COSMOLOGICAL FRAMEWORKS

FOR TESTING GRAVITY

TESSA BAKER

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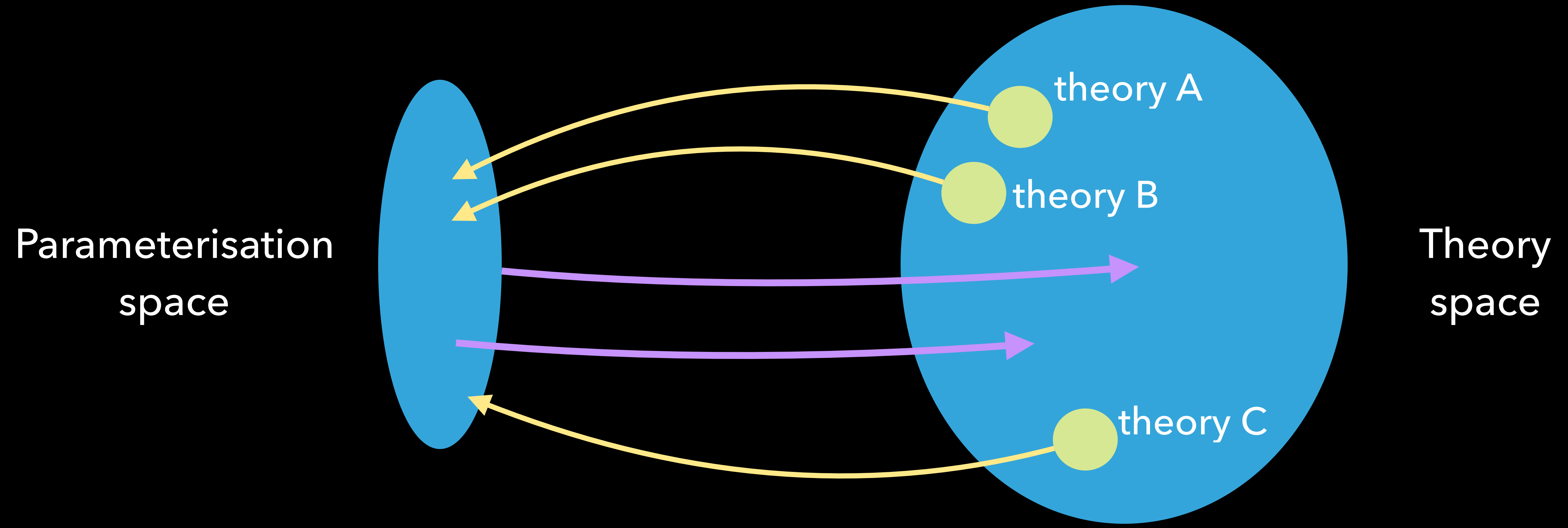
OUTLINE

- A few remarks.
- Frameworks version 1: simple / data-friendly
- Frameworks version 2: EFT-inspired / theory-friendly
  - Formalism
  - Current constraints
- Forecast constraints on version 2.

PHILOSOPHY

- Cosmology driver: accelerated expansion.
- Dissatisfaction with current models on offer.
- Historical precedent set by PPN is encouraging.



CAVEAT EMPTOR

- **Not** directly analogous to PPN in implementation.
- **Not** a true EFT à la particle physics.
- Linear regime only — screening not manifest.
- Important to balance mathematical rigour with observational usefulness.
- Still under development.

SIMPLE TREATMENT

$$ds^2 = -dt^2\,(1+2\Psi) + a^2(t)\,(1-2\Phi)\,dx^2$$

Poisson eq.: $$2\nabla^2\Psi = 8\pi G\,\mu(a,k)\,\rho_M a^2\Delta_M$$

`Slip' ratio: $$\gamma(a,k) = \frac{\Phi}{\Psi}$$

Lensing potential: $$\Phi + \Psi = \Sigma(a,k)(\Phi_{GR} + \Psi_{GR})$$

SIMPLE TREATMENT

$$ds^2 = -dt^2\,(1+2\Psi) + a^2(t)\,(1-2\Phi)\,dx^2$$

What's happening behind the scenes?

1) Use of the quasi-static approximation (QSA):

$$|\dot{\Phi}| \ll |\nabla\Phi|, \qquad |\ddot{\Phi}| \ll |\nabla^2\Phi|$$ + similar for Ψ

⇒ OK well below cosmological horizon.

$$|\delta\dot{\phi}| \ll |\nabla\delta\phi|, \qquad |\delta\ddot{\phi}| \ll |\nabla^2\delta\phi|$$

⇒ OK below the *sound horizon* of the new scalar.

SIMPLE TREATMENT

$$ds^2 = -dt^2\,(1+2\Psi) + a^2(t)\,(1-2\Phi)\,dx^2$$

Checks of the QSA in specific theories:

Galileons	*1208.0600*	*f(R)*	*1411.6128*
DGP	*0906.0858*	*Symmetron*	*1312.6026*

2) The QSA reduces Poisson, slip and e.o.m. to **algebraic** relations between Φ, Ψ and $\delta\varphi$.

3) Combine equations to eliminate $\delta\varphi$.

SIMPLE TREATMENT

$$ds^2 = -dt^2\,(1+2\Psi) + a^2(t)\,(1-2\Phi)\,dx^2$$

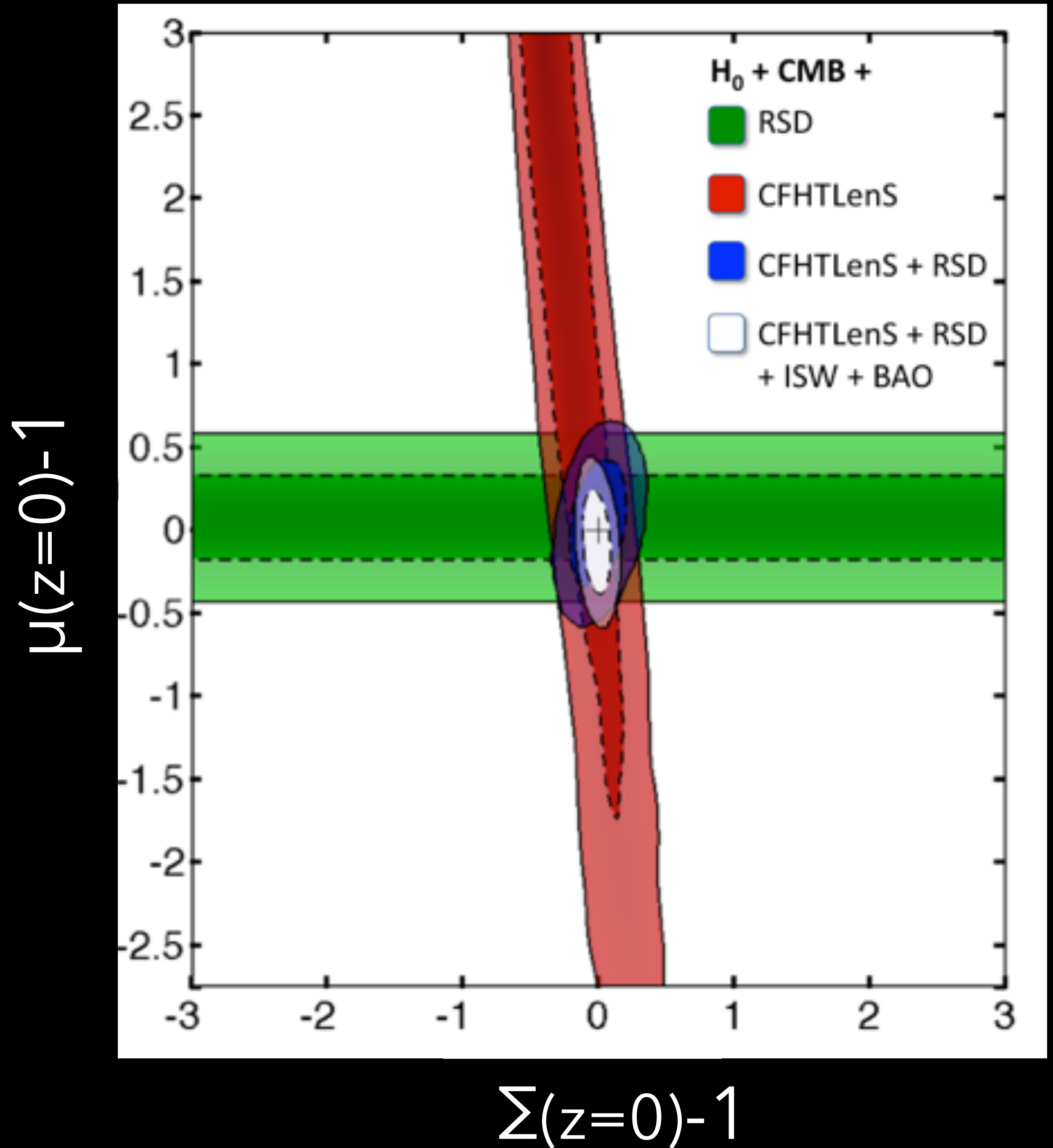
Poisson eq.: $$2\nabla^2\Psi = 8\pi G\,\mu(a,k)\,\rho_M a^2 \Delta_M$$

`Slip' ratio: $$\gamma(a,k) = \frac{\Phi}{\Psi}$$

Lensing potential: $$\Phi + \Psi = \Sigma(a,k)(\Phi_{GR} + \Psi_{GR})$$

⇒ All properties of new scalar folded into μ and Σ (or ɣ).

SIMPLE TREATMENT



Simpson et al. (2012)
Leonard et al. (2015)
Coming soon: KiDS.

Good: Simple to test.

Bad: All interesting behaviour folded away into μ, Σ .

(BRIEFLY: PPF)

PPF = Post-Parameterised Friedmann formalism.

Tried to keep track of the new scalar d.o.f. more explicitly.

$$2\nabla^2\Psi = 8\pi G_N a^2 \rho_M \Delta_M$$

$$+A(k,a)\Phi + B(k,a)\Psi + C(k,a)\dot{\Phi}$$

$$+D(k,a)\delta\phi + E(k,a)\delta\dot{\phi}$$

Too many free slots / ‘parameters’ to be constrainable.

WHAT'S GONE WRONG?

$$\text{ACTION} \longrightarrow \boxed{\text{FIELD EQUATIONS}} \longrightarrow \text{OBSERVABLES}$$

WHAT'S GONE WRONG?

ACTION

↓

FIELD EQUATIONS

↓

OBSERVABLES

We want to parameterise linear cosmological perturbation theory.

⇒ Need an action quadratic in perturbations.

Good: Reflects mathematical structure of MG theories better.

Bad: A step further away from observables.

EFT-INSPIRED APPROACHES

Specify the field content and symmetries.

↓

Construct most general quadratic action from allowed building blocks.

↓

Enforce symmetries ⇒ fix relationships between new terms.

↓

Maximal set of `parameters' to be constrained.

EFT-INSPIRED APPROACHES

Specify the field content and symmetries.

- Do we want to add new scalar, vector or tensor fields to gravity?

  E.g. Horndeski bigravity

  Einstein-Aether

- Isotropic + homogeneous cosmological background.

  $$\Rightarrow \quad a(t)\,, \quad H(t)$$

- Linear diffeomorphism invariance.

  i.e. Reparameterisation invariance of manifold.

EFT-INSPIRED APPROACHES

Specify the field content and symmetries.

↓

Construct most general quadratic action from allowed building blocks.

EFT-INSPIRED APPROACHES

Construct most general quadratic action from allowed building blocks.

$$\delta_2 S = \int dt\, d^3x\, N\sqrt{-h}\, \Big[L_{hR}(t)\, \delta h^i_j \delta R^j_i \;+\; L_{NK}(t)\, \delta N \delta K$$

$$+\; L_{h\,\partial N^i}(t)\, \delta h_{ij}\, \partial^i \delta \dot{N}^j \;+\; L_{\partial N \partial N}(t)\, \partial^i \delta N\, \partial_i \delta N \;+\; \ldots$$

$$+\; L_{\partial\phi\partial\phi}(t)\, \partial^i \delta\phi\, \partial_i \delta\phi \;+\; L_{\phi R}(t)\, \delta\phi\, \delta R \;+\; \cdots$$

$$+\; \text{usual fluid matter sector} \;\Big]$$

EFT-INSPIRED APPROACHES

Specify the field content and symmetries.

↓

Construct most general quadratic action from allowed building blocks.

↓

Enforce symmetries ⇒ fix relationships between new terms.

EFT-INSPIRED APPROACHES

Enforce symmetries ⇒ fix relationships between new terms.

- i.e. the following must vanish:

$$\Big[\,(\ldots)\,\delta N + (\ldots)\,\partial_i\delta N^i + (\ldots)\,\partial^i\partial^j(\delta h_{ij}) + (\ldots)\,\delta\phi\,\Big]\pi$$

$$+$$

$$\Big[\,(\ldots)\,\delta N + (\ldots)\,\partial_i\delta N^i + (\ldots)\,\partial^i\partial^j(\delta h_{ij}) + (\ldots)\,\delta\phi\,\Big]\epsilon$$

$+$ (many terms not shown)

EFT-INSPIRED APPROACHES

Q: What's sitting inside those (…) ?

Ans: Linear combinations of the 'Taylor' coefficients, e.g.

$$4\dot{H}L_{KK\times} + \rho_M + P_M = 0$$

$$2L_{hh\times} - \dot{L}_{hK\times} - 3HL_{hK\times} = 0$$

$$L_{\dot{N}^i\dot{N}^j} = L_{K\dot{N}} = L_{\dot{N}\dot{N}} = 0$$

Complicated (but doable) elimination of variables.

⇒ Reduce action down to maximum set of 'true' free coeffs.

EFT-INSPIRED APPROACHES

Gauge invariance is **seriously** powerful.

Fields	# Naive coeffs.	# True free functions	Theory family
$g_{\mu\nu}$	32	1	GR
$g_{\mu\nu},\ \phi$	72	5	Horndeski
$g_{\mu\nu},\ A^{\mu}$	66	10	Vector-tensor
$g_{\mu\nu},\ A^{\mu},\ \lambda$	67	4	Einstein-Aether
$g_{\mu\nu},\ q_{\mu\nu}$	?	? (in progress)	Bigravity

1-SCALAR CASE (HORNDESKI)

$$\delta_2 S = \int d^3x\, dt\; a^3 \frac{M(t)^2}{2} \Big[R^{(4D)} + \alpha_T(t)\, \delta_2\left(\sqrt{h} R / a^3\right)$$
$$+ \alpha_K(t) H^2 \delta N^2 + 4\alpha_B(t) H \delta K \delta N \Big]$$

$\alpha_T(t)$: speed of gravitational waves, $c_T^2 = 1 + \alpha_T$.

$\alpha_K(t)$: kinetic term of scalar field.

$\alpha_B(t)$: `braiding' – mixing of scalar + metric kinetic terms.

$\alpha_M(t) = \dfrac{1}{H} \dfrac{d \ln M^2(t)}{dt}$: running of effective Planck mass.

1-SCALAR CASE (HORNDESKI)

$$
\begin{aligned}
S_G^{(2)} = \int d^4x\, a^3 M^2 \Big\{ & \frac{1}{2} H^2 \left(\alpha_K - 12\alpha_B - 6\right)\Phi^2 - 6H\left(1+\alpha_B\right)\Phi\dot{\Psi} + 2\left(1+\alpha_H\right)\Psi\partial^2\Phi \\
- & \, 3\dot{\Psi}^2 - \left(1+\alpha_T\right)\Psi\partial^2\Psi + 2a^2 H\left(1+\alpha_B\right)\Phi\partial^2\dot{E} - 2H\left(1+\alpha_B\right)\Phi\partial^2 B + 2a^2\Psi\partial^2\dot{E} \\
- & \, 2\dot{\Psi}\partial^2 B - 3\left(\frac{\rho_m + P_m}{M^2} + 2\dot{H}\right)\dot{\Psi}\delta\chi + 2\alpha_H\dot{\Psi}\partial^2\delta\chi + 6H\alpha_B\dot{\Psi}\delta\dot{\chi} + H^2\left(6\alpha_B - \alpha_K\right)\Phi\delta\dot{\chi} \\
- & \, 2H\left[\alpha_T - \alpha_H - \frac{d\ln M^2}{d\ln a}\left(\alpha_H + 1\right) - \frac{d\alpha_H}{d\ln a}\right]\Psi\partial^2\delta\chi - 2H(\alpha_B - \alpha_H)\Phi\partial^2\delta\chi \\
- & \, 3H\left[\frac{(\rho_m + P_m)}{M^2} + 2\dot{H}\left(1+\alpha_B\right)\right]\Phi\delta\chi - \left[\frac{(\rho_m + P_m)}{M^2} + 2\dot{H}\right]\delta\chi\left(\partial^2 B - a^2\partial^2\dot{E}\right) \\
+ & \, 2H\alpha_B\delta\dot{\chi}\left(\partial^2 B - a^2\partial^2\dot{E}\right) - \Big[3\left(\dot{H}^2 + H\ddot{H} + 3H^2\dot{H} + H^2\dot{H}\frac{d\ln M^2}{d\ln a}\right)\alpha_B + 3H\dot{H}\dot{\alpha}_B \\
+ & \, \frac{3}{2}\dot{H}\frac{(\rho_m + P_m)}{M^2} + 3\dot{H}^2\Big]\delta\chi^2 - \Big[\left(\dot{H} + H^2 + H^2\frac{d\ln M^2}{d\ln a}\right)\left(\alpha_B - \alpha_H\right) + H\left(\dot{\alpha}_B - \dot{\alpha}_H\right) \\
+ & \, H^2\alpha_T + \dot{H} - H^2\frac{d\ln M^2}{d\ln a} + \frac{1}{2}\frac{(\rho_m + P_m)}{M^2}\Big]\delta\chi\partial^2\delta\chi + \frac{1}{2}H^2\alpha_K\delta\dot{\chi}^2 \qquad (4.15) \\
- & \, P_m\left(\frac{3}{2}\Psi^2 - a^2\Psi\partial^2 E - \frac{a^4}{2}\partial^2 E\partial^2 E\right) - \rho_m\left(\frac{1}{2}\Phi^2 + \frac{1}{2}B\partial^2 B + 3\Phi\Psi - a^2\Phi\partial^2 E\right)\Big\},
\end{aligned}
$$

CONSTRAINTS:

- $\alpha_K(z)$ ('kineticity') drops out of e.o.m.s on small scales.
- $\alpha_T(z)$ (tensor speed) has little impact on scalar perturbations.

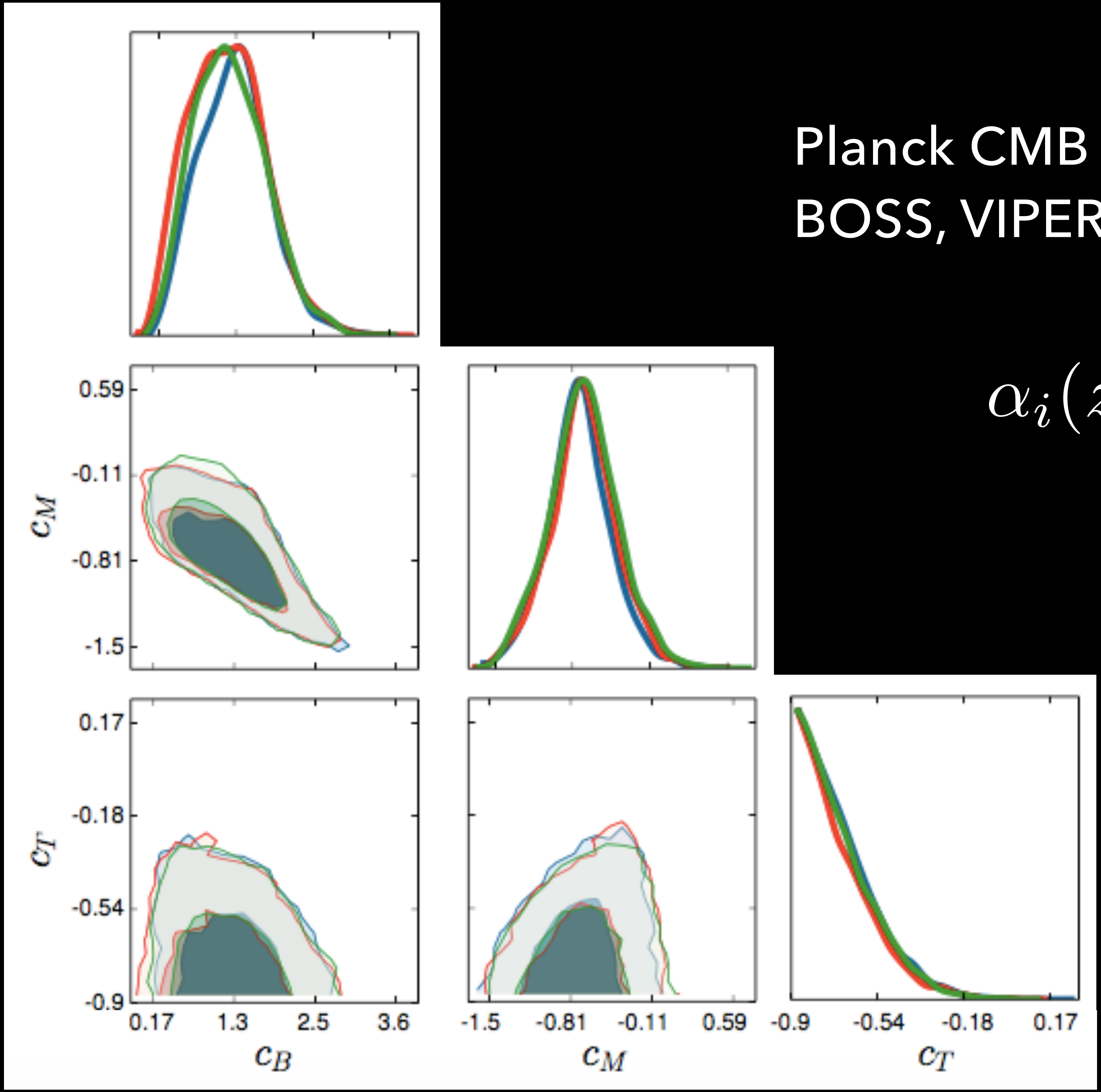
  $\Rightarrow$ Focus on $\alpha_B(z)$ and $\alpha_M(z)$.

- Need an ansatz for redshift dependence of the $\alpha_i(z)$.

  Common choice:

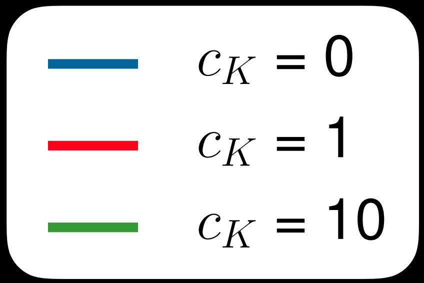
$$\alpha_i(z) = c_i \, \Omega_\Lambda(z)$$

CONSTRAINTS: CURRENT



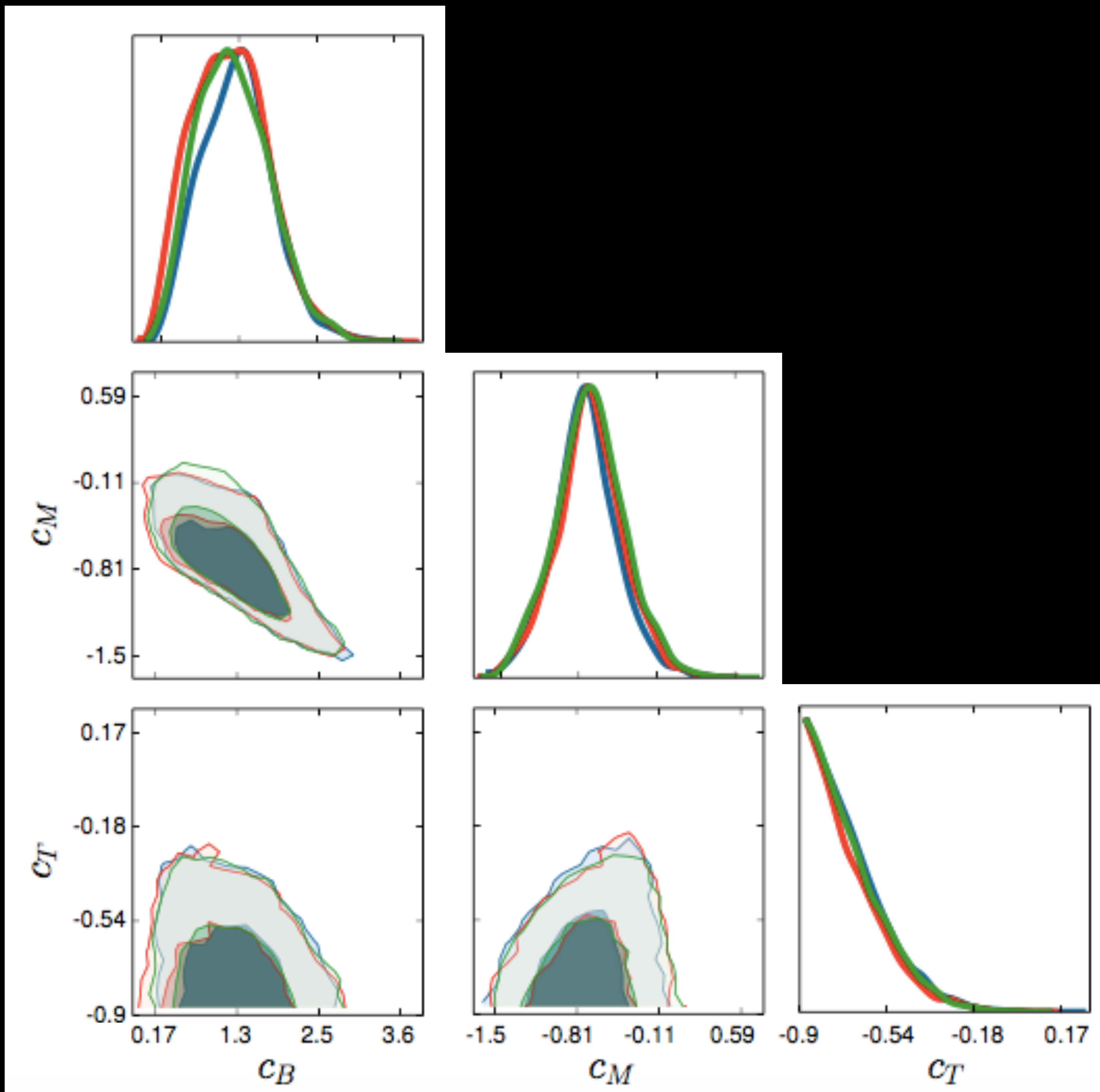
Planck CMB data + galaxy surveys: BOSS, VIPERS, WiggleZ.

$$\alpha_i(z) = c_i \; \Omega_\Lambda(z)$$



Bellini et al., 2015.

CONSTRAINTS: CURRENT



2σ constraints:

$0.24 < c_B < 2.32$

$-1.36 < c_M < -0.13$

$-0.90 < c_T < -0.39$

$c_K = 0$
$c_K = 1$
$c_K = 10$

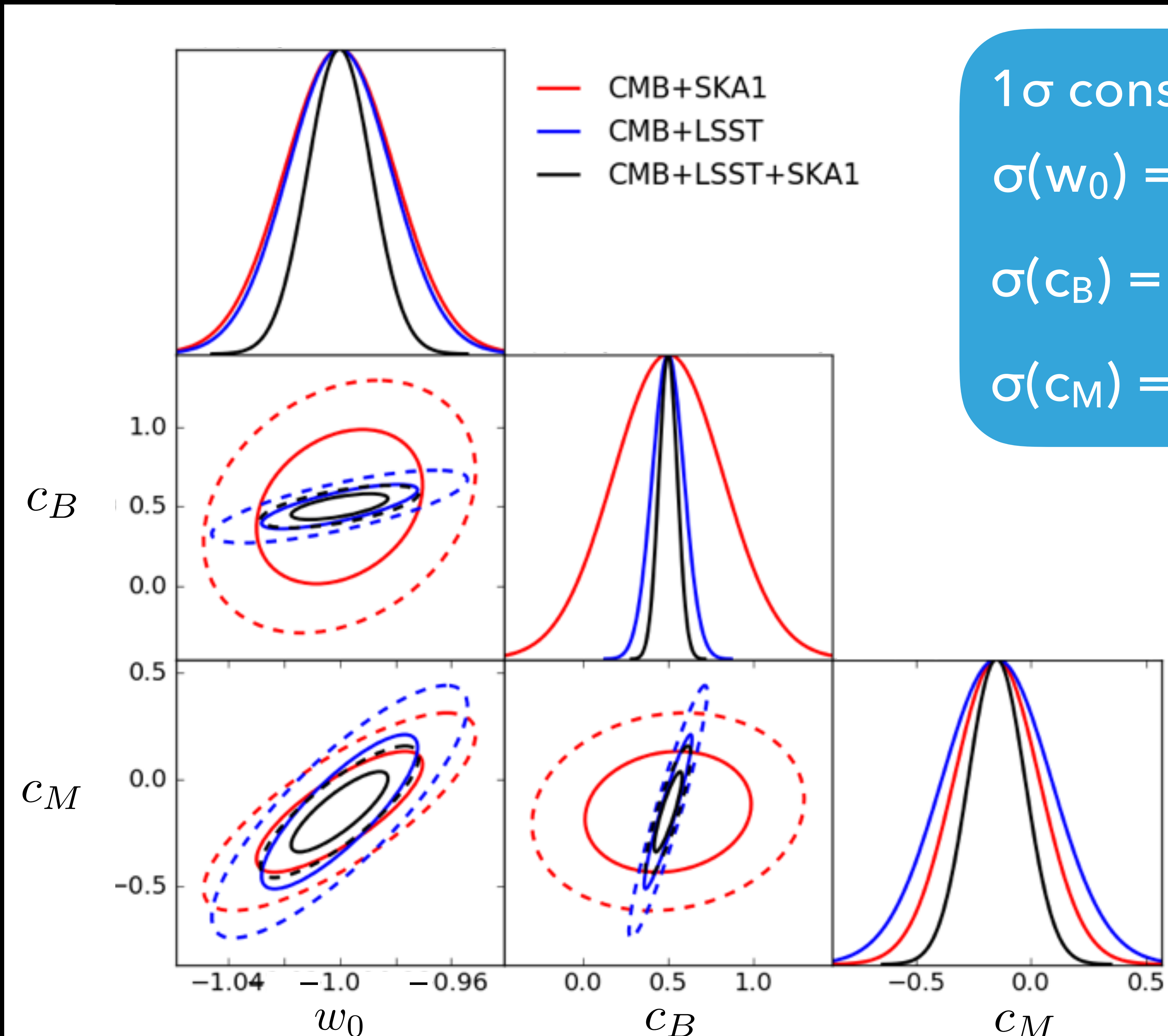
Bellini et al., 2015.

CONSTRAINTS:FUTURE

- ~ 20,000 deg^2 visited ~ 1000 times over 10 years.
- Focus areas:
  - weak+strong lensing
  - large-scale structure
  - galaxy clusters
  - supernovae
- Lensing + clustering power spectrum cross-correlations.

- Phase 1 2020.
- Survey types:
  - H1 intensity mapping (IM)
  - H1 galaxy survey
  - continuum survey
- Fine redshift resolution .
- Different systematics to optical surveys.

CONSTRAINTS:FUTURE



1σ constraints:

$\sigma(w_0) = 0.011$

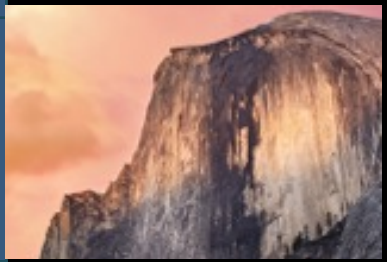
$\sigma(c_B) = 0.054$

$\sigma(c_M) = 0.124$

Plots courtesy of *David Alonso*.

CONCLUSIONS

Version 1: μ, Σ	Version 2: EFT
Simple	More theoretical baggage
Sub-horizon scales only (due to quasi-static approx.)	All linear scales , incl. near-horizon.
2 free functions (time, scale)	Depends on field content (5 for 1 scalar)



We have code!

xIST – **Mathematica** routines for **l**inear **S**calar **T**ensor theories.

CoPPer – **Co**smological **P**arameterised **Per**turbations.

Available from https://github.com/noller/xIST .

CONCLUSIONS

- Full formalism:

  Lagos, TB, Ferreira & Noller — 1604.01396

- EFT of DE / Horndeski:

  Gleyzes, Langlois, Mancarella & Vernizzi — 1509.02191

  + references therein.

- Connecting EFT & (μ, Σ) :

  Pogosian & Silvestri — 1606.05339

- hi_class ⇒ Horndeski EFT in CLASS:

  Zumalacárregui, Bellini, Sawicki & Lesgourges — 1605.06102

WHY THE 3+1 SPLIT?

- Makes the constraint structure manifest.

  E.g. Lapse (N) and shift (N^i) are usually non-dynamical fields.

- Makes Lorentz violation and higher-derivative theories easier to write down.

- We have a preferred timelike vector in cosmology.

- Easier to compare to existing literature.