The Detection of Gravitational Waves and the Two Body Problem in General Relativity

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- Asked about the ramifications of his discoveries, Hertz replied, “Nothing, I guess”

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- GR is the current best description of gravitation which unifies special relativity and Newton's law of universal gravitation, and describes gravity as a geometric property of spacetime.
- The curvature of spacetime is directly related to the Energy-Momentum tensor of whatever matter and radiation are present. The relation is specified by the Einstein field equations, a system of ten non-linear partial differential equations.

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- 1922: Eddington: Corrected factor of 2 in AE's work, pointed inapplicability of AE's derivation for self gravitating systems. Described the situation reg gauge effects as `GW propagate at speed of thought!`
- Appears AE wished to forget he had predicted GW. Reasonable judgement about slim chance that GW might be detected.

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- 1936 Einstein's letter to Born
  Together with a young collaborator (Rosen), I arrived at the interesting result that GW do not exist, although they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we believed up to now.

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- Einstein dismissed referee's comments and withdrew the paper. He wrote

  'We had sent you our manuscript for *publication* and not authorised you to show it to specialists before it is printed. I see no reason to address the - in any case erroneous - comments of your anonymous expert. On the basis of this incident, I prefer to publish the paper elsewhere'.

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- Did not distinguish sufficiently between co-ordinate and physical singularities..(Recall Schwarzschild singularity!).
  Referee was Robertson.

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- Feynman, Bondi..
  GW could in principle heat a suitably contrived mechanical system!

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- Chandra saw the need for a careful step by step approach starting from Newtonian limit and proceeding PN order by order. No one had attempted PN approximation for continuous bodies in an exhaustive way..
- Realised that previous works used simplifications that could have led to fallacies .. Decided to avoid any tricks..Do a complete and honest calculation. Studied previous works until he knew what to emulate and what to discard

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- Technical issues concerned use of point particles and the related infinite self-field energy problems in a non-linear theory, imposition of no-incoming boundary condition in a PN scheme, dealing with conservative (even in v/c) and dissipative (odd in v/c) effects separately, validity of the use of matched asymptotic expansions to isolate terms in EOM coupling to radiation far away..

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- Important applications immediately followed:
  (i) GW induced non-axisymmetric instability of rotating stars
  (ii) Faulkner: Cataclysmic binary systems: Competition of GW RR and mass transfer

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- Chandra unhappy about the criticism reg divergent terms since it prevented him from being given *adequate* credit for significance of his PN work. Only body of work *not immortalized* by a book unlike all his other research endeavours!!

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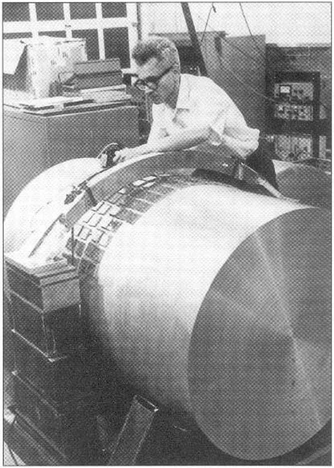
- The first attempts to detect GW were by Bar detectors in the sixties

The pioneer - Joe Weber and the Bar detector

1960 - 1975



Narrow Band Detectors

$h \sim 10^{-19}$ - Cryogenic Bars;

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- Other more sensitive bar detectors did not see such signals (Braginsky, Tyson, Drever, Garwin and Levine,..)

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- Fascinating Book: Gravity’s Shadow by Harry Collins

It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to heaven, we were all going direct the other way - in short, the period was so far like the present period, that some of its noisiest authorities insisted on its being received, for good or for evil, in the superlative degree of comparison only.

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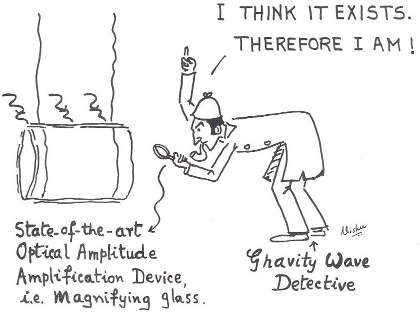
The GW detective (Goa- 1987)



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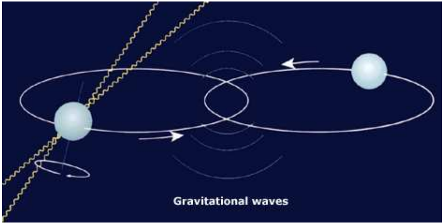

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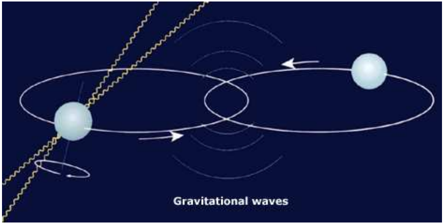
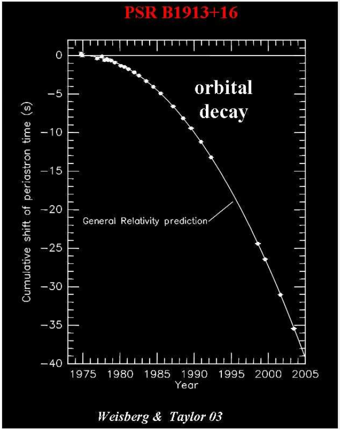


The system has now been monitored for $\sim$ 30 years

Indeed ..Gravitational Waves exist ..

- If General relativity is right (and Newtonian Gravity is incorrect) the system must emit GW. Orbit shrinks by 3 mm/orbit..Orbital period slowly decreasing at just the rate predicted by GR for emission of GW!!!



Nobel Prize (1993).

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- (ii) If radiation is present, inconvenient to iterate using Newtonian-like Poisson equations.. Retardation effects cannot be neglected..Successful formalisms are all formulated in terms of retarded integrals rather than Poisson-like Green functions.. (Damour, Blanchet, Will and Walker, Thorne, Haridass and Soni...)

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- Iterated Einstein's Eqns to sufficient order of non-linearity to obtain EOM of compact binaries including v^5/c^5 terms (1983)

  (Einstein-Infeld-Hoffmann approach)

$$a_i = a_i^{\rm Newton} + a_i^{\rm 1PN} + a_i^{\rm 2PN} + a_i^{\rm 2.5PN}$$

Laplace-Eddington effect (at 2.5PN)

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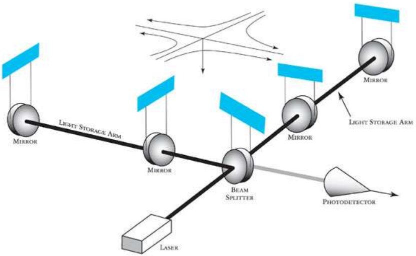
- As a GW passes, the arm lengths of km scale ITF change (10^{-18}m) tidally causing the interference pattern to change at the photodiode
- The miniscule strain and associated tiny displacement must be measured to detect the GW.

Laser Interferometric Gravitational Wave Detectors?



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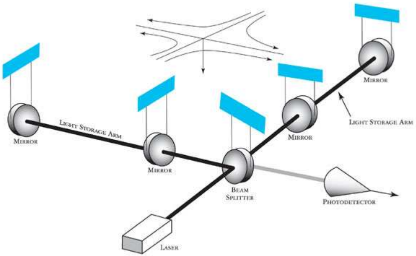

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GW detection is about seeing the biggest things that ever happen by measuring the smallest changes that have ever been measured - Harry Collins.

MTW - Interferometry cannot work!

The Last Three Minutes..
Can Chirping Binaries be detected?

- Can we detect the GW from 1913+16 today???
  No! Since $P_{orb} \sim 8$ hrs, $f_{GW} \sim 10^{-4}$ Hz. Interferometers on Earth cannot be sensitive at this frequency due to seismic noise.

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- In 2003 a new binary (Double) pulsar J0737-3039 with orbital period of 2.5 hrs ($e = .0877$) was discovered which will coalesce in 86 Myrs. Infall due to Grav radn Damping 7 mm/day!
  Even more unique Laboratory for relativistic gravitational physics in the strong field regime

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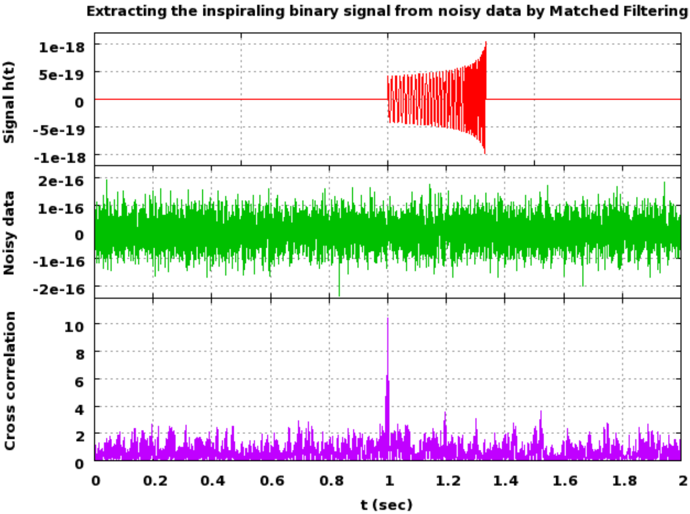
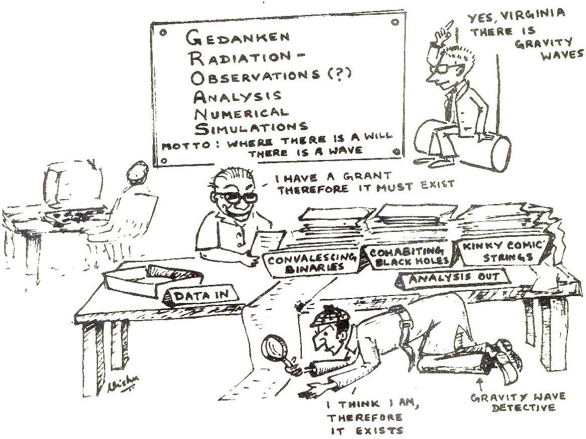
- Chirps (ICB), Bursts (SN, GRB),
  Continuous wave (Pulsars), Stochastic (Early Universe)

Chirp Signal, Matched Filtering



Courtesy Anand Sengupta (IUCAA)

Return of the GW detective (Ahmedabad 1991)



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- (iii) The inspiral can be treated in the adiabatic approximation as a sequences of circular orbits..This allows one to treat separately the radiation reaction effects and the conservative effects

GW from ICB - Three Modules

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- Motion: Given a Binary system, iterate Einstein's Eqns to discuss conservative motion of the system. Compute CM Energy E
- Generation: Given the motion of the binary system on a fixed orbit, iterate EE to compute multipoles of the Grav field and hence the FZ flux of energy and AM carried by GW. Compute $\mathcal{L}$ and $\mathcal{J}$

GW from ICB - Three Modules

- (iii) One can go to higher PN orders in the inspiral without getting technically bogged down in controlling the much more difficult higher order conservative PN terms
- MPM - (iv) For compact objects the effects of finite size and quadrupole distortion induced by tidal interactions are of order 5PN. Hence, neutron stars and black holes can be modelled as point particles represented by Dirac δ-functions.
- Thus modelling ICB waveforms for inspiral involves three tasks
- Motion: Given a Binary system, iterate Einstein's Eqns to discuss conservative motion of the system. Compute CM Energy E
- Generation: Given the motion of the binary system on a fixed orbit, iterate EE to compute multipoles of the Grav field and hence the FZ flux of energy and AM carried by GW. Compute $\mathcal{L}$ and $\mathcal{J}$
- Radiation Reaction: Given the Conserved energy and Radiated Flux of Energy and AM, *ASSUME* the Balance Eqns to Compute the effect of Radiation on the Orbit. Compute $F(t)$ and $\phi(t)$; (GW) Phasing of Binary $\sim$ (EMW) Timing of Pulsars

A personal aside

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- Soon after I was visiting Thibault at IHES and this led to a collaboration between the three of us. Using Thibault's insight into a treatment of the cubic non-linearities we three completed the 2PN phasing for ICB (1995).

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- Control of this next order - more formidable; limitation of earlier regularisation methods for the self-field using Hadamard regularisation.

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- Bliss was it in that dawn to be alive, But to be young was very heaven!

Multipolar Post Minkowskian (MPM) formalism

- Successful wave-generation formalisms are a cocktail of post-Minkowskian (PM) methods [expansions in G - non-linearity expns], post-Newtonian (PN) methods [expansions in $1/c$], multipole (M) expansions [expansions in irreducible representations of the rotation group], and perturbations around curved backgrounds.

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- (i) The general method (MPM expansion) applicable to extended or fluid sources with compact support, based on the mixed PM and multipole expansion matched to some PN (slowly moving, weakly gravitating, small-retardation) source. IR divergences arising from the retardation expansion dealt by analytic continuation

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- (ii) The particular application to describe inspiralling compact binaries (ICB) by use of point particle models. Self-field regularisation to deal with UV divergences arising from use of Delta functions to model point particles - Riesz, Hadamard partie finie, Dimensional regularisation

MPM formalism - Some Technical details

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- In MPM formalism both radiative and canonical moments are of two types: Mass type and Current type. The generation formalism enables one to compute the radiative moments as nonlinear functionals of the source moments. The whole idea is to connect the 2 radiative moments (U & V) which the detector sees, to the 2 canonical source moments (M & S) via the 6 general 'source' moments (I, J, W, X, Y, Z) (last 4 gauge moments)

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- Computation of the source moments is so far done in the cases of slow moving, weakly stressed (PN) sources.
- The relationship between the radiative and source moments involve many nonlinear multipole interactions causing different contributions to the waveform and fluxes.

FZ flux - Radiative Multipoles

Following Thorne (1980), the expression for the 3PN accurate far zone energy flux in terms of symmetric trace-free (STF) radiative multipole moments read as

$$\left(\frac{d\mathcal{E}}{dt}\right)_{\mathrm{far-zone}} = \frac{G}{c^5}\left\{\frac{1}{5}U^{(1)}_{ij}U^{(1)}_{ij} + \frac{1}{c^2}\left[\frac{1}{189}U^{(1)}_{ijk}U^{(1)}_{ijk} + \frac{16}{45}V^{(1)}_{ij}V^{(1)}_{ij}\right] + \frac{1}{c^4}\left[\frac{1}{9072}U^{(1)}_{ijkm}U^{(1)}_{ijkm} + \frac{1}{84}V^{(1)}_{ijk}V^{(1)}_{ijk}\right] + \frac{1}{c^6}\left[\frac{1}{594000}U^{(1)}_{ijkmn}U^{(1)}_{ijkmn} + \frac{4}{14175}V^{(1)}_{ijkm}V^{(1)}_{ijkm}\right] + \mathcal{O}(8)\right\}.$$

- For a given PN order only a finite number of Multipoles contribute
- At a given PN order the mass l-multipole is accompanied by the current $l-1$-multipole (Recall EM)
- To go to a higher PN order Flux requires new higher order l-multipoles and more importantly higher PN accuracy in the known multipoles.
- 3PN Energy flux requires 3PN accurate Mass Quadrupole, 2PN accurate Mass Octupole, 2PN accurate Current Quadrupole,........ N Mass 2^5-pole, Current 2^4-pole

Relation connecting radiative MQ and Canonical MQ

$$\begin{aligned} U_{ij}(T_R) \;=\; & \Bigg[M^{(2)}_{ij}(T_R) + \frac{G}{c^5}\Bigg\{ \frac{1}{7} M^{(5)}_{a<i} M_{j>a} - \frac{5}{7} M^{(4)}_{a<i} M^{(1)}_{j>a} \\ & - \frac{2}{7} M^{(3)}_{a<i} M^{(2)}_{j>a} + \frac{1}{3}\varepsilon_{ab<i} M^{(4)}_{j>a} S_b \Bigg\}\Bigg] \\ & + \Bigg[\frac{2Gm}{c^3} \Bigg\{ \int_{-\infty}^{T_R} dV \left[\ln\left(\frac{T_R - V}{2b}\right) + \frac{11}{2} \right] M^{(4)}_{ij}(V) \Bigg\} \\ & + \frac{G}{c^5} \Bigg\{ -\frac{2}{7} \int_{-\infty}^{T_R} dV M^{(3)}_{a<i}(V) M^{(3)}_{j>a}(V) \Bigg\} \Bigg] + \mathcal{O}(6) \end{aligned}$$

Canonical moments $\{M_L, S_L\}$ linked to general source moments $\{I_L,\ J_L,\ W_L,\ ...,\ Z_L\}$ which for MQ reads as,

$$M_{ij} \;=\; I_{ij} - \frac{4G}{c^5}\left[W^{(1)} I^{(1)}_{ij} - W^{(2)} I_{ij} \right] \text{where, } W = \left[\frac{1}{3}\, \nu m\, \mathbf{x}.\mathbf{v} \right]$$

Relation connecting radiative MQ and Canonical MQ

The relations connecting the different radiative moments U_L and V_L to the corresponding source moments I_L and J_L are given below. For the mass type moments we have (Blanchet 92.. 98)

$$
\begin{aligned}
U_{ij}(U) \;=\;& I_{ij}^{(2)}(U) + \frac{2GM}{c^3}\int_0^{+\infty} d\tau \left[\ln\left(\frac{c\tau}{2r_0}\right) + \frac{11}{2}\right] I_{ij}^{(4)}(U-\tau) \\
&+\frac{G}{c^5}\left\{-\frac{2}{7}\int_0^{+\infty} d\tau I_{a<i}^{(3)}(U-\tau) I_{j>a}^{(3)}(U-\tau)\right. \\
&\quad +\frac{1}{7} I_{a<i}^{(5)} I_{j>a} - \frac{5}{7} I_{a<i}^{(4)} I_{j>a}^{(1)} - \frac{2}{7} I_{a<i}^{(3)} I_{j>a}^{(2)} + \frac{1}{3}\varepsilon_{ab<i} I_{j>a}^{(4)} J_b \\
&\quad \left. +4\left[W^{(2)} I_{ij} - W^{(1)} I_{ij}^{(1)}\right]\right\} \\
&+2\left(\frac{GM}{c^3}\right)^2 \int_0^{+\infty} d\tau I_{ij}^{(5)}\left(U-\tau\right) \\
&\left[\ln^2\left(\frac{c\tau}{2r_0}\right) + \frac{57}{70}\ln\left(\frac{c\tau}{2r_0}\right) + \frac{124627}{44100}\right] \\
&+\mathcal{O}(7),
\end{aligned}
$$

General Source Moments

$$I_L(t) = \underset{B=0}{\mathrm{FP}} \int d^3\mathbf{x}\, |\tilde{\mathbf{x}}|^B \int_{-1}^{1} dz \left\{ \delta_l(z)\hat{x}_L \Sigma - \frac{4(2l+1)}{c^2(l+1)(2l+3)} \delta_{l+1}(z)\hat{x}_{iL}\dot{\Sigma}\right.$$

$$\left. + \frac{2(2l+1)}{c^4(l+1)(l+2)(2l+5)} \delta_{l+2}(z)\hat{x}_{ijL}\ddot{\Sigma}_{ij} \right\} (\mathbf{x}, t + z|\mathbf{x}|/c)$$

$$J_L(t) = \underset{B=0}{\mathrm{FP}}\ \varepsilon_{ab<i_l} \int d^3\mathbf{x}\, |\tilde{\mathbf{x}}|^B \int_{-1}^{1} dz \left\{ \delta_l(z)\hat{x}_{L-1>a}\Sigma_b\right.$$

$$\left. - \frac{2l+1}{c^2(l+2)(2l+3)} \delta_{l+1}(z)\hat{x}_{L-1>ac}\dot{\Sigma}_{bc} \right\} (\mathbf{x}, t + z|\mathbf{x}|/c)\ .$$

Blanchet(1995,98); Damour, BRI (1990) - Linearised Gravity

General Source Moments

$$\tau^{\mu\nu} = |g| T^{\mu\nu} + \frac{c^4}{16\pi G} \Lambda^{\mu\nu} \left[h, \partial h, \partial^2 h \right] ,$$

$$\overline{\tau}^{\mu\nu} = \mathrm{PN}(\tau^{\mu\nu})$$

.

$$\Sigma = \frac{\overline{\tau}^{00} + \overline{\tau}^{ii}}{c^2} \; ; \quad \Sigma_i = \frac{\overline{\tau}^{0i}}{c} \; ; \quad \Sigma_{ij} = \overline{\tau}^{ij}$$

$$\delta_l(z) = \frac{(2l+1)!!}{2^{l+1} l!} (1 - z^2)^l \; ; \quad \int_{-1}^{1} dz \delta_l(z) = 1 \; .$$

$$\int_{-1}^{1} dz \delta_l(z) S(\mathbf{x}, t + z|\mathbf{x}|/c) = \sum_{j=0}^{\infty} \frac{(2l+1)!!}{2^j j! (2l+2j+1)!!} |\mathbf{x}|^{2j} \left(\frac{\partial}{c \partial t} \right)^{2j} S(\mathbf{x}, t) \; .$$

General Source Moments - (d+1) dimn

Derive multipole moments of an isolated slowly moving source in d spatial dimensions to apply DimReg

$$I_L(t) = \frac{d-1}{2(d-2)} \mathrm{FP}_B \int d^d\mathbf{x} \left(\frac{|\mathbf{x}|}{r_0}\right)^B \Big\{ \hat{x}_L \, \Sigma_{[\ell]} - \frac{4(d+2\ell-2)}{c^2(d+\ell-2)(d+2\ell)} \hat{x}_{aL} \, \Sigma^{(1)}_{[\ell+1]a} + \frac{2(d+2\ell-2)}{c^4(d+\ell-1)(d+\ell-2)(d+2\ell+2)} \times \hat{x}_{abL} \, \Sigma^{(2)}_{[\ell+2]ab} \Big\}$$

Redo all calculations from the beginning in $d+1$ dimensions with all d-dependent coeffs

$$\sigma = \frac{2}{d-1} \frac{(d-2)T^{00} + T^{ii}}{c^2} \Rightarrow \Box V = -4\pi G \sigma$$

$$g_{ij} = \delta_{ij} \left\{ 1 + \frac{2}{(d-2)c^2} V + \cdots \right\} + \frac{4}{c^2} \hat{W}^{ij} + \cdots$$

$$\Box \hat{W}_{ij} = -4\pi G \left(\sigma_{ij} - \delta_i j \frac{\sigma_{kk}}{d-2} \right) - \frac{1}{2} \left(\frac{d-1}{d-2} \right) \partial_i V \partial_j V$$

$$I_{ij} = \frac{d-1}{2(d-2)} \int d^d\vec{x} x^{\langle i} x^{j\rangle} \left\{ \sum_k \frac{\Gamma\left(2+\frac{d}{2}\right)}{2^{2k} k! \Gamma\left(2+\frac{d}{2}+k\right)} \left(\frac{\| \vec{x} \|}{c} \right)^{2k} \frac{d^{2k}}{dt^{2k}} \sigma + \cdots \right\}$$

(Many d-dependent coeffs) All Coeffs needed because $\exists$ poles $\propto \frac{1}{d-3}$

$$\Rightarrow \frac{f(d)}{d-3} = \frac{f(3)}{d-3} + f'(3) + \mathcal{O}(d-3)$$

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  Blanchet Liv Rev Rel 9:4 2006; Gravitational Waves - M. Maggiore

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  Blanchet Liv Rev Rel 9:4 2006; Gravitational Waves - M. Maggiore
- 3.5PN results for non-spinning ICB on *quasi-circular* orbits

  Blanchet, Damour, BRI, Esposito-Farese, Faye, Arun, Qusailah, Sinha

  3PN results for non-spinning ICB on *quasi-elliptical* orbits (Gopakumar, Arun, Qusailah, Sinha, Blanchet, BRI, Damour, Konigsdorffer, Tessmer) and 2.5PN results for *spinning* binaries (Arun, Blanchet, Buonanno, Faye, Schäfer et al, Damour) have recently been completed. In the test particle limit results are known to order 5.5PN by perturbation method (Sasaki,Tagoshi, Tanaka, Mano, Suzuki, Takasugi, Fujita, BRI).

Other approaches

- ADM (Damour, Schäfer, Jaranowski),
- Direct Integration of Relaxed Einstein Eqns - DIRE (Epstein, Thorne, Will and Wiseman, Pati);
- Strong field point particle limit (Schutz, Futamase, Asada, Itoh);
- Effective field theory techniques (Goldberger, Porto, Rothstein..)
- Self-force approaches for EMRI's...
- NR-AR (Cornell-Caltech, Goddard, Jena, RIT, IHES, Maryland) and Self force-PN (Blanchet, Tiec, Whiting, Detweiler...) comparisons....

Basic Inputs - 3PN Energy and 3.5PN Energy Flux $x \equiv (\pi GMF/c^3)^{2/3}$

$$\begin{aligned} E_3(x) &= -\frac{1}{2}\nu x\left[1-\left(\frac{3}{4}+\frac{1}{12}\nu\right)x-\left(\frac{27}{8}-\frac{19}{8}\nu+\frac{1}{24}\nu^2\right)x^2\right. \\ &\quad \left.-\left\{\frac{675}{64}-\left(\frac{34445}{576}-\frac{205}{96}\pi^2\right)\nu+\frac{155}{96}\nu^2+\frac{35}{5184}\nu^3\right\}x^3\right], \end{aligned}$$

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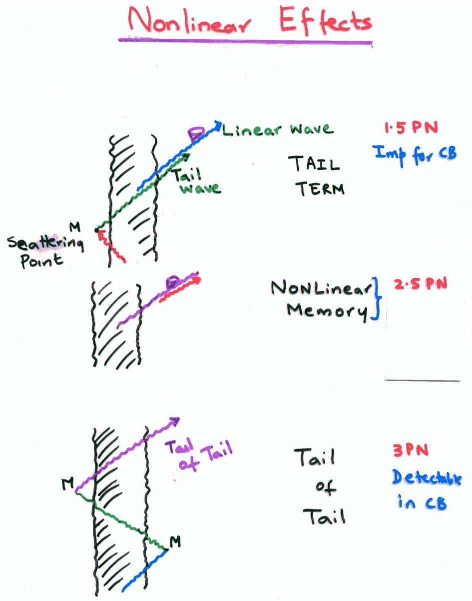
\mathcal{L} &= \frac{32c^5}{5G} x^5 \nu^2 \left\{1 + \left(-\frac{1247}{336} - \frac{35}{12}\nu\right) x + 4\pi x^{3/2} \right. \\
&+ \left(-\frac{44711}{9072} + \frac{9271}{504}\nu + \frac{65}{18}\nu^2\right) x^2 + \left(-\frac{8191}{672} - \frac{535}{24}\nu\right) \pi x^{5/2} \\
&+ \left(\frac{6643739519}{69854400} + \frac{16\pi^2}{3} - \frac{1712}{105} C - \frac{856}{105} \ln(16x) \right. \\
&+ \left. \left[\frac{41\pi^2}{48} - \frac{134543}{7776}\right]\nu - \frac{94403}{3024}\nu^2 - \frac{775}{324}\nu^3\right) x^3 \\
&+ \left. \left(-\frac{16285}{504} + \frac{176419}{1512}\nu + \frac{19897}{378}\nu^2\right) \pi x^{7/2} + \mathcal{O}(x^4)\right\}
\end{aligned}$$

3PN GW Flux includes..



Are we there???

Contributions to the accumulated number $\mathcal{N} = \frac{1}{\pi}(\phi_{\rm ISCO} - \phi_{\rm seismic})$ of gravitational-wave cycles. Frequency entering the bandwidth is $f_{\rm seismic} =$ 10 Hz; terminal frequency is assumed to be at the Schwarzschild innermost stable circular orbit $f_{\rm ISCO} = \frac{c^3}{6^{3/2}\pi G m}$.

A$\equiv 2 \times 1.4 M_\odot$ B$\equiv 10 M_\odot + 1.4 M_\odot$ C$\equiv 2 \times 10 M_\odot$

RR Order	A	B	C
Newtonian	16031	3576	602
1PN	441	213	59
1.5PN	−211	−181	−51
2PN	9.9	9.8	4.1
2.5PN	−12.2	−20.4	−7.5
3PN	2.6	2.3	2.2
3.5PN	−1.0	−1.9	−0.9

Blanchet, Faye, BRI and Joguet

Blanchet, Damour, Esposito-Farese and BRI

Post Newtonian Approximants - Different Families

Damour, BRI, Sathyaprakash

- PNA computes orbital phase $\phi(t)$ of a CB as perturbative expn in a small parameter, $v = (\pi MF)^{1/3}$ (characteristic velocity in the binary), or $x = v^2$, although other variants exist.

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- Different PN families arise because one can choose to treat the ratio $\mathcal{F}(v)/E'(v)$ differently starting from the same PN order inputs.

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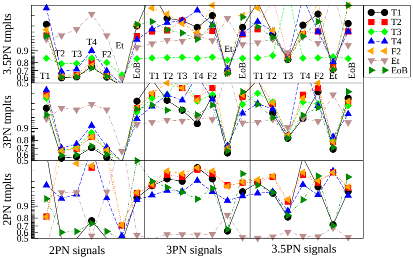
- Effective-one-body (EOB): Analytically provides plunge, merger and ringdown..EOB can be calibrated to Num Rel simulations

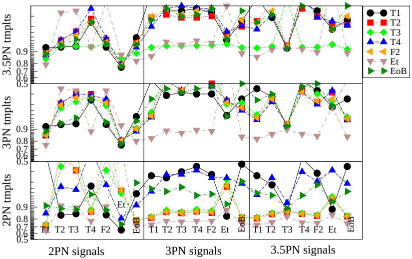
Adv LIGO - Effectualness of PN Templates & Signals

Buonanno, BRI, Ochsner, Pan, Sathyaprakash arXiv:0907.0700

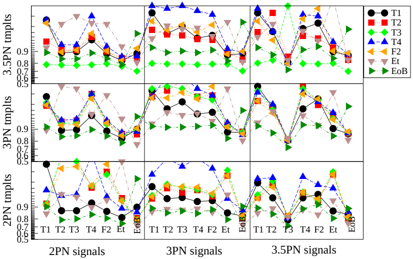
BNS: (1.38, 1.42) solar masses



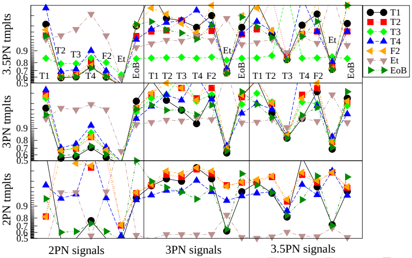
BBH: (4.8, 5.2) solar mases



BBH: (9.5, 10.5) solar masses



NSBH: (1.4, 10) solar masses



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- Estimated complete GW signal emitted by inspiralling, plunging, merging and ringing binary black holes

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- Assumption of sharp transition around BBH merger, between the "plunge" and a ringdown behavior, inspired by classic "plunging test-mass" result of Davis 1972. Matching time t_m at location of maximum EOB orbital frequency. Well confirmed by results of NR simulations

Complete Waveform from EOB - Inspiral, Plunge, Merger, Ringdown (Buonanno and Damour, 2000)

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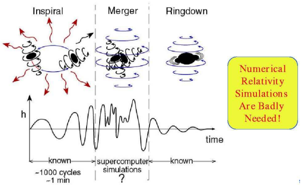

How Complicated will it be??

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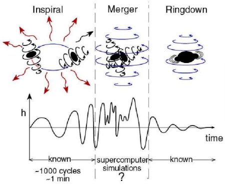

Numerical Relativity Simulations Are Badly Needed!

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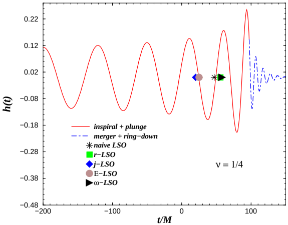

EOB predicted a blurred transition from inspiral to plunge that is a smooth continuation of inspiral+ sharp transition around merger of continued inspiral and ringdown signal

Pretorius and the Numerical Relativity Breakthrough

- Pretorius (2005) produced the first simulation with large number of orbits through merger using Mharmonic coords, compactification of Num Dom at spatial infinity, singularity excision and damping of constraints. With this amazing breakthrough in NR, one has reliable waveforms for the late inspiral and merger parts of the binary evolution which can be used for constructing templates.

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- In 8 months other groups using other methods like BSSN eqns and puncture methods have followed.. Provide access to accurate knowledge of the waveform emitted during late inspiral and merger (Pretorius 2005; Campanelli et al 2005; Baker et al 2005; Brügmann et al 2008; Husa et al 2008; Hannam et al 2008; Boyle et al 2007, 2008; Scheel et al 2009; Vaishnav et al 2007; Hannam et al 2009).

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- Results for sparse sample of BBH systems. BBH simulations: time consuming. NR simulations currently too expensive to solely build required bank of GW templates and densely fill multidimensional space of BBH physical parameters (masses and spins).

Confronting Num Rel with PNA

- WF calibrated and interpreted by our PN inspiral results.

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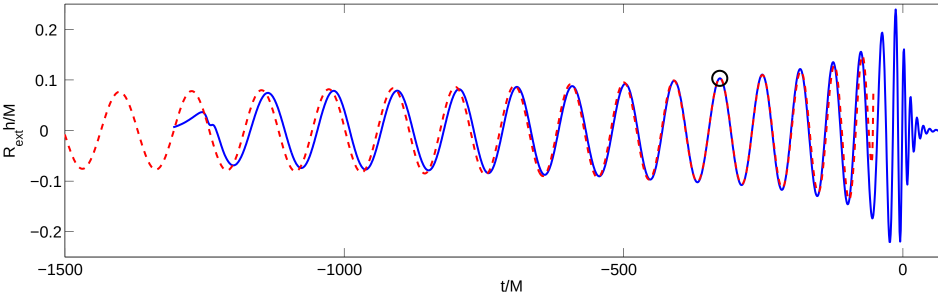
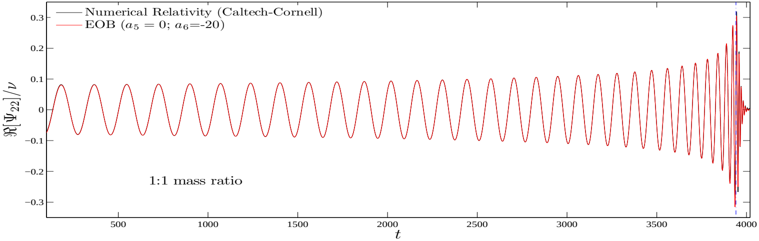
- There is exciting progress in matching the PN waveforms to the Numerical Relativity ones (Buonanno, Cook, Pretorius 06; Damour, Nagar 06, Groups at Caltech-Cornell, Goddard, Jena, Rochester, ..)

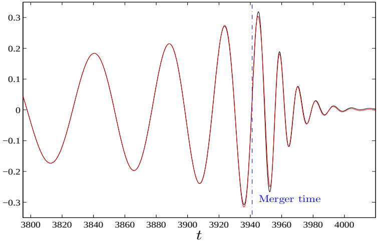
Baker et al



Improved EOB-based (red) and NR (black)

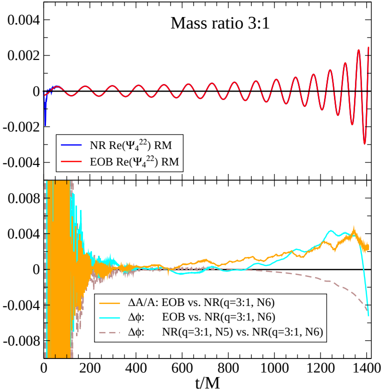
$\ell = m = 2$ metric waveforms;Damour and Nagar 2009; Equal-mass case





EOB vs NR - Mass ratio 3:1

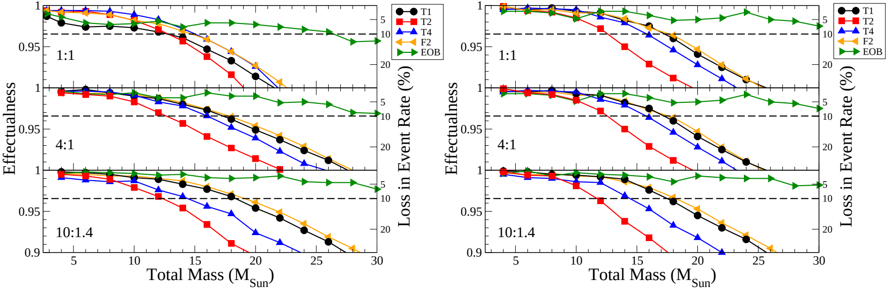
Buonanno, Pan, Pfeiffer, Scheel, Kidder, Buchman (2009): arXiv: 0902.079



The upper panel shows the numerical and EOB mode Ψ_4^{22}, and the lower panel shows phase and amplitude differences between EOB and numerical run. The dashed brown line is the estimated phase-error of the numerical simulation, obtained as the difference between simulations at high resolution 'N6' and lower resolution 'N5'.

Recommendation for Future GWDA of CB's

Buonanno, BRI, Ochsner, Pan, Sathyaprakash arXiv:0907.0700



Effectualness and correspg loss in Event rate of 3.5PNA with EOB inspiral-merger-ringdown signal calibrated to NR. Initial LIGO (left); Adv LIGO (right)

Use TaylorF2 below $M_{\rm crit} \sim 12 M_\odot$

Use EOB calibrated to NR simulations above $M_{\rm crit}$.

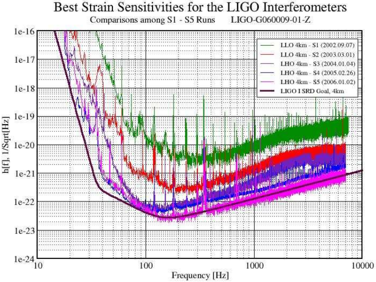
Summary

Buonanno, BRI, Ochsner, Pan, Sathyaprakash arXiv:0907.0700

- A physical model with physically meaningful parameters is a far safer bet as search templates unless, of course, if the model in question is not in agreement with the waveform predicted by numerical relativity. EOB is the best physical model we have and this is what we recommend be used to search for binaries with masses greater than about 12 $M_\odot$.
- Purely from the point of view of computational burden TaylorF2 is the least expensive and it is recommended that TaylorF2 at 3.5 PN order be deployed as search templates below a total mass of 12 $M_\odot$.
- Alternative approach - Phenomenological Waveforms [Ajith et al 2007, 08,09] arXiv:0704.3764, arXiv: 0901.4936
- Most recent EOB models are in near perfect agreement with the most accurate numerical simulations to date, for systems corresponding to different mass ratios studied so far.

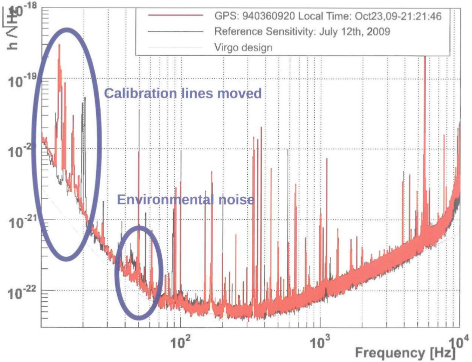
LIGO and Virgo TODAY

Field reached a *Milestone* with decades-old plans to build and operate *large* interferometric GW detectors now realized at several locations worldwide



Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-01-Z



S5: Nov 2005 -Sep 2007. Unprecedented sensitivity allows to place Upper Limits on GW from a variety of Ap sources.. E.g. Fairhurst et al arXiv:0908.4006

Astrophysical results from GW observations - LIGO Science Collaboration

- Upper limits on the strength of the cosmological stochastic background of GWs better than existing limits from big bang (BB) nucleosynthesis and the cosmic microwave background. Rule out several of the BB scenarios based on some string theories (LIGO +Virgo)
- Crab pulsar (spinning down at a rate of 3.7×10^{-10} Hz/sec gives strain amplitude $h \sim 1.4 \times 10^{-24}$ if spindown all due to GW emission) S5 run - no GW signal observed even at $h \sim 2 \times 10^{-25}$ less than 2 % energy loss can be due to GW; significantly constraining spin-down mechanism
- Absence of GW signal during GRB 070201 excluded CB progenitor in M31 galaxy. If not in M31, excludes BNS merger within 3.5 Mpc.
- S4 run - strong limits on the presence of GW bursts from cosmic (super) strings
- S5 - Stringent upper limits on the GW strengths associated with 3 SGRs. For three distinct SGR events, GW observations could put excellent upper limits on the GW strengths. One case Order of magnitude better.

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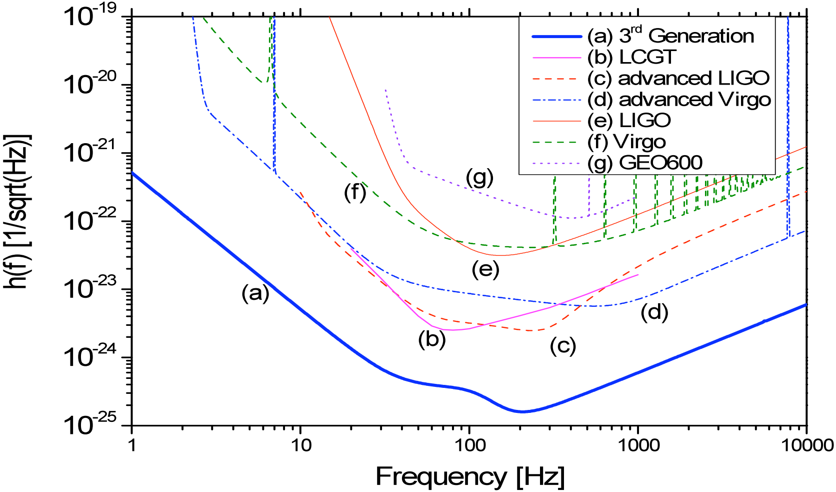
- 3G Detectors: Einstein Telescope (2027 -)
  100× increase in sensitivity; Over 10^6× increase in rate
  ET: Conceptual design study(EC: 3 years; 3M Euros; Sathyaprakash)

Sensitivity Today, Sensitivity Tomorrow



Expected Annual Coalescence Rates

- Rates quoted are mean of the distribution.

Detector	NS-NS	NS-BH	BH-BH
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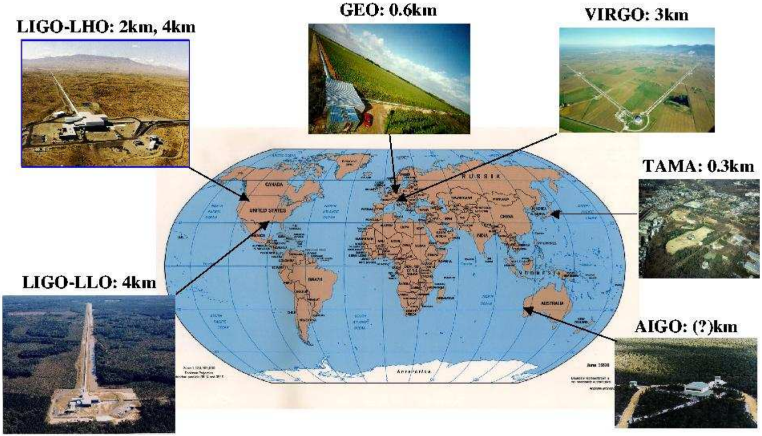
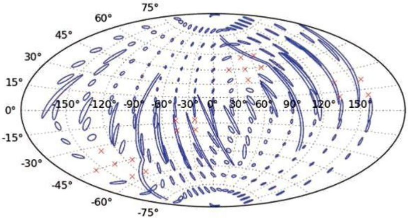
In a 95% confidence interval, rates uncertain by 3 orders of magnitude
Extrapolations from obsvd Bin Psrs,Stellar birth rate estimates,
Population Synthesis models
NS-NS $(0.4 - 400)$; NS-BH $(0.2. - 300)$; BH-BH $(2. - 4000)$ yr^{-1}

Global GW Network



Towards GW Astronomy - LIGO - Australia



LIGO Hanford Livingston + Virgo

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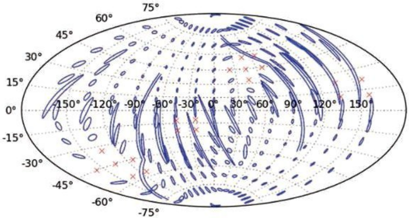

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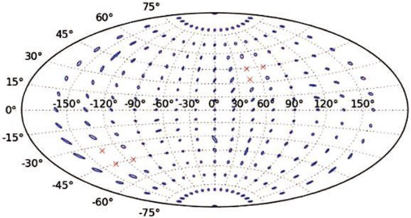

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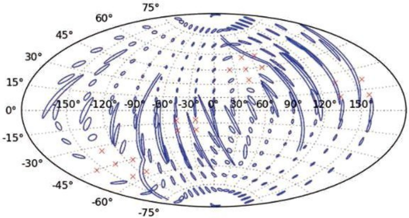

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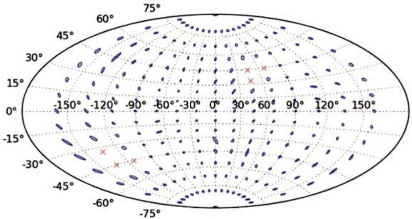

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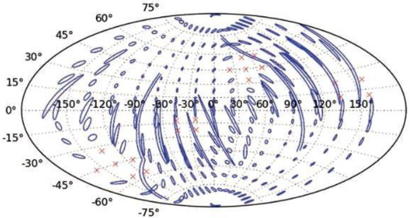

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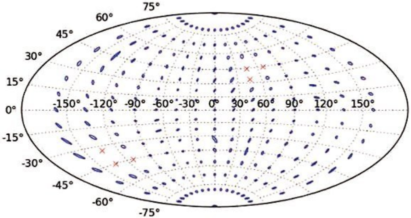

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IndIGO (Indian Initiative in GW Observations) Consortium will seek funds to collaborate with ACIGA to participate in LIGO-Australia.

Concluding Remarks

- Any Experimental Physicist marvels at the audacity of the attempt to detect GW. Detection of GW is nearly *impossible*.
  Involves technological challenges that appear *insurmountable*.
  That we are close to detecting it is remarkable.
  When we succeed it will be truely WONDERFUL (Peter Saulson)

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- Initial ITF could detect NS-NS binary inspirals up to 30 Mpc, Enhanced ITF to 60 Mpc and Adv ITF expected up to 450 Mpc.
  Most promising sources for Initial Interferometers are the Black Hole-Black Hole Binaries. $10 - 10M_\odot$ BBH to 160 Mpc for Initial ITF and 2200 Mpc for Advanced ITF

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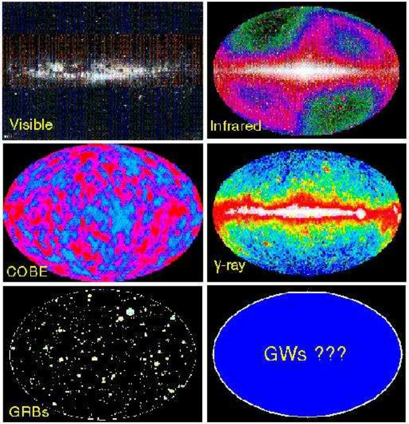
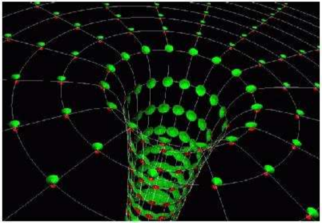
- Joint GW and optical observations can provide a new cosmological tool

Universe in Various windows





Gravitational Waves will provide a new way to view the dynamics of the Universe

The Neutrino story and possible GW analog..

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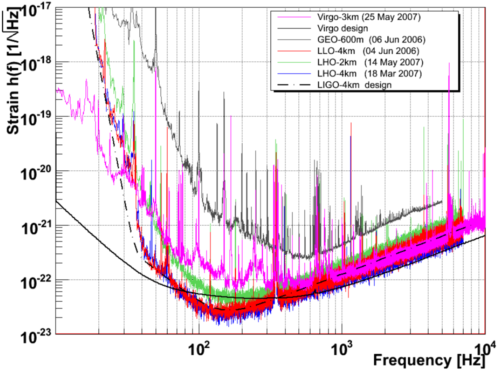
  If it is bad, then Gravity has other new and subtler modes of Expression!!

First generation detectors achieve Design sensitivity

Four Hundred years after Galileo's telescope launched Optical Astronomy, a major revolution in astronomy using GW is around the corner.



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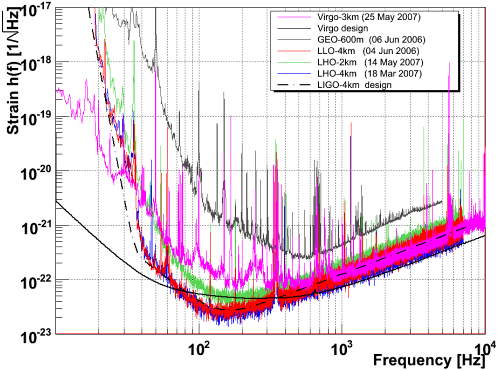

Wonderful tribute in the past Year of Astronomy to Galileo from 100's of brave GW Experimenters over decades who believed *impossible is nothing!*

The dilemma of the GW detective (Kochi - 2004)