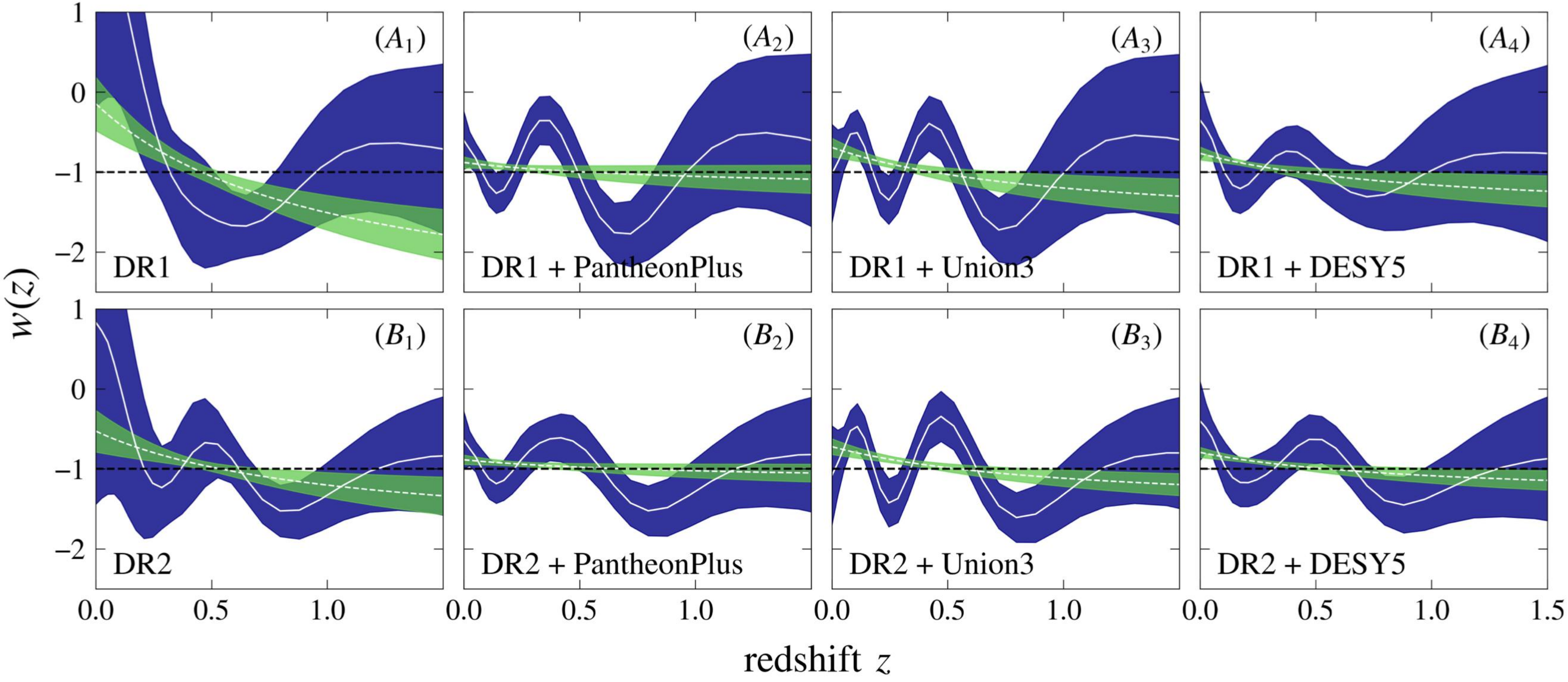
$$\mathcal{S} = \int d^4x\sqrt{-g}\left\{ \frac{m_0^2}{2}\left[1+\Omega(\tau)\right]R + \Lambda(\tau) - c(\tau)\,a^2\delta g^{00} + \frac{M_2^4(\tau)}{2}\left(a^2\delta g^{00}\right)^2 - \frac{\bar{M}_1^3(\tau)}{2}\,a^2\delta g^{00}\,\delta K_\mu^\mu + \frac{\bar{M}_3^2(\tau)}{2}\left[\left(\delta K_\mu^\mu\right)^2 - \delta K_\nu^\mu\,\delta K_\mu^\nu - \frac{a^2}{2}\delta g^{00}\,\delta\mathcal{R}\right] + \dots \right\} + S_m[g_{\mu\nu},\chi_m], \qquad (1)$$



Raveri et al, 1703.05297

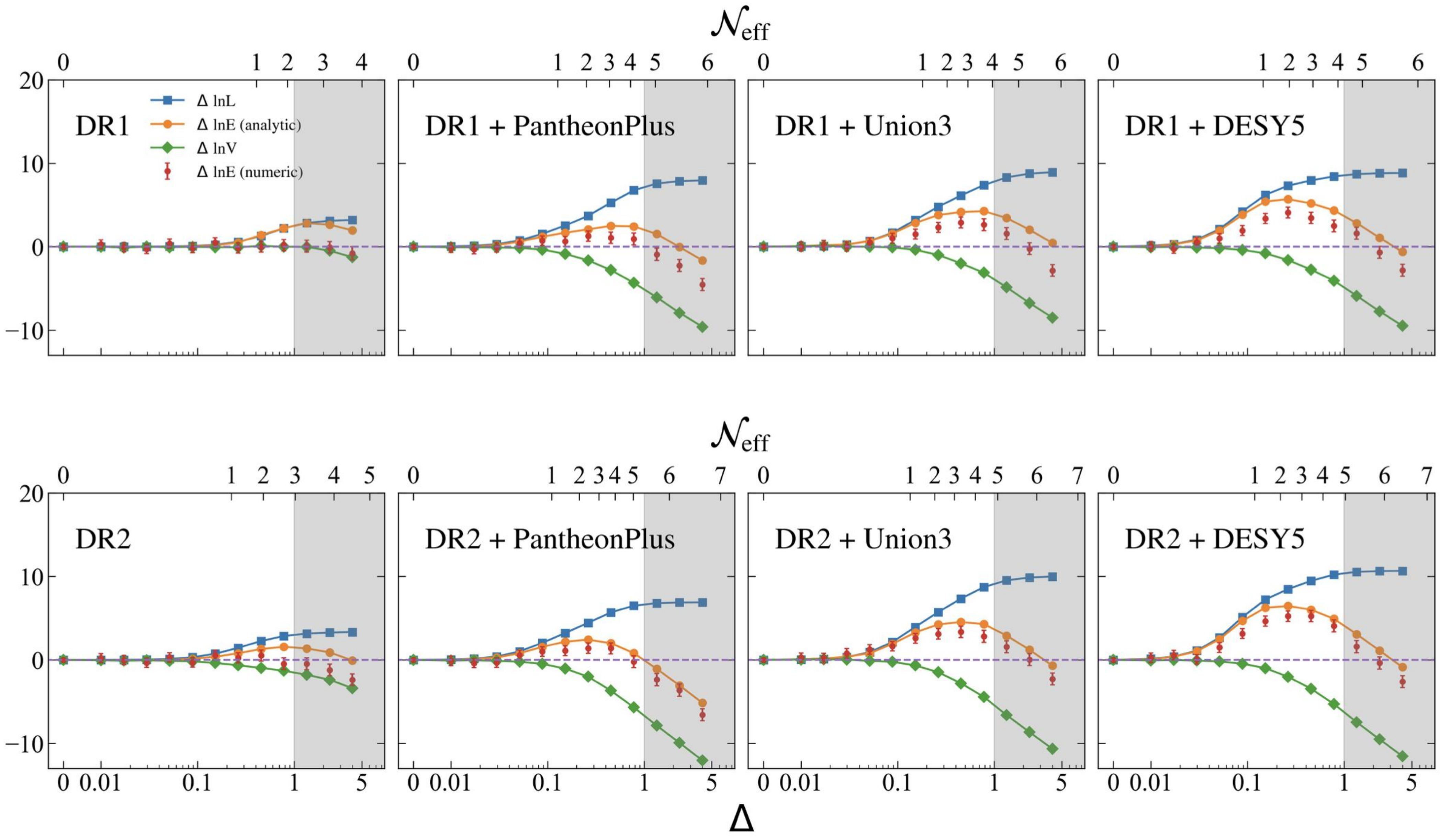
$$
\begin{aligned}
C(a, a') &\equiv \langle [w(a) - w_{\rm fid}(a)][w(a) - w_{\rm fid}(a')] \rangle \\
&= \sqrt{C(a)C(a')}R(a, a'),
\end{aligned}
$$

$$
\begin{aligned}
C(a) &= 0.05 + 0.8a^2, \\
R(a, a') &= \exp\left[-\left(\left|\ln\, a - \ln\, a'\right| / 0.3\right)^{1.2}\right]
\end{aligned}
$$



Gu, Wang, Wang, GBZ, et al [DESI collaboration], 2504.06118, to appear in **Nature Astronomy**

Bayesian Evidence



Summary and next steps

- DESI BAO data show interesting signs of new physics, awaiting confirmation of Y5 and later observations;
- As statistical errors get reduced, more work is needed to mitigate the systematics;
- New statistics (MFs, wavelets, etc) and new ideas (tests of parity, etc) are needed to probe new physics from future galaxy surveys.