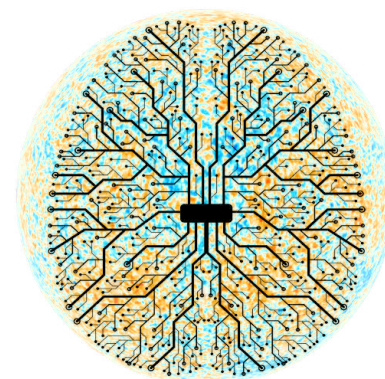


Is Einstein Enough? Cosmology in Extended Theories of Gravity

Sinah Legner

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

Astrophysics Group, Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, UK
Kavli Institute for Cosmology, Madingley Road, Cambridge CB3 0HA, UK



**UNIVERSITY OF
CAMBRIDGE**

Cavendish Laboratory
Department of Physics



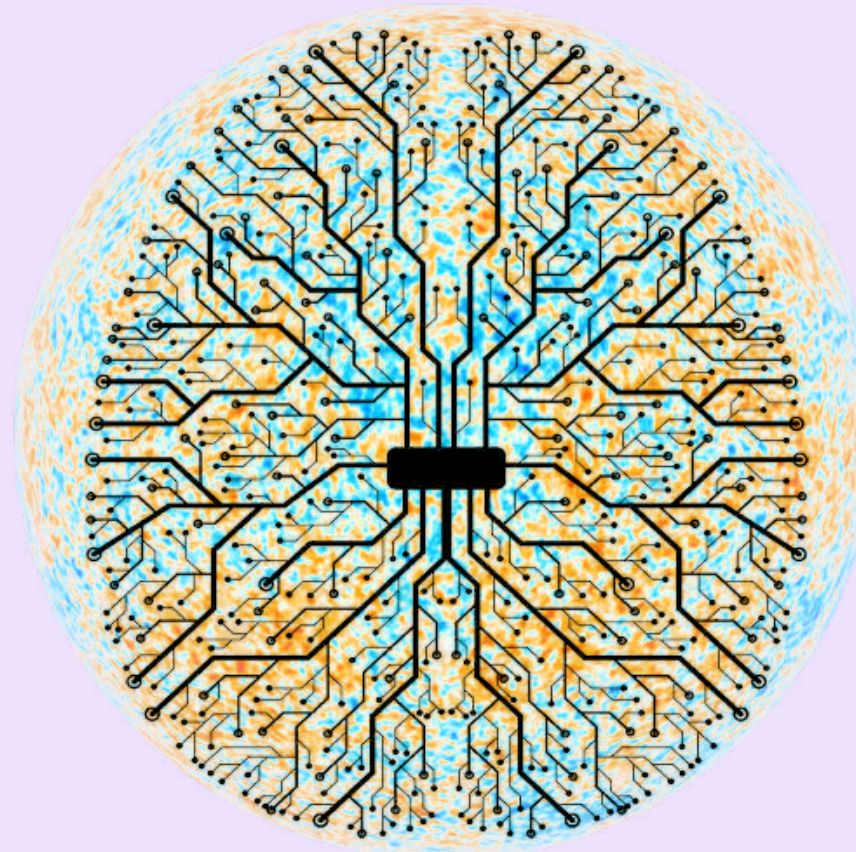
Who am I ?



Sinah Legner

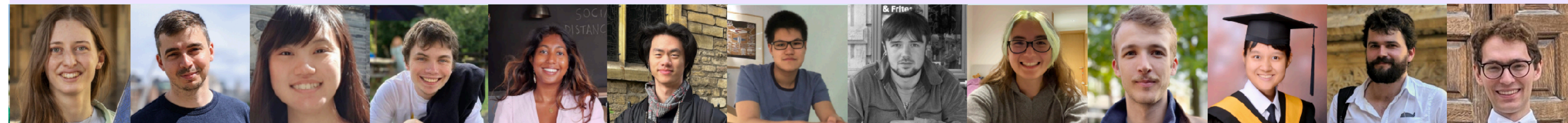
- PhD student
- Astrophysics group, Cavendish Laboratory
- Supervisors: Will Handley, Will Barker

Handley lab

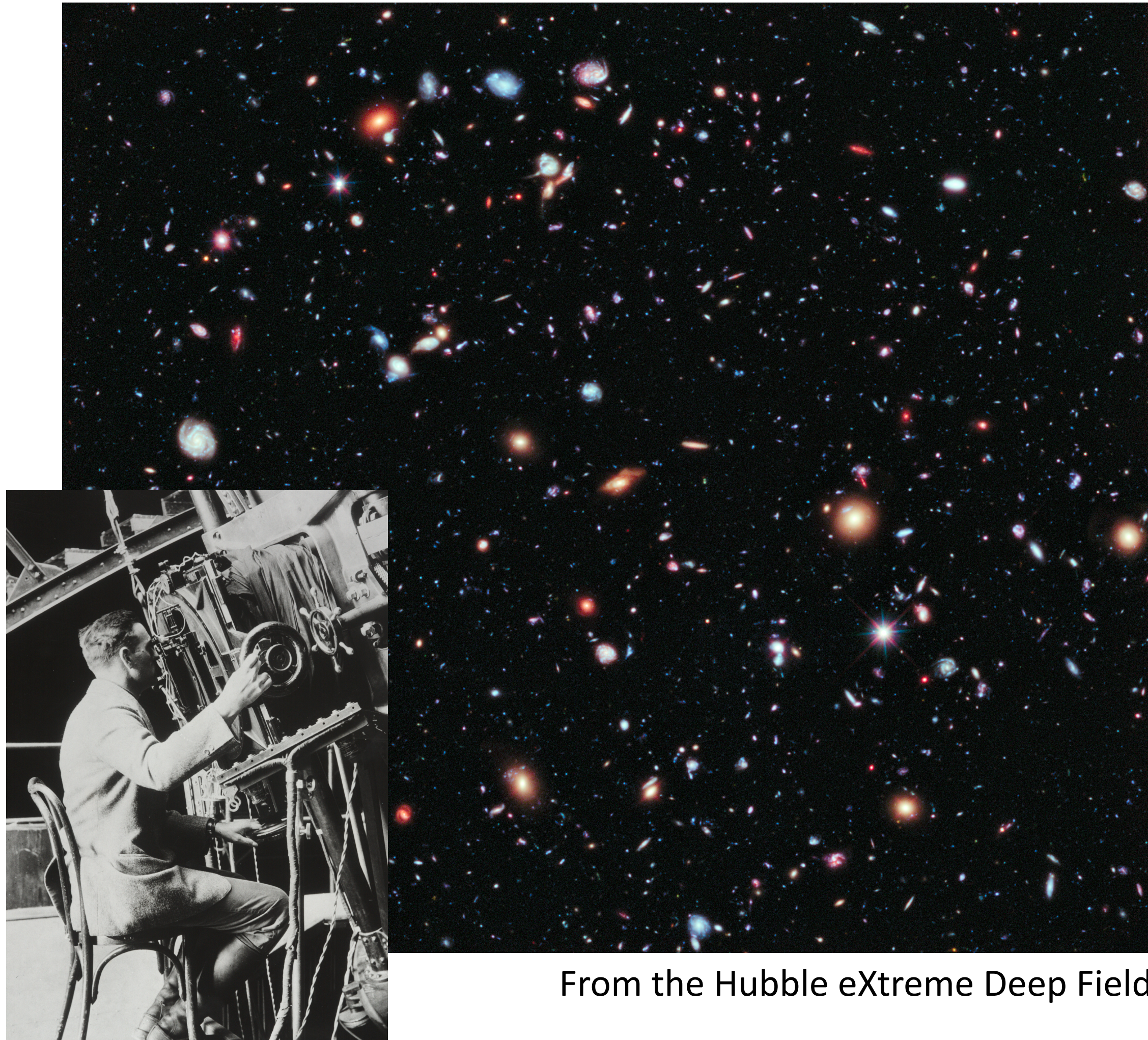


handley-lab.co.uk

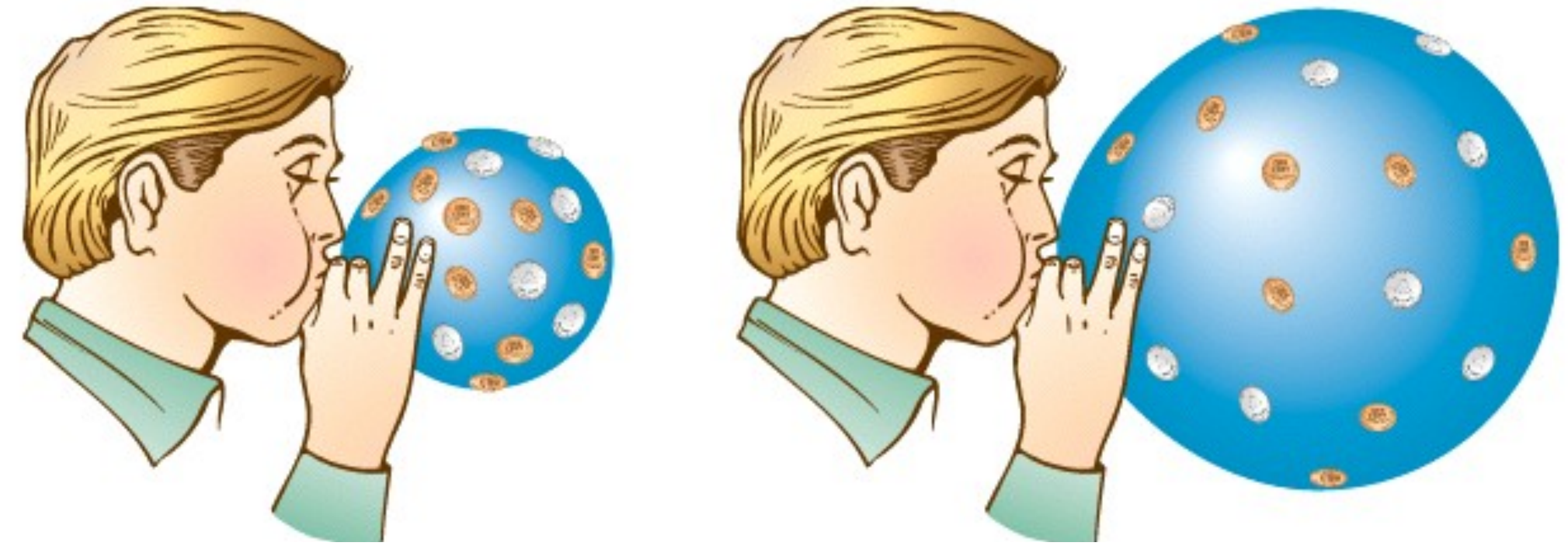
- Exploring the Universe using tools from **Bayesian statistics, AI, and Machine Learning.**
- **Research Area:**
 - Early Universe & Inflation
 - Dark Energy & Dark Matter
 - 21-cm Cosmology & the Epoch of Reionisation
 - Gravitational Wave Astrophysics
- **Softwares:** PolyChord, anesthetic, margarine,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



The Universe is Expanding — gateway to Cosmology



From the Hubble eXtreme Deep Field



- More distant galaxies move away faster
- Hubble's law:

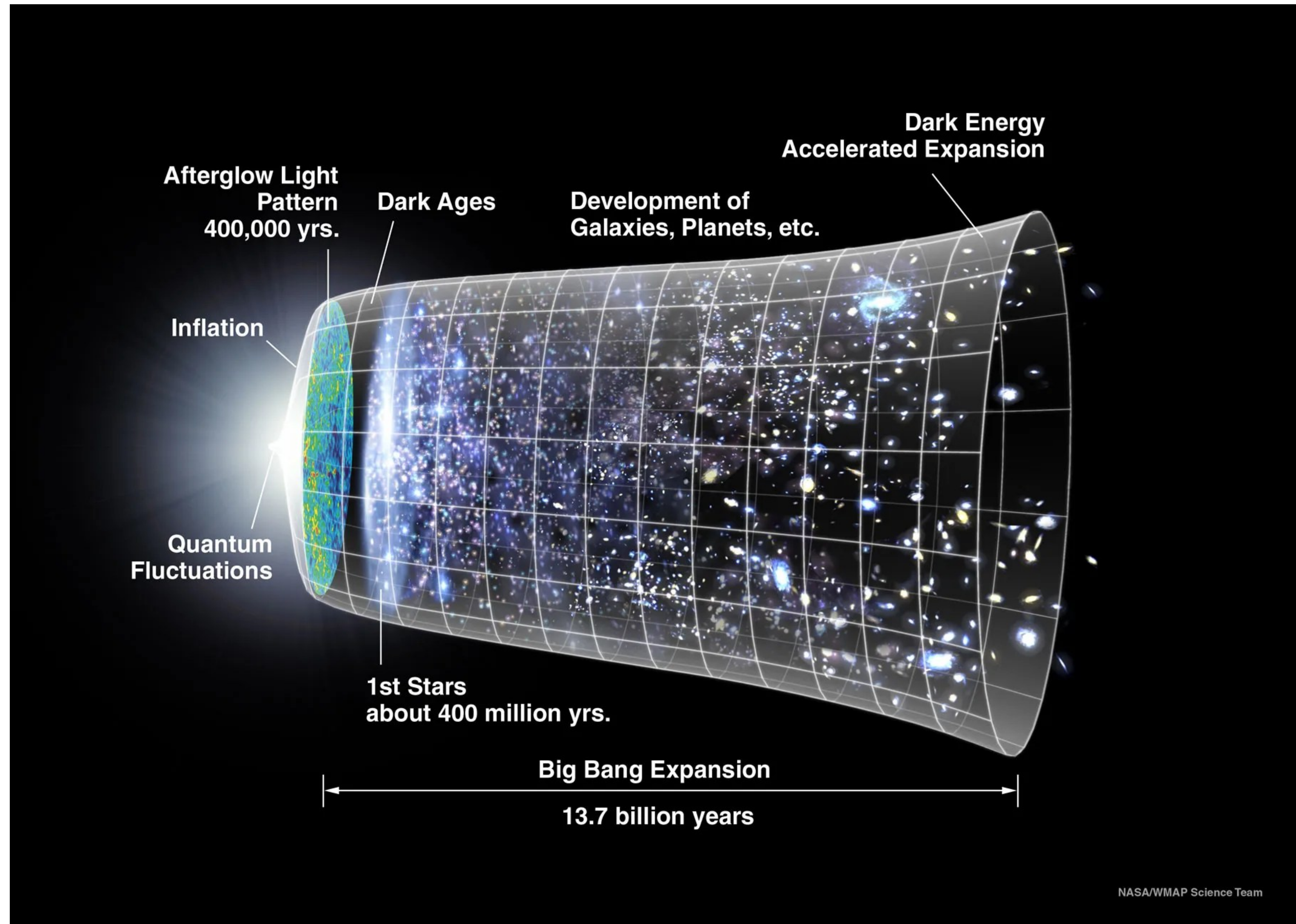
$$v = H_0 d$$

- Velocity increases, when distance increases

What is Cosmology?

Cosmology studies the Universe as a whole

- How did the Universe begin?
- How has the Universe evolved over time?
- What determines cosmic expansion?
- What is the Universe made of?



Current standard model of Cosmology - Λ CDM

Cosmological Principle

- **Homogeneous:** the same everywhere
- **Isotropic:** the same in every direction

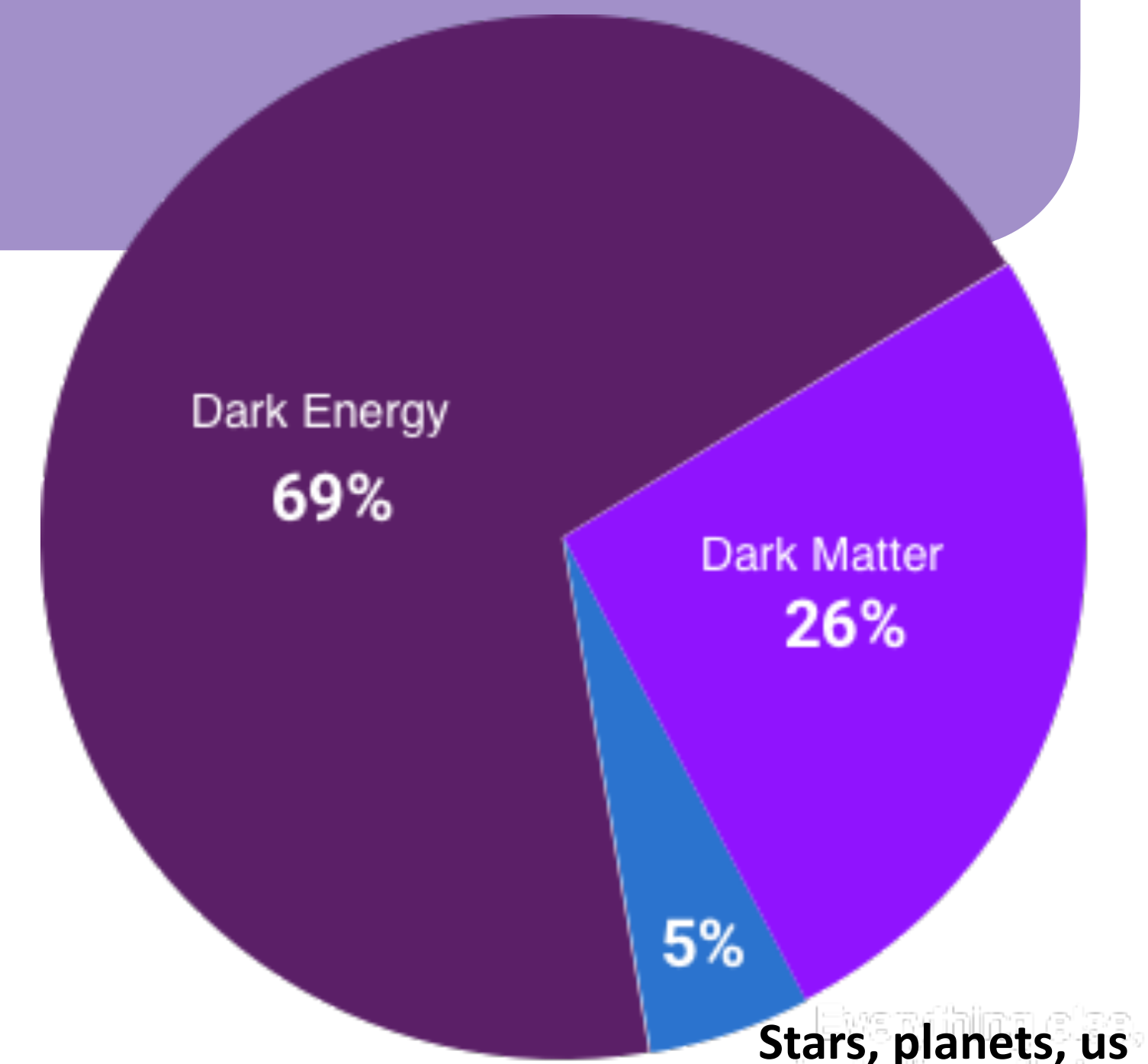
Content of the Universe

- Λ (Lambda) \rightarrow dark energy
- Cold Dark Matter (CDM) \rightarrow structure

Λ CDM

General Relativity

- Matter and energy curve spacetime
- This curvature determines how the Universe expands

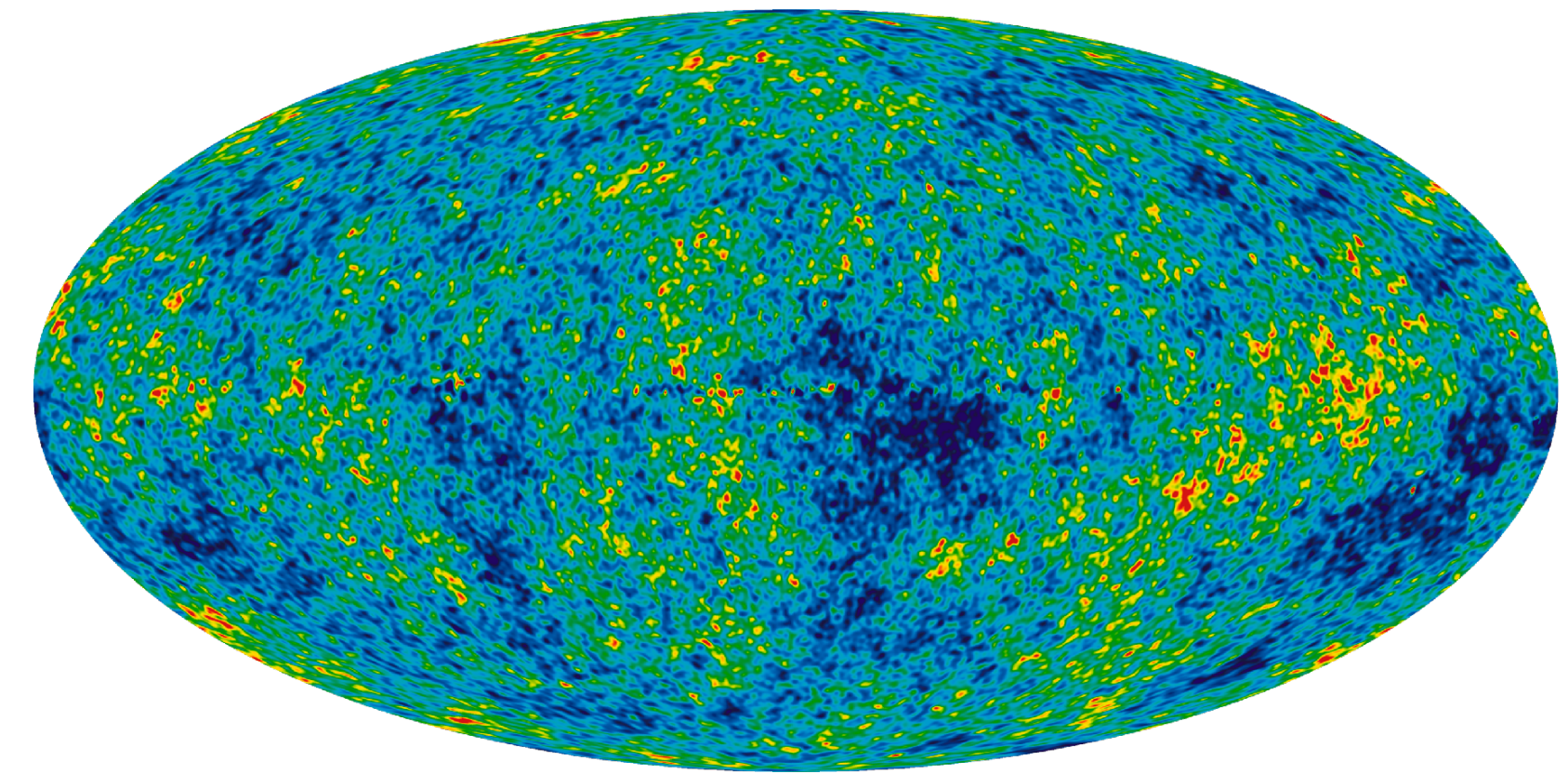


Expanding Universe

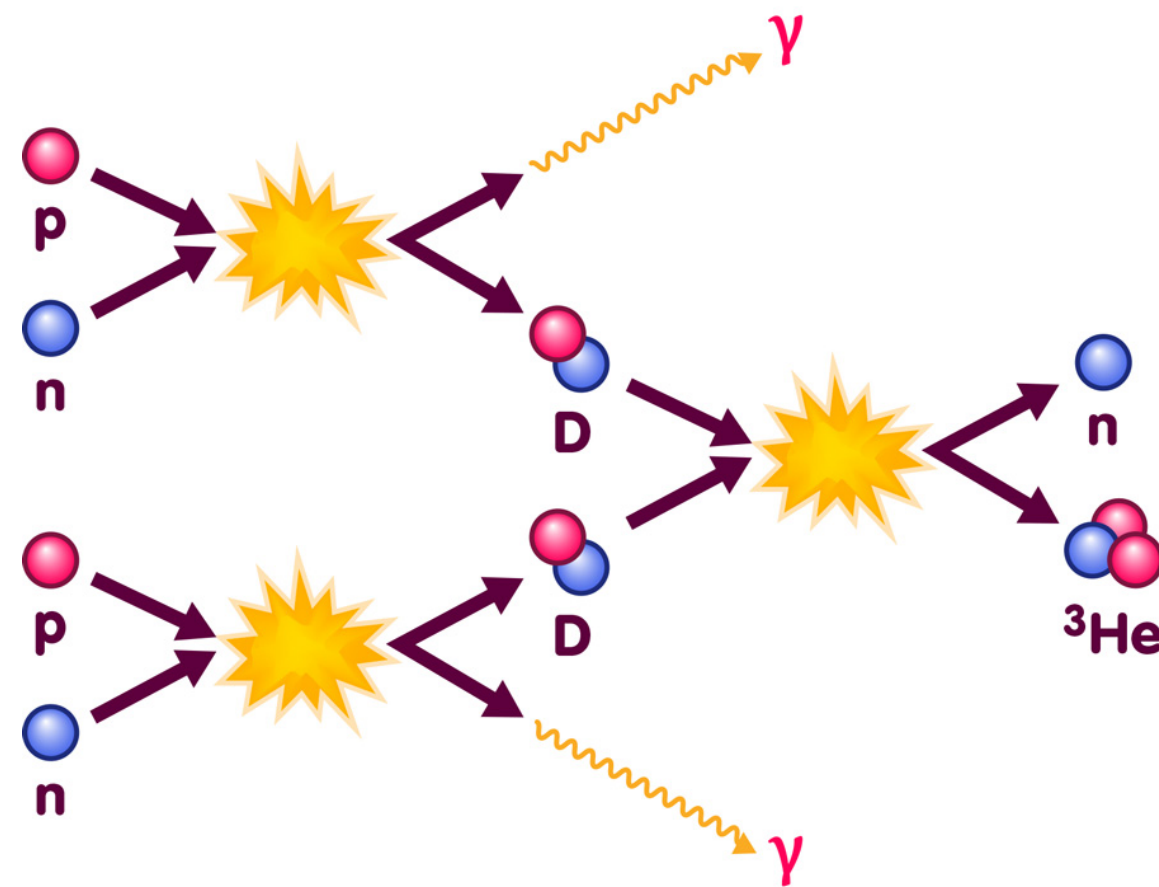
Success of Λ CDM

Cosmic Microwave Background

- Oldest light in the Universe
- Nearly uniform temperature
- Λ CDM predicts the statistical pattern of its fluctuations



Λ CDM



Primordial element abundances

- Early Universe produced light elements
- Predicted abundances of hydrogen, helium, deuterium, etc.
- Observations match theoretical predictions

Accelerated Expansion

- Distant supernovae appear dimmer than expected
- Indicates the expansion of the Universe is accelerating
- Consistent with dark energy (Λ)

Tension in Cosmology - Hubble Tension

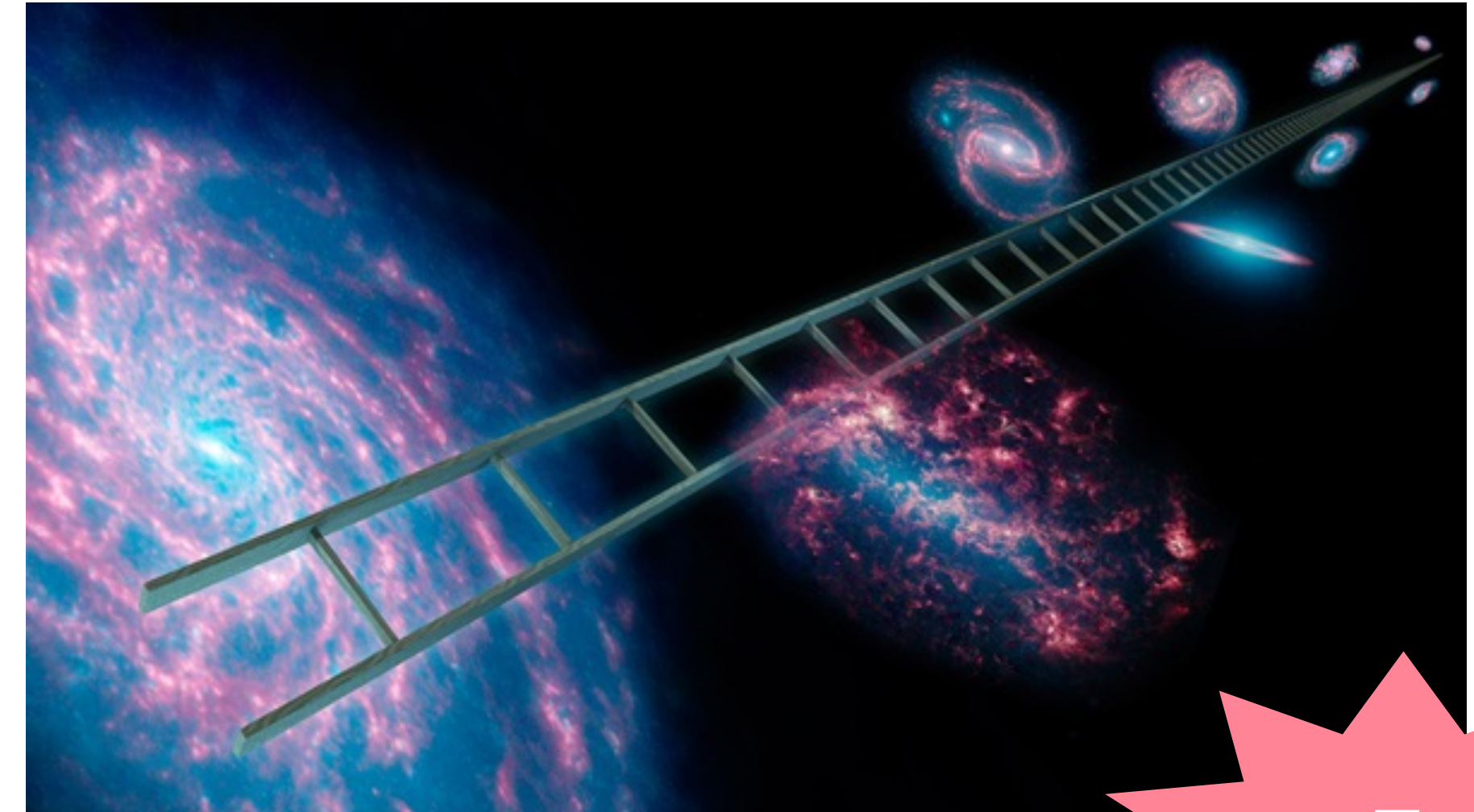
Measuring the expansion rate of the Universe (H_0)

Cosmic Distance Ladder (Late Universe):

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

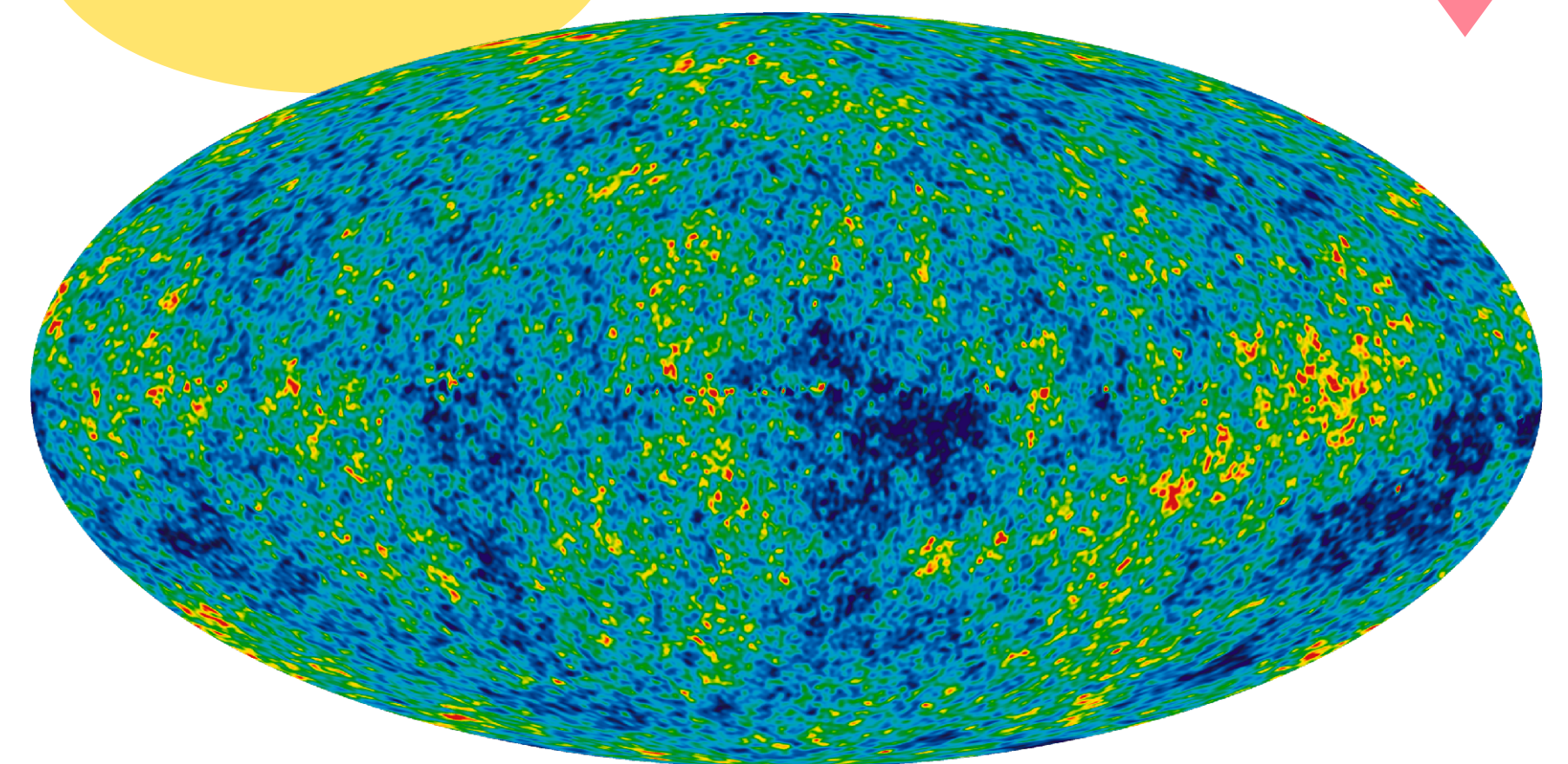
Cosmic Microwave Background (Early Universe):

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



$\sim 5\sigma$

Λ CDM



Tension in Cosmology - Hubble Tension

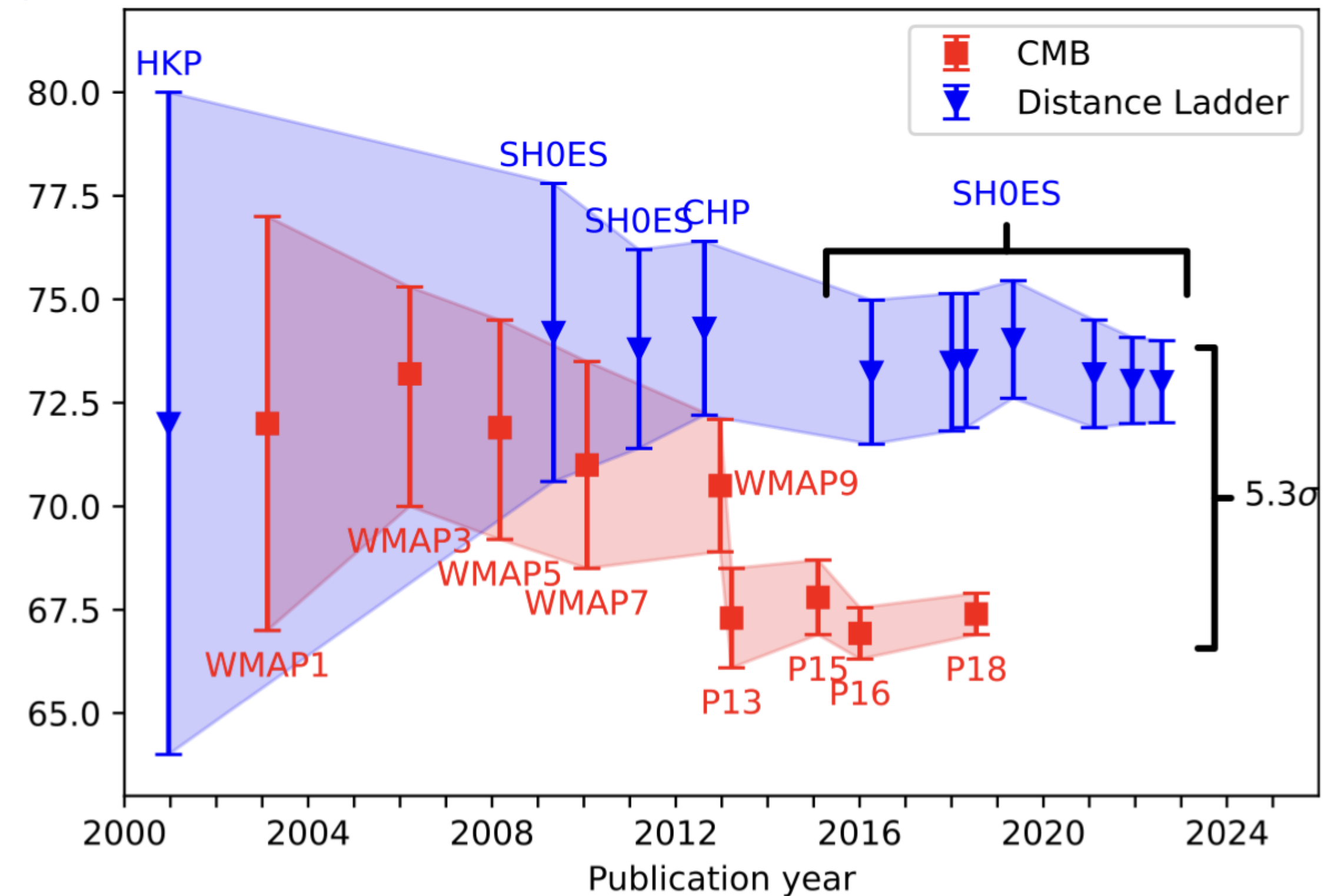
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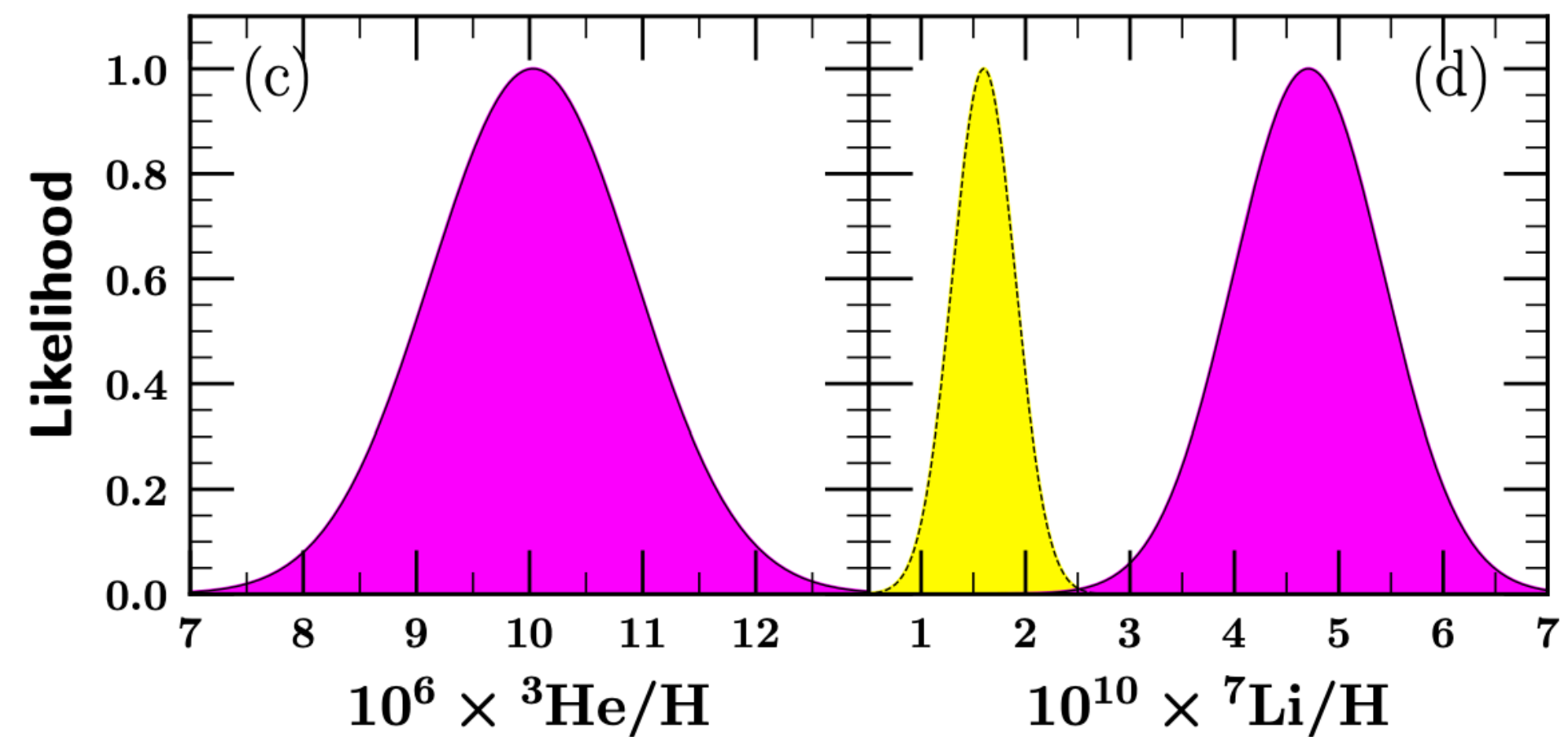
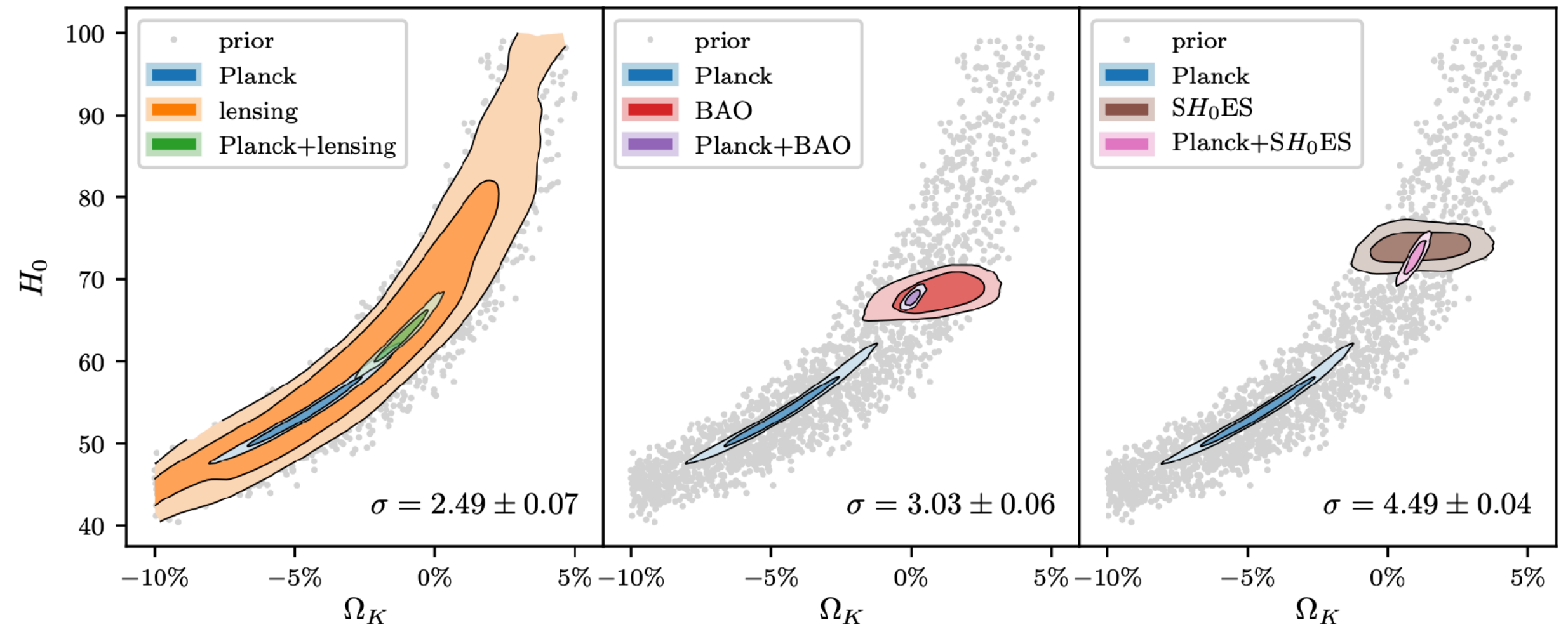
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[Evolution of the Hubble tension in the last 23 years](#)

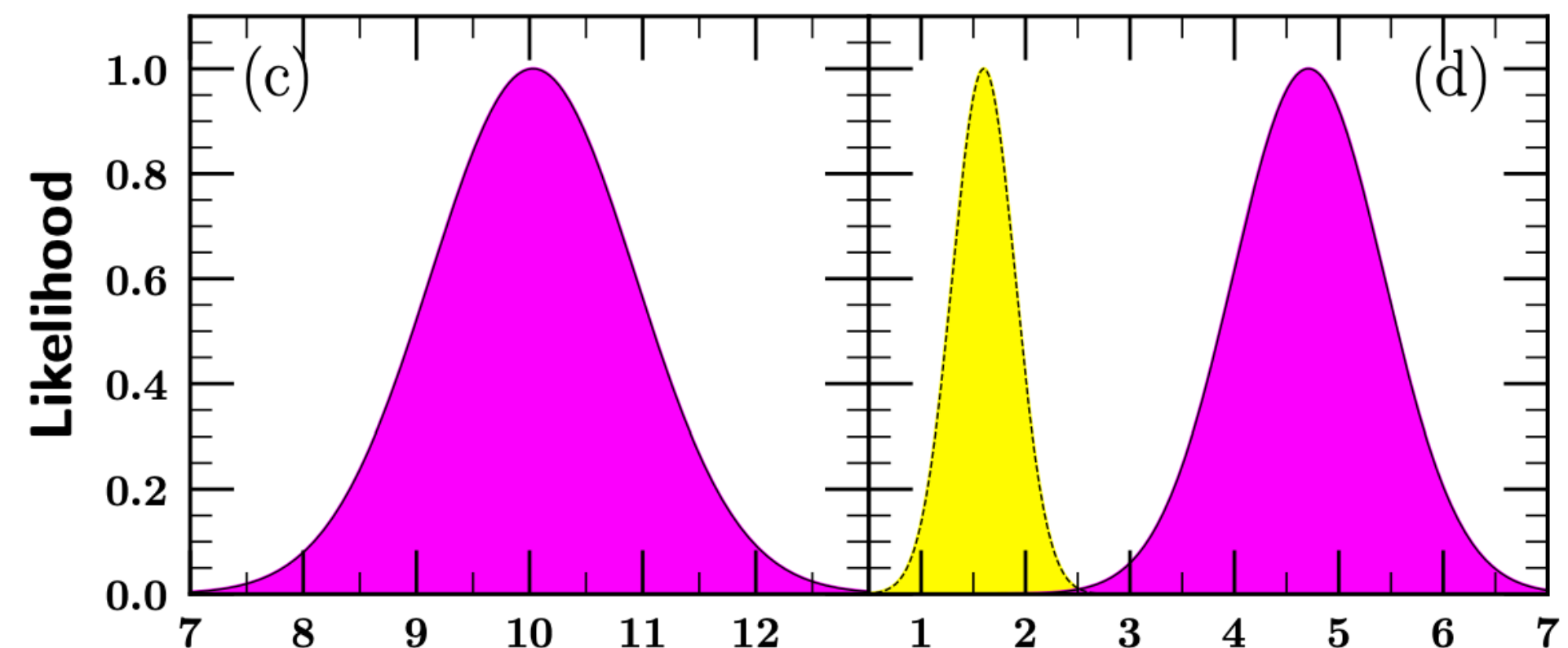
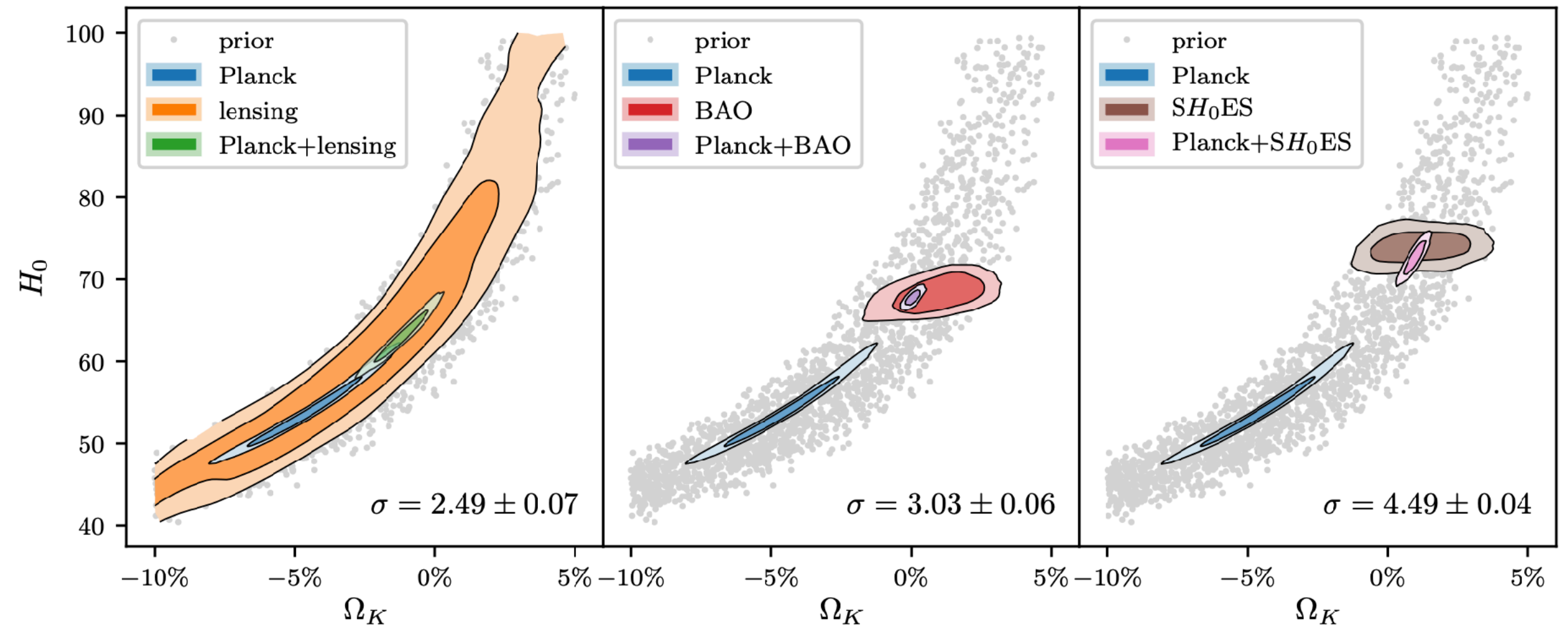
Tension in Cosmology - other tensions

- **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

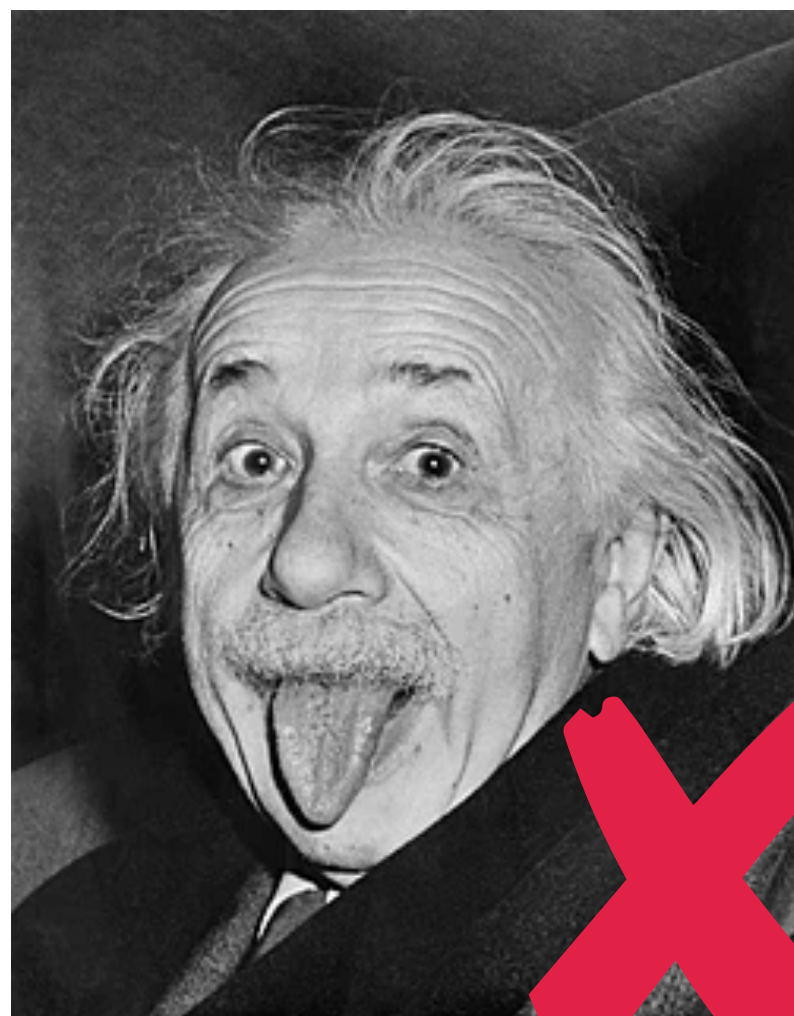
Gravity consisting of Torsion?

Will Barker



Einstein's General Relativity

- Based on **Curvature** Only
- Matter tells spacetime how to curve, curvature tells matter how to move



Torsion Condensation (TorC)

- How Feynman might have constructed gravity
- Inspired by how other fundamental forces are described in **quantum field theory**
- Built by enforcing a local spacetime symmetry (translations and rotations)
- Leads to a richer spacetime geometry containing both **Curvature and Torsion**
- Equations take a quadratic form, similar to those in other forces

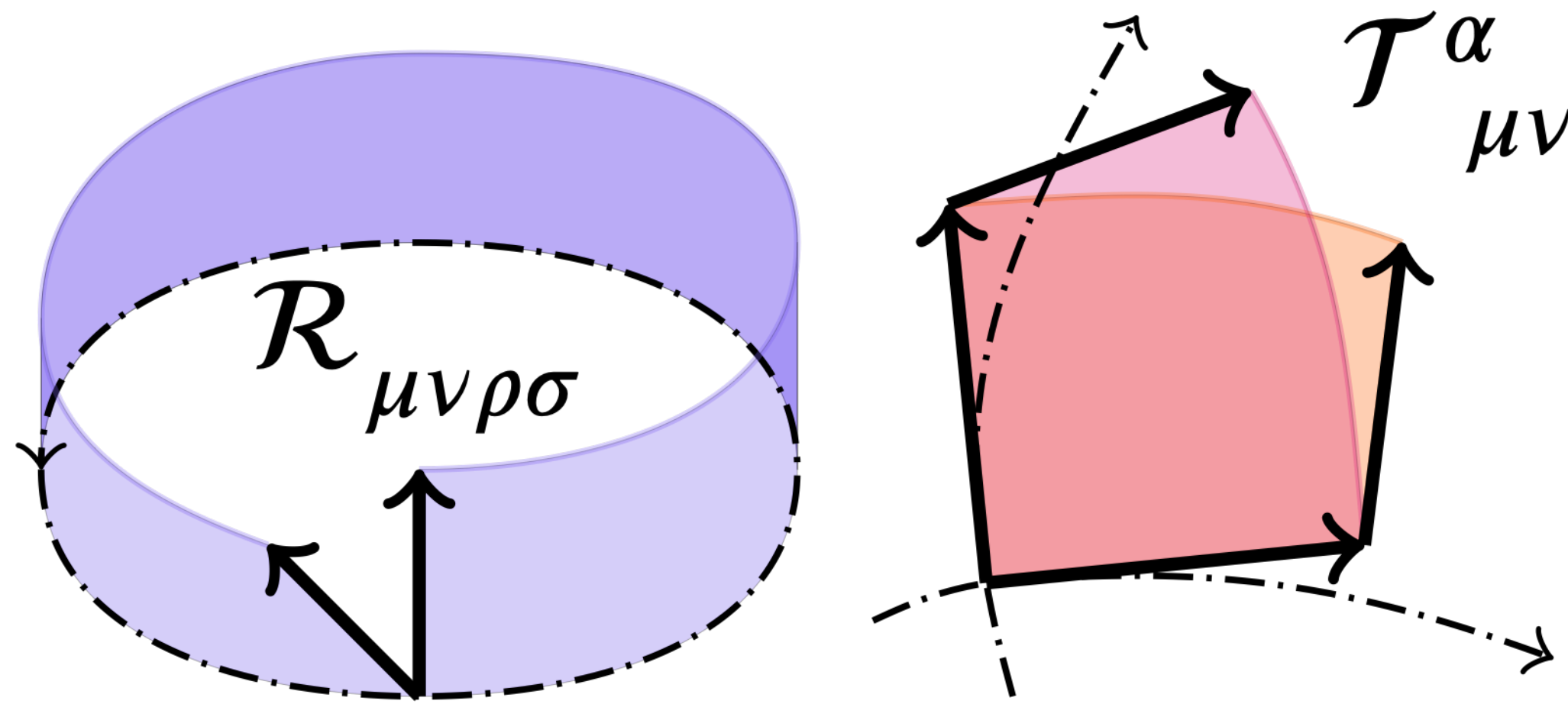
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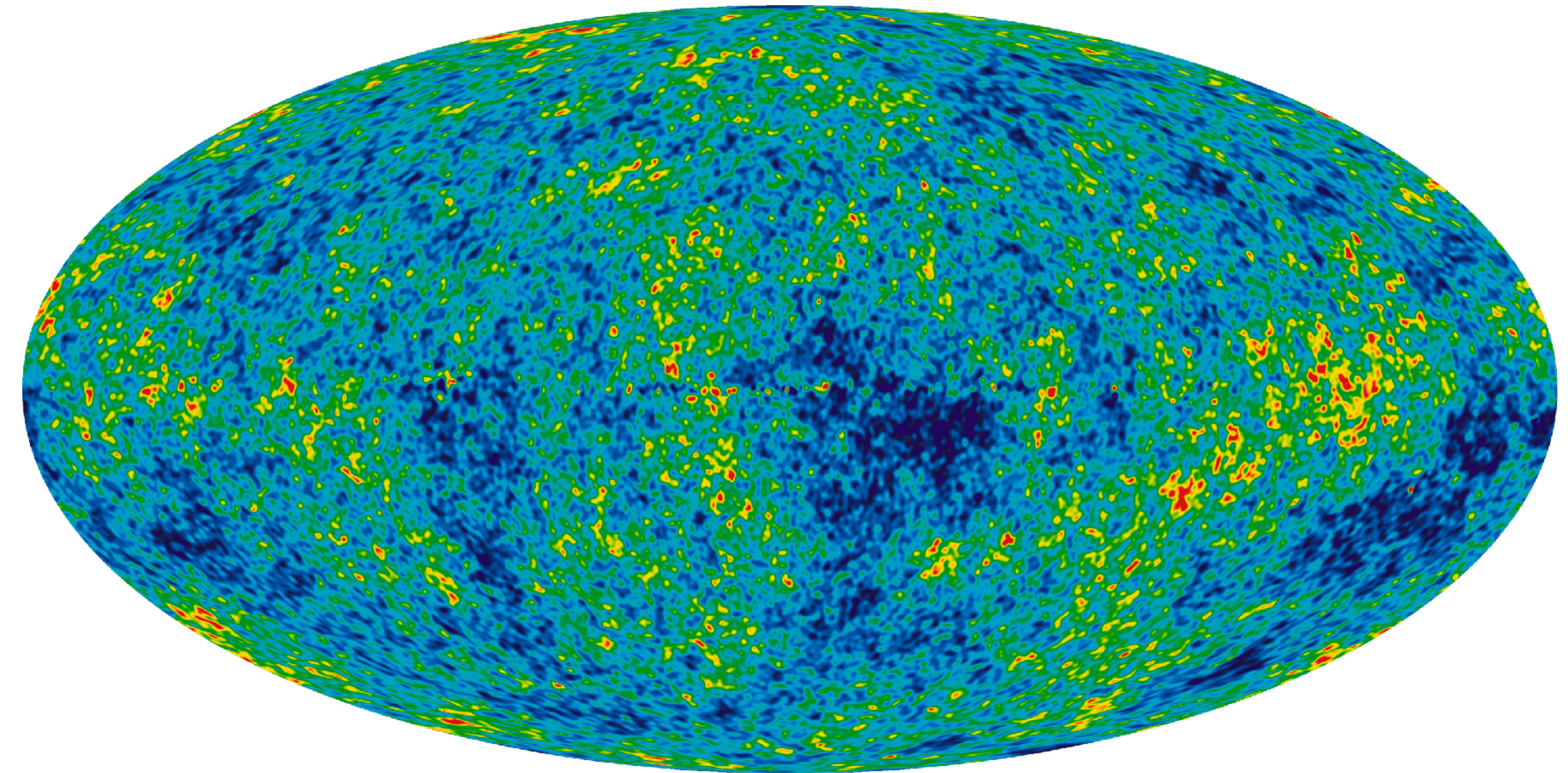
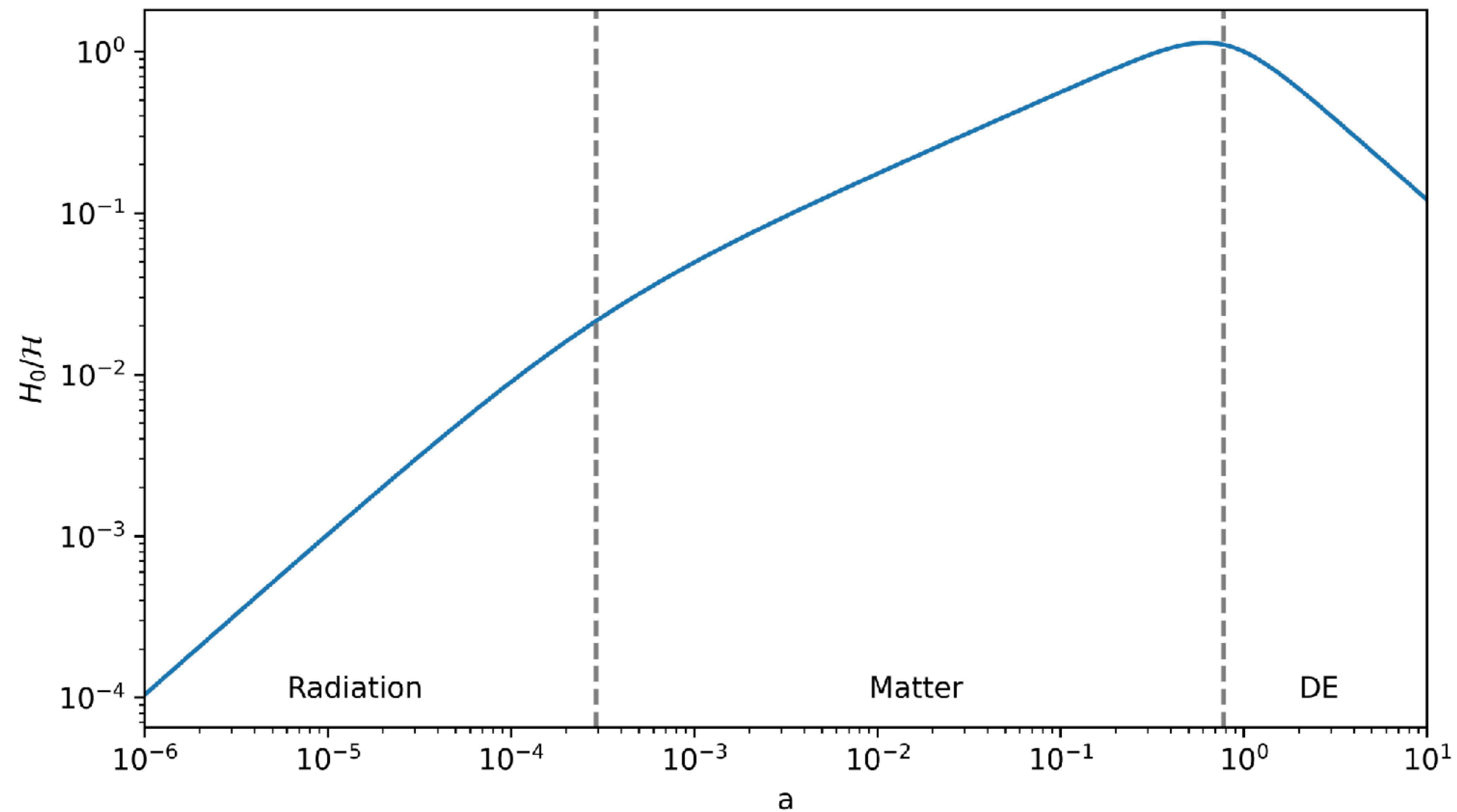
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How does model affect cosmology?



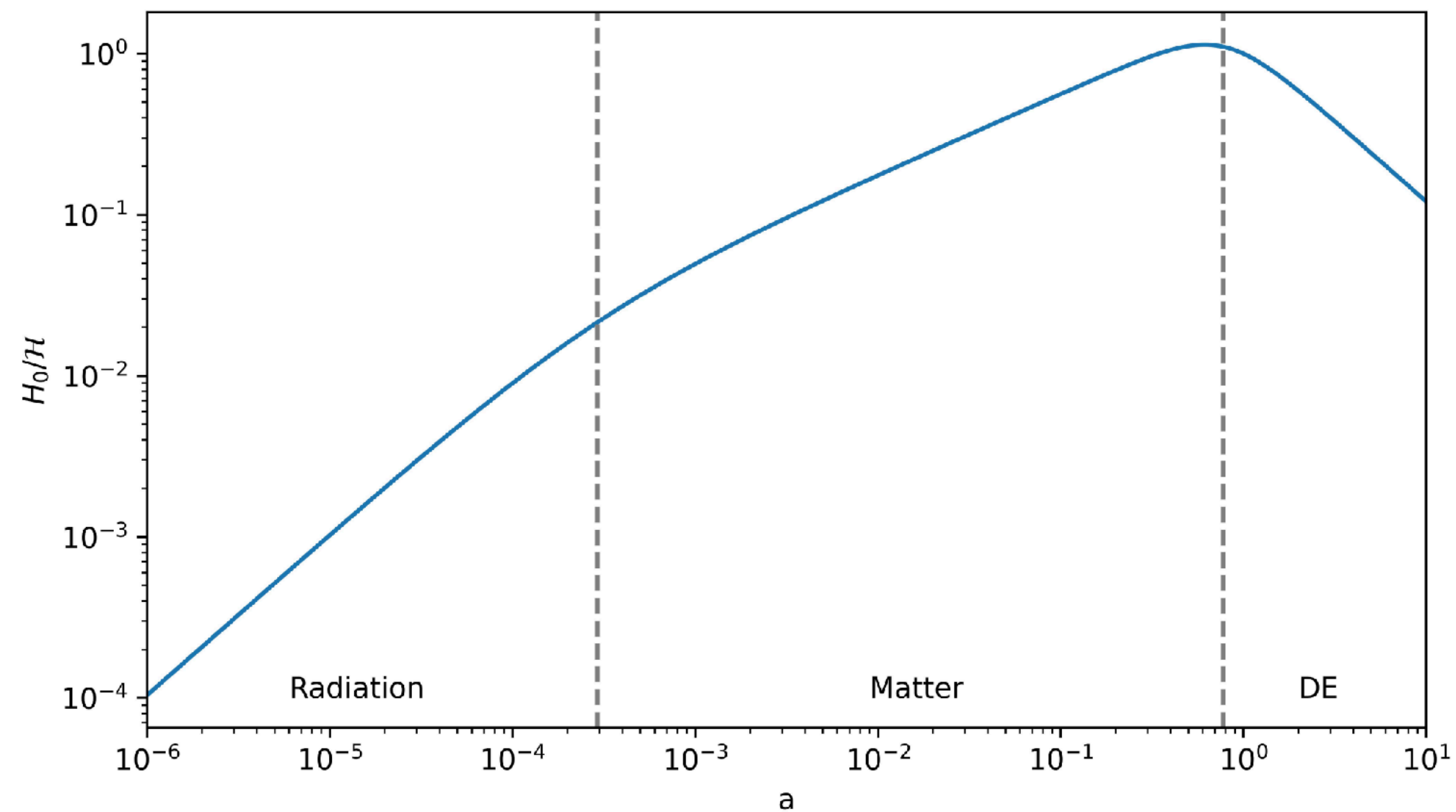
Hubble horizon

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

CMB power spectrum

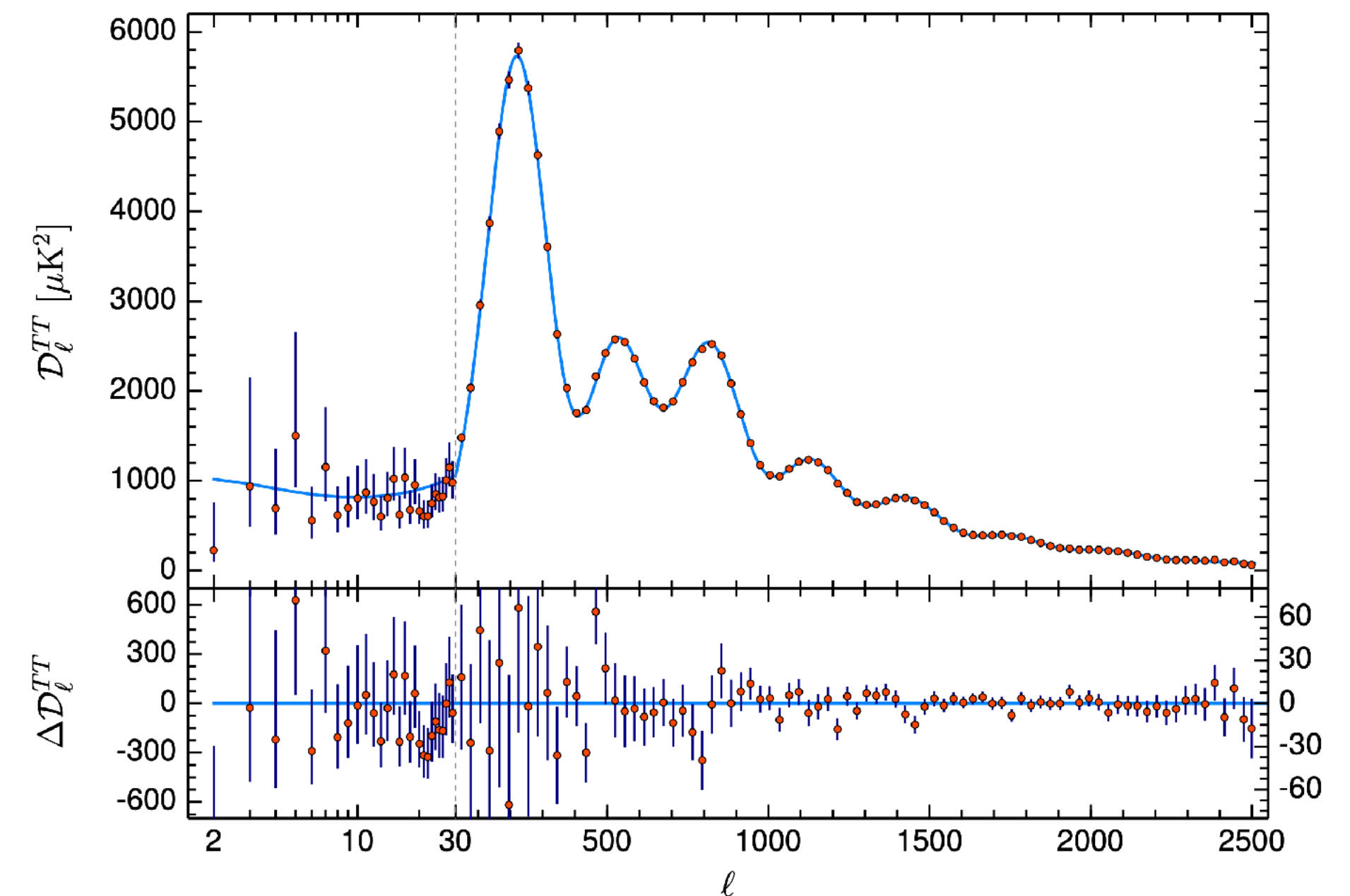
- Statistical property of temperature fluctuations of cosmic microwave background
- Contains a wealthy amount of information

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Hubble horizon

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CMB power spectrum

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TorC Cosmological Parameters

- H_0 - Expansion rate of the Universe today
- Ω_b - Amount of normal matter
- Ω_c - Amount of dark matter
- τ_{reio} - When the first stars lit up the Universe
- n_s - How fluctuations depend on scale
- A_s - Strength of the fluctuations

- ϖ_r - How much twisting of spacetime
- Ω_L - Amount of Dark energy

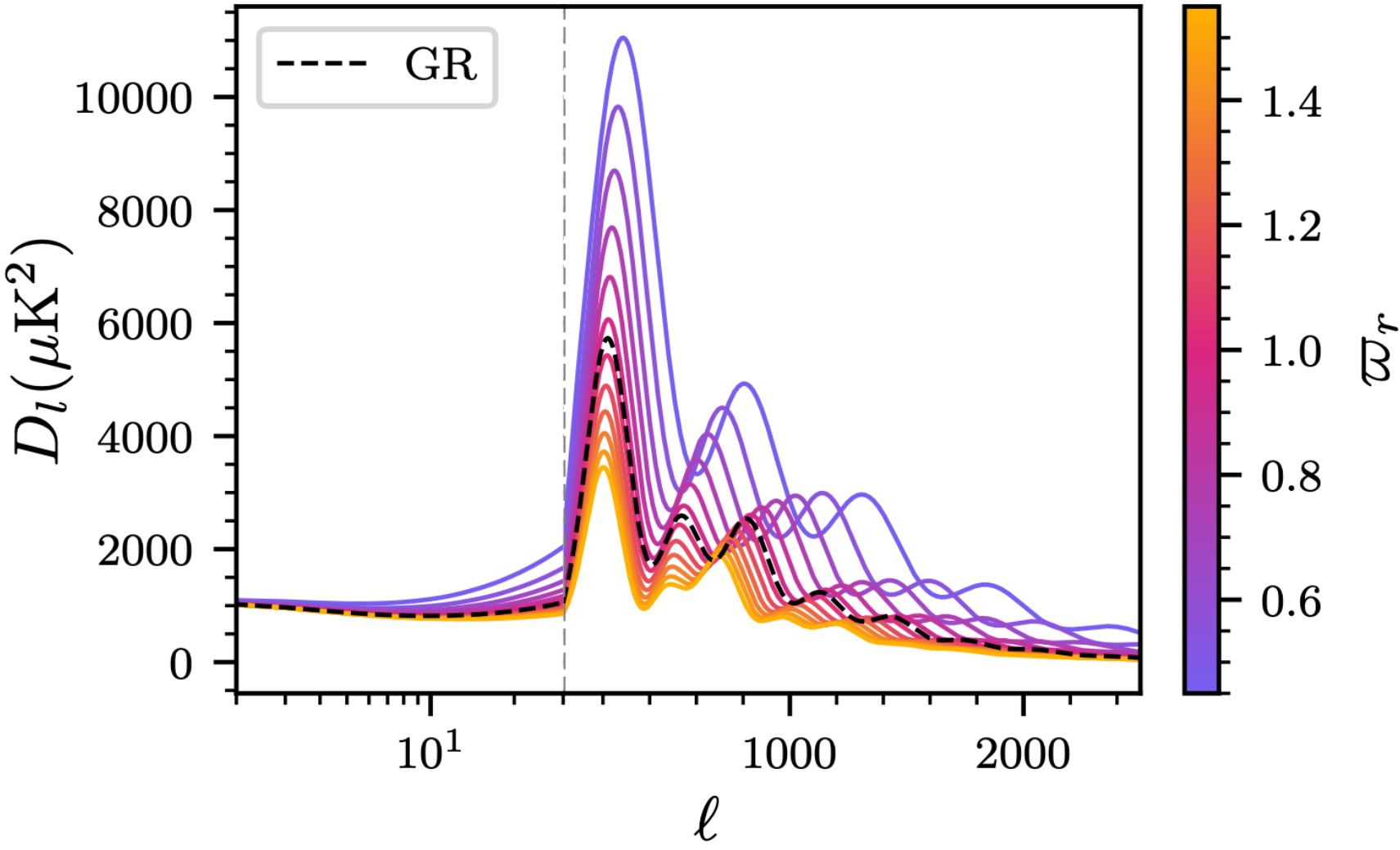
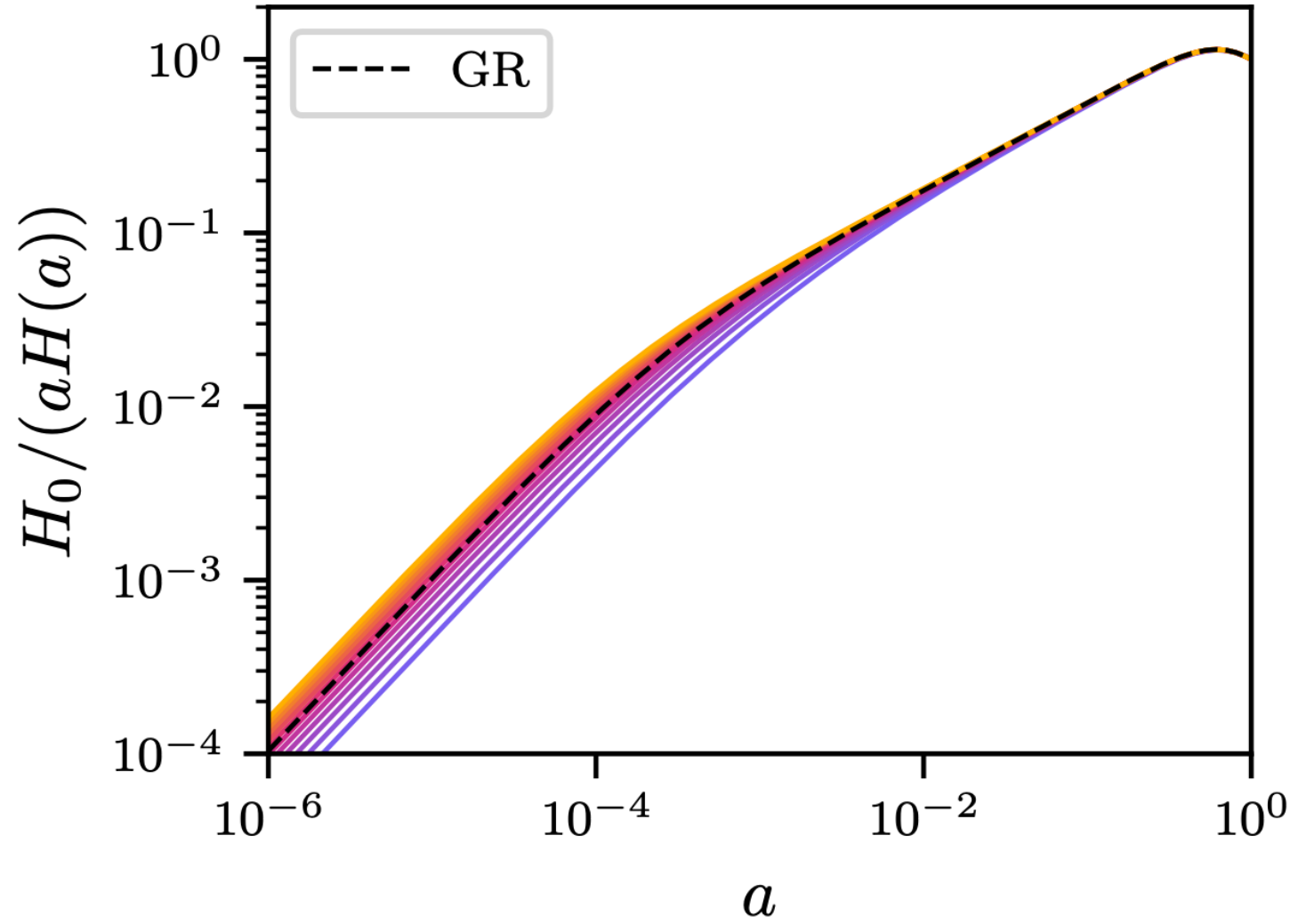
Λ CDM parameters

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

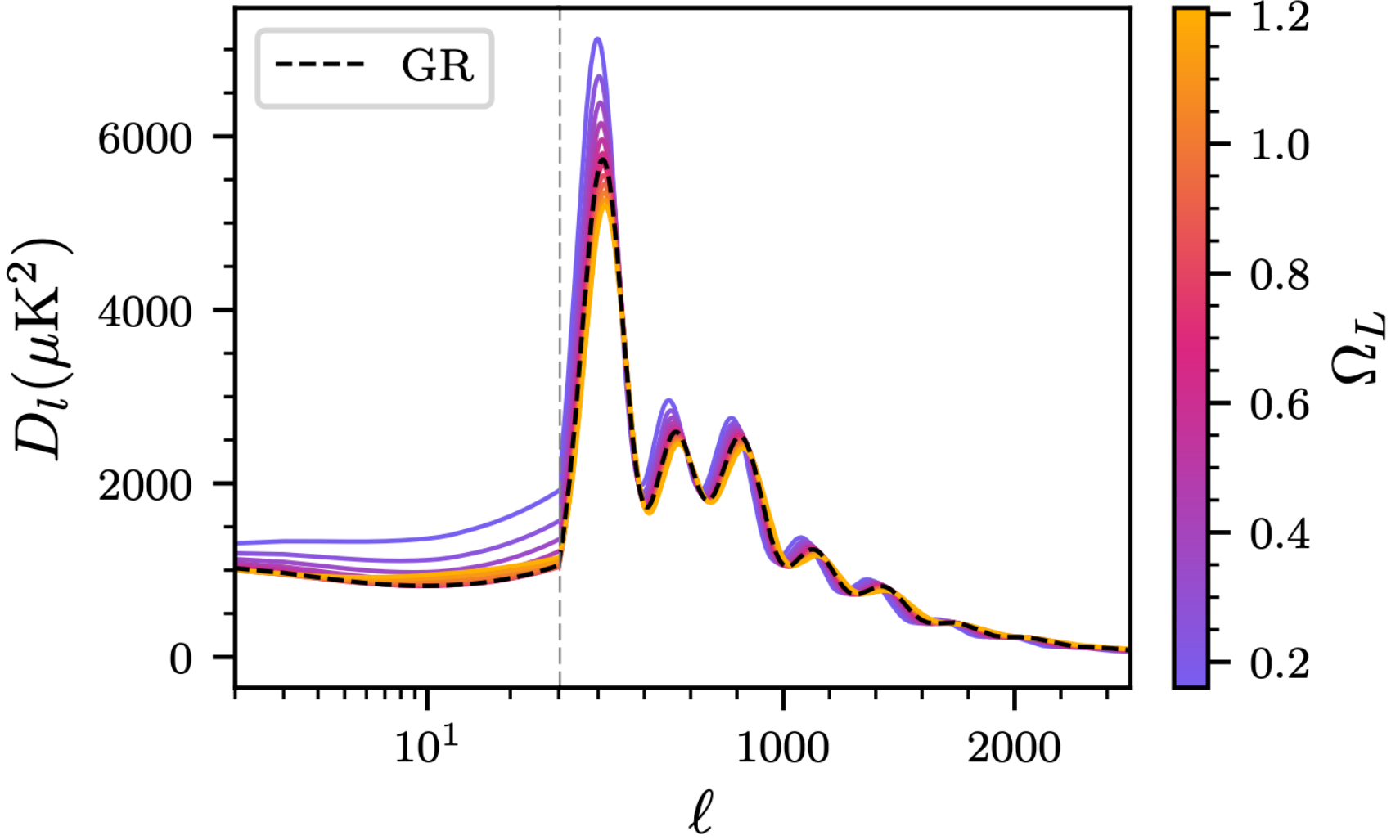
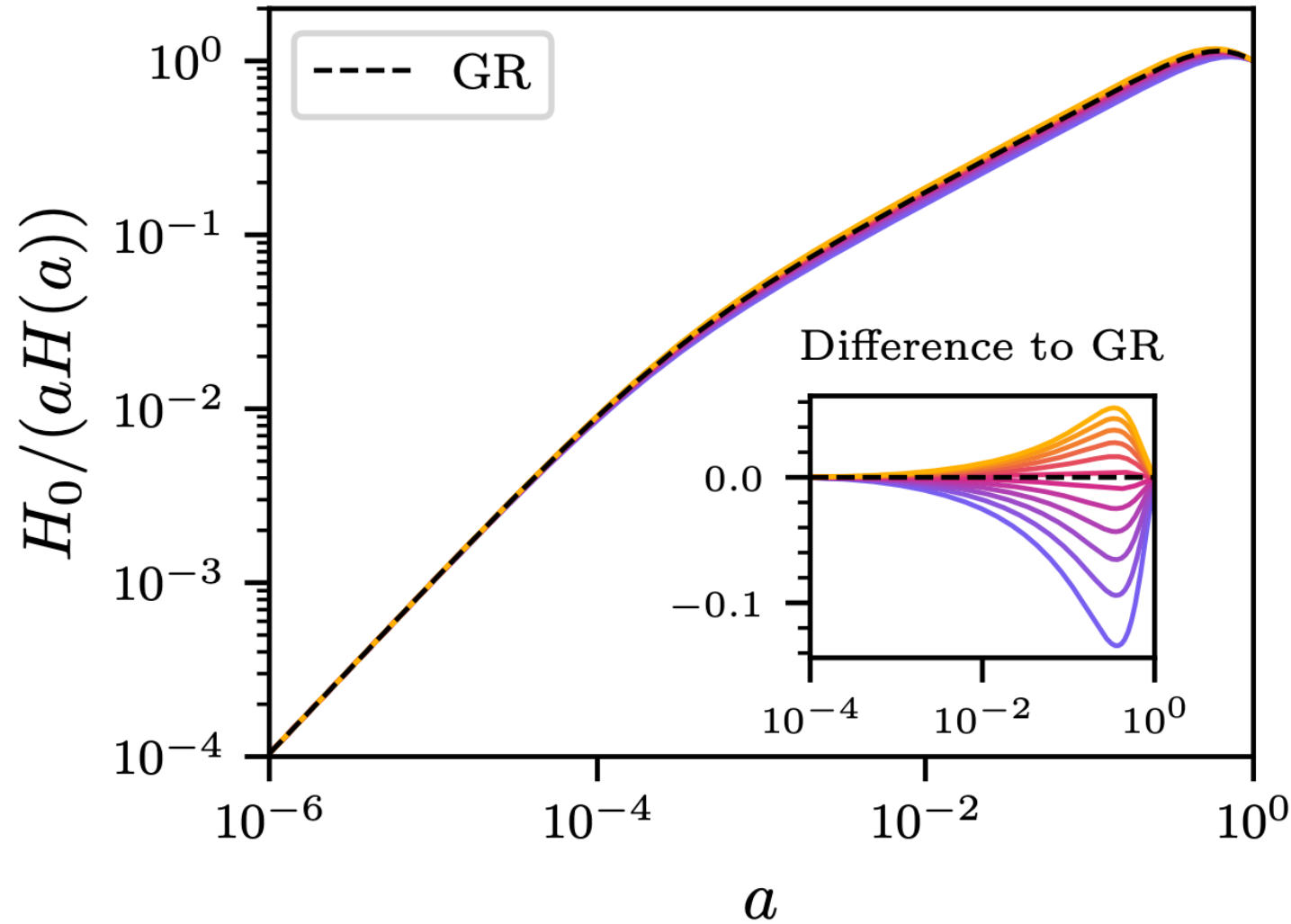
TorC parameters

How the New Parameters Affect Cosmology

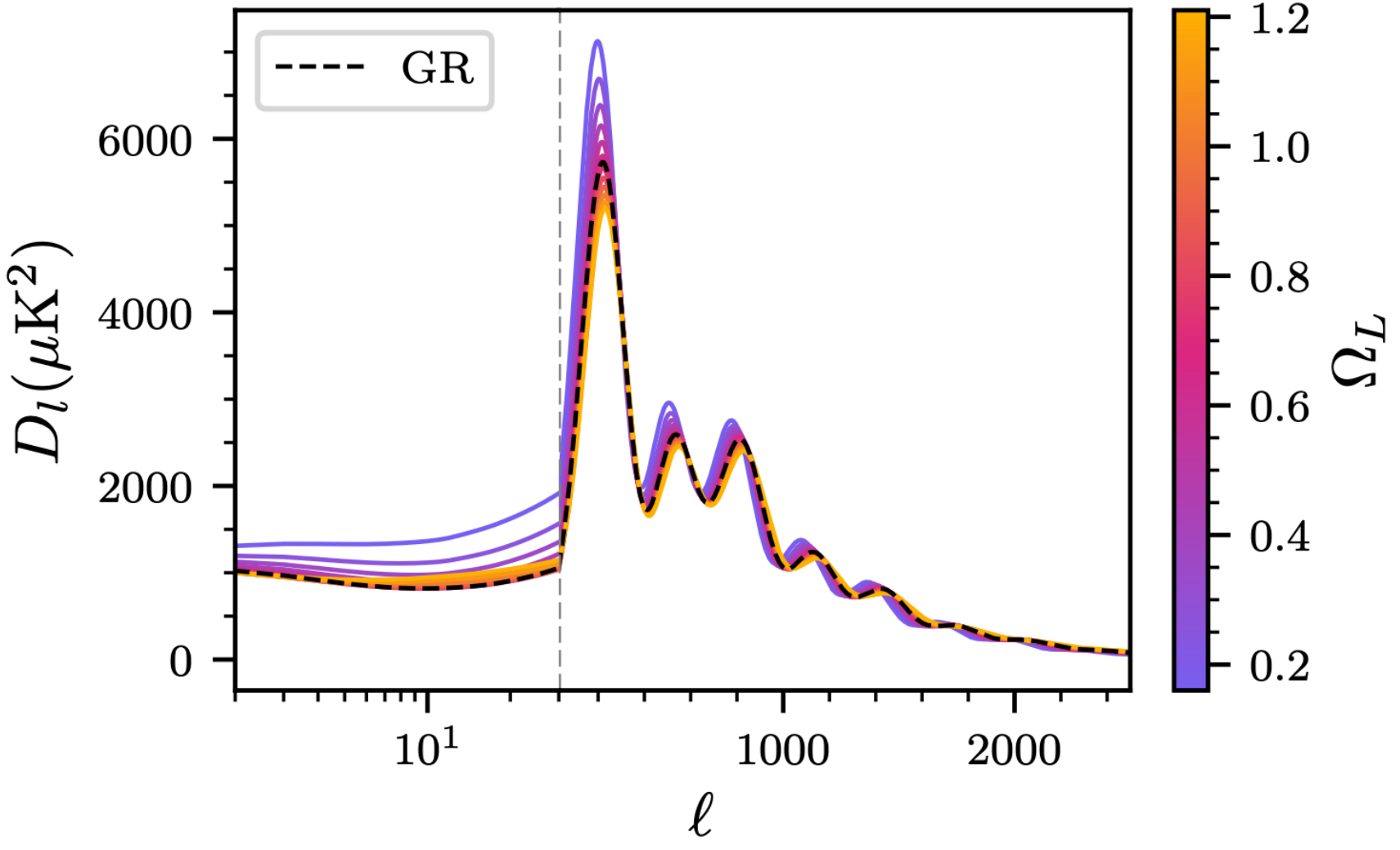
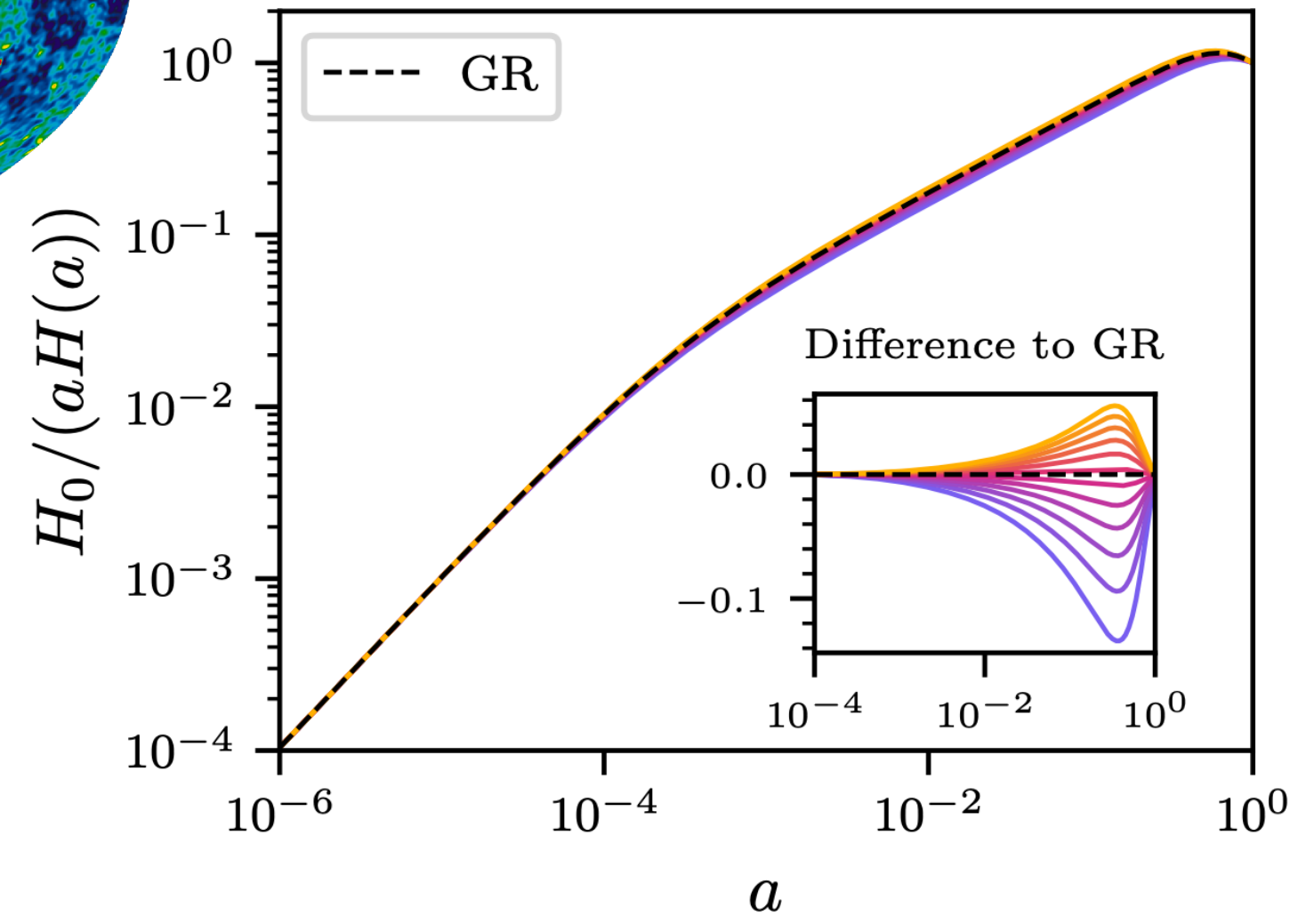
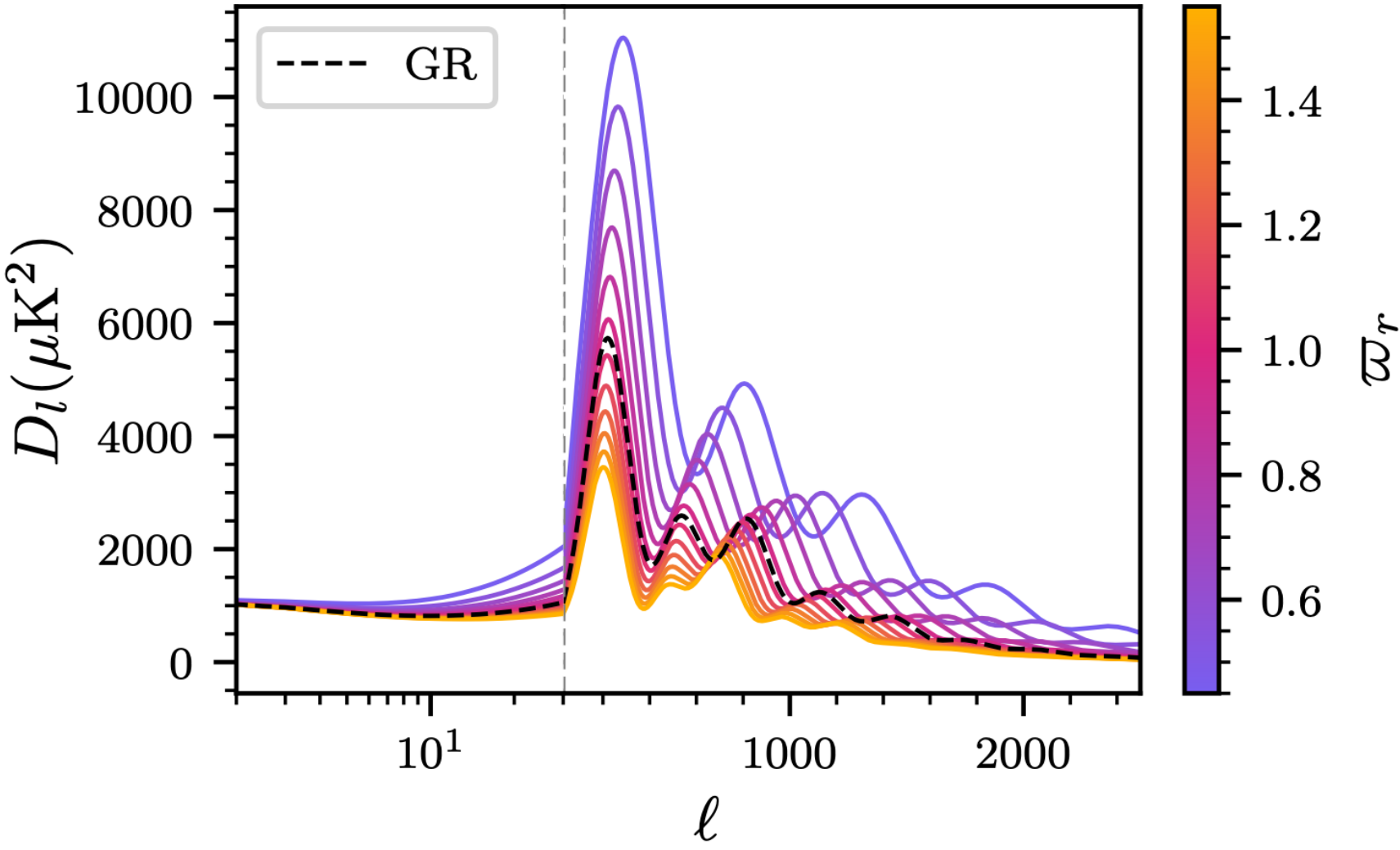
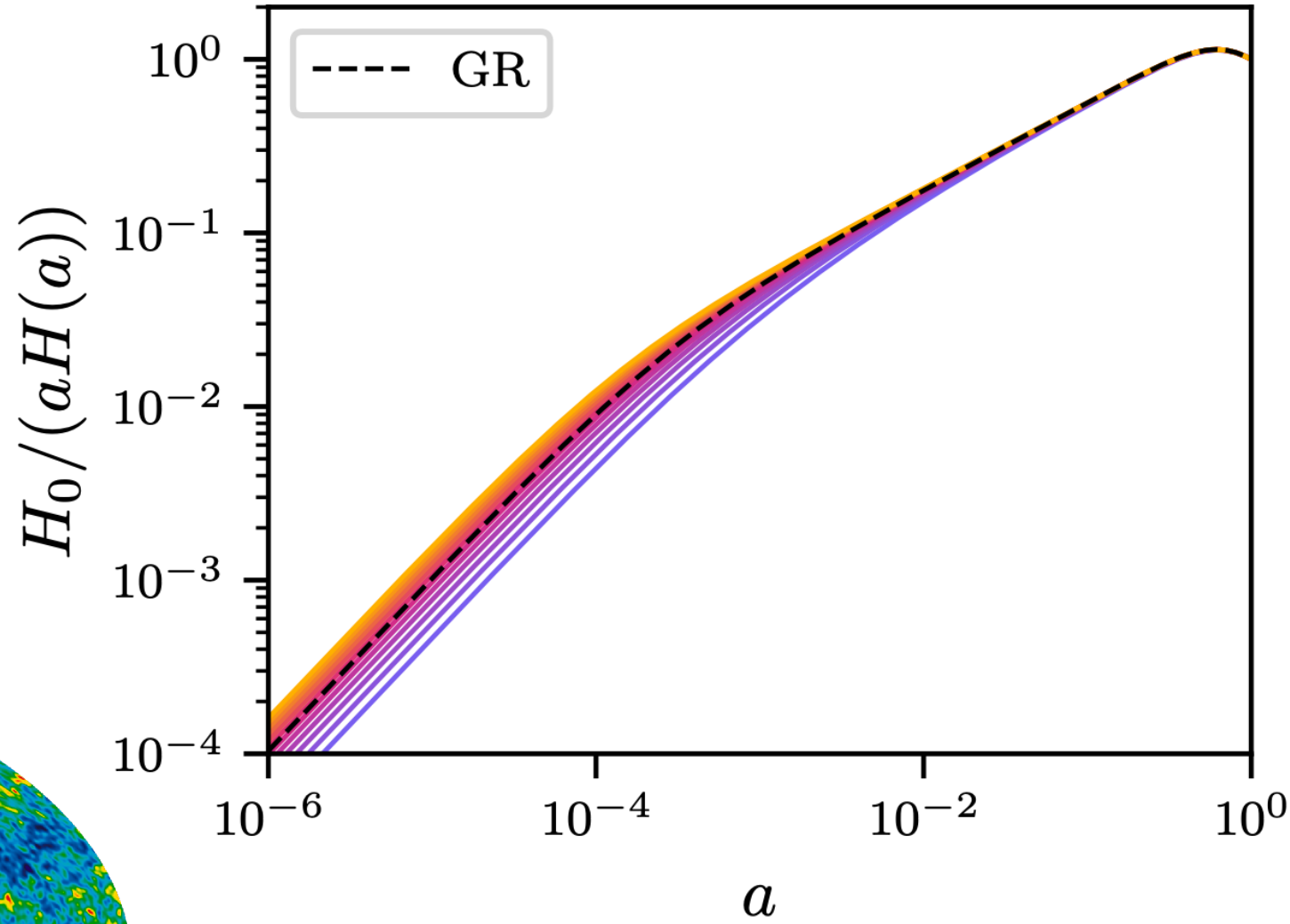
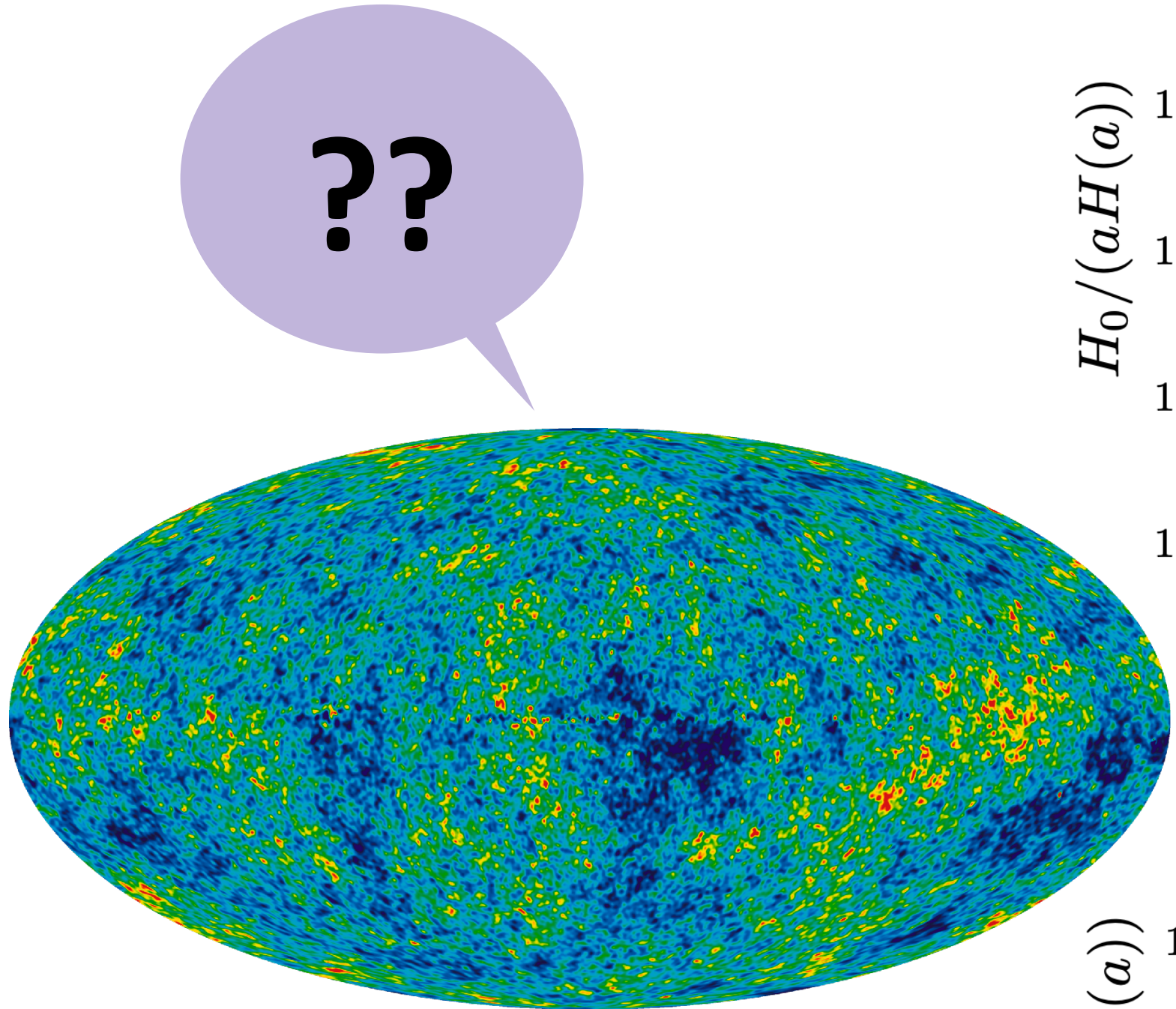
Affects Early Universe



Affects Late Universe



How the New Parameters Affect Cosmology



Bayesian Inference and Nested Sampling

Will Handley

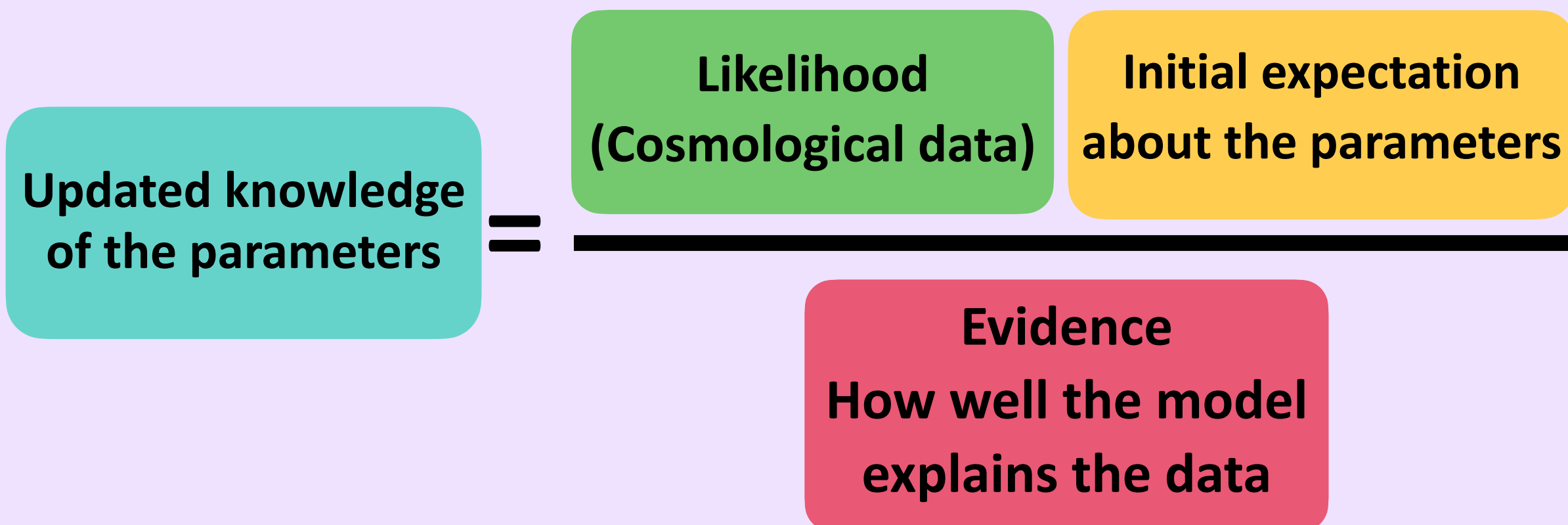


Parameter Estimation:

- 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

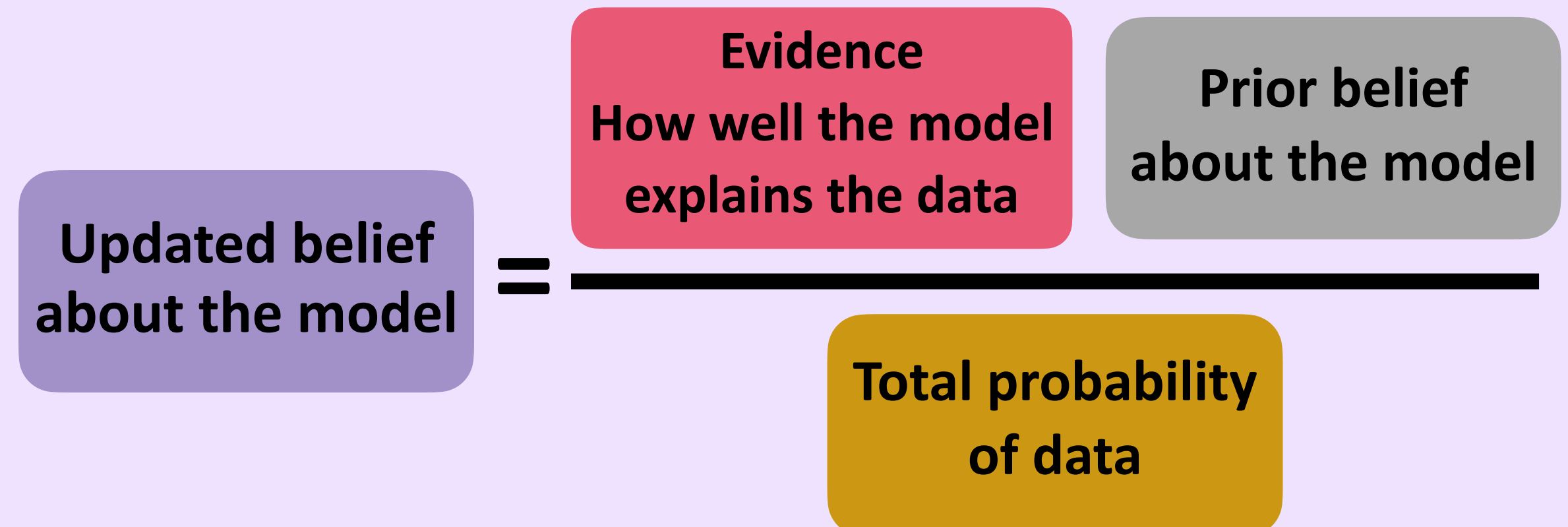


Model Comparison:

- How much does data support the model?

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

- Higher evidence favours a model



Bayesian Inference and Nested Sampling

Will Handley

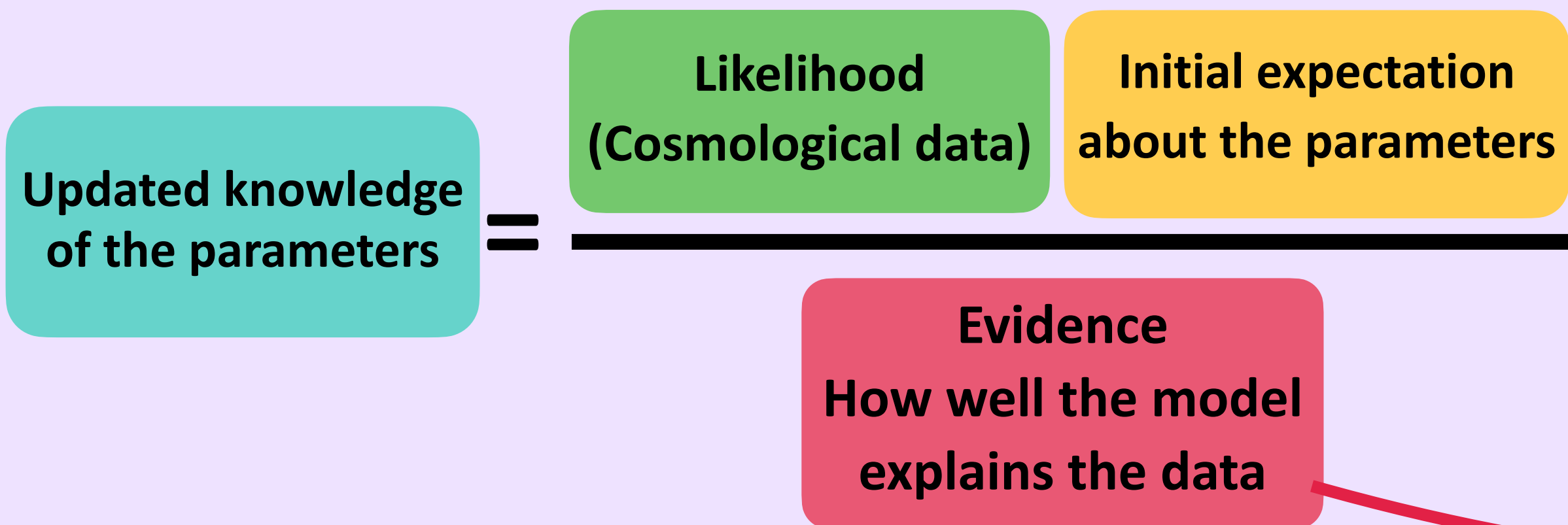


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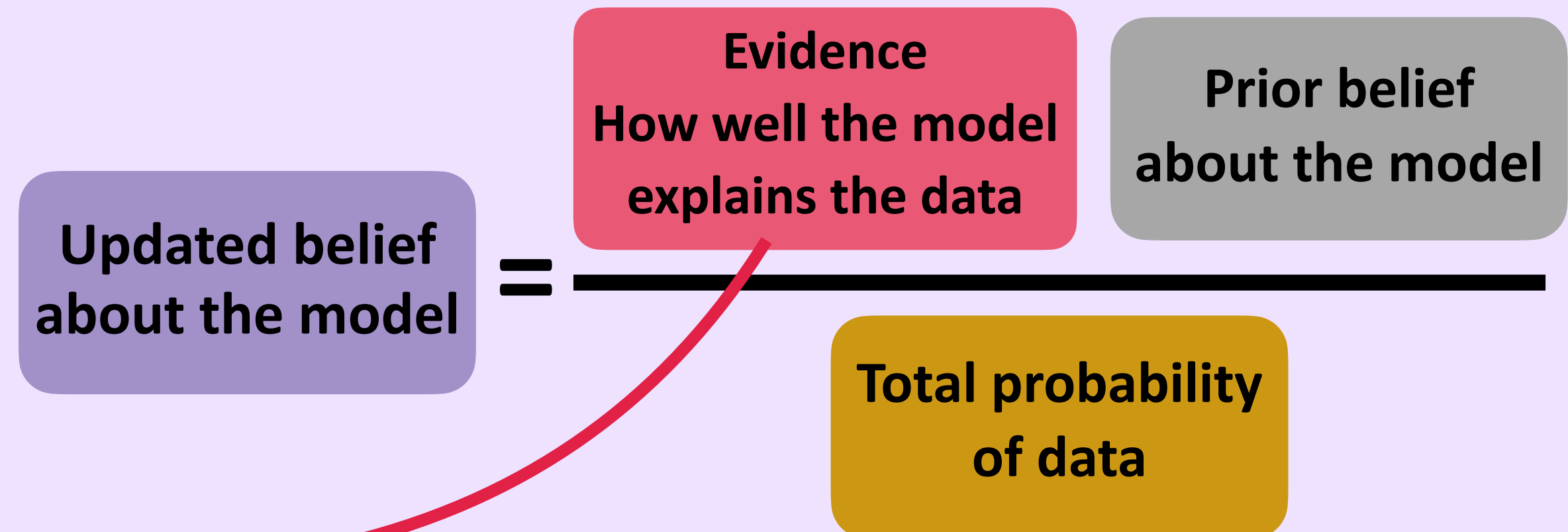


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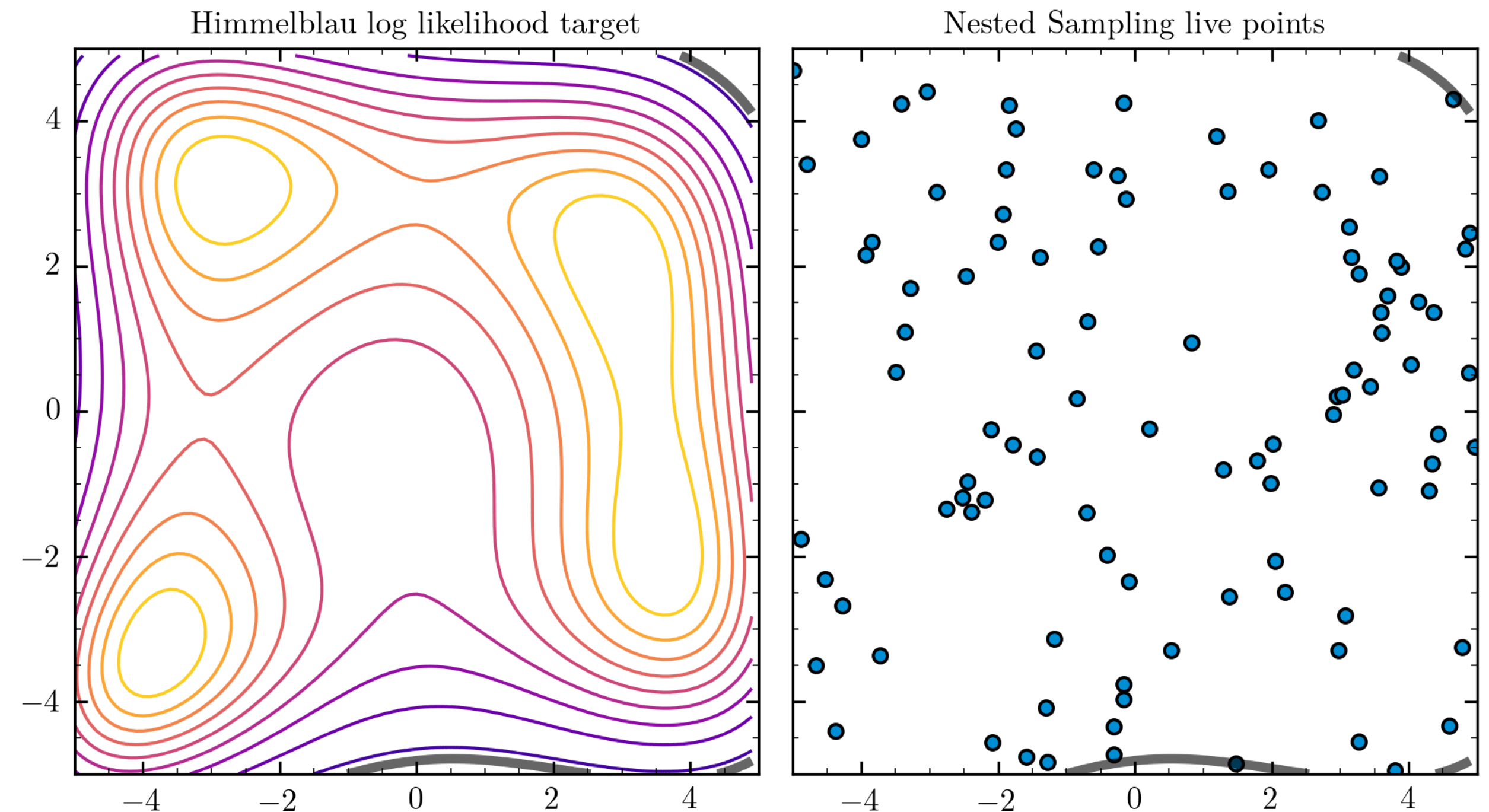


Nested Sampling:

- Computes evidence directly
- Handles multimodal posteriors

Evidence
How well the model
explains the data

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



[Gif from David Yallup](#)

Method: The Analysis Pipeline — Cobaya

Cobaya - code for **bayesian** analysis [[2005.05290](https://arxiv.org/abs/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

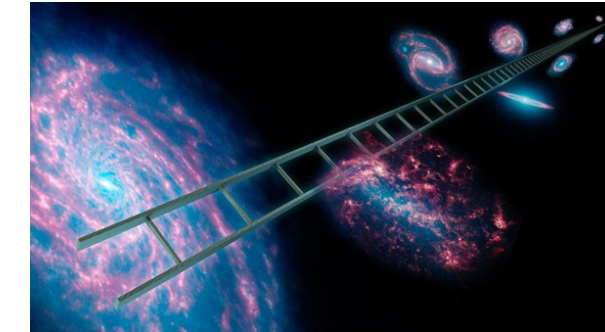
CAMB:

- Computes CMB Power spectrum for each parameter set.

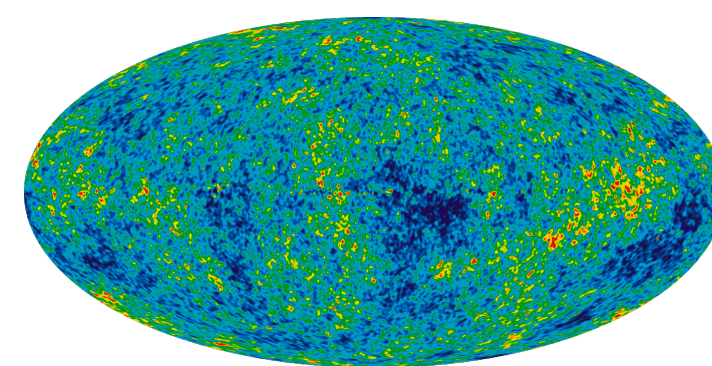
Polychord:

- Explore parameter space with nested sampling

SHOES 2020



Planck 2018



Result:

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



Bayesian Evidence

- Compare the overall viability of models

Log Evidence

Log Evidence

=

How well the model fits the data

-

Complexity penalty

- Naturally incorporates ‘Occam’s razor’
- Direct comparison on how well the model fits, and how complex the model is.

Tension Quantification

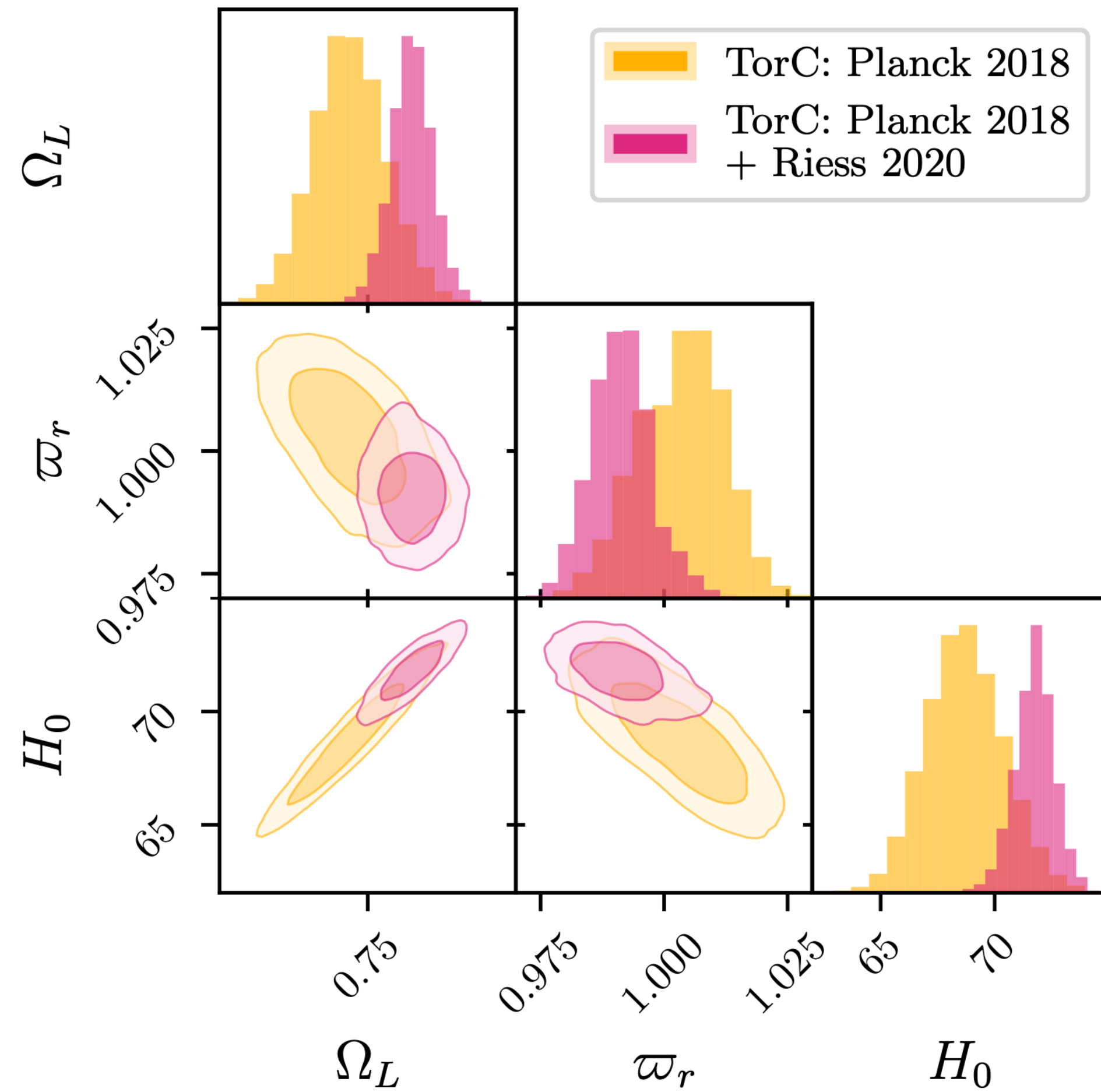
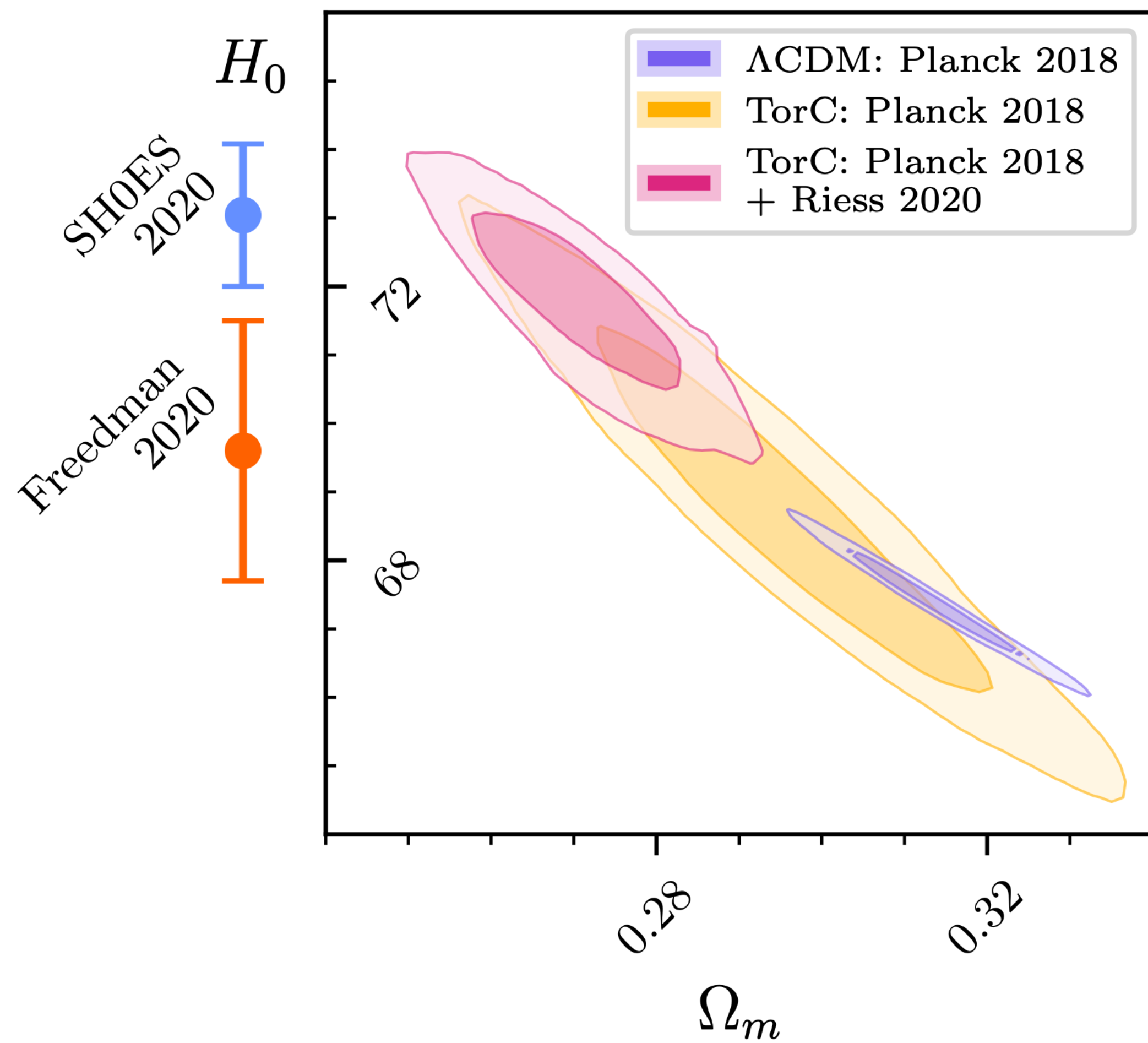
- Assess the level of agreement between two datasets under a model

R-statistic

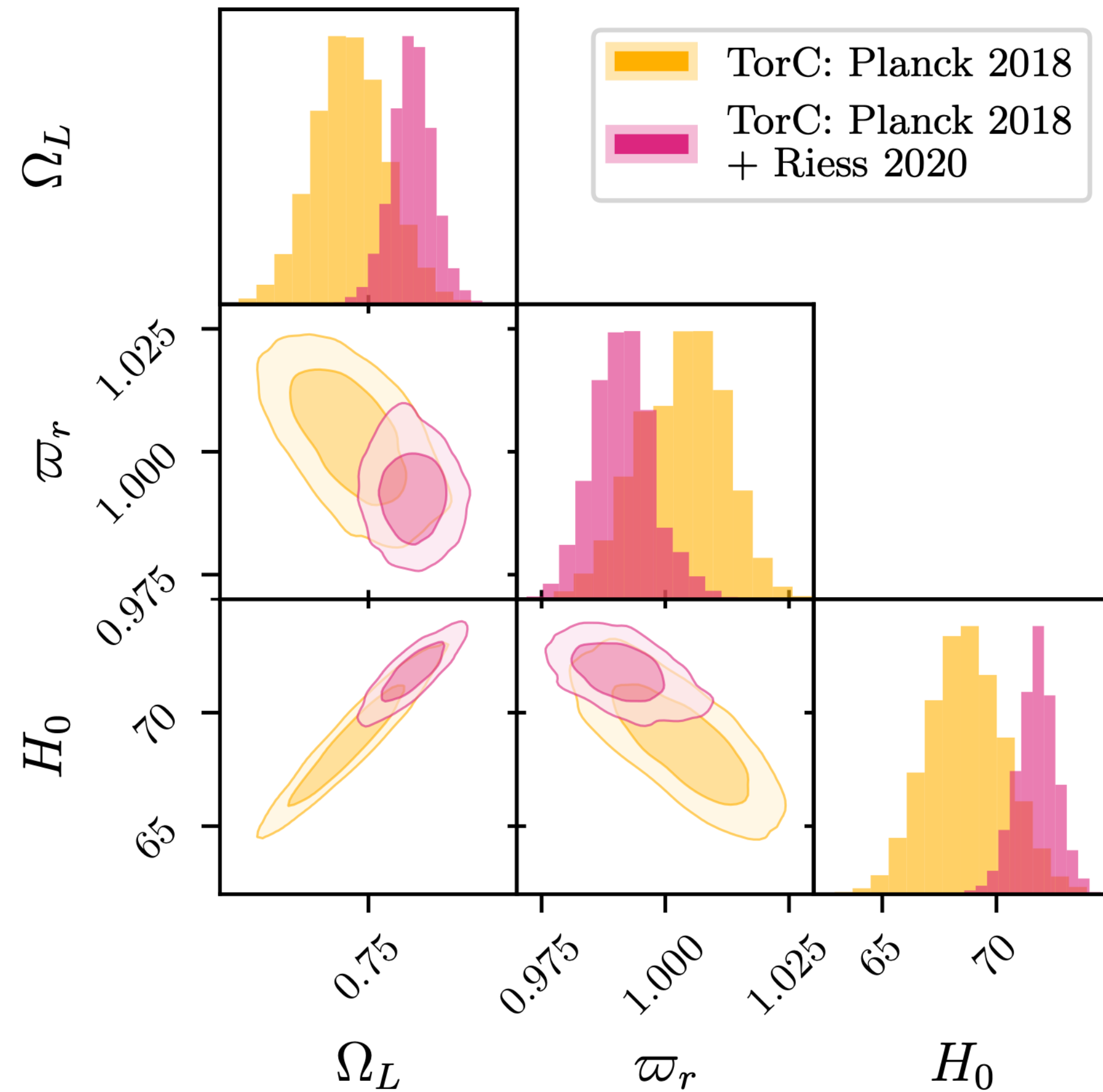
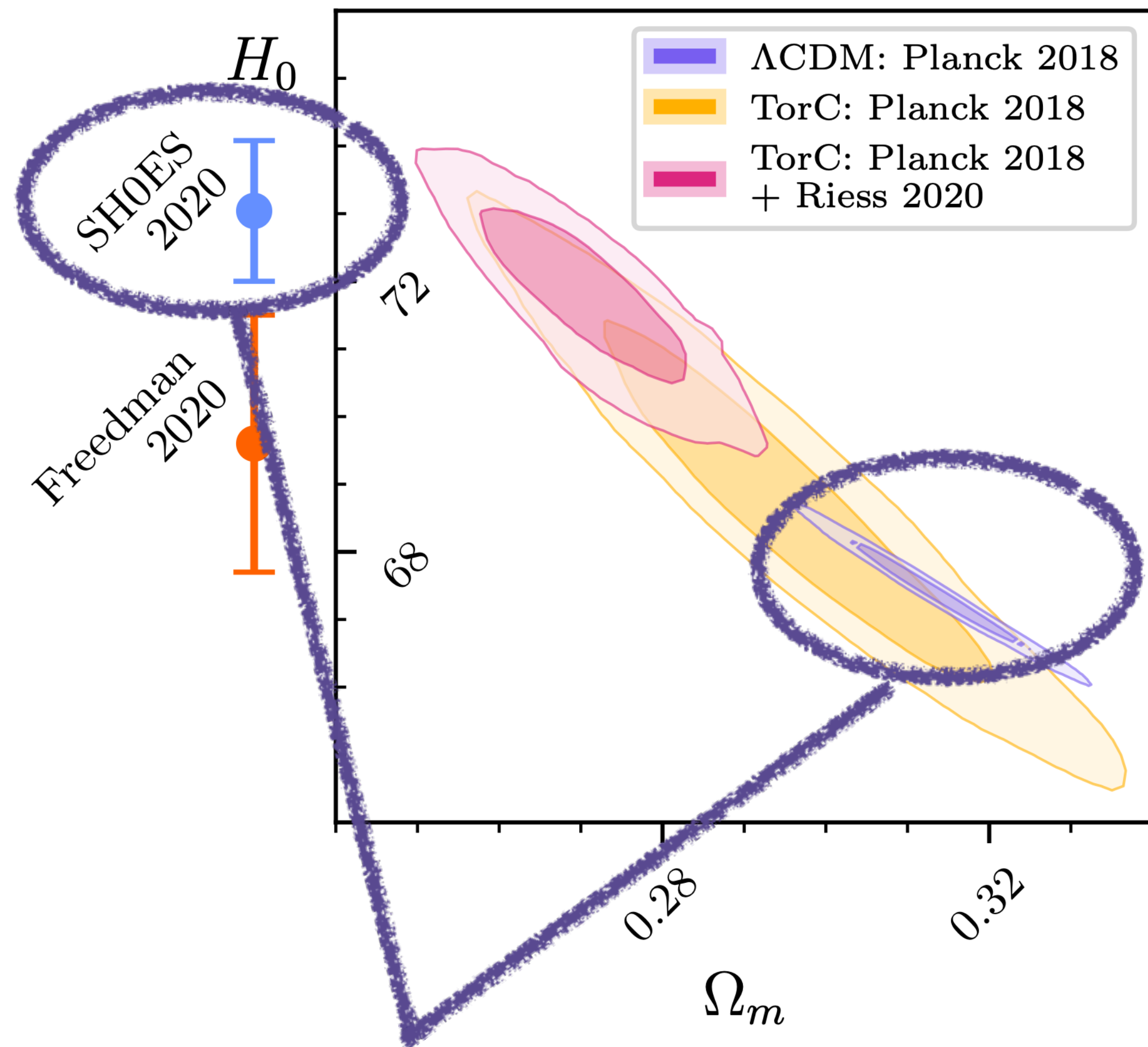
- Measures relative confidence in dataset A given dataset B, compared to its self-consistency.

- $R \gg 1$: indicates that dataset B strengthen confidence in dataset A by a factor of R
- $R \ll 1$: indicates tension

The Main Result: Alleviating the Hubble Tension

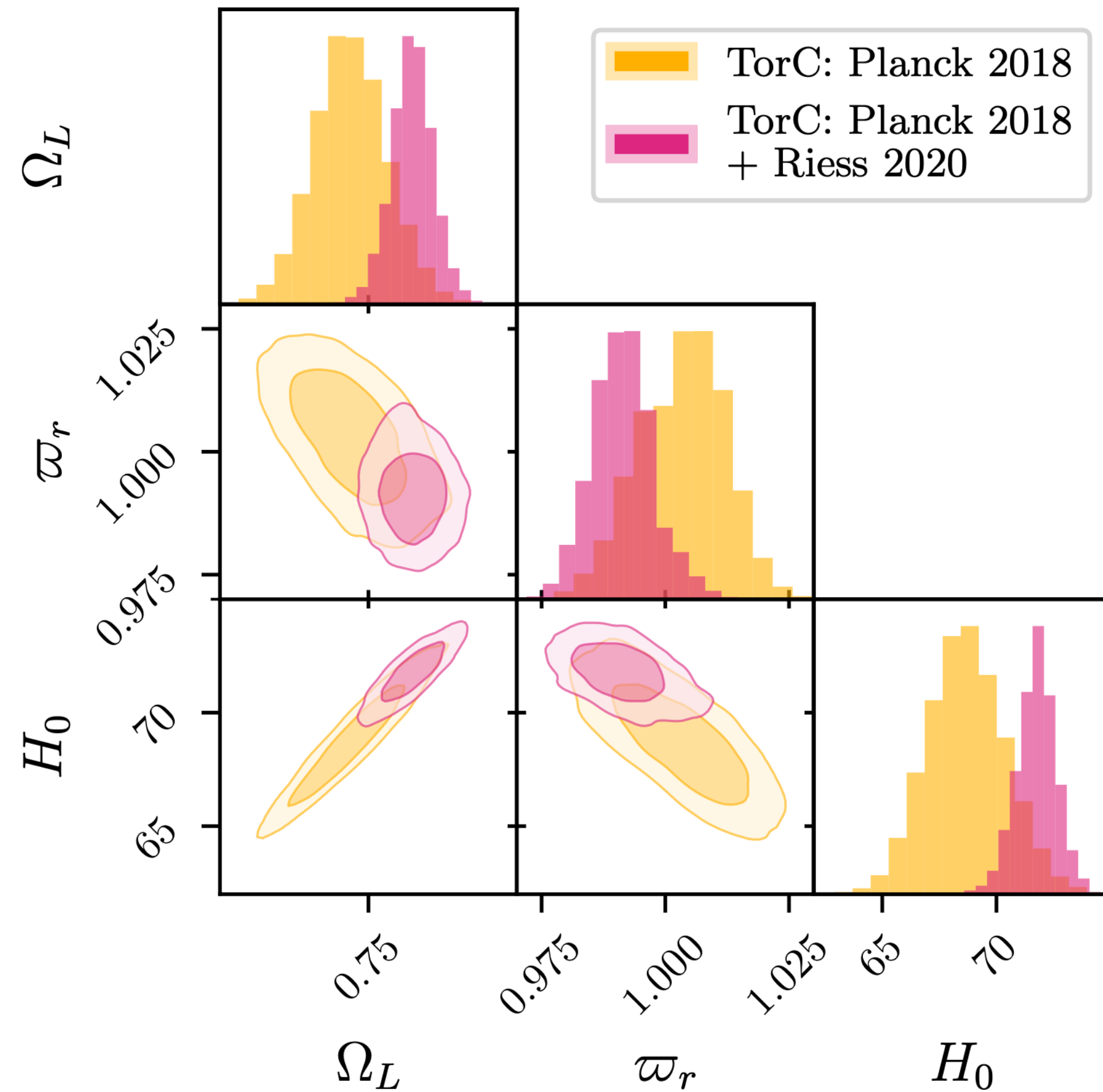
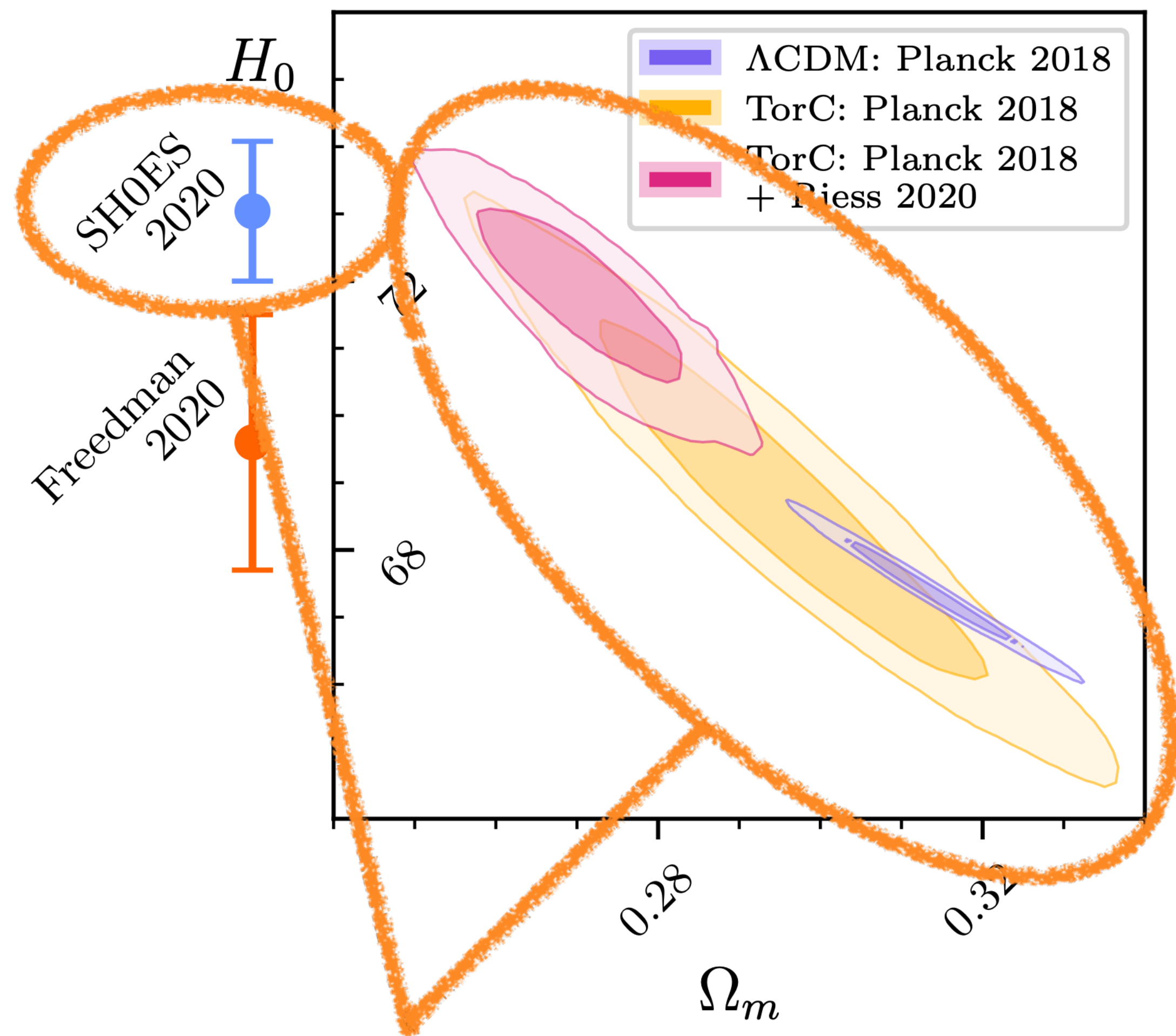


The Main Result: Alleviating the Hubble Tension



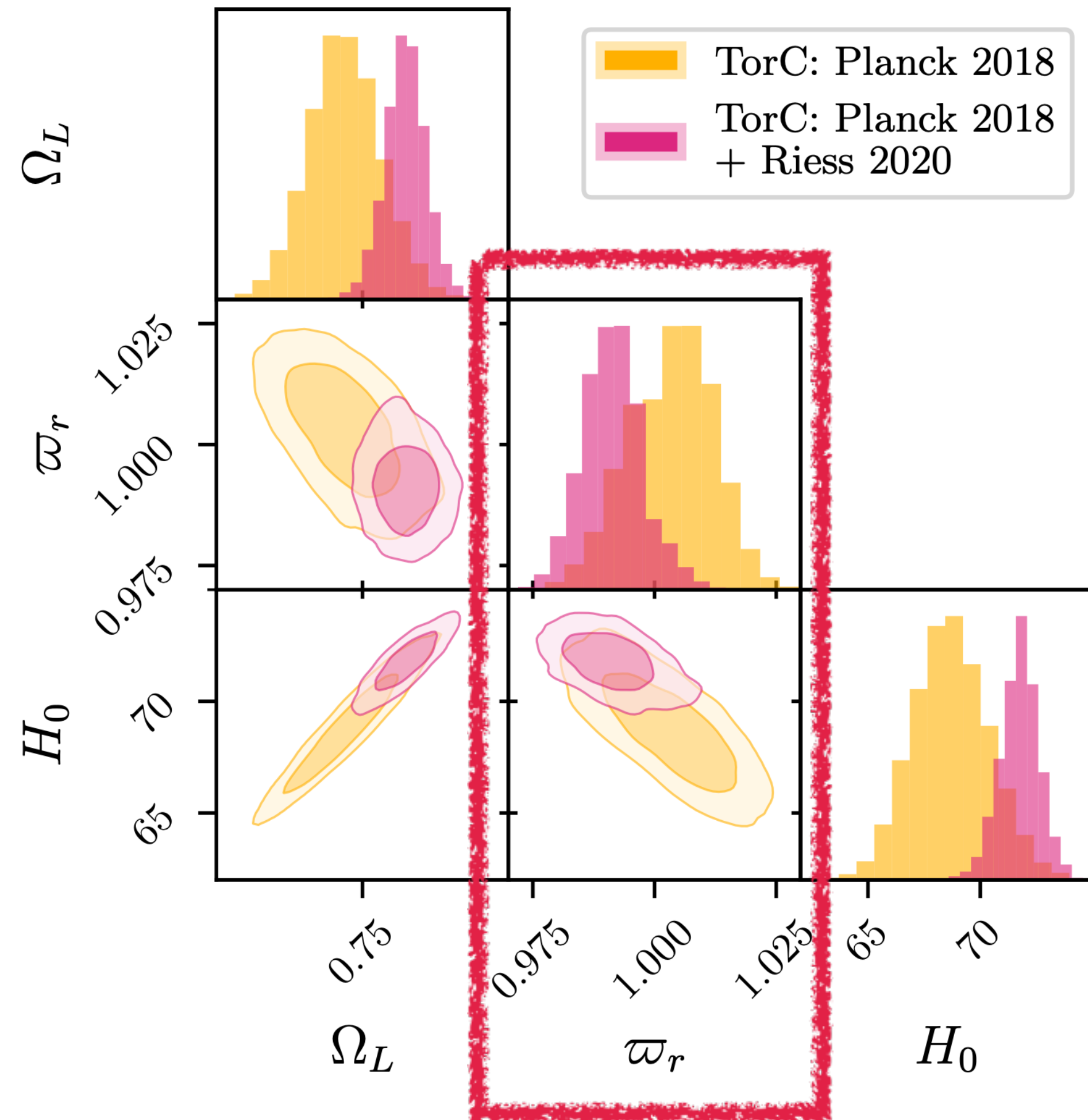
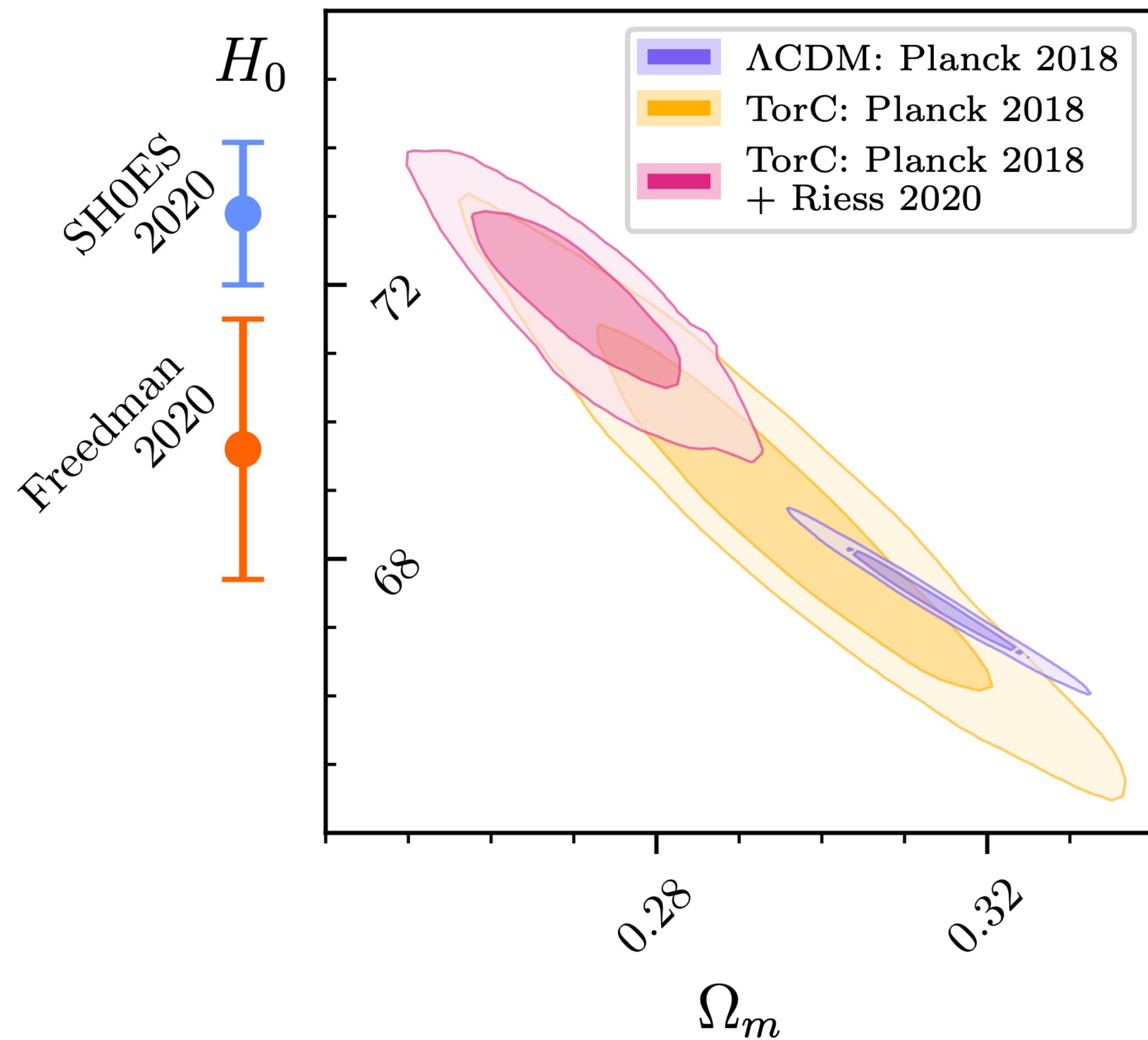
Λ CDM: SHOES 2020 & Planck 2018 data in tension

The Main Result: Alleviating the Hubble Tension



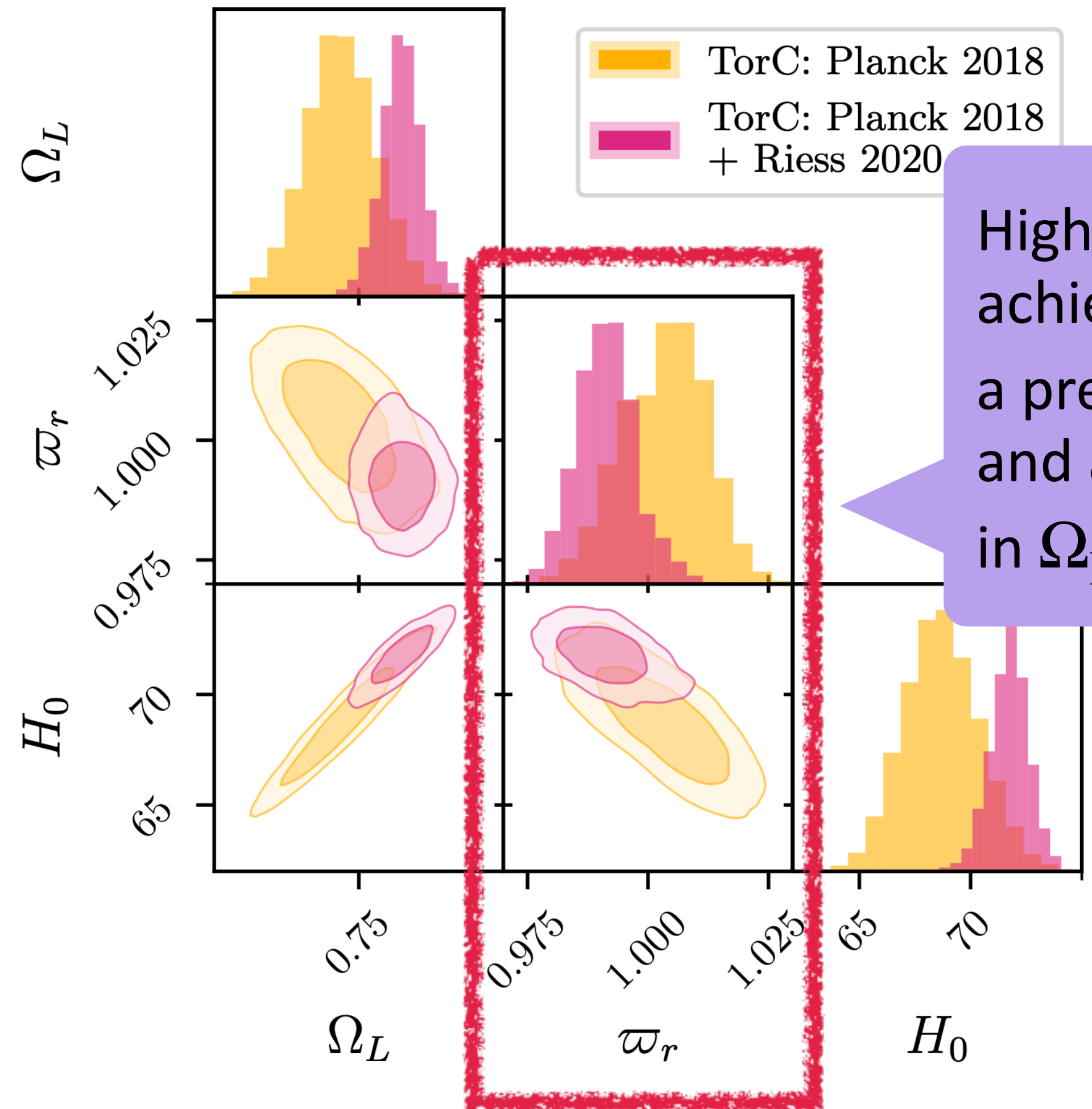
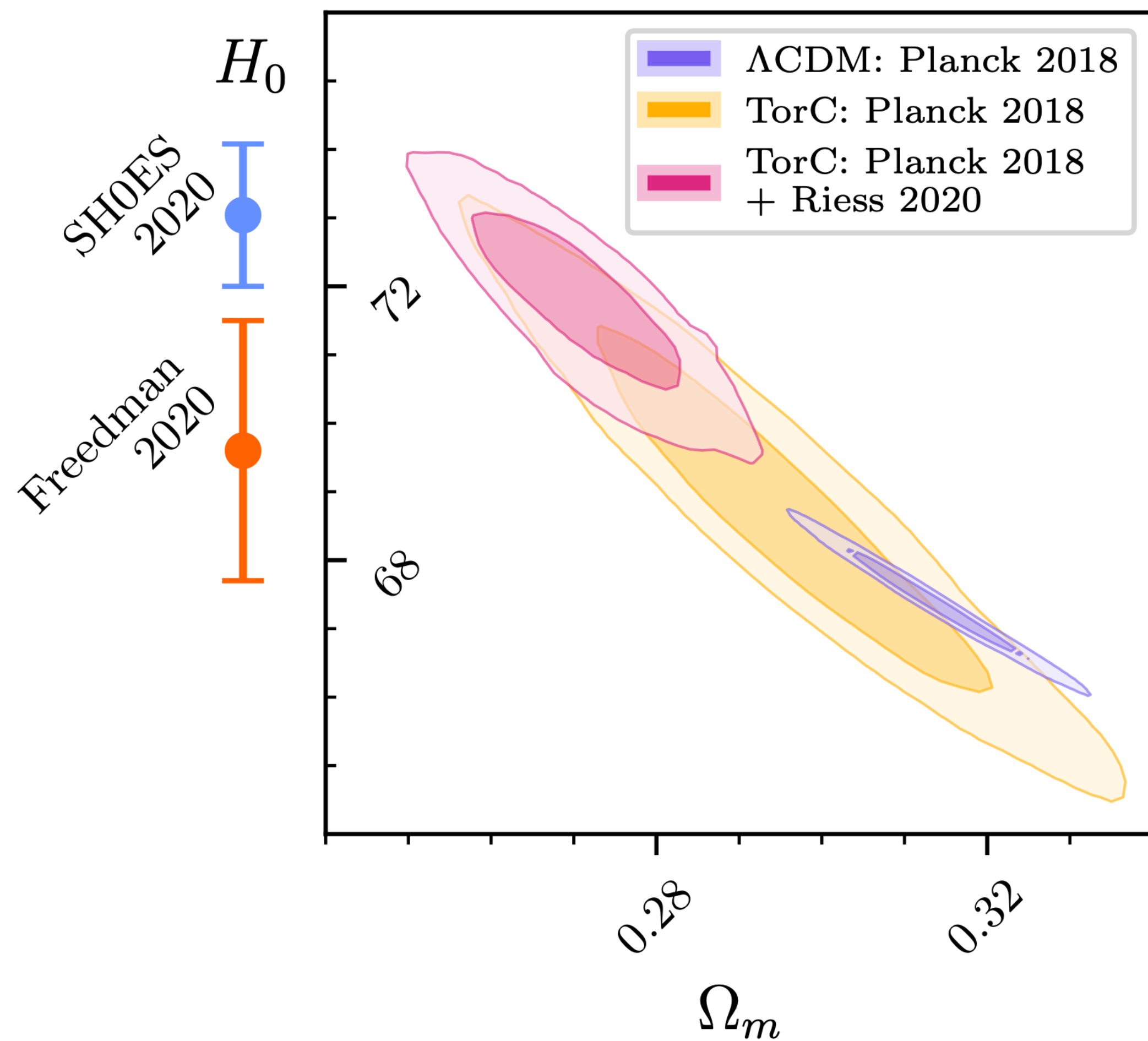
TorC: Planck 2018 data is consistent with SHOES

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

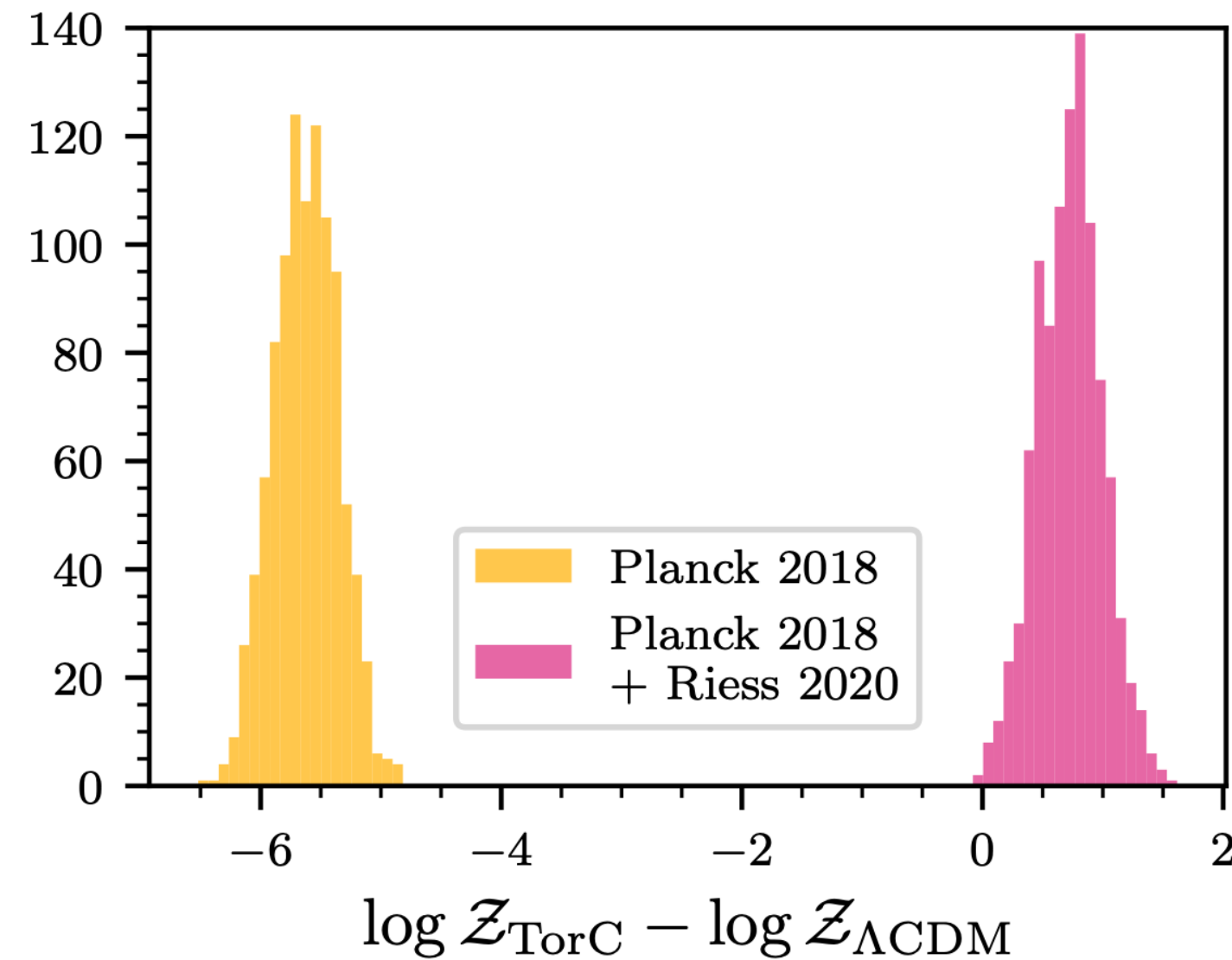


Higher H_0 is achieved through a presence of w_r and an increase in Ω_L .

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
- Λ CDM

$$\Delta \log Z^{\text{Planck}}$$

$$= 0.417 \pm 0.114 - 6.044 \pm 0.265$$

$$\Delta \log Z^{\text{Joint}}$$

$$= 6.792 \pm 0.113 - 6.071 \pm 0.263$$

Log Evidence

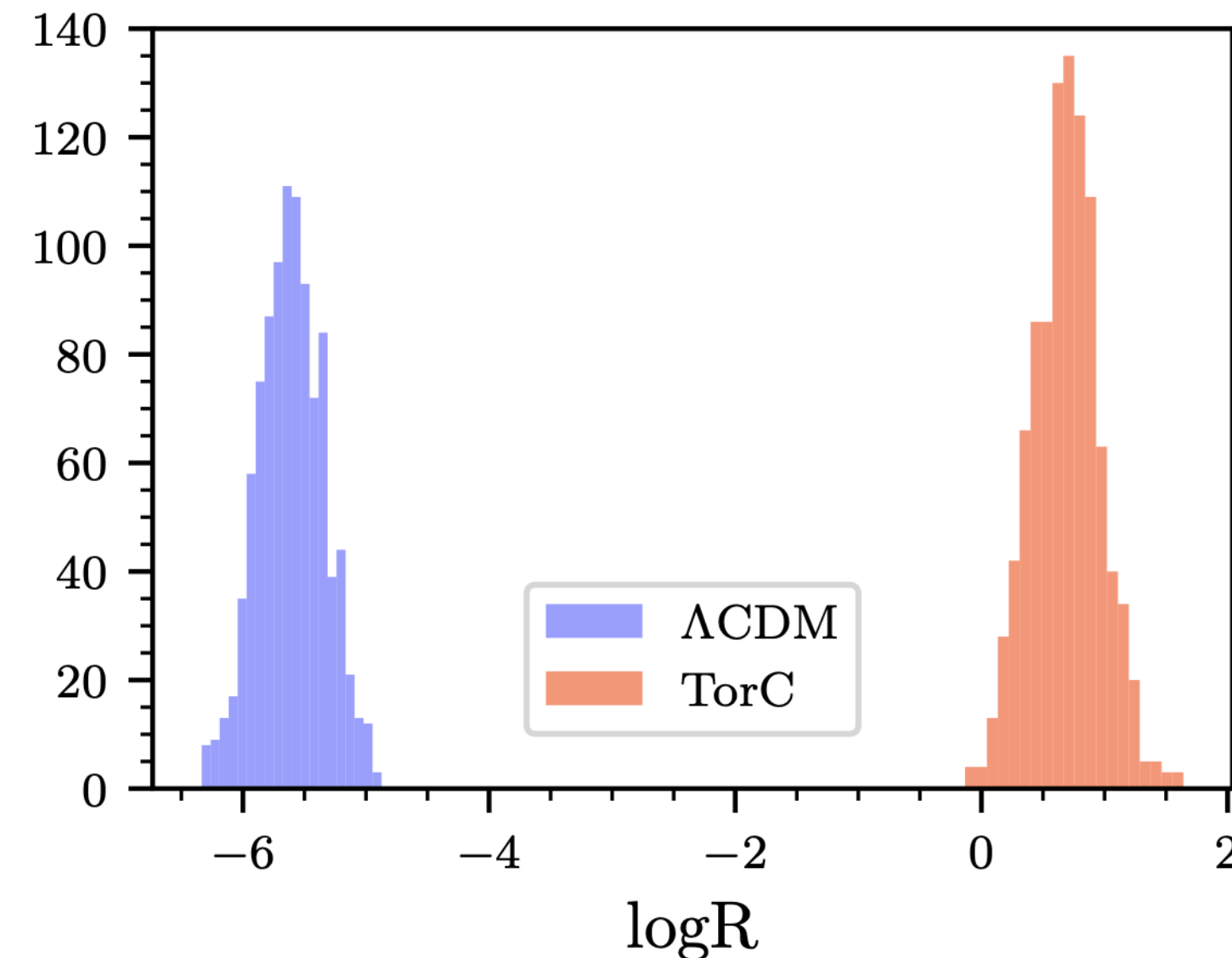
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How well the model fits the data

- Complexity penalty

The TorC model is not decisively favoured

Tension Quantification



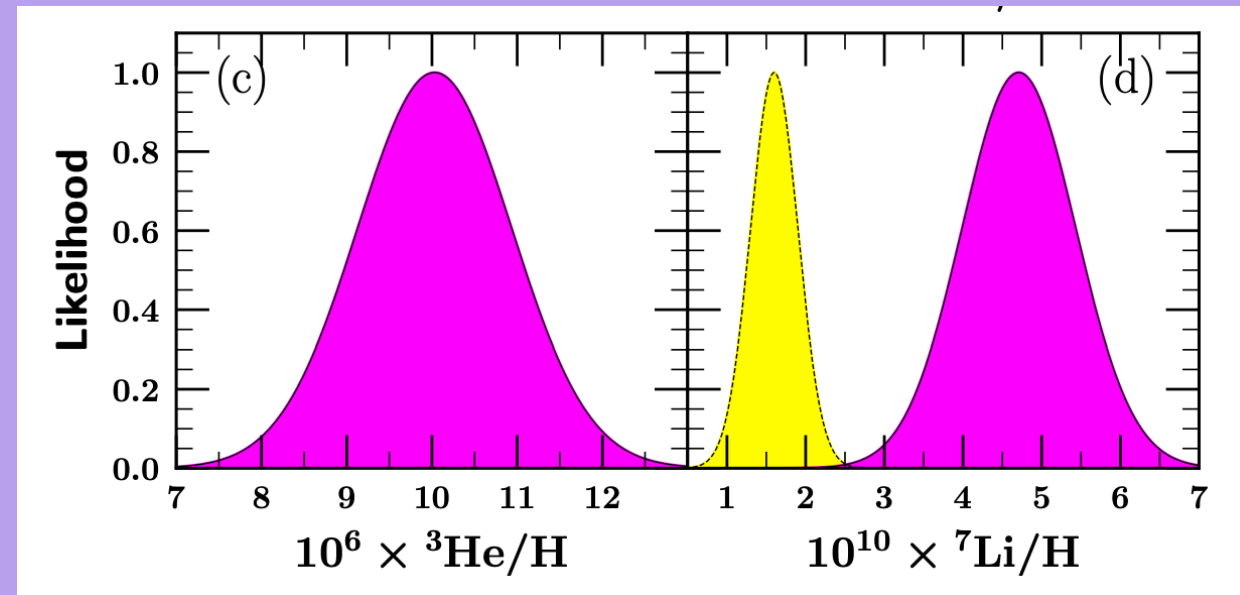
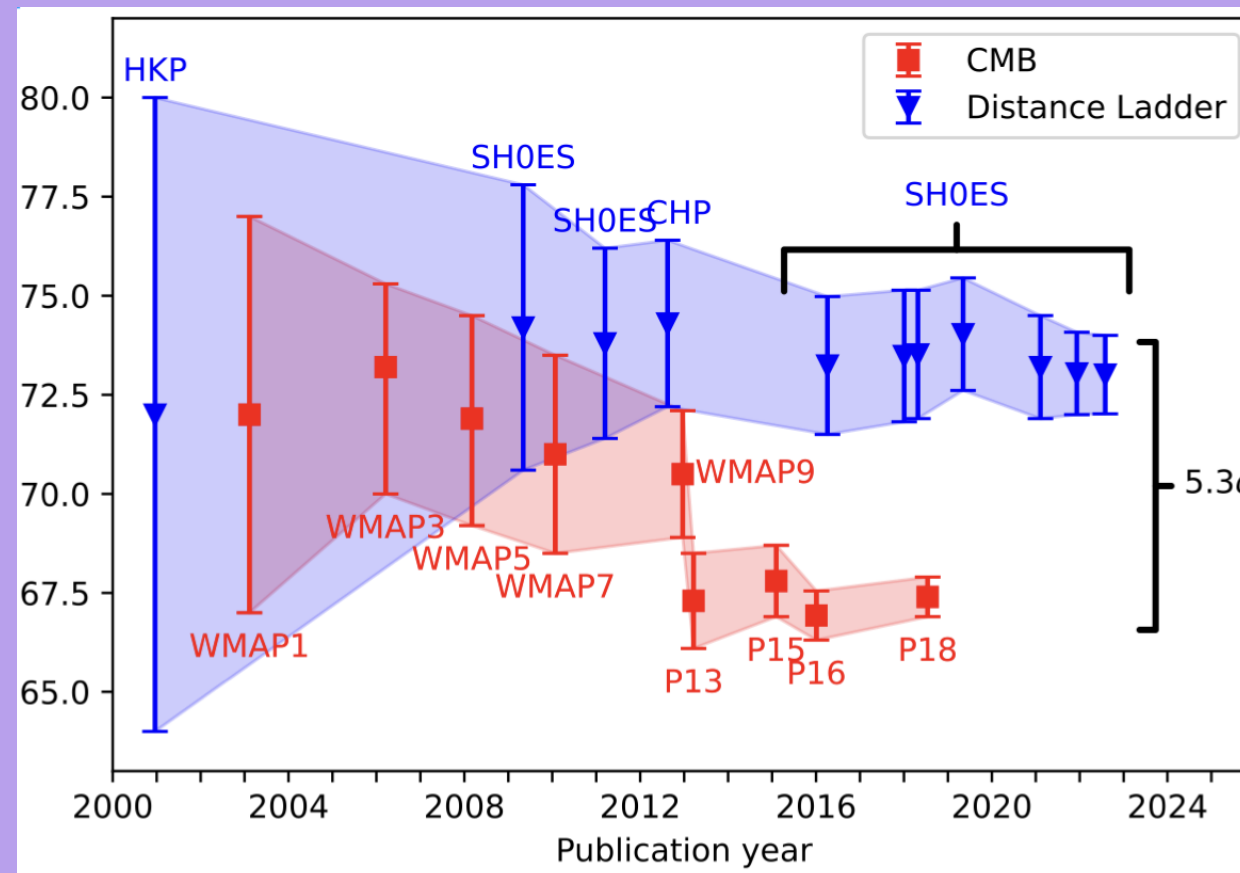
Assess the level of agreement between two datasets:

- Planck 2018
- SHOES 2020

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

Alleviating the Hubble tension with TorC

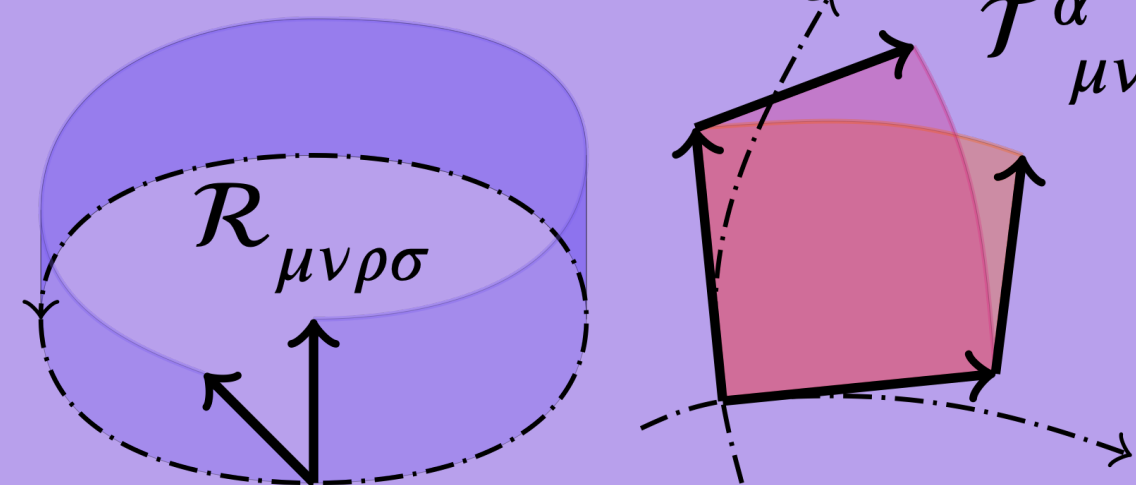
Cosmological Tensions



Exploration of different theory of gravity

Torsion Condensation (TorC)

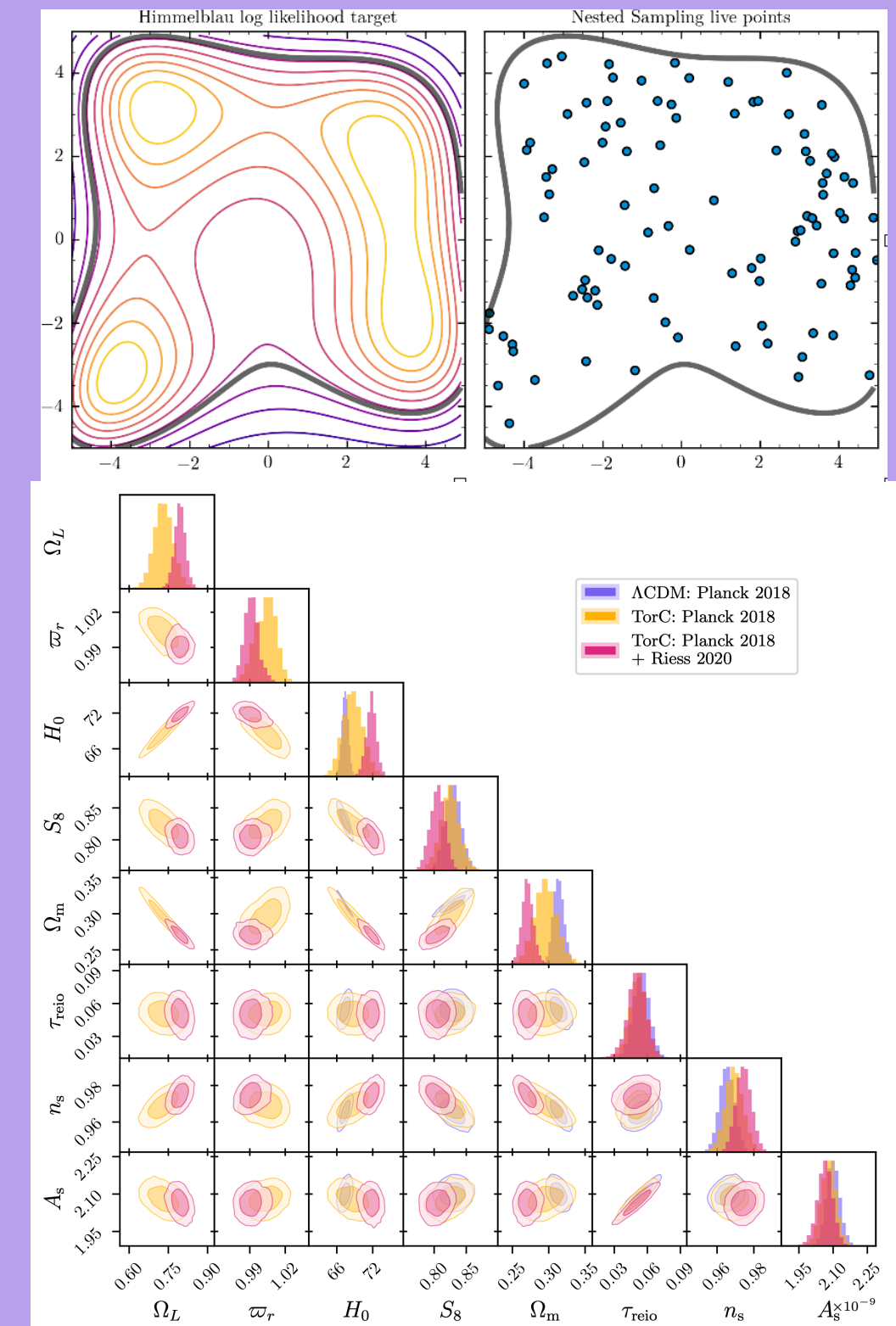
$$\mathcal{L} \propto R^2 + T^2 \quad [2003.02690]$$



Motivates

Analysis

Constraining TorC parameters



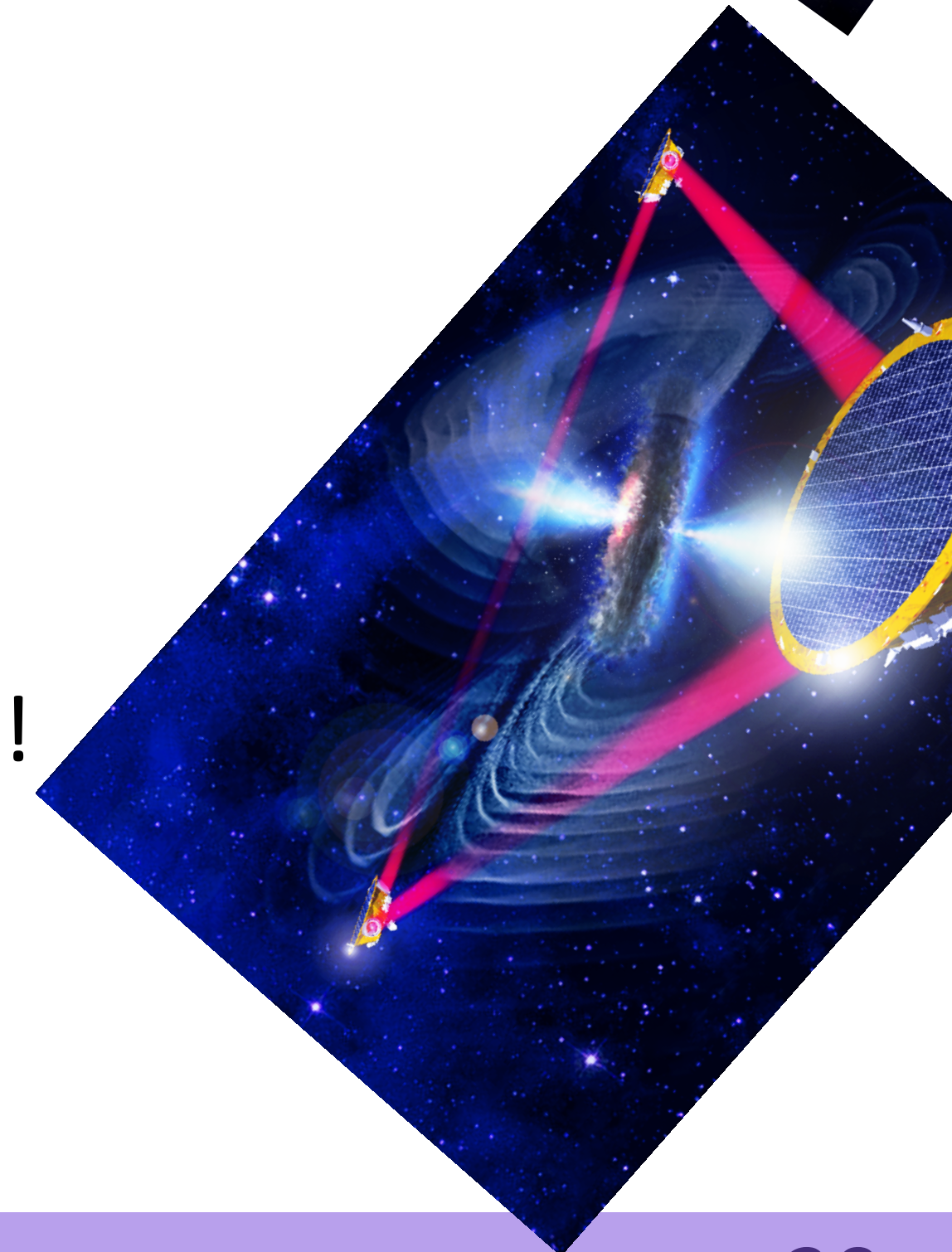
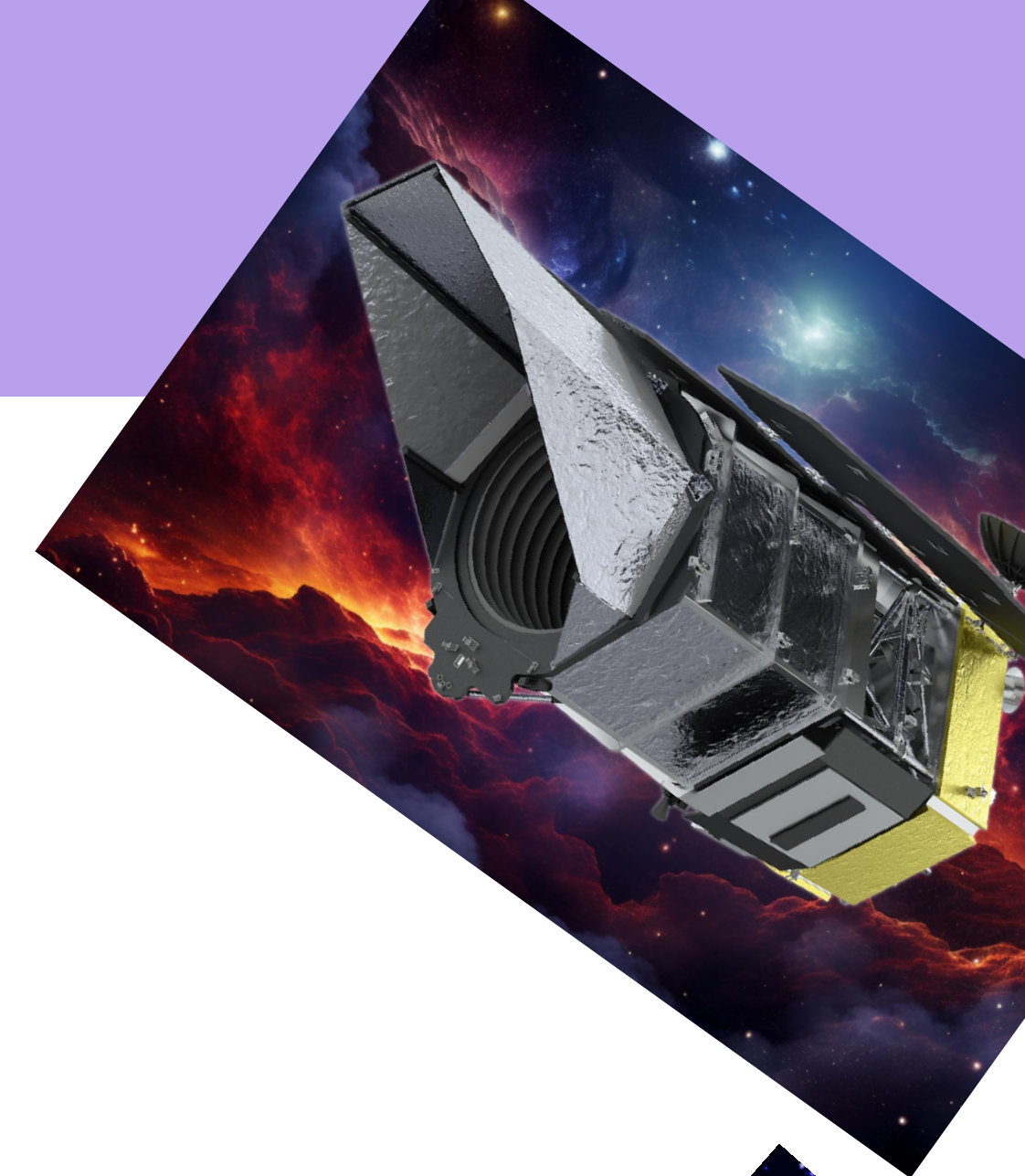
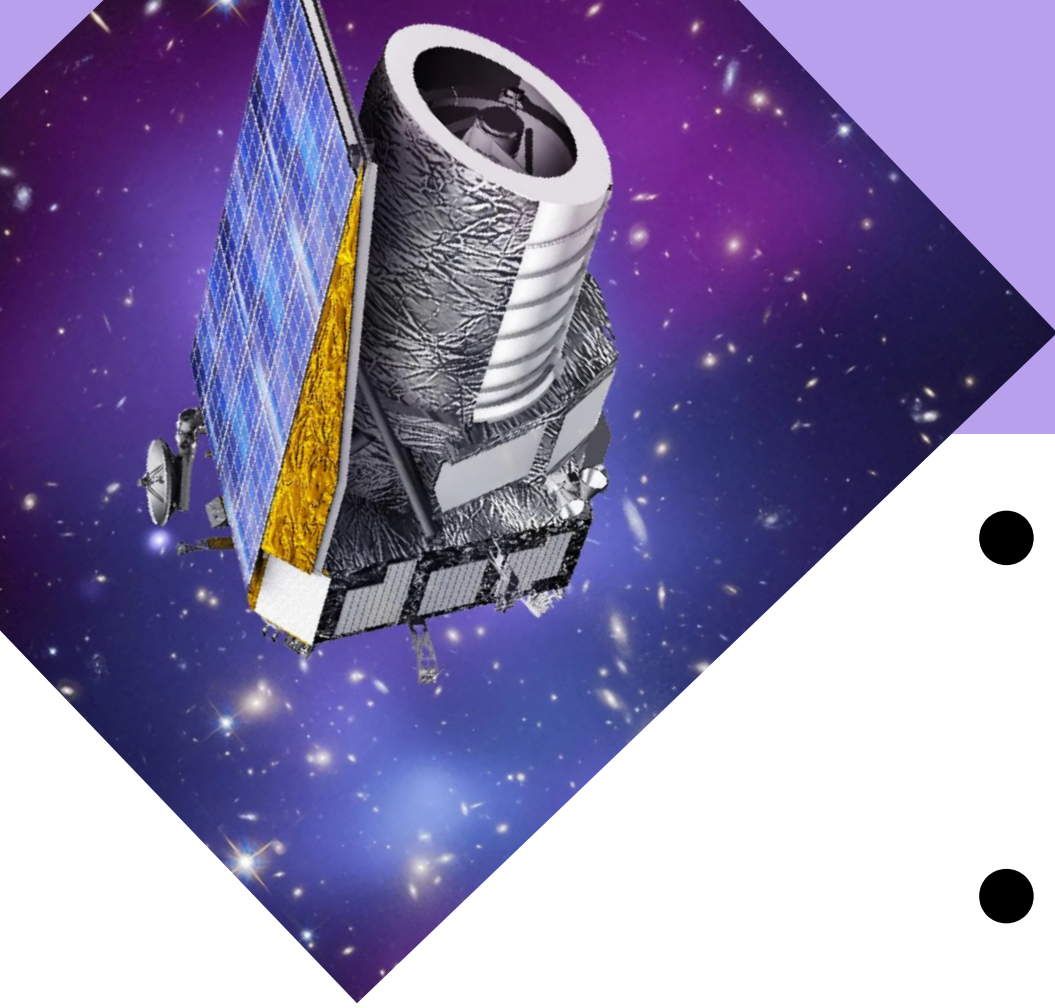
Alleviate Tension?

ArXiv: 2507.09228

Comparison with Λ CDM

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



COSMIC TWIST: A TORSION CONDENTATION

Backup Slides:



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 homogeneous and isotropic Universe:

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

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

Two additional parameters in TorC:

- ϖ_r : initial condition at early time
- Ω_L : bare dark energy density

PGT Lagrangian

PGT Lagrangian is obtained via enforcing local Poincare transformation.

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

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

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

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

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

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 $\Omega_L = \Omega_\Lambda$.

TorC Cosmology

Will Barker



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

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

Λ CDM: $H^2 = H_0^2(\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_\Lambda)$ $1 - \Sigma\Omega_{i,0}$

TorC: $H^2 = H_0^2 \frac{\Omega_r a^{-4} + \Omega_n a^{-3} + \Omega_{\text{free}}}{\varpi^2}$ **parameter**

$$\frac{\dot{\varpi} \left(6H\varpi + \frac{(1 + 3\varpi^2)\dot{\varpi}}{\varpi^2 - 1} \right)}{3\varpi^2}$$

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

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

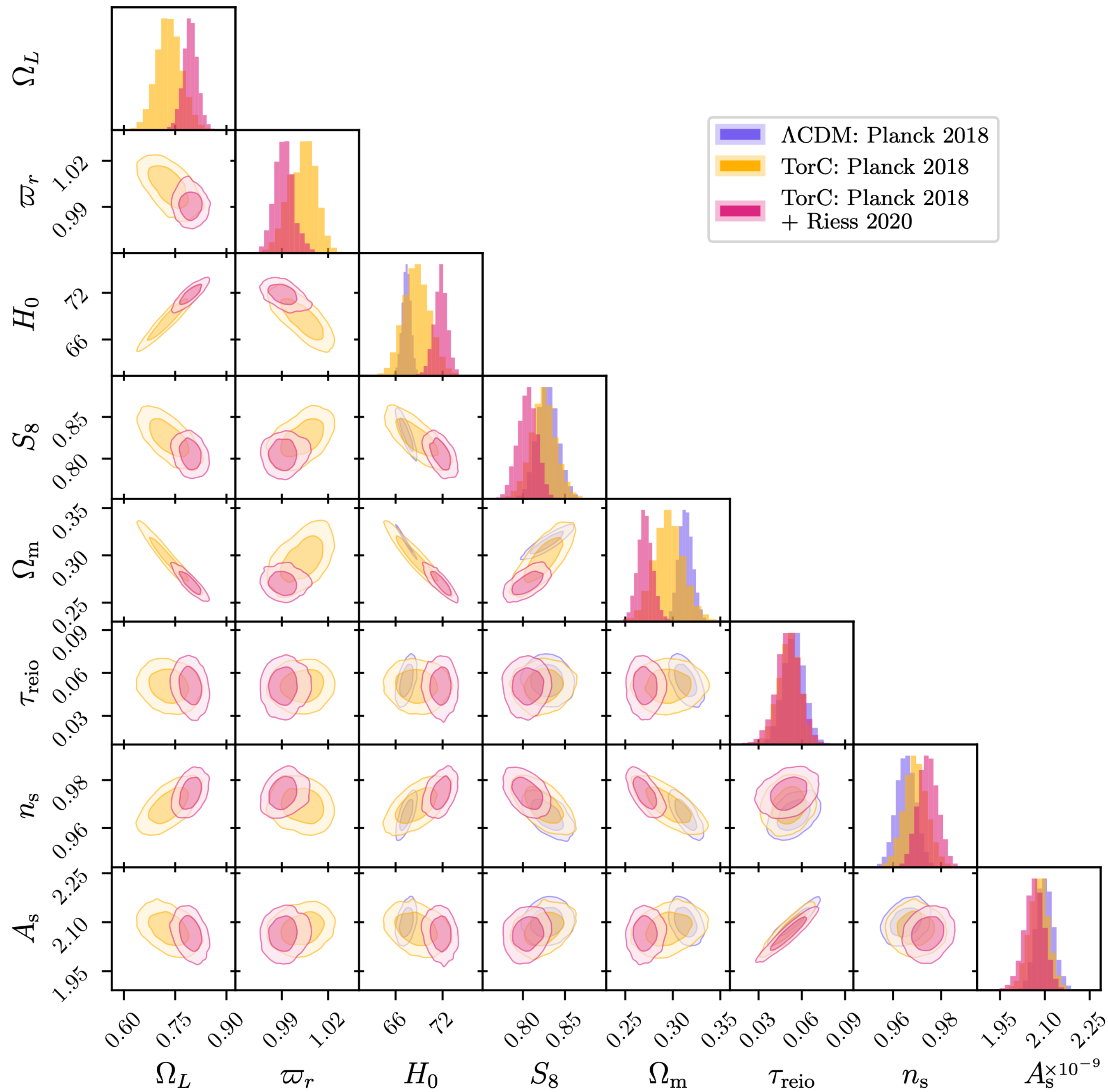
- Assess the level of agreement between two datasets. (e.g. Planck & SHOES)

R-statistic: measures relative confidence in dataset A given dataset B, compared to its self-consistency.

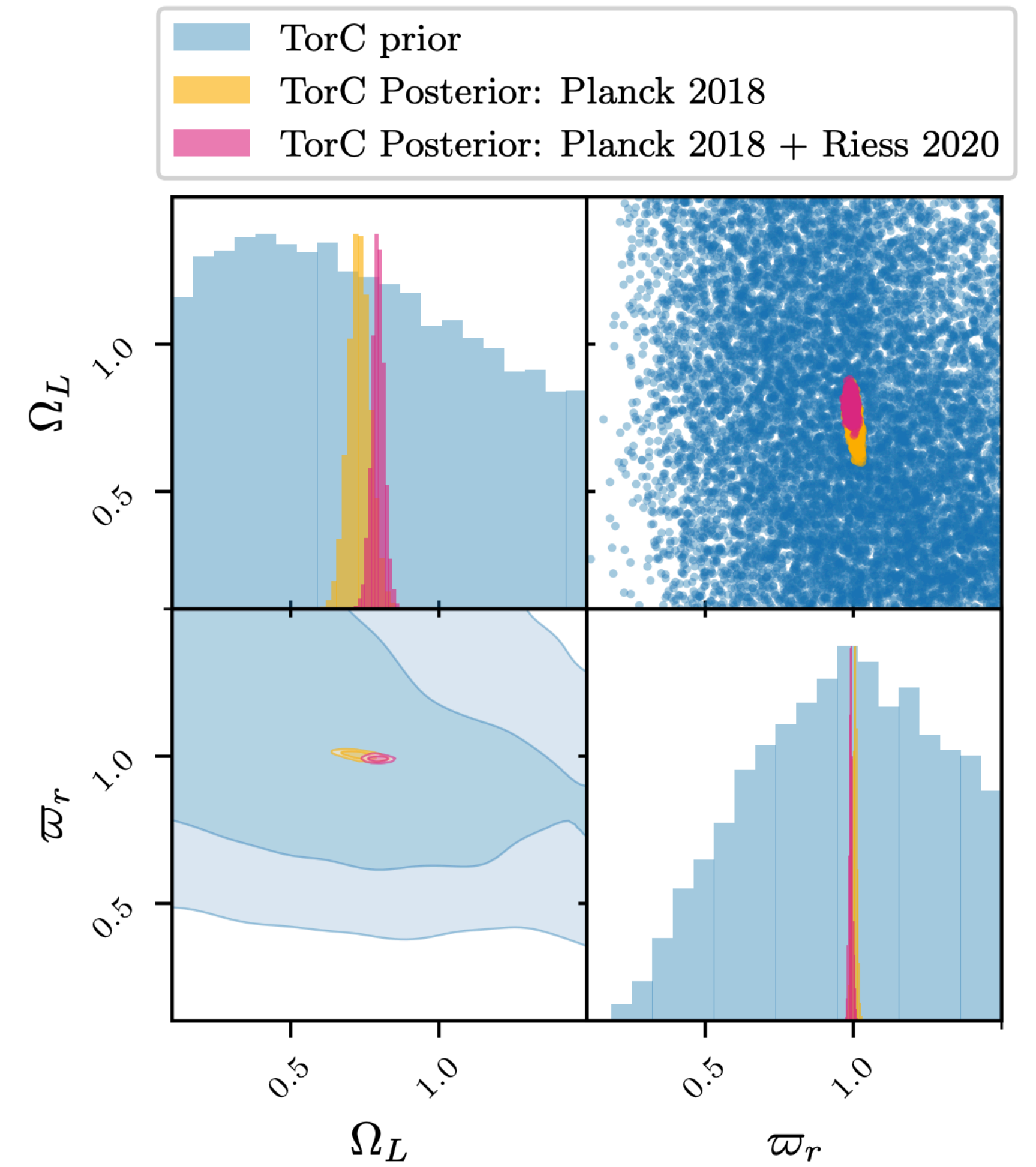
- $R \gg 1$: indicates that B strengthen confidence in A by a factor of R
- $R \ll 1$: indicates tension

- For each model, given datasets A and B :

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



Posterior



Space-time Geometries

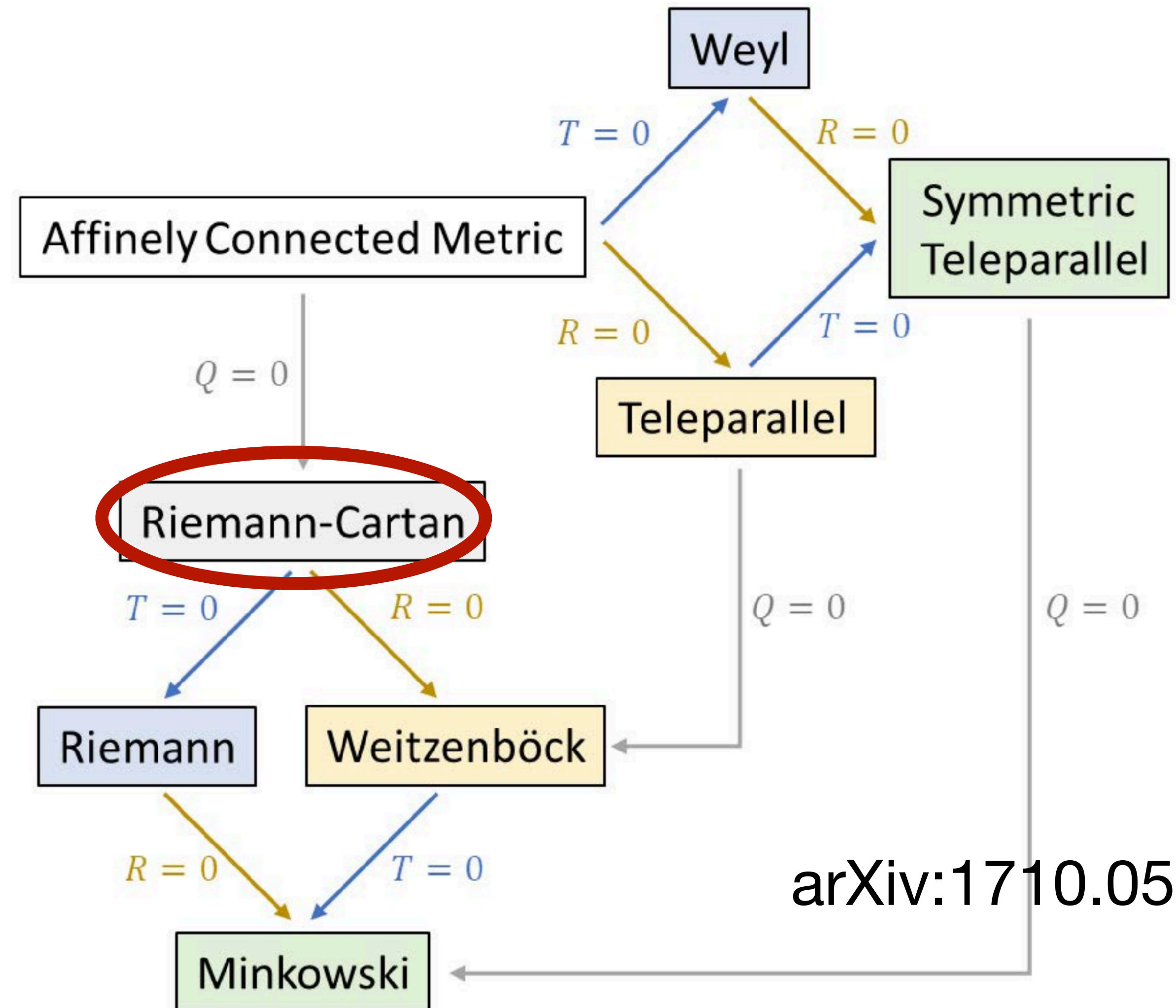
To ensure local Minkowskian structure, Metricity condition is required:

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

Connection becomes:

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

(Contorsion)



arXiv:1710.05708.

Geometrical Analogies

Riemann Cartan space-time

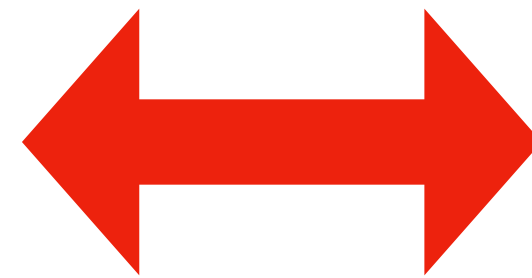
$$e_i^\mu \quad e^i_\mu$$

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

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

$$\mathbb{R}^\mu_{\nu\lambda\rho} = 2e^\mu_i e^s_\nu \left(\partial_{[\lambda} \omega_{s\rho]} + \omega^i_{j[\lambda} \omega^j_{s\rho]} \right)$$

$$\mathbb{T}^\lambda_{\nu\mu} = -2e^\lambda_i \nabla^{(\omega)}_{[\nu} e^i_{\mu]}$$



Poincare Gauge Theory

$$h^\mu_a \quad b^a_\mu$$

$$A_\mu^{ab}$$

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

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

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