Fundamental fields in strong gravity environments

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Science & Technology Facilities Council

Plan for the talk

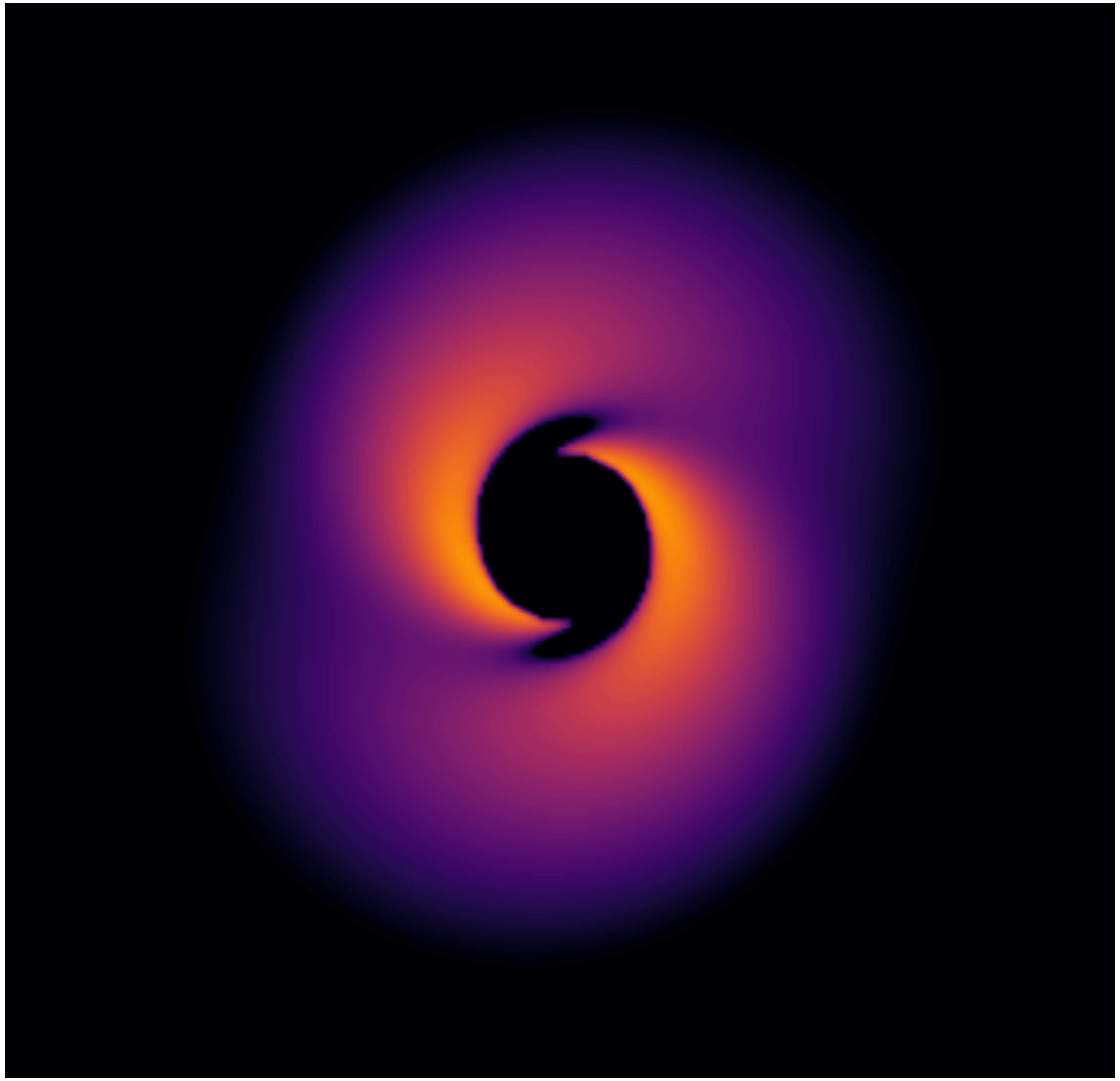
Motivation:

- Black holes have no hair
- Loopholes - dynamical hair
- Simulating dynamical hair in strong gravity

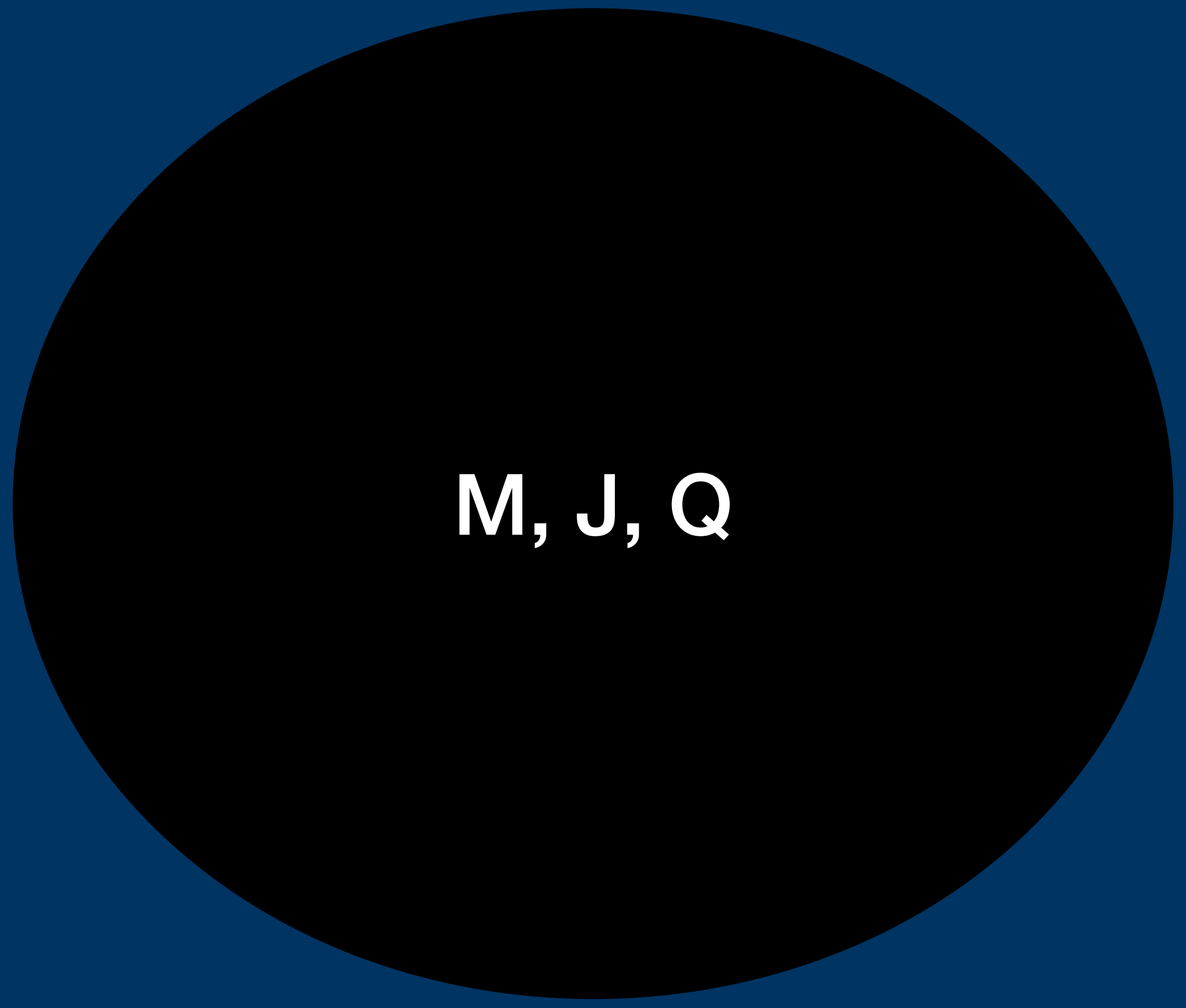
Role of numerical simulations:

- Robustness of dynamical hair
- Gravitational signatures of dynamical hair

Outstanding challenges



Black holes have no hair

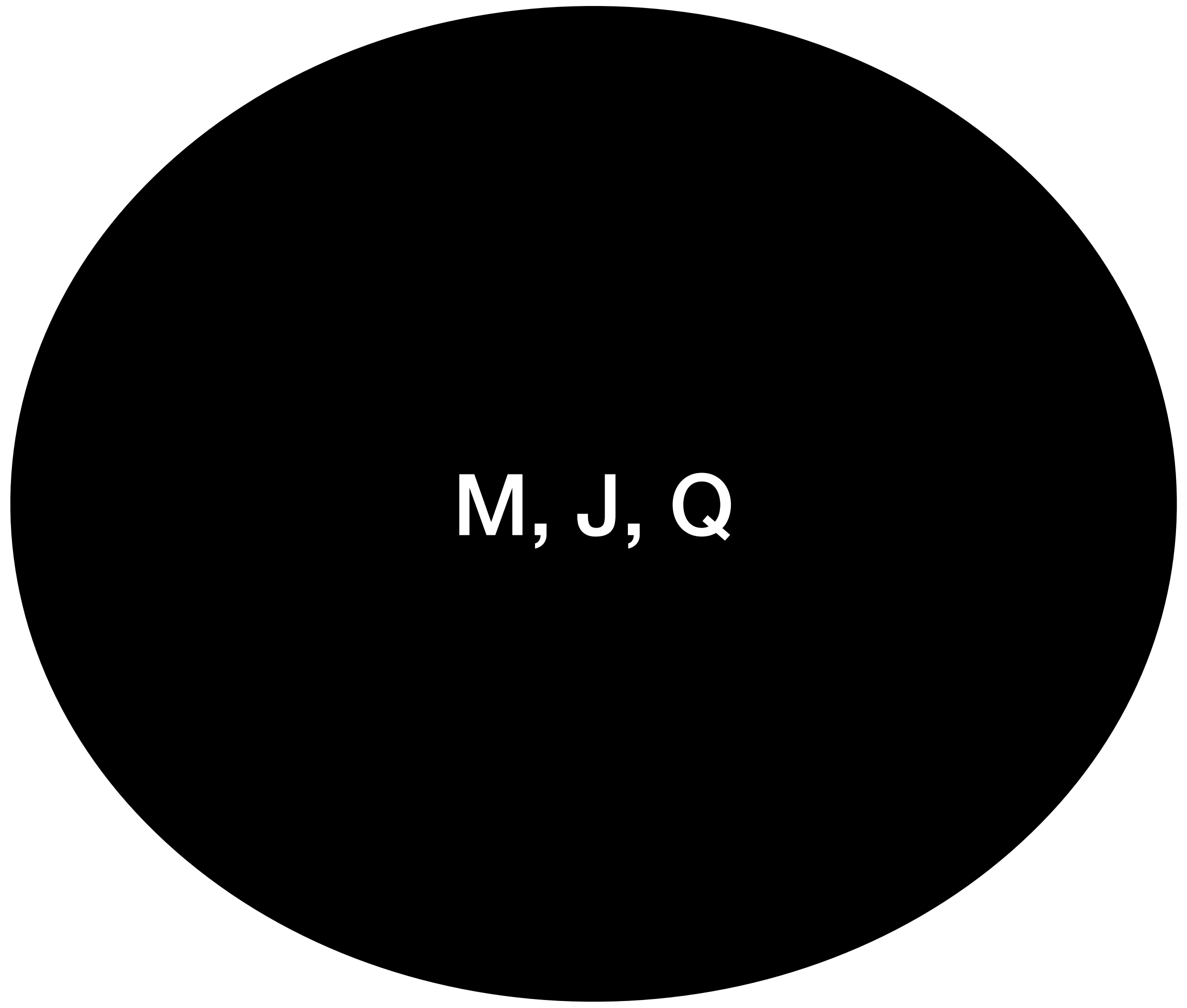


Event Horizon Telescope

Black holes have no hair

(see e.g. Herdeiro & Radu International Journal of Modern Physics D, Vol. 24, No. 09, 1542014 (2015))

- No stationary solutions to BH + matter exist
- Implies that over time all matter either falls into a BH or is radiated away
- Once bare BH remains, it is fully characterised by its mass, spin and charge, no details of the original matter remain
- Also usually means that (classically) fields cannot be “sourced” by curvature



Loopholes

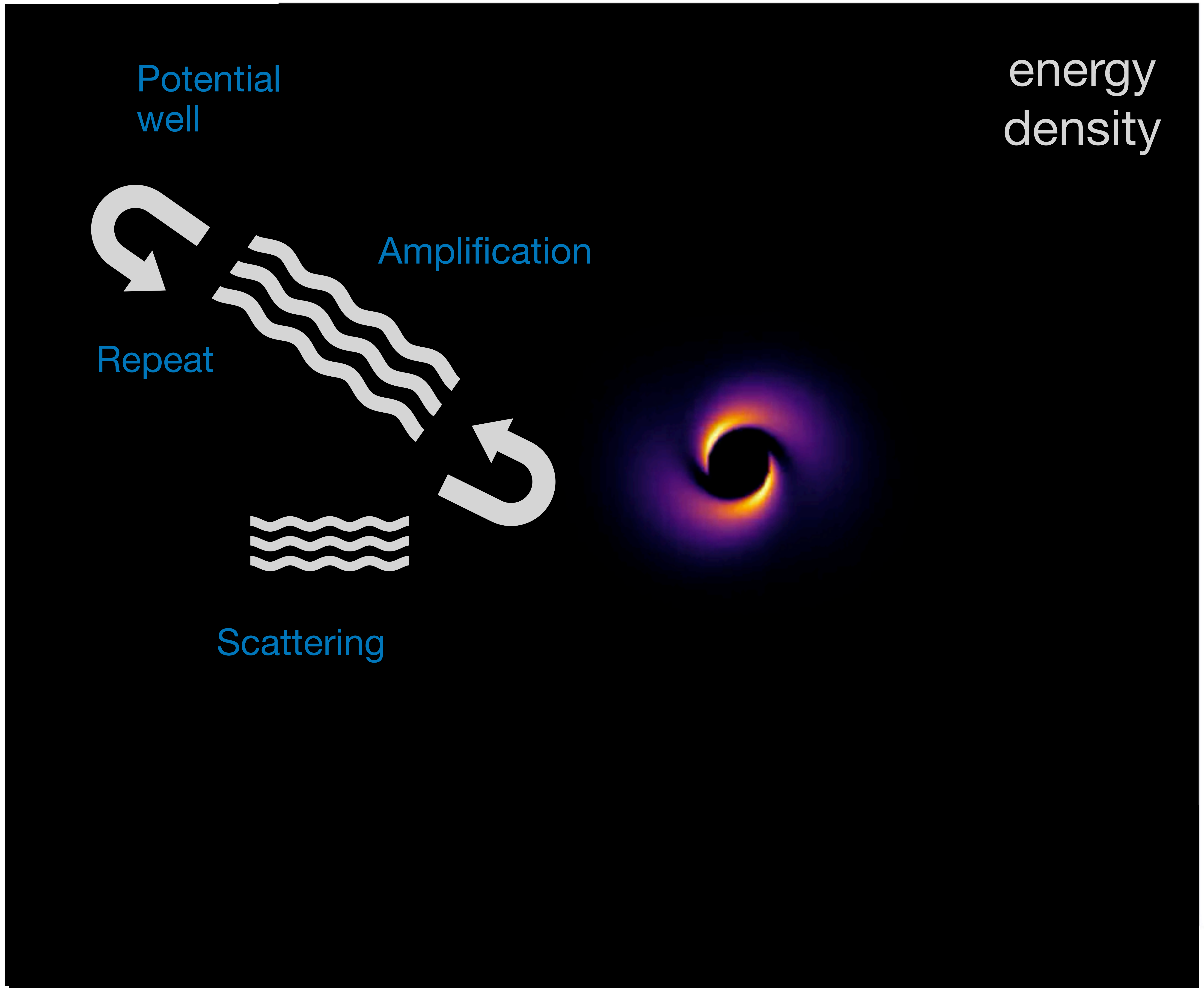
Assumptions:

✗ 1. Metric and matter fields are stationary

2. Embedded in an asymptotically flat spacetime

3. Hair is regular at the horizon

4. “Standard” GR



Superradiance

see R Brito’s review Superradiance : New Frontiers in Black Hole Physics

Loopholes

Assumptions:

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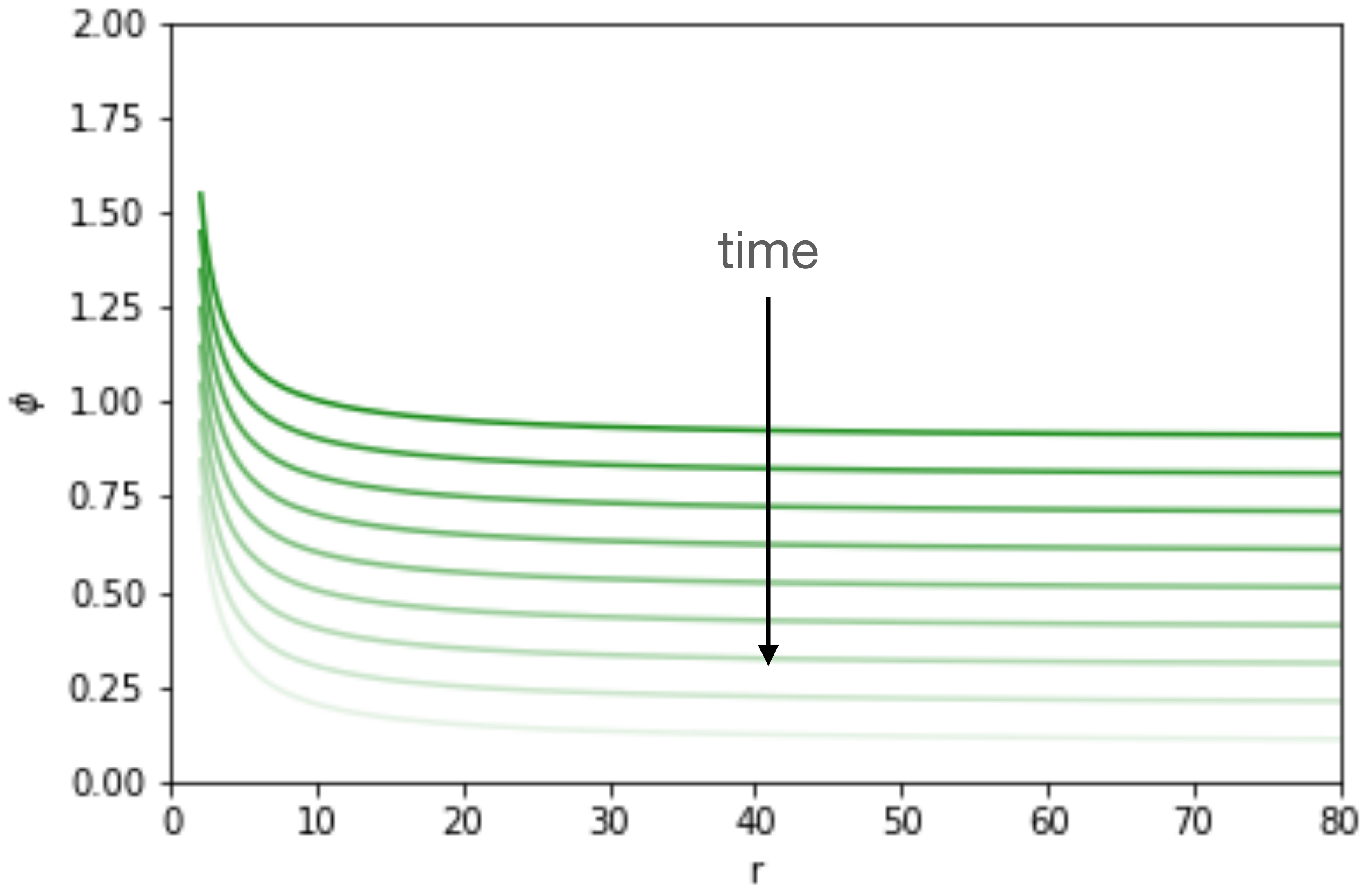
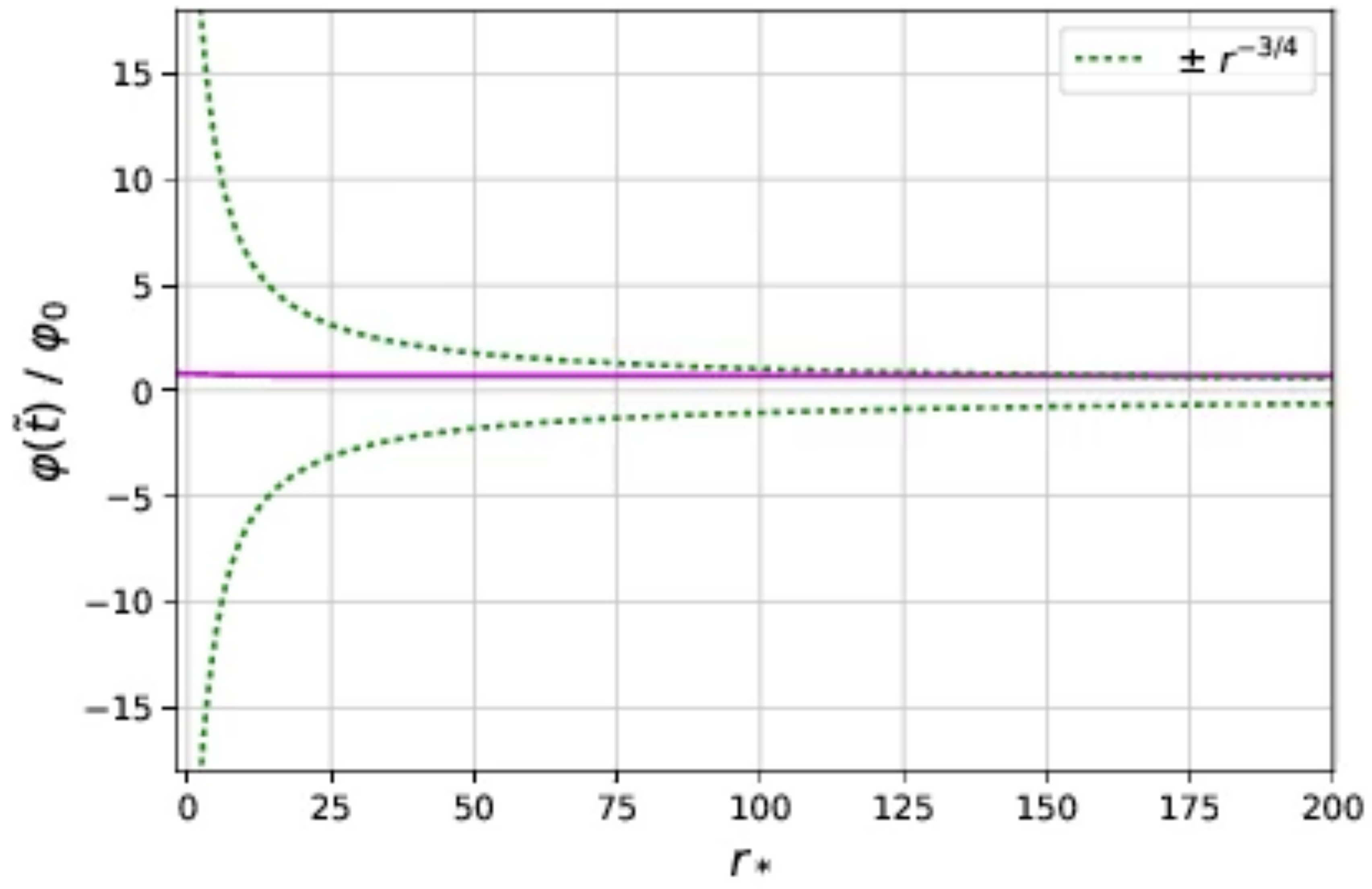


T. Jacobson Phys. Rev. Lett. 83 (1999), 2699)



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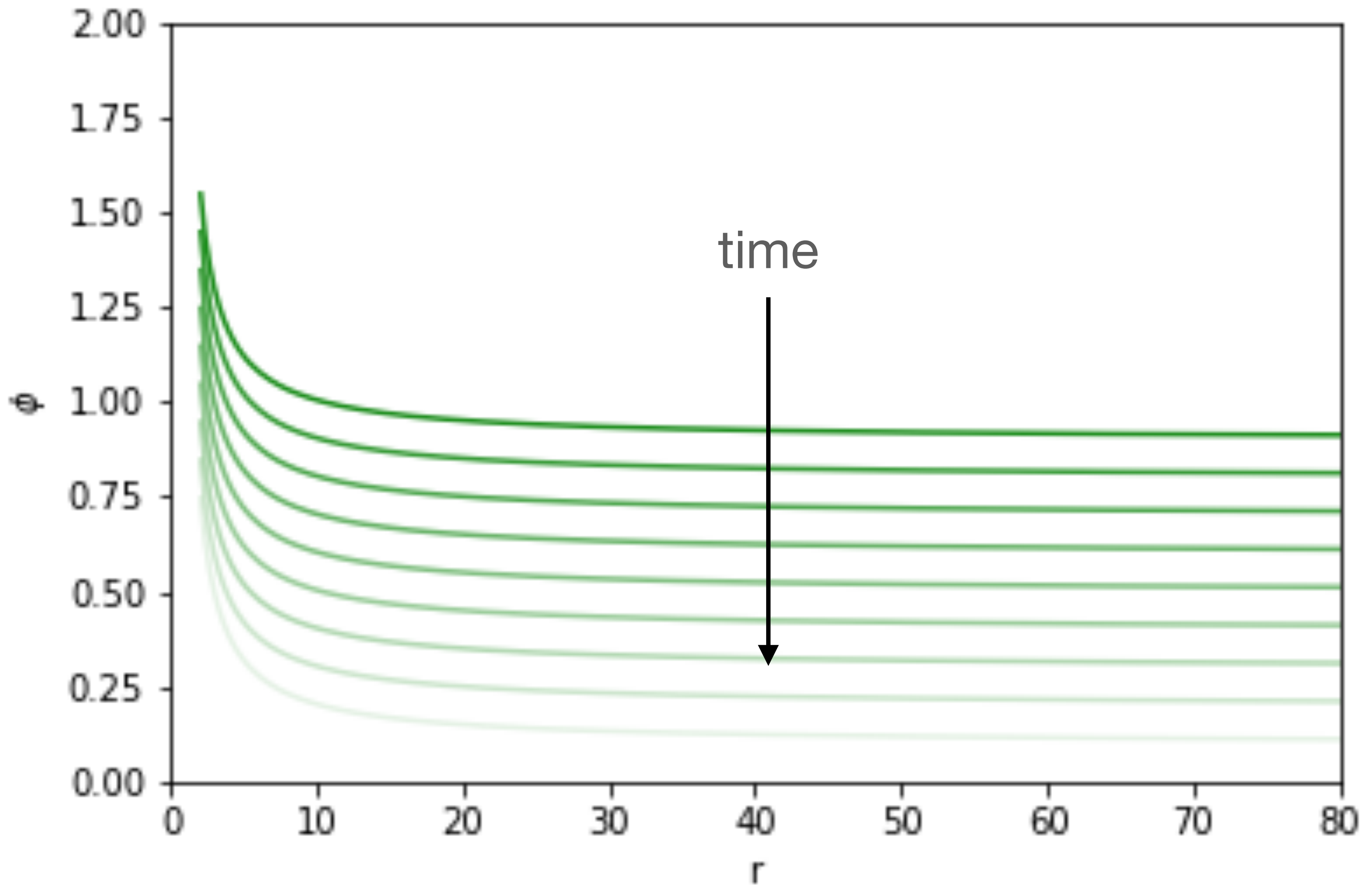

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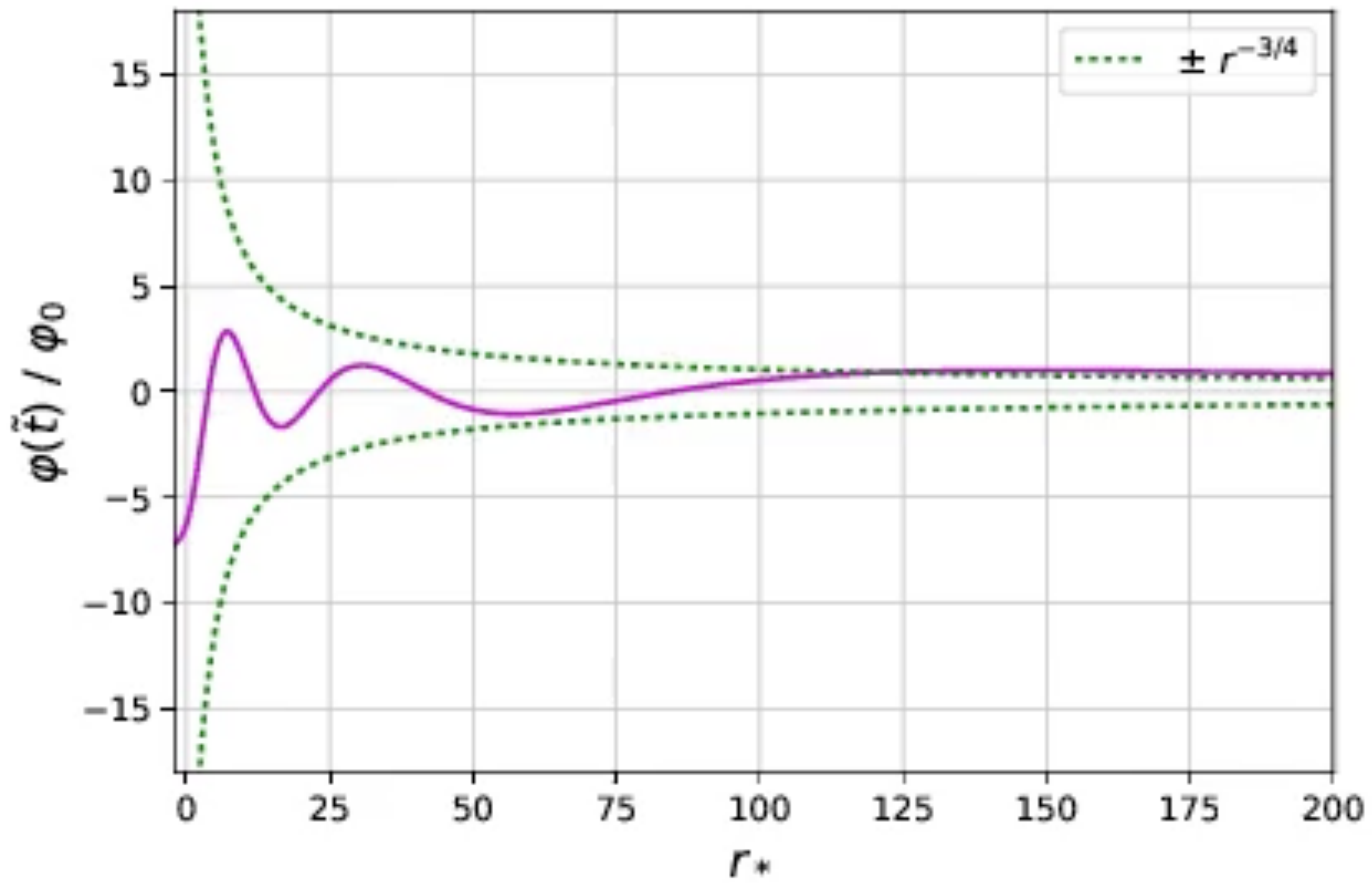

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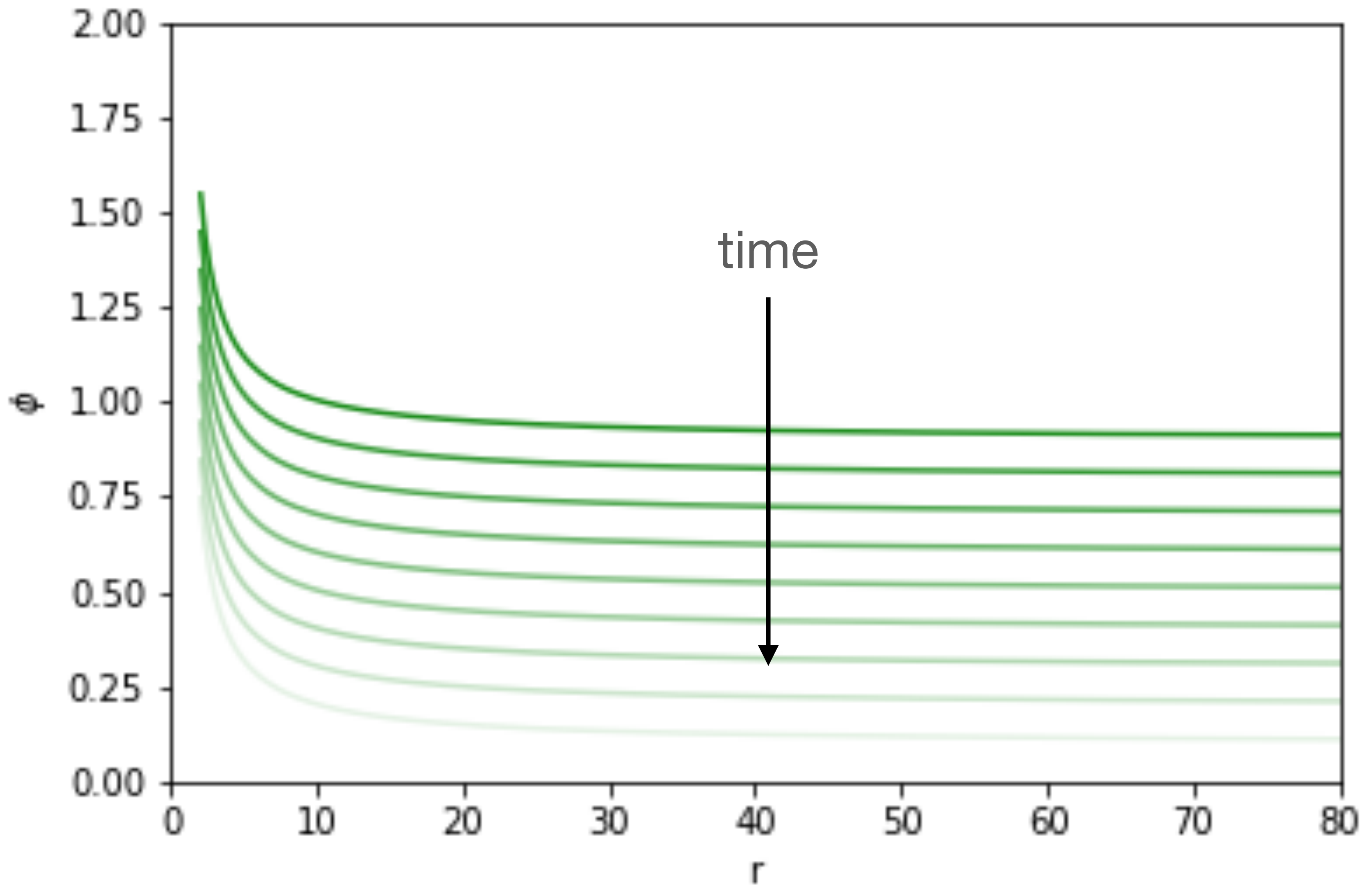
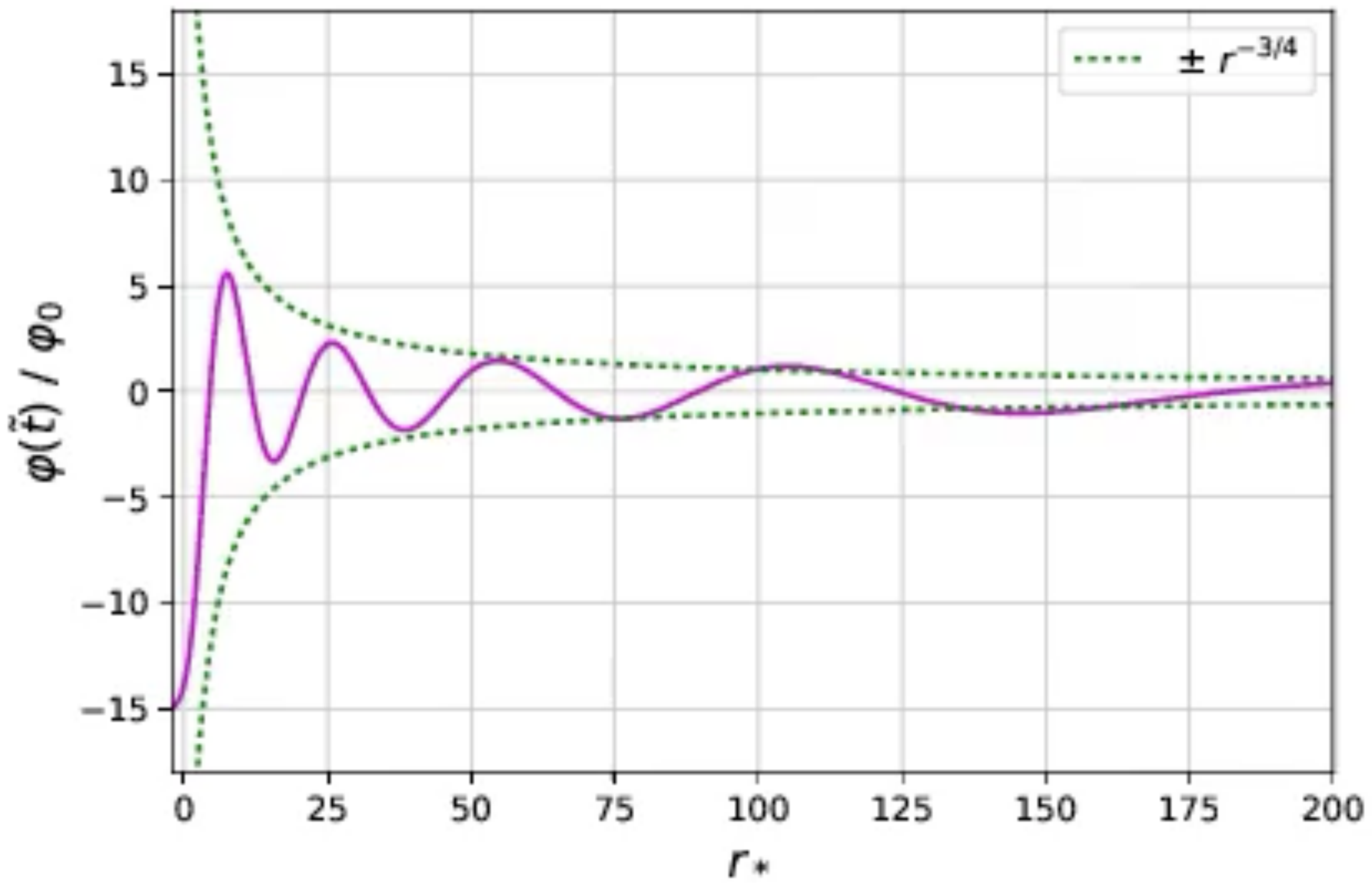
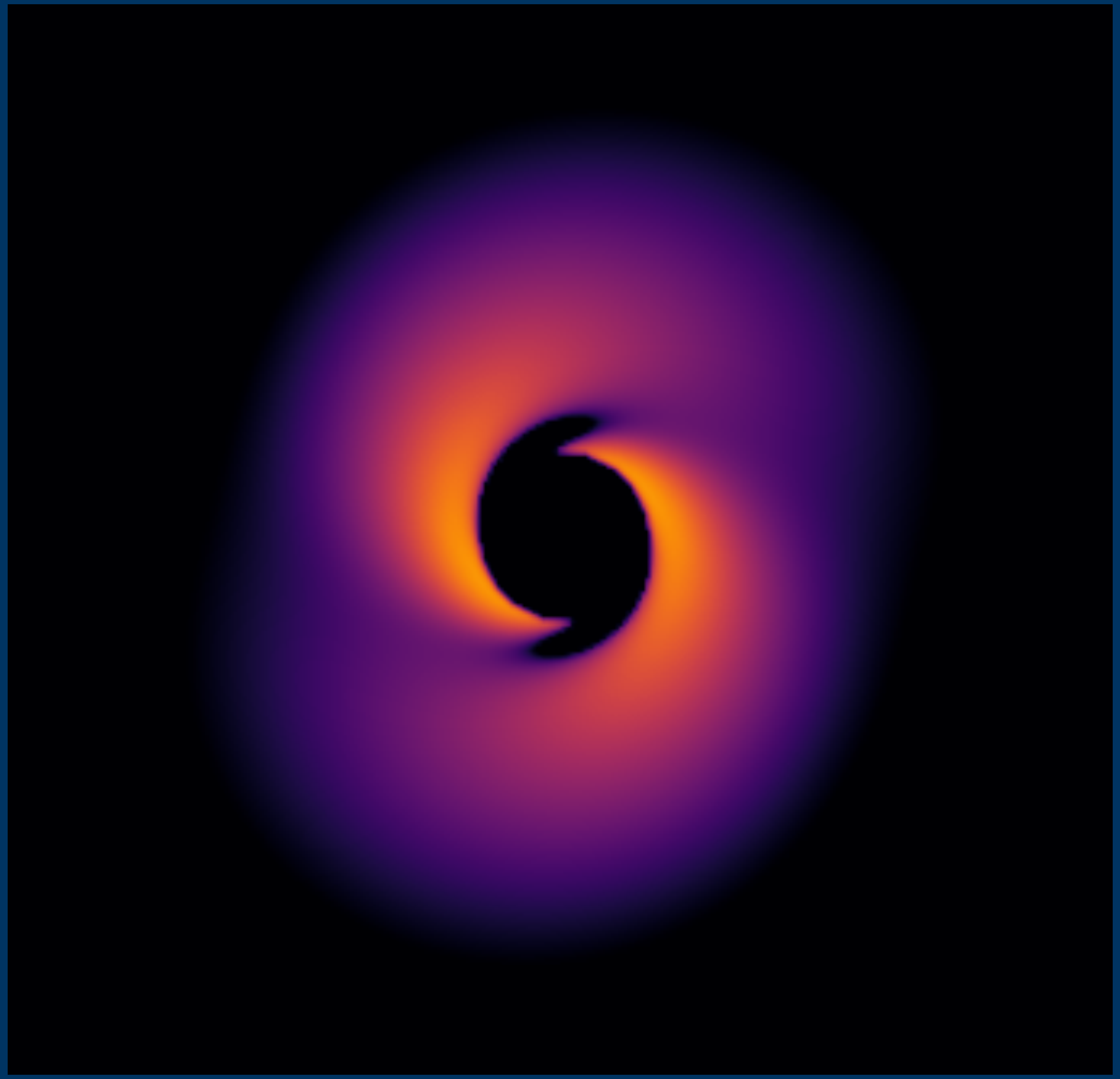


T. Jacobson Phys. Rev. Lett. 83 (1999), 2699)

Accretion



Simulating dynamical hair in strong gravity

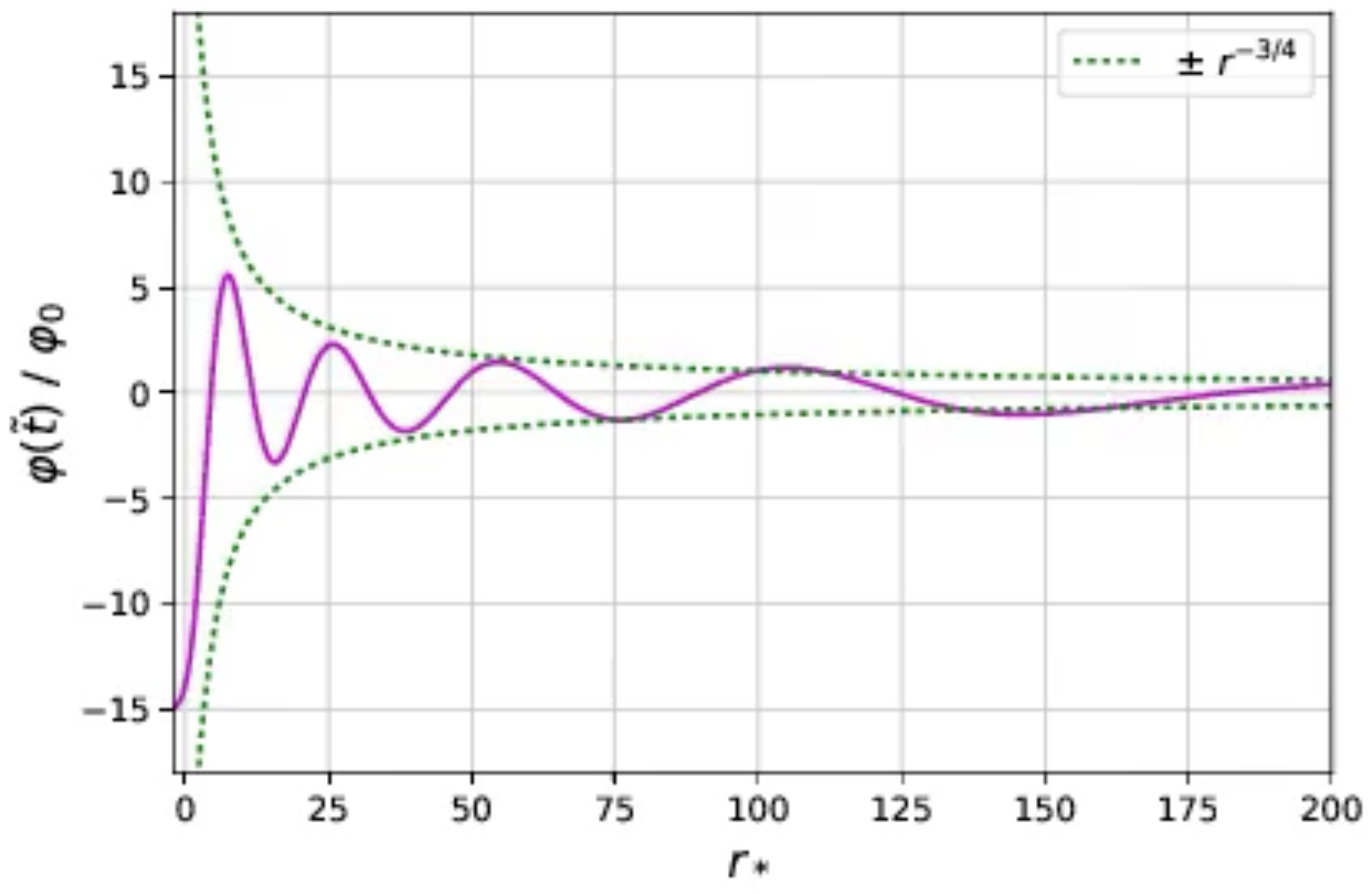


Bosonic fields in GR - spin 0

- If the number density is high, bosonic matter is well described by a classical field obeying the Klein Gordon equation:

$$\nabla^\mu \nabla_\mu \phi = \mu^2 \phi$$

- It has a **wave like behaviour**, and **pressure support** on length scales of order 1/mu
- The underlying properties of the particles (number density, velocity) at each point can be inferred by considering the stress energy tensor of the field, for example:
  - Momentum density $k_i \sim \dot{\phi}\ \partial_i \phi$
  - Energy density $\rho \sim \dot{\phi}^2 + \mu^2 \phi^2 + (\partial_i \phi)^2$
- Numerous motivations in particle physics, e.g. axions, scalars from string theory, “fuzzy” dark matter



Growth of massive scalar hair around a Schwarzschild black hole
KC, P.G. Ferreira, M Lagos
Phys.Rev.D 100 (2019) 6, 063014

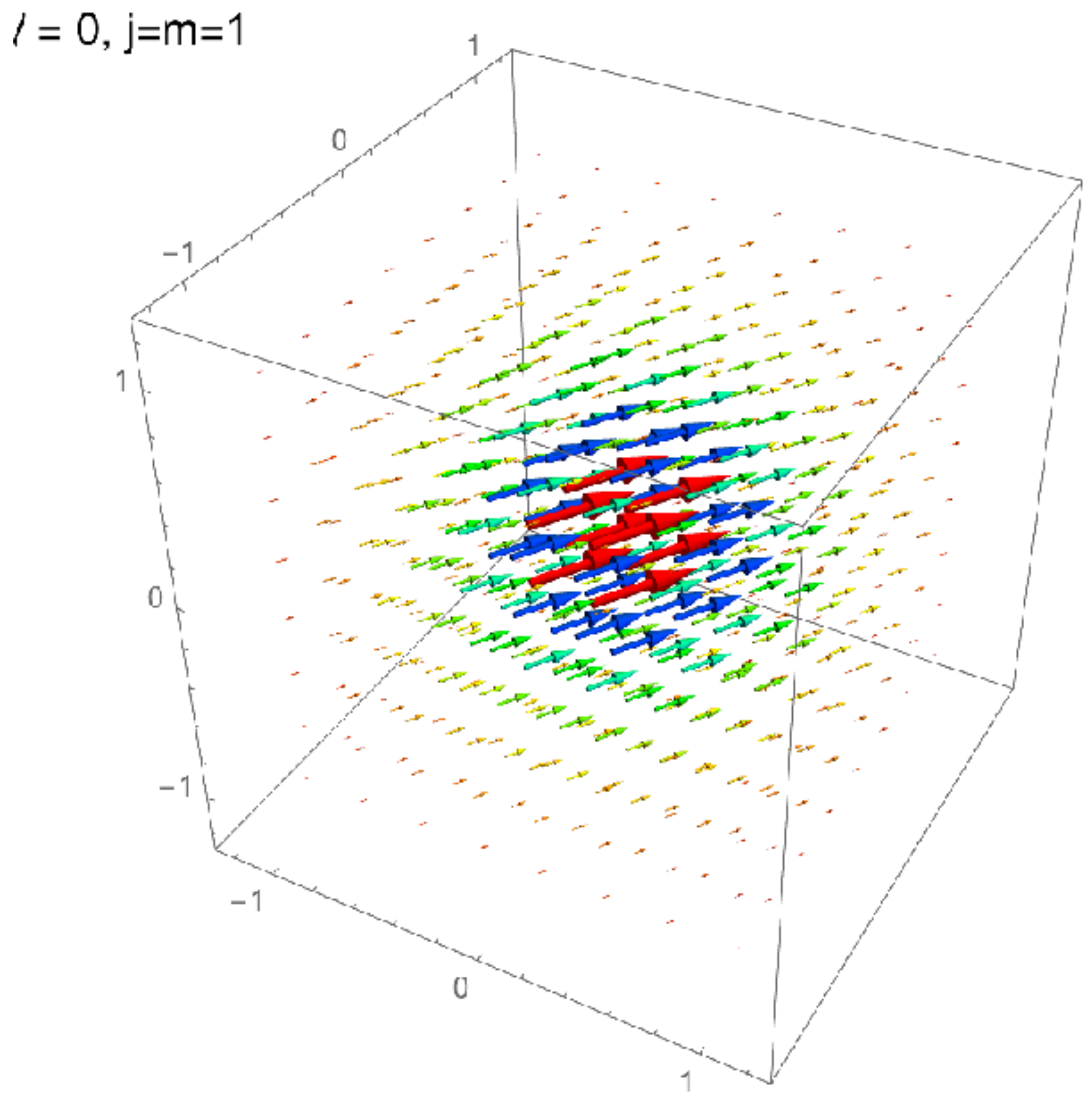
Bosonic fields in GR - spin 1

- For massive spin 1 bosonic particles, the field obeys the Proca equation

$$\nabla_\mu F^{\mu\nu} = \mu^2 A^\nu$$

- The underlying properties of the particles (number density, velocity) at each point can be inferred by considering the stress energy tensor of the field, for example:

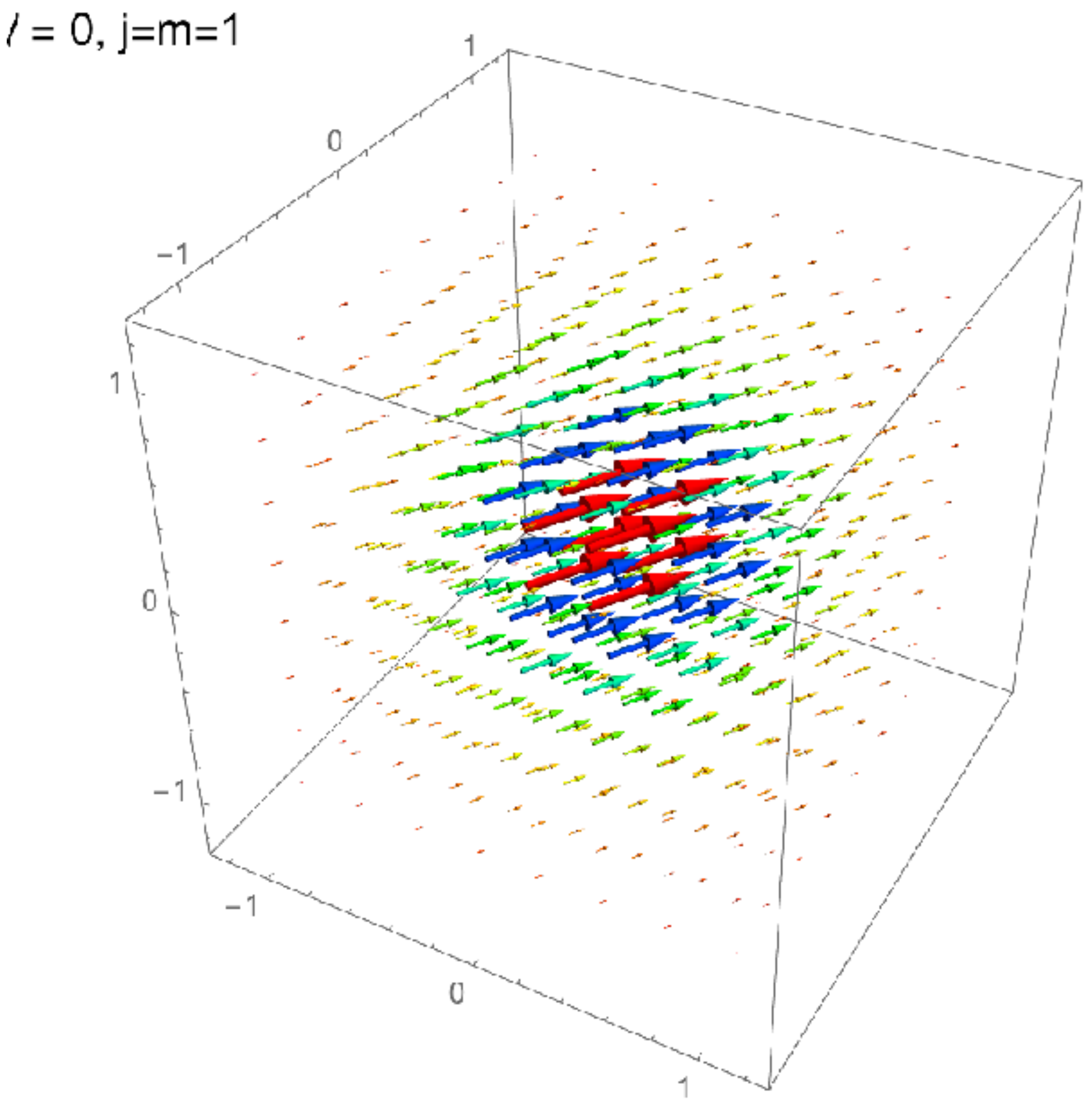
  - Momentum density $k_i \sim \epsilon_{ijk} E^j B^j + \mu^2 \phi A_i$
  - Energy density $\rho \sim E^i E_i + B^i B_i + \mu^2 (A_i A^i + \phi^2)$



Black Hole Superradiance Signatures of Ultralight Vectors
M Baryakhtar, R Lasenby, M Teo
Phys.Rev.D 96 (2017) 3, 035019

Bosonic fields in GR - spin 1

- Dark photons? / Potential for photons to acquire an effective mass in a plasma? Toy model for a scalar?
- The spin 1 case is in principle similar to the scalar case but differs in important ways
  - Vectors scatter more efficiently off spinning BHs and have closer bound states, making long numerical timescales of superradiance less challenging
  - 3 dynamical degrees of freedom and a constraint on initial data of $\nabla^\mu A_\mu = 0$
  - Having a non zero asymptotic value of a vector field is prohibited by cosmological isotropy (although possible to have non zero scalar combination like A^\mu A_\mu)



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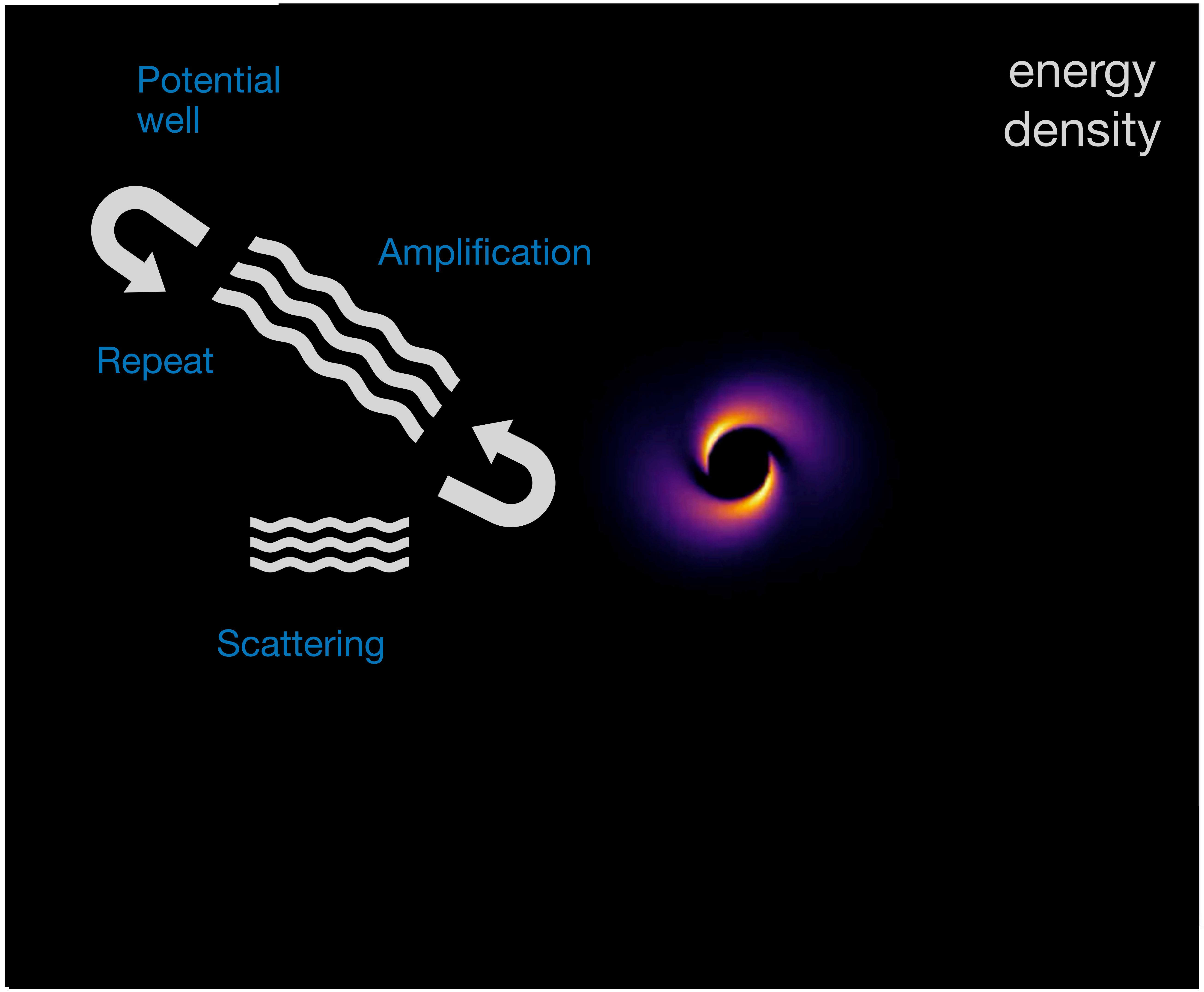
Superradiance



Just a few of the key numerical works:

H Witek et al
Phys.Rev.D 87 (2013) 4, 043513

M Zilihao et al
Class.Quant.Grav. 32 (2015) 234003

W East
Phys.Rev.D 96 (2017) 2, 024004

W East and F. Pretorius
Phys.Rev.Lett. 119 (2017) 4, 041101

N Sanchis-Gual, et al
Phys.Rev.D 102 (2020) 10

T Ikeda et al
Phys.Rev.D 102 (2020) 10, 101504

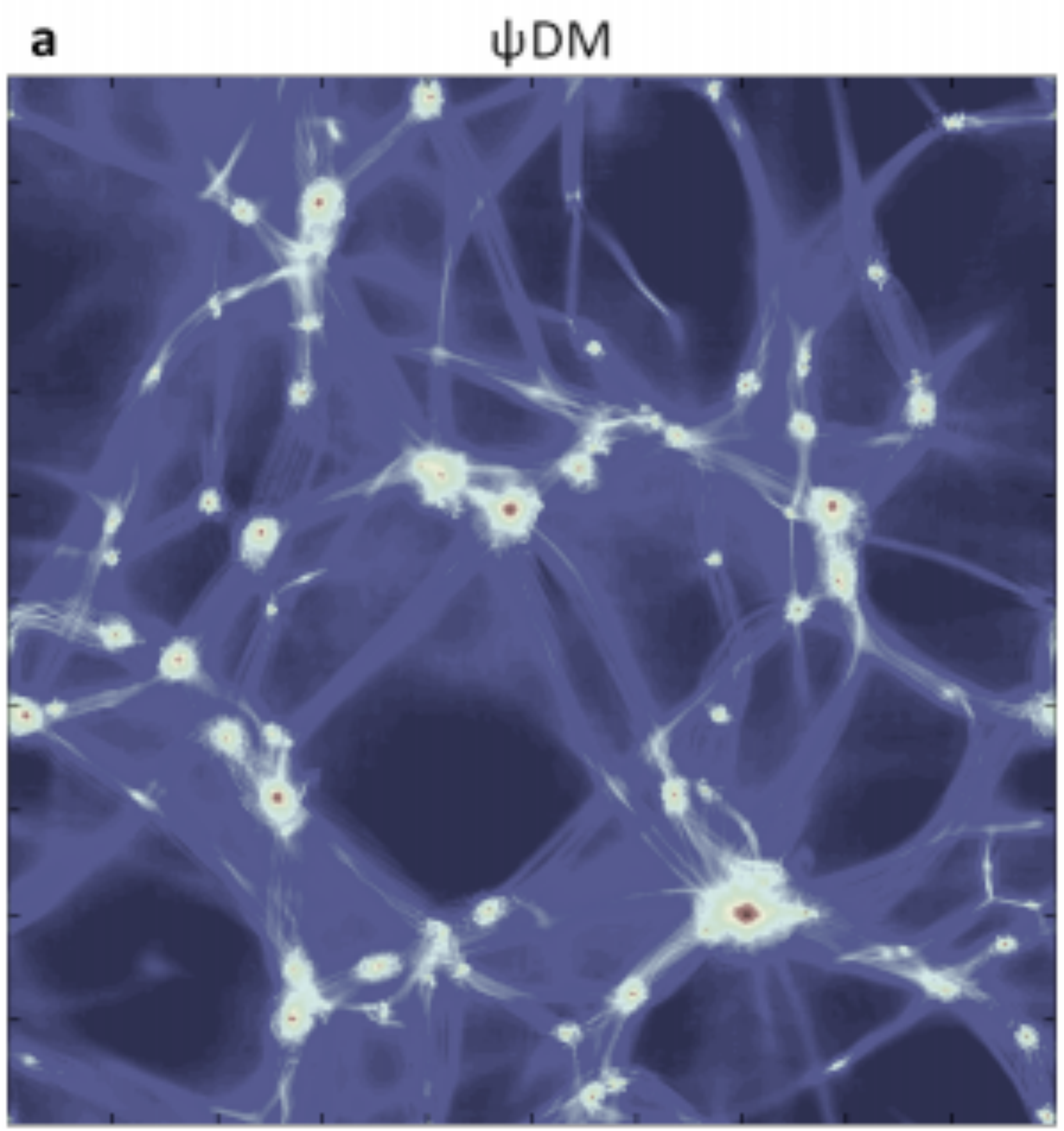
$$\frac{\rho}{[R_s^{-2}]} \sim \frac{0.1 M_{BH}}{\frac{4\pi}{3}(10R_s)^3} \sim 10^{-5}$$

Comment on the non relativistic description

- Modulo out the oscillations:

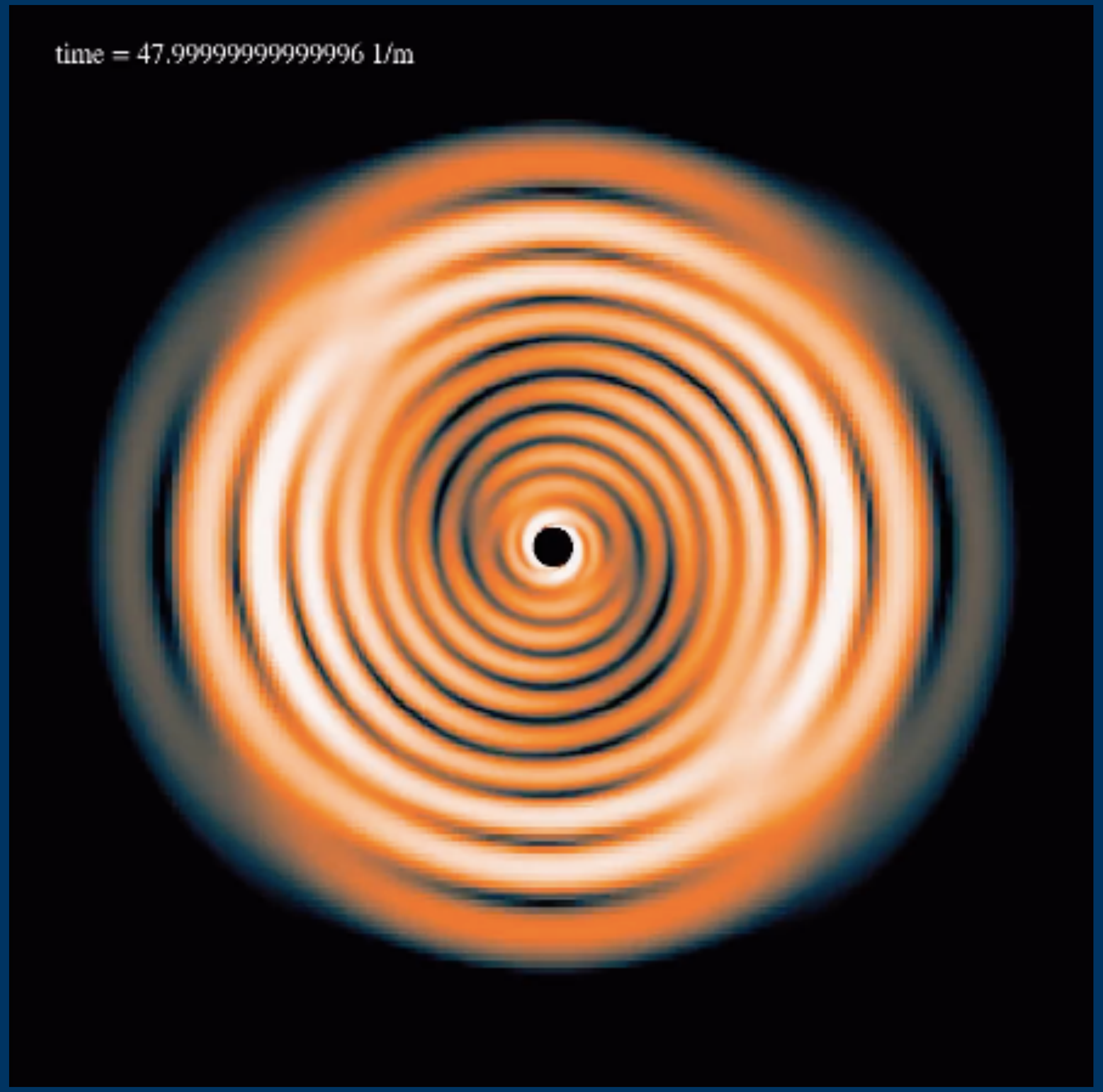
$$\phi(x,t) = \psi(x,t)\ e^{i\mu t} + c\,.\,c\,.$$

- Assuming that $\dot{\psi} \ll \mu\psi$ one can show that ψ obeys the Schroedinger-Poisson equations
- In relativistic simulations the timescales are similar and cannot be separated



Nature Phys. 10, 496-499
Schive et al. 2014

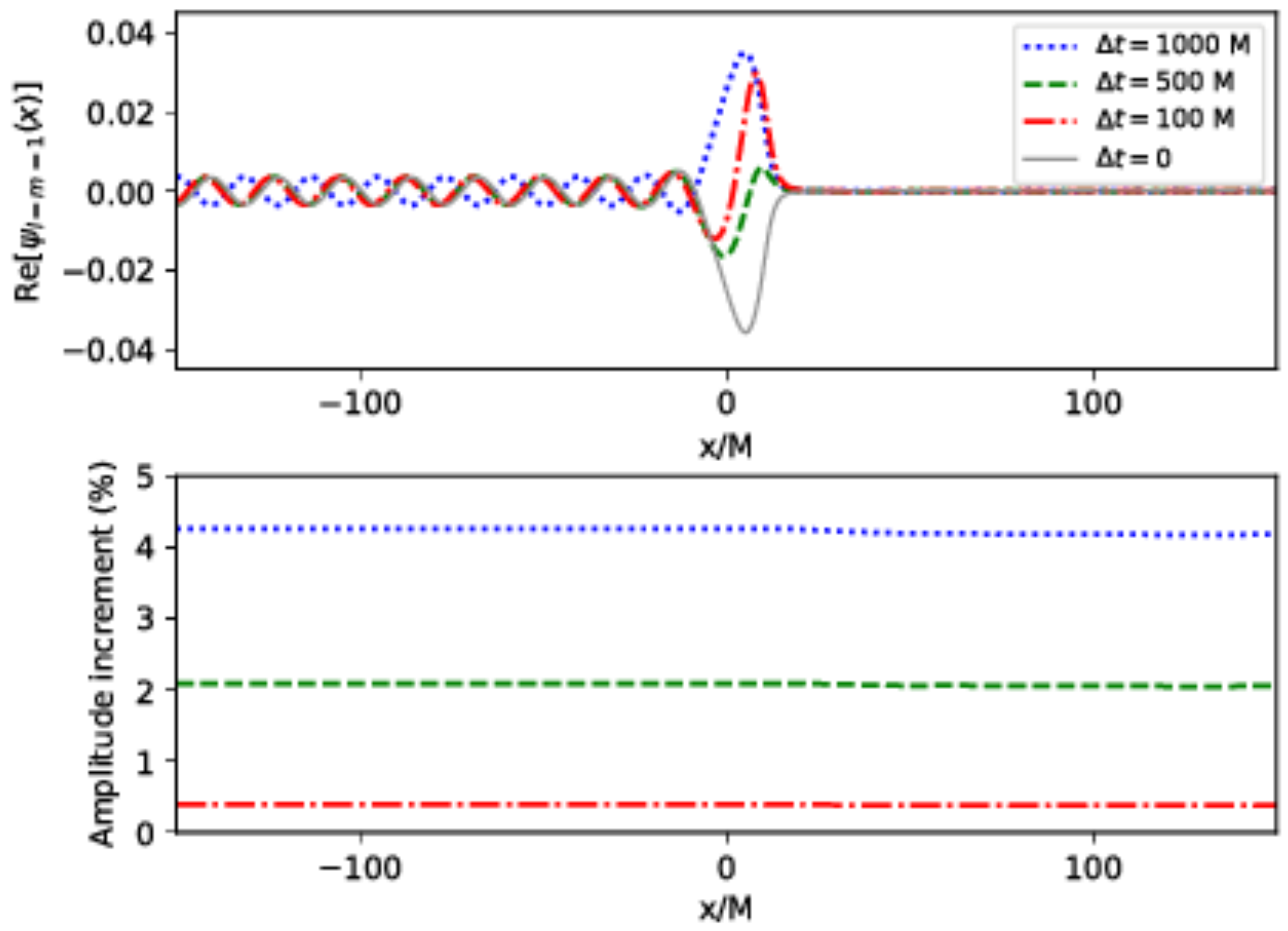
Robustness of dynamical hair



Work with Thomas Helfer
(currently postdoc at JHU)

Interactions with an environment

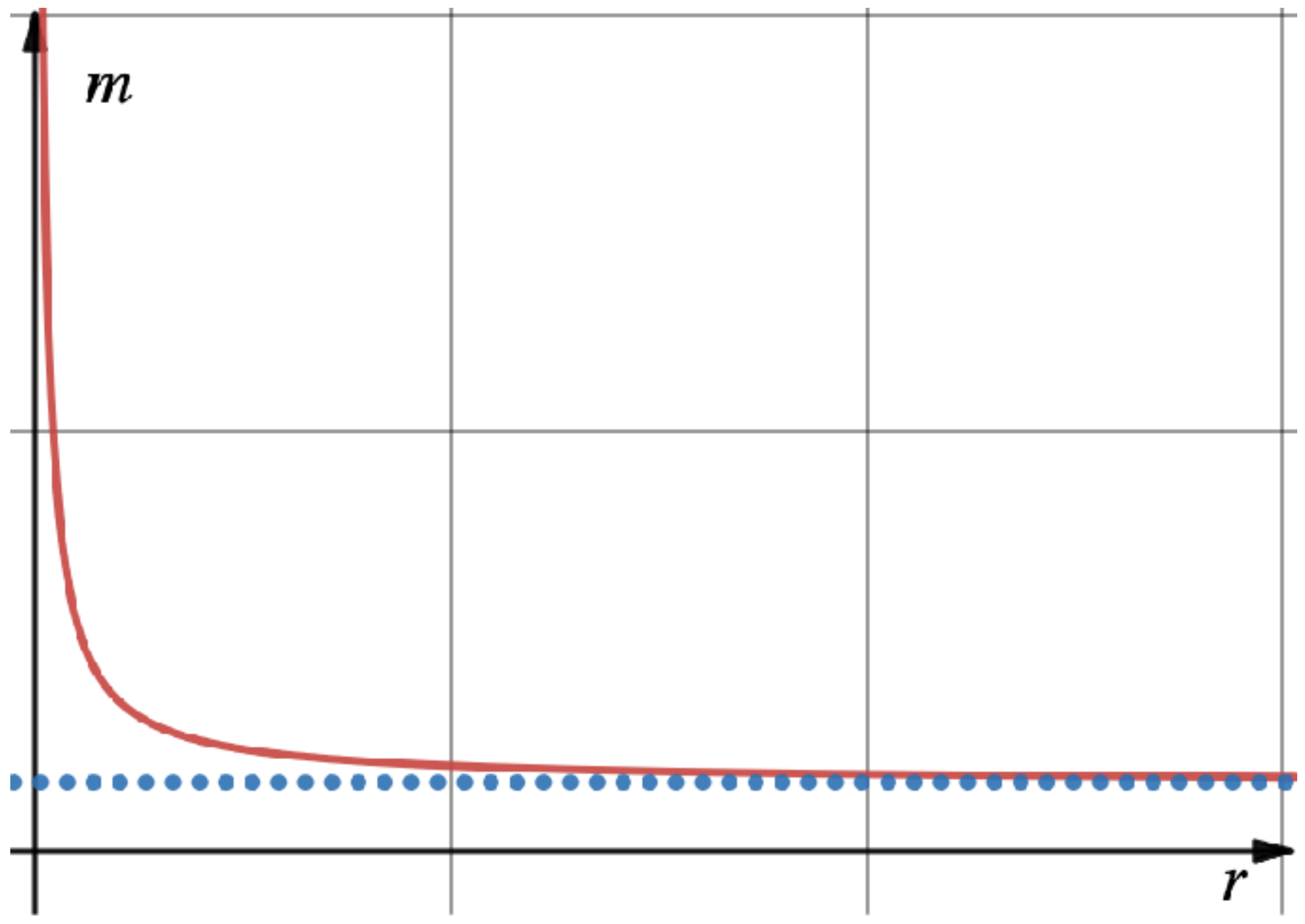
- Motivated by the idea of photons acquiring a mass in a astrophysical plasma around BHs (Herdeiro & Conlon, Phys.Lett.B 780 (2018) 169-173)
- Toy model to test robustness - spatially dependent mass function
- Dima & Barausse performed simulations of a scalar field using Dolan's method of decomposing the field into spherical harmonics and considering a sum over ℓ modes for each value of m
- Conclusions: astrophysical configurations of the plasma likely to disrupt superradiance



Numerical investigation of plasma-driven superradiant instabilities
A. Dima, E. Barausse
Class.Quant.Grav. 37 (2020) 17, 175006

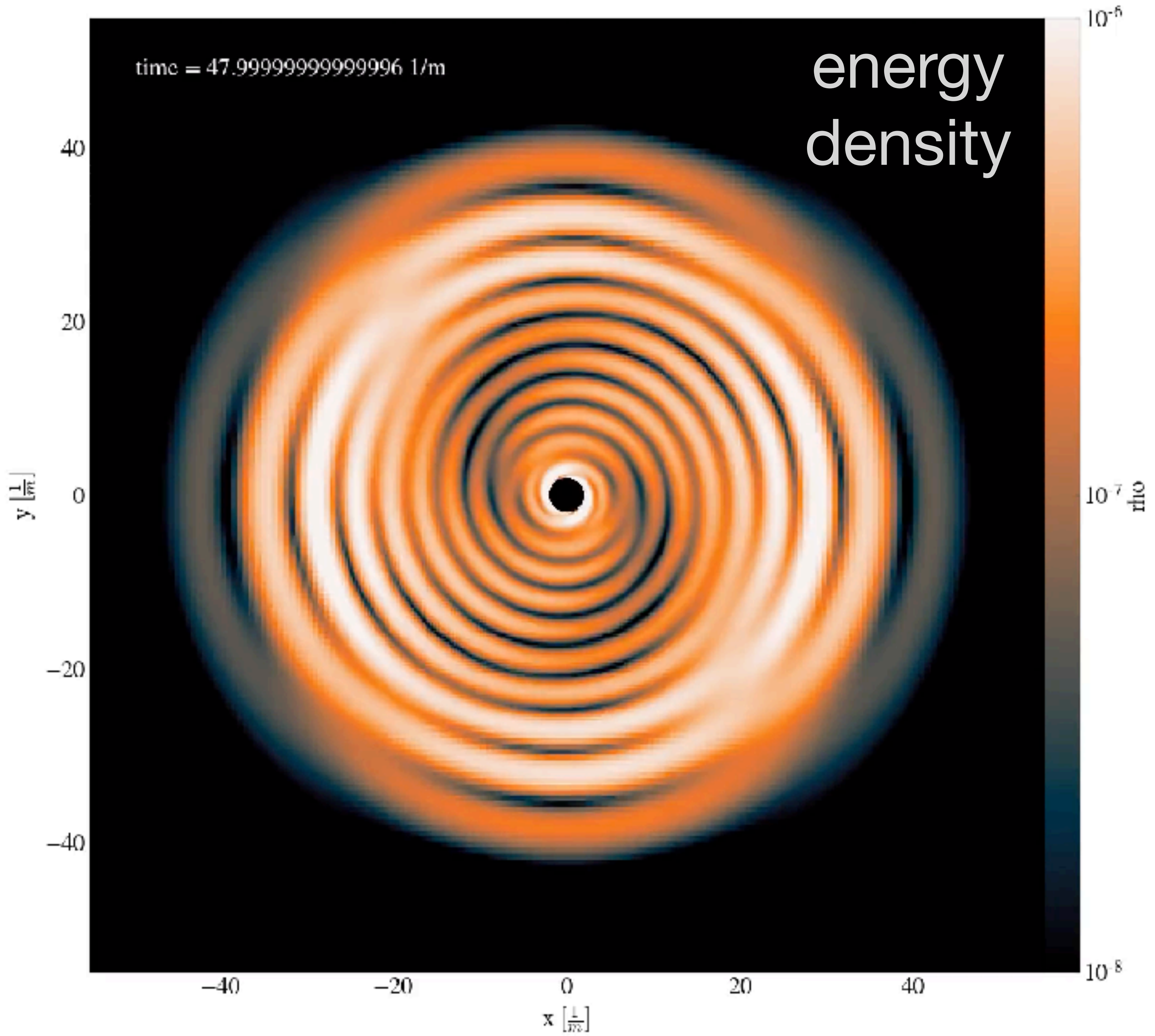
Self interactions in the field

- Perform simulations with vector field which is more consistent with photon case
- $\nabla_\mu F^{\mu\nu} = \mu^2(r,\theta,\phi)\ A^\nu$
- Conclusion: so far behaviour for vector field is consistent with that of the scalar case
- Can extend to more configurations of mass which have a more general spatial dependence

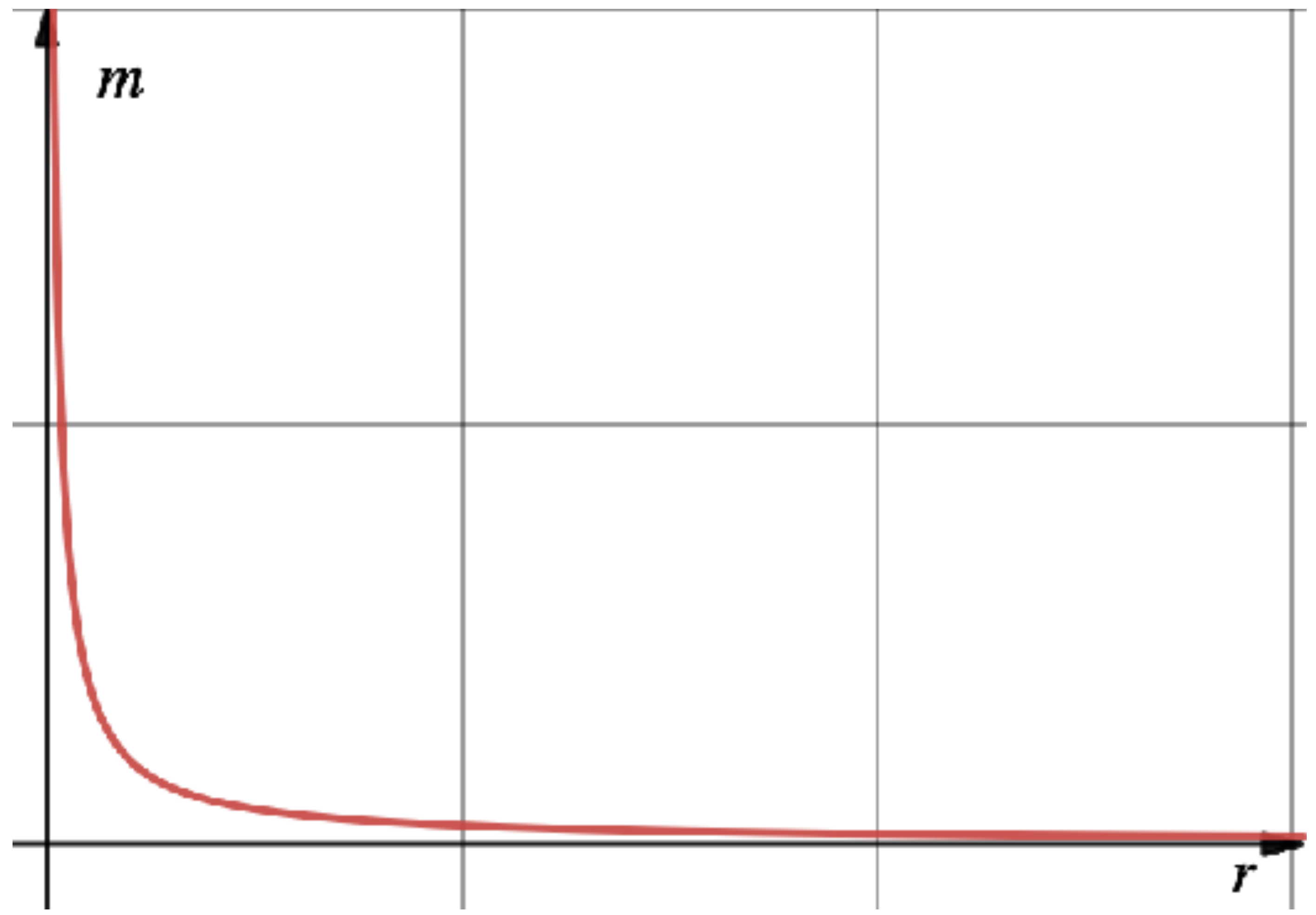


Zipeng Wang, Thomas Helfer, KC, E. Berti
Superradiance in massive vector fields with spatially varying mass
(To appear)

Interactions with an environment



$$\mu^2(r) = \mu_H^2 \left(\frac{r_+}{r} \right)^{\lambda}$$



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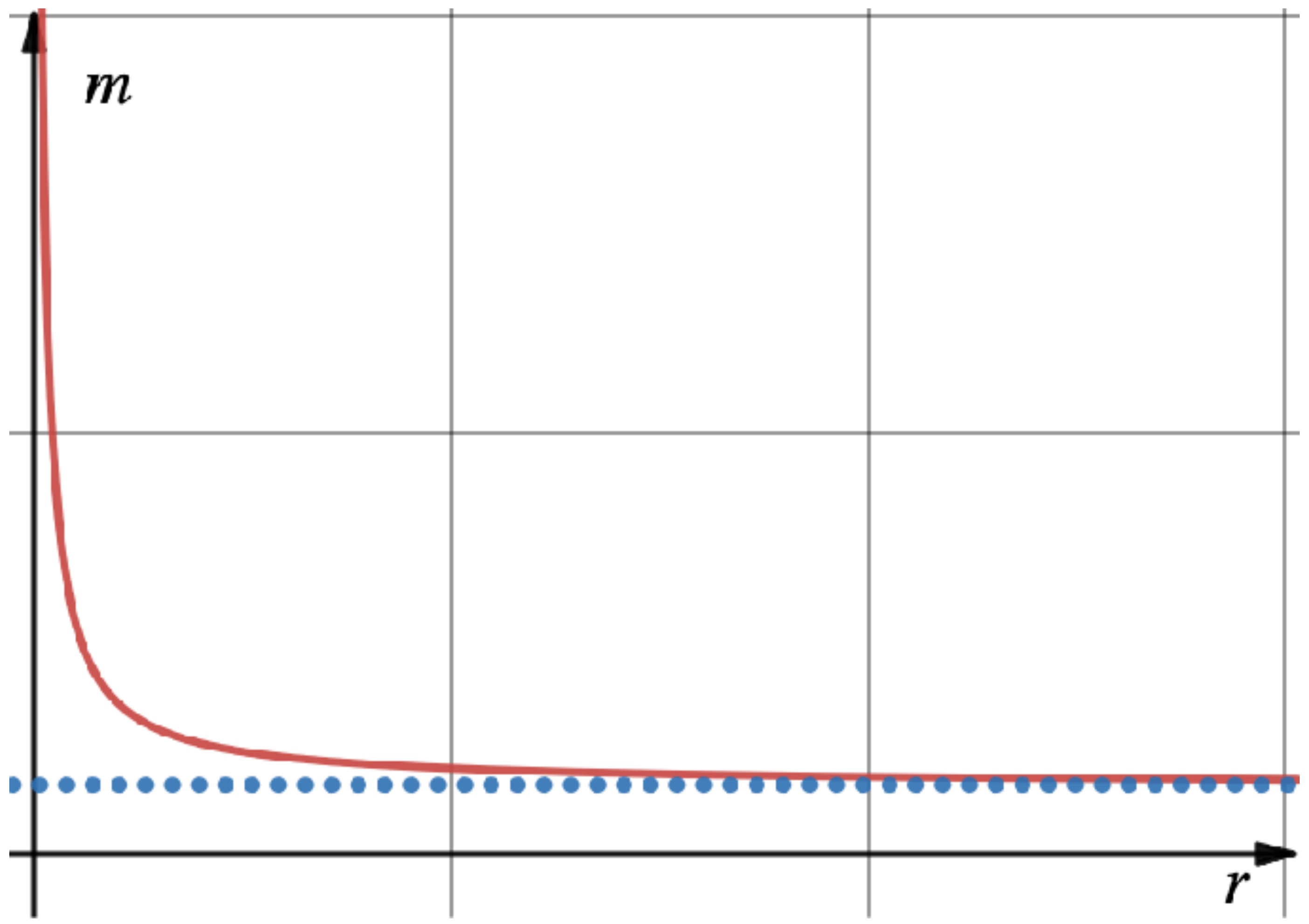
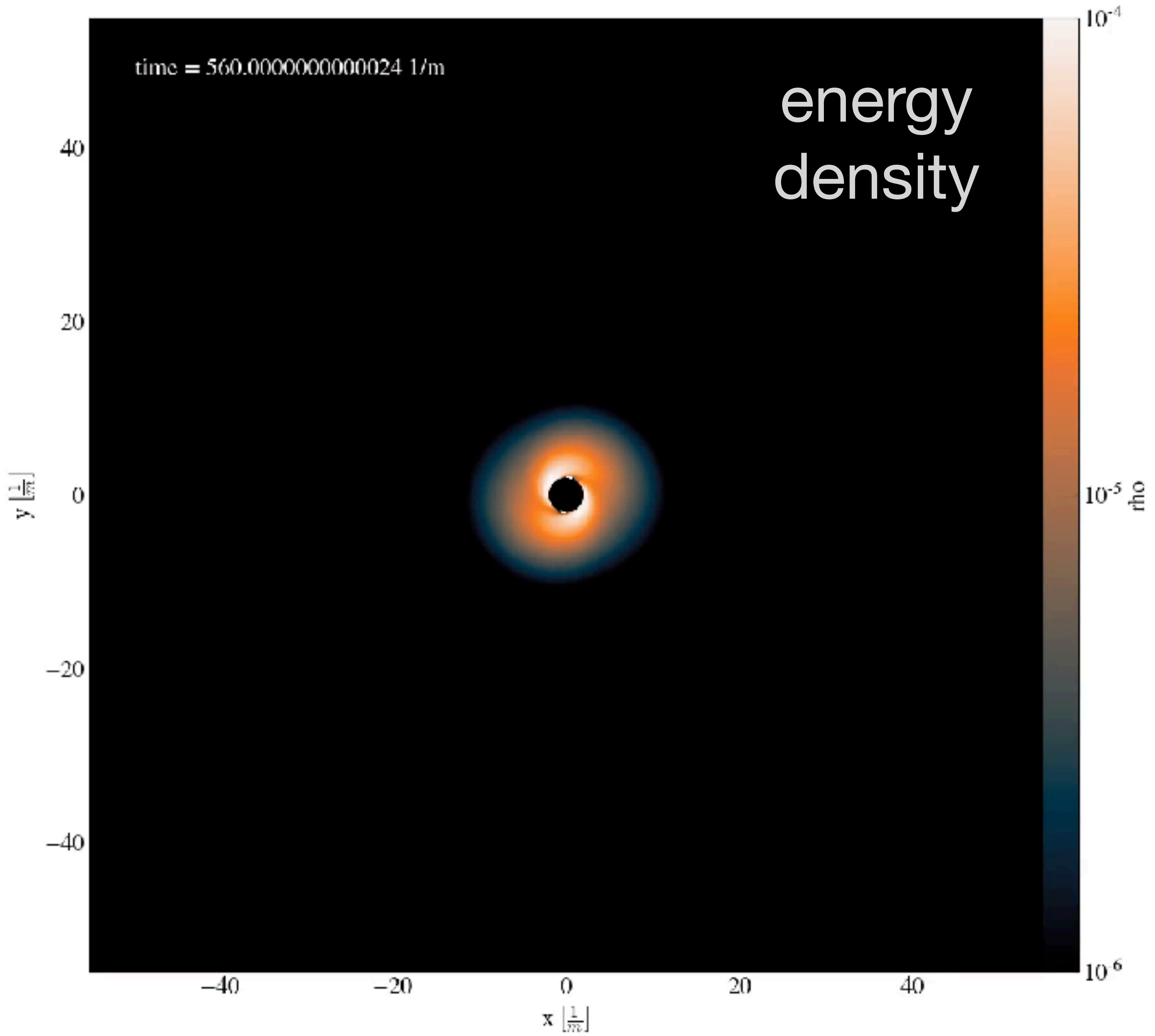
Interactions with an environment

$$\mu^2(r) = \mu_H^2 \left(\frac{r_+}{r}\right)^\lambda + \mu_c^2$$

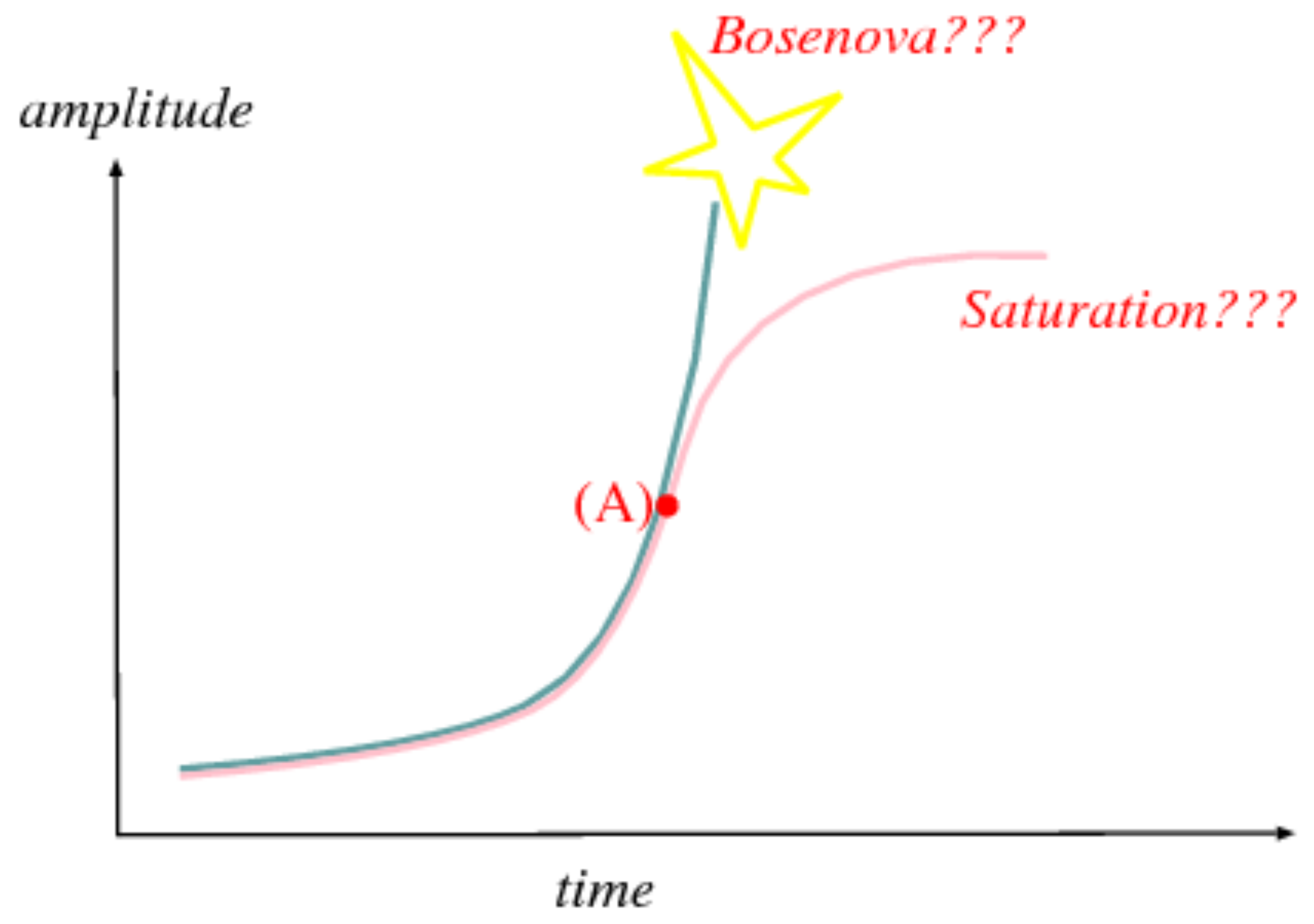




Zipeng Wang, Thomas Helfer, KC, E. Berti
Superradiance in massive vector fields with spatially varying mass
(To appear)

Self interactions in the field

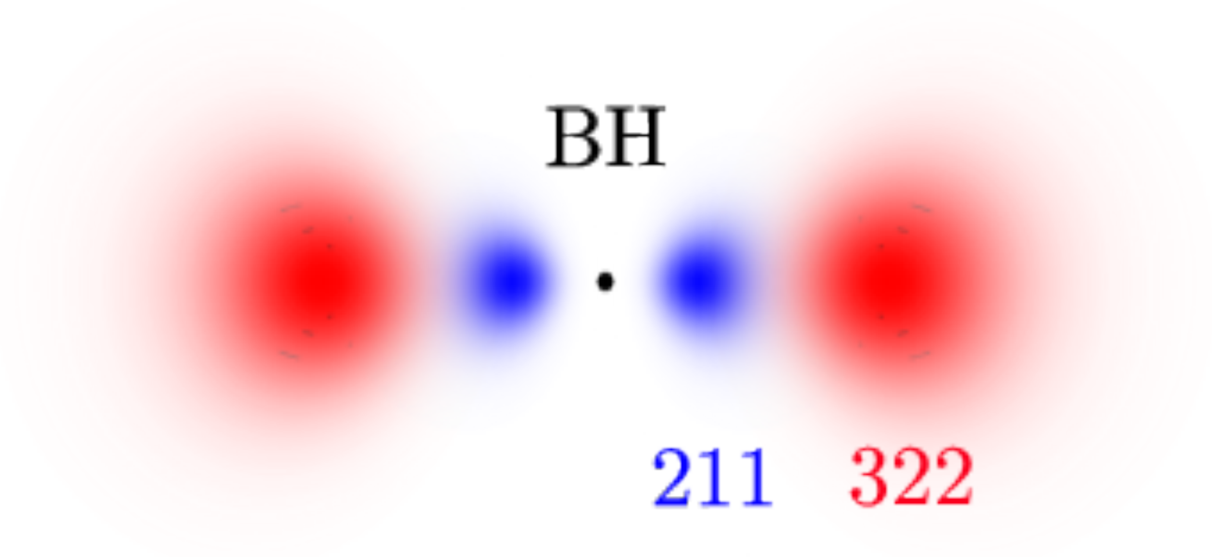
- Attractive self interactions can lead to an explosive collapse of the bosonic cloud, a "bosenova".
- Does a bosenova actually occur?
- Studies so far focus on the scalar case
- Simulations required for relativistic regime where wavelength of scalar $\lambda_s \sim R_s$
- Perturbative regime for non relativistic case $\lambda_s \gg R_s$

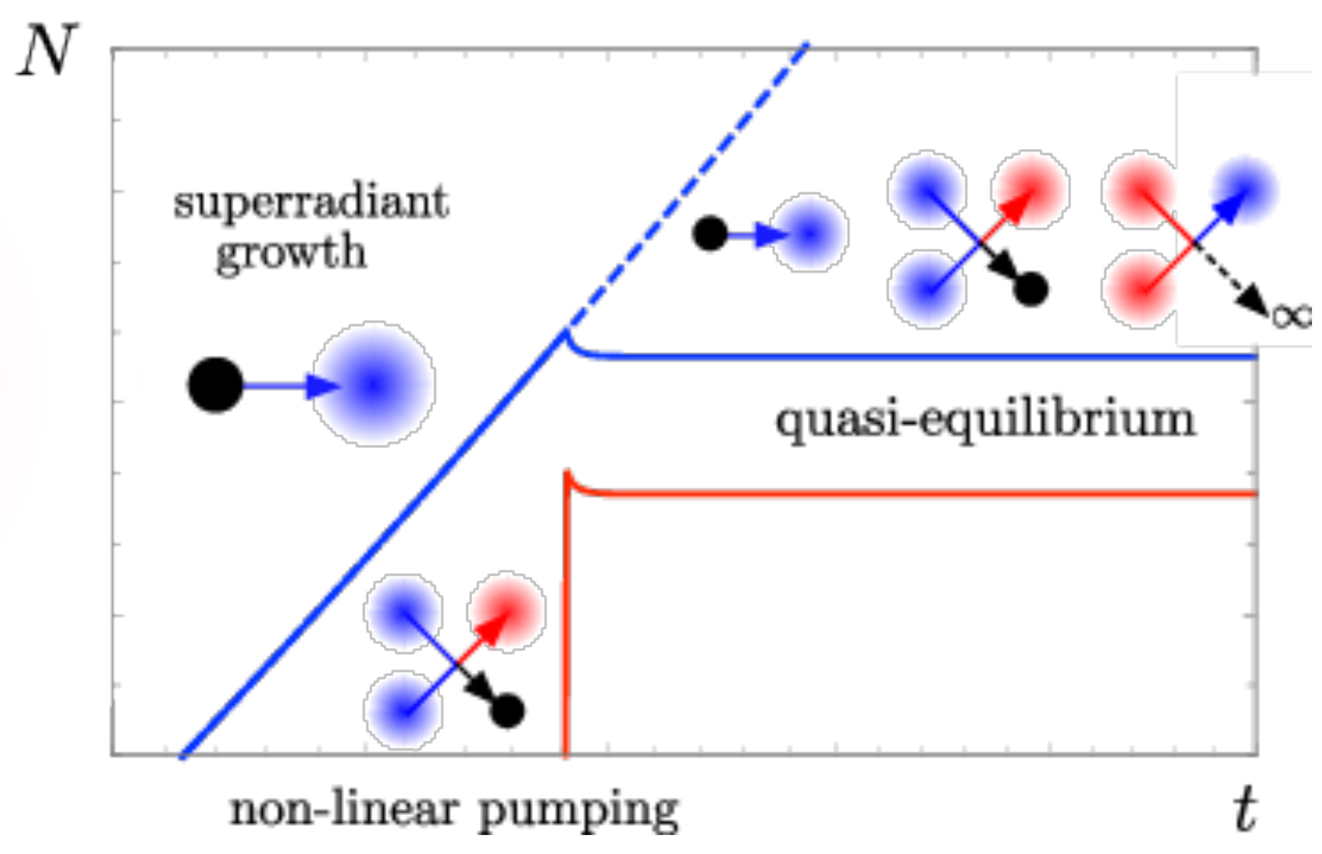


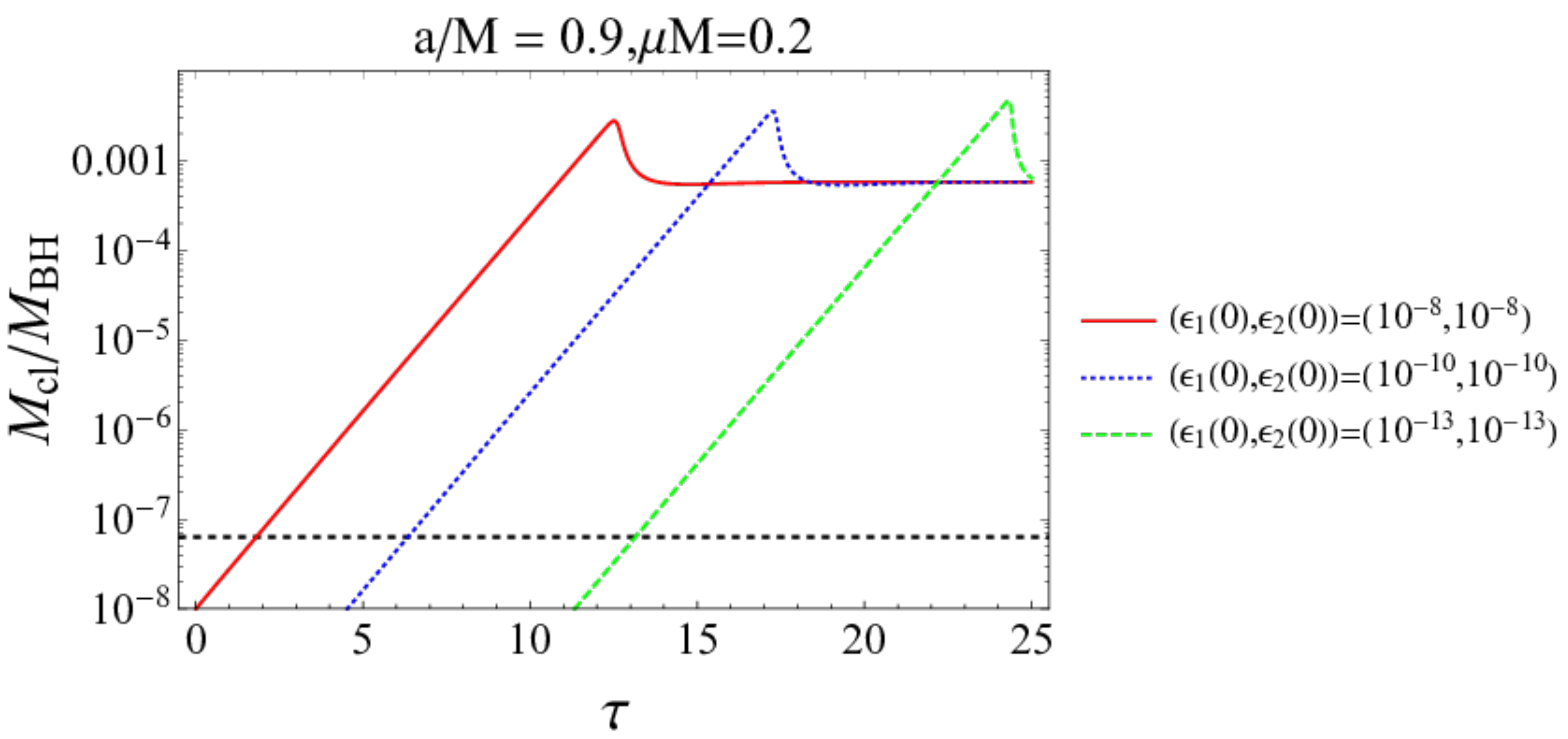
Bosenova collapse of axion cloud around a rotating black hole
H. Yoshino & H. Kodama
Prog.Theor.Phys. 128 (2012) 153-190

Yes (in relativistic regime)

Self interactions in the field







Black hole superradiance of self-interacting scalar fields
M Baryakhtar, M Galanis, R Lasenby, O Simon
Phys.Rev.D 103 (2021) 9, 095019

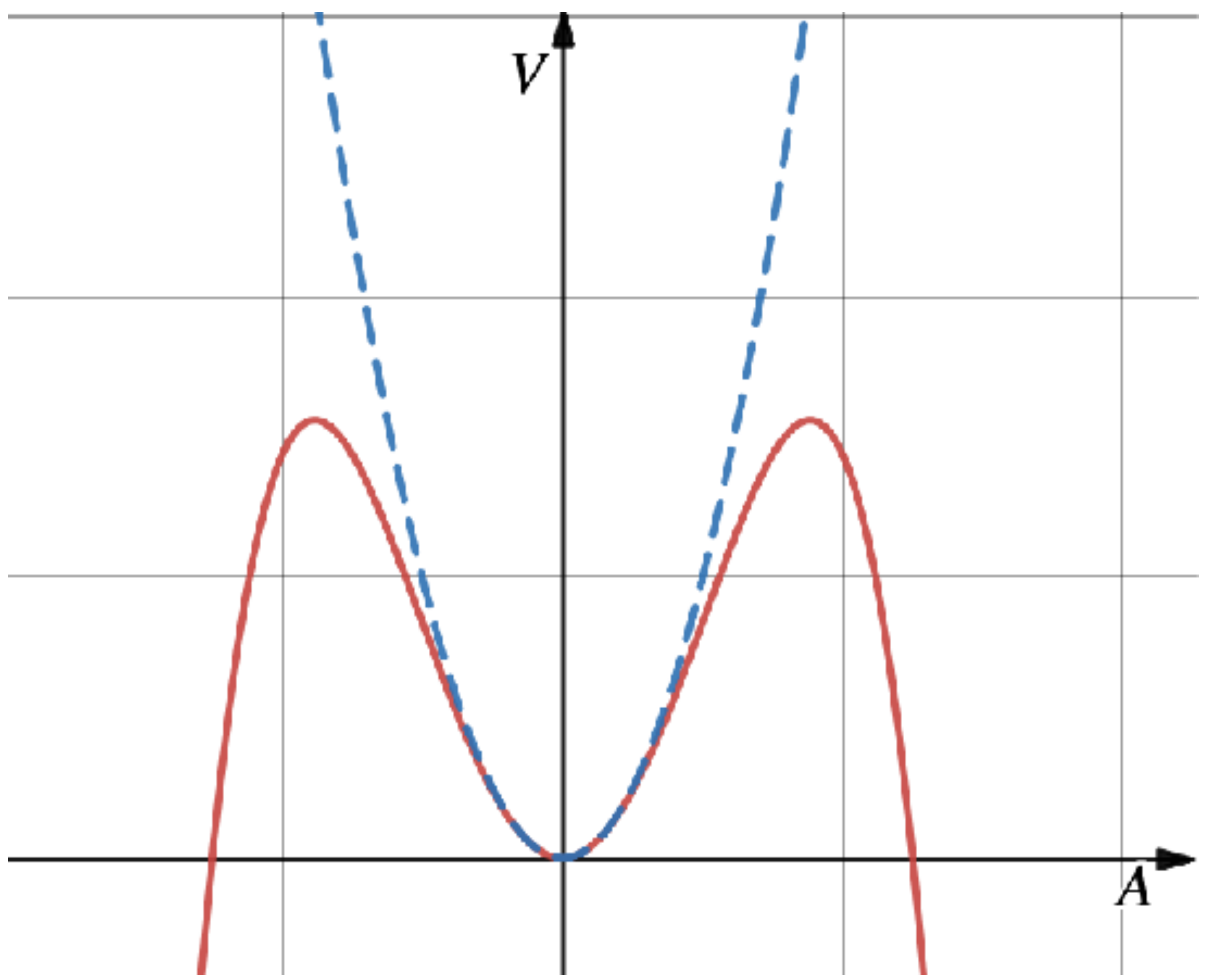
Renormalization group analysis of superradiant growth of self-interacting axion cloud
H. Omiya, T. Takahashi, T. Tanaka
PTEP 2021 (2021) 4, 043E02

No (in non relativistic regime)
Probably not (in relativistic regime)

Not clear (in either regime)

Self interactions in the field

- Perform simulations with vector field where full build up can be observed
- $\nabla_\mu F^{\mu\nu} = \mu^2 A^\nu (1 + \lambda A^\mu A_\mu)$
- Pick fastest growing mode $\mu M = 0.5$
- In simulations we neglect backreaction, so only the combination $\lambda A^\mu A_\mu$ determines the onset of self interactions
- Can always find a regime where this is consistent with an early stage of the superradiant build up - ie, a smaller amplitude and a larger coupling



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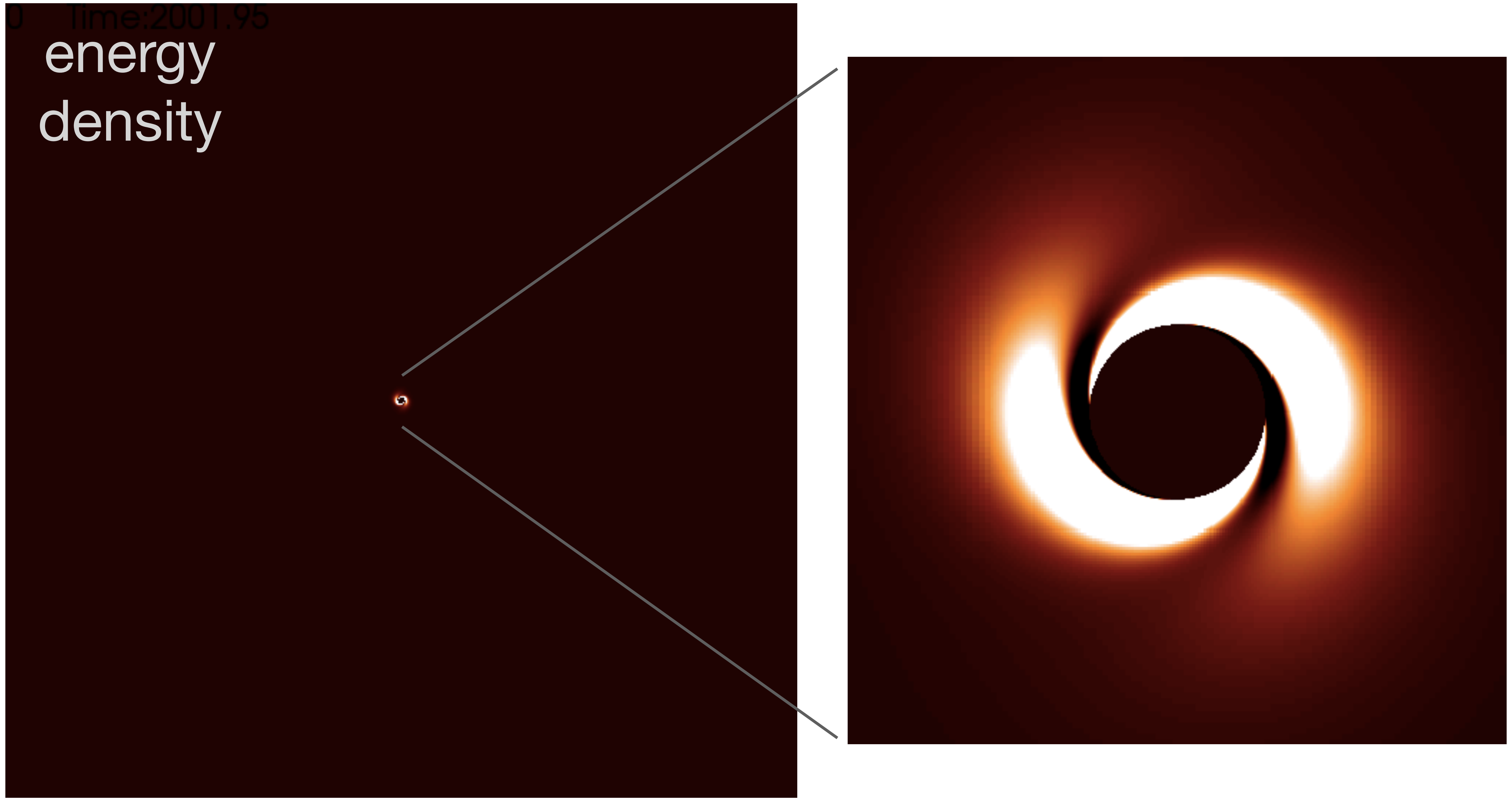

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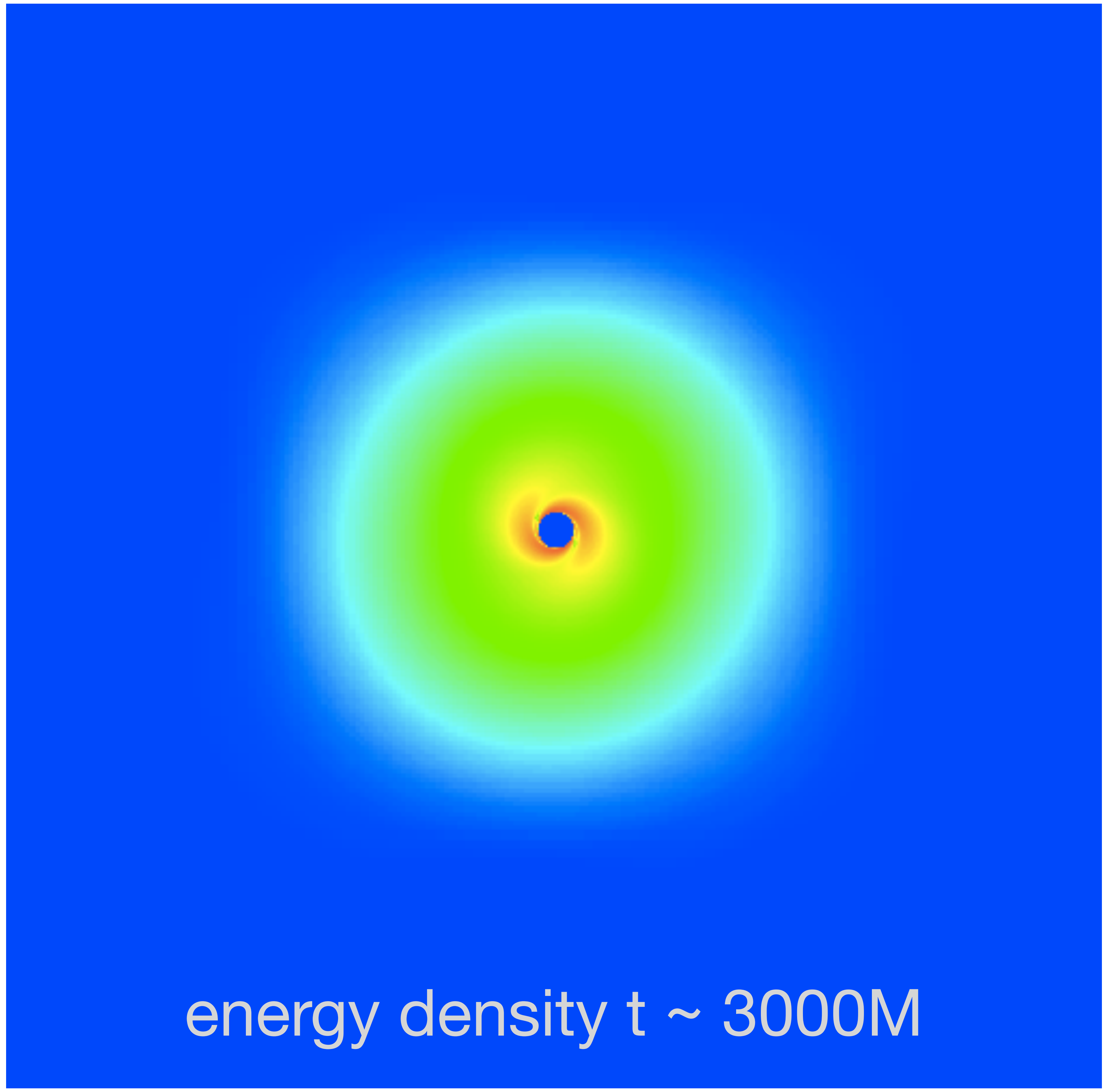

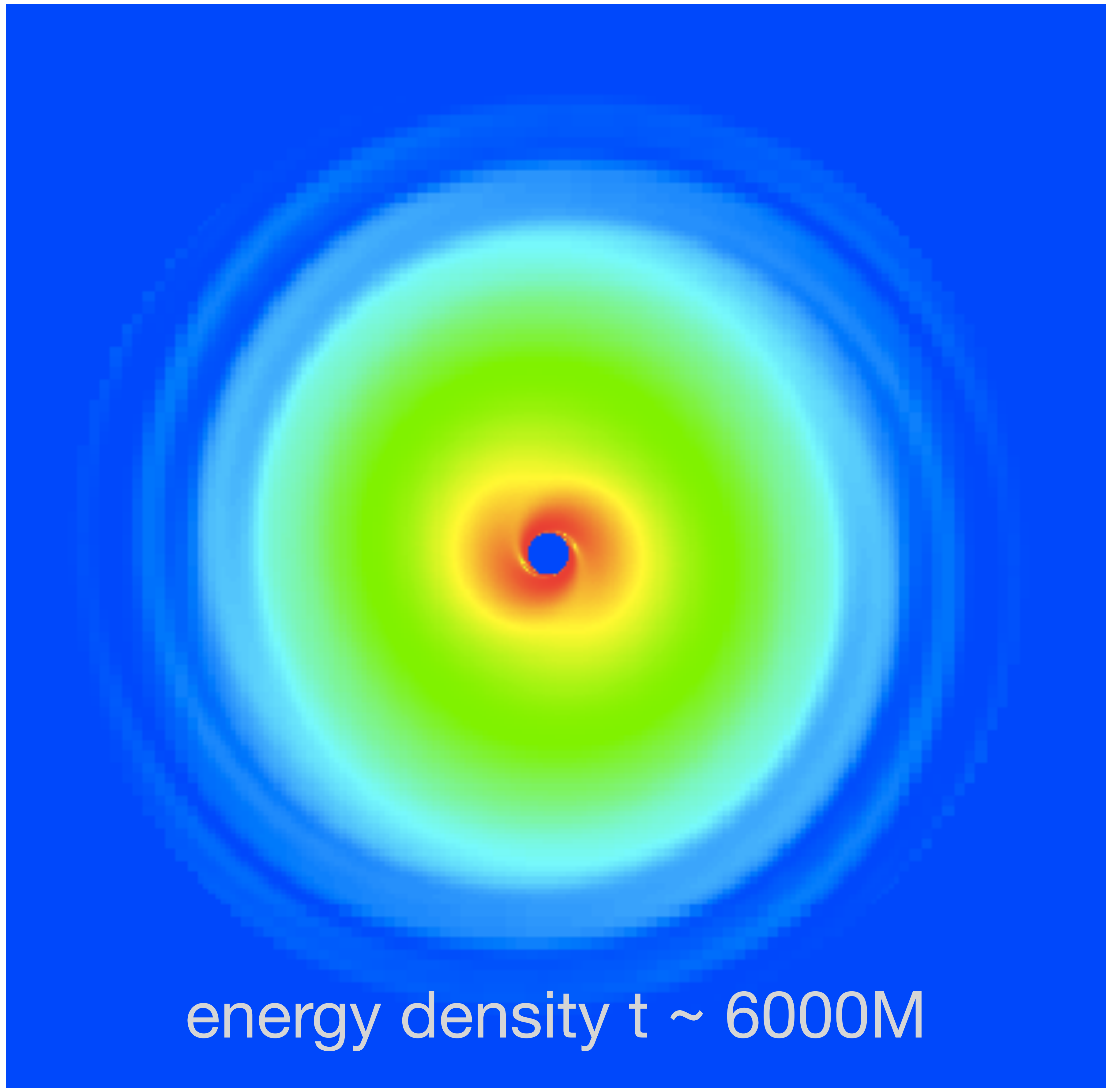

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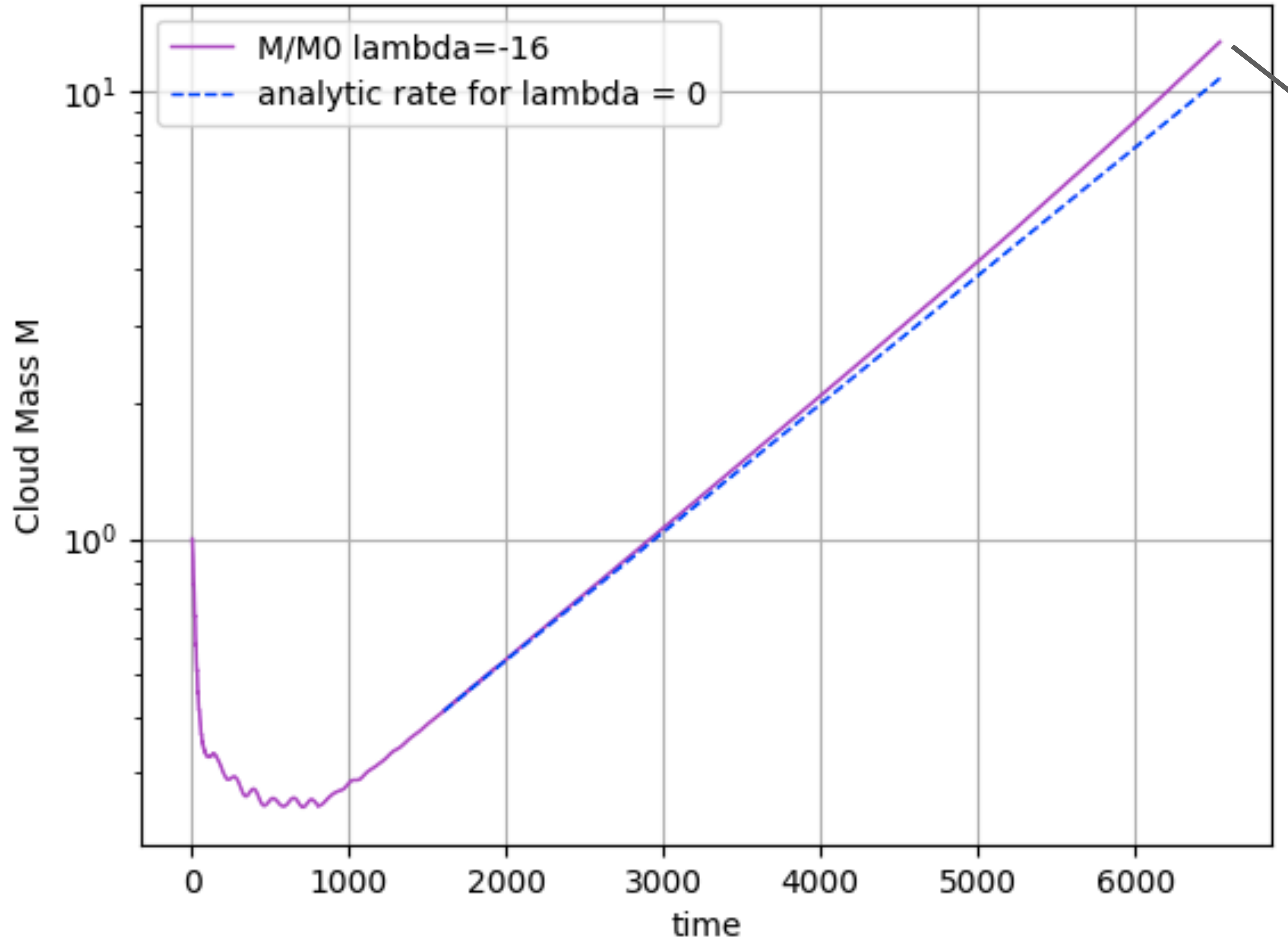
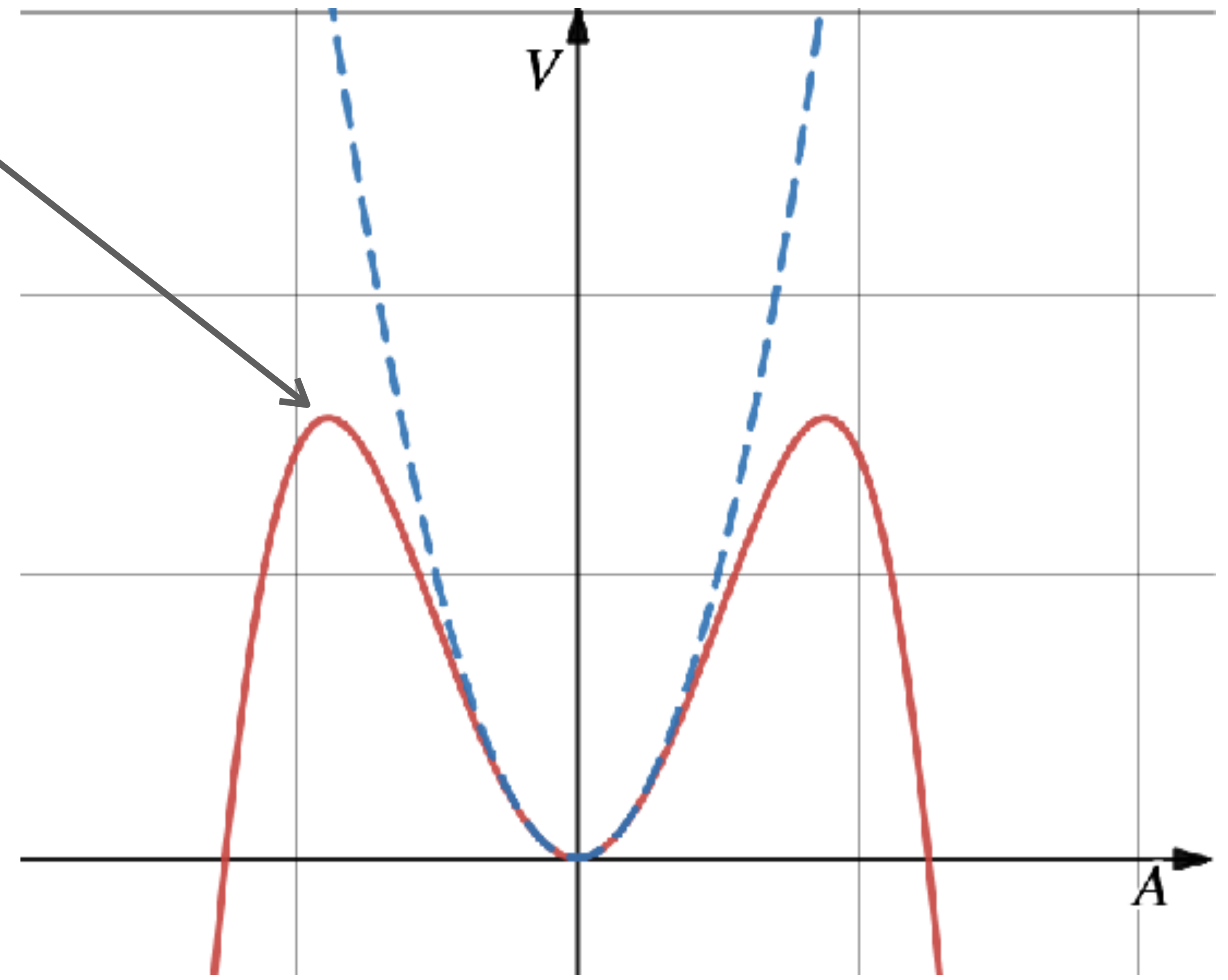
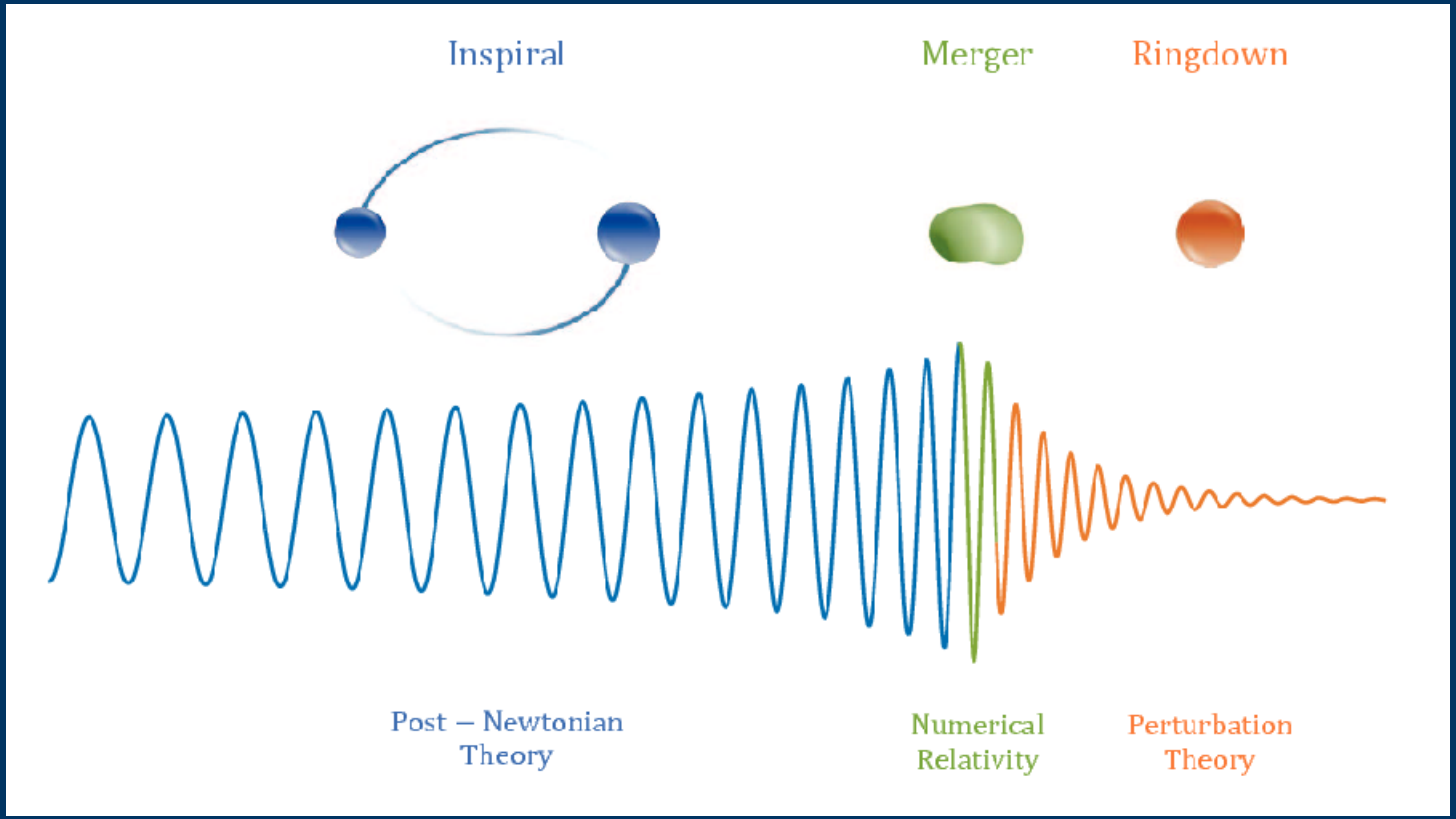


KC, T. Helfer, E. Berti, H. Witek
Vector superradiance with self interactions
(In prep)



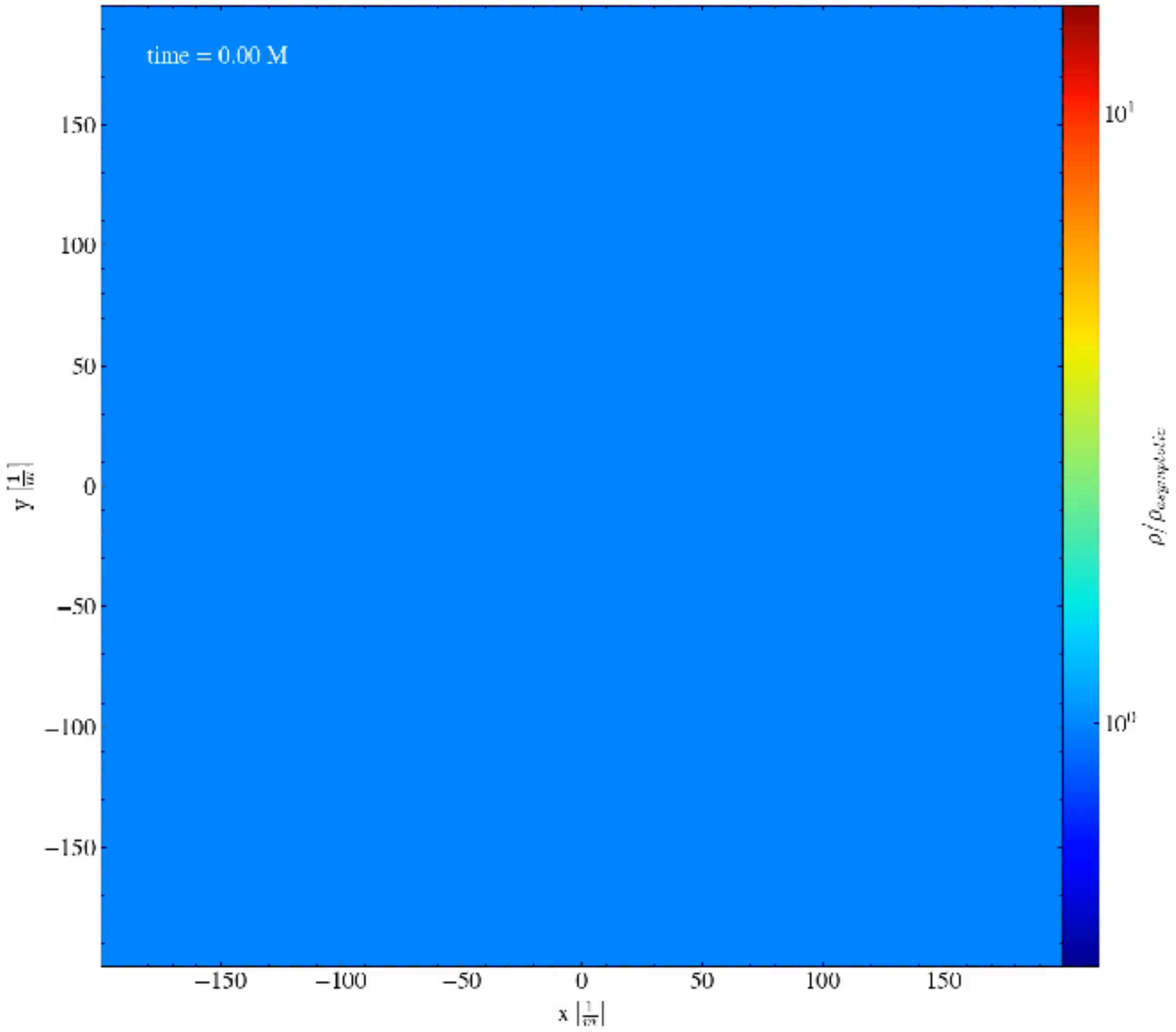
Probably for vector fields (in relativistic regime)

Gravitational signatures of dynamical hair

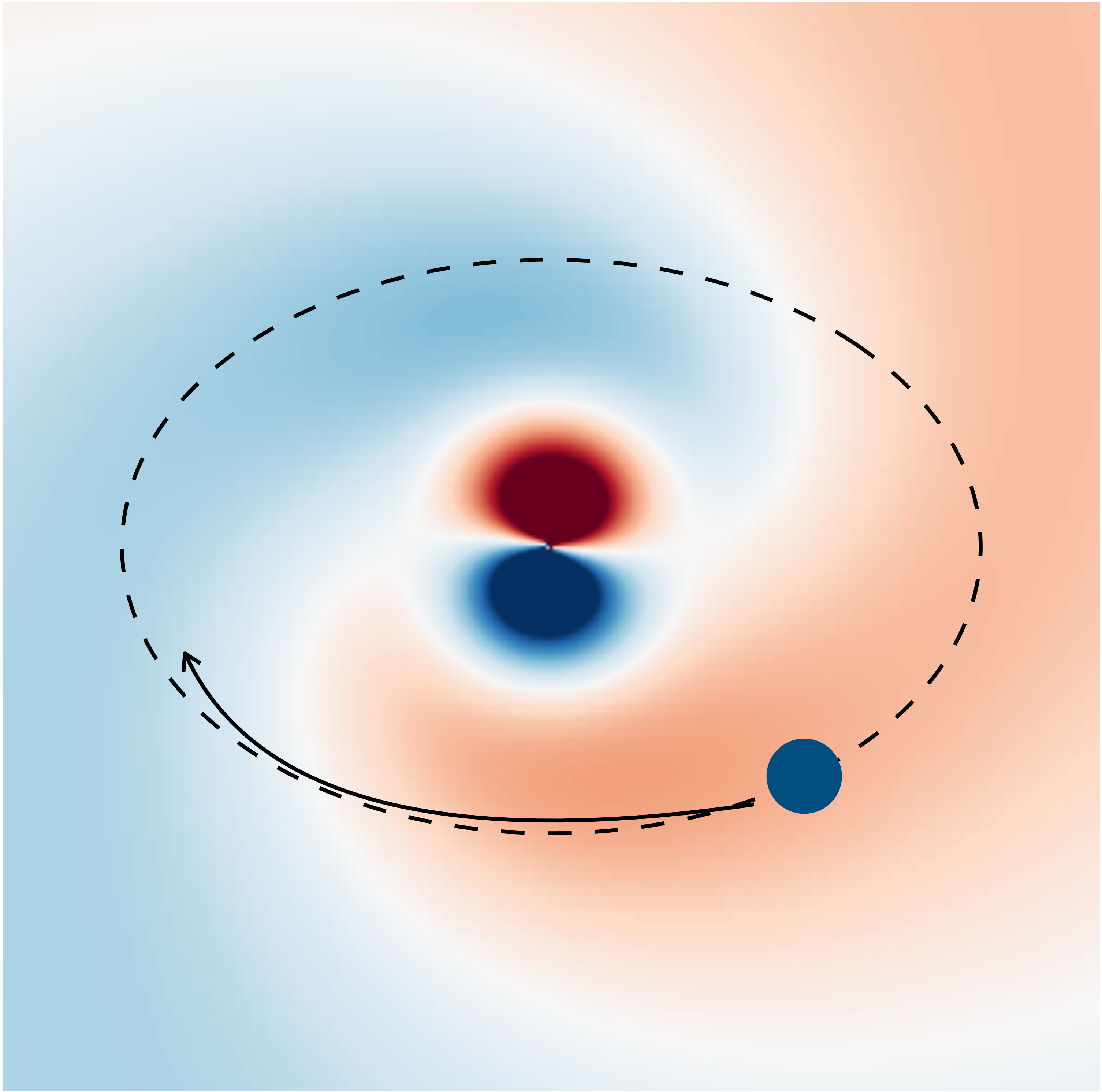


Obtaining gravitational waves from inspiral binary systems using LIGO data, Eur. Phys. J. Plus (2017) 132: 10
JM Antelis and C Moreno

Impact on inspiral



Dynamical friction from scalar dark matter in the relativistic regime
arXiv:2106.08280 (To appear PRD)
Dina Traykova, KC, Thomas Helfer, E Berti, P Ferreira, L Hui



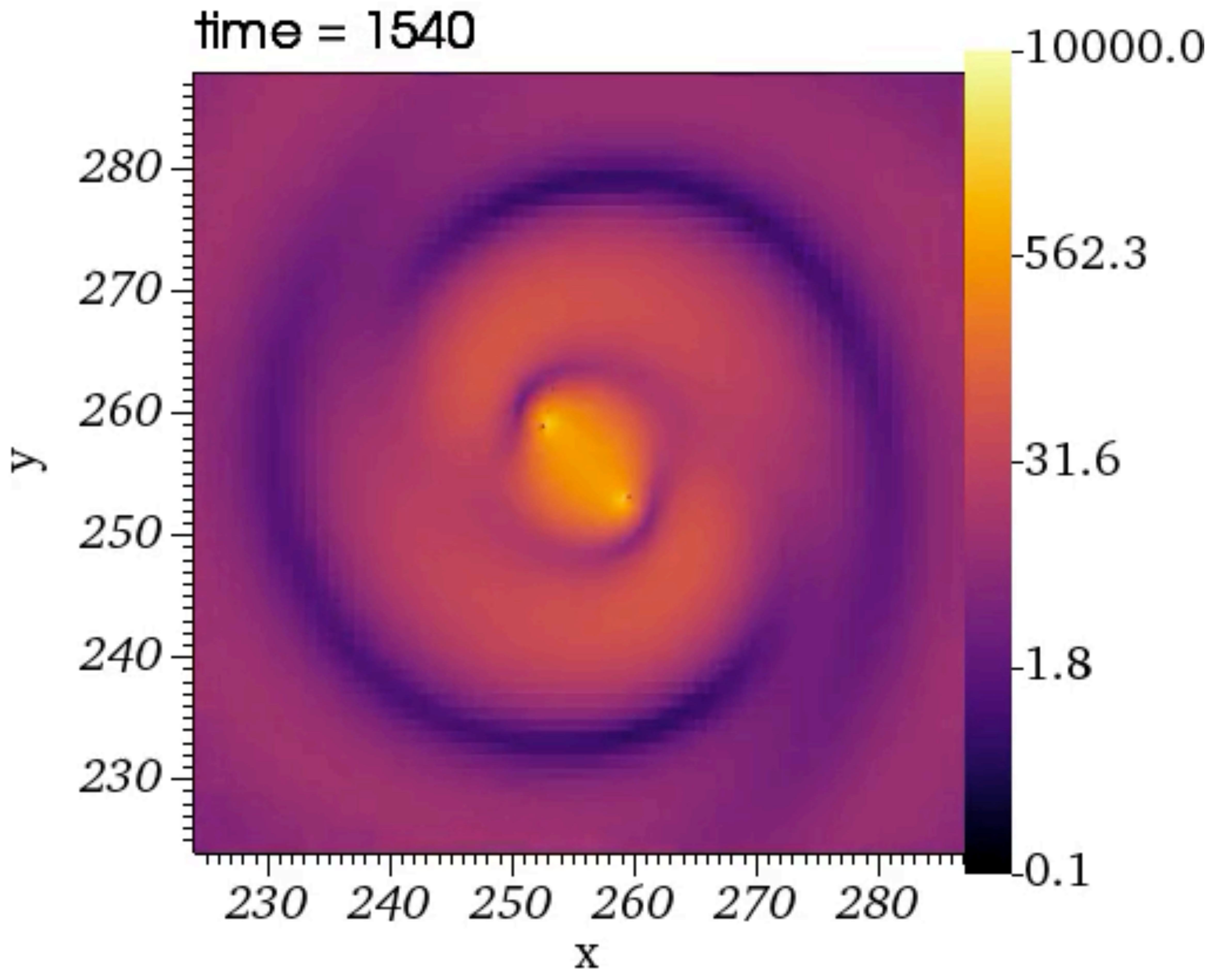
See for example:

Probing the existence of ultralight bosons with a single gravitational-wave measurement
OA Hannuksela , K Wong , R Brito , E Berti , TGF Li
Nature Astronomy volume 3, pages 447–451(2019)

Impact on merger

Work in progress!
J Bamber, KC, P Ferreira, L Hui, M. Lagos

Also work to come by Giuseppe Ficarra and Helvi Witek



energy density

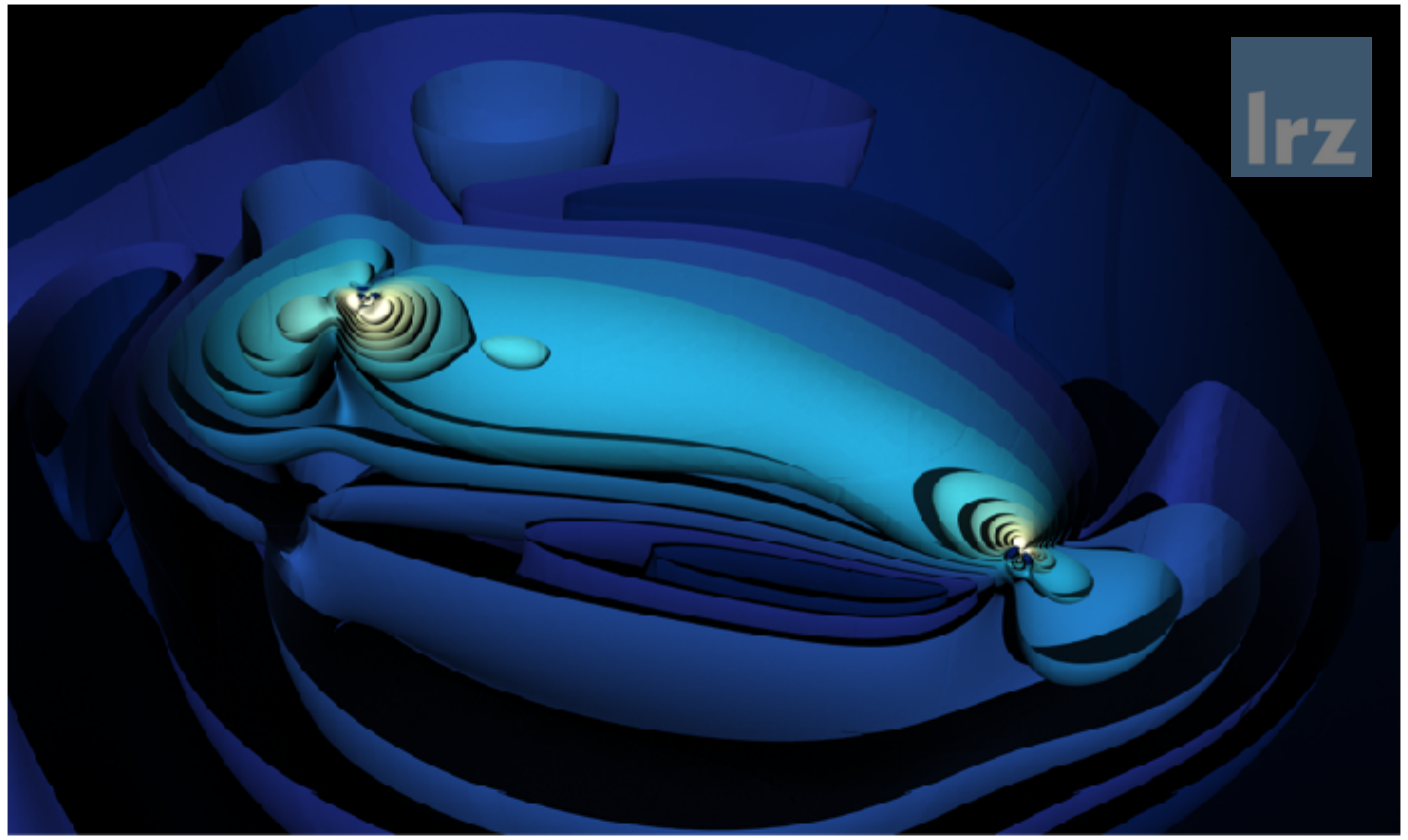


Image credit: Bamber/KC/Cielo

Outstanding challenges

- Timescales of simulations to understand robustness - hybrid numerical / analytic solutions required

- What are the appropriate initial conditions for merger simulations?

- Degeneracies with other environmental effects - full characterisation of effects required