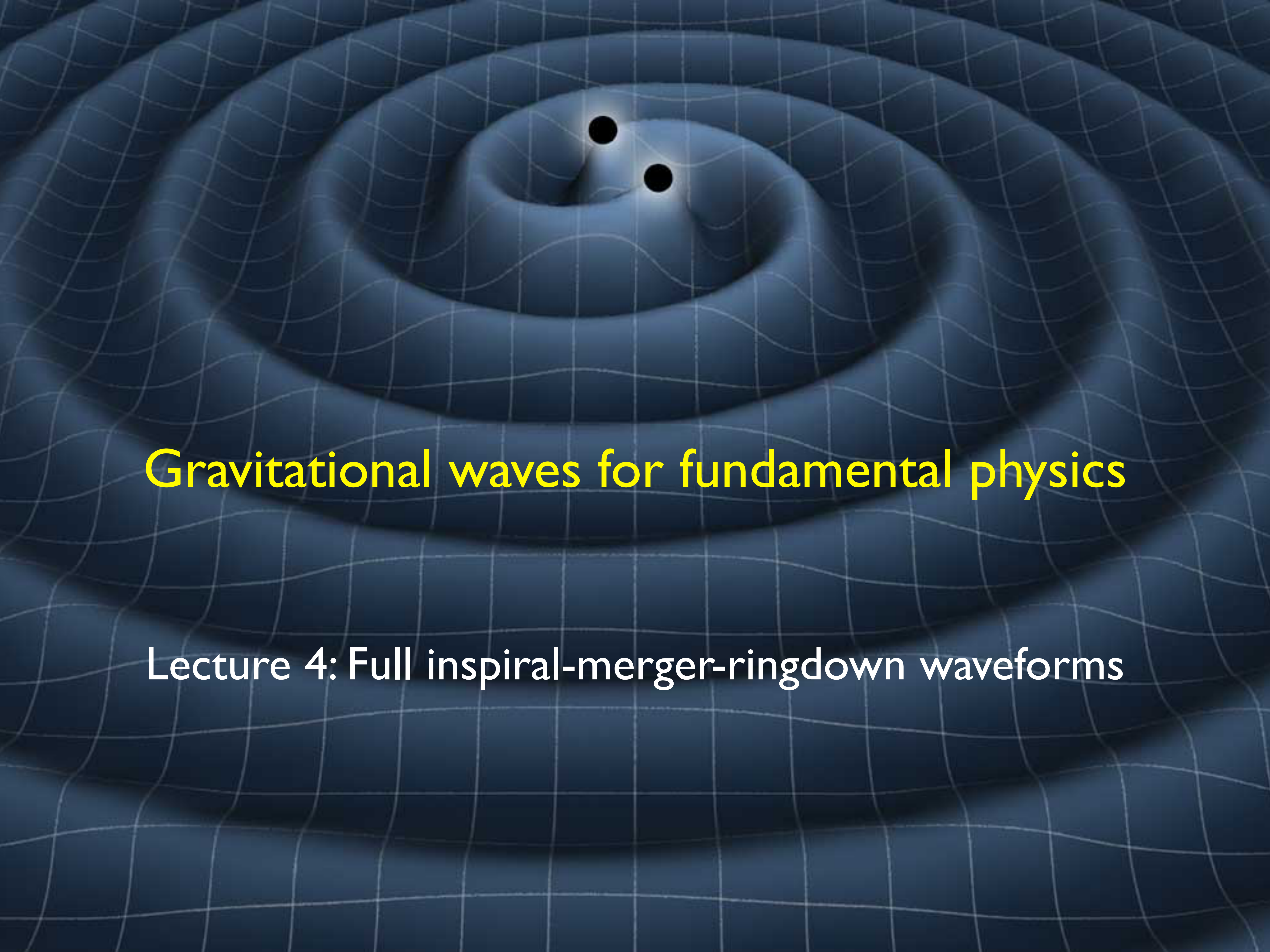
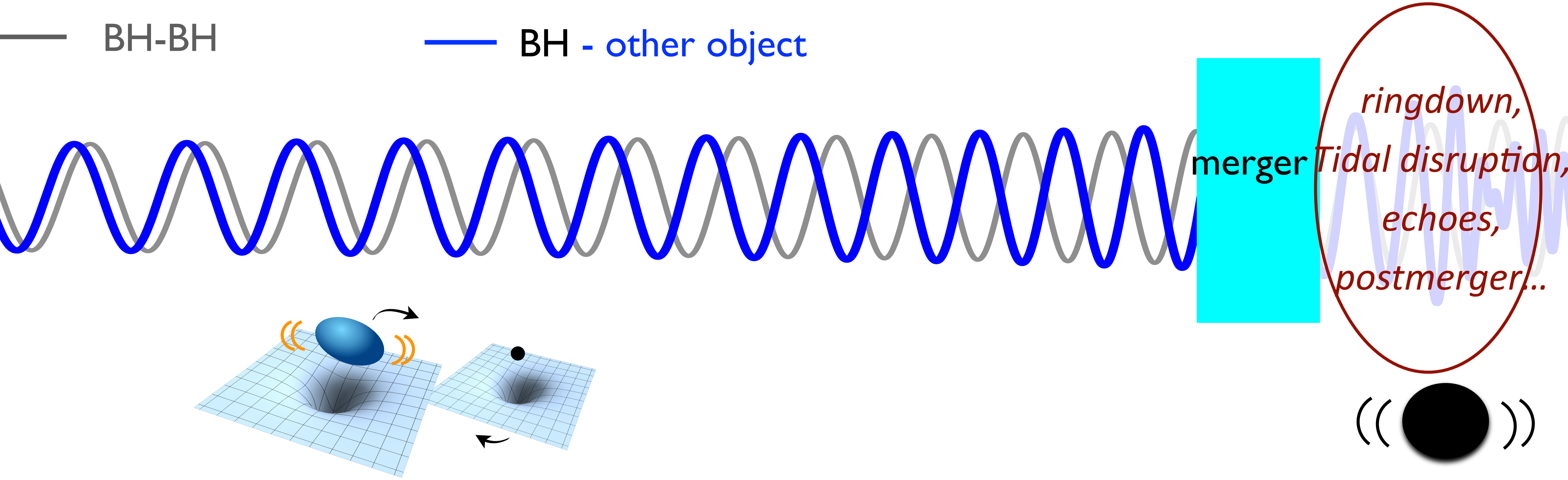


Gravitational waves for fundamental physics

Lecture 4: Full inspiral-merger-ringdown waveforms

Recall from last time: GW signatures of an object's structure



Inspiral:

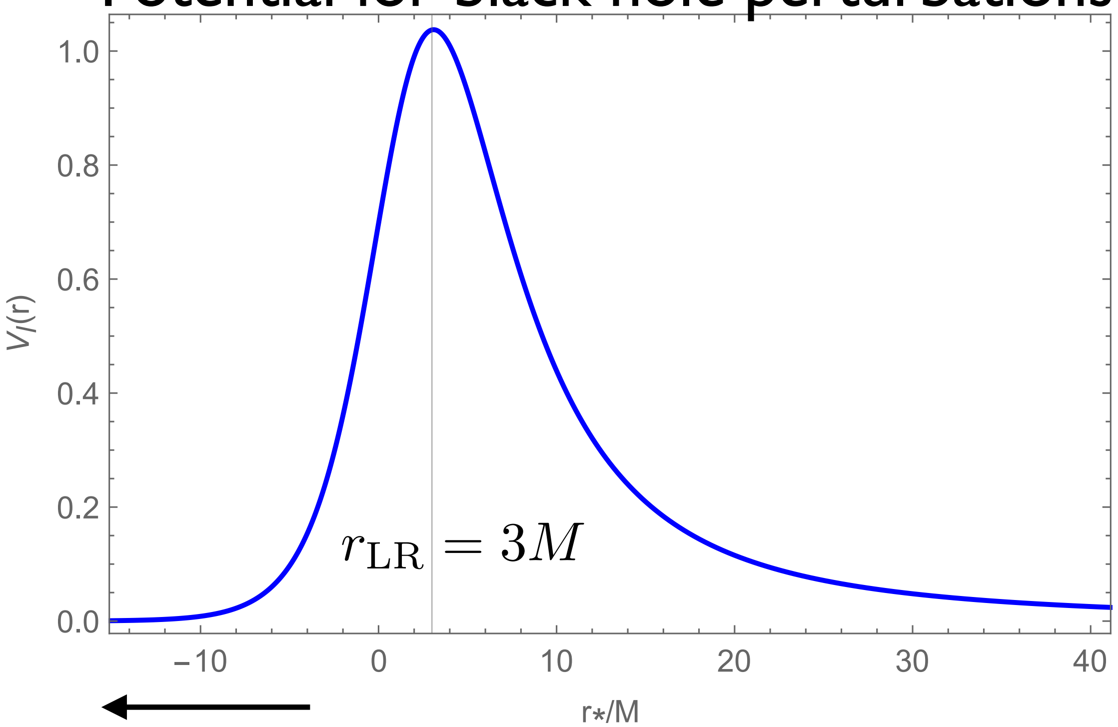
- Small but clean and cumulative GW signatures of more general objects than black holes
- occur due to deviations from spherical symmetry, e.g. from spin or tidal effects
- spacetime multipole moments transmit information from object's interior to dynamics & GWs
- key characteristic GW parameters, e.g. tidal deformability
  - Computed from linear perturbations to a relativistic equilibrium configuration

Recall from last time: quasi-normal modes (QNMs)

- QNMs are the characteristic free oscillations of an object/its spacetime
- GW damping is always present: complex frequencies
- Determined by solutions to a Schrödinger-like equation with a complicated potential

(xAct tutorial on the derivation posted on Teams for your reference: RW_Zerilli_Tutorial.nb)

Potential for black hole perturbations

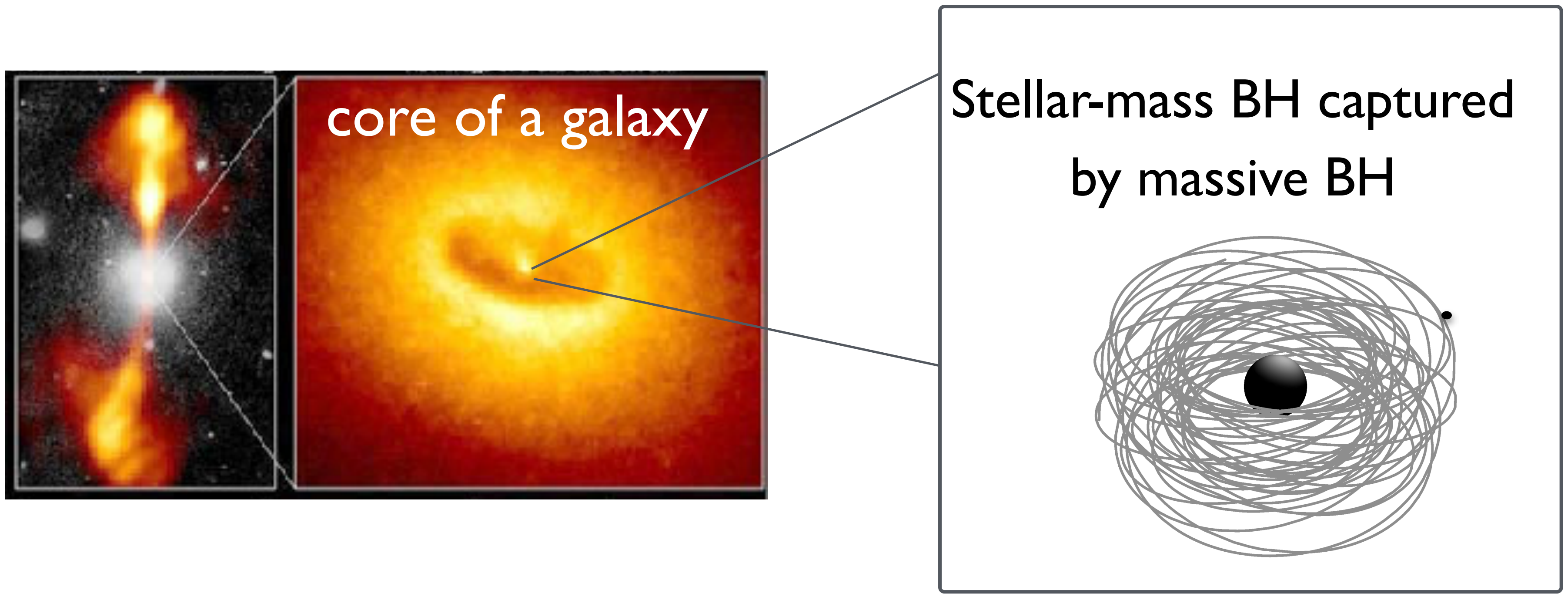


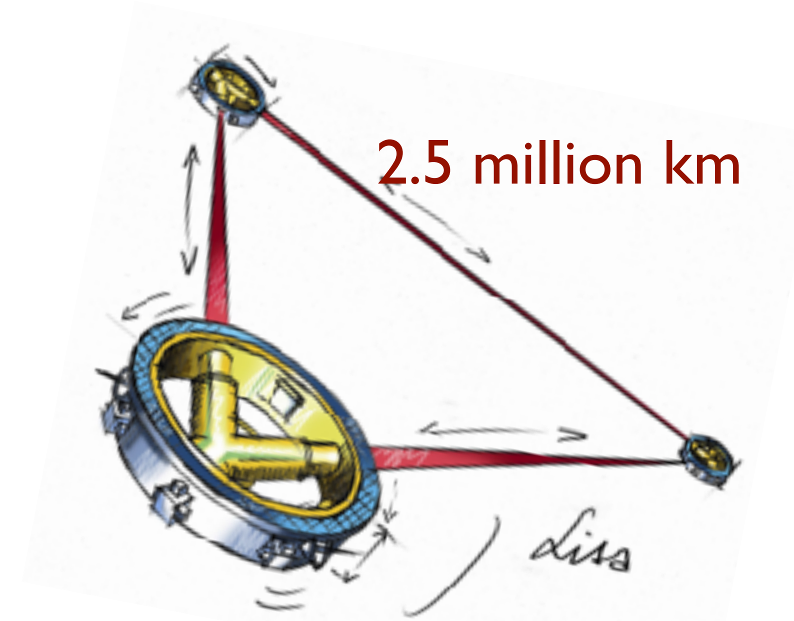
horizon

- for black holes, the potential has a peak near the light ring (unstable photon orbit)
- this impacts the properties of black hole QNMs
- More general objects have a different potential - different mode spectrum, echoes, …

Another key application of BH perturbation theory:

Highly relativistic binaries (large mass ratio)





Planned space-based GW detector LISA (Launch 2034)

- Small BH lingers on relativistic orbits close to the large BH's horizon for ~ year of inspiral visible to LISA
- extremely high precision studies

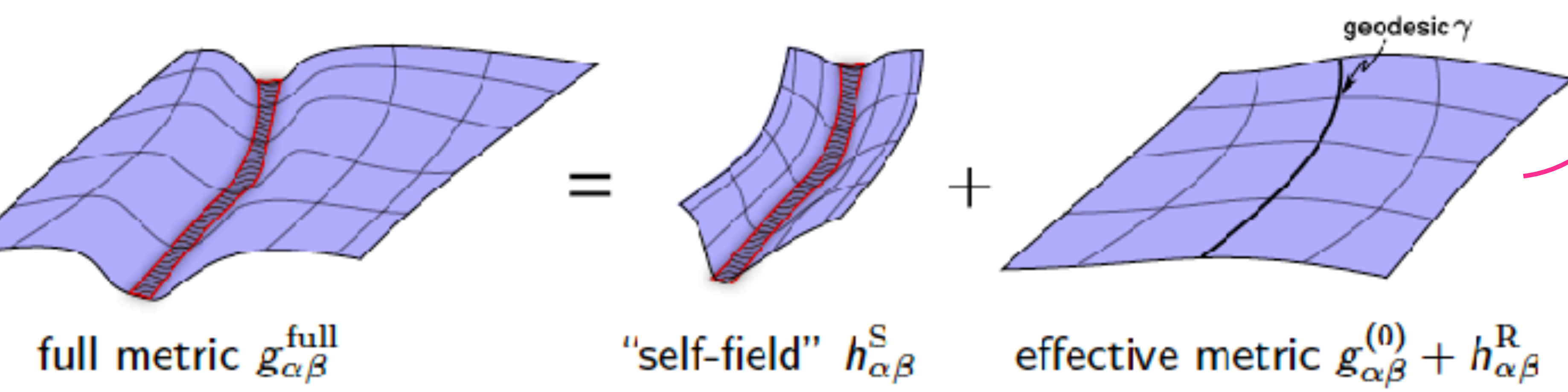
Accurately map spacetime, test no-hair property, new features of strong-field dynamics, probe inner galactic cores, growth of massive BHs

Role of black hole perturbation theory

- Data analysis will require extremely accurate models
- Must account for corrections to the spacetime due to the small BH and the resulting effects
- black hole perturbation theory (with source), also known as “gravitational self-force” in this context, needed to 2nd order in the perturbations
- Formally established but practical calculations very difficult

Coulomb-field of the small BH

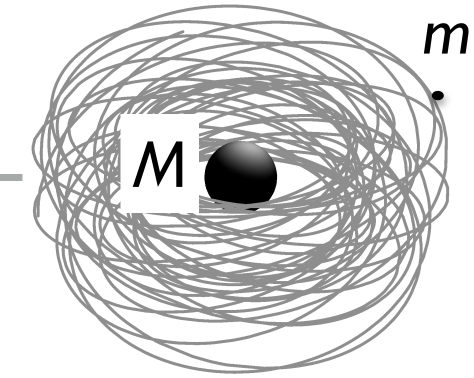
Geodesic motion in an effective, regular metric



Can also map this to forced motion in M’s background spacetime

Figure credit: Adam Pound

Additional complexity: timescales



Foundation: $\epsilon = m/M \ll 1$, perturbative treatment

- *On short timescales:* $\tau_{\rm orb} \sim M \qquad \sim 50\,{\rm s}\left(\frac{M}{10^7 M_\odot}\right)$ *m* moves ~ on a geodesic
- *On longer timescales:* $\tau_{\rm insp} \sim M/\epsilon \qquad \sim 1.6\,{\rm yrs}\left(\frac{M}{10^7 M_\odot}\right)\left(\frac{10^{-6}}{\epsilon}\right)$

  gravitational radiation reaction causes the orbit to slowly evolve

- *A fixed geodesic and the true orbit dephase by ~ 1 cycle after:*

$$\tau_{\rm deph} \sim M/\sqrt{\epsilon} \qquad \sim 13\,{\rm hrs}\left(\frac{M}{10^7 M_\odot}\right)\left(\frac{10^{-6}}{\epsilon}\right)^{1/2}$$

Computing inspirals and waveforms requires a specialized multi-scale approximation scheme

(Leading order is a slowly inspiraling relativistic orbit)

Simple example of a multi-scale expansion

- Consider the oscillator $\boxed{\ddot{x} + x + 2\,\epsilon\,\dot{x} = 0}$ with initial conditions $\begin{cases} x(0) = 0 \\ \dot{x}(0) = 1 \end{cases}$
- Usual approach: ansatz for the asymptotic expansion of the solution

$$x(t;\epsilon) = x_0(t) + \epsilon\, x_1(t) + O(\epsilon^2)$$

- Substitute into the equation of motion, collect powers of ϵ:

$$O(\epsilon^0):\quad \ddot{x}_0 + x_0 = 0 \quad \text{with} \quad x_0(0) = 0,\ \dot{x}_0(0) = 1 \quad \Longrightarrow \quad \boxed{x_0(t) = \sin(t)}$$

$$O(\epsilon^1):\quad \ddot{x}_1 + x_1 = -2\,\dot{x}_0 = -2\cos(t) \quad \text{with} \quad x_1(0) = \dot{x}_1(0) = 0$$

$$\Longrightarrow \quad \boxed{x_1 = -t\,\sin(t)}$$

'Secular term'

- The solution then has the expansion $x(t;\epsilon) = \sin(t) - \epsilon\, t\,\sin(t) + O(\epsilon^2)$

for large *t*, the second term becomes much larger than the first ⇒ the expansion fails

Simple example of a multi-scale expansion cont.

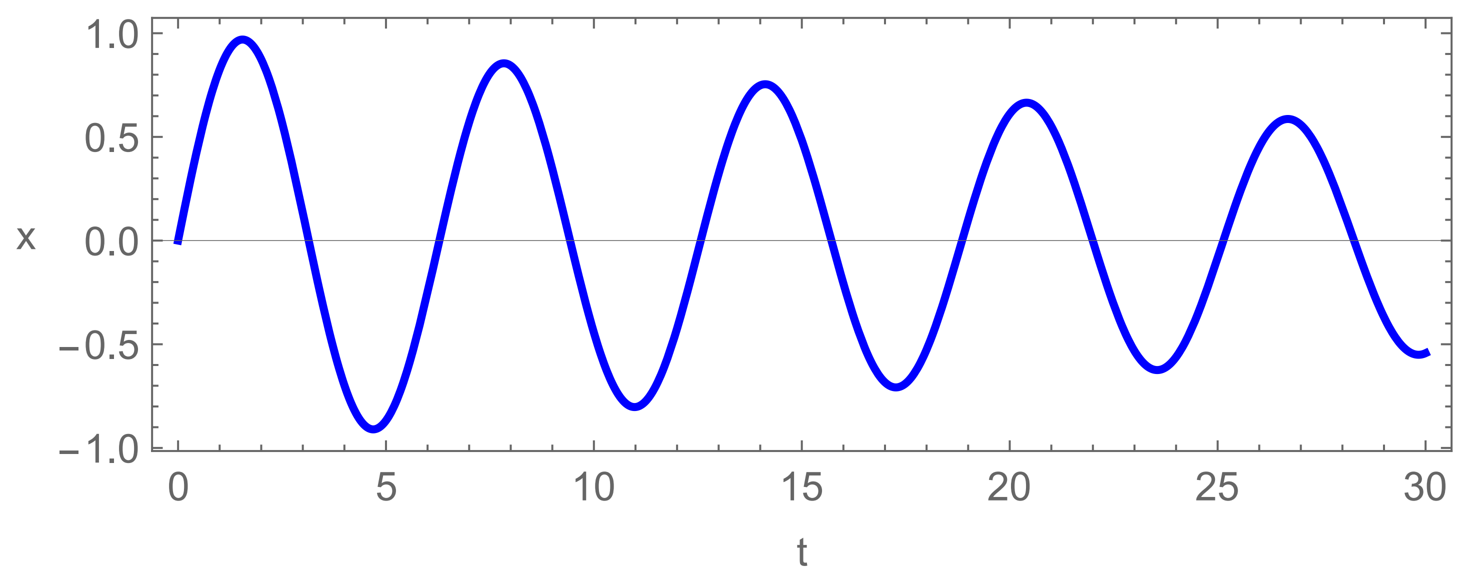
- Consider the oscillator $\boxed{\ddot{x} + x + 2\,\epsilon\,\dot{x} = 0}$ with initial conditions $\begin{cases} x(0) = 0 \\ \dot{x}(0) = 1 \end{cases}$

- This problem happens to have an exact solution, from which we can get insight:

$$x = \frac{e^{-\epsilon t}}{\sqrt{1-\epsilon^2}} \sin(t\sqrt{1-\epsilon^2})$$

Involves two different timescales:

$T = \epsilon\, t$ ('slow time') and $\tau = t$



rapid oscillations with slow damping

Two-timescale method:

treat T and τ as independent variables, convert everything back to t only at the very end

Simple example of a multi-scale expansion cont.

- Consider the oscillator $\boxed{\ddot{x} + x + 2\,\epsilon\,\dot{x} = 0}$ with initial conditions $\begin{cases} x(0) = 0 \\ \dot{x}(0) = 1 \end{cases}$

- Two timescales: $T = \epsilon\, t$ and $\tau = t$

Trick: treat T and τ as independent variables, convert everything back to *t* only at the very end

- Two-timescale ansatz for the asymptotic expansion of the solution at fixed T:

$$x(t;\epsilon) = x_0(\tau, T) + \epsilon\, x_1(\tau, T) + O(\epsilon^2) \qquad \text{and} \qquad \boxed{\dot{x} = \frac{\partial x}{\partial \tau} + \epsilon\, \frac{\partial x}{\partial T}}$$

- Substitute and solve order by order in ϵ

$$O(\epsilon^0): \quad \frac{\partial^2 x}{\partial \tau^2} + x_0 = 0 \quad \text{with} \quad x_0(0) = 0,\ \frac{\partial x_0}{\partial \tau} = 1$$

$$\Longrightarrow \quad x_0 = A(T)\sin\tau$$

Integration constant, determined at the next order in ϵ

Simple example of a multi-scale expansion cont.

- Consider the oscillator $\boxed{\ddot{x} + x + 2\,\epsilon\,\dot{x} = 0}$ with initial conditions $\begin{cases} x(0) = 0 \\ \dot{x}(0) = 1 \end{cases}$

- Two timescales: $T = \epsilon\, t$ and $\tau = t$

$$x(t;\epsilon) = x_0(\tau, T) + \epsilon\, x_1(\tau, T) + O(\epsilon^2)$$

$$\boxed{\dot{x} = \frac{\partial x}{\partial \tau} + \epsilon\,\frac{\partial x}{\partial T}}$$

- Substitute, solve order by order

$$O(\epsilon): \quad \frac{\partial^2 x_1}{\partial \tau^2} + x_1 = -2\frac{\partial^2 x_0}{\partial T \partial \tau} - 2\frac{\partial x_0}{\partial \tau}$$

$$x_0 = A(T)\sin\tau$$

$$= -2\,[A'(T) + A(T)]\cos\tau$$

To avoid secular terms that grow with τ in the solution, need $A'(T) + A(T) = 0$

$$A = e^{-T}$$ [A(0) chosen to satisfy the boundary conditions]

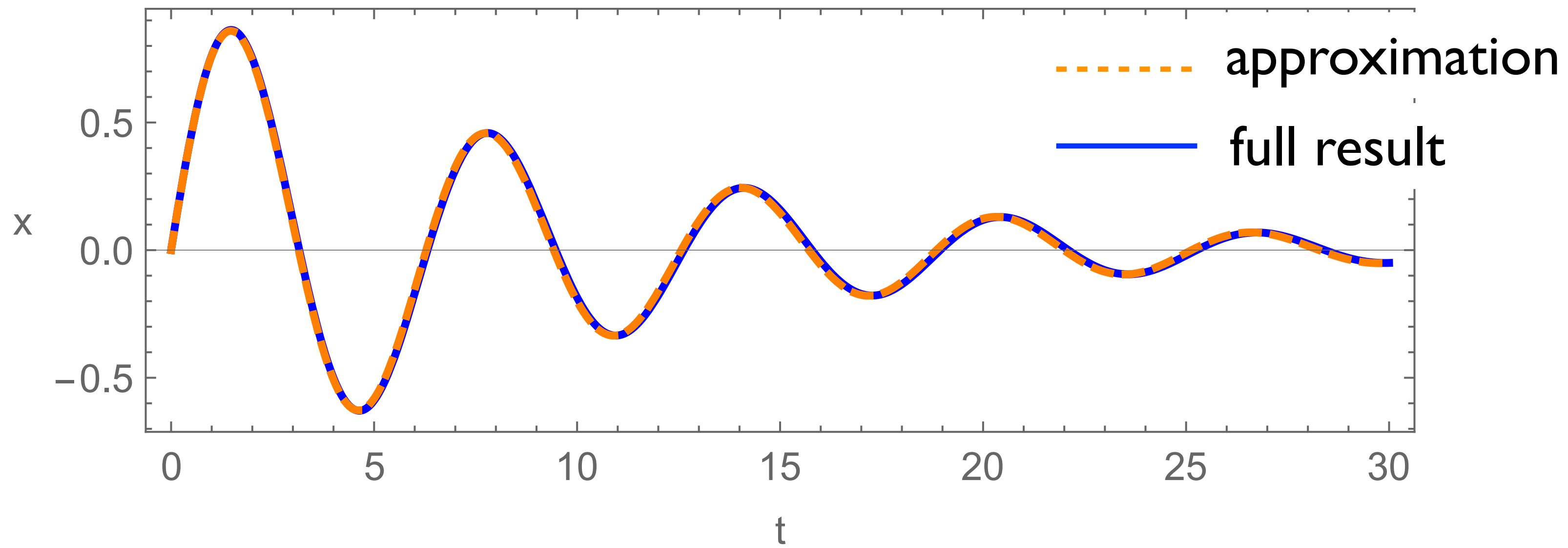
Final result

- Collecting the results so far from the two-timescale expansion

$$x = e^{-T} \sin \tau + O(\epsilon)$$

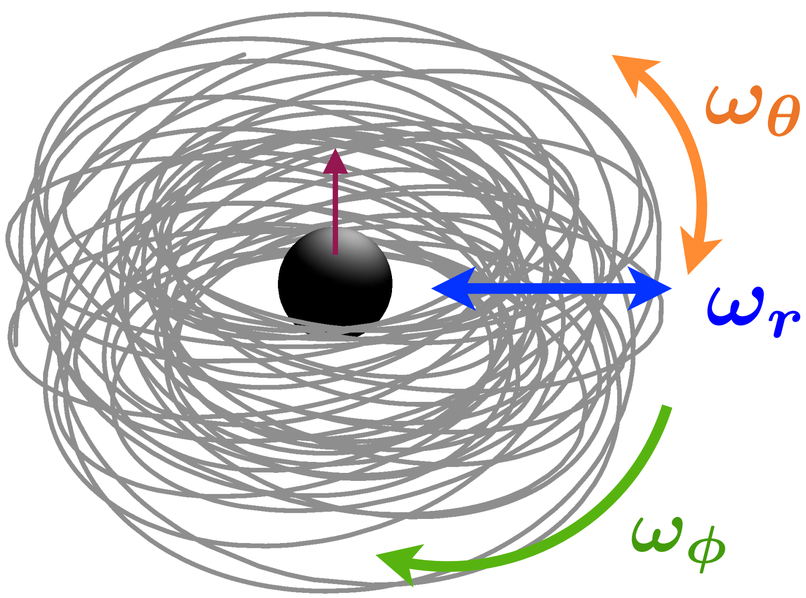
- Now write in terms of *t*: $x = e^{-\epsilon t} \sin t + O(\epsilon)$

- c.f. exact solution: $x = \dfrac{e^{-\epsilon t}}{\sqrt{1-\epsilon^2}} \sin(t\sqrt{1-\epsilon^2})$



New strong-field feature: transient resonances

generic orbit (inherits features of geodesics in Kerr)

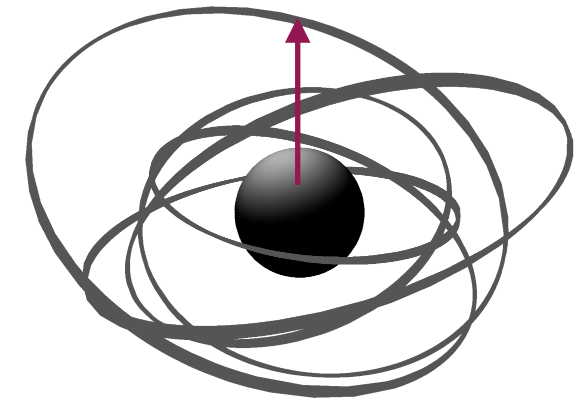


- frequencies slowly evolve: occurrence of resonances

$$\omega_\theta/\omega_r = k/n$$

small integers

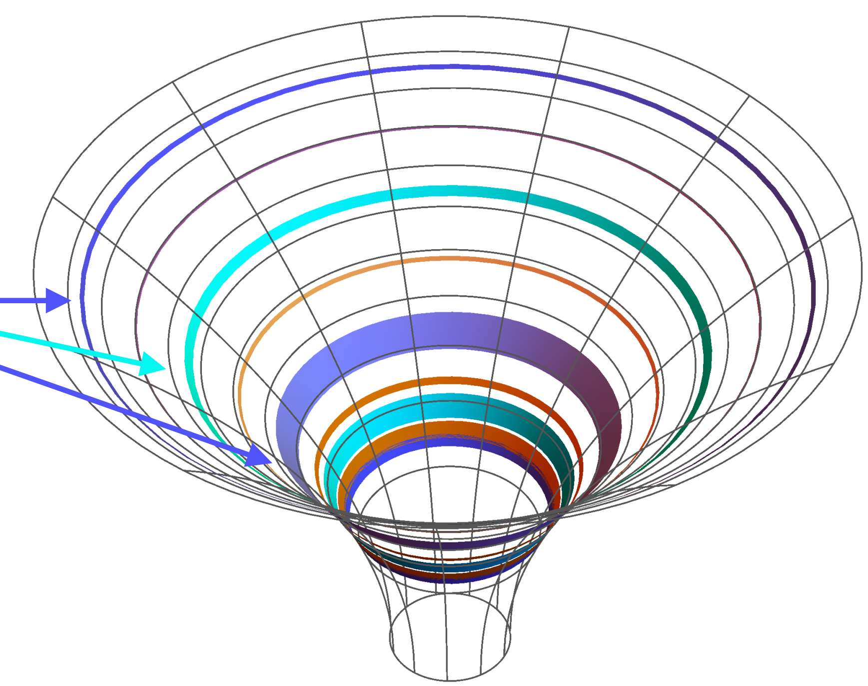
resonant orbit



- Newtonian gravity: frequencies are the same

- GR: small-integer resonances located in the strong-field region close to the event horizon

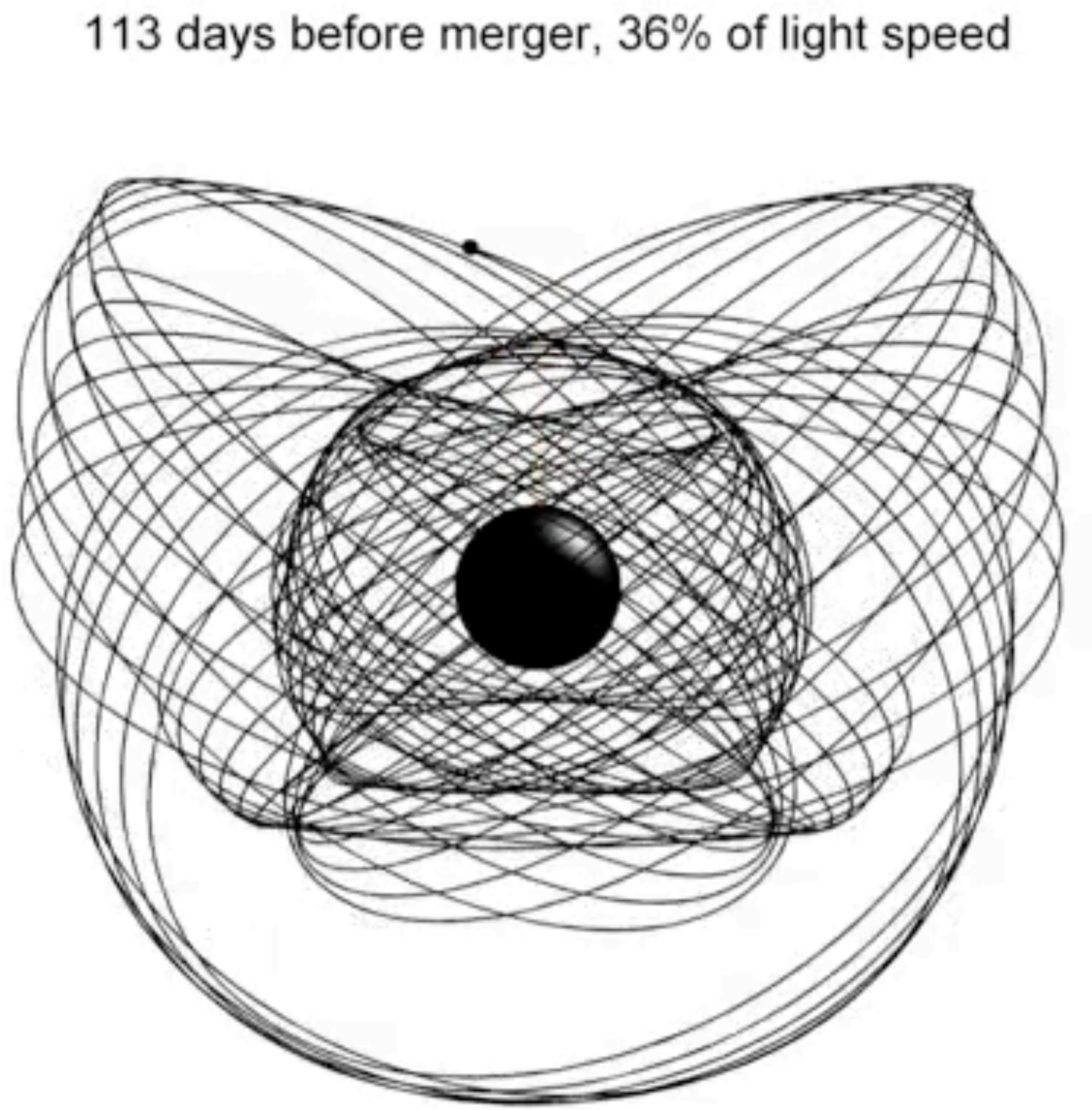
resonances



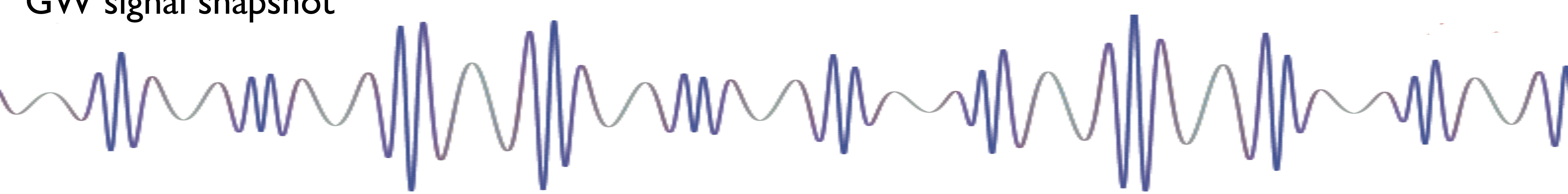
M's event horizon

Approximate inspiral evolution

Movie by S. Drasco

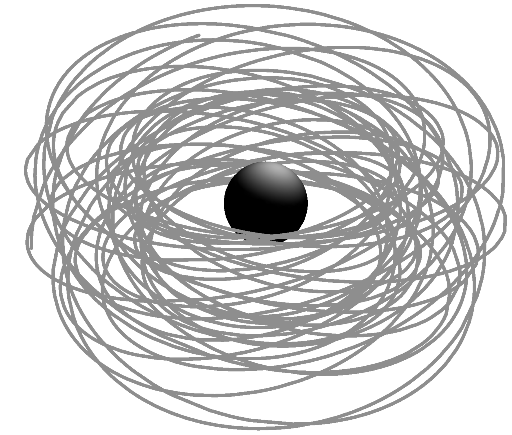


GW signal snapshot



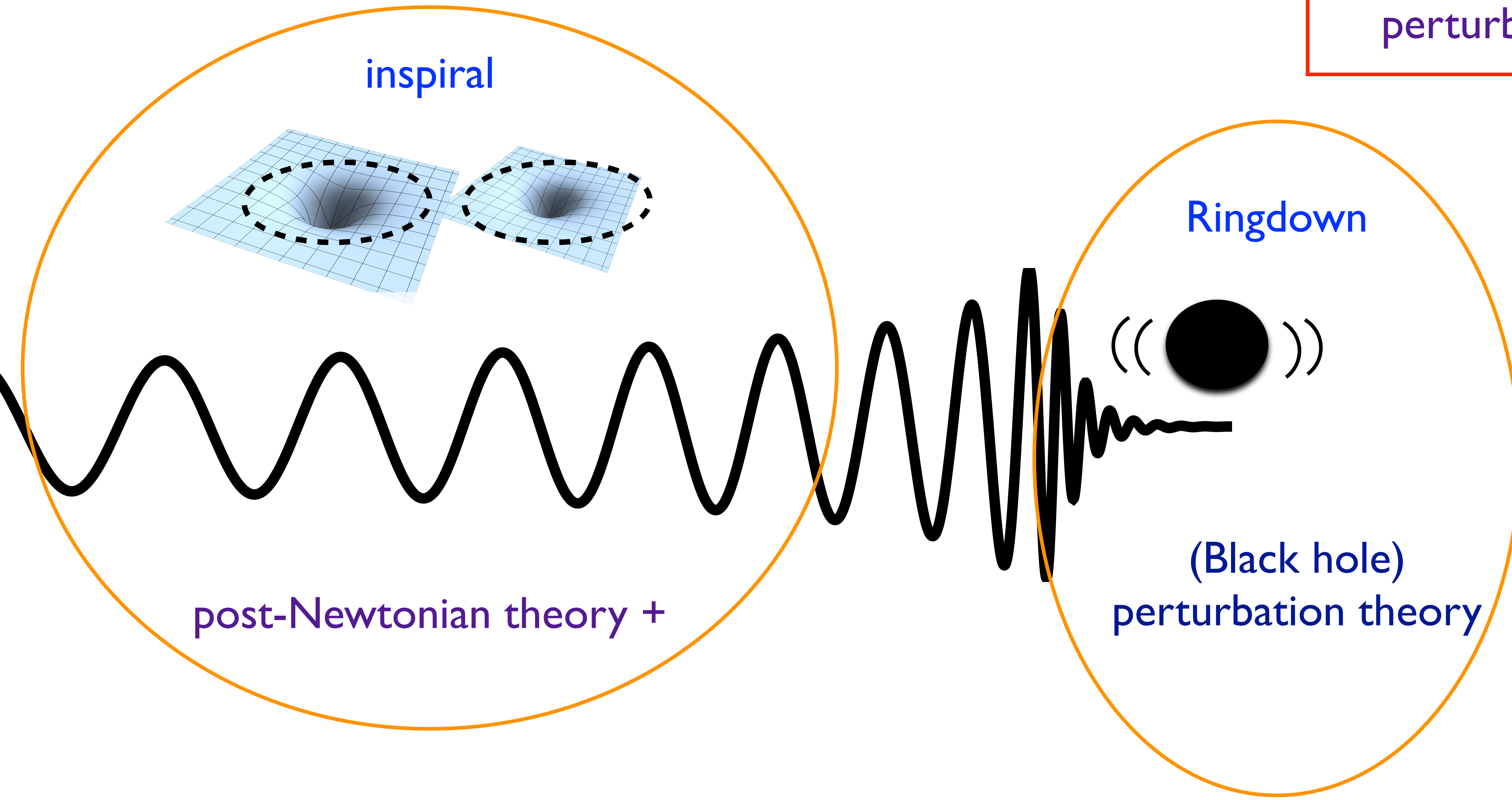
Aspects of GWs we discussed so far

Highly relativistic binaries

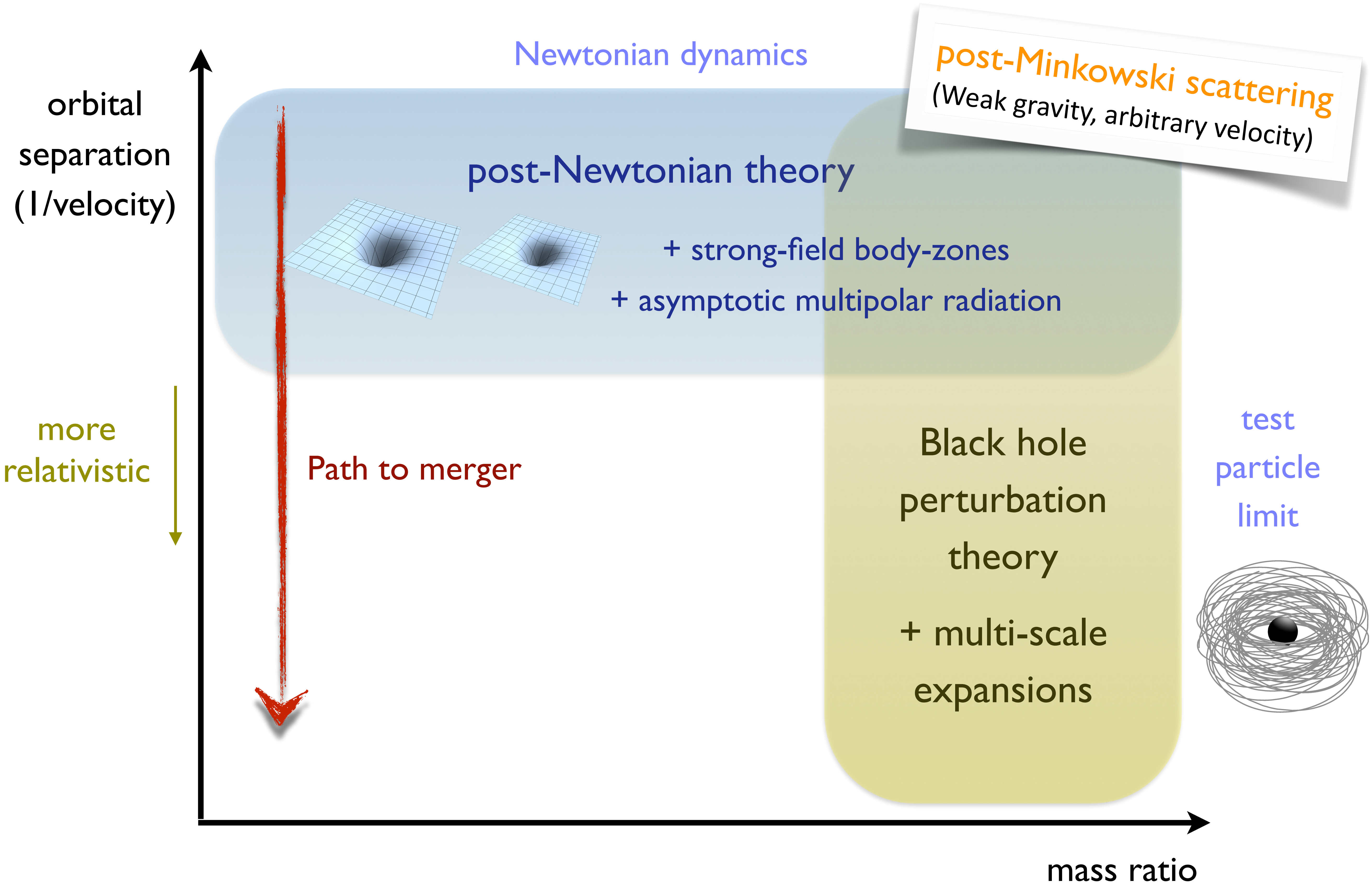


Described entirely by perturbative schemes

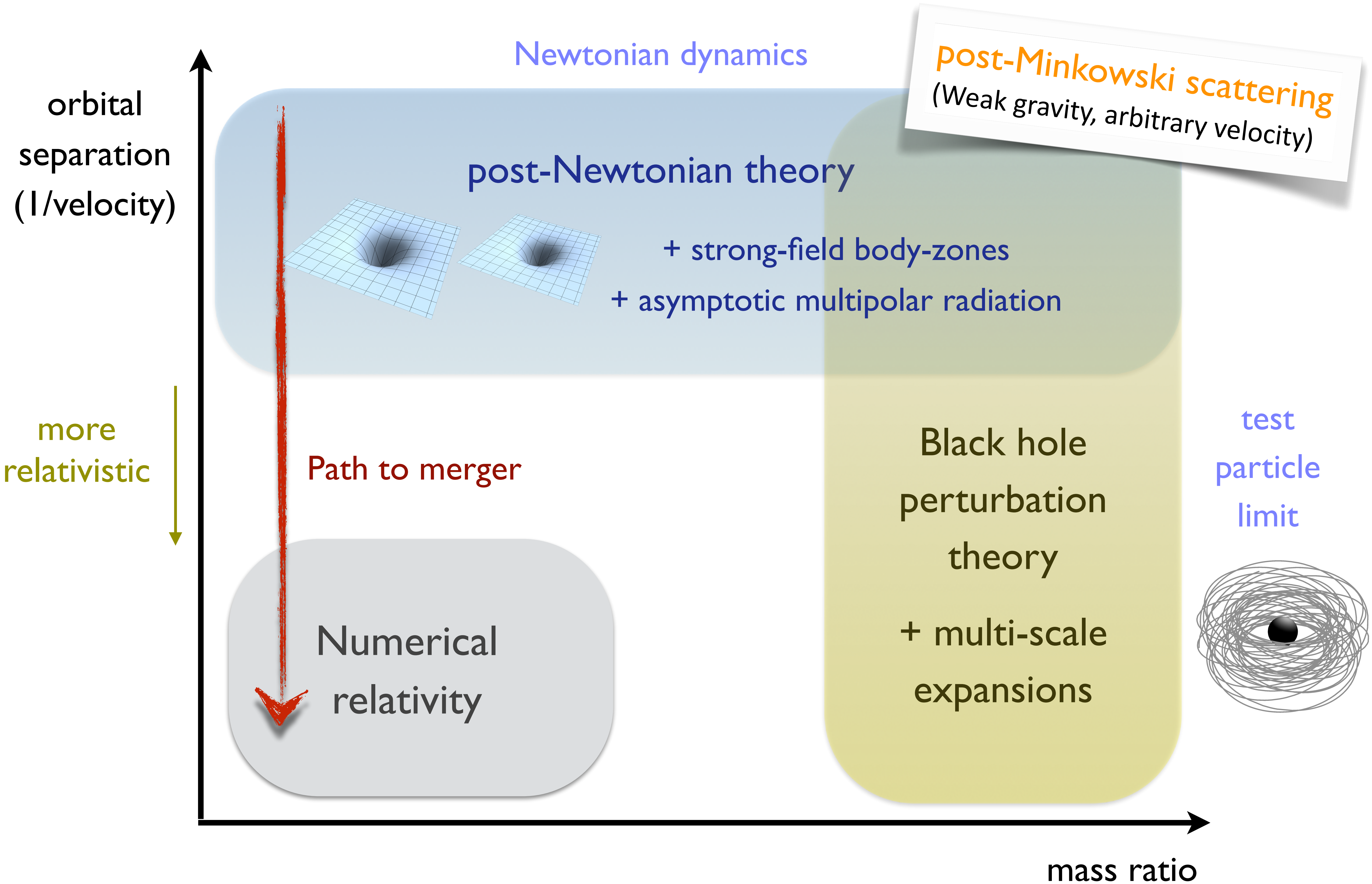
Comparable-mass binaries



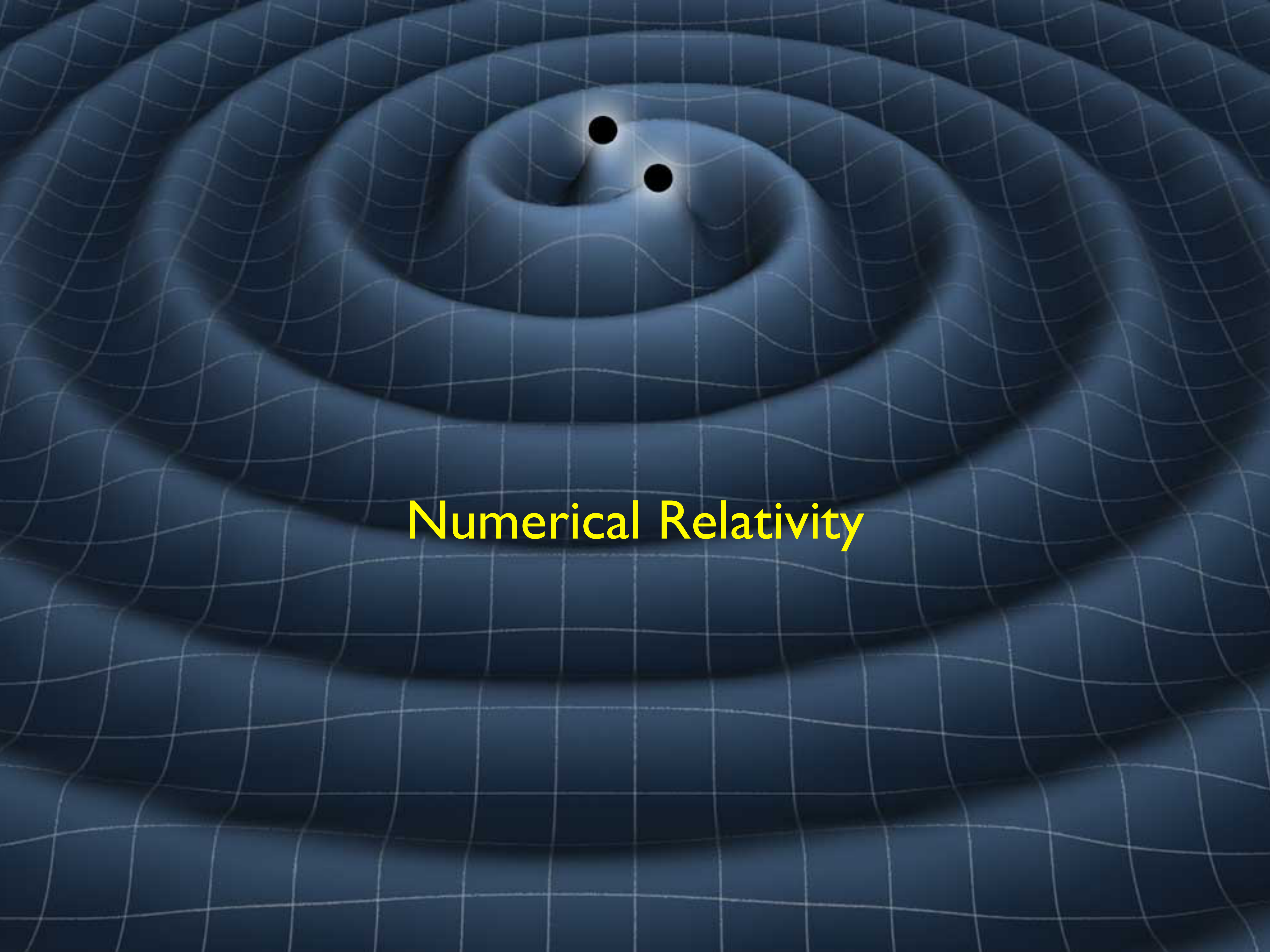
Approaches to computing waveforms



Approaches to computing waveforms



Numerical Relativity



Starting point

- must solve for the dynamical spacetime of the binary system.

dynamical spacetime geometry

matter sources

$$\underbrace{G_{\mu\nu}\left[g_{\alpha\beta}\right] = \frac{8\pi G}{c^4} T_{\mu\nu}}$$

nonlinear differential operator

=0 for black holes

$$\nabla^{\nu} G_{\mu\nu}\left[g_{\alpha\beta}\right] = 0$$

complicated differential eqs.

coupled nonlinear partial differential equations

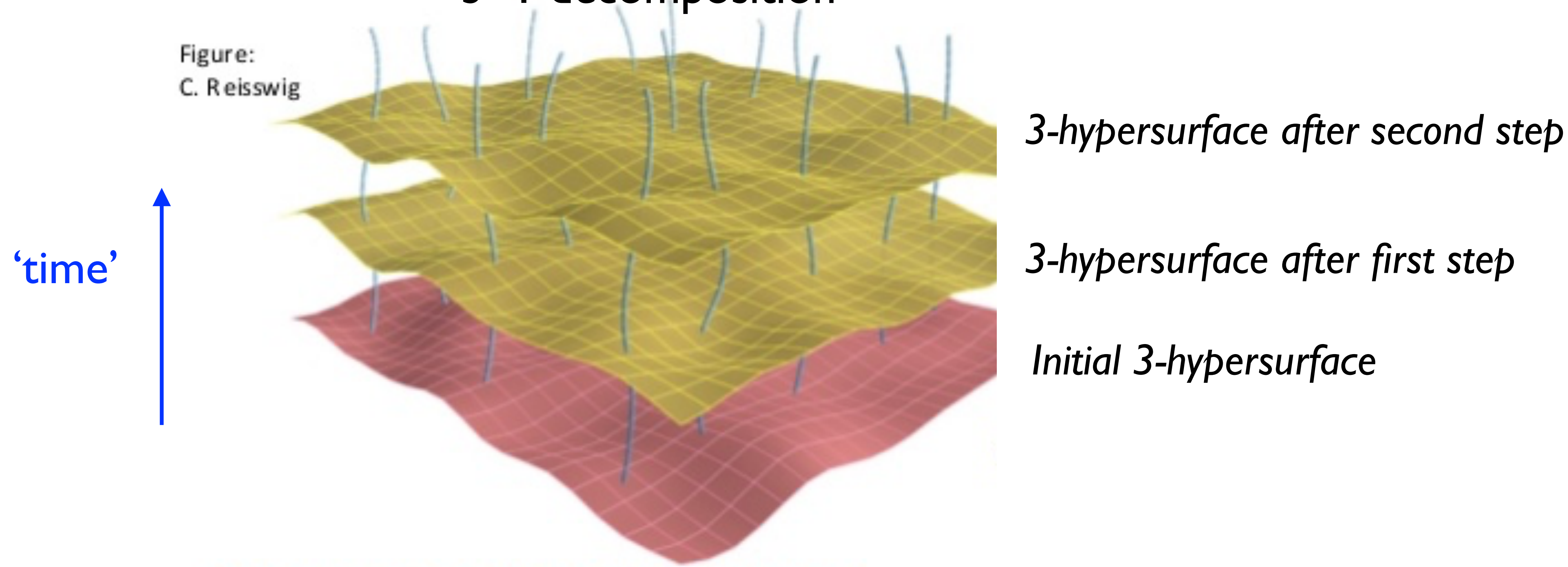
when written with first order derivatives:

52 equations, each with hundreds of terms

Numerical relativity formulation - basic idea

- Formulate the system of equations as a computable time-step iteration process (Cauchy problem)

3+1 decomposition



Details e.g. in the review article E. Gourgoulhon [3+1 Formalism and Bases of Numerical Relativity]

xAct notebook to compute all the equations available as lecture materials for 'Black hole evolutions' at [NRHEP2 school]

First proof of principle simulation

- 1964: Susan Hahn (IBM) & Richard Lindquist: [The Two-Body Problem in Geometrodynamics]

(Black Hole was not yet a term)

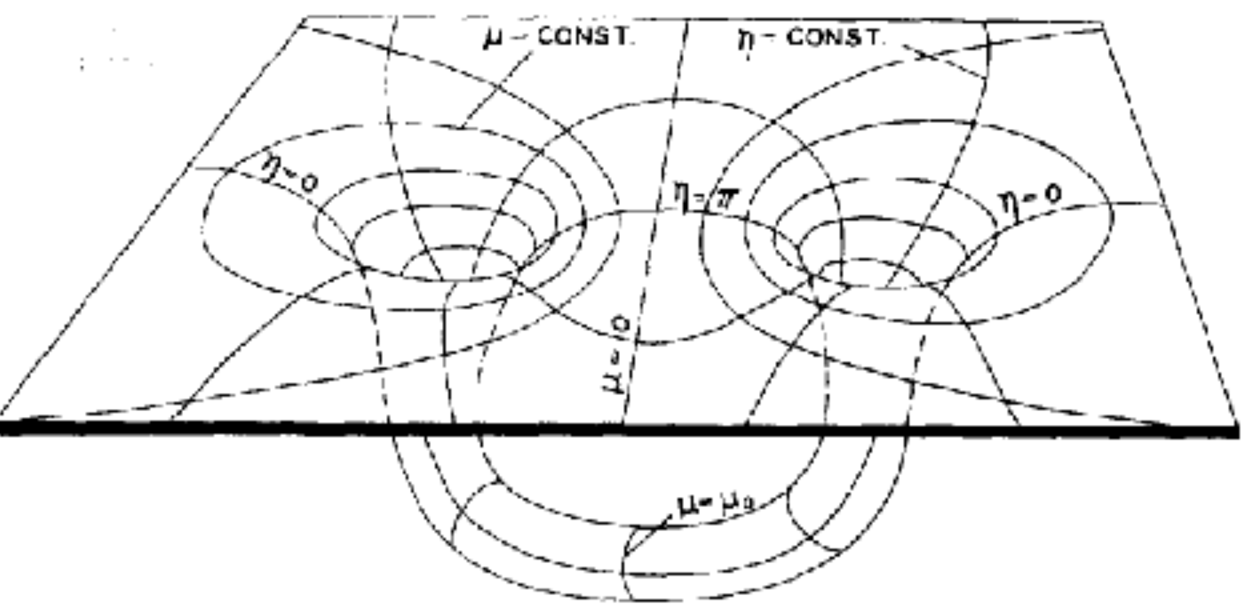


TABLE II

Time step	Time elapsed	Area of throat
1	0	777.765
5	0.16334	777.597
10	0.34645	777.001
15	0.52907	776.008
20	0.71143	774.591
25	0.89352	772.761
30	1.07528	770.523
35	1.25667	767.881
40	1.43762	764.840
45	1.61808	761.404
50	1.79798	757.581

3 hours on IBM 7090, one Processor, 0.2 Mflops (~millionth the speed of an iPhone 7)

integrated for a very short time until inaccuracies became too large

" In summary, the numerical solution of the Einstein field equations presents no insurmountable difficulties. ..."

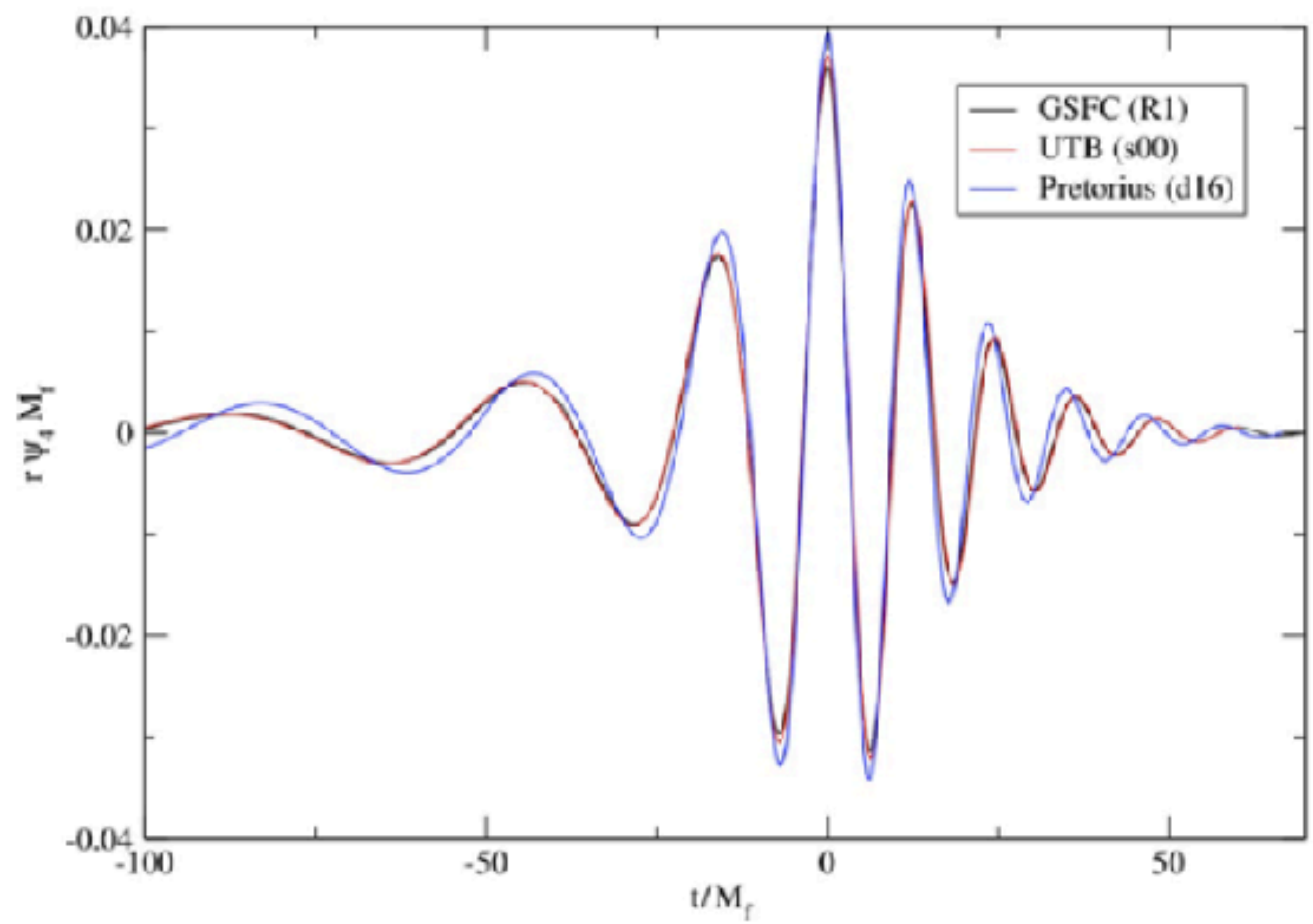
But going beyond this initial study to actually compute black hole mergers from inspirals turned out to be *much, much, much* harder than expected

Examples of challenges

- Gauge choices have turned out to be key to controlling e.g.:
  - well-posedness of the equations as an initial value problem
  - numerical stability, convergence
  - coordinate & physical singularities
  - Boundary problems at horizons
- Some mathematically very appealing formulations/gauges simply do not work in practice
- Need astrophysically realistic initial data
- Deal with finite computational domain, extracting GWs, truncation errors
- Need lots of supercomputing time
  - To date: feasible only when all scales involved are not too different

A 50-year effort until numerical relativity breakthrough

- Multi-decade search for ways to write equations, understand the role of gauge choices, etc.
- In the US: NSF Black Hole Grand Challenge Alliance (1993-98)
- Finally, in 2005: codes by multiple groups produce stable head-on collisions of black holes for the first time



From Eisenstein 2019
Annals of Physics review

Since 2005

- Binary black hole simulations are now routine …

  …. for cases with nearly equal masses, moderate spins, not-to-large initial separation

- extremely computationally expensive

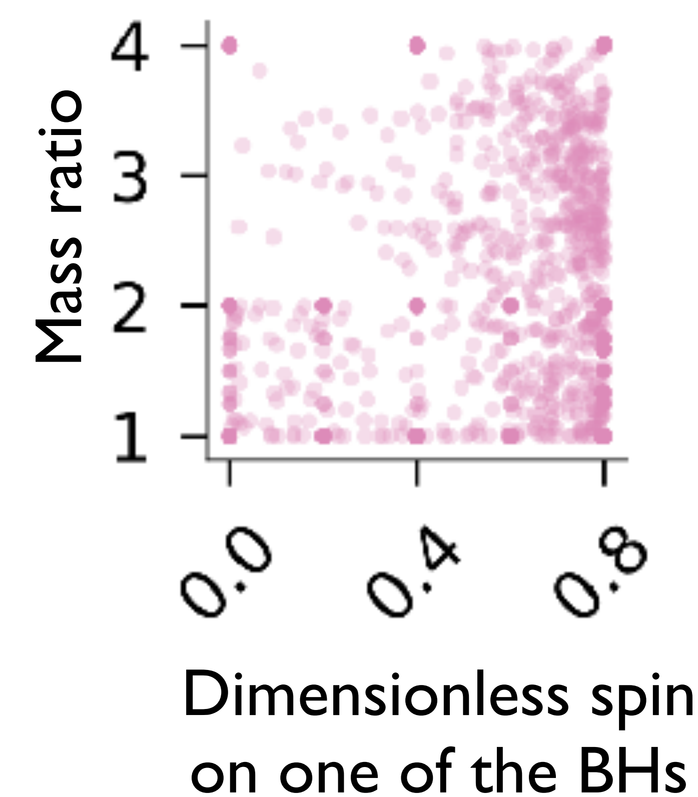
  ~ month for one case with smallish spins<0.6 on supercomputers

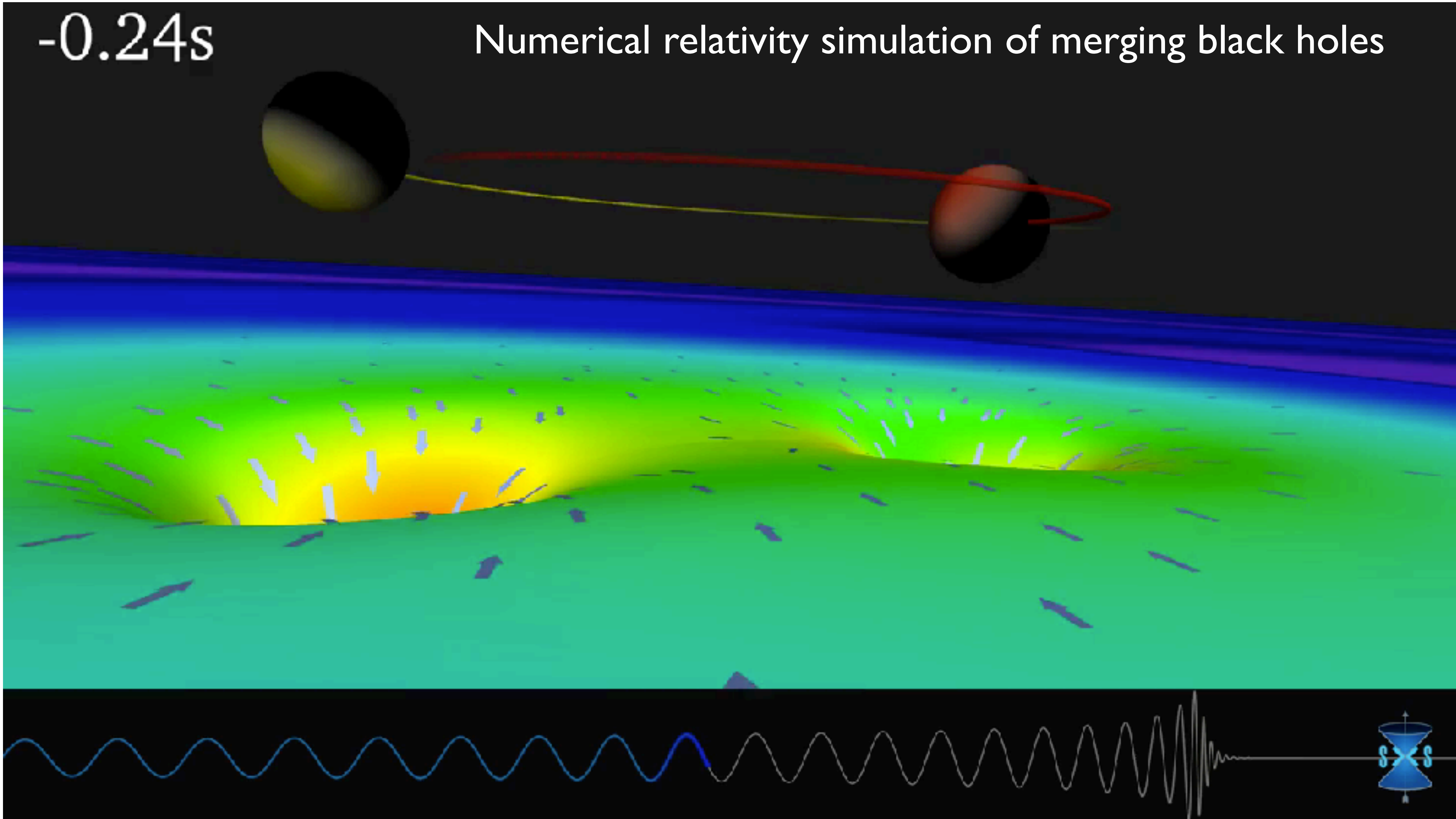
  Number of time steps ~ (mass ratio)^2 / (initial separation)^4

Currently available:

- several thousands of black hole waveforms in a limited corner of parameter space
- Few hundreds of double neutron star waveforms, but limited physics (some also of unknown accuracy)
- Few tens of neutron-star — black hole waveforms

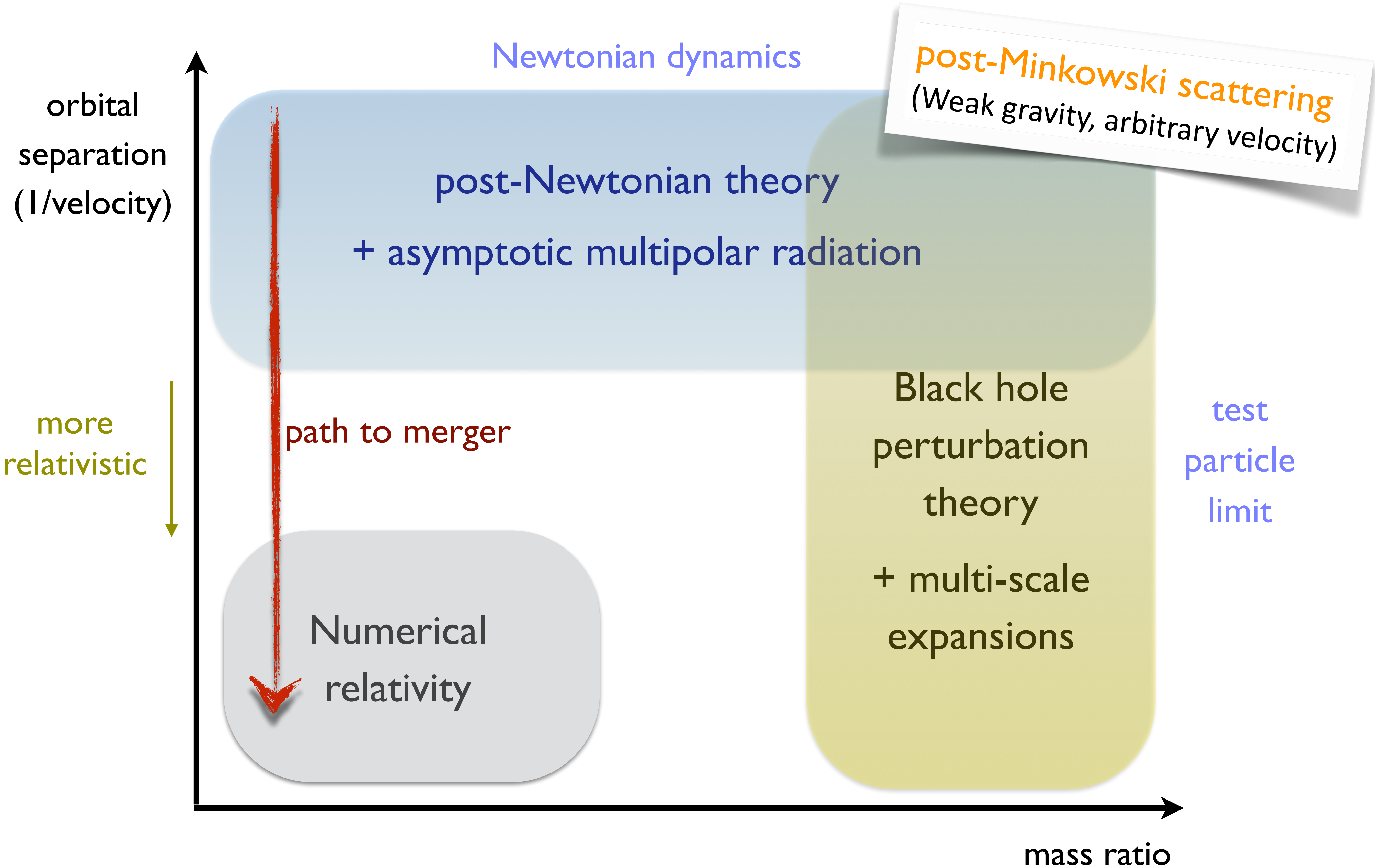
Most explored corner of parameter space



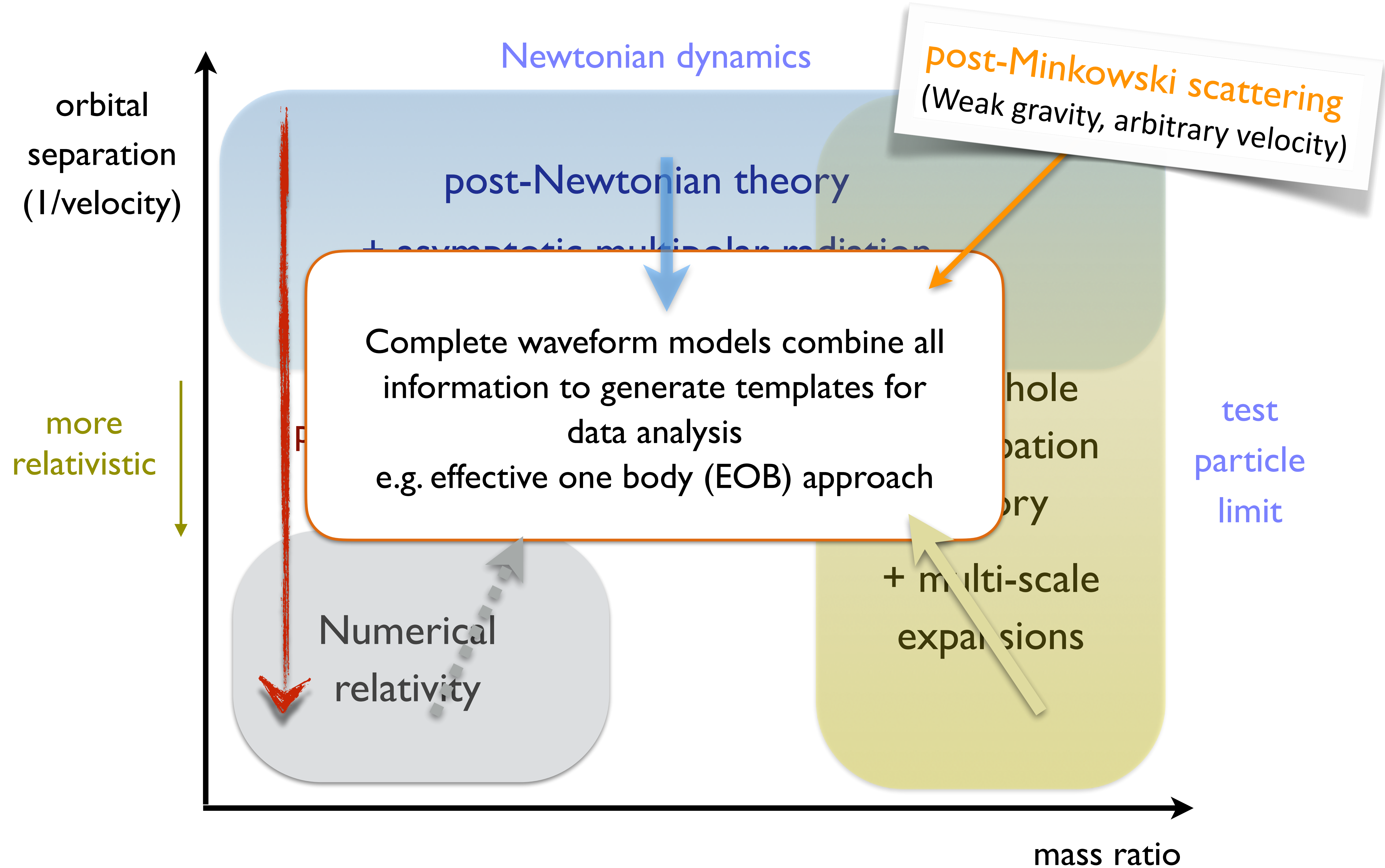


https://youtu.be/1agm33iEAuo

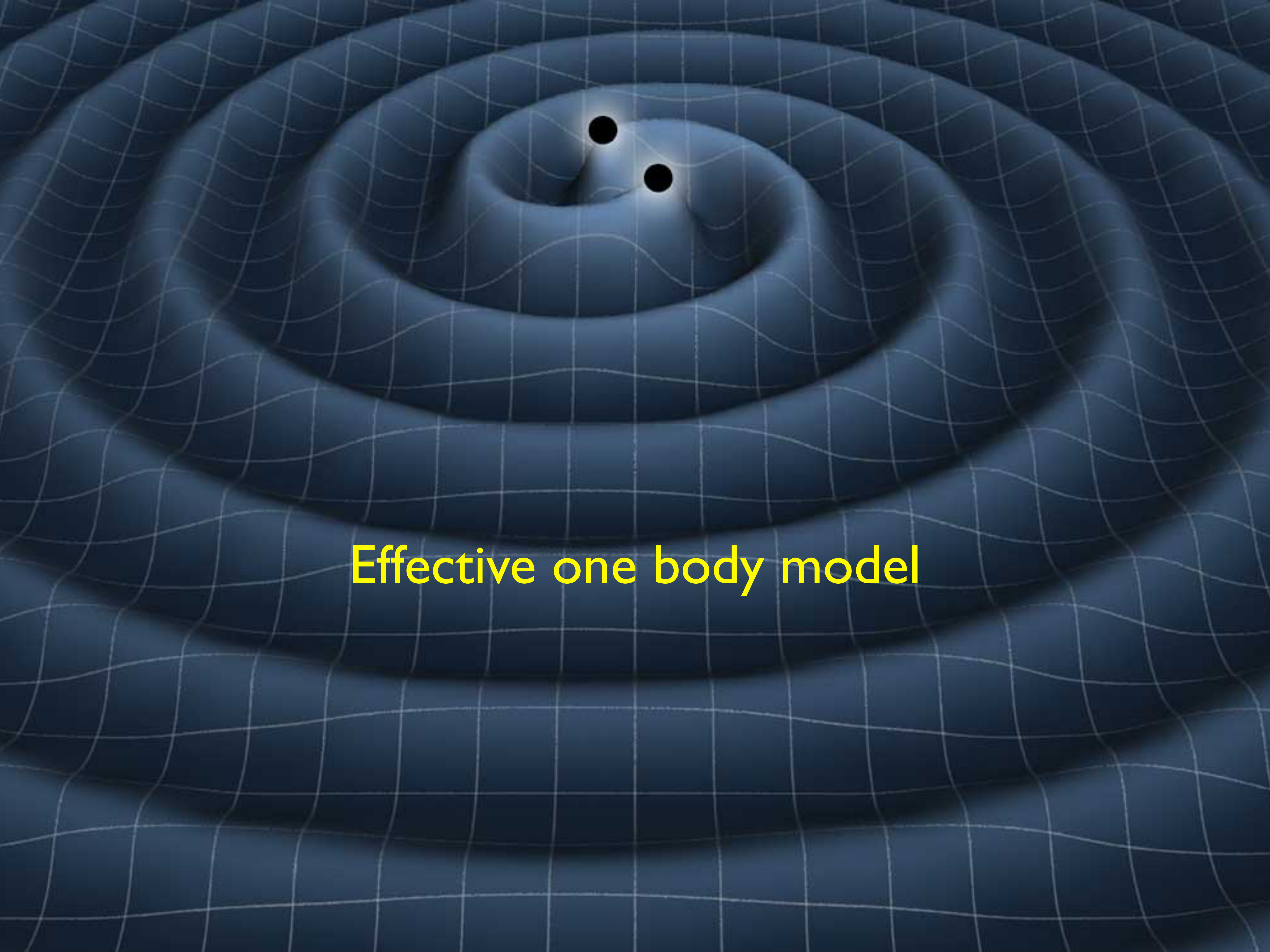
Approaches to computing waveforms



Approaches to computing waveforms



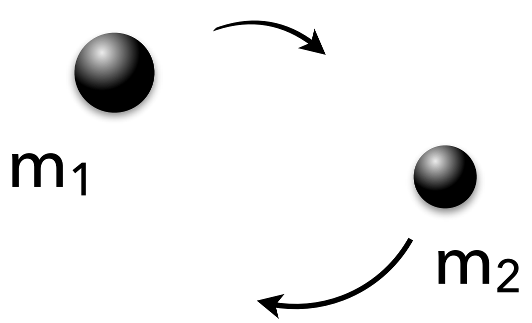
Effective one body model

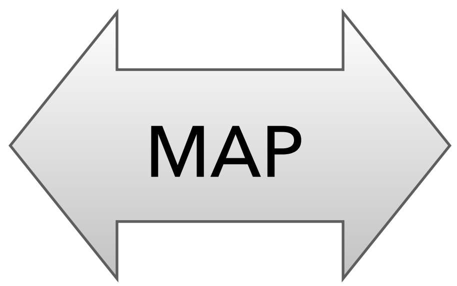


Effective One-Body (EOB) model

- Basic picture for non-spinning black holes:

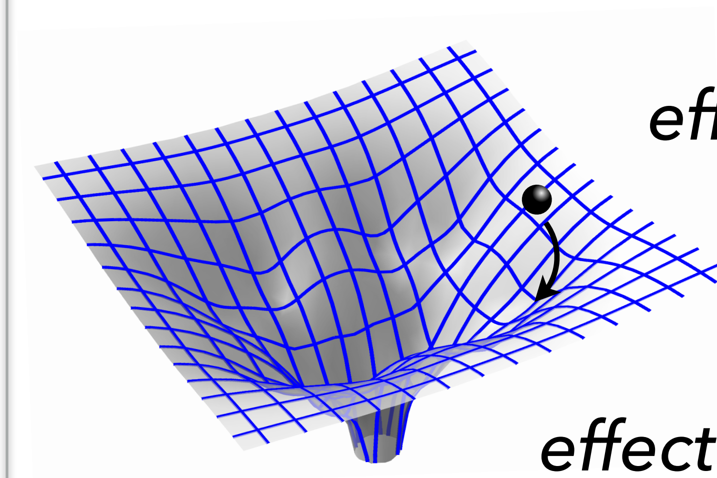
Binary problem





[Buonanno, Damour 1999, 2000]

Effective description



effective particle

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

effective spacetime

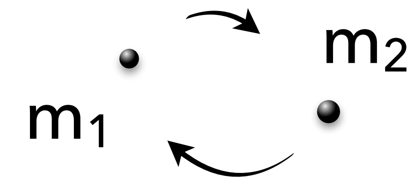
$$M = m_1 + m_2 \qquad \nu = \mu/M \in [0, 1/4]$$

EOB Hamiltonian + GW dissipation + wave generation + merger-ringdown

Original paper https://arxiv.org/abs/gr-qc/9811091

Conservative dynamics

- Recall Newtonian 2-body dynamics:



$$H_{\rm Newt} = \frac{\boldsymbol{p_1}^2}{2m_1} + \frac{\boldsymbol{p_2}^2}{2m_2} - \frac{Gm_1m_2}{|\boldsymbol{r_1} - \boldsymbol{r_2}|} = \frac{\boldsymbol{p}^2}{2\mu} - \frac{G\mu M}{r} + \frac{\boldsymbol{P}^2_{\rm COM}}{2M}$$

$$\boldsymbol{p} = \boldsymbol{p}_1/\mu = -\boldsymbol{p}_2/\mu$$

particle in external field

trivial center-of mass motion

- post-Newtonian (PN) description in the COM frame, harmonic gauge, *G*=*c*=*1*:

$$\boldsymbol{x} = (\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

$$\frac{H_{\rm PN}}{\mu} = \frac{\boldsymbol{p}^2}{2} - \frac{M}{|\boldsymbol{x}|} + \frac{1}{c^2}\left[\frac{1}{2}(3\nu - 1)\,\boldsymbol{p}^4 - \left(\frac{1}{2}(3+\nu)\,\boldsymbol{p}^2 + \frac{\nu}{2}\frac{(\boldsymbol{p}\cdot\boldsymbol{x})^2}{\boldsymbol{x}^2}\right)\frac{M}{|\boldsymbol{x}|} + \frac{M^2}{|\boldsymbol{x}|^2}\right] + \ldots$$

Currently known to 4PN order (very long expression)

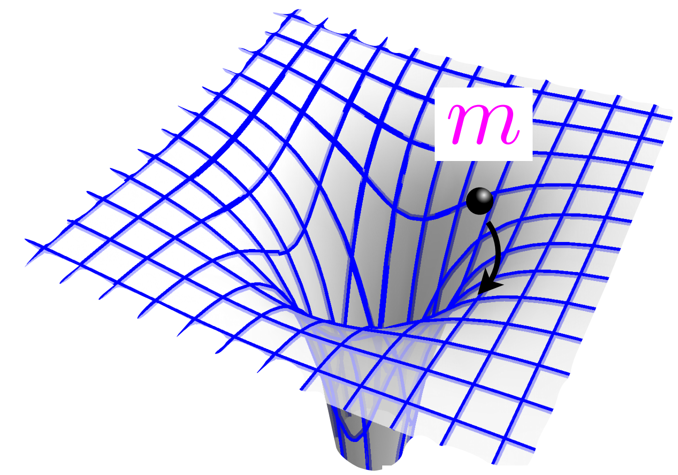
breaks down in strong-field regime

Consider a simple but exact strong-field scenario

- Setup for the effective description: first consider exact strong-field test particle

$$g_{\mu\nu}dx^\mu dx^\nu = -A\, dT^2 + B\, dR^2 + R^2 d\Omega^2$$

$$A = 1 - \frac{2\mathcal{M}}{R}$$



Hamiltonian (8-d phase space): $$\mathcal{H} = \frac{1}{2}g^{\mu\nu}P_\mu P_\nu = -\frac{1}{2}m^2$$

for timelike geodesics ($g^{\mu\nu}u_\mu u_\nu = -1,\ \ P_\nu = m u_\nu$)

Want a global evolution parameter: use coordinate time, reduce to 6-d phase space by solving for

$P_t = - H_{geodesic}$ $\longrightarrow$ $$\frac{H_{\rm geodesic}}{m} = \sqrt{A\left(1 + \frac{P_R^2}{m^2 B} + \frac{P_\phi^2}{m^2 R^2}\right)}$$

Going beyond a test-particle description

- viewpoint: use strong-field geodesics as the underlying structure for an effective description. Next, include finite-mass ratio effects

- Assume finite mass ratio effects are smooth deformations of the test particle limit.

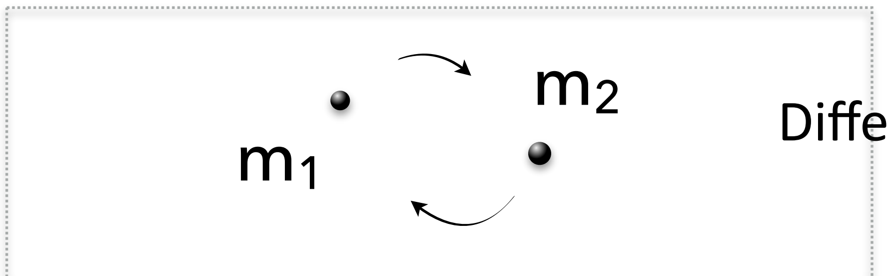
Potentials acquire corrections, e.g. $A^{\rm eff} = 1 - \frac{2\mathcal{M}}{R} + \frac{m}{\mathcal{M}}\,\delta A$ *Correction yet to be determined*

- No longer an exact solution to the Einstein field equations, but:
  - It becomes exact in the test-particle limit
  - finite mass-ratio corrections chosen to match post-Newtonian results $\Longrightarrow$ it also becomes exact for any mass ratio in the semi-relativistic regime
  - The in-between interpolation is informed by numerical relativity results

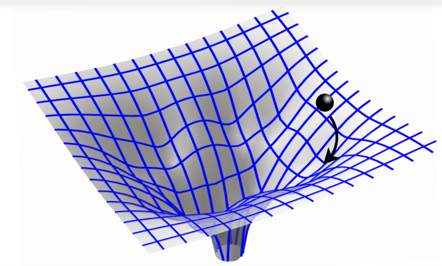
- Next: make an identification between such an effective description and the two-body dynamics

Mapping to the effective description

- Constants of motion in both cases: energy E (=Hamiltonian) and angular momentum $L=P_\phi$
- invariant quantities measuring phase space areas are the action variables



Different canonical coordinates



$$J_r(E,L) = \frac{1}{2\pi}\oint p_r\,dr$$

$$J_\phi(E,L) = L$$

Identify

$$J_r(E^{\rm eff},L^{\rm eff}) = \frac{1}{2\pi}\oint P_R\,dR$$

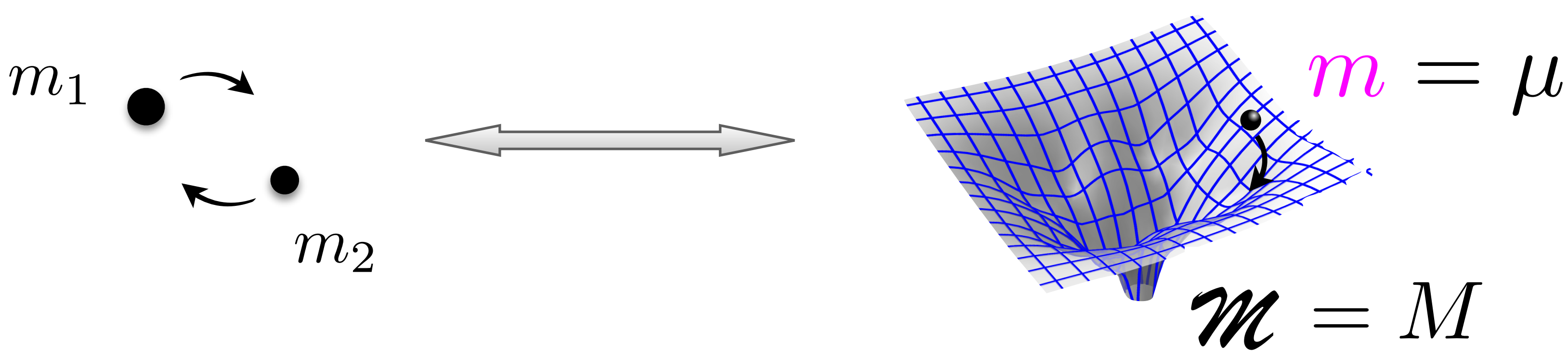
$$J_\phi(E^{\rm eff},L^{\rm eff}) = L^{\rm eff}$$

$$L_{\rm eff} = L$$

$$E_{\rm eff} = \frac{E^2 - m_1^2 - m_2^2}{2M}$$

Mapping to the effective description cont.

- Re-arrange the 'energy map' (energy ⇨ Hamiltonian,) to obtain the EOB Hamiltonian:



$$\boxed{H_{\rm EOB} = M\sqrt{1 + 2\nu\left(\frac{H_{\rm eff}}{\mu} - 1\right)}} \qquad \nu = \frac{\mu}{M}$$

- Evolution and physical quantities are computed from $H_{\rm EOB}$
- To recover Newtonian two-body reduced-mass motion requires

$$\mathcal{M} \leftrightarrow M = m_1 + m_2 \qquad\qquad m \leftrightarrow \mu = m_1 m_2 / M$$

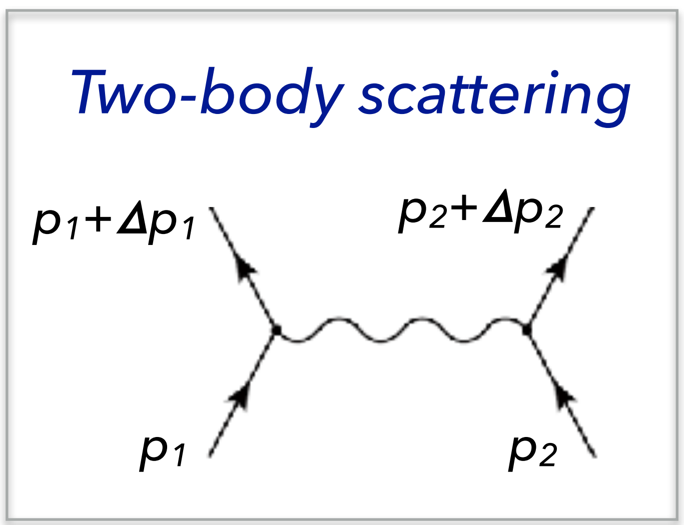
EOB energy map in other contexts

- Similar map in QED inspired the original EOB idea

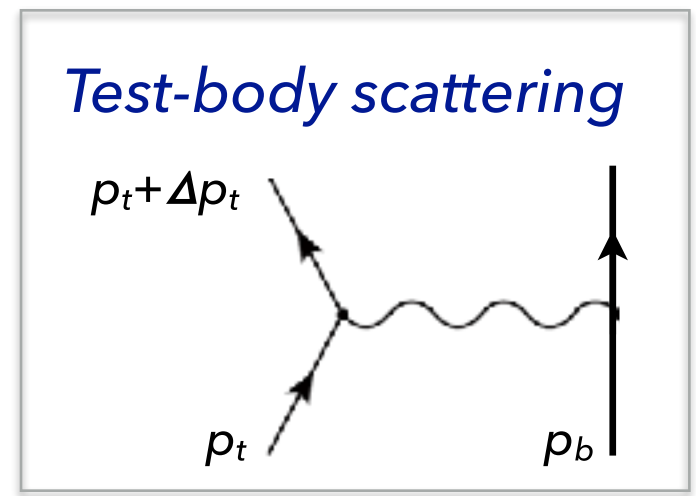
  [``Relativistic Balmer Formula Including Recoil Effects'', Brezin, Itzykson, Zinn-Justin (1970)]

- Also found in relativistic scattering [Damour 2016, 2017; Vines 2017]

To $O(G)$:



identify scattering angles



Dynamics equivalent with the energy map

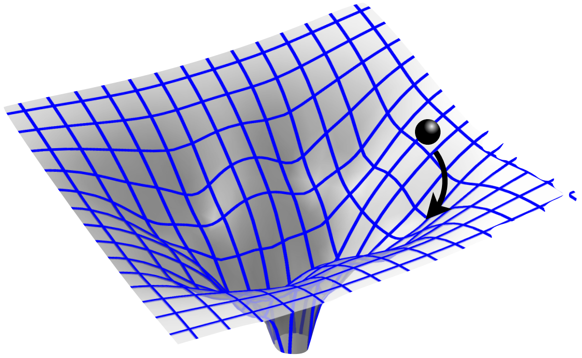
$$E = M\sqrt{1 + 2\nu\left(\frac{E_t}{\mu} - 1\right)}$$

Post-Minkowski (scattering)

$$\frac{GM}{Rc^2} \ll 1 \qquad \frac{v^2}{c^2} \lesssim 1$$

EOB model for the dynamics

$$H_{\rm EOB} = M\sqrt{1+2\nu\left(\frac{H_{\rm eff}}{\mu}-1\right)}$$



- 2PN (post-Newtonian) order dynamics recovered with:

$$\frac{H_{\rm eff}^2}{\mu^2} = A\left(1+\frac{p_r^2}{\mu^2 B}+\frac{p_\phi^2}{\mu^2 r^2}\right)$$

$$A = \underbrace{1-\frac{2M}{r}}_{\text{Newtonian \& Schwarzschild}} + \underbrace{2\nu\frac{M^3}{r^3}}_{\text{2PN}}$$

- beyond 2PN: a few non-geodesic terms $O(p_r^4, p_r^6)$ appear in H_{eff}
- More terms in the potentials A, B . Expressions are re-summed (written as non-analytic functions)
- Extra new higher-order-like terms included with coefficients calibrated to numerical relativity

c.f. post-Newtonian results at 2PN

$$\hat{H}[\mathbf{r},\mathbf{p}] = \hat{H}_{\mathrm{N}}(\mathbf{r},\mathbf{p}) + \frac{1}{c^2}\hat{H}_{1\mathrm{PN}}(\mathbf{r},\mathbf{p}) + \frac{1}{c^4}\hat{H}_{2\mathrm{PN}}(\mathbf{r},\mathbf{p})$$

$$\hat{H}_{\mathrm{N}}(\mathbf{r},\mathbf{p}) = \frac{p^2}{2} - \frac{1}{r},$$

$$\hat{H}_{1\mathrm{PN}}(\mathbf{r},\mathbf{p}) = \frac{1}{8}(3\nu - 1)p^4 - \frac{1}{2}\left[(3+\nu)p^2 + \nu p_r^2\right]\frac{1}{r} + \frac{1}{2r^2},$$

$$\begin{aligned}\hat{H}_{2\mathrm{PN}}(\mathbf{r},\mathbf{p}) = &\frac{1}{16}(1 - 5\nu + 5\nu^2)p^6 \\ &+ \frac{1}{8}\left[(5 - 20\nu - 3\nu^2)p^4 - 2\nu^2 p_r^2 p^2 - 3\nu^2 p_r^4\right]\frac{1}{r} \\ &+ \frac{1}{2}\left[(5 + 8\nu)p^2 + 3\nu p_r^2\right]\frac{1}{r^2} - \frac{1}{4}(1 + 3\nu)\frac{1}{r^3},\end{aligned}$$

[Schaefer & Jaranowski, Living Reviews in Relativity 21:7 (2018)]

Beyond the conservative dynamics

- Include GW dissipation as radiation reaction forces in equations of motion:

$$\frac{dP_i}{dt} = \{P_i, H^{\mathrm{EOB}}\} + \mathcal{F}_{\mathrm{rr}}$$

- Waveforms: PN results for dominant mode of GW strain amplitudes

$$h_{22}^{\mathrm{PN}}(t) = -\frac{8\pi}{5}\frac{\eta M}{\mathcal{R}} v^2\, e^{-2i\Phi}\left\{1 - \left(\frac{107}{42} - \frac{55}{42}\eta\right) v^2 + \left[2\pi + 12i \log\left(\frac{v}{v_0}\right)\right] v^3 + \dots\right\}$$

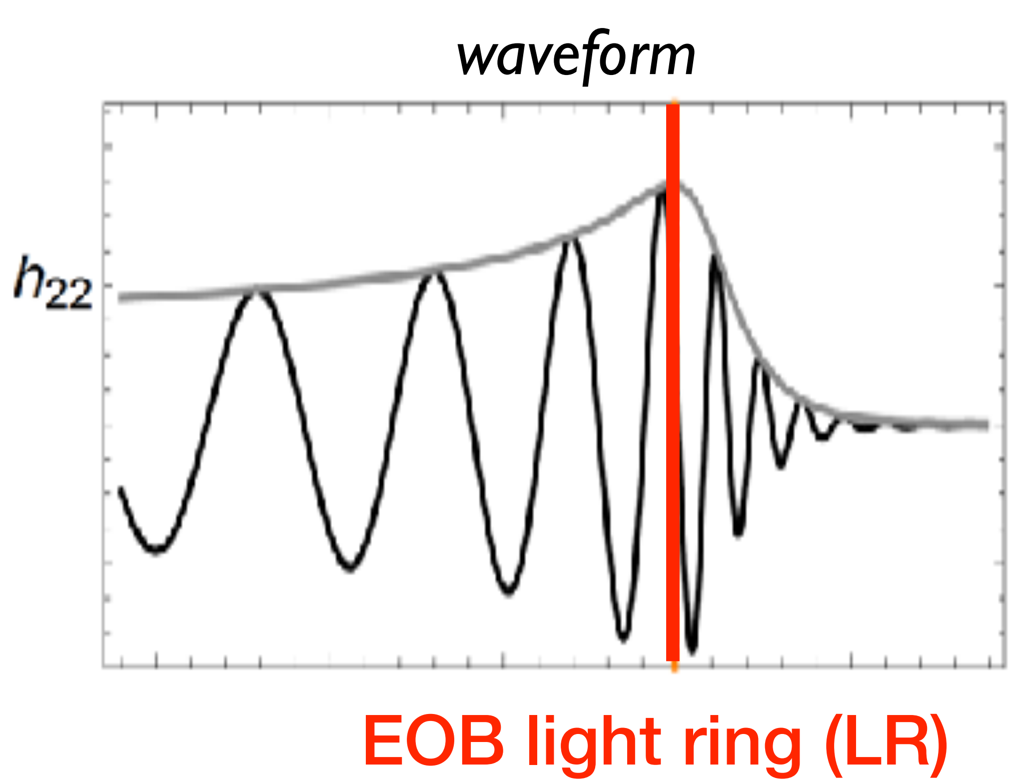
- EOB: factorized form, inspired by test-particle limit

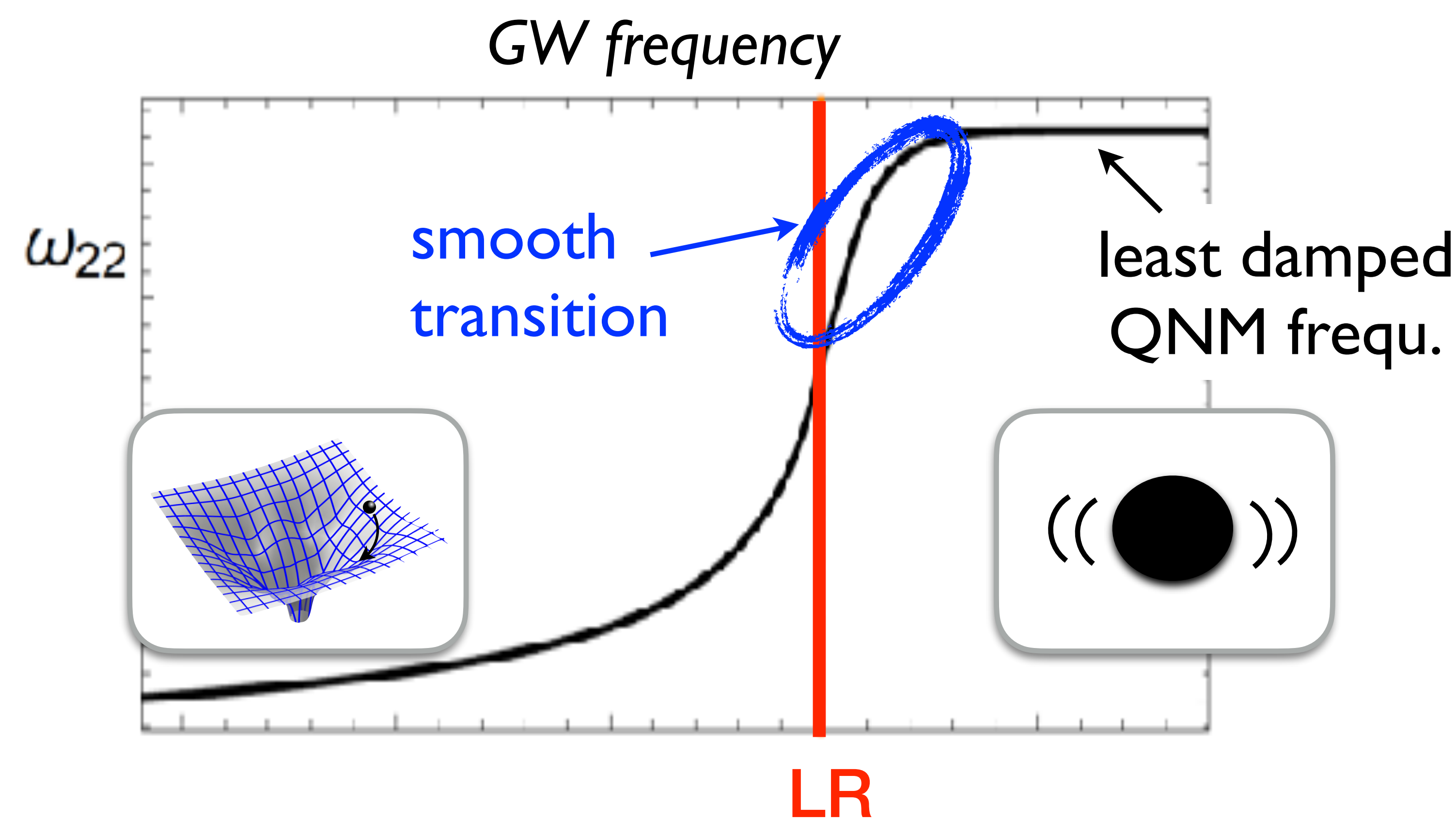
$$h_{22}^{\mathrm{EOB}}(t) = h^{\mathrm{Newt}} e^{-2i\Phi} \mathcal{S}_{\mathrm{eff}}\, \rho^2\, T e^{i\delta}\, h^{\mathrm{NQC}}$$

non-quasi-circular correction,
important near merger,
tuned to numerical relativity results

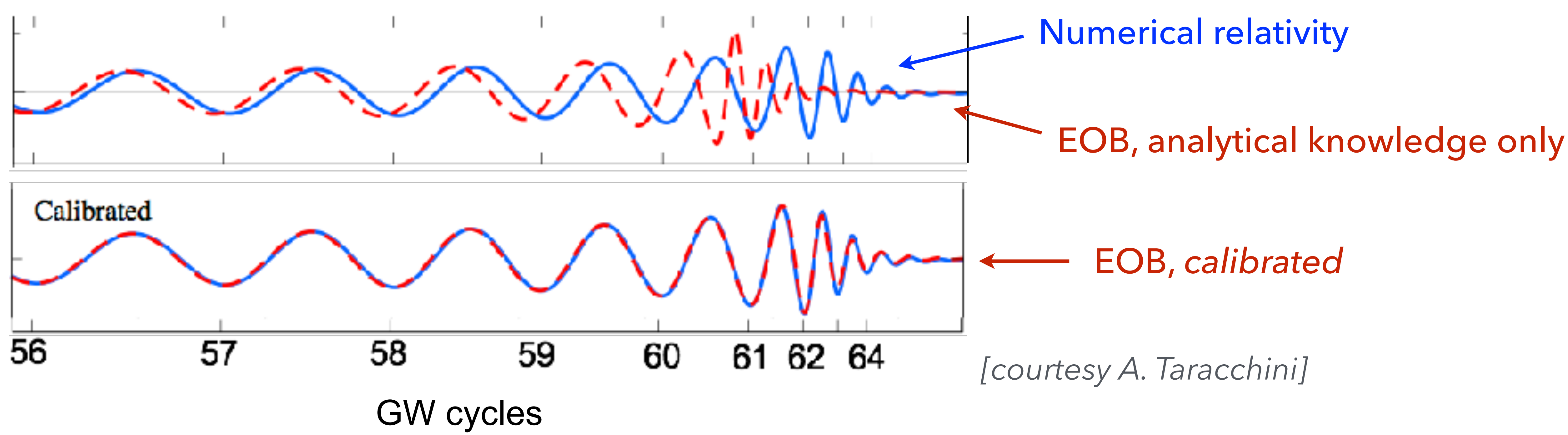
tail effects

Complete EOB waveforms for black hole binaries





- performance of EOB waveforms:

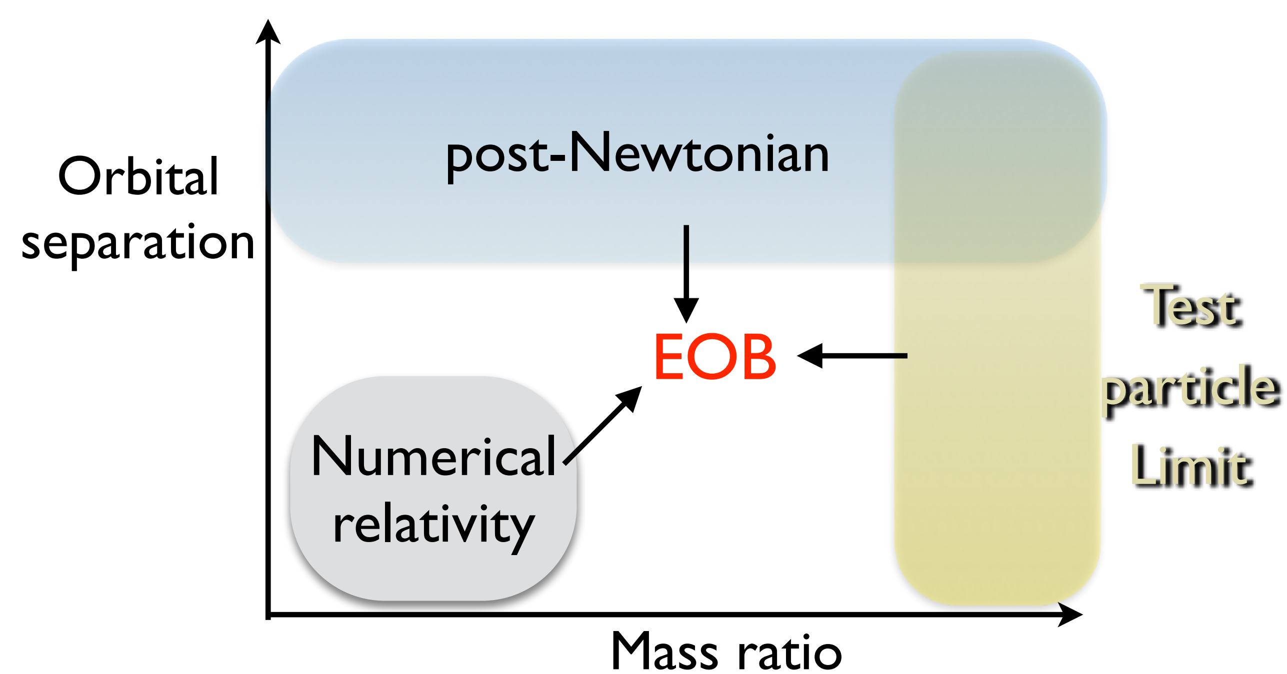


[courtesy A. Taracchini]

EOB model

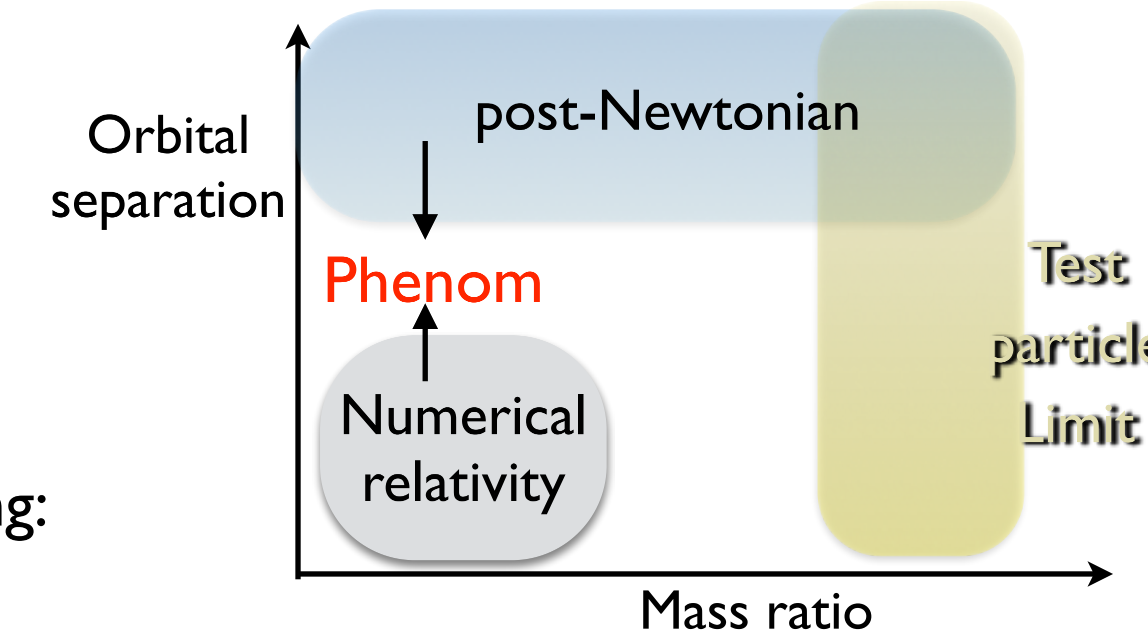
The EOB model is not a full exact solution to the Einstein field equations, but:

- It becomes exact in the limits of
    - Infinitely large mass ratio (test-particle)
    - for any mass ratio in the semi-relativistic regime
- The interpolation between these regimes is adjusted to match numerical relativity results
- Framework that can incorporate new advances in analytical/numerical calculations to produce more robust waveforms over a large parameter space
- Spin and finite-size effects also included



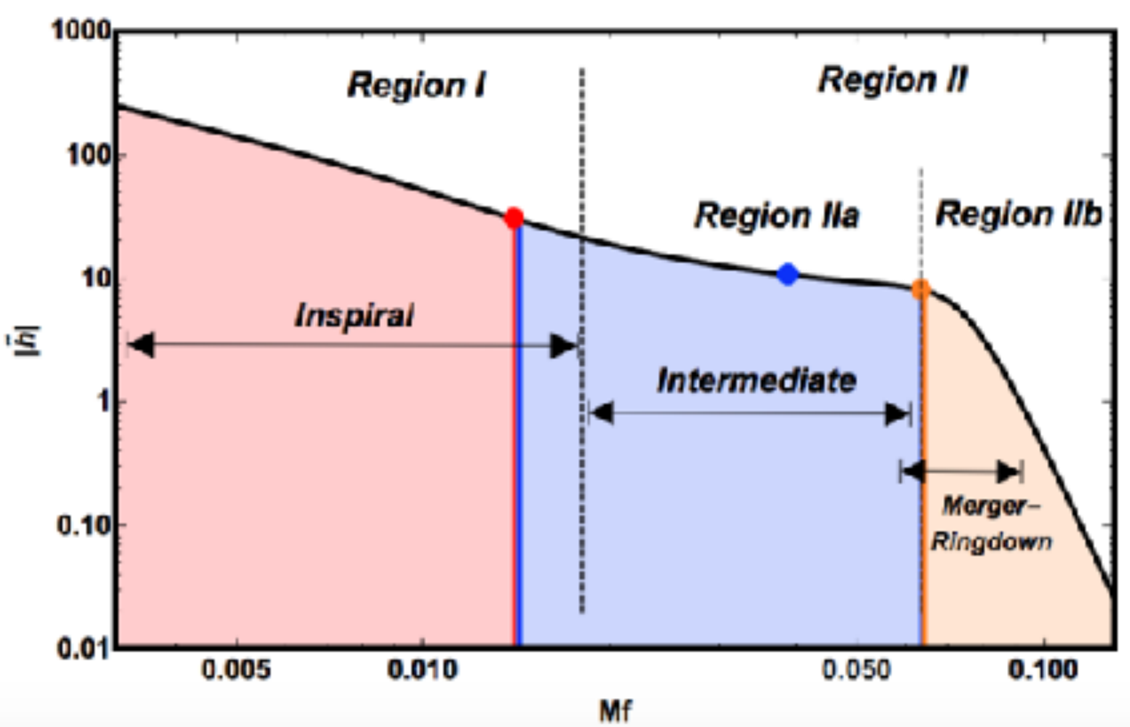
Another approach to computing full waveforms: Phenomenological models

- Efficient frequency-domain models for GWs
- Closed-form expressions
- fits for GW amplitude and phase in different regions



Post-newtonian results for the frequency-domain phasing:

$$\psi_{\rm PN} = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\nu}(\pi M f)^{-5/3} \sum_{k=0}^{7} \alpha_i (\pi M f)^{k/3}$$



are augmented by extra terms whose coefficients are calibrated to match numerical relativity

$$\psi_{\rm Phenom}^{\rm inspiral} = \psi_{\rm PN} + \frac{1}{\nu} \sum_{k=0}^{6} \sigma_k f^{k/3}$$

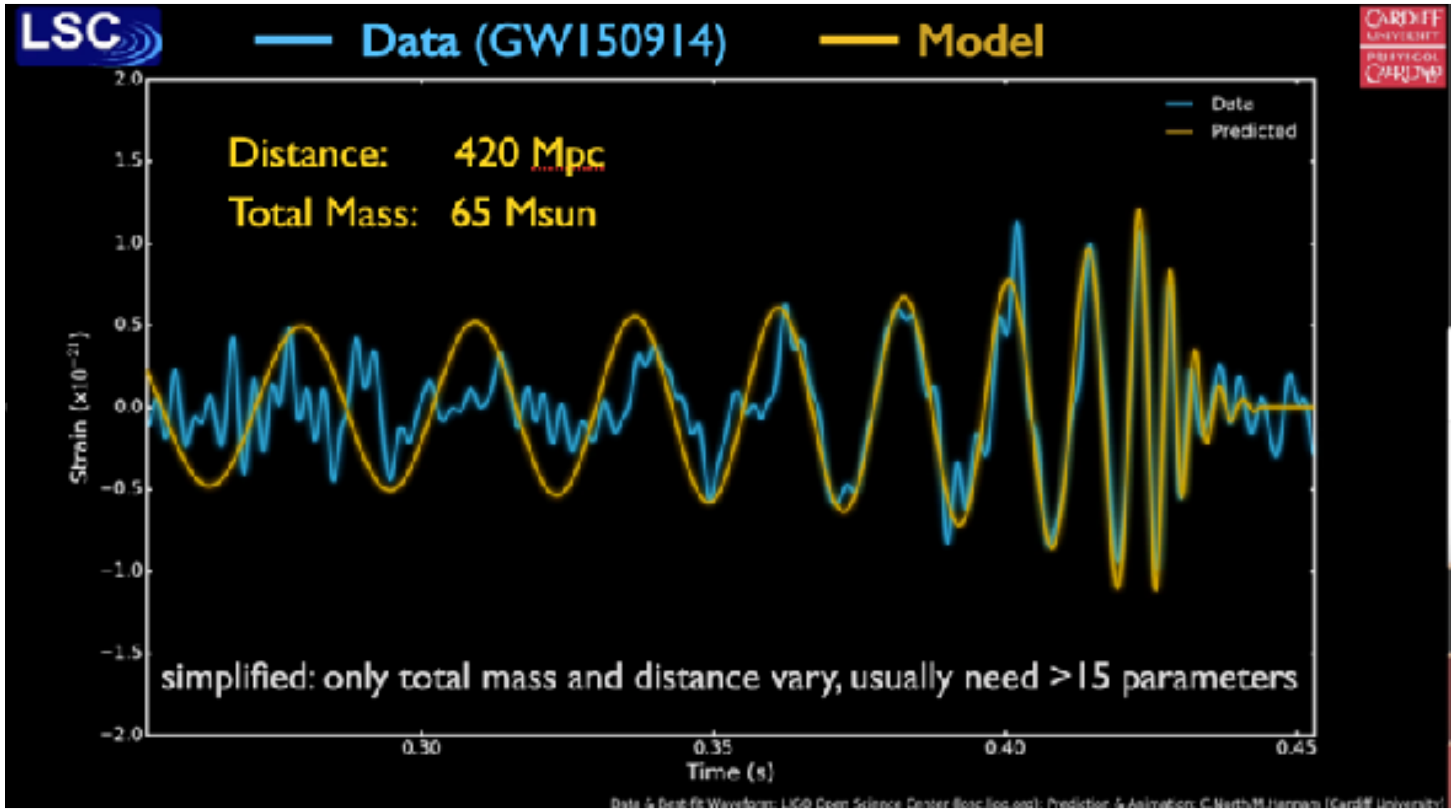
Fitting parameters

& smoothly connected with merger-ringdown fits

Khan+2015

Recall: models are crucial for extracting science from GWs

Measurements rely on models to interpret the signals



Data analysis requires millions of model waveforms for each event

Need models that

- Are highly accurate, cover the entire plausible parameter space (and computationally efficient)
- include all relevant physical effects
- retain flexibility to discover new phenomena

Modeling uncertainties and limitations

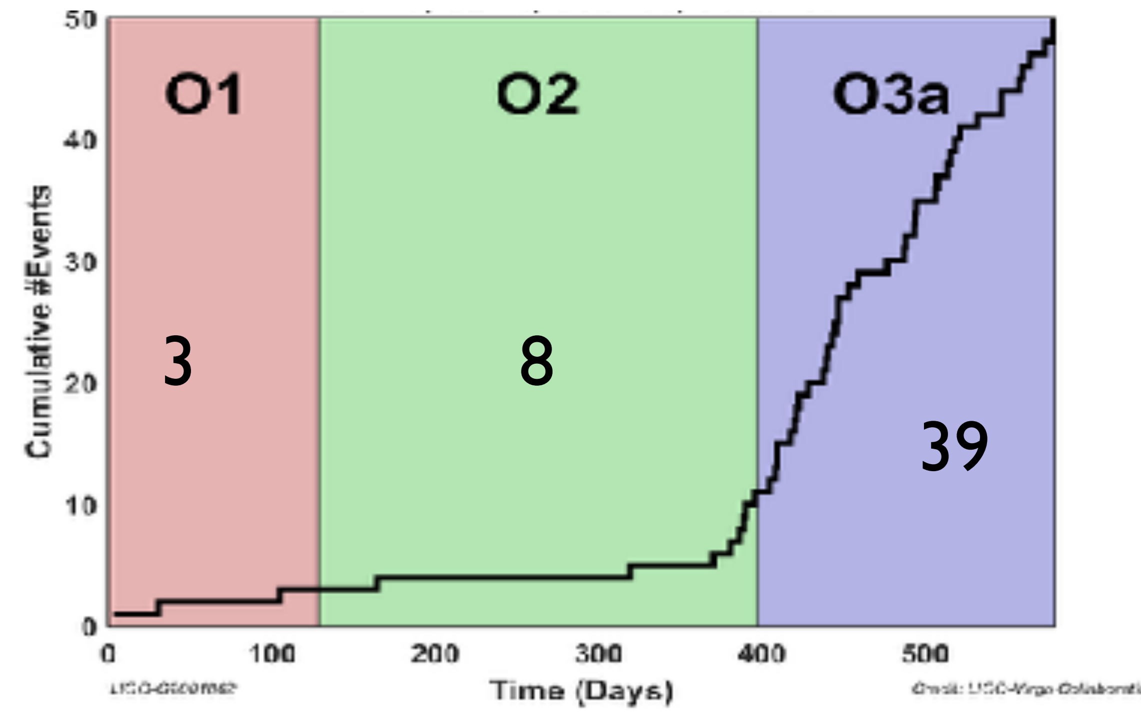
- Two sources of inaccuracies:
  - Same physics, different modeling choices (e.g. EOB, Phenom)
  - Missing physics

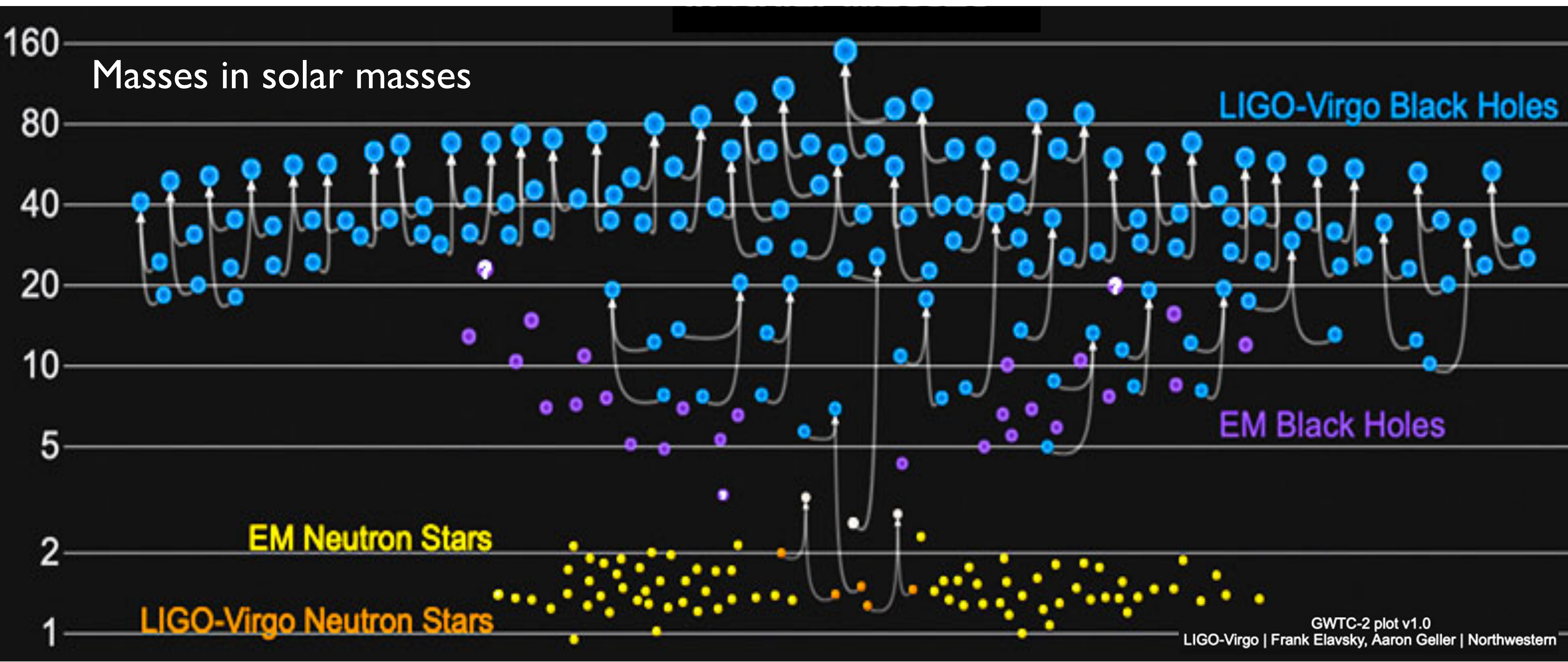
- For events measured to date:

  impact of modeling uncertainties still subdominant compared to statistical errors but starting to become noticeable in some cases

Abbot+2020, GWTC-2 (Appendix on waveform systematics)

GW observations of 50 binary events published so far





Plans for future ground-based detectors underway

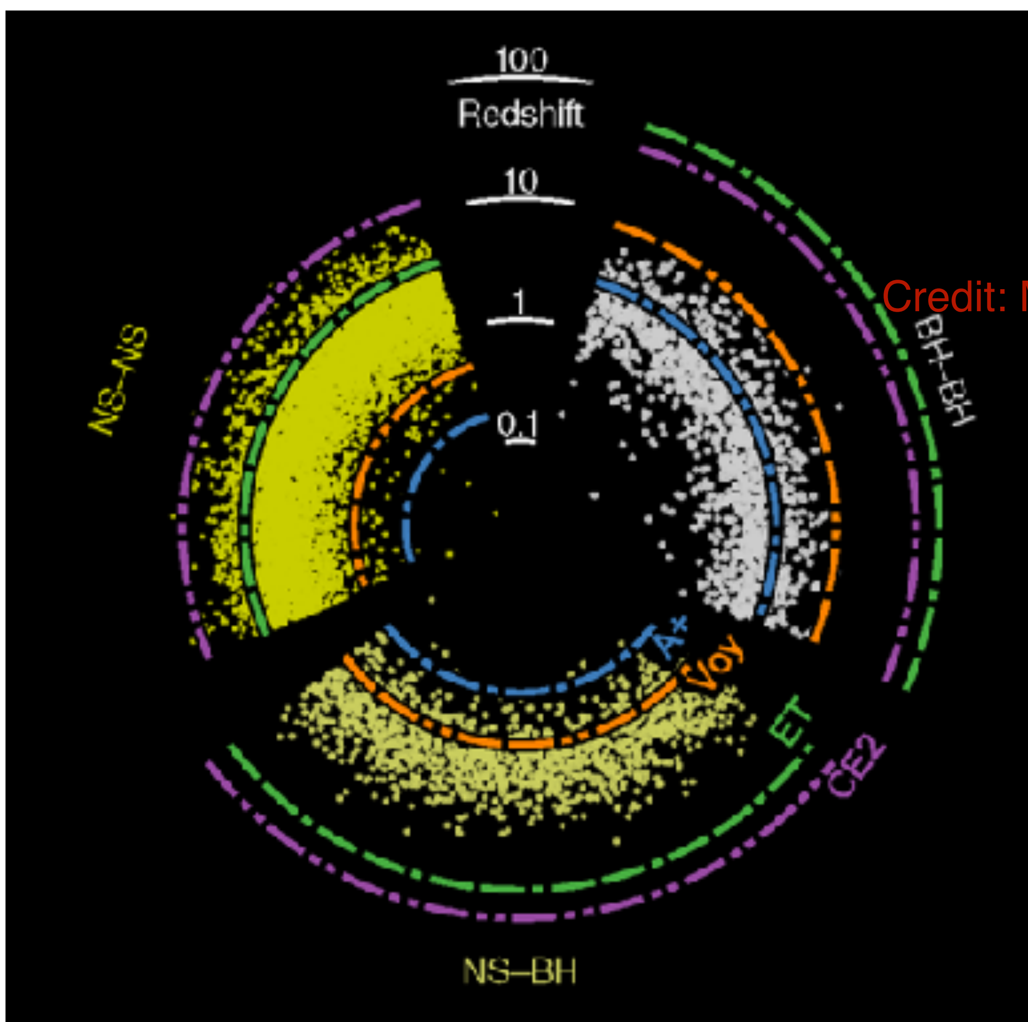
O4 observing run to start mid 2022, reaching design sensitivity

Planned upgrades: LIGO,Virgo A+ upgrade ~mid/late 2020s

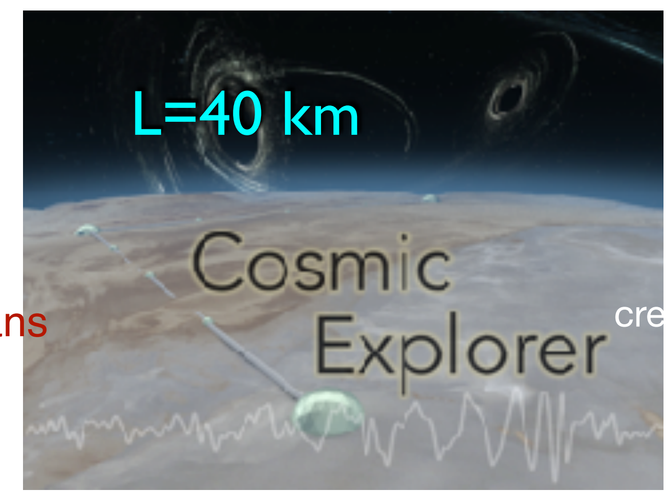
Science case & funding pathways for new detectors:

~ 2035 Einstein Telescope [with a possible site in in the NL-D-B tri-border area near Maastricht]

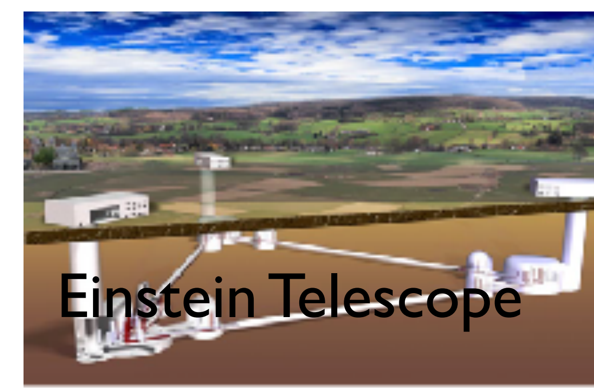
Cosmic Explorer(s) [US]



Credit: M. Evans



L=10 km triangle

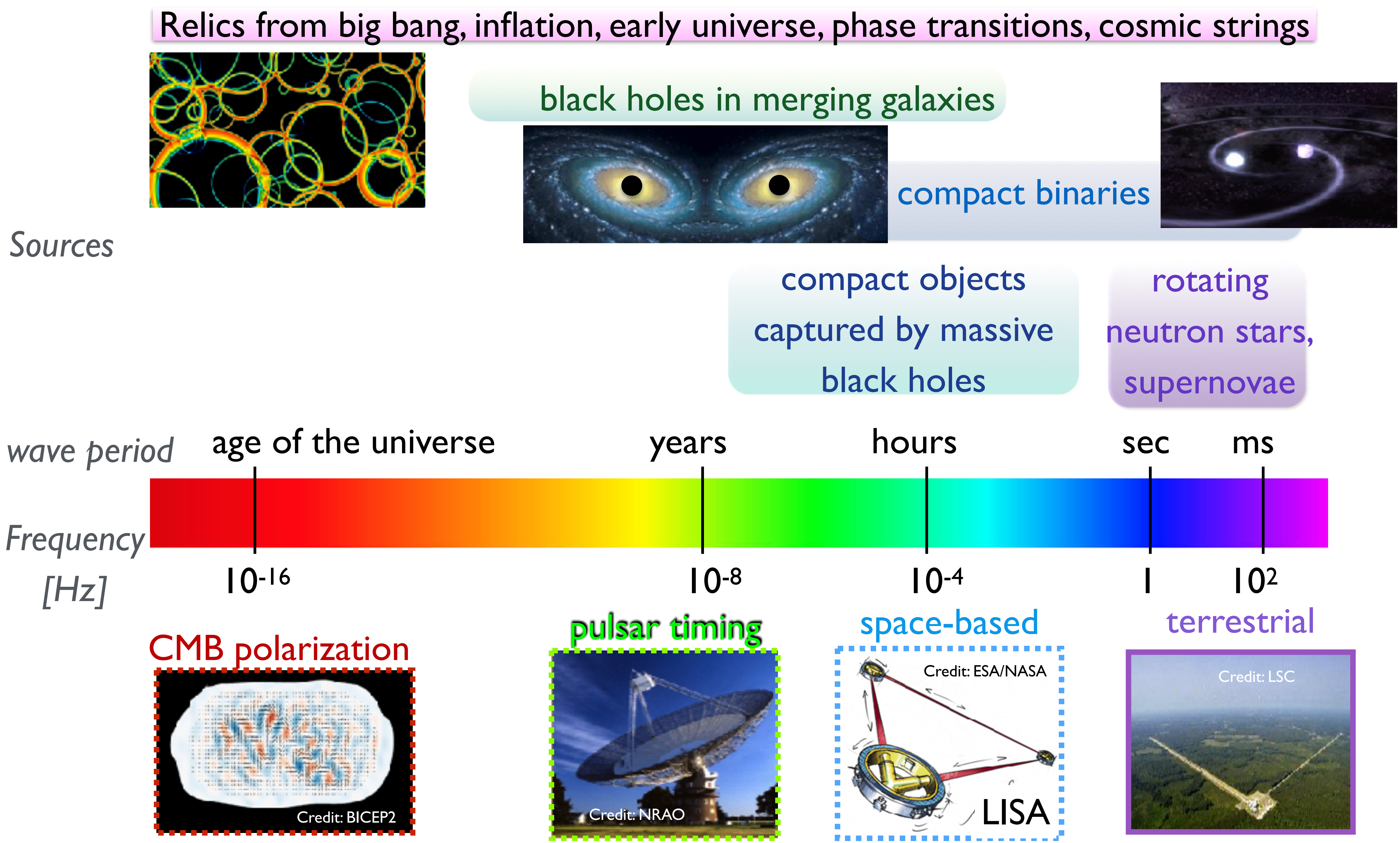


O(10^5) binary detections / year

Greater number and diversity of GW events,

Higher measurement accuracy for nearby sources

The GW spectrum: over 20 decades in frequency



GWs as a new tool for fundamental physics

Gravity in nonlinear, strong-field, dynamical regimes?

Nature of black holes?

Number of black holes in the universe? How & when formed?

Dark matter? Beyond standard model particle physics?

Matter at extreme density in neutron stars?

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