From Precision Cosmology to Accurate Spacetimes

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

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Virgo Cluster - LSST

A very peculiar moment for cosmology

⇒ Stage IV surveys

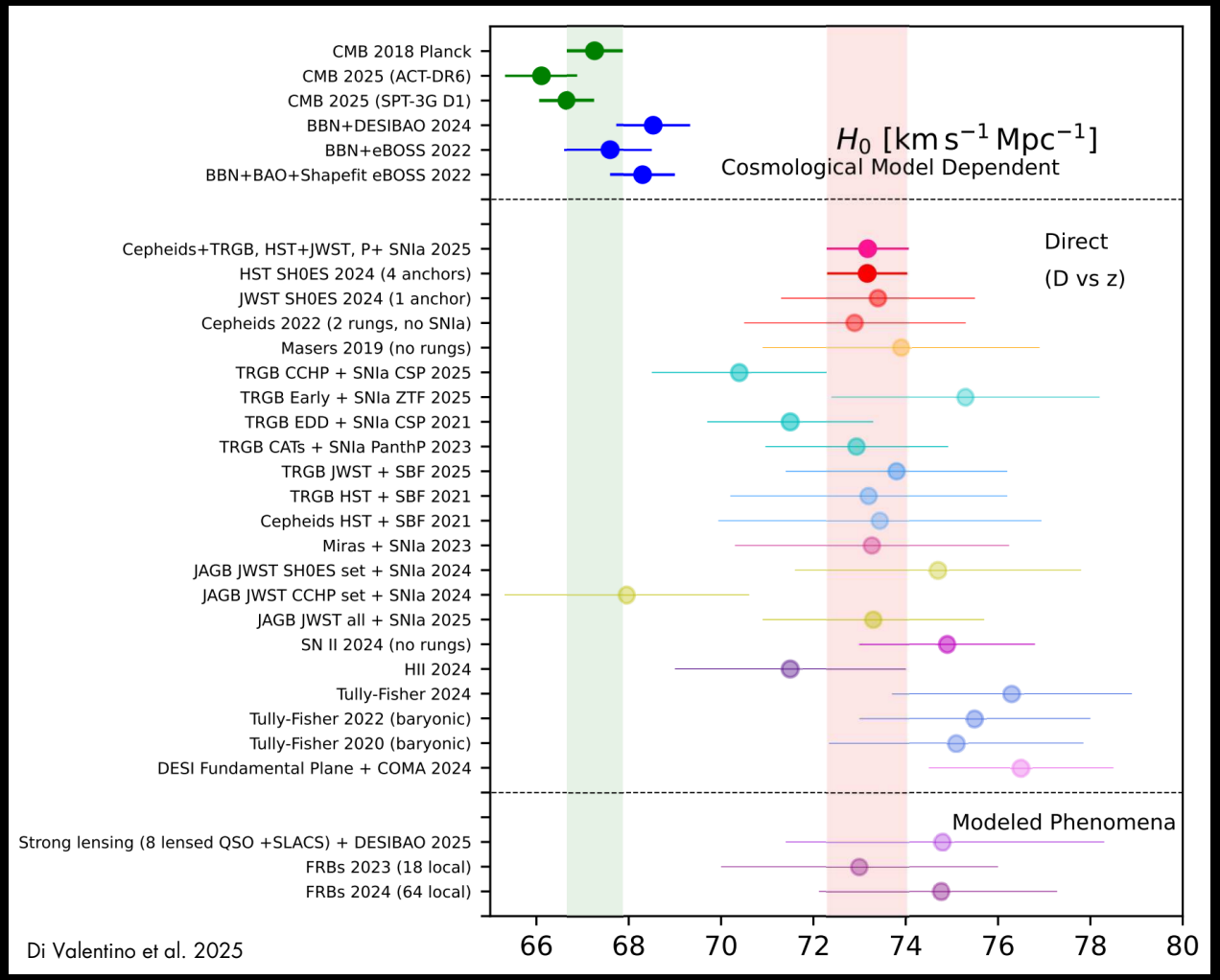
⇒ Data (and more data)

⇒ "Precision cosmology"

⇒ Advanced analyses pipelines

⇒ Leading-edge algorithms

... but persistent tensions

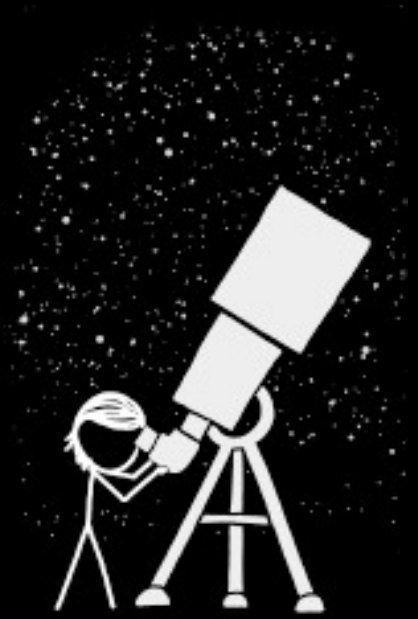




What do we expect from new surveys?

An unconvenient question

How do we expect new surveys and precision cosmology to solve existing tensions in practice?



Step 1
Stage IV surveys
Precision cosmology
Data

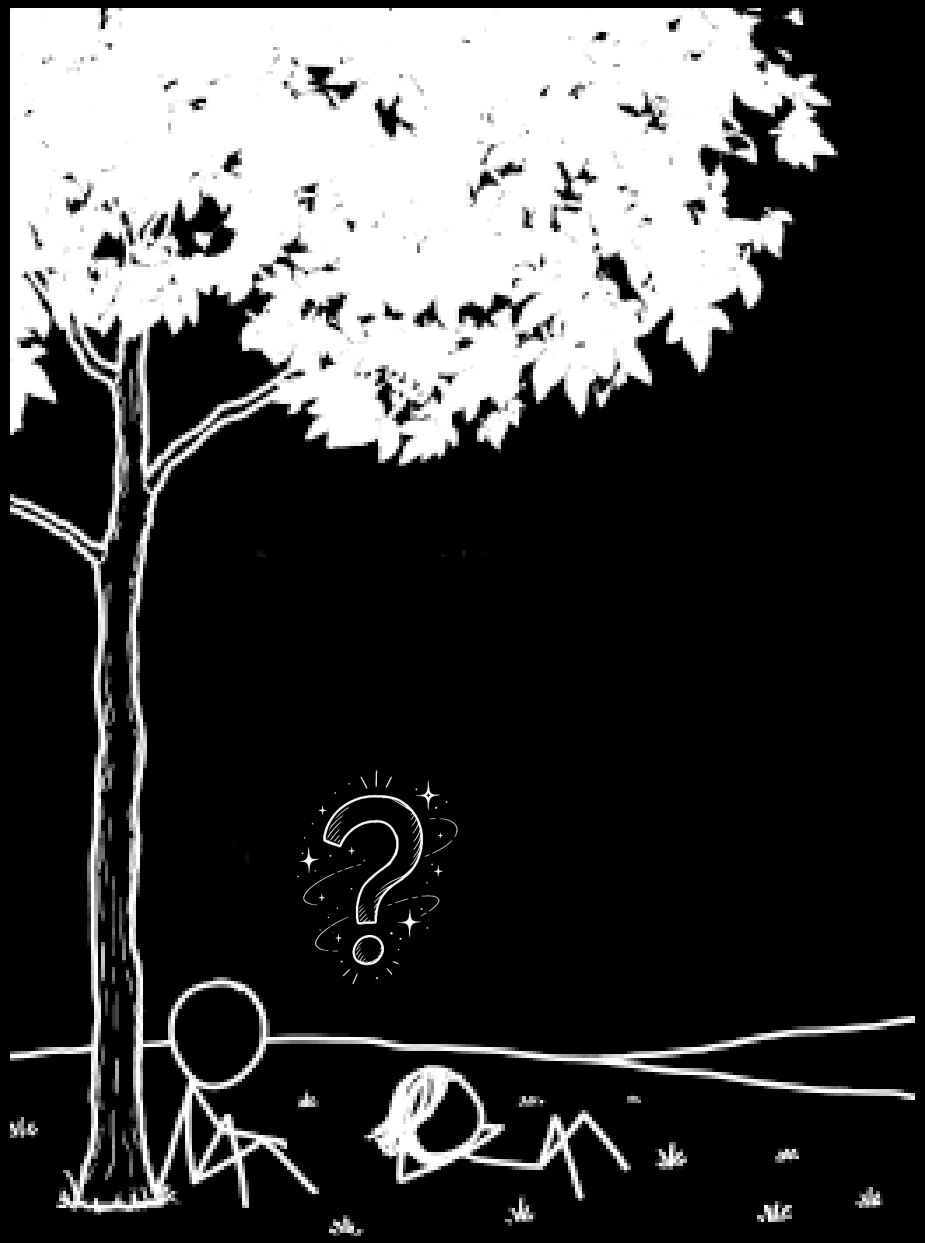


Step 2
Something



Step 3
Solved tensions

What is this talk about



- 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

Statistical fluctuation

- We are in an unlikely realization

Misestimated uncertainties

- Incorrect error bars, covariance matrices, noise models, or correlations

Systematic biases

- Instrumental effects, calibration errors, selection biases, or inadequate astrophysical modeling

Incorrect physics or modeling

- Incorrect theory, model or assumptions about fundamental physics

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
- **Requires alternatives and priors**

Falsification: is our model wrong?

- Natural fit for frequentist hypothesis testing
- Are observations compatible with ΛCDM?
- Reject predictions with statistically significant discrepancies
- **No alternative required**

Model selection asks which alternative works best

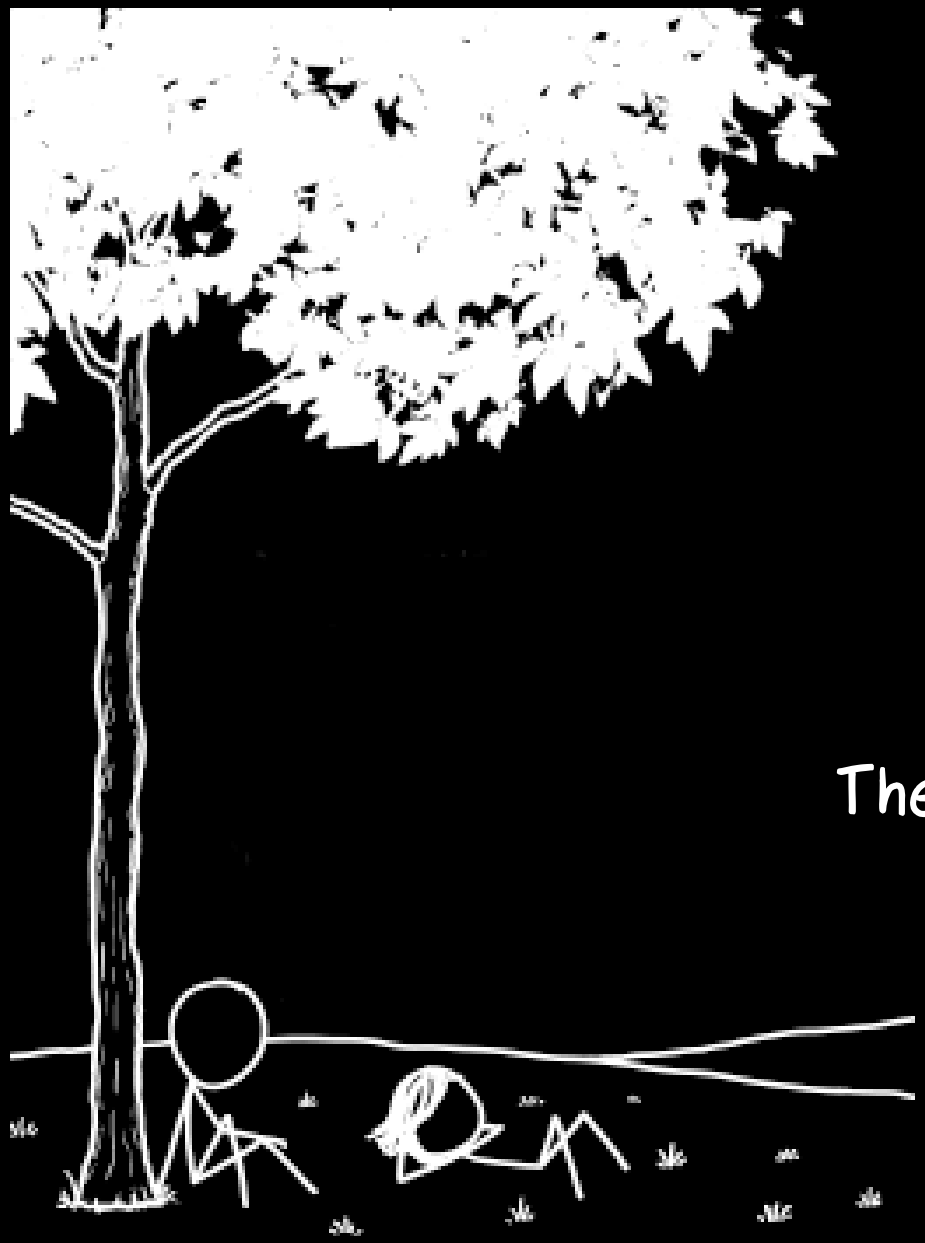
Does any alternative outperform ΛCDM?

Falsification asks whether we need an alternative

Does ΛCDM survive the data?



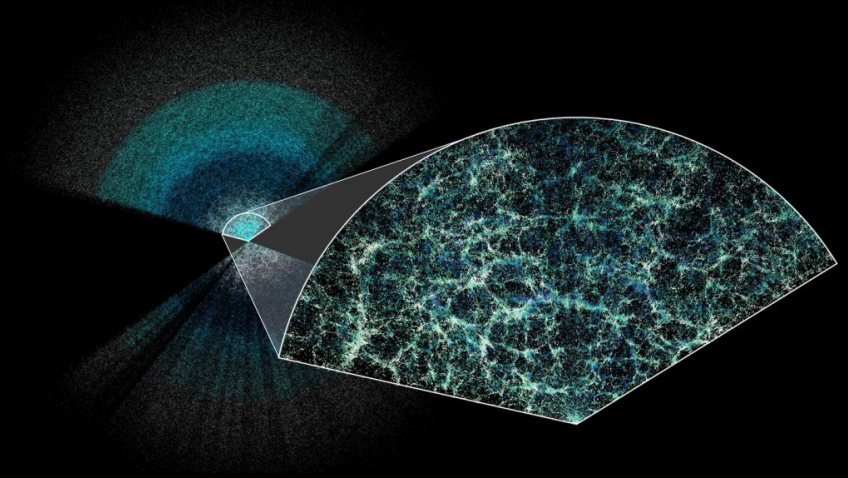
The first question

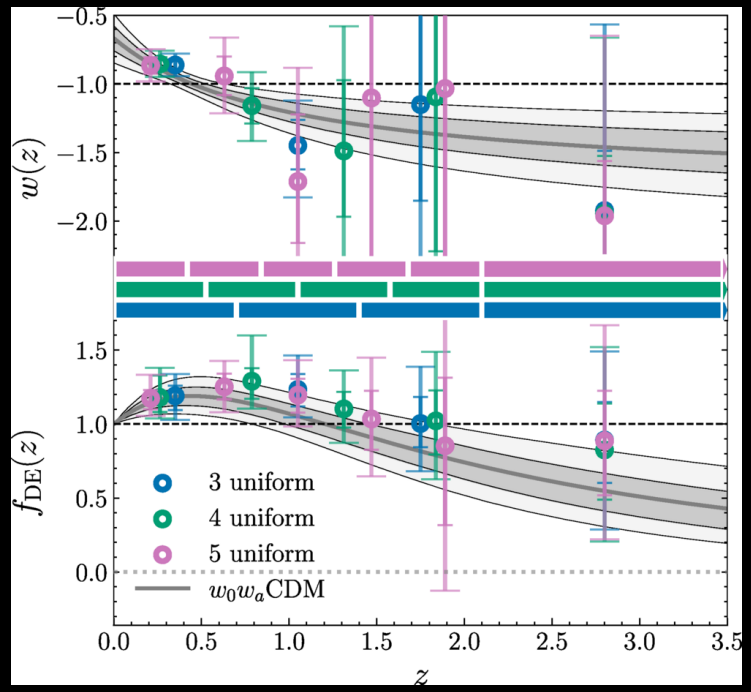


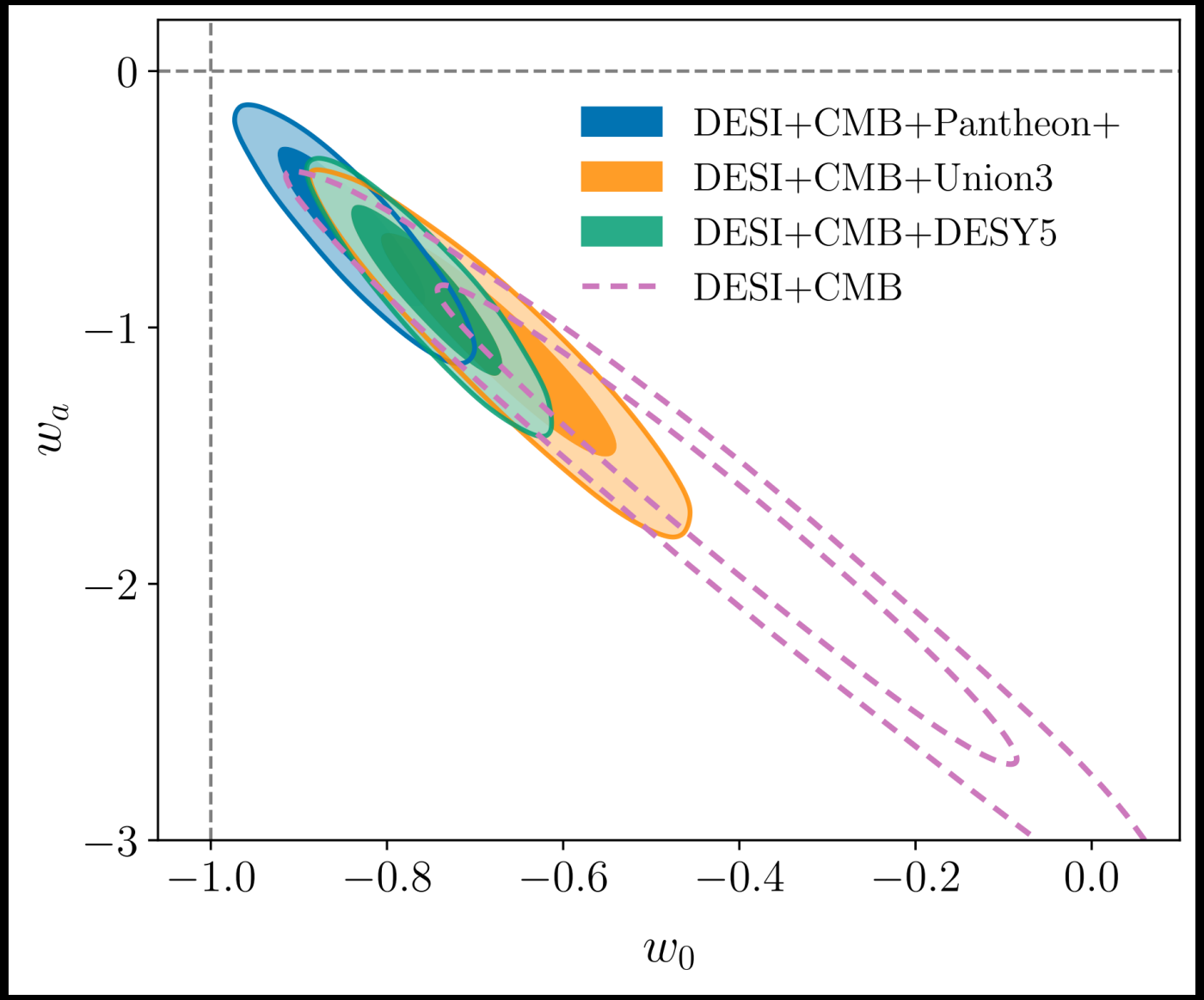
Before searching for the right answer,
we must first ask the right question

The first question isn't which alternative wins,
but where to look for one

Going beyond ΛCDM: a varying dark energy?







The problem with $w_0 w_a$

The equation of state (CPL parameterization)

$$w(t) = \frac{P_{DE}(t)}{\rho(t)c^2} = w_0 + w_a\left(1 - \frac{a(t)}{a(t_0)}\right)$$

Observational cosmology

- A nice extension for observational fits

Theoretical cosmology

- A local equation of state that depends on global parameters
- $w_0 w_a$ parametrizes the background without specifying a local, diffeomorphism-invariant theory
- Probably one of the worst possible choice from the theoretical standpoint

Congratulations, you just broke physics!

Some confusion

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Λ on the spacetime geometry side $G_{\mu\nu}$

- Λ is constant (per Lovelock theorem)
- Λ is a fundamental property of spacetime
- No need for an underlying explanation

Λ on the stress-energy tensor side $T_{\mu\nu}$

- $w_{DE} = \frac{P_{DE}}{\rho_{DE} \times c^2} = -1$, constant equation of state
- Dark energy interpretation

ΛCDM

In the context of ΛCDM, the geometrical and stress-energy descriptions of Λ happen to be exactly equivalent, independently of the spacetime geometry

$w_0 w_a$

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

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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 :

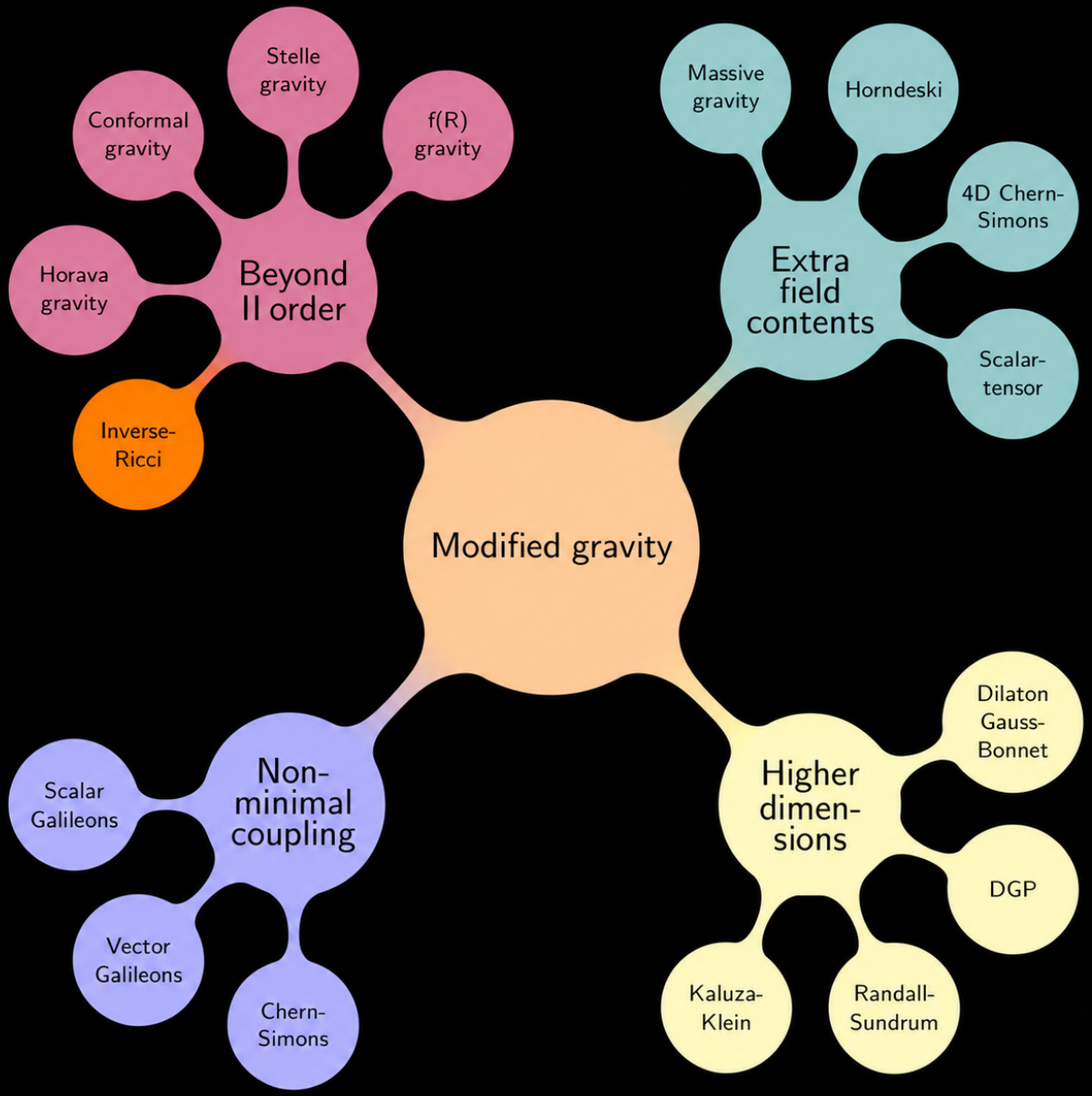
$$A_{\mu\nu} = aG_{\mu\nu} + bg_{\mu\nu}$$

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

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

Do we even need modified gravity?

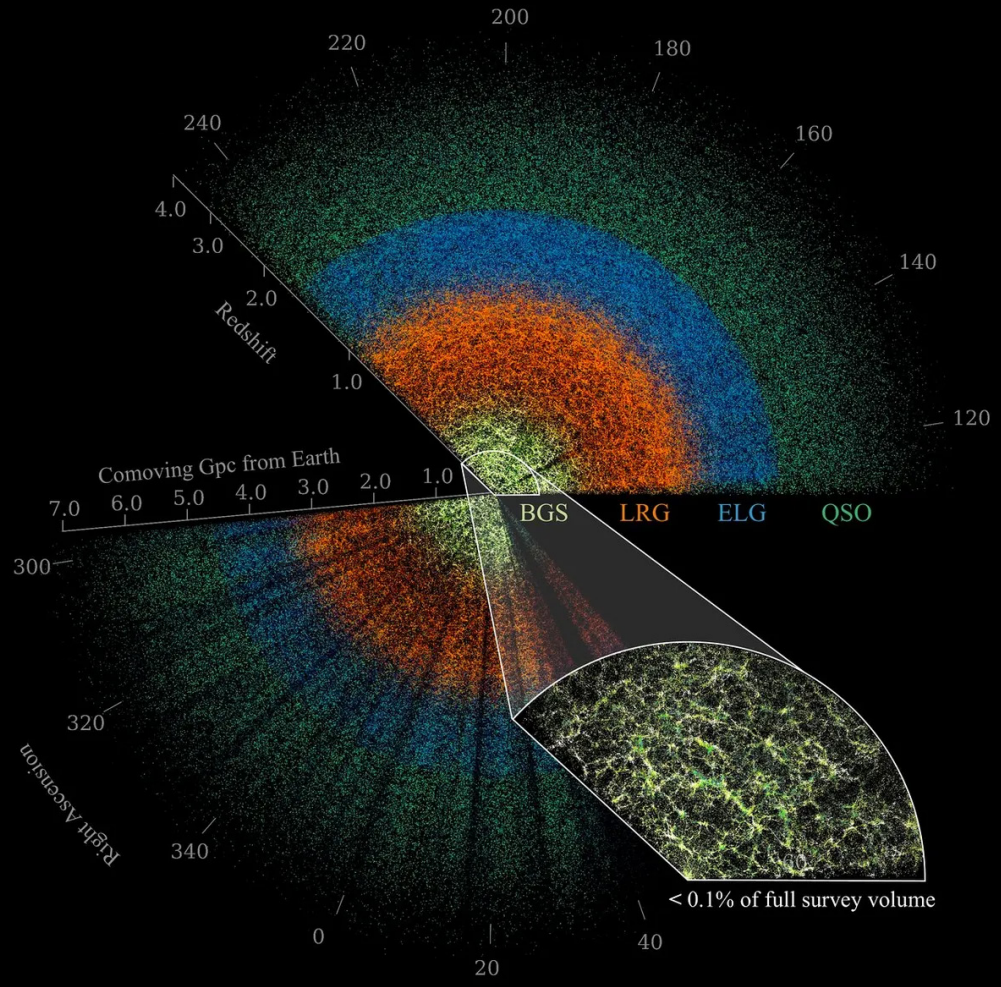
FLRW = General Relativity + Cosmological principle

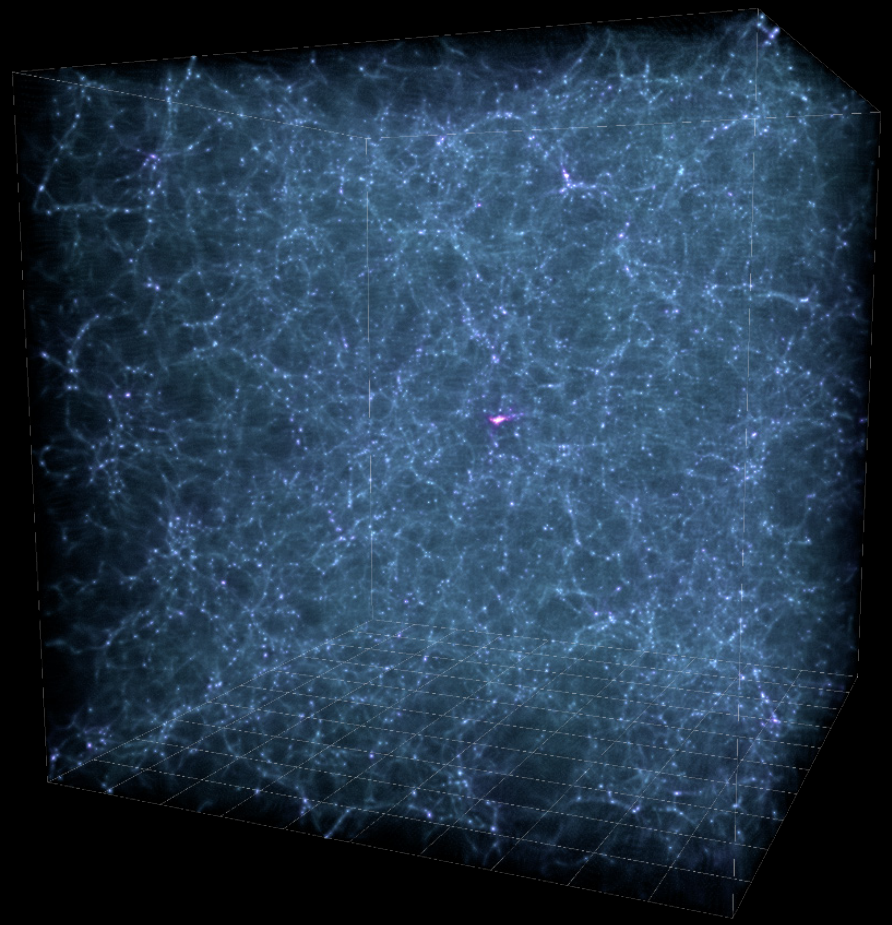


Cosmological tensions
do not break, by themselves, General Relativity,
they break ΛCDM or FLRW

Asking the right question

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





I was wrong all along

What relativistic cosmology is NOT about

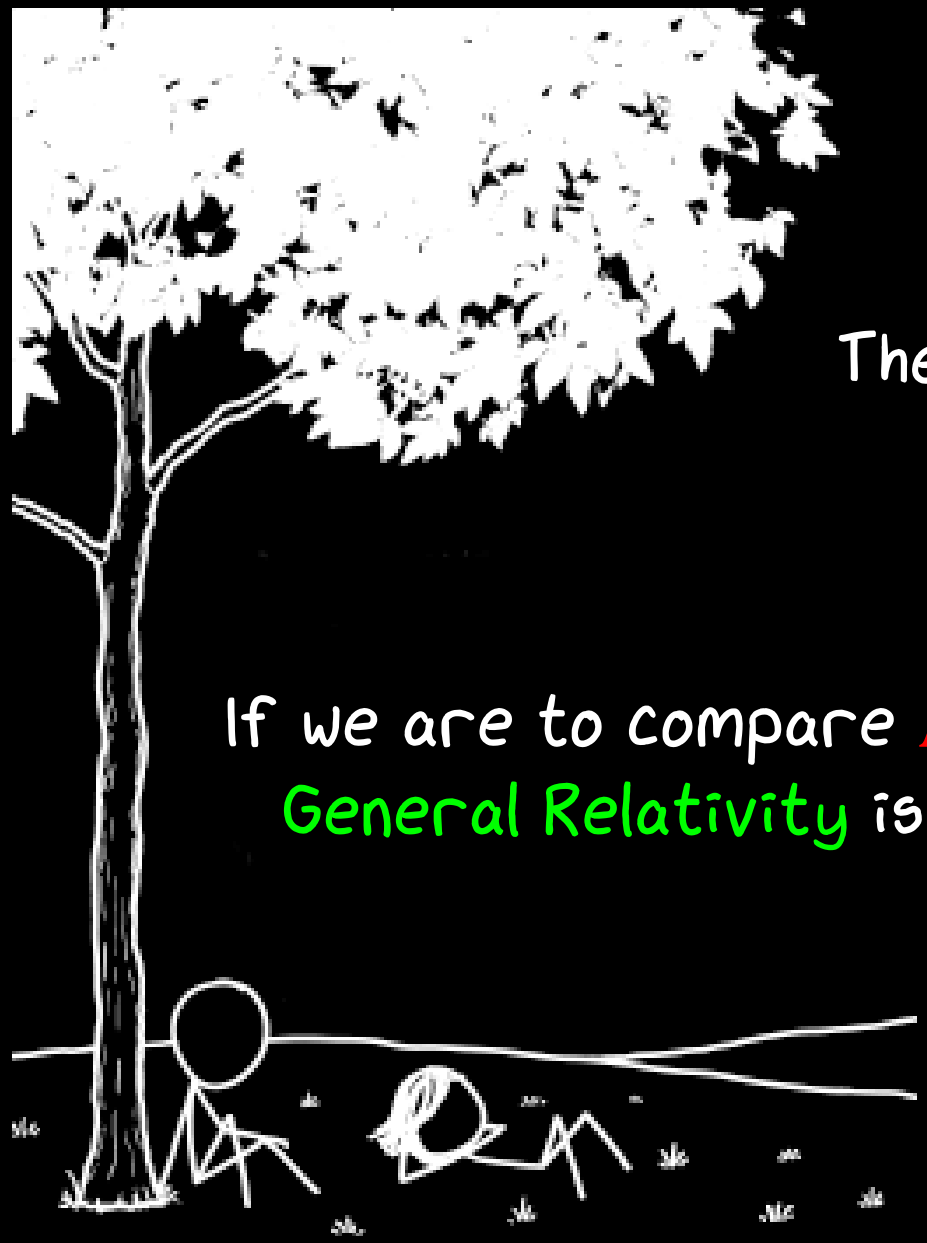
- Relativistic cosmology is mainly not about relativistic effects
- Gives the wrong impression that we are looking for tiny or subtle effects

FLRW − Cosmological principle = General Relativity

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 first question isn't which alternative wins,
but where to look for one

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

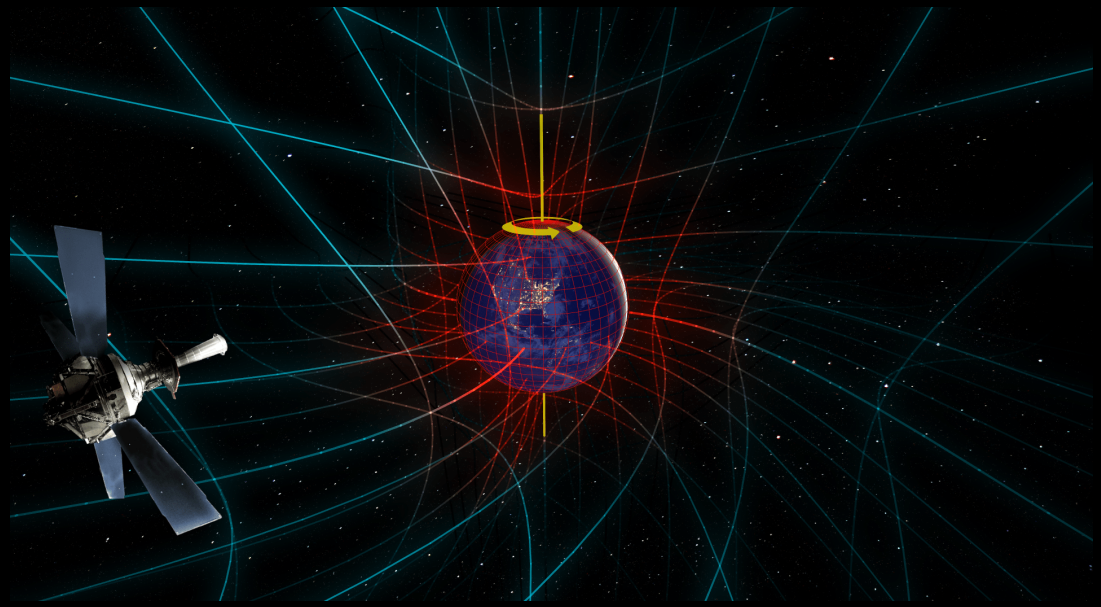
General Relativity

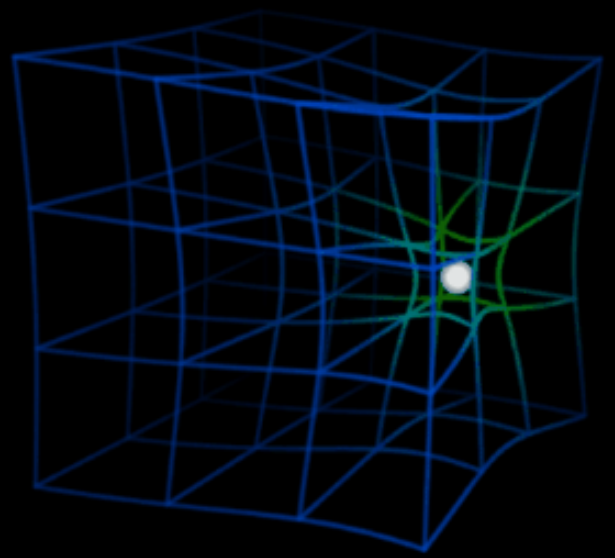
Numerical cosmology

Observational cosmology

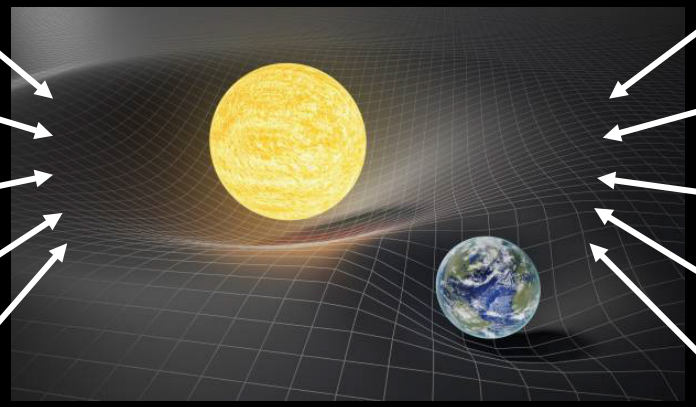


Coming back to Einstein's original idea, and a local theory of spacetime

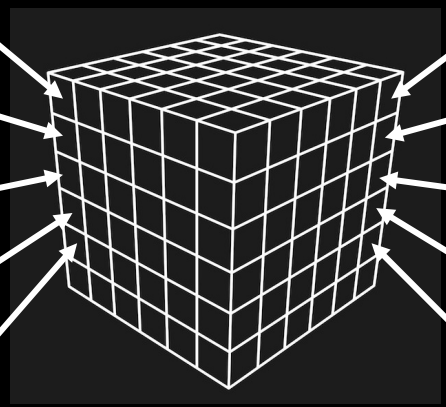




$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



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$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein Field Equations

$$\begin{pmatrix} G_{tt} & G_{tx} & G_{ty} & G_{tz} \\ & G_{xx} & G_{xy} & G_{xz} \\ & & G_{yy} & G_{yz} \\ & & & G_{zz} \end{pmatrix} = \frac{8\pi G}{c^4} \begin{pmatrix} T_{tt} & T_{tx} & T_{ty} & T_{tz} \\ & T_{xx} & T_{xy} & T_{xz} \\ & & T_{yy} & T_{yz} \\ & & & T_{zz} \end{pmatrix}$$

10 coupled, nonlinear, second-order Partial Differential Equations
with 4 constraints and 4 gauge freedoms
to solve at each point of space-time

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

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

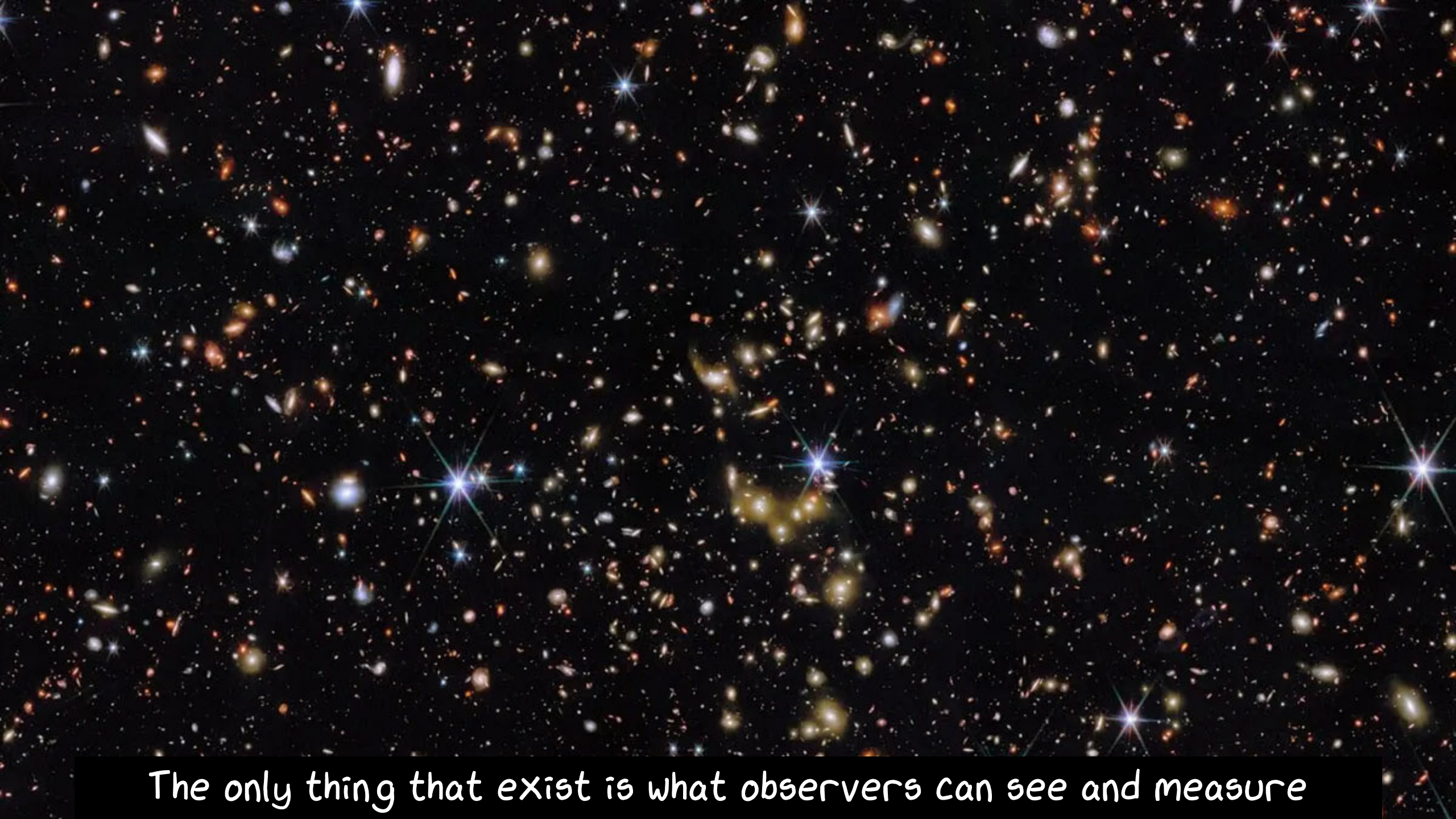
What is lost

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

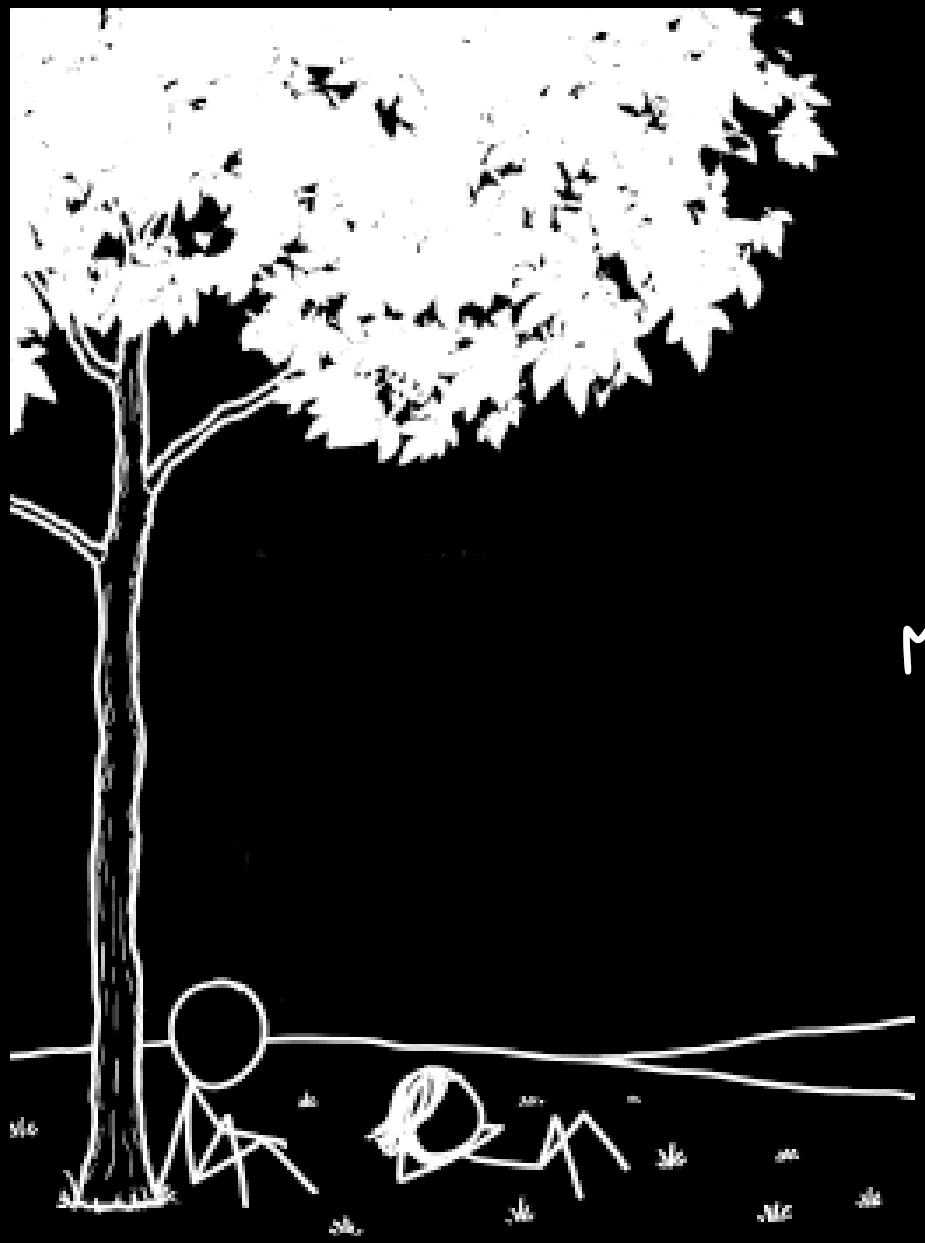
What is gained

- 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

Silent universes

Spacetimes filled with irrotational, pressureless dust, in which the magnetic part of the Weyl tensor vanishes

PDEs ⇒ ODEs

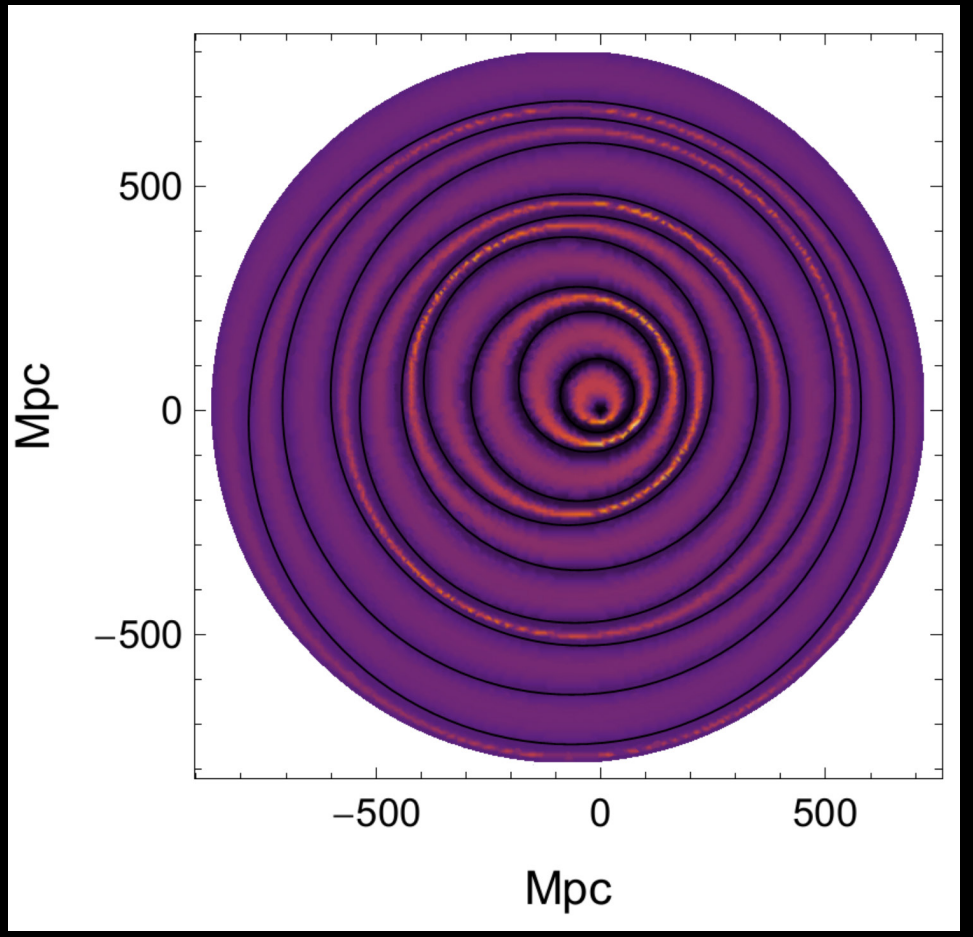
The Szekeres models

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

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

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

(see Marie-Noëlle Célérier's work)

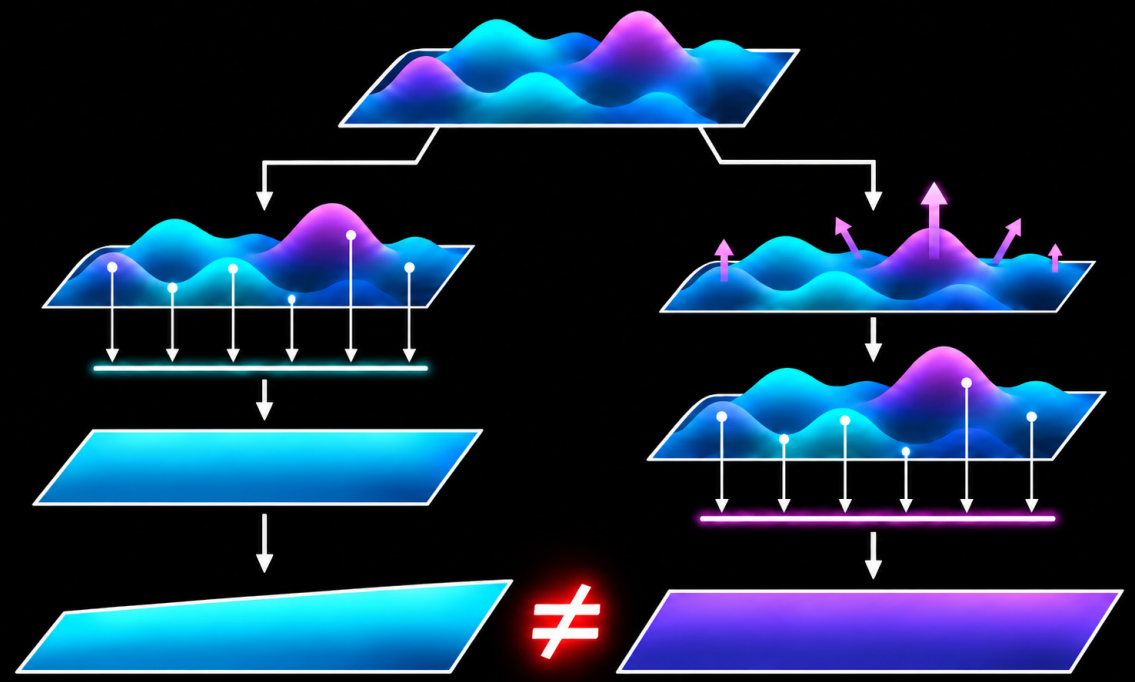


The analytical road: backreaction and the Buchert formalism

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

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

Non-commutativity of averaging procedures



The computational road: Numerical Relativistic Cosmology

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

Reliable physics conclusions ⇒ Fine control of numerical modeling, approximations and errors

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

The computational road: example of an unsolved problem

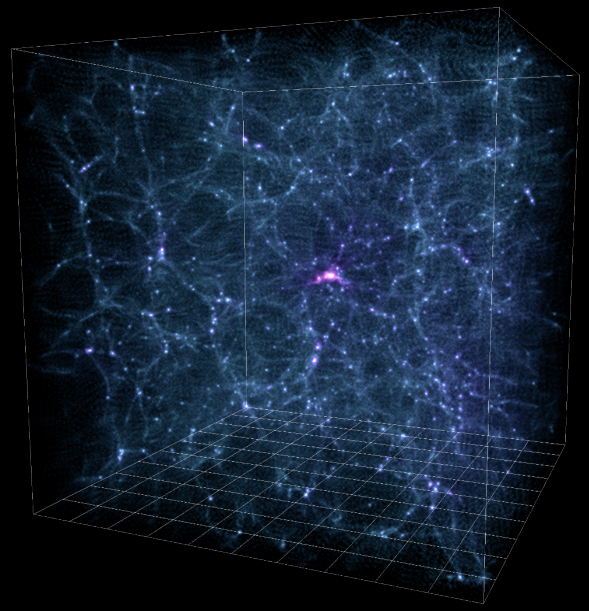
Even for FLRW

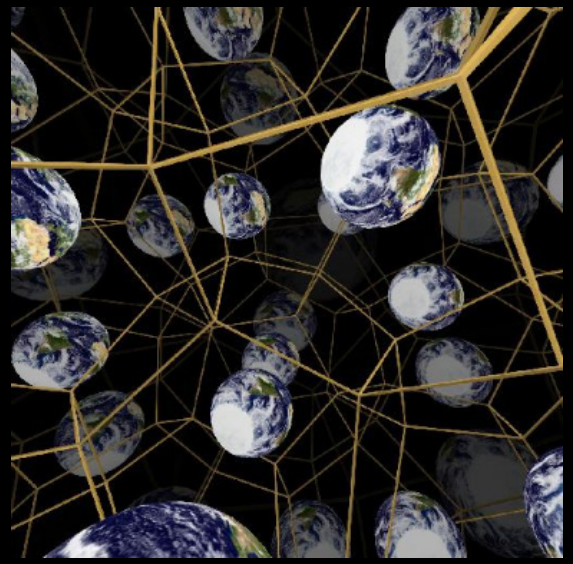
- No rigorous simulation of structure formation has ever been performed for $\Omega_k \neq 0$

In general relativity

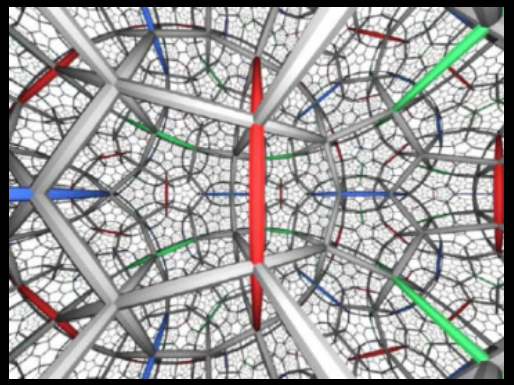
- A topological manifold should be provided as an initial condition

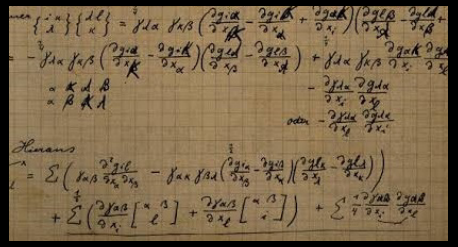
All simulations are on $\mathbb{T}^3$ (flat torus) with trivial periodic boundary conditions (or a space embedded in $\mathbb{T}^3$)

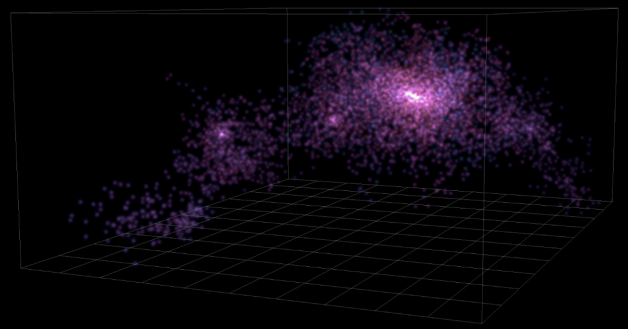




The computational road: example of an unsolved problem







How to represent non-trivial topologies, fundamental domains, and gluing conditions?

What theory of gravity to solve?

How to translate existing structure detection algorithms to curved spaces?

The computational road in the LSST team at LAPP (V. Reverdy & N. Lorenzo Martinez)

Raytracing and geodesics (Laurent Magri-Stella, 2025→2028)

- How to reconstruct lensing observables directly from a metric tensor field? How to provide a unified treatment of the weak and strong regime?

Topology and curvature (Tetautahi Maamaatuaiahutapu, 2026→2029)

- How to simulate Universes beyond the flat torus? What is the imprint of the Universe's curvature on non-linear large scale structure formation?

Numerical methods (Gautier Miguet, 2026→2029)

- How to generate numerical methods that preserve relativity's invariants, minimize errors, and maximize computing speed?

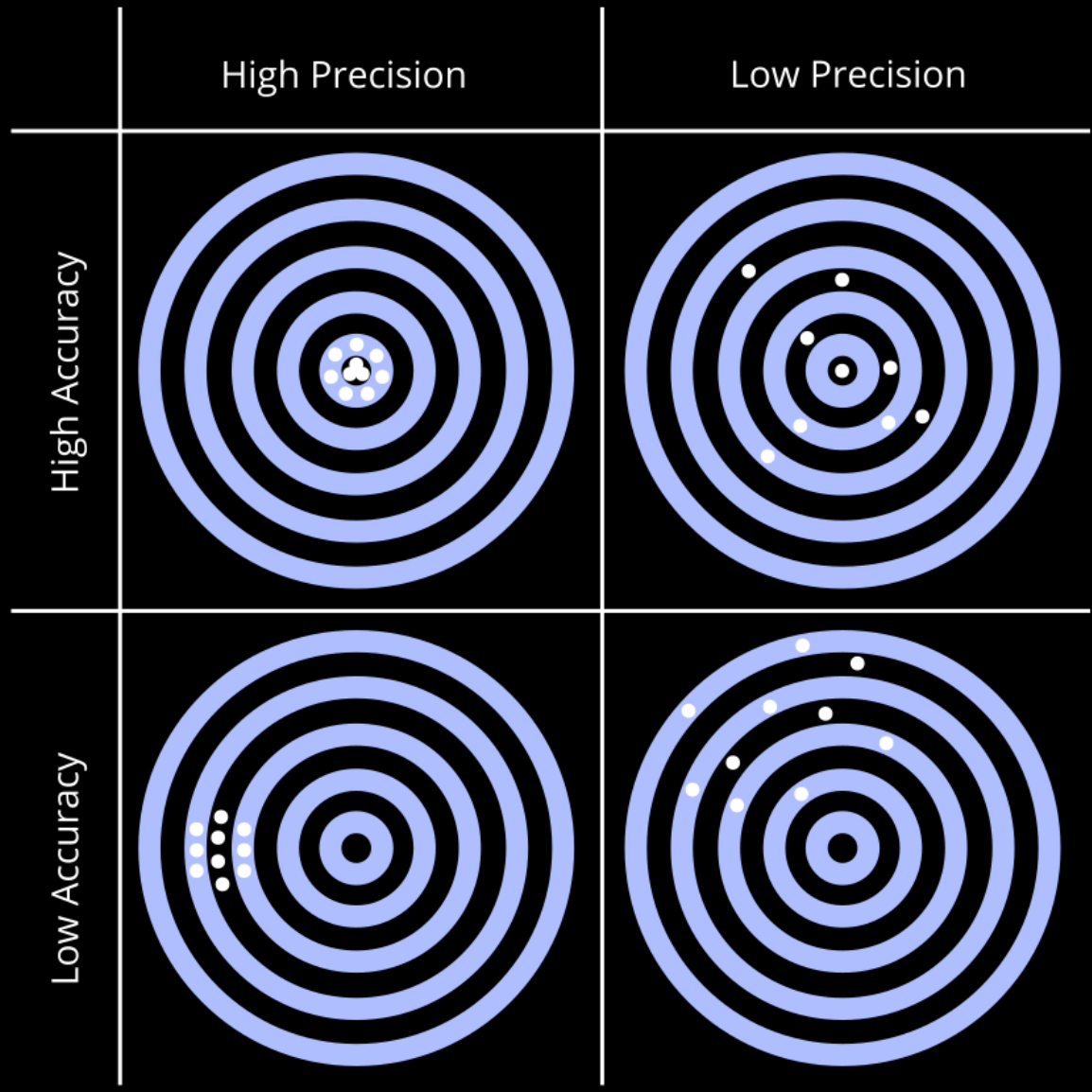
Observational consequences (Noah Orazi, 2026→2029)

- How to correctly propagate relativistic corrections into analysis pipelines? What consequences on uncertainties?

Initial conditions (Upcoming intern, 2027→2030)

- How to rigorously solve the Cauchy problem for numerical relativistic cosmology?

From precision cosmology to accurate spacetimes



Conclusions

1) We cannot resolve cosmological tensions without questioning the framework in which they arise.

2) We are entering the era of precision cosmology with a century-old cosmological model developed for pen & paper calculations.

3) Before knowing which alternatives to LCDM wins, we need to know where to look for.

4) Relativistic cosmology is not primarily about relativistic effects. GR is just the best theory we have to frame cosmological questions.



5) Relativistic cosmology is still an unexplored territory full of mathematical, physical, and computational open problems.