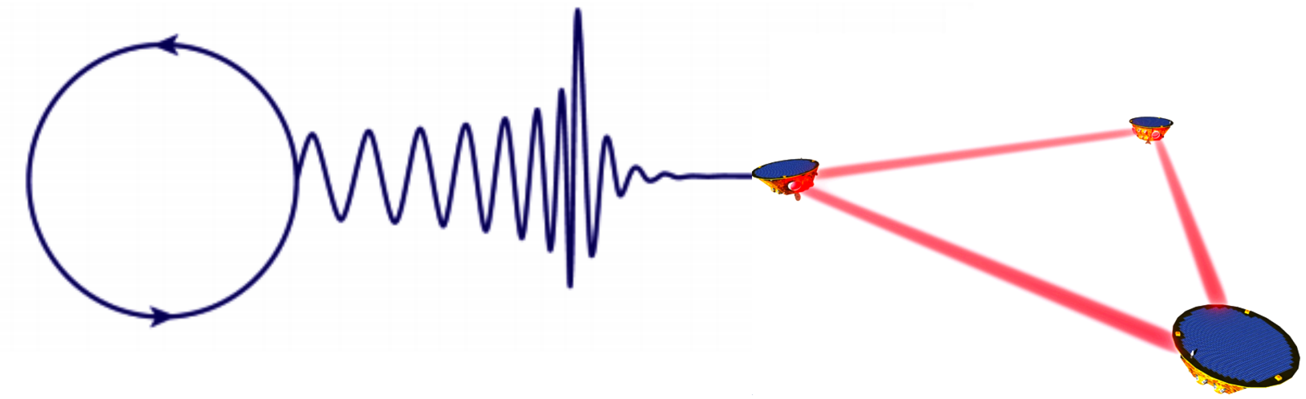
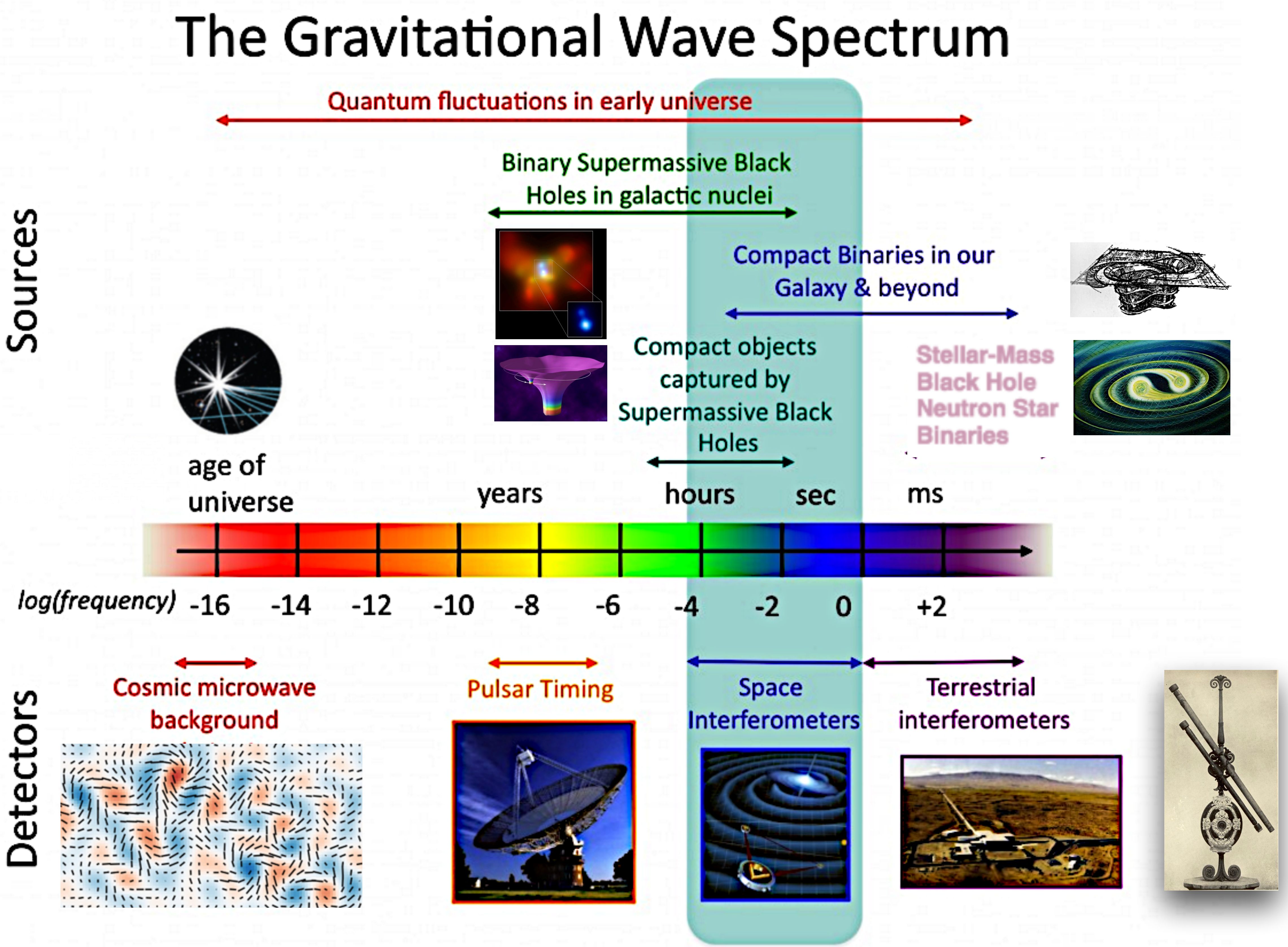
The Gravitational Collider:
The future of Precision GW physics

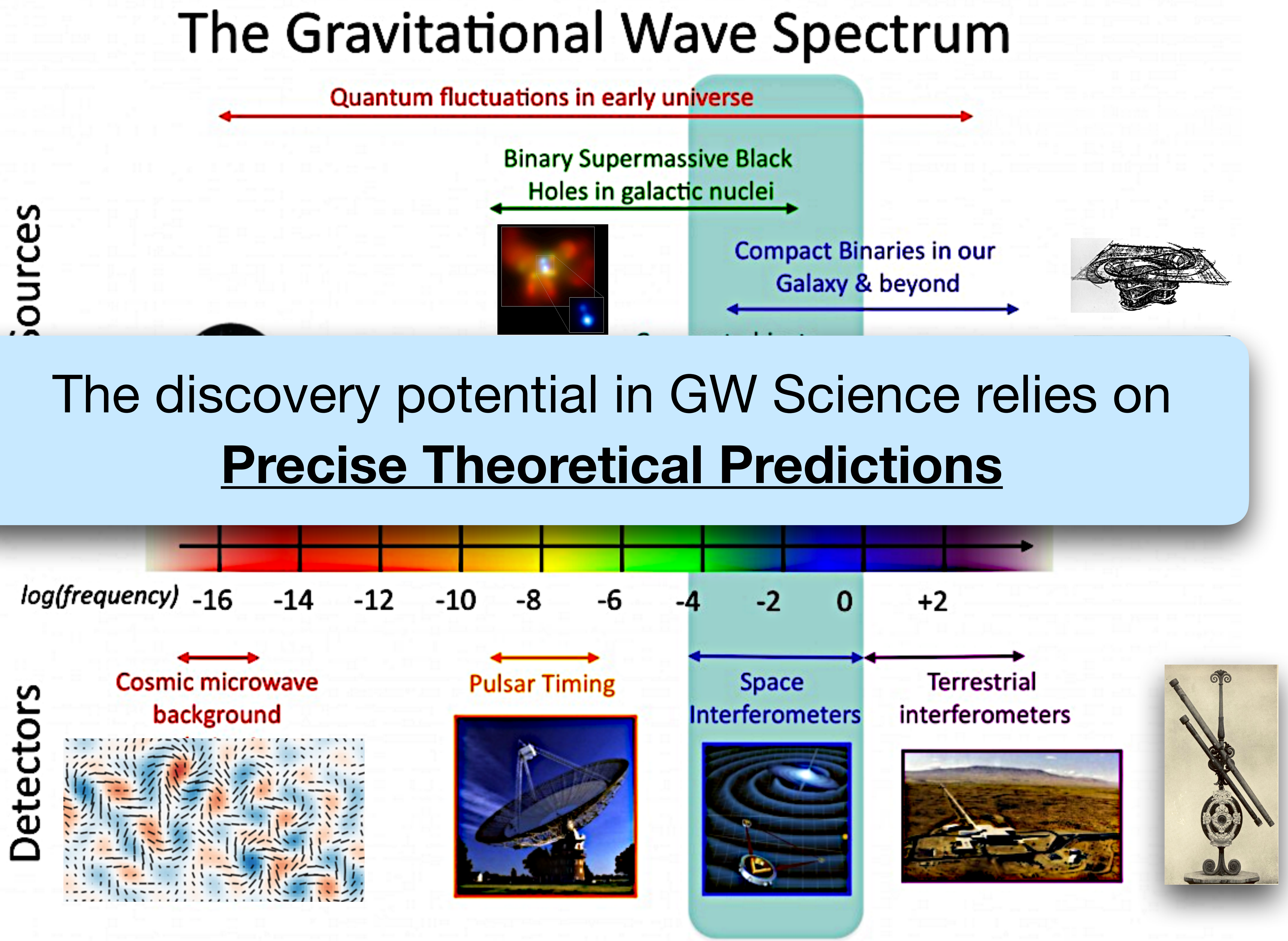


Rafael A. Porto

QCD meets Gravity
Nordita 2018

DESY. ICTP SAIFR FAPESP SÃO PAULO RESEARCH FOUNDATION SIMONS FOUNDATION Advancing Research in Basic Science and Mathematics DFG Deutsche Forschungsgemeinschaft erc


The Gravitational Wave Spectrum
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Stellar-Mass Black Hole Neutron Star Binaries
Sources
age of universe
years
hours
sec
ms
log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2
Cosmic microwave background
Pulsar Timing
Space Interferometers
Terrestrial interferometers
Detectors

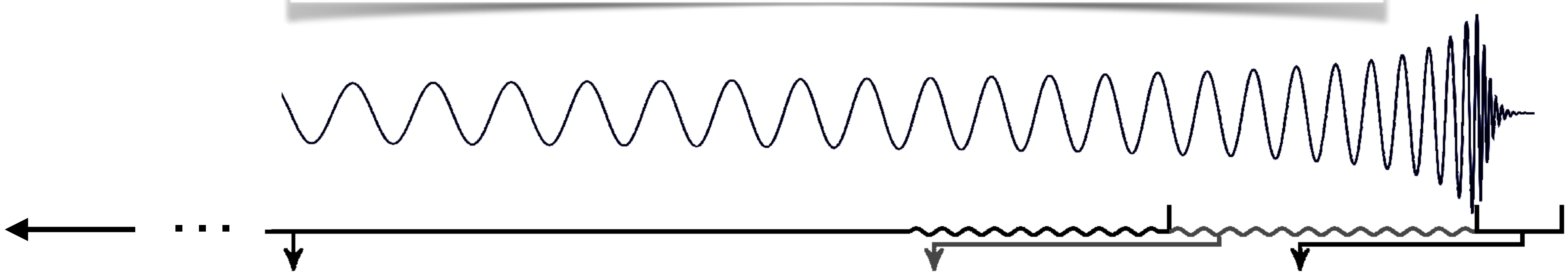


The discovery potential in GW Science relies on

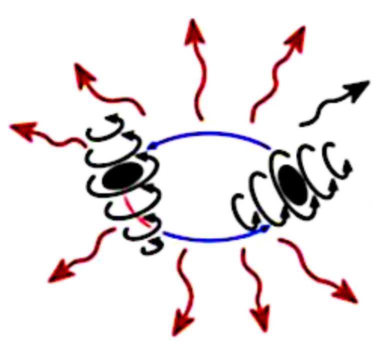
Precise Theoretical Predictions

Challenge: Two-body problem in General Relativity

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



Inspiral

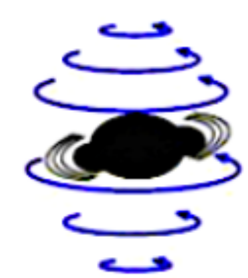


Analytic/Perturbative
(Approx. but fast)

Merger

Numerical
(exact but slow)

Ringing



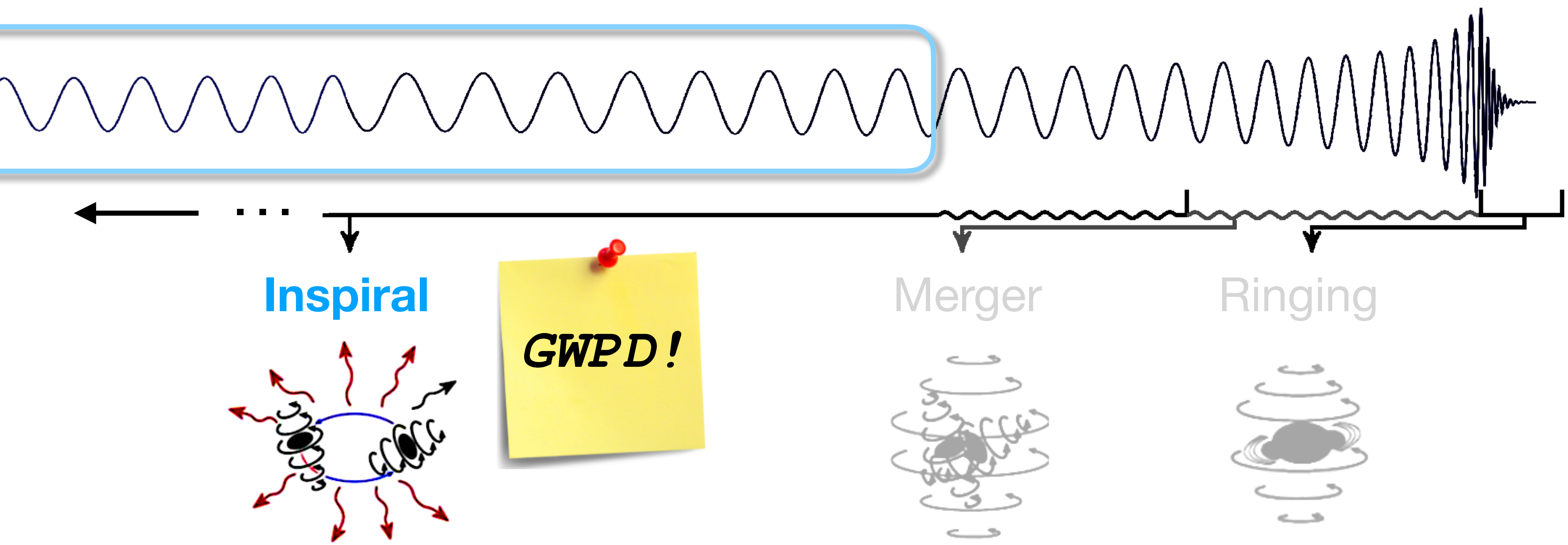
Analytic/
Perturbative

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

Main Goal: Extremely accurate Post-Newtonian waveforms

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

100+ events per year!



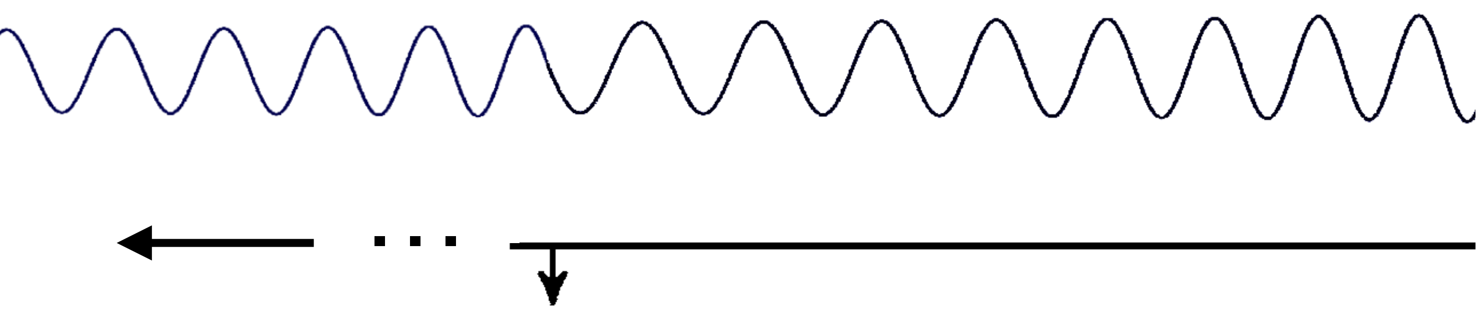
Post-Newtonian Expansion

'New Physics' searches through <u>GW Precision Data</u> (**GWPD**) *TM*

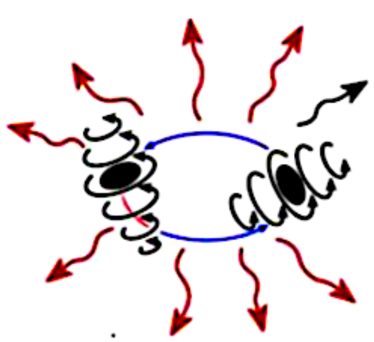
State-of-the-art

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

100+ events per year!



Inspiral



3.5PN order

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

$\nu \sim m_2/m_1$

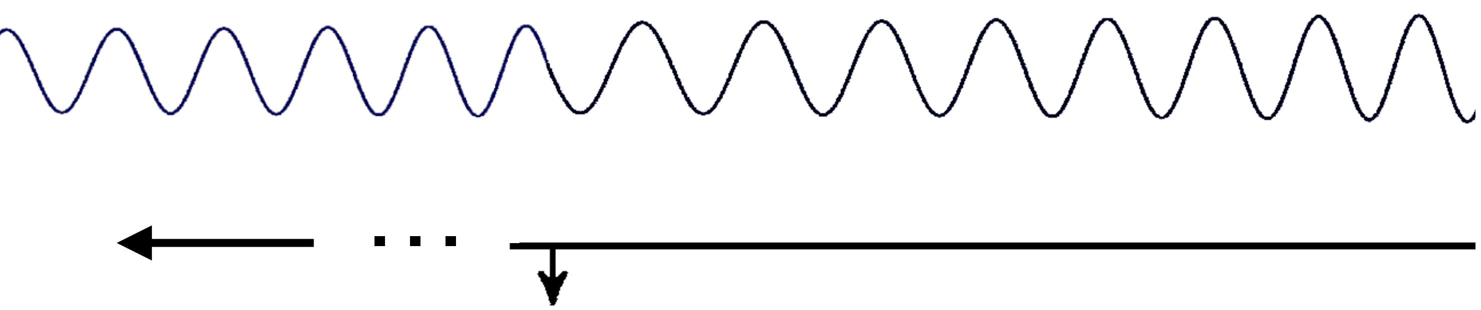
$x \sim (v/c)^2$

Quadrupole Formula

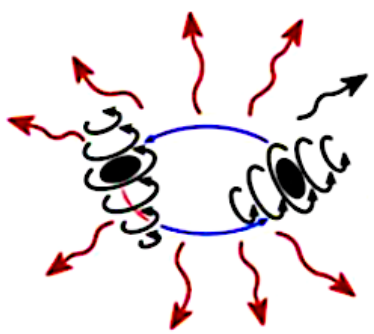
$$4\pi R^2 \bar{\mathfrak{S}} = \frac{\varkappa}{40\pi}\left[\sum_{\mu\nu}\dddot{\mathfrak{J}}_{\mu\nu}^2 - \frac{1}{3}\left(\sum_\mu \dddot{\mathfrak{J}}_{\mu\mu}\right)^2\right]$$

Are we ready for the future?

Theoretical uncertainties may dominate over planned empirical reach



Inspiral



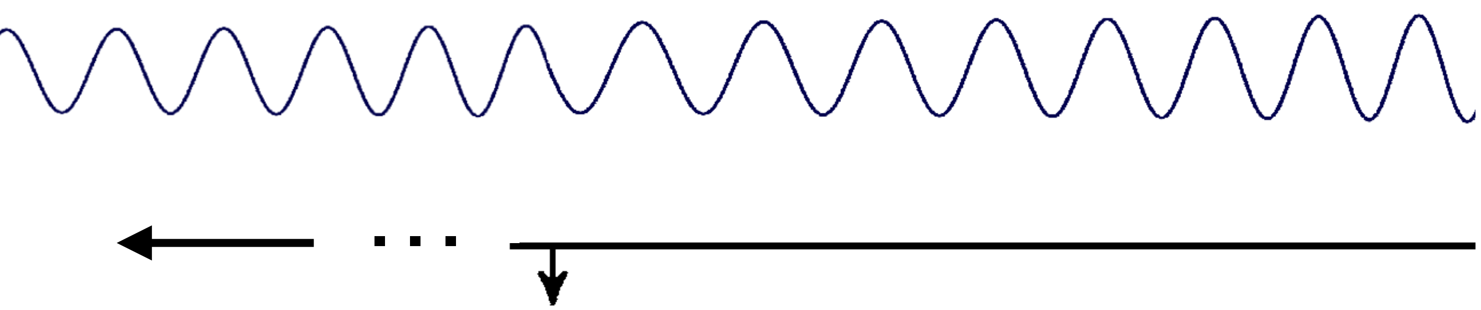
NOT GOOD ENOUGH

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

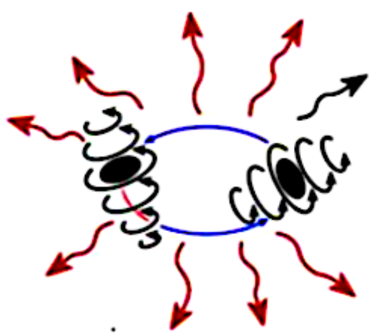
SNR: LIGO/VIRGO ~ 30 but ET & LISA ~ 100-1000!

Are we ready for the future?

We haven't reached the precision to distinguish (from PN) between compact bodies!



Inspiral



New Physics <u>Threshold</u>

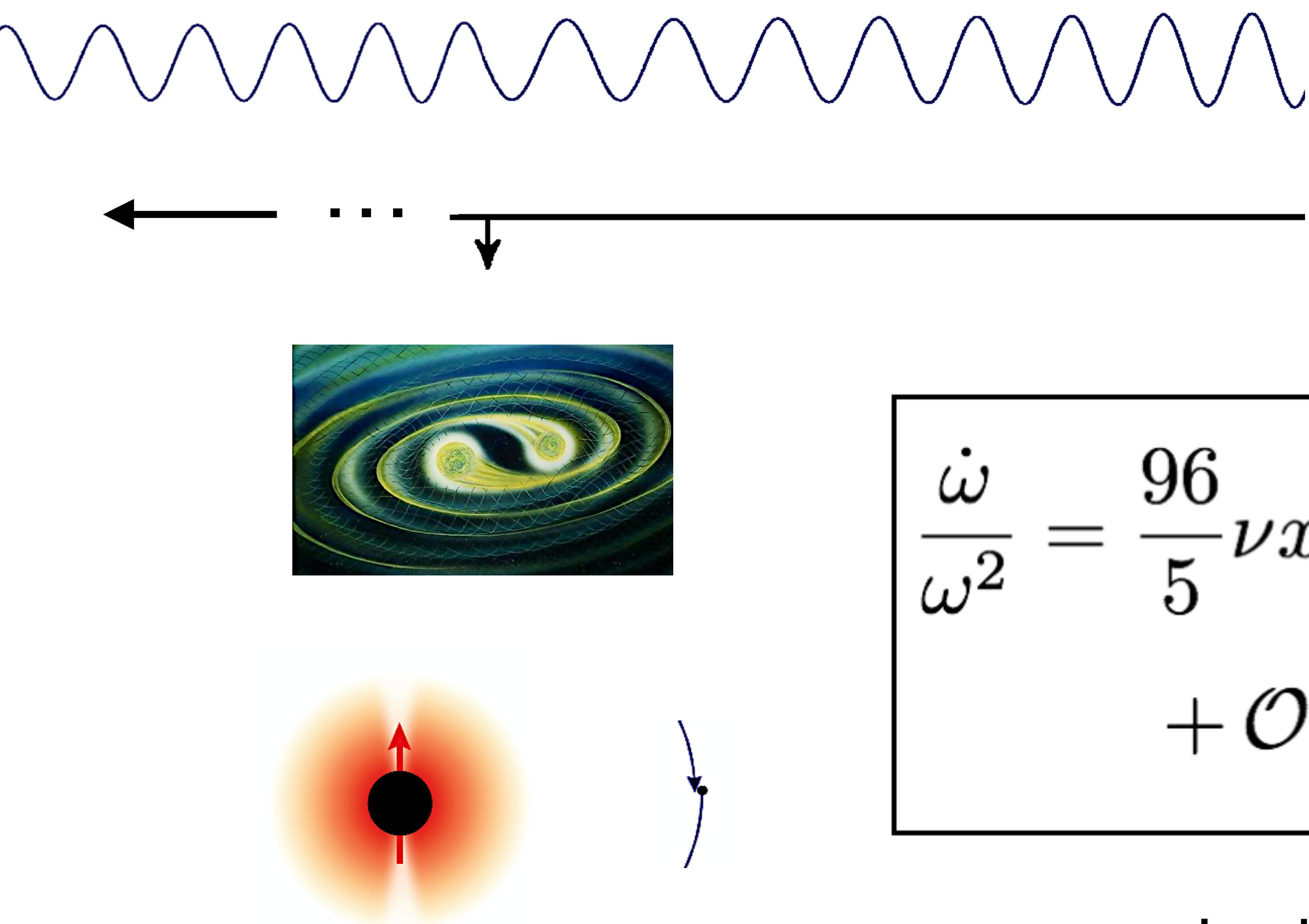
$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{1 + \cdots + [\cdots]x^{7/2} + \mathcal{O}(x^4) + \mathcal{O}(x^5)\right\}$$

N^5LO
5PN

Inner structure of compact objects

Finite-size Threshold

Impact: ‘New Physics’ searches with **GWPD**



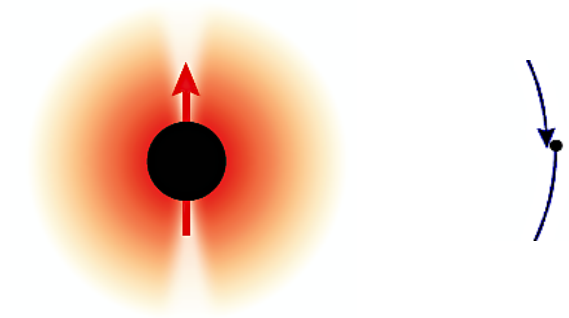
- **Strong Interaction** (Neutron star’s state)
- **Spacetime** (Black holes in GR)
- **Dark Matter** (Axions, Exotics)

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

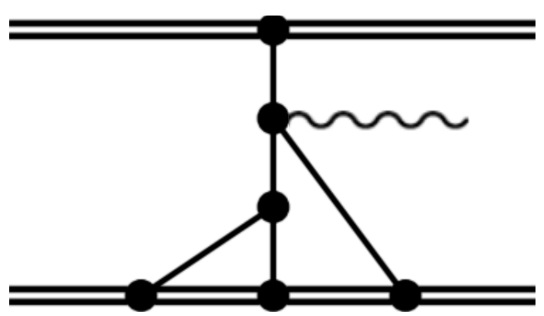
N^5LO
$5PN$

sample diagrams to ‘5 loops’

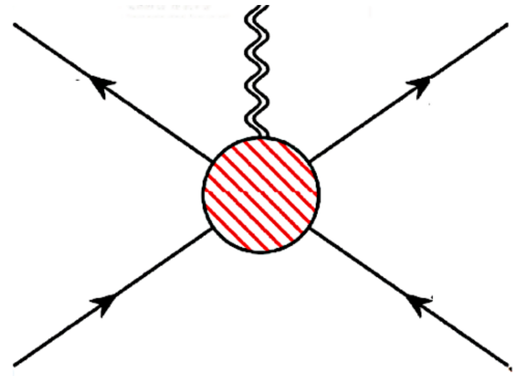
- **Opportunities**: 'Future of GW Science'



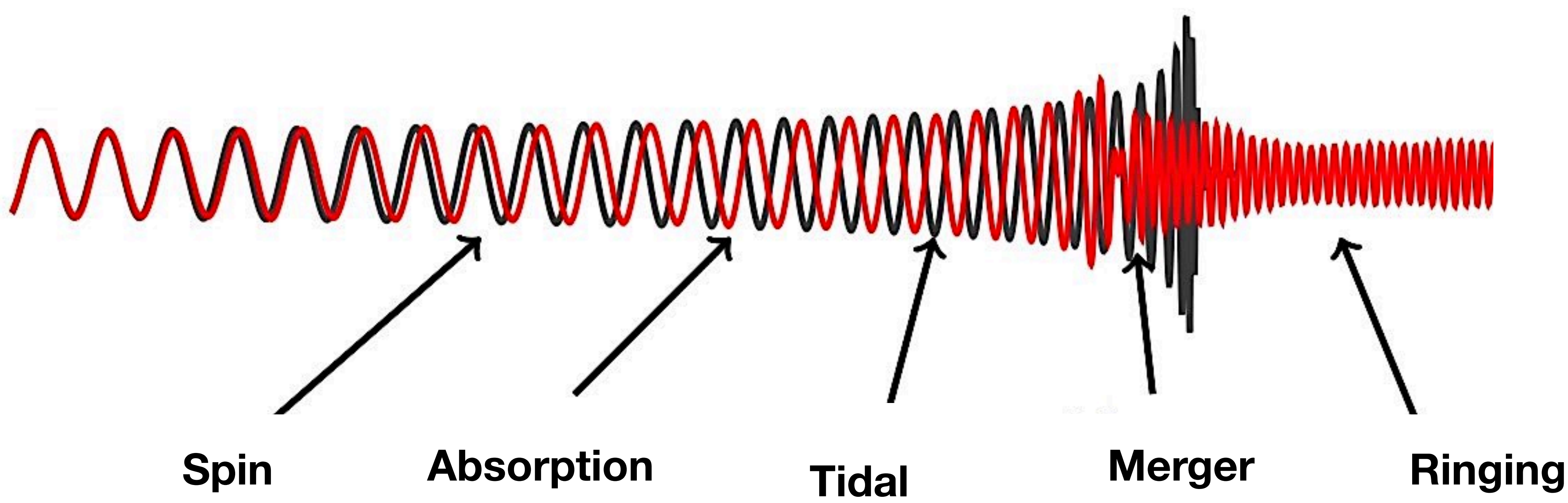
- **Now**: Feynman



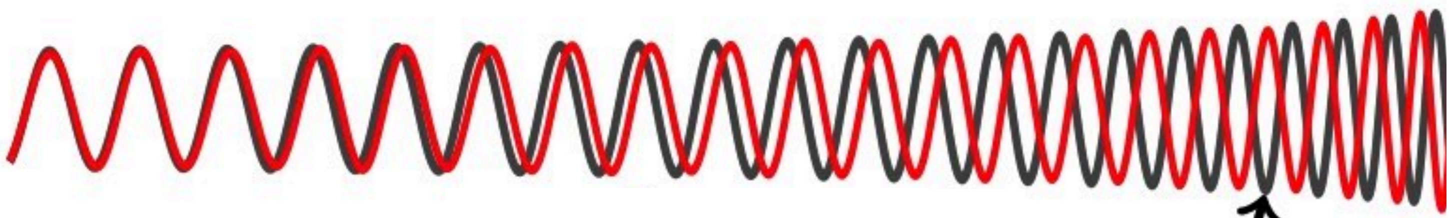
- **Challenges**: New tools?



Opportunities

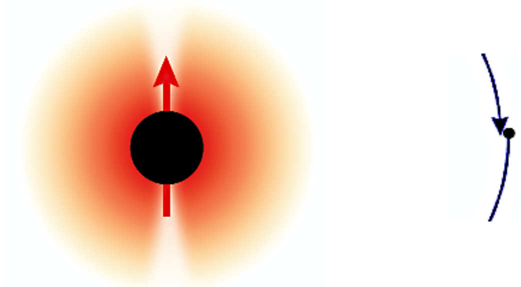


- **Strong Interaction** (Neutron stars' EOS)
- **Spacetime** (Black holes in General Relativity)
- **Dark Matter** (Axions, Exotic Compact Objects)
- **Unknown Unknowns!**



Inspiral

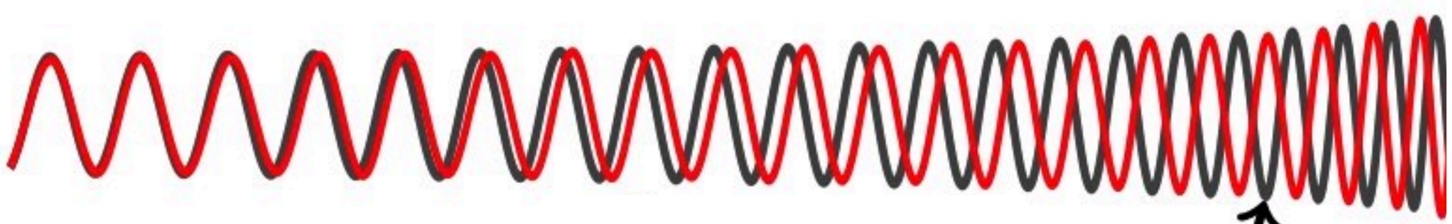
Tidal (5PN)

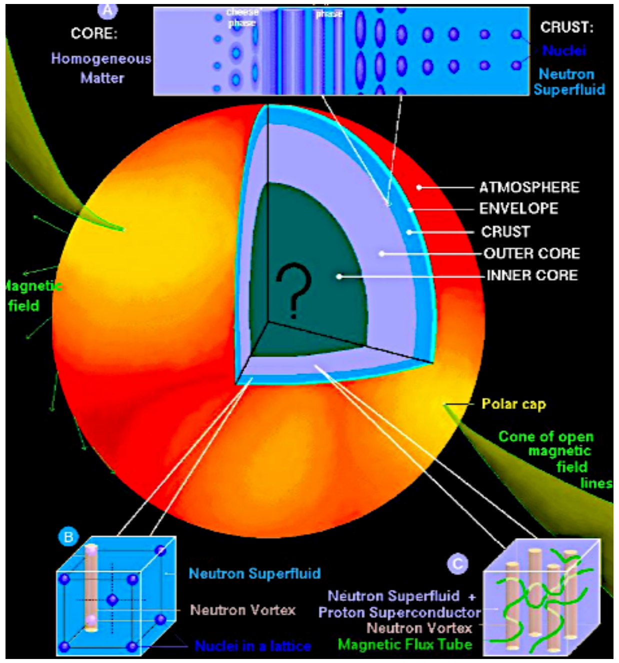


$$\Psi(v) = \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v)$$

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

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





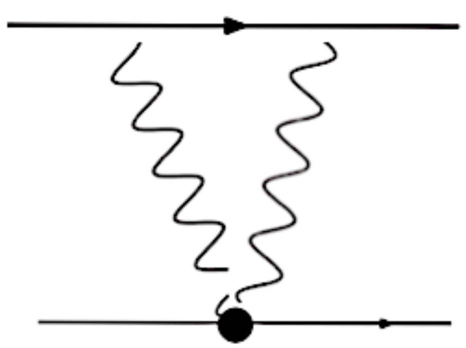
Static Limit: $\int dt\, Q^{ij} E_{ij}$

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

Tidal (5PN)

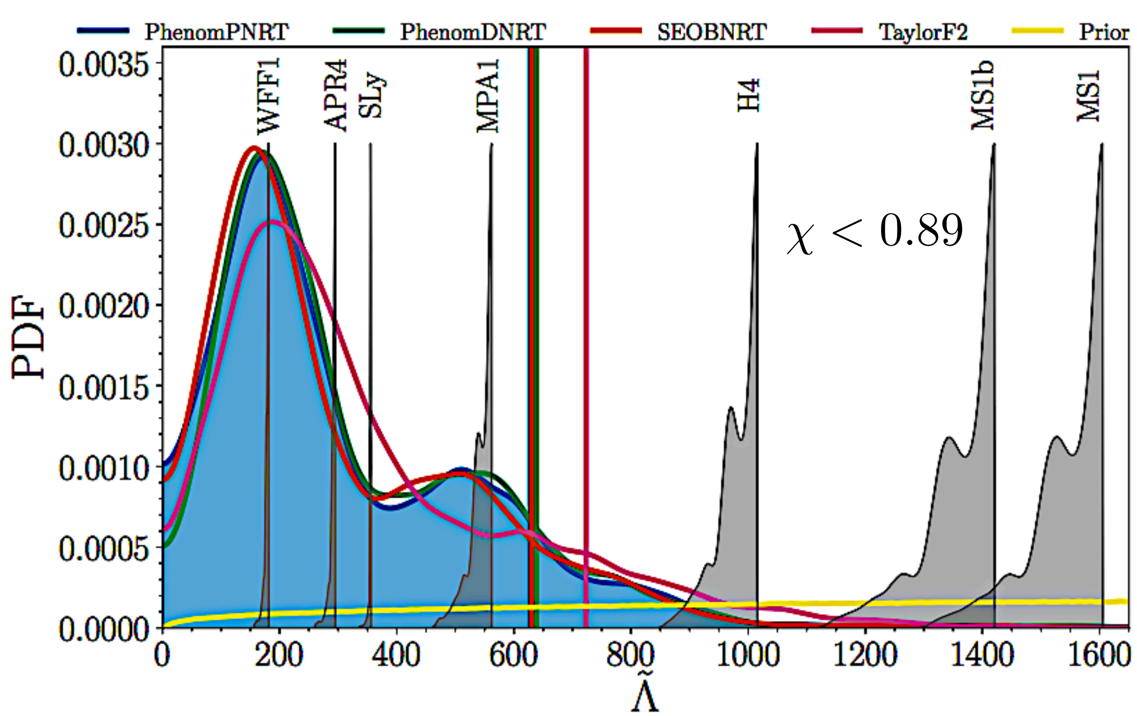
$$\Psi(v) = \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v)$$

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

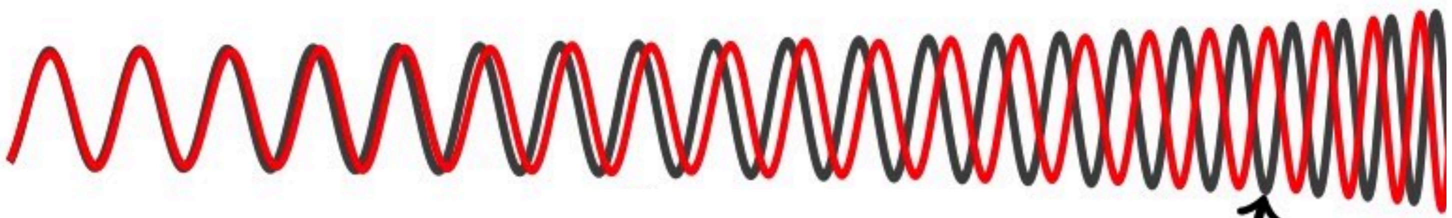


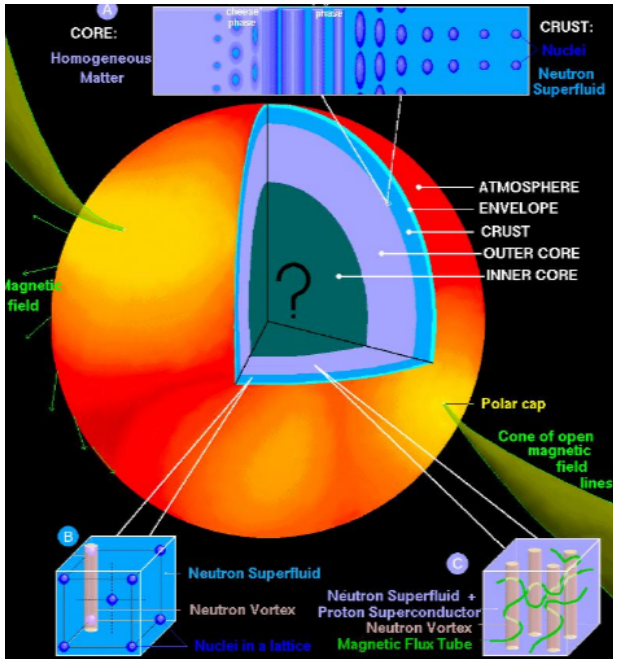
$$C_E \sim R^5$$

$$\tilde{\Lambda} \sim C_E/M^5$$



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





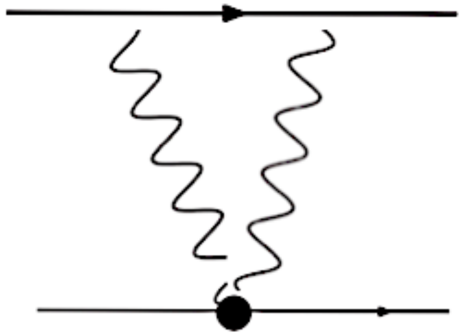
Static Limit: $$\int dt\, Q^{ij} E_{ij}$$

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

Tidal (5PN)

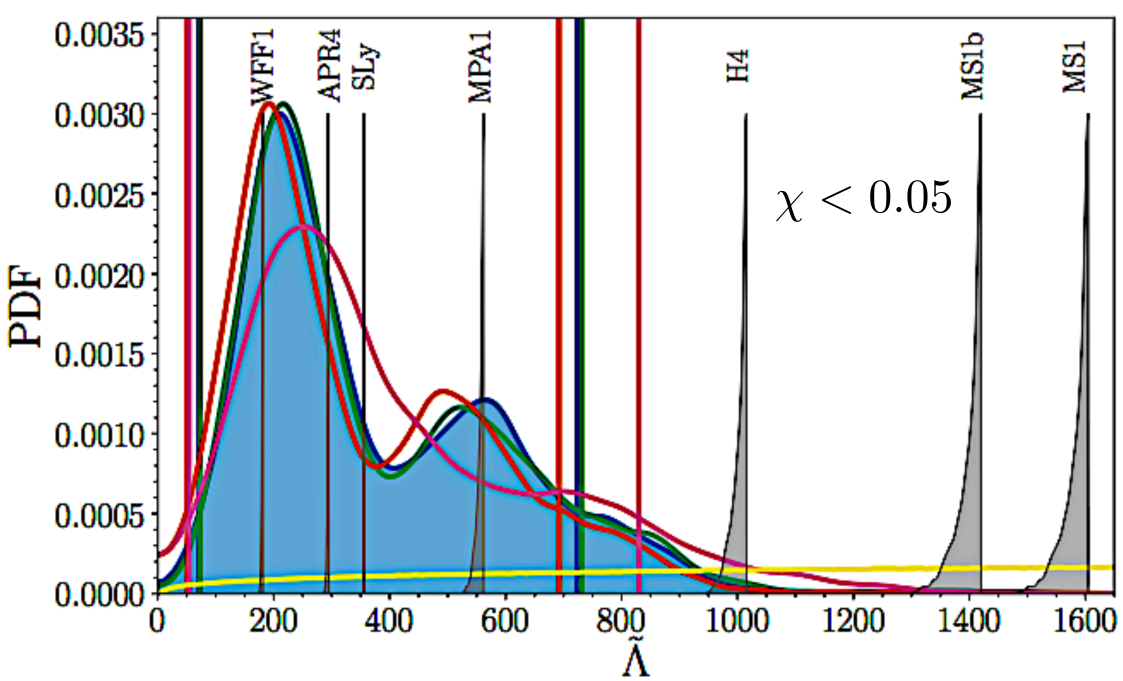
$$\Psi(v) = \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v)$$

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



$$C_E \sim R^5$$

$$\tilde\Lambda \sim C_E/M^5$$

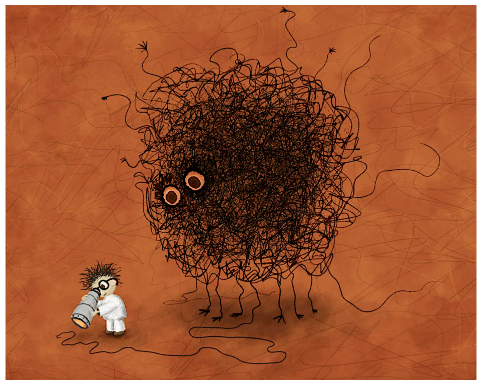


Fortschr. Phys. 64, No. 10, 723–729 (2016) / DOI 10.1002/prop.201600064

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

Rafael A. Porto*

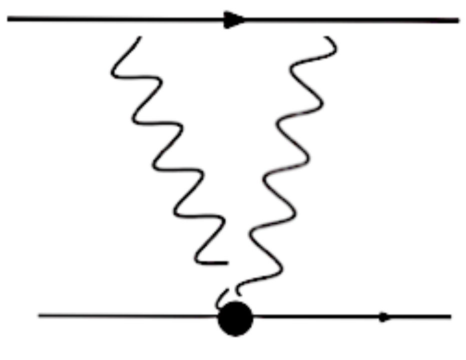
???



Tidal (5PN)

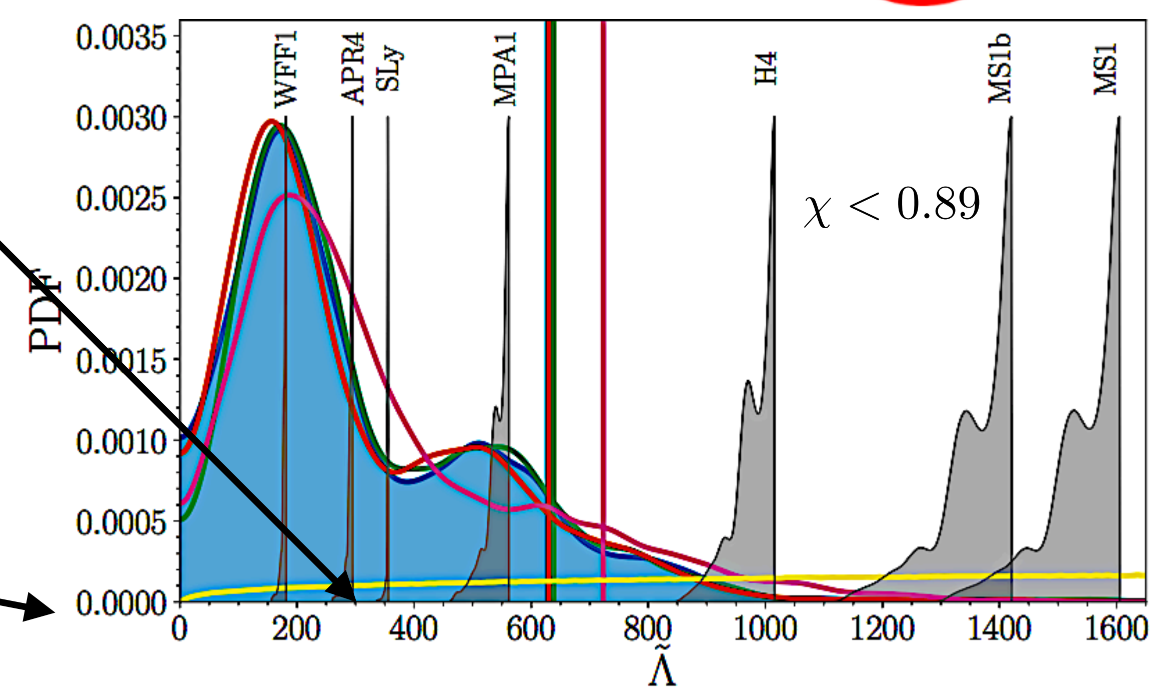
$$\Psi(v) = \Psi_{\rm PP}(v) +$$

NO 'Standard Model Background'!



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

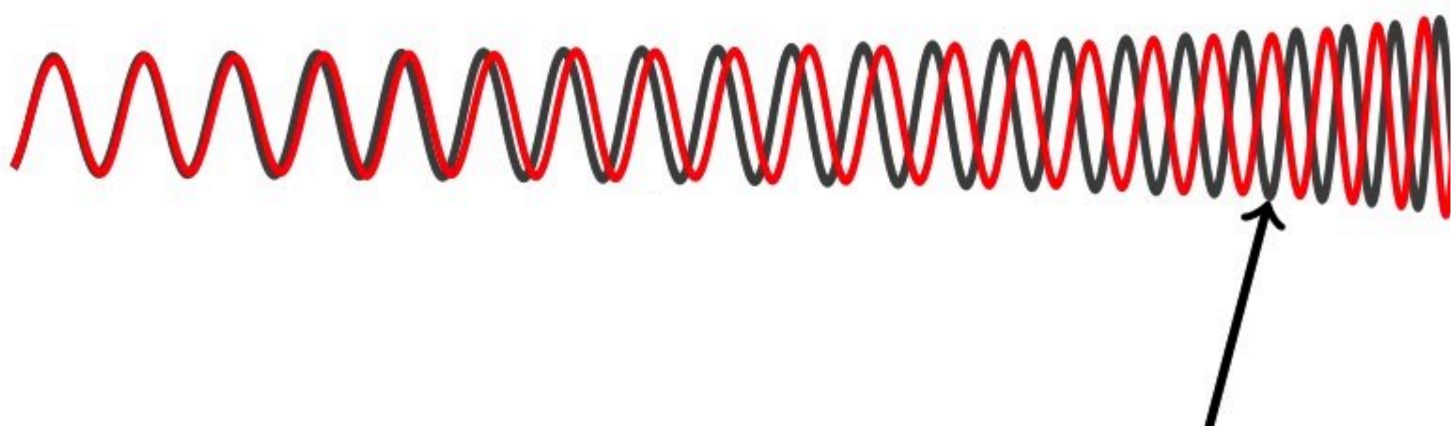
Unrelated to no-hair!
(only zero in d=4)



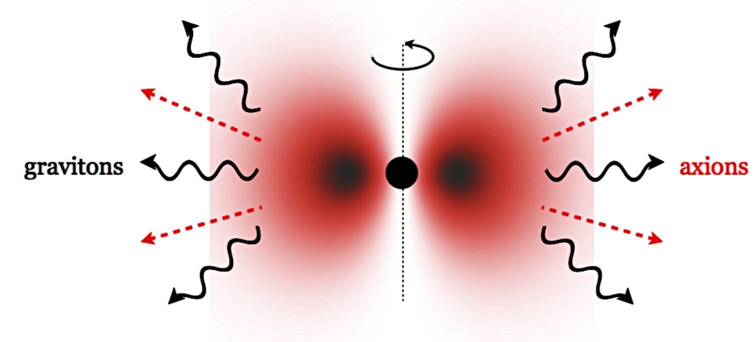
Damour Nagar
Bennington Poisson
Kol Smolkin

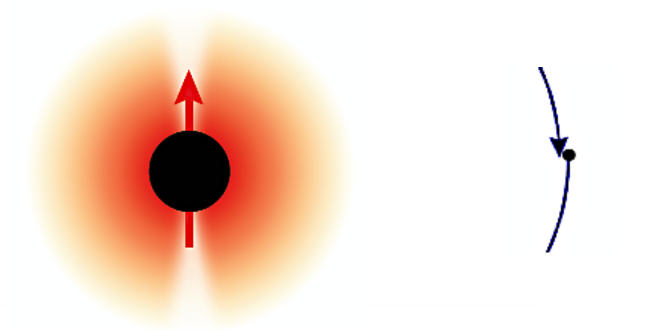
Probing Ultralight Bosons with Binary Black Holes

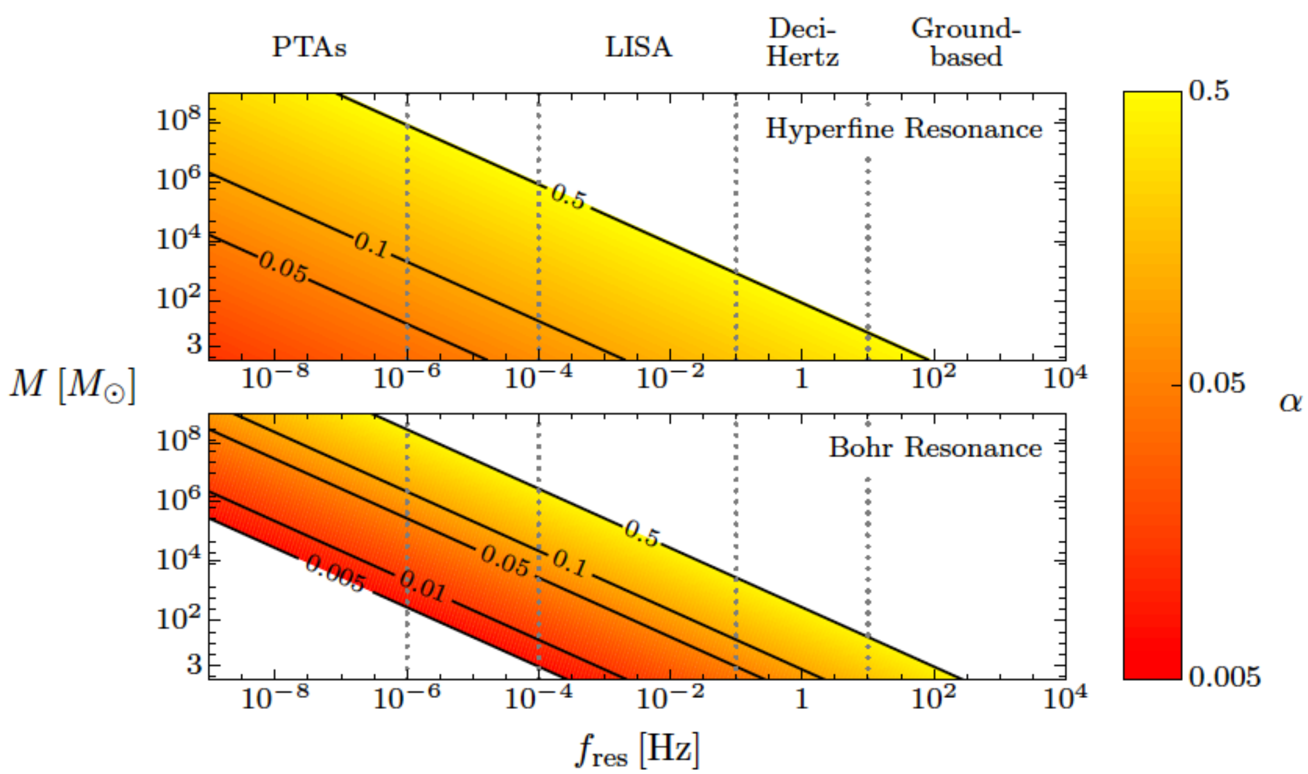
Daniel Baumann,[1] Horng Sheng Chia,[1] and Rafael A. Porto[2,3,4]



Tidal (5PN)



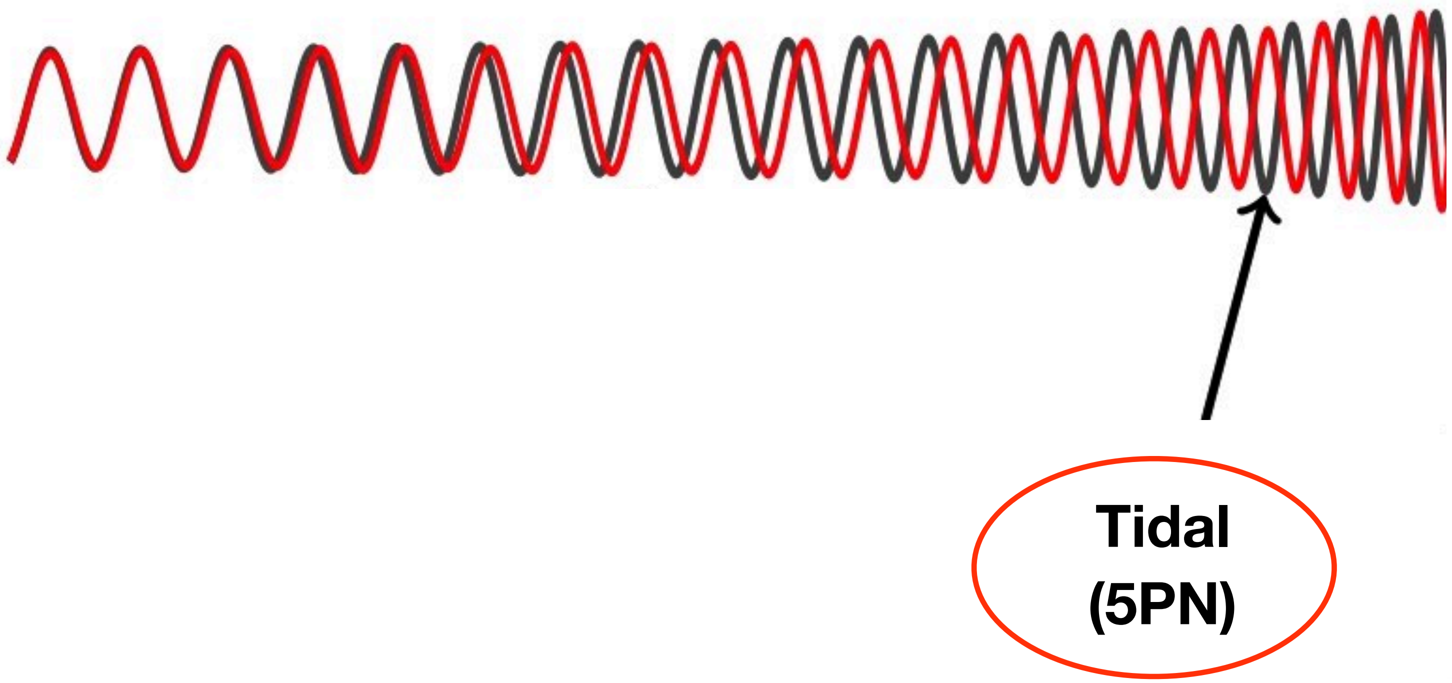




$$\Lambda_c(\alpha)v^{10} \sim 10^{-6}\left(\frac{M_c/M}{0.1}\right)\left(\frac{\alpha}{0.1}\right)^2\left(\frac{v}{\alpha/2}\right)^{10}$$

Masses (and spin) of ultralight particles

GW Precision Data



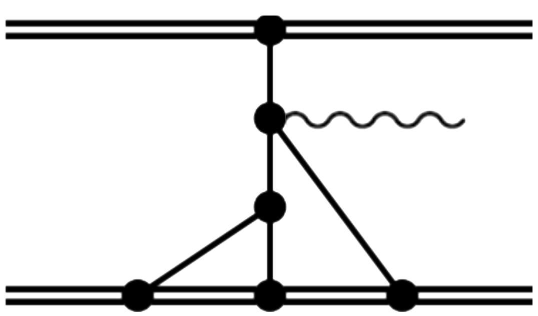
- ***Opportunities:***
  New physics threshold
- **More accurate templates!**

  (Feynman, New tools…)

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

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

- **Now**: Feynman



- **Challenges:** New tools?

Now: Feynman (thus far)

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

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

Alessandra Buonanno and B.S. Sathyaprakash

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

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

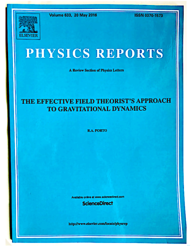
[134] **Porto, R. A.** 2006. *Phys. Rev. D*, **73**, 104031.
[135] **Porto, R. A.**, Rothstein, I. Z. 2006. *Phys. Rev. Lett.*, **97**, 021101.
[136] Kol, B., Smolkin, M. 2008. *Class. Quant. Grav.*, **25**, 145011.
[137] **Porto, R. A.**, Rothstein, I. Z. 2008. *Phys. Rev. D*, **78**, 044013.
[138] **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.

The effective field theorist's approach to gravitational dynamics

Rafael A. Porto

Physics Reports

Volume 633, 20 May 2016, Pages 1-104



Brand new: Binding energy to 4PN

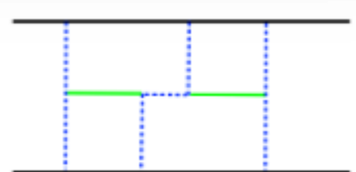
$$E^{\mathrm{4PN}} = -\frac{\mu c^2 x}{2}\left\{1+\left(-\frac{3}{4}-\frac{\nu}{12}\right)x+\left(-\frac{27}{8}+\frac{19}{8}\nu-\frac{\nu^2}{24}\right)x^2\right.$$
$$+\left(-\frac{675}{64}+\left[\frac{34445}{576}-\frac{205}{96}\pi^2\right]\nu-\frac{155}{96}\nu^2-\frac{35}{5184}\nu^3\right)x^3$$
$$+\left(-\frac{3969}{128}+\left[-\frac{123671}{5760}+\frac{9037}{15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

Damour Jaranowski Schaefer (2014, 2016)
Blanchet, Faye et al. (2015, 2017)

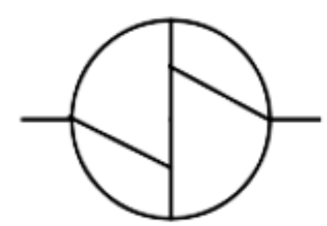
$$\nu \sim m_2/m_1$$
$$x \sim (v/c)^2$$

Brand new: Binding energy to 4PN

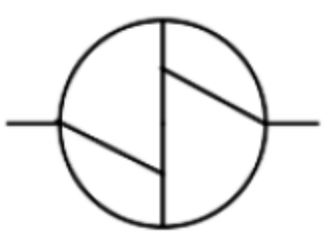
$$
\begin{aligned}
E^{\text{4PN}} = -\frac{\mu c^2 x}{2}\Bigg\{ & 1 + \left(-\frac{3}{4} - \frac{\nu}{12}\right)x + \left(-\frac{27}{8} + \frac{19}{8}\nu - \frac{\nu^2}{24}\right)x^2 \\
& + \left(-\frac{675}{64} + \left[\frac{34445}{576} - \frac{205}{96}\pi^2\right]\nu - \frac{155}{96}\nu^2 - \frac{35}{5184}\nu^3\right)x^3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



$$= -2\,\mathrm{i}\,(8\pi G_N)^5 \left(\frac{(d-2)}{(d-1)}\, m_1 m_2\right)^3$$



$$[N_{49}]$$

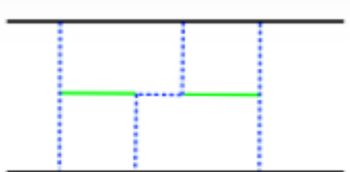


$$[N_{49}] \equiv \int_{k_1,k_2,k_3,k_4} \frac{N_{49}}{k_1^2\ p_2^2\ k_3^2\ p_4^2\ k_{12}^2\ k_{13}^2\ k_{23}^2\ k_{24}^2\ k_{34}^2}\,,$$

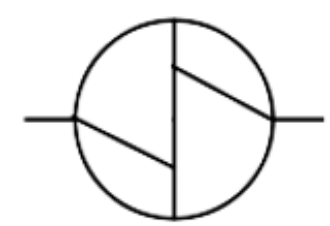
Foffa Sturani (2012)
Galley Porto Leibovich Ross (2015)
Foffa Sturani Mastrolia Sturm (2016)
Foffa Sturani (to appear)
Foffa Porto Sturani Rothstein (to appear)

Challenging computations!

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



$$= -2\,\mathrm{i}\,(8\pi G_N)^5 \left(\frac{(d-2)}{(d-1)}\, m_1 m_2\right)^3$$



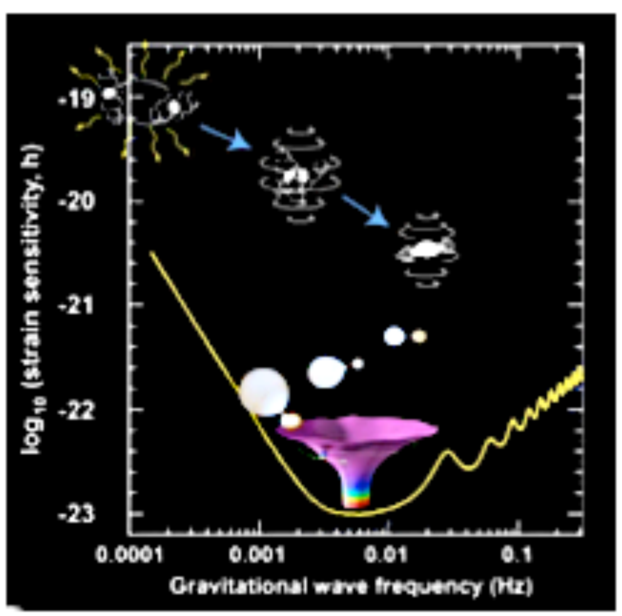
$$[N_{49}]$$

$$[N_{49}] \equiv \int_{k_1,k_2,k_3,k_4} \frac{N_{49}}{k_1^2\ p_2^2\ k_3^2\ p_4^2\ k_{12}^2\ k_{13}^2\ k_{23}^2\ k_{24}^2\ k_{34}^2},$$

Complexity escalates quickly

Different expansion parameters

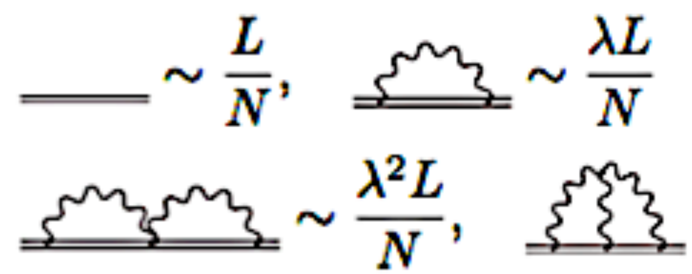
$$
\begin{aligned}
E^{\text{4PN}} = -\frac{\mu c^2 x}{2}\Bigg\{ & 1 + \left(-\frac{3}{4} - \frac{\nu}{12}\right) x + \left(-\frac{27}{8} + \frac{19}{8}\nu - \frac{\nu^2}{24}\right) x^2 \\
& + \left(-\frac{675}{64} + \left[\frac{34445}{576} - \frac{205}{96}\pi^2\right]\nu - \frac{155}{96}\nu^2 - \frac{35}{5184}\nu^3\right)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



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]



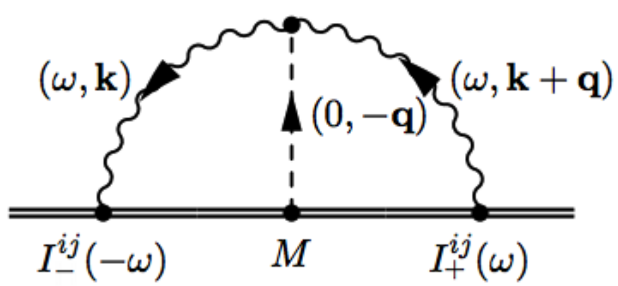
$$\sim \frac{L}{N}, \quad \sim \frac{\lambda L}{N}, \quad \sim \frac{\lambda^2 L}{N}, \quad \sim \frac{\lambda^2 L}{N^2}$$

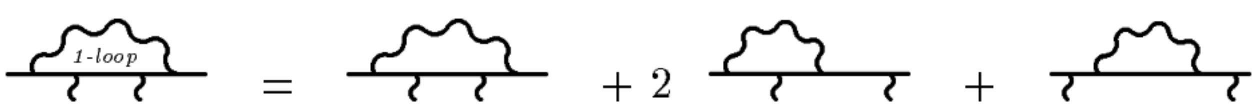
$$N \equiv \gamma^2$$

$$\lambda = \epsilon N$$

There are logs!

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





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

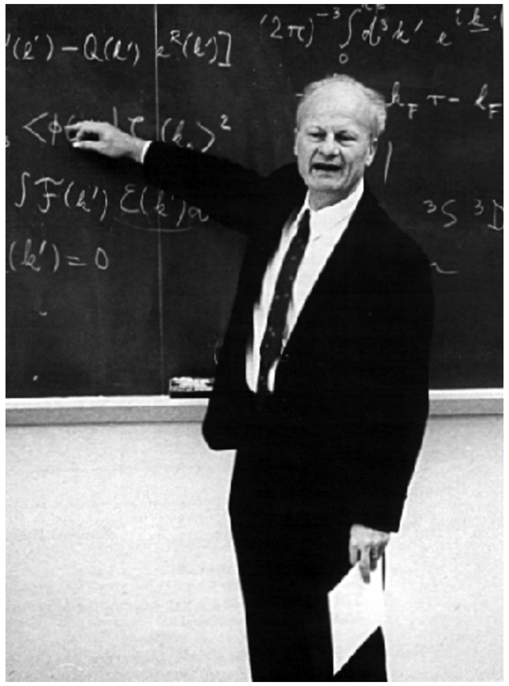
Tail effect in gravitational radiation reaction: Time nonlocality and renormalization group evolution

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



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,

$$H_{4PN}^{\text{near-zone (s)}}[\mathbf{x}_a, \mathbf{p}_a] = H_{4PN}^{\text{loc0}}[\mathbf{x}_a, \mathbf{p}_a] + F[\mathbf{x}_a, \mathbf{p}_a]\left(\ln\frac{r_{12}}{s} + C\right)$$

<u>Ambiguity parameter</u>
associated to IR divergences
(Similar to Lamb shift)

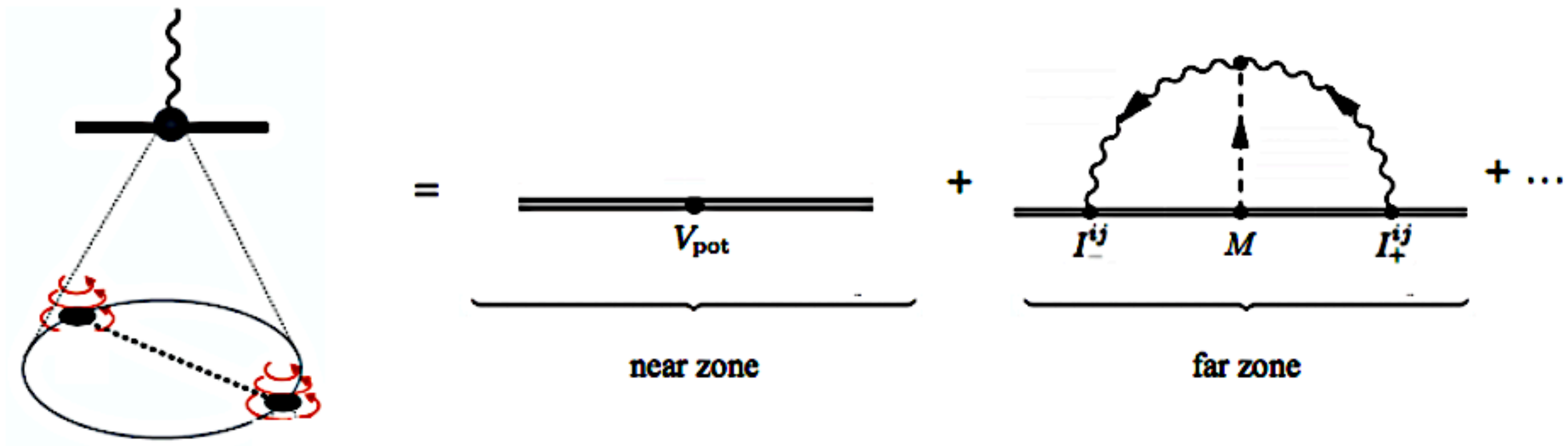
$$C = -\frac{1681}{1536}$$

Originally not determined from first principles within PN framework.

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]



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

“IR/UV” cancelation
There are no ambiguities!

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

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

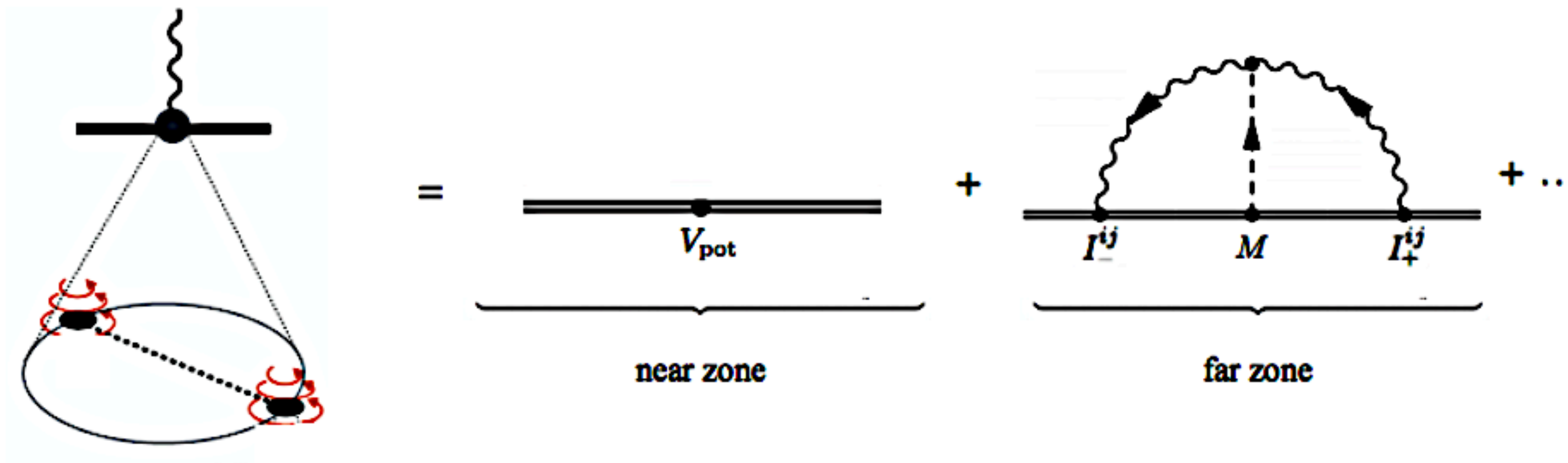
Chad R. Galley,[1] Adam K. Leibovich,[2] Rafael A. Porto,[3] and Andreas Ross[4]

The divergence is due to split into regions
The ambiguity arises from independent regularizations of the near/far zone

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

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

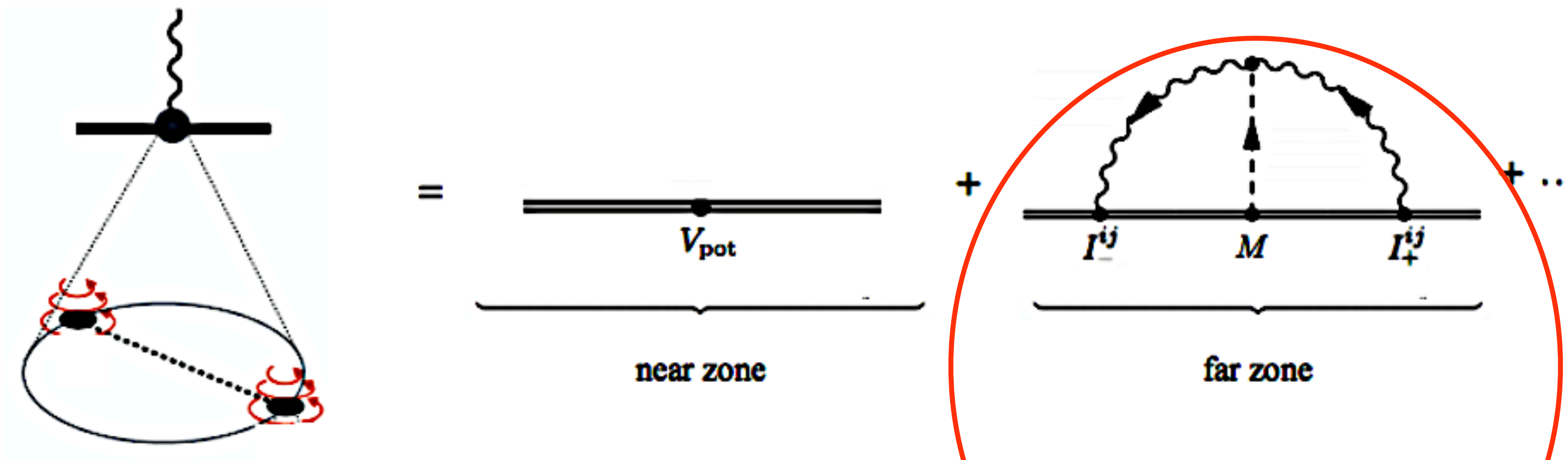
correct value w/out ambiguities!

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!

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

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

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,§]

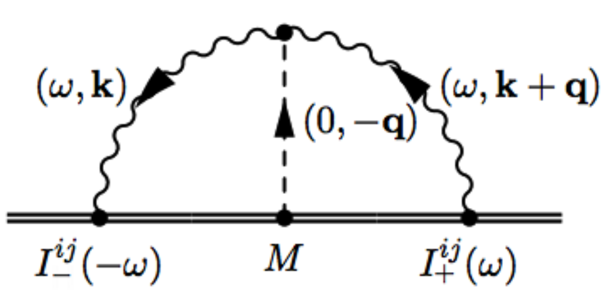
V. DETERMINATION OF THE AMBIGUITY PARAMETERS

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)

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,§]

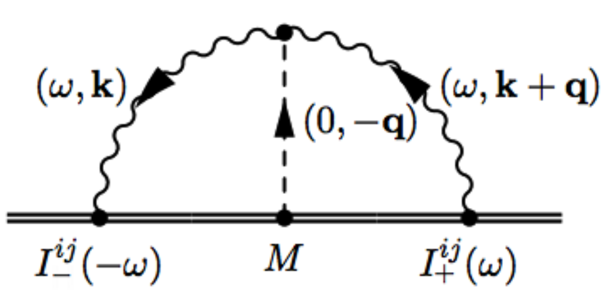
V. DETERMINATION OF THE AMBIGUITY PARAMETERS

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]



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

$$\frac{P_{\rm tail}}{P_{\rm LO}} = 4\pi x^{3/2}$$

This includes everything

Accounts for non-conservative part

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,§]

The elimination of **IR divergences** in Marchand et al. isn't fully *kosher.* It works because physical logs appear at higher orders.

$$\boldsymbol{\xi}_1 = \frac{11}{3}\frac{G^2 m_1^2}{c^6}\left[\frac{1}{\varepsilon} - 2\ln\left(\frac{\overline{q}^{1/2} r_1'}{\ell_0}\right) - \frac{327}{1540}\right]\boldsymbol{a}^{(d)}_{1,\mathrm{N}} + \frac{1}{c^8}\boldsymbol{\xi}_{1,\,4\mathrm{PN}}$$

Some of those poles are infrared.

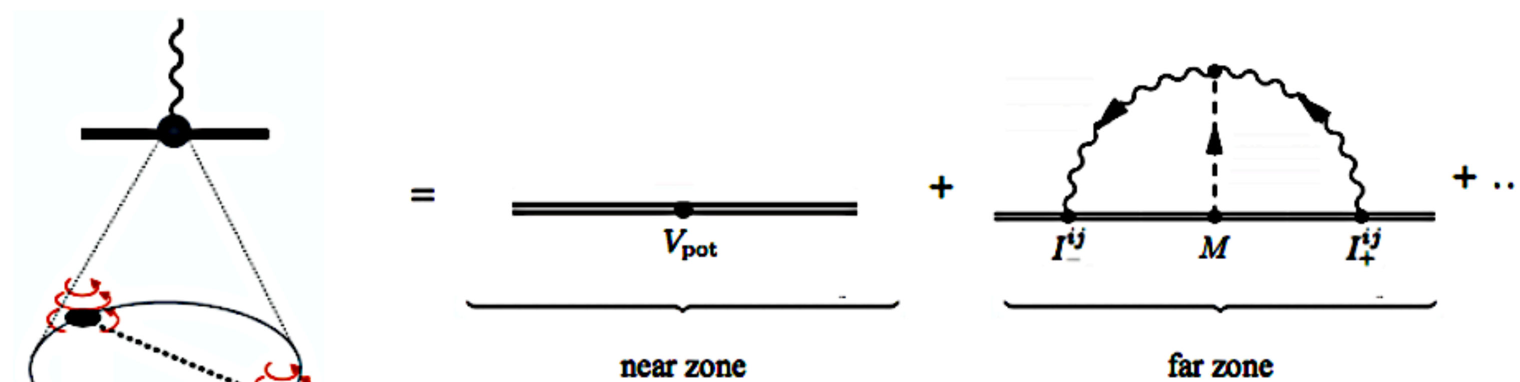
Must not be absorbed into WL (short-distance)

Unambiguous/Consistent derivation in EFT
(UV renormalization and IR/UV identification in dim. reg.)

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

UV counter-terms (can be removed by field-redef. at 4PN)

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



IR/UV

(would-be IR) => UV in EFT

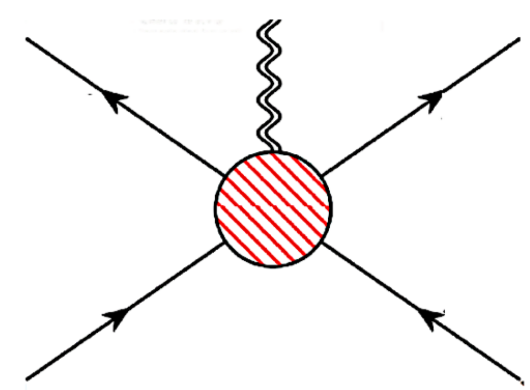
Conservative dynamics of binary systems to fourth Post-Newtonian order in the EFT approach II: Ambiguity-free renormalization and physical results

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

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

- **Now**: Feynman

- **Challenges**: New tools?

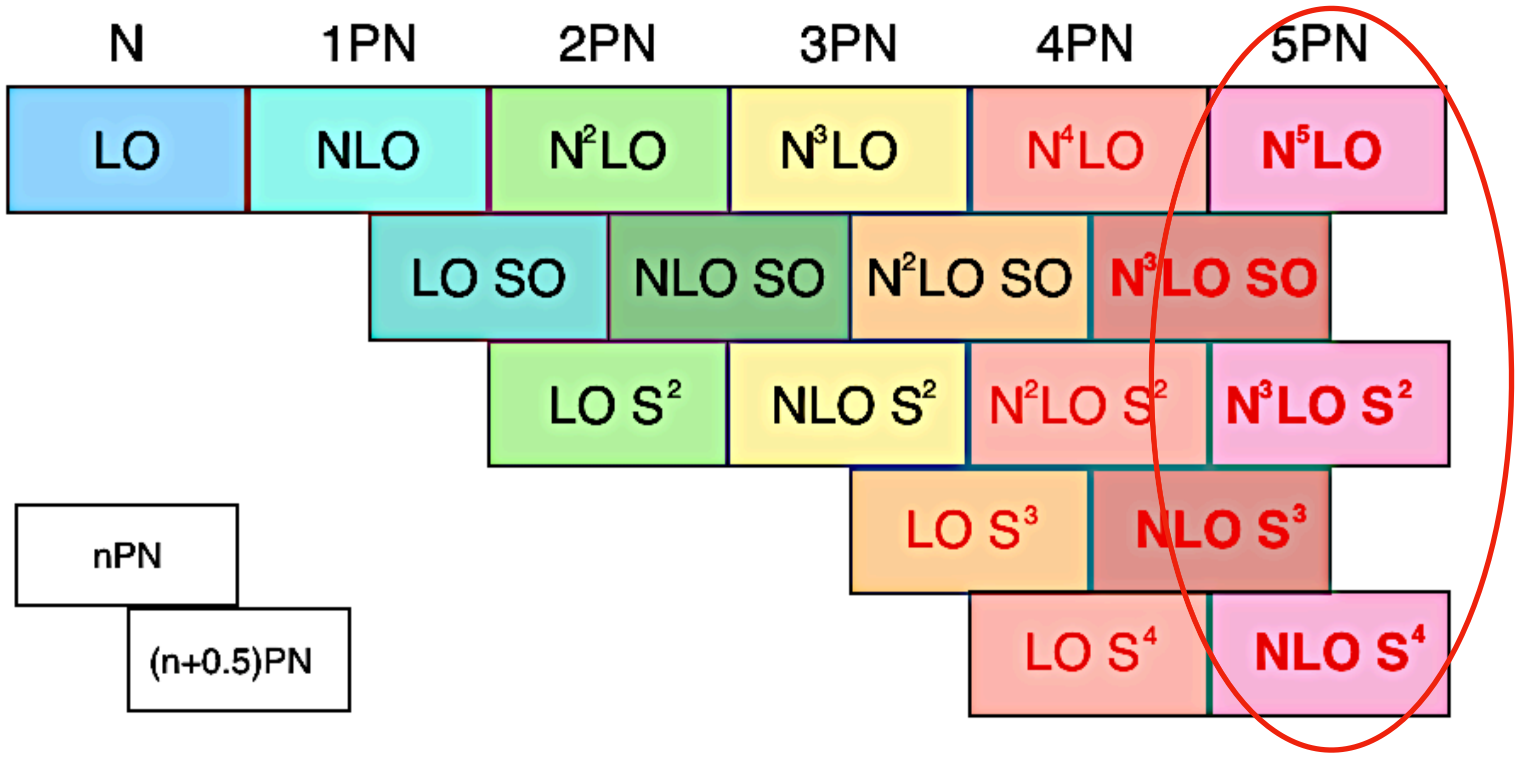


Challenges: New tools?

known

only binding

missing

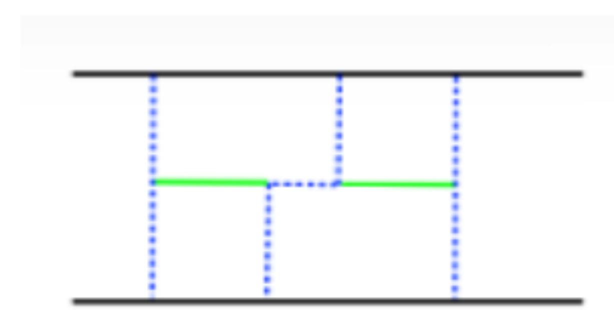


We know (EFT) how to compute the integrals
to reach the 5PN threshold (See Pier-Paolo's talk)

(If we know G^n integrals we know (n+1)PN)

There is a Z2 bulk sym. for the static case (\phi->-\phi)

$$S[\phi,\gamma_{ij}] = \frac{1}{16\pi G}\int \sqrt{-\gamma}\, d^d x \left[-\left(1+\frac{1}{\hat{d}}\right)\gamma^{ij}(x)\,\partial_i\phi\,\partial_j\phi + R[\gamma]\right]$$

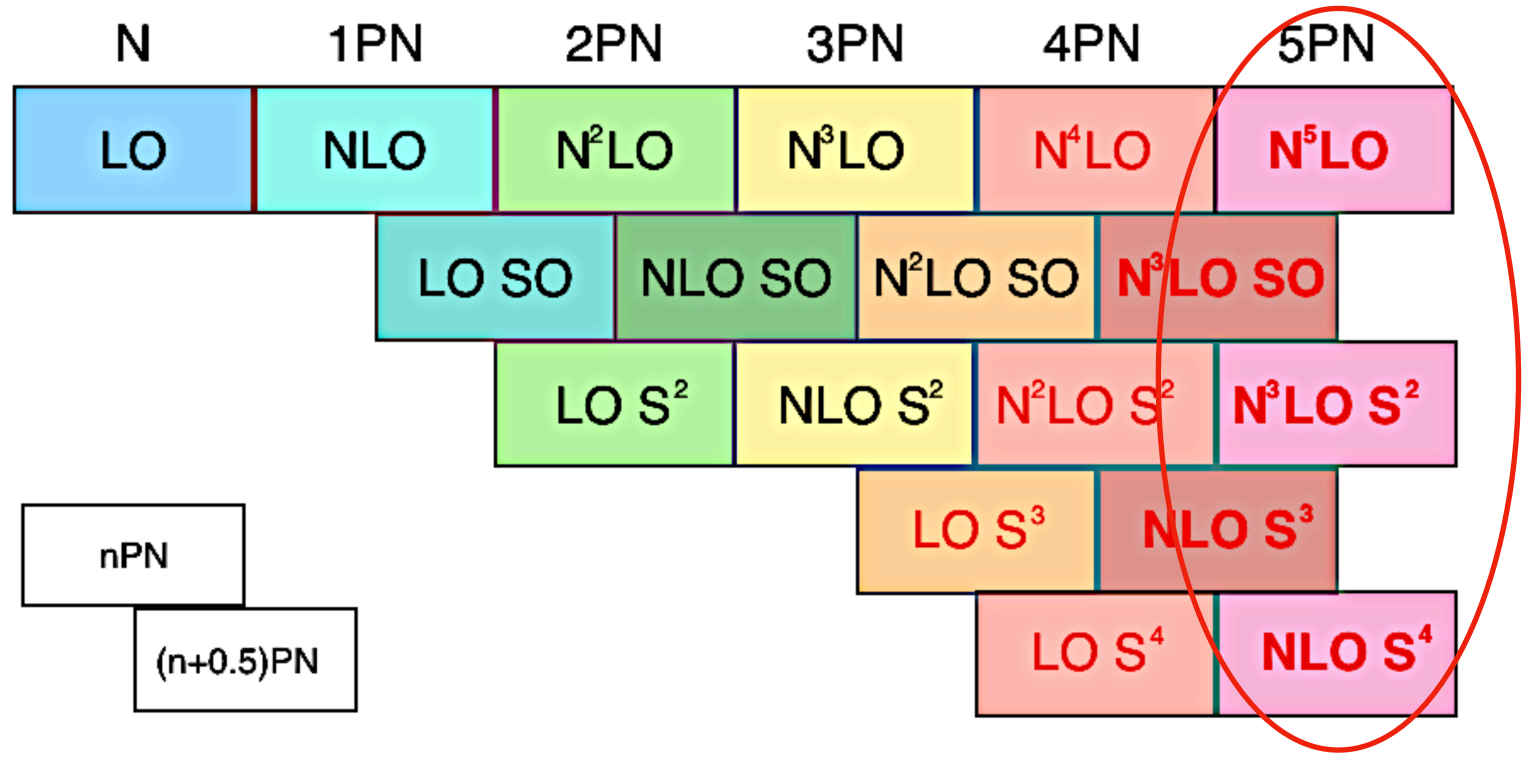


Challenges: New tools?

known

only binding

missing



We know (EFT) how to compute the integrals
to reach the 5PN threshold (See Pier-Paolo's talk)

(If we know G^n integrals we know (n+1)PN)

Challenge: Combinatorial & 5loops for nPN with n>5

(Spinning part is 'easier': New vertices in the Feynman rules)

Challenges: New tools?

N		1PN		2PN		3PN		4PN		5PN
LO		NLO		N^2LO		N^3LO		N^4LO		N^5LO
			LO SO		NLO SO		N^2LO SO		N^3LO SO	
				LO S^2		NLO S^2		N^2LO S^2		N^3LO S^2
							LO S^3		NLO S^3	
								LO S^4		NLO S^4

known

only binding

missing

nPN

(n+0.5)PN

Radiation moments are *simpler* than computing the binding energy

The N^(n+1) LO multipoles depend on N^n LO integrals

Challenges for New tools

Bern-Carrasco-Johansson
Bjerrum-Bohr Donoghue et al.
Cachazo et al.
Cheung Rothstein Solon
Damgaard Vanhove et al.
Damour
Goldberger et al.
Ladha Sen
O'Connell et al.
O'Connell Kosower Maybee
Neill Rothstein
Plefka Steinhoff
Vines
…

Gauss' law!? $\frac{e^4}{mr^2}$

$m_2 \gg m_1$

- **Gauge (in)variant quantities**

$$V^{\text{one-loop}}(q) = \frac{M^{\text{non-rel.}}(q)}{4m_1m_2} = \frac{e^4}{8\pi^2 m_1 m_2}\left(\frac{7}{3}\log(\vec{q}^{\,2}) - \pi^2\frac{m_1+m_2}{|\vec{q}|}\right)$$

Darwin
Feinberg Sucher

✓ Non-instantaneous correction (shift in WL)
+ EOM (field re-definition)

Challenges for New tools

Bern-Carrasco-Johansson
Bjerrum-Bohr Donoghue et al.
Cachazo et al.
Cheung Rothstein Solon
Damgaard Vanhove et al.
Damour
Goldberger et al.
Ladha Sen
O'Connell et al.
O'Connell Kosower Maybee
Neill Rothstein
Plefka Steinhoff
Vines
...

- **Deflection angle (integrated vs instantaneous)**

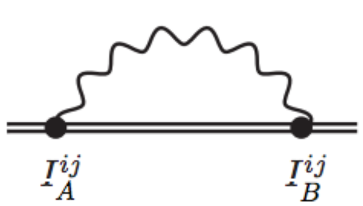
$$\Delta p_1^{\mu,(1)}\big|_{m_2\to\infty} = \int \hat{d}^4\bar{q}\,\hat{\delta}(\bar{q}\cdot u_1)\hat{\delta}(\bar{q}\cdot u_2)e^{-i\bar{q}\cdot b}\,\frac{e^4Q_1^2Q_2^2}{2m_1}\int \hat{d}^4\bar{\ell}\,\frac{\hat{\delta}(\bar{\ell}\cdot u_2)}{\bar{\ell}^2(\bar{\ell}-\bar{q})^2}$$
$$\times\left[i\bar{q}^\mu\left(1+\frac{\bar{\ell}\cdot(\bar{\ell}-\bar{q})(u_1\cdot u_2)^2}{(\bar{\ell}\cdot u_1+i\epsilon)^2}\right)+\bar{\ell}^\mu\,\bar{\ell}\cdot(\bar{\ell}-\bar{q})(u_1\cdot u_2)^2\,\hat{\delta}'(\bar{\ell}\cdot u_1)\right].$$

Non-instantaneous correction (shift in WL)

$$\Delta^{(1)}x_1^\mu(\tau_1) = -i\frac{e^2Q_1Q_2}{m_1}\int \hat{d}^4\bar{q}\,\hat{\delta}(\bar{q}\cdot u_2)\,e^{-i\bar{q}\cdot(b+u_1\tau_1)}\,\frac{\bar{q}^\mu\,u_1\cdot u_2-u_2^\mu\,\bar{q}\cdot u_1}{\bar{q}^2(\bar{q}\cdot u_1+i\epsilon)^2}.$$

IN-IN classical formalism vs. IN-OUT Scattering Amplitudes

Galley
Leibovich



$$(\boldsymbol{a}_a^i)_{\rm rr}(t) = -\frac{2G_N}{5}I^{(5)ij}(t)\boldsymbol{x}_a^j(t).$$

RR force includes everything!
(Modulo Schott terms)

Maia Galley Leibovich Porto

IN-IN double(double)-copy?

Challenges for New tools

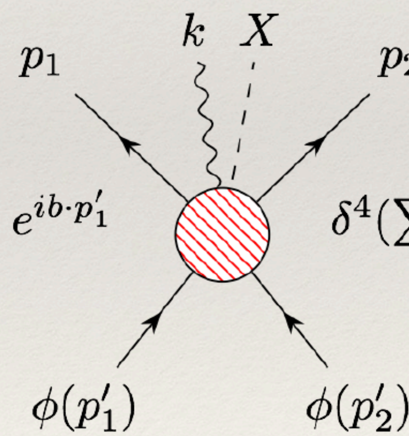
Bern-Carrasco-Johansson
Bjerrum-Bohr Donoghue et al.
Cachazo et al.
Cheung Rothstein Solon
Damgaard Vanhove et al.
Damour
Goldberger et al.
Ladha Sen
O'Connell et al.
O'Connell Kosower Maybee
Neill Rothstein
Plefka Steinhoff
Vines
...

- **Radiation (Flux vs Multipoles)**

'large N'?

- Find:

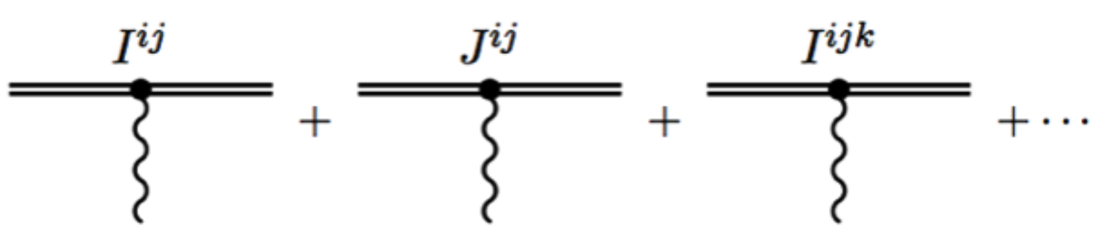
$$\langle k^\mu \rangle = \sum\nolimits_X \int Dp_1 Dp_2 Dk\, k^\mu \left| \int Dp_1' Dp_2'\, e^{ib\cdot p_1'} \quad [\text{diagram}] \quad \delta^4\left(\sum p\right) \right|^2$$



O'Connell

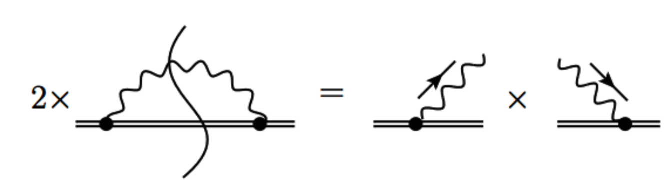
Multipole PN expansion in EFT:

$i\mathcal{A}_h(\omega, \boldsymbol{k}) =$



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

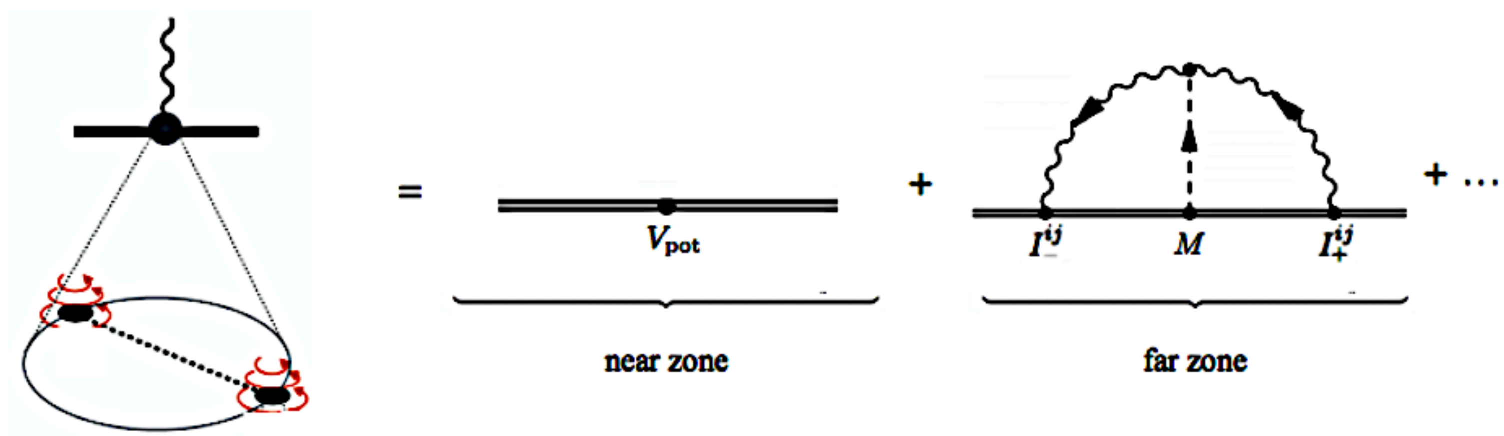
Amplitude:
Imaginary part +
optical theorem (?)



Challenges for New tools

Bern-Carrasco-Johansson
Bjerrum-Bohr Donoghue et al.
Cachazo et al.
Cheung Rothstein Solon
Damgaard Vanhove et al.
Damour
Goldberger et al.
Ladha Sen
O'Connell et al.
O'Connell Kosower Maybee
Neill Rothstein
Plefka Steinhoff
Vines
…

- **'Gravitational Lamb shift' (PN vs PM)**



$$G^4 v^2 \quad \frac{2G_N^2 M}{5} I^{(3)ij} I^{(3)ij} \left(-\frac{1}{\epsilon_{\rm IR}} + 2\log(\mu r) + \cdots\right) + \left(\frac{1}{\epsilon_{\rm UV}} + 2\log(\Omega/\mu) + \cdots\right)$$

- There are **no** IR divergences in S-matrix (PM does not have zones!)
- ***Classically***, region which contributes to kick (real part) is 'potential' q0~v.q (with q~1/b)
- Yet, 'Lamb-shift' logarithm(s) must show up — resummed — at 4PM (O(G^4p^2+…)) from 'soft modes' p0~p.

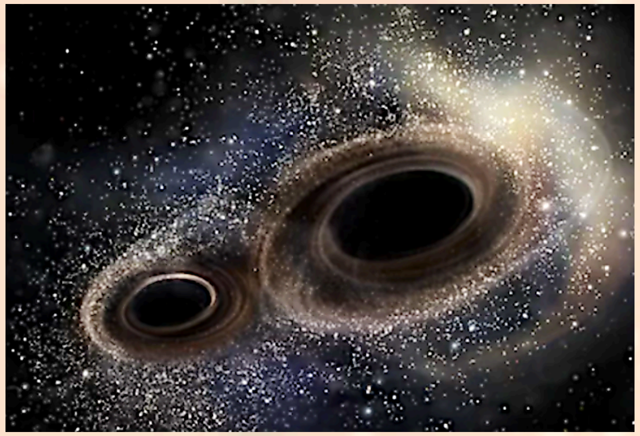
Thank you…

no.203.078

Precision Gravity: from LHC to LISA

New era of foundational investigations established—through GWPD.

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



New particles discovered!

New objects found!

Neutron stars unveiled!

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