New perspectives onto the Universe in the era of multi-messenger astronomy

Samaya Nissanke,
GRAPPA - Center of Excellence in Gravitation and Astroparticle Physics,
University of Amsterdam, NL

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Group and collaborations

Dr Tanja Hinderer, Delta ITP Fellow
Dr Andrew Williamson, outgoing postdoc —> Portsmouth
Geert Raaijmakers, PhD
Banafshe Shiralou, incoming PhD
Suvodip Mukherjee incoming GRAPPA fellow from IAP/CCA

Dr David Nichols, outgoing postdoc —> faculty at U. Virginia
Andreas Guerra-Chavas, BSc
Archisman Ghosh DITP postdoc (joint Leiden-Amsterdam)
Bob Jacobs, MSci

COLLABORATIONS
LIGO Scientific - Virgo Collaborations
GROWTH team
JAGAWR team
BlackGEM team, NL
LOFAR, MeerKAT, APERTIF, NL
Francois Foucart (New Hampshire)
Kenta Hotokezaka (Princeton)
Gregg Hallinan (Caltech)
Mansi Kasliwal (Caltech)
Kunal Mooley (Caltech)
Alessandra Corsi (Texas Tech)
Shri Kulkarni (Caltech)
Dale Frail (NRAO)
David Tsang (Southampton)
Jennifer Barnes (Columbia)
Hiranya Peiris (UCL, Stockholm)
Daniel Mortlock (Imperial)
Stephen Feeney (Flatiron, Simons)
Neal Dalal (PI)
Chris Hirata (OSU)
Matthew Liska (Harvard)
Philipp Moesta (new faculty at GRAPPA)
A new revolution in the past four years: gravitational waves (GW), black holes and neutron stars

Black Holes (BHs)

2015-2017:
Ten+
Black Hole-Black Hole Mergers
[~ 7.5 - 50 M☉]

Neutron Stars (NSs)

2017:
One Neutron Star - Neutron Star Merger
“GW170817”
[~ 1.1 - 1.6 M☉]
A new revolution in the past four years: gravitational waves (GW), black holes and neutron stars


2017: One Neutron Star - Neutron Star Merger “GW170817”

Third science run began 1st April 2019: 21 binary black hole and 6 neutron star binary merger candidates
Gravitational Physics

Multiple Discoveries of GW170817  
[the gift that keeps on giving]

First Binary Neutron Star detected in Gravitational Waves
First Electromagnetic Counterpart of a GW merger in every waveband!
First Gravitational Wave Standard Siren Hubble Constant Constraint
First Short Gamma Ray Burst - Binary Neutron Star Merger Association
First kilonova discovery and astrophysical sites of r-process heavy elements
First tests of the speed of light and gravity with a GW+EM event ...

Nuclear Physics

[see talks by Holz and Palmese]

Cosmology

[Note: ~ 2700 papers]
From a discovery era to one of precision (astro)physics

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Part I:
The Physics of GW measurements
First Measurement of GWs from a Binary Neutron Star Merger

August 17th 2017 at 12:41:04 UTC (14:41, one hour after lunch!)

Loudest (SNR ~ 32.2) and longest (~ 100 s) signal so far:
False alarm rate < 1 in 80 000 years
GWs are perturbations in spacetime curvature measurable by a network of detectors.

Measurable GW strain \( h(t) \sim \frac{1}{\text{distance}} \) two polarizations \( h_+ \) and \( h_\times \)

24 - 2048 Hz
Simplest “Newtonian” model explains frequency chirp

\[
\left( \frac{dE}{dt} \right)_{\text{rad}} + \left( \frac{dE}{dt} \right)_{\text{orb}} = 0
\]

⇒ Frequency chirp:

\[
\frac{df}{dt} = \frac{96 \pi}{5} \left( \frac{\pi GM}{c^3} \right)^{5/3} f^{11/3}
\]

Chirp mass:

\[
\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}
\]

[LVC, PRL 119, 161101 (2017)]
The GW waveform encodes source parameters.

figure courtesy of Tanja Hinderer
The GW waveform encodes source parameters

Merger
Post-merger/ringdown

\[ \text{Merger} \rightarrow \text{Post-merger/ringdown} \]

\[ \sim \text{10 cycles of merger for } \sim 10 \, M_\odot \text{ BHs: seconds} \]

[Numerical Relativity: Pretorius, Sperhake, Campanelli, Baker, Pfeiffer, Scheel ...]
The GW waveform encodes source parameters

\[ ~10^3 \text{ cycles of the inspiral for few } M_\odot \text{ with LIGO/Virgo: minutes} \]
The GW waveform encodes source parameters

post-Newtonian (PN) Inspiral — driven by the chirp mass

\[ 1\text{PN} \sim \frac{v^2}{c^2} \sim \frac{Gm}{rc^2} \ll 1 \]
The GW waveform encodes source parameters

\[ \Phi_{GW}(t) \Rightarrow \text{chirp mass, reduced mass (1PN), spin-orbit (1.5PN), } \ldots \]

\text{tidal deformability (5PN)}
**Task 1**: GW waveforms require more physics

\[ \Phi_{GW}(t) \Rightarrow \text{chirp mass, reduced mass (1PN), spin-orbit (1.5PN), ...} \]

\[ \text{tidal deformability (5PN)} \]
Extract source information from GWs

\[ h_+(t) = \frac{A[M f(t)]}{\sqrt{D}} (1 + \cos^2 \iota) \cos \Phi_{GW}(t) \]

Detector output

Model h(t)

h(t): 9-16 parameters

- **Redshifted** Masses
- Spins
- Tidal deformability
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Explicitly map out: 

\[ p(\theta | s) \propto p(\theta) L_{\text{total}}(s | \theta) \]

\[ \text{Likelihood} \]

Using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

[see LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]
[see Nissanke et al. 2010, 11, 13a, 13b]
Task 2: we require faster analysis

\( h_+(t) = \frac{A[M f(t)]}{D} (1 + \cos^2 \iota) \cos \Phi_{\text{GW}}(t) \)

**Model \( h(t) \)**

Detector output

**Explicitly map out:** \( p(\theta|s) \propto p(\theta) L_{\text{total}}(s|\theta) \)

**Likelihood**

<table>
<thead>
<tr>
<th>Parameter 1</th>
<th>Parameter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>( M )</td>
</tr>
<tr>
<td>( \iota )</td>
<td>( \Phi_{\text{GW}} )</td>
</tr>
<tr>
<td>( D )</td>
<td>( f(t) )</td>
</tr>
<tr>
<td>( \text{GW Phase} )</td>
<td>( \text{frequency} )</td>
</tr>
<tr>
<td>( \text{distance} )</td>
<td>( \text{inclination angle} )</td>
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**h(t): 9-16 parameters**

+ **Redshifted** Masses
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[see LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]
[see Nissanke et al. 2010, 11, 13a, 13b]
Retrieving GW170817 progenitor masses and spins

\[ M = 1.186^{+0.001}_{-0.001} \, M_\odot \]

Low spin prior

[LVC, PHYS. REV. X 9, 011001, 2019, and arXiv:1805.11581; see also LVC, PRL, 119, 161101, 2017]
Pinpointing GW170817’s location with “GW volumes” and galaxy catalogs

[LVC, PRL, 119, 161101 (2017),

[Nissanke et al. 2011, 13, Kasliwal and Nissanke 2014,
Gehrels...SN + 2015, Singer....SN + 2016,
Hotokezaka, Nissanke + 2016, ]
First optical transient at 11 hours was the real deal: the NS-NS merger

[Image: NGC 4993 and SSS17a observed with Hubble Space Telescope and Swope Telescope]

NGC 4993: 40 Mpc (elliptical galaxy)

Not the case for weaker signal events: needle in the haystack of other astrophysical transients

[Coulter et al. 2017, Science]
Task 3: characterizing other astrophysical transients & variables

NGC 4993: 40 Mpc (elliptical galaxy)

Not the case for weaker signal events: needle in the haystack of other astrophysical transients
Part II:
The Multi-messenger discovery of GW170817
The first month(s) of multi-messenger observations of GW170817


Global ground and space-based effort:
70+ teams, 100+ instruments, over 3500 co-authors
Panchromatic View of GW170817

[still going on ... ! see Haleja+ 2018]

figure courtesy of Kunal Mooley
### A Tale of Two Matter Outflows ⇒ EM counterparts

1. **Tidal Tails + Disk Winds + Core-bounce Heating**
   - \( M_{ej} \approx 0.01-0.05 \, M_{\odot} \)
   - \( E \approx 10^{50} \text{ ergs} \)
   - \( v \approx 0.1-0.3c \)

   - **Kilonova: Ultraviolet Optical IR** (days-week, more isotropic)


2. **Ultra-relativistic Jet**
   - \( M_{ej} \approx 10^{-6} \, M_{\odot} \)
   - \( E \approx 10^{49} - 10^{50} \text{ ergs} \)
   - \( v \approx 0.99c - 0.99995c \)

   - **Short Gamma Ray Burst + afterglow**
     - (seconds - months, collimated)

   [Eichler+ 1989, Paczynski 1989,...]

**Outflows’ kinetic energy is converted into internal energy.**

Expands, cools and heated by shocks or radioactivity.

(cf. Supernova: \( 10^{51} \text{ ergs} \); \( L_{\text{sun}}: 4 \times 10^{26} \text{ W} \) or \( 4 \times 10^{33} \text{ erg/s} \))
F_χ(t): 15 parameters

- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position (1")
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss
Task 4: modelling of outflows’ microphysics

see talk by Campanelli

\[ F_\lambda(t): \text{15 parameters} \]

+ Energetics and beaming
+ R-process nucleosynthesis
+ Mass ejecta and velocity
+ Environment
+ Redshift, Accurate Position (1")
+ Stellar populations
+ Magnetic field strength
+ Previous binary evolution & mass loss
EM SGRB VLBI $\Rightarrow$ superluminal jet with structure


$\left<_{\theta_{\text{jet}}} \leq 5^\circ\right>$

$n \approx 10^{-4} - 5 \times 10^{-3} \text{ cm}^{-3}$

$E \approx 10^{49} - 10^{50} \text{ erg}$

[see also Lazzati 2017,18, Ghirlanda + 2019, Troja+ 2018]

Proper motion of 2.7 mas, $\beta_{\text{app}} \sim 4.7$
Part III:
What have we learnt from GW170817 with GW+EM?

i. Hubble parameter constraint
ii. Equation of State
New field: break degeneracies to measure properties of BHs and NSs

**h(t): 9-16 parameters**
- Redshifted Masses *(several to tens %)*
- Spins *(tens of %)*
- NS radii *(tens of %)*
- Geometric properties: *(tens of %)*
  - Inclination angle
  - Source Position
  - Luminosity distance

**F_\lambda(t): 15 parameters**
- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position *(1″)*
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss

**Strong signal binary: Characterisation**

**Population: Demographics, ecology and census**
Task 5: break degeneracies to measure properties of BHs and NSs

$h(t)$: 9-16 parameters
- Redshifted Masses (several to tens %)
- Spins (tens of %)
- NS radii (tens of %)
- Geometric properties: (tens of %)
  - Inclination angle
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$F_\chi(t)$: 15 parameters
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Strong signal binary: Characterisation

Population: Demographics, ecology and census
1) **GW+radio**: Hubble measurement improves by a factor of 2

[Hotokezaka, ..SN, + 2019; see Schutz 1986, Dalal + 2006, SN + 2010]

![Graph showing the Hubble parameter distribution]

\[ H_0 = 68.9^{+4.7}_{-4.6} \text{ km/s/Mpc} \]

\[ H_0 = 70^{+12}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

Peculiar velocity error of 150 km/s; Hubble flow velocity of 3017 +/- 166 km s\(^{-1}\)
**GW+ radio**: Hubble measurement improves by a factor of 2

![Graph showing measurements with error bars for different methods: Hydro Jet, GW, VLBI+LC, GW+VLBI+LC.](image)

[cos inc- DL; see SN+ 2010; see Guirdozi + 2017, Finstead + 2018, Mandel 2018]

[Hotokezaka, ..SN, + 2019, Nature Astro.]
1) GW + EM: peculiar velocity corrections

see talk on BORG by Lavaux

PaVES (Peculiar Velocity Estimation for Sirens)

\[ H_0 = 69.3^{+4.5}_{-4.0} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

our method: 16% higher mean value and about 13% less standard deviation
1) **GW+EM**: importance of populations to potentially resolve “Hubble trouble”

![Graphs illustrating joint probability density functions for $H_0$ (km/s/Mpc) and SNR.](image)

[Feeney, Peiris, Williamson, SN,..+,PRL, 2019; Mortlock, ... SN, 2018]

[see also Chen+ 2018, ...]

50 binaries (≈8-10 years) to reach a precision of 1.8 % (1/√N); high SNR binaries dominate joint PDF; assumes EM
2) **GW+EM** probes NS Equation of State

BHNS binaries compatible with LIGO observations

[Hinderer, Nissanke + 2018]

![Graph showing mass ratio of BH and NS vs. neutron star radius.](null)

**Compatible with EM signal**

Disfavoured by nuclear physics

Incompatible with EM signal

Semi-analytical formula for remnant mass for wide range of mass ratio, NS EoS, BH spin

\[ M_{\text{rem}} \left( \frac{m_{\text{BH}}}{m_{\text{NS}}} , \frac{Gm_{\text{NS}}}{R_{\text{NS}}c^2} , \chi_{\text{BH}} \right) \]

[Foucart, Hinderer, Nissanke 2018; Foucart, .. SN+ 2019; Raaijmakers + in prep; used in LIGO-Virgo alerts]

[Stiffer EoS cf. 11.8 +/-1.4 km assuming NS-NS only (GW+EM); LVC]

See talk by Agathos
GW170817: follow-up was easy — very close by and bright, small GW volume

BBH merger rate: $9.7-101 \text{ Gpc}^3 \text{ yr}^{-1}$
NS-NS merger rate: $110-3840 \text{ Gpc}^3 \text{ yr}^{-1}$
NS-BH merger rate: $< 610 \text{ Gpc}^3 \text{ yr}^{-1}$

1. **GW+EM**: Expect a diversity of EM counterparts

![Diagram showing the relationship between total binary mass and remnant types, including blue and red kilonova outcomes.](image)

*figure courtesy of Dale Frail*
2) GW+EM: New discovery space — NS-BH mergers!

Movie courtesy of Francois Foucart
3. **GW+EM** challenge remains to build a coherent model: a key step to joint characterization.

Outflows carry energy from small (10^6 cm) to large distances (10^{14}-10^{16} cm) for radiation to escape.

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**Outflows**
- Binary evolution
  - t \sim 10^6 - 10^9 yr
  - r - 1 AU

**Inspiral**
- Merger Dynamics
  - t \sim ms - s
  - r - 40 AU

**GW emission**
- Radiation transport
  - t \sim secs - months;
  - r - 100 - 1000 AU

**GW Measurements**
- EM Observations

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see talk by Campanelli
4. **GW+EM challenge**: from individual objects to statistics

**2019-2023 (LIGO+Virgo+...):**
- NS-NS: 0 to 42 year\(^{-1}\)
- NS-BH: 0 to 96 per year\(^{-1}\)
- BH-BH: tens to hundred year\(^{-1}\)

**2019-2023:**
Wide-field optical and radio telescopes (ZTF, BlackGEM, LOFAR, Apertif, SKA, LSST, ELT ..)

4. **GW+EM** challenge: how many this year?

[B. P. Abbott et al., Living Rev Relativ, 2019, 1304.0670]
4. **GW+EM** challenge: how many this year?

[B. P. Abbott et al., Living Rev Relativ, 2019, 1304.0670]

- **NS-NS**: Expect $0-8$ $[1-50]$ yr$^{-1}$
  $250-320$ $[30-48]$ deg$^2$ (90 c.r.)

- **NS-BH**: $0-19$ $[0-96]$ yr$^{-1}$
  $310-390$ $[48-69]$ deg$^2$ (90 c.r.)

- **BH-BH**: $5-34$ $[30-149]$ yr$^{-1}$
  $250-340$ $[33-47]$ deg$^2$ (90 c.r.)
4. Mid 2020s: small GW areas, depth and rate

[B. P. Abbott et al., Living Rev Relativ, 2019, 1304.0670]

Expect 11 - 180 BNS detections per year

Median 90% credible region: 9 - 12 deg$^2$

65 - 73% of BNS expected to localise < 20 deg$^2$
Task 6: First NS-NS binary trigger candidate in 2019: confirmed GW but no EM counterpart

S190425z: Thursday 25th April, 10am CET

FAR: 1 per 70 000 years

Distance: 156 Mpc +/- 40 Mpc
  (x4 GW170817)

Sky error: 1/4 of the sky!
  (x320 GW170817)

O(100) GCNs;
ZTF scanned volume in 3 hours!

$10^5$ false positives
(supernova and M-dwarf)

p(NS-NS) > 0.99;
p(terrestrial) < 0.01;
p(remnant) > 0.99

[see https://gcn.gsfc.nasa.gov/notices_l/S190426z.lvc
https://gcn.gsfc.nasa.gov/notices_l/S190426c.lvc]
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GROWTH: Coughlin + 1907.12645

[see https://gcn.gsfc.nasa.gov/notices_l/S190426z.lvc
https://gcn.gsfc.nasa.gov/notices_l/S190426c.lvc]
Mid 2020s - 2030a: aLIGO+, Einstein Telescope

Factor of $2/10$ in sensitivity; $x 8/1000$ in rates
2030s: Einstein Telescope and Cosmic Explorer have cosmological reach

Horizon reach!

GW170817: z \sim 10^{-2}

MMA co-chairs: Bailes, Kasliwal, Nissanke
LISA MMA work package leads: Baker, Haiman, Nissanke
Task 7: MMO in 2030s is not just EM follow up!

EM follow up of single sources

Cross correlating GW and EM source catalogs

Cherry Pick Loud events - golden for GW+EM

Large Scale Structure; Extragalactic Astronomy
Gravitational-wave sources

Cosmological backgrounds

Supermassive BH Binaries

Pulsars

Galactic binaries
captures into MBHs

Early-Universe quantum fluctuations

massive black-hole binaries

rotating NS
merging NS, BH

Gravitational-wave sources

CMB
Astrometry
pulsar timing
LISA
future space
LIGO

White dwarf binaries

Extreme mass-ratio inspirals

Supernova

First-order phase transitions, superstring kink & cusps, inflationary signature, new sources!
The future is both loud and bright!

**Immediately:** GW detector sensitivity & network increases => First NS-BH merger! SNe! Tens of BBH mergers yr$^{-1}$ and several of NS-NS yr$^{-1}$

**Key step for GW+EM:** joint analysis for masses, spins, sky position and redshifts for populations of compact object mergers are necessary for fundamental physics and astrophysics.

Understanding systematics and finding the EM counterpart are critical for H0 measurement: independent to the cosmological distance level.

**Beyond LIGO, Virgo era:** Witness the opening of the entire GW spectrum with CMB, PTAs, LISA, new generation ground-based detectors ...together with next generation of wide-field synoptic surveys LSST, SKA ... and E-ELTs.
The future is both loud and bright!

**New Opportunities:** GW+EM for astrophysics
- How, when and where do BHs and NSs form? What is the intrinsic nature of compact objects?
- How do compact object mergers impact and drive the evolution of the Universe?
- How do the fundamental laws of physics interact with each other in strong-field gravity?

**Challenges:** combining GW+EM
- Observations of GW & EM
- Modelling GW + EM simultaneously (microphysics)
- Interpretation (astrophysics and cosmology)