Addressing the H_0 and S_8 Tensions in f(Q) Cosmology

Maria Petronikolou

IAASARS, National Observatory of Athens

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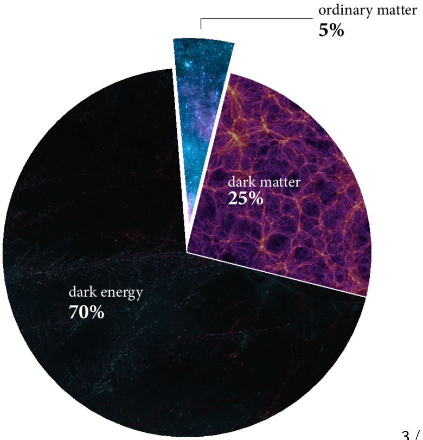
Overview

1. Current issues in Cosmology
2. The H_0 and S_8 tensions and Approaches to Resolve them
3. Addressing the H_0 and S_8 tensions in f(Q) cosmology
4. Conclusions

Current issues in Cosmology

ΛCDM model: Cosmological constant **Λ** + **C**old **D**ark **M**atter

- **Open Issues**: The Cosmological constant problem, origin and properties of dark energy and dark matter, exact mechanism for inflation, non-renormalizability of General Relativity, H_0 and S_8 tensions



The H_0 tension

- **Planck Collaboration**: Indirect measurements from the Cosmic Microwave Background (assuming the ΛCDM)
- **SH0ES Collaboration (R19)**: Direct measurements using Hubble Space Telescope observations of 70 long period Cepheids in the Large Magellanic Cloud.

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$H_0 = 67.27 \pm 0.6$ km/s/Mpc	$H_0 = 74.03 \pm 1.42$ km/s/Mpc

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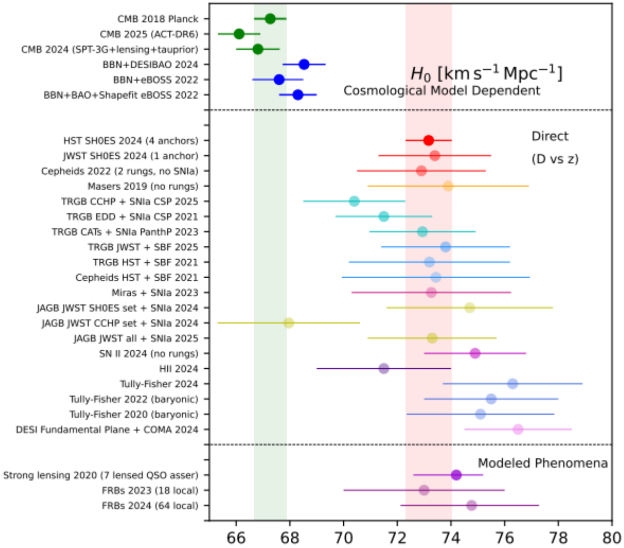
Currently in tension at $\sim 5\sigma$!

Hubble Parameter: $H \equiv \dot{a}/a$, a: the scale factor

The discrepancy in the Hubble constant measurements by early observations (CMB, assuming ΛCDM) and late time model-independent methods



CosmoVerse White Paper 2025

The S_8 tension

- The distribution of galaxies and matter in the late Universe's evolution, appears smoother than anticipated based on the evolution of fluctuations observed in the CMB.

Planck Collaboration	**LSS Surveys: KiDS-450, DES**
$S_8 = 0.834 \pm 0.016$	$S_8 = 0.745 \pm 0.039$ and $S_8 = 0.783^{+0.021}_{-0.025}$

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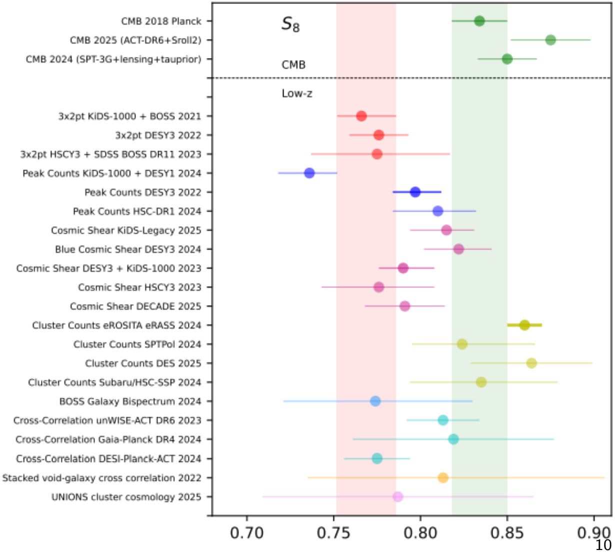
In tension at $\sim 2 - 3\sigma$!

$S_8 = \sigma_8(\Omega_{m0}/0.3)^{0.5}$: amplitude of matter clustering
σ_8: root mean square of the amplitude of matter perturbations flattened over $8h^{-1}$ Mpc
h: Hubble constant in units of 100 km/s/Mpc

The S_8 tension

The discrepancy in the S_8 measurements by early and late Universe observations

CosmoVerse White Paper 2025



Approaches for Addressing the H_0 and S_8 tensions

Extensions/
modifications of the
concordance cosmology

Alter the universe
content and interactions
GR:
gravitational theory

Modify gravity,
GR: as particular limit

f(Q) gravity

The total action of the theory is

$$S = -\frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}f(Q) \tag{1}$$

- $Q = -\frac{1}{4}Q_{\alpha\beta\gamma}Q^{\alpha\beta\gamma} + \frac{1}{2}Q_{\alpha\beta\gamma}Q^{\gamma\beta\alpha} + \frac{1}{4}Q_\alpha Q^\alpha - \frac{1}{2}Q_\alpha\tilde{Q}^\alpha$
- where $Q_\alpha \equiv Q_\alpha{}^\mu{}_\mu$, and $\tilde{Q}^\alpha \equiv Q_\mu{}^{\mu\alpha}$ are contractions of the non-metricity tensor: $Q_{\alpha\mu\nu} \equiv \nabla_\alpha g_{\mu\nu}$

(STEGR recovered: $f = Q/8\pi G$)

J. Beltrán Jiménez et al, Phys. Rev. D 101 (2020) no.10, 103507, arXiv:1906.10027

f(Q) Cosmology

We consider an expanding Universe, described by a flat homogeneous and isotropic Friedmann-Lemaitre-Robertson-Walker (FLRW) geometry and given the field equations we obtain the modified Friedmann equations:

$$6f_Q H^2 - \frac{1}{2}f = \rho_m \quad (2)$$

$$\left(12H^2 f_{QQ} + f_Q\right)\dot{H} = -\frac{1}{2}(\rho_m + p_m) \quad (3)$$

where: $Q = 6H^2$, $H \equiv \dot{a}/a$.

For $f(Q) = Q - 2\Lambda$, we recover ΛCDM

f(Q) Cosmology

At the perturbation level for a general f(Q) form we obtain

$$\delta'' + \mathcal{H}\delta' = \frac{4\pi G \rho_m}{f_Q}\delta \quad (4)$$

where

$\delta = \delta\rho_m/\rho_m$: matter overdensity
$\mathcal{H} = a'/a = aH$ and $f_Q = \partial f/\partial Q$

The effective Newton's constant is given by

$$G_{\rm eff} \equiv \frac{G}{f_Q} \quad (5)$$

Addressing H_0 and S_8 tensions

C. G. Boiza, M. Petronikolou, M. Bouhmadi-Lopez, E.N. Saridakis, arXiv:2505.18264

We explore the observational implications of 3 specific f(Q) forms

$$f_1(Q) = Q\exp\{(\lambda Q_0/Q)\} \tag{6}$$
$$f_2(Q) = Q + Q_0\exp\{(-\lambda Q_0/Q)\} \tag{7}$$
$$f_3(Q) = Q + \lambda Q_0[1 - \exp\{(-Q_0/Q)\}] \tag{8}$$

Setting $z = 0$, $(H = H_0)$, in the Friedmann eqs., the λ parameter for each model is given by:

- $\lambda = 0.5 + \mathcal{W}_0\left(-\frac{\Omega_{m0}}{2\sqrt{e}}\right)$
- $\lambda = 0.5 - \mathcal{W}_0\left[-\frac{\sqrt{e}}{2}(\Omega_{m0} - 1)\right]$
- $\lambda = \frac{e}{1+e}(1 - \Omega_{m0})$

where $\mathcal{W}_0$ is the principal branch of the Lambert function and Ω_{m0} the present matter density parameter

Data and Methodology

We perform likelihood analysis using Markov Chain Monte Carlo (MCMC)

Data sets:

- Combination I: Cosmic chronometers (CC), supernovae (SNIa) and Gamma-ray bursts (GRB), with $\boldsymbol{\theta} = \{H_0, \Omega_{m0}\}$
- Combination II: Baryon acoustic oscillations (BAO) and Redshift-space distortions (RSD), with $\boldsymbol{\theta} = \{\Omega_{m0}, S_8\}$
- Combination III: CC + SN + GRB + BAO + RSD (Full combination), with $\boldsymbol{\theta} = \{H_0, \Omega_{m0}, r_d, S_8\}$

where $r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$

Results: Combinations I (CC + SN + GRB) & II (BAO + RSD)

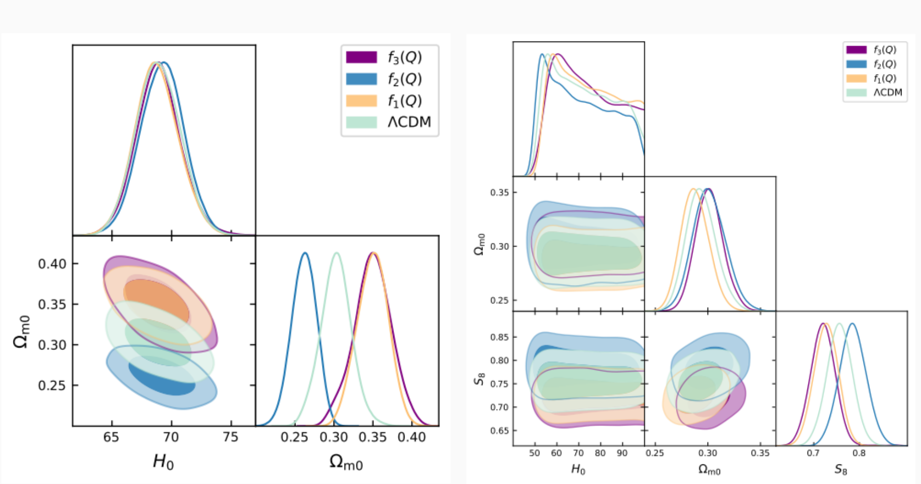


Figure: Two-dimensional posterior distributions for the f (Q) models and ΛCDM scenario. The contours correspond to the 68% and 95% confidence levels (C.L.) in the Ωm0 - H0 plane

Results: Combination III (CC + SN + GRB + BAO + RSD)

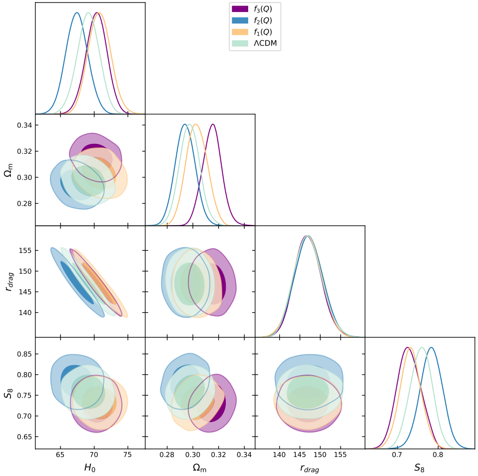


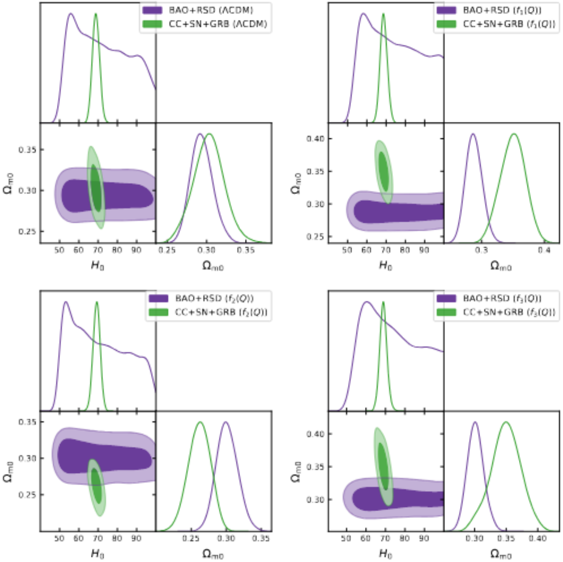
Figure: Two-dimensional posterior distributions for the f(Q) models and ΛCDM scenario, using Combination III (CC + SN + GRB + BAO + RSD). The contours correspond to the 68% and 95% confidence levels (C.L.).

Parameter Estimation

Model	H_0	Ω_{m0}	r_d	S_8	ΔAIC
		CC + SN + GRB			
$f_3(Q)$	68.91 ± 1.90	0.3495 ± 0.0241	–	–	-0.23
$f_2(Q)$	69.20 ± 1.84	0.2616 ± 0.0160	–	–	1.67
$f_1(Q)$	68.76 ± 1.85	0.3497 ± 0.0200	–	–	0.17
ΛCDM	68.89 ± 1.86	0.3027 ± 0.0198	–	–	–
		BAO + RSD			
$f_3(Q)$	–	0.3015 ± 0.0133	–	0.7206 ± 0.0285	2.63
$f_2(Q)$	–	0.3013 ± 0.0156	–	0.7856 ± 0.0294	0.51
$f_1(Q)$	–	0.2877 ± 0.0132	–	0.7270 ± 0.0263	2.30
ΛCDM	–	0.2937 ± 0.0142	–	0.7567 ± 0.0279	–
		CC + SN + GRB + BAO + RSD			
$f_3(Q)$	70.31 ± 1.71	0.3163 ± 0.0117	147.09 ± 3.49	0.7280 ± 0.0270	6.08
$f_2(Q)$	68.01 ± 1.67	0.2827 ± 0.0109	147.62 ± 3.46	0.7773 ± 0.0280	5.19
$f_1(Q)$	70.56 ± 1.69	0.3080 ± 0.0113	146.98 ± 3.43	0.7361 ± 0.0264	8.90
ΛCDM	69.15 ± 1.73	0.2958 ± 0.0115	147.33 ± 3.57	0.7580 ± 0.0271	–

$\mathrm{AIC} = -2 \ln L_{\mathrm{max}} + 2k$, where L_{max} is the maximum likelihood of the model
k is the number of free parameters

Combination I (CC + SN + GRB) and II (BAO + RSD)



Conclusions

- In this work, we explored f(Q) gravity, introducing late-time modifications that not only reproduce the observed cosmological behavior, but also show potential in alleviating the H_0 and S_8 tensions.

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- Key findings from dataset analysis:
  - Models 1 & 3 favor higher Ω_{m0} in background probes, H_0 increases when all datasets are combined.
  - Model 2 favors lower Ω_{m0}, shows suppressed growth and $G_{eff} < G$, potentially addressing S_8 tension.

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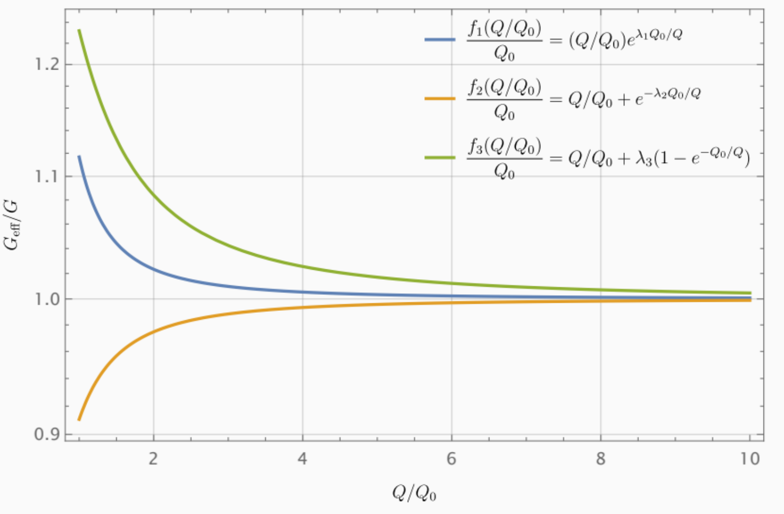
  - Model 2 favors lower Ω_{m0}, shows suppressed growth and $G_{eff} < G$, potentially addressing S_8 tension.
- Future work: Incorporate additional probes (e.g. CMB) and explore more flexible $f(Q)$ functional forms.

Thank you for your attention!

Appendix

Evolution of *Geff* / *G*



AIC (Akaike Information Criterion)

Interpretation of AIC values based on Jeffreys' scale.

ΔAIC	Interpretation
> 10	Desively disfavoured
$5 \sim 10$	Strongly disfavoured
$2 \sim 5$	Moderately disfavoured
$-2 \sim 2$	Compatible
$-5 \sim -2$	Moderately favoured
$-10 \sim -5$	Strongly favoured
< -10	Decisively favoured

Field Equations

$$\frac{2}{\sqrt{-g}}\nabla_\alpha\left\{\sqrt{-g}g_{\beta\nu}f_Q\left[-\frac{1}{2}L^{\alpha\mu\beta}+\frac{1}{4}g^{\mu\beta}\left(Q^\alpha-\tilde{Q}^\alpha\right)\right.\right.$$
$$\left.\left.-\frac{1}{8}\left(g^{\alpha\mu}Q^\beta+g^{\alpha\beta}Q^\mu\right)\right]\right\}$$
$$+f_Q\left[-\frac{1}{2}L^{\mu\alpha\beta}-\frac{1}{8}\left(g^{\mu\alpha}Q^\beta+g^{\mu\beta}Q^\alpha\right)\right.$$
$$\left.+\frac{1}{4}g^{\alpha\beta}\left(Q^\mu-\tilde{Q}^\mu\right)\right]Q_{\nu\alpha\beta}+\frac{1}{2}\delta^\mu_\nu f=T^\mu{}_\nu\,, \tag{9}$$

where
$L^\alpha{}_{\mu\nu}\equiv\frac{1}{2}Q^\alpha{}_{\mu\nu}-Q^\alpha{}_{(\mu\nu)}$ is the disformation tensor, and $T^\mu{}_\nu$ is the standard energy–momentum tensor.