Gravitational waves searches by the network of ground-based interferometers

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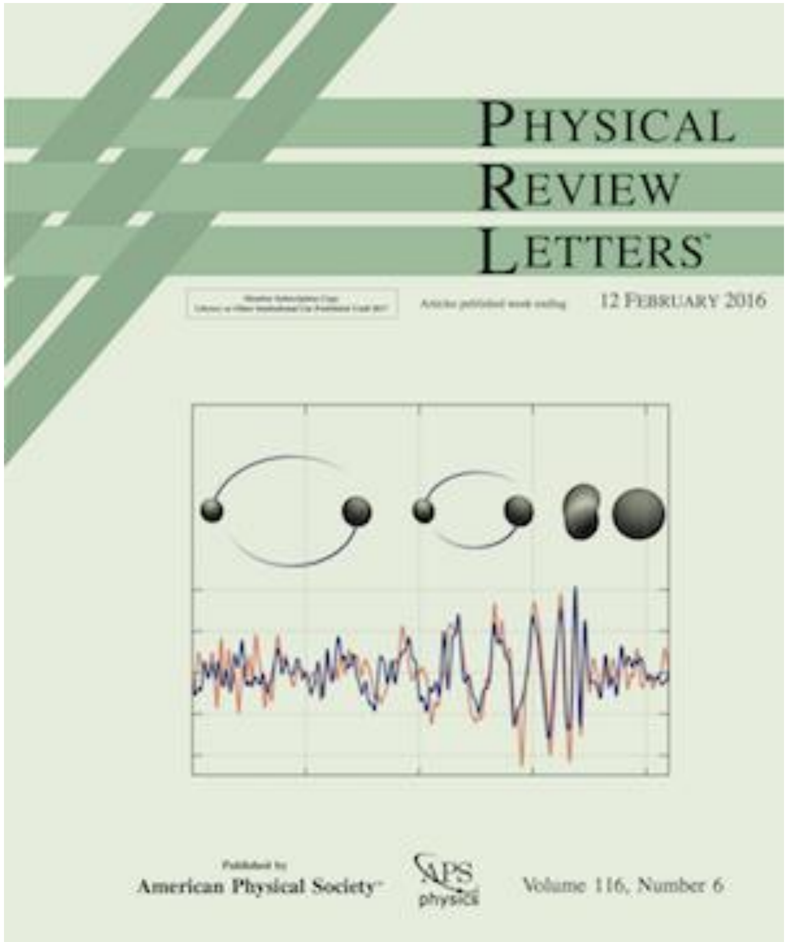
Kolymbari, Greece, *Aug. 2017*

This talk:

- What We Measure
- Network of Detectors
- Observation Campaigns
- LIGO-Virgo Gravitational Wave Searches and Results,
- Multimessenger Searches with LIGO-Virgo

next talk: instrument science
Annalisa Allocca on the Advanced Virgo detector



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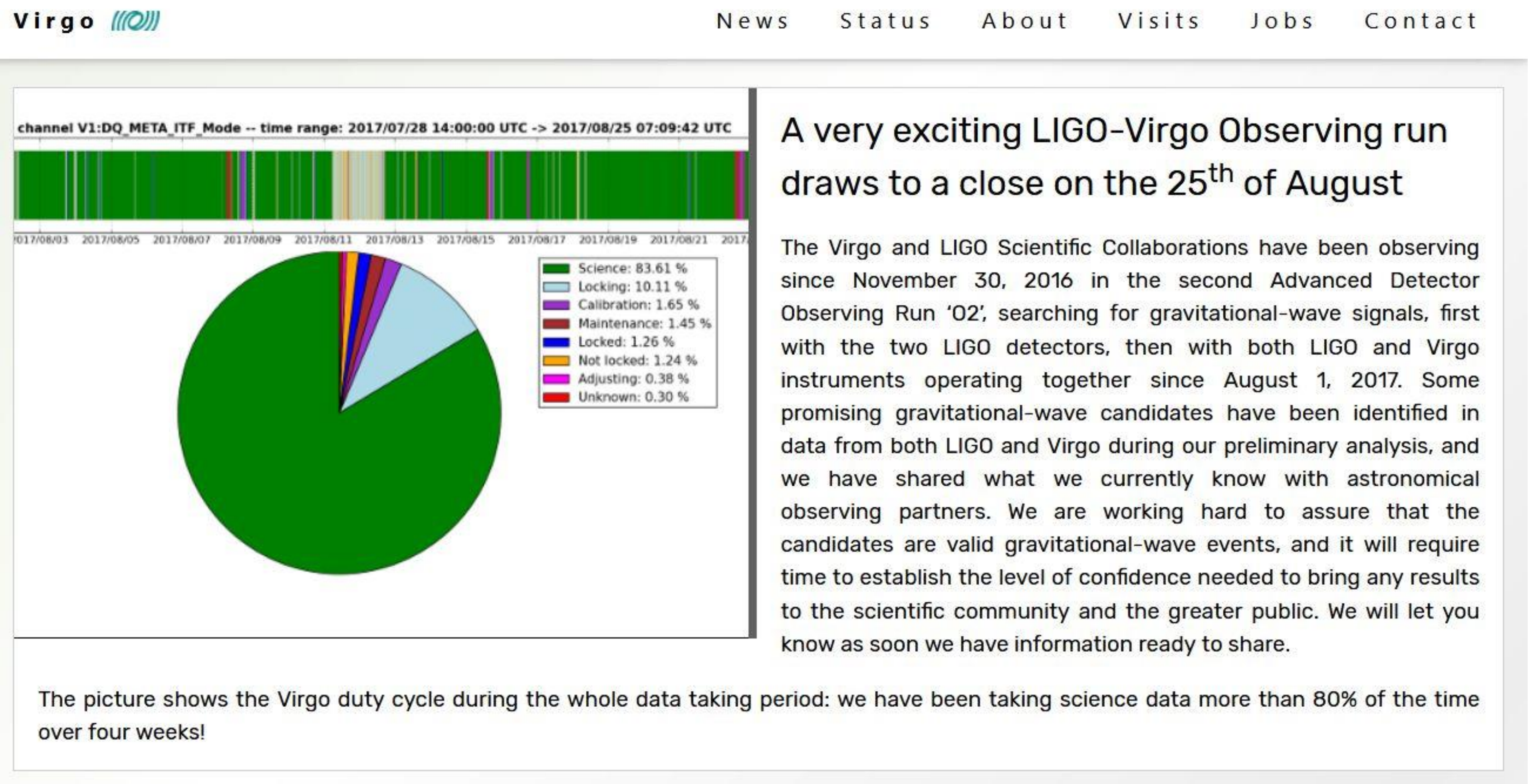
LIGO-Virgo observation run just ended



A very exciting LIGO-Virgo Observing run draws to a close on the 25th of August

The Virgo and LIGO Scientific Collaborations have been observing since November 30, 2016 in the second Advanced Detector Observing Run 'O2', searching for gravitational-wave signals, first with the two LIGO detectors, then with both LIGO and Virgo instruments operating together since August 1, 2017. 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 as we have information ready to share.

The picture shows the Virgo duty cycle during the whole data taking period: we have been taking science data more than 80% of the time over four weeks!

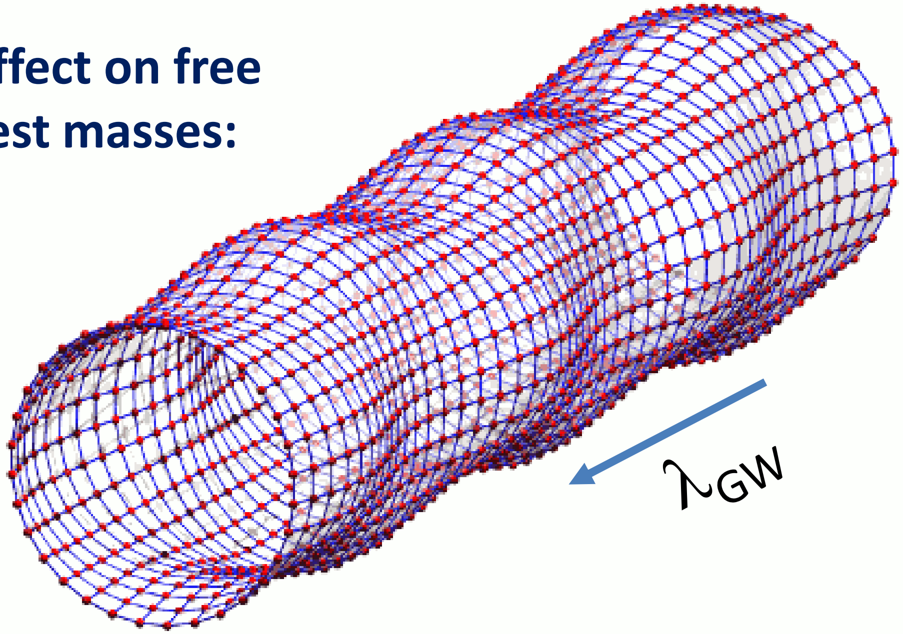
Gravitational Waves far away from sources

- ❑ gravitational waves carry curvature, energy, momentum, angular momentum
- ❑ weak-field linear approximation of General Relativity
  - analogies with electromagnetic waves:

    light speed, transverse, 2 polarization components
  - peculiarities of GWs:

    tidal deformations of extended bodies, no measurable local effect

Effect on free test masses:

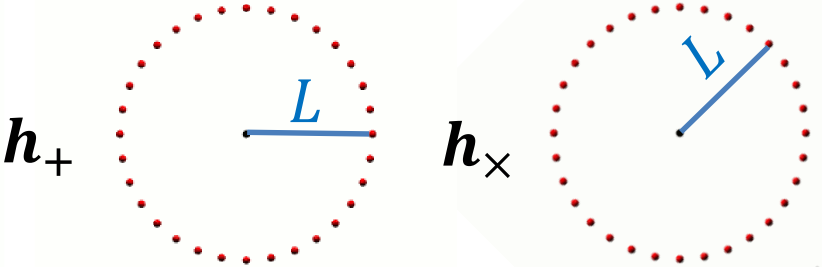


www.einstein-online.info

GW amplitude is strain:

$$h = \frac{\Delta L}{2\,L}$$

tensor polarizations h_+ $h_\times$ *rotated by* $\frac{\pi}{4}$ ***in the wavefront plane:***



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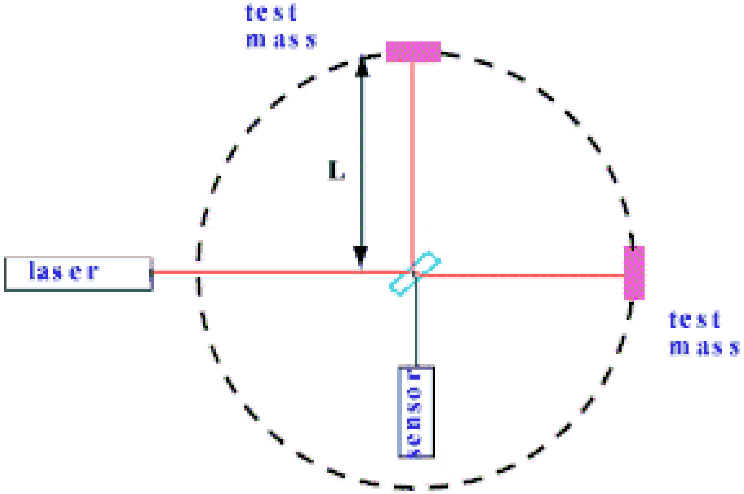
Interferometric detectors for GW

Measure differential arm changes ΔL by laser light beams:

optical phase difference $\Delta\phi$ at the antisymmetric port

$\Rightarrow$ light power variations at sensor

$$\frac{P_{out}}{P_{in}} = \sin^2\left(\frac{2\pi\Delta L}{\lambda_{Laser}}\right)$$



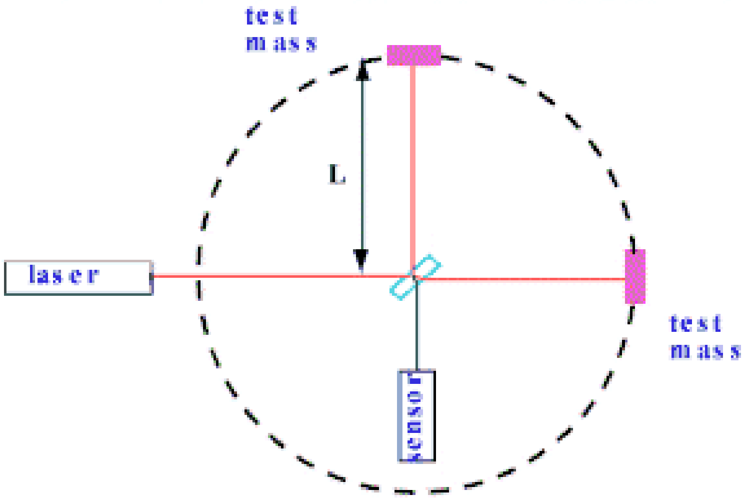
- 2 **balanced-length arms** allow common mode rejection of many technical noises.
- Operation close to **dark fringe** ($P_{out} \sim 0$) allows a «null measurement», i.e. more favorable $\Delta P_{out}/P_{out}$
- Want **high P_{in}** : signal scales with circulating power
- Target audio frequency gravitational waves:

optical arm length: $L = \frac{\lambda_{GW}}{4} = 750km\left(\frac{100Hz}{f_{GW}}\right)$

$\Rightarrow$ **Km-scale arms** plus increase optical path by **optical resonant cavities**

directional sensitivity of detectors

Each interferometer senses only one of the two GW polarizations:



- measures the linear combination

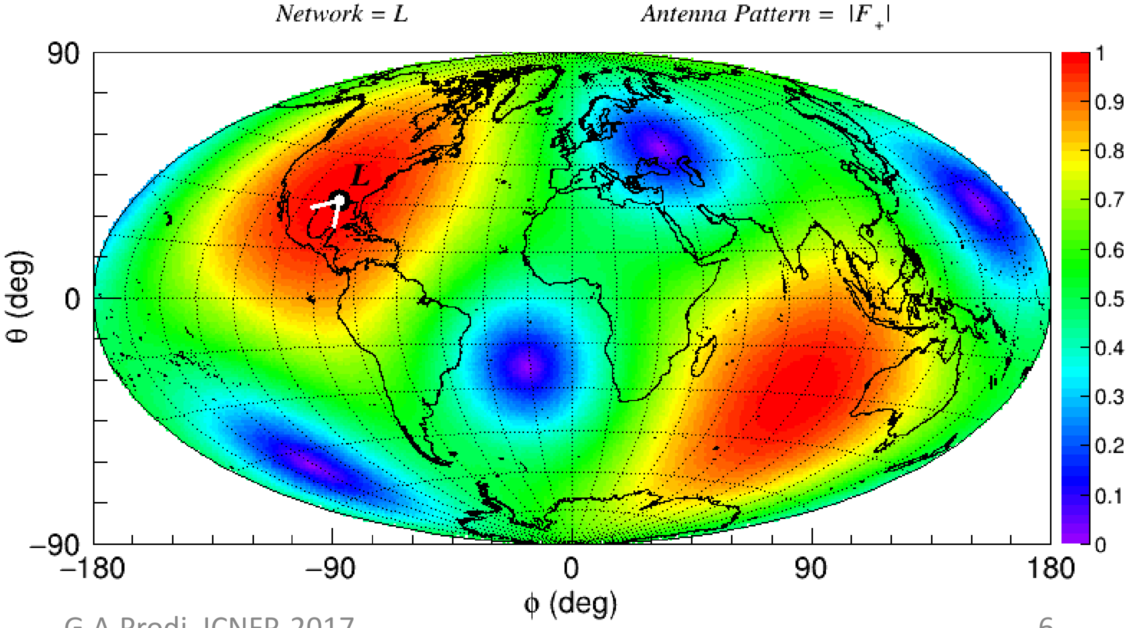
$$h = F_{+}h_{+} + F_{\times}h_{\times}$$

$$F_{+,\times}(\text{sky direction})$$

antenna patterns for + and x

- misses the orthogonal combination

Broad directional sensitivity:



The LIGO network of two detectors

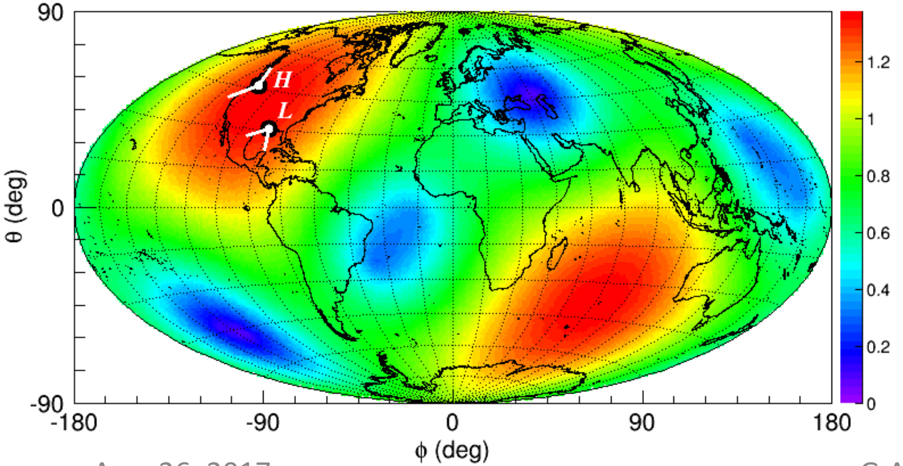
- **Detection confidence: discriminate GW candidates from noise fluctuations**
  - ✓ **At least two detectors in coincidence observation are required** unless for searches of persistent and well parametrized signals, e.g. periodic GWs
  - ✓ multimessenger searches with other detectors can help

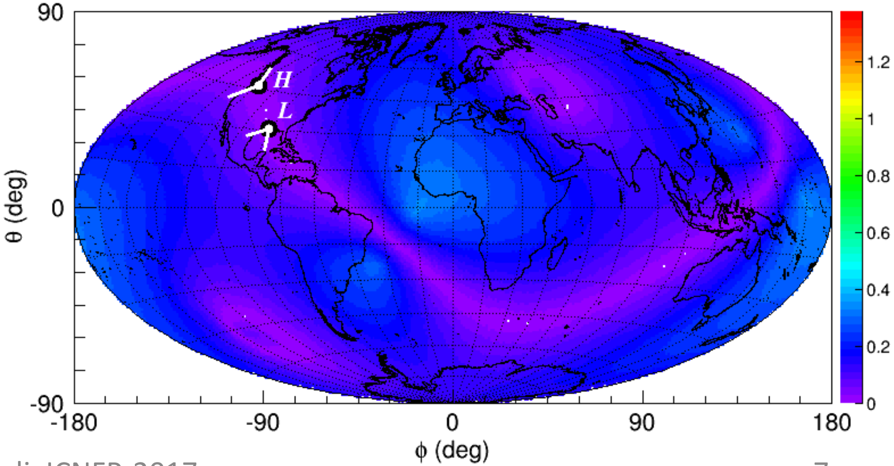
LIGOs arms are almost aligned

- **Sky coverage of LIGOs is very similar to that of a single detector**

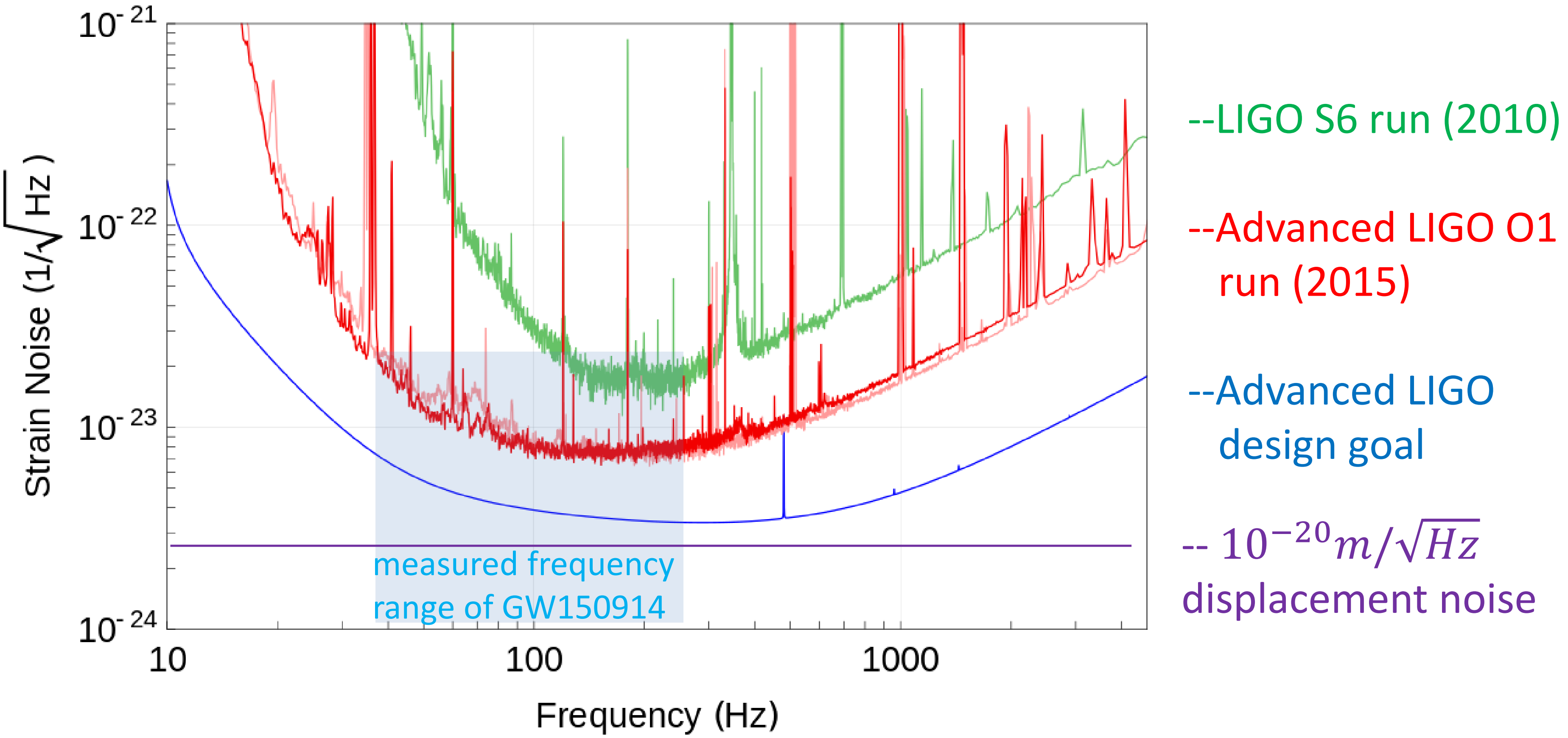
$\Rightarrow$ **almost blind to one GW polarization per each direction:**

$|\vec{F}_+|$ LIGO Hanford + LIGO Livingston $|\vec{F}_\times|$





Spectral sensitivity of Advanced LIGO detectors



- observations 2015 vs 2010:

gain in averaged observable volume of Universe : **~100x** for **BBH** like GW150914
~30x gain for **BNS** coalescences

- **the recent observations greatly exceed detection potential of all previous ones**

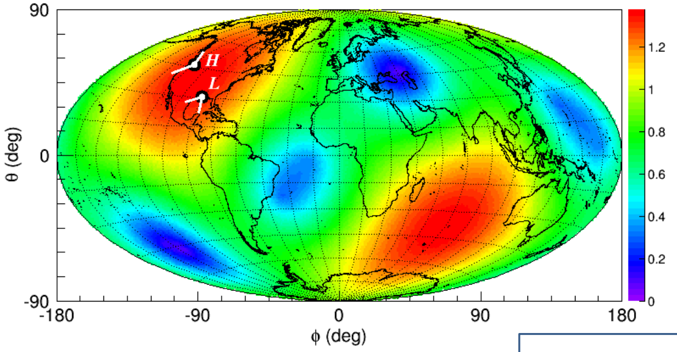
Benefits of adding Virgo detector

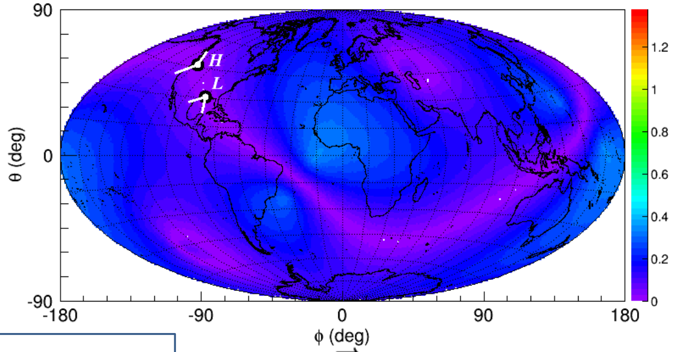
- **Detection confidence**: lower background and higher Signal-to-Noise Ratio
- Increased **time coverage of the survey** by detector pairs
- **coverage of sky and both GW polarizations**: better waveform reconstruction

$|\vec{F}_{+}|$

LIGO H1 + LIGO L1

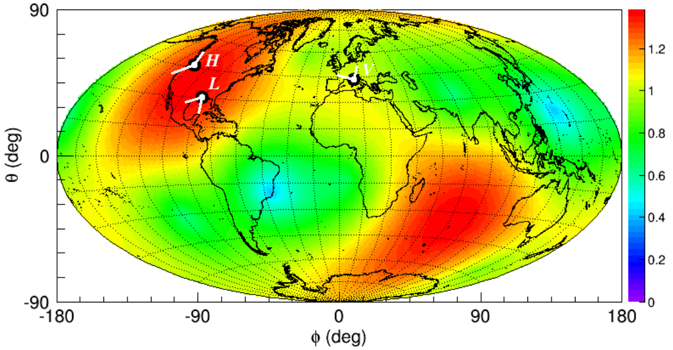
$|\vec{F}_{\times}|$





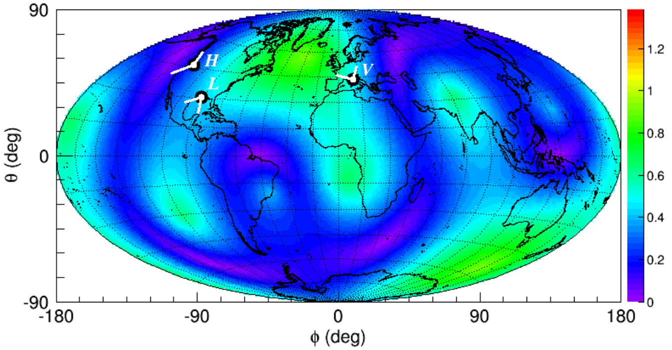
LIGO H1 + LIGO L1 **+ Virgo**

$|\vec{F}_{+}|$



assuming same spectral sensitivity

$|\vec{F}_{\times}|$

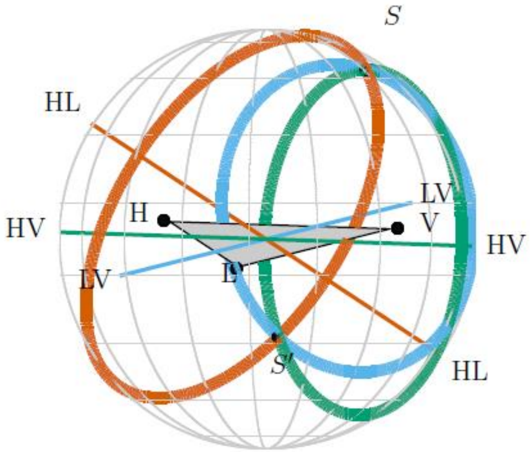


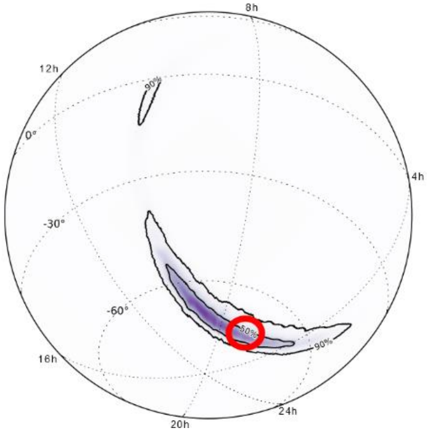
Benefits of adding Virgo

- **sky localization** greatly improved

e.g. for GW150914:

consistency of measured amplitude with directional sensitivities
+
triangulation

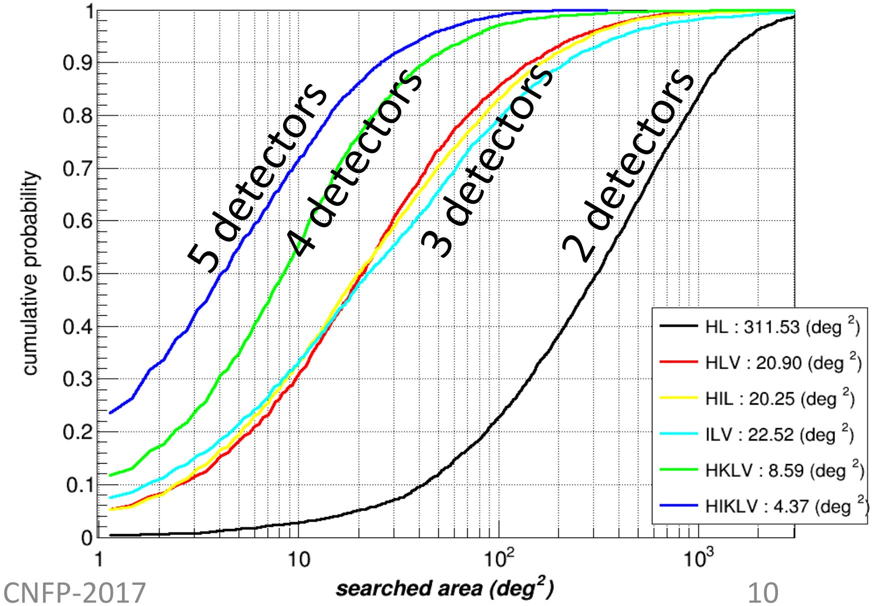




L1H1: 600 deg^2

L1H1V1: ≈20 deg^2
expected reduction by ~30 times of sky area *at 90% confidence*

- ✓ the more the detectors, the better.
- ✓ comparable peformances for 3 detectors configurations
- ✓ performances vary on waveform morphology, Signal-to-Noise ratio, source direction in the network frame



recap of recent observational campaigns

- **«O1»** [Sept.2015, Jan. 2016]

  ~ 49 days of coincident observations by LIGO Hanford and Livingston with science quality data

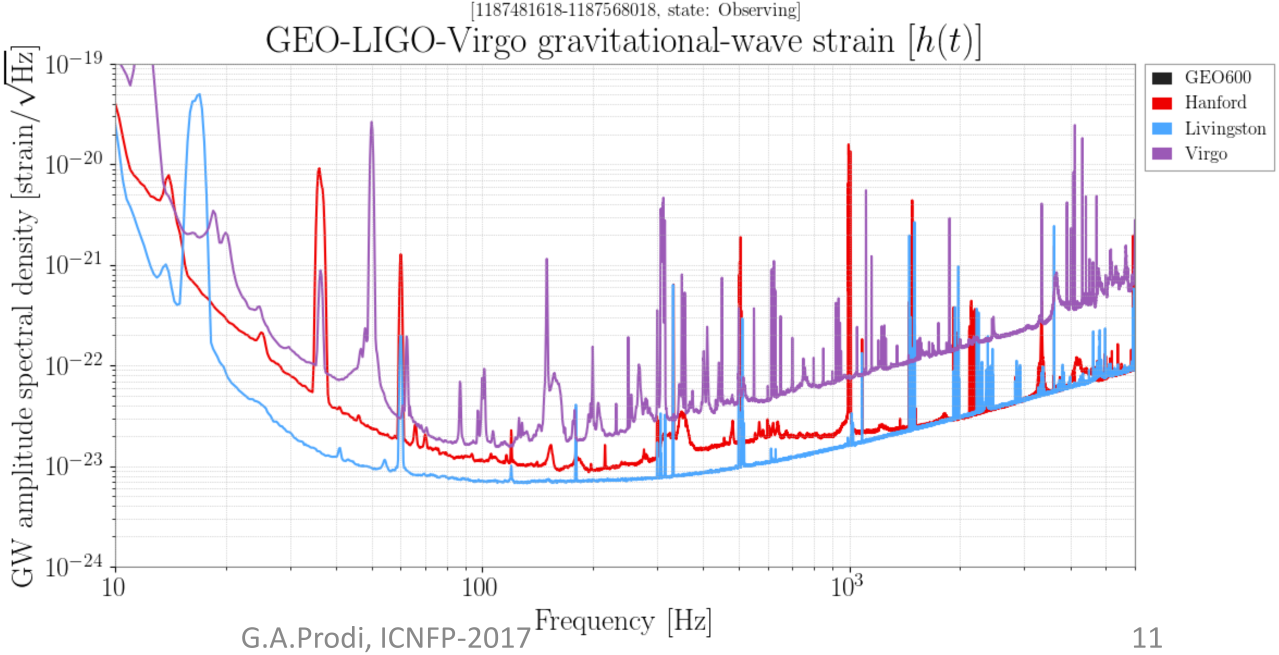
- **«O2»** [Nov. 2016, Aug. 25 2017]

  ~ 100 days of coincident observations by LIGO up to July

  8 GW alerts sent to LIGO-Virgo partners for multimessenger followup until June 23

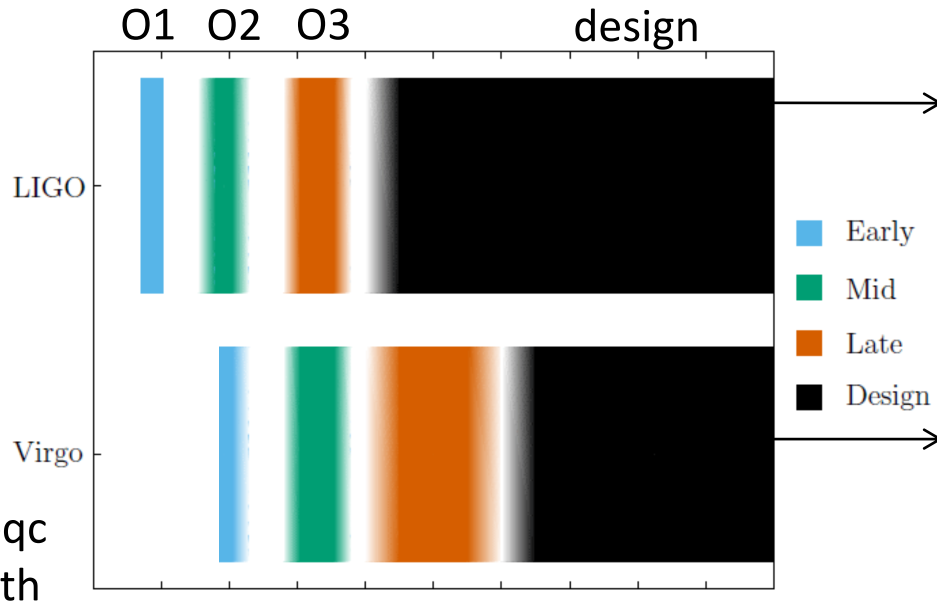
  Virgo joined the science run from Aug. 1

online monitoring of detectors:
losc.ligo.org
www.virgo-gw.eu/status.html



plans for LIGO-Virgo surveys

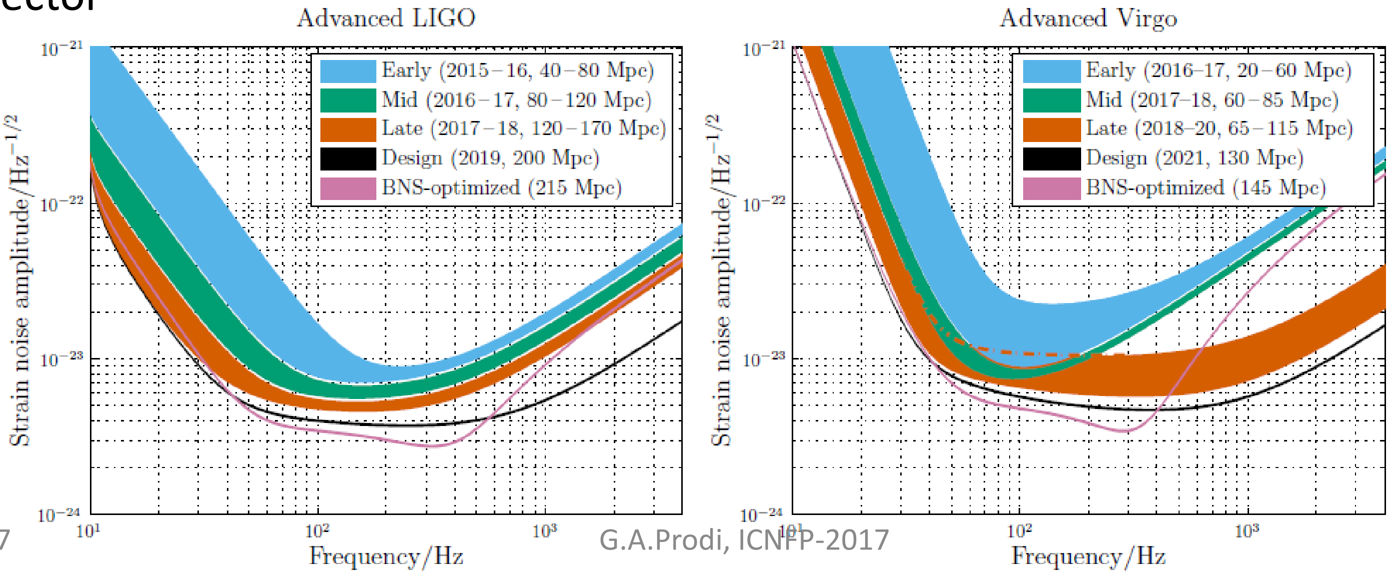
Performance upgrades by steps, interleaved by scientific observation runs: O1, O2, O3, design



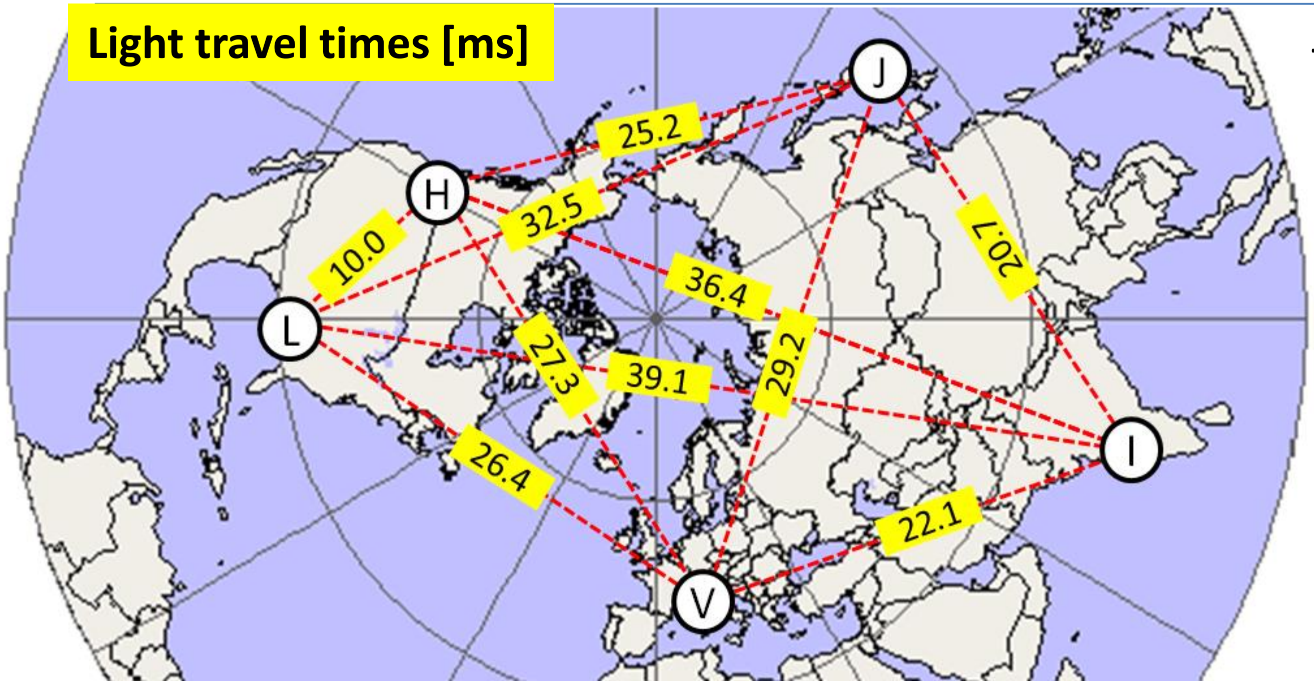
Design sensitivity:

- 1000x gain in surveyed volume of the Universe
- Binary BH detection rate: 50-500 /year
- Binary NS detection rate: 0.2-200 /year

arXiv: 1304.0670v2 gr-qc to be updated soon with Japanese detector KAGRA



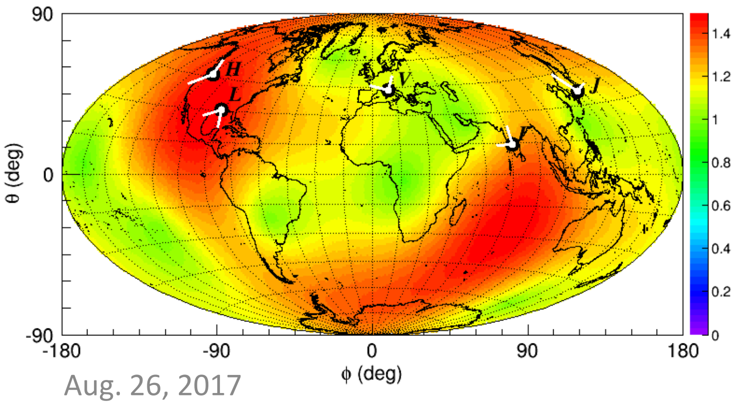
global 2019+ scenario


Light travel times [ms]

Two more interferometers will join LIGO and Virgo:
KAGRA (Japan, 2019) and
LIGO India - IndIGO -
(approved in 2016)

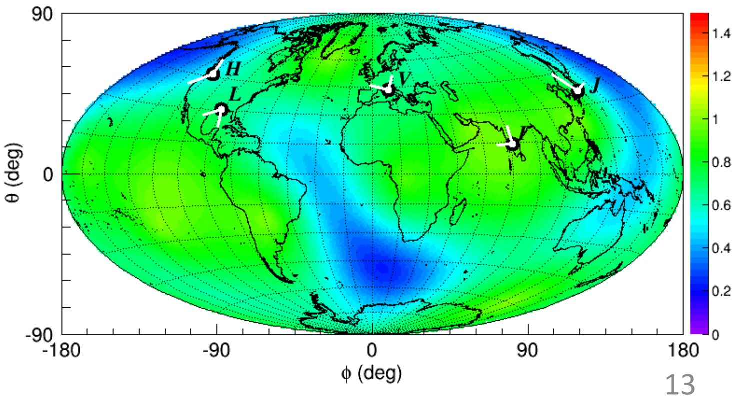
sky coverage of the whole observatory

$|\vec{F}_+|$



almost omni-directional

$|\vec{F}_\times|$



The main LIGO-Virgo searches for GWs

GW transients

- **Compact Binary Coalescences**
  - ✓ using stringent waveform models (phase evolution of signals)
- …
- **Generic transient searches**
  - ✓ minimal assumptions on waveforms
- …

Persistent GWs

- **Stochastic Background**
  - ✓ superposition of many unresolved cosmological and/or astrophysical sources
- **fast spinning NS**
  - ✓ quasi periodic signals

Probes of
- most extreme compact objects
- space-time dynamics
- early universe

Searches for Compact Binary Coalescences

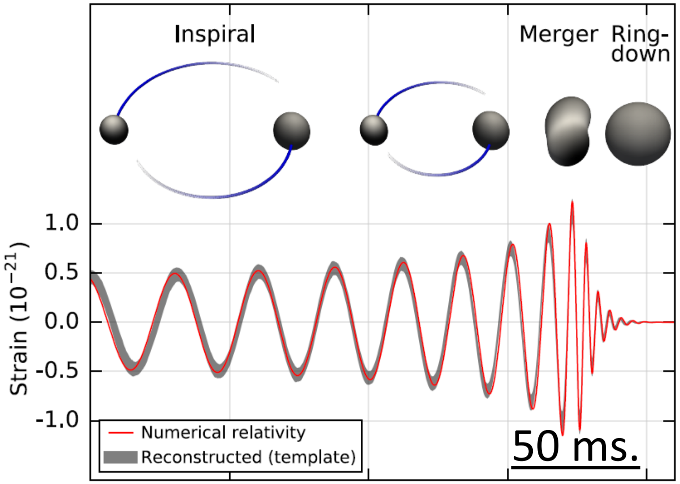
Black Holes, Neutron Stars and BH-NS Binaries

- **signal templates:** amplitude&phase evolution of the GW

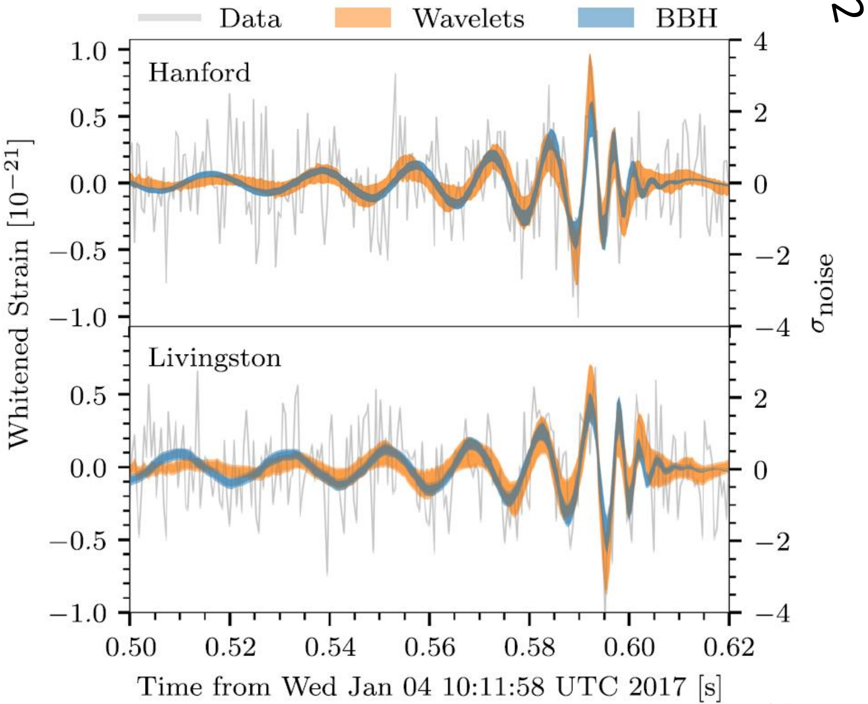
  bank of templates allow **optimal data analysis** methods for detection and parameter estimation in a wide range of parameters, e.g. progenitor masses [0.9, 100s] M_{sun} (17 parameters describe the simpler case of a BH Binary)

- **generic transient searches** look for time-frequency patterns consistent in multiple detectors

  complement the optimal searches providing generality/robustness at the cost of being «less sensitive»



GW150914, PRL **116**, 061102

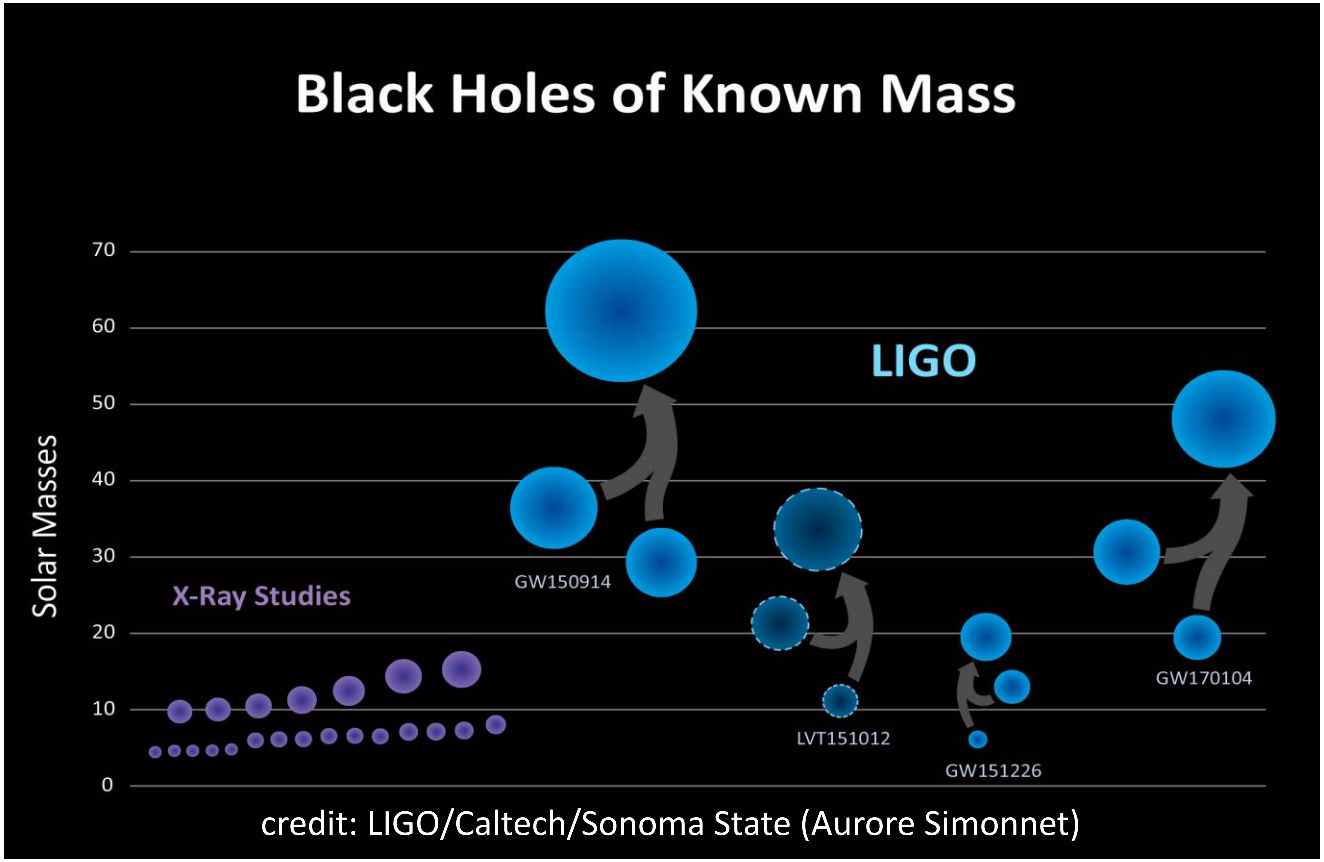


GW170104, PRL 118, 221101 (2017)

Detected Black Hole Coalescences

- **Detection Confidence:**

background reference built by time-shifting the detector data and repeating same analysis. Measured False Alarm Rates of candidates as low as ~1/10^5 yr using ~10 d of observation.

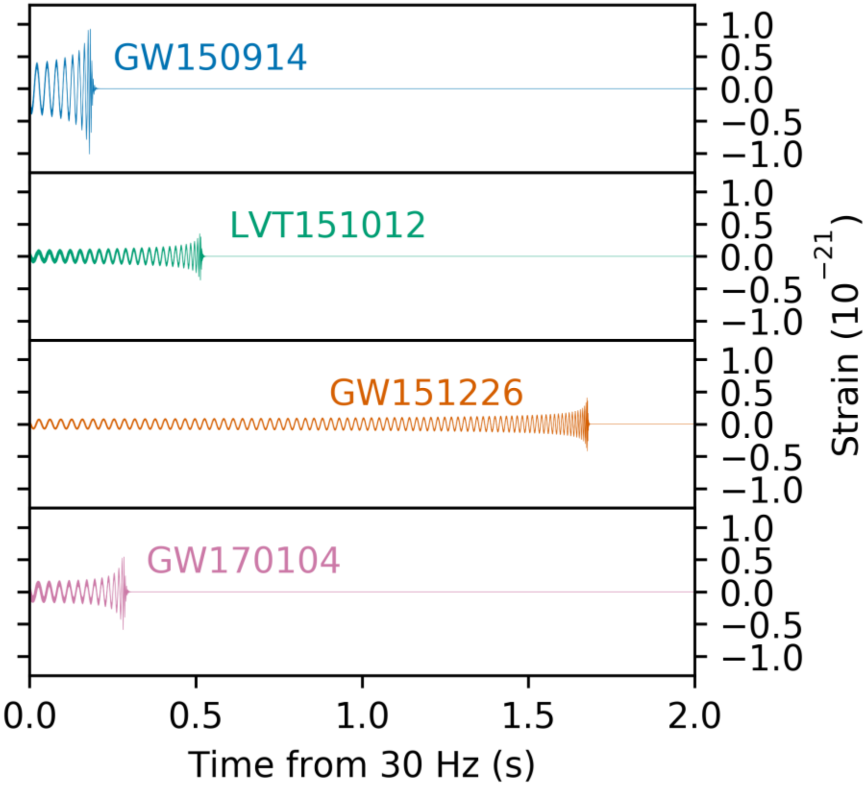


credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)

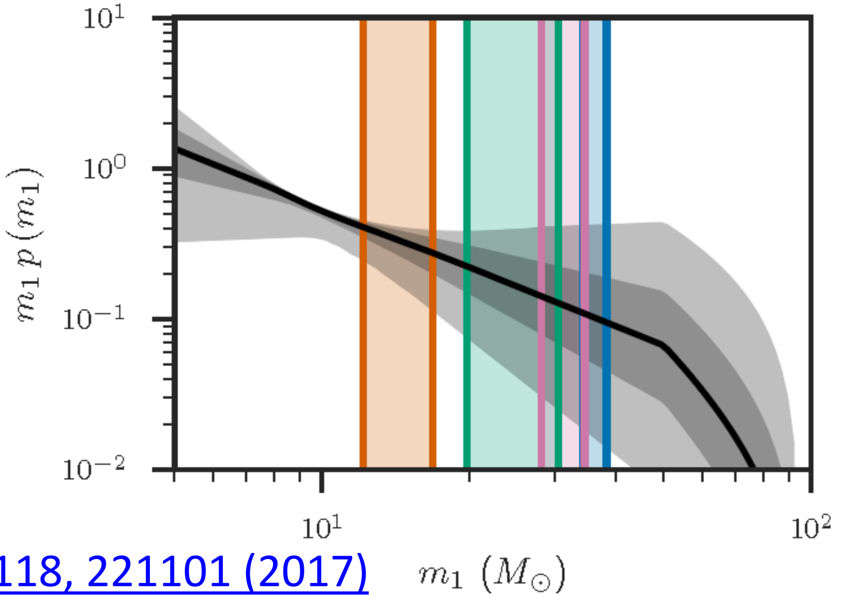
Detected Black Hole Coalescences

- **Selected BH Binary Properties:**

matching templates comparison:

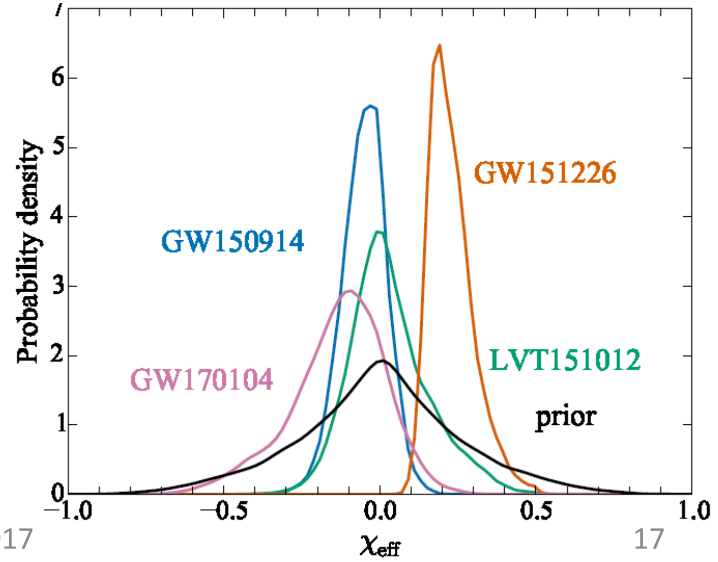


distribution of primary BH component mass



PRL 118, 221101 (2017)

distribution of effective BH spin along orbital angular momentum

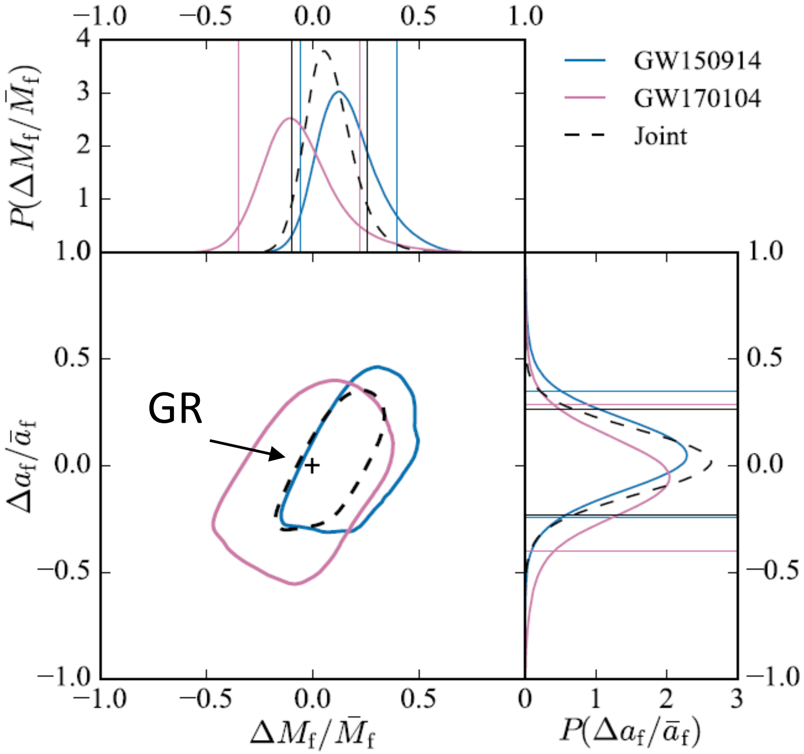


-> BBH formation models

Detected Black Hole Coalescences

- **selected tests of consistency with General Relativity:**

self-consistency test on reconstructed remnant mass and spin from different part of the signal (inspiral and merger-ringdown phases)



upper bound on graviton mass

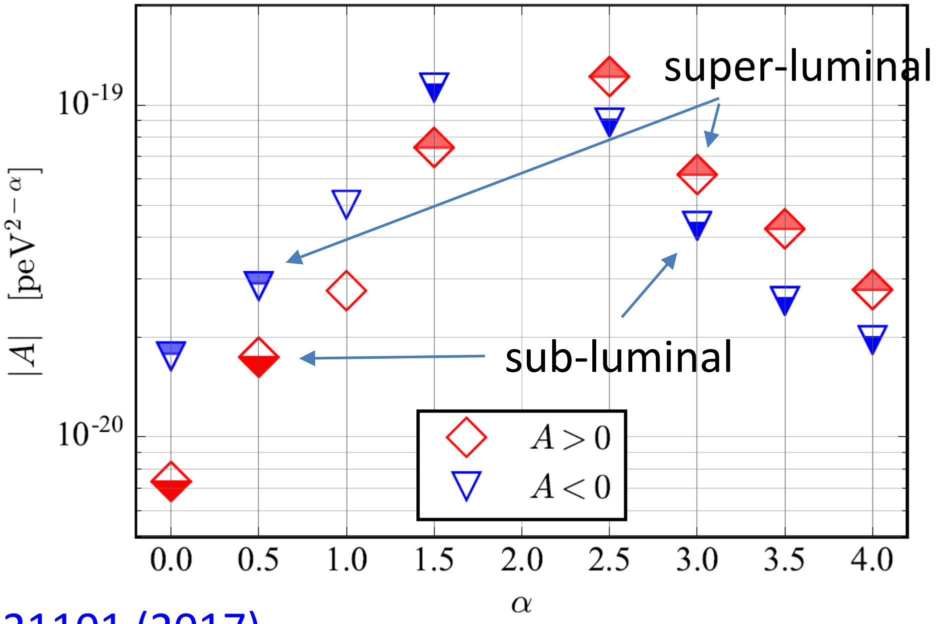
$$m_g \leq 7.7\; 10^{-23} eV \quad , 90\%$$

testing the dispersion relation

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha \quad with\ \alpha \geq 0$$

GR *A*=0, massive graviton (α=0 , *A*>0), …

first local Lorentz invariance test with GWs



PRL 118, 221101 (2017)

Stochastic GW Background Searches

unresolved sources/processes:

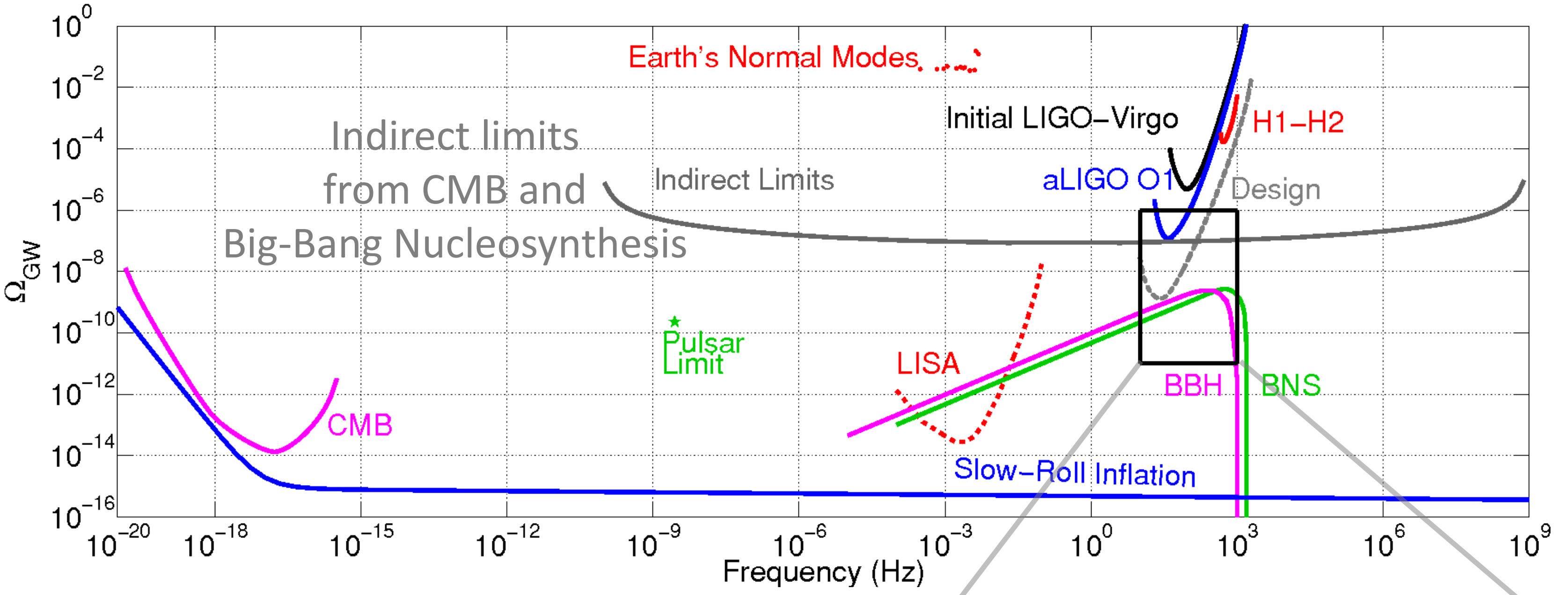
- **cosmological origin:** from the earliest phases of the Universe
  vacuum fluctuations amplified by inflation, phase transitions, cosmic strings, pre-Big Bang models
- **astrophysical origin:**
  Binary BH coalescences (estimated from the observed mergers)
  other compact binary coalescences, Core Collapses to NS and BH, NS

- ✓ **search for isotropic SGWB: main target**
  optimally filtered correlations for the tensor GW polarizations
- ✓ **search for anisotropic SGWB: widest scope «hot spot» search**
  extended sources by spherical harmonic decomposition
  point sources by broadband radiometer
  point sources by narrowband radiometer vs frequency

best
upper
limits
from O1
~30d of
useful
data

- ✓ **search for non-GR polarizations, under development**
  scalar and vector polarizations

Isotropic Stochastic GW Background



$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

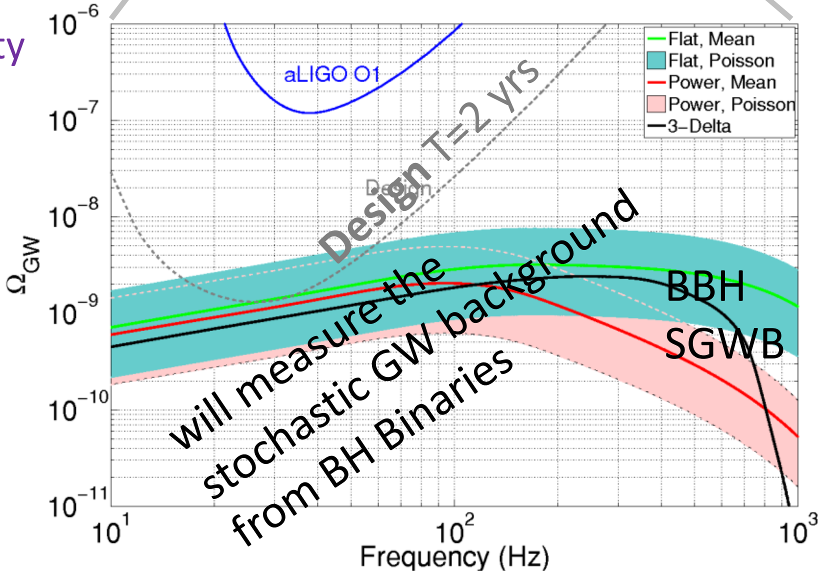
GW energy density per unit ln(f)

critical energy density

$$\rho_c = \frac{3c^2H_0^2}{8\pi G} \;,\; H_0 = 68\,\frac{km}{s\ Mpc}$$

[Phys. Rev. Lett. 118, 121101 (2017)]

direct upper limit (33 times better)



Design T=2 yrs

will measure the stochastic GW background from BH Binaries

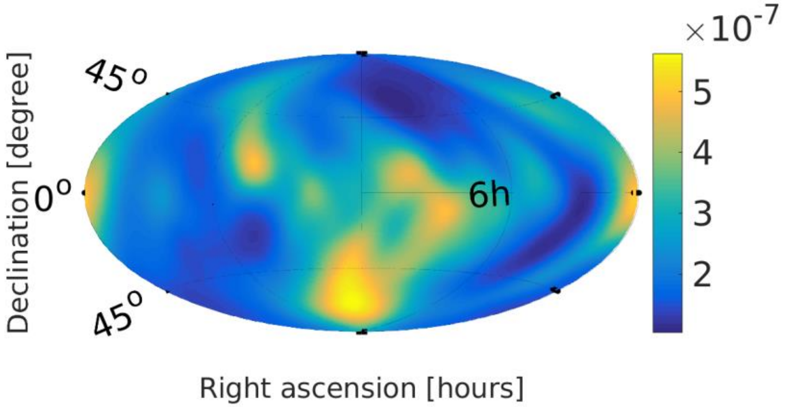
BBH SGWB

Anisotropic Stochastic GW Background

no spots of persistent GW flux in the sky:

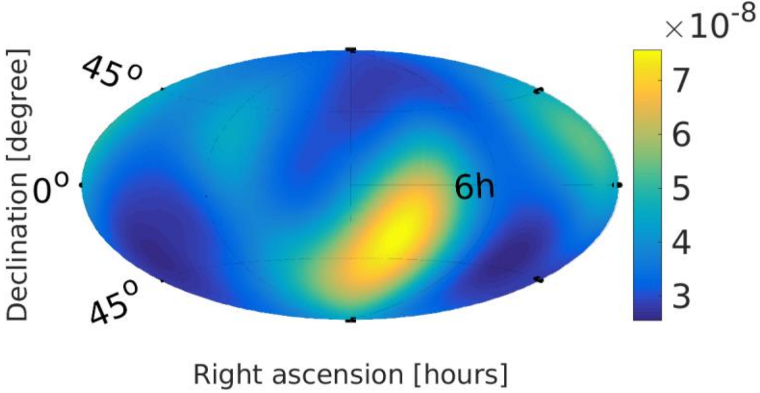
[Phys. Rev. Lett. 118, 121102 (2017)]

new upper limits are ∼10 times better

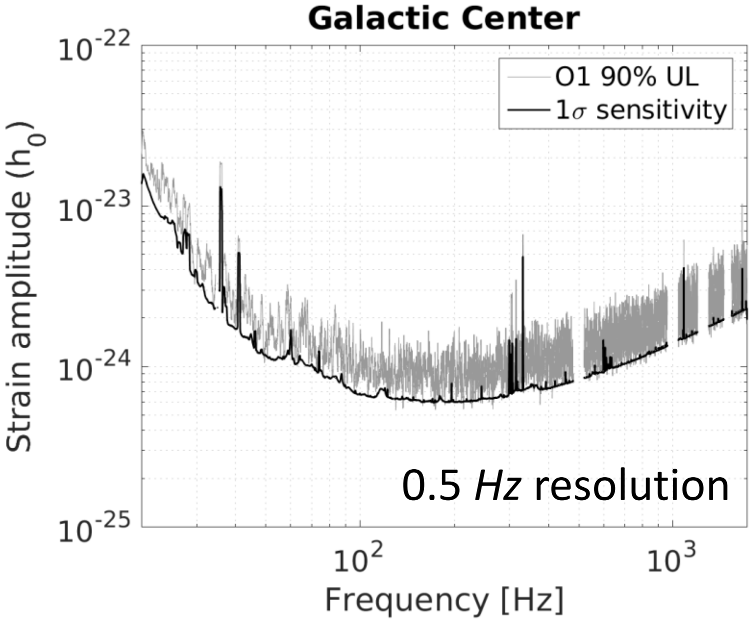


point-like sources emitting broadband GW energy flux [erg cm^{-2} s^{-1} Hz^{-1}] u.l. 90% (frequency flat model)

extended sources upper limit, 90%
Ω_{GW}/sr (frequency flat model)



point-like sources
emitting narrowband
strain amplitude u.l. 90%



0.5 *Hz* resolution

Stochastic GW Background Searches

Future sensitivity:

- scale as the energy PSD of detectors and $\sqrt{T_{observation}}$
- gains in terms of Ω_{GW} by extending PSD at lower frequencies

Future challenges: Schumann resonances

- correlated noise source at distant detectors $\Rightarrow$ bias on the results
- lightening strikes excite the global Schumann resonances at 8, 14, 20, ... Hz, correlated magnetic field variations (pT)
- noise cancellation strategy is possible

Virgo joining the LIGOs

- benefits the directional searches for persistent GWs

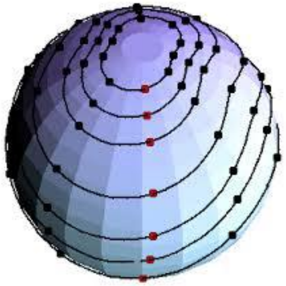
More detectors

- non-GR polarization search: easier to disambiguate the possible contributions from tensor, scalar and vector polarizations
- two detectors are however sufficient in principle to detect presence of non GR effects in persistent GWs

Periodic GW Searches

Search for persistent quasi-periodic GW emission from spinning NS:

- **> 2500 NS are known,** O(10^9) expected in our galaxy
- **GW emission from non-axisymmetry** originating from
  - deformation due to elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2\, f_r$)
  - free precession around rotation axis ($f_{GW} \sim f_r + f_{prec}$; $f_{GW} \sim 2\, f_r + 2\, f_{prec}$)
  - excitation of long-lasting oscillations (e.g. r-modes; $f_{GW} \sim 4/3\, f_r$)
  - deformation due to matter accretion (e.g. LMXB; $f_{GW} \sim 2\, f_r$)



equatorial non-axisymmetry

ellipticity: $\varepsilon = (I_{XX} - I_{YY}) \,/\, I_{ZZ}$

GW strain amplitude on Earth:

$$h_0 = 4\ 10^{-25} \left(\frac{\varepsilon}{10^{-5}}\right) \left(\frac{I_{zz}}{10^{45} g\ cm^2}\right) \left(\frac{f_r}{100\ Hz}\right)^2 \left(\frac{1\ kpc}{d}\right)$$

Maximum ellipticity depends on NS composition:

normal NS: $\varepsilon < 10^{-5}$ → hybrid NS: $\varepsilon < 10^{-3}$ → quark NS: $\varepsilon < 10^{-1}$ *PRD 87, 129903 (2013)*

Periodic GW Searches

- **known PSRs show a spin-down**

  $\dot{f}_r < 0.01 Hz / yr \quad \Rightarrow$ up to very high rotational energy losses
  - magnetic dipole radiation ...
  - possible GW emission ?

- **spin-down limit:**

  assuming all spin-down is by GW emission, one can set upper limits on the GW strain amplitude and on NS ellipticity from EM observations alone

✓ **Targeted Searches for GWs from known PSRs**

ephemeris available for all source parameters
search at EM ephemeris or in narrow bands
optimal analysis is computationally light

✓ **Directed Searches for GWs from NSs**

only sky location is available
optimal analysis requires computer farms

✓ **All-Sky Searches for GWs from yet unknown isolated NSs**

computationally limited (e.g. Einstein@home, GRID)
«semi-coherent» analysis to trigger a few coherent followups

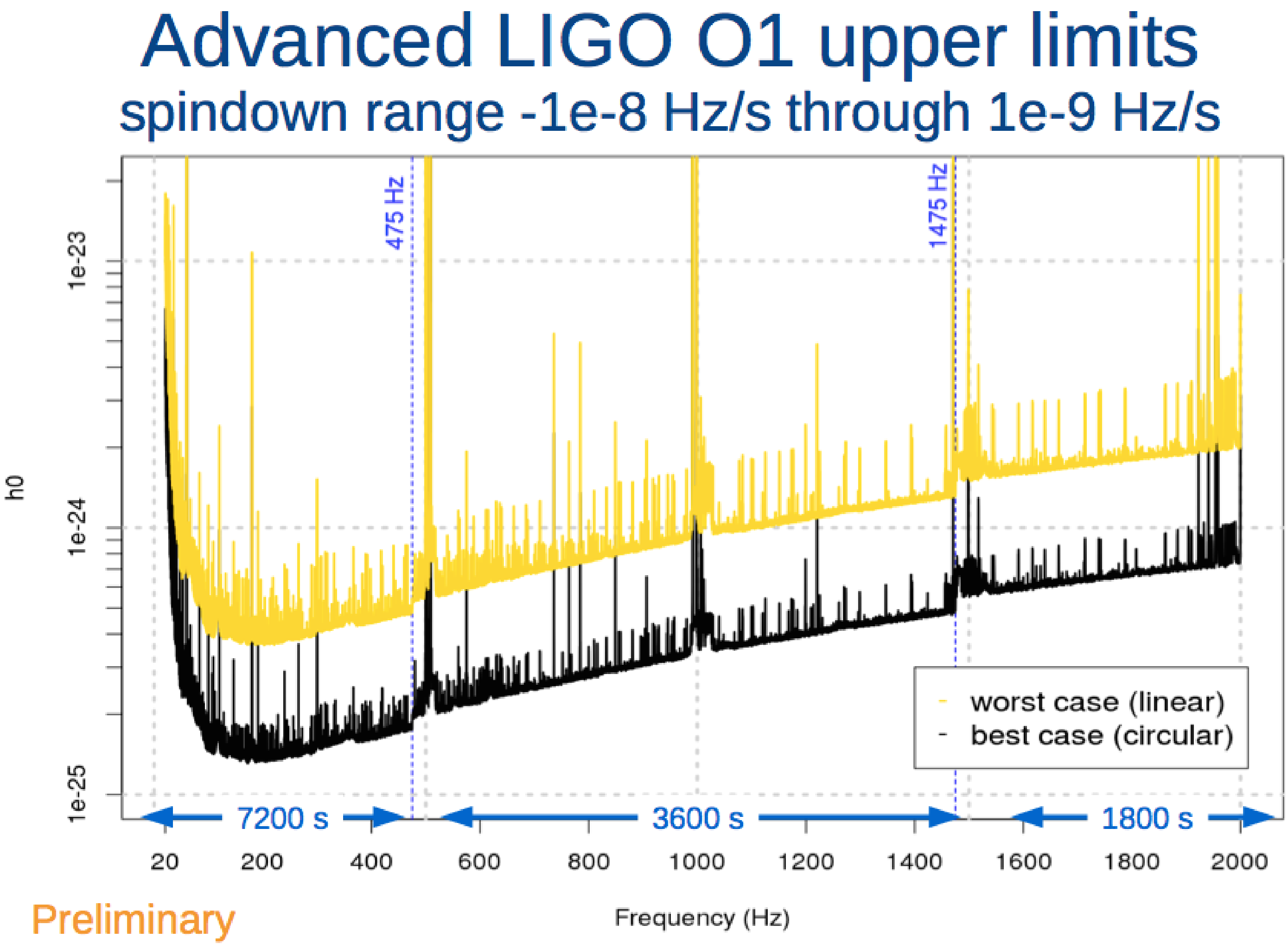
Combination of
single detector
analyses

tot. ~ 135d of
available LIGO
data in O1

All-sky Searches for GWs from unknown isolated NSs

arxiv:1707.02667 for the bandwidth [20,475] Hz, PRD in press

h_0 upper limit 95%



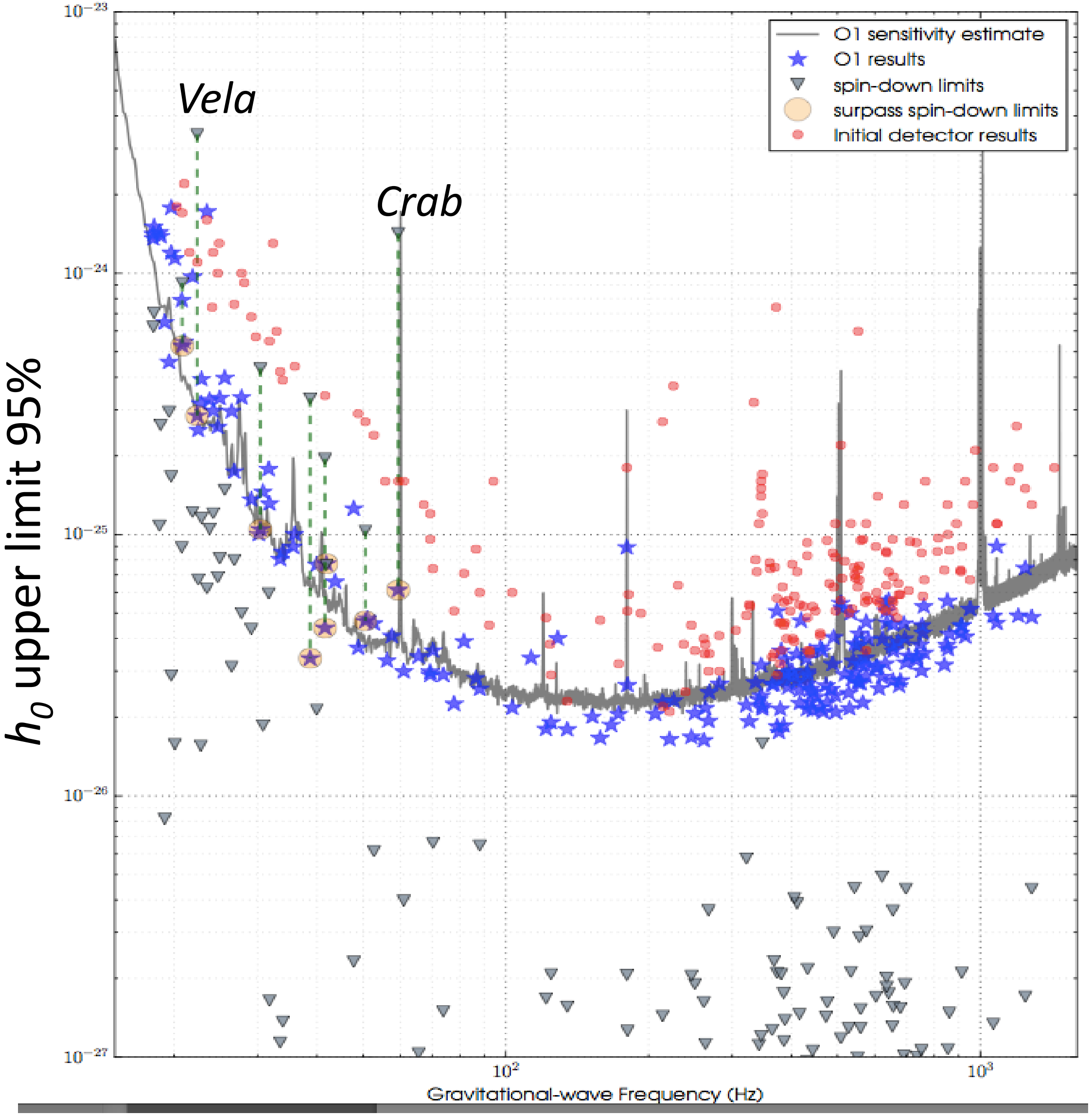
linearly polarized

circularly polarized

Preliminary

see also arxiv:1707.02669

Targeted GW Searches from known PSRs



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

- ✓ **200 known PSRs (119 in binary systems)**
- ✓ **8 spin-down limits beaten**

  Crab h_0 u.l. 20 times lower

  Vela h_0 u.l. 10 times lower

- ✓ ***h_0* upper limits improved by factor 2.5 wrt initial detectors**

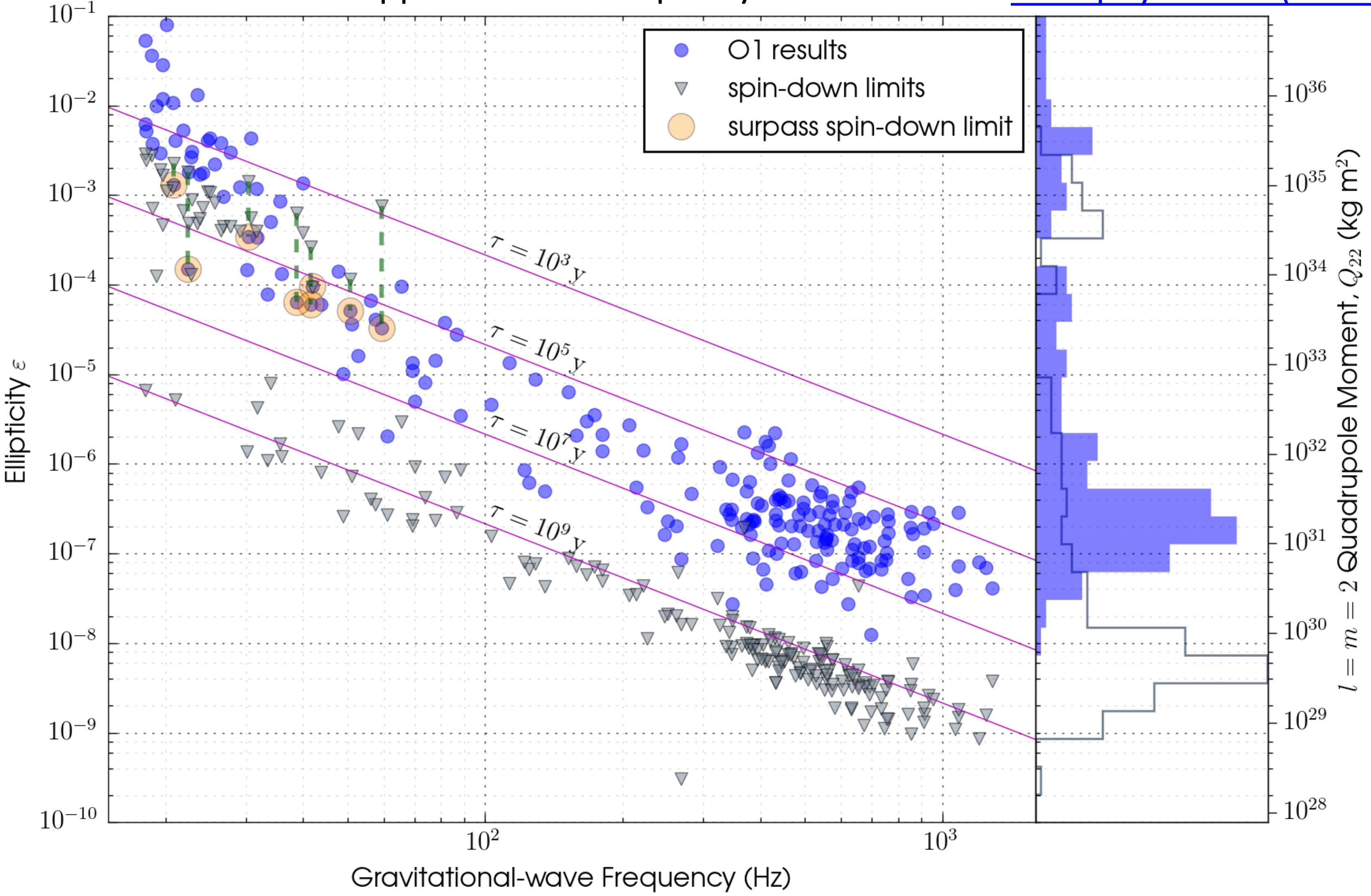
  sensitivity improvement

  T_{obs} 78d H1 plus 66d L1

Targeted GW Searches from known PSRs

Upper limits on ellipticity

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



Directed searches for accreting NS in binaries

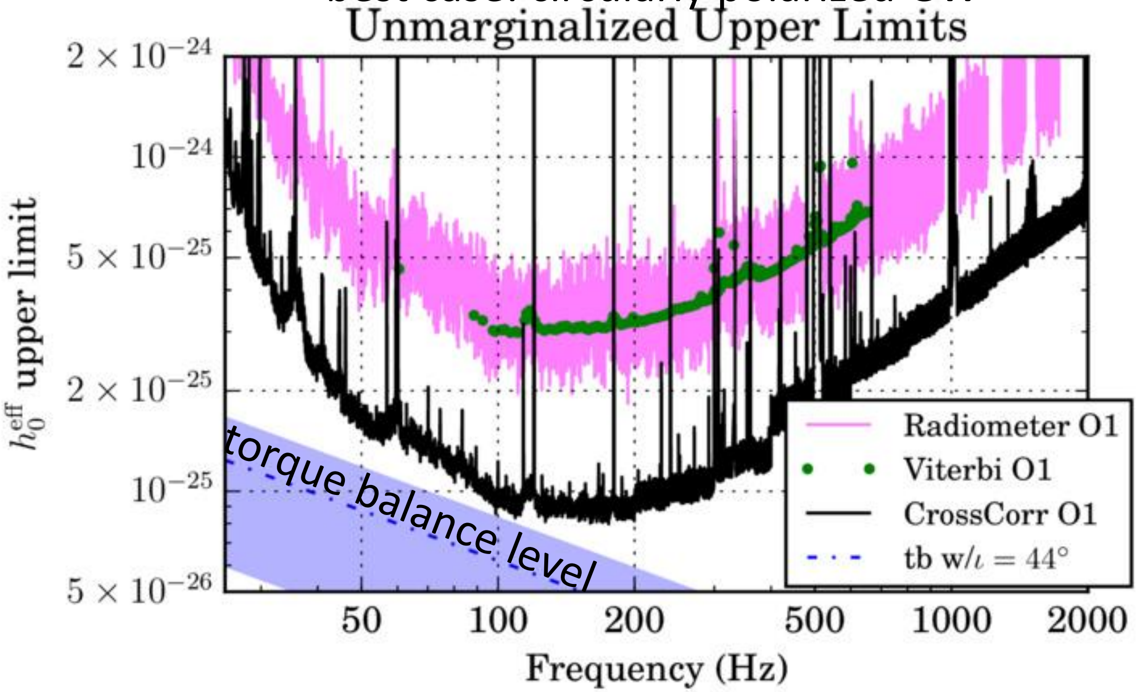
- **accretion from a companion may cause ellipticity in the spinning NS**
  need to track **wandering of the NS spin frequency**
- **Low Mass X-ray Binaries**
  - show X pulsations ⇒ hint for asymmetry
  - LMXB NSs do not spin up at very high frequencies: accretion torques balanced by GW emission torque ? [ApJ 501, L89 (1998)]
  - Best candidate:

Scorpius X-1
(brightest LMXB)
with known binary
orbital parameters

latest results arxiv:1706.03119
comparable upper limits to all-sky isolated NS analyses,

Phys. Rev. D 95, 122003 (2017)

~ Radiometer stochastic limit



best case: circularly polarized GW

torque balance level

Searches for Generic GW Transients

➢ **Transient GW astronomy using minimal assumptions:**

Sources include core-collapse supernovae, the merger phase of binary compact objects, NS instabilities, accretion disk instabilities, fallback accretion, cosmic string cusps/kinks, and the unexpected!

Whenever waveform morphologies are too uncertain to build a template bank.

✓ **Search for generic transients**
- a coherent excess power search in different detectors
- the waveform is reconstructed without imposing a priori time-frequency and phase evolution
- more information can be included, e.g. time window, sky region

✓ **robustness:**
- potential for discovering new sources of gravitational waves
- complement and extend searches for well modeled signals (e.g. compact binary coalescences)

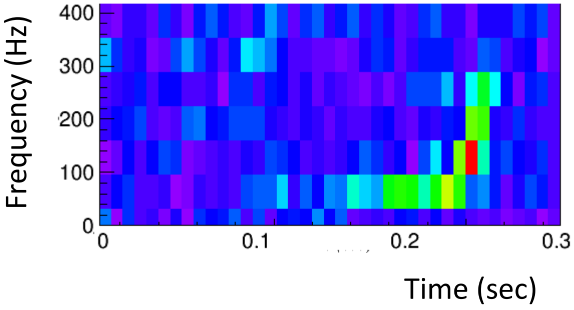
✓ **more challenging discrimination of false alarms** wrt well modeled signal case
- coherence tests on candidates
- classification of outcomes informed by morphology of false alarm outliers

generic transient search algorithm

Phys.Rev. D93, 042004 (2016) - arXiv: 1511.05999

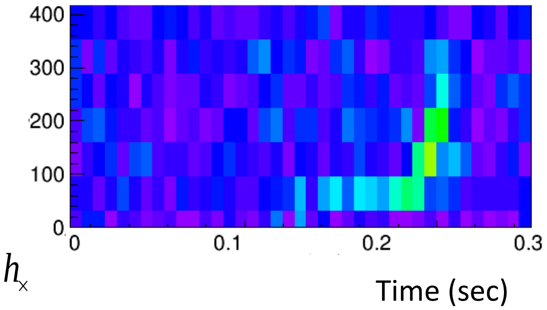
Credits to G. Vedovato

H1 Multiresolution time-frequency transforms



Select pixels above threshold

L1 Multiresolution time-frequency transforms

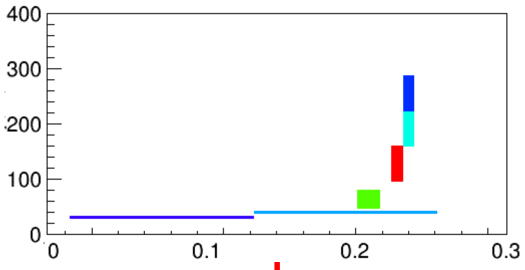


For each sky location ***maximum likelihood*** *Is used to extract the signal from noise*

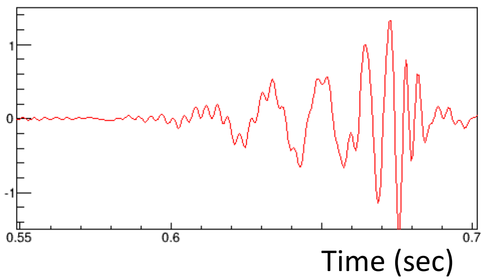
Time delay

$h_{ifo} = F_{+}^{ifo} h_{+} + F_{x}^{ifo} h_{\times}$

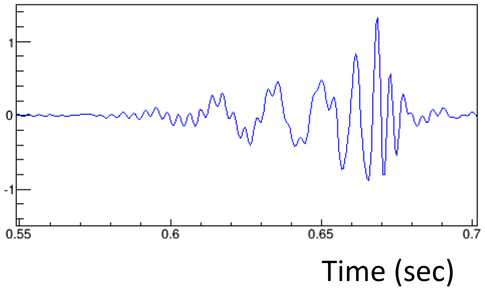
H1 & L1 Synthesis



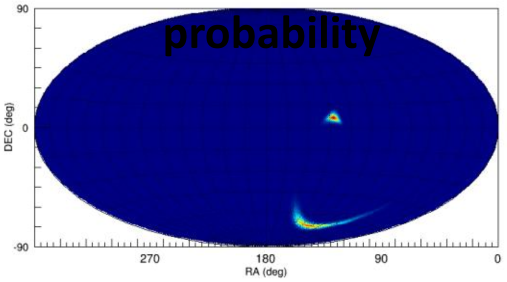
Reconstructed Signal H1



Reconstructed Signal L1



sky localization map probability



waveform parameters

detections statistic

$\eta_c = SNR \cdot Coherence$

The sky location with highest probability is used to reconstruct signal & its detection statistic

All-Sky Search for Generic GW Transients

Most general search for transients:

- in the detector bandwidth 40 *Hz* – 4 *kHz*
- with signal durations from O(1 ms) to O(100 s)

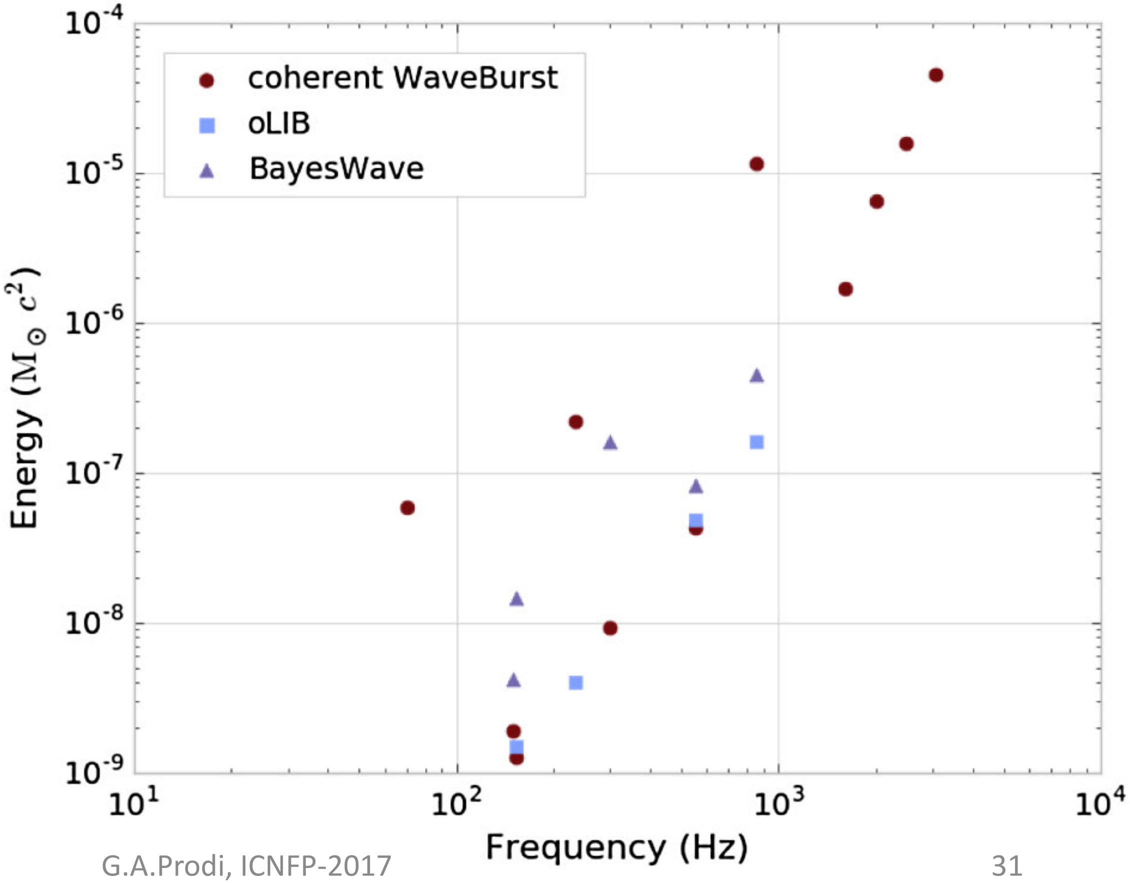
➢ **also in low latency mode for alerting Electromagnetic Followups**
provided alert to the collaboration for the unexpected GW150914

Phys. Rev. D 95, 042003 (2017)
short duration transients
results (few s)
~48 d useful data from O1

detectable GW energy E_{GW}
radiated from $d = 10\ kpc$
at False Alarm Rate < 1/century

$E_{GW} \propto d^2$

Different waveform morphologies



All-Sky Search for Generic GW Transients

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Phys. Rev. D 95, 042003 (2017)

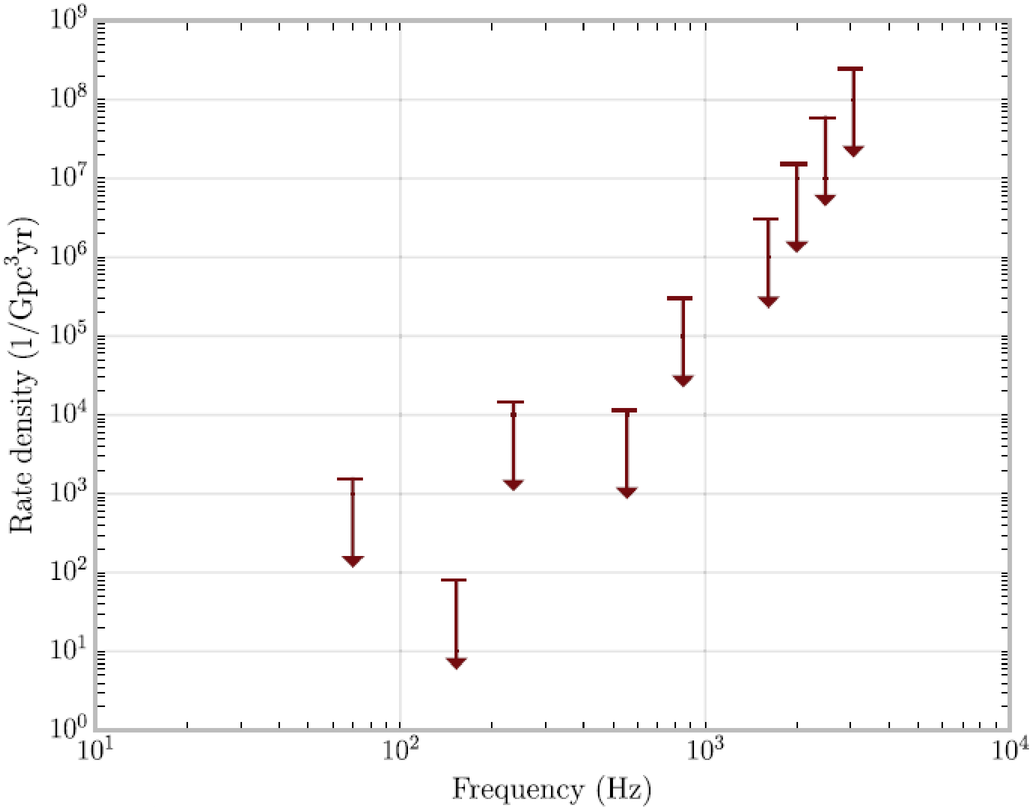
short duration transients results (few s)

~48 d useful data from O1

upper limits on rate density for $E_{GW} = 1\ M_{sun}$ at False Alarm Rate < 1/century

Rate density $\propto E_{GW}^{-3/2}$

Different waveform morphologies



All-Sky Search for Intermediate Mass BH Binaries

- **Intermediate Mass BH:** 100-10^5 M_{sun}
  missing link to Super Massive BH: a discovery would be ground-breaking

✓ **Joint analysis on O1 data**

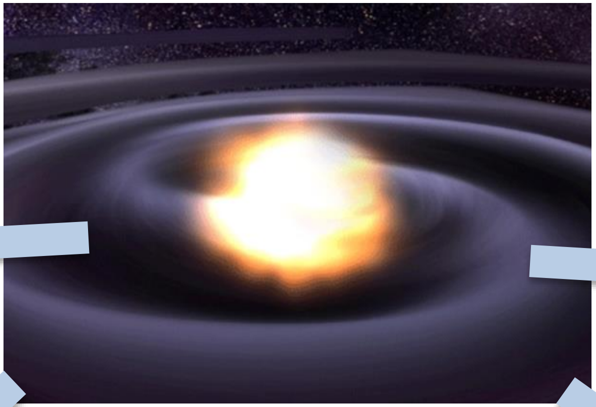
optimal matched filtering:
- single detectors filtered separately plus coincidence search
- coverage of total mass up to 600 M_{sun} , mass ratio up to 1:10 , spin
- no precession and no higher order modes

generic transient
- waveform agnostic in 16-500 Hz , coherent analysis of the network
- complements sensitivity in case e.g. of higher order modes and higher masses

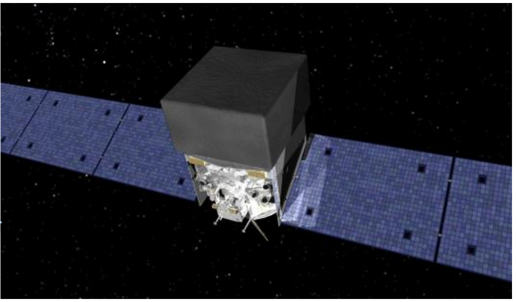
Phys. Rev. D 96, 022001 (2017)
O1 improved range by ~ 6 times, sensitive distance 0.5-1.6 *Gpc*
no detections of IMBHB mergers
new rate upper limits improved by a factor almost 100:
best u.l. ~ 0.3 per Globular Cluster per Gyr

Multimessenger Astronomy

Coalescent Binary Systems



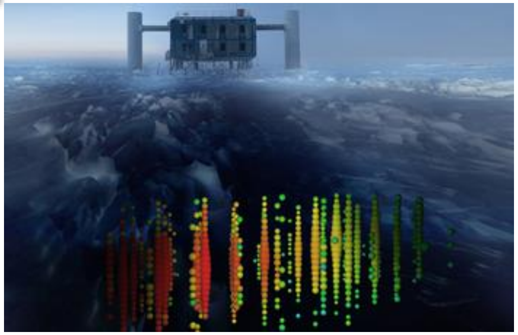
Gravitational Waves



Gamma and X Rays

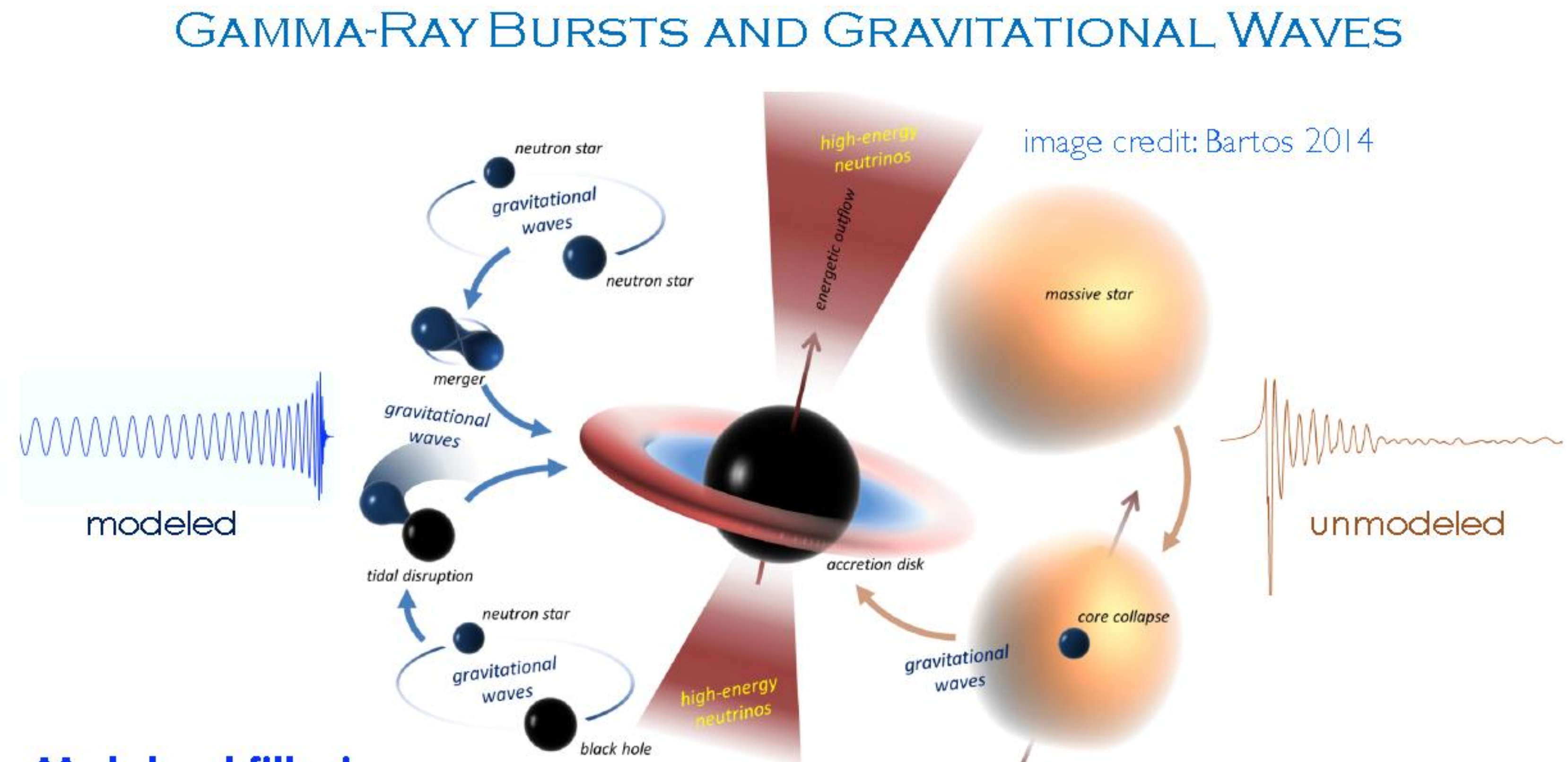
Visible and Infrared Light

Radio Waves



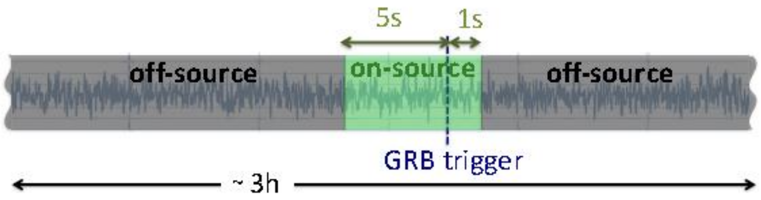
Neutrino Detectors

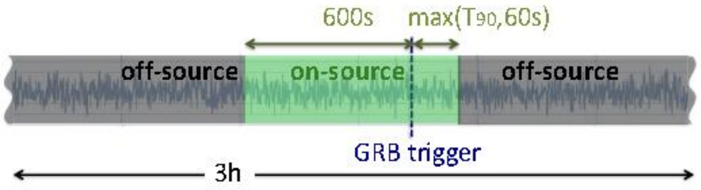
Searches for GWs on a GRB trigger



Matched filtering
(short GRBs)

Generic burst
time-frequency mapping
(all GRBs)



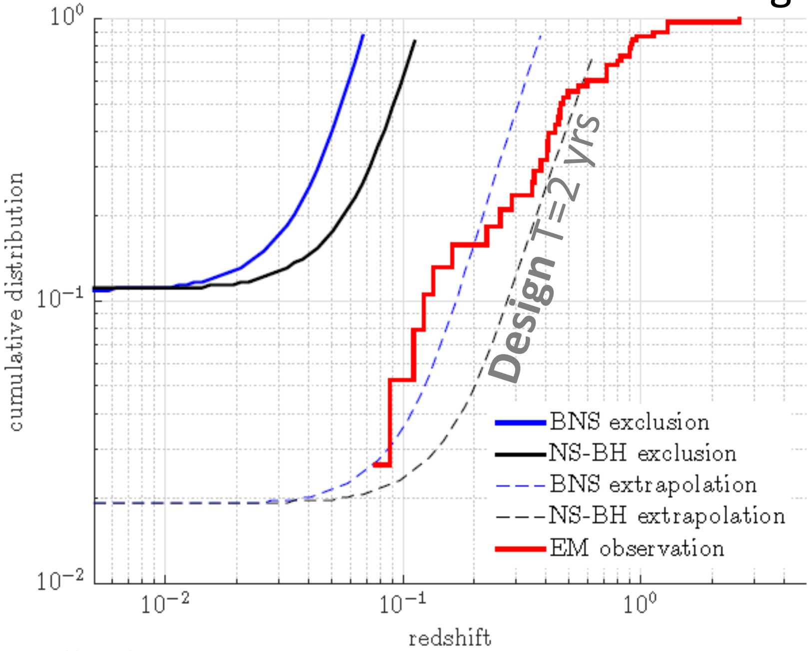


Searches for GWs on a GRB trigger

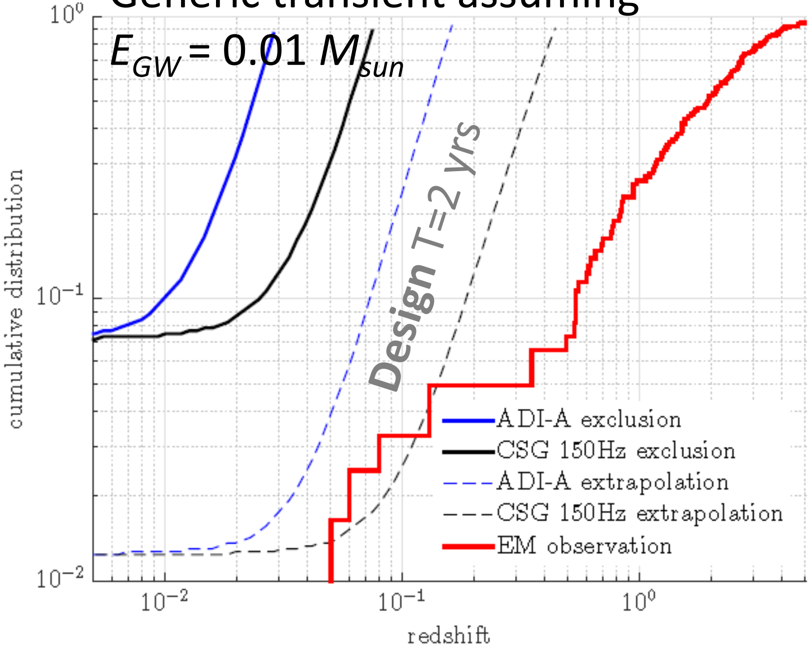
- **Short-hard GRBs:** **optimal matched filtering**
  - Binary NS coalescences plus NS-BH coalescences consistent with remnant disk (1-25 M_{sun} companion)
  - onsource window: -5*s*, +1*s*
- **both Short-hard and Long-soft GRBs:** **generic transient**
  - waveform agnostic in 16-500 Hz
  - onsource window: -600*s*, +max{60*s*, T_{90}}

Astrophys.J. 841 (2017) no.2, 89
41 GRBs analyzed in O1
(19 short-hard)
no GW detections

Short-hard GRBs: matched filtering



median exclusion distance 90-150 Mpc

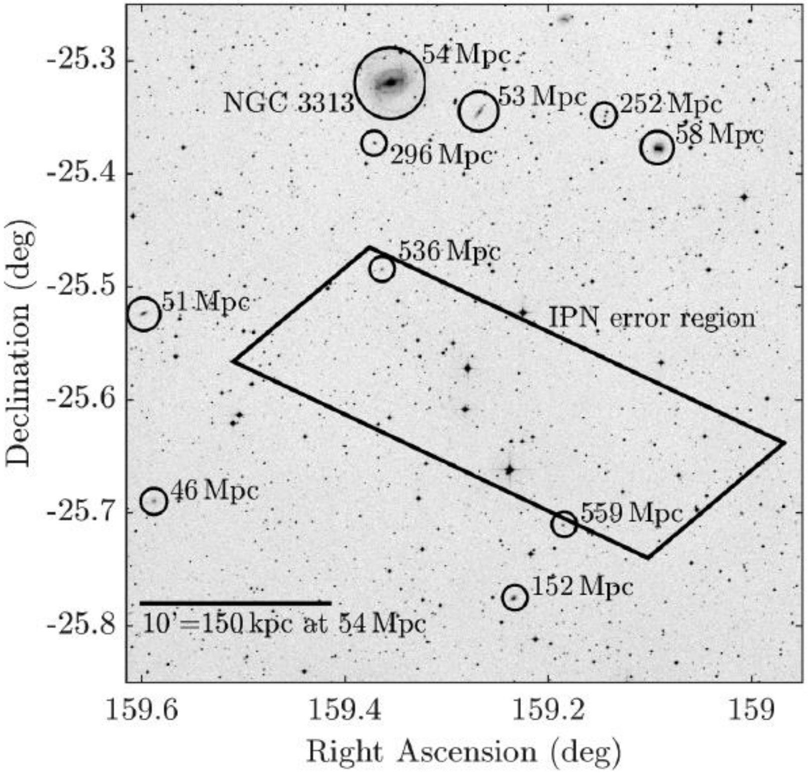

Generic transient assuming $E_{GW} = 0.01\ M_{sun}$

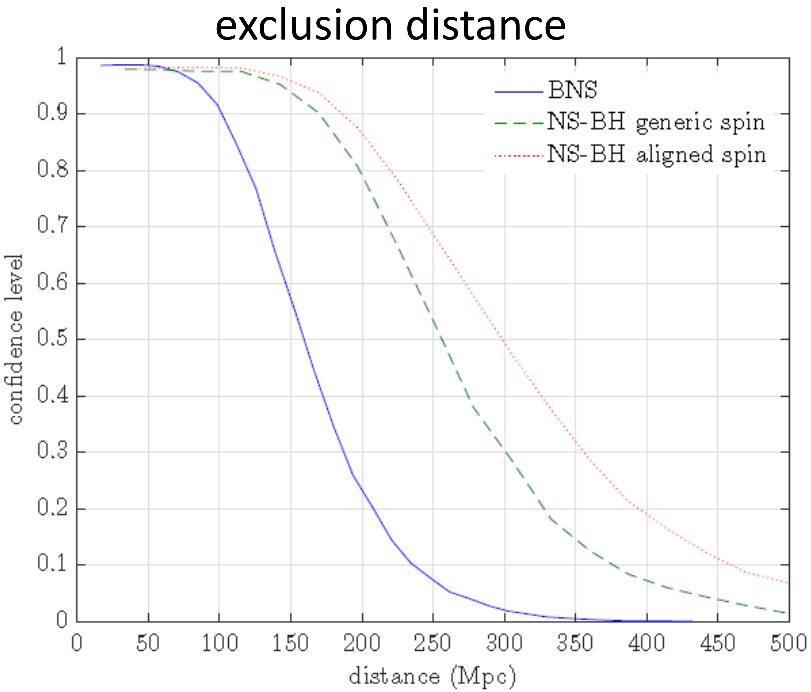
Searches for GWs on GRB 150906B

- **Short-hard GRB: optimal matched filtering**
- **only Hanford was operating**
- **direction** close to local galaxy NGC 3313, **distance = 54 Mpc**

Astrophys.J. 841 (2017) no.2, 89

no detection: exclude BNS progenitor in NGC 3313 or closer than< 100Mpc





High Energy Neutrino followup of GW detections

- ✓ **GW150914**

  three neutrinos were detected by **IceCube** within a ±500s window, no detections by **ANTARES**. Consistent with background.

  No directional coincidence.

  [Phys. Rev. D 93, 122010 (2016)]

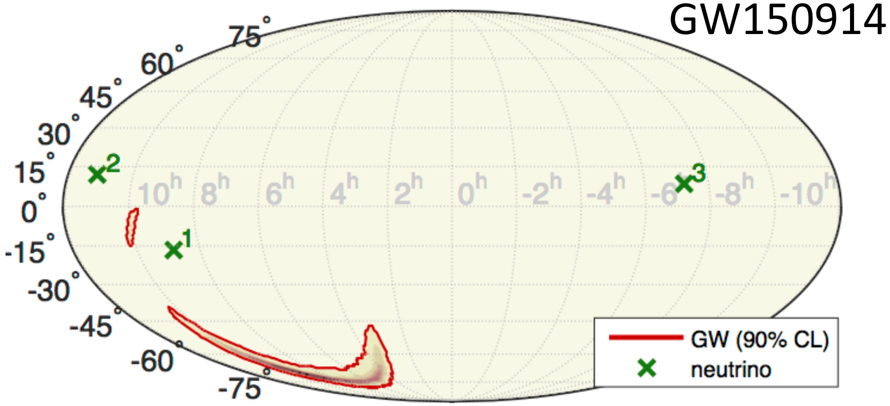
- ✓ **GW151226 and LVT151012**

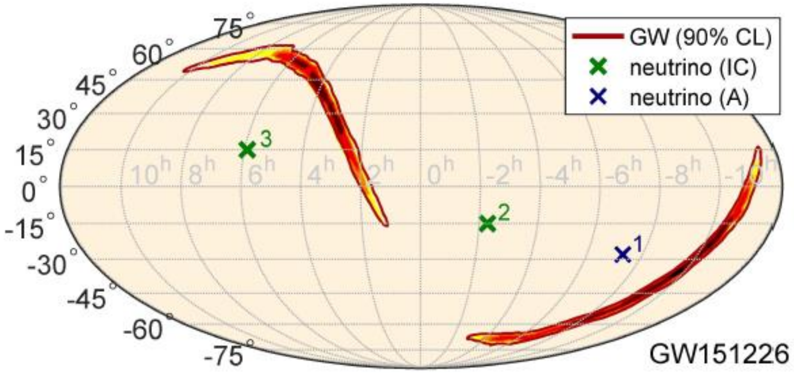
  2 and 4 neutrinos [1 and 0] detected by **IceCube** [**ANTARES**] within a ±500s window. Consistent with background

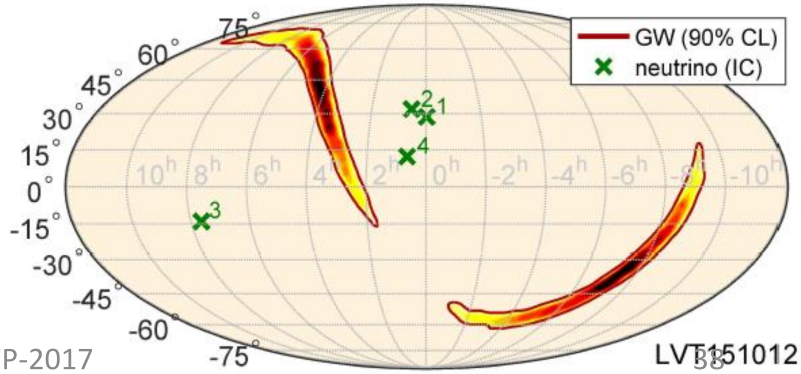
  No directional coincidence.

  [Phys. Rev. D 96, 022005 (2017)]

  limit to isotropic-equivalent high-energy neutrino emission from GW151226 < 10^{51} -10^{54}erg

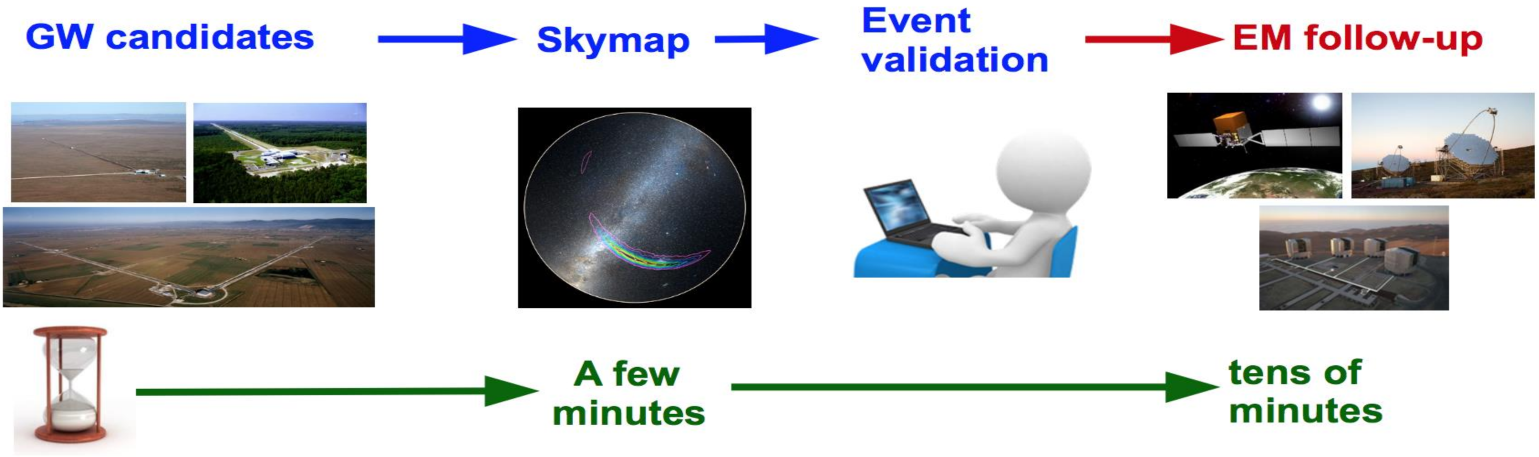






multimessenger followup of GW detections

prompt
alerts on
transient GW
detections



GW candidates → **Skymap** → **Event validation** → **EM follow-up**

A few minutes → **tens of minutes**

prompt alerting from GWs enables to hunt for EM transient counterparts

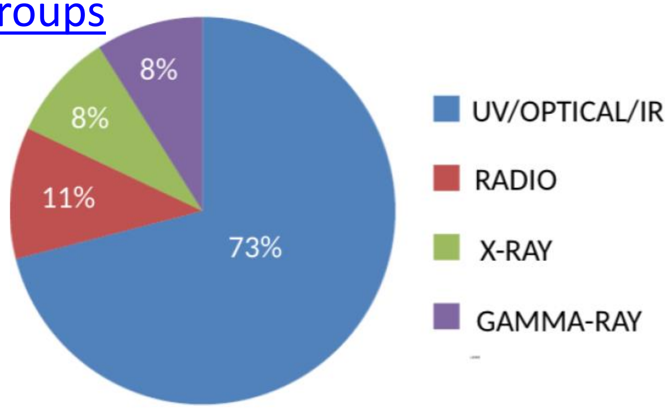
complementary insight into the physics of the sources and their environment

mass, spins, quadrupolar deformability
orbital parameters
luminosity distance
process asymmetry
GW polarizations
…

local environment, host galaxy
precise localization
Redshift,
Hubble constant measurement
process beaming
nuclear astrophysics
…

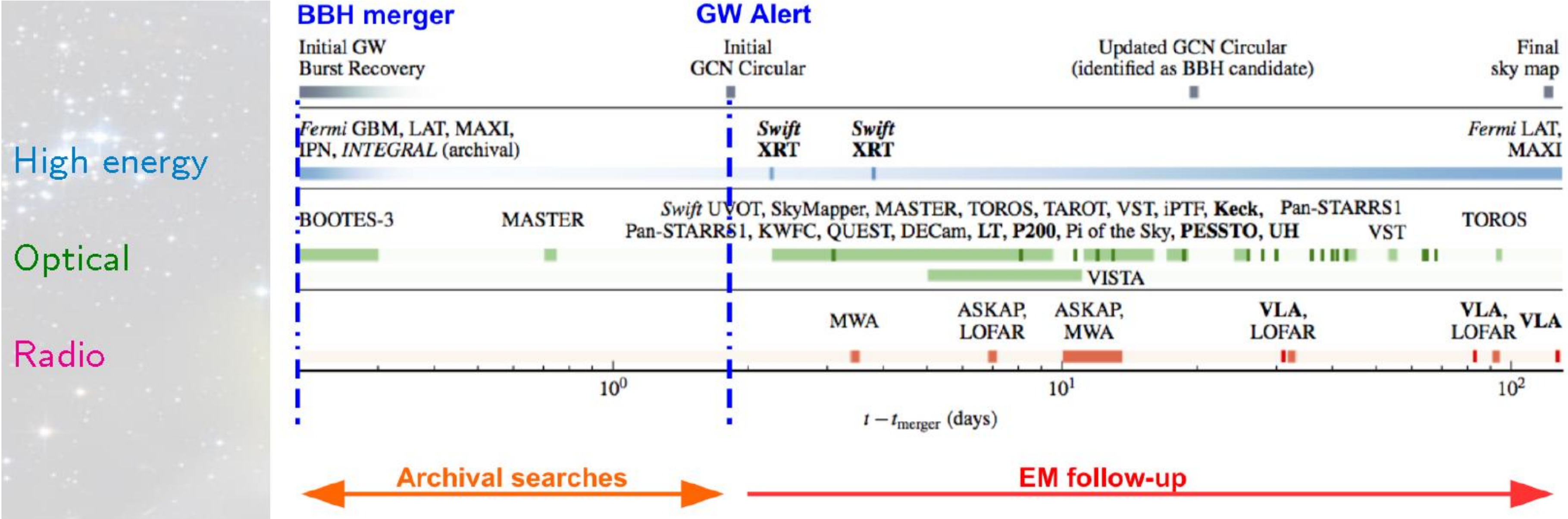
LIGO-Virgo GW – EM Followup Program

https://gw-astronomy.org/wiki/LV_EM/PublicParticipatingGroups



>90 formal agreements (MoU)
involving >170 instruments covering full EM spectrum from radio to hard Gamma rays, high energy neutrinos

multimessenger observations triggered by GW150914 Astrophys.J. 826 (2016) no.1, L13

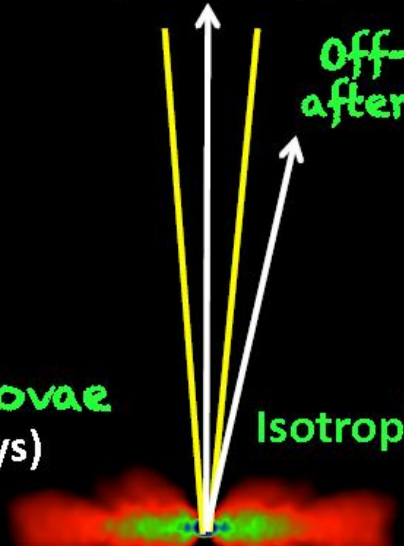


EM emissions

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)

→ Afterglows X-ray, optical, radio
(minutes, hours, days, months)



Off-axis afterglow

Kilonovae
(days)

Isotropic emission

X-ray (min, hrs)

Radio remnants
(months, years)

Core-collapse


Palomar

SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Radio
(years)

+ Long GRB

Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

Radio/gamma-ray Pulsar glitches

Credits to M.Branchesi

Remarks

- ***the fun just started:*** expecting to build a catalog of Binary Black Hole mergers and looking forward to discover new source classes (e.g. Neutron Stars, etc.). Is impacting on fundamental physics and astrophysics.
- multimessenger astronomy with GWs is expected to provide results in the short term thanks to the addition of Virgo detector
- earth-based detectors can improve performances by large factors in one-two decades:
    - 3 x gain in amplitude sensitivity is planned in 4-6 years
    - 2 to 4 x further gain possible with current infrastructures
    - more is possible with new underground infrastructures
- Space based detectors are now safer: after the recent success of the ESA technology demonstrator mission, LISA should fly in the 2030's

Thank you for your attention

detector layout

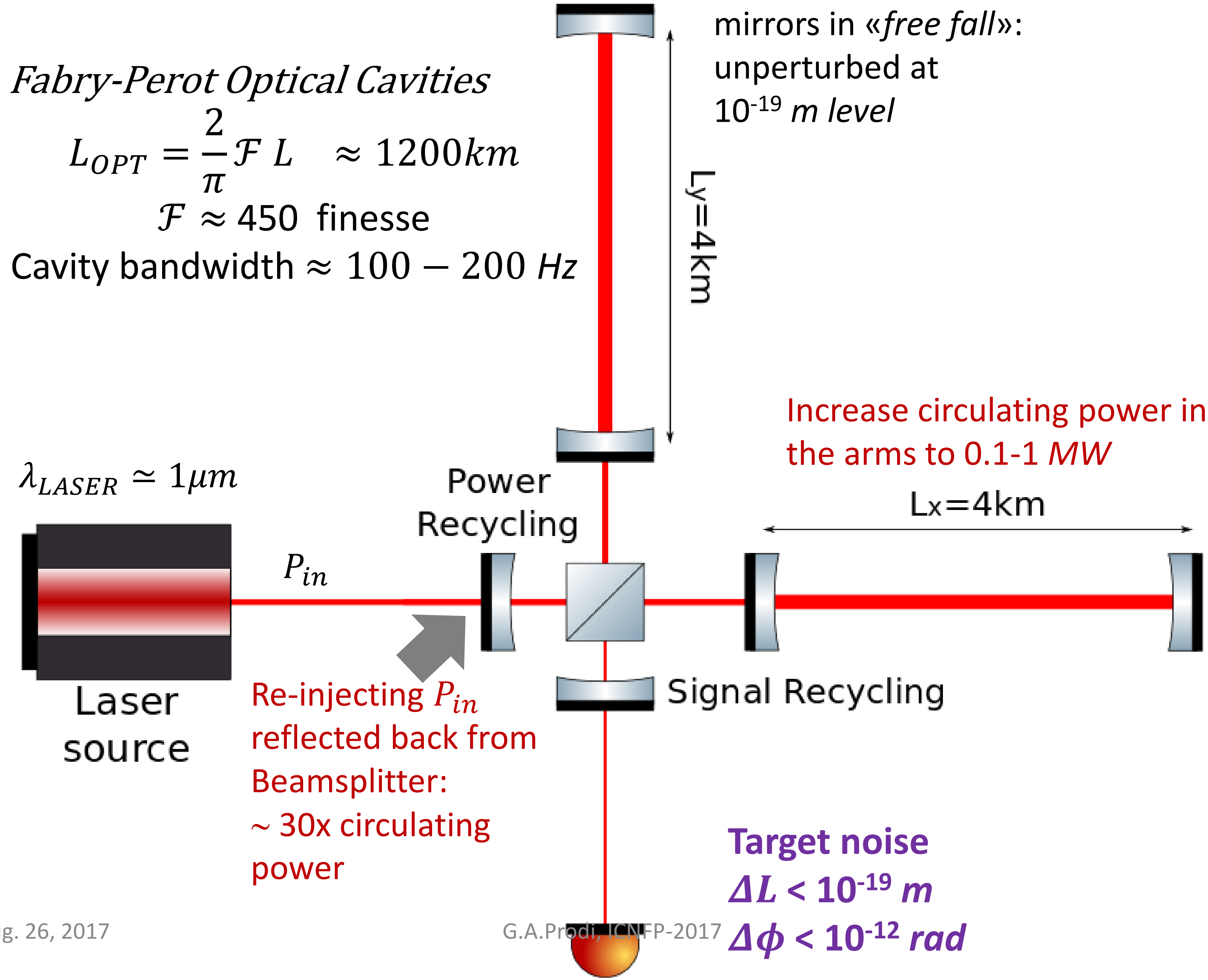
Fabry-Perot Optical Cavities

$$L_{OPT} = \frac{2}{\pi} \mathcal{F}\, L \quad \approx 1200 km$$

$$\mathcal{F} \approx 450 \ \text{finesse}$$

Cavity bandwidth $\approx 100 - 200\ Hz$

mirrors in «*free fall*»:
unperturbed at
10^{-19} *m level*



$\lambda_{LASER} \simeq 1 \mu m$

Increase circulating power in the arms to 0.1-1 *MW*

Re-injecting P_{in} reflected back from Beamsplitter: ~ 30x circulating power

Target noise
ΔL* < 10^{-19} *m
Δϕ* < 10^{-12} *rad

detector layout

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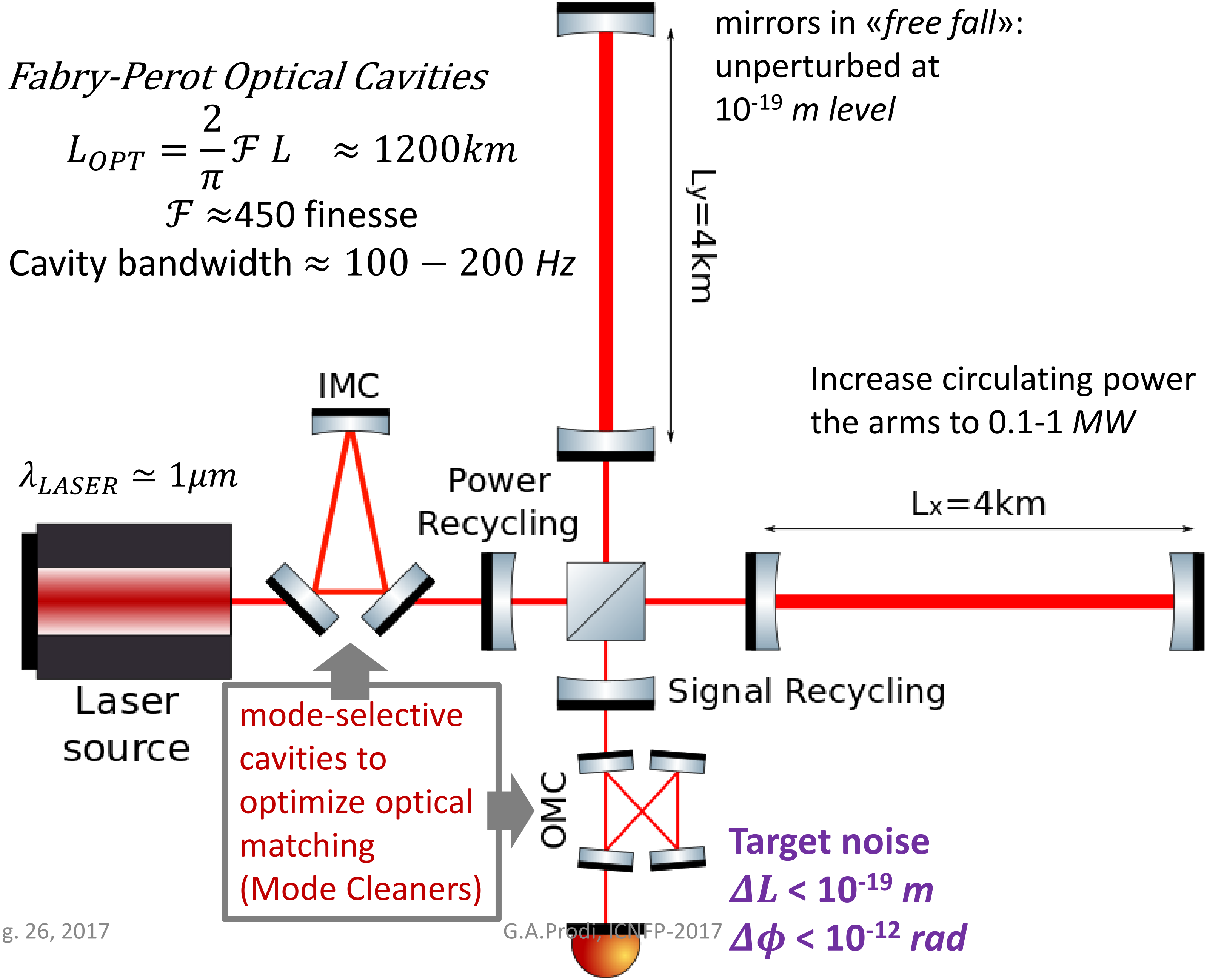


Increase circulating power in the arms to 0.1-1 *MW*

$\lambda_{LASER} \simeq 1\mu m$

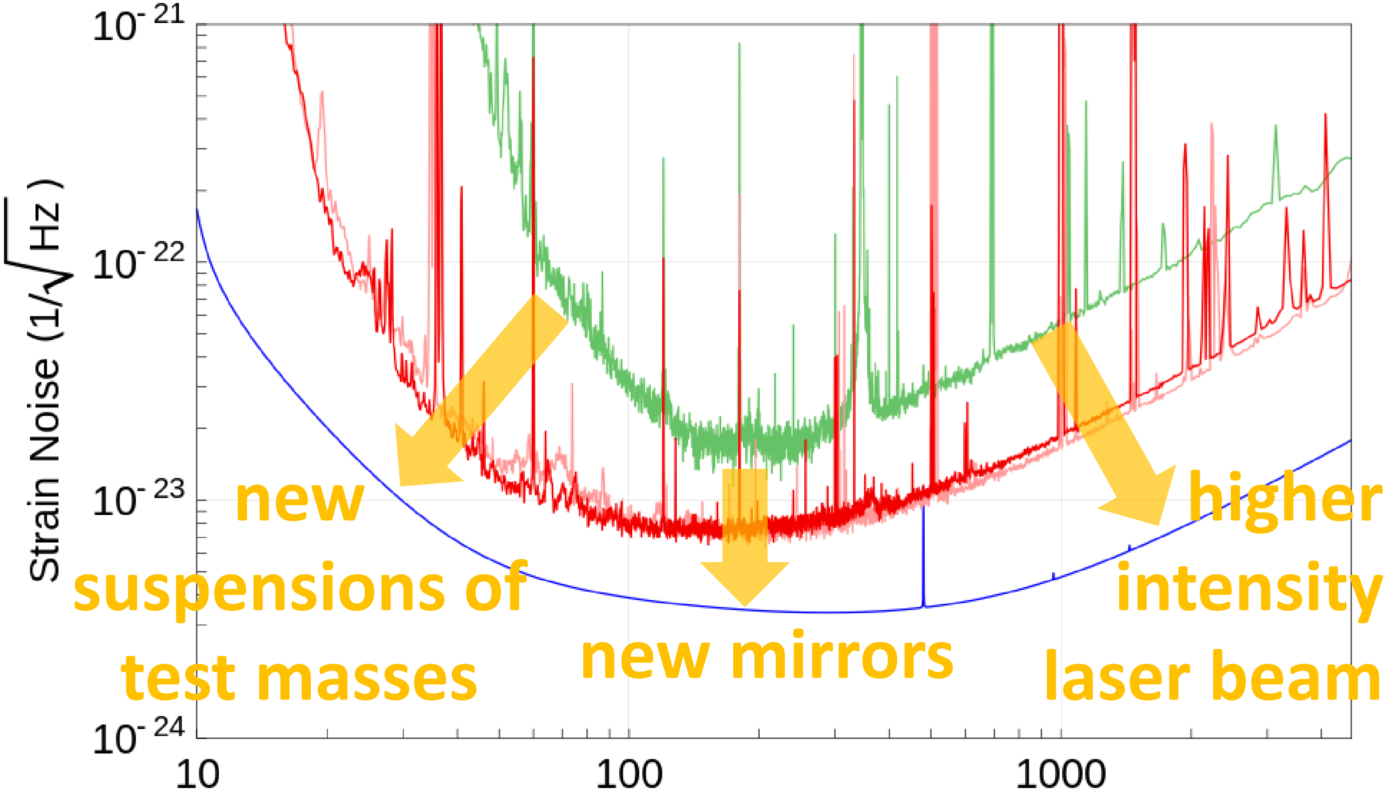
mode-selective cavities to optimize optical matching (Mode Cleaners)

Target noise

$\Delta L < 10^{-19}\ m$

$\Delta\phi < 10^{-12}\ rad$

spectral sensitivity enhancement



Frequency (Hz)

--LIGO S6 run (2010)

--Advanced LIGO O1 run (2015)

--Advanced LIGO design goal

-- $10^{-20} m/\sqrt{Hz}$ displacement noise (single arm)

Higher Mass Binary
BH Coalescences
(Intermediate Mass)

Earlier detections of
coalescences

BBH mergers
BH ring-down

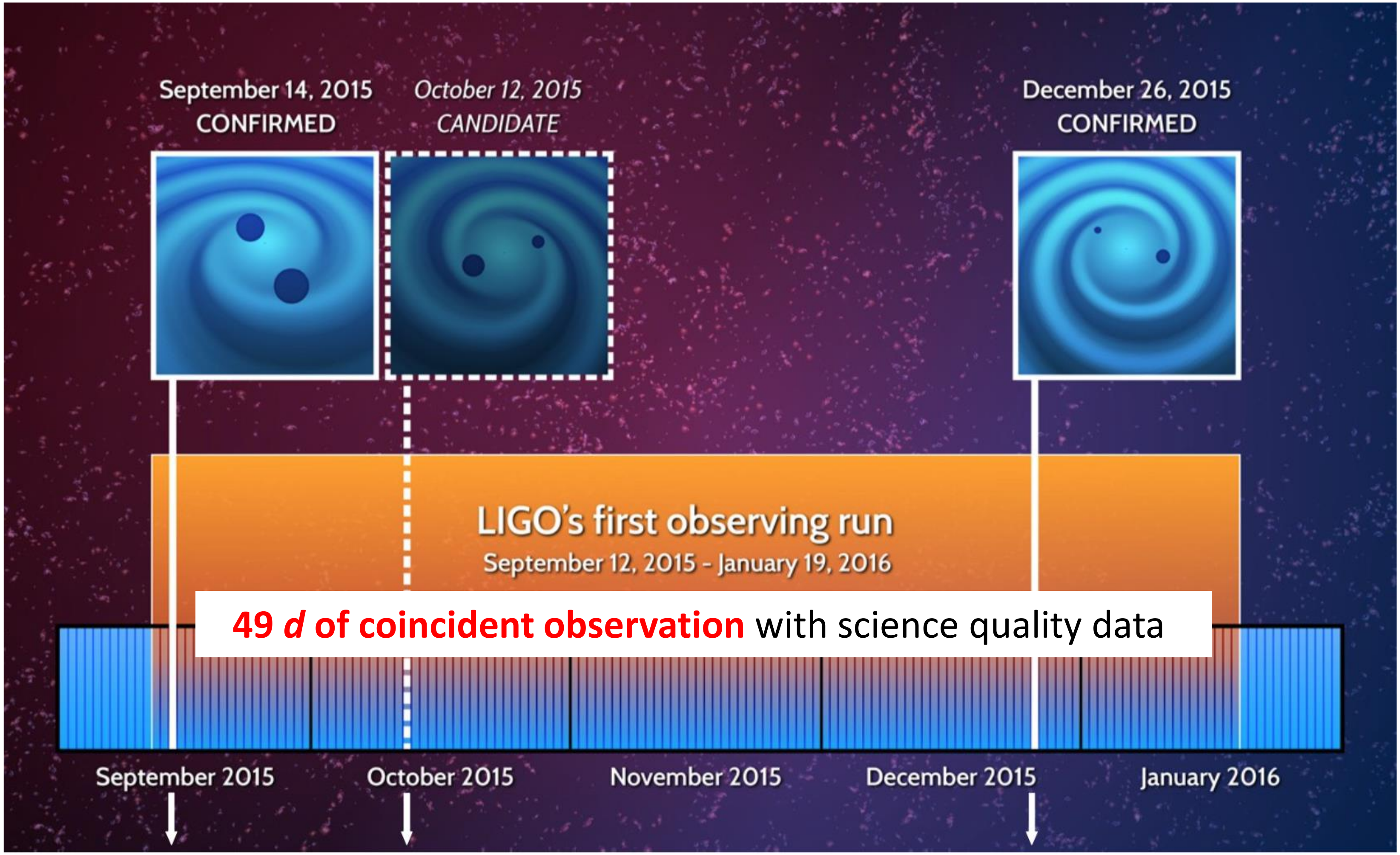
NS transients

and yet UNKNOWN SOURCES

Stochastic background
NS periodic emission
SN

sample target sources

Published discoveries: Binary Black Hole mergers



49 *d* of coincident observation with science quality data

SNR=23.7
FAR $< 6\ 10^{-7}\ \mathrm{yr}^{-1}$
Significance $> 5.3\ \sigma$

SNR=9.7
FAR $=0.37\ \mathrm{yr}^{-1}$
Significance $= 1.7\ \sigma$

SNR=13.0
FAR $< 6\ 10^{-7}\ \mathrm{yr}^{-1}$
Significance $> 5.3\ \sigma$