Observation of gravitational wave signals
and Polgraw group contributions to LIGO and Virgo projects

Andrzej Królak

INSTITUTE OF MATHEMATICS
Polish Academy of Sciences

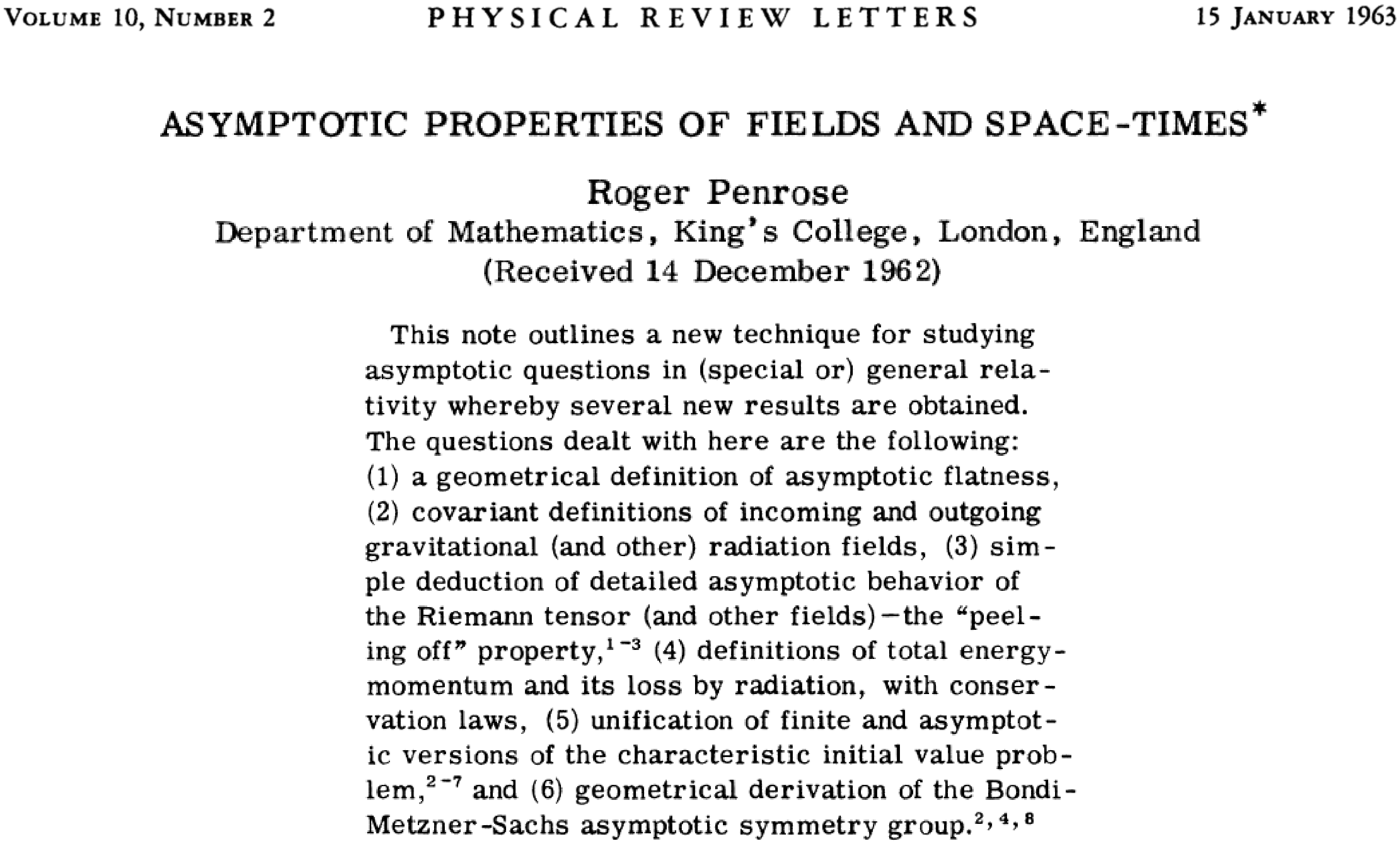
Outline

- **Status of gravitational wave observations by LIGO and Virgo consortium**

- **Contributions of Polgraw group to LIGO and Virgo projects**

- **Annoucement**

Fundamentals of gravitational wave theory



Volume 10, Number 2 PHYSICAL REVIEW LETTERS 15 January 1963

ASYMPTOTIC PROPERTIES OF FIELDS AND SPACE-TIMES*

Roger Penrose
Department of Mathematics, King's College, London, England

(Received 14 December 1962)

This note outlines a new technique for studying asymptotic questions in (special or) general relativity whereby several new results are obtained. The questions dealt with here are the following: (1) a geometrical definition of asymptotic flatness, (2) covariant definitions of incoming and outgoing gravitational (and other) radiation fields, (3) simple deduction of detailed asymptotic behavior of the Riemann tensor (and other fields)—the "peeling off" property,[1-3] (4) definitions of total energy-momentum and its loss by radiation, with conservation laws, (5) unification of finite and asymptotic versions of the characteristic initial value problem,[2-7] and (6) geometrical derivation of the Bondi-Metzner-Sachs asymptotic symmetry group.[2,4,8]

GW from a binary system in quadrupole approximation

Chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

$$h_{CB} = 1.0\times10^{-21}\left(\frac{M_c}{31.6\mathrm{Ms}}\right)^{5/3}\left(\frac{f_{GW}}{100\mathrm{Hz}}\right)^{2/3}\left(\frac{410\mathrm{Mpc}}{r}\right)$$

Evolution time

$$\tau_{\mathrm{GW}} = 46.8\mathrm{ms}\left(\frac{M_c}{31.6\mathrm{Ms}}\right)^{-5/3}\left(\frac{f_{GW}}{100\mathrm{Hz}}\right)^{-8/3}$$

Fourier transform

$$\bar{h}_{CB} = 1.4\times10^{-23}\left(\frac{M_c}{31.6\mathrm{Ms}}\right)^{5/6}\left(\frac{f_{GW}}{100\mathrm{Hz}}\right)^{-7/6}\left(\frac{410\mathrm{Mpc}}{r}\right)$$

Innermost stable circular orbit

$$f_{\mathrm{isco}} = 116\mathrm{Hz}\left(\frac{m_1+m_2}{65\,\mathrm{Ms}}\right)^{-1}$$

Precision Interferometry a la LIGO and Virgo

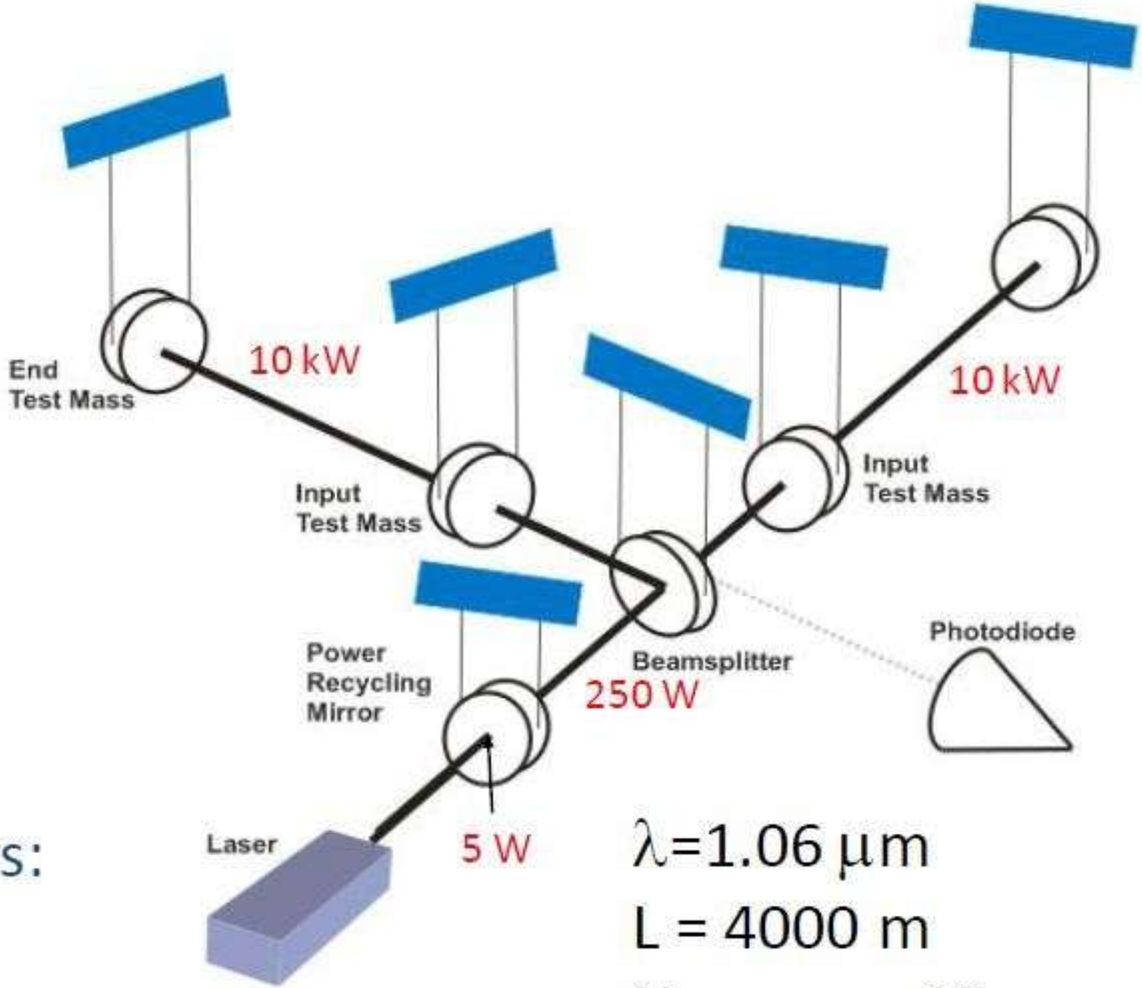
$$h \sim \frac{\lambda}{L}$$

$$\times \frac{1}{N_{roundtrip}}$$

$$\times \sqrt{\frac{1}{\dot{N}_{photon} \tau_{storage}}}$$

Putting in numbers:

$h \sim 10^{-21}$



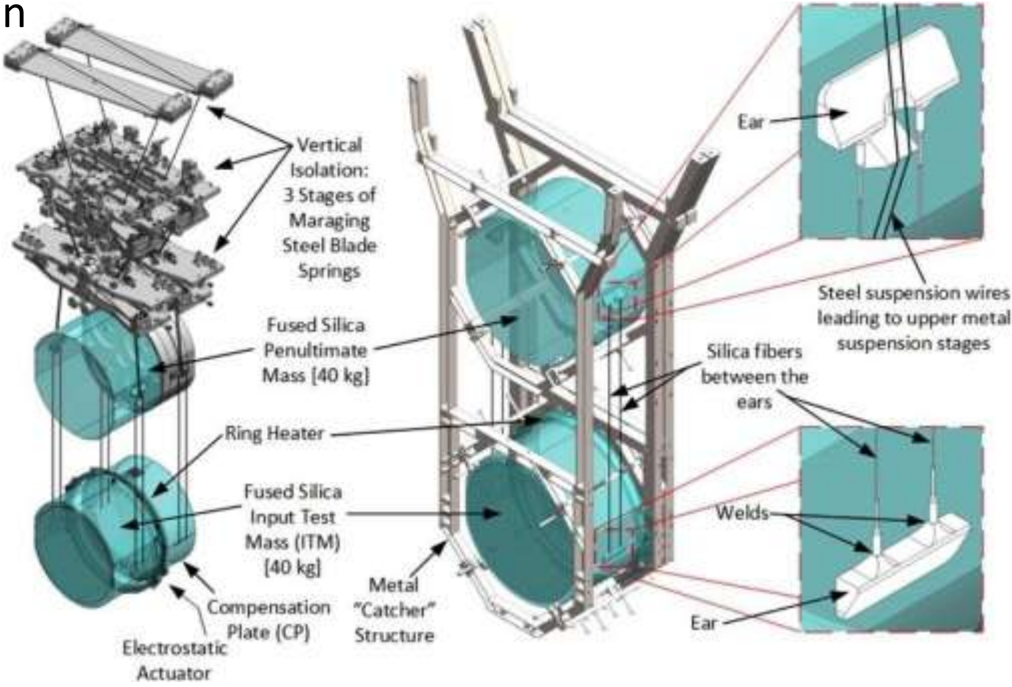
$\lambda = 1.06\ \mu\text{m}$

$L = 4000$ m

$N_{roundtrip} = 40$

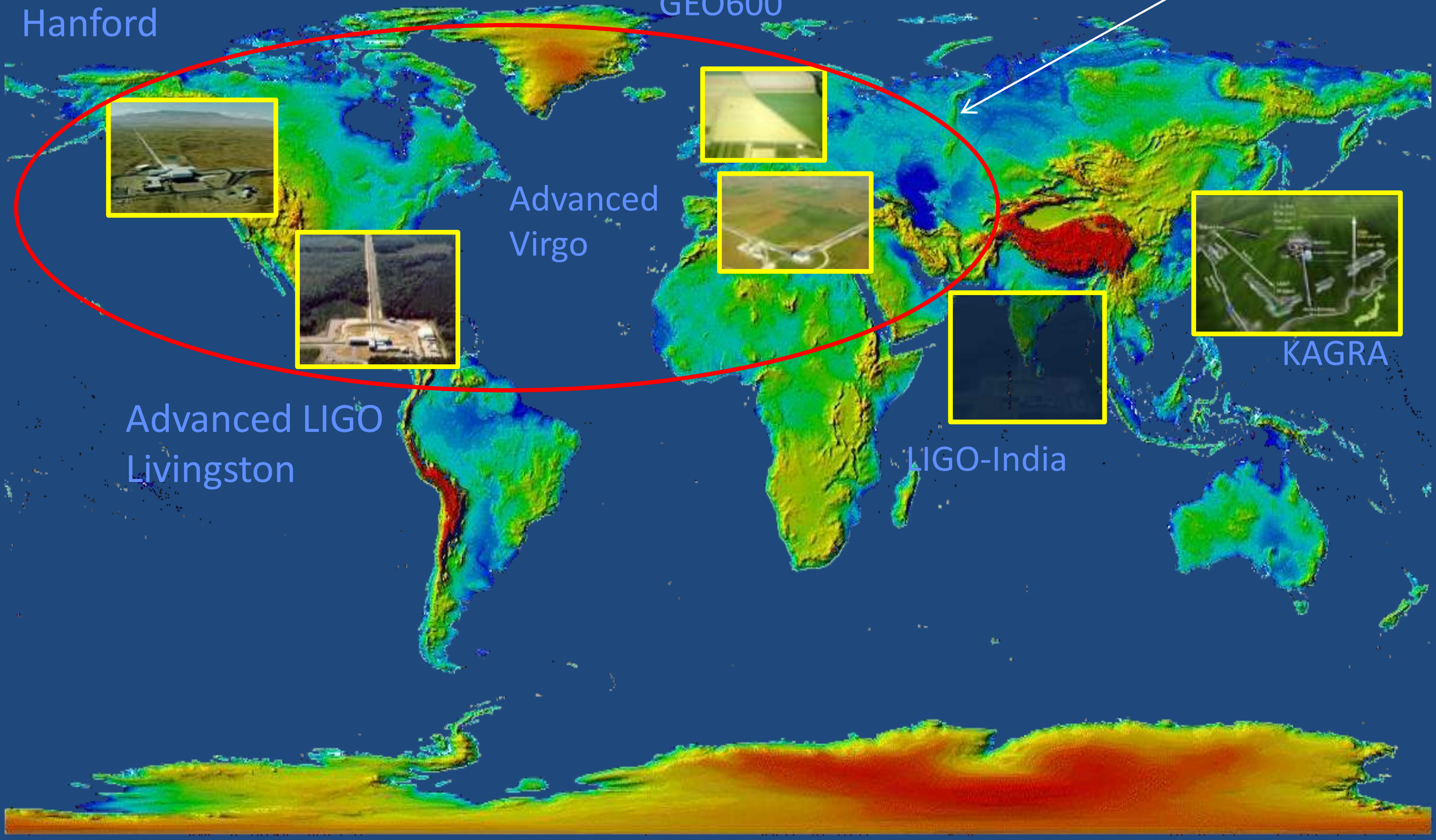
Advanced LIGO ‘Test Mass’ Mirrors and suspensions

- ***Truly the ‘crown jewels’ of the detector***
- Physical specifications:
    - Ultra-pure, ultra-homogeneous fused silica
    - 340 mm diameter, 200 mm thick, 40 kg mass
- Surface figure: super-polish followed by ion beam ‘spot’ polish
    - ***< 0.15 nm RMS deviation from sphere***
- Coatings: TiO_2-dhoped Ta_2O_5/SiO_2
    - Reflectivity depends upon type of mirror
    - Ultralow absorption (< 0.5 ppm)



Credit: D. Reitze

Network of gravitational wave detectors



Advanced LIGO Hanford

GEO600

Operating

Advanced Virgo

KAGRA

Advanced LIGO Livingston

LIGO-India

ADVANCED VIRGO

6 EU countries
20 labs, ~250 authors

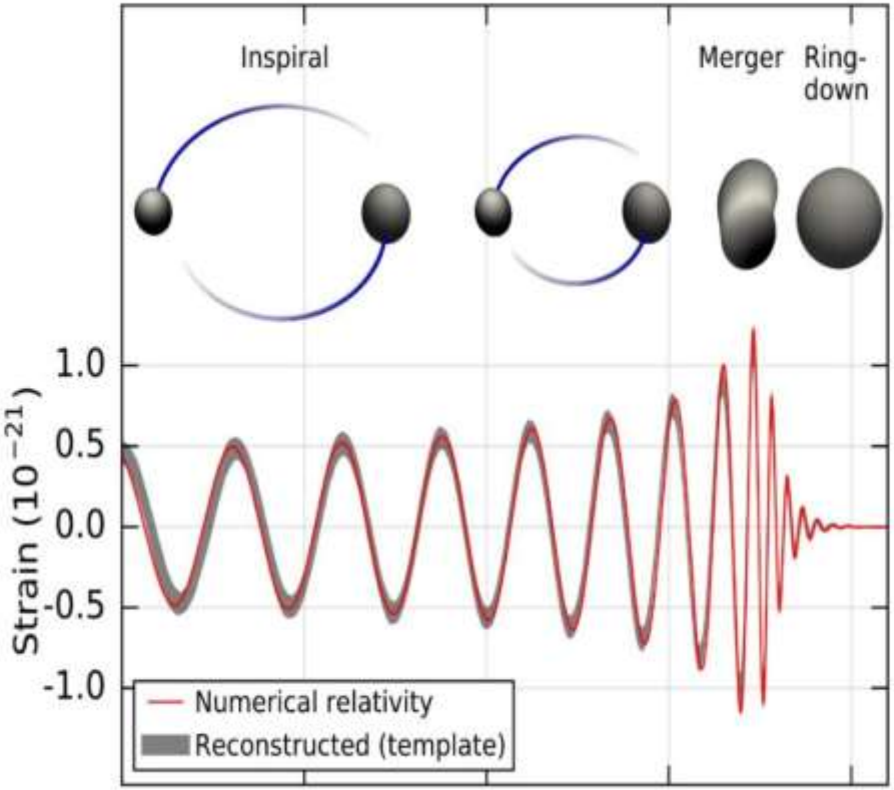
- APC Paris
- ARTEMIS Nice
- EGO Cascina
- INFN Firenze-Urbino
- INFN Genova
- INFN Napoli
- INFN Perugia
- INFN Pisa
- INFN Roma La Sapienza
- INFN Roma Tor Vergata
- INFN Trento-Padova
- LAL Orsay – ESPCI Paris
- LAPP Annecy
- LKB Paris
- LMA Lyon
- NIKHEF Amsterdam
- POLGRAW(Poland)
- RADBOUD Uni.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

Gravitational Wave from a Binary Black Hole Merger

Early inspiral: low velocity & weak gravitational field.

- **Late inspiral/plunge:** high velocity & strong gravitational field.
- **Merger:** nonlinear & non perturbative effects; rapidly varying gravitational field
- **Ringdown:** excitation of quasinormal modes

Phase/amplitude evolution **encodes unique information** about the source

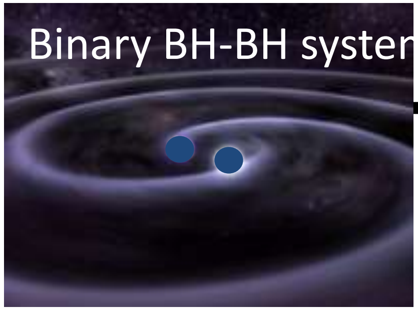


[Abbott et al. 2016, PRL 116, 061102]

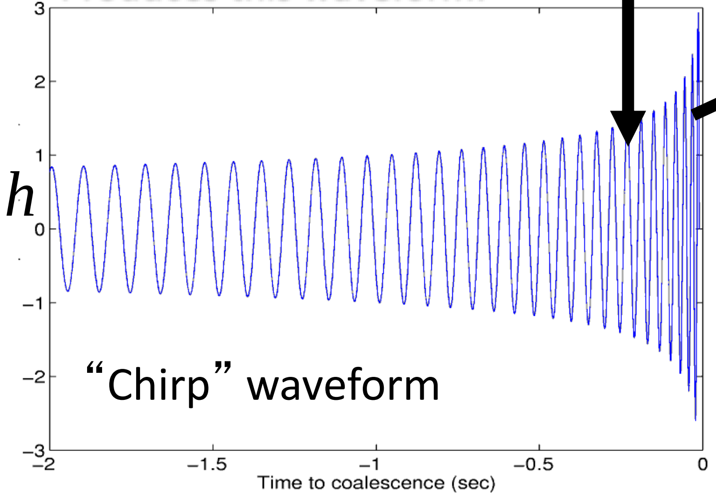
- **BBH merger GW signal can now be modeled very well numerically**
- **Accurate semi-analytical models exist**

Searching for Compact Binary Coalescences

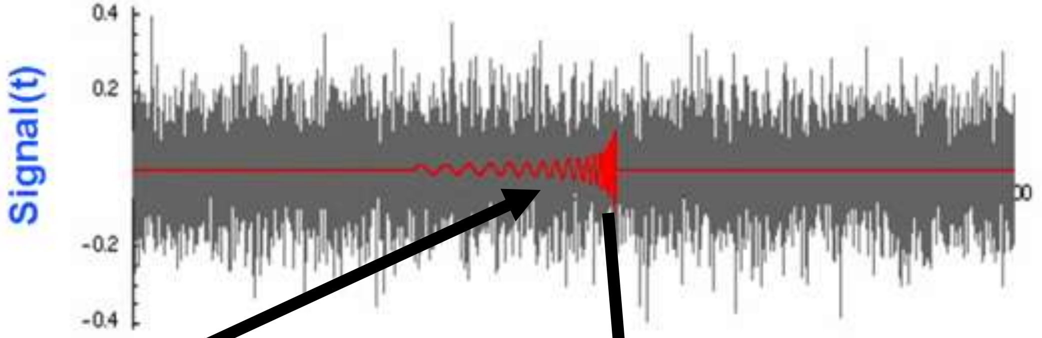
This source:



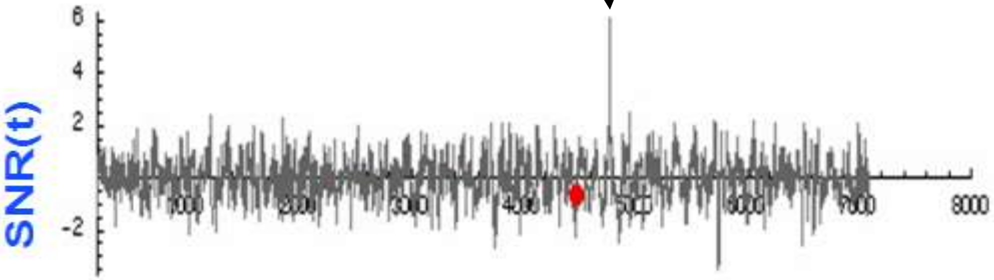
Produces this waveform:



Buried in this noise stream:

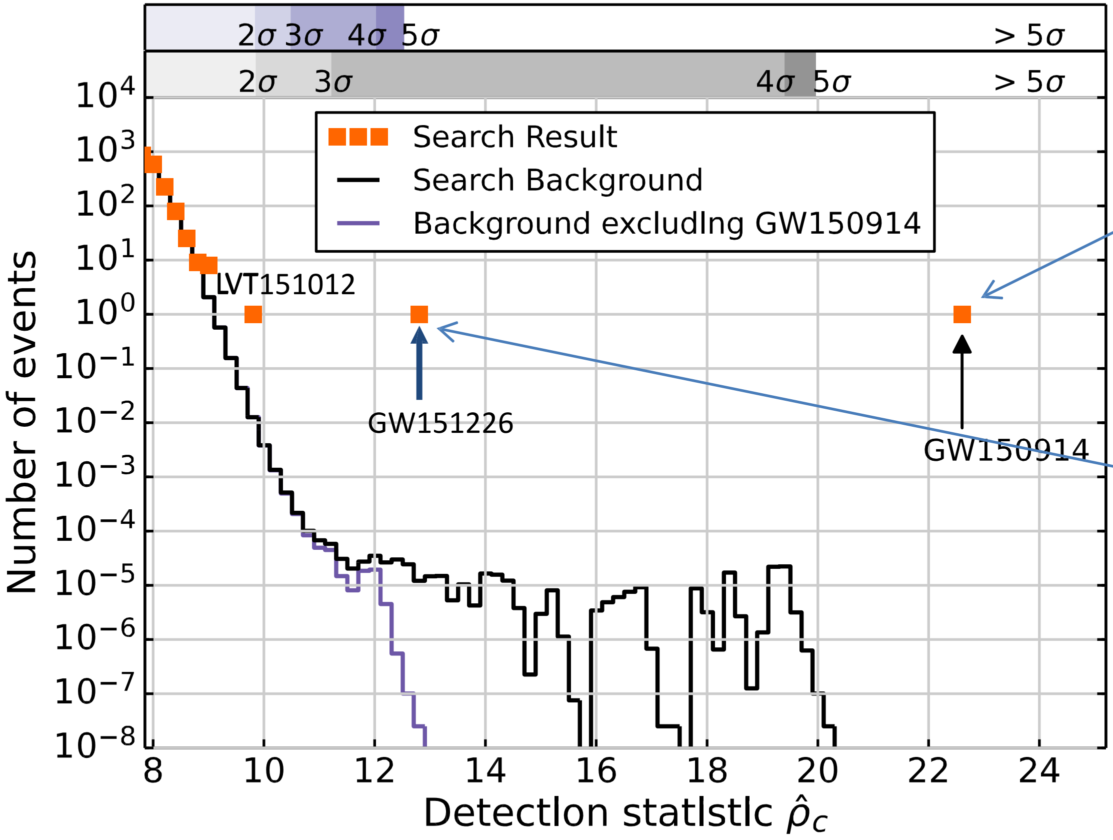


Matched templates to pull signal from the noise:



Advanced LIGO’s first observing run (O1) GW events

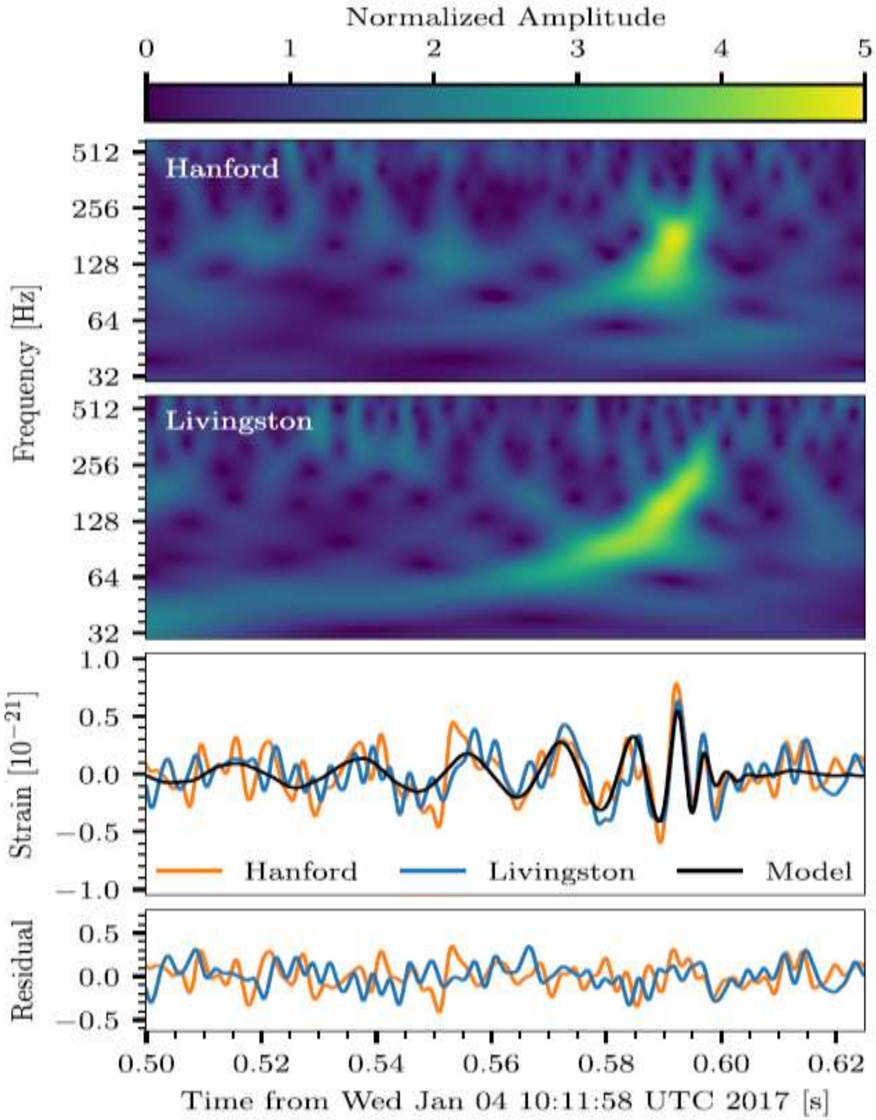
Search for binary black holes systems with black holes larger than 2 $M_\odot$ and total mass less than 100 $M_\odot$, in O1 (Sep 12, 2015-Jan 19, 2016, ~48 days of coincident data)



[Phys. Rev. Lett. 116, 061102 (2016)](https://doi.org/10.1103/PhysRevLett.116.061102)

Phys. Rev. Lett. 116, 241103 (2016)

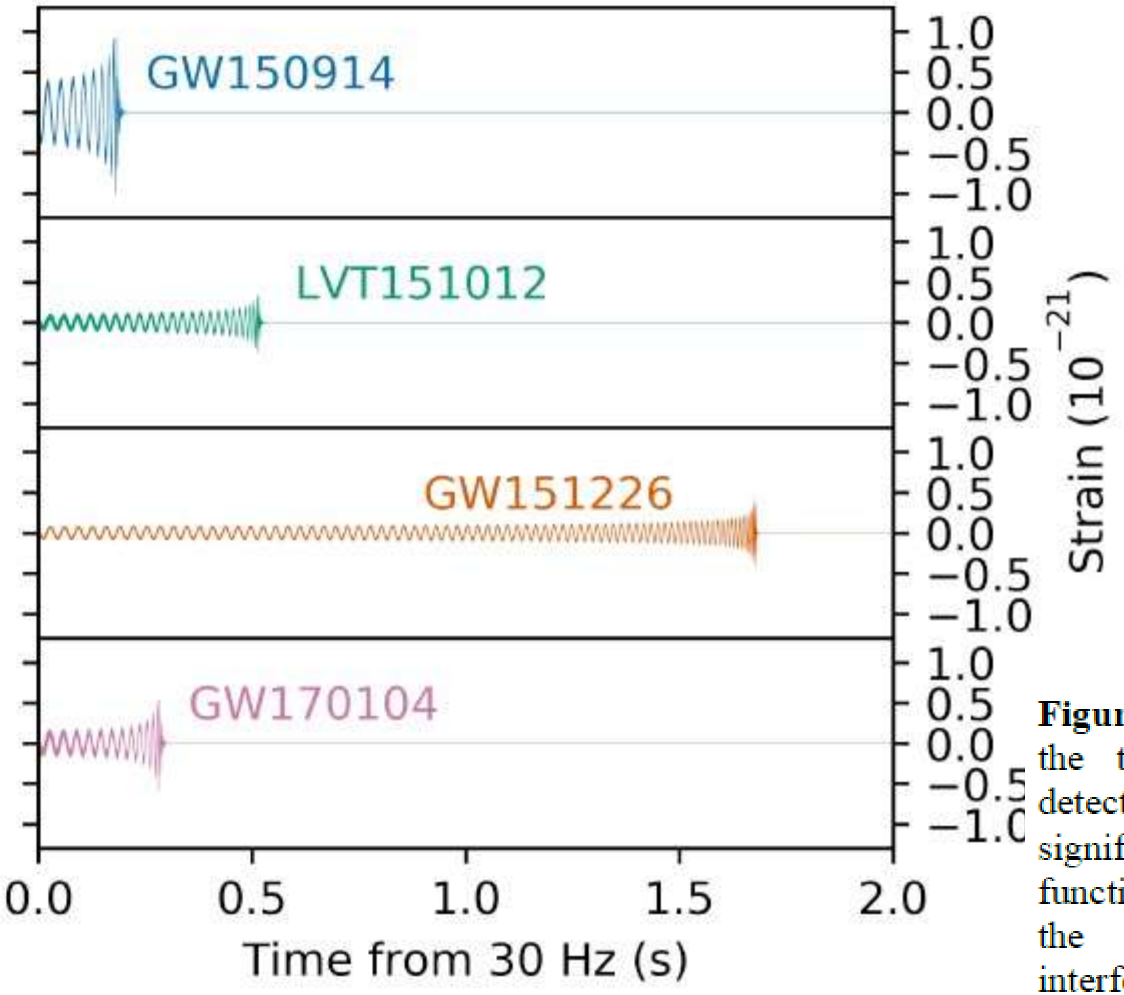
First Event from the Advanced LIGO O2 Run



GW170104 – another GW from a binary black hole merger

Abbott et al. 2017, PRL 118, 221101

Waveform reconstruction of detected signals

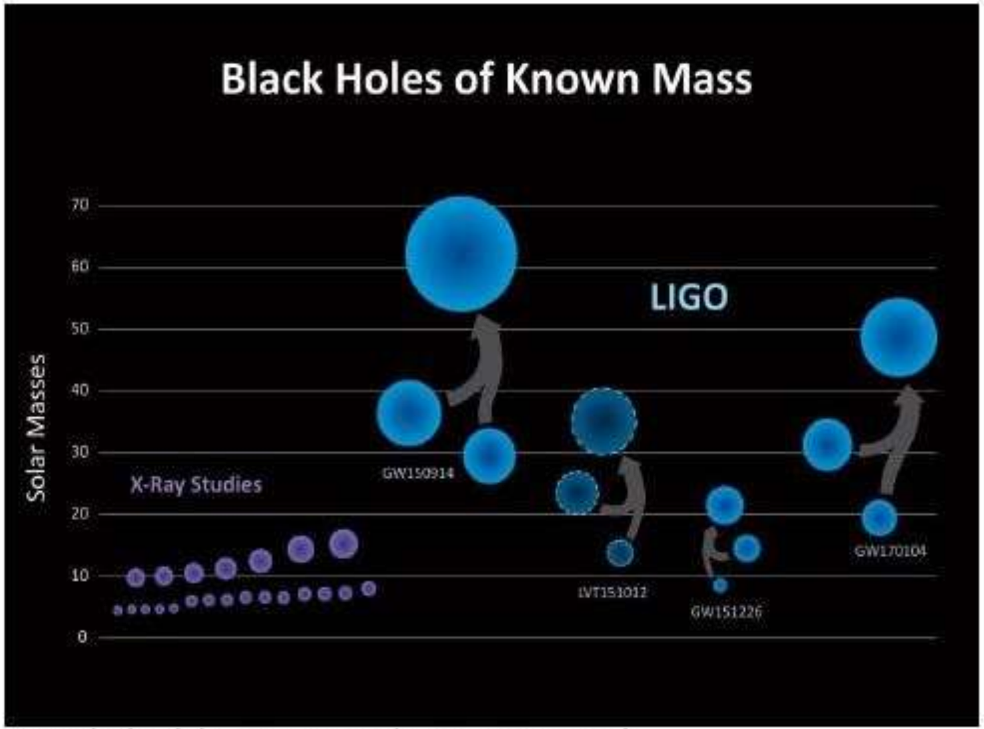


Phys. Rev. X 6, 041015 (2016)

Figure 6 – Waveform reconstructions of the three confirmed gravitational-wave detections and the less statistically significant event candidate displayed as a function of time, referenced from the time the signals cross into the LIGO interferometers' frequency band at 30 Hz.

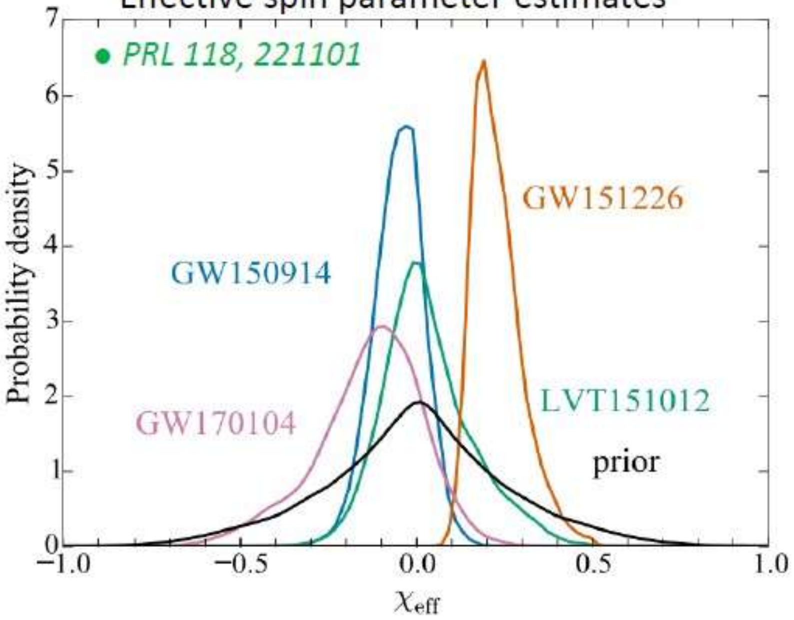
Credit: D. Reitze

Observed black hole mergers parameters



LIGO/Caltech/Sonoma State (Aurore Simonnet)

Effective spin parameter estimates

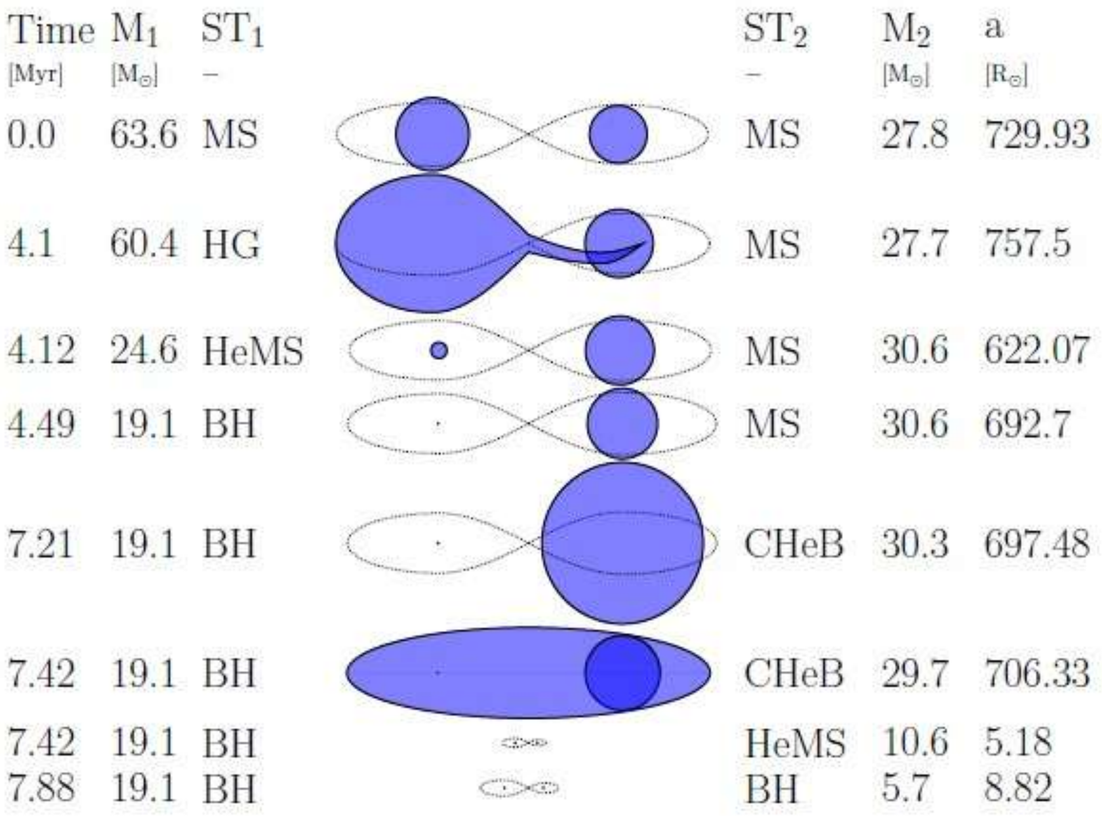


Reconstructed sky locations

LIGO/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger)

Main evolution scenarios

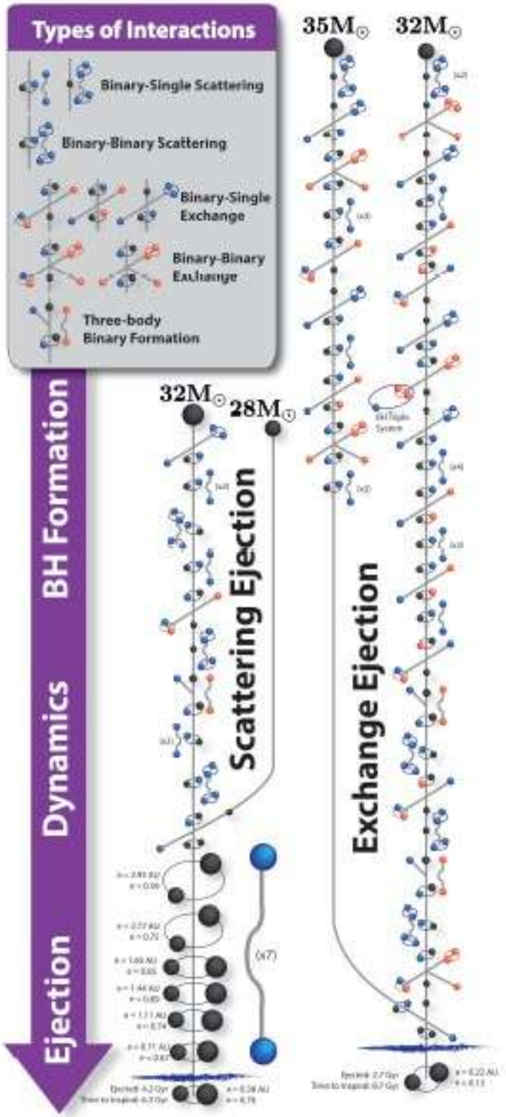
- **Massive** binary stars **undergoing core-collapse**



Time [Myr]	M_1 [$M_\odot$]	ST_1 –	ST_2 –	M_2 [$M_\odot$]	a [$R_\odot$]
0.0	63.6	MS	MS	27.8	729.93
4.1	60.4	HG	MS	27.7	757.5
4.12	24.6	HeMS	MS	30.6	622.07
4.49	19.1	BH	MS	30.6	692.7
7.21	19.1	BH	CHeB	30.3	697.48
7.42	19.1	BH	CHeB	29.7	706.33
7.42	19.1	BH	HeMS	10.6	5.18
7.88	19.1	BH	BH	5.7	8.82

(Stevenson et al. 2017)

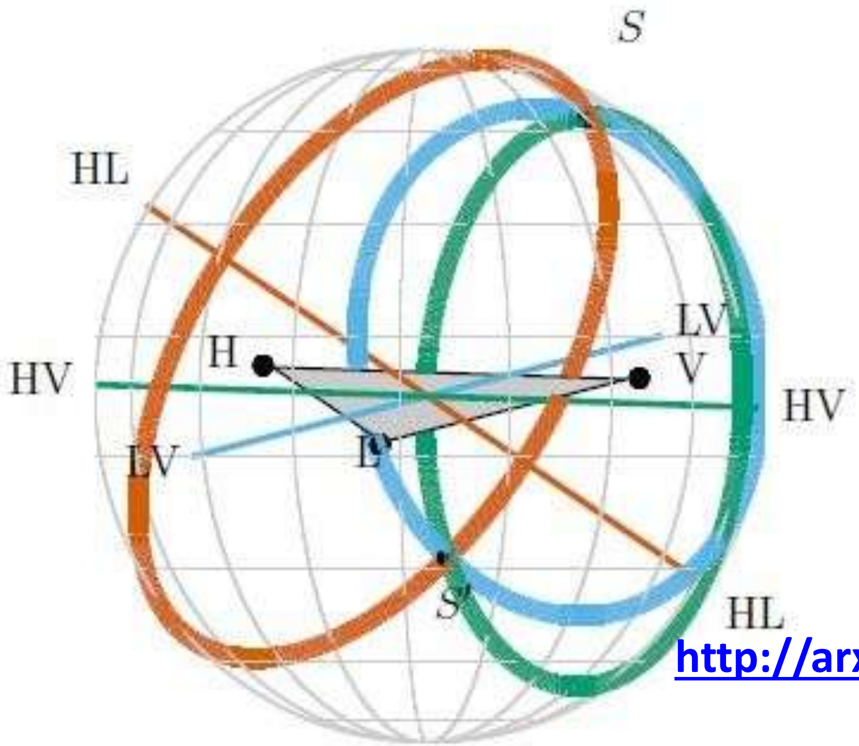
- **Dynamical capture**



(Rodriguez et al. 2016)

Importance of the 3rd detector: source localization

Jaranowski & **Królak** , Optimal solution to the inverse problem for the gravitational wave signal of a coalescing compact binary, *Phys. Rev. D*, ***49, 1723–1739, (1994)***



http://arxiv.org/abs/gr-qc/0605002

Figure 4: Source localization by triangulation for the aLIGO–AdV network. The locations of the three detectors are indicated by black dots, with LIGO Hanford labeled H, LIGO Livingston as L, and Virgo as V. The locus of constant time delay (with associated timing uncertainty) between two detectors forms an annulus on the sky concentric about the baseline between the two sites (labeled by the two detectors). For three detectors, these annuli may intersect in two locations. One is centered on the true source direction (S), while the other (S') is its mirror image with respect to the geometrical plane passing through the three sites. For four or more detectors there is a unique intersection region of all of the annuli. Figure adapted from [41].

What the LIGO-Virgo Detections Tell Us About the Validity of General Relativity

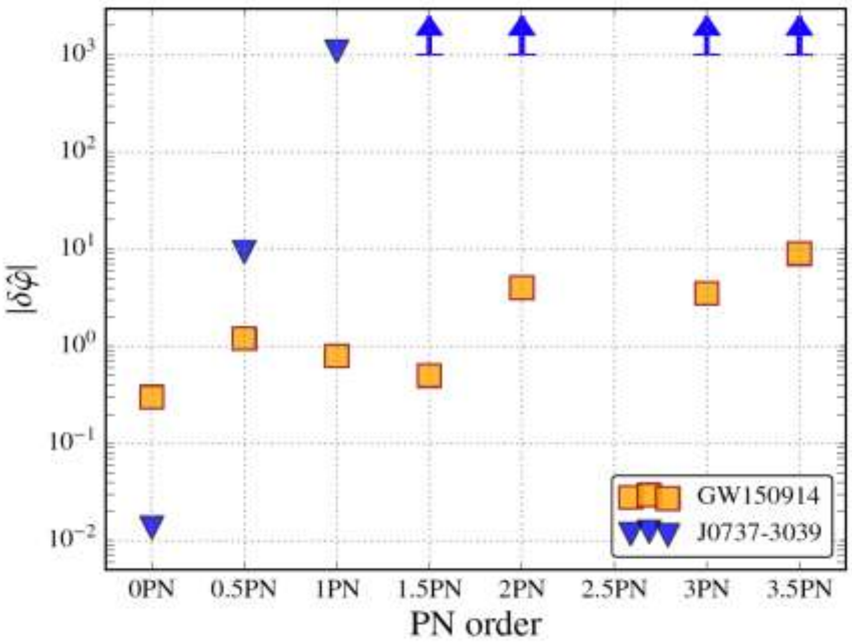
Post-Newtonian Approximation to GR

$$h(f) = A(f)e^{i\phi(f)}$$

$$\phi(f) = \phi_{ref} + 2\pi f t_{ref} + \phi_{Newton}(Mf)^{-5/3} + \phi_{0.5PN}(Mf)^{-4/3}$$

$$+\phi_{1PN}(Mf)^{-1} + \phi_{1.5PN}(Mf)^{-2/3} + \ldots$$

Post-Newtonian Approximation to GR

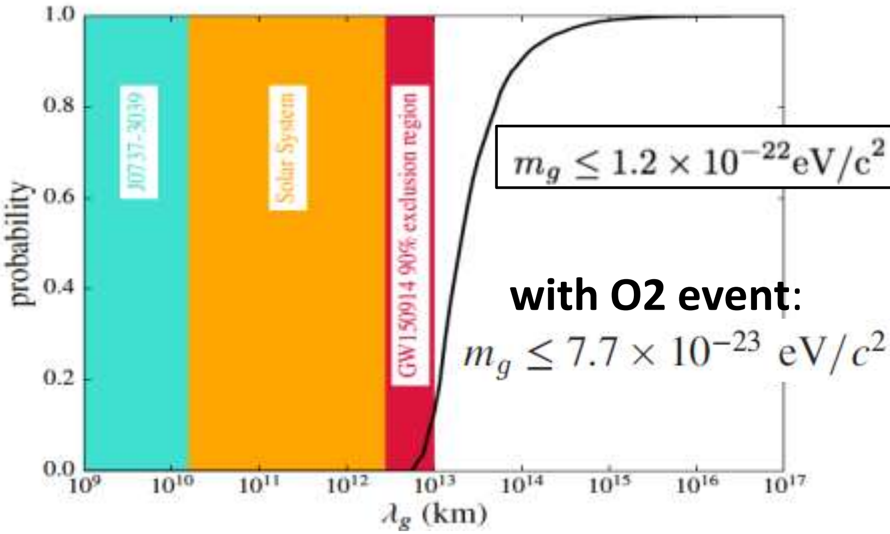


Upper Bound on the Graviton Mass

$$E^2 = p^2c^2 + m_g^2c^4 \qquad \lambda_g = \frac{h}{m_g c}$$

$$\frac{v_g^2}{c^2} \approx 1 - \frac{h^2c^2}{\lambda_g^2 E^2}$$

Compton Wavelength of the Graviton



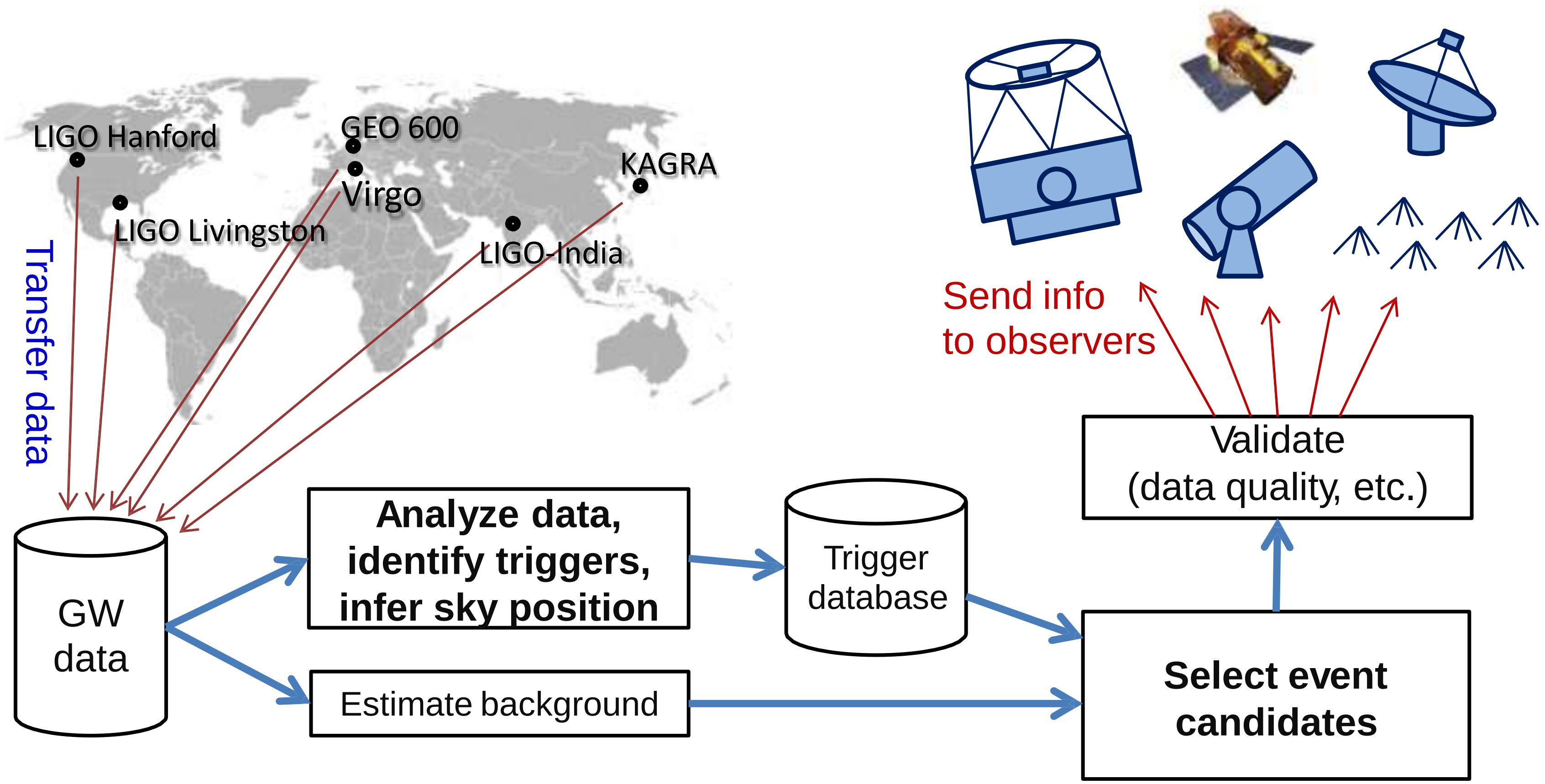
$m_g \leq 1.2 \times 10^{-22}\mathrm{eV/c^2}$

with O2 event:

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

Abbott, et al. ,LSC and Virgo, “Tests of general relativity with GW150914”, Phys. Rev. Lett. 116, 221101 (2016), Binary Black Hole Mergers in the first Advanced LIGO Observing Run, https://arxiv.org/abs/1606.04856

GW observations follow up program



GW data

Analyze data, identify triggers, infer sky position

Estimate background

Trigger database

Select event candidates

Validate (data quality, etc.)

Send info to observers

Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

LIGO & Virgo have signed MOUs with >90 groups for EM/neutrino follow-up, in addition to a number of triggered / joint search MOUs

Follow-up Observations During O1

- About half of those with observing capability responded to at least one of the 3 alerts during the run

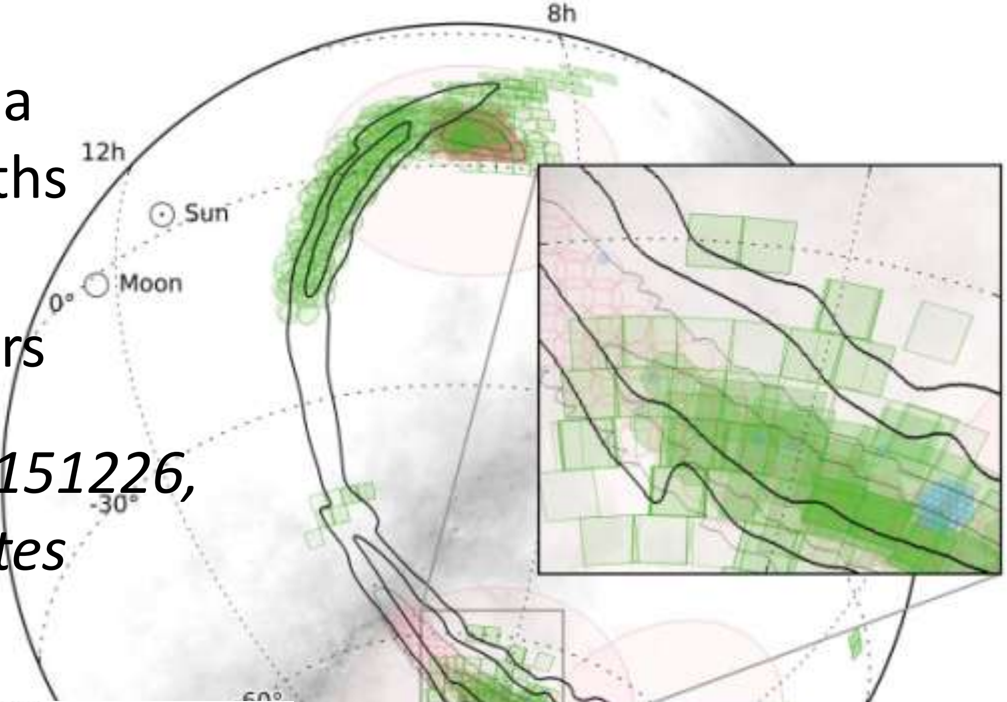
– *For GW150914:*

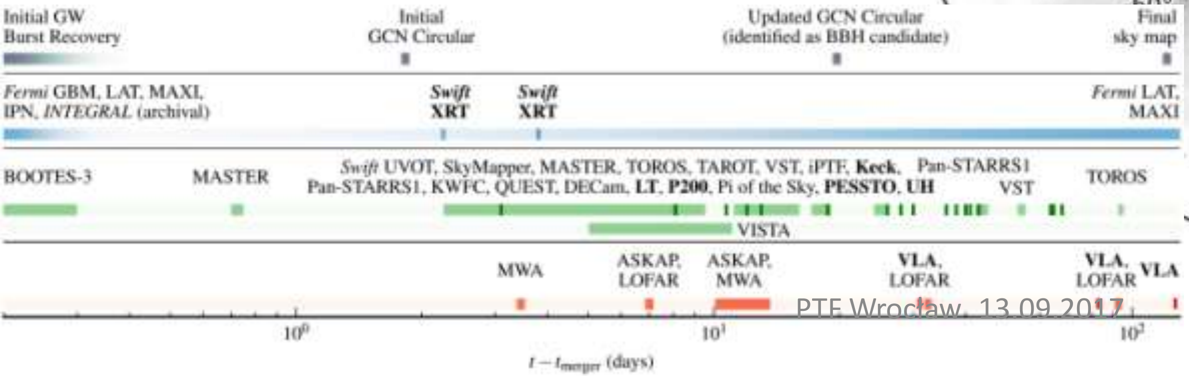
– Covered most of skymap area at a wide range of wavelengths starting within a few hours

– ~50 GCN Circulars, ~12 papers

– *Also strong response for GW151226, GW170104, and other candidates*

[Abbott et al. 2016, ApJL 826, L13]





Searches for other GW sources

(upper limits only)

Bursts (Supernovae) Phys. Rev. D 95, 042003 (2017)

All-sky search for short gravitational-wave bursts in the first Advanced LIGO run

h_{UL} 10x less than for 1st generation of detectors

Other binary systems (NSNS and NSBH) ApJL, L21 (2016)

Upper limits on the rates of binary neutron star and neutron-star--black-hole mergers from Advanced LIGO's first observing run

NSNS M=1.35+/-0.13 M_s detectable to 70Mpc

NSBH MBH > 5 M_s detectable to 110Mpc

Periodic signals (pulsars)

Astrophys.J. 839 (2017) no.1, 12

Crab pulsar : Energy in GW < 0.002 $E_{TotalRadiated}$

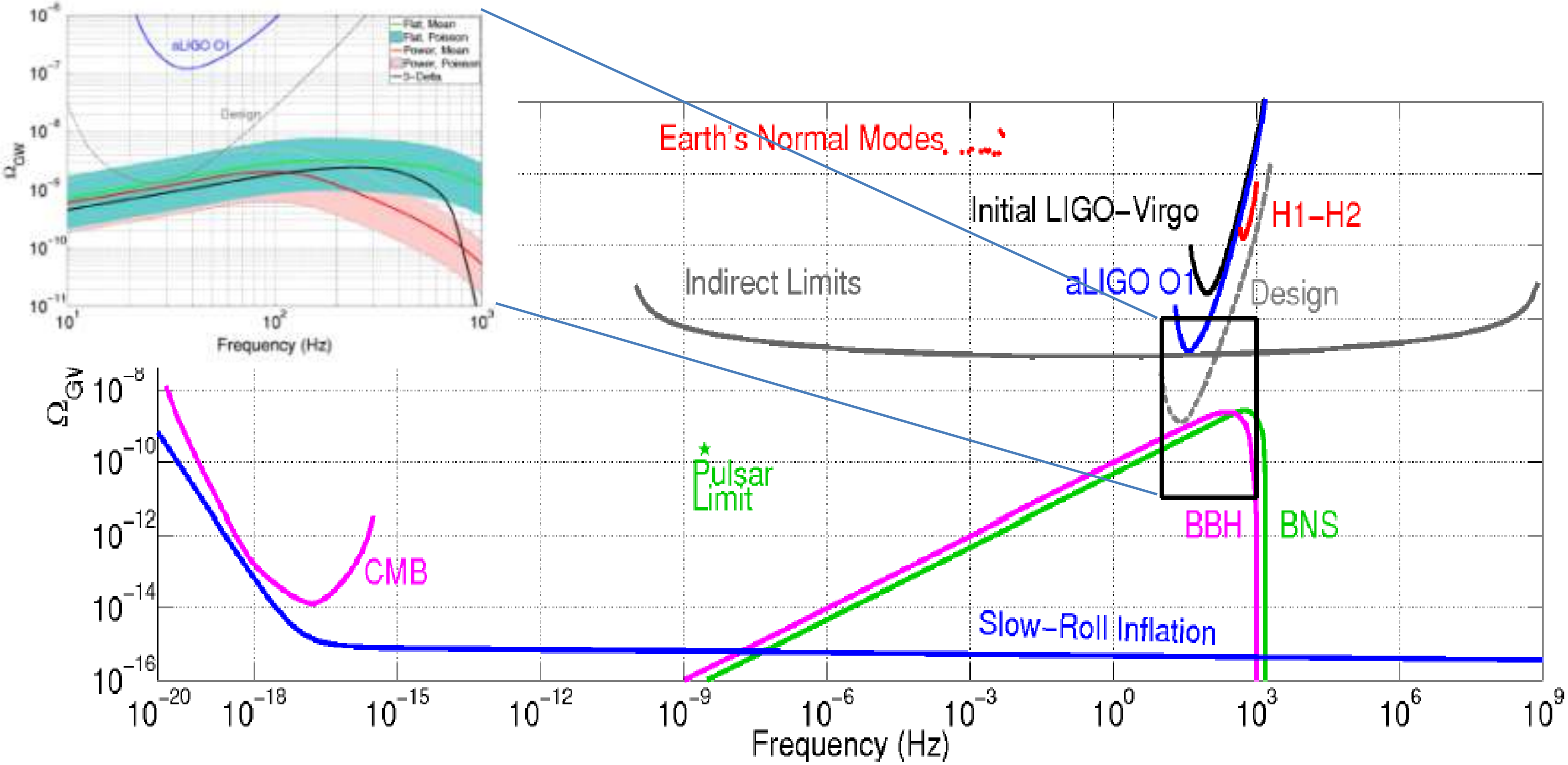
Vela pulsar : Energy in GW < 0.01 $E_{TotalRadiated}$

Phys. Rev. D 95, 042003 (2017)

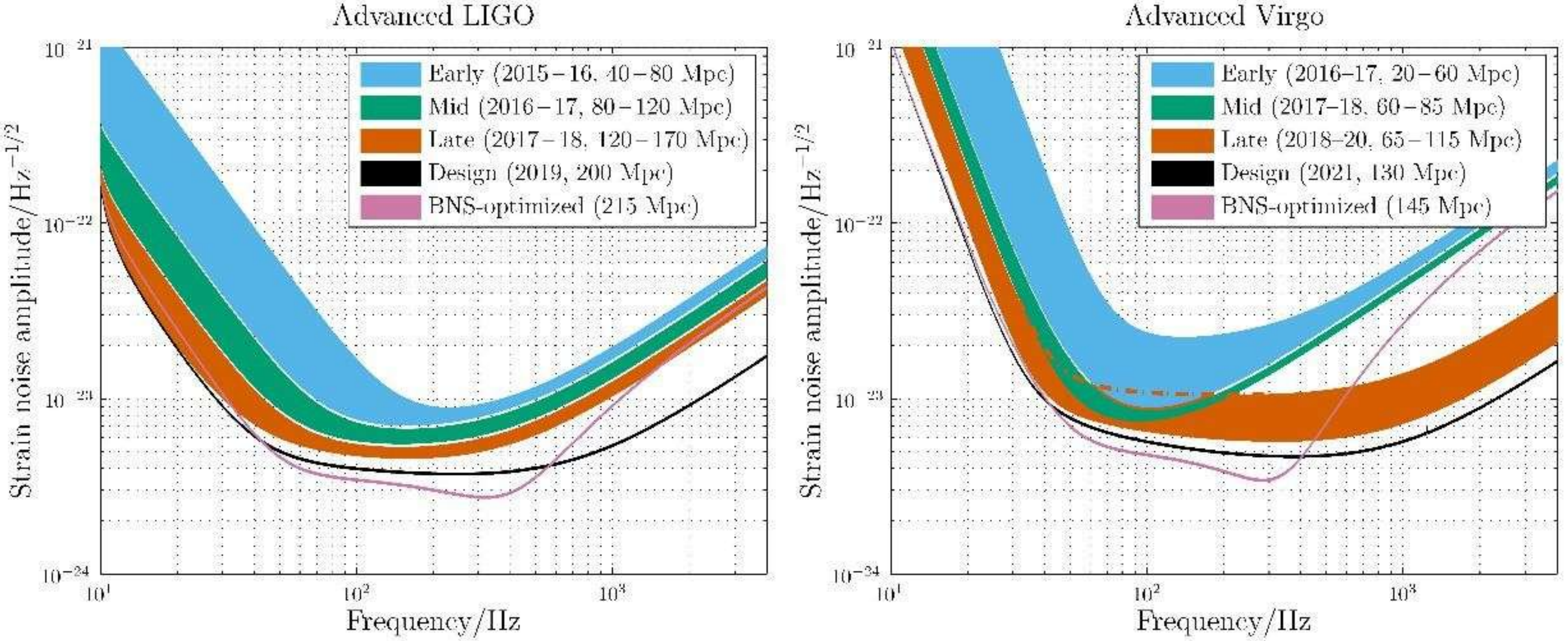
Blind searches h_{GW} < $4e^{-25}$ at 170 Hz

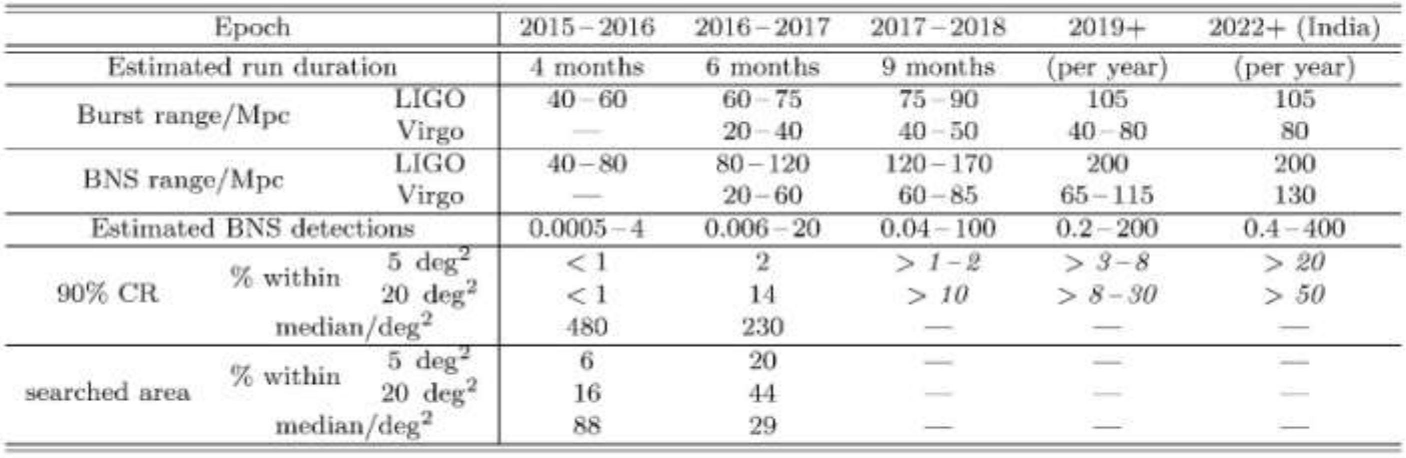
Stochastic background

Upper limit: dimensionless energy density $\Omega_{GW} < 1.7\times10^{-7}$ (33 better than before) [Phys. Rev. Lett. 118, 121101 (2017)]



Outlook

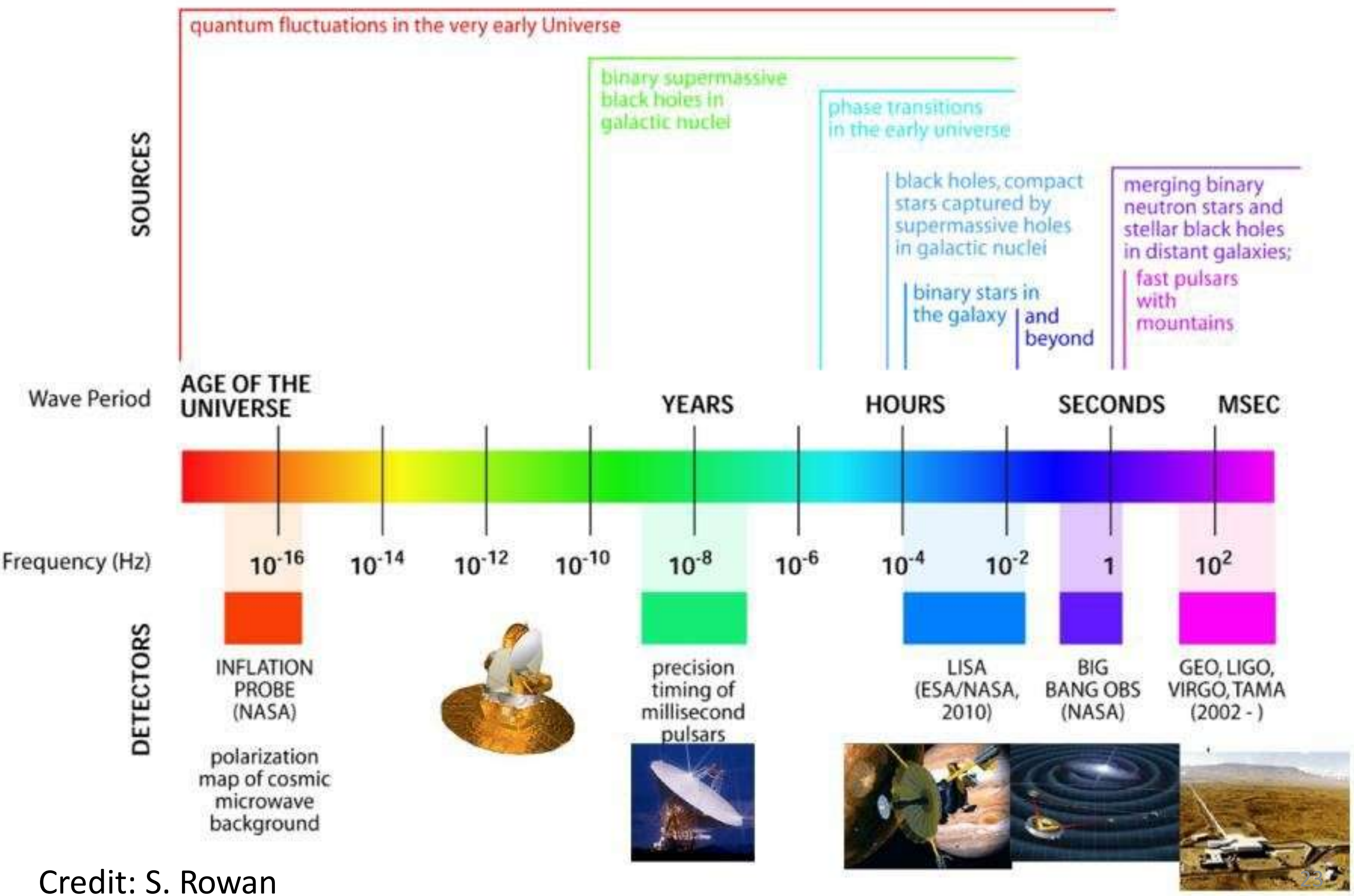




Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	*> 1 – 2*	*> 3 – 8*	*> 20*
		20 deg^2	< 1	14	*> 10*	*> 8 – 30*	*> 50*
		median/deg^2	480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
		median/deg^2	88	29	—	—	—

http://relativity.livingreviews.org/Articles/lrr-2016-1/

THE GRAVITATIONAL WAVE SPECTRUM



Credit: S. Rowan

Conclusions

- General relativity has been tested in extreme gravity regime where the gravitational field is strong and dynamical
- A new field – gravitational wave astronomy has been opened.

POLGRAW

LIGO

VIRGO

Virgo-Polgraw

20 scientists and engineers form 10 institutions in Poland

Instytut Matematyczny Polskiej Akademii Nauk

Uniwersytet Zielonogórski

Narodowe Centrum Badań Jądrowych Świerk

Uniwersytet Mikołaja Kopernika w Toruniu

AGH

Uniwersytet Warszawski

Uniwersytet Wrocławski

Uniwersytet Jagielloński w Krakowie

Virgo-Polgraw activities

- Astrophysics - OA UW, UZG, CAMK (**T. Bulik - Rates predictions of BBH coalescences**)

- Data Analysis - IMPAN, CAMK, NCBJ, UwB, Torun, UWr (**A. Królak and P. Jaranowski – Foundations for algorithms for detections of GW signals from binaries**)

- Advanced Virgo detector (gavity gradient noise cancelation) - UW, SI, NCBJ

- Correlated magnetic field measurements - UJ, AGH, UW

- EM follow up - NCBJ
- GR – two body problem – UwB
  (**P. Jaranowski 3rd and 4th PN Hamiltonian**)

Polgraw searches for gravitational wave from rotating neutron stars in LIGO O1 data

Tools

- **We have two pipelines:**

1. Targeted searches - GW from known pulsars (Matlab codes)
2. All-sky searches – GW from unknown isolated rotating stars
   (C-codes maintained by M. Bejger (CAMK) optimized by P. Ciecielag (CAMK))

Can run on tens of thousand of cores

Computations done on Pl-Grids and CIŚ (NCBJ)

Method (matched filtering)

- **Robust waveform:**

sky position

detector motion

$$\phi(t) \simeq 2\pi \sum_{k=0}^{s} f_k \frac{t^{k+1}}{(k+1)!} + \frac{2\pi}{c} \mathbf{n}_0 \cdot \mathbf{r}_{\mathrm{d}}(t) \sum_{k=0}^{s} f_k \frac{t^k}{k!},$$

- **F-statistic** (P. Jaranowski, A. Królak, and B. F. Schutz, *Phys. Rev.* D **58**, 063001 (1998).

$$\boldsymbol{\xi} = (\mathbf{f}, \delta, \alpha)$$

$$F_a := \int_0^{T_o} x(t) a(t) \exp[-\mathrm{i}\phi(t)]\,\mathrm{d}t$$

$$F_b := \int_0^{T_o} x(t) b(t) \exp[-\mathrm{i}\phi(t)]\,\mathrm{d}t$$

$$\mathcal{F}[x;\boldsymbol{\xi}] \cong \frac{2}{S_0 T_o} \frac{B|F_a|^2 + A|F_b|^2 - 2C\Re(F_a F_b^*)}{D}$$

O1 data searches

- **Search for known pulsars:**

LIGO and Virgo Collaborations, *First Search for Gravitational Waves from Known Pulsars with Advanced LIGO,* (B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), ASTROPHYSICAL JOURNAL Volume: 839, 1, 12 (2017)

- **All sky search:**

All-sky search for periodic gravitational waves in the O1 LIGO data, B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. D **96**, 062002

Highlighted by PRD:

https://physics.aps.org/synopsis-for/10.1103/PhysRevD.96.062002

Sources of CW

- Asymmetric spinning neutron stars are the most obvious source of CW (for Earth-bound detectors).

- **We know that potential sources of CW exist**: 2400+ NS are observed (mostly pulsars) and O(10^8-10^9) are expected to exist in the Galaxy.

- A fraction of these is expected emit in the sensitivity band of detectors

- **We do not know the typical amplitude of the signals.**

Signal amplitude: $h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{r}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$

ε : ellipticity (adimensional number measuring the star's degree of asymmetry)

f : signal frequency, proportional to star rotation frequency

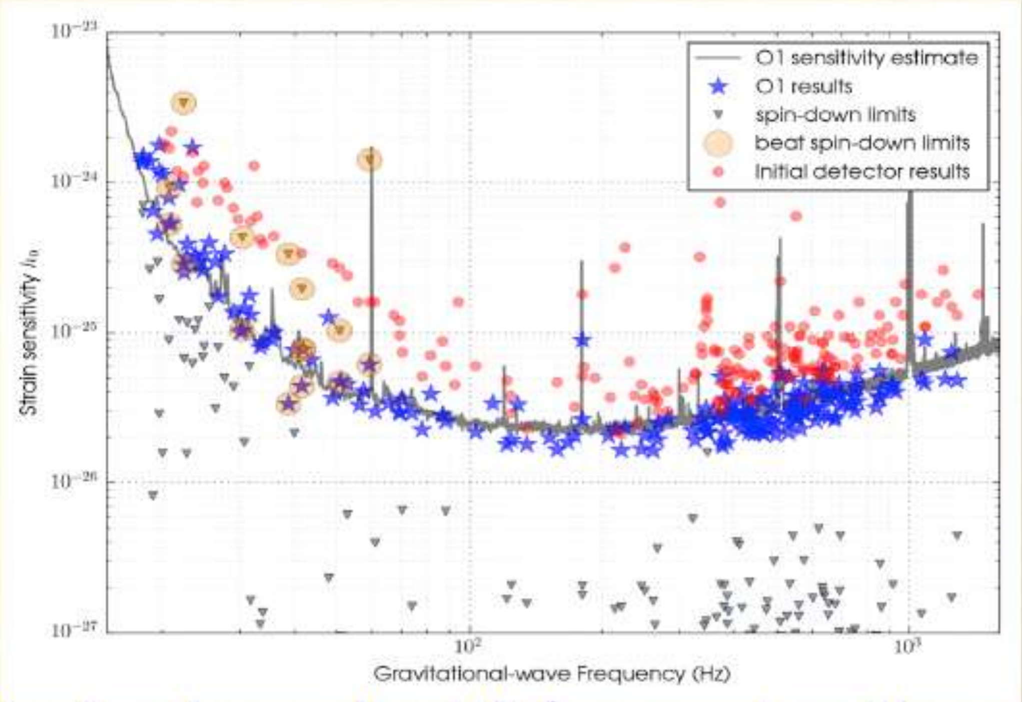
The ellipticity can be due to different mechanisms [e.g. Lasky, PASA, 32, e034, 2015 for a recent review]:

- ○ distortion due to elastic stresses or magnetic field
- ○ distortion due to matter accretion (e.g. LMXB)
- ○ free precession around rotation axis
- ○ excitation of long-lasting oscillations (e.g. r-modes)
- ○ …

- ○ ε_{max} ~10^{-5} / ~ 10^{-3} depending on the mechanism and on the star EOS

✧ **We do not know which are the typical values of ε.**

Highlights on O1 targeted searches



LVC, ApJ 839, 12, 2017

Analysis done over ~200 pulsars

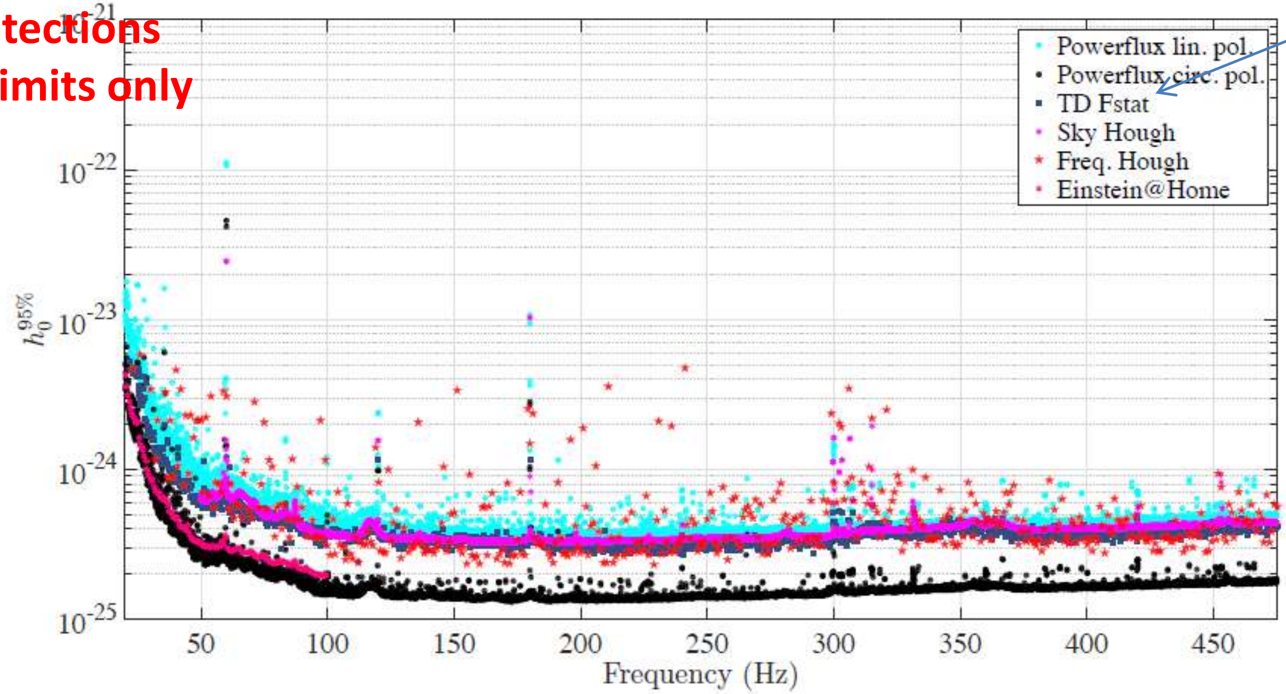
Pulsar ephemeris from Jodrell Bank, Hartebeesthoek and Fermi/LAT telescopes

- Indirect “spin-down limit” (assuming the source spin-down is fully due to emission of GW):

$$h_{sd} = 8\cdot 10^{-25}\sqrt{\left(\frac{|\dot{f}|}{10^{-10}\,Hz/s}\right)\left(\frac{f}{100Hz}\right)^{-1}}\left(\frac{d}{1kpc}\right)^{-1}$$

- UL below the “spin-down limit” for 8 pulsars
- For pulsar Crab it implies a constraint of ~2/1000 on the fraction of rotational energy lost to GWs ($\varepsilon<3*10^{-5}$)

All-sky searches



No detections
Upper limits only

POLGRAW

FIG. 21. (Color online) Upper limit comparison for the four search pipelines used in this analysis. The curves represent the source strain amplitude h_0 at which 95% of simulated signals would be detected. Three of the pipelines (*FrequencyHough*, *SkyHough*, *Time-Domain $\mathcal{F}$-statistic*) present population-averaged limits over the full sky and source polarization, while one pipeline (*PowerFlux*) presents strict all-sky limits for circular-polarization (most favorable orientation – black) and linear-polarization (least favorable orientation – cyan) sources. Converting the *PowerFlux* upper limits to validated population-averaged upper limits would require extensive, band-dependent Monte Carlo simulations, but previous studies suggest that such limits would lie in a region similar to that of the other pipelines. In addition, the population-averaged upper limits from the most recent Einstein@Home search are shown for comparison [32]. The Einstein@Home search explored the low frequencies, and a narrower spindown range using a much longer coherence length (210 hours).

Virgo joins O2

1st of August Virgo detector joined the second LIGO observational run O2 with an excellent duty cycle and a reasonable sensitivity

The three detectors were collecting scientific data untill 25th of August when O2 ended

From the end of the run statement:
Some promising gravitational-wave candidates have been identified in data from both LIGO and Virgo during our preliminary analysis, and we have shared what we currently know with astronomical observing partners. We are working hard to assure that the candidates are valid gravitational-wave events, and it will require time to establish the level of confidence needed to bring any results to the scientific community and the greater public. We will let you know as soon we have information ready to share.

G7 Science: Update on gravitational waves science from the LIGO-Virgo scientific collaborations

WHAT: Media are invited to join the LIGO-Virgo collaboration for an update on gravitational wave science
in the presence of the G7 Science Ministers, focusing in particular on findings from a new observation made on Aug. 14.

WHEN: Wednesday, September 27, 2017 at 06:30 PM CET

VENUE: Reggia di Venaria Media center, Torino (Italy)

Confirmed speakers:
Jo van den Brand, Spokesperson, Virgo Collaboration
David Shoemaker, Spokesperson, LIGO Scientific Collaboration
France Córdova, Director of the National Science Foundation
Federico Ferrini, Director ofthe European Gravitational Observatory