Gravitational waves from a quantum-field-theory perspective

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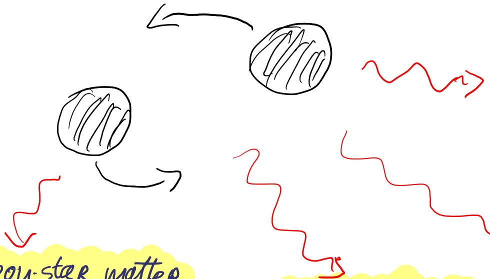
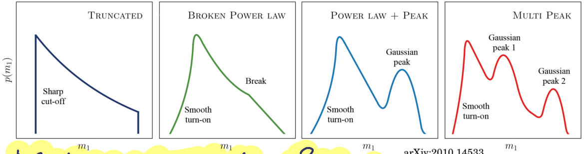
String Theory as a Bridge between Gauge Theory and Quantum Gravity
Rome, February 18, 2025

Gravitational waves and their applications

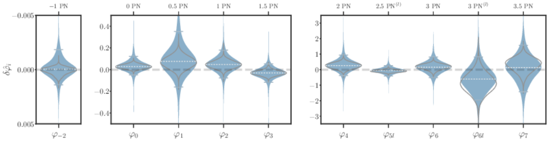




arXiv:2010.14533

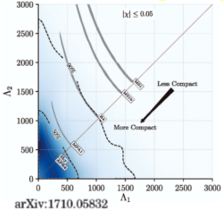
black-hole population & formation

testing gravity



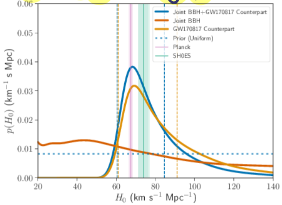
arXiv:2112.0686

neutron-star matter



arXiv:1710.05832

cosmology



arXiv:1908.06060

Frequency of gravitational waves

sensitive frequency range

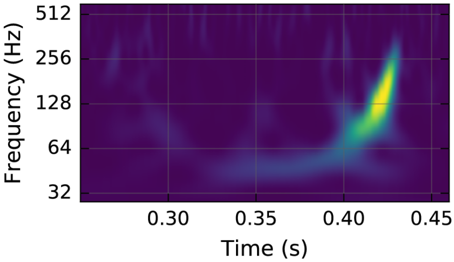
$$f \sim 40 - 400\text{Hz}$$

3rd Kepler: $r^3(2\pi f)^2 = GM$

GW150914: binary black hole

$$\rightarrow \frac{v}{c} \sim \frac{GM}{c^2 r} \sim 0.12 \ldots 0.5$$

need numerical simulations



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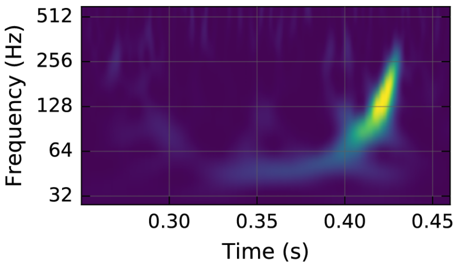
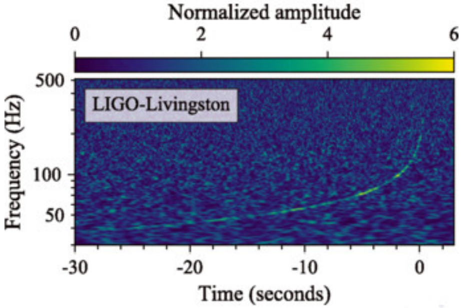
GW170817: binary neutron star

$$\rightarrow \quad \frac{v}{c} \sim \frac{GM}{c^2 r} \sim 0.01 \ldots 0.07$$

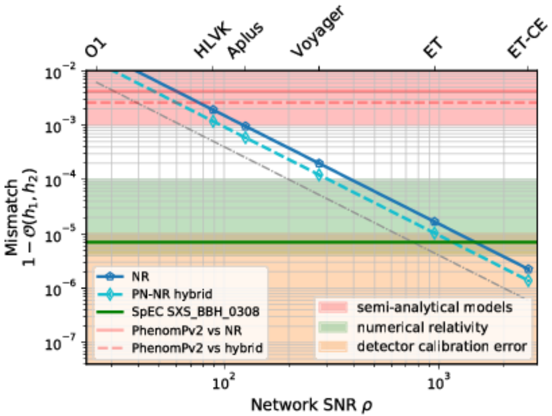
weak field and slow motion
(post-Newtonian) approximation





"Ready for what lies ahead?"

[M. Pürrer, C.-J. Haster, arXiv:1912.100]

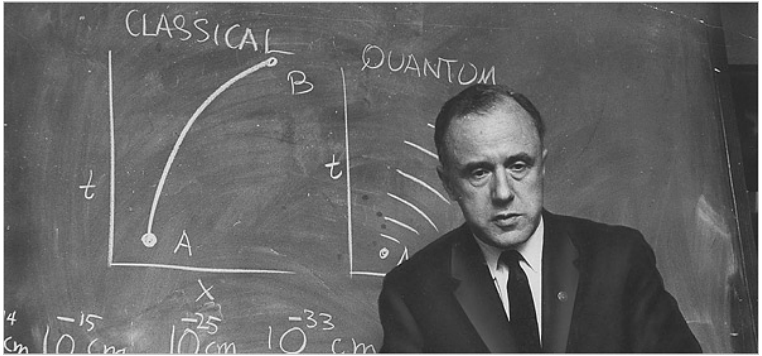


Pürrer, Haster, arXiv:1912.10055

→ need better analytic (and numeric) predictions!

on top of that, include more physical effects (eccentricity+precession, tides, . . .)

Look at the relativistic binary problem from a quantum perspective!



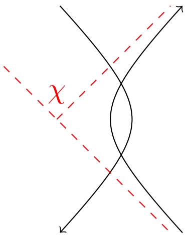
J. A. Wheeler

nytimes.com

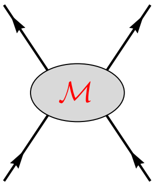
"The Hamilton-Jacobi description of motion:
natural because ratified by the quantum principle"

Box 25.3 in [*Gravitation*, Misner, Thorne, Wheeler (MTW)]

Particle physics perspective: scattering black holes are natural!



- classical scattering: scattering angle χ
  (more for spinning black holes)
- quantum scattering: probability amplitude $\mathcal{M}$



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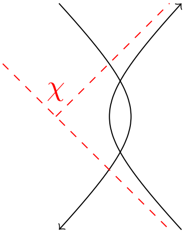

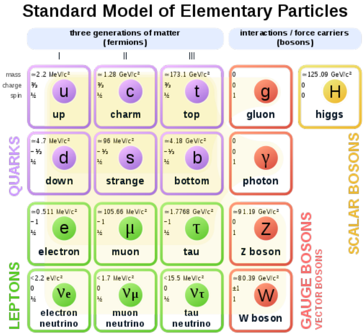

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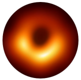
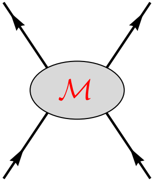


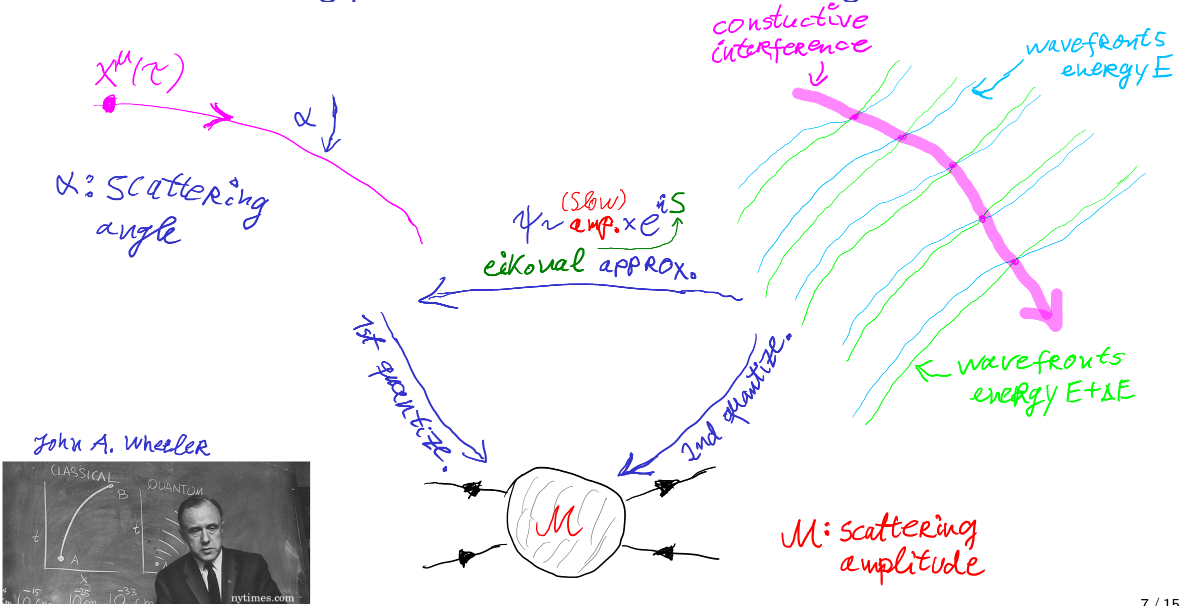
black holes
(∼ higher-spin
massive particles

graviton



- classical scattering: scattering angle χ
  (more for spinning black holes)
- quantum scattering: probability amplitude $\mathcal{M}$
- black holes $\sim$ higher-spin massive particles ?
  e.g. [Arkani-Hamed, Huang, Huang (2017)]

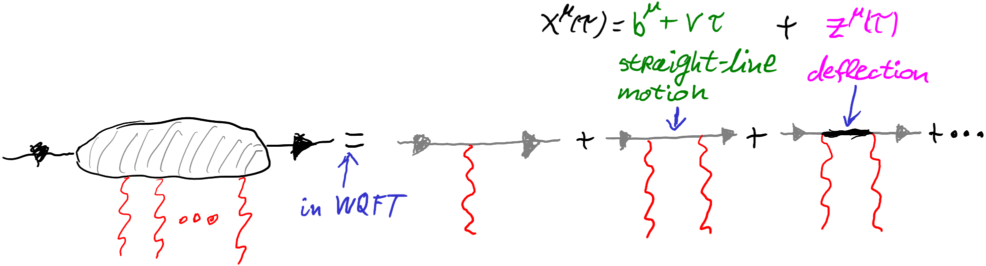
scattering particles vs scattering waves



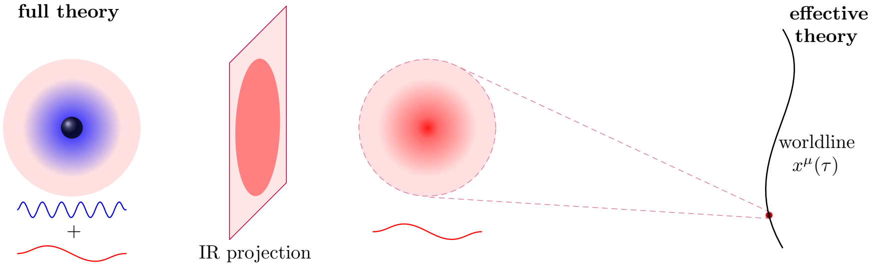
Worldline quantum field theory (WQFT)

[Jakobsen, Mogull, Plefka, Sauer, JS, '20+]

- connecting quantum fields to worldlines:
  $\rightarrow$ Schwinger-Feynman dressed massive propagator
- scattering: expansion around straight worldline
  $\rightarrow$ Feynman rules with manifest $\hbar$ counting
  $\rightarrow$ classical limit $\hbar \rightarrow 0$ and eikonal exponentiation manifest
- calculate classical ($\hbar \rightarrow 0$) scattering observables: scattering angle, waveform



Black holes as particles? Effective field theory (EFT)!



[adopted from arXiv:1906.08161]

- black holes have ≈ minimal coupling in amplitudes / quantum fields
- black holes have nonminimal couplings in worldline action
- EFT framework can be applied to larger scales:
  → binary dynamics, gravitational waves

Continuing the EFT to larger scales: binaries / post-Newtonian approx.

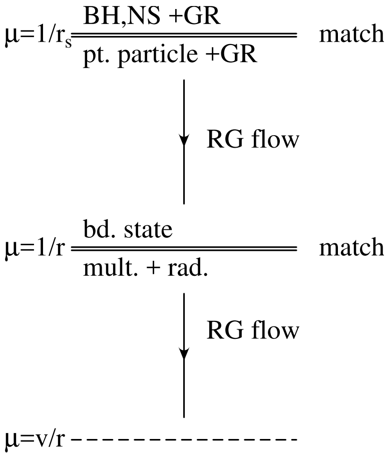
[Goldberger, Rothstein, PRD **73** (2006) 104029; Goldberger, arXiv:hep-ph/0701129]

requirement:
separation of scales (scale μ)

- object size r_s
- orbital size r
- wavelength $\sim \frac{r}{v}$

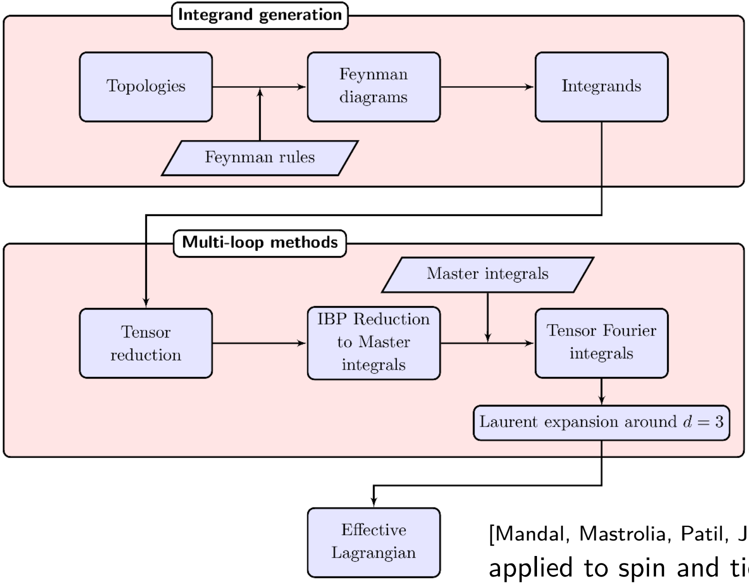
applicable to:

- bound orbits
- scattering (close connection to WQFT)
- beyond general relativity



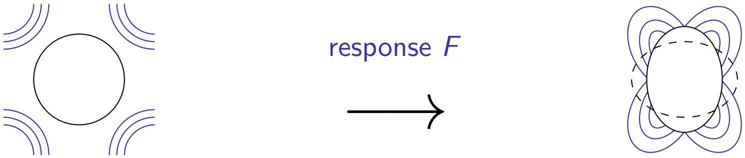
from [Goldberger, arXiv:hep-ph/0701129]

Conservative binary potential from EFT and Feynman integral calculus



[Mandal, Mastrolia, Patil, JS, '22+]
applied to spin and tidal effects

Dynamical tidal response of neutron stars



external quadrupolar field $\longrightarrow$ deformation $\longrightarrow$ quadrupolar response

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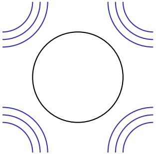
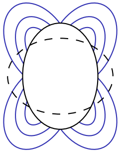


response F $\longrightarrow$



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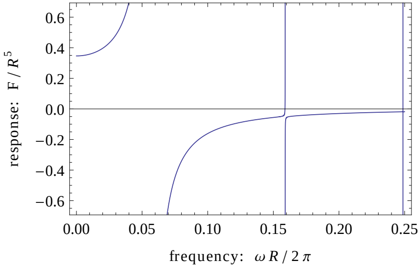
oscillation modes
$\rightarrow$ harmonic oscillator response
$\rightarrow$ (transient) resonances!



[Chakrabarti, Delsate, JS, arXiv:1304.2228]

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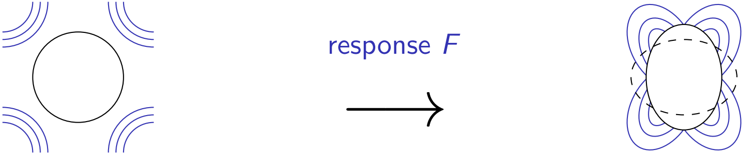

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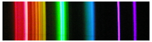
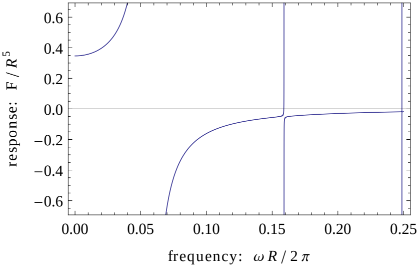
resonance $\leftrightarrow$ gravitational wave phase shift

gravitational wave spectroscopy!



matching F is difficult: high loop order, divergences
[Goldberger, Ross, arXiv:0912.4254]



[Chakrabarti, Delsate, JS, arXiv:1304.2228]

EFT modeling tides of spinning compact objects

black-hole horizon absorption (tidal heating):

- calculated absorption in binaries to 1.5PN
  [Saketh, JS, Vines, Buonanno, arXiv:2212.13095]
- disagreement with previous result
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neutron-star gravitomagnetic tides:
[Gupta, JS, Hinderer, arXiv:2011.03508]

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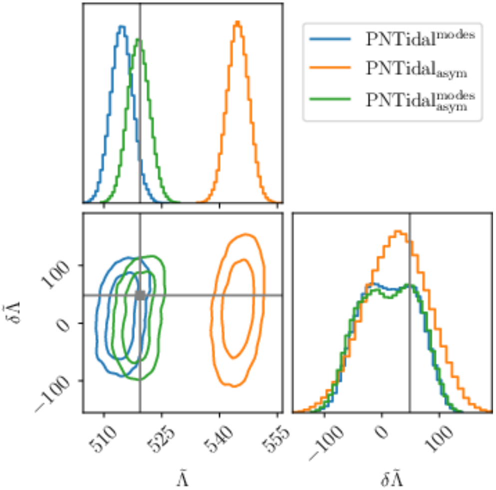
- **plot:** effect on data analysis



spins $\chi = 0.01$, SNR $= 1800$
[Gupta, JS, Hinderer, arXiv:2302.11274]

Beyond general relativity

Ideally, consider realistic modifications:

- higher curvature corrections,
  $\rightarrow$ strong-field effects from:
  - modified spin-induced multipoles
  - modified tidal response
- adding scalar fields
  $\rightarrow$ strong-field effect from scalarization
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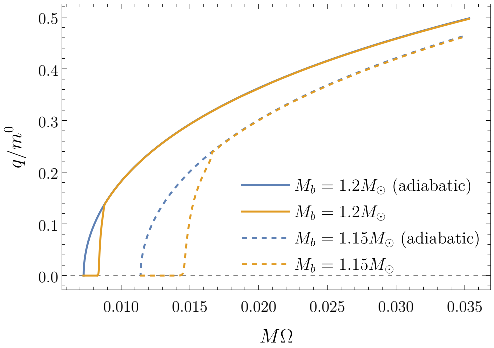


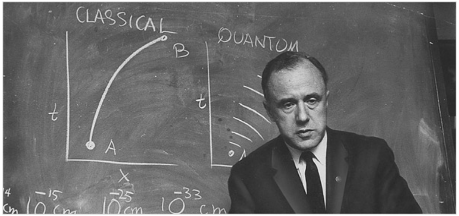
scalar charge q over orbital frequency Ω
[Khalil, Mendes, Ortiz, JS, arXiv:2206.13233]

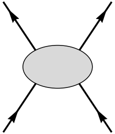
scalarization:

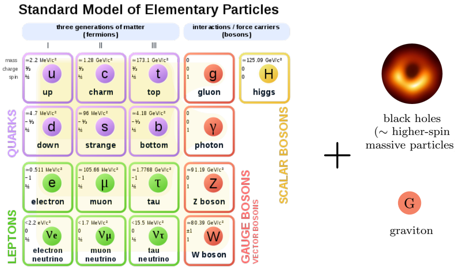
- spontaneous scalarization:
  $\rightarrow$ linearly unstable scalar mode $\omega^2_{\text{mode}} < 0$
- dynamical scalarization:
  $\rightarrow$ barely stable scalar mode $\omega^2_{\text{mode}} \sim \text{small} > 0$

Gravitational waves from a quantum-field-theory perspective

- need more accurate gravitational waveforms
- EFT and Feynman diagrammatic expansion are powerful tools
  - to predict gravitational waves
  - to include spin and tides
  - to go beyond general relativity
- connecting GW to scattering amplitudes may allow application of modern “on-shell” methods







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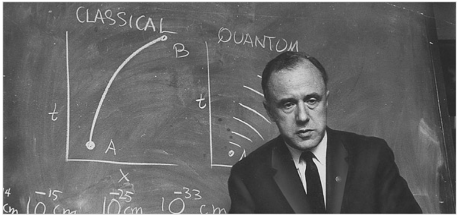

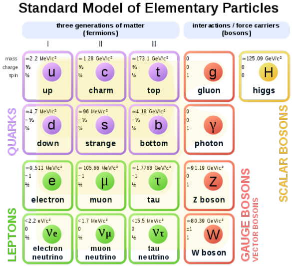

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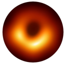

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Thank you!