Gravitational waves from a particle physics perspective

Jan Steinhoff

Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute), Potsdam, Germany

Niels Bohr International Academy, Copenhagen, November 29, 2022

Gravity: from Galileo and Newton to Einstein

Newton's theory of gravity:

- things fall down due to a gravitational force
- universality of free fall

London Science Museum

Gravity: from Galileo and Newton to Einstein

Newton's theory of gravity:

- things fall down due to a gravitational force
- universality of free fall

London Science Museum

Einstein's theory of gravity

a.k.a. general relativity

a.k.a. our best theory of gravity:

- free fall = force-free motion
- no gravitational force
- space & time are curved
  $\rightarrow$ gravitational waves!

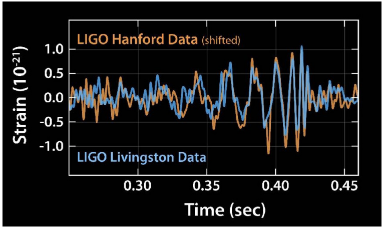
International Space Station, nasa.gov

Gravitational waves

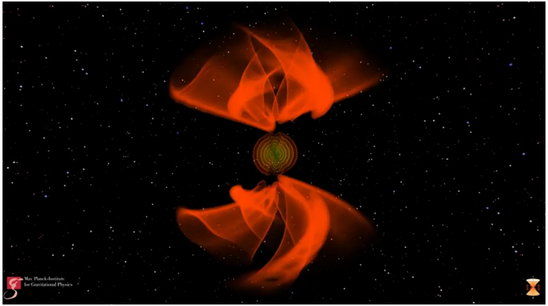
gravitational waves:
small ripples in the fabric of spacetime

best source: black hole/neutron star binaries

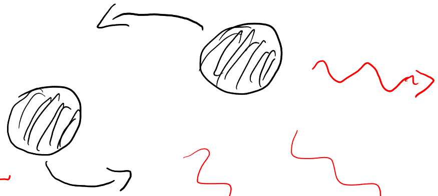
$\rightarrow$ chirp signal 

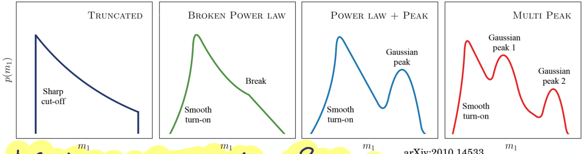


GW150914 (binary black hole), ligo.caltech.edu



Applications of gravitational waves

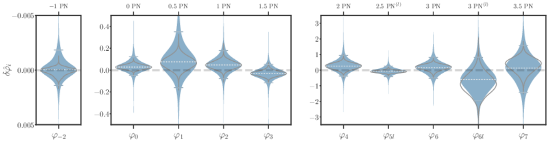




arXiv:2010.14533

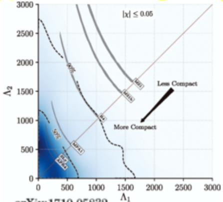
black-hole population & formation

testing gravity



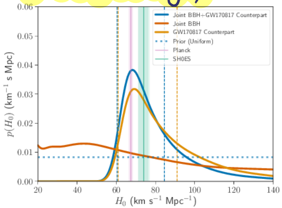
arXiv:2112.0686

neutron-star matter



arXiv:1710.05832

cosmology



arXiv:1908.06060

Frequency of gravitational waves

sensitive frequency range

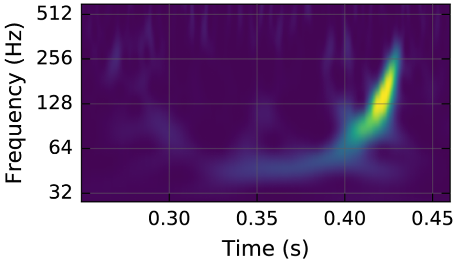
$$f \sim 40 - 400\text{Hz}$$

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



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

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

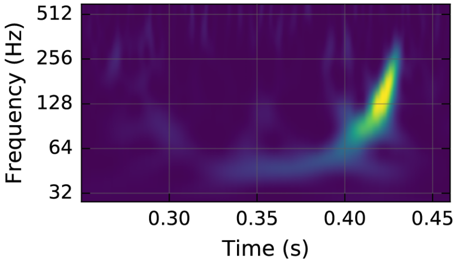
need numerical simulations

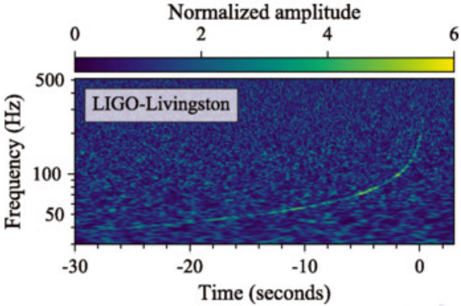
GW170817: binary neutron star

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

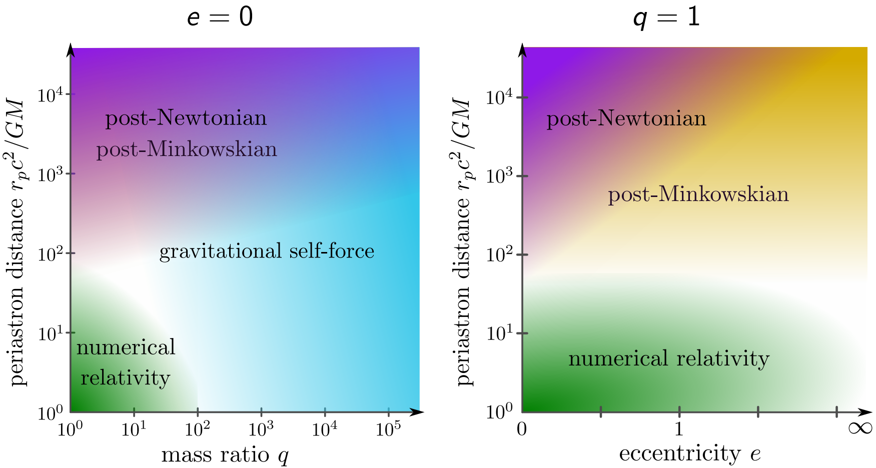
weak field and slow motion

(post-Newtonian) approximation



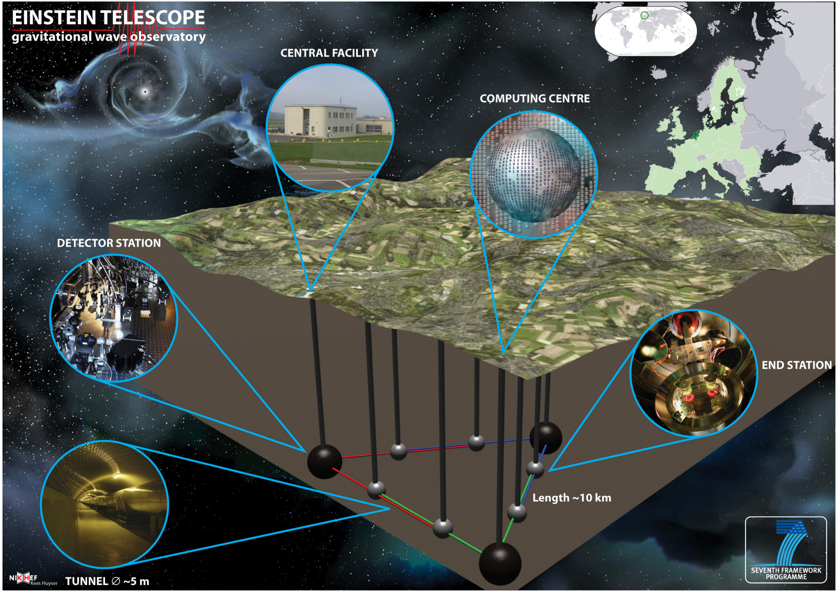


Methods for predicting gravitational waves and their regimes



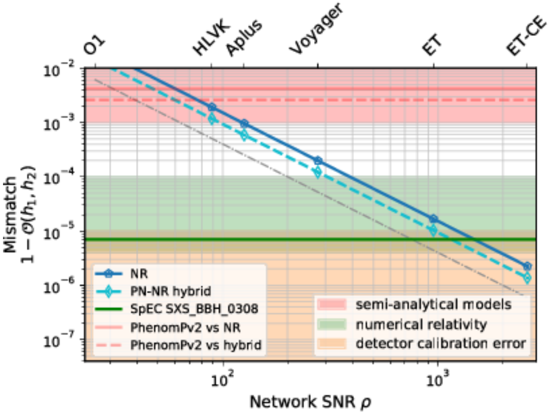
[Khalil, Buonanno, JS, Vines, arXiv:2204.05047]

Possible future



“Ready for what lies ahead?”

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

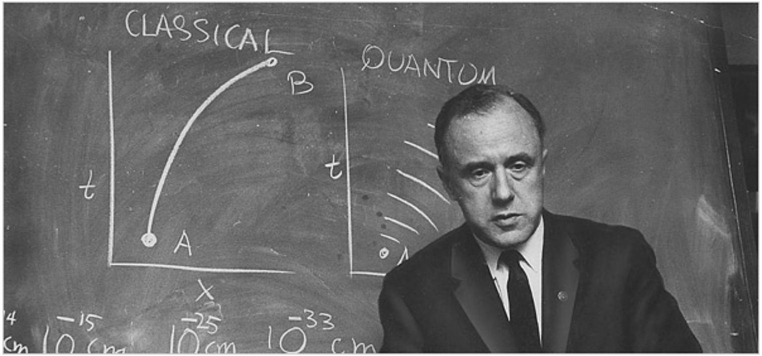


Pürrer, Haster, arXiv:1912.10055

→ need better analytic (and numeric) predictions soon!

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

Look at the relativistic binary problem from a quantum perspective!

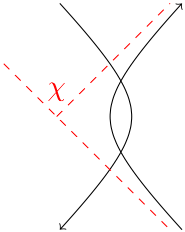


J. A. Wheeler nytimes.com

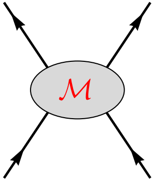
"The Hamilton-Jacobi description of motion:
natural because ratified by the quantum principle"

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

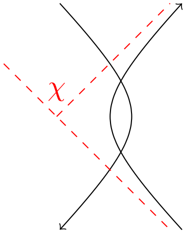
Particle physics perspective: scattering black holes are natural!

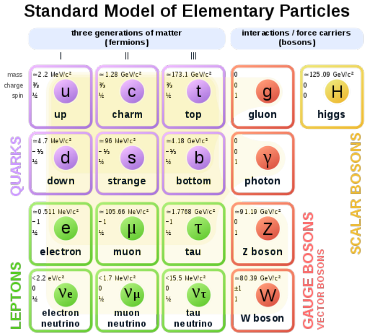


- classical scattering: scattering angle χ
  (more for spinning black holes)
- quantum scattering: probability amplitude $\mathcal{M}$

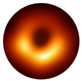


Particle physics perspective: scattering black holes are natural!



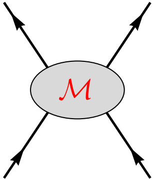


+



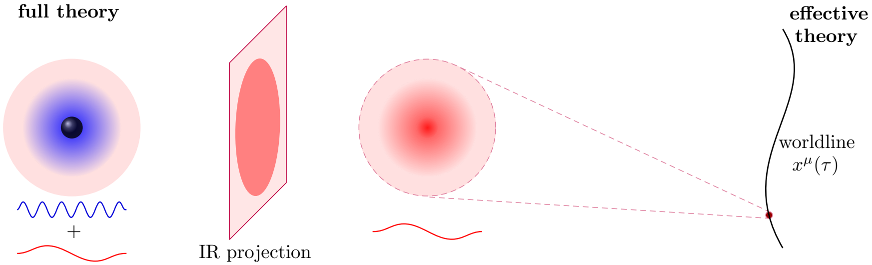
black holes
(∼ higher-spin
massive particles

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)]

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



[adopted from arXiv:1906.08161]

weird:

- black holes have ≈ minimal coupling in amplitudes / quantum fields
- black holes have nonminimal couplings in worldline action

EFT for post-Newtonian approximation

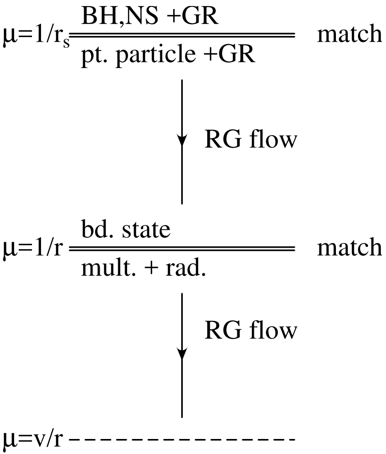
[Goldberger, Rothstein, PRD **73** (2006) 104029; Goldberger, arXiv:hep-ph/0701129]

for generic binaries in general relativity:

- black holes
- neutron stars

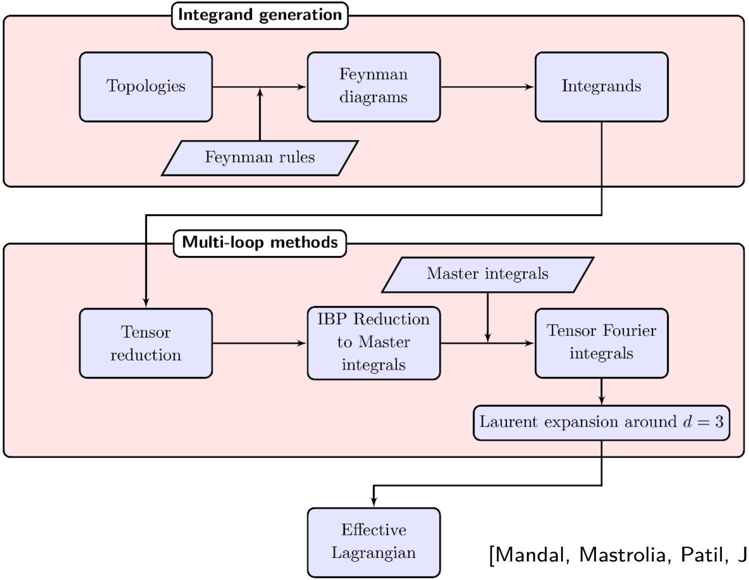
separation of scales (scale μ):

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



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

Next EFT: conservative binary potential



[Mandal, Mastrolia, Patil, JS, arXiv:2209.00611]

Results for the (conservative) post-Newtonian potential

post-Newtonian (PN) approximation: expansion around $\frac{1}{c} \to 0$ (Newton)

order	c^0	c^{-1}	c^{-2}	c^{-3}	c^{-4}	c^{-5}	c^{-6}	c^{-7}	c^{-8}	c^{-9}	c^{-10}
	N		1PN		2PN		3PN		4PN		5PN
non spin	✓		✓		✓		✓		✓		✓?
spin-orbit				✓		✓		✓		✓	
Spin^2					✓		✓		✓		✓
Spin^3								✓		✓	
Spin^4									✓		✓
⋮											⋱

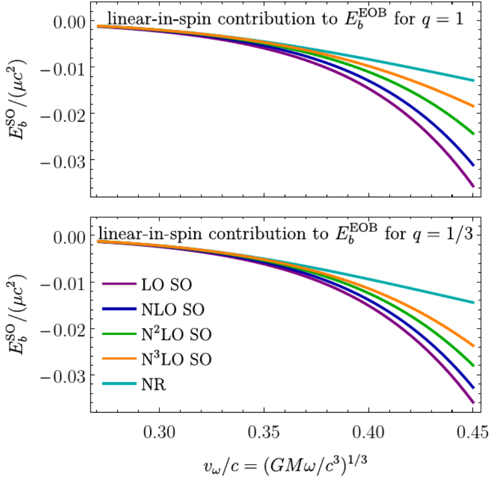
recent work: Antonelli, Blümlein, Foffa, Von Hippel, Kavanagh, Khalil, Kim, Levi, Maier, Mandal, Marquard, Mastrolia, Mcleod, Morales, Mougiakakos, Patil, Schäfer, JS, Sturani, Teng, Vines, Yin, Luz Almeida

Comparison against numerical relativity (NR) . . .

. . . of the N^{3}LO spin-orbit (SO) binding energy E_b^{SO} $\longrightarrow$

- for two mass ratios $q = 1, \frac{1}{3}$
- using effective-one-body resummation

(method in that paper: uniquely constrain potential using self-force and mass-ratio dependence of scattering angle)

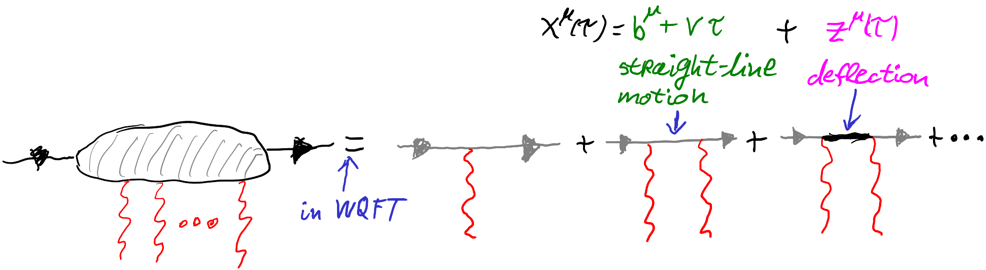


[Antonelli, Kavanagh, Khalil, JS, Vines, arXiv:2003.11391]

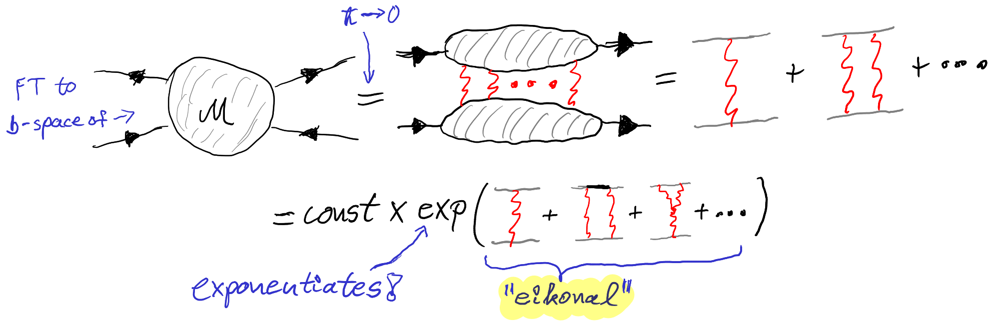
Worldline quantum field theory (WQFT)

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

- integrate out worldline variables → observables
- Schwinger-Feynman dressed massive propagator → quantum fields
- scattering → expansion around straight line:

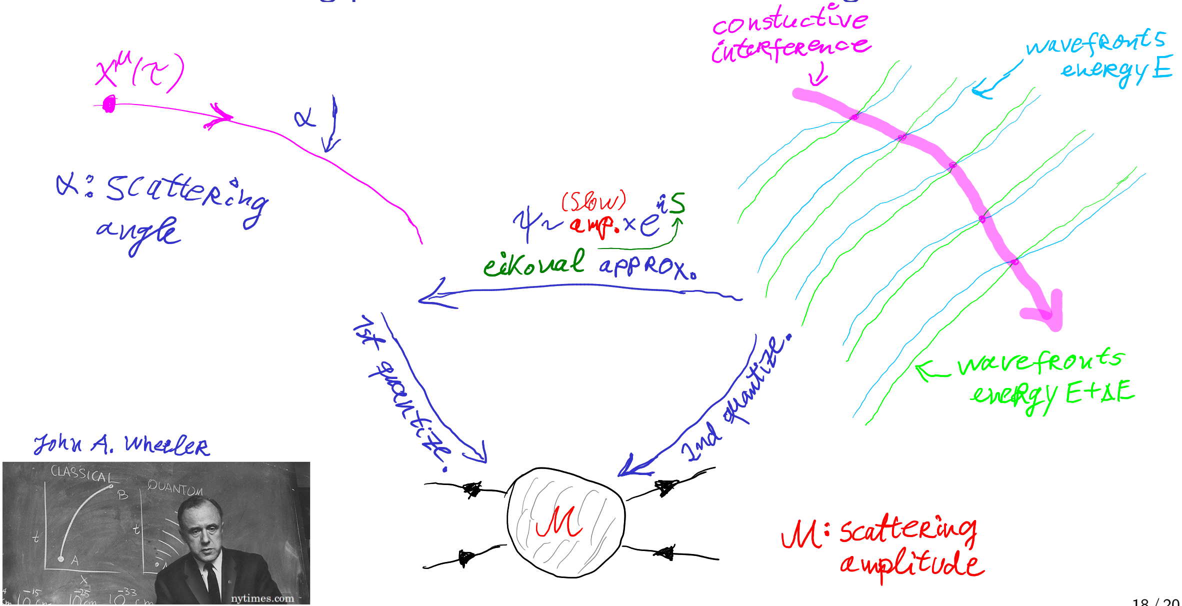


Connection to scattering amplitudes

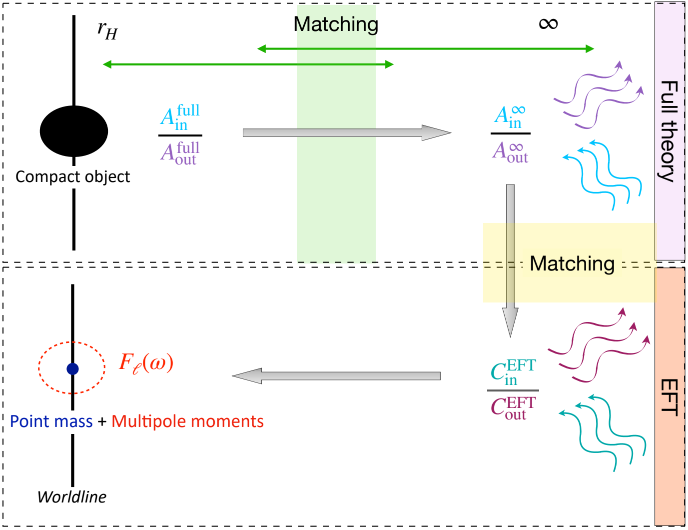


- can expand scattering amplitudes in $\hbar$ using worldlines !
- modern "on-shell" methods $\rightarrow$ classical methods ?
- can be applied to other observables,
  waveforms (for scattering black holes),
  extended to spin, tides

scattering particles vs scattering waves

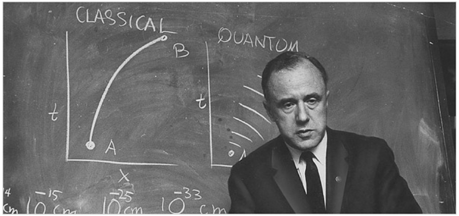


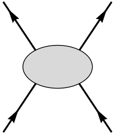
Tidal response from scattering [Creci, Hinderer, JS, 2108.03385]

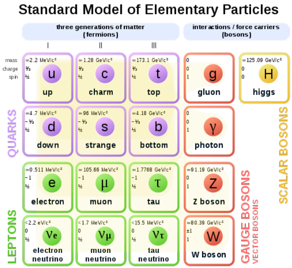


Gravitational waves from a particle physics perspective

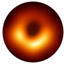
- more accurate gravitational-wave predictions needed in the near future
- EFT and Feynman diagrammatic expansion are powerful tools to predict gravitational waves
- connecting GW to scattering amplitudes may allow application of modern "on-shell" methods
- inspiral waveforms from amplitudes? improve eccentric waveforms?







+

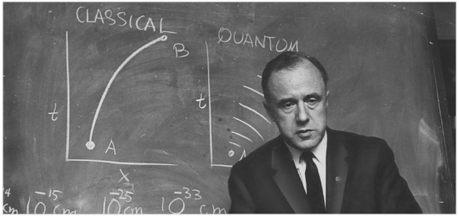


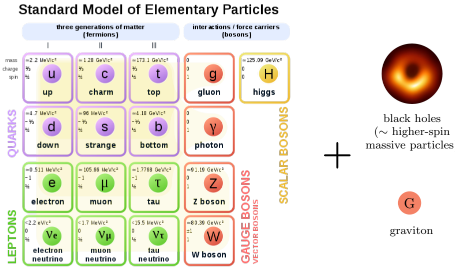
black holes
(∼ higher-spin
massive particles

graviton

Gravitational waves from a particle physics perspective

- more accurate gravitational-wave predictions needed in the near future
- EFT and Feynman diagrammatic expansion are powerful tools to predict gravitational waves
- connecting GW to scattering amplitudes may allow application of modern "on-shell" methods
- inspiral waveforms from amplitudes? improve eccentric waveforms?





Thank you!