From Precision Cosmology to Accurate Spacetimes

Action Dark Energy – November 4th, 2026 – Institut Henri Poincarré, Paris

Vincent Reverdy, CNRS IN2P3/INS2I, LAPP – Laboratoire d'Annecy de Physique des Particules




Virgo Cluster - LSST

A very peculiar moment for cosmology



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⇒ Stage IV surveys



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⇒ Data (and more data)



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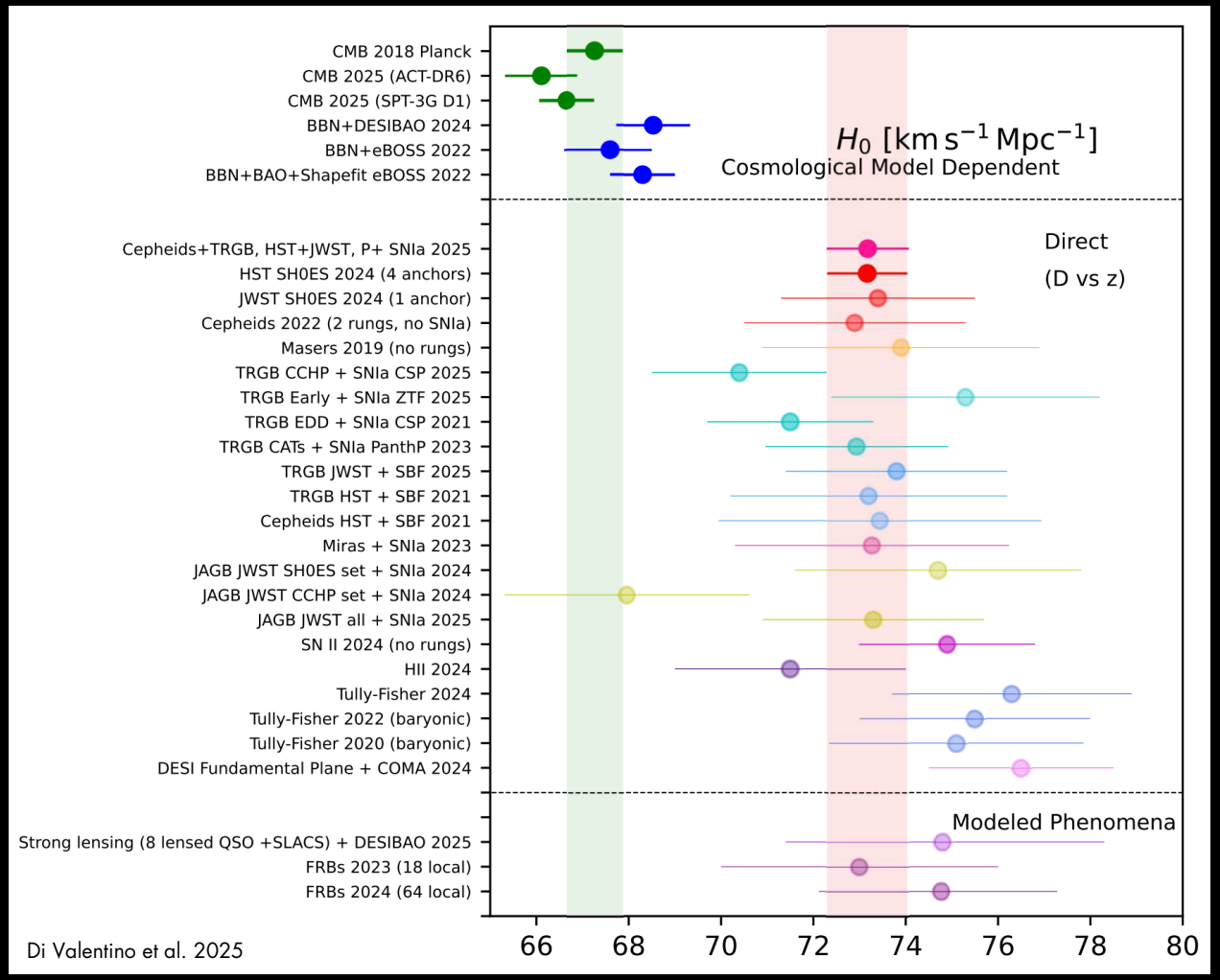
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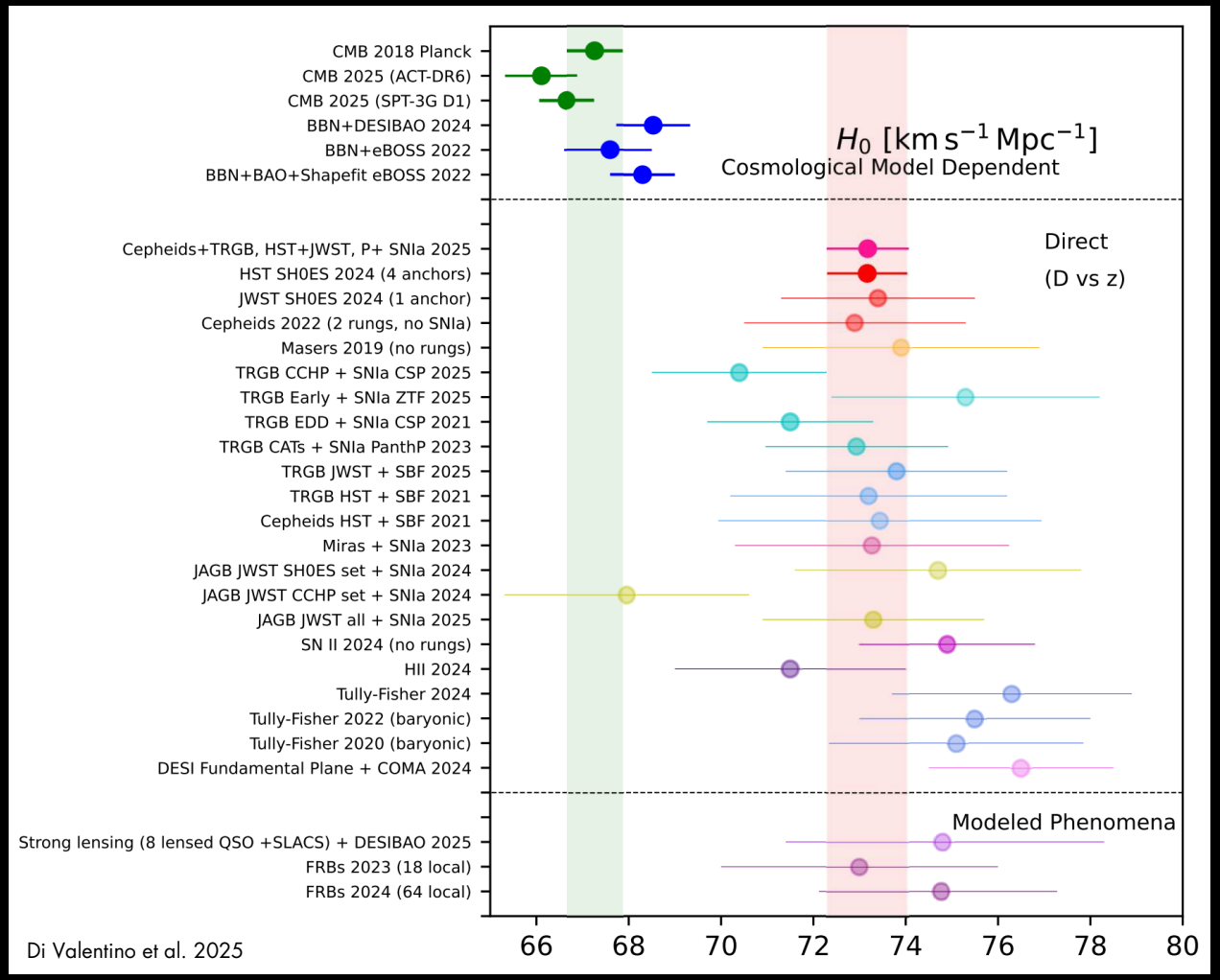
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What do we expect from new surveys?

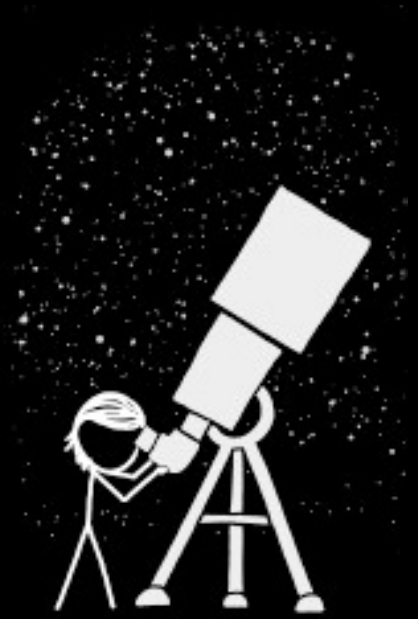
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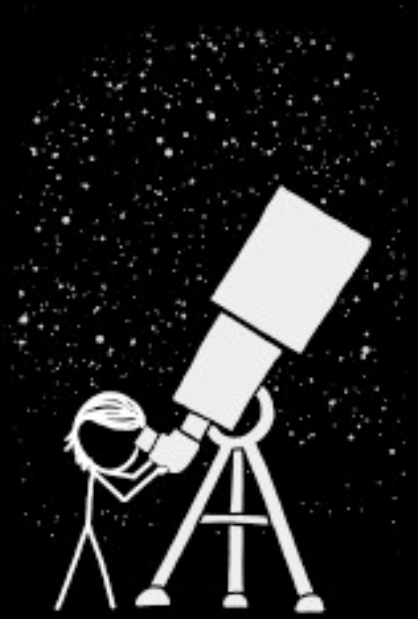
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Step I
Stage IV surveys
Precision cosmology
Data

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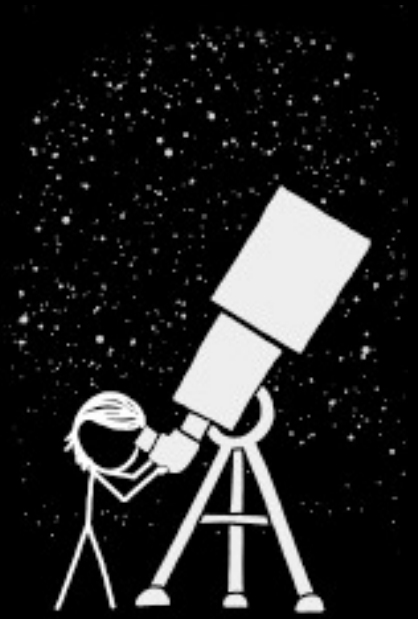
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Step 3
Solved tensions

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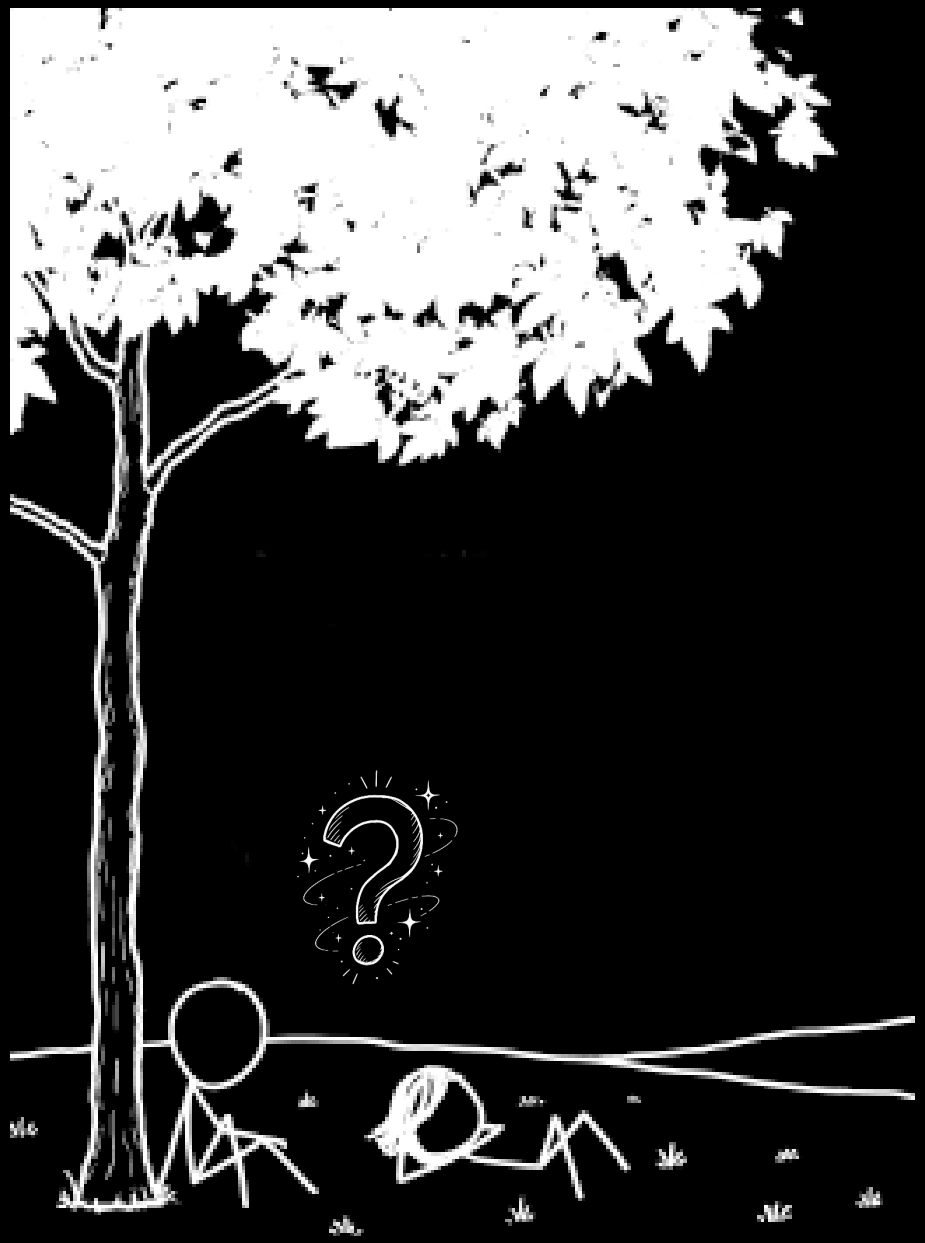


Step 2
Something

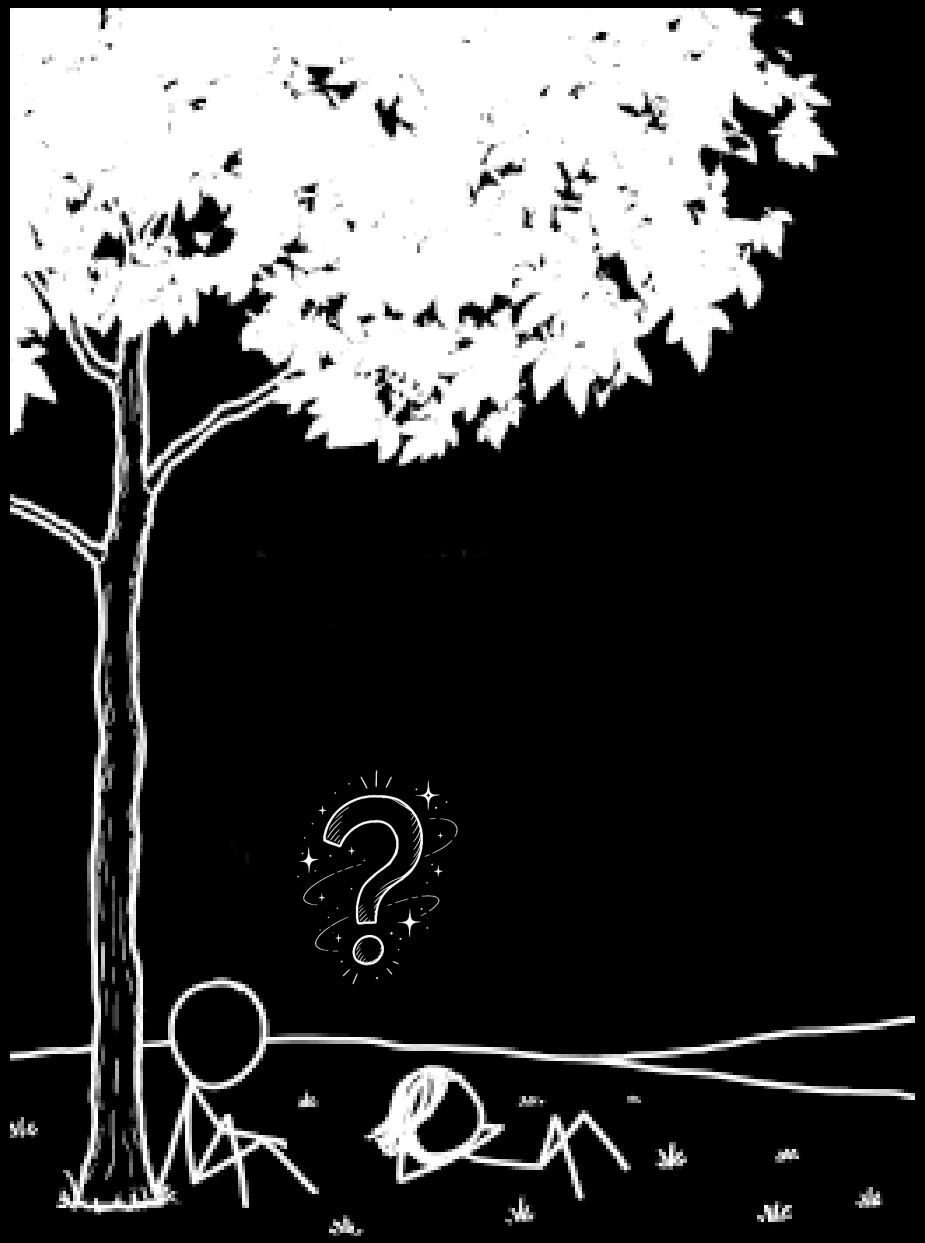


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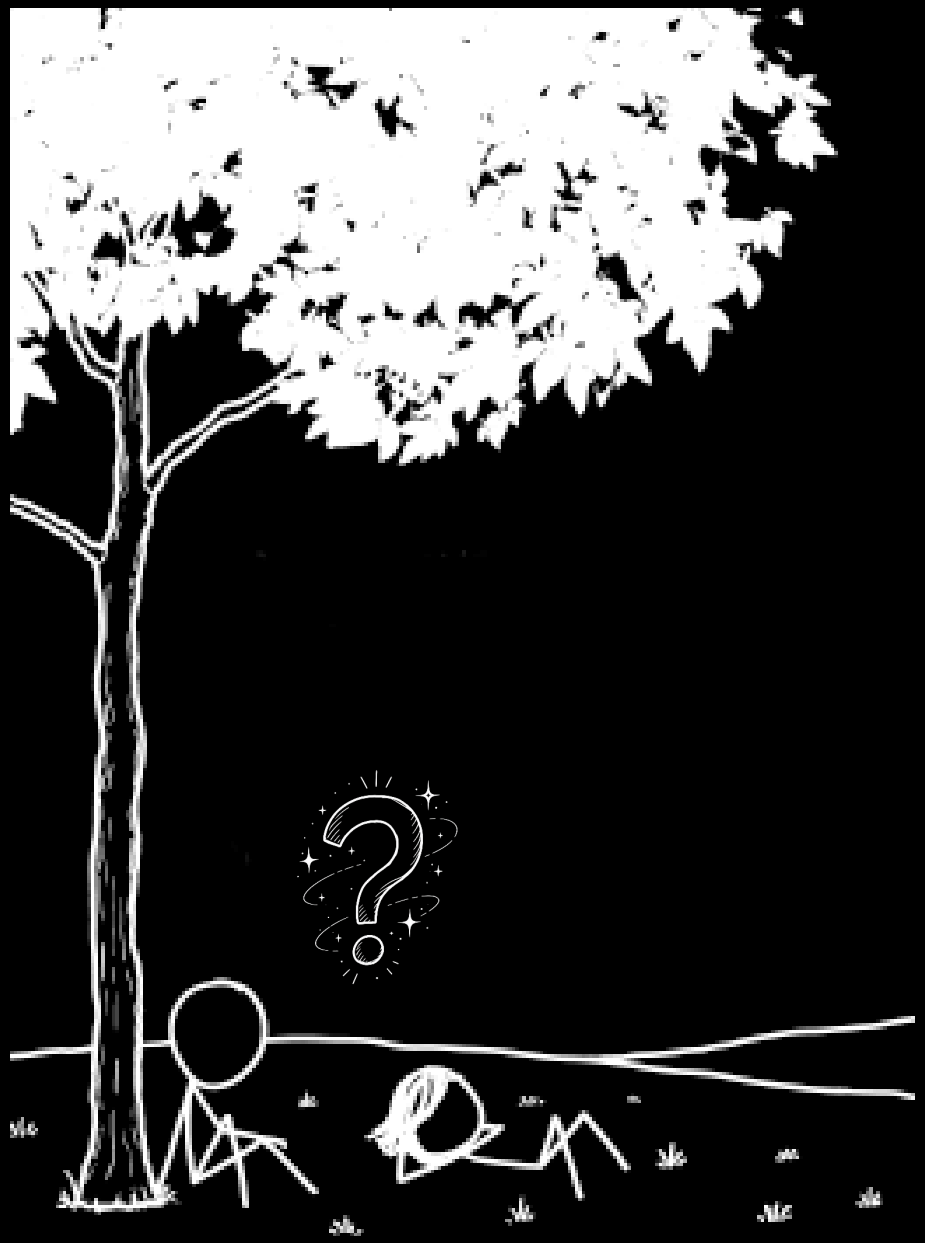


What is this talk about



– A take on how to approach tensions in the current cosmology landscape

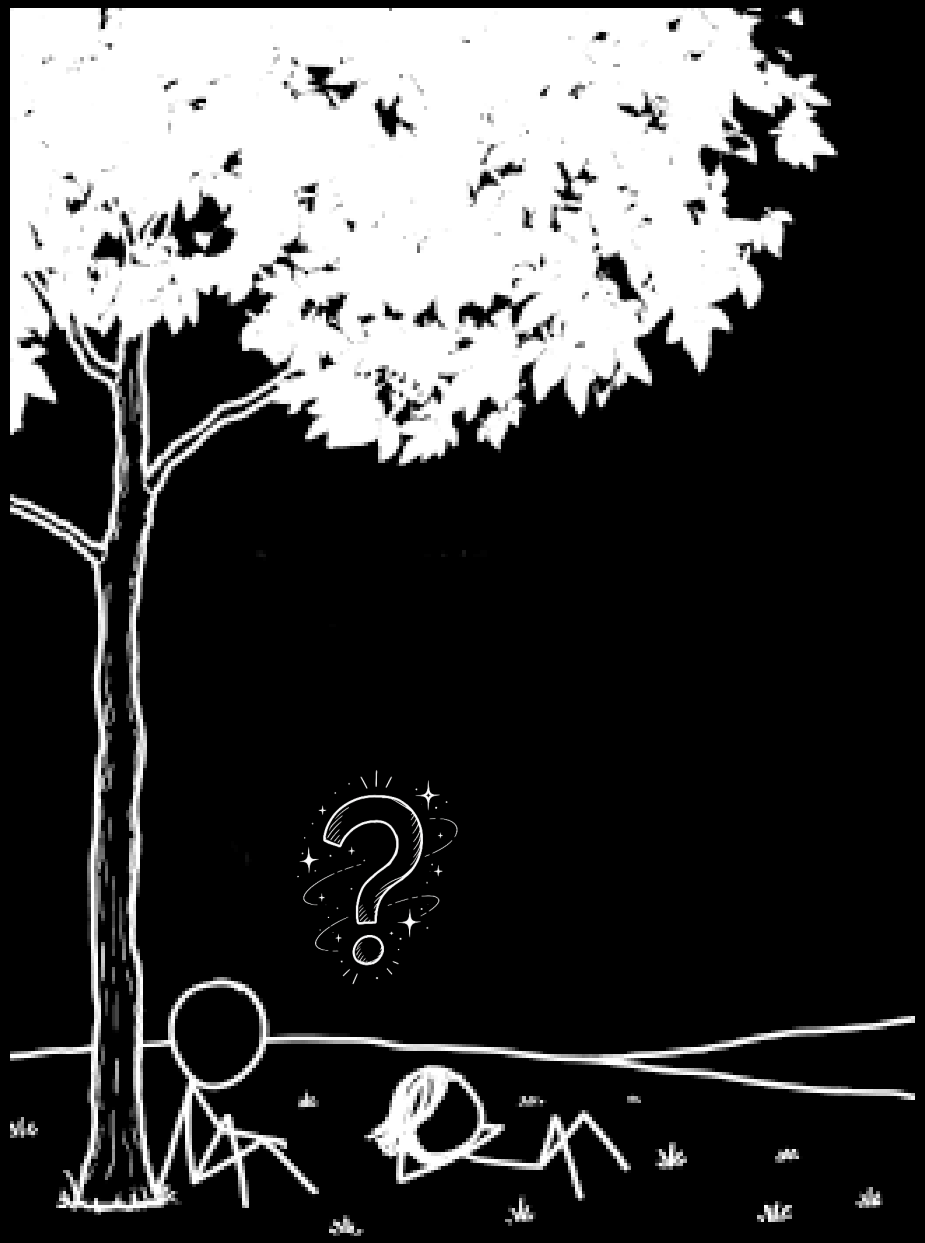
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– A glimpse into what lies in this (largely unexplored) territory

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- A take on how to approach tensions in the current cosmology landscape

- A glimpse into what lies in this (largely unexplored) territory

- Work currently being done at LAPP (Annecy) in the cosmology group

Possible origins of cosmological tensions

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Statistical fluctuation

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Incorrect physics or modeling

- Incorrect theory, model or assumptions about fundamental physics

Model selection versus falsification



Model selection versus falsification

Model selection: Which model is better?

- Natural fit for bayesian model comparison
- Compare ΛCDM, $w_0 w_a$, modified gravity…
- Evaluate relative evidence, accounting for model complexity
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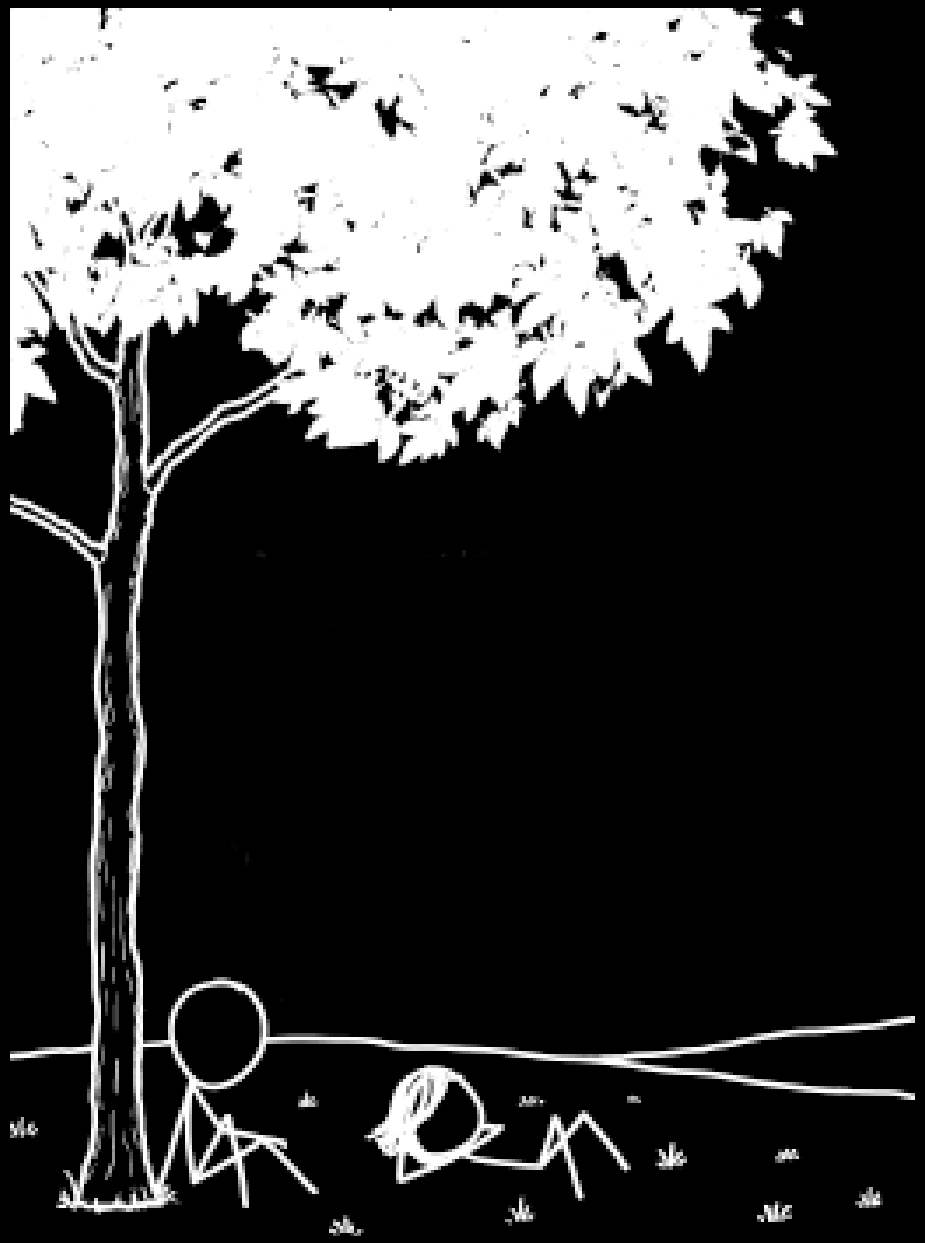
Does any alternative outperform ΛCDM?

Falsification asks whether we need an alternative

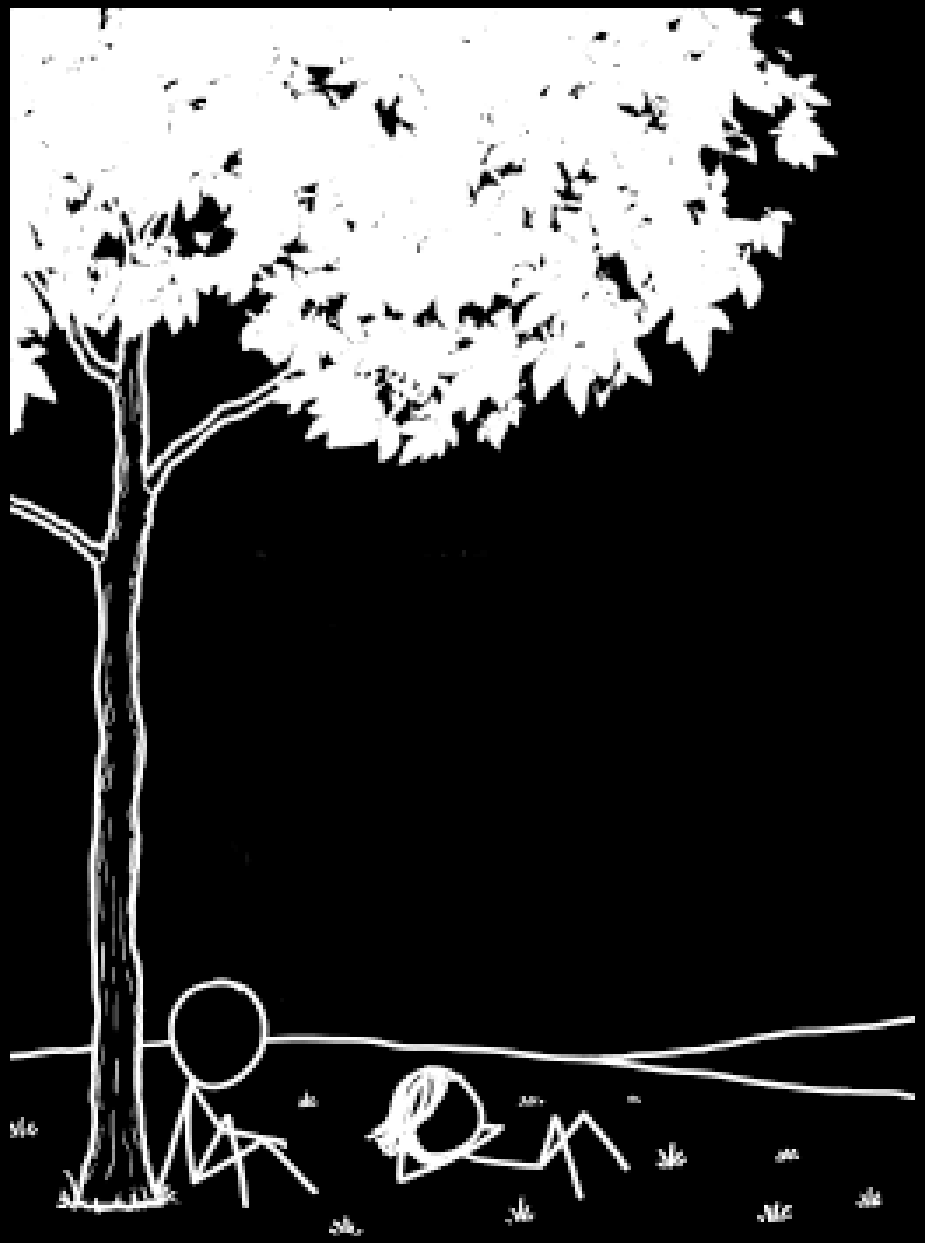
Does ΛCDM survive the data?



The first question

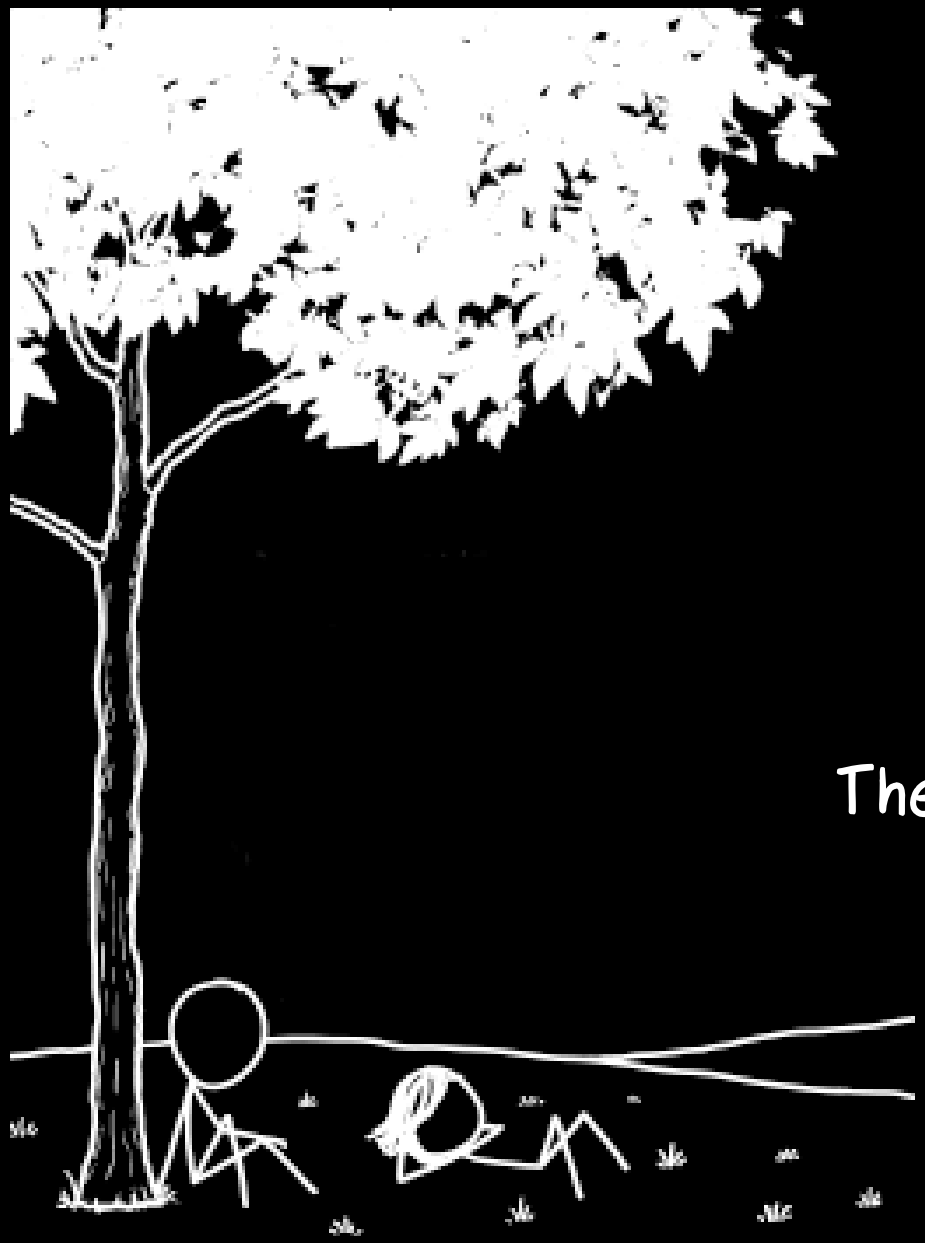


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Before searching for the right answer,
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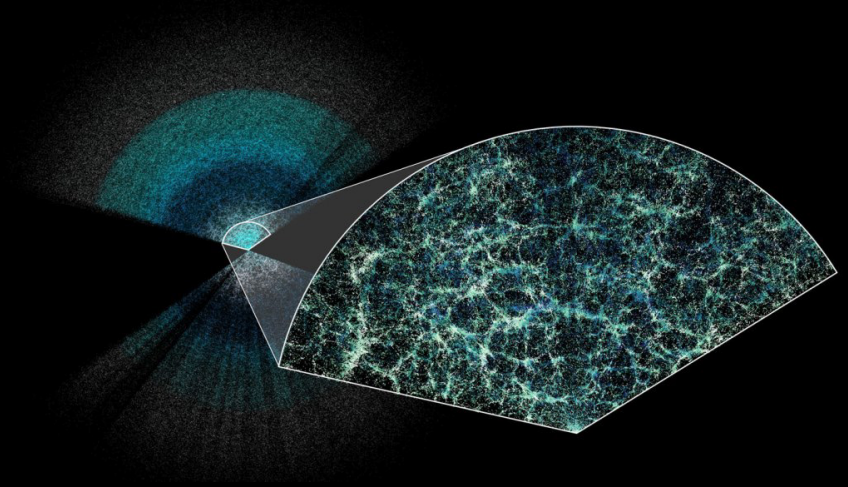


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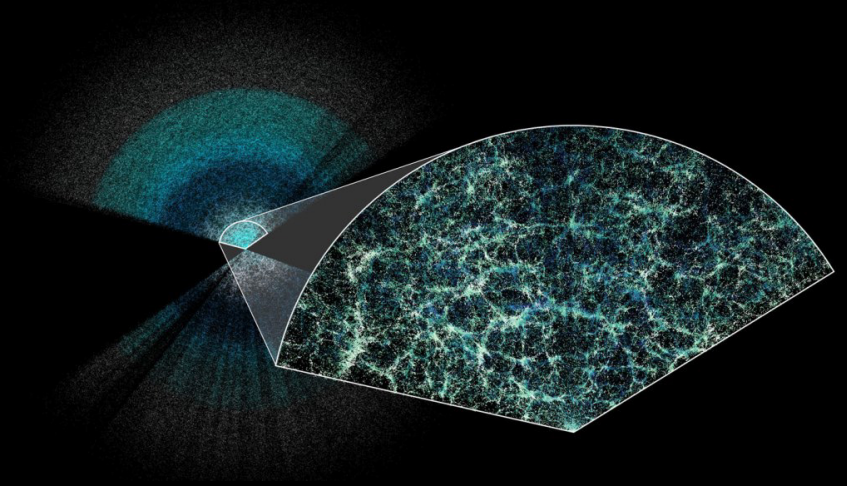
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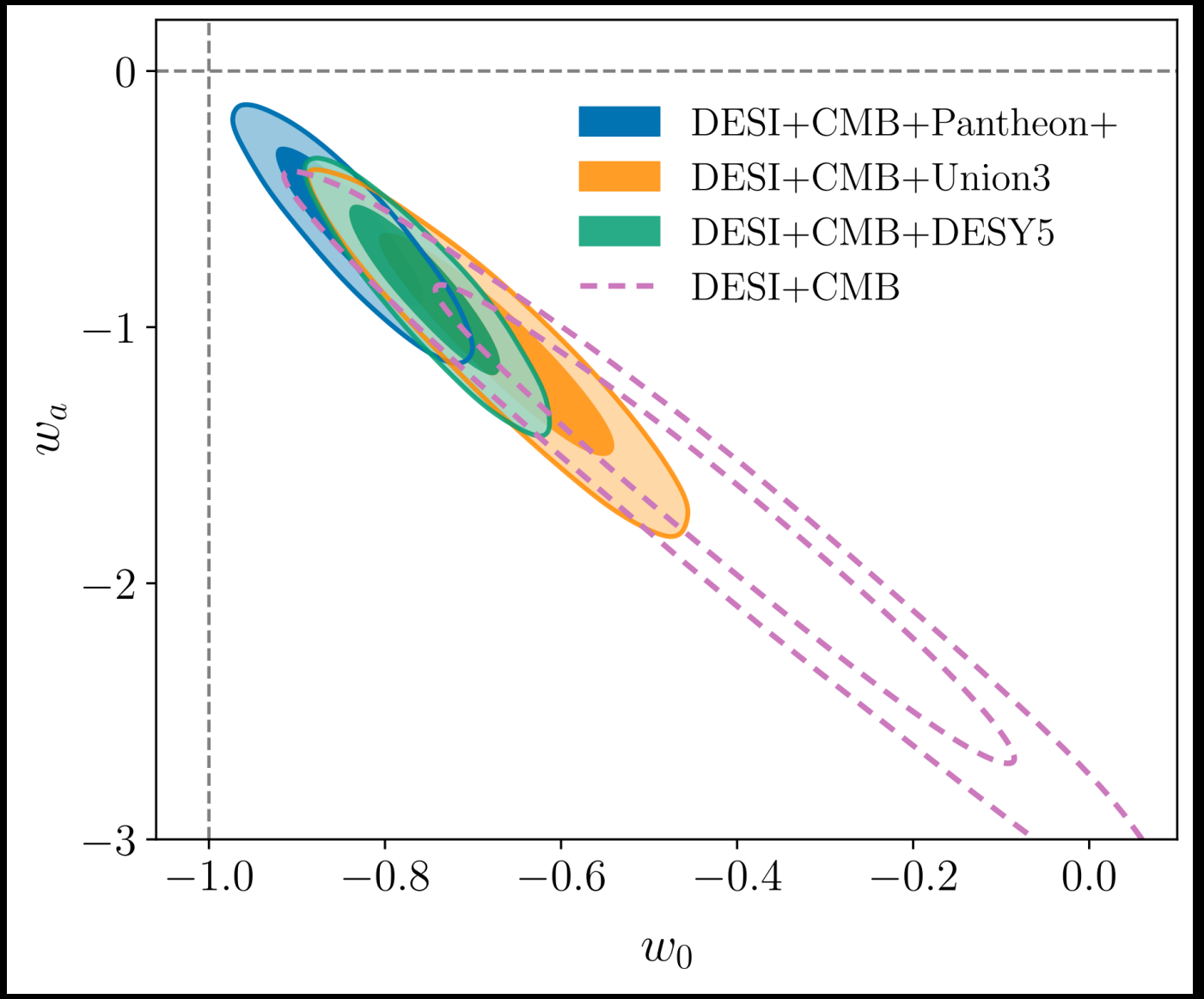
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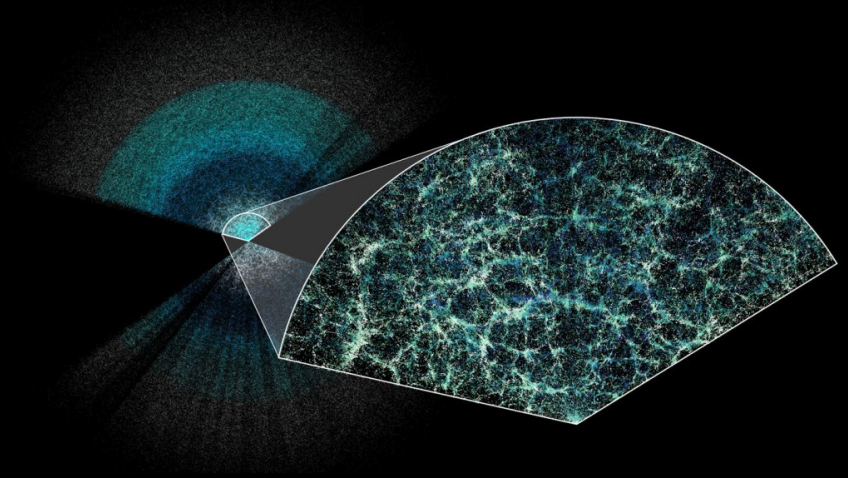


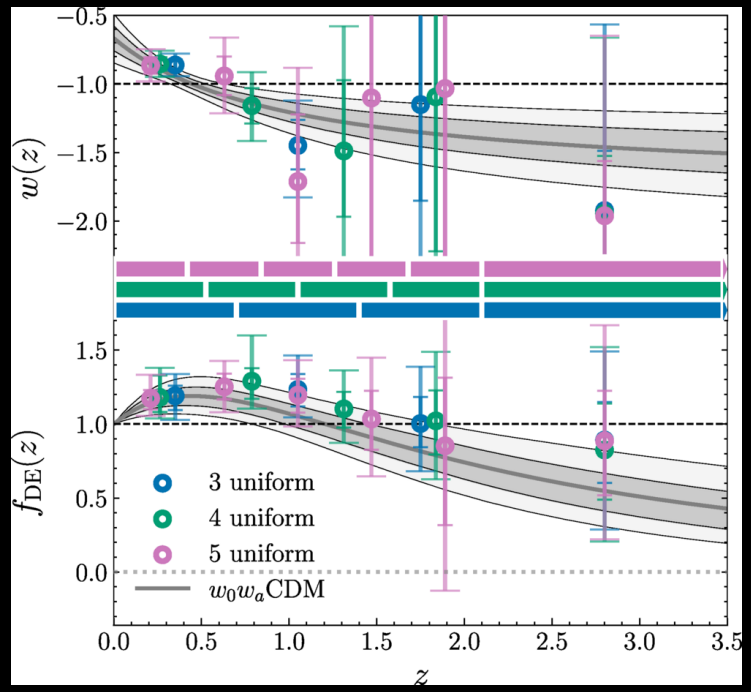
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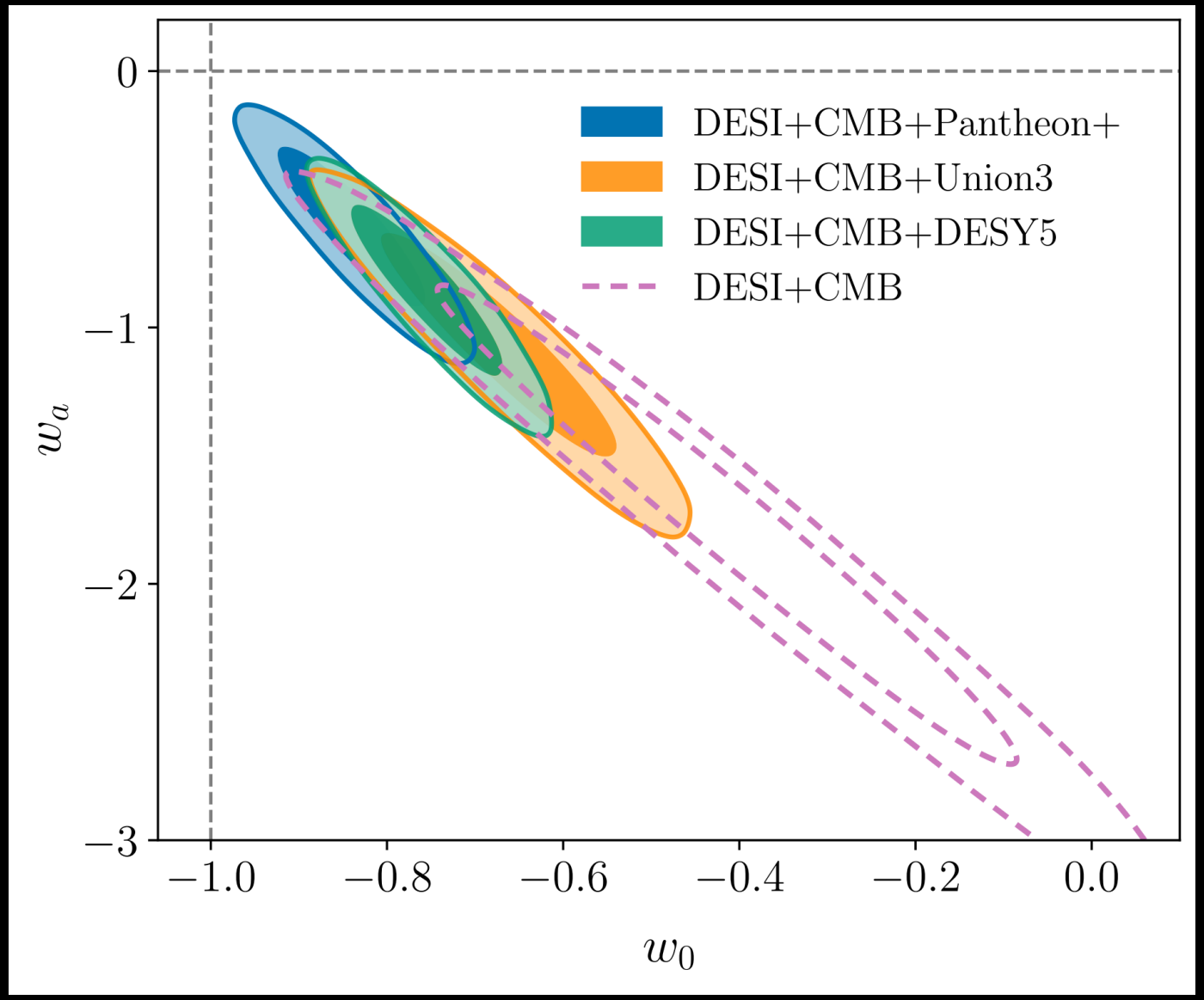




Going beyond ΛCDM: a varying dark energy?







The problem with $w_0 w_a$

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The equation of state (CPL parameterization)

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Congratulations, you just broke physics!

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- Λ is a fundamental property of spacetime
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$w_0 w_a$

- Breaks this equivalence
- Requires a covariant specification of the dark-energy stress-energy tensor and its dynamics

General relativity and extensions

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Lovelock's theorem

In four dimensional spacetime, any tensor $A_{\mu\nu}$ whose components are functions of the metric tensor $g^{\mu\nu}$ and its first and second derivatives (second derivatives being linear), and also symmetric and divergence-free is necessarily of the form :

$$A_{\mu\nu} = aG_{\mu\nu} + bg_{\mu\nu}$$

where a and b are constants and $G_{\mu\nu}$ is the Einstein tensor.

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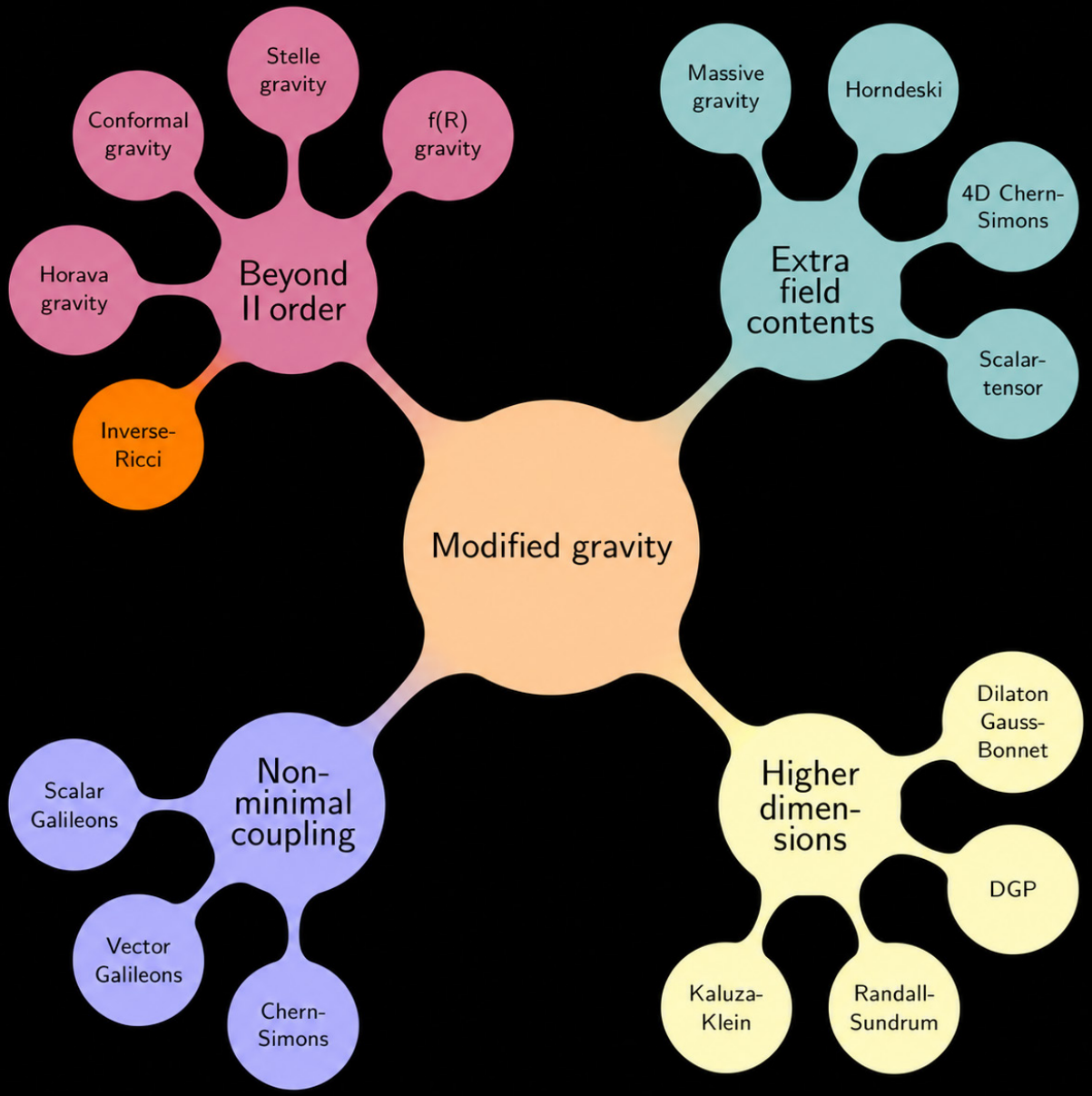
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Beyond general relativity

- Add other fields rather than the metric tensor
- Use more or fewer than four spacetime dimensions
- Add more than second order derivatives of the metric
- Non-locality
- Non-minimal coupling to matter fields

Lovelock as a framework beyond general relativity



A fundamental misconception



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Do we even need modified gravity?



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FLRW



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FLRW = General Relativity



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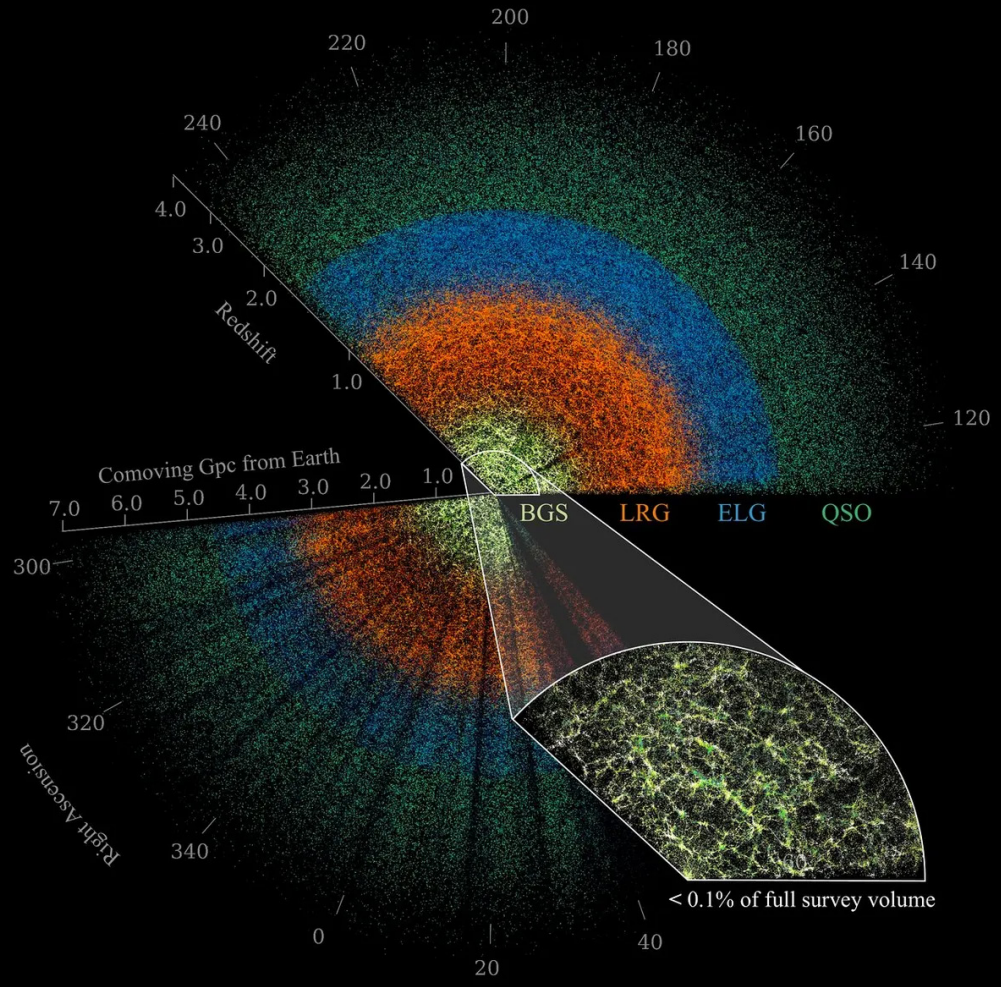
Cosmological tensions
do not break, by themselves, General Relativity,
they break ΛCDM or FLRW

Asking the right question

What if we start by relaxing the cosmological principle (at least locally)?

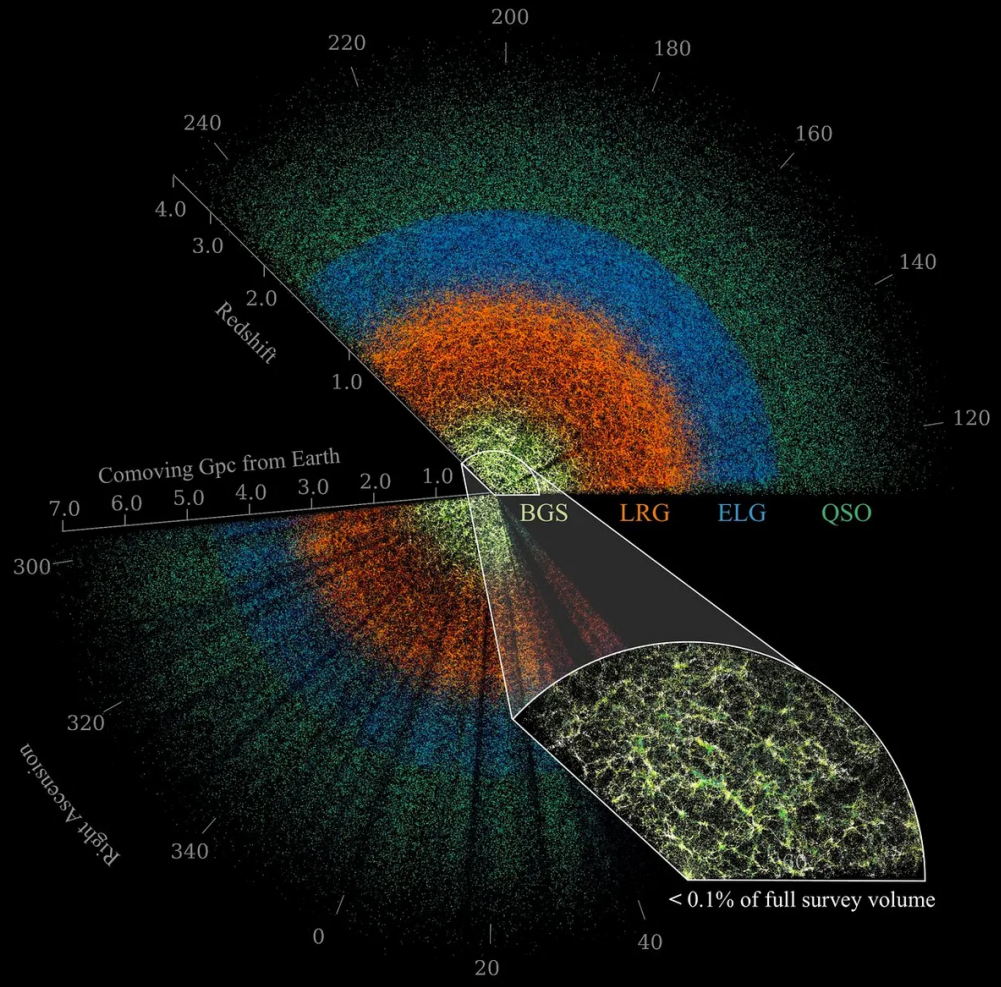
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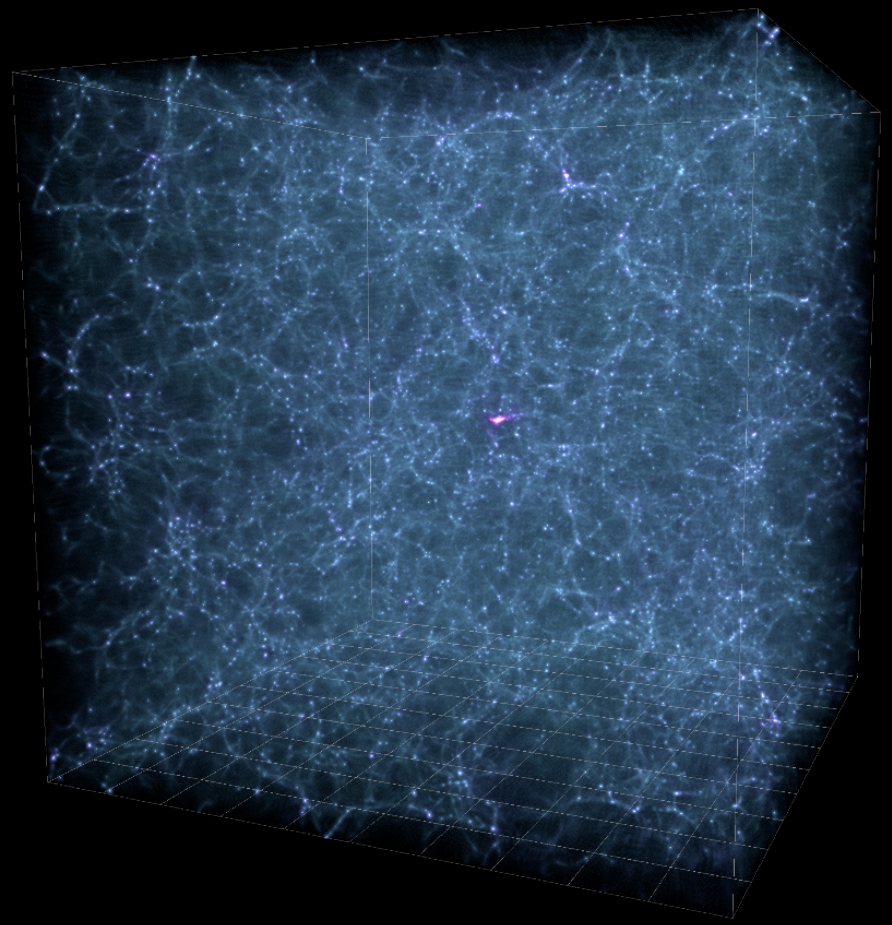
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FLRW – Cosmological principle

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FLRW − Cosmological principle = General Relativity

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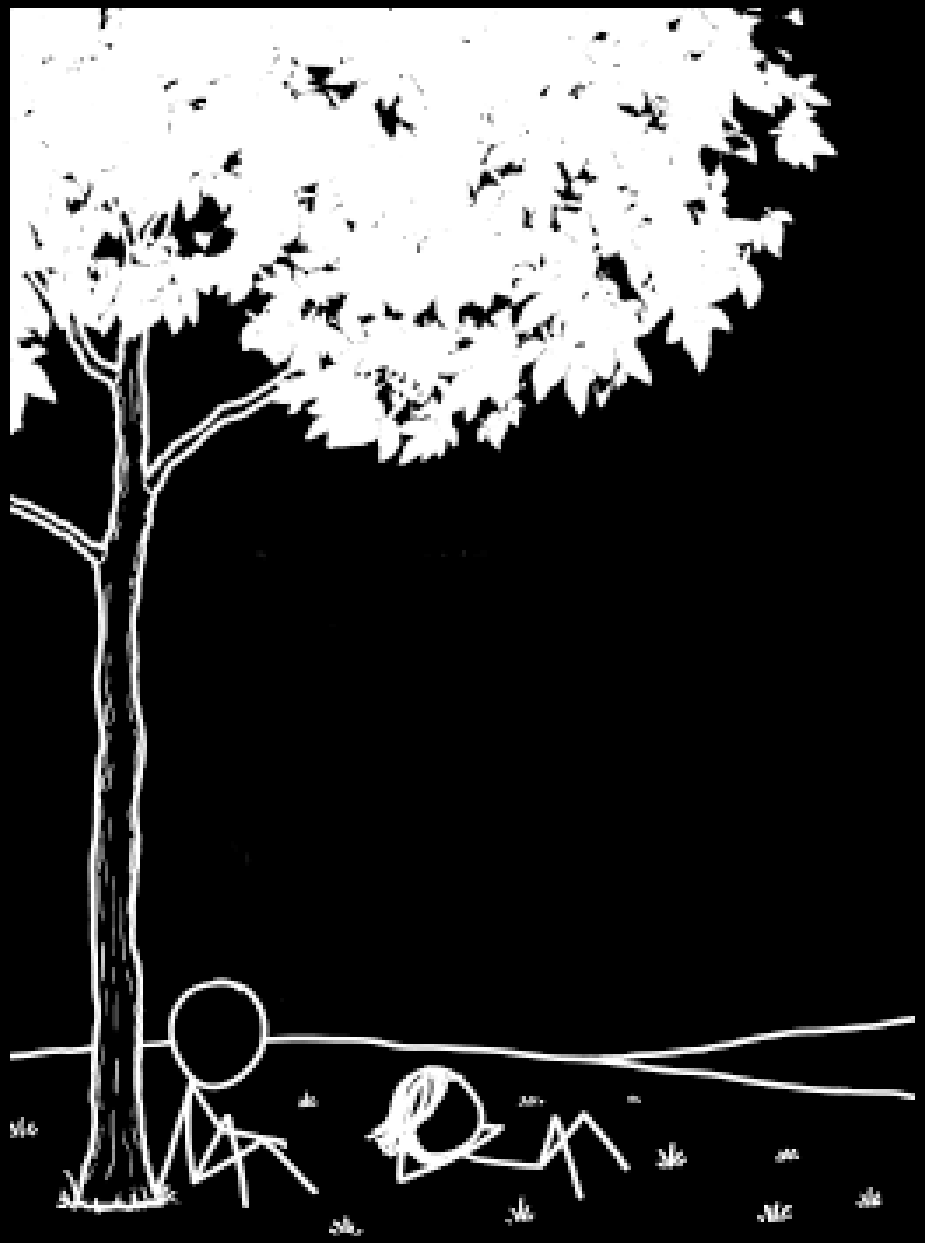
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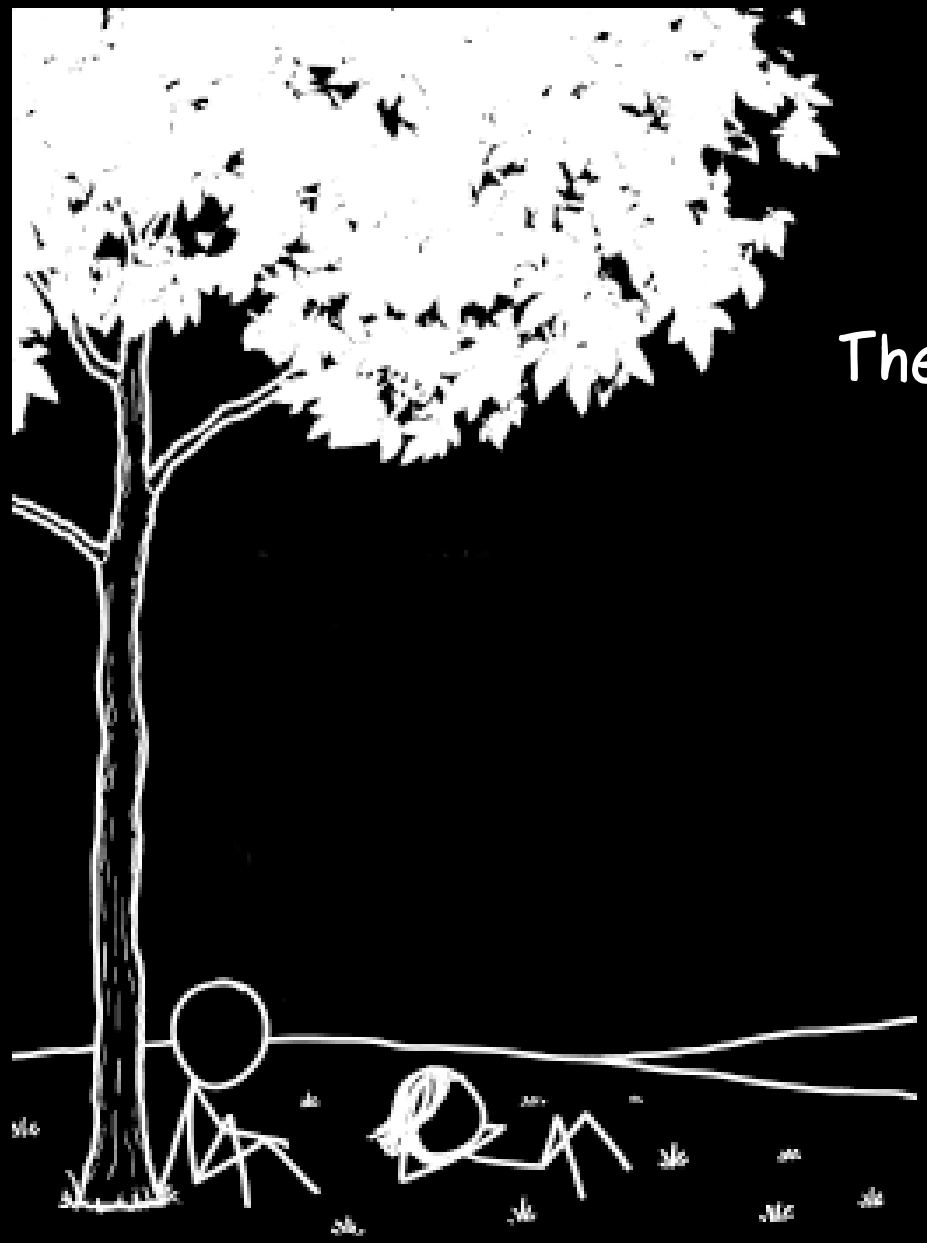
What relativistic cosmology is about

- Relativistic cosmology is about what remains when you relax the cosmological principle from FLRW
- The minimal departure from FLRW with no new physics, just fewer symmetry assumptions
- The most well-established and well-tested framework for relaxing the cosmological principle without introducing new fundamental physics

The right framework

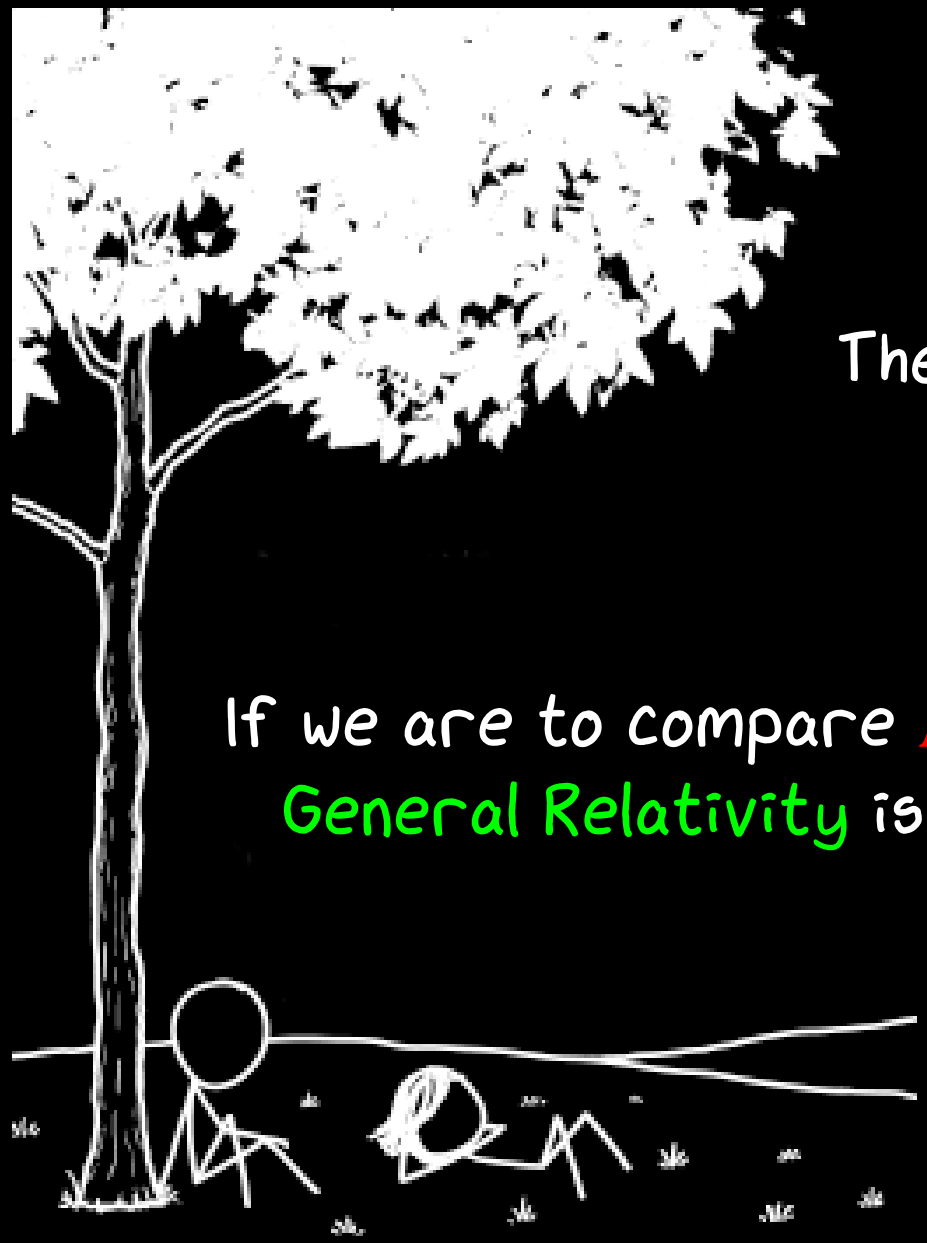


The right framework



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If we are to compare ΛCDM with physically well-founded alternatives,
General Relativity is the natural framework in which to formulate
the question

A sociological challenge



Theoretical cosmology



Theoretical cosmology

Numerical cosmology



Theoretical cosmology

Numerical cosmology

Observational cosmology



A sociological challenge

Theoretical cosmology

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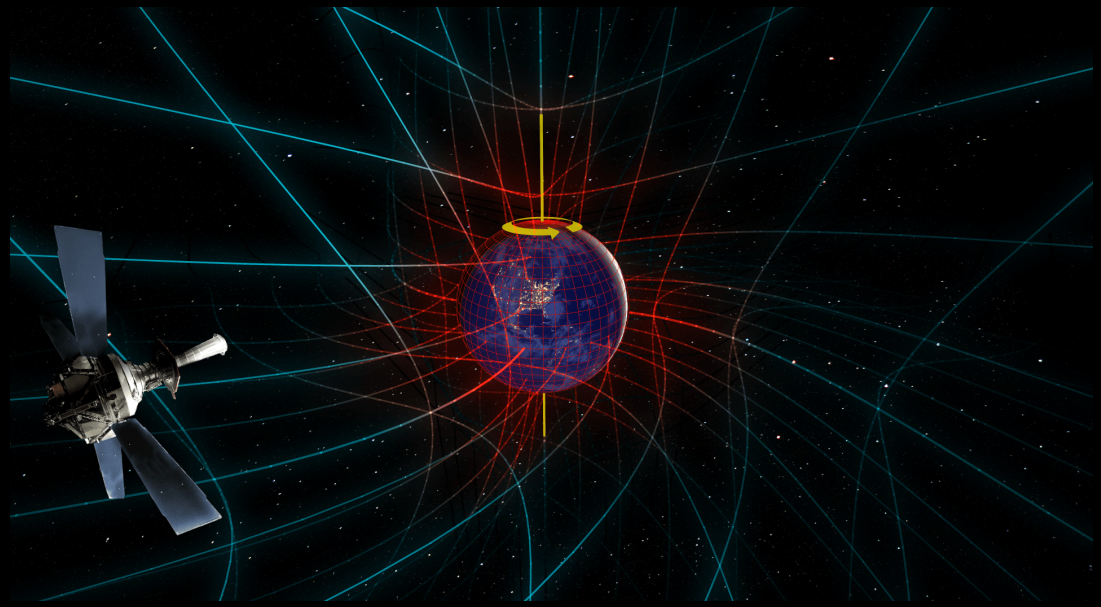
Numerical cosmology

Observational cosmology

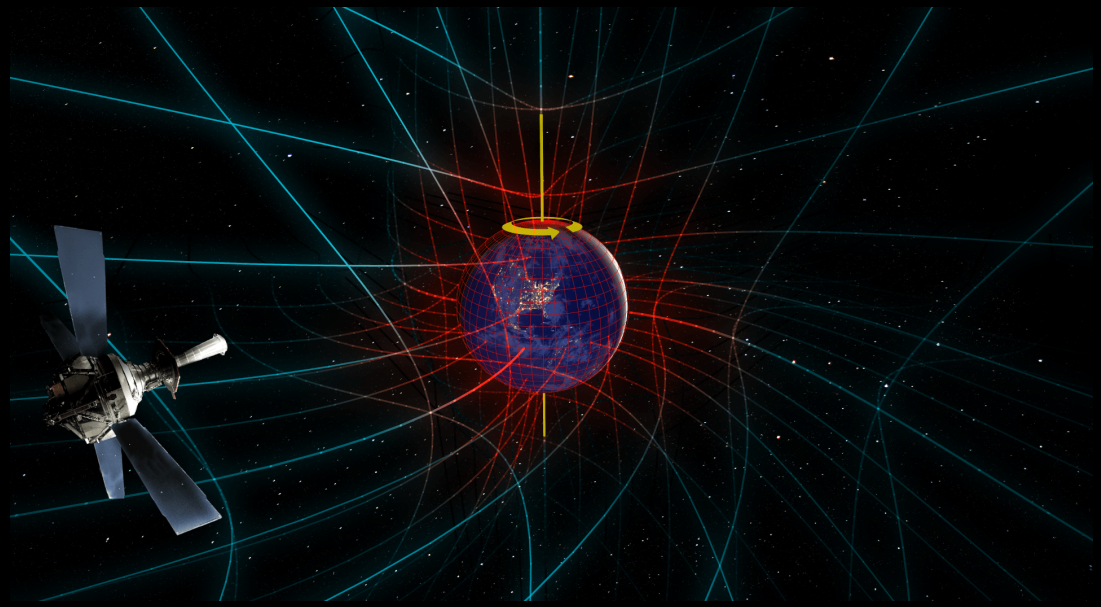


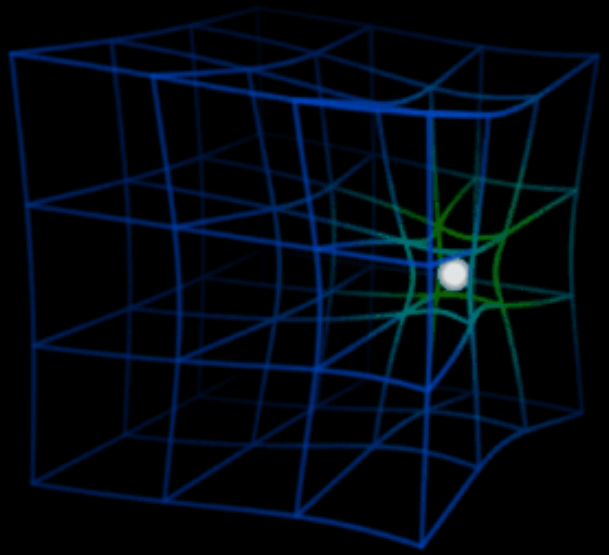
Coming back to Einstein's original idea, and a local theory of spacetime

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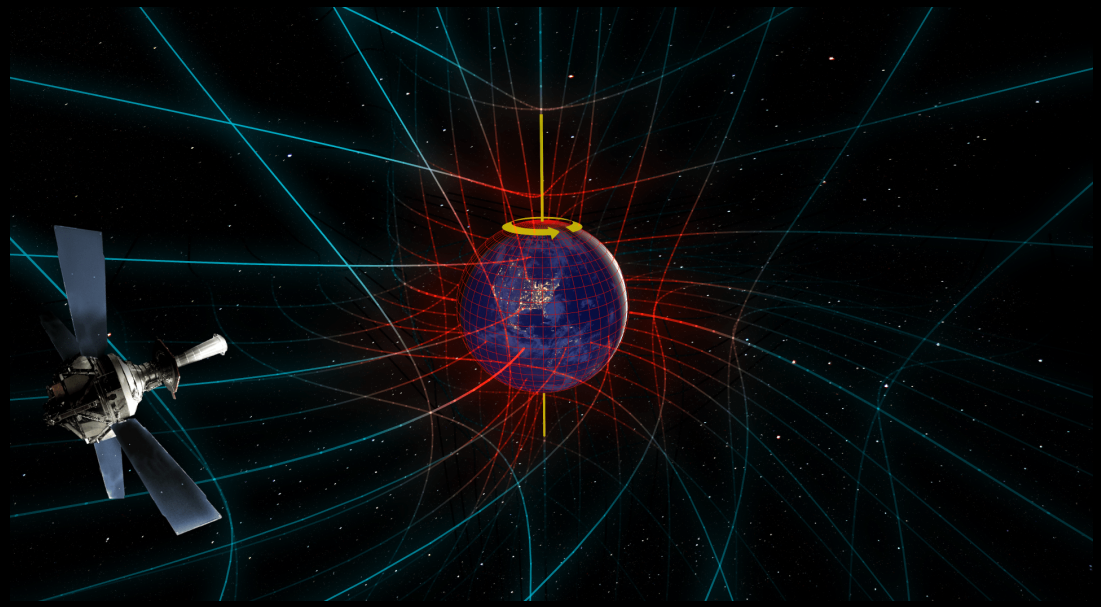


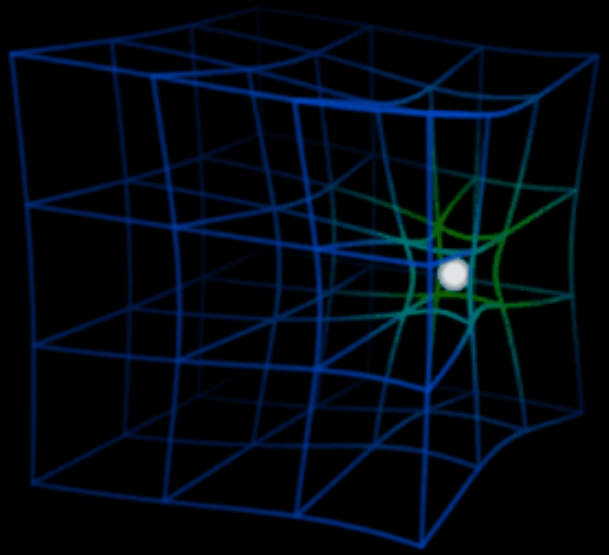
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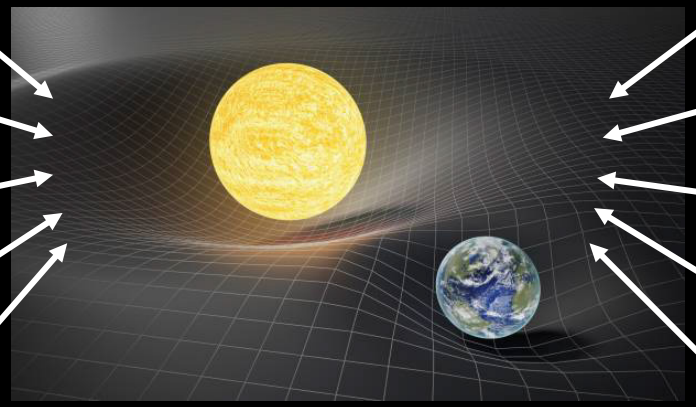


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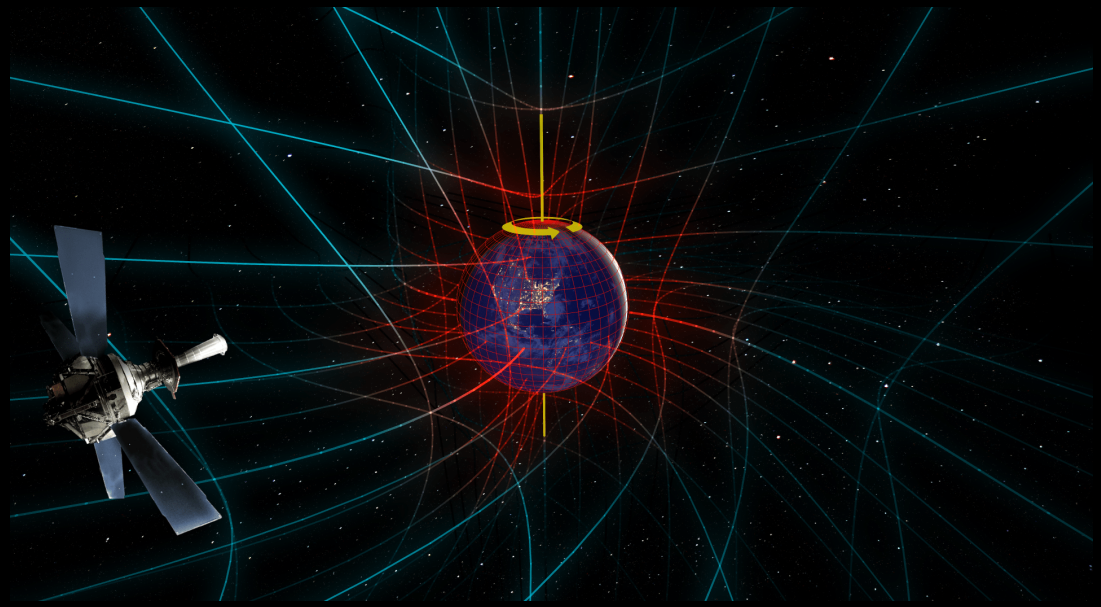


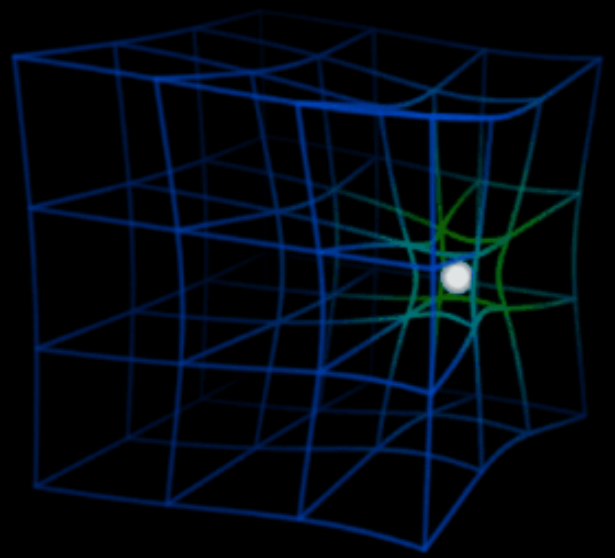
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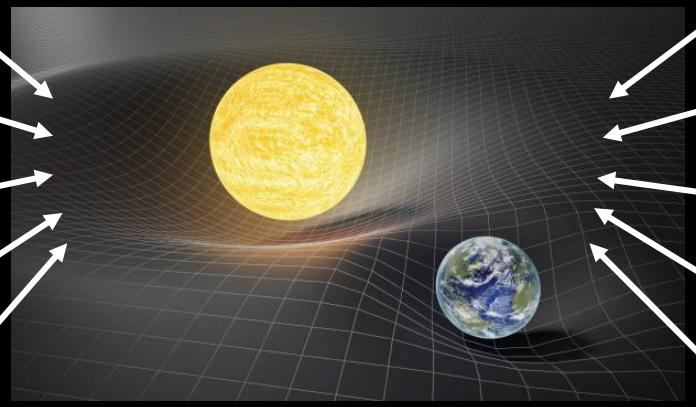
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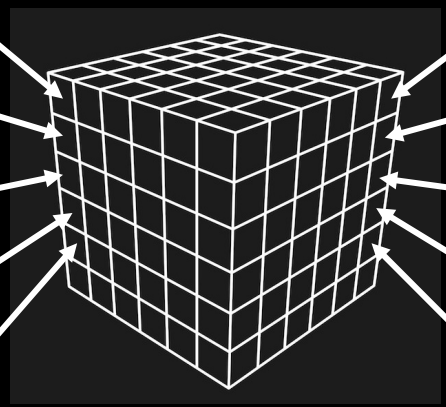




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Current status

- Intractable analytically except in very specific settings
- No existing cosmological code actually solves that
- The vast majority of cosmological code never solve any tensor equation

A paradox



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We analyze petabytes of data with the most advanced statistical frameworks, leading-edge algorithms, on GPUs, with differentiable simulations, machine learning pipelines, and neural networks...



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We analyze petabytes of data with the most advanced statistical frameworks, leading-edge algorithms, on GPUs, with differentiable simulations, machine learning pipelines, and neural networks...

...on a century-old model designed to be solvable with pen and paper while most cosmological simulations still never compute a single tensor



What is lost, what is gained going from FLRW to General Relativity

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What is lost

- Comoving space
- Universal cosmic time t
- Universal scale factor a
- FLRW parameterization Ω_M, Ω_R, Ω_Λ, Ω_k…

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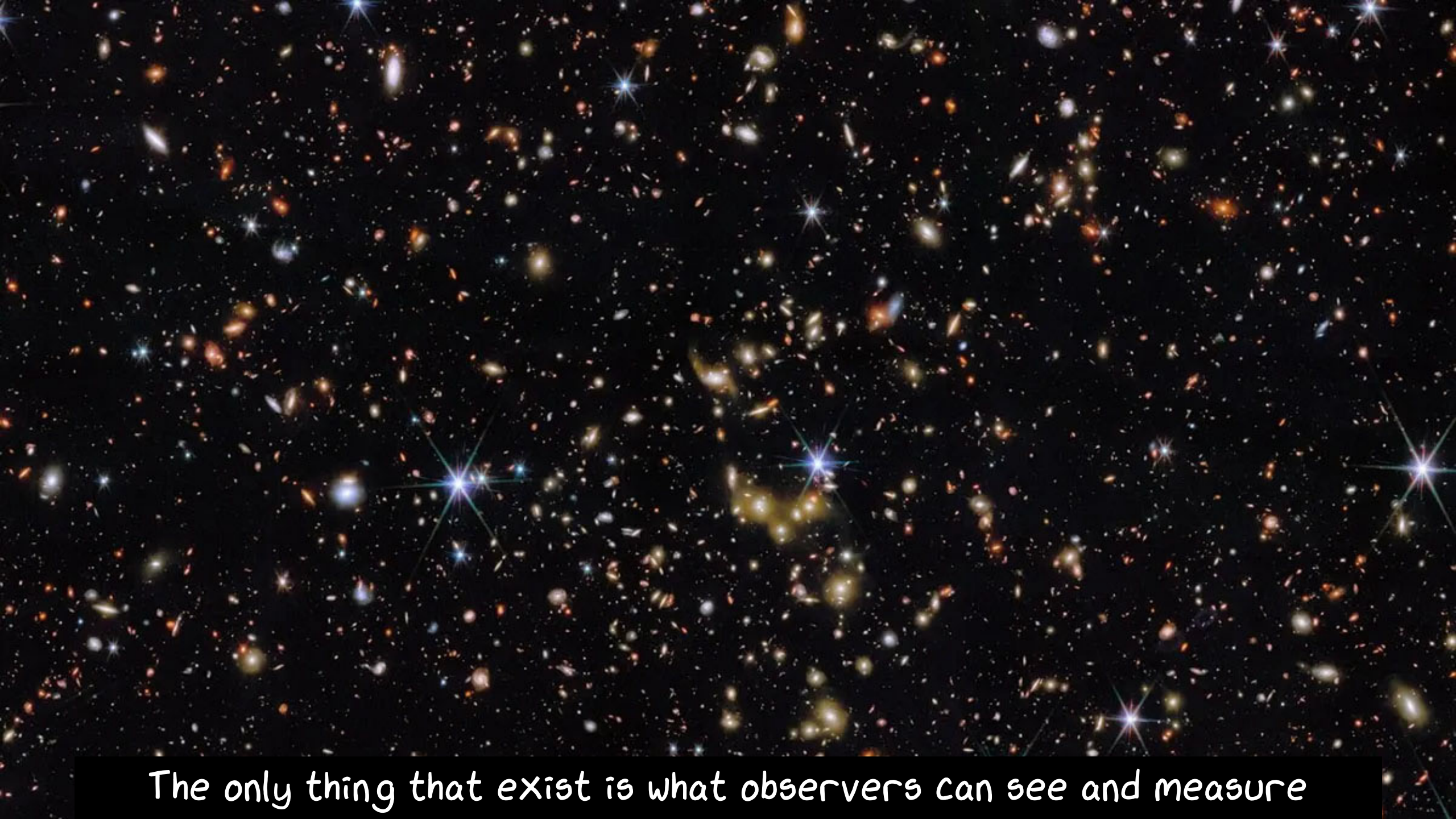
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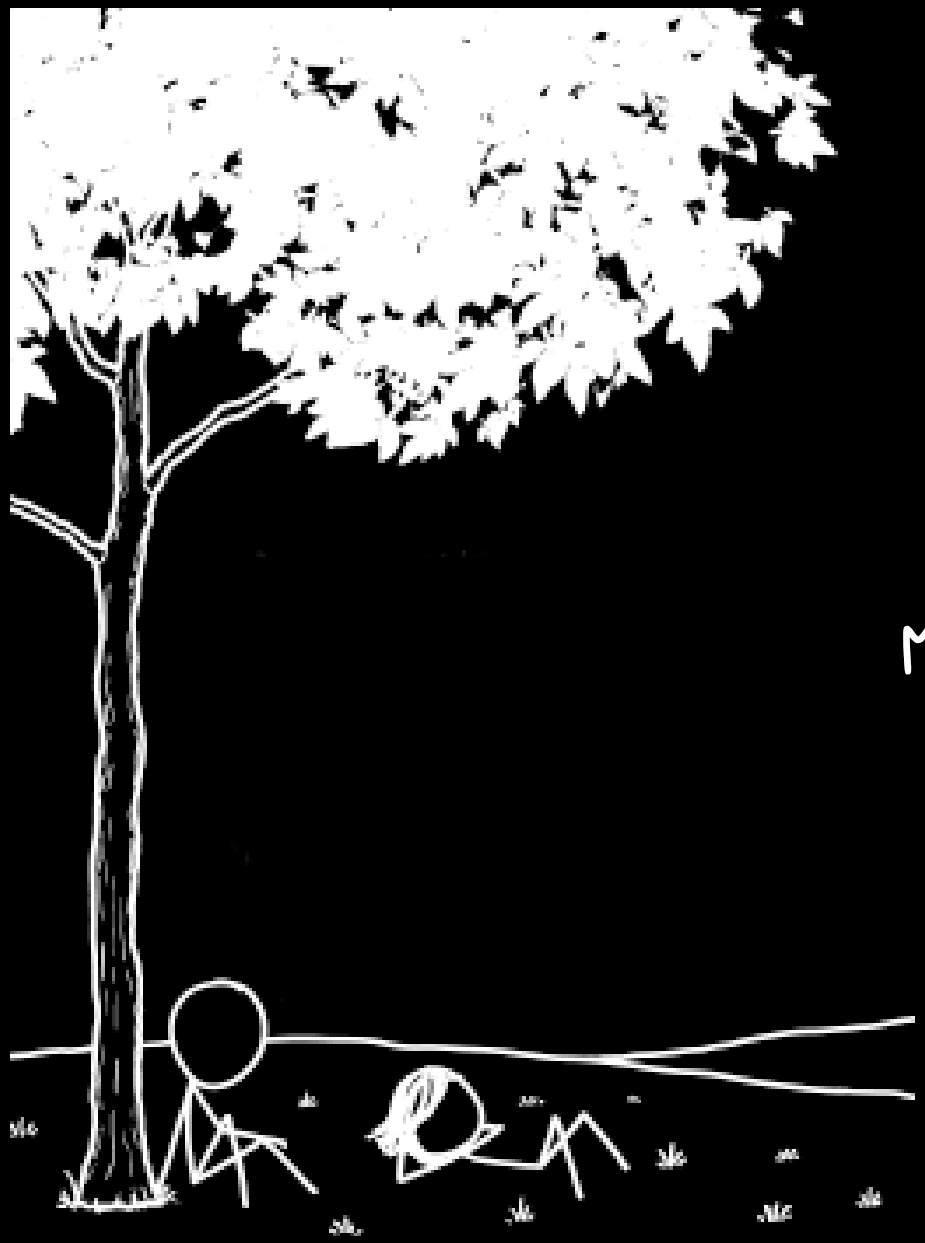
What is gained

- Genericity in which FLRW is a particular subcase
- The most well-tested theory of space-time
- Conceptual simplicity and minimal assumptions


Comoving slices do not really exist anymore


The only thing that exist is what observers can see and measure

The unexplored landscape of relativistic cosmology



Many, many open questions

The analytical road: Swiss-Cheese, Lemaître-Tolman-Bondi (LTB), Szekeres, …

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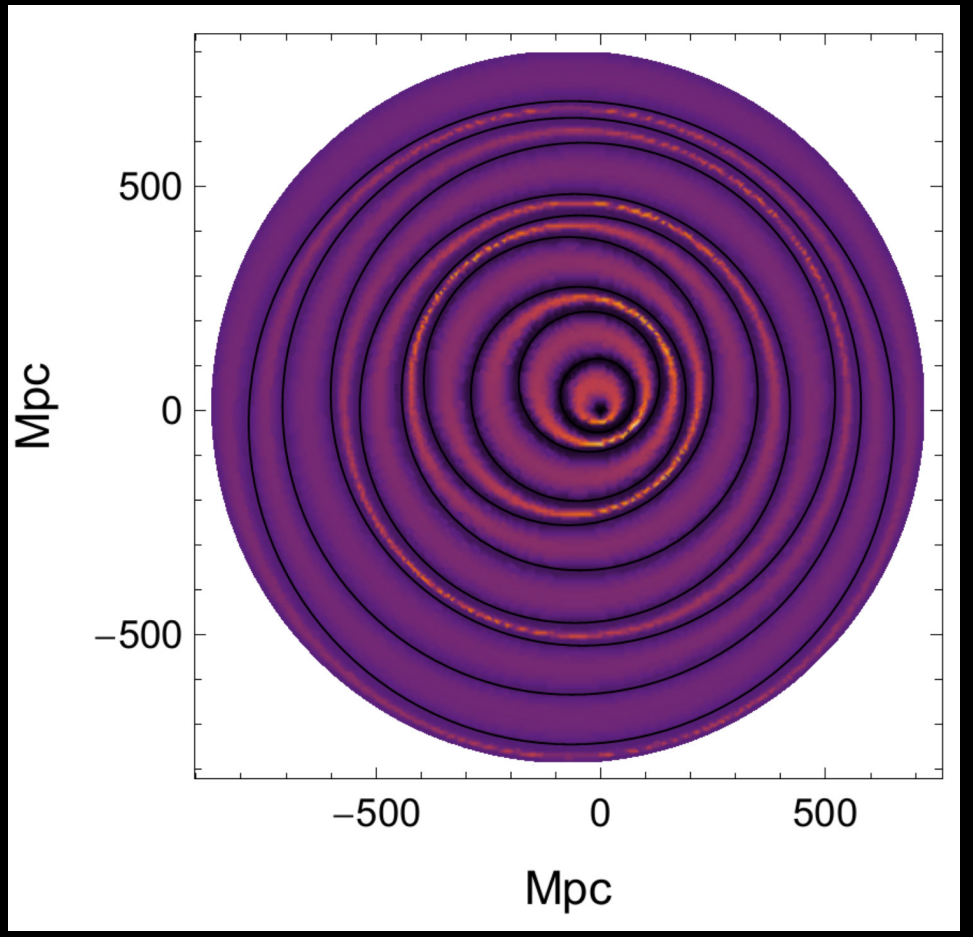
The Szekeres models

$$ds^2 = -c^2dt^2 + \frac{\left(\Phi_{,r} - \Phi\frac{E_{,r}}{E}\right)^2}{1-k(r)}dr^2 + \frac{\Phi^2}{E^2}\left(dp^2+dq^2\right)$$

$$E(r,p,q) = \frac{\left(p-P(r)\right)^2 + \left(q-Q(r)\right)^2 + S(r)^2}{2S(r)}$$

$$\dot{\Phi}^2 = \frac{2GM(r)}{\Phi} - c^2k(r) + \frac{\Lambda c^2}{3}\Phi^2$$

(see Marie-Noëlle Célérier's work)



The analytical road: backreaction and the Buchert formalism

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$$H_{\mathcal{D}}^2 = 8\pi G\langle\rho\rangle_{\mathcal{D}} - \frac{c^2}{2}\left\langle {}^{(3)}R\right\rangle_{\mathcal{D}} - \frac{1}{2}\mathcal{Q}_{\mathcal{D}} + \Lambda c^2 \qquad 3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} = -4\pi G\langle\rho\rangle_{\mathcal{D}} + \mathcal{Q}_{\mathcal{D}} + \Lambda c^2$$

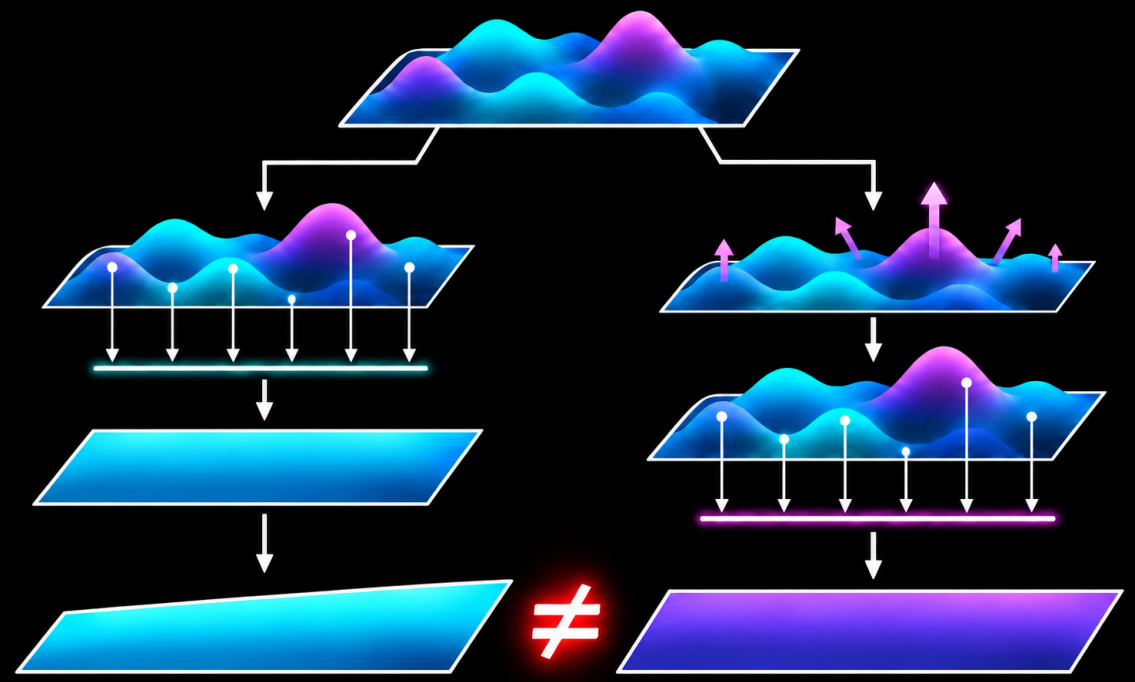
$$\mathcal{Q}_{\mathcal{D}} = \frac{2}{3}\left(\left\langle\theta^2\right\rangle_{\mathcal{D}} - \langle\theta\rangle_{\mathcal{D}}^2\right) - 2\left\langle\sigma^2\right\rangle_{\mathcal{D}}$$

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Non-commutativity of averaging procedures



The computational road: Numerical Relativistic Cosmology

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Codes are still in their infancy

- Limited resolution and dynamical range
- Restricted gravitational approximations
- Simplified matter and kinetic descriptions
- Inadequate treatment of multistreaming and shell crossing
- Lack of fully relativistic, constraint-consistent initial conditions
- Numerical formulations not optimized for cosmology
- Limited end-to-end connection to observables

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How to map the structure of General Relativity into the structure of the code?

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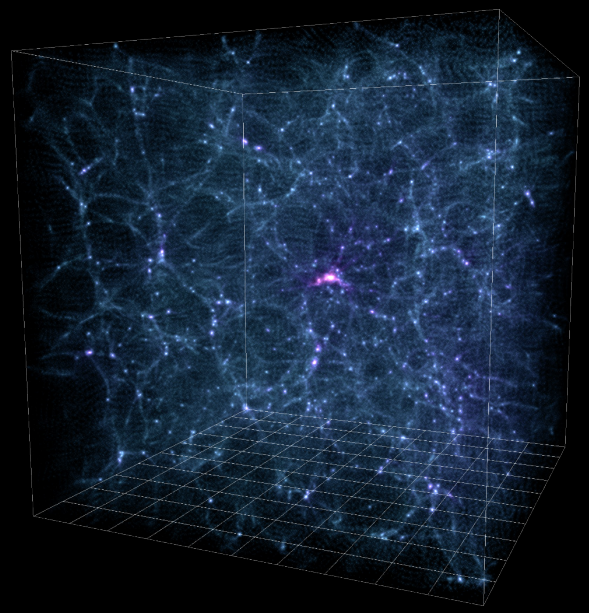
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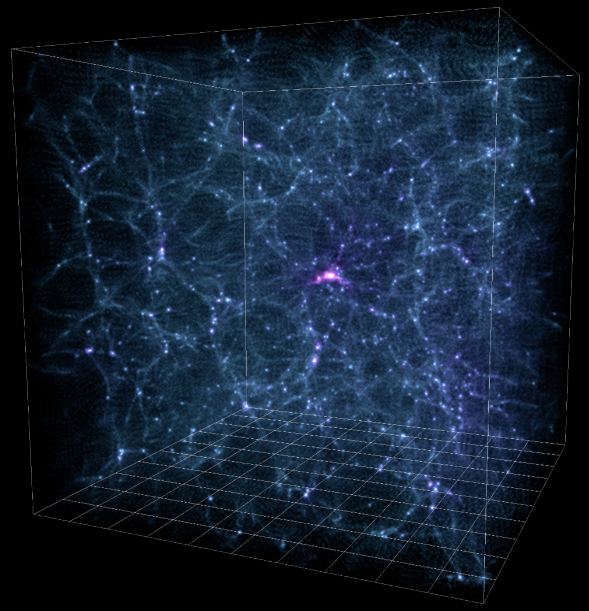
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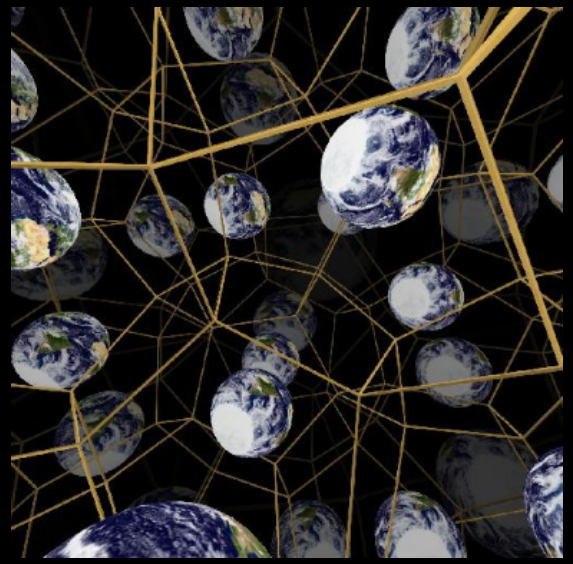
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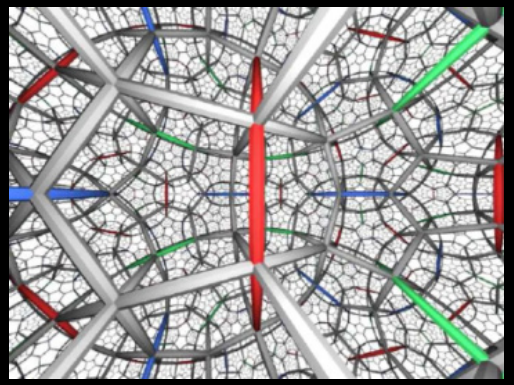
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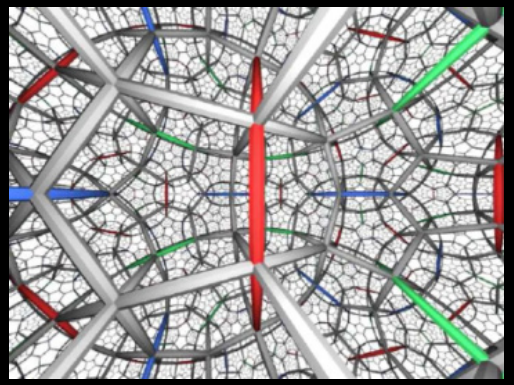
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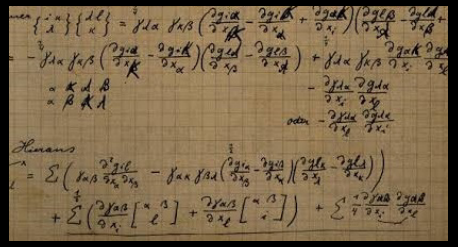
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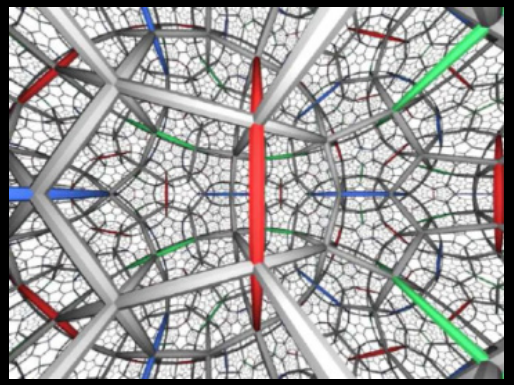


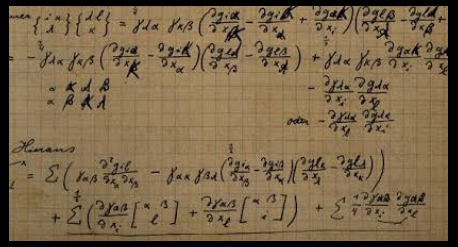


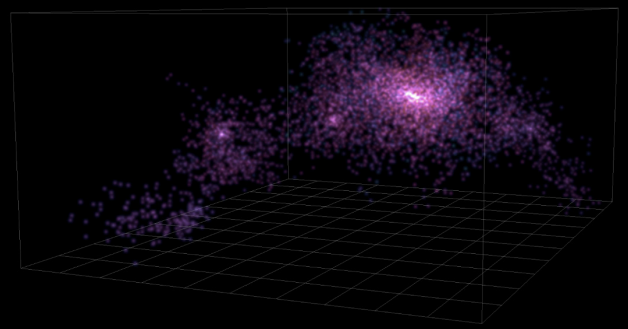
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How to translate existing structure detection algorithms to curved spaces?

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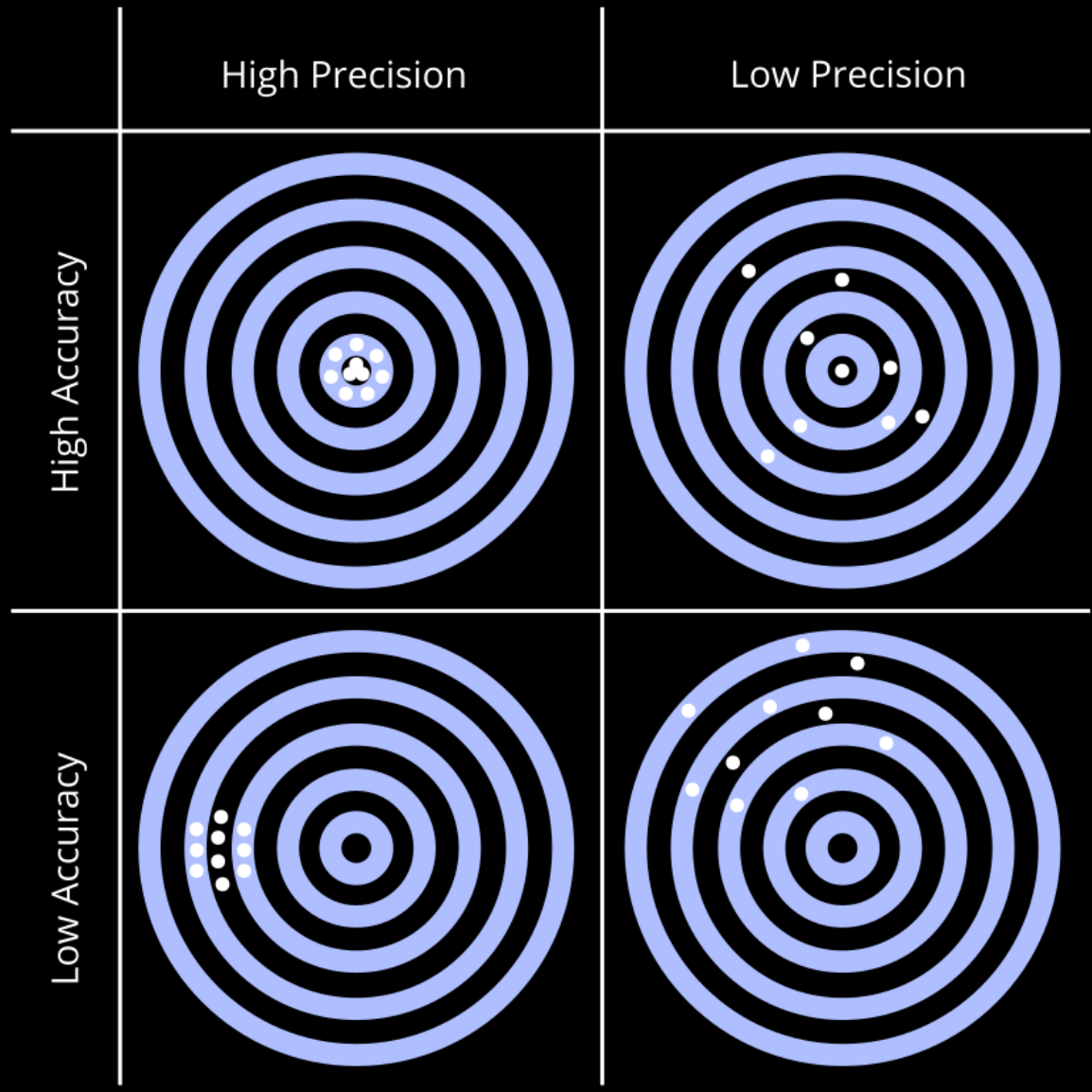
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Initial conditions (Upcoming intern, 2027→2030)

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From precision cosmology to accurate spacetimes



Conclusions



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