Science with Gravitational-Wave Events

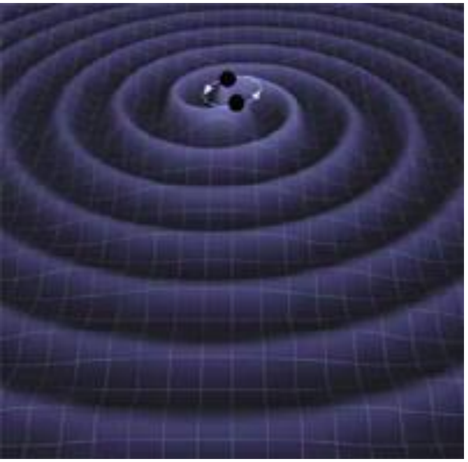
Peter S. Shawhan

University of Maryland Department of Physics
and Joint Space-Science Institute

Fermi Summer School
June 5, 2018

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters
(NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

The Promise and the Challenge



Gravitational waves can be emitted by astrophysical systems with rapidly changing mass distribution

- Compact binary $\left\{\begin{matrix}\text{neutron stars}\\ \text{black holes}\end{matrix}\right\}$ orbit, inspiral and merger
- Core collapse of a massive star (supernova engine)
- Non-axisymmetric spinning neutron stars
- Cosmic strings, early universe physics, …

Bill Saxton, NRAO/AUI/NSF

GWs come directly from the central engine

Not obscured or scattered by material

➔ Complements photon and neutrino emissions from photosphere, outflows, circumburst medium, shocks

But challenging to detect…

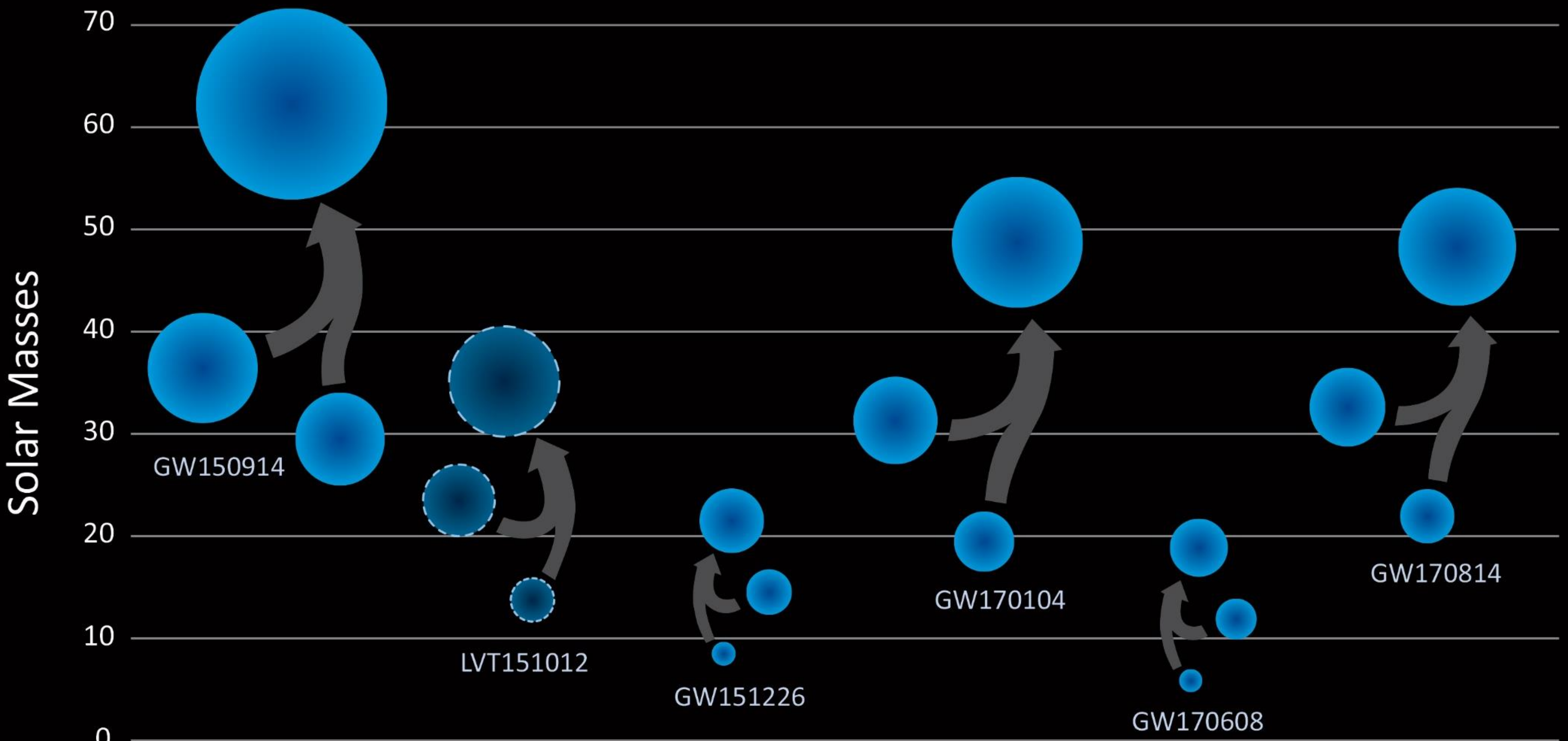
Strain amplitude is inversely proportional to distance from source

➔ Have to be able to detect weak signals to search a large volume of space

➔ Mostly working in the low signal-to-noise limit

Binary black hole mergers

Binary Black Hole Mergers – so far



LIGO/Caltech/Sonoma State (Aurore Simonnet)

Exploring the Properties of a GW Event

Bayesian parameter estimation: **Adjust physical parameters of waveform model to see what fits the data from both detectors well**

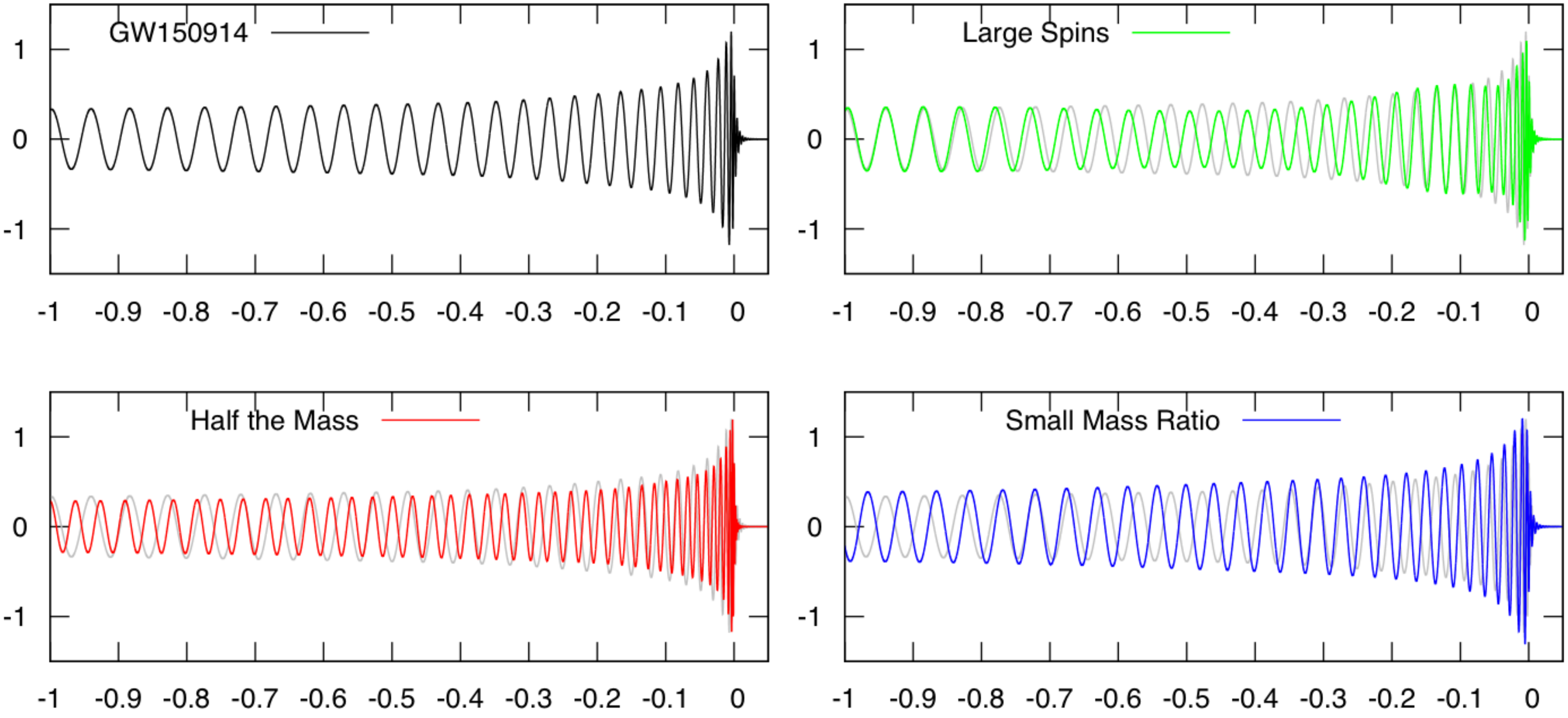
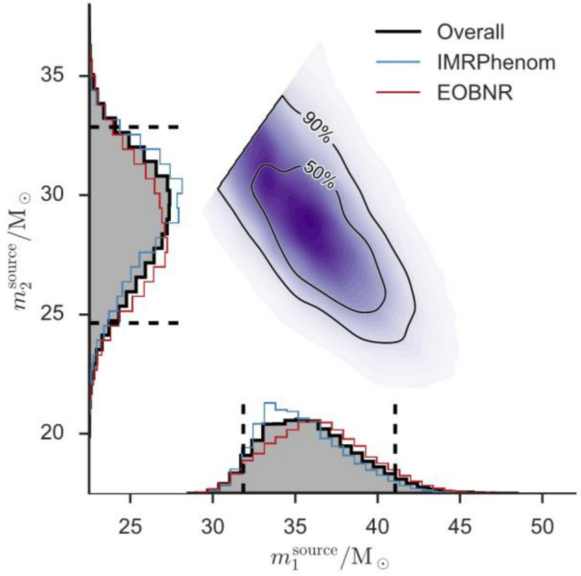


Illustration by N. Cornish and T. Littenberg

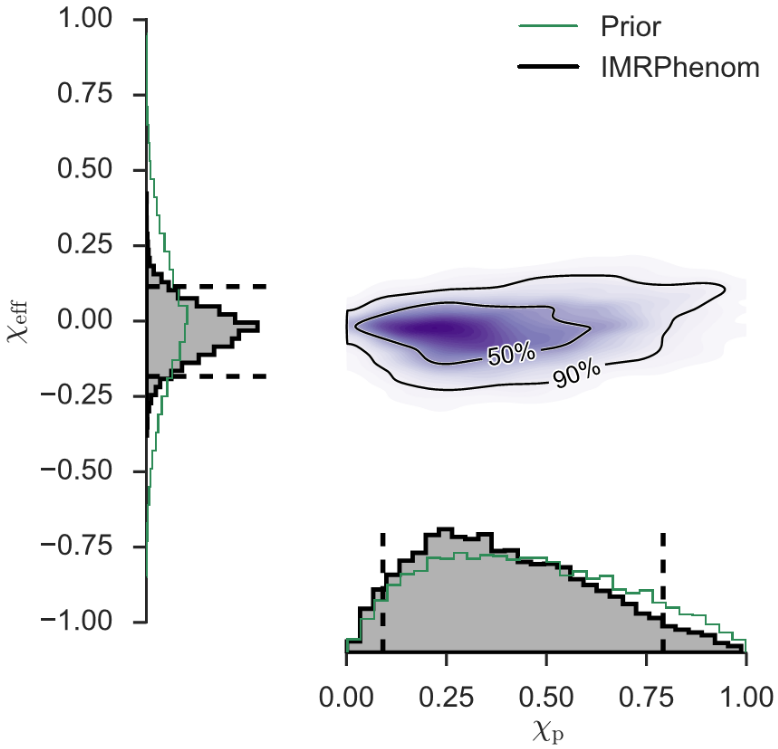
➔ **Get ranges of likely (“credible”) parameter values**

Spins of component BHs

Spin vector components aligned with orbital axis have significant degeneracy with mass parameters, in producing GW waveform



Other components can cause precession, modulating the GW signal received at Earth



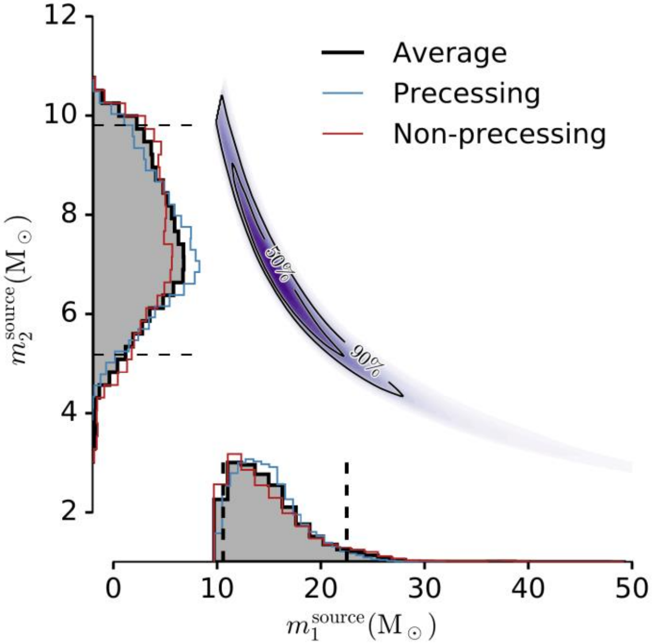
GW150914 data is consistent with the component BHs having had zero spin!

Properties of GW151226

GW151226 has lower mass than GW150914

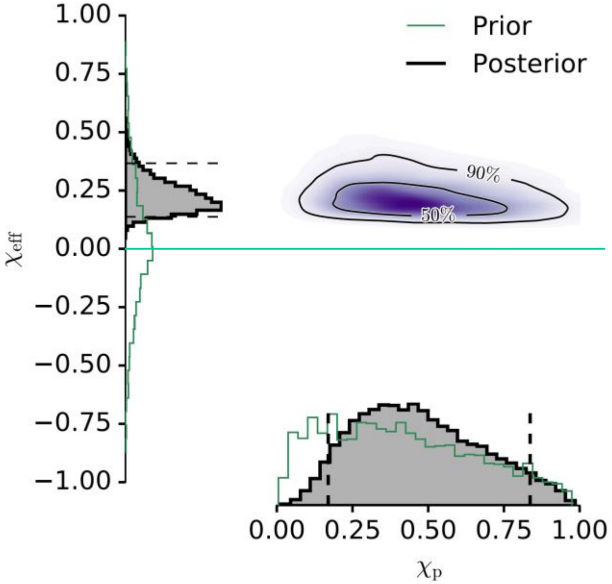
Initial masses: $14.2^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\ M_\odot$
Final BH mass: $20.8^{+6.1}_{-1.7}\ M_\odot$
Energy radiated: $1.0^{+0.1}_{-0.2}\ M_\odot c^2$

Luminosity distance: 440^{+180}_{-190} Mpc



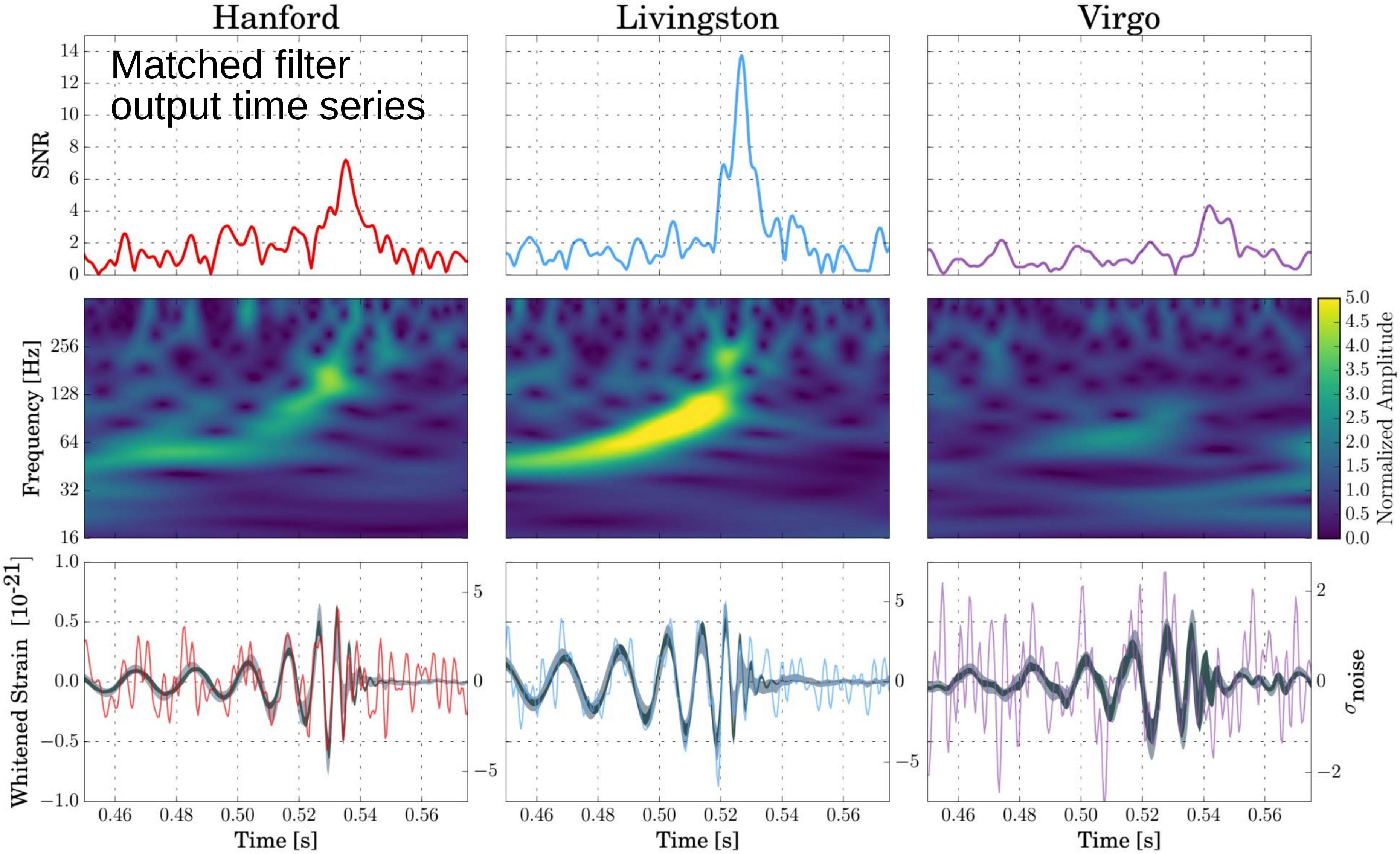
[Abbott et al. 2016, PRL 116, 241103]

… and nonzero spin !



Effective signed spin combination definitely positive
⇒ at least one of the initial BHs has nonzero spin
(we can't tell how the spin is divided up between them due to waveform degeneracy)

GW170814



Matched filter output time series

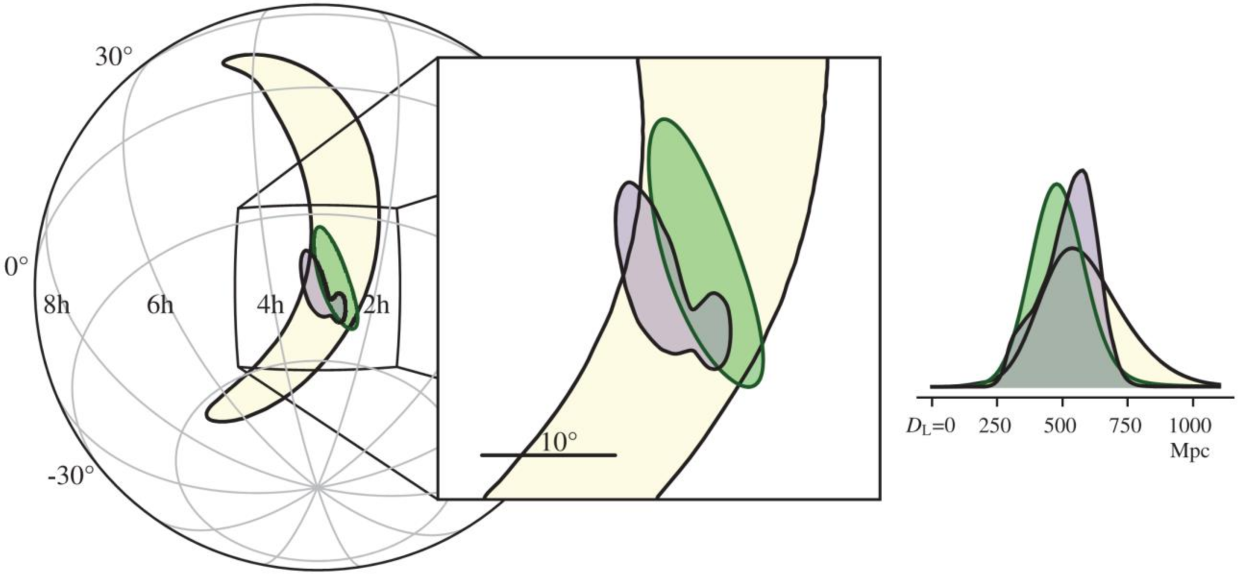
[Abbott et al. 2017, PRL 119, 141101]

GW170814

Masses ~ 30 and $\sim 25\ \mathrm{M}_\odot$ at a distance of 540^{+130}_{-210} Mpc

The triple detection allowed us to localize the event better

To a $\sim 60\ \mathrm{deg}^2$ region, after offline recalibration and noise removal

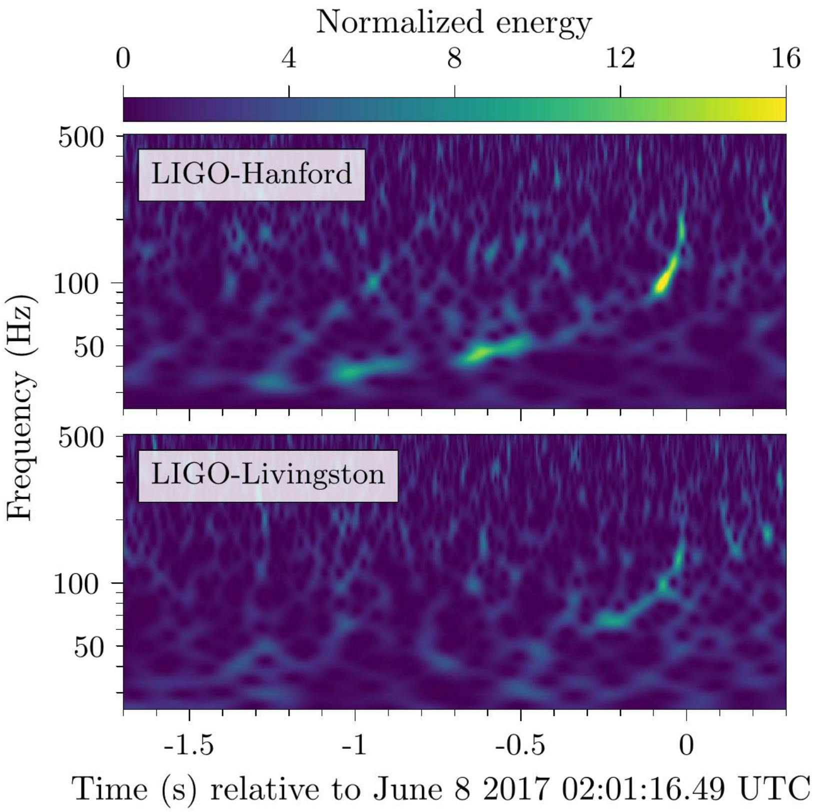


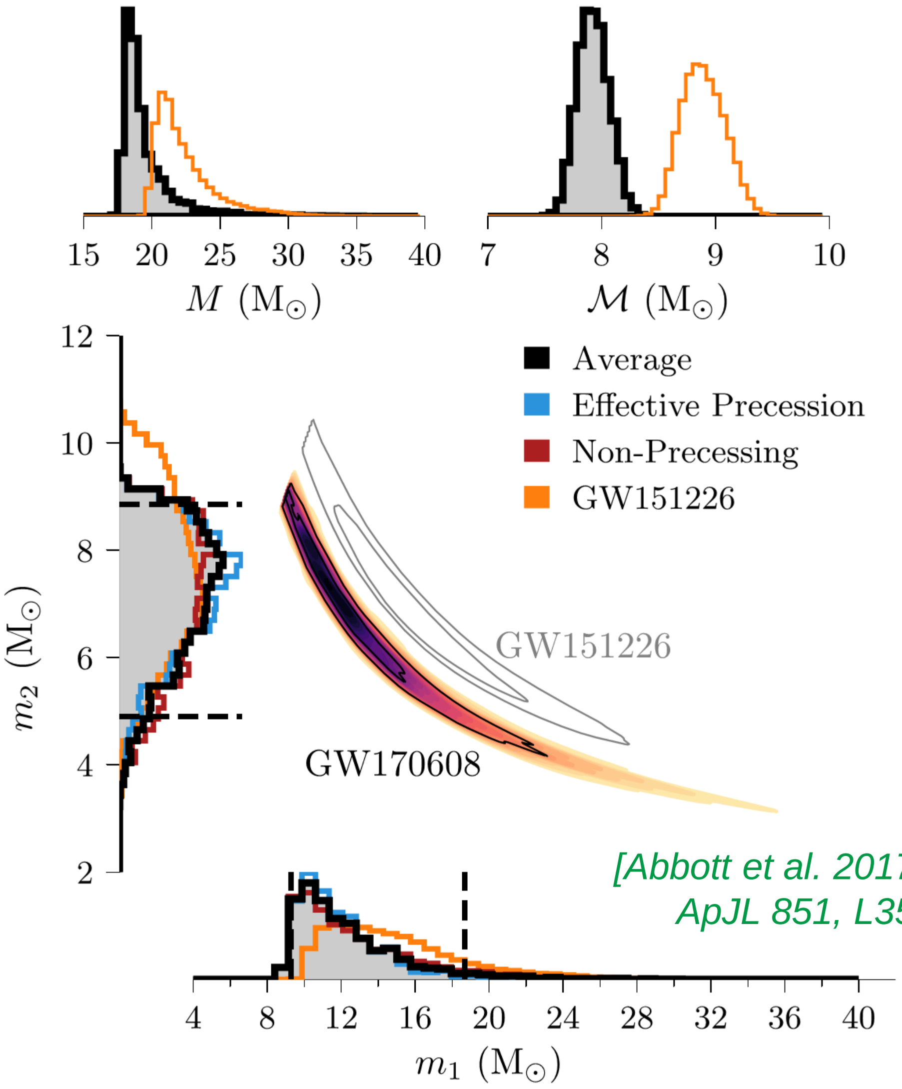
[Abbott et al. 2017, PRL 119, 141101]

Also enabled a direct test of the polarization of the GW signal

Pure tensor polarization is strongly favored over pure scalar or vector

GW170608



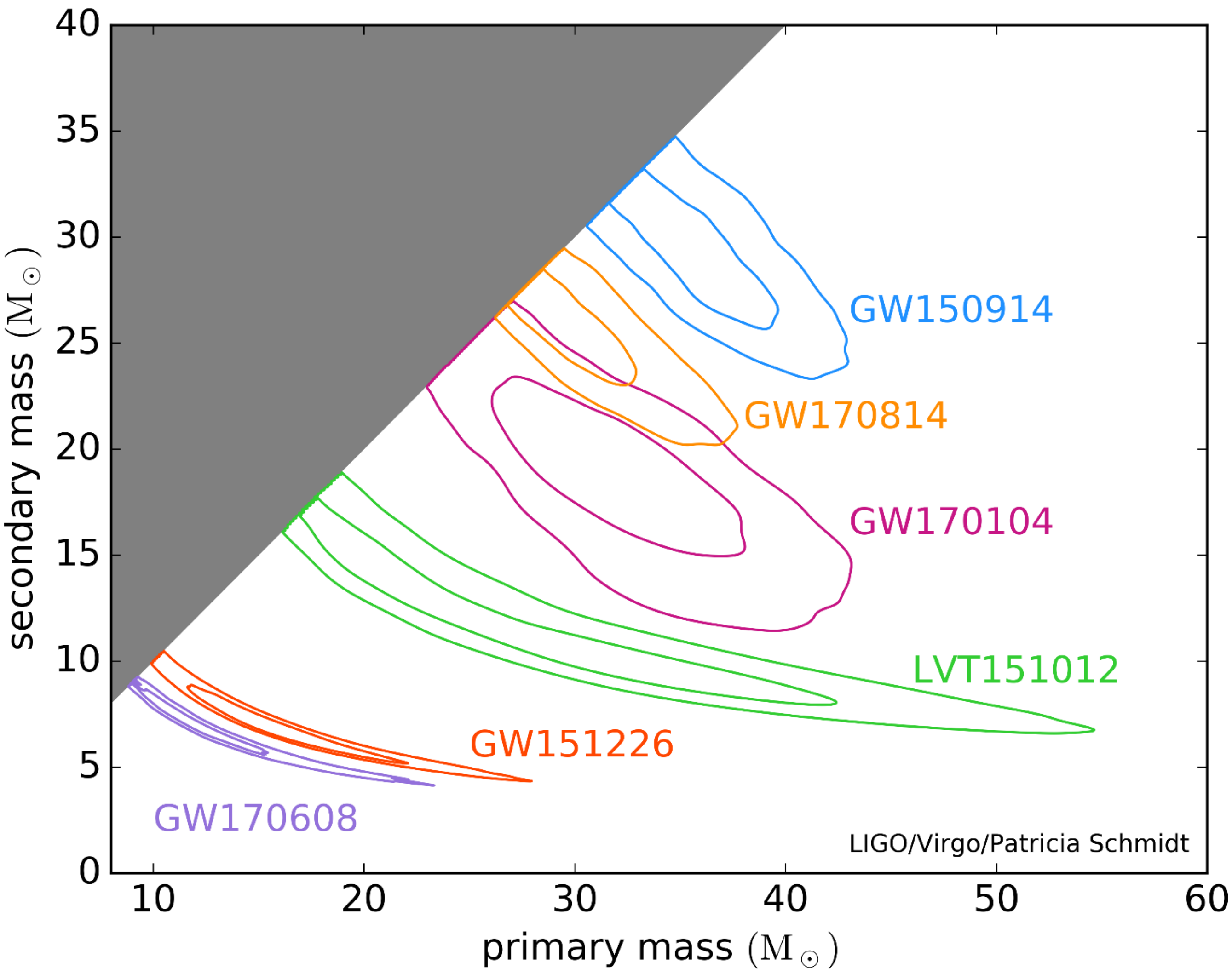


[Abbott et al. 2017, ApJL 851, L35]

(Probably) the lowest-mass BBH merger detected by LIGO so far

$$12^{+7}_{-2} \text{ and } 7^{+2}_{-2}\ M_\odot$$

Binary BH population: masses



LIGO/Virgo/Patricia Schmidt

Astrophysical Implications

There are black hole binaries out there, orbiting closely enough to merge, and *heavy !*

For comparison, reliable BH masses in X-ray binaries are typically $\sim 10\ M_\odot$

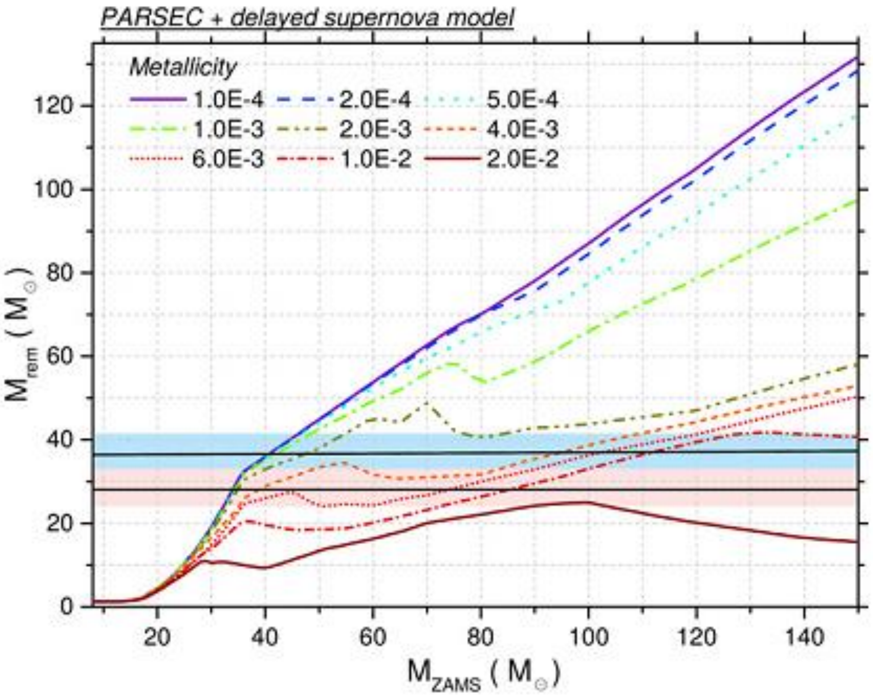
We presume that each of our BHs formed directly from a star

➔Low metallicity is required to get such large masses

Otherwise, strong stellar winds limit the final BH mass

We can't tell when the binaries formed

Inspiral may have taken many billion years



Spera et al., MNRAS 451, 4086

[Abbott et al. 2016, ApJL 818, L22]

Astrophysical Implications

Different formation pathways are possible:

- A massive binary star system with sequential core-collapses
- Chemically homogeneous evolution of a pair of massive stars in close orbit
- Dynamical formation of binary from two BHs in a dense star cluster
- Binaries formed from a population of primordial black holes

Key piece of evidence: spins of the initial black holes

Orbit-aligned components: $\chi_{\mathrm{eff}} = 0.21^{+0.21}_{-0.10}$ for GW151226,
but consistent with zero for the other events

In-plane components (which would cause precession during inspiral):
little information from the events detected so far

All we can really say now is that these binary systems did not have large black-hole spins positively aligned with the orbital axis

➔ Disfavors chemically homogeneous evolution model

[Abbott et al. 2017, PRL 118, 221101]

What if General Relativity is Wrong?

Alternative theories of gravity permit additional modes

Besides the tensor modes of GR

e.g. scalar-tensor theories

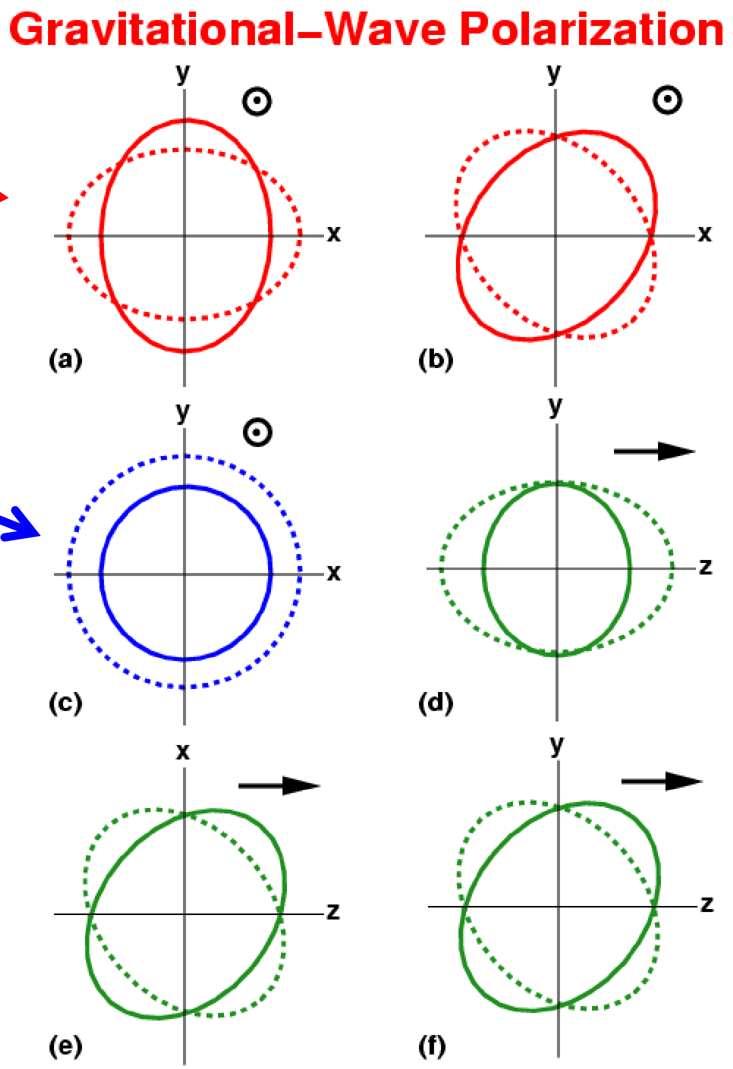
Brans-Dicke is one

Coupling depends on the specific theory

Could allow core-collapse supernova to be detected from farther away?

Also, GW modes could travel at speeds different from *c*

Comparison of signals in multiple detectors allows us to check for deviations from GR



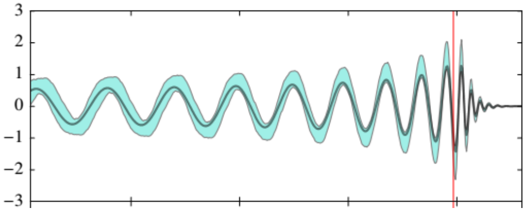
Tests of GR

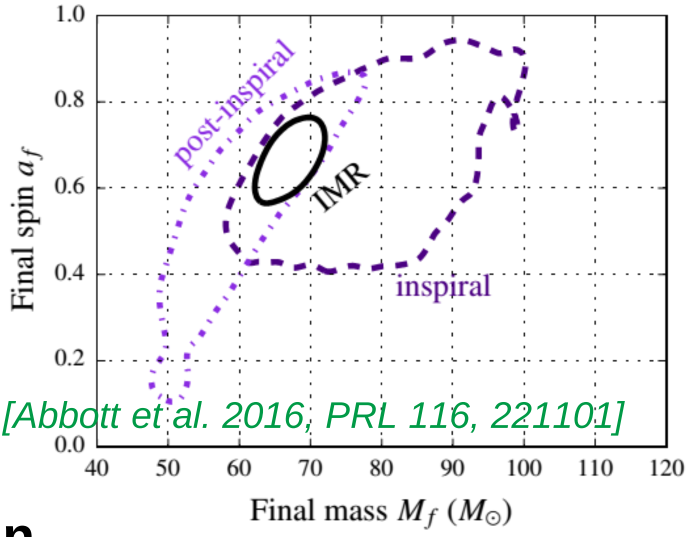
We examine the waveforms of the detected events in several ways to see whether there is any deviation from the GR predictions

Known through post-Newtonian (analytical expansion) and numerical relativity

Inspiral / merger / ringdown consistency

Compare estimates of mass and spin from before vs. after merger





[Abbott et al. 2016, PRL 116, 221101]

Consider possibility of a massive graviton

Would distort waveform due to dispersion

From lack of distortion, we place a limit on graviton Compton wavelength: $\lambda_g > 1.5 \times 10^{13}$ km

➔ $m_g < 7.7 \times 10^{-23}\ \mathrm{eV}/c^2$

[Abbott et al. 2017, PRL 118, 221101]

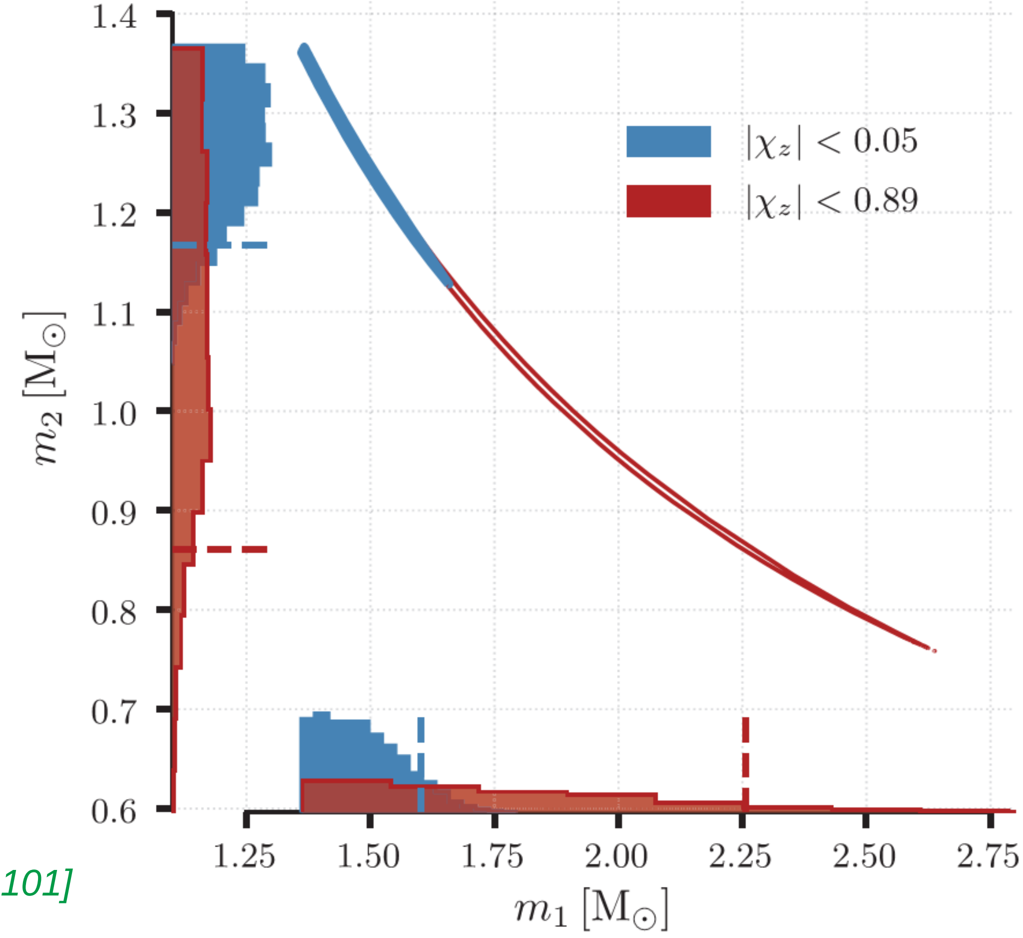
Binary neutron star mergers

GW170817 component masses

“Chirp mass” determined very precisely: $\mathcal{M} = 1.188^{+0.004}_{-0.002} M_{\odot}$

Component masses could be equal at $m_1 = m_2 = 1.36\ M_{\odot}$ or could be unequal

Mass ratio and spins have similar influence on the waveform recorded by the GW detectors



[Abbott et al. 2017, PRL 119, 161101]

Parameters estimated from the signals

Network signal-to-noise ratio: 32.4

18.8 in LIGO-Hanford, 26.4 in LIGO-Livingston, ~2.0 in Virgo

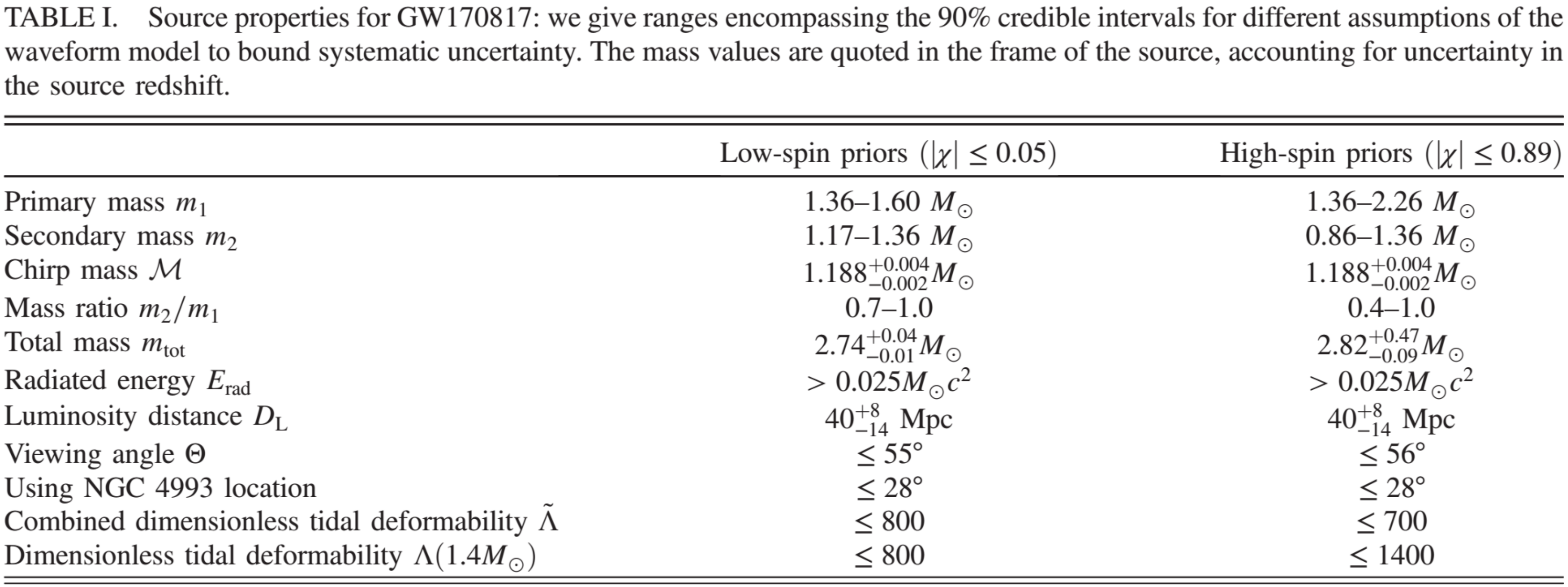


TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

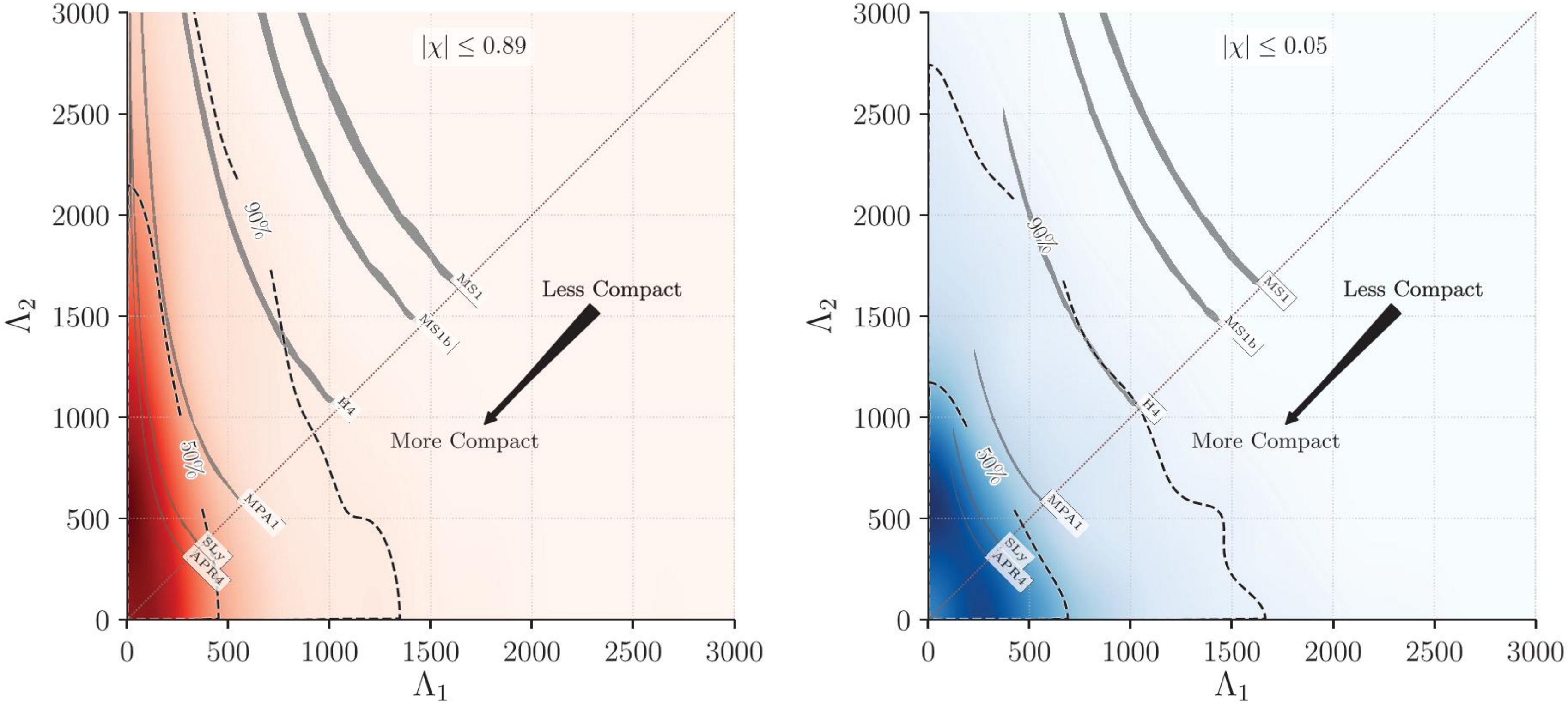
	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	$1.36–1.60\ M_\odot$	$1.36–2.26\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$	$0.86–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Note luminosity distance, viewing angle limits

[Abbott et al. 2017, PRL 119, 161101]

Constraints on tidal deformability

Ruled out some “stiff” equations of state which correspond to particularly un-compact neutron stars



[Abbott et al. 2017, PRL 119, 161101]

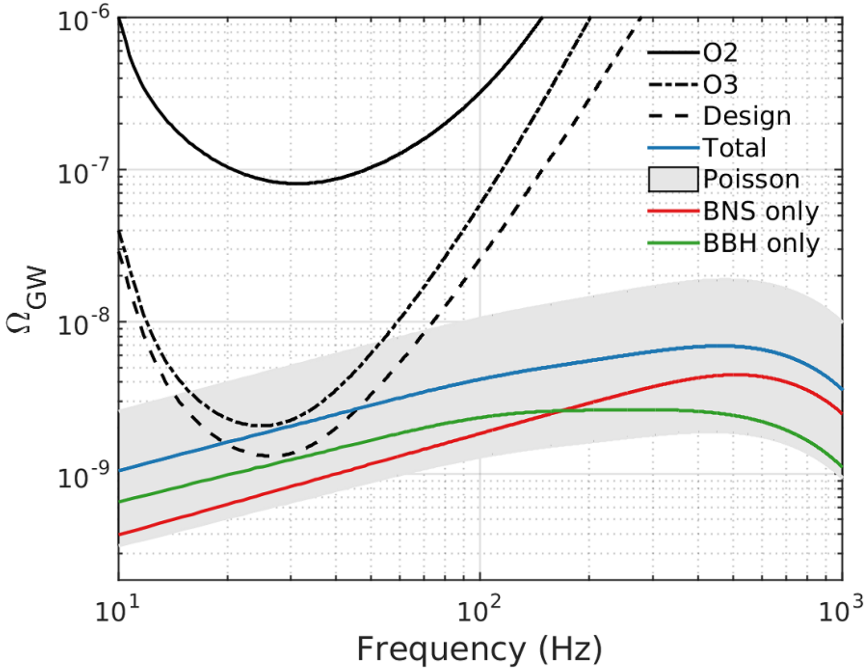
Improved LSC analyses of tidal deformability and neutron star EoS are now available: arXiv:1805.11579, arXiv:1805.11581

What else can we determine from the event?

Rate of binary neutron star mergers: $R = 1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

[Abbott et al. 2017, PRL 119, 161101]

➔ Expect stochastic background of GWs from BNS mergers to be comparable to background of GWs from binary black hole mergers, and potentially detectable with a few years of data at design sensitivity



[Abbott et al. 2018, PRL 120, 091101]

Using binary mergers to probe cosmology

GR relates absolute GW signal amplitude to luminosity distance

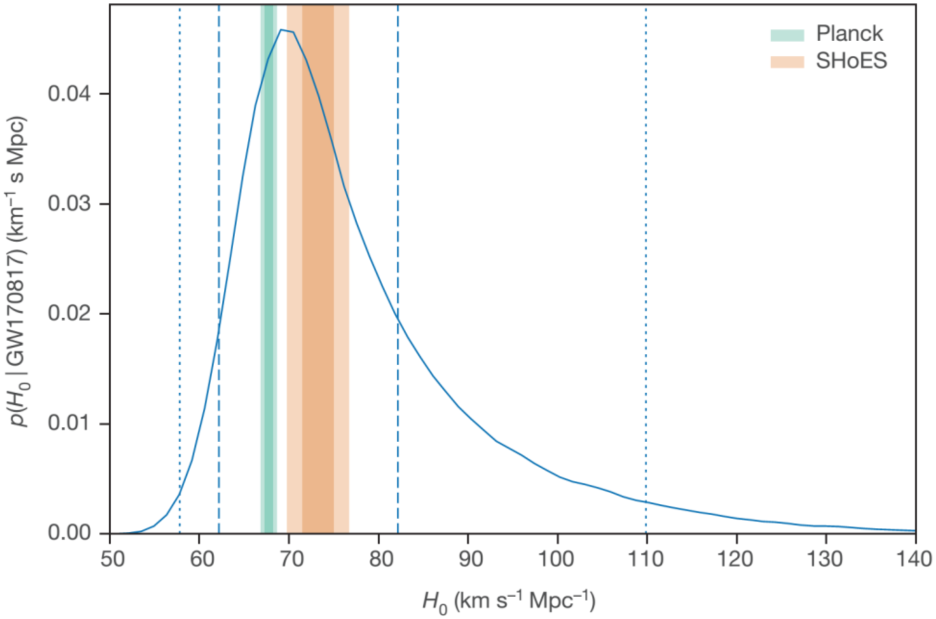
… assuming that other source parameters are known:
masses, orbit inclination angle, etc.

➔ A binary merger is a "standard siren", measuring distance
(but with uncertainty if other source parameter aren't known precisely)

For GW170817, combined GW distance estimate with measured redshift of its host (NGC 4993)

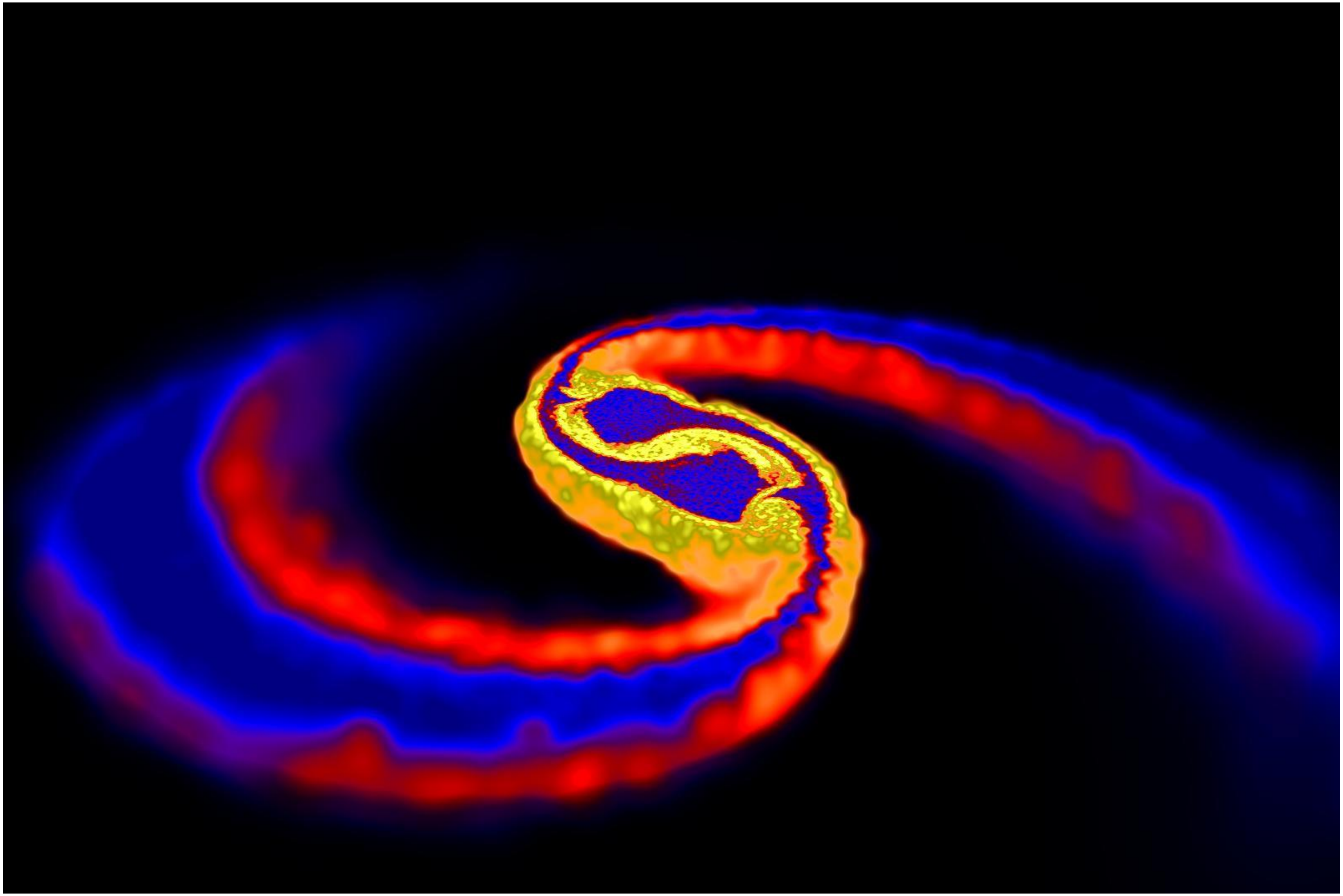
➔ $H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

[Abbott et al. 2017, Nature doi:10.1038/nature24471]



There are also a couple of tricks to enable measuring H_0 from GW events without EM counterparts

Tidal Disruption of Neutron Stars

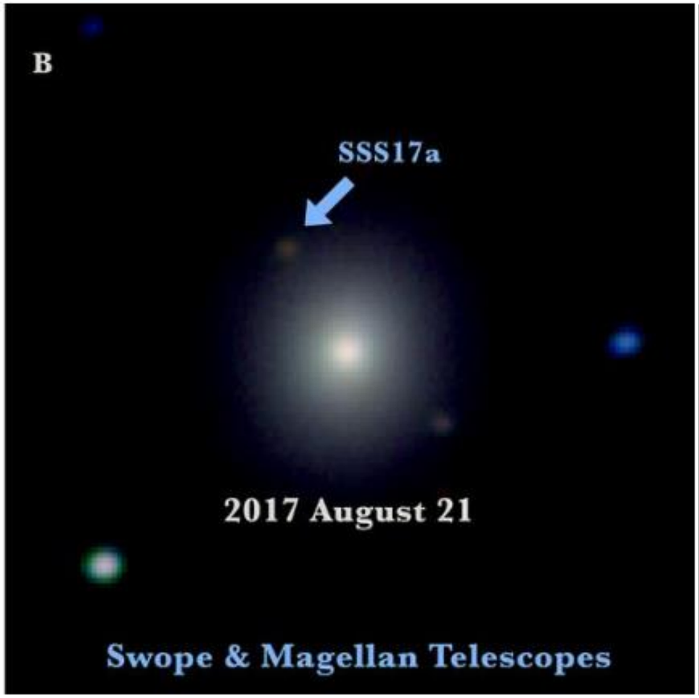


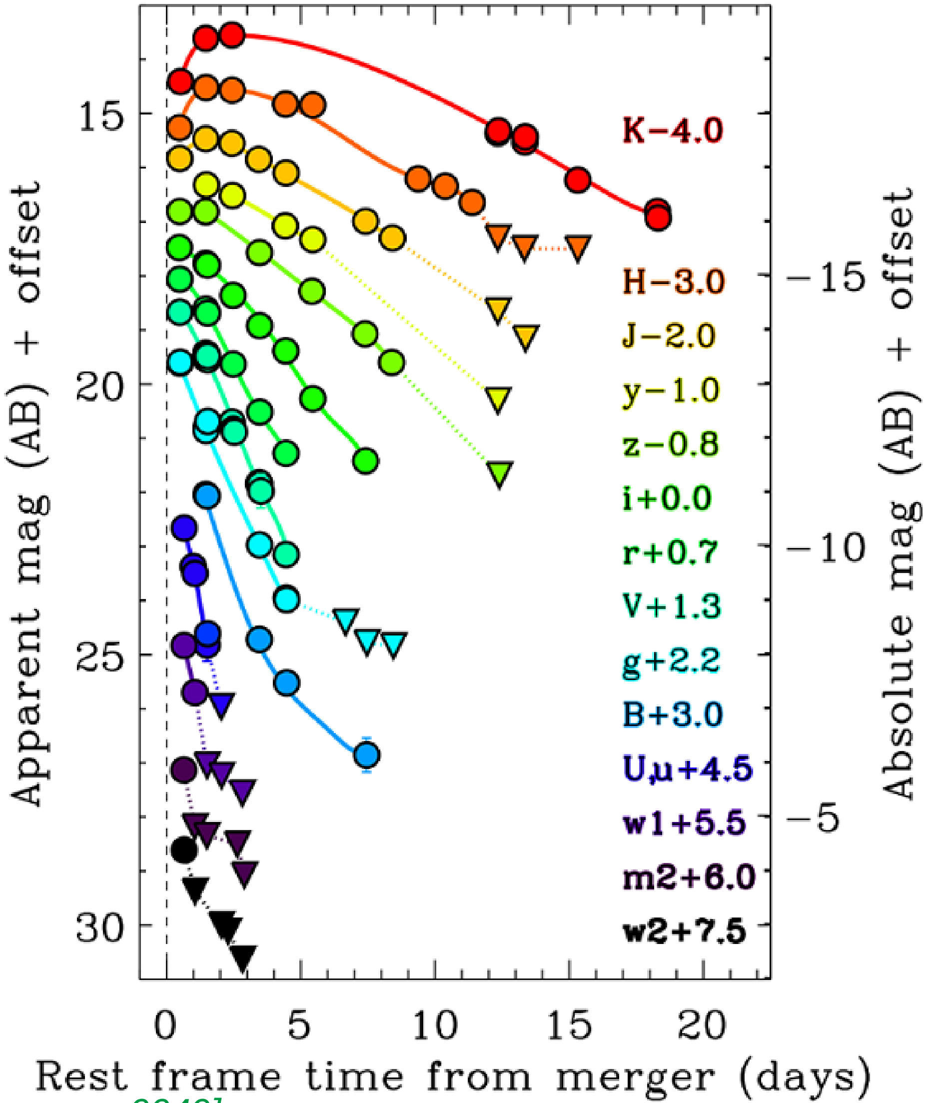
Price/Rosswog/Press

Saw the GW170817 counterpart fade – and change color

Initially visible in ultraviolet and blue – but those faded quickly

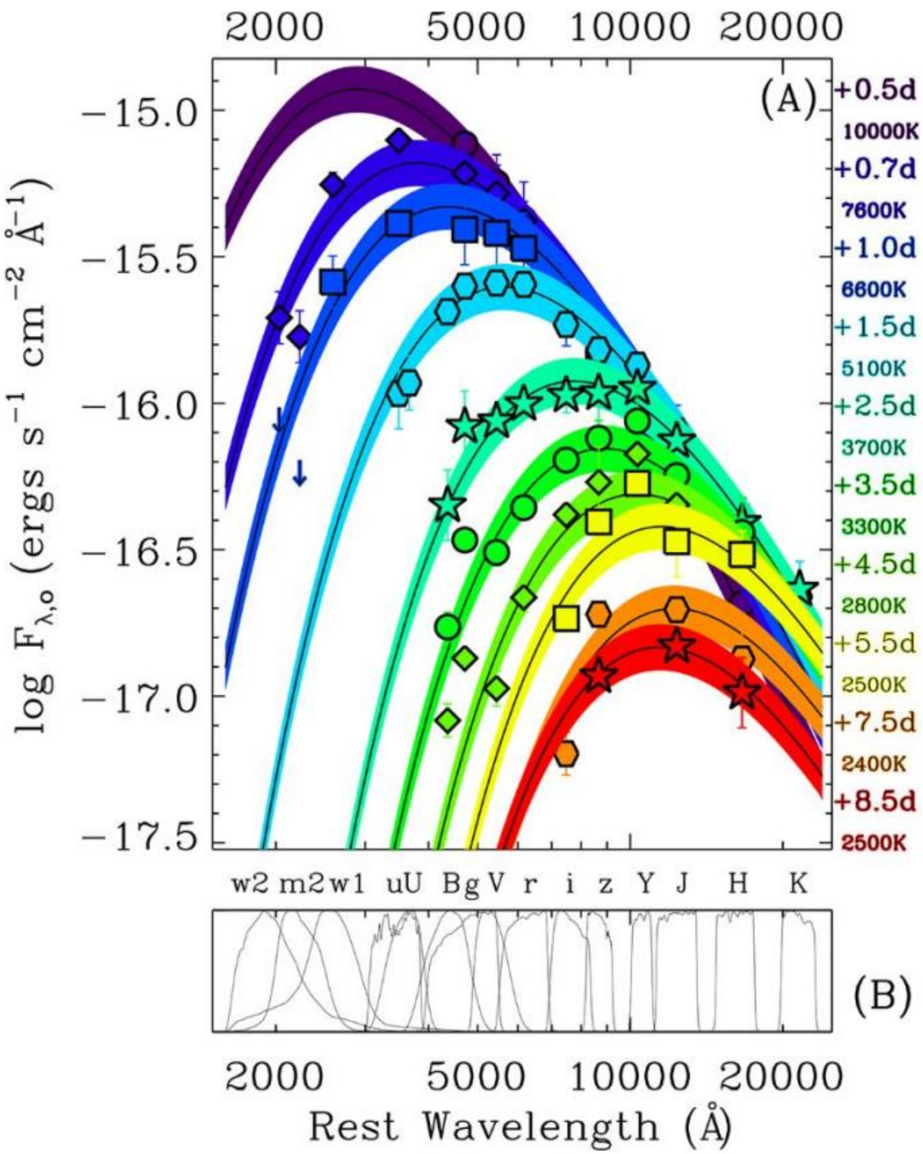
Infrared peaked after 2-3 days, remained visible for weeks





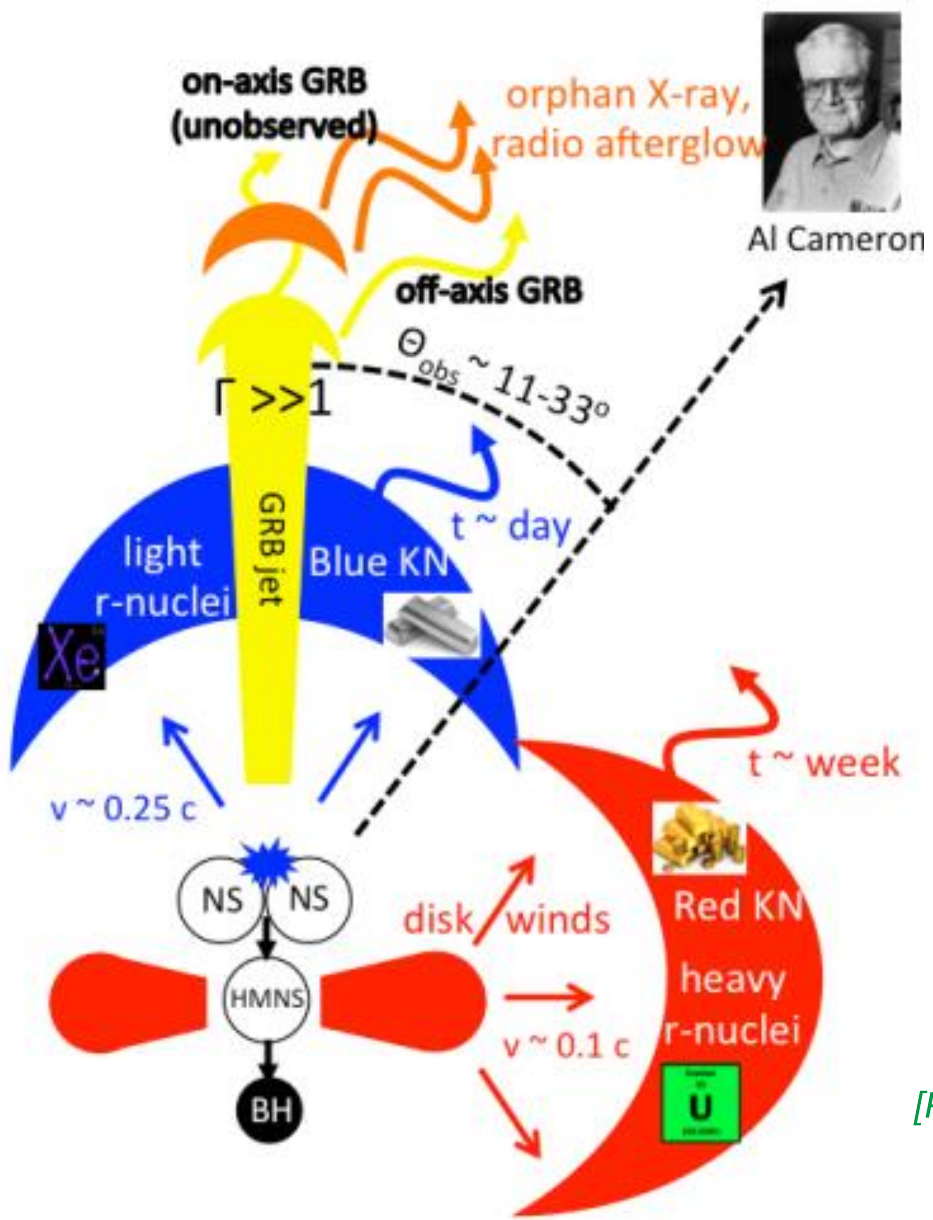
[Drout et al. 2017, Science 10.1126/science.aaq0049]

… as it cooled



[Drout et al. 2017, Science 10.1126/science.aaq0049]

Confronting kilonova models

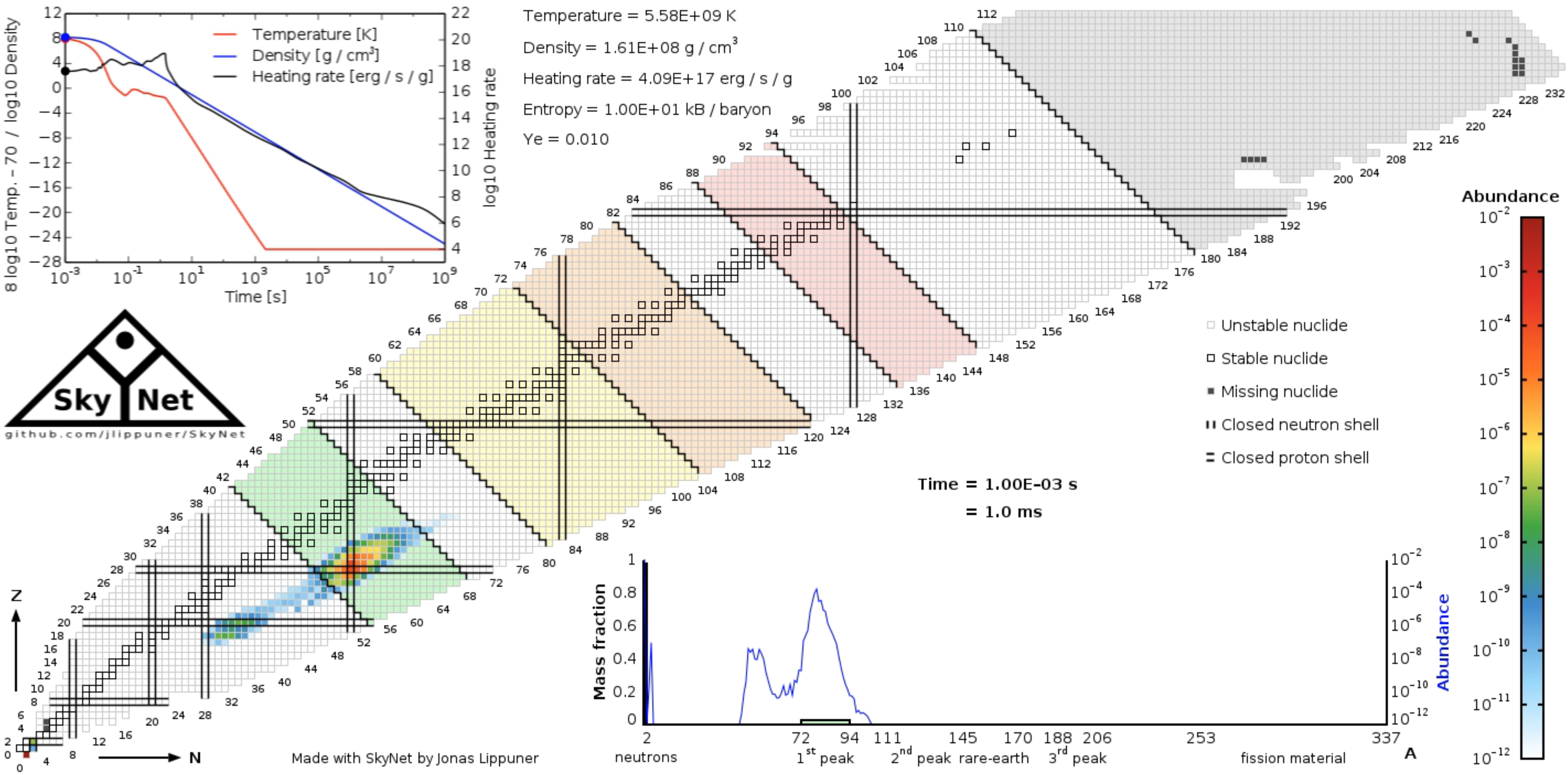


"Blue" (lanthanide-poor) and "red" (lanthanide-rich) ejecta – different r-process elements produced ➔ different opacities

Hypermassive neutron star may irradiate ejecta with neutrinos, converting neutrons to protons

[Figure from Metzger, arXiv:1710.05931]

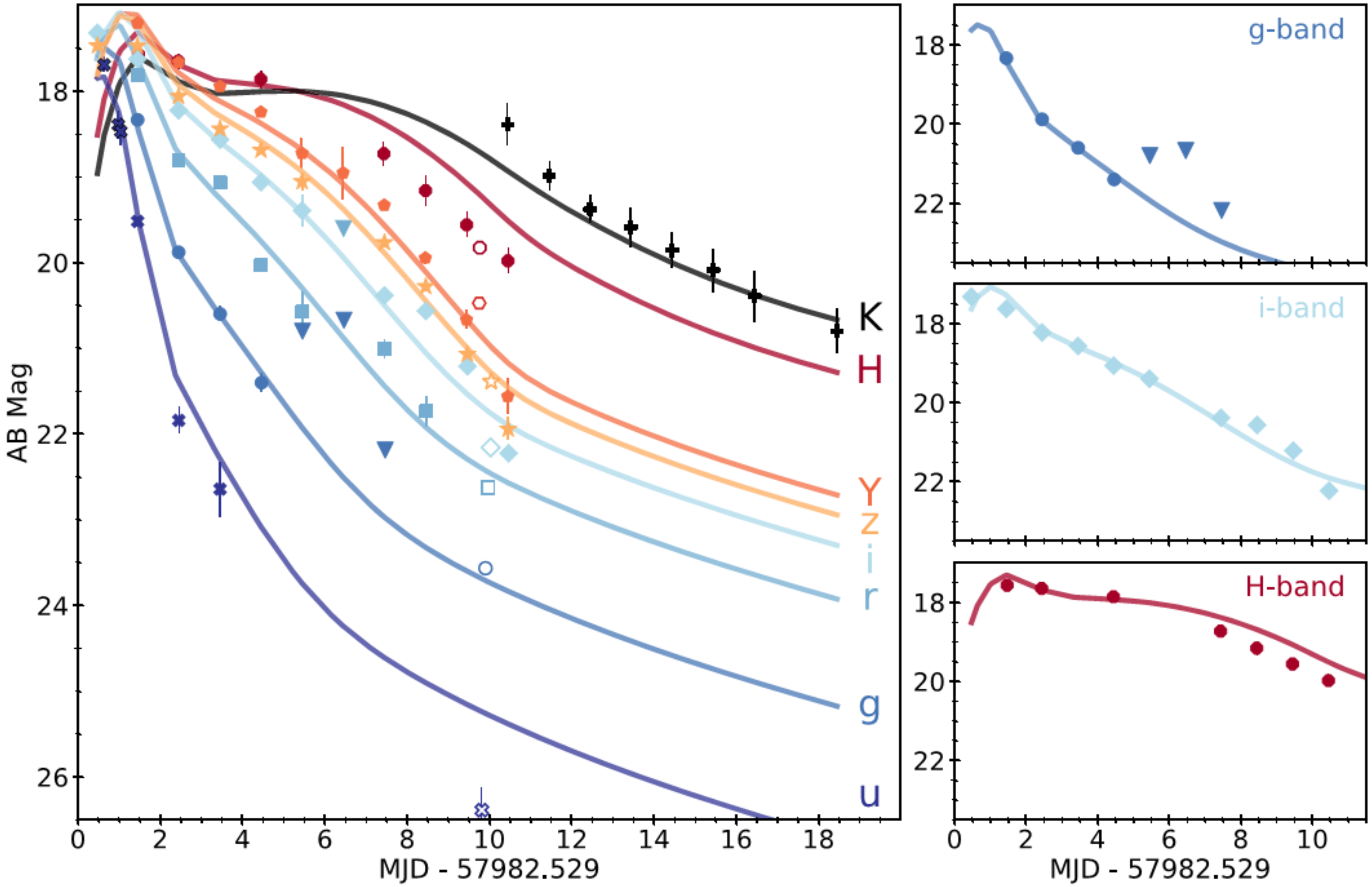
r-process nucleosynthesis in action



Credit: J. Lippuner, author of SkyNet simulation software

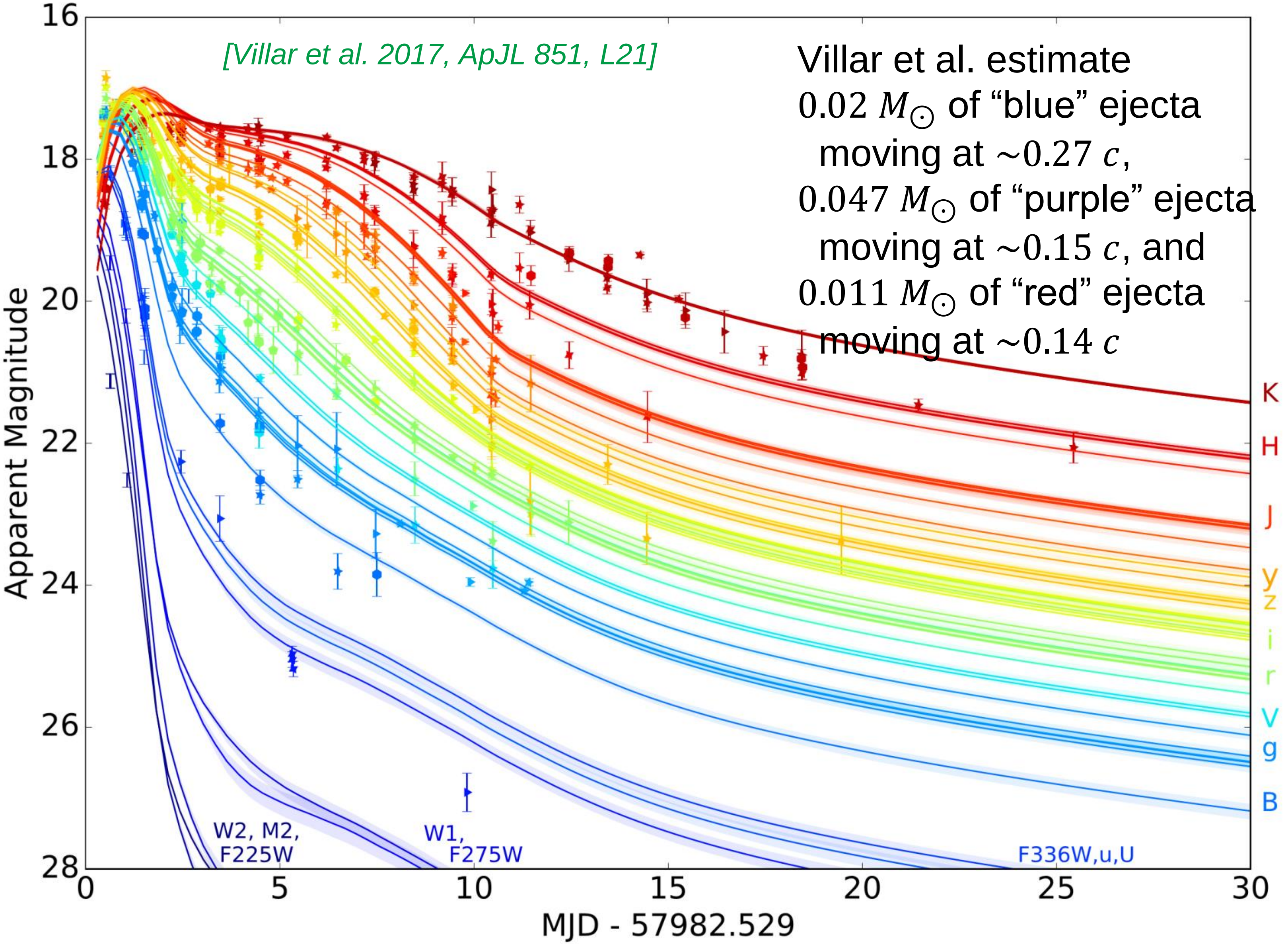
Confronting kilonova models

Cowperthwaite et al. estimate $0.01\ M_\odot$ of "blue" ejecta moving at $\sim 0.3\ c$ plus $0.04\ M_\odot$ of "red" ejecta moving at $\sim 0.1\ c$



[Cowperthwaite et al. 2017, ApJL 848, L17]

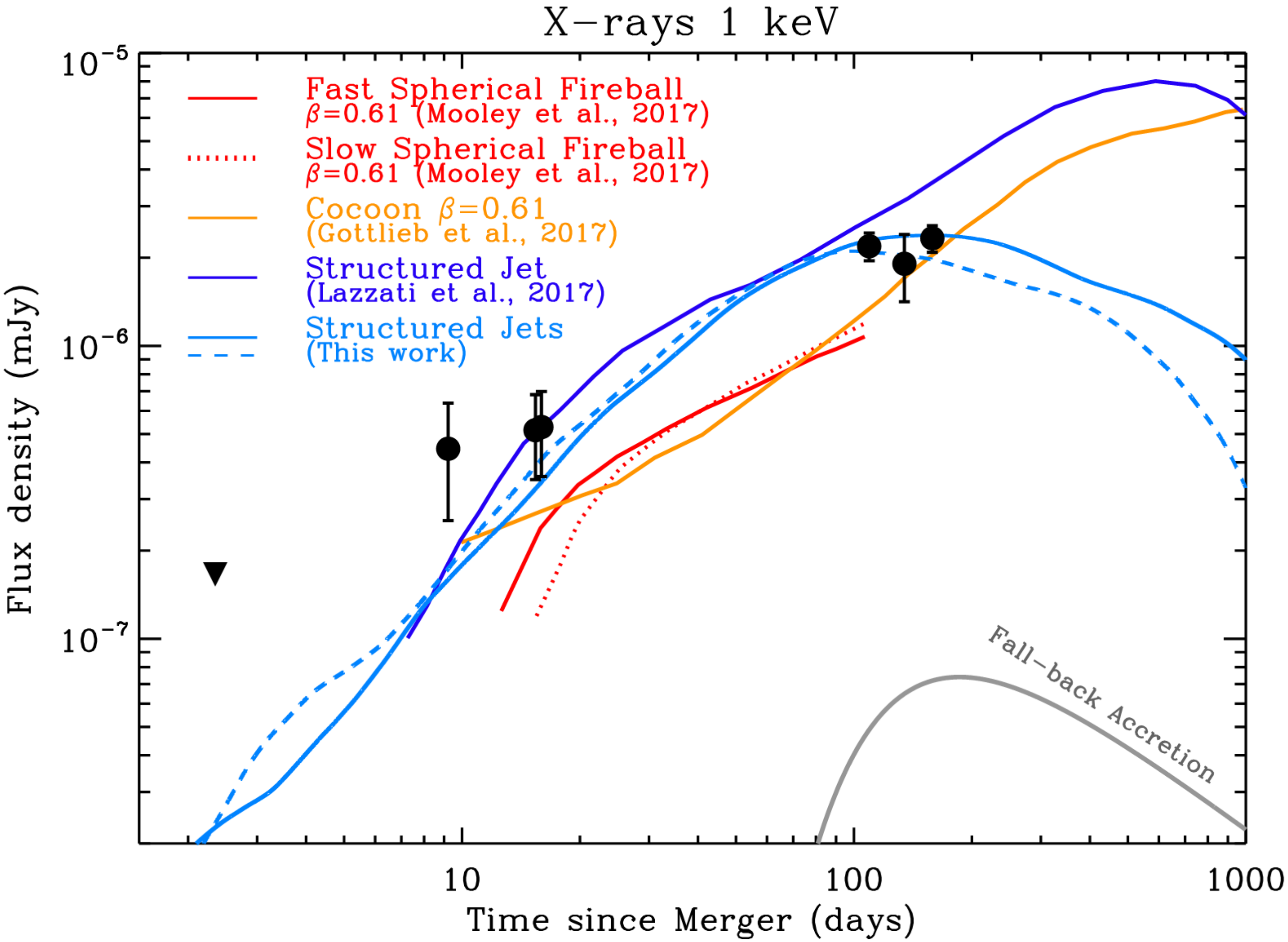
… or maybe three components



[Villar et al. 2017, ApJL 851, L21]

Villar et al. estimate
$0.02\ M_{\odot}$ of “blue” ejecta
moving at $\sim 0.27\ c$,
$0.047\ M_{\odot}$ of “purple” ejecta
moving at $\sim 0.15\ c$, and
$0.011\ M_{\odot}$ of “red” ejecta
moving at $\sim 0.14\ c$

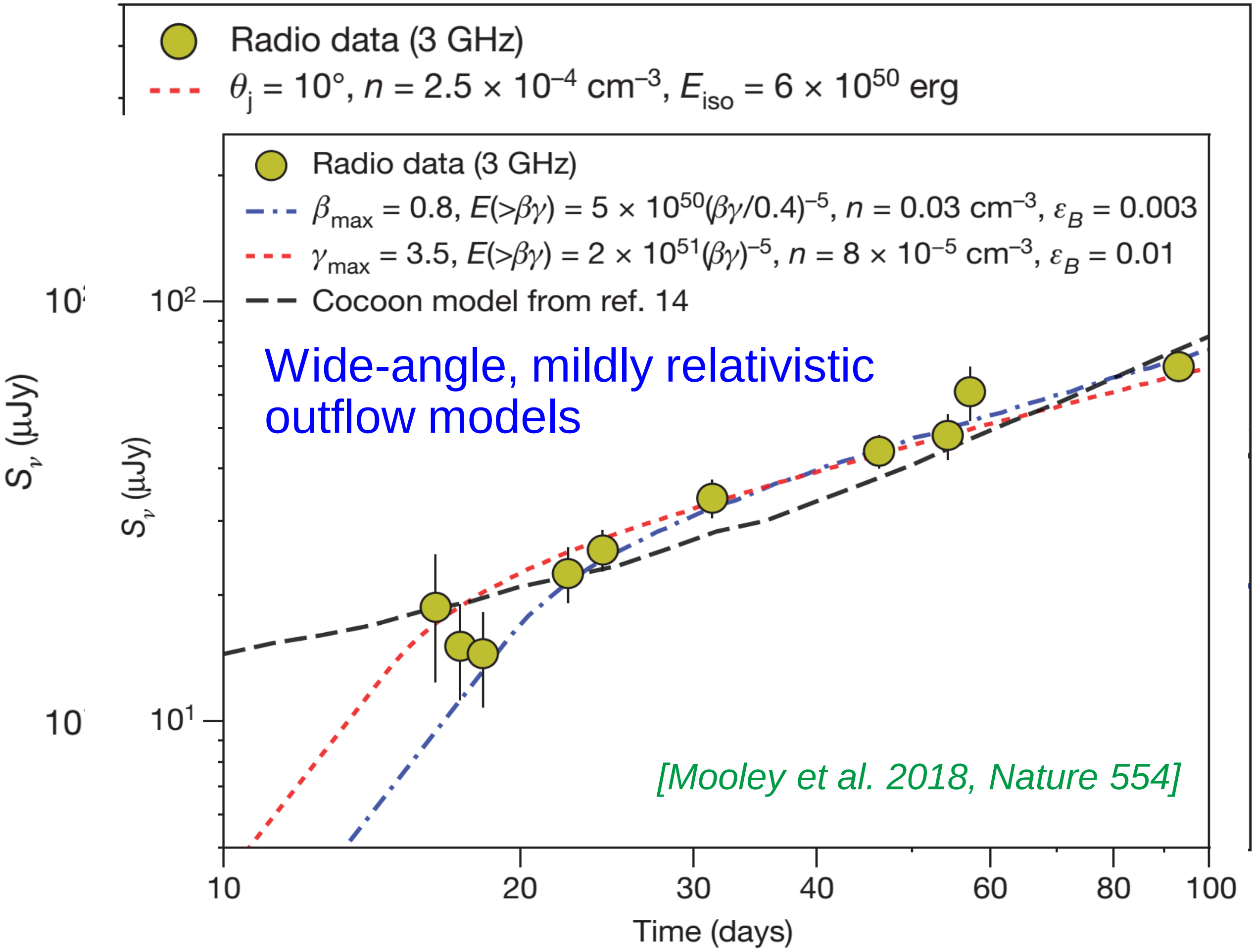
Understanding outflows: X-ray data



[Margutti et al. 2018, ApJL 856, L18]

Understanding outflows: radio data

Consistent with X-ray flux, with constant spectral index



Wide-angle, mildly relativistic outflow models

[Mooley et al. 2018, Nature 554]

Putting it all together (?)

Lots of possible signatures

GRB prompt emission

GRB rapidly-fading afterglow (X-ray, UV/optical?)

High-energy neutrino counterpart

Kilonova signature (multiwavelength light curves)

Late-time afterglow in X-ray, radio

… can, in principle, tell us about binary orbit inclination, mass ratio and spins

➔ Break degeneracies in parameter estimation from the GW data

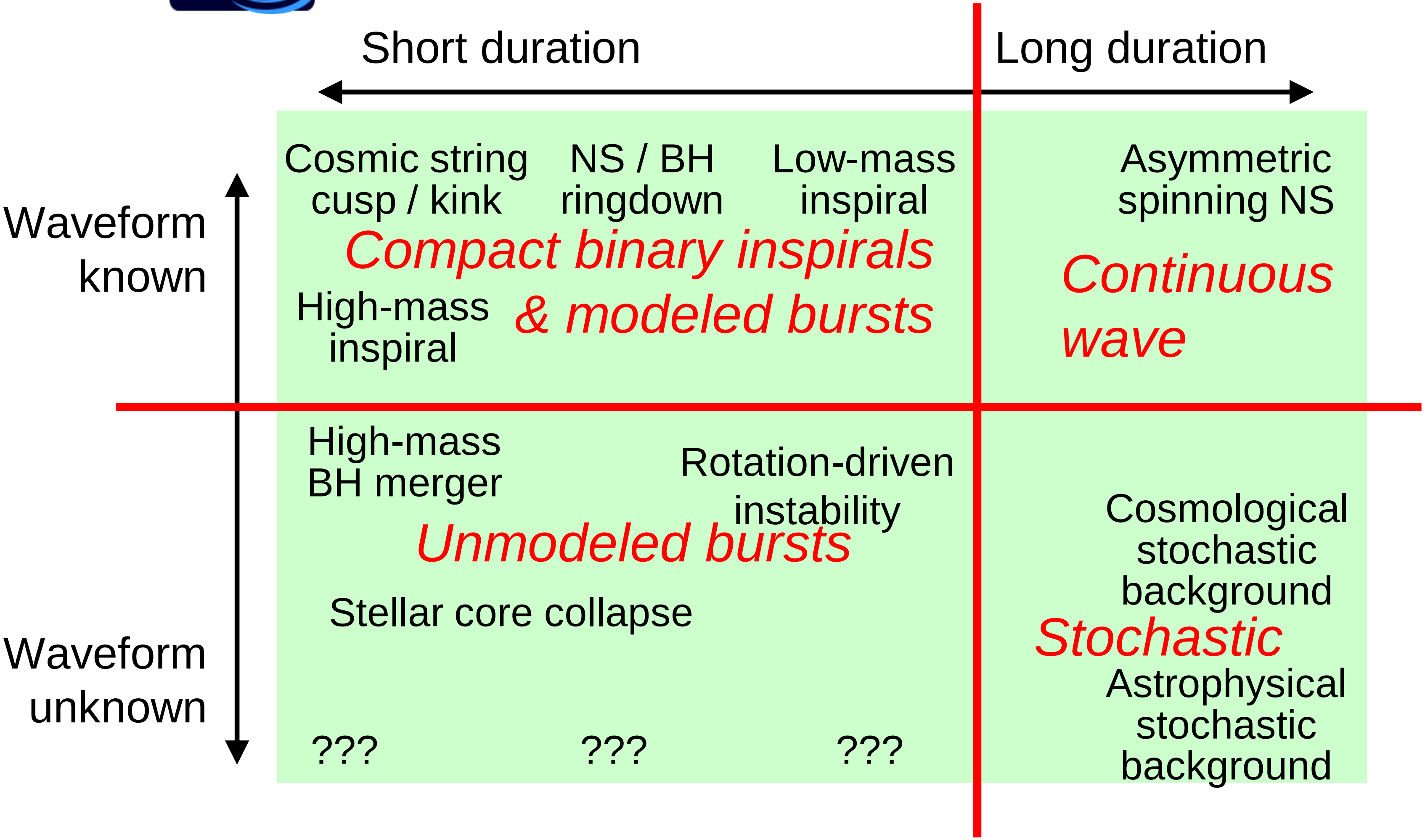
This requires detailed modeling as well as rich observational data

A grand challenge we now face as a broad community!

Other GW signal searches

Gravitational Wave Sources...

And LSC – VIRGO data analysis working groups



Short duration

Long duration

Waveform known

Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Compact binary inspirals & modeled bursts

High-mass inspiral

Asymmetric spinning NS

Continuous wave

High-mass BH merger

Rotation-driven instability

Unmodeled bursts

Stellar core collapse

??? ??? ???

Cosmological stochastic background

Stochastic

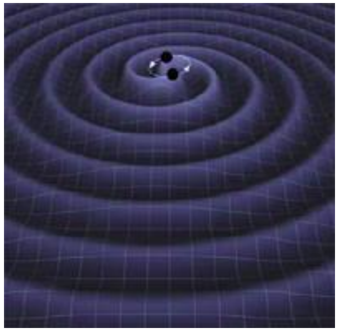
Astrophysical stochastic background

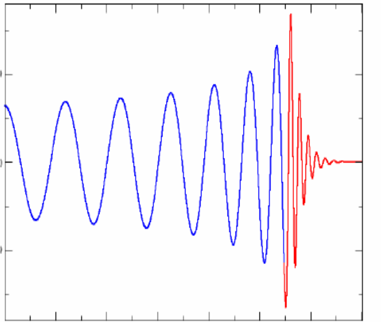
Searches for GW Transient Sources

GW data streams are analyzed jointly

Initially LIGO Hanford+Livingston and Virgo; later others too

Two main types of transient searches:

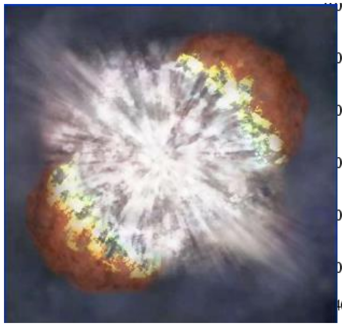


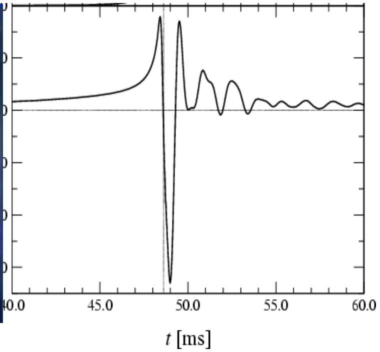


Compact Binary Coalescence (CBC)

Known waveform ➔ Matched filtering

Templates for a range of component masses
(spin affects waveforms too, but not so important
for initial detection)





Unmodelled GW Burst (< ~1 sec duration)
e.g. from stellar core collapse

Arbitrary waveform ➔ Excess power

Require coherent signals in detectors,
using direction-dependent antenna response

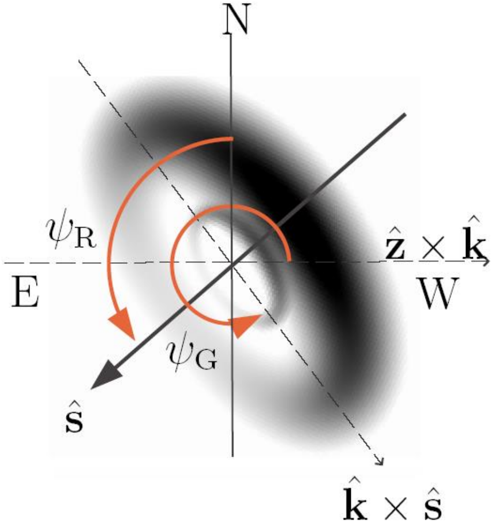
Search for GWs from the Crab Pulsar

The Crab pulsar spin rate is slowing down – why?

Search for a continuous-wave signal, demodulating detector motion
X-ray observations tell us the orientation of the spin axis

Chandra image

Model



No GW signal detected

[Abbott et al., ApJ 839, 12 (2017)]

Upper limit on GW strain amplitude: $h_0 < 5 \times 10^{-26}$

Implies that GW emission accounts for < 0.2% of total spin-down power

Projected number of events in O3

Slide made by Chris Pankow – at https://gw-astronomy.org/wiki/OpenLVEM/TownHallMeetings2018

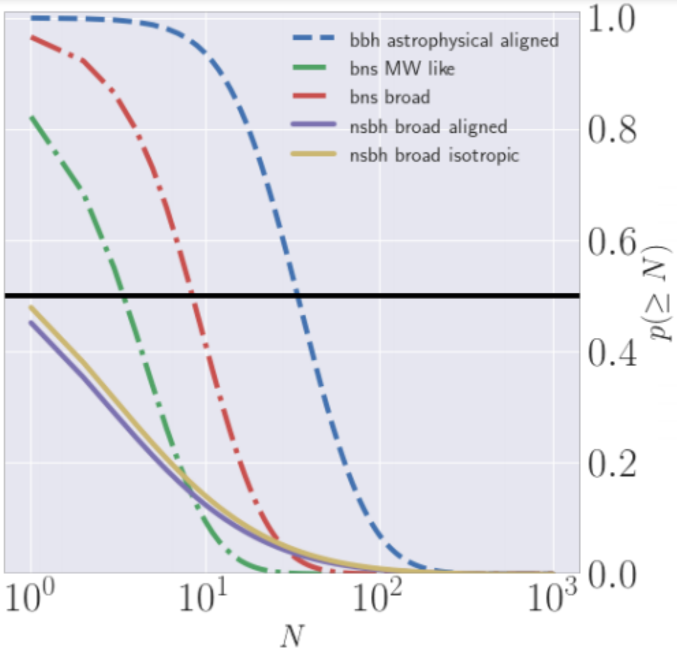
Note: sensitive to assumed population distributions (masses, etc.)

BBH rate will **dominate**, possibly by more than an order of magnitude, up to **~few/wk., at least ~few/mo.**

1-10 BNS, possibly up to **~1/mo.**

VT has **strong mass dependence** but **very mild dependence** on assumed spin distribution

NSBH: N=0 not ruled out in any scenario, most give **~50% N>0**



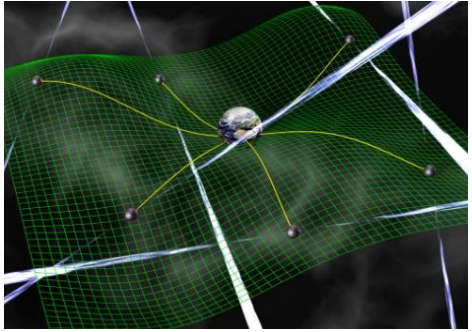
source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	34^{+79}_{-25}
BNS / bns_astrophysical	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	5.0×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

Maybe a continuous-wave GW signal ??

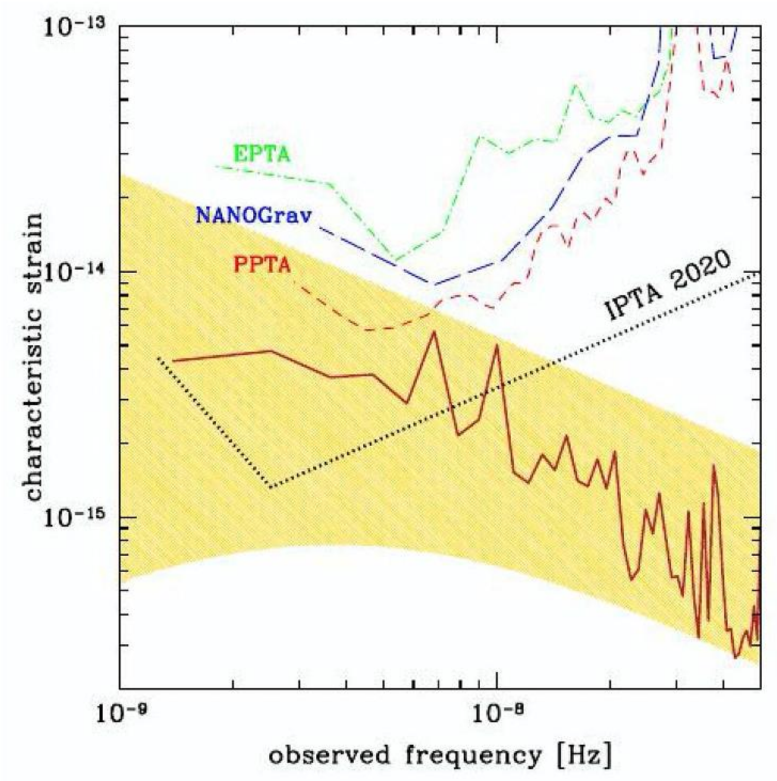
Pulsar Timing Results and Prospects

Sensitivity improves with observation time span, number of pulsars monitored, and pulse timing precision

New pulsars are added as they are discovered



D. Champion



Pulsar timing is getting close to the expected stochastic signal from supermassive black hole binaries in the universe

[Figure by A. Sesana, in Hobbs+Dai, arXiv:1707.01615]

Also searching for individual black hole binaries, cosmic strings, and arbitrary transient signals

Note: some of these radio telescopes are at risk of being shut down! See article in July 2017 issue of *Physics Today*

What future detectors will give us

Evolution of the GW Detector Network

Adding similar detectors (KAGRA, LIGO-India) will give us:

- More robustness against detector downtimes ➔ higher GW detection rate
- Better localization of GW events candidates ➔ more EM counterparts
- Better distance estimates
- GW polarization consistency tests
- (However, binary mergers viewed within ~45° of orbital axis are essentially circularly polarized. EM counterpart may tell us more about inclination.)

Advanced LIGO can be made even better

- The "A+" upgrade effort

Future detectors designs, with greater sensitivity, are under study

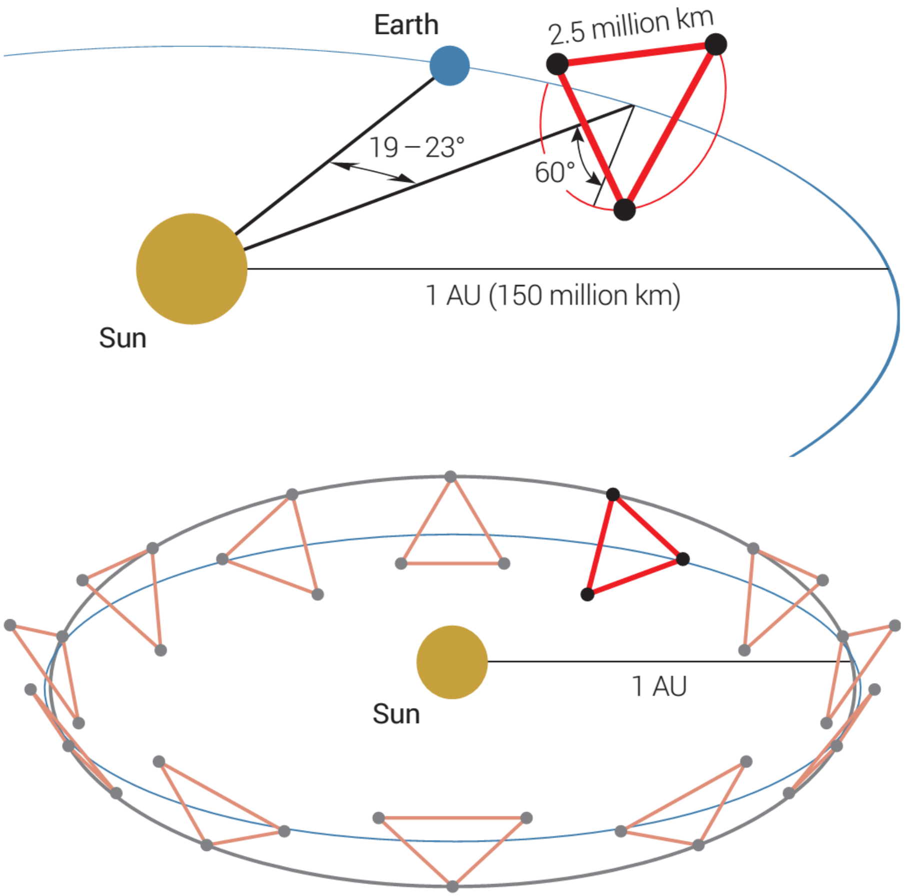
- Einstein Telescope, Voyager, Cosmic Explorer

Space-based detectors will open up a new frequency band

- Complementary observations of compact object binaries
- Possibility of "multi-band" observing of some binary black hole events

GW Detection with Spacecraft: LISA

Use laser interferometry to measure changes in the distances among a trio of spacecraft in orbit around the Sun



- Forms two independent Michelson interferometers plus a Sagnac null channel

~milliHertz sources:

- Supermassive black hole binaries
- Intermediate mass BH binaries
- Extreme mass ratio inspirals (maps spacetime near BH)
- Galactic compact binaries
- Stochastic GW background?

[Danzmann et al. 2017, LISA Proposal to ESA]

Summary

Gravitational waves give us a unique view of (some) astrophysical events and objects

Parameter estimation from GW signals tells us about physical properties, and enables tests of GR, but there are degeneracies

Starting to get a statistical picture of the population: masses, spins, etc.

Combining with other messengers gives us complementary information and can break parameter degeneracies

Binary mergers are only one type of GW source;
we are also analyzing the data to search for others