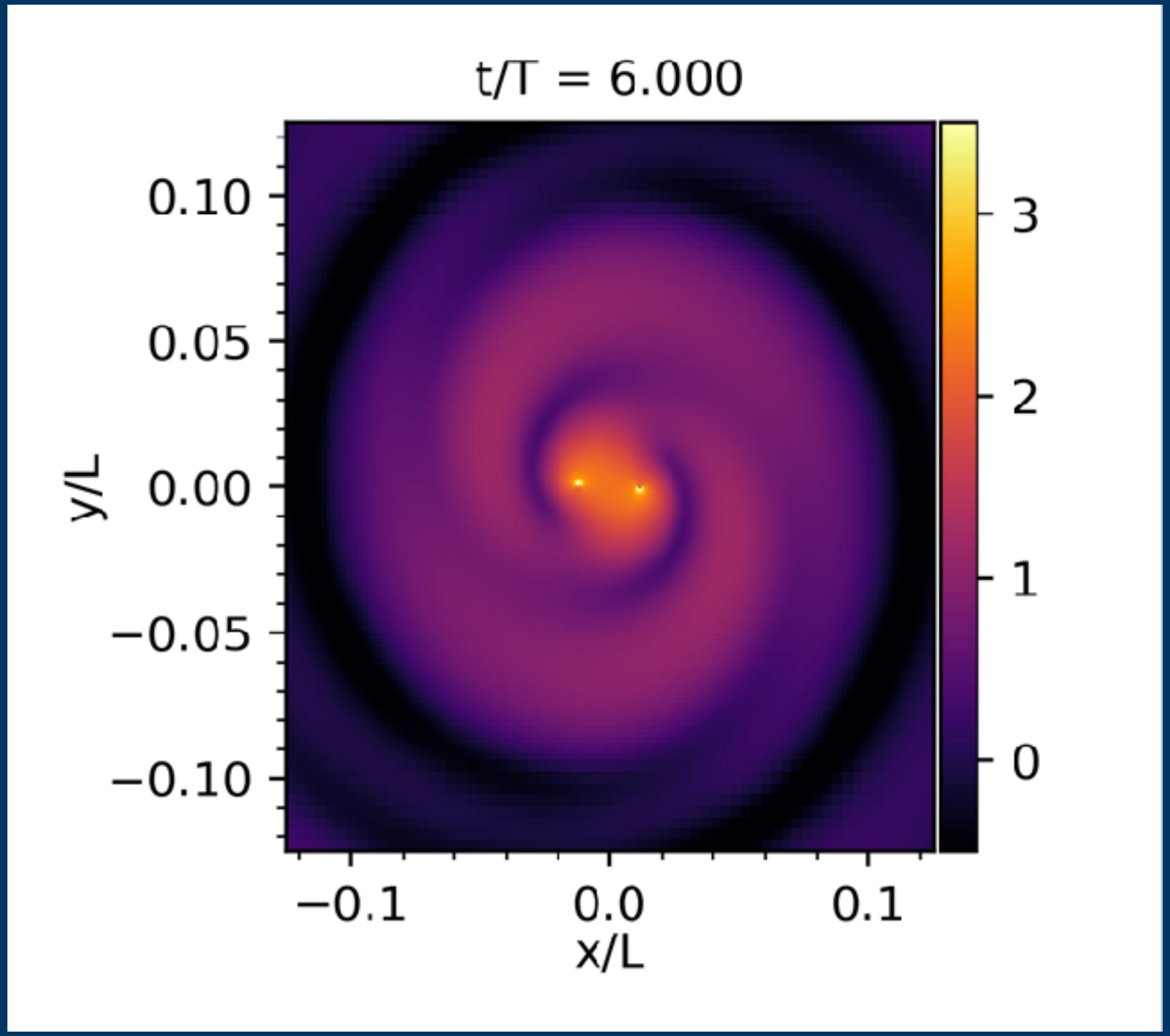
How much do dark matter initial conditions matter?

Numerical relativity simulations in DM environments

Katy Clough



Black hole merger simulations in wave dark matter environments
Jamie Bamber, Josu C. Aurrekoetxea, Katy Clough, Pedro G. Ferreira
Phys.Rev.D 107 (2023) 2, 024035 gr-qc 2210.09254

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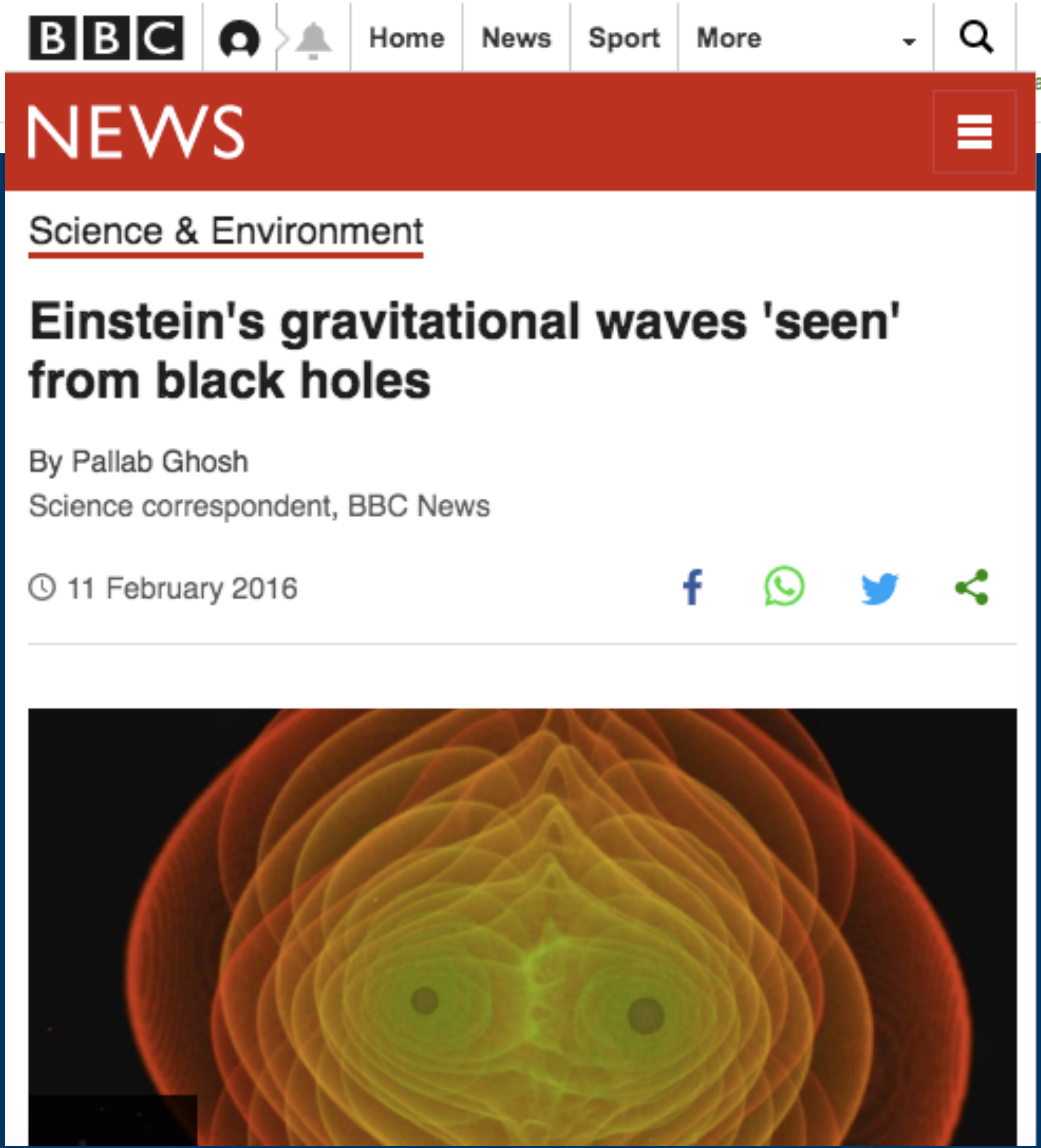
Science & Environment

First ever black hole image released

By Pallab Ghosh
Science correspondent, BBC News

6 hours ago



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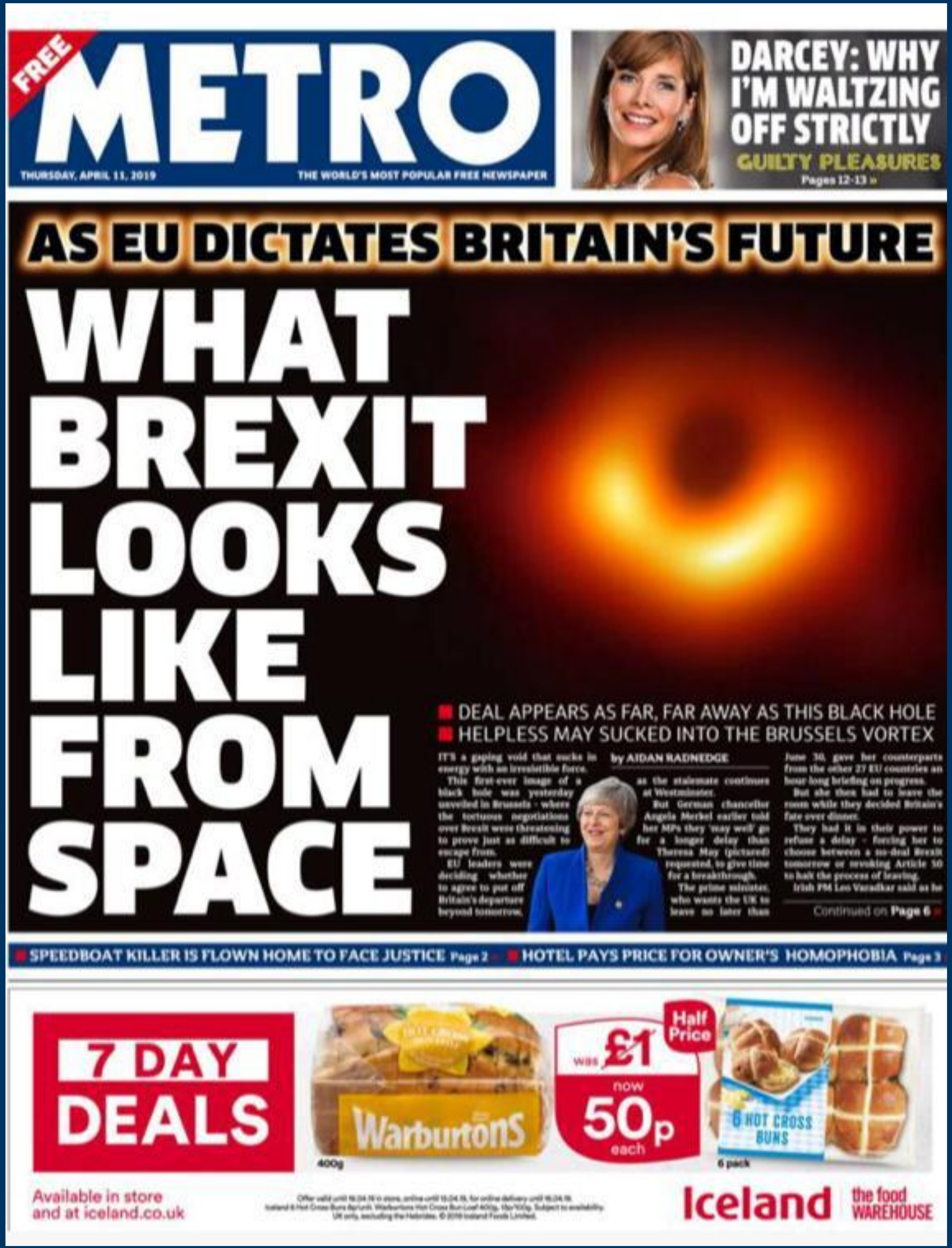
Science & Environment

Einstein's gravitational waves 'seen' from black holes

By Pallab Ghosh
Science correspondent, BBC News

11 February 2016



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AS EU DICTATES BRITAIN'S FUTURE

WHAT BREXIT LOOKS LIKE FROM SPACE

- DEAL APPEARS AS FAR, FAR AWAY AS THIS BLACK HOLE
- HELPLESS MAY SUCKED INTO THE BRUSSELS VORTEX

by AIDAN RADNEDGE

IT'S a gaping void that sucks in energy with an irresistible force.

This first-ever image of a black hole was yesterday unveiled in Brussels - where the tortuous negotiations over Brexit were threatening to prove just as difficult to escape from.

EU leaders were deciding whether to agree to put off Britain's departure beyond tomorrow, as the stalemate continues at Westminster.

But German chancellor Angela Merkel earlier told her MPs they 'may well' go for a longer delay than Theresa May (pictured) requested, to give time for a breakthrough.

The prime minister, who wants the UK to leave no later than June 30, gave her counterparts from the other 27 EU countries an hour-long briefing on progress.

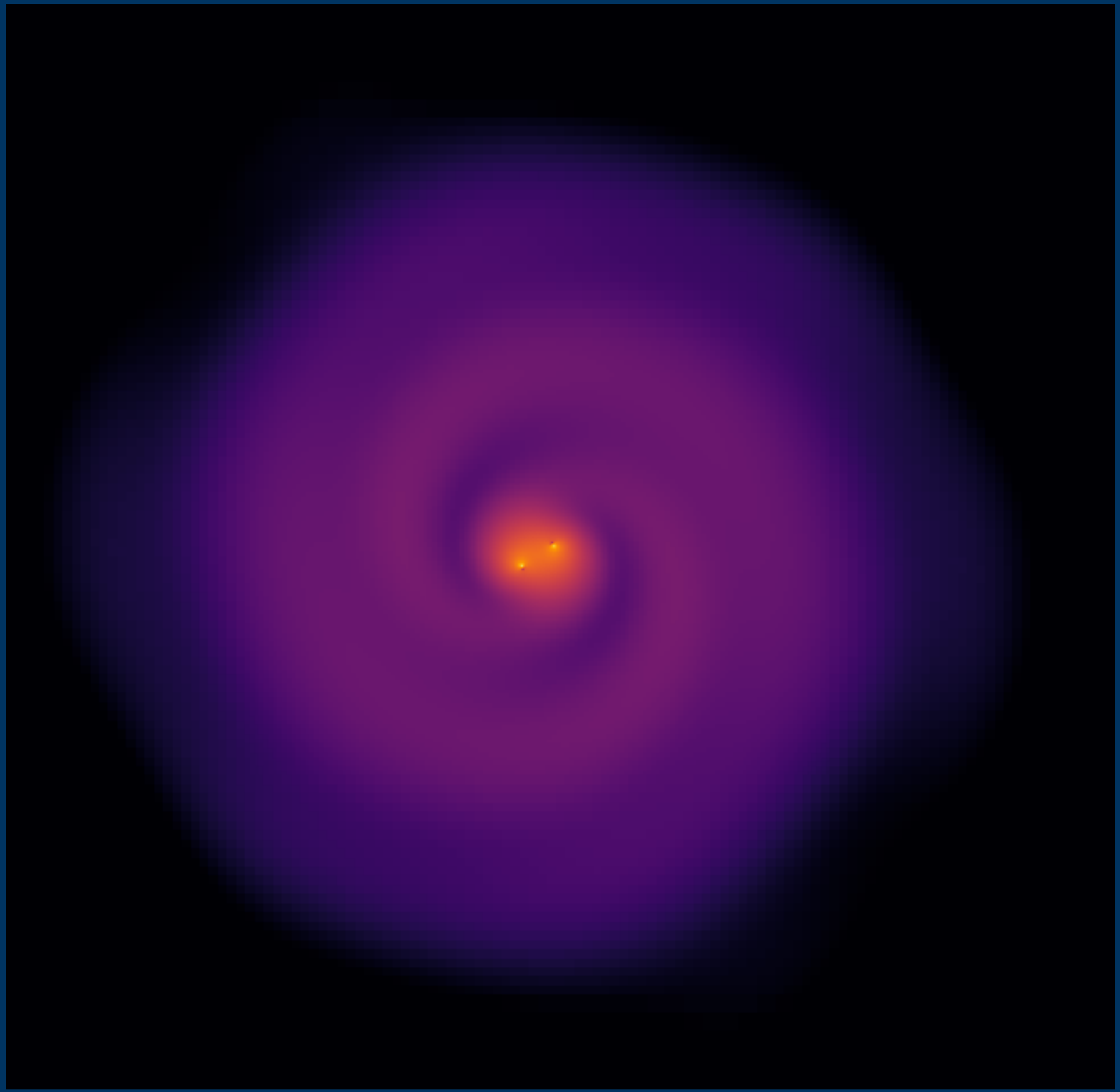
But she then had to leave the room while they decided Britain's fate over dinner.

They had it in their power to refuse a delay - forcing her to choose between a no-deal Brexit tomorrow or revoking Article 50 to halt the process of leaving.

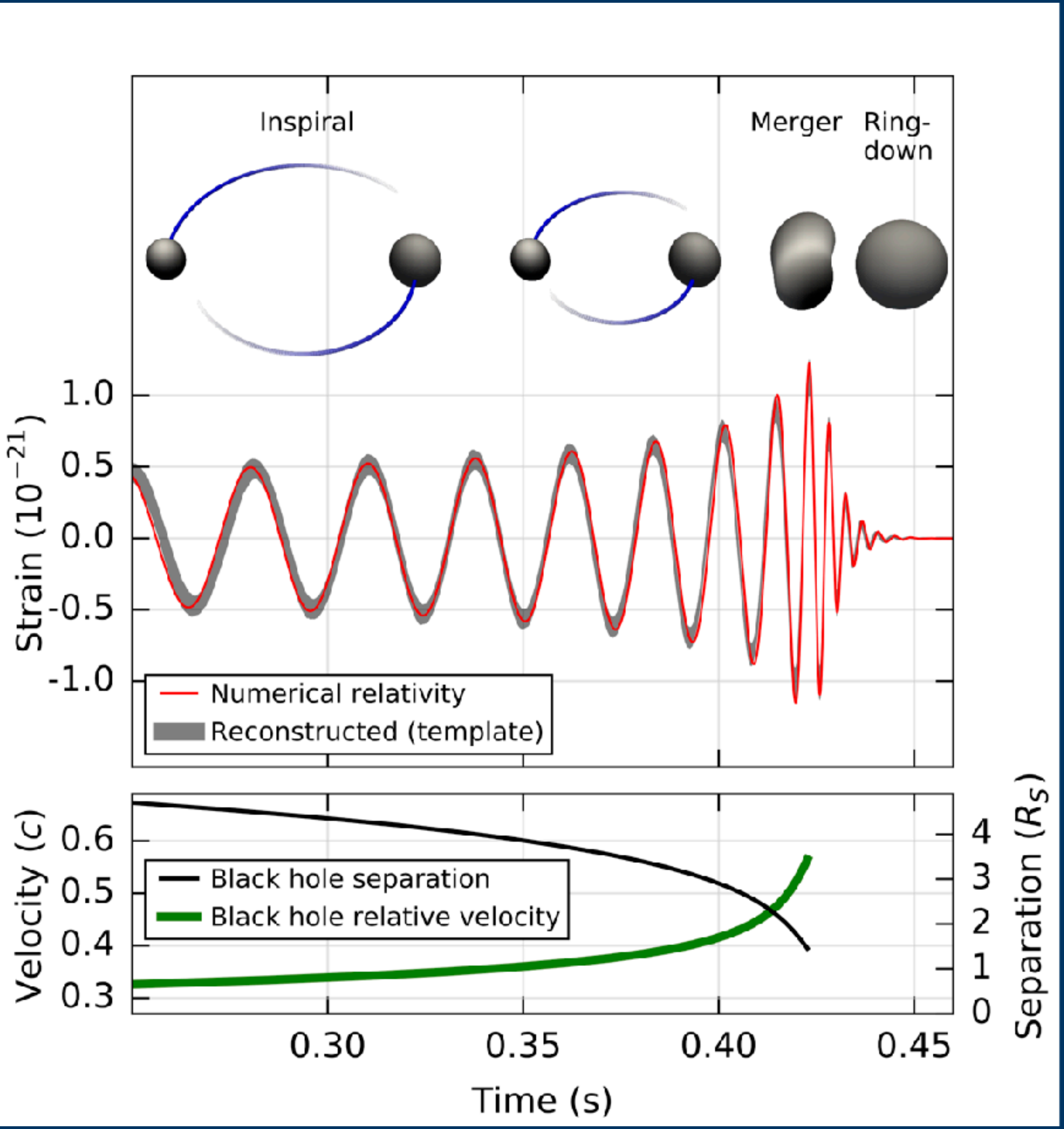
Irish PM Leo Varadkar said as he

Continued on Page 6 »

SPEEDBOAT KILLER IS FLOWN HOME TO FACE JUSTICE Page 2 | HOTEL PAYS PRICE FOR OWNER'S HOMOPHOBIA Page 3



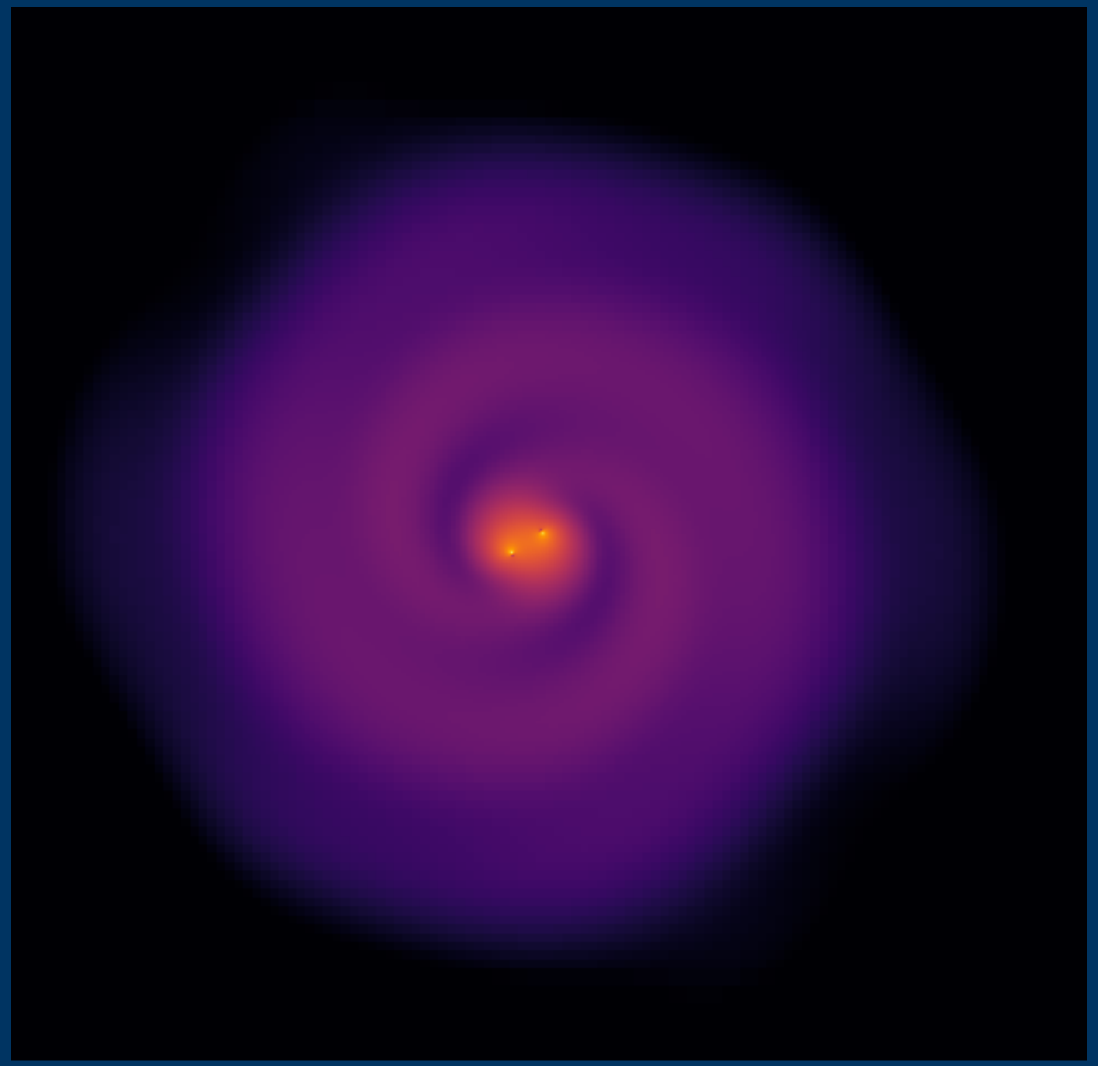
Interesting idea:
Can we use this new data to learn about the environments of the black holes that we observe?



LIGO 2016

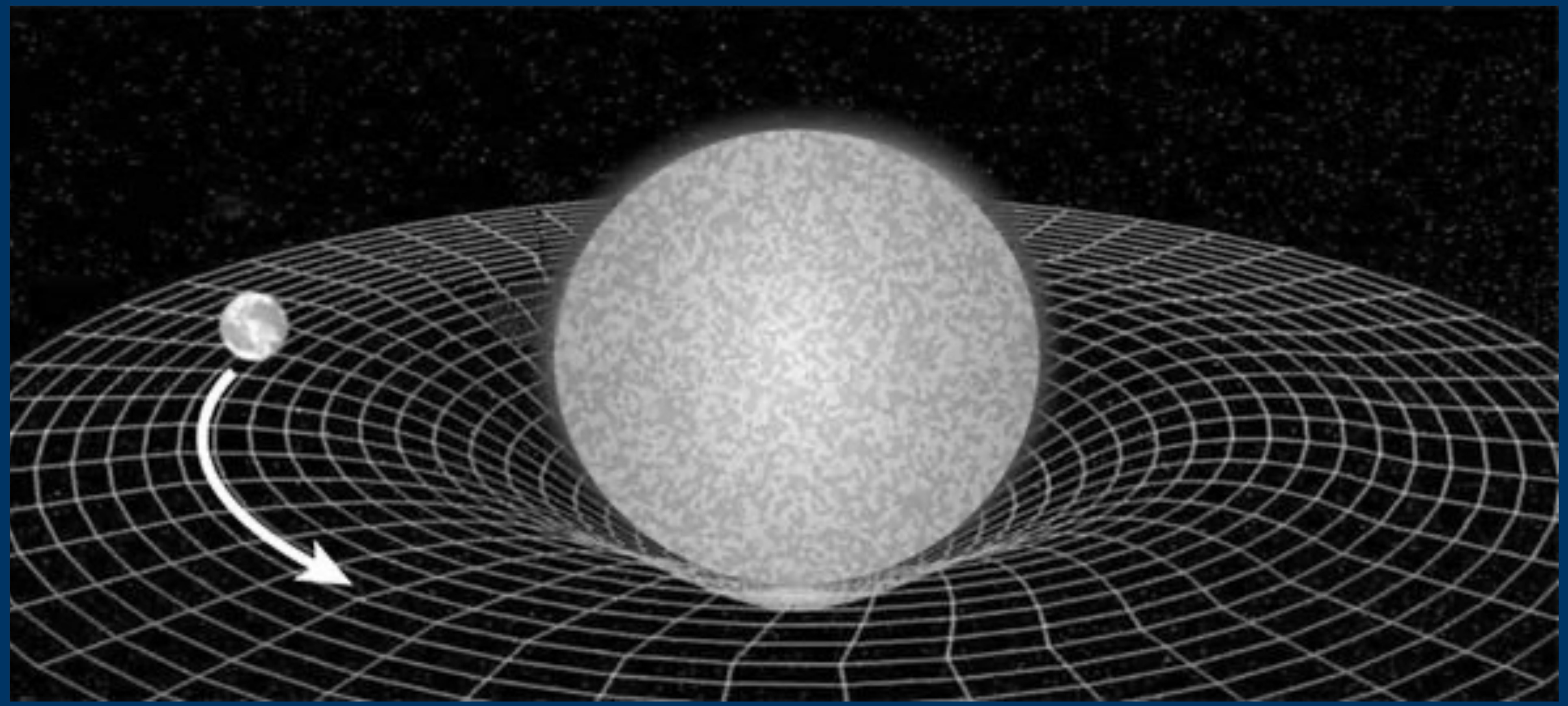
More concrete idea: Having additional matter around BHs will change the different parts of the waveform in a distinctive way

Radiation of the environment



Dynamical friction and accretion

Change in curvature of space results in new trajectories

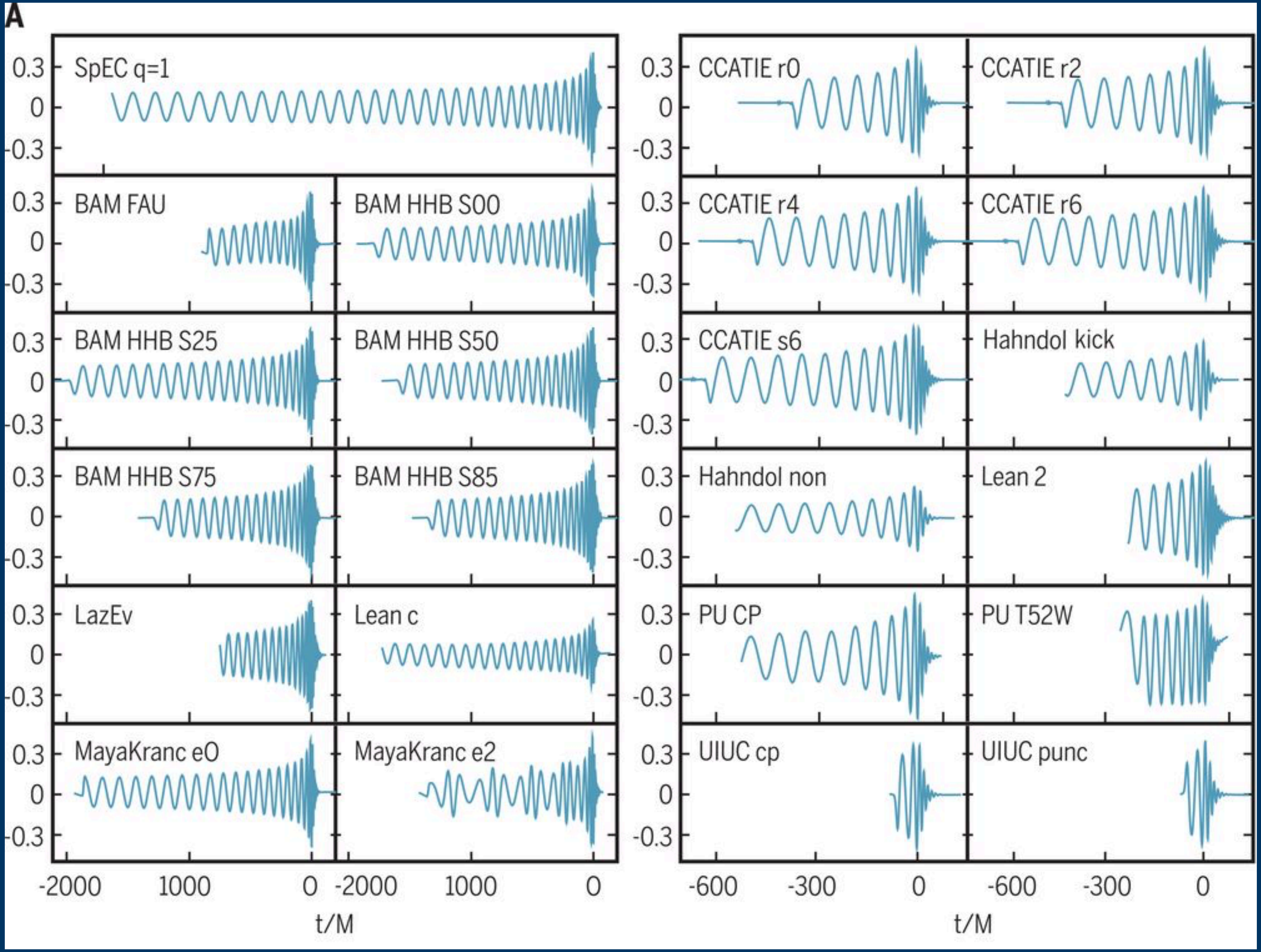


Plan:

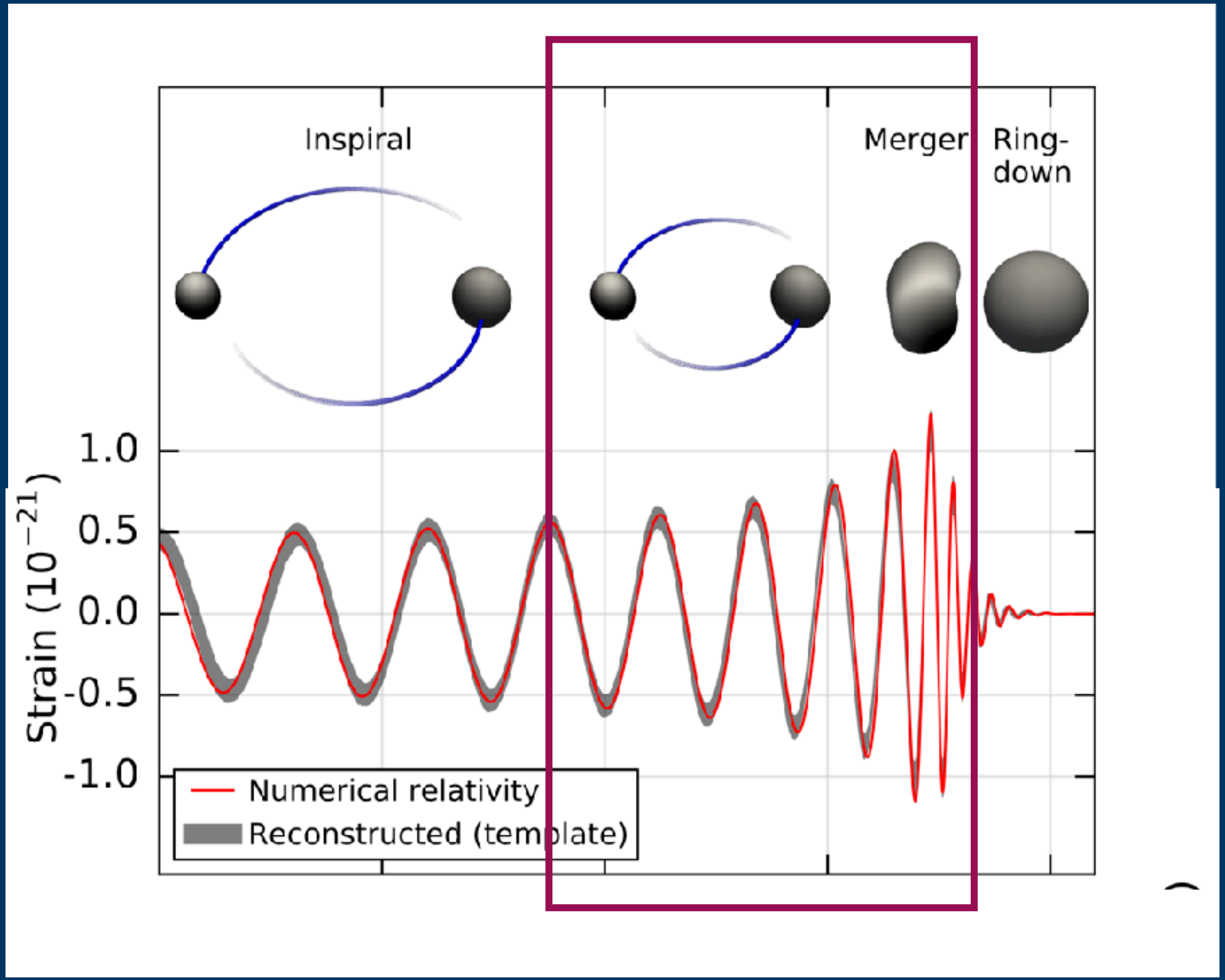
- Generate GW templates with environments

- Match them to signals

- Detect environments



Numerical relativity part



Potential problem: How important is it to have the “right” initial conditions for our simulations?

Concern:

We are not ready to generate template banks and do inference about the effects of matter environments on the merger part of the signal because we don't have control over our initial conditions and understand how they affect the results.

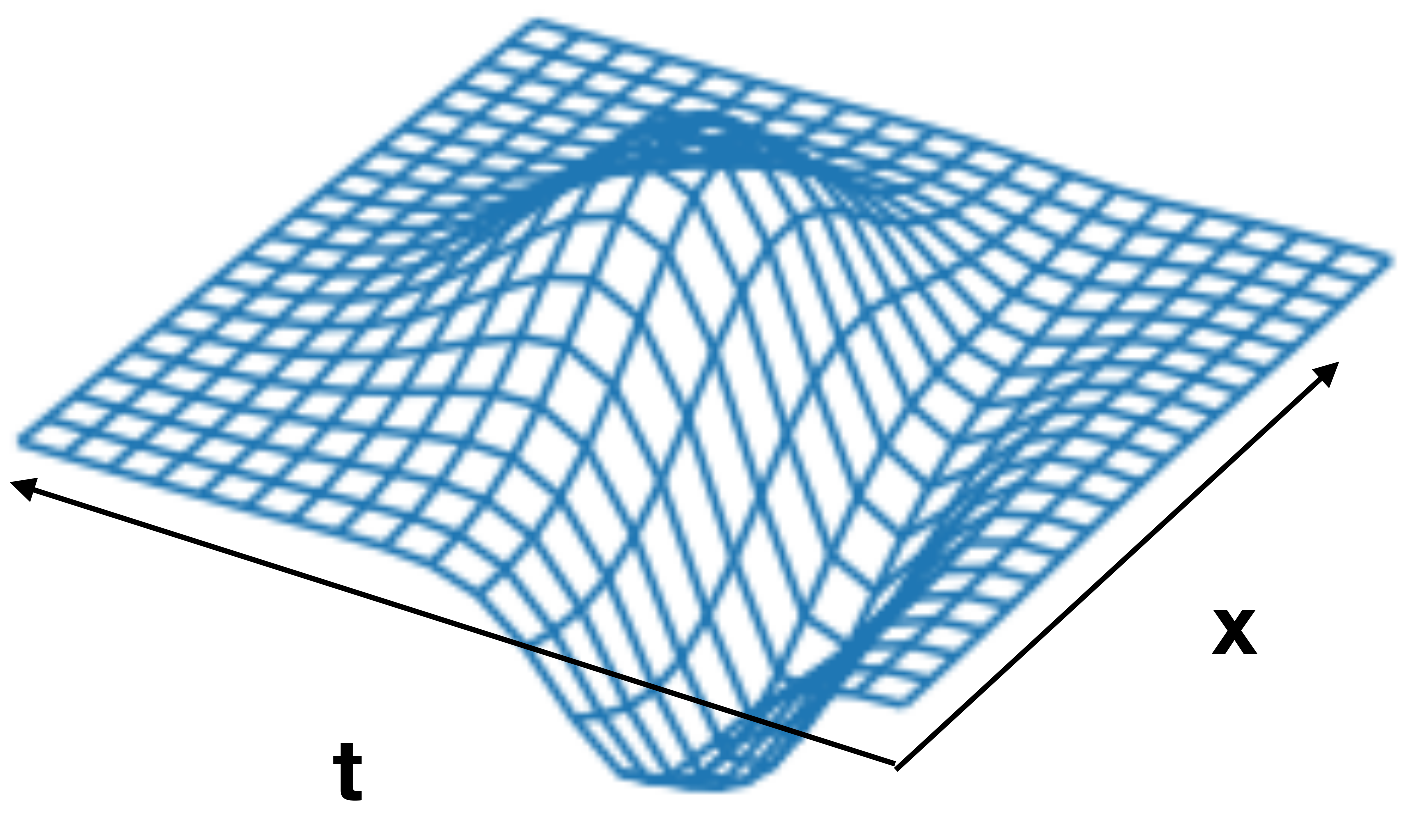
What is numerical relativity? Why do initial conditions matter?

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"

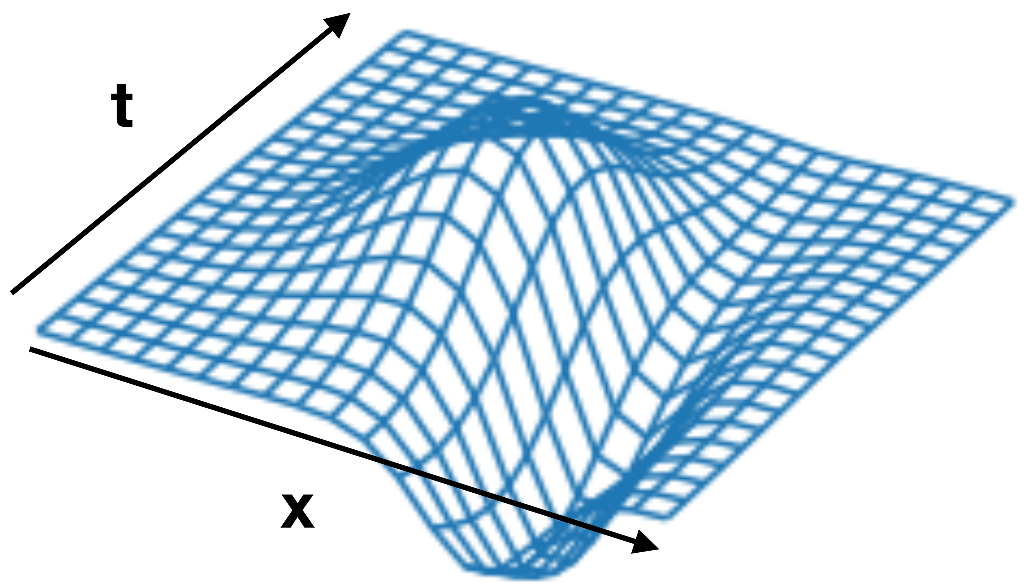
$$g_{ab}(t, \vec{x})$$



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

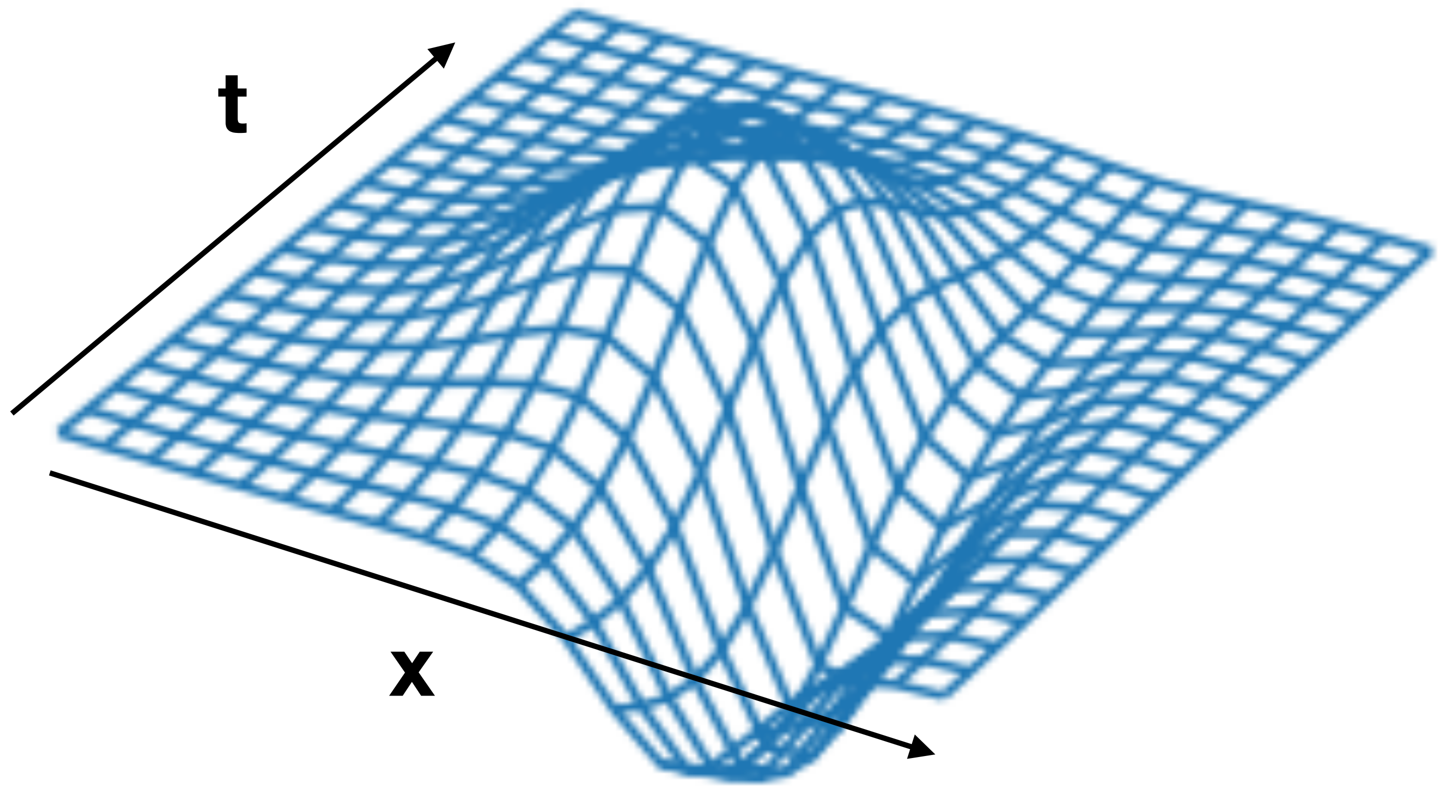
$$R_{ab} - R/2\, g_{ab} = 8\pi\, T_{ab}$$

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

"Curvature"

"Energy-Momentum"

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



R_{ab} - R/2 g_{ab} = 8π T_{ab}

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

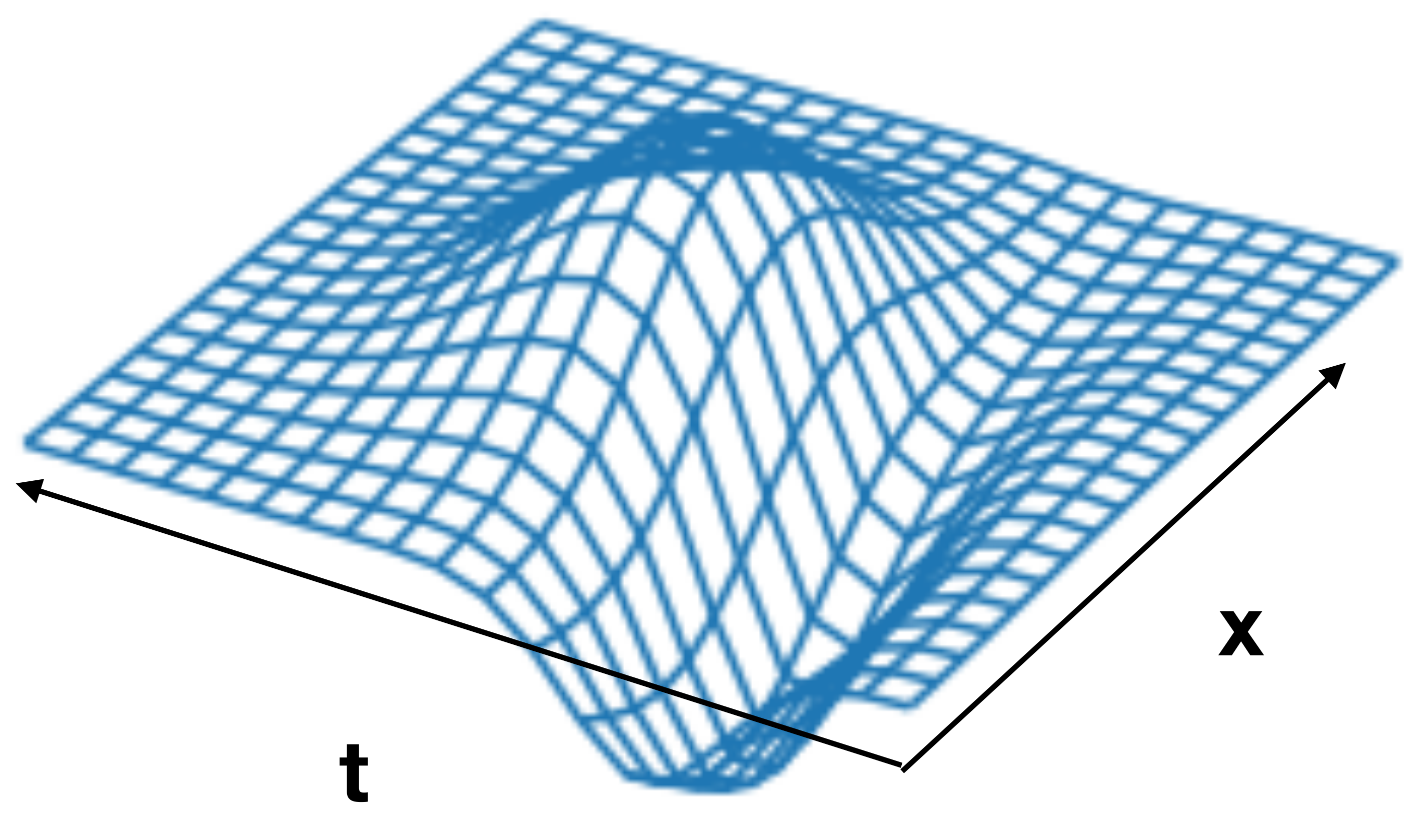
$$\frac{\partial^2 g}{\partial x^2} + \text{non linear terms} = f(\text{energy, momentum})$$

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



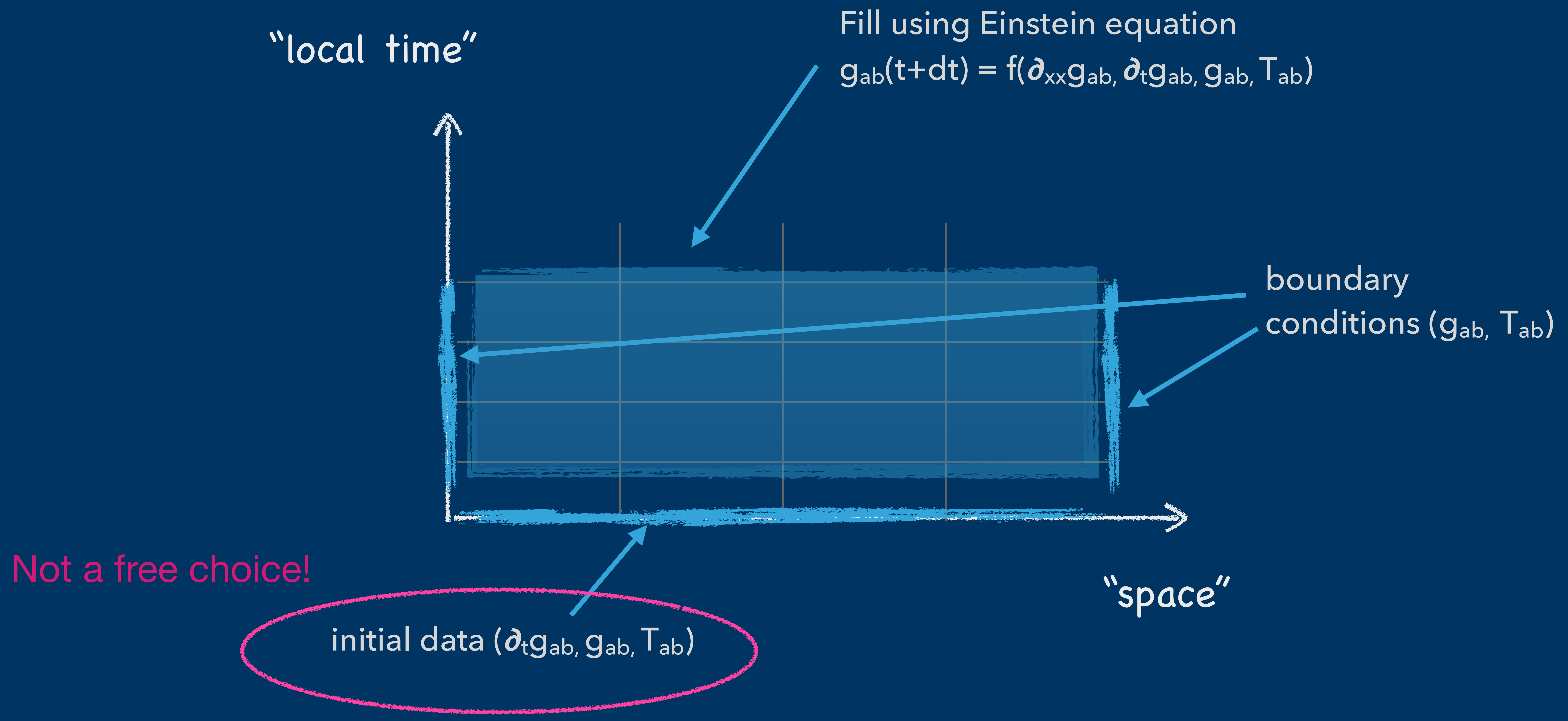
Continuity equation

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

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

"…spacetime tells matter how to move."

In reality numerical relativity is done in a finite region of spacetime

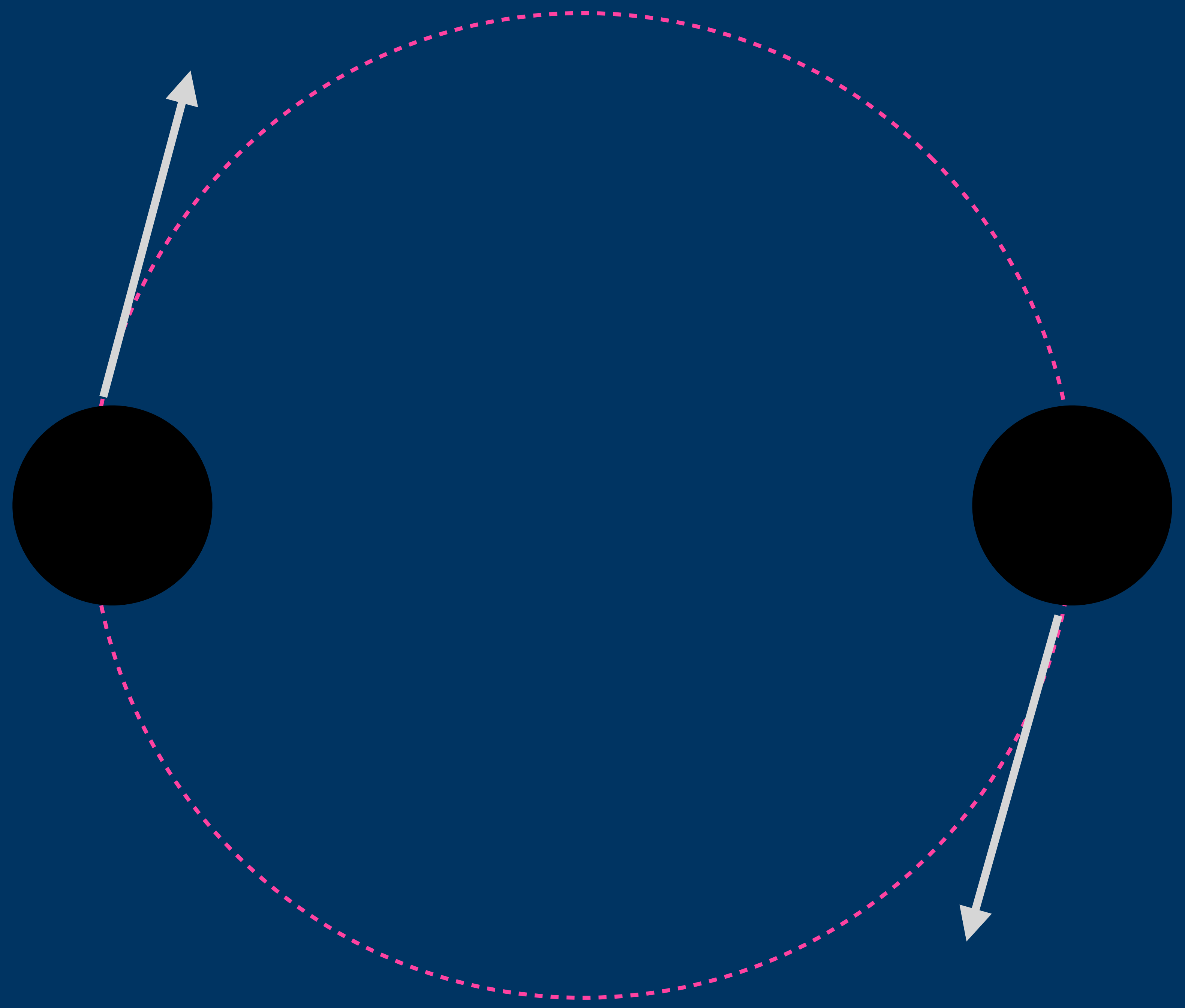


Numerical relativity - the initial condition problem

describe BHs

(Masses, momenta, using PN calculations)

make 16 (arbitrary?) choices of free components



solve 4 constraints on energy and momentum

is this the system I was looking for?

(Are orbits actually circular, are masses what I wanted?)

Numerical relativity - the initial condition problem

describe BHs

(Masses, momenta, using PN calculations)

make 16 (arbitrary?) choices of free components

Iterate

solve 4 constraints on energy and momentum

is this the system I was looking for?

(Are orbits actually circular, are masses what I wanted?)

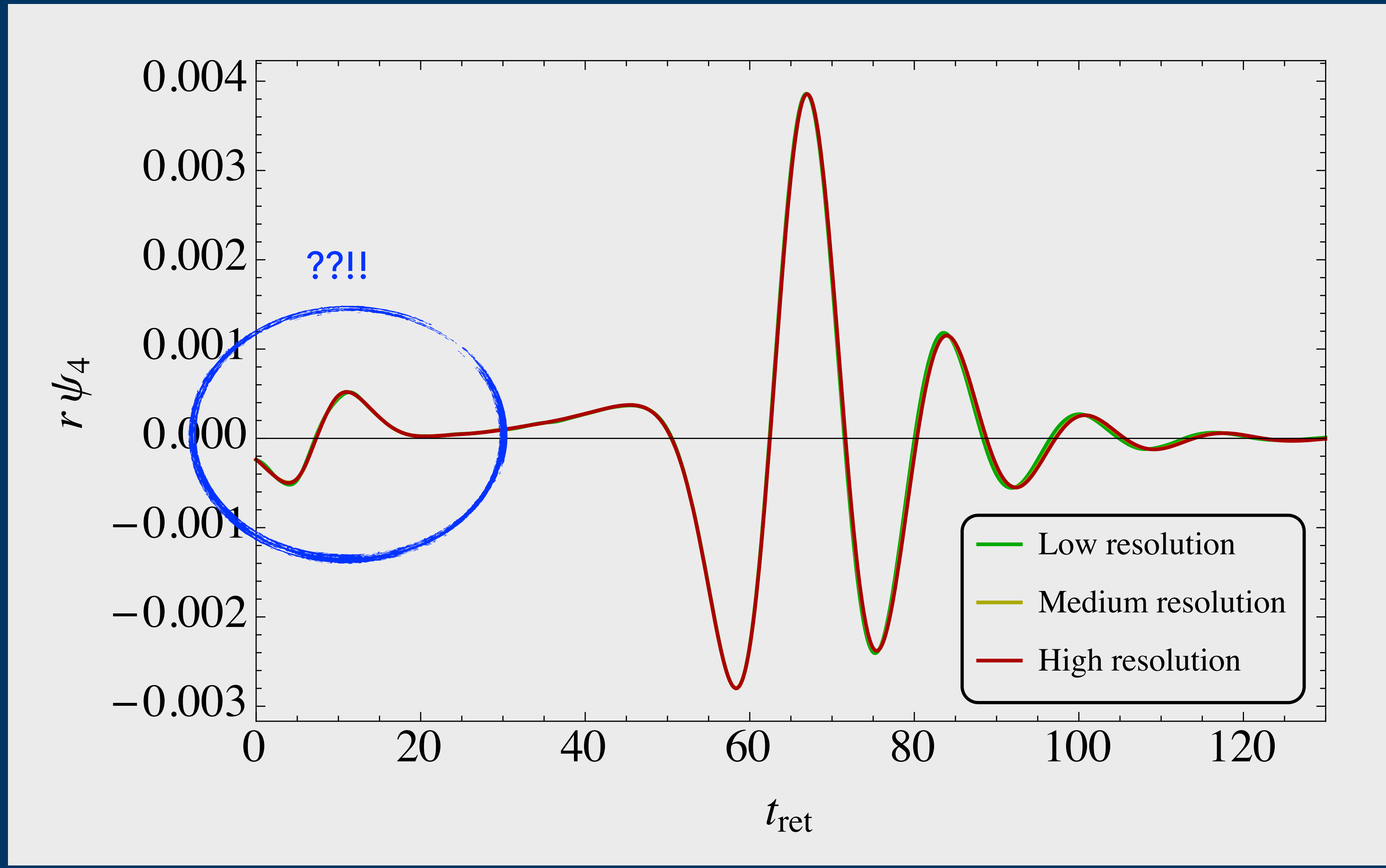
Numerical relativity - the initial condition problem

describe BHs

(Masses, momenta, using PN calculations)

make 16 (arbitrary?) choices of free components

This will just have to be good enough



solve 4 constraints on energy and momentum

is this the system I was looking for?

The “right” initial condition means:

1. Solves the energy and momentum constraints of GR

2. Is the correct physical scenario that we are looking for

Dark matter environments

Particle dark matter parameters

Self interaction

Mass

Fraction of total DM (locally/ globally)

Standard model interactions

Self interaction

(Small, ignore for this talk)

Mass

Particle dark matter parameters

Fraction of total DM (locally/ globally)

Standard model interactions

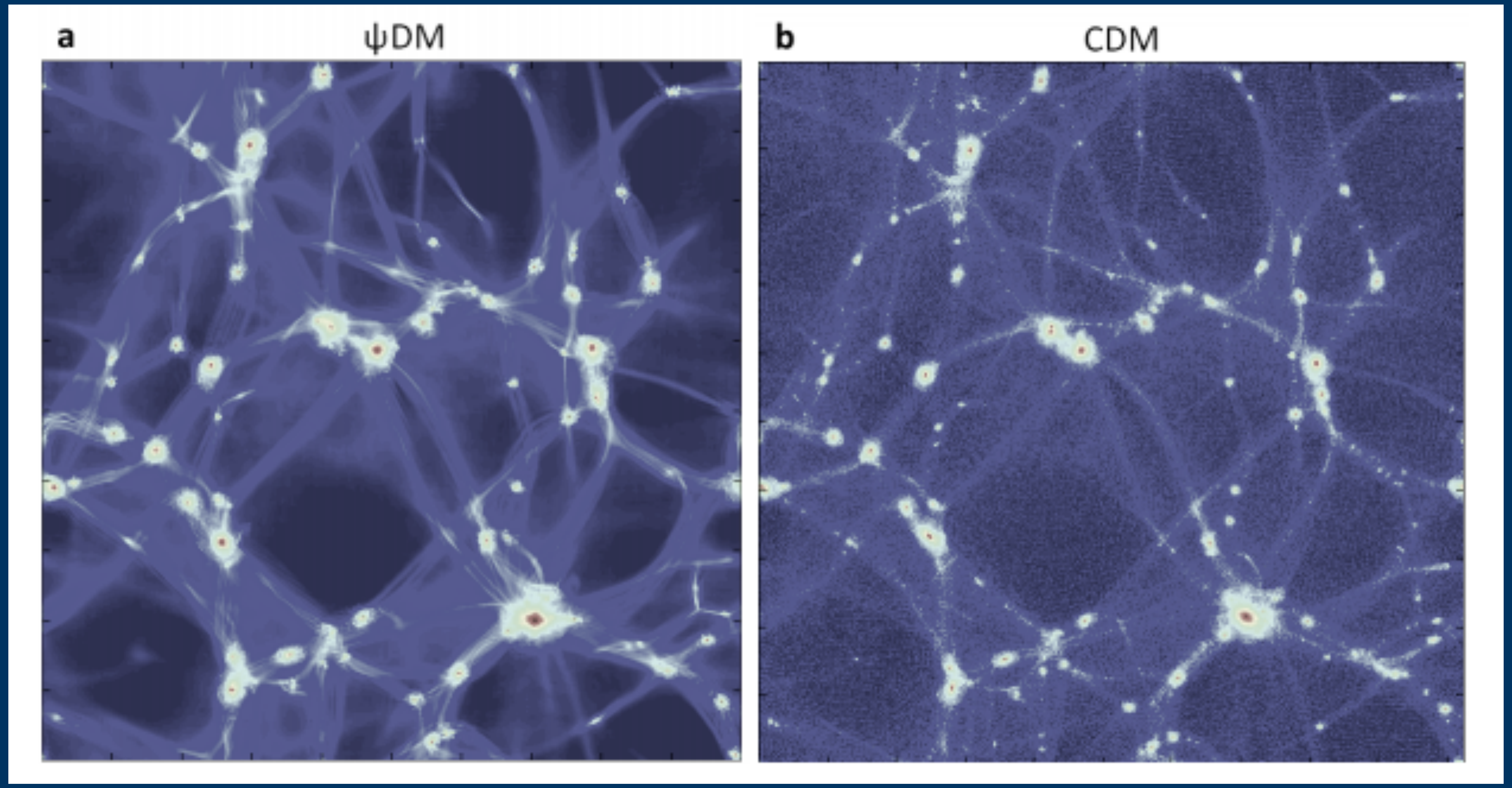
(Small, ignore for this talk)

A vast range of potential masses

Mass

Particle dark matter parameters

Wave DM
e.g. axions
10^{-23} eV - 1 eV



Particle DM
e.g. WIMPS
1 eV - 10^{13}eV

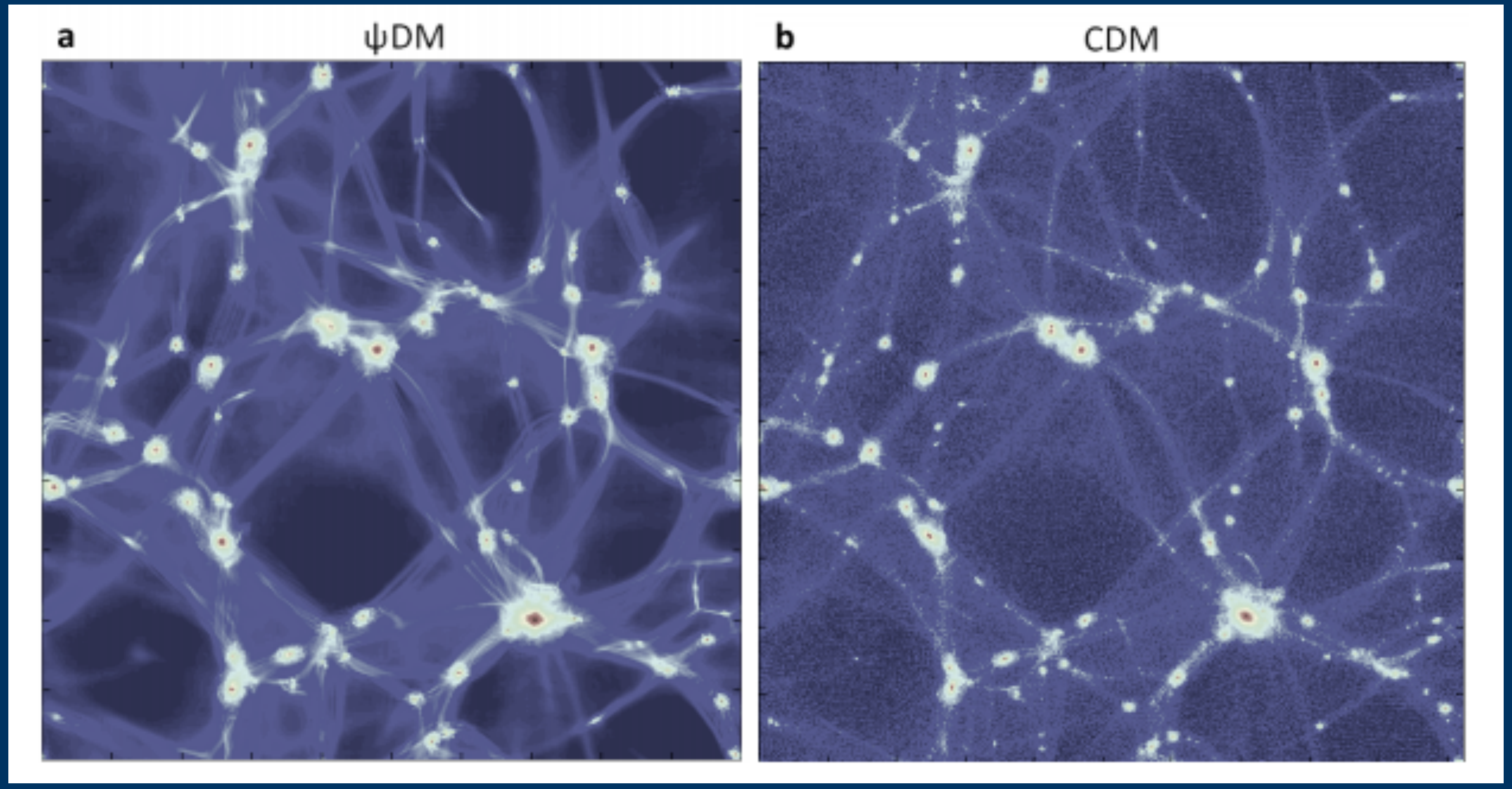
Schive et al. 2014
Cosmic structure as the quantum interference of a coherent dark wave

A useful distinction is between wave-like and particle DM

Mass

Particle dark matter parameters

Wave DM
e.g. axions
10^{-23} eV - 1 eV



Particle DM
e.g. WIMPS
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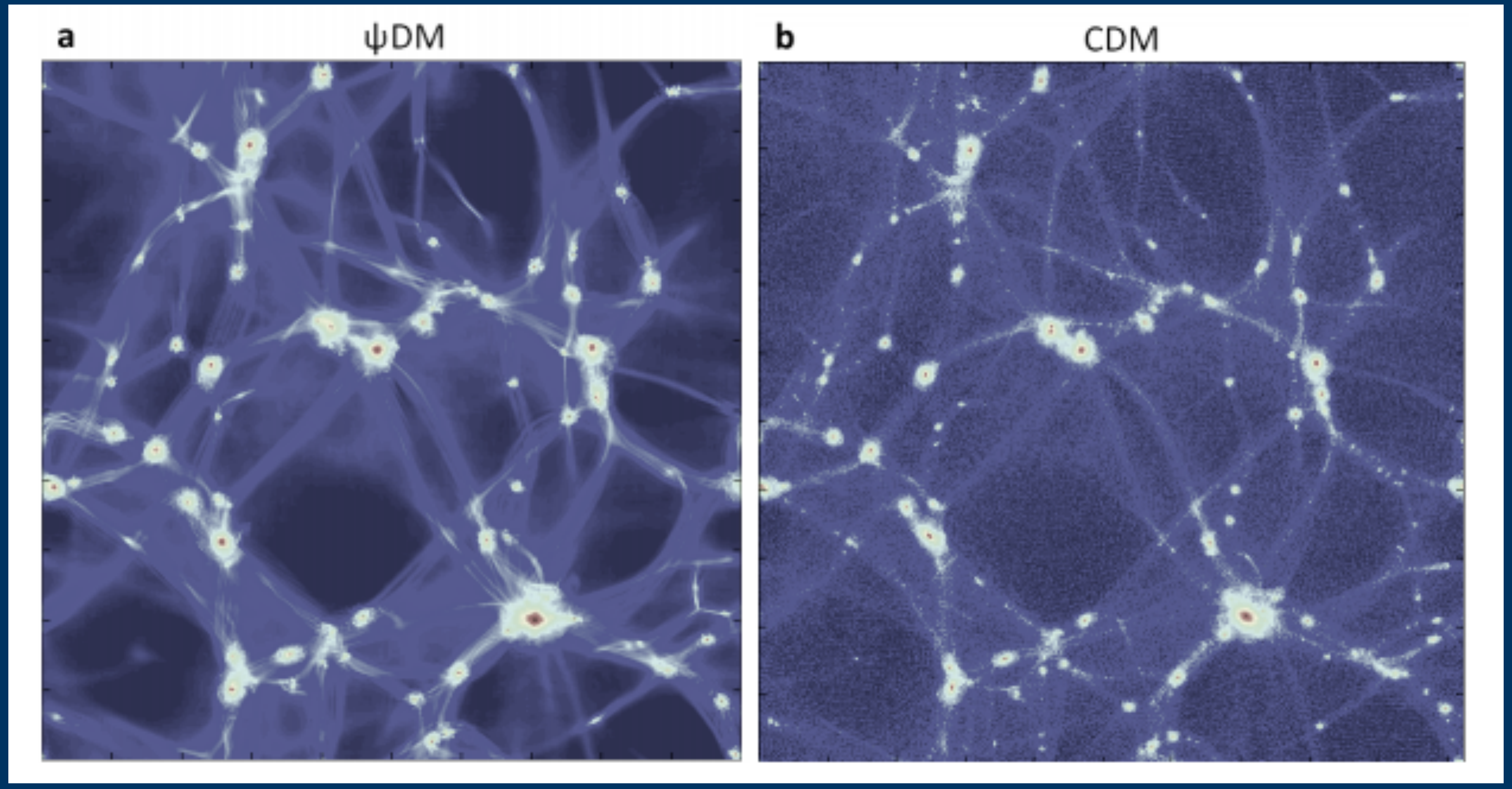

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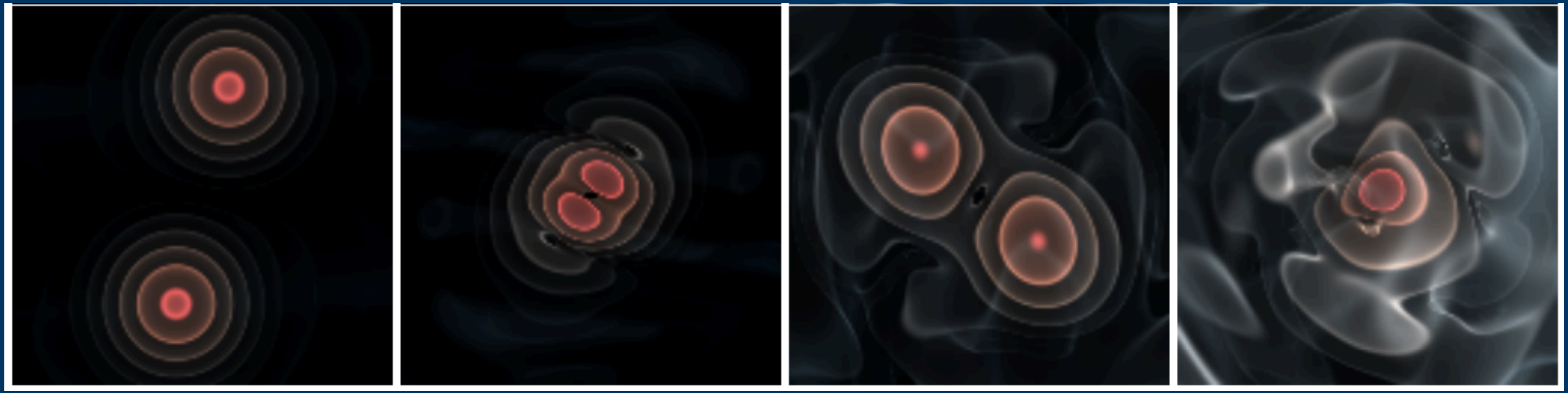


Schwabe et al, 2016
Simulations of solitonic core mergers in ultralight axion dark matter cosmologies

Particle dark matter parameters

Fraction of total DM (locally/ globally)

Detection / constraints rely heavily on fraction of DM composed by the candidate, and its distribution (uniform/clumpy)

Bad news: average DM density is very low :-(

Barausse et al. 2014
Can environmental effects spoil precision gravitational-wave astrophysics?

(Answer: Broadly no - for inspiral and ringdown, assuming uniform density)

What do you mean "low"?

$\rho \sim 1\ \mathrm{GeV/cm^3}$ **or** $1\ \mathrm{M_\odot/pc^3}$

(Particle physicist) (Astrophysicist)

What do you mean "low"?

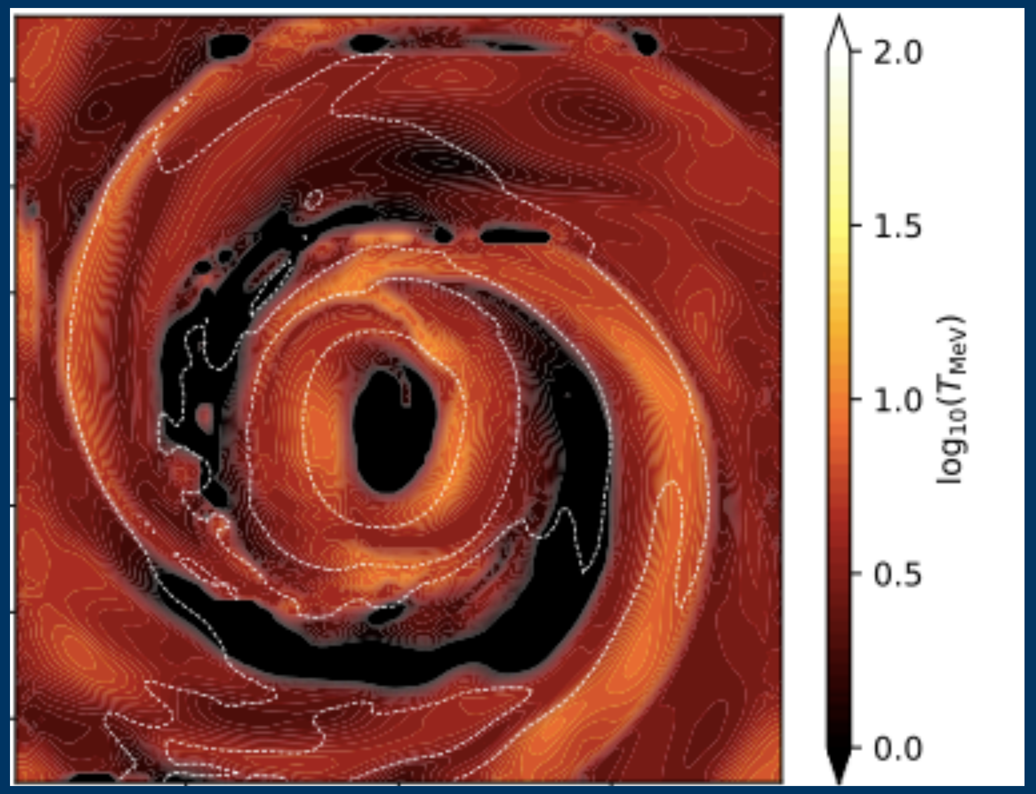
$$\frac{\rho}{1/R_s^2} \sim 10^{-30} \left(\frac{M_{BH}}{10^6 M_\odot} \right)^2$$

(Numerical relativist)

What DM density enhancement is required to have an observable impact on GW signals? Do such enhancements arise naturally?

Dark matter overdensity scenarios

Interactions e.g. bremsstrahlung, or attractive self interactions



Dietrich et. al. 2019
Cooling binary neutron star remnants via nucleon-nucleon-axion bremsstrahlung

Superradiance

Review by Brito et. al. (updated 2020)
Superradiance: New Frontiers in Black Hole Physics

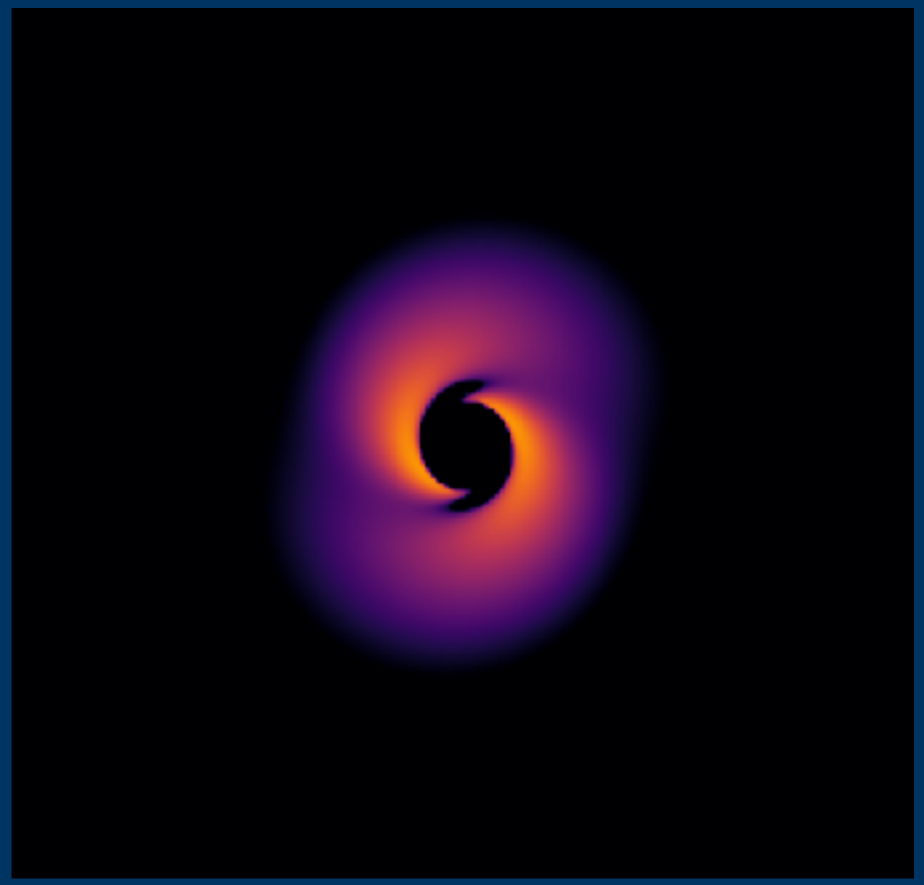
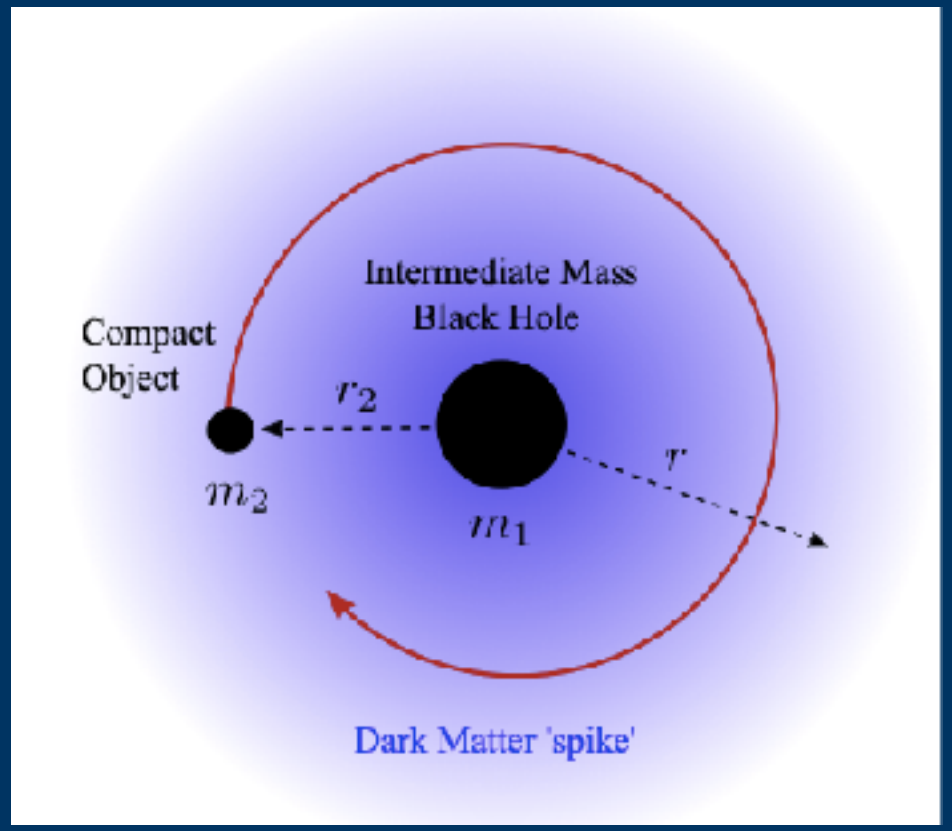


Image credit: Helfer / Clough

Dark matter minispikes (adiabatic growth, accretion)

Bamber et. al. 2021
Growth of accretion driven scalar hair around Kerr black holes

Kavanagh et. al. 2020, Coogan et. al. 2022
Measuring the dark matter environments of black hole binaries with gravitational waves



Exotic compact objects e.g. boson stars

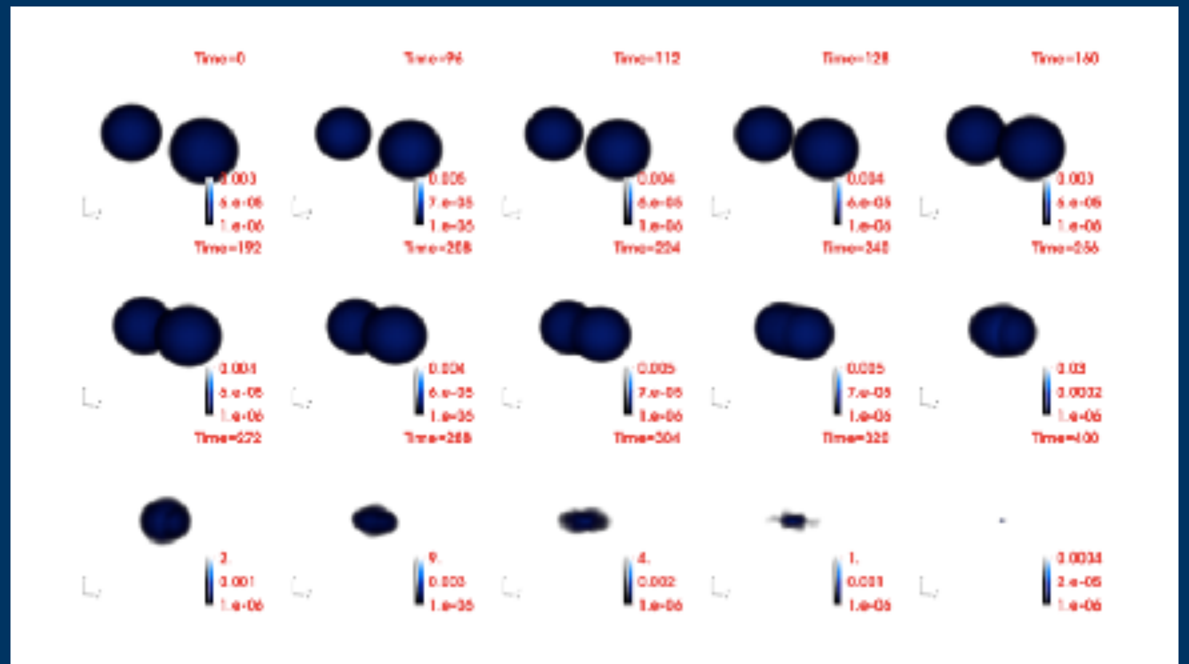
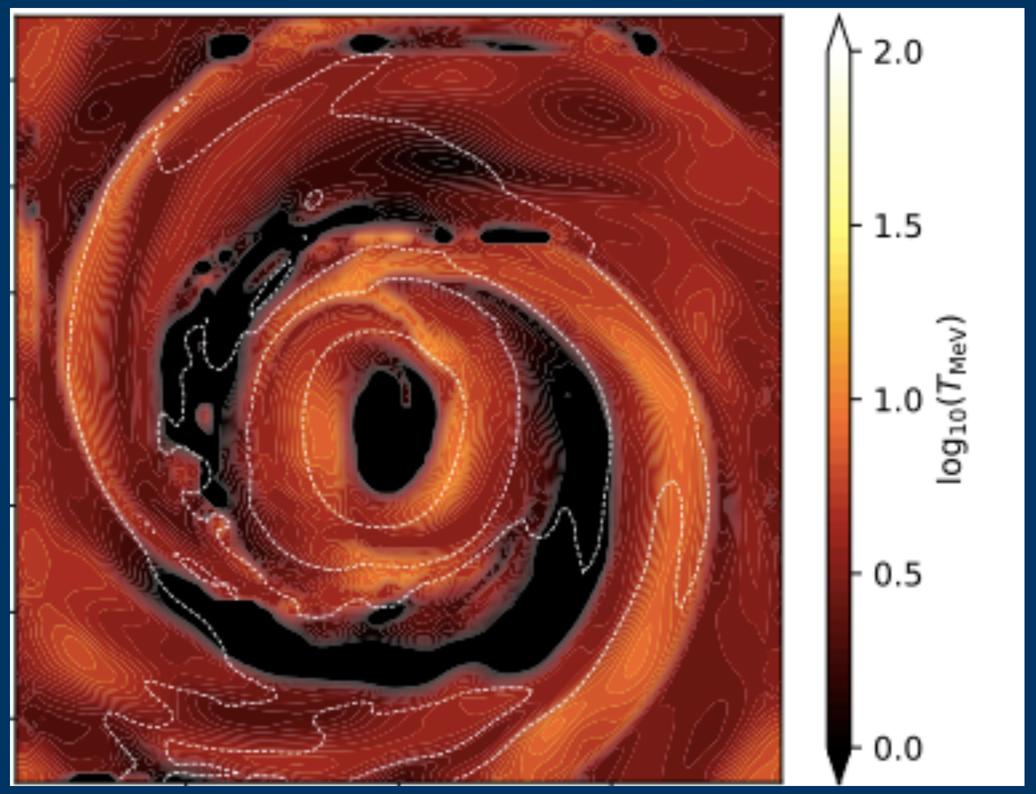


FIG. 5. Snapshots of the time evolution of the energy density during the head-on collision of two PSs with $\omega/\mu_V = 0.8925$. Time is given in code units.

Bustillo et. al. 2021
GW190521 as a merger of Proca stars: a potential new vector boson of 8.7 × 10−13 eV



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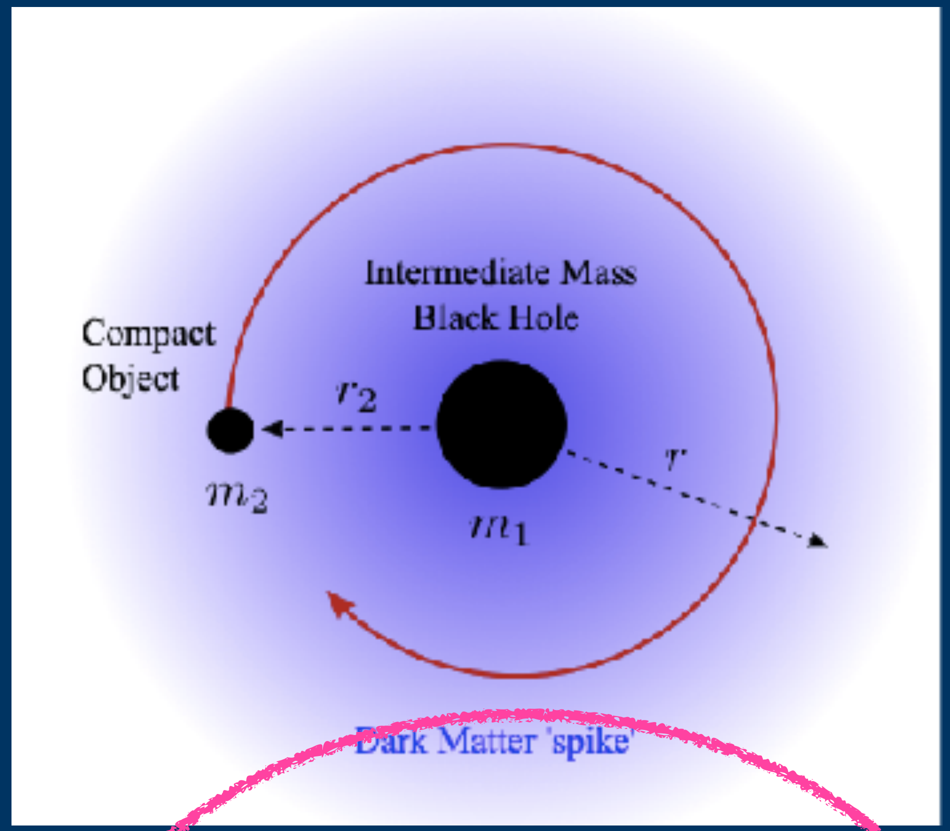

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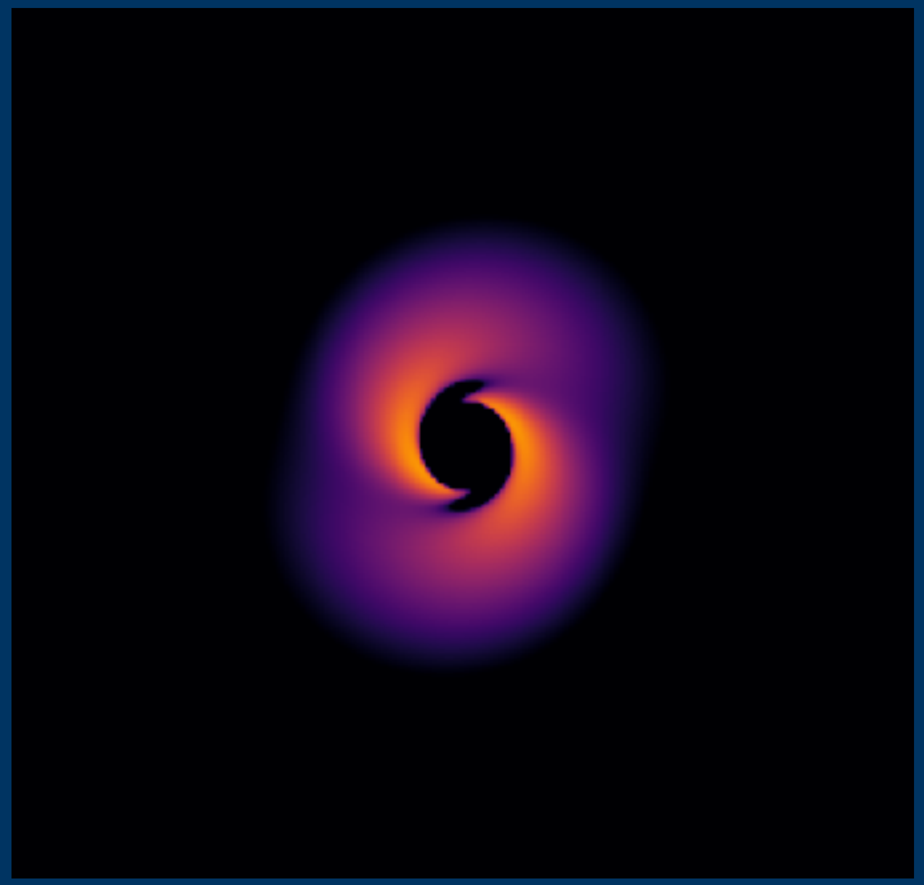


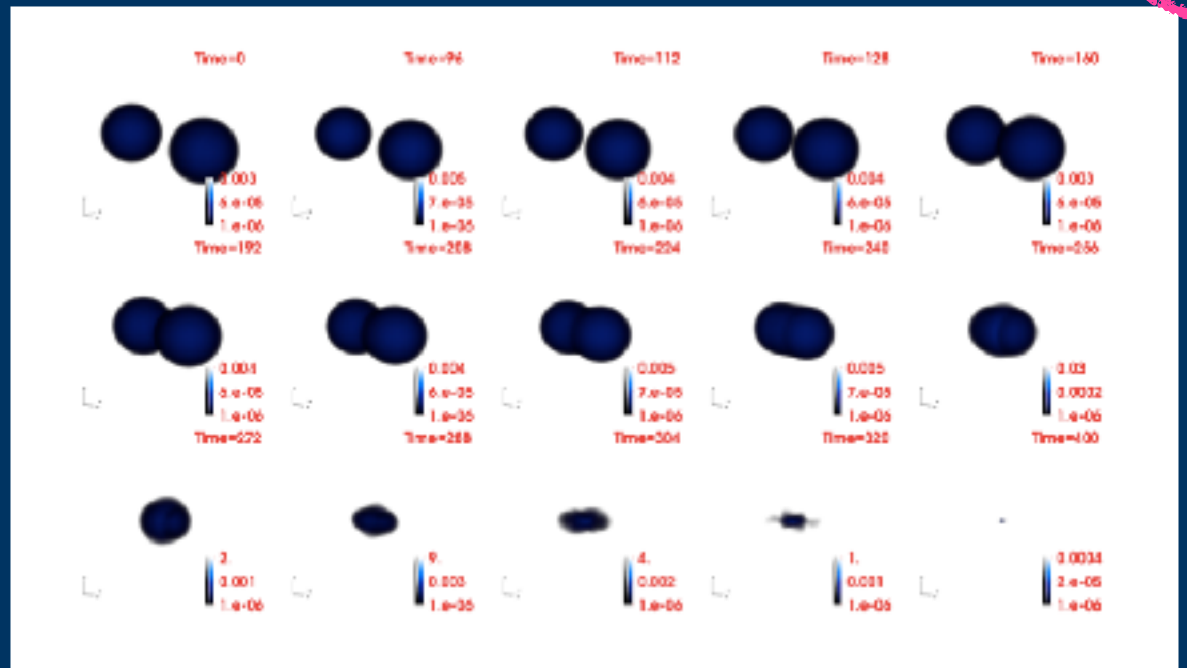
Image credit: Helfer / Clough

Dark matter overdensity scenarios

Dark matter minispikes (adiabatic growth, accretion)

Focus of this talk!

Exotic compact objects e.g. boson stars



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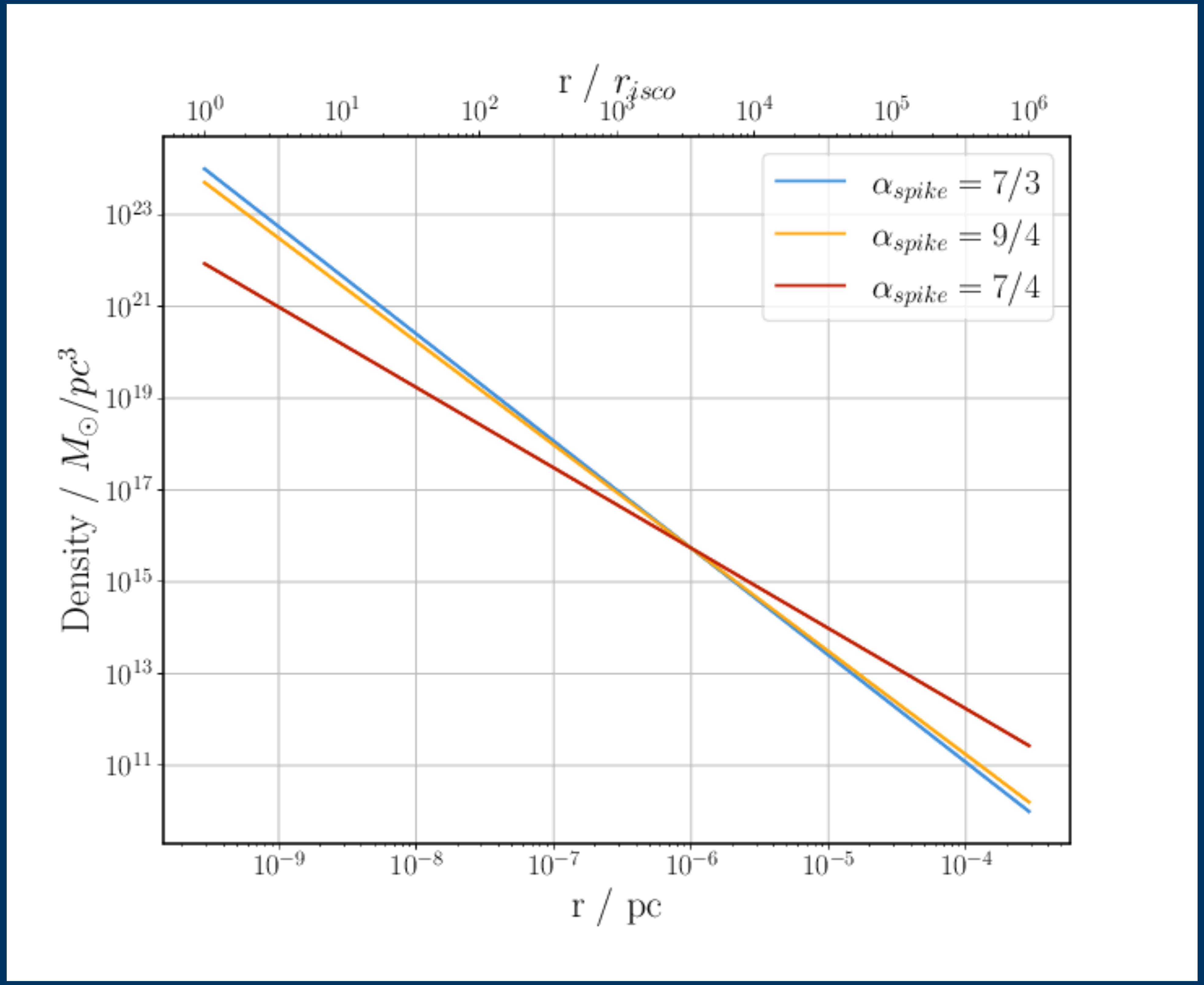
Bustillo et. al. 2021
GW190521 as a merger of Proca stars: a potential new vector boson of 8.7 × 10−13 eV

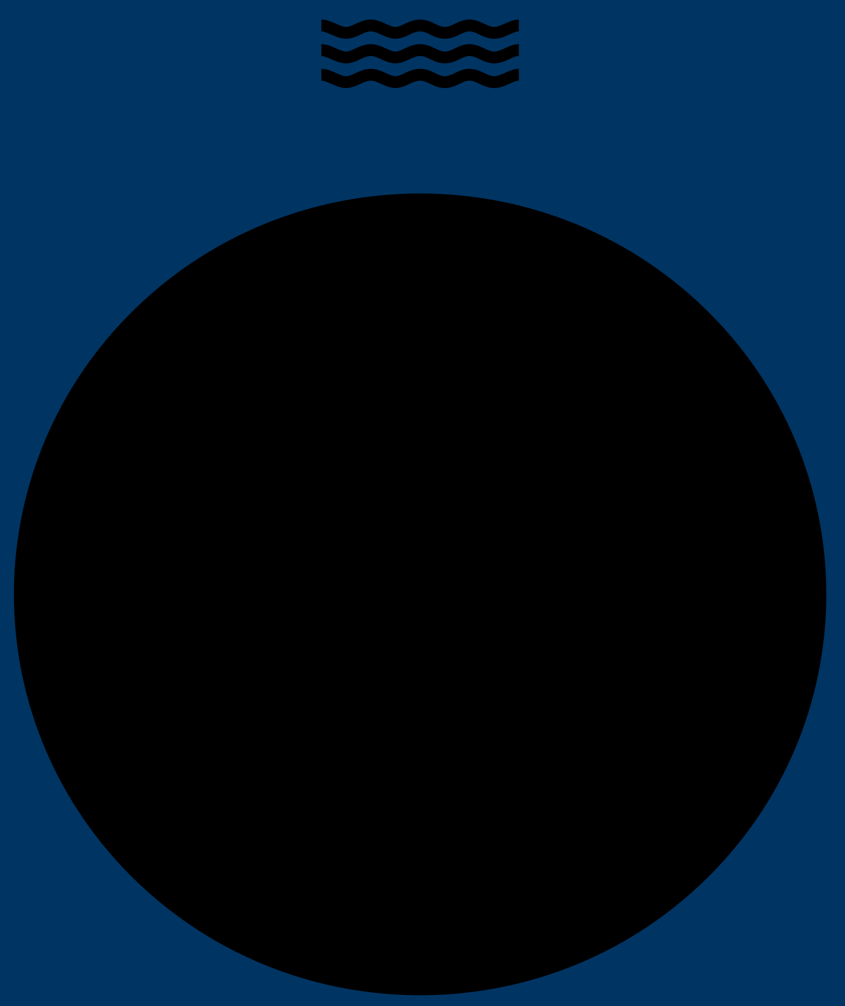
Accretion in the particle DM case - “DM spikes”



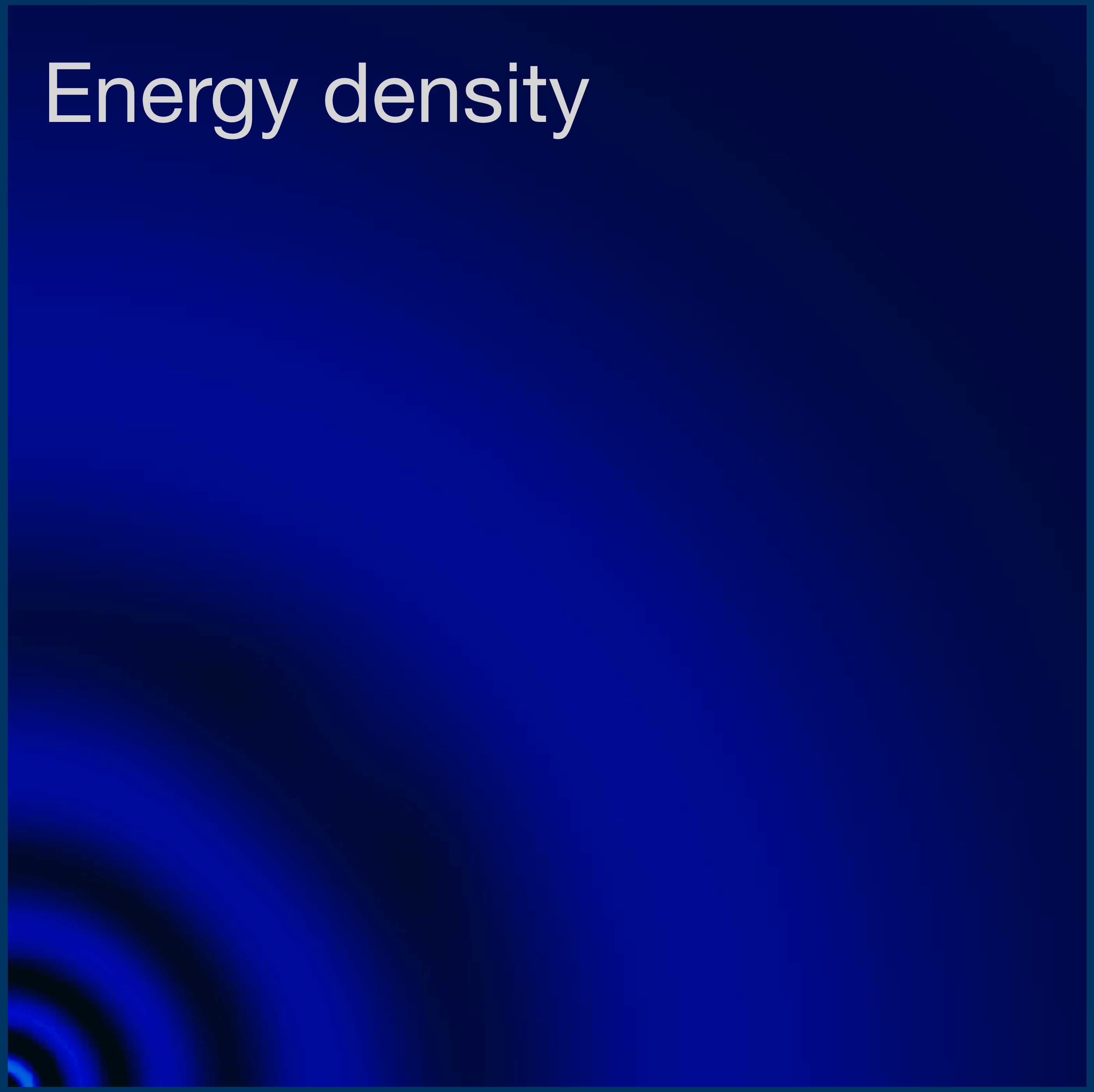
- Becker et.al. 2021
  Circularization vs. Eccentrification in Intermediate Mass Ratio Inspirals inside Dark Matter Spikes

Gondolo & Silk found that adiabatic growth led to a DM overdensity described by a power law

$$\rho \sim \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma}$$



Accretion in the low mass DM case - scalar accretion



Clough et. al. 2019,
Bamber et. al. 2021
Growth of accretion driven scalar hair around Kerr black holes

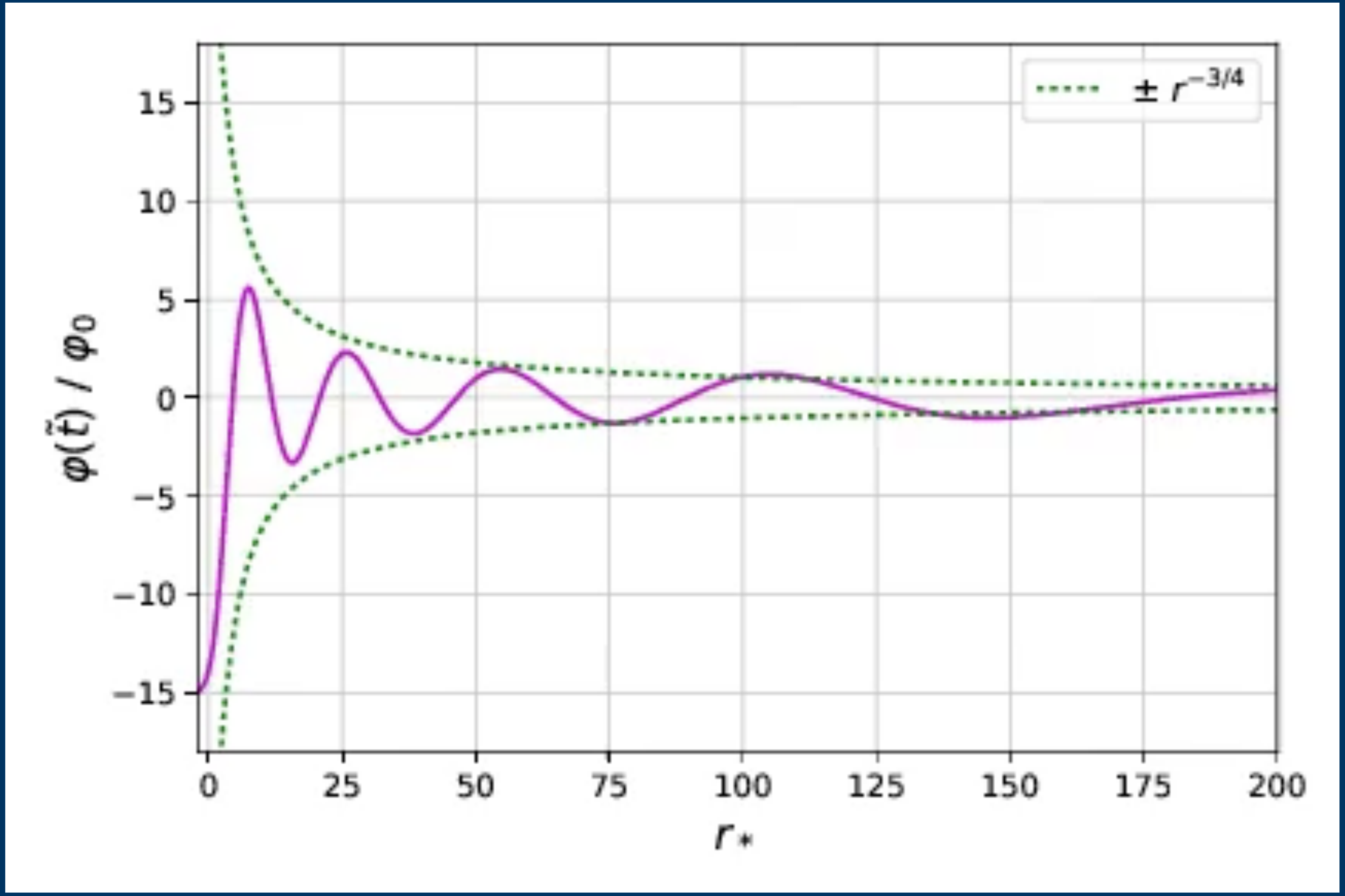
DM overdensity described by power law plus oscillations on the scale of the Compton wavelength of the light particle

In the isolated BH case solutions are known exactly (they are the confluent Heun functions)

Black Hole Hair from Scalar Dark Matter
Lam Hui, Daniel Kabat, Xinyu Li, Luca Santoni, Sam S. C. Wong
JCAP 1906 (2019) no.06, 038

Accretion in the wave DM case - scalar accretion

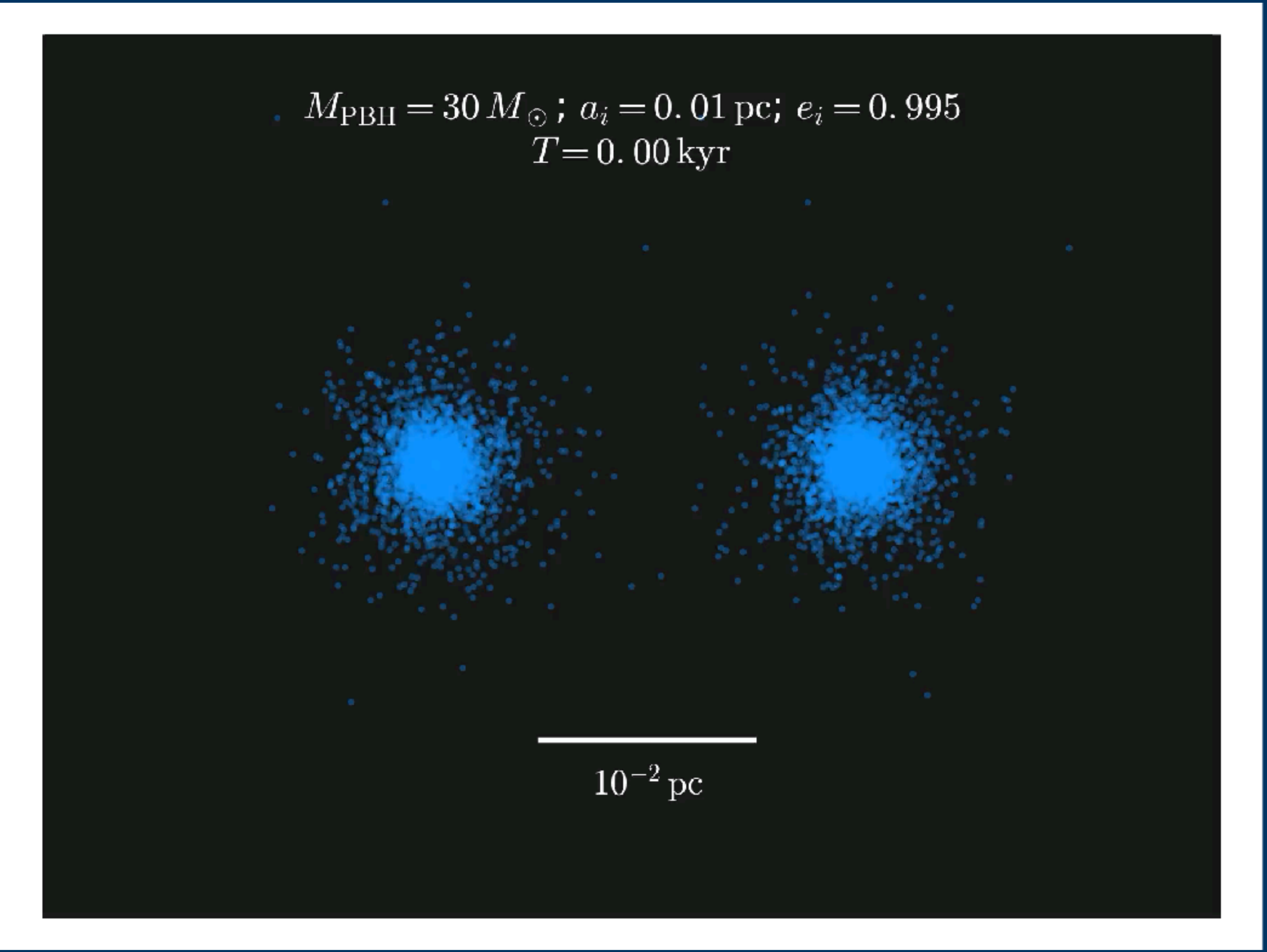
Field profile



Clough et. al. 2019,
Bamber et. al. 2021
Growth of accretion driven scalar hair around Kerr black holes

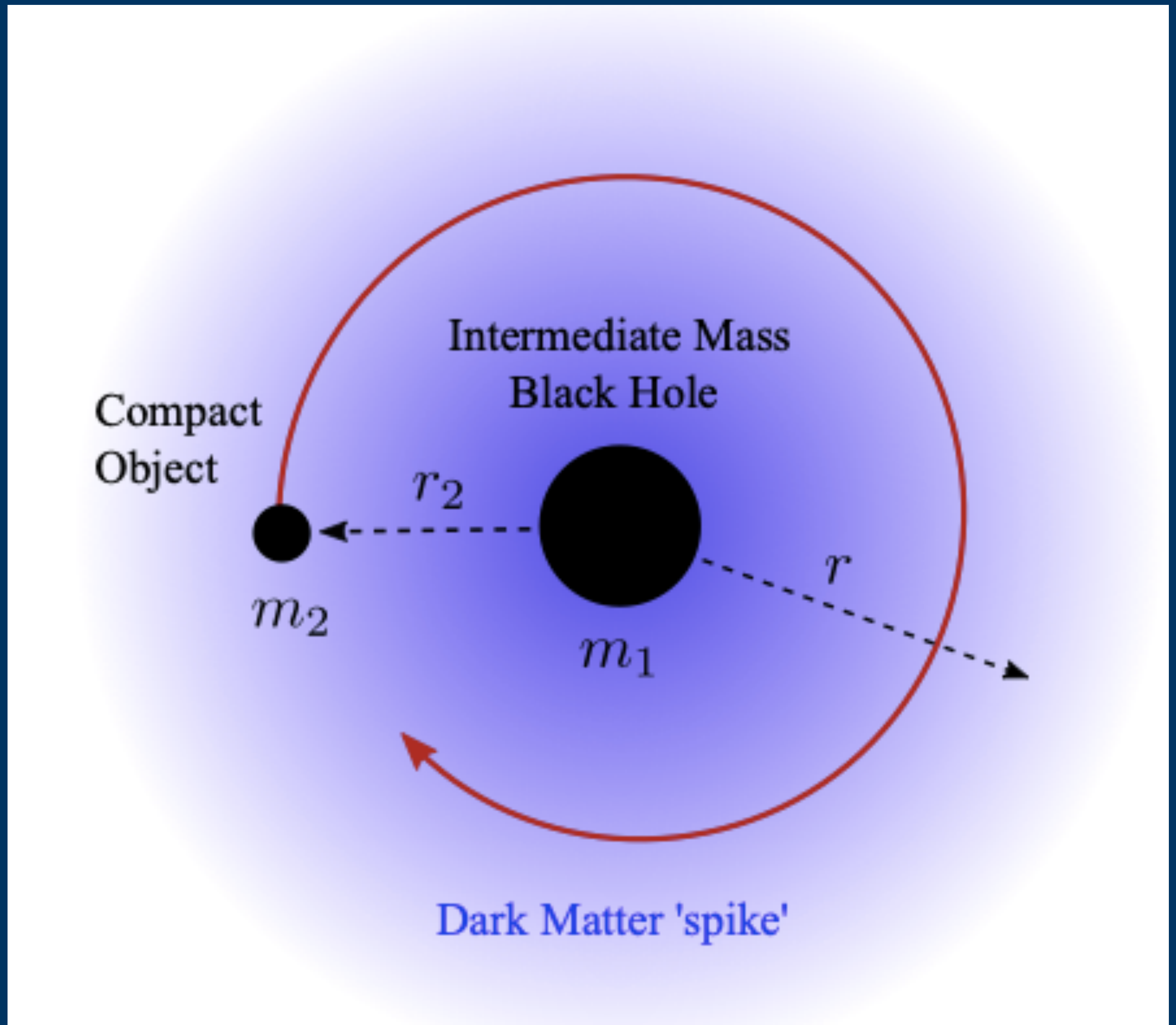
Ok, so maybe you have concentrations of dark matter around isolated black holes, but do you have them around binaries?

Binaries in the particle DM case



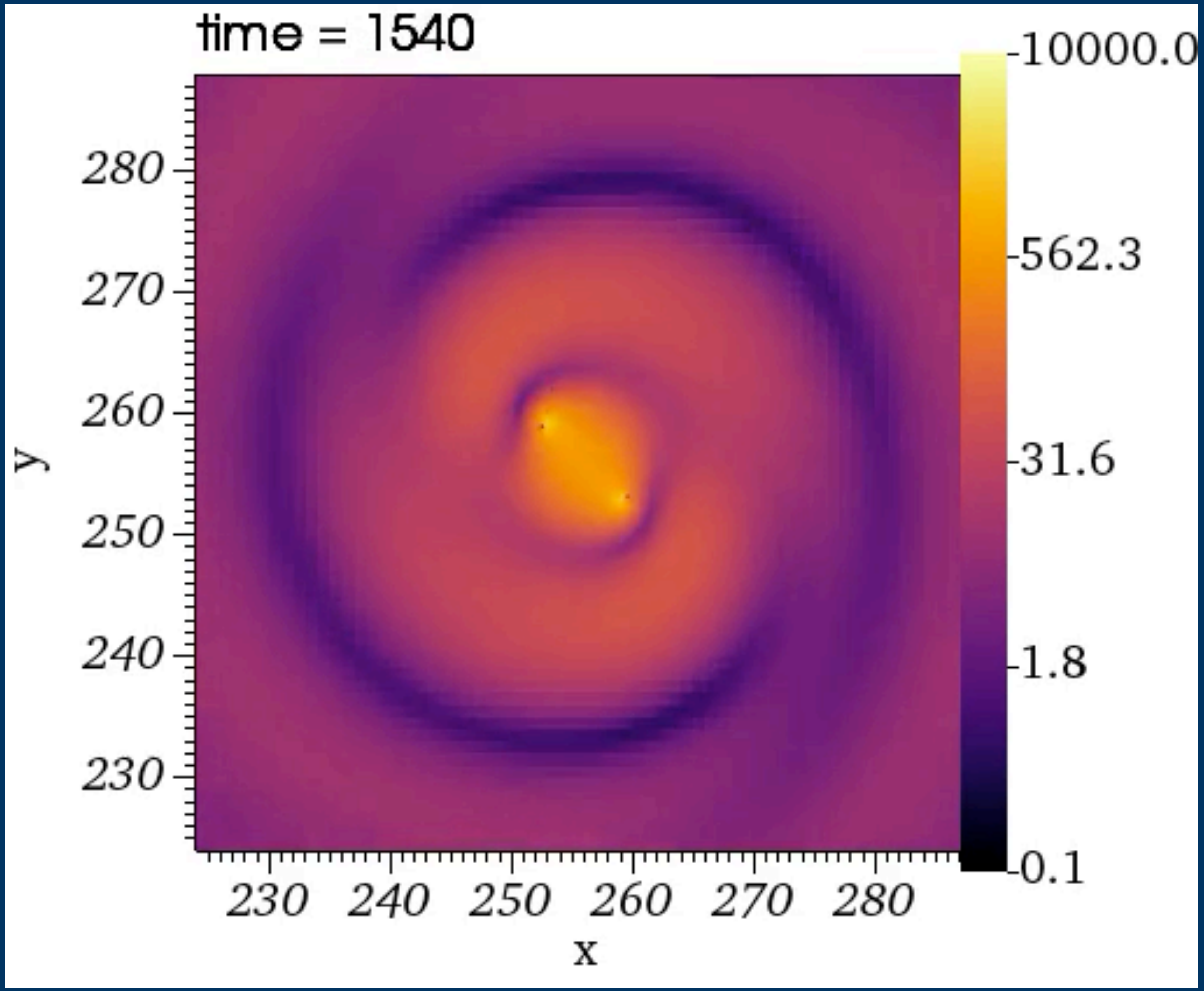
Bertone et. al. 2020
Gravitational wave probes of dark matter: challenges and opportunities

As a result there is a focus on high mass ratio merger events

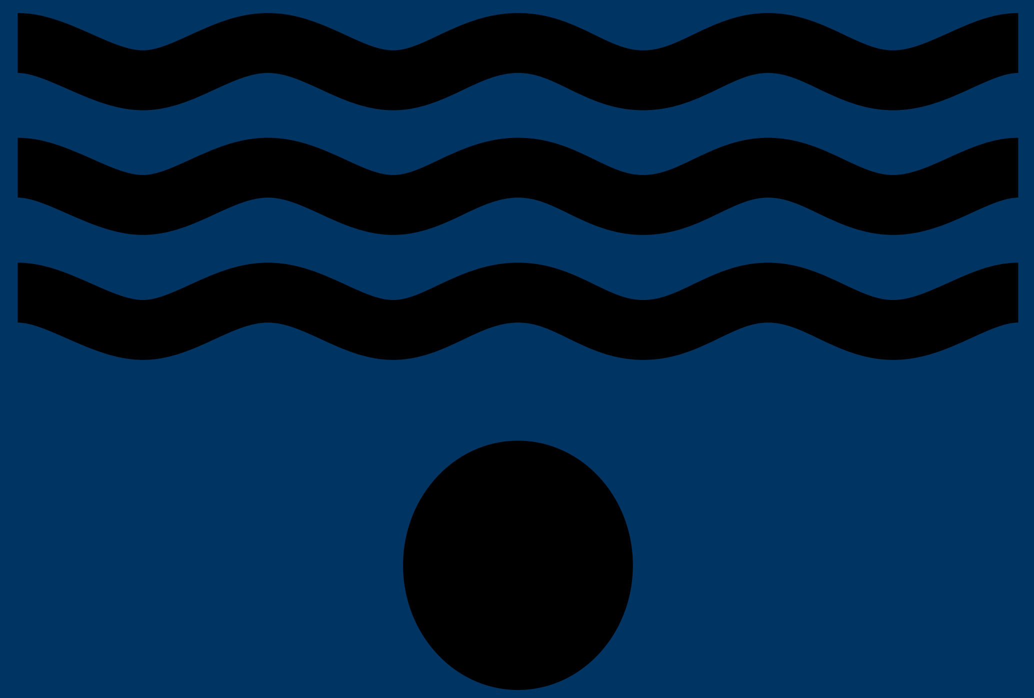


Kavanagh et. al. 2020, Coogan et. al. 2022
Detecting dark matter around black holes with gravitational waves: Effects of dark-matter dynamics on the gravitational waveform

Binaries in the wave DM case



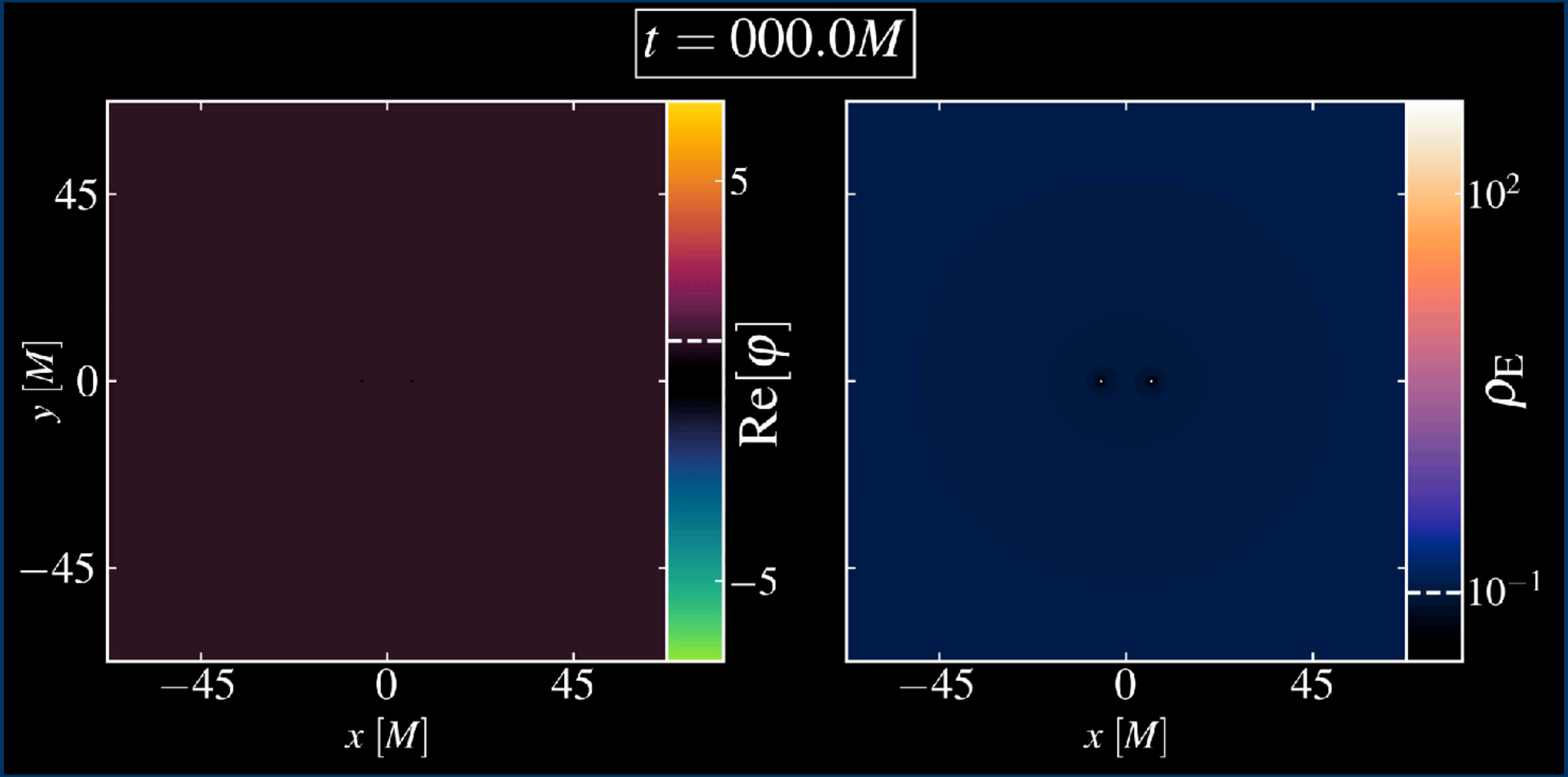
energy density



Bamber et. al., 2022
Black hole merger simulations in wave dark matter environments

Binaries in the wave DM case

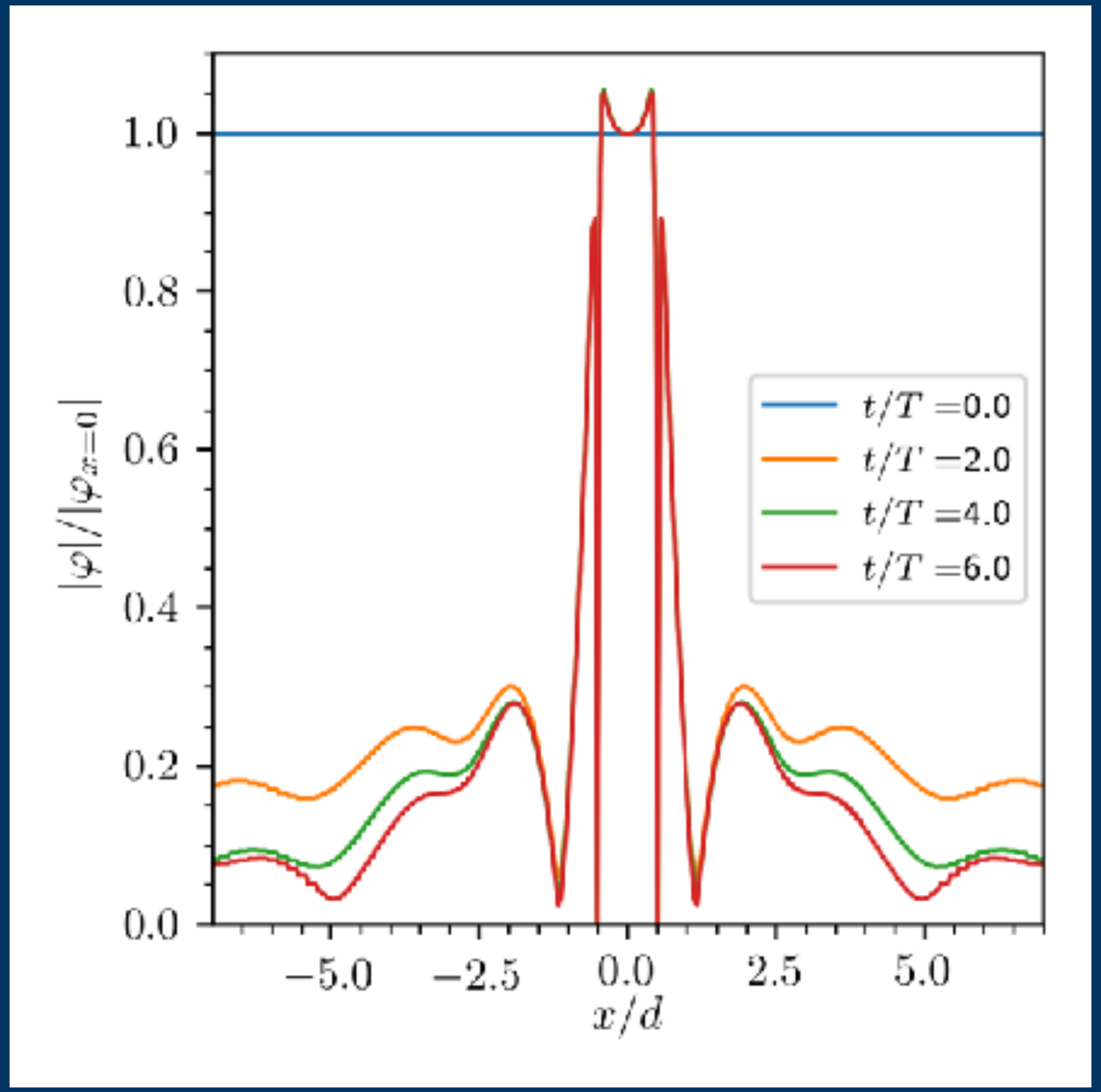
Field



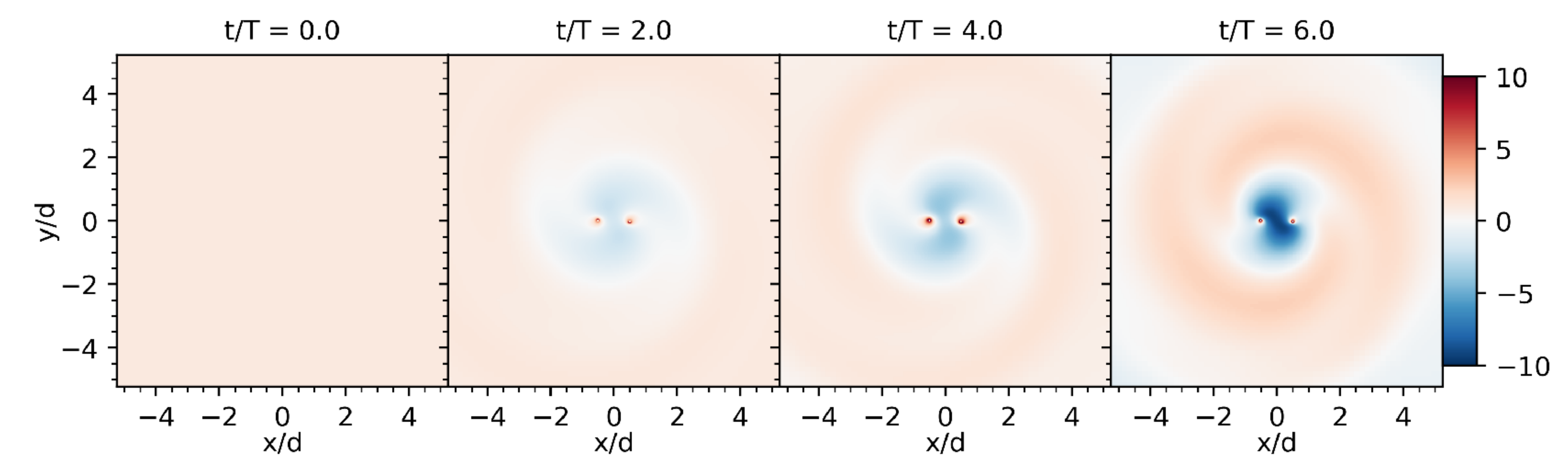
energy density

Bamber et. al., 2022
Black hole merger simulations in wave dark matter environments

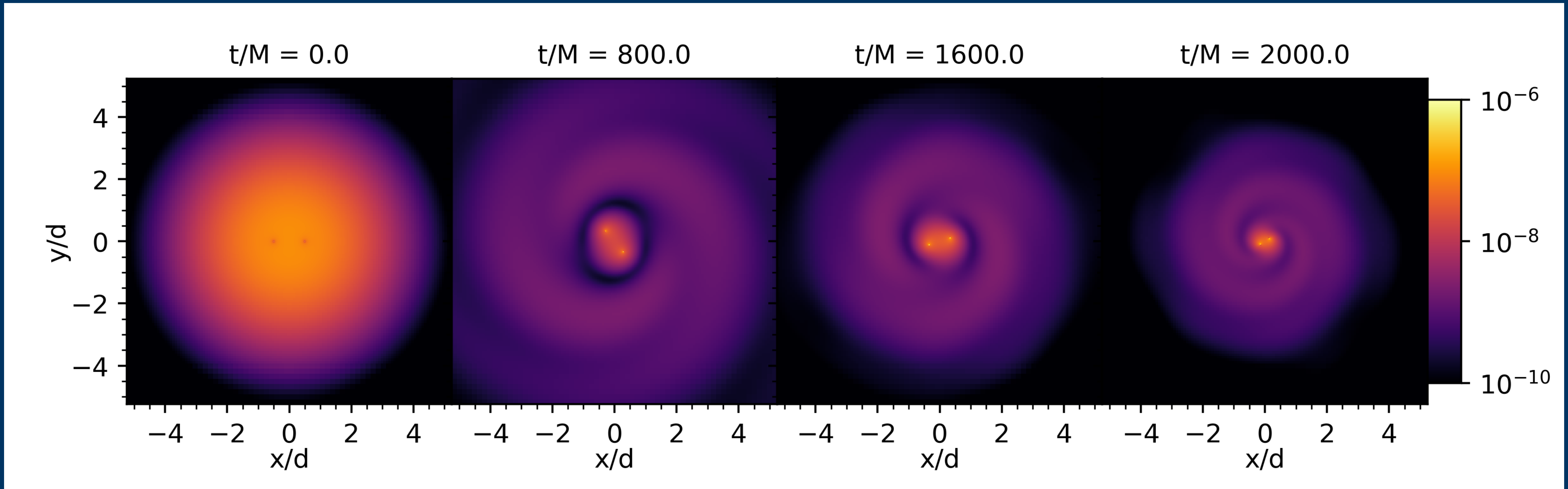
Using fixed orbit simulations to simulate stationary orbits, we find a stationary profile with a scaling symmetry



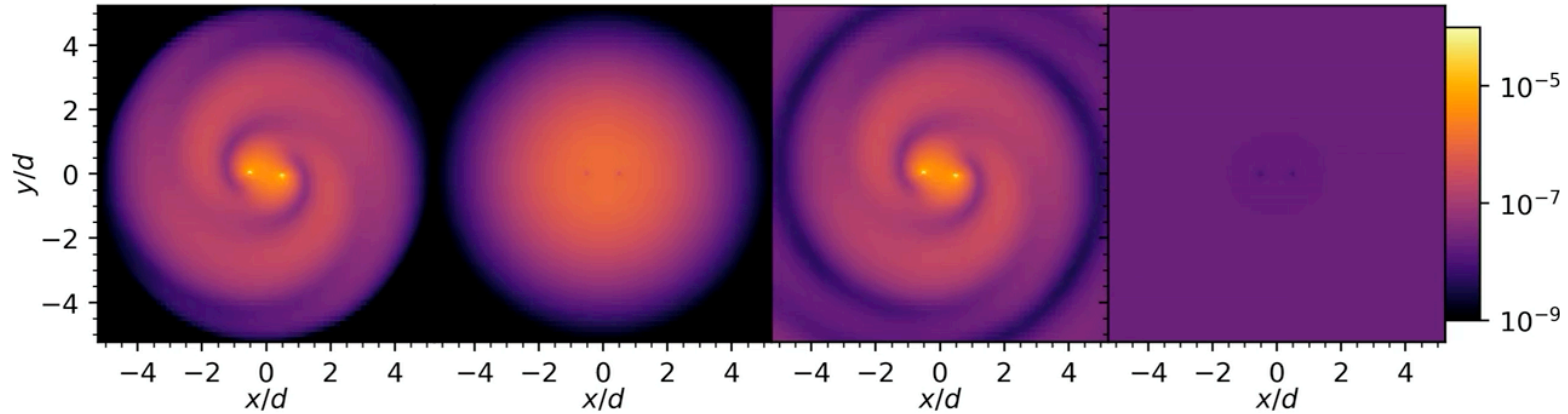
Field profiles



So there is a “right” initial condition for the dark matter component. But what if we start with something else?



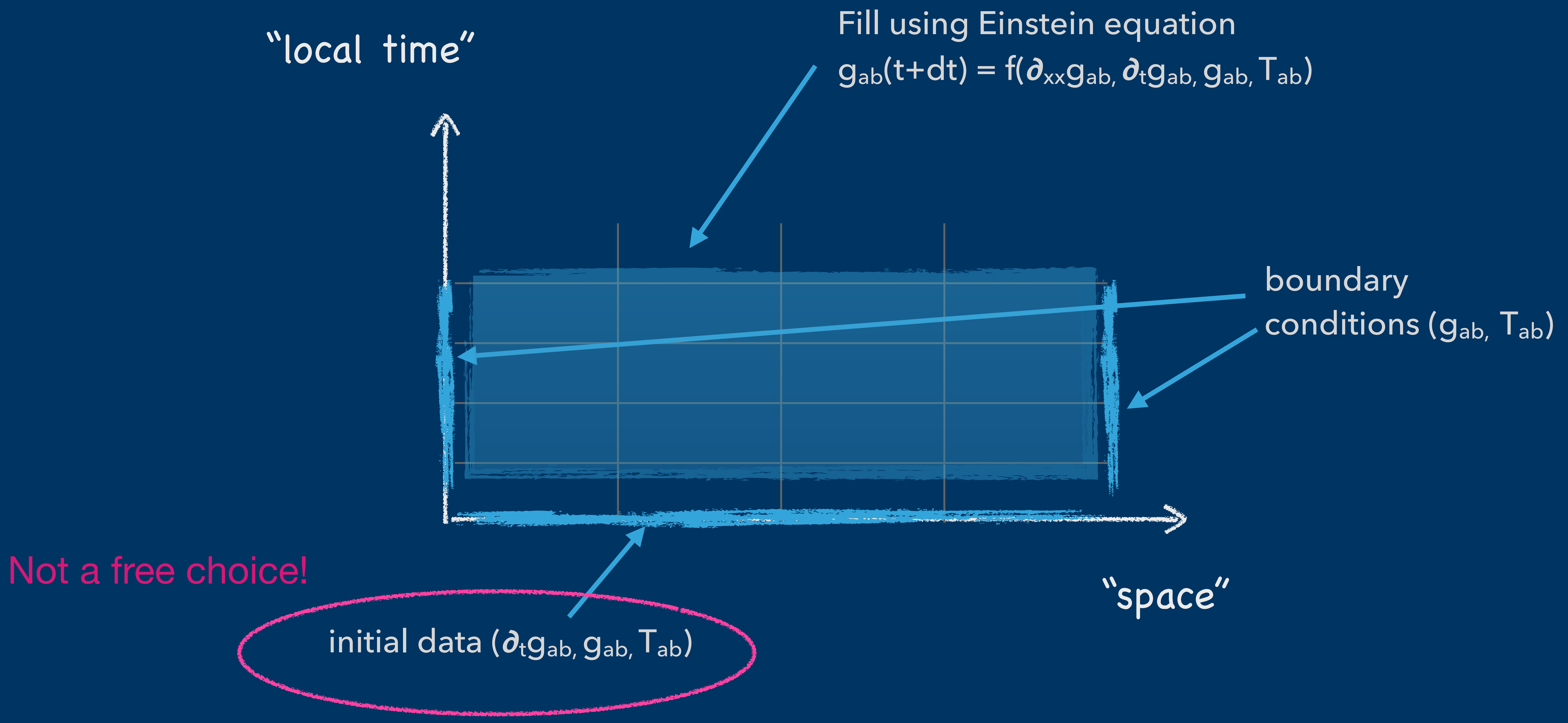
In full NR, different initial clouds converge to the same solution within a few orbits but there are significant transients



Energy density

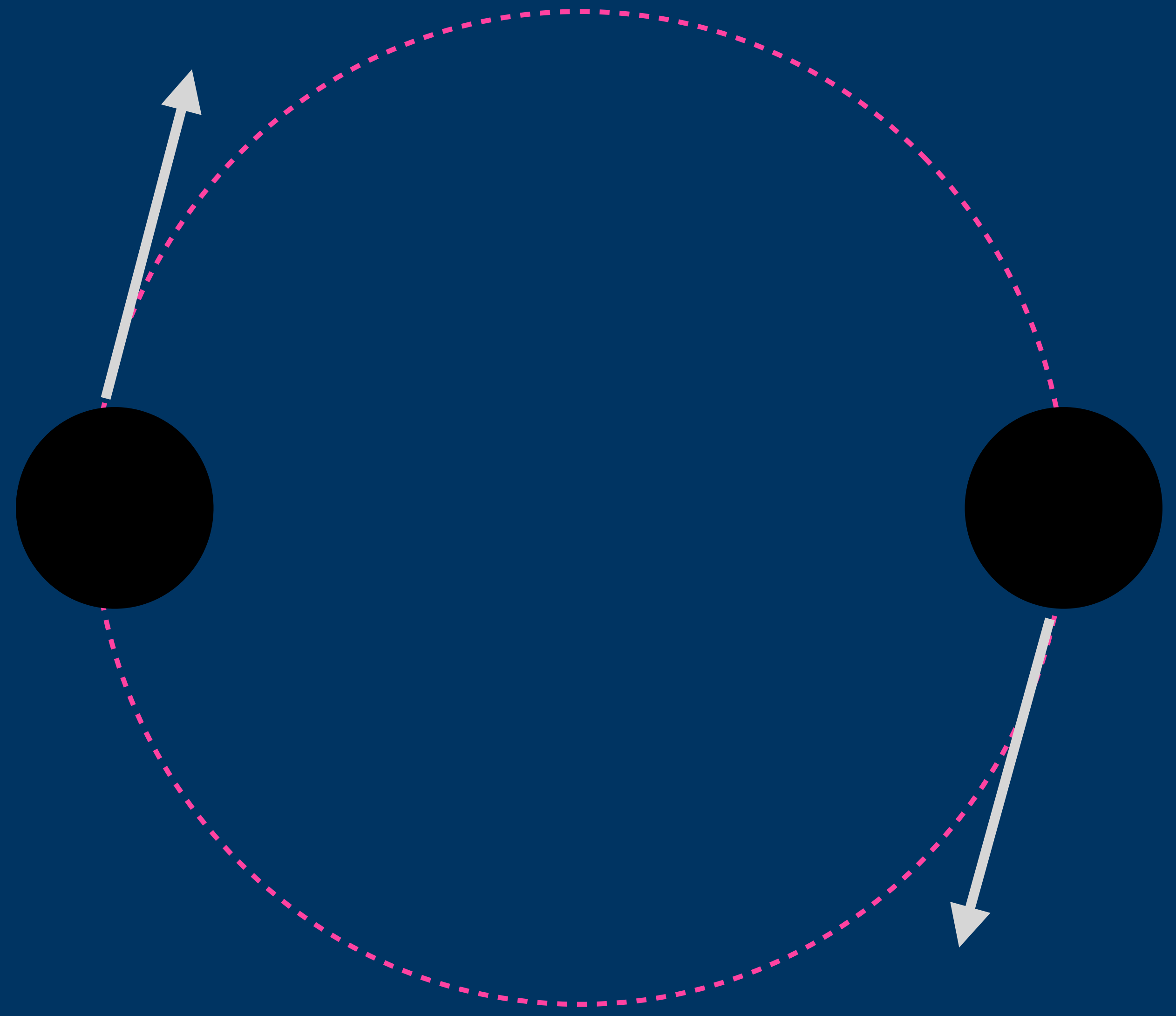
How does this affect the solution of the constraint equations?

Numerical relativity is done in a finite region of spacetime



Problem 1

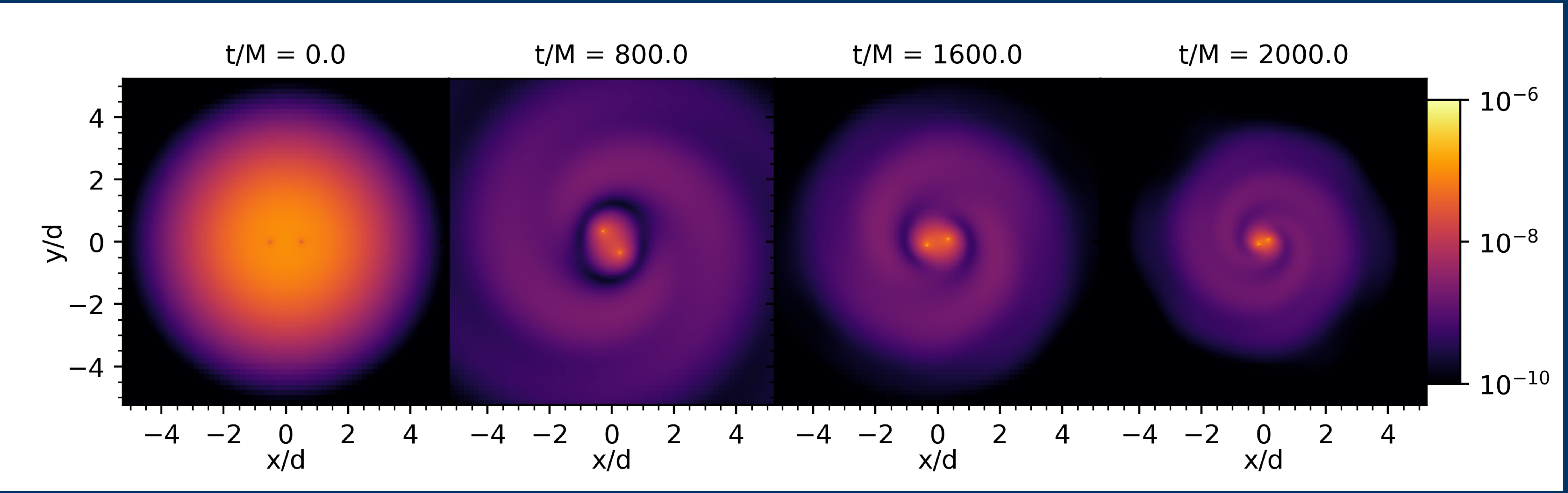
1. The initial matter density will push the BHs off circular orbits compared to the vacuum case



-> Need to adjust the initial momenta so circular again

Problem 2

2. The subsequent *transient* evolution of the field will potentially look like a signal



-> Need to start with the closest initial condition to the "stationary" case

Key points

- To see any signal we need a DM density enhancement mechanism - one possibility is accretion of wave like dark matter

- Numerical relativity simulations will not give the right answer unless you give them the right initial conditions

- We need to do better in modelling physical environments of interest before generating waveforms

Thank you, questions?

Commercial break: