Gravitational Wave Astronomy with LIGO-Virgo

IGFAE – LIP April 26 2019

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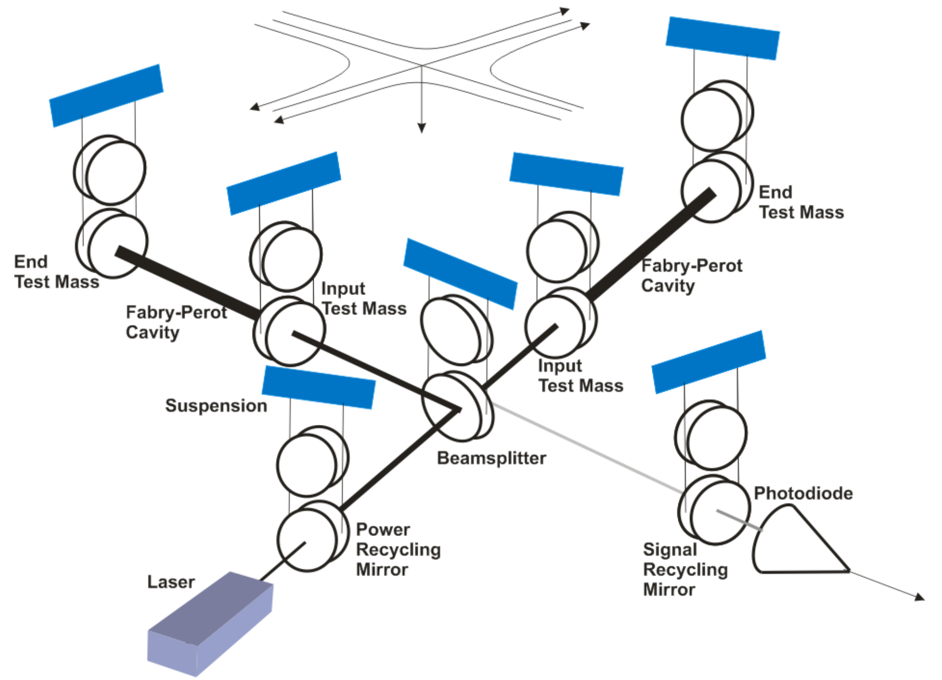
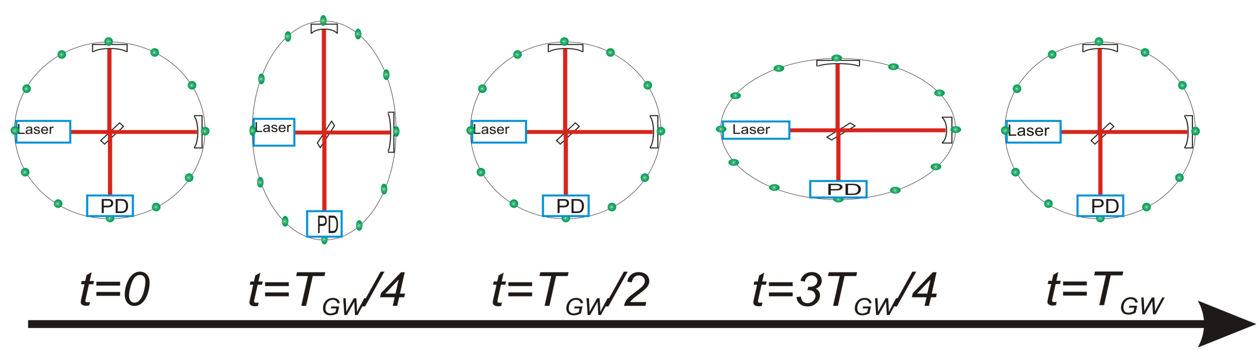
J. Alvarez-Muñiz, E. Zas

Image Credit: NASA/GSFC

Laser interferometric detection

- ‘Michelson interferometer’ : **end mirrors** free to move along arms
- Differential length change $\delta(L_x - L_y) = h(t) \cdot L$
  - $\Rightarrow$ time of flight difference
  - $\Rightarrow$ relative phase difference @ beam splitter
  - $\Rightarrow$ transmitted intensity variation @ PD





LIGO

Funding

- 1984: LIGO founded as a Caltech/MIT project
- 1990: LIGO Construction Project approved by NSF
- 1992: LIGO Construction Project funded by NSF

Construction

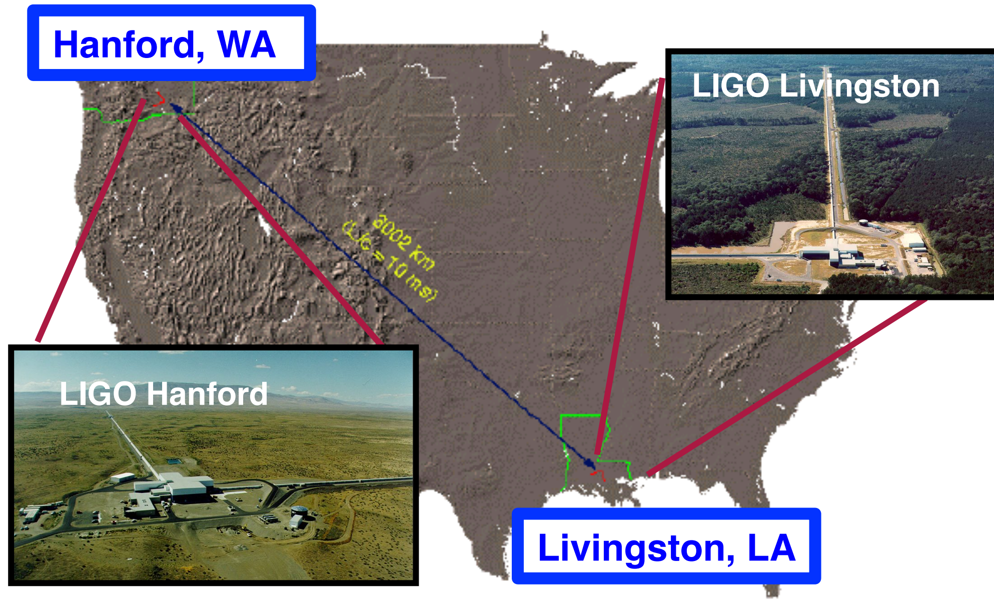
- 1992 – 1995: Site selection, vacuum prototyping
- 1995 – 1999: LIGO facilities construction at Hanford and Livingston
- 1998 – 2002: Installation/integration of initial LIGO interferometers

Initial LIGO

- 2002 – 2005: Interferometer commissioning interleaved with science runs (S1-S4)
- Nov 4, 2005 – Sep 31, 2007: S5 science run
  - Design sensitivity reached
  - 15 Mpc range; > 1 year of triple coincidence data
- 2007 – 2009: Enhanced LIGO instrument upgrade
  - Tests key Advanced LIGO technologies
- Jul 7, 2009 – Oct 20, 2010: S6 science run
  - 18 Mpc range to merging binary neutron stars

Advanced LIGO

- Apr 2008: Advanced LIGO Construction begins
- Dec 2011: Advanced LIGO detector installation begins
- Mar 2015: Advanced LIGO Construction complete
- Sep 2015: First Advanced LIGO Observing Run 'O1'
- Sep 14, 2015: First binary black hole detection
- Nov 30, 2016: Advanced LIGO O2 run starts



LIGO Laboratory:
180 staff located at Caltech, MIT, Hanford, Livingston

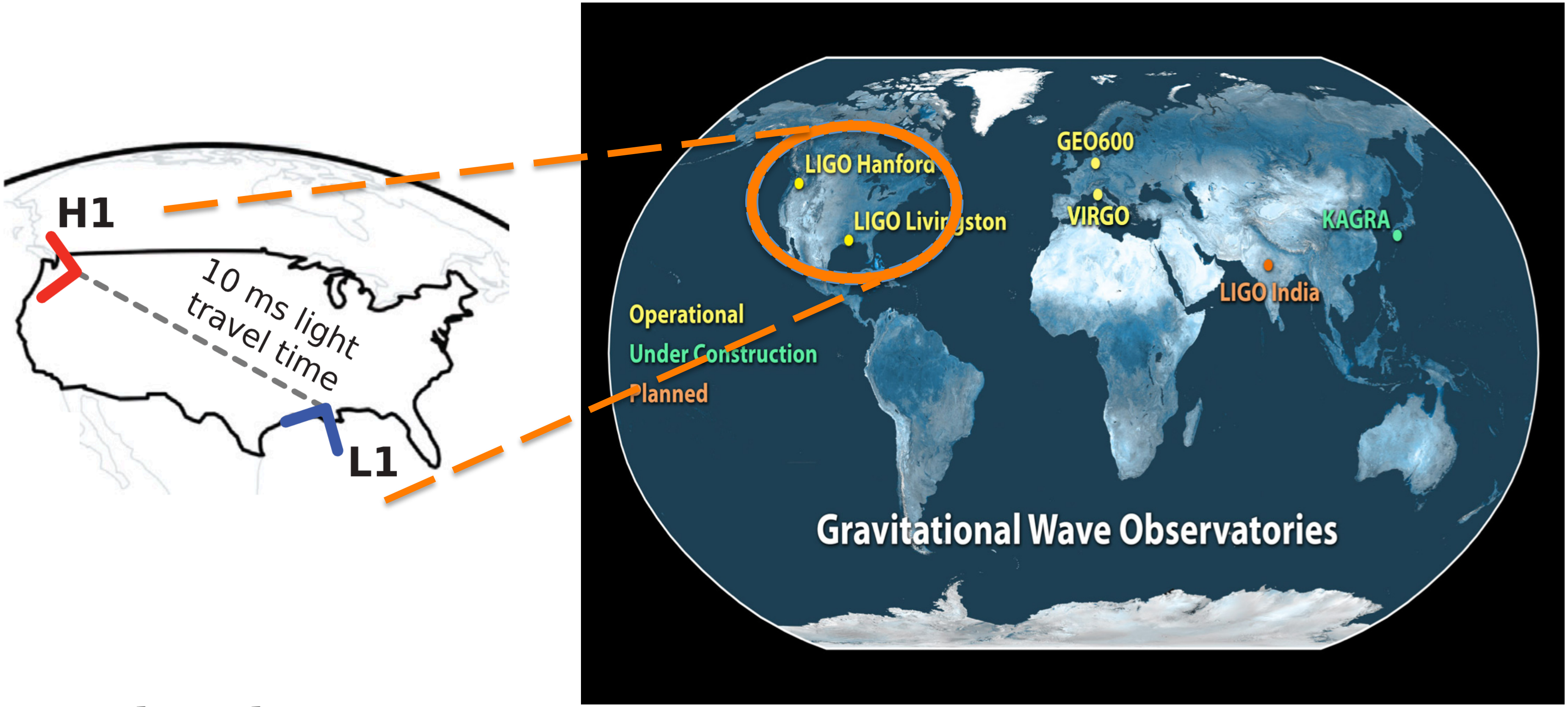
LIGO Scientific Collaboration:
~ 1200 scientists, ~100 institutions, 16 countries

ADVANCED VIRGO

6 EU countries: France, Hungary, Italy, Poland, Spain, and The Netherlands
20 labs, ~280 authors

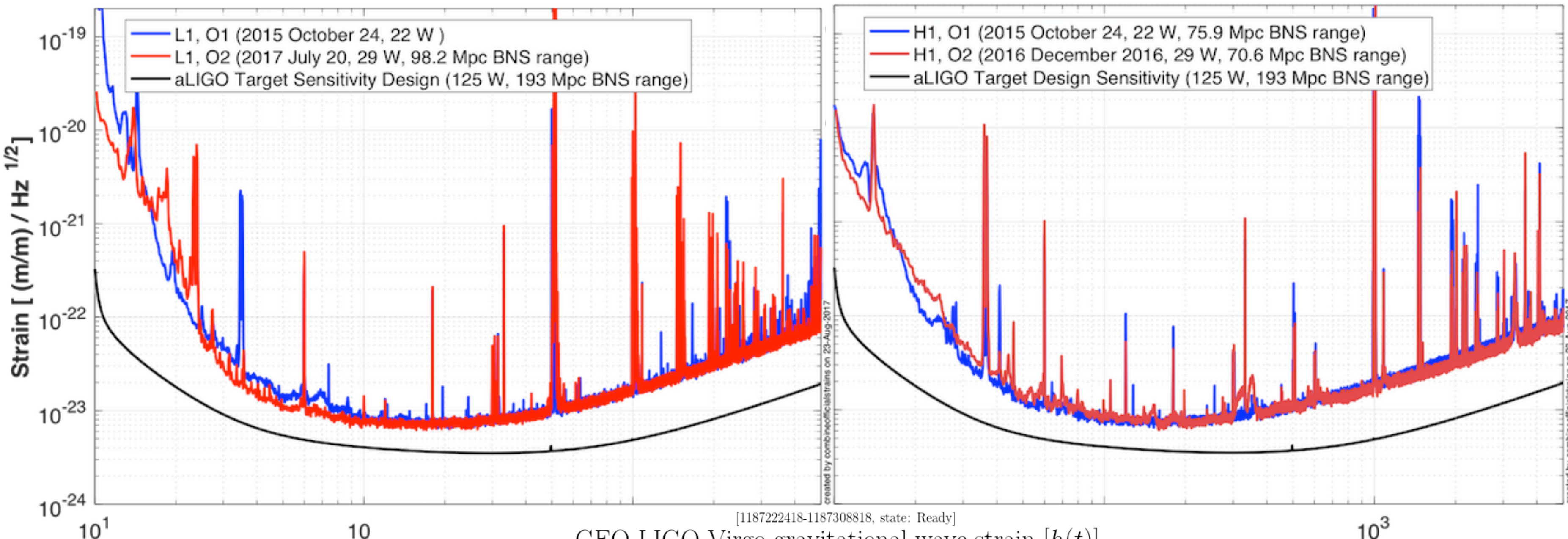
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest
University of Valencia

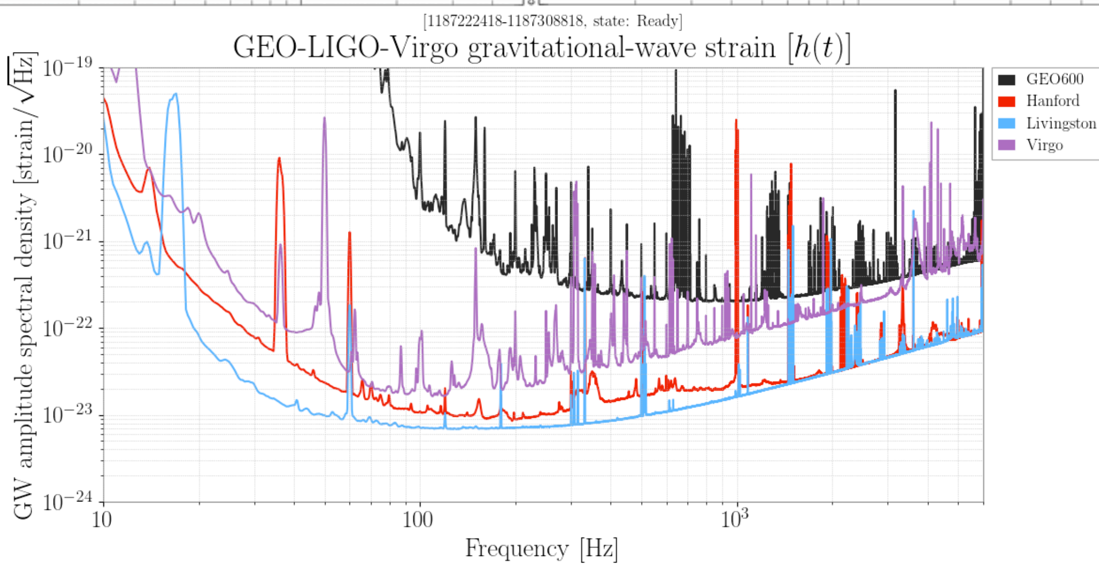
A global network



- Higher detection rate
- Greater accuracy on source parameters
  - distance, sky direction, GW polarization ...

LIGO-Virgo performance in 2016-17





GW sources : Transients

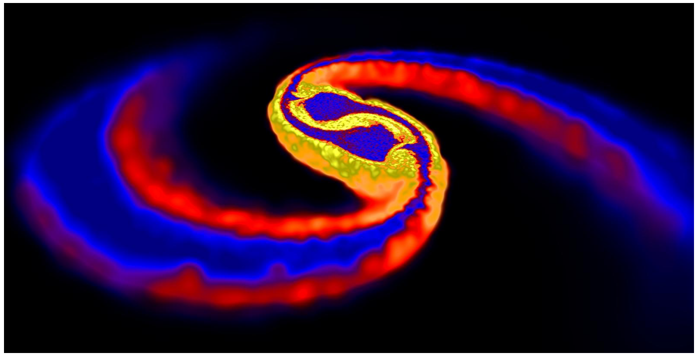
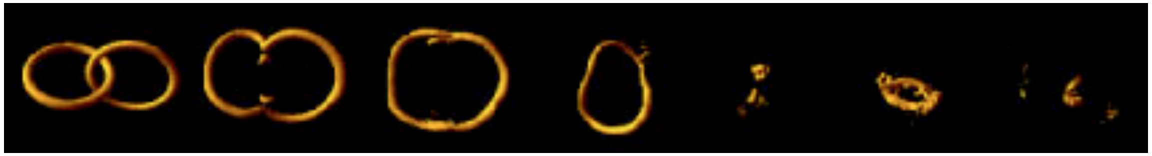
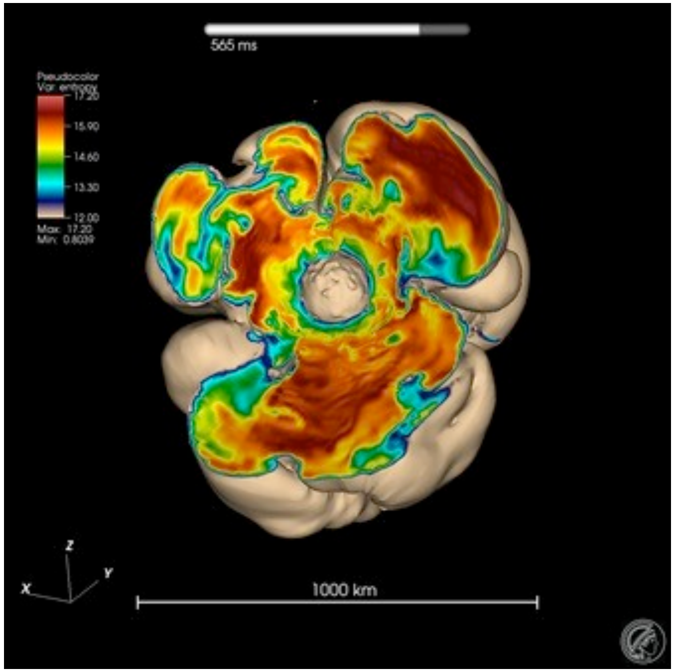


Image credit: D. Price (Exeter) & S. Rosswog (Int. U/Bremen)





Simulation: F. Hanke et al. (MPIA Garching)

Cataclysmic events of compact astrophysical objects

- Mergers of **N**eutron**S**tars, **B**lack**H**oles "**C**ompact **B**inary **C**oalescence"
- **C**ore**C**ollapse**S**uper**N**ovae
- Pulsar glitches / oscillation modes ?
- Exotics : cosmic string kinks ? …

GW sources : Continuous / Persistent

Less intense GW over long times (days → years)

- ***Continuous Wave*** :
  sinusoids from rotating NS
  - many potential sources in Galaxy

- ***Stochastic*** : random
  'background' from superposition of unresolved sources
  - astrophysical
    transients at high redshift
  - primordial
    quantum fluctuations / critical phenomena in very early Universe

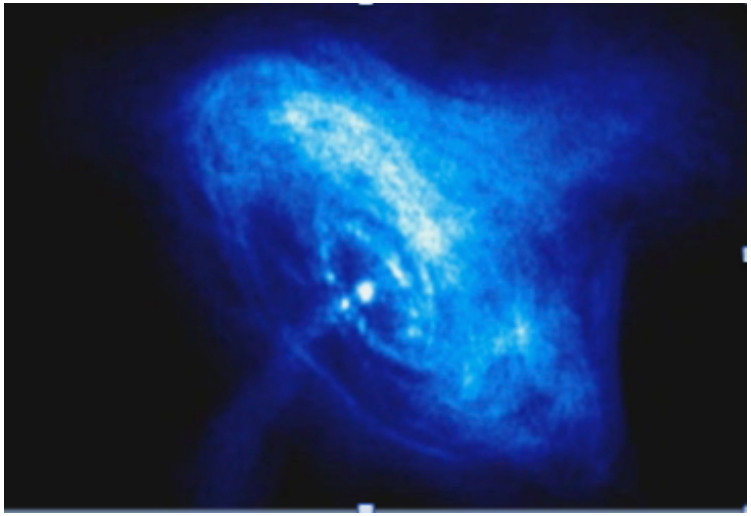
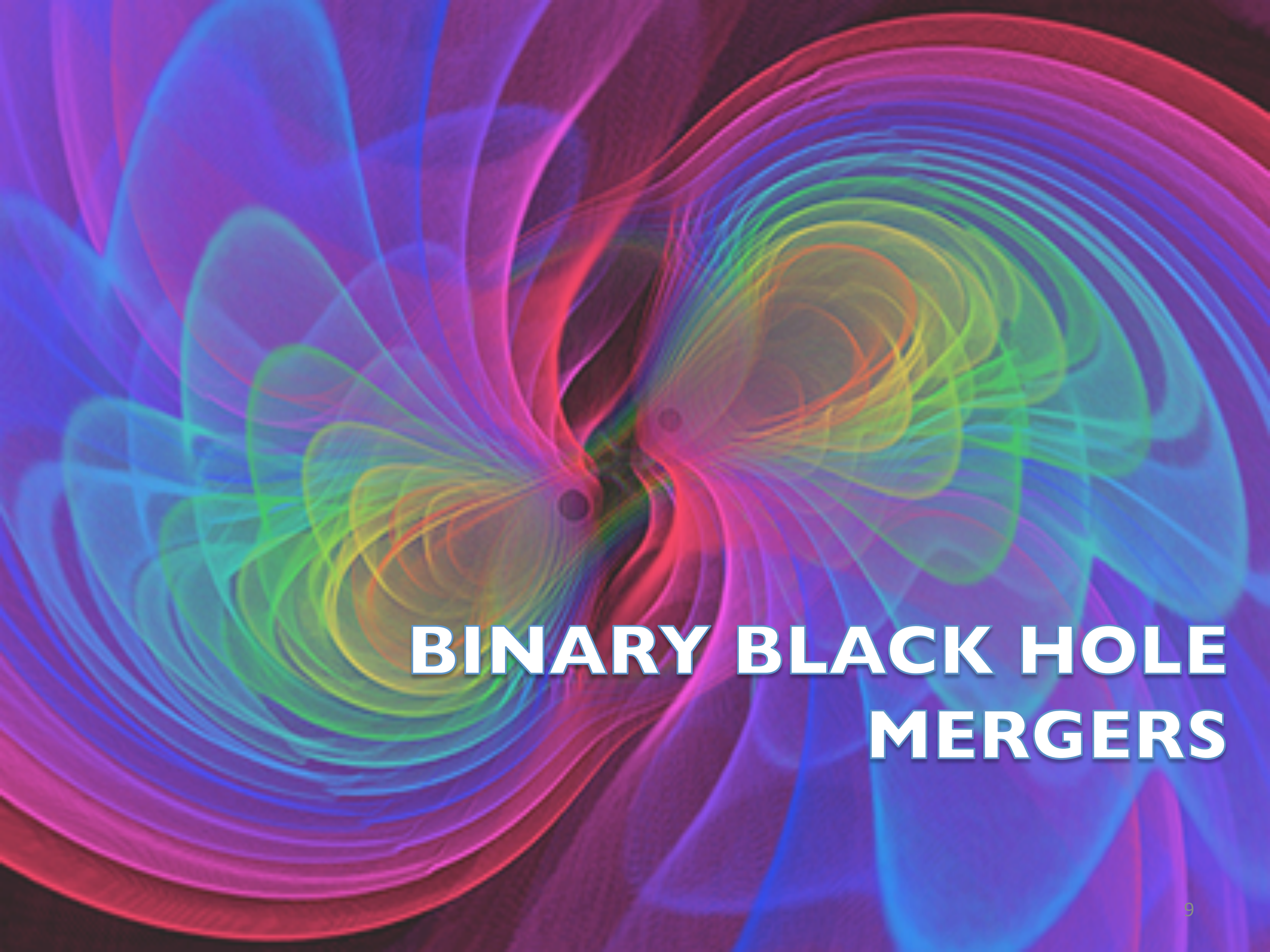
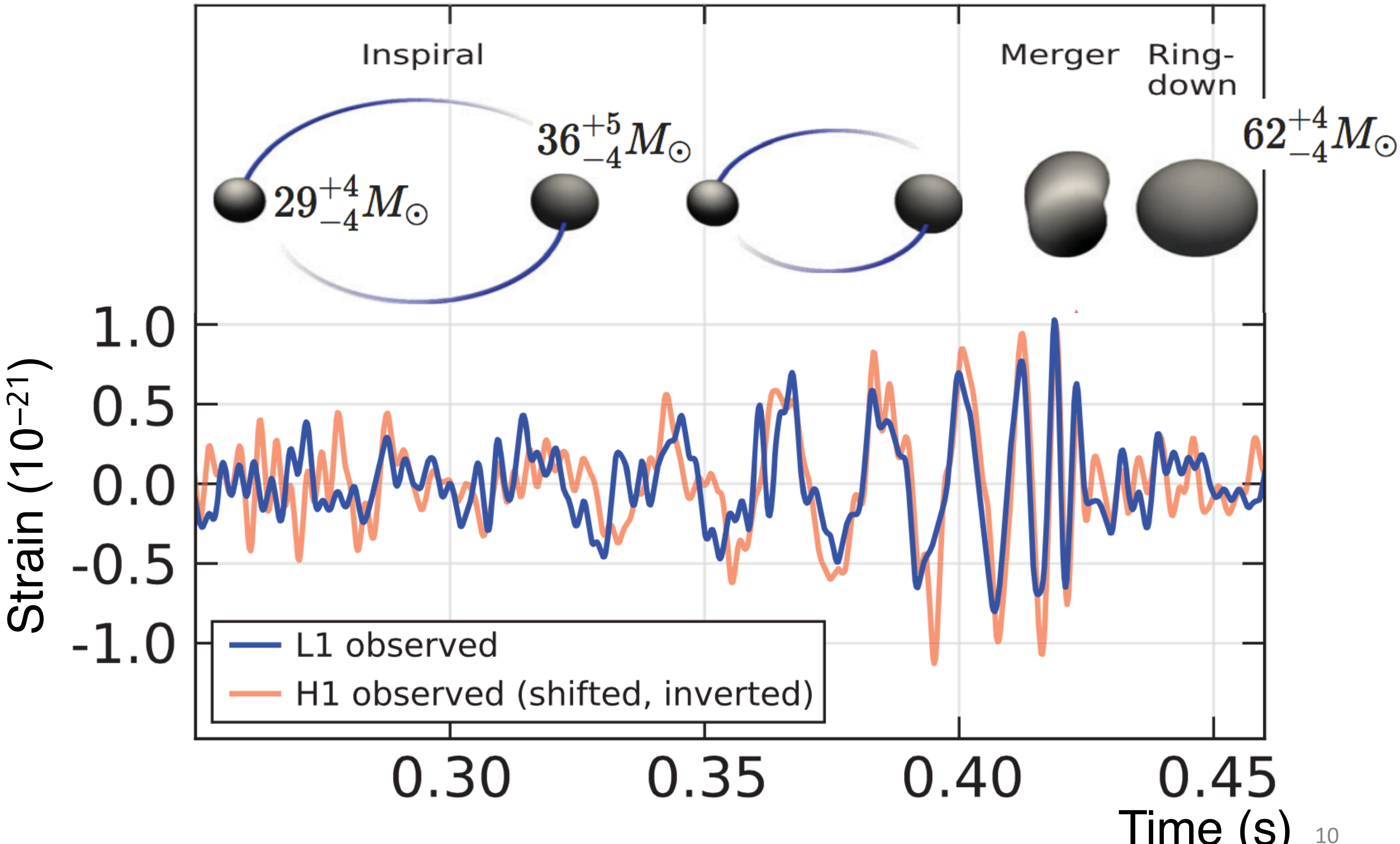


Image : Chandra X-ray images of Crab pulsar

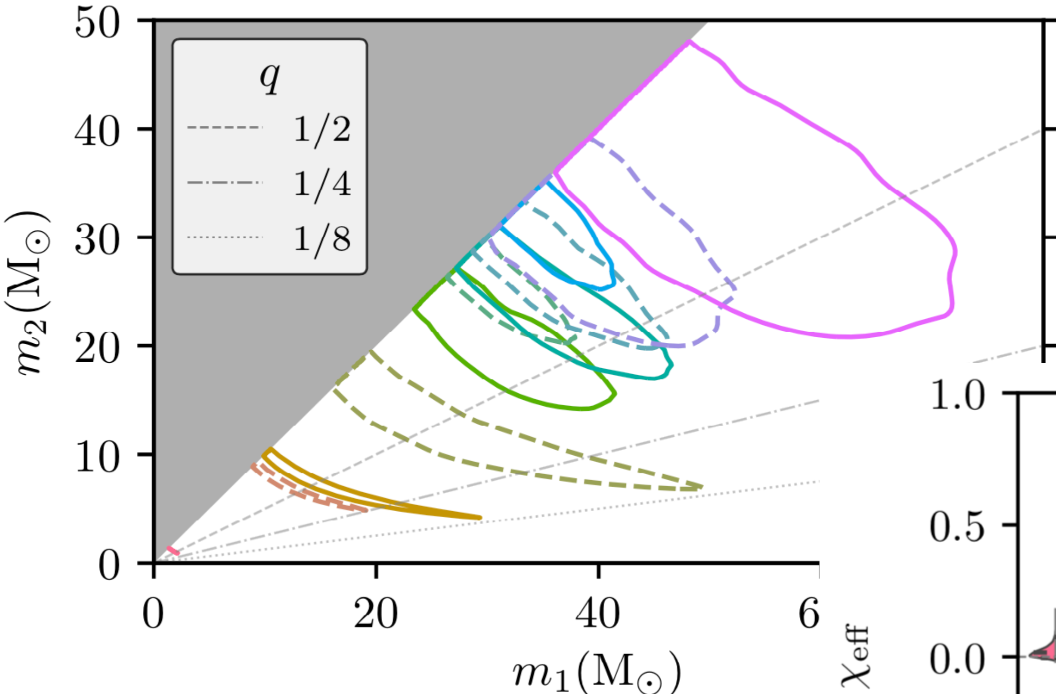


BINARY BLACK HOLE MERGERS

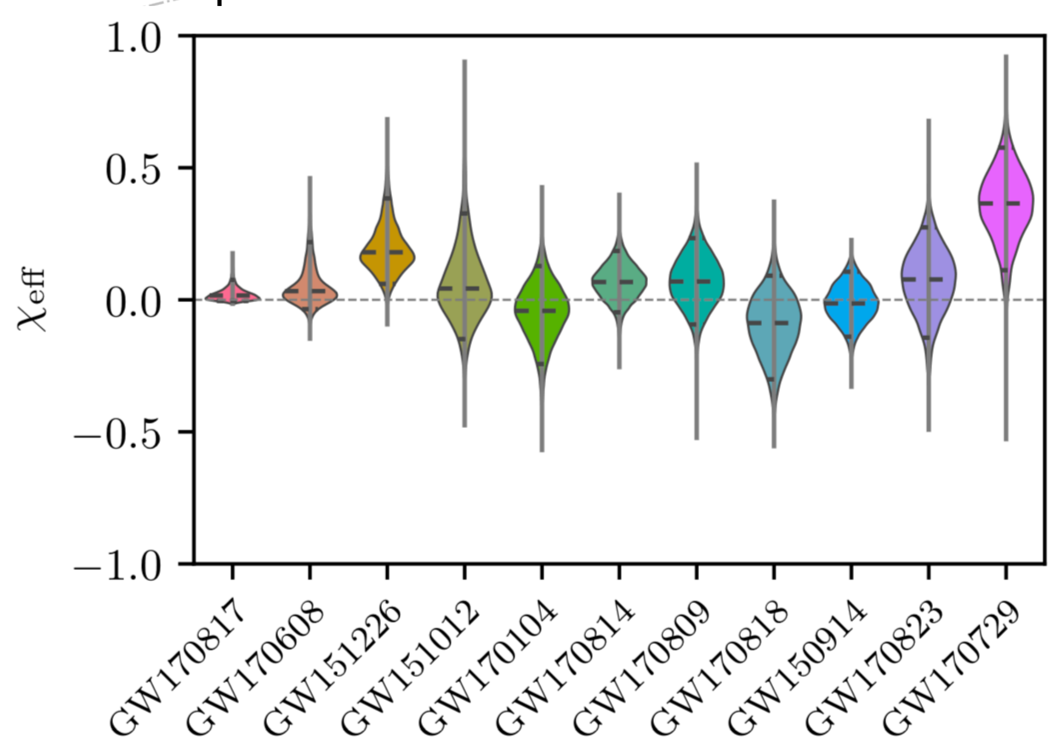
14 September 2015



Merging black hole masses & spins



LVC, arXiv:1811.12907



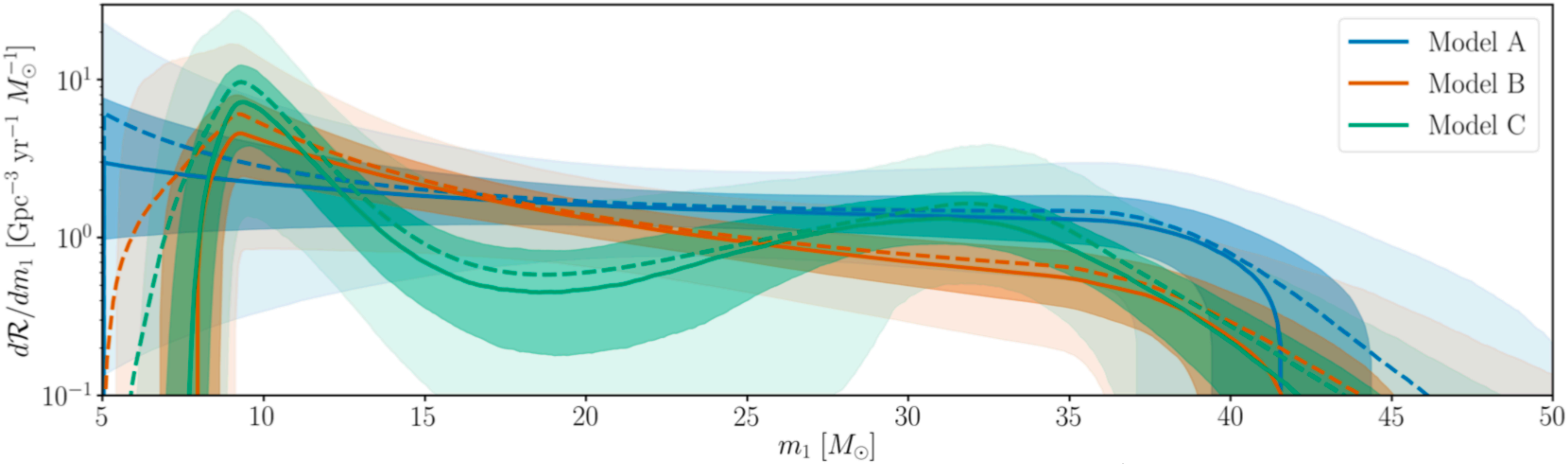
- High masses relative to known X-ray BH
- Spin magnitudes appear smaller than maximum allowed by GR

BH merger rate and mass distribution

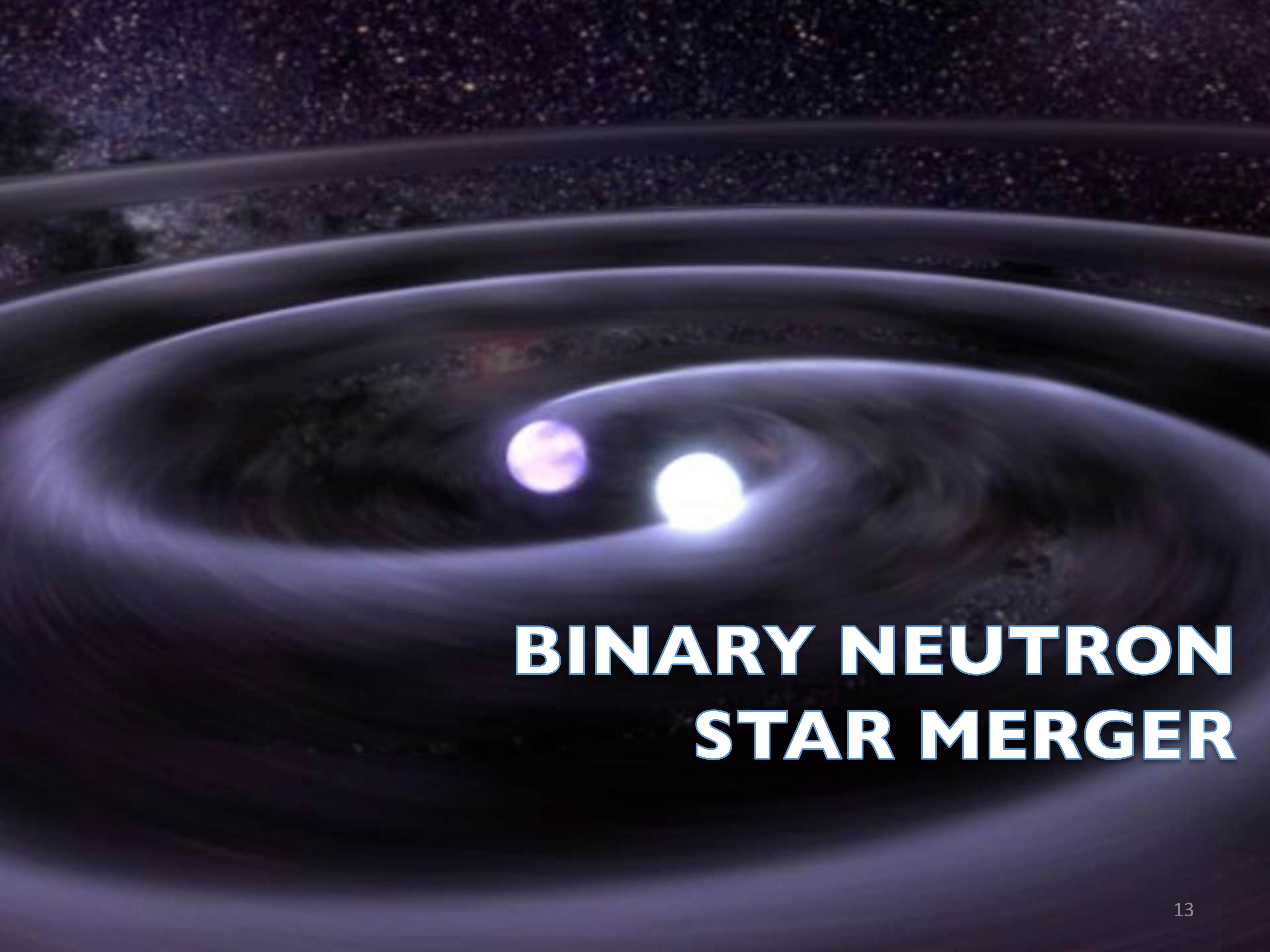
- Prediction from 2010 : **0.1**, **5**, **300** /Gpc^3 /y
  (**low**, **realistic**, **high**)

$$R = 52.9^{+55.6}_{-27.0}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

- Mass distribution of merging BH : nearly flat up to 40-45 $M_\odot$



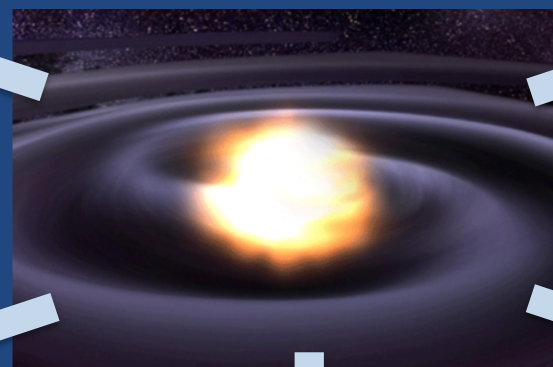
LVC, arXiv:1811.12940



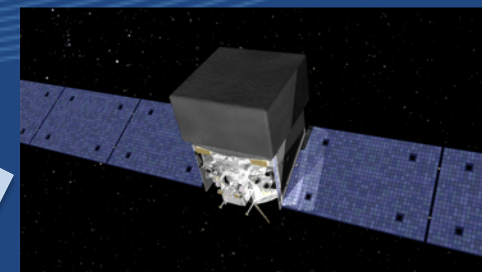
BINARY NEUTRON STAR MERGER

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star / Neutron Star – Black Hole Merger



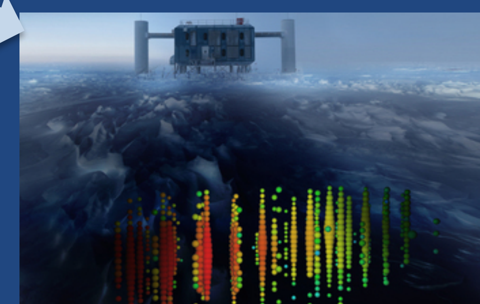
Gravitational Waves



X-rays / Gamma-rays

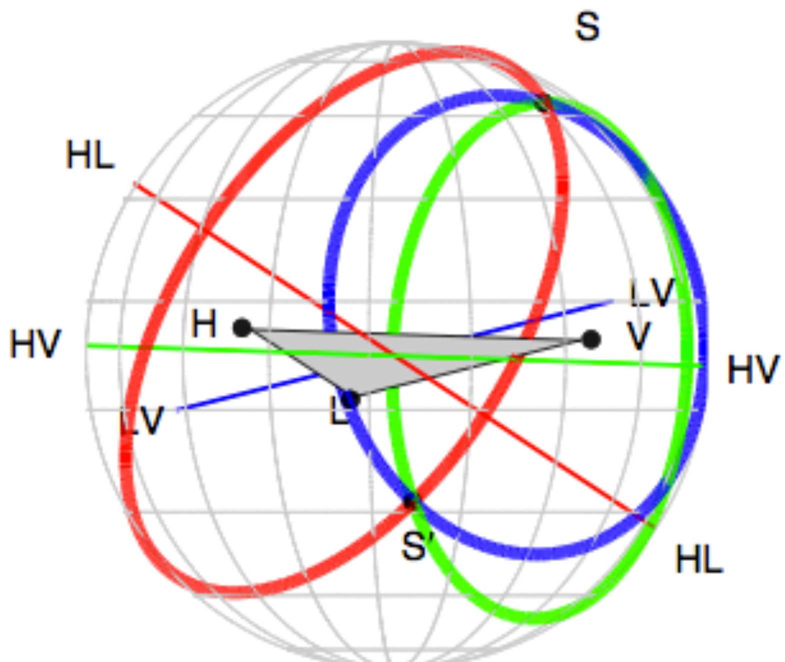
UV / Visible / Infrared Light

Radio

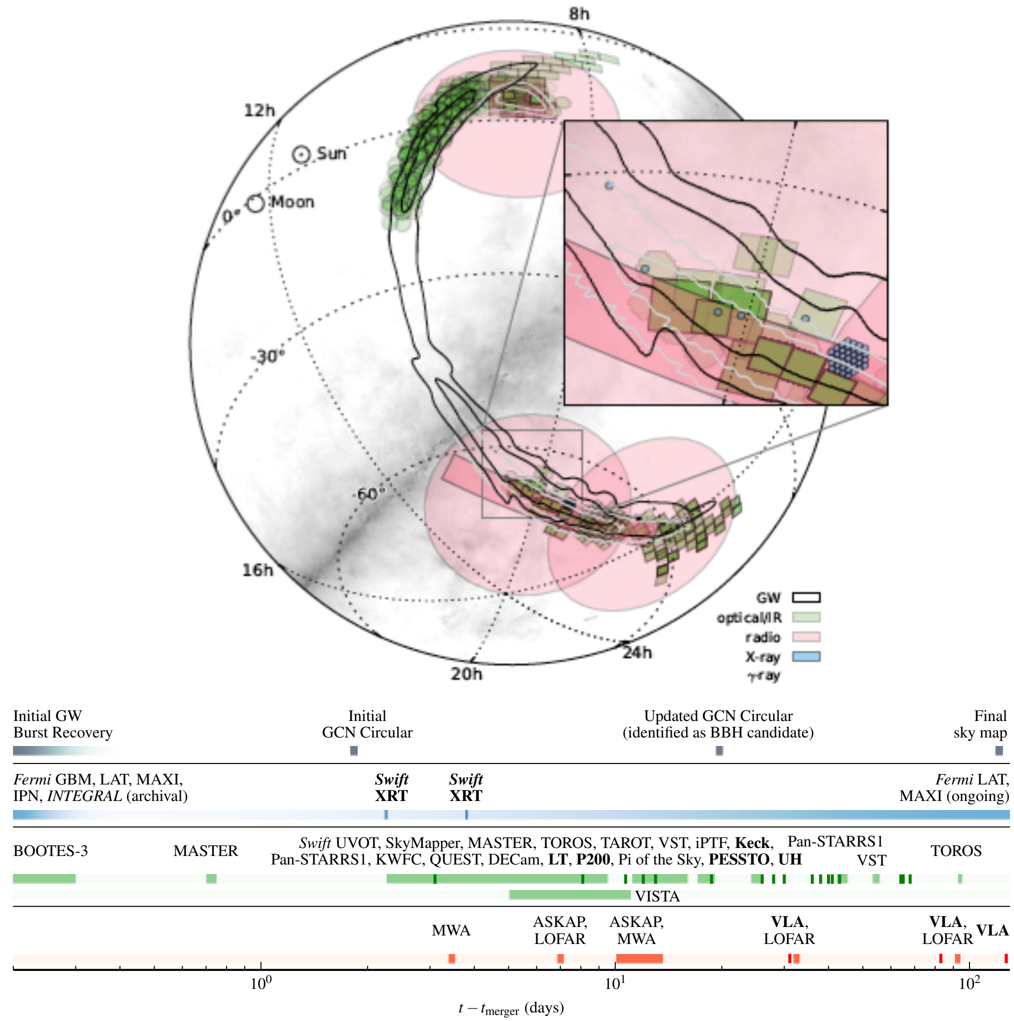


HE Neutrinos

Search for EM counterparts

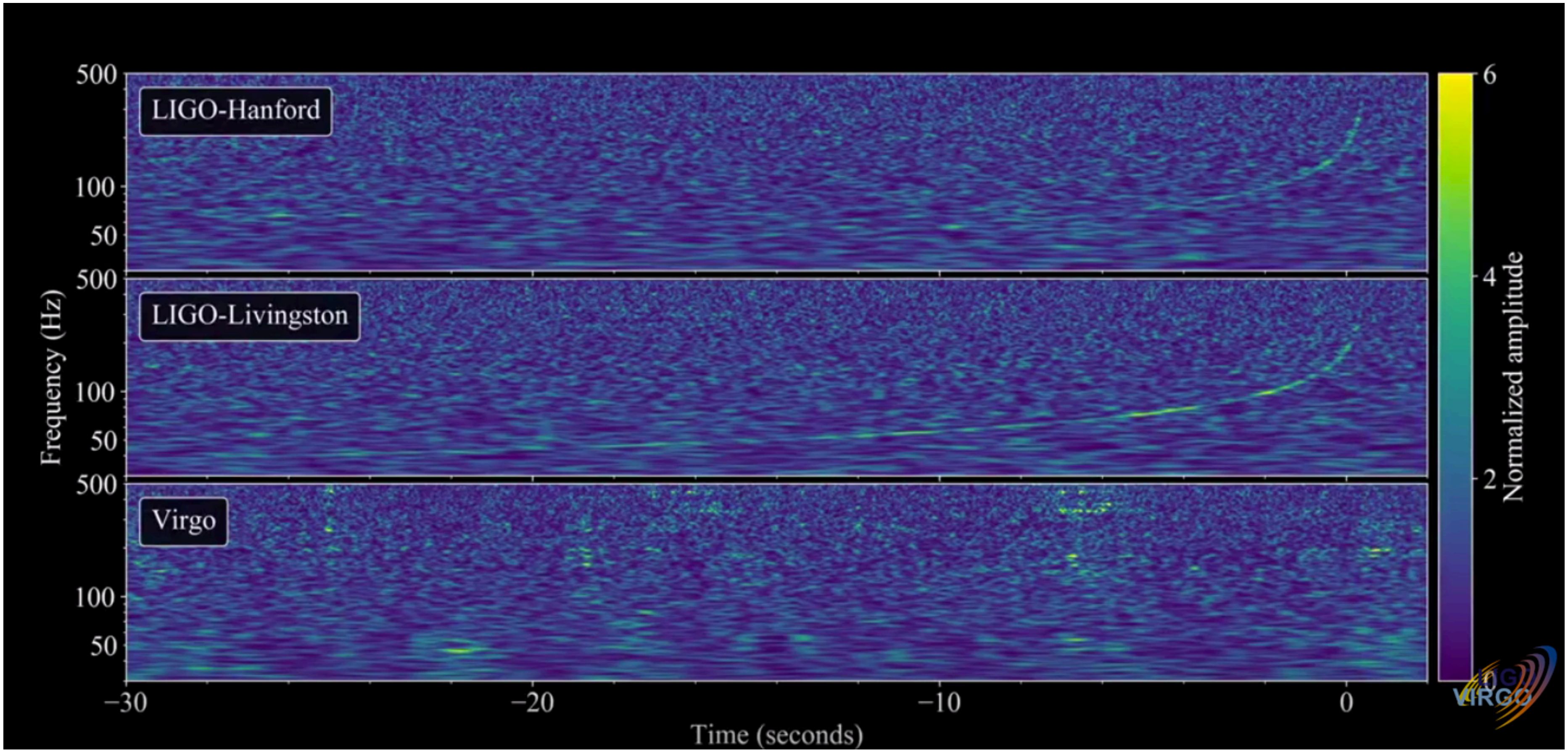


- Source of GW can be localized
  - time difference
  - GW amplitudes
  - oscillation phase



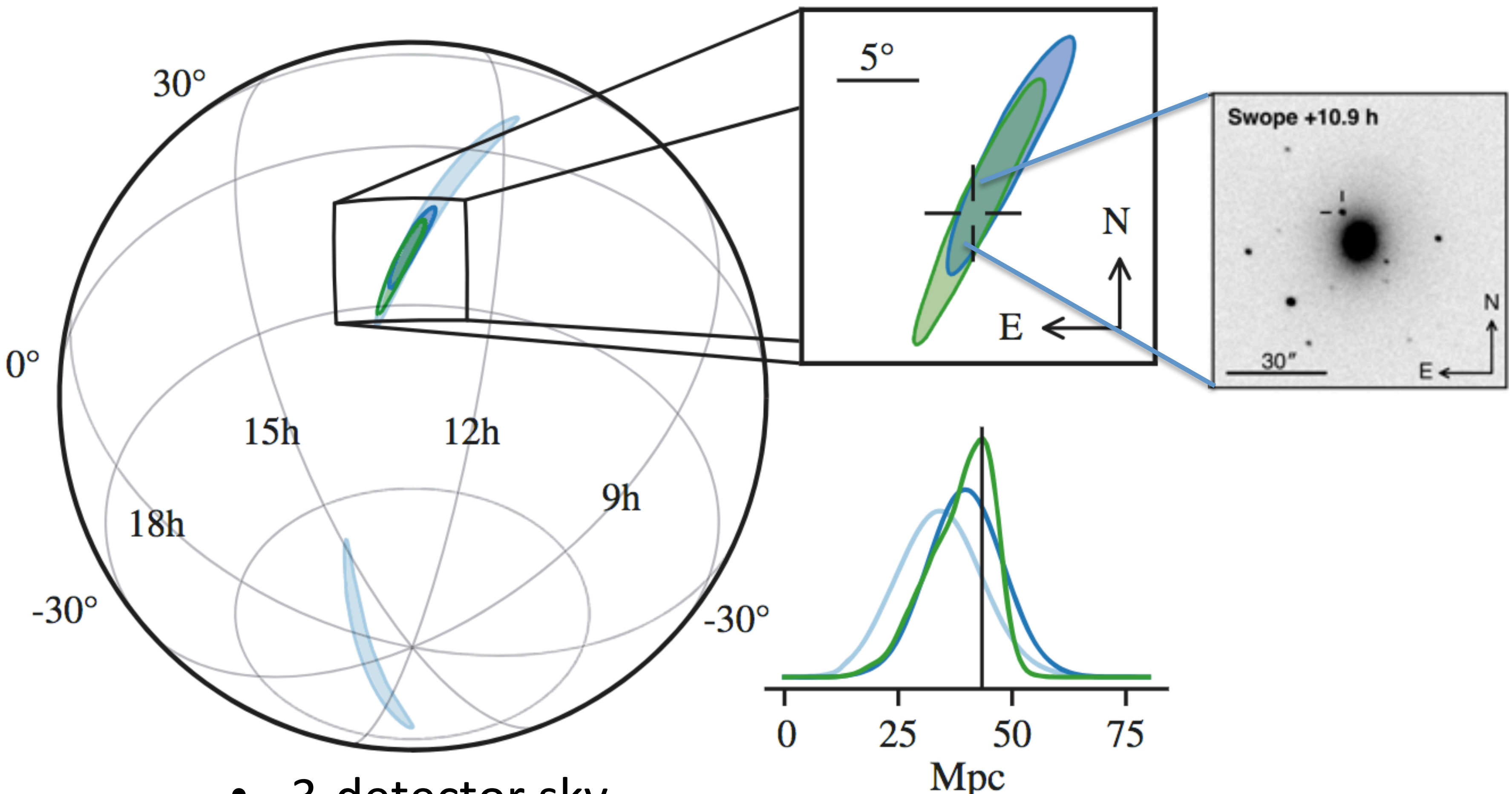
Localization and broadband follow-up of the gravitational-wave transient GW150914 (LSC-Virgo + many authors)

17th August 2017



https://www.youtube.com/watch?v=aWX-BY-A9CY

GW170817 on the sky

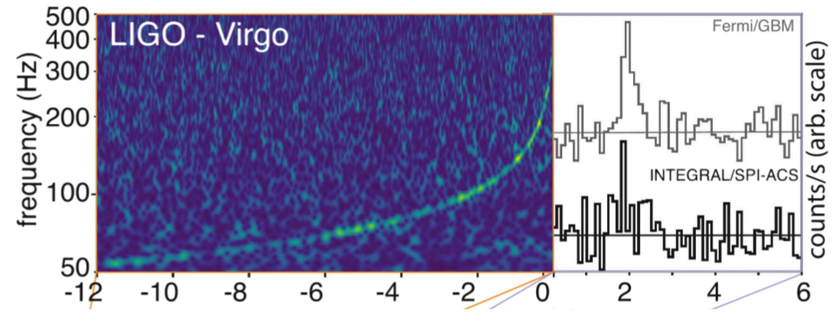


- 3-detector sky area ~30 deg^2

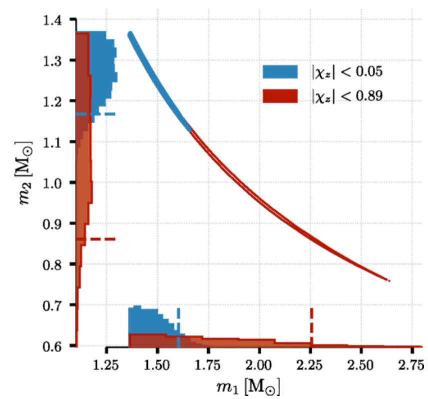
A few science results

- Speed of gravity = speed of light

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$



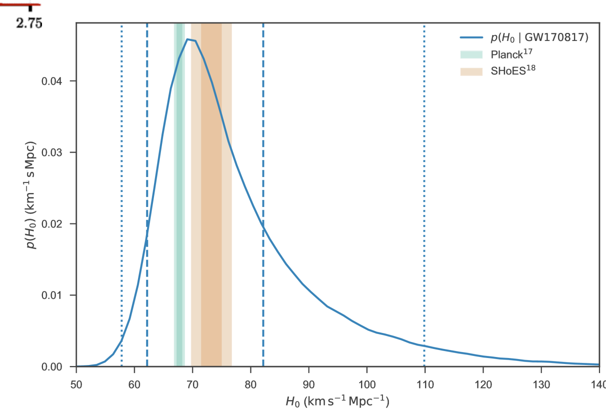
- **B**inary**N**eutron**S**tar mergers create many heavy elements ('kilonova')



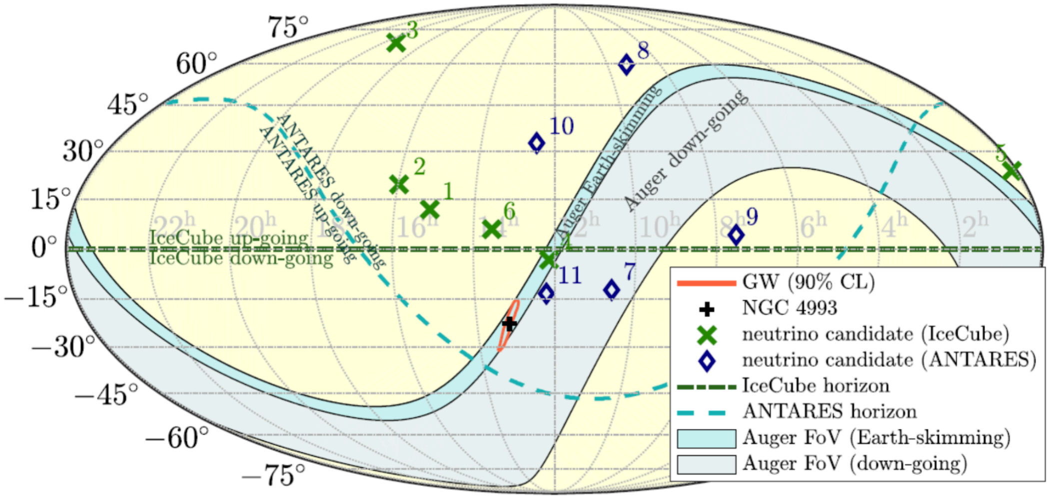
- BNS masses consistent with Galactic binaries

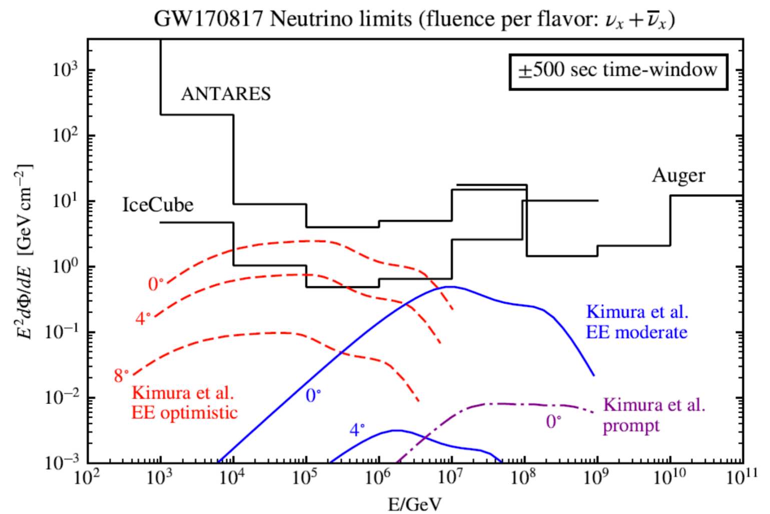
- Amplitude of GW $\Rightarrow$ distance estimate
  Host galaxy ID $\Rightarrow$ redshift
  Independent estimate of Hubble constant

$$H_0 \quad = \quad 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



GW170817 HE neutrino search





- Host galaxy ideally situated relative to Pierre Auger observatory
- No significant HE neutrino events
  Upper limits on emission from BNS merger

LVC+IceCube+ANTARES+Pierre Auger
Astrophys. J. Lett. 850, L35 (2017)

IGFAE activities within LSC

Major current/planned contributions

- Offline search : correlate $10^5 - 10^6$ binary waveform models with data from global network, reproducible results for publication, optimize sensitivity
- Rates/Populations : interpret search results by comparing to models of binary merger population in Universe
- Multi-messenger search : associate GW events with EM/ν/CR events

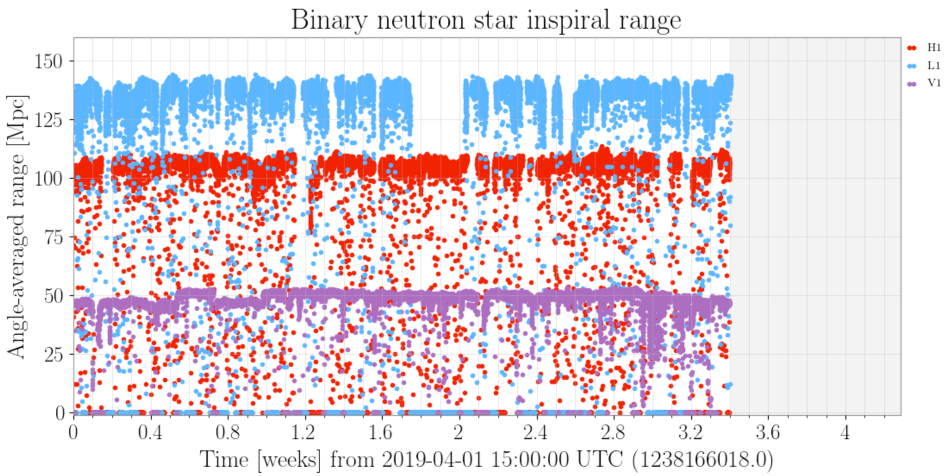
Minor contributions

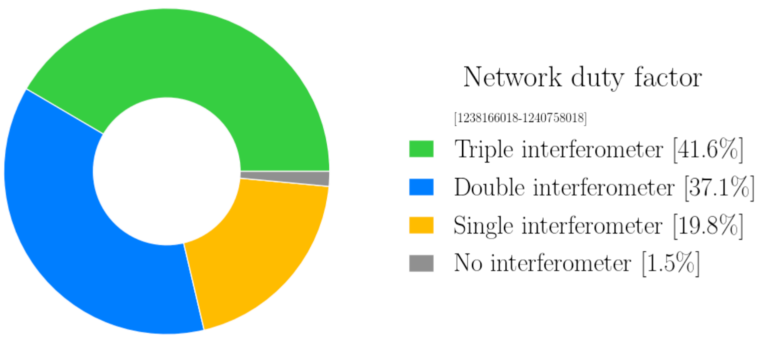
  - Low latency search : preliminary identification of events (minutes to hours) for EM followup
  - DetChar & DQ : diagnose state of detectors, select data for analysis
  - Tests of GR : search for non-GR effects, bounds on deviations

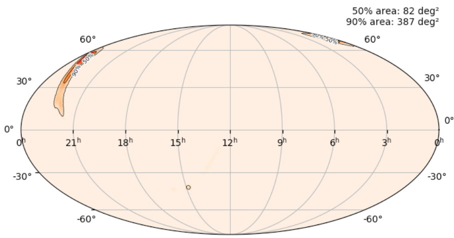
IGFAE-GW related events

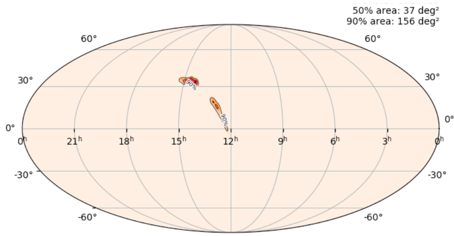
- Galician Gravitational Wave Week – GGWW
  Jan 14-18 : 15 lectures on GW & related topics
  https://indico.cern.ch/event/779256/
- 9th Iberian GW meeting : June 3-5, SdC
- GR/Amaldi meeting : July 7-12, Valencia
  IGFAE/USC represented on LOC

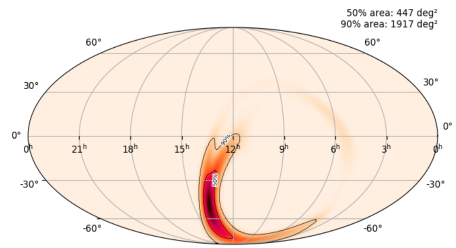
Latest News : O3 observing run

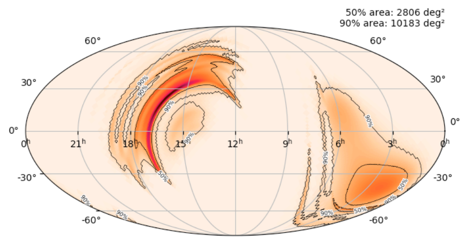








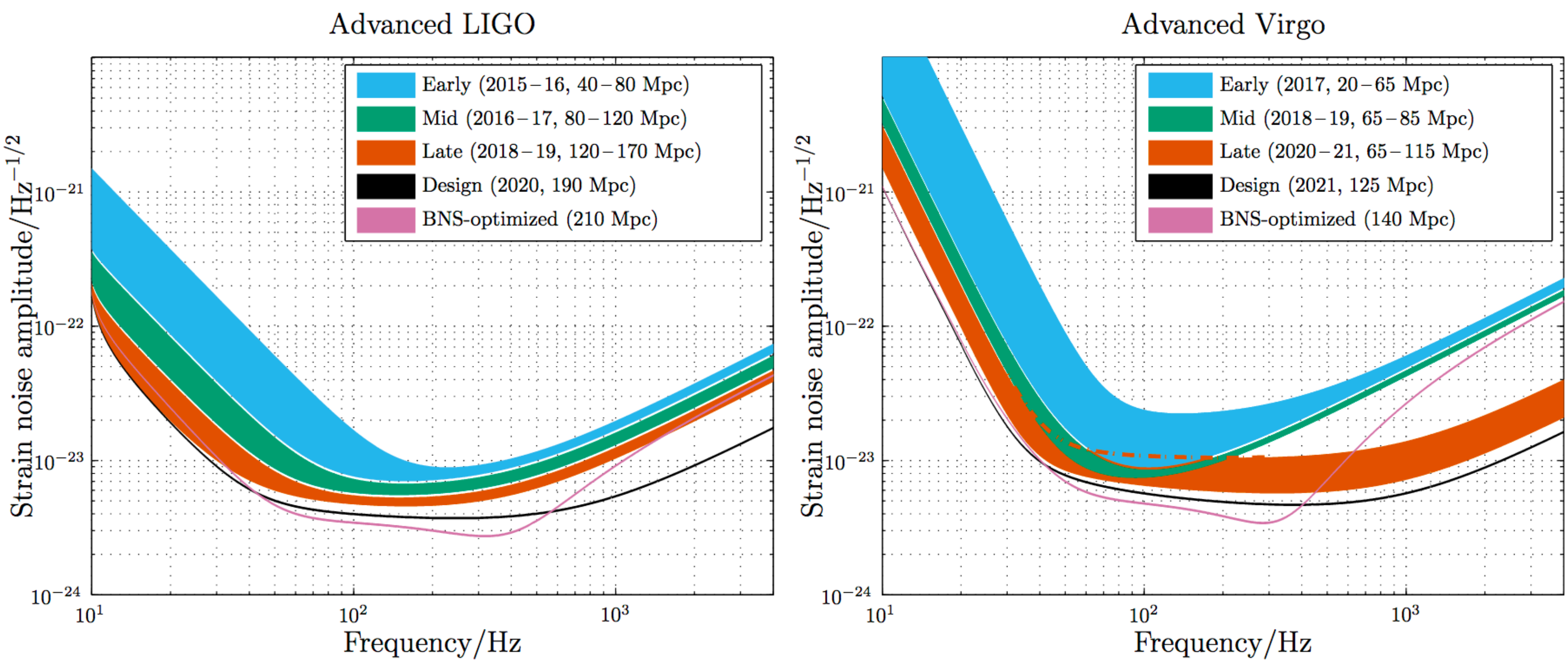




- In progress since April 1st , HLV network
- Public alerts for significant candidate events
  - sky map, distance, probabilistic classification of source
- 4 so far ! (probable BBH / BBH / BBH / BNS)

THE FUTURE …

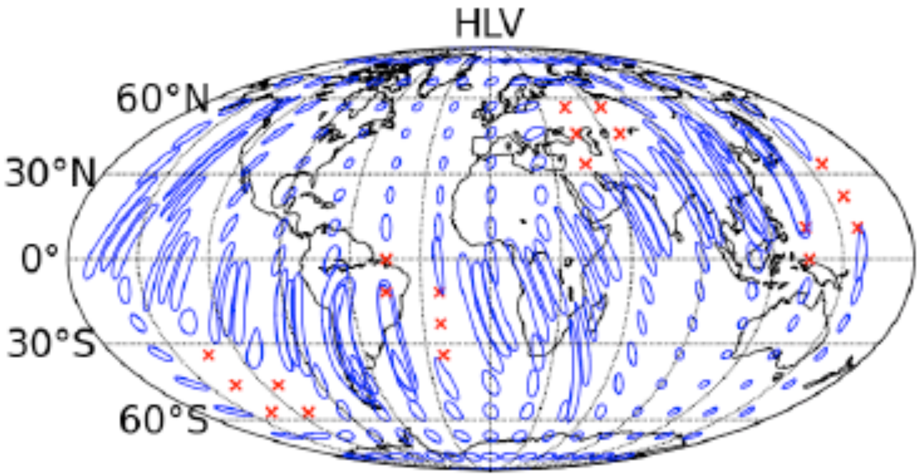
Upcoming science runs



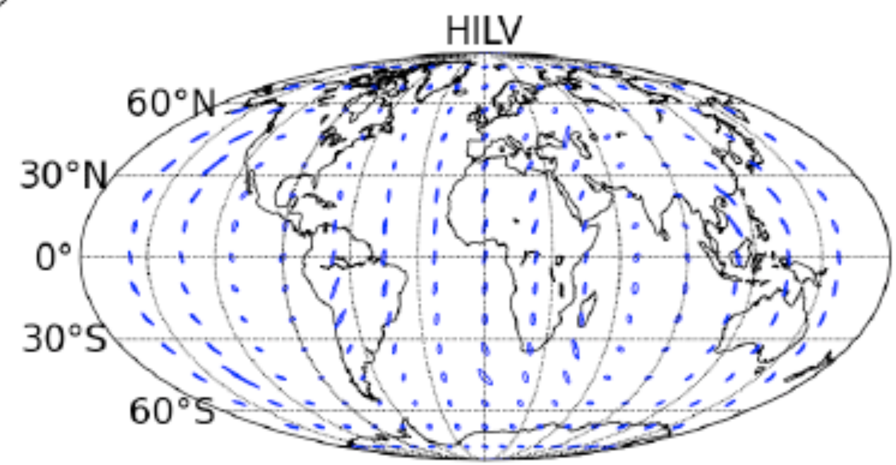
Projections from Living Rev. Relativity vol.19 (2016) 1

- O3 run started April 2019, duration ~1 year
- Advanced LIGO design sensitivity by 2021-22

Extending the network



~ 2017+



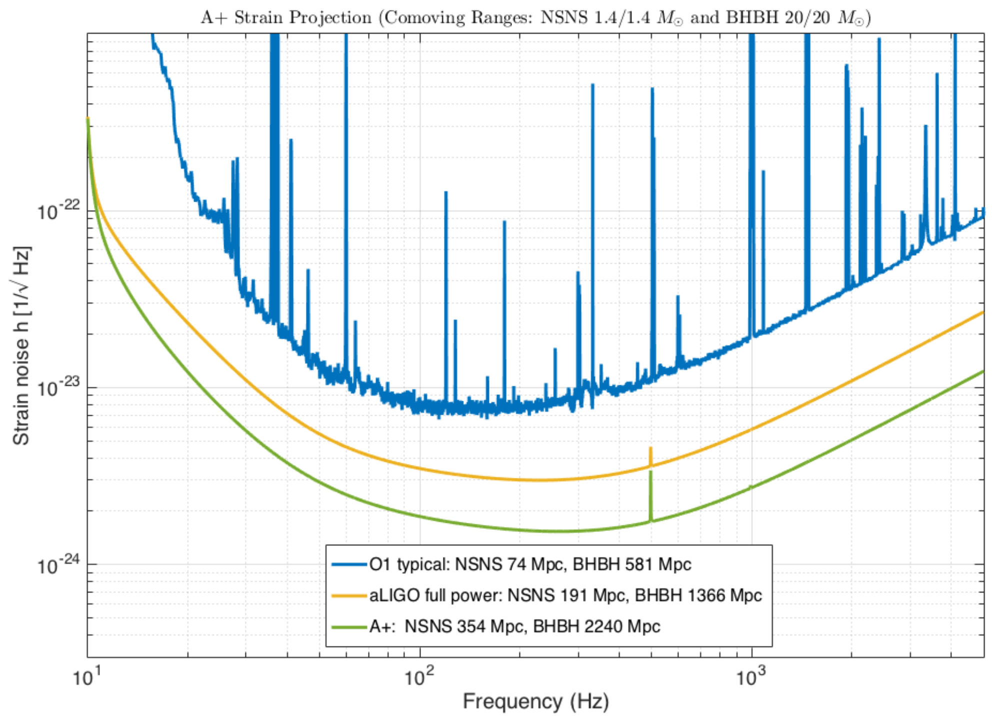
2022+
with LIGO-India

‘A+’ Advanced LIGO Mid-scale Upgrade

- Upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk
- Target: average 1.7x increase in range over aLIGO

➔ ***~ 5x greater event rate than Advanced LIGO***
~ 40 times greater than current Advanced LIGO sensitivity

- Stepping stone to future detector technologies
- Two year down time; back online by 2023



A+ key parameters

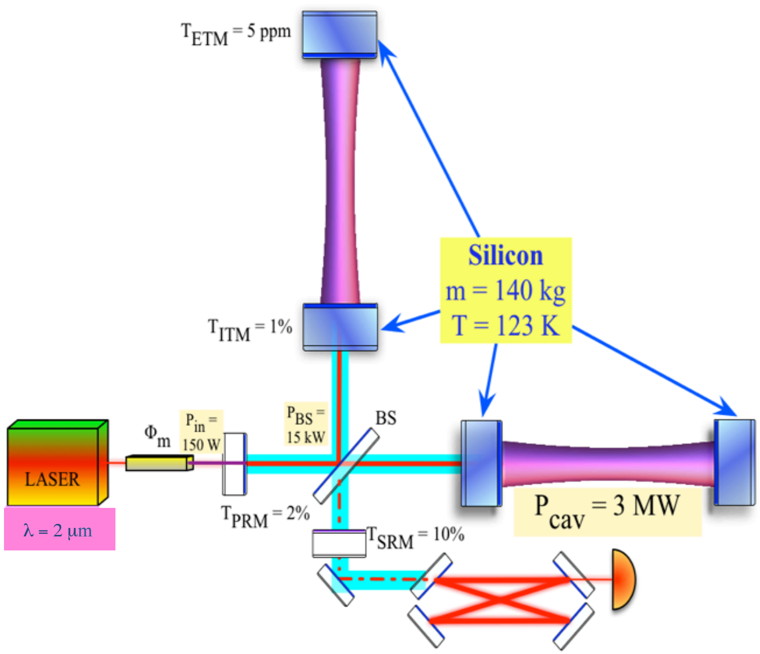
12 dB injected squeezing
15% readout loss
100 m filter cavity (FC)
20 ppm round trip FC loss
Coating Thermal Noise half of aLIGO

Instrumentation for Advanced(+) interferometers

- Mid-2020 : LHCb upgrade over – window of opportunity for IGFAE members to engage in detector hardware development
- Contribute to reaching & surpassing Advanced design sensitivities
- Expertise in microelectronics, silicon radiation detectors and readout, sensor photodiodes, monitoring and control systems
- In contact with Virgo spokesperson & others
  - decision to be taken 2019

Further on: Voyager, Einstein Telescope, Cosmic Explorer

LIGO Voyager – exploiting the LIGO Observatory facility limits



Longer Arm Length Interferometers