ELEGANCI - Exascale Lensing Engine for Gravitational Astrophysics and Numerical Cosmology Investigations

GDR Cophy Tools – November 4th, 2025 – Laboratoire d'Astrophysique de Marseille

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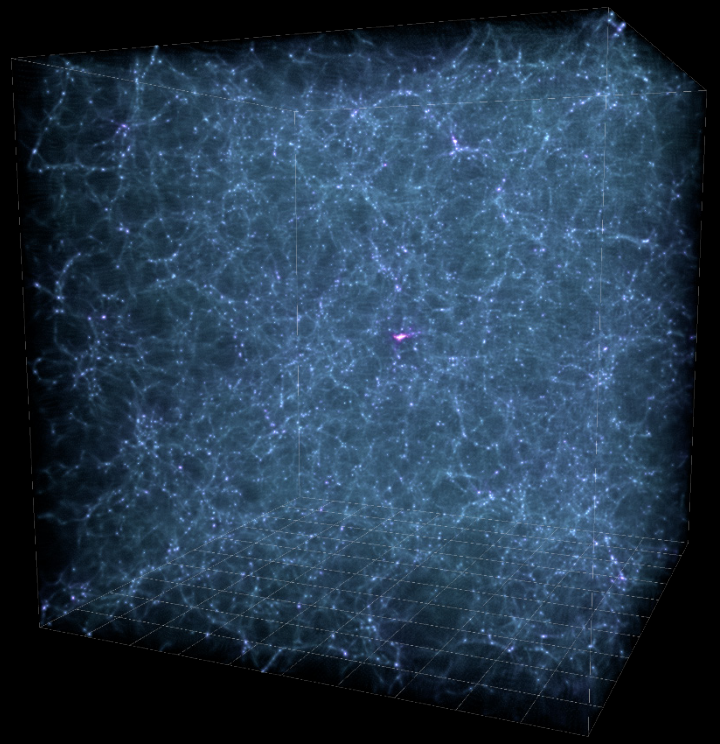
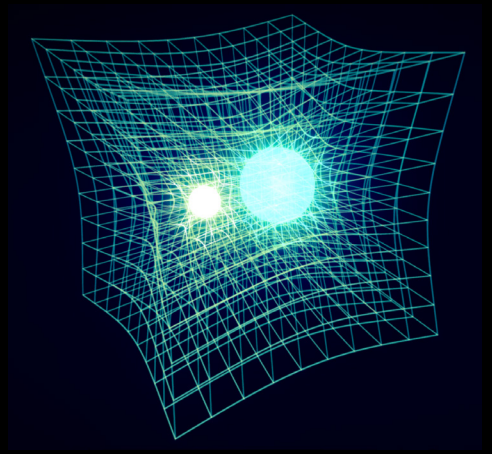
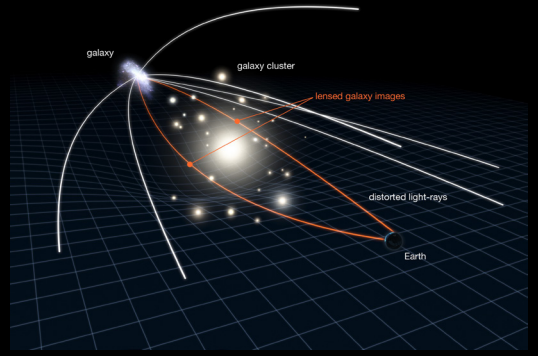


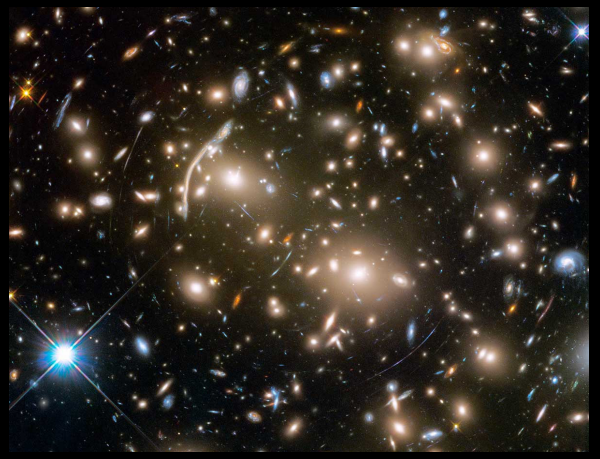
Starting from relativistic raytracing for cosmology



$g_{\mu\nu}$

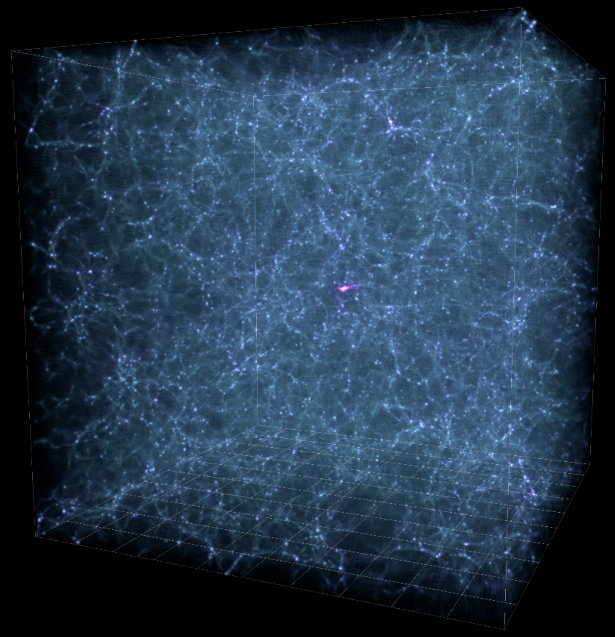


relativistic raytracing (computation of geodesics)

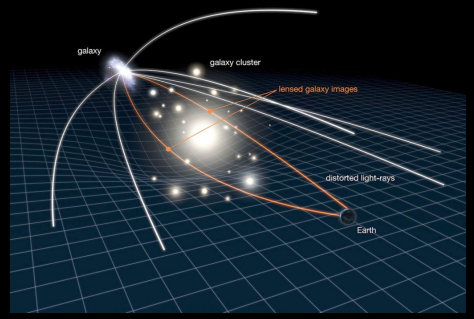


strong-lensing
weak-lensing
redshift
…

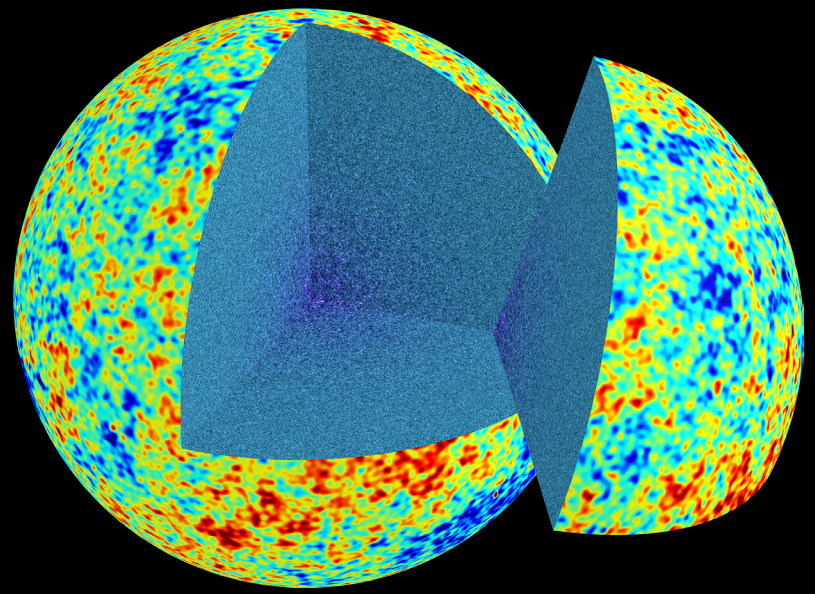
The case of weak-field perturbations of FLRW



Comoving space

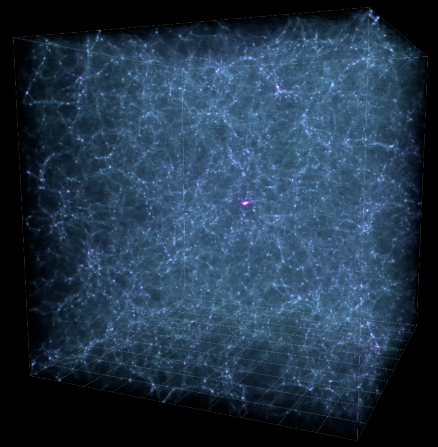


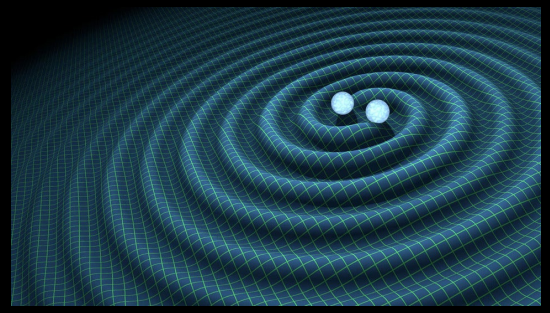
Relativistic raytracing

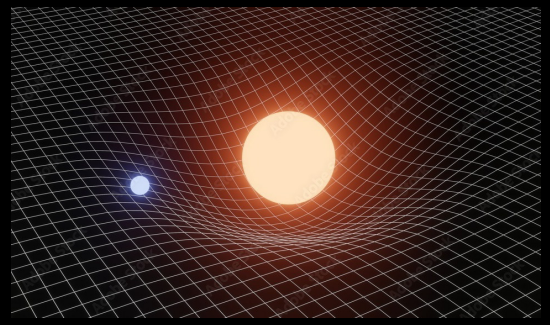


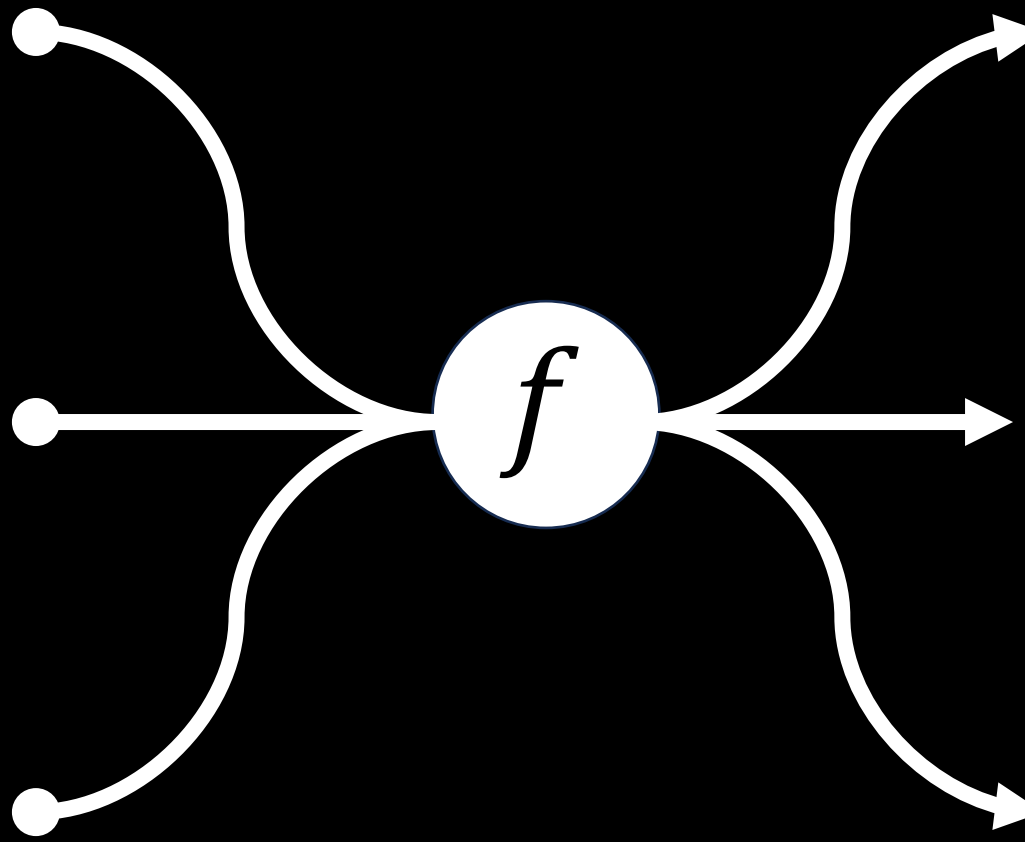
Redshift space

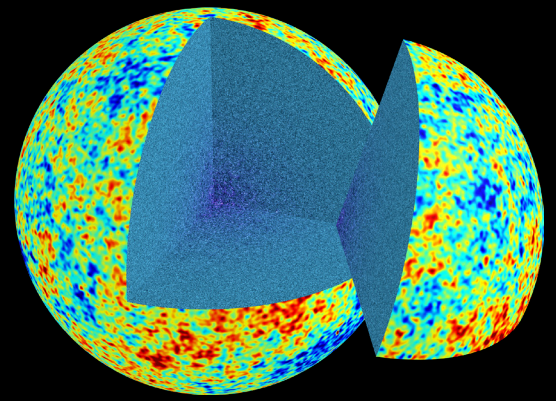
Moving to a general tool for relativistic astrophysics



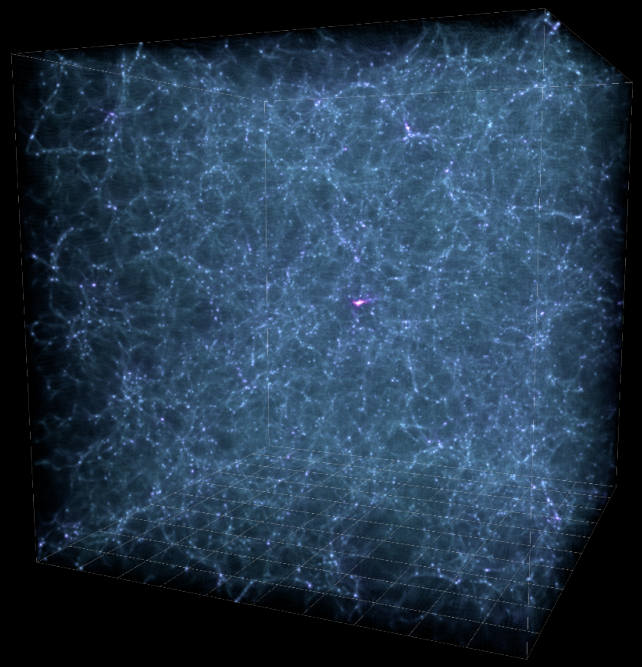




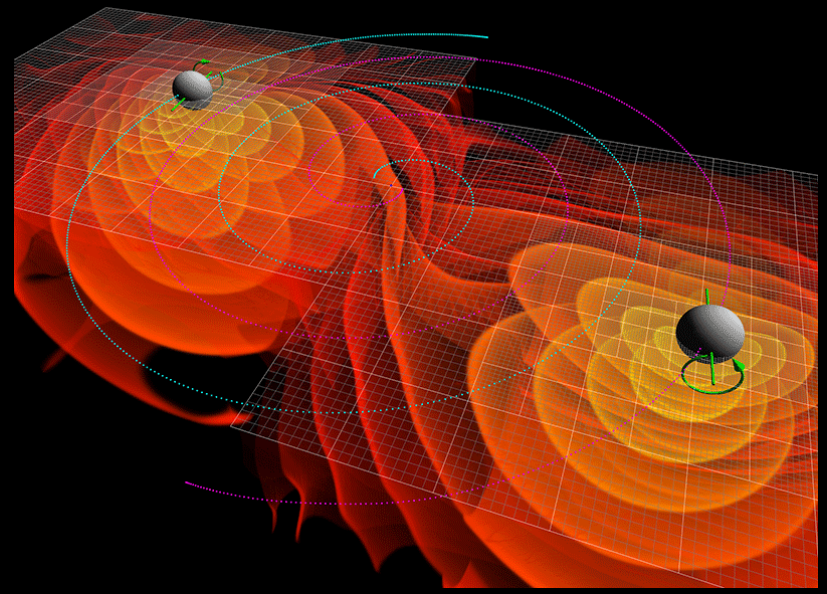




Genericity of inputs



Cosmological simulations (FLRW metric)



Relativistic simulations (black hole mergers)

General relativity and extensions

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 :

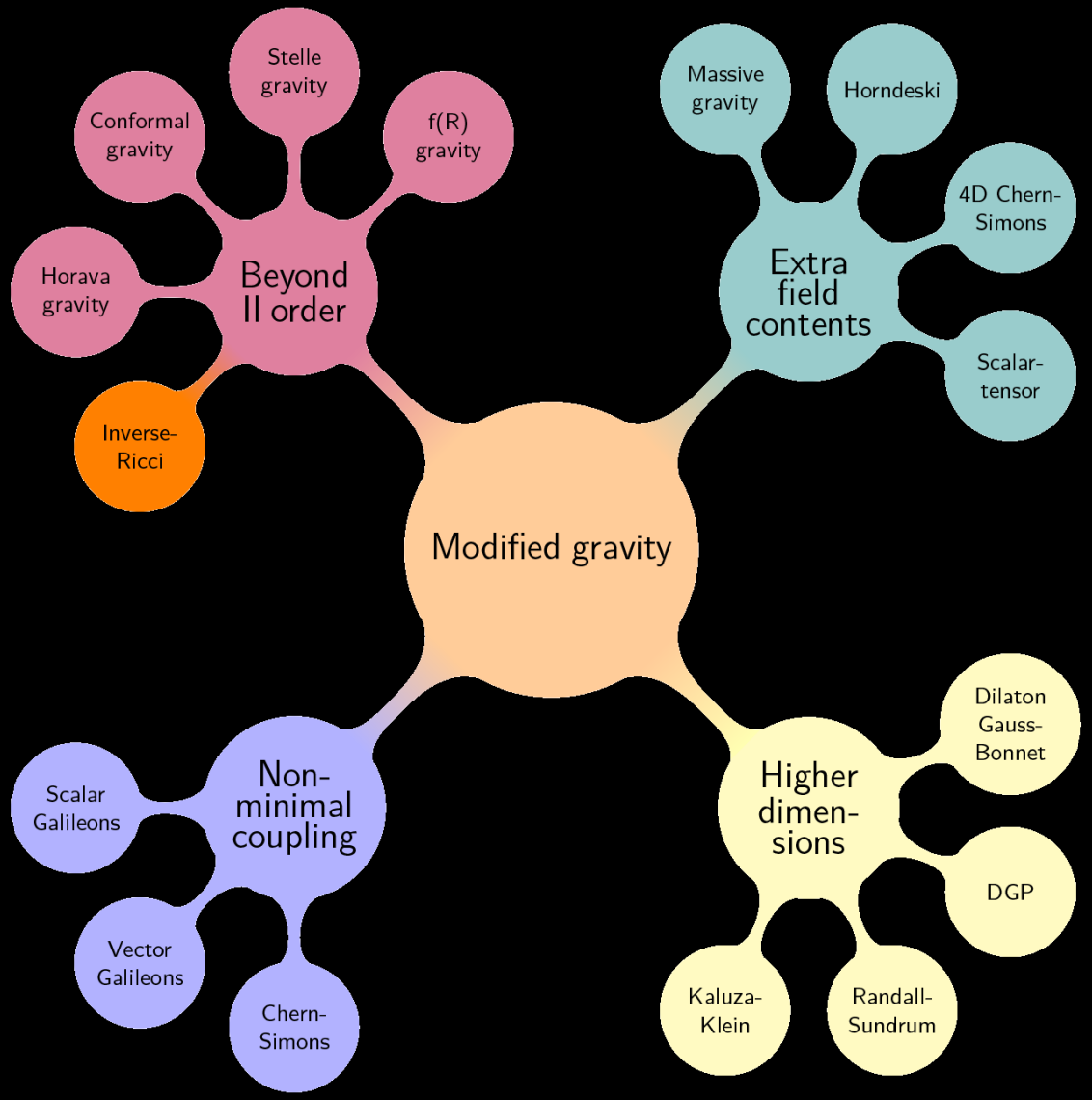
$$A^{\mu\nu} = aG^{\mu\nu} + bg^{\mu\nu}$$

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

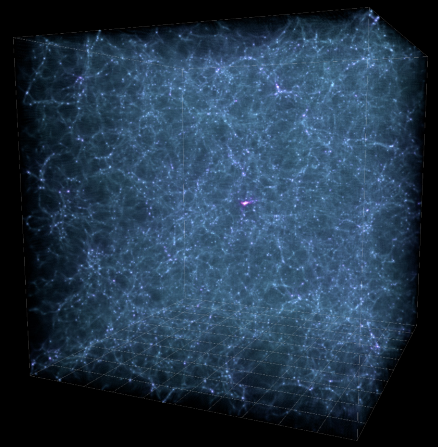
Beyond general relativity

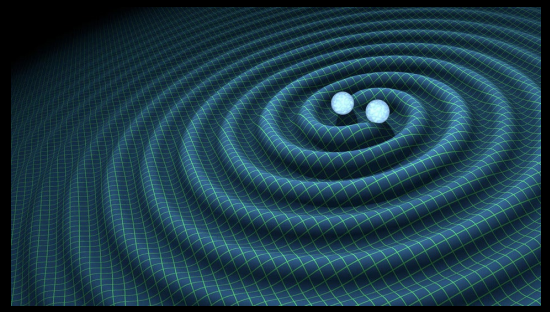
- Add other fields rather than the metric tensor
- Use more or fewer than four spacetime dimensions
- Add more than second order derivatives of the metric
- Non-locality
- Non-minimal coupling to matter fields

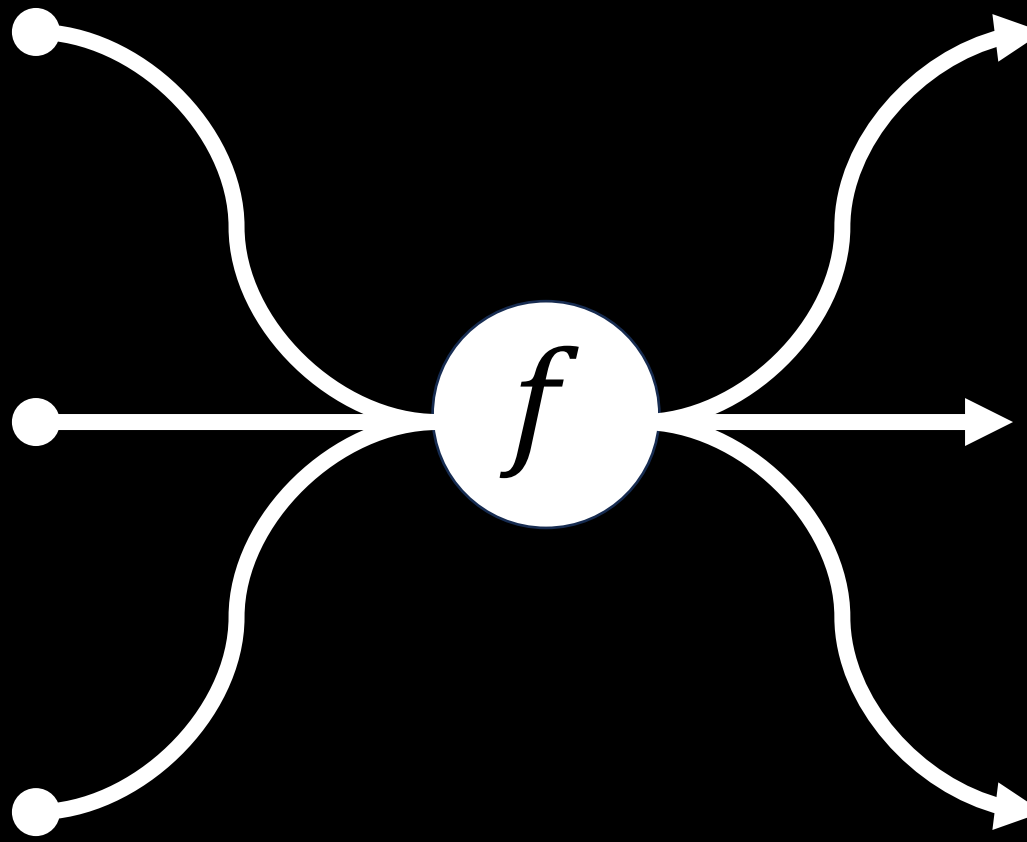
The landscape of modified gravity

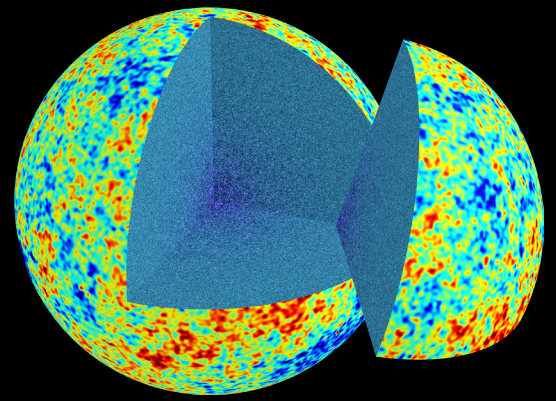


Generalizing further









x

y

Abstraction

What is the nature of x ?

What is the nature of y?

Topology and differential geometry

Geodesic = Shortest line

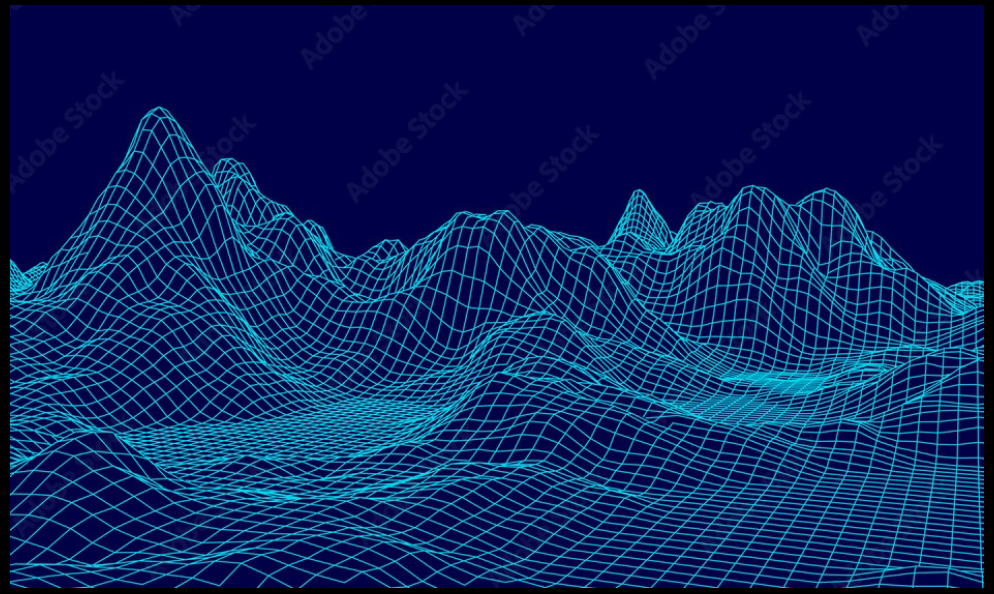
- Metric space $\mathcal{M}$ with a distance d

Geodesic = Straightest line

- Topological space $\mathcal{T}$ with a connection ∇

Challenge

- Compute the space of geodesics $\mathcal{G}$ given any abstract topological space equipped with d, ∇ or both



GDX: The GeoDesiX engine

Math challenge

- Topology and differential geometry abstractions in type theory

Computer science challenge

- Exploit everything that is known on the input space to generate the most efficient code

High-performance computing challenge

- Exploit every available resource (CPUs, GPUs, TPUs…) to compute billions of geodesics

$$(\mathcal{M}, d)$$
$$(\mathcal{T}, \nabla)$$
$$\mathcal{R}$$

$$\mathcal{G}$$

Applications

Analysis of cosmological simulations

- Snapshots from codes like RAMSES or Dyablo

Observations analyses

- Mass distribution reconstruction from lensing images

Lensing

- Weak lensing
- Strong lensing
- Time delays

Numerical general relativity

- Black hole mergers
- Relativistic cosmology

Beyond FLRW and GR

- Other metrics: szekeres…
- Modified gravity

More to come in the next 4 years