Gravity in the strong field regime

Dr Katy Clough,
Queen Mary University of London

Plan for the talk

1. What is numerical relativity?

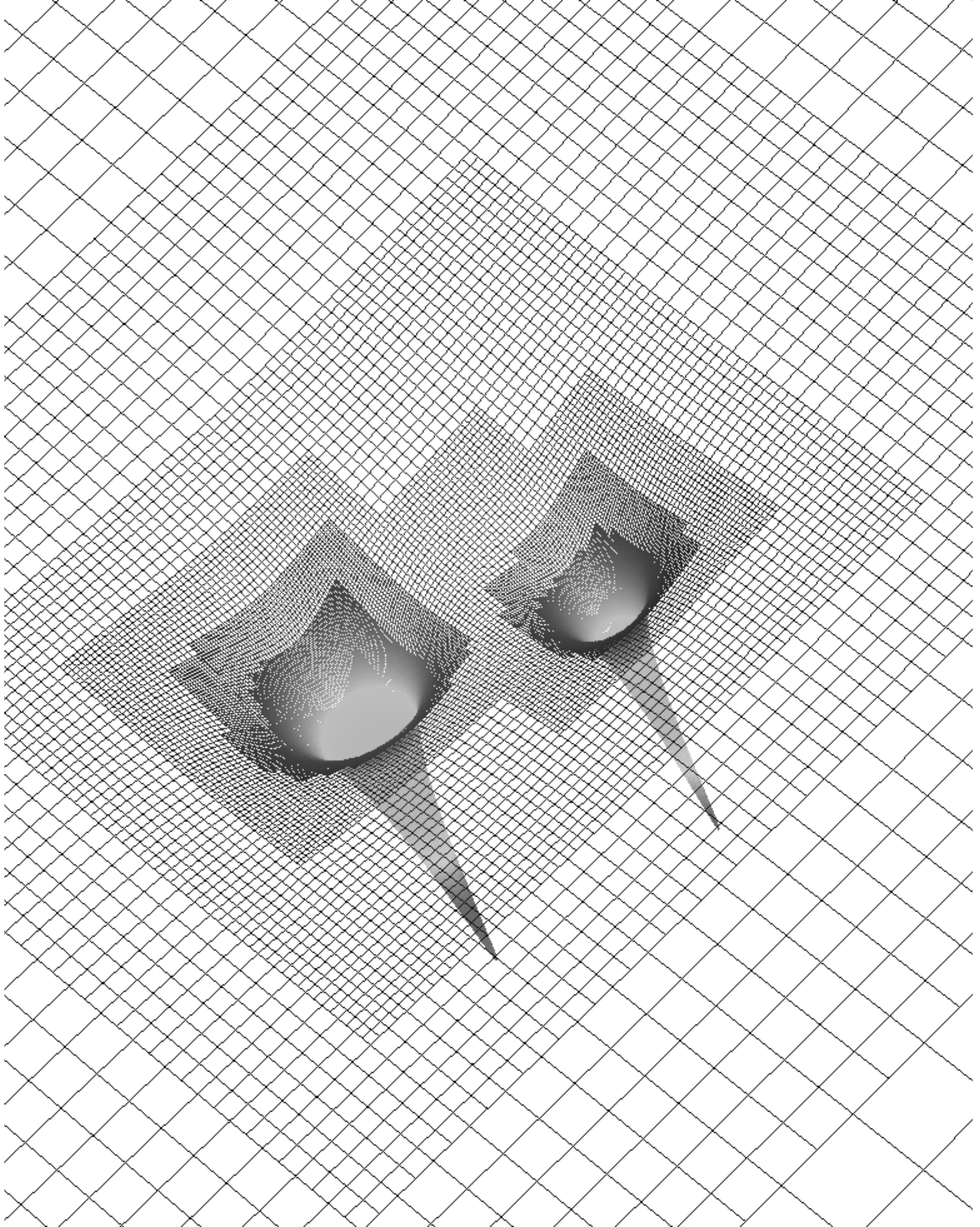
2. Applications to fundamental physics with black holes

3. Applications to fundamental physics beyond black holes

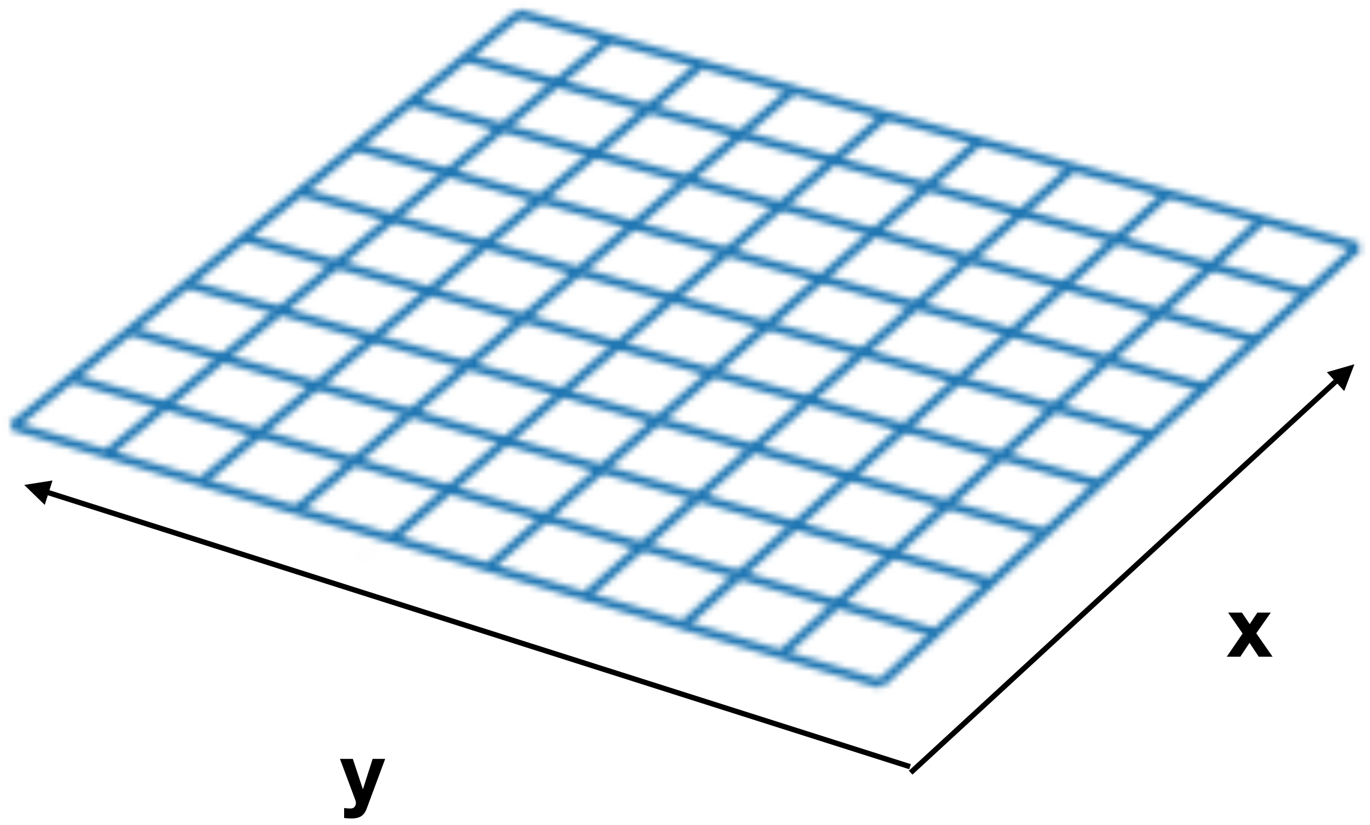
What is numerical relativity?

Numerical relativity is the numerical solution of the Einstein Equations of general relativity (“without approximation”).

It allows us to describe the curvature of spacetime in strong gravity regimes.



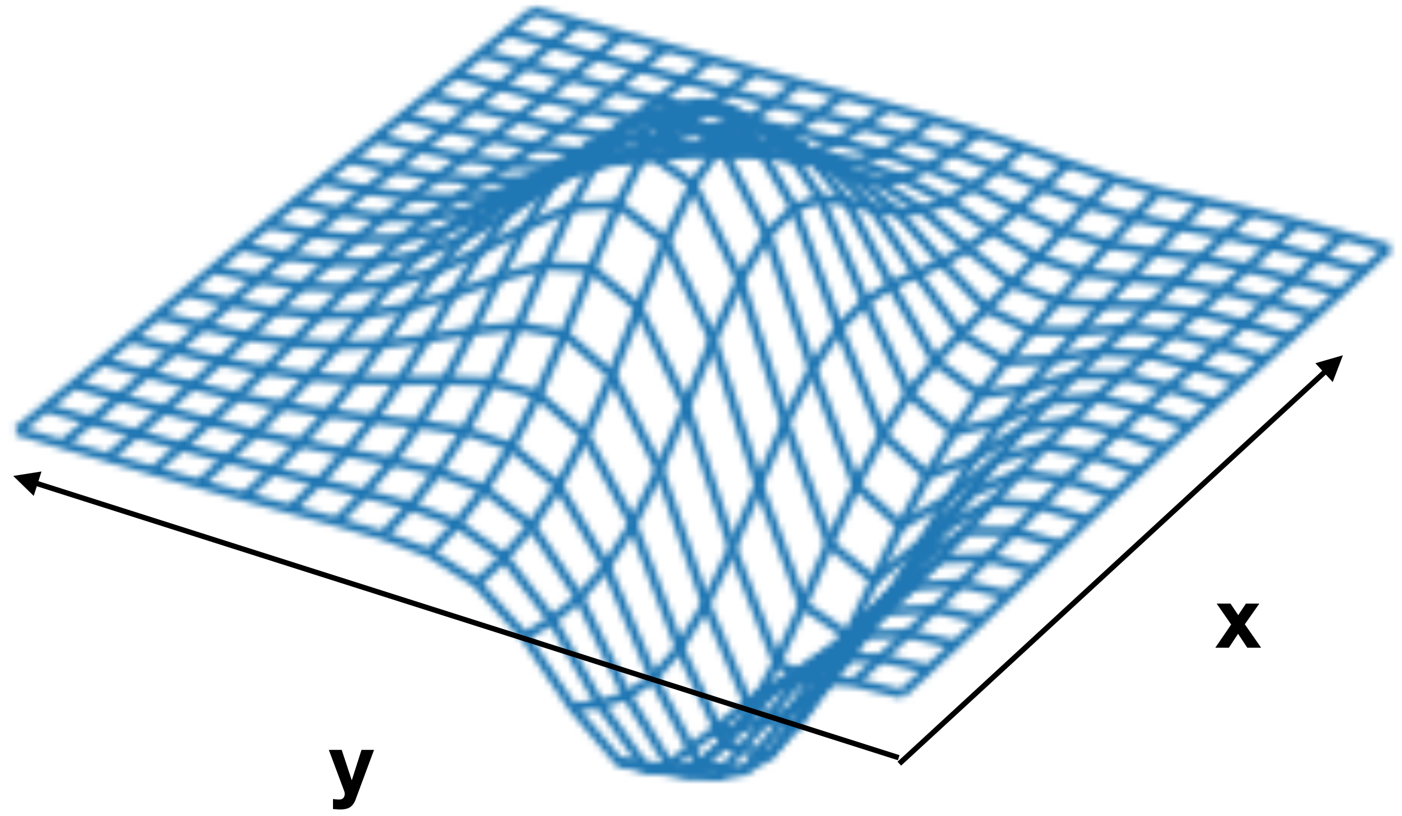
Flat space



$$dl^2 = dx^2 + dy^2$$

$$dl^2 = \begin{pmatrix} dx & dy \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} dx \\ dy \end{pmatrix}$$

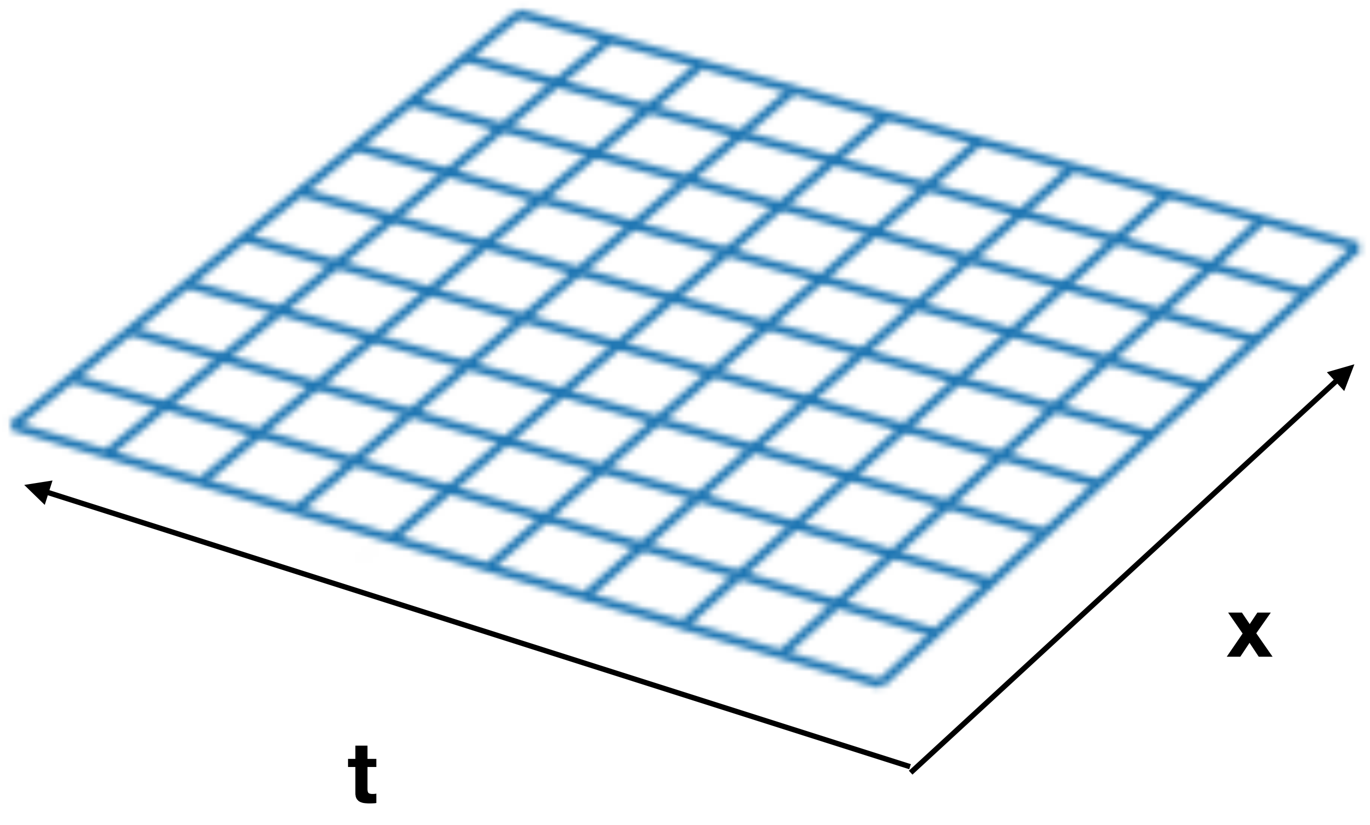
Curved space



$$dl^2 = f(x,y)\ dx^2 + g(x,y)\ dy^2 + 2h\,(x,y)\ dx\,dy$$

$$dl^2 = \begin{pmatrix} dx & dy \end{pmatrix} \begin{pmatrix} f(x,y) & h(x,y) \\ h(x,y) & g(x,y) \end{pmatrix} \begin{pmatrix} dx \\ dy \end{pmatrix}$$

Flat spacetime

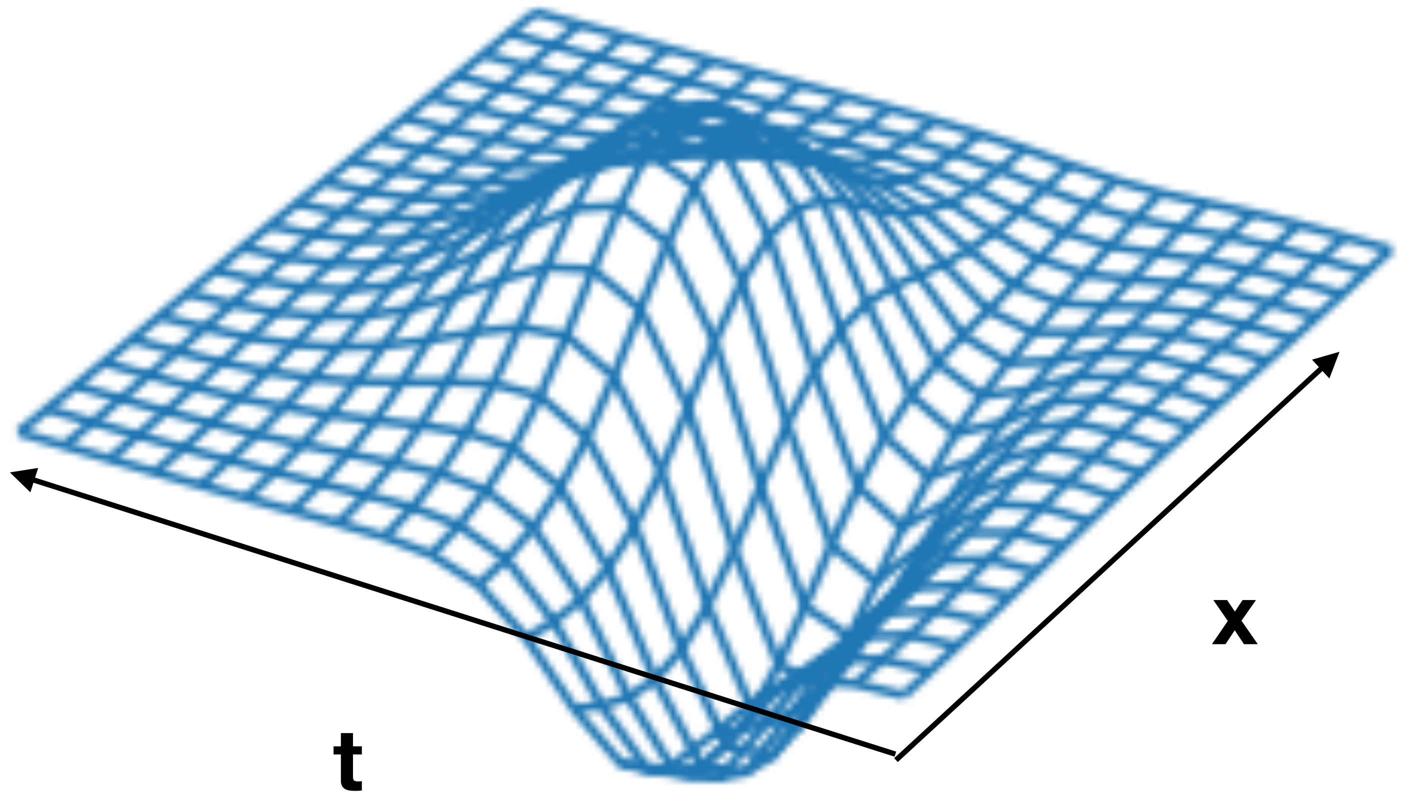


$$ds^2 = -c^2 dt^2 + dx^2$$

$$ds^2 = \begin{pmatrix} dt & dx \end{pmatrix} \begin{pmatrix} -c^2 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} dt \\ dx \end{pmatrix}$$

Curved spacetime

$$ds^2 = \begin{pmatrix} dt & dx & dy & dz \end{pmatrix} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$



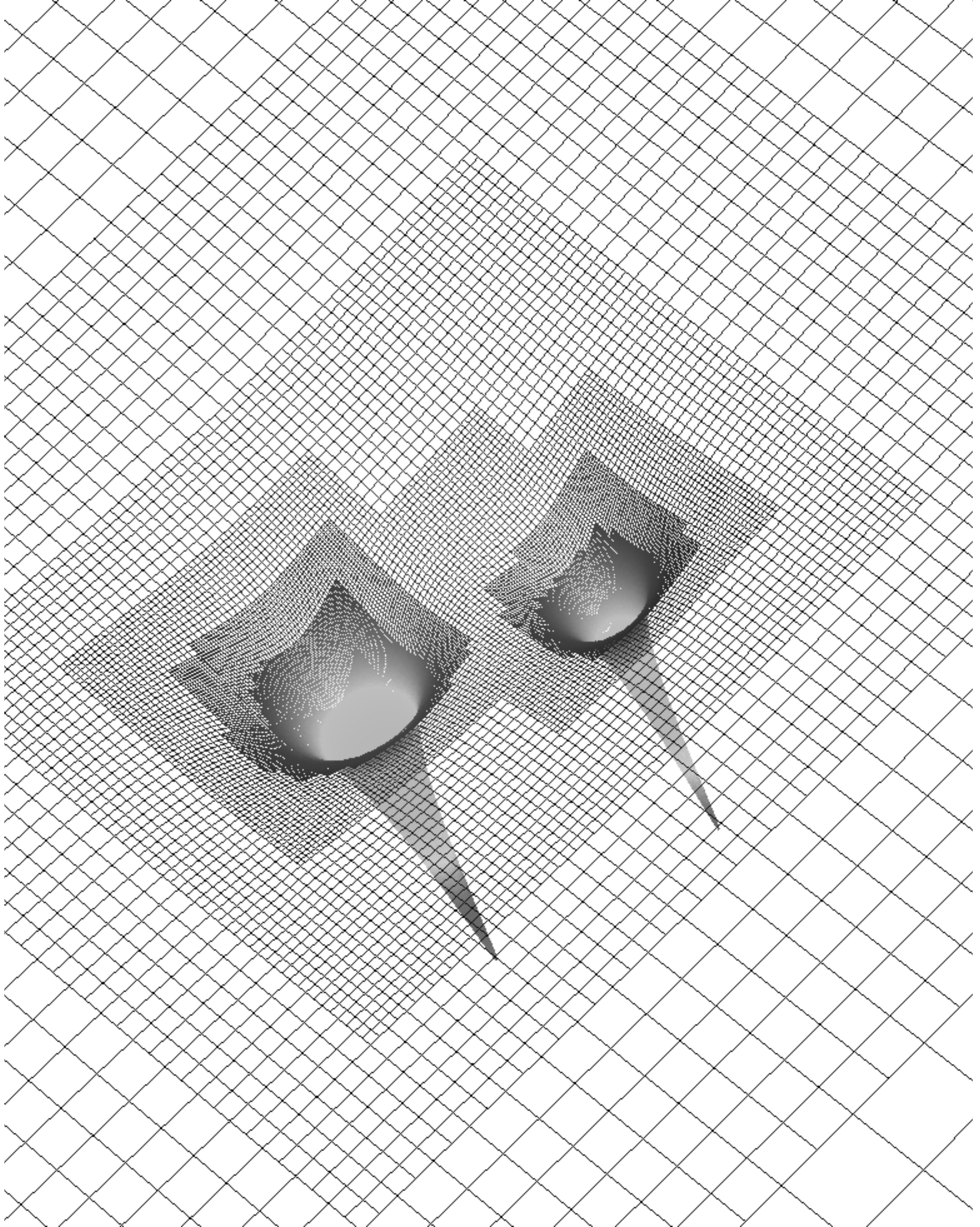
"The spacetime metric"

$$g_{ab}(t, \vec{x})$$

Numerical relativity allows us to describe the curvature of spacetime in strong gravity regimes

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi T_{\mu\nu}$$

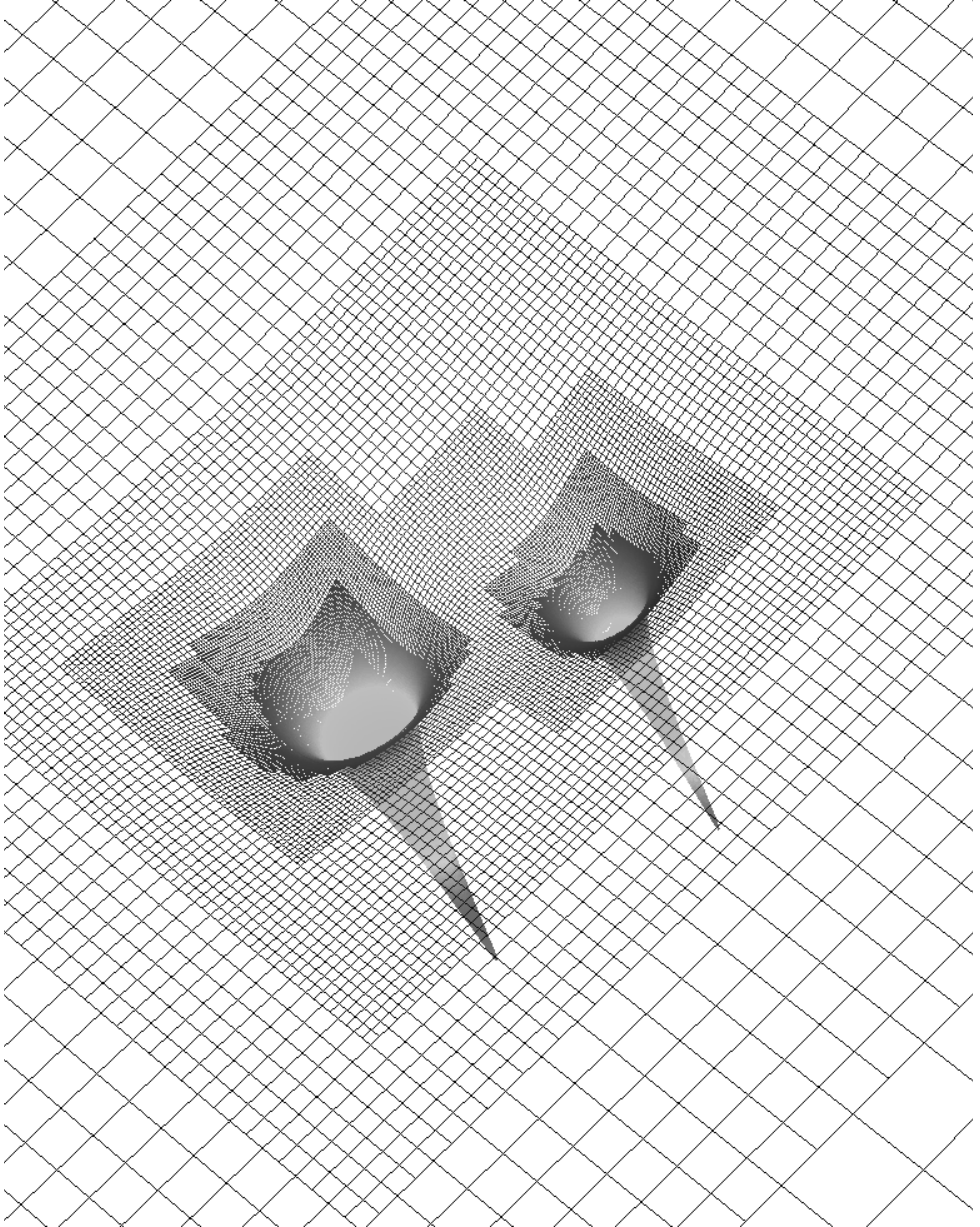
$$\begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$$



Numerical relativity allows us to describe the curvature of spacetime in strong gravity regimes

$$\frac{\partial^2 g}{\partial t^2} - \frac{\partial^2 g}{\partial x^2} + \text{non linear terms} = f(\text{energy, momentum})$$

$$\begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$$



These calculations take ~~weeks~~ days on supercomputers (~~CPUs~~ GPUs)

EuroHPC
Joint Undertaking

What about the “new physics”?

Numerical relativity allows us to describe the curvature of spacetime in strong gravity regimes

+ NEW MATTER?

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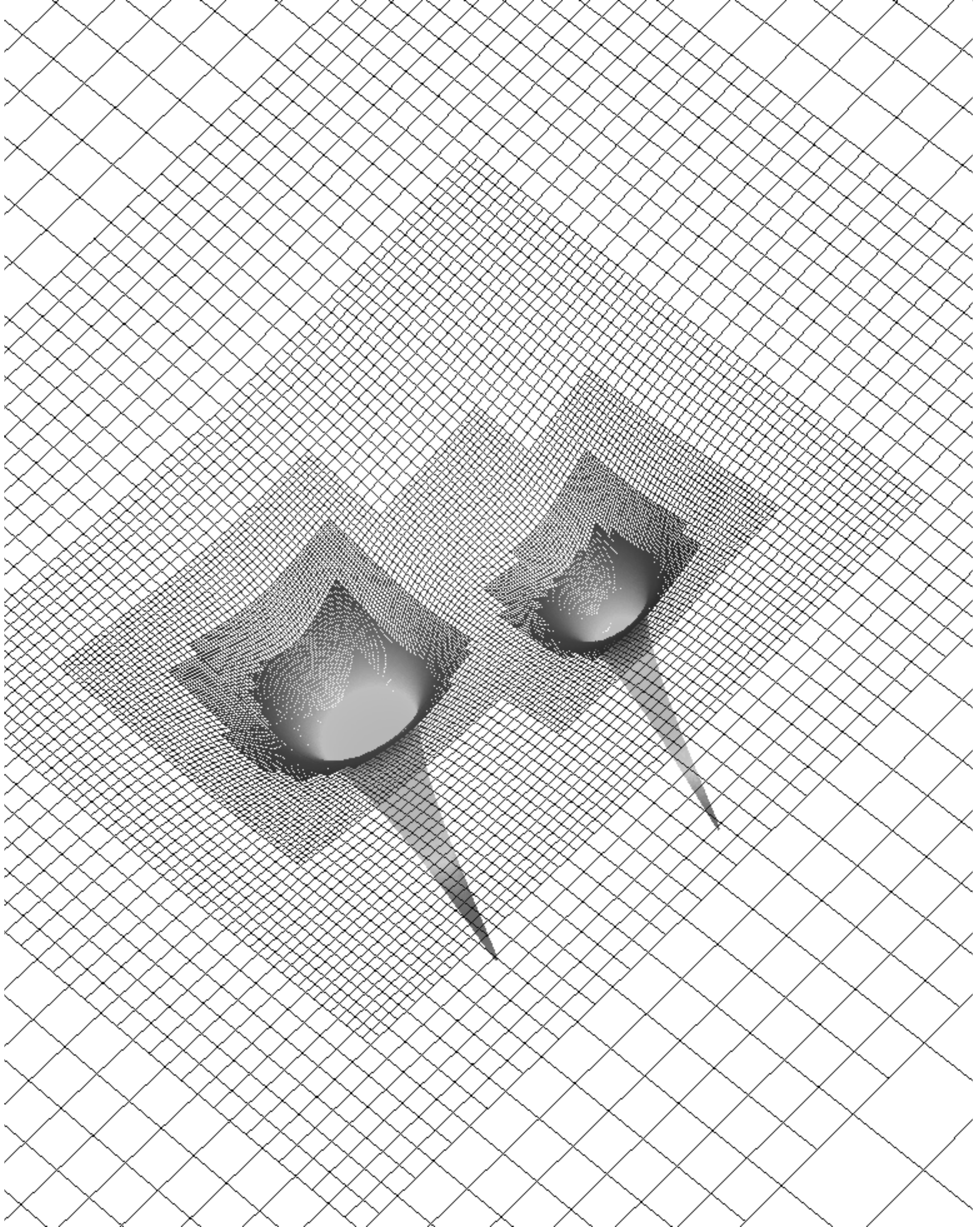

Numerical relativity allows us to describe the curvature of spacetime in strong gravity regimes

+ MODIFIED GRAVITY?

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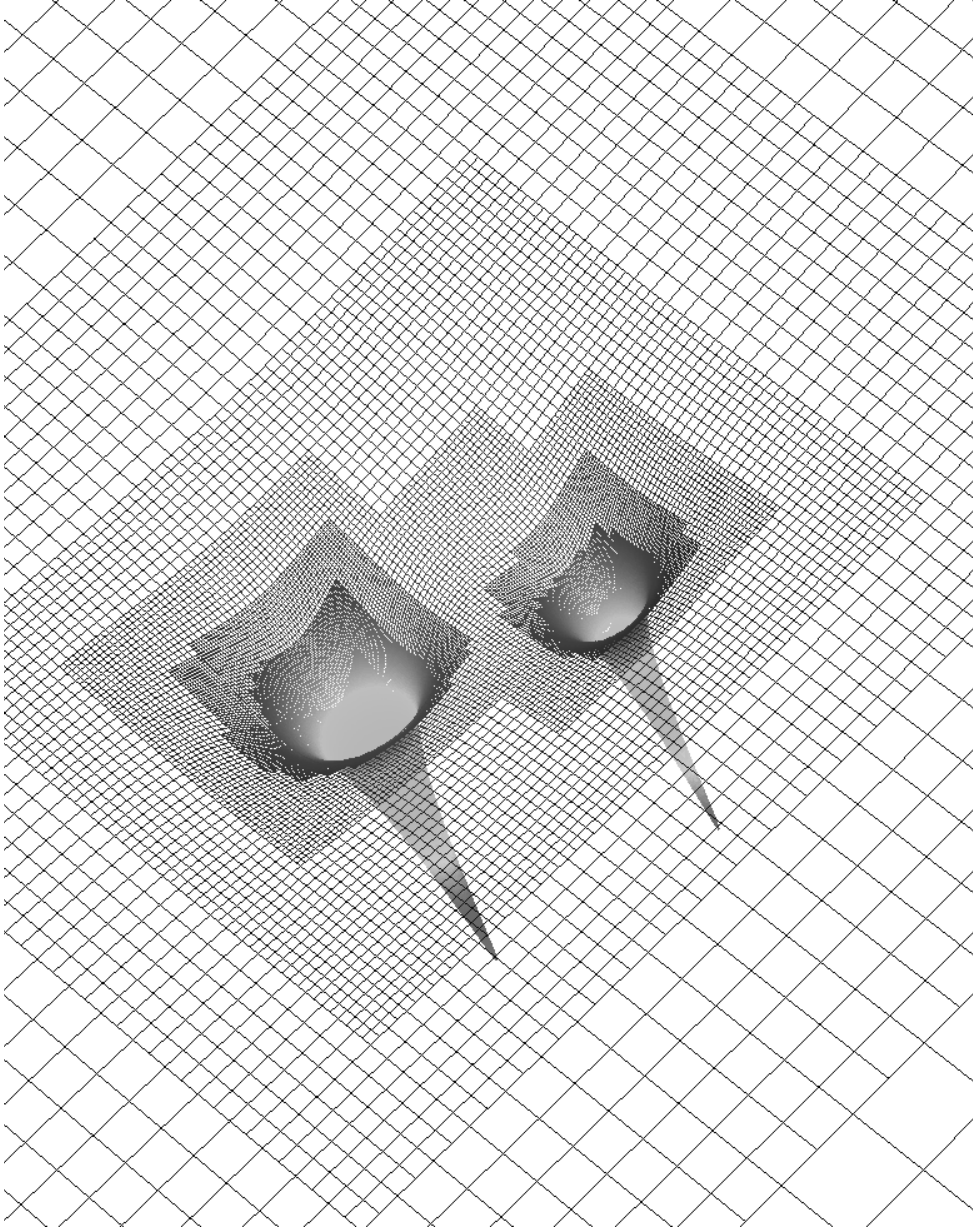
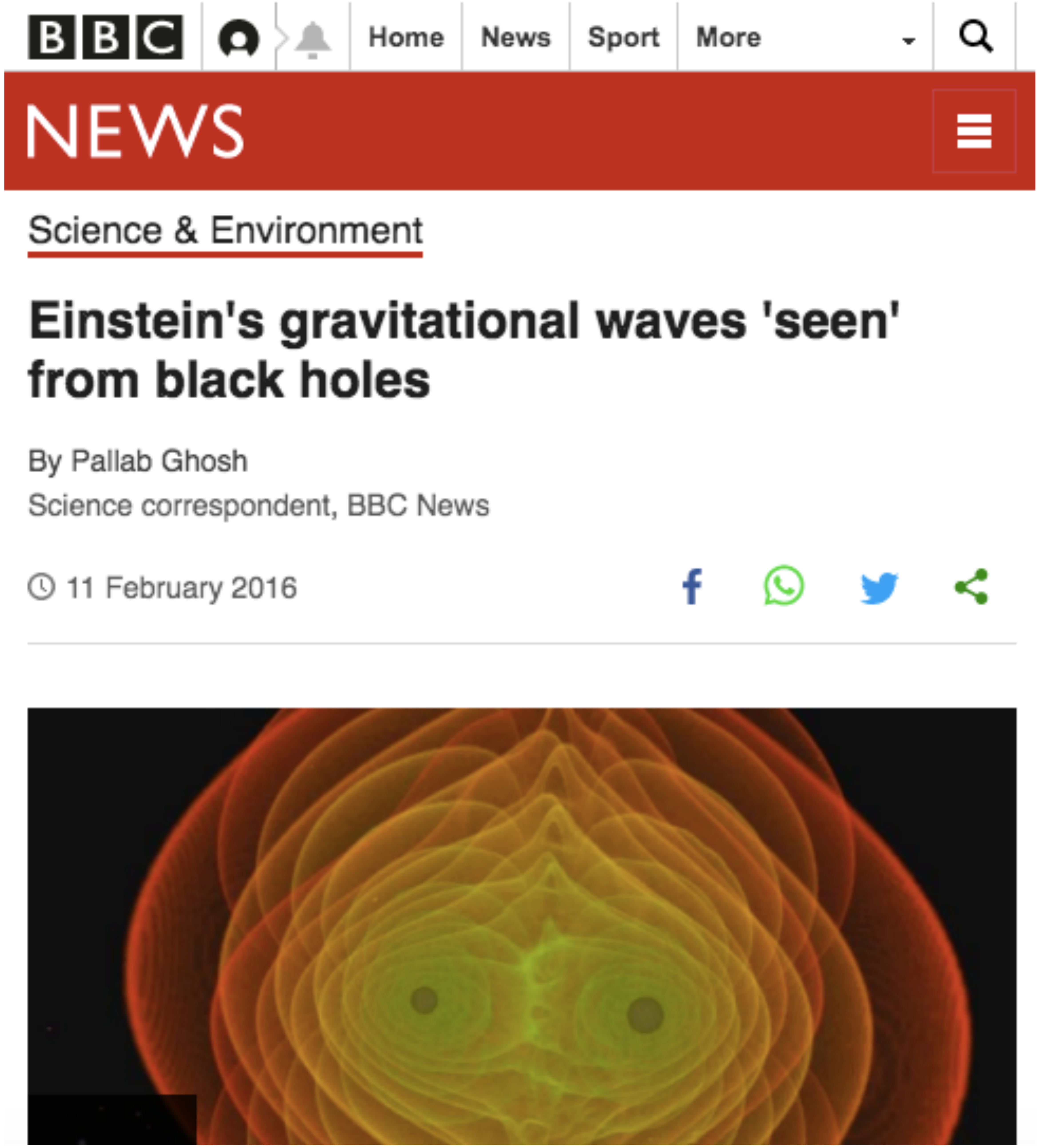


Application to fundamental physics with black holes

For ten years we have been able to observe black holes merging.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NEWS

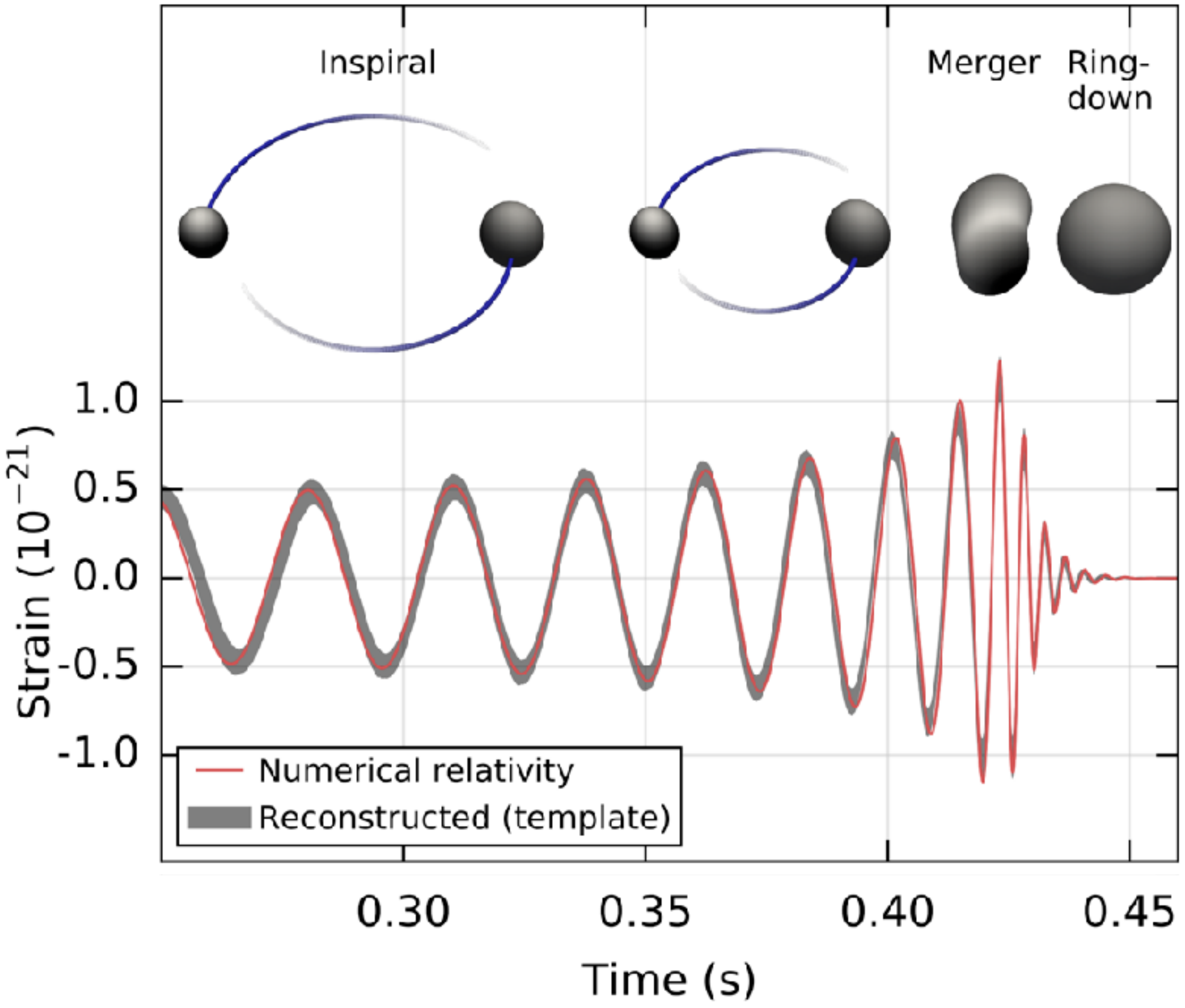
Science & Environment

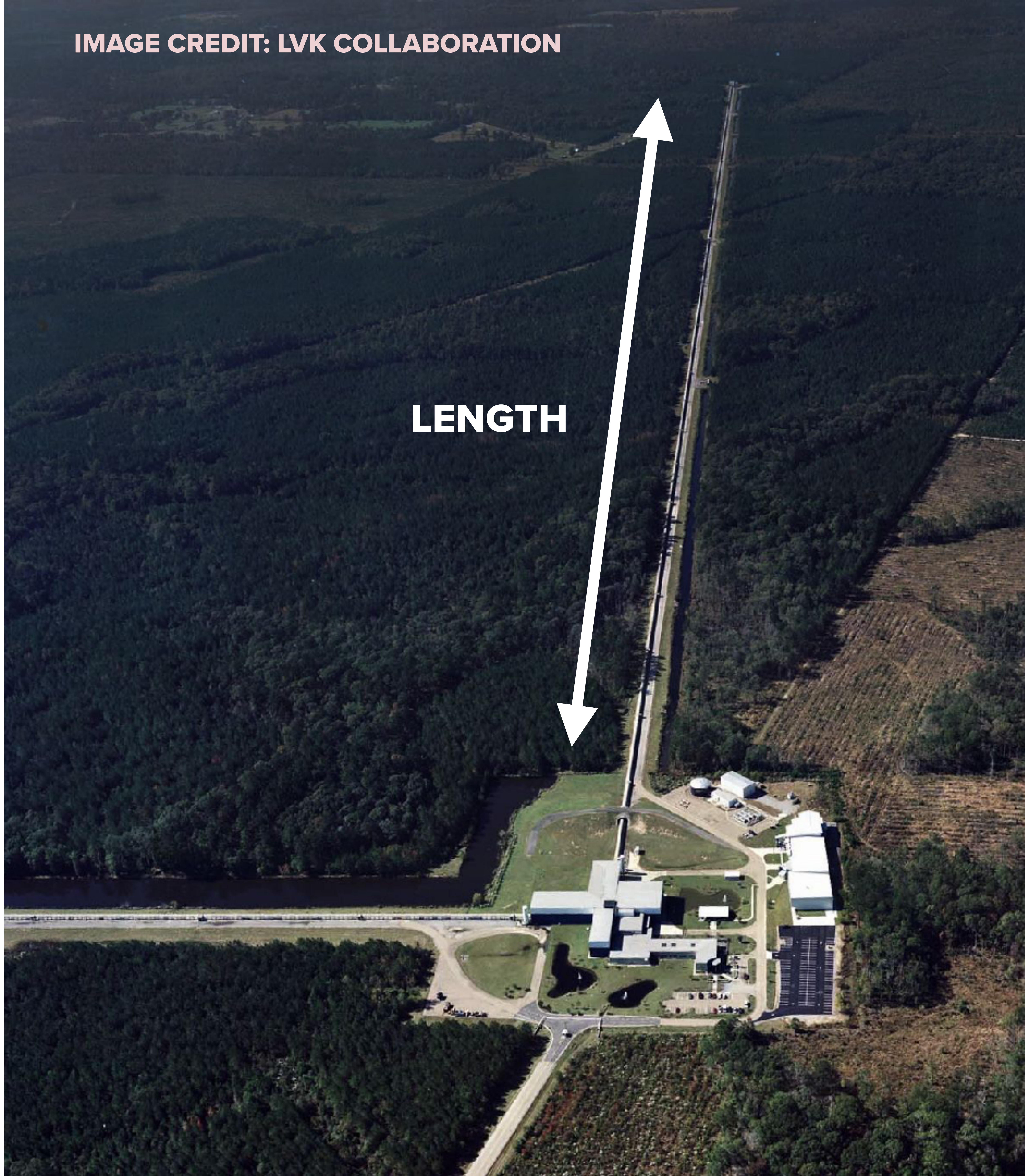
Einstein's gravitational waves 'seen' from black holes

By Pallab Ghosh
Science correspondent, BBC News

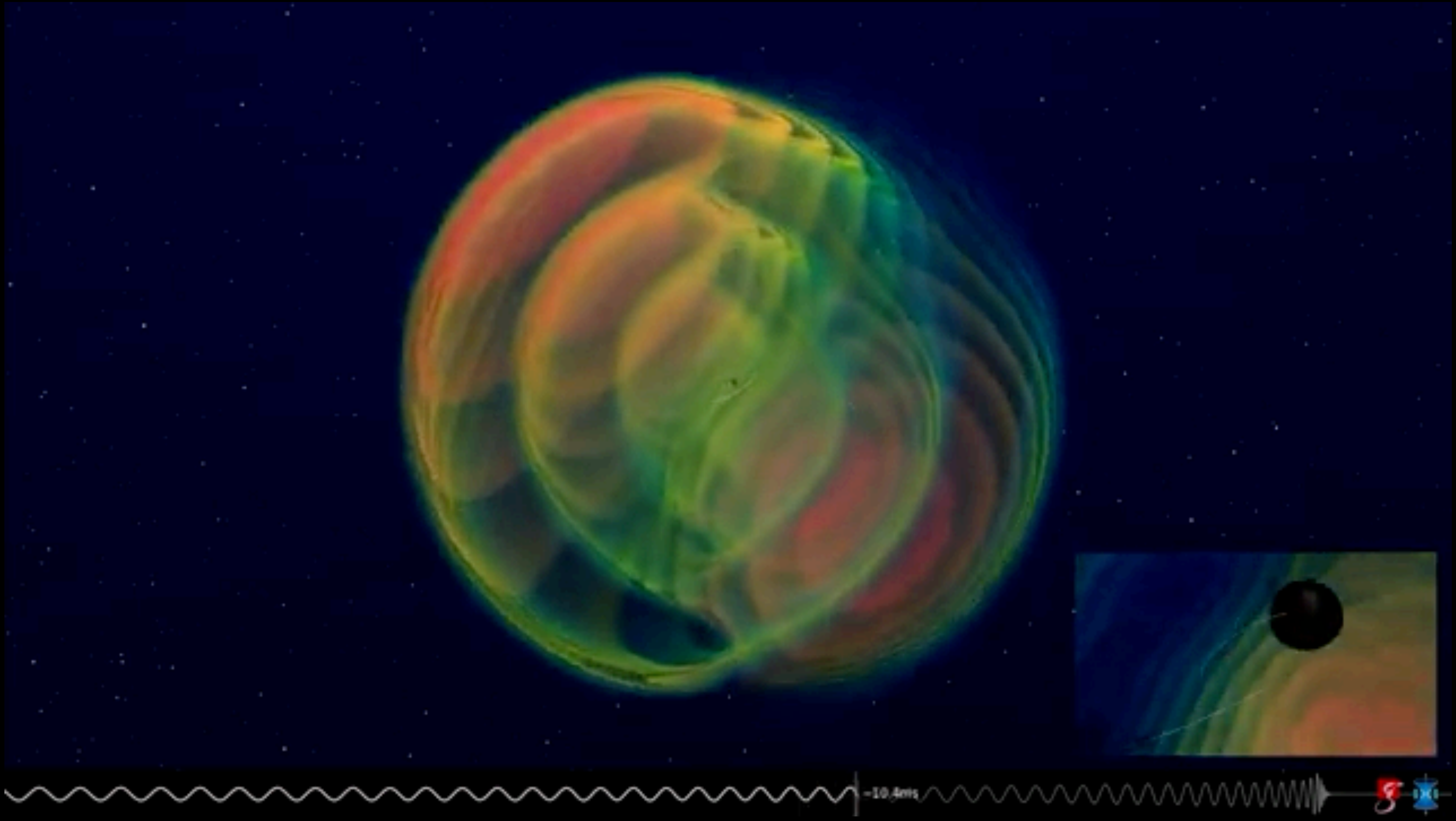
11 February 2016

IMAGE CREDIT: LVK COLLABORATION

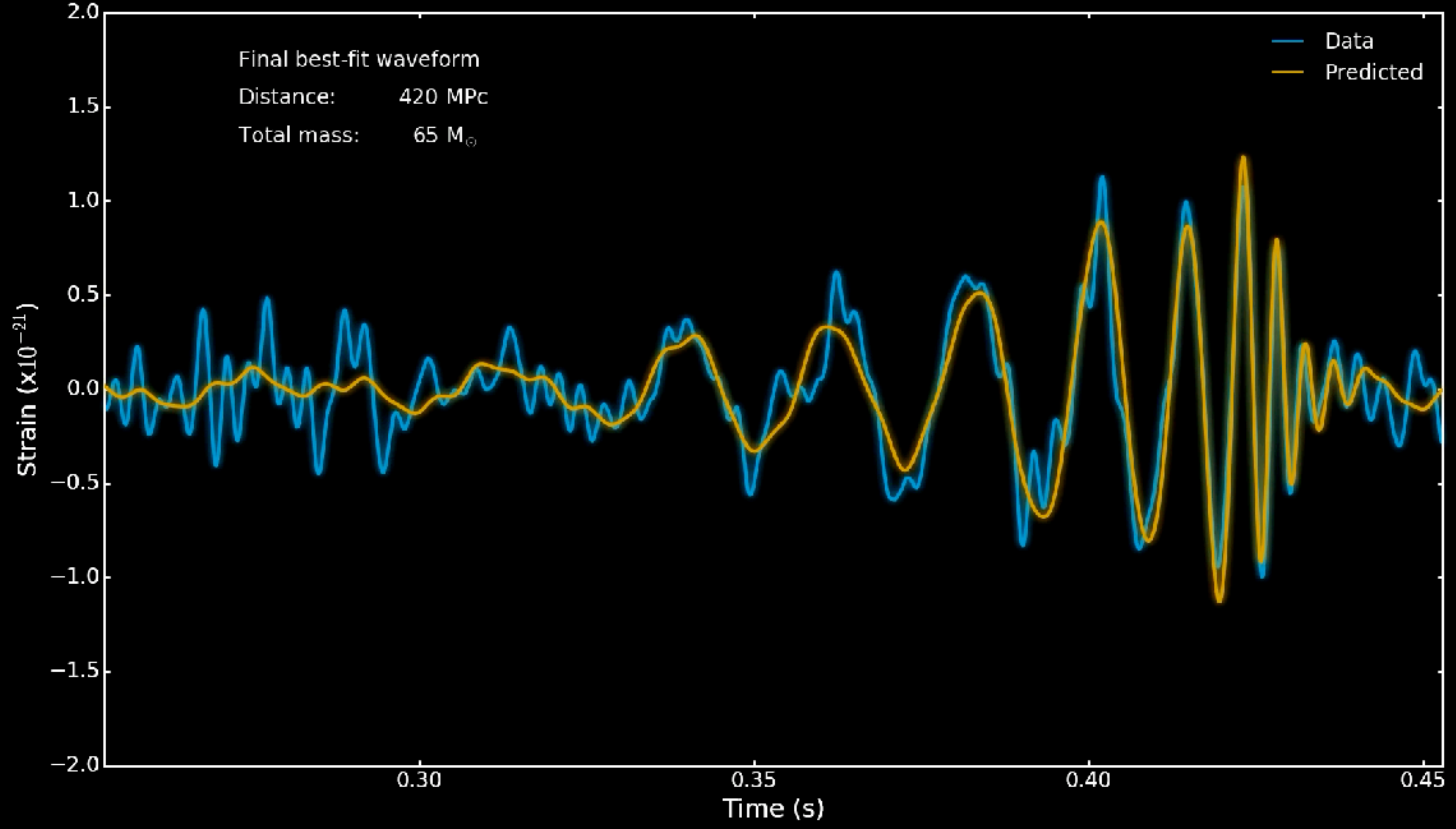




We use numerical relativity to model the signals



We then have to find the simulation that best matches the data



Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)

We are currently only looking in a small range of wavelengths

LVK

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LVK

LISA
(2035)

???

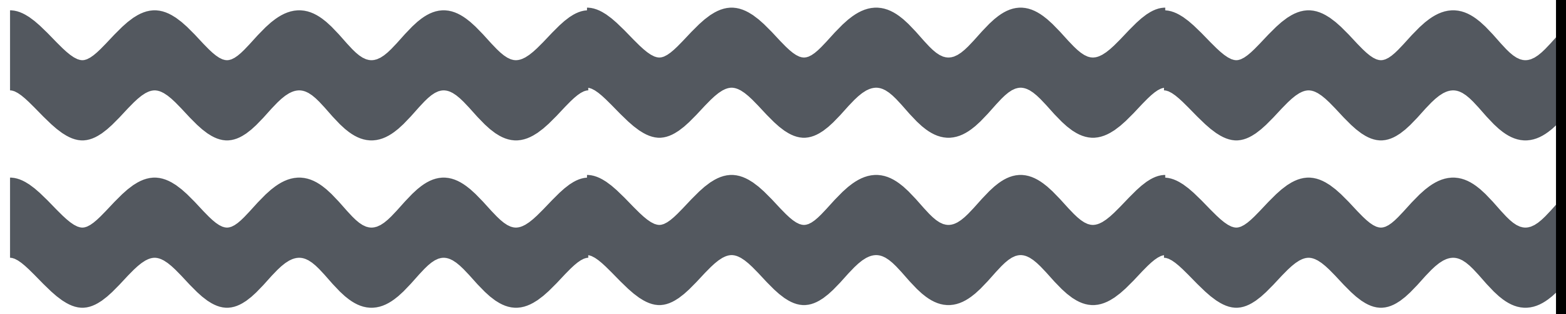
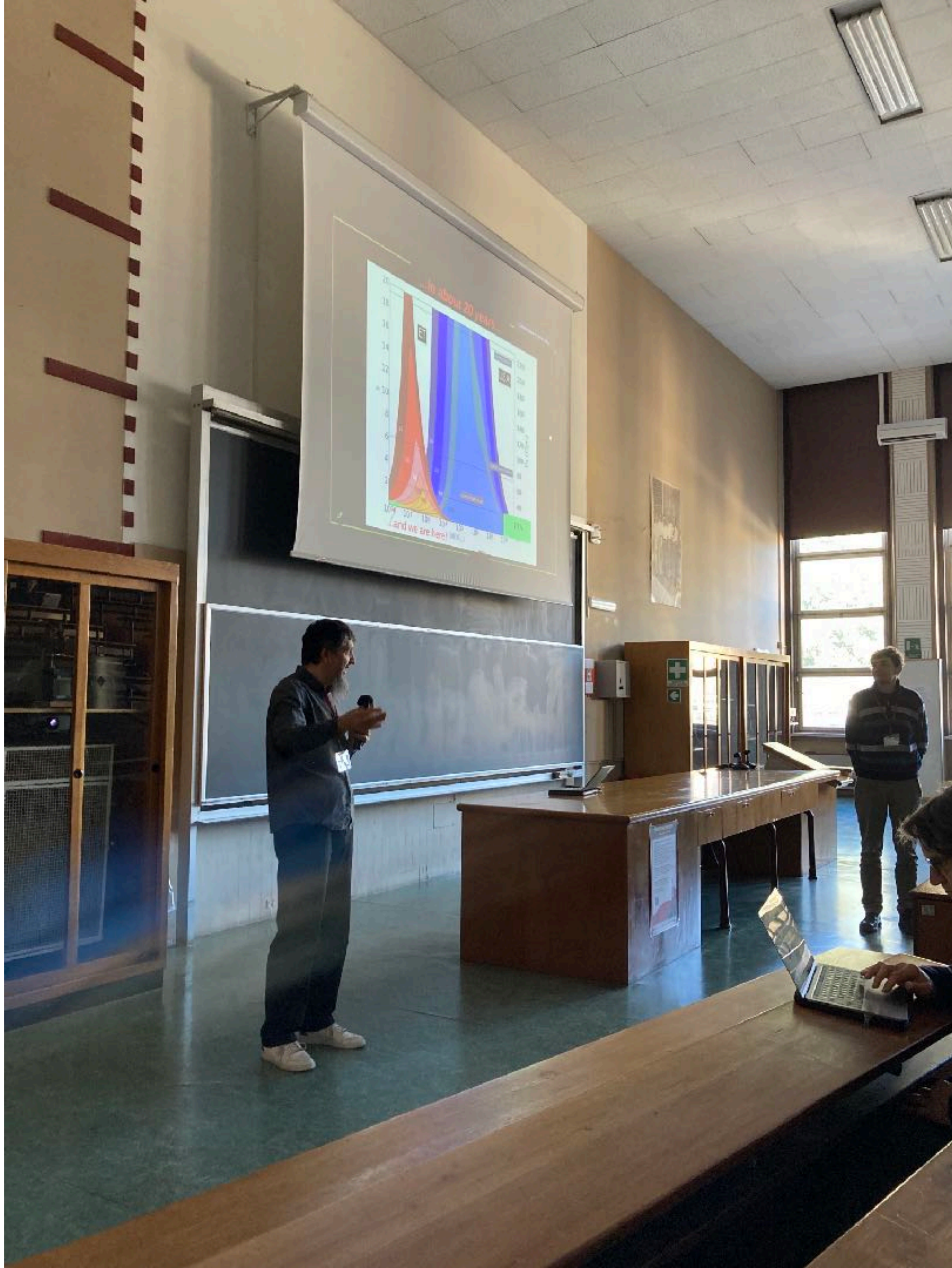


IMAGE CREDIT: LVK

???

???

Imagine what discovery potential the future holds!



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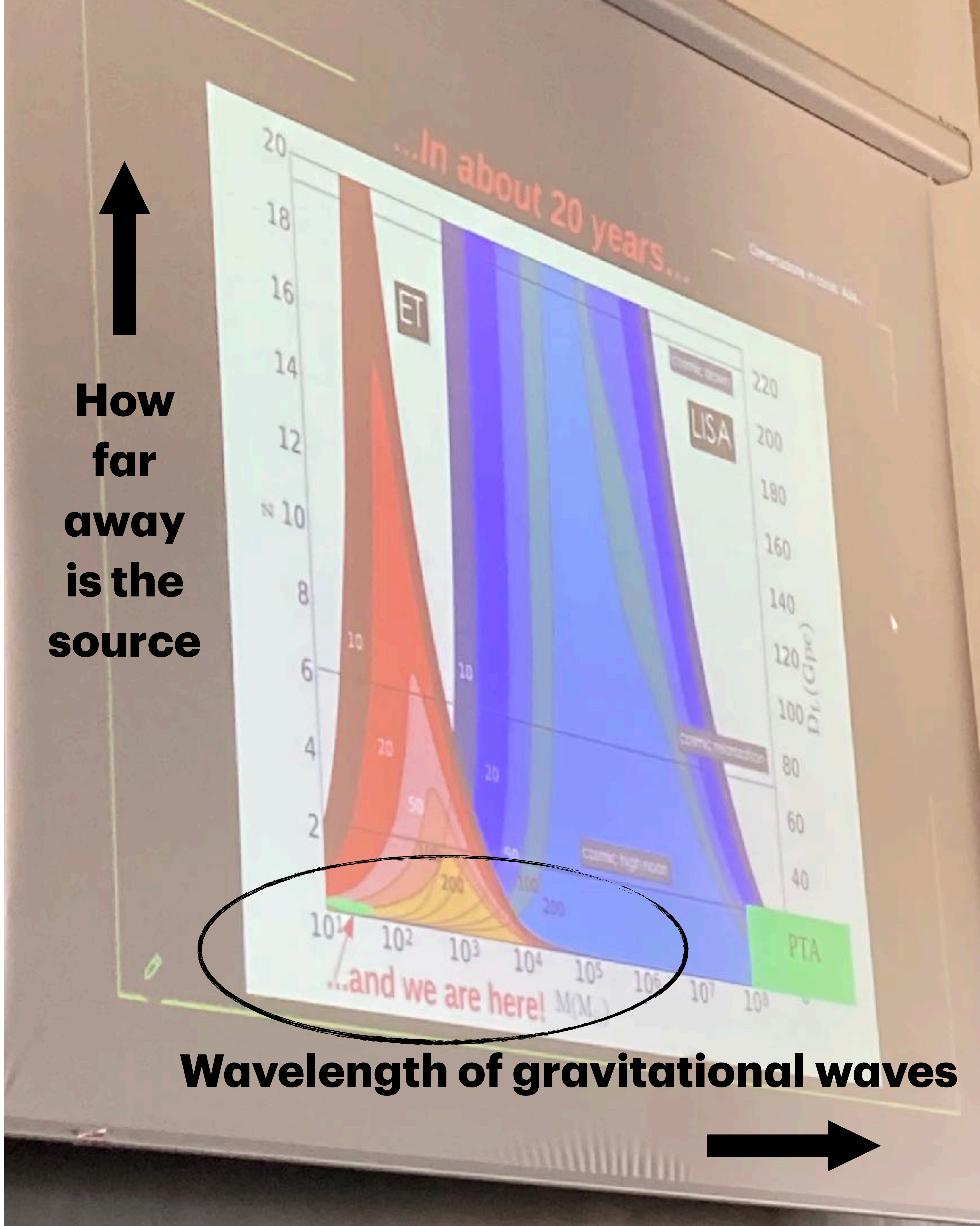
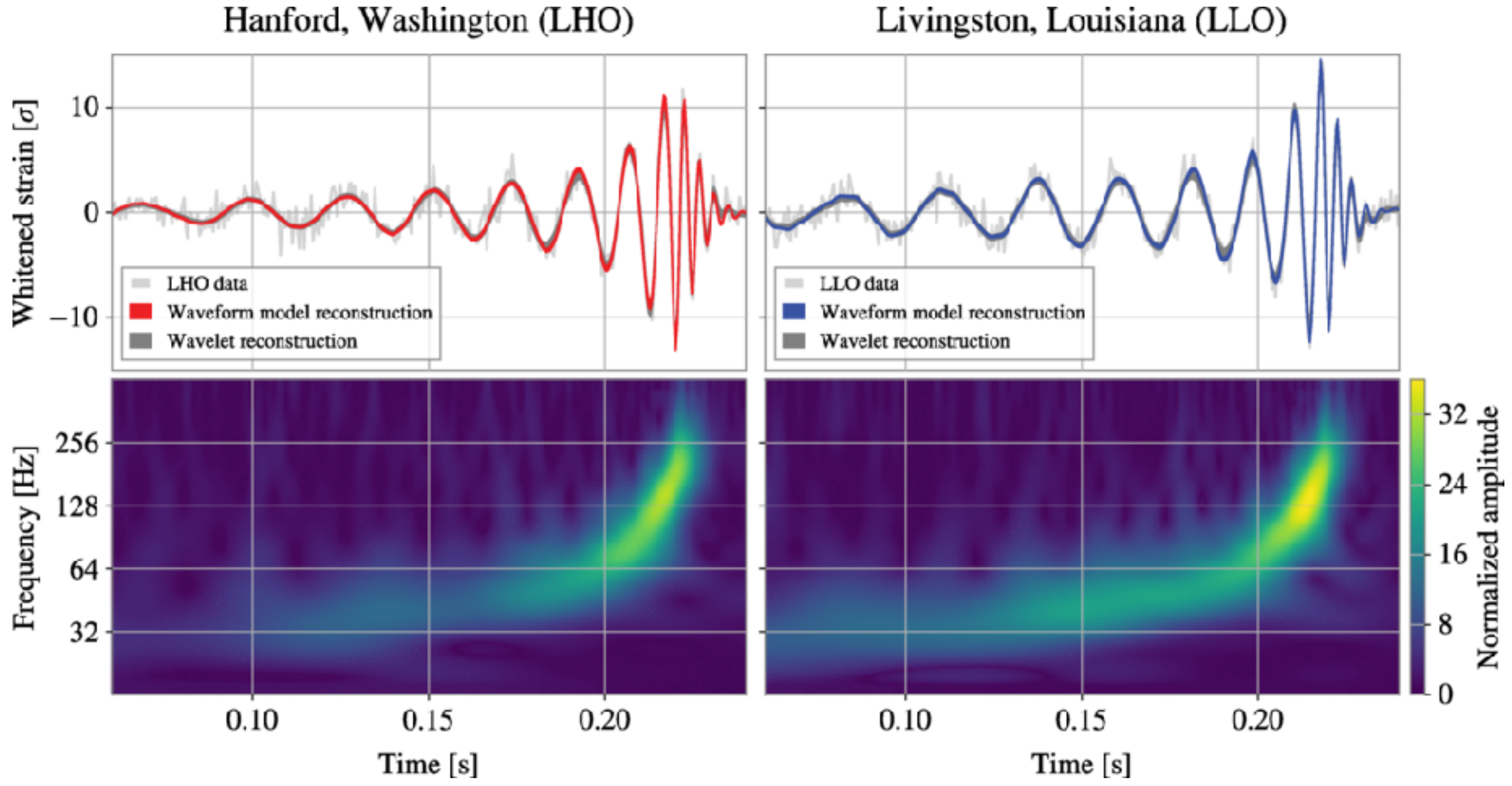


What about the “new physics”?

There is nothing wrong with the null hypothesis:

Black holes on all observable scales are described by Einstein's GR and environments will not be detectable with current or future planned signal to noise ratios

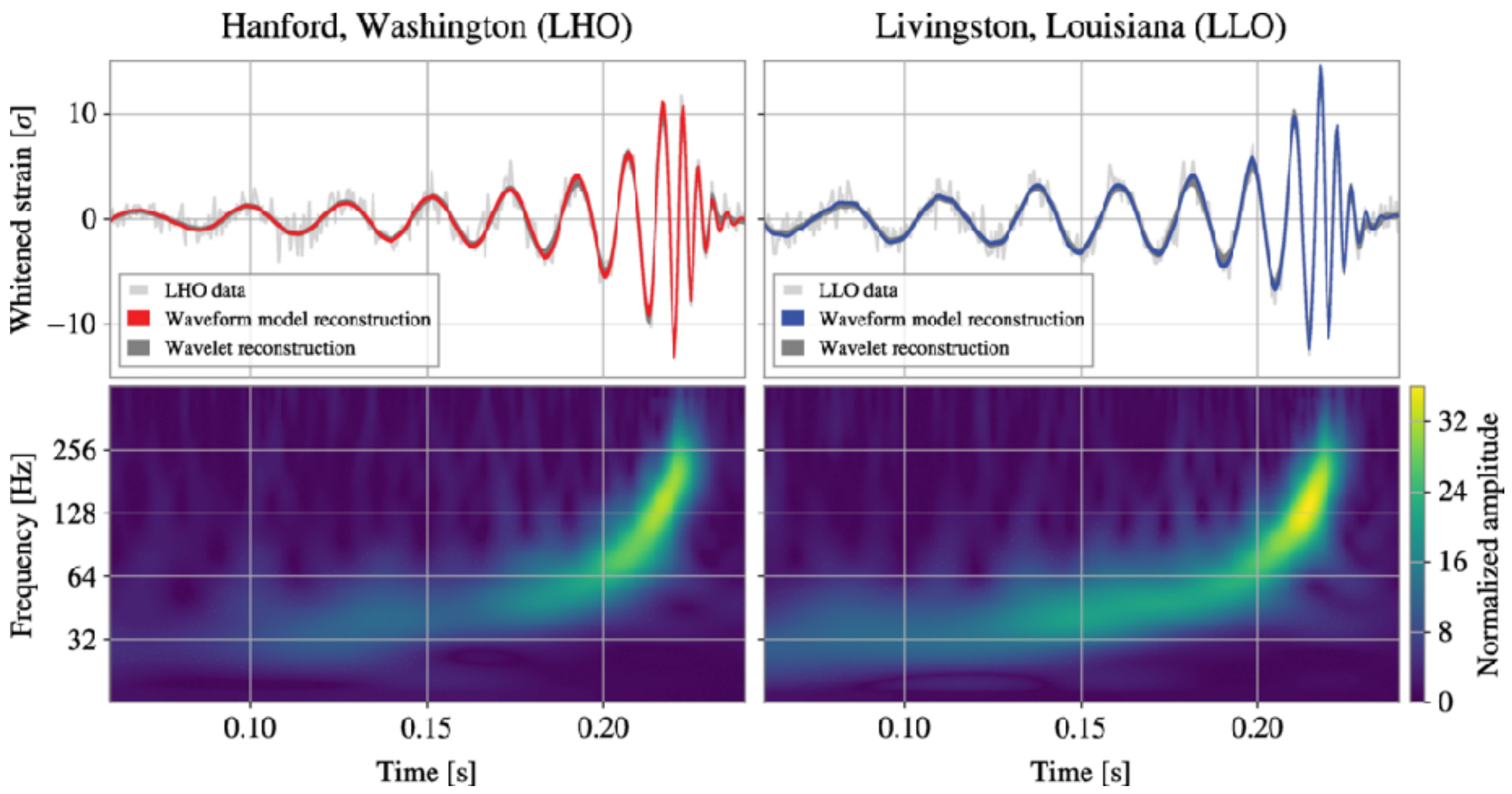
GW250114



LIGO Scientific, Virgo and KAGRA Collaborations 2025
Phys.Rev.Lett. 135, 111403

Nevertheless, it would be scientifically negligent not to test this hypothesis with our data.

GW250114



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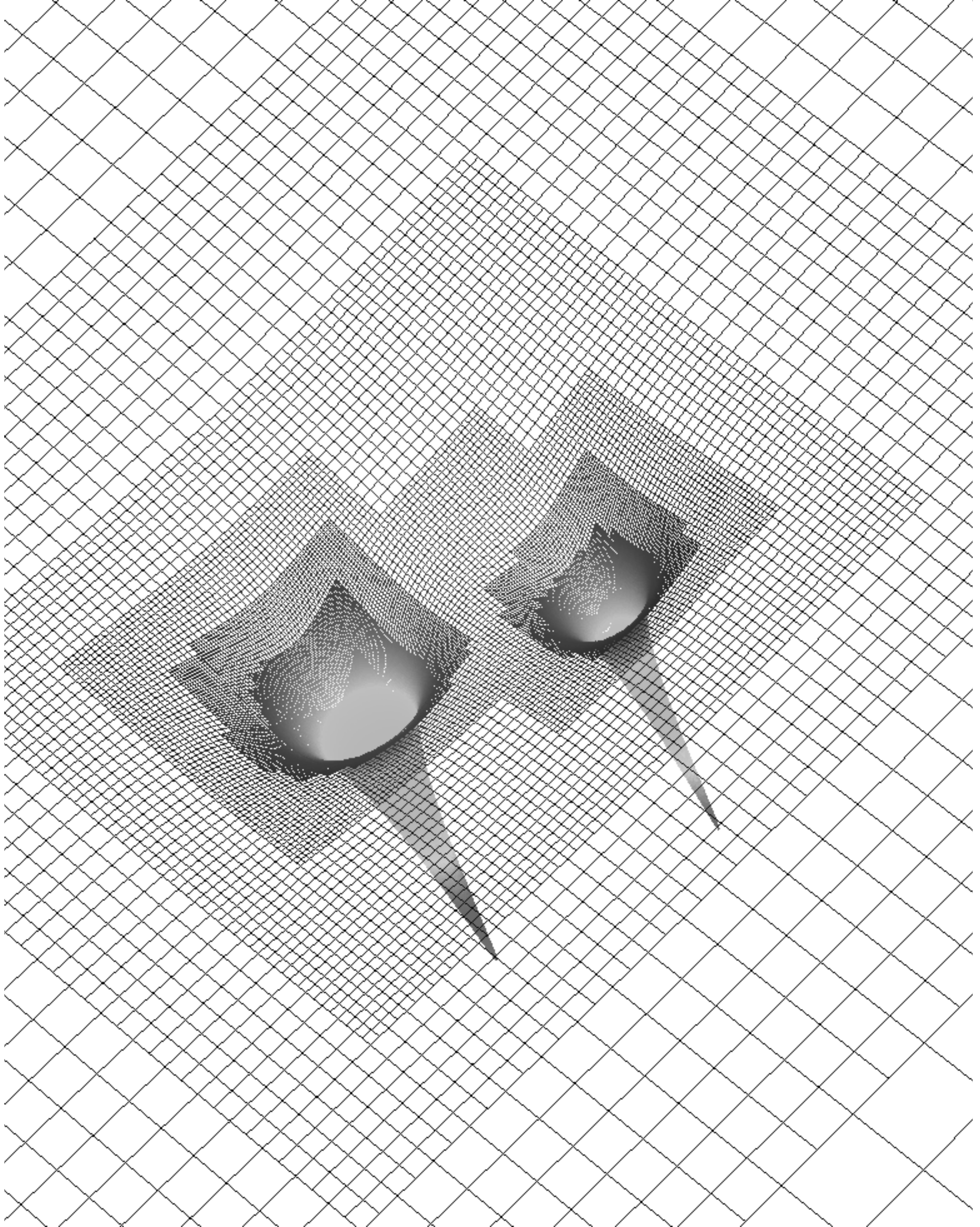


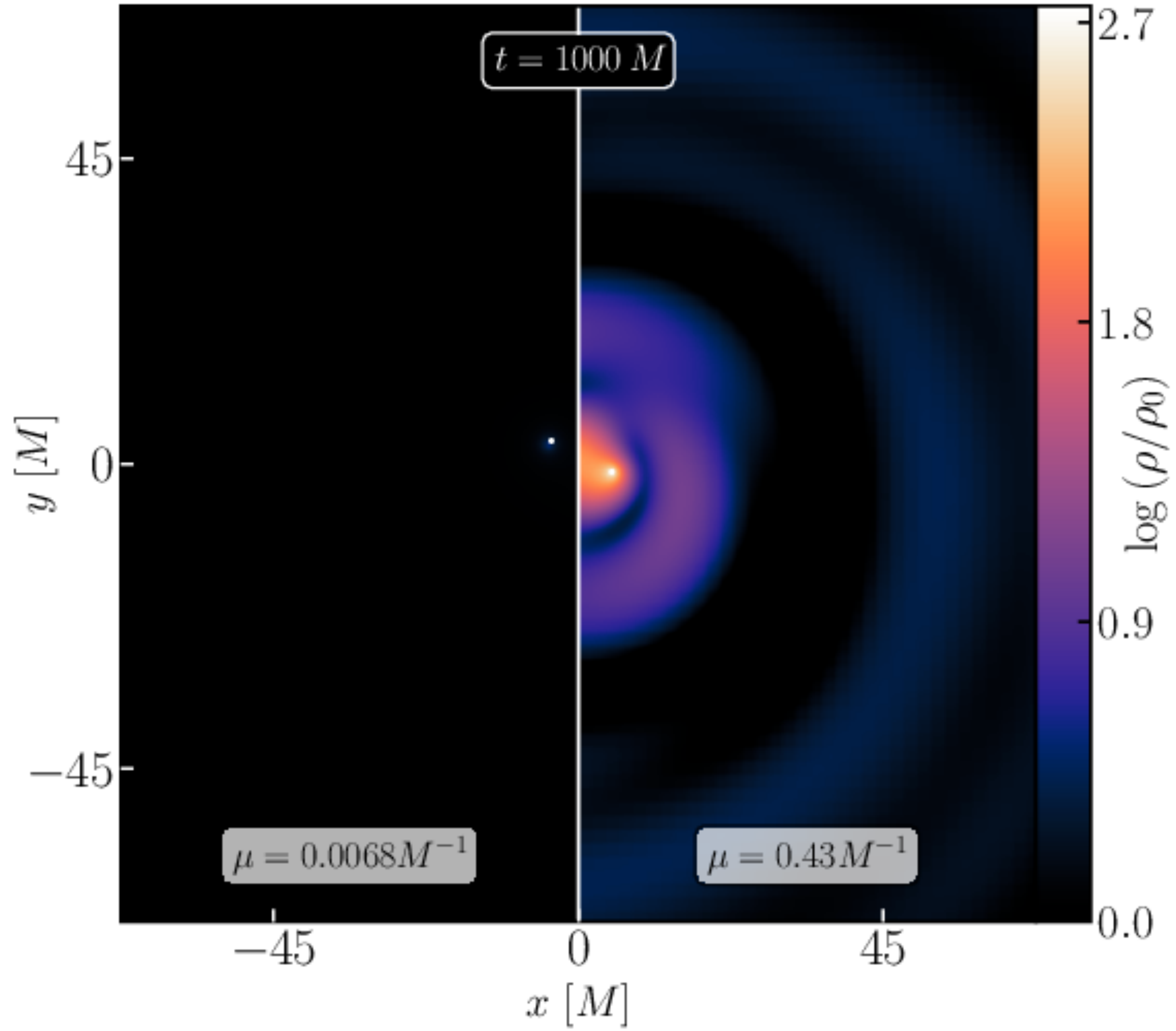
Dark matter

Can black holes act as particle detectors?

What is the endpoint of instabilities in the presence of light particles?

Would dark matter environments be observable with gravitational waves?

density of DM



J. Aurrekoetxea, KC, J Bamber, P Ferreira 2023
Effect of Wave Dark Matter on Equal Mass Black Hole Mergers
Phys.Rev.Lett. 132 (2024) 21, 211401

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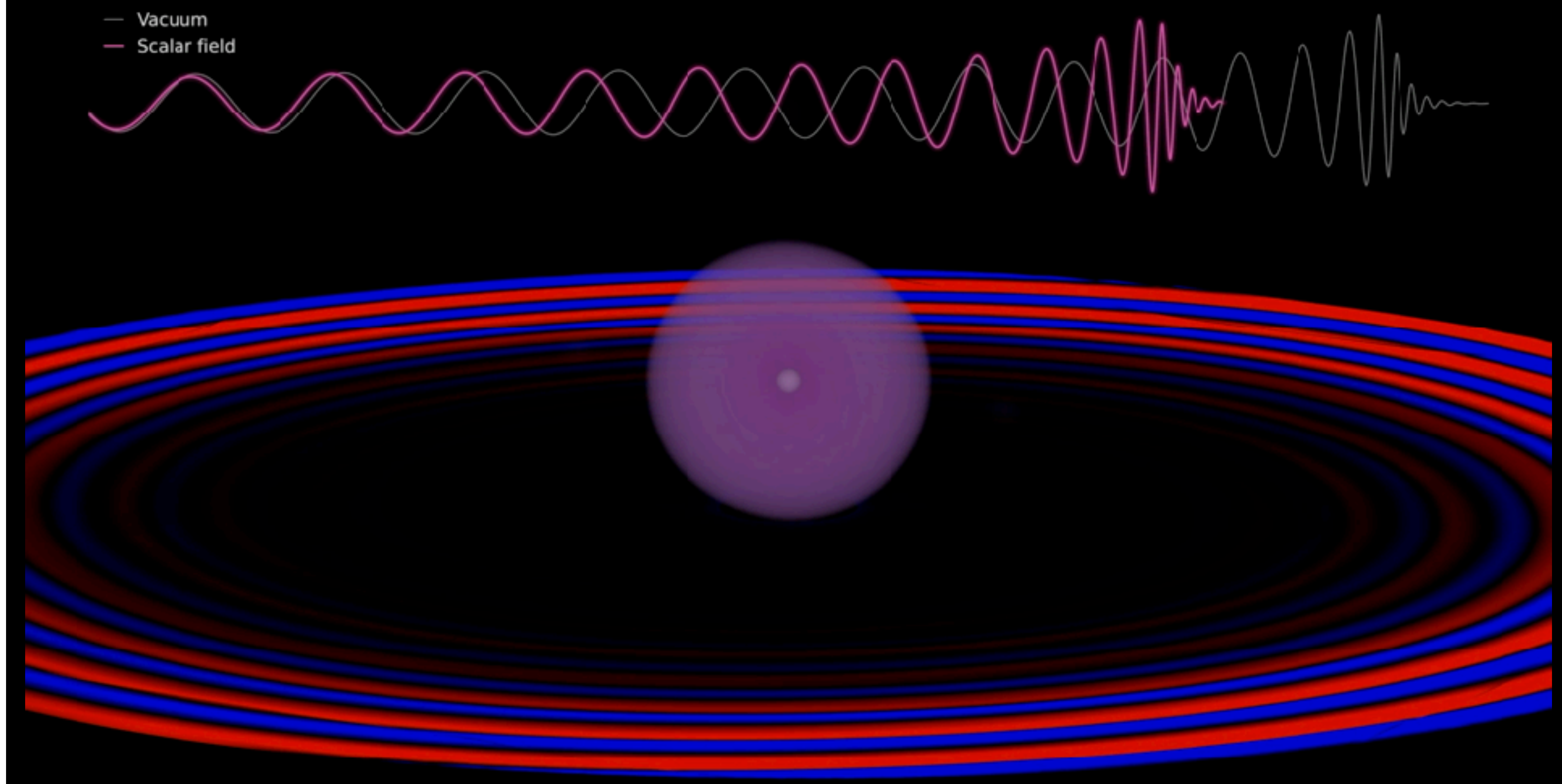

S. Roy, R Vicente, J Aurrekoetxea, KC, P Ferreira. 2025
Scalar fields around black hole binaries in LIGO-Virgo-KAGRA
2510.17967 [gr-qc]

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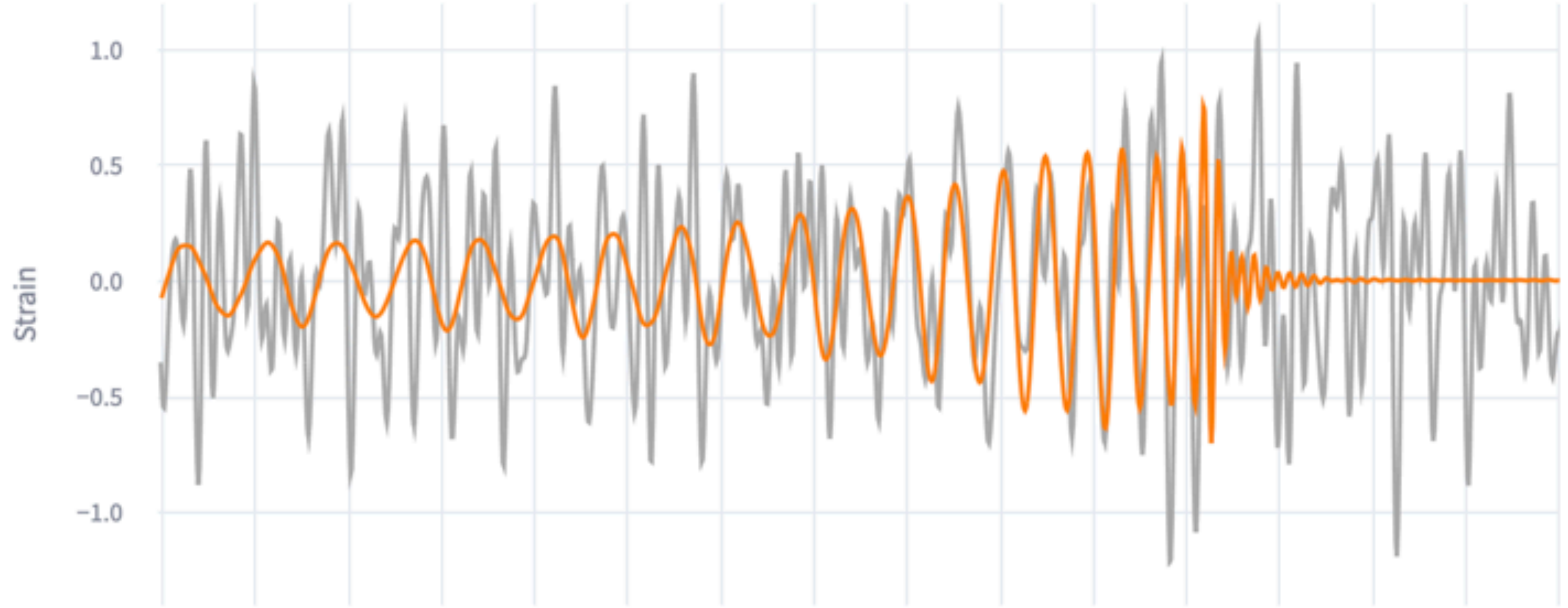
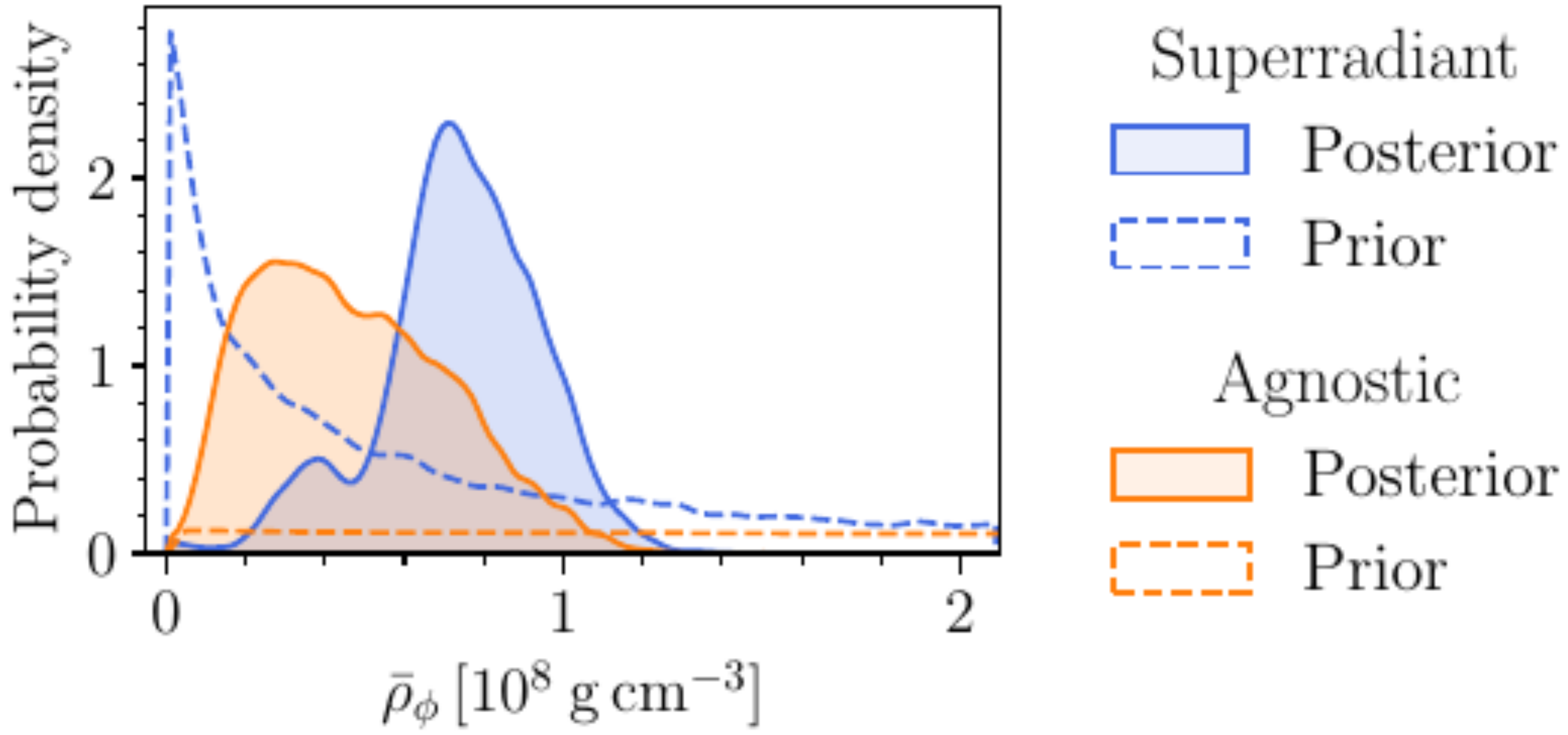
Event GW190728





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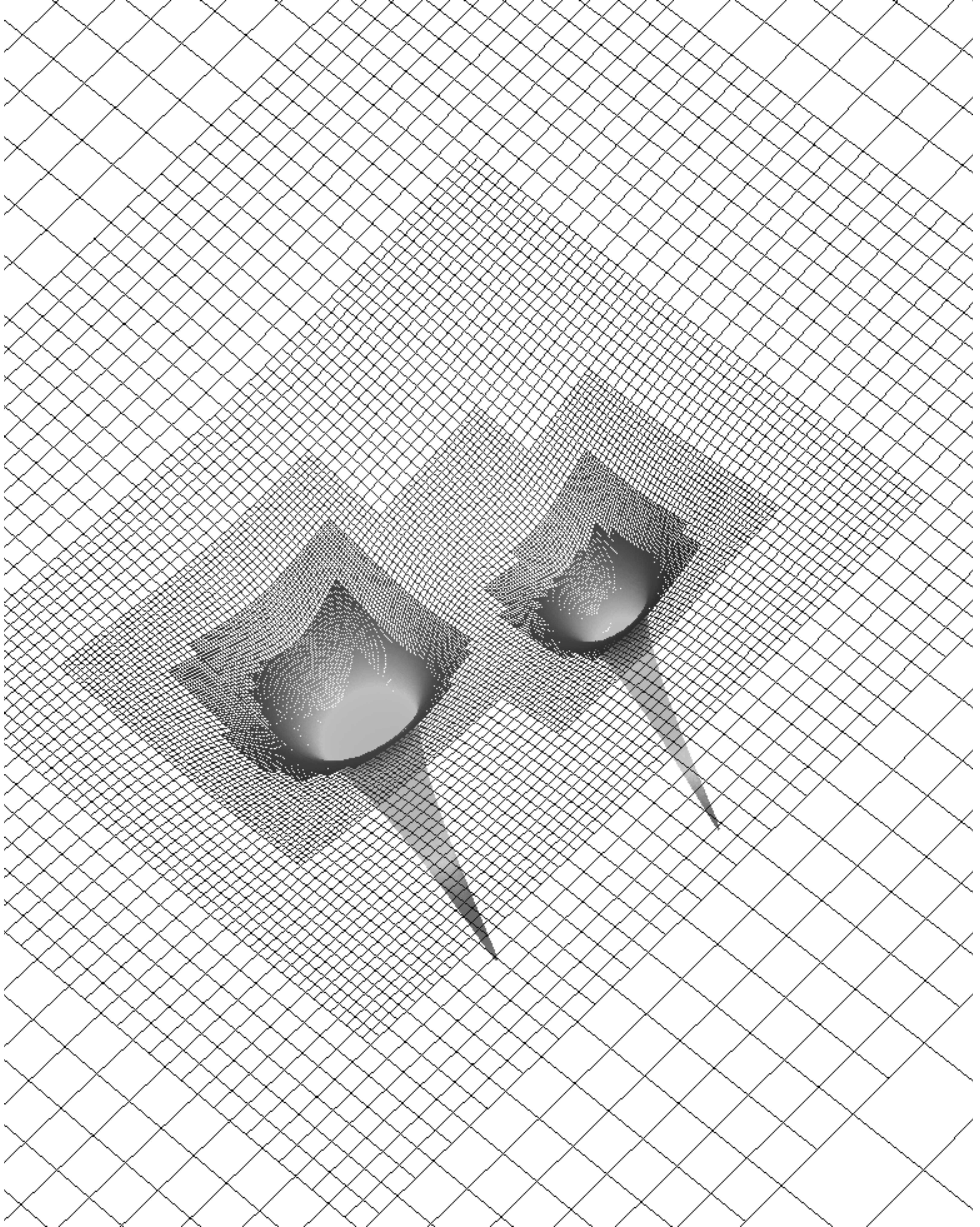


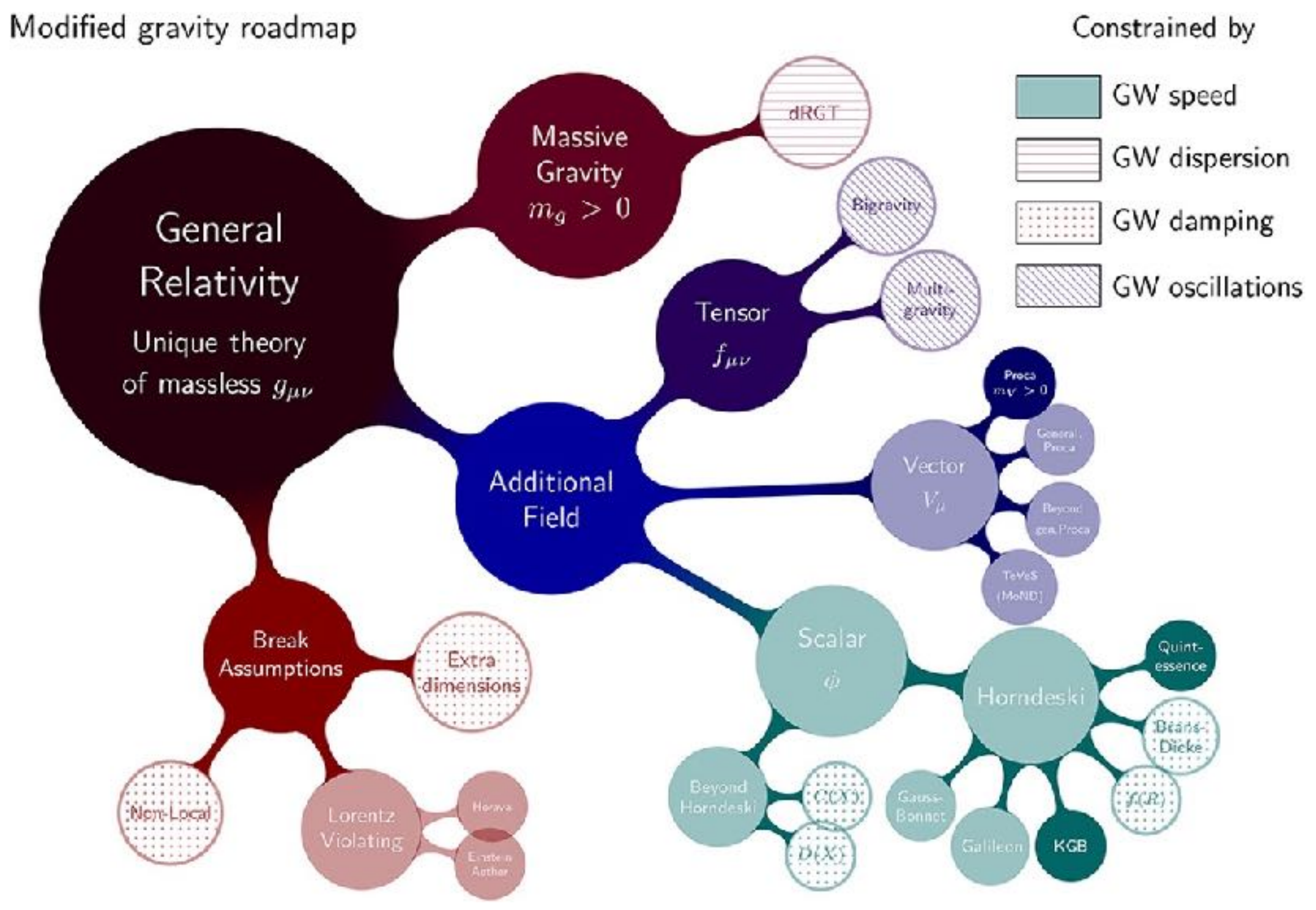
Modified gravity

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\;\underbrace{R}_{2\partial\text{ theory}} + \underbrace{\ldots}_{\text{higher }\partial\text{ terms}}$$

What effective field theories beyond GR are dynamically stable?

What are the smoking gun signatures of EFT corrections?

Can corrections to general relativity be detected?



JM Ezquiaga et al 2018
Front. Astron. Space Sci. 5 44

Modified gravity

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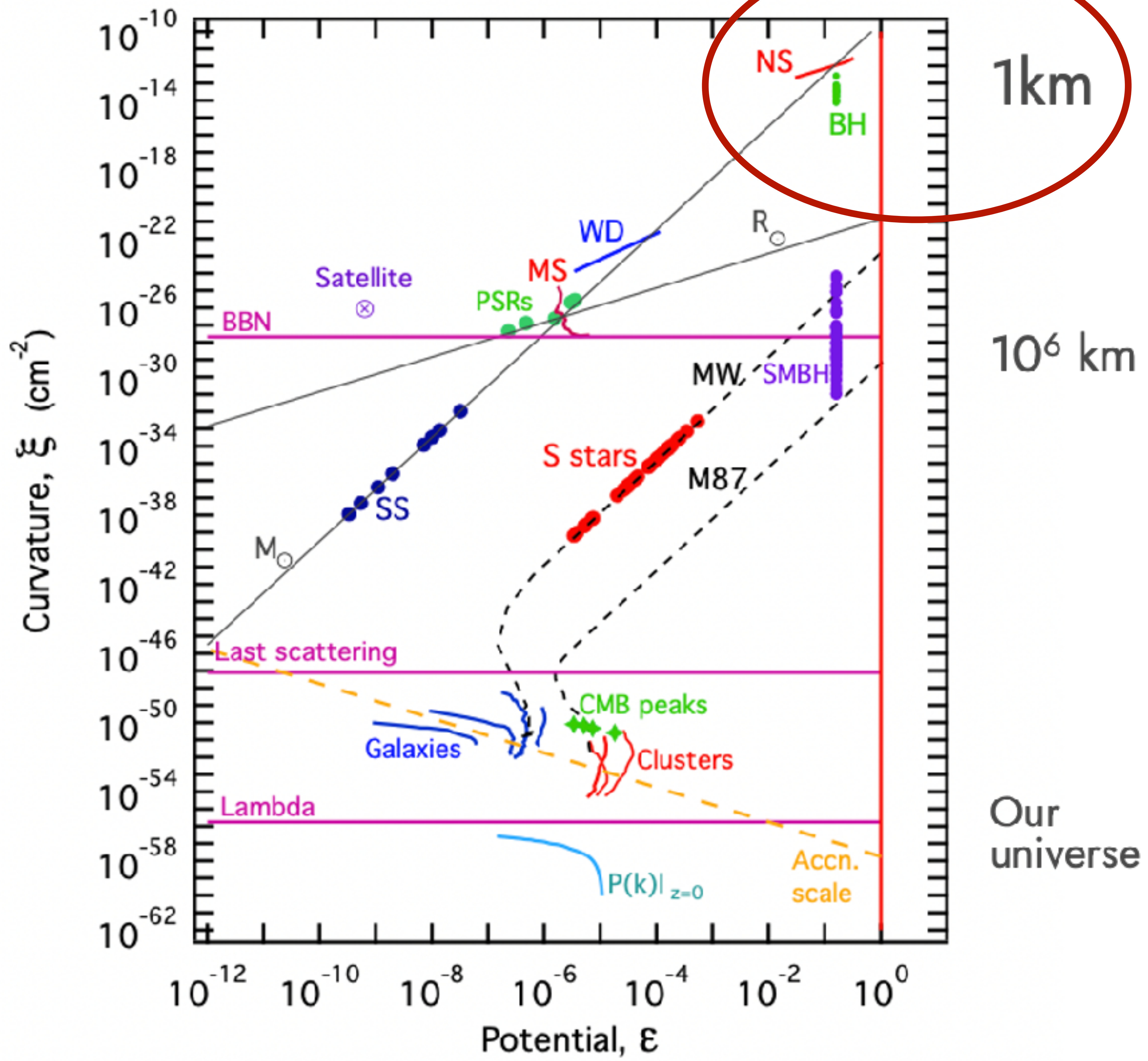
T Baker et. al. 2015
Astrophys. J. 802 (2015) 63



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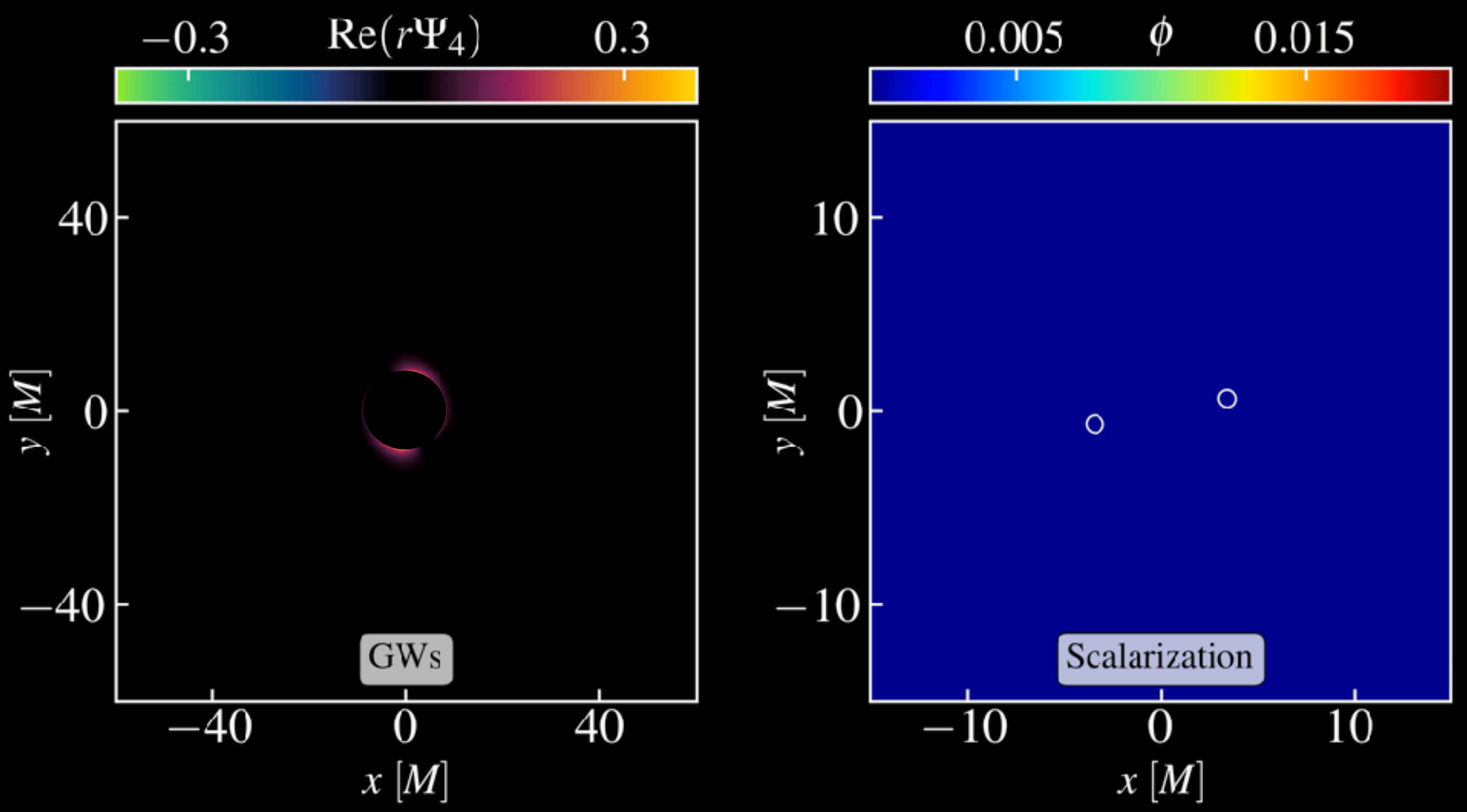

L Areste Salo, KC, P Figueras 2022
Well-Posedness of the Four-Derivative Scalar-Tensor Theory of Gravity in Singularity Avoiding Coordinates
Phys.Rev.Lett. 129 (2022) 26, 261104

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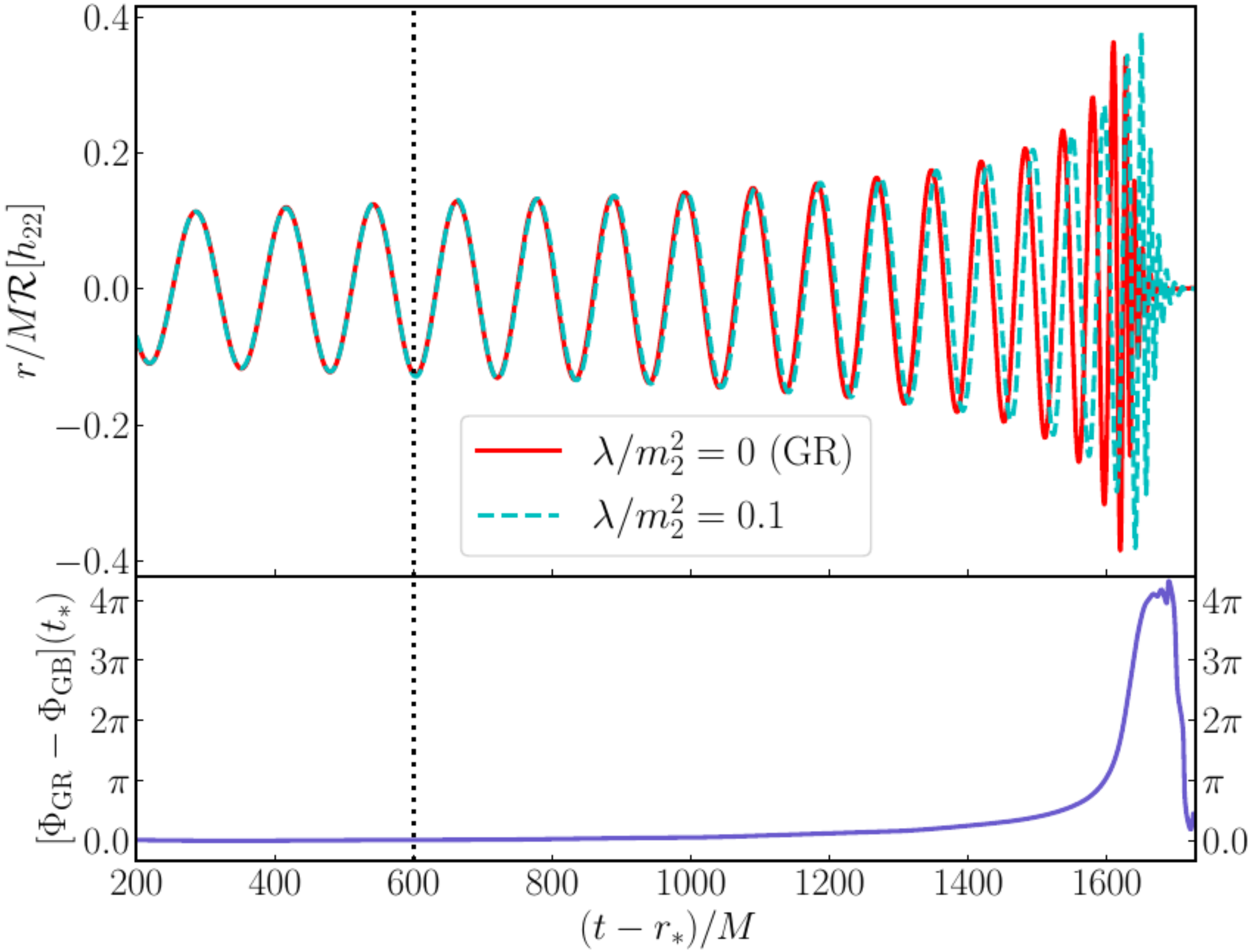
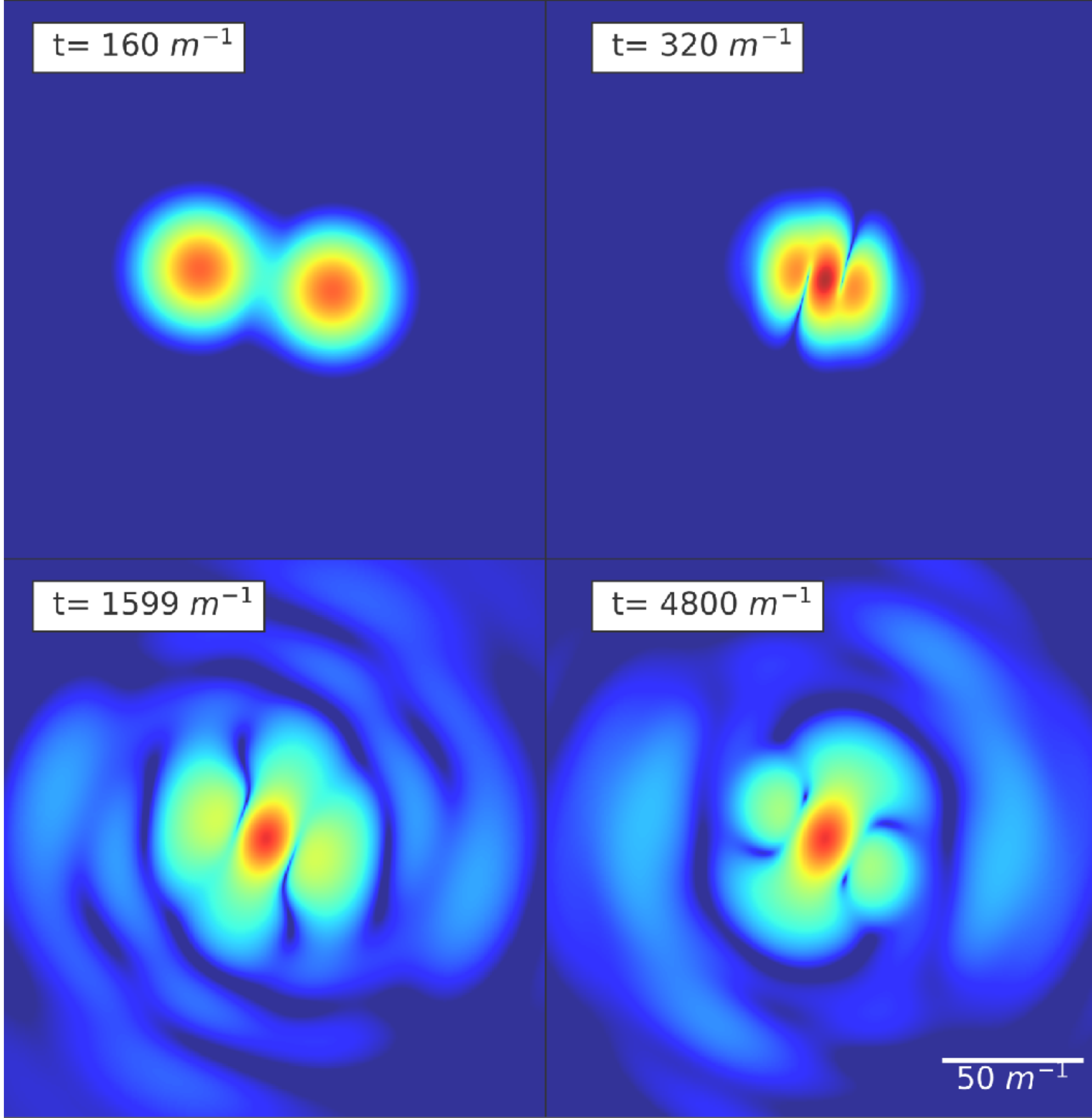


M Corman, L Areste Salo, KC 2025
Black hole binaries in shift-symmetric Einstein-scalar-Gauss-Bonnet gravity experience a slower merger phase
2511.19073 [gr-qc]

Application to fundamental physics beyond black holes

Simulations allow us to test new possibilities that we haven't seen before



R Croft et al 2023
The gravitational afterglow of boson stars
Class.Quant.Grav. 40 (2023) 6, 065001

Early universe cosmology

What is the nature of the cosmological singularity?

Can inflation begin?

Can cosmological bounces occur?

Do primordial black holes form during preheating?

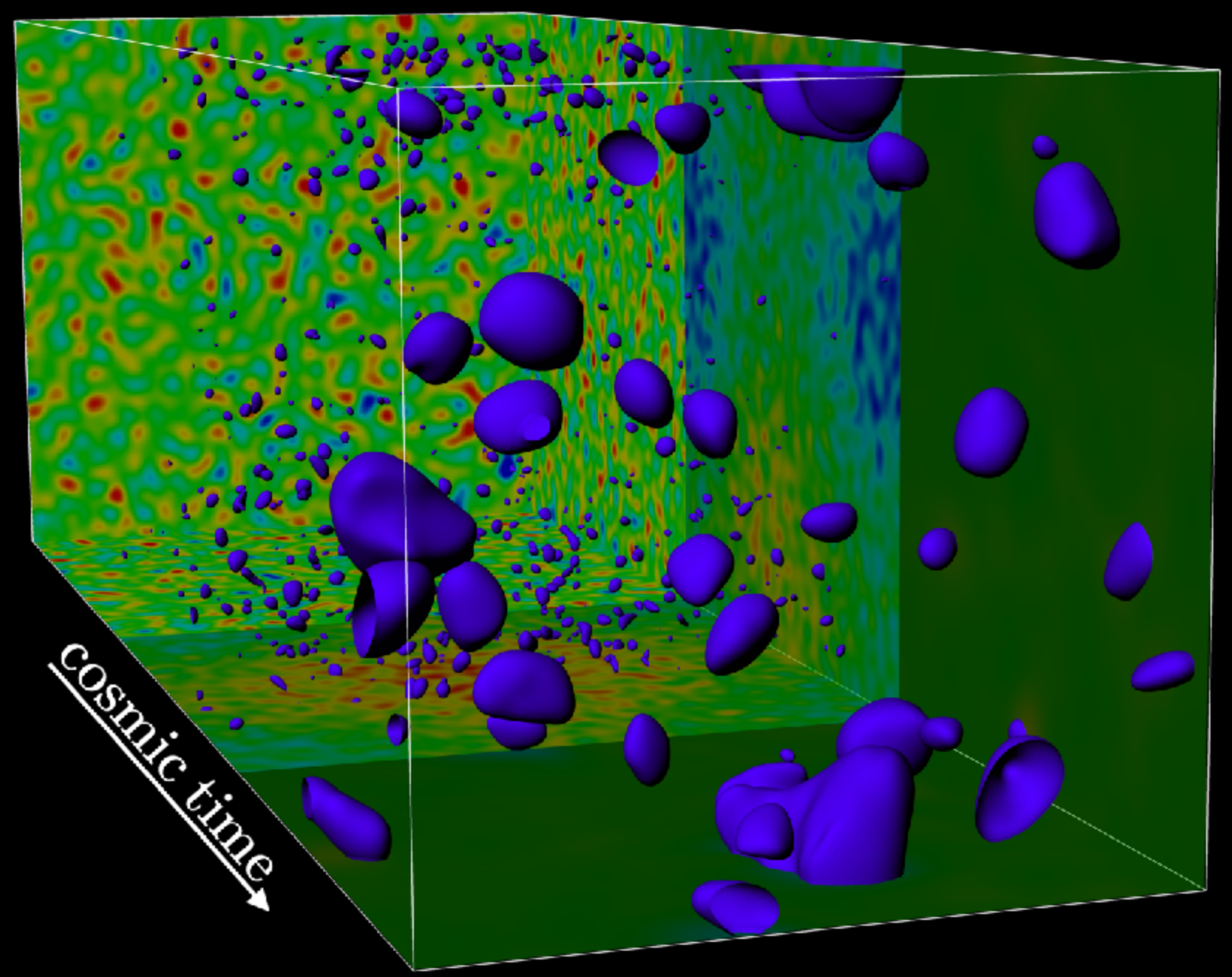
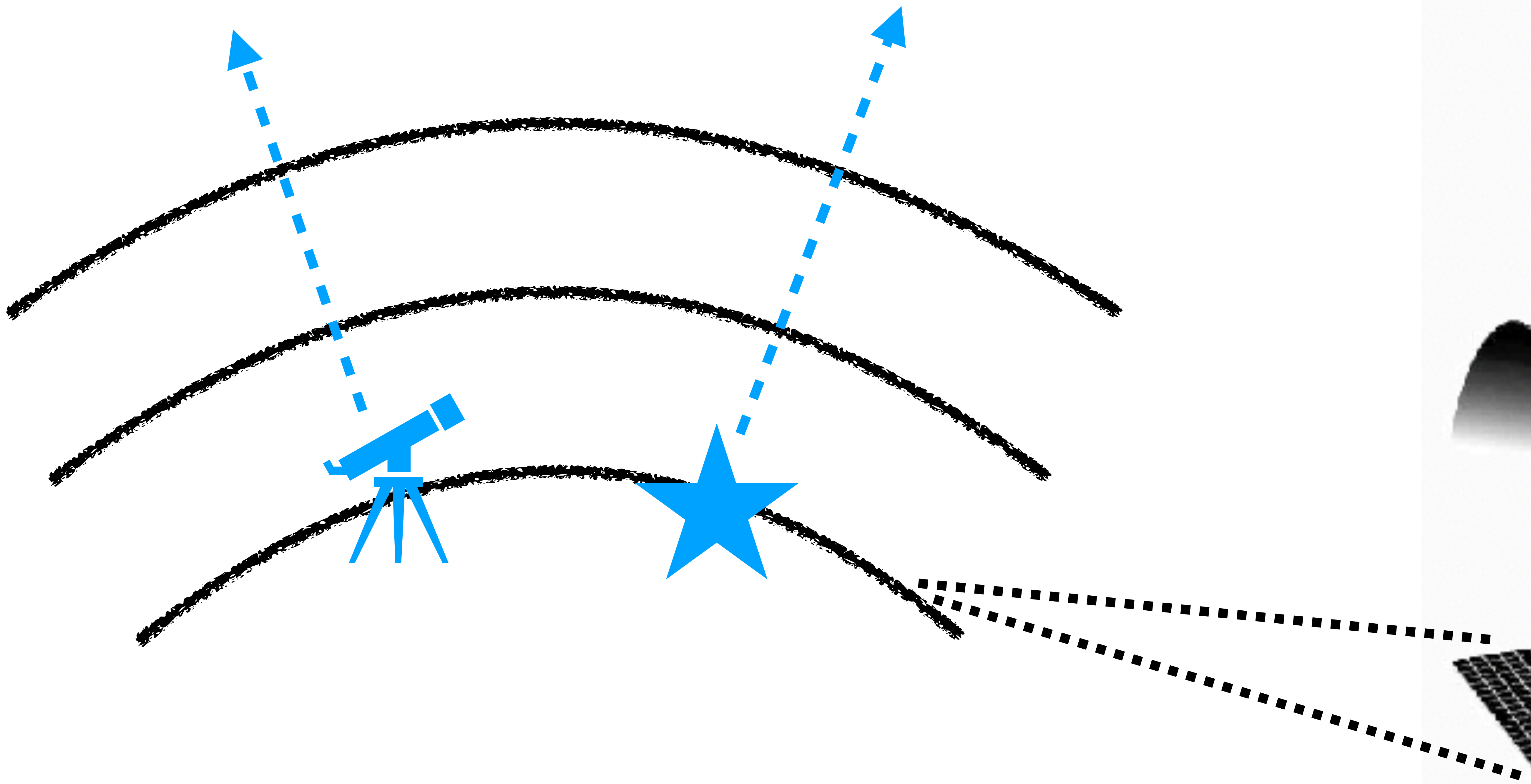


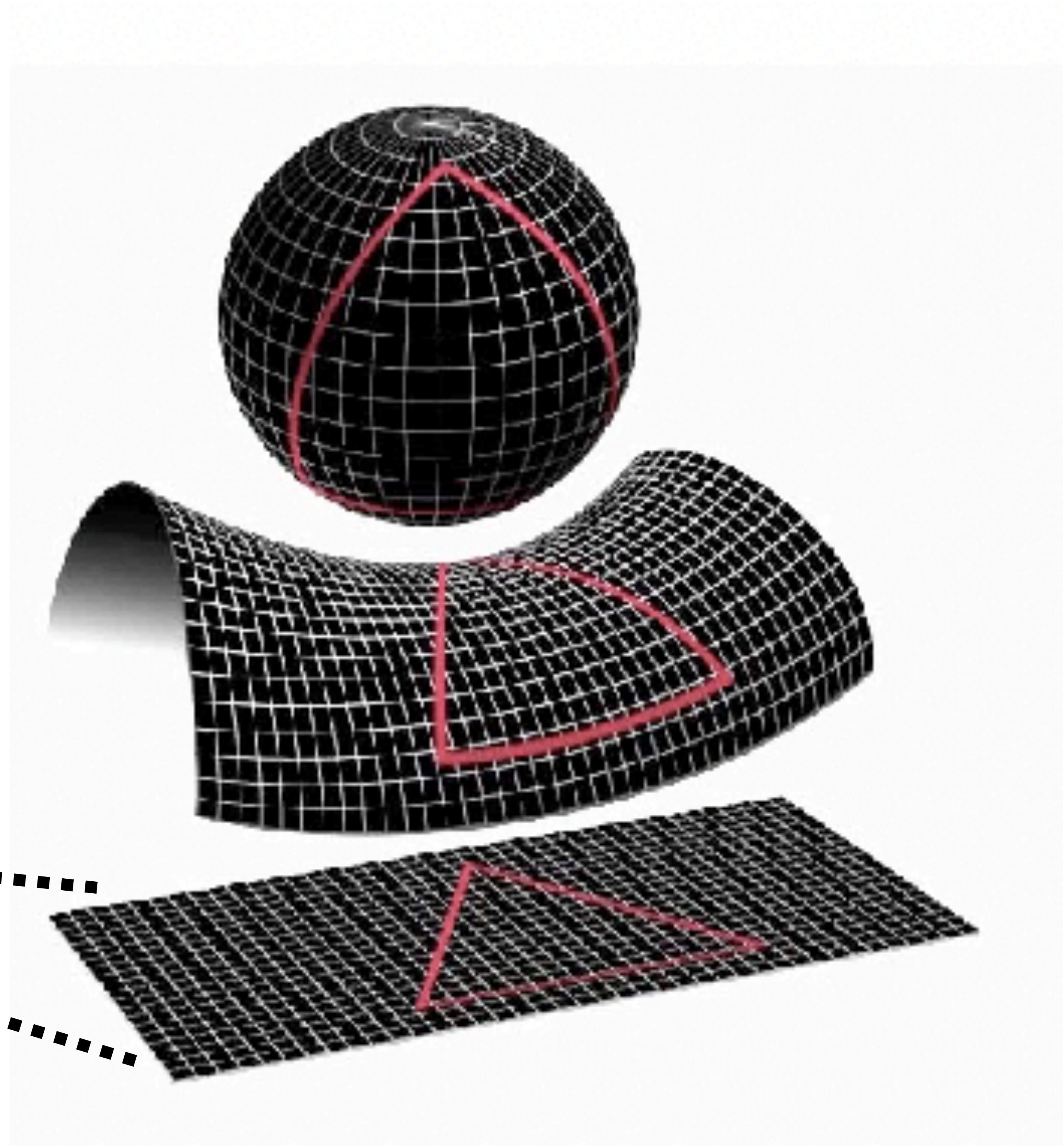
Image credit: Josu Aurrekoetxea, KC, Francesco Muia

J. Aurrekoetxea, KC, E A Lim
Cosmology using Numerical Relativity
Living Rev.Rel. 28 (2025) 1, 5

Our 4D universe is also a strongly curved spacetime



1 dimensional “time” is curved



3 dimensional “space” is (roughly) flat

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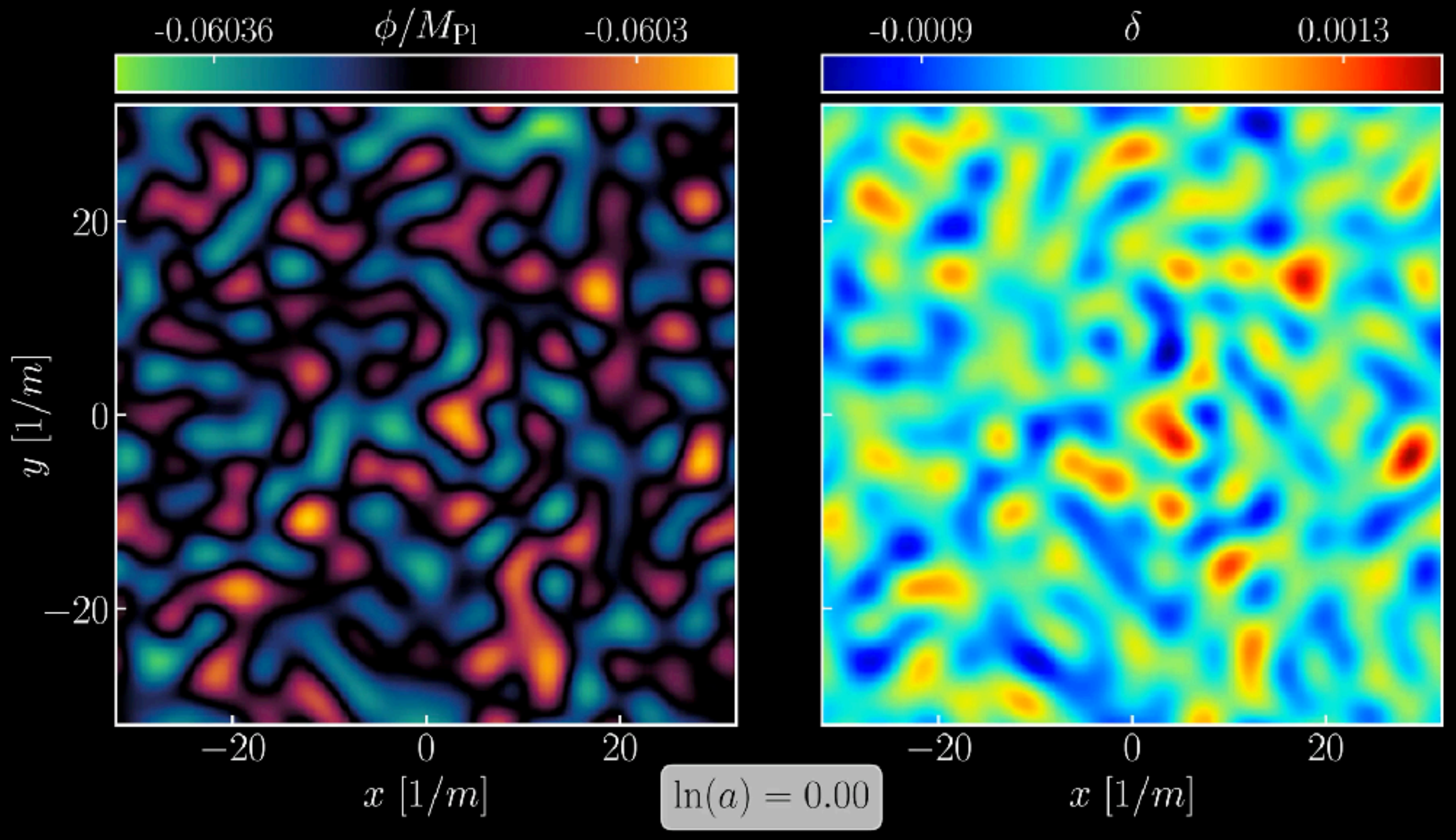
J. Aurrekoetxea, KC, F Muia
Oscillon formation during inflationary preheating with general relativity
Phys.Rev.D 108 (2023) 2, 023501

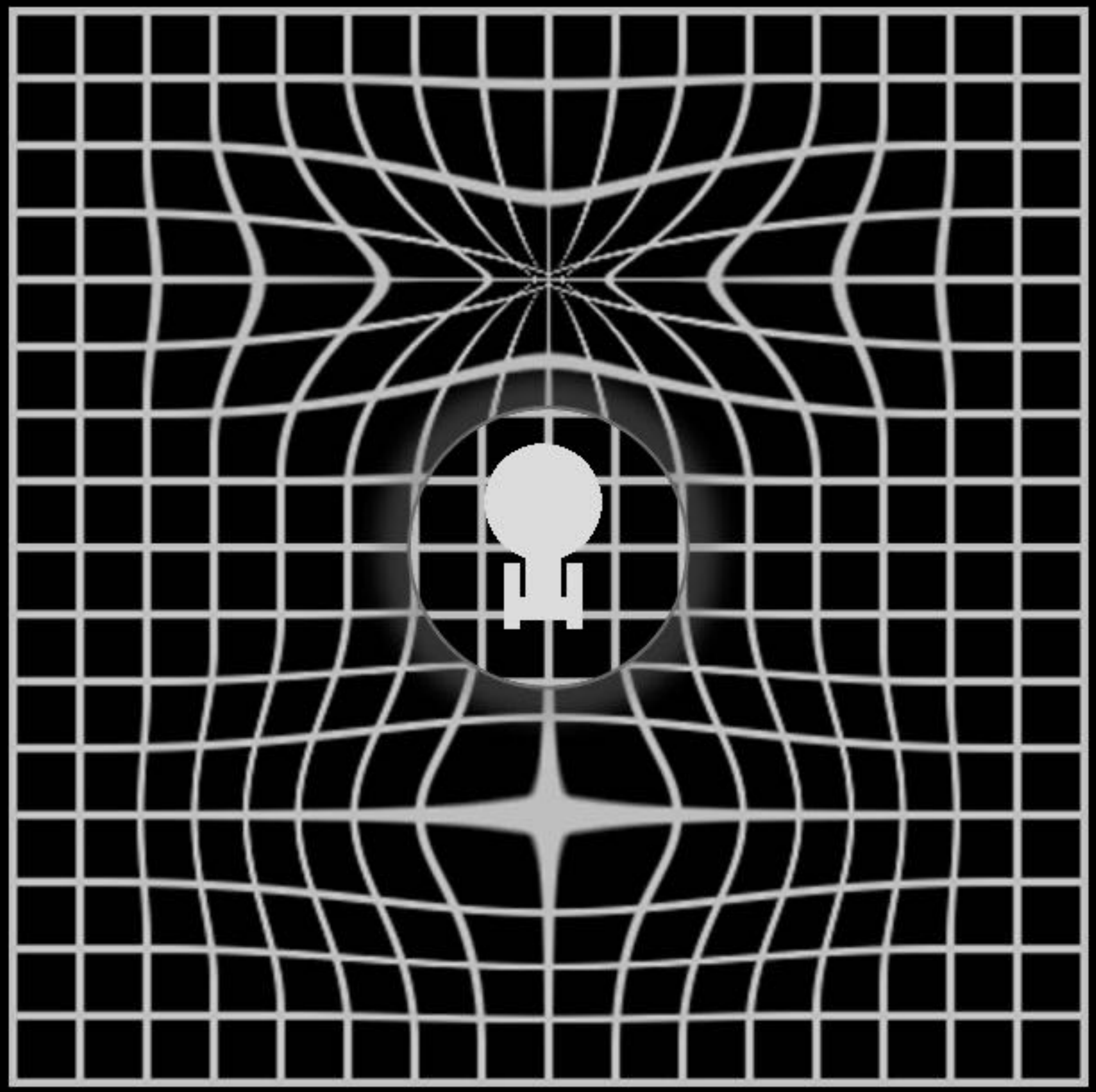


Anything else?

What no one has seen before…

Are warp drive spacetimes stable?

Can we detect them in gravitational waves?



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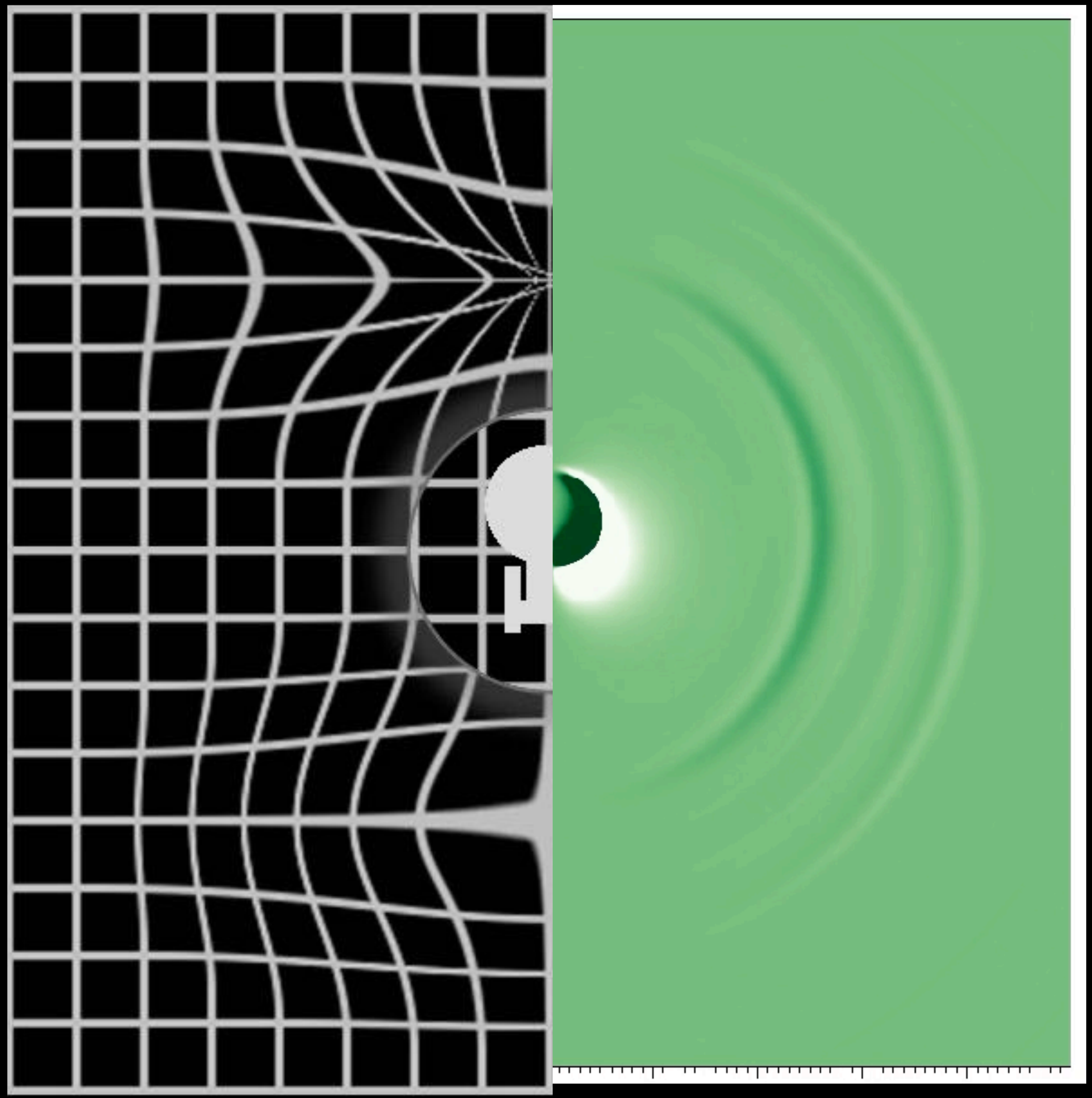

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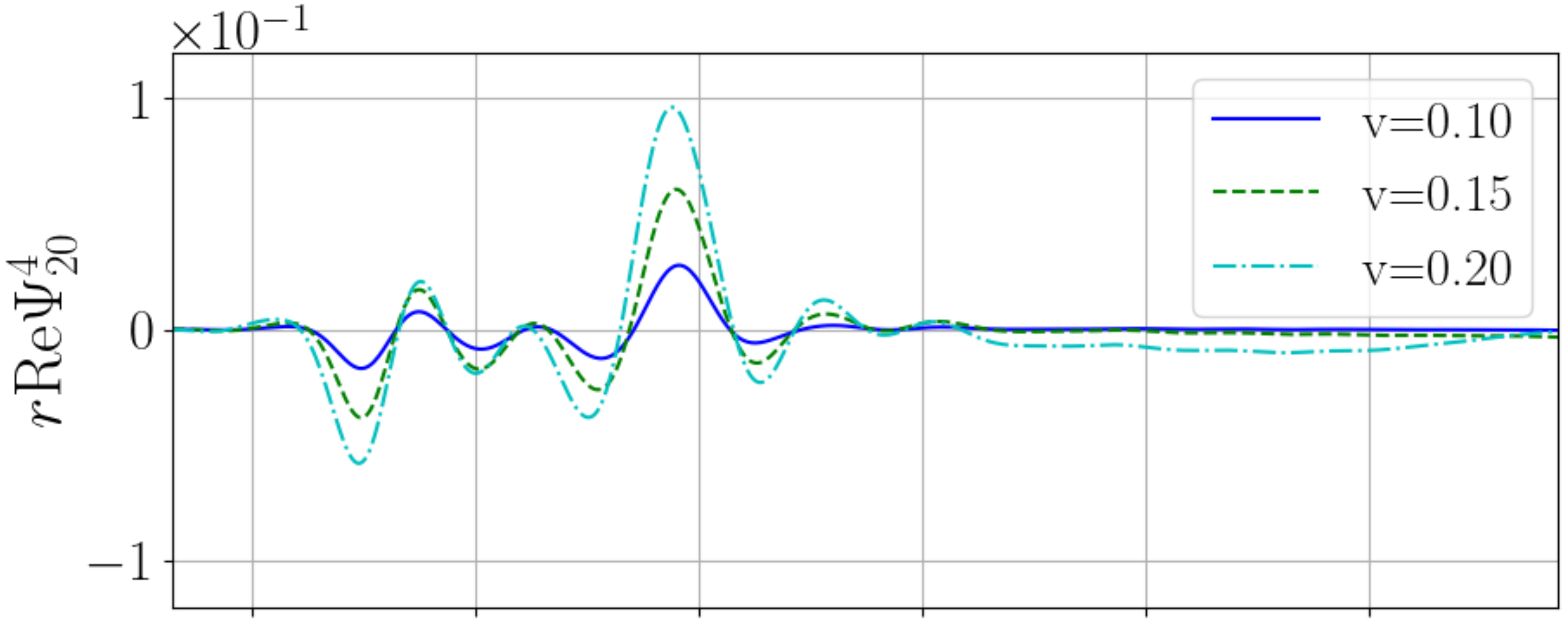
KC,T Dietrich, S Khan
What no one has seen before: gravitational waveforms from warp drive collapse
Open J.Astrophys. 7 (2024)



Amplitude ~ 0.01/ R at a distance of R

Frequency ~ 1/R

What no one has seen before...

R = 1 km bubble in our galaxy, travelling at 10% of the speed of light

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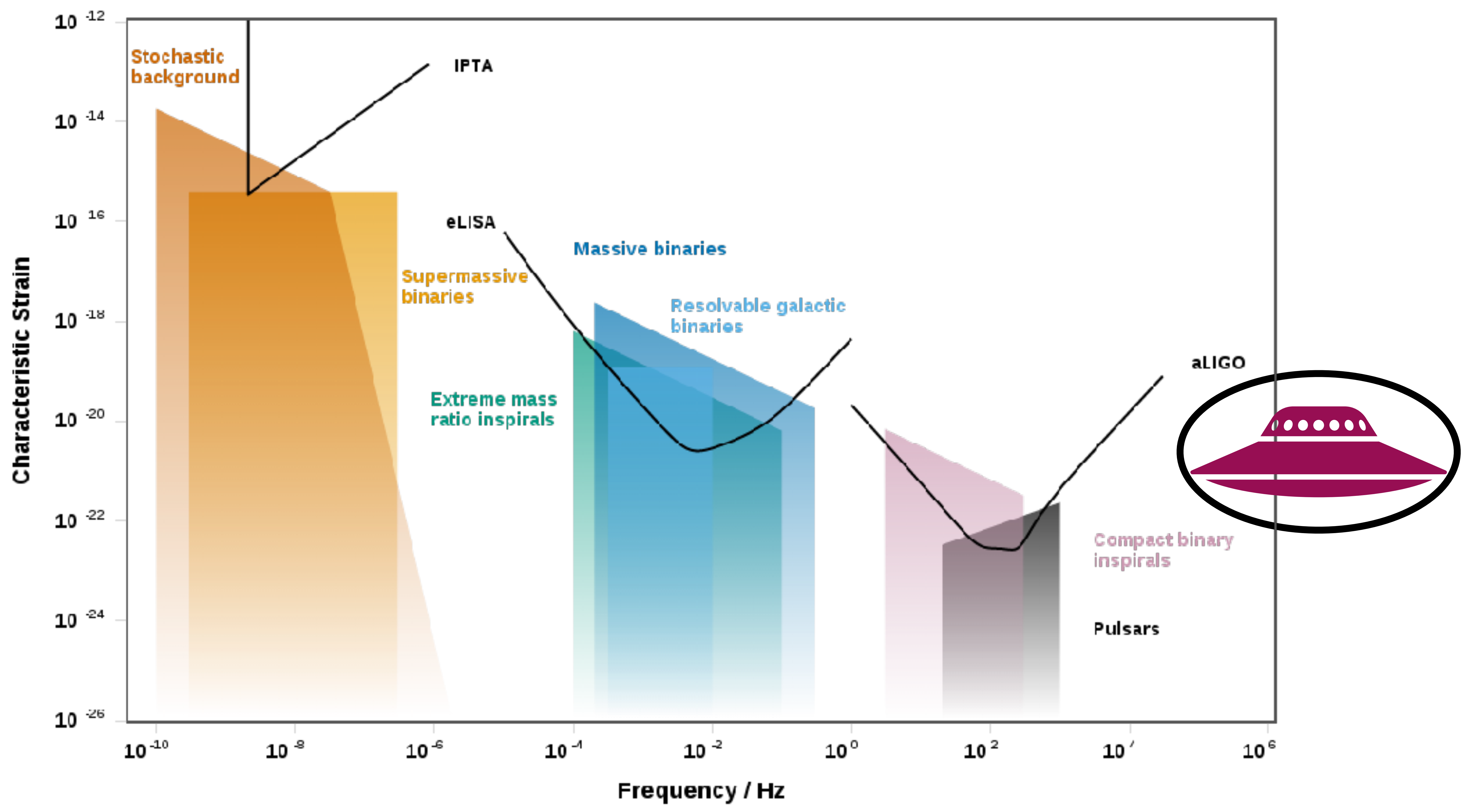

Image credit: Chris Berry (aliens added)

Thank you for listening!