

Gravitational Waves and the dawning of multimessenger astronomy

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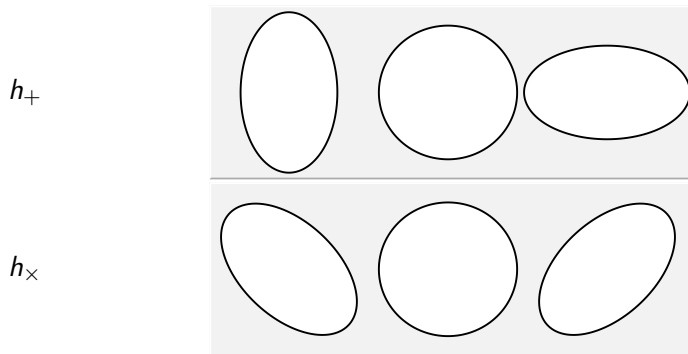
XXXIX Encontro Nacional de Física de Partículas e Campos,
September 26th 2018

GW basics in 1 slide

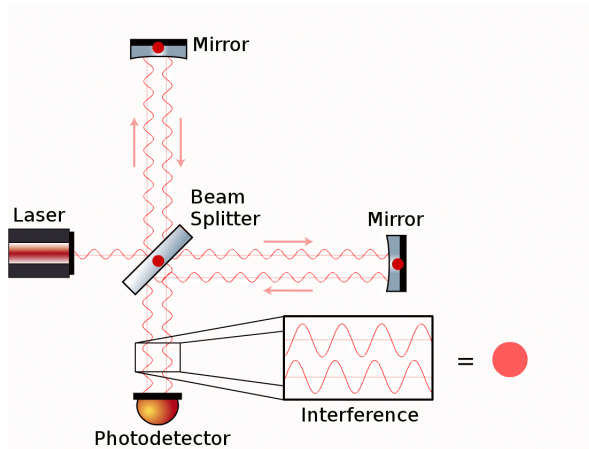
Gauged fixed metric perturbations $h_{\mu\nu}$ after discarding $h_{0\mu}$ components, which are not radiative \rightarrow **transverse** waves

$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

2 pol. state like any mass-less particle



LIGO and Virgo: very precise rulers



Light intensity \propto light travel difference in perpendicular arms

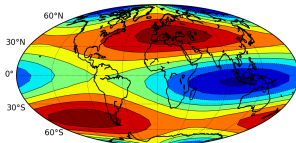
Effective optical path increased by factor $N \sim 500$ via Fabry-Perot cavities

Phase shift $\Delta\phi \sim 10^{-8}$ can be measured $\sim 2\pi N\Delta L/\lambda \rightarrow \Delta L \sim 10^{-15}/N$ m

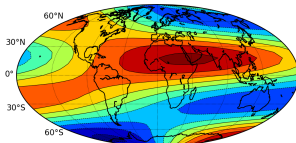
Almost omnidirectional detectors

Detectors measure h_{det} : linear combination $F_+ h_+ + F_\times h_\times$

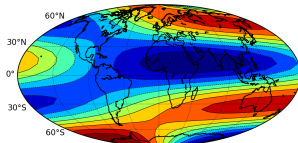
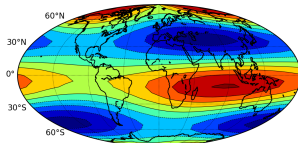
$-1 \ 0 \ 1$
 F_+



F_\times



L



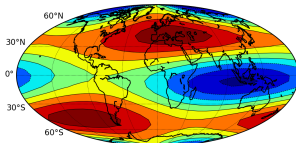
$h_{+,\times}$ depend on source

pattern functions $F_{+,\times}$ depend on orientation source/detector

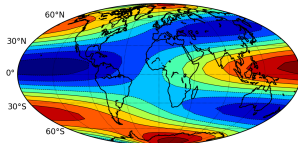
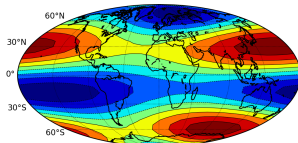
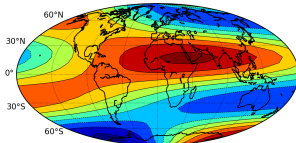
Almost omnidirectional detectors

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 H V

-1 0 1
 F_+



F_\times



$h_{+,\times}$ depend on source

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The LIGO and Virgo observatories



- Observation run **O1** Sept '15 - Jan '16
~ 130 days, with 49.6 days of actual data, PRX (2016) 4, 041014, **2 detectors**, **2BBH**
- **O2** Dec. '16 – Jul'17 **2 det's** + Aug '17 **3 det's**
2(+1) BBH + **1BNS** in **double (triple) coinc.**
- **O3**, **3 detectors**, scheduled to start in ~ Feb 2019, last ~ 1yr

In ~ 2020 Japanese KAGRA and 2020+ Indian INDIGO will join the collaboration

Wave generation: localized sources

Einstein formula relates h_{ij} to the source quadrupole moment Q_{ij}

$$Q_{ij} = \int d^3x \rho \left(x_i x_j - \frac{1}{3} \delta_{ij} x^2 \right), \quad v^2 \simeq G_N M / r, \quad \eta \equiv m_1 m_2 / M^2$$

$$h_{ij} \sim g(\theta_{LN}) \frac{2G_N}{D} \frac{d^2 Q_{ij}}{dt^2} \simeq \frac{2G_N \eta M v^2}{D} \cos(2\phi(t))$$

$$f = 2\text{kHz} \left(\frac{r}{30\text{Km}} \right)^{-3/2} \left(\frac{M}{3M_\odot} \right)^{1/2} < f_{\text{Max}} \simeq 12\text{kHz} \left(\frac{M}{3M_\odot} \right)^{-1}$$

$$v = 0.3 \left(\frac{f}{1\text{kHz}} \right)^{1/3} \left(\frac{M}{M_\odot} \right)^{1/3} < \frac{1}{\sqrt{6}}$$

Geometric factor $g(\theta_{LN})$ takes account of **transversality** projection (angular momentum L of the binary, observation direction N)

$$h_+ \sim \frac{1 + \cos^2(\theta_{LN})}{2} \eta \frac{M v^2}{r} \cos \phi(t_s / M, \eta, S_i^2 / m_i^4, \dots)$$

$$h_\times \sim \cos(\theta_{LN}) \eta \frac{M v^2}{r} \sin \phi(t_s / M, \eta, \dots)$$

Amplitudes of 2 polarizations modulated by θ_{LN} ($h \nearrow$ for $\theta_{LN} \searrow 0$), never both vanishing unlike dipolar motion for the electromagnetic case

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$$h_+ \sim \frac{1 + \cos^2(\theta_{LN})}{2} \eta \frac{M v^2}{d_L} \cos \phi(t_0/M, \eta, S_i^2/m_i^4, \dots)$$

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h sensitive to **red-shifted** masses $M \rightarrow M(1+z) \equiv \mathcal{M}$

Black hole binary systems detected so far

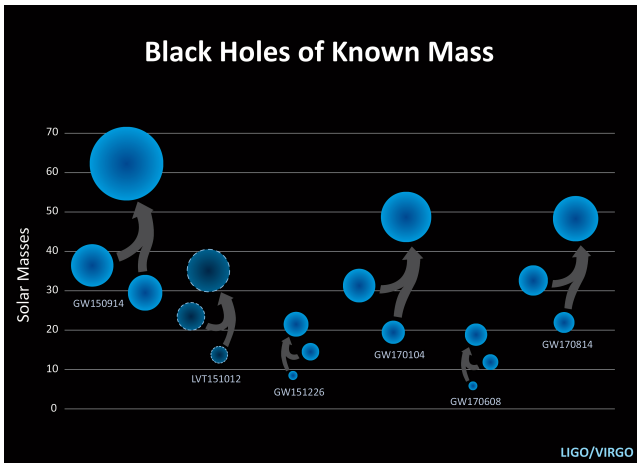
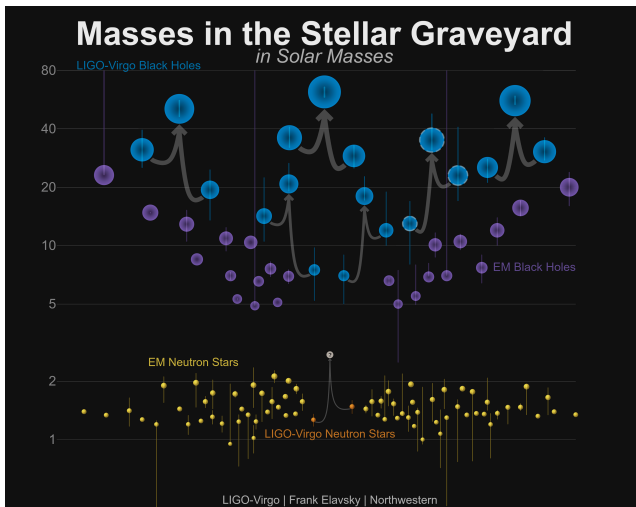


Image by Aurore Simmonet, Sonoma University

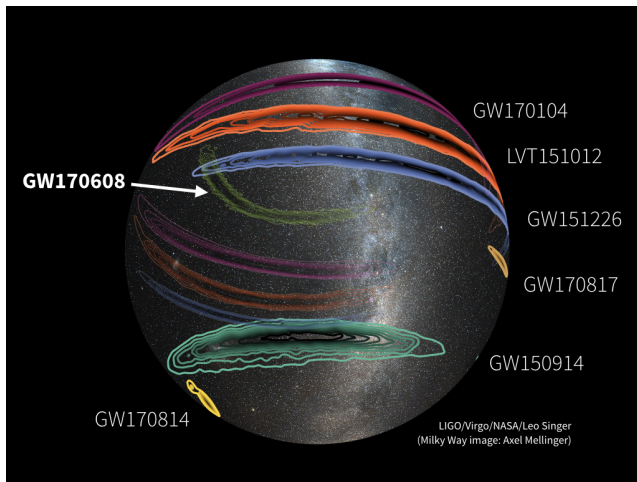
Binary systems and compact detected so far



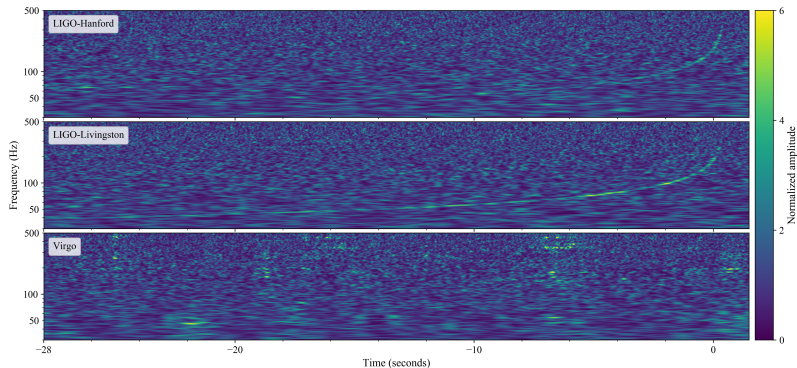
known masses of neutron stars, including 11 BNS systems

Ozel & Freire, *Ann.Rev.Astron.Astrophys.*, 54, (2016) 401 for NS

Sky localization of GW binary systems detected so far



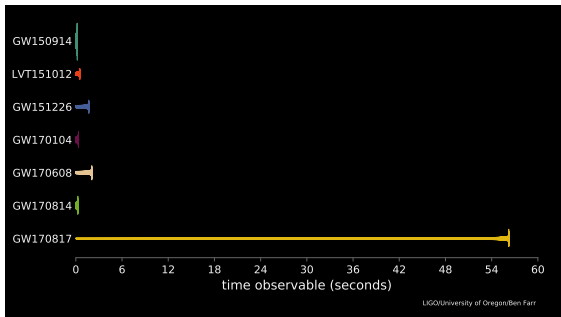
Distances 400, (1000), 400, 350, 900, 500, 50 Mpc ($\pm \sim 20\%$)
3rd detector matters!



BNS horizon (Mpc) was 218 for LL, 107 for LH, 58 for V

LIGO/Virgo Phys.Rev.Lett. 119 (2017) 161101

Detected waves (best fit)



Smaller objects can get closer \implies reach higher frequency before merger

EM/ ν from binary black hole coalescences?

BHs with accretion disks may lead to relativistic outflows with TeV - PeV ν (hadrons accelerated by jets, if magnetic fields and long-lived debris from BH progenitor, or dense gaseous environment) exotic but not impossible

e.g. R. Perna et al. Ap.J. 821 (2016) 1, L18, I. Bartos et al., Ap.J. 835 (2017) 2, 165

- GW150914:

- γ, X optical, radio counterparts not found

Ap.J. 826 (2016) 1, L13

- ν : $E \gg O(100)$ GeV, time window ± 500 sec, coincidences \sim backg.
Limit on ν spectral fluence (10% - 90%): $< 10^{51} - 10^{54}$ erg

LIGO, ANTARES and ICECube Phys.Rev. D93 (2016) no.12, 122010

- GW151226 (LVT151012): $E_{iso} < 2 \times 10^{51} - 2 \times 10^{54}$ erg

LIGO, ANTARES, IceCube, Phys.Rev. D96 (2017) 2, 022005

- GW170104: No ν detection with a ± 500 sec window, nor in ± 3 months

ANTARES Eur.Phys.J. C77 (2017) 12, 911

For reference: $E_{GW150914} \sim 10^{54}$, long(short) GRB $E_{iso} \sim 10^{51}$, (10^{49} erg)

EM/ ν from binary black hole coalescences? **Nope**

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Astro sources emitting transient GWs/EM/ ν radiation

- Coalescing binary systems of compact objects: $\eta \equiv m_1 m_2 / M^2$

$$\Delta E_{GW} \sim 4 \times 10^{-2} M_{\odot} \eta \left(\frac{M}{3M_{\odot}} \right)^{5/3} \left(\frac{f_{max}}{1 \text{ kHz}} \right)^{2/3}$$

A good proxy of the f_{max} is the Innermost Stable Circular Orbit frequency

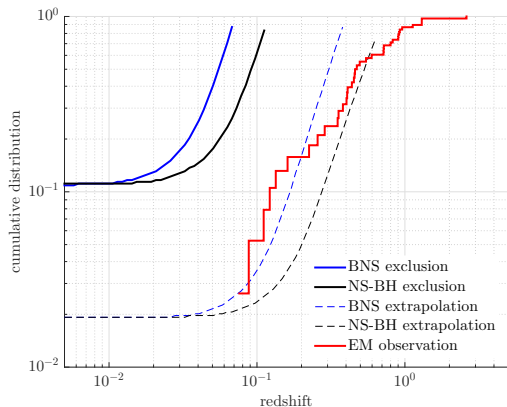
$$f_{ISCO} = \frac{1}{6\sqrt{6}} \frac{1}{M} \simeq 2 \text{ kHz} \left(\frac{M}{M_{\odot}} \right)^{-1}$$

For NS-NS/BH ejected material supposed to produce **short (< 2 sec) GRBs**
 $E_{\gamma} \sim \text{keV-MeV}$, ejected sub-relativistic material may produce **radio signals**

ν : baryon loaded jets may emit ν s:
TeV-PeV ν s @ γ emission
PeV-EeV ν @ optical afterglow

- NS-NS/BH \rightarrow energetic outflows at different timescale/wavelength
- Relativistic jet \rightarrow prompt short γ -ray burst (GRB) duration $\lesssim 1$ sec followed by X, optical, radio afterglows (hrs – days)
- Rapid neutron capture in the sub-relativistic ejecta can produce a **kilonova** or **macronova**, with optical and near-infrared signal (hours - weeks)
- Eventually radio blast from sub-relativistic outflow (months to years)
Several seconds prior to or tens of minutes after merger, coherent radio burst lasting milliseconds may be emitted

Association with 20 short GRB during O1 (before GW170817)

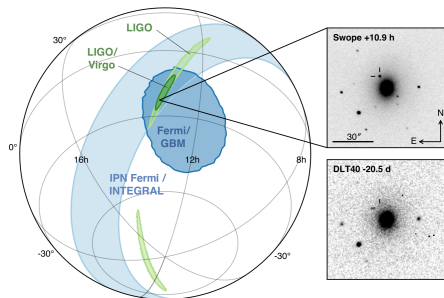


GW searched in a $[-5,+1)$ sec window with GRB

GW constraints far from EM exclusion distance, but extrapolation to design Advanced LIGO sensitivity (2 years of data) will lead to detection/non-trivial constraints

LIGO/Virgo Astrophys. J. 841 (2017) no.2, 89

- GW trigger on Aug 17th, 2017, ended at 12h 41' 04.4" UTC, first in in LIGO Hanford, then confirmed as a triple coincidence → localized in an area of $\sim 28 \text{ deg}^2$
- GRB trigger from Fermi-GBM 1.7" after
- first optical image 10.87 hr afterwards by One-Meter Two Hemisphere team with Swope telescope at Las Campanas Observatory in Chile
- X obtained by the X-Ray Telescope on Swift after 14.9 h (NuSTAR 16.8 h)
- radio ($\sim 3,6 \text{ GHz}$) by VLA 16 days after GW event



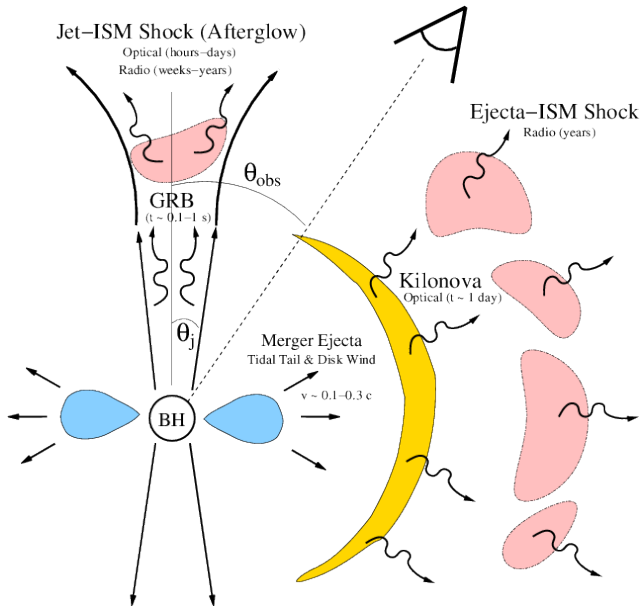
LIGO/Virgo & Partner Astronomy groups, *Astrophys.J.* 848 (2017) no.2, L12

An example of the optical image



Transient Optical Robotic Observatory of the South





Metzger & Berger *Astrophys.J.* 746 (2012) 48

NS merger \rightarrow short γ RB \rightarrow kilonova

- Jet **models** for the ejecta (spherical fireball model)



BNS merger emitted γ rays, expected opening angles $\theta_j \simeq 3^\circ - 10^\circ$:
early time $\theta_j \sim 1/\gamma$ (jet collimated and relativistic), prompt emission from energy dissipation inside relativistic jet: X rays \sim energy output and geometry
Shock wave from sGRB jet hitting surrounding medium, $\theta_j < 1/\gamma_{late}$



broadband synchrotron afterglow, with radio source \sim months and UV, optical & IR emission from sub-relativistic ejecta

ν s expected only from near GRB (or in late emission by flares and plateaus)

Alexander et al., *Astrophys. J.* **848** (2017) no.2, L21

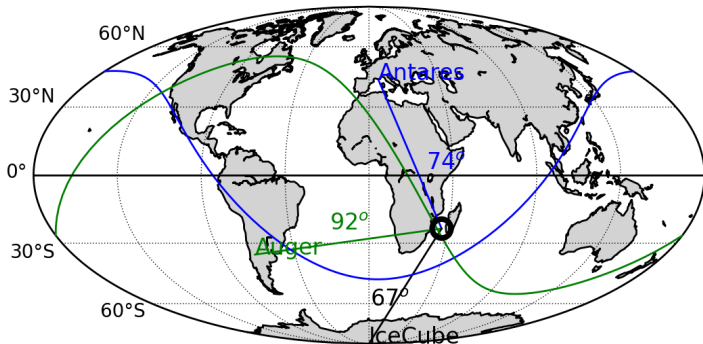
NS merger frees neutron-rich radioactive species, decaying in **kilonova** in \sim days

- **Observation**: Faint gamma ray emission: 10^{46} erg (isotropic), raising Xray flux 2.4 - 5.4 day, continued up to 15 days (Chandra), delayed afterglow



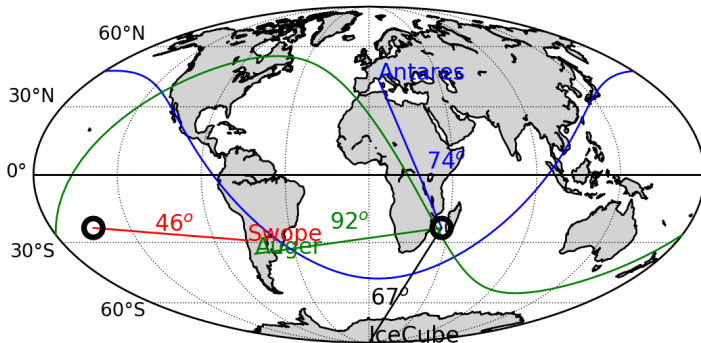
short GRB viewed off-axis $\theta_{obs} \gtrsim 20^\circ$

GW170817 and ν detectors



Potential ν s down-going for Antares and IceCube, grazing for Auger

GW170817 and ν detectors



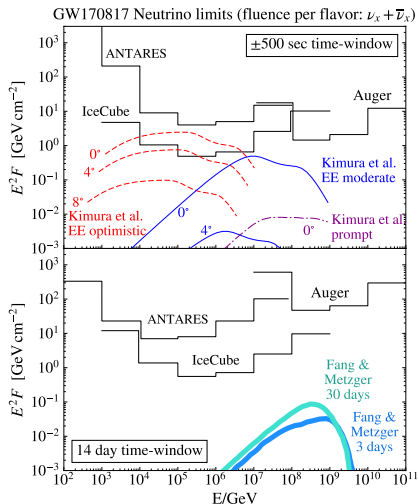
Potential ν s down-going for Antares and IceCube, grazing for Auger
Source location at optical detection

ANTARES and ICECube look for ν

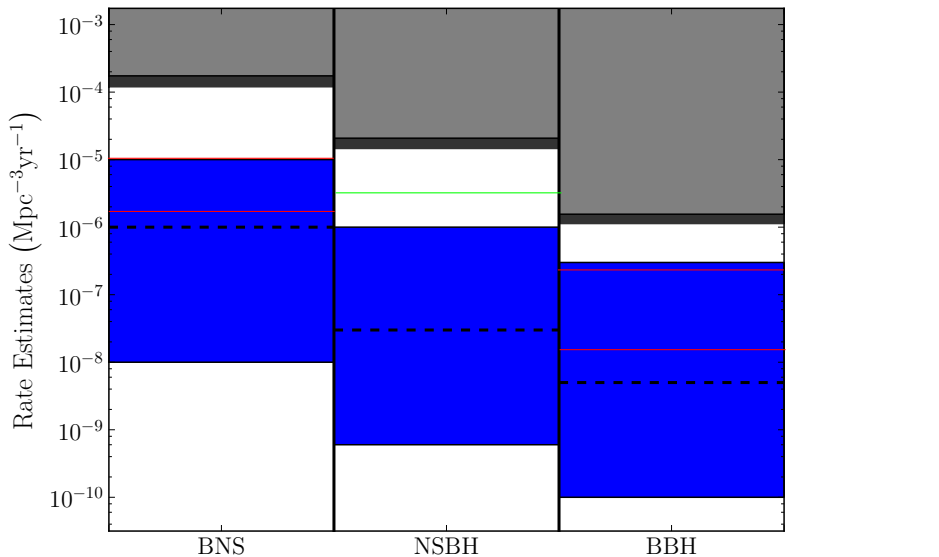
IceCube and ANTARES looked for $\mu - \nu$ at ± 500 sec, observation for 2 weeks

no detection

Pierre Auger for $> 10^{17}$ eV, grazing good for τ production at 10^{18} eV



LIGO/Virgo, ANTARES, ICECUBE and Pierre Auger, *Astrophys.J.* 850 '17 2, L35



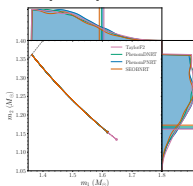
Astrophysical predictions, upper limit from S5/6/O1 and observation from O1/O2

LIGO/Virgo CQG ('10) 27 173001, PRX ('16), APJ (2016), PRL 119 ('17)

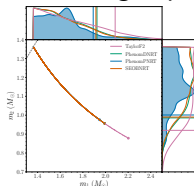
Parameter estimation for GW170817

Low spin prior

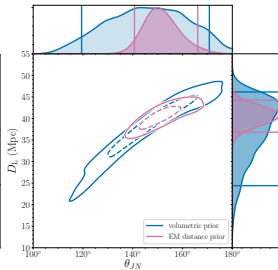
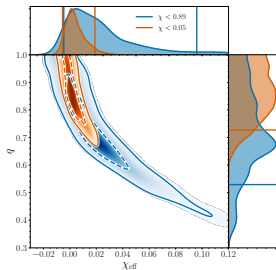
$m_{1,2}$



High spin prior



Spin $\chi_{\text{eff}} = (m_1 S_{1z} + m_2 S_{2z})/M$ - mass ratio q , distance - inclination

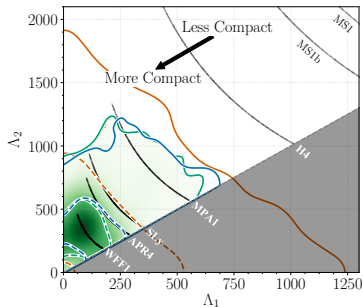


LIGO/Virgo PRL 119, 161101 (2017), [arXiv:1805.11579](https://arxiv.org/abs/1805.11579)

Fundamental physics of Neutron stars

Tidal deformability $\Lambda \simeq R^{-5} Q_{ab} / (\partial_a \partial_b U_{tidal})$ depends on Equation of State

Determinator of $\Lambda_{1,2}$
(assuming same EoS for 1,2)



Shading Common EoS for 2 bodies and constrain for $m_{max} > 1.97 M_{\odot}$
Lines 50%, 90% countours, No minimum m_{max} , independent EoS

LIGO/Virgo collaboration, arXiv:1805.11581

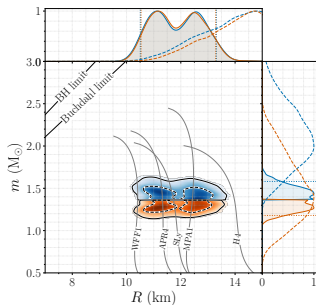
Fundamental physics of Neutron stars II

Parametrizing EoS with $\Gamma \equiv \frac{\epsilon+p}{\rho} \frac{d\rho}{d\epsilon}$, $\Gamma(x) = \exp(\sum_k \gamma_k x^k)$, $x \equiv \log \frac{\rho}{\rho_0}$

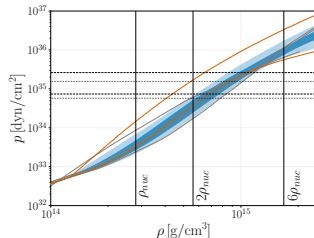
$\gamma_0 \in [0.2, 2], \gamma_1 \in [1.6, 1.7], \gamma_2 \in [0.6, 0.6], \gamma_3 \in [0.02, 0.02], \Gamma(\rho) \in [0.6, 4.5]$

L. Lindblom PRD 82, 103011 (2010)

Constraints on Mass vs- radius and ρ vs. ρ



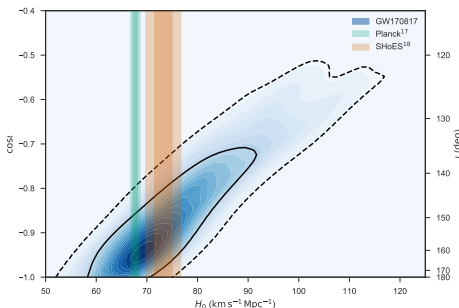
lighter, heavier



90% prior, posterior

LIGO/Virgo collaboration, arXiv:1805.11581

- From GWs only: luminosity distance
 $d_L \sim 40_{-14}^{+8} \text{ Mpc}$, viewing angle
 $\theta_{LN} > 125^\circ$
- Fixing d_L from info from EM location
+ Hubble relation $d_L H_0 = z$
 - 1 Hubble constant from SuperNovae (SHoES)
 $148^\circ < \theta_{LN} < 166^\circ$
Riess et al. ApJ 826, 56 '16
 - 2 from Planck
 $157 < \theta_{LN} < 177^\circ$
Planck A&A, 594, A13 '16
- GW almost coincident with EM
 $\implies \Delta v_{GW}/c \sim 10^{-15}$
LIGO/Virgo, Fermi Gamma-Ray Burst Monitor, INTEGRAL Ap.J. 848 (2017) 2, L13



LIGO/Virgo Nature 551 '17 7678, 85

Fundamental Gravity tests at cosmological scale

GWs travel at the speed of light, with deviations $\lesssim 10^{15}$

Model of dark energy/modified gravity with a single scalar degree of freedom drastically constrained



standard conformal coupling to the Ricci scalar (for Horndeski theories)

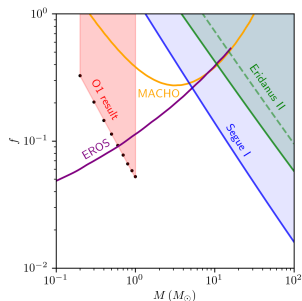
- G. W. Horndeski, Int. J. of Th. Phys. (1974) 10, 6, 363384
- T. Baker, E. Bellini, P. G. Ferreira, M. Lagos, J. Noller, and I. Sawicki, Phys. Rev. Lett. 119, 251301 (2017)
- P. Creminelli & F. Vernizzi, Phys. Rev. Lett. 119, 251302 (2017)
- J. Sakstein & J. Jain, Phys. Rev. Lett. 119, 251303 (2017)
- J. M. Ezquiaga & M. Zumalacregui, Phys. Rev. Lett. 119, 251304 (2017)
- L. Amendola, M. Kunz, I. D. Saltas and I. Sawicki arXiv:1711.04825

Upper bounds on sub-solar mass compact binaries coalescence rate

Mass/ M_{\odot}	Rate($Gpc^{-3}yr^{-1}$)	Horizon(Mpc)
1	$< 10^6$	100
0.2	$< 2 \times 10^4$	30

$$SNR \propto M_c^{5/6}, M_c \equiv \eta^{3/5} M$$

LIGO/Virgo Scientific Collaboration arXiv 1808.04771



Fraction f of MACHOs in binary
 $\sim 10\% \times \Omega_{MachO} \implies$
 $\sim 10^{-3} \Omega_{MachO}$ in coalescing binaries
 coalescing within H_0^{-1}

T. Nakamura et al. in *Astrophys.J.* 487
 (1997) L139-L142

Fundamental GR: inspiral analytic model

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

Virial relation:

$$\nu \equiv (G_N M \pi f_{GW})^{1/3} \quad \nu = \frac{m_1 m_2}{(m_1 + m_2)^2}$$

$$\begin{aligned} E(\nu) &= -\frac{1}{2} \nu M \nu^2 (1 + \#(\nu) \nu^2 + \#(\nu) \nu^4 + \dots) \\ P(\nu) \equiv -\frac{dE}{dt} &= \frac{32}{5 G_N} \nu^{10} (1 + \#(\nu) \nu^2 + \#(\nu) \nu^3 + \dots) \end{aligned}$$

$E(\nu)(P(\nu))$ known up to 3(3.5)PN

$$\begin{aligned} \frac{1}{2\pi} \phi(T) &= \frac{1}{2\pi} \int^T \omega(t) dt = - \int^{\nu(T)} \frac{\omega(\nu) dE/d\nu}{P(\nu)} d\nu \\ &\sim \int (1 + \#(\nu) \nu^2 + \dots + \#(\nu) \nu^6 + \dots) \frac{d\nu}{\nu^6} \end{aligned}$$

Fundamental GR: inspiral analytic model

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

Virial relation:

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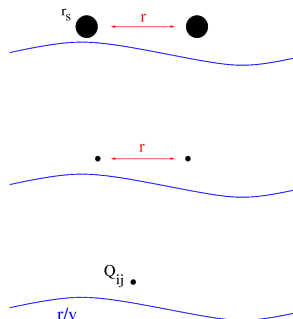
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PN Coefficients

The EFT point of view on the 2-body problem

Different scales in EFT:

- Very short distance
 $\lesssim r_s = G_N M$
negligible up to 5PN
(effacement principle)
- Short distance: **potential gravitons** $k_\mu \sim (v/r, 1/r)$
with $r \sim r_s/v^2$
- Long distance: **GW's**
 $k_\mu \sim (v/r, v/r)$ coupled to
point particles with moments



W. Goldberger and I. Rothstein, PRD '06

Fundamental

- Fundamental gravitational fields
- Fundamental coupling to particle world line

$$\exp [iS_{\text{eff}}(x_a, h_{GW})] = \int \mathcal{D}H(x) \exp [iS_{EH}(H + h_{GW}) + iS_{pp}(H + h_{GW})]$$

$$S_{pp} = -m \int d\tau$$

$$S_{EH} = \frac{1}{32\pi G_N} \int d^4x \left[(\partial h)^2 + h(\partial h)^2 + h^2(\partial h)^2 \dots \right]$$

Fundamental

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$$\exp [iS_{\text{eff}}(x_a, h_{\text{GW}})] = \int \mathcal{D}H(x) \exp [iS_{\text{EH}}(H + h_{\text{GW}}) + iS_{\text{pp}}(H + h_{\text{GW}})]$$

$$S_{\text{pp}} = -m \int dt d^3x \delta(\vec{x} - \vec{x}_a(t)) \left(h_{00}/2 + v_i h_{0i} + v^i v^j h_{ij}/2 + h_{00}^2 \dots \right)$$
$$S_{\text{EH}} = \frac{1}{32\pi G_N} \int d^4x \left[(\partial_i h)^2 - (\partial_t h)^2 + h(\partial h)^2 + h^2(\partial h)^2 \dots \right]$$

Fundamental

- Fundamental gravitational fields
- Fundamental coupling to particle world line

$$\exp [iS_{\text{eff}}(x_a, h_{GW})] = \int \mathcal{D}H(x) \exp [iS_{EH}(H + h_{GW}) + iS_{pp}(H + h_{GW})]$$

$$S_{pp} = -m \int dt d^3x \delta(\vec{x} - \vec{x}_a(t)) \left(\sqrt{G_N} \left(h_{00}/2 + v_i h_{0i} + v^i v^j h_{ij}/2 \right) + G_N h_{00}^2 \dots \right)$$
$$S_{EH} = \frac{1}{2} \int d^4x \left[(\partial_i h)^2 - (\partial_t h)^2 + \sqrt{G_N} h (\partial h)^2 + G_N h^2 (\partial h)^2 \dots \right]$$

EFT for compact binary systems

Fundamental

- Fundamental gravitational fields
- Fundamental coupling to particle world line

Effective

- Generic v -dependent potential terms
- Instantaneous couplings between world-line particles

$$\exp [iS_{\text{eff}}(x_a, h_{GW})] = \int \mathcal{D}H(x) \exp [iS_{EH}(H + h_{GW}) + iS_{pp}(H + h_{GW})]$$

$$S_{pp} = -m \int dt d^3x \delta(\vec{x} - \vec{x}_a(t)) \left(\sqrt{G_N} \left(h_{00}/2 + v_i h_{0i} + v^i v^j h_{ij}/2 \right) + G_N h_{00}^2 \dots \right)$$

$$S_{EH} = \frac{1}{2} \int d^4x \left[(\partial_i h)^2 - (\partial_t h)^2 + \sqrt{G_N} h (\partial h)^2 + G_N h^2 (\partial h)^2 \dots \right]$$

$$S_{\text{eff}} = m_1 \int dt d^3x \left[\frac{1}{2} v_1^2 + \frac{G_N m_2}{2r} + \frac{1}{8} v_1^4 + \frac{G_N^2 m_2}{2r^2} \left(\frac{G_N m_1}{2r} + v_1^2 + v_{1r} v_{2r} \right) + 1 \leftrightarrow 2 \right]$$

3PN: Jaranowski, Schäfer, Damour; Blanchet, Faye; Itoh Futamase; Foffa & RS

4PN: Jaranowski, Schäfer, Damour; Blanchet et al, RS Foffa; RS Foffa, Mastrolia, Sturm

How to compute effective potential?

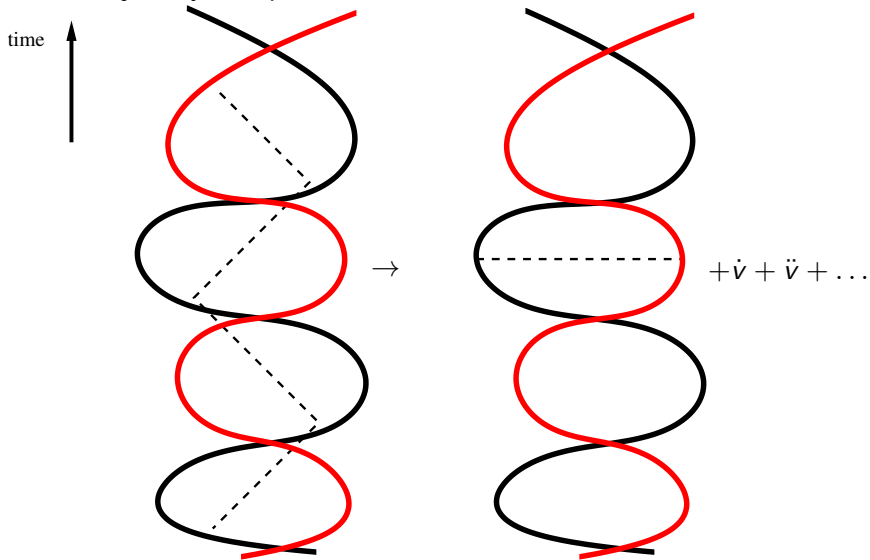
Iteratively solve Einstein equations:

$$\begin{aligned} - \int dt V_{1-2}(t, r) &\sim \int dt dt' d^3x d^3x' J(x) G(x - x') J(x') \\ &= 32\pi G_N m_1 m_2 \int dt dt' \frac{d^4k}{(2\pi)^4} \frac{e^{ik(x_1(t_1) - x_2(t_2))}}{k^2 - k_0^2} \\ &\simeq G_N \int dt dt' \delta(t - t') \frac{m_1 m_2}{|x_1(t) - x_2(t')|} \end{aligned}$$

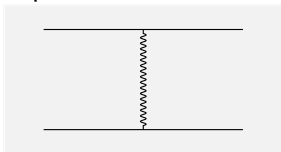
where k_0 has been neglected. Considering effects of v

$$\begin{aligned} V &\propto \int d\omega d^3k \frac{e^{-i\omega t_{12} + ikx_{12}}}{k^2 - \omega^2} = \int d\omega d^3k \frac{e^{-i\omega t_{12} + ikx_{12}}}{k^2} \left(1 + \frac{\omega^2}{k^2} + \dots \right) \\ &= \delta(t_{12}) \int d^3k \frac{e^{ikx_{12}}}{k^2} \left(1 + \frac{\partial_{t_1} \partial_{t_2}}{k^2} + \dots \right) = \int d^3k \frac{e^{ikx_{12}}}{k^2} \left(1 - \frac{k \cdot v_1 k \cdot v_2}{k^2} + \dots \right) \end{aligned}$$

Trading knowledge over the full trajectory with knowledge of all derivatives of the trajectory at equal time

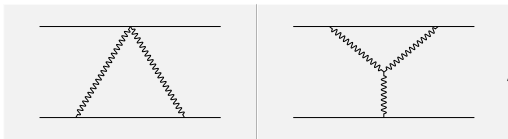


Newtonian potential:

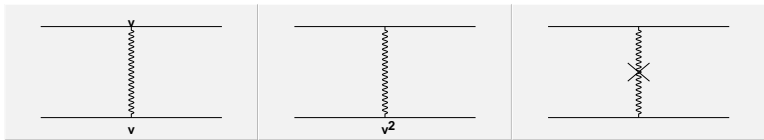


$$S_{\text{eff}} \sim \int dt \frac{G_N m_1 m_2}{r} \sim L$$

At 1PN:



$$S_{\text{eff}} = \int dt \frac{G_N^2 m_1^2 m_2}{r^2} \sim L v^2$$

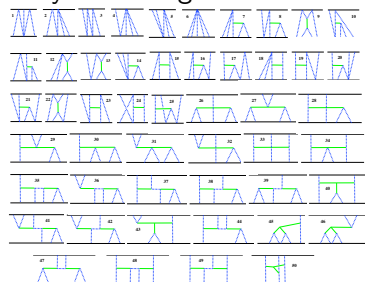


$$V_{1PN} = -\frac{Gm_1 m_2}{2r} \left[1 - \frac{G_N m_1}{2r} + \frac{3}{2}(v_1^2) - \frac{7}{2}v_1 v_2 - \frac{1}{2}v_1 \hat{r} v_2 \hat{r} \right] +$$

$1 \leftrightarrow 2$

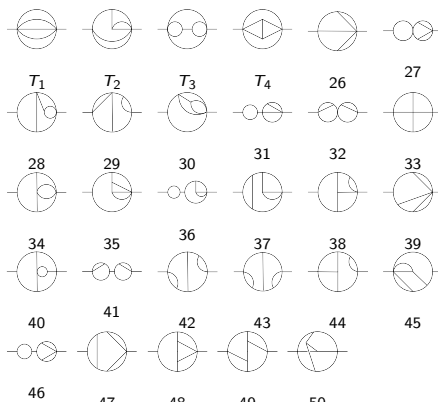
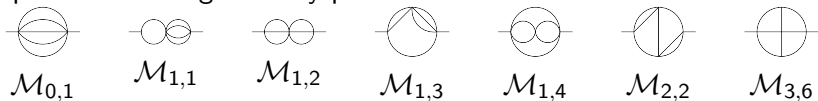
The 4PN static sector

50 Feynman diagrams:



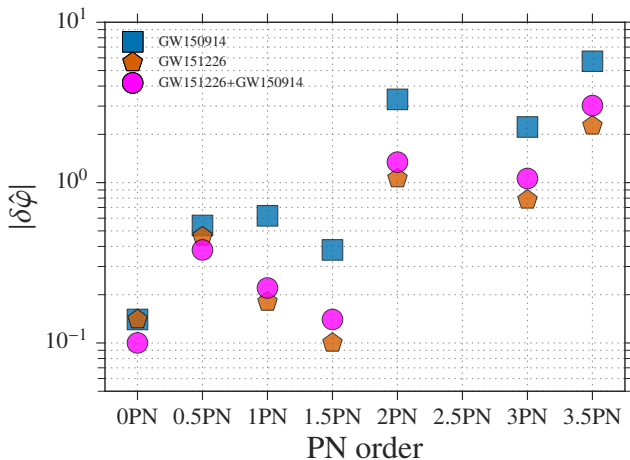
belonging to 29 topologies \rightarrow

expressed via integration by parts reduction in terms of 7 master integrals:



RS, S. Foffa, P. Mastrolia, C. Sturm PRD (2017) 104009

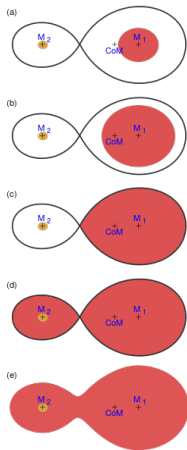
Testing the PN series with GW150914 and GW151226



Precision in measuring the PN coefficients $\sim 100\%$: one cannot both **measure the astro parameters** and **test GR** with **1** detection! Still better precision than with binary pulsars

LIGO/Virgo Phys.Rev. X6 (2016) 4, 041015

How binary systems progenitors formed? I



Izzard et al. Proc. IAU 2012

A binary system of massive stars ($M_{binary} < 100M_{odot}$) can go through a **common envelope** phase that shrinks considerably the orbit and **align the spins** → collapse to compact objects

BNS requires complex evolution from massive binaries + mass transfer and 2 core-collapse SN explosions through which the binary system survives
Asymmetries in collapse imparts natal kick to the (galactic pulsar proper motion)

LIGO/Virgo Ap.J. 850 (2017) L40

vs.

For BBH another mechanism is possible

Globular Cluster: medium with high density of **black holes**/stars, when 3 black holes meet one is ejected and the binary shrinks

LIGO/VirgoAstrophys.J. 818 (2016) no.2, L22

Remnants of the first stars, produced at $z \sim 6$ can give only a small contribution to the total rate

T. Hartwig et al. Mon.Not.Roy.Astron.Soc. 460 (2016) L74

Primordial black-holes? viable if $10^{-2} \lesssim M_{BH}/M_{\odot} \lesssim 1$ (constraints from evaporation, microlensing and CMB) but could grow later to 20-100 M_{\odot} by merger

If present in globular cluster may also explain their cosmological abundance as dark matter

Sasaki M. et al. PRL 2016, Bird S. et al. PRL 2016, Clesse S. and García-Bellido Phys.

Dark Univ. 2017

- After the beginning of GW astronomy, we have witnessed the start of multi-messenger astronomy
- New input for fundamental physics: test of gravity in the strong field at short scale, radiative gravity sector tested at large distances
- New era for Cosmology: H_0 from GWs! (and EM)
- For ν let us wait for a closer source

Conclusions? Not really. Just the beginning!

- After the beginning of GW astronomy, we have witnessed the start of multi-messenger astronomy
- New input for fundamental physics: test of gravity in the strong field at short scale, radiative gravity sector tested at large distances
- New era for Cosmology: H_0 from GWs! (and EM)
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The International Institute of Physics in Natal



Deadline in November 20xx for workshops/program to take place in 20xx+2
Council decision about workshop proposal around March 20xx+1

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More advertisements:

- *IV José Plínio Baptista School on Cosmology: Gravitational Waves* Pedra Azul - Domingos Martins, ES, Brazil. October 15-19, 2018
www.cosmo-ufes.org/jpbcosmo4.html
- *The sound of spacetime*, ICTP-SAIRF school on GWs 26/11 - 14/12 (São Paulo, Brazil) www.ictp-saifr.org
- *Gravitational Wave challenges in cosmology*, school/workshop on GWs, 3-14/6 2019, IIP-UFRN Natal (Brazil) www.iip.ufrn.br