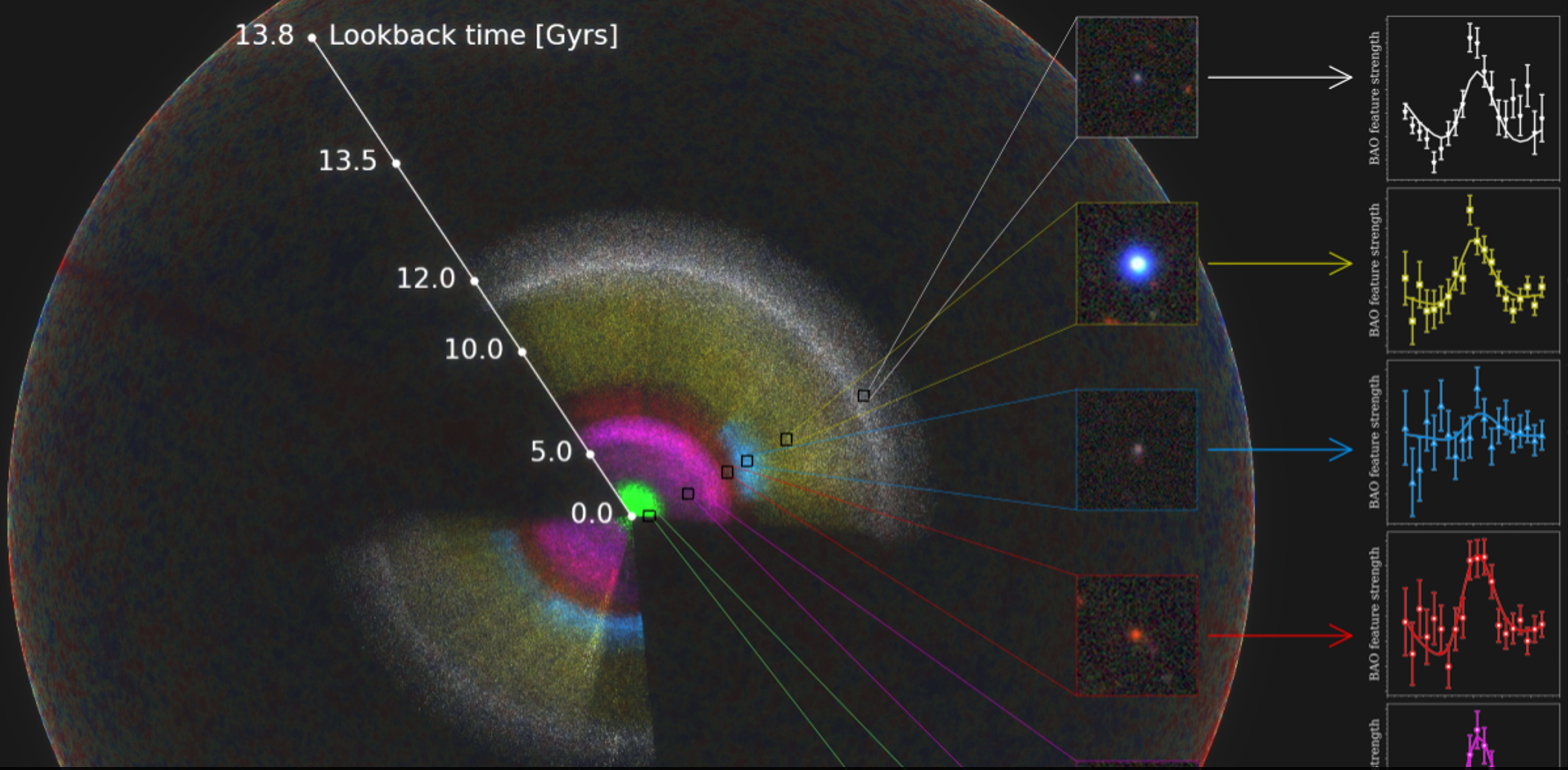


Cosmological tensions in light of the eBOSS DR16 observations

IPMU seminar

Gong-Bo Zhao

National Astronomical Observatories, CAS

November 5, 2020

Multiple cosmological probes

CMB

Multiple cosmological probes

CMB

1978, 2006

Multiple cosmological probes

CMB

SNe

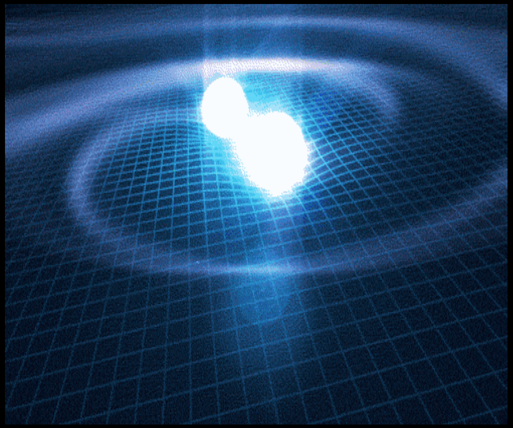
Multiple cosmological probes

CMB

SNe

Multiple cosmological probes

CMB



Gravitational waves

SNe

Multiple cosmological probes

CMB

Gravitational waves

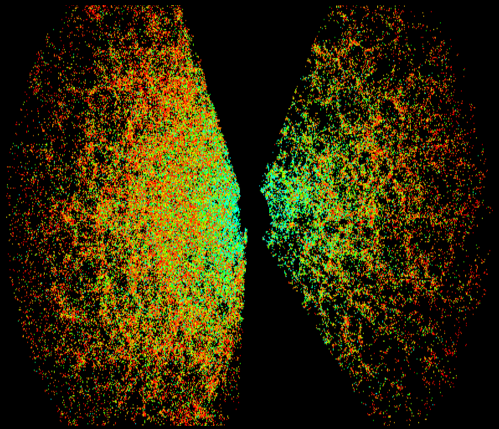
SNe

Multiple cosmological probes

CMB

Gravitational waves

SNe



LSS

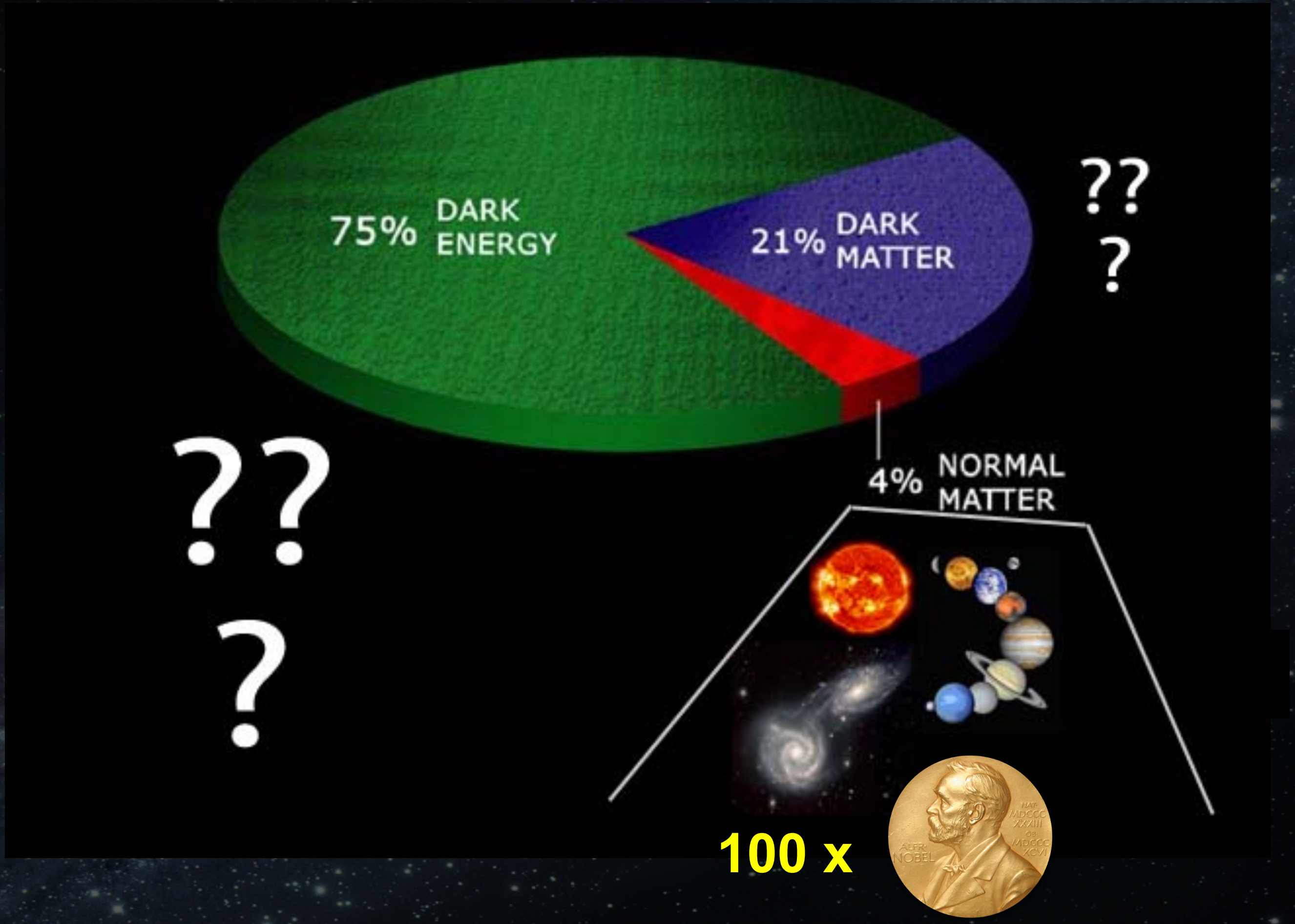
Multiple cosmological probes

CMB

Gravitational waves

SNe

LSS


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

CMB (1978)

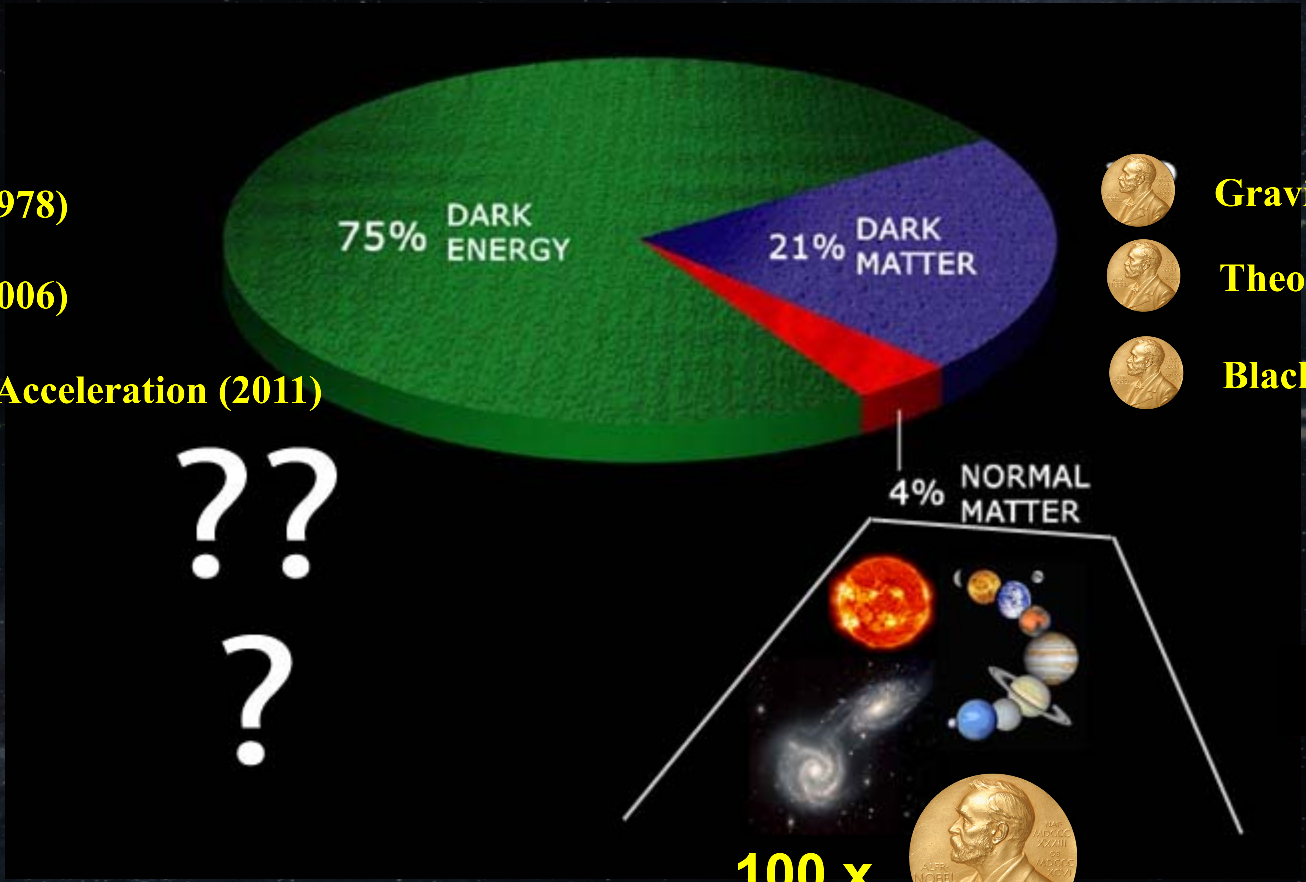
CMB (2006)

Cosmic Acceleration (2011)

Gravitational waves (2017)

Theoretical cosmology (2019)

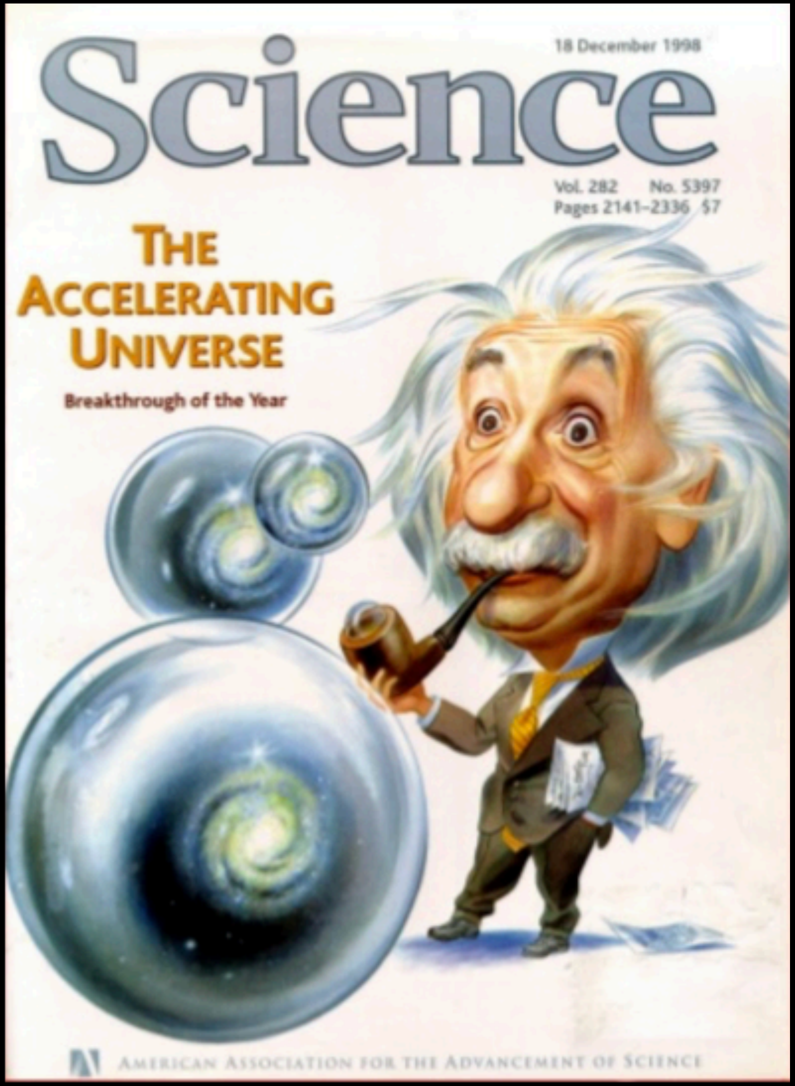
Black holes (2020)



100 x

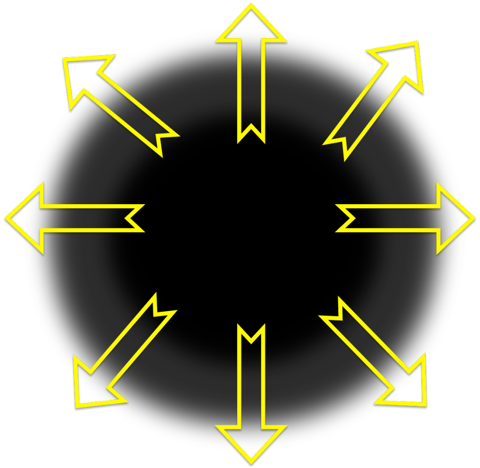
The accelerating Universe!

2011



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

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



Dark Energy

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

To modify General Relativity

Modified Gravity

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

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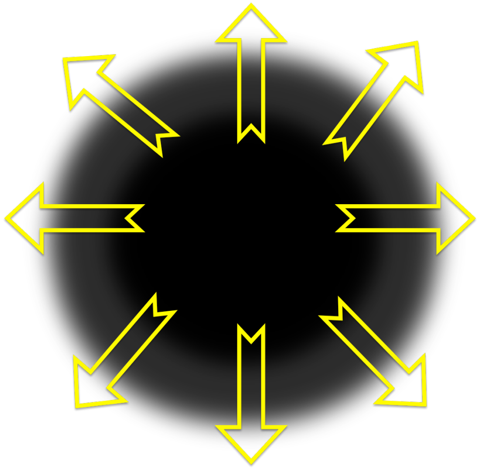

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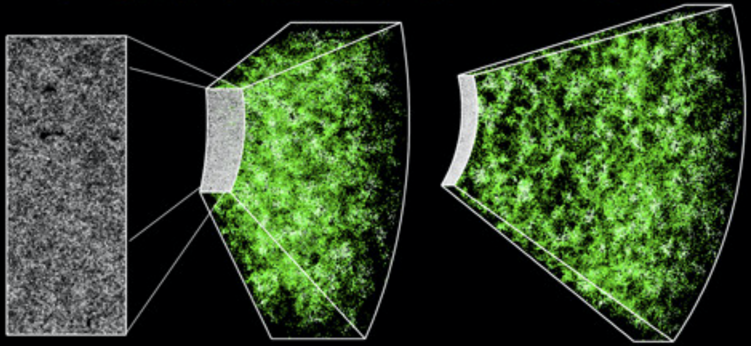
To modify General Relativity

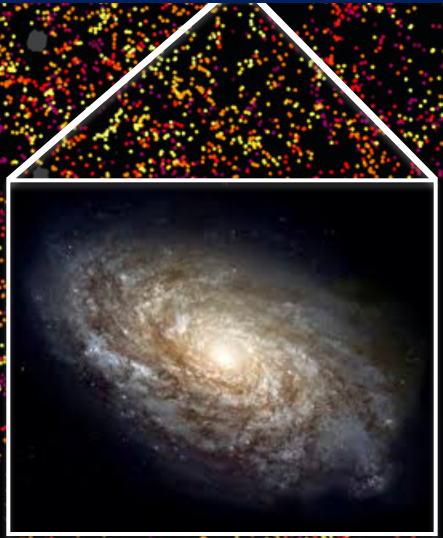
Modified Gravity

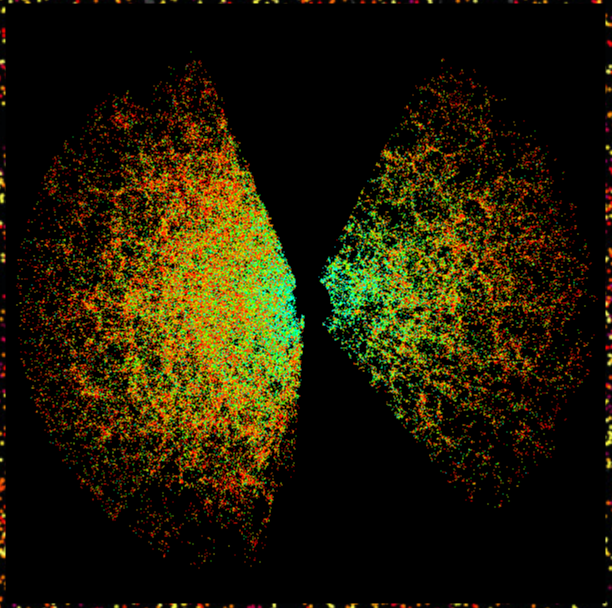
$$\widetilde{G}_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Galaxy surveys can break the dark degeneracy!



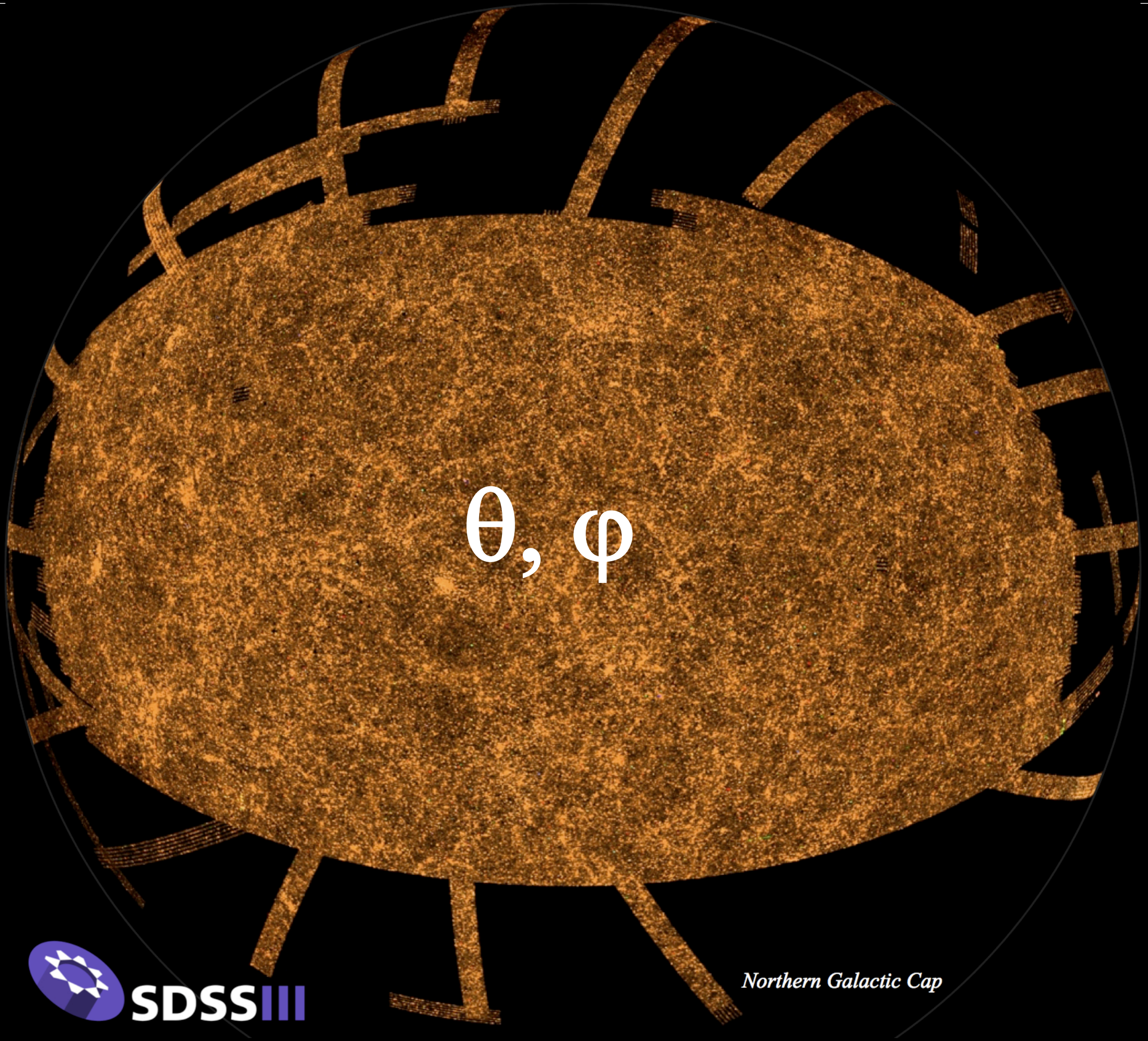
Massive redshift surveys as a key cosmological probe



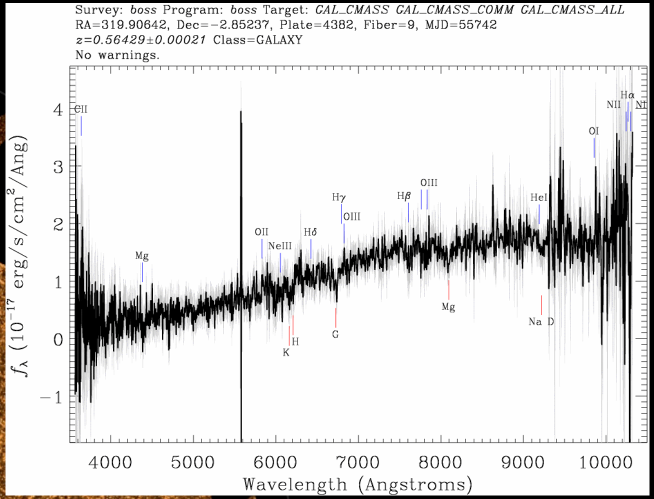


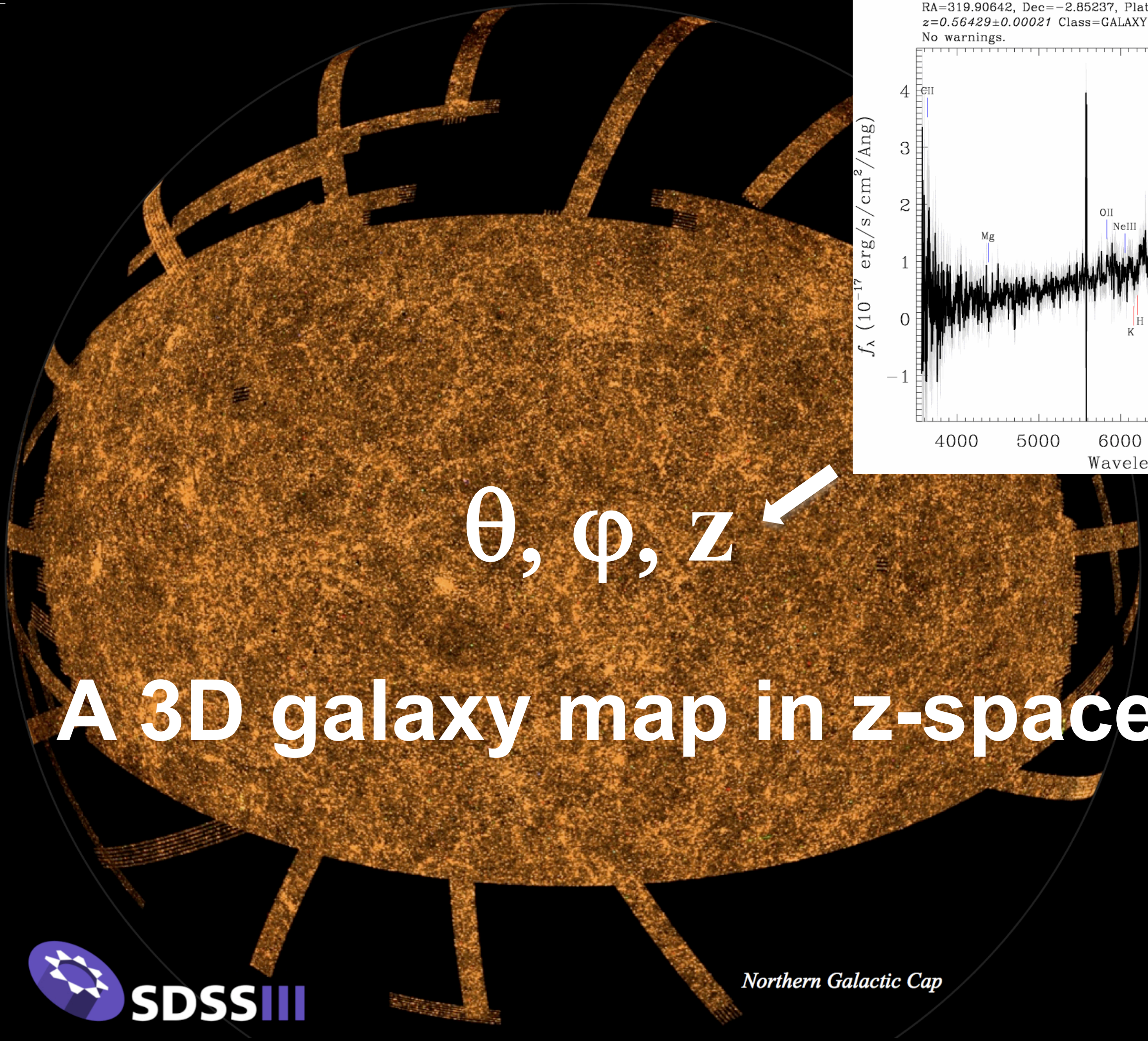
BOSS
SDSS III

What do redshift surveys measure?



What do redshift surveys measure?





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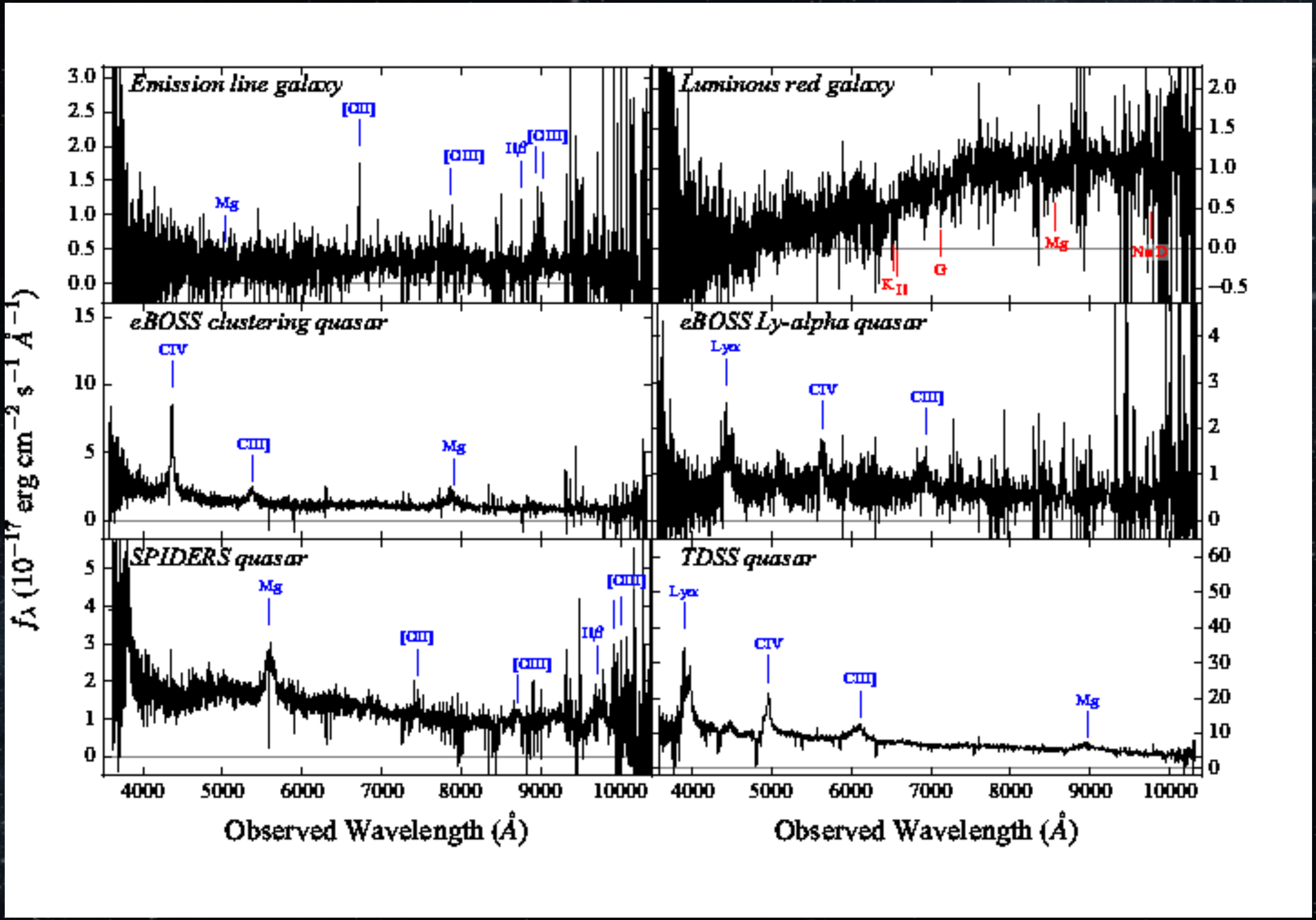
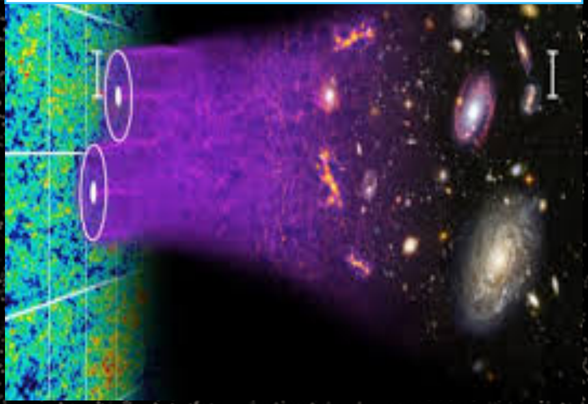
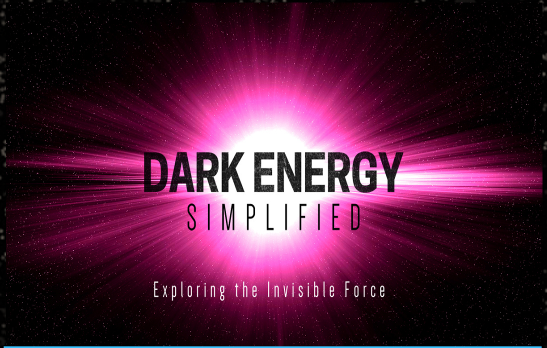


Large z-surveys : a key probe of the Universe

BAO

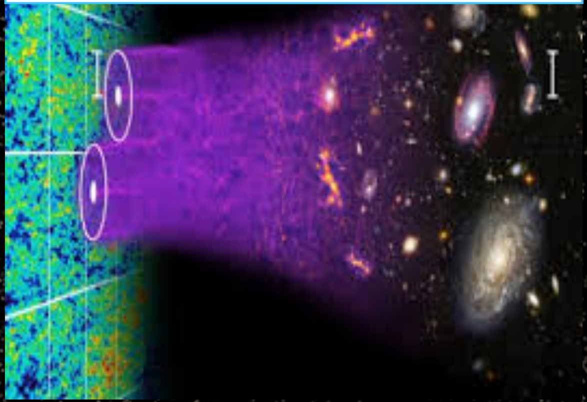




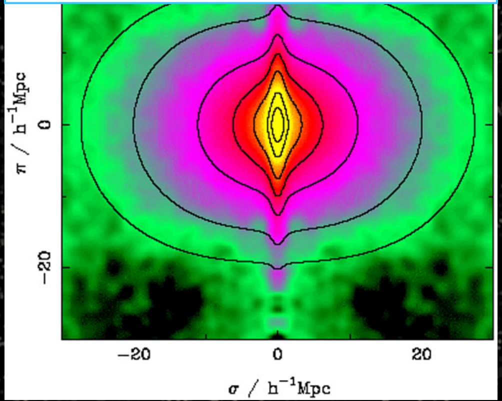
Dark Energy

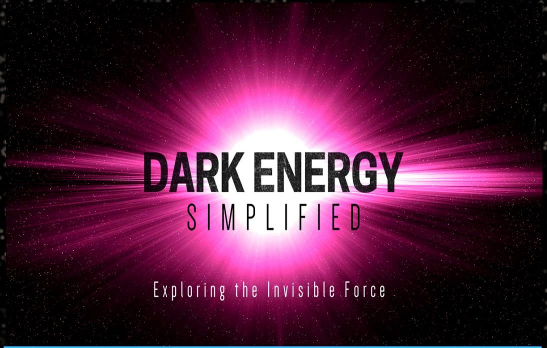
Large z-surveys : a key probe of the Universe

BAO



RSD



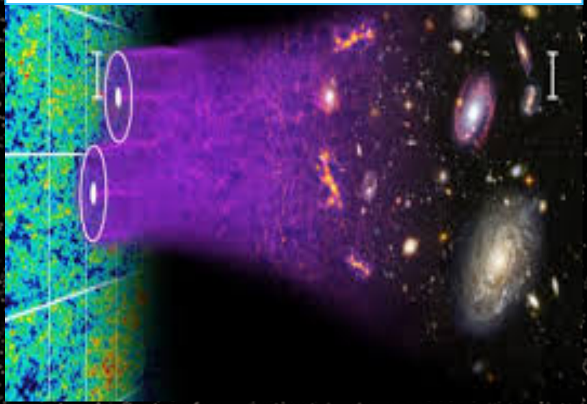


Dark Energy

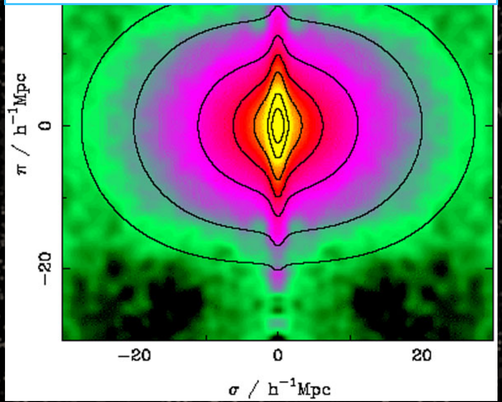
Modified Gravity

Large z-surveys : a key probe of the Universe

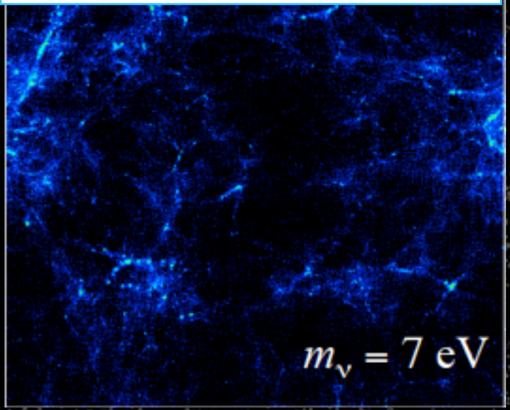
BAO

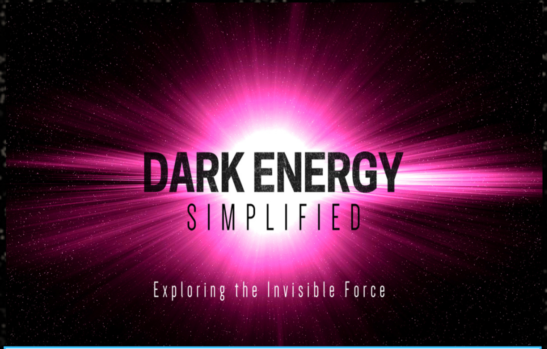


RSD



Free-streaming



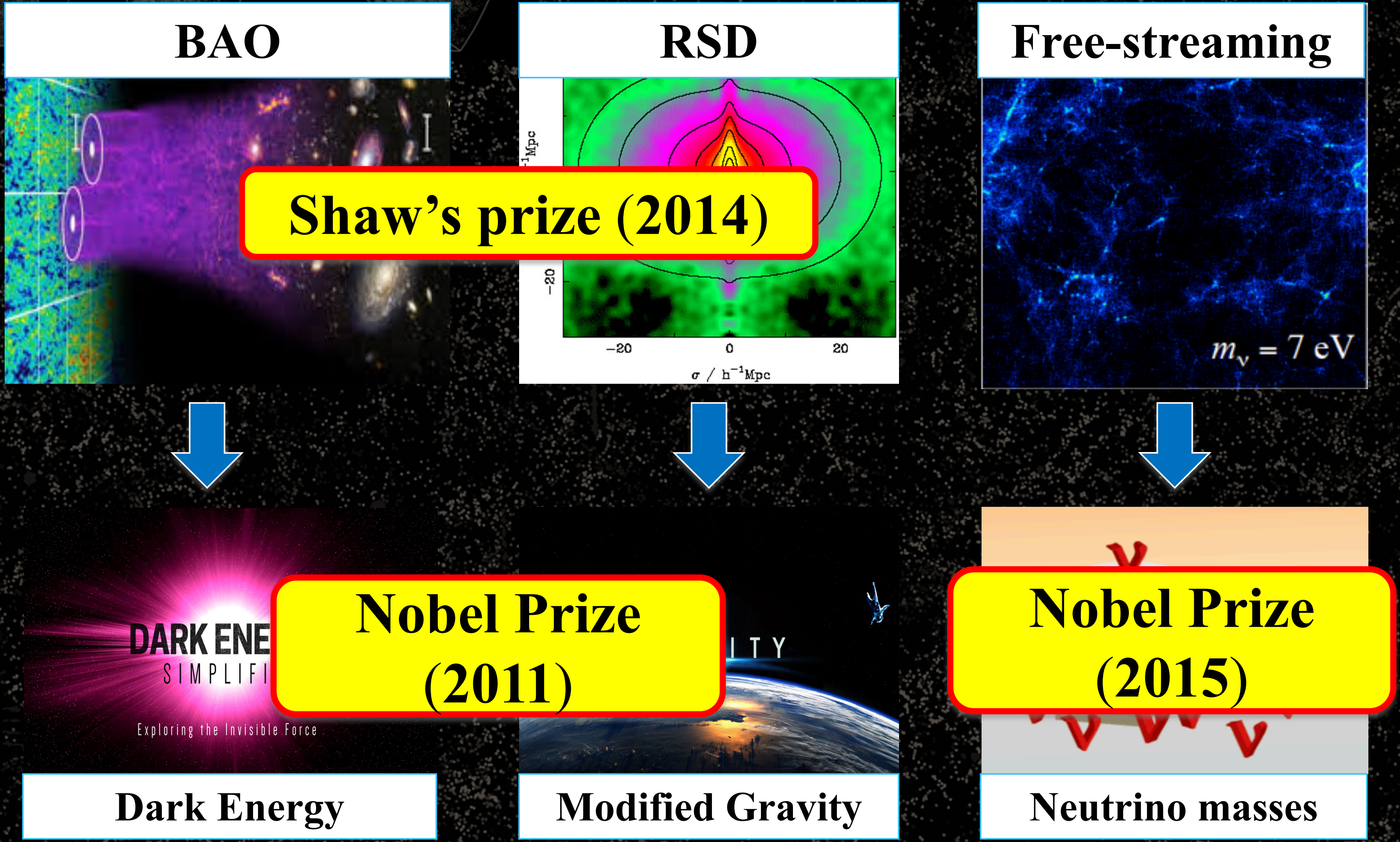


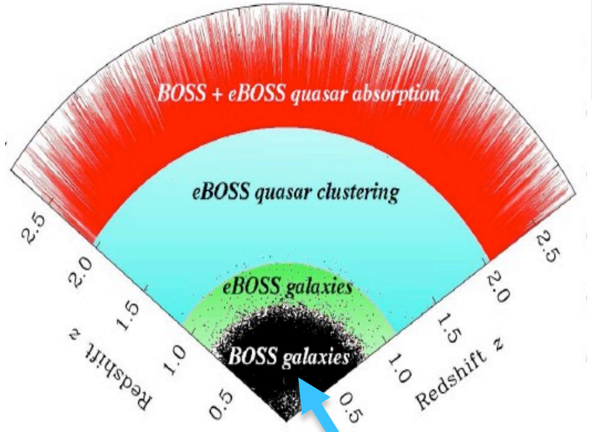
Dark Energy

Modified Gravity

Neutrino masses

Large z-surveys : a key probe of the Universe

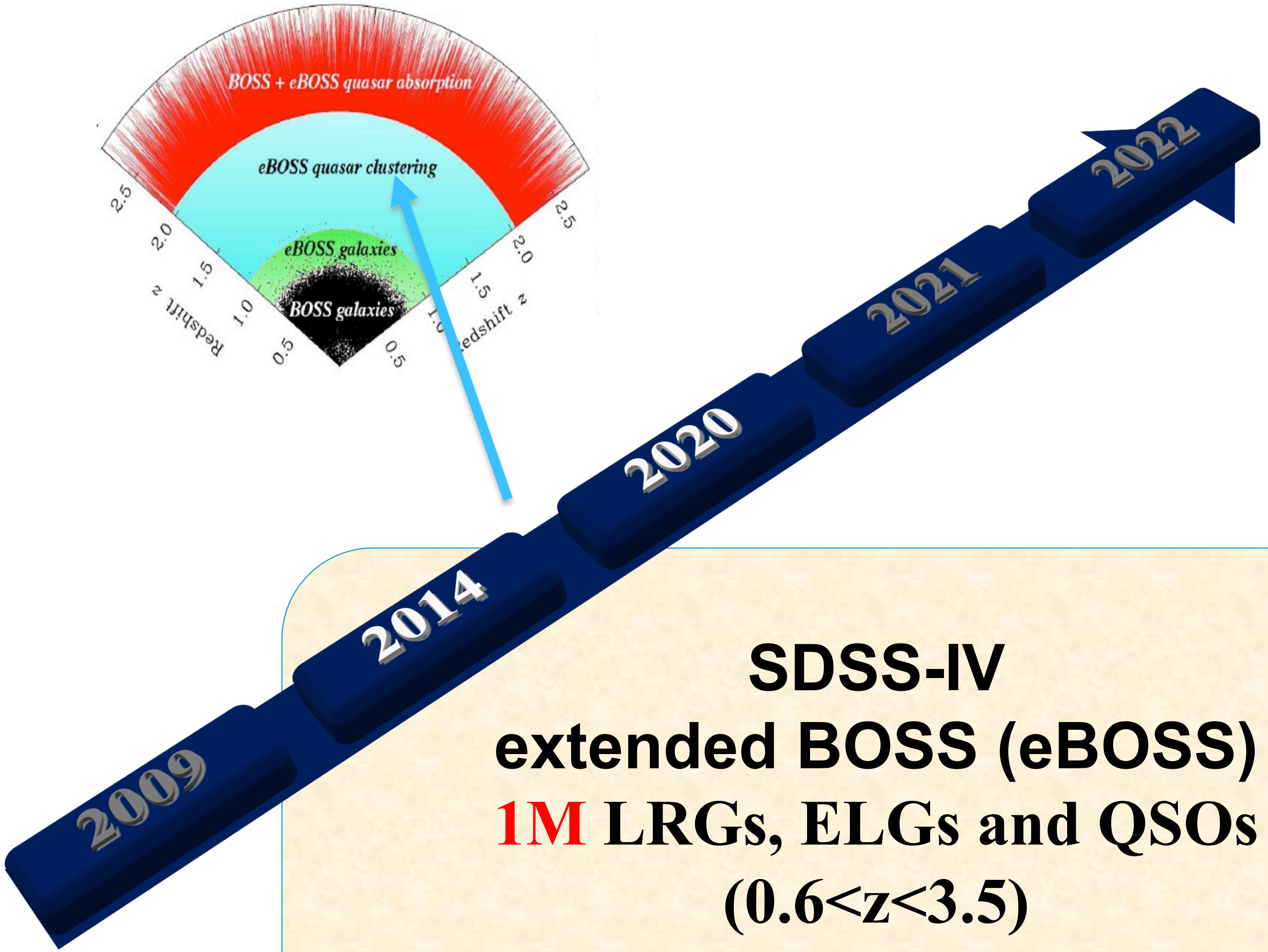




New Mexico
2.5m

2009
2014
2020
2021
2022

SDSS-III
Baryon Oscillation Spectroscopic Survey (BOSS) (z<0.6)
1.6M LRGs
The largest in the past 5 years



SDSS-IV

extended BOSS (eBOSS)

1M LRGs, ELGs and QSOs

(0.6<z<3.5)

Largest ongoing survey

DESI & PFS

>30M LRGs, ELGs and QSOs

($0<z<3.5$)

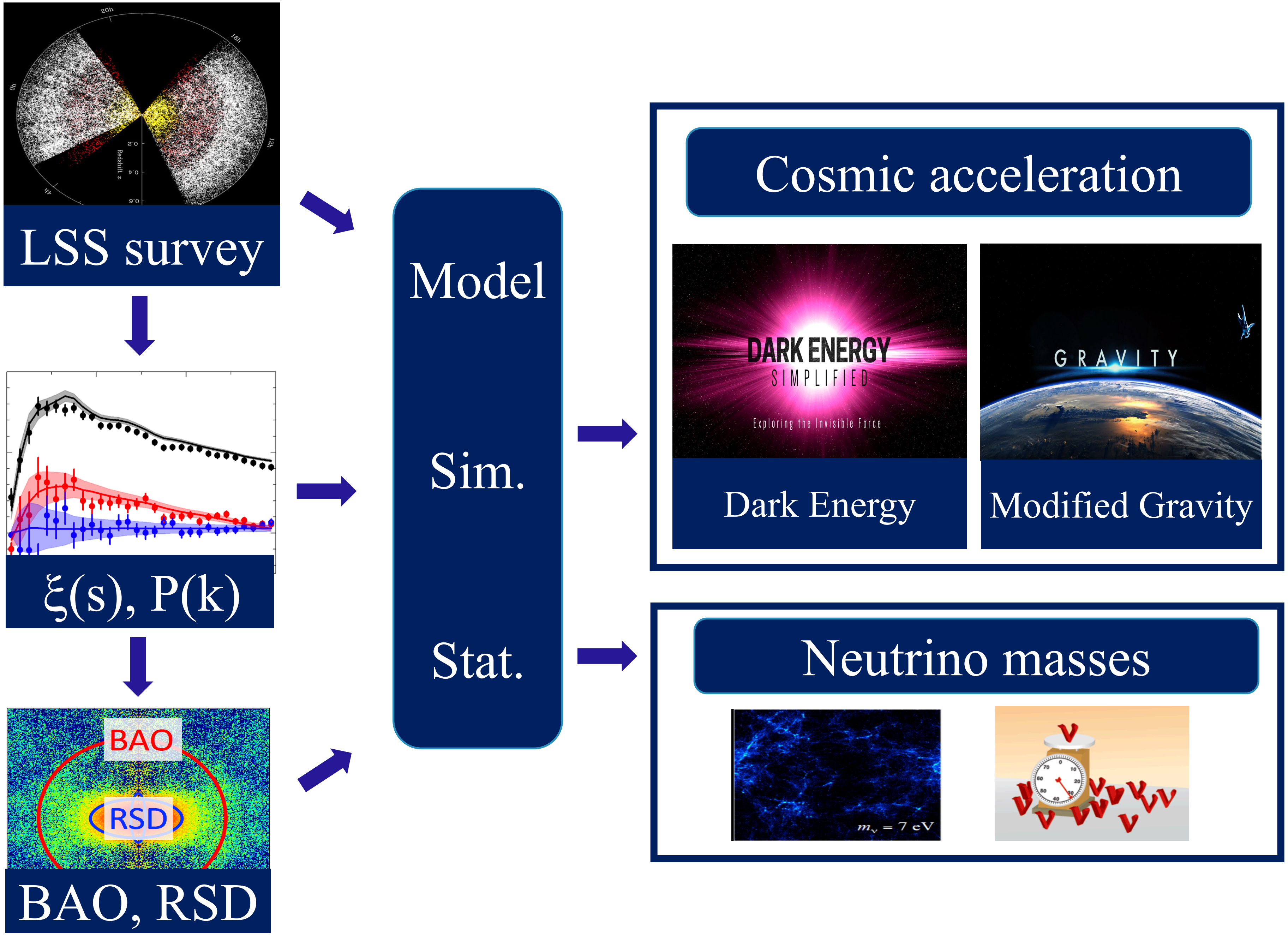
Largest in the next 5 years

Prime Focus Spectrograph
SuMIRe

PFS, 10m, (2021-2025)

Dark Energy Spectroscopic Instrument

DESI, 4m, (2020-2024)


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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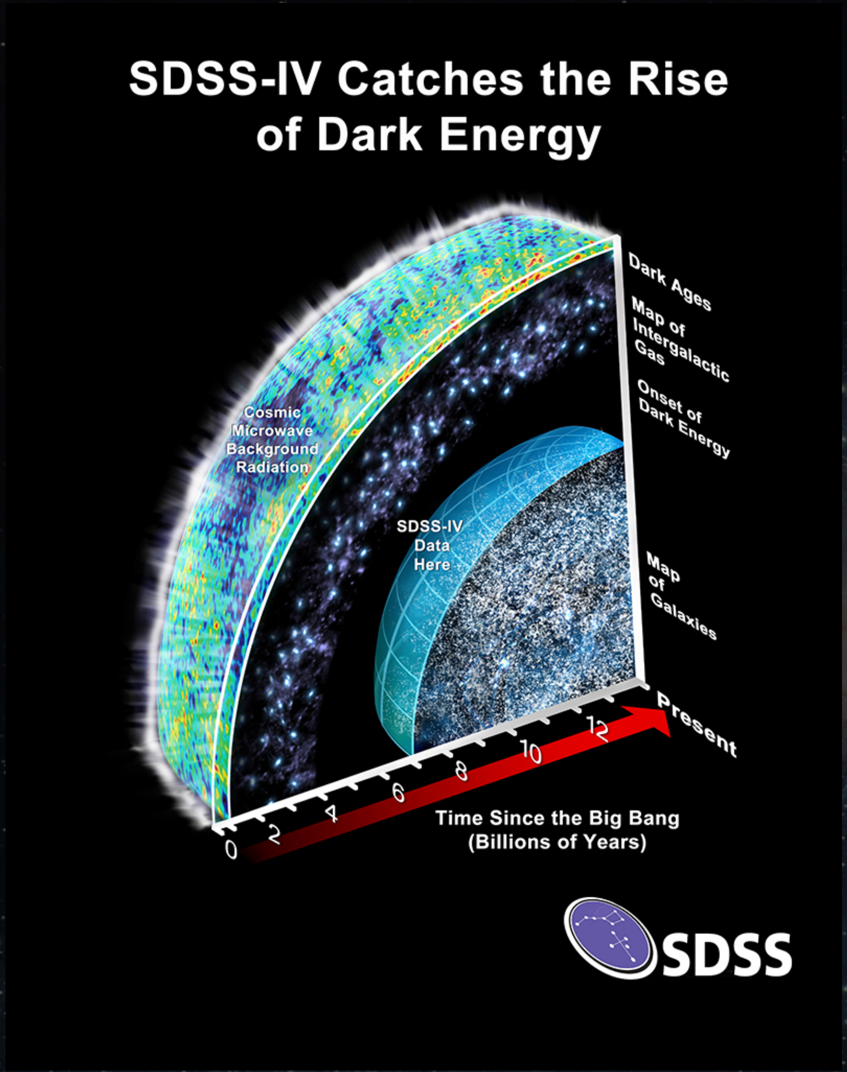
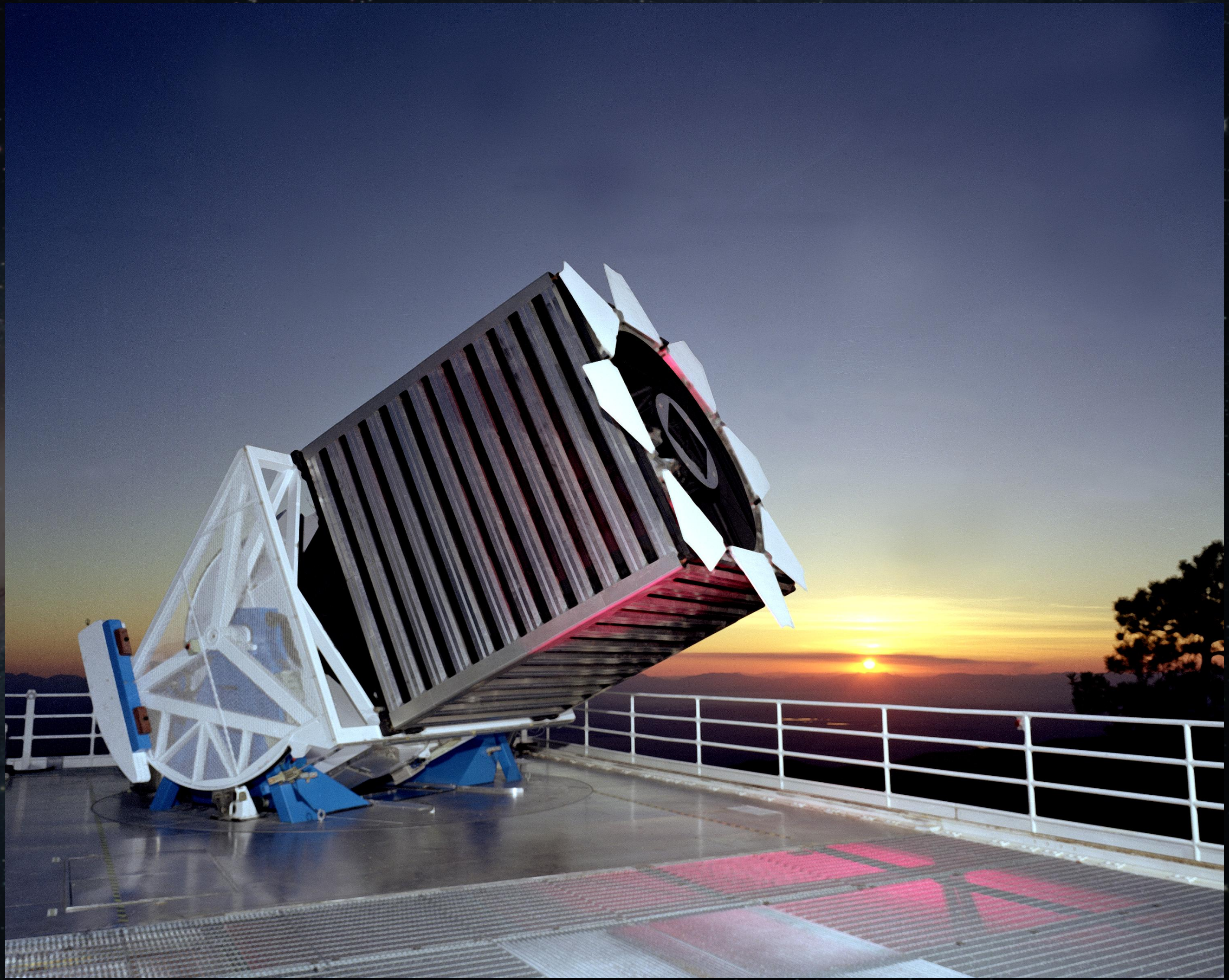


eBOSS (2014-2020)



2.5 m SDSS telescope @ New Mexico

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.

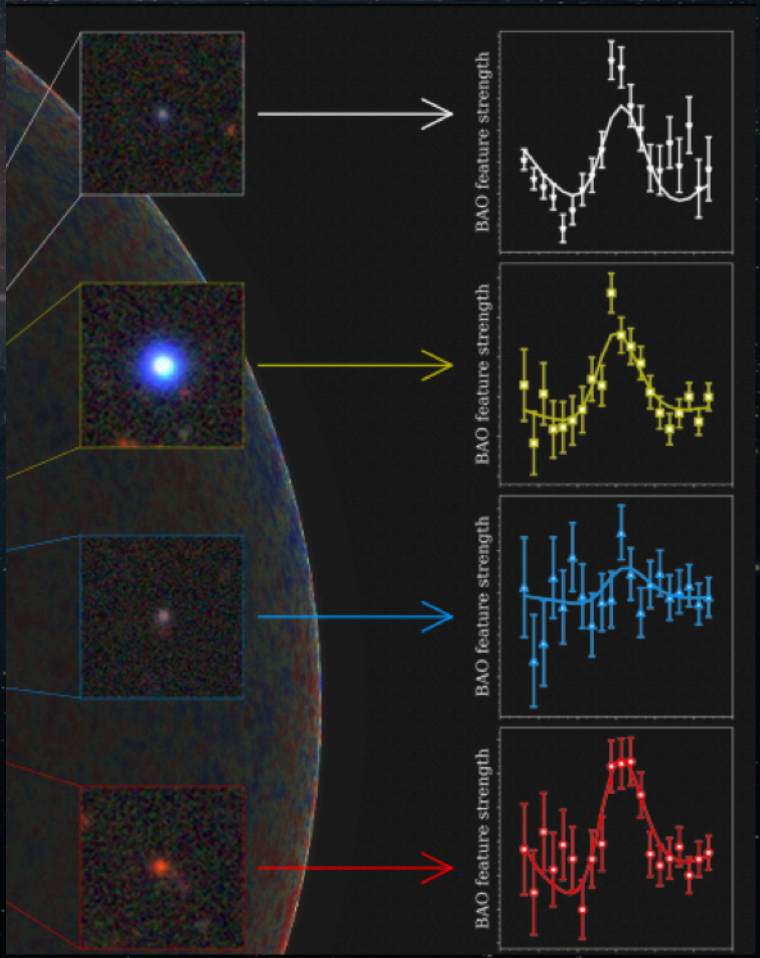
eBOSS tracers

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

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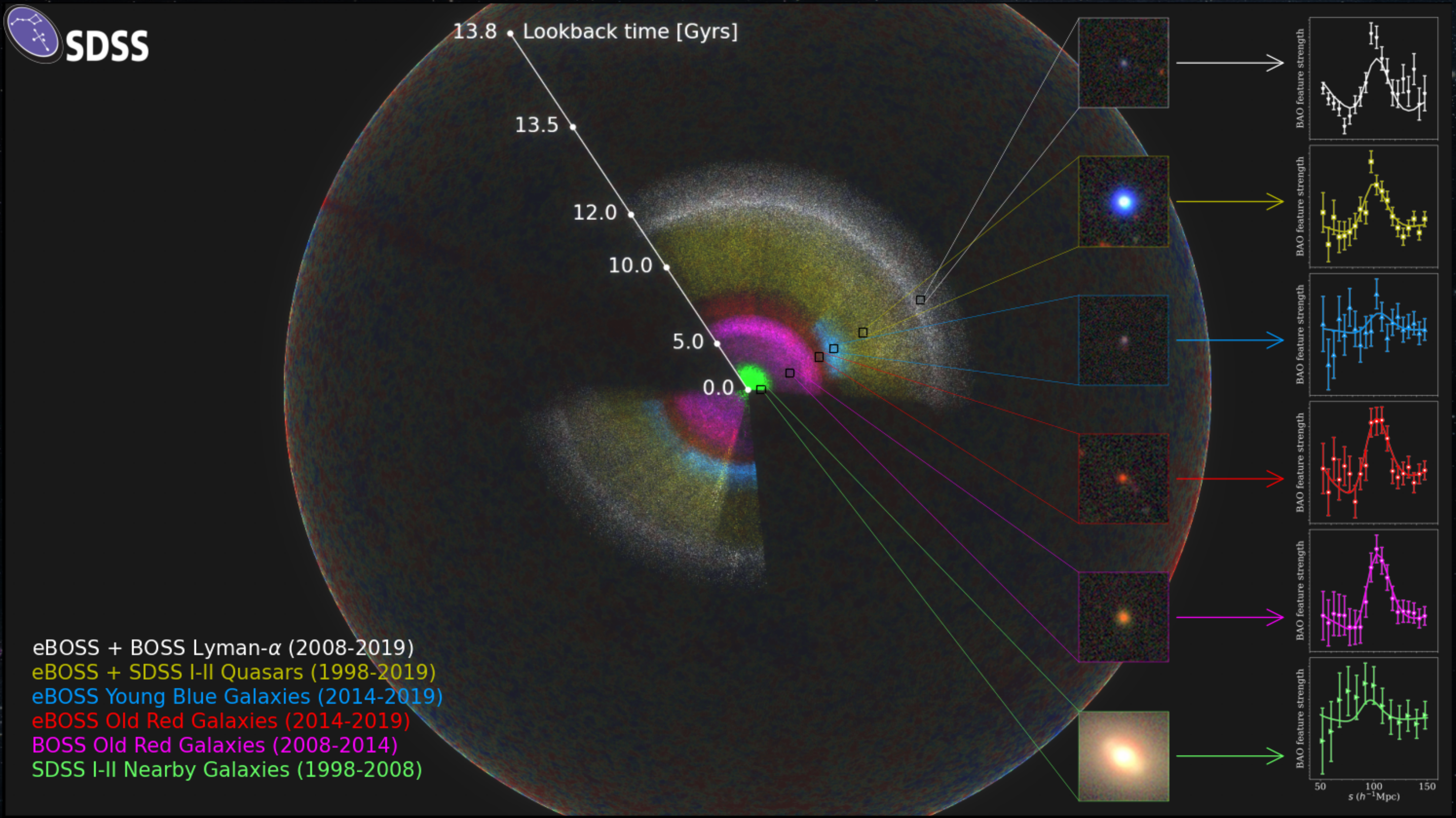

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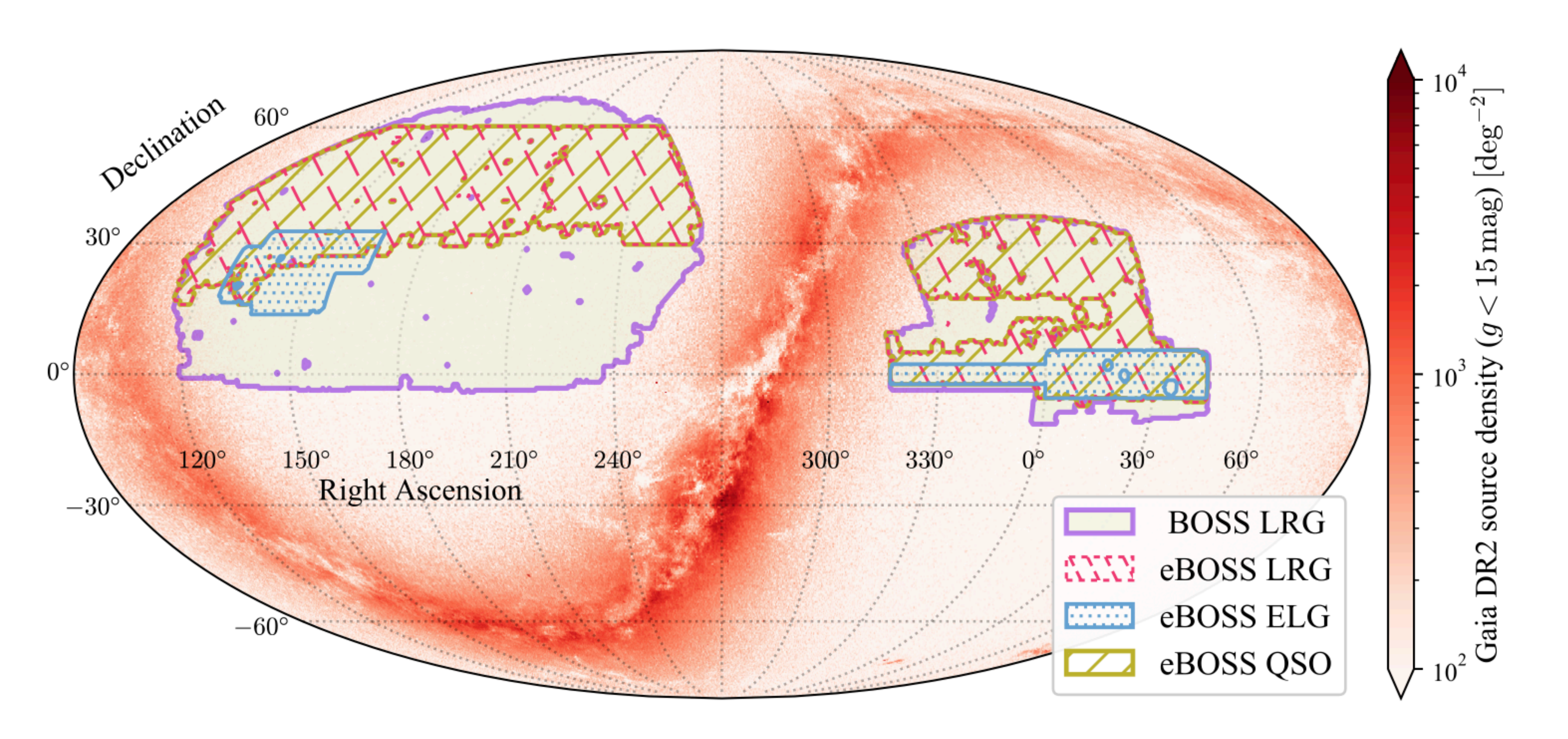
eBOSS footprint



C. Zhao+, 2020

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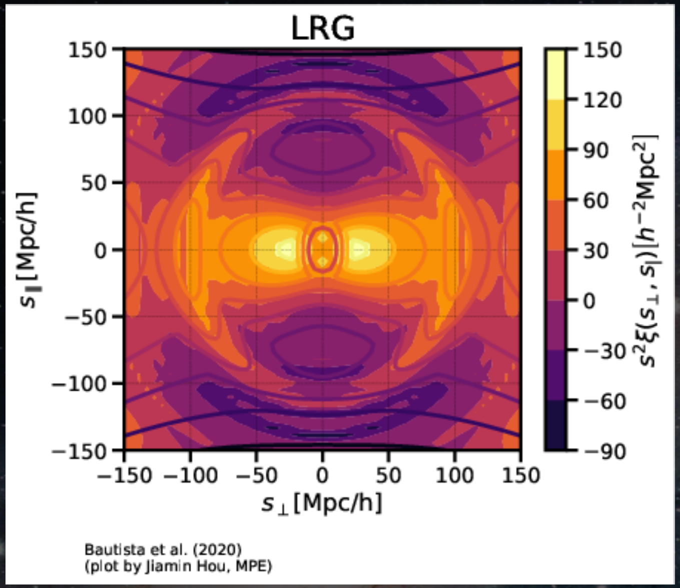
Luminous Red Galaxies (LRGs)

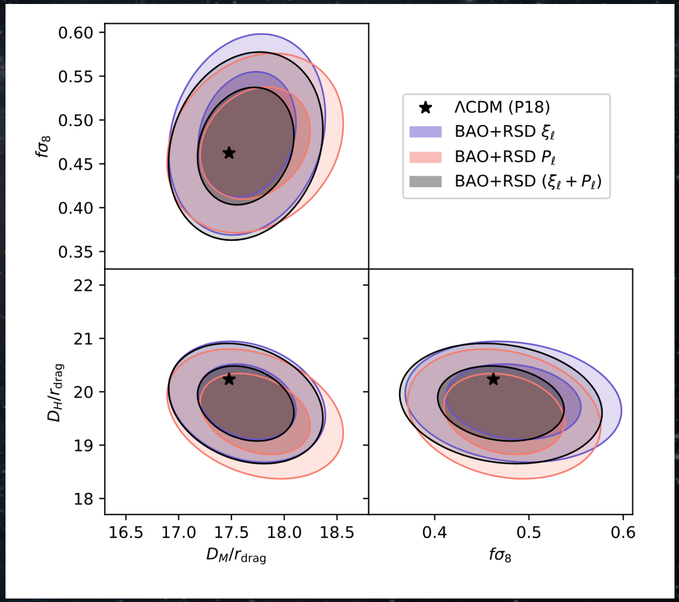
$0.6 < z < 1.0$, $z_{eff} = 0.77$

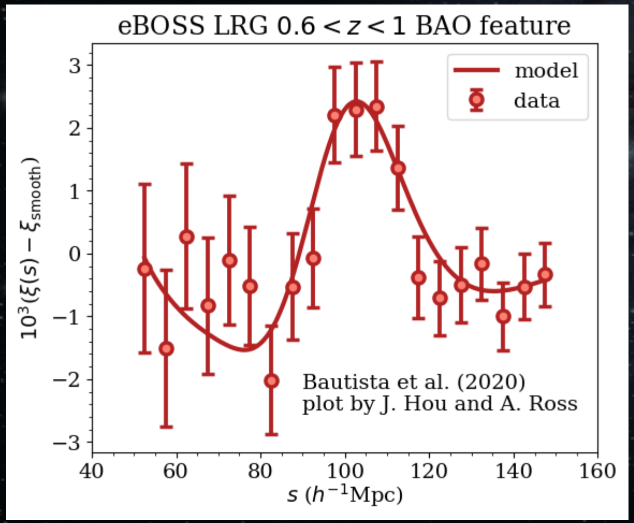
~9500 deg^2

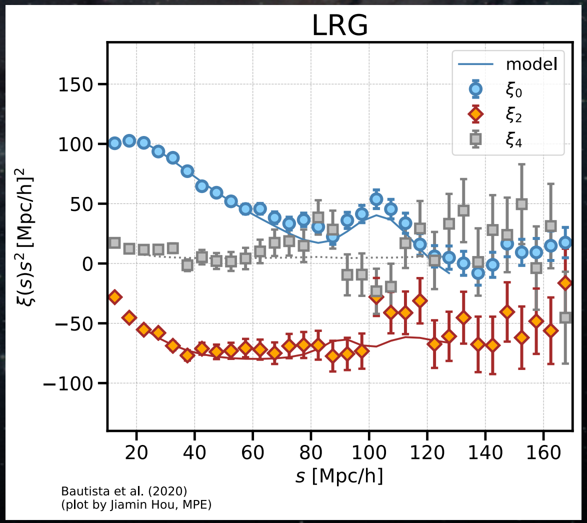
~400 K spectra

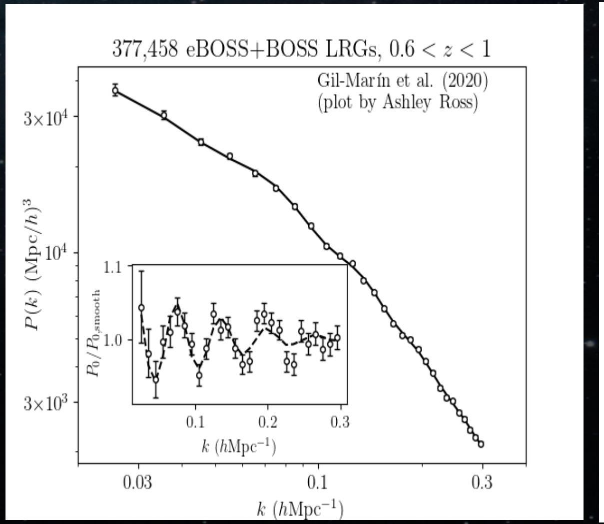
Bautista+, 2020; Gil-Marin+, 2020

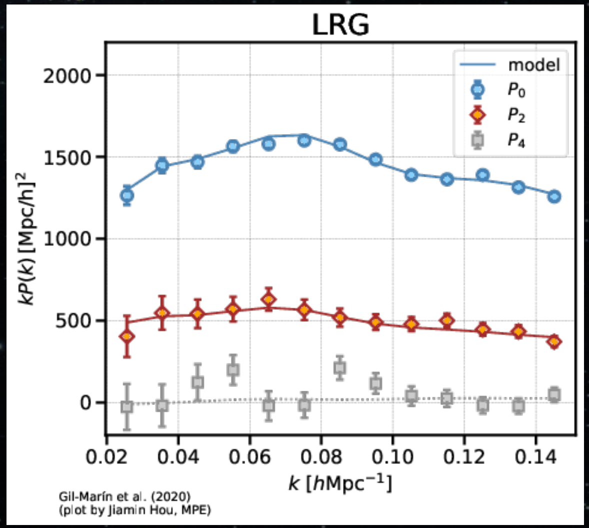












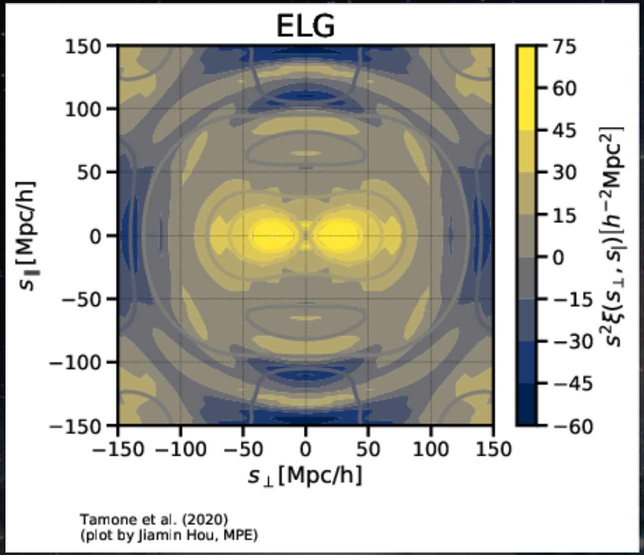
Emission line Galaxies (ELGs)

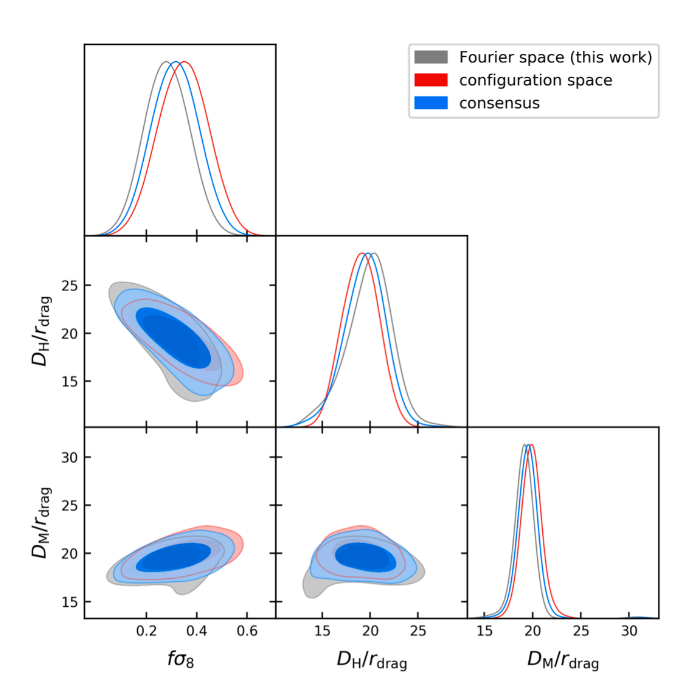
$0.6 < z < 1.1$, $z_{eff} = 0.845$

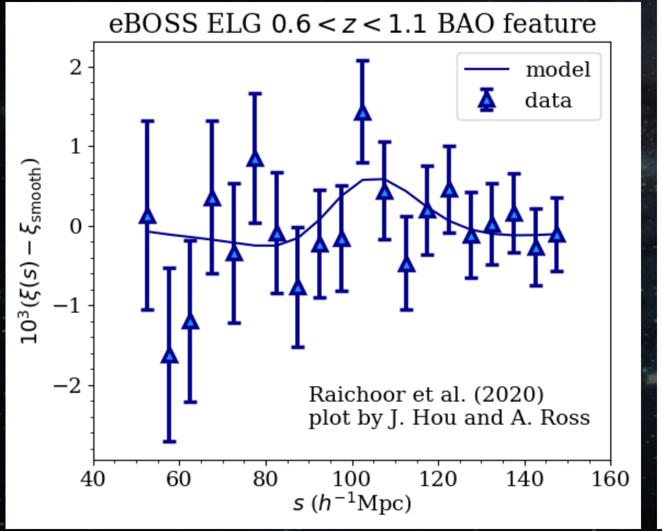
~730 deg^2

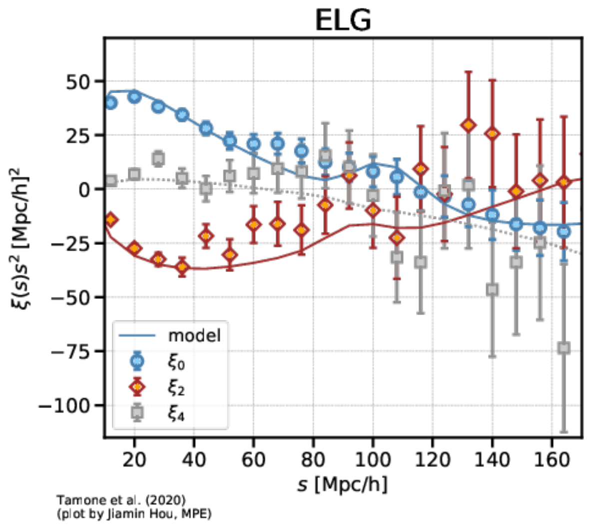
~170 K spectra

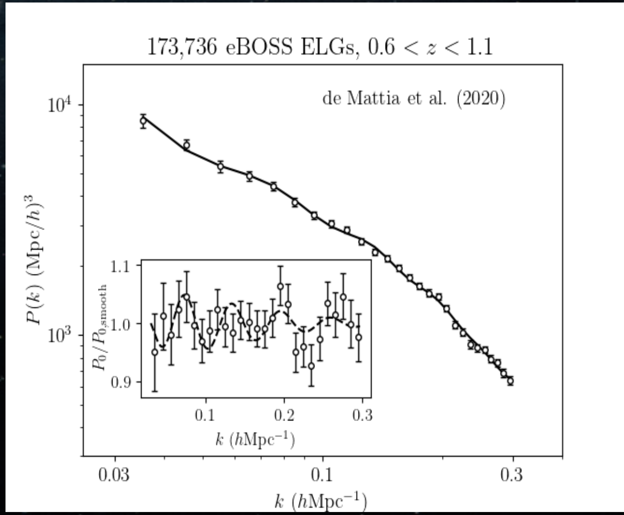
de Mattia+, 2020; Tamone+, 2020

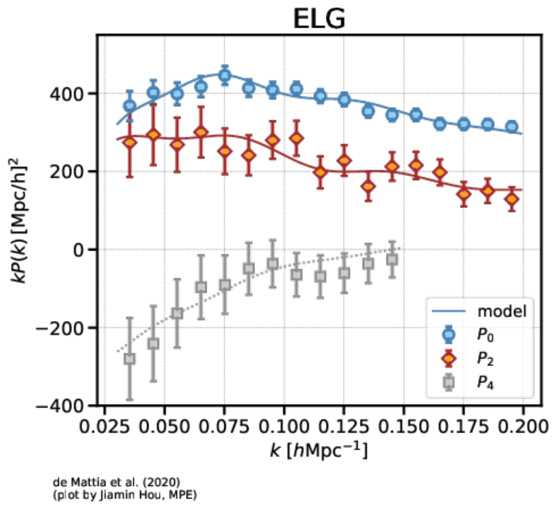












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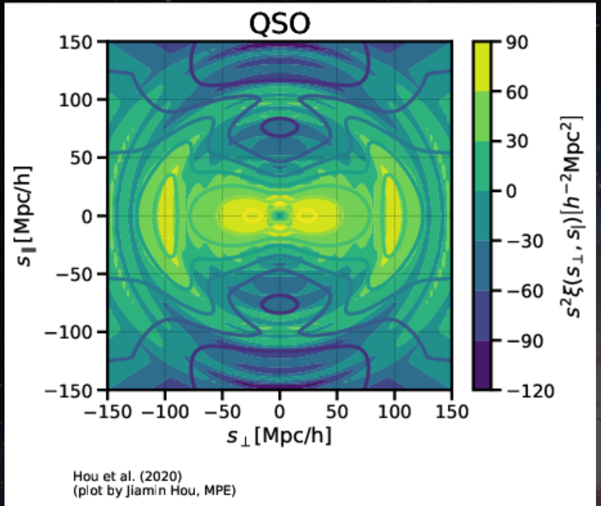
Clustering quasars (QSOs)

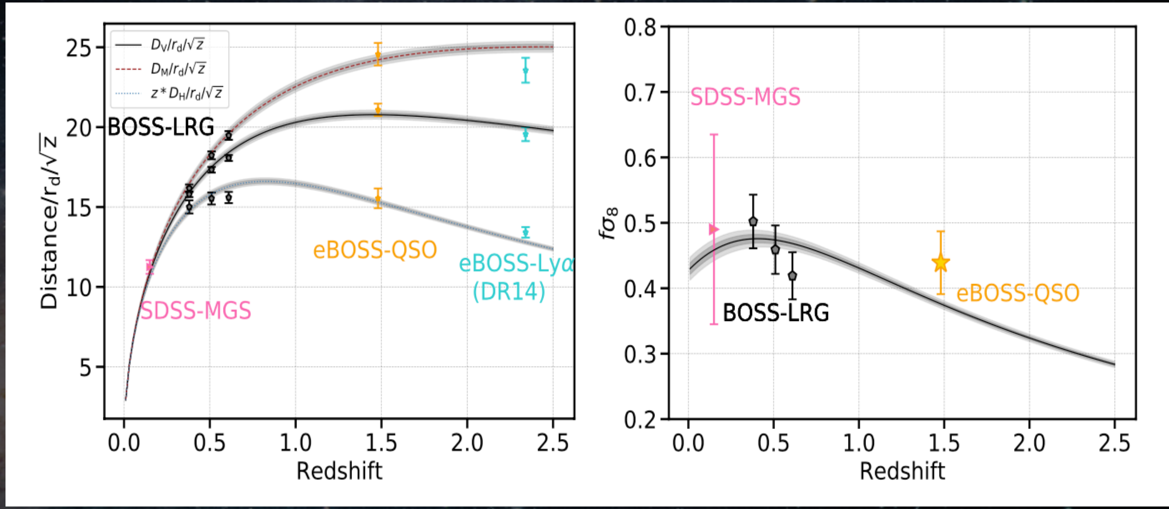
$0.8 < z < 2.2$, $z_{eff} = 1.48$

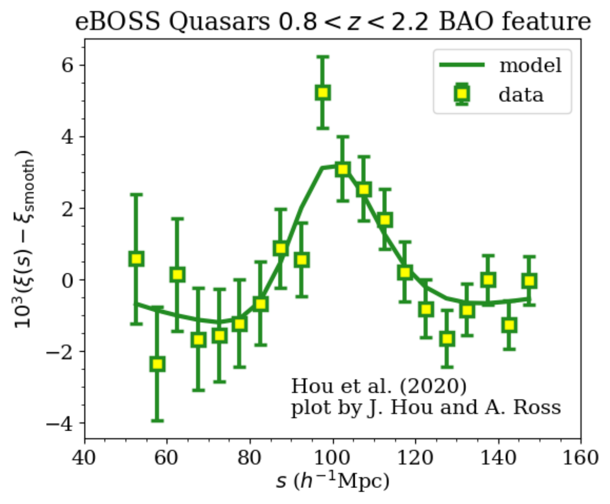
~4700 deg^2

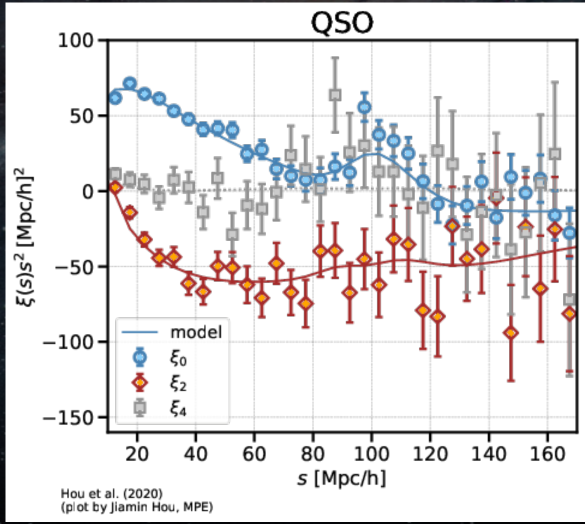
~340 K spectra

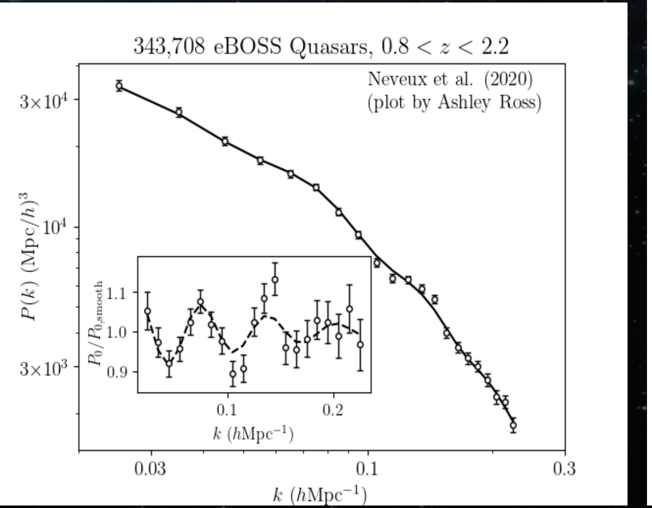
Hou+, 2020; Neveux+, 2020

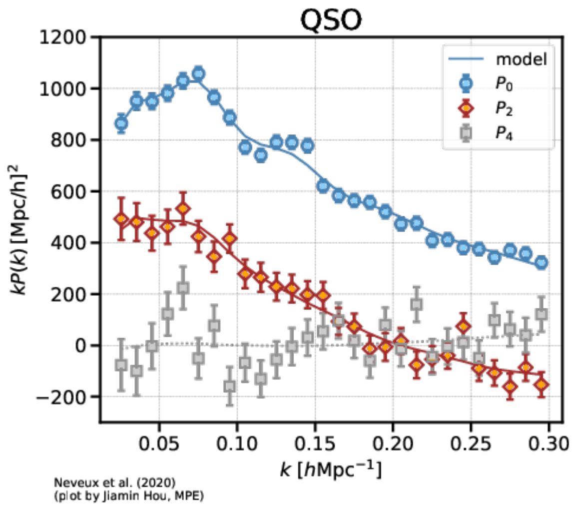












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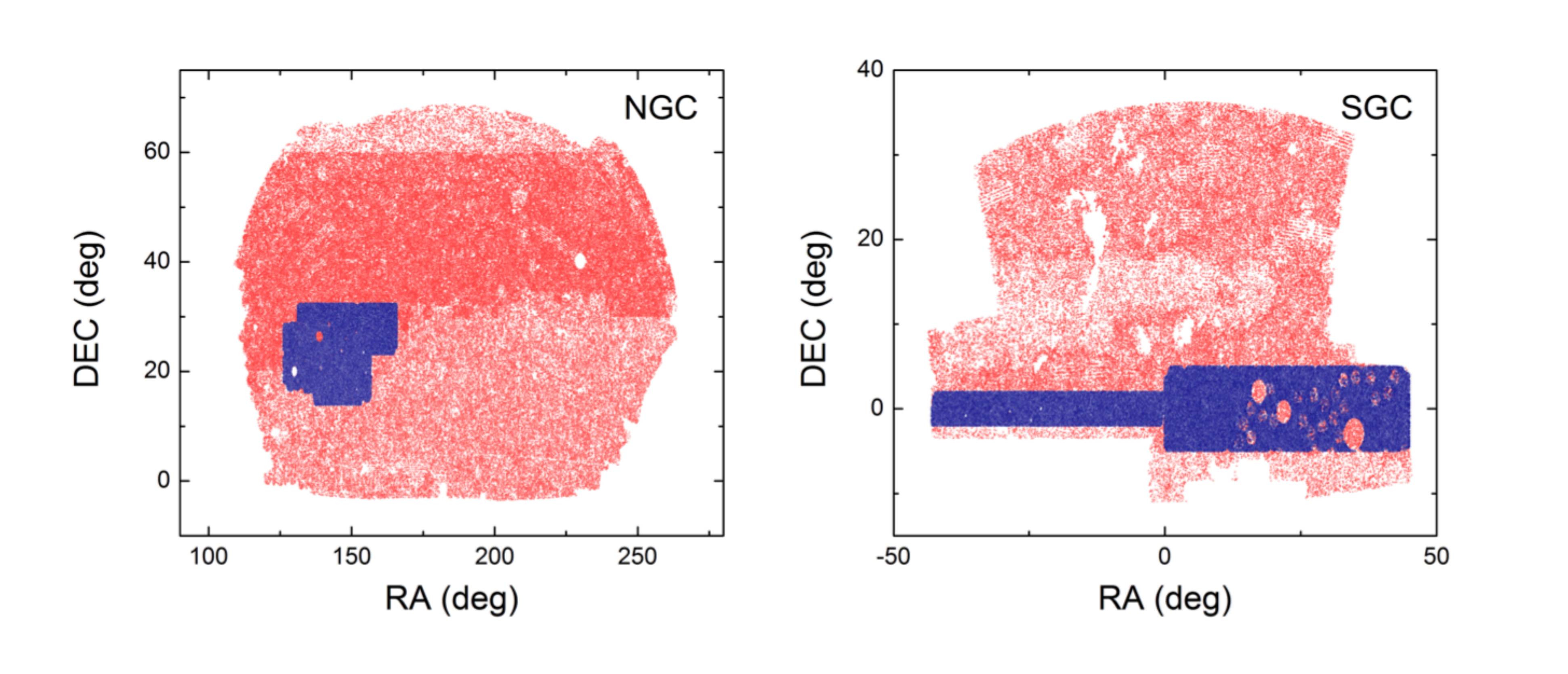
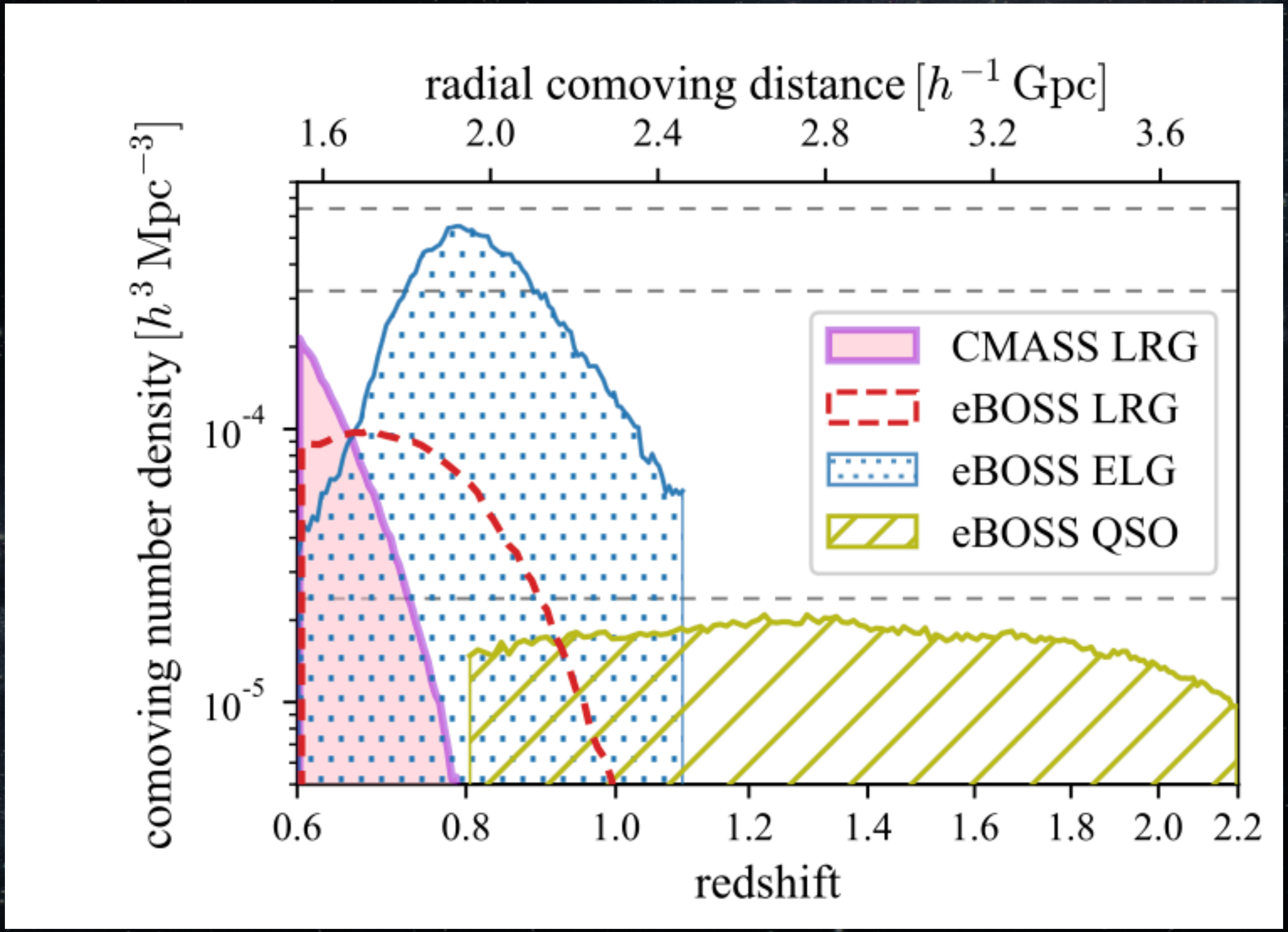
Angular overlap



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

Why cross-correlation is cool?

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

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

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

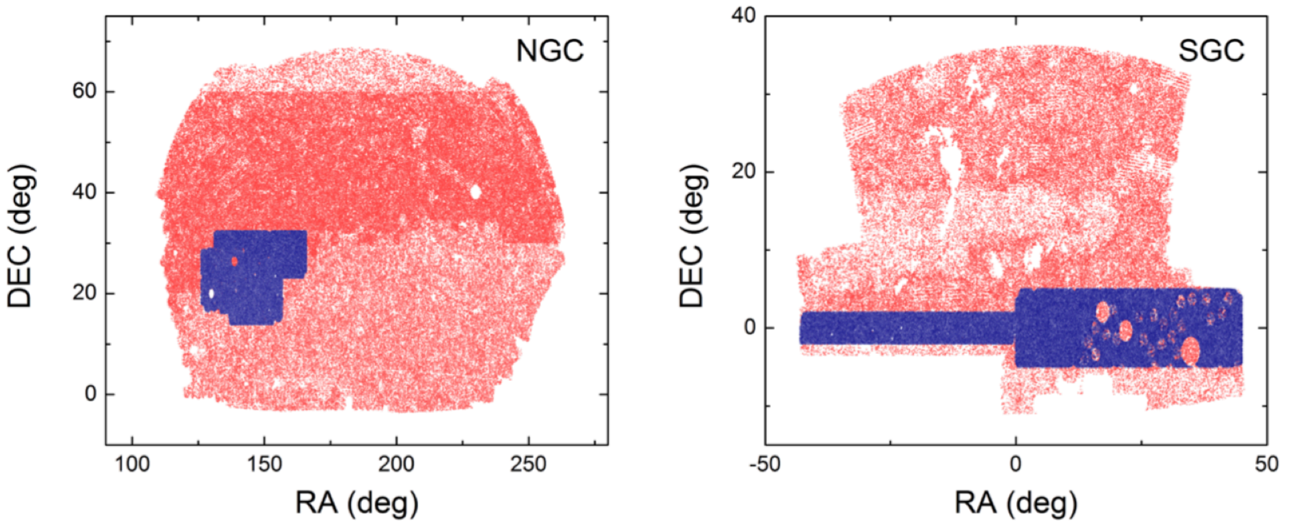
2-tracers: $\delta_{g1} = f\left(\beta^{-1} + \mu^2\right)\delta + \epsilon_1$ $\delta_{g2} = f\left(\alpha\beta^{-1} + \mu^2\right)\delta + \epsilon_2$

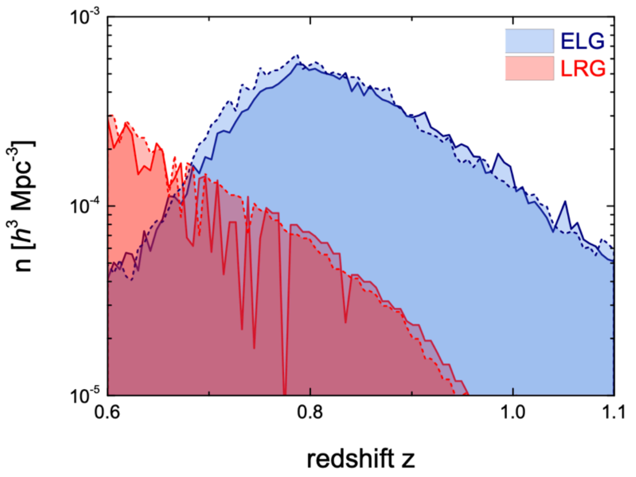
$$C \equiv \begin{bmatrix} \langle\delta_{g1}^2\rangle & \langle\delta_{g1}\delta_{g2}\rangle \\ \langle\delta_{g2}\delta_{g1}\rangle & \langle\delta_{g2}^2\rangle \end{bmatrix} = \frac{P_{\theta\theta}}{2}\begin{bmatrix} \left(\beta^{-1}+\mu^2\right)^2 & \left(\beta^{-1}+\mu^2\right)\left(\alpha\beta^{-1}+\mu^2\right)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

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

McDonald & Seljak 2008; Seljak 2009

- 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)

$$\hat{P}_\ell(k) = \frac{2\ell+1}{I}\int \frac{\mathrm{d}\Omega_k}{4\pi}\left[\int \mathrm{d}\boldsymbol{r}_1 F(\boldsymbol{r}_1)\,\mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}_1} \times \int \mathrm{d}\boldsymbol{r}_2 F(\boldsymbol{r}_2)\,\mathrm{e}^{-\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}_2}\mathcal{L}_\ell\left(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{r}}_2\right) - P_{\mathrm{shot}}\right]$$

$$\widehat{P}_\ell(k) = \frac{2\ell+1}{2I}\int \frac{\mathrm{d}\Omega_k}{4\pi}\left[F_{0,\mathrm{A}}(\mathbf{k})F_{\ell,\mathrm{B}}(-\mathbf{k}) + F_{0,\mathrm{B}}(\mathbf{k})F_{\ell,\mathrm{A}}(-\mathbf{k})\right],$$

$$F(\boldsymbol{r}) = \frac{w(\boldsymbol{r})}{I^{1/2}}\left[n(\boldsymbol{r}) - \alpha n_{\mathrm{s}}(\boldsymbol{r})\right],$$

$$F_\ell(\mathbf{k}) \equiv \int \mathrm{d}\mathbf{r}\, F(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}}\mathcal{L}_\ell(\hat{\mathbf{k}}\cdot\hat{\mathbf{r}}) = \frac{4\pi}{2\ell+1}\sum_{m=-\ell}^{\ell} Y_{\ell m}(\hat{\mathbf{k}})\int \mathrm{d}\mathbf{r}\, F(\mathbf{r}) Y^*_{\ell m}(\hat{\mathbf{r}}) e^{i\mathbf{k}\cdot\mathbf{r}}$$

$$I \equiv \int \mathrm{d}\boldsymbol{r}\; w^2(\boldsymbol{r}) n^2(\boldsymbol{r}) \simeq \alpha \sum_i w_i^2 n_{s,i}$$

GBZ+, 2020

Modelling the general P(k) including the cross-correlation

$$P_{\mathrm{g}}^{\mathrm{AB}}(k,\mu) = D_{\mathrm{FoG}}(k,\mu)\Big[P_{\mathrm{g},\delta\delta}^{\mathrm{AB}}(k) + 2f\mu^2 P_{\mathrm{g},\delta\theta}^{\mathrm{AB}}(k) + f^2\mu^4 P_{\theta\theta}^{\mathrm{AB}}(k) + A^{\mathrm{AB}}(k,\mu) + B^{\mathrm{AB}}(k,\mu)\Big],$$

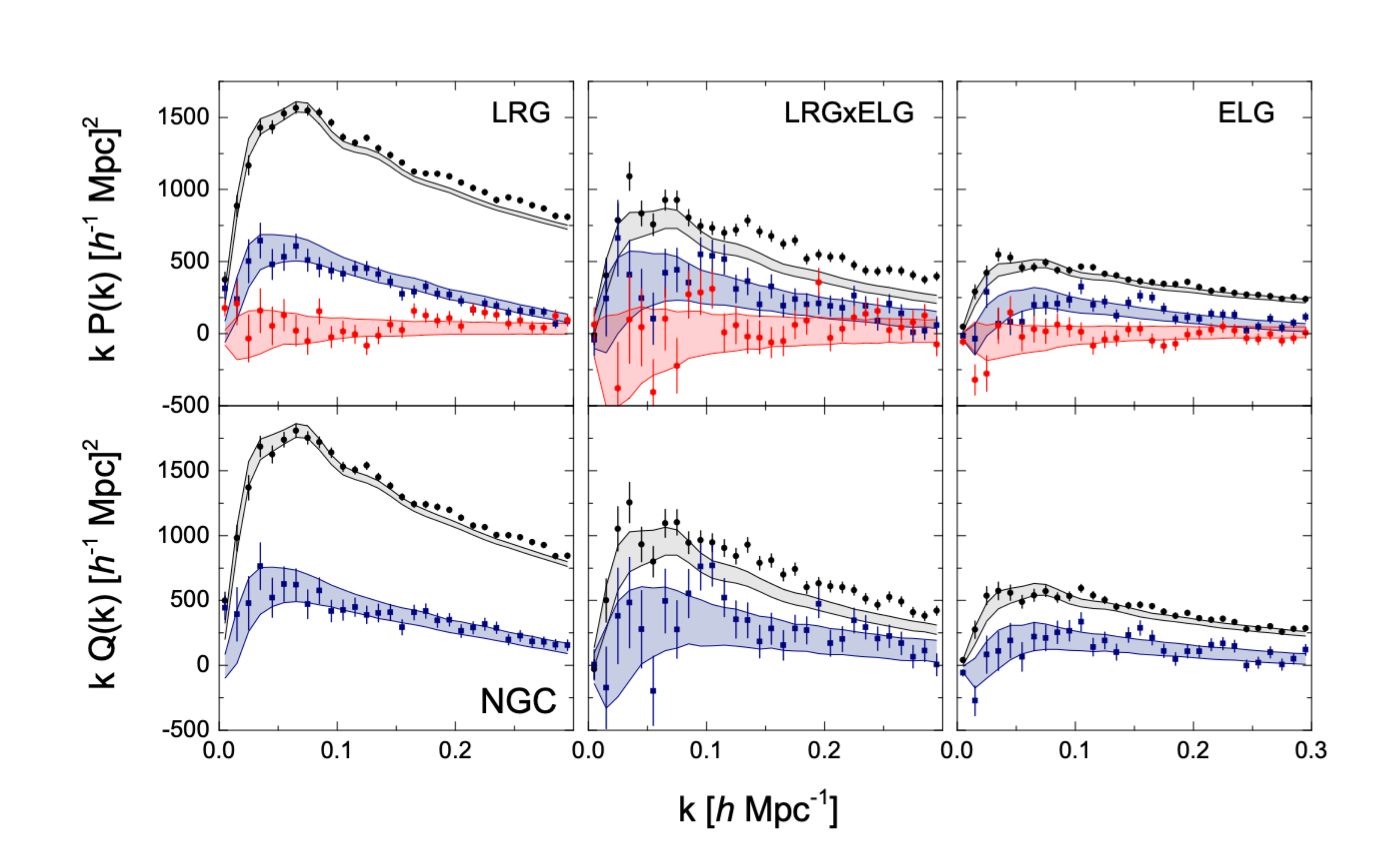
$$\begin{aligned} P_{\mathrm{g},\delta\delta}^{\mathrm{AB}}(k) &= b_1^{\mathrm{A}} b_1^{\mathrm{B}} P_{\delta\delta}(k) + \left(b_1^{\mathrm{A}} b_2^{\mathrm{B}} + b_1^{\mathrm{B}} b_2^{\mathrm{A}}\right) P_{\mathrm{b2},\delta}(k) \\ &+ \left(b_{\mathrm{s2}}^{\mathrm{A}} b_1^{\mathrm{B}} + b_{\mathrm{s2}}^{\mathrm{B}} b_1^{\mathrm{A}}\right) P_{\mathrm{bs2},\delta}(k) \\ &+ \left(b_{\mathrm{s2}}^{\mathrm{A}} b_2^{\mathrm{B}} + b_{\mathrm{s2}}^{\mathrm{B}} b_2^{\mathrm{A}}\right) P_{\mathrm{b2s2}}(k) \\ &+ \left(b_{\mathrm{3nl}}^{\mathrm{A}} b_1^{\mathrm{B}} + b_{\mathrm{3nl}}^{\mathrm{B}} b_1^{\mathrm{A}}\right) \sigma_3^2(k) P_m^{\mathrm{L}}(k) \\ &+ b_2^{\mathrm{A}} b_2^{\mathrm{B}} P_{\mathrm{b22}}(k) + b_{\mathrm{s2}}^{\mathrm{A}} b_{\mathrm{s2}}^{\mathrm{B}} P_{\mathrm{bs22}}(k) + N_{\mathrm{AB}}, \end{aligned} \tag{25}$$

$$\begin{aligned} P_{\mathrm{g},\delta\theta}^{\mathrm{AB}}(k) &= \frac{1}{2}\Big[\left(b_1^{\mathrm{A}} + b_1^{\mathrm{B}}\right) P_{\delta\theta}(k) + \left(b_2^{\mathrm{A}} + b_2^{\mathrm{B}}\right) P_{\mathrm{b2},\theta}(k) \\ &+ \left(b_{\mathrm{s2}}^{\mathrm{A}} + b_{\mathrm{s2}}^{\mathrm{B}}\right) P_{\mathrm{bs2},\theta}(k) \\ &+ \left(b_{\mathrm{3nl}}^{\mathrm{A}} + b_{\mathrm{3nl}}^{\mathrm{B}}\right) \sigma_3^2(k) P_m^{\mathrm{L}}(k)\Big], \end{aligned} \tag{26}$$

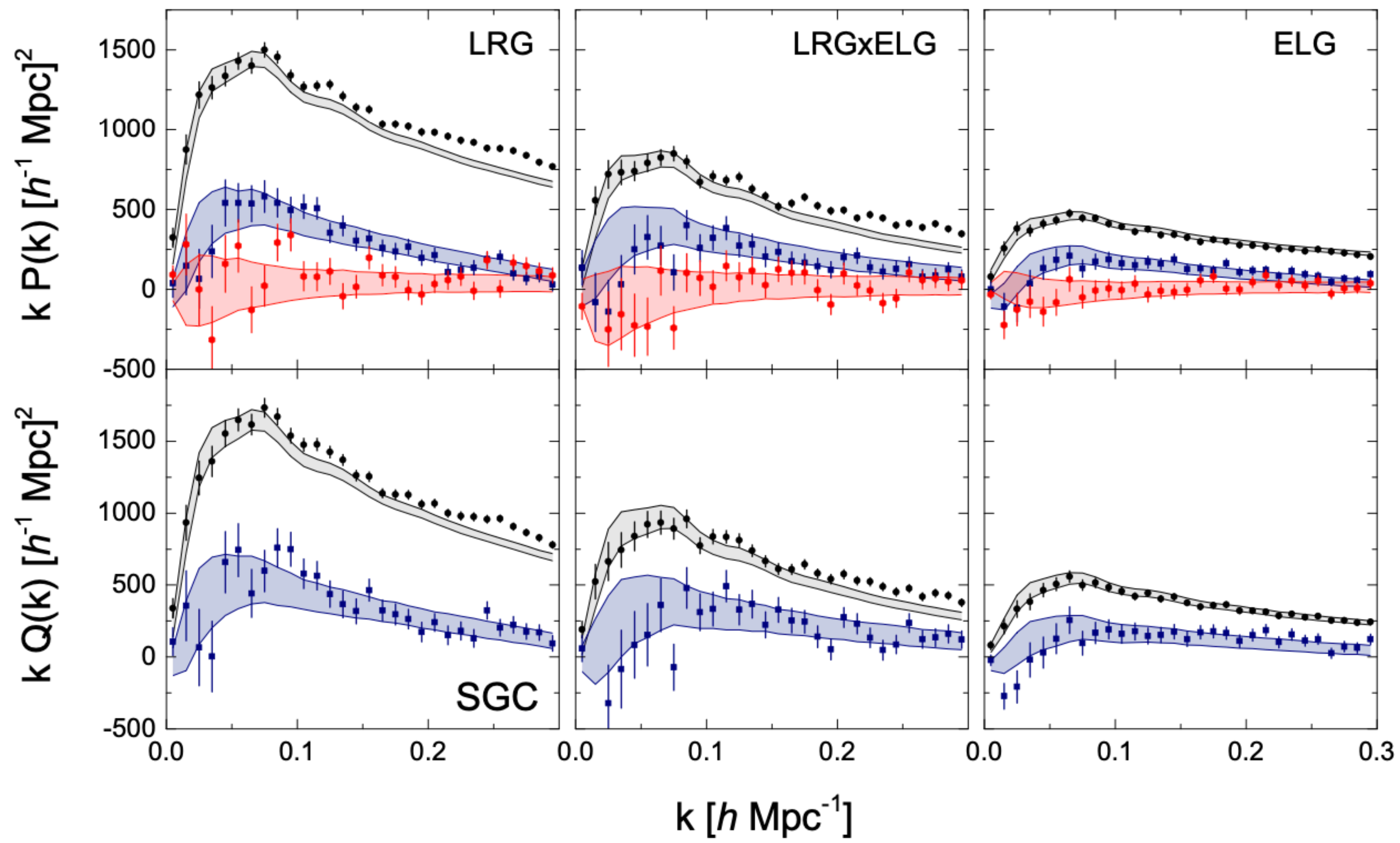
$$P_{\mathrm{g},\theta\theta}(k) = P_{\theta\theta}(k), \tag{27}$$

$$D_{\mathrm{FoG}}(k,\mu) = \left\{1 + [k\mu\sigma_v]^2/2\right\}^{-2}, \tag{28}$$

GBZ+, 2020


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


LRG
LRGxELG
ELG
SGC
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

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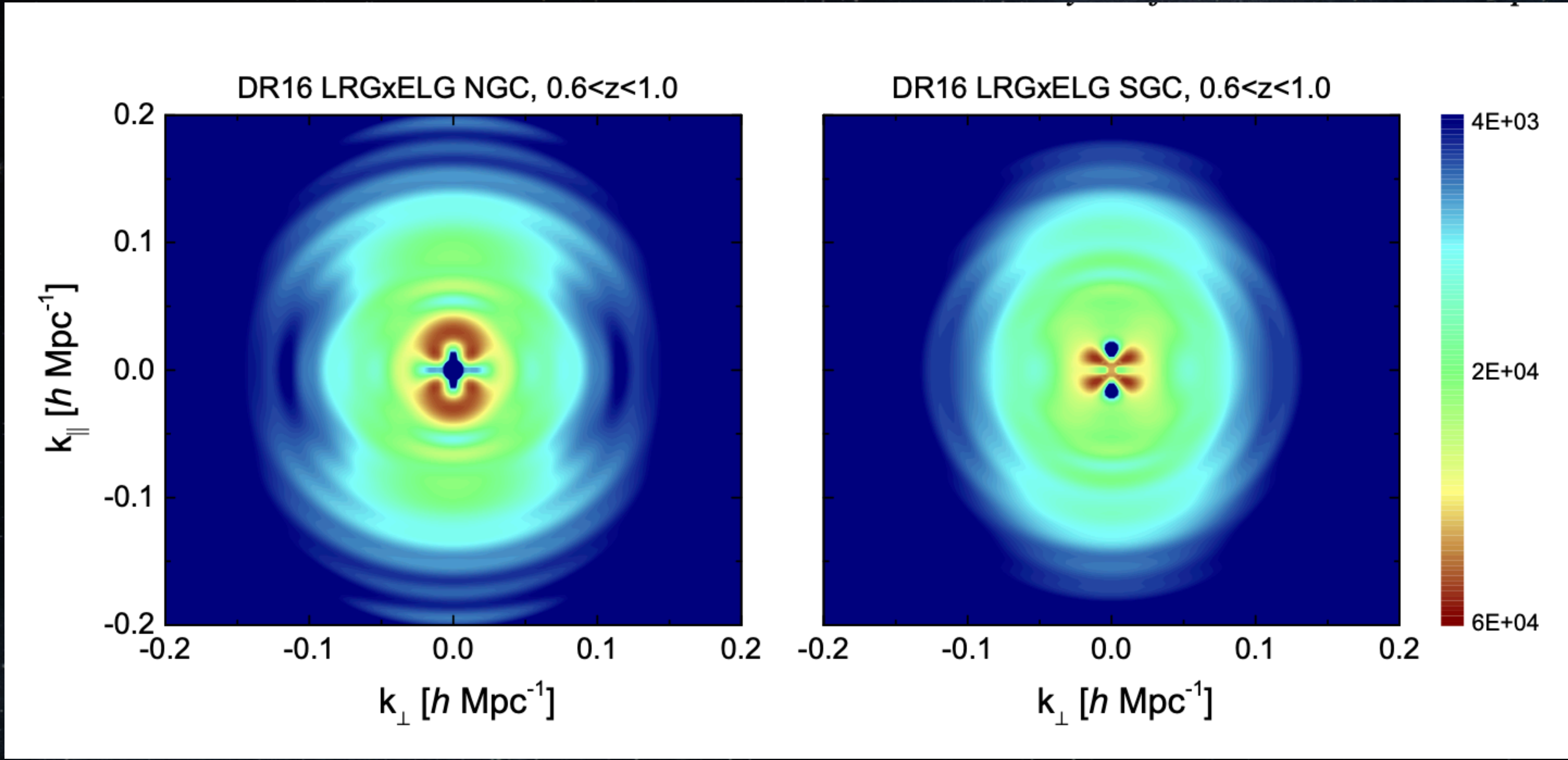

GBZ+, 2020

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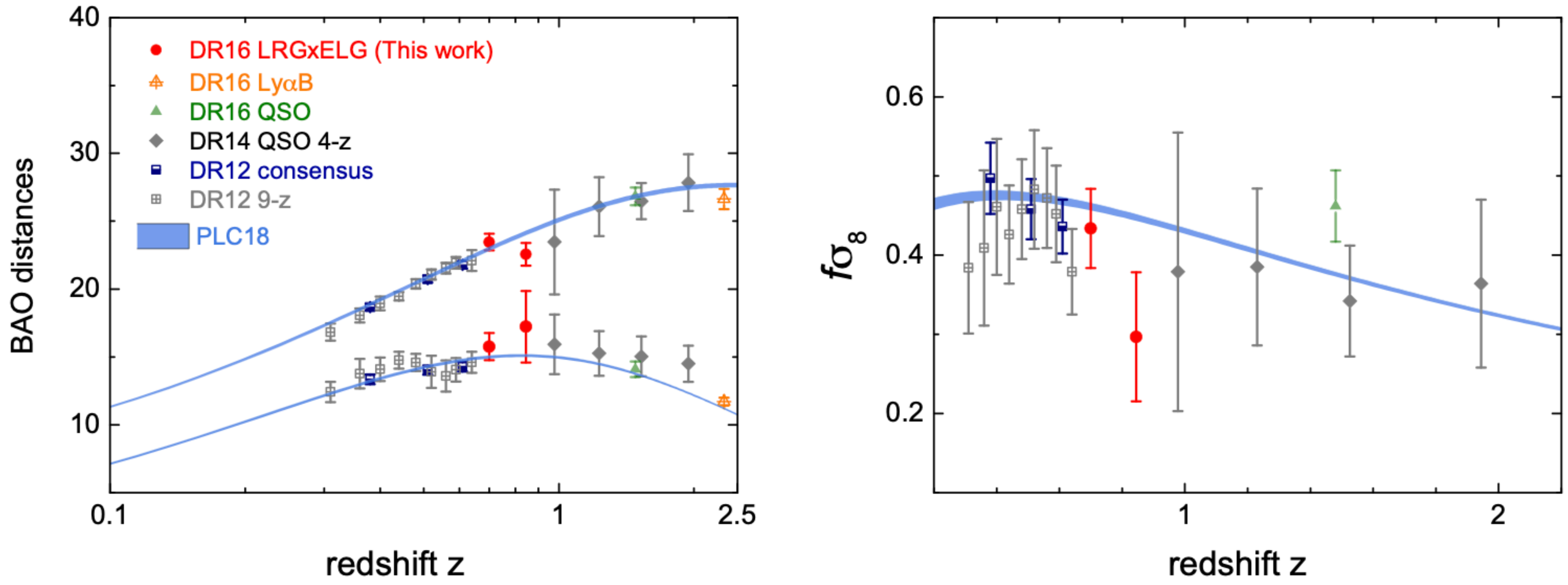

GBZ+, 2020

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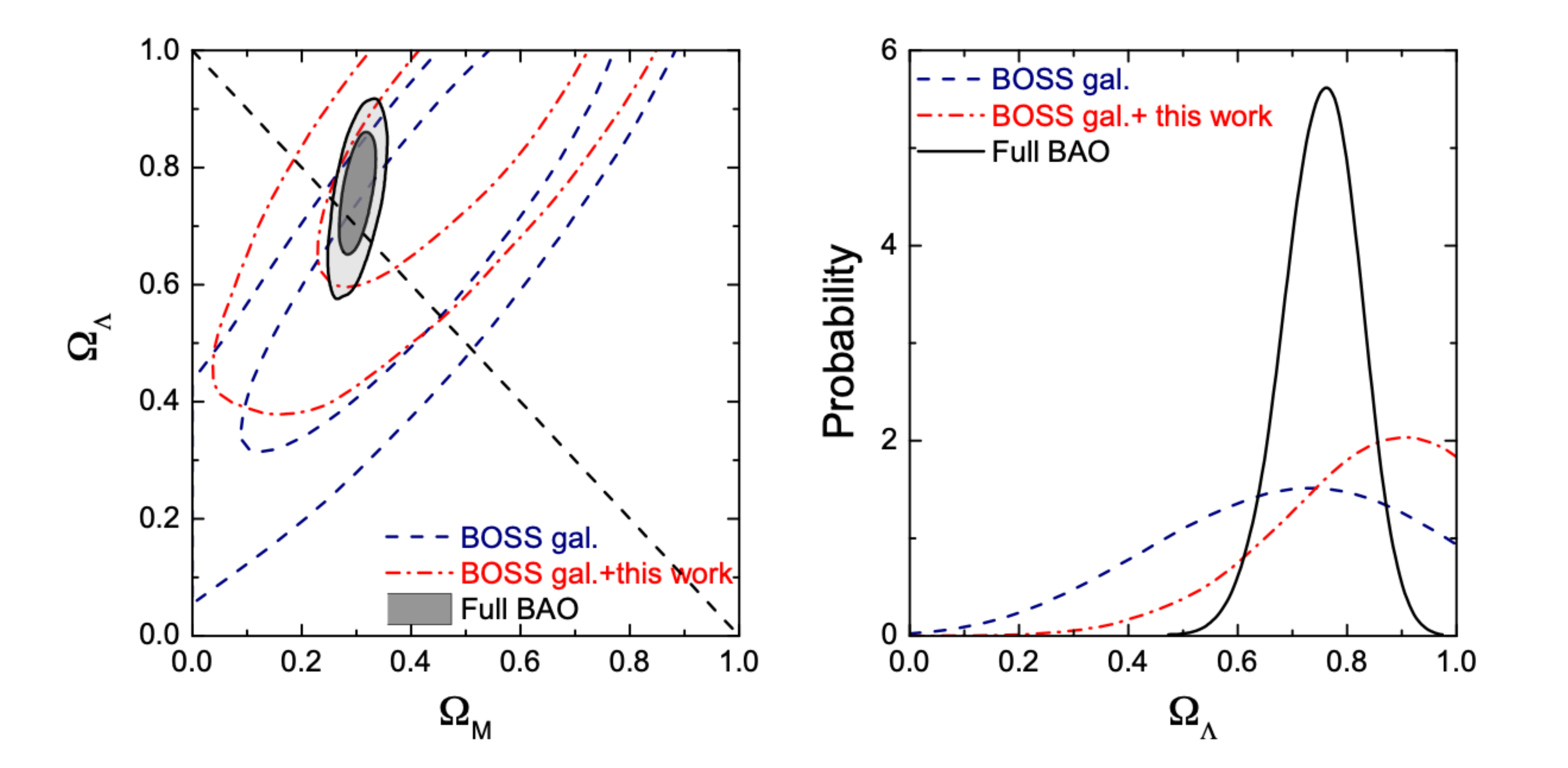
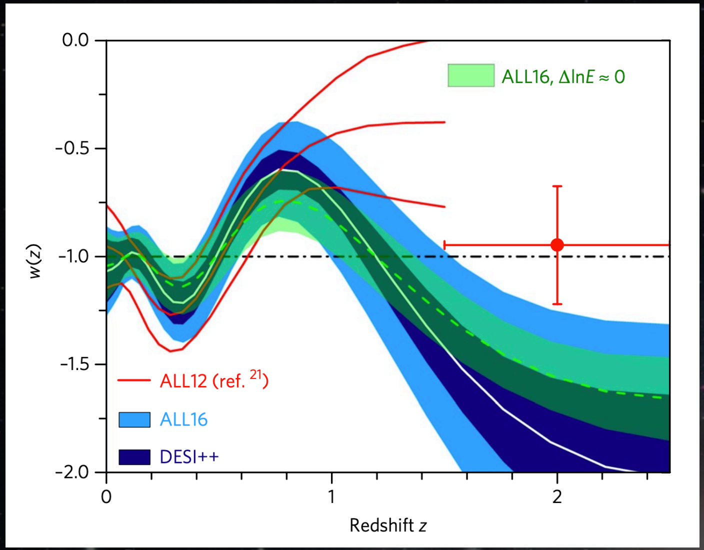
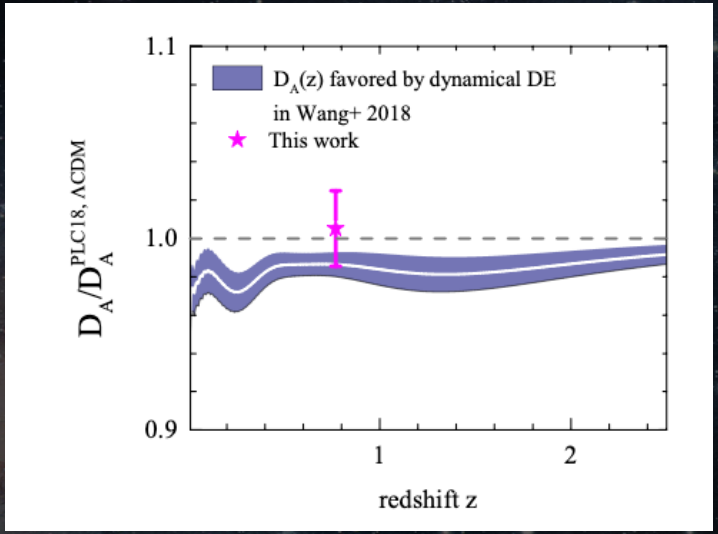


A 11σ detection of $\Omega_\Lambda > 0$

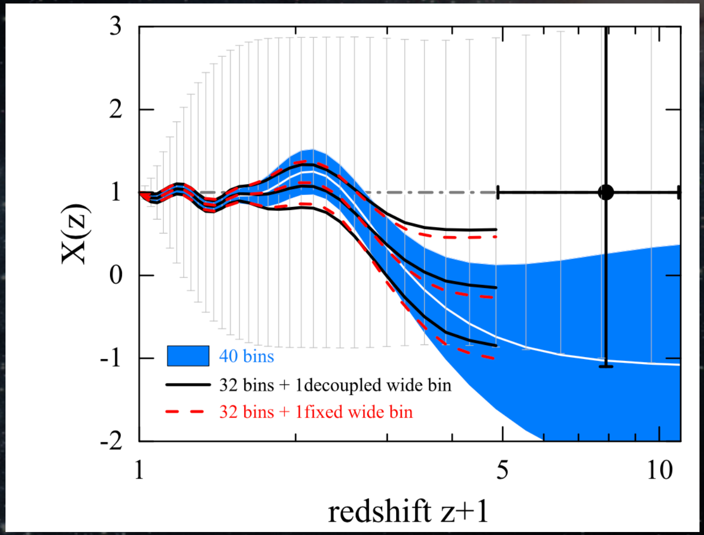
Zhao, Wang et al, (eBOSS), 2007.09011



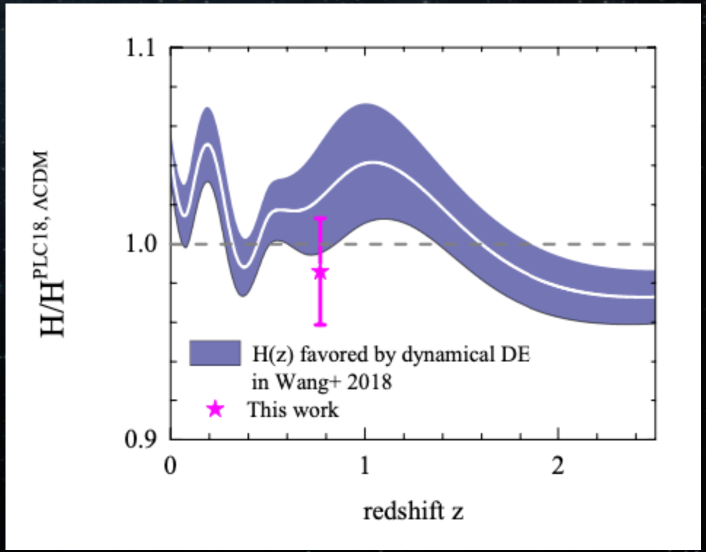
GBZ+, 2017, Nature Astronomy



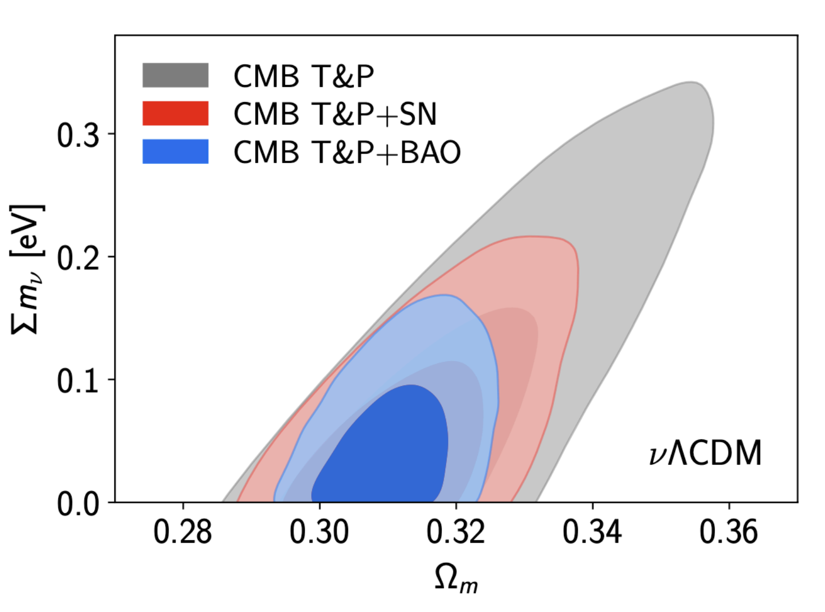
Wang+, 2020



Wang+, 2018, ApJL



Wang+, 2020



Determine the neutrino mass hierarchy?

Not there yet!

$$\sum m_\nu > 0.0588\,\text{eV} \qquad \text{normal hierarchy,}$$
$$\sum m_\nu > 0.0995\,\text{eV} \qquad \text{inverted hierarchy.}$$

Data	95% upper limit [eV]
Planck	0.252
Planck + BAO	0.129
Planck + BAO + RSD	0.102
Planck + SN	0.170
Planck + BAO + RSD + SN	0.099
Planck + BAO + RSD + SN + DES	0.111
Planck + BAO + RSD + SN (νwCDM)	0.139
Planck + BAO + RSD + SN + DES (νwCDM)	0.161

Measuring H_0 from BAO

BAO measures $\beta_\perp(z) = D_M(z)/r_\mathrm{d}$, and $\beta_\parallel(z) = H(z) r_\mathrm{d}$,

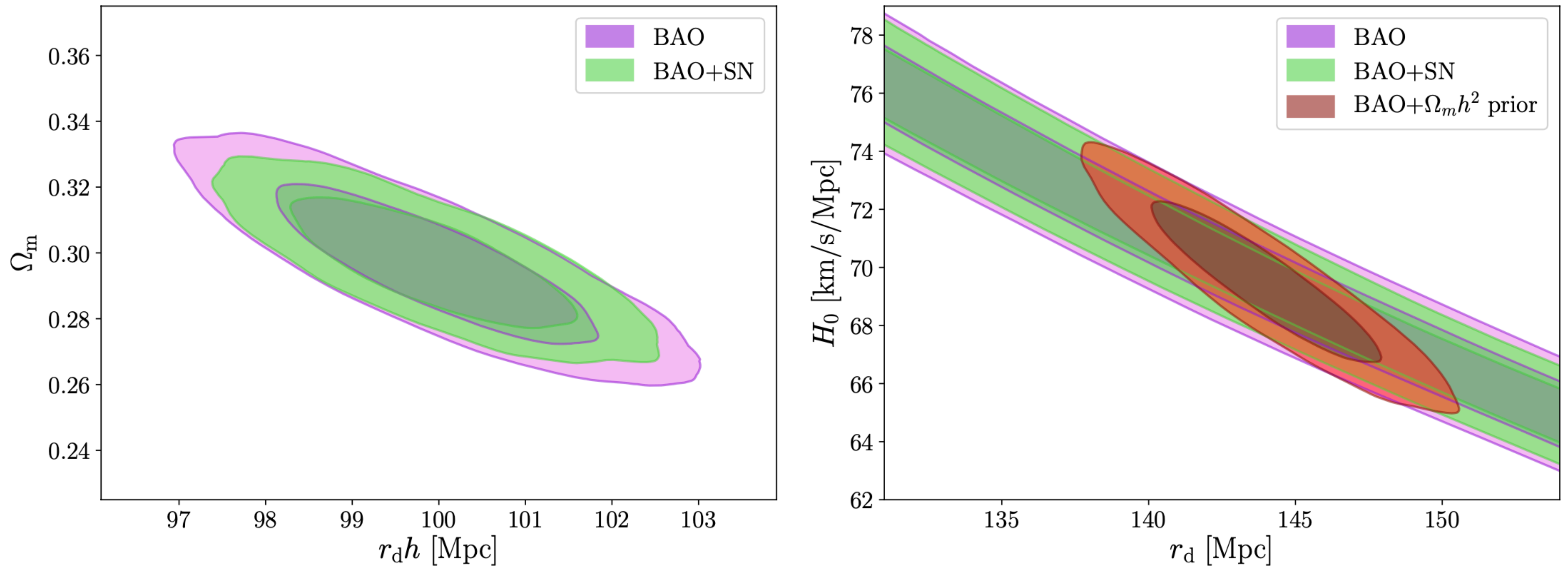
and

$$\beta_\perp(z) = \int_0^z \frac{2998 \text{ Mpc } \mathrm{d}z'}{r_\mathrm{d} h \sqrt{\Omega_\mathrm{m}(1+z')^3 + 1 - \Omega_\mathrm{m}}} \longrightarrow \{r_d h, \Omega_m\}$$

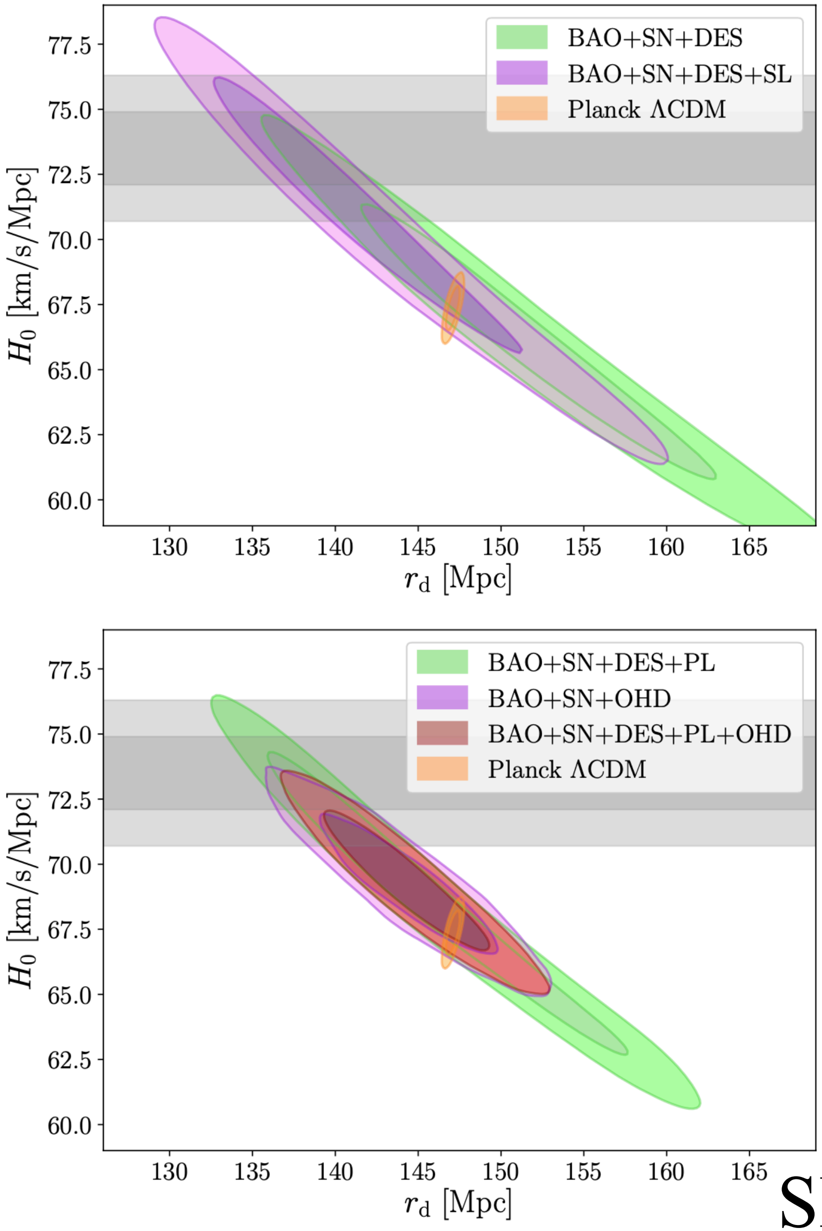
$$= \int_0^z \frac{2998 \text{ Mpc } \mathrm{d}z'}{r_\mathrm{d} \omega_m^{1/2} \sqrt{(1+z')^3 + h^2/\omega_m - 1}}. \longrightarrow \{r_d, h, \omega_m\}$$

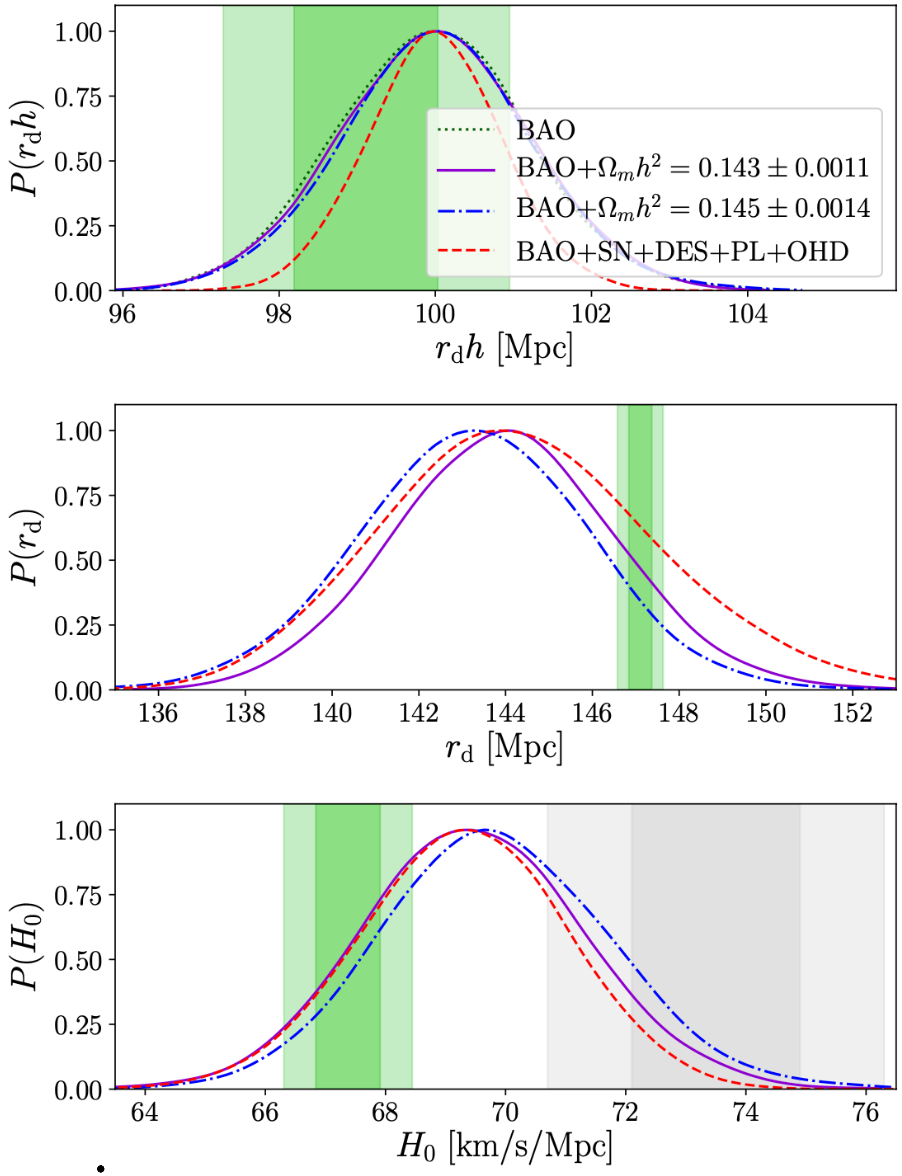
$$h = \frac{H_0}{100}, \ \omega_m = \Omega_m h^2$$

A prior on ω_m is needed to get h!



Pogosian, GB, Jedamzik, 2009.08455



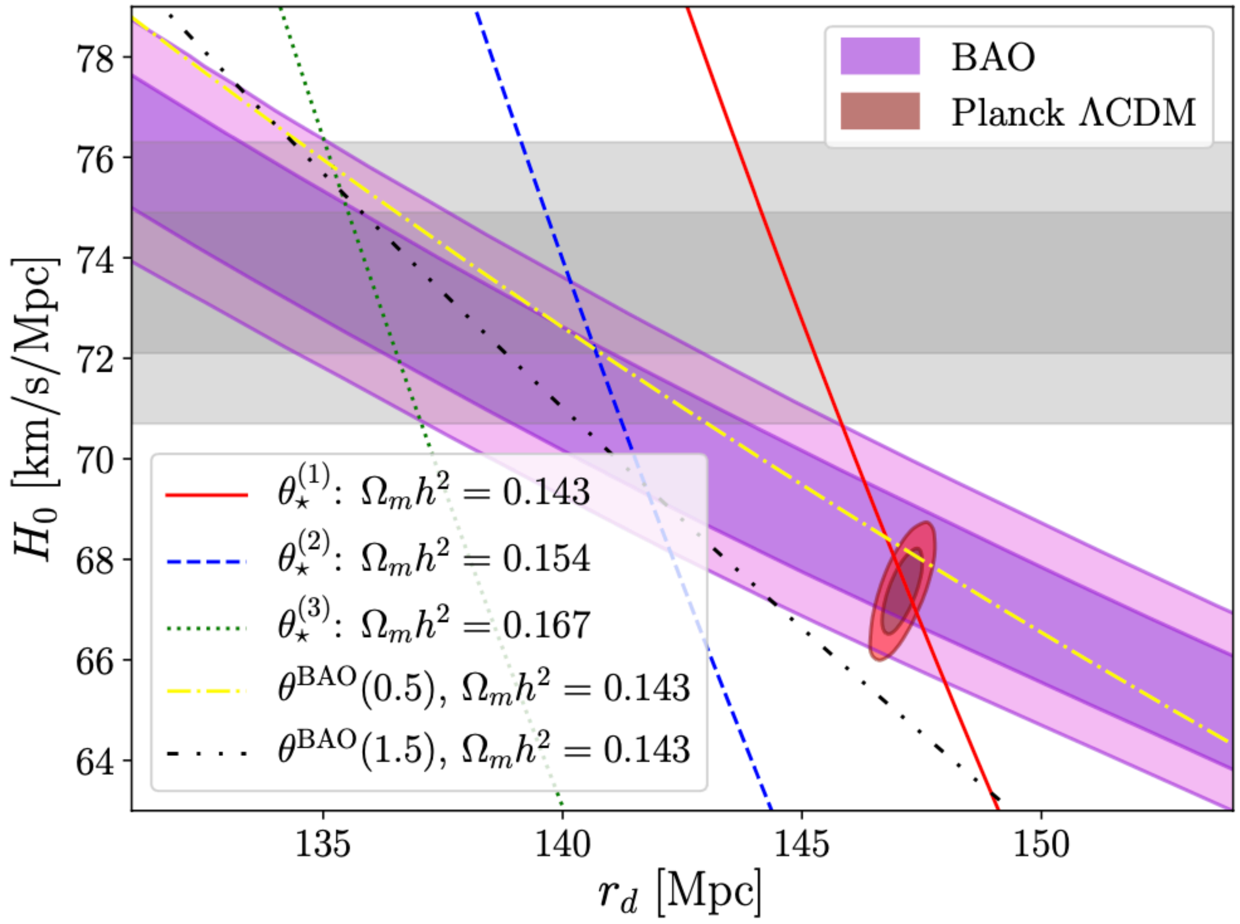


SL: SPTpol lensing

PL: Planck lensing

Pogosian, GB, Jedamzik, 2009.08455

Can the H_0 tension be solved by reducing $r_{\rm d}$?

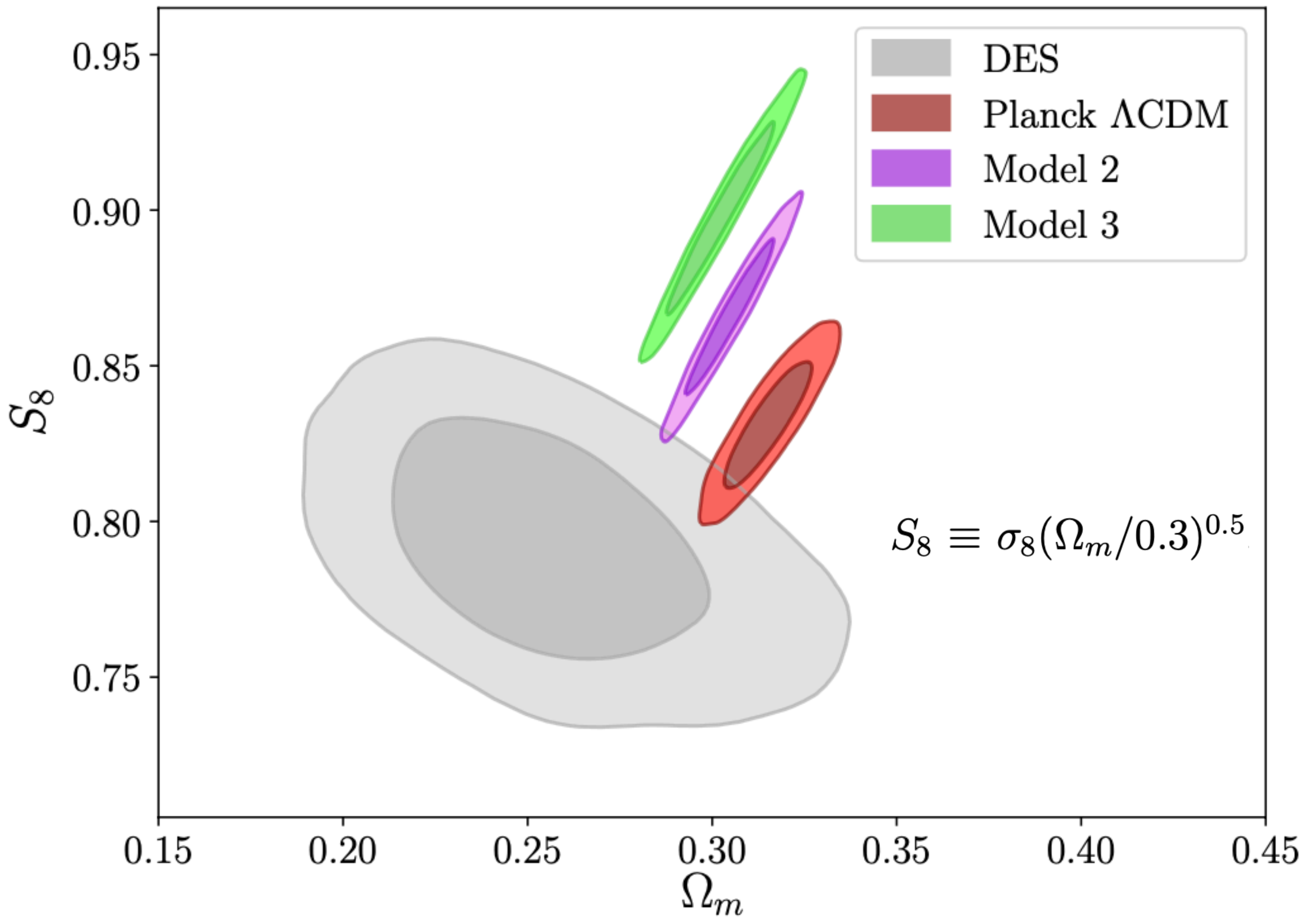


$$\theta_\star \equiv \frac{r_\star}{D(z_\star)} = \frac{\int_{z_\star}^{\infty} c_s(z)\mathrm{d}z/H(z)}{\int_0^{z_\star} c\,\mathrm{d}z/H(z)}\,,$$

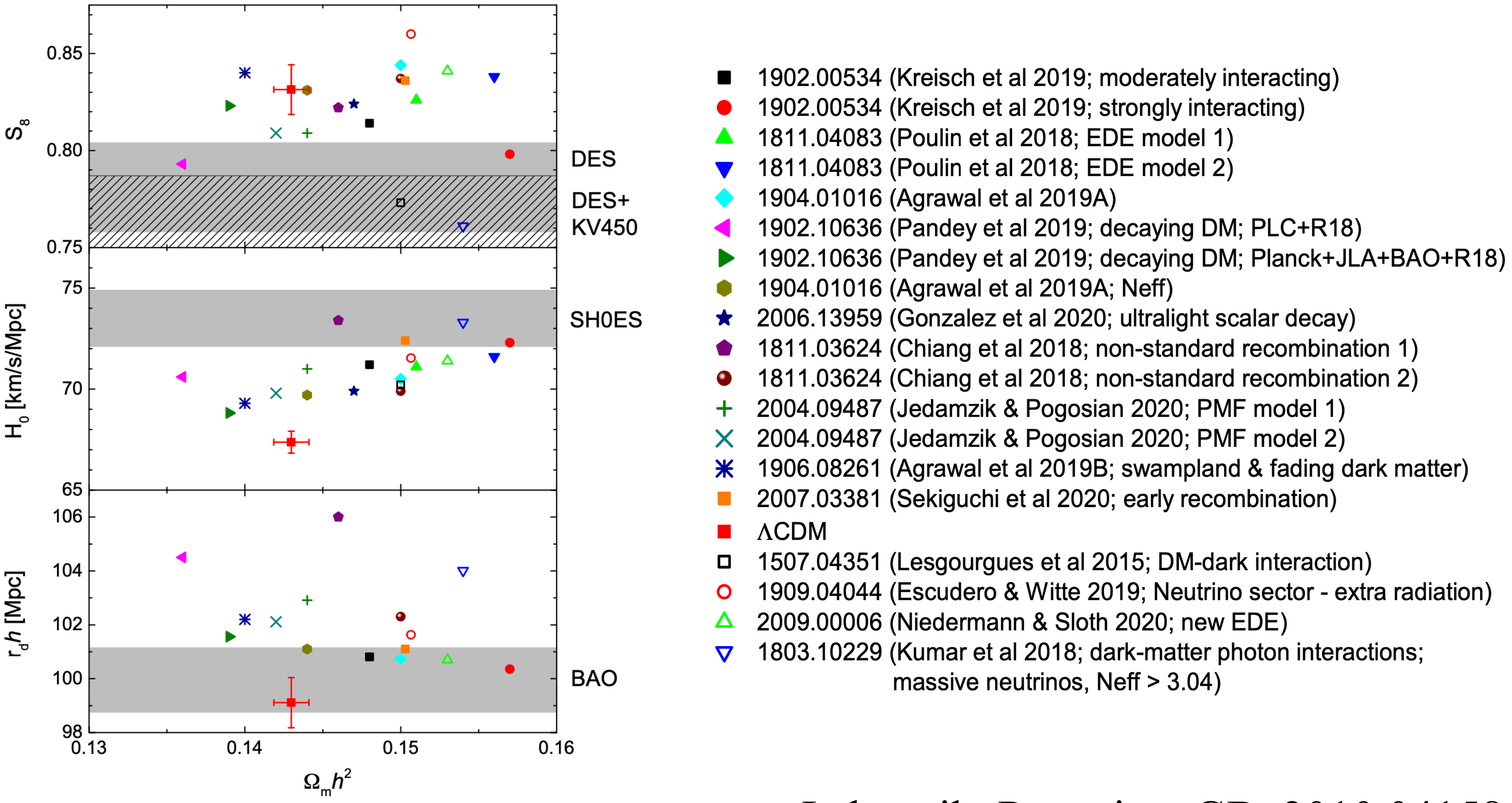
$$\theta^{\rm BAO}(z_{\rm obs}) \equiv \frac{r_{\rm d}}{D(z_{\rm obs})} = \frac{\int_{z_{\rm d}}^{\infty} c_s(z)\mathrm{d}z/H(z)}{\int_0^{z_{\rm obs}} c\,\mathrm{d}z/H(z)}\,,$$

Jedamzik, Pogosian, GB, 2010.04158

Can the H_0 tension be solved by reducing r_d? NO!!



Jedamzik, Pogosian, GB, 2010.04158



Jedamzik, Pogosian, GB, 2010.04158

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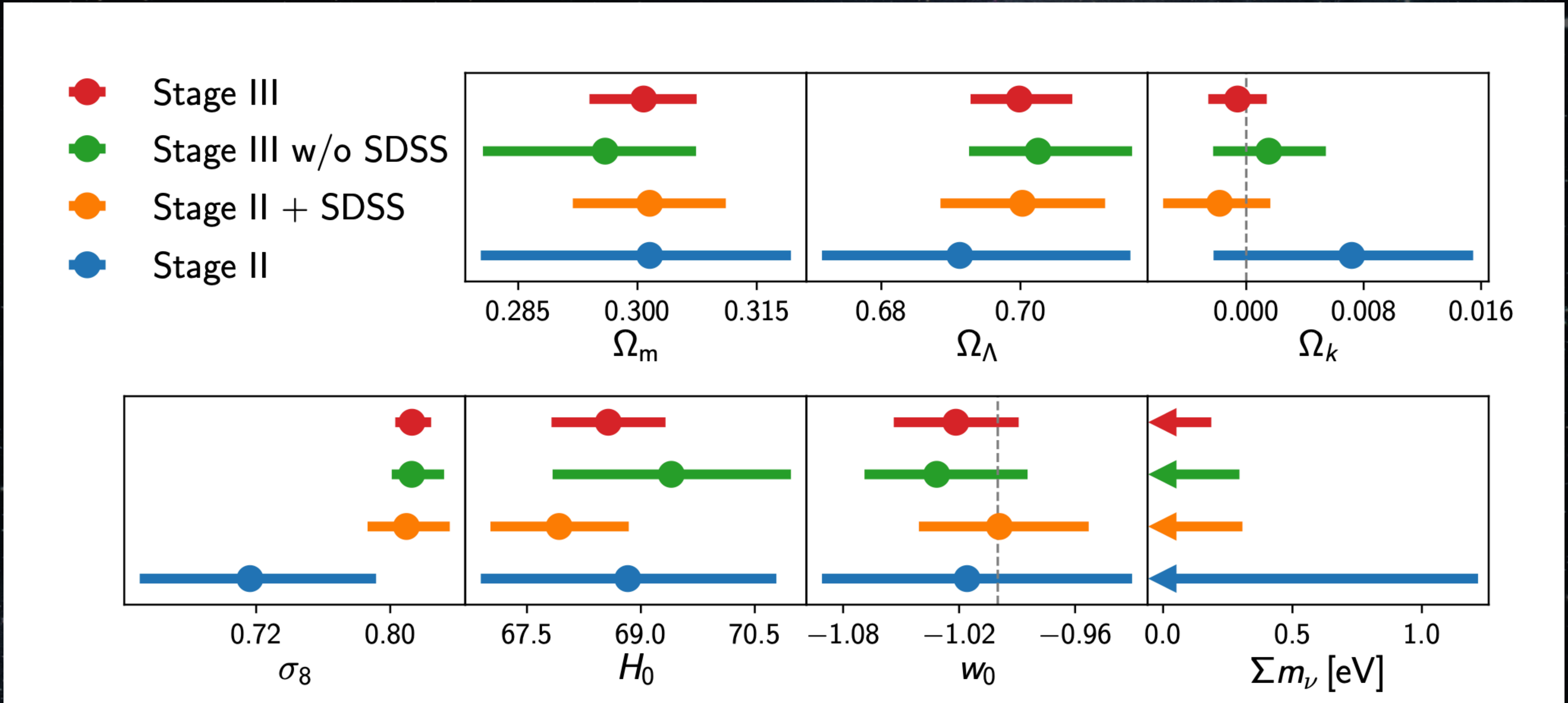

Alam+, 2020

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.