Gravitational Waves as test-beds for fundamental physics and cosmology

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GW detectors

All are now being upgraded to their Advanced version due to start data taking in 2015

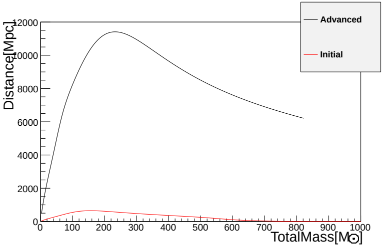
2017+ for design sensitivity

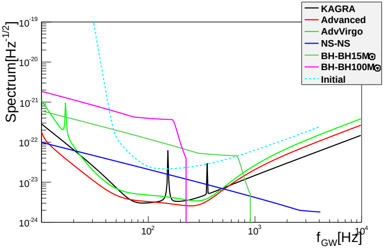
KAGRA and INDIGO will join in 2020+

Old coincident runs ended in October 2010

Advanced detectors

Sensitivity vs. signals @ 200Mpc with optimal orientation





Distance reach for compact binary coalescence

Observational rate estimates

LIGO/Virgo Advanced Observatories will detect

($SNR = 8$, optimal orientation)

	NS-NS	10 $M_\odot$ BH-BH
Distance (Mpc)	$450\mathrm{Mpc}$	$1\mathrm{GPc}$
Rates $\mathrm{MWEG}^{-1}\mathrm{Myear}^{-1}$	$1 \div 10^3$	$4 \cdot 10^{-2} \div 100$

$$N = 0.011 \times \frac{4}{3}\pi \left(\frac{D_H/\mathrm{Mpc}}{2.26}\right)^3 \mathrm{MWEG}$$

Realistic case:

$$R_{NS-NS} \sim O(10)\mathrm{yr}^{-1} \qquad R_{BH-BH} \sim O(10^2)\mathrm{yr}^{-1}$$

for LIGO/Virgo at design sensitivity

LIGO/Virgo CQG 2010

Data analysis technique: Matched filtering

An experimental apparatus output: time series

$$O(t) = h(t) + n(t) \qquad h(t) = D^{ij} h_{ij}(t)$$

Noise is conveniently characterized by its spectral function

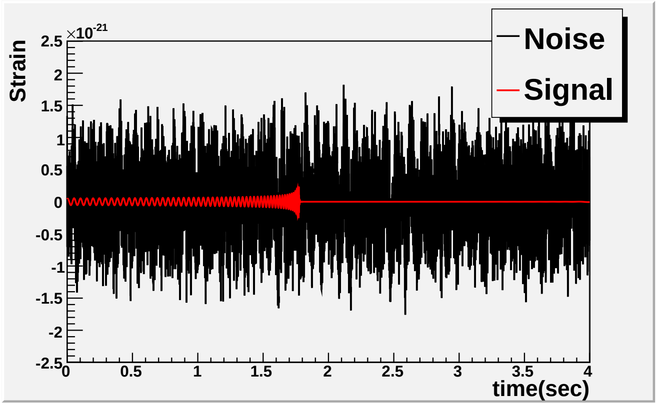
$$\langle \tilde{n}(f) \tilde{n}^*(f') \rangle = \delta(f - f') S_n(f) \qquad [Hz^{-1}]$$

Matched filter enhances the sensitivity

$$\frac{1}{T}\int_0^T O(t)h(t)\,dt = \frac{1}{T}\int_0^T h^2(t)\,dt + \frac{1}{T}\int_0^T n(t)h(t)\,dt \sim h_0^2 + \sqrt{\frac{\tau_0}{T}} n_0 h_0$$

Hunting for tiny signals

Detector's output is flooded with noise:

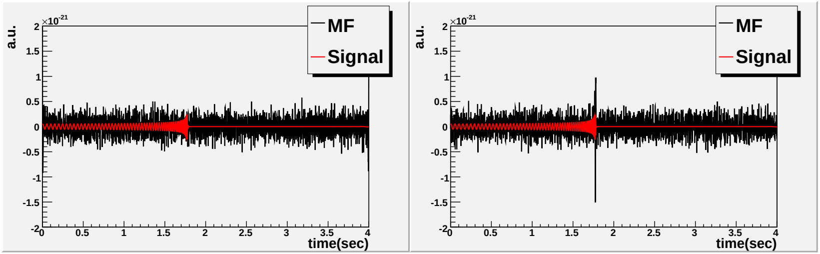


Noise + GW signal from 2+12 $M_{\odot}$ system at 50 Mpc distance

Matched filtering

Matched filtering enhances sensitivity:

$$O(t) \to MF(t) \propto \int \frac{O(f)h^*(f)}{S_n(f)} e^{2\pi i f t} df$$



MF with $h' \neq h$ MF with h

but requires good model of the signal h

or a complete bank of $h's$

Testing GR with GW detection

Inspiral $h = A\cos(\phi(t))$ $\quad \frac{\dot{A}}{A} \ll \dot{\phi}$

in the 2-body inspiral regime $\phi(t)$ admits generic, analytic parametrization via post-Newtonian approximation to GR

$$\phi(t) = v^{-5}(t) \sum_{n=0}^{7} \left(\phi_n + \phi_n^{(l)} \log(v(t)) \right) v^n(t)$$

Odds ratio allows Bayesian model selection between 2 hypotheses:

- $\mathcal{H}_{GR}$
- $\mathcal{H}_{modGR}$: one or more ϕ_i's are not as predicted by GR

$$\mathcal{O}_{GR}^{modGR} \equiv \frac{P\left(\mathcal{H}_{modGR}|d, I\right)}{P\left(\mathcal{H}_{GR}|d, I\right)}$$

In absence of noise $\mathcal{O}_{GR}^{modGR} \gtrless 0$ favours $\begin{matrix}\textbf{modGR}\\ \textbf{GR}\end{matrix}$

Li, RS et al. PRD (2012), Li et al. PRD (2013)

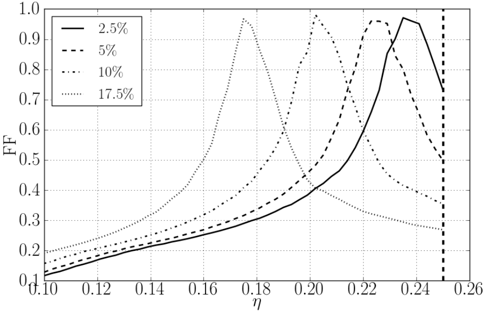
Degeneracy: astrophysical vs fundamental parameters

Parameter estimation bias

Waveform match (fitting factor)

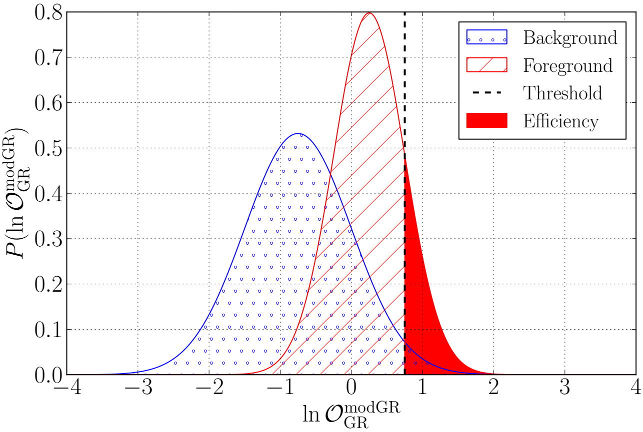
$$FF = \int df \frac{h_1^*(f)h_2(f) + h_1(f)h_2^*(f)}{S_n(f)}$$

for injections with $\Delta\phi_3$ vs. varying η (maximized over other params)



Background vs. Foreground

General method: allow a threshold in the background (false alarm)

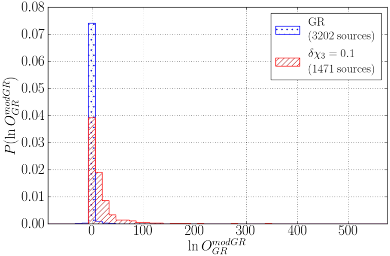


then look for efficiency

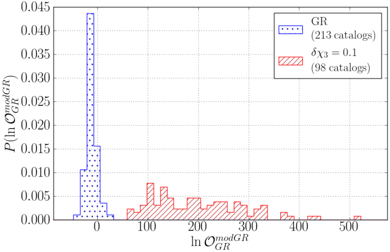
Simulated signals in noise

Constant shift in $\phi_3 \to \phi_3(1 + \delta\chi_3)$ SNR's limited to 8-25

Single sources with noise:
Odds ratio overlaps



15-sources catalogs can disentangle fundamental effects



Future directions for testing GR

- Are waveforms accurate enough? In early inspiral yes (see Li et al. PRD (2013))
- For neutron stars: are finite size and matter effects important? Mostly after 450Hz (Hinderer et al. PRD (2010))
- Is the effect of spin important?
  Not for neutron stars, but for BH it has to be considered (Li et al. PRD (2013))
- Are internal calibration errors under control? Yes

  Vitale et al. PRD (2012)
- What about inclusion of merger and ring-down?
  Work in progress
- Can the computational challenge be satisfied? Maybe yes...

Standard sirens

Coalescing binary systems are standard sirens:

$$h(t) = \frac{G_N \eta M^{5/3} f_s^{2/3}}{D} \cos\left[\phi(t)\right]$$

In cosmological settings source and observer clocks tick differently:

$$dt_o = (1+z)dt_s \qquad f_o(1+z) = f_s$$

$$h(t_o) = \frac{G_N \eta f_o^{2/3} M^{5/3} (1+z)^{2/3}}{a(t_o) D} \qquad \cos\left[\phi(t_s(t_o))\right]$$

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$$M \frac{d\phi(t_s/M)}{dt_o} = \frac{M}{(1+z)} \frac{d\phi(t_s/M)}{dt_s} \propto \frac{1}{1+z} g\left(\frac{(1+z)M}{\eta \Delta t_o}\right) \Longrightarrow$$

$$\phi\left(t_o/\mathcal{M}\right) = \phi\left(t_s/M\right) \qquad \mathcal{M} \equiv M(1+z)$$

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Measuring d_L, no information about z, but ...

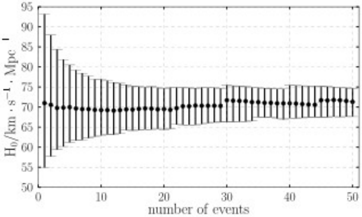
Determining H_0 Part I

Hubble law: $z = H_0 d_L$

D_L can be measured, z degenerate with M, however if

- the source in the sky has been localized (α, δ)
- GW sources are in the galaxy catalog with known red-shift

$$P(z, D_L|c_i) = \int d\mathcal{M}\, d\vec{\theta}\, d\alpha\, d\delta\, P(D_L\mathcal{M}, \vec{\theta}, \alpha, \delta|c_i)\pi(z, |\alpha, \delta)$$



Schutz, Nature '86
W. Del Pozzo, arXiv:1108.1317

Determining H_0 Part II

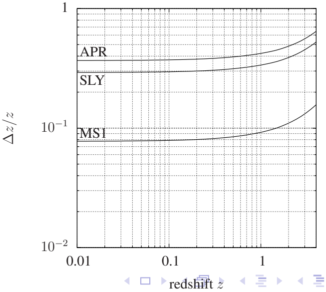
Focusing on neutron star binaries:

$$\phi_{NS}(t) = v^{-5}\sum_n \left(\phi_n + \phi_n^{(l)}\log(v)\right)v^n + \sum_{a=1}^{2}\frac{3\lambda_a}{128\eta M^5}\left(A_{2.5}(\eta,\chi_a)v^{10} + A_{3.5}v^7(\eta,\chi_a)v^{12}\right)$$

with $A_{2.5} \sim A_{3.5} \sim O(R/M)^5 \sim 10^5$

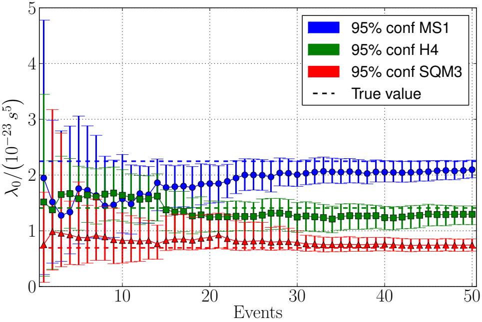
Scaling under $M \to M(1+z)$, $t \to t(1+z)$ broken

C. Messenger, J. Read PRL 2011



Measuring neutron star equation of state

Parameter estimation: deformability λ



Del Pozzo et al. PRD 2011, Read et al. PRD2009, PRD 2010

for MS1: hard EOS, H4 moderate, moderate SQM3

Conclusions

GW astronomy/cosmology is not yet started, but promising indications that a new window will be opened onto the Cosmo and fundamental Gravity

Stay tuned!