Title: The Spatial Curvature Endgame: Reaching the Limit of Curvature Determination; Group Meeting

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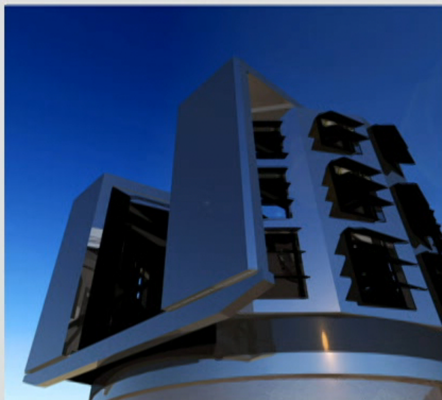
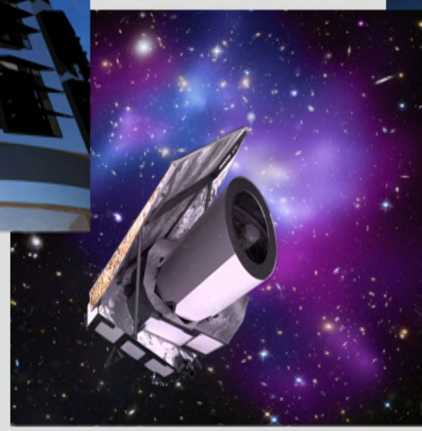
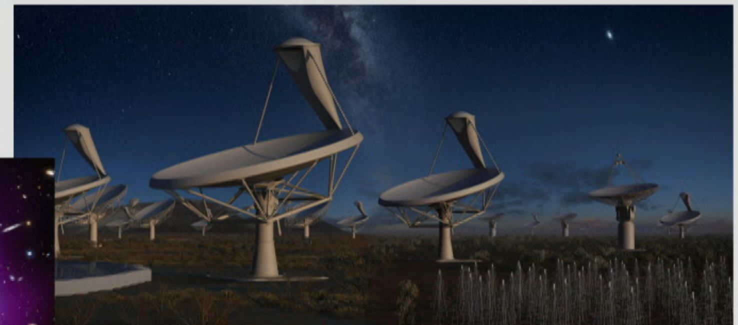
Abstract: <p>Current constraints on spatial curvature demonstrate it to be dynamically negligible at late times. However, neglecting it as a cosmological parameter would be premature, as it offers a valuable test of eternal inflation models and probes novel large-scale structure phenomena. I will discuss a recent project in which a broad and conservative approach was employed to systematically forecast spatial curvature constraints from a suite of upcoming cosmology surveys, while also examining important degeneracies with cosmological parameters and potential sources of systematic error.</p>

The Spatial Curvature Endgame:
Reaching the limits of curvature determination

Based on **arXiv:1604.01410**, with Phil Bull (JPL) and Rupert Allison (Cambridge)







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March 9, 2017

Images: http://www.euclid-ec.org/ , http://www.lsst.org/,
https://www.skatelescope.org

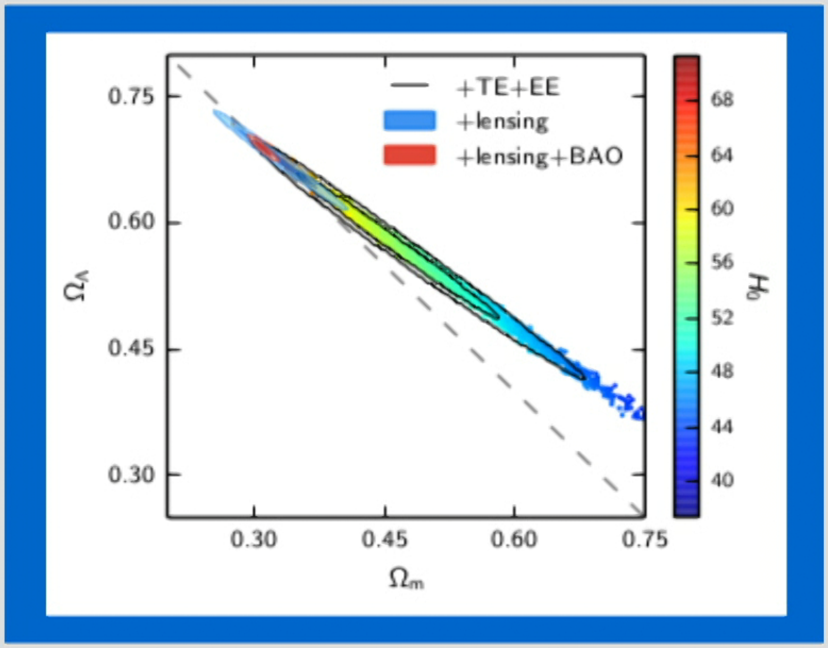
Giving away the punchline

1. Forecast $\sigma(\Omega_K)$ > the curvature floor
2. Forecast $\sigma(\Omega_K)$ ~ 0.2 x current $\sigma(\Omega_K)$
3. Constraining Ω_K: a litmus test for precision cosmology?

Talk Outline

1. Background & Motivation
   - Why care about spatial curvature?
   - Review of other forecasting work
2. Methods
   - Forecasting set-up
   - Observables
3. Results & Conclusions

Why care about curvature?



$$\sigma(\Omega_K) = 0.005\,(95\%\mathrm{CL})$$

Planck CMB (T, E, B & lensing) + BOSS BAO

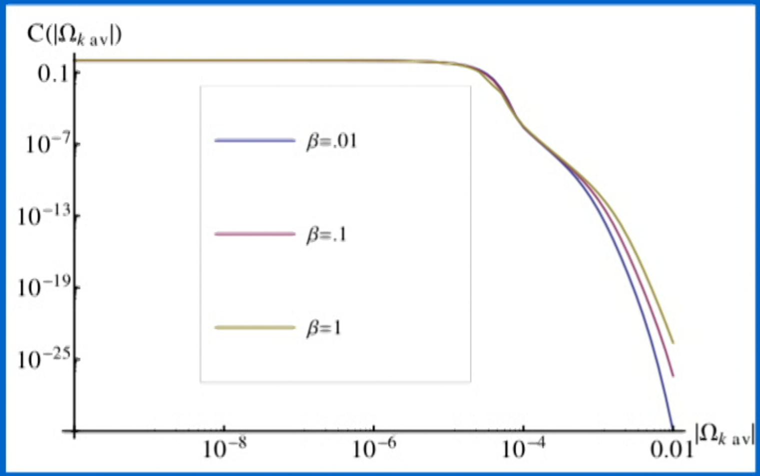
Image: Planck Collaboration 2015

Why care about curvature?

1. Constraints on inflationary models
2. Probe of large-scale structure effects
3. Reaching the 'curvature floor'

Why care about curvature?

1. Constraints on inflationary models



Eternal inflation:

Slow roll

$$|\sigma(\Omega_K)| < 10^{-4}$$

False vacuum

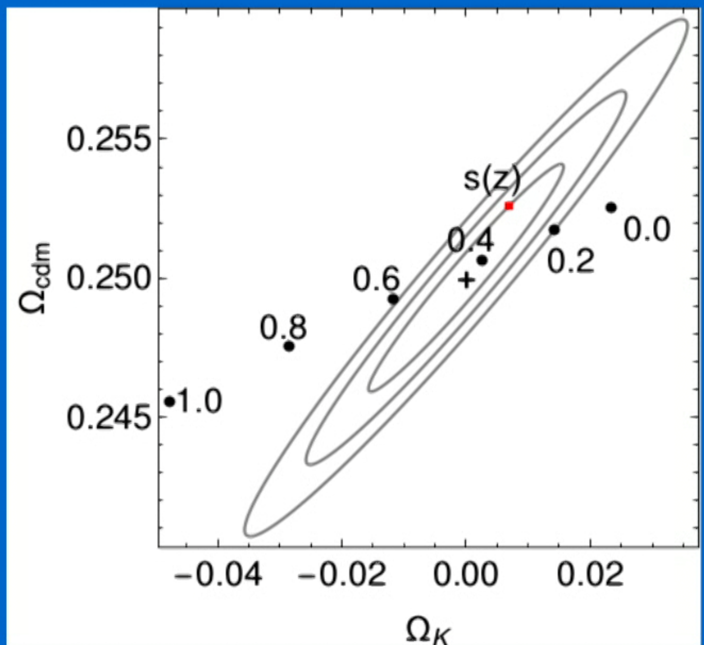
$$\sigma(\Omega_K) > -10^{-4}$$

Kleban & Schillo, 2012

Image: Kleban & Schillo 2012

Why care about curvature?

2. Probe of large-scale structure effects



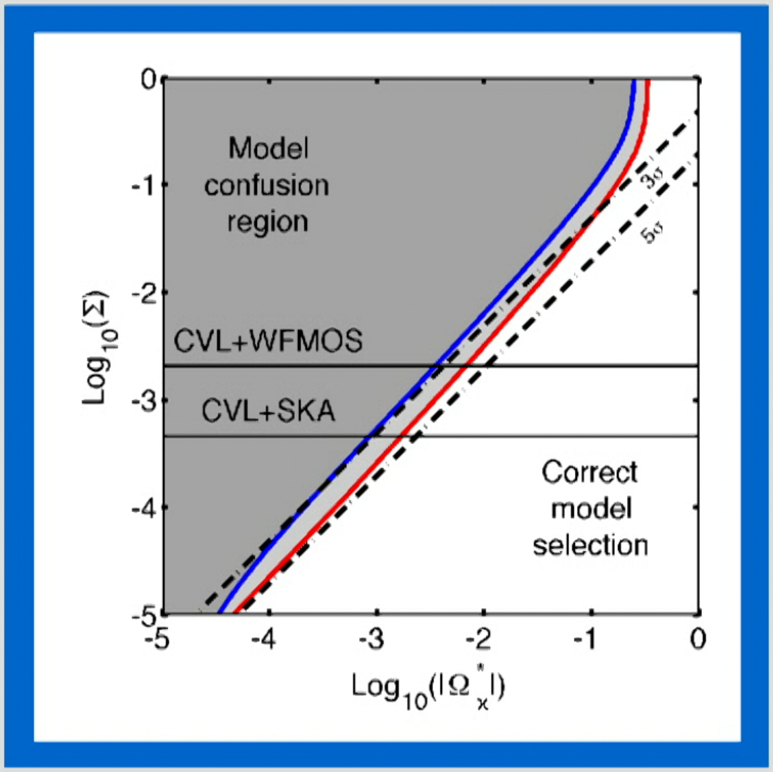
Measuring $\sigma(\Omega_K) \neq 0$ may be due to:

- 2^{nd} order D-z effects
- local inhomogeneities
- super-sample modes
- GR effects

Image: Di Dio et al 2016

Why care about curvature?

3. Reaching the 'curvature floor'



- 10^{-5} from primordial perturbations at horizon scale
- 10^{-4} from Bayesian model confusion considerations

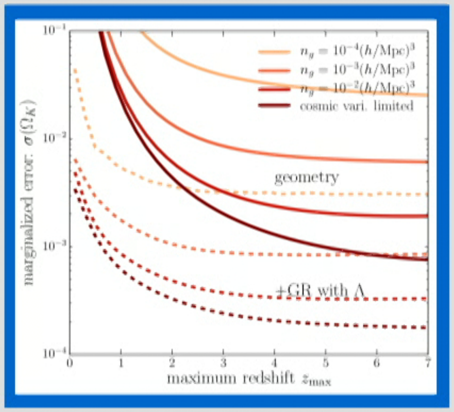
Image: Vardanyan et al. 2009

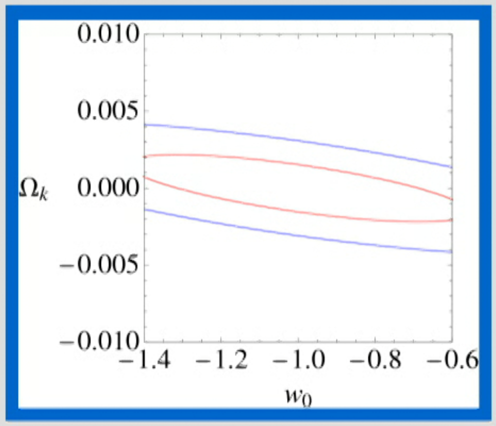
Other recent work

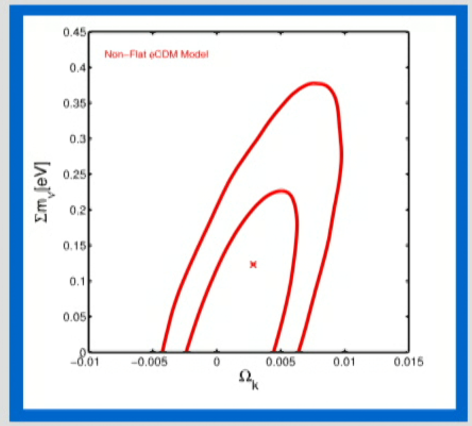
"State of the Nation":
Constraints and forecasts on Ω_K , circa 2015

- Lots of interest in forecasts

- Mostly focused on particular scenarios of interest: specific survey, observable, or parameter degeneracy



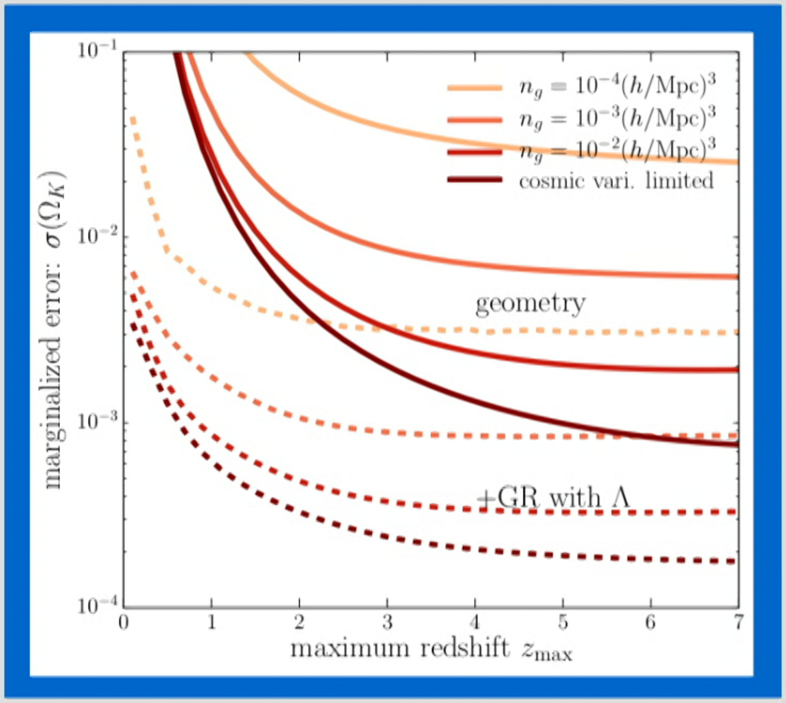




Images: Takada & Dore 2015, Barenboim et al. 2010, Chen et al. 2016

Other recent work: examples

Takada & Dore, 2015, 1508.02469



Forecast or constraints: Forecasts

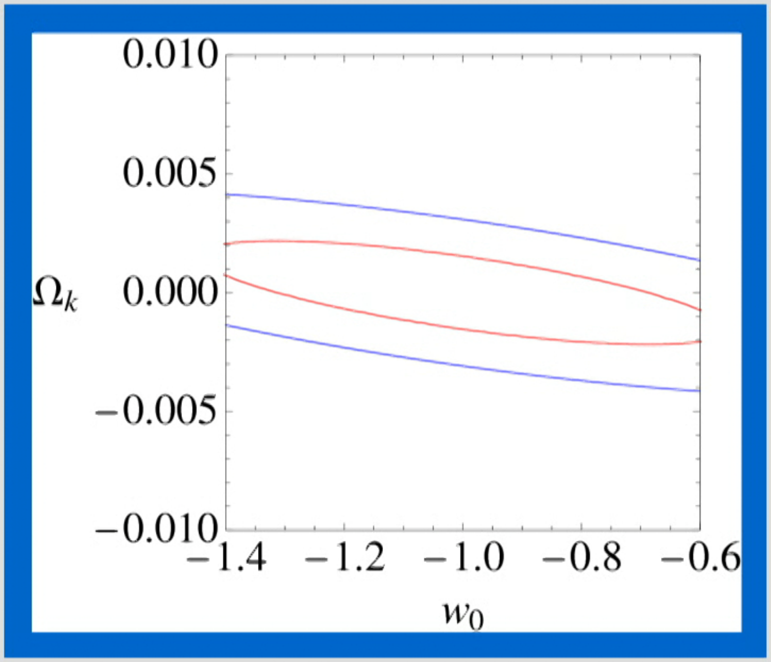
Observable(s): BAO

Fixed parameters: m_ν

Image: Takada & Dore 2015

Other recent work: examples

Barenboim et al., 2010, 0910.0252



LSST + Planck

Forecasts or constraints: Forecasts

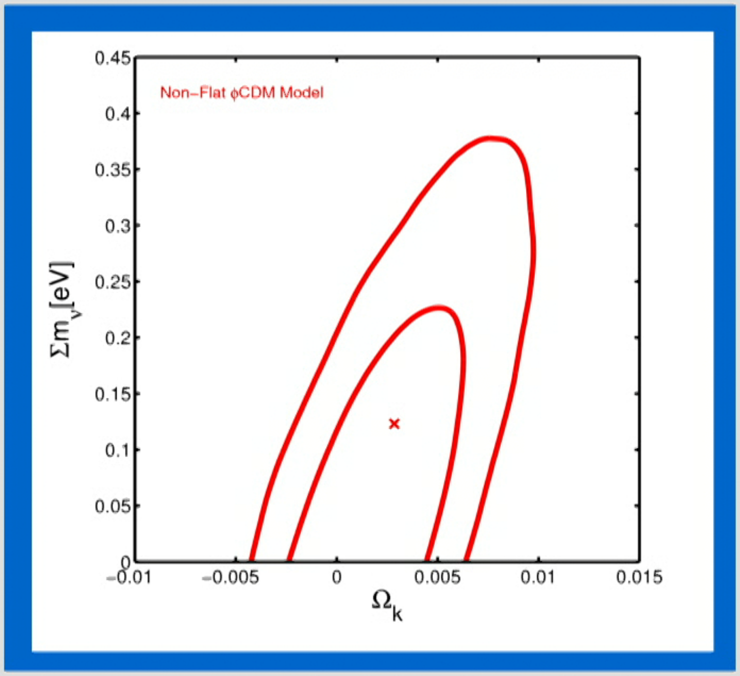
Observable(s): BAO, CMB

Fixed parameters: $m_\nu,\ b,\ f$

Image: Barenboim et al 2010

Other recent work: examples

Chen et al. 2016, 1603.07115



Forecasts or constraints: Constraints

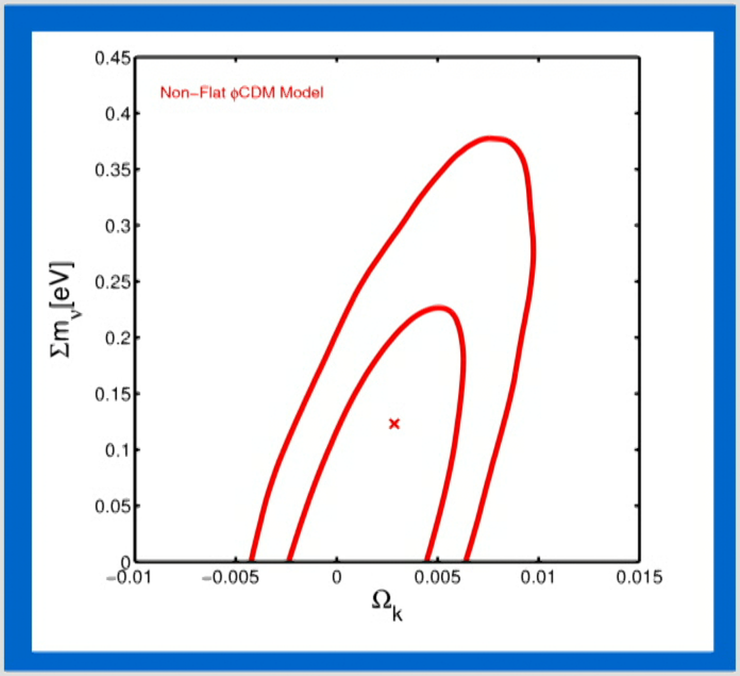
Observable(s): CMB, BAO, SN

Fixed parameters: $b,\ f,\ \alpha_s$

Image: Chen et al. 2016

Other recent work: examples

Chen et al. 2016, 1603.07115



Forecasts or constraints: Constraints

Observable(s): CMB, BAO, SN

Fixed parameters: $b,\ f,\ \alpha_s$

Many other examples of relevant work: *Aslanyan et al. 2015, Clarkson et al. 2011, Di Dio et al. 2016, Knox et al. 2006, Mortonson et al. 2009, Sapone et al. 2014, Smith et al. 2012, Valkenburgh et al. 2012, Zhan et al. 2008*
… and others

Image: Chen et al. 2016

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Fisher forecasting

The Fisher information matrix:

$$\mathcal{F}_{ab} = -\left\langle \frac{\partial^2 \ln \mathcal{L}(\vec{d};\vec{p})}{\partial p_a \partial p_b} \right\rangle$$

$\mathcal{L}(\vec{d};\vec{p})$ - Likelihood of the *data*, *d*, given the parameters, *p*

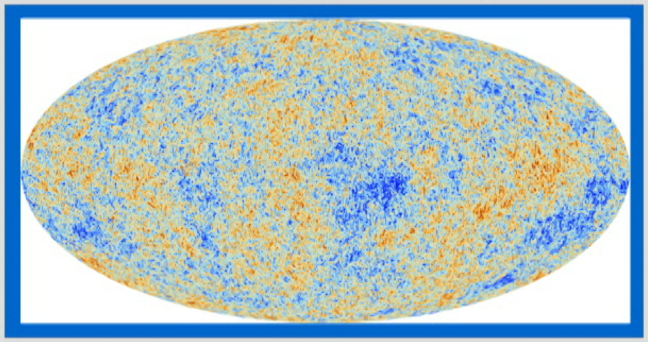
$\mathcal{F}$ ~ Inverse *parameter* covariance matrix

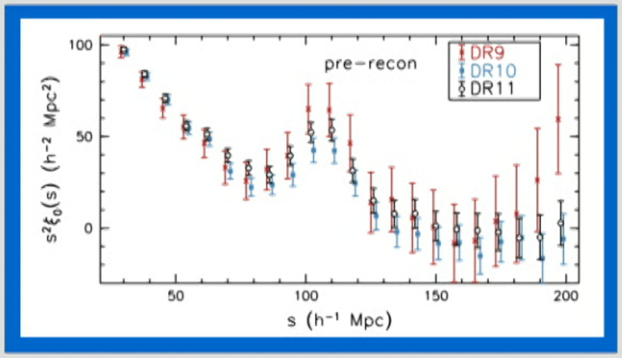
Takes information about the expected *data* and gives information about the expected *parameters*.

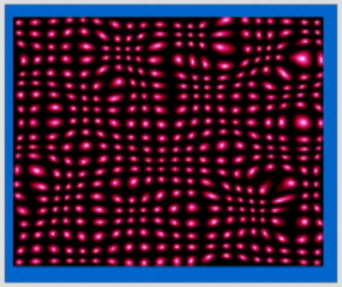
Cosmological Observables

We consider:

- Cosmic Microwave Background (CMB)
- Baryon Acoustic Oscillations (BAO)
- Weak lensing of galaxies







Images: Planck Collaboration 2013, Anderson et al. 2013, iCosmo group

Cosmological Observables

1. Cosmic Microwave Background

- Temperature, Polarization, and Lensing

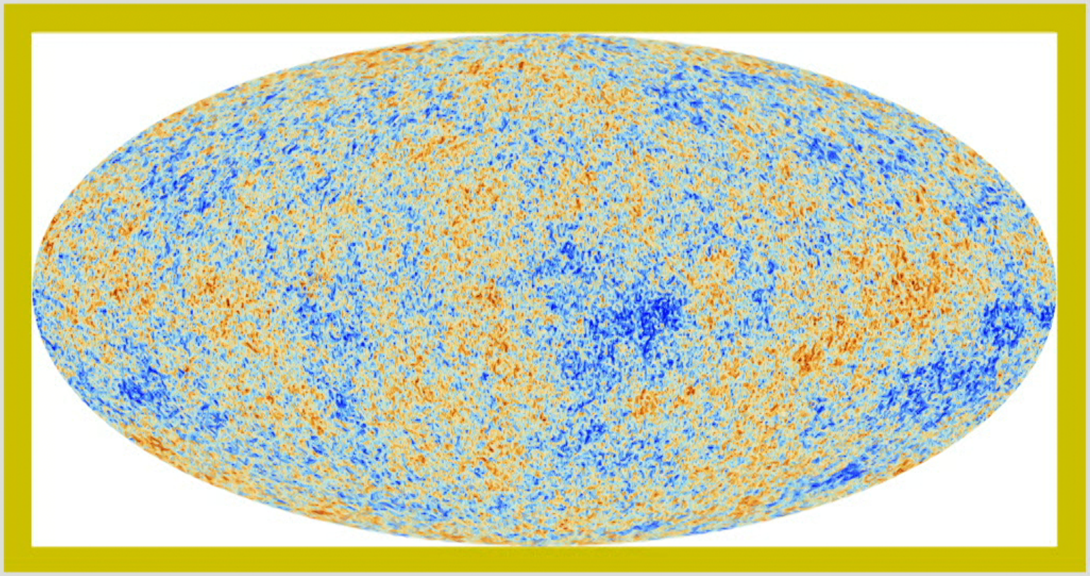


Image: Planck Collaboration 2013

Cosmological Observables

2. Baryon Acoustic Oscillations

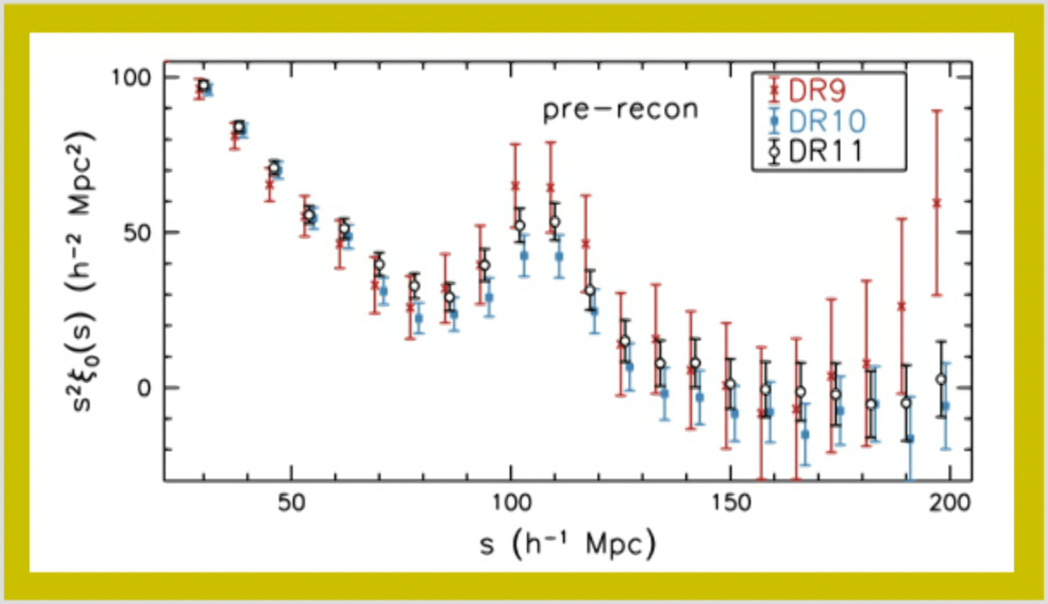


Image: Anderson et al. 2013

Cosmological Observables

2. Baryon Acoustic Oscillations

Galaxy bias → b^2

Growth rate → f

$$P^s_{gg}(k,\mu) = b^2 \left(1 + \frac{f}{b}\mu^2\right)^2 P_{\rm sm}(k)$$

$$\times \left[1 + f_{\rm BAO}(k')\right] e^{-\frac{k^2}{2}([1-\mu^2]\Sigma_\perp^2 + \mu^2\Sigma_{||}^2)}$$

$$(k')^2 = \alpha_s^2 \left[(\alpha_\perp k_\perp)^2 + (\alpha_{||}k_{||})^2\right]$$

Shift in BAO scale from nonlinearities → α_s

$b,\ f,\ \alpha_s$ are varied

Cosmological Observables

3. Weak lensing of galaxies

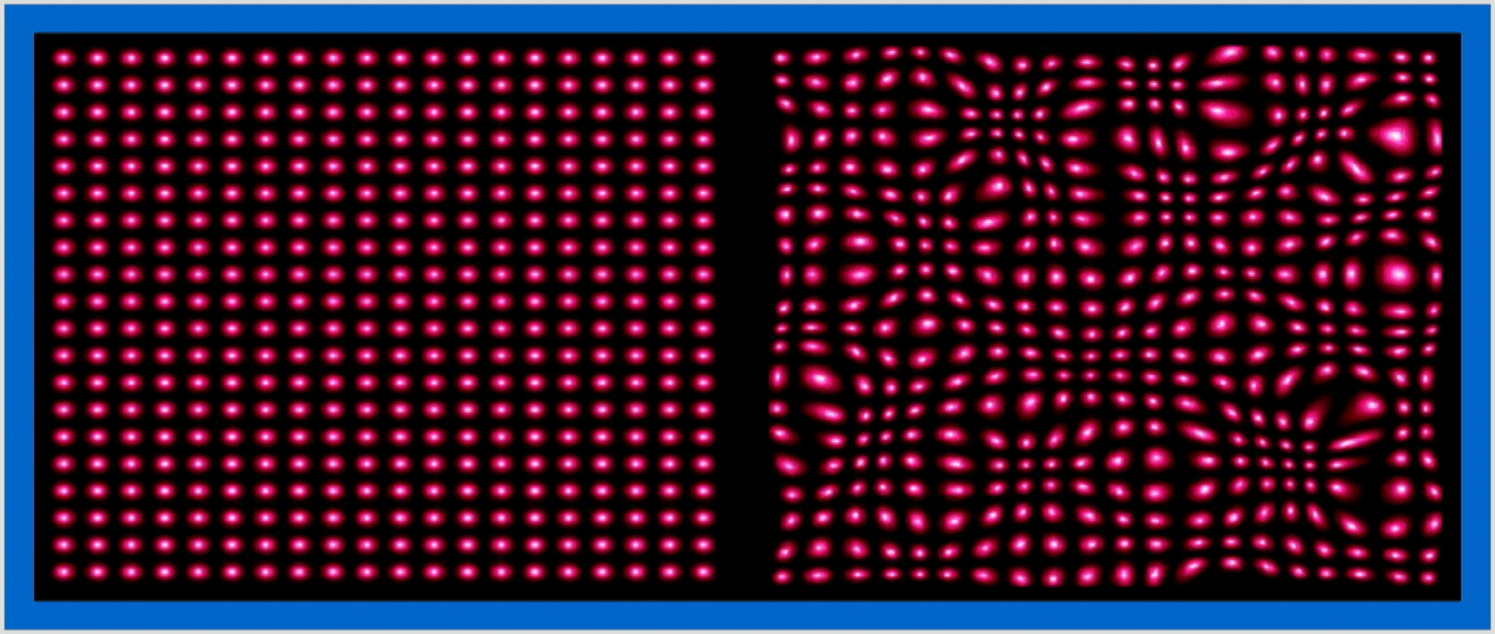


Image: iCosmo group (http://gravitationallensing.pbworks.com)

Cosmological Observables

3. **Weak lensing of galaxies**

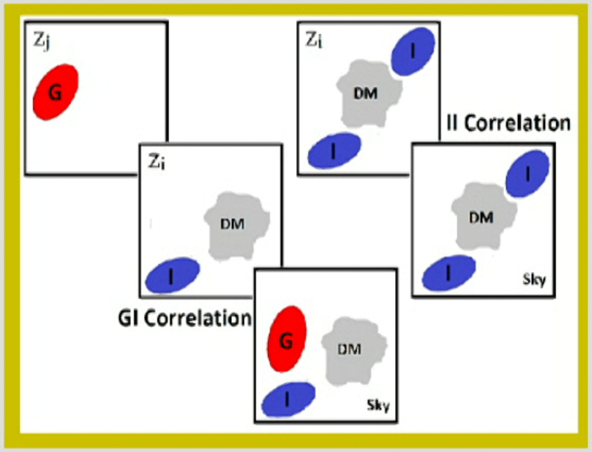
Shear-shear angular power spectrum (2-point function)

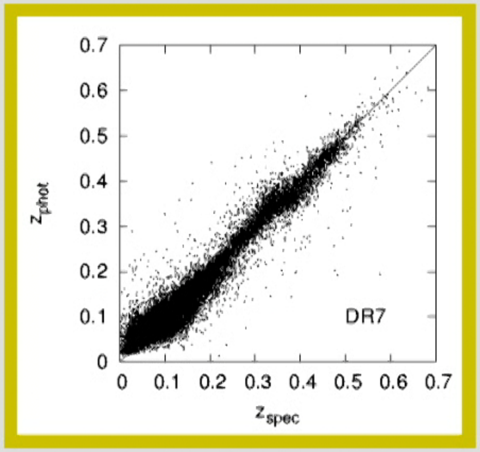
Intrinsic Alignments

- Nonlinear alignments model

Photometric redshifts

- larger variance → less source redshift bins





Images: Troxel & Ishak 2012, K. Abazajian & the SDSS Collaboration)

Cosmological Observables

3. **Weak lensing of galaxies**

Shear-shear angular power spectrum (2-point function)

Intrinsic Alignments

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Photometric redshifts

- larger variance → less source redshift bins

Side note: *Numerical issues on non-linear scales*

- Fisher forecasting require numerical derivatives
- Nonlinear scales → no convergent derivatives for some parameters
- **Restrict to linear scales:** $\ell_{\text{max}} = 300$

Parameters

We consider: $\Omega_{\rm K}$, and:

- $\Omega_c h^2$ - CDM density
- $\Omega_B h^2$ - baryon density
- h - Hubble parameter
- n_s - tilt of primordial P(k)
- A_s - amp. of primordial P(k)
- τ - optical depth

- b_i - galaxy bias in each z bin
- f_i - growth rate in each z bin
- f_C - Intrinsic alignment amp.
- w_0 - Dark energy parameter
- w_a - Dark energy parameter
- m_ν - Neutrino mass
- α_s - BAO nonlinear shift

Generations of Surveys

Cosmic Microwave Background:

- *Planck*
- Advanced ACTPol
- Stage 4 (S4)

Baryon Acoustic Oscillations:

- Baryon Oscillation Spectroscopic Survey (BOSS)
- Euclid
- Square Kilometer Array, Phase 2 (SKA2)

Weak lensing of galaxies:

- Dark Energy Survey (DES)
- Euclid
- Large Synoptic Survey Telescope (LSST)

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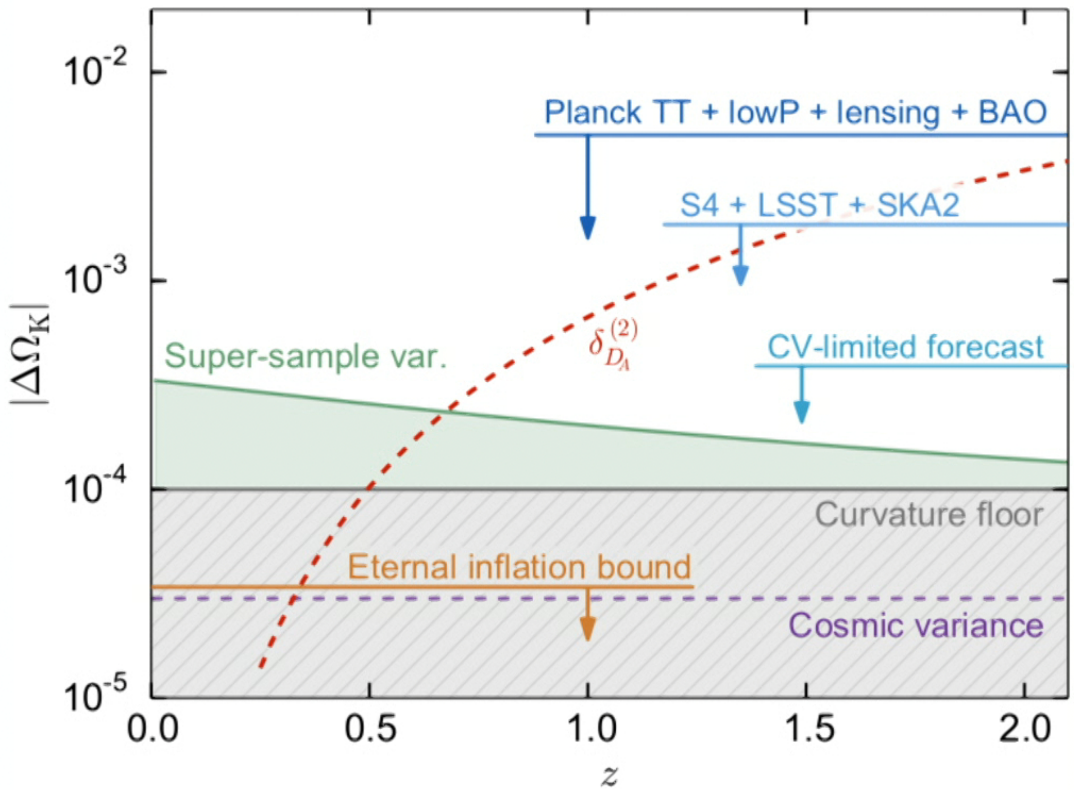
Forecast constraints



Forecast constraints

Experiments	Uninformative priors	Mild priors	Fixed w	Fixed α_s	Fixed M_ν	Fixed τ	Fixed f_c	Fixed b_i	$\ell_{max} =$ 2000	Fixed all
Planck CMB	393.4	280.7	239.3	280.7	258.4	267.9	280.7	280.7	280.7	4.6
+BOSS BAO	382.0	144.2	59.5	144.1	138.1	142.7	144.2	144.2	144.2	4.6
+DES WL	312.9	240.4	228.6	240.4	219.6	232.8	220.4	240.4	188.8	4.6
+both	305.9	118.0	56.4	117.8	114.1	116.7	118.0	118.0	105.8	4.6
Adv. ACTPol CMB	164.1	128.7	116.1	128.7	76.3	123.7	128.7	128.7	128.7	1.2
+Euclid BAO	153.6	44.1	18.8	43.4	29.1	41.0	44.1	44.1	44.1	1.2
+Euclid WL	97.9	83.4	70.2	83.4	43.0	80.7	74.4	83.4	42.7	1.2
+both	87.7	25.3	18.3	23.2	23.3	23.5	24.0	25.3	19.7	1.2
S4 CMB	94.1	74.9	63.6	74.9	39.2	73.4	74.9	74.9	74.9	0.9
+SKA2 BAO	68.2	31.4	13.9	30.6	21.7	28.5	31.4	31.4	31.4	0.9
+LSST WL	56.6	51.8	31.2	51.8	23.6	51.2	45.0	51.8	24.7	0.9
+both	47.8	22.2	12.7	19.4	17.3	21.3	21.1	22.2	15.0	0.9
CV-limited	3.6	3.5	3.3	2.2	3.5	1.9	3.4	3.5	—	0.4

$10^4 \times \sigma(\Omega_K)$ (95% confidence level)

Forecast constraints

Uninformative priors

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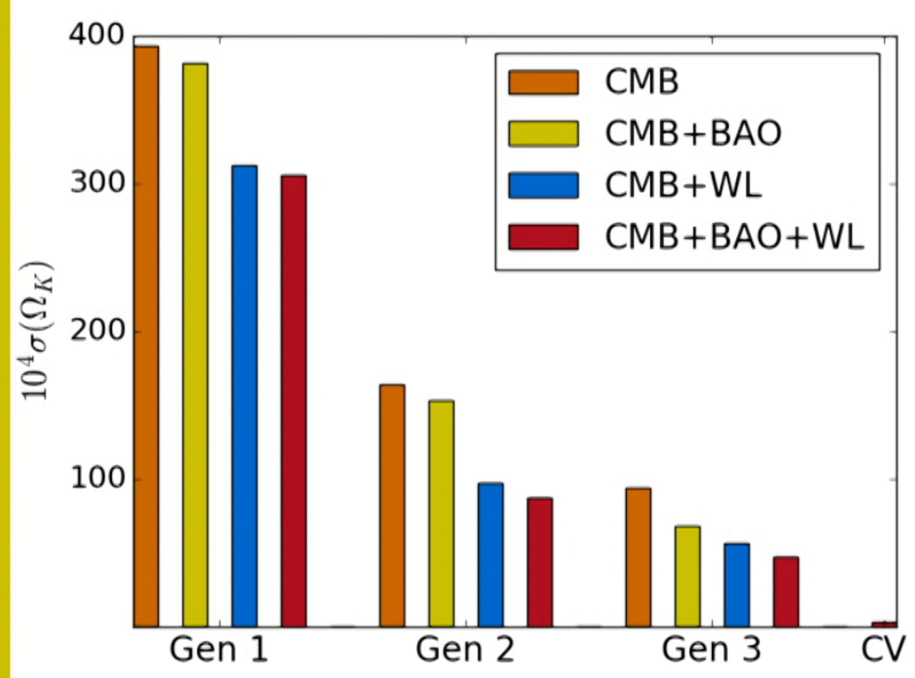
$10^4 \times \sigma(\Omega_K)$ (95% confidence level)

Forecast constraints

Uninformative priors



Forecast constraints

Mild priors

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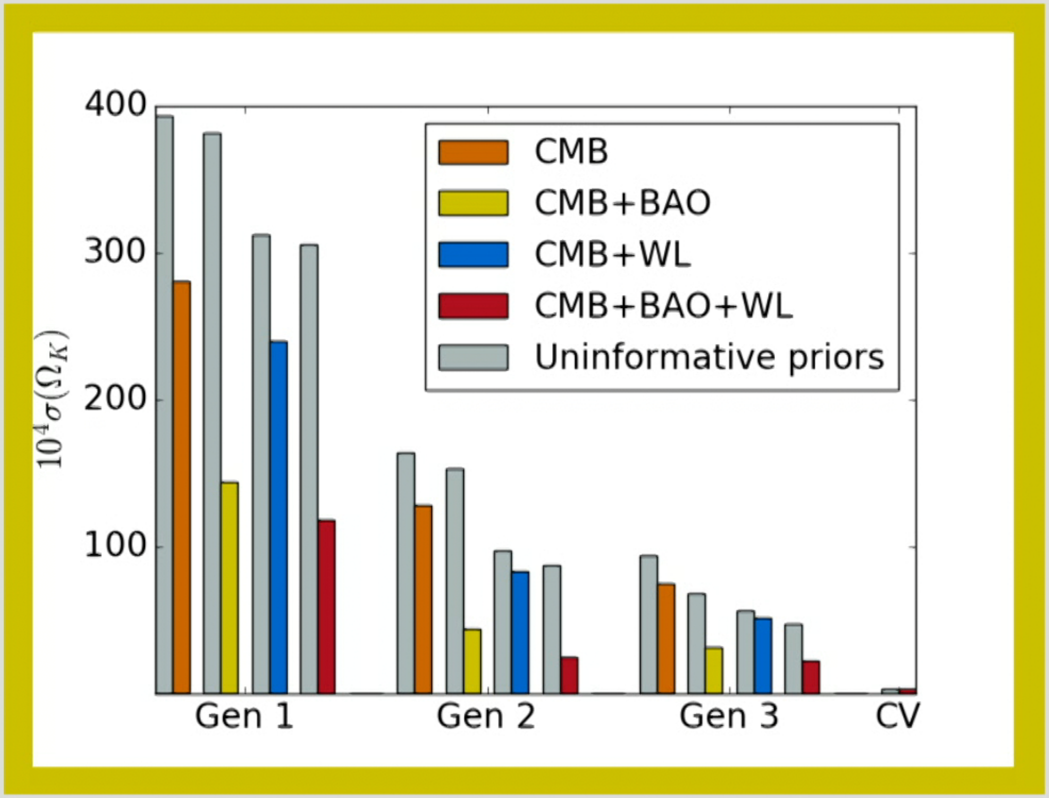
Forecast constraints

Mild priors



Forecast constraints

Fixed w

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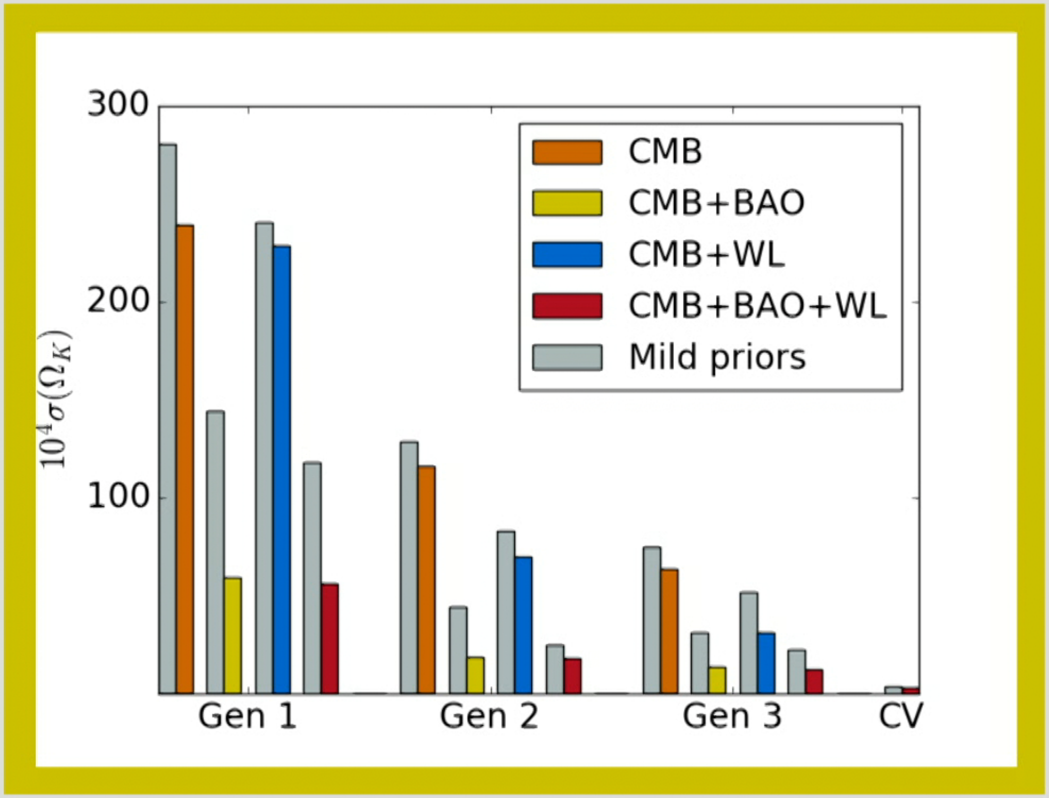
Forecast constraints

Fixed w



Forecast constraints

Fixed α_s

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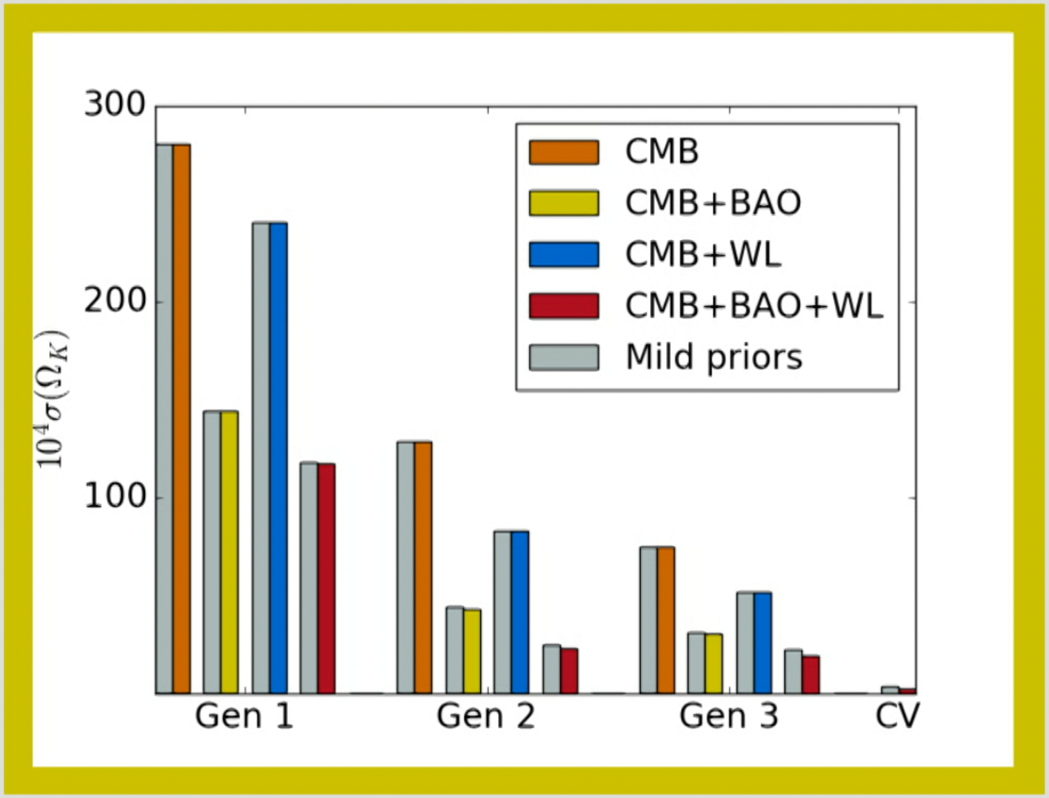
+both	87.7	25.3	18.3	23.2	23.3	23.5	24.0	25.3	19.7	1.2
S4 CMB	94.1	74.9	63.6	74.9	39.2	73.4	74.9	74.9	74.9	0.9
+SKA2 BAO	68.2	31.4	13.9	30.6	21.7	28.5	31.4	31.4	31.4	0.9
+LSST WL	56.6	51.8	31.2	51.8	23.6	51.2	45.0	51.8	24.7	0.9
+both	47.8	22.2	12.7	19.4	17.3	21.3	21.1	22.2	15.0	0.9
CV-limited	3.6	3.5	3.3	2.2	3.5	1.9	3.4	3.5	—	0.4

$10^4 \times \sigma(\Omega_K)$ (95% confidence level)

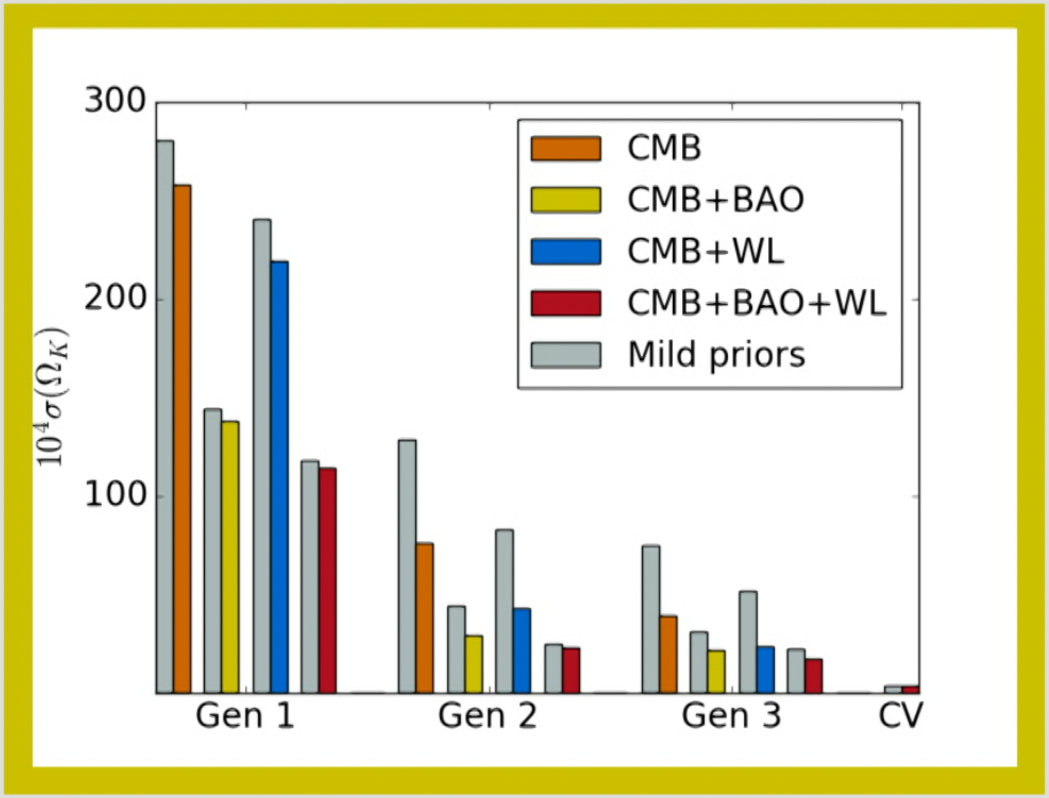
Forecast constraints

Fixed α_s



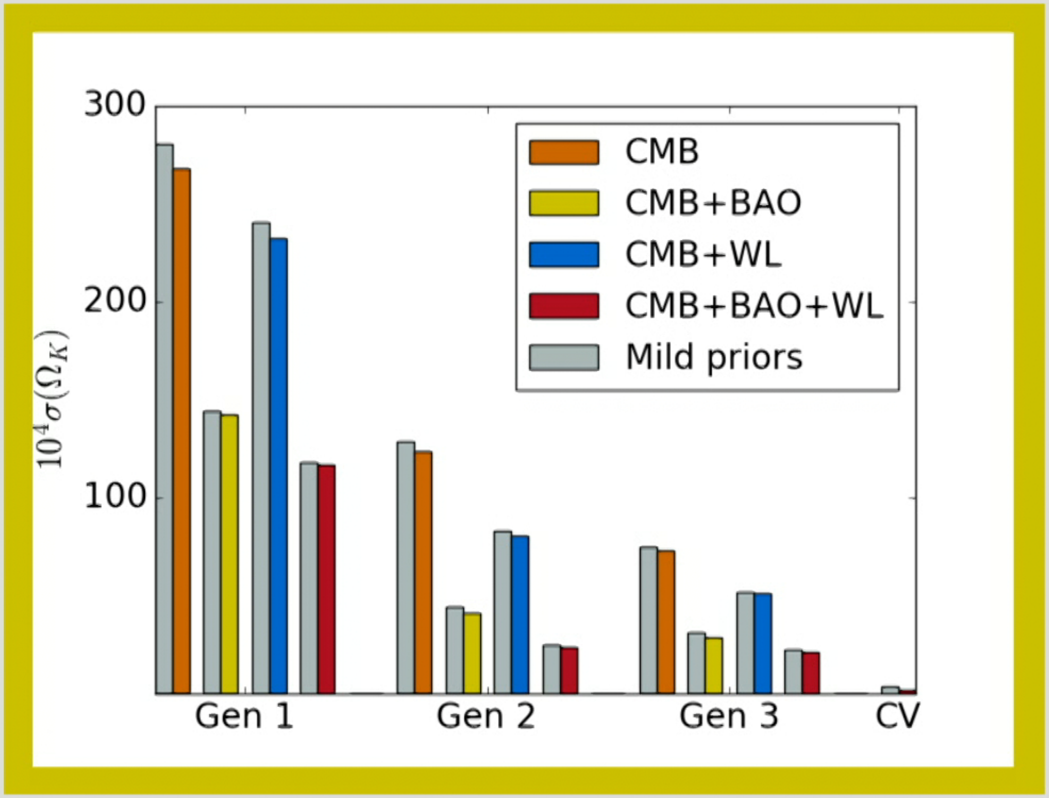
Forecast constraints

Fixed m_ν



Forecast constraints

Fixed τ



Forecast constraints

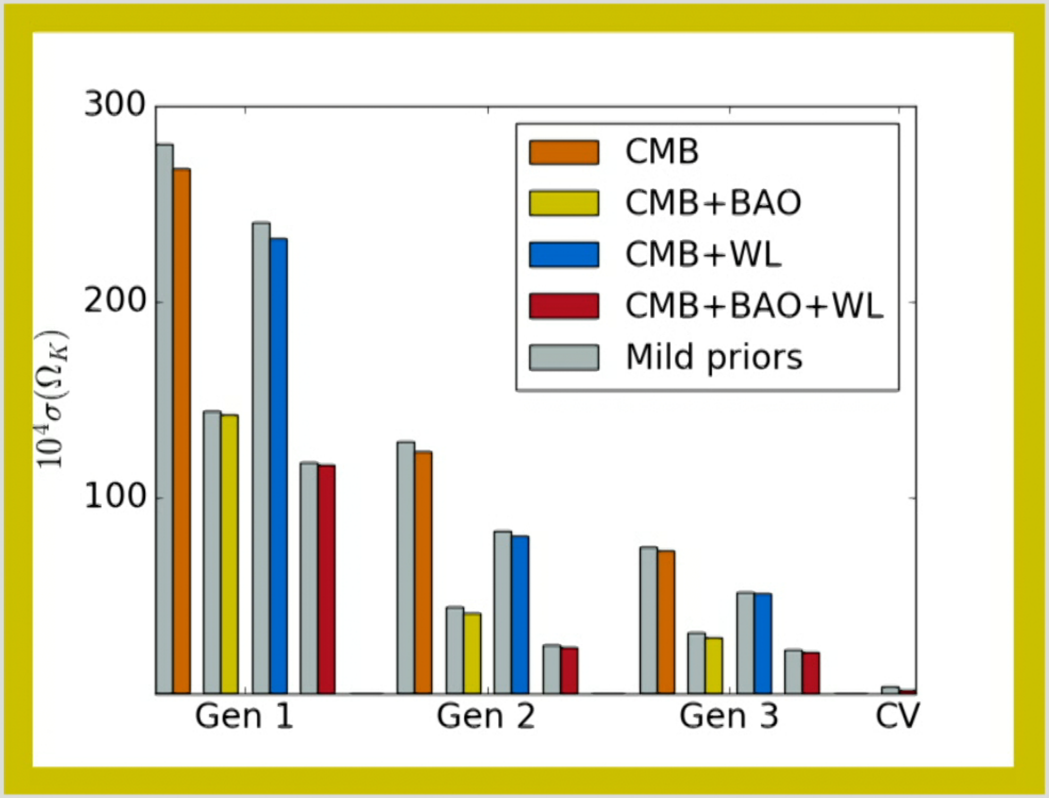
Fixed τ

Experiments	Uninformative priors	Mild priors	Fixed w	Fixed α_s	Fixed M_ν	Fixed τ	Fixed f_c	Fixed b_i	$\ell_{\max} = 2000$	Fixed all
Planck CMB	393.4	280.7	239.3	280.7	258.4	267.9	280.7	280.7	280.7	4.6
+BOSS BAO	382.0	144.2	59.5	144.1	138.1	142.7	144.2	144.2	144.2	4.6
+DES WL	312.9	240.4	228.6	240.4	219.6	232.8	220.4	240.4	188.8	4.6
+both	305.9	118.0	56.4	117.8	114.1	116.7	118.0	118.0	105.8	4.6
Adv. ACTPol CMB	164.1	128.7	116.1	128.7	76.3	123.7	128.7	128.7	128.7	1.2
+Euclid BAO	153.6	44.1	18.8	43.4	29.1	41.0	44.1	44.1	44.1	1.2
+Euclid WL	97.9	83.4	70.2	83.4	43.0	80.7	74.4	83.4	42.7	1.2
+both	87.7	25.3	18.3	23.2	23.3	23.5	24.0	25.3	19.7	1.2
S4 CMB	94.1	74.9	63.6	74.9	39.2	73.4	74.9	74.9	74.9	0.9
+SKA2 BAO	68.2	31.4	13.9	30.6	21.7	28.5	31.4	31.4	31.4	0.9
+LSST WL	56.6	51.8	31.2	51.8	23.6	51.2	45.0	51.8	24.7	0.9
+both	47.8	22.2	12.7	19.4	17.3	21.3	21.1	22.2	15.0	0.9
CV-limited	3.6	3.5	3.3	2.2	3.5	1.9	3.4	3.5	—	0.4

$10^4 \times \sigma(\Omega_K)$ (95% confidence level)

Forecast constraints

Fixed τ



Forecast constraints

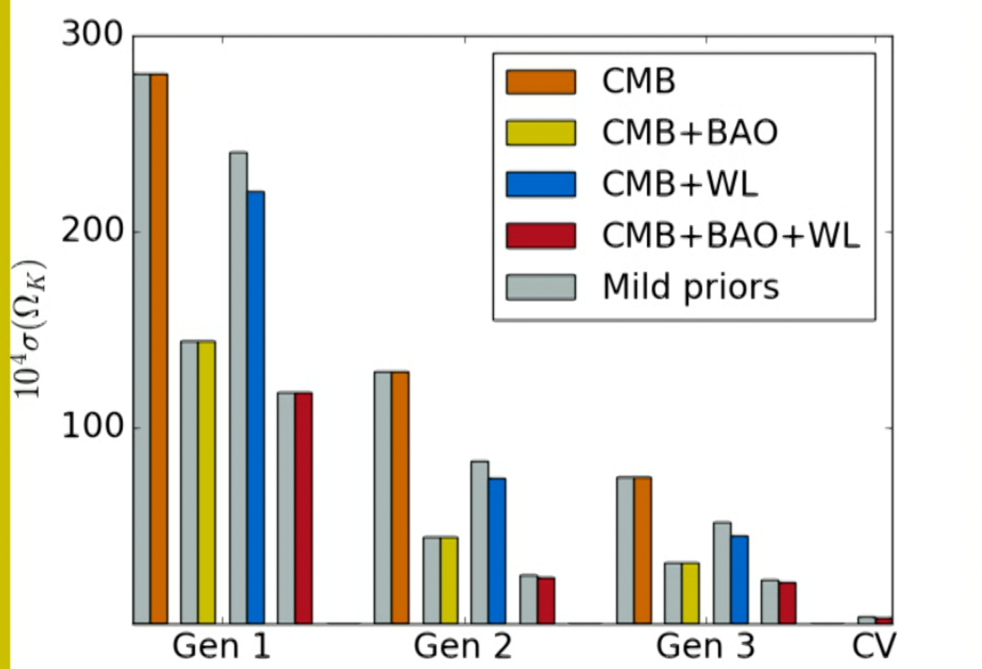
Fixed f_c

Experiments	Uninformative priors	Mild priors	Fixed w	Fixed α_s	Fixed M_ν	Fixed τ	Fixed f_c	Fixed b_i	$\ell_{\max} =$ 2000	Fixed all
Planck CMB	393.4	280.7	239.3	280.7	258.4	267.9	280.7	280.7	280.7	4.6
+BOSS BAO	382.0	144.2	59.5	144.1	138.1	142.7	144.2	144.2	144.2	4.6
+DES WL	312.9	240.4	228.6	240.4	219.6	232.8	220.4	240.4	188.8	4.6
+both	305.9	118.0	56.4	117.8	114.1	116.7	118.0	118.0	105.8	4.6
Adv. ACTPol CMB	164.1	128.7	116.1	128.7	76.3	123.7	128.7	128.7	128.7	1.2
+Euclid BAO	153.6	44.1	18.8	43.4	29.1	41.0	44.1	44.1	44.1	1.2
+Euclid WL	97.9	83.4	70.2	83.4	43.0	80.7	74.4	83.4	42.7	1.2
+both	87.7	25.3	18.3	23.2	23.3	23.5	24.0	25.3	19.7	1.2
S4 CMB	94.1	74.9	63.6	74.9	39.2	73.4	74.9	74.9	74.9	0.9
+SKA2 BAO	68.2	31.4	13.9	30.6	21.7	28.5	31.4	31.4	31.4	0.9
+LSST WL	56.6	51.8	31.2	51.8	23.6	51.2	45.0	51.8	24.7	0.9
+both	47.8	22.2	12.7	19.4	17.3	21.3	21.1	22.2	15.0	0.9
CV-limited	3.6	3.5	3.3	2.2	3.5	1.9	3.4	3.5	—	0.4

$10^4 \times \sigma(\Omega_K)$ (95% confidence level)

Forecast constraints

Fixed f_c



Forecast constraints

Fixed b_i

Experiments	Uninformative priors	Mild priors	Fixed w	Fixed α_s	Fixed M_ν	Fixed τ	Fixed f_c	Fixed b_i	$\ell_{\max} =$ 2000	Fixed all
Planck CMB	393.4	280.7	239.3	280.7	258.4	267.9	280.7	280.7	280.7	4.6
+BOSS BAO	382.0	144.2	59.5	144.1	138.1	142.7	144.2	144.2	144.2	4.6
+DES WL	312.9	240.4	228.6	240.4	219.6	232.8	220.4	240.4	188.8	4.6
+both	305.9	118.0	56.4	117.8	114.1	116.7	118.0	118.0	105.8	4.6
Adv. ACTPol CMB	164.1	128.7	116.1	128.7	76.3	123.7	128.7	128.7	128.7	1.2
+Euclid BAO	153.6	44.1	18.8	43.4	29.1	41.0	44.1	44.1	44.1	1.2
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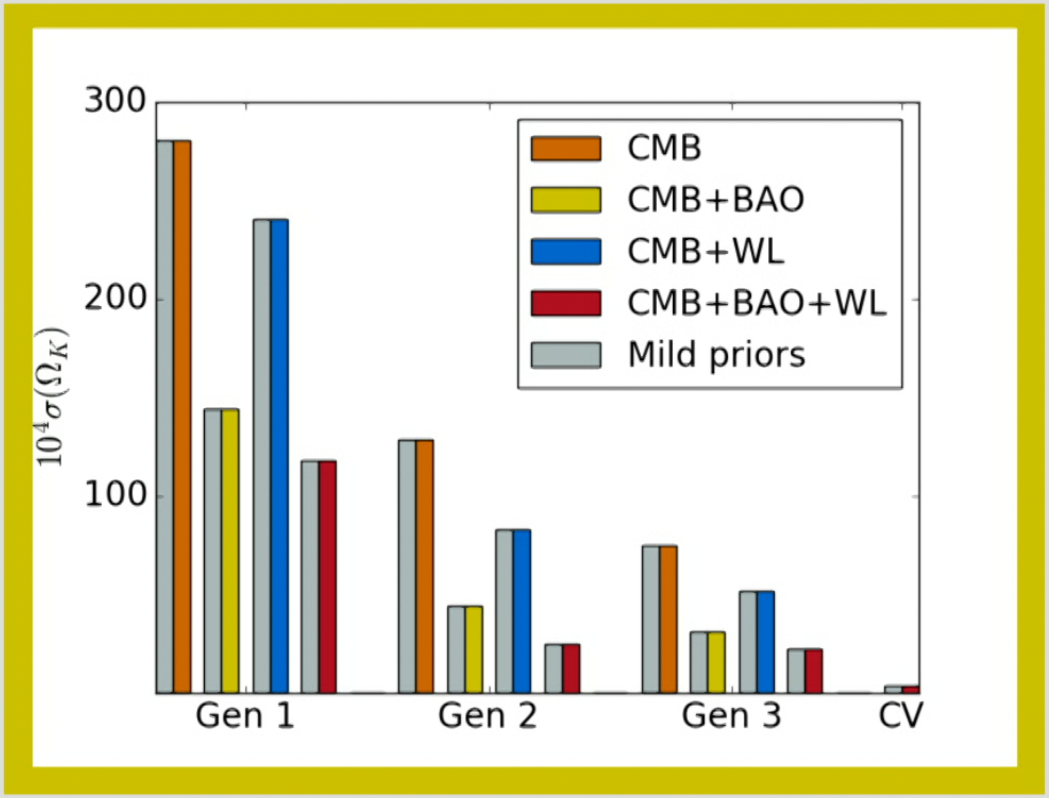
S4 CMB	94.1	74.9	63.6	74.9	39.2	73.4	74.9	74.9	74.9	0.9
+SKA2 BAO	68.2	31.4	13.9	30.6	21.7	28.5	31.4	31.4	31.4	0.9
+LSST WL	56.6	51.8	31.2	51.8	23.6	51.2	45.0	51.8	24.7	0.9
+both	47.8	22.2	12.7	19.4	17.3	21.3	21.1	22.2	15.0	0.9
CV-limited	3.6	3.5	3.3	2.2	3.5	1.9	3.4	3.5	—	0.4

$10^4 \times \sigma(\Omega_K)$ (95% confidence level)

Forecast constraints

Fixed b_i



Forecast constraints

$$\ell_{\rm max} = 2000$$

Experiments	Uninformative priors	Mild priors	Fixed w	Fixed α_s	Fixed M_ν	Fixed τ	Fixed f_c	Fixed b_i	$\ell_{\rm max} =$ 2000	Fixed all
Planck CMB	393.4	280.7	239.3	280.7	258.4	267.9	280.7	280.7	280.7	4.6
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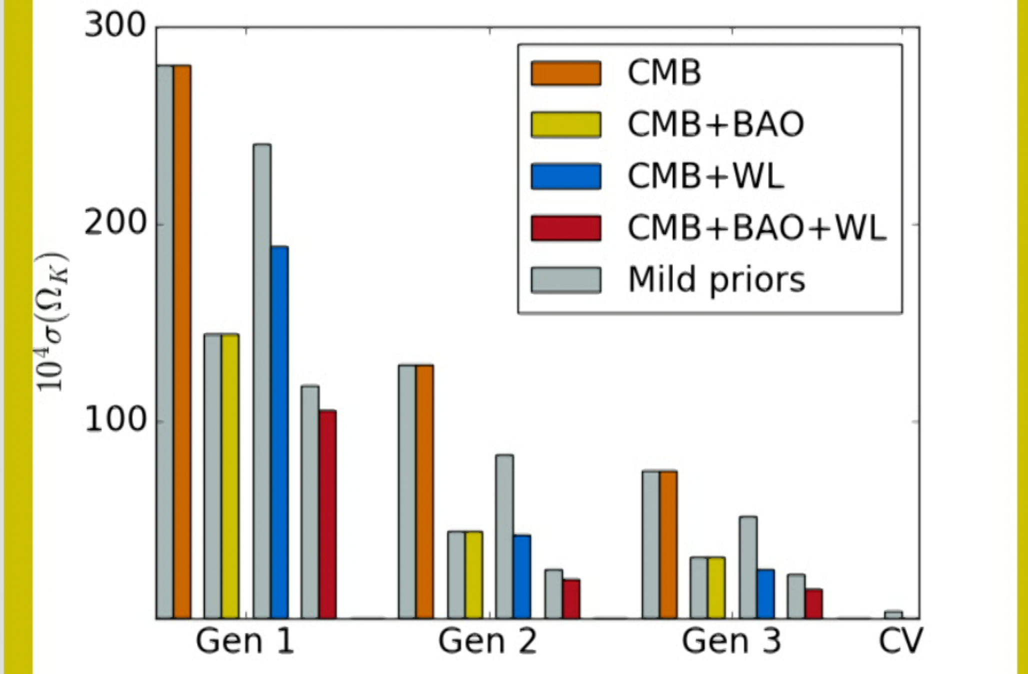
+both	47.8	22.2	12.7	19.4	17.3	21.3	21.1	22.2	15.0	0.9
CV-limited	3.6	3.5	3.3	2.2	3.5	1.9	3.4	3.5	—	0.4

$10^4 \times \sigma(\Omega_{\rm K})$ (95% confidence level)

Forecast constraints

$$\ell_{\max} = 2000$$



Forecast constraints

Fixed all

Experiments	Uninformative priors	Mild priors	Fixed w	Fixed α_s	Fixed M_ν	Fixed τ	Fixed f_c	Fixed b_i	$\ell_{\max} = 2000$	Fixed all
Planck CMB	393.4	280.7	239.3	280.7	258.4	267.9	280.7	280.7	280.7	4.6
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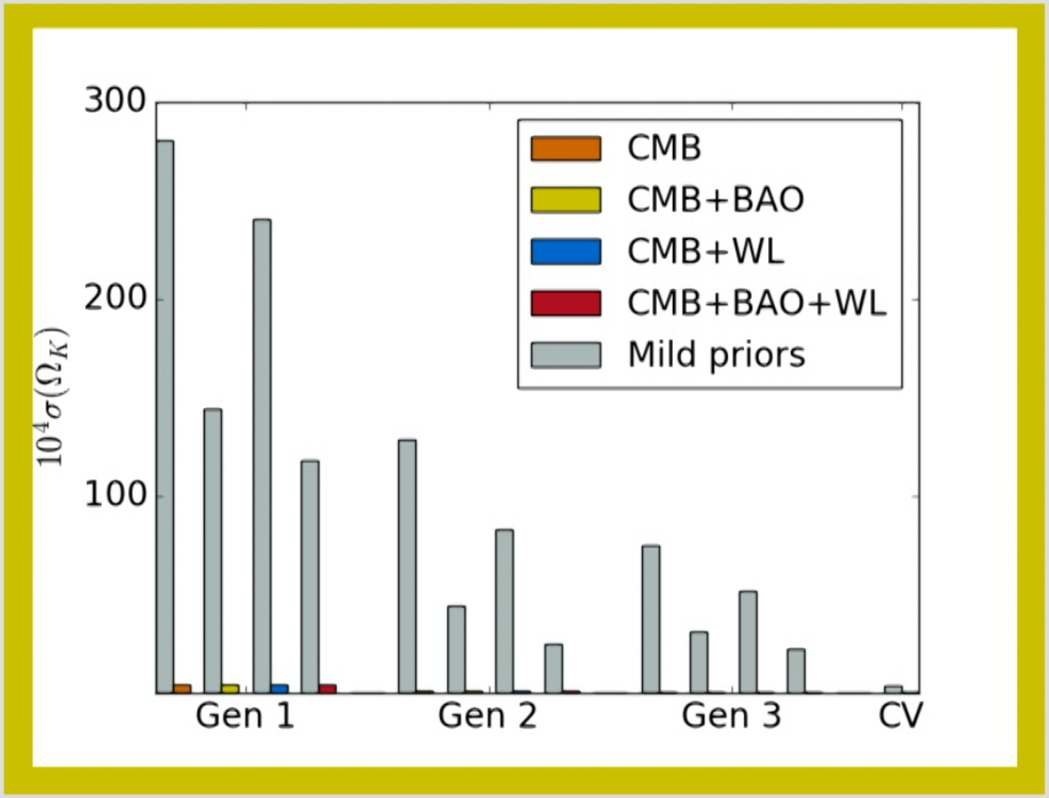
$10^4 \times \sigma(\Omega_K)$ (95% confidence level)

Forecast constraints

Fixed all



Forecast constraints

Summary of forecasting results:

- Parameters where fixing affects constraints non-negligibly:

$$w_0,\ w_a,\ m_\nu,\ \tau$$

- Parameters where fixing has little or no effect:

$$\alpha_s,\ b_i,\ f_C$$

- Setting $\ell_{\rm max} = 2000$ improves lensing constraints.

- Only fixing all other parameters reaches the curvature floor.

A few notes on systematic effects

Intrinsic alignments:

- increasing fiducial amplitude → better constraints

Large scale structure effects:

- super sample modes
- local inhomogeneities
- higher order perturbation theory quantities

Photometric redshifts

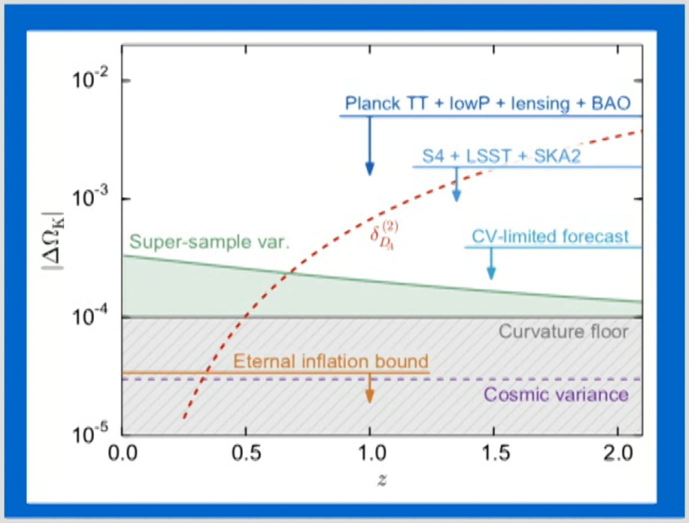
- we assume Gaussian – probably not the case

Summary & Conclusions

From CMB, BAO, and WL, likely to obtain $\sigma(\Omega_K) \approx 10^{-3}$.

Other observables may help:
21 cm, supernovae, redshift-space distortions...

Spatial curvature constraints can serve as a litmus test for precision cosmology.



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