Large Scale Structure — Observations

Testing gravity one of the primary drives of future cosmological surveys

SKA, EUCLID, RUBIN (LSST), ROMAN (WFIRST)

Already an integral part of current analysis

- BOSS
- eBOSS
- KIDS
- DES
- VIKING/VIPER

...

Large Scale Structure — Observations

Key observables:

- **Distances**: $(z, D(z)) \to$ constrain $H(z) \to$ pin down w ← equation of state

- **Growth**: $f = \frac{d\ln\delta}{d\ln a}$

$$f' + q(\ln a) f + f^2 = \frac{3}{2}\Omega_m \xi$$

where

$$q(\ln a) = \frac{1}{2}\left(1 - 3w(1-\Omega_m)\right]$$

- **Lensing**: γ_{ij}

$$\gamma_{ij} \sim \int d\chi\, \partial_i \partial_j (\Phi + \Psi) \sim \int d\chi\, \overbrace{\mu\left(1+\frac{1}{\gamma}\right)}^{\Sigma} \delta\rho$$

Large Scale Structure — observations

Constrain parameters (functions of time)

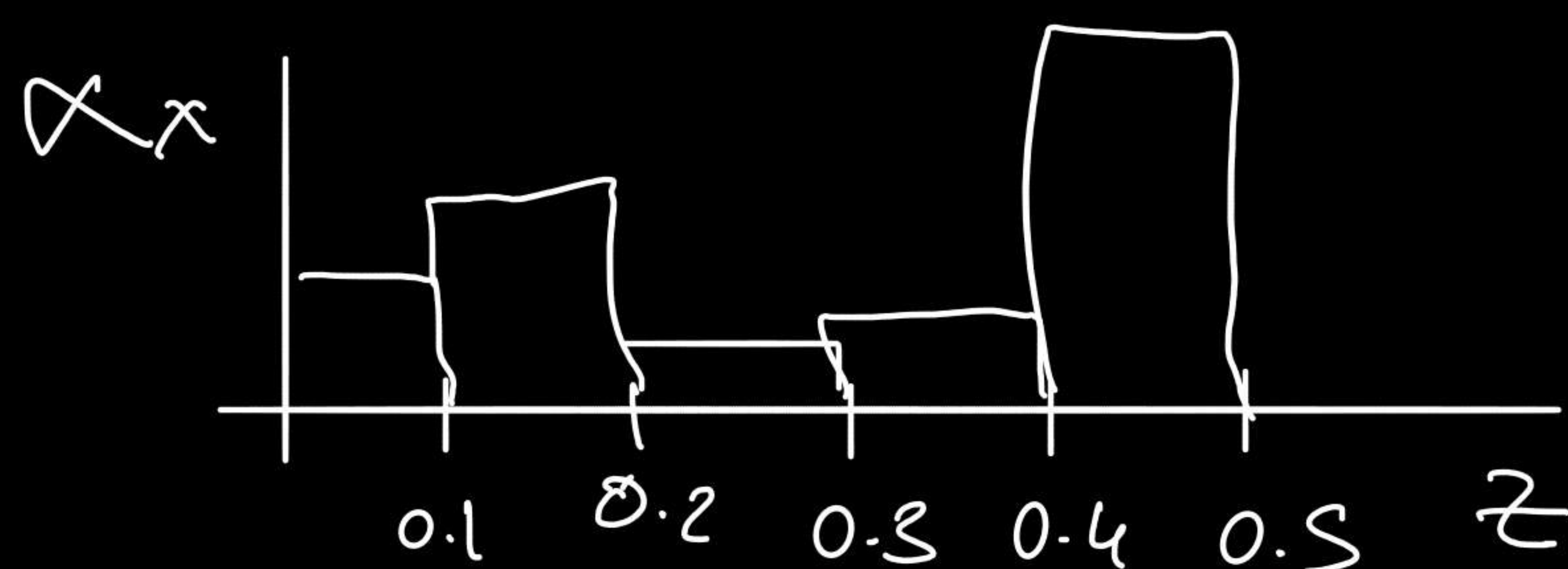
- $w(z)$
- $\alpha_M, \alpha_B, \alpha_K, \alpha_T, \ldots$
- γ, μ

How do they depend on time?

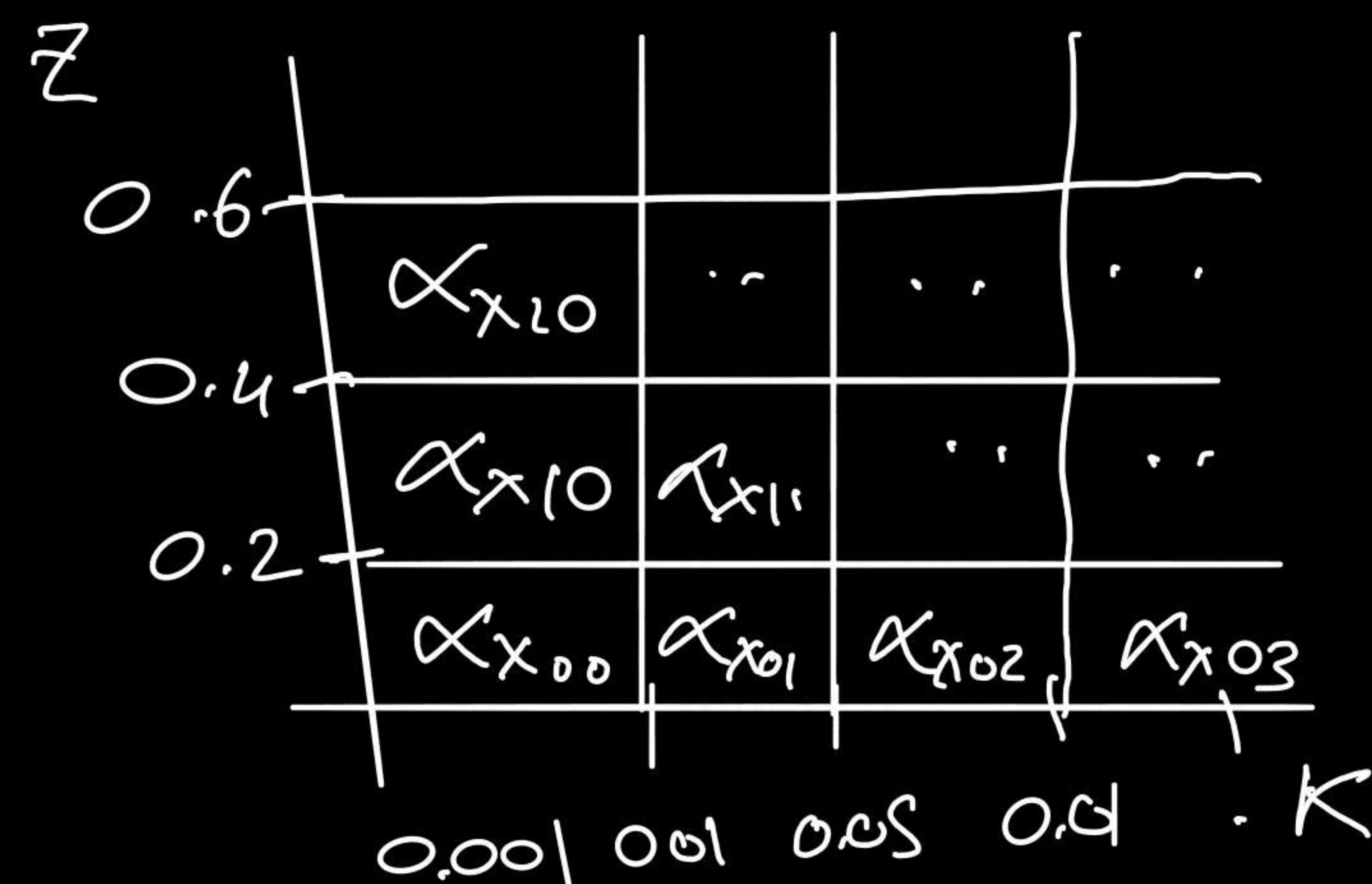
- $w = w_0 + w_a(1-a)$ (CPL)
- $\alpha_X = c_X \Omega_{DE}$ ← tied to acceleration
- $\alpha_X = \alpha_{X0}$ ← extreme
- $\alpha_X = \{\alpha_{X1}, \alpha_{X2}, \alpha_{X3}, \ldots\}$ ← bins.

Large Scale Structure — Observations

Parameters: Bins



Scale dependence



Note: more bins, the weaker the constraints.

Large Scale Structure — observations

Parameters

Results depend on parameterization...

Question: is there a physically motivated choice for the time dependence?

Are there "physical priors"?

See later...

Large Scale Structure — Observations

$$\mu = \frac{G_{eff}}{G_0}$$

"effective Newton's constant"

$$\nabla^2 \Phi = 4\pi G_0 \mu a^2 \bar{\rho} \delta$$

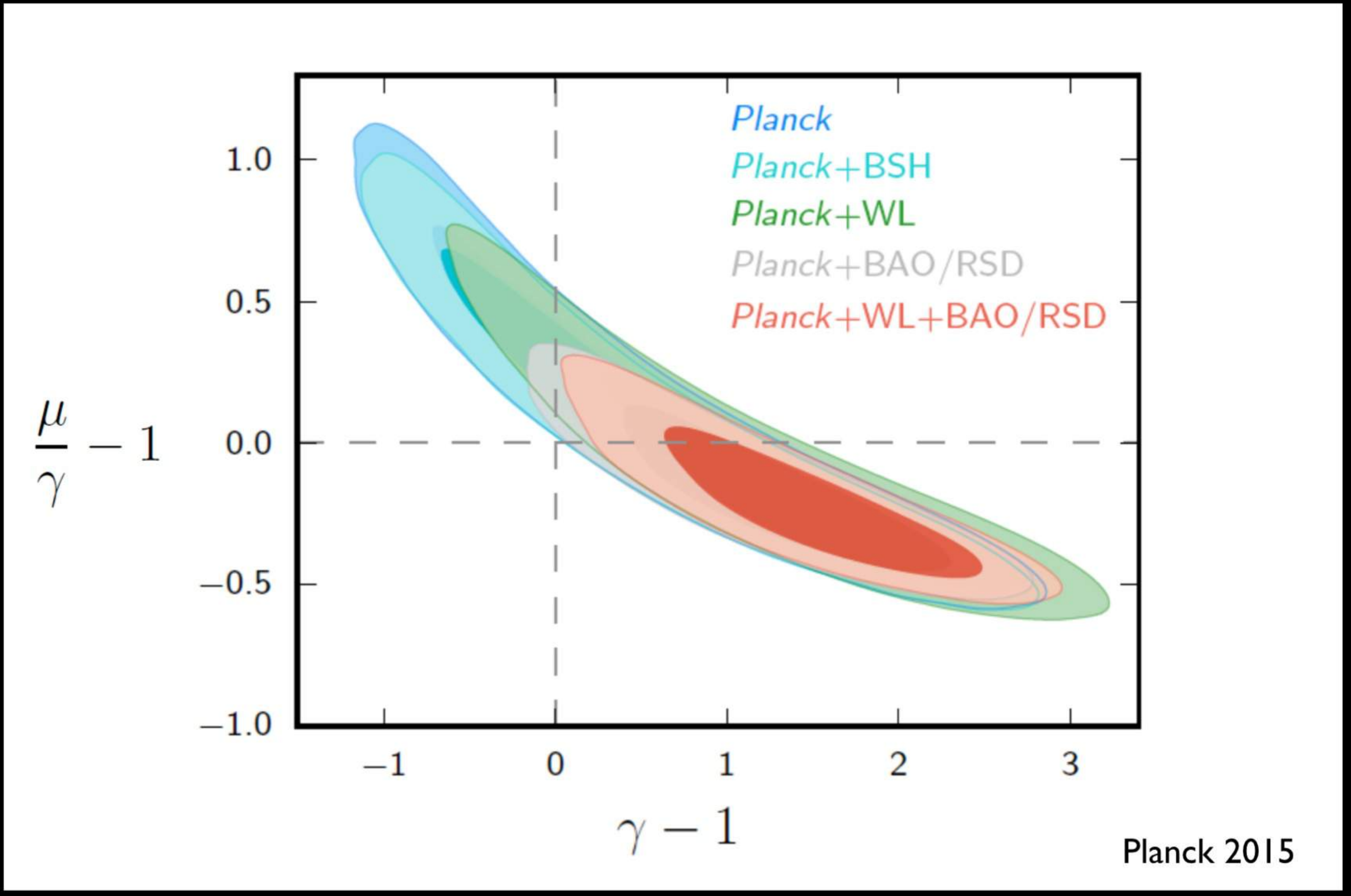
$$\Phi = \gamma \Psi$$

"gravitational slip"

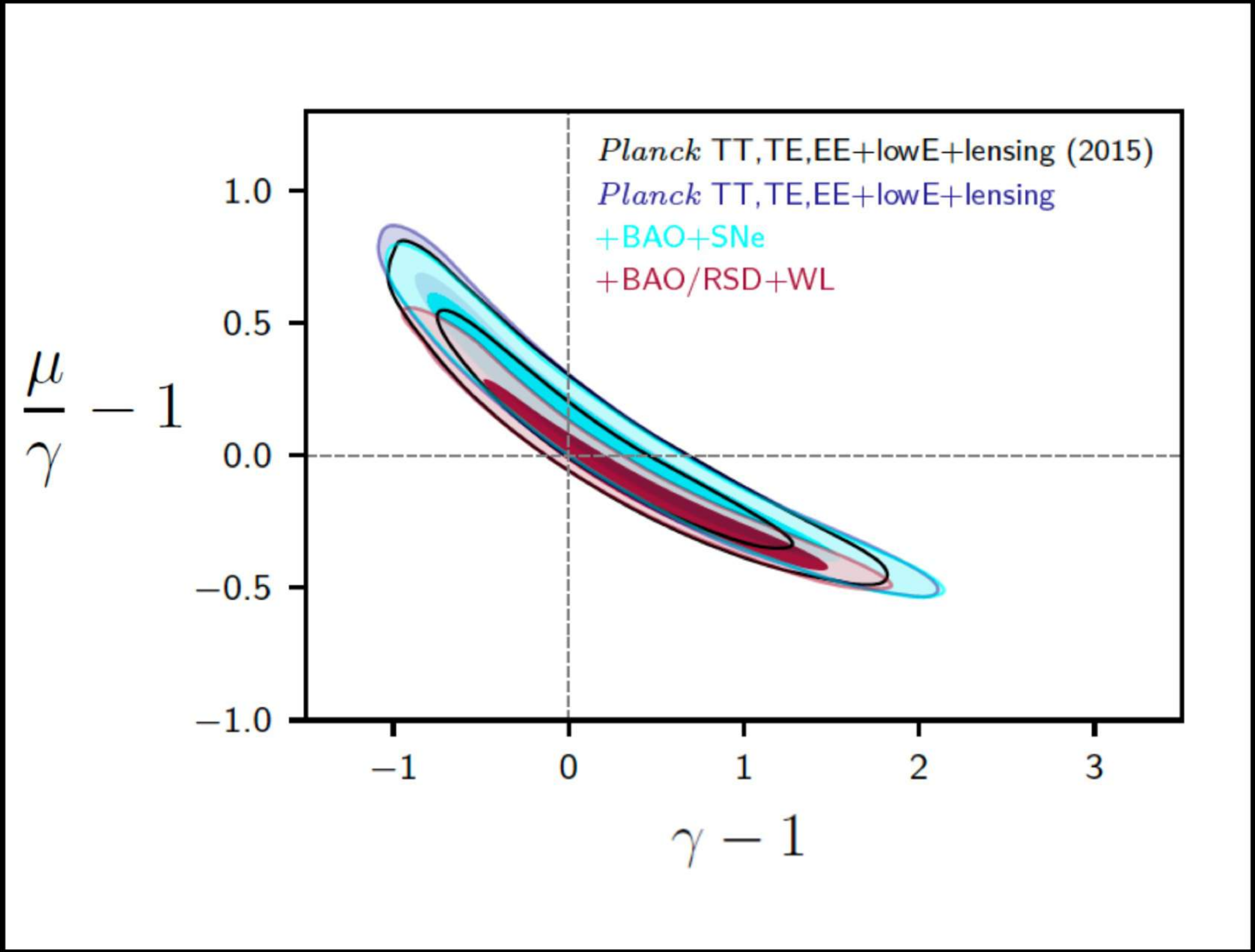
$$\Sigma = \mu\left(1 + \frac{1}{\gamma}\right)$$

"Weak lensing parameter"

Large Scale Structure — Observations



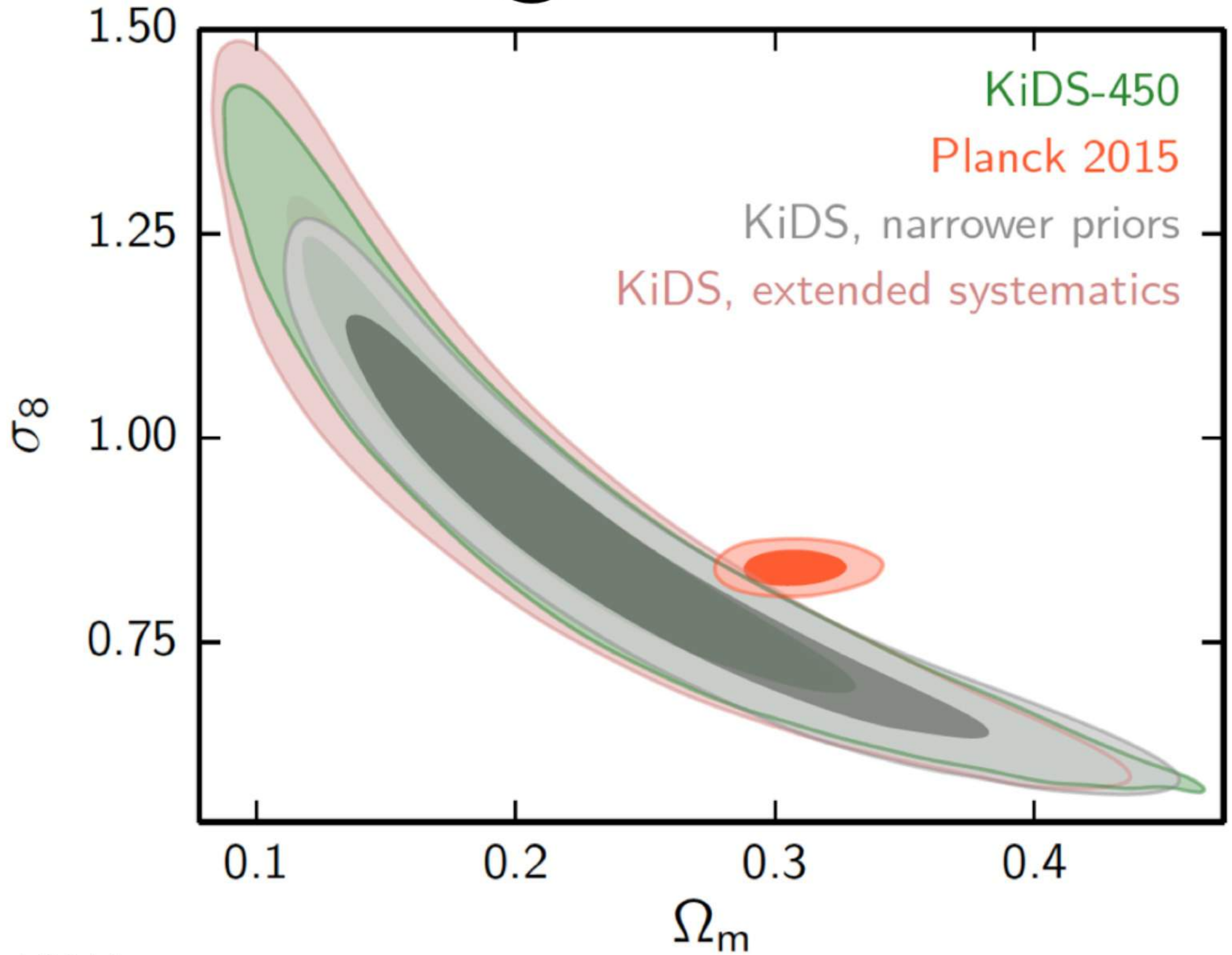
Large Scale Structure — Observations



Planck 2018

Large Scale Structure — Observations

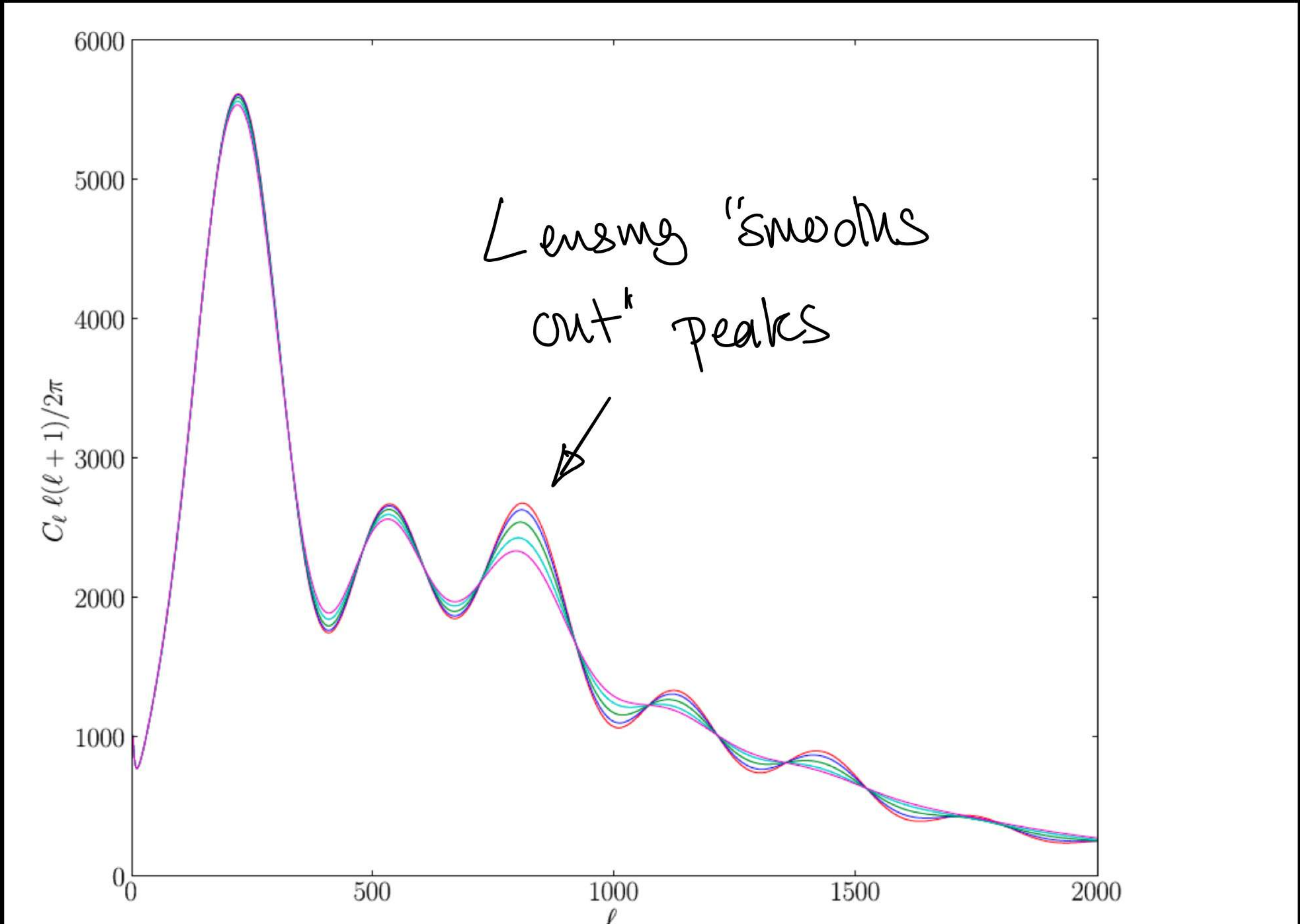
"amplitude of clustering at 8 h^{-1} Mpc"



Joudaki et al 2016

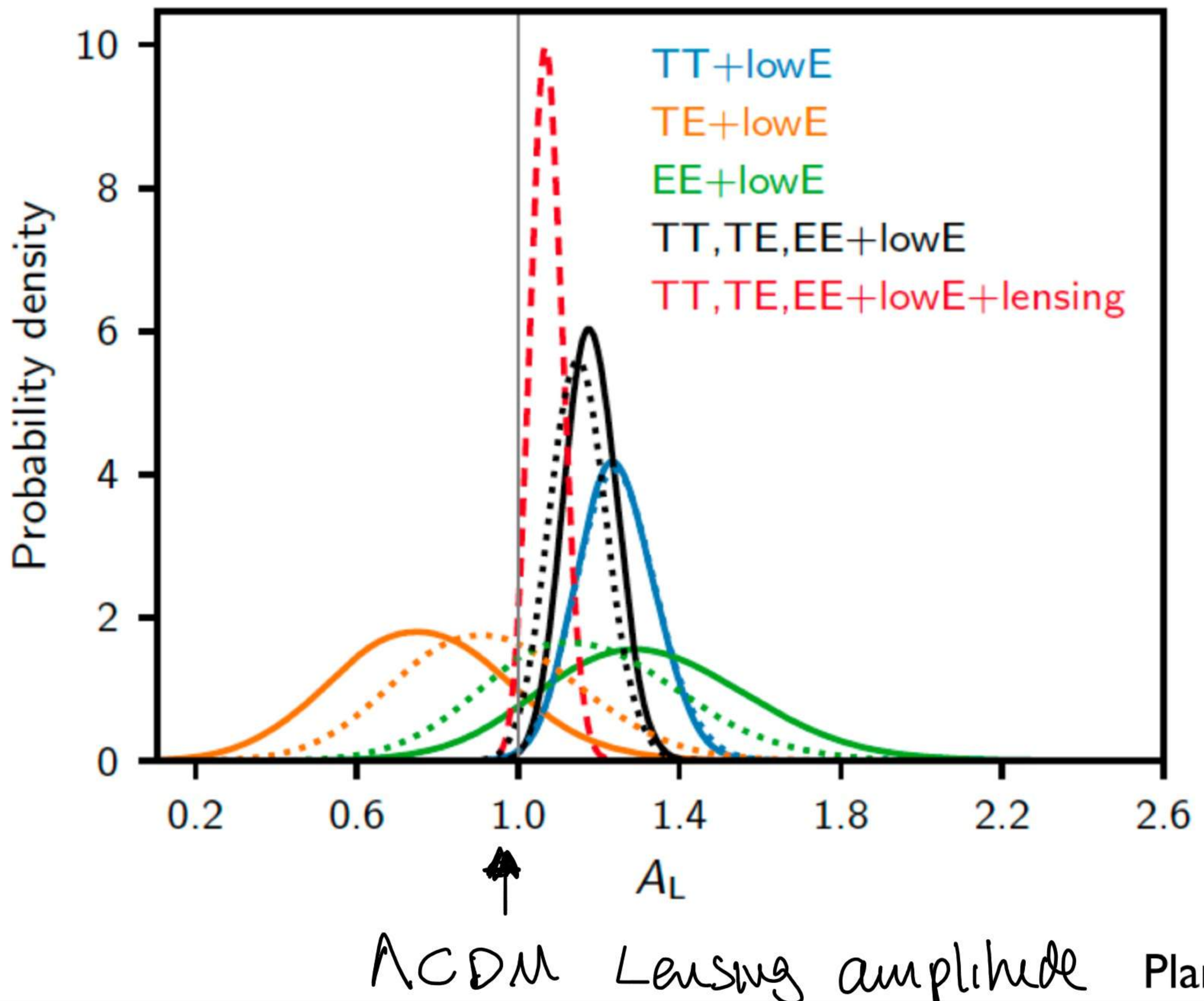
"matter density"

Large Scale Structure — Observations



Calabrese et al 2008

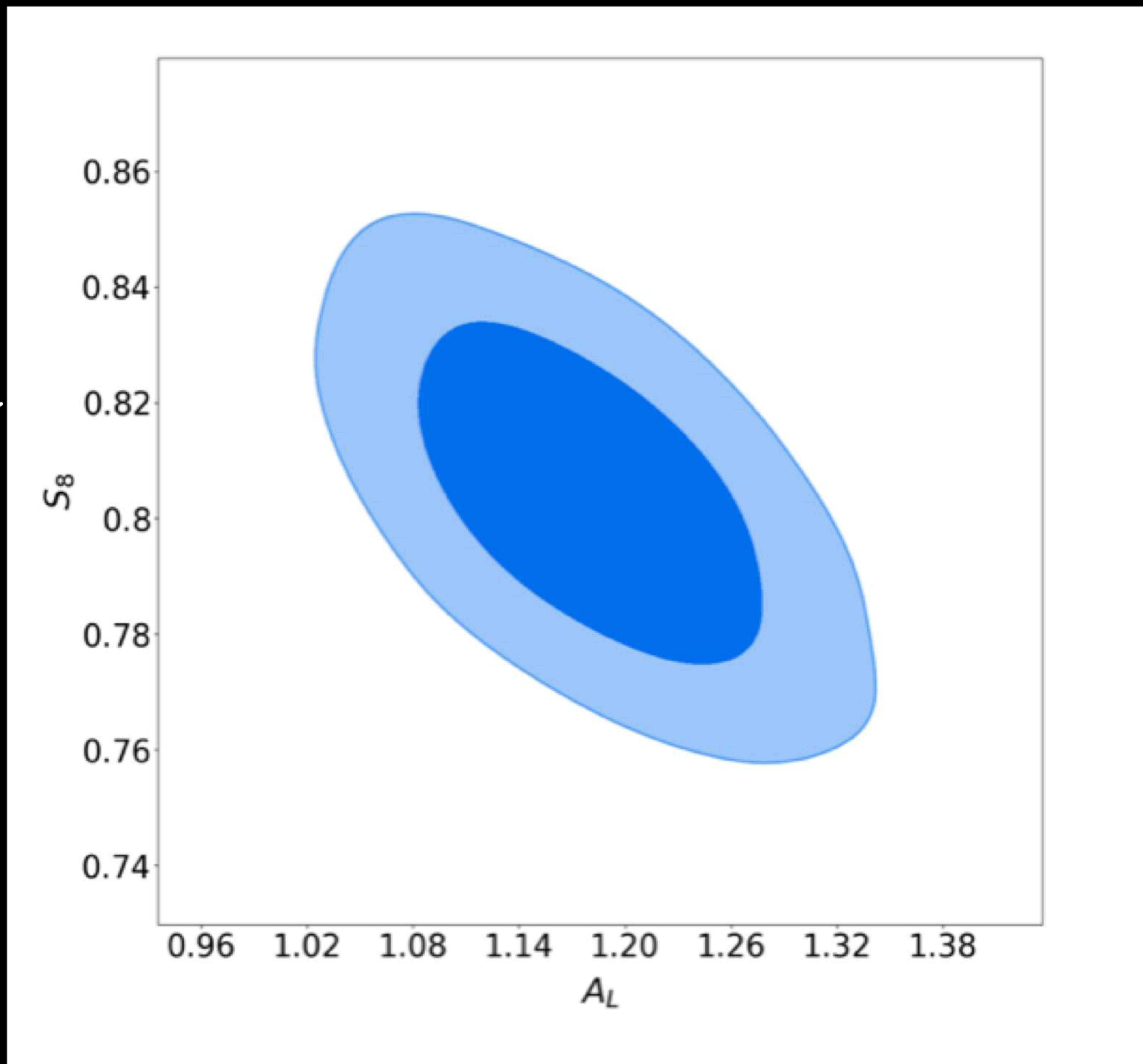
Large Scale Structure — Observations



Planck 2018

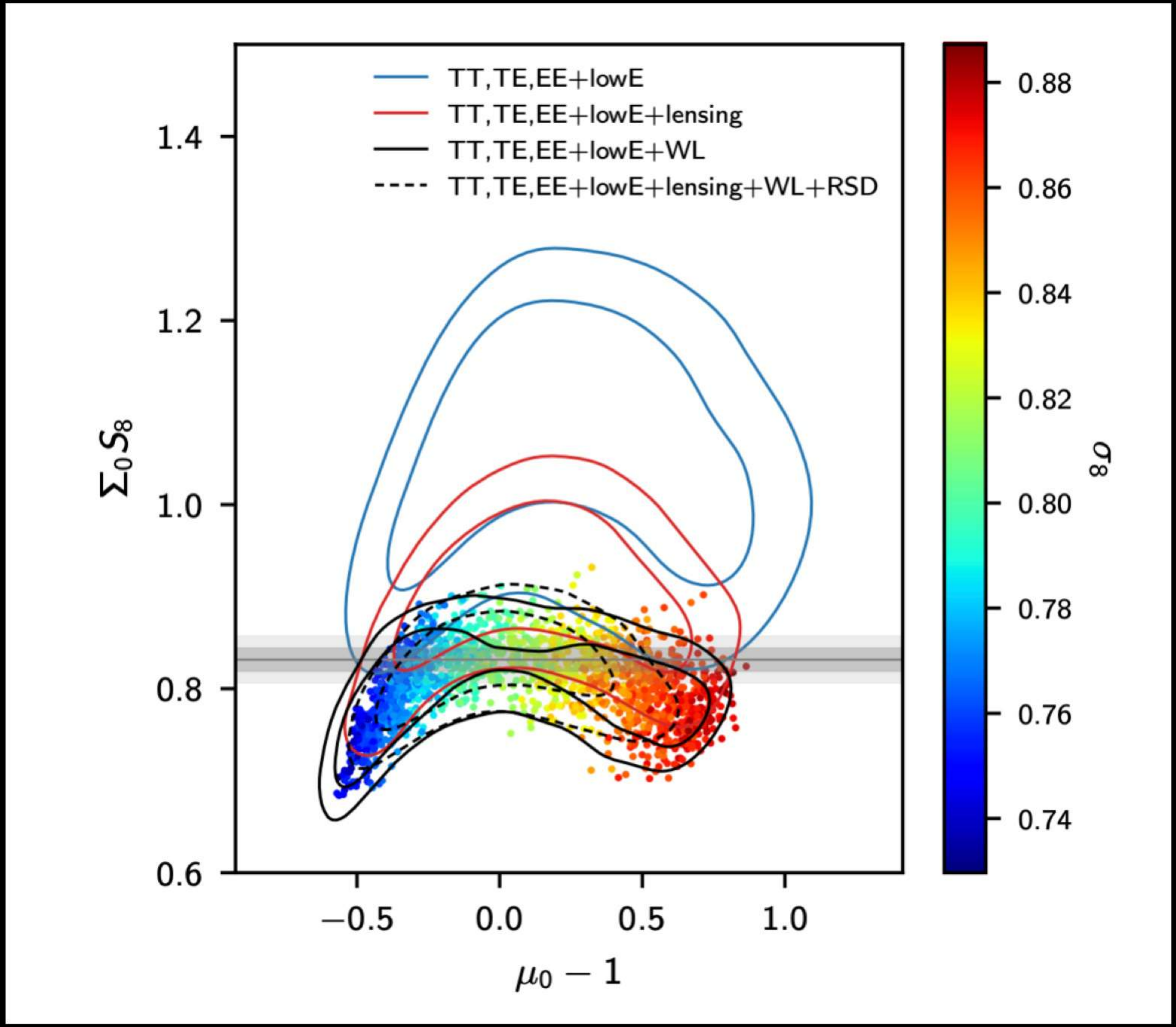
Large Scale Structure — Observations

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{1/2}$$



(Antony Lewis, Private C.)

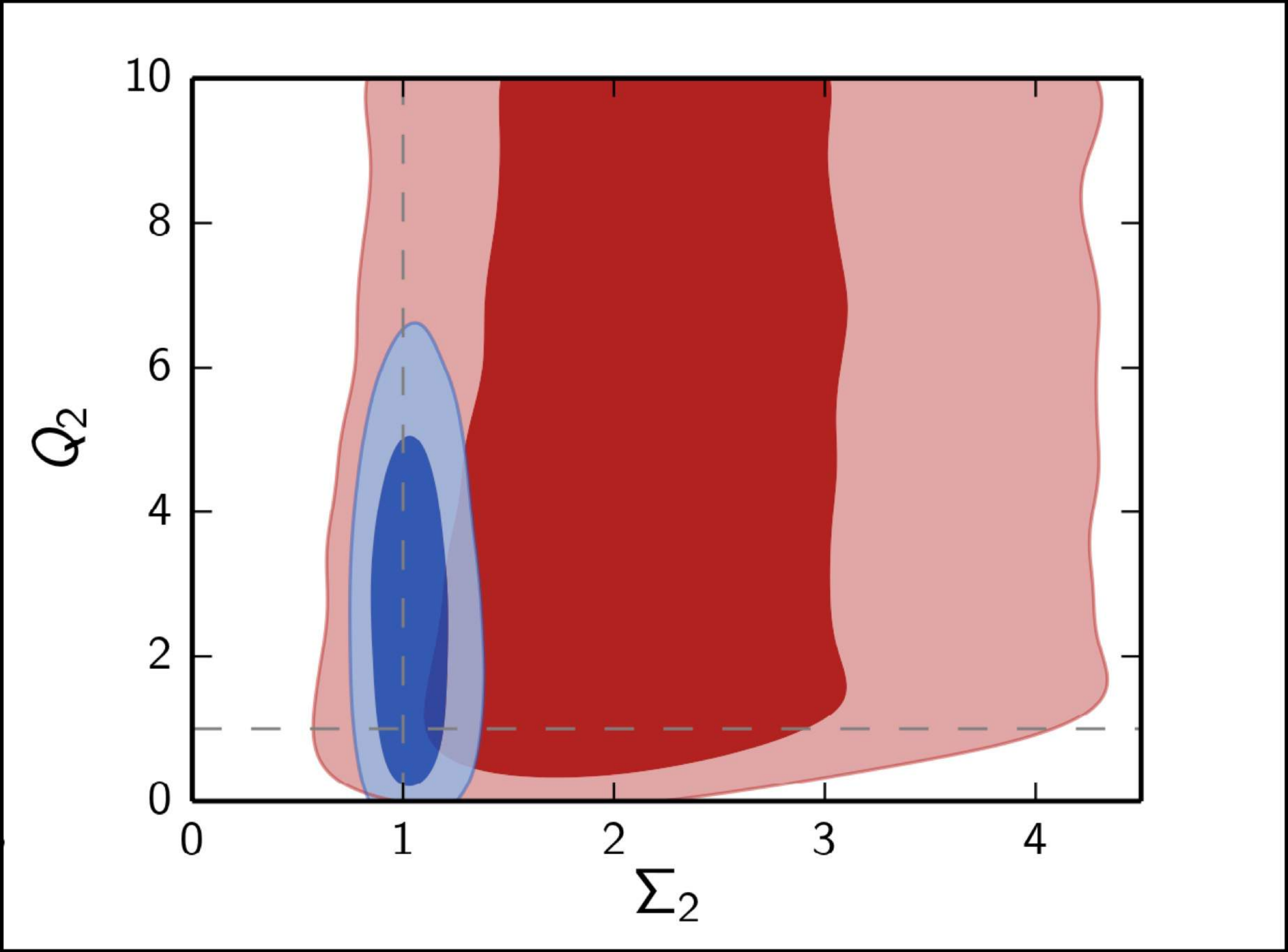
Large Scale Structure — Observations



$\hookrightarrow \mu_0 = \frac{\mu}{\gamma}$ (Planck 2018)

Large Scale Structure — Observations

$Q_2 = \mu$

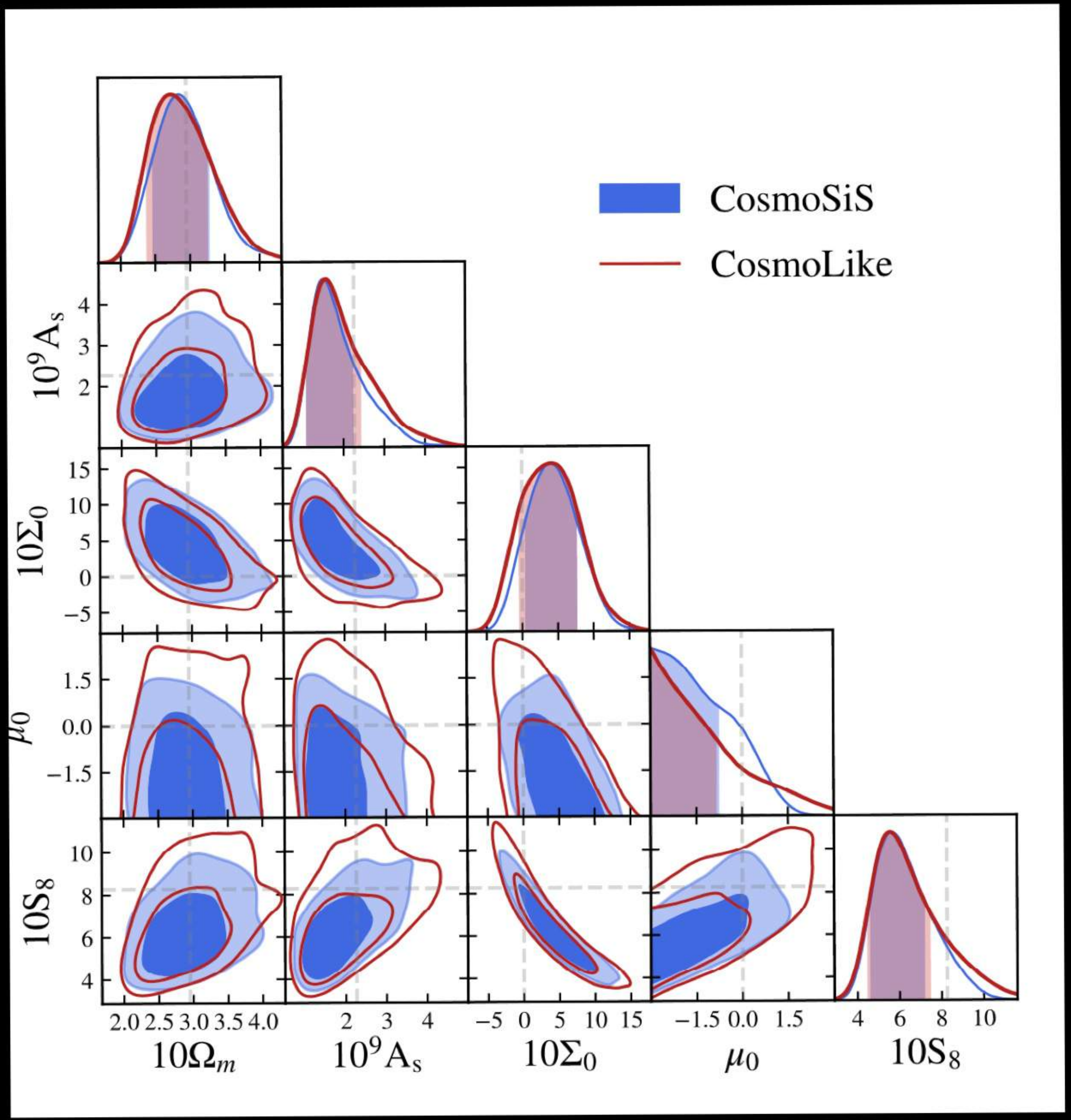


(KIDS-450 2017)

Large Scale Structure — Observations

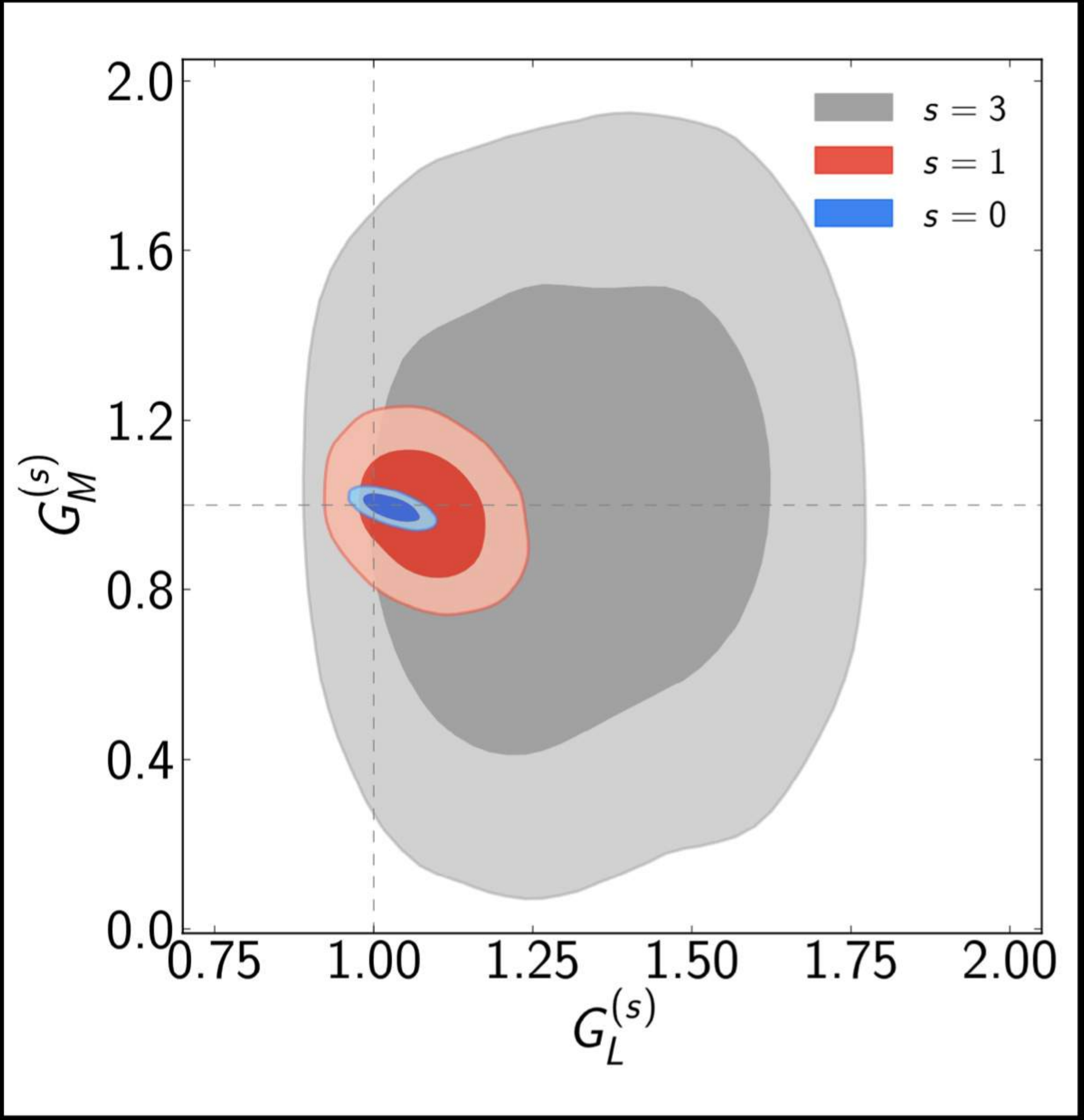
$\Sigma_0 = \Sigma - 1$

$\mu_0 = \frac{\mu}{\gamma} - 1$



(DES 2018)

Large Scale Structure — Observations

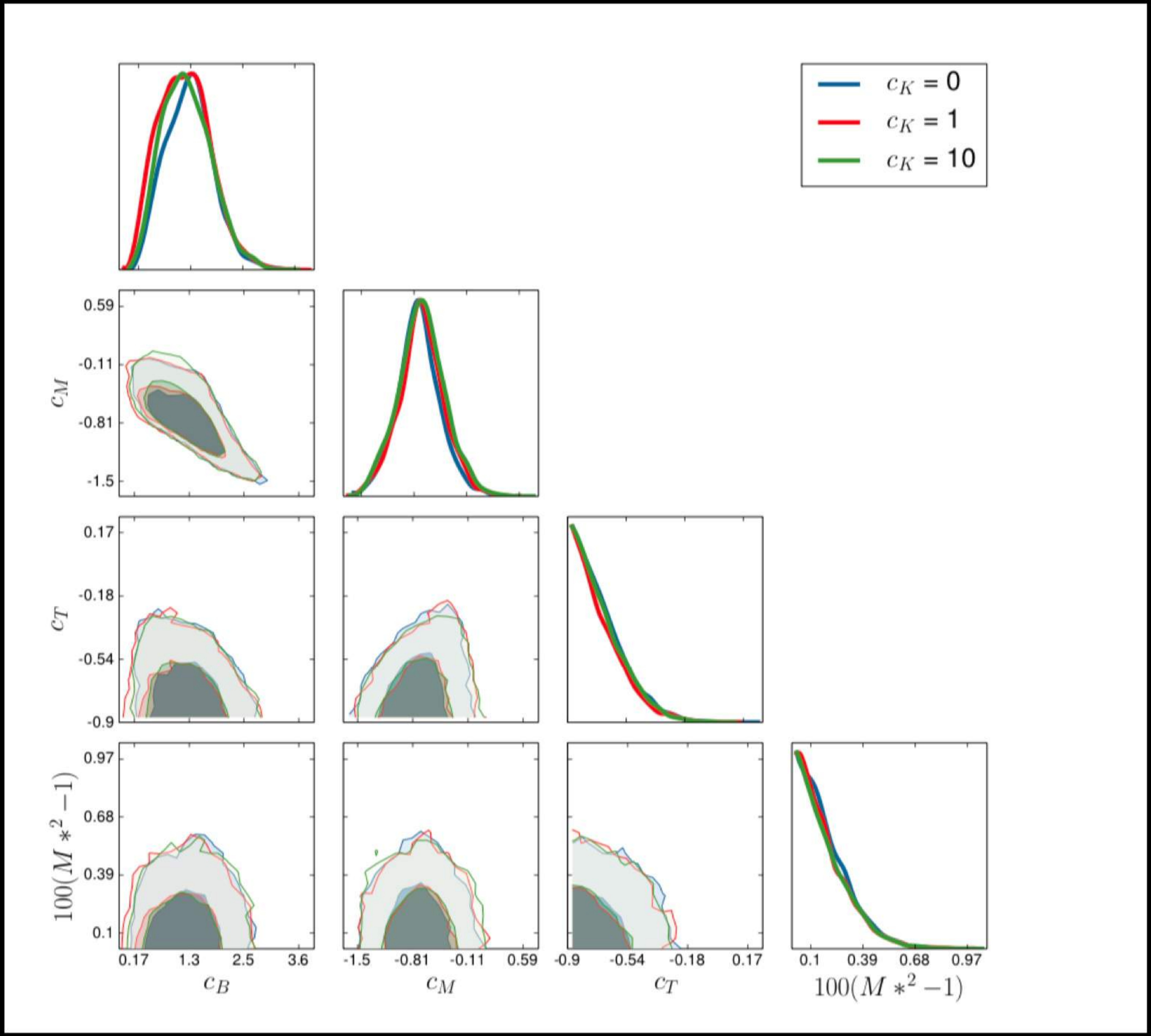


(BOSS 2017)

$$\frac{\mu}{\gamma} = G_M = 1 + (G_M^{(s)} - 1)\, a^s \qquad G_L = 1 + (G_L^{(s)} - 1)\, a^s$$

$\hookrightarrow \Sigma$

Large Scale Structure — Observations



$\alpha_X = c_X \Omega_{DE}$

Recall

$\alpha_X = 0$

for GR

↑

doesn't cross zero!

(2015)

Bellini et al, JCAP, 05, 057

Large Scale Structure – observations + priors

Recap

- We pick parametrization $\left\{ \begin{array}{l} \mu, \gamma, \Sigma \\ \text{or} \\ \alpha_M, \alpha_B, \ldots \end{array} \right.$ + $w(z)$ ← equation of state

- Let them vary freely (pick time dependence)

But

What are their physically allowed ranges?

Must depend on model for ϕ (or any other field).

Large Scale Structure - observations + priors

Example : "thawing" quintessence

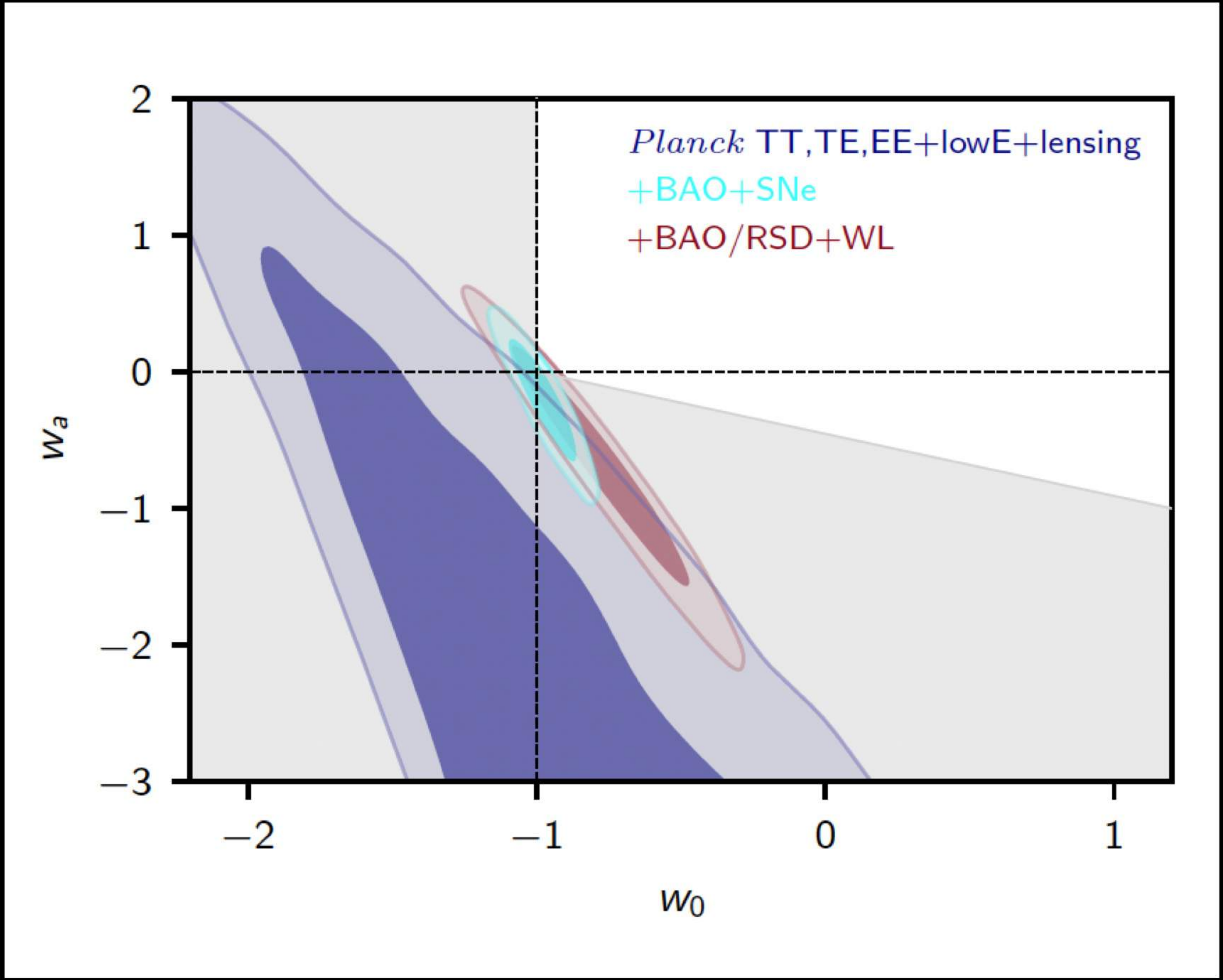
$\dot\phi \sim 0$ initially and then starts rolling

Standard parametrization

$$w = \frac{\frac{1}{2}\dot\phi^2 - V}{\frac{1}{2}\dot\phi^2 + V} \simeq w_0 + w_a(1-a)$$

Assume uniform priors for (w_0, w_a)

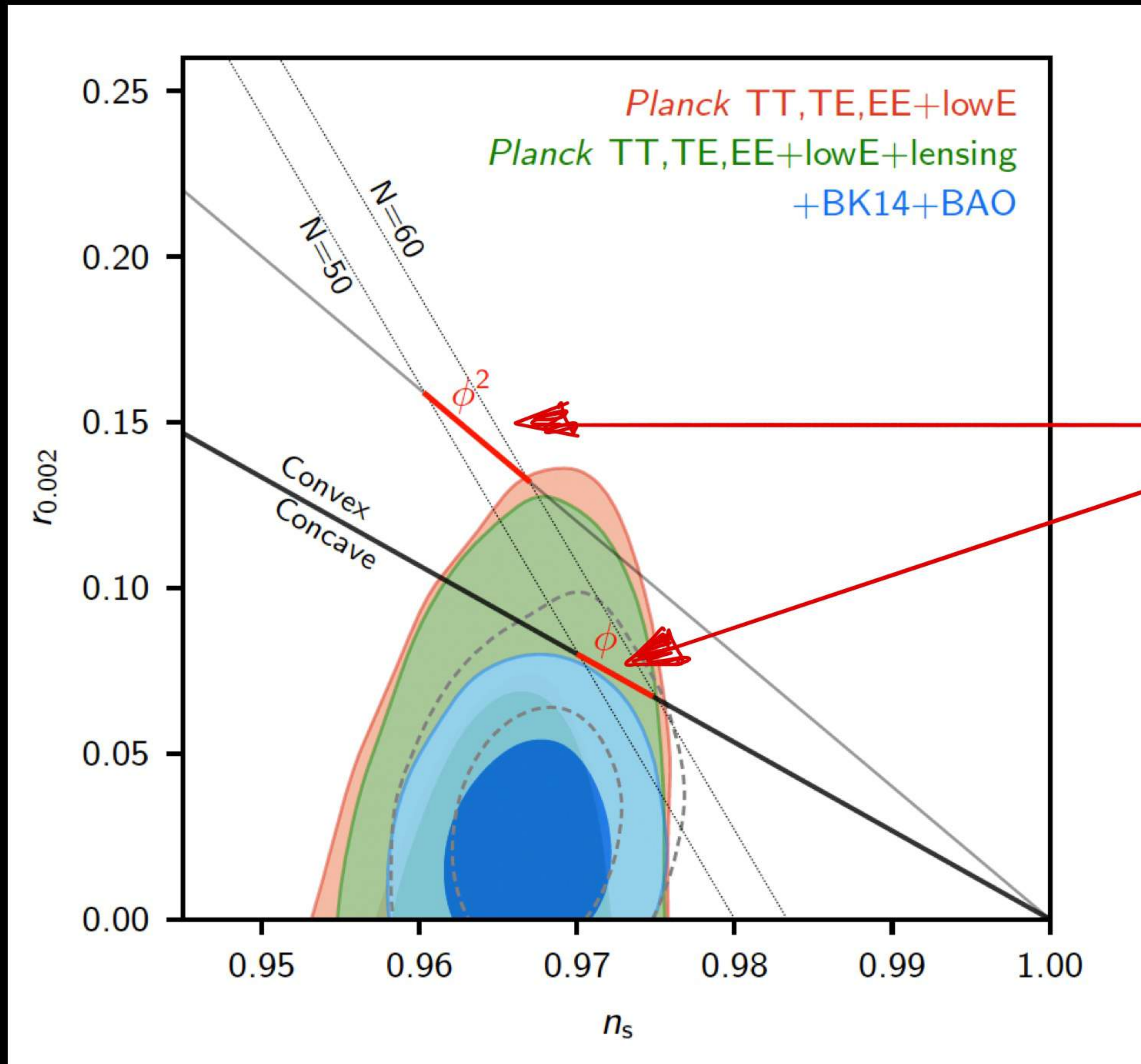
Large Scale Structure - observations + priors



Planck 2018 Constraints

Large Scale Structure - observations + priors

Tensor to scalar ratio

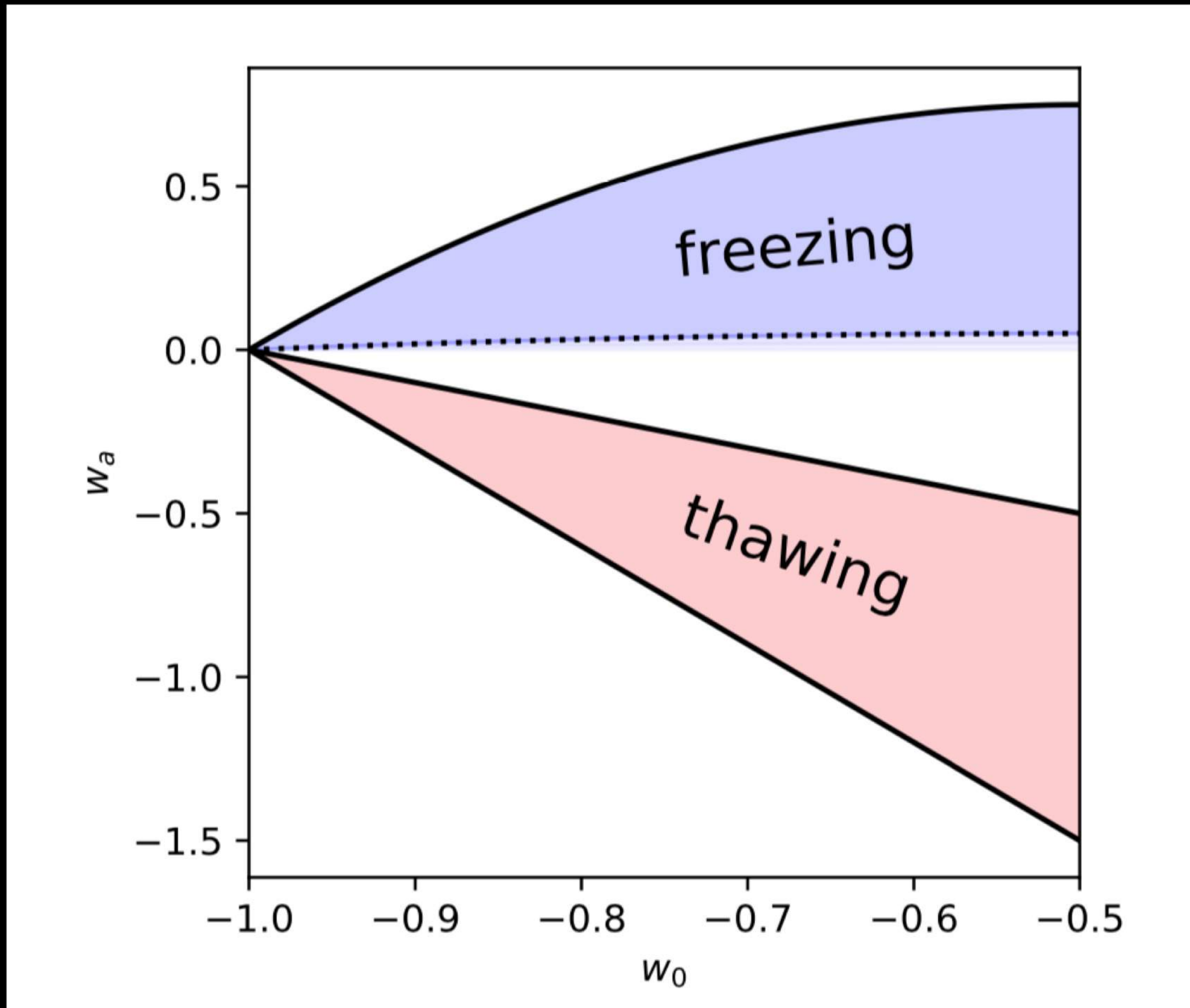


Models live here "theoretical priors"

Spectral index

Planck 2018

Large Scale Structure - observations + priors

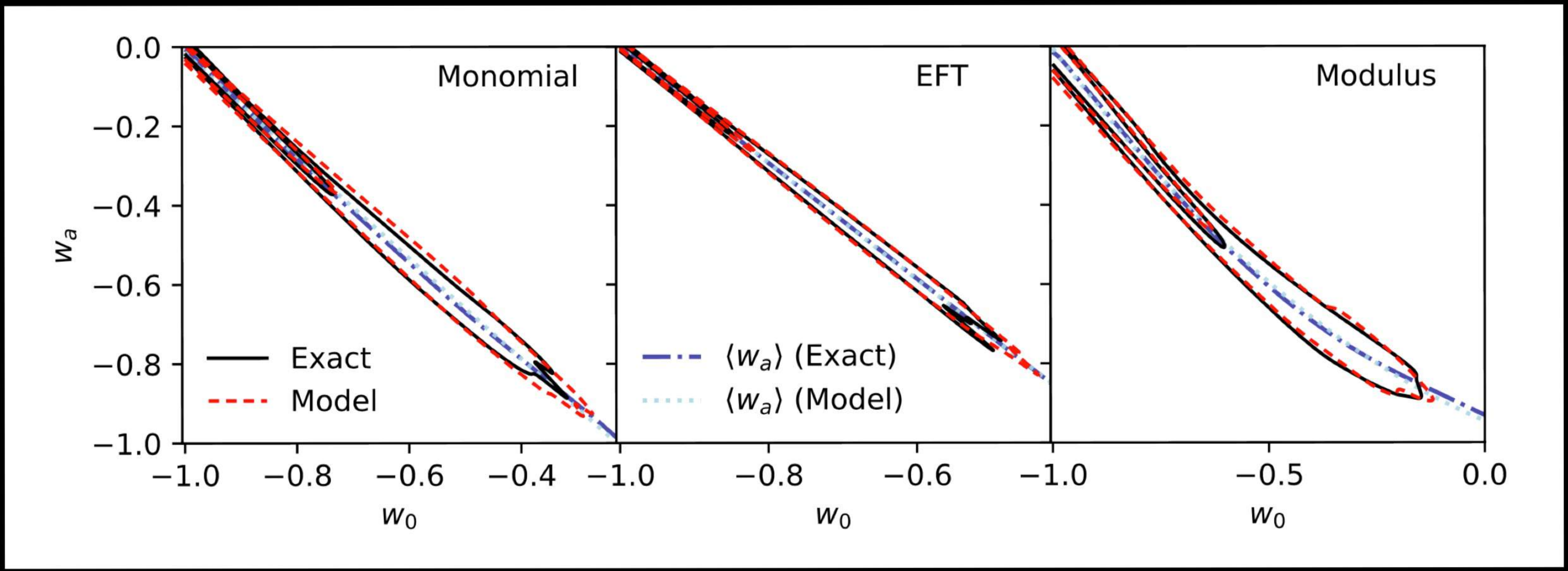


$\dot{\phi} \longrightarrow 0$

$\xrightarrow{\quad} t$

$\dot{\phi} \longrightarrow \neq 0$

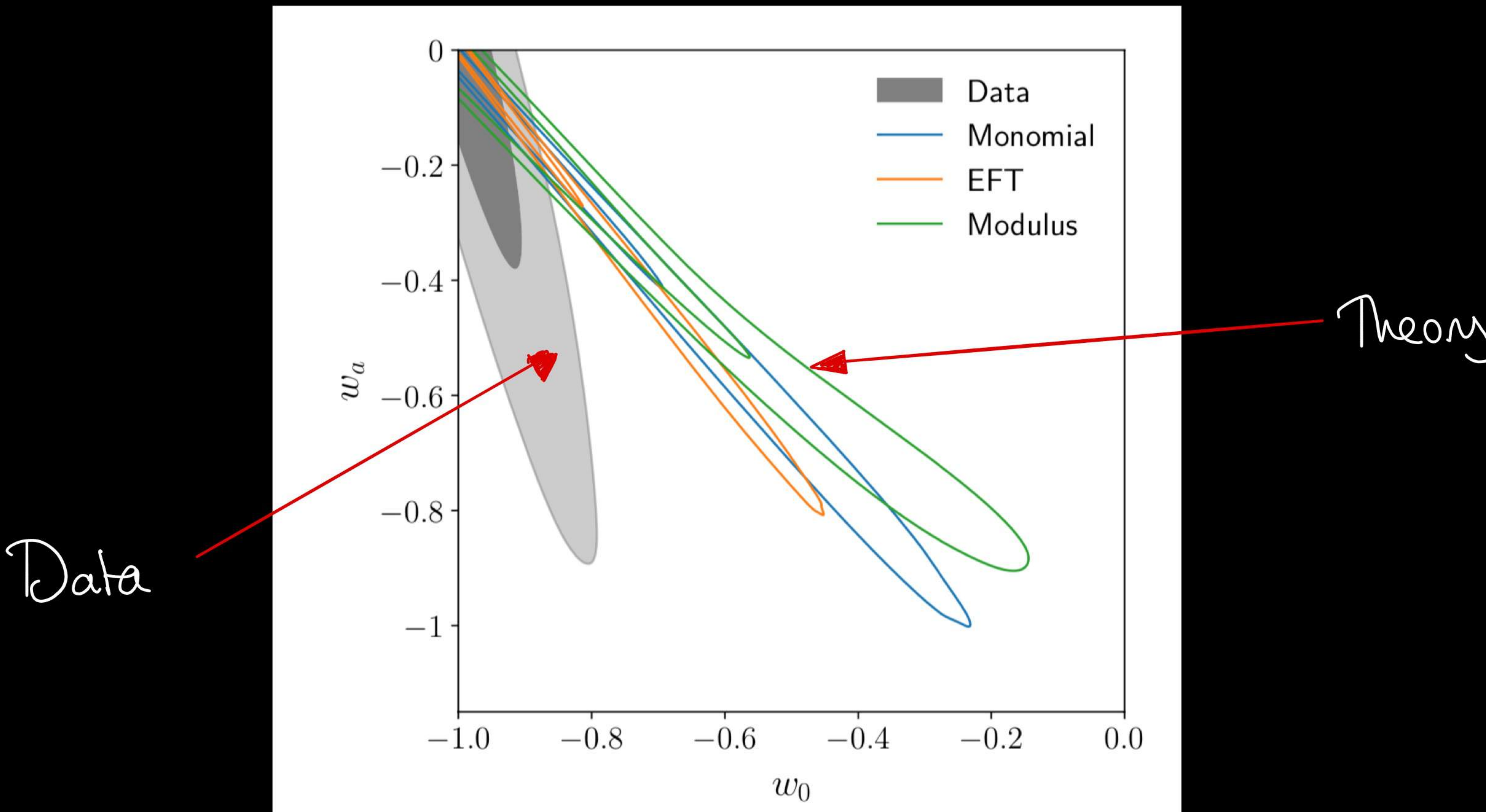
Large Scale Structure – observations + priors



C. Garcia-Garcia et al

Arxiv: 1911.02868

Large Scale Structure - observations + priors



Large Scale Structure - observations + priors

Extend this approach to Horndeski models ...

... many more parameters (functions of time)

Subset: Shift-symmetric models

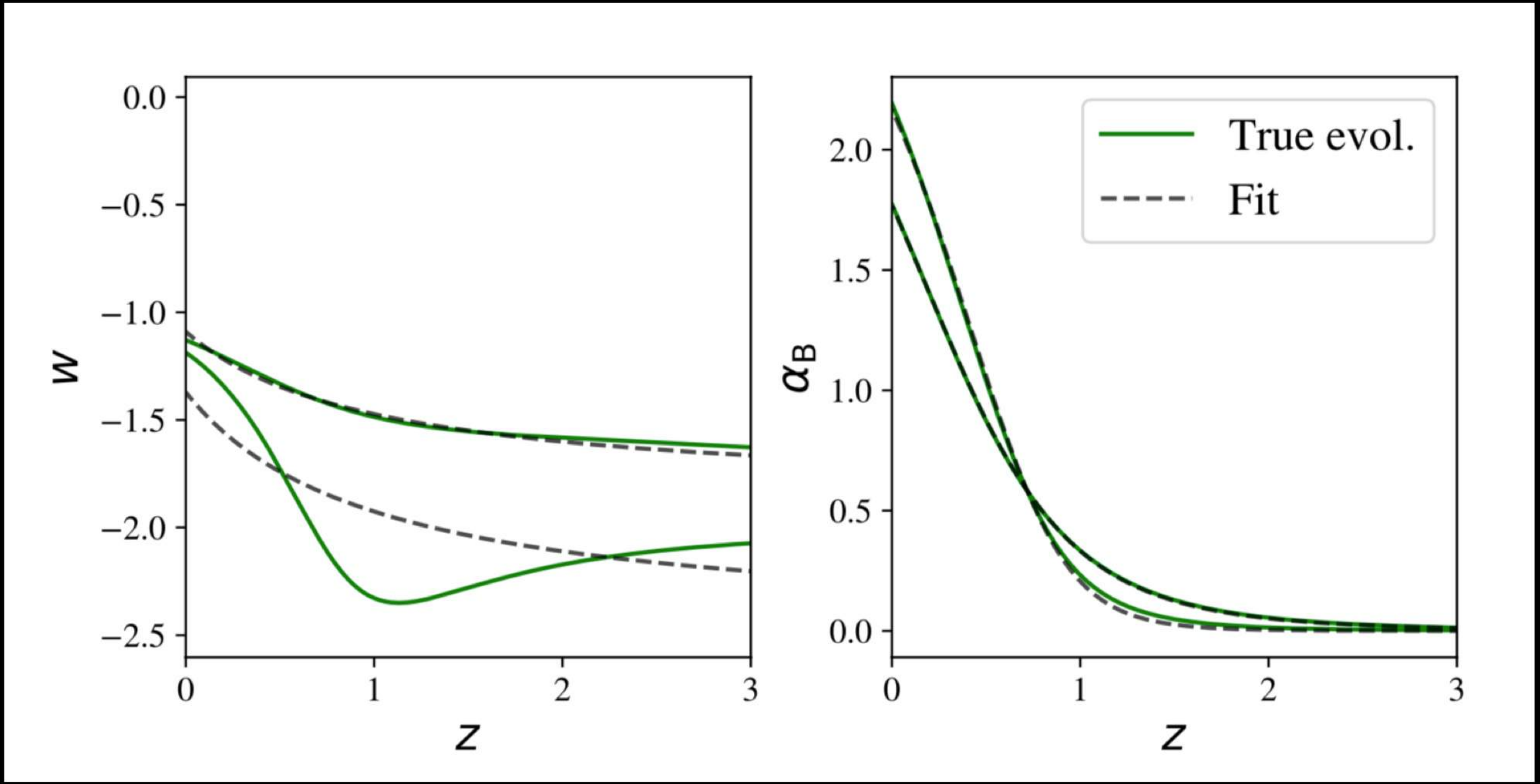
$\phi \rightarrow \phi + c$ invariance

Action:

$$S = \int d^4x \sqrt{-g} \left\{ \frac{M_{Pl}^2}{2} R + c_{01} X + \frac{c_{02}}{\Lambda_2^4} X^2 + \Box\phi \left[\frac{d_{01}}{\Lambda_3^3} X + \frac{d_{02}}{\Lambda_4^4} X^2 \right] \right\}$$

Free constants: $\left(c_{01}, \frac{c_{02}}{\Lambda_2^4}, \frac{d_{01}}{\Lambda_3^3}, \frac{d_{02}}{\Lambda_4^4} \right)$

Large Scale Structure - observations + priors



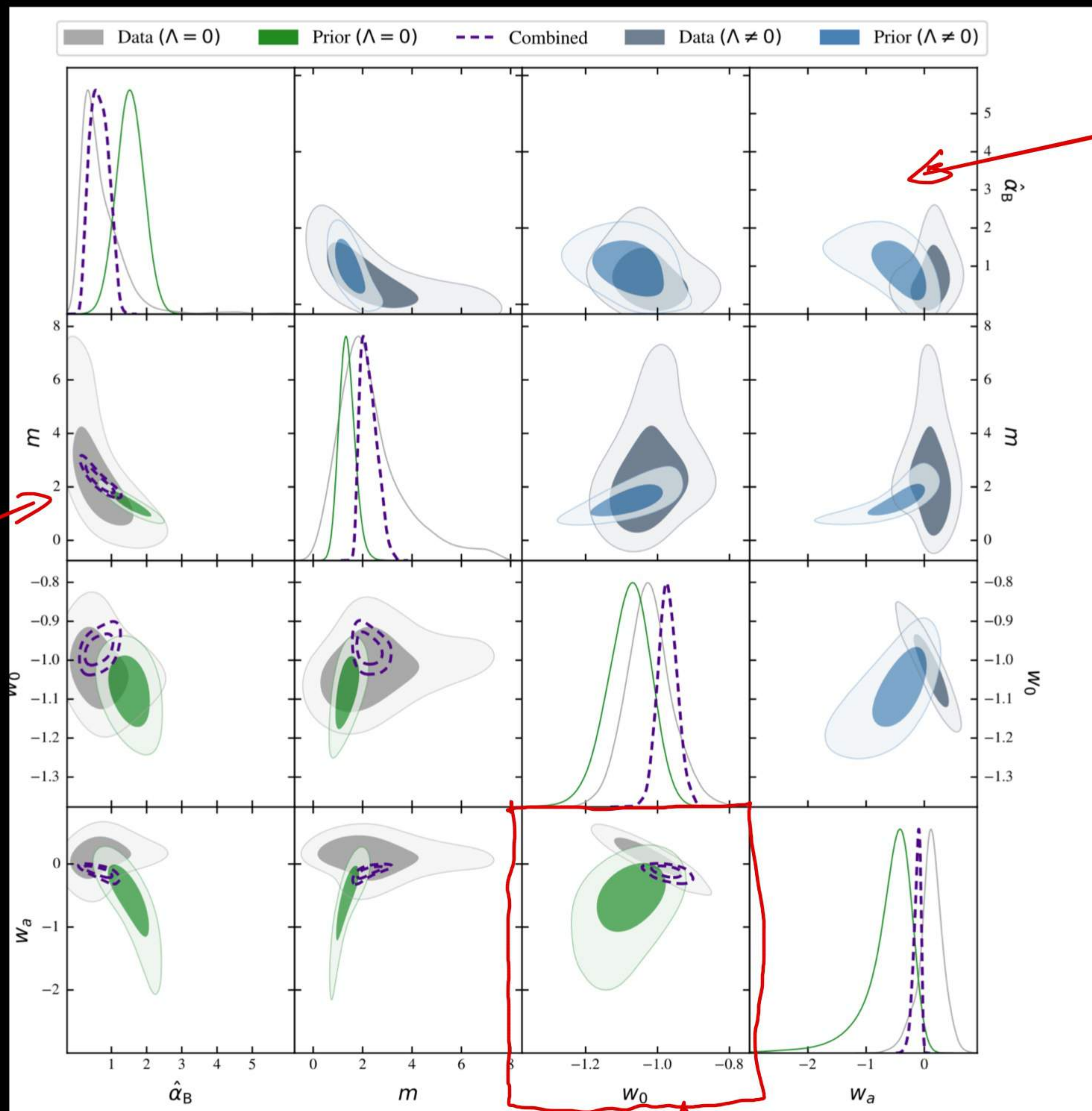
$$w = w_0 + w_a(1-a)$$

$$\alpha_B = \hat{\alpha}_B \left(\frac{H_0}{H}\right)^{\frac{4}{m}}$$

Parameters: $(w_0, w_a, \hat{\alpha}_B, m)$.

Traykova et al (in prep)

Large Scale Structure - observations + priors



With Λ

Without Λ

(w_0, w_a)

Traykova et al (in prep)

Large Scale Structure – Test case JBD

Worry about the details!

- Analytic understanding of evolution
- Accurate implementation of linear evolution (LEFTCAMB, HiClass, others...)
- Model for non-linearities
- Model for Baryonic effects
- Understand degeneracies
- Understand priors

Joudaki et al, 2010.15728

Large Scale Structure – Test case JBD

Action:

$$S_{BD} = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} \left(\phi R - \frac{\omega_{BD}}{\phi} (\partial\phi)^2 - 2V \right) + \mathcal{L}_m \right]$$

Some analytic results. (see Joudaki et al ArXiv: 2010.15278)

Background (with dust):

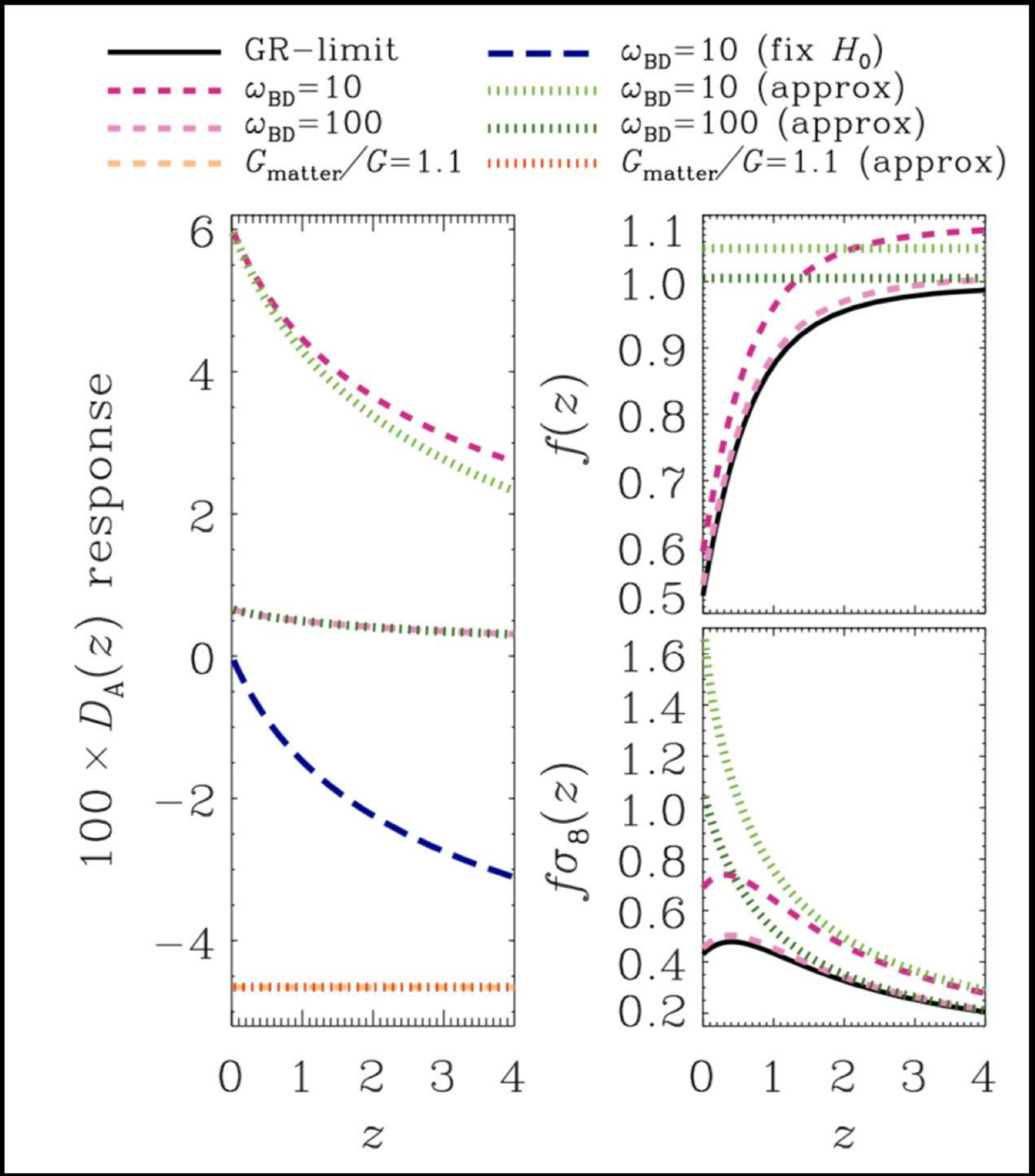
$$a(t) = \left(\frac{t}{t_0}\right)^{\frac{2+2\omega}{4+3\omega}} \xrightarrow{\omega\to\infty} t^{2/3}$$

$$\phi = \phi_0 a^{\frac{1}{1+\omega}} \xrightarrow{\omega\to\infty} \text{constant}.$$

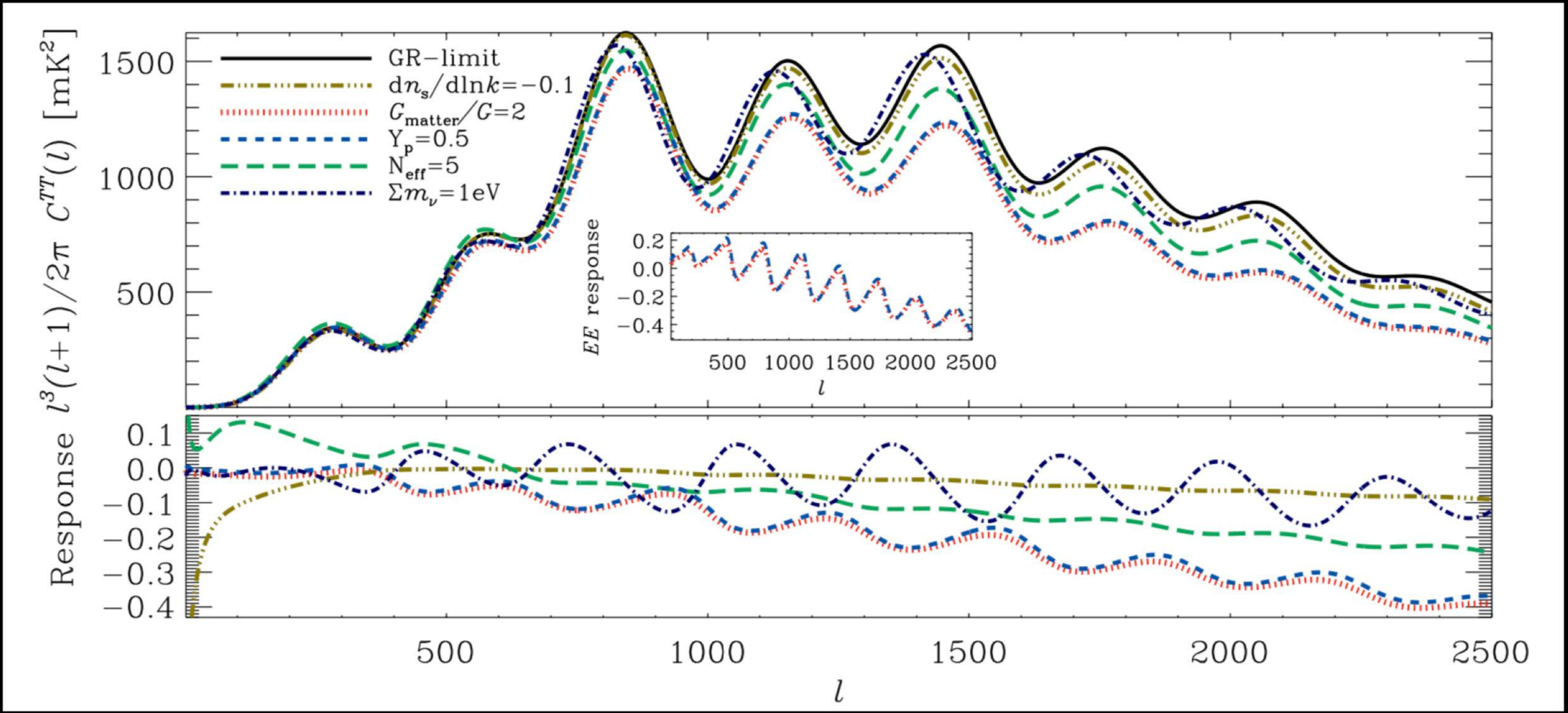
Observables: $\Delta P_A \sim \frac{1}{\omega}$ function (z)

$\Delta f \sim \frac{1}{\omega}$ function (z)

Large Scale Structure — Test case JBD



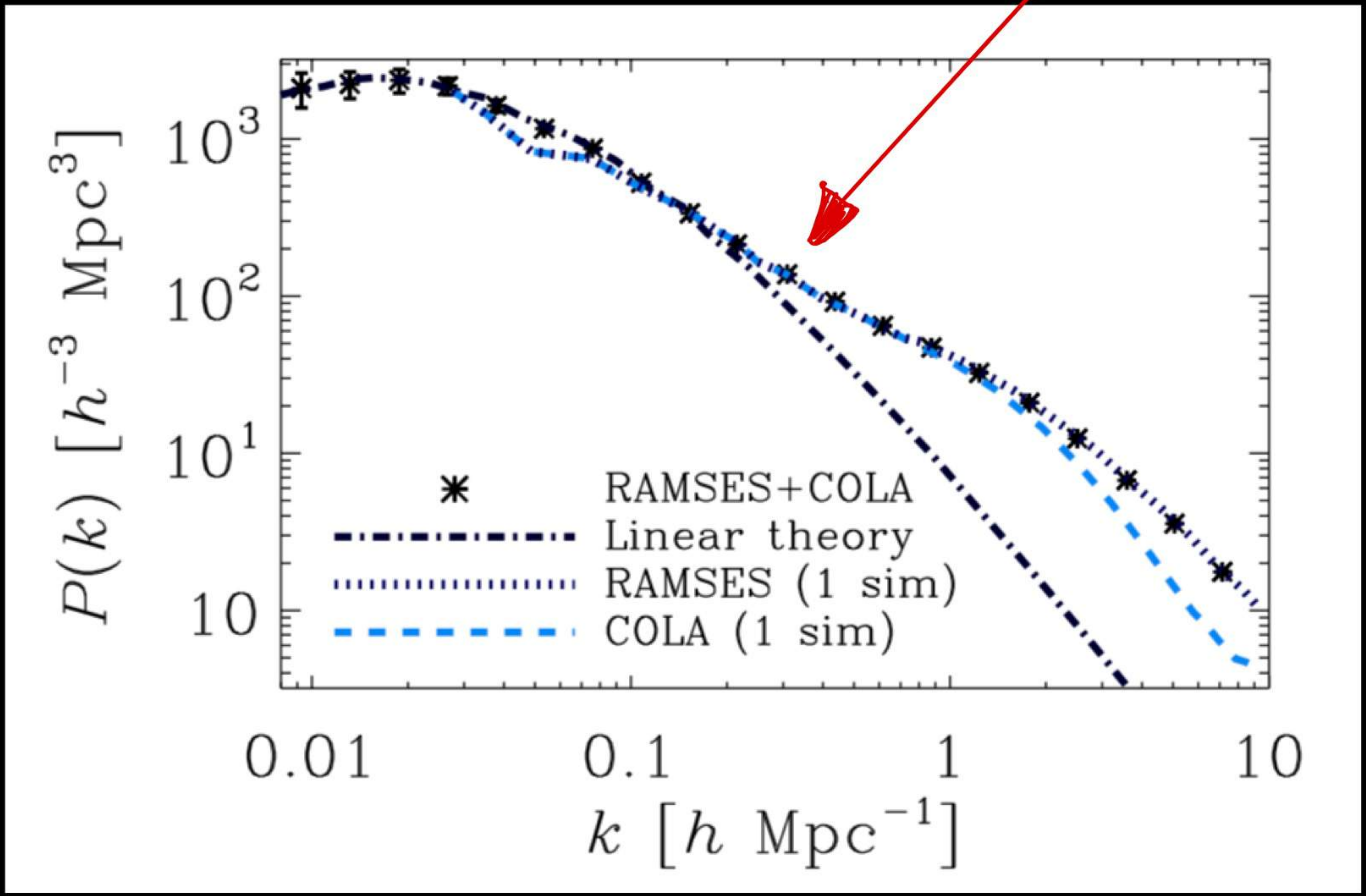
Large Scale Structure – Test case JBD



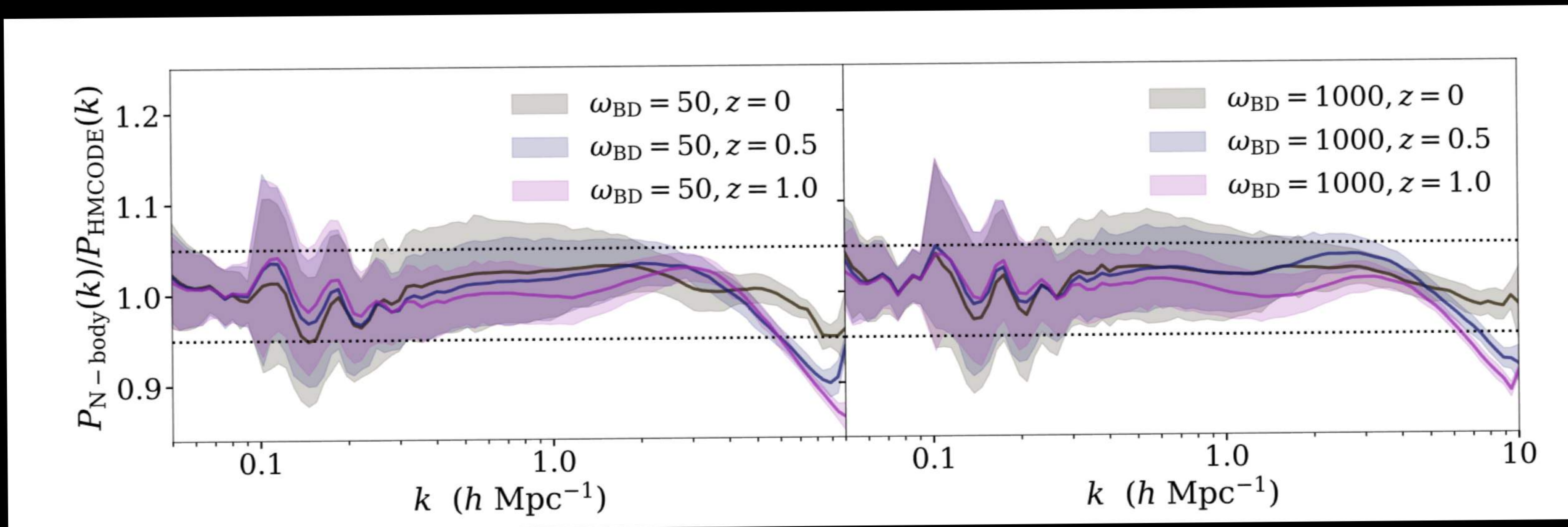
Degeneracies between normal (cosmological) parameters and gravitational parameters.

Large Scale Structure – Test case JBD

Non linear corrections kick in here.



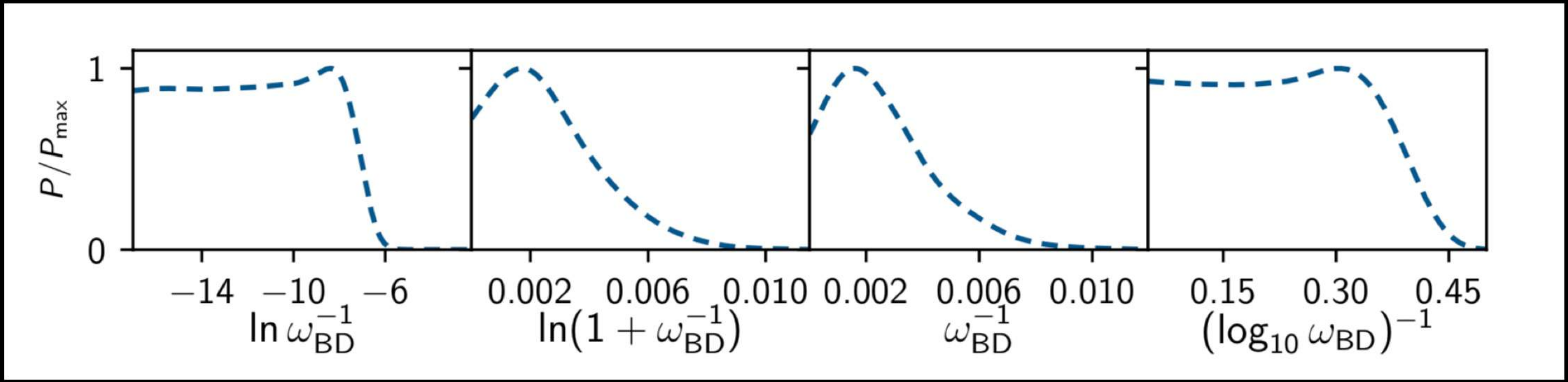
Large Scale Structure – Test case JBD



'Analytic' approximation to nonlinearities

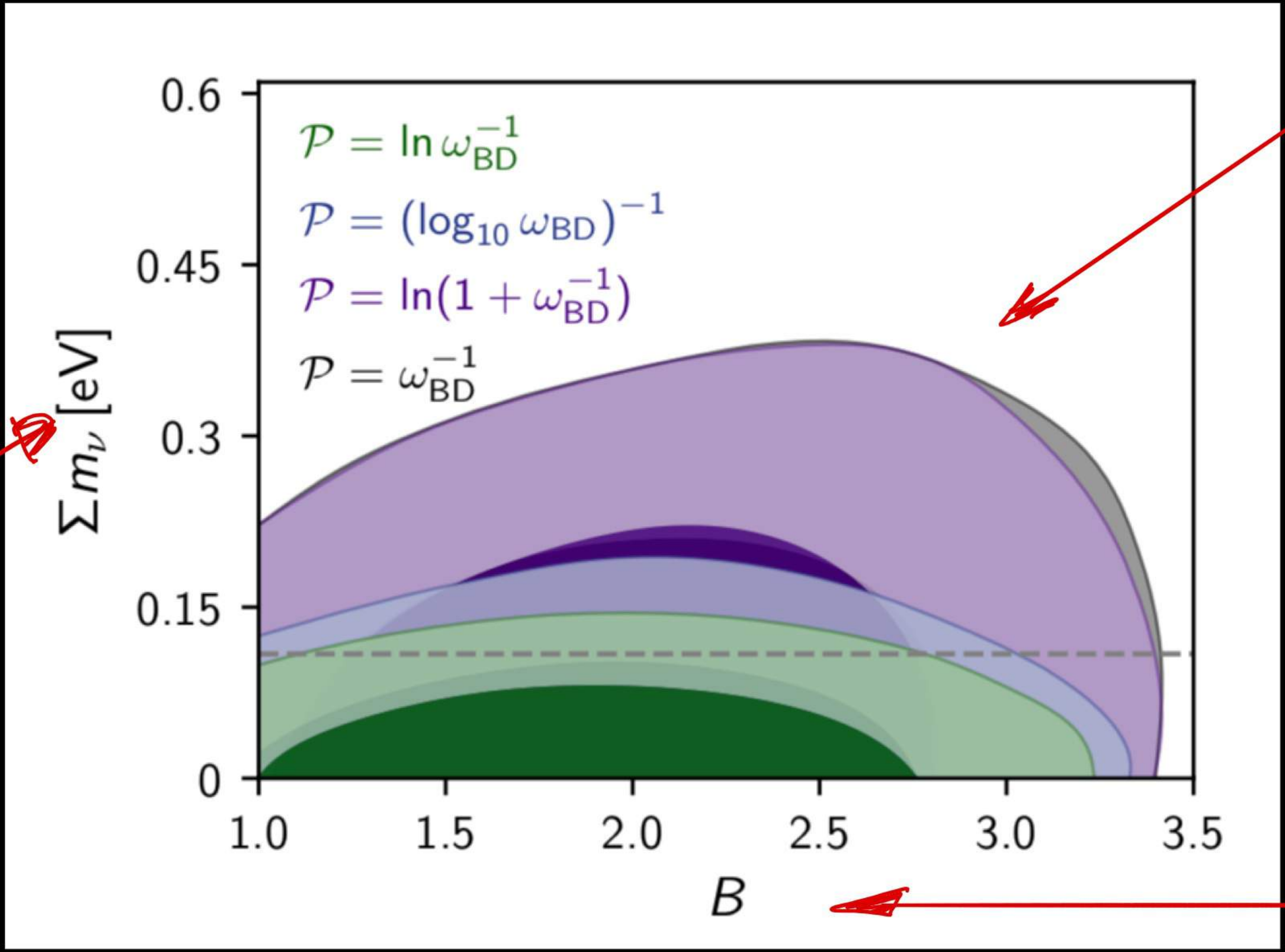
"Emulator"

Large Scale Structure – Test case JBD



Different choices of uniform prior for ω_{BD}

Large Scale Structure - Test case JBD

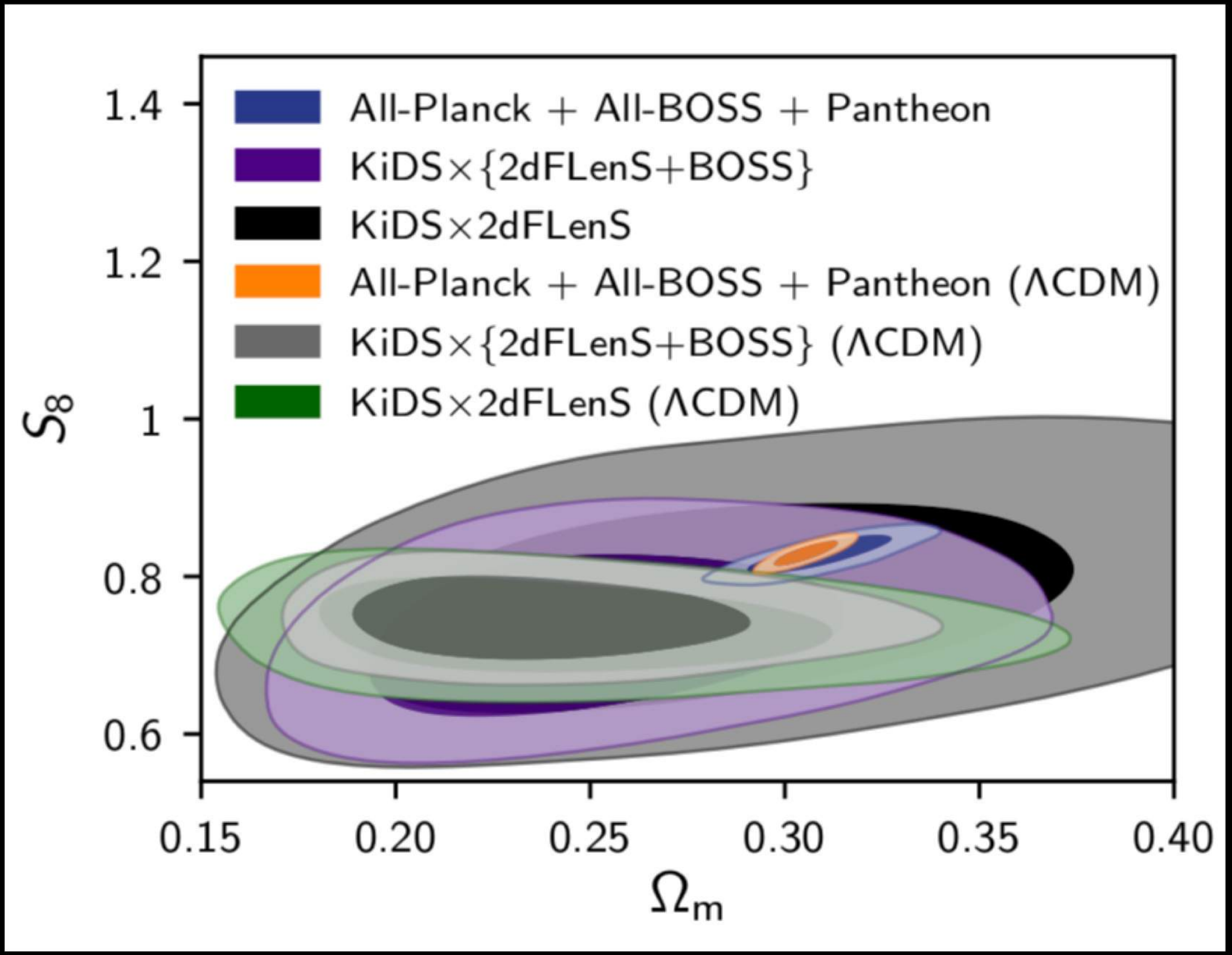


Different priors lead to different constraints.

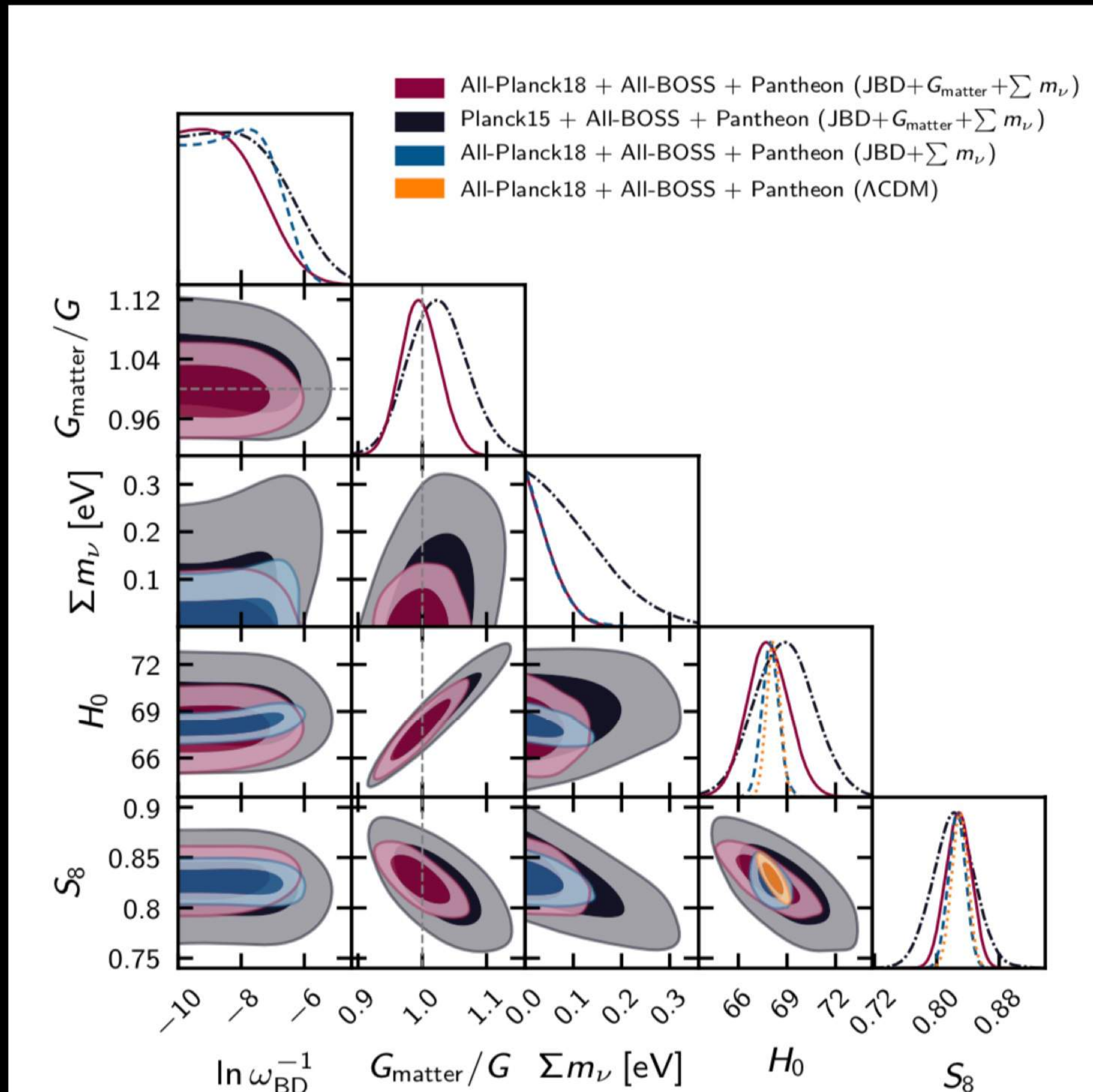
Neutrino Masses

Baryon Feedback

Large Scale Structure – Test case JBD



Large Scale Structure – Test case JBD



Large Scale Structure – Test case JBD

Summary

- Now possible to constrain gravity with LSS
- Observables: expansion rate, Distances, growth rate,
- General approach: α_x, (μ, γ, Σ) → how to parametrize → what priors
- Current constraints: inconsistencies → evidence for deviations
- Priors may play a role
- What to watch out for
  - → precision linear
  - → model non-linear
  - → Baryons
  - → Degeneracies
  - → Priors