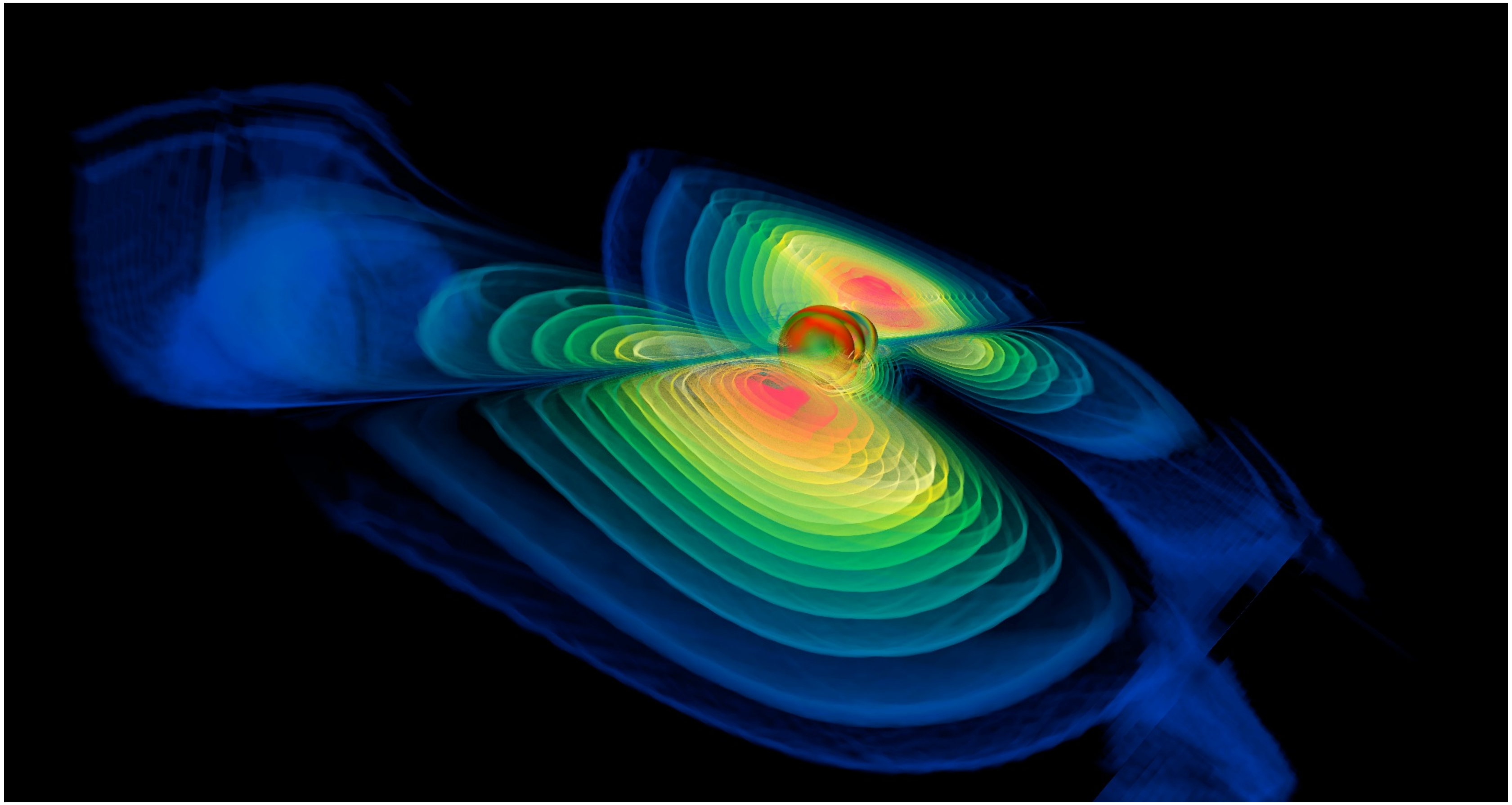
Prospects for Gravitational-wave Observations Associated with Gamma-ray Bursts



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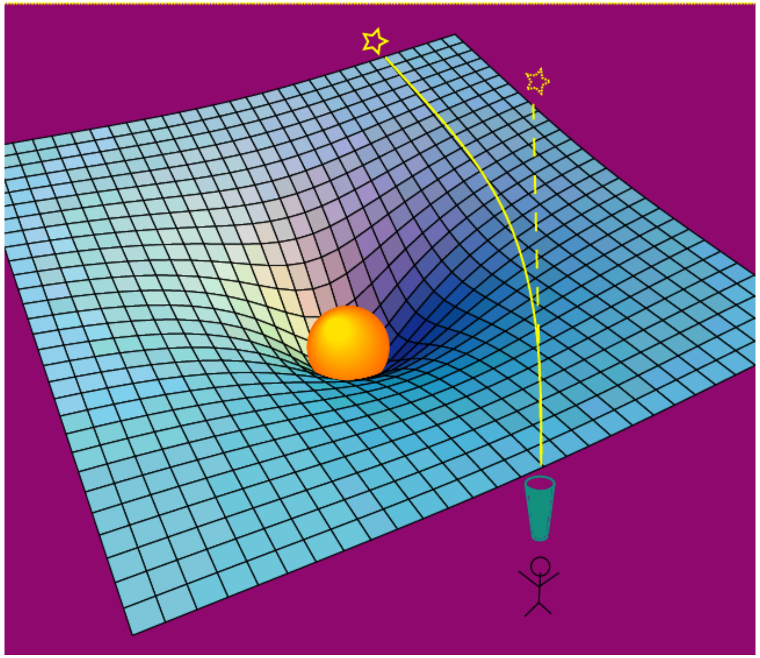
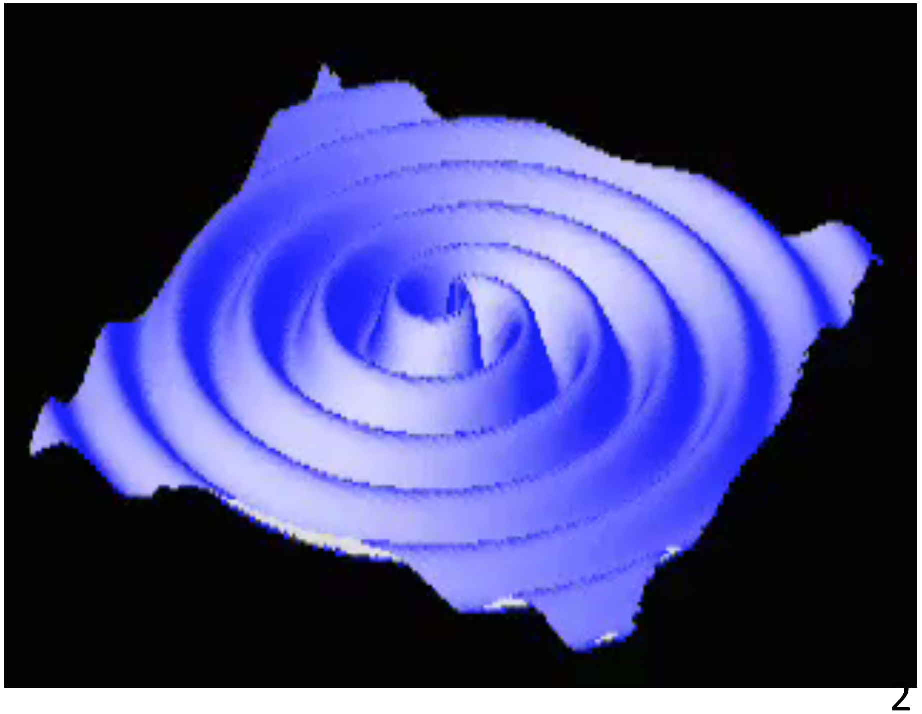
Gravitational Waves

- Predicted by General Relativity, 1916-1918.
- Massless, spin-2 field, 2 polarization states
- Very weak: need compact stars with large accelerations. Einstein thought they would be undetectable.

$$L = \frac{G}{5c^5}\left(\frac{d^3}{dt^3}Q_{ab}\right)\left(\frac{d^3}{dt^3}Q_{ab}\right)$$

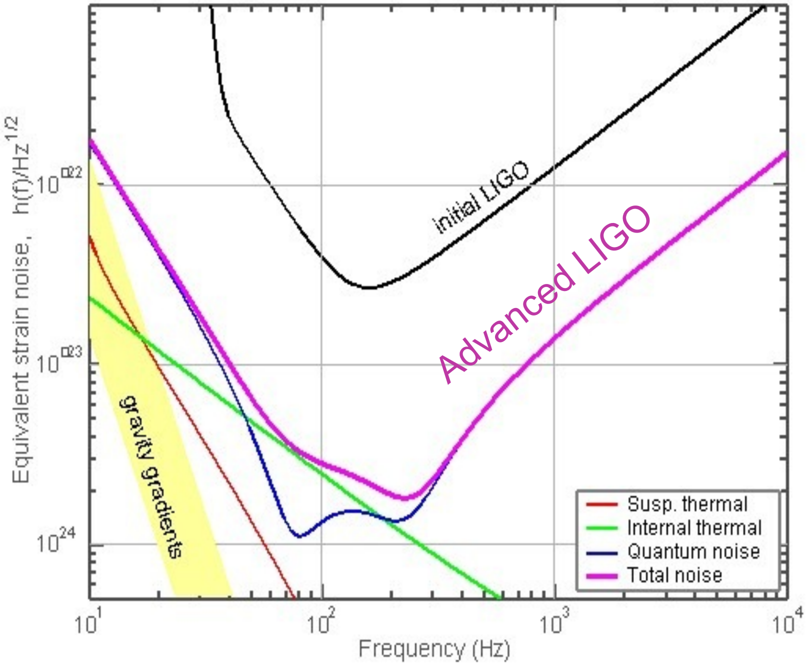
- Existence proof: 1993 Nobel prize for the orbital decay of the binary pulsar PSR B1913+16





Gravitational Wave Detectors

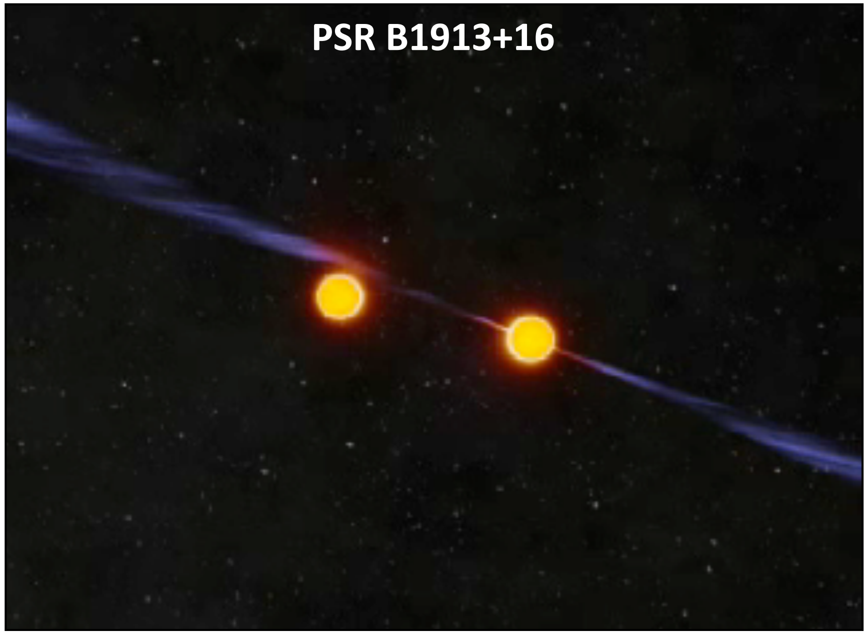
- Troubled history 1960s, 70s
- Large-scale “suspended interferometers” 1994 - present
- USA: Laser Interferometer Gravitational-wave Observatory (LIGO, 2 + 1)
- Italy/France: VIRGO
- Japan: KAGRA
- Collaboration: 1500 people
- Sensitive frequency range 40-1000 Hz
- First generation 2005-2010: 0 detections
- Second generation starts operations 2015, will see ten times farther (1000 times as many sources!)
- ~~Lower frequency detectors: space-based, pulsar timing arrays, cosmic microwave background radiation~~

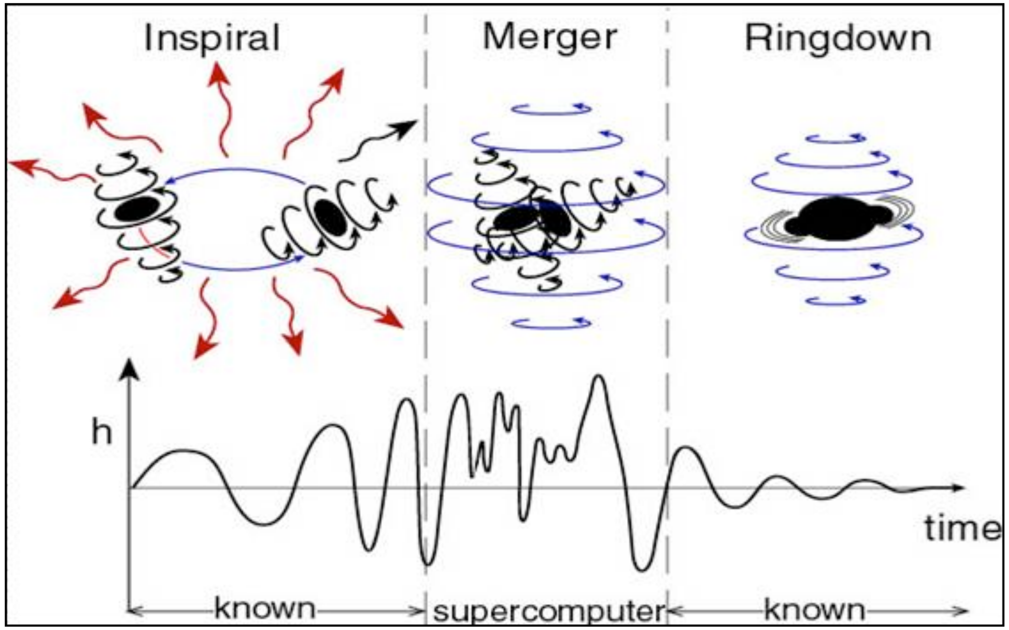


Nagoya 24.10.2014

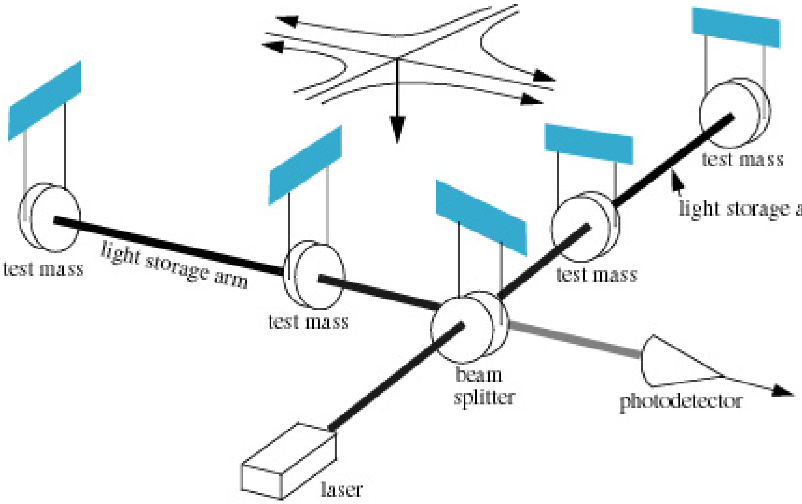
Astrophysical Gravitational Wave Signals

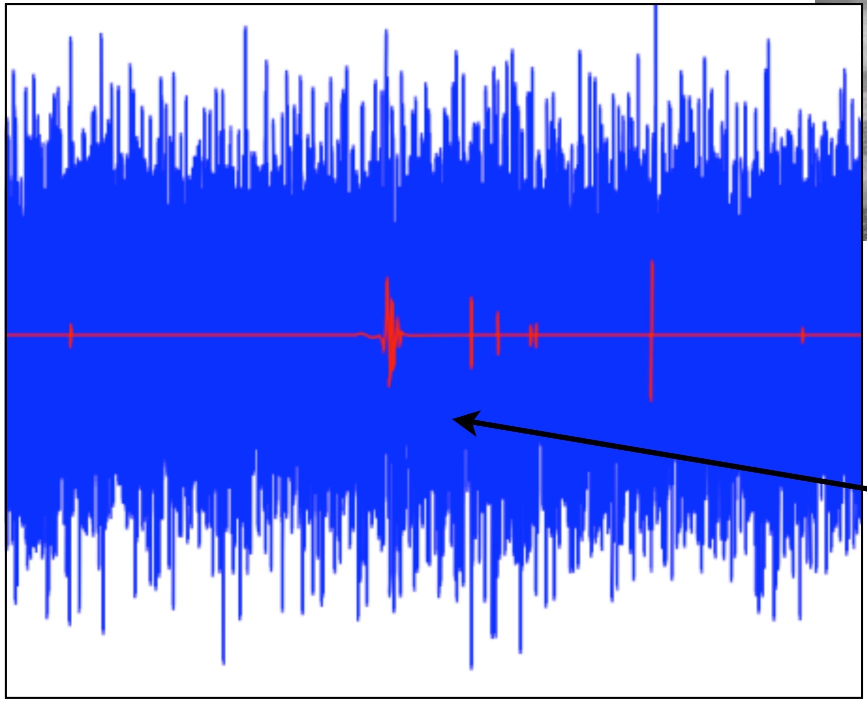
- Many possible types: continuous, stochastic, burst,…
- Benchmark design source: compact binary inspiral and coalescence
- Hulse/Taylor binary discovered 1974: two orbiting neutron stars (17 Hz pulsar). Period: 8h, smallest separation: 2 Gm
- Nobel prize: each orbit is 3mm smaller. **Orbital binding energy being radiated away as gravitational waves**
- In 300 million years: BANG!
- Gravitational-wave network will “see” the last few minutes of such a process (matched filtering needed)





Signals Hidden in Noise





A typical signal (red) is hidden in the detector noise (blue)

Event Rates / Uncertainties

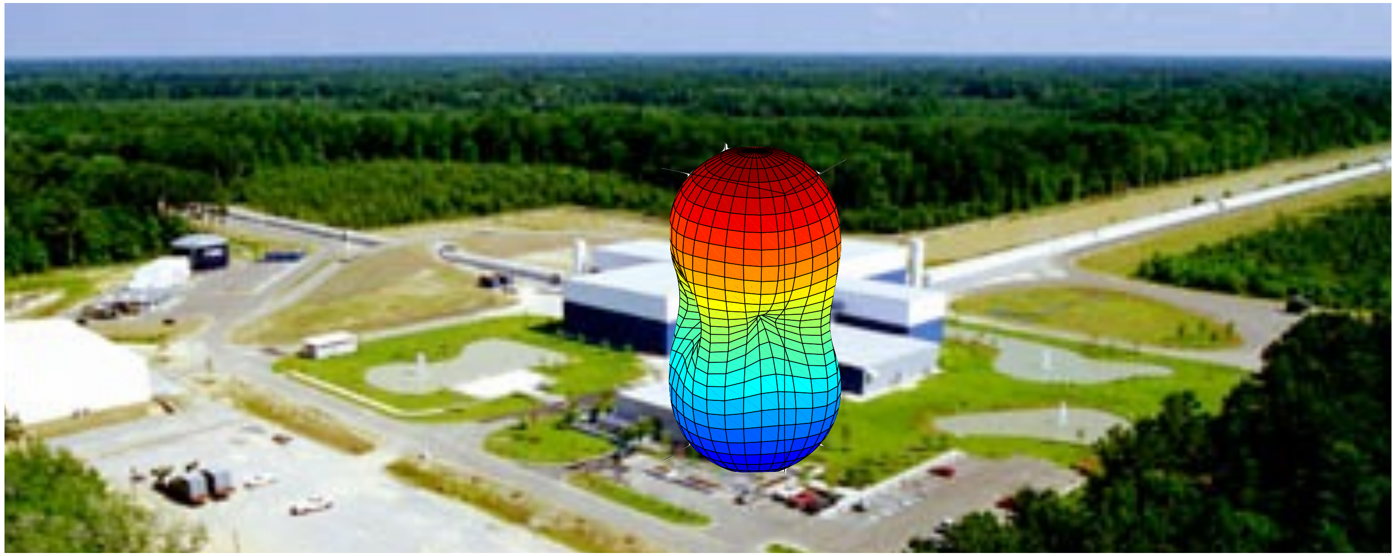
Table 5. Detection rates for compact binary coalescence sources.

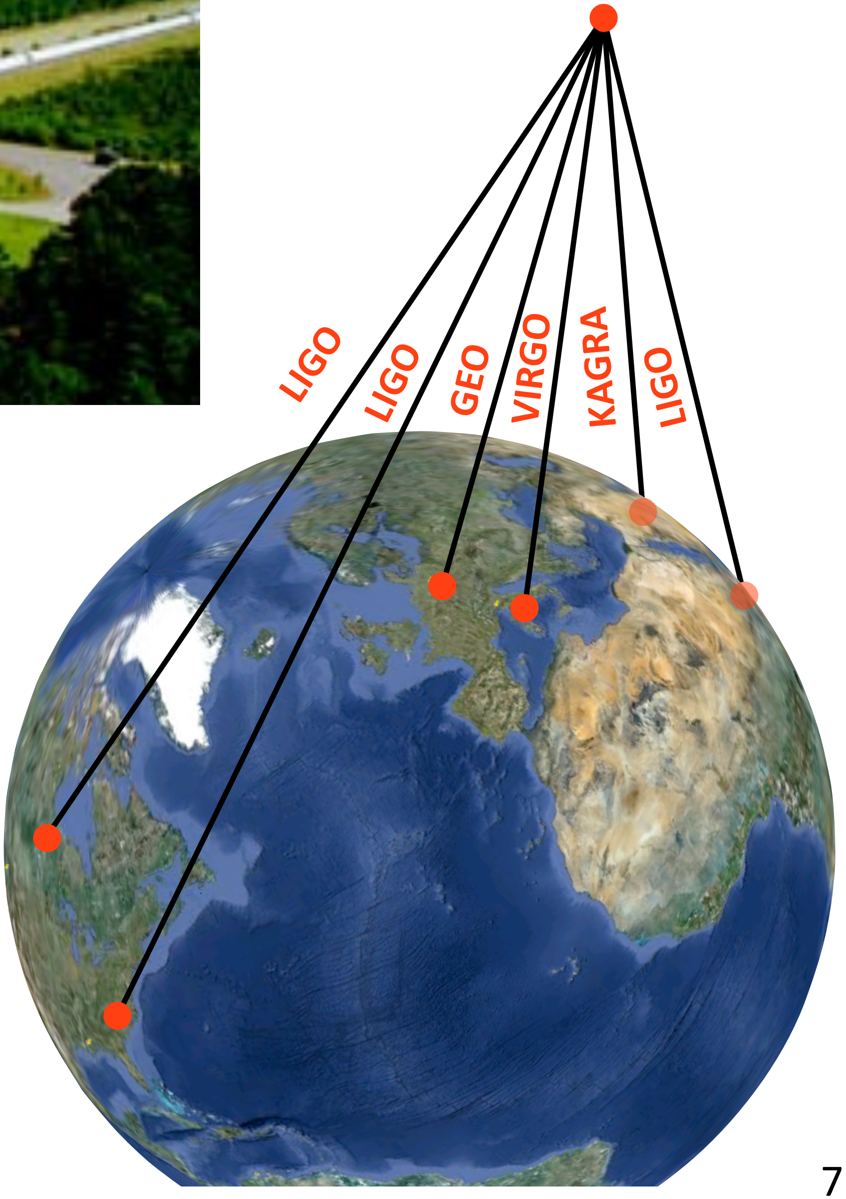
Detector	Source[a]	$\dot{N}_{\mathrm{low}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{re}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{high}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{max}}\ \mathrm{yr}^{-1}$
Initial LIGO 20 Mpc	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$<0.001^{\mathrm{b}}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,\mathrm{d}}$	$10^{-3\,\mathrm{e}}$
Advanced LIGO 200 Mpc	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
	BH–BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

Abadie et al, Class. Quantum Grav. 27 173001 (2010)

Expected detection rate for neutron star/neutron star inspiral: about one event per week!

Source Localization

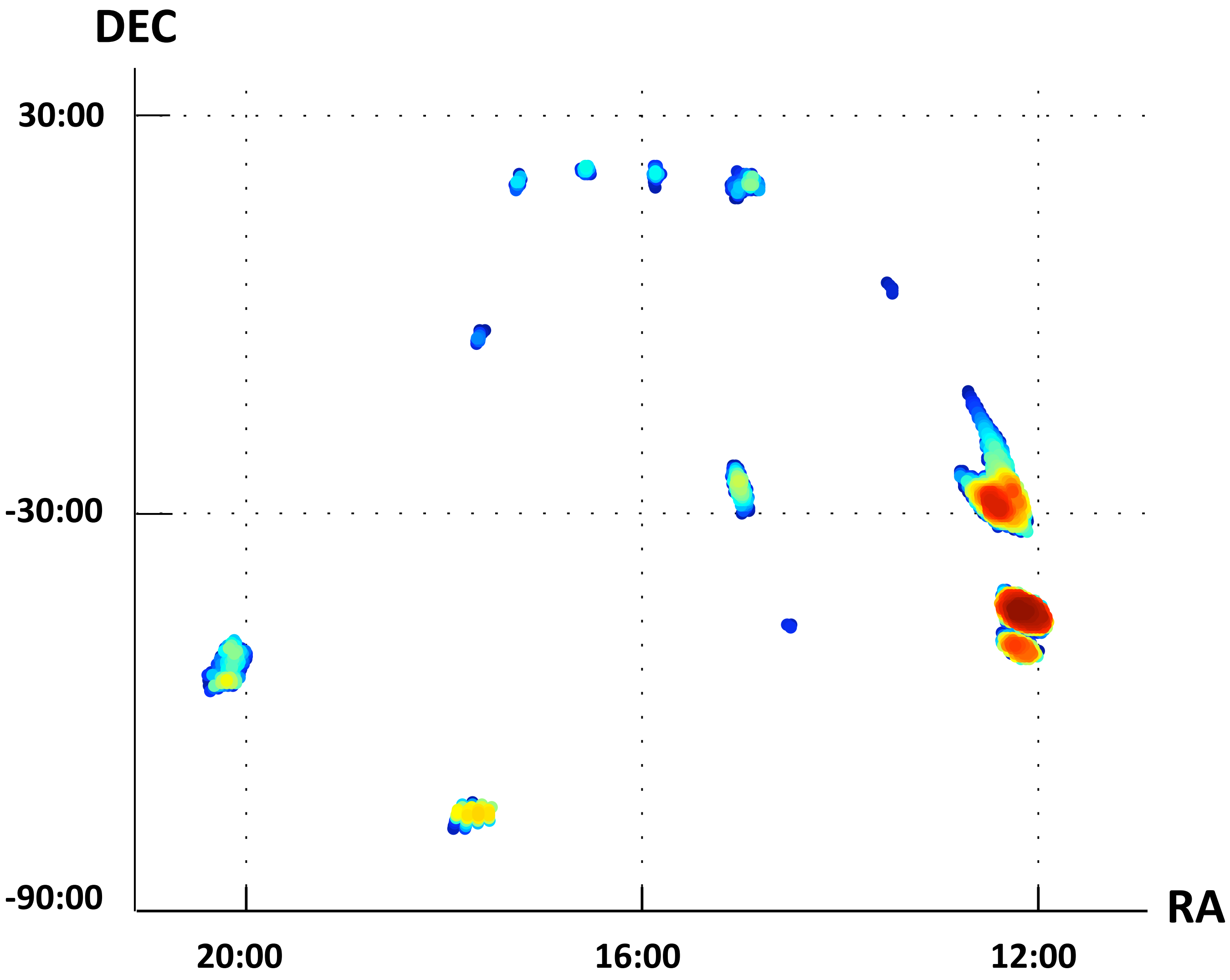




- A single gravitational wave “antenna” can not “point”. The detector pattern covers whole sky!
- Use time-of-arrival delay at multiple detectors to locate source on the sky
- All detector projects (exception: KAGRA) belong to a world-wide data-sharing collaboration
- Angular precision: $\Delta\theta \approx c\, \Delta t / R_{earth}$ radians
  Uncertainty $\Delta t \approx 0.3$ ms $\Rightarrow$ $\Delta\theta \approx$ few degrees

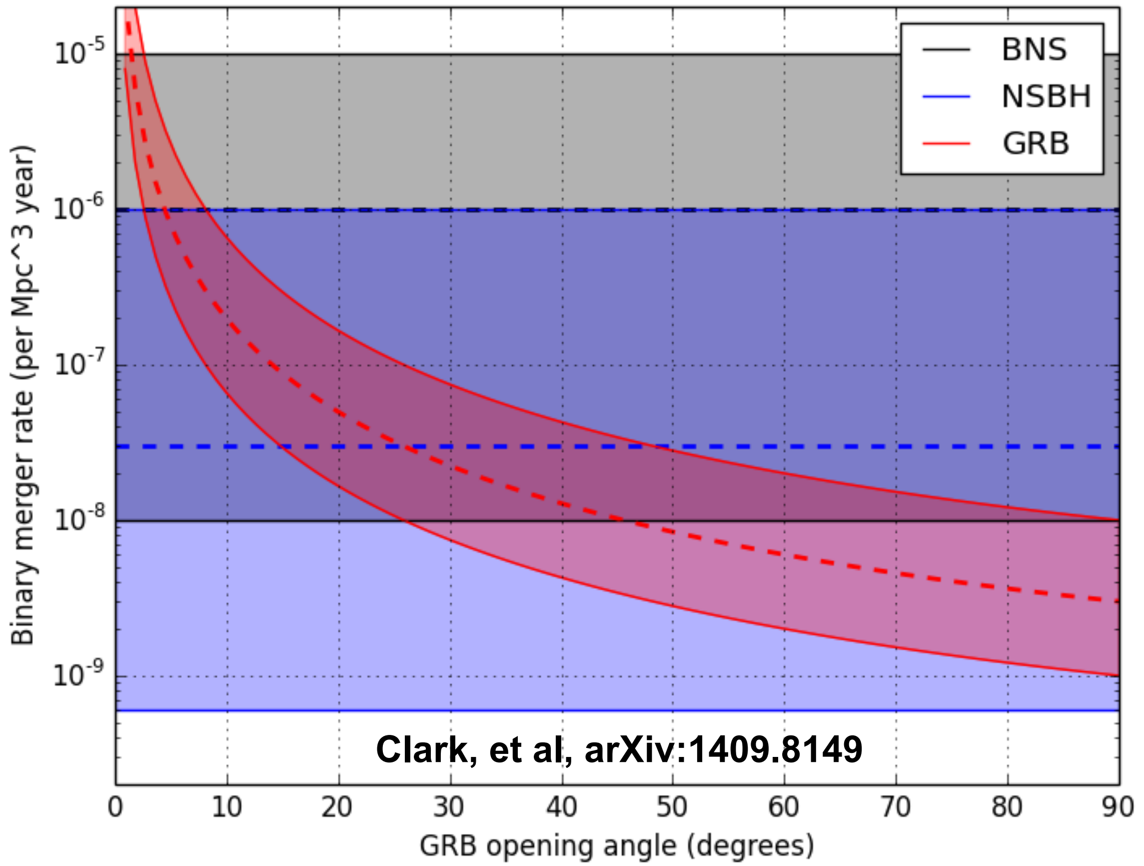
“Point-spread function” messy

- Triangulation time delays can be uncertain by one or two cycles
- Detectors not sensitive to the same combination of polarizations
- Uncertainty regions are not clean ellipses, but scattered probability regions
- Can contain hundreds of square degrees, or more!

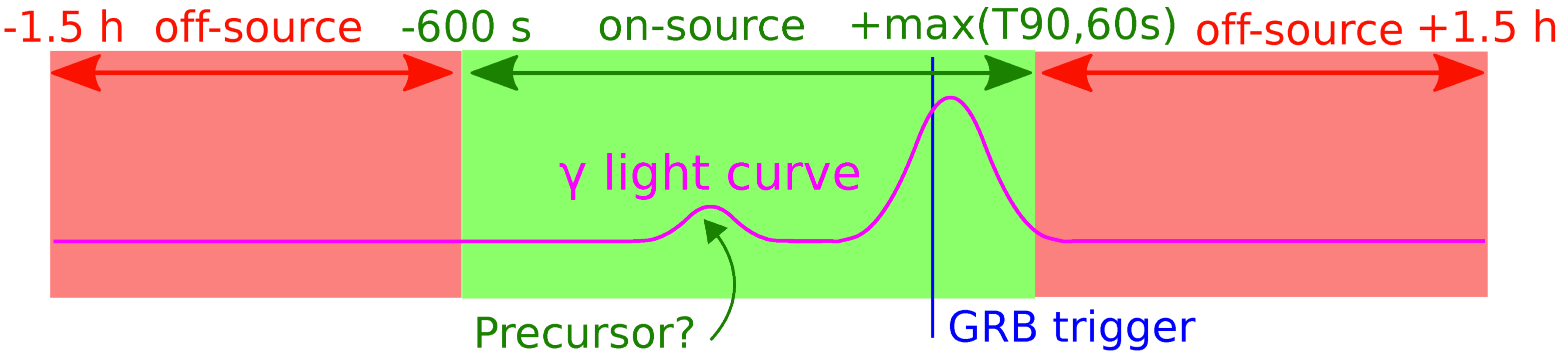


Short GRBs ⇔ Compact Binary Coalescence

- Short GRBs probably result from neutron star/neutron star or neutron star/black hole coalescence (Nakar, Phys. Rept. 442: 166-236, 2007).
- Numerical work (Rezzolla et al. Astrophys. J. 732, L6, 2011) has shown that neutron star merger produces jet-like structures which could power short GRBs.
- Rates “match” for GRB opening angles of 10-20 degrees (GW rates from slide 6, short GRB rate 8-30/yr from Guetta and Piran, Astron. Astrophys, 2006).



Combining Gravitational Wave & GRB Data



- If you know time of GRB, search near that TIME for gravitational waves.
- If you know time and sky location of GRB, search near that TIME with appropriate TIME DELAY between instrumental data streams

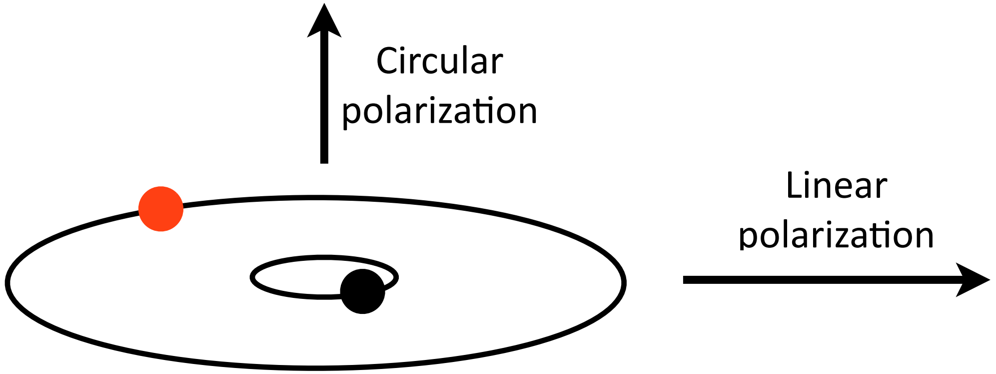
  Reducing the size of "search space" with these triggers increases the distance reach of a GW search by 1.25 - 2 compared with an all-sky / all-time search. Makes sense since GW detector "sees the whole sky".

- If you know gravitational wave location and time, search SKY NEARBY for GRB or afterglow

  Useful to "dig into the GW noise", for follow-up studies, and to increase confidence. ***But****: GW error boxes are tens to hundreds of square degrees.*

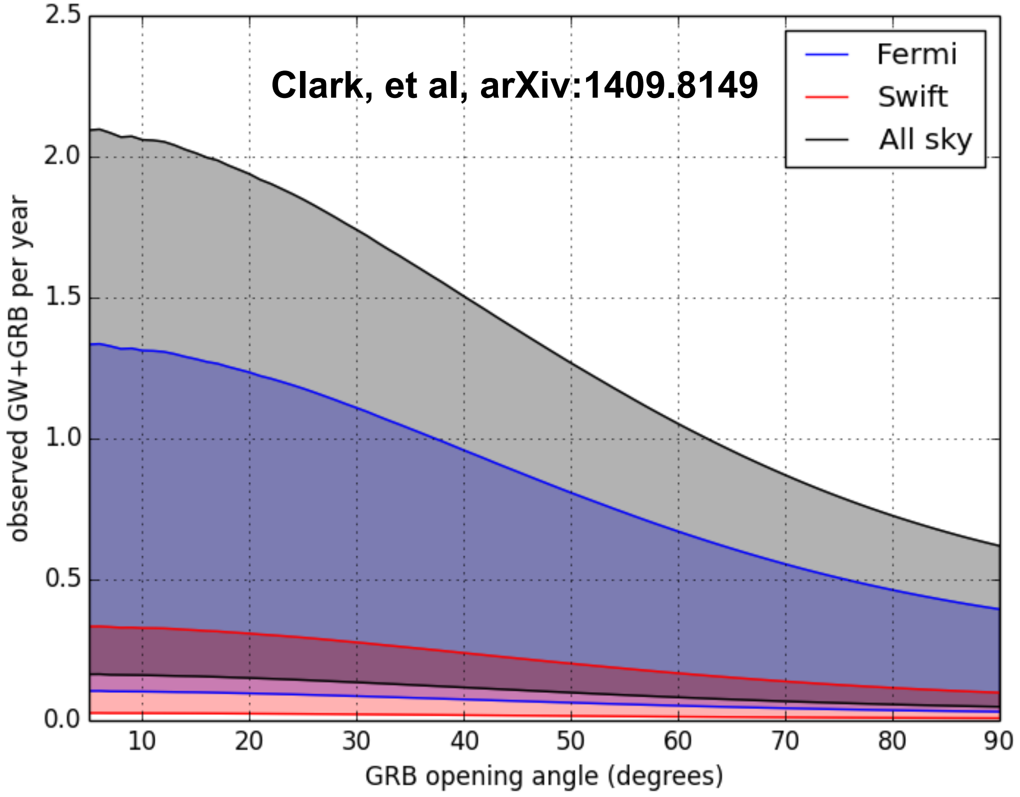
Joint Gravitational-Wave / Short GRB Detection Rates

- GRB beam probably orthogonal to orbital plane. This enhances joint detection probability: more gravitational-wave energy is emitted in that direction
- Assumptions:
  - full aLIGO sensitivity (2018+)
  - all mergers are NS-NS
  - all GRBs within FOV and GW range (200 Mpc) are detected by Fermi GBM
- Should observe ~1 coincident gravitational-wave/GRB event every 1-3 years (Metzger & Berger, ApJ., 746, 48, 2012; Clark, et al, arXiv:1409.8149)
- Optical counterparts (few day time-scale) might also be possible (Nissanke, Kasliwal et al., ApJ, 767, 124 (2013))



Circular polarization

Linear polarization



Conclusions

- Joint searches with first-generation gravitational wave detectors + GRB triggers did not make any detections.
- By the end of the decade, the second-generation LIGO-VIRGO network should make first GW detections. (Table below from arXiv:1304.0670)
- Most likely GW sources: compact binary coalescence of NS and/or BH systems.
- GW pointing precision: tens to hundreds of square degrees
- Exciting target for potential simultaneous gamma-ray burst observations, though unlikely to be found in coincidence with first gravitational wave detection
- Longer term prediction: X-ray astronomy went from first cosmic detections to the Chandra telescope in 40 years. GW astronomy will proceed at a similar rate after first detections.

	Estimated Run	$E_{\rm GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS
Epoch	Duration	LIGO	Virgo	LIGO	Virgo	Detections
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	105	80	200	130	0.4 – 400