Probing traces of quantum gravity in observations of black holes

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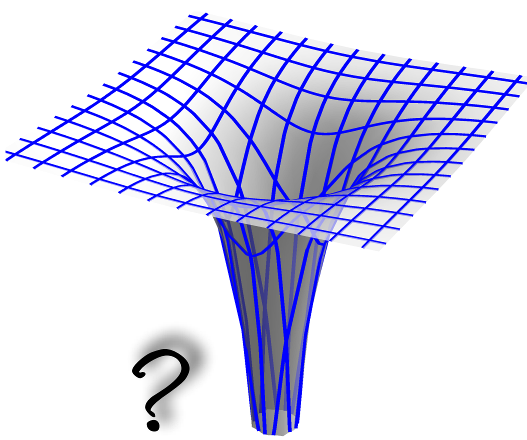
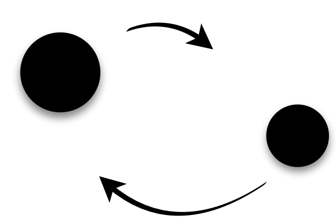
QG-MMA meeting

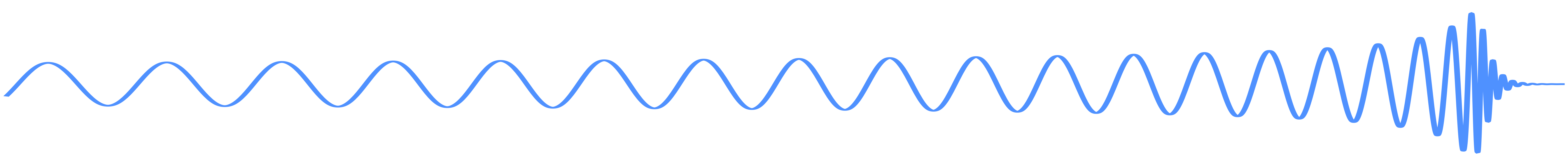
Oct 3, 2019

Outline of this talk

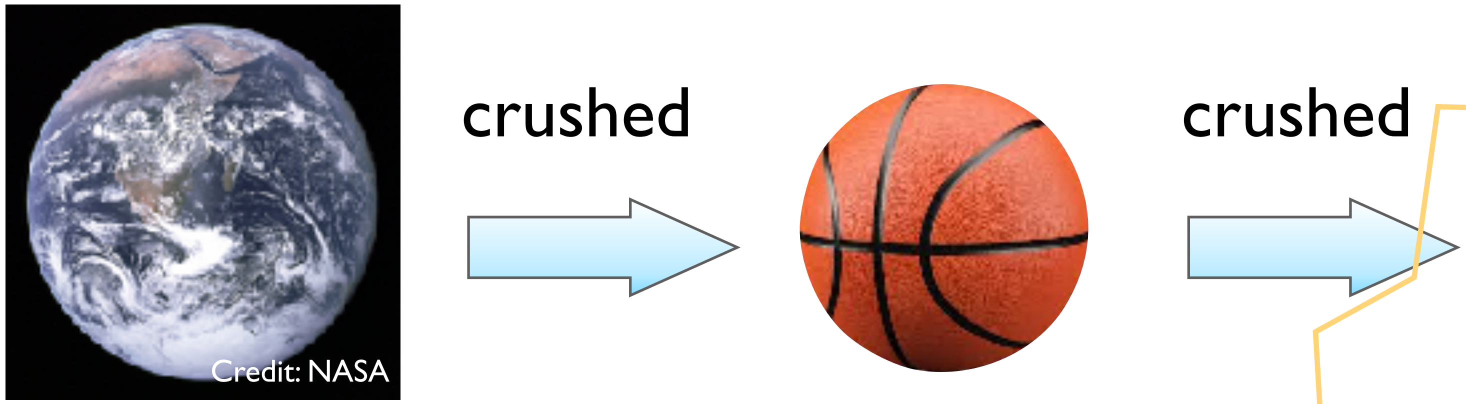
- Motivations for quantum corrections at black hole (BH) horizon scales
- Features of proposed models
- Observational signatures with focus on gravitational waves (GWs)
  - Binary inspiral: nature of the progenitors
    - clean, cumulative, generic phenomena
  - Merger, ringdown: nature of the remnant
- Outlook



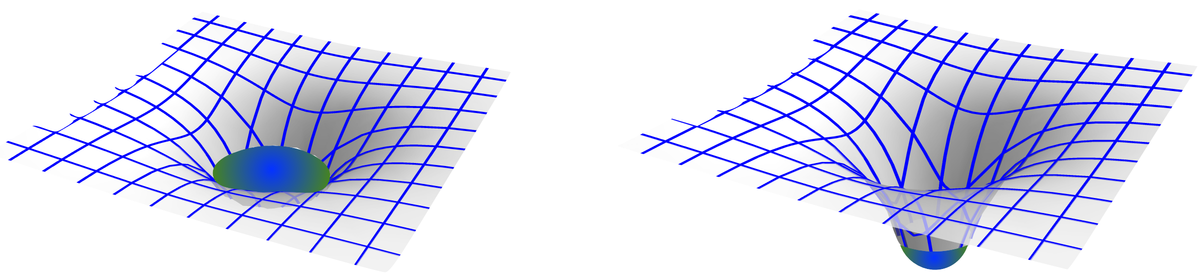


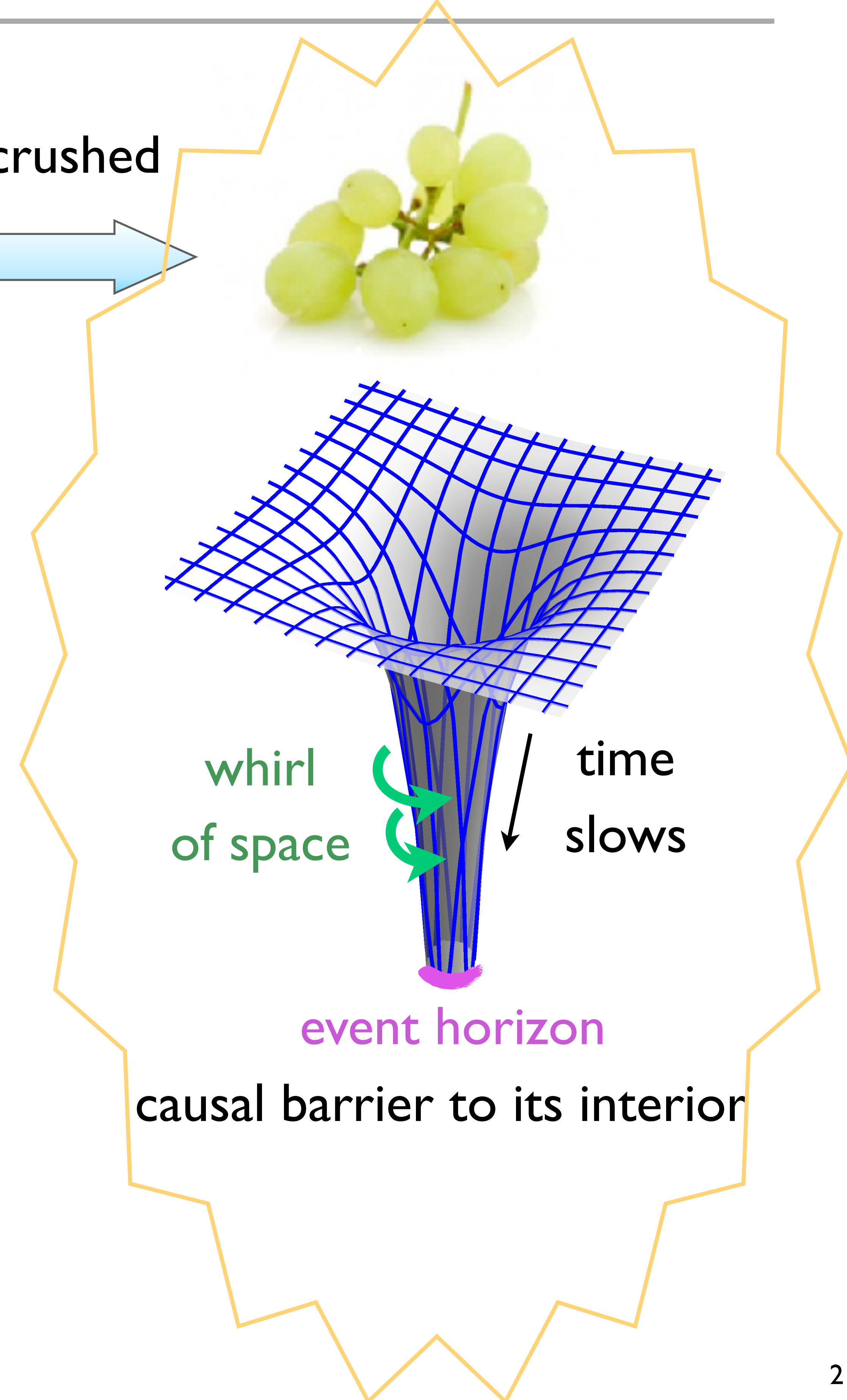


Classical Black holes (BHs) in General Relativity



curvature



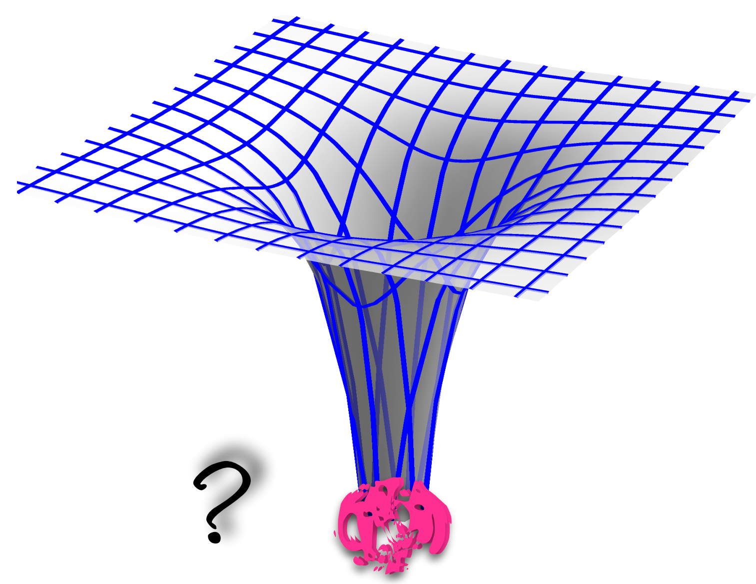


black hole (BH)

- region of immense spacetime curvature
- no surface
- described entirely by its mass and spin

Why consider QG traces at BH horizon scales?

- For astrophysical BHs: curvature at horizon is far from the Planck scale
- However, deep theoretical puzzles with classical horizons, e.g.
  - **Quantum Field Theory + horizons: Information paradox**
  - **Microscopic interpretation of BH entropy?**

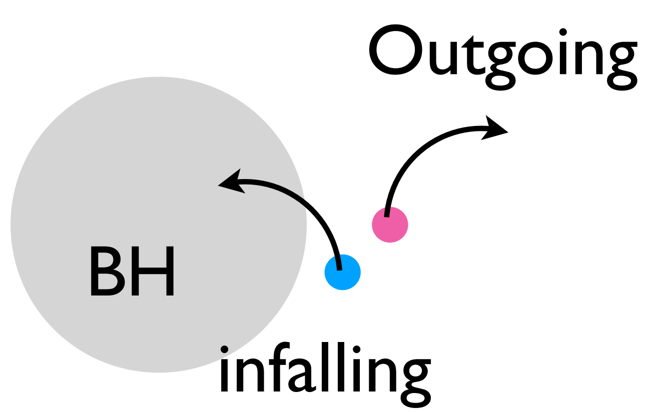


Disclaimer: non-expert view follows …

Information Paradox

Hawking 1975 [semiclassical QFT on BH background]:

entangled particle pairs are produced near a horizon



- Hawking radiation
- ultimately, the BH evaporates
- only thermal radiation remains but nothing it is entangled with [does not make sense]

Or more simply: Where does the information on the initial state go?

See e.g. arXiv:1902.04504v3 for a modern view and details of logical inconsistencies

Could including sub-leading order quantum corrections cure this problem?

Mathur 2009 [quantum information calculation] *(also Giddings2011, Avery 2011):*

would need order unity quantum-gravity corrections at the horizon

Where are the microstates corresponding to BH entropy?

Bekenstein, Hawking: BHs have entropy proportional to horizon area A

$$S_{\mathrm{BH}} = \frac{A}{4G}\frac{c^3}{\hbar}$$

$$A = 16\pi M^2$$ For a nonspinning BH

Huge!

~ 10^{77} $(M/M_{\odot})$ Joule/Kelvin

Boltzmann: entropy counts microscopic configurations: $S \sim \ln(N)$

Where and what are all those microstates?

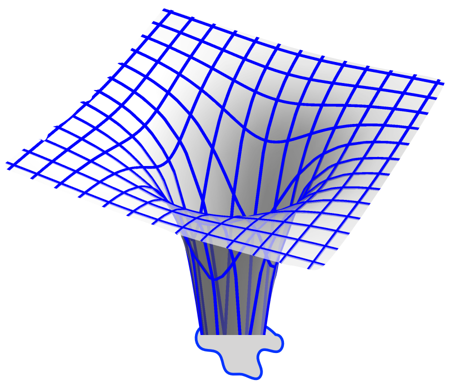
Example possible explanation [Strominger & Vafa 1996]:

BH microstates in supergravity (branes & strings) match BH entropy

Also explained within Loop quantum gravity [see e.g. the review 1703.09149]

Examples of how quantum effects may modify BH horizons

- String theory (10d supergravity) bound states of branes. see e.g. arXiv:1409.1231
  - Microstate geometries/Fuzzballs [Mathur, Warner, Bena, Turton, …+]



BH-like object = ensemble of horizonless micro state geometries

note: these are supersymmetric (near-)extremal BHs

Smooth cap + topology in extra dimensions

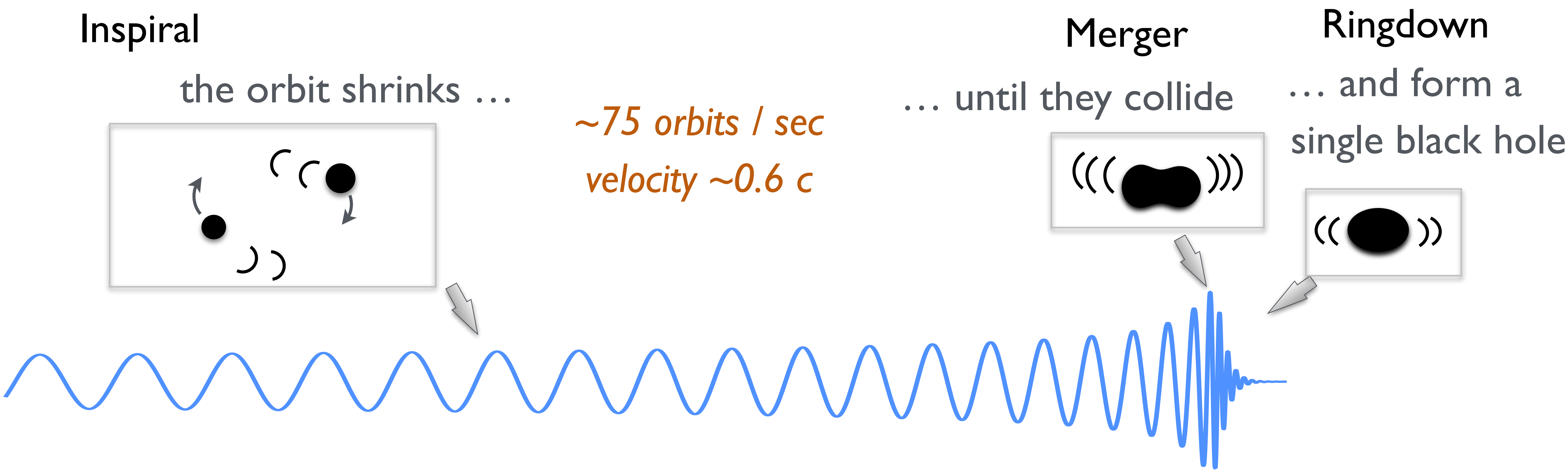
- Gravastars [Mazur, Mottola +]

  Negative pressure interior (de Sitter spacetime) matched to Schwarzschild exterior

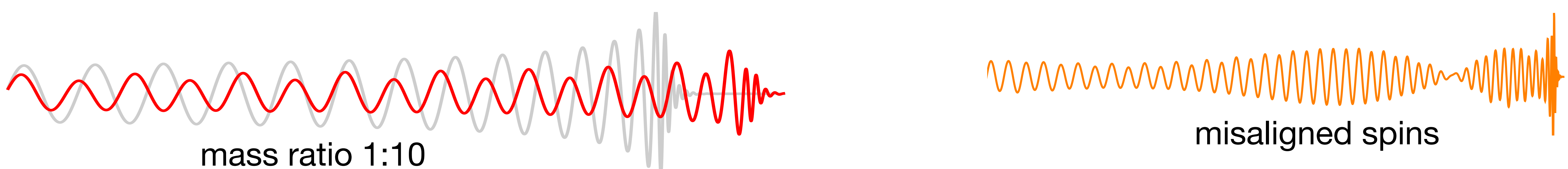
- Collapsed polymers [Barcelo+]
- Quantum bounces [Holdon, Ren, Brusten, Medved +]
- black stars, nonlocal stars [Mazumdar, Frolov+]
- BH-white hole tunneling [Rovelli+]
- …

What are observational signatures of horizon structures?

GW signals from classical BH binary systems in GR



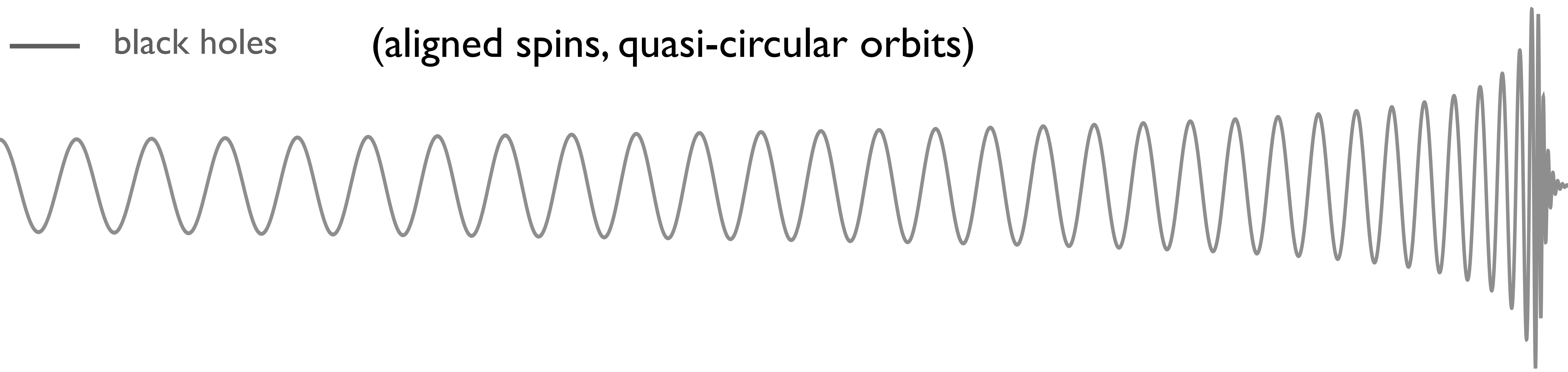
- Details of the waveform encode fundamental source properties



Interpretation of signals based on

cross-correlating the data with theoretical models (templates)

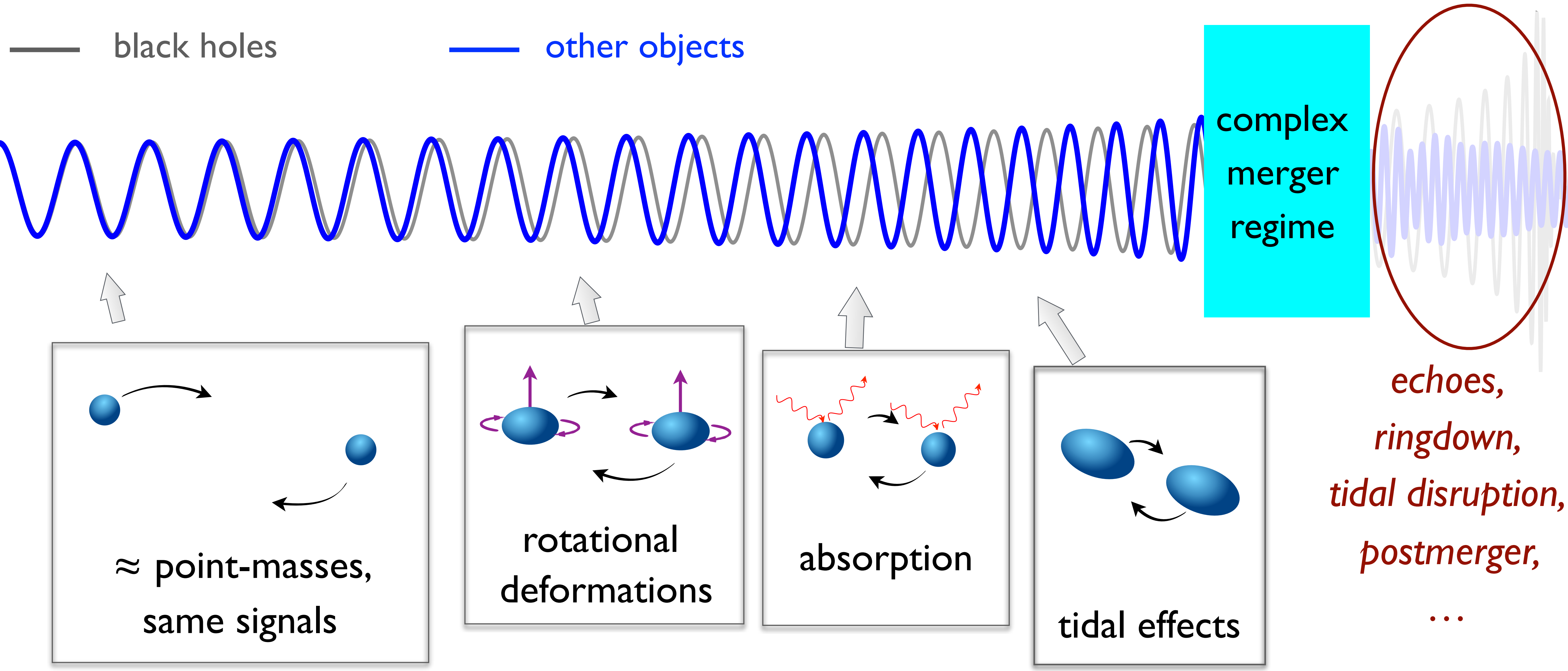
GW signatures of the nature of the objects



(aligned spins, quasi-circular orbits)

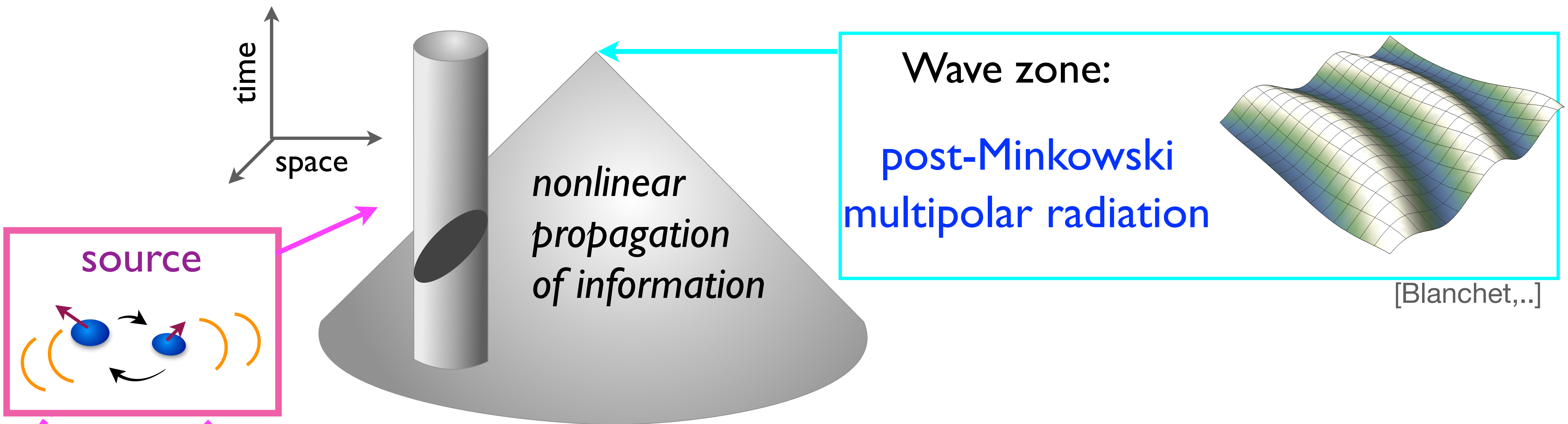
What changes for other objects (comparable masses)?

GW signatures of the nature of the objects



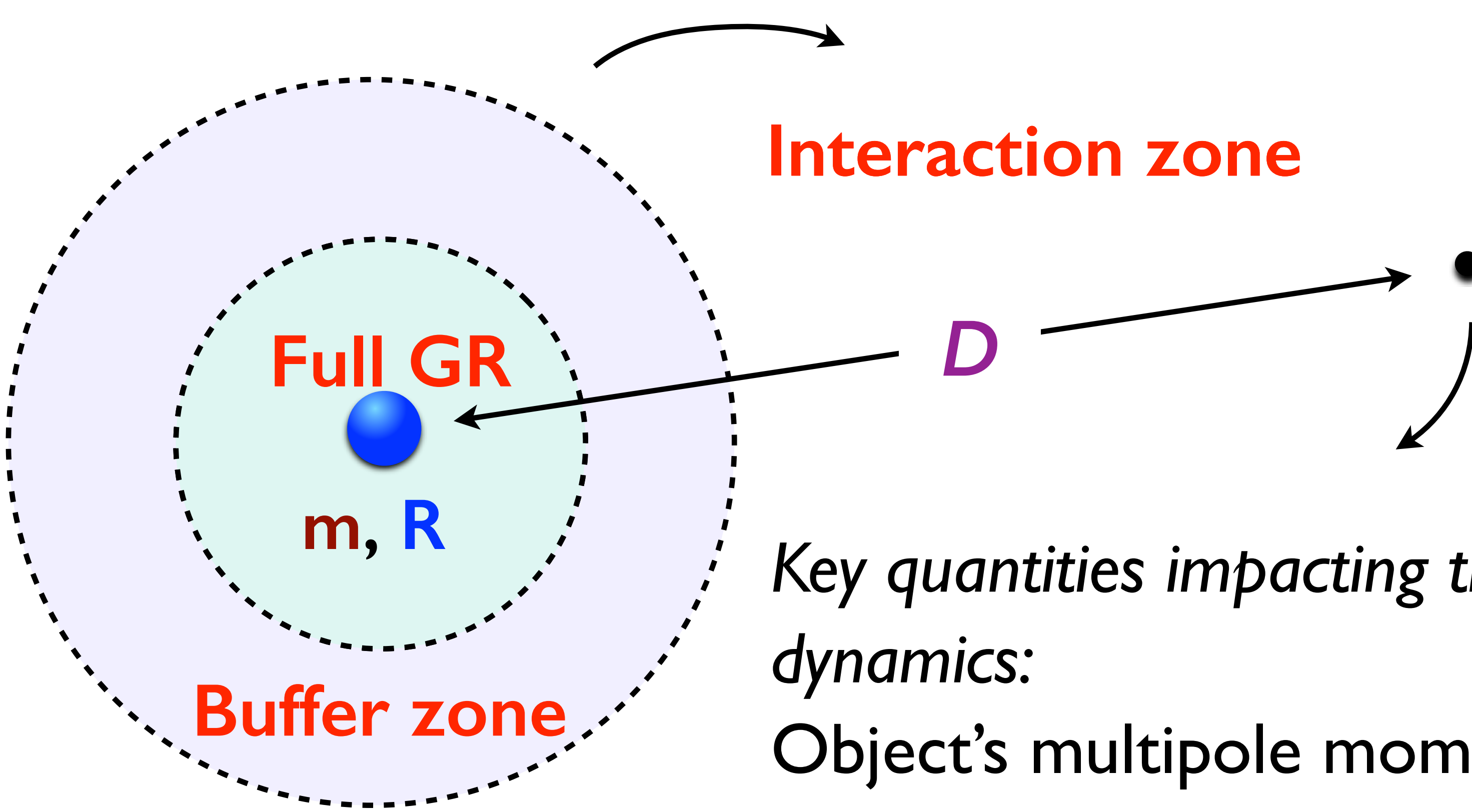
+ tidal excitation of oscillation modes

What specifically influences the GWs?



[Blanchet,..]

[Flanagan 1998, Racine, …]



Key quantities impacting the dynamics:
Object's multipole moments

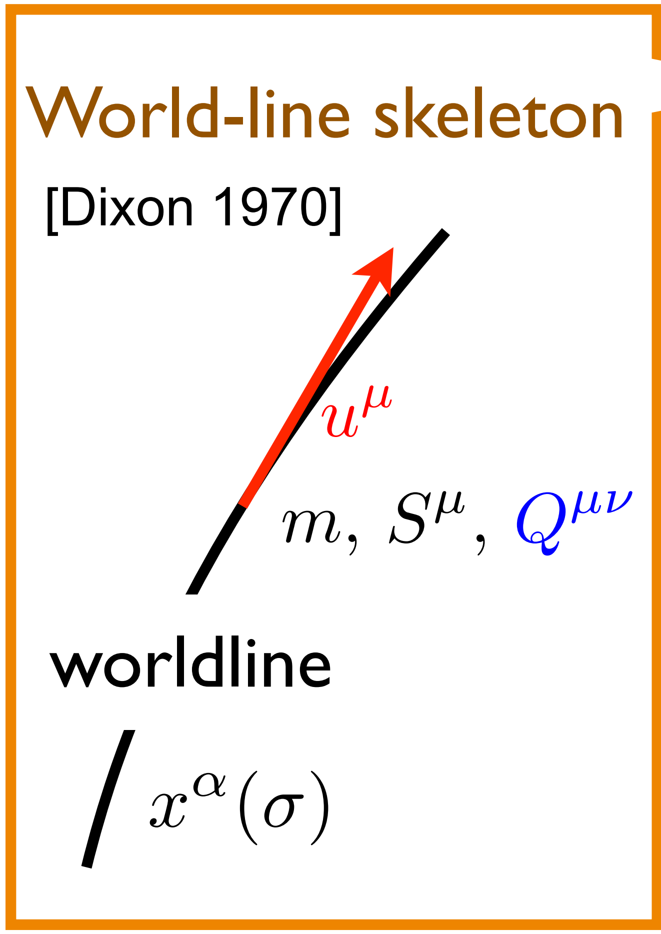
Dimensionless parameters:

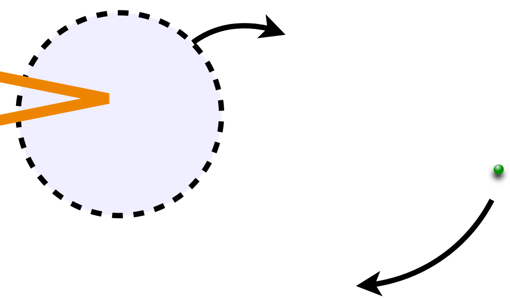
$$\delta = \frac{Gm}{Rc^2}$$ *NS's internal gravity (no approximation)*

$$\alpha = \frac{R}{D}$$ *Tidal expansion*

$$\epsilon = \frac{GM}{Dc^2}$$ *post-Newtonian expansion*

Interaction-zone dynamics





Buffer zone interior reduced to center-of-mass motion + multipoles

$$z = \sqrt{-u_\mu u^\mu}$$

Dynamics described by an effective action:

$$\boldsymbol{S = S_{\rm pp} + \int d\sigma \left[-\frac{z}{2} \mathcal{E}_{\mu\nu} Q^{\mu\nu} + L_{\rm int} + \dots \right]}$$

Point masses

Multipoles couple to companion's curvature

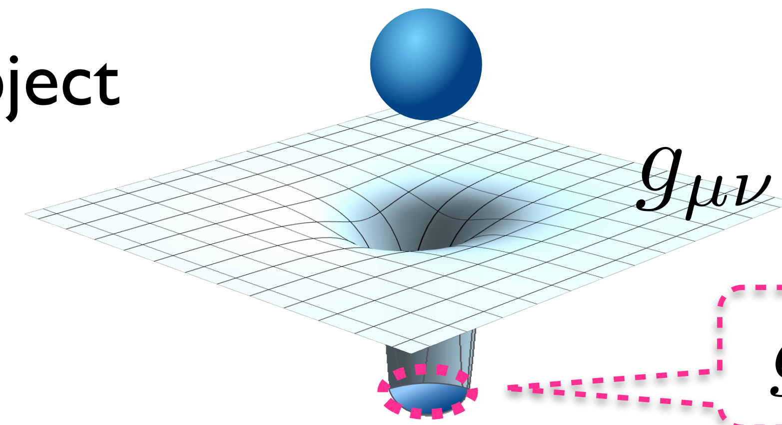
internal dynamics of $Q^{\mu\nu}$

$$\mathcal{E}_{\mu\nu} = C_{\mu\alpha\nu\beta} \frac{u^\alpha u^\beta}{z^2}$$ *Weyl tensor (companion)*

[Steinhoff, TH+ 2017; Pani, Vines, Landry, Poisson, Racine, +]

Body zone: example sources of multipole moments

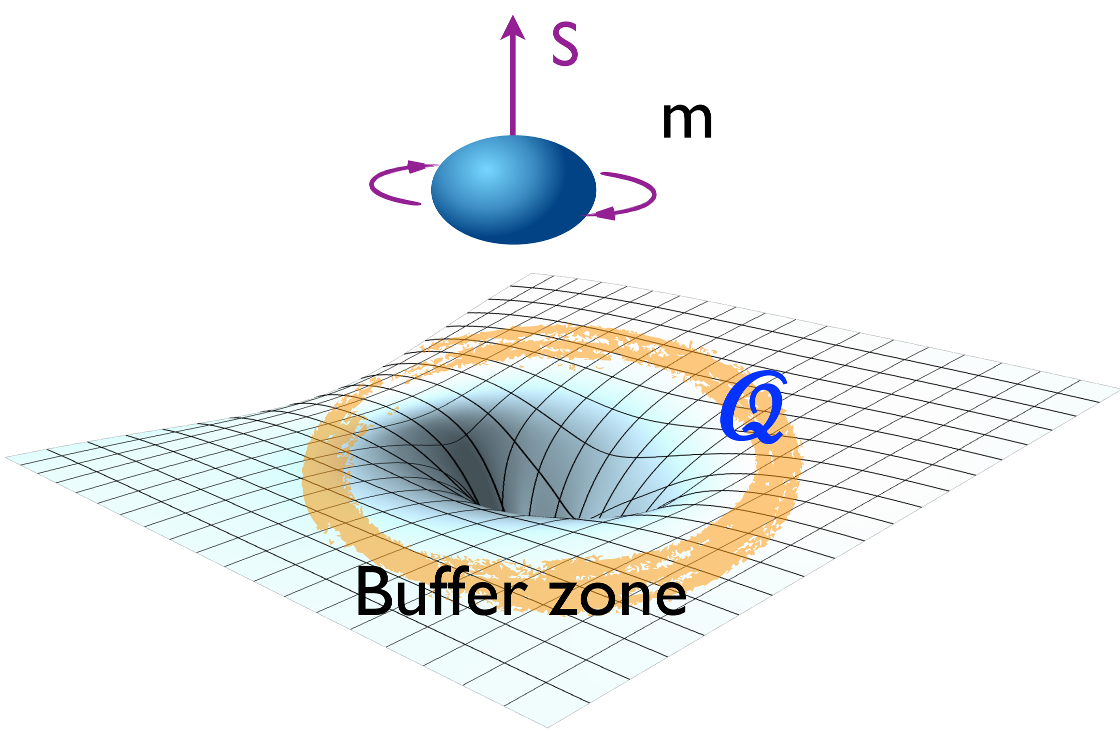
- Isolated non-spinning compact object



Spherically symmetric

$g_{\mu\nu}, T_{\mu\nu}$

- **Rotation**



$$\chi = \frac{S}{m^2}$$

(≤1 for BHs
≲0.4 for NSs)

Rotational multipoles

$$Q_{\rm spin} = -\kappa\, \chi^2 m^3$$

=1 for BHs

Characteristic parameter

No-hair theorem: $M_\ell + i S_\ell = m(i\chi m)^\ell$

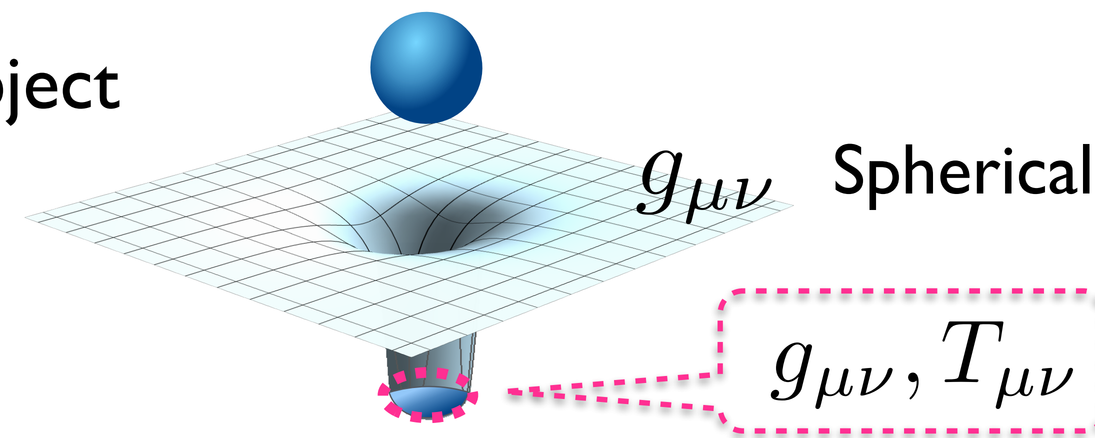
Mass moments

Current moments

[Poisson, Laraakers, 1999, …]

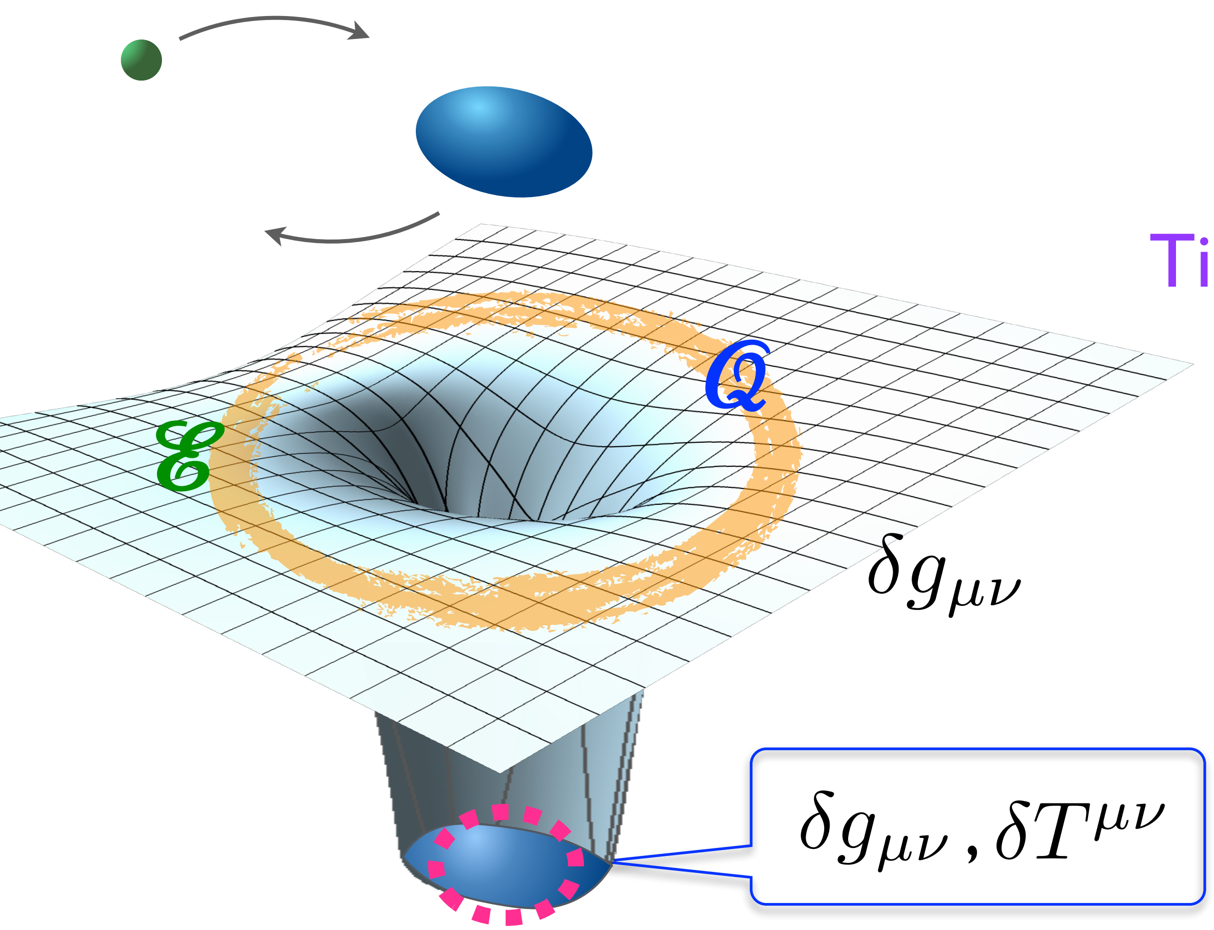
Body zone: example sources of multipole moments

- Isolated non-spinning compact object



Spherically symmetric

- **Tidal effects**



Tidally induced multipoles

- Adiabatic limit: $Q_{ij} = -\lambda\, \mathcal{E}_{ij}$

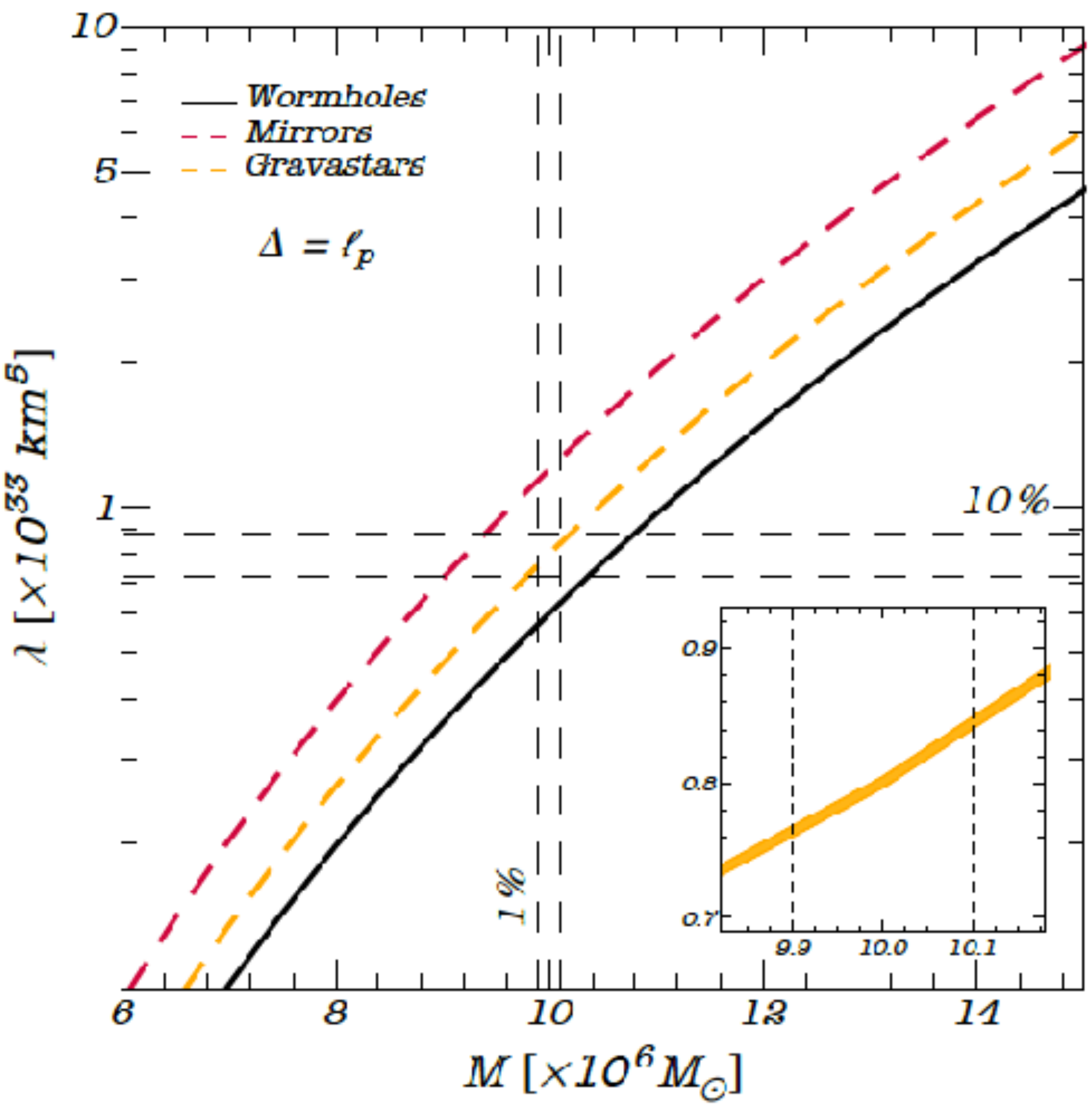
=0 for BHs in GR (in 4d)

Characteristic parameter

[Flanagan, TH 2008, TH 2008, Damour,Nagar, Binnington, Poisson, Kol, Smolkin, Chakrabaty+,…]

Examples of tidal deformability

- Toy examples with structures at small distance Δ from the horizon exhibit scaling:



$$\lambda \sim \left[a + b \log\left(\frac{\Delta}{4M}\right)\right]^{-1}$$

Review article by Maselli, Pani, Cardoso+

arXiv:1811.03689

Approximate influence on the GWs

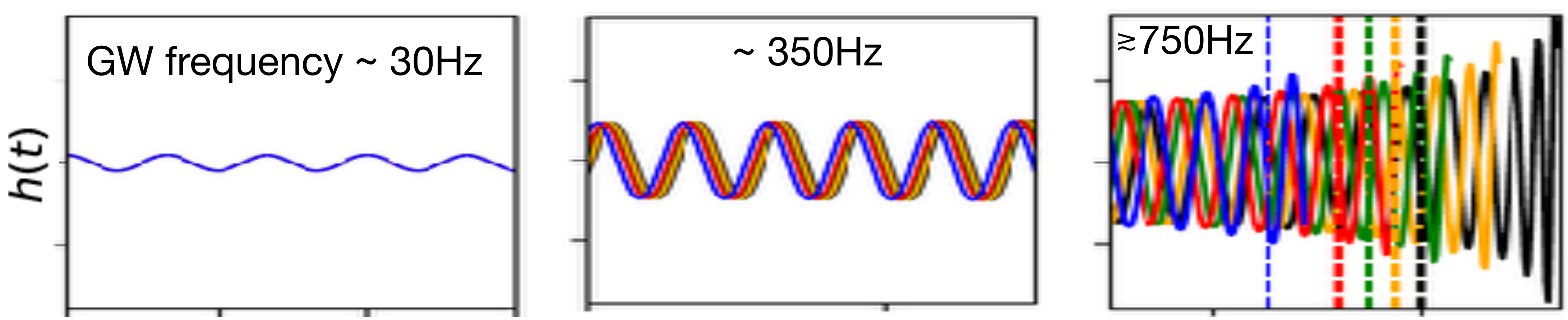
- Energy goes into deforming the object $E \sim E_{\rm orbit} + \frac{1}{4}\mathcal{Q}\,\mathcal{E}$

- moving multipoles contribute to gravitational radiation $\dot{E}_{\rm GW} \sim \left[\frac{d^3}{dt^3}\left(Q_{\rm orbit} + \mathcal{Q}\right)\right]^2$

- approx. GW phase: $\frac{d\phi_{\rm GW}}{dt} = 2\Omega, \qquad \frac{d\Omega}{dt} = \frac{\dot{E}_{\rm GW}}{dE/d\Omega}$

$$\Delta\phi_{\rm GW}^{\rm tidal} \sim \lambda \frac{(M\Omega)^{10/3}}{M^5} \qquad \Delta\phi^{\textit{spin-Q}} \sim \kappa\,\chi^2\,(M\Omega)^{4/3}$$

examples:



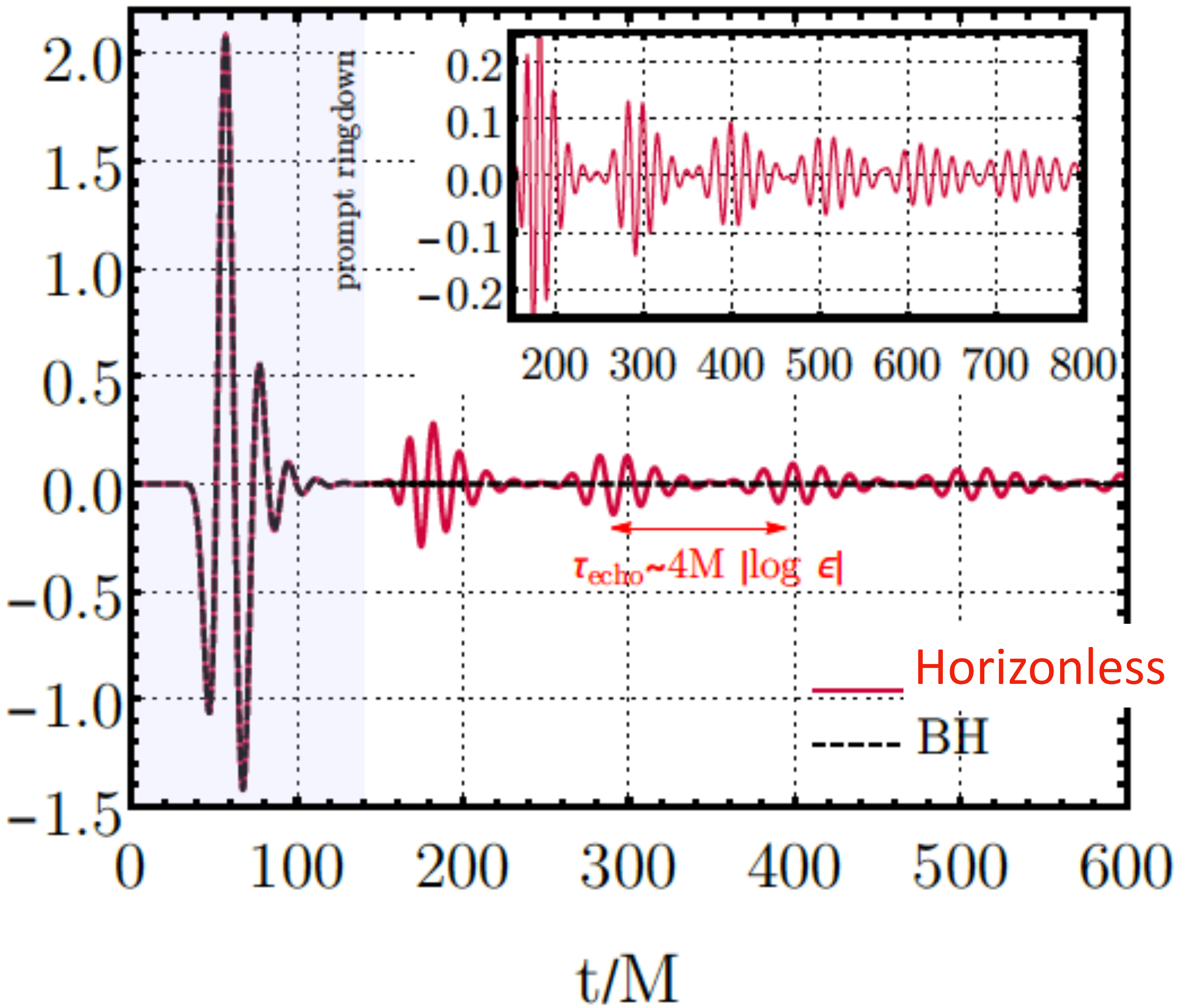
Flanagan, TH 2008, Vines, Flanagan, TH 2011, Schmidt, TH 2019, Arun+ 2017, Poisson 2000

Examples of other finite size effects during the inspiral

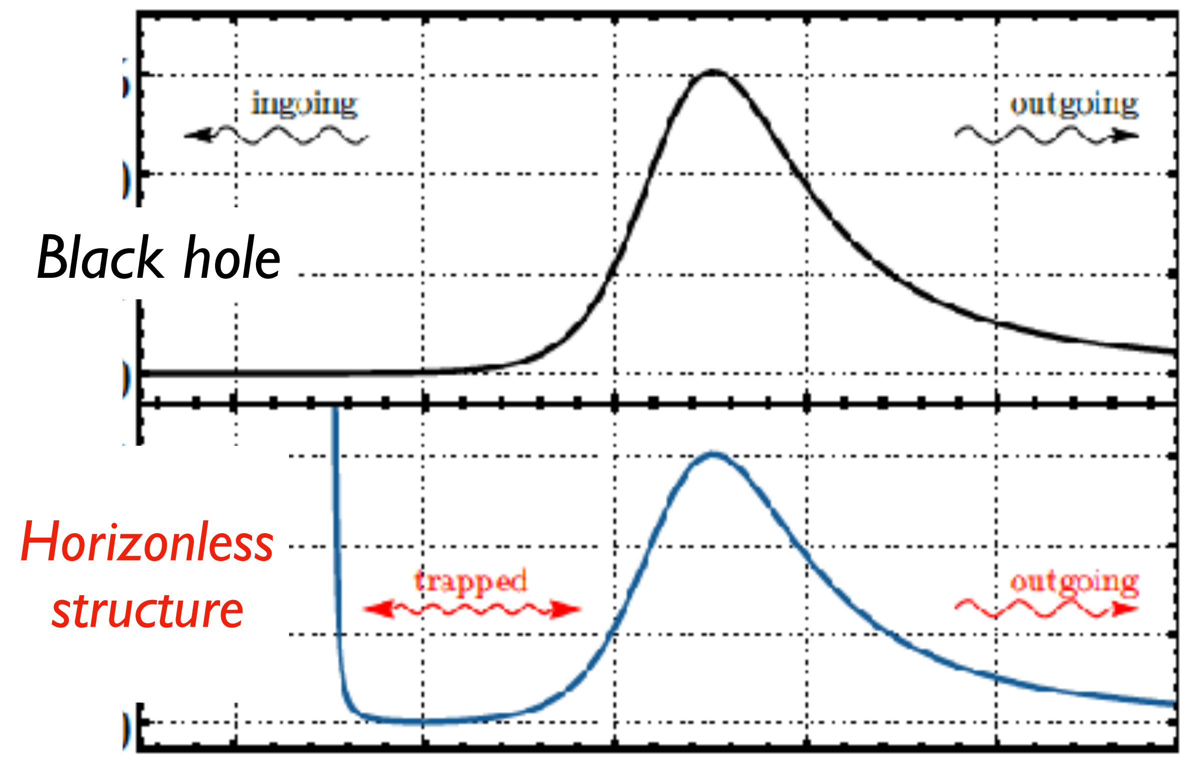
- Tidal excitation of various modes
  - GW spectroscopy during inspiral
  - Need quasi-normal-mode frequencies + tidal excitation factors
- absorption
  - Absence can signify a surface/reflecting features in geometry
  - Presence could be due to horizon or huge number of nonlocal quantum states
- Spin-tidal interactions
  - shifts of mode resonances
  - new couplings
- Gravitomagnetic tidal interactions

Ringdown tests

- Consistency between characteristic modes as expected for Kerr BHs?
- Echoes?



Effective potential

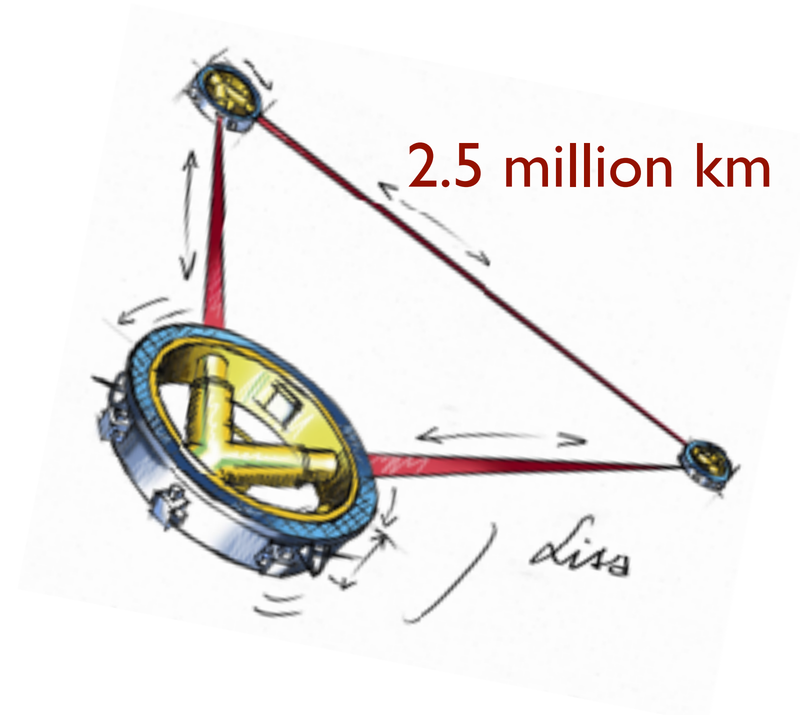


review article:

Cardoso & Pani arXiv:1904.05363

Next step for transient GW discovery space: LISA

- ESA L3 mission Laser Interferometer Space Antenna
- Scheduled for launch in 2034
- Preparatory science studies needed now, before mission adoption in 2024

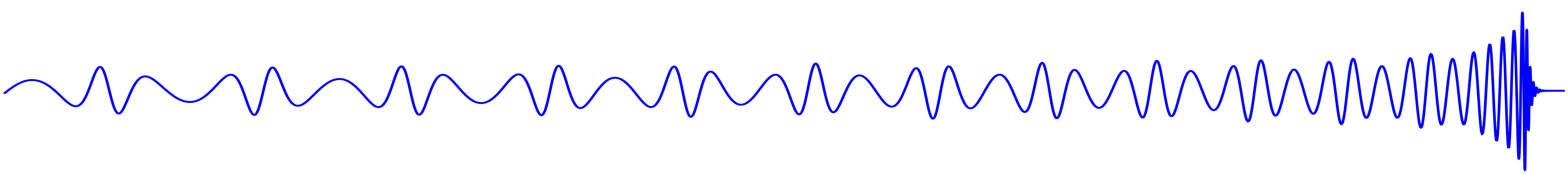


Key source: merging supermassive BHs:

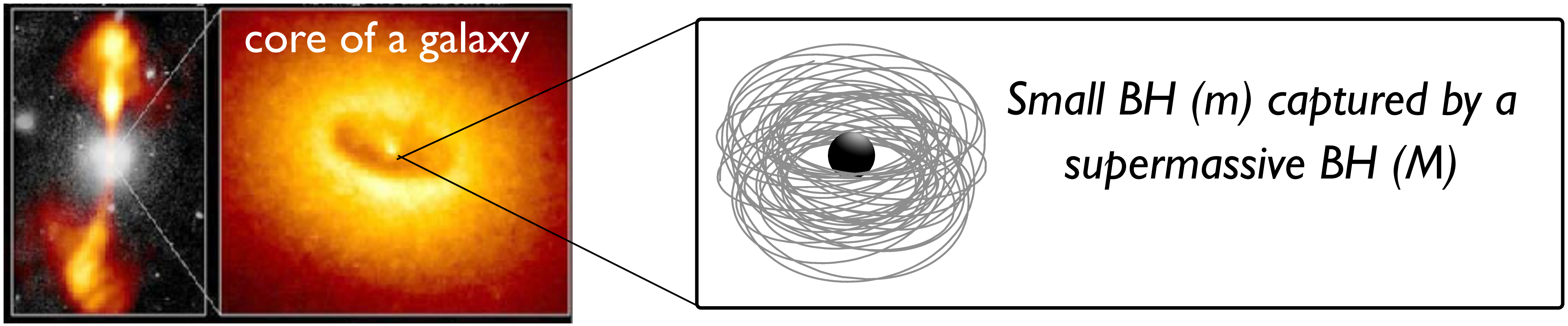
Signal-to-noise ~ several thousand

Eccentric orbits & spins

Richer structure of dynamics, GWs

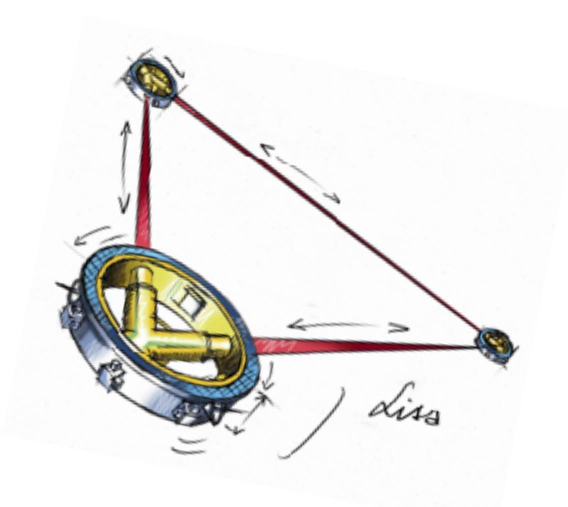


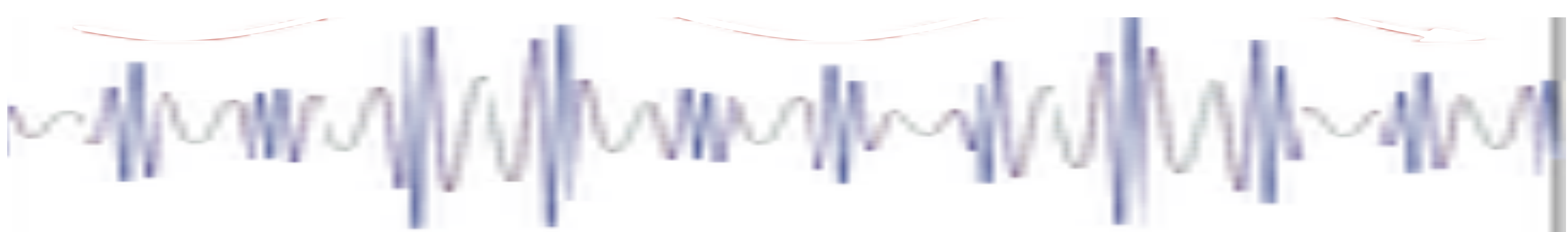
Extreme mass ratio binaries



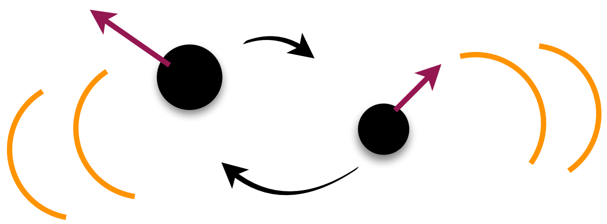
- Orbital timescales ~ minutes
- Last ~ year of inspiral visible to LISA
- extremely high precision studies

map large object's spacetime in exquisite detail





Summary & outlook



- GWs are a unique tool for probing BHs
- Detections of merging BH candidates events now frequent
    - Starting to move from discovery era to detailed studies of BHs
- In the next years:
    - population studies, combine information, more accurate measurements of loud sources
- Requires further advances in modeling, theory, analysis, expertiment
- Expect a wealth of new insights in the coming years-decades