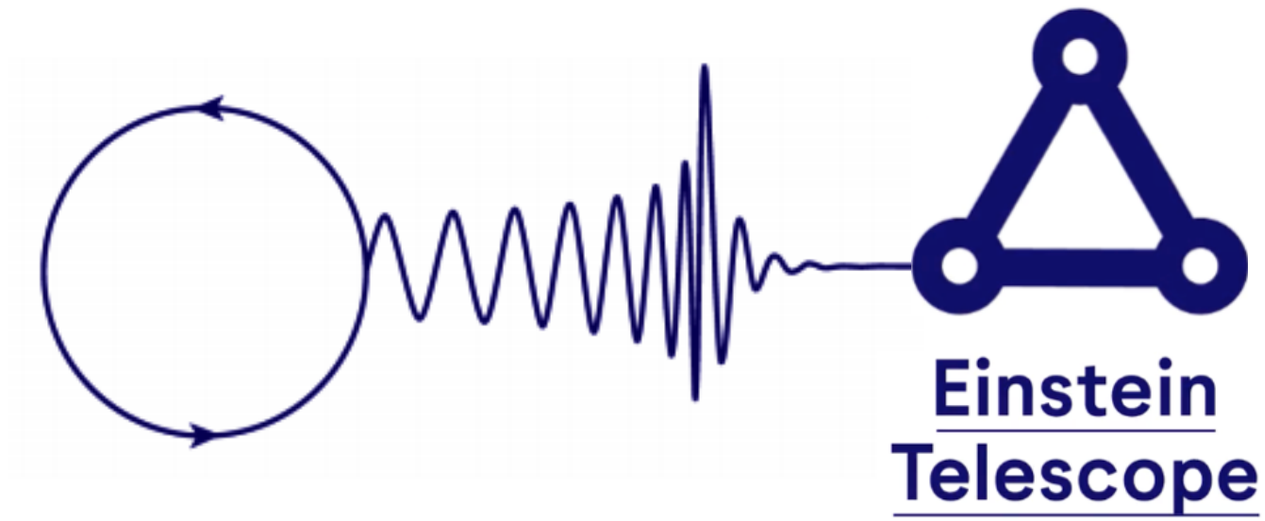


Rafael A. Porto

The Gravitational Wave Spectrum

Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

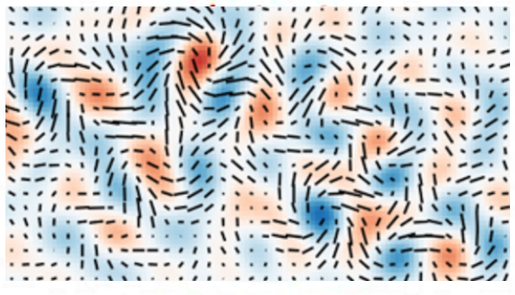
Compact Binaries in our

universe years hours sec ms

log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2

Detectors

Cosmic microwave background



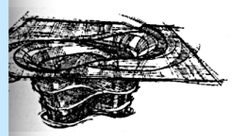
Pulsar Timing

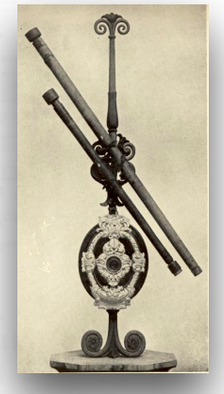
Space Interferometers

Terrestrial interferometers

Discovery Potential =

<u>Precise Theoretical Predictions</u>

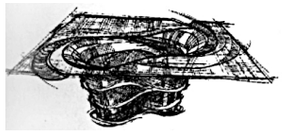


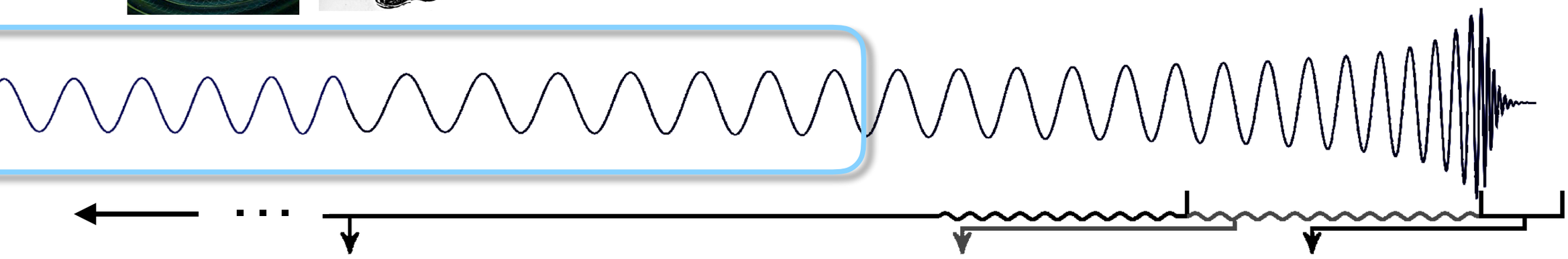


Challenge:

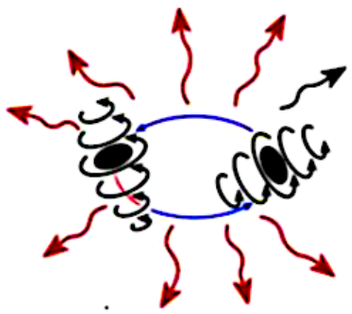
1000+ cycles in band @ Design-Sensitivity

100+ events per year!



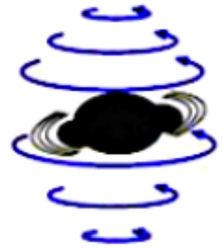


Inspiral



Merger

Ringing

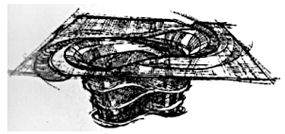


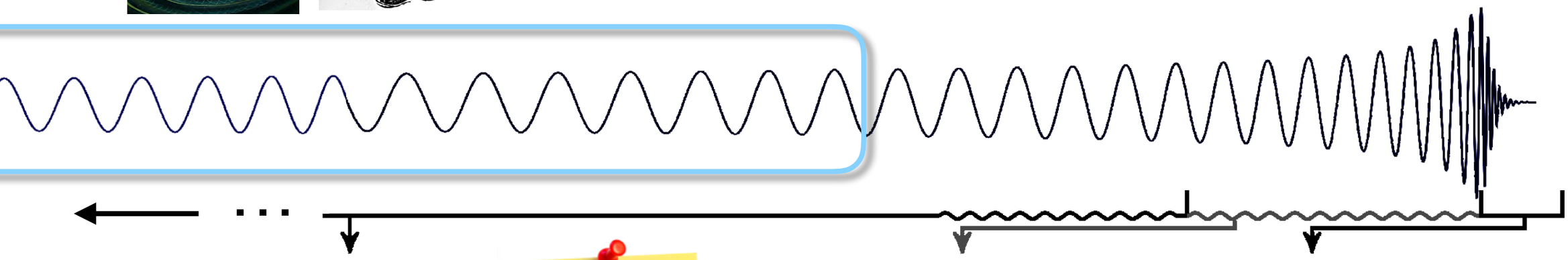
$$R_{im} = \sum_{l} \frac{\partial \Gamma^{l}_{im}}{\partial x_l} + \sum_{l,l'} \Gamma^{l}_{il'} \Gamma^{l'}_{ml} = -\varkappa \left(T_{im} - \frac{1}{2} g_{im} T \right)$$

‘GW Precision Data’ (**GWPD**)™

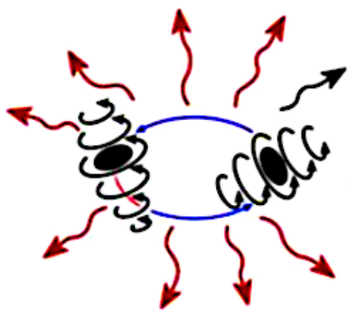
1000+ cycles in band @ Design-Sensitivity

100+ events per year!





Inspiral



GWPD!

Merger

Ringing

$$R_{im} = \sum_{l} \frac{\partial \Gamma^{l}_{lm}}{\partial x_l} + \sum_{l,l'} \Gamma^{l}_{ll'} \Gamma^{l'}_{ml} = -\varkappa \left(T_{im} - \frac{1}{2} g_{lm} T \right)$$

GWPD for Beyond the Standard Model (BSM)

QCD axion?
String axiverse?
Light dark matter?

BH Collider

Particle collider

Cosmo collider

Hubble scale

Neutrinos

Standard Model

Planck scale

Energy [eV]

10^{-30} 10^{-20} 10^{-10} 1 10^{10} 10^{20} 10^{30}

Probing ultralight bosons with binary black holes

Daniel Baumann, Horng Sheng Chia, and Rafael A. Porto

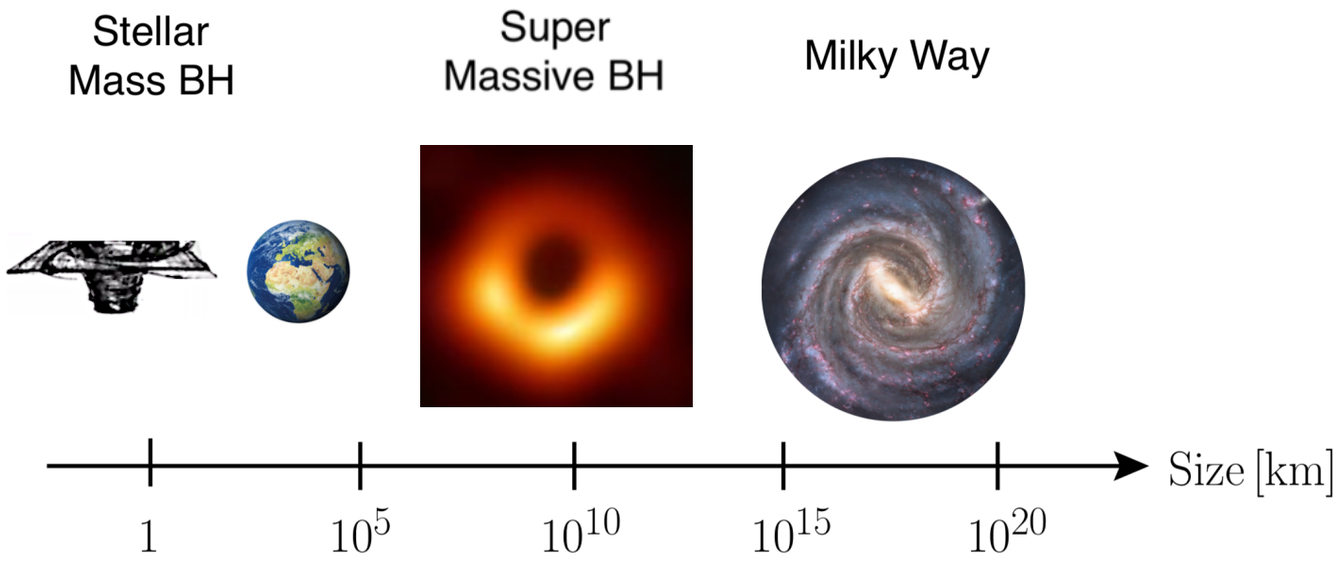
Phys. Rev. D 99, 044001 (2019)

Published February 4, 2019

Physics See Synopsis:

Black Holes Could Reveal New Ultralight Particles

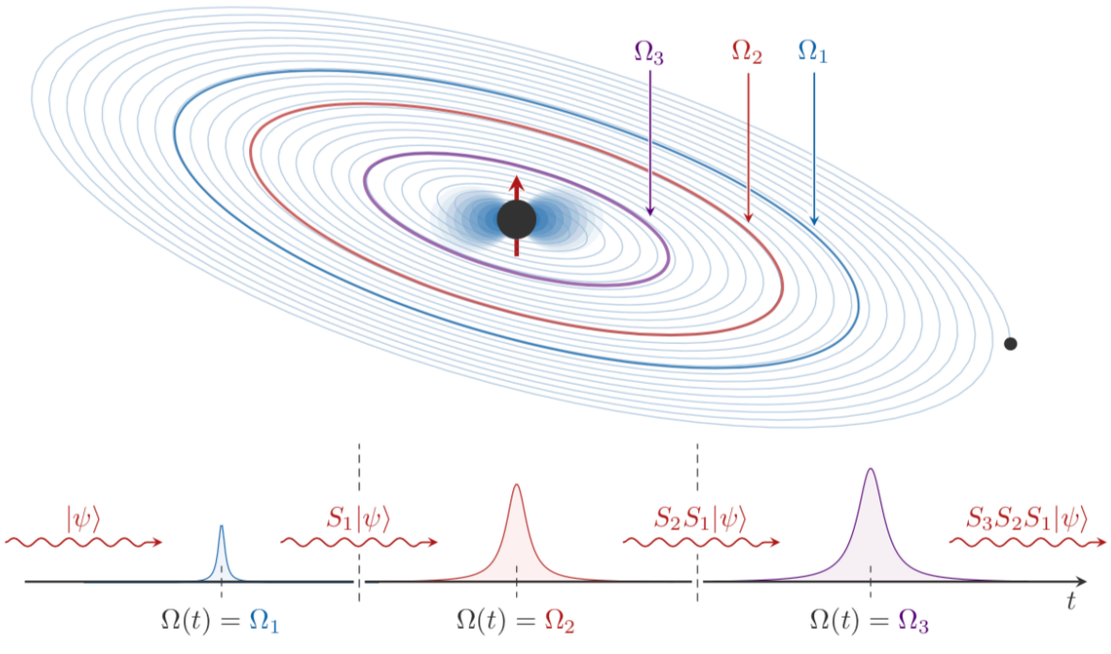
GWPD for Beyond the Standard Model (BSM)



$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{1 + \cdots + [\cdots]x^{7/2} + \mathcal{O}(x^4) + \mathcal{O}(x^5)\right\} \quad \begin{matrix} N^5LO \\ 5PN \end{matrix}$$

$$\Psi(v) = \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v)$$

Gravitational 'susceptibility'
Vanishes for BHs in isolation!



Gravitational Collider Physics

(Baumann, Chia, **RAP**, Stout, to appear)

Fortschr. Phys. 64, No. 10, 723–729 (2016) / DOI 10.1002/prop.201600064

The tune of love and the *nature(ness)* of spacetime

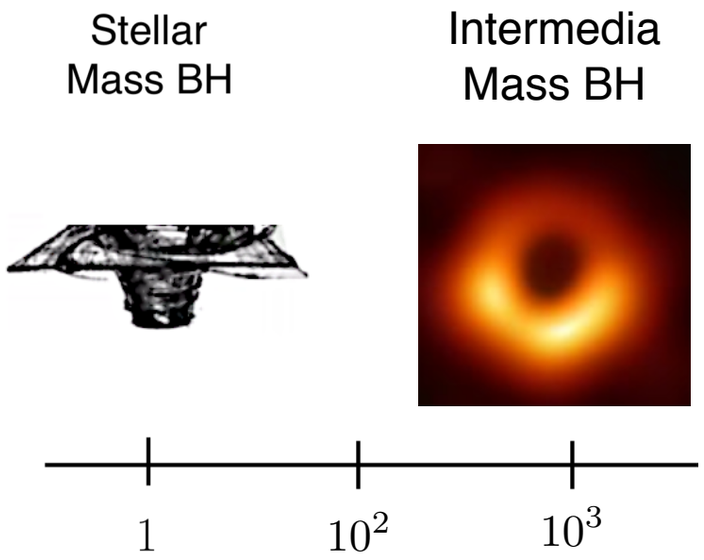
*Rafael A. Porto**

The effective field theorist's approach to gravitational dynamics

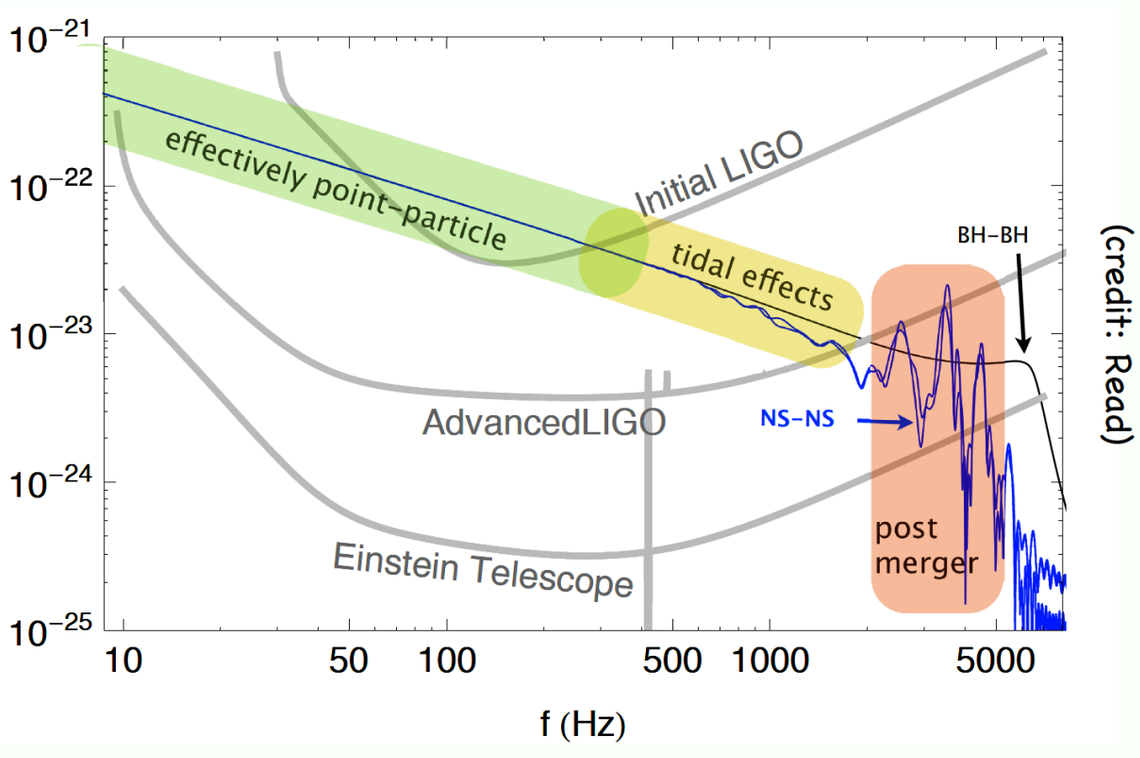
Rafael A. Porto

Physics Reports
Volume 633, 20 May 2016, Pages 1-104

GWPD for Beyond the Standard Model (BSM)



$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{1 + \cdots + [\cdots]x^{7/2} + \mathcal{O}(x^4) + \mathcal{O}(x^5)\right\} \quad \begin{matrix} N^5LO \\ 5PN \end{matrix}$$



Gravitational Collider Physics

$$\Psi(v) = \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v)$$

Gravitational 'susceptibility'
Vanishes for BHs in isolation!

Fortschr. Phys. 64, No. 10, 723–729 (2016) / DOI 10.1002/prop.201600064

The tune of love and the *nature(ness)* of spacetime

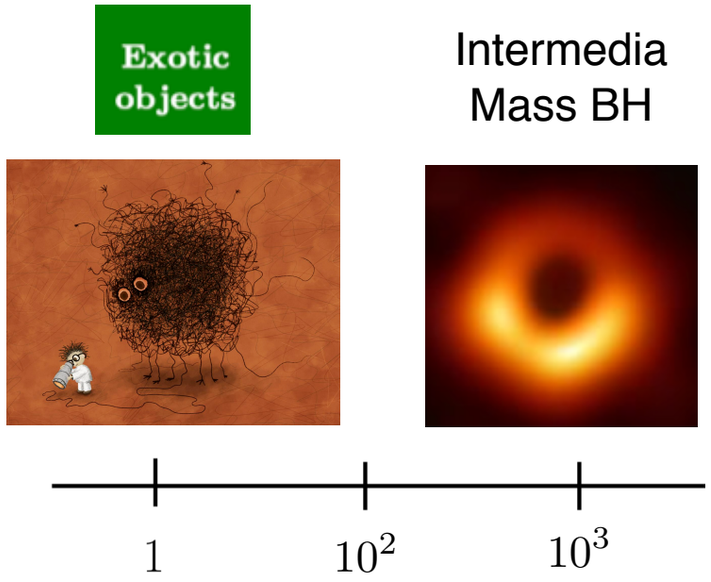
*Rafael A. Porto**

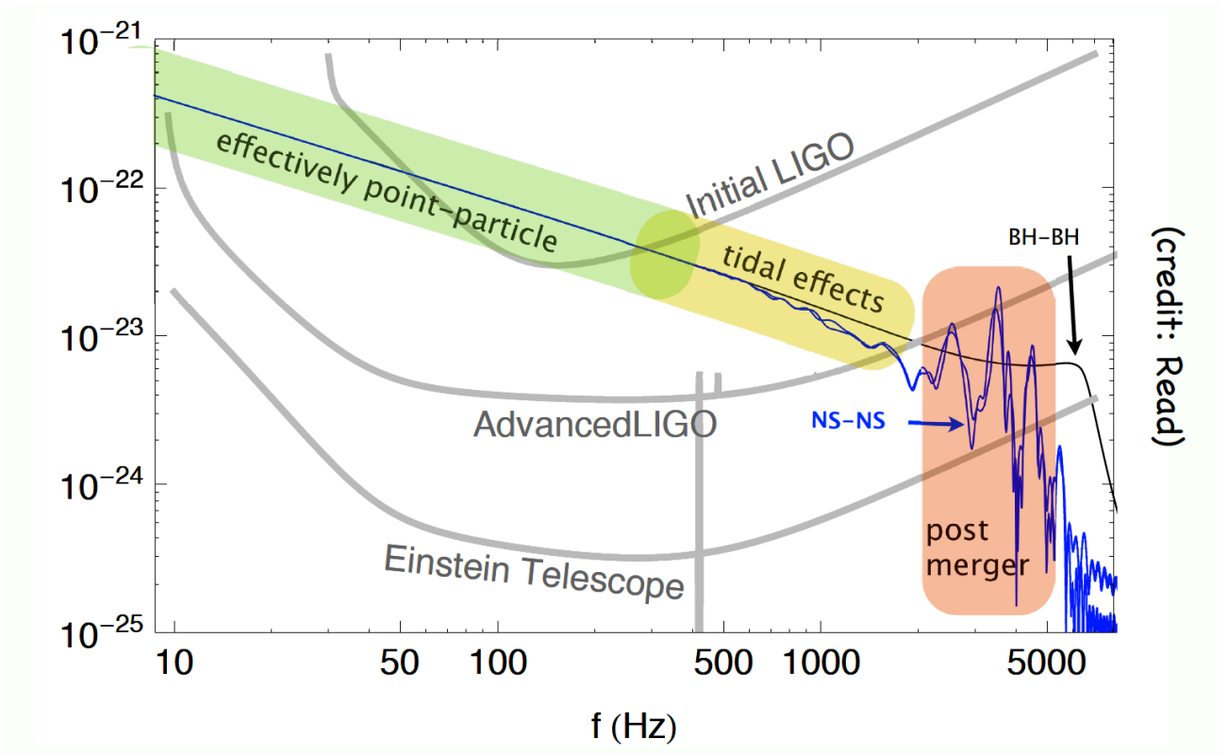
The effective field theorist's approach to gravitational dynamics

Rafael A. Porto

Physics Reports
Volume 633, 20 May 2016, Pages 1-104

GWPD for Beyond the Standard Model (BSM)



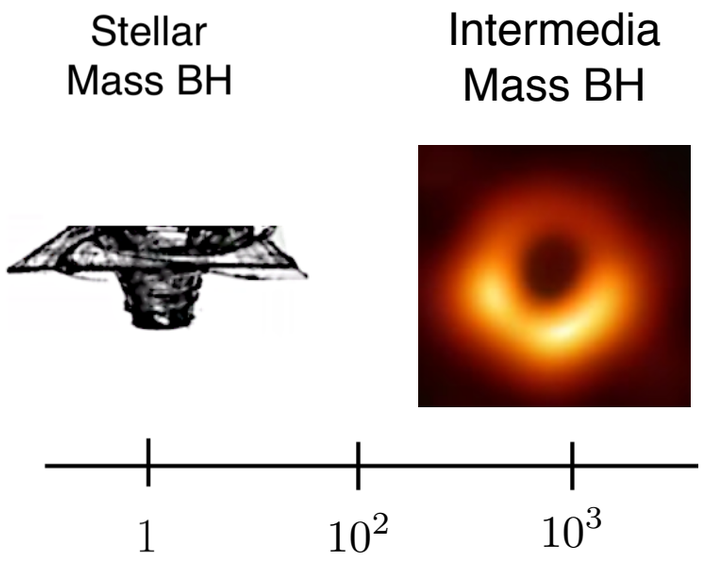


Gravitational Collider Physics

Gravitational wave probes of dark matter: challenges and opportunities

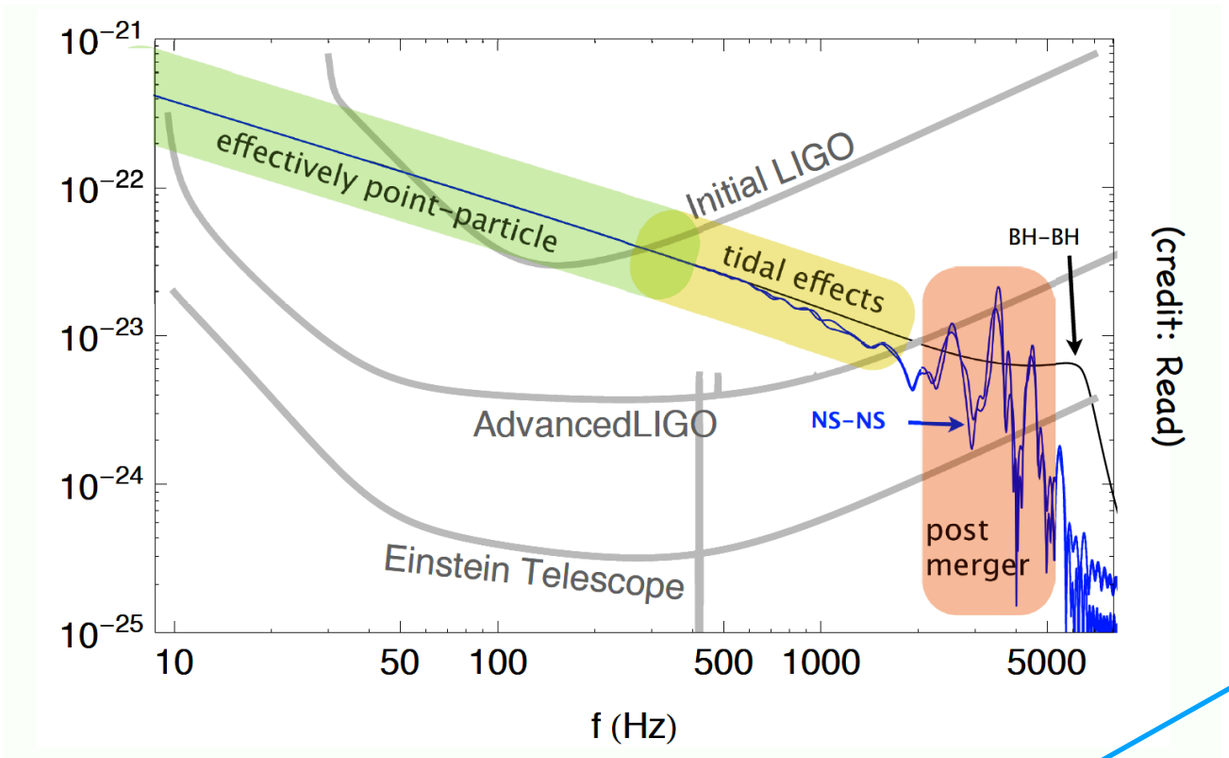
Gianfranco Bertone,[1,*] Djuna Croon,[2,†] Mustafa A. Amin,[3,‡] Kimberly K. Boddy,[4,§] Bradley J. Kavanagh,[1,¶] Katherine J. Mack,[5,‖] Priyamvada Natarajan,[6,**] Toby Opferkuch,[7,††] Katelin Schutz,[8,‡‡] Volodymyr Takhistov,[9,§§] Christoph Weniger,[1,¶¶] and Tien-Tien Yu[10,***]

GWPD for Beyond the Standard Model (BSM)



Gravitational wave probes of dark matter: challenges and opportunities

Gianfranco Bertone,[1,*] Djuna Croon,[2,†] Mustafa A. Amin,[3,‡] Kimberly K. Boddy,[4,§] Bradley J. Kavanagh,[1,¶] Katherine J. Mack,[5,‖] Priyamvada Natarajan,[6,**] Toby Opferkuch,[7,††] Katelin Schutz,[8,‡‡] Volodymyr Takhistov,[9,§§] Christoph Weniger,[1,¶¶] and Tien-Tien Yu[10,***]

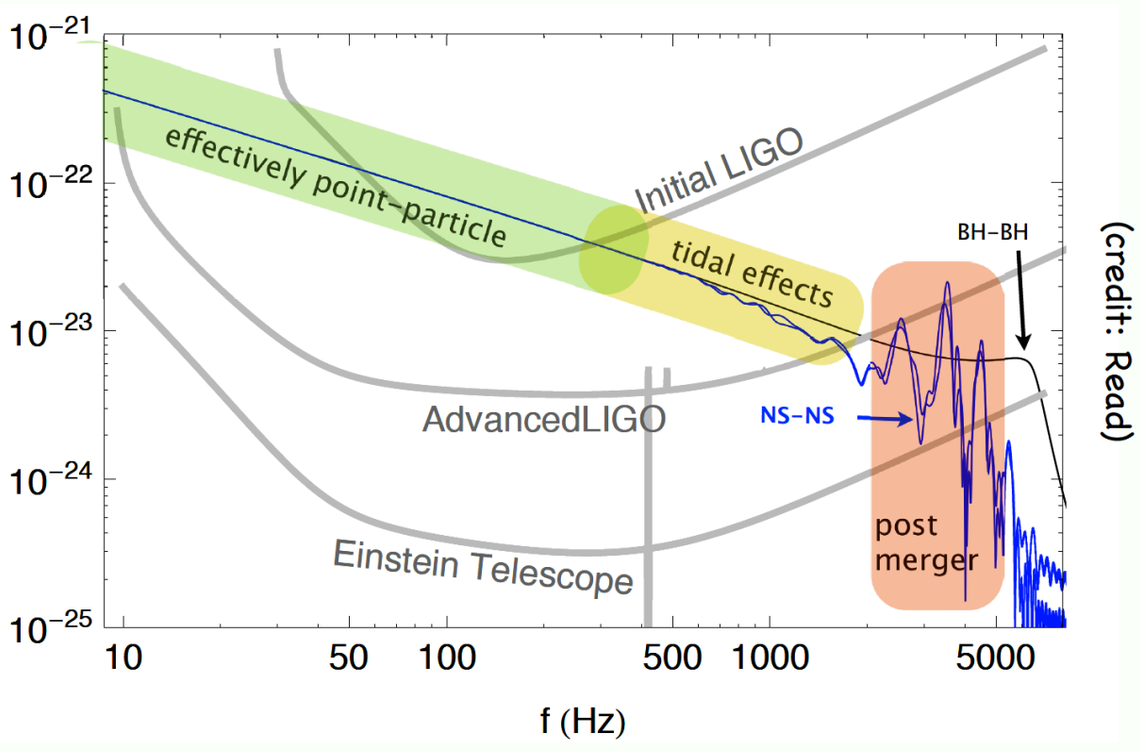


Gravitational Collider Physics

ET = more ‘luminosity/sensitivity’ at ‘higher/lower energies’

“Waveforms will be far more complex and carry more information than expected. Improved modeling will be needed for extracting the GW’s information” <u>1993</u>

Kip Thorne ‘Last 3 minutes’ paper
<u>20+ years prior to first detection!</u>



Gravitational Collider Physics

- **Energy/Sensitivity Frontier**

  Lower Frequency: Long-Distance/Bigger IMBHs, ECOs,…
  Higher Frequency: Short-Distance/Smaller NSs, Low-mass BHs, PBHs…

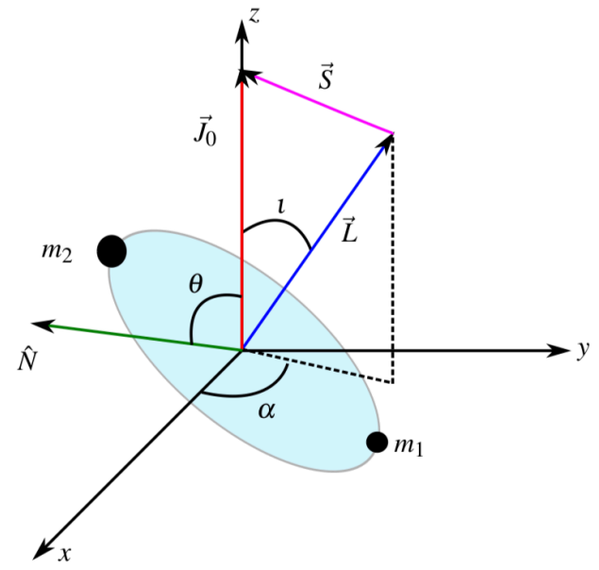
- **Luminosity Frontier**

  Precision Gravity: Longer/high-SNR signals
  Tidal Effects: NSs, Light DM, ECOs, …

The last three minutes: Issues in gravitational-wave measurements of coalescing compact binaries

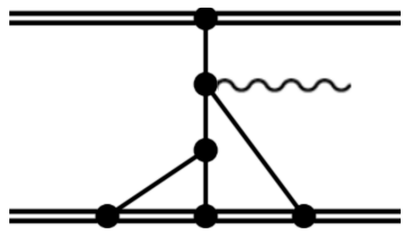
Curt Cutler, Theocharis A. Apostolatos, Lars Bildsten, Lee Smauel Finn, Eanna E. Flanagan, Daniel Kennefick, Dragoljub M. Markovic, Amos Ori, Eric Poisson, Gerald Jay Sussman, and Kip S. Thorne
Phys. Rev. Lett. **70**, 2984 – Published 17 May 1993

$$\frac{d\mathcal{N}_{\rm cyc}}{d\ln f} = \frac{5}{96\pi}\frac{1}{\mu M^{2/3}(\pi f)^{5/3}}\left\{1+\left(\frac{743}{336}+\frac{11}{4}\frac{\mu}{M}\right)x \right.$$
$$\left. -[4\pi+\text{S.O.}]x^{1.5}+[\text{S.S.}]x^2+O(x^{2.5})\right\}.$$



Knowledge at the time

Where are we now?



$$\frac{d\mathcal{N}_{\rm cyc}}{d\ln f} = \frac{5}{96\pi}\frac{1}{\mu M^{2/3}(\pi f)^{5/3}}\left\{1+\left(\frac{743}{336}+\frac{11}{4}\frac{\mu}{M}\right)x\right.$$

$$\left.-[4\pi+\text{S.O.}]x^{1.5}+[\text{S.S.}]x^2+[\text{S.O.}]x^{2.5}+[\text{S.S.}]x^3+O(x^4)\right)$$

PHYSICAL REVIEW D **100,** 024048 (2019)

Conservative dynamics of binary systems to fourth post-Newtonian order in the EFT approach. II. Renormalized Lagrangian

Stefano Foffa,[1] Rafael A. Porto,[2,3] Ira Rothstein,[4] and Riccardo Sturani[5]

The effective field theorist's approach to gravitational dynamics

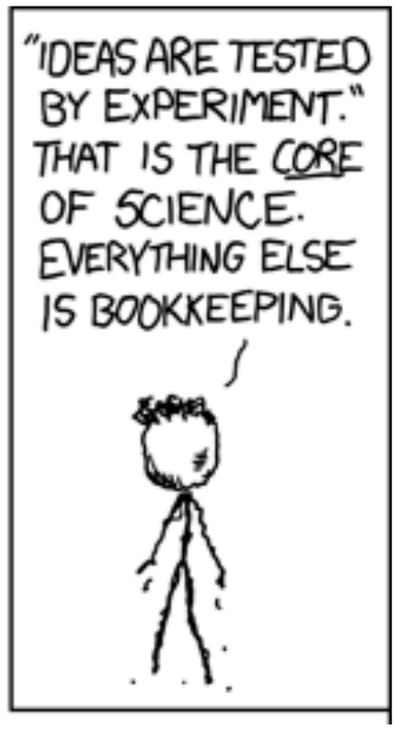
Rafael A. Porto

Physics Reports

Volume 633, 20 May 2016, Pages 1-104

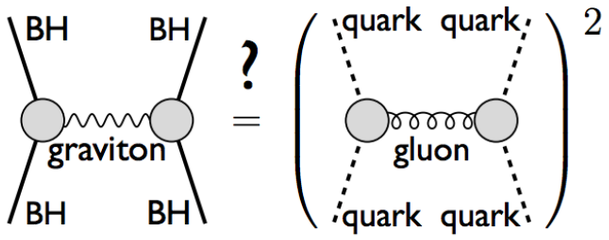
HEP **GWs**

Are we ready for the future?



$$\frac{d\mathcal{N}_{\rm cyc}}{d\ln f} = \frac{5}{96\pi}\frac{1}{\mu M^{2/3}(\pi f)^{5/3}}\left\{1+\left(\frac{743}{336}+\frac{11}{4}\frac{\mu}{M}\right)x\right.$$

$$\left.-[4\pi+\text{S.O.}]x^{1.5}+[\text{S.S.}]x^2+[\text{S.O.}]x^{2.5}+[\text{S.S.}]x^3+O(x^4)+O(x^5)\right\}.$$



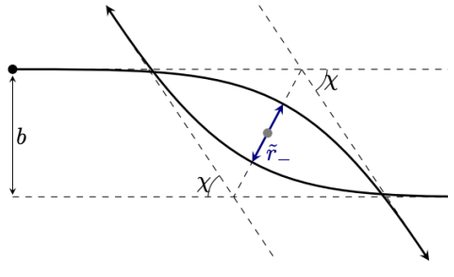
PRECISION GRAVITY: FROM THE LHC TO LISA

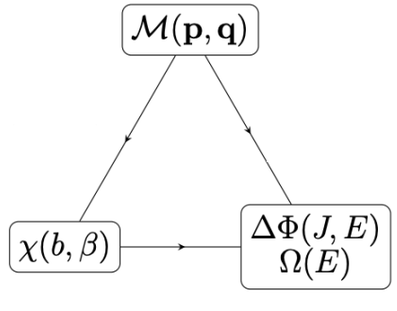
26 August - 20 September 2019 MIAPP Munich Institute for Astro- and Particle Physics

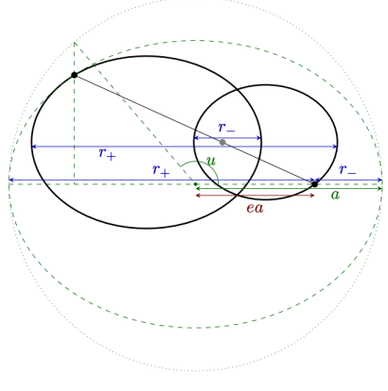
John Joseph Carrasco, Ilya Mandel, Donal O'Connell, Rafael Porto, Fabian Schmidt

From Boundary Data to Bound States

Gregor Kälin[a] **and Rafael A. Porto**[b,c]







NYT 1991

Experts Clash Over Project To Detect Gravity Wave

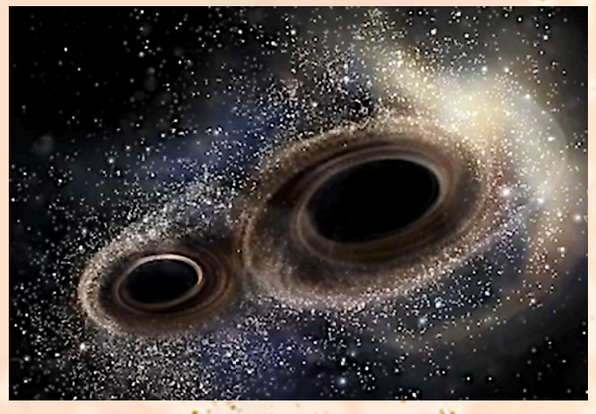
Physicists say device could help them fathom black holes, but others fault its price.

Die Zeit

no.203.078 — 01.01.203X

EinsTein Reloaded!

New era of foundational investigations established through GWPD.



New particles discovered!

New objects found!

Neutron stars unveiled!

Experts Clash Over Project To Detect Gravity Wave

Physicists say device could help them fathom black holes, but others fault its price.

Extra Slides

"New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in a new way. The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson, "Imagined Worlds"

QUANTUM THEORY OF GRAVITATION*

By R. P. Feynman

(Received July 3, 1963)

Møller: May I, as a non-expert, ask you a very simple and perhaps foolish question. Is this theory really Einstein's theory of gravitation in the sense that if you would have here many gravitons the equations would go over into the usual field equations of Einstein?

Feynman: Absolutely.

[...] gravitational radiation when two stars — excuse me, two particles — go by each other, to any order you want (not for stars, then they have to be particles of specified properties; because obviously the rate of radiation of the gravity depends on the give of the starstides are produced). If you do a real problem with real physical things in in then I'm sure we have the right method that belongs to the gravity theory. There's no question about that.

5PN threshold!