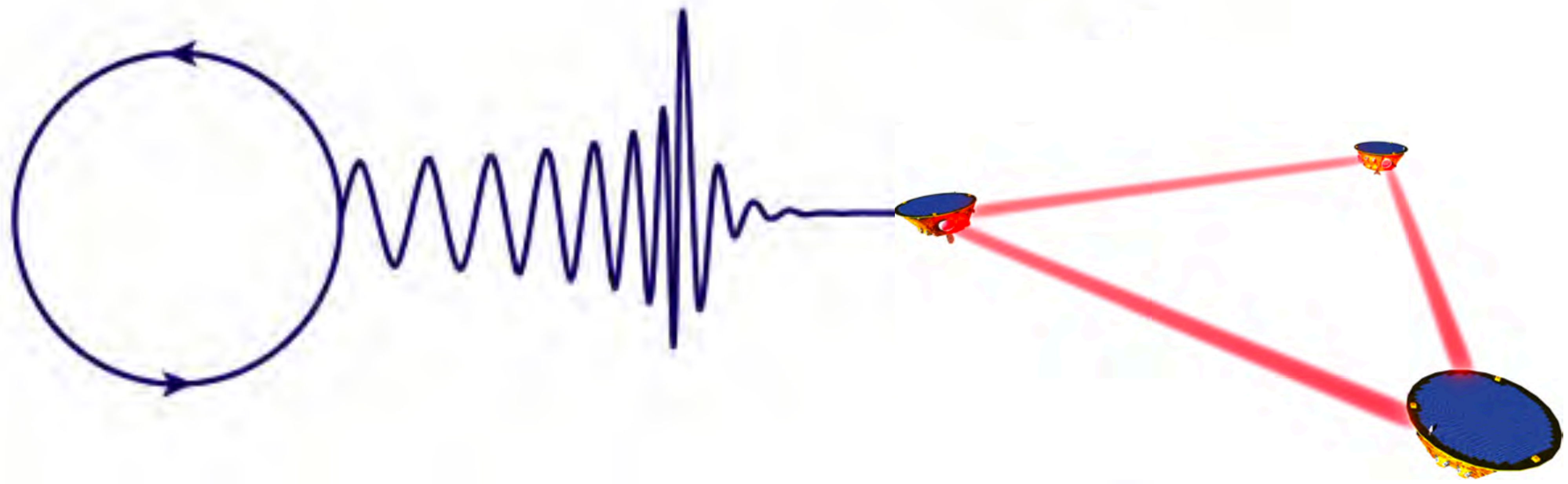
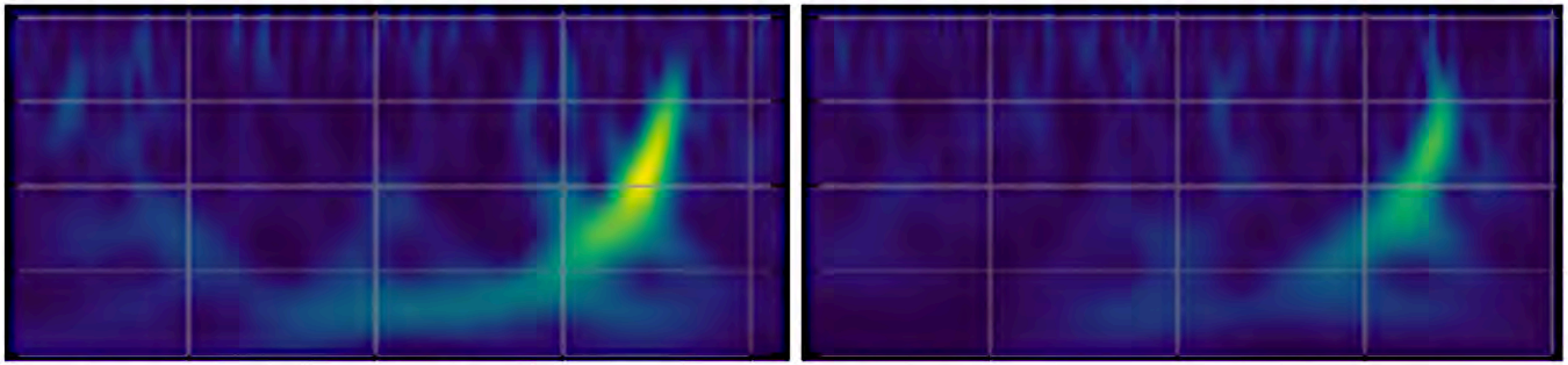
Precision Gravity: From the LHC to LISA



Rafael A. Porto

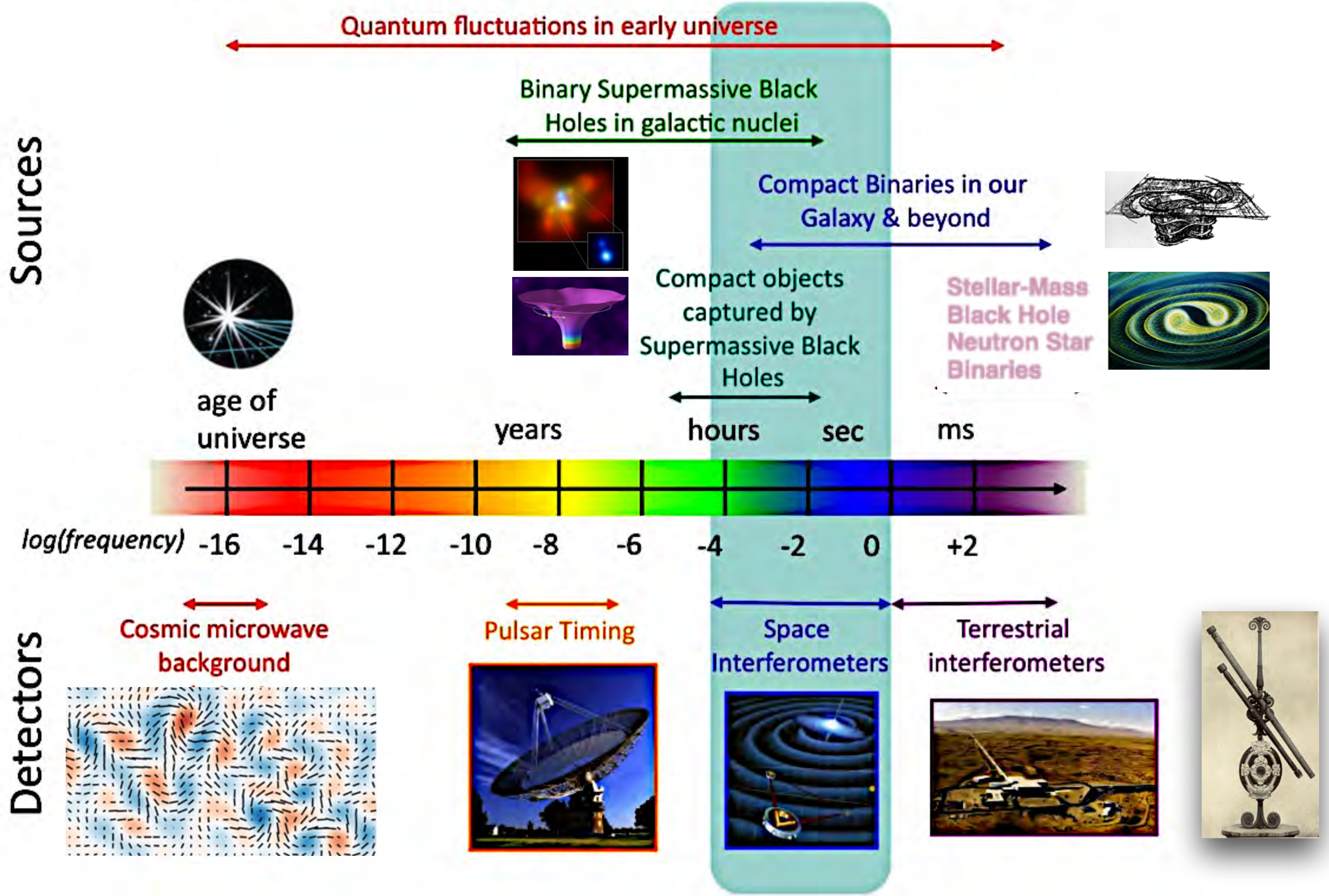
DESY. ICTP erc

Observation of Gravitational Waves from a Binary Black Hole Merger

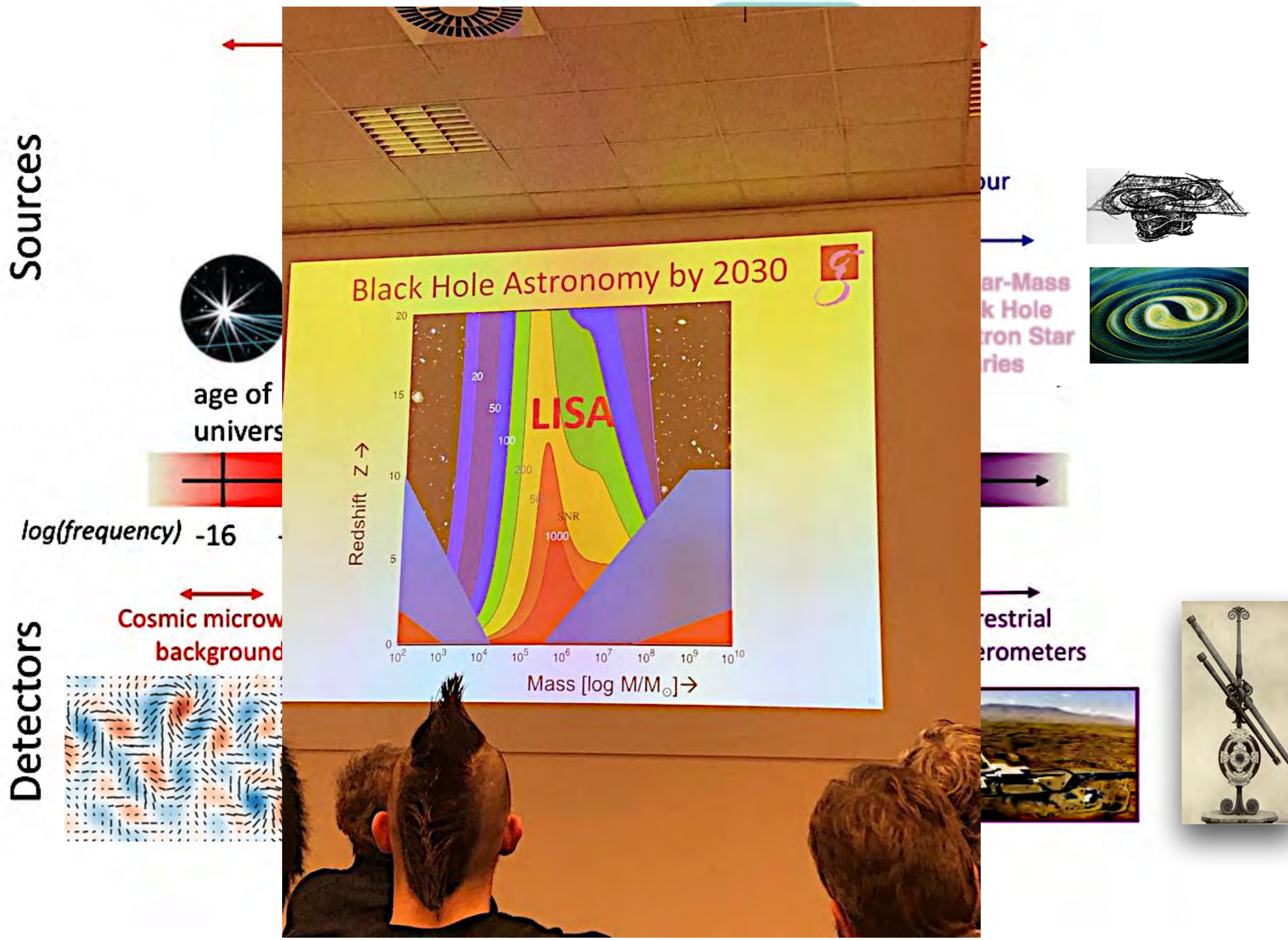


B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **116**, 061102

The Gravitational Wave Spectrum

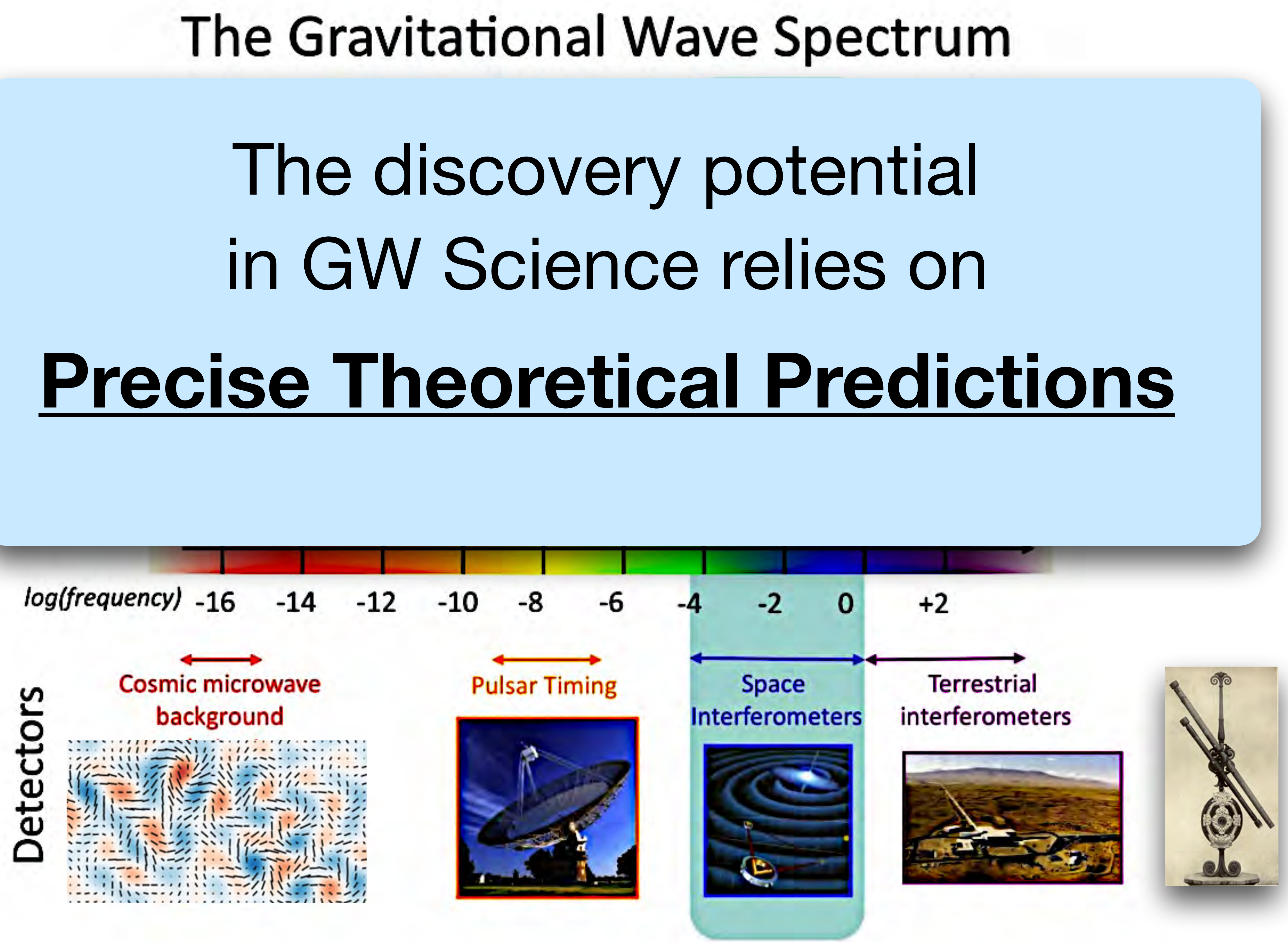


The Gravitational Wave Spectrum



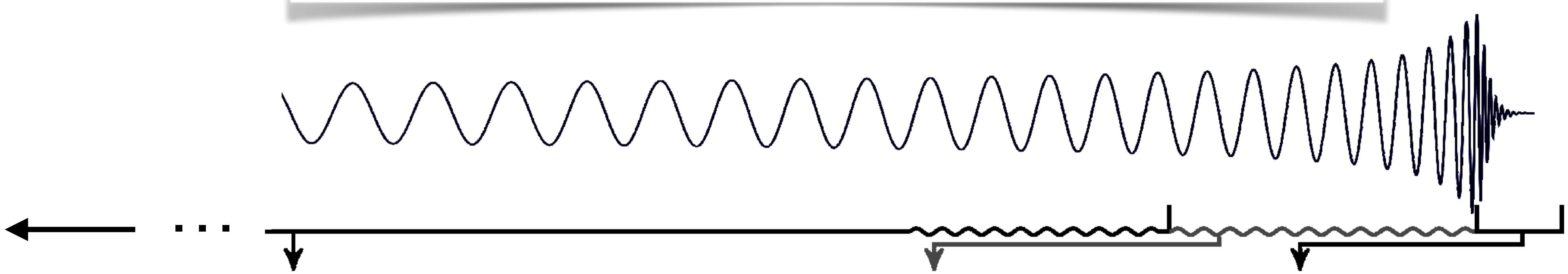
The discovery potential
in GW Science relies on

<u>Precise Theoretical Predictions</u>

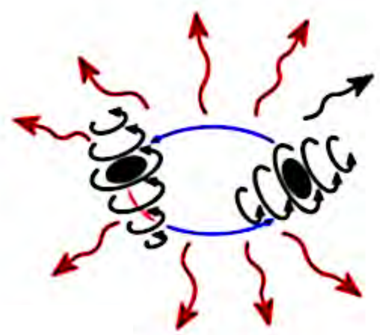


Challenge: Two-body problem in General Relativity

$$R_{im} = \sum_l \frac{\partial \Gamma^l_{im}}{\partial x_l} + \sum_{\rho l} \Gamma^\rho_{il}\Gamma^l_{m\rho} = -\kappa\left(T_{im} - \frac{1}{2} g_{im} T\right)$$



Inspiral



Analytic/Perturbative
(Approx. but fast)

Merger

Numerical
(exact but slow)

Ringing

Analytic/
Perturbative

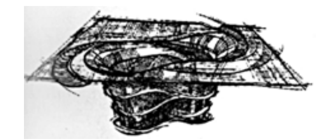
Waveforms need to **match data** over <u>all cycles</u>

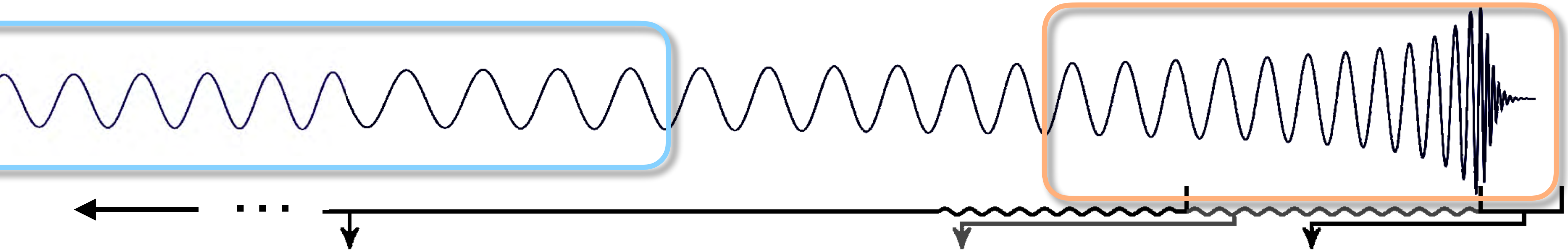
Challenge: Two-body problem in General Relativity

1000+ cycles in band @ **Design-Sensitivity**

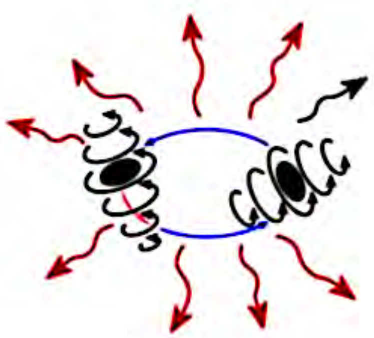
GW170817

GW150914





Inspiral



Post-Newtonian Expansion

Merger

Numerical (exact but slow)

Ringing

Analytic/ Perturbative

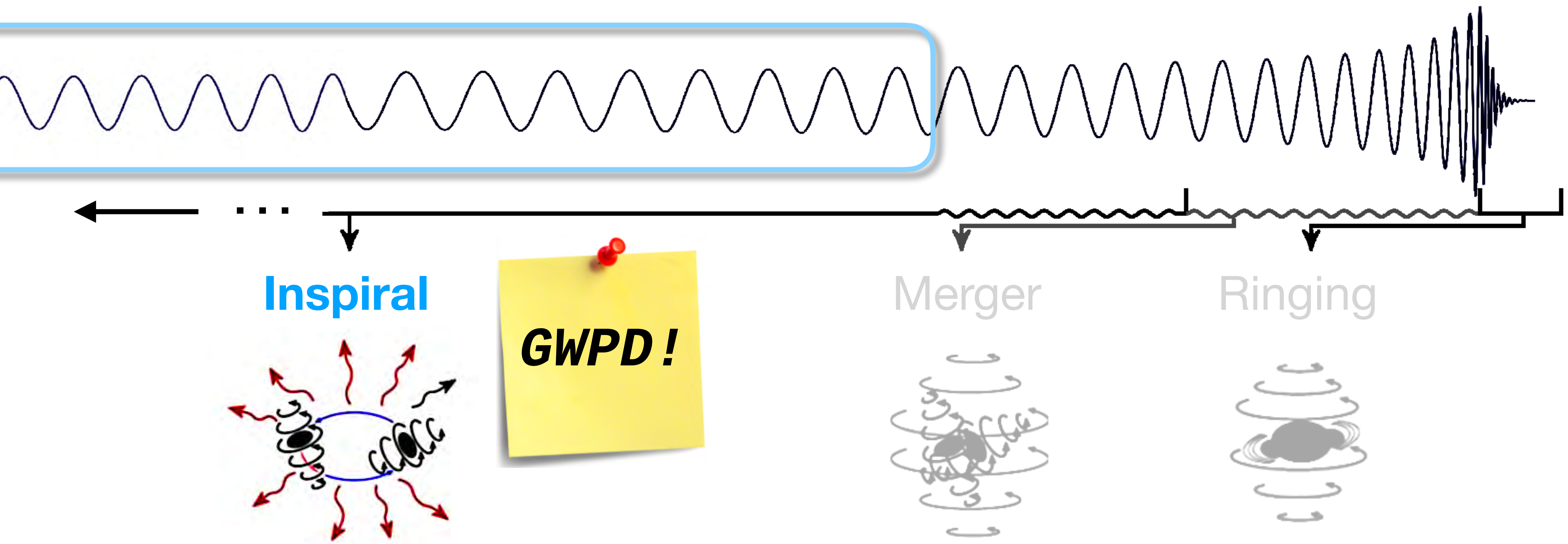
Waveforms need to **match data** over <u>all cycles</u>

Unfeasible with only numerical methods

Main Goal: Extremely accurate Post-Newtonian waveforms

1000+ cycles in band @ **Design-Sensitivity**

100+ events per year!



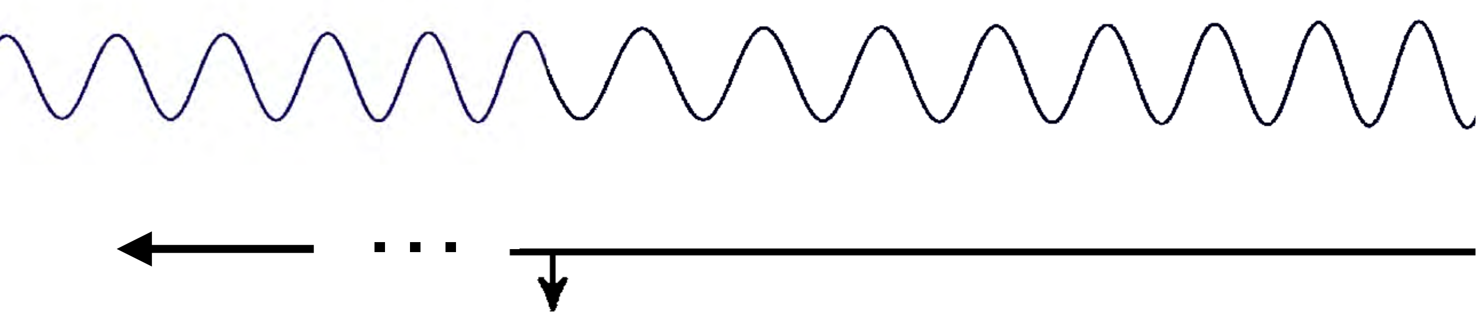
Post-Newtonian Expansion

GW Precision Data (**GWPD**) ***TM***

State-of-the-art & Methodology

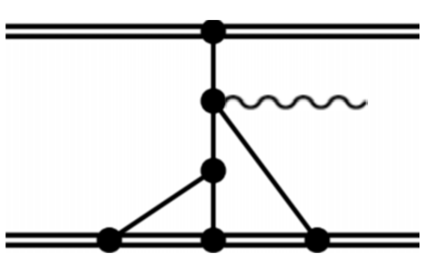
1000+ cycles in band @ **Design-Sensitivity**

100+ events per year!



3.5PN order

Inspiral



classical

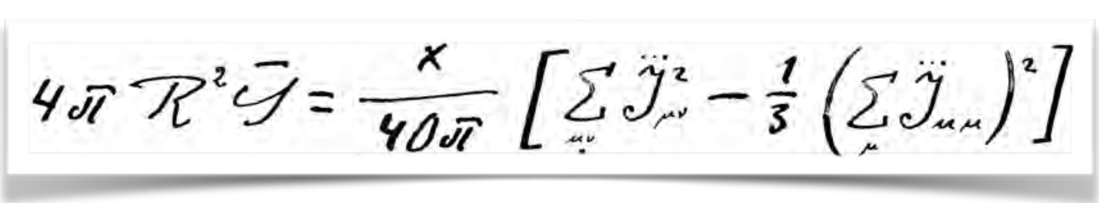
Feynman diagrams

$$\frac{\dot\omega}{\omega^2} = \underbrace{\frac{96}{5}\nu x^{5/2}}\left\{1 + \overbrace{\cdots + [\cdots]x^{7/2}}\right\}$$

$\nu \sim m_2/m_1$

$x \sim (v/c)^2$

Quadrupole Formula

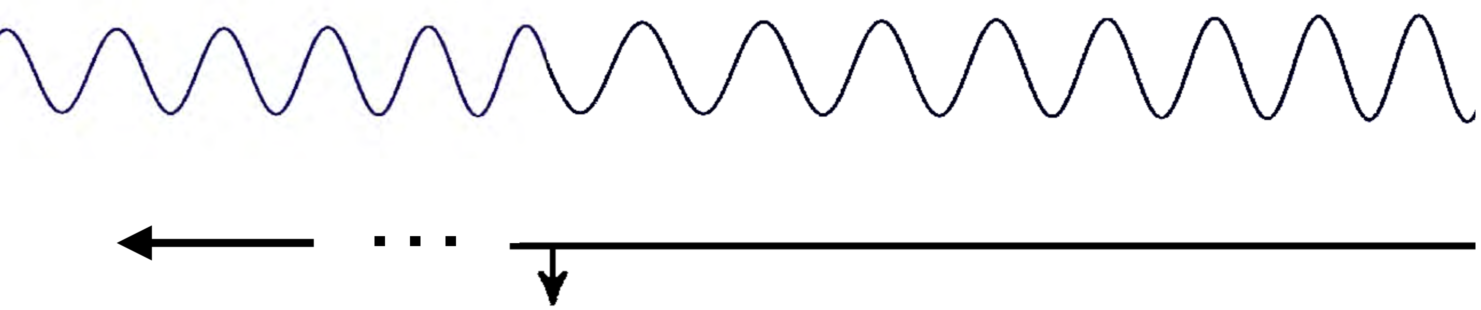


The effective field theorist's approach to gravitational dynamics

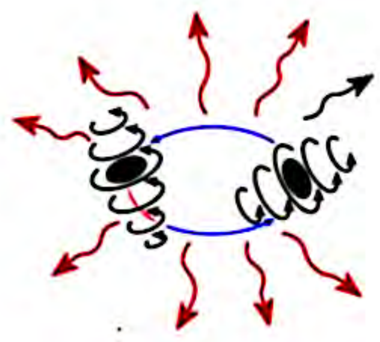
Physics Reports

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

Are we ready for the future?



Inspiral



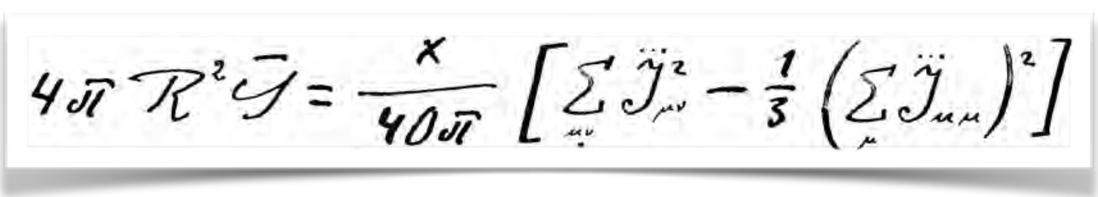
Good Enough?

$$\frac{\dot{\omega}}{\omega^2} = \underbrace{\frac{96}{5}\nu x^{5/2}\Big\{1}\overbrace{+\cdots+[\cdots]x^{7/2}}\Big\}$$

$\nu \sim m_2/m_1$

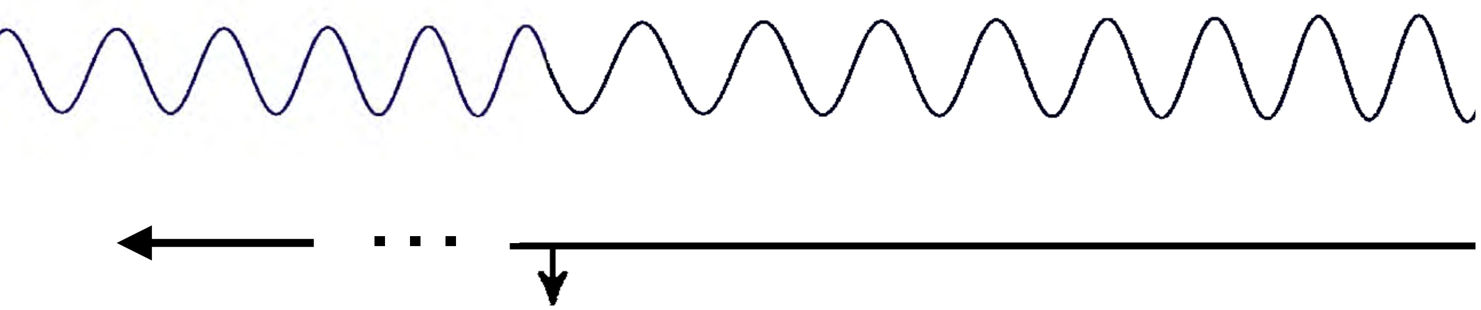
$x \sim (v/c)^2$

Quadrupole Formula

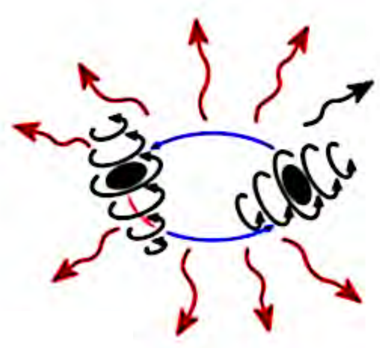


Are we ready for the future?

Theoretical uncertainties dominate over planned empirical reach



Inspiral



NOT GOOD ENOUGH

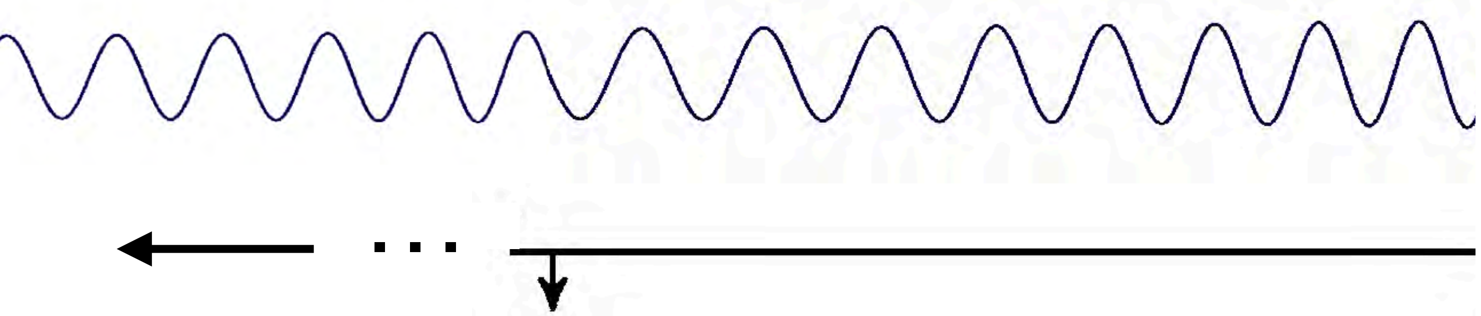
$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{1 + \overbrace{\cdots + [\cdots]x^{7/2}}\right\}$$

SNR: LIGO/VIRGO ~ 30

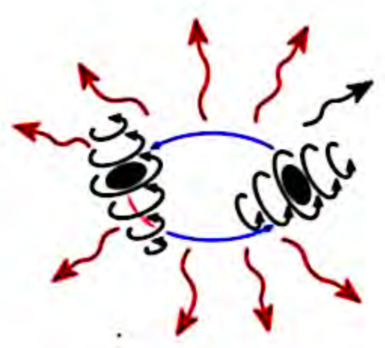
but ET/CE & LISA ~ 100-1000!

Are we ready for the future?

We haven't reached the precision to distinguish between compact bodies!



Inspiral



'New Physics' Threshold

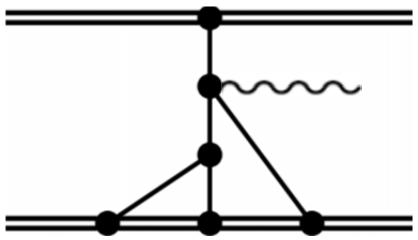
$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{1 + \cdots + [\cdots]x^{7/2} + \mathcal{O}(x^4) + \mathcal{O}(x^5)\right\}$$

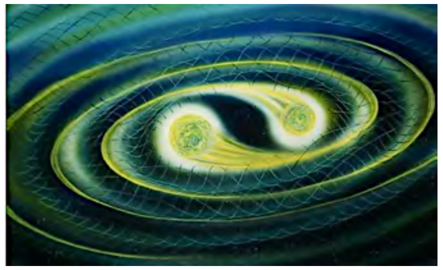
N^5LO 5PN

Inner structure of compact objects

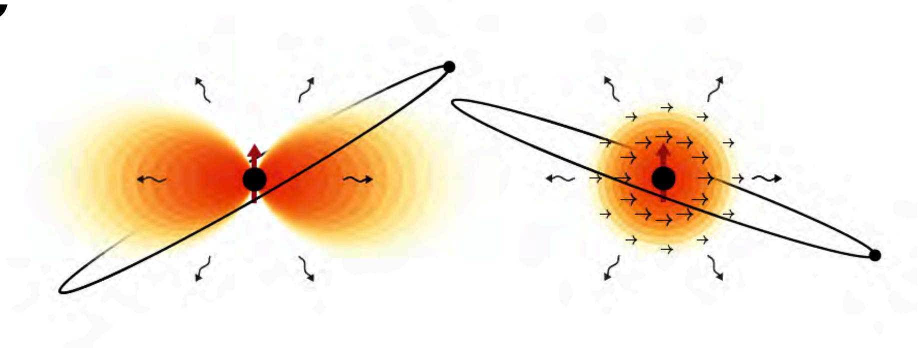
GW precision physics

- EFT approach to binary problem



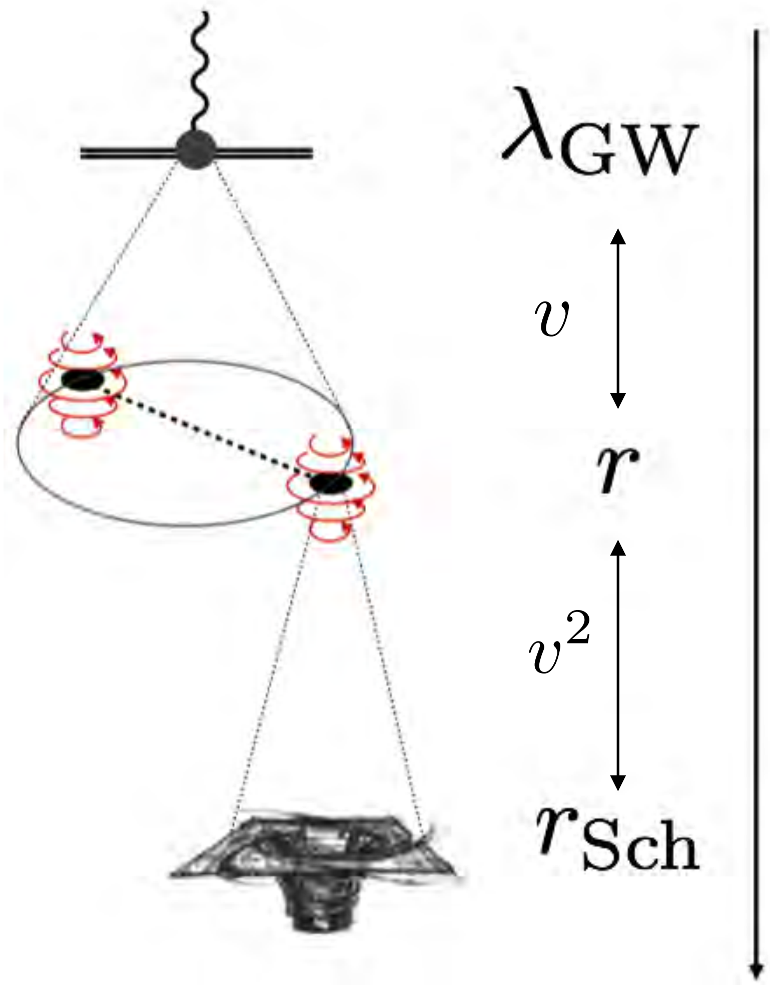


- **Opportunities**: 'Future of GW Science'



- **Challenges**: How do we get there?

The EFT approach

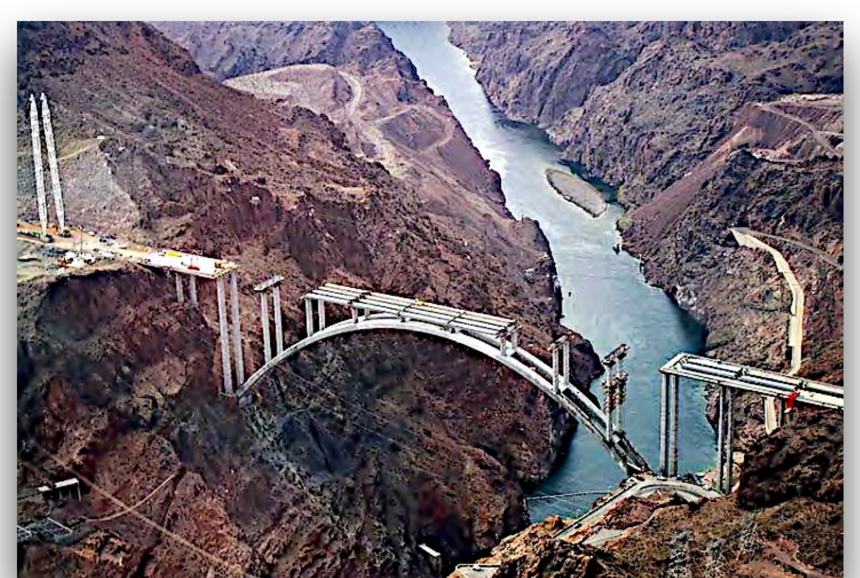


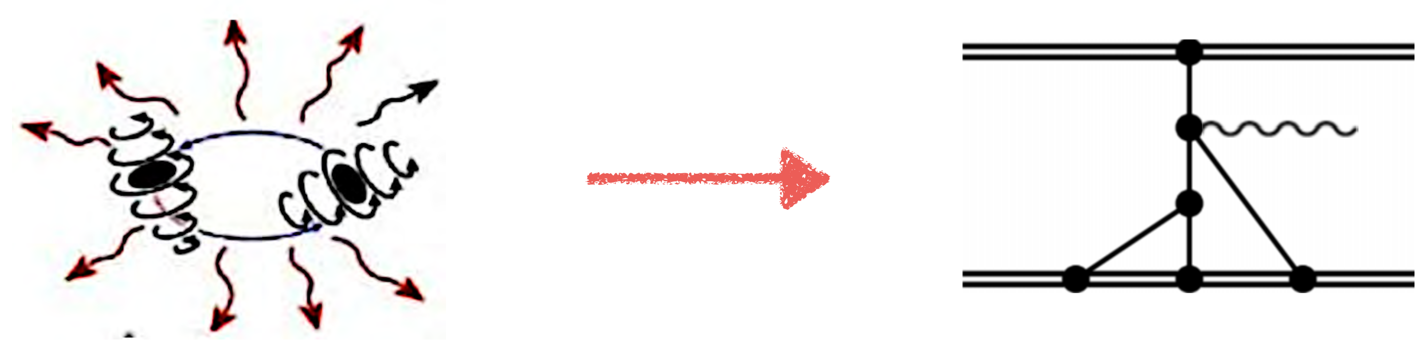
- **Separation of Scales (2-body in GR):**

$$r_{\rm Sch} \ll r \ll \lambda_{\rm GW}$$

- **Effective Field Theory:**
  One scale at a time

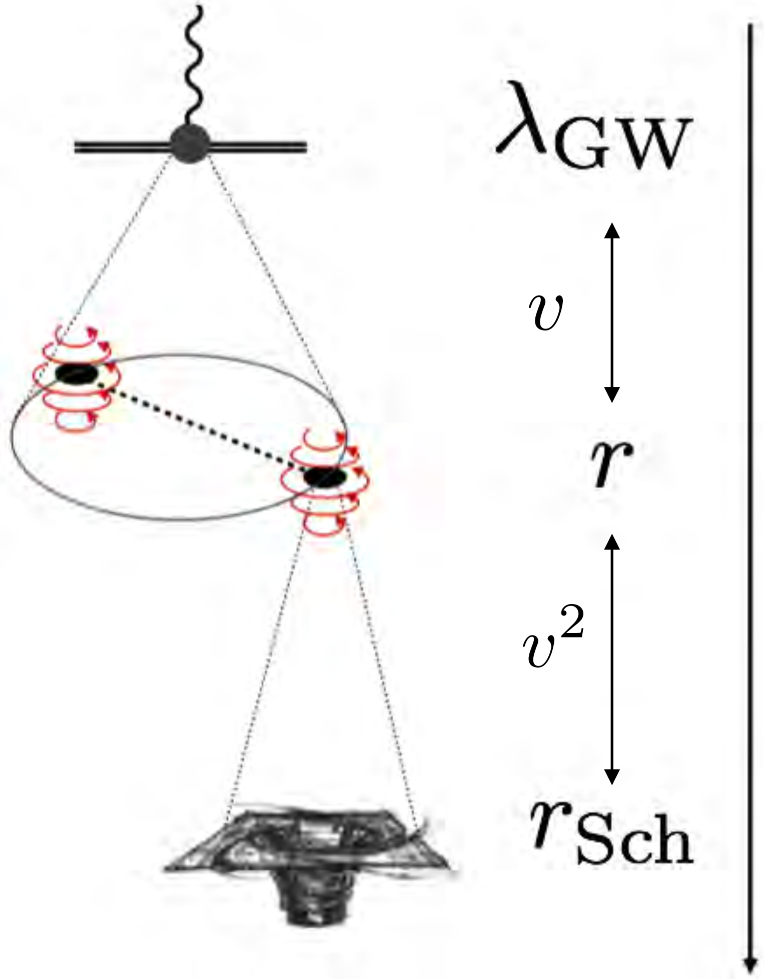
- **Tools from HEP:** Feynman diagrams, regularization/renormalization/RG-flow





Goldberger Rothstein (2006)
Porto (2006)

The EFT approach



$$e^{iW} = \int D[\lambda_{\rm rad}^{-1}]\, D[r^{-1}]\, D[r_s^{-1}]\, e^{iS_{\rm full}}$$

radiation modes (on-shell GW)

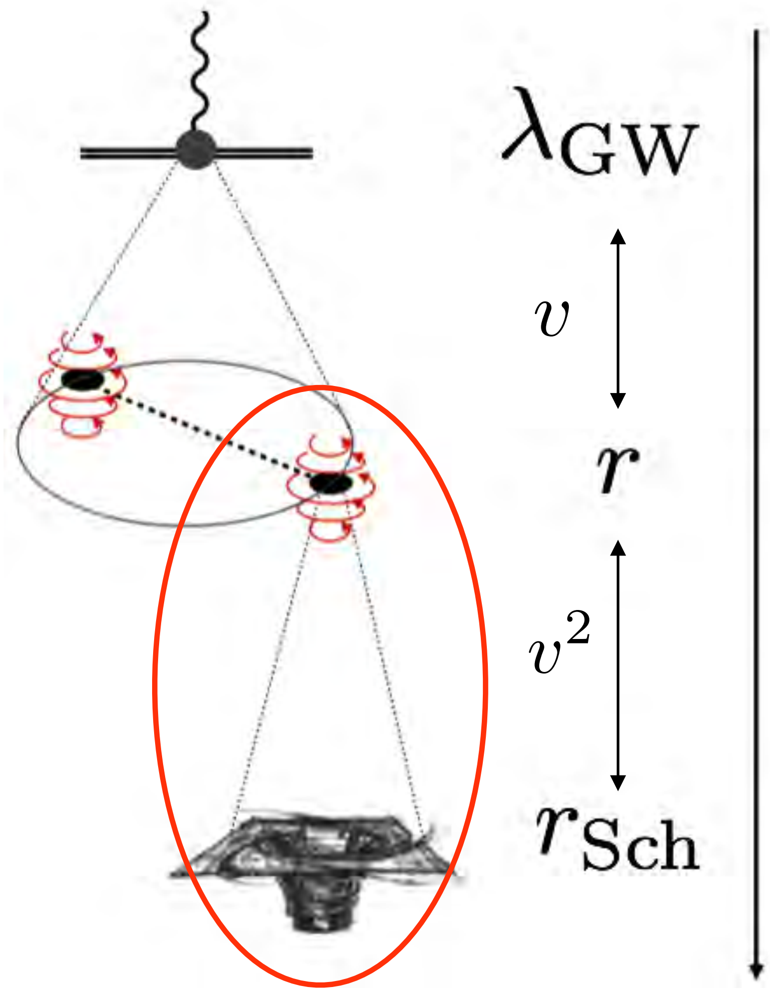
potential modes (off-shell binding)

finite size

$$\int D[\mu]\, e^{iS} \to e^{iS_{\rm eff}}$$

Goldberger Rothstein (2006)
Porto (2006)

The EFT approach



$$e^{iW} = \int D[\lambda_{\rm rad}^{-1}]\,D[r^{-1}]\,D[r_s^{-1}]\,e^{iS_{\rm full}}$$

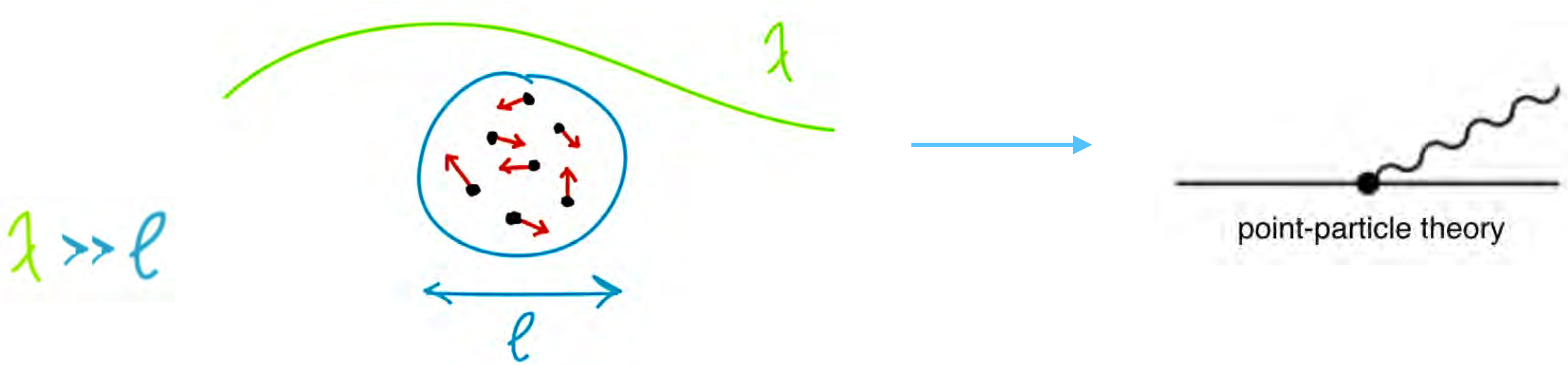
radiation modes (on-shell GW)

potential modes (off-shell binding)

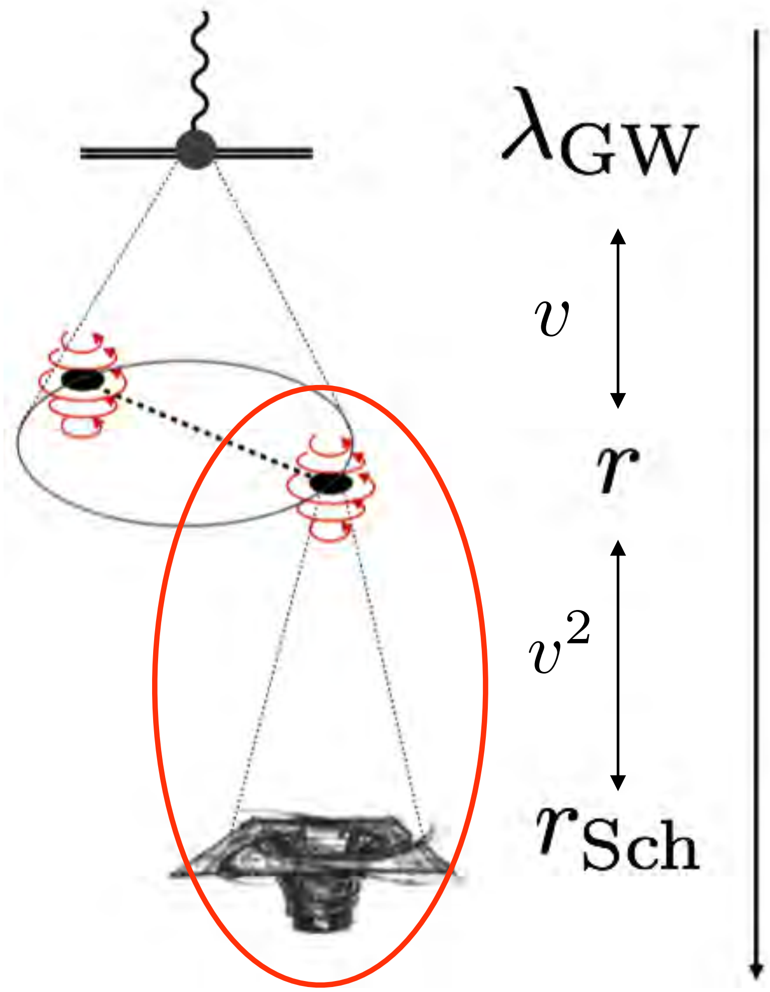
finite size

$$S_{\rm pp} = -\int d\tau\,(m + q\; v^\mu A_\mu + \dots)$$

$$\dots = \vec{p}\cdot\vec{E} + \dots$$



The EFT approach



$$e^{iW} = \int D[\lambda_{\rm rad}^{-1}]\, D[r^{-1}]\, D[r_s^{-1}]\, e^{iS_{\rm full}}$$

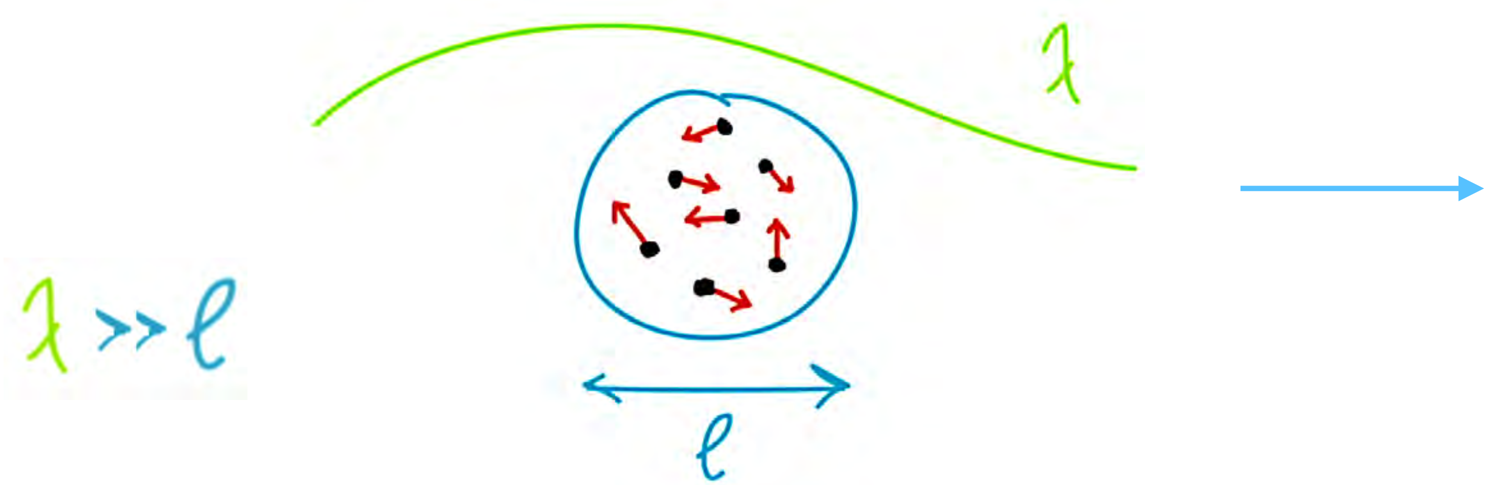
radiation modes (on-shell GW)

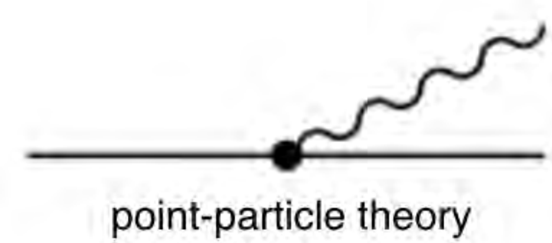
potential modes (off-shell binding)

finite size

$$S_{\rm pp} = -\int dt\,(m\sqrt{v^\mu v_\mu} + \ldots)$$

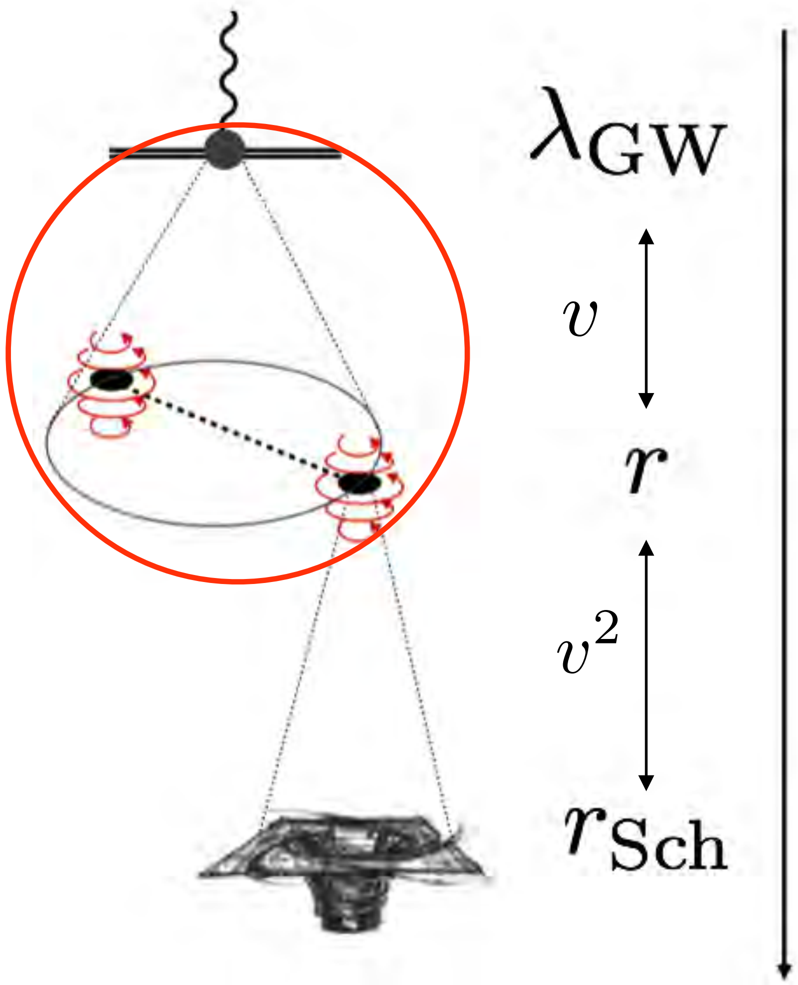
$$\ldots = \frac{1}{2} Q_{ij} E^{ij} + \ldots$$





$$(E_{ab} = e^a_\mu e^b_\nu W^{\alpha\mu\beta\nu} v_\alpha v_\beta)$$

The EFT approach



$$e^{iW} = \int D[\lambda_{\rm rad}^{-1}]\, D[r^{-1}]\, D[r_s^{-1}]\, e^{iS_{\rm full}}$$

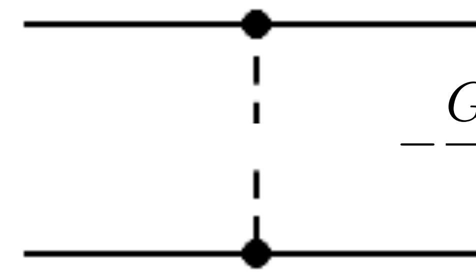
radiation modes (on-shell GW)

potential modes (off-shell binding)

finite size

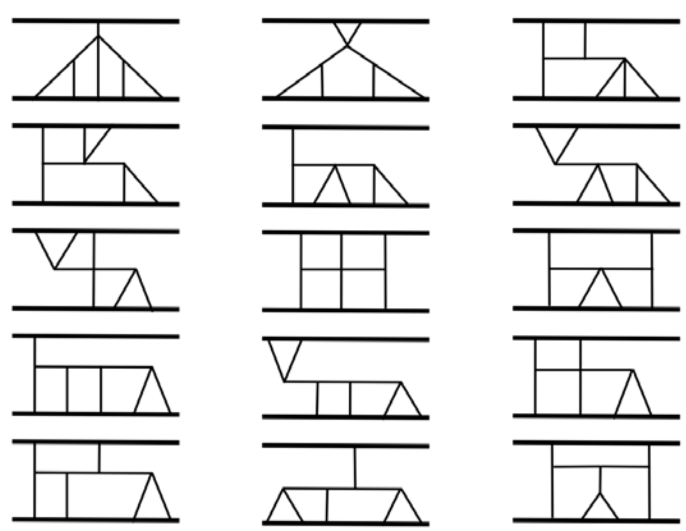
('Mass')

$$\int V dt$$



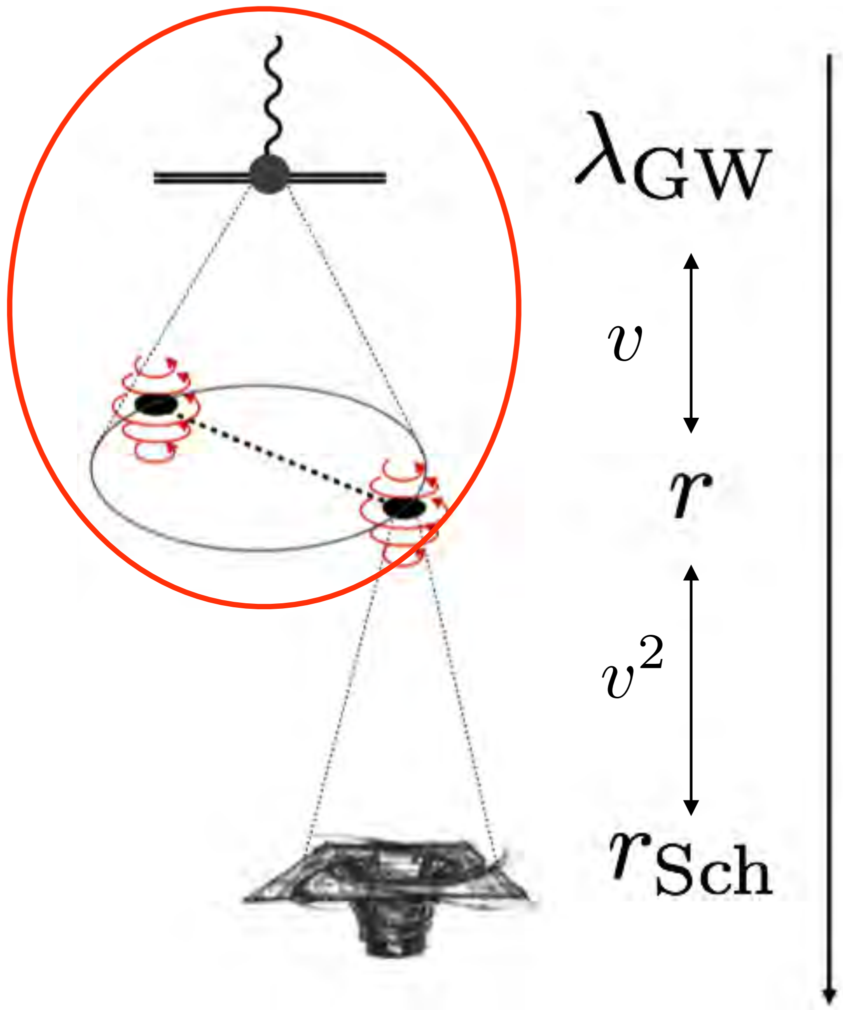
$$-\frac{Gm_1m_2}{r}$$

$$\underbrace{\mathrm{Re}\, W[\boldsymbol{x}_a]}_{\text{binding}}$$



*Iterating Green's functions (point-particle sources) leads to **UV(IR)** divergences: **Renormalization**

The EFT approach

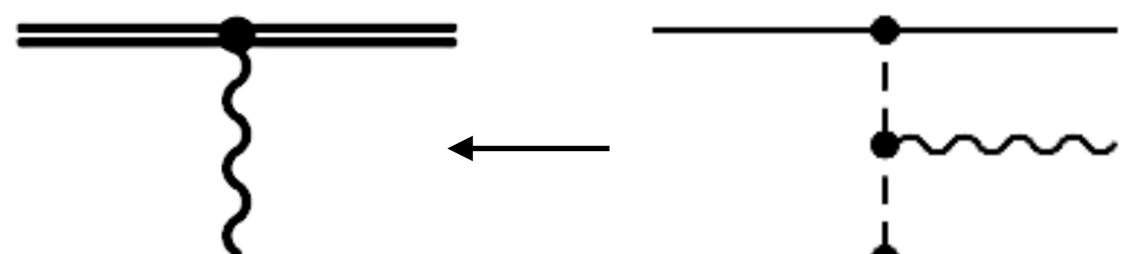


$$e^{iW} = \int D[\lambda_{\rm rad}^{-1}]\, D[r^{-1}]\, D[r_s^{-1}]\, e^{iS_{\rm full}}$$

radiation modes (on-shell GW)

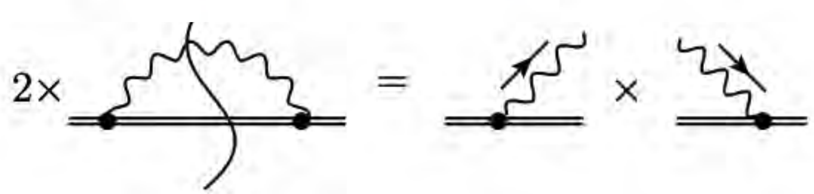
potential modes (off-shell binding)

finite size

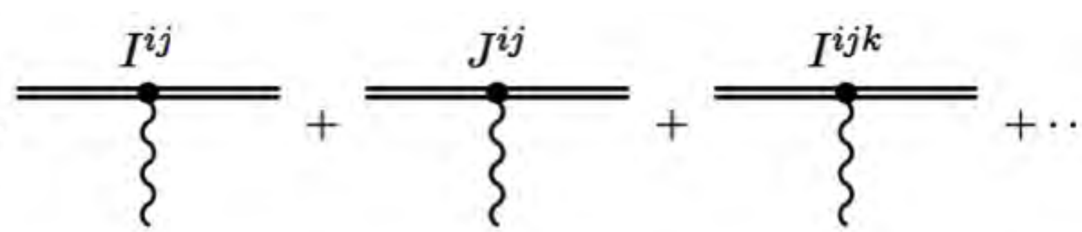


$$\frac{1}{2}\int dt\, I^{ij} E_{ij} + \dots \qquad I^{ij} = \sum_a \int m_a (1 - G m_b/r + \dots)[x_a^i x_a^j]_{TF} + \dots$$

$$\underbrace{\mathrm{Re}\, W[\boldsymbol{x}_a]}_{\text{binding}} + i\, \underbrace{\mathrm{Im}\, W[\boldsymbol{x}_a]}_{\text{radiation}}$$



$iA_h(\omega, \boldsymbol{k}) =$



$$\mathcal{F}_{\rm inst} = \frac{G}{c^5}\left\{\frac{1}{5}\mathrm{I}_{ij}^{(3)}\mathrm{I}_{ij}^{(3)} + \frac{1}{c^2}\left[\frac{1}{189}\mathrm{I}_{ijk}^{(4)}\mathrm{I}_{ijk}^{(4)} + \frac{16}{45}\mathrm{J}_{ij}^{(3)}\mathrm{J}_{ij}^{(3)}\right] + \cdots\right.$$

'That's nice, but what can you do with it?'

Key contributions to State-of-the-art

*** General Relativity and Gravitation: A Centennial Perspective**

Chapter 6: **Sources of Gravitational Waves: Theory and Observations**

Alessandra Buonanno and B.S. Sathyaprakash

$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{1 + \cdots + \underbrace{\cdots + [\cdots]x^{7/2}}\right\}$$

* the EFT approach has extended the knowledge of the conservative dynamics and multipole moments to high PN orders [134–145].

[134] **Porto, R. A.** 2006. *Phys. Rev. D*, **73**, 104031.
[135] **Porto, R. A.**, Rothstein, I. Z. 2006. *Phys. Rev. Lett.*, **97**, 021101.
[136] Kol, B., Smolkin, M. 2008. *Class. Quant. Grav.*, **25**, 145011.
[137] **Porto, R. A.**, Rothstein, I. Z. 2008. *Phys. Rev. D*, **78**, 044013.
[138] **Porto, R. A.**, Rothstein, I. Z. 2008. *Phys. Rev. D*, **78**, 044012.
[139] **Porto, R. A.**, Ross, A., Rothstein, I. Z. 2011. *JCAP*, **1103**, 009.
[140] **Porto, R. A.** 2010. *Class. Quant. Grav.*, **27**, 205001.
[141] Levi, M. 2010. *Phys. Rev. D*, **82**, 104004.
[142] Levi, M. 2012. *Phys. Rev. D*, **85**, 064043.
[143] Hergt, S., Steinhoff, J., Schaefer, G. 2012. *Annals Phys.*, **327**, 1494–1537.
[144] Hergt, S., Steinhoff, J., Schaefer, G. 2014. *J.Phys.Conf.Ser.*, **484**, 012018.
[145] **Porto, R. A.**, Ross, A., Rothstein, I. Z. 2012. *JCAP*, **1209**, 028.

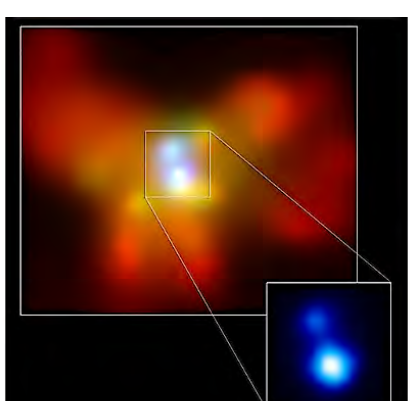
Key contributions to State-of-the-art

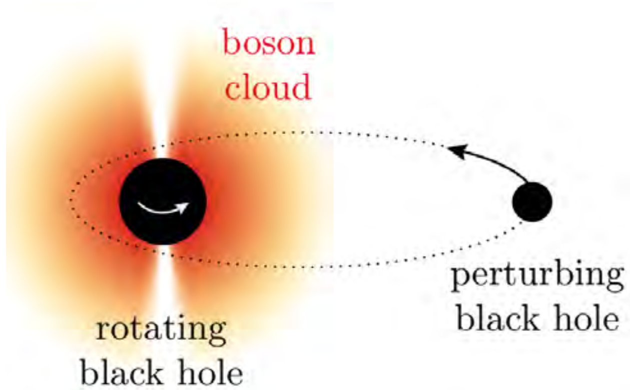
Porto (2006)
Porto Rothstein (2006)
Porto (2007)
Porto Rothstein (2008)
Porto Rothstein (2008)
Porto (2010)
Porto Ross Rothstein (2011)
Porto Ross Rothstein (2012)
Galley **Porto** Leibovich Ross (2015)
Levi Steinhoff (2014, 2015)
Blanchet et al. (2016)

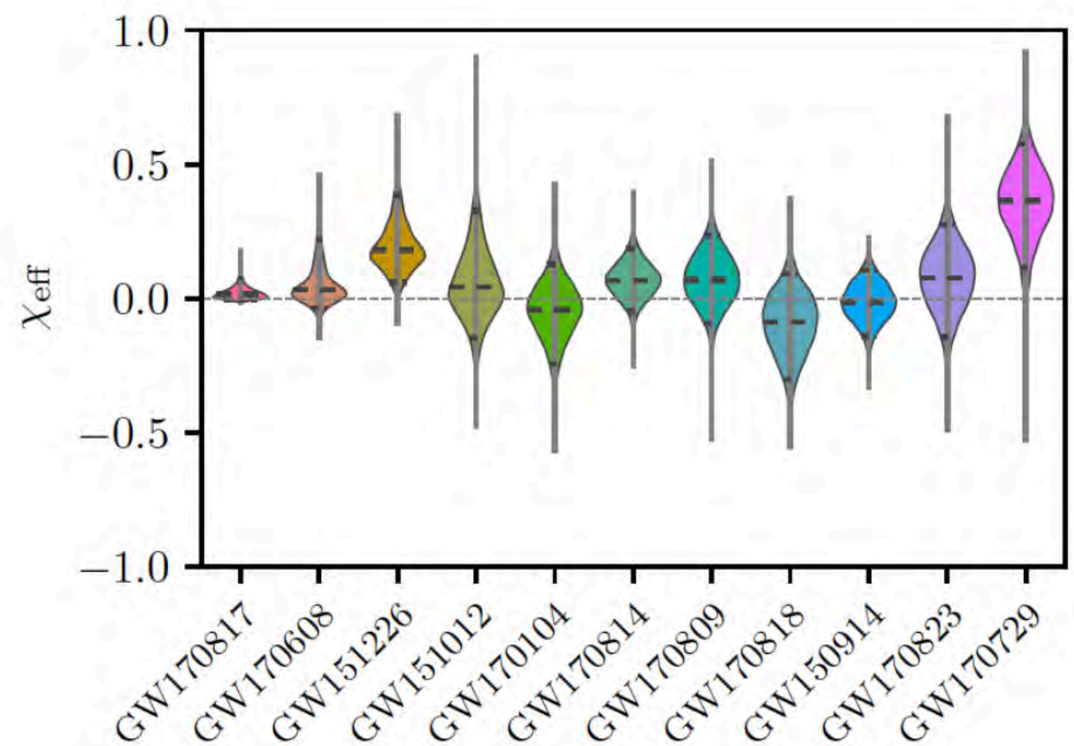
$$\frac{\dot\omega}{\omega^2} = \frac{96}{5}\nu x^{5/2}\Big\{\overbrace{1 + x\,[\cdots] + x^{3/2}\,[\cdots] + x^2\,[\cdots] + x^{5/2}\,[\cdots] + x^3\,[\cdots]}^{\text{non-spin terms}}$$
$$+ \underbrace{[\cdots]\,x^{3/2}}_{\text{1.5PN SO}} + \underbrace{[\cdots]\,x^2}_{\text{2PN SS}} + \underbrace{[\cdots]\,x^{5/2}}_{\text{2.5PN SO}} + \underbrace{[\cdots]\,x^3}_{\text{3PN SO}_{\text{tail}}\ \&\ \text{SS}}$$
$$+ \underbrace{[\cdots]\,x^{7/2}}_{\text{3.5PN SO}} + \underbrace{[\cdots]\,x^4}_{\text{4PN SO}_{\text{tail}}\ \&\ \text{SS}} + \mathcal{O}\left(x^4\right)\Big\}$$

<u>A wealth of information, e.g.:</u>

- The formation of **stellar/ super-massive** BHs
- The possibility of '**clouds**' of light particles (e.g. axion)





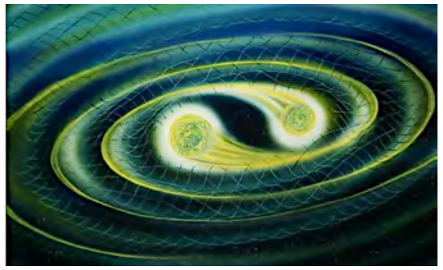


$$\chi_{\text{eff}} = \frac{\mathbf{S}_1/m_1 + \mathbf{S}_2/m_2}{m_1 + m_2}\cdot\hat{\mathbf{L}} = \frac{\chi_1\cos\theta_1 + q\chi_2\cos\theta_2}{1+q}$$

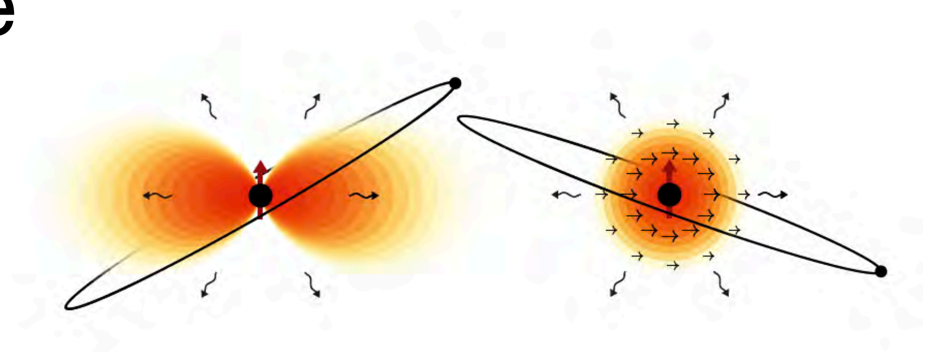
$$q = m_2/m_1$$

GW precision physics

- EFT approach to binary problem

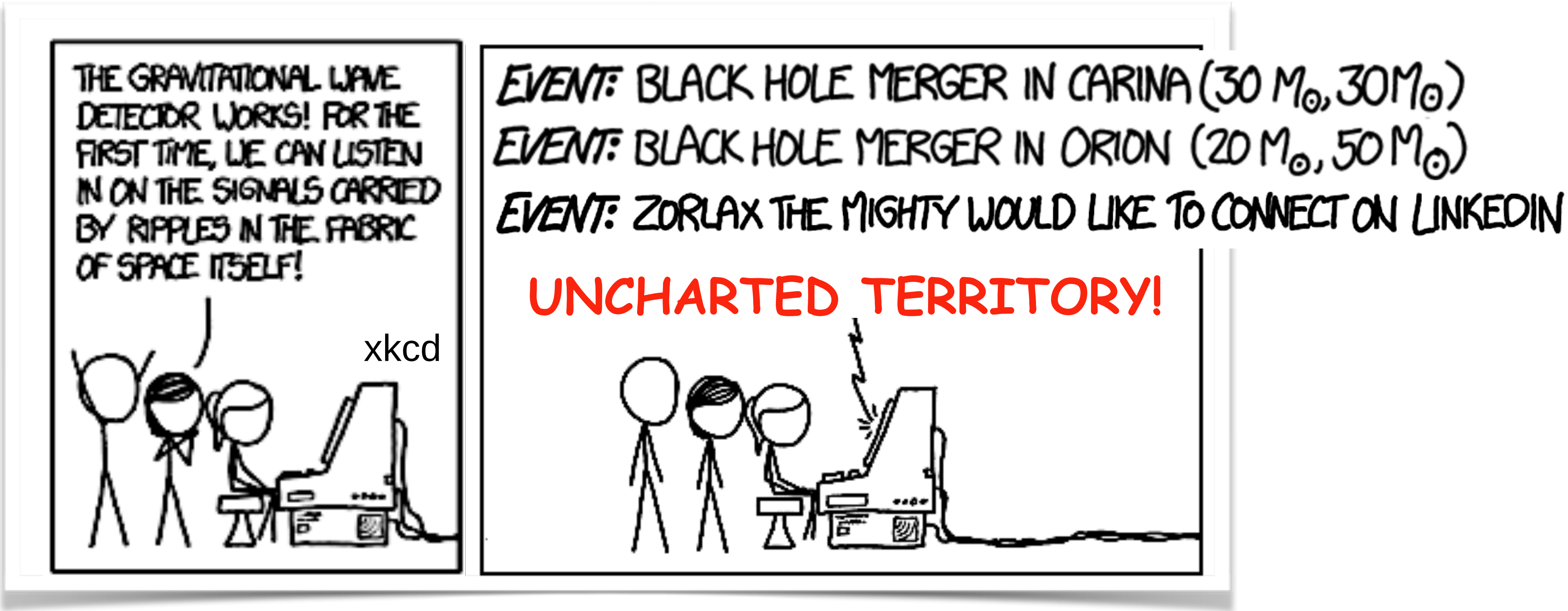


- **Opportunities**: ‘Future of GW Science’



- **Challenges:** How do we get there?

The future of GW Science



AdvLIGO/VIRGO

Several events/year @ design20’

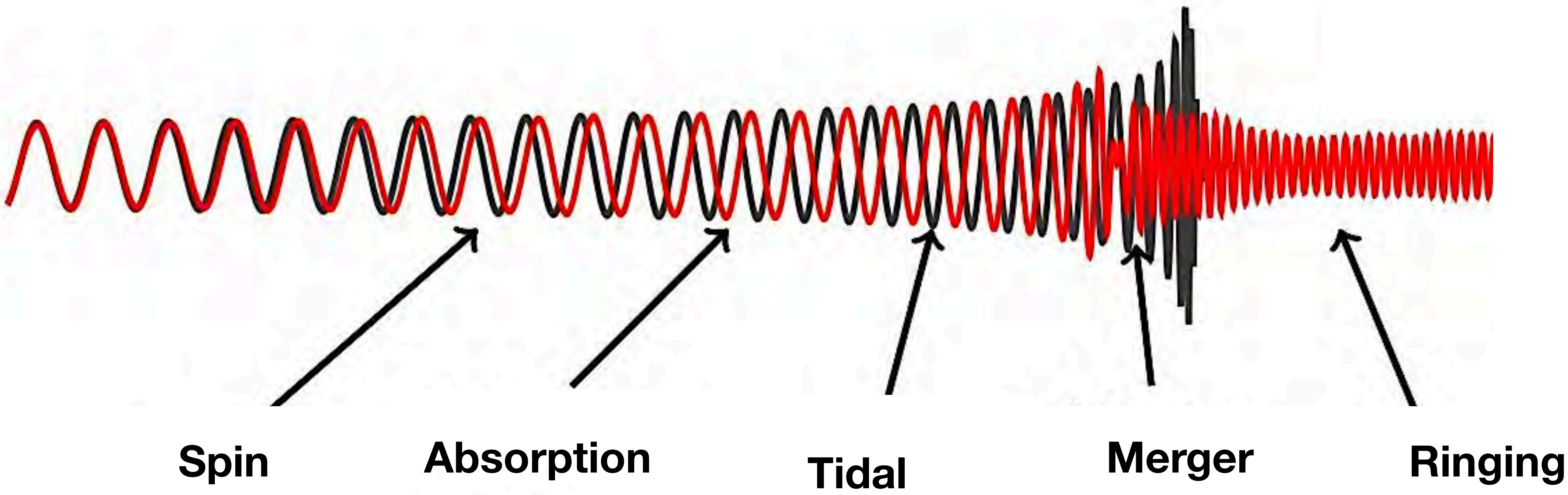
Nature of sources!

LISA, Cosmic E. & Einstein T.

High-precision detectors

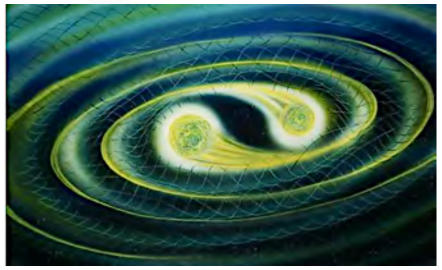
Ready for 3rd Gen. GW Science!

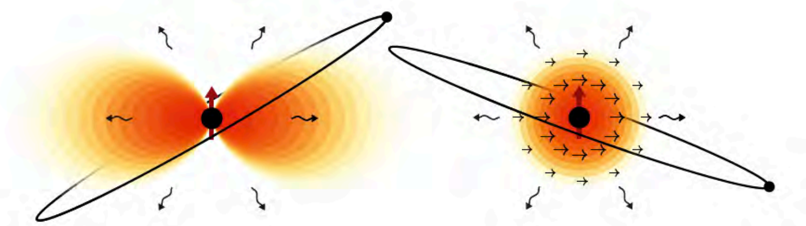
The future of GW Science

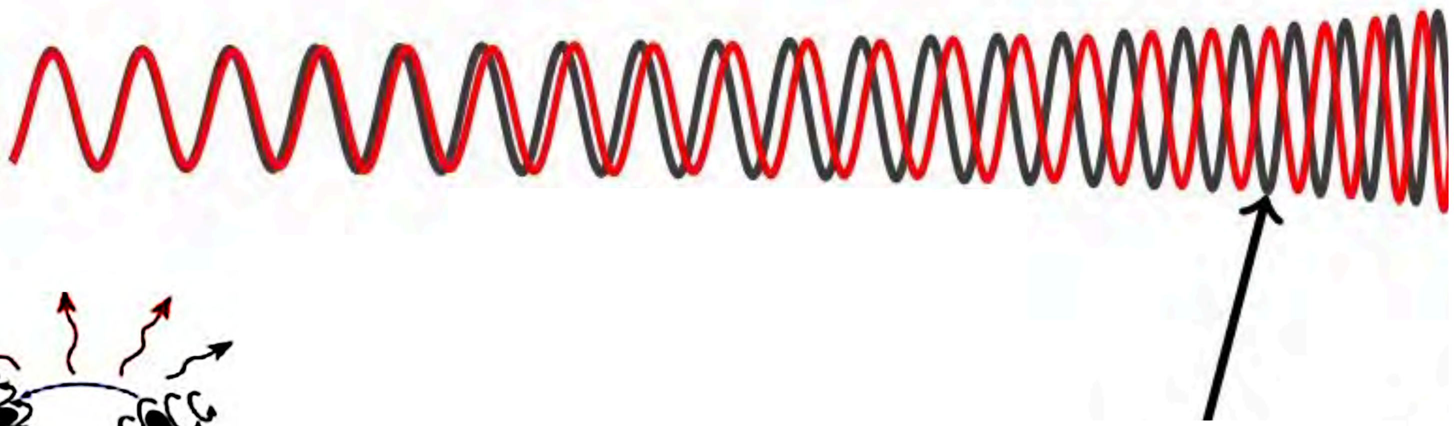


- **Strong Interaction** (Neutron stars’ EOS)
- **Spacetime** (Black holes in General Relativity)
- **Dark Matter** (Axions, Exotic Compact Objects)
- **Unknown Unknowns!**

The future of GW Science





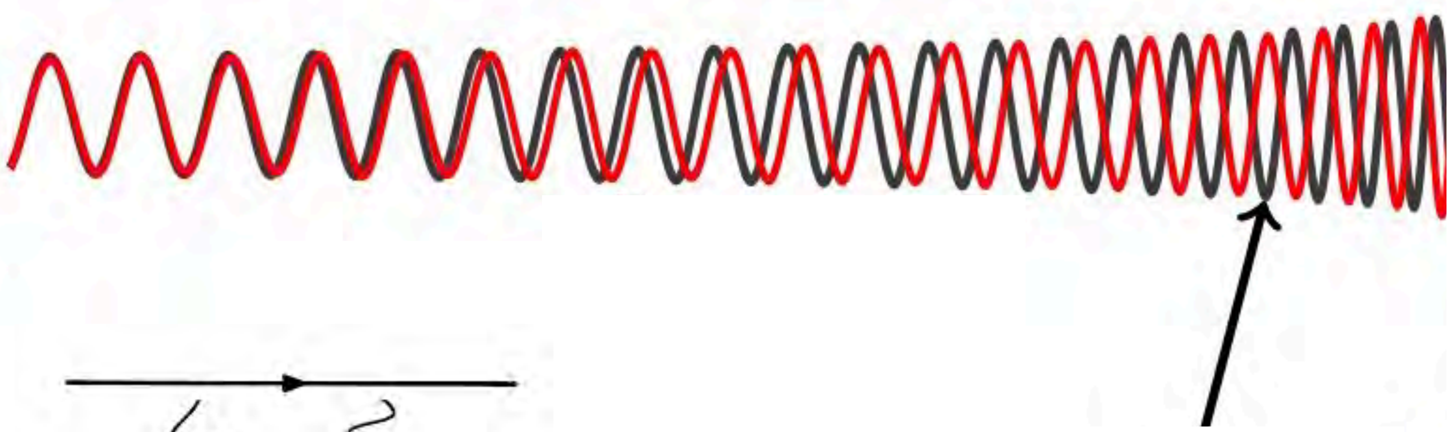

Tidal
(5PN)

Inspiral

Clean **analytic** control for the majority of cycles (10^4+!) during the **inspiral** phase (many astrophysical sources)

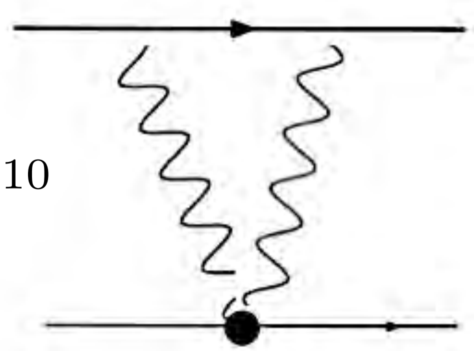
The future of GW Science

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



Tidal (5PN)

$$\left(\frac{R}{r}\right)^5 \sim v^{10}$$



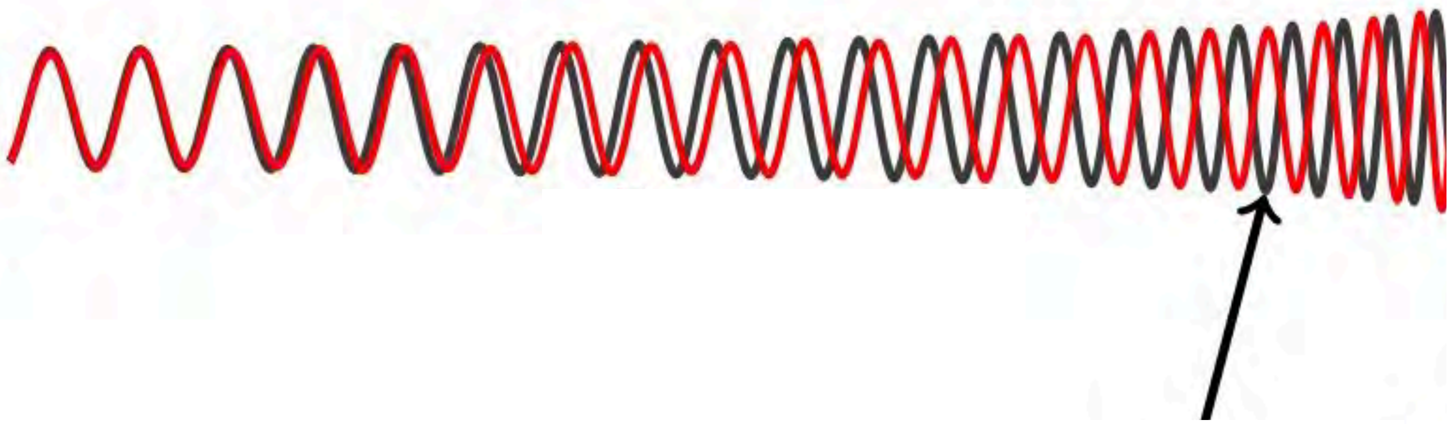
$$Q_{ij} = C_E E_{ij}$$

('Susceptibility')

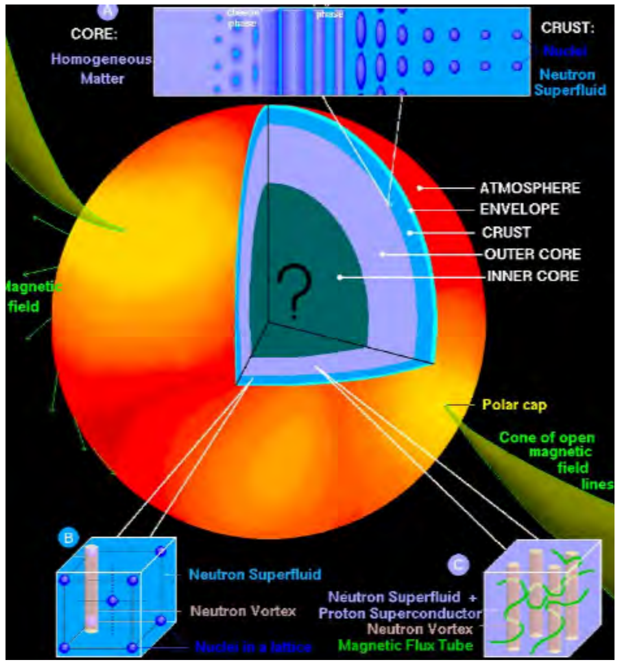
$$C_E \sim R^5$$

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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

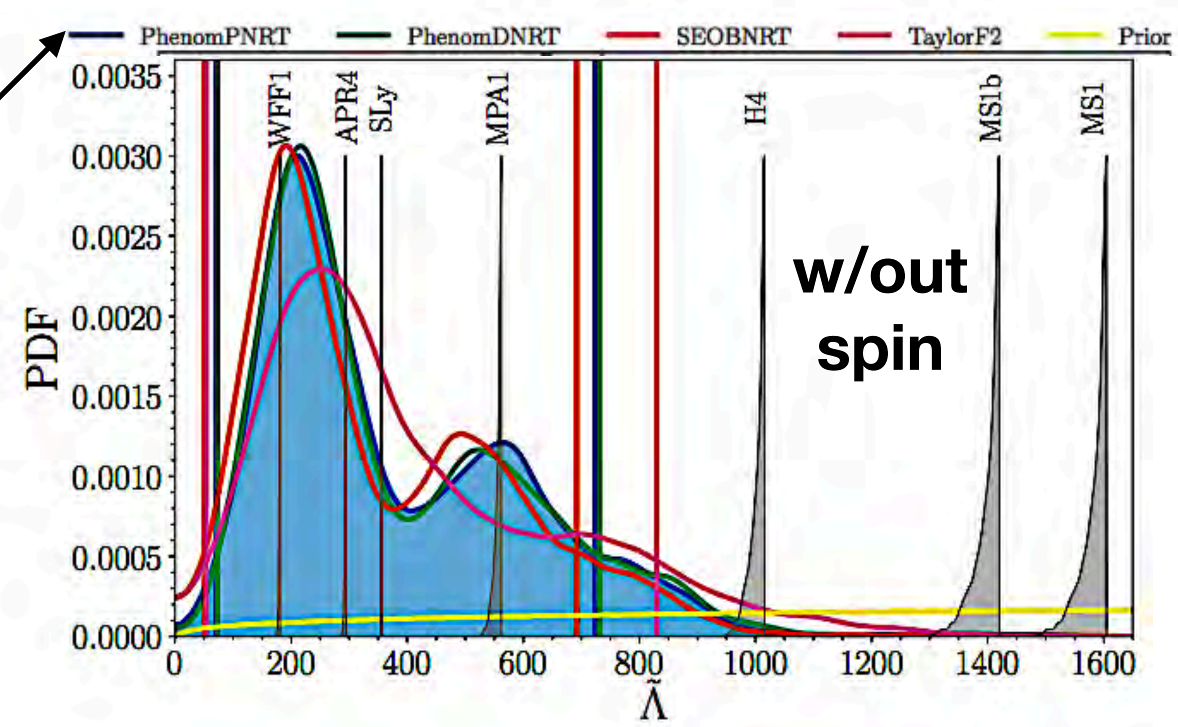


Tidal (5PN)



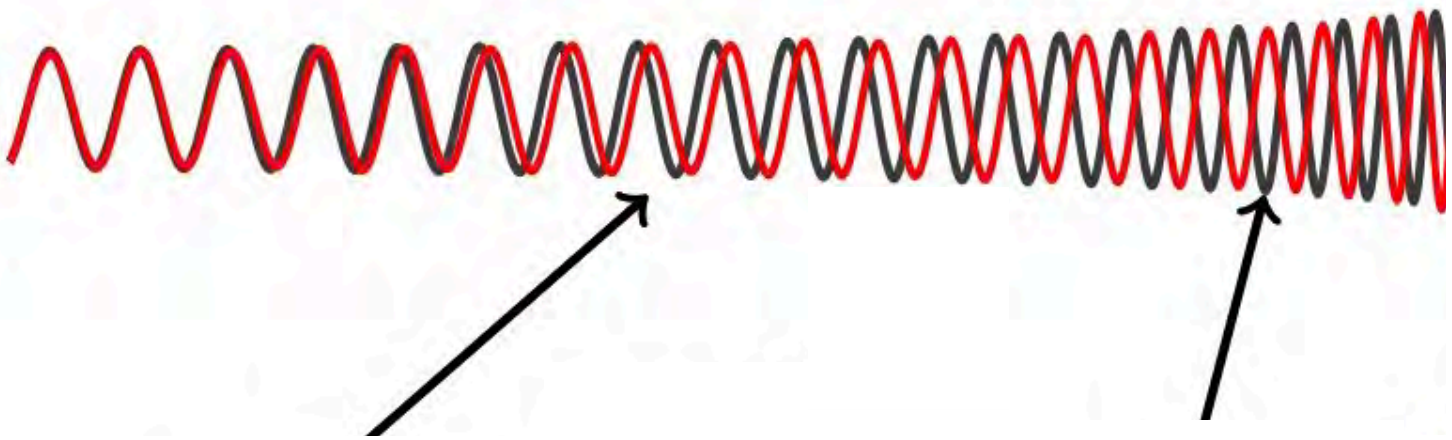
$$\Lambda = \frac{C_E}{M^5}$$

Systematics waveform modeling



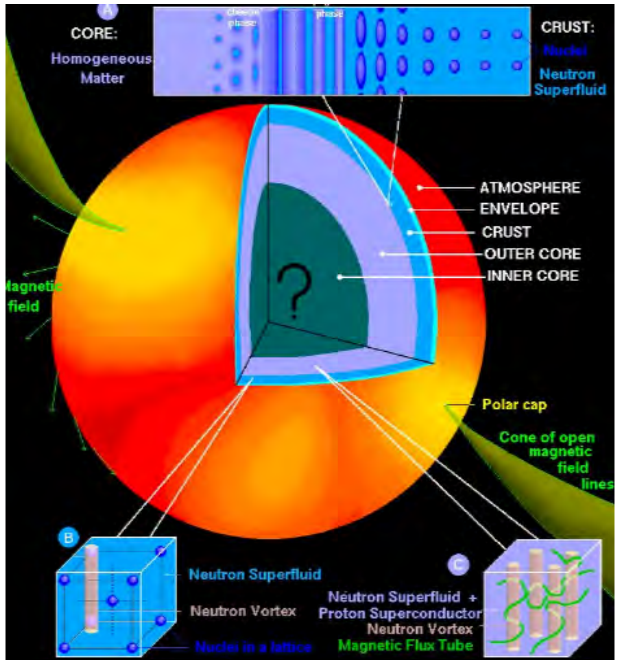
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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

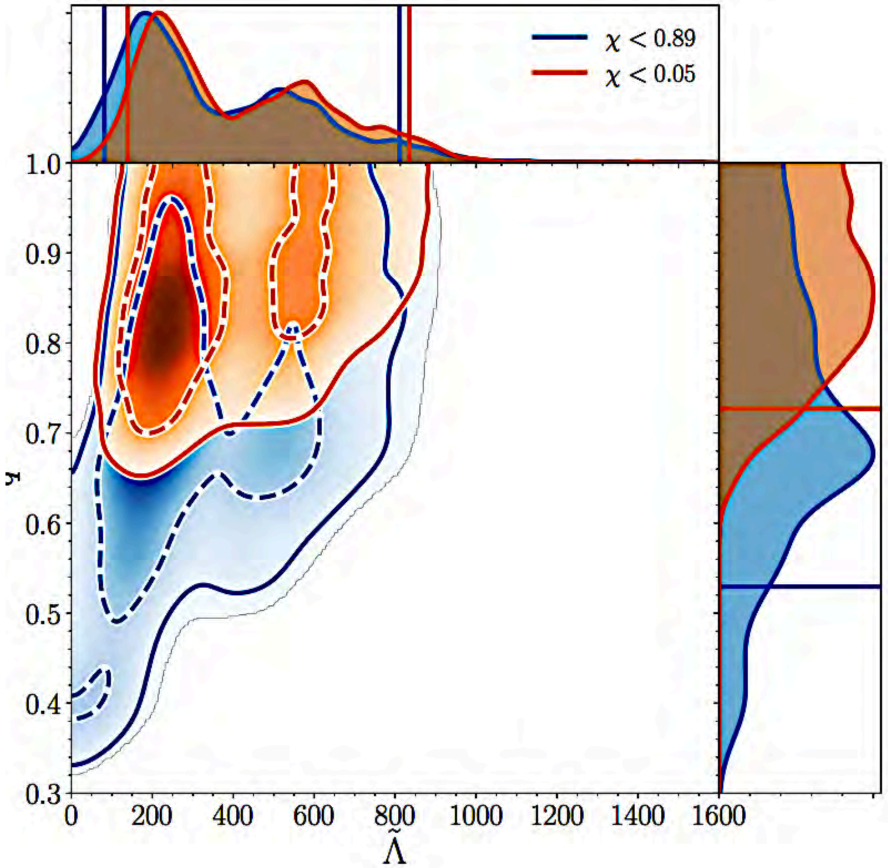


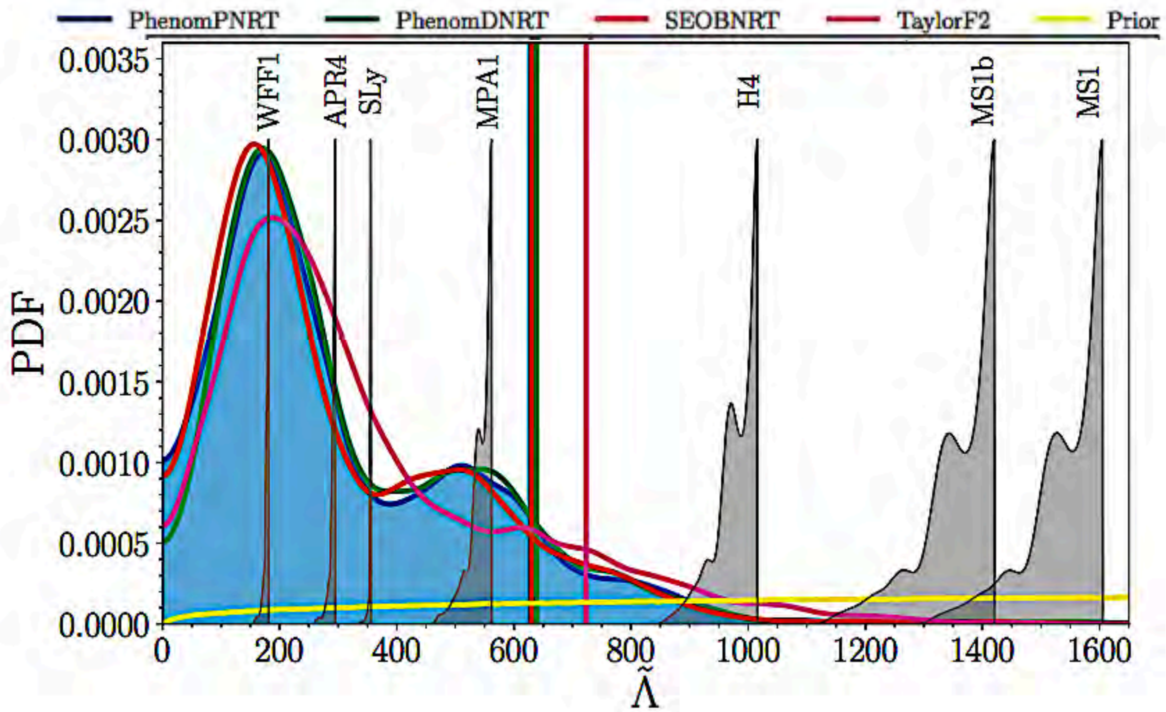
Spin

Tidal (5PN)



mass ratio





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

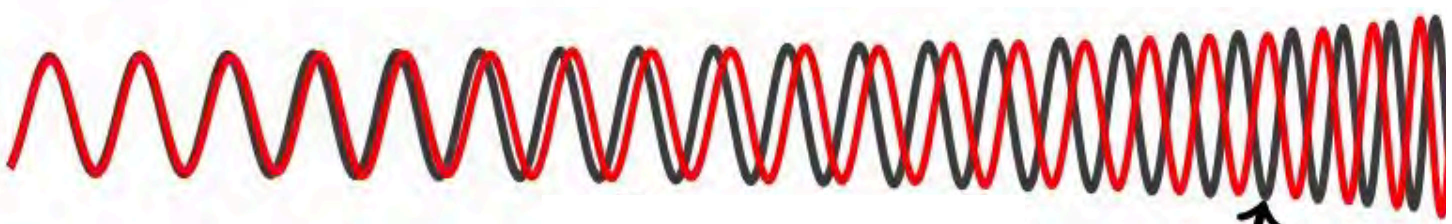
The tune of love and the *nature(ness)* of spacetime

*Rafael A. Porto**

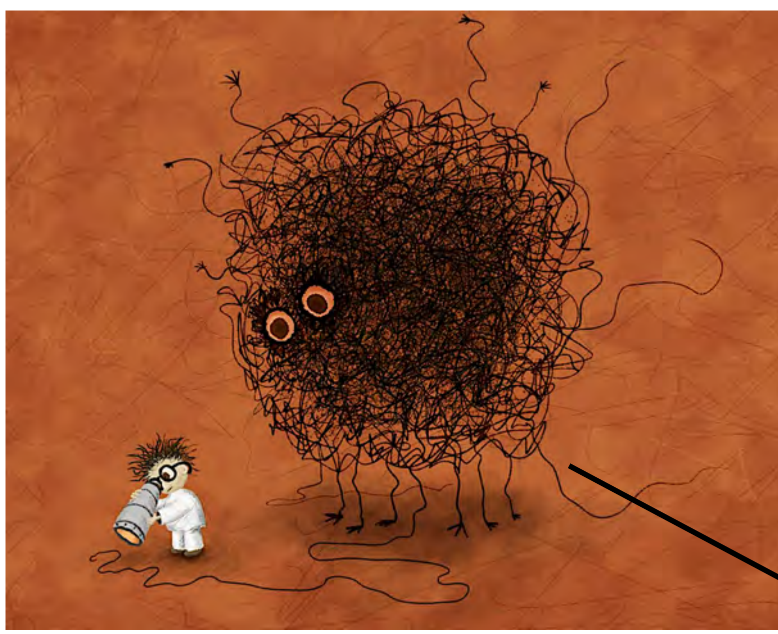
$$\Psi(v) = \Psi_{\rm PP}(v) + \ldots$$

$$C^{\rm bh}_{E(B)}(\mu) = 0$$

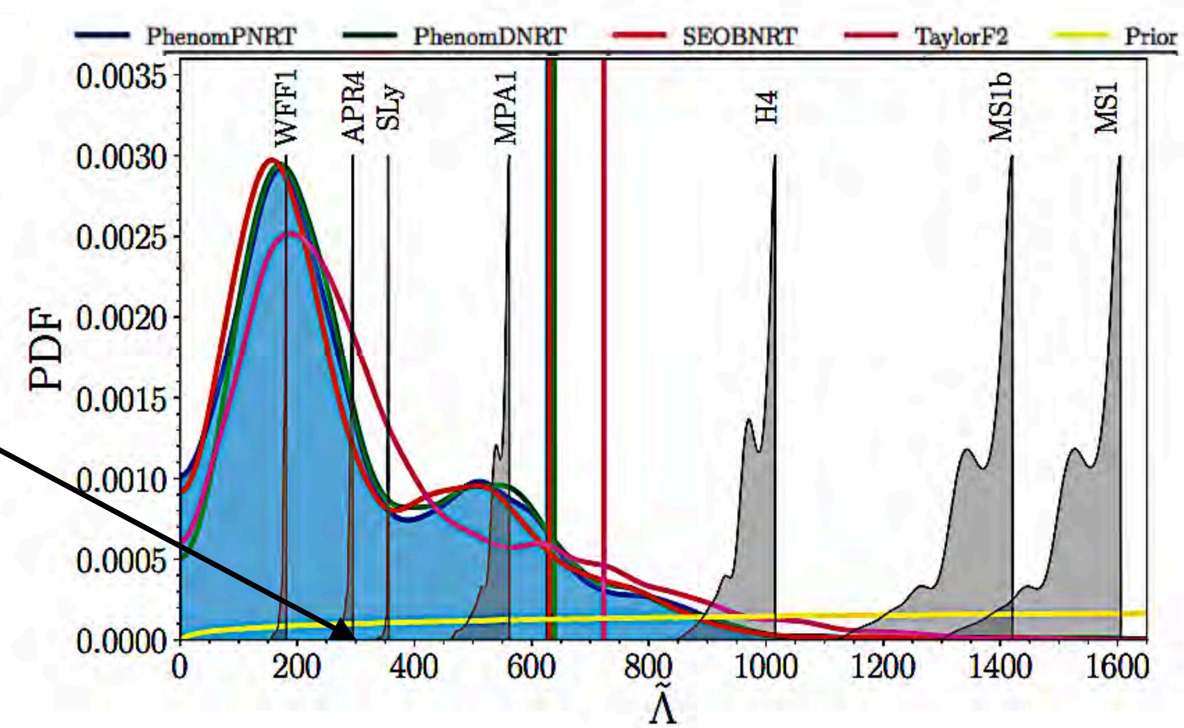
Unrelated to no-hair!
(only zero in d=4)



Tidal (5PN)

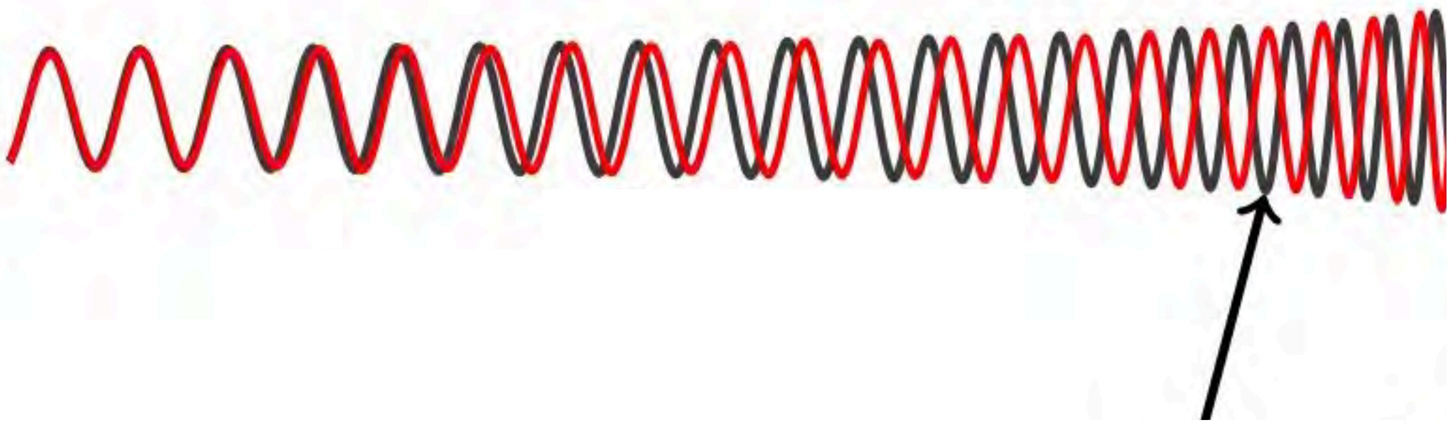


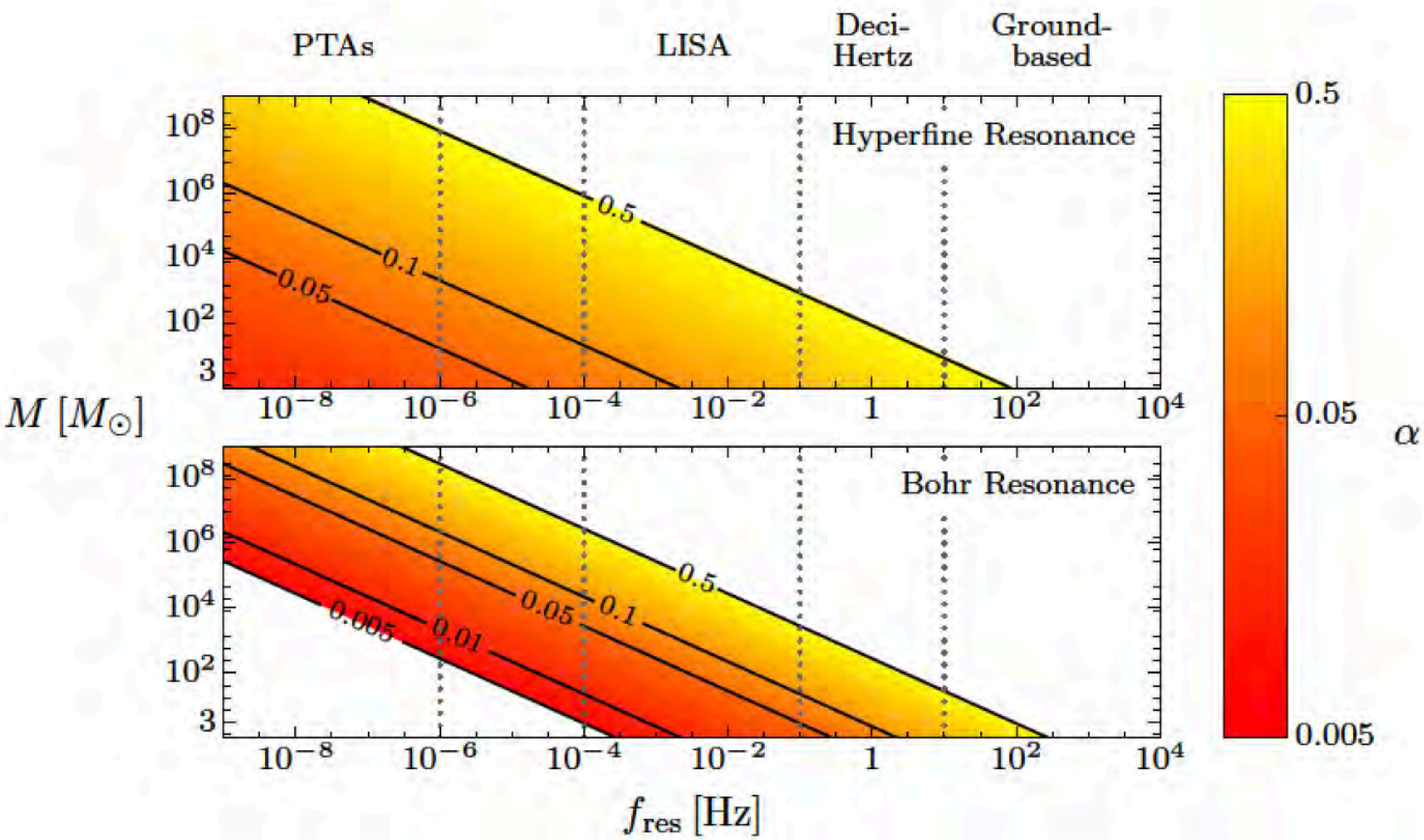
NO 'Standard Model Background'!



Physics See Synopsis:

Black Holes Could Reveal New Ultralight Particles





Probing ultralight bosons with binary black holes

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

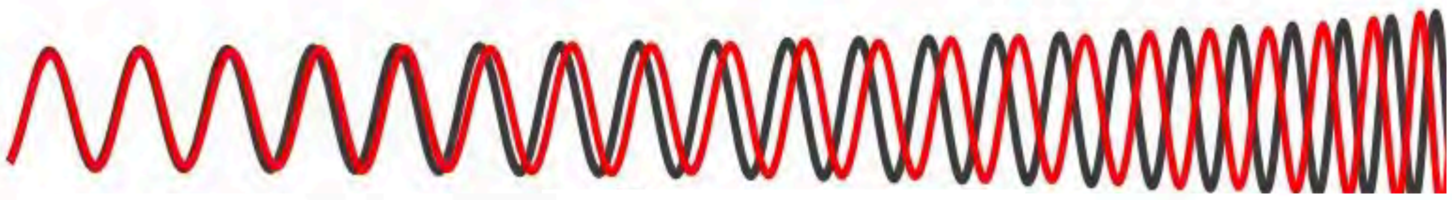
Phys. Rev. D 99, 044001 (2019)

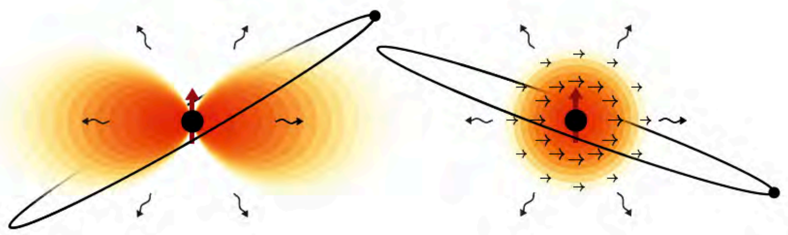
Published February 4, 2019

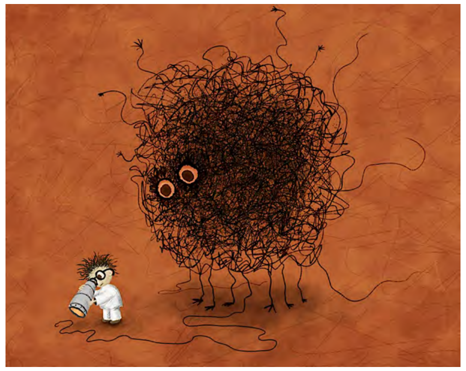
Can be distinguished due to 'resonances'

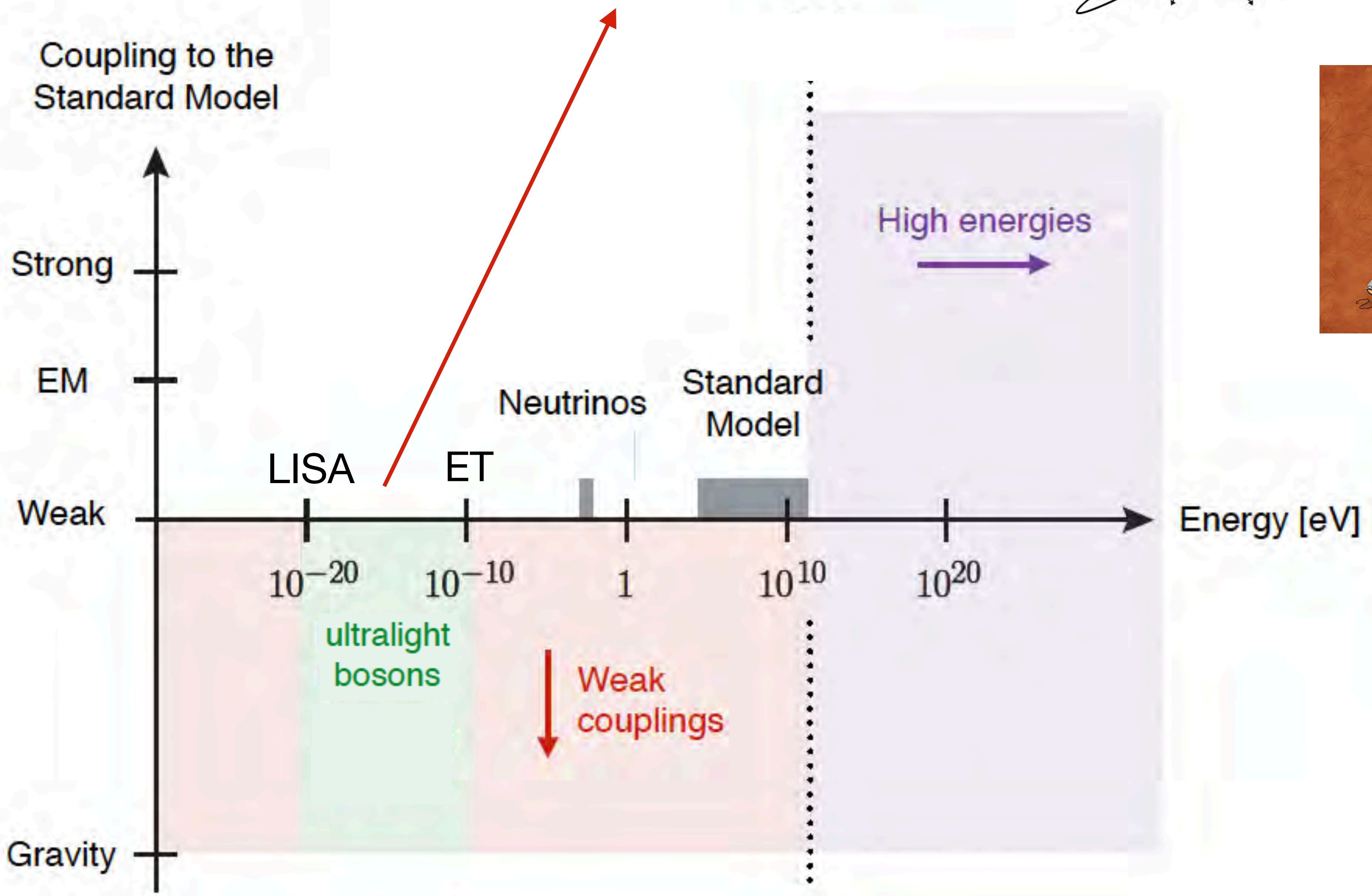
Physics See Synopsis:

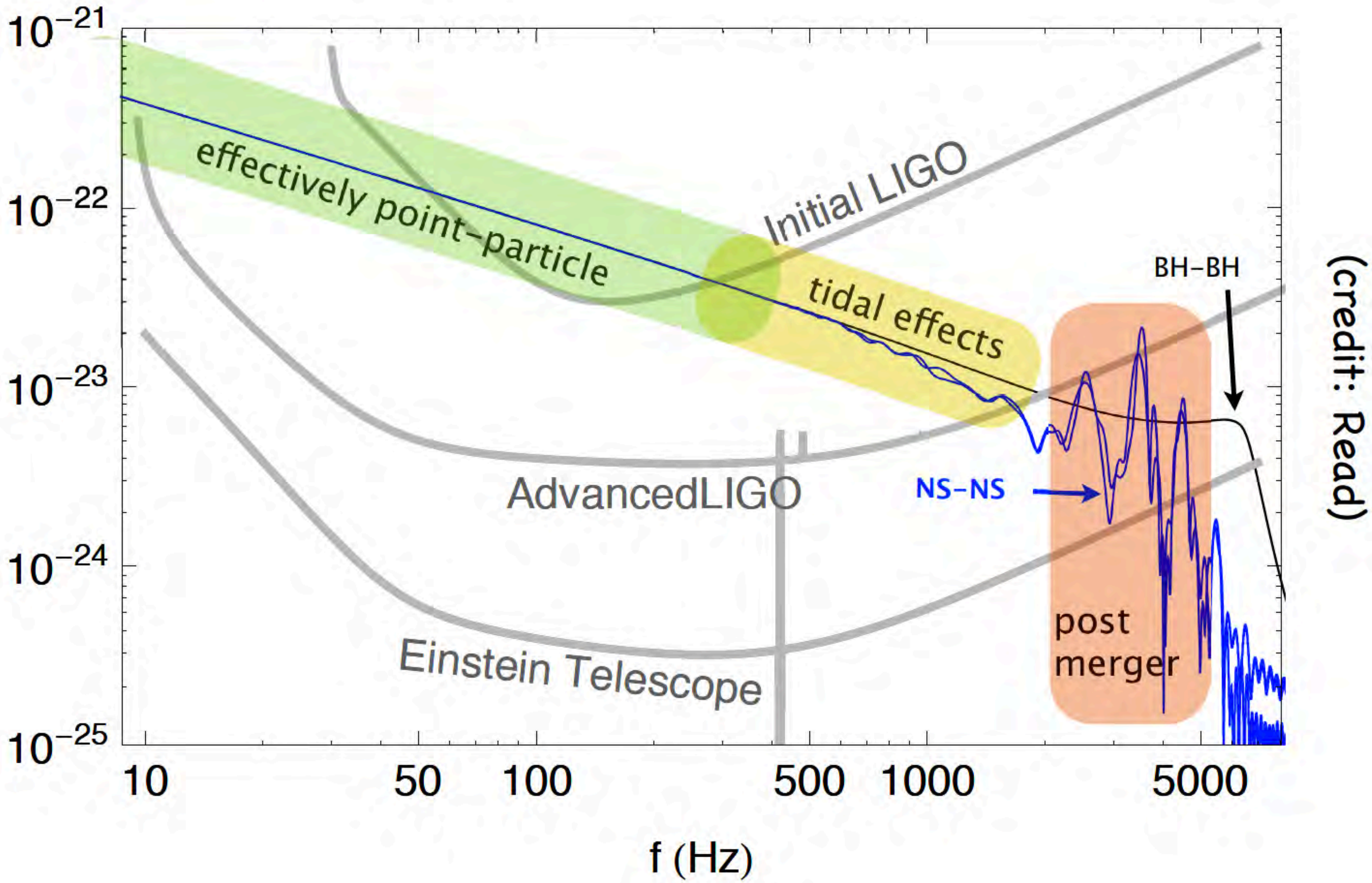
Black Holes Could Reveal New Ultralight Particles











"Waveforms will be far more complex and carry more information than expected. Improved modeling will be needed for extracting the GW's information"

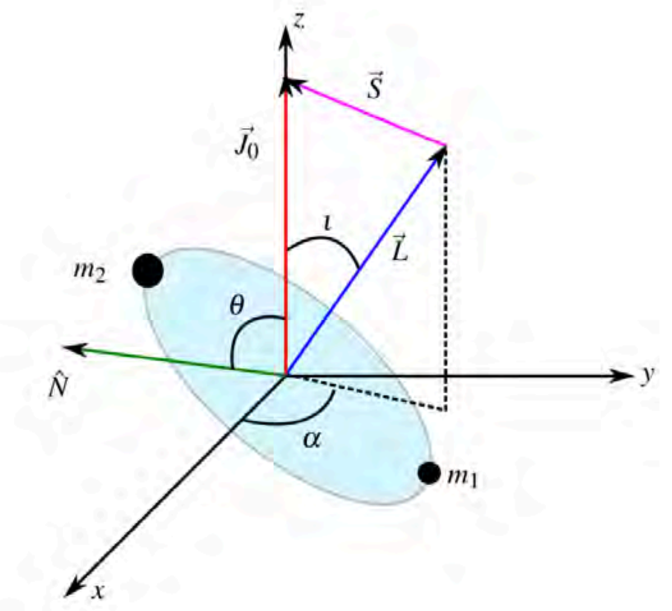
Kip Thorne 'The last 3 minutes: […]' 1993

20+ years prior to first detection!

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

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



knowledge at the time!

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

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

PRL 97, 021101 (2006) PHYSICAL REVIEW LETTERS week ending 14 JULY 2006

Calculation of the First Nonlinear Contribution to the General-Relativistic Spin-Spin Interaction for Binary Systems

Rafael A. Porto and Ira Z. Rothstein

Spin induced multipole moments for the gravitational wave flux from binary inspirals to third Post-Newtonian order

Rafael A. Porto *et al* JCAP03(2011)009

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

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

Conservative dynamics of binary systems to fourth Post-Newtonian order in the EFT approach II: Renormalized Lagrangian
Stefano Foffa (Geneva U.), Rafael A. Porto (DESY, Zeuthen & ICTP, Trieste), Ira Rothstein (Carnegie Mellon U.), Riccardo Sturani (IIP, Brazil). Mar 12, 2019. 39 pp.
e-Print: arXiv:1903.05118 [gr-qc] | PDF

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

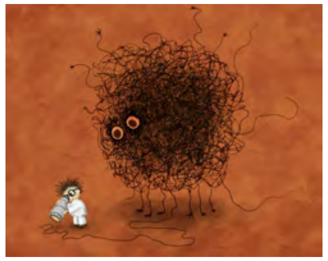
Curt Cutler, Theocharis A. Apostolatos, Lars Bildsten, Lee Smauel Finn, Eanna E. Flanagan, Daniel Kennefick, Dragoljub M. Markovic, Amos Ori, Eric Poisson, Gerald Jay Sussman, and Kip S. Thorne

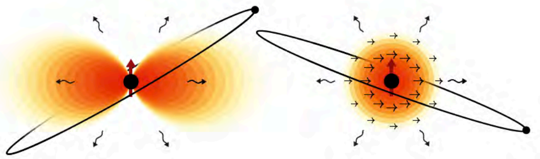
Phys. Rev. Lett. **70**, 2984 – Published 17 May 1993

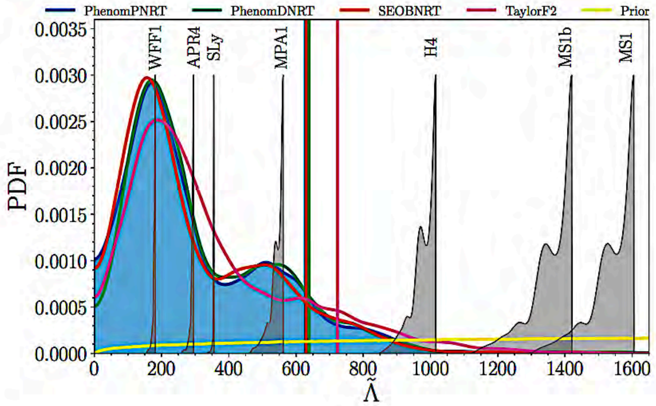
$$\frac{dN_{\rm cyc}}{d\ln f} = \frac{5}{96\pi}\frac{1}{\mu M^{2/3}(\pi f)^{5/3}}\left\{1 + \left(\frac{743}{336} + \frac{11}{4}\frac{\mu}{M}\right)x - [4\pi + \text{S.O.}]x^{1.5} + [\text{S.S.}]x^2 + [\text{S.O.}]x^{2.5} + [\text{S.S.}]x^3 + O(x^4) + O(x^5)\right\}.$$

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

Gravitational-wave observations alone are able to measure the masses of the two objects and set a lower limit on their compactness, but the results presented here do not exclude objects more compact than neutron stars such as quark stars, black holes, or more exotic objects [57–61].



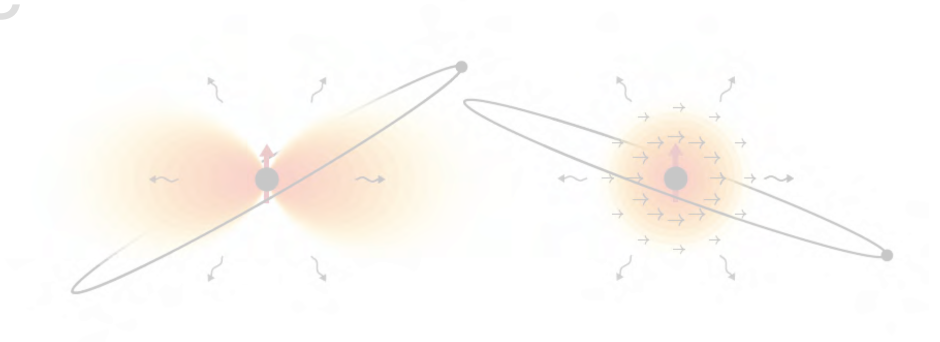




GW precision physics

- EFT approach to binary problem

- **Opportunities:** ‘Future of GW Science’



- **Challenges:** How do we get there?

Challenge: Towards ‘new physics’ 5PN threshold

$$E^{\rm 4PN} = -\frac{\mu c^2 x}{2}\left\{1 + \left(-\frac{3}{4} - \frac{\nu}{12}\right)x + \left(-\frac{27}{8} + \frac{19}{8}\nu - \frac{\nu^2}{24}\right)x^2 + \left(-\frac{675}{64} + \left[\frac{34445}{576} - \frac{205}{96}\pi^2\right]\nu - \frac{155}{96}\nu^2 - \frac{35}{5184}\nu^3\right)x^3 + \left(-\frac{3969}{128} + \left[-\frac{123671}{5760} + \frac{9037}{1536}\pi^2 + \frac{896}{15}\gamma_{\rm E} + \frac{448}{15}\ln(16x)\right]\nu + \left[-\frac{498449}{3456} + \frac{3157}{576}\pi^2\right]\nu^2 + \frac{301}{1728}\nu^3 + \frac{77}{31104}\nu^4\right)x^4\right\}$$

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

Stefano Foffa (Geneva U.), Rafael A. Porto (DESY, Zeuthen & ICTP, Trieste), Ira Rothstein (Carnegie Mellon U.), Riccardo Sturani (IIP, Brazil). Mar 12, 2019. 39 pp.

e-Print: arXiv:1903.05118 **[gr-qc]** | PDF

PHYSICAL REVIEW D **96,** 024062 (2017)

Apparent ambiguities in the post-Newtonian expansion for binary systems

Rafael A. Porto[1] and Ira Z. Rothstein[2]

PHYSICAL REVIEW D **93,** 124010 (2016)

Tail effect in gravitational radiation reaction: Time nonlocality and renormalization group evolution

Chad R. Galley,[1] Adam K. Leibovich,[2] Rafael A. Porto,[3] and Andreas Ross[4]

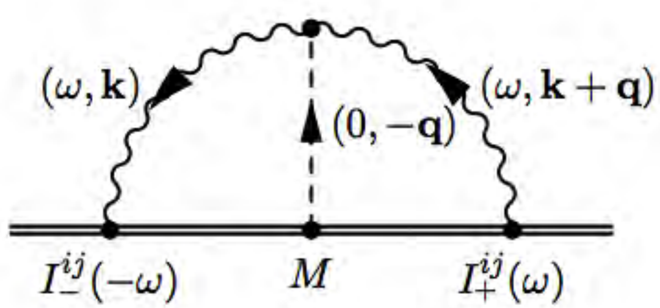
PHYSICAL REVIEW D **96,** 024063 (2017)

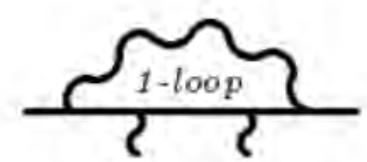
Lamb shift and the gravitational binding energy for binary black holes

Rafael A. Porto

Challenge: Towards 'new physics' 5PN threshold

$$
\begin{aligned}
E^{4\mathrm{PN}} = -\frac{\mu c^2 x}{2}\Bigg\{ 1 &+ \left(-\frac{3}{4}-\frac{\nu}{12}\right)x + \left(-\frac{27}{8}+\frac{19}{8}\nu-\frac{\nu^2}{24}\right)x^2 \\
&+ \left(-\frac{675}{64}+\left[\frac{34445}{576}-\frac{205}{96}\pi^2\right]\nu-\frac{155}{96}\nu^2-\frac{35}{5184}\nu^3\right)x^3 \\
&+ \left(-\frac{3969}{128}+\left[-\frac{123671}{5760}+\frac{9037}{1536}\pi^2+\frac{896}{15}\gamma_E+\frac{448}{15}\ln(16x)\right]\nu \right.\\
&\left. + \left[-\frac{498449}{3456}+\frac{3157}{576}\pi^2\right]\nu^2+\frac{301}{1728}\nu^3+\frac{77}{31104}\nu^4\right)x^4\Bigg\}
\end{aligned}
$$





PHYSICAL REVIEW D **93,** 124010 (2016)

Tail effect in gravitational radiation reaction: Time nonlocality and renormalization group evolution

Chad R. Galley,[1] Adam K. Leibovich,[2] Rafael A. Porto,[3] and Andreas Ross[4]

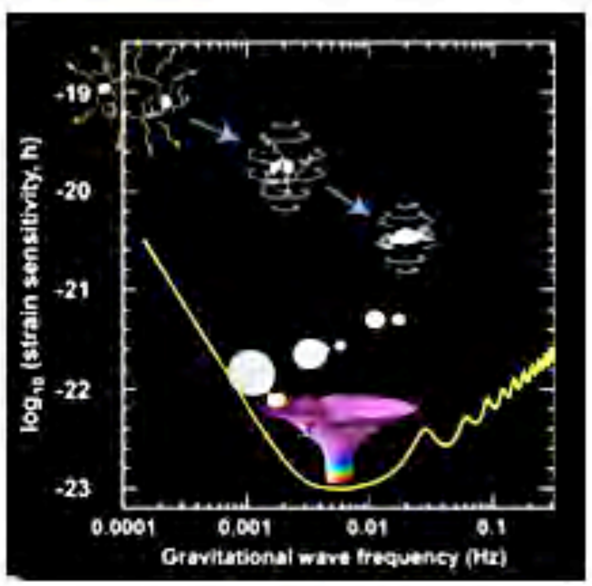
PHYSICAL REVIEW D **96,** 024063 (2017)

Lamb shift and the gravitational binding energy for binary black holes

Rafael A. Porto

Challenge: Towards 'new physics' 5PN threshold

$$
\begin{aligned}
E^{4\mathrm{PN}} = -\frac{\mu c^2 x}{2}\Bigg\{ 1 &+ \left(-\frac{3}{4} - \frac{\nu}{12}\right) x + \left(-\frac{27}{8} + \frac{19}{8}\nu - \frac{\nu^2}{24}\right) x^2 \\
&+ \left(-\frac{675}{64} + \left[\frac{34445}{576} - \frac{205}{96}\pi^2\right]\nu - \frac{155}{96}\nu^2 - \frac{35}{5184}\nu^3\right) x^3 \\
&+ \Bigg(-\frac{3969}{128} + \left[-\frac{123671}{5760} + \frac{9037}{1536}\pi^2 + \frac{896}{15}\gamma_E + \frac{448}{15}\ln(16x)\right]\nu \\
&\quad + \left[-\frac{498449}{3456} + \frac{3157}{576}\pi^2\right]\nu^2 + \frac{301}{1728}\nu^3 + \frac{77}{31104}\nu^4\Bigg) x^4 \Bigg\}
\end{aligned}
$$

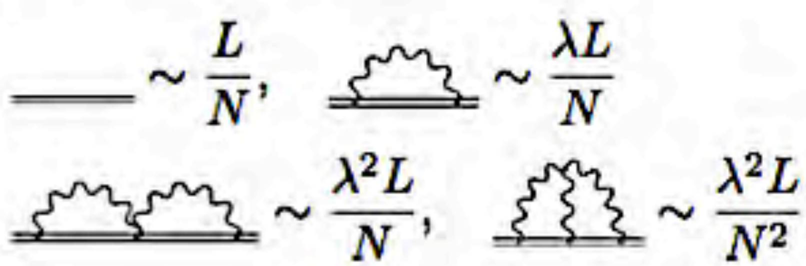


eLISA

Super-massive BHs (EMRIs)

Gravitational self-force in the ultra-relativistic limit: the "large-N" expansion

Chad R. Galley[a] and Rafael A. Porto[b]



$$N \equiv \gamma^2$$
$$\lambda = \epsilon N$$

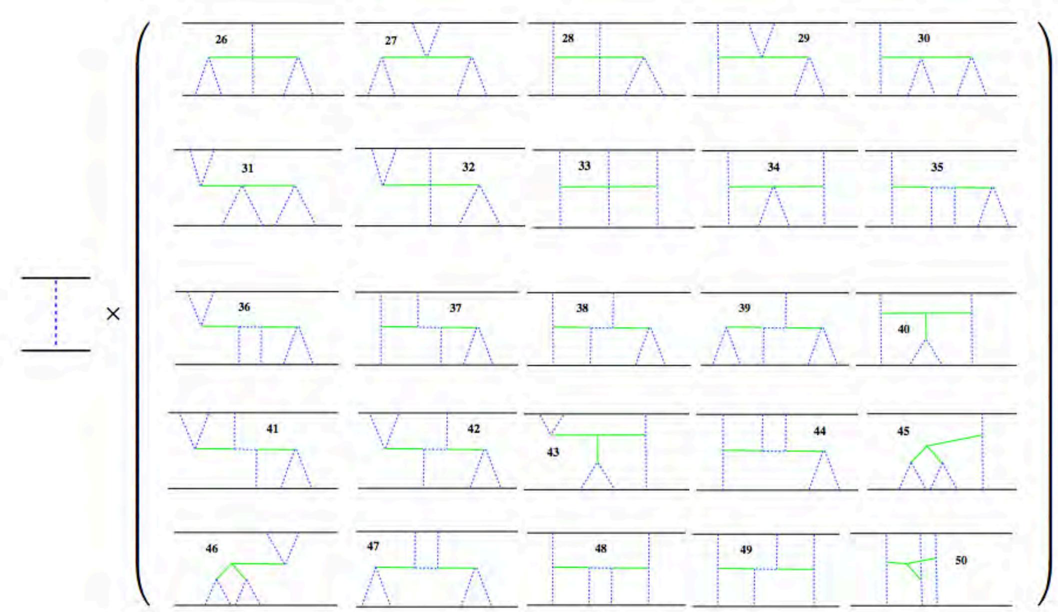
Challenge: Towards 'new physics' 5PN threshold

$$\mathcal{V}^{(5\mathrm{PN})}_{\mathrm{static}} = \frac{5}{16}\frac{G_N^6 m_1^6 m_2}{r^6} + \frac{91}{6}\frac{G_N^6 m_1^5 m_2^2}{r^6} + \frac{653}{6}\frac{G_N^6 m_1^4 m_2^3}{r^6} + (m_1 \leftrightarrow m_2)$$

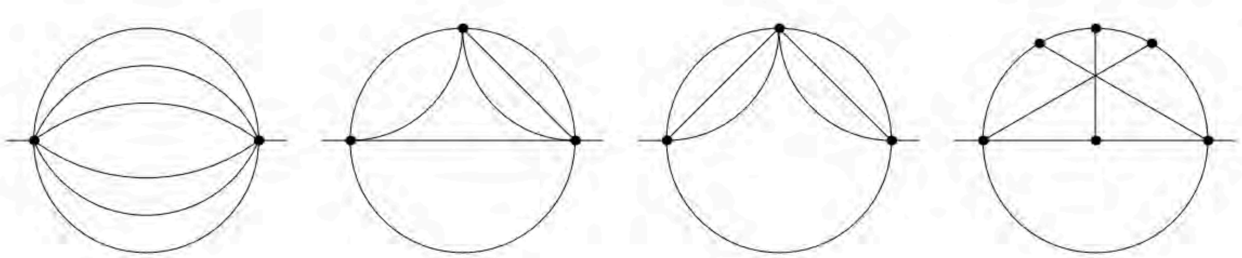
Static two-body potential at fifth post-Newtonian order
Stefano Foffa (Geneva U.), Pierpaolo Mastrolia (U. Padua, Dept. Phys. Astron.), Riccardo Sturani (IIP, Brazil), Christian Sturm (Wurzburg U.), William J. Torres Bobadilla (Valencia U.). Feb 27, 2019. 7 pp.
e-Print: arXiv:1902.10571 **[gr-qc] |** PDF

Five-Loop Static Contribution to the Gravitational Interaction Potential of Two Point Masses
J. Blümlein, A. Maier, P. Marquard (DESY, Zeuthen). Feb 28, 2019. 15 pp.
DESY 19-029, DO-TH 19/01, DESY-19-029, DO-TH-19/01
e-Print: arXiv:1902.11180 **[gr-qc] |** PDF

Factorization



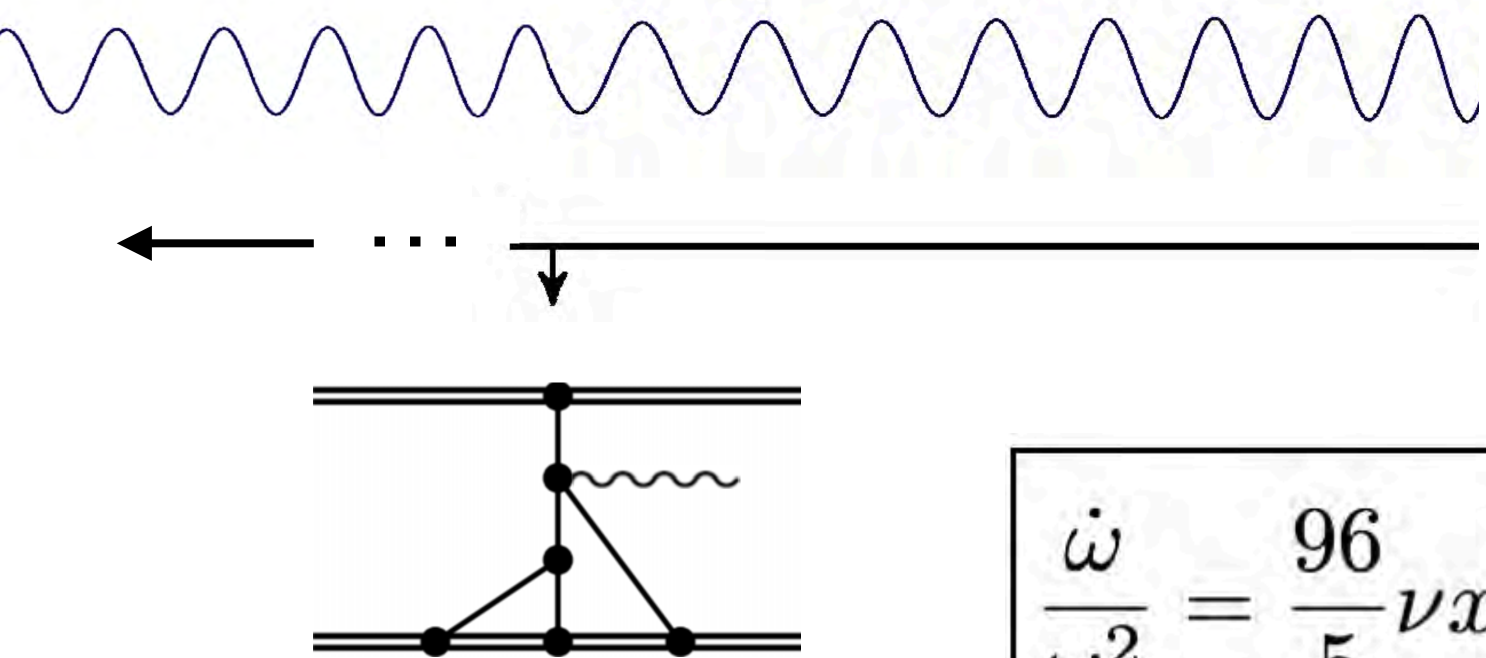
Master Integrals at '5 loops'



M_{61} M_{72} M_{74} M_{91}

Ambitious:

Analytic control:
reach physical threshold at **5PN**



- **Strong Interaction** (Neutron star's state)
- **Spacetime** (Black holes in GR)
- **Dark Matter** (Axions, Exotics)

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

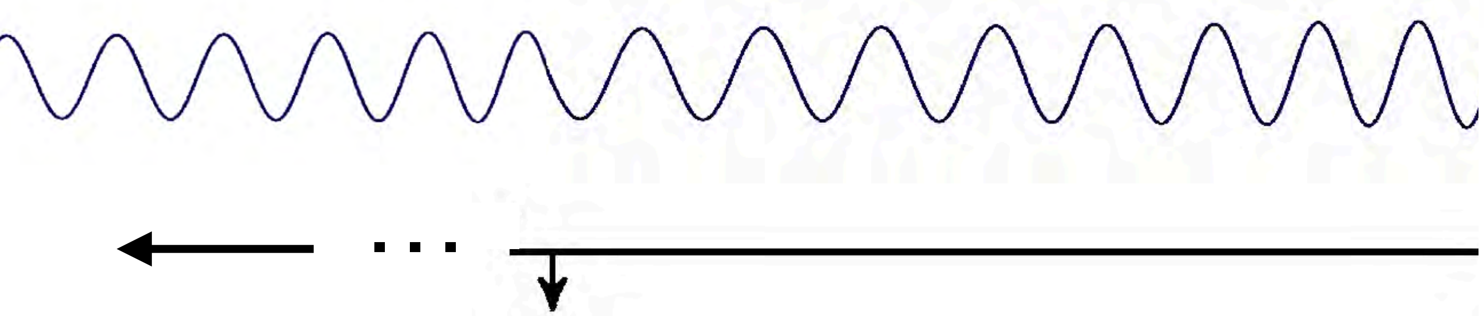
N^5LO
$5PN$

Impact: 'New Physics' searches with **GWPD**

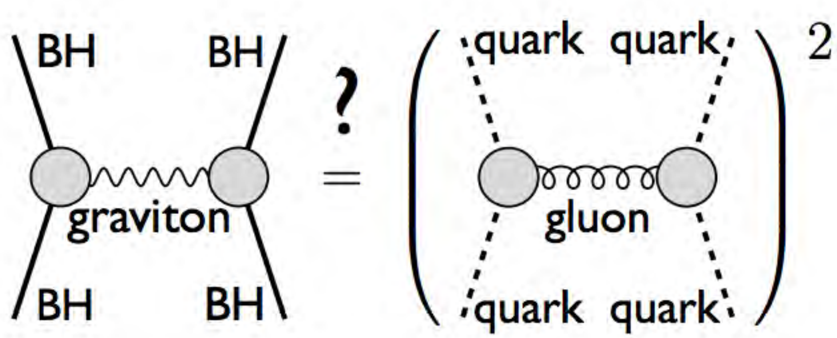
Challenge: Number of Feynman diagrams

Very Ambitious:

Analytic control:
beyond (Feynman)



Adapt tools from **'Scattering Amplitudes'** in HEP to the binary inspiral problem in GR



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

Impact: Deeper understanding of gravity

Feynman’s Gravity (ala QFT)

QUANTUM THEORY OF GRAVITATION*

By R. P. Feynman

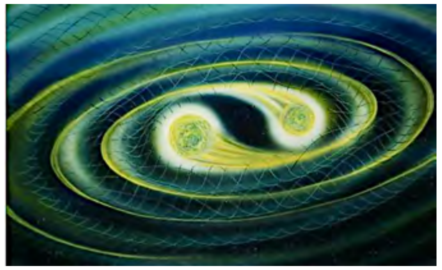
(Received July 3, 1963)

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!



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

Die Zeit

no.203.078 01.01.2025

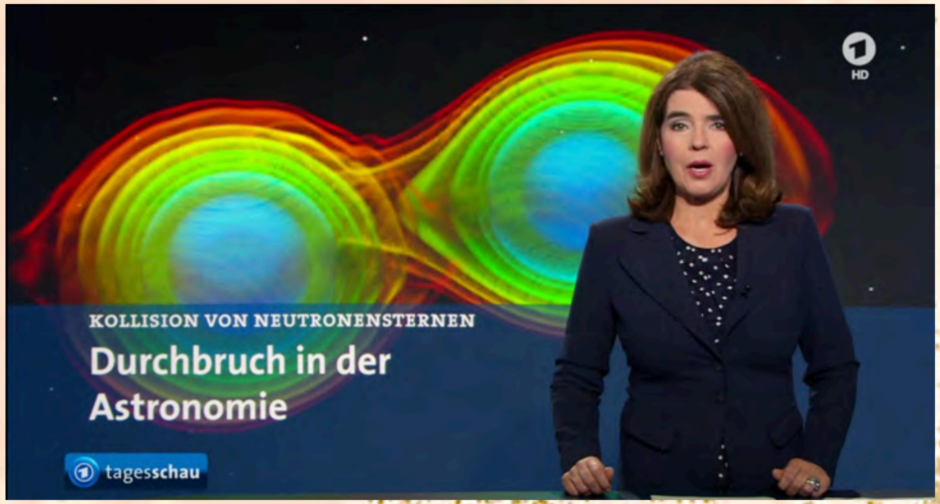
Einstein Reloaded!

From the LHC to LISA

By Rafael A. Porto

New era of foundational investigations established through GWPD.

$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\Big\{1 + \cdots + [\cdots]x^{7/2} + [\cdots]x^4 + [\cdots]x^5\Big\}$$



New particles discovered!

New objects found!

Neutron stars unveiled!

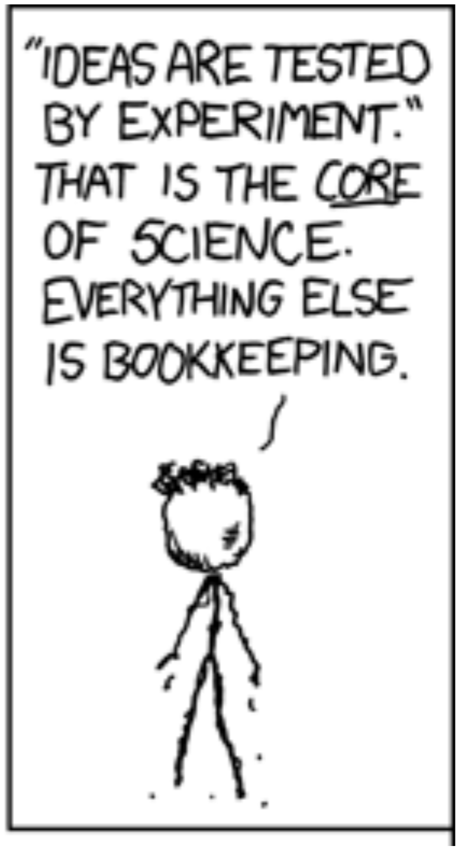
Experts Clash Over Project To Detect Gravity Wave

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

"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"

Extra Slides



PHYSICAL REVIEW D **89**, 064058 (2014)

Nonlocal-in-time action for the fourth post-Newtonian conservative dynamics of two-body systems

T. Damour, P. Jaranowski, and G. Schäfer,

$$H_{4\mathrm{PN}}^{\text{near-zone }(s)}[\mathbf{x}_a, \mathbf{p}_a] = H_{4\mathrm{PN}}^{\mathrm{loc}0}[\mathbf{x}_a, \mathbf{p}_a] + F[\mathbf{x}_a, \mathbf{p}_a]\left(\ln\frac{r_{12}}{s} + C\right)$$

Ambiguity parameter
associated to IR divergences
(Similar to Lamb shift)

$$C = -\frac{1681}{1536}$$

Originally not determined from first principles within PN framework.

PHYSICAL REVIEW D **93,** 084037 (2016)

Fokker action of nonspinning compact binaries at the fourth post-Newtonian approximation

Laura Bernard,[1,*] Luc Blanchet,[1,†] Alejandro Bohé,[2,‡] Guillaume Faye,[1,§] and Sylvain Marsat[3,4,‖]

However, we find that it differs from the recently published result derived within the ADM Hamiltonian formulation of general relativity [T. Damour, P. Jaranowski, and G. Schäfer, Phys. Rev. D **89**, 064058 (2014)]. More work is needed to understand this discrepancy.

PHYSICAL REVIEW D **93,** 084014 (2016)

Conservative dynamics of two-body systems at the fourth post-Newtonian approximation of general relativity

T. Damour, P. Jaranowski, and G. Schäfer,

(iii) several claims in a recent harmonic-coordinates Fokker-action computation [L. Bernard *et al.*, arXiv:1512.02876v2 [gr-qc]] are incorrect, but can be corrected by the addition of a couple of *ambiguity parameters* linked to subtleties in the regularization of infrared and ultraviolet

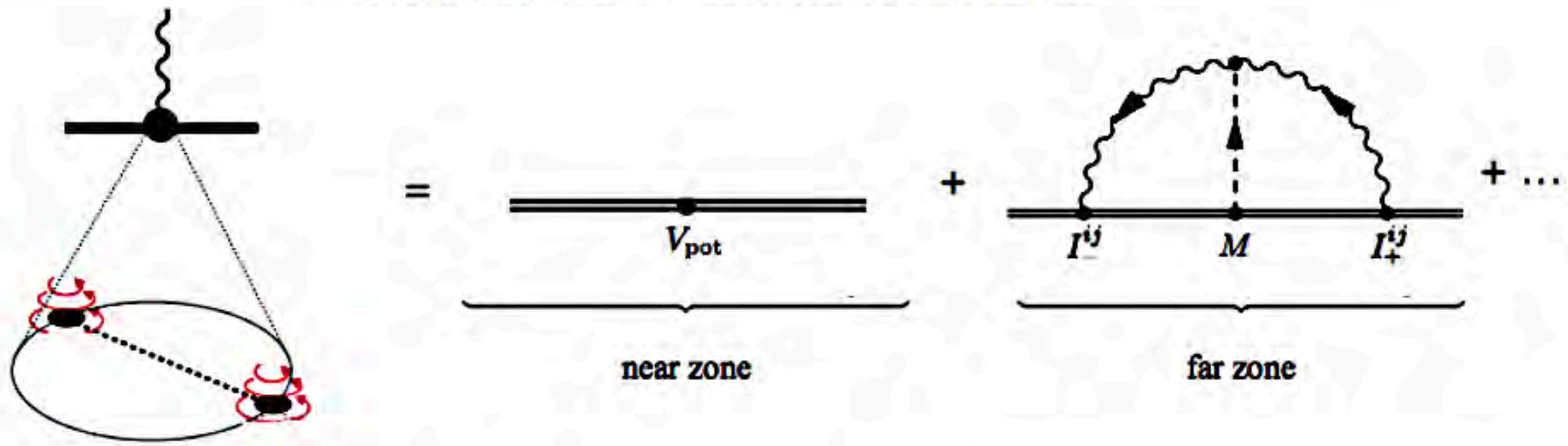
VII. SUGGESTION FOR ADDING MORE IR AMBIGUITY PARAMETERS IN REF. [21]

$$(a, b, c)^{\text{new}}_{\text{B}^3\text{FM}} = (a, b, c)_{\text{B}^3\text{FM}} + \Delta C\,\frac{16}{15}(-11, 12, 0).$$

PHYSICAL REVIEW D **96**, 024062 (2017)

Apparent ambiguities in the post-Newtonian expansion for binary systems

Rafael A. Porto[1] and Ira Z. Rothstein[2]



PHYSICAL REVIEW D **96**, 024063 (2017)

Lamb shift and the gravitational binding energy for binary black holes

Rafael A. Porto

$$
\begin{aligned}
\delta E_{n,\ell} &= (\delta E_{n,\ell})_{US} + (\delta E_{n,\ell})_{cV} + \cdots \\
&= \frac{2\alpha_e}{3\pi}\left[\frac{5}{6}e^2\frac{|\psi_{n,\ell}(\boldsymbol{x}=0)|^2}{2m_e^2} - \sum_{m\neq n,\ell}\left\langle n,\ell\left|\frac{\boldsymbol{p}}{m_e}\right|m,\ell\right\rangle^2 (E_m - E_n)\log\frac{2|E_n - E_m|}{m_e}\right] + \\
&\quad + \frac{4\alpha_e^2}{3m_e^2}\left(\frac{1}{\epsilon_{\rm UV}} - \frac{1}{\epsilon_{\rm IR}}\right)|\psi_{n,\ell}(\boldsymbol{x}=0)|^2 .
\end{aligned}
$$

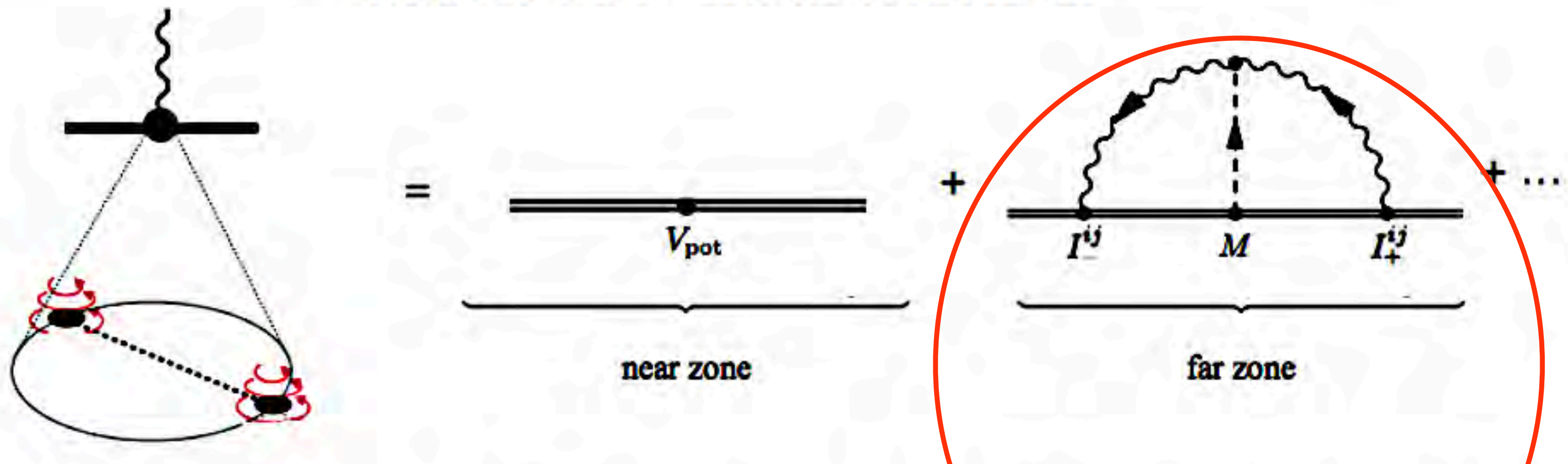
finite term uniquely determined!

IR/UV cancelation in dim. reg. (non-trivial in other schemes)

PHYSICAL REVIEW D **96**, 024062 (2017)

Apparent ambiguities in the post-Newtonian expansion for binary systems

Rafael A. Porto[1] and Ira Z. Rothstein[2]



$$\frac{2G_N^2 M}{5} I^{(3)ij} I^{(3)ij} \left(-\frac{1}{\epsilon_{\rm IR}} + 2\log(\mu r) + \cdots\right) + \left(\frac{1}{\epsilon_{\rm UV}} + 2\log(\Omega/\mu) + \cdots\right)$$

PHYSICAL REVIEW D **93**, 124010 (2016)

Tail effect in gravitational radiation reaction: Time nonlocality and renormalization group evolution

Chad R. Galley,[1] Adam K. Leibovich,[2] Rafael A. Porto,[3] and Andreas Ross[4]

Logarithmic contribution to energy!

$$\mu \frac{d}{d\mu} V_{\rm ren}(\mu) = \frac{2G_N^2 M}{5} I^{ij(3)}(t) I^{ij(3)}(t)$$

$$E_{\log} = -2G_N^2 M \langle I^{ij(3)}(t) I^{ij(3)}(t)\rangle \log v$$

PHYSICAL REVIEW D 97, 044023 (2018)

Ambiguity-free completion of the equations of motion of compact binary systems at the fourth post-Newtonian order

Tanguy Marchand,[1,2,*] Laura Bernard,[3,†] Luc Blanchet,[1,‡] and Guillaume Faye[1,§]

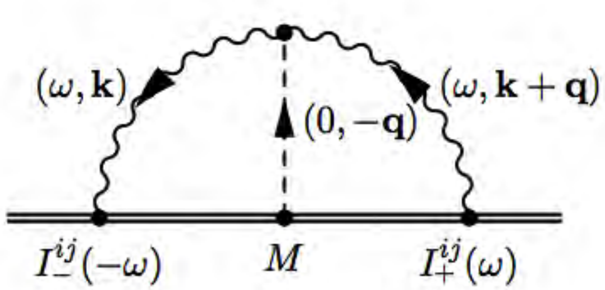
V. DETERMINATION OF THE AMBIGUITY PARAMETERS

Remarkably, the value $\kappa = \frac{41}{60}$ we have obtained in our result for the tail [see Eq. (4.13)], agrees with the result found by Galley *et al* [10] in their computation of the tail term in d

PHYSICAL REVIEW D 93, 124010 (2016)

Tail effect in gravitational radiation reaction: Time nonlocality and renormalization group evolution

Chad R. Galley,[1] Adam K. Leibovich,[2] Rafael A. Porto,[3] and Andreas Ross[4]



$$W_{\rm tail}[\boldsymbol{x}_a^\pm] = \frac{2G_N^2 M}{5} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi}\, \omega^6\, I^{ij}_-(-\omega) I^{ij}_+(\omega) \left[-\frac{1}{(d-4)_{\rm UV}} - \gamma_E + \log\pi - \log\frac{\omega^2}{\mu^2} + \frac{41}{30} + i\pi\,{\rm sign}(\omega) \right].$$

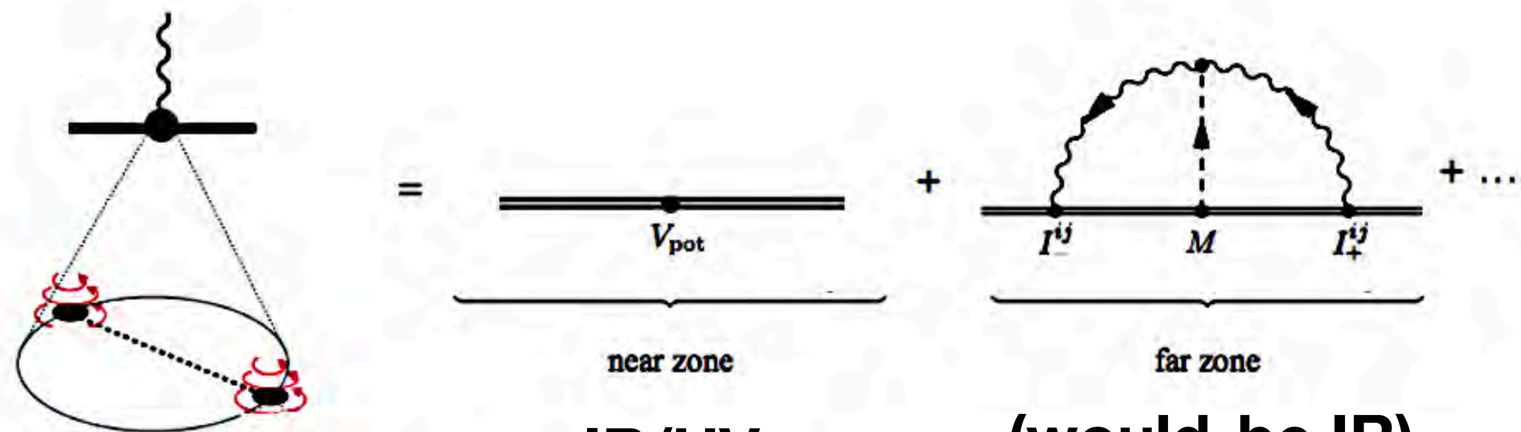
The 41/30 ***only makes sense*** if IR/UV poles (and \mu!) are properly removed as in the Lamb shift (Otherwise you have scheme dependence = ambiguity)

Unambiguous/Consistent derivation in EFT

(UV renormalization and IR/UV identification in dim. reg.)

$$S_{\rm pp}[x_a^\alpha(\tau_a)] = \sum_a \int d\tau_a \left(-m_a + \sum_i c_i \mathcal{O}_i \left[x_a^\alpha(\tau_a), \dot{x}_a^\alpha(\tau_a), \cdots; g_{\mu\nu}, \partial_\beta g_{\mu\nu}, \cdots \right] \right)$$

The cancelation is by construction. Entirely due to regions. It is not there in PM expansion!



IR/UV

(would-be IR) => UV in EFT

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

Stefano Foffa (Geneva U.), Rafael A. Porto (DESY, Zeuthen & ICTP, Trieste), Ira Rothstein (Carnegie Mellon U.), Riccardo Sturani (IIP, Brazil). Mar 12, 2019. 39 pp.

e-Print: arXiv:1903.05118 [gr-qc] | PDF

ON THE MOTION OF PARTICLES IN GENERAL RELATIVITY THEORY

A. EINSTEIN and L. INFELD

1. Introduction. The gravitational field manifests itself in the motion of bodies. Therefore the problem of determining the motion of such bodies from the field equations alone is of fundamental importance. This problem was solved for the first time some ten years ago and the equations of motion for two particles were then deduced [1]. A more general and simplified version of this problem was given shortly thereafter [2].

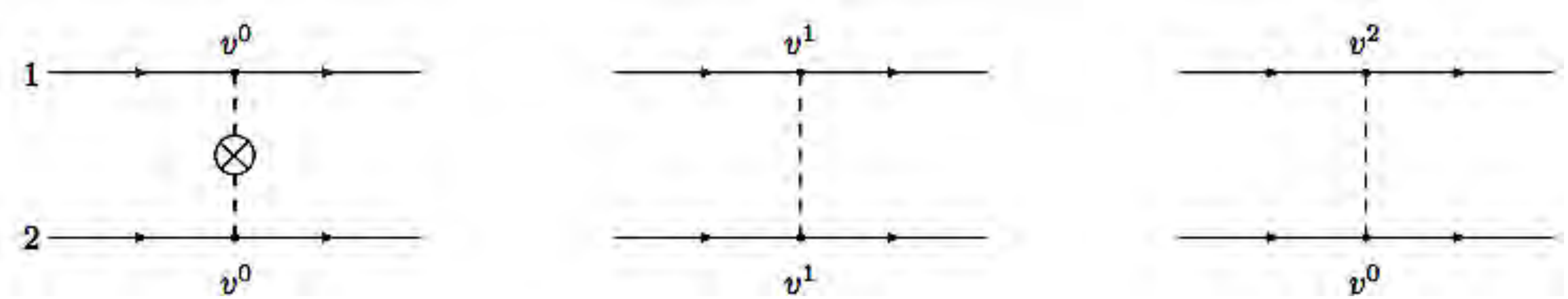
Mr. Lewison pointed out to us, that from our approximation procedure, it does not follow that the field equations can be solved up to an arbitrarily high approximation. This is indeed true. We believe that the present work not only removes this difficulty, but that it gives a new and deeper insight into the problem of motion. From the logical point of view the present theory is considerably simpler and clearer than the old one. But as always, we must pay for these logical simplifications by prolonging the chain of technical argument.

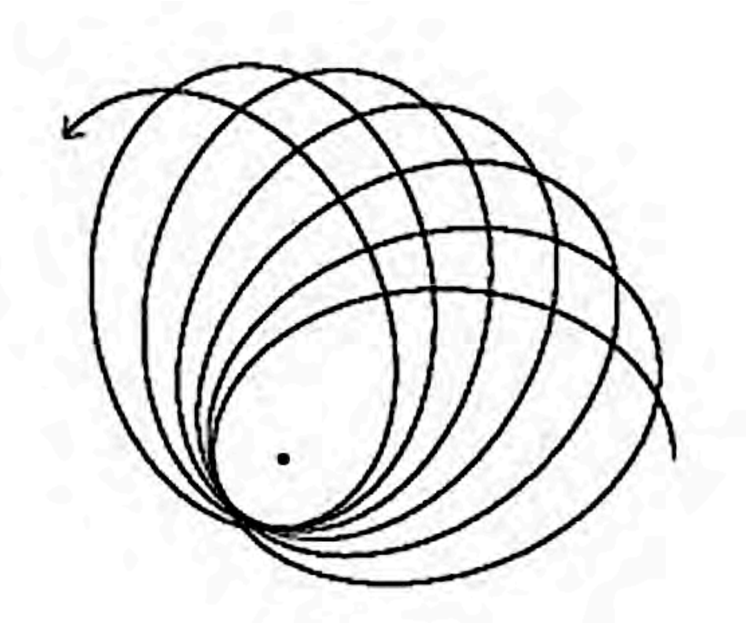
TABLE OF SURFACE INTEGRALS FOR $\int_6^1 \Lambda_{ms} n_s \, dS$

No.	Expression	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	Result	Remarks
1	$\overset{1}{m}\bar g_{,s}\dot\eta^s\dot\eta^m$	$-\frac{16}{3}$				$-\frac{4}{3}$		$-\frac{8}{3}$	$-\frac{4}{15}$		$\frac{8}{15}$	$\frac{4}{15}$				$\frac{4}{5}$			-8	$\bar g_{,s} = -2\overset{2}{m}\frac{\partial \overset{1}{r}}{\partial \eta^s}$
2	$\overset{1}{m}\bar g\ddot\eta^m$	-2						-4	$-\frac{4}{3}$			$-\frac{29}{3}$	3	$\frac{11}{3}$	$-\frac{5}{3}$	$\frac{2}{3}$	$\frac{32}{3}$	$-\frac{22}{3}$	-8	$\bar g = -\frac{2\overset{2}{m}}{r}$; $\ddot\eta^m = -\frac{1}{2}\bar g_{,m}$
3	$\overset{1}{m}\bar g_{,m}\dot\eta^s\dot\eta^s$	1					$-\frac{4}{3}$	$-\frac{4}{5}$			$\frac{8}{5}$	$\frac{4}{5}$	1	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{4}{15}$			2	$\bar g_{,m} = -2\overset{1}{m}\ddot\eta^m$
4	$\overset{1}{m}\bar g_{,m}\dot\zeta^s\dot\zeta^s$											2	$\frac{1}{3}$	1	$-\frac{1}{3}$				3	
5	$\overset{1}{m}\bar g_{,m}\bar f$	$\frac{4}{3}$				2	$\frac{2}{3}$					$\frac{1}{2}$	$\frac{1}{6}$	$\frac{1}{2}$	$-\frac{1}{6}$				5	$\bar g_{,m}\bar f = -\bar g\bar f_{,m}$; $\bar f = -\frac{2\overset{1}{m}}{r}$
6	$\overset{1}{m}\overset{2}{m}\bar r_{,00m}$											-2							-2	$\bar r_{,00m} = (\overset{2}{\bar r}_{,00m})$ for $x^s = \eta^s$ *
7	$\overset{1}{m}\bar g_{,s}\dot\zeta^m\dot\eta^s$	$\frac{16}{5}$				$\frac{8}{3}$	$\frac{4}{5}$	$\frac{4}{3}$											8	
8	$\overset{1}{m}\bar g_{,s}\dot\zeta^s\dot\eta^m$	$\frac{16}{5}$					$-\frac{8}{15}$	4	$\frac{4}{3}$	-2									6	
9	$\overset{1}{m}\bar g_{,m}\dot\eta^s\dot\zeta^s$	$-\frac{32}{15}$		$-\frac{16}{3}$	$-\frac{8}{3}$		$\frac{4}{5}$		$\frac{4}{3}$										-8	
10	$\overset{1}{m}\bar g_{,s}\dot\zeta^s\dot\zeta^m$	$-\frac{8}{3}$				-4	$-\frac{4}{3}$												-8	

* $\bar r_{,00m} = \frac{\partial^3 r}{\partial\eta^s\partial\eta^r\partial\eta^m}\dot\zeta^s\dot\zeta^r$, as $\frac{\partial^2 r}{\partial\eta^s\partial\eta^m}\frac{\partial \overset{1}{r}}{\partial\eta^s} = 0$.

Feynman's EFT computation (Anomalous shift at 1PN)





Perihelion of Mercury:

One of the first confirmations of Einstein theory

Precision gravity!

(Jupiter is the leading effect)