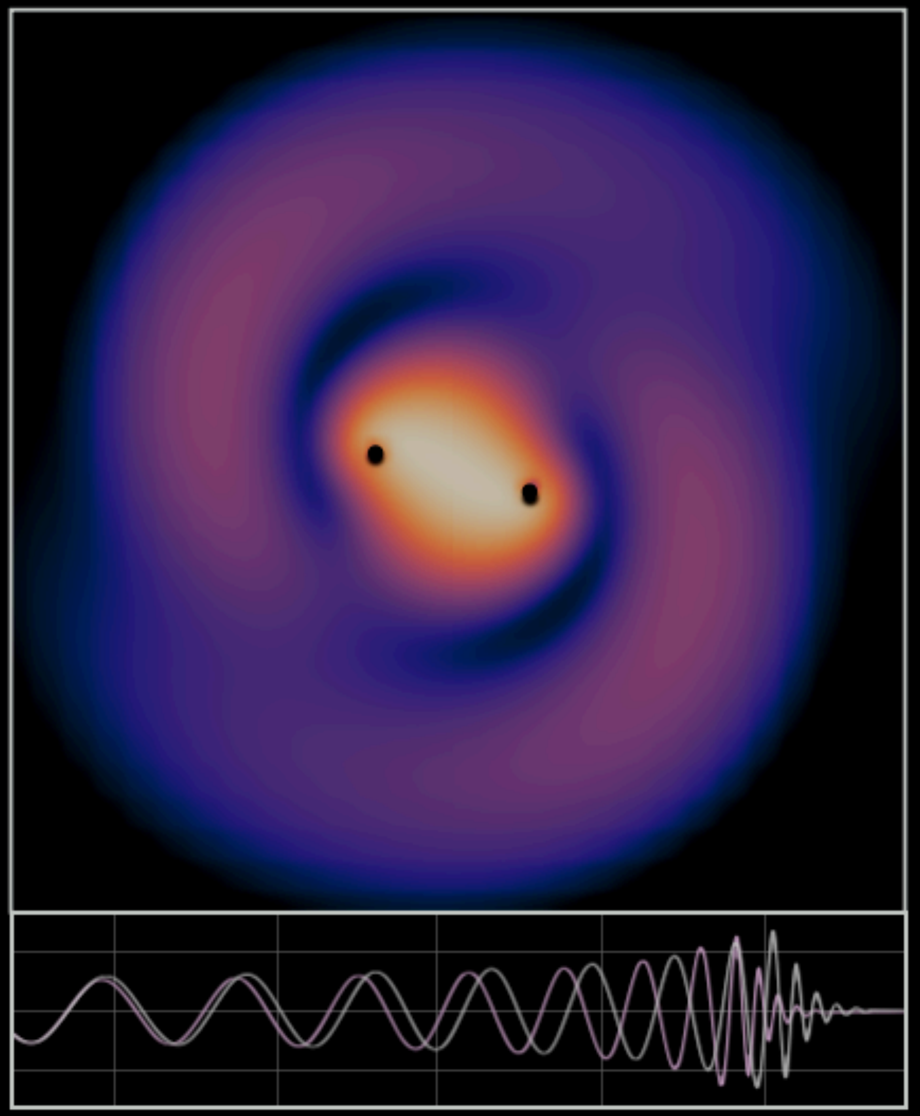
Physics and simulations of scalar dark matter around black holes

Dr Katy Clough,
Queen Mary University of London



UKNR
SIMONS FOUNDATION
UKRI Science and Technology Facilities Council

Questions to answer

1. Can dark matter be ***detected*** around black holes using GWs?

Questions to answer

0. Are the impacts of dark matter ***distinguishable*** from binary parameters (with and without modelling)?

1. Can dark matter be ***detected*** around black holes using GWs?

Questions to answer

-1. How can we ***model*** the impacts of dark matter on GWs?

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Questions to answer

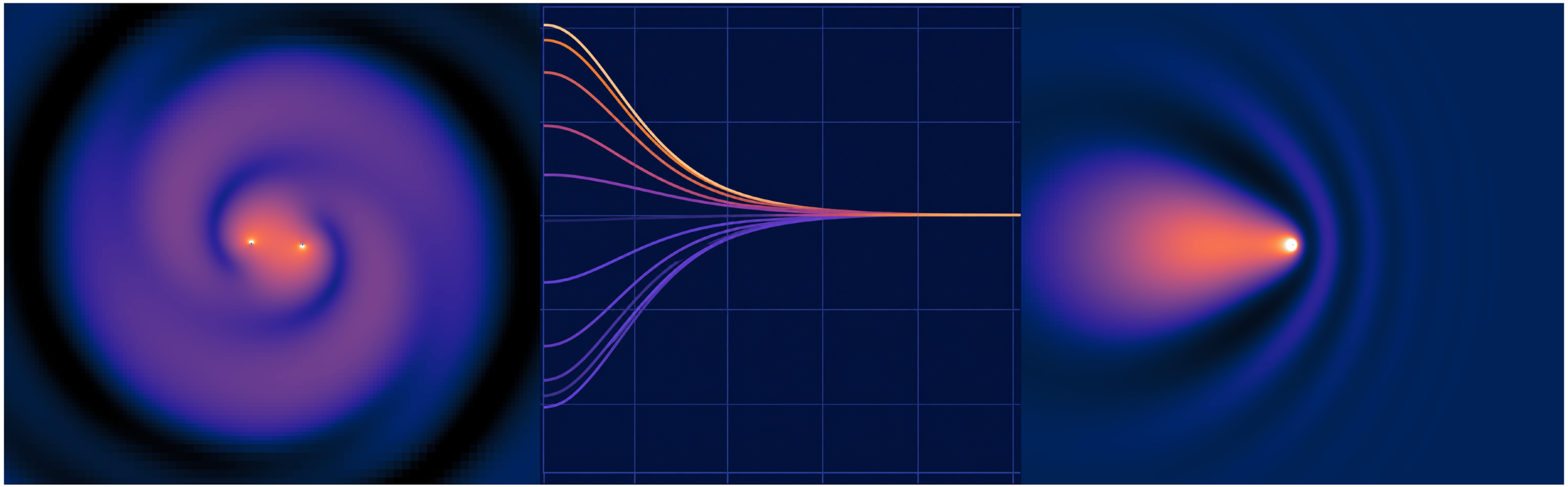
-2. How does dark matter ***behave*** around black holes?

-1. How can we ***model*** the impacts of dark matter on GWs?

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Numerical simulations of general relativity

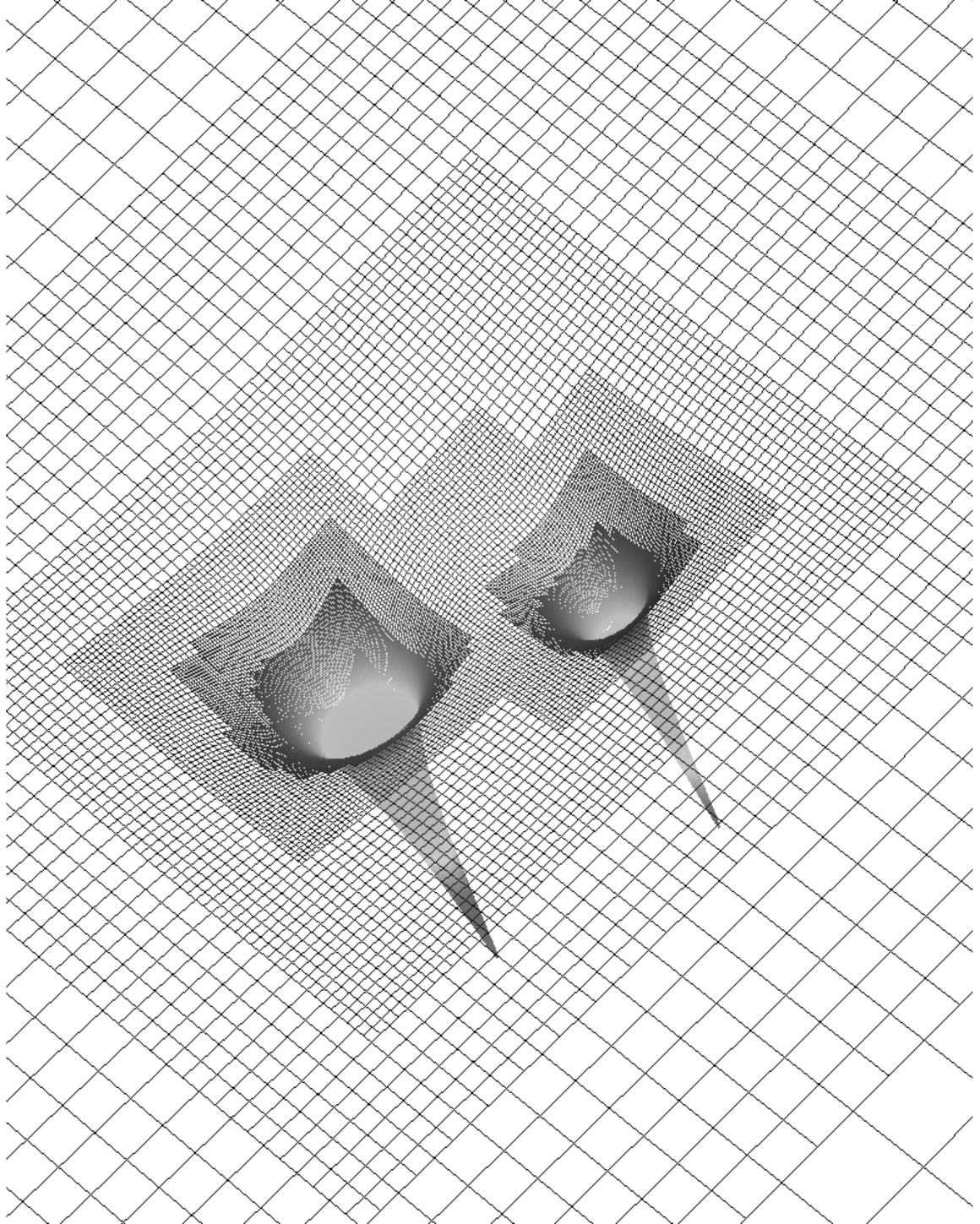


Provide experimental probes of general relativity
(and theoretical extensions)
in the strong field regime

We can solve the Einstein Equations of general relativity as an initial value problem.

This allows us to describe the time evolution of the curvature of spacetime in strong gravity regimes.

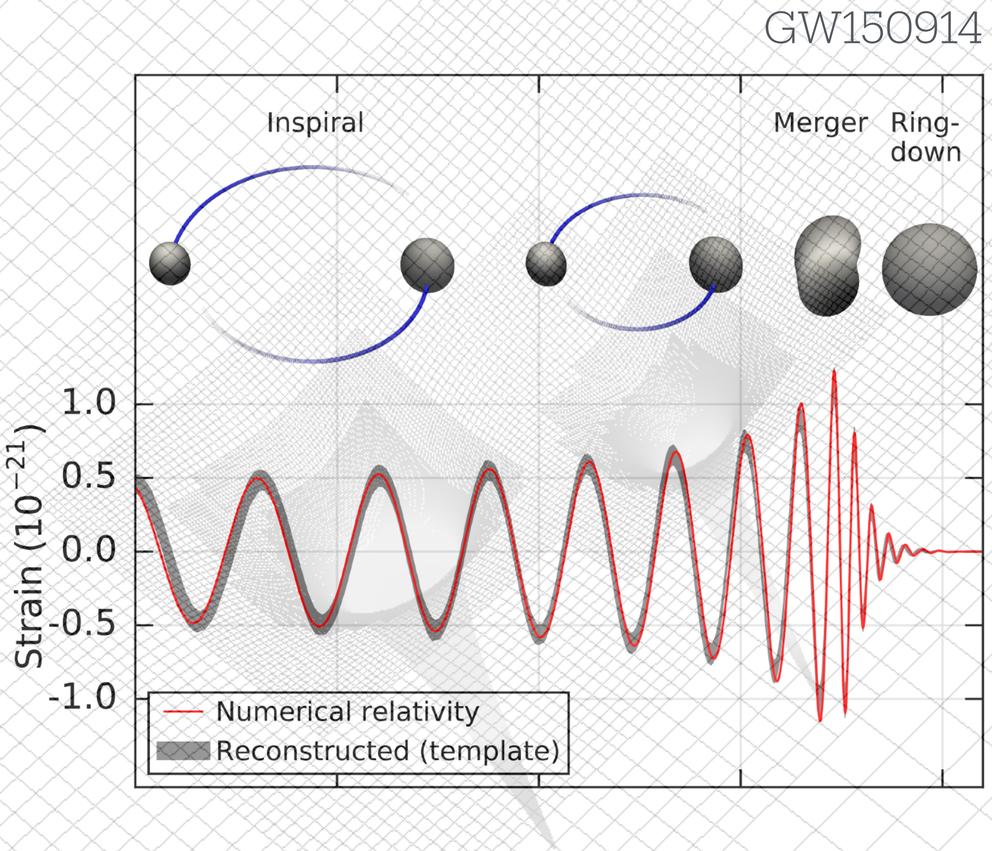
$$\frac{\partial^2 g}{\partial t^2} - \frac{\partial^2 g}{\partial x^2} + \text{non linear terms} = f(\text{energy, momentum})$$



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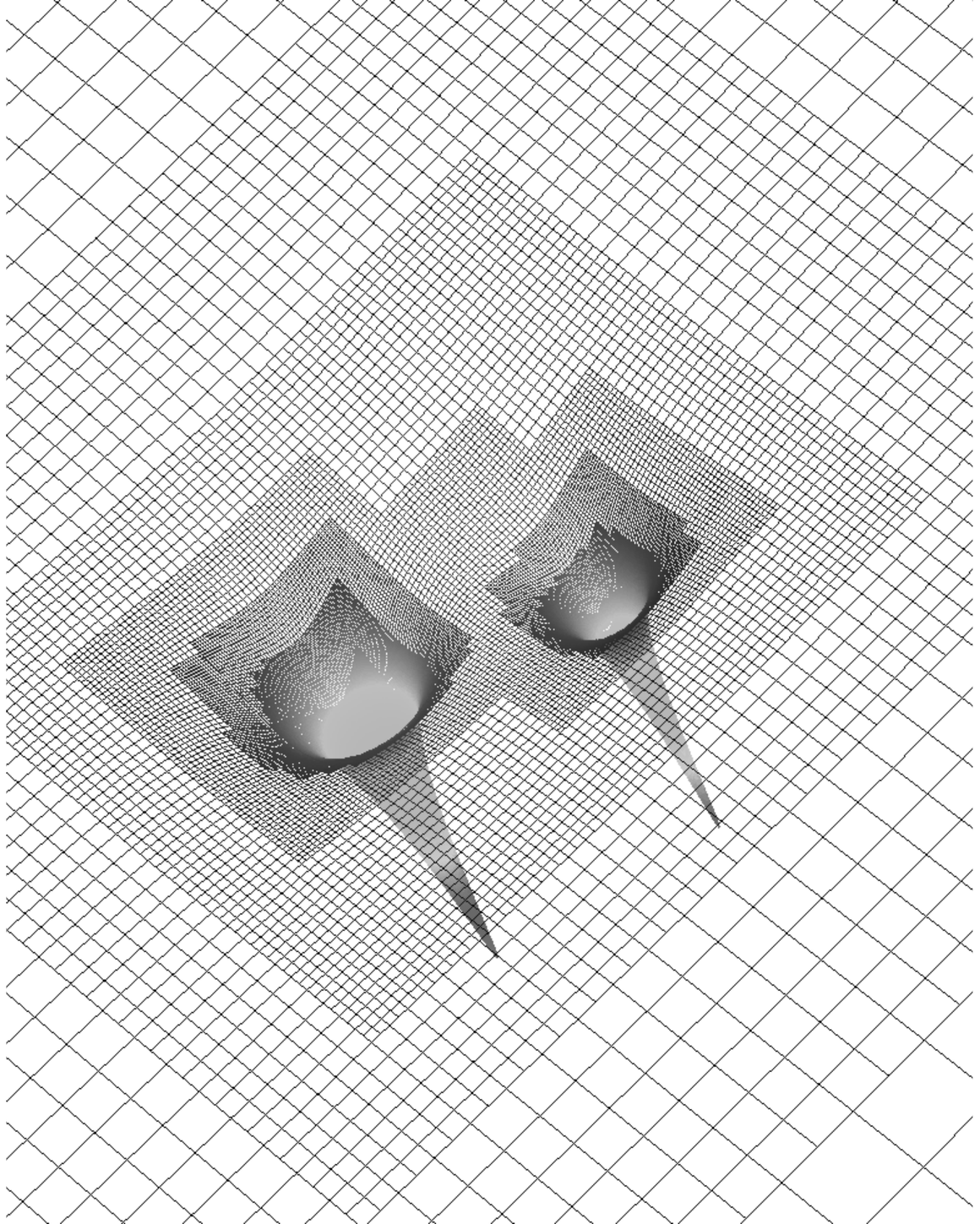
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$$\frac{\partial^2 g}{\partial t^2} - \frac{\partial^2 g}{\partial x^2} + \text{non linear terms} = f(\text{energy, momentum})$$



We can also describe **new physics** in strong gravity regimes.

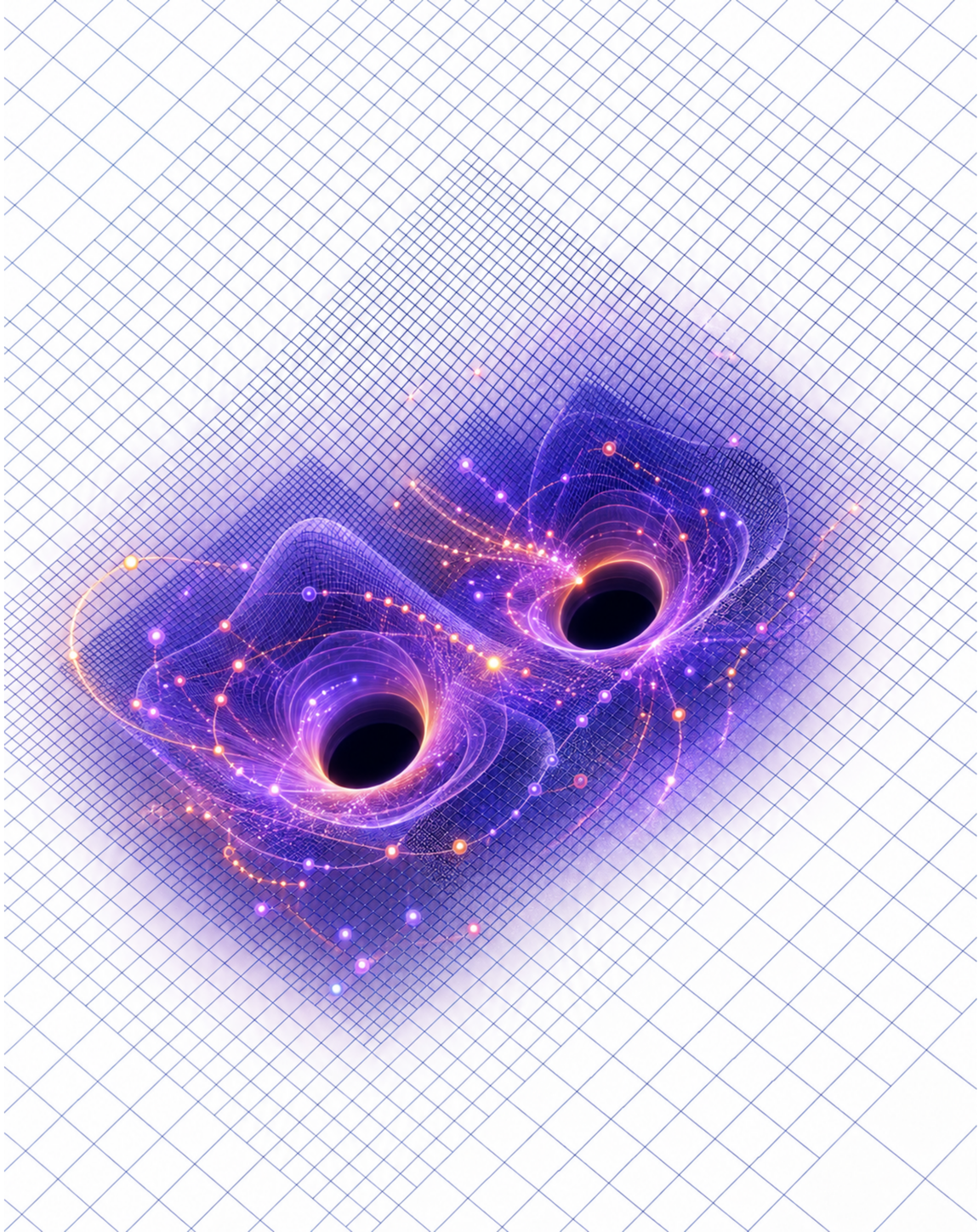
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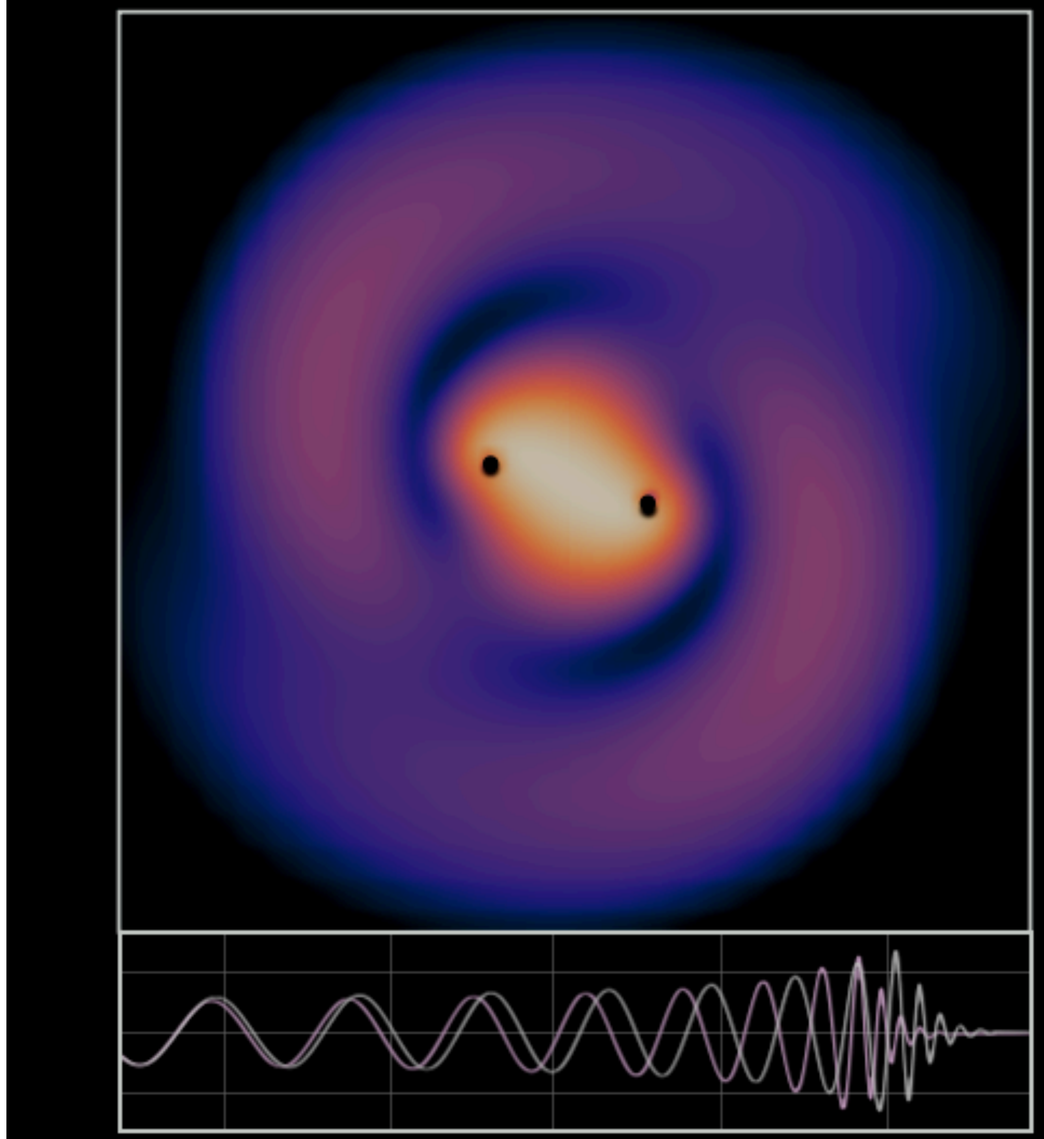
$$\frac{\partial\ (\text{new fields})}{\partial t} = f(\text{metric, fields, matter})$$



We can also describe **new physics** in strong gravity regimes.

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

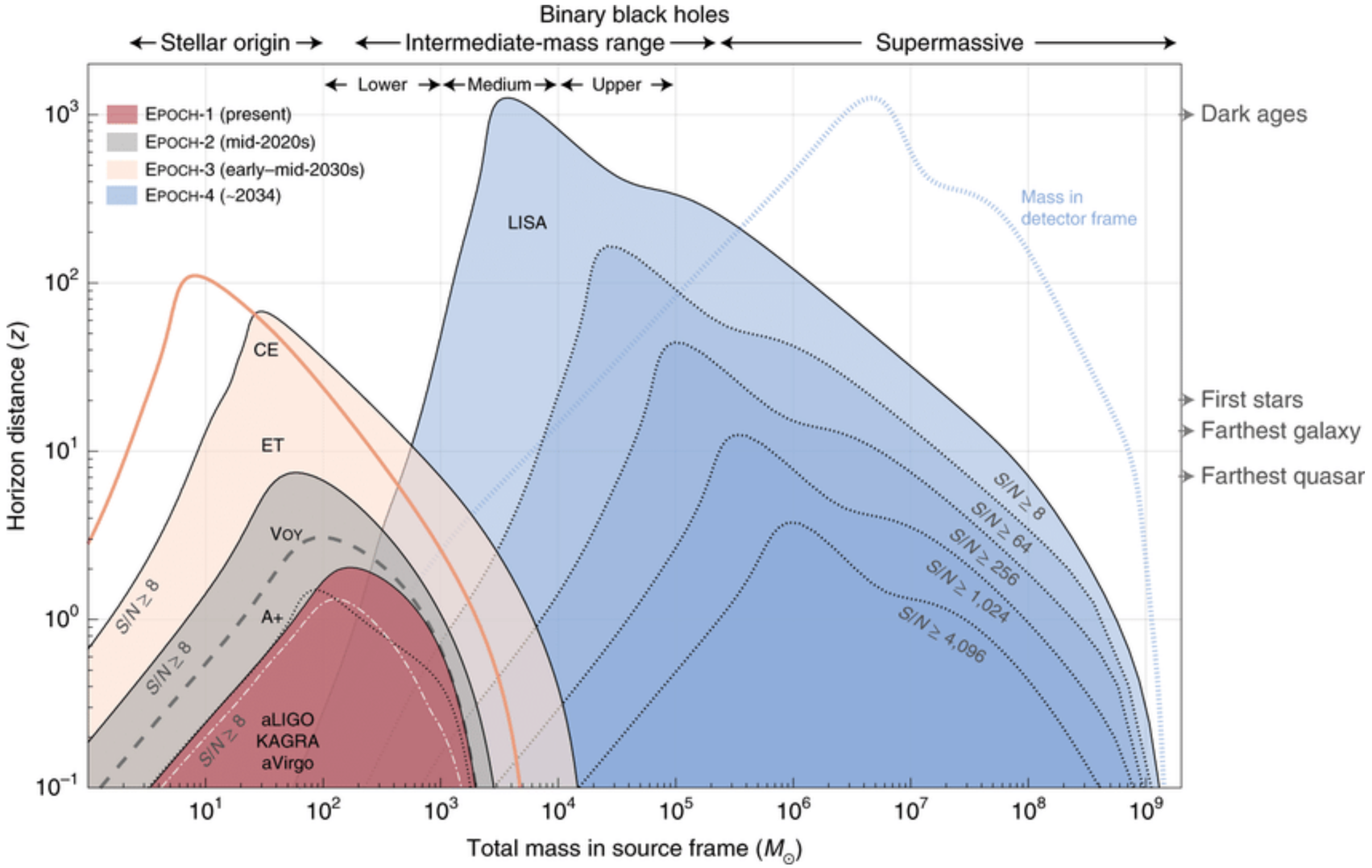
$$\frac{\partial\ (\text{new fields})}{\partial t} = f(\text{metric, fields, matter})$$



What is the motivation for studying dark matter with gravitational waves?

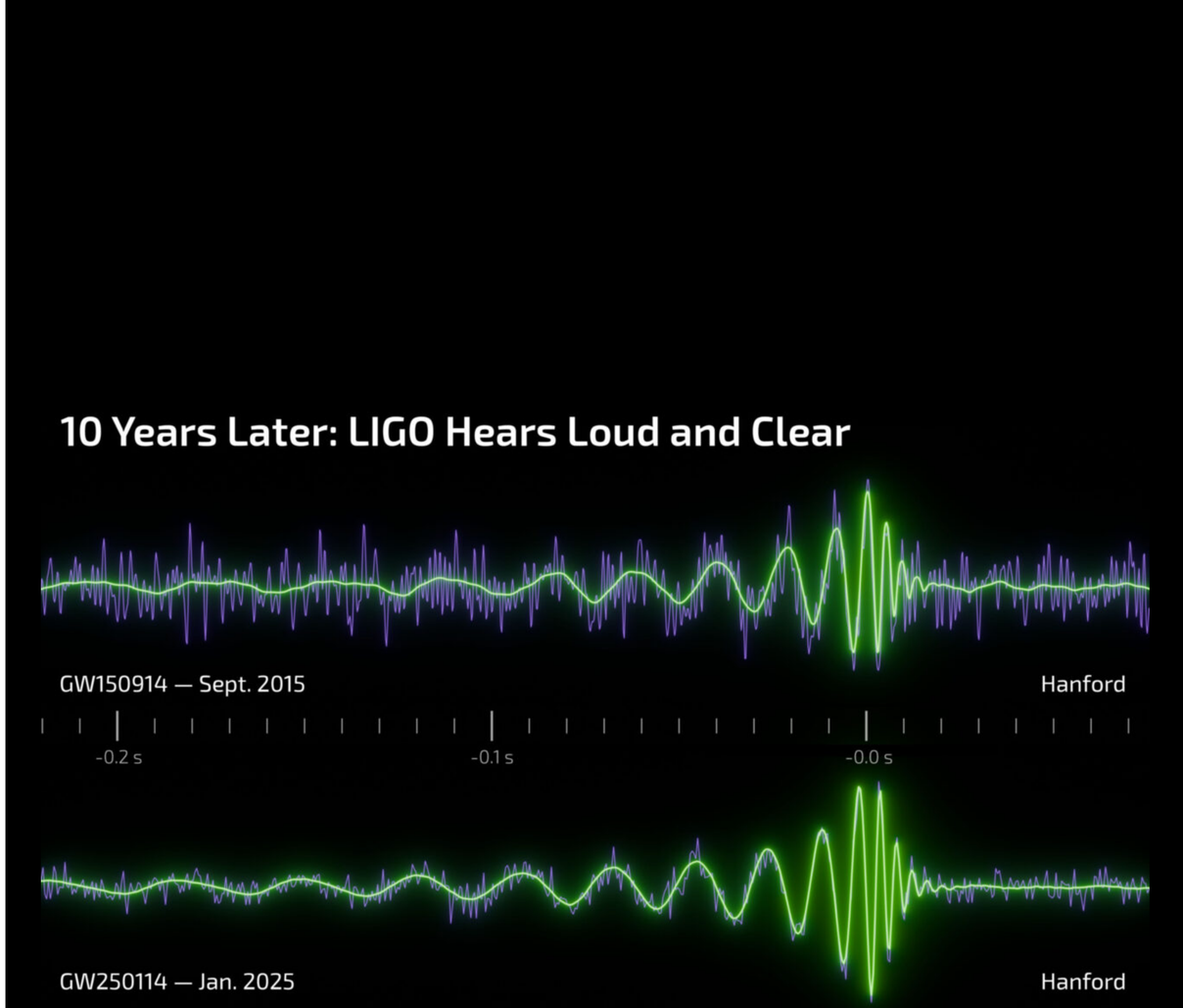
The future has a huge discovery potential.

K Jani, D Shoemaker, C Cutler (2020)
Detectability of intermediate-mass black holes in multiband gravitational wave astronomy.
Nature Astronomy. 4. 1-6. 10.1038/s41550-019-0932-7.



There is nothing obviously wrong with the null hypothesis:

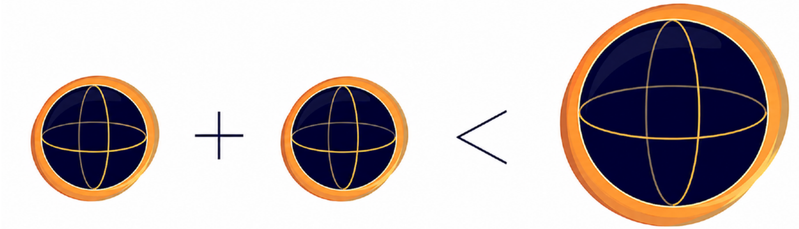
Black holes at all observable scales and SNRs are *well described by Einstein's GR in vacuum*.

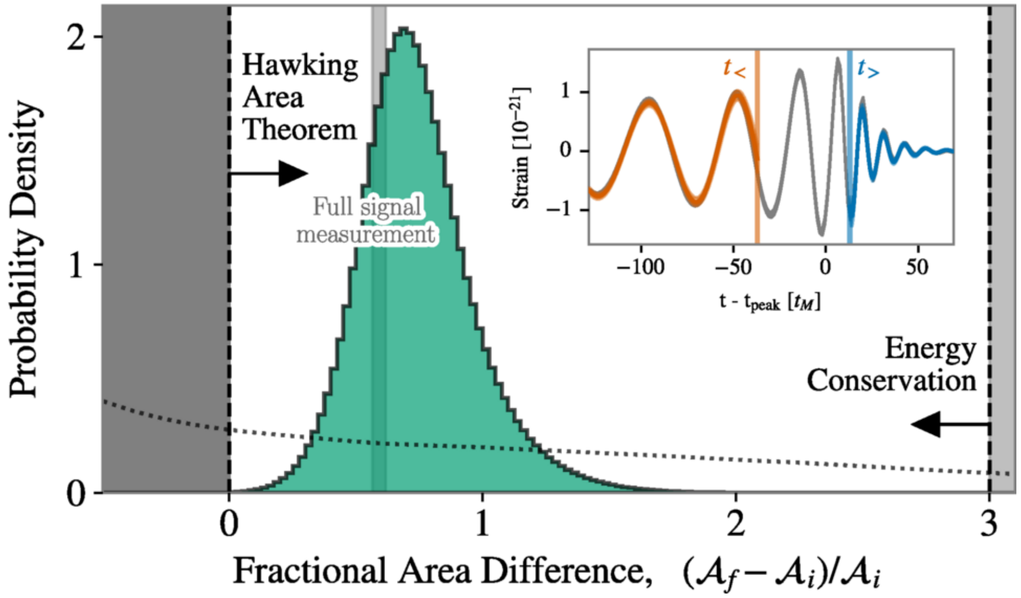


LIGO Scientific, Virgo and KAGRA Collaborations 2025
Phys.Rev.Lett. 135, 111403

So isn’t it just obvious that we are seeing vacuum GR?

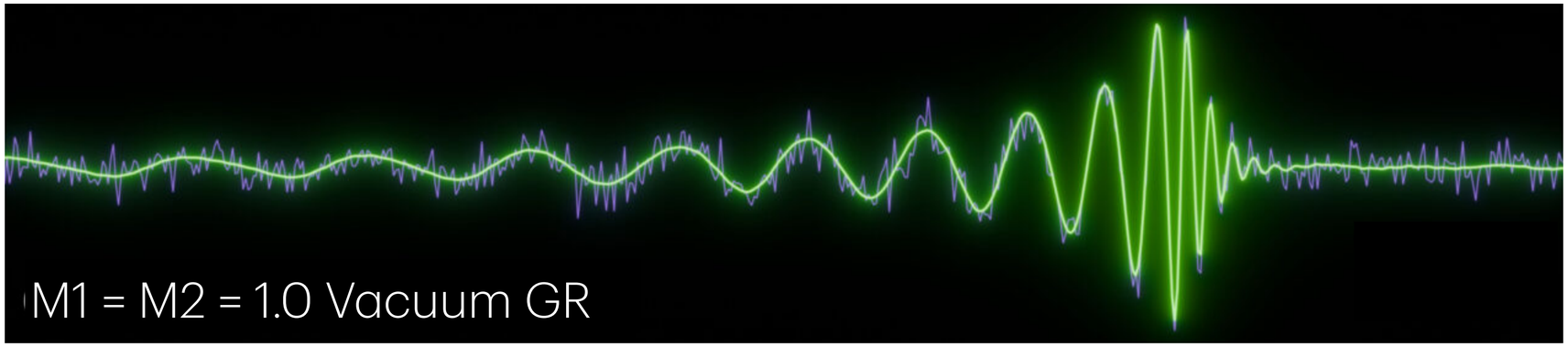
Tests of GR are currently almost all model agnostic consistency checks





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Phys.Rev.Lett. 135, 111403

Potential for degeneracies





Signals from LIGO don't have labels!

Questions to answer

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Galactic dark matter densities are usually small

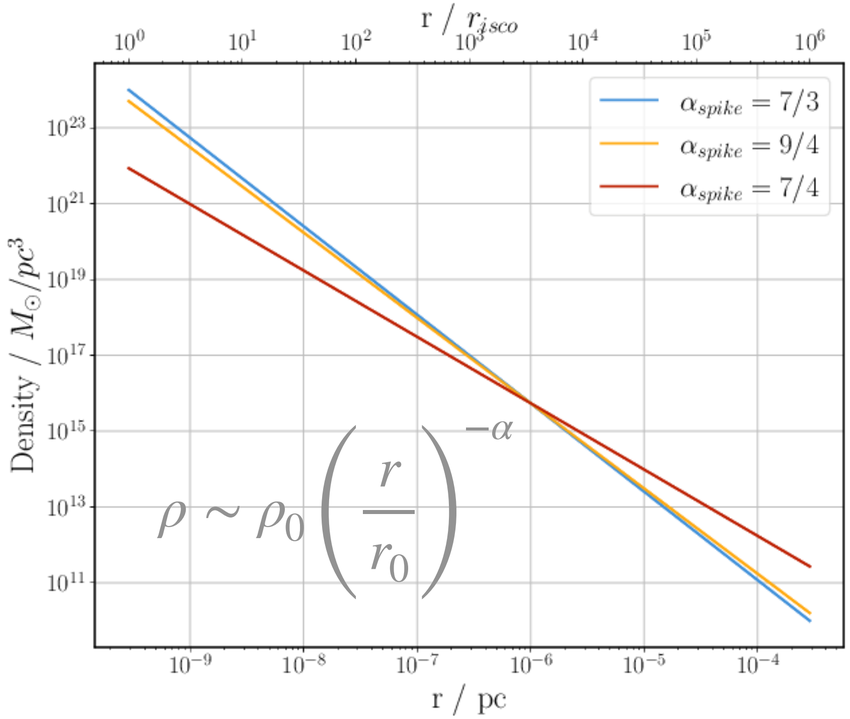
$$\rho \sim 1 \text{ GeV/cm}^3 \textbf{ or } 1 \text{ M}_\odot/\text{pc}^3$$

(Particle physicist) (Astrophysicist)

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

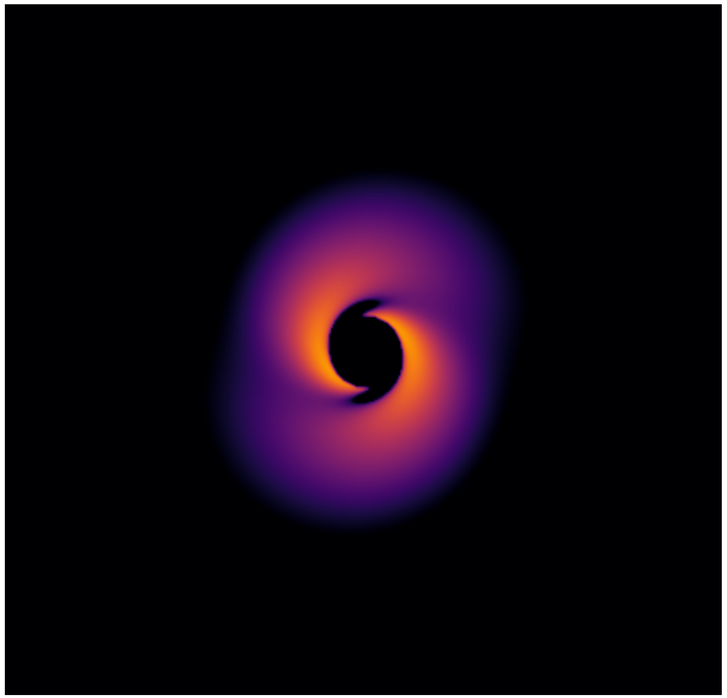
(Numerical relativist)

But can be enhanced around a BH by some mechanisms



Accretion

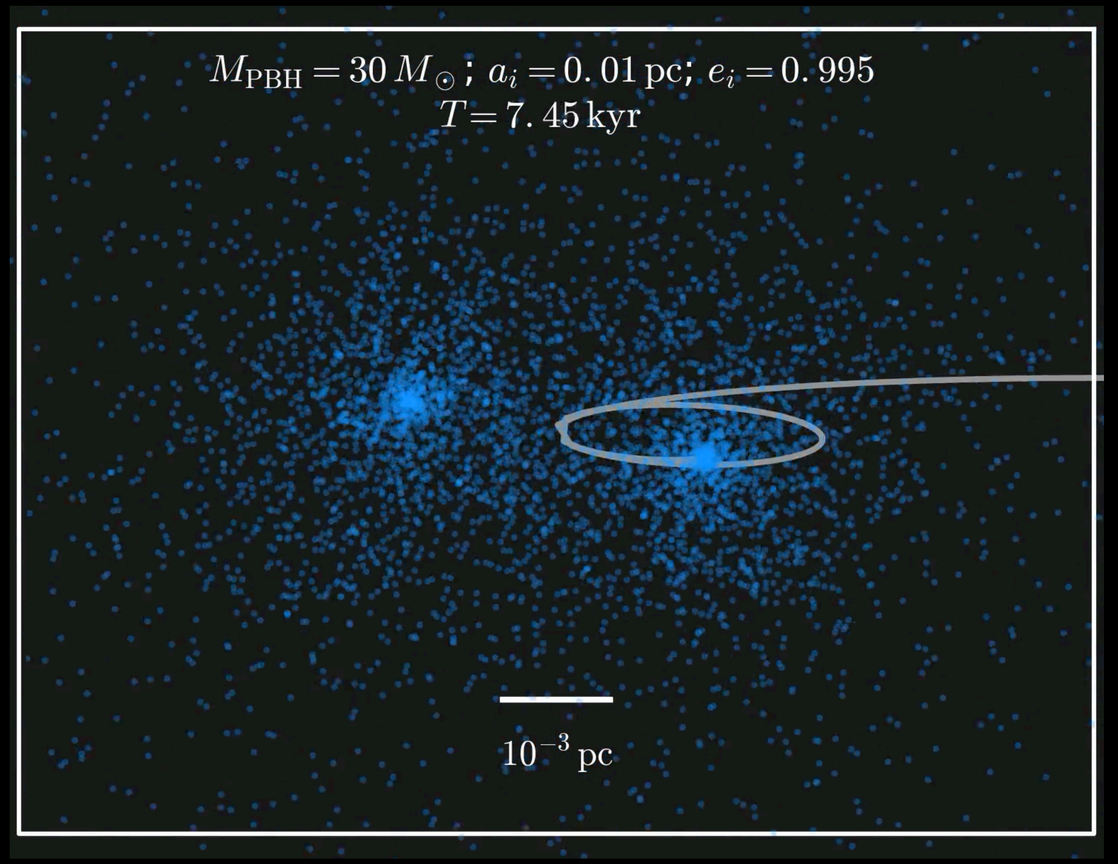
Becker et.al. 2021
Circularization vs. Eccentrification in Intermediate Mass Ratio Inspirals inside Dark Matter Spikes



Superradiance

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

Particle dark matter disperses around binaries

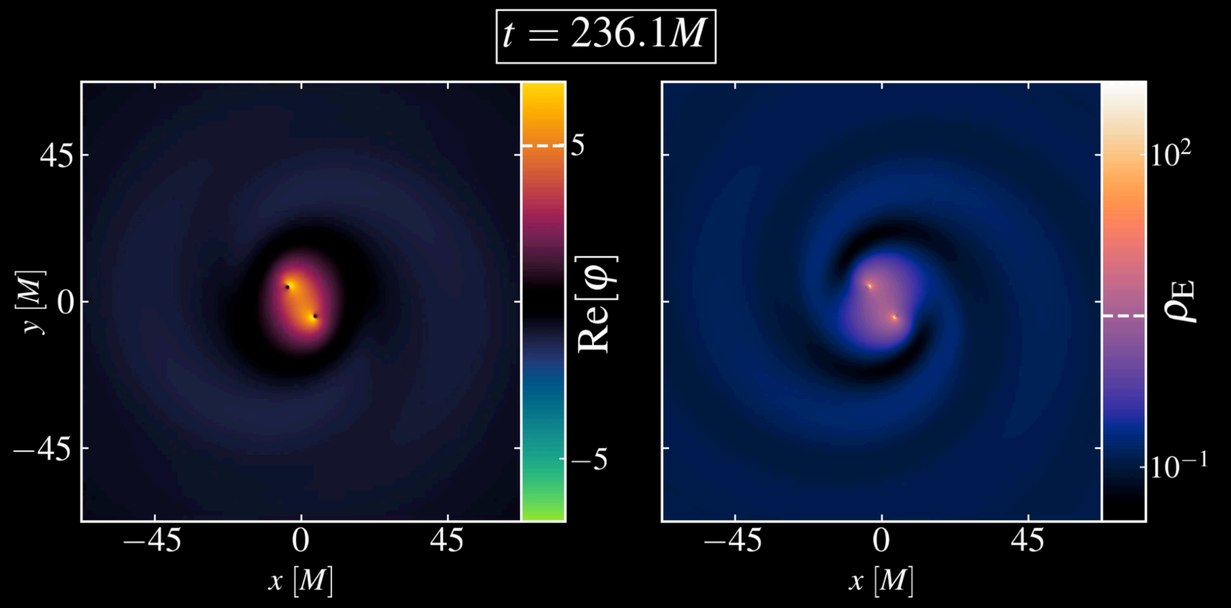


Bertone et. al. 2020
Gravitational wave probes of dark matter: challenges and opportunities

But certain types of dark matter (light, axion-like) appears to resist dispersal

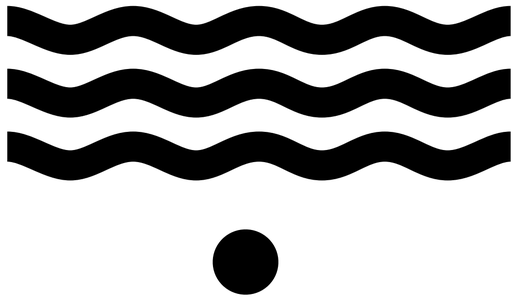
field value

density of DM



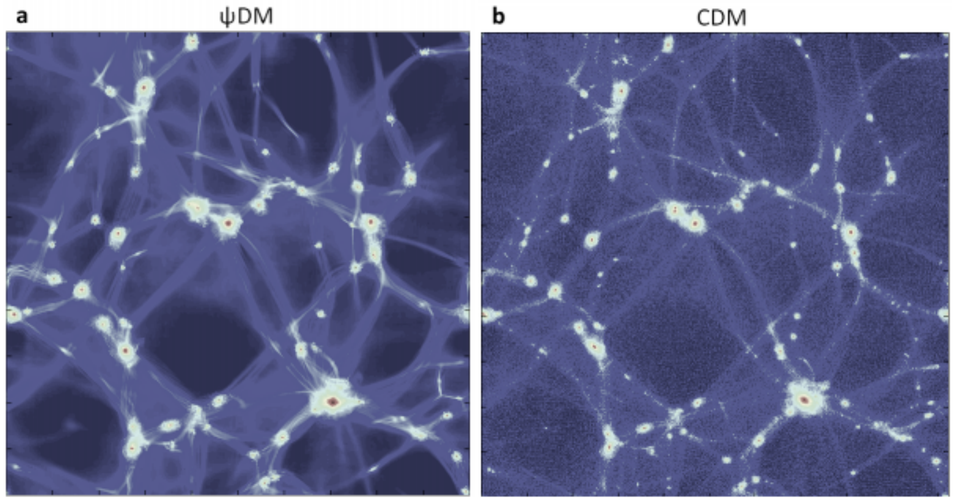
J. Bamber, J. Aurrekoetxea, KC, P. Ferreira 2023
Phys Rev D 107 2, 024035

Wave-like regime



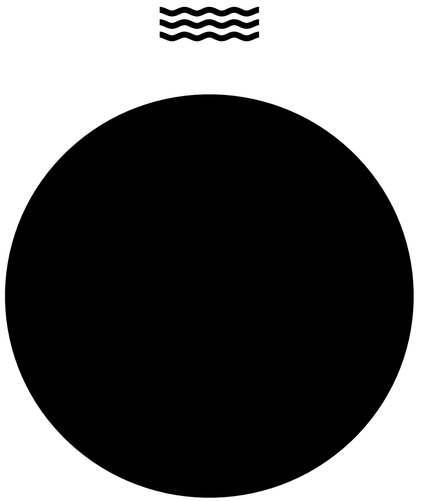
Wave

$\mu M \ll 1$



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

See also Wave Dark Matter review by Lam Hui
Ann.Rev.Astron.Astrophys. 59 (2021) 247-289

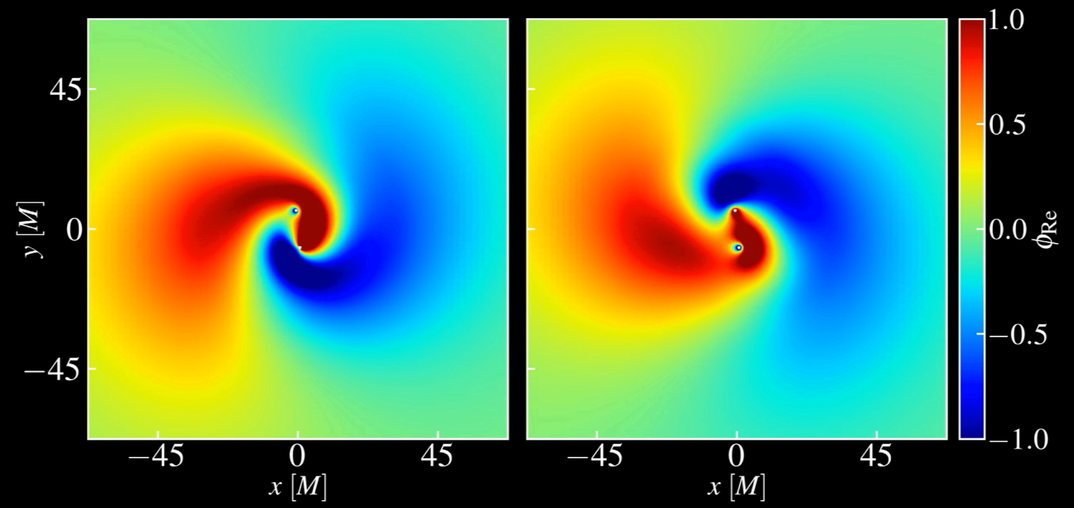


Particle

$\mu M \gg 1$

Work in progress

Can superradiant clouds around isolated BHs actually survive the equal mass binary inspiral?



J Aurrekoetxea, KC, P Ferreira, S Ghosh, T Spieksma (In prep)

Questions to answer

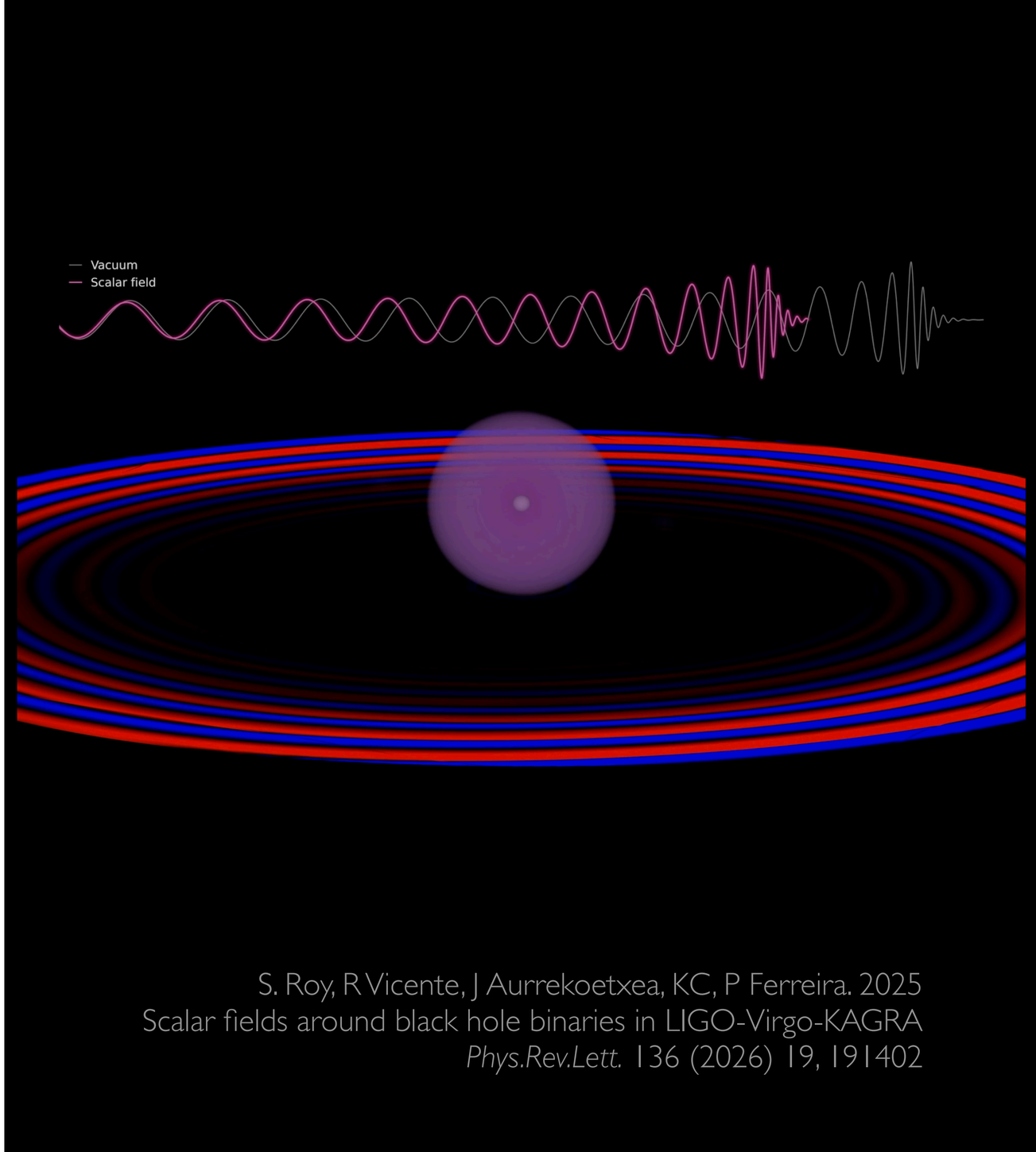
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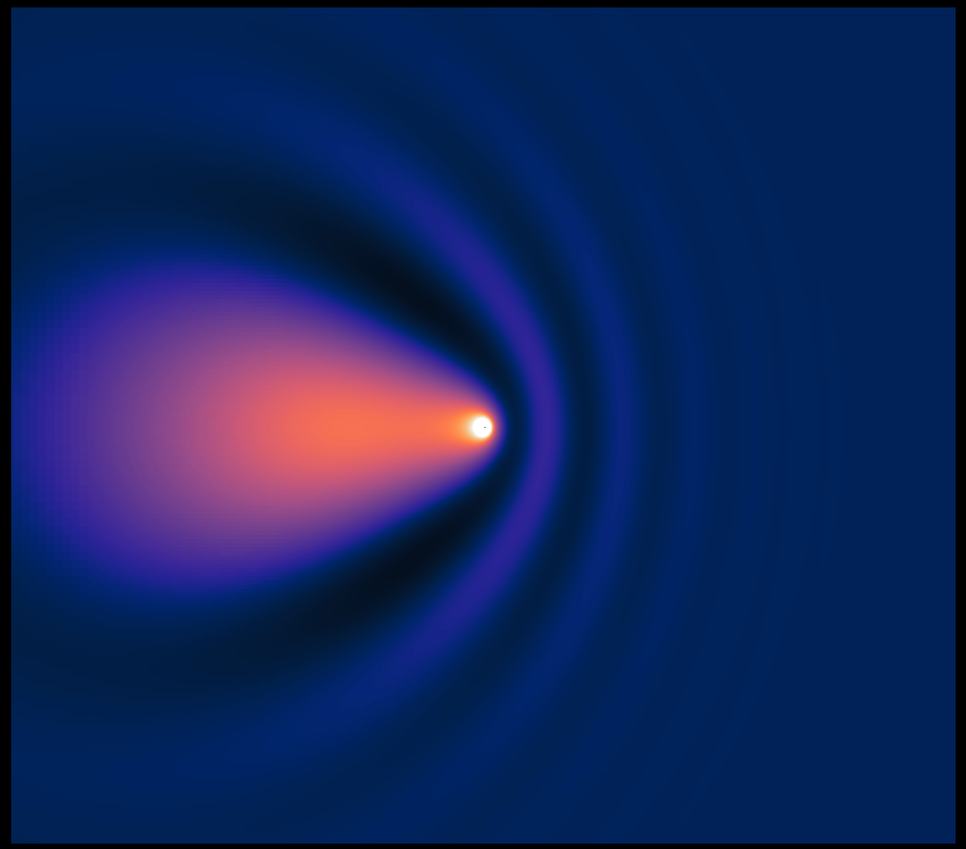
1. Can dark matter be ***detected*** around black holes using GWs?

Running a numerical relativity simulation gives us an answer for one specific case



S. Roy, R Vicente, J Aurrekoetxea, KC, P Ferreira. 2025
Scalar fields around black hole binaries in LIGO-Virgo-KAGRA
Phys.Rev.Lett. 136 (2026) 19, 191402

To generalise, need to correctly model interactions between binary and scalar field

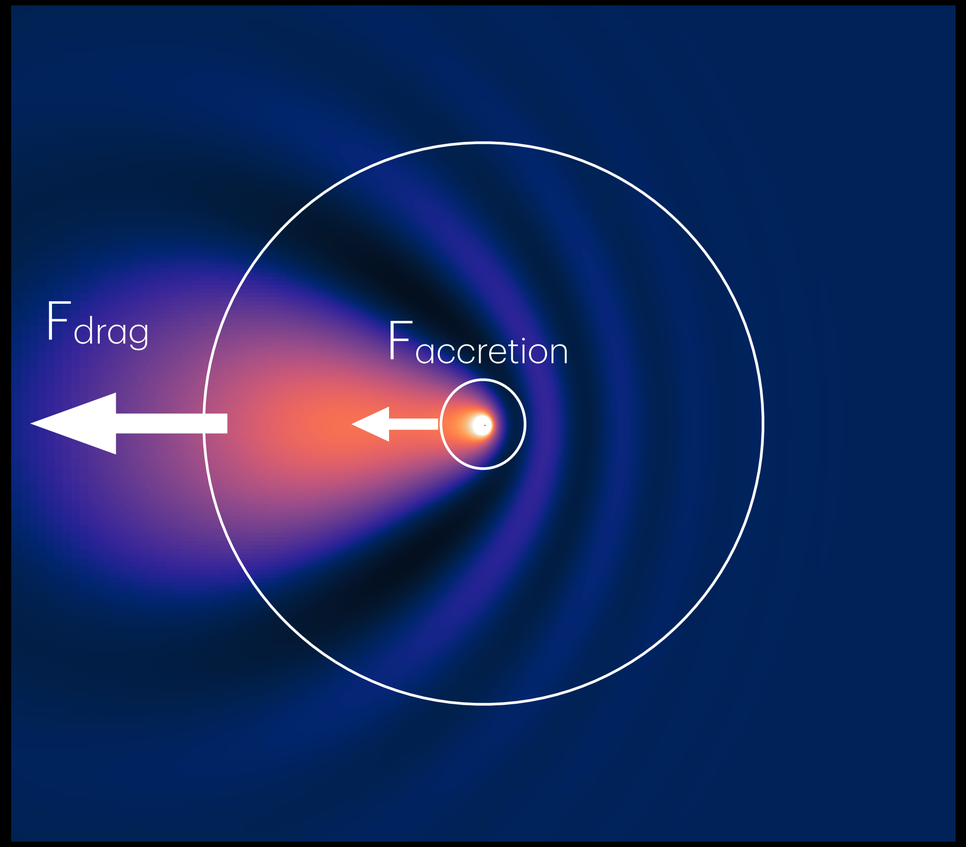


D Traykova, R Vicente, KC et. al.
Phys.Rev.D 108 (2023) 12, L121502

Dynamical friction

Dynamical Friction. I. General Considerations: the Coefficient of Dynamical Friction.
S. Chandrasekhar, Astrophysical Journal, vol. 97, p.255

$$\partial_t P_{BH}(\zeta^\mu) = -\underbrace{\int_\Sigma \alpha T^{\mu\nu}\, \nabla_\nu \zeta_\mu \, dV}_{dynamical\ friction} - \underbrace{\int_{\partial\Sigma} \alpha T^{\mu\nu} \zeta_\mu \, dS_\nu}_{accretion}$$



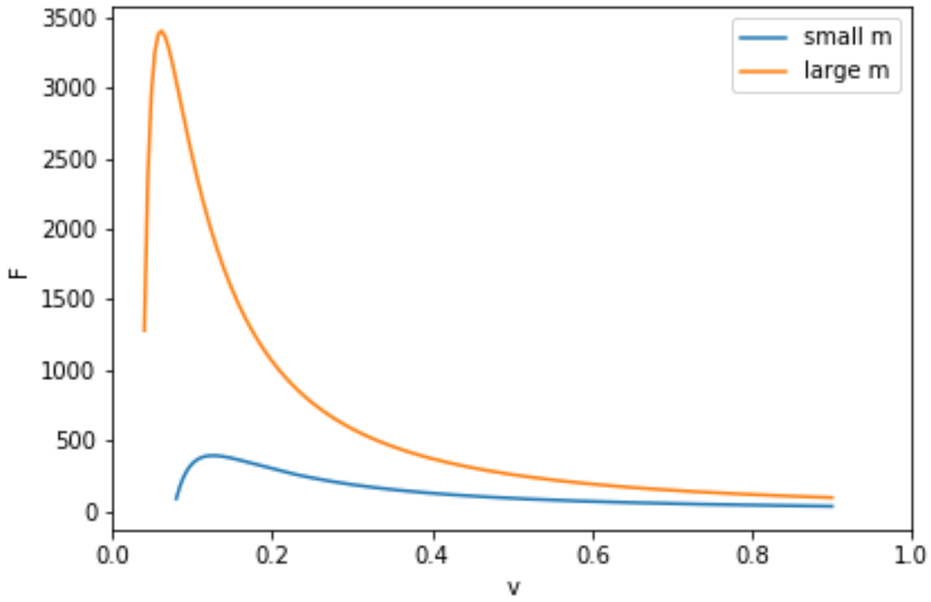
D Traykova, R Vicente, KC et. al.
Phys.Rev.D 108 (2023) 12, L121502

K Clough
Class.Quant.Grav. 38 (2021) 16, 167001

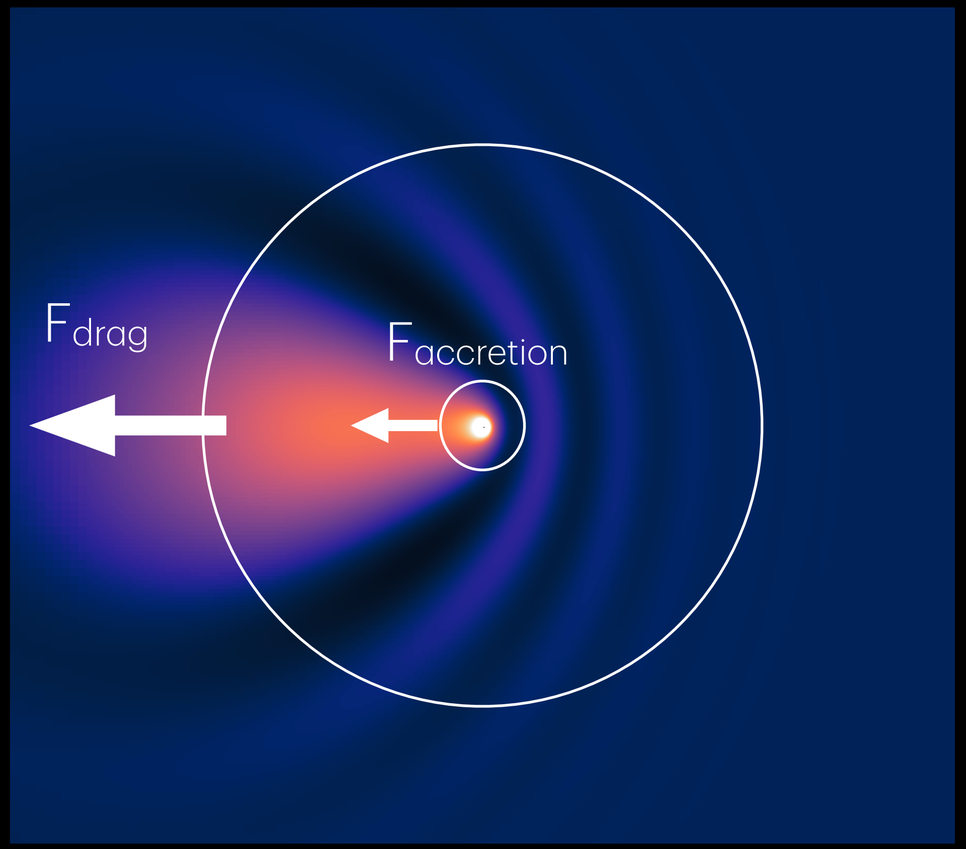
Dynamical friction - Newtonian calculation for DM

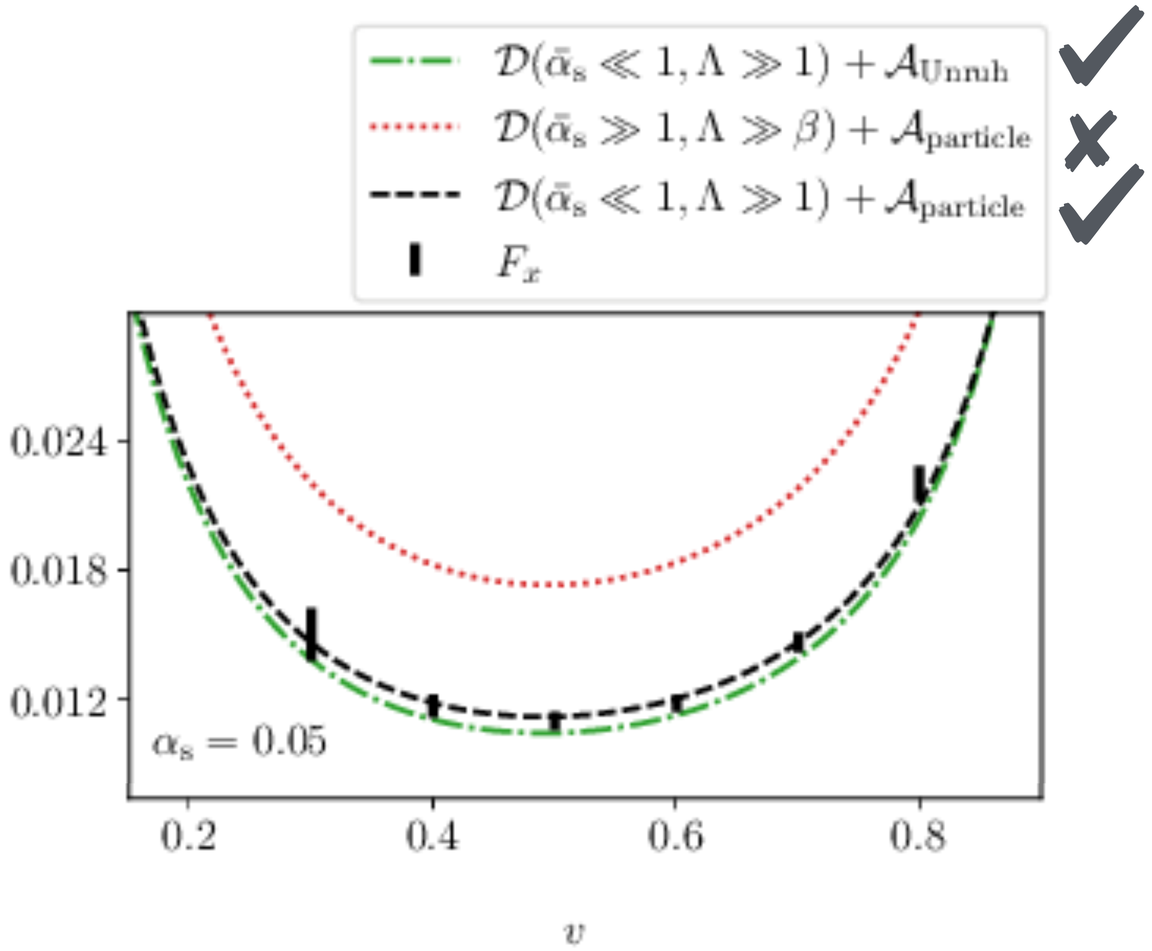
$$F \sim \rho \left(\frac{GM}{v} \right)^2 \ln(2\mu v r)$$

Force versus velocity



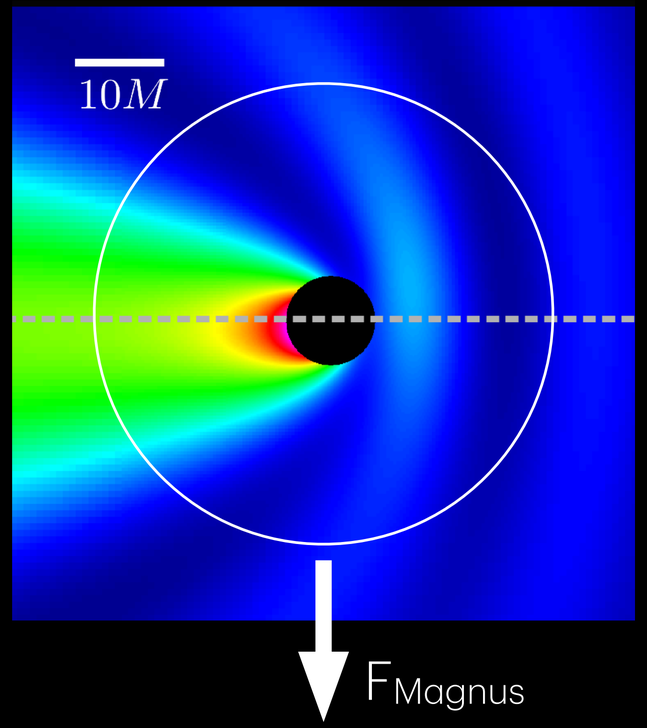
Ultralight scalars as cosmological dark matter
L. Hui, J. Ostriker, S. Tremaine, E. Witten, Phys. Rev. D 95, 043541 (2017)





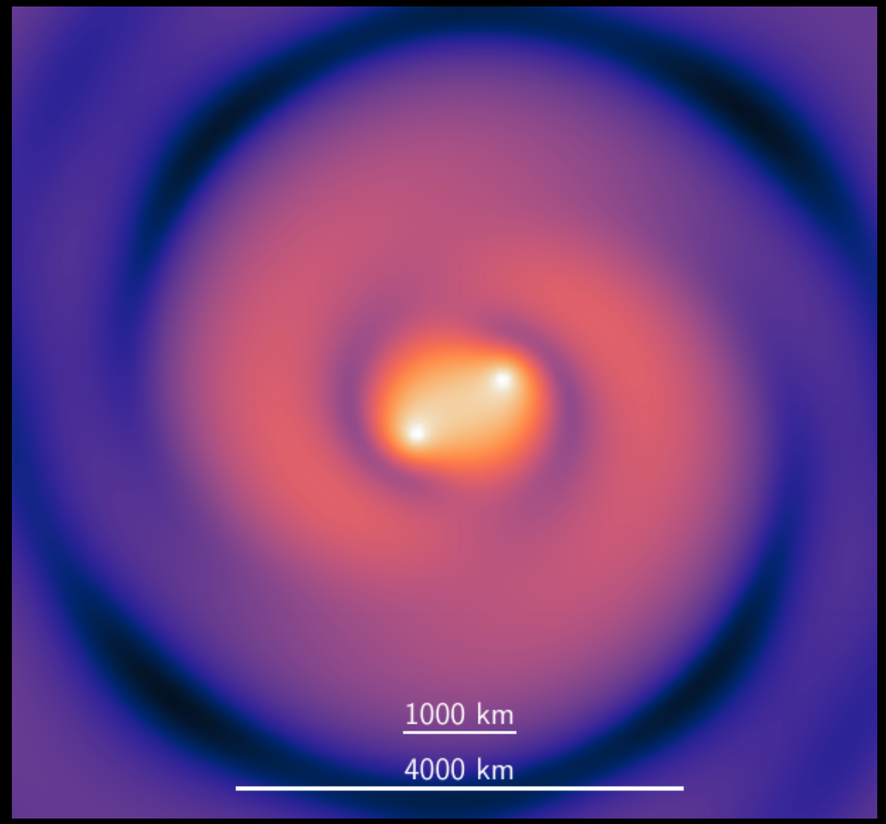
D Traykova, R Vicente, KC et. al.
Phys.Rev.D 108 (2023) 12, L121502

For spinning black holes, there is also a gravitational "Magnus force"



Z Wang, T Helfer, D Traykova, KC, E Berti
Phys.Rev.D 110 (2024) 2, 024009

Equal mass binaries near merger not so simple



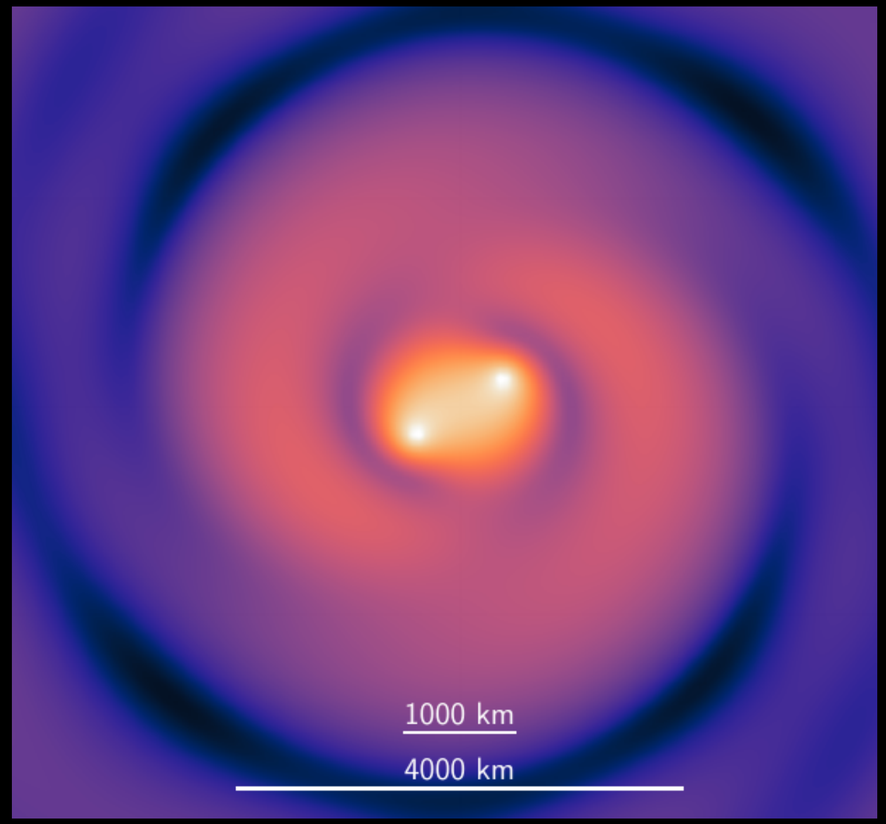
S. Roy, R Vicente, J Aurrekoetxea, KC, P Ferreira. 2025
Scalar fields around black hole binaries in LIGO-Virgo-KAGRA
Phys.Rev.Lett. 136 (2026) 19, 191402

Model the additional loss of angular momentum from scattering of the field in a time varying potential

$$\dot{L} = \dot{L}_{GW} + \dot{L}_{\phi}$$

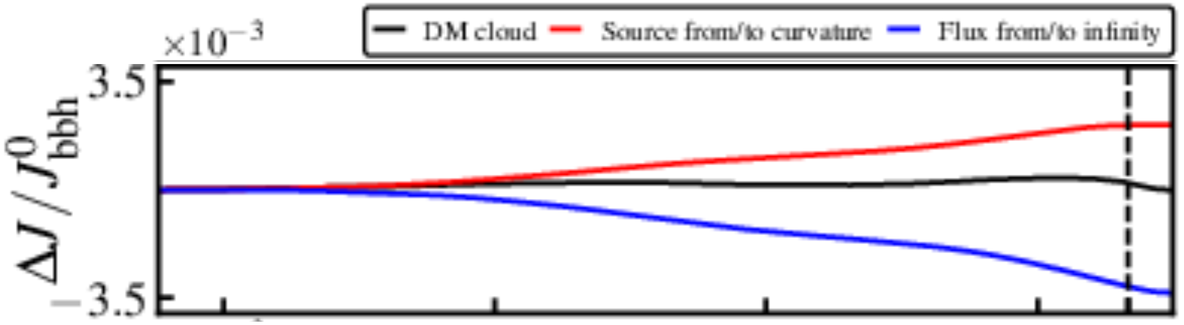
Where

$$\frac{\dot{L}_{\phi}}{M} = -\frac{4\pi\bar{\rho}_{\phi}}{(\pi f M)^{4/3}}\,\mathcal{J}(fM, \mu M, q)$$



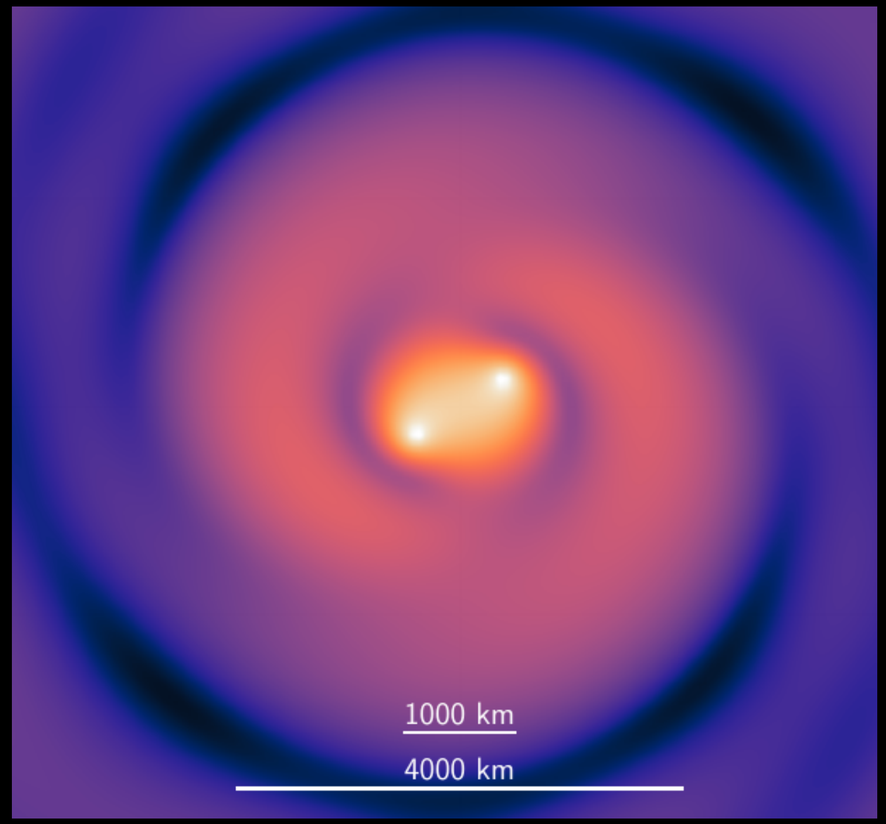
S. Roy, R Vicente, J Aurrekoetxea, KC, P Ferreira. 2025
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Can validate this loss from simulation measurements

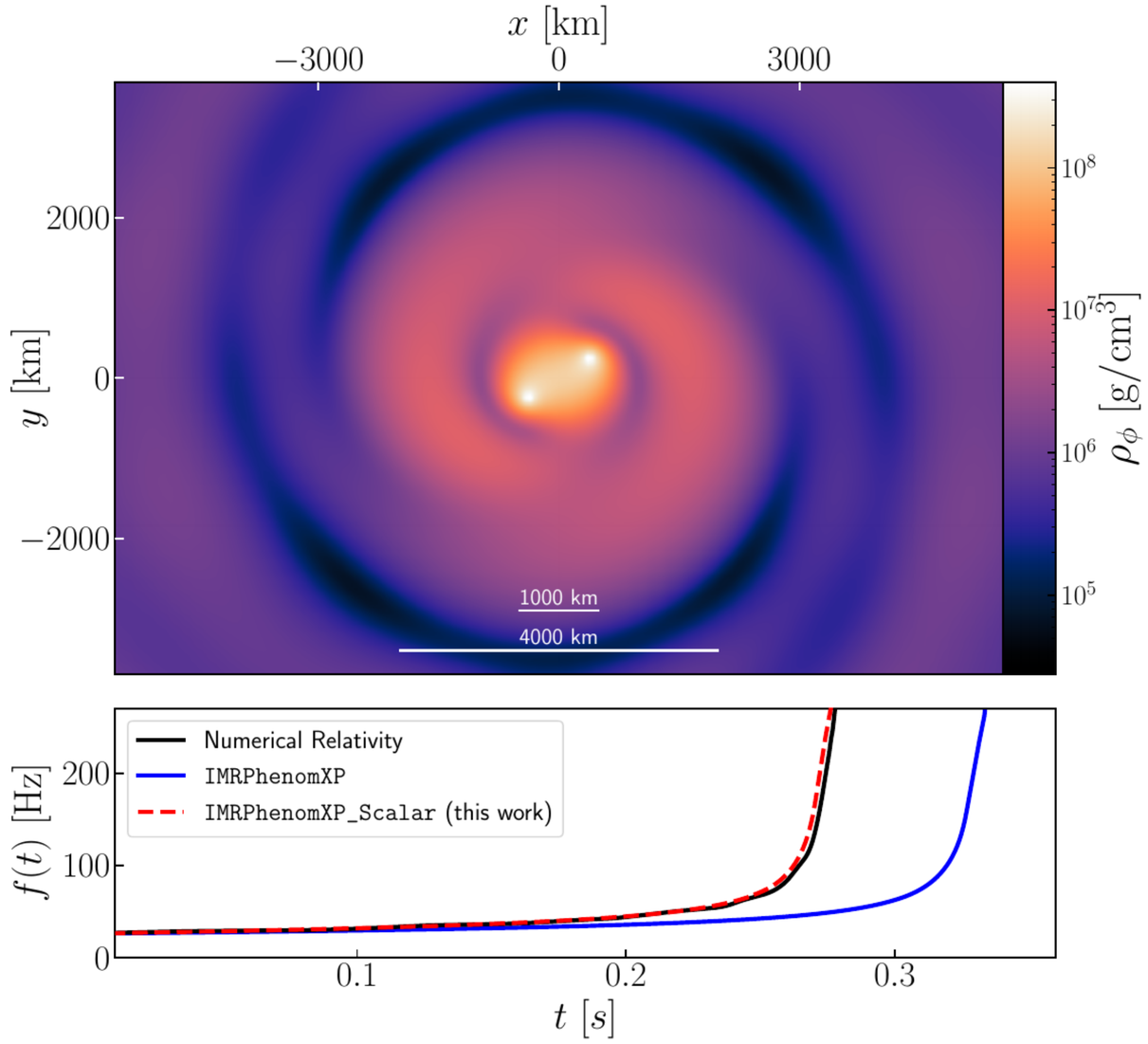


J. Aurrekoetxea, KC, J Bamber, P Ferreira 2023
Phys.Rev.Lett. 132 (2024) 21, 211401

$$\partial_t P_{BH}(\zeta^\mu) = -\underbrace{\int_\Sigma \alpha T^{\mu\nu}\, \nabla_\nu \zeta_\mu \, dV}_{\textit{dynamical friction}} - \underbrace{\int_{\partial\Sigma} \alpha T^{\mu\nu} \zeta_\mu \, dS_\nu}_{\textit{accretion}}$$



Can validate the model from the waveform



S. Roy, R Vicente, J Aurrekoetxea, KC, P Ferreira. 2025
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Questions to answer

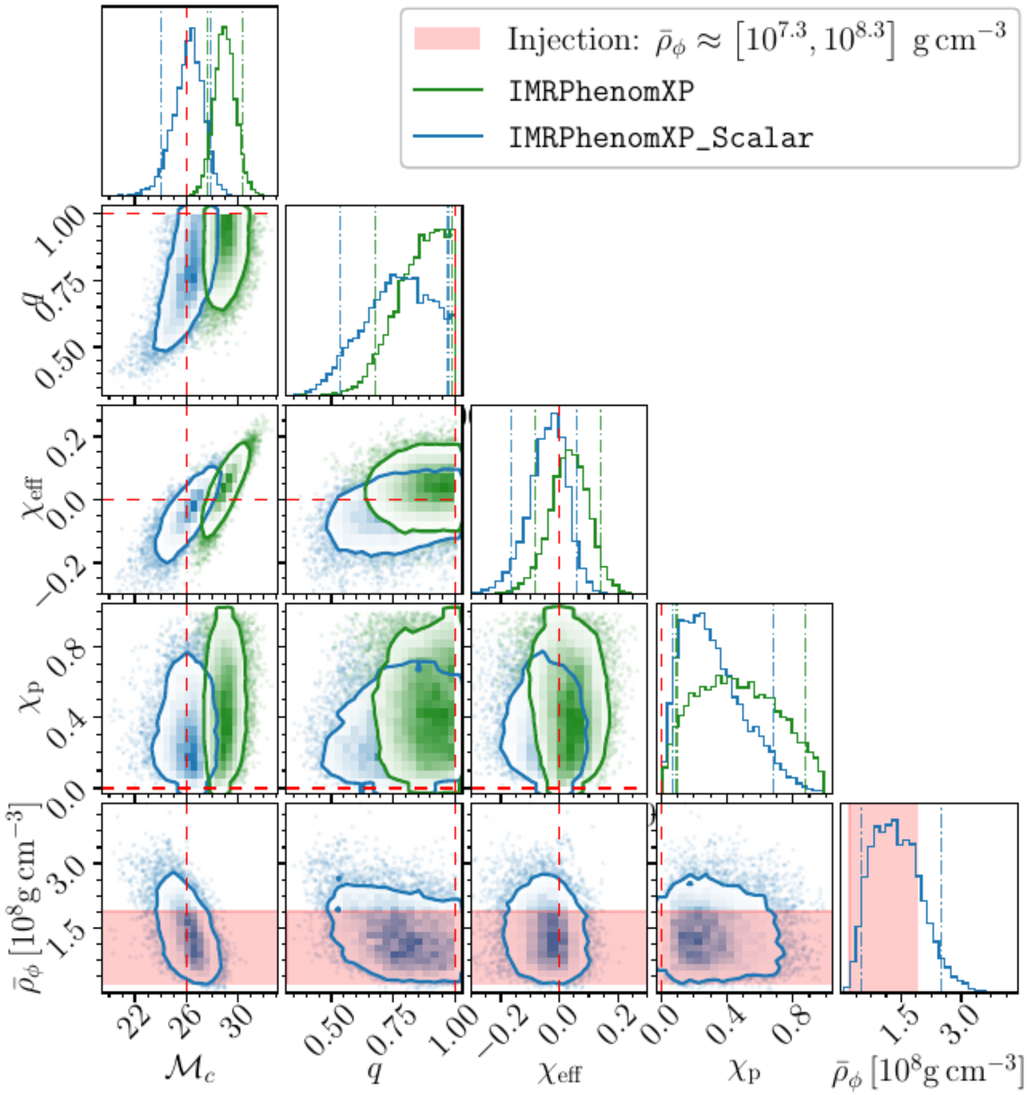
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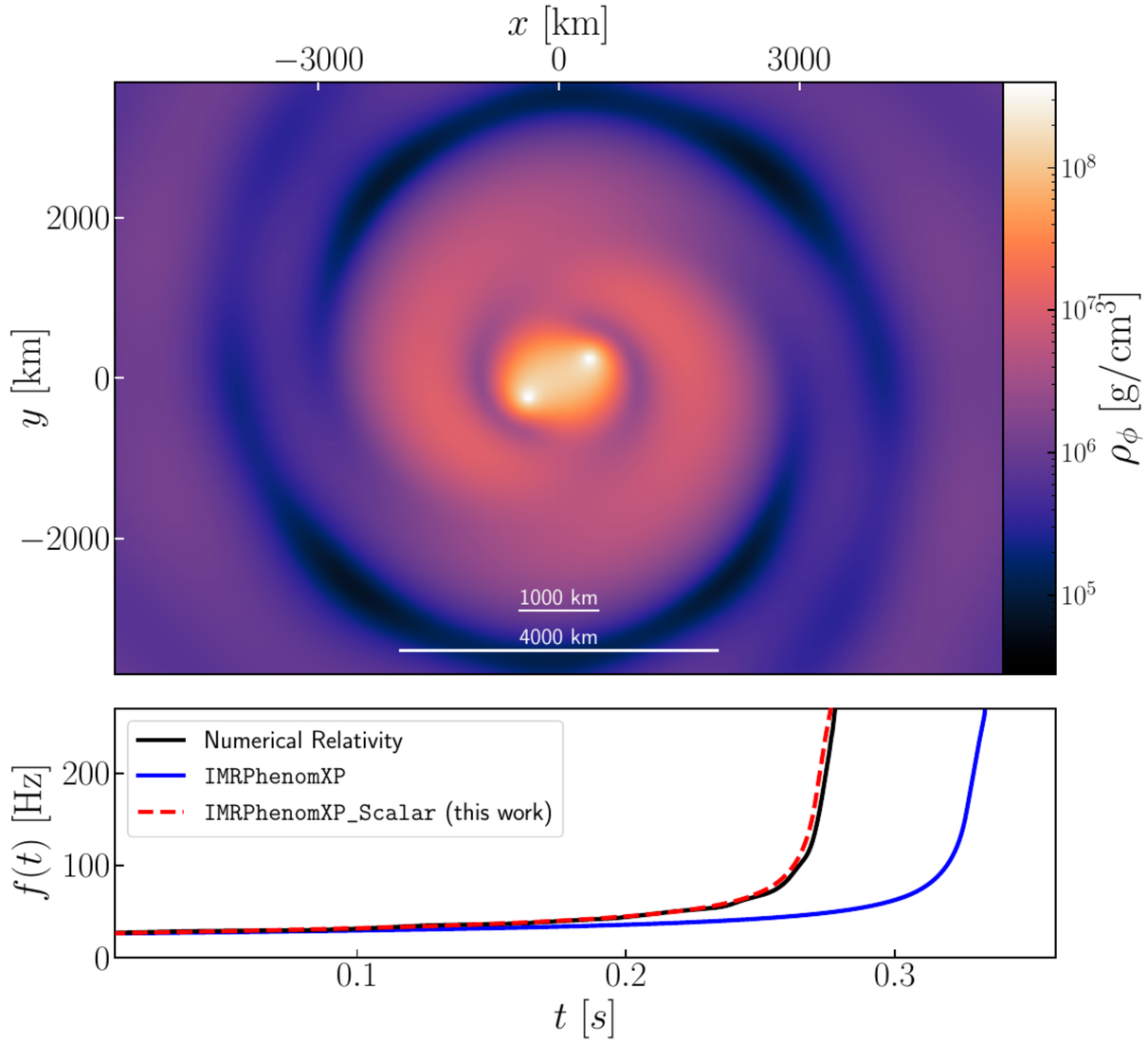
1. Can dark matter be ***detected*** around black holes using GWs?

Current models would interpret dark matter as a shift in the binary parameters.



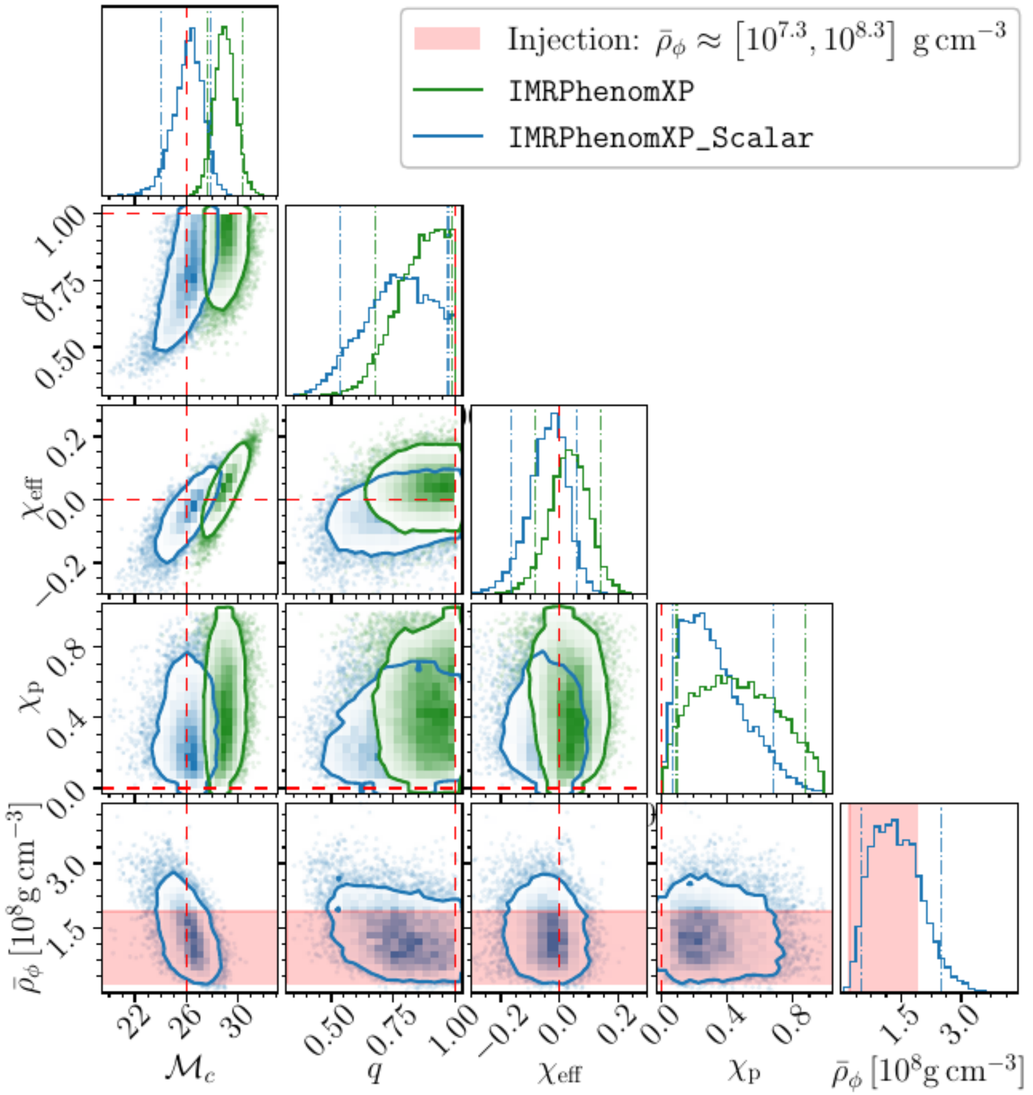
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Our simple model better recovers the frequency evolution and parameters.



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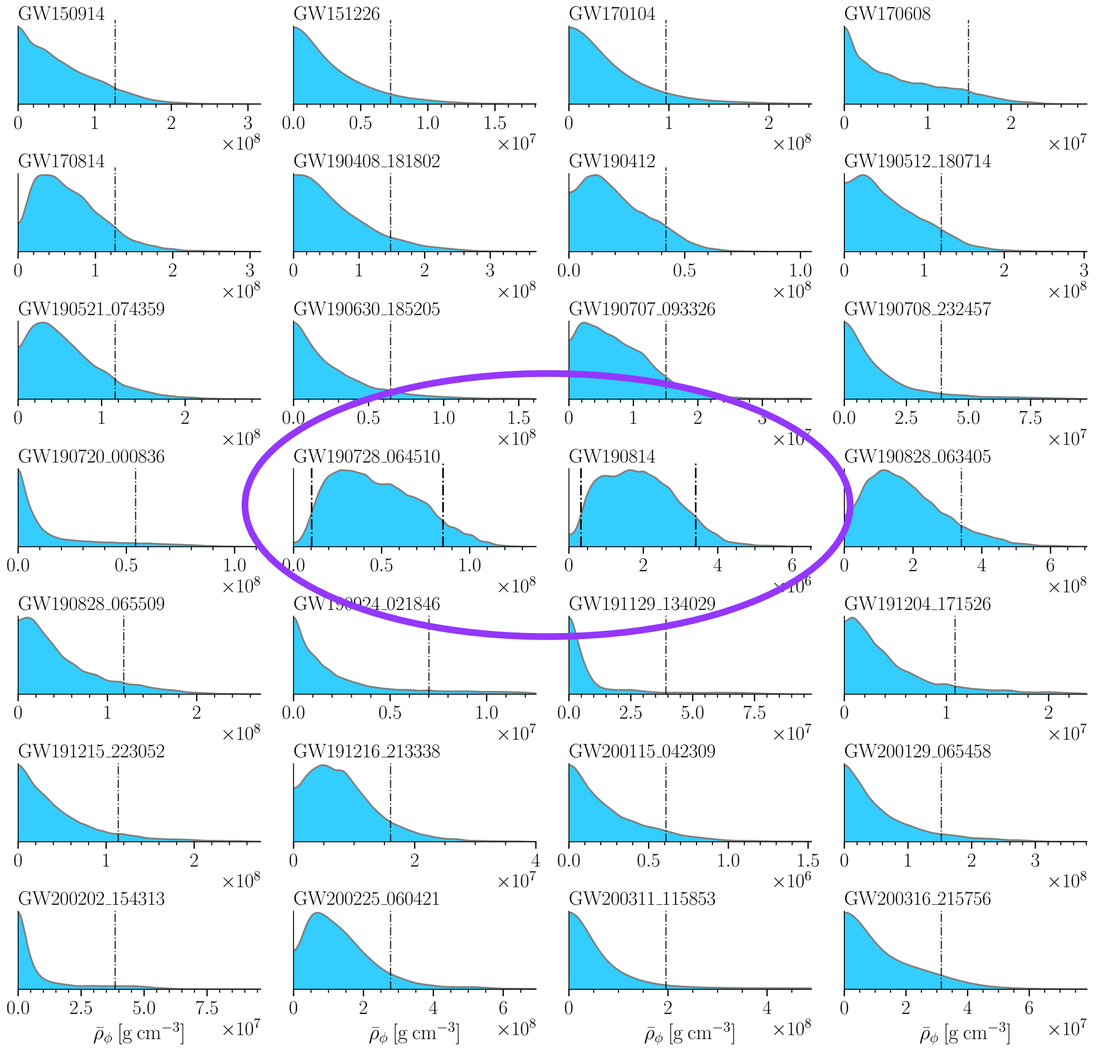
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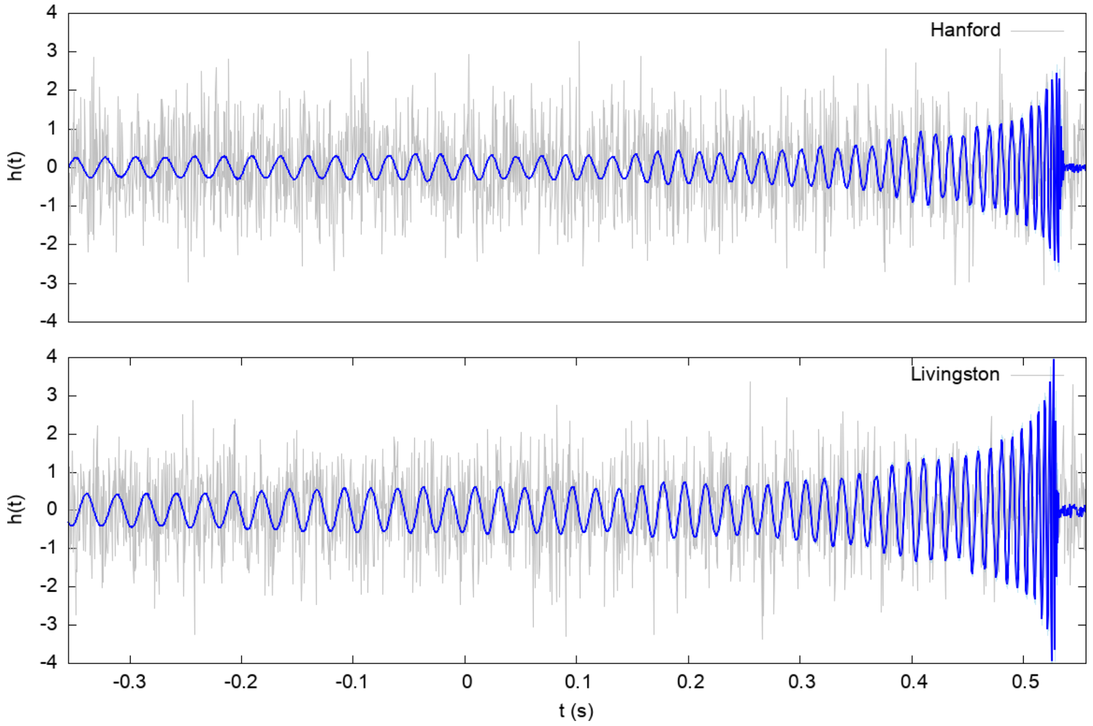
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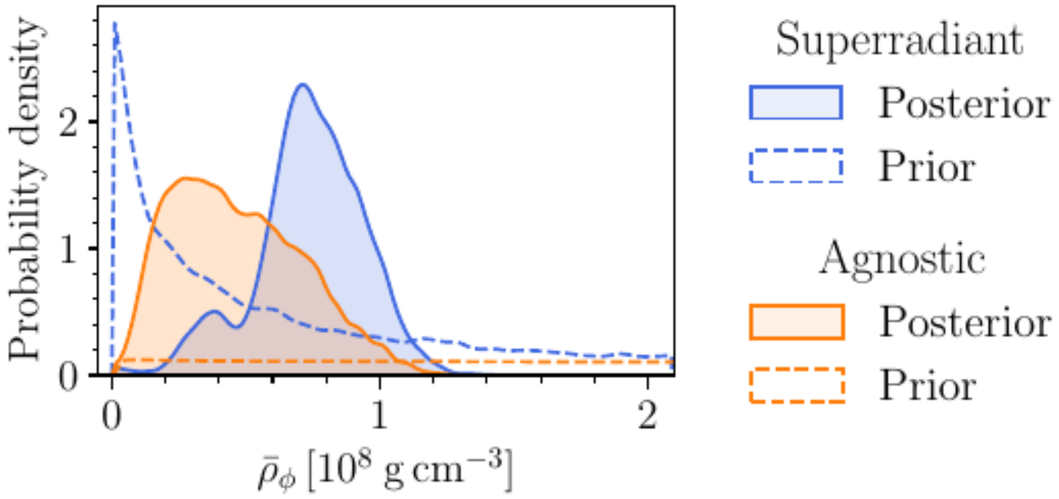
We (unexpectedly) found a preference for the model with an environment in some events in GWTC-3.



S. Roy, R Vicente, J Aurrekoetxea, KC, P Ferreira. 2025
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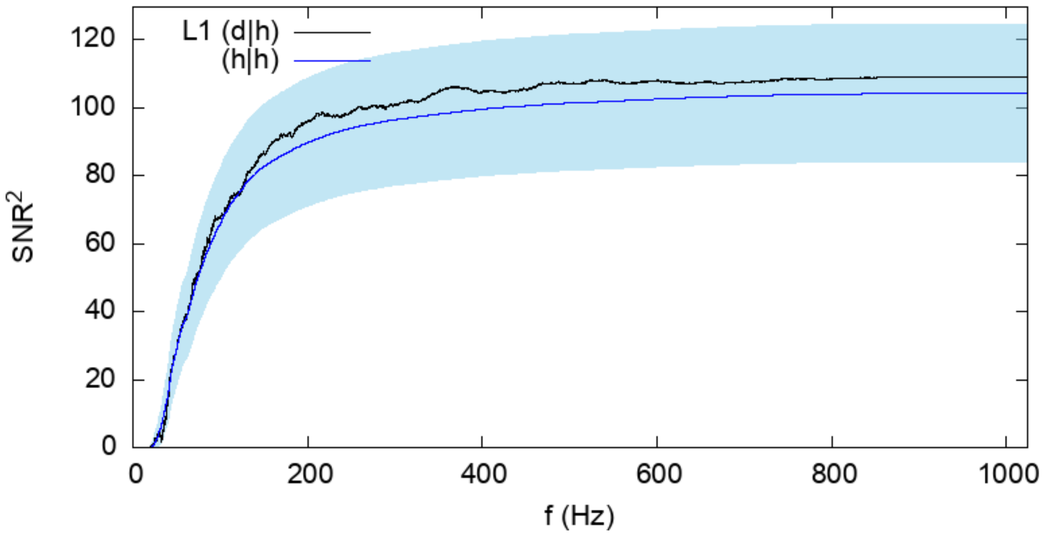
Event GW190728

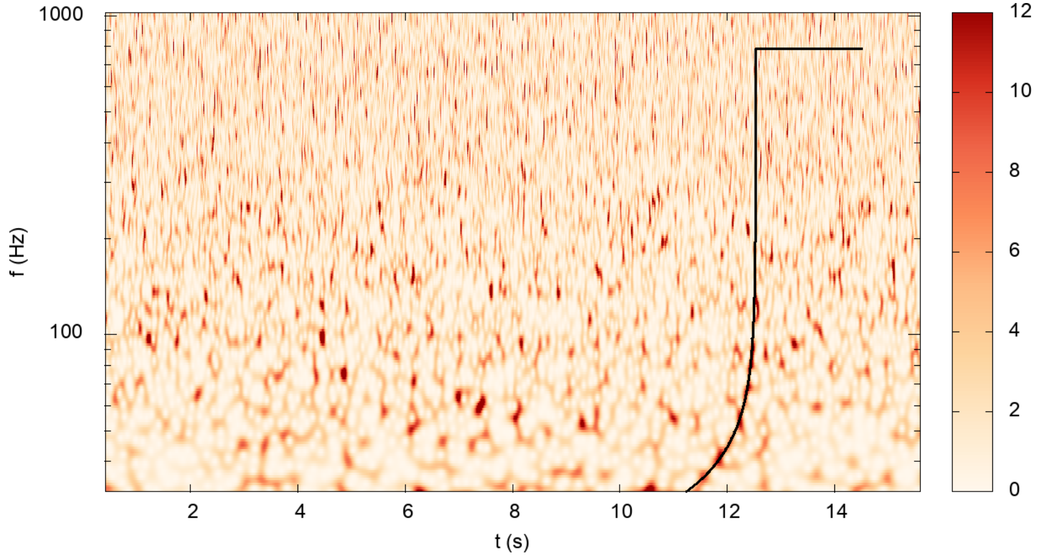




S. Roy, R Vicente, J Aurrekoetxea, KC, P Ferreira. 2025
Scalar fields around black hole binaries in LIGO-Virgo-KAGRA
Phys.Rev.Lett. 136 (2026) 19, 191402

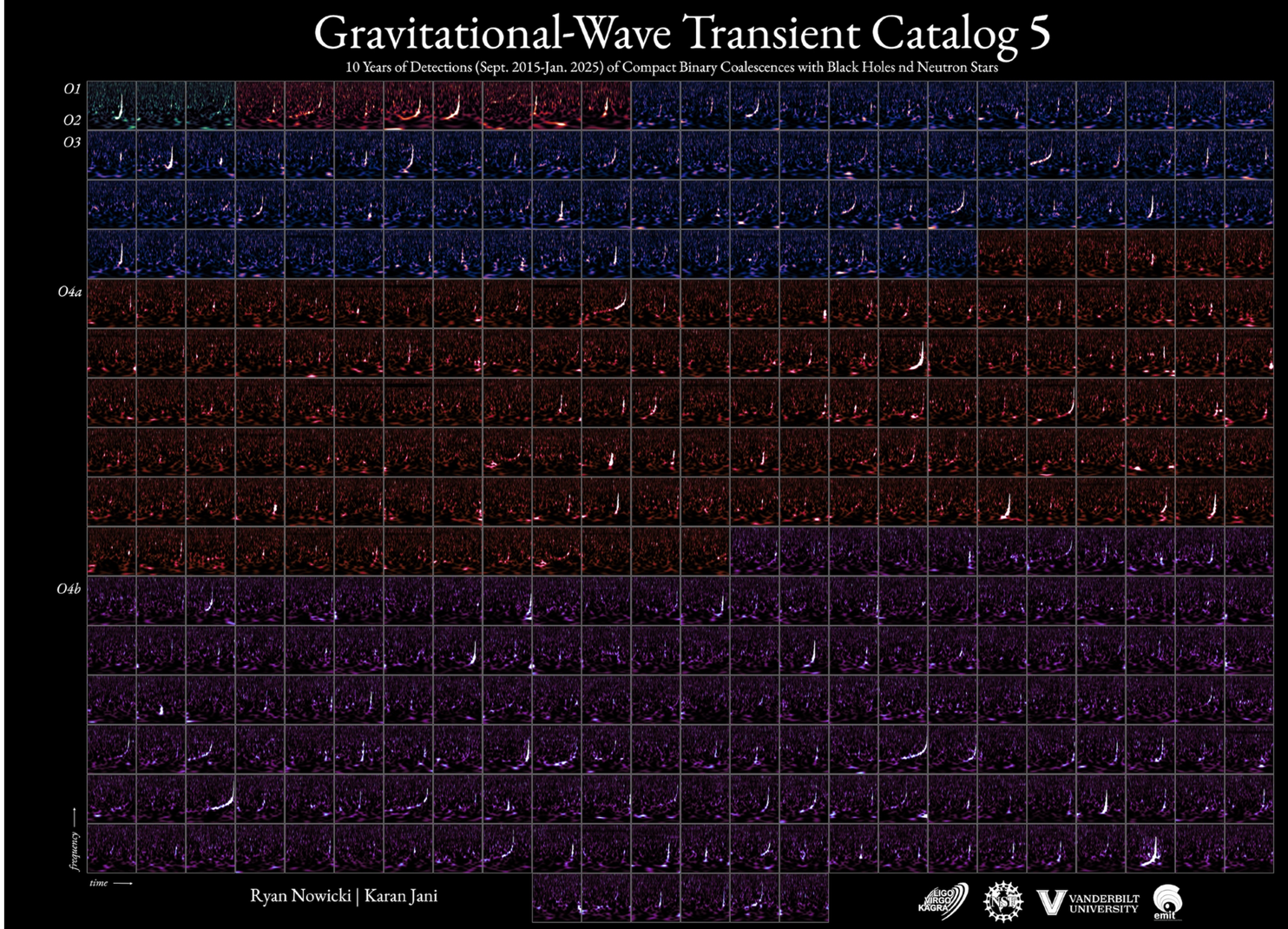
Event GW190728 - no obvious noise or glitches



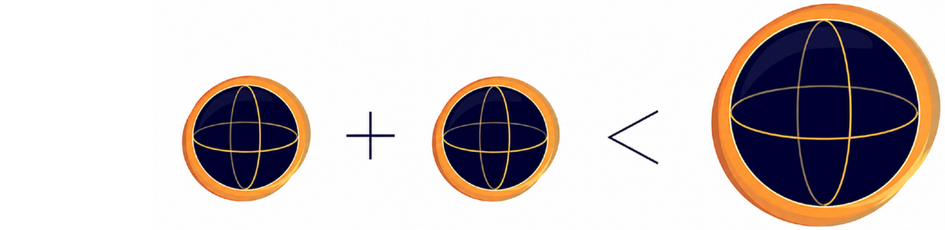


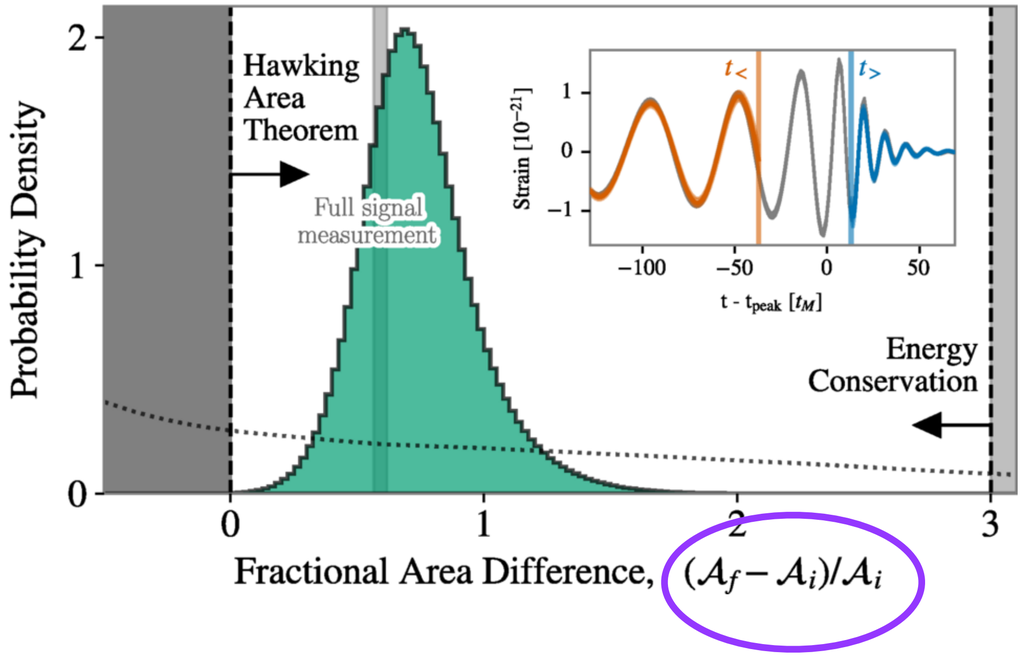
Work with Neil Cornish, Nico Yunes (ongoing)

No single event will detect deviations from the GR + vacuum hypothesis



The goal should be to ensure that the agnostic model parameters "add up" over multiple events





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

To conclude

Conclusions

We are only at the beginning of modelling how dark matter impacts on the merger part of the waveform.

Any changes are likely to be small and potentially degenerate with other parameters - there is still work to do to quantify this.



Questions?

