Testing Gravity on Cosmic scales: A case study of Jordan-Brans-Dicke Gravity

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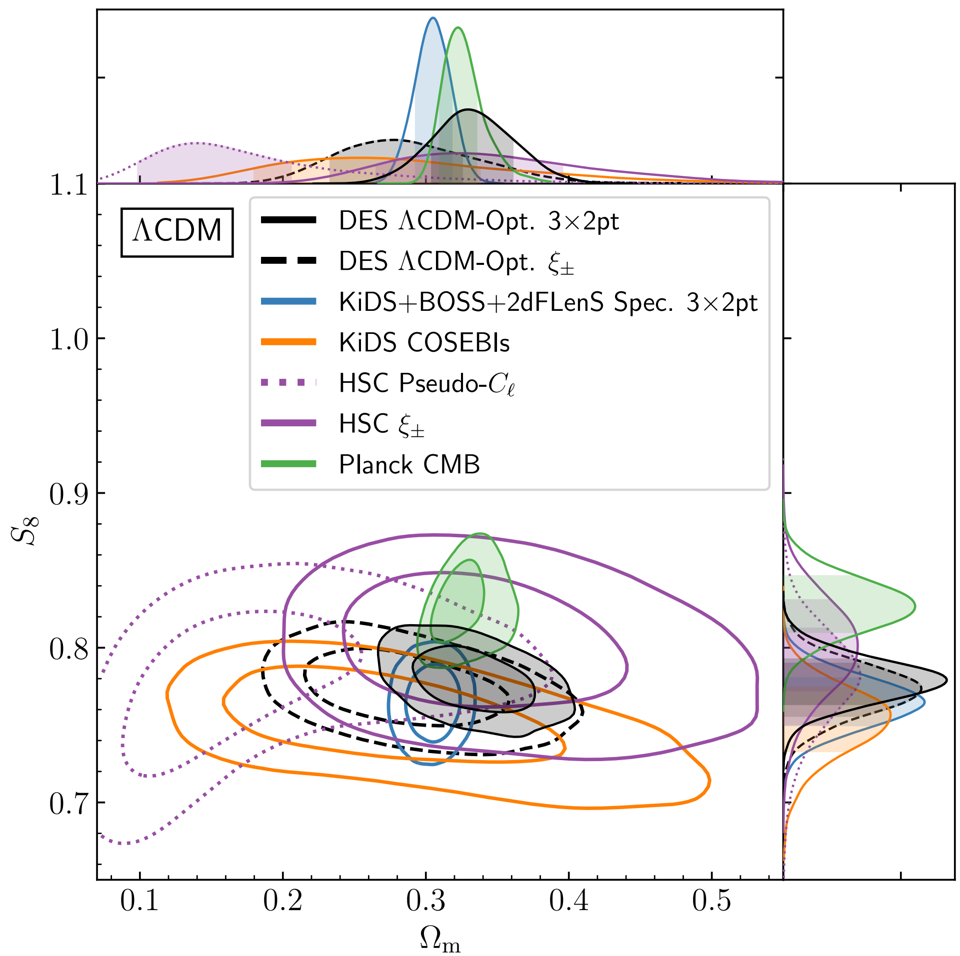
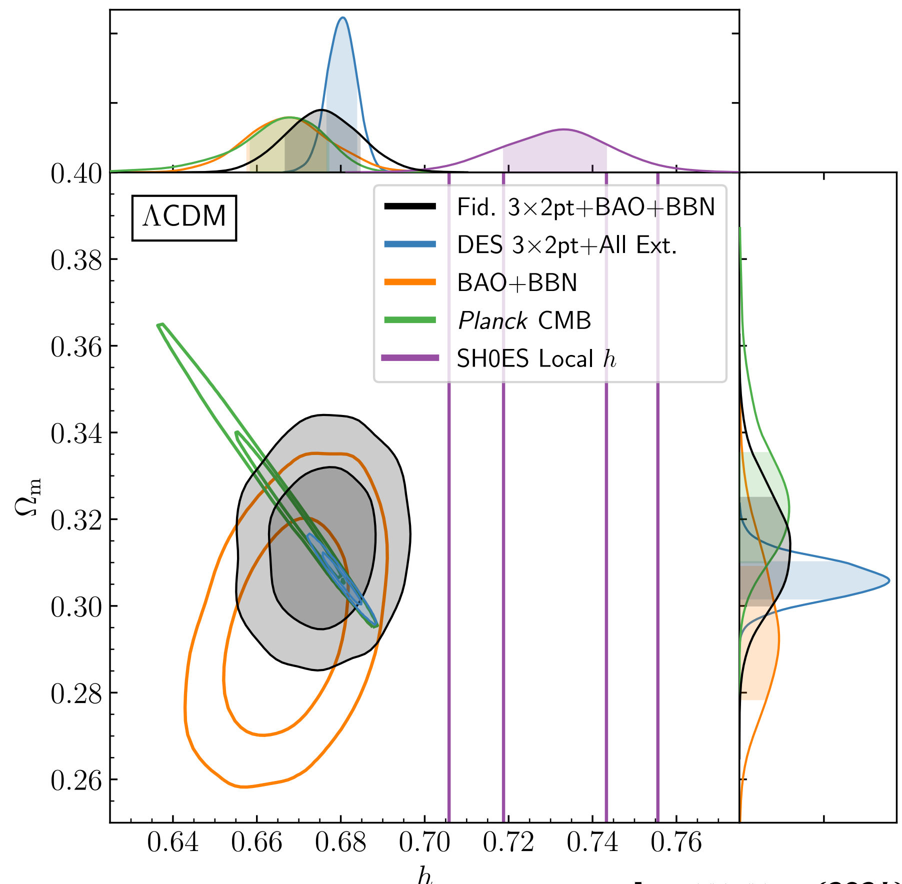
Why explore modified gravity?

- Test laws of gravity on cosmic scales, up to 15 orders of magnitude larger than the Solar System where GR is well-established
- Universe accelerates (Λ has fine-tuning and coincidence problems)
- Cosmic tensions (S_8 and H_0) and absence of obvious candidates



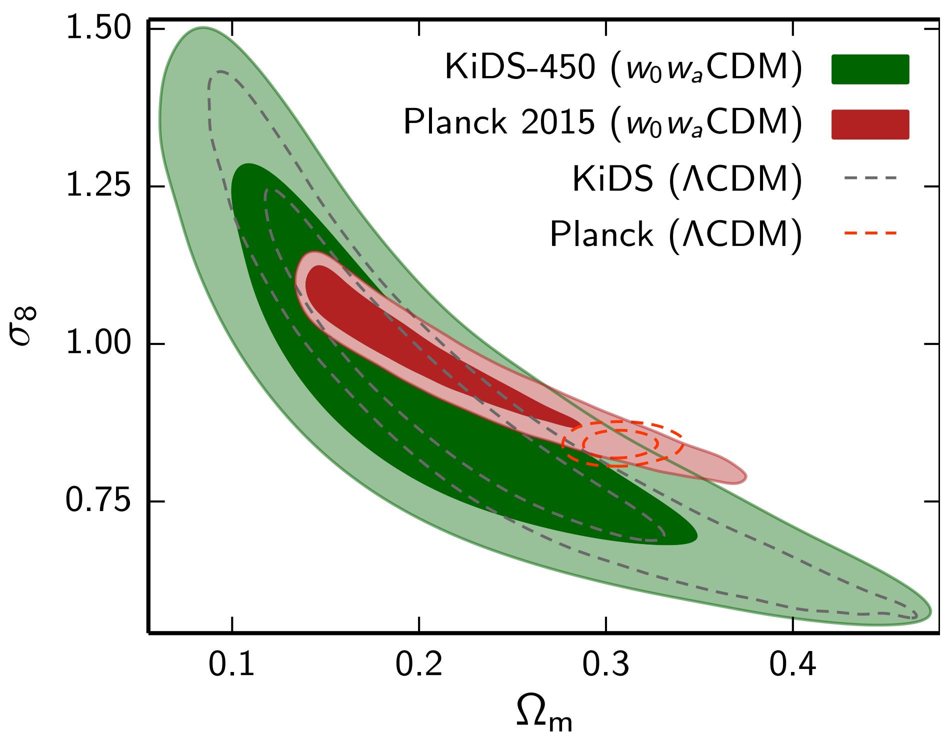


Abbott et al (2021)

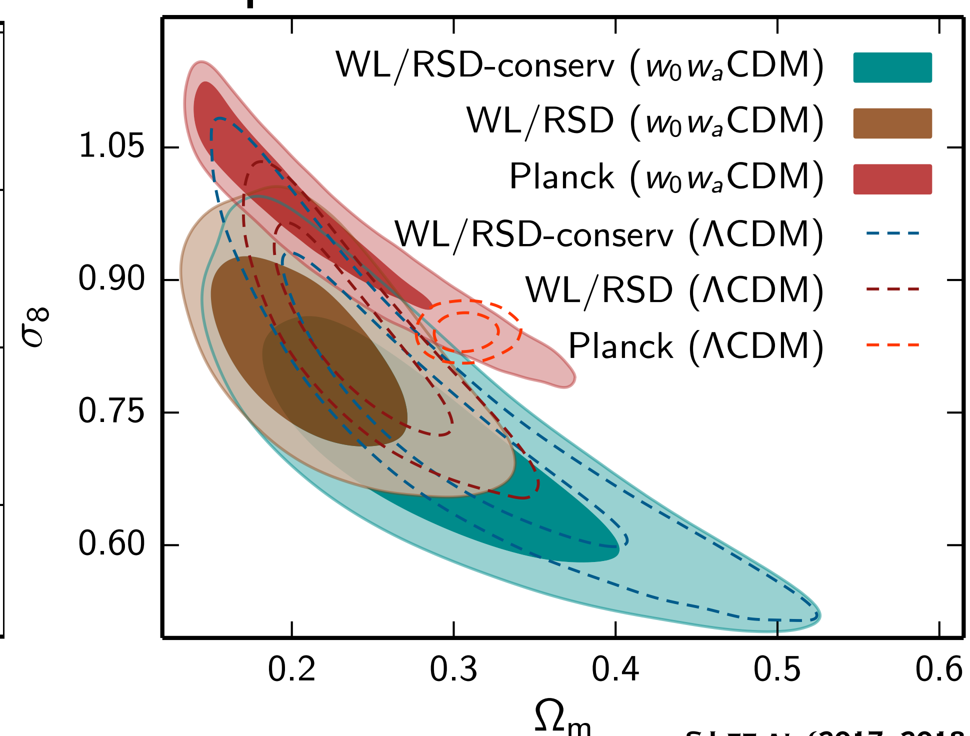
Requirements on any new model

- Bring about concordance among probes. Ideally, but not necessarily, among all probes (both H_0 & S_8).
- Be favored in model selection sense (e.g. evidence, goodness of fit, DIC).
- Exhibit greater than 5σ deviation in additional parameters (wrt fiducial model).
- Stay robust when confronted with additional data.

Cosmic shear vs CMB



3×2pt vs CMB



SJ et al (2017, 2018a)

Two approaches to modified gravity

- “Model-independent” modified gravity

  — G_{matter} - G_{light} modifying Ψ and $\Psi + \Phi$
  — Index γ_G modifying linear growth rate
  — Horndeski α_i encompassing a subset of stable scalar-tensor theories
  — E_G encapsulating $(g \times \kappa)$ / $(g \times v)$ cross-correlations

- Model-specific modified gravity

  — Constrain a distinct model. Examples include: JBD, general $f(R)$, DGP, DHOST, non-local gravity, bigravity

Model-independent *vs* model specific

- Why take "model-independent" approach?

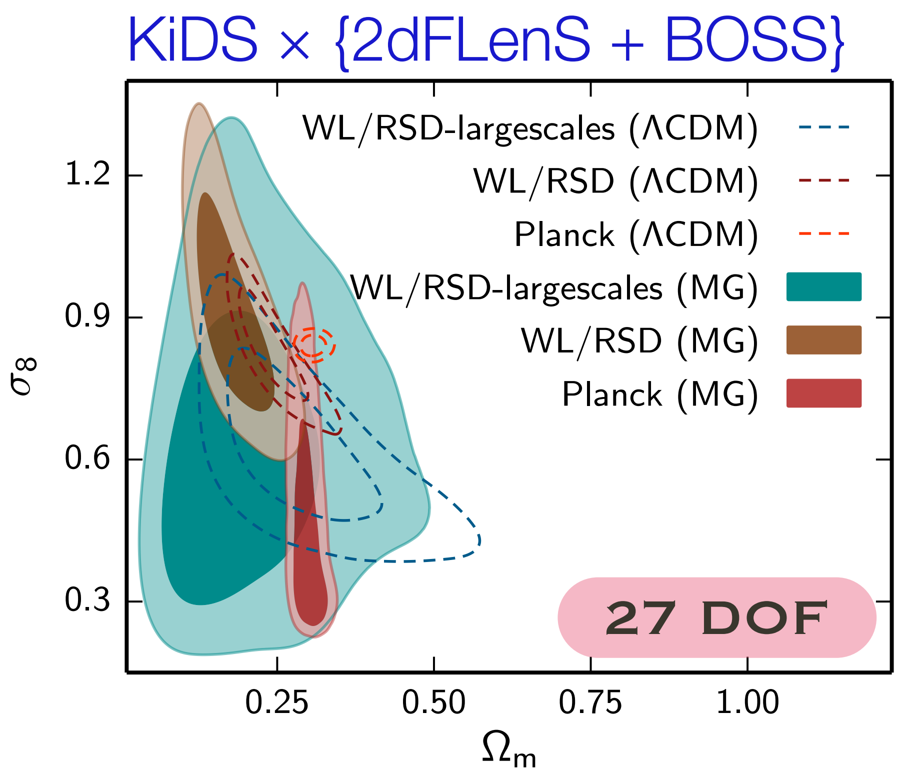
— Zeroth-order approach: search for *any* deviations from GR
— Simultaneously constrain large classes of models

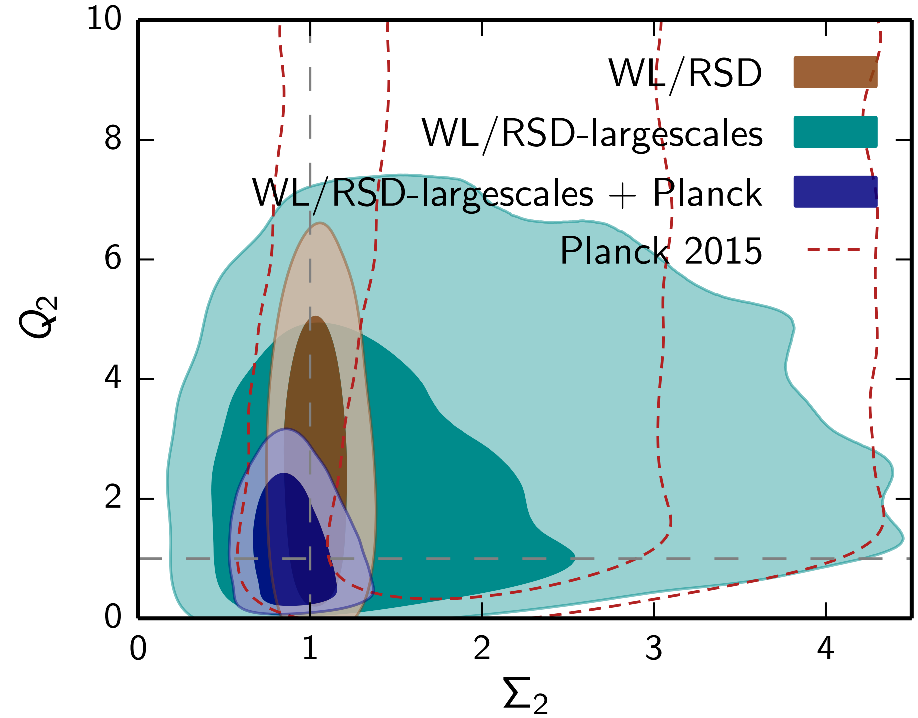
- Why take model-specific approach?

— Simulate/model the nonlinear scales (screening mechanism is highly model-dependent) *—> increase constraining power*

— Changes to both expansion and growth (expansion commonly fixed to ΛCDM in model-independent approaches)
—> increase ability to resolve multiple tensions (i.e. both H_0 & S_8)

"Model-independent" test of gravity





$Q(k, z)$ modifies Poisson equation

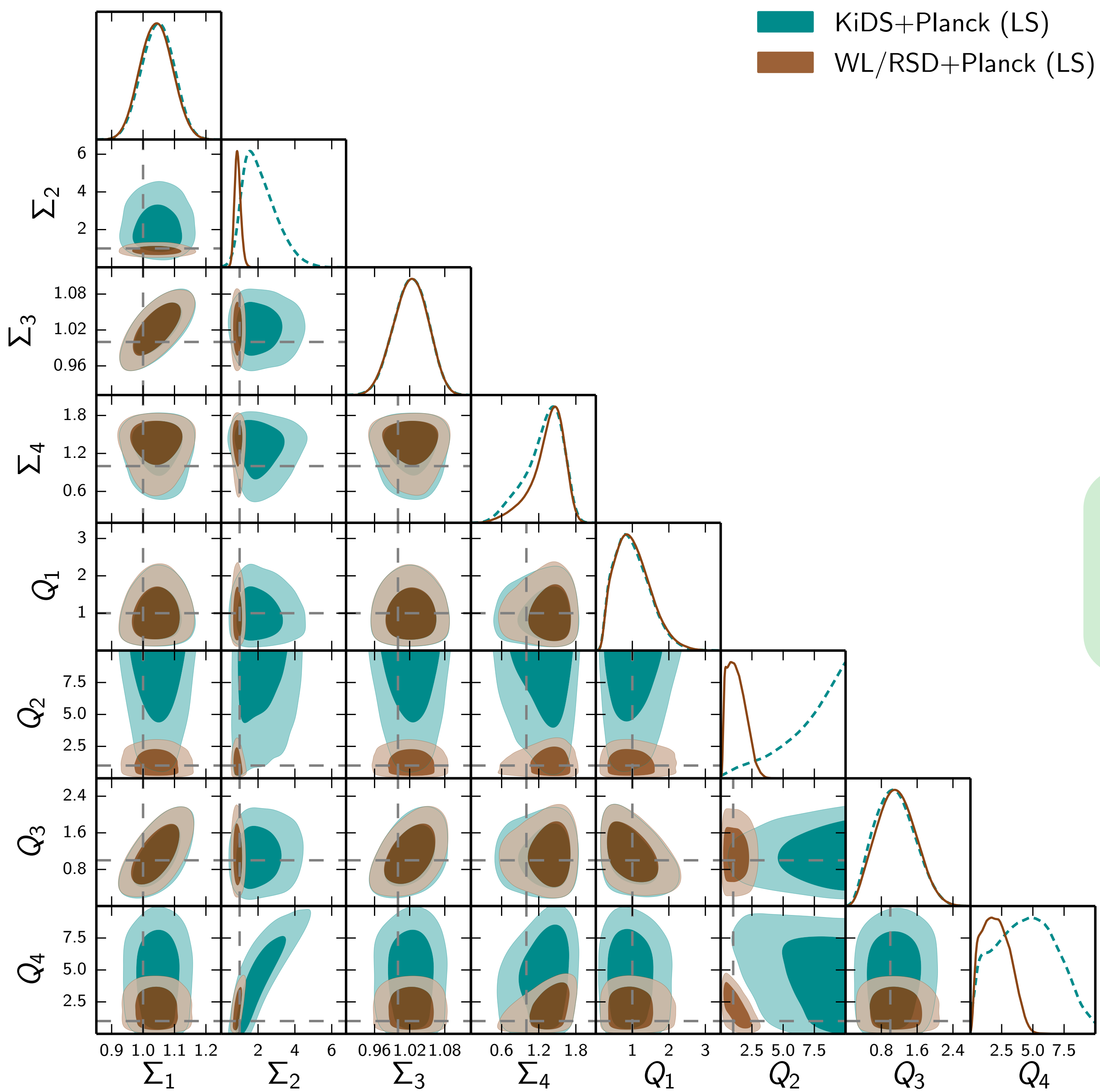
$\Sigma(k, z)$ modifies light deflection

1 low z low k	2 low z high k
3 high z low k	4 high z high k

10-15% level constraints on Σ_2 in fiducial and LS+Planck cases, Q_2 bounded from above, S_8 constraint improves by up to factor of 3.

SJ et al (2018a)

“Model-independent” test of gravity: *full MG subspace*



Large-scale data cuts

Complete agreement with GR

Extension not favored relative to ΛCDM

1 low z low k	**2** low z high k
3 high z low k	**4** high z high k

SJ et al (2018a)

Model-specific approach: A case study of Jordan-Brans-Dicke (JBD) Gravity

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

$S_{\rm BD}$ = JBD action, R = Ricci scalar, $L_{\rm m}$ = matter Lagrangian
ϕ = real scalar field, V = potential (taken to be constant)
$g^{\mu\nu}$ = metric (with determinant g)
$M_{\rm Pl} = (8\pi G)^{-1/2}$ = reduced Planck mass (G is bare grav. constant)
$\omega_{\rm BD}$ = JBD coupling constant

Varying the action with respect to the metric and scalar field:

$$3H^2 = \frac{\rho}{M_{\rm Pl}^2\phi} - 3H\frac{\dot\phi}{\phi} + \frac{\omega_{\rm BD}}{2}\frac{\dot\phi^2}{\phi^2} + \frac{V}{\phi}$$

$$2\dot H + 3H^2 = -\frac{P}{M_{\rm Pl}^2\phi} - \frac{\omega_{\rm BD}}{2}\frac{\dot\phi^2}{\phi^2} - 2H\frac{\dot\phi}{\phi} - \frac{\ddot\phi}{\phi} + \frac{V}{\phi}$$

$$\ddot\phi + 3H\dot\phi = \frac{1}{M_{\rm Pl}^2}\left(\frac{\rho - 3P}{3+2\omega_{\rm BD}}\right) + \frac{4V - 2\phi V_\phi}{3+2\omega_{\rm BD}}$$

RD: ϕ = constant —> $a \sim (t/\phi)^{1/2}$
MD: $\phi = \phi_0\, a^{1/(1+\omega_{\rm BD})}$ —> $a = (t/t_0)^{(2+2\omega_{\rm BD})/(4+3\omega_{\rm BD})}$
VD: $\phi \sim a^{4/(1+2\omega_{\rm BD})}$ —> acceleration expansion driven by V

Scalar field has effect throughout full evolution of Universe

Linear perturbations in JBD gravity

Modified Poisson equation:

$$\frac{k^2}{a^2}\Psi \simeq -4\pi G_{\rm matter}\rho_{\rm m}\delta_{\rm m}$$

Effective gravitational constant:

$$\frac{G_{\rm matter}}{G} \simeq \frac{1}{\bar{\phi}}\frac{4+2\omega_{\rm BD}}{3+2\omega_{\rm BD}}$$

Two types of JBD gravity

restricted: vary $\omega_{\rm BD}$, fix $G_{\rm matter}/G|_{a=1} = 1$
unrestricted: vary both $\omega_{\rm BD}$ and $G_{\rm matter}/G|_{a=1}$

On subhorizon scales:

$$\delta''_{\rm m} + \left[1+\frac{\mathcal{H}'}{\mathcal{H}}\right]\delta'_{\rm m} - \frac{3}{2}\frac{G_{\rm matter}}{G}\Omega_{\rm m}(a)\delta_{\rm m} \simeq 0$$

Gravitational slip (both JBD types):

$$2\frac{\Psi}{\Psi+\Phi} = \frac{2\gamma}{1+\gamma} \simeq \frac{4+2\omega_{\rm BD}}{3+2\omega_{\rm BD}}$$

Why explore JBD gravity?

1. Testbed for cosmological analyses of modified gravity (and extended cosmologies more broadly), given its rich history and the role it plays in some of the fundamentally motivated extensions to SM of particle physics (particularly in string theory, extra-dimensional theories, and the decoupling limit of theories with higher spin fields).

2. Simplest modified gravity theory. Approximates a wider range of scalar-tensor theories (within Horndeski) on cosmological scales where gradients are suppressed.

3. One of remaining viable theories after LIGO-VIRGO measurement of the speed of gravitational waves ($\alpha_T = 0$).

4. Use model-specific approach to simultaneously constrain and explore degeneracies between modified gravity, neutrino mass, and baryonic feedback.

5. Explore whether the theory can help to alleviate cosmic tensions (H_0 & S_8) whilst being favored in model selection sense.

Earlier constraints on JBD gravity

- Shapiro time delay by *Cassini*: $\omega_{BD} > 4.0 \times 10^4$ (95% CL)

BERTOTTI ET AL (2003)

- Pulsar-white dwarf binary: $\omega_{BD} > 1.2 \times 10^4$ (95% CL)

FREIRE ET AL (2012)

- Cosmology (early & late): $\omega_{BD} \gtrsim 10^2 - 10^3$ (95% CL)
  Not competitive, but probing different redshifts and scales.

AVILEZ & SKORDIS (2014)
SOLÀ PERACAULA ET AL. (2019 & 2020)
BALLARDINI ET AL (2016 & 2020)

- Big Bang Nucleosynthesis:
  $\{\omega_{BD} > 300, G_{BBN}/G = 0.98 \pm 0.06\}$ (95% CL)

CLIFTON ET AL (2005)
ALVEY ET AL (2020)

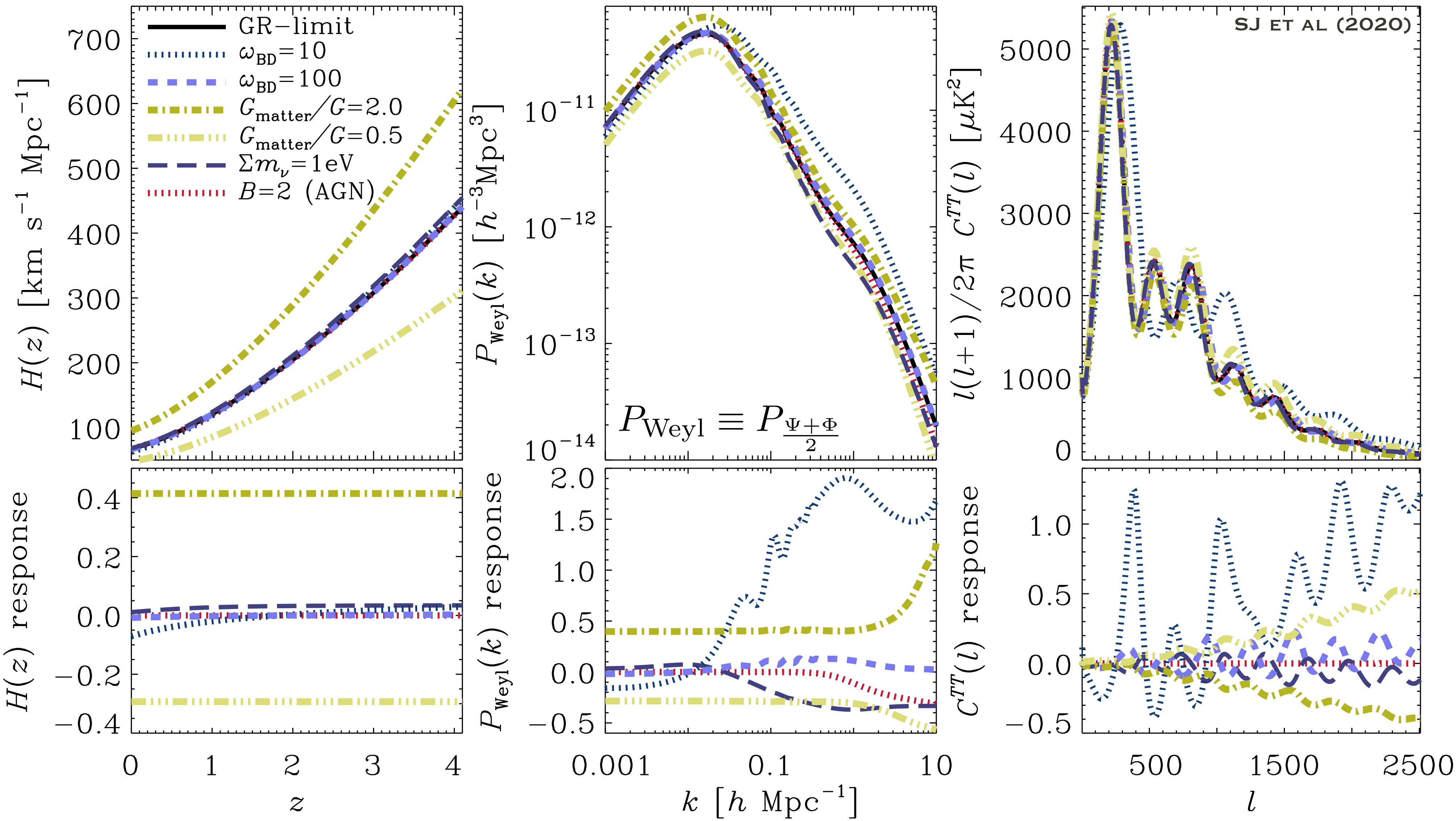
Astrophysical constraints much more powerful. However, expect nonlinear corrections (screening) in *generalized* JBD gravity, which may completely shield astrophysical systems.

End-to-end approach

- Analytical and numerical description of the background expansion and linear perturbations.
- Nonlinear regime captured with hybrid suite of *N*-body simulations —> modified fitting function for matter power spectrum
- Cosmological constraints from existing probes of the expansion history, large-scale structure, and CMB.
  Simultaneous constraints on modified gravity, massive neutrinos, and baryonic feedback for the first time.

- Accurately account for observational systematics (e.g. baryonic feedback, intrinsic alignments, photo-*z* and shear calibration uncertainties, galaxy bias).
- Accurately account for theoretical systematics from modeling new physics such as neutrino mass, dark matter, DE/MG.
- Understand the role of degeneracies between different parameters (cosmological, astrophysical, gravitational, instrumental).

JBD impact on the expansion, growth, CMB



$$H^2_{JBD}/H^2_{GR} \simeq 1/\phi = \left(\frac{3+2\omega_{BD}}{4+2\omega_{BD}}\right)\frac{G_{matter}}{G}$$

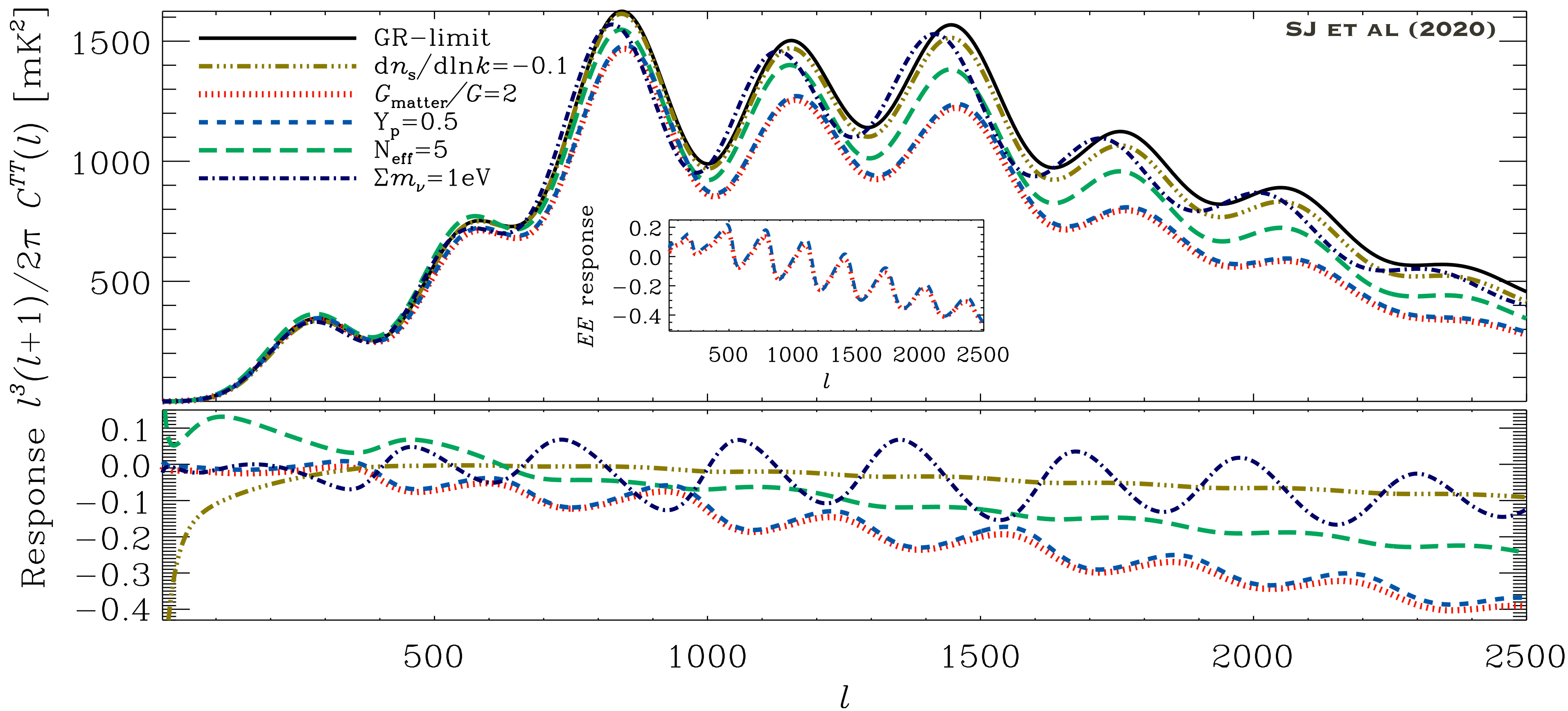
$$G_{light}/G = 1/\phi$$

1-sided ω_{BD}, 2-sided G_{matter}/G

CMB degeneracies

$$H^2 \propto \phi^{-1} \propto f(\omega_{\rm BD})\, G_{\rm matter}/G$$

$$\theta_{\rm d}/\theta_{\rm s} \propto \sqrt{H(a)/n_{\rm e}} \propto (G_{\rm matter}/G)^{1/4}(1+\mathcal{C}N_{\rm eff})^{1/4}/\sqrt{1-Y_{\rm P}}$$



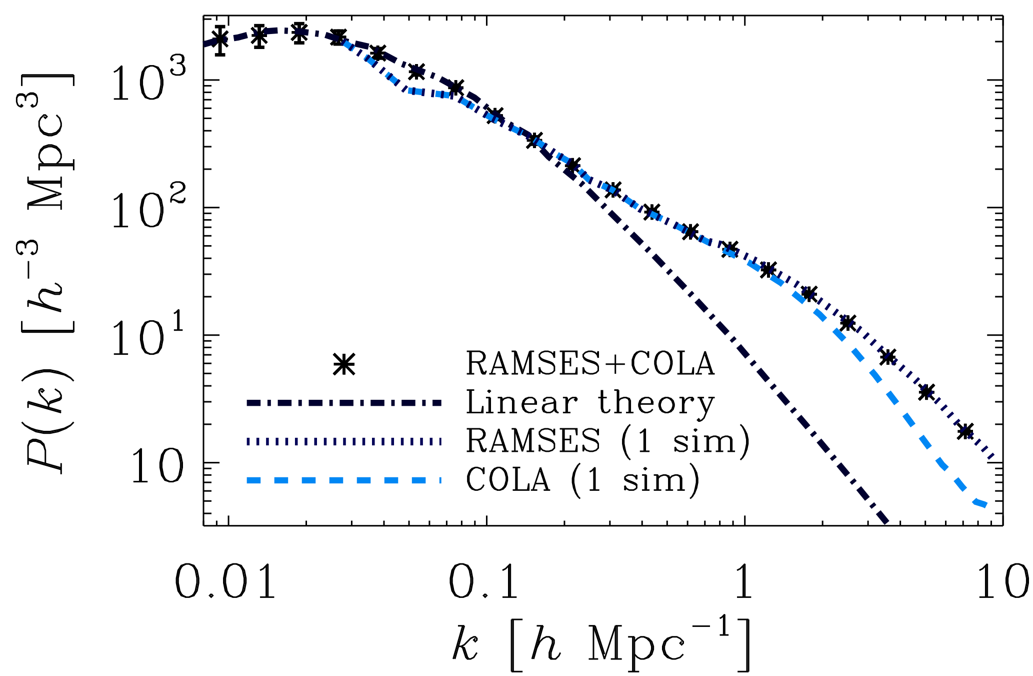
Partly break degeneracy between $N_{\rm eff}$ and $Y_{\rm P}$ (and between $N_{\rm eff}$ and $G_{\rm matter}/G$) via early ISW, potential high baryon fraction as $N_{\rm eff}$ increases, phase shift in acoustic oscillations due to neutrino perturbations.

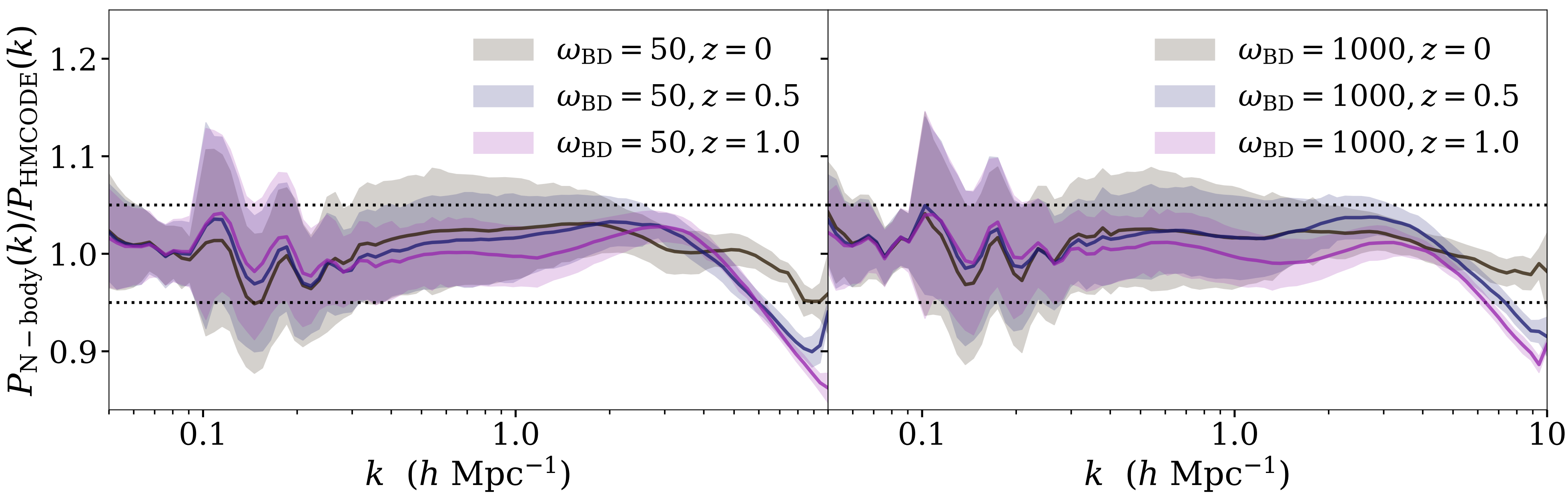
Nonlinear regime

1) Modify geodesic and poisson equations. Generate initial conditions using 2LPT.

2) Run a hybrid suite of Ramses and COLA simulations.

3) Modify HMCODE to match simulations (MG, neutrino mass, baryonic feedback).





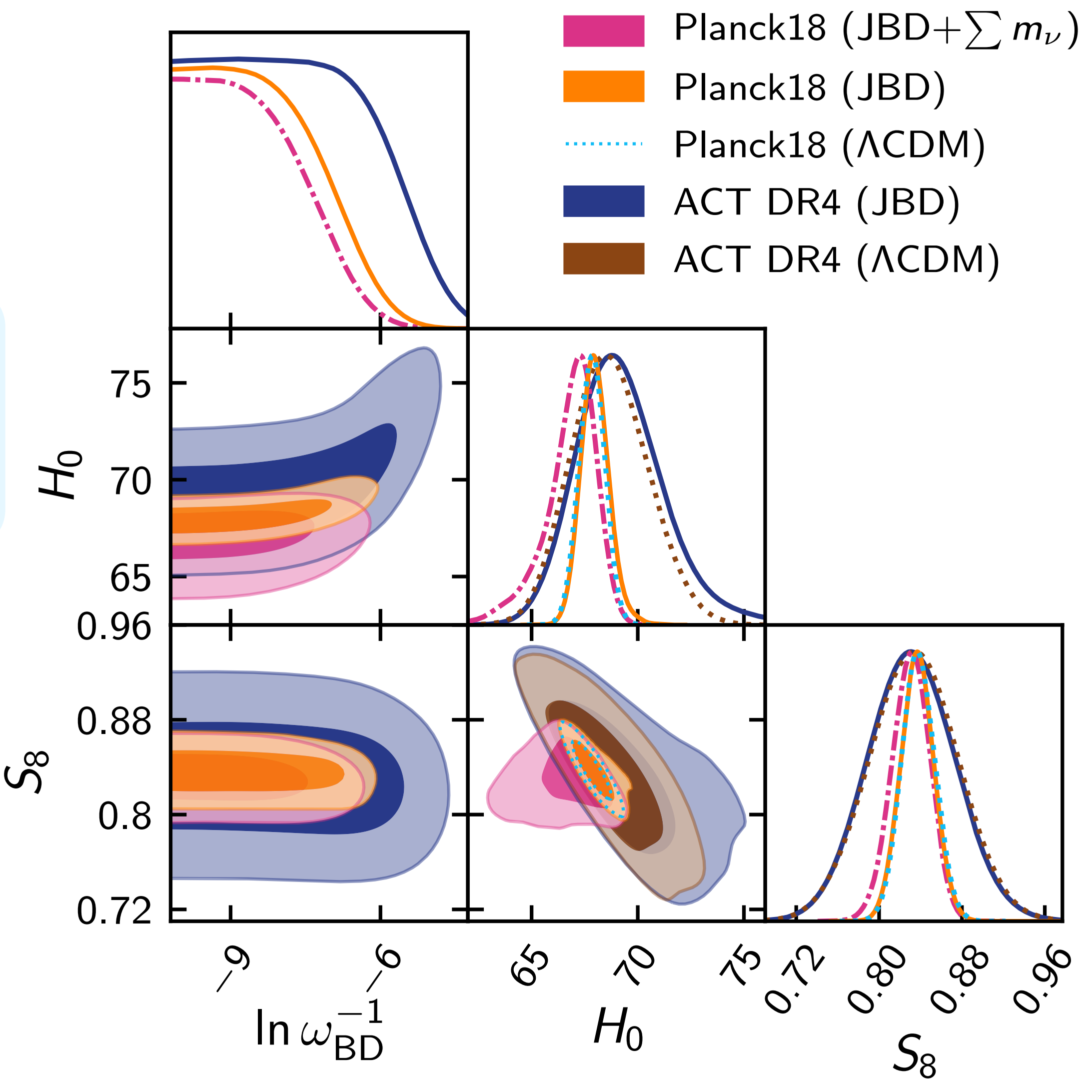
SJ et al (2020)

CMB constraints on restricted JBD gravity

Restricted JBD:
Vary ω_{BD} (GR-limit as ω_{BD} —> -∞)
Fix $G_{matter}/G|_{a=1}$ = 1

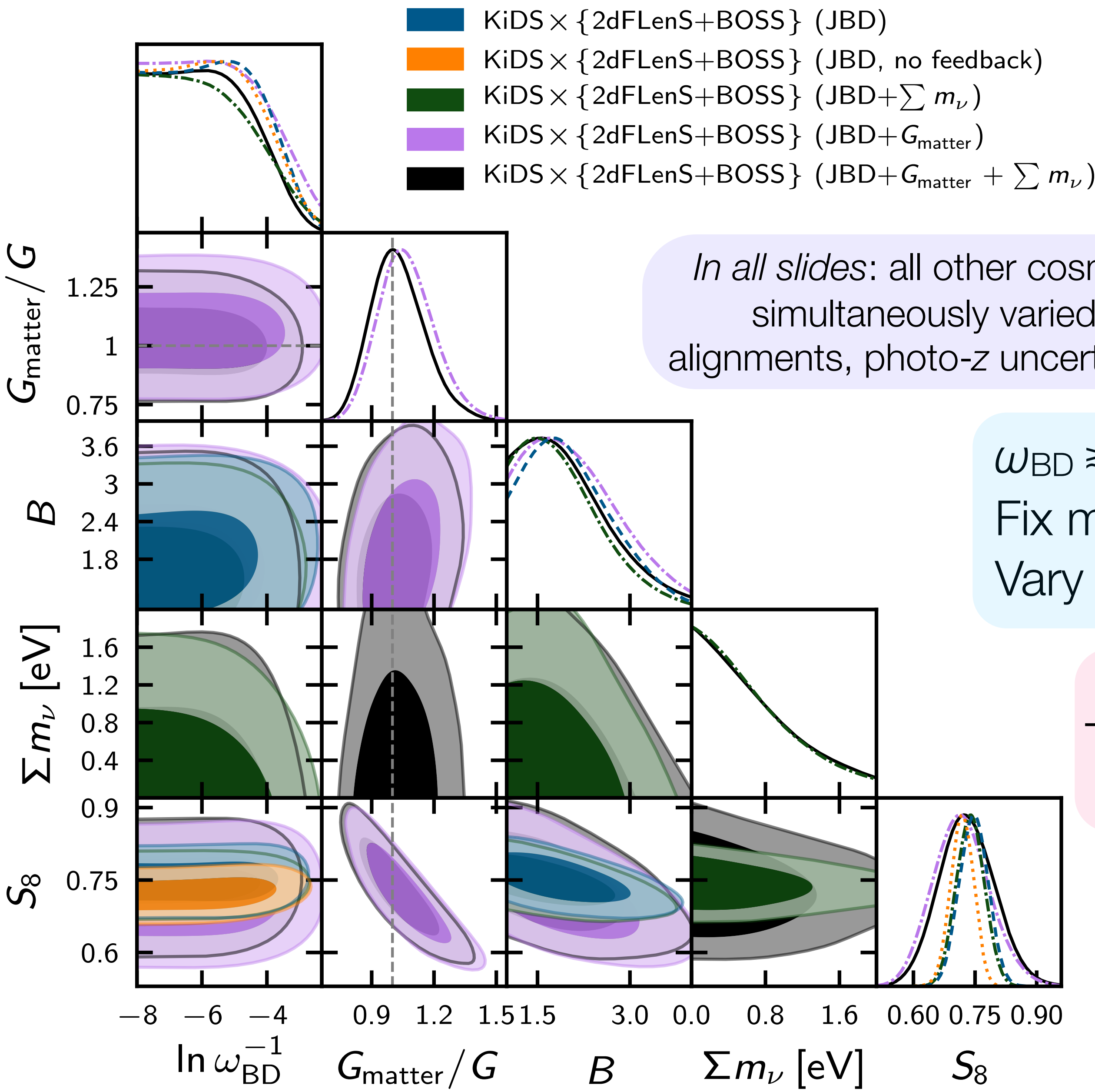
Planck18: $\omega_{BD} > 1150$ (95% CL)
ACT DR4: $\omega_{BD} > 330$ (95% CL)
Planck + ACT: $\omega_{BD} > 1380$ (95% CL)

Small impact on H0 tension
(more substantial for ACT).
Negligible impact on S8 tension.



SJ et al (2020)

3×2pt constraints on JBD gravity



In all slides: all other cosmological and systematics parameters simultaneously varied. (systematics include e.g. intrinsic alignments, photo-z uncertainties, galaxy bias, velocity dispersion)

$\omega_{\rm BD} \gtrsim 100$ (95% CL)

Fix m_ν: $G_{\rm matter}/G = 1.07^{+0.12}_{-0.15}$

Vary m_ν: $G_{\rm matter}/G = 1.03^{+0.11}_{-0.15}$

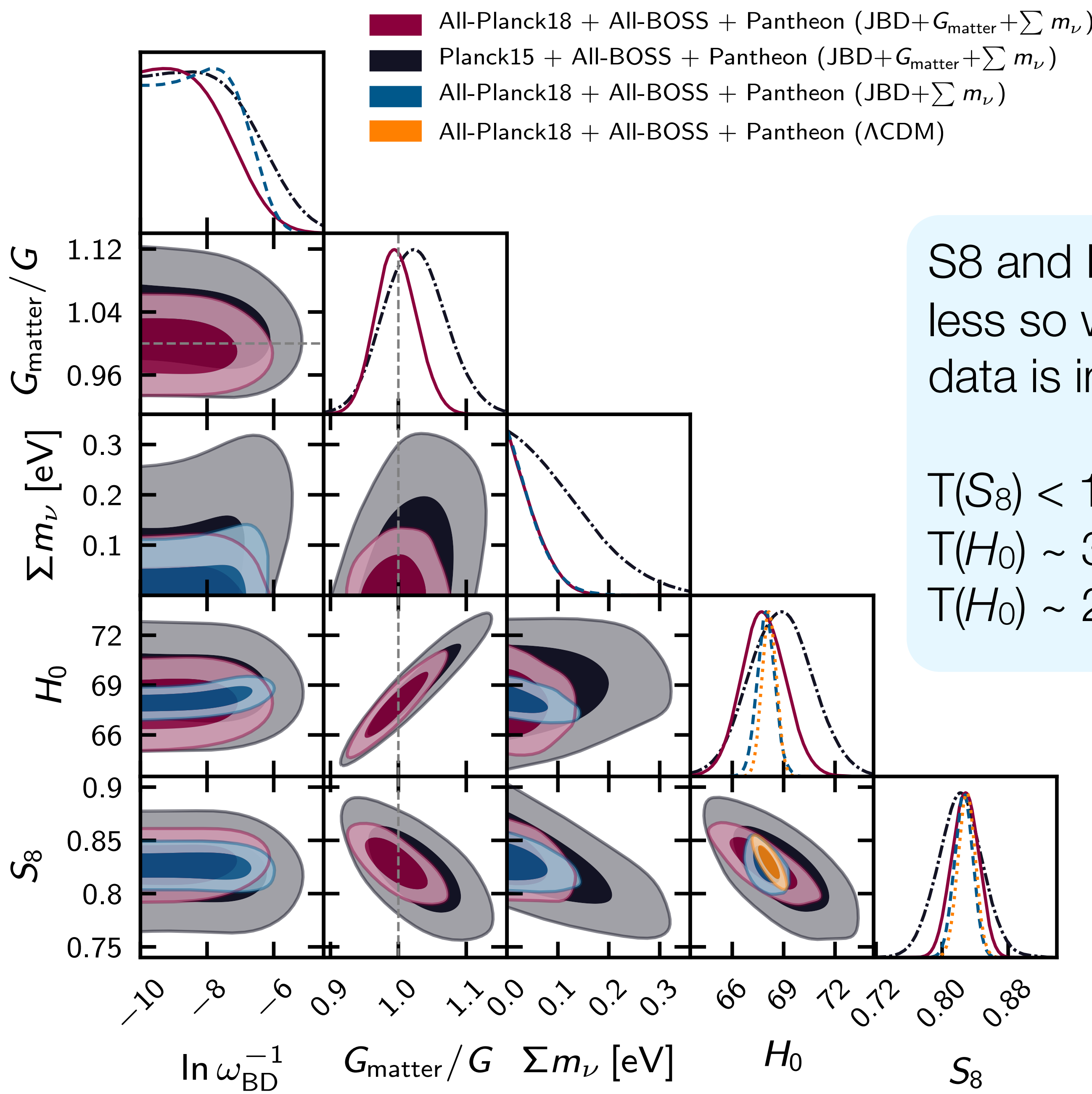
Unrestricted JBD:

$T(S_8) = 1.6$ (down by nearly 1σ)

ΔDIC = -1

SJ et al (2020)

Joint CMB/LSS/SN constraints on JBD gravity



S8 and H0 tensions alleviated, less so when CMB polarization data is included.

T(S_8) < 1σ (wrt KiDS × 2dFLenS)
T(H_0) ~ 3σ with polarization
T(H_0) ~ 2σ without polarization

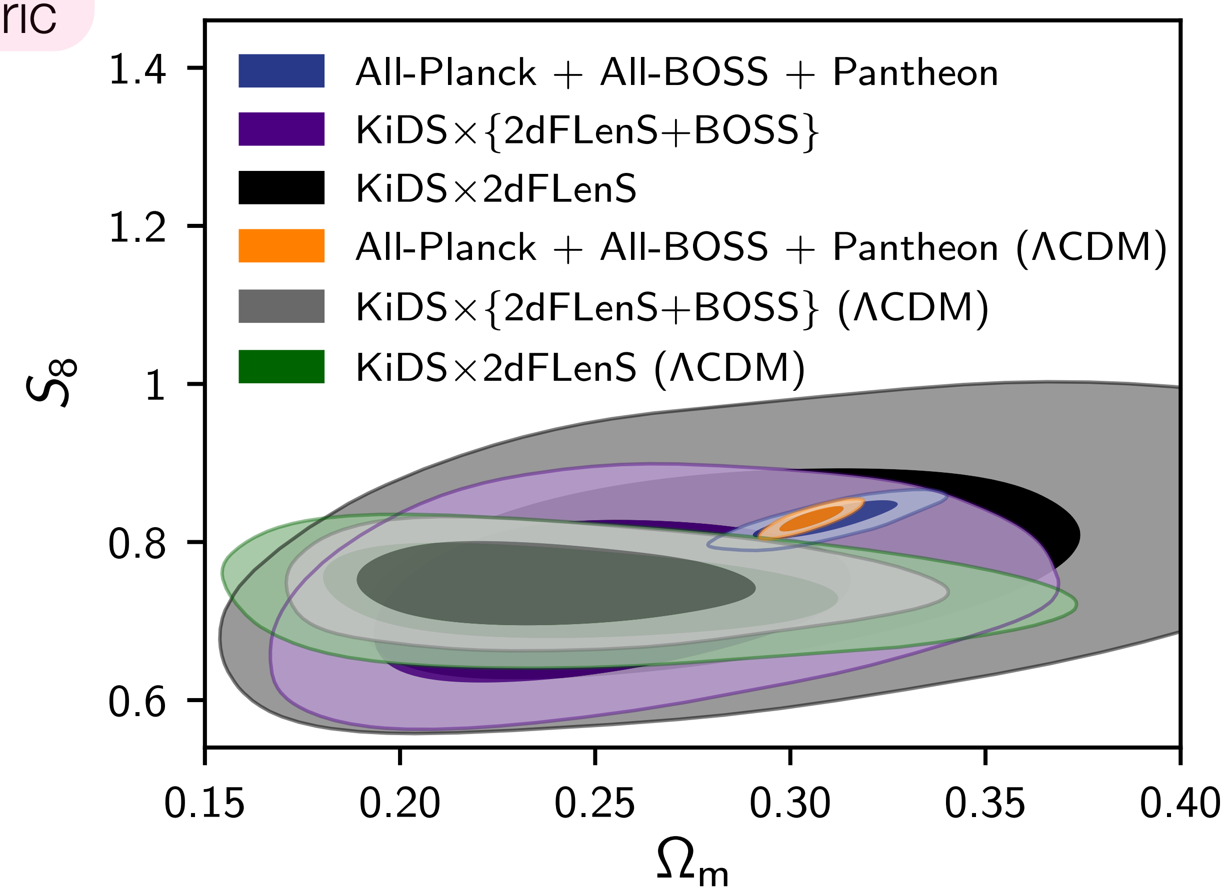
SJ et al (2020)

Assessing concordance as a requirement for combining datasets

Use the log $\mathscr{I}$ statistic to assess concordance.
S = suspiciousness metric
Q_{DMAP} = goodness of fit metric

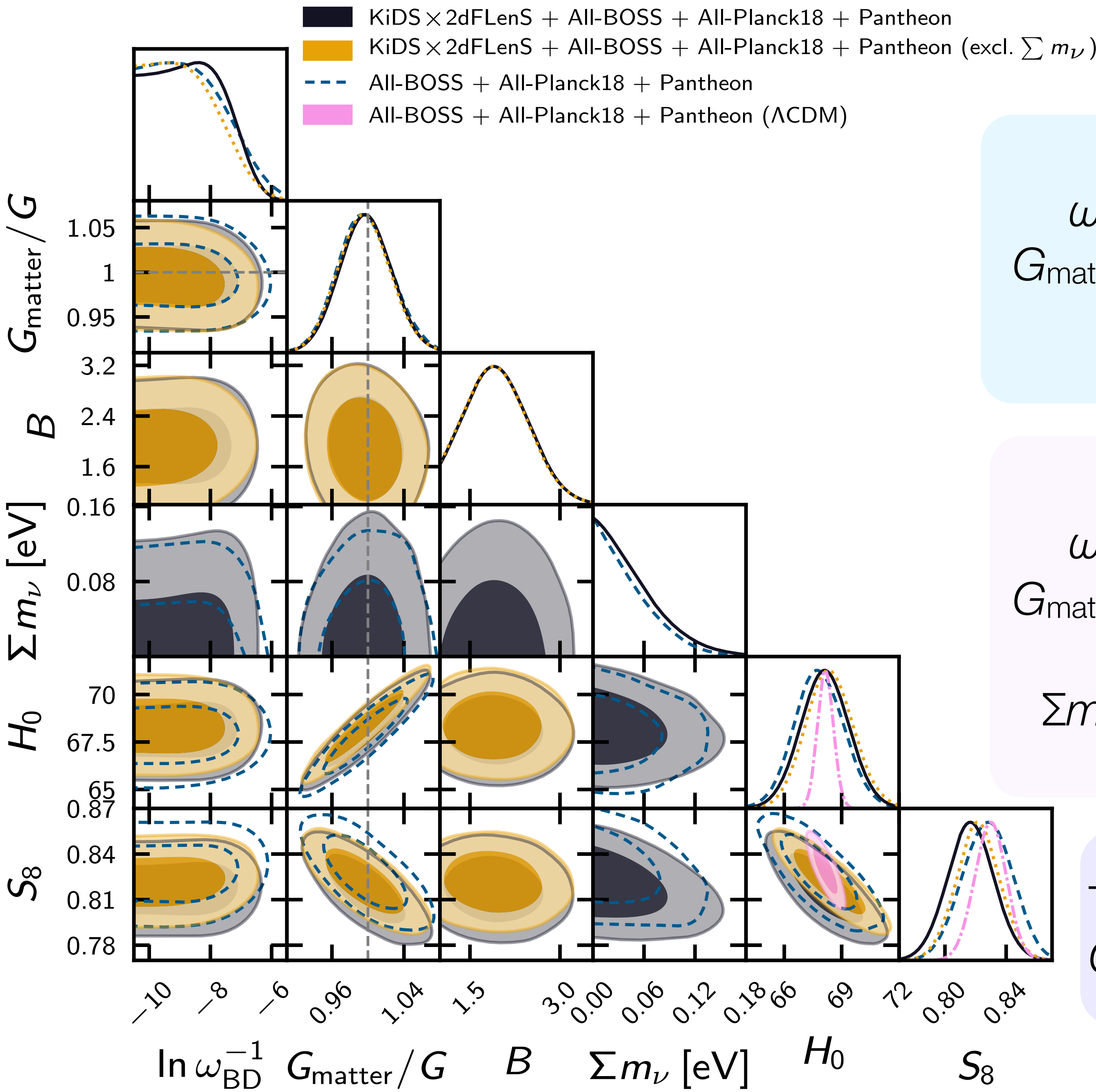
$$\log \mathcal{I} = [2\ln(10)]^{-1}[Q_{\mathrm{DMAP}} + 4\ln S]$$

Unrestricted JBD:
$\Delta\log \mathscr{I}$ = 0.93 (fix m_ν)
$\Delta\log \mathscr{I}$ = 0.37 (vary m_ν)
Swapping order changes by $\Delta\log \mathscr{I}$ by ~1.



SJ et al (2017a, 2020)

Full constraints on JBD gravity



Fix m_ν:

$\omega_{BD} > 1540$ (95% CL)

$G_{matter}/G = 0.996$ +/- 0.029

$T(H_0) = 3.0$

ΔDIC = 2.0

Vary m_ν:

$\omega_{BD} > 2230$ (95% CL)

$G_{matter}/G = 0.997$ +/- 0.029

$T(H_0) = 3.1$

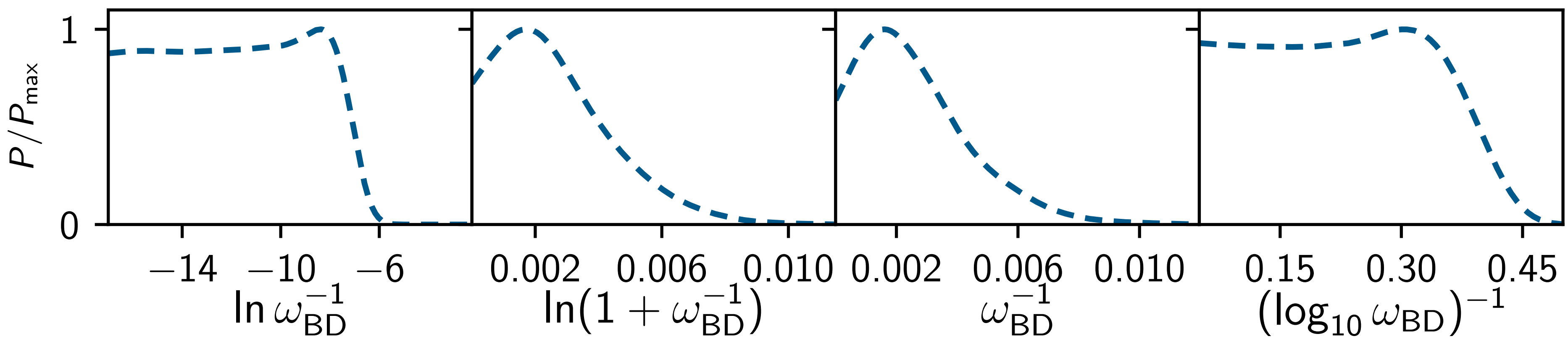
$\Sigma m_\nu < 0.12$ eV (95% CL)

ΔDIC = 4.6

Translating above to BBN:
$G_{BBN}/G = 0.99$ +/- 0.03

SJ et al (2020)

JBD parameterization

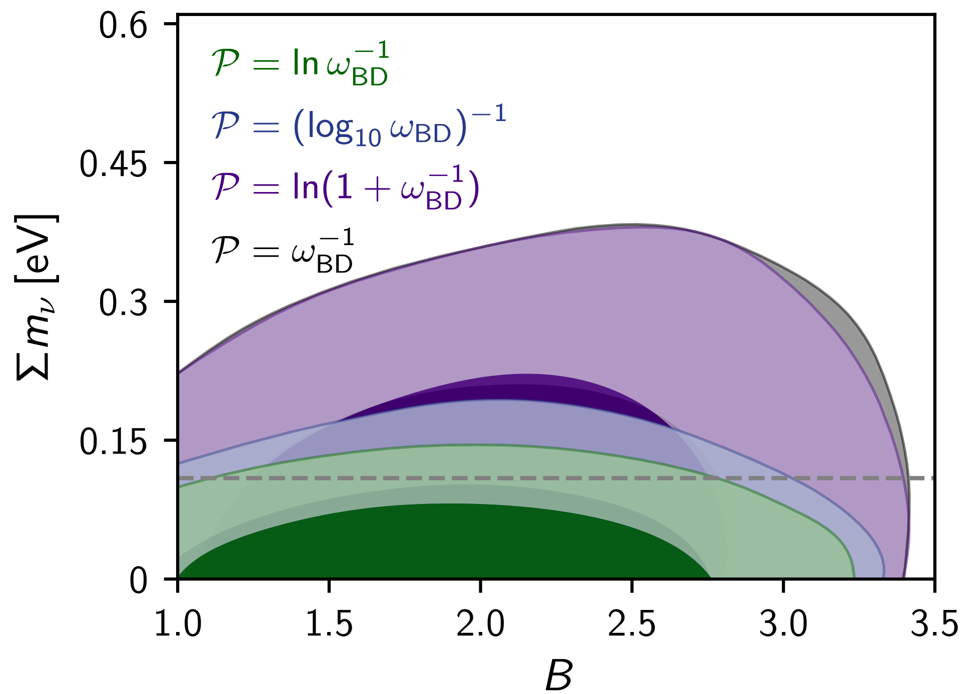


$\omega_{\rm BD} > \{1540, 160, 160, 350\}$ (95% CL)

Fiducial: $G_{\rm matter}/G$ = 0.996 +/- 0.029
—> $G_{\rm matter}/G$ = 0.970 +/- 0.033

Fiducial: B > 2.8 (95% CL)
—> B > 3.1 (95% CL)

Fiducial: Σm_ν < 0.12 eV (95% CL)
—> Σm_ν < 0.32 eV (95% CL)



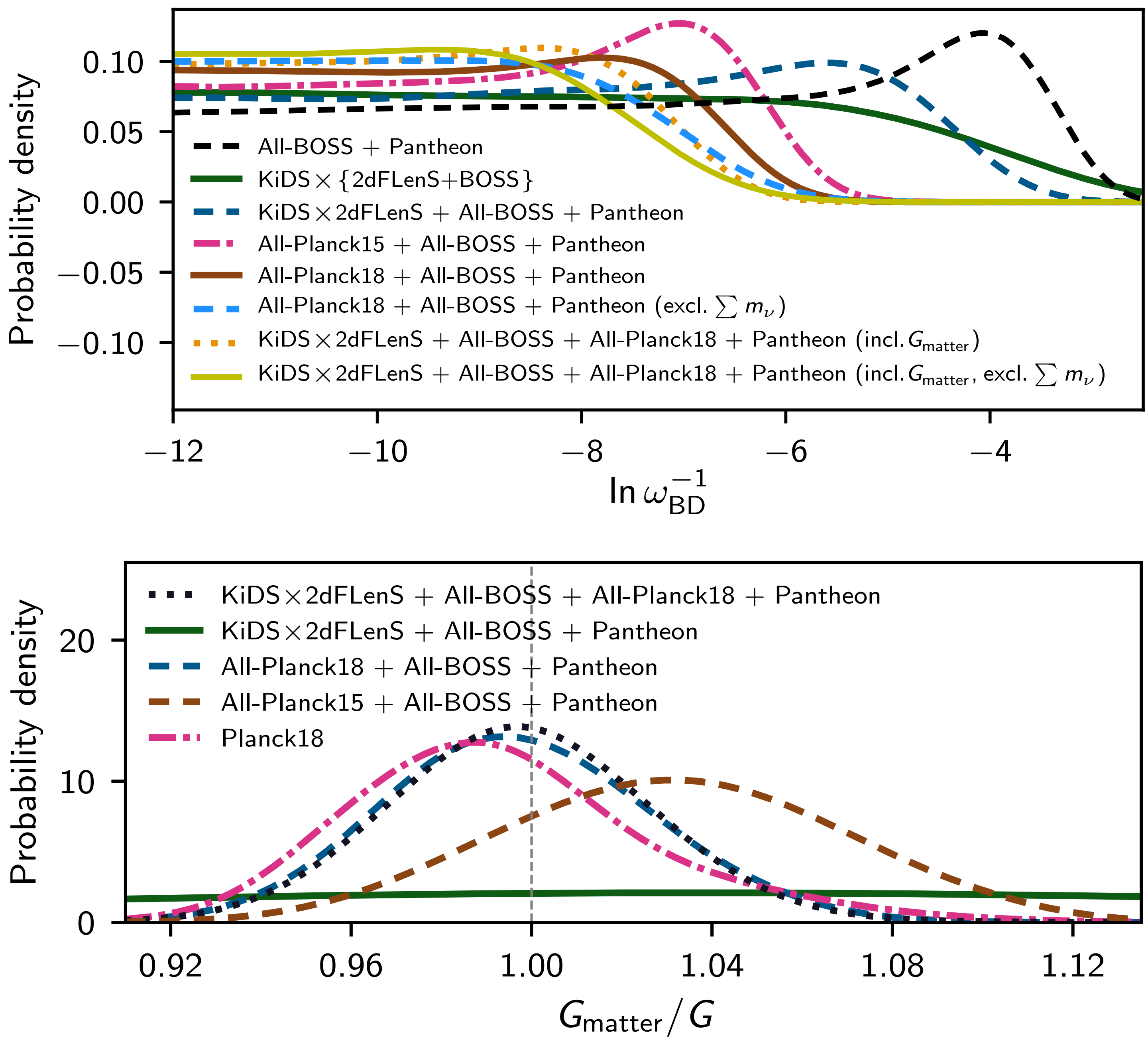
SJ et al (2020)

Summary

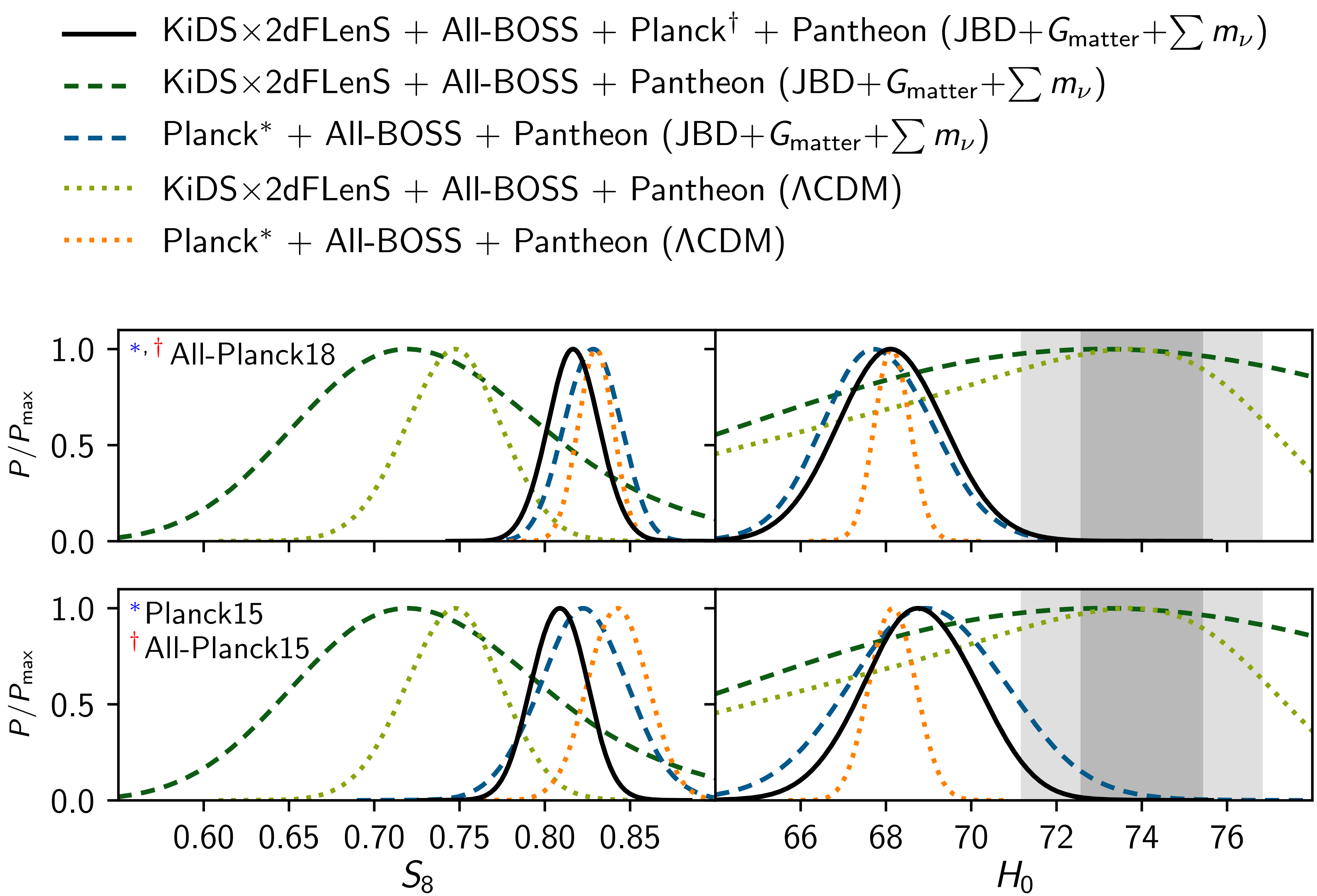
- End-to-end exploration of a distinct modified gravity theory (analytic description, numerical simulations, cosmological constraints from existing probes).
- Simultaneous constraints on modified gravity, massive neutrinos, and baryonic feedback for the first time. Neutrino mass bound can degrade by up to factor of 3 in JBD gravity.
- Cosmic tensions partly alleviated (S8 fully, H0 down to 3σ), due to increased uncertainty rather than deviations in new parameters. Extended model not found favored in model selection sense.
- A positive shift in the effective gravitational constant suppresses the CMB damping tail, which might complicate future inferences of small-scale physics.
- Expect order of magnitude improvements in JBD constraints with Stage-IV surveys. Will allow for comparable constraints from cosmology and astrophysics.

Extra slides

Constraints on JBD gravity



S_8 and H_0 tensions



Degeneracies and systematics