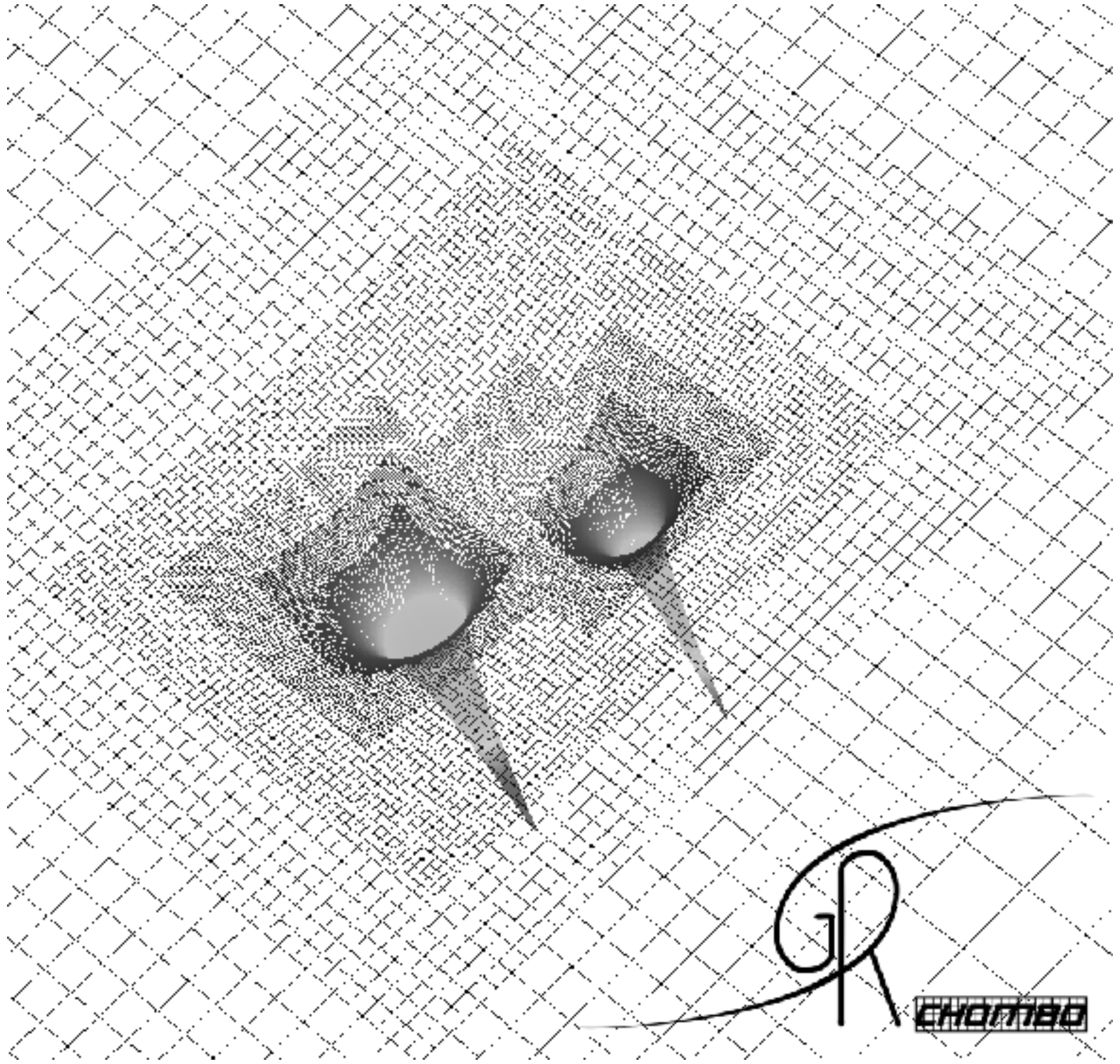


Numerical relativity for fundamental physics

Katy Clough, STFC Ernest Rutherford Fellow
Queen Mary University of London

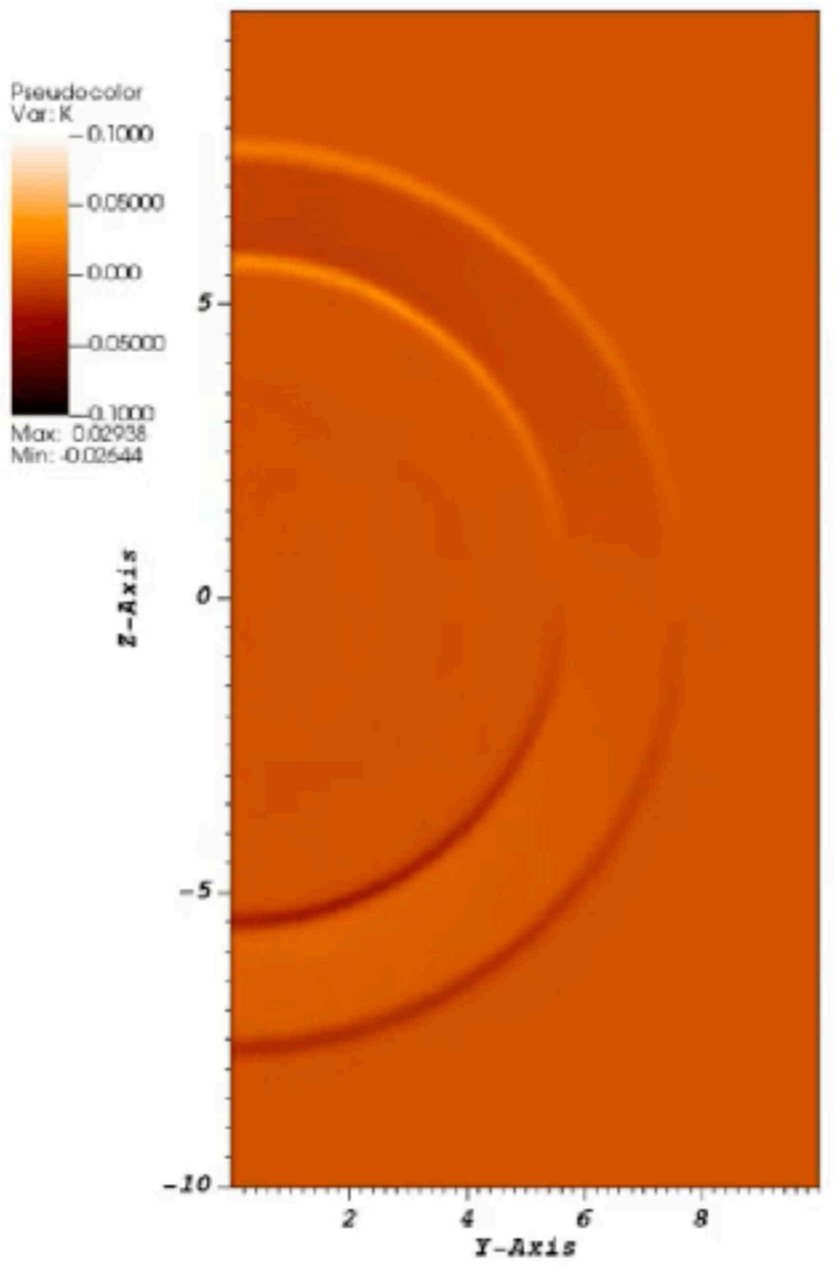
DiRAC

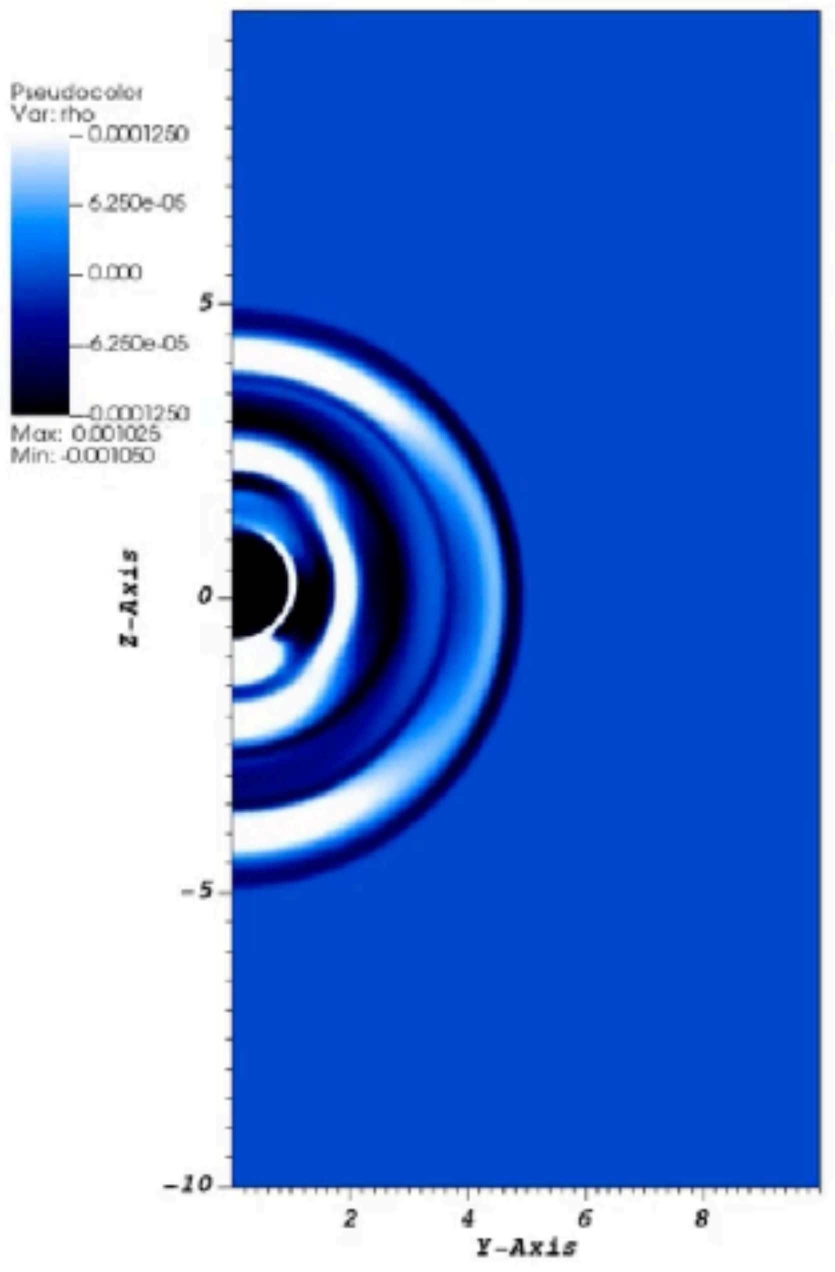
Science & Technology Facilities Council

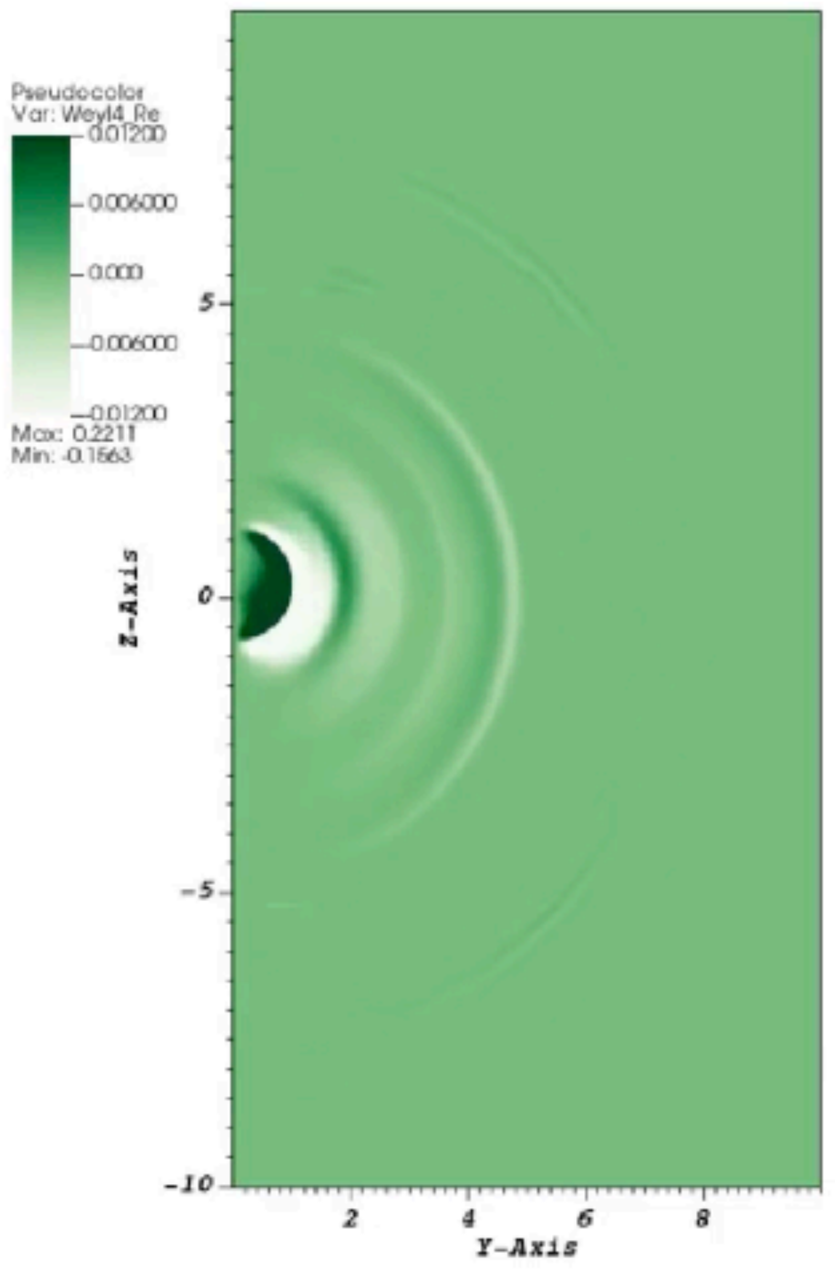
Queen Mary University of London

Plan for the talk

- What is numerical relativity?
- What can it do? What can't it do?
- A fun(damental) example - warp drive collapse

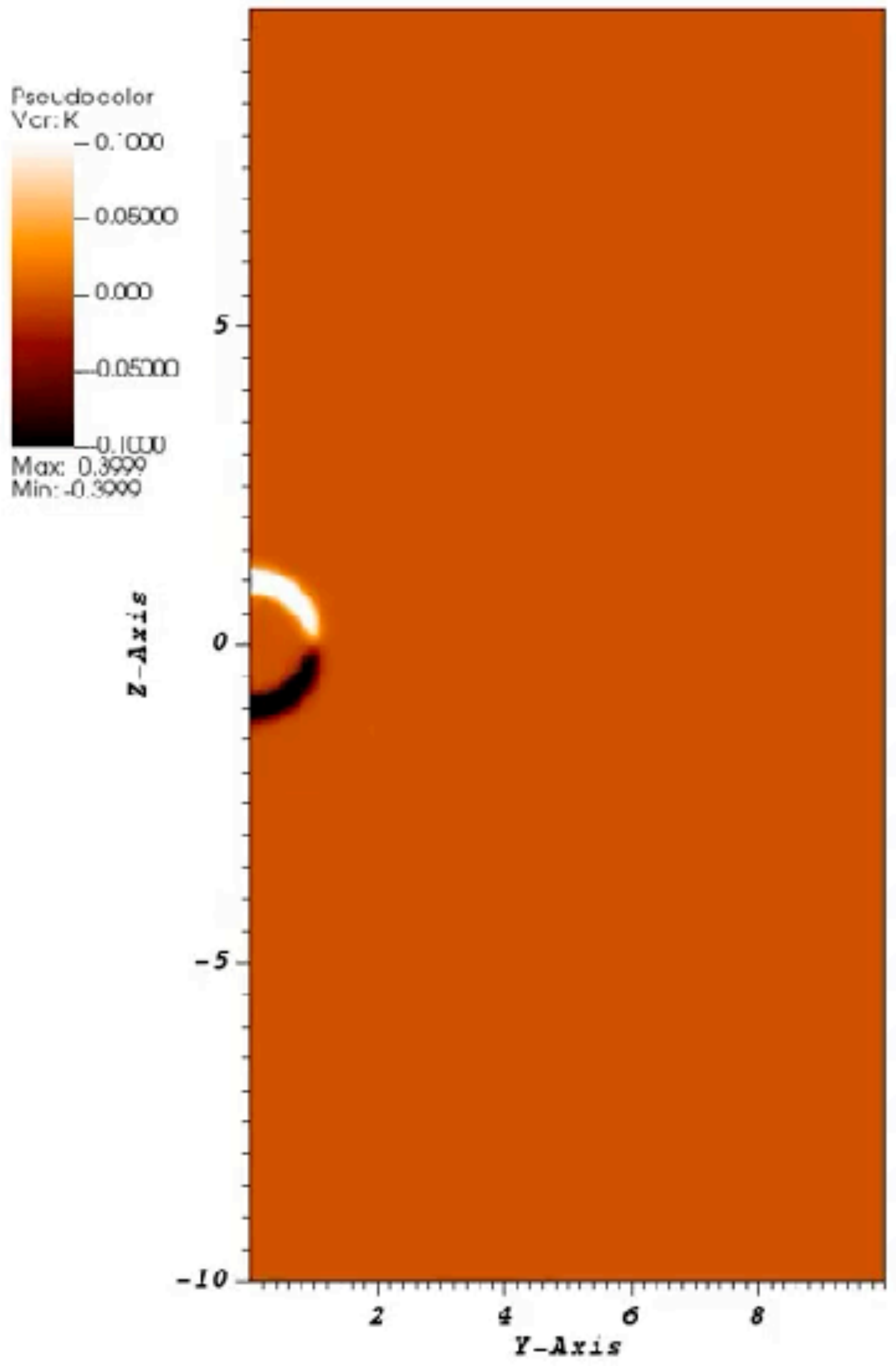


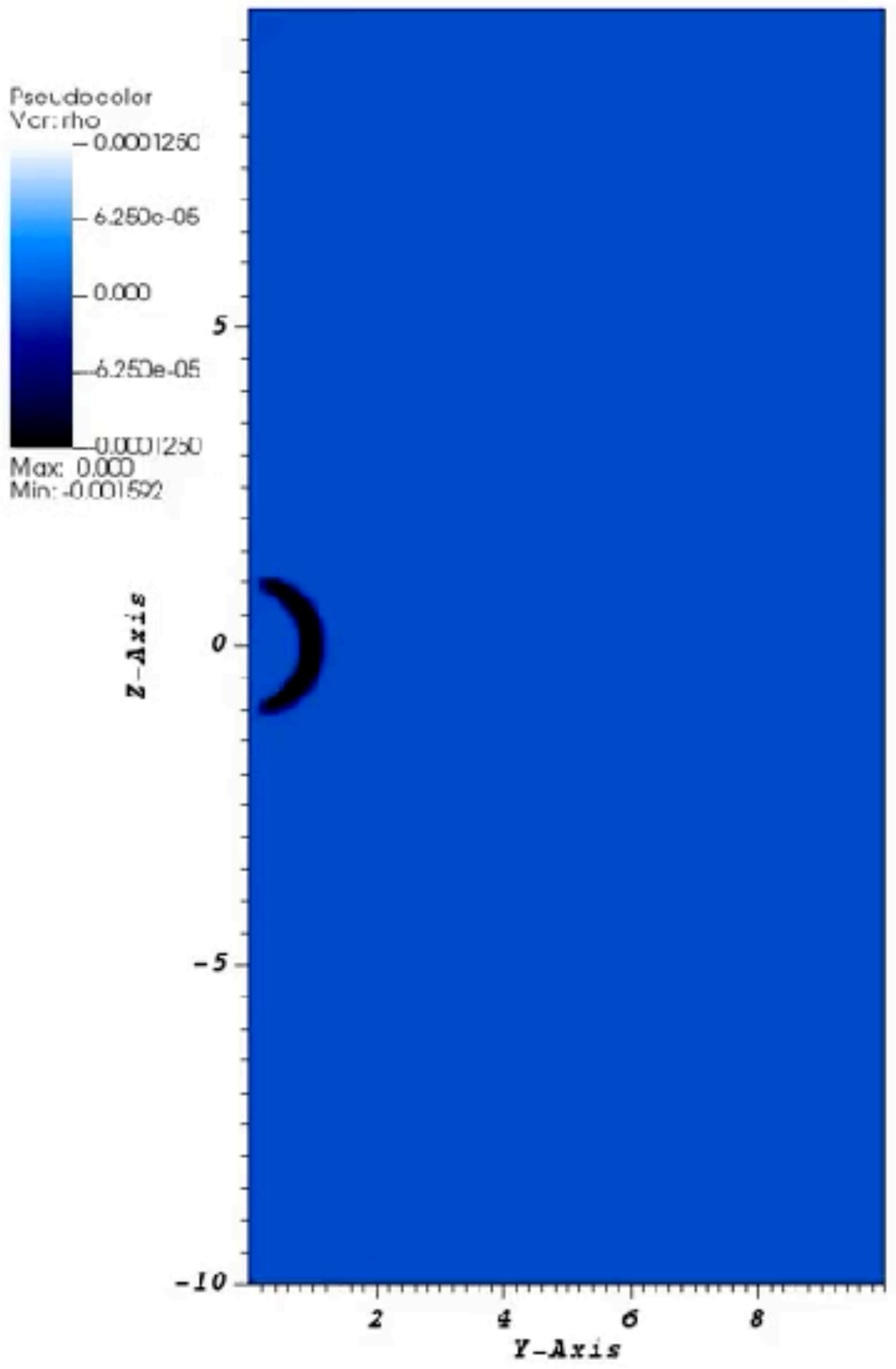


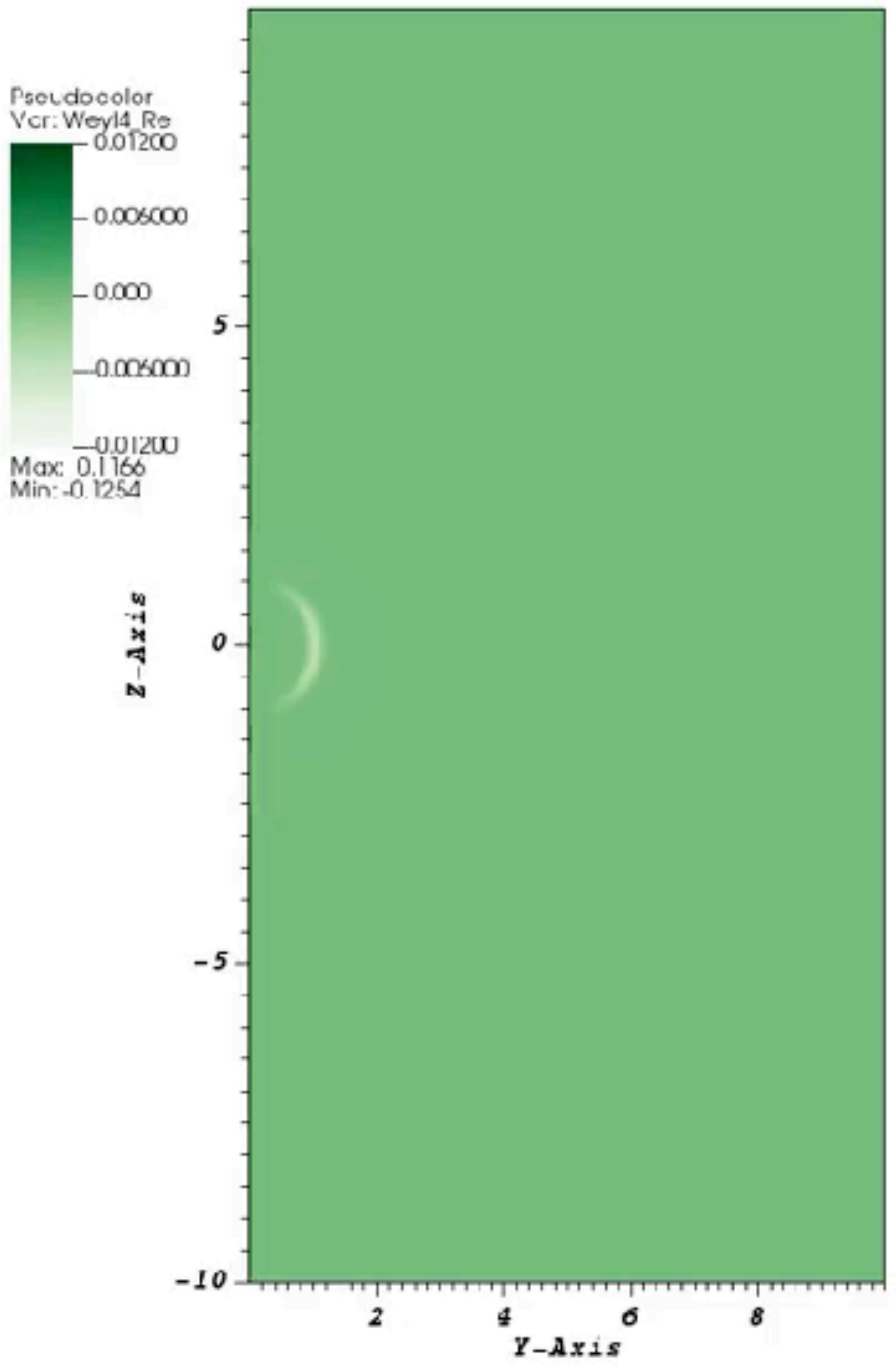


Main message:

Numerical relativity simulations can be used as a tool to investigate the consequences of fundamental physics in strong gravity regimes. They are a modern day gedanken experiment.



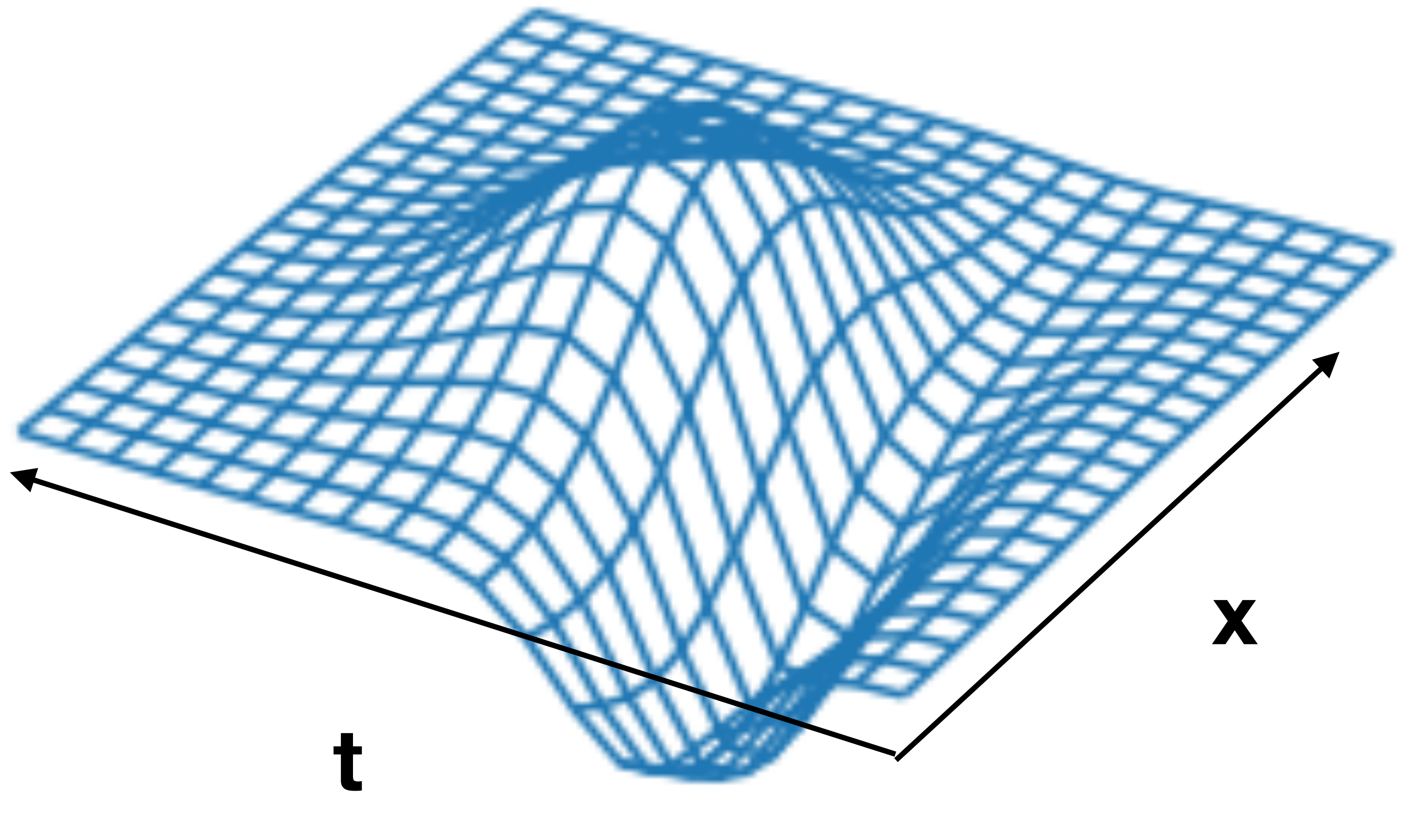




What is numerical relativity?

Curved spacetime

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



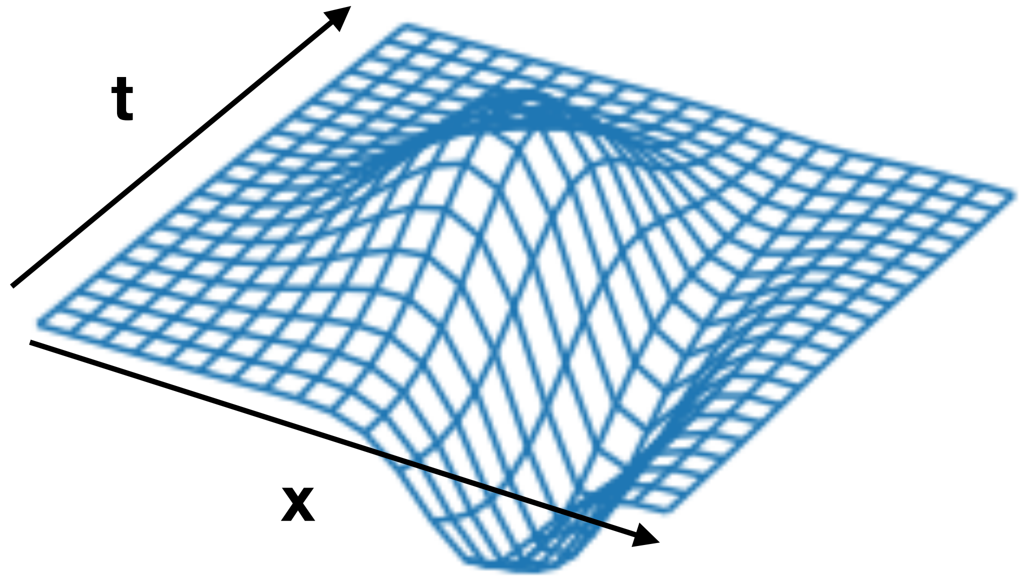
"The spacetime metric"

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

What is the goal of NR?

The metric

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



"The spacetime metric"

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

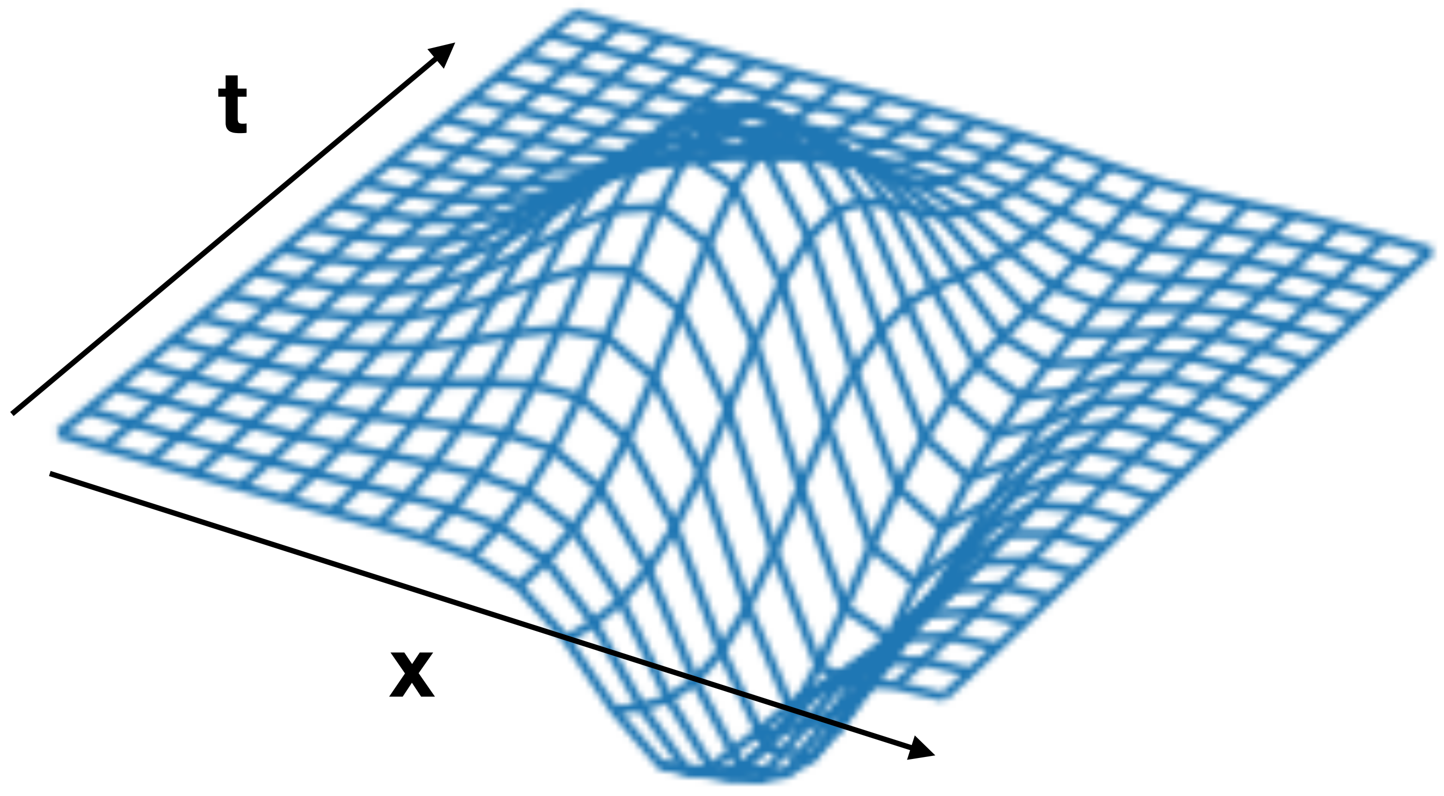
The Einstein equation

$$R_{ab} - R/2\, g_{ab} = 8\pi\, T_{ab}$$

$f(\partial^2 g_{ab}, \partial g_{ab}, g_{ab})$
"Curvature"

"Energy-Momentum"

The Einstein equation tells us how the metric should look, given some energy/matter distribution



$R_{ab} - R/2\ g_{ab} = 8\pi\ T_{ab}$

Four constraint equations for any time slice - non linear elliptic/Poisson equation

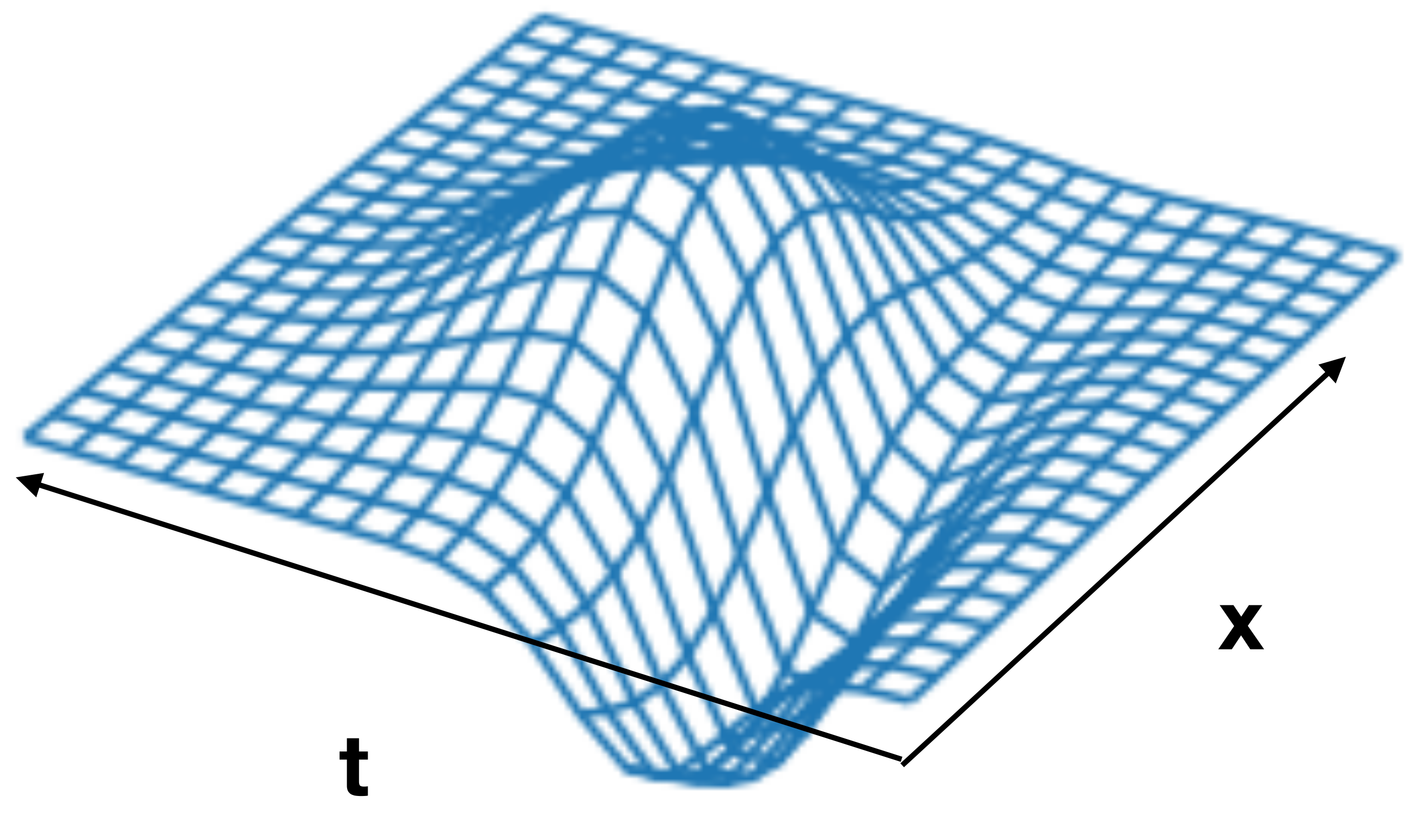
$$\frac{\partial^2 g}{\partial x^2} + \text{non linear terms} = f(\text{energy, momentum})$$

An evolution equation for all time - non linear hyperbolic/wave equation

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

"Matter tells spacetime how to curve…"

The metric determines the motion of matter



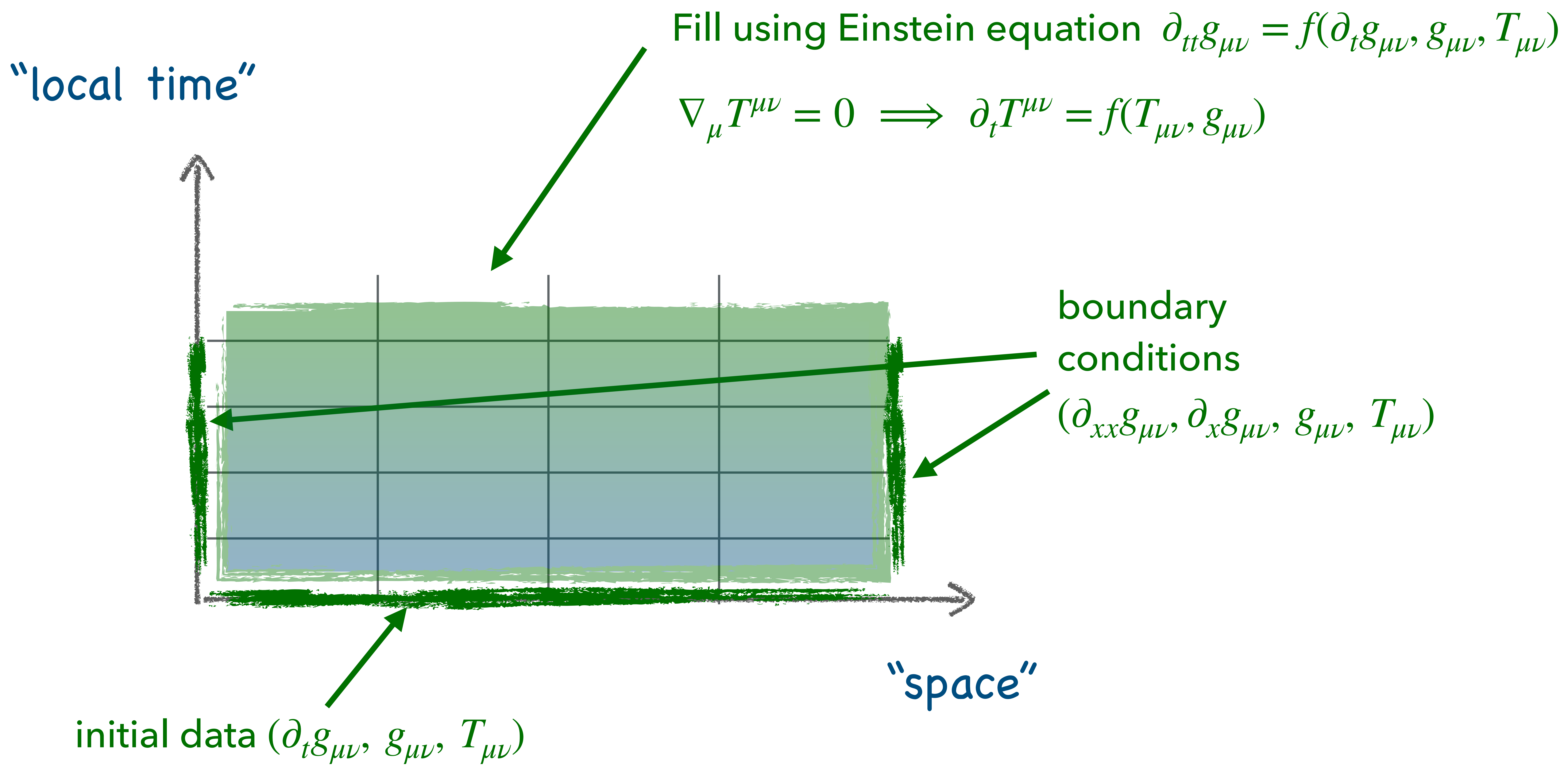
Continuity equation

$$\frac{\partial \rho}{\partial t} + \underbrace{\nabla}_{g_{ab}} \cdot \mathbf{j} = \underbrace{\text{source}}_{g_{ab}}$$

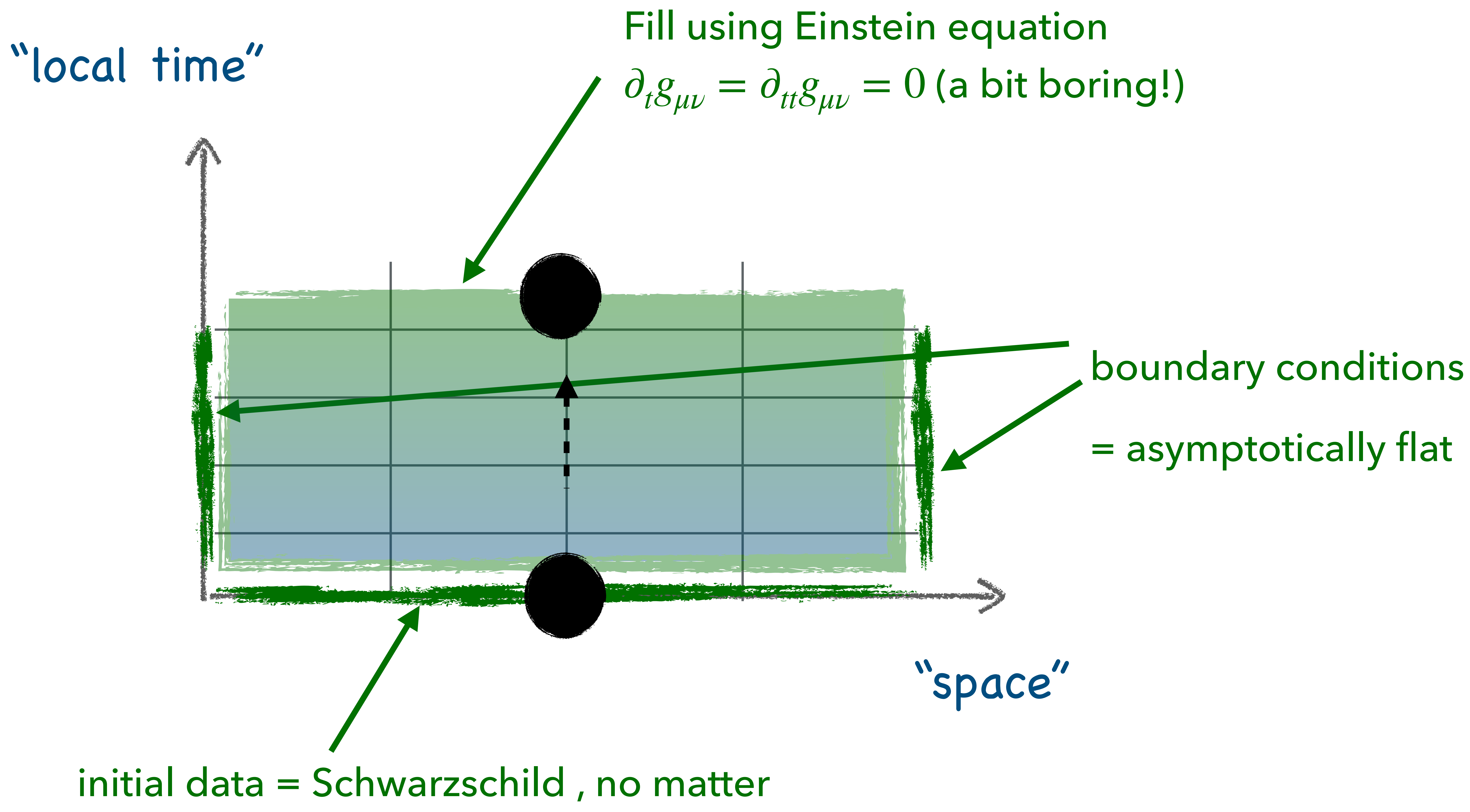
$$\nabla^a (R_{ab} - R/2 \, g_{ab}) = \nabla^a (8\pi \, T_{ab}) = 0$$

"...spacetime tells matter how to move."

What is NR?


Fill using Einstein equation $\partial_{tt} g_{\mu\nu} = f(\partial_t g_{\mu\nu}, g_{\mu\nu}, T_{\mu\nu})$
$\nabla_\mu T^{\mu\nu} = 0 \implies \partial_t T^{\mu\nu} = f(T_{\mu\nu}, g_{\mu\nu})$
"local time"
boundary conditions
$(\partial_{xx} g_{\mu\nu}, \partial_x g_{\mu\nu}, g_{\mu\nu}, T_{\mu\nu})$
"space"
initial data $(\partial_t g_{\mu\nu}, g_{\mu\nu}, T_{\mu\nu})$

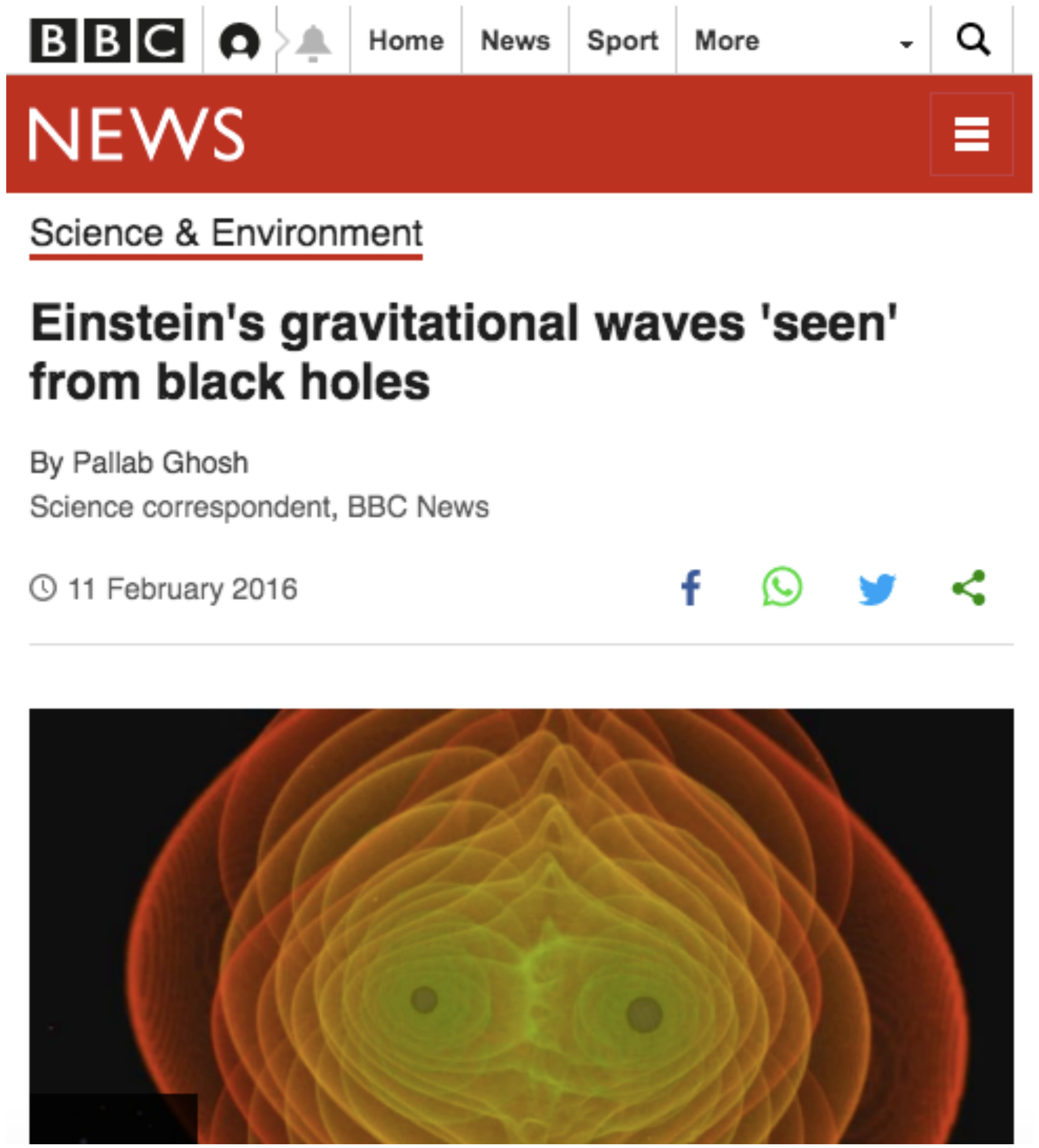
What is NR?

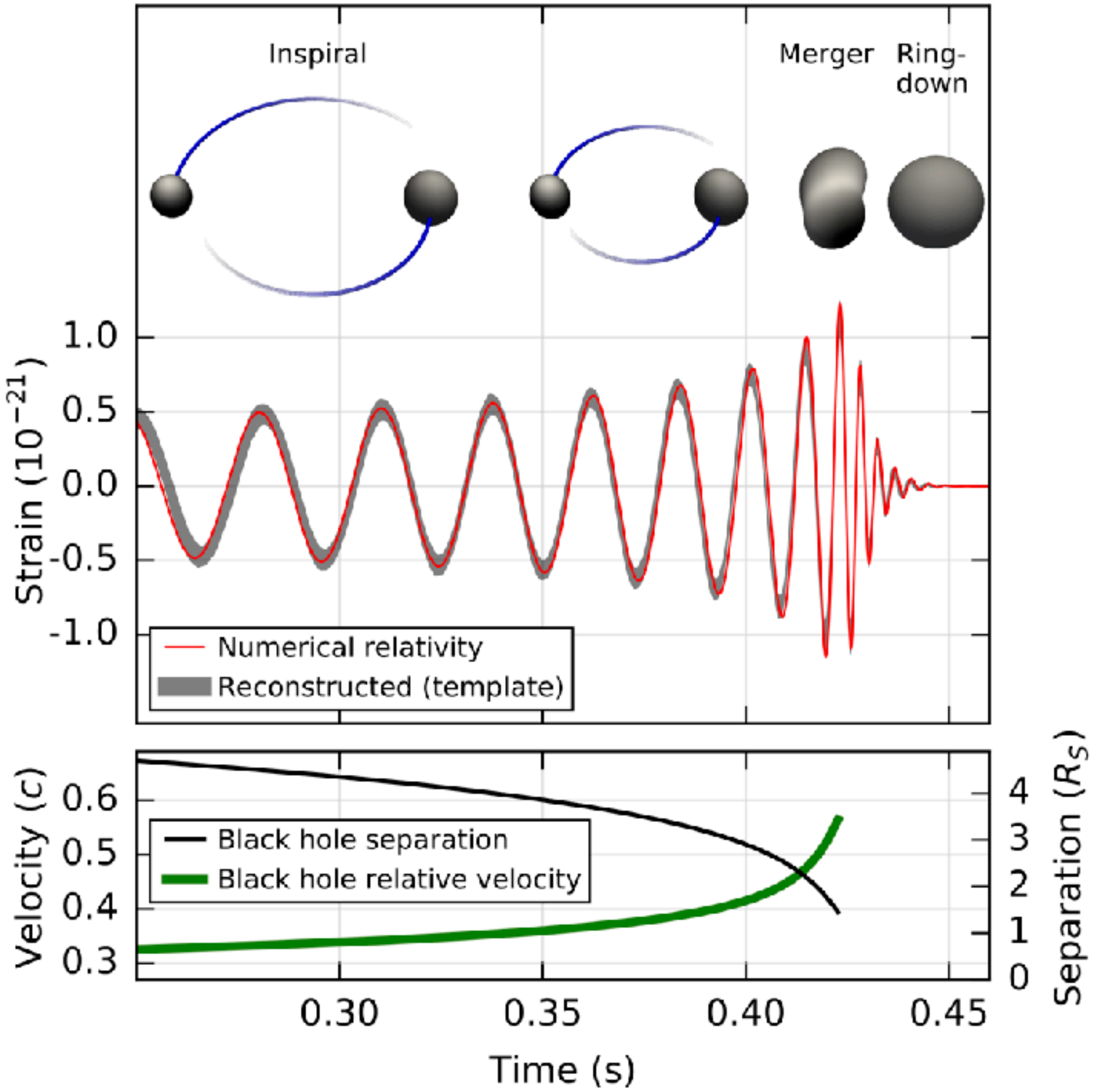


"local time"
Fill using Einstein equation
$\partial_t g_{\mu\nu} = \partial_{tt} g_{\mu\nu} = 0$ (a bit boring!)
boundary conditions
= asymptotically flat
"space"
initial data = Schwarzschild , no matter

What can it do?

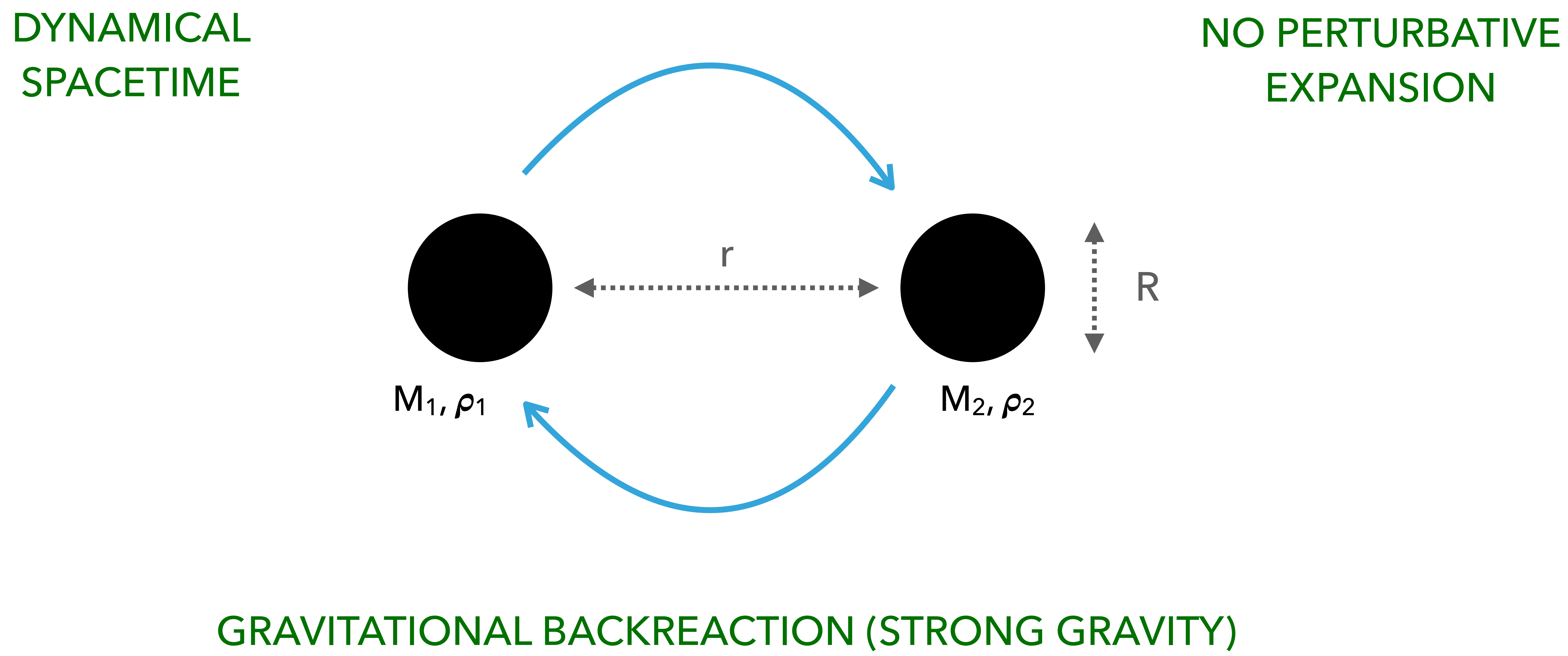
The poster child for numerical relativity is a binary black hole merger



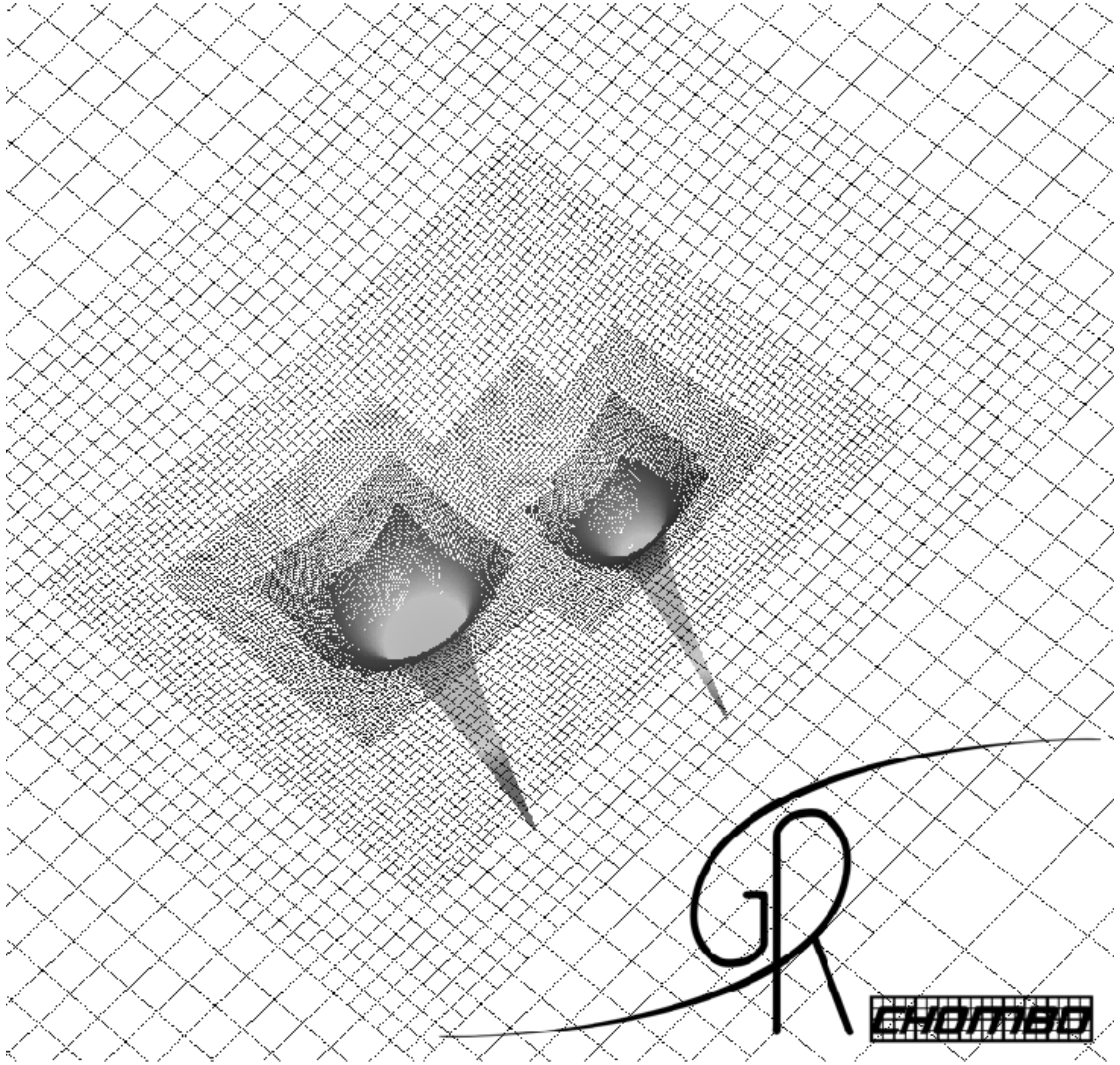


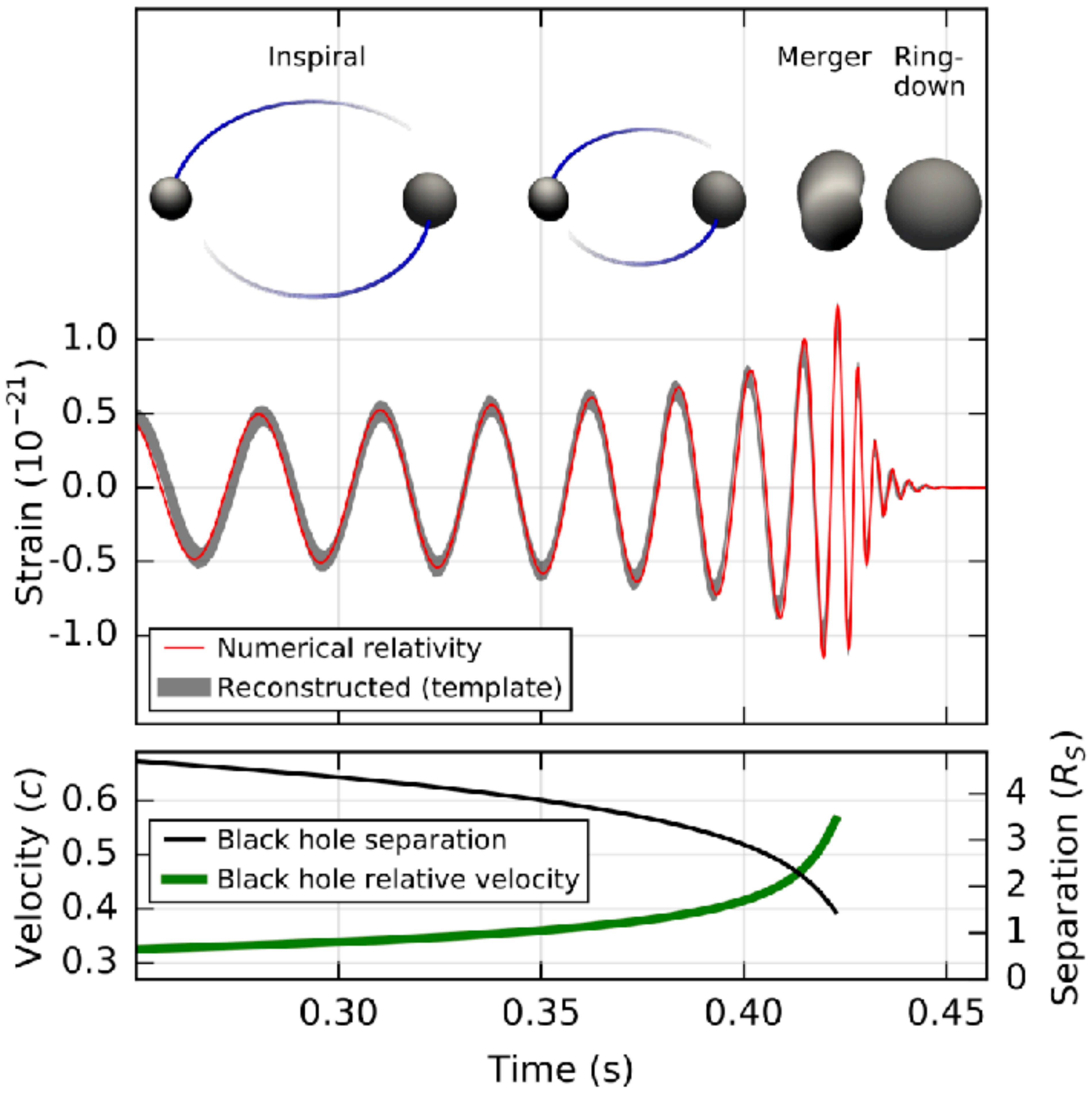
Credit: LIGO Collaboration

Why is NR necessary for the binary merger?



Numerical simulations play a key role in understanding black hole populations



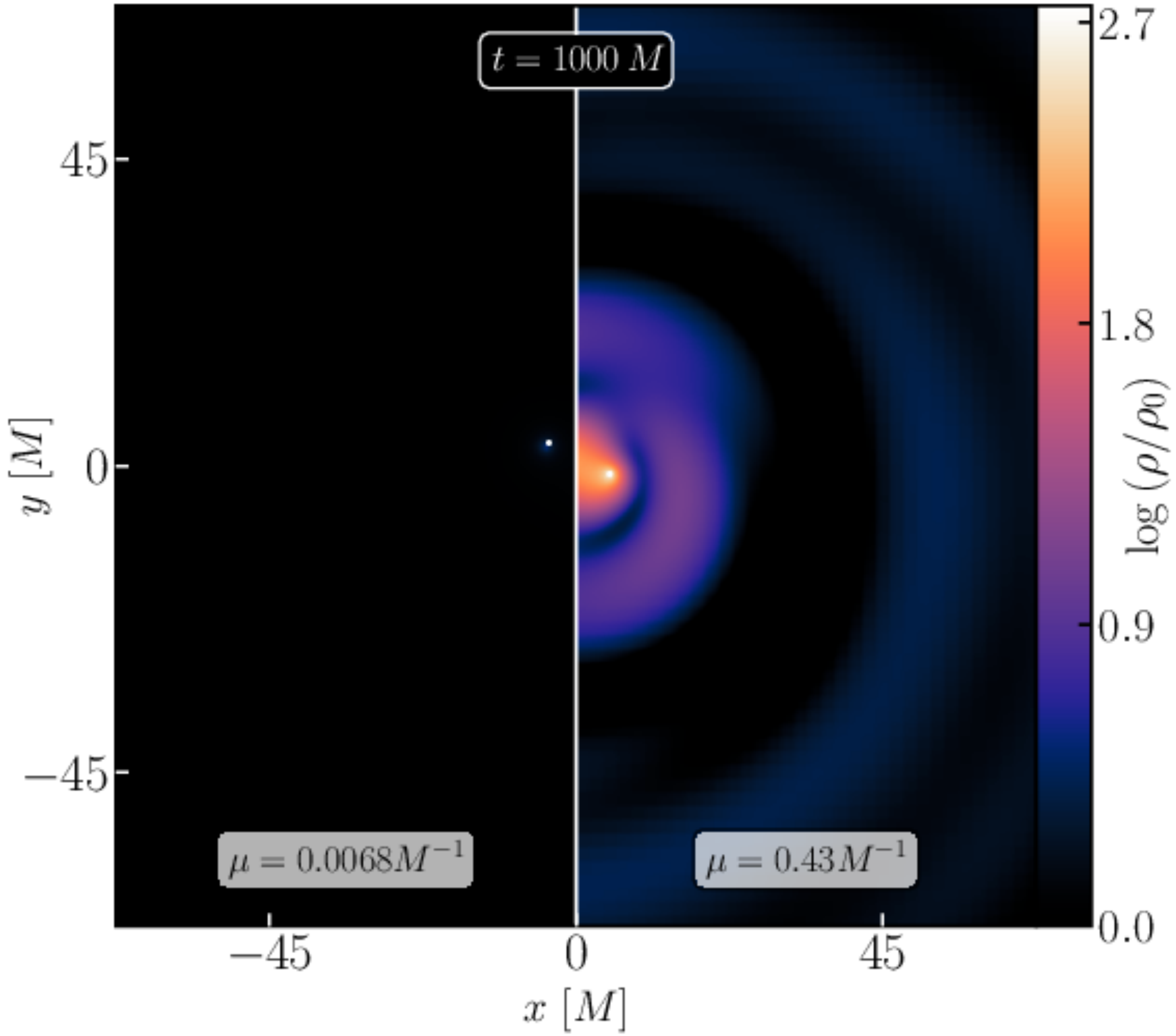


Credit: LIGO Collaboration

And maybe dark matter too

(Somewhat unexpectedly) there can be a significant enhancement of light DM around equal mass binary BHs

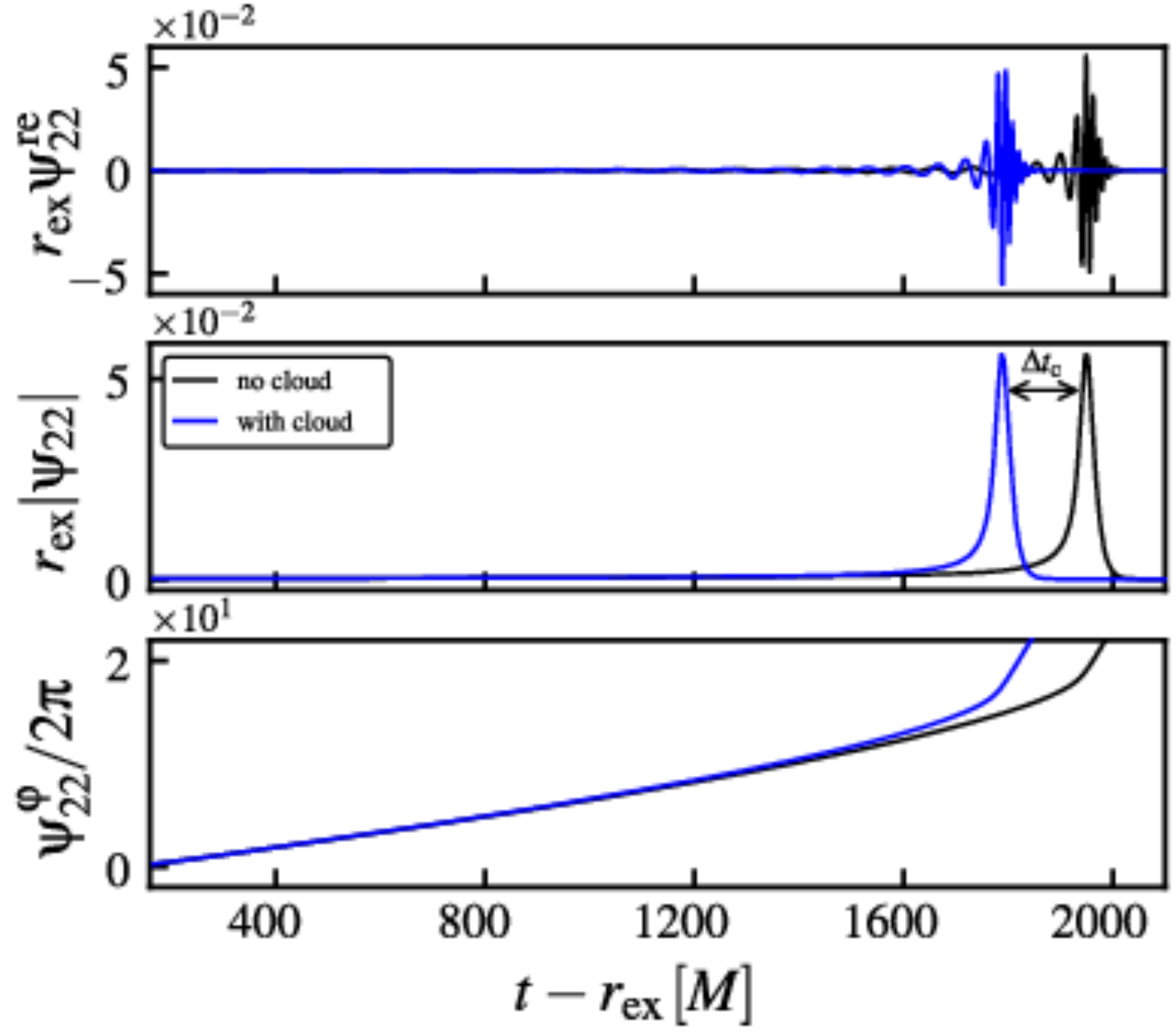
density of dark matter



J. Aurrekoetxea, KC, J Bamber, P Ferreira 2023
Phys.Rev.Lett. 132 (2024) 21, 211401

Dark matter

This can result in a significant dephasing, with potential to introduce bias in parameter estimation

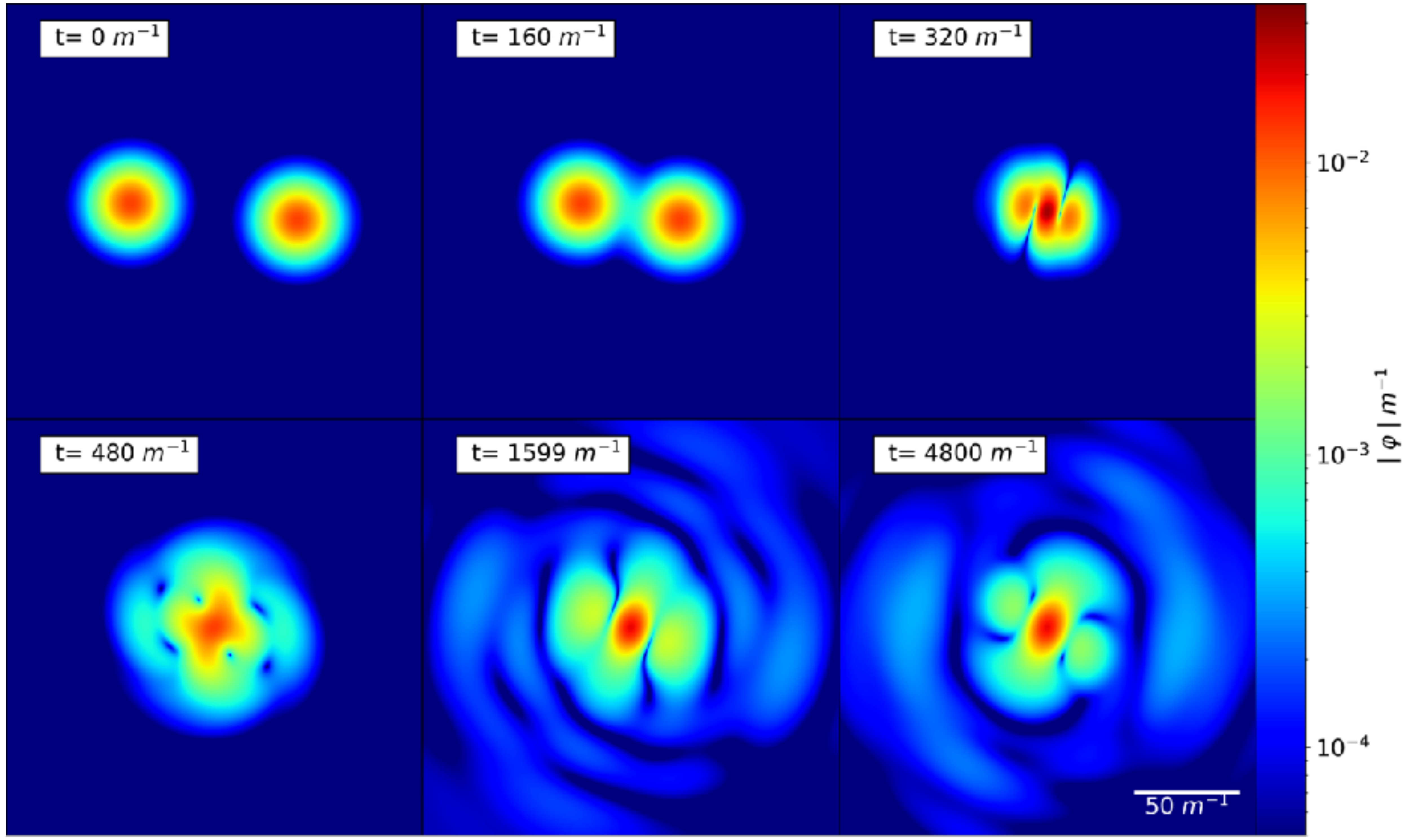


J. Aurrekoetxea, KC, J Bamber, P Ferreira 2023
Phys.Rev.Lett. 132 (2024) 21, 211401

Which may include exotic compact objects

Our understanding of the potential to miss or mischaracterise these signals is improving

density of dark matter



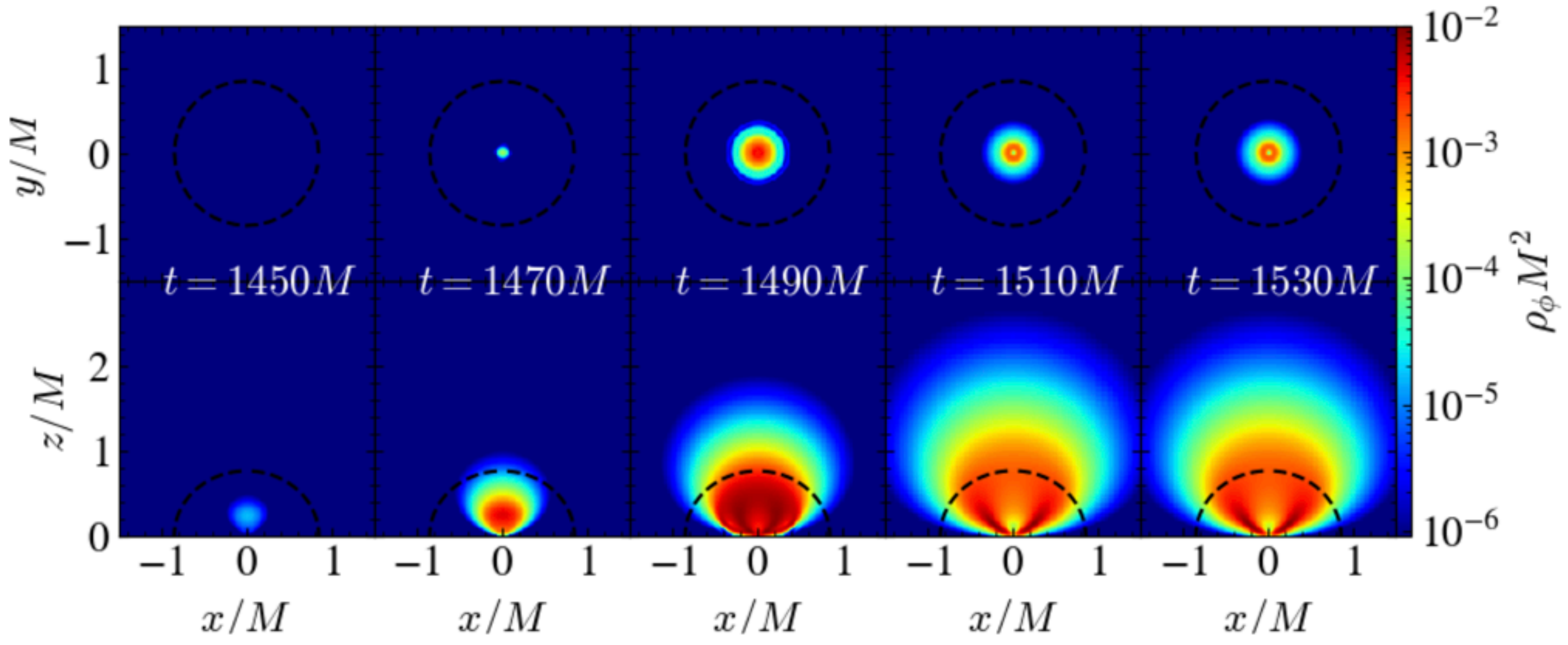
R Croft, T Helfer, B Ge, M Radia, T Evstafyeva, E Lim, U Sperhake, KC
Class.Quant.Grav. 40 (2023) 6, 065001

See in particular:
Tamara Evstafyeva et. al.. *Phys.Rev.Lett.* 133 (2024) 13, 131401
Nils Siemonsen *Phys.Rev.Lett.* 133 (2024) 3, 031401

Also modified gravity

(Somewhat unexpectedly) we are able to simulate beyond GR theories (well posed formulations can be found)

density/curvature contribution of additional gravitational scalar



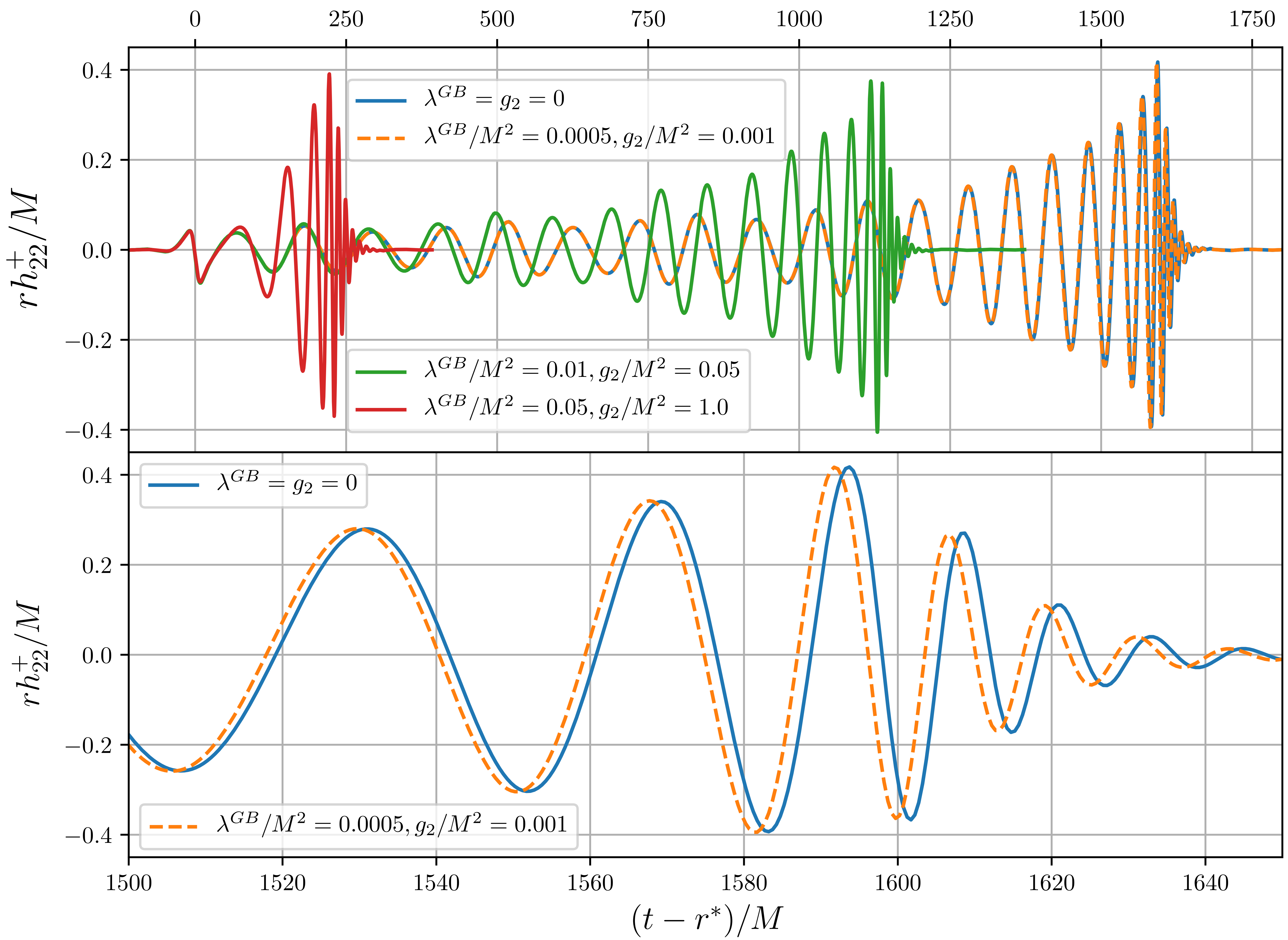
L Areste Salo, KC, P Figueras 2022
Phys.Rev.Lett. 129 (2022) 26, 261104

See in particular: P Figueras, A Held, A Kovacs 2022
Well-posed initial value formulation of general effective field theories of gravity
gr-qc 2407.08775

Modified gravity

Simulations in the early phases of testing and development, but dephasing also has the potential to create systematic bias

gravitational waves



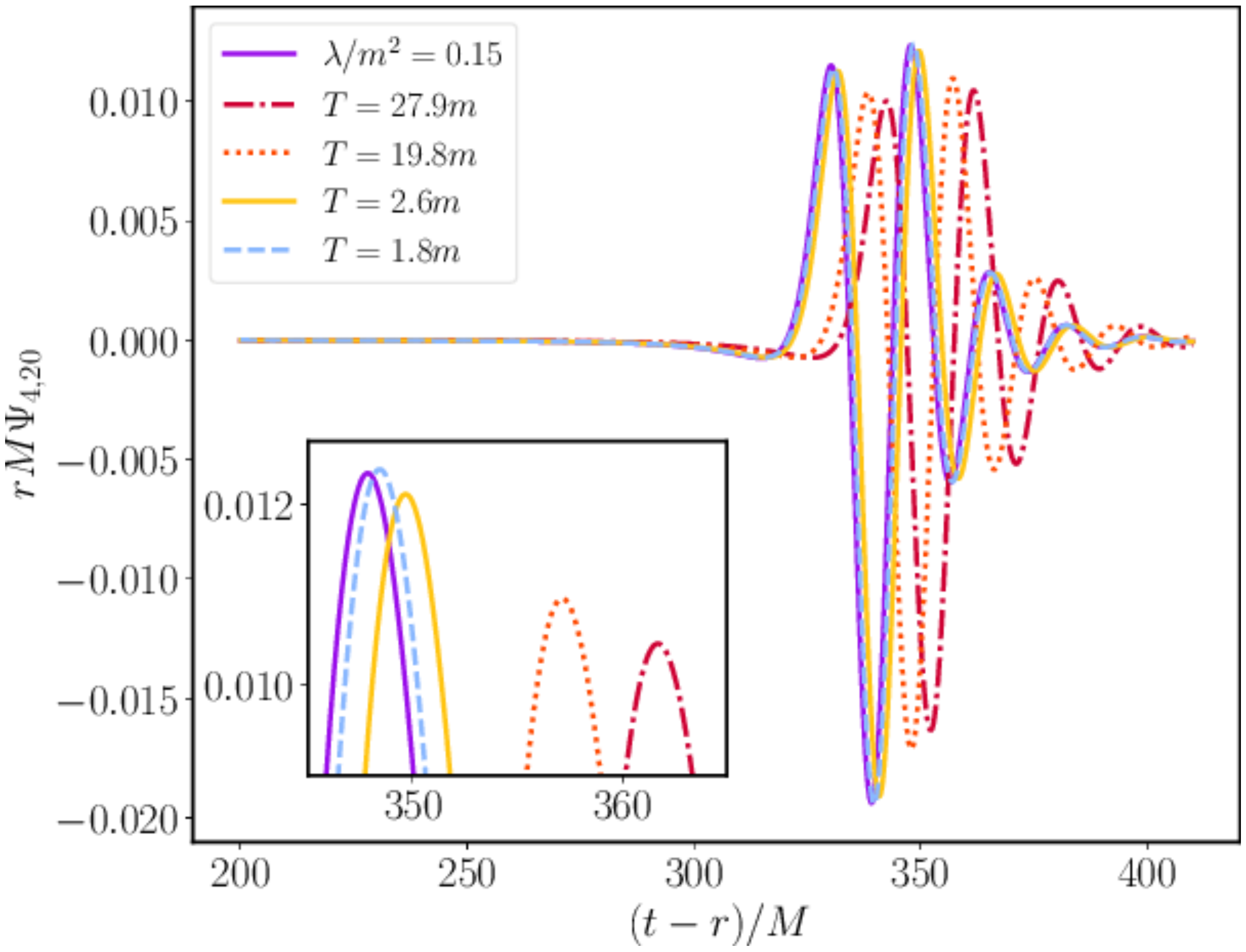
L Areste Salo, KC, P Figueras 2022

Phys.Rev.Lett. 129 (2022) 26, 261104

Modified gravity

Simulations in the early phases of testing and development, but dephasing also has the potential to create systematic bias

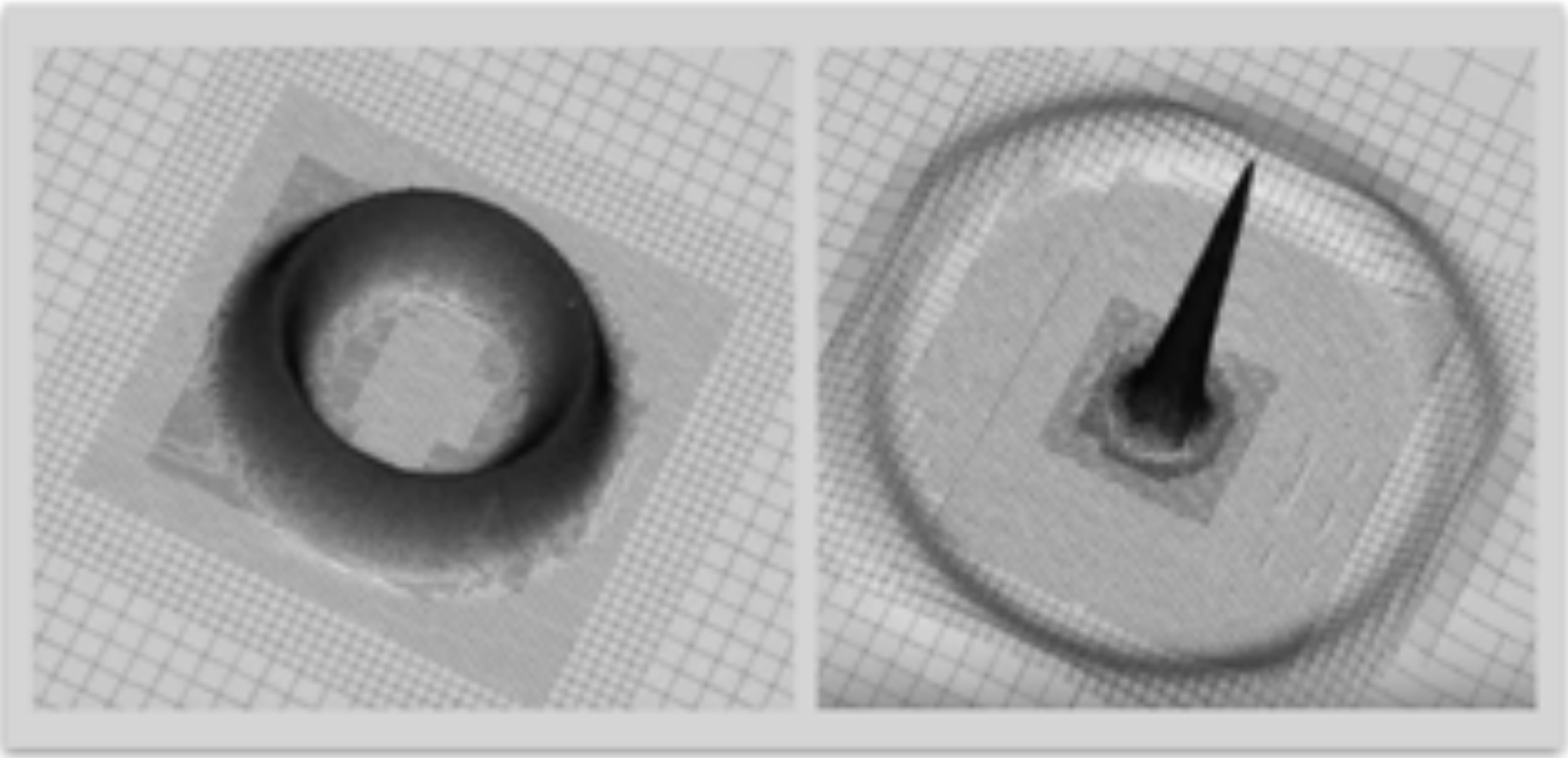
gravitational waves

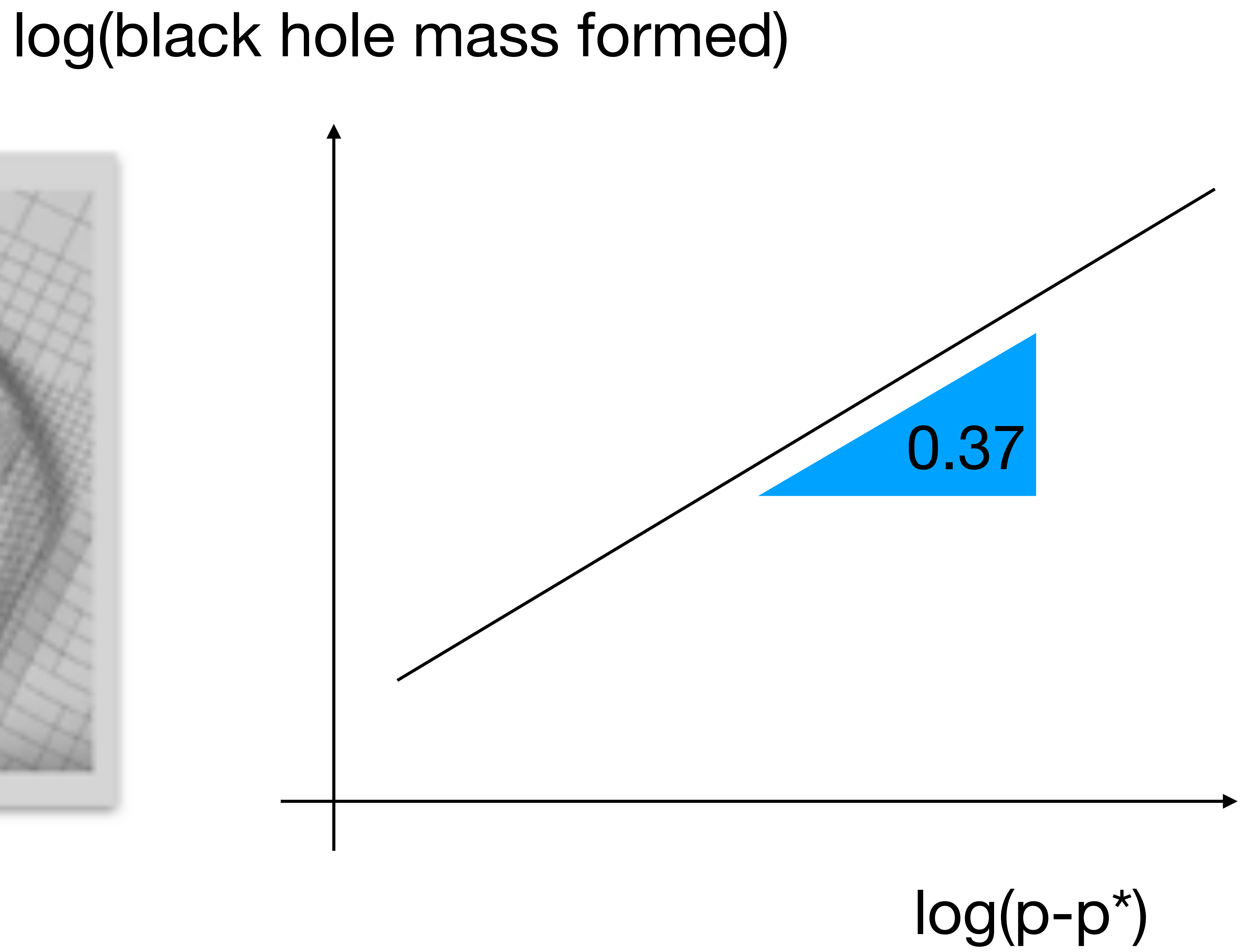


Maxence Corman, Luis Lehner, William E. East, Guillaume Dideron
Phys.Rev.D 110 (2024) 8, 084048

But numerical relativity is not just for gravitational waves!

Historical precedent for using these simulations as “numerical experiments” in strong gravity

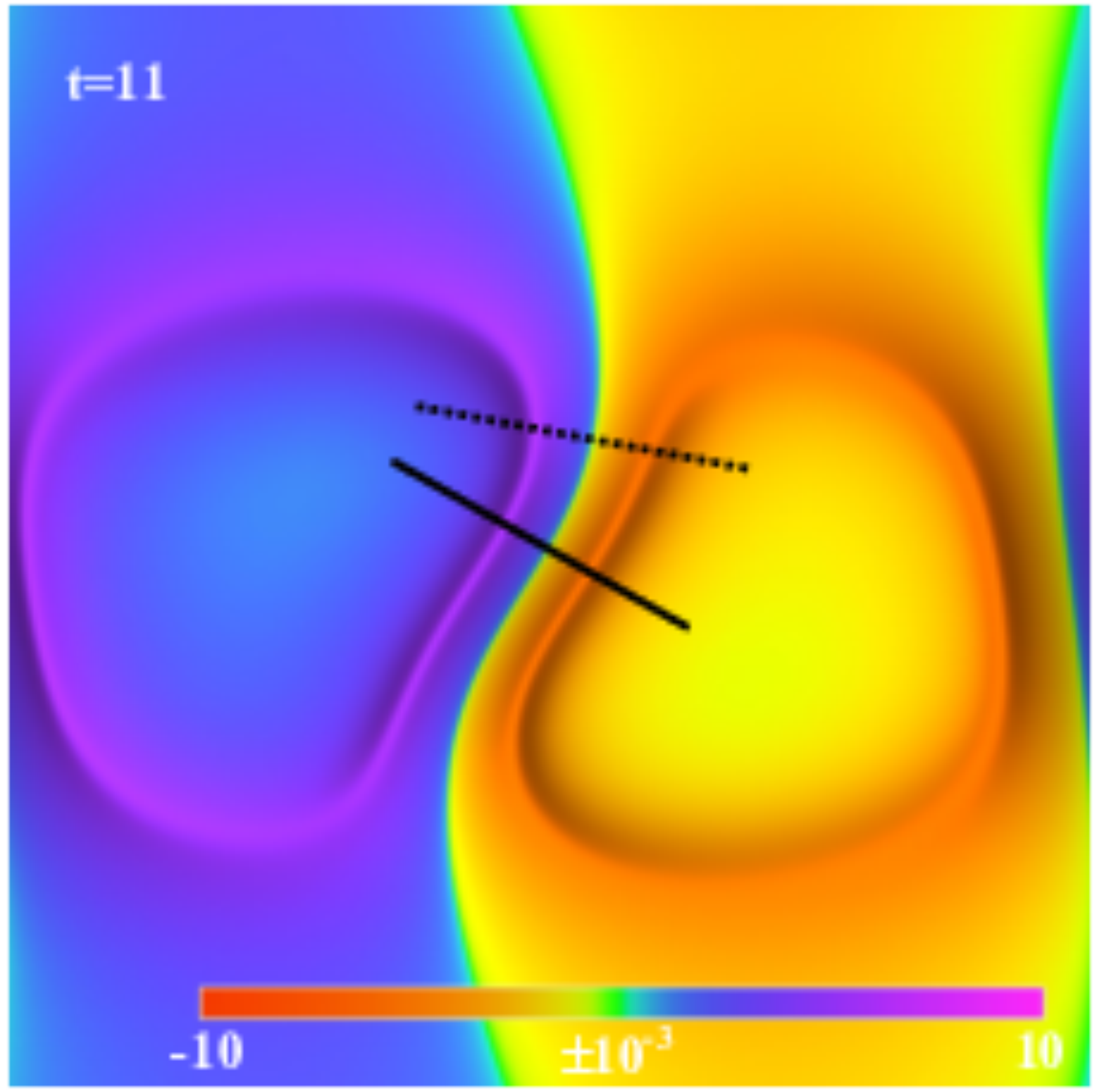




Universality and scaling in gravitational collapse of a massless scalar field
Matthew W. Choptuik
Phys.Rev.Lett. 70 (1993) 9-12

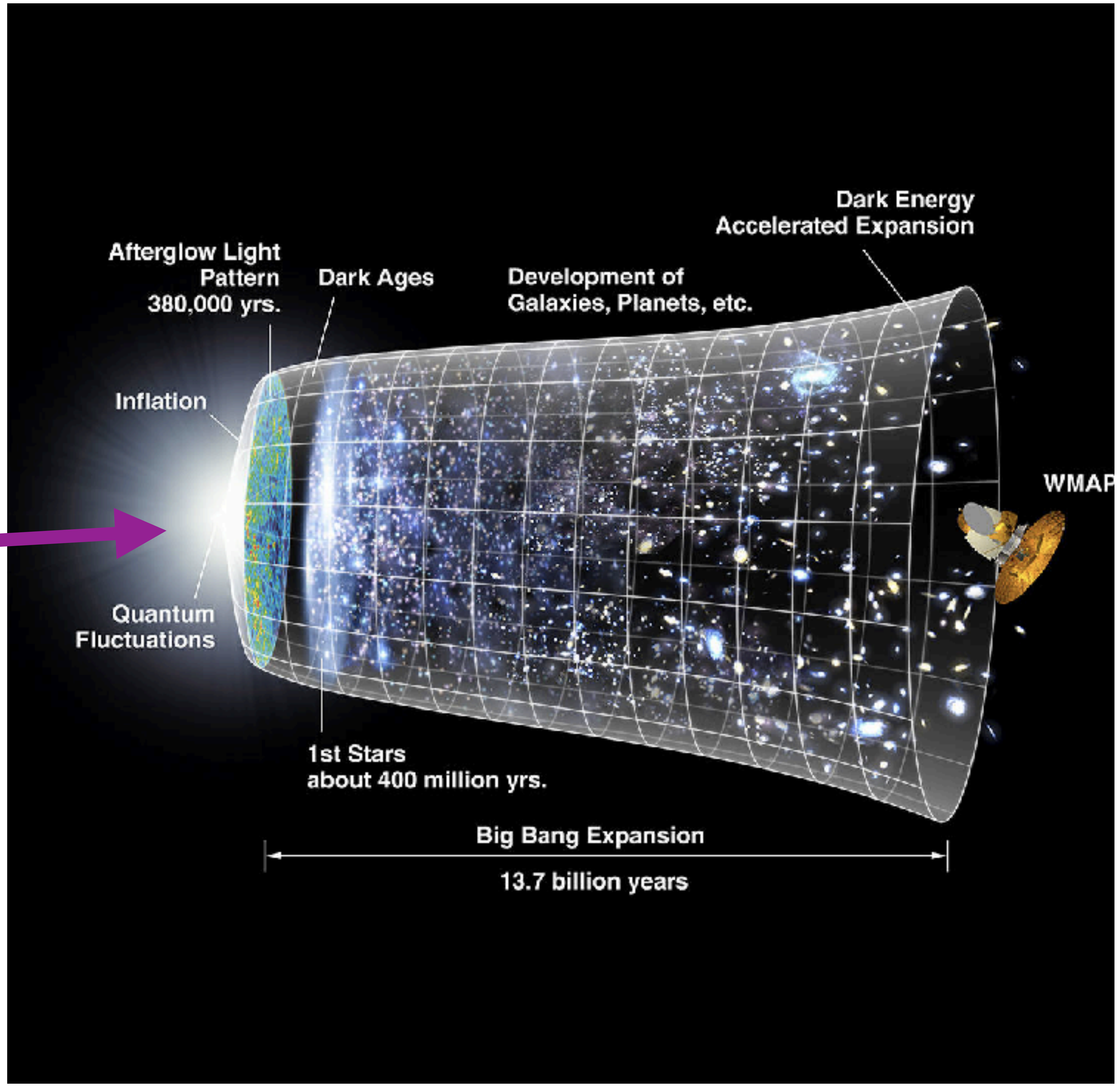
Historical precedent for using these simulations as "numerical experiments" in strong gravity

Berger, Moncrief and Garfinkle's work on the nature of BKL singularities



D. Garfinkle & F Pretorius, Spike behavior in the approach to spacetime singularities
Phys.Rev.D 102 (2020) 12, 124067

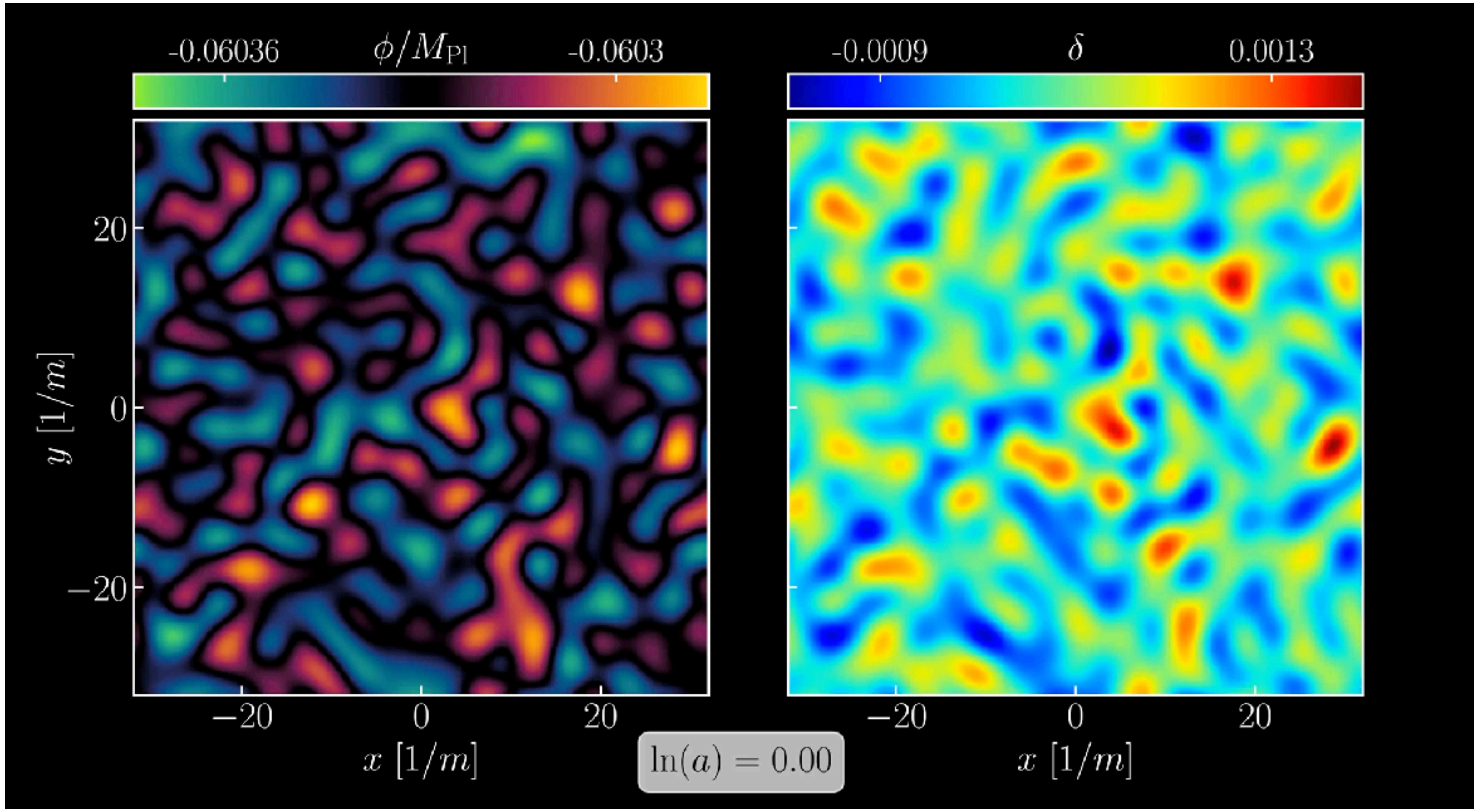
Highly relevant for the beginning of the Universe, about which we know very little



NR provides a numerical “experiment” for very inhomogeneous universes

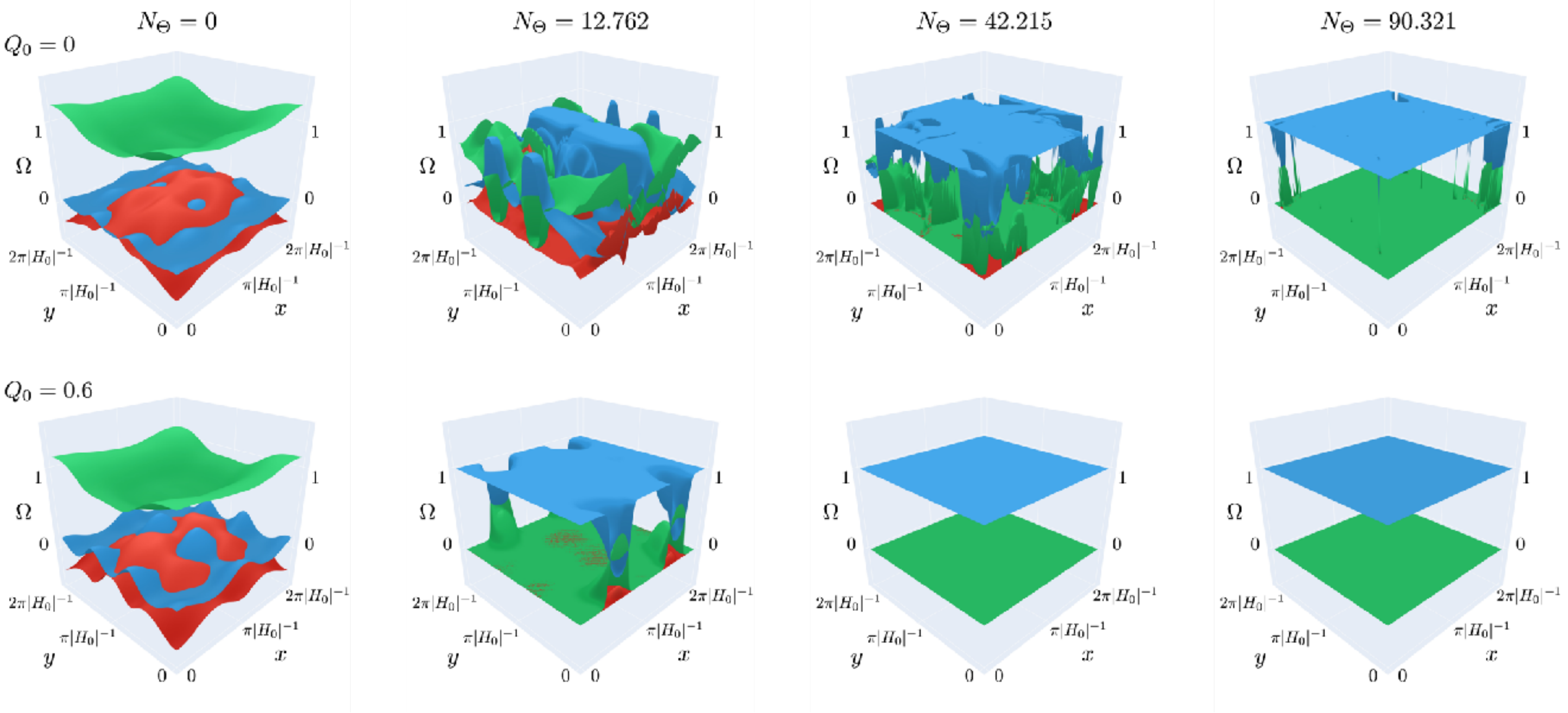
Field

Density perturbations



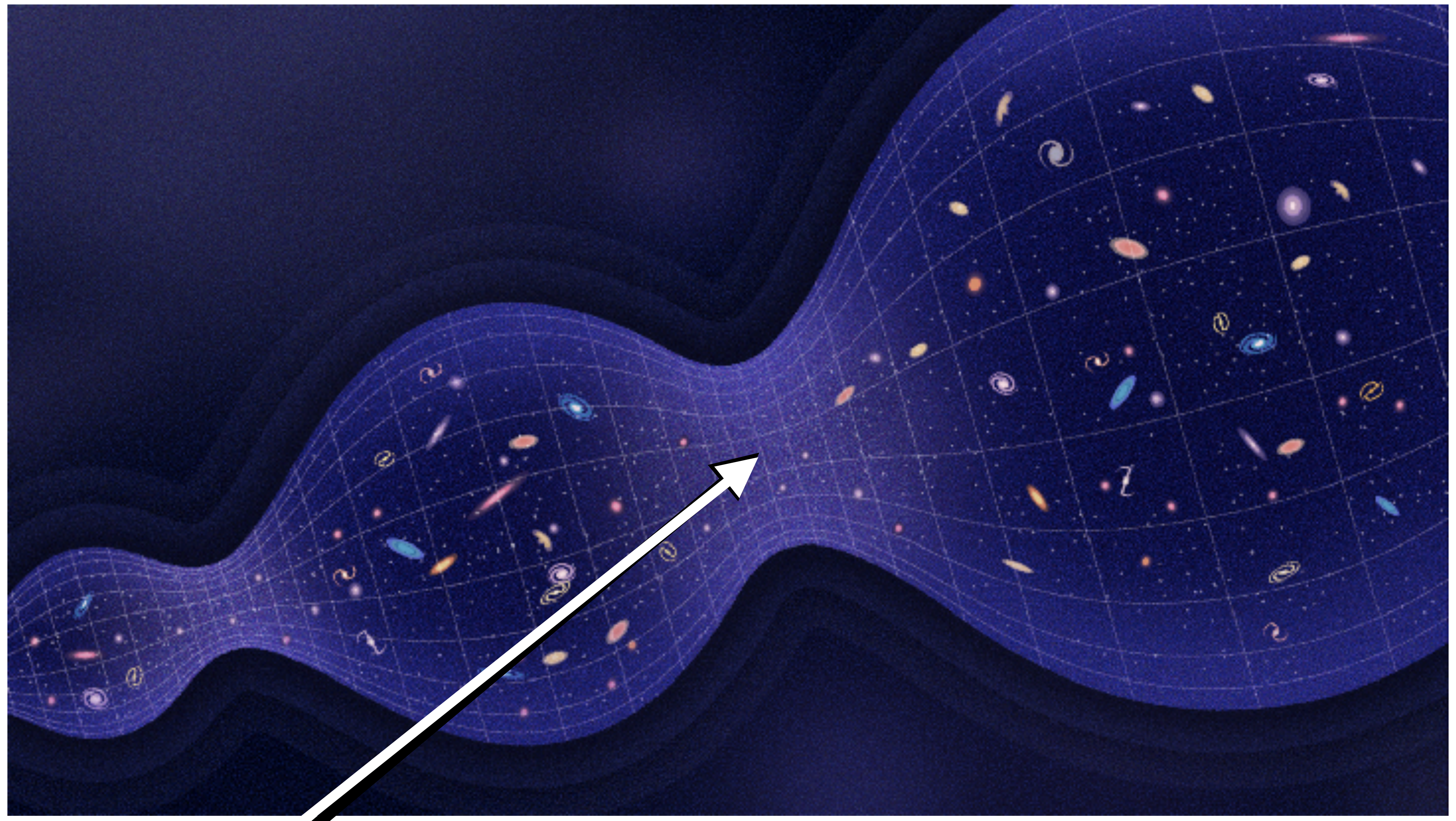
J. Aurrekoetxea, KC, F Muia
Oscillon formation during inflationary preheating with general relativity
Phys.Rev.D 108 (2023) 2, 023501

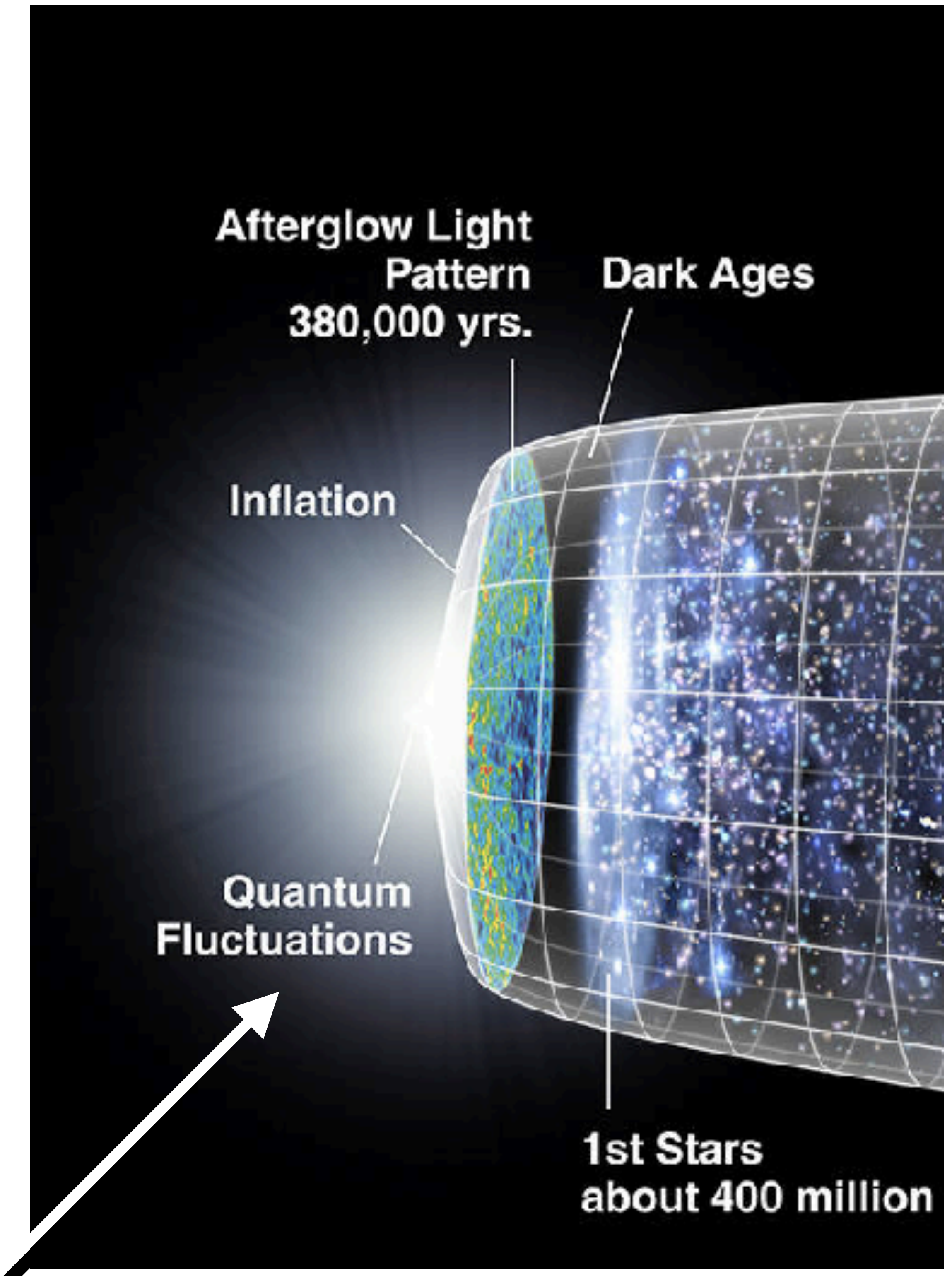
Studying bouncing cosmologies with Numerical Relativity



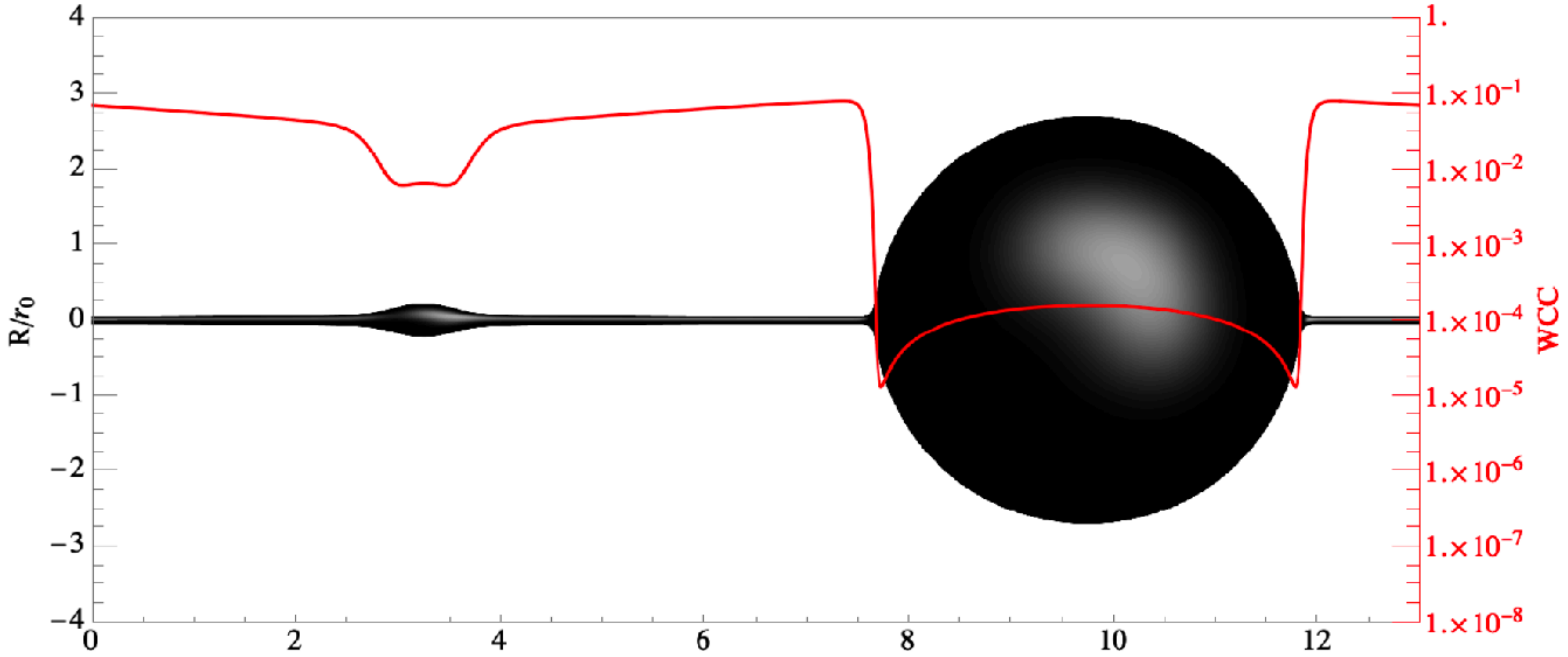
The robustness of slow contraction and the shape of the scalar field potential
Timo Kist, Anna Ijjas
JCAP 08 (2022) 08, 046

Do modifications to gravity change the story?



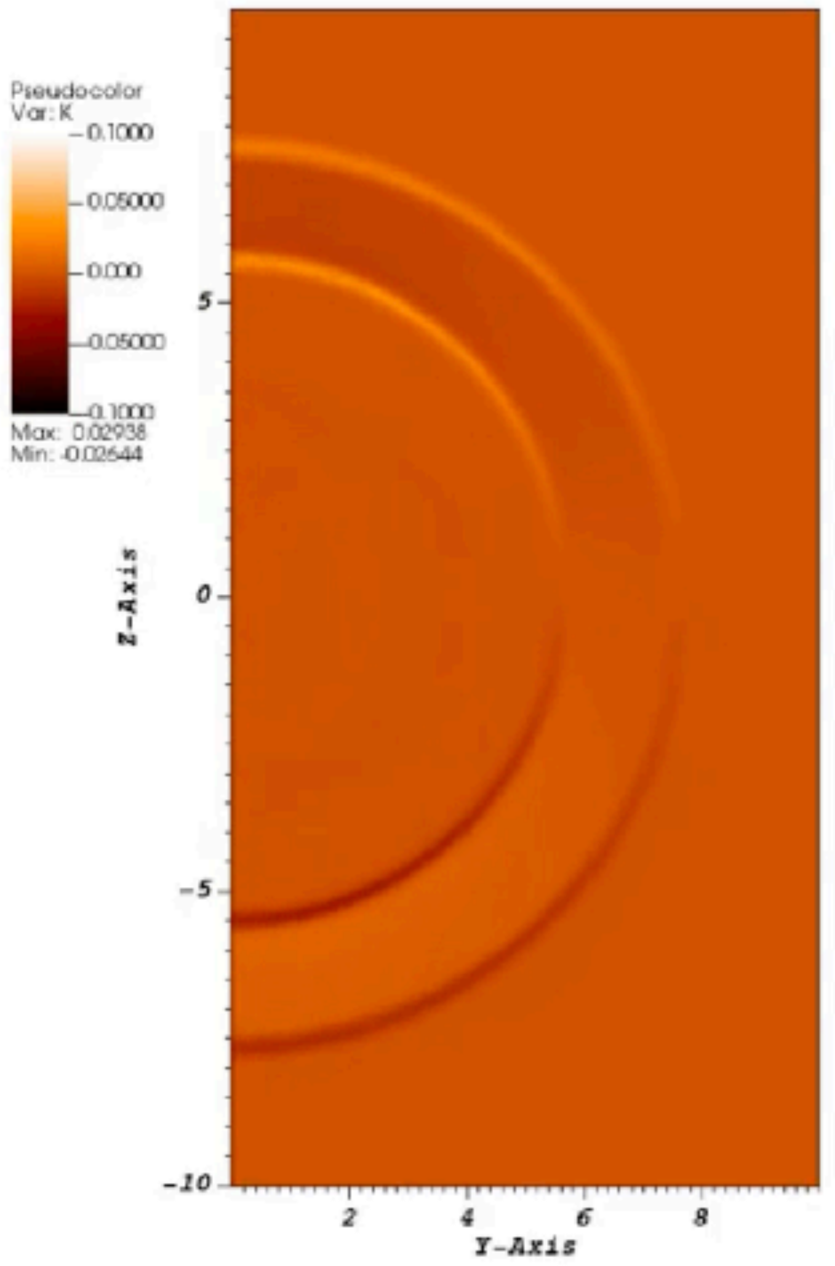


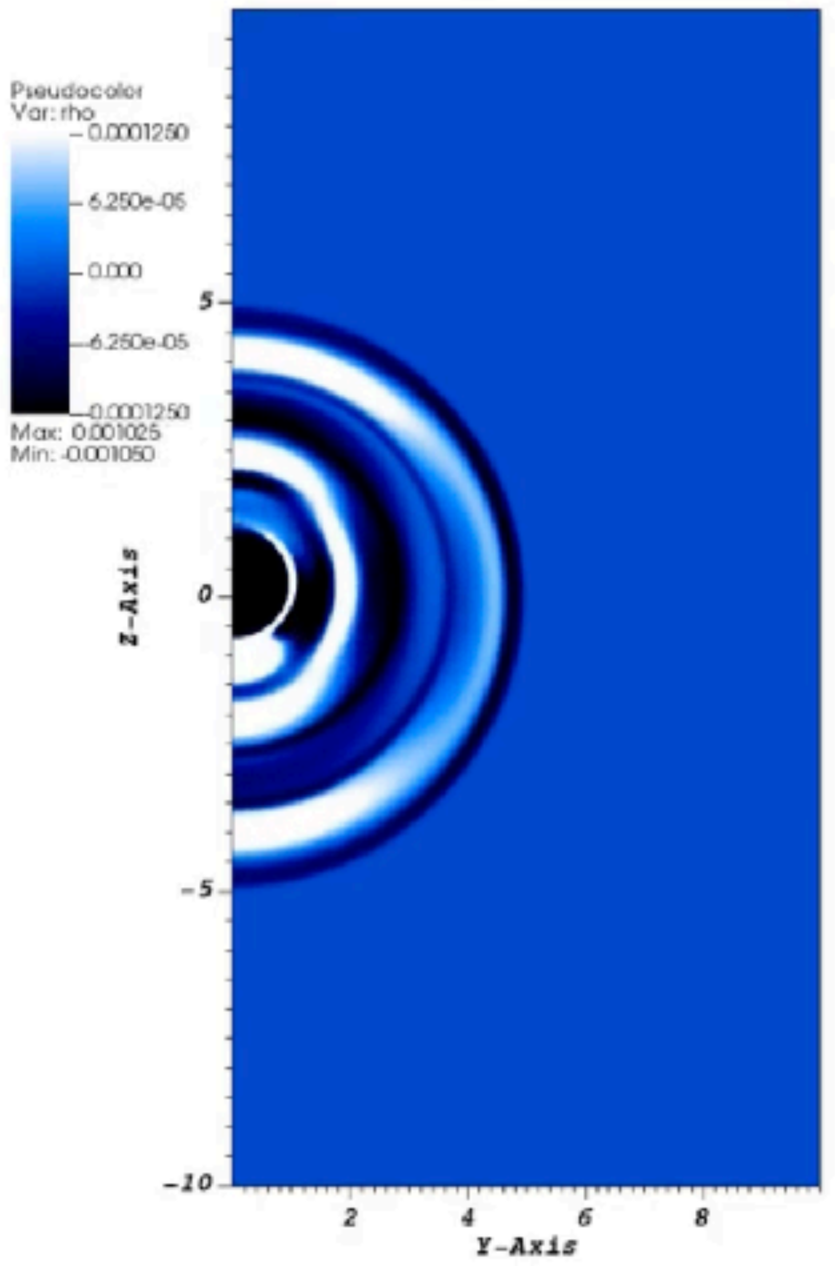
Higher dimensional spacetimes - do corrections to GR protect cosmic censorship?

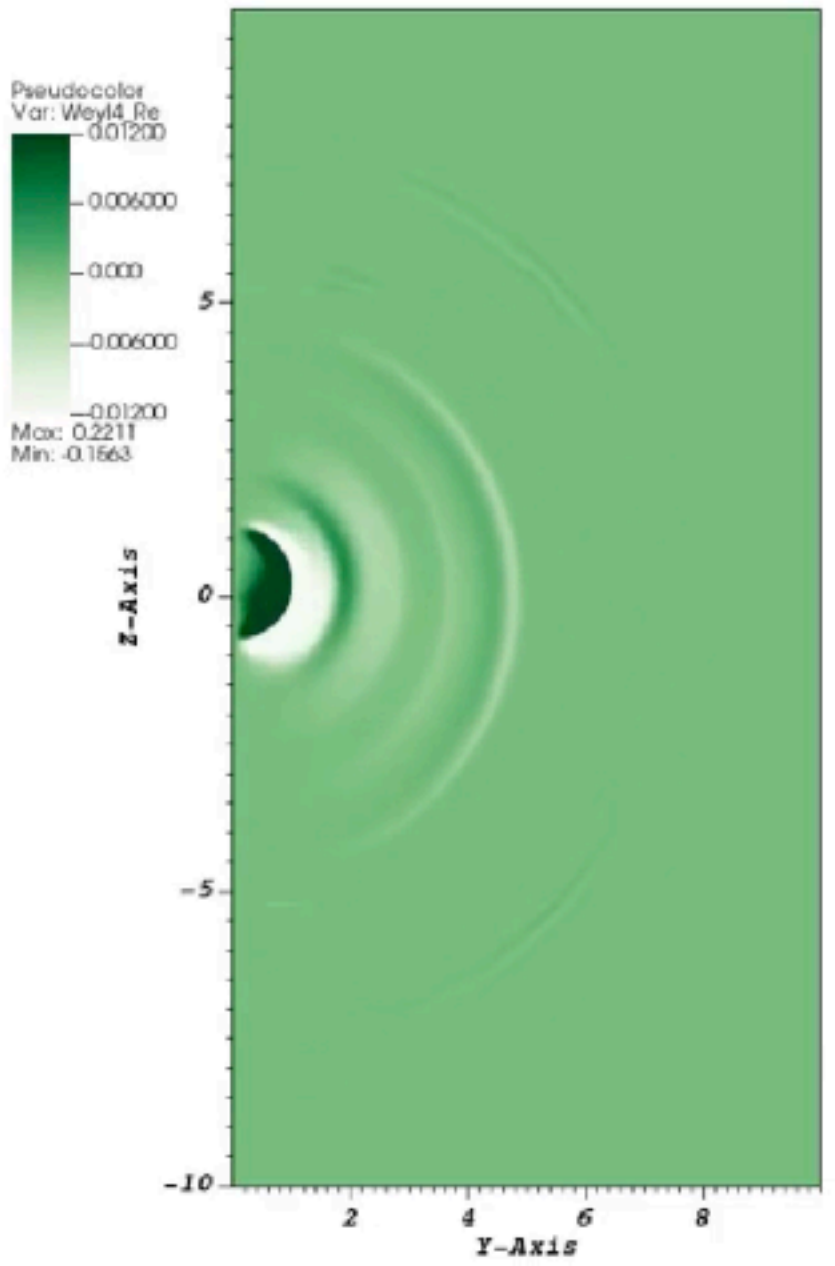


P Figueras, A Kovacs, S Yao 2024
in prep

And warp drives…?





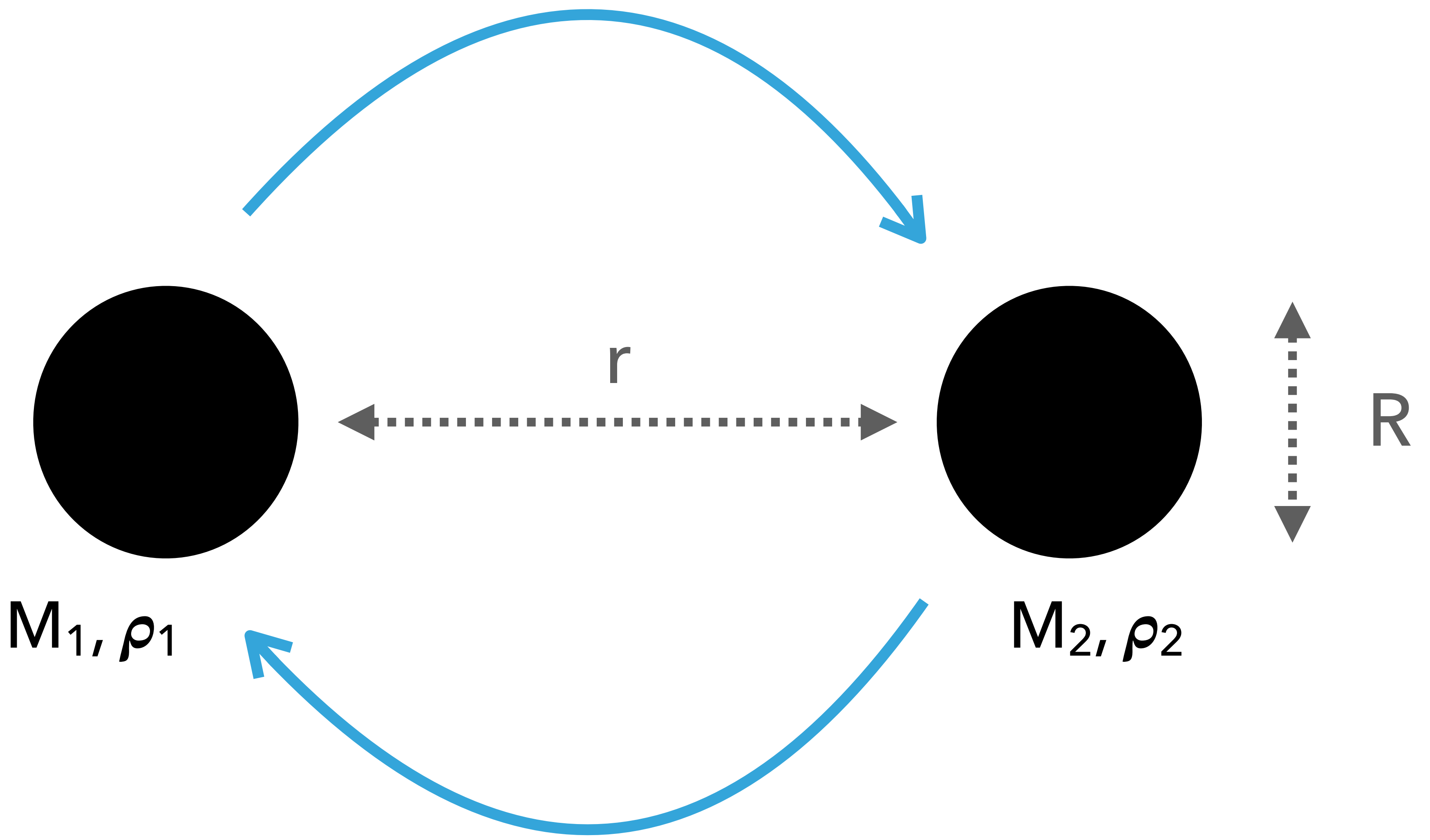


What can’t it do?

Similarity of scales is a feature and a bug

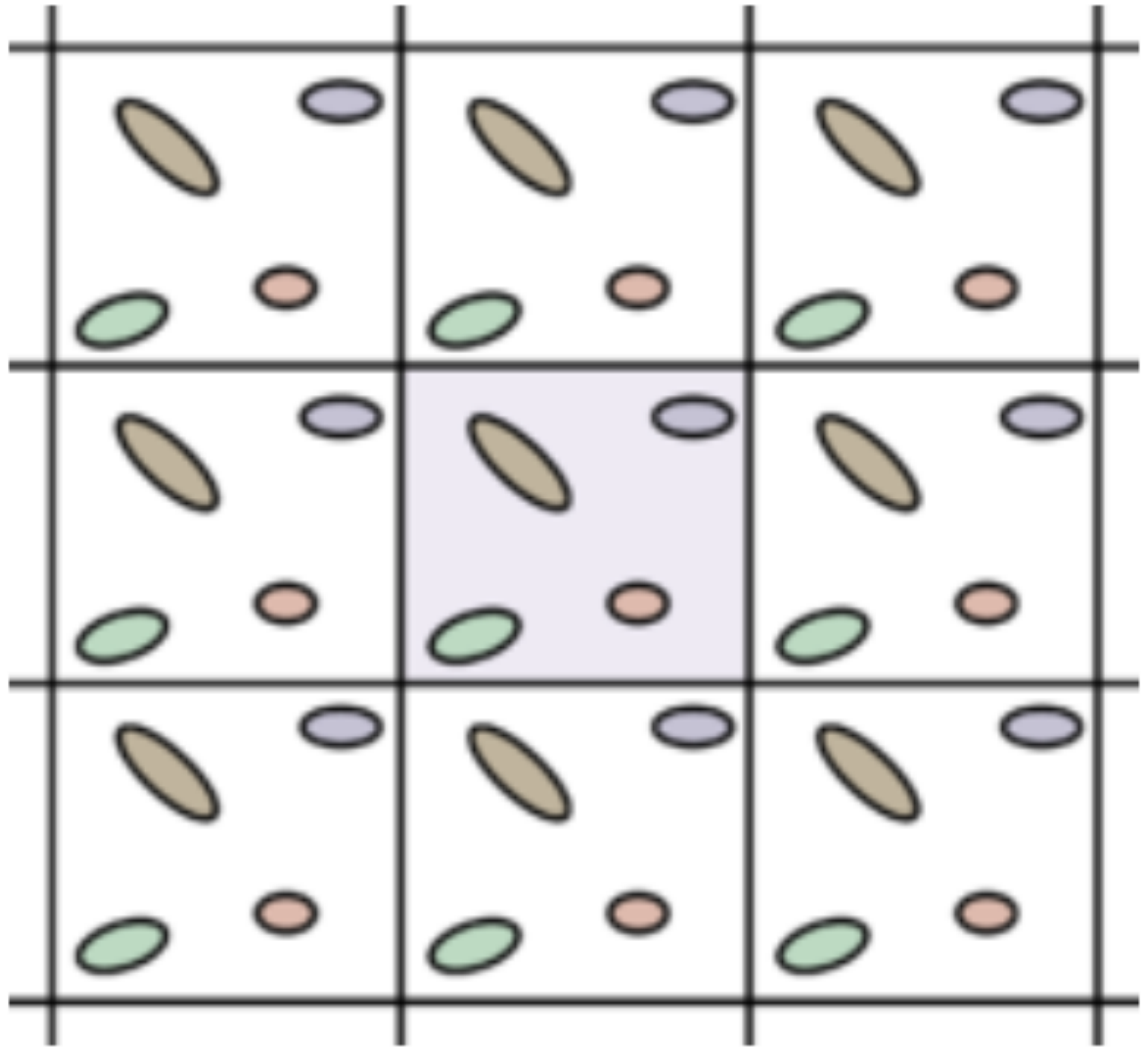
DYNAMICAL SPACETIME

NO PERTURBATIVE EXPANSION

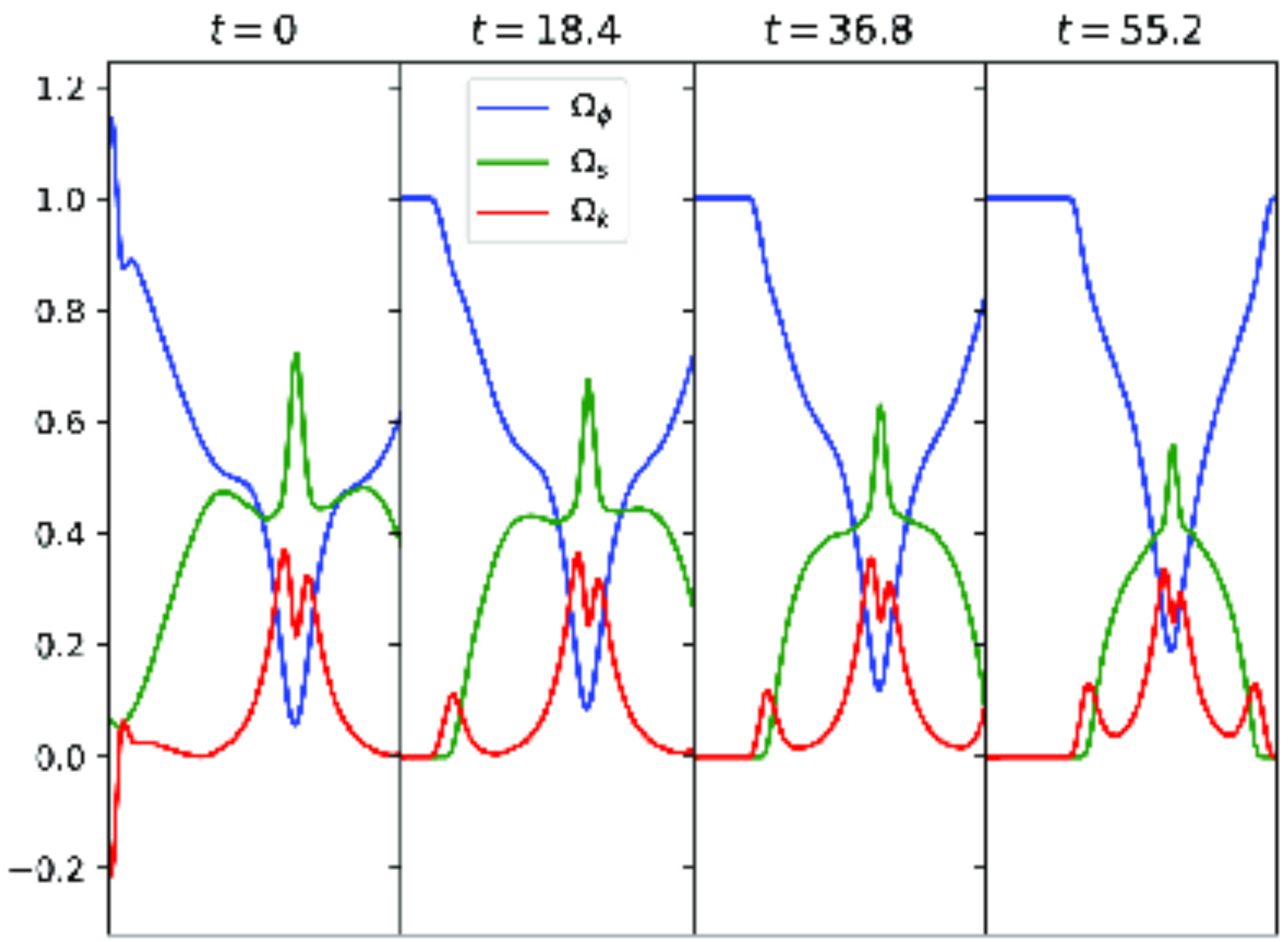


GRAVITATIONAL BACKREACTION (STRONG GRAVITY)

Finite space of simulations



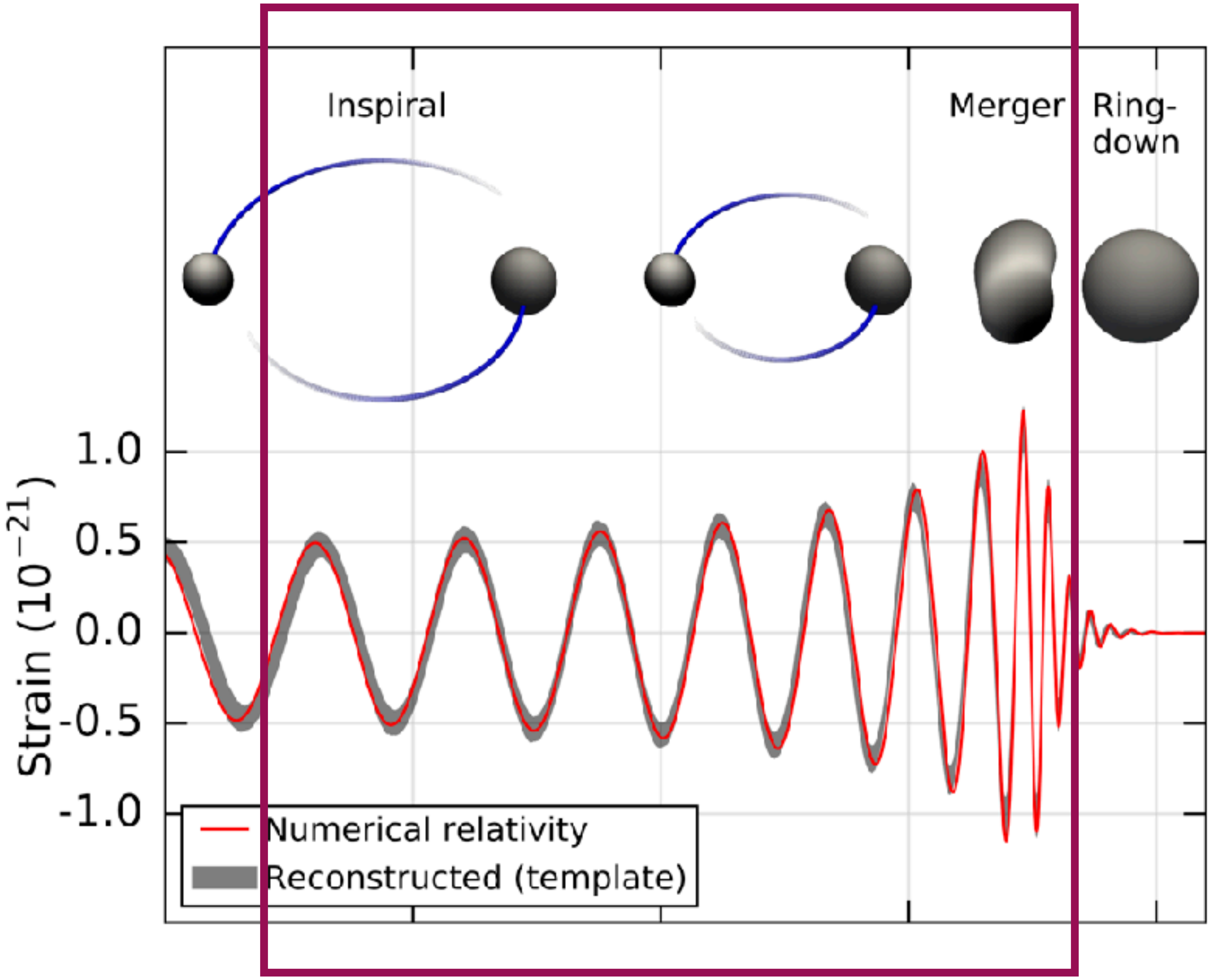
periodic boundary conditions



Initial conditions problem in cosmological inflation revisited
D. Garfinkle, A Ijjas, P Steinhardt
Phys.Lett.B 843 (2023) 138028

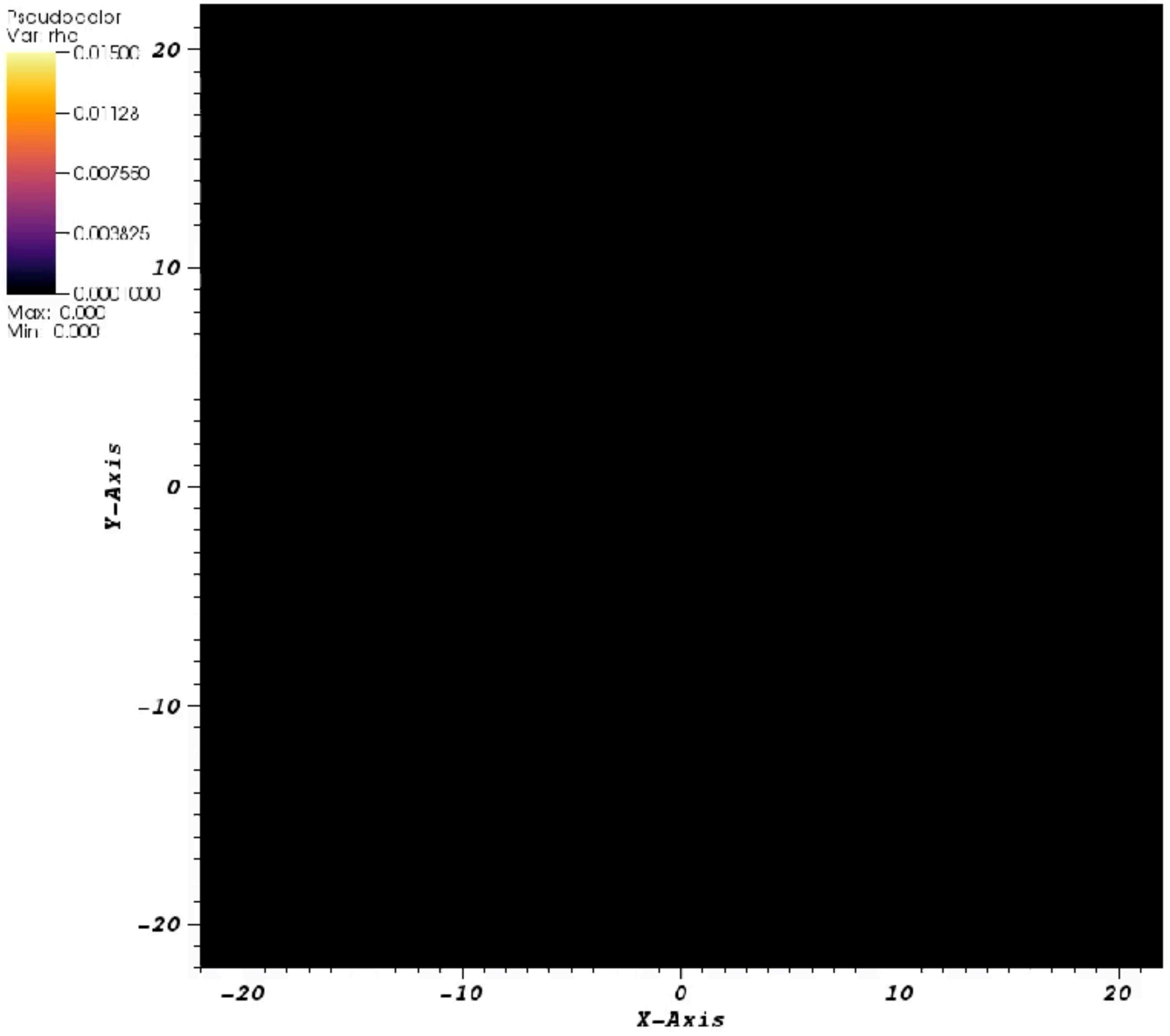
Effect on conclusions?

Finite time of simulations



Numerical relativity part

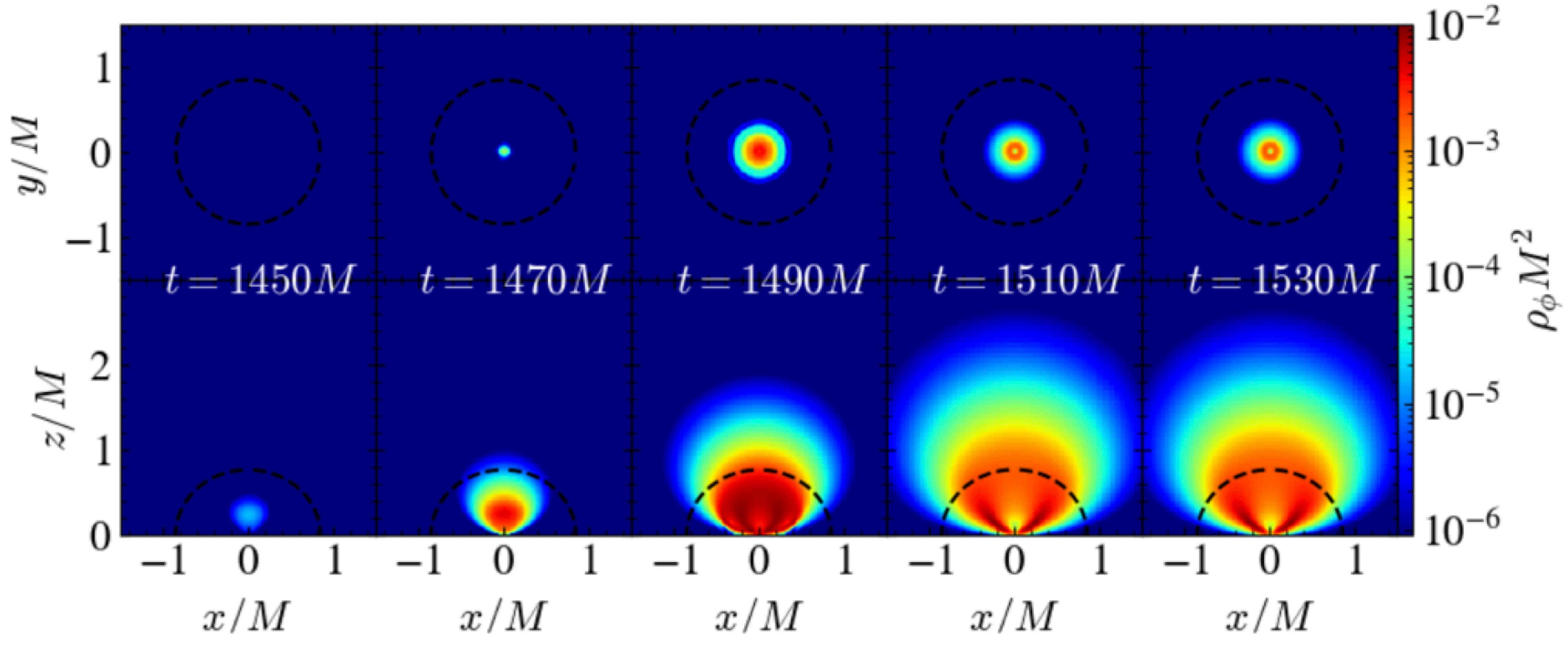
Transients can dominate over the physical effect of interest



energy density of a vector field during a superradiant phase

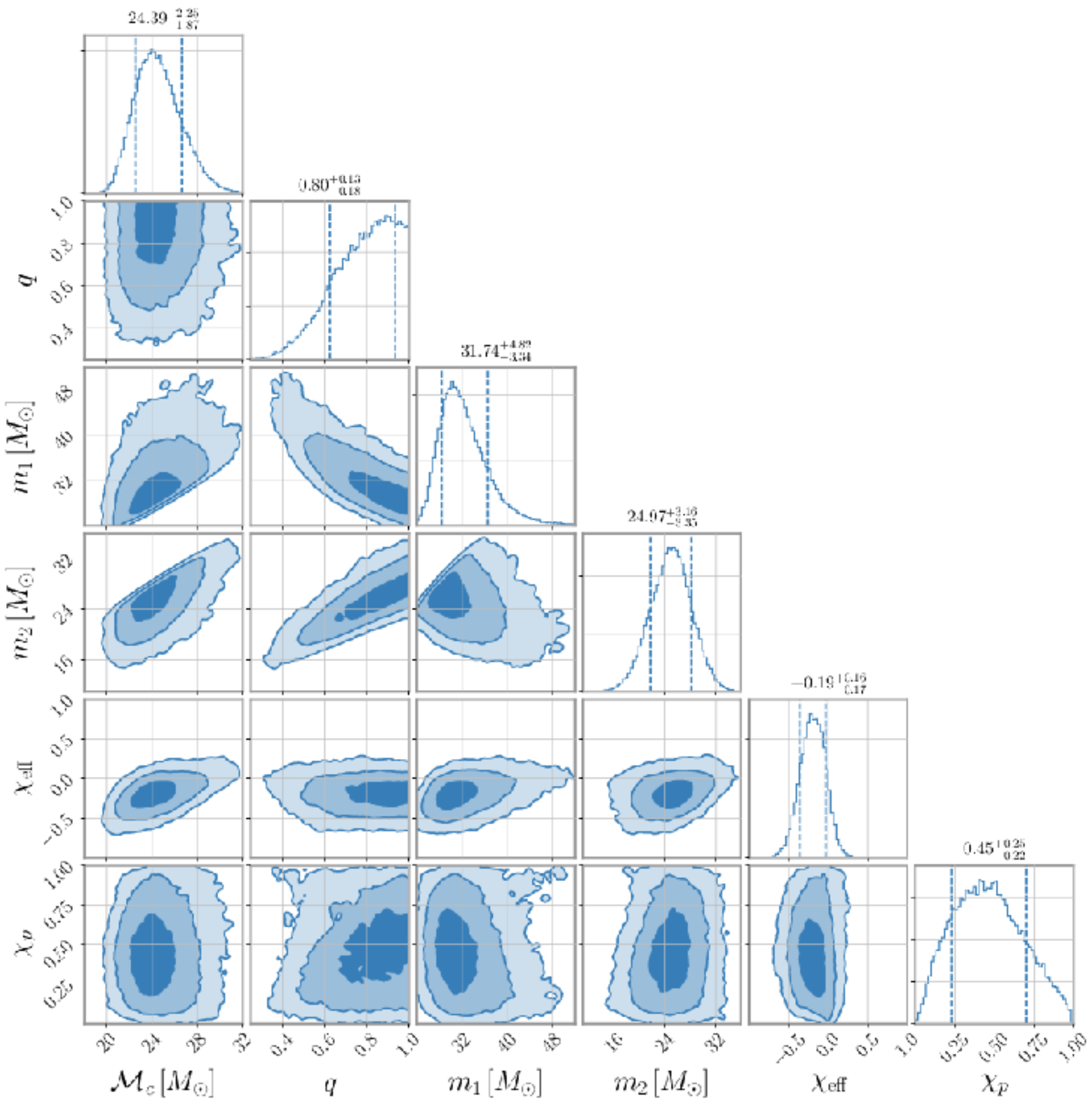
Need a well posed formulation of the equations

e.g. EsGB gravity



L Areste Salo, KC, P Figueras 2022
Phys.Rev.Lett. 129 (2022) 26, 261104

Too much parameter space?

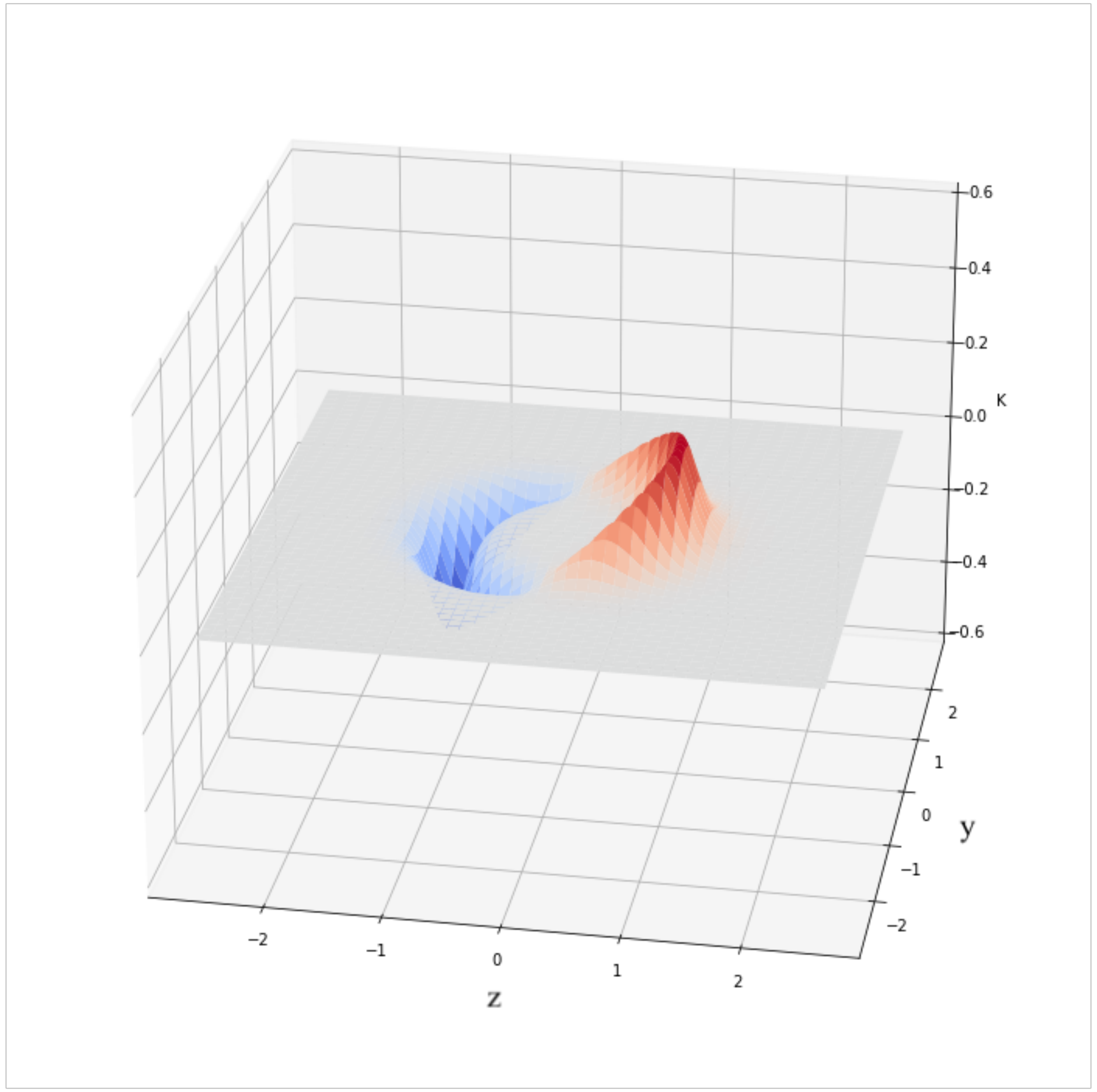


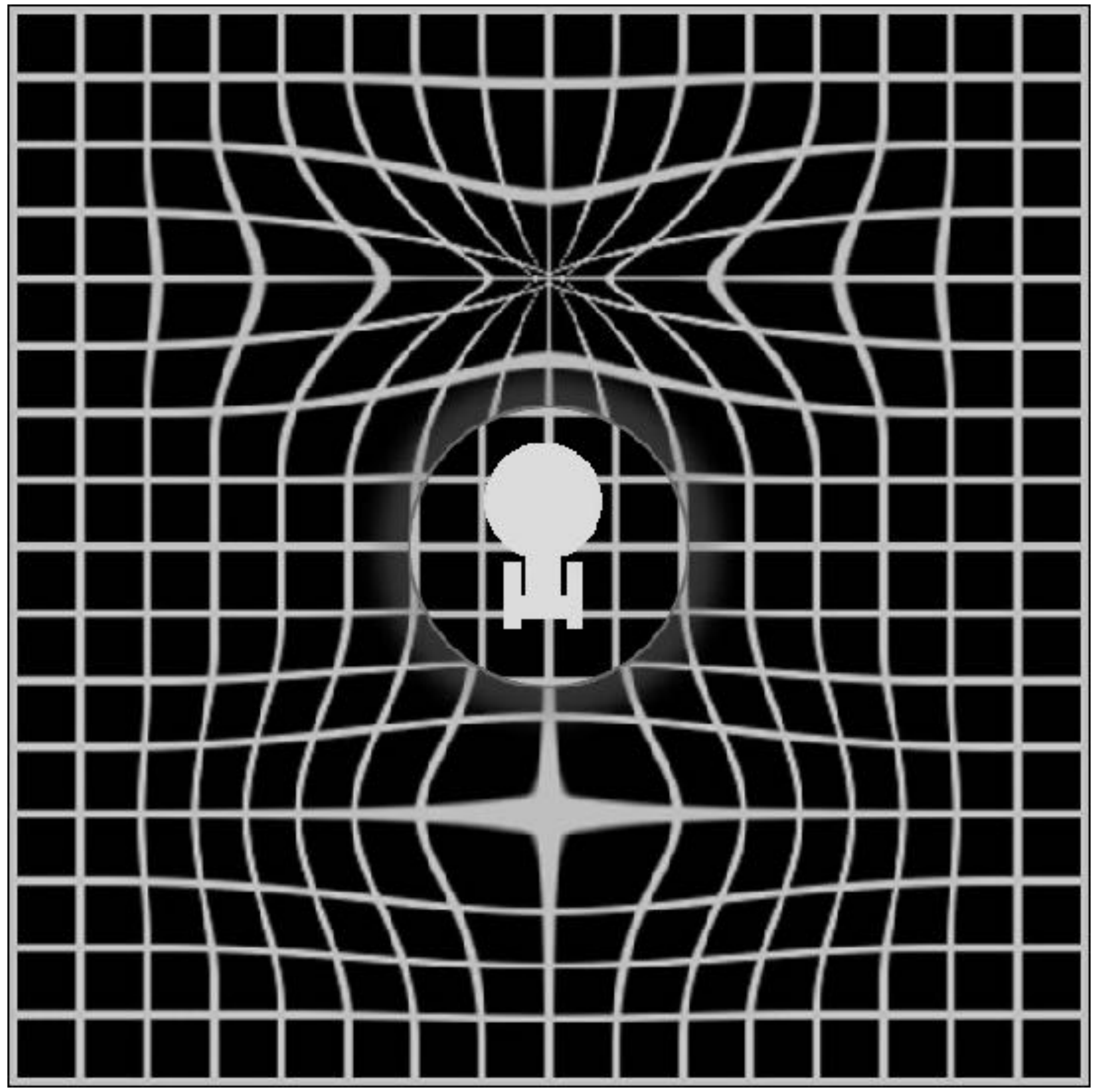
Pratten et. al. 2021
Assessing gravitational-wave binary black hole candidates with Bayesian odds

+ additional params?

A fun(damental) example

A warp drive metric exists





Alcubierre, The warp drive: hyper-fast travel within general relativity, CQG 1994

What happens if the warp drive containment field fails?

Could we see gravitational waves from alien warp drive ships?

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Could we see gravitational waves from alien warp drive ships?

WHAT NO ONE HAS SEEN BEFORE: GRAVITATIONAL WAVEFORMS FROM WARP DRIVE COLLAPSE

Katy Clough[1,2], Tim Dietrich[3,4], and Sebastian Khan[5]
[1] School of Mathematical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
[2] Astrophysics, University of Oxford, DWB, Keble Road, Oxford OX1 3RH, UK
[3] Institut für Physik und Astronomie, Universität Potsdam, Haus 28, Karl-Liebknecht-Str. 24/25, 14476, Potsdam, Germany
[4]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany and
[5] School of Physics and Astronomy, Cardiff University, Queens Buildings, Cardiff, CF24 3AA, United Kingdom
Version July 25, 2024

ABSTRACT

Despite originating in science fiction, warp drives have a concrete description in general relativity, with Alcubierre first proposing a spacetime metric that supported faster-than-light travel. Whilst there are numerous practical barriers to their implementation in real life, including a requirement for negative energy, computationally, one can simulate their evolution in time given an equation of state describing the matter. In this work, we study the signatures arising from a warp drive 'containment failure', assuming a stiff equation of state for the fluid. We compute the emitted gravitational-wave signal and track the energy fluxes of the fluid. Apart from its rather speculative application to the search for extraterrestrial life in gravitational-wave detector data, this work is interesting as a study of the dynamical evolution and stability of spacetimes that violate the null energy condition. Our work highlights the importance of exploring strange new spacetimes, to (boldly) simulate what no one has seen before.

The Open Journal of Astrophysics 7 (July). https://doi.org/10.33232/001c.121868, arXiv:2406.02466

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[4]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany and
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Boffins admit we already have tech to detect UFOs using Star Trek-style Warp Drives

EXCLUSIVE: Experts believe that technology already available to us could be used to detect specific gravitational waves, meaning we could be one step away from spotting alien spaceships

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By Isobel Dickinson 19:22, 5 SEP 2024

Bild

Hey_ KI-HELFER

Deutscher Forscher will Warp-Antriebe von Aliens finden

Foto: Thomas Roese, imago images/Everett Collection

Konstantin Marrach

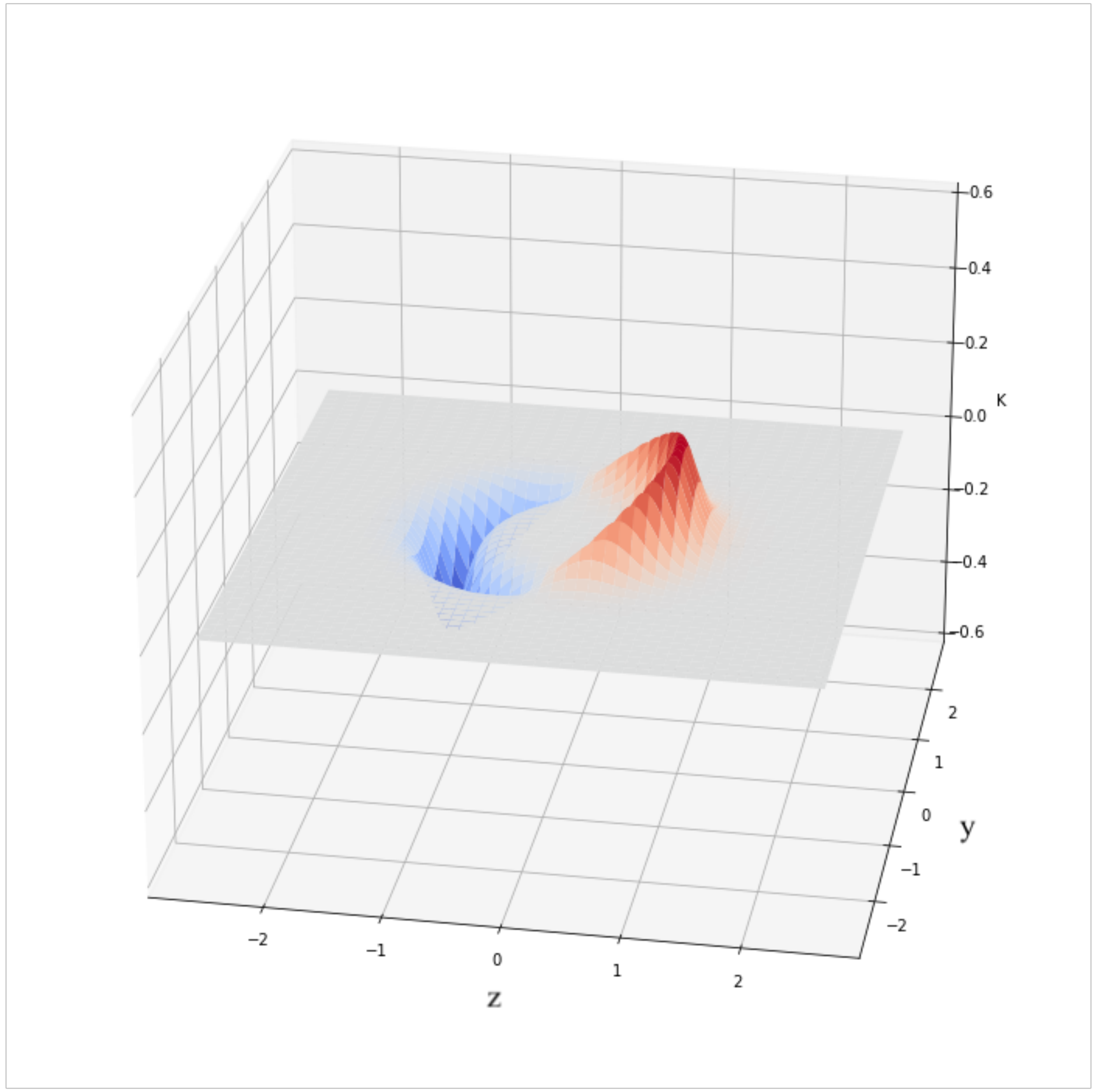
28.06.2024 - 20:34 Uhr

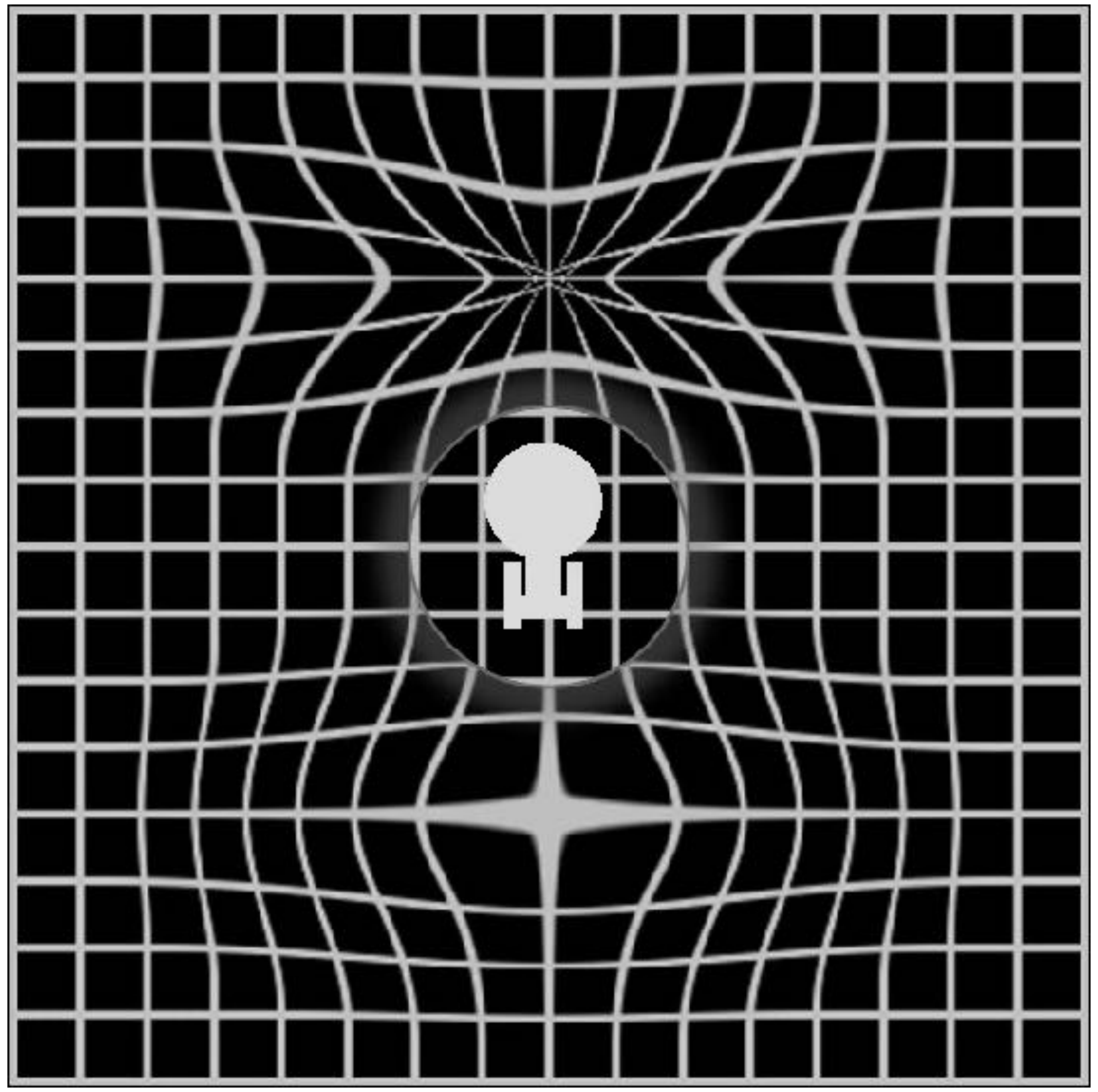
Der Weltraum. Unendliche Weiten. Dies sind die Abenteuer der Wissenschaft, die ganz tief ins All blickt und dabei vielleicht sogar Außerirdische entdecken kann.

Was nach Science Fiction klingt, ist tatsächlich

bild.de

A warp drive metric exists





Alcubierre, The warp drive: hyper-fast travel within general relativity, CQG 1994

A “designer spacetime” that needs exotic matter

$$T_{\mu\nu}(t=0) = G_{\mu\nu}^{alcubierre}(t=0)/(8\pi)$$

f(matter) = g(curvature)

The solution requires matter that violates the Null Energy Condition

We need to decide how the matter evolves

Local energy conservation tells us how 4 components evolve:

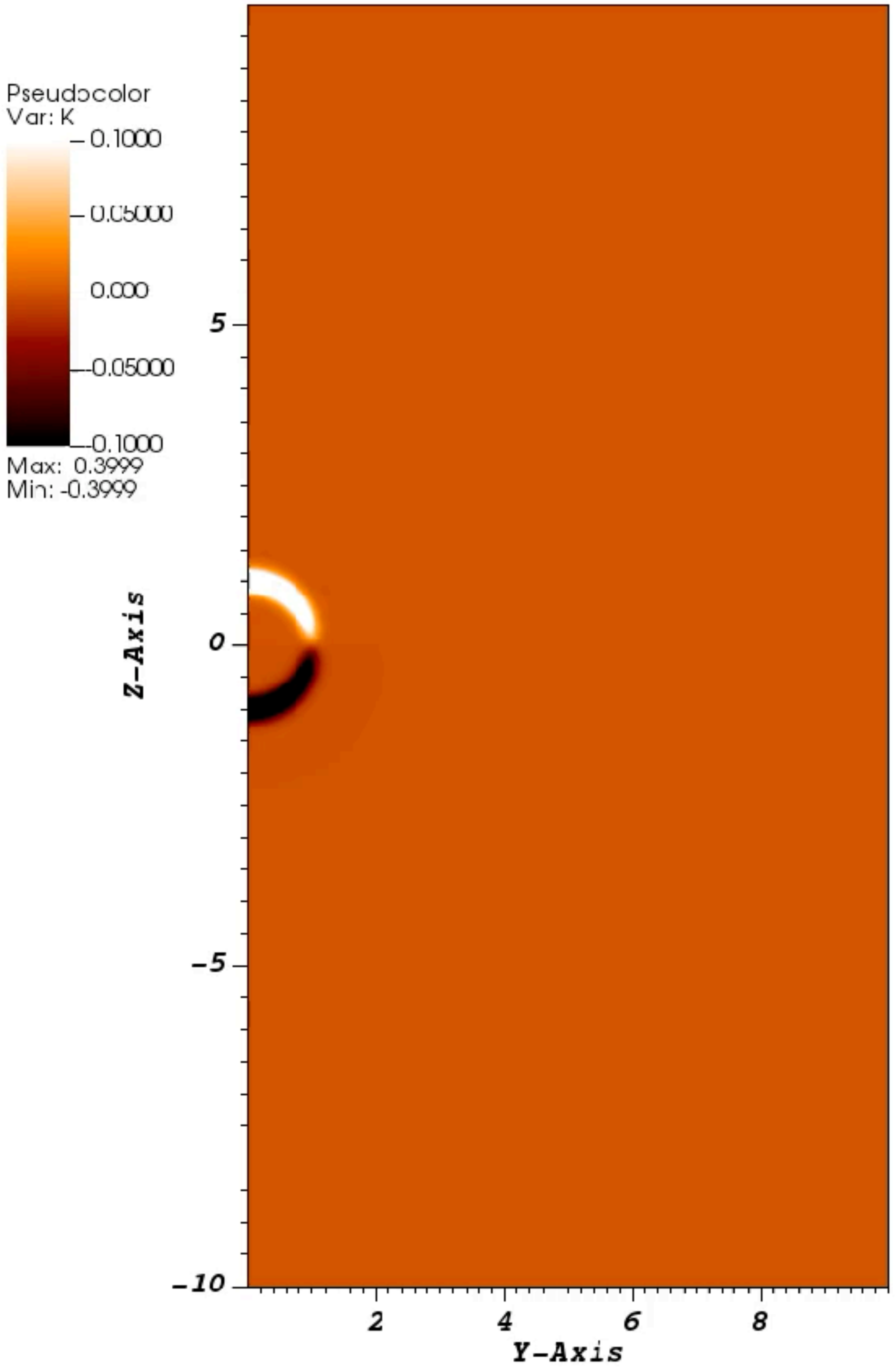
$$\nabla^\mu T_{\mu\nu} = 0$$

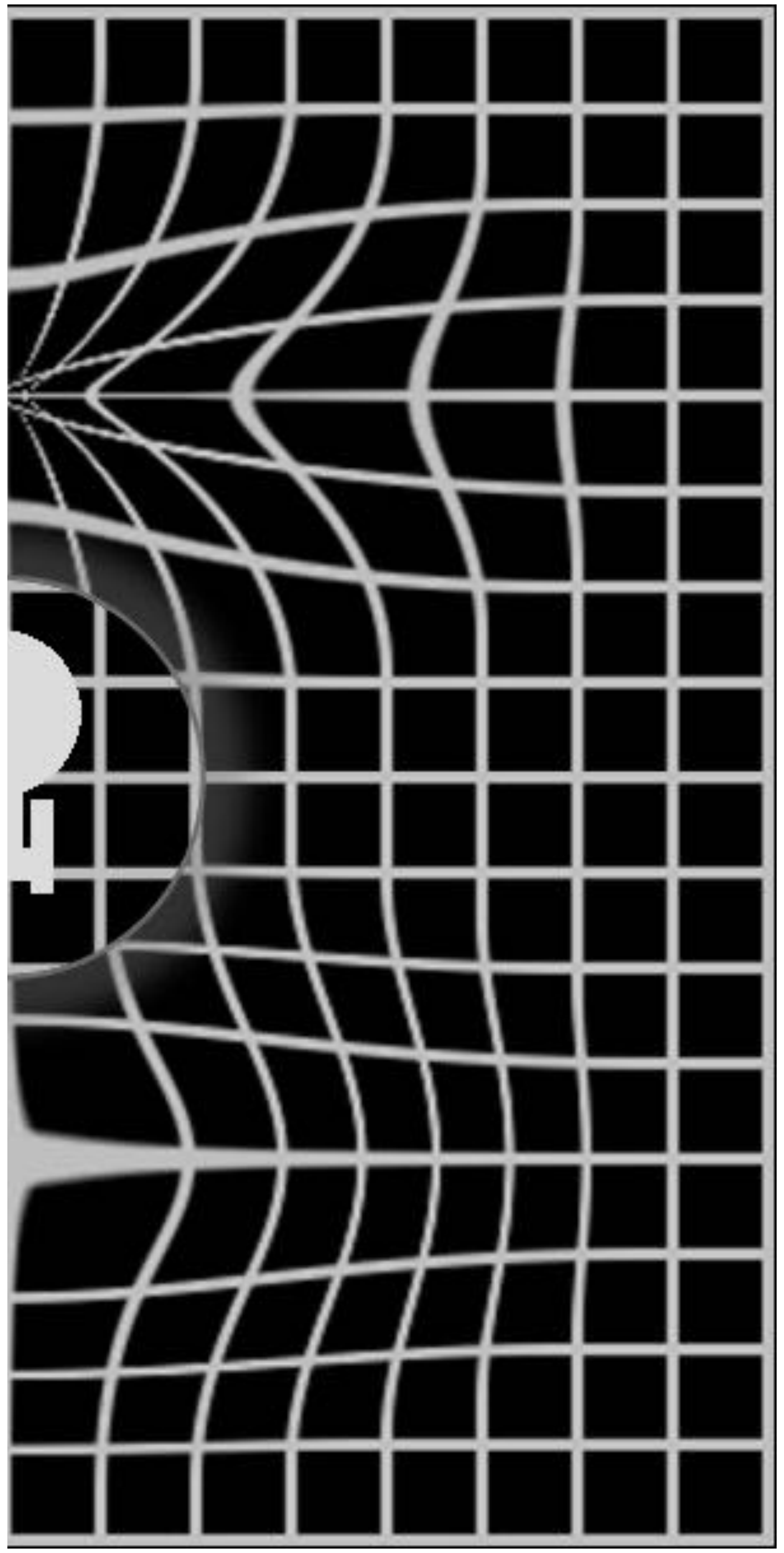
$$\implies \partial_t \rho = f(\rho, S_i, S_{ij}, g_{\mu\nu})$$ energy density

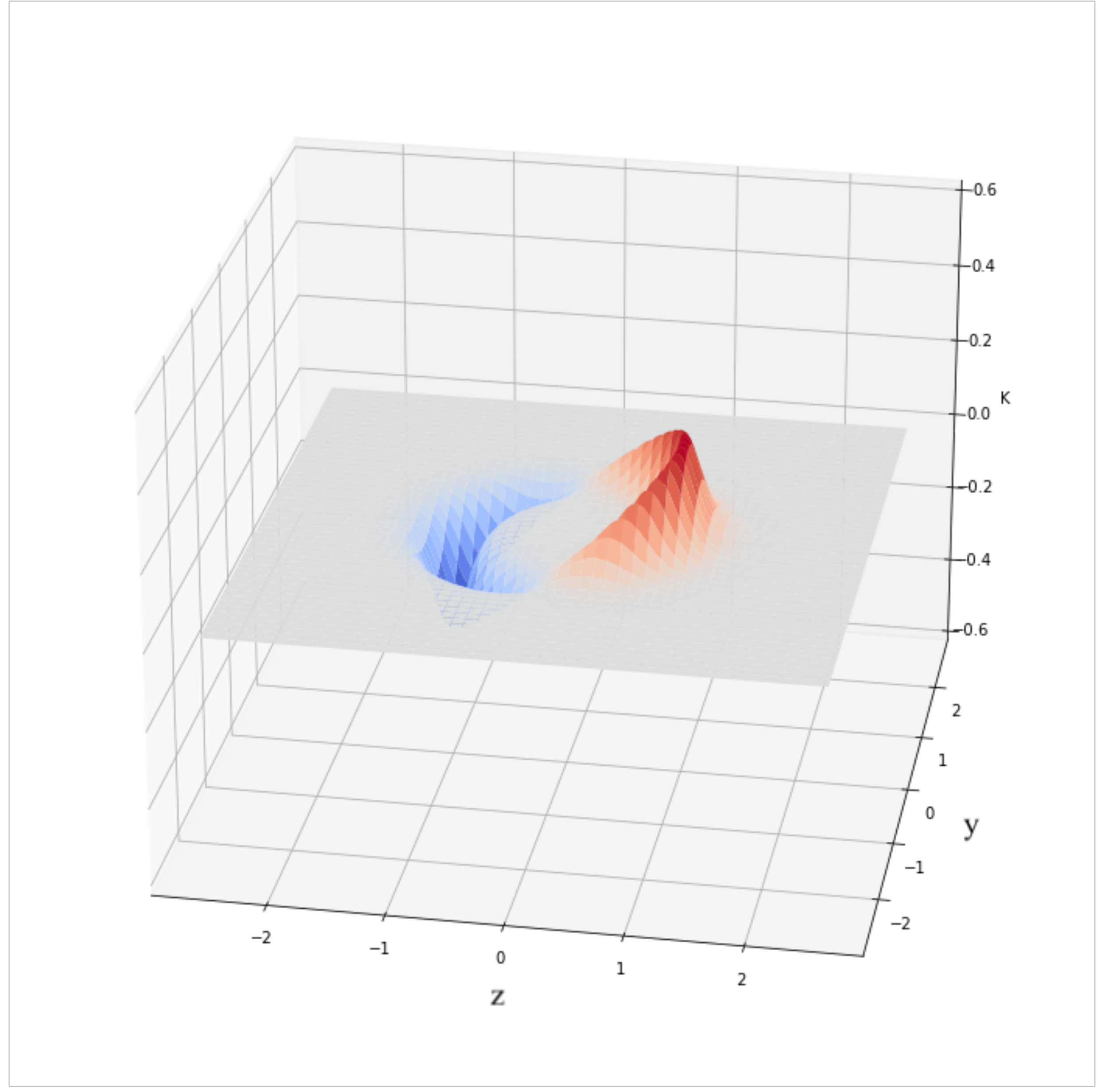
$$\implies \partial_t S_i = f(\rho, S_i, S_{ij}, g_{\mu\nu})$$ momentum density

Need equation of state to close the system (we choose $\bar{p} = \rho$, decaying anisotropic stresses)

What no one has seen before…

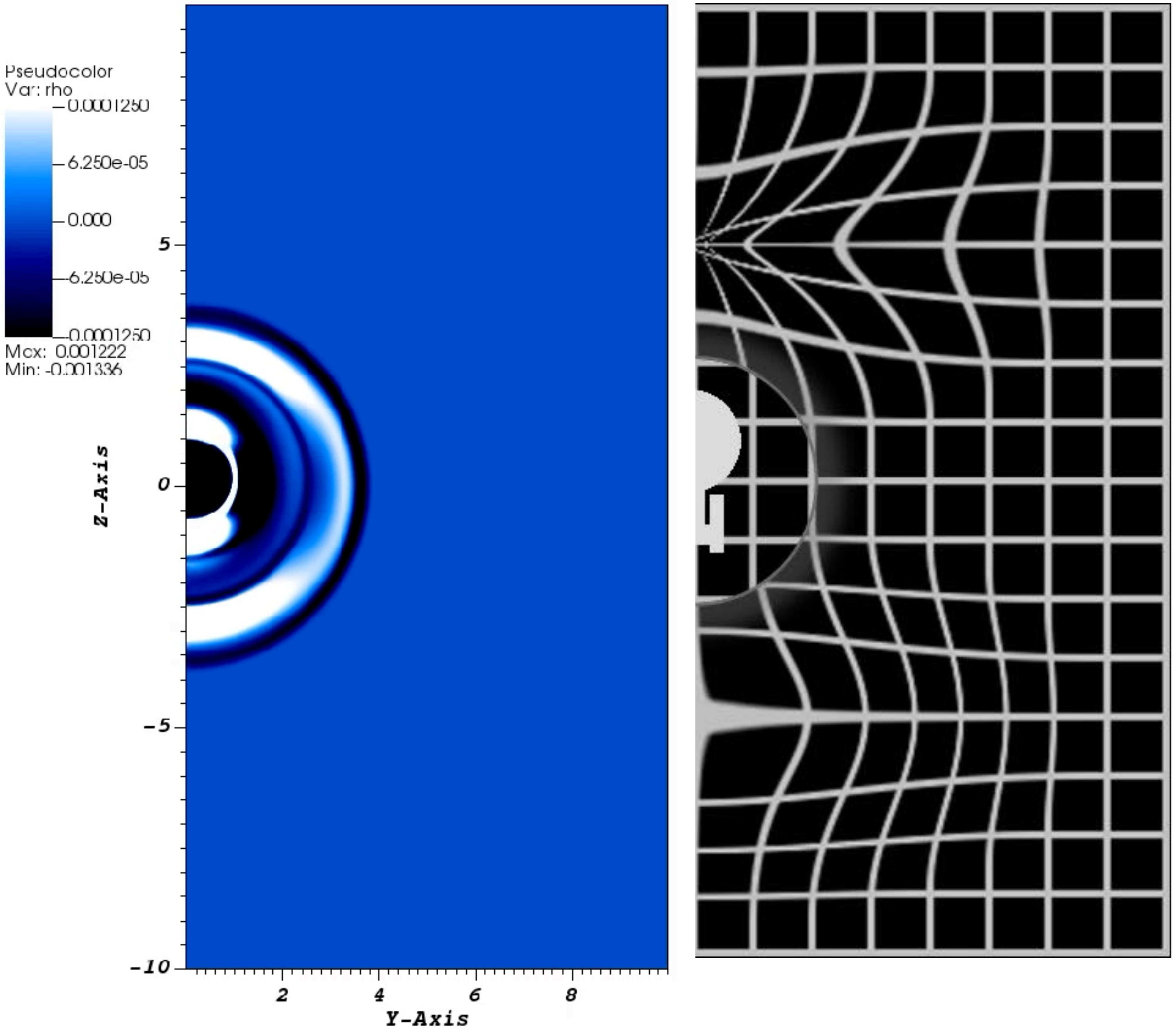






K
(Trace of extrinsic curvature of spatial slice)

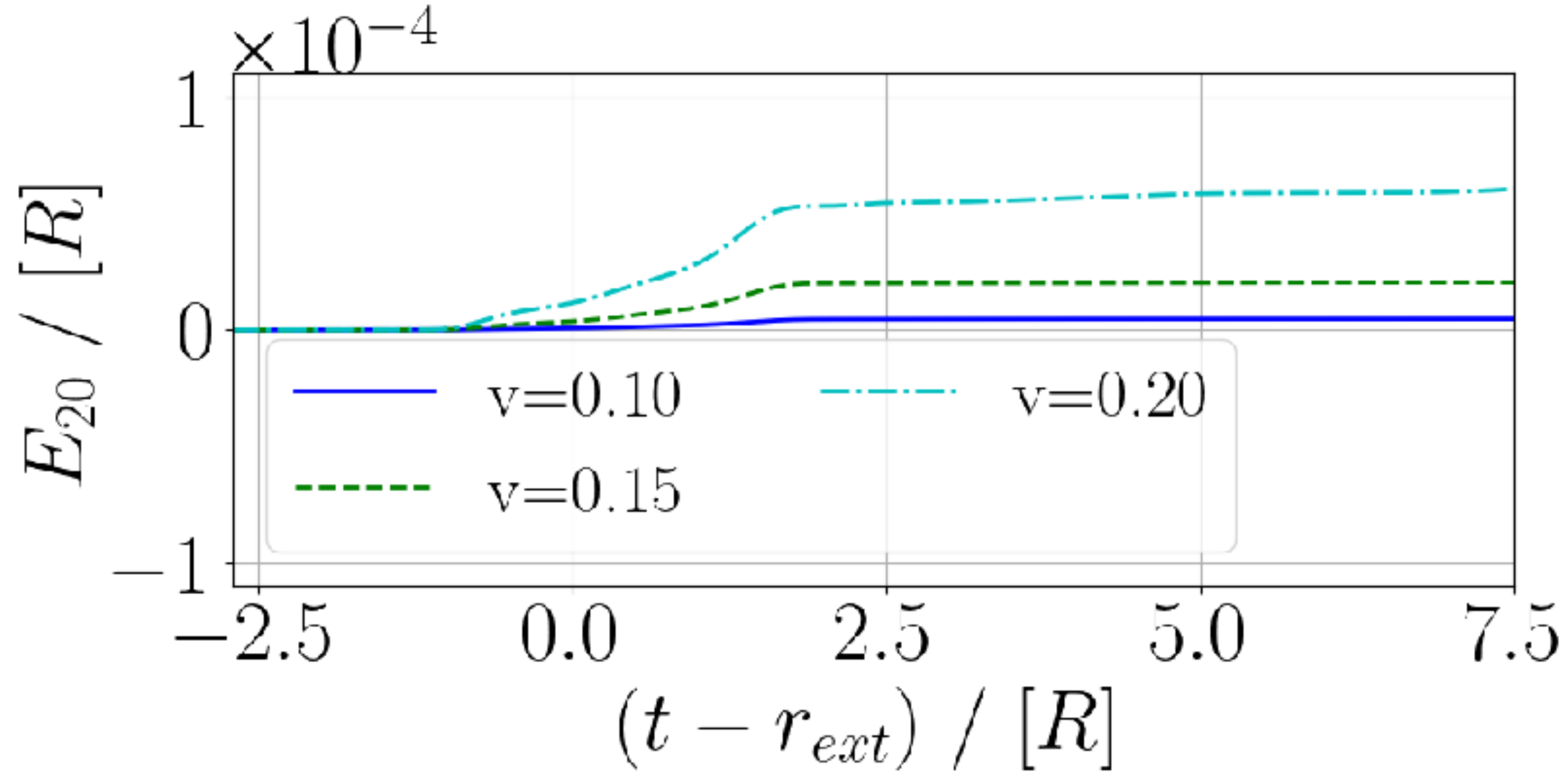
Evolution of the exotic matter from the bubble



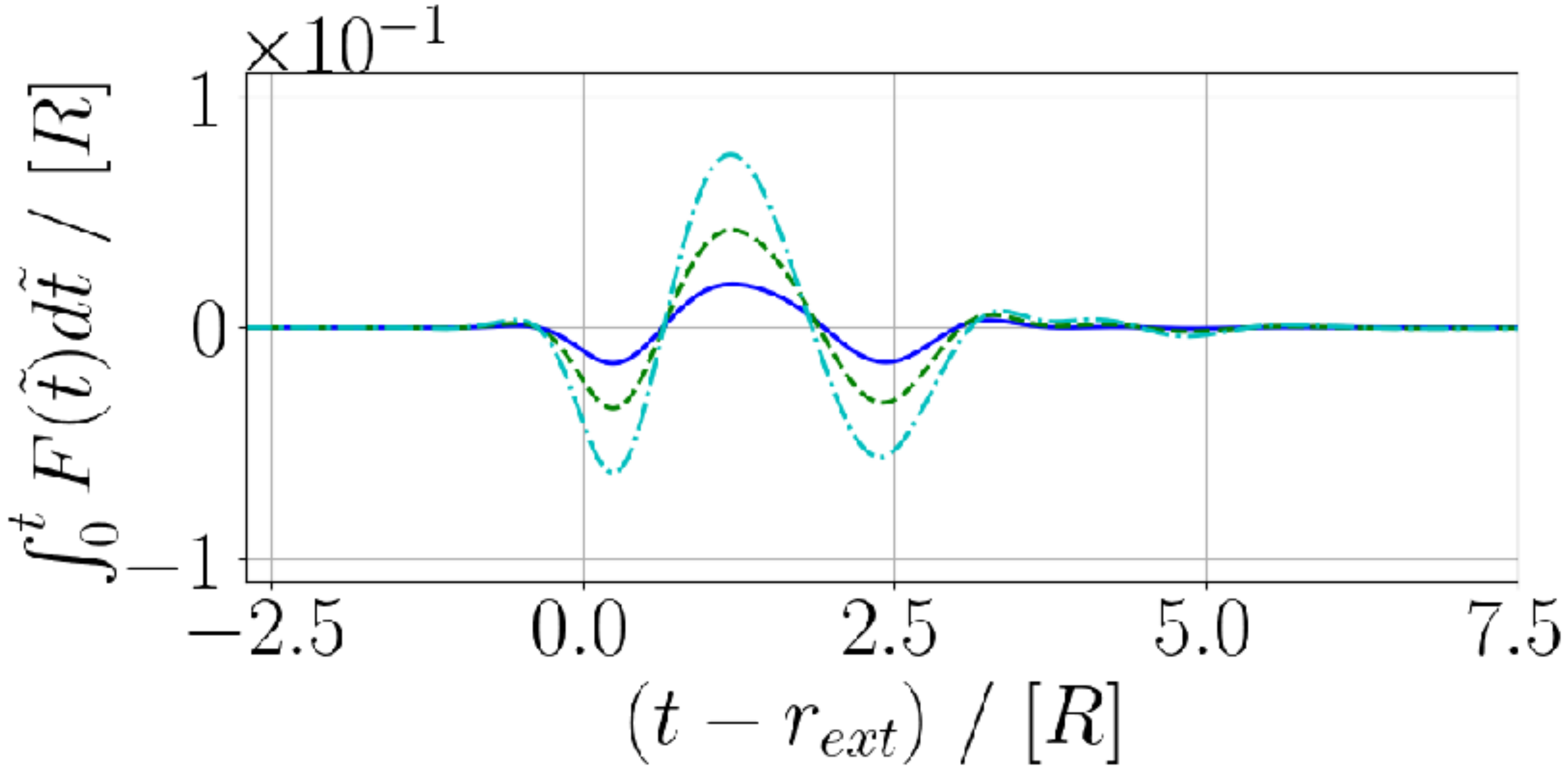
Energy density of warp fluid

See: Negative Mass in General Relativity (Bondi 1957)

Matter energy radiation is both negative and positive



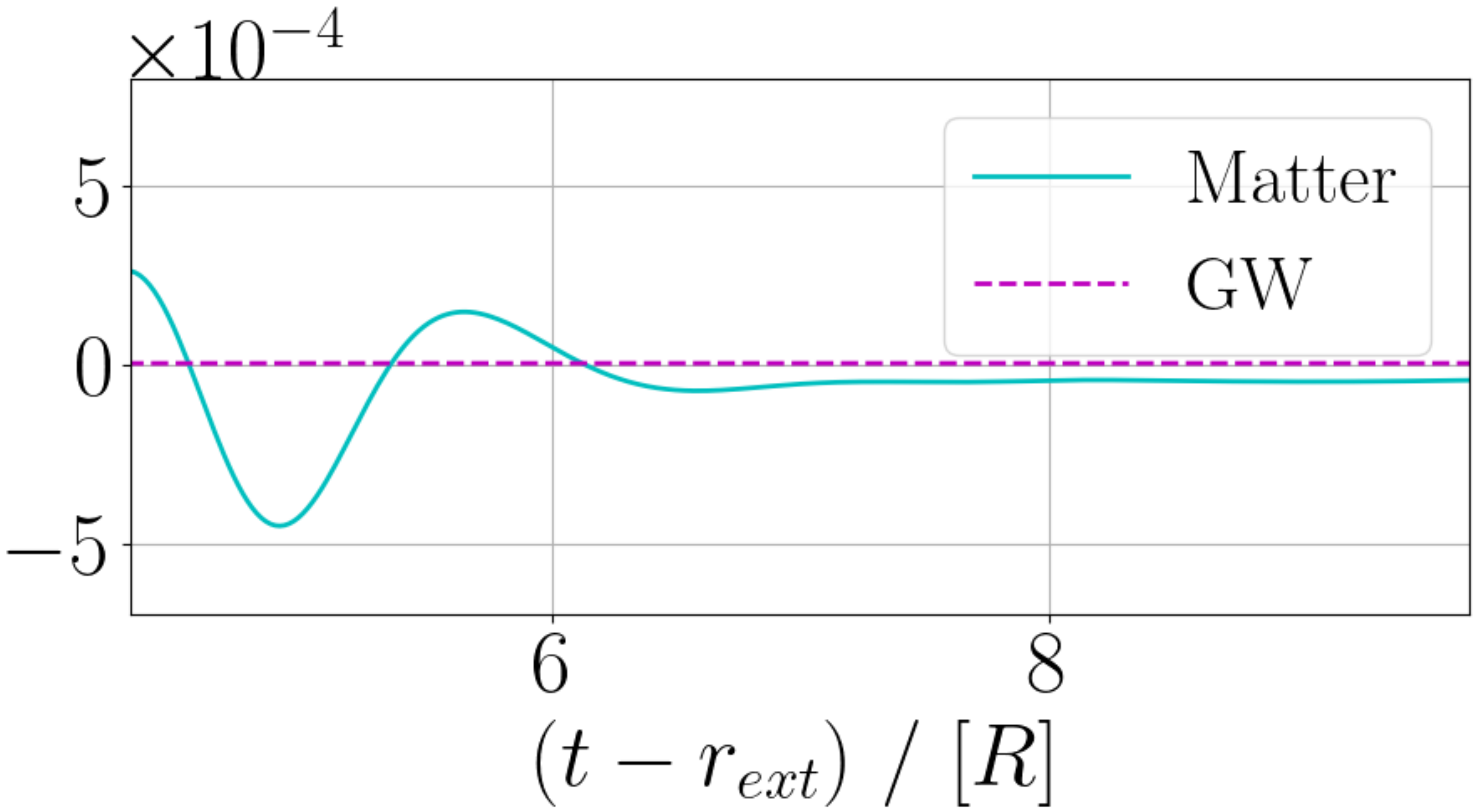
Energy flux
of gravitational
waves



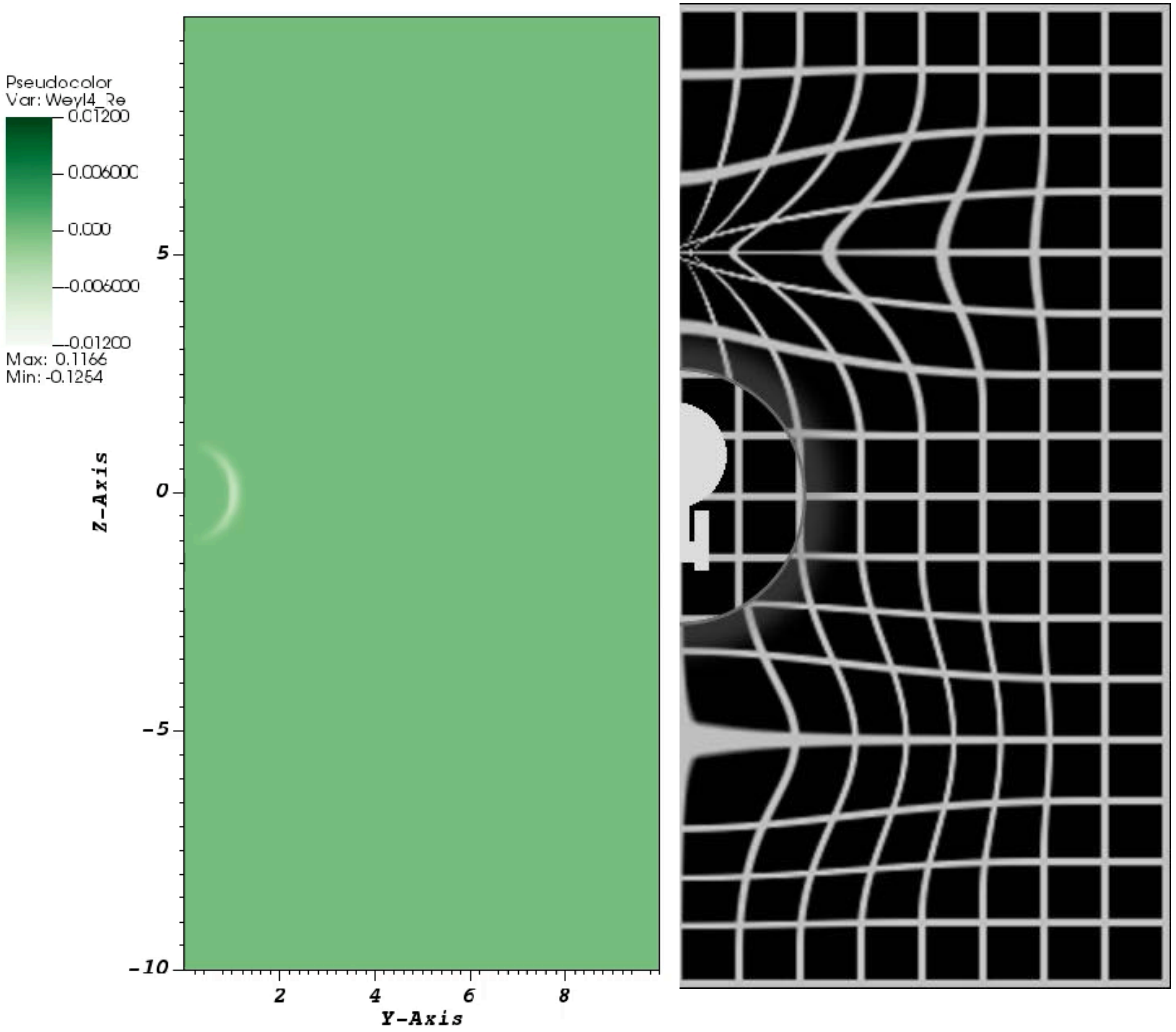
Energy flux
of warp fluid

Final result is a loss of negative energy, so a positive final mass

Total energy flux of warp fluid



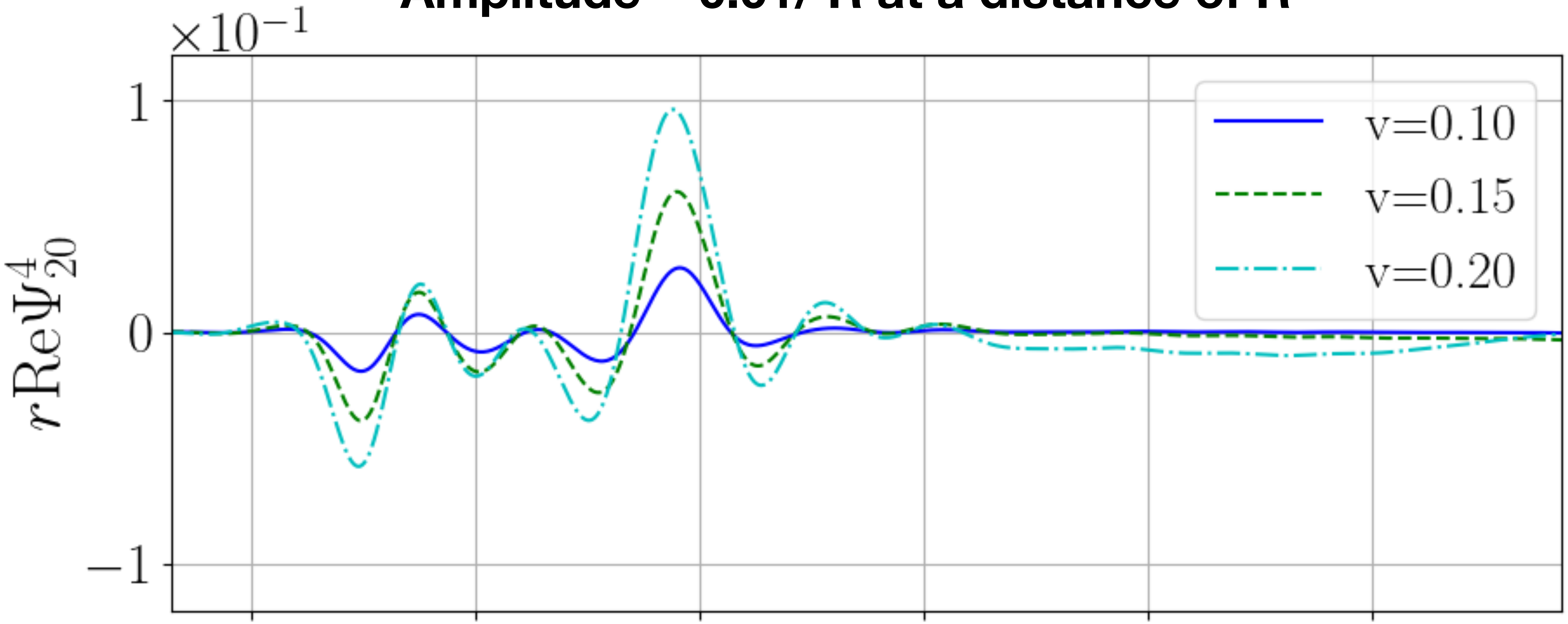
One can of course extract the gravitational wave signals



Weyl4 scalar (~ Second time derivative of GWs)

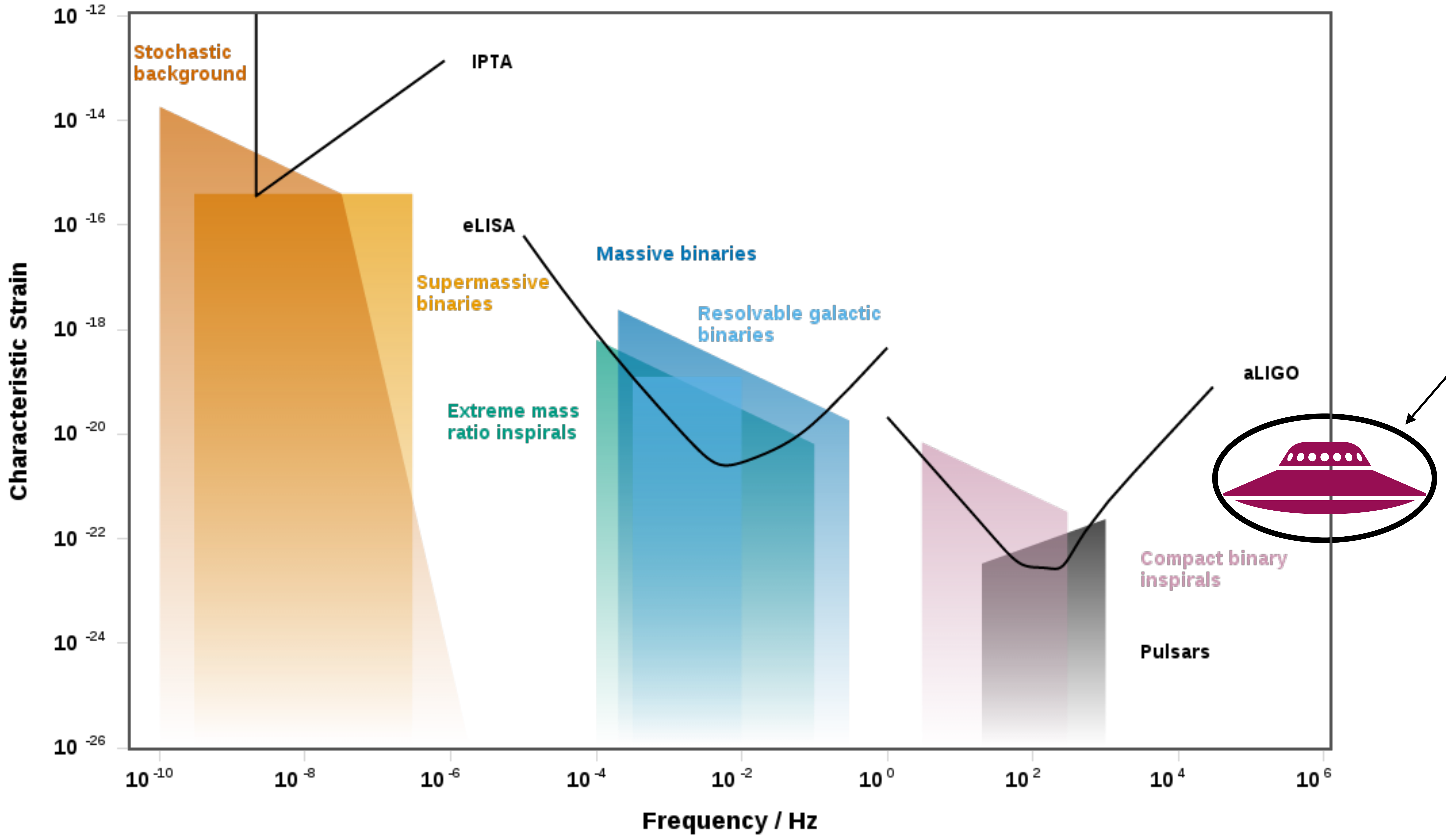
Can it be detected?

Amplitude ~ 0.01/ R at a distance of R



Frequency ~ 1/R

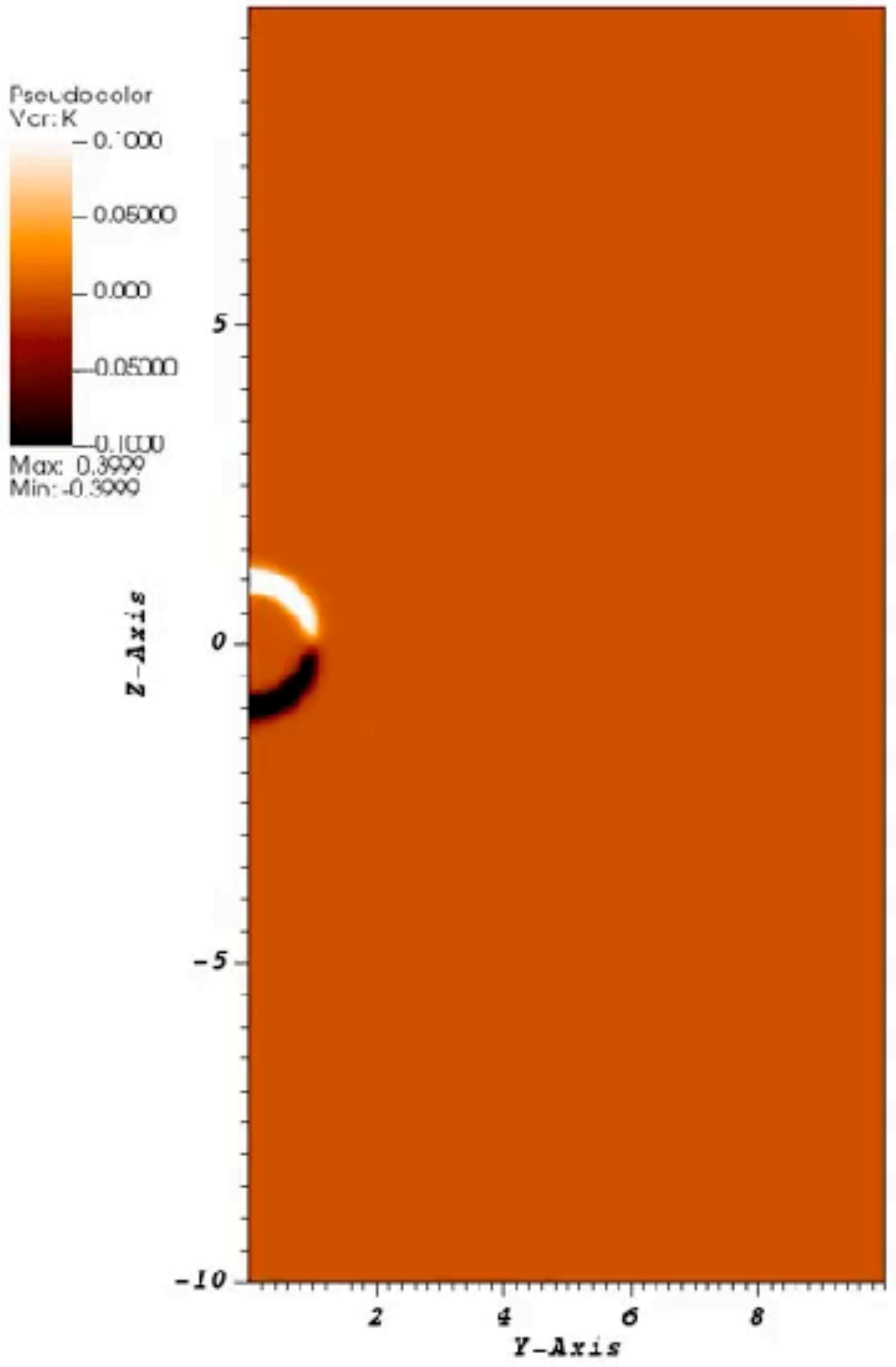
Can it be detected?

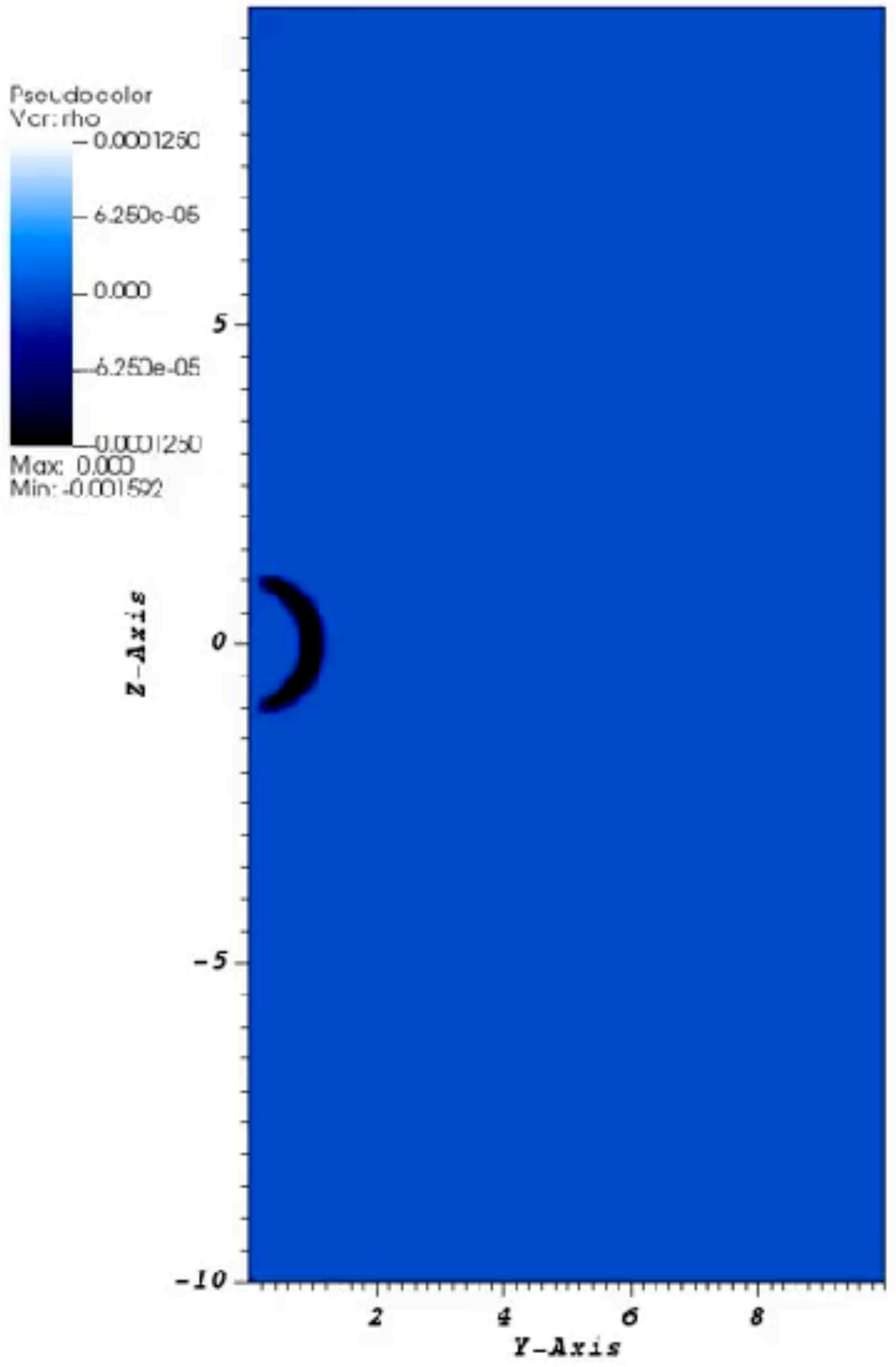


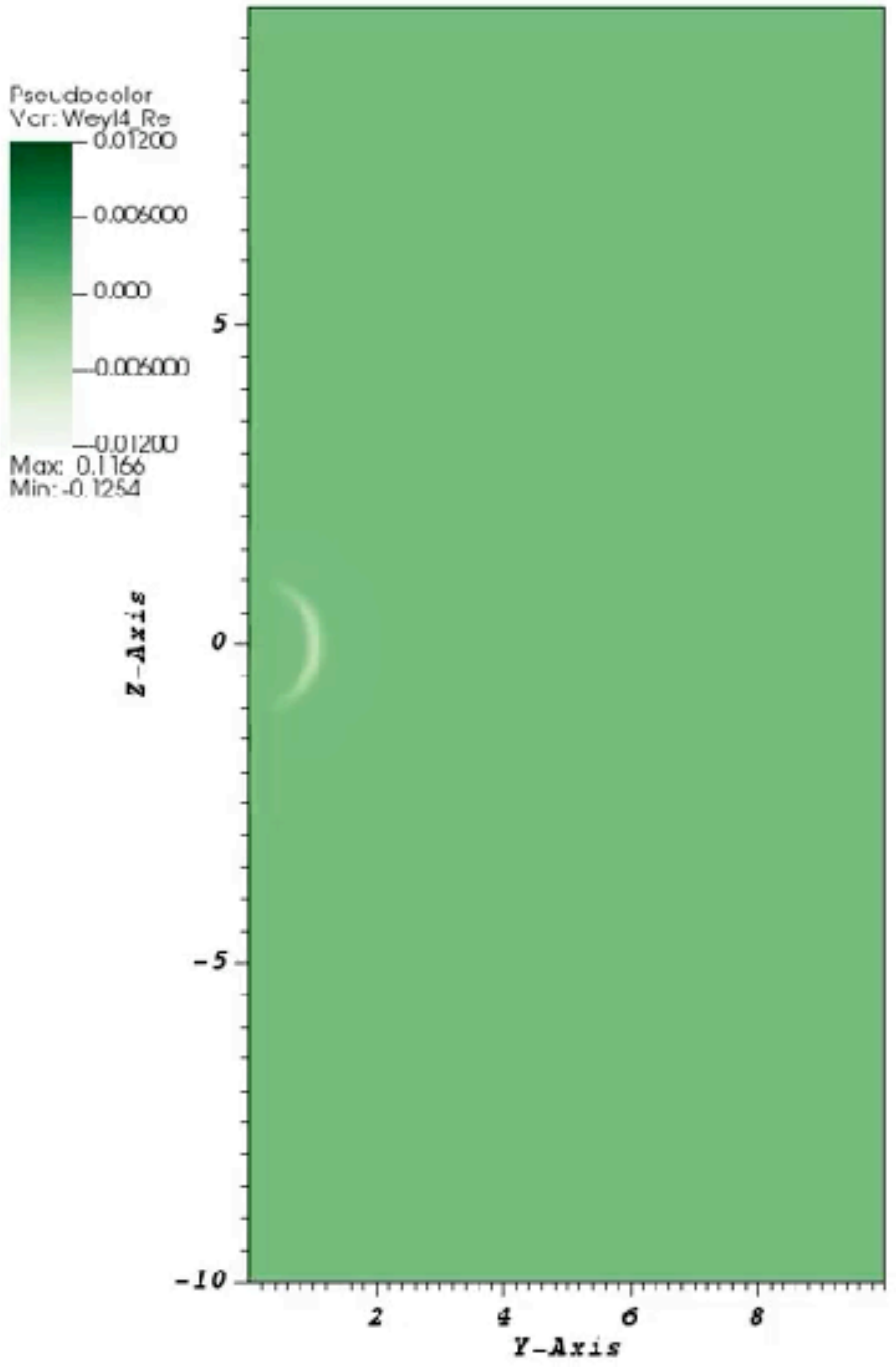
1 km bubble in our galaxy, travelling at 10% of the speed of light

Image credit: Christopher Berry (aliens added)

Maybe it’s not the destination that matters… it’s the journey

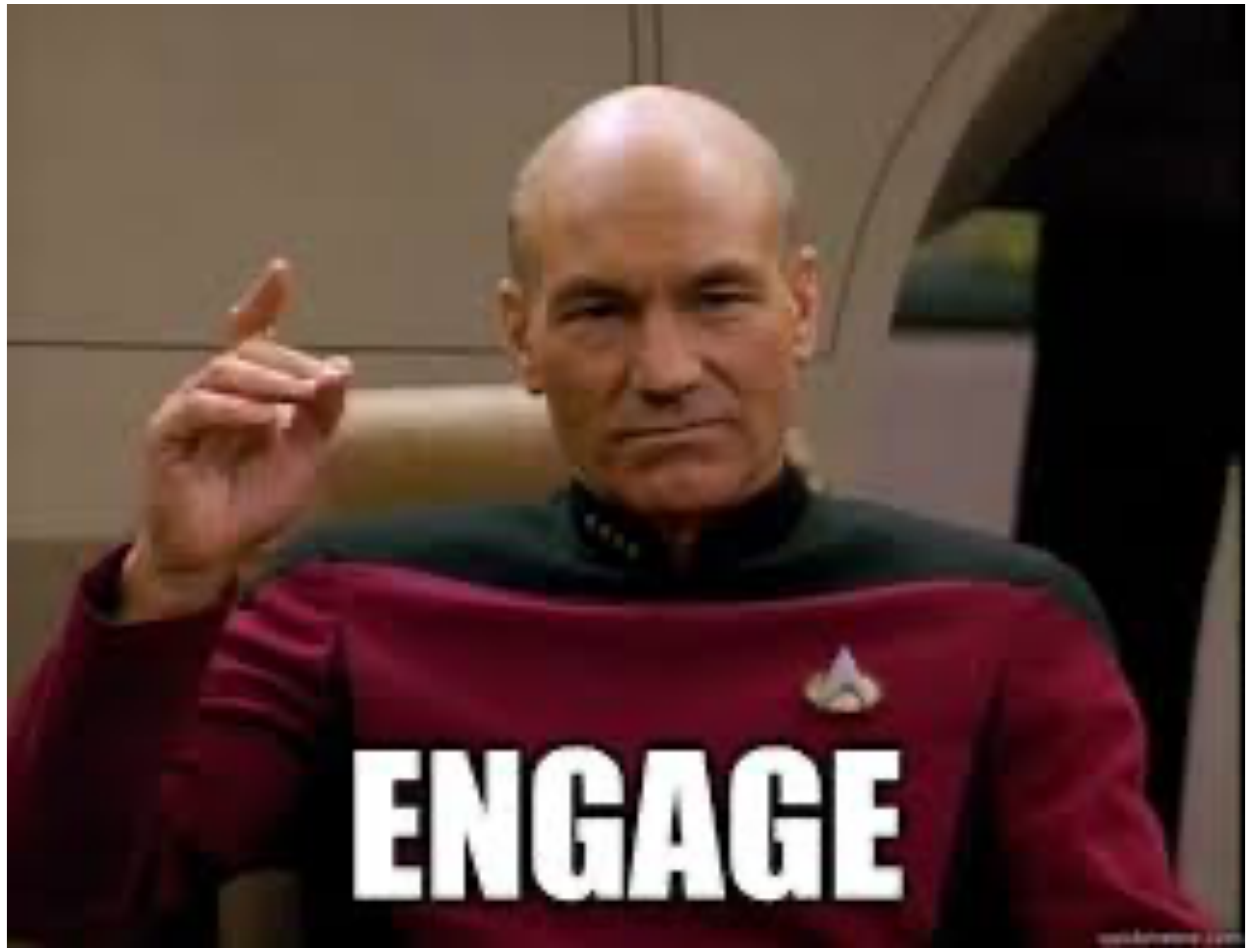






And now, the conclusion…

- Exciting times ahead in numerical relativity studies!
- NR simulations can be used as a tool to investigate the consequences of fundamental physics in strong gravity regimes. They are a modern day gedanken experiment.
- Potential to understand fundamental properties of gravity and extensions to GR (and discover aliens).



Questions?