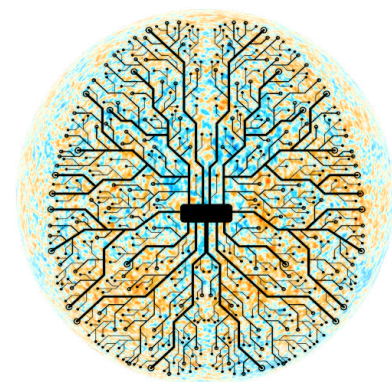


Alleviating the Hubble tension with Torsion Condensation (TorC)

Sinah Legner

[<sl2091@cam.ac.uk>](mailto:sl2091@cam.ac.uk)

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Kavli Institute for Cosmology, Madingley Road, Cambridge CB3 0HA, UK



UNIVERSITY OF
CAMBRIDGE

Cavendish Laboratory
Department of Physics



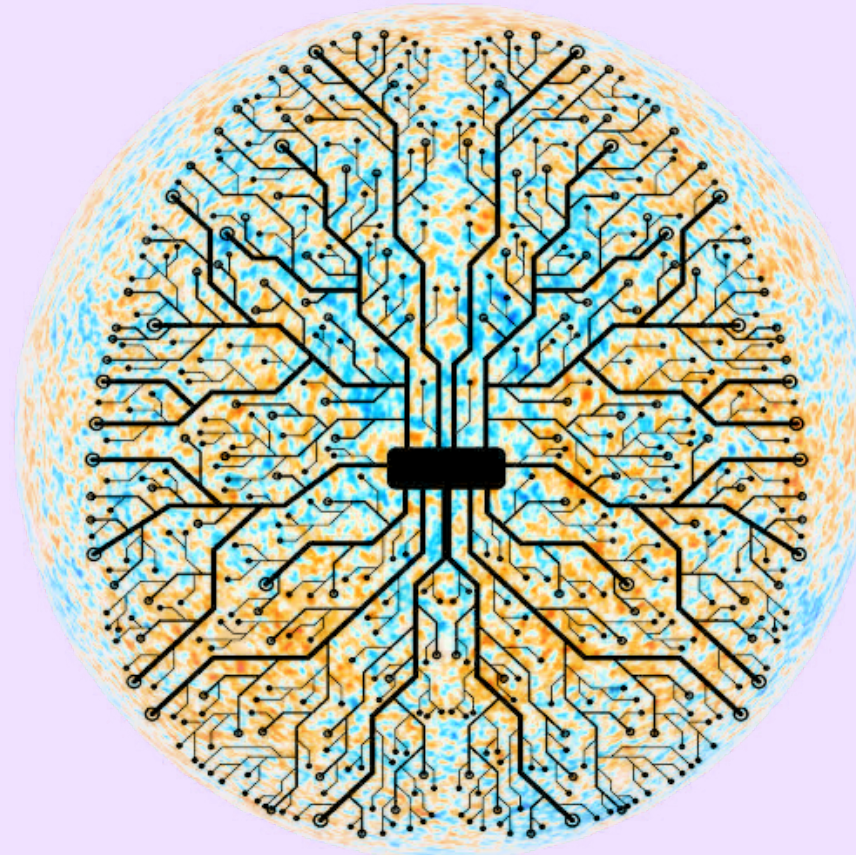
Who am I ?



Sinah Legner

- PhD student
- Astrophysics group, Cavendish Laboratory
- Supervisors: Will Handley, Will Barker

Handley lab



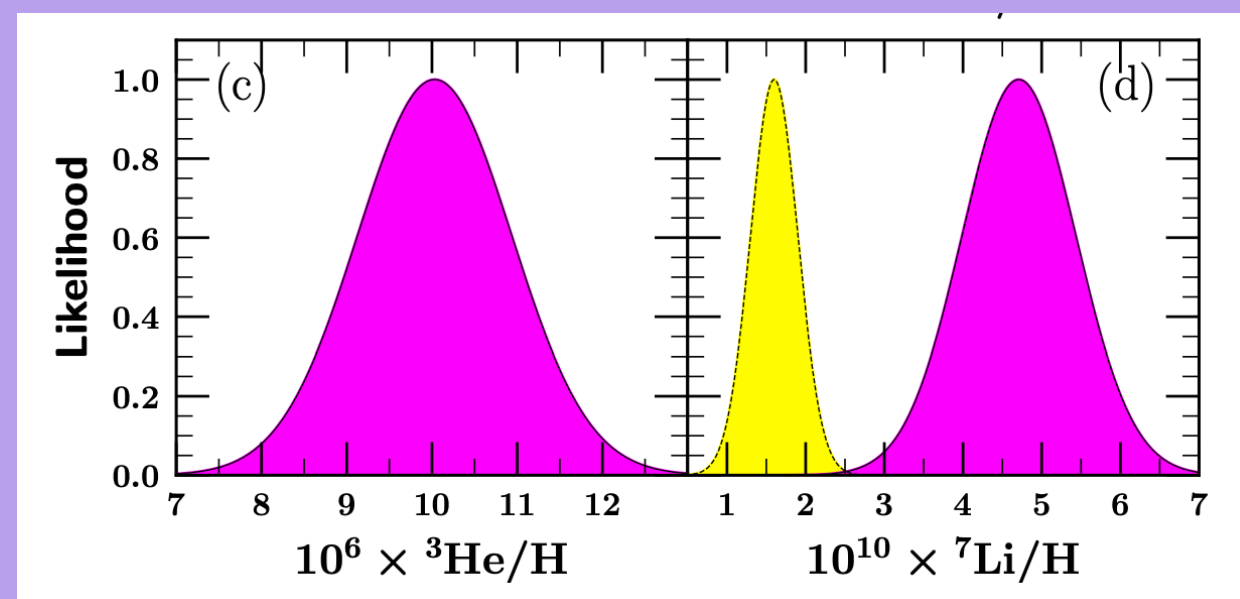
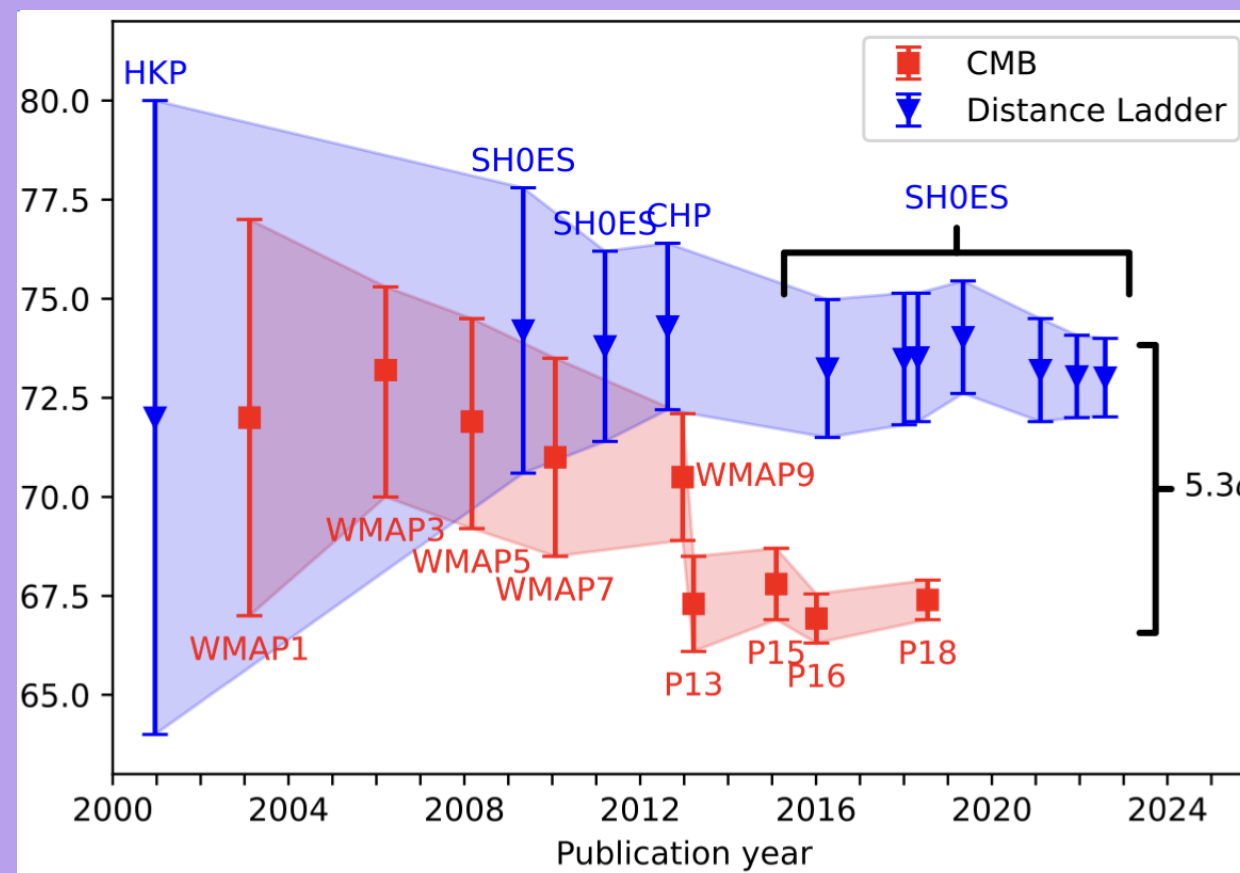
handley-lab.co.uk

- Exploring the Universe using tools from **Bayesian statistics, AI, and Machine Learning.**
- **Research Area:**
 - Early Universe & Inflation
 - Dark Energy & Dark Matter
 - 21-cm Cosmology & the Epoch of Reionisation
 - Gravitational Wave Astrophysics
- **Softwares:** PolyChord, anesthetic, margarine, GLOBALEMU, maxsmooth, fgivenx, and nestcheck



Alleviating the Hubble tension with TorC - Overview

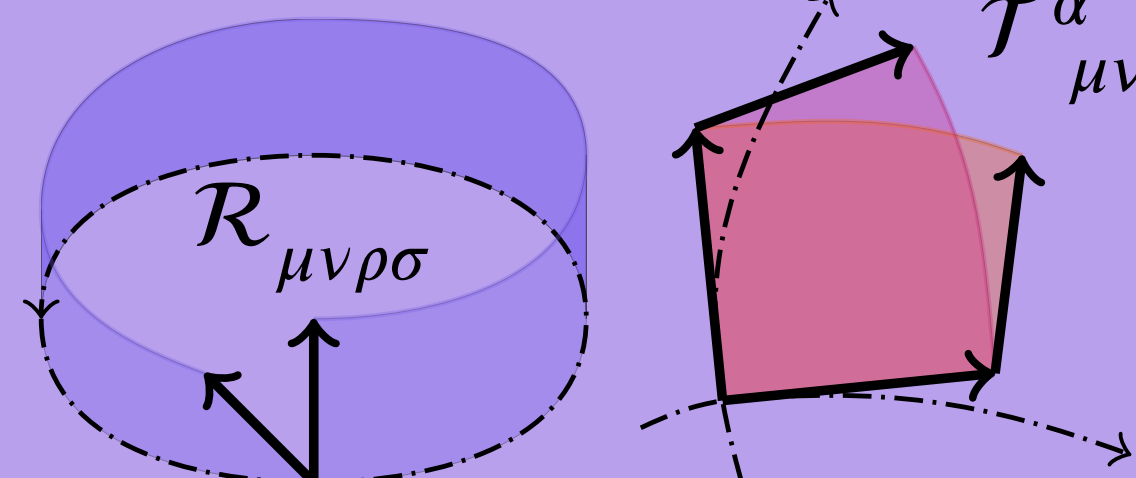
Cosmological Tensions



Exploration of different theory of gravity

Torsion Condensation (TorC)

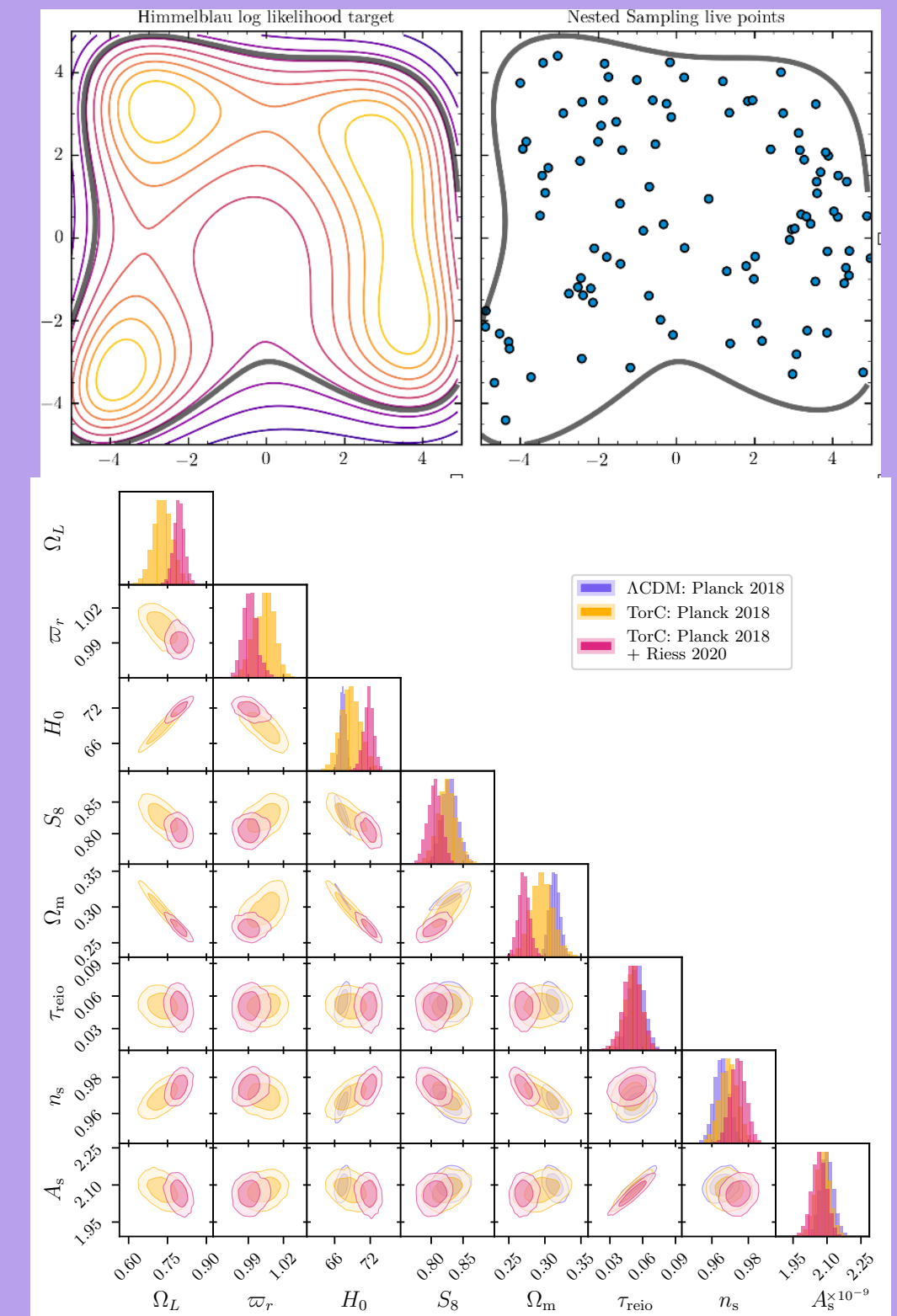
$$\mathcal{L} \propto R^2 + T^2 \quad [2003.02690]$$



Motivates

Analysis

Constraining TorC parameters



Alleviate Tension?

ArXiv: 2507.09228

Comparison with ΛCDM

Tension in Cosmology - Hubble Tension

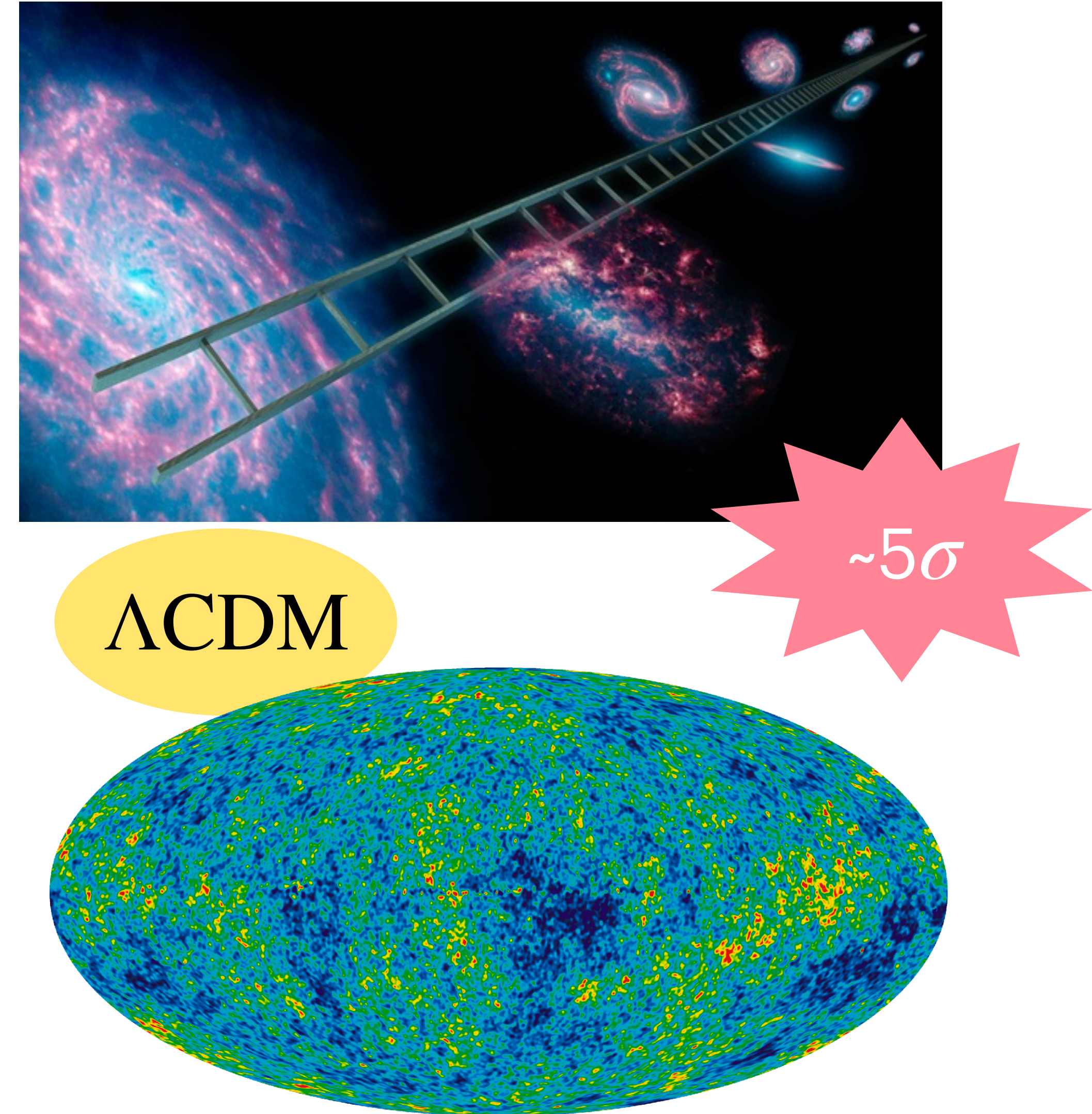
H_0 : Characterises Universe's expansion today.

SH0ES(Cosmic Distance Ladder):

- $H_0 = 73.2 \pm 1.3$ km/s/Mpc. [[2112.04510](#)]
- Determined using Supernovae observations
- Challenges: Crowding, dust, metallicity, and calibration issues

Cosmic Microwave Background (CMB):

- $H_0 = 67.4 \pm 0.5$ km/s/Mpc. [[1807.06209](#)]
- CMB fluctuation data, fitted with Λ CDM model
- Measurement trusted, but Λ CDM assumptions are debated
- Tension at 5σ



Tension in Cosmology - Hubble tension

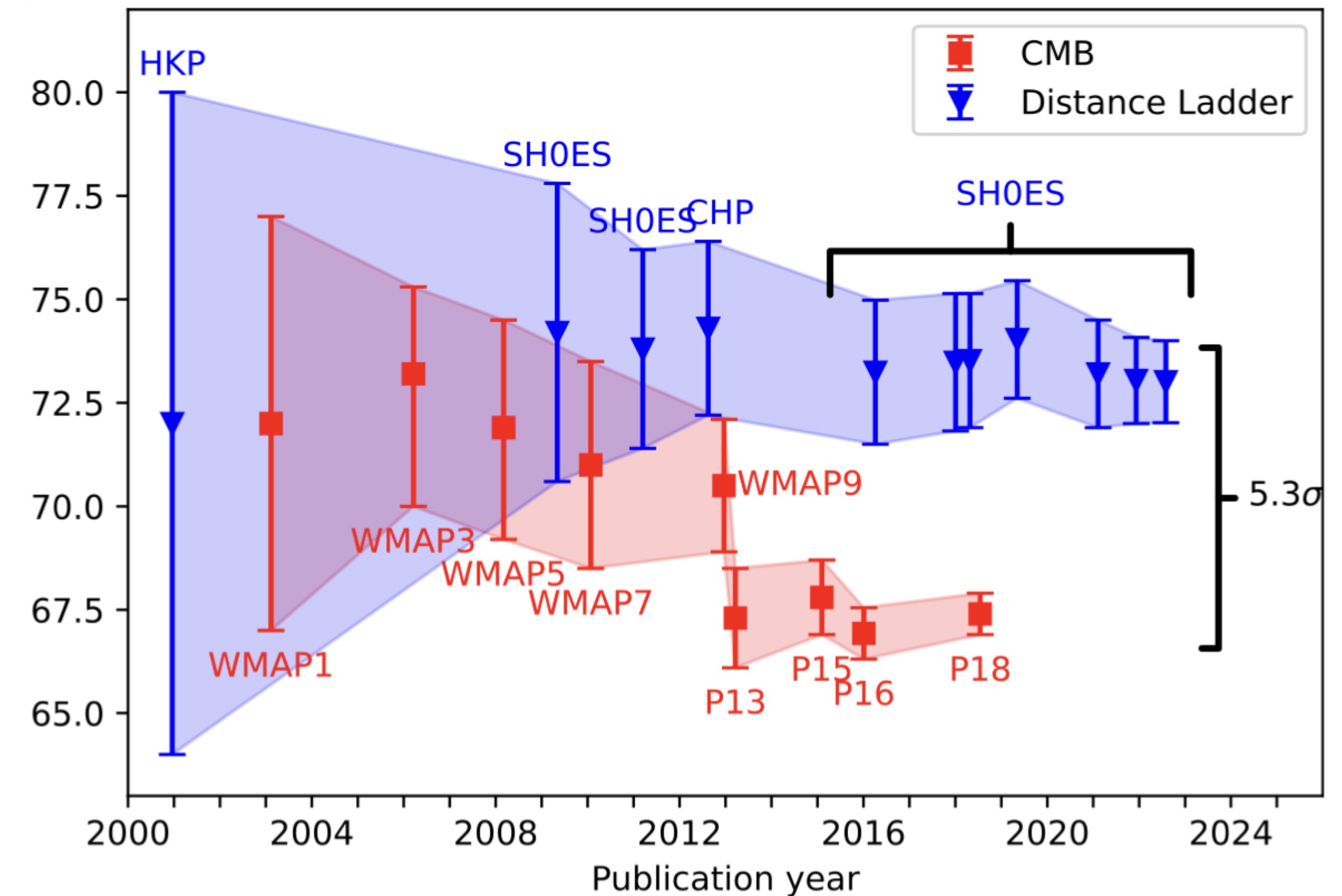
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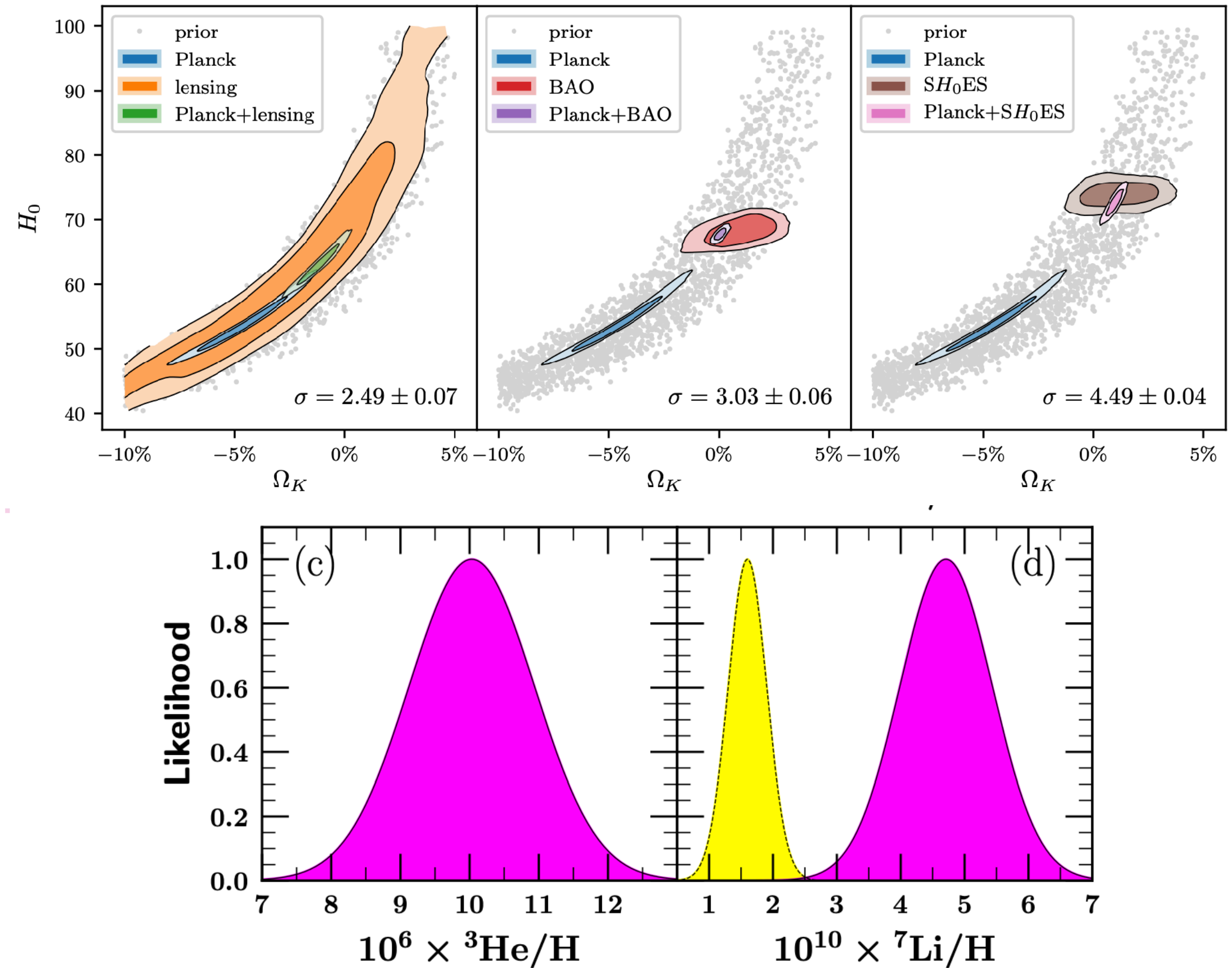
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Evolution of the Hubble tension in the last 23 years

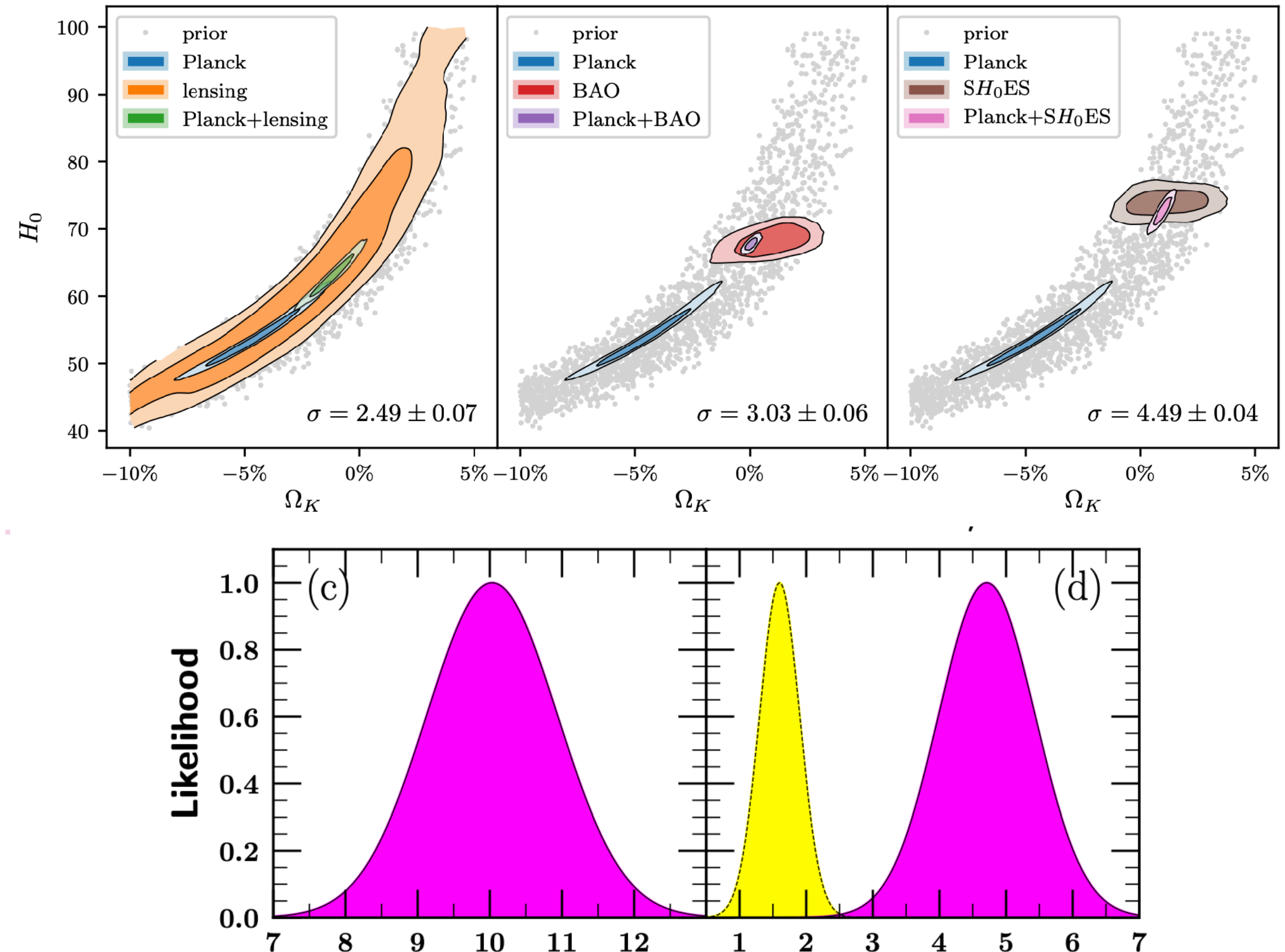
Tension in Cosmology - other tensions

- **Curvature Tension:** CMB data (Planck) prefers closed universe [[1908.09139](#)]
- **CMB hemispherical power asymmetry:** Challenging isotropy [[1510.07929](#)]
- **BBN:** Discrepancy in light element abundance, Lithium problem [[1912.01132](#)]



Tension in Cosmology - other tensions

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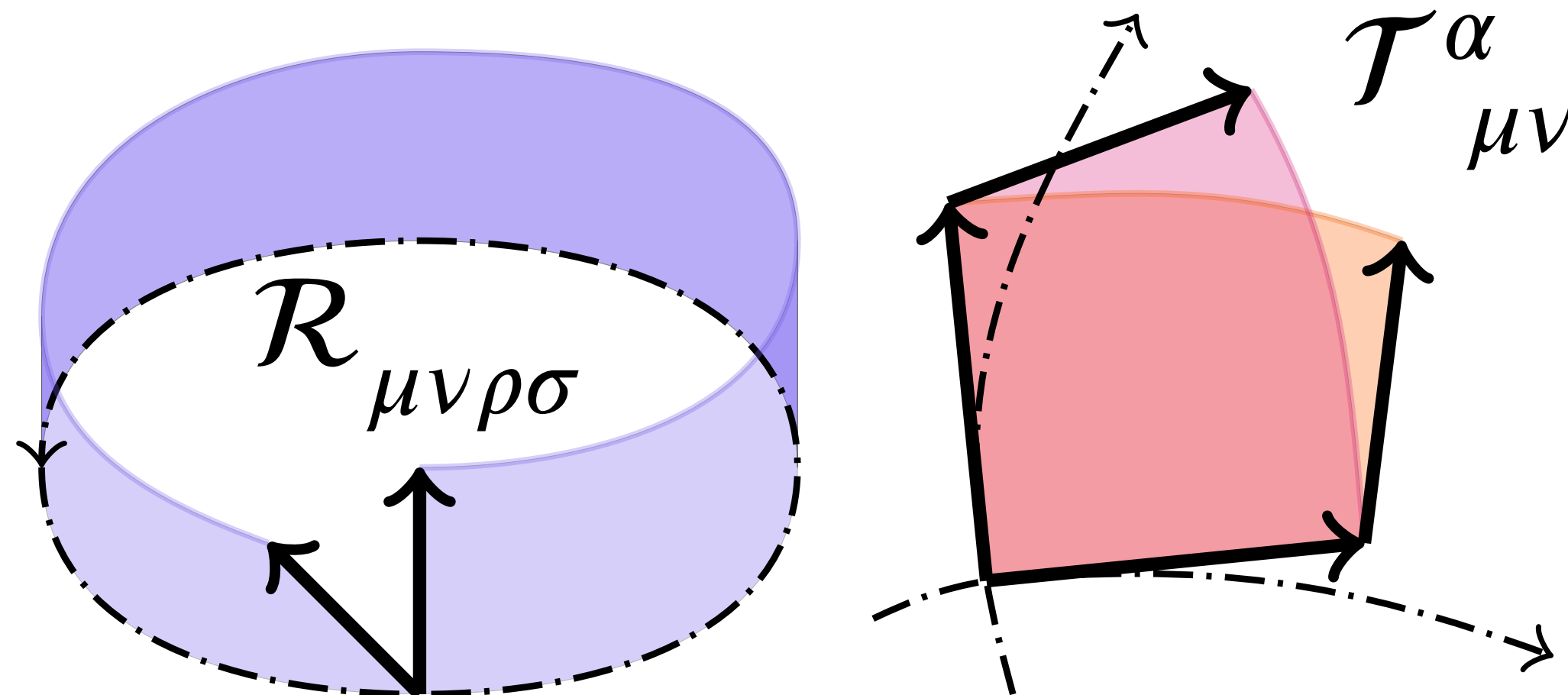


If not systematics — need new theory to replace Λ CDM

The Gauge Approach to Gravity: PGT

Poincaré group

- Four spacetime translation
- Lorentz group: Three spatial rotation and three Lorentz boosts



Poincaré gauge theory (PGT)

- Gauge fields correspond to translations and Lorentz rotations of the Poincaré group
- Lagrangian is constructed from field strengths, identified as **torsion** T and **curvature** R , up to quadratic order
- $\mathcal{L} \propto R + R^2 + T^2$

General Relativity (GR)

- $\mathcal{L} \propto R$ - **curvature** only

Torsion condensation: a case of PGT

Will Barker



450 critical cases of PGT
[1812.02675]

- Ghost-free
- Tachyon-free

58 cases [1910.14197]

- Power-counting renormalisable

★ **Torsion condensation:**

$$\mathcal{L} \propto R^2 + T^2$$

Under a homogeneous and isotropic background, torsion has a unique form:

$$T \propto \{\phi, \varpi\}$$

Properties of TorC:

- Ghost-free, Tachyon-free, Power-counting renormalisable
- Has a Einsteinian limit
- Screened from curvature
- Field equation shows ϕ can be expressed in terms of other fields



Under a homogeneous and isotropic background, torsion has a unique form:

$$T \propto \{\phi, \varpi\}$$

TorC can be mapped to a bi-scalar-tensor theory:

$$\mathcal{L} \propto F(\varpi) R + F(\partial\phi, \partial\varpi) - V(\phi, \varpi)$$

Flat FLRW background

$$ds^2 = -dt^2 + a^2(t)(dr^2 + r^2 d\Omega^2)$$

$$\Lambda\text{CDM: } H^2 = H_0^2 \left(\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_\Lambda \right)$$

$$\text{TorC: } H^2 = H_0^2 \frac{\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_L}{\varpi^2} - \frac{\dot{\varpi} \left(6H\varpi + \frac{(1+3\varpi^2)\dot{\varpi}}{\varpi^2 - 1} \right)}{3\varpi^2}$$

To evolve the system of cosmological equations, initial conditions of fields at early time is required: ϖ_i



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Free parameter

To evolve the system of cosmological equations, initial conditions of fields at early time is required: ϖ_i



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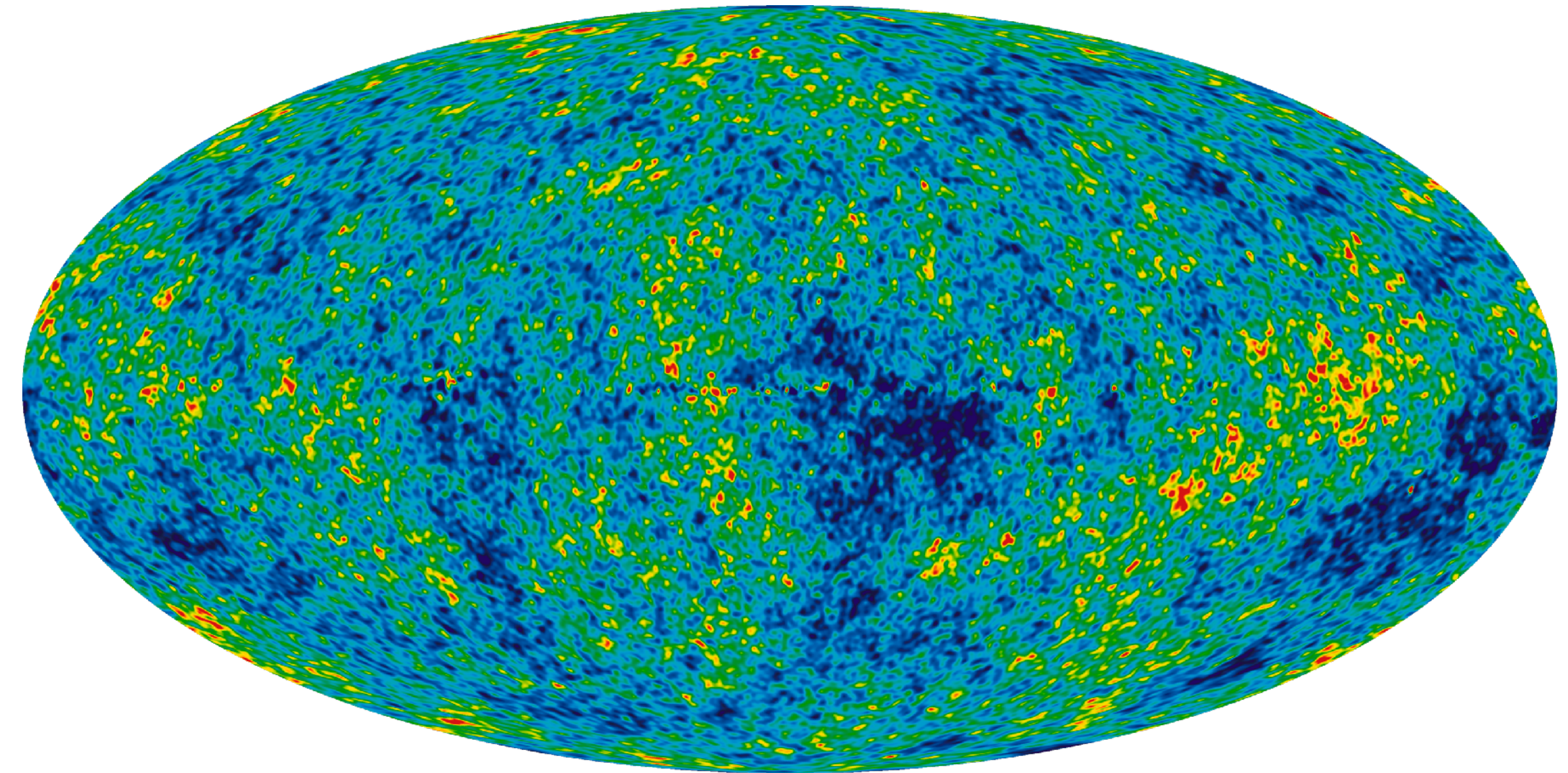
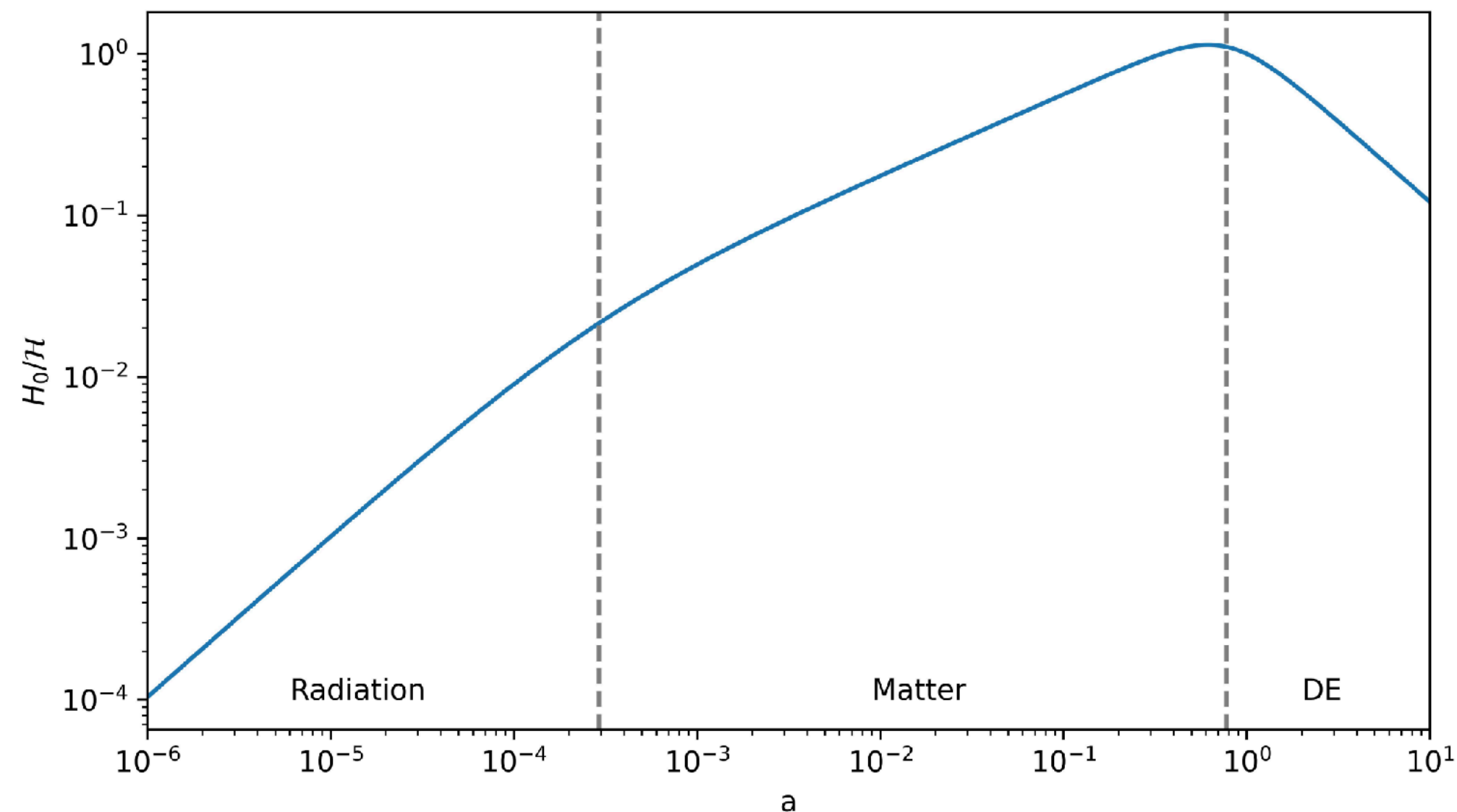
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Free parameter

To evolve the system of cosmological equations, initial conditions of fields at early time is required: ϖ_i

Free parameter

Λ CDM cosmology



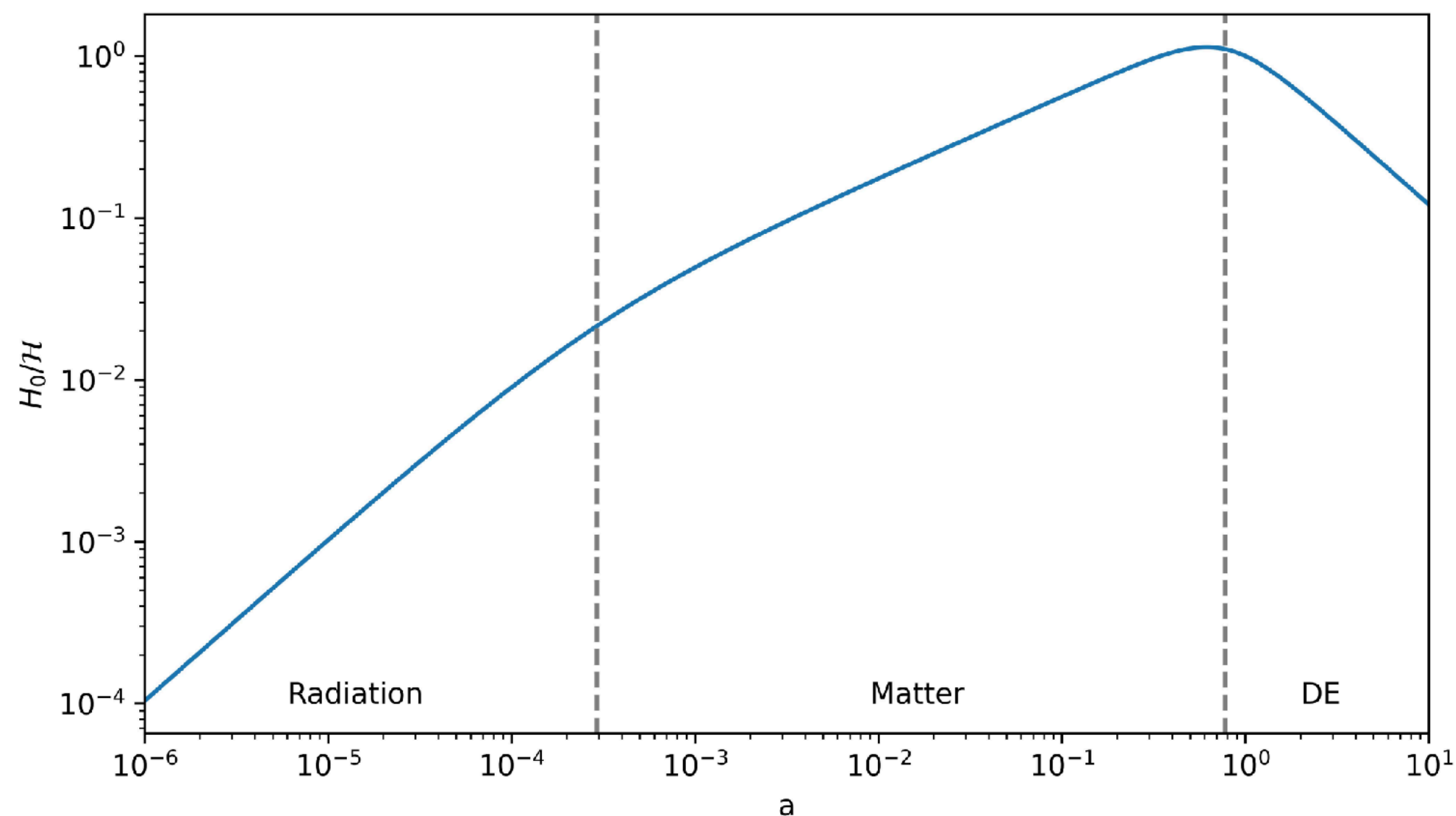
Hubble horizon

- $r_H = c/H$
- The dividing line between particles that move slower or faster than the speed of light

CMB power spectrum

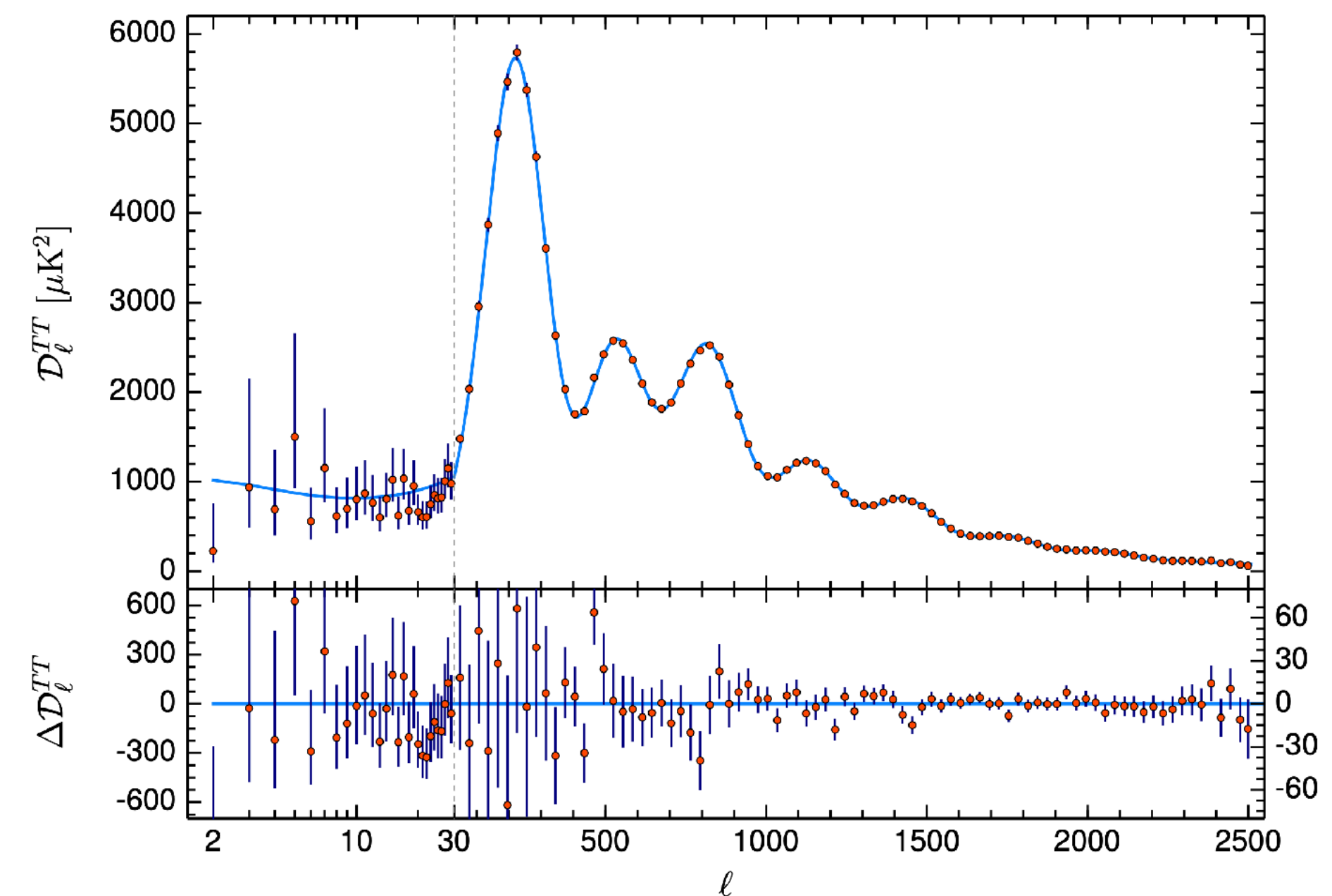
- Statistical property of temperature fluctuations of cosmic microwave background
- Contains a wealthy amount of information

Λ CDM cosmology



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TorC Cosmological Parameters

- H_0 - Hubble parameter today
- Ω_b - Density of baryonic matter
- Ω_c - Density of cold dark matter
- τ_{reio} - Optical depth due to reionisation
- n_s - Scalar spectral index
- A_s - Amplitude of the primordial scalar power spectrum

- ϖ_r - Initial value of the torsion scalar field ϖ
- Ω_L - Bare dark energy density parameter

Λ CDM parameters

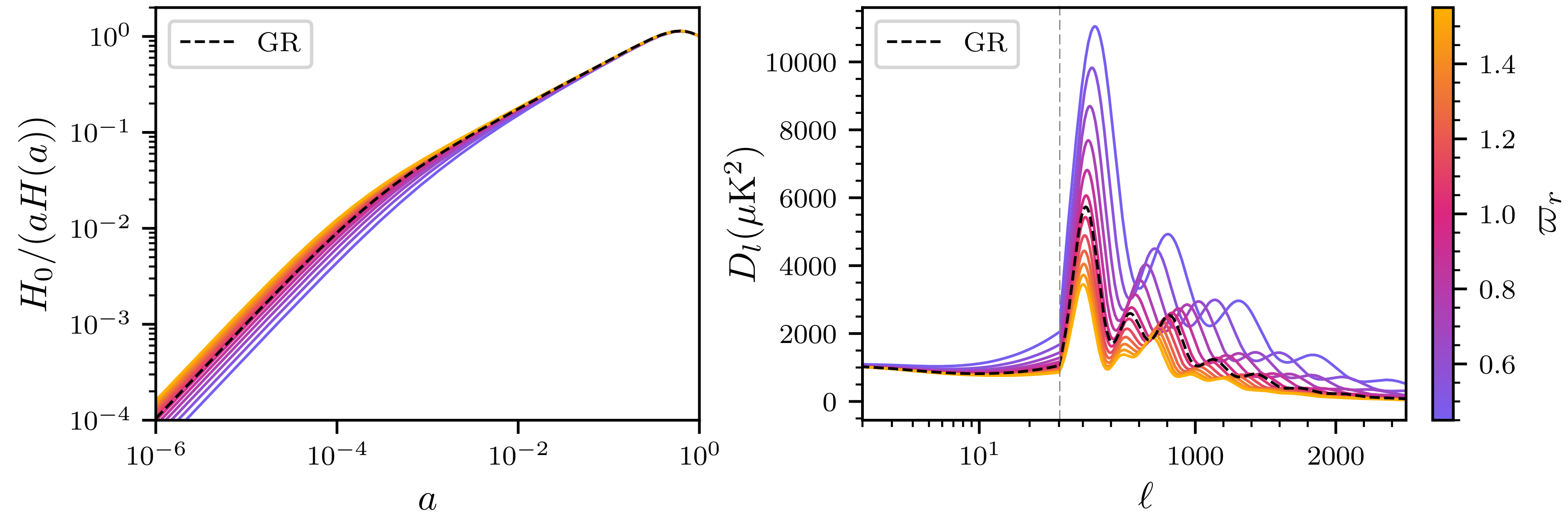
$$\begin{aligned}\varpi_r &\rightarrow 1 \\ \Omega_L &\rightarrow \Omega_\Lambda\end{aligned}$$

TorC parameters

How the New Parameters Affect Cosmology: ϖ_r

CAMB

- Boltzmann code for calculating CMB and other cosmological power spectra, given cosmological parameters.
- Modified to incorporate ϖ_r and Ω_L through effective dark energy density and pressure

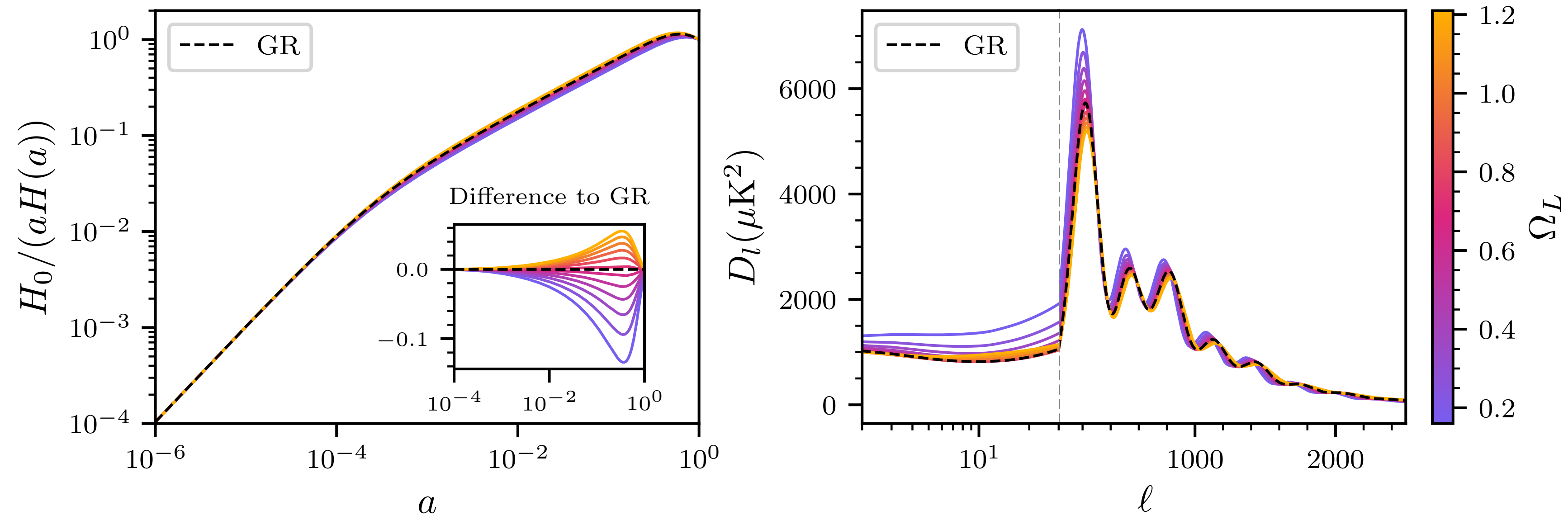


- Smaller ϖ_r reduces the Hubble horizon in early Universe
- Results in a reduced sound horizon at decoupling (first peak)
- Shift of acoustic peaks to higher multipoles ℓ and an increase in amplitude

How the New Parameters Affect Cosmology: Ω_L

CAMB

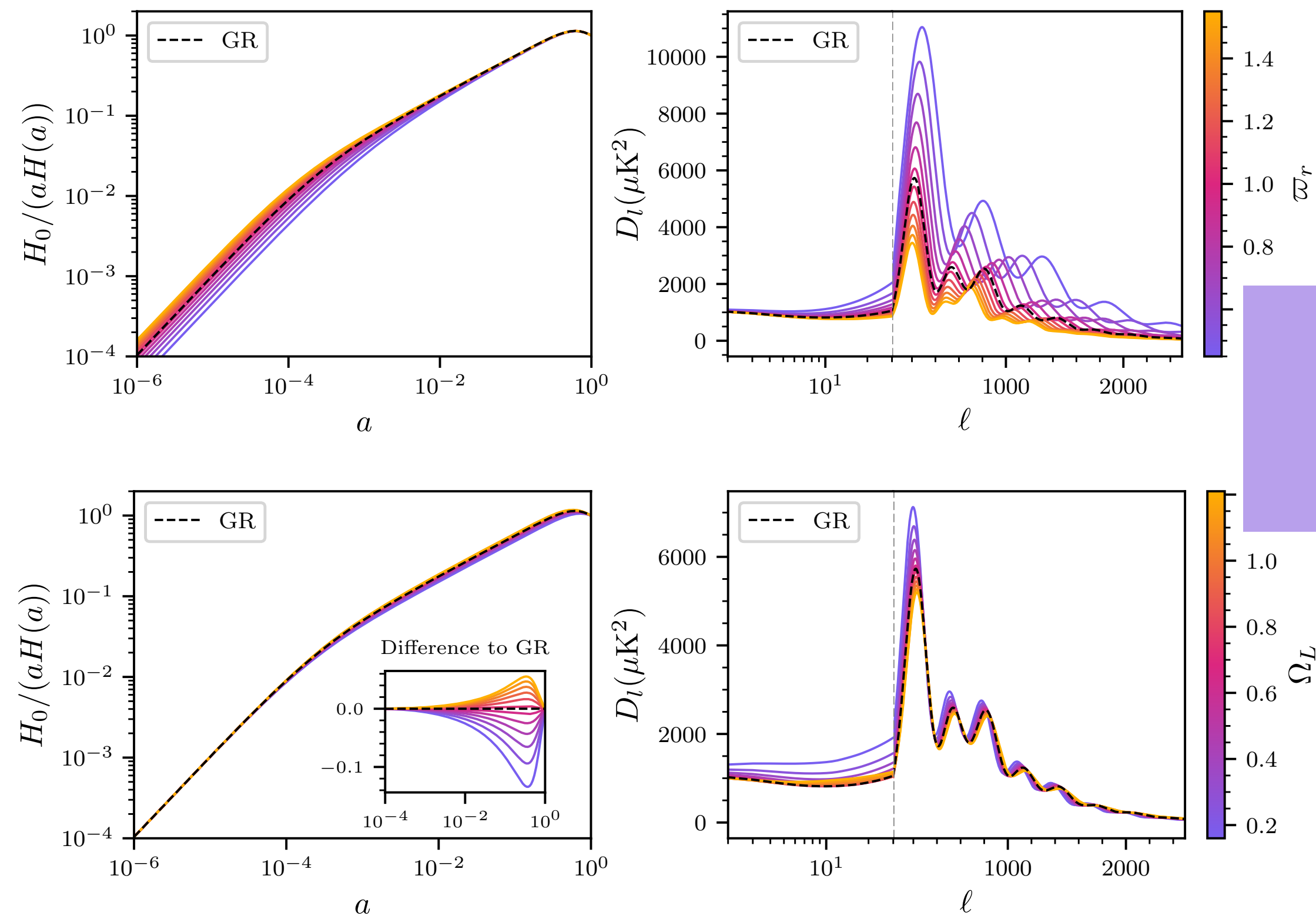
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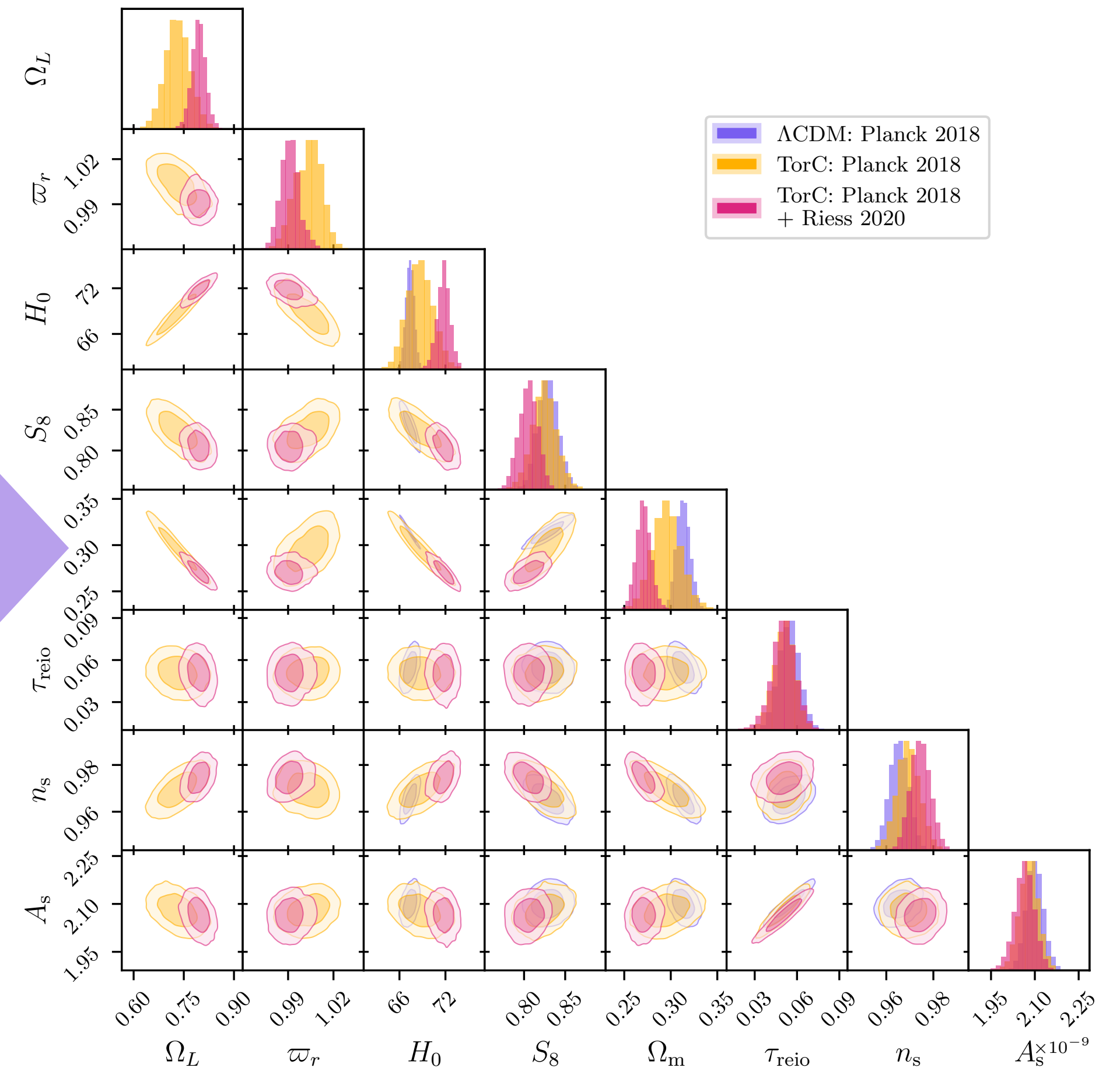
- Adjusting dark energy in this way is not possible in Λ CDM model
- Ω_L influences the late-time expansion, most significant in late-matter dominated epoch
- A lower Ω_L leads to reduction in both sound horizon and angular diameter distance to the last scattering surface

Method

We know what the parameter do to cosmology...



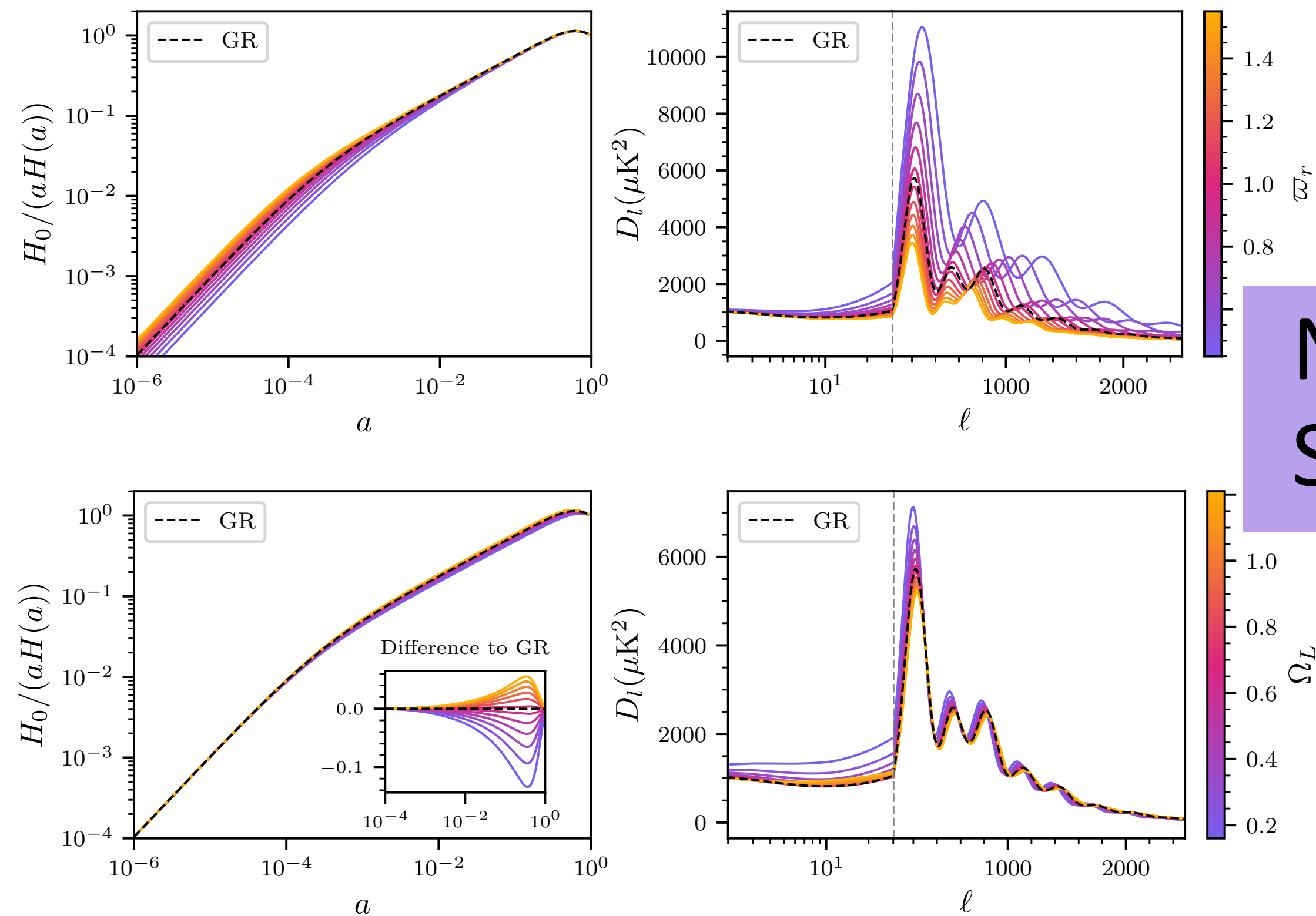
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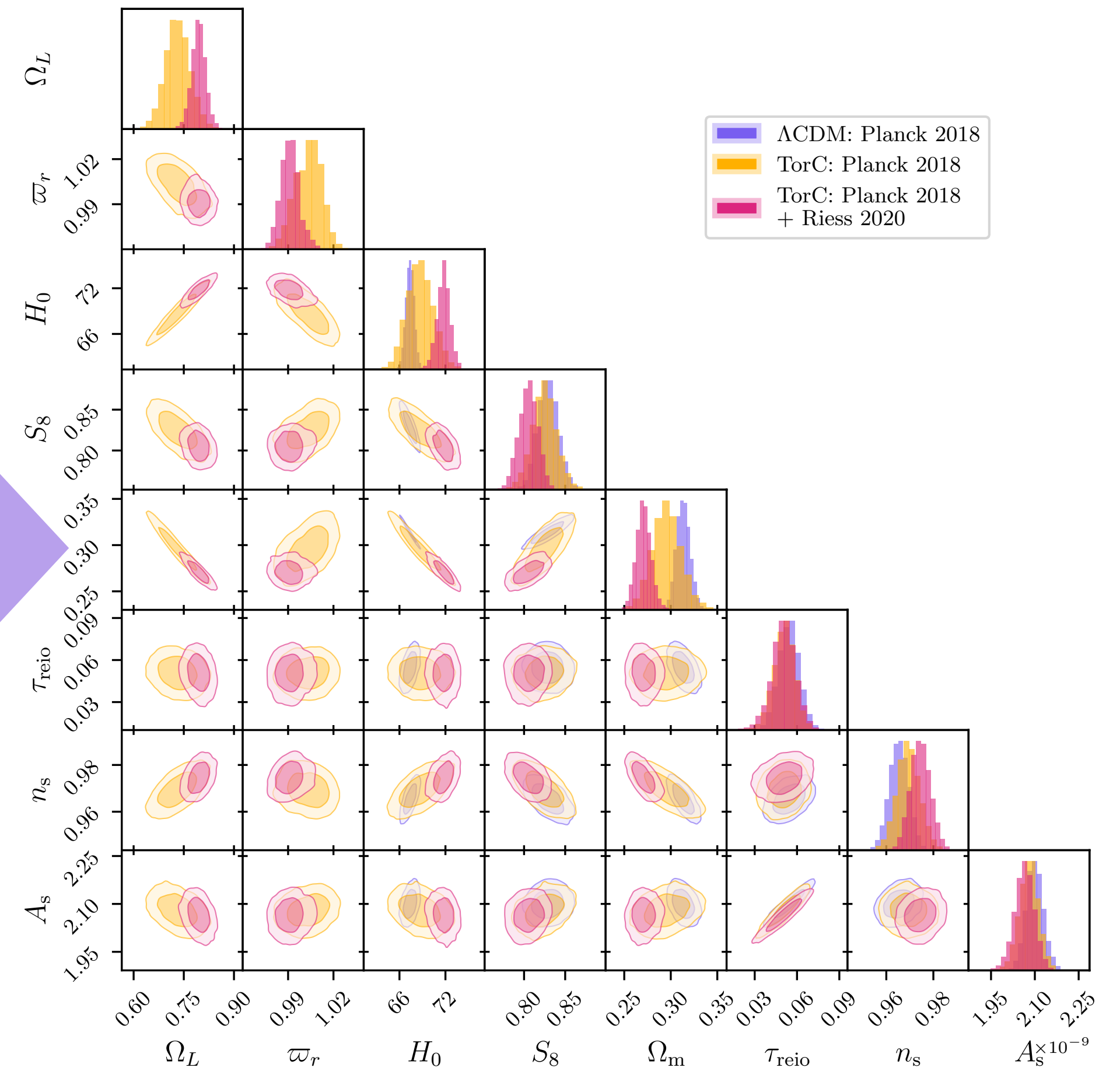
... but what does data tell us about the parameters?

Method

We know what the parameter do to cosmology...



Nested Sampling



... but what does data tell us about the parameters?

Bayesian Inference and Nested Sampling

Will Handley



Parameter Estimation:

- What does data tell us about parameters?

- $P(\theta | D, M) = \frac{P(D | \theta, M)P(\theta | M)}{P(D | M)}$
P - posterior
L - likelihood
 π - prior
Z - evidence

Model Comparison:

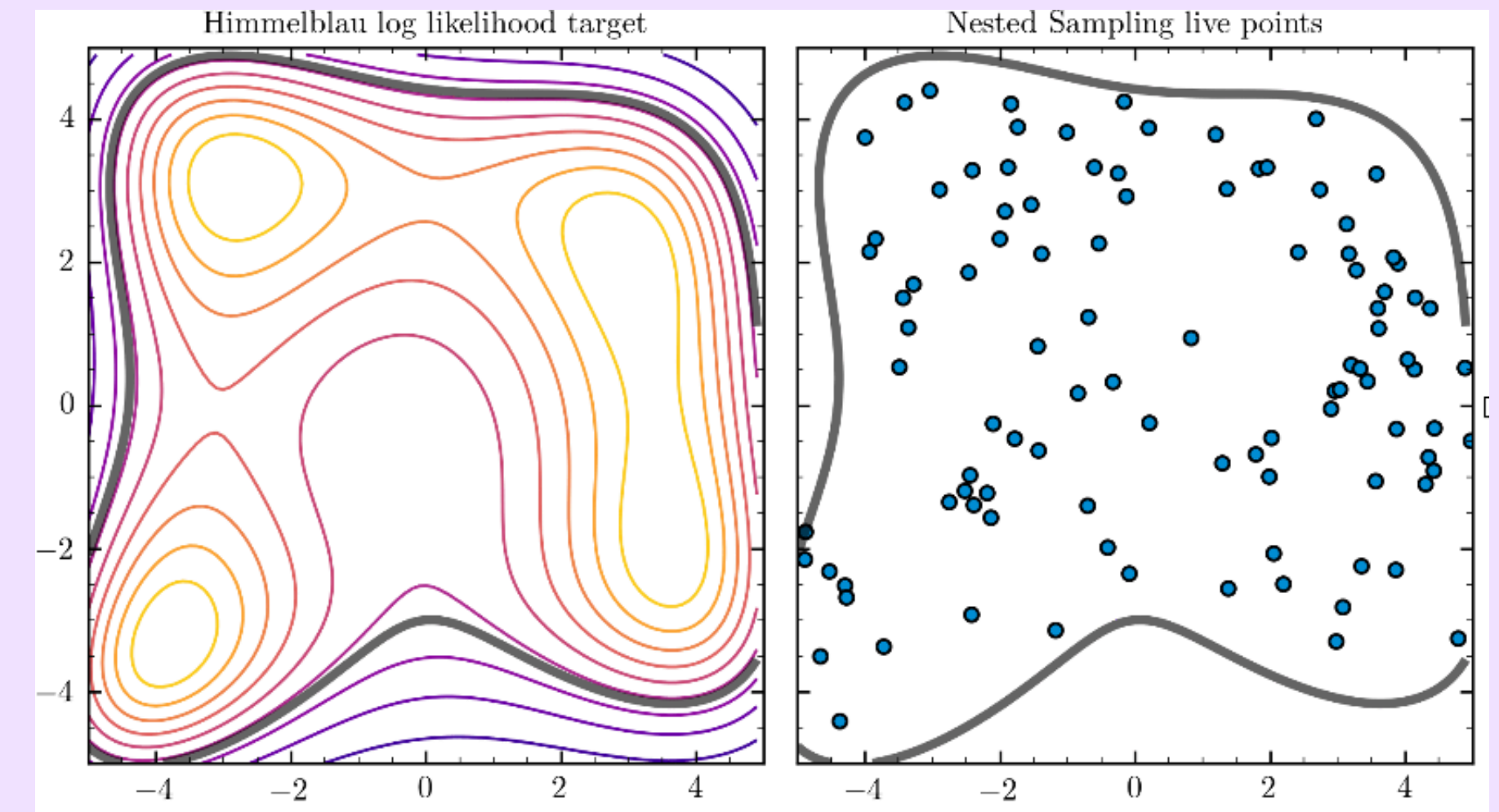
- How much does data support the model?

- $P(M | D) = \frac{P(D | M)P(M)}{P(D)}$

- Higher evidence favours a model
- Penalises complexity

Nested Sampling:

- Computes evidence directly
- Handles multimodal posteriors



Gif from David Yallup

- **Polychord**: nested sampling algorithm tailored for high-dimensional parameter spaces. [[1506.00171](#)]

Method: The Analysis Pipeline — Cobaya

Cobaya - code for **bayesian** analysis [[2005.05290](#)]

- A framework for sampling and statistical modelling, providing interfaces to cosmological theory codes and likelihoods from cosmological experiments.

Cobaya:

- Sets up cosmological model

likelihoods:

- Planck 2018
- SHOES 2020

CAMB:

- Computes CMB Power spectrum for each parameter set.

Polychord:

- Explore parameter space with nested sampling

Result:

- Posterior distribution for cosmological parameters
- Compare models through evidence (Z)

Method: Comparison Metrics

Bayesian Evidence

- Compare the overall viability of models
- Naturally incorporates '*Occam's razor*':

$$\log Z = \langle \log L(\theta) \rangle_P - D_{\text{KL}}$$

$\langle \log L(\theta) \rangle_P$ - how well the model fits the data, averaged over the posterior

D_{KL} - complexity penalty

- Given uniform prior for two models, they can be compared using Bayes factor

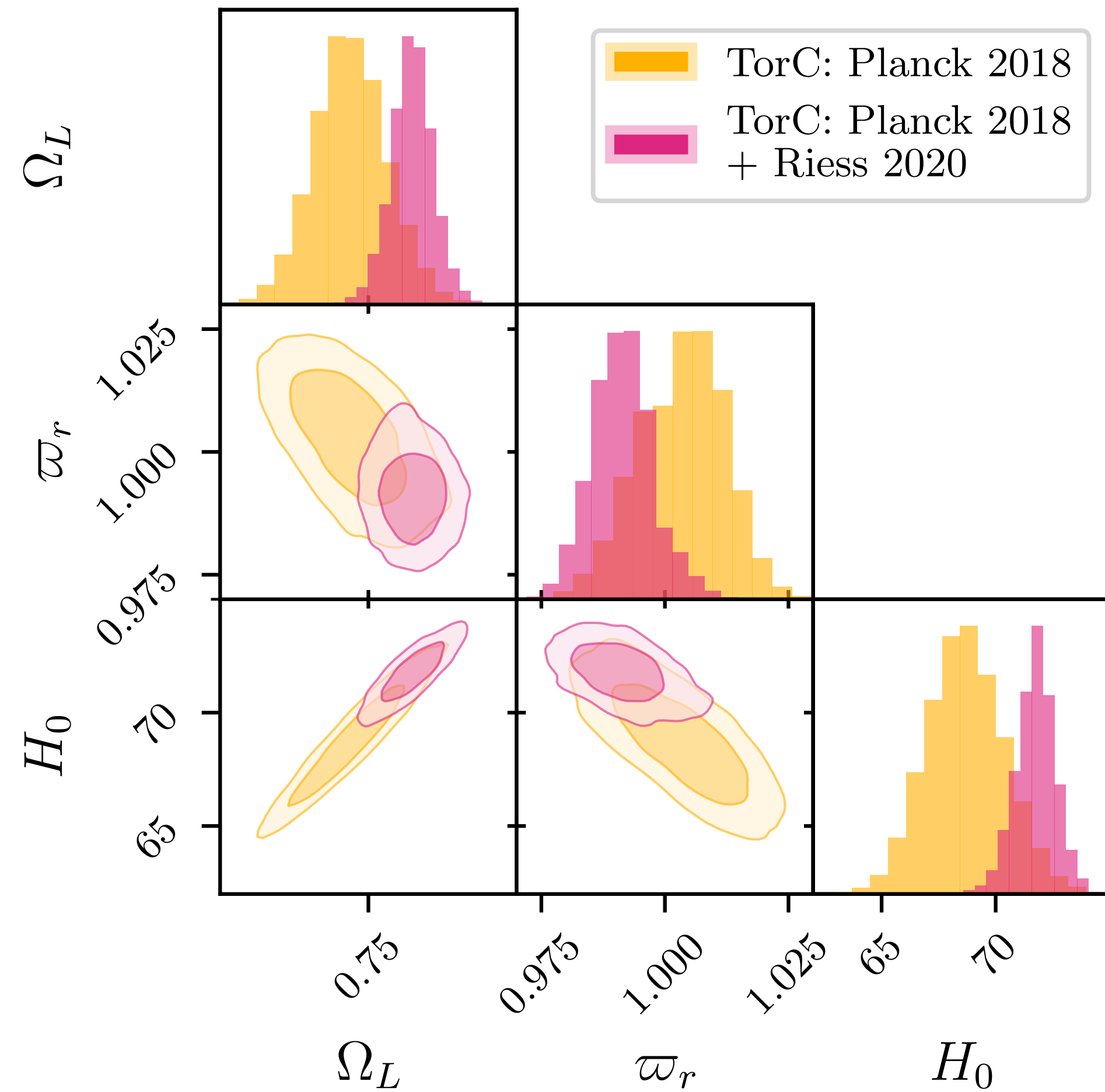
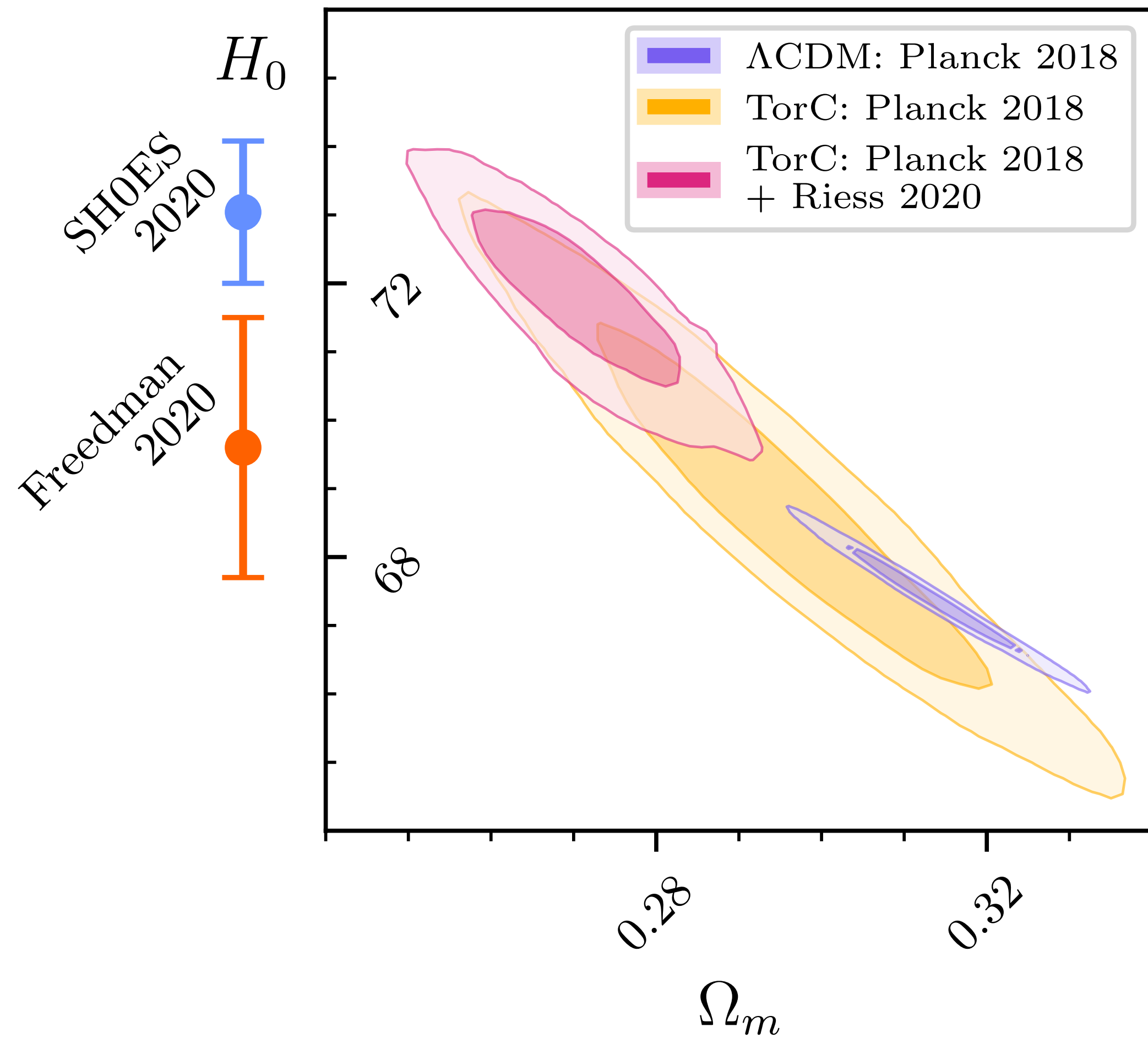
$$\begin{aligned} \Delta \log Z &= \log Z_1 - \log Z_2 \\ &= \Delta \langle \log L(\theta) \rangle_P - \Delta D_{\text{KL}} \end{aligned}$$

Tension Quantification

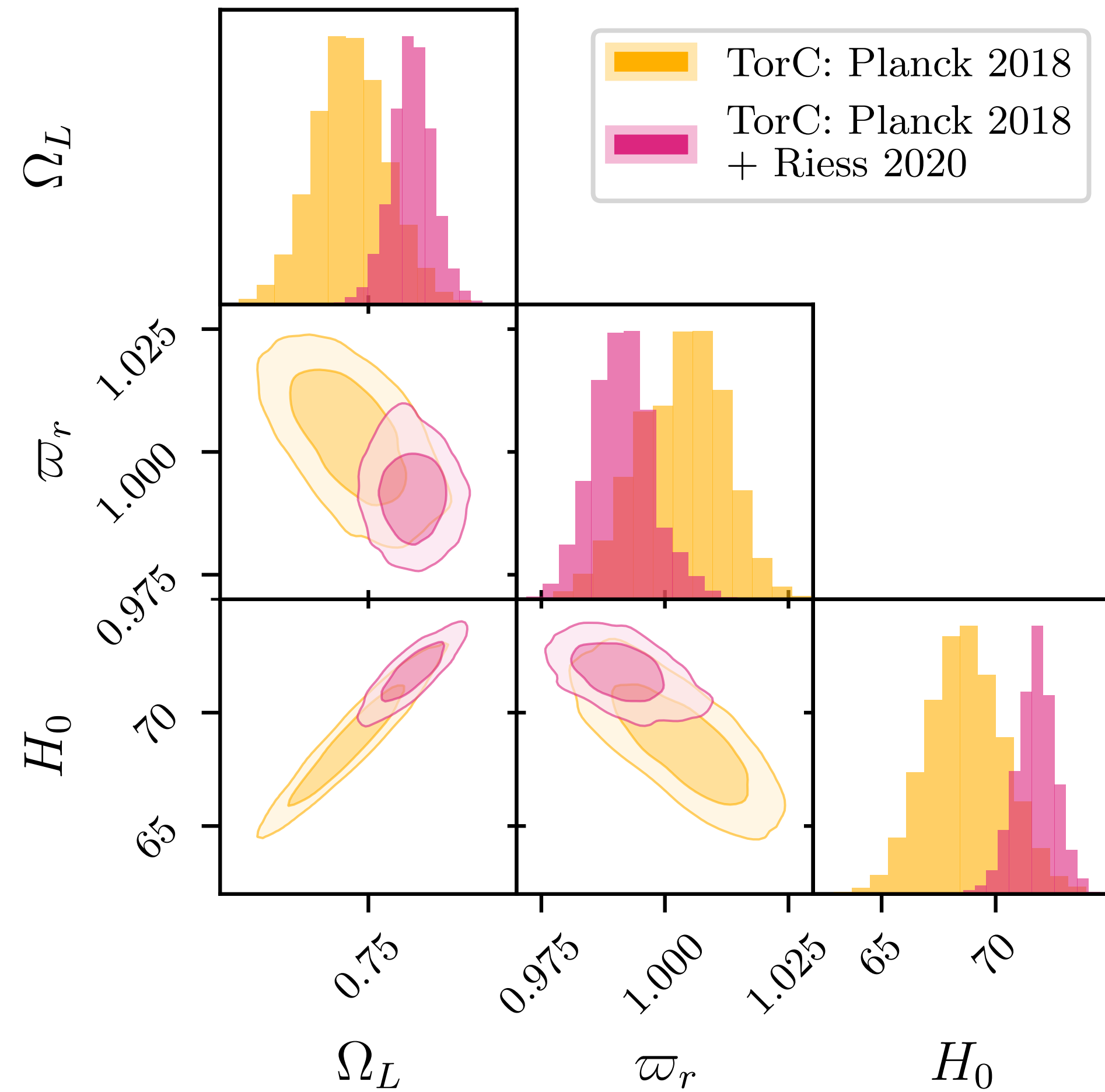
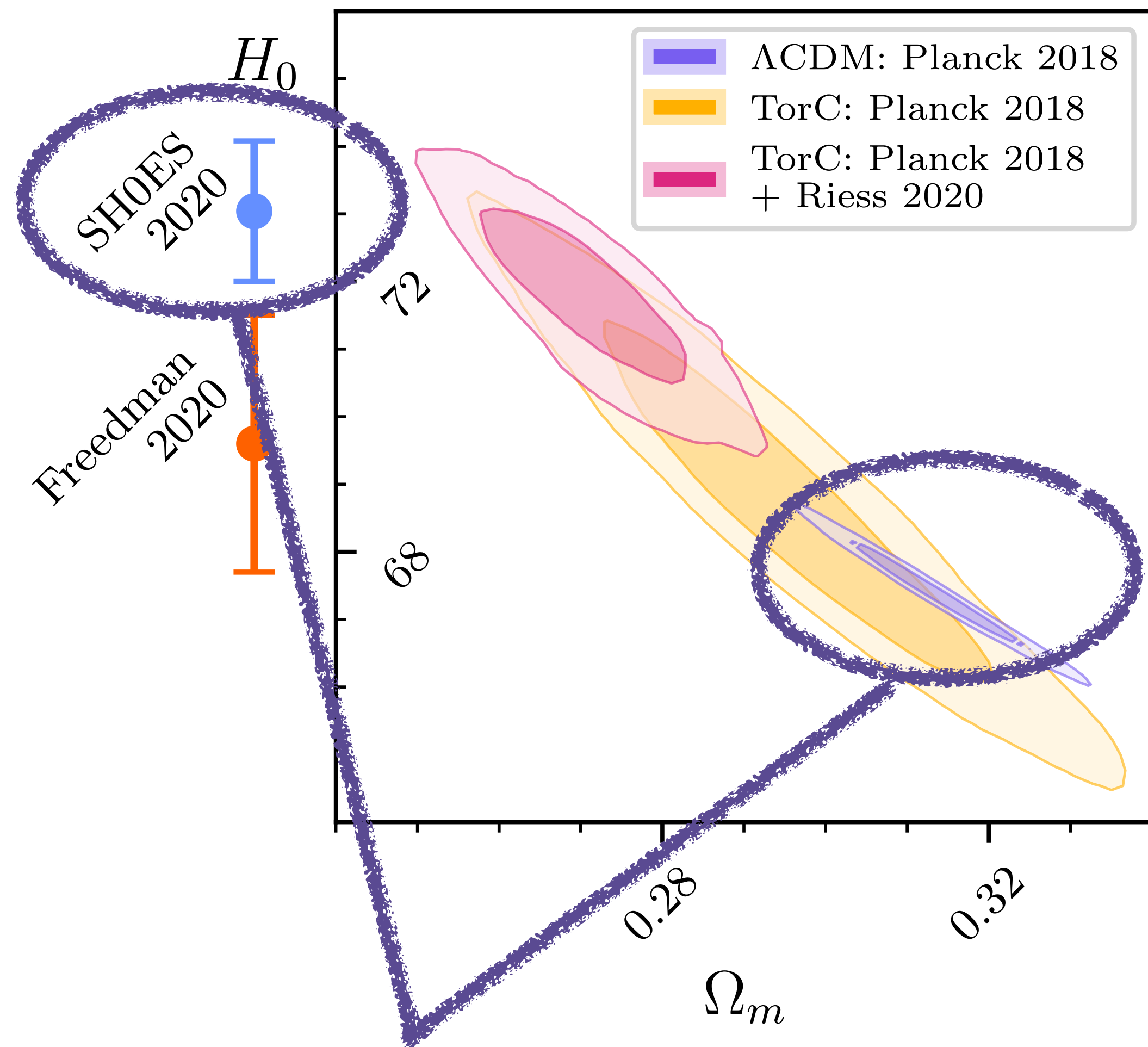
- Assess the level of agreement between two datasets. (e.g. Planck & SHOES)
- R-statistic: measures relative confidence in dataset A given dataset B, compared to its self-consistency.
 - $R \gg 1$: indicates that B strengthen confidence in A by a factor of R
 - $R \ll 1$: indicates tension
- For each model, given datasets A and B :

$$R = \frac{Z_{AB}}{Z_A Z_B} = \frac{P(A, B)}{P(A)P(B)} = \frac{P(A | B)}{P(A)} = \frac{P(B | A)}{P(B)}$$

The Main Result: Alleviating the Hubble Tension

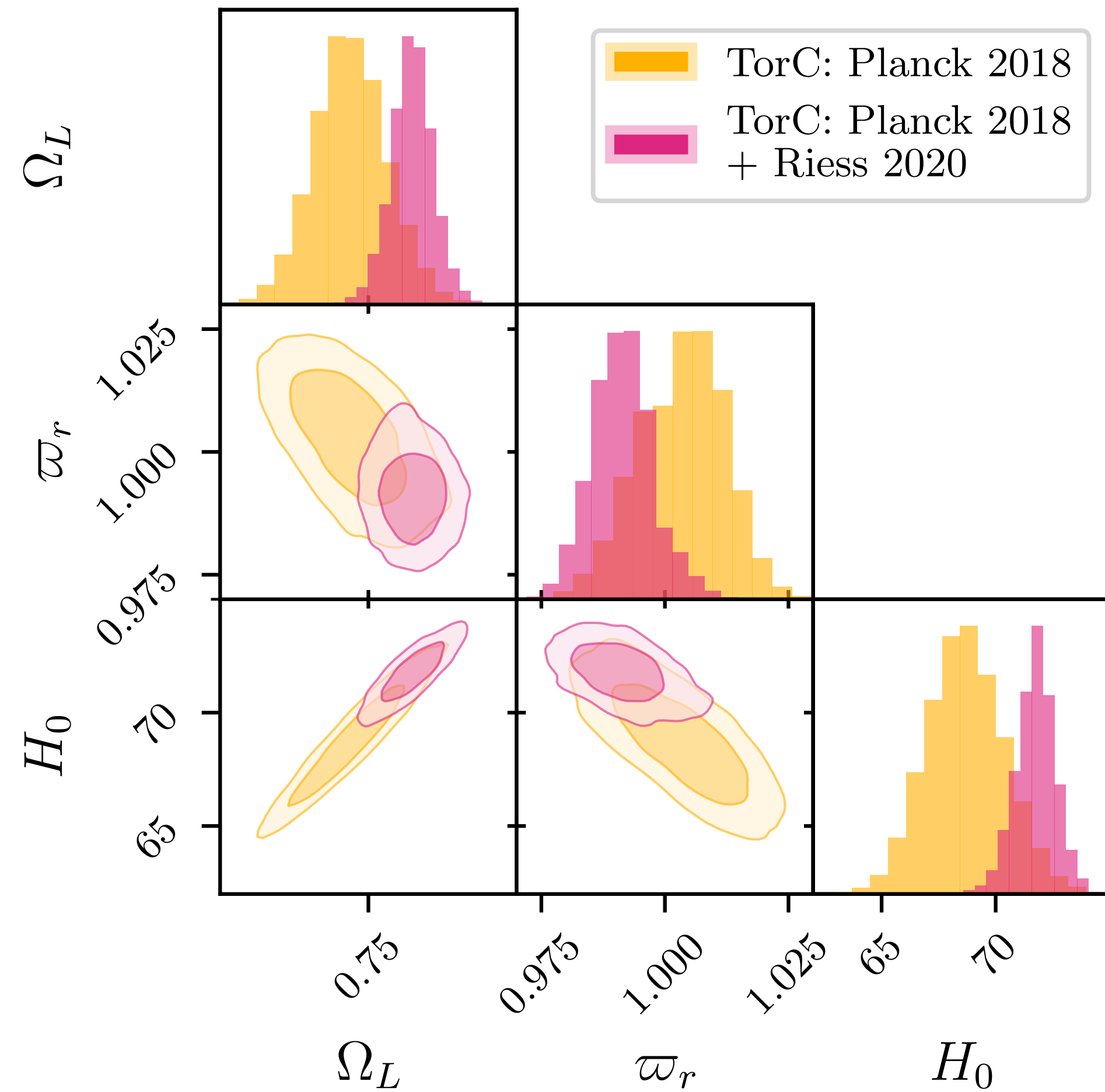
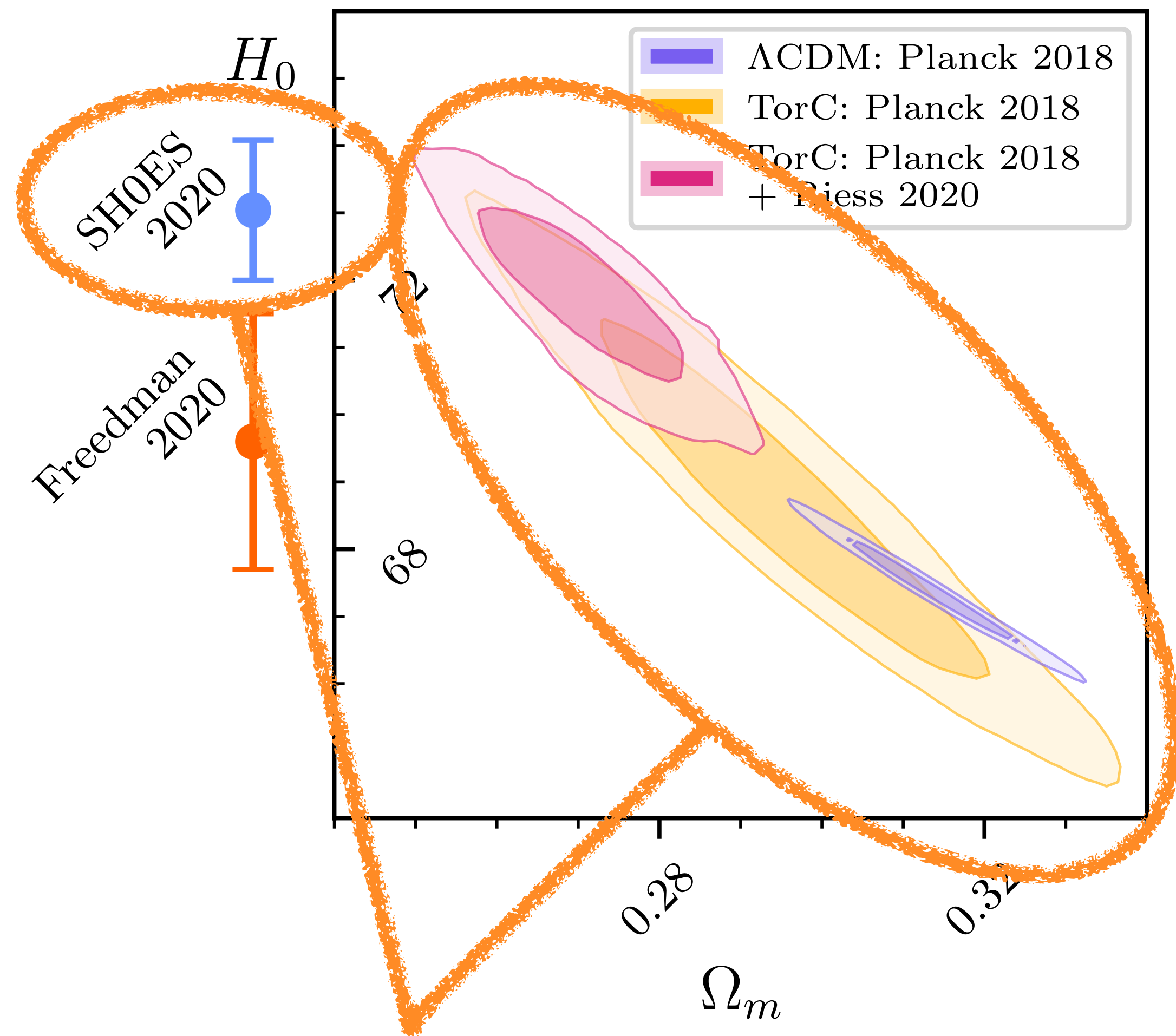


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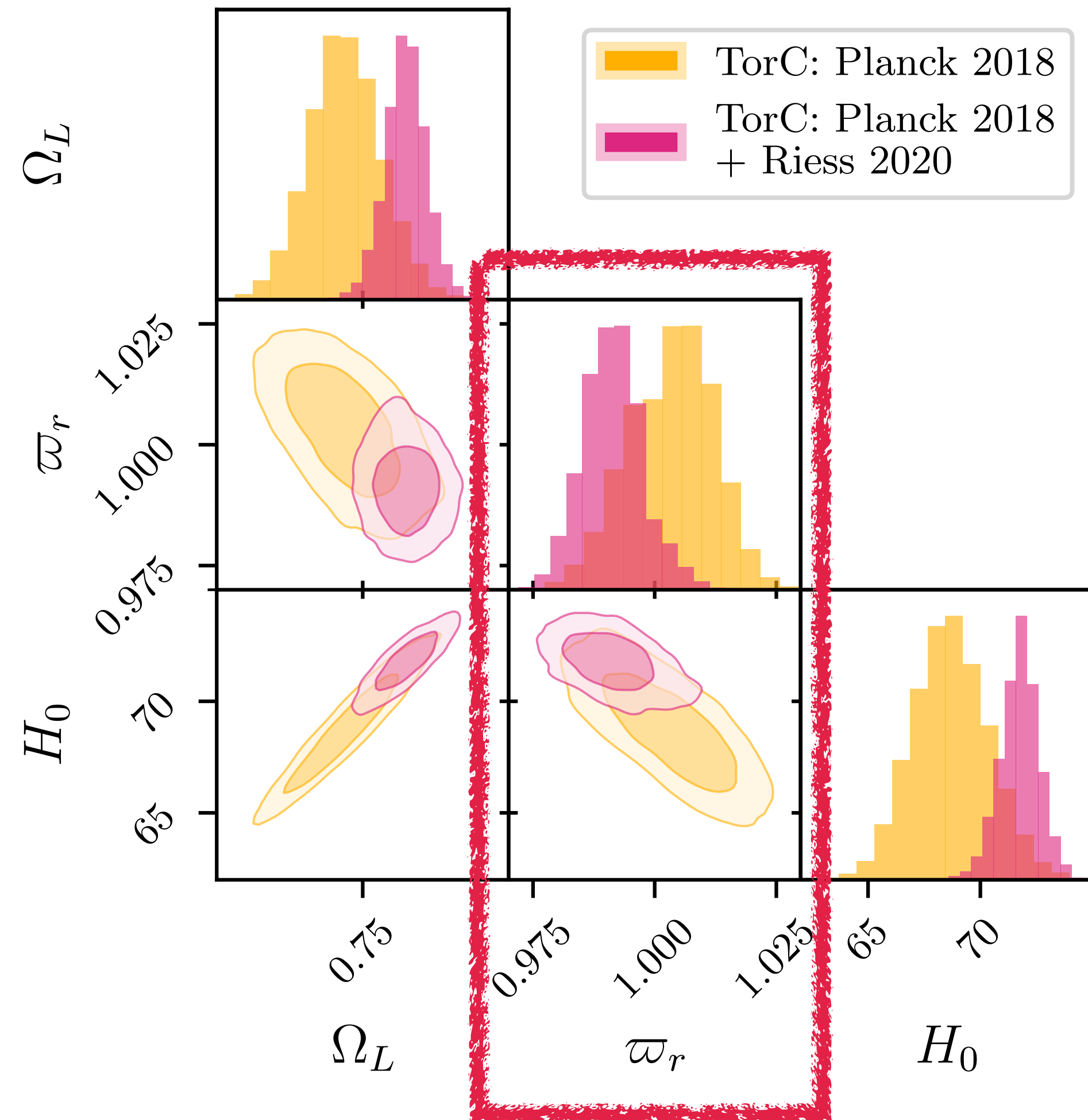
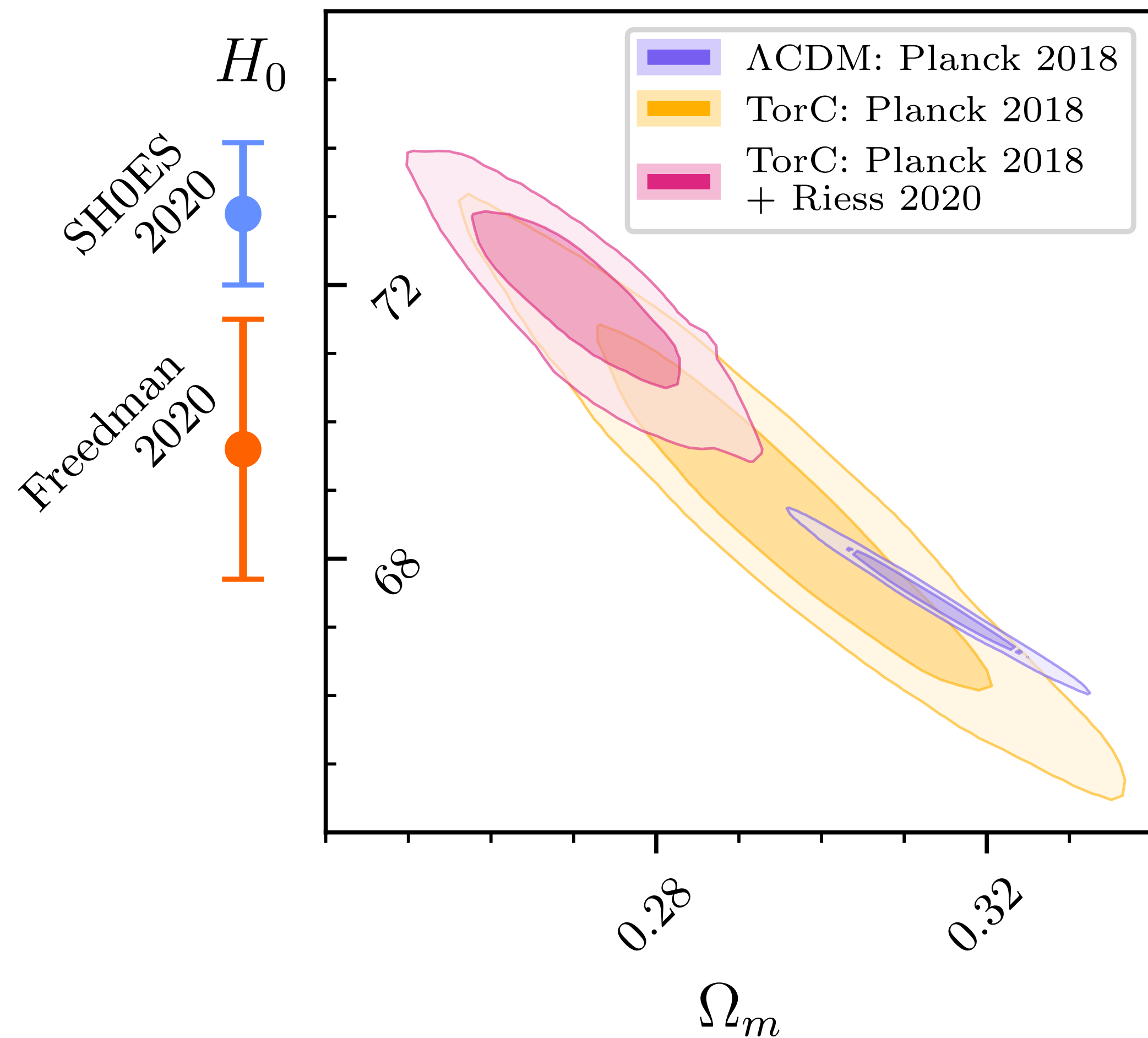
Λ CDM: SH0ES 2020 & Planck 2018 data in tension

The Main Result: Alleviating the Hubble Tension



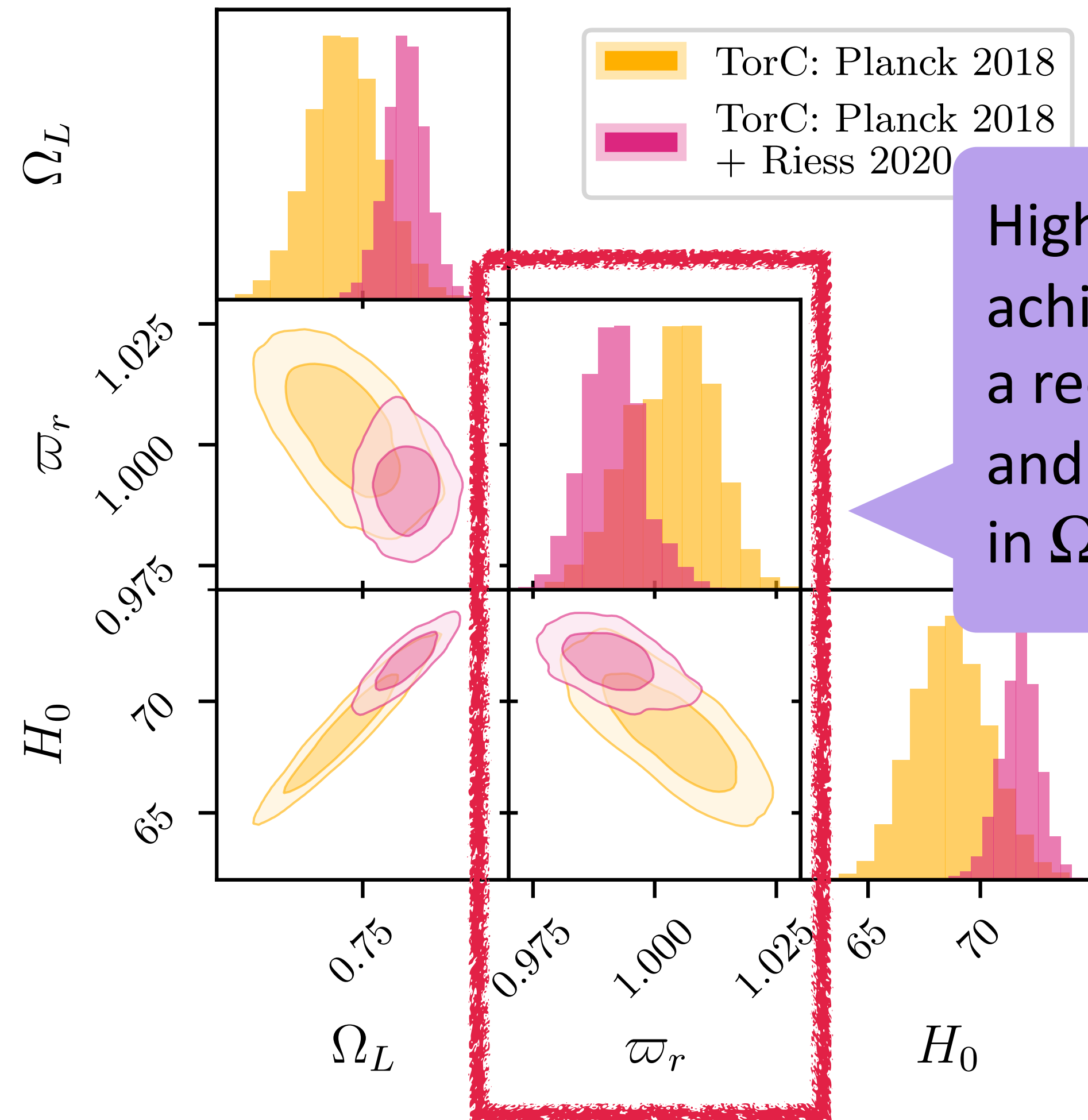
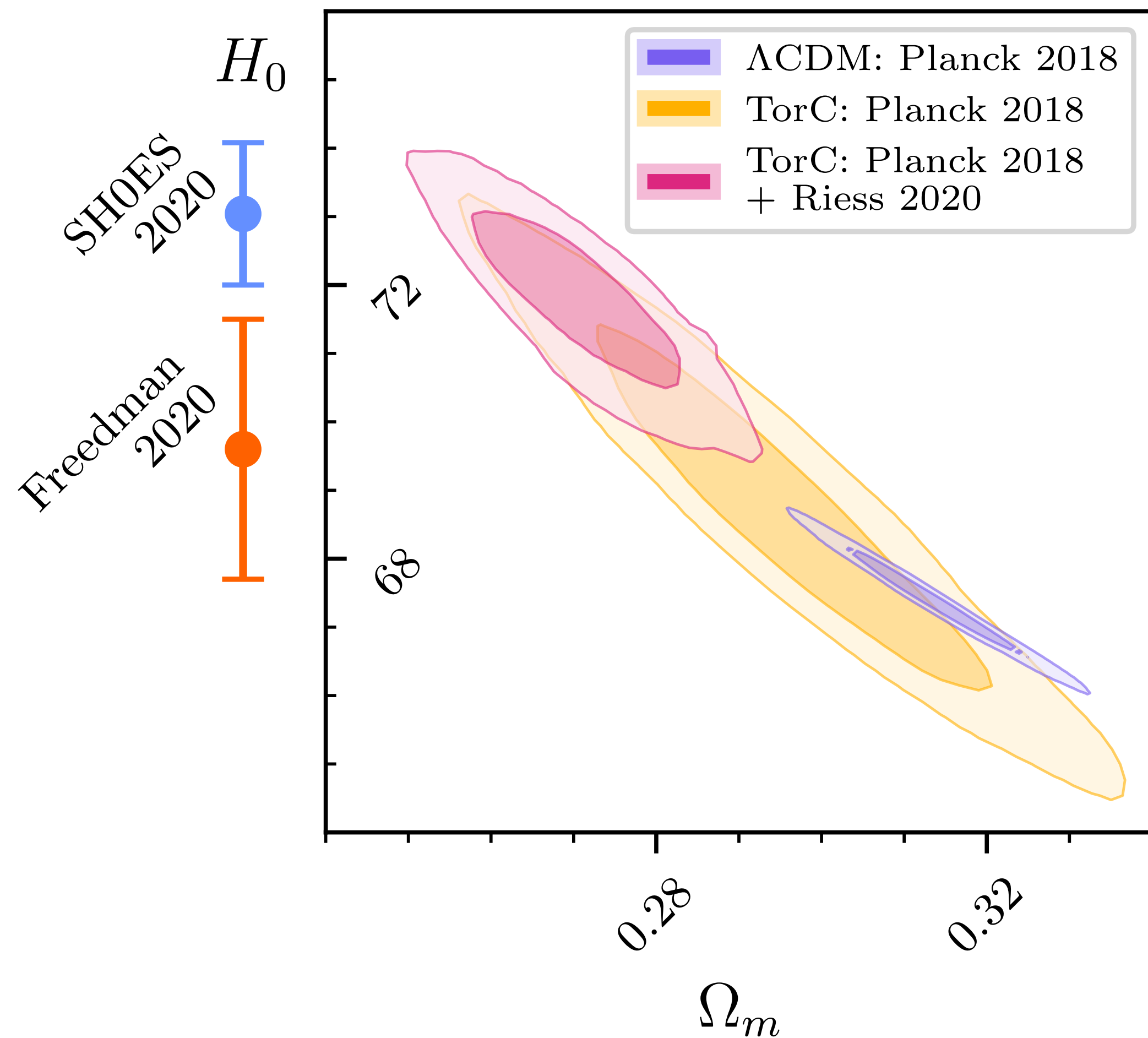
TorC: Planck 2018 data is consistent with SH0ES

The Main Result: Alleviating the Hubble Tension



Consistent with Λ CDM, but allows higher H_0 through presence of torsion

The Main Result: Alleviating the Hubble Tension

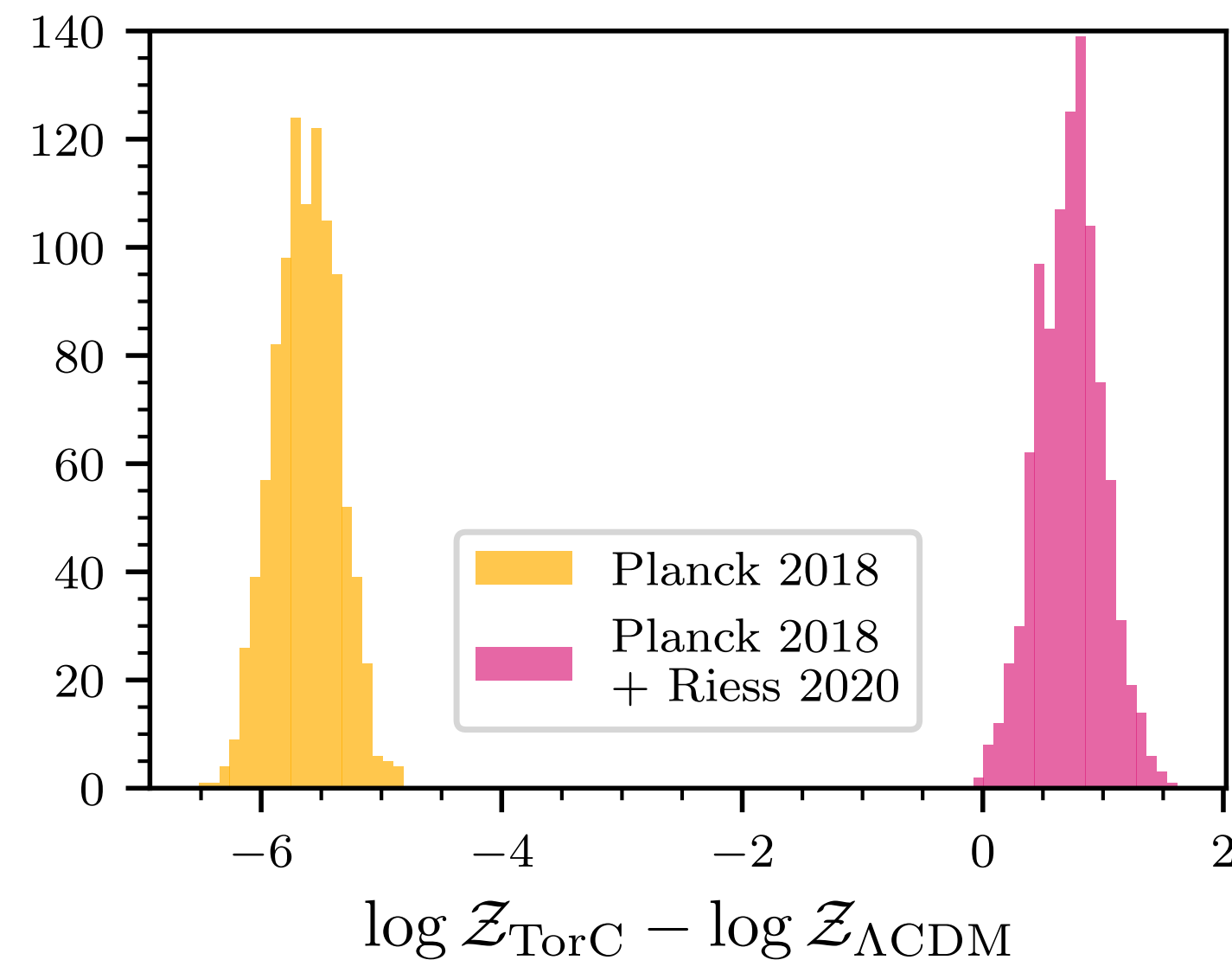


Higher H_0 is achieved through a reduction of w_r and an increase in Ω_L .

Consistent with Λ CDM, but allows higher H_0 through presence of torsion

Model Comparison: Is TorC Better?

Bayesian Evidence



Given data, compare the overall viability of models:

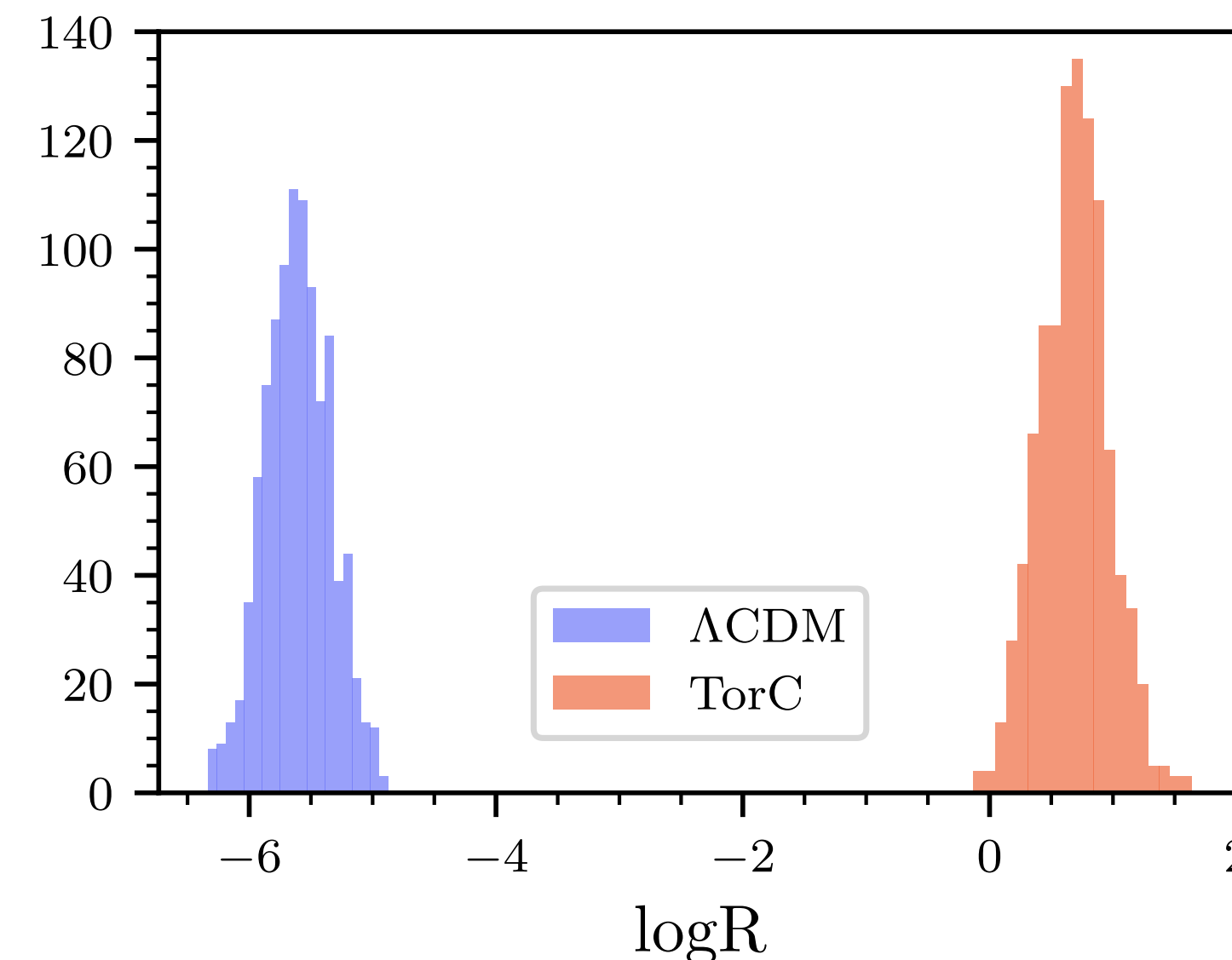
- TorC
- ΛCDM

$$\begin{aligned}\Delta \log Z^{\text{Planck}} &= \Delta \langle \log L(\theta) \rangle_P - \Delta D_{\text{KL}} \\ &= 0.417_{\pm 0.114} - 6.044_{\pm 0.265}\end{aligned}$$

$$\begin{aligned}\Delta \log Z^{\text{Joint}} &= \Delta \langle \log L(\theta) \rangle_P - \Delta D_{\text{KL}} \\ &= 6.792_{\pm 0.113} - 6.071_{\pm 0.263}\end{aligned}$$

The TorC model is not decisively favoured

Tension Quantification



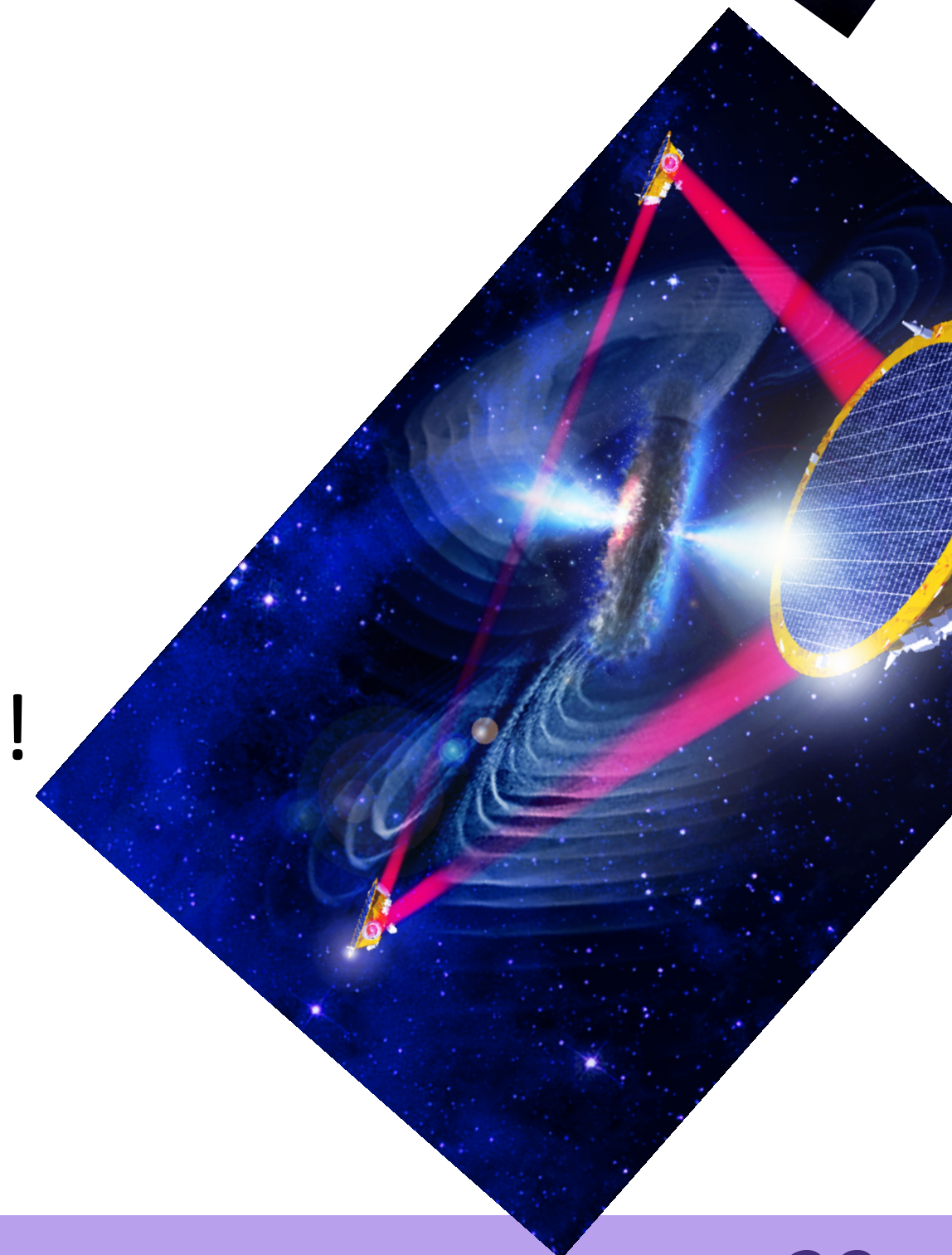
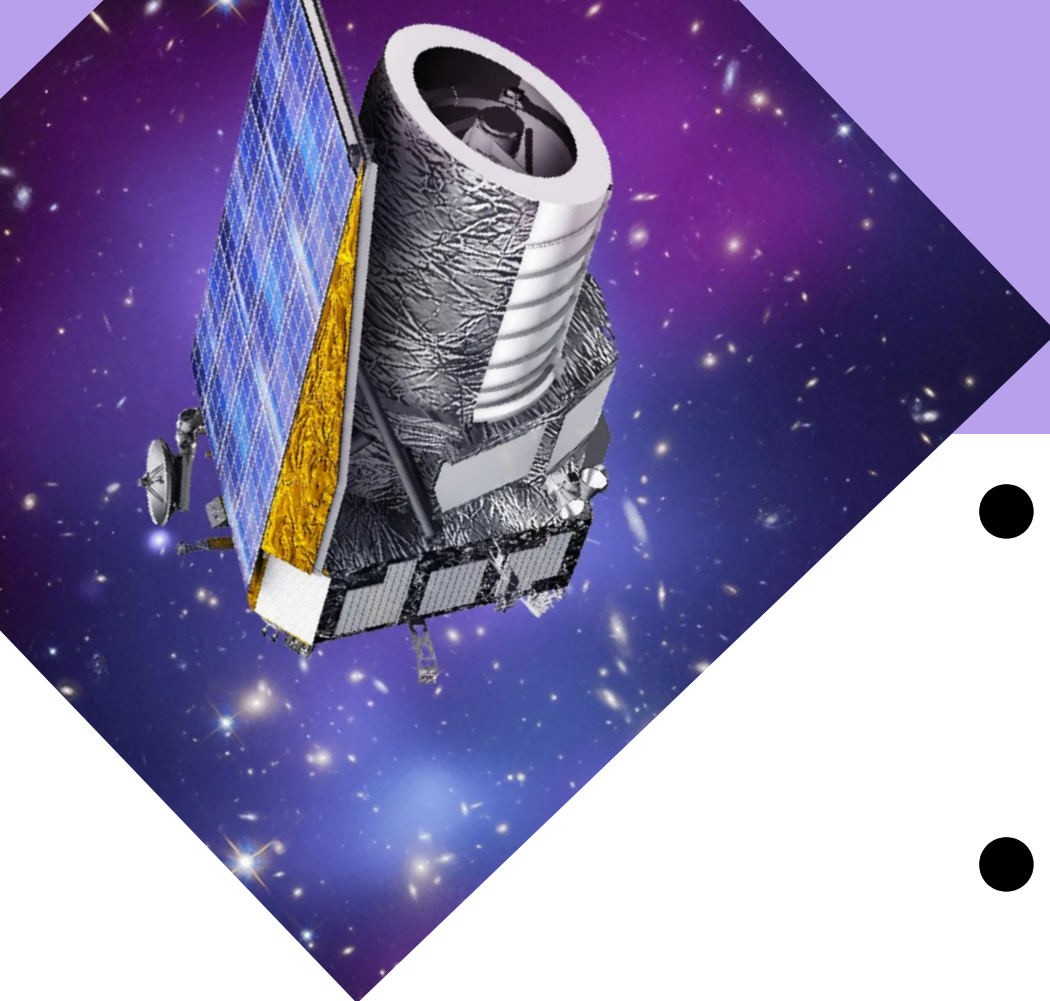
Assess the level of agreement between two datasets:

- Planck 2018
- SH0ES 2020

- ΛCDM : $\log R \ll 0$ - Significant tension between the two datasets
- TorC: $\log R > 0$ - Improved consistency between the two datasets

Conclusions

- Studied TorC as an extension of Λ CDM model with two extra cosmological parameters (ϖ_r & Ω_L).
- Using Cobaya, constrained parameters with PolyChord + CAMB, using Planck 2018 & SH0ES data.
- H_0 shows a negative correlation with ϖ_r and a positive correlation with Ω_L , existence of torsion raises H_0 .
- R-statistic: Planck–SH0ES tension reduced under TorC.
- Bayes factors: TorC not decisively favoured over Λ CDM.
- Current & upcoming surveys will critically test models like TorC, making this a pivotal time for extended gravity theories!



Questions or comments?

Thank you!

Nanobanana's drawing based on my slides' content



Backup Slides:

PGT Lagrangian

PGT Lagrangian is obtained via enforcing local Poincare transformation.

$$\mathcal{L}_{\text{PGT}} = h^{-1} \left[L_{\mathcal{R}^2} + \kappa^{-1} (L_{\mathcal{R}} + L_{\mathcal{T}^2} + L_{\Lambda}) + L_m(\Phi, \Psi; h, A) \right]$$

$$L_{\mathcal{R}} = -\frac{1}{2} \alpha_0 \mathcal{R},$$

$$L_{\Lambda} = -\Lambda,$$

$$L_{\mathcal{R}^2} = \alpha_1 \mathcal{R}^2 + \alpha_2 \mathcal{R}_{ab} \mathcal{R}^{ab} + \alpha_3 \mathcal{R}_{ab} \mathcal{R}^{ba} + \alpha_4 \mathcal{R}_{abcd} \mathcal{R}^{abcd} + \alpha_5 \mathcal{R}_{abcd} \mathcal{R}^{acbd} \\ + \alpha_6 \mathcal{R}_{abcd} \mathcal{R}^{cdab},$$

$$L_{\mathcal{T}^2} = \beta_1 \mathcal{T}_{abc} \mathcal{T}^{abc} + \beta_2 \mathcal{T}_{abc} \mathcal{T}^{bac} + \beta_3 \mathcal{T}_a \mathcal{T}^a.$$

Gauge Fields:

$$h_a^\mu$$

Translational

$$A_\mu^{ab}$$

Lorentz

Field Strength Tensors:

$$\mathcal{R}^{ab}_{cd} = 2h_c^\mu h_d^\nu \left(\partial_{[\mu} A^{ab}_{\nu]} + A^a_{e[\mu} A^{ae}_{\nu]} \right),$$

$$\mathcal{T}^a_{bc} = -2b^a_\mu D_{[b} h_{c]}^\mu.$$

Torsion Condensation (TorC)

- Lagrangian density:

$$\tilde{\mathcal{L}} = M_{\text{p}}^2 v_2 \left[\frac{1}{2} \left(1 - \frac{\varpi^2}{4\zeta} \right) \mathcal{R} - \frac{3}{2\zeta} X^{\varpi\varpi} + \sqrt{|\tilde{J}_\mu \tilde{J}^\mu|} + \frac{3}{4} \phi^2 - \frac{3}{4\zeta} \phi^2 \varpi^2 \right],$$

$$\tilde{J}_\mu = 4\varpi^3 \partial_\mu (\phi/\varpi) + \partial_\mu \phi.$$

$$X^{\pi\pi} = 1/2 g^{\mu\nu} \partial_\mu \pi \partial_\nu \pi.$$

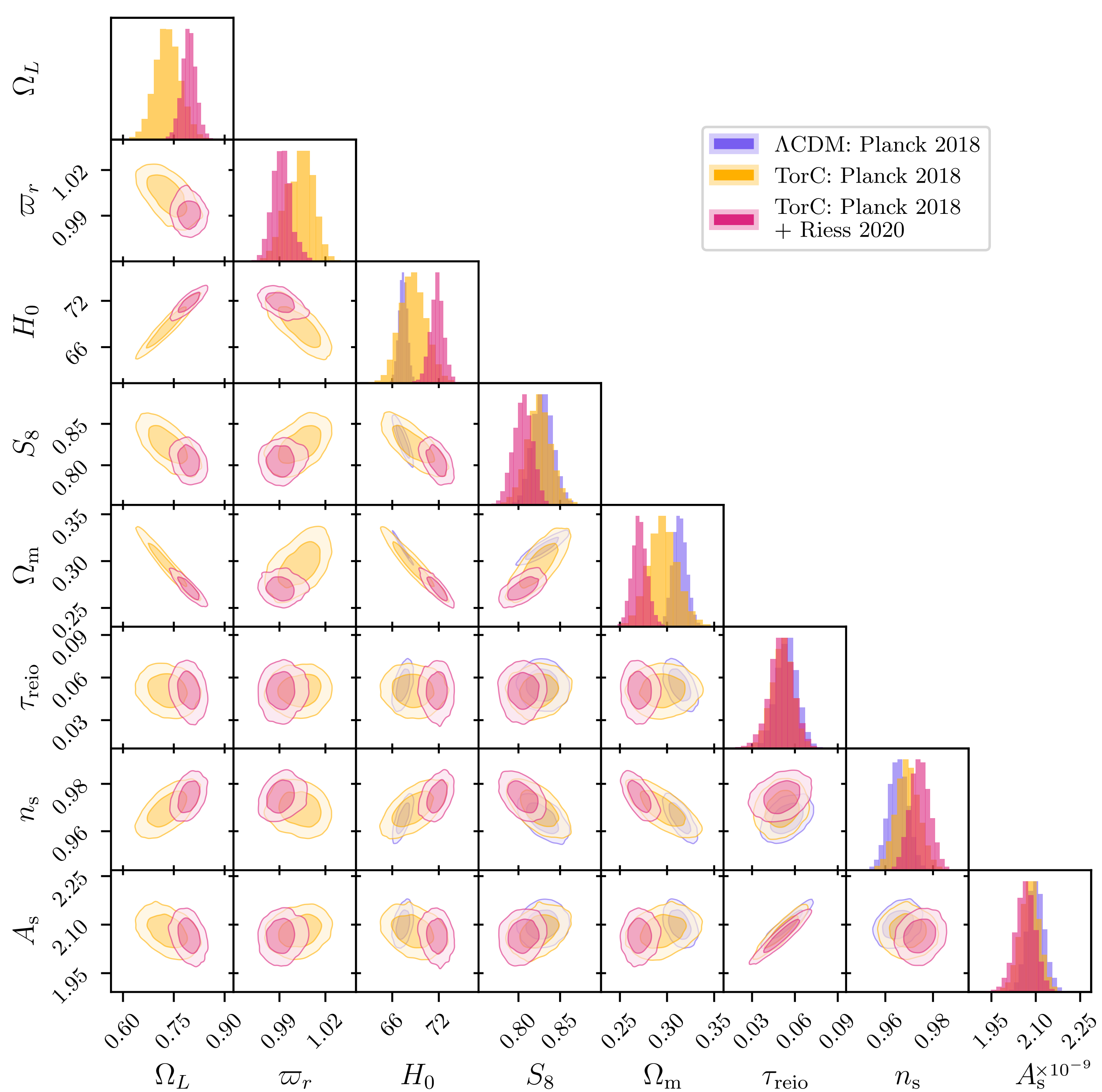
- ϖ_r : Initial value of the scalar field ϖ .
- Coincident with LCDM when $\varpi_r = 1$.

- Field Equation (1st Friedmann Eq.):

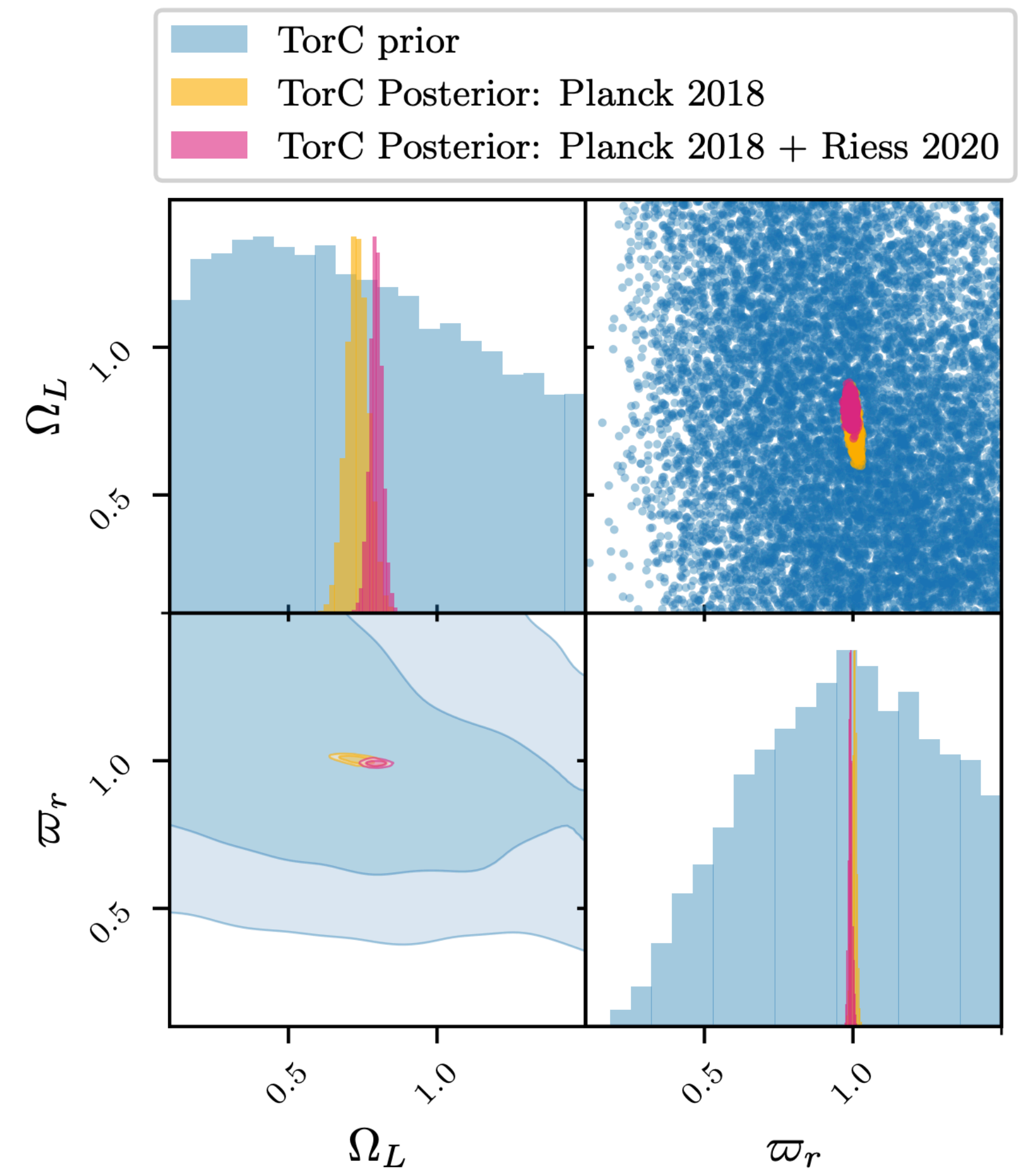
$$\text{GR: } H(t)^2 = H_0^2 (\Omega_r a(t)^{-4} + \Omega_m a(t)^{-3} + \Omega_\Lambda)$$

$$\text{TorC: } H(t)^2 = H_0^2 \left(\frac{\Omega_r a(t)^{-4} + \Omega_m a(t)^{-3} + \Omega_L}{\varpi(t)^2} \right) - \frac{\dot{\varpi}(t) \left(6H(t)\varpi(t) + \frac{(1 + 3\varpi(t)^2)\dot{\varpi}(t)}{\varpi(t)^2 - 1} \right)}{3\varpi(t)^2}$$

- Ω_L : bare dark energy density parameter
- Coincident with LCDM when $\Omega_L = \Omega_\Lambda$.



Posterior



Space-time Geometries

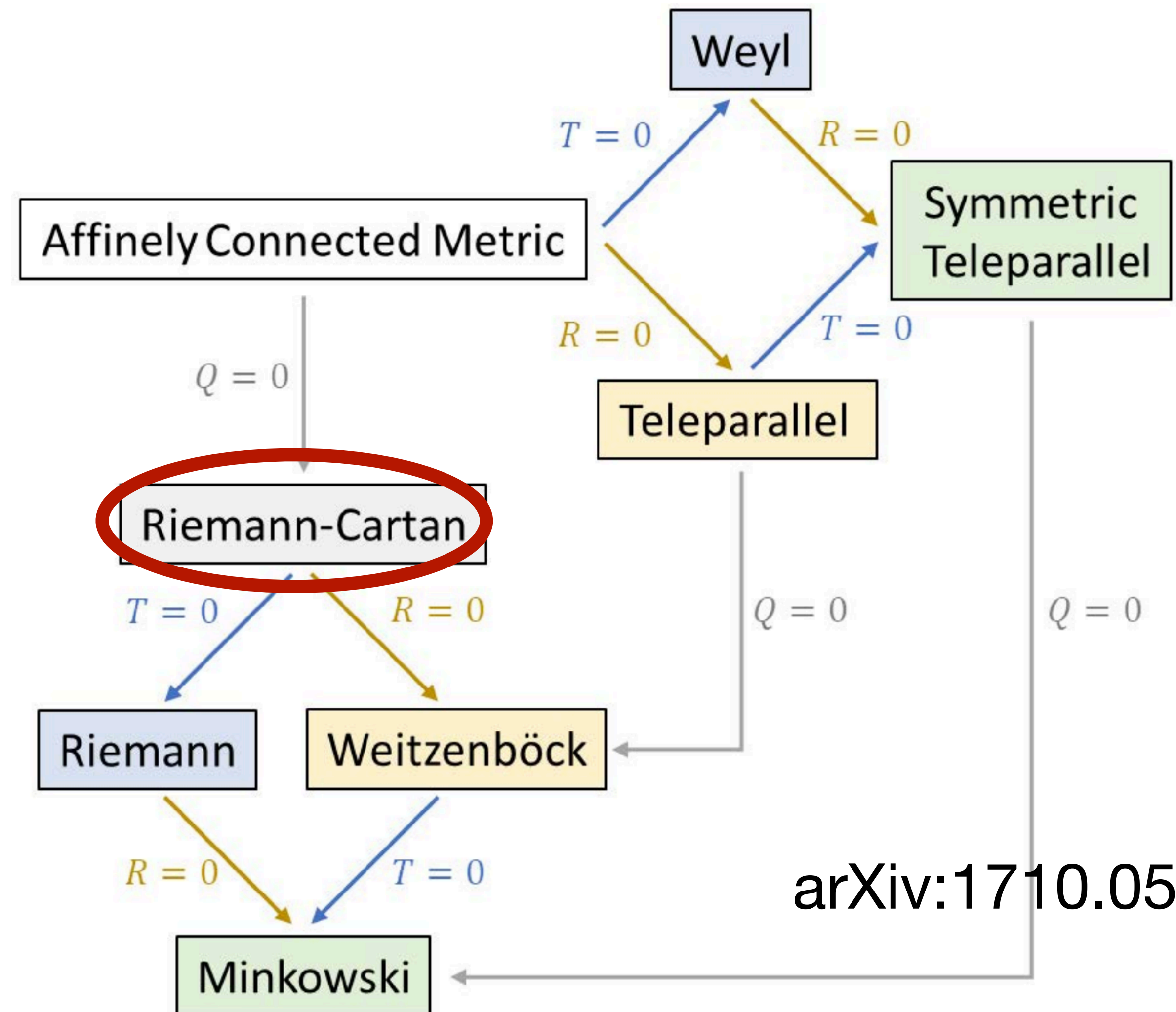
To ensure local Minkowskian structure, Metricity condition is required:

$$\nabla_{\mu}^{(\Gamma)} g_{\mu\nu} = 0$$

Connection becomes:

$$\Gamma_{\lambda\nu}^{\mu} = \left\{ \begin{smallmatrix} \mu \\ \lambda\nu \end{smallmatrix} \right\} + K^{\mu}_{\lambda\nu}$$

(Contorsion)



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Geometrical Analogies

Riemann Cartan space-time

$$e_i{}^\mu \quad e^i{}_\mu$$

$$\omega^{ij}{}_\mu$$

$$\nabla_\mu^{(\omega)} \phi = (\partial_\mu + \frac{1}{2} \omega_\mu^{ij} \Sigma_{ij}) \phi$$

$$\mathbb{R}^\mu{}_{\nu\lambda\rho} = 2e^\mu{}_i e^s{}_\nu \left(\partial_{[\lambda} \omega_{s\rho]} + \omega^i{}_{j[\lambda} \omega^j{}_{s\rho]} \right)$$

$$\mathbb{T}^\lambda{}_{\nu\mu} = -2e^\lambda{}_i \nabla^{(\omega)}_{[\nu} e^i{}_{\mu]}$$

Poincare Gauge Theory

$$h^\mu{}_a \quad b^a{}_\mu$$

$$A_\mu^{ab}$$

$$D_a \psi = h^\mu{}_a (\partial_\mu + \frac{1}{2} A^{cd}{}_\mu \Sigma_{cd}) \psi$$

$$\mathcal{R}^{ab}{}_{cd} = 2h_c{}^\mu h_d{}^\nu \left(\partial_{[\mu} A^{ab}{}_{\nu]} + A^a{}_{e[\mu} A^{ae}{}_{\nu]} \right),$$

$$\mathcal{T}^a{}_{bc} = -2b^a{}_\mu D_{[b} h_{c]}{}^\mu.$$

