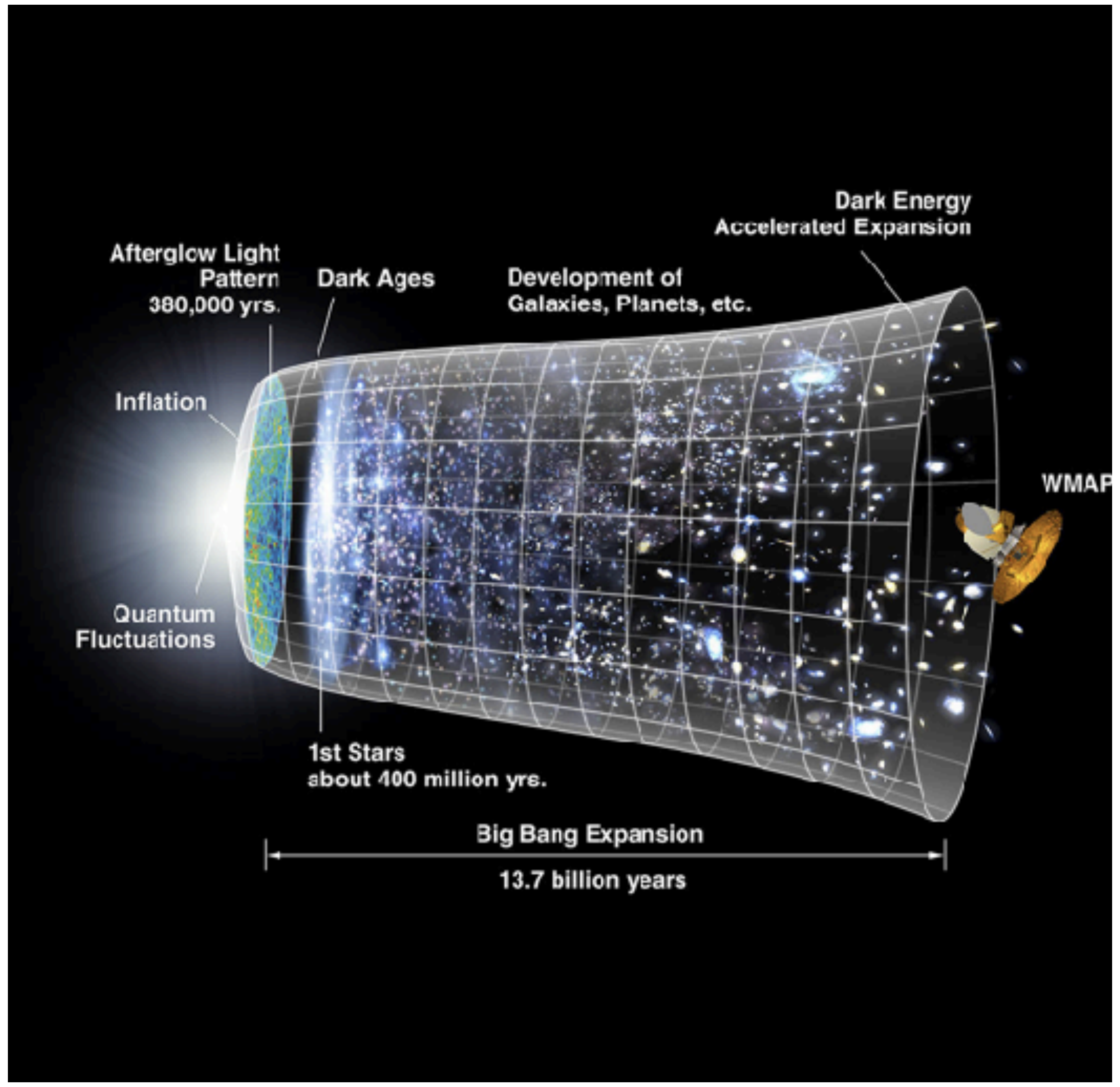


What can strong gravity simulations tell us about the beginning of time?

Katy Clough

Archer2 Celebration of Science, March 2024

GRChombo

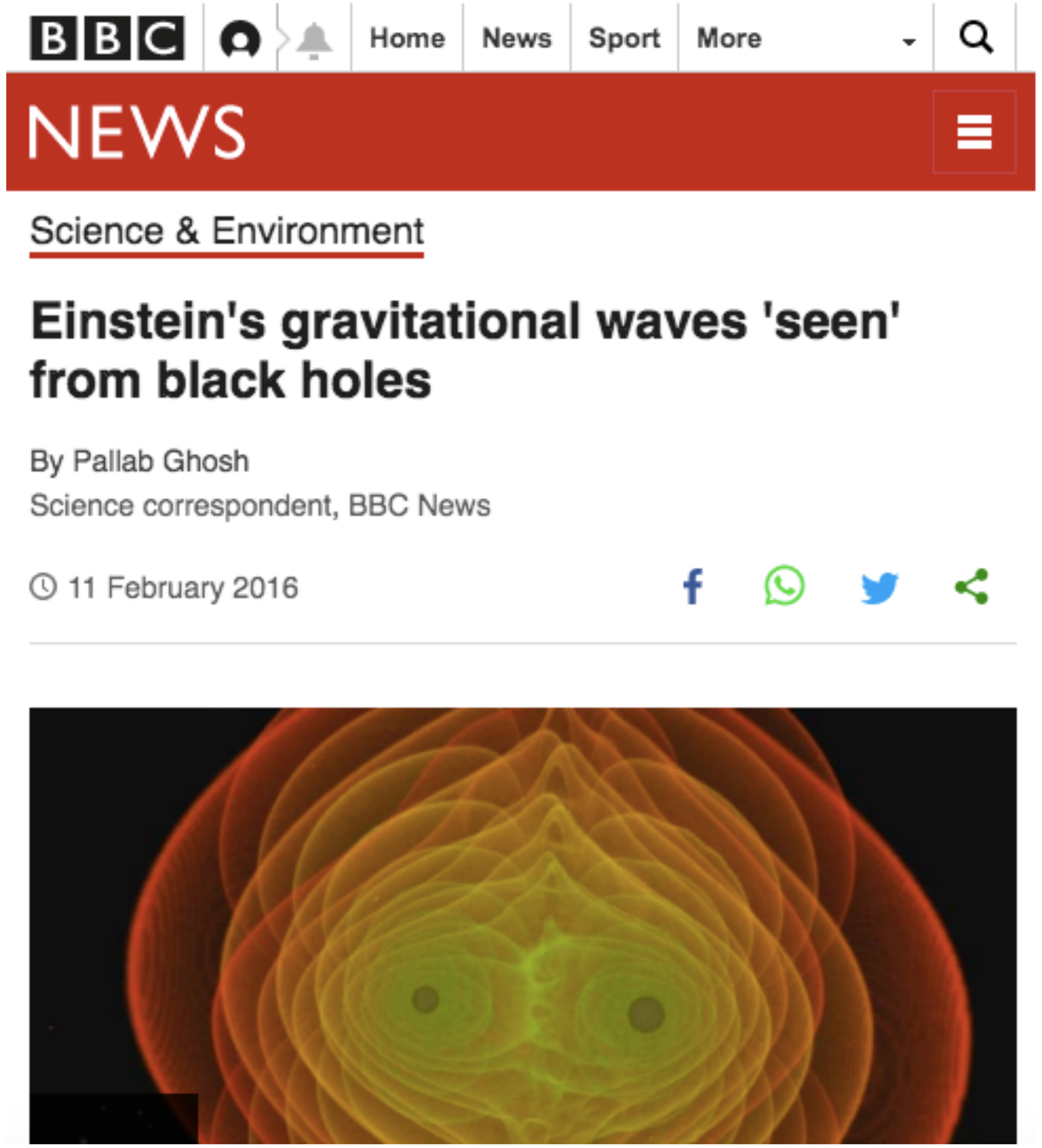
DiRAC

Science & Technology Facilities Council

Queen Mary University of London

What are strong gravity simulations?

The poster child of strong gravity is a black hole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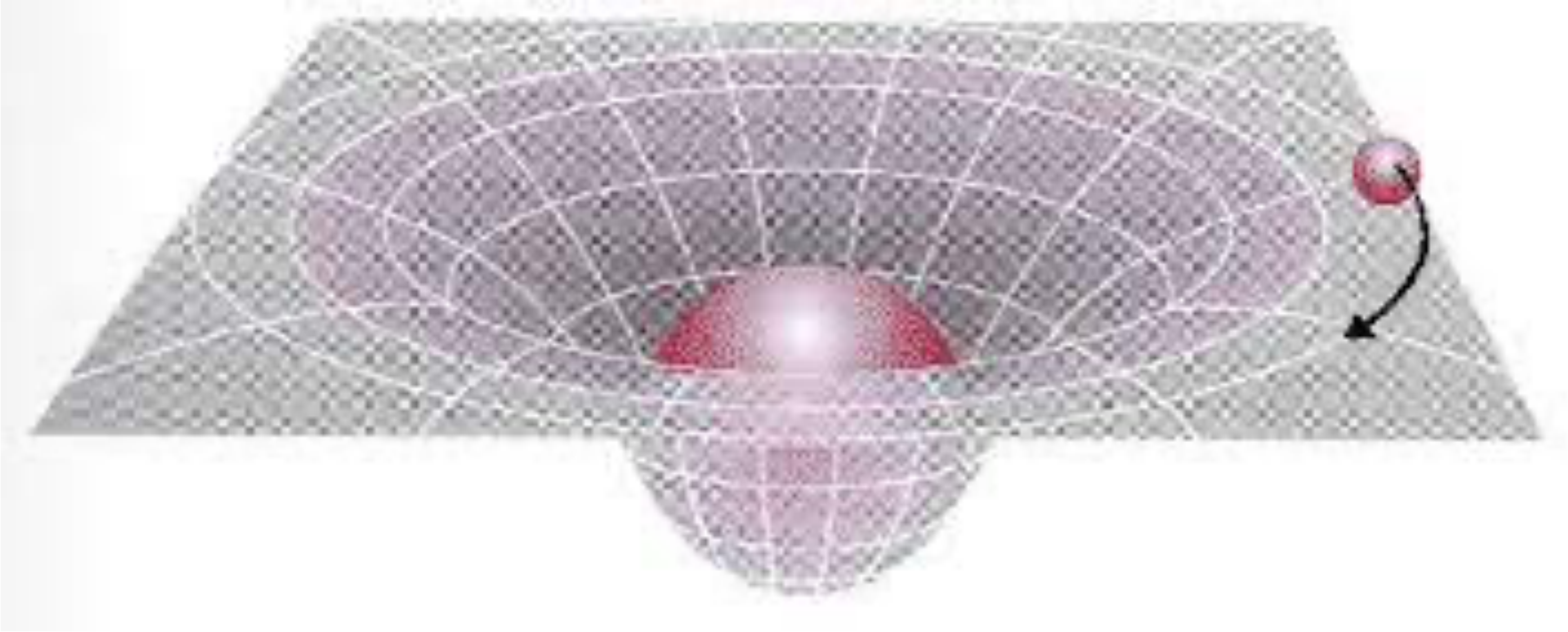
Einstein's gravitational waves 'seen' from black holes

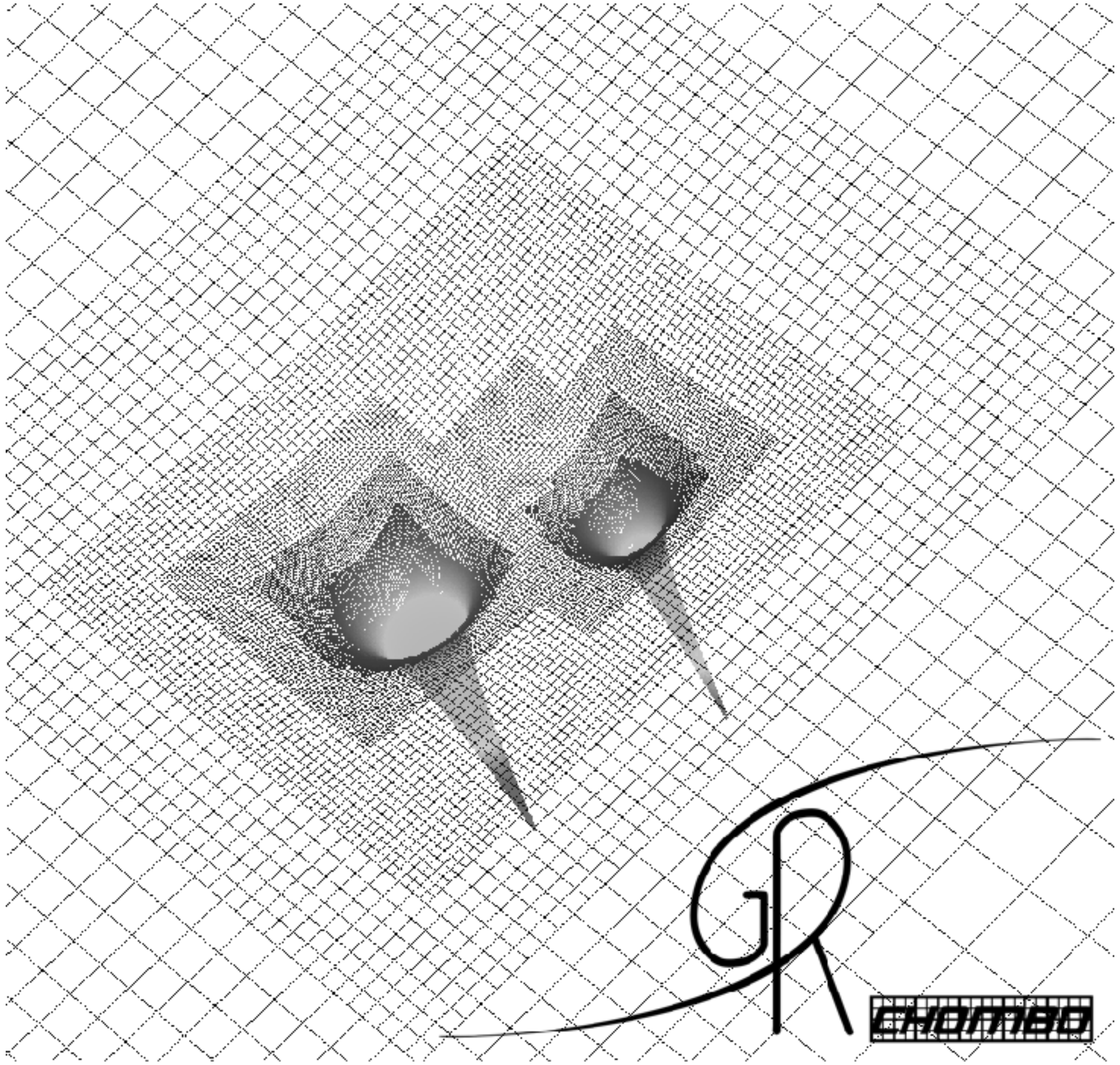
By Pallab Ghosh
Science correspondent, BBC News

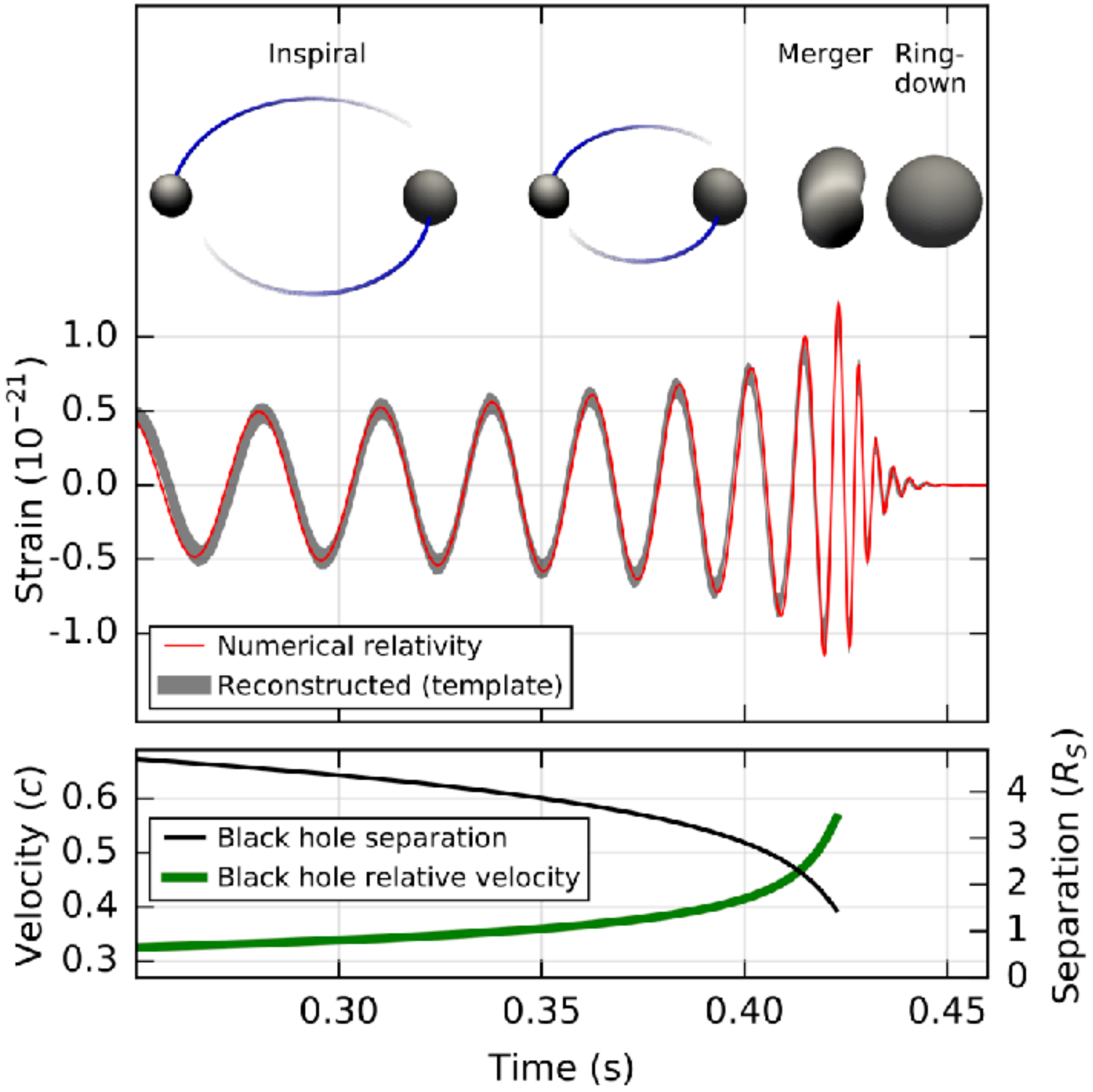
11 February 2016



(2d surface represents 4d spacetime)

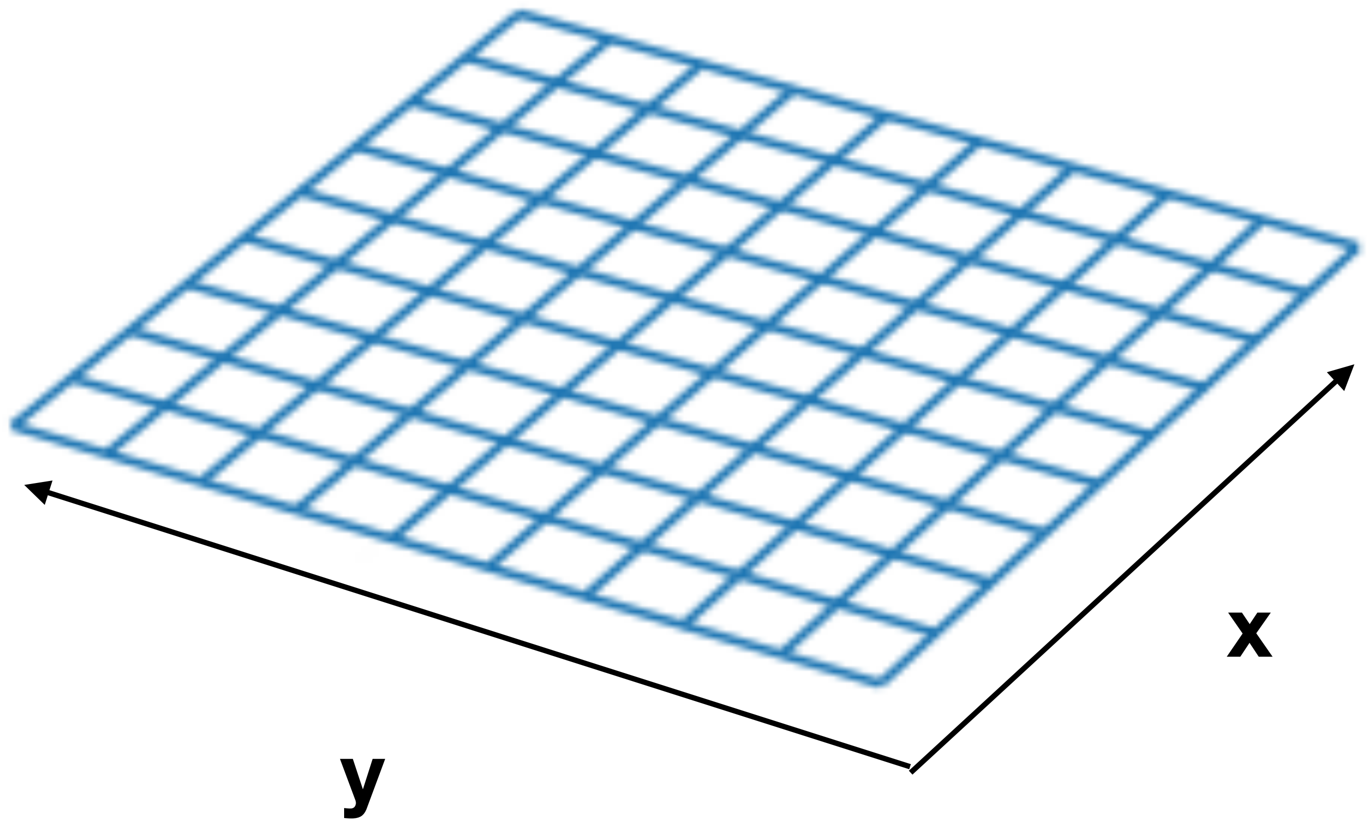
Numerical simulations play a key role in understanding black holes





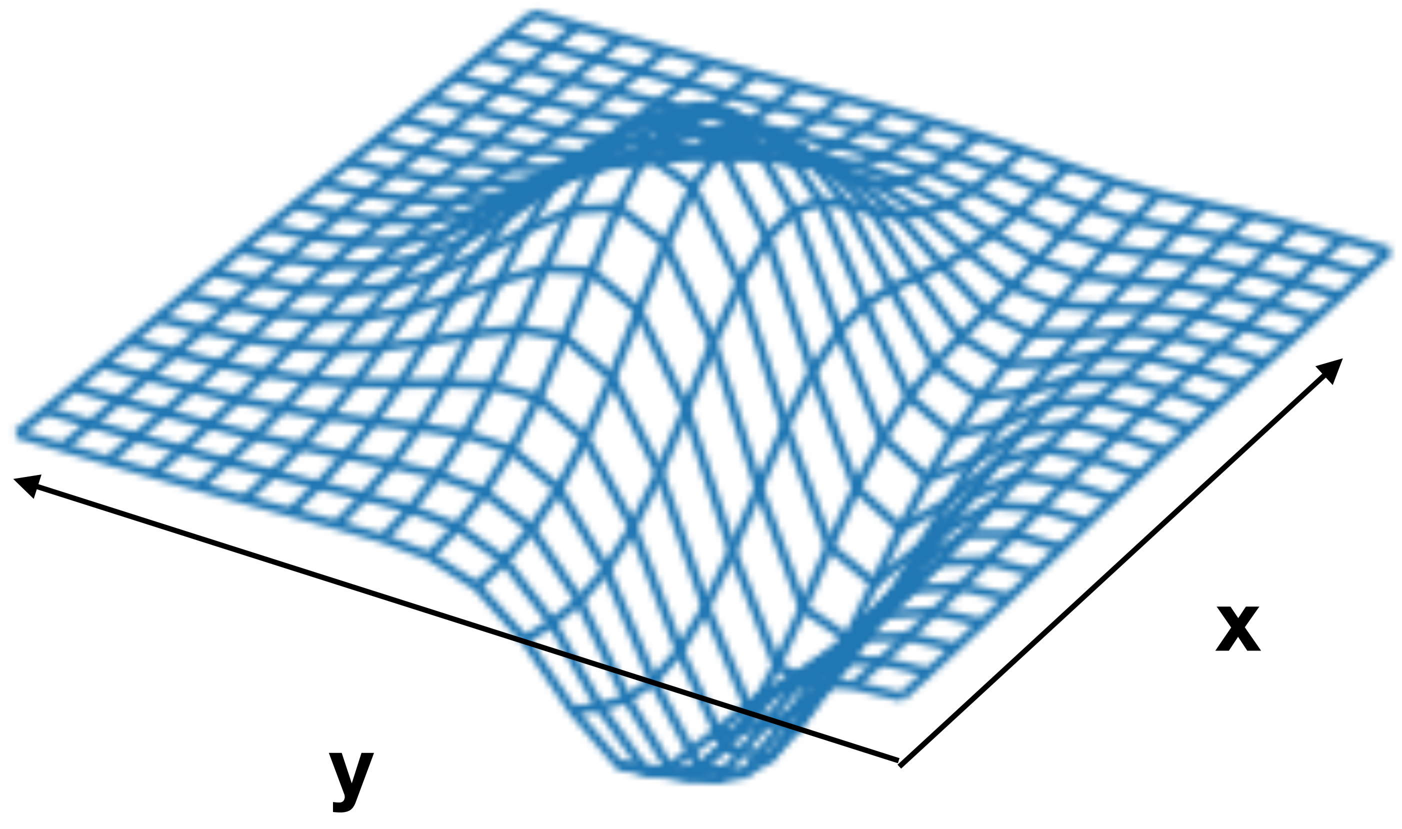
Flat space

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



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

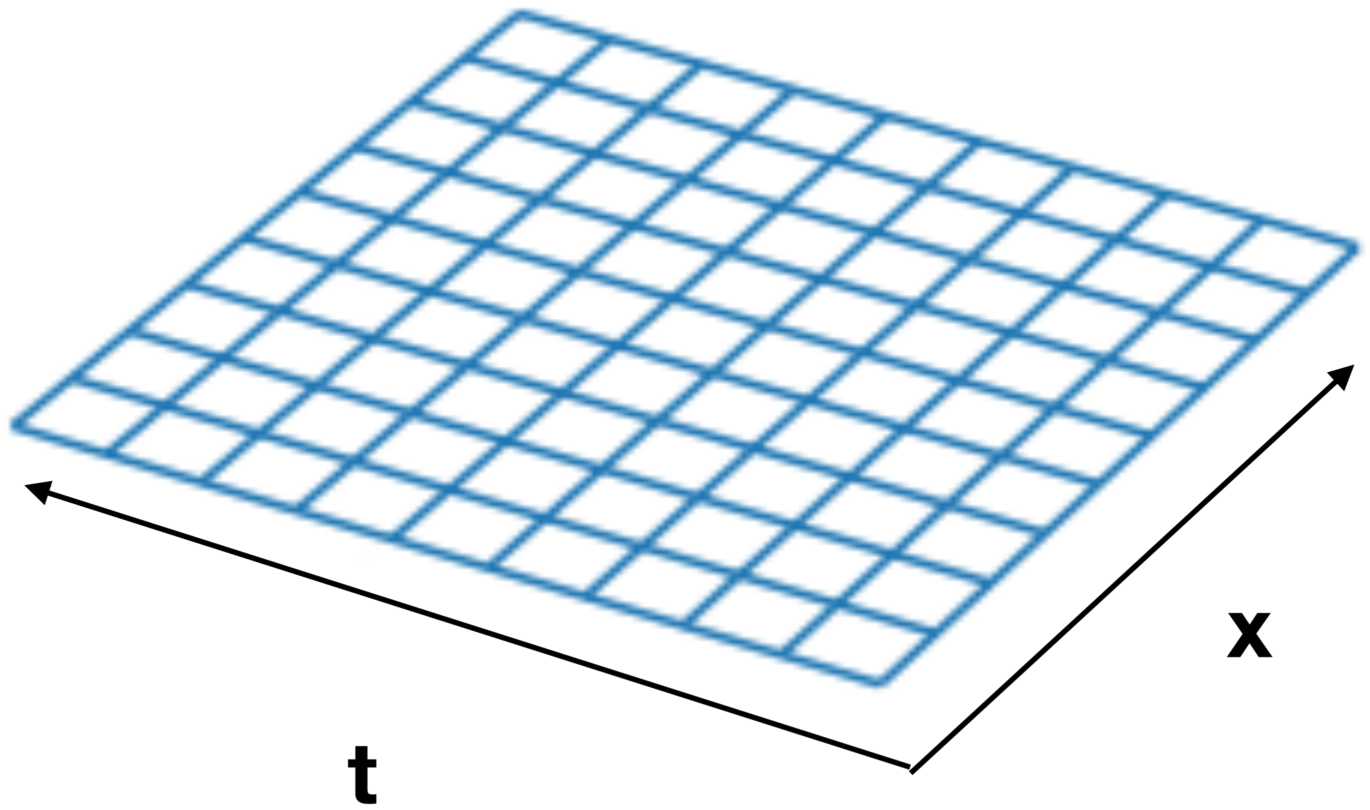
Curved space



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

$$dl^2 = \begin{pmatrix} dx & dy \end{pmatrix} \begin{pmatrix} f(x,y) & 0 \\ 0 & g(x,y) \end{pmatrix} \begin{pmatrix} dx \\ dy \end{pmatrix}$$

Flat spacetime



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

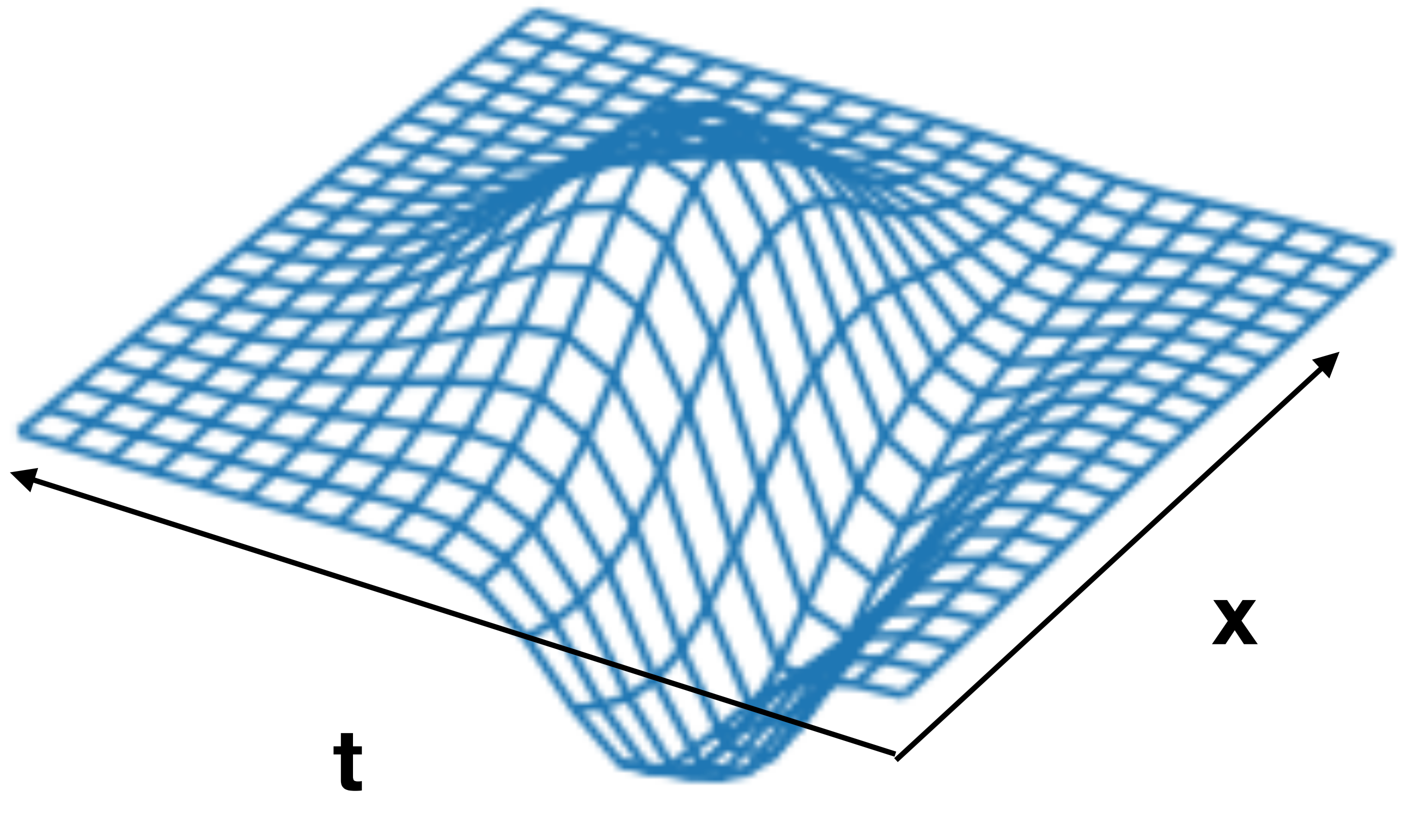
$$ds^2 = \begin{pmatrix} dt & dx \end{pmatrix} \begin{pmatrix} -c^2 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} dt \\ dx \end{pmatrix}$$

Curved spacetime

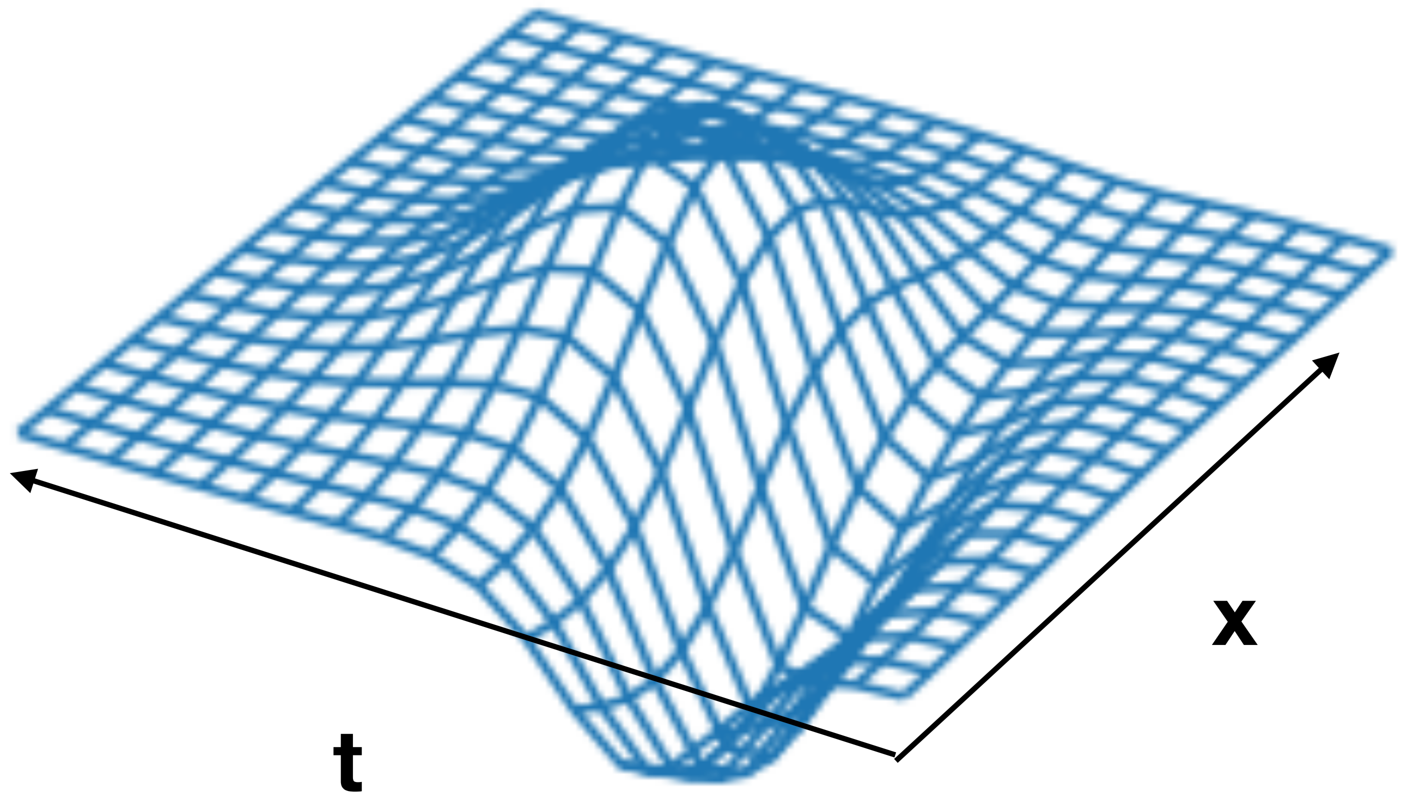
$$ds^2 = \begin{pmatrix} dt & dx & dy & dz \end{pmatrix} \underbrace{\begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$

"The spacetime metric"

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



The Einstein equation is a non linear wave equation for the metric, given some energy/matter distribution



R_{ab} - R/2 g_{ab} = 8π T_{ab}

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

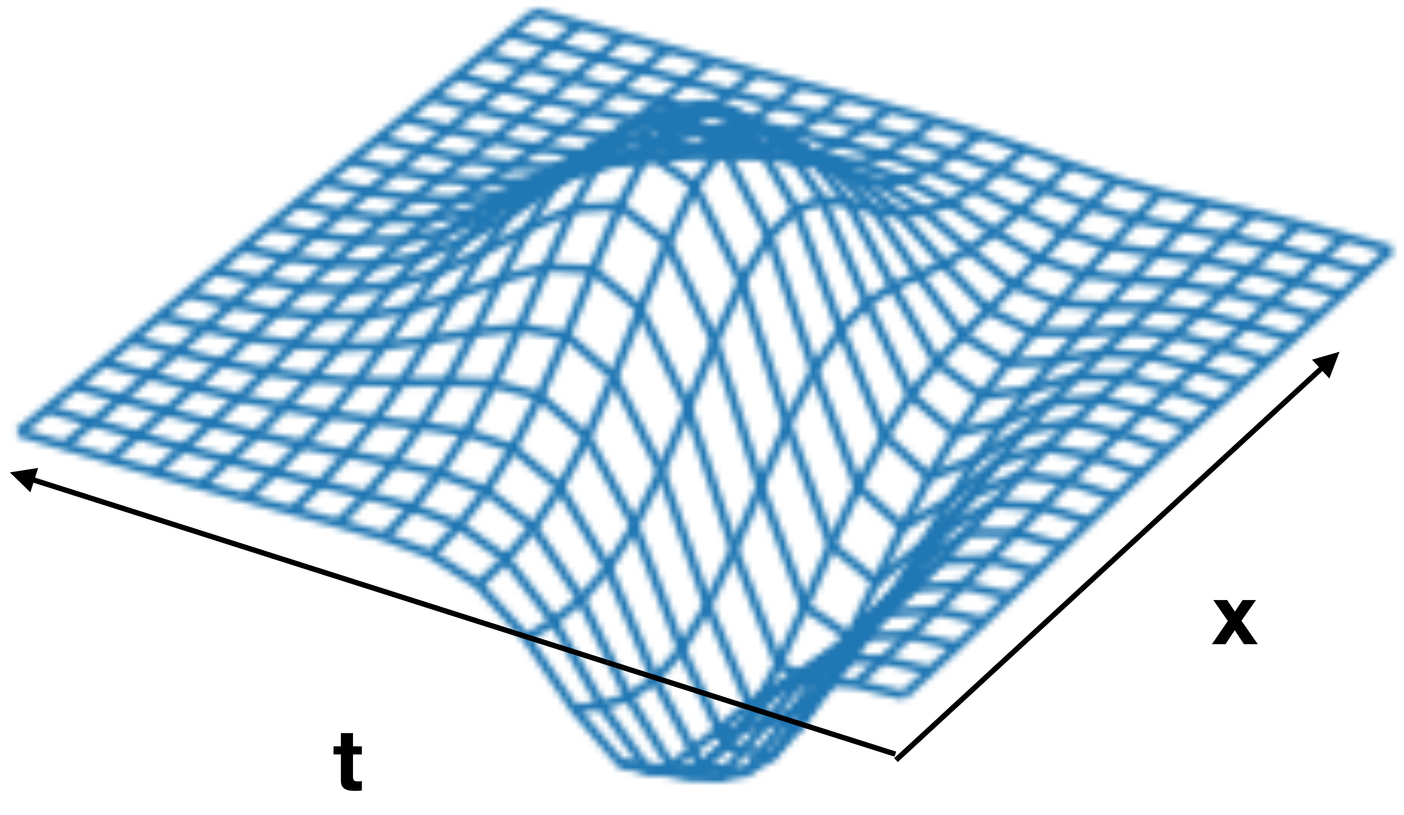
"Matter tells spacetime how to curve…"

Why do we need HPC?

Curved spacetime

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

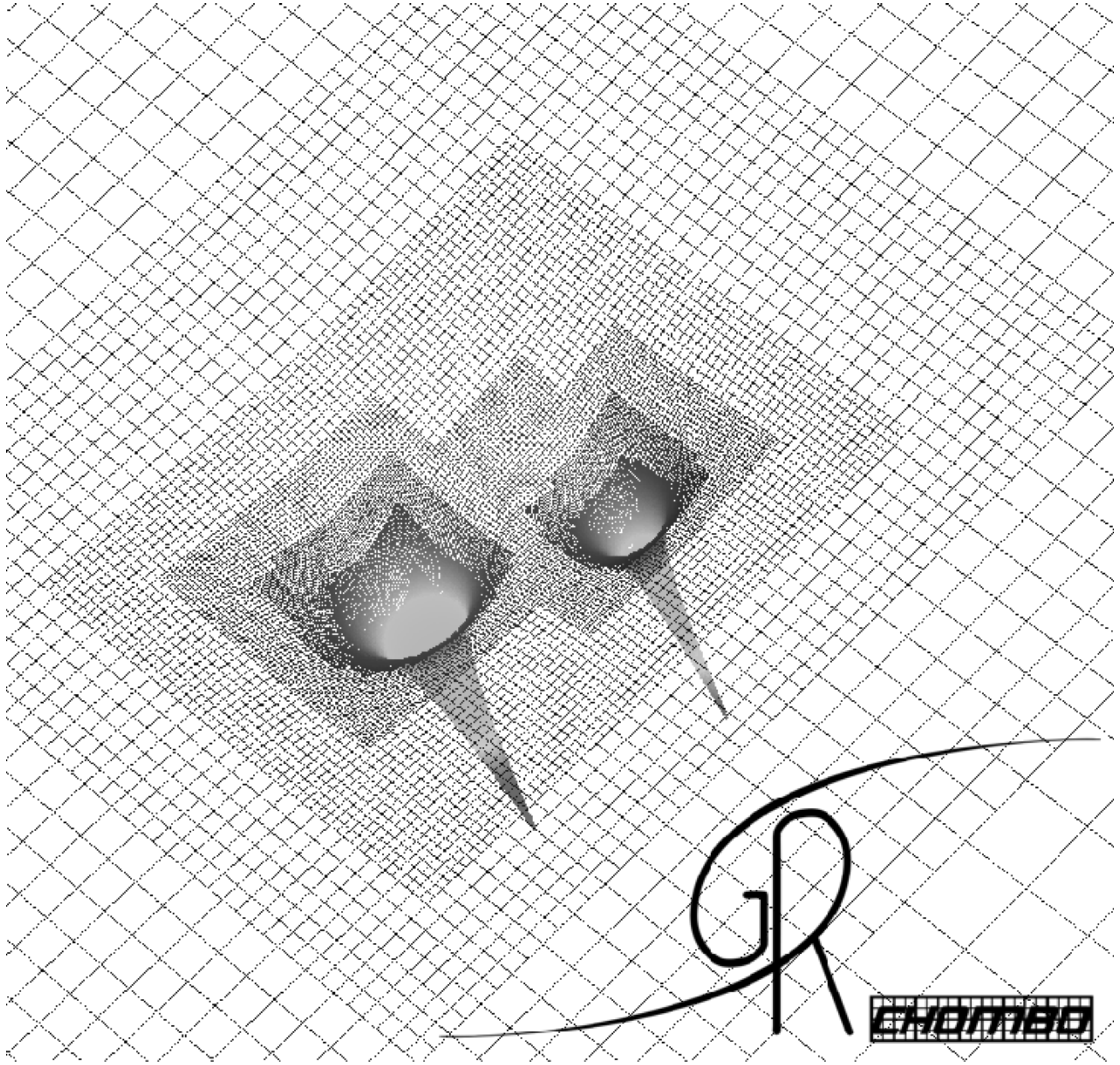
$$ds^2 = \begin{pmatrix} dt & dx & dy & dz \end{pmatrix} \underbrace{\begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$

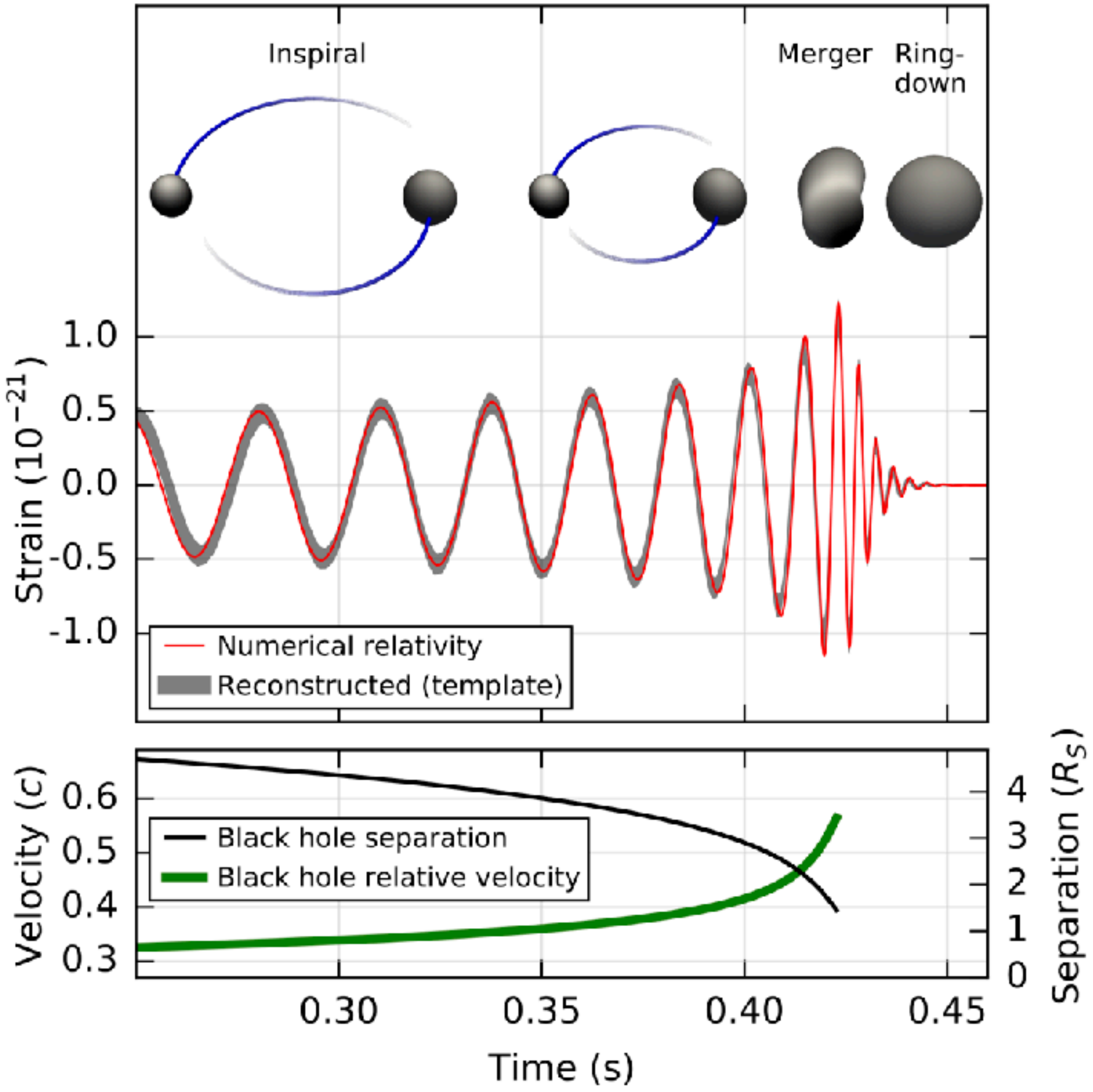


"The spacetime metric"

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

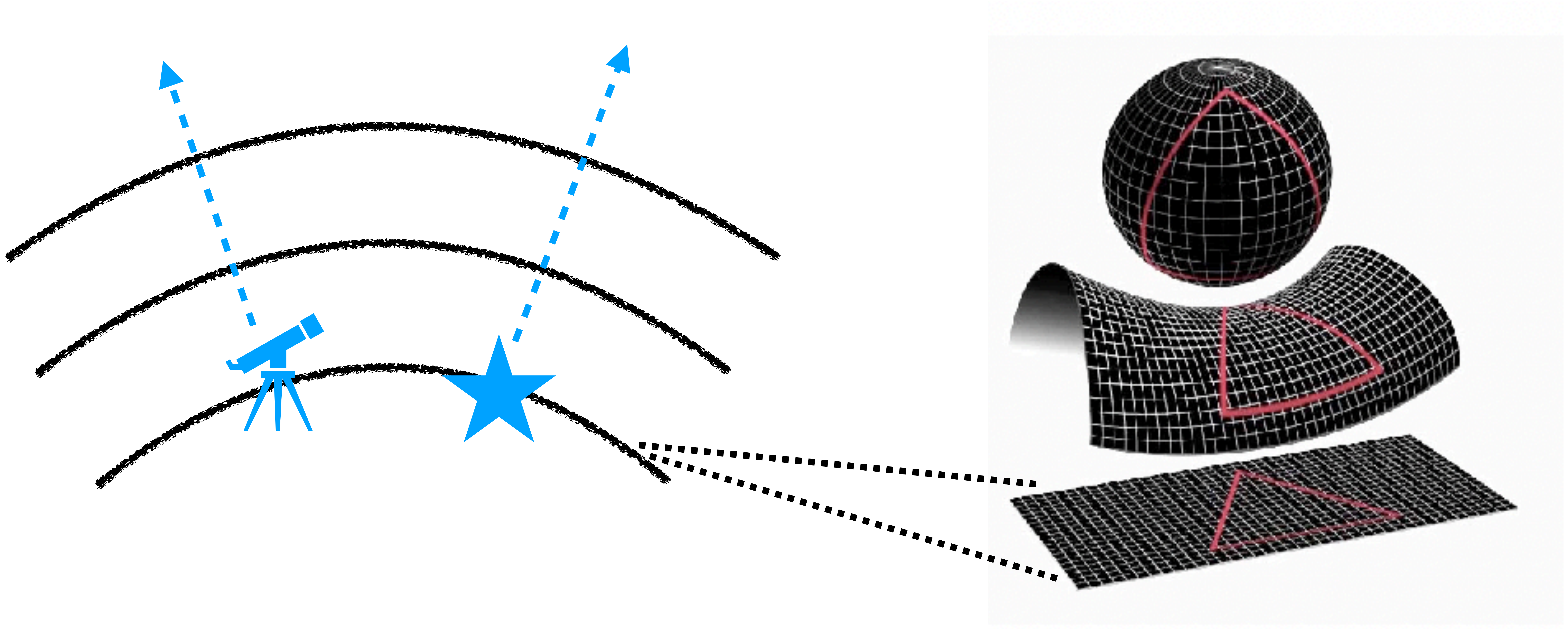
Numerical simulations play a key role in understanding black holes





What does strong gravity have to do with the beginning of time?

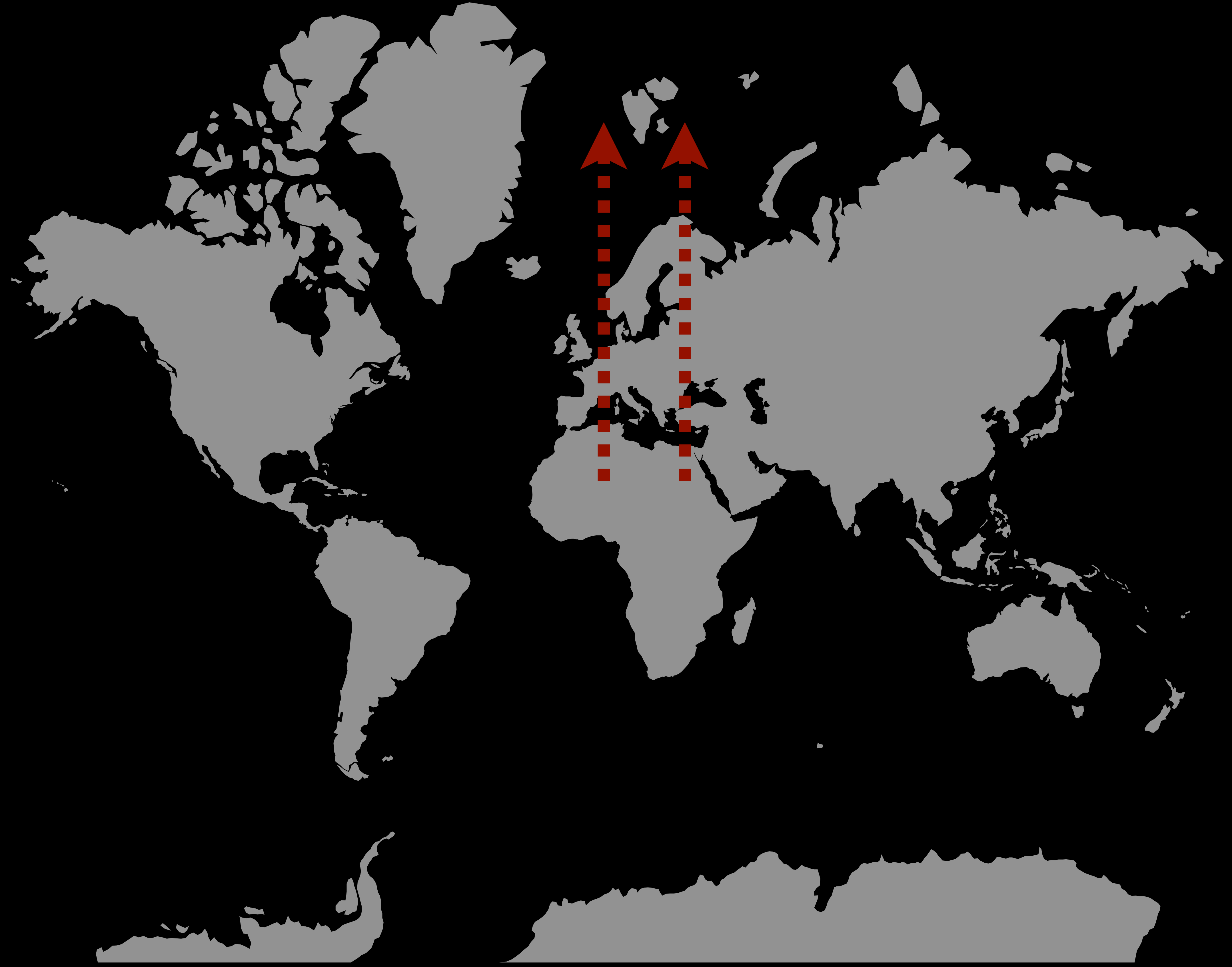
Our 4D universe is *also* a strongly curved spacetime



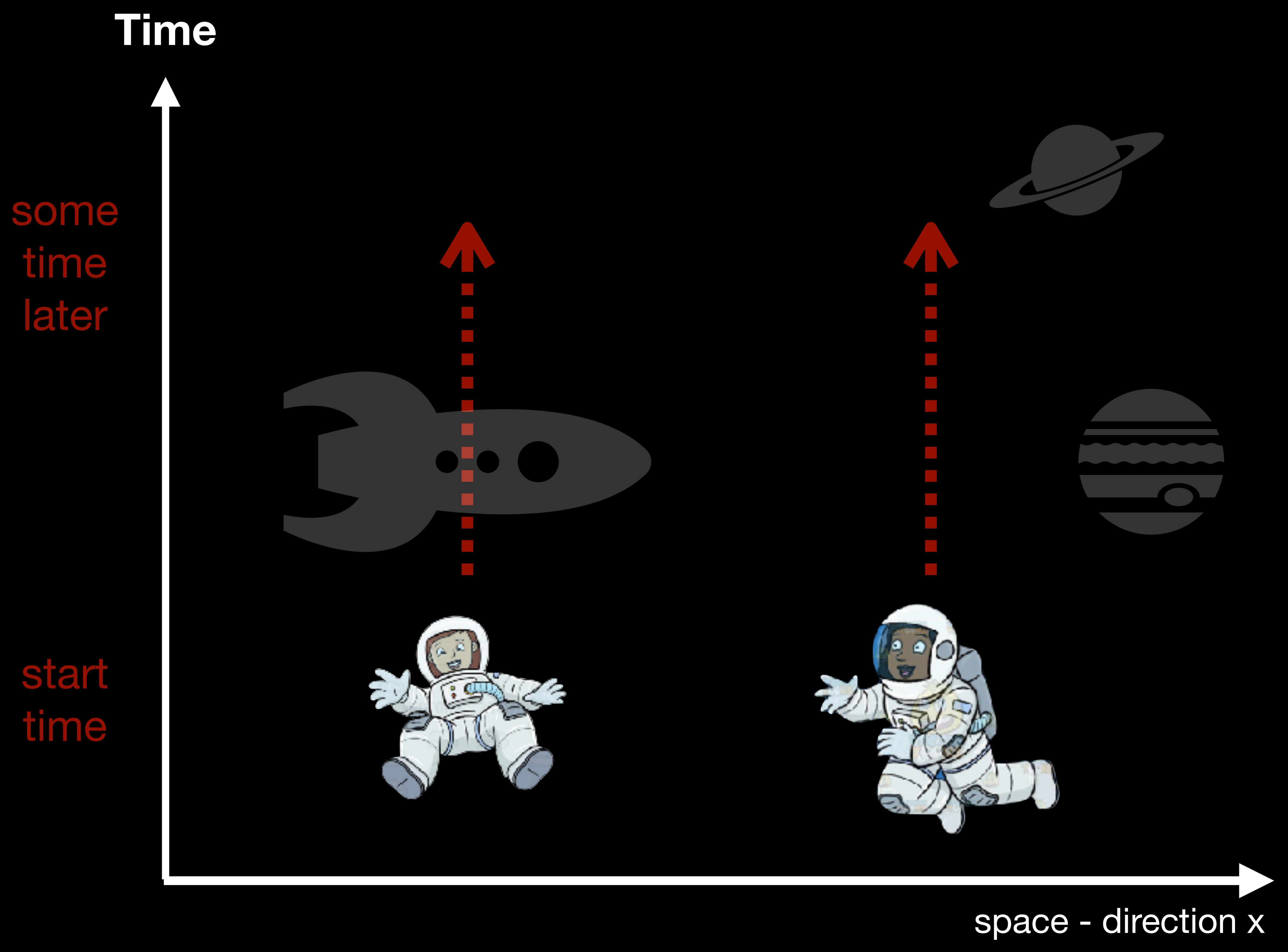
1 dimensional "time" is curved

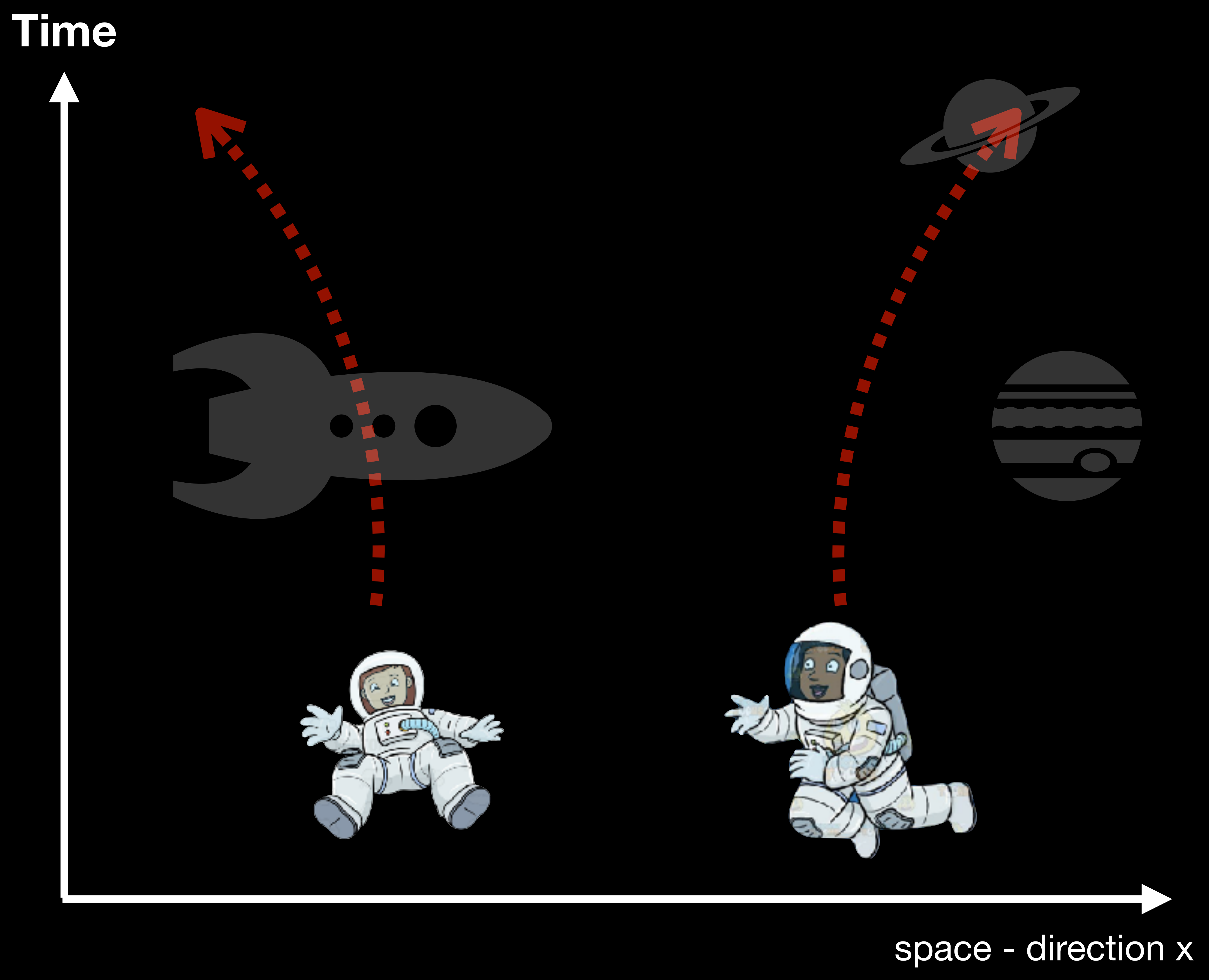
3 dimensional "space" is (roughly) flat

Flat Earth view versus curved Earth view

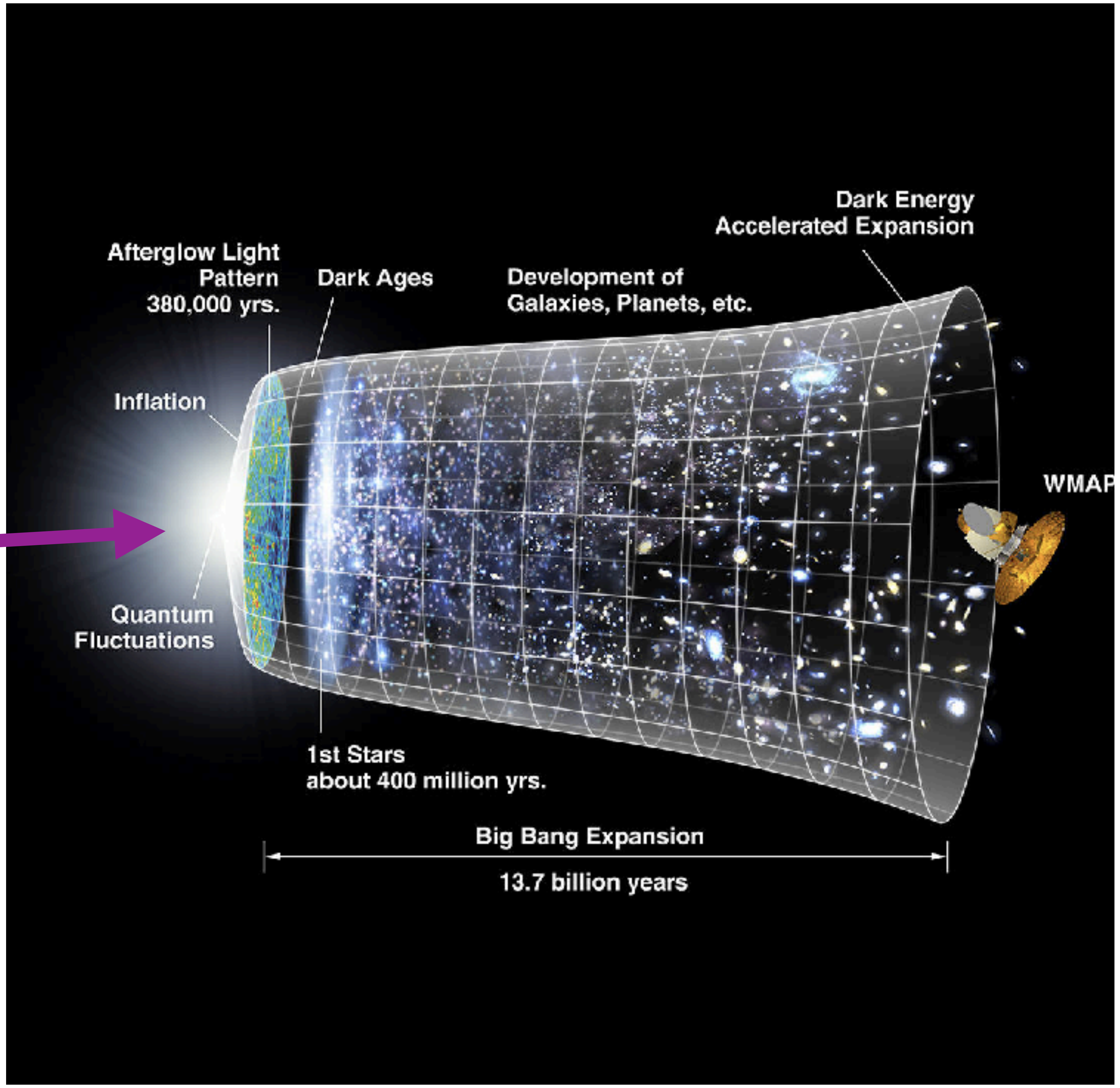


Flat Universe view versus curved Universe view





Simulations provide “numerical experiments” that explore possible beginnings of the Universe



Looking at the formation and suppression of inhomogeneity and anisotropy

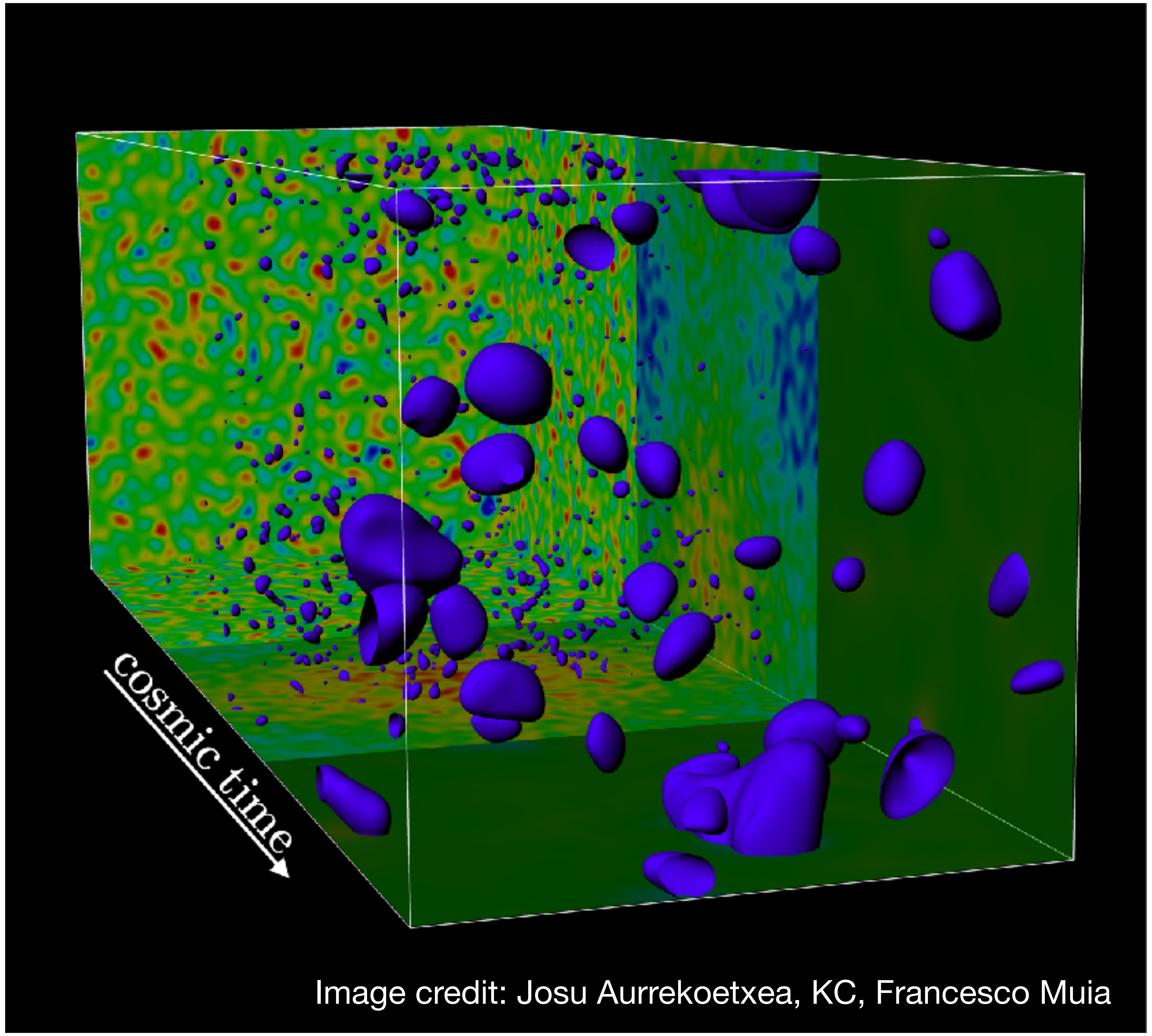


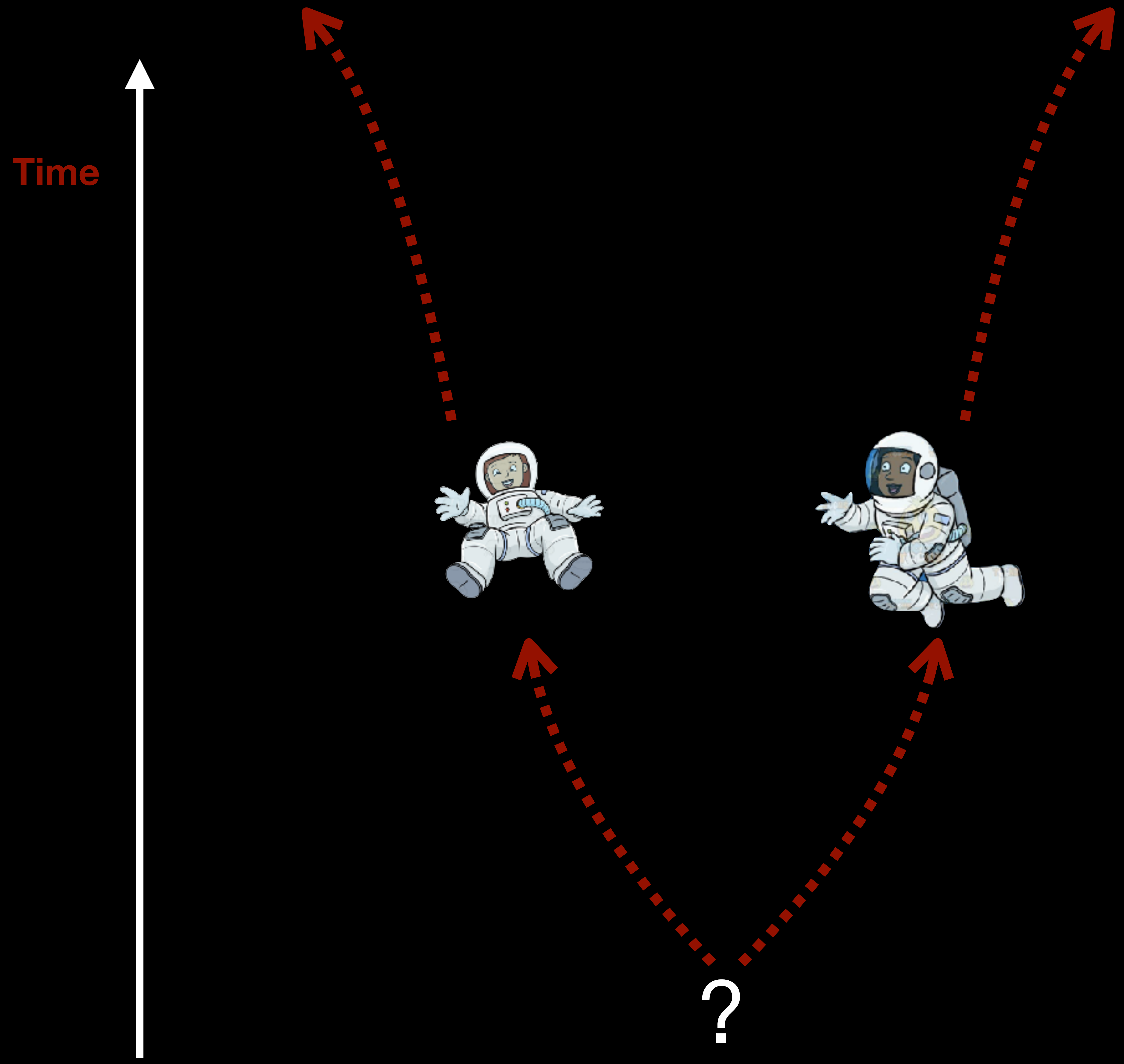
Image credit: Josu Aurrekoetxea, KC, Francesco Muia

Formation of strong overdensities during reheating using GRChombo

In particular there are two problems to solve:

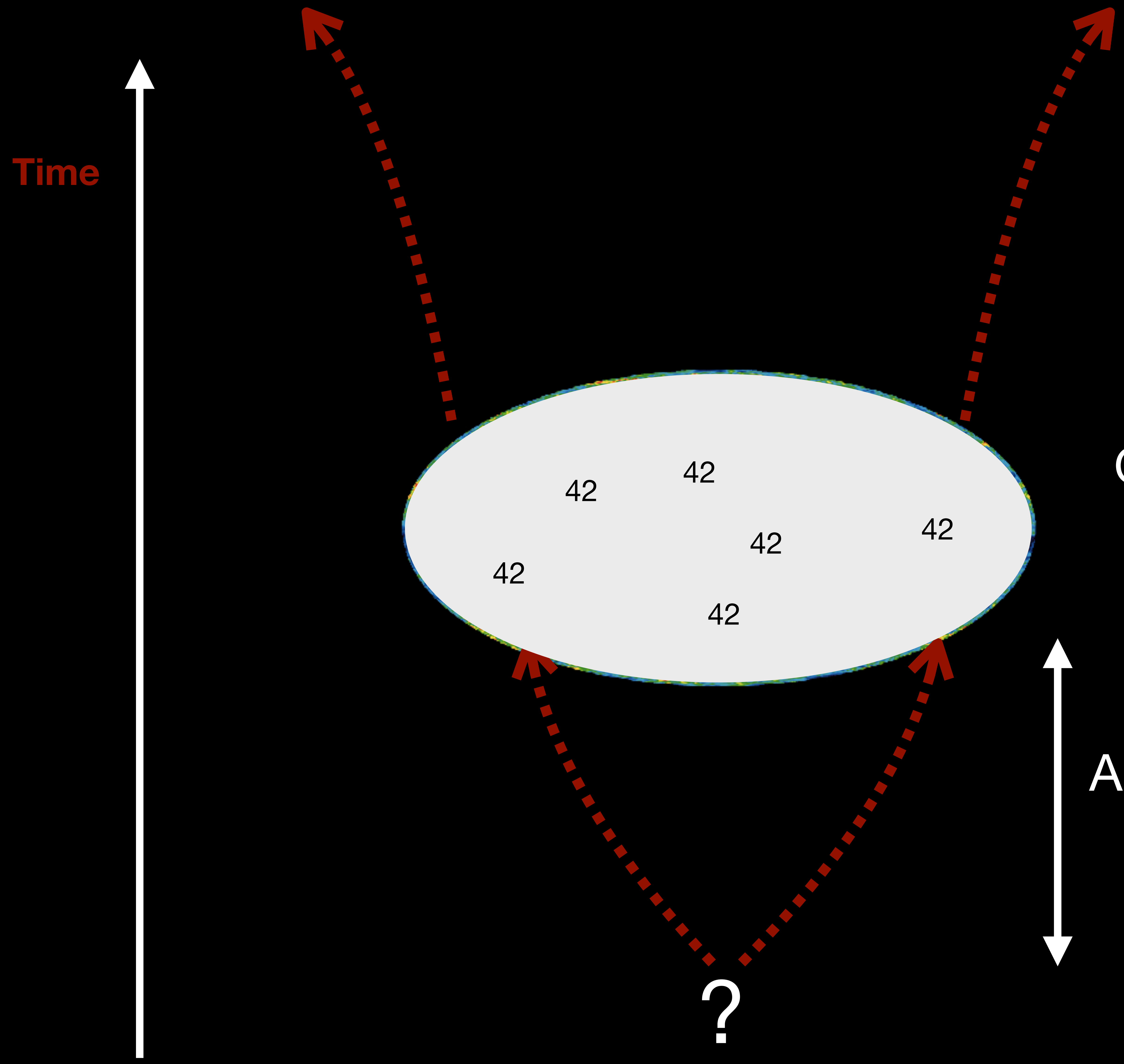
1. There is a “singularity” at the beginning of time
2. The Universe looks too uniform at early times

Problem 1 : The cosmological singularity



Penrose-Hawking
singularity theorems

Problem 2 : The uniform universe

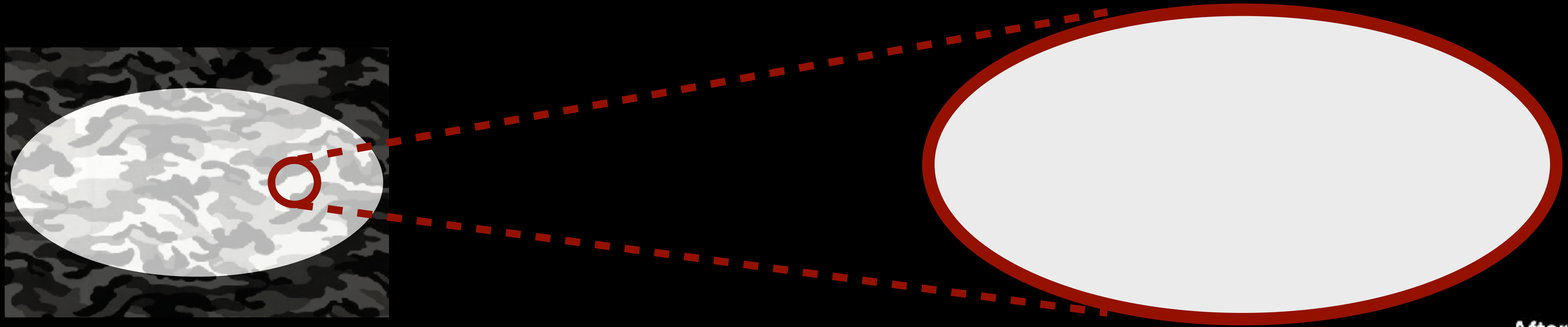


Our earliest picture of the Universe - the cosmic microwave background

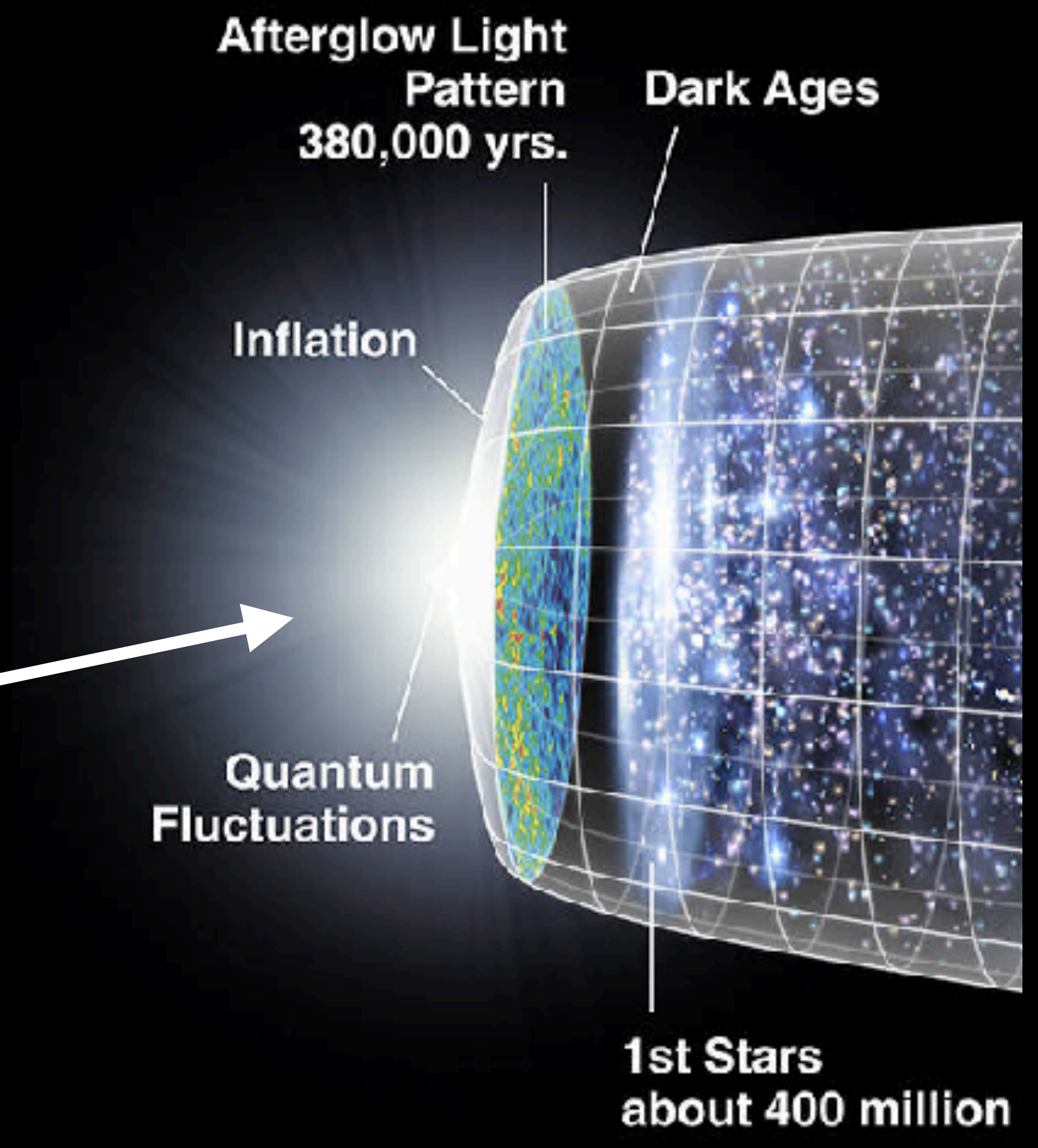
A very short time later (380,000 years)

How do we resolve these problems?

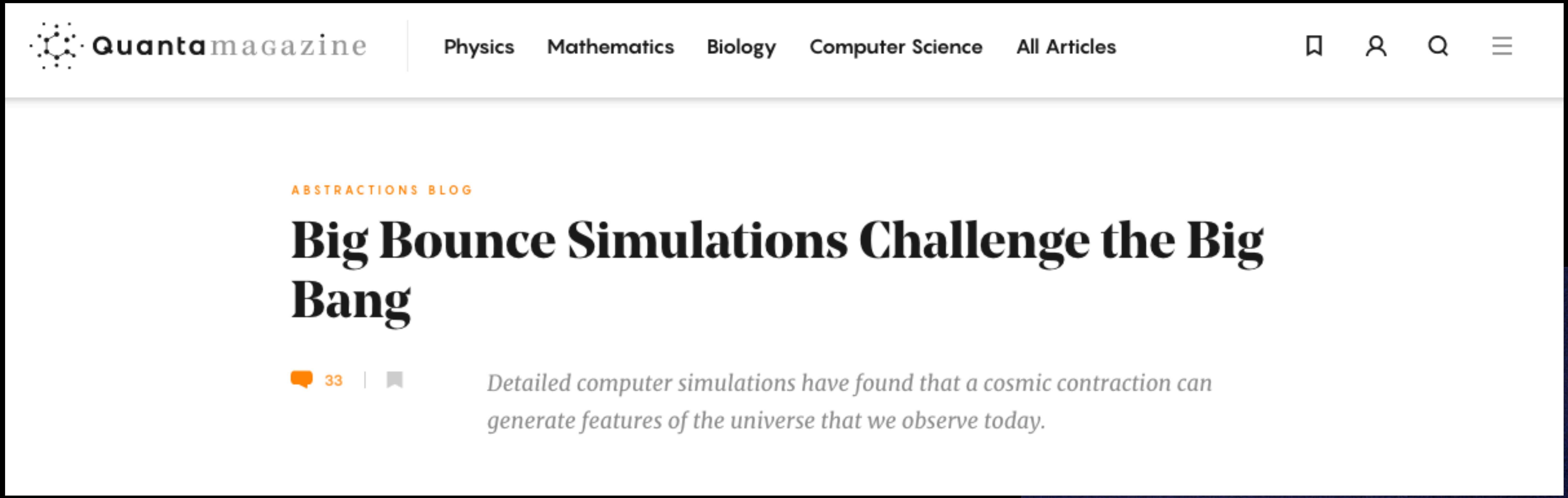
Partial solution 1 : Inflationary cosmology

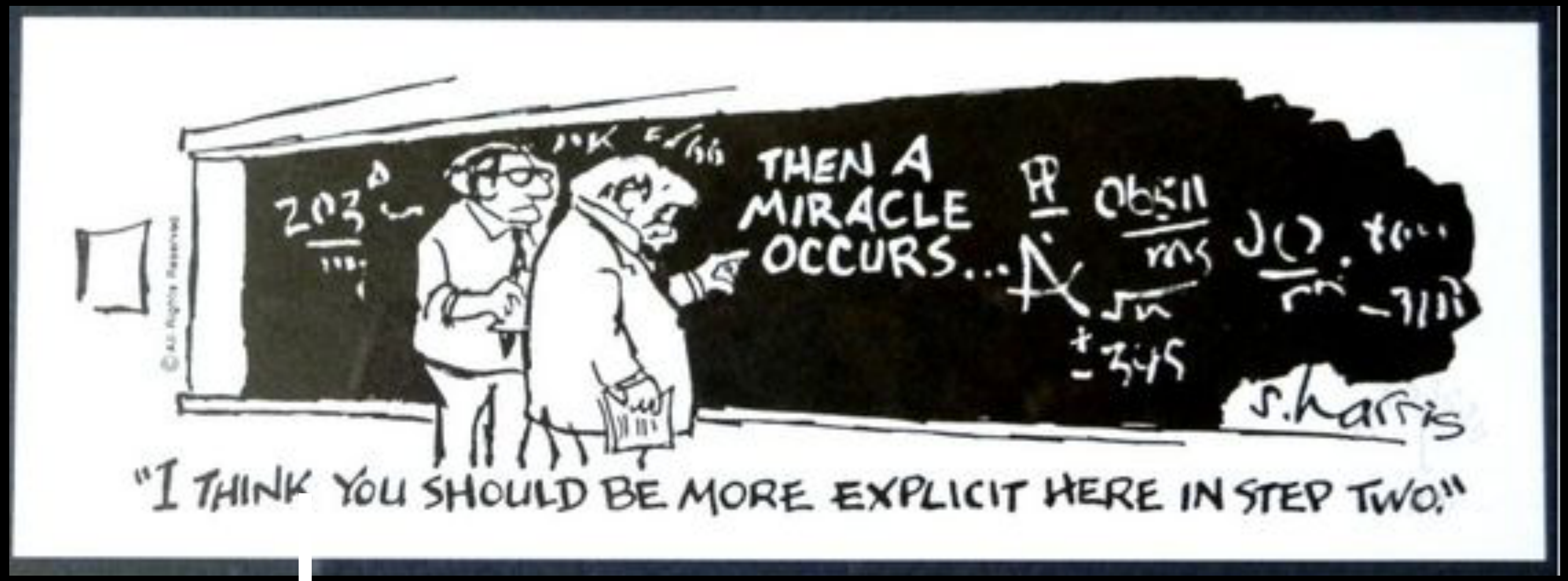


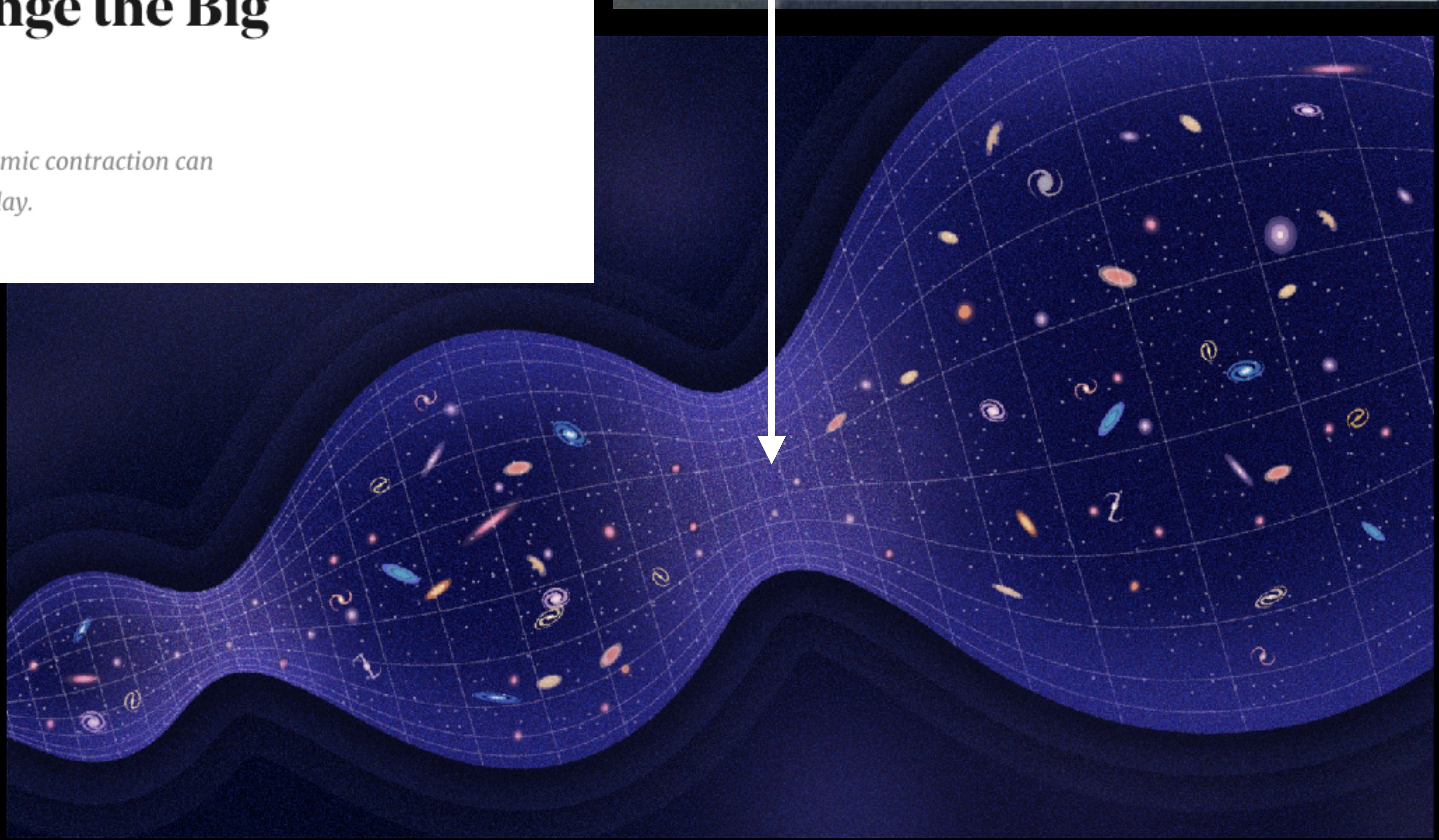
See work by: Will East, Maxence Corman, Katy Clough, Eugene Lim, Raphael Flauger, Josu Aurrekoetxea and others



Partial solution 2 : Bouncing cosmologies

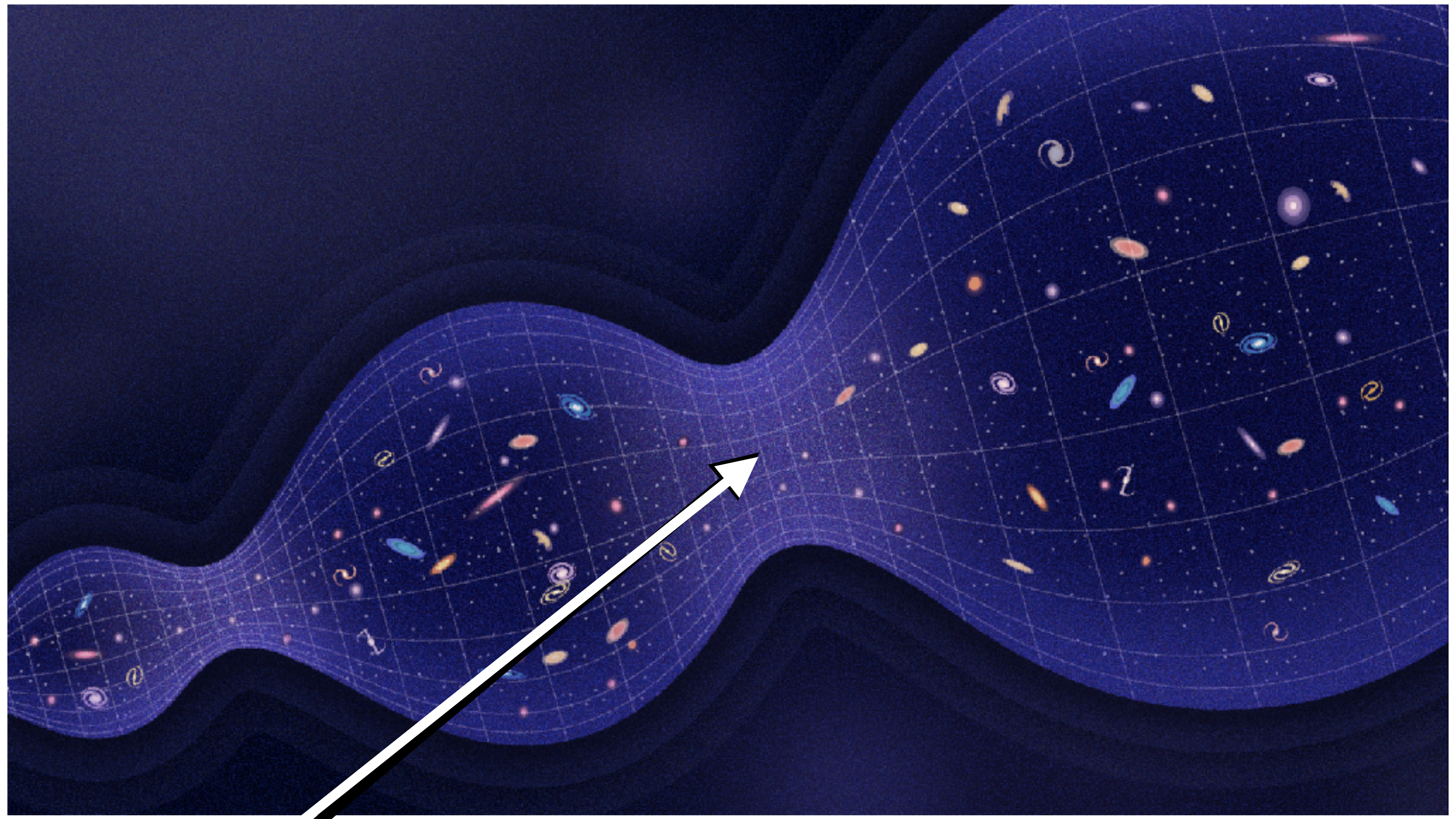


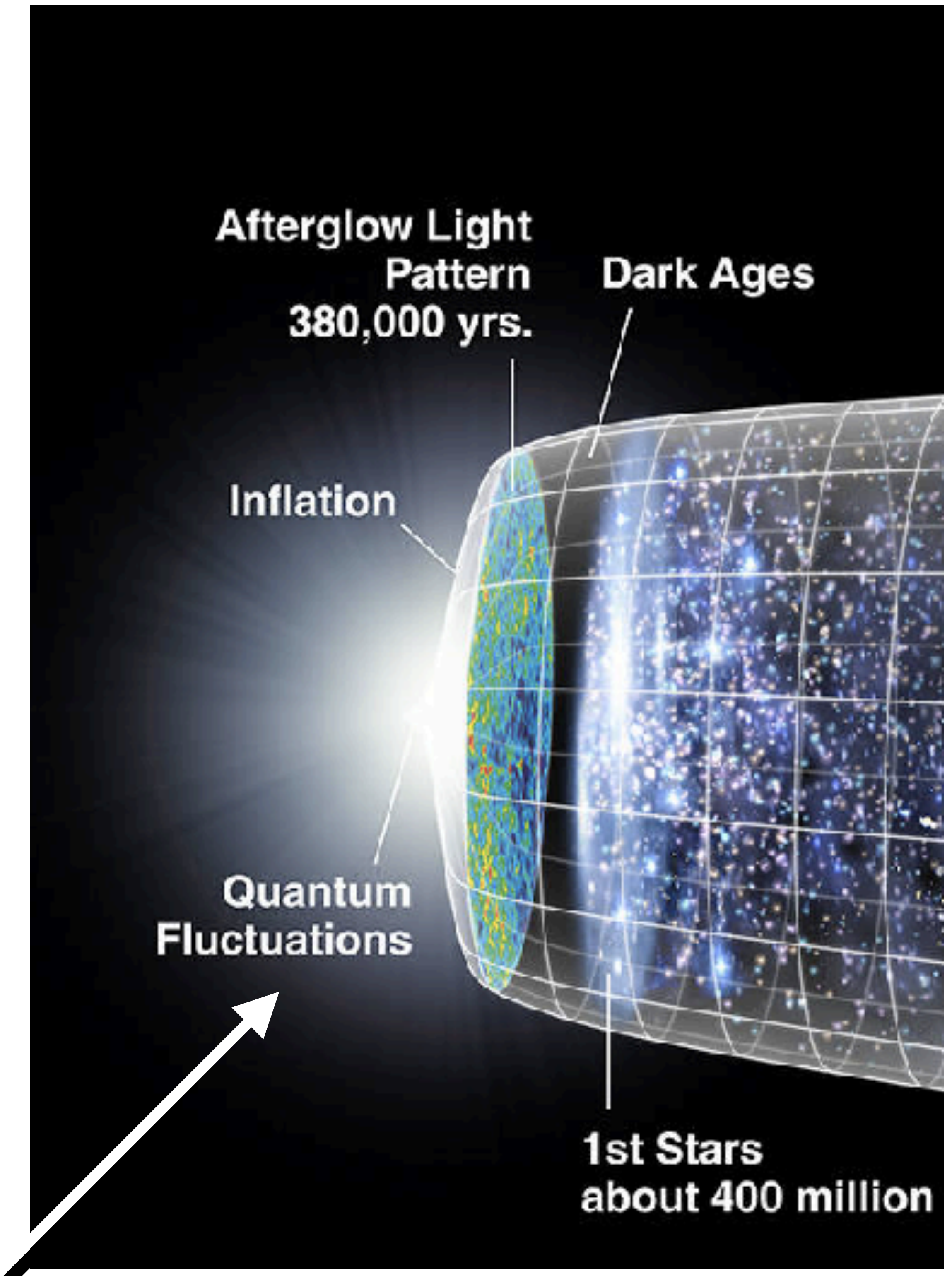




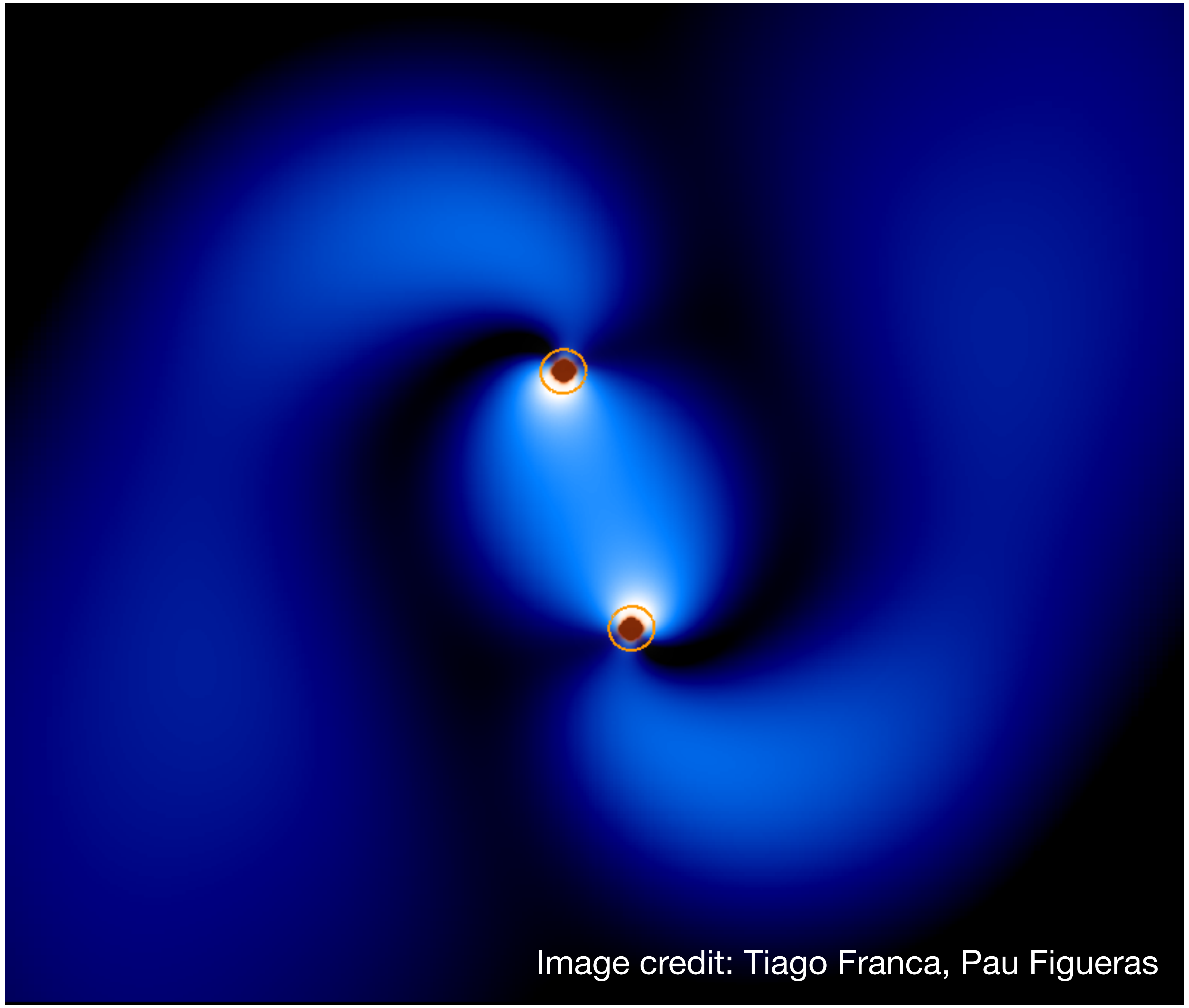
See work by: Anna Ijjas, Will Cook, David Garfinkle, Frans Pretorius, Paul Steinhardt and others

Do modifications to gravity change the story?



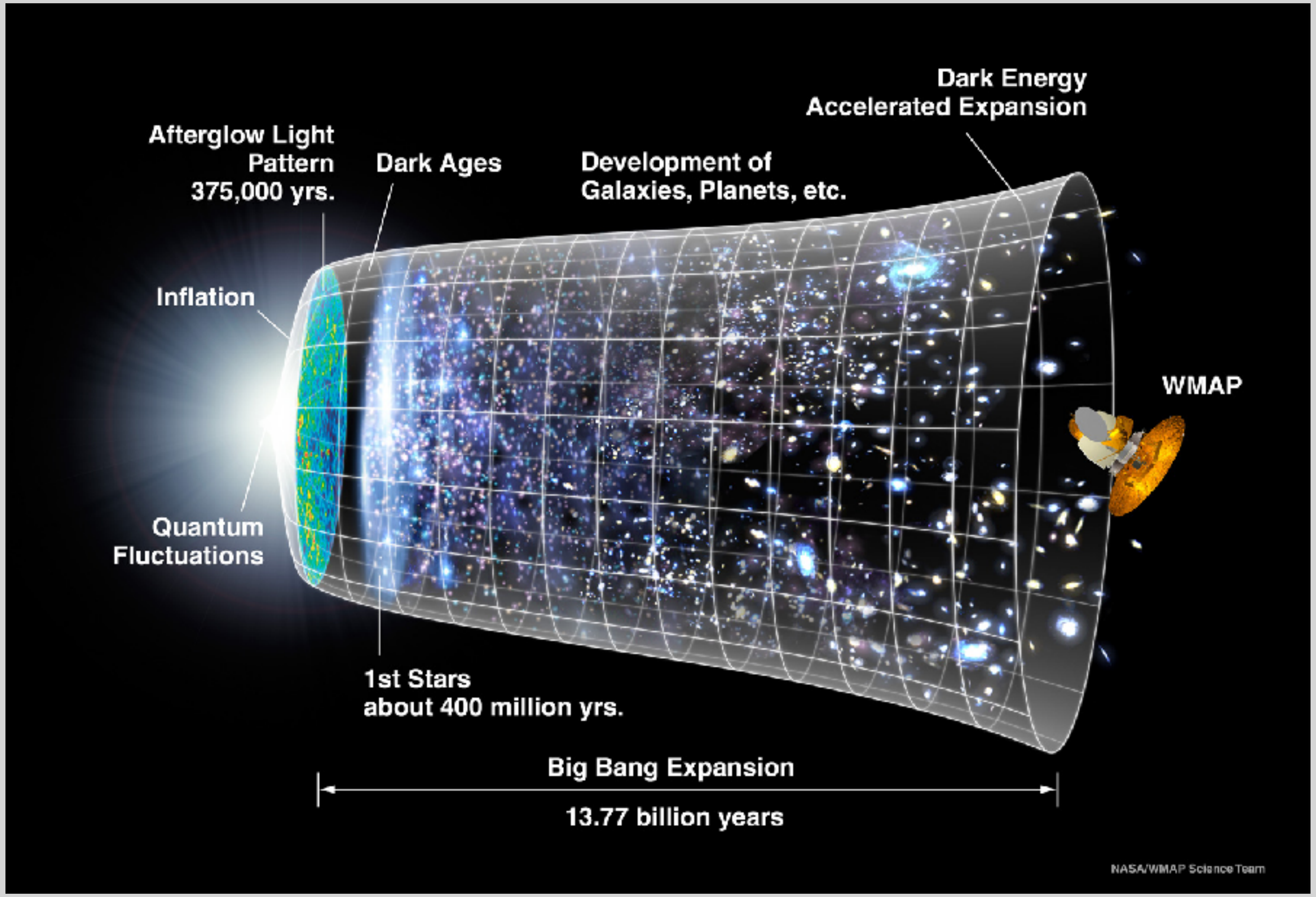


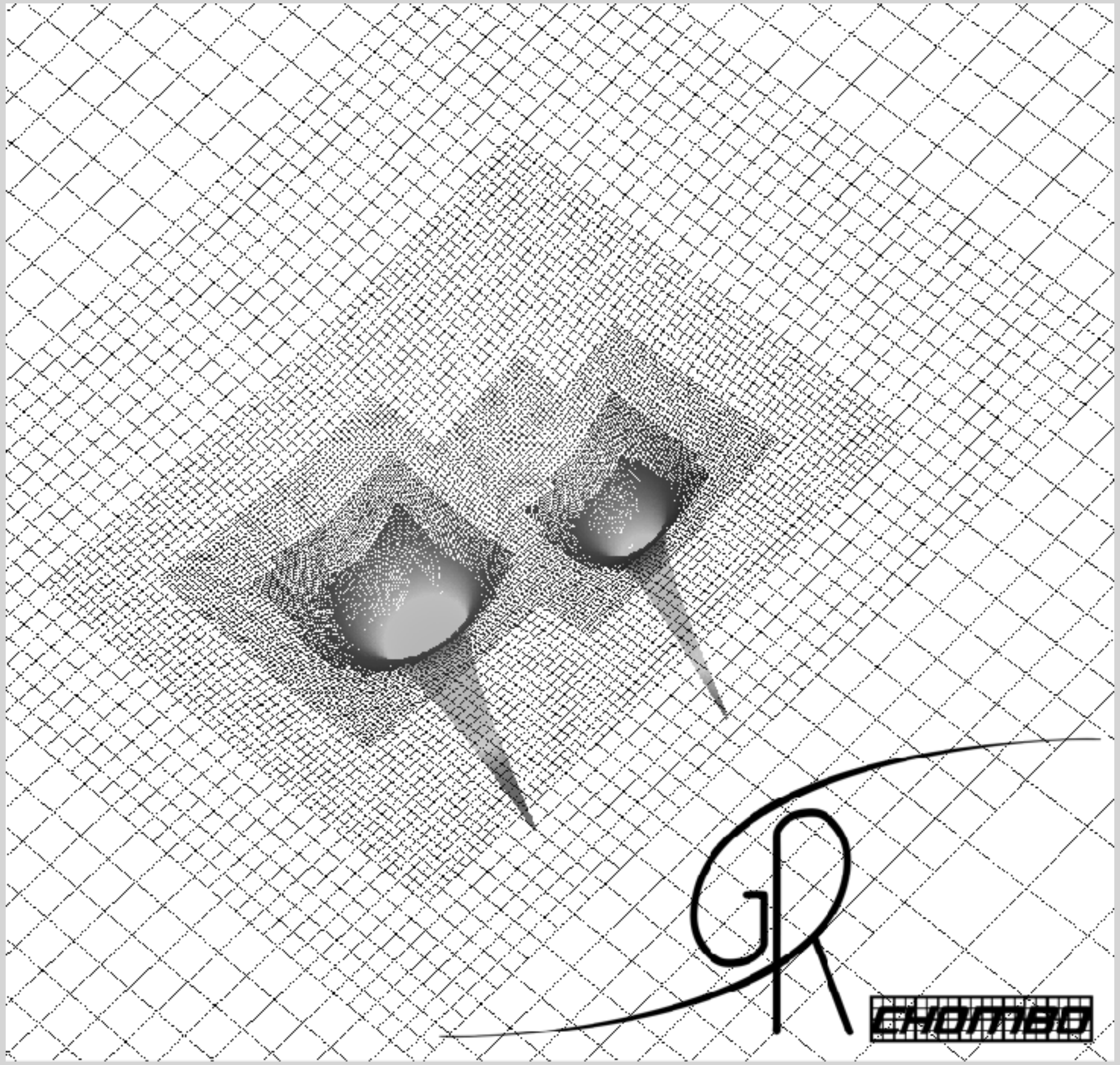
Do modifications to gravity change the story?



Conclusions

Simulations of cosmological spacetimes provide numerical experiments of how gravity behaves in extreme regimes





These simulations are technically challenging and costly - they rely on developing new numerical techniques and will need to adapt to benefit from the transition to exascale

Questions?