A test of the standard cosmological model with geometry and growth

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A test of the standard cosmological model with geometry and growth

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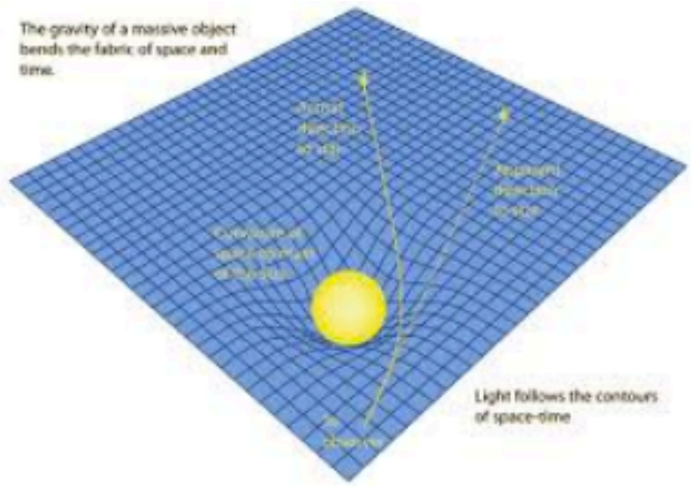
TO DO LIST
1. Introduction
2. The splitting technique
3. Cosmological probes
4. Results
5. Conclusions and perspectives…

Introduction

(Late-time) Standard Cosmological Model:

GR and FLRW metric



+

CDM

+

Cosmological Constant

Λ

ΛCDM model

Introduction

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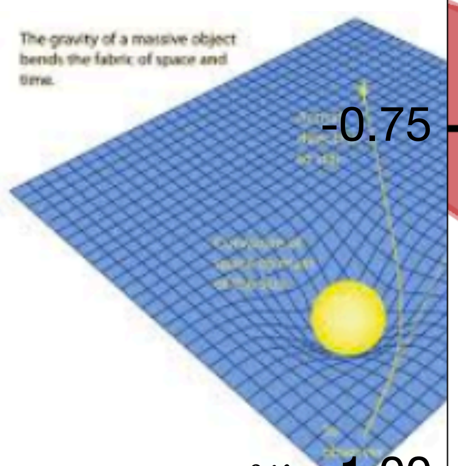

Cosmological Constant

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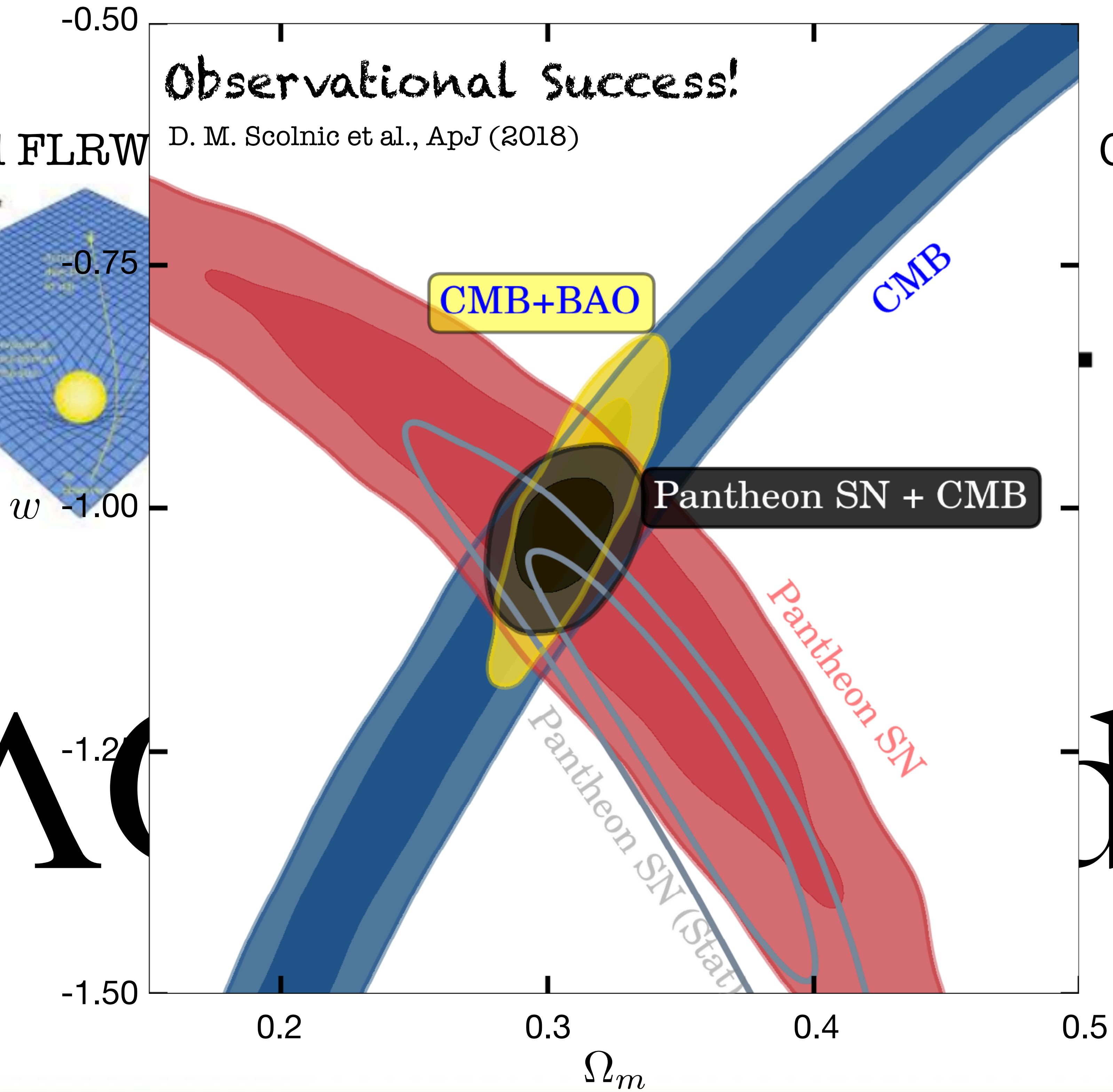


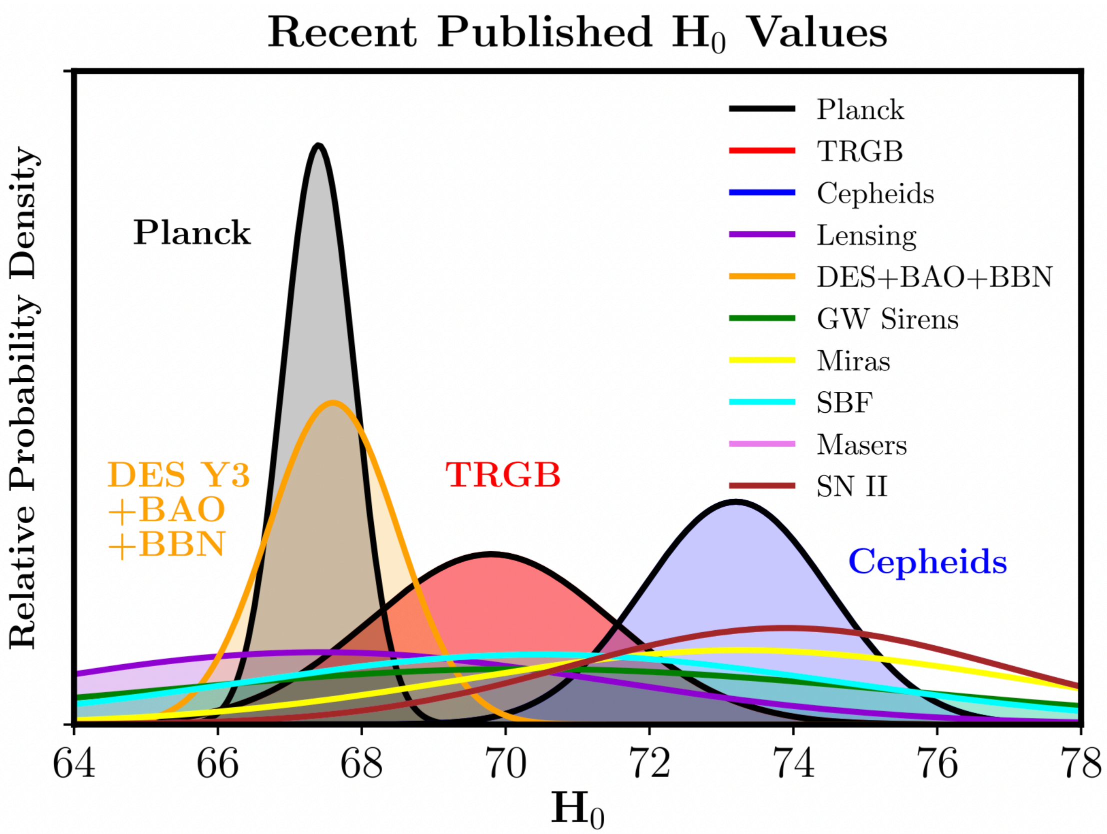
ΛC ... del

Introduction

Current status of the ΛCDM model:

Observational challenges:

1. H_0 tension;



Wendy L. Freedman ApJ 919 16 (2021).

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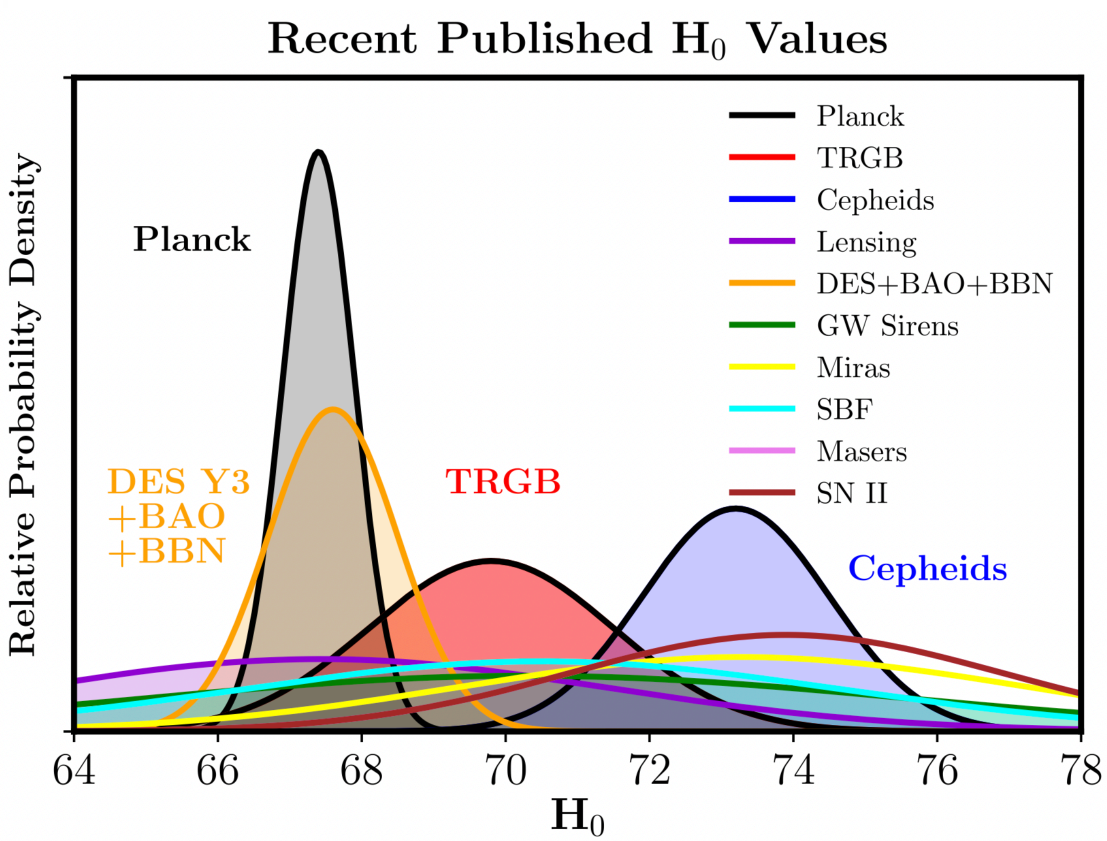
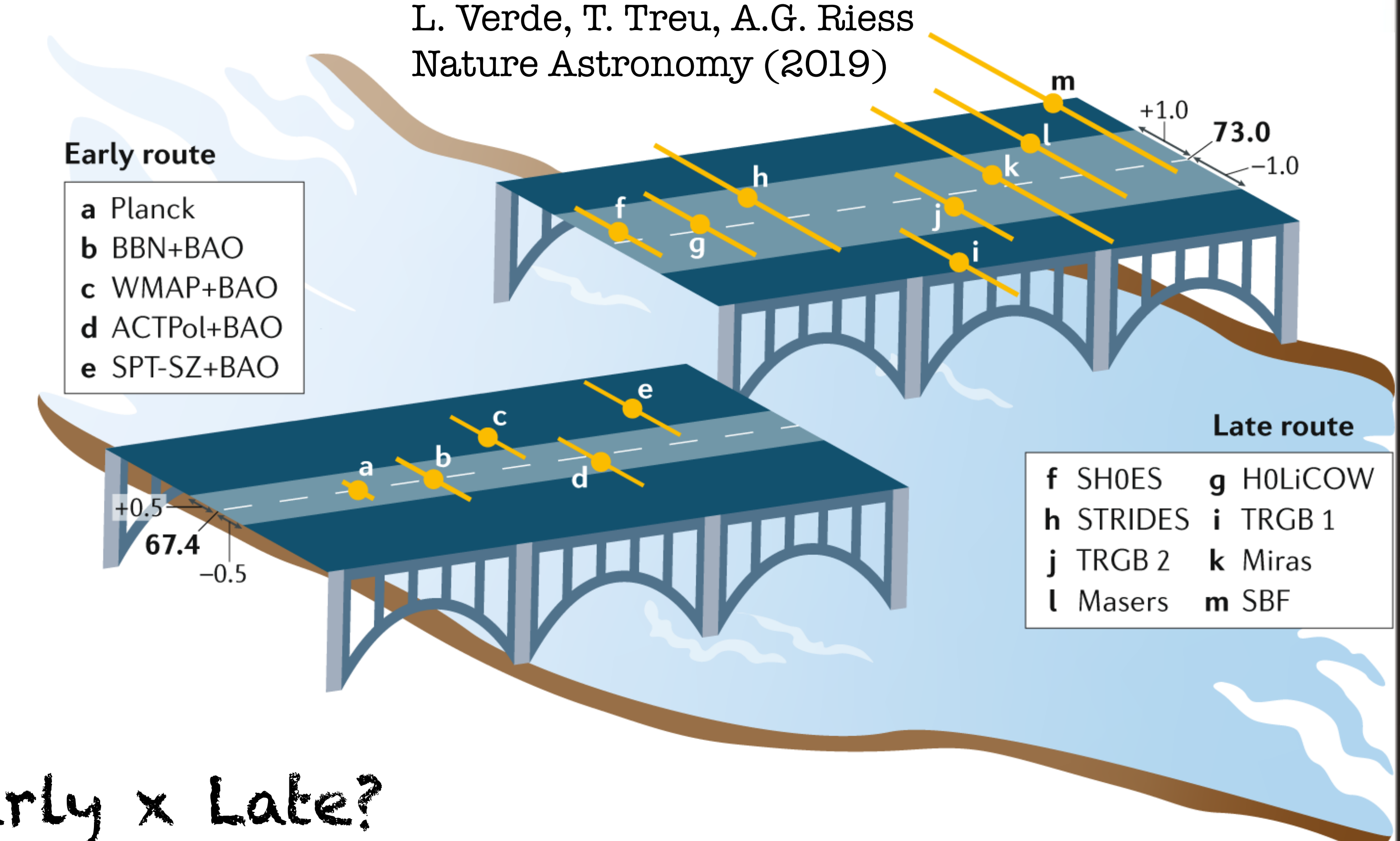


Wendy L. Freedman ApJ 919 16 (2021).

L. Verde, T. Treu, A.G. Riess
Nature Astronomy (2019)



Early x Late?

The tension is emphatically not "early vs late" cosmology since baryon acoustic oscillations (BAO) distances (together with primordial element abundances [19–21] or marginalizing over or sidestepping the sound horizon at the baryon drag epoch [22, 23]), i.e. without use of the primordial CMB, gives the same answer as from the CMB.

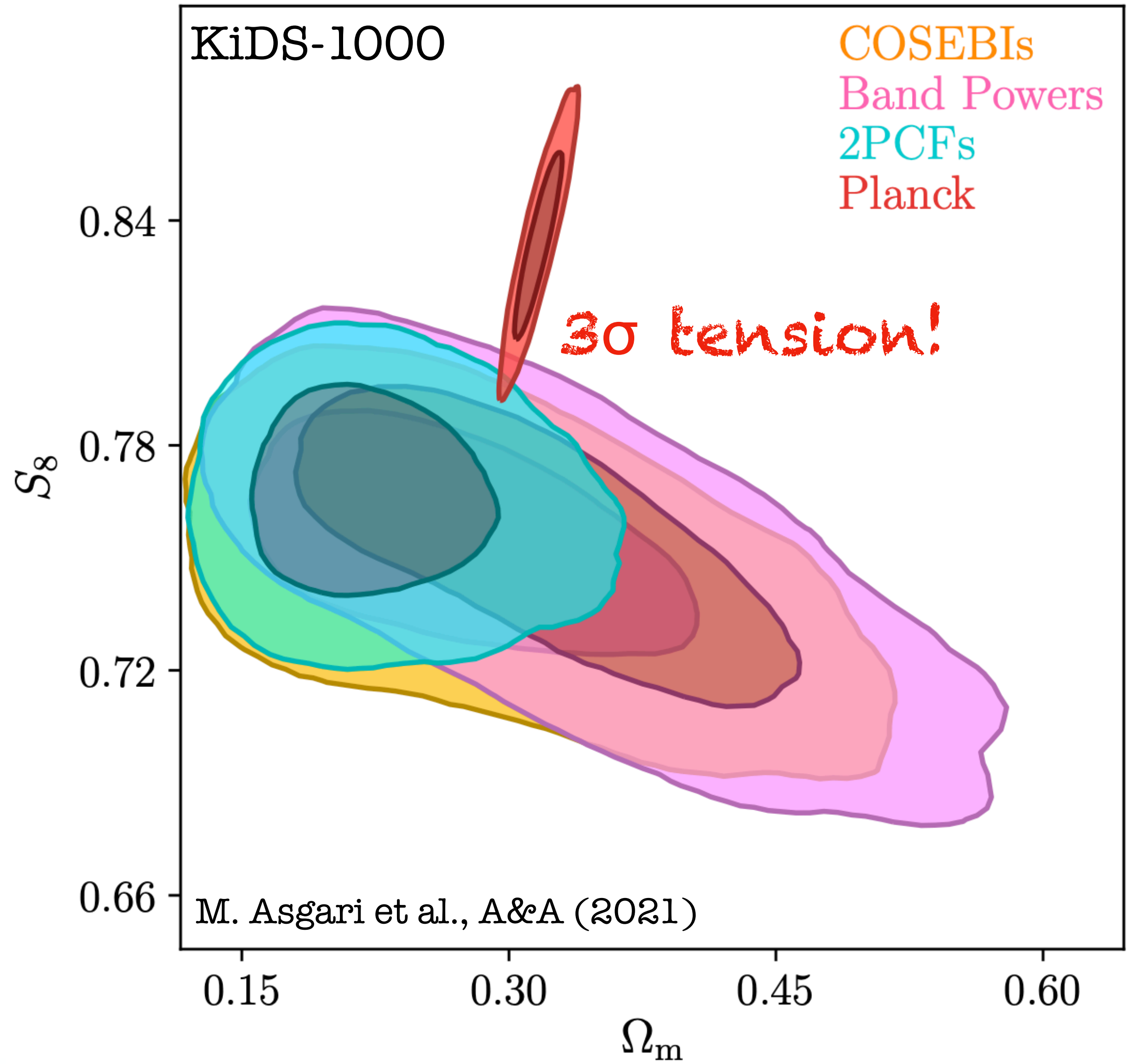
Eric V. Linder, arXiv: 2105.02903

Introduction

Current status of the ΛCDM model:

Observational challenges:

2. S_8 tension;



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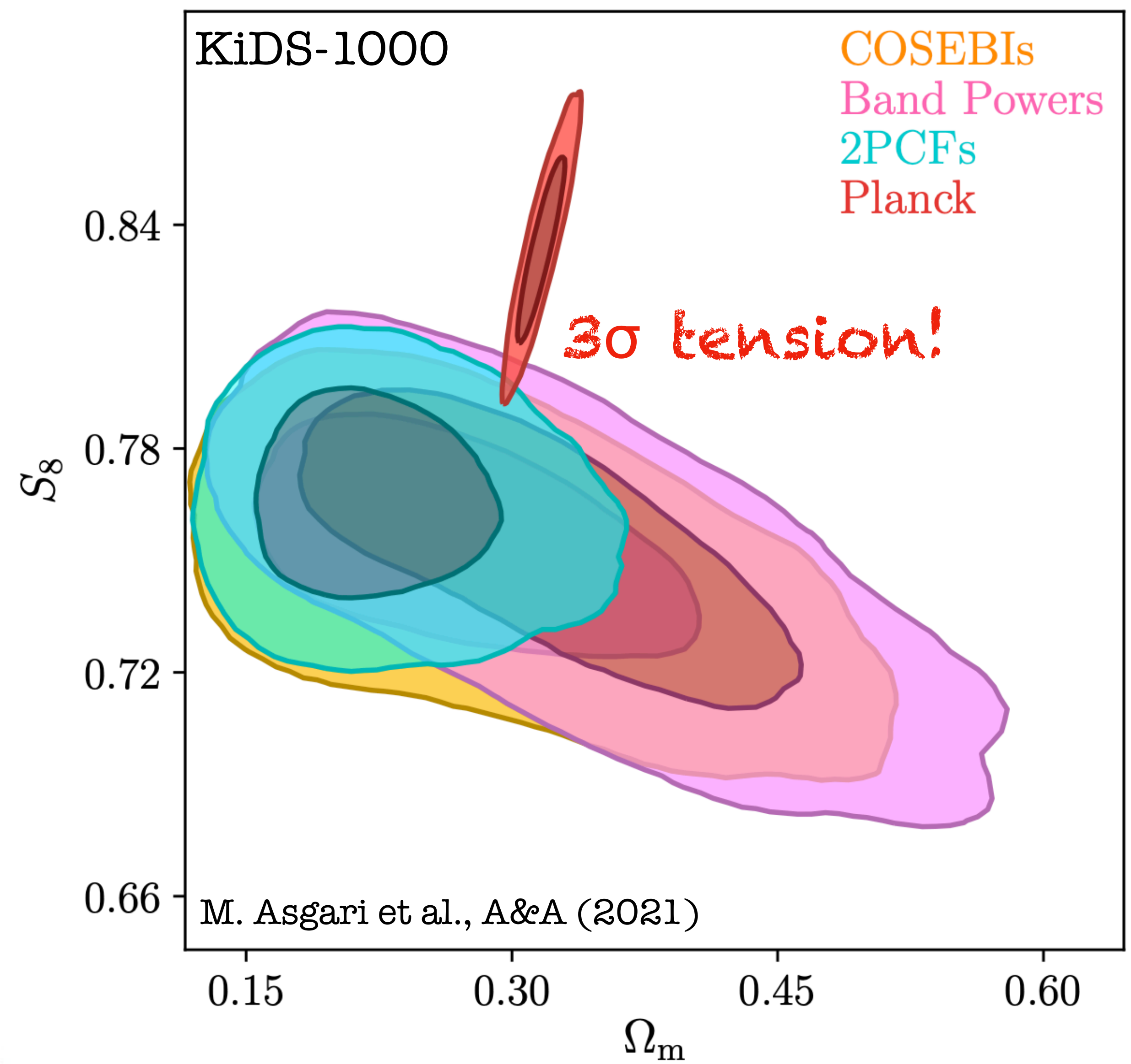
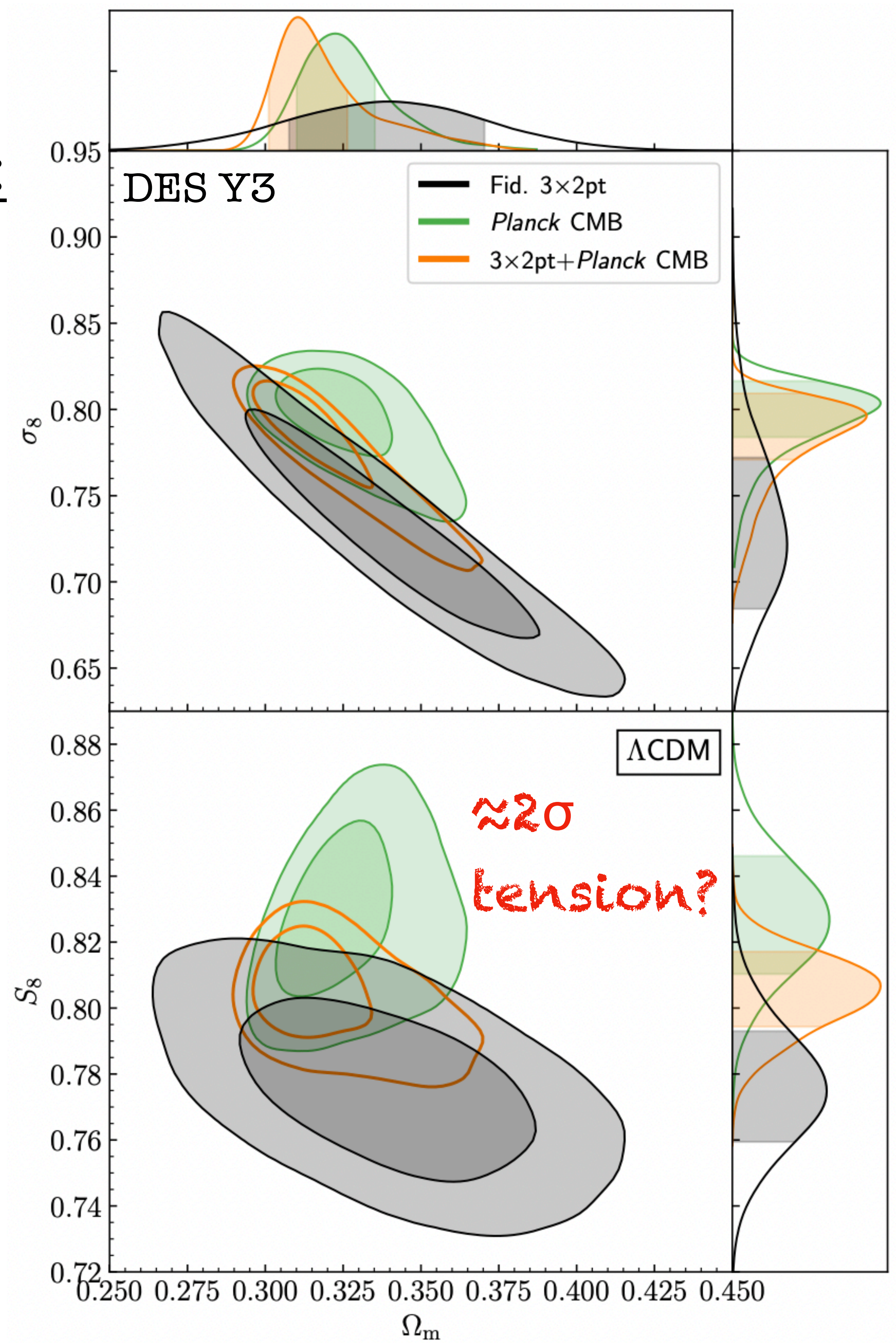


T. M. C. Abbott et al., Phys. Rev. D 105, 023520



Testing the limits of the standard cosmological model is a crucial task to understand whether the ΛCDM still holds the status of a concordance model...

In particular, comparing measurements with geometric nature with those describing growth of structure is particularly interesting because a key signature of many modified gravity theories is a mismatch between geometry and growth.

The splitting technique

The split technique:

The splitting technique consists in turn a conventional cosmological parameter into new two meta-parameters: $X \longrightarrow \{X^{\rm geom}, X^{\rm grow}\}$

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$$\Lambda\text{CDM split}: \Omega_M \longrightarrow \{\Omega_M^{\rm geom}, \Omega_M^{\rm grow}\}$$

$$w\text{CDM split}: \Omega_M, w \longrightarrow \{\Omega_M^{\rm geom}, \Omega_M^{\rm grow}, w^{\rm geom}, w^{\rm grow}\}$$

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Ex 1: Luminosity distance

$$H(\tilde{z}) = H_0\sqrt{(1-\Omega_M^{\text{geom}})(1+z)^{3(1+w^{\text{geom}})} + \Omega_M^{\text{geom}}(1+z)^3}$$

$$d_L = c(1+z)\int_0^z \frac{d\tilde{z}}{H(\tilde{z})}$$

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Ex 2: Sub-horizon matter fluctuations

$$\rho_m = \frac{8\pi G}{3H_0^2}\Omega_M^{\mathrm{grow}}(1+z)^3$$

$$\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m$$

$$H = H_0\sqrt{(1-\Omega_M^{\mathrm{grow}})(1+z)^{3(1+w^{\mathrm{grow}})} + \Omega_M^{\mathrm{grow}}(1+z)^3}$$

The splitting technique

What can we learn from this test?

Let us define:

$$\Delta\Omega_M = \Omega_M^{\text{grow}} - \Omega_M^{\text{geom}} \qquad \Delta w = w^{\text{grow}} - w^{\text{geom}}$$

Using the splitting approach to perform a parameter selection, the following conclusions are possible:

- $\Delta\Omega_M = 0$ (and $\Delta w = 0$) :

  ΛCDM (or wCDM) is consistent with the data;

- $\Delta\Omega_M \neq 0$ (and $\Delta w \neq 0$) :

  ΛCDM (or wCDM) is not consistent with the data;

- $\Delta\Omega_M = 0$ (and $\Delta w \neq 0$) :

  Clustering of the DE component (possibly scale dependent!);

  Modified gravity;

Hybrid quantity
Grow quantity
Geom quantity

Cosmological probes

Cosmic Microwave Background (CMB):

Angular Power Spectrum of the CMB Temperature Anisotropy:

$$C_\ell^{TT} = \frac{1}{2\pi^2}\int \frac{dk}{k}\Theta\left(k, z=0\right)\mathcal{P}_R\left(k\right)$$

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Temperature fluctuations:

$$\Theta\left(k, z=0\right) = \int dz' S_T\left(k, z'\right) j_\ell\left[k\chi\left(z'\right)\right]$$

$S_T\left(k, z'\right)$: Source function (obtained via Einstein – Boltzmann equations)

$\chi\left(z'\right)$: Comoving distance

Similar for the TE, EE and lensing spectra!

Cosmological probes

Hybrid quantity
Grow quantity
Geom quantity

Weak Lensing (WL):

Two-point correlation function:

$$\xi_{\pm}^{ij} = \frac{1}{2\pi} \int d\ell \; \ell P_{\kappa}^{ij}(\ell) J_{0,4}(\ell\theta)$$

Cosmological probes

Hybrid quantity
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Weak Lensing (WL):

Two-point correlation function:

$$\xi_{\pm}^{ij} = \frac{1}{2\pi} \int d\ell \; \ell P_{\kappa}^{ij}(\ell) J_{0,4}(\ell\theta)$$

Convergence power spectrum (Limber approximation):

$$P_{\kappa}^{ij}(\ell) = \int_0^{\chi_H} d\chi \frac{q_i(\chi) q_j(\chi)}{\chi^2} P_{\delta}\left(\frac{\ell + 1/2}{\chi}, \chi\right)$$

Hybrid quantity
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Cosmological probes

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Lensing efficiency function:

$$q_i(\chi) = \frac{3H_0\Omega_M}{2c^2}\frac{\chi}{a(\chi)}\int_{\chi}^{\chi_H} d\chi' n_i(\chi') \frac{\chi' - \chi}{\chi}$$

Cosmological probes

Hybrid quantity
Grow quantity
Geom quantity

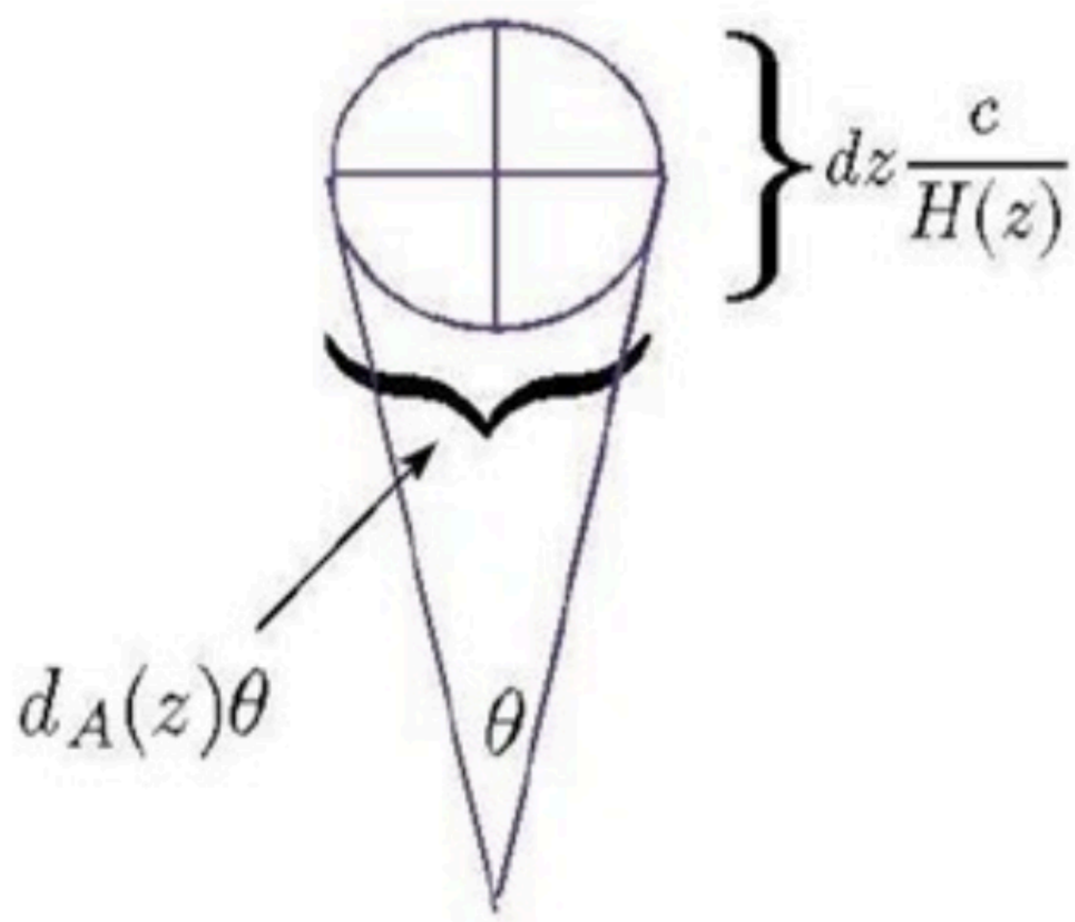
Baryon Acoustic Oscillations and Redshift Space Distortion:

- Transverse BAO:

$$\text{Observable} = \frac{(1+z)\, D_A}{r_d}$$

- Radial BAO:

$$\text{Observable} = \frac{D_H}{r_d}$$



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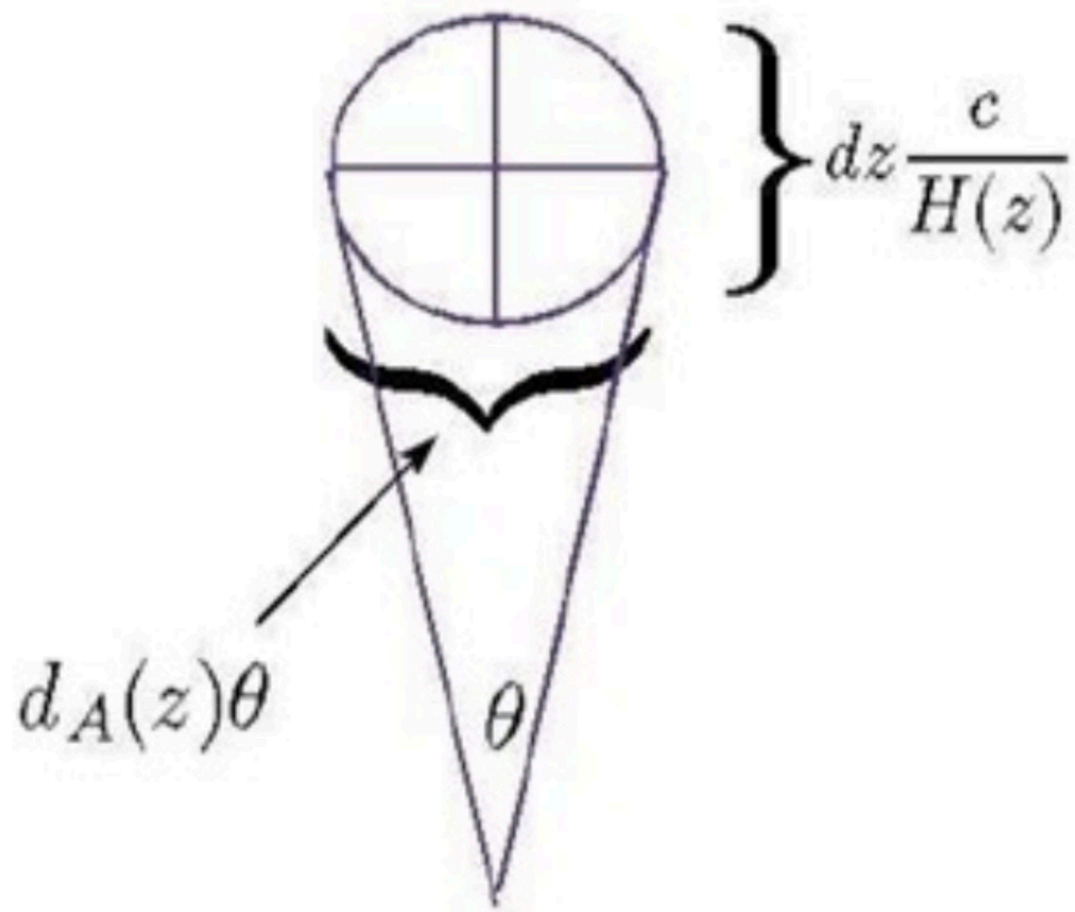
- RSD:

$$\text{Observable} = f\sigma_8$$



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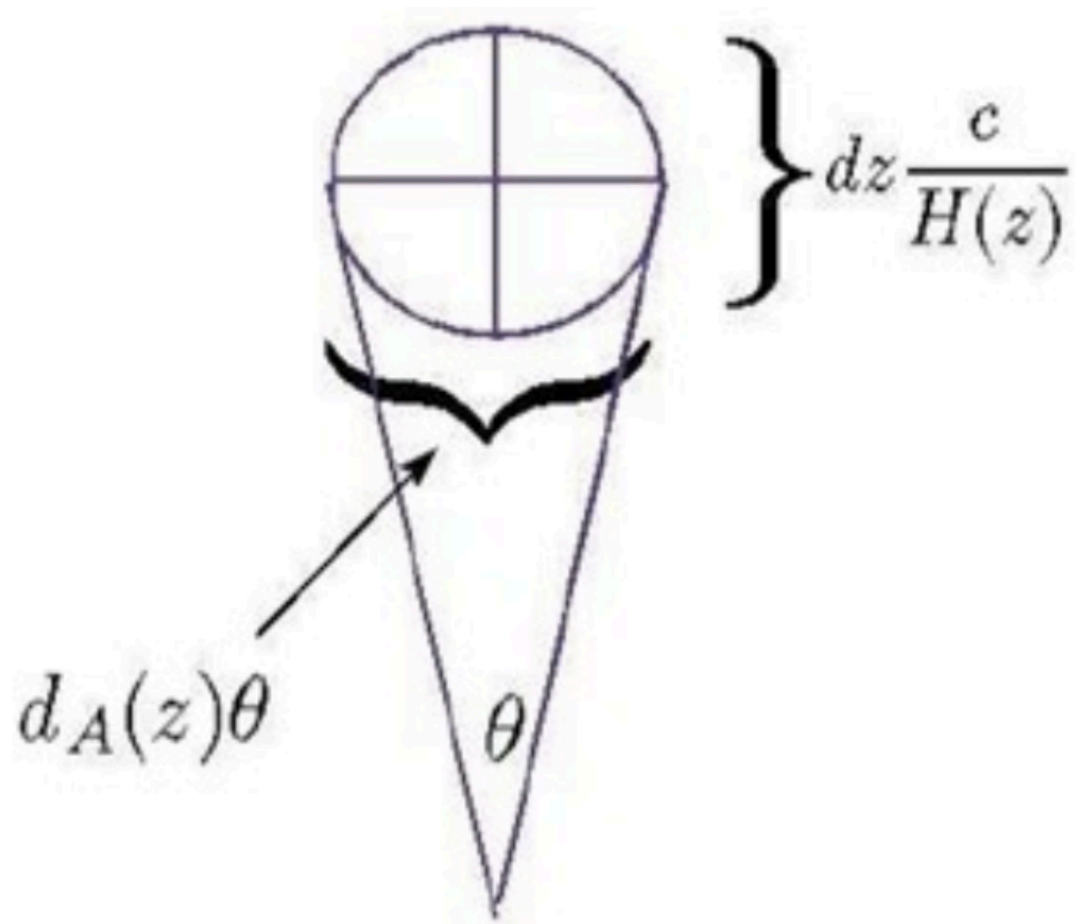


Type Ia Supernovae (SN Ia):

Apparent magnitude:

$$m(z) = 5\log_{10}(H_0 D_L) + \mathcal{M}$$

Cosmological probes

Summary:

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\{D_M(z); D_H(z)\}$	$r_d(z_d)$
CMB	$j_\ell[k\chi(z)]$	$S_T(k, z)$
Weak lensing	$\frac{d\chi(z)}{d(z)} g_i(z) g_j(z)$	$\Omega_m^2 P_\delta\left(\frac{\ell}{\chi}, z\right)$
RSD	—	$f(z)\sigma_8(z)$

Results

The analysis:

Our analysis consists in constraining the geometry and growth parameters in the (extended) ΛCDM model, and in the (extended) wCDM model

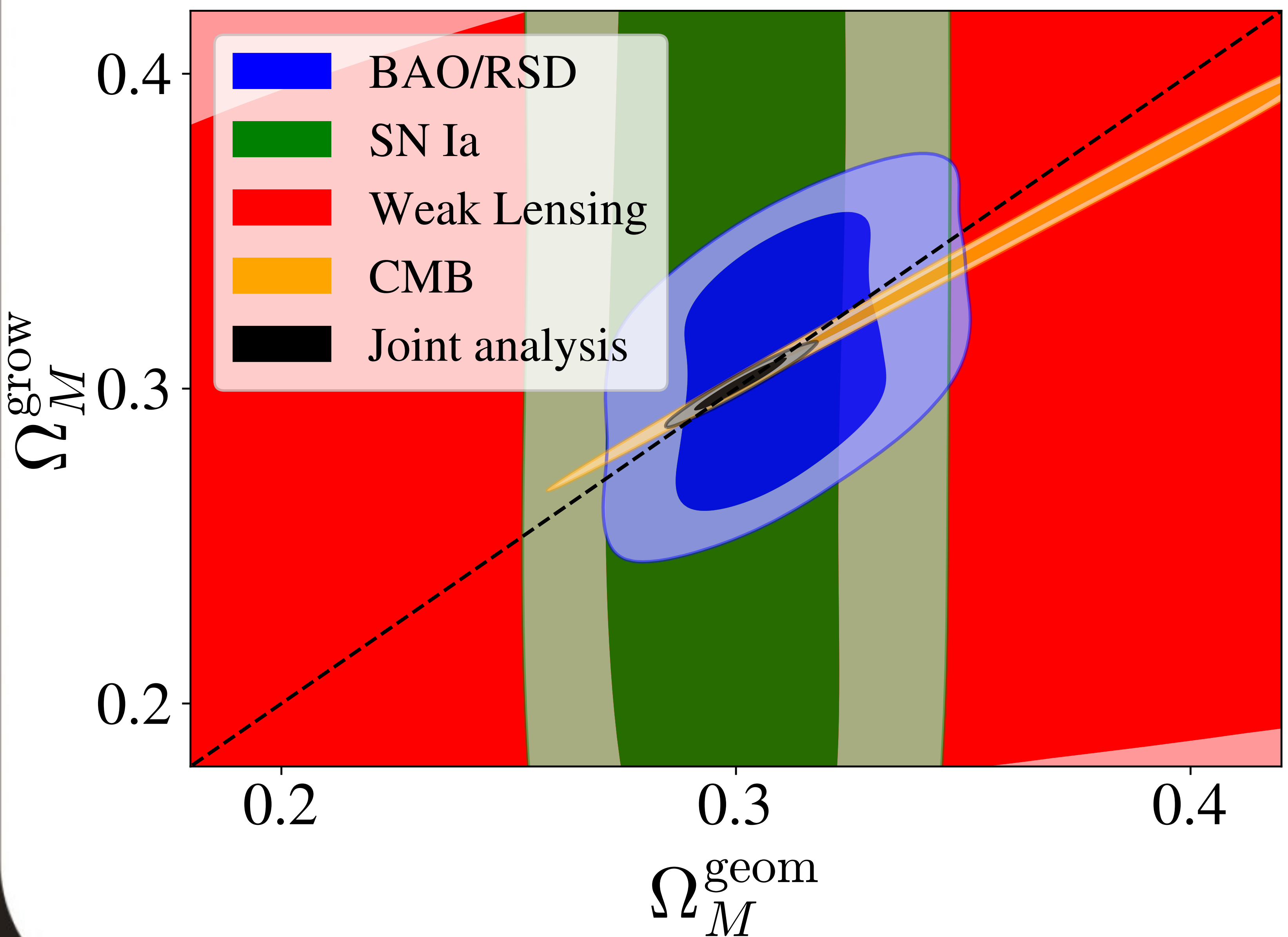
Cosmological data:

Paper	Data				
	CMB	Weak lensing	BAO/RSD	SN Ia	Galaxy clusters
This work	Planck 2018 (TTTEEE+lensing)	KiDS-1000 (COSEBIs)	eBOSS DR16	Pantheon	—
Wang et. al [20]	WMAP3, ACBAR, BOOMERanG and CBI (TTTEEE)	CTIO (Aperture mass statistic)	2dFGRS and SDSS LRG	SNLS	—
Ruiz & Huterer [21]	Planck 2013 (Shift parameter and early universe priors)	CFHTLens (Shear 2PCF $\xi_{\pm}^{ij}$)	6dFGS, SDSS LRG and BOSS CMASS	SNLS	MaxBCG (Cluster counts)
Bernal et. al [22]	Planck 2015 (TTTEEE+lensing)	—	6dFGS, SDSS-MGS, BOSS-LOWZ, BOSS-CMASS and BOSS-Lyα	JLA	Chandra X-ray and Planck tSZ $\left(\sigma_8 \left(\frac{\Omega_M}{\alpha}\right)^{\beta}\right)$
Muir et. al [23]	Planck 2018 (Shift parameter)	DES Y1 (Shear 2PCF $\xi_{\pm}^{ij}$)	DES Y1 and BOSS DR12	DES Y1	—
Ruiz-Zapatero et. al [24]	Planck 2018 (Shift parameter and primordial power spectrum)	KiDS-1000 (Band powers spectrum)	6dFGS, BOSS DR12 and BOSS DR14	—	—

Results

(Extended) ΛCDM model:

Parameter selection

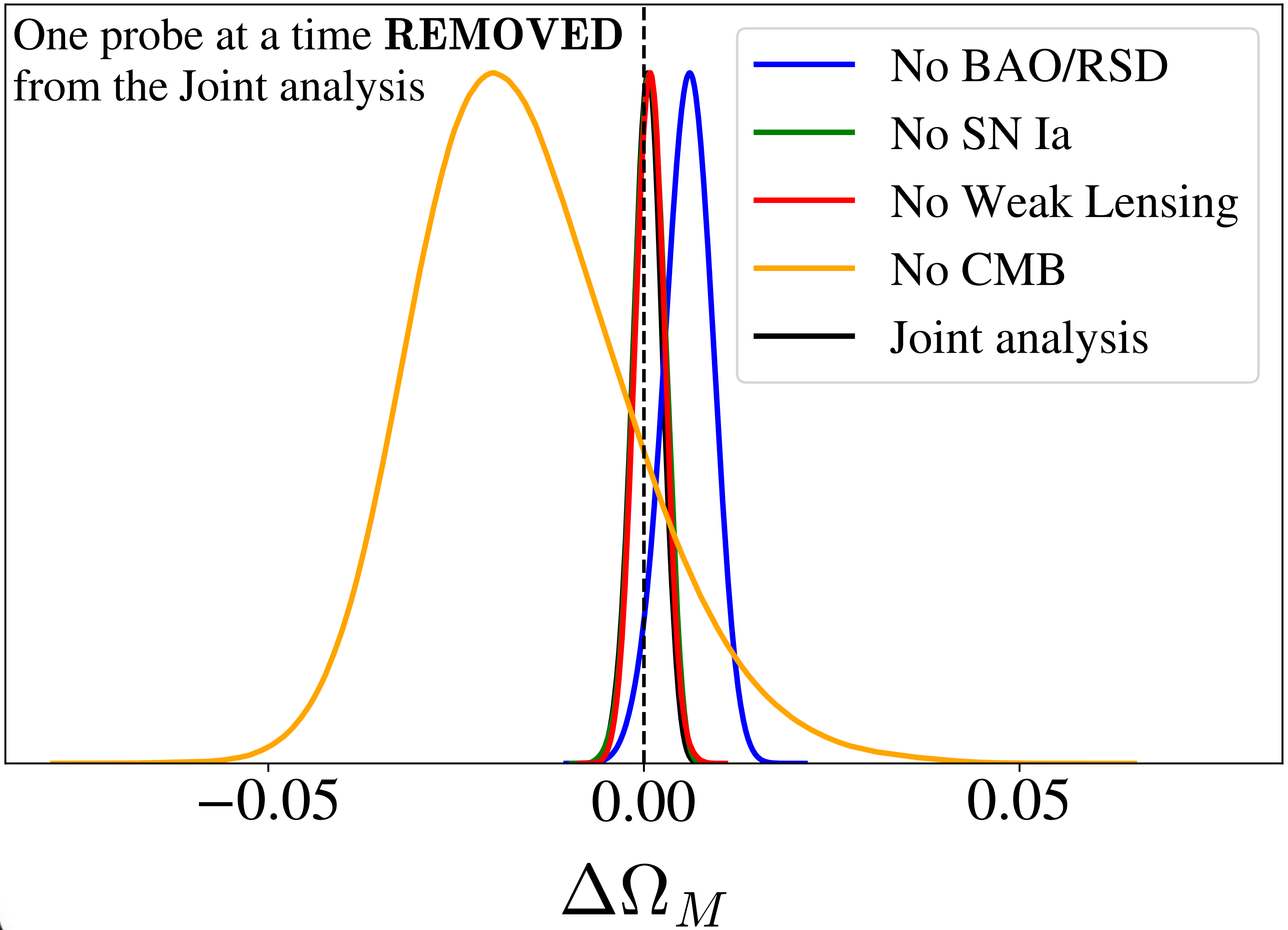


- WL doesn't have enough power to provide significant constraints;
- SN Ia only constraints geometry contribution;
- BAO/RSD provides significant constraints in both, geometrical and growth parameters;
- CMB provides strong constraints, however, we can see a degeneracy between geometrical and growth parameters;

Results

(Extended) ΛCDM model:

How important is each of the data sets?

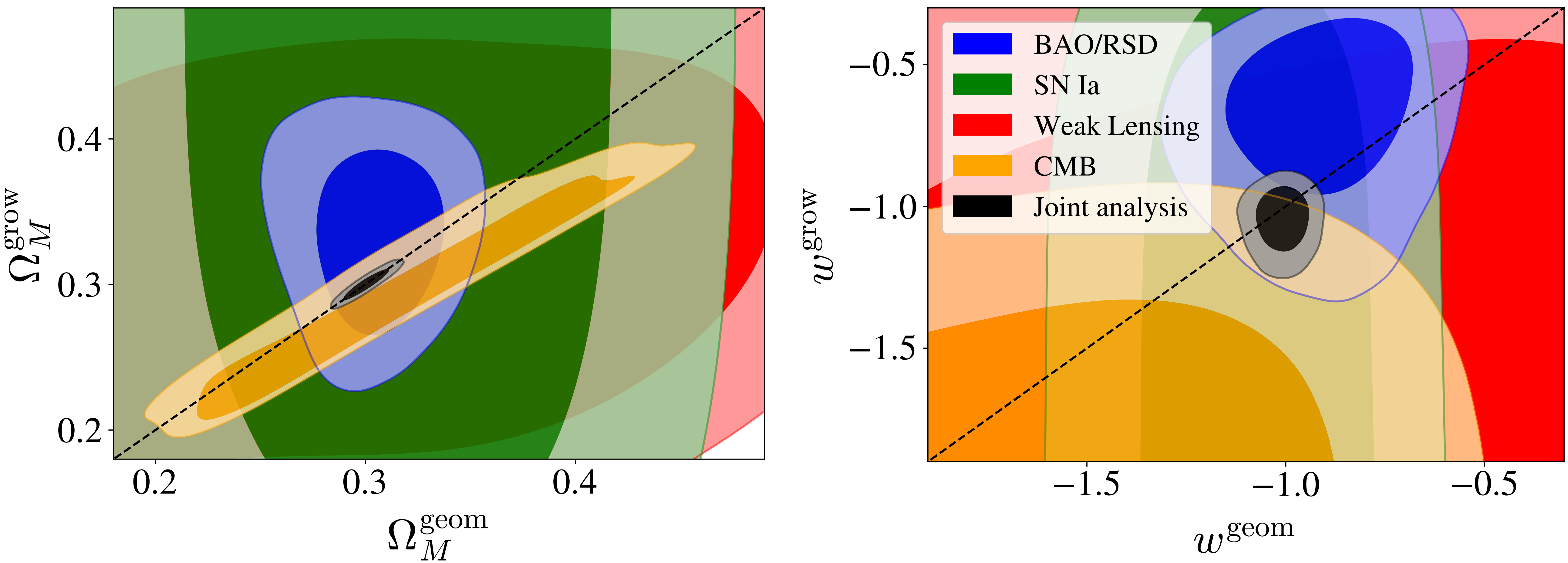


- Removing WL data doesn't affect the final result;
- Removing SN Ia also doesn't affect considerably the final result;
- Removing BAO/RSD indicates a deviation in the growth direction, however, compatible in 1σ with the null-hypothesis;
- Removing CMB results in a deviation in the geometry direction, however, also compatible in 1σ with ΛCDM;

Results

(Extended) wCDM model:

Parameter selection



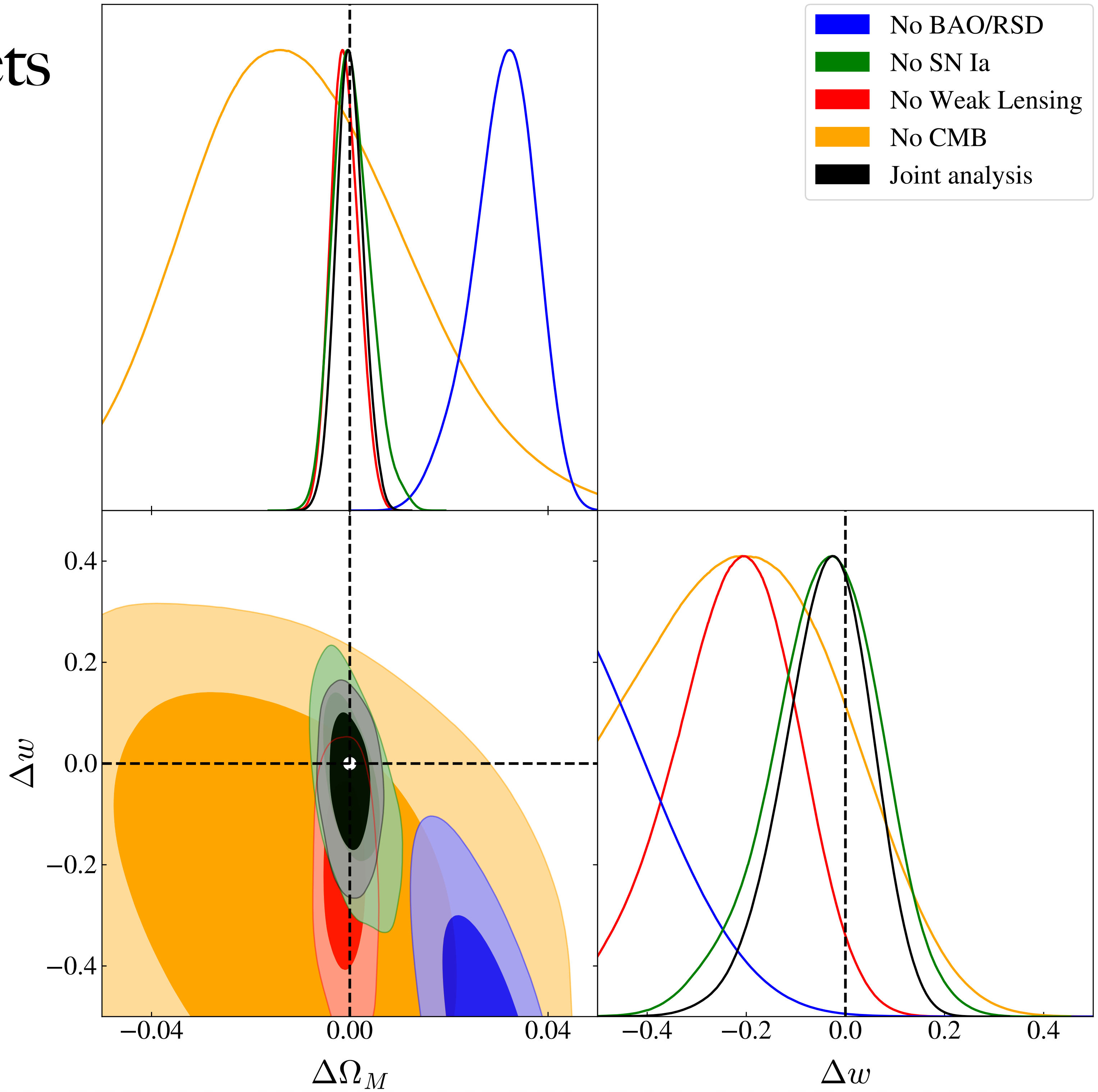
Similarly to the (extended) ΛCDM case, WL and SN Ia provide the weakest constraints, and BAO and CMB are the most relevant data sets. The **Joint analysis** satisfy the null-hypothesis as well.

Results

(Extended) wCDM model:

Importance of the data sets

- Removing WL data doesn't affect the final result;
- Removing SN Ia also doesn't affect considerably the final result;
- Removing CMB indicates a deviation in the geometry direction for both parameters and increase the error bars, however, compatible in 1σ with wCDM;
- Removing BAO/RSD results in a 4.2σ discrepancy with the null-hypothesis;



Conclusions and perspectives

1.(Extended) ΛCDM analysis: all data sets are individually compatible, and the posteriors for the joint analysis are consistent with the null-hypothesis, showing no preference for departures from GR;

2. (Extended) wCDM analysis: the joint-probe posteriors are entirely consistent with the null. Interestingly, the individual constraints from BAO/RSD prefer a deviation for w in the growth direction. Removing BAO/RSD from the joint analysis results in an anomalous deviation in the geometry direction;

3. The (extended) wCDM can be interpreted as a consequence of the well-known preference of the CMB data for phantom DE models. However, it might also indicates a possible signal for a new physics;

4. It is possible to apply the split approach to different scenarios with only a single extra parameter;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धन्यवाद
təşəkkür
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감사
感謝
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diolch
grazie
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faleminderit
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მადლობა
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דאַנק
bedankt
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ありがとうございます
આભારદર્શક શબ્દો
Dank
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благодаря
хвала
շնորհակալություն
感谢
با تشکر
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