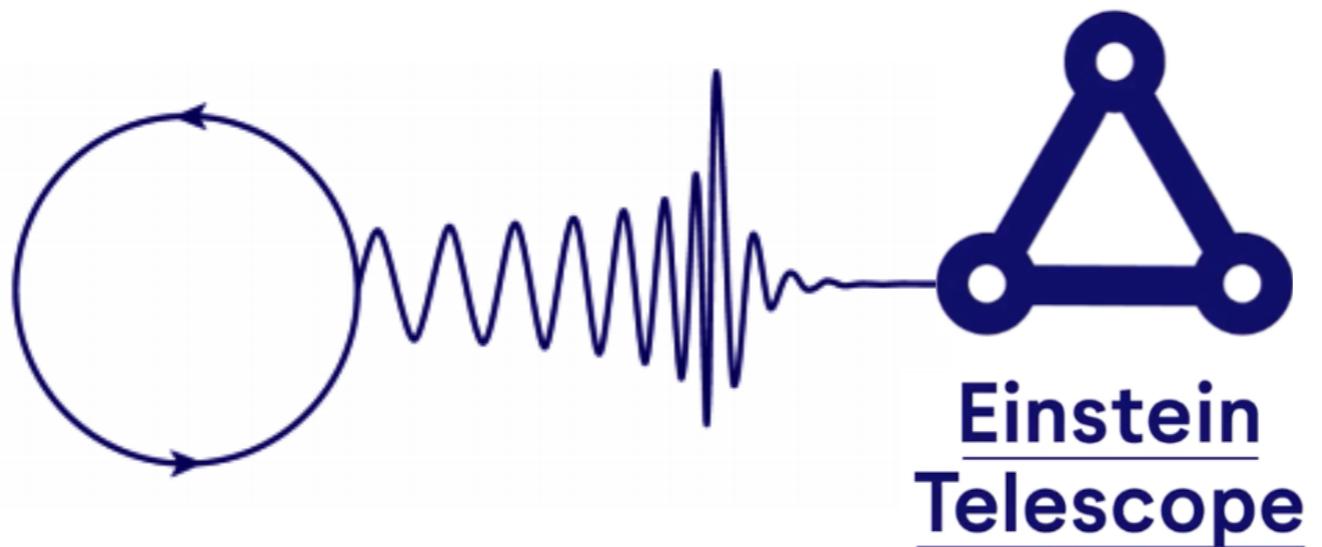
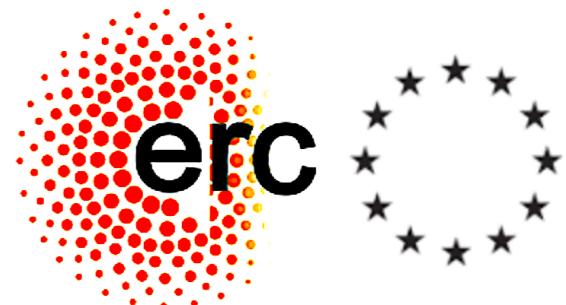


# Precision Gravity: From the LHC to ET

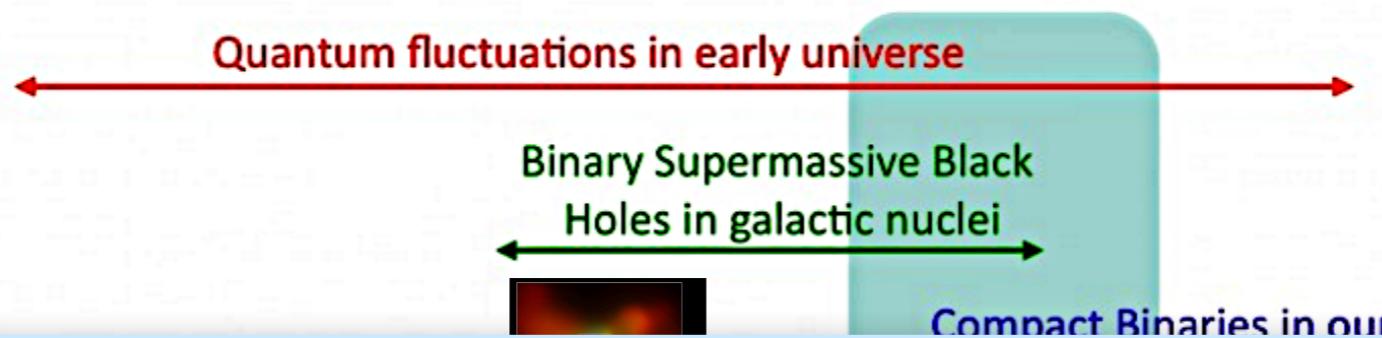


*Rafael A. Porto*



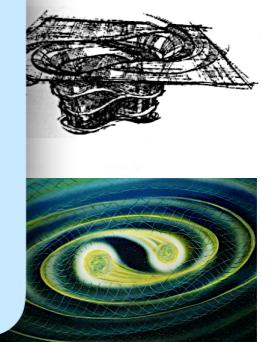
# The Gravitational Wave Spectrum

Sources

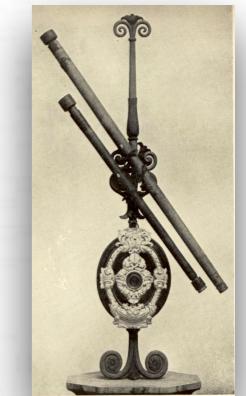
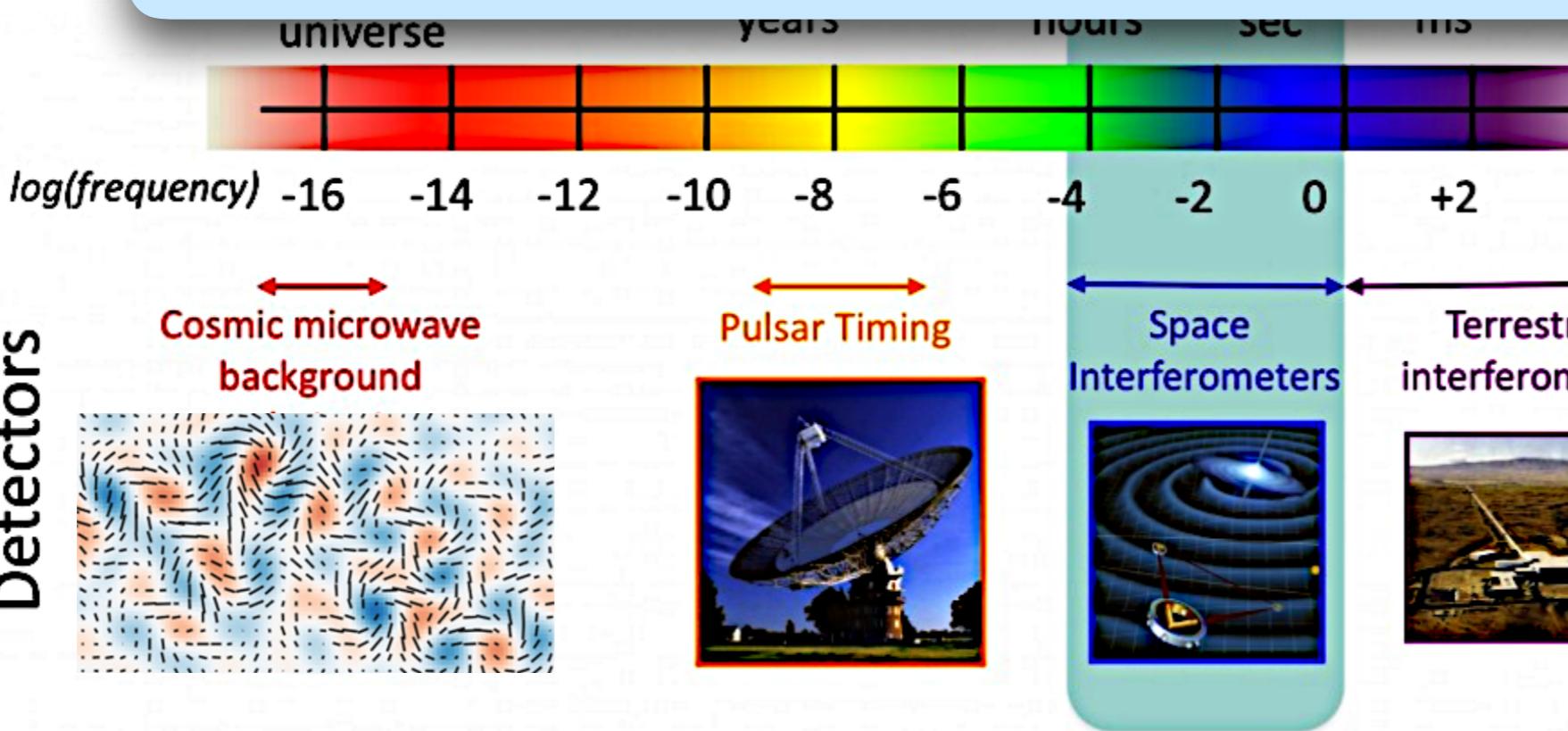


Discovery Potential =

Precise Theoretical Predictions



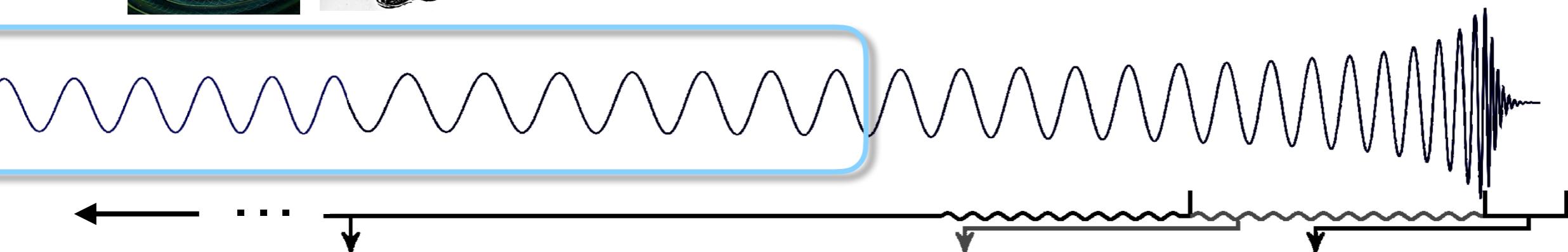
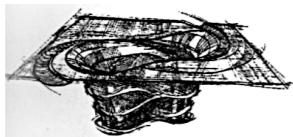
Detectors



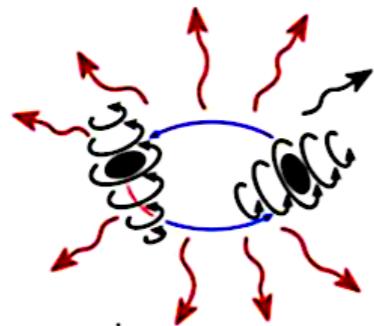
# Challenge:

1000+ cycles in band @ Design-Sensitivity

100+ events per year!



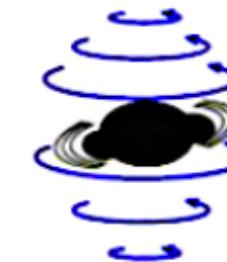
Inspiral



Merger



Ringing

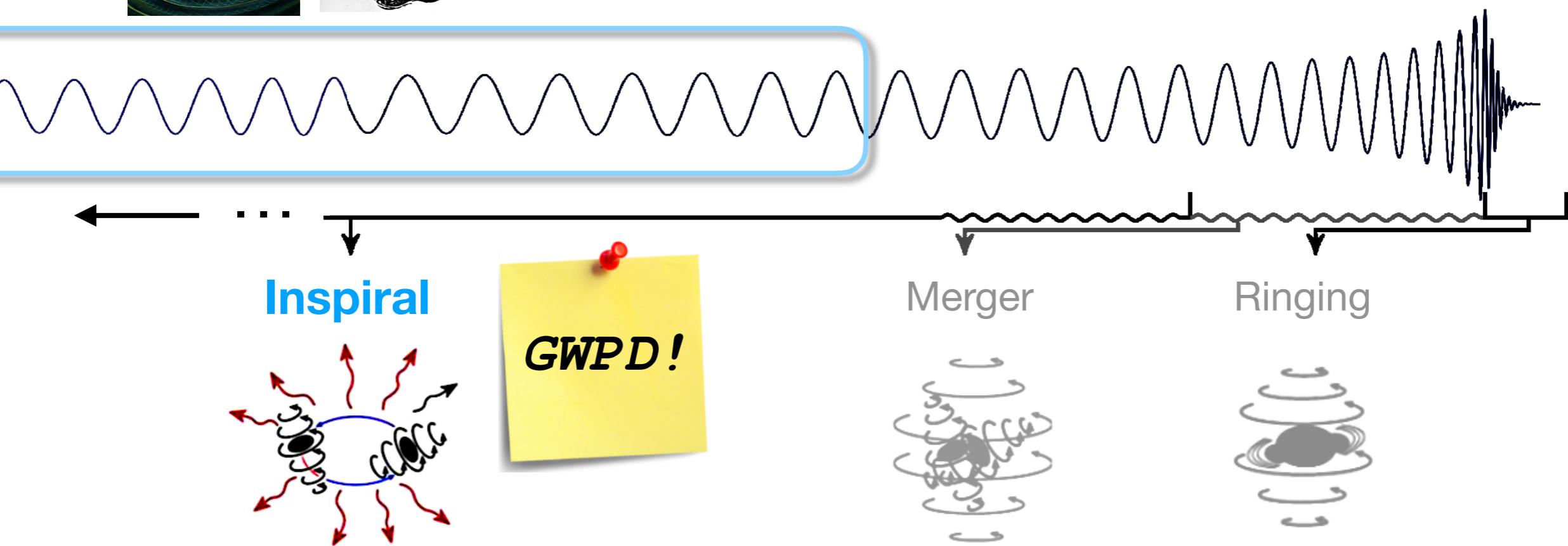
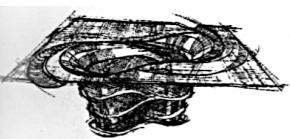


$$R_{im} = \sum_i \frac{\partial \Gamma_{im}^i}{\partial x_i} + \sum_{ij} \Gamma_{ij}^i \Gamma_{im}^j = -x \left( T_{im} - \frac{1}{2} g_{im} T \right)$$

# 'GW Precision Data' (GWPD)™

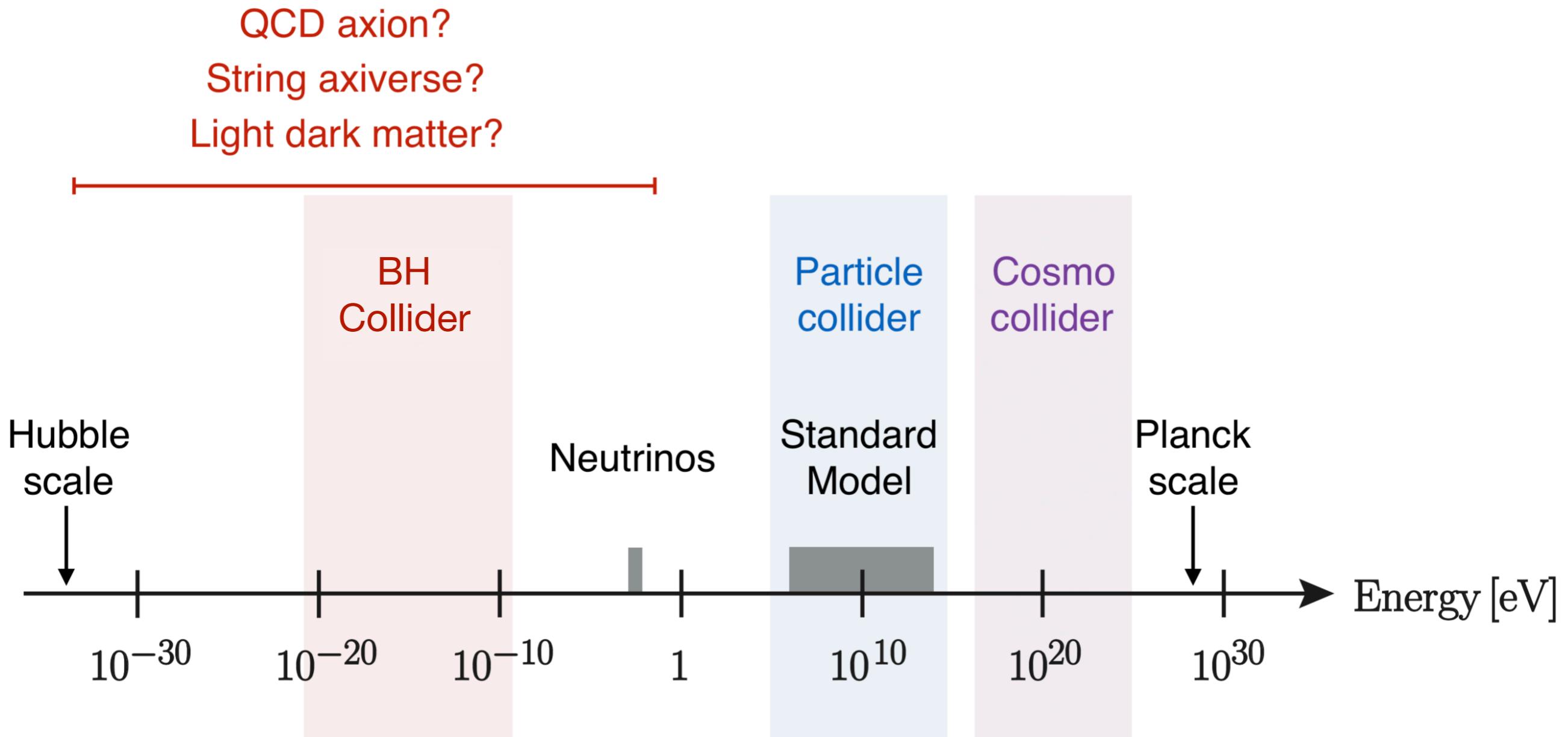
1000+ cycles in band @ Design-Sensitivity

100+ events per year!



$$R_{im} = \sum_i \frac{\partial \Gamma_{im}^i}{\partial x_i} + \sum_{ij} \Gamma_{ii}^j \Gamma_{jm}^i = -x \left( T_{im} - \frac{1}{2} g_{im} T \right)$$

# GWPD for Beyond the Standard Model (BSM)



Probing ultralight bosons  
with binary black holes

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

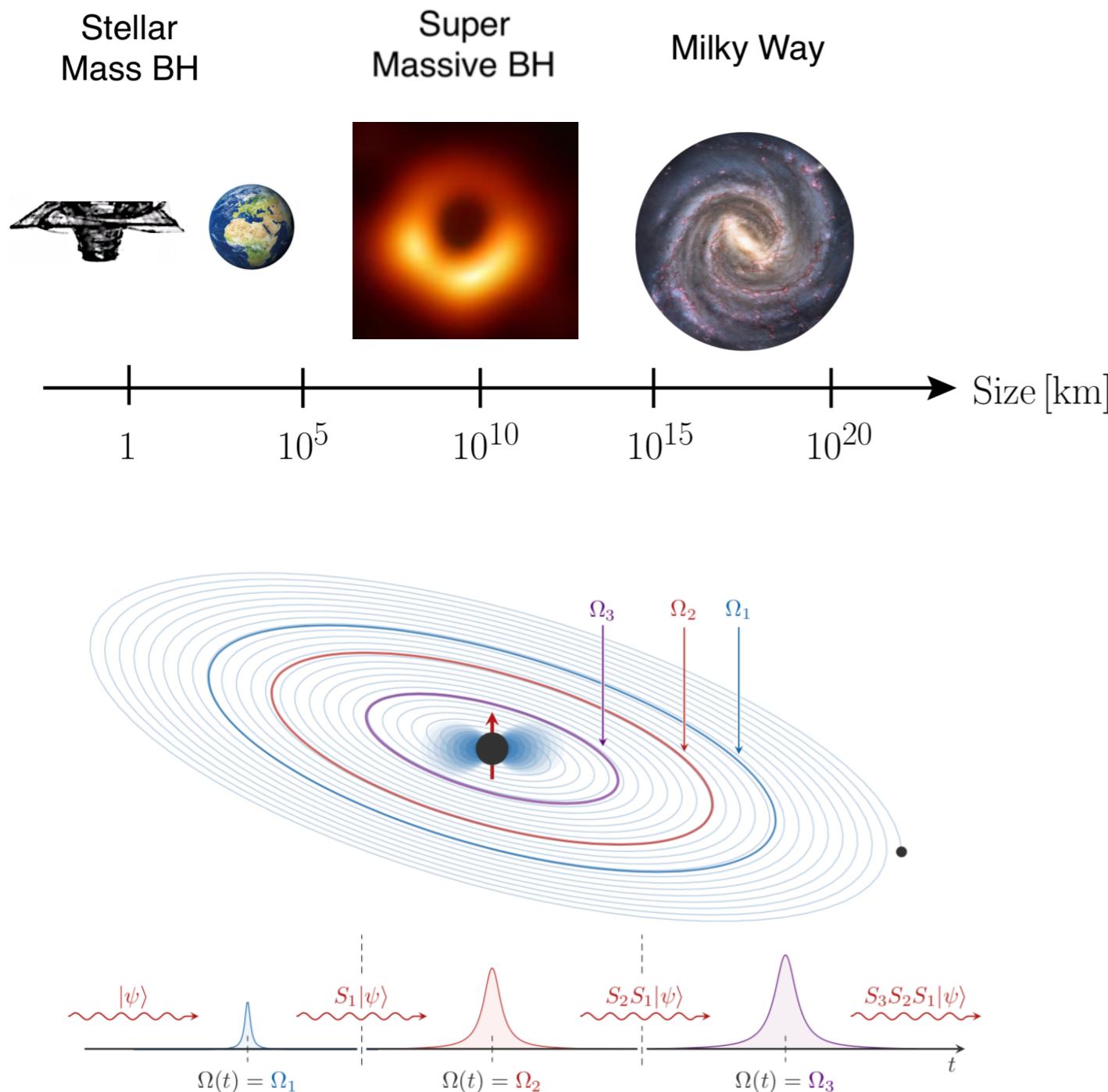
Phys. Rev. D 99, 044001 (2019)

Published February 4, 2019

Physics See Synopsis:

Black Holes Could Reveal  
New Ultralight Particles

# GWPD for Beyond the Standard Model (BSM)



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

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

Gravitational ‘susceptibility’  
Vanishes for BHs in isolation!

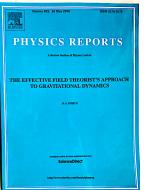
Fortschr. Phys. 64, No. 10, 723–729 (2016) / DOI 10.1002/prop.201600064

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

Rafael A. Porto\*

The effective field theorist’s approach to gravitational dynamics  
Physics Reports

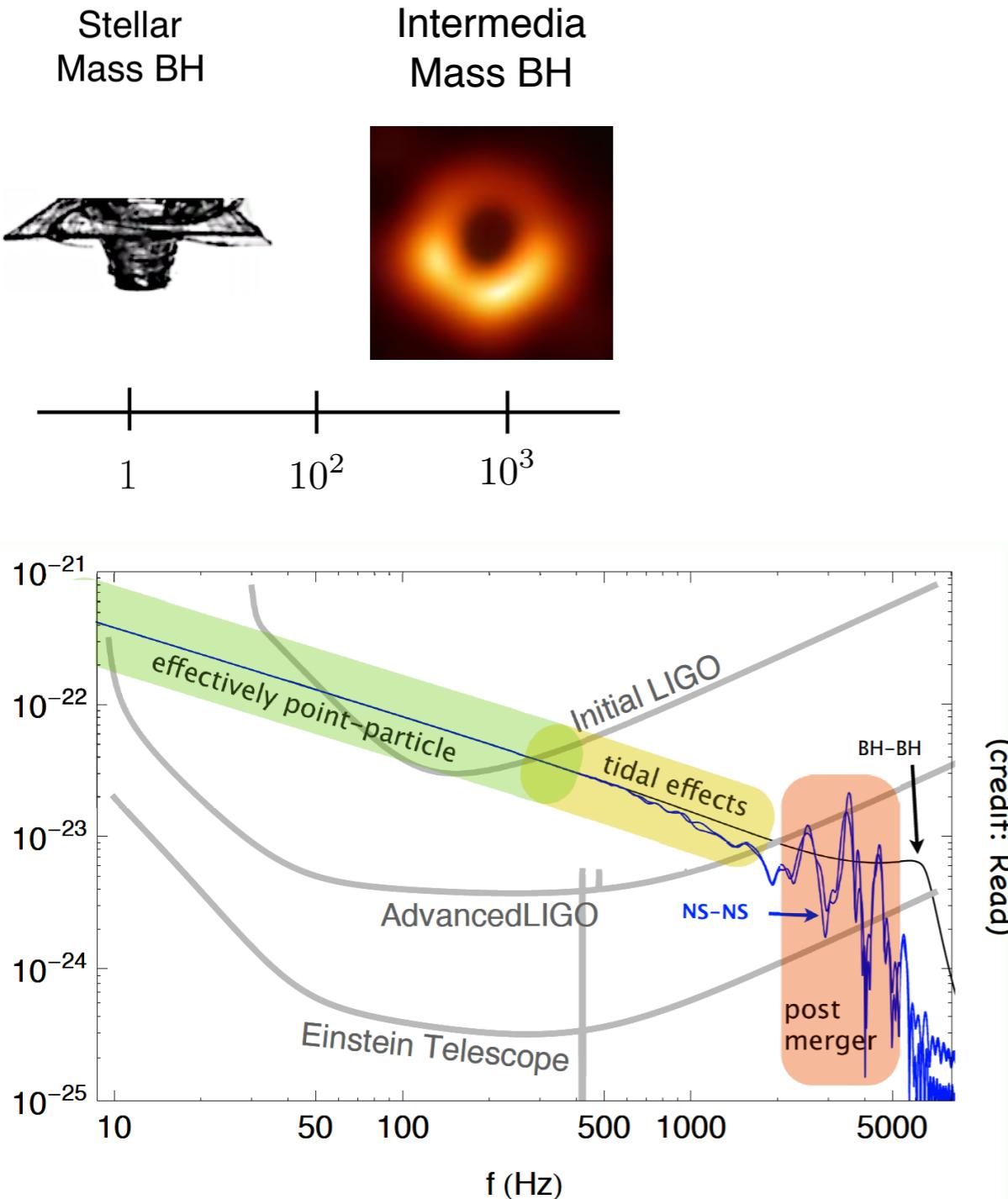
Rafael A. Porto      Volume 633, 20 May 2016, Pages 1-104



## Gravitational Collider Physics

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

# GWPD for Beyond the Standard Model (BSM)



## Gravitational Collider Physics



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

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

**Gravitational ‘susceptibility’ Vanishes for BHs in isolation!**

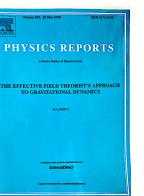
Fortschr. Phys. 64, No. 10, 723–729 (2016) / DOI 10.1002/prop.201600064

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

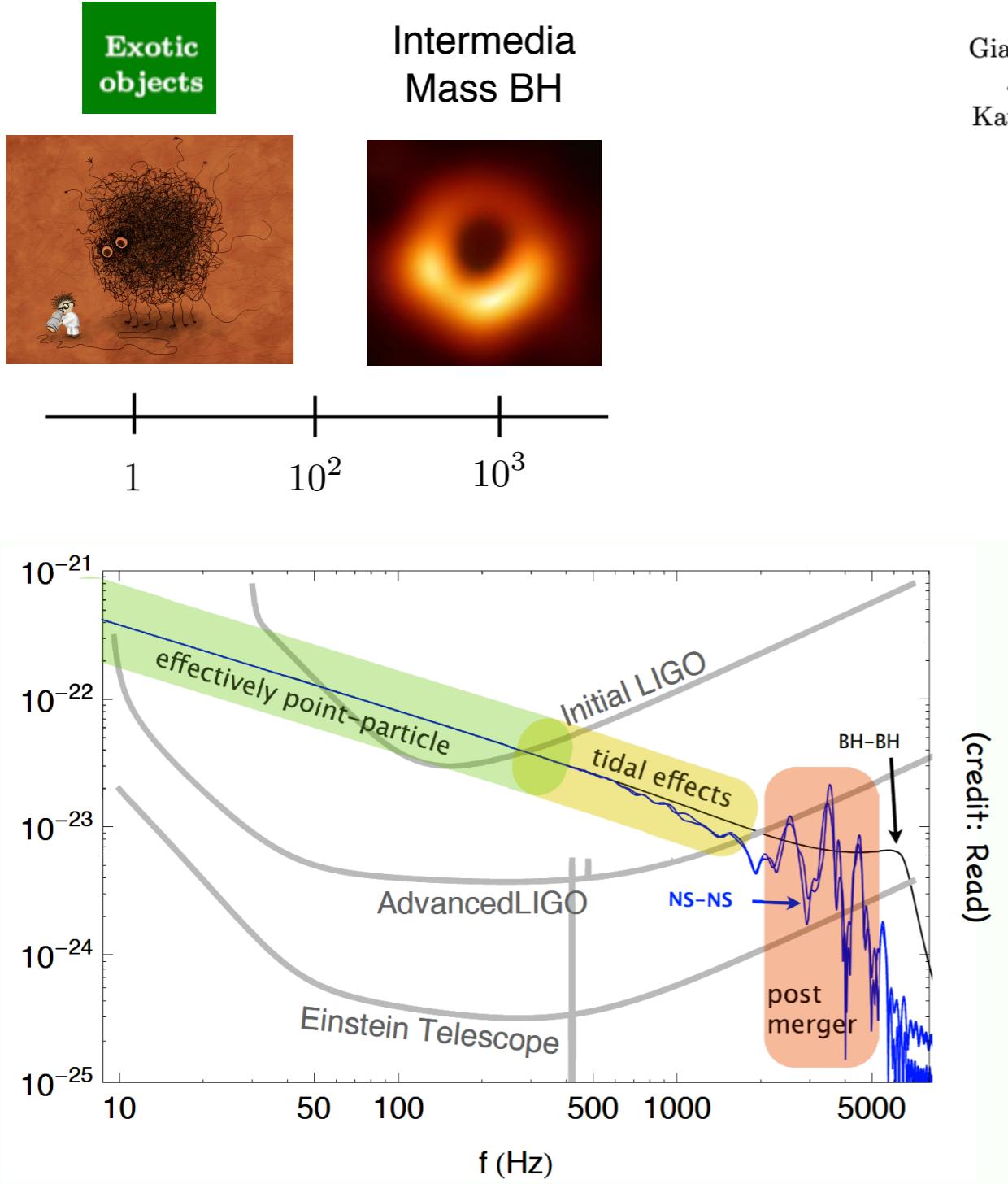
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The effective field theorist’s approach to gravitational dynamics  
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Rafael A. Porto Volume 633, 20 May 2016, Pages 1-104

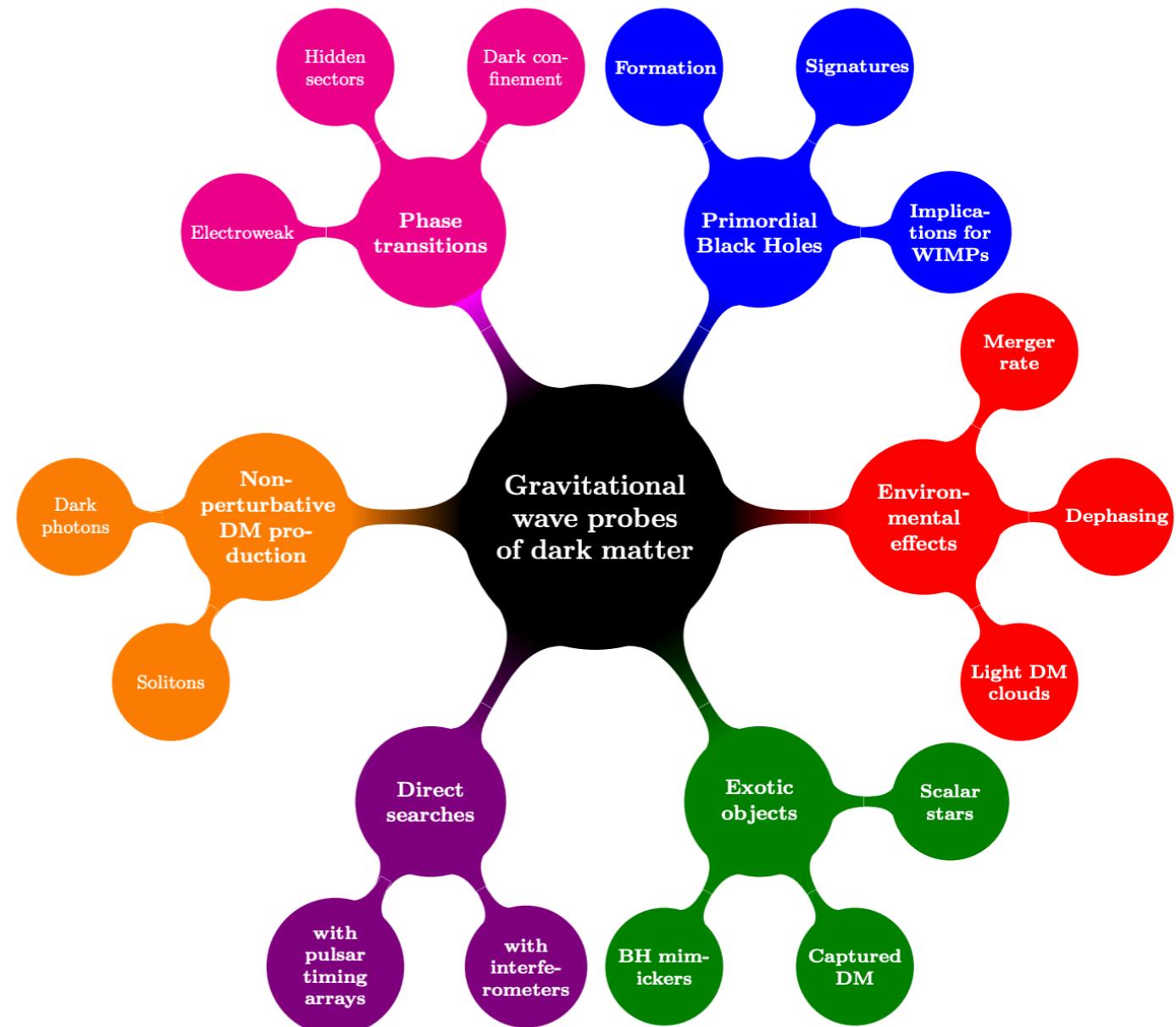


# GWPD for Beyond the Standard Model (BSM)

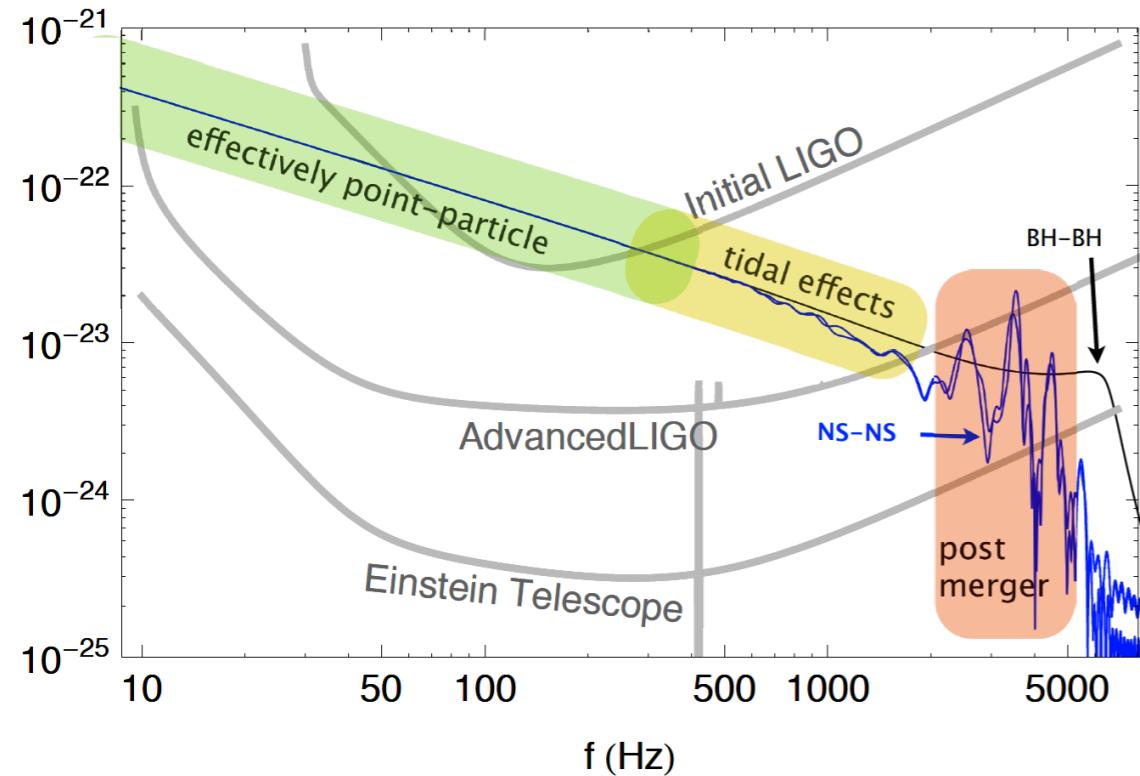
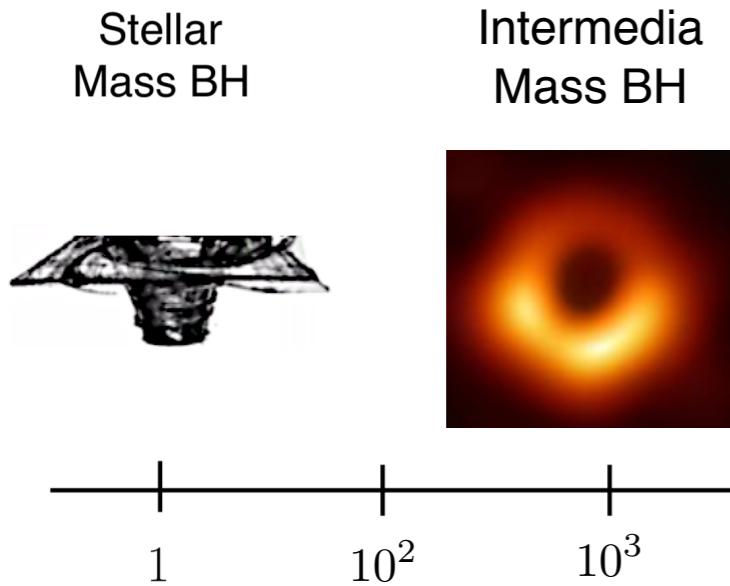


## Gravitational wave probes of dark matter: challenges and opportunities

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



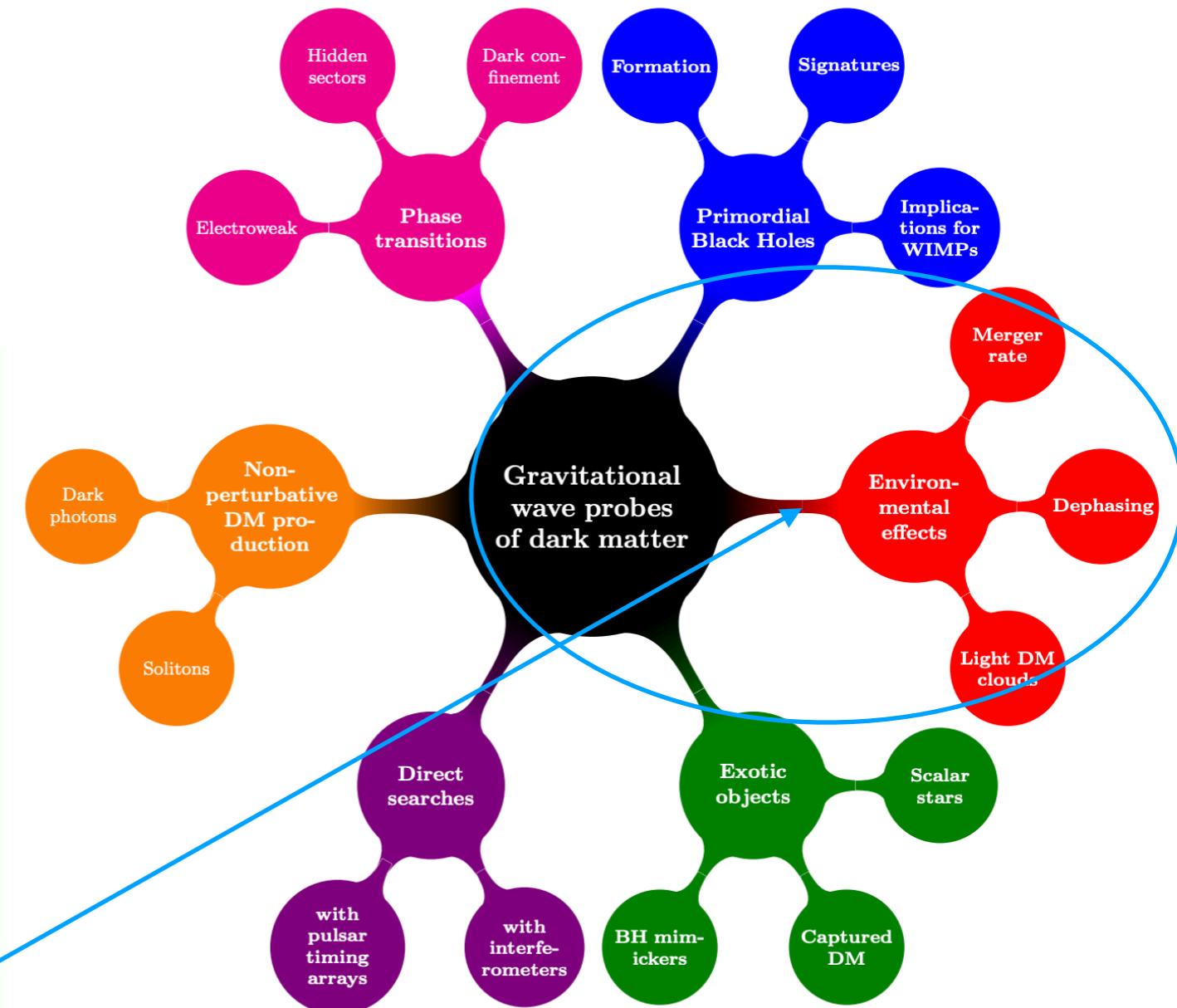
# GWPD for Beyond the Standard Model (BSM)



## Gravitational Collider Physics

### Gravitational wave probes of dark matter: challenges and opportunities

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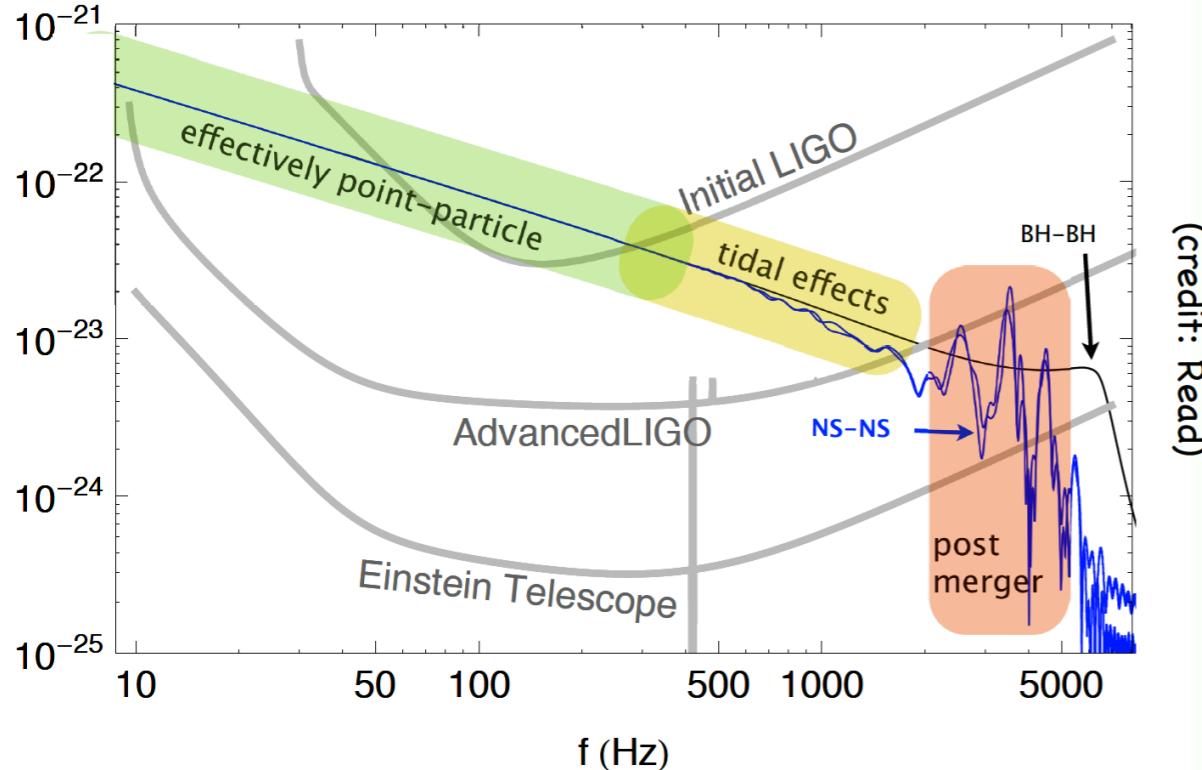


# ET = more ‘luminosity/sensitivity’ at ‘higher/lower energies’



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

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

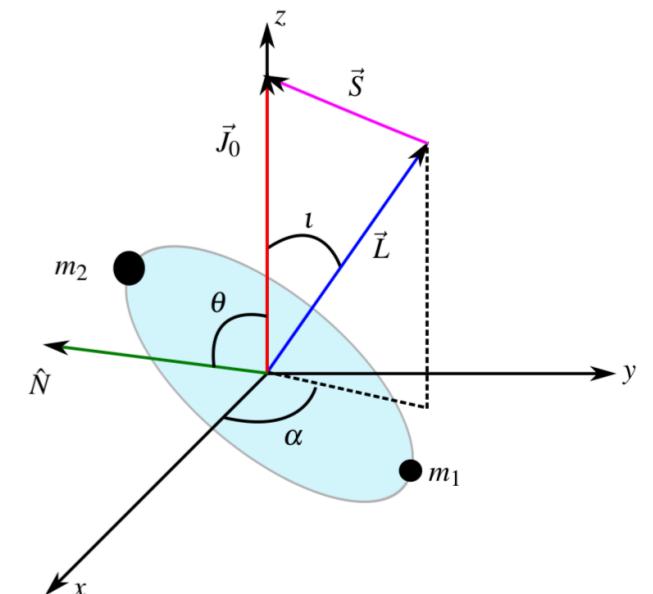


- **Energy/Sensitivity Frontier**  
Lower Frequency: Long-Distance/Bigger IMBHs, ECOs,...  
Higher Frequency: Short-Distance/Smaller NSs, Low-mass BHs, PBHs...
- **Luminosity Frontier**  
Precision Gravity: Longer/high-SNR signals  
Tidal Effects: NSs, Light DM, ECOs, ...

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

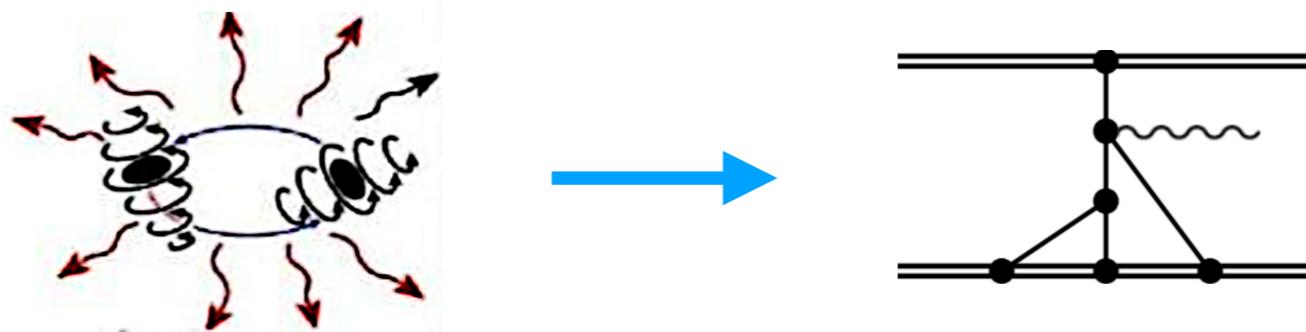
Curt Cutler, Theocharis A. Apostolatos, Lars Bildsten, Lee Smauel Finn, Eanna E. Flanagan, Daniel Kennefick, Dragoljub M. Markovic, Amos Ori, Eric Poisson, Gerald Jay Sussman, and Kip S. Thorne  
Phys. Rev. Lett. **70**, 2984 – Published 17 May 1993

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



## Knowledge at the time

# Where are we now?



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

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,<sup>1</sup> Rafael A. Porto,<sup>2,3</sup> Ira Rothstein,<sup>4</sup> and Riccardo Sturani<sup>5</sup>

The effective field theorist's approach to gravitational dynamics  
Physics Reports

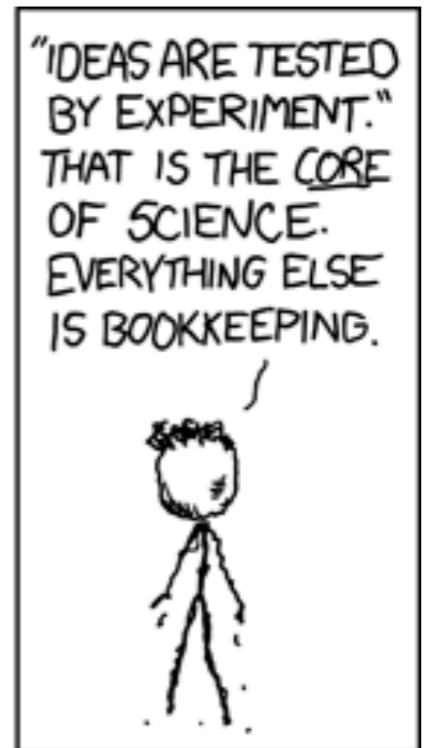
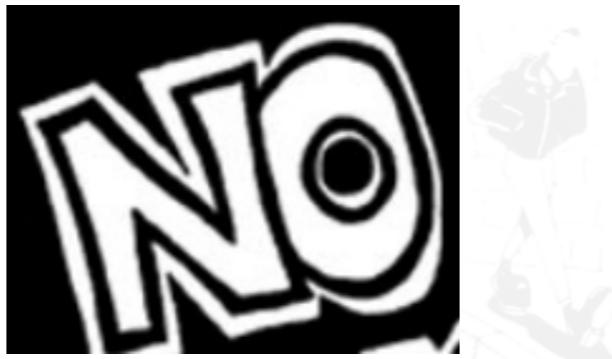
Rafael A. Porto    Volume 633, 20 May 2016, Pages 1-104



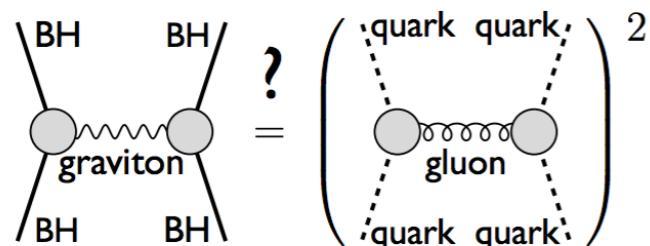
HEP

GWs

# Are we ready for the future?



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



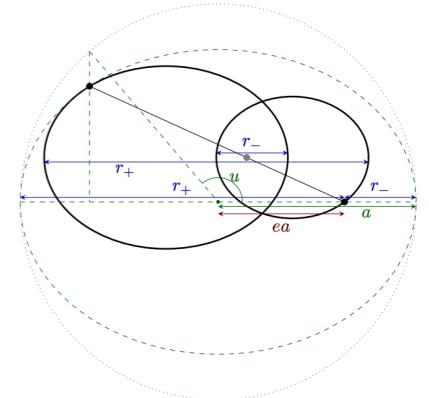
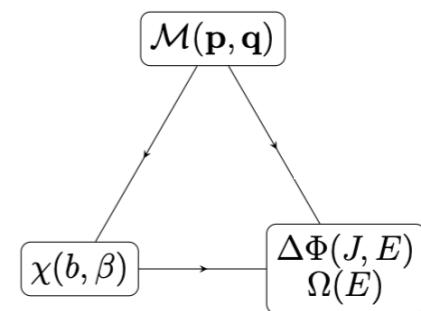
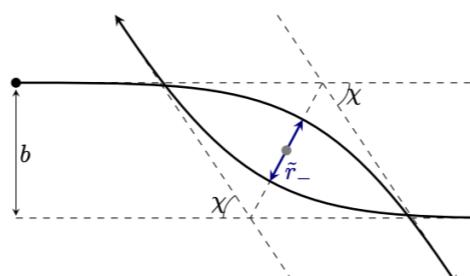
PRECISION GRAVITY: FROM THE LHC TO LISA

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<sup>a</sup> and Rafael A. Porto<sup>b,c</sup>



## Experts Clash Over Project To Detect Gravity Wave

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

By MICHAEL J. BERNSTEIN

**A**PROPOSAL to build three orbiting test masses on the moon that would detect gravitational waves from exploding stars, colliding galaxies and other astronomical events has been rejected by the National Research Council.

The review panel, which included members of Congress and the National Academy of Sciences, found the project's scientific merit too great to justify its cost, estimated at \$1 billion to \$2 billion over 15 years.

Proposed by the University of Texas, the Laser Interferometer Space Antenna (LISA) would have been the first space-based gravitational-wave detector.

It would have been able to detect gravitational waves from exploding stars, colliding galaxies and other astronomical events that cannot be studied from Earth because they are too far away or too faint.

Scientists acknowledge the scientific importance of the search for gravitational waves, but most of them are not fully satisfied with the project's funding, a sum that may be too large for the mission to be successful.

There is also concern about the project's scientific merit, which is not fully understood.

"There is no question that it is a very interesting project, but there is a lack of understanding of how it will work," said Dr. Robert L. Kulsrud, a member of the review panel.

Dr. Kulsrud, a physicist at the University of Texas, said the project's cost, the amount of time it would take to build it and the amount of fuel it would require to operate it are not fully understood.

He said the project's scientific merit is not fully understood.

Continued on Page C2



# Die Zeit

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## 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.

By MICHAEL BIERMAN

**A**PROPOSAL to build \$100 million in new detectors on the ocean floor off the coast of Italy has been submitted to Italian science today, and the project's proponents have already elicited mixed reactions from experts who are trying to decide whether the proposal is indeed a difficult decision or the most feasible.

The source of the proposal, the National Institute of Nuclear Physics, a part of the National Research Council of Italy, says the detector will be used to detect gravitational waves from the Sun and other celestial bodies.

Proposed by the scientific project, the Laser Interferometer Gravitational-Wave Observatory, the detector will be built in the next few years, and it will be used to detect gravitational waves from the Sun and other celestial bodies.

Scientists acknowledge the scientific importance of the wave for gravity waves, but one of them has not fully chosen to support the project, saying a wave that may represent more than a few months of gravitational waves from the Sun and other celestial bodies.

Other scientists are also skeptical of the project's scientific value.

"I am not sure if the project is worth the cost," said Dr. John C. Miller, a member of the project's board. "The detector is not able to detect gravitational waves from the Sun and other celestial bodies.

"There are other ways to detect gravitational waves from the Sun and other celestial bodies," he said.

He added, "I am not sure if the project is worth the cost."

Continued on Page C1



# 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!**