Title: Fundamental physics from the strong-field regime of gravity

Speakers: Josu Aurrekoetxea

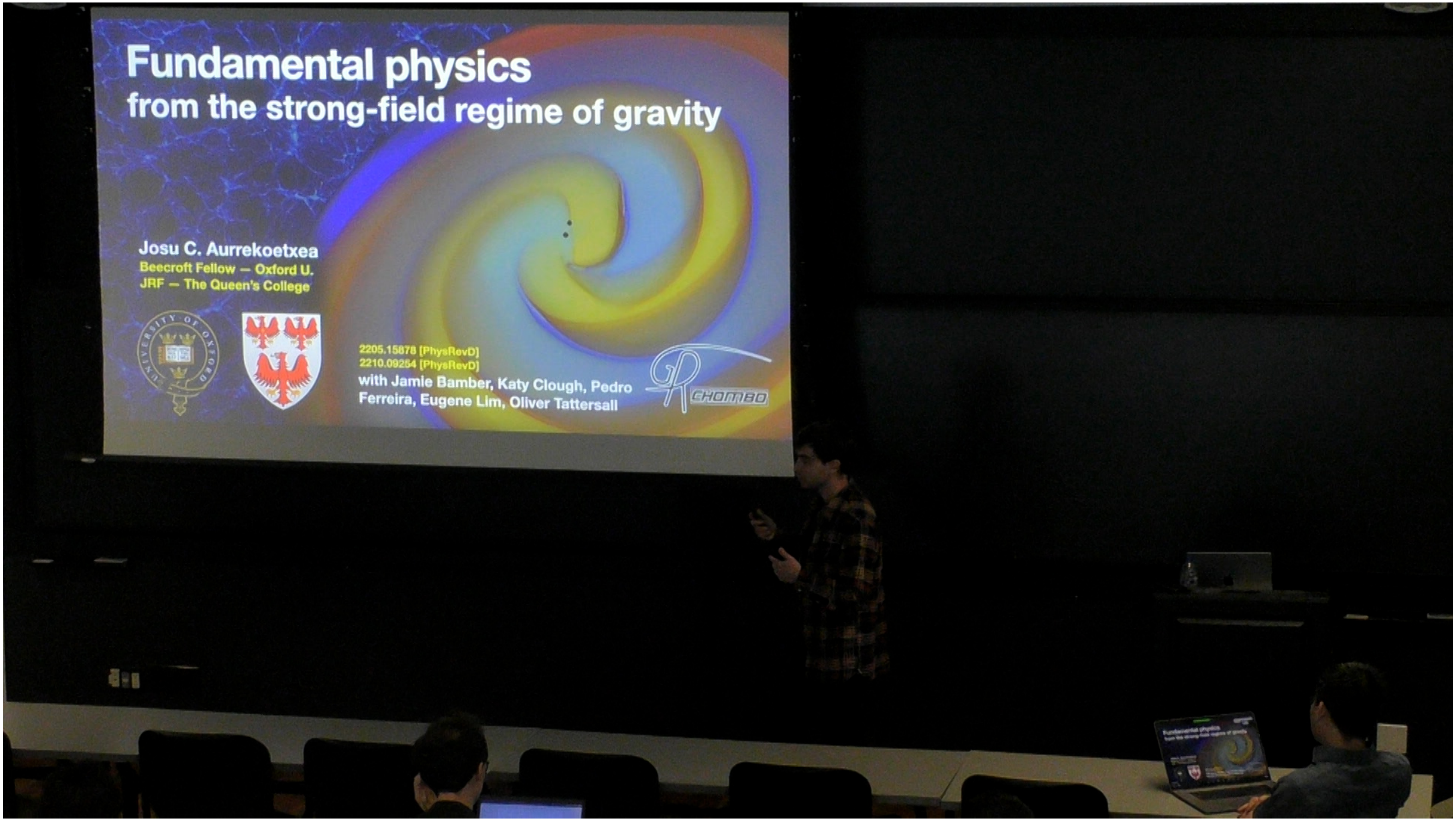
Series: Strong Gravity

Date: May 04, 2023 - 1:00 PM

URL: https://pirsa.org/23050019

Abstract: We are in a new era of gravitational physics in which both gravitational-wave measurements and cosmological observations can be used to test fundamental physics. Moreover, recent computational developments allow us to investigate (at present largely unexplored) regimes where the gravitational force is strong - a very promising area to search for new physics. In this talk I will overview two cases in which we aim to use strong-gravity to learn about the dark components of the universe: the interaction of binary black hole mergers with their dark matter environments and the emission and propagation of scalar gravitational waves, a distinct signature of theories aiming to explain dark energy.

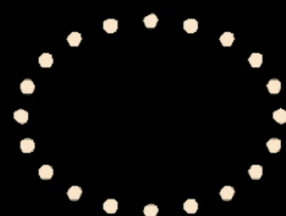
Zoom link: https://pitp.zoom.us/j/92308918921?pwd=UEk1aEt3bmRxdklqUUpSNlRocldVdz09


Fundamental physics
from the strong-field regime of gravity
Josu C. Aurrekoetxea
Beecroft Fellow — Oxford U.
JRF — The Queen's College
2205.15878 [PhysRevD]
2210.09254 [PhysRevD]
with Jamie Bamber, Katy Clough, Pedro Ferreira, Eugene Lim, Oliver Tattersall
GRCHOMBO

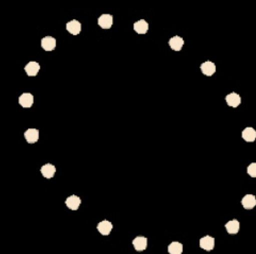
General Relativity + Standard Model

$$S = \int d^4x \sqrt{-g} \left[L_{\mathrm{GR}} + L_{\mathrm{SM}} \right]$$

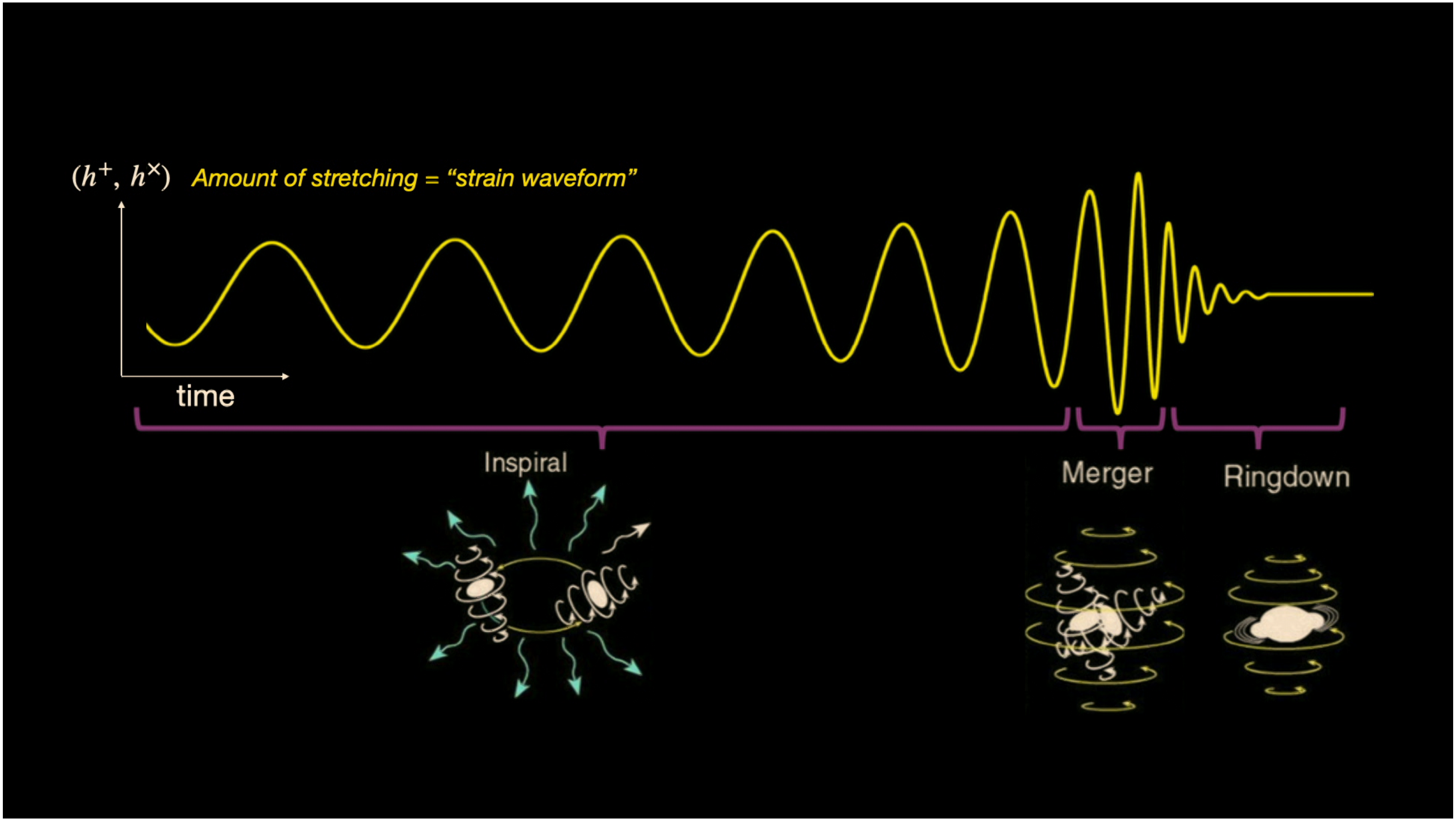
GWs

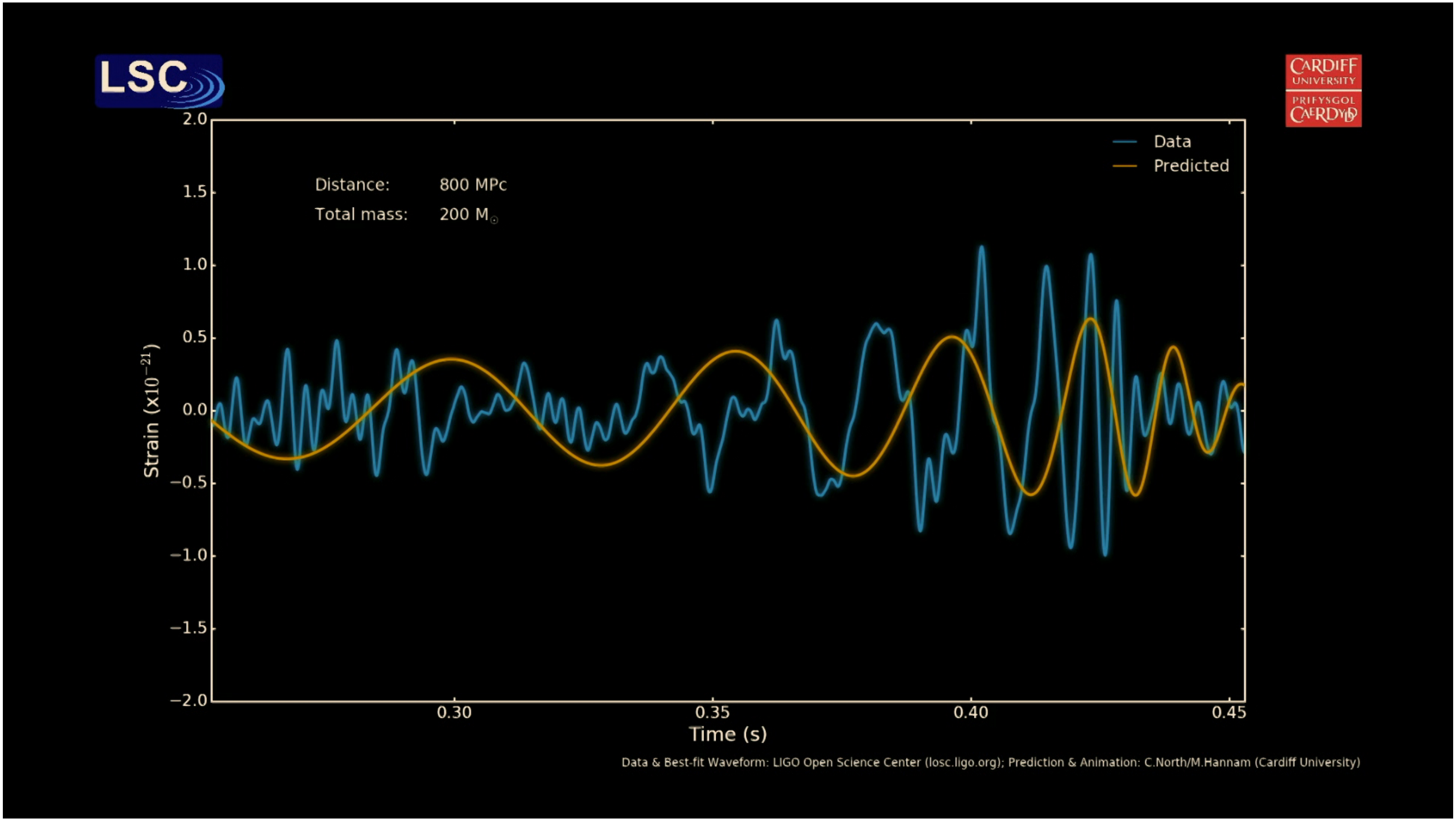


h^+

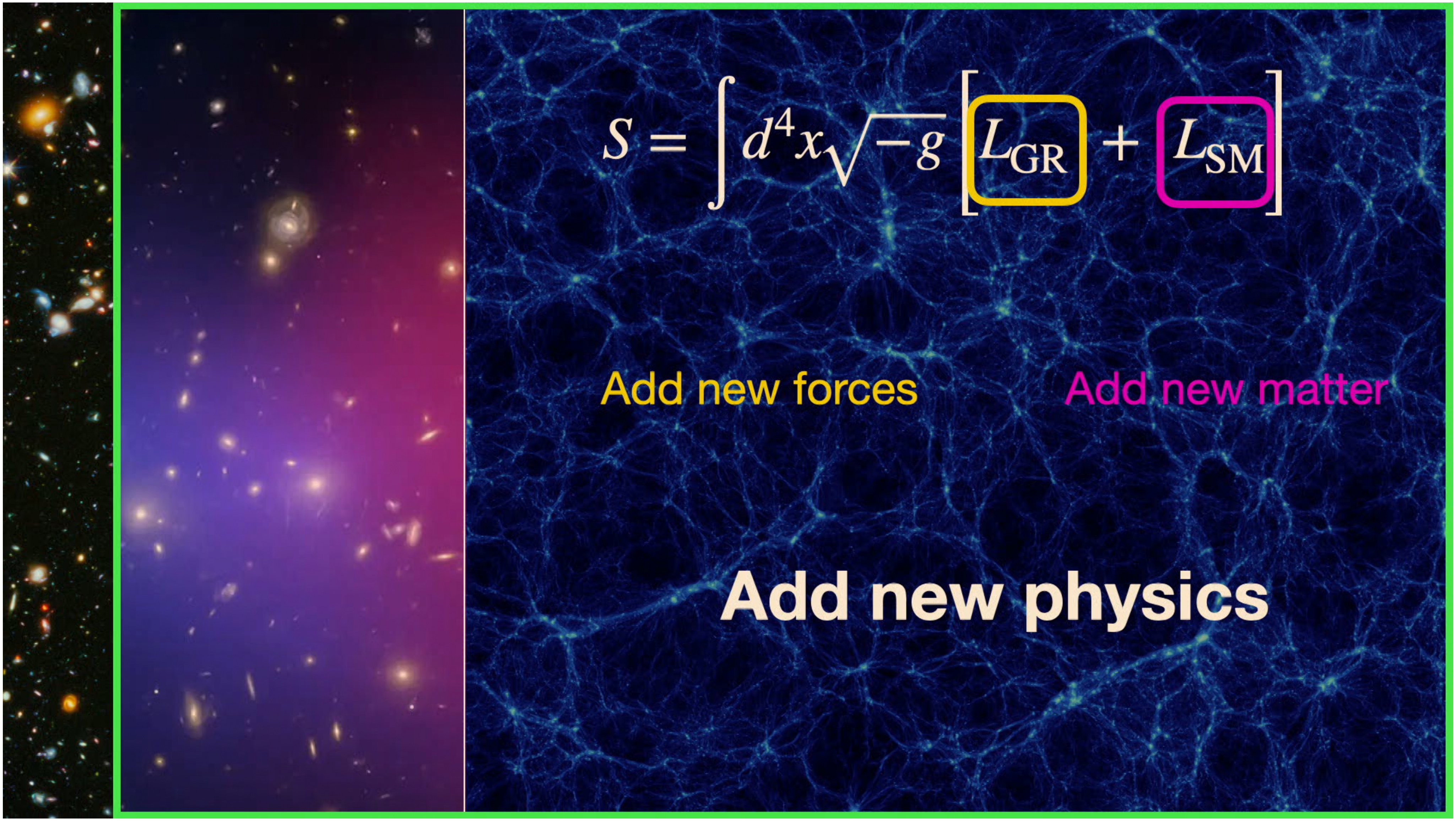


$h^\times$


$(h^+, h^\times)$
Amount of stretching = "strain waveform"
time
Inspiral
Merger
Ringdown



LSC
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
Data
Predicted
Distance: 800 MPc
Total mass: 200 $M_\odot$
Strain ($\times 10^{-21}$)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0.30
0.35
0.40
0.45
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)


$S = \int d^4x \sqrt{-g} \left[L_{\rm GR} + L_{\rm SM} \right]$
Add new forces
Add new matter
Add new physics

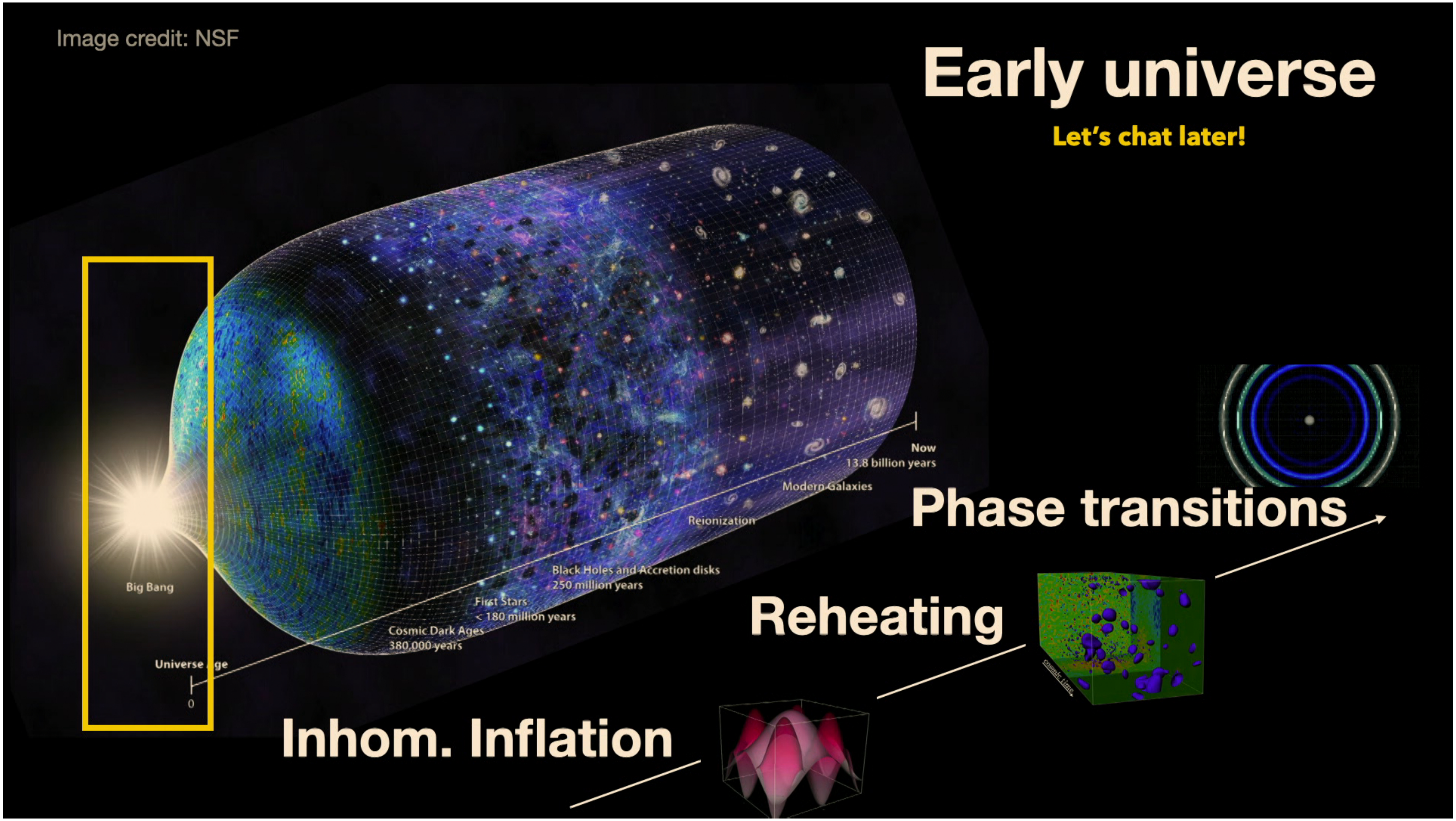


Image credit: NSF
Early universe
Let's chat later!
Big Bang
Universe Age
0
Cosmic Dark Ages
380,000 years
First Stars
< 180 million years
Black Holes and Accretion disks
250 million years
Reionization
Modern Galaxies
Now
13.8 billion years
Phase transitions
Reheating
Inhom. Inflation


Near black holes
Having additional matter around BHs will change the different parts of the waveform in a distinctive way
Add new matter
Having additional gravitational forces will source new GW signatures
Add new forces

Ingredient 1:
Solving GR in a computer:

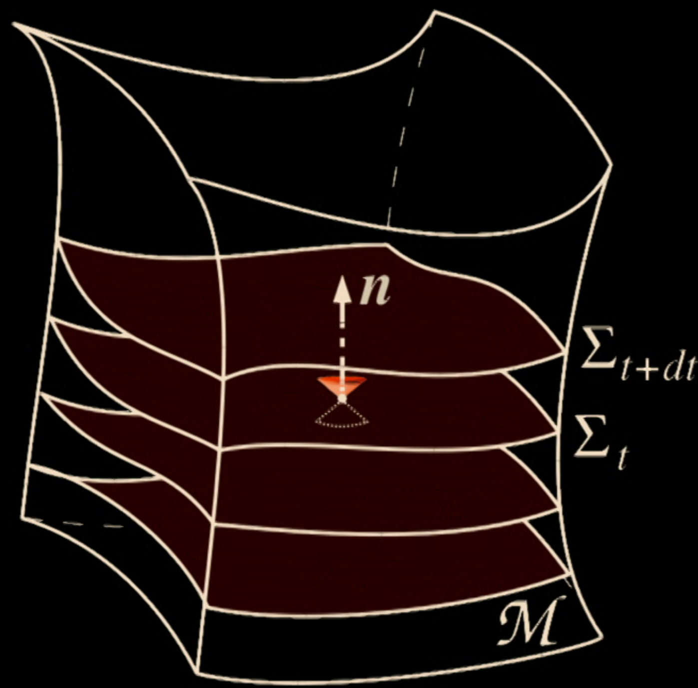
Solving GR in a computer:

Covariant form

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

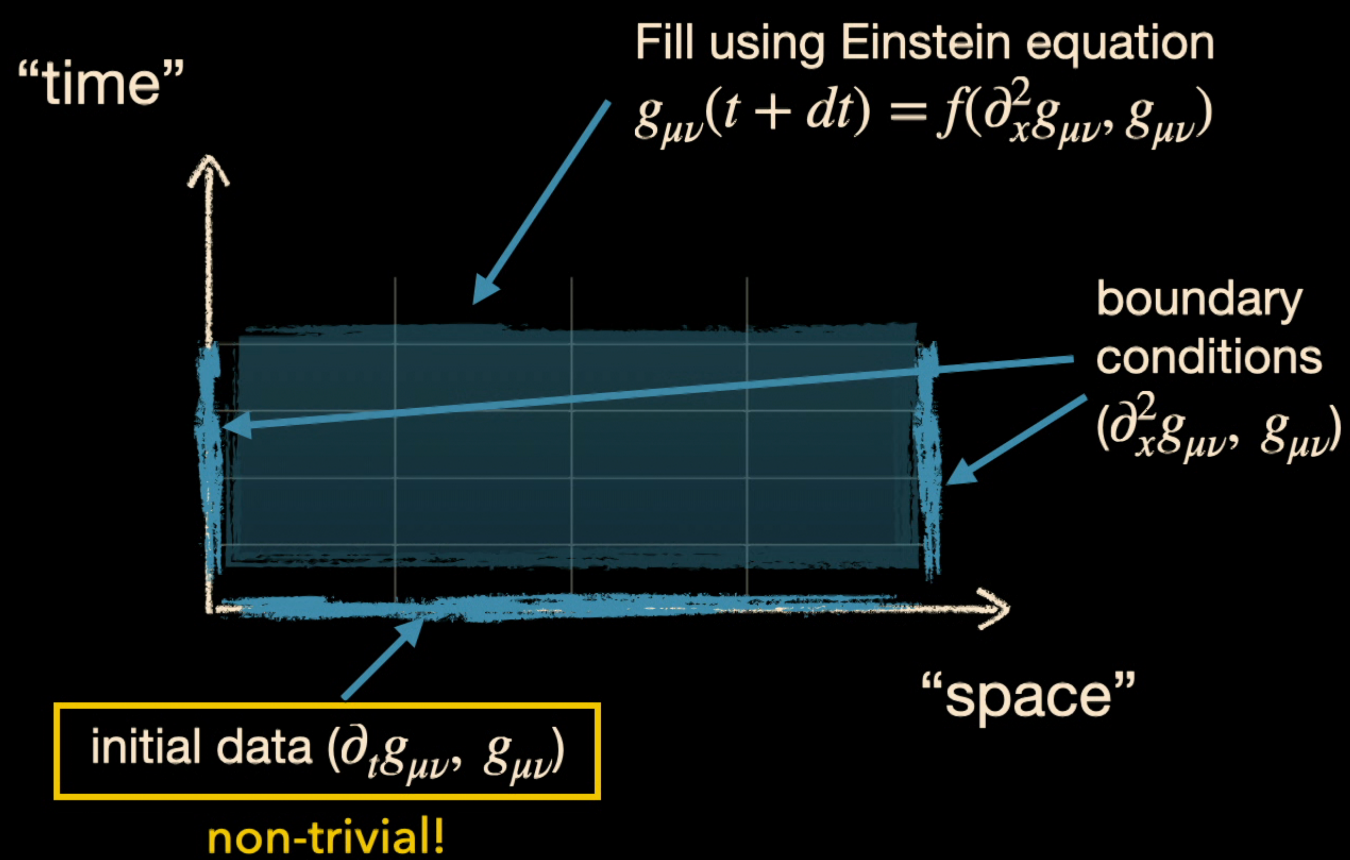
$$\partial_t g_{\mu\nu} = \ldots$$

Initial value form

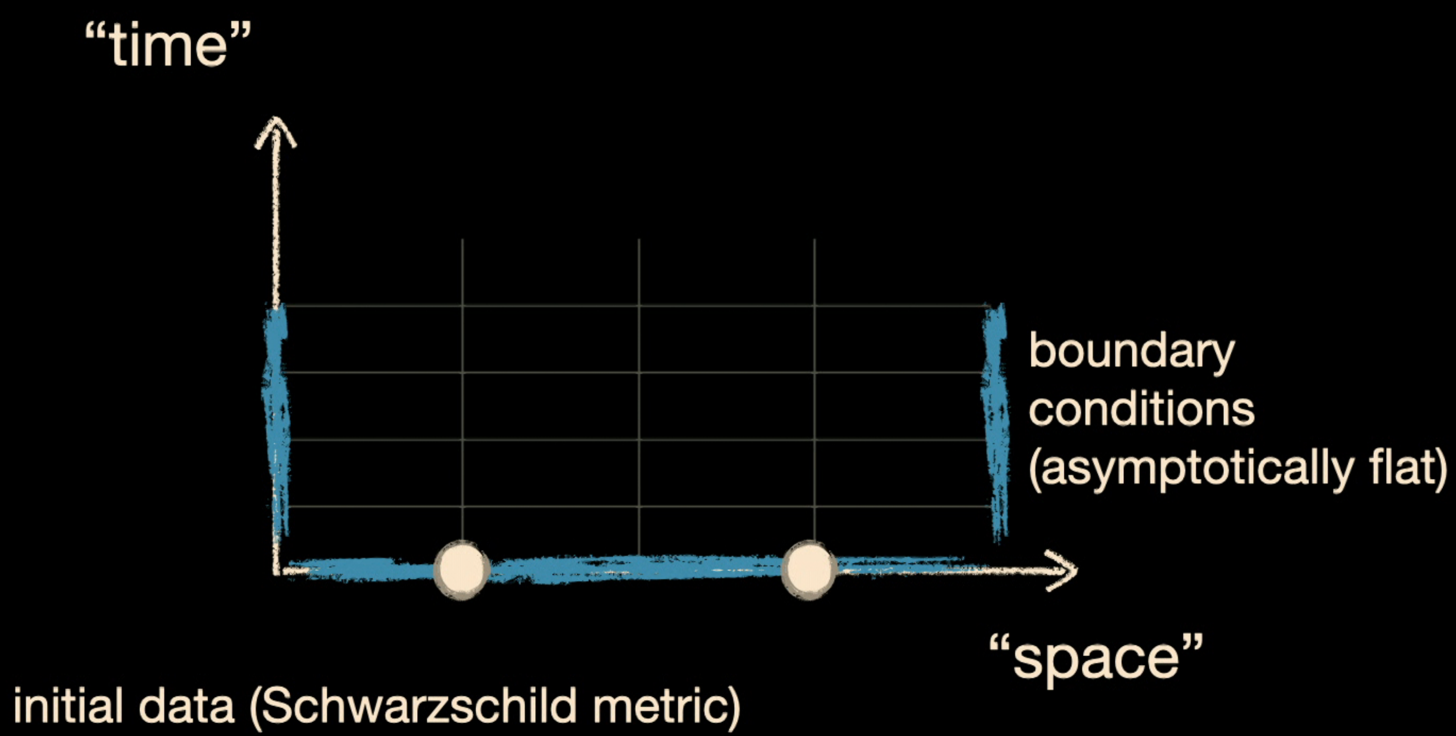


Arnowitt, Deser, Misner
Baumgarte, Shapiro, Shibata, Nakamura

Solving GR in a computer:

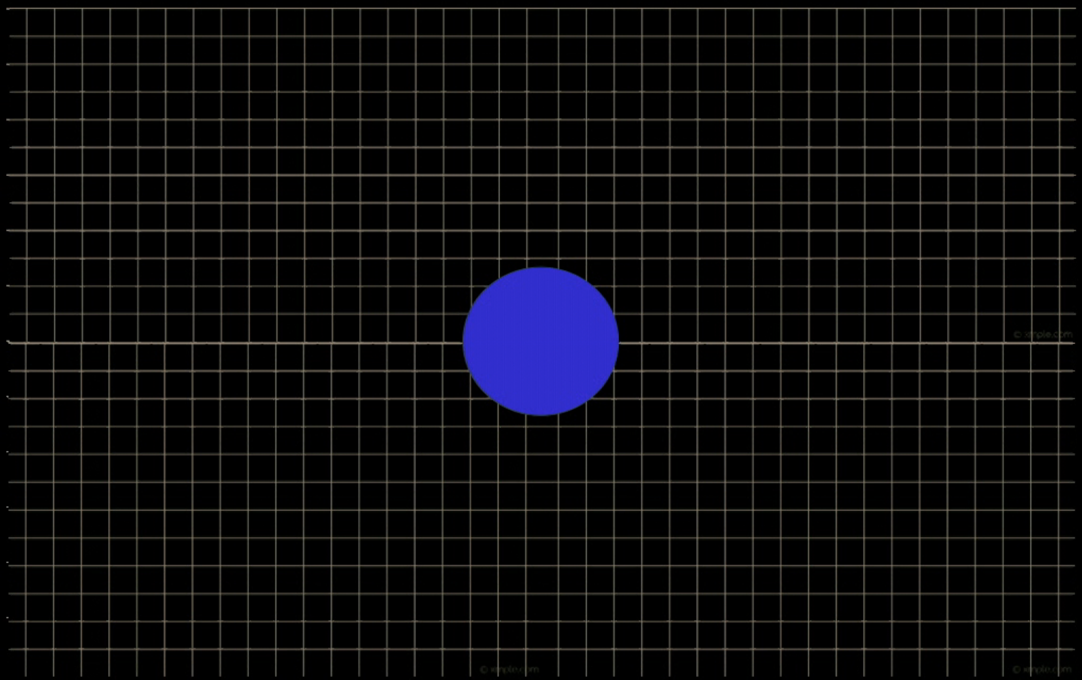


Solving GR in a computer:

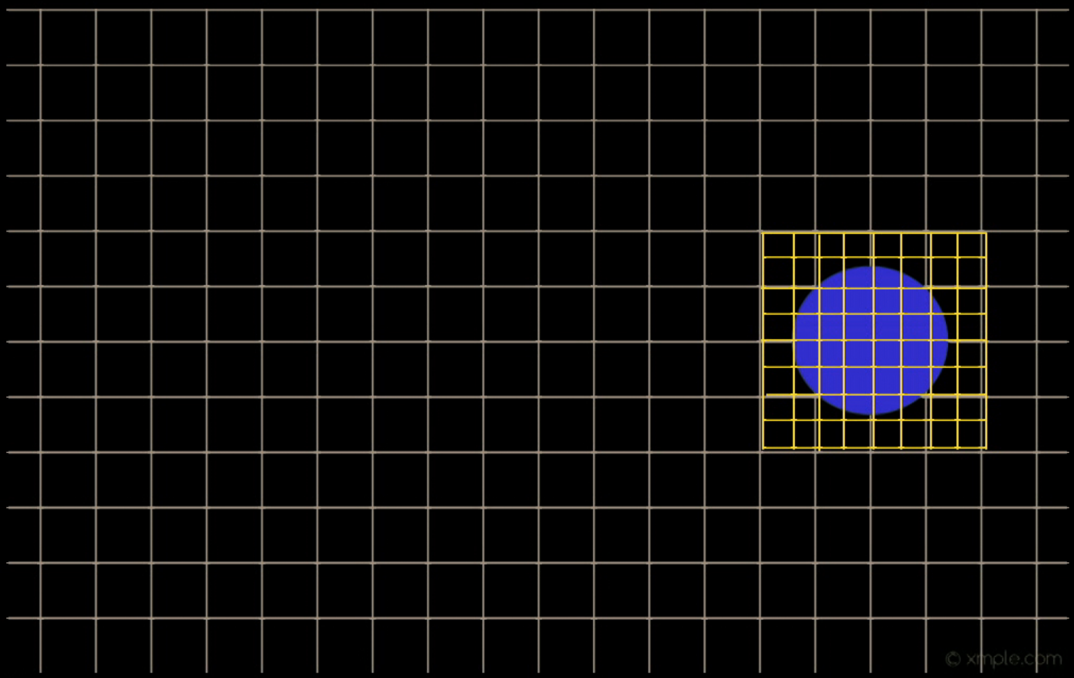


Ingredient 2:
Adaptive Mesh Refinement

Adaptive Mesh Refinement

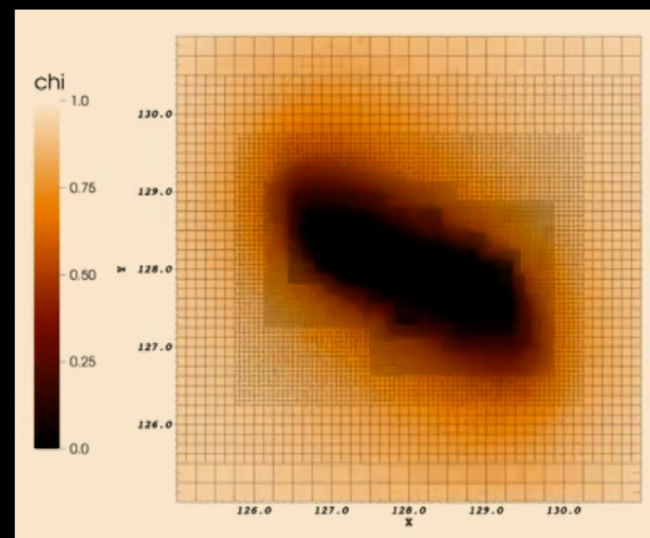


Adaptive Mesh Refinement

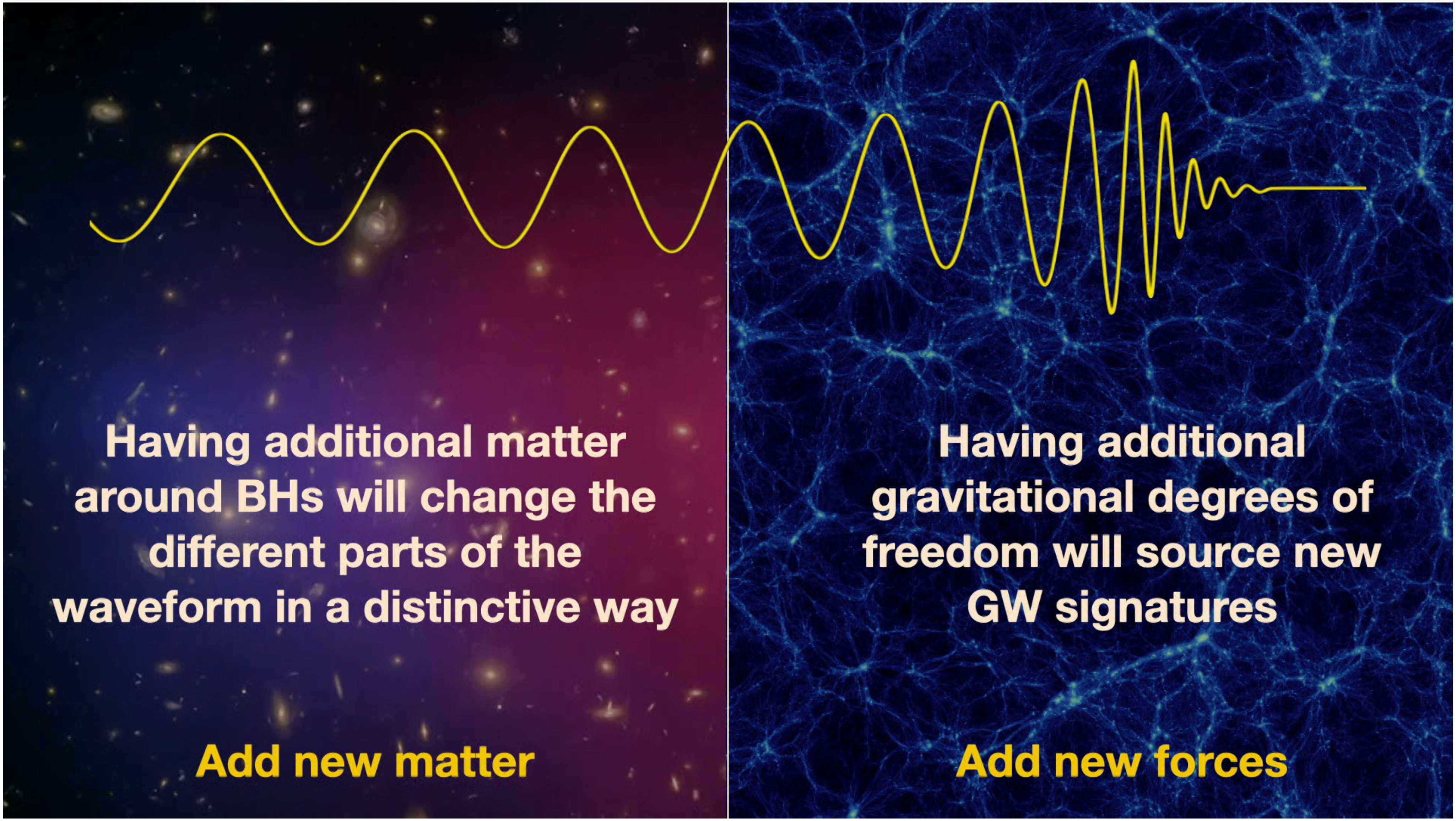


Numerical relativity with Adaptive Mesh Refinement

www.grchombo.org



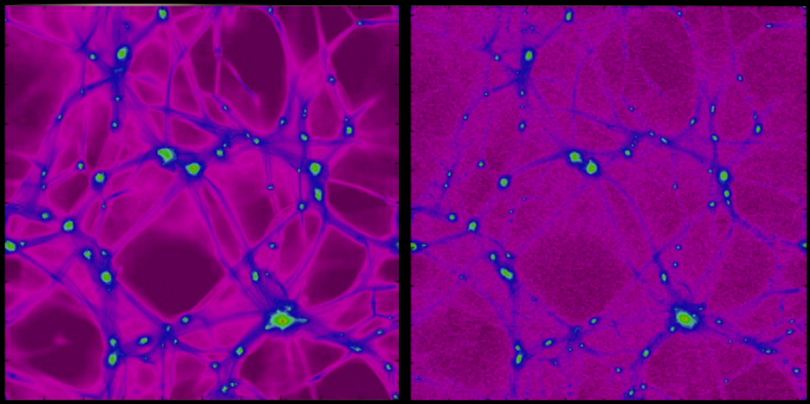
Figueras et al.


Having additional matter around BHs will change the different parts of the waveform in a distinctive way
Add new matter
Having additional gravitational degrees of freedom will source new GW signatures
Add new forces

A vast range of potential DM masses

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

Wave-like DM



Schive et al. 2014

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

Particle DM

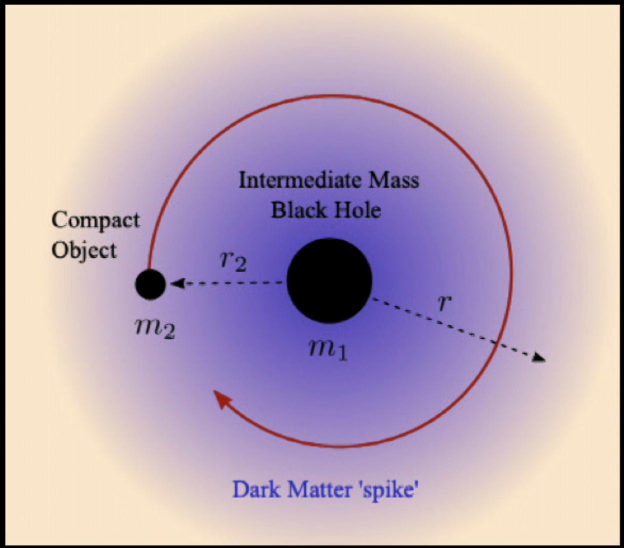
Bad news: average DM density is very low

What DM density enhancement is required to have an observable impact on GW signals?

Do such enhancements arise naturally?


Dark matter overdensity scenarios
Superradiance
Dark matter minispikes (accretion)
Exotic compact objects e.g. boson stars

Particle DM accretion



Kavanagh et al. 2020
Coogan et al. 2022

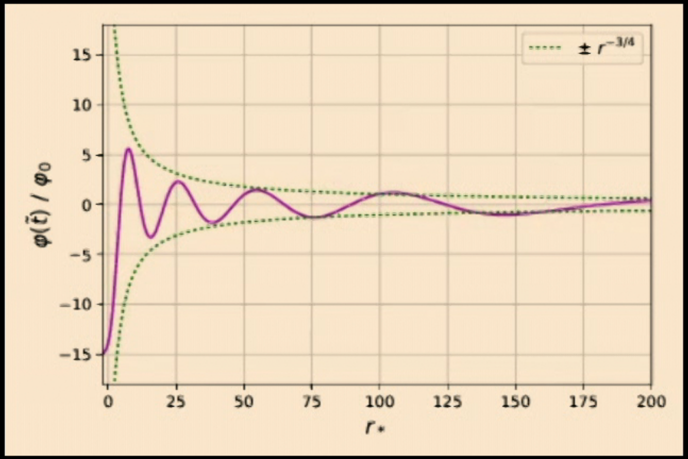
Gondolo & Silk found DM overdensity described by a power law

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

- Dephasing of GW signal mainly due to dynamical friction

Wave DM accretion - scalar accretion

Field profile



Clough et al. 2019
Hui et al. 2019
Bamber et al. 2021

- For small mass μ (sub eV), DM = classical field

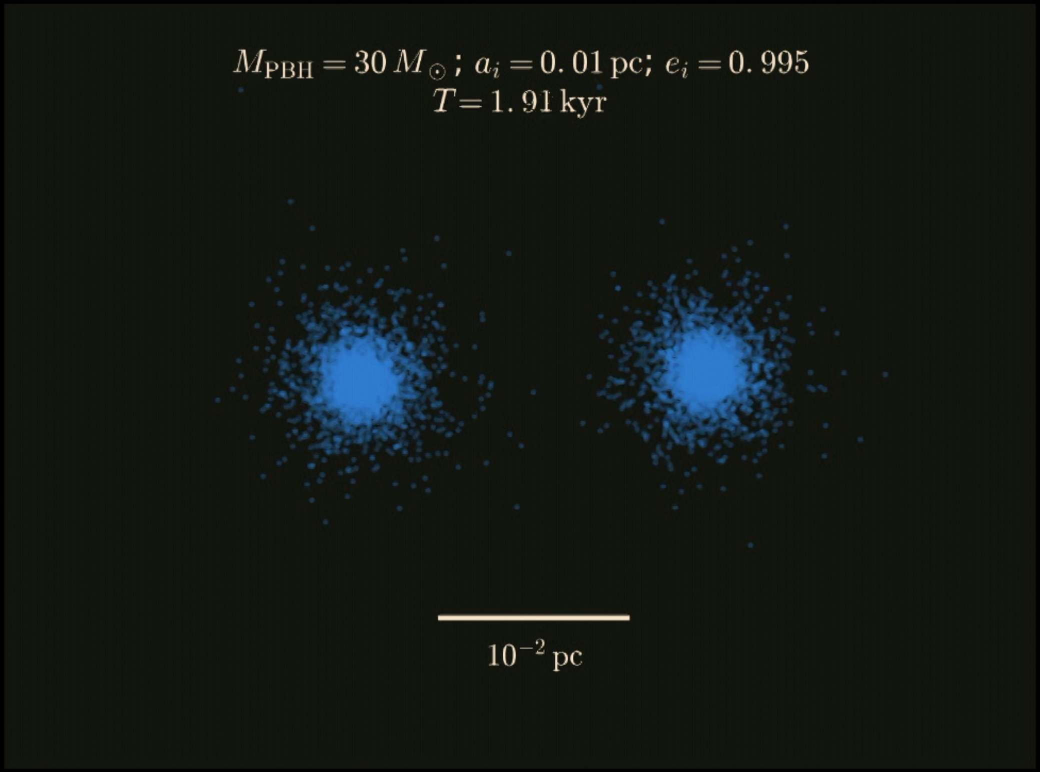
$$[\nabla^\alpha \nabla_\alpha + \mu^2]\phi = 0$$

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

- Dephasing of GW signal due to dynamical friction, accretion…

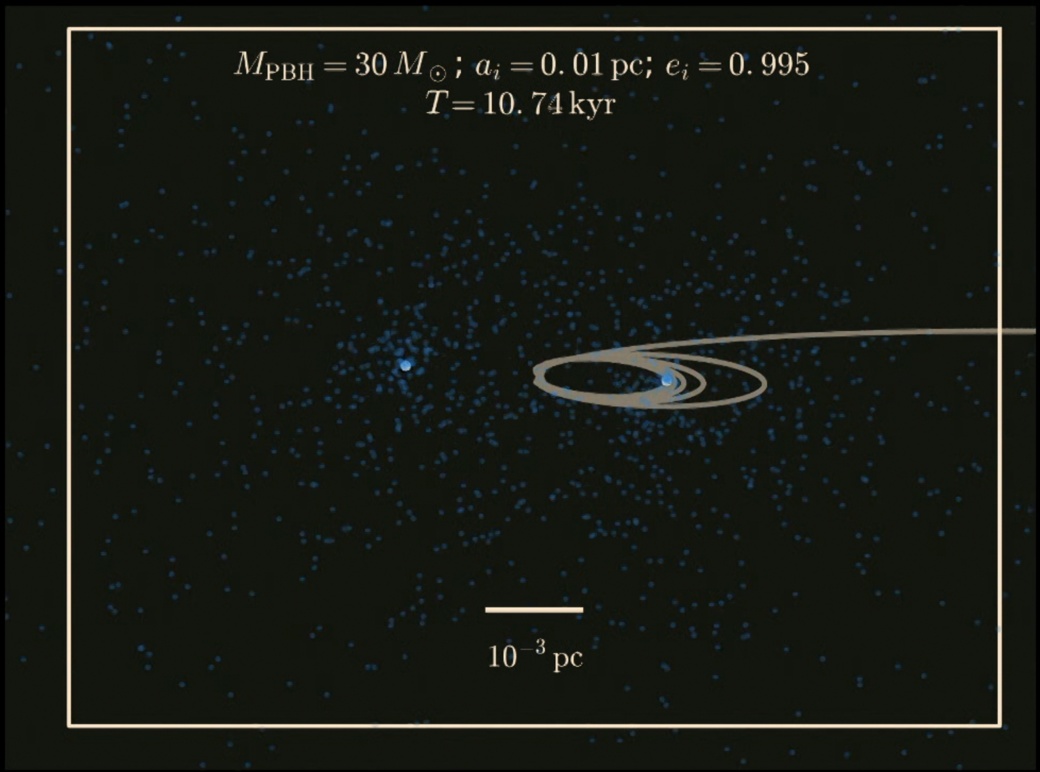
Do such environments persist during the binary inspiral?

Binaries in the particle DM case



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

Binaries in the particle DM case

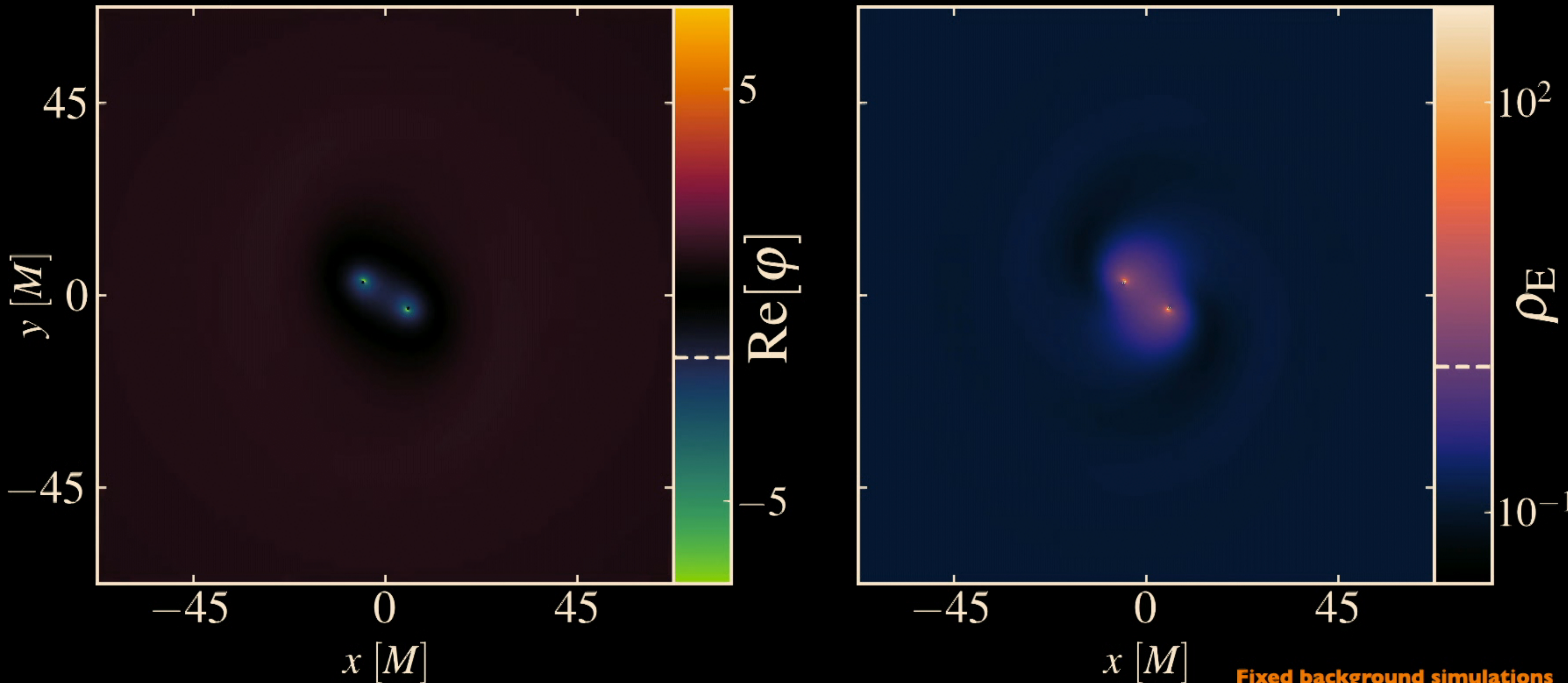


Bertone et al. 2020
Gravitational wave probes of dark matter: challenges and opportunities

Binaries in the wave DM case

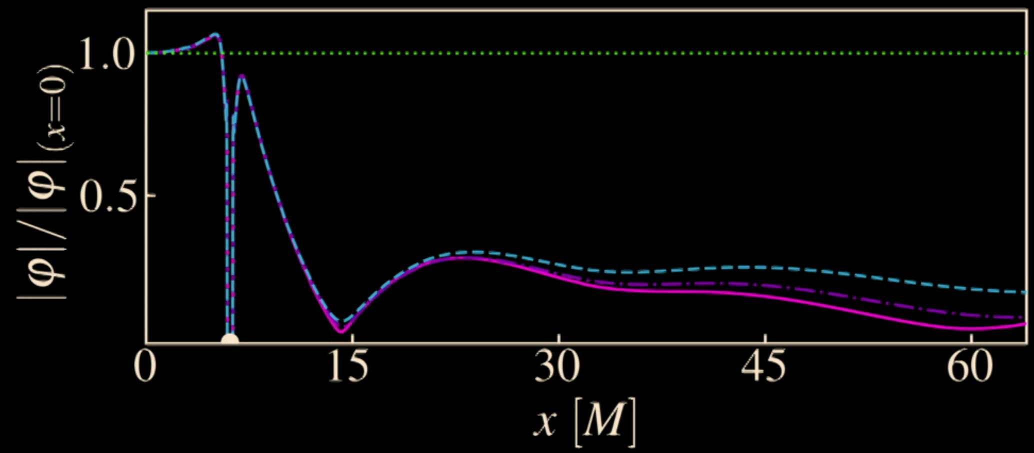
Compton wavelength of the particle is similar to the separation

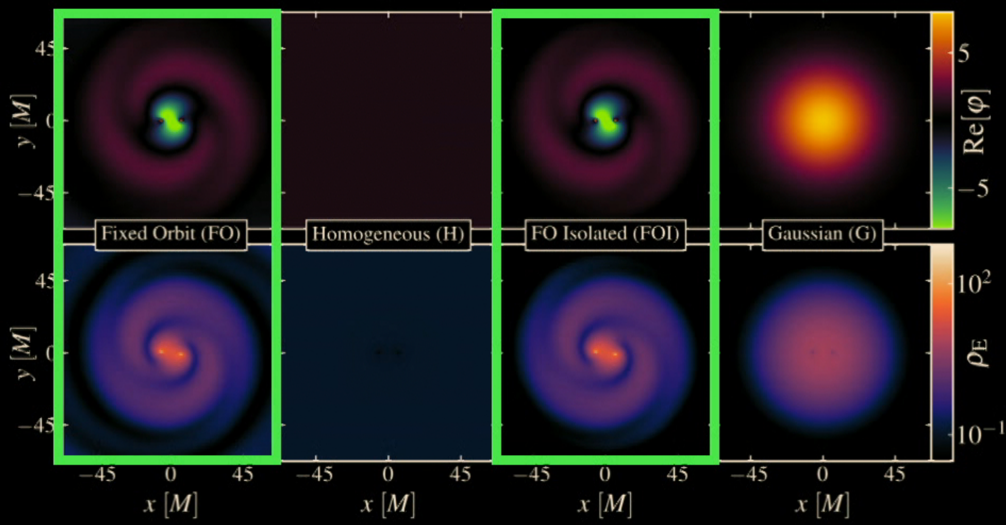
Bamber, Aurrekoetxea, Clough, Ferreira (2022)
Black hole merger simulations in wave dark matter environments



Fixed background simulations

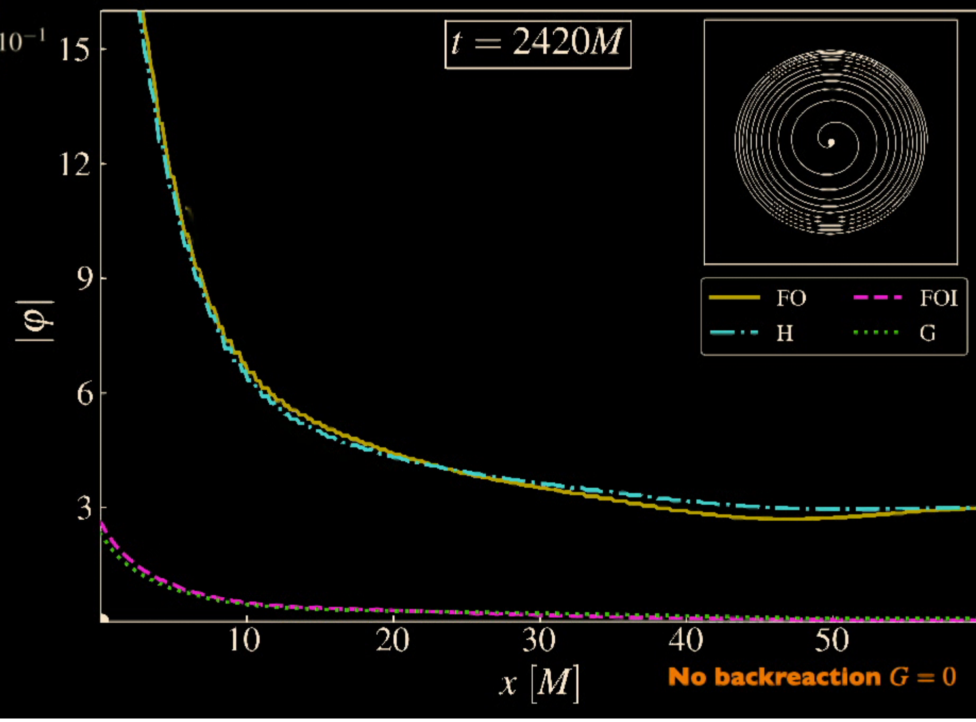
Stationary profile with a scaling symmetry





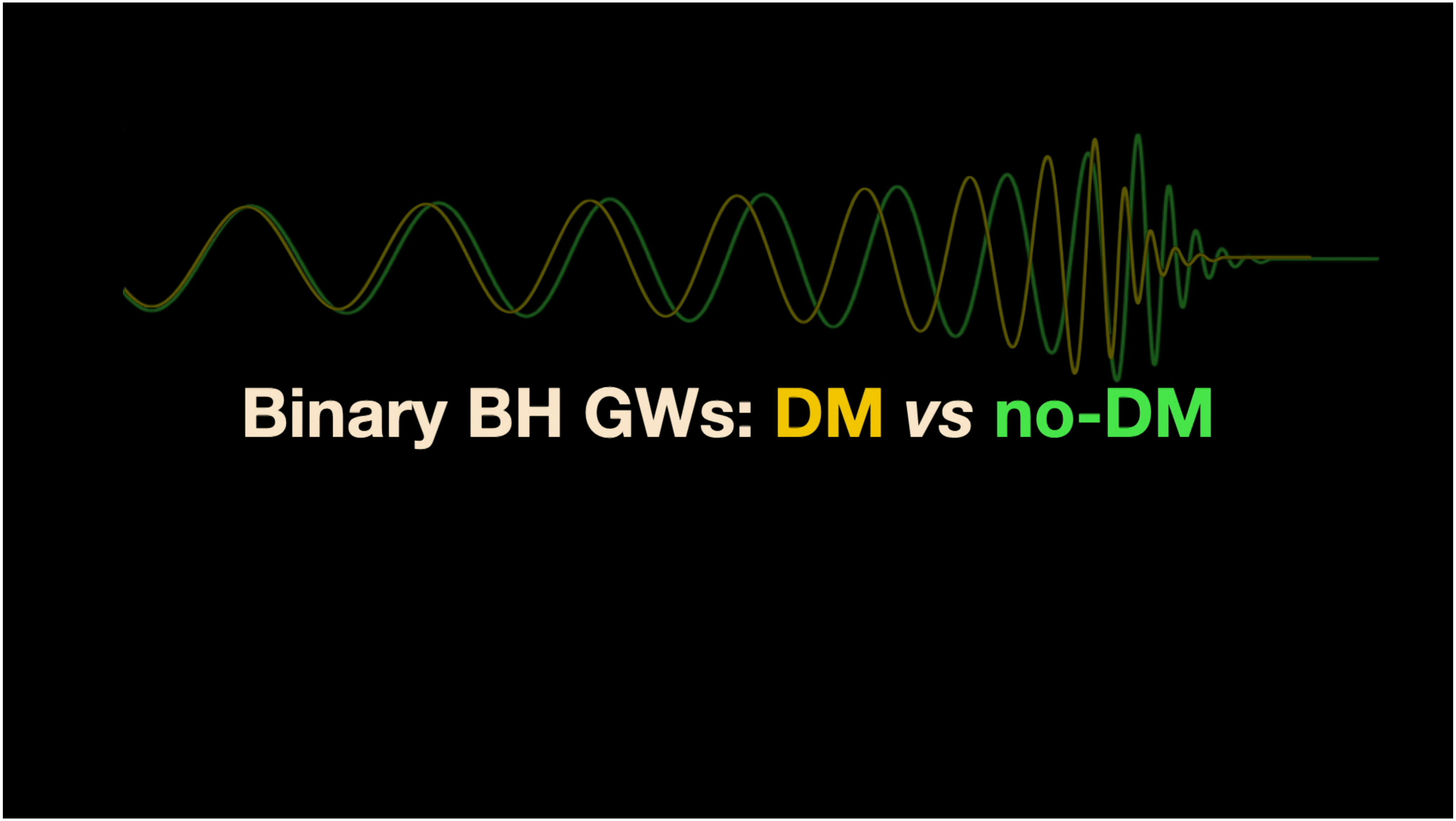
What if starting with different initial conditions?

Yang et al. (2018)
Choudary et al. (2021)
Zhang et al. (2022)



All converge to the same quasi-stationary profile within a few orbits

Transients are important!


Binary BH GWs: DM vs no-DM

What about the comparison of GWs *vs* DM-free BBH?

Need to solve the constraints

Aurrekoetxea, Clough, Lim (2022)
CTTK: A new method to solve the initial data constraints

$$8D^2\psi = -\psi^{-7}\bar{A}_{ij}\bar{A}^{ij} + \frac{2}{3}\psi^5 K^2 - 16\pi\psi^5\rho$$

$$D_j\bar{A}^{ij}_{\mathrm{L}} - \frac{2}{3}\psi^6 D_i K = 8\pi\psi^{10}S^i$$

What about the comparison of GWs *vs* DM-free BBH?

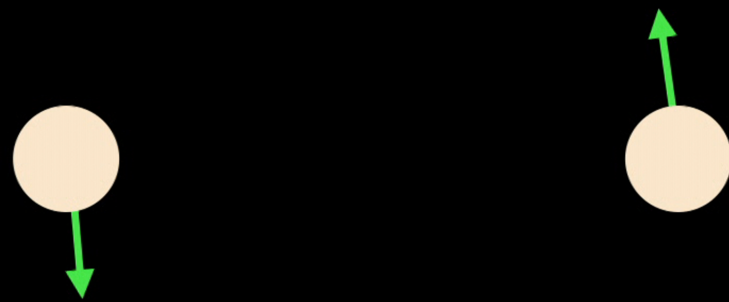
Need to solve the constraints

Aurrekoetxea, Clough, Lim (2022)
CTTK: A new method to solve the initial data constraints

$$K^2 = 24\pi\rho$$

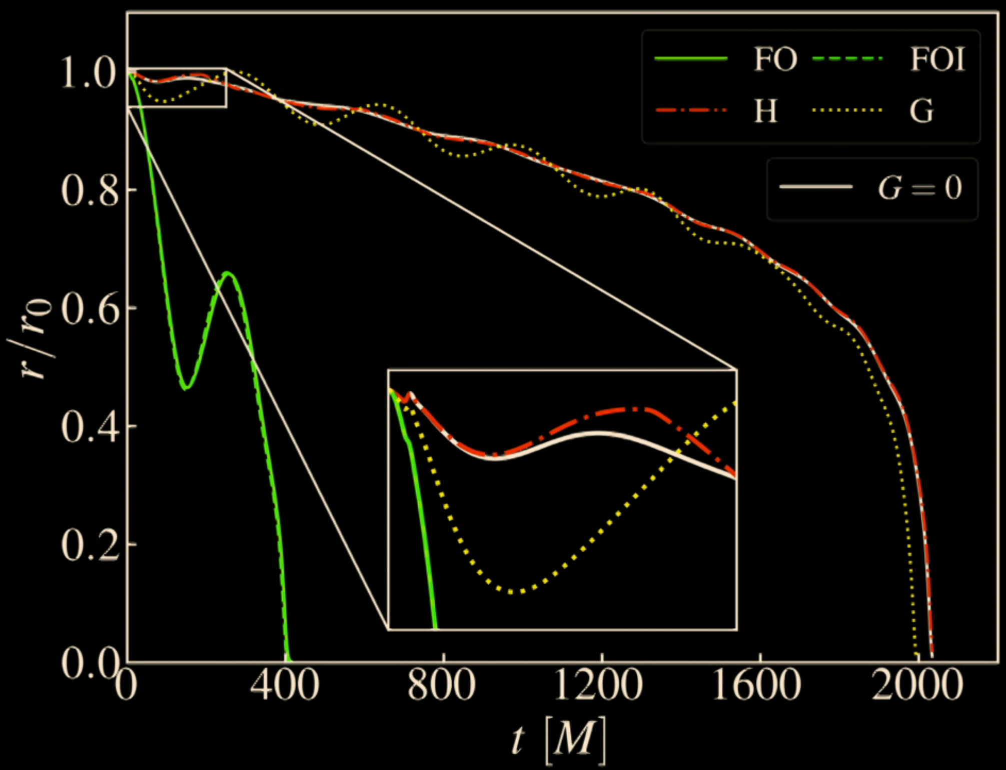
$$8D^2\psi = -\psi^{-7}\bar{A}_{ij}\bar{A}^{ij} + \boxed{\frac{2}{3}\psi^5K^2 - 16\pi\psi^5\rho}$$

$$D_j\bar{A}^{ij}_{\mathrm{L}} - \frac{2}{3}\psi^6 D_i K = 8\pi\psi^{10}S^i$$



DM pushes BHs to highly eccentric orbits

No meaningful comparison yet



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What we have learnt so far

- Persistent and quasi-stationary profile for accretion onto binaries of wave-like DM
- Attractor profile (but transients are important!)
- Further work needed to obtain quasi-circular inspirals

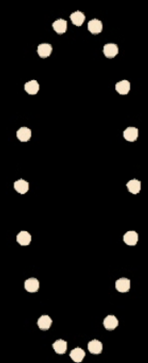
Add new matter

Add new forces

If scalar field non-minimally couples to gravity...

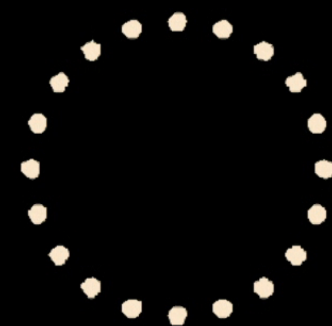
$$S = \int d^4x \sqrt{-g} \left[F(\phi) R + L_{\rm SM} \right]$$

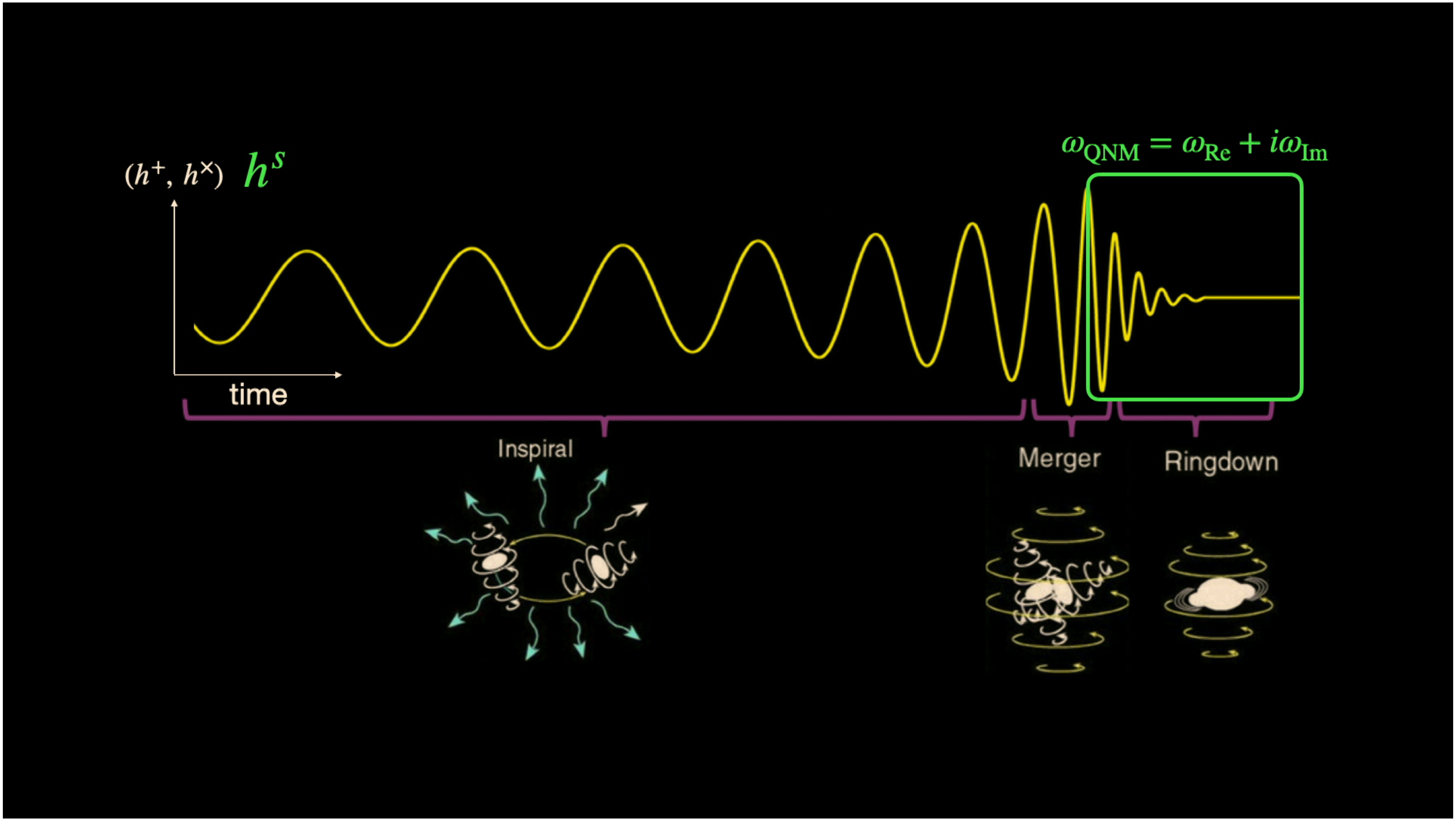
h^+

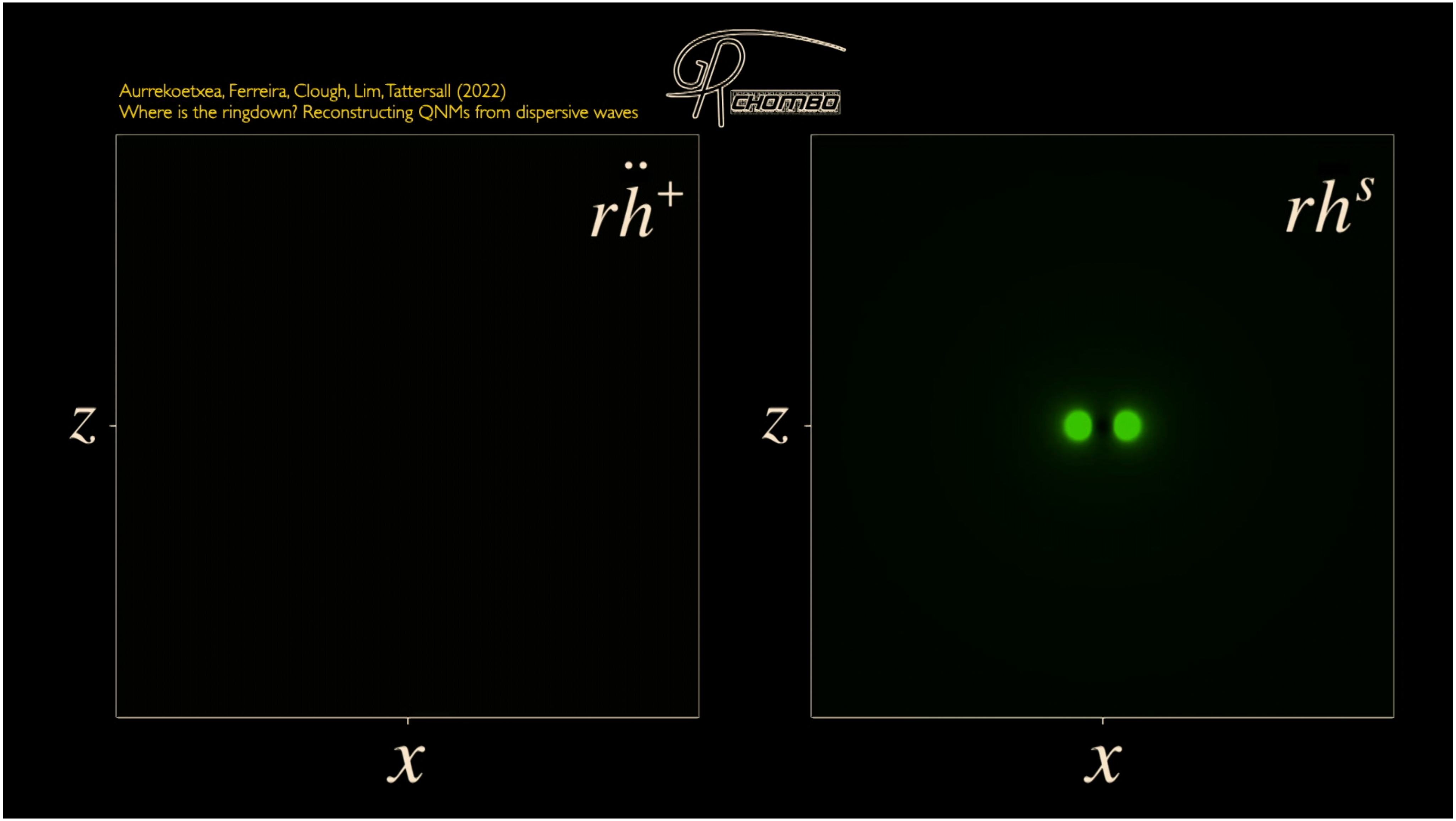


$h^\times$

$h^s \sim \phi$




$\omega_{\text{QNM}} = \omega_{\text{Re}} + i\omega_{\text{Im}}$
$(h^+, h^\times)$ h^s
time
Inspiral
Merger
Ringdown



Aurrekoetxea, Ferreira, Clough, Lim, Tattersall (2022)
Where is the ringdown? Reconstructing QNMs from dispersive waves
GRCHOMBO
$r\ddot{h}^{+}$
rh^{s}
z
x
z
x

Aurrekoetxea, Ferreira, Clough, Lim, Tattersall (2022)
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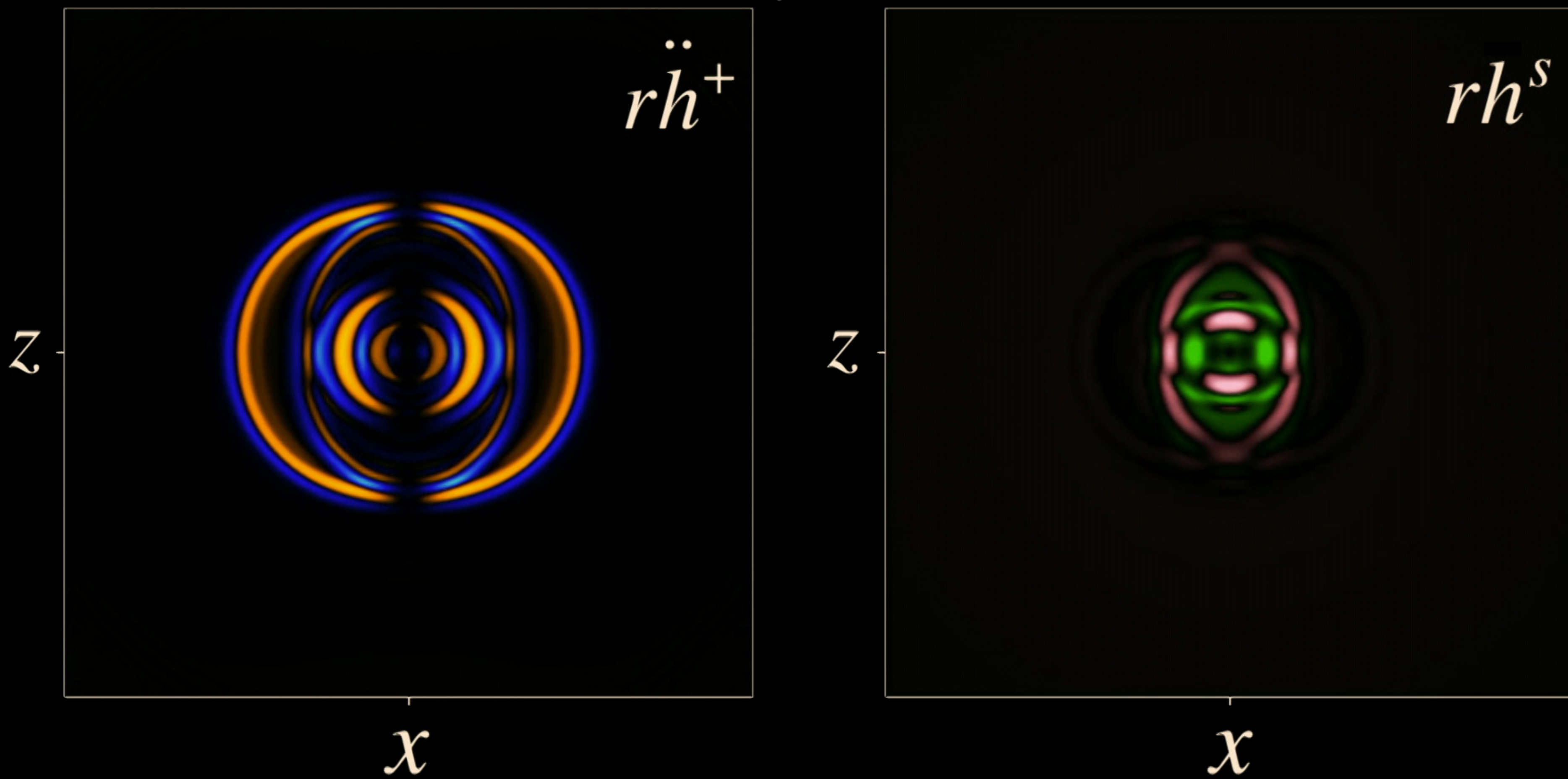

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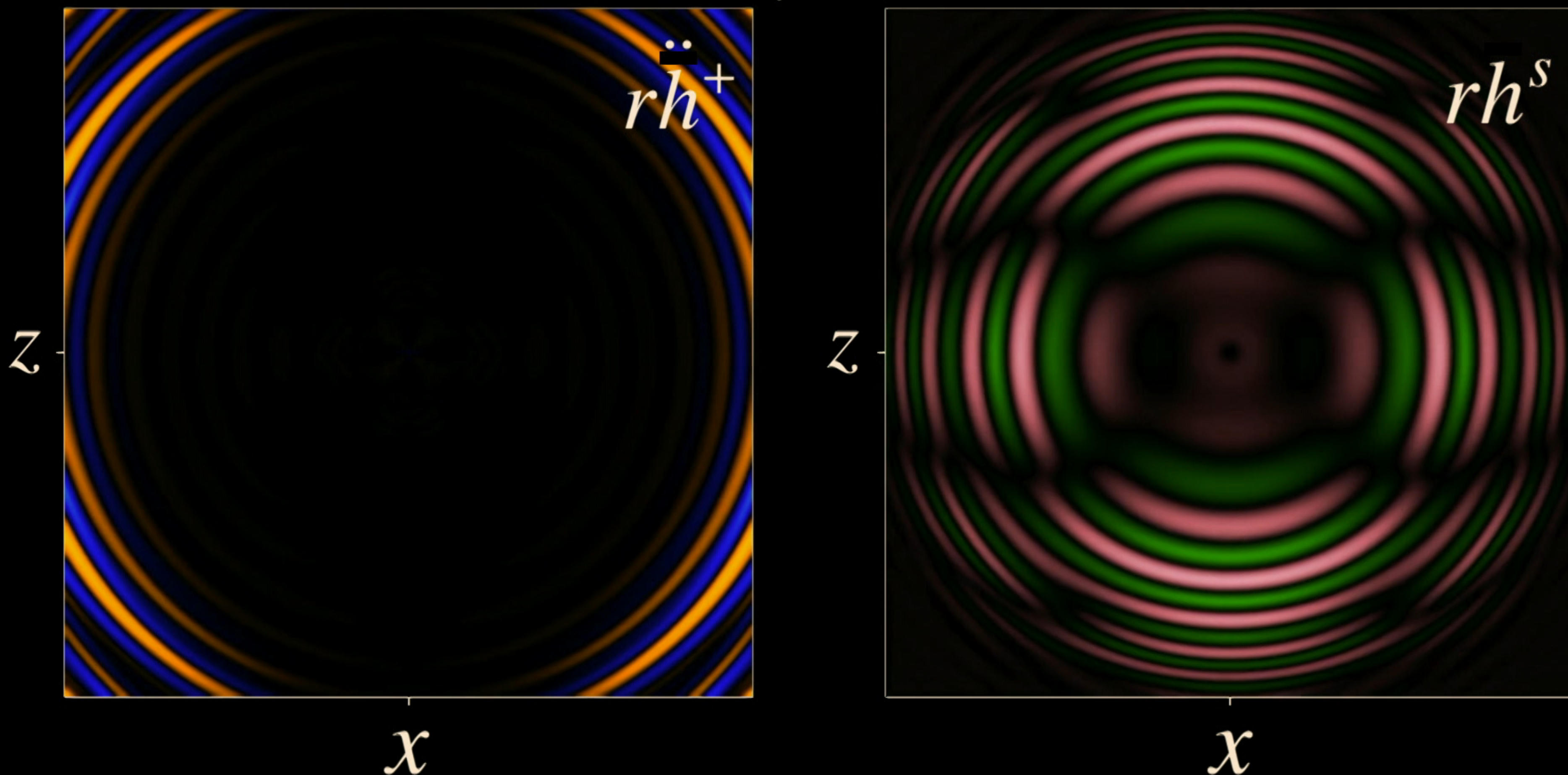
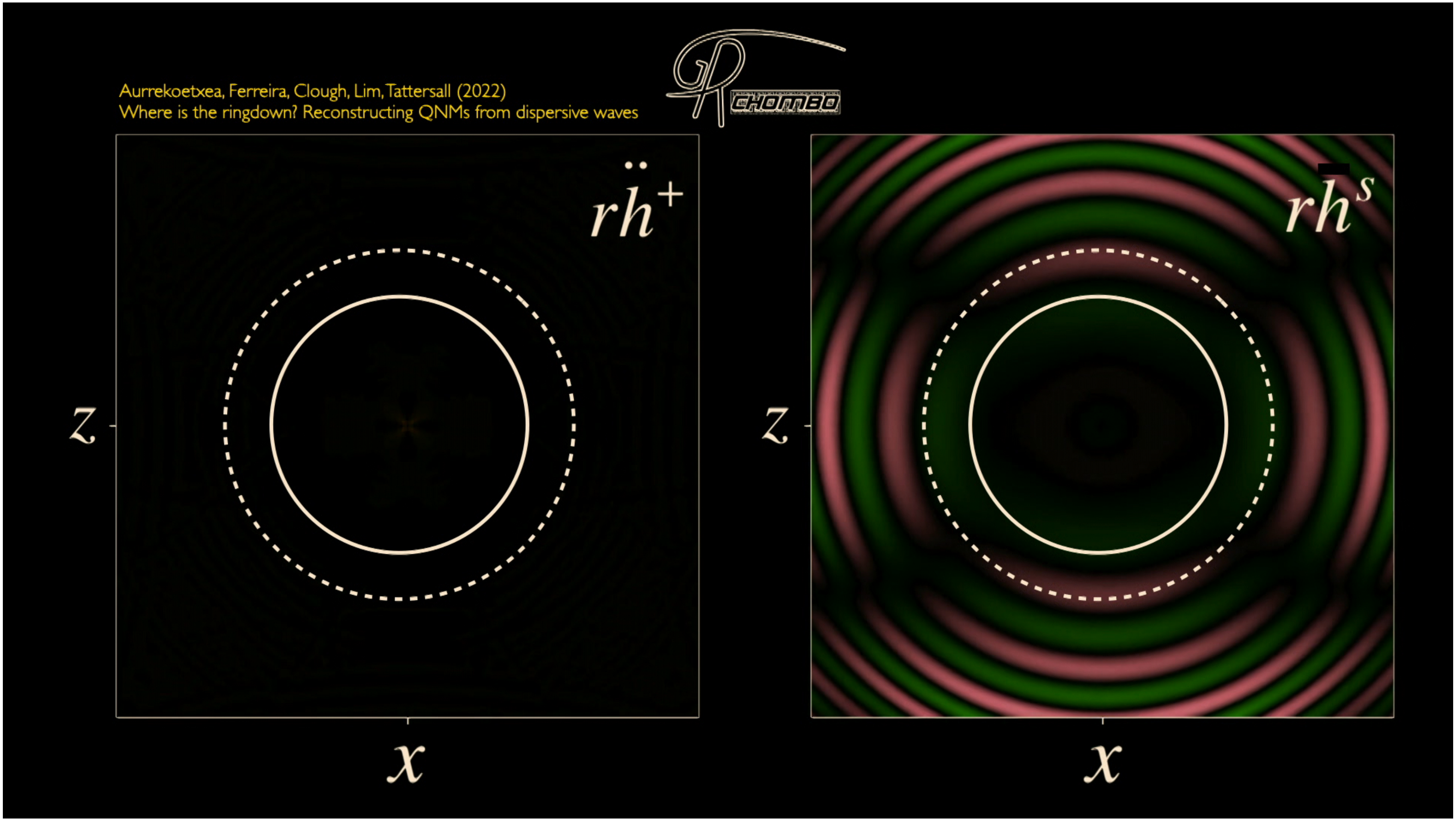
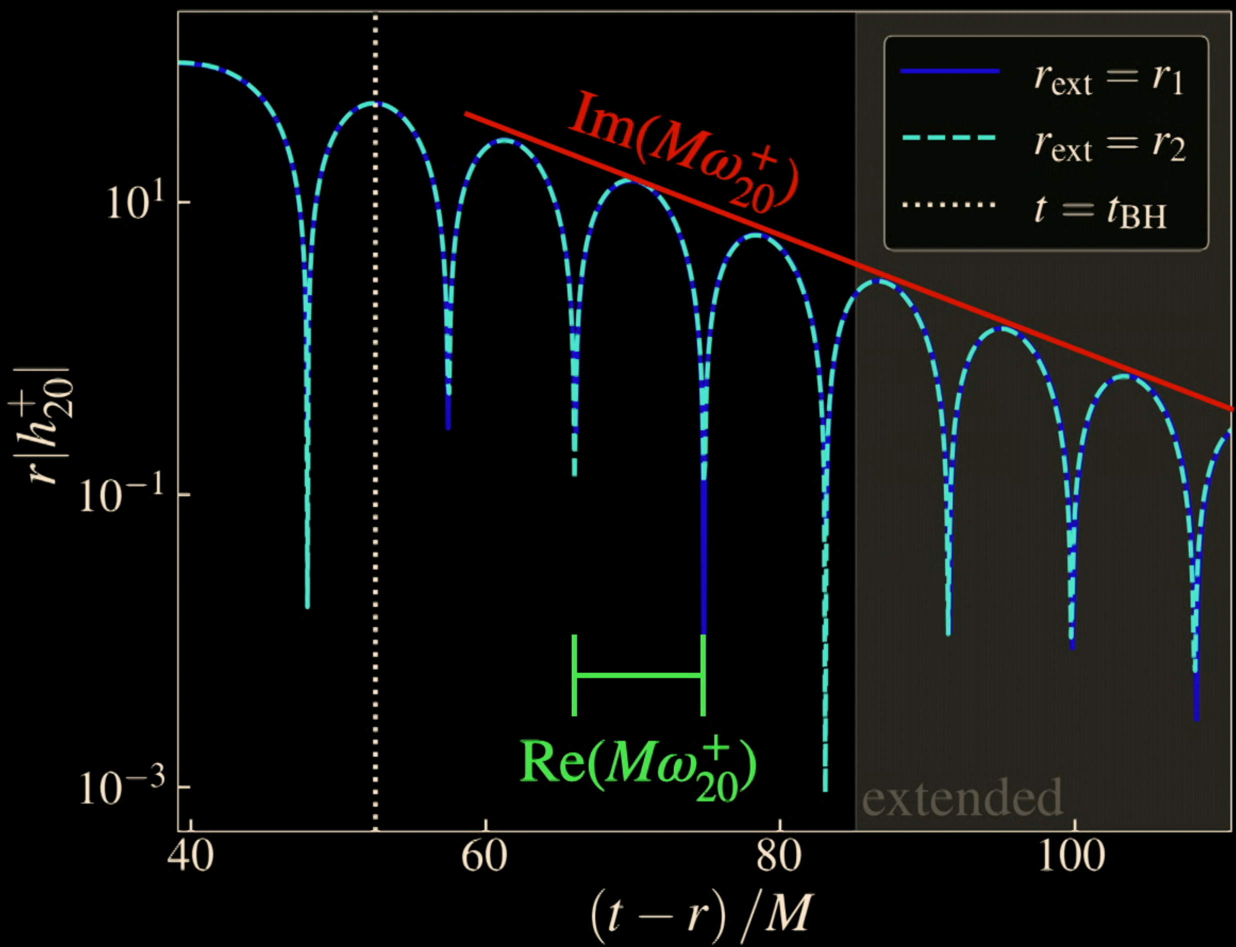



Aurrekoetxea, Ferreira, Clough, Lim, Tattersall (2022)
Where is the ringdown? Reconstructing QNMs from dispersive waves
CHOMBO
$r\ddot{h}^{+}$
z
x
$r\bar{h}^{s}$
z
x

Tensor waveform

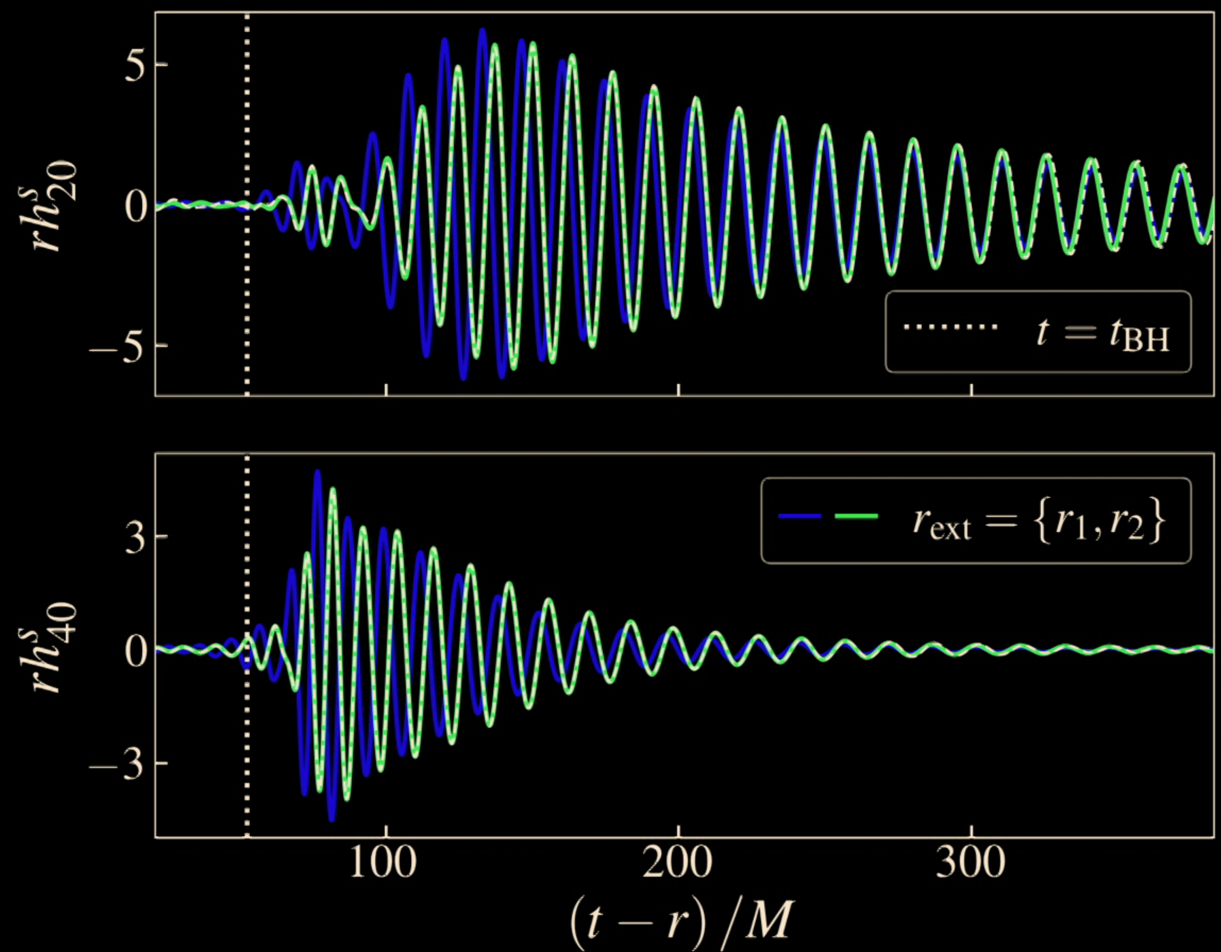


Properties:

- $v = c$
- $1/r$ decay

$$M\omega_{20}^{+} = 0.3735 - i0.0890$$

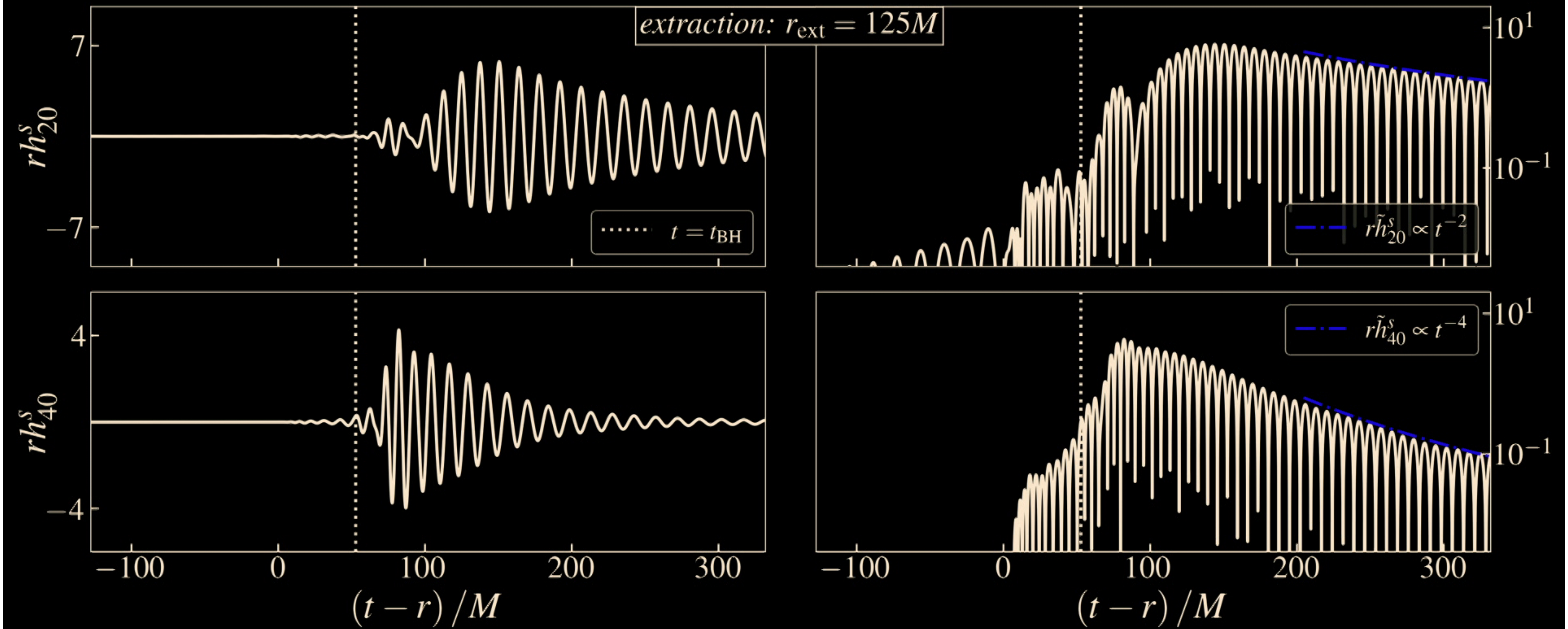
Scalar waveform



Properties:

- $v < c$

Where is the ringdown?



Wave equation in Schwarzschild

$$\left[\partial_t^2 - \partial_{r_*}^2 + V_s(r)\right] r h_l^s = 0$$

$$V_s(r) = \left(1 - \frac{2M}{r}\right)\left(\mu^2 + \frac{l(l+1)}{r^2} + \frac{2M}{r^3}\right)$$

$$r \to \infty$$

$$\left[\partial_t^2 - \partial_r^2 + \mu^2\right] r h_l^s = 0$$

Wave solution

$$rh^s = Ae^{-i(\omega t + k_i x^i)} \longrightarrow \omega^2 = k^2 + \mu^2$$

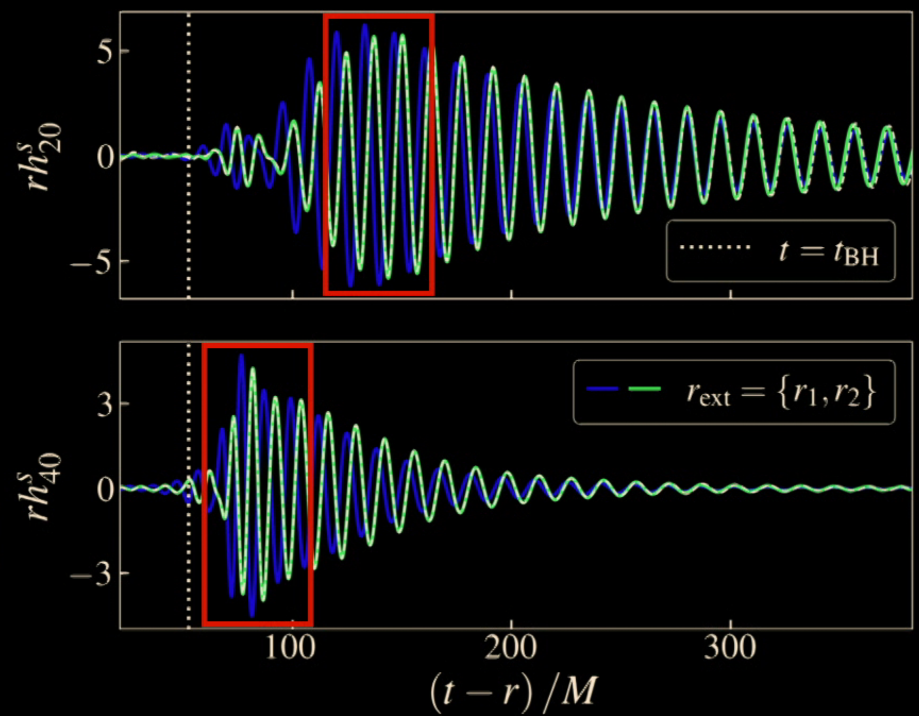
$$k = \pm\sqrt{\omega^2 - \mu^2}$$

$\omega^2 < \mu^2$ $\omega^2 > \mu^2$

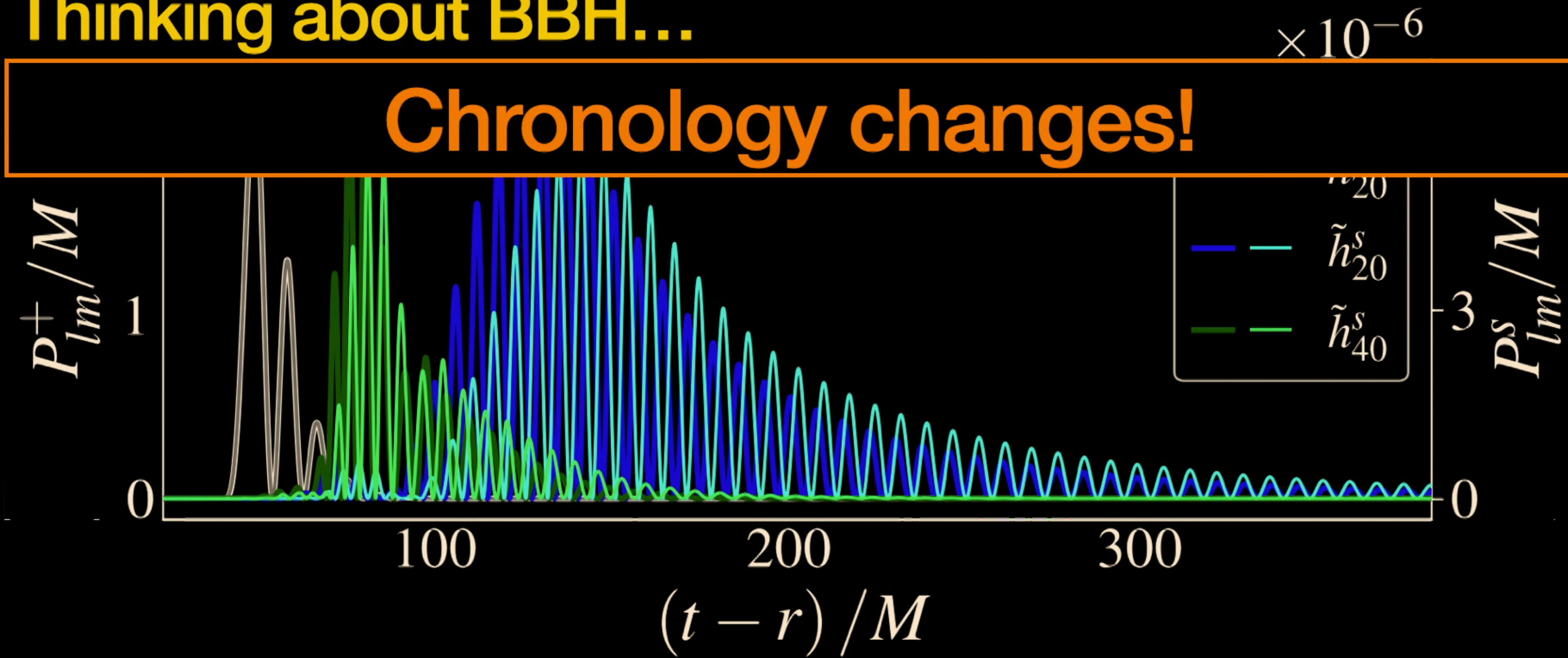
$rh^s \propto e^{-\mu r}$ Yukawa suppression

$$v_g \equiv \frac{\partial \omega}{\partial k} = \sqrt{1 - \frac{\mu^2}{\omega^2}}$$

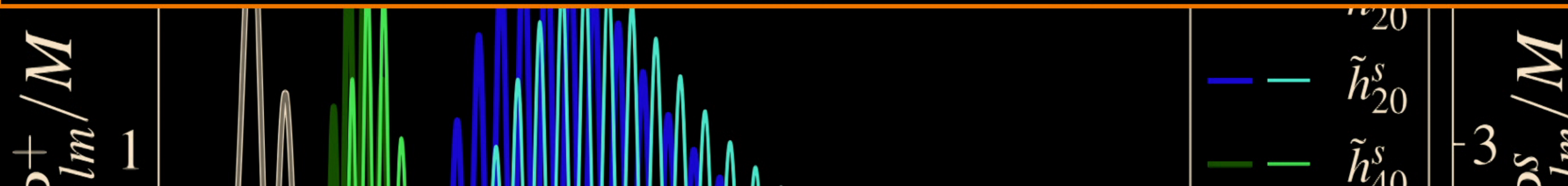
Different frequencies propagate at different speeds!



Thinking about BBH…



Thinking about BBH…



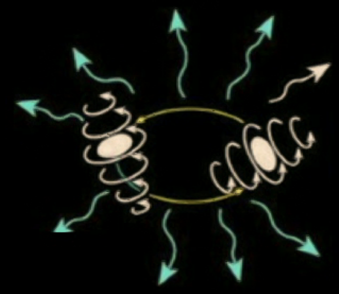
Chronology changes!

GWs at emission

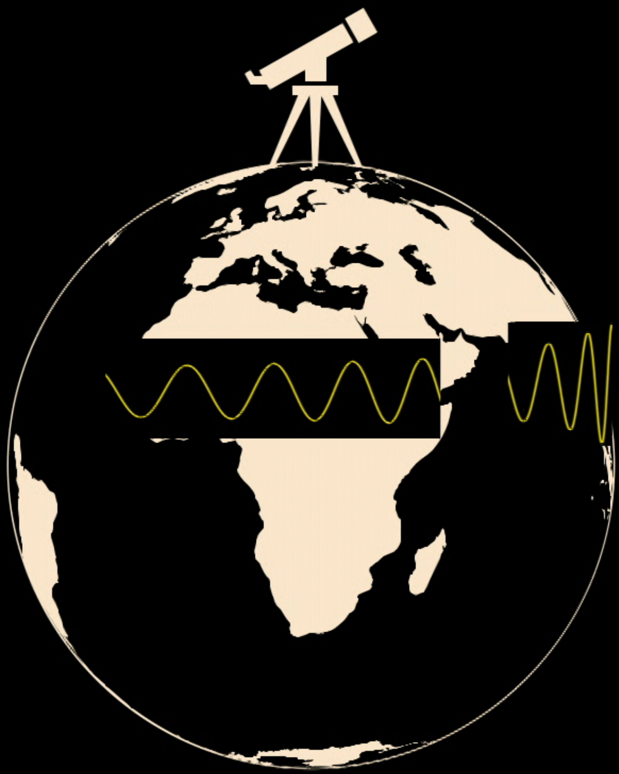
$\neq$

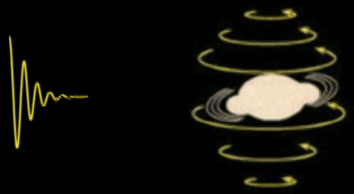
GWs at detection

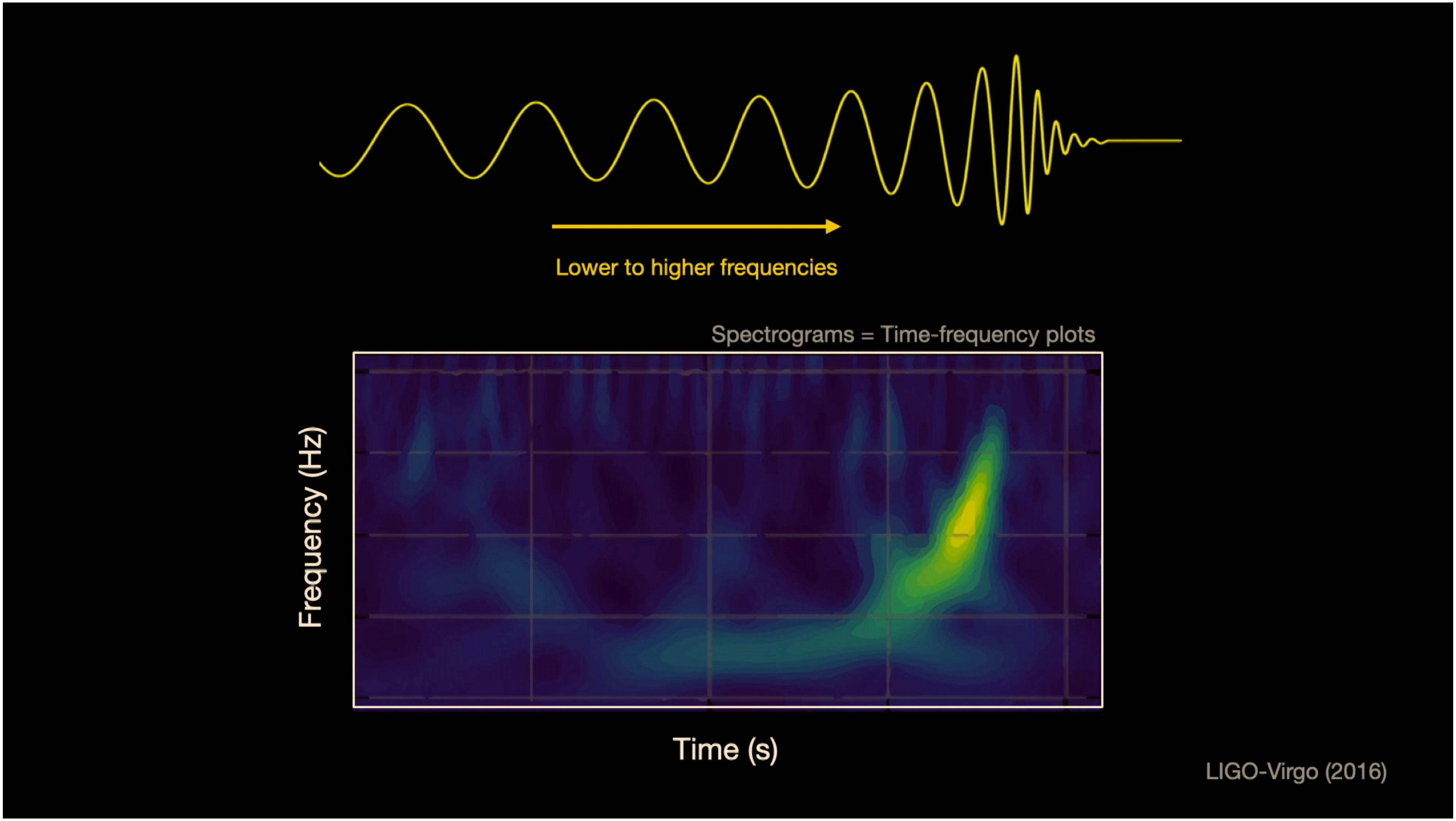
Massless waveforms



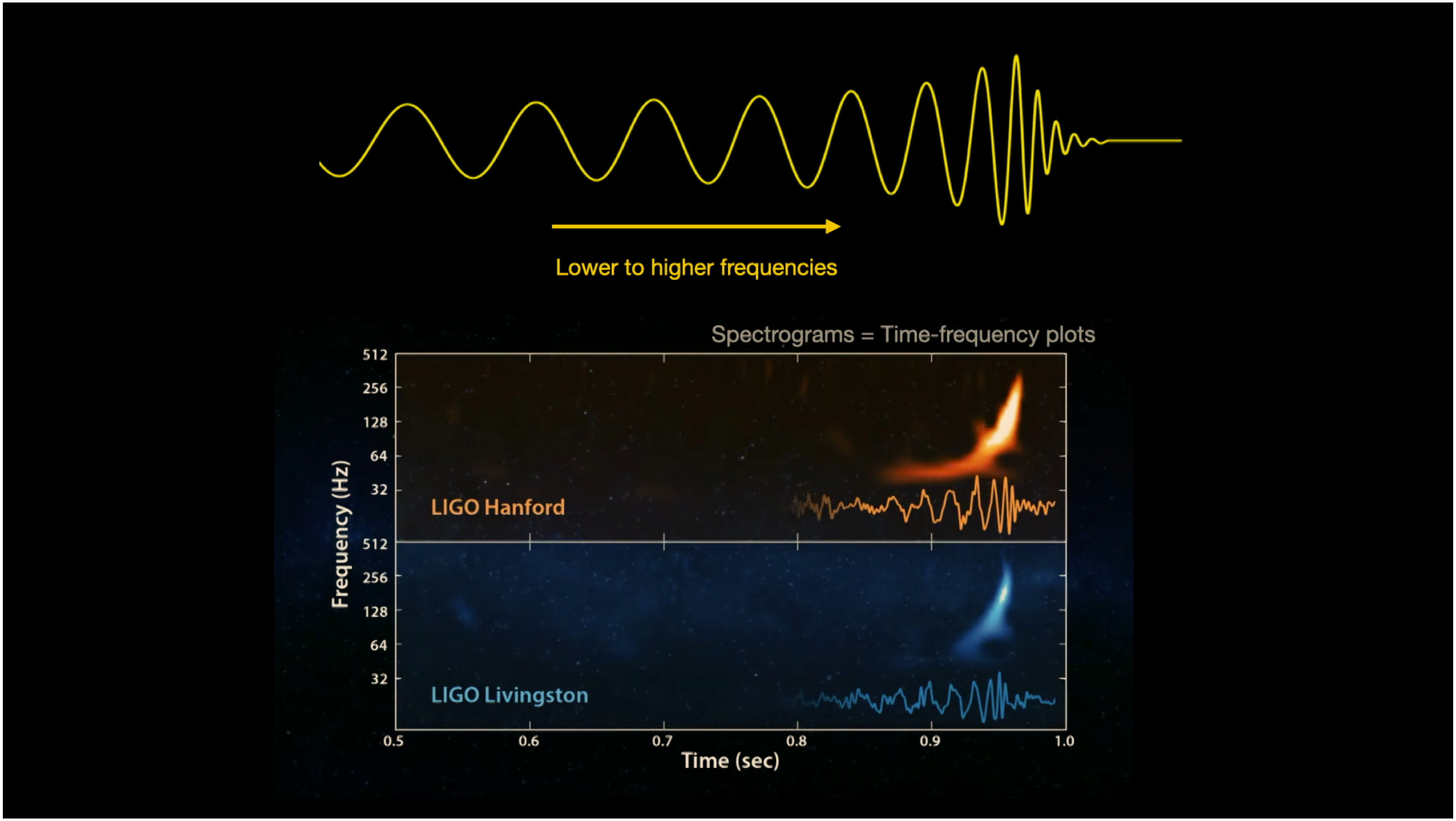
Massless waveforms





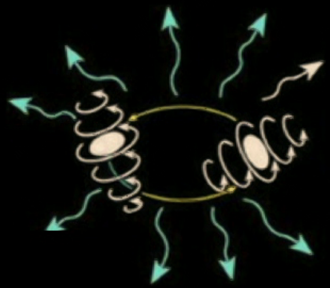


Lower to higher frequencies
Spectrograms = Time-frequency plots
Frequency (Hz)
Time (s)
LIGO-Virgo (2016)

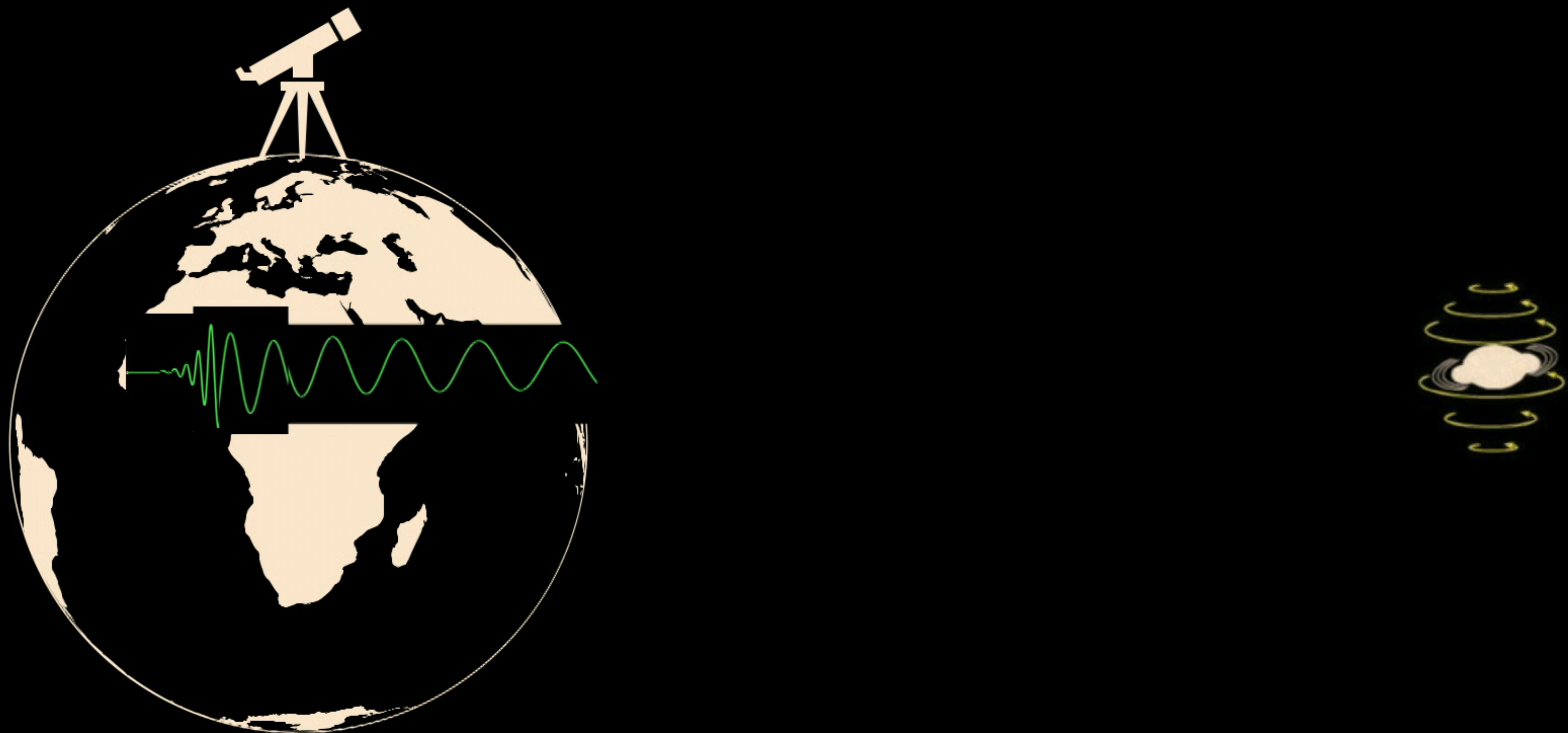


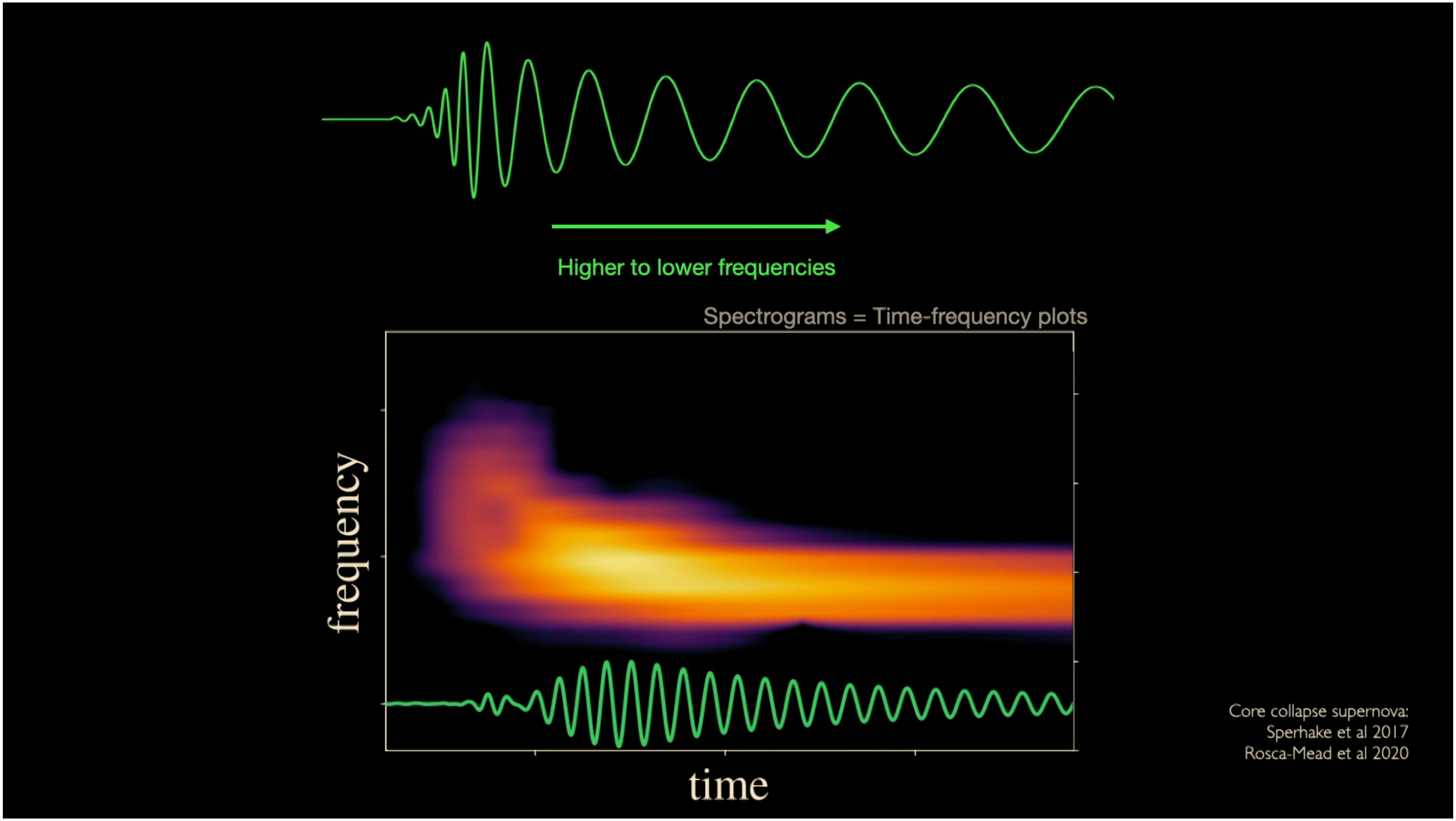
Lower to higher frequencies
Spectrograms = Time-frequency plots
Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

Massive waveforms

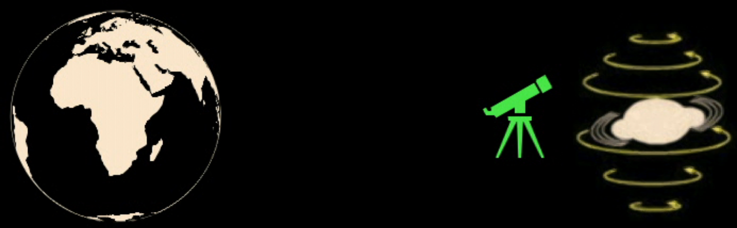


Massive waveforms



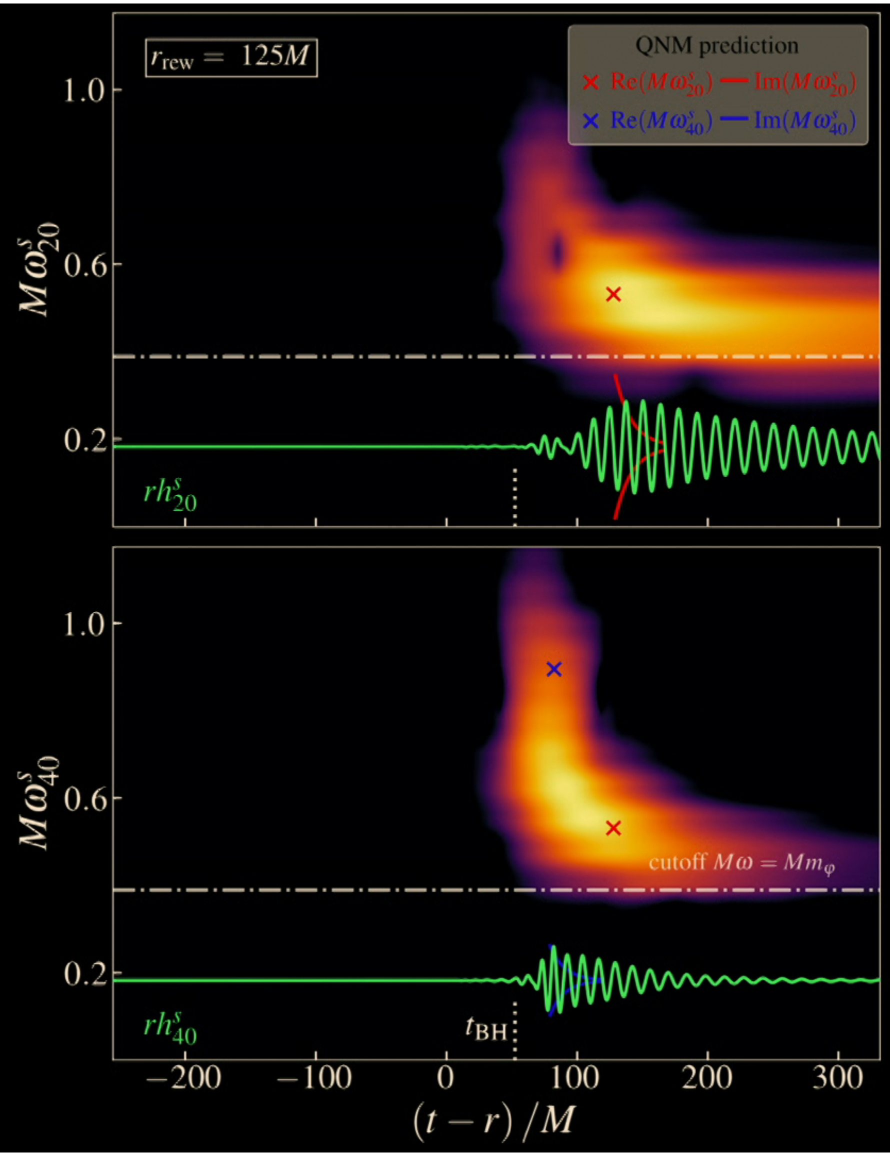

Higher to lower frequencies
Spectrograms = Time-frequency plots
frequency
time
Core collapse supernova:
Sperhake et al 2017
Rosca-Mead et al 2020

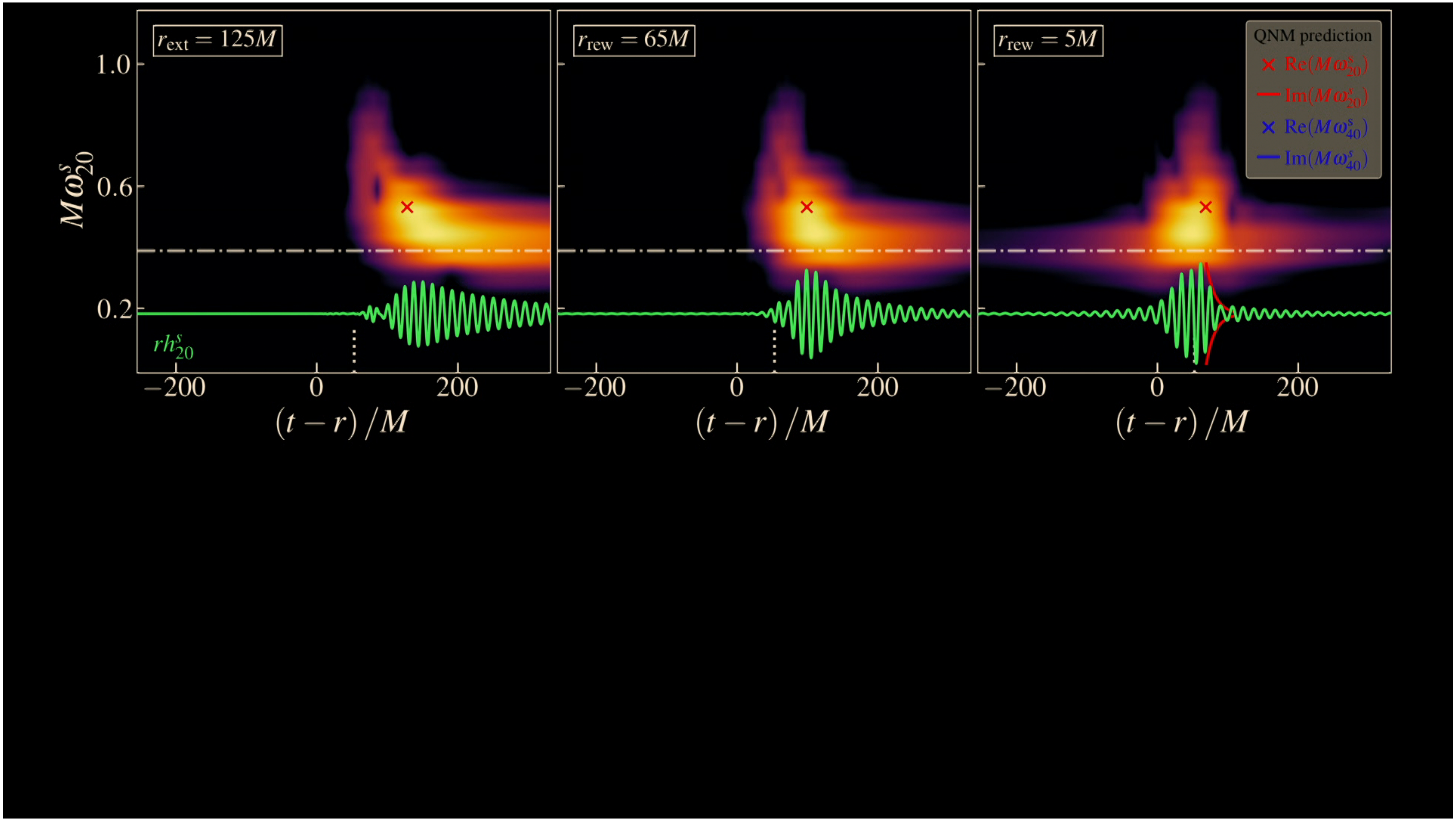
Can we recover the ringdown of h^s?



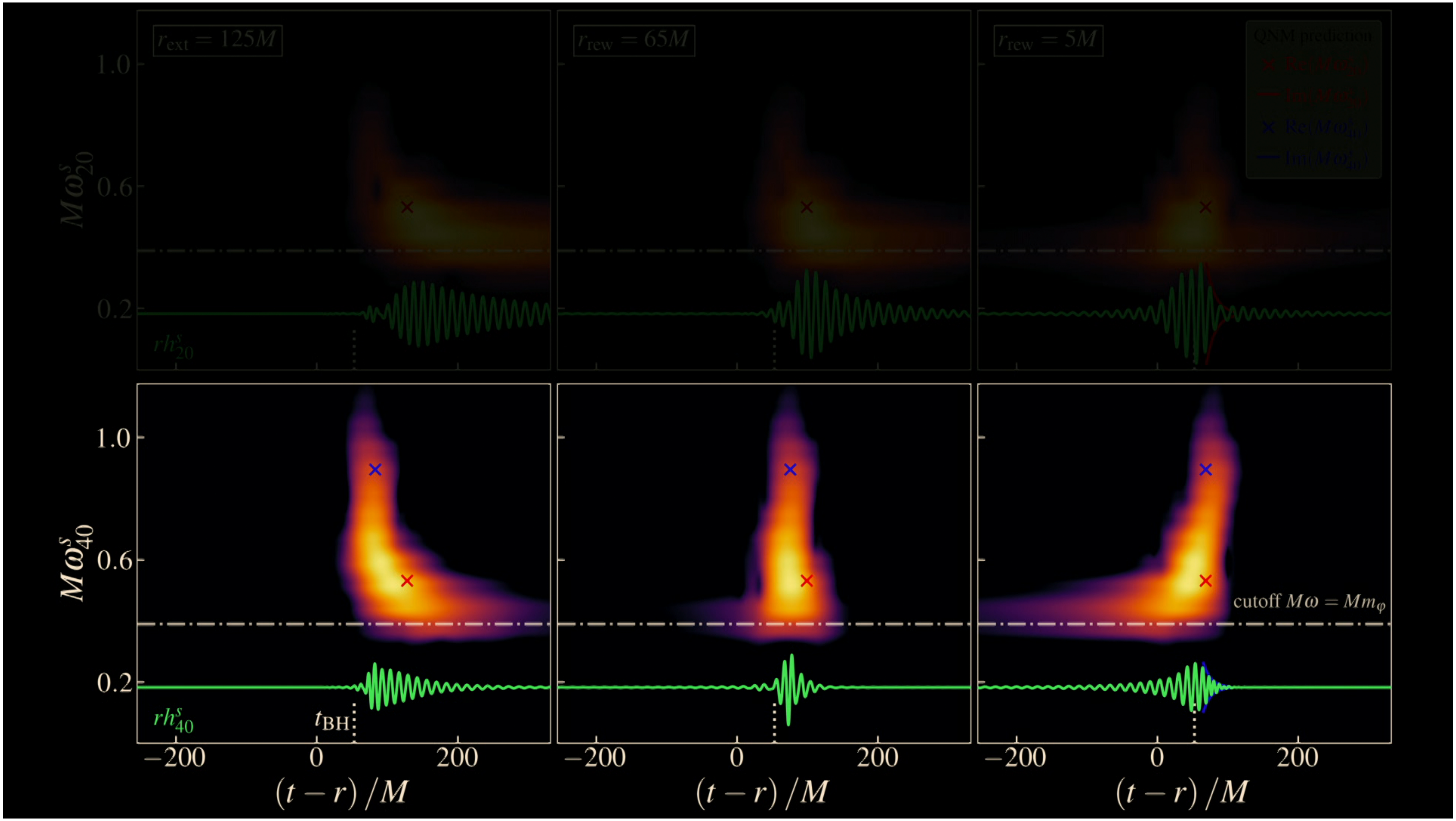
Evolve waveform backwards — *rewind*

$$\left[\partial_t^2 - \partial_r^2 + \mu_{\text{eff}}^2\right] rh^s = 0$$

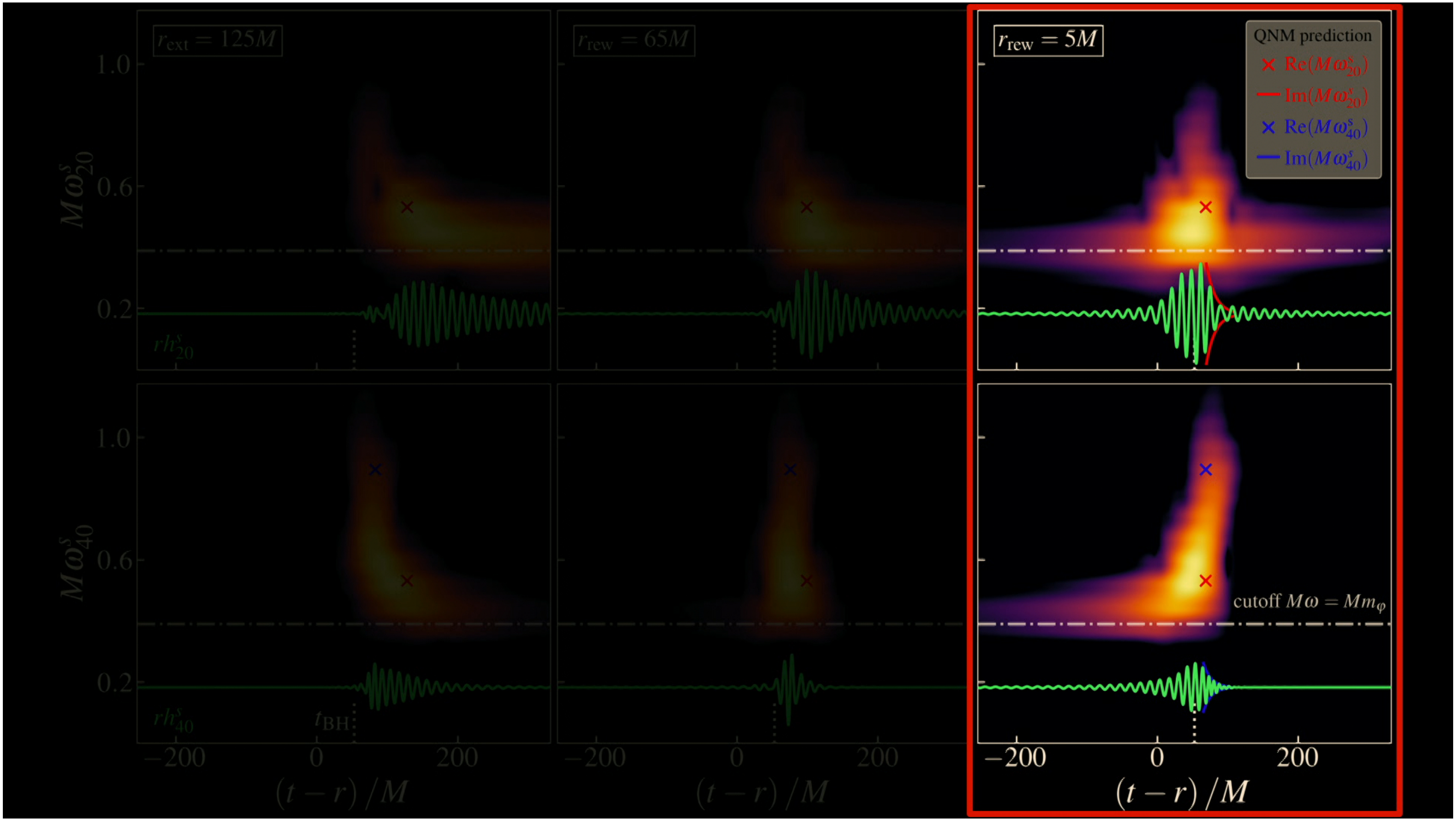




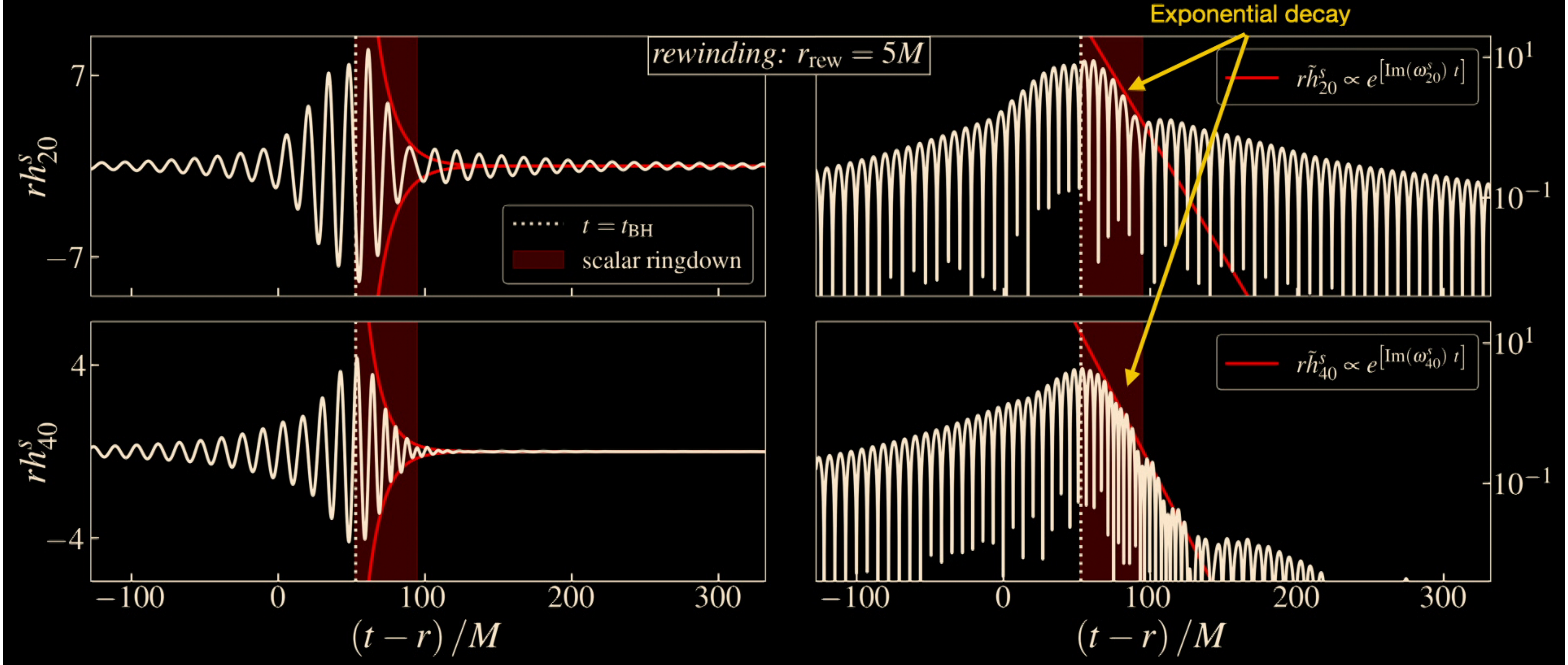
$r_{\rm ext} = 125M$
$r_{\rm rew} = 65M$
$r_{\rm rew} = 5M$
$M\omega^s_{20}$
1.0
0.6
0.2
rh^s_{20}
−200
0
200
$(t-r)/M$
QNM prediction
$\mathrm{Re}(M\omega^s_{20})$
$\mathrm{Im}(M\omega^s_{20})$
$\mathrm{Re}(M\omega^s_{40})$
$\mathrm{Im}(M\omega^s_{40})$



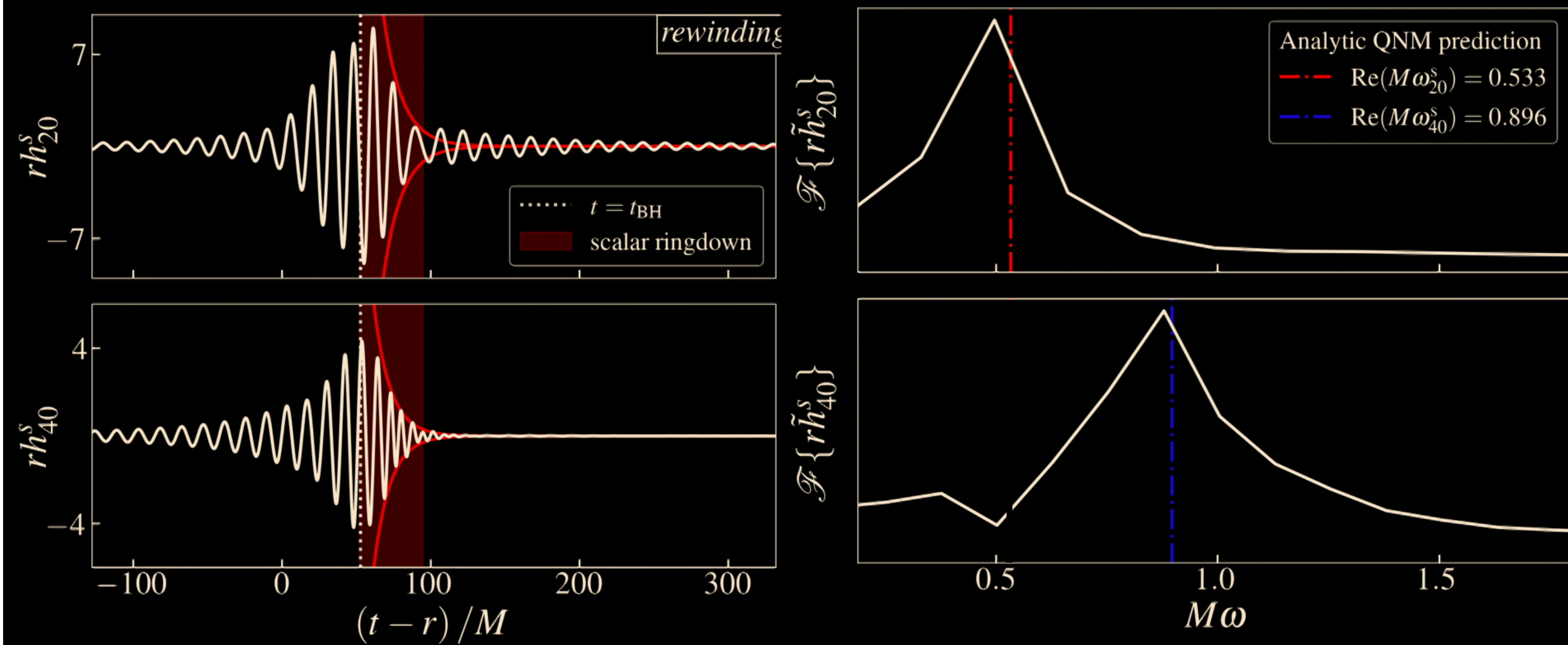
$r_{ext} = 125M$
$r_{rew} = 65M$
$r_{rew} = 5M$
QNM prediction
$M\omega_{20}^s$
rh_{20}^s
$M\omega_{40}^s$
rh_{40}^s
t_{BH}
cutoff $M\omega = Mm_\varphi$
1.0
0.6
0.2
−200
0
200
$(t-r)/M$

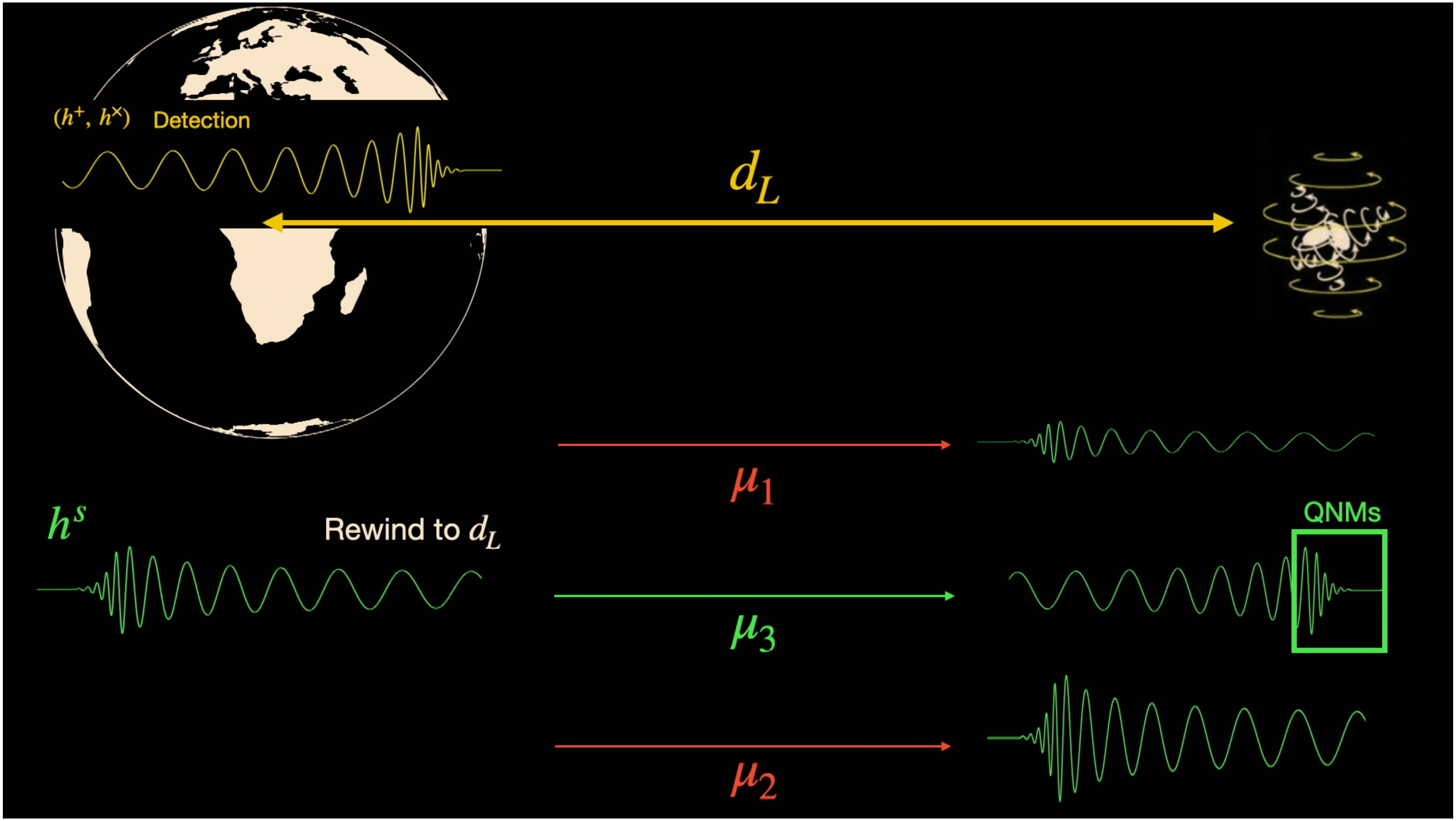

$r_{ext} = 125M$
$r_{rew} = 65M$
$r_{rew} = 5M$
QNM prediction
$\times$ Re$(M\omega^s_{20})$
Im$(M\omega^s_{20})$
$\times$ Re$(M\omega^s_{40})$
Im$(M\omega^s_{40})$
$M\omega^s_{20}$
$M\omega^s_{40}$
1.0
0.6
0.2
rh^s_{20}
rh^s_{40}
t_{BH}
cutoff $M\omega = Mm_\varphi$
−200
0
200
$(t-r)/M$

Here is the ringdown



Here is the ringdown




$(h^+, h^\times)$ Detection
d_L
μ_1
h^s
Rewind to d_L
QNMs
μ_3
μ_2

Summary

- Persistent and quasi-stationary profile for accretion onto binaries of wave-like DM
- Attractor profile (but transients are important!)
- Further work needed to obtain quasi-circular inspirals
- Additional scalar GWs, which if massive, chronology is mixed.
- Standard waveforms might not capture these signals in match-filtering searches

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