The Dawn of Gravitational-Wave Astronomy

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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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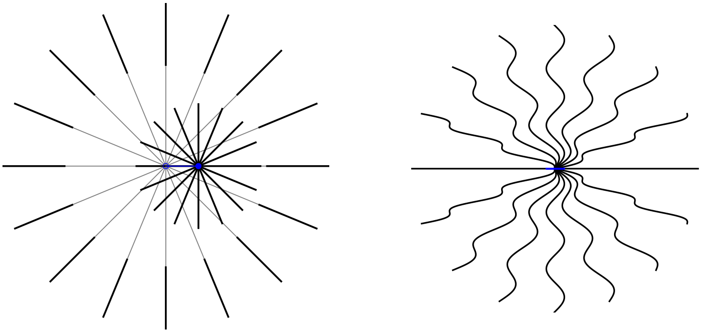
What are Gravitational Waves?

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

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

Gravity as Geometry

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

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

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

- General Spacetime:

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

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

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 $\{h_{ij}\}$:

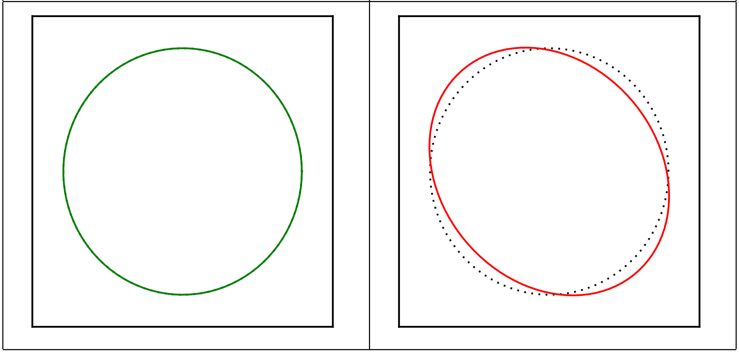
    $$\left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}+\nabla^2\right)h_{ij}=0$$

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

Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:

Plus $(+)$ Polarization	Cross $(\times)$ Polarization



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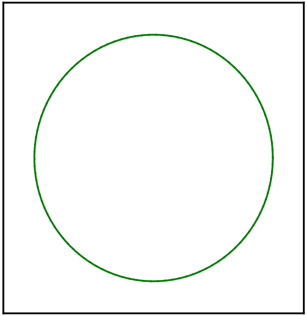
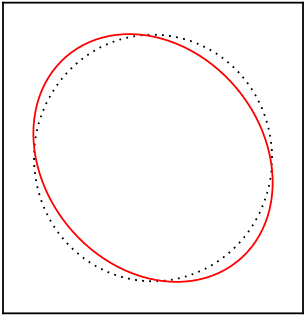
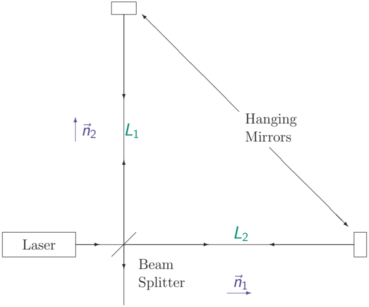
	

Measuring GWs w/Laser Interferometry

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: $h \lesssim 10^{-20}$ → need L_0 very big!
- For LIGO, $L_0 = 4\,\mathrm{km}$

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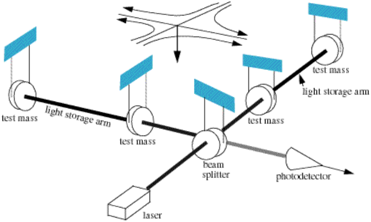

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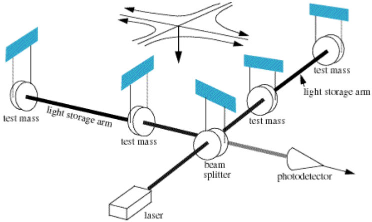

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Note: other detection methods include resonant bars, pulsar timing arrays & planned space-based interferometers (space-based ifos measure low-freq GWs, PTA very low-freq)

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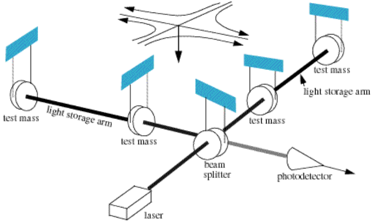

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Note: other detection methods include resonant bars, pulsar timing arrays & planned space-based interferometers (space-based ifos measure low-freq GWs, PTA very low-freq)
Note: LISA Pathfinder technology mission underway!

Rogues' Gallery of Ground-Based Interferometers

LIGO Hanford
(Washington, USA)

GEO-600 (Germany)

LIGO Livingston
(Louisiana, USA)

Virgo (Italy)

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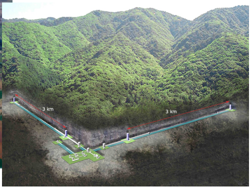
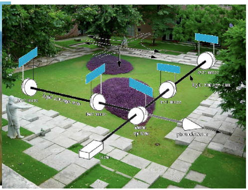


KAGRA (Japan)

LIGO Livingston
(Louisiana, USA)

Virgo (Italy)



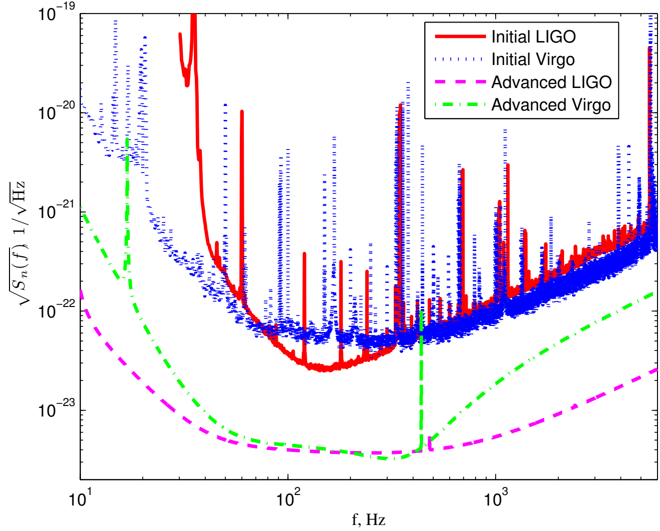
LIGO India

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

Sensitivity of Initial & Advanced Detectors



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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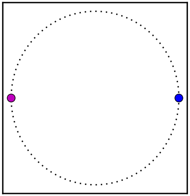
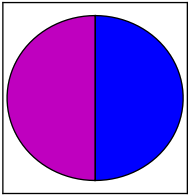
Generation of Gravitational Waves

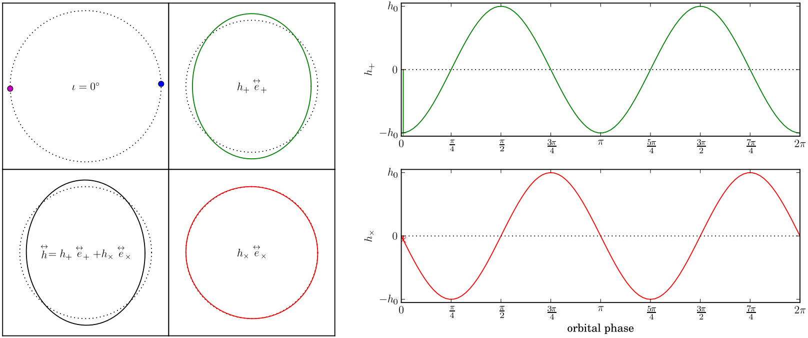
- EM waves generated by moving/oscillating charges
- GW generated by moving/oscillating masses
- Lowest multipole is quadrupole
- Different types of signals:
  - Burst (transient, unmodelled)
  - Stochastic (long-lived, unmodelled)
  - Binary coalescence (transient, modelled)
  - Periodic (long-lived,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





Gravitational Waves from Binary Orbit

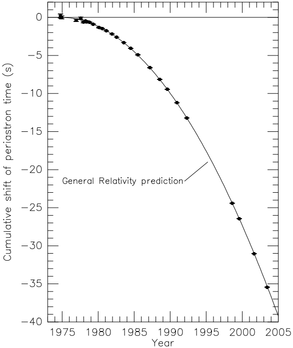
- Orbital motion → oscillating quadrupole moment → GWs



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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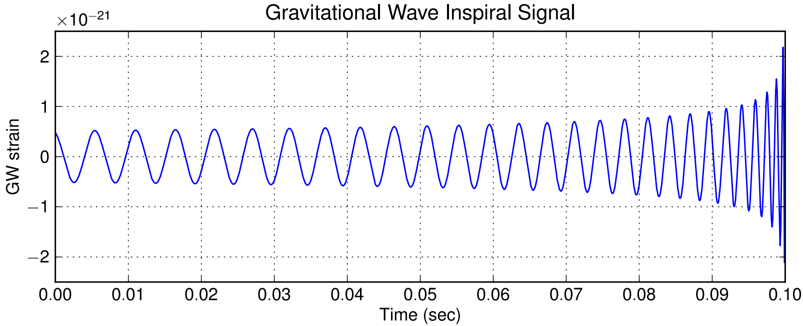

Compact Binary Inspiral

- 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
    $1.4M_{\odot}/1.4M_{\odot}$ NS/NS binary has $v \approx 0.3c$ @ 800 Hz;
    PN OK in LIGO band
  - High Mass $\longrightarrow$ plunge @ low freq
    $10M_{\odot}/10M_{\odot}$ BH/BH binary has $v \approx 0.4c$ @ 200 Hz;
    merges in LIGO band
- Different template families used for different mass ranges

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×
- 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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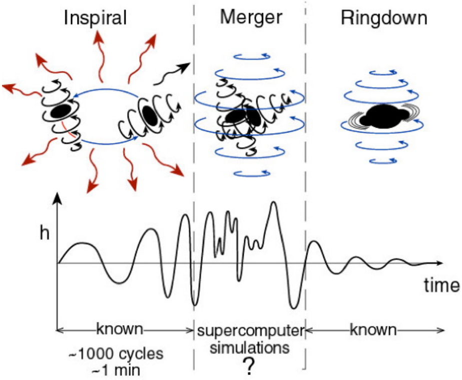
Template Waveforms for Binary Coalescence

- 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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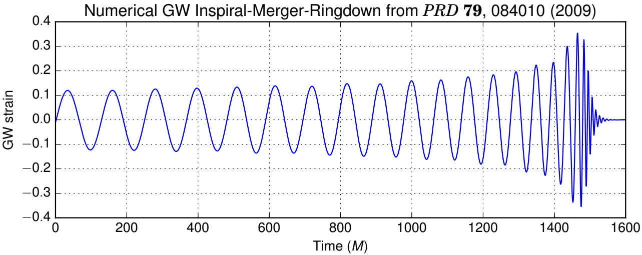

Campanelli et al, *PRD* **79**, 084010 (2009)

http://ccrg.rit.edu/downloads/waveforms

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

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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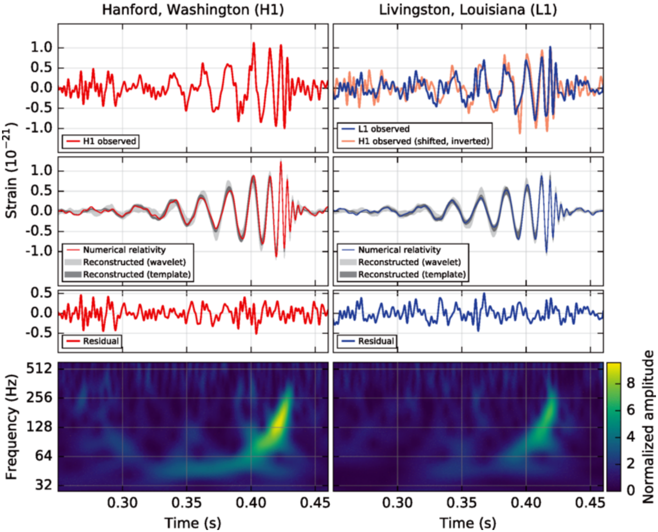
Observation of a BBH Merger

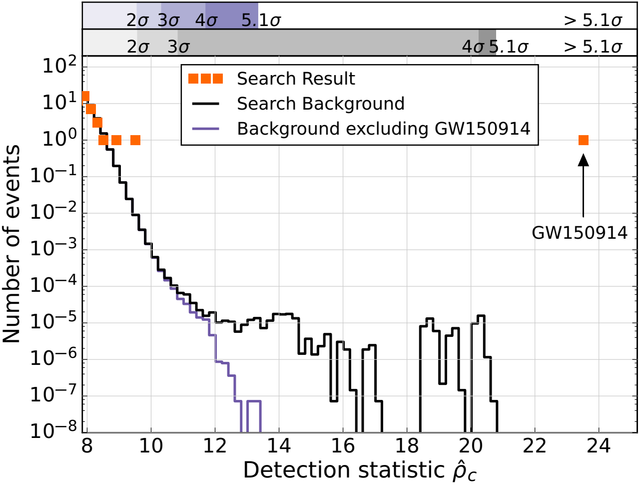
- While preparing for 1st Observing Run (O1) start in 2015 Sep
  End of 8th Engineering Run (ER8) meant "soft start": experimental, data collection & analysis systems transitioning to final configuration
- Online burst analysis reported "loud" trigger on 2015 Sep 14 consistent with high-mass binary black 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)

Convincing Pictures



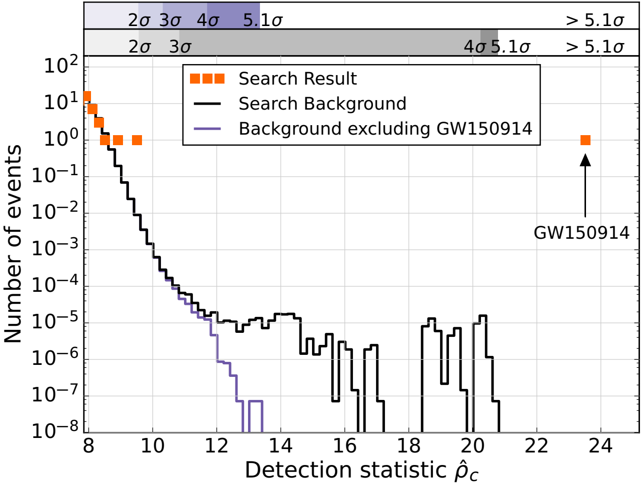
arXiv:1602.03837; *PRL* **116**, 061102 (2016)

Detection Confidence: Matched Filter #1



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

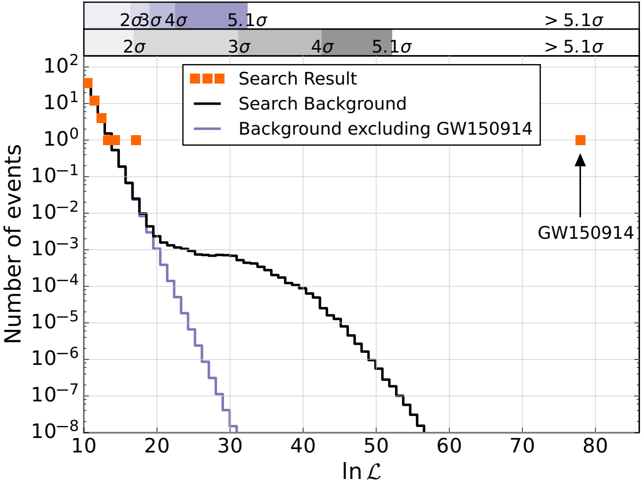
Detection Confidence: Matched Filter #1



arXiv:1602.03839; Second, marginal candidate "LVT151012" w/FAR $1/2.3\,\mathrm{yr}$

No detection claim, but influences rate estimates

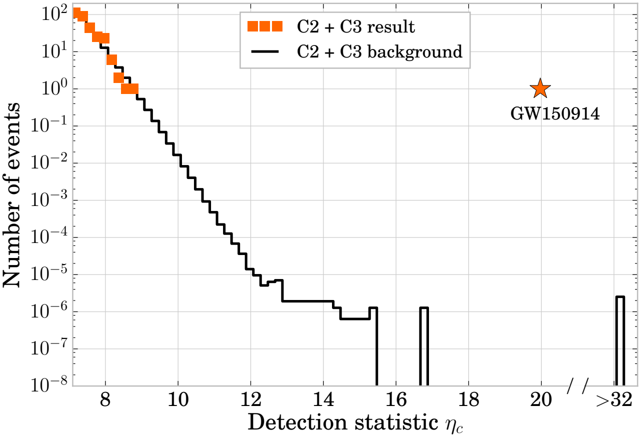
Detection Confidence: Matched Filter #2



Estimate coincident false alarm probability from singles rates

arXiv:1602.03839

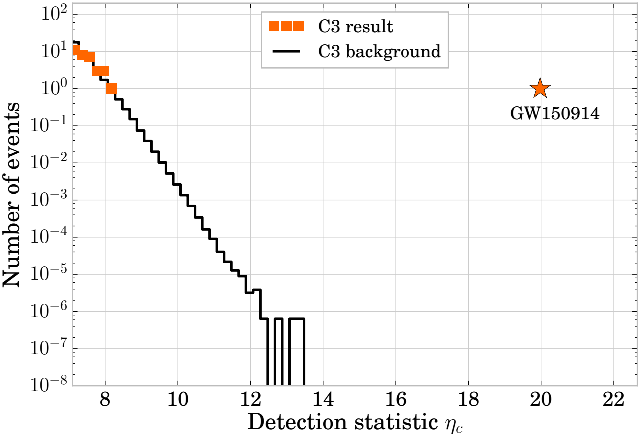
Detection Confidence: Unmodelled Coherent Search



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

arXiv:1602.03843

Detect. Conf.: Minimally Modelled Coherent Search



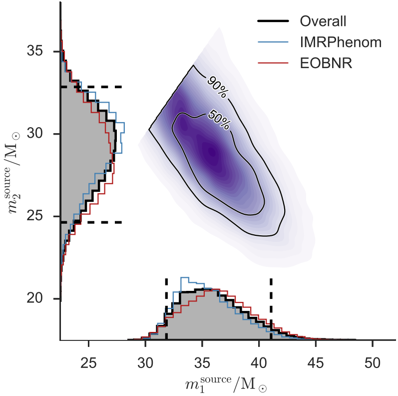
Estimate coincident false alarm rate w/time shifts: $< 1/2 \times 10^4$ yr

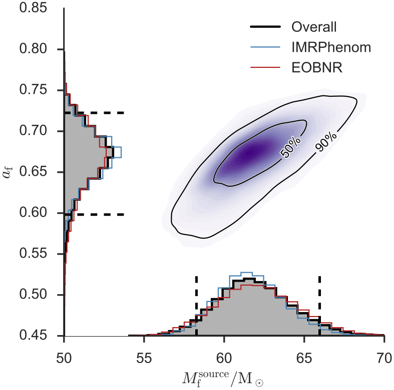
arXiv:1602.03843

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

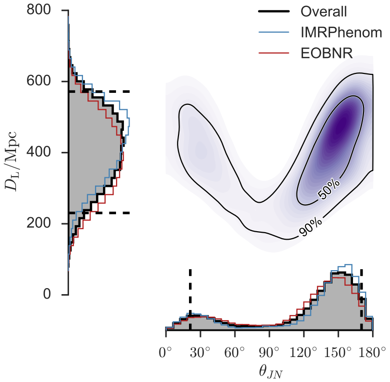
Parameter Estimation: Masses & Spins

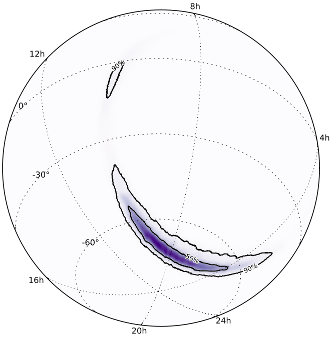




arXiv:1602.03840

Parameter Estimation: Distance & Sky Position





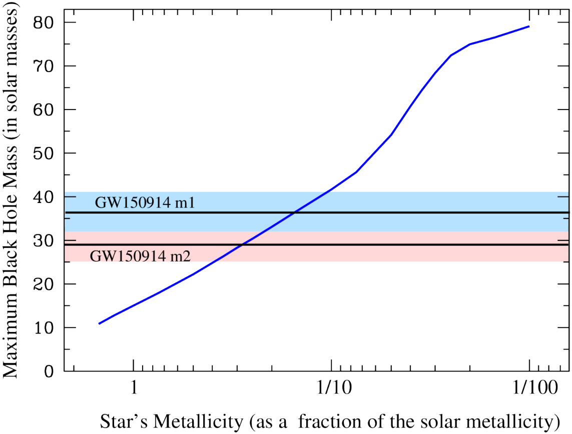
arXiv:1602.03840: Distance degenerate w/inclination angle; Triangulation gives ring on sky, broken by polarization: 90% credible region is 590 deg^2

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)

Astrophysical Implications: Metallicity



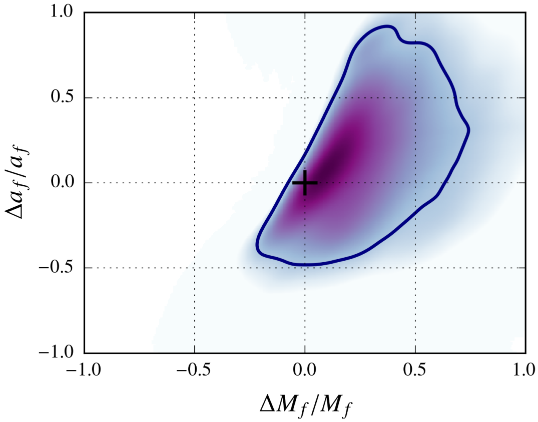
arXiv:1602.03846; *ApJL* **818**, L22 (2016)
(Belczynski et al arXiv:0904.2784; *ApJ* **714**, 1217 (2010))

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 × time
  16-day data set had $VT = 0.082^{+0.053}_{-0.032}\,\mathrm{Gpc}\,\mathrm{yr}$ 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

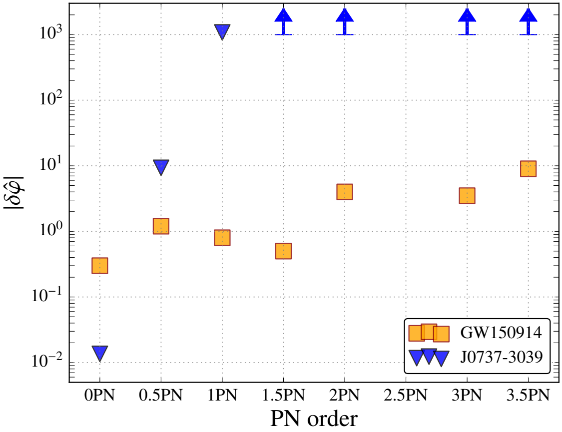
Testing General Relativity w/GW150914 (“Einstein was right”)



Final BH mass & spin

arXiv:1602.03841

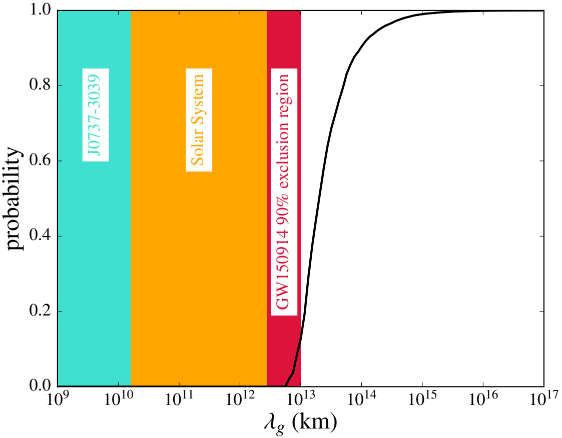
Testing General Relativity w/GW150914 ("Einstein was right")



Post-Newtonian phasing (compare double pulsar)

arXiv:1602.03841

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



Graviton compton wavelength

arXiv:1602.03841

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

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/

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
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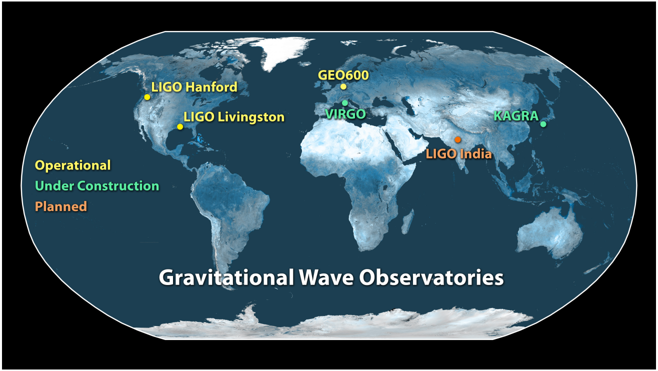
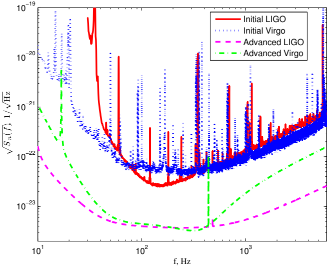
Advanced GW Detector Network

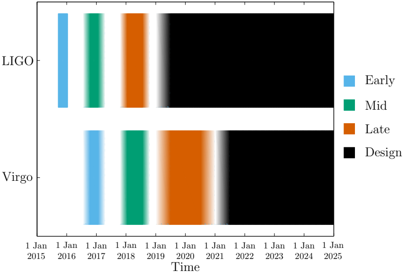


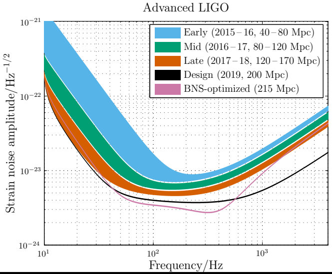
Credit: LIGO

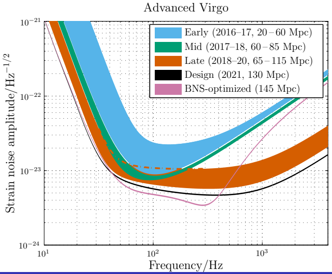
Advanced Detector Timeline

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









Expansion of the GW Detector Network

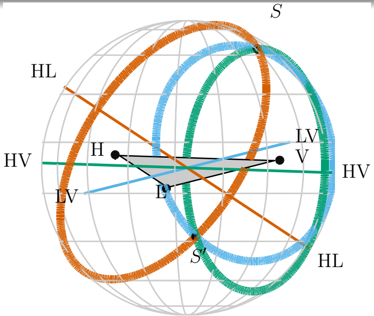
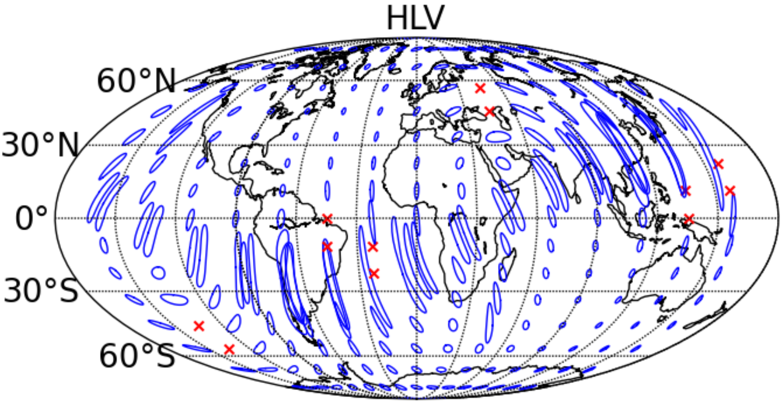


Figure from *Liv. Rev. Rel.* **19**, 1 (2016); arXiv:1304.0670

- 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!

Improvement in Triangulation with LIGO-India



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

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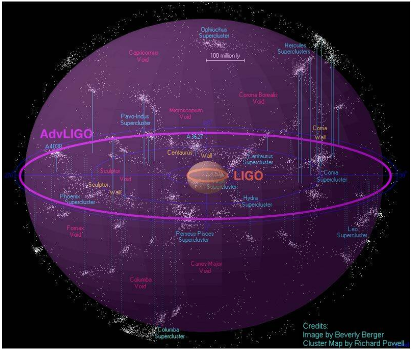
Expected Event Rates w/Advanced Detectors

CQG **27**, 173001 (2010)

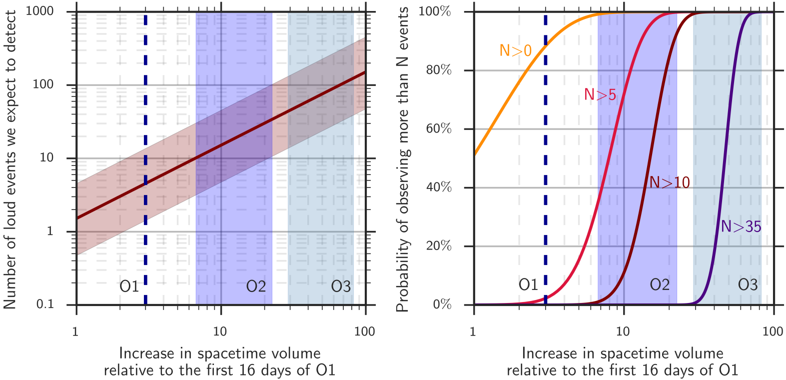
- Advanced detectors should see NS binary inspiral up to 400 Mpc & BH binary coalescence up to 2 Gpc away

⟹ Expect between a few and hundreds of events/year



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Predicted BBH Event Rates Going Forward



arXiv:1602.03842

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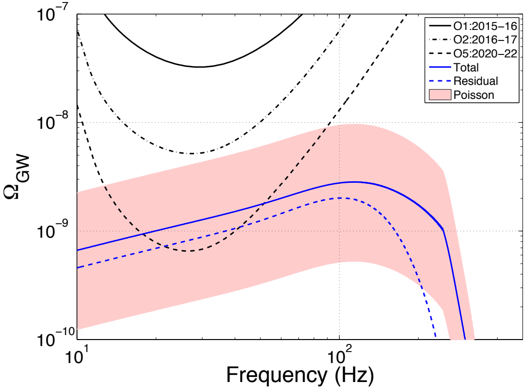
GW150914 Implications for Stochastic Background



arXiv:1602.03847 BBH mergers more common than expected; unresolved background might be detectable at advanced design

Periodic GW From Spinning Neutron Stars

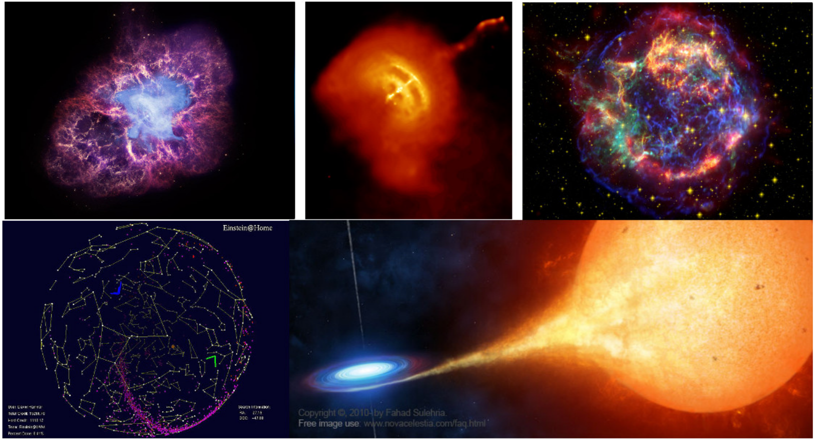


Image Credits (clockwise): Hubble/Chandra; Chandra; Spitzer/Hubble/Chandra; Fahad Sulehria, http://www.novacelestia.com/; http://www.einsteinathome.org/

Gravitational Waves from Low-Mass X-Ray Binaries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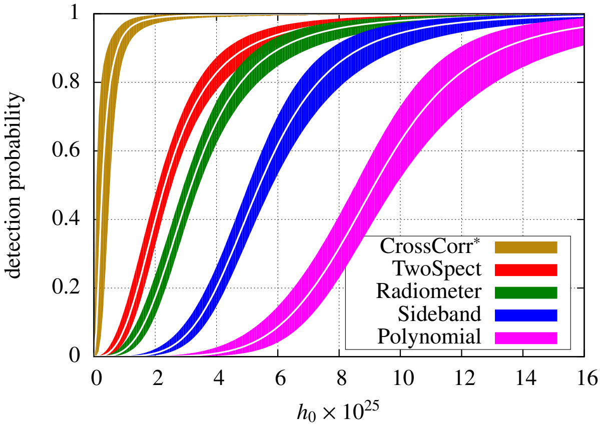
Free image use: www.novacelestia.com/faq.html

- 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 $\approx$ constant GW freq
- Signal at solar system modulated by binary orbit

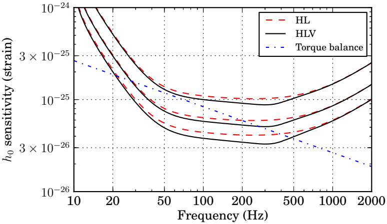
Scorpius X-1 Mock Data Challenge

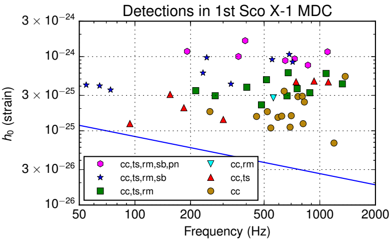
Scorpius X-1: brightest LMXB & promising ADE source



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

Prospects for Sco X-1 w/Advanced Detectors





Detections in 1st Sco X-1 MDC

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)

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

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

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
    - GEO 600 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)