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The Dawn of Gravitational-Wave Astronomy

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LIGO-G1600265-v2

Gravitational Waves
Road to the First Detection
Outlook for Gravitational Wave Astronomy

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Outline

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Basics
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GW Sources

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What are Gravitational Waves?

- PopSci answer: Ripples in the fabric of spacetime
- Physics answer:
  - Gravitational analogue of electromagnetic waves
  - Consequence of relativistic causality

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Gravity + Causality = Gravitational Waves
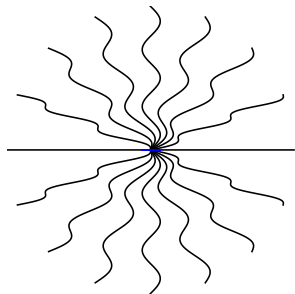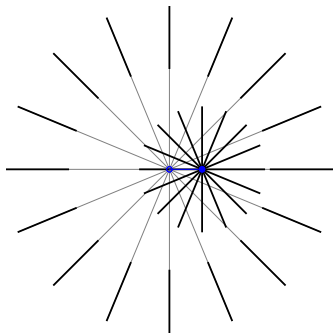
- In Newtonian gravity, force dep on distance btwn objects
- If massive object suddenly moved, grav field at a distance would change instantaneously
- In relativity, no signal can travel faster than light
  $\longrightarrow$ time-dep grav fields must propagate like light waves

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Gravity as Geometry

- Minkowski Spacetime (Special Relativity):
  Invariant spacetime interval (all inertial observers agree):

$$ds^2 = -c^2(dt)^2 + (dx)^2 + (dy)^2 + (dz)^2$$

$$= \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}^{tr} \begin{pmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix} = \sum_{\mu=0}^{3} \sum_{\nu=0}^{3} \eta_{\mu\nu} dx^\mu dx^\nu$$

- General Spacetime:

$$ds^2 = \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix}^{tr} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} = \sum_{\mu=0}^{3} \sum_{\nu=0}^{3} g_{\mu\nu} dx^\mu dx^\nu$$

Metric tensor $\{g_{\mu\nu}(\{x^\lambda\})\}$ determined by masses
via Einstein's equations. (10 non-linear PDEs!)

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Gravitational Wave as Metric Perturbation

- For GW propagation & detection, work to 1st order in $h_{\mu\nu} \equiv$ difference btwn actual metric $g_{\mu\nu}$ & flat metric $\eta_{\mu\nu}$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

  ($h_{\mu\nu}$ "small" in weak-field regime, e.g. for GW detection)

- $h_{\mu\nu}$ analogous to electromagnetic potential $\{A_\mu\} = \{\varphi, \vec{A}\}$
- Small coord changes induce "gauge transformation" on $h_{\mu\nu}$
  Convenient choice of gauge is transverse-traceless:
  In this gauge:
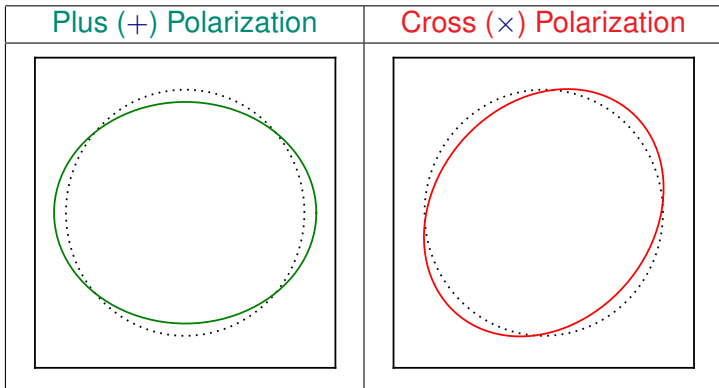   - Vacuum Einstein eqns $\Longrightarrow$ wave equation for $\{h_{ij}\}$:

$$\left(-\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{ij} = 0$$

      - Test particles w/constant coords are freely falling
- EM (spin-1 massless photon) & grav (spin-2 massless "graviton") waves both have two polarization states

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Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:

| Plus (+) Polarization | Cross (×) Polarization |

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Measuring GWs w/Laser Interferometry

Interferometry: Measure GW-induced distance changes

- Measure small change in
$$L_1 - L_2 \approx L_0 \frac{h_{11} - h_{22}}{2} \sim L_0 h_+$$

- Plausible signals: $h \lesssim 10^{-20}$
  $\rightarrow$ need L_0 very big!

- For LIGO, $L_0 = 4\,\text{km}$

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Measuring GWs w/Laser Interferometry

Interferometry: Measure GW-induced distance changes

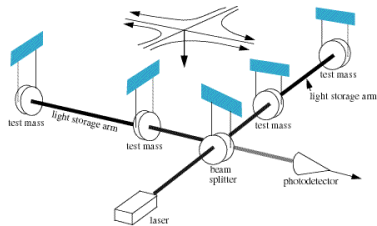- Measure small change in
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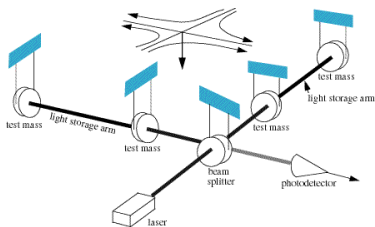
Interferometry: Measure GW-induced distance changes

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Note: other detection methods include resonant bars, pulsar timing arrays & planned space-based interferometers (space-based ifos measure low-freq GWs, PTA very low-freq)

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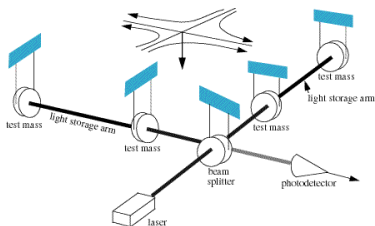

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Note: other detection methods include resonant bars,
pulsar timing arrays & planned space-based interferometers
(space-based ifos measure low-freq GWs, PTA very low-freq)
Note: LISA Pathfinder technology mission underway!

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Rogues' Gallery of Ground-Based Interferometers

LIGO Hanford
(Washington, USA)

GEO-600 (Germany)

LIGO Livingston
(Louisiana, USA)

Virgo (Italy)

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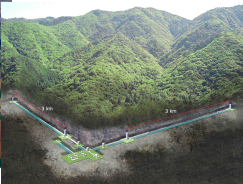RELATIVITY AND
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Rogues' Gallery of Ground-Based Interferometers

LIGO Hanford
(Washington, USA)

GEO-600
(Germany)

KAGRA (Japan)

LIGO Livingston
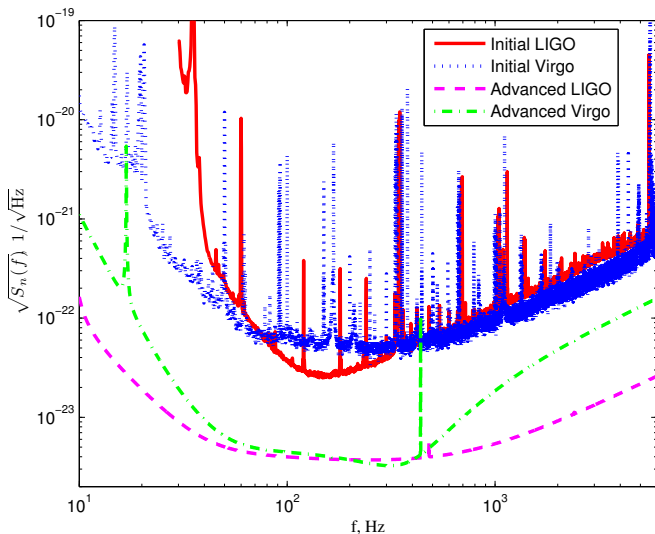(Louisiana, USA)

Virgo (Italy)

LIGO India

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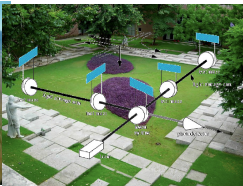
GW Observatory Network

- "Initial Detector Era" for large ground-based interferometers $\sim 2002 - 2011$
- "Advanced Detector Era" started September 2015
  - Germany: GEO-600 (600m) used for technology development (laser power, squeezed light, . . .) & "astrowatch" in case a transient event occurs when other detectors offline.
  - USA: LIGO Hanford & LIGO Livingston (4km) First observing run ("O1") Sept 2015-Jan 2016
  - Italy: Virgo (3km) Expected to start observing 2016
  - Japan: KAGRA (formerly LCGT) (3km, underground, cryogenic, under construction)
  - India: LIGO India (4km, planned)

Detectors distributed on the Earth useful for sky localization of transient signals

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Sensitivity of Initial & Advanced Detectors

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Results of Initial Detector Observations

- $\sim$ 100 Observational papers from initial LIGO/Virgo/GEO:
  https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html
- No detections (although some analyses still trickling out)
- Assortment of null results and upper limits
- As sensitivity improved, some results gave new information to complement other astronomical observations: "Multi-Messenger Astronomy"
- Some highlights:
    - GW associated w/γ-ray bursts (rule out nearby NS merger)
    - GW from known pulsars (beat spindown limit)
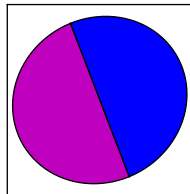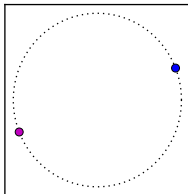   - Stochastic background of GWs (beat nucleosynthesis limit)

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Outline

1 **Gravitational Waves**
  - Crash Course in Gravitational Wave Physics
  - Gravitational Wave Detectors
  - Gravitational-Wave Sources & Signals

2 Road to the First Detection
  - Inspiral-Merger-Ringdown Signals and Searches
  - Observation of the Binary Black Hole Merger GW150914

3 Outlook for Gravitational Wave Astronomy
  - Future Advanced Detector Observations
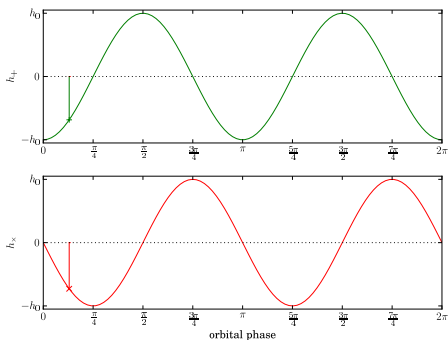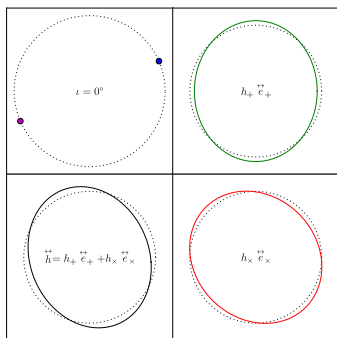 - Transient Signals
  - Long-Lived Signals

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Generation of Gravitational Waves

- EM waves generated by moving/oscillating charges
- GW generated by moving/oscillating masses
- Lowest multipole is quadrupole
- Different types of signals:
    - Burst (transient, unmodelled)
    - Stochastic (long-lived, unmodelled)
    - Binary coalescence (transient, modelled)
    - Periodic (long-lived, modelled)

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Gravitational Waves from Binary Orbit

- Orbital motion $\rightarrow$ oscillating quadrupole moment $\rightarrow$ GWs

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Gravitational Waves from Binary Orbit

- Orbital motion → oscillating quadrupole moment → GWs
- GW emission removes energy → orbit gets tighter
  → amplitude & freq increase in "chirp"
- Hulse & Taylor saw this evolution in binary pulsar 1913+16
  1993 Nobel Prize

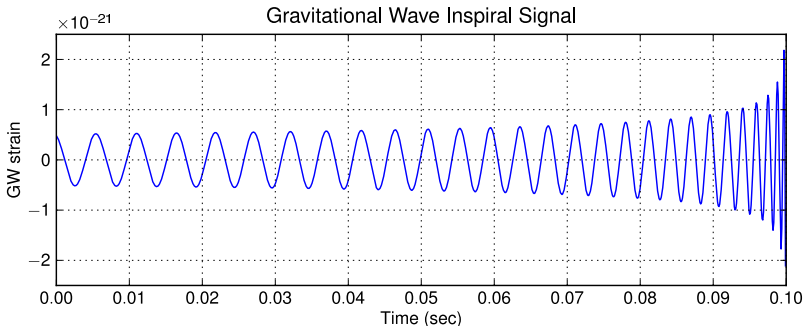Weisberg, Nice & Taylor
ApJ **722**, 1030 (2010)
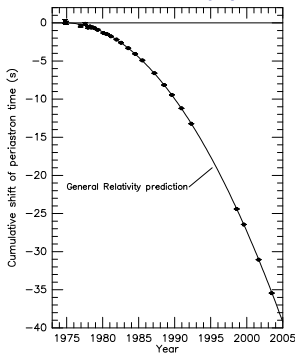
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Compact Binary Inspiral

- For first part of inspiral, orbits not too relativistic
  can expand in powers of $\frac{v}{c} \longrightarrow$ post-Newtonian methods
  Can estimate orb vel from Kepler's 3rd law: $v \approx (\pi G M f)^{1/3}$

  - Low Mass $\longrightarrow$ plunge @ high freq
    $1.4 M_\odot / 1.4 M_\odot$ NS/NS binary has $v \approx 0.3c$ @ 800 Hz;
    PN OK in LIGO band
  - High Mass $\longrightarrow$ plunge @ low freq
    $10 M_\odot / 10 M_\odot$ BH/BH binary has $v \approx 0.4c$ @ 200 Hz;
    merges in LIGO band

- Different template families used for different mass ranges

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Compact Binary Coalescence

- GR is scale-invariant: inspiral of $15M_\odot+20M_\odot$ binary looks just like $1.5M_\odot+2.0M_\odot$, but with times & distances increased $10\times$
- Perturbation theory breaks down when the binary merges
  - For neutron stars, matter breaks the scaling, but it happens at higher frequencies
    - ☞ Inspiral-only waveforms adequate for detection
  - Black holes merge in LIGO's most sensitive band; have to model
    Inspiral: post-Newtonian perturbation theory
    Merger: requires numerical simulations
    Ringdown: final black hole settles down; also perturbative

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IMR Signals & Searches
Observation of GW150914

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Template Waveforms for Binary Coalescence

- Inspiralling binaries produce well-modelled GW signals; Search with pattern-match filter
- Compact object binary coalescence consists of inspiral / plunge / merger / ringdown

Cartoon by Kip Thorne

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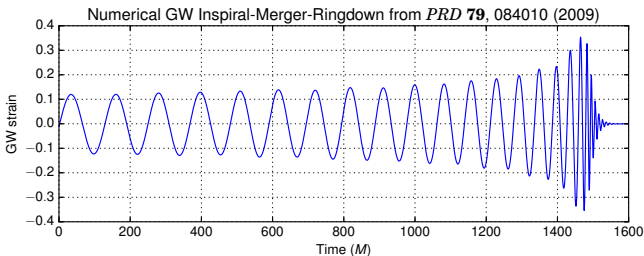GRAVITATION

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Template Waveforms for Binary Coalescence

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Campanelli et al, *PRD* **79**, 084010 (2009)
http://ccrg.rit.edu/downloads/waveforms

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Numerical Simulations of Binary Black Holes

Anecdotal history:

- Despite "Grand Challenge" of 1990s,
  simulations of orbiting BHs were stymied by instabilities
- "Next Generation" of numerical relativists addressed
  the problem w/novel coordinates & methods
  (excision, punctures) in 2000s
- Major breakthroughs came in 2005:
  - Pretorious *PRL* **95**, 121101 (2005); gr-qc/0507014
  - Campanelli et al *PRL* **96**, 111101 (2006); gr-qc/0511048
  - Baker et al *PRL* **96**, 111102 (2006); gr-qc/0511103
- Many groups now have long simulations:
  - Initially stitched onto PN inspiral for "hybrid" waveforms
  - Now the whole inspiral-merger-ringdown can be simulated

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Inspiral-Merger-Ringdown Template Families

- For binary neutron star inspiral searches, post-Newtonian waveforms generated on a grid of points in m_1-m_2 space

- Even with scale invariance & long simulations, impractical to build full "template bank" of numerical waveforms for BBH

- Use analytical waveform families tuned to mimic NR
  - EOBNR: effective-one-body waveforms w/extra NR-tuned terms
    Buonanno et al *PRD* **79**, 124028 (2009); arXiv:0902.0790 etc
  - IMRPhenom: parametrized functional models w/coeffs from NR
    Ajith et al *PRD* **77**, 104017 (2008); arXiv:0710.2335 etc

- First IMR searches in initial LIGO S5 & S6 runs
  PRD **83**, 122005 (2011); arXiv:1102.3781
  PRD **87**, 022002 (2013); arXiv:1209.6533

- Including spin can improve SNR; initial attempts increased FAR too much
  First demonstration of improved efficiency at same FAR: Privitera,
  Mohapatra et al *PRD* **89**, 024003 (2014); arXiv:1310.5633
  As of O1, detection templates include one spin parameter

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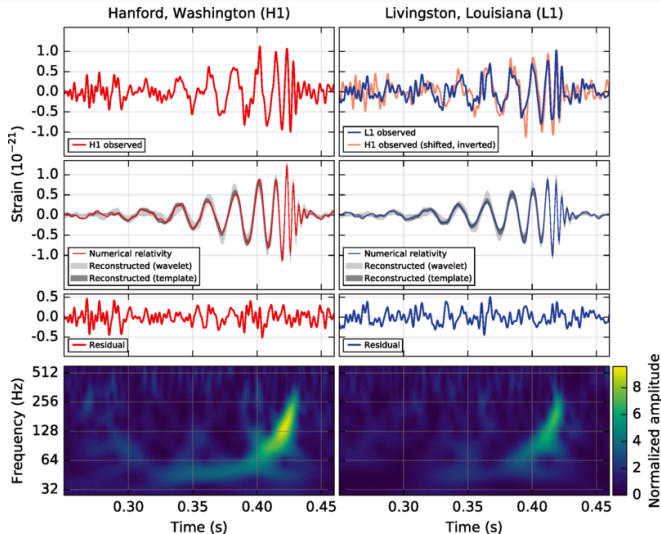CENTER FOR
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Observation of a BBH Merger

- While preparing for 1st Observing Run (O1) start in 2015 Sep
  End of 8th Engineering Run (ER8) meant "soft start":
  experimental, data collection & analysis systems
  transitioning to final configuration

- Online burst analysis reported "loud" trigger on 2015 Sep 14
  consistent with high-mass binary black hole merger
  Real-time inspiral analysis looks for lower-mass systems
  (Expect electromagnetic counterpart only if neutron star
  involved)

- Configuration frozen to collect 16 days of two-detector data:
  Observing period 2015 Sep 12-Oct 20 (BBH analysis results released)

- Official O1 2015 Sep 18-2016 Jan 12 (analyses still under review)

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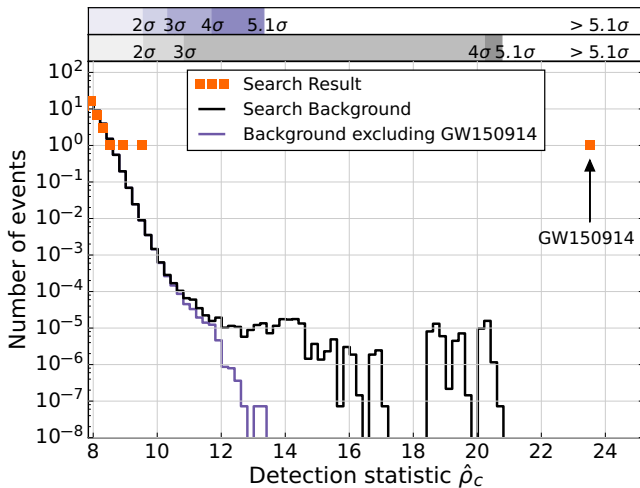Road to the First Detection
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Convincing Pictures

arXiv:1602.03837; *PRL* **116**, 061102 (2016)

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Detection Confidence: Matched Filter #1

Estimate coincident false alarm rate w/time shifts: $< 1/2 \times 10^5$ yr

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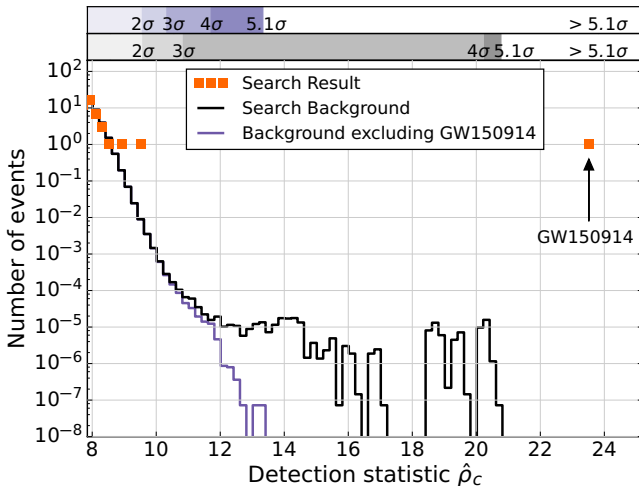
arXiv:1602.03839; Second, marginal candidate "LVT151012" w/FAR 1/2.3 yr

No detection claim, but influences rate estimates

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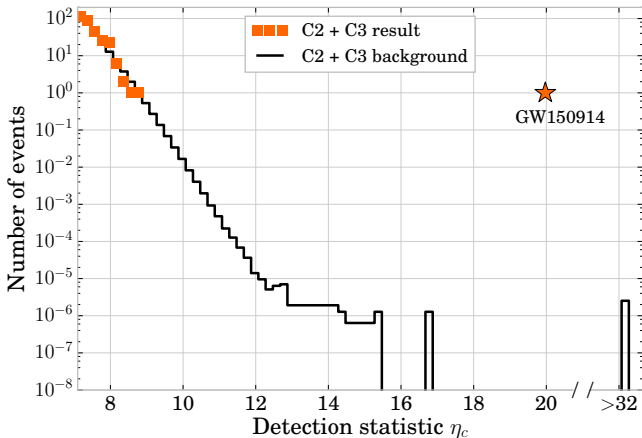
Detection Confidence: Matched Filter #2
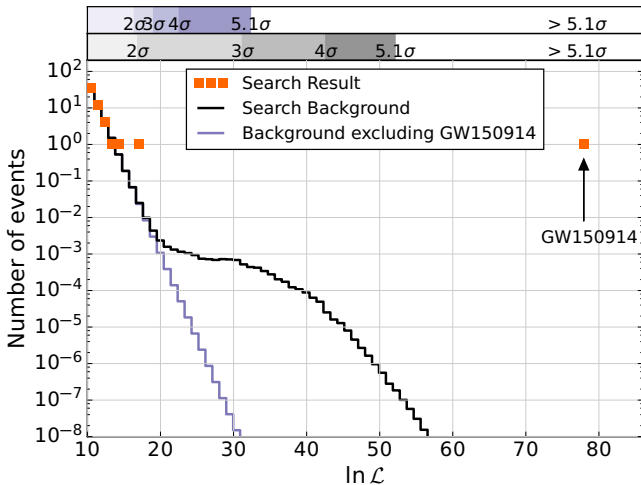
Estimate coincident false alarm probability from singles rates

arXiv:1602.03839

Gravitational Waves
Road to the First Detection
Outlook for Gravitational Wave Astronomy

IMR Signals & Searches
Observation of GW150914

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Detection Confidence: Unmodelled Coherent Search

Estimate coincident false alarm rate w/time shifts: $< 1/8 \times 10^3$ yr

arXiv:1602.03843

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Detect. Conf.: Minimally Modelled Coherent Search
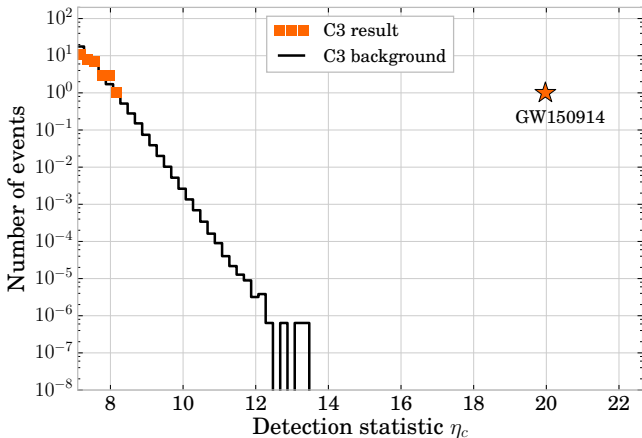
Estimate coincident false alarm rate w/time shifts: $< 1/2 \times 10^4$ yr

arXiv:1602.03843

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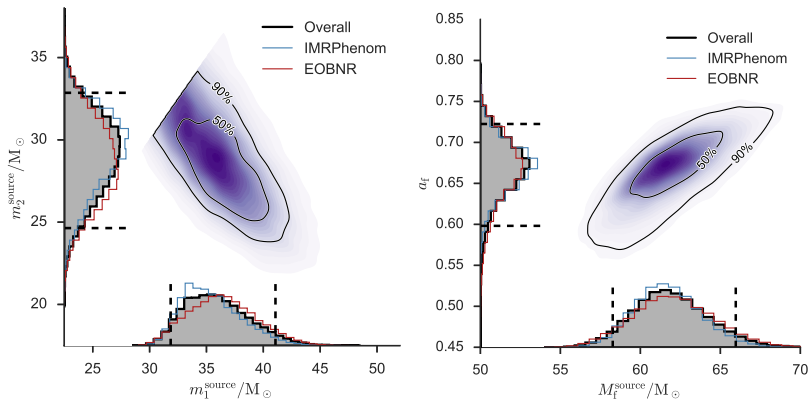GRAVITATION

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Parameter Estimation

- Determine properties (masses, spins, location)
  using Markov Chain Monte Carlo & Nested Sampling
  with parametrized waveforms
- Main waveforms are EOB & Phenom families tuned to NR
- Also check w/some numerical waveforms

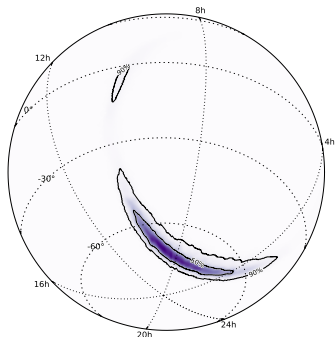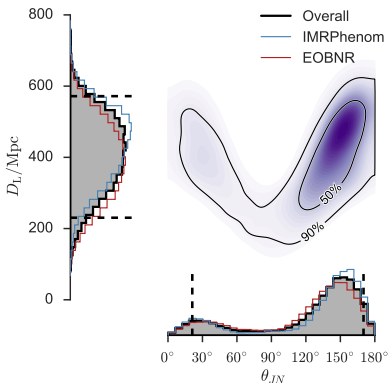Gravitational Waves
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Parameter Estimation: Masses & Spins

arXiv:1602.03840

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Parameter Estimation: Distance & Sky Position

arXiv:1602.03840: Distance degenerate w/inclination angle;
Triangulation gives ring on sky, broken by polarization:
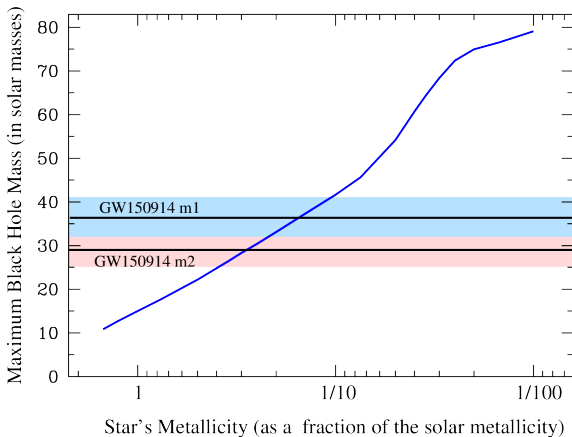90% credible region is 590 deg^2

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Astrophysical Implications

- GW150914 masses: $29 \pm 4 M_\odot$ & $36^{+5}_{-4} M_\odot$; final $62 \pm 4 M_\odot$
- Electromagnetic observations of black holes:
  - X-ray binaries: most $5 - 10 M_\odot$; some $10 - 20 M_\odot$; maybe pushing $30 M_\odot$.
  - Quasars: supermassive $\gtrsim 10^7 M_\odot$, at centers of galaxies
- Discovery of "heavy" stellar-mass black holes implies higher metallicity than previously known

arXiv:1602.03846; *ApJL* **818**, L22 (2016)

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Astrophysical Implications: Metallicity

arXiv:1602.03846; *ApJL* **818**, L22 (2016)
(Belczynski et al arXiv:0904.2784; *ApJ* **714**, 1217 (2010))

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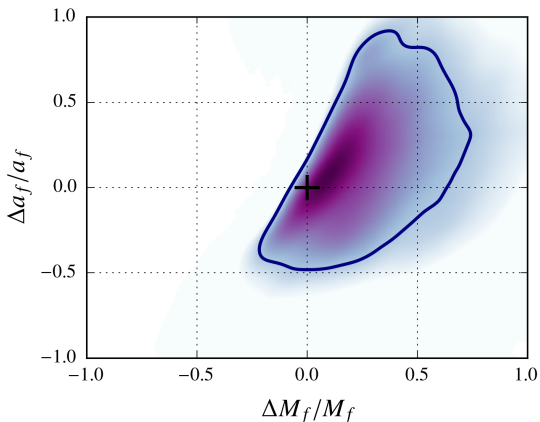CENTER FOR
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Astrophysical Implications: Event Rates

- Pre aLIGO BBH rate estimates $0.1/5/300\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (low/"realistic"/high) *CQG* **27**, 173001 (2010); arXiv:1003.2480

- Expected # events scales like observable volume $\times$ time 16-day data set had $VT = 0.082^{+0.053}_{-0.032}\,\mathrm{Gpc\,yr}$ for BBH

- Observation of GW150914 & LVT151012
  - ☞ rate estimates of $2\text{–}400\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

- Expected # events $\propto$ volume$\times$time $\propto$ sensitivity$^3\times$time
  - ☞ 16 days of O1 $>$ all of initial LIGO!

arXiv:1602.03842

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Testing General Relativity w/GW150914 ("Einstein was right")

Final BH mass & spin

arXiv:1602.03841

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Testing General Relativity w/GW150914 ("Einstein was right")
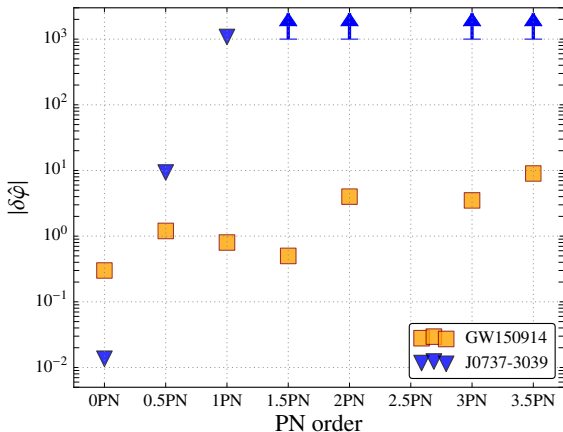
Post-Newtonian phasing (compare double pulsar)

arXiv:1602.03841

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Testing General Relativity w/GW150914 ("Einstein was right")
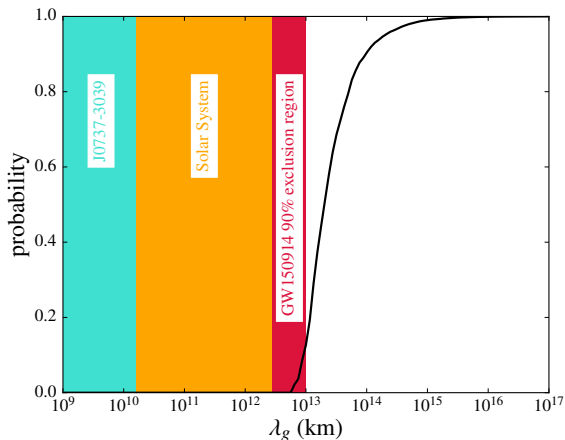
Graviton compton wavelength

arXiv:1602.03841

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List of Papers

http://papers.ligo.org/ http://dcc.ligo.org/P150914/public

1. Observation of Gravitational Waves from a Binary Black Hole Merger
   arXiv:1602.03837; *PRL* **116**, 061102 (2016)

2. GW150914: The Advanced LIGO Detectors in the Era of First Discoveries arXiv:1602.03838

3. GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
   arXiv:1602.03839

4. Properties of the binary black hole merger GW150914 arXiv:1602.03840

5. Tests of general relativity with GW150914 arXiv:1602.03841

6. The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding
   GW150914 arXiv:1602.03842

7. Observing gravitational-wave transient GW150914 with minimal assumptions arXiv:1602.03843

8. Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
   arXiv:1602.03844

9. Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
   arXiv:1602.03845

10. Astrophysical Implications of the Binary Black-Hole Merger GW150914
    arXiv:1602.03846; *ApJL* **818**, L22 (2016)

11. GW150914: Implications for the stochastic gravitational-wave background from binary black holes
    arXiv:1602.03847

12. High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and
    ANTARES arXiv:1602.05411

13. Localization and broadband follow-up of the gravitational-wave transient GW150914 LIGO-P1500227

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Public Outreach Science Summaries

http://ligo.org/science/outreach.php

- Main detection paper:
  http://ligo.org/science/Publication-GW150914/
- Parameters/Astrophysics/Rates:
  http://ligo.org/science/Publication-GW150914Astro/
- Implications for stochastic background:
  http://ligo.org/science/Publication-GW150914Stoch/
- More to come!

Also public data release:
https://losc.ligo.org/events/GW150914/

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   - Crash Course in Gravitational Wave Physics
   - Gravitational Wave Detectors
   - Gravitational-Wave Sources & Signals

2. Road to the First Detection
   - Inspiral-Merger-Ringdown Signals and Searches
   - Observation of the Binary Black Hole Merger GW150914

3. Outlook for Gravitational Wave Astronomy
   - Future Advanced Detector Observations
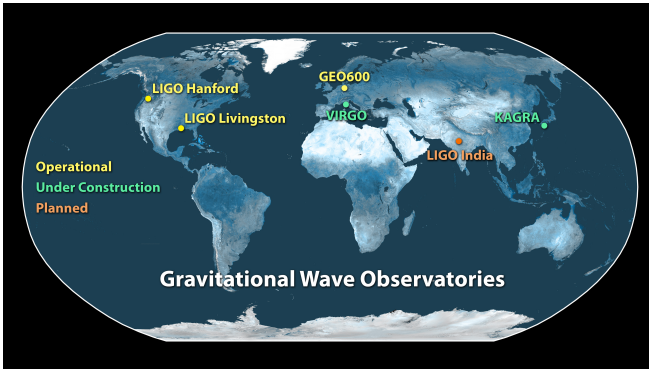   - Transient Signals
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Advanced GW Detector Network

Credit: LIGO

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Advanced Detector Timeline

Liv. Rev. Rel. **19**, 1 (2016); arXiv:1304.0670

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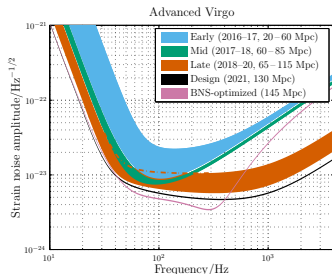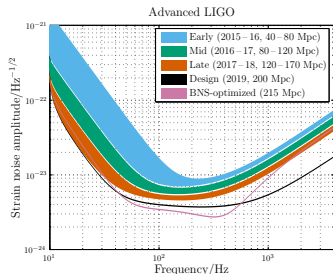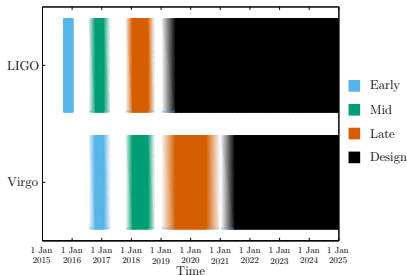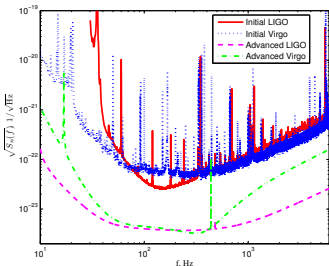
Expansion of the GW Detector Network
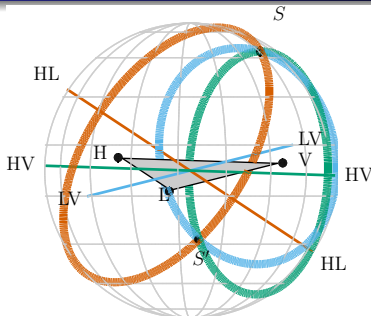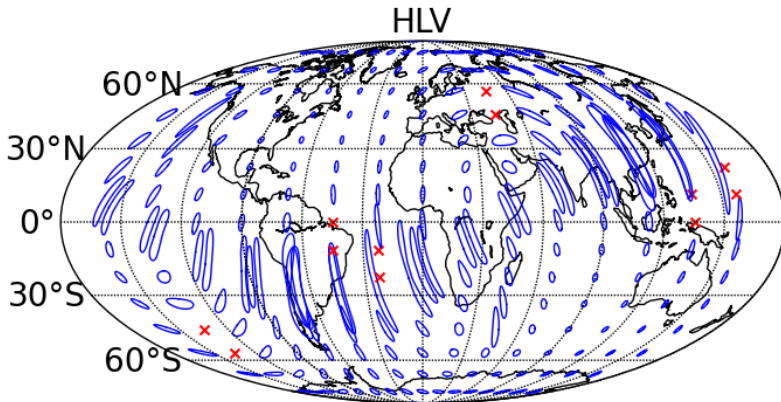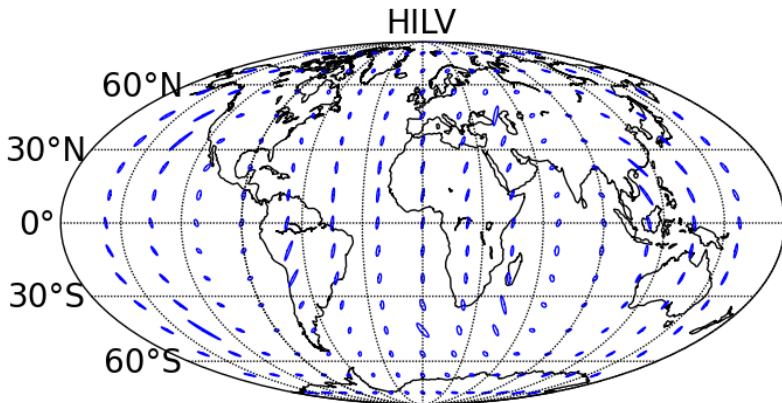

Figure from *Liv. Rev. Rel.* **19**, 1 (2016); arXiv:1304.0670

- Sky loc for GW transients can be found by triangulation
- Spread detectors around globe to make this more accurate
- Put 3rd LIGO detector in India to improve sky localization
  and aid in identification of electromagnetic counterparts
- 2016 Feb 17: "In Principle" approval from Indian cabinet!

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Improvement in Triangulation with LIGO-India

Figures from *Liv. Rev. Rel.* **19**, 1 (2016); arXiv:1304.0670

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Figures from *Liv. Rev. Rel.* **19**, 1 (2016); arXiv:1304.0670

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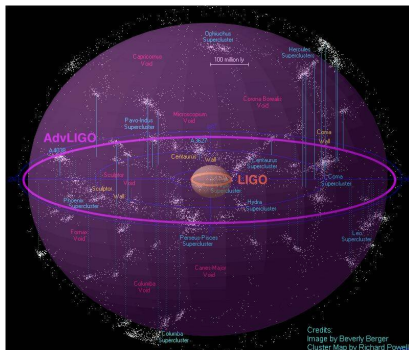RELATIVITY AND
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Expected Event Rates w/Advanced Detectors

CQG **27**, 173001 (2010)

- Advanced detectors should see NS binary inspiral up to 400 Mpc
  & BH binary coalescence up to 2 Gpc away
⟹ Expect between a few and hundreds of events/year

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Predicted BBH Event Rates Going Forward
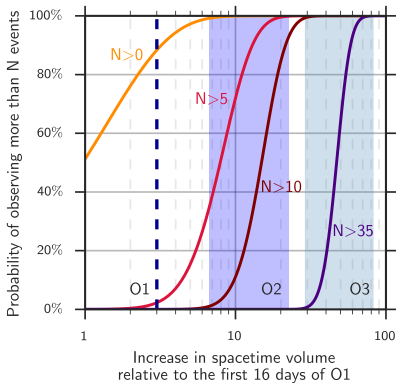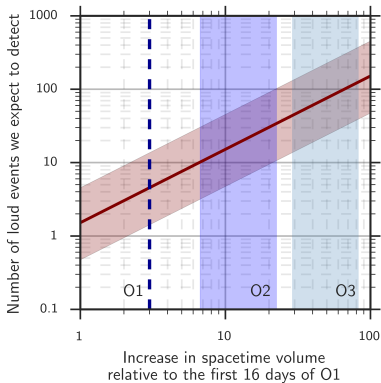
arXiv:1602.03842

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GW150914 Implications for Stochastic Background
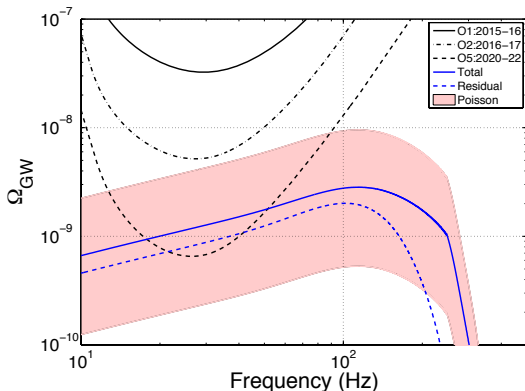
arXiv:1602.03847 BBH mergers more common than expected; unresolved background might be detectable at advanced design
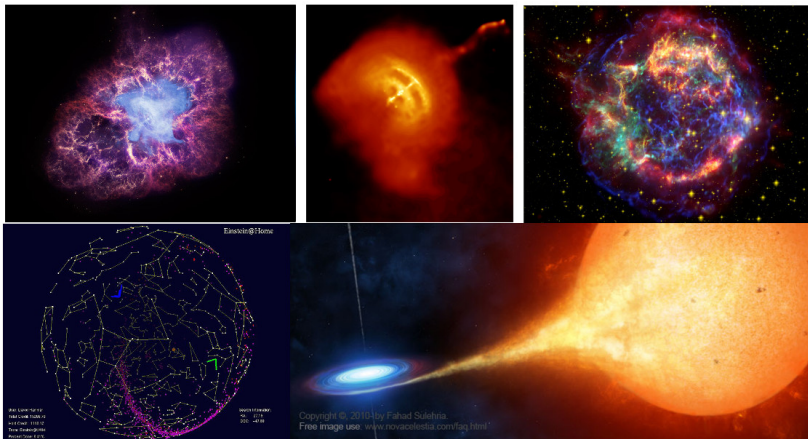
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Periodic GW From Spinning Neutron Stars

Image Credits (clockwise): Hubble/Chandra; Chandra; Spitzer/Hubble/Chandra;

Fahad Sulehria, http://www.novacelestia.com/; http://www.einsteinathome.org/

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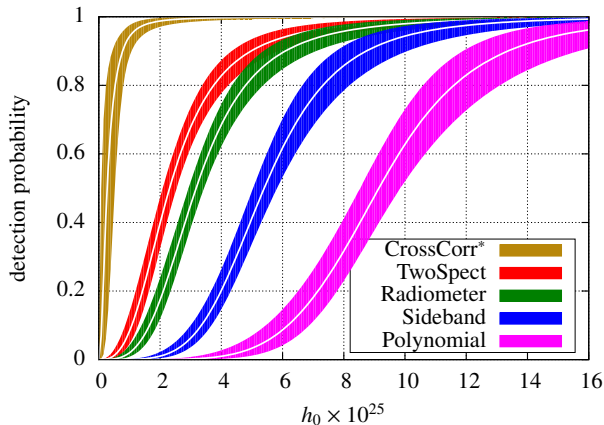# Gravitational Waves from Low-Mass X-Ray Binaries

- LMXB: compact object (neutron star or black hole) in binary orbit w/companion star
- If NS, accretion from companion provides "hot spot"; rotating non-axisymmetric NS emits gravitational waves
- Bildsten *ApJL* **501**, L89 (1998) suggested GW spindown may balance accretion spinup; GW strength can be estimated from X-ray flux
- Torque balance would give ≈ constant GW freq
- Signal at solar system modulated by binary orbit

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Scorpius X-1 Mock Data Challenge

Scorpius X-1: brightest LMXB & promising ADE source

Messenger et al *PRD* **92**, 023006 (2015)

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Prospects for Sco X-1 w/Advanced Detectors
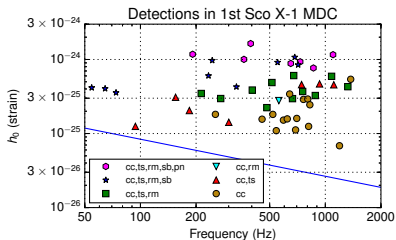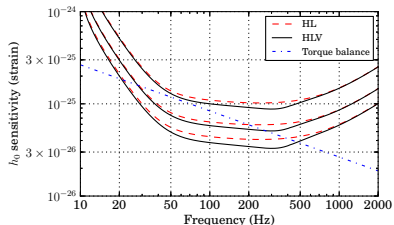
Whelan et al arXiv:1504.05890; *PRD* **91**, 102005 (2015)
Messenger et al arXiv:1504.05889; *PRD* **92**, 023006 (2015)
Leaci & Prix arXiv:1502.00914; *PRD* **91**, 102003 (2015)

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Summary

- Gravitational waves: predicted by Einstein
  confirmed indirectly (Hulse-Taylor binary pulsar)
- Advanced LIGO has made 1st direct detection of GW
  GW150914: Binary Black Hole Merger
- The era of gravitational-wave astronomy has begun

Links:

- http://ccrg.rit.edu/GW150914
- http://papers.ligo.org/
- https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html
- https://losc.ligo.org/events/GW150914/

EXTRA SLIDES

Gravitational Wave Polarization States

- Far from source, GW looks like plane wave prop along $\vec{k}$
- TT conditions mean, in convenient basis,

$$\{k_i\} \equiv \boldsymbol{k} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad \{h_{ij}\} \equiv \mathbf{h} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where $h_+\left(t - \frac{x^3}{c}\right)$ and $h_\times\left(t - \frac{x^3}{c}\right)$ are components
in "plus" and "cross" polarization states

- EM (spin-1 massless photon) & grav (spin-2 massless "graviton")
  waves both have two polarization states

Methods for Measuring Gravitational Waves

- Cosmic Microwave Background Perturbations
  ($f_{gw} \sim H_0 \sim 10^{-18}$ Hz)
- Pulsar Timing Arrays (10^{-9} Hz $\lesssim f_{gw} \lesssim 10^{-7}$ Hz)
- Laser Interferometers
  - Space-Based (10^{-3} Hz $\lesssim f_{gw} \lesssim 10^{-1}$ Hz)
    (eLISA scheduled for 2034;
    LISA Pathfinder technology demonstration underway now)
  $\Longrightarrow$ Ground-Based (10^1 Hz $\lesssim f_{gw} \lesssim 10^3$ Hz)

Note, observable GW freq cover 20 orders of magnitude,
similar to EM radiation, but the frequencies are much lower
(10^3 Hz $\lesssim f_{em} \lesssim 10^{23}$ Hz)

A Few Words About Collaborations

- LIGO Scientific Collaboration **LSC**: hundreds of researchers at dozens of institutions world-wide working on instrument science, data analysis, astrophysics, etc.
    - LSC scientists operate LIGO & GEO detectors
    - and indigo consortium are LSC members
- VIRGO Collaboration operates Virgo (Italy) and includes institutions in Italy, France, Netherlands, Poland & Hungary

    - LIGO & Virgo conduct data analysis jointly

- KAGRA: Japanese collaboration constructing detector in Kamioka mine

Brightest LMXB: Scorpius X-1

- Scorpius X-1
  - $1.4 M_\odot$ NS w/$0.4 M_\odot$ companion
  - unknown params are f_0, $a \sin i$, orbital phase
  - Parameters from Steeghs & Casares *ApJ* **568**, 273 (2002)
    Update by Galloway et al *ApJ* **781**, 14 (2014)
- Promising source for Advanced Detectors
- Initial LSC/Virgo searches for Sco X-1:
  - Coherent $\mathcal{F}$-stat search w/6 hr of S2 data
    Abbott et al (LSC) *PRD* **76**, 082001 (2007)
  - Directed stochastic ("radiometer") search (unmodelled)
    Abbott et al (LSC) *PRD* **76**, 082003 (2007)
    Abbott et al (LSC) *PRL* **107**, 271102 (2011)
- Mock data challenge to compare Sco X-1 search methods
  Poster by Messenger et al at GWPAW 2013
- One method: Cross-corr specialized to periodic signal
  Dhurandhar et al *PRD* **77**, 082001 (2008)