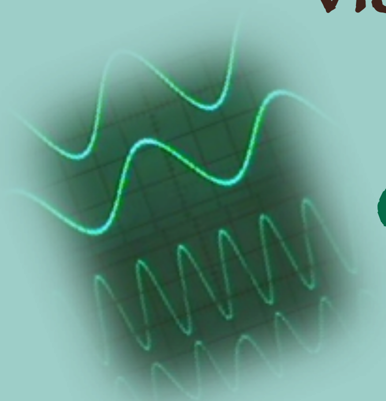
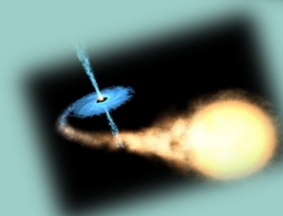
Sifting the Gravitational-Wave Universe via Multimessenger Astronomy: Forthcoming Prospects for Continuous-Wave detection





PAOLA LEACI

SciNeGHE 2016, Pisa (Italy)

OUTLINE

- Fundamental Physics, Astrophysics and Cosmology with Gravitational Waves
- Global GW detector network
- GW sources
- Multi-messenger searches
- Continuous Waves (CWs)
- Conclusions

Fundamental Physics, Astrophysics and Cosmology with Gravitational Waves

… a few examples

Fundamental Physics

- Properties of GWs
  - Testing GR
  - How many polarisations are there?
  - From the dispersion relation of GWs we can constrain the Compton wavelength of the graviton
- EoS of supranuclear matter
  - Signature of EoS in GWs emitted when neutron stars merge

Astrophysics

- Formation and evolution of compact binaries and their populations
  - masses, mass ratios, spin distributions, demographics
- Understanding Supernovae
- Finding why pulsars glitch
  - sudden excursions in pulsar spin frequencies
- Ellipticity of neutron stars
  - mountains of what size can be supported on neutron stars?

… a few examples

Cosmology

- **Primordial GWs**
  - quantum fluctuations in the early Universe produce a stochastic background
- **Production of GWs during early Universe phase transitions**
  - phase transitions, pre-heating, re-heating, etc., could produce detectable stochastic GWs

Challenges

- **Models and simulations of sources**
  - neutron star cores, corner cases of parameter space in binary systems…
- **Rapid parameter estimation of GW events**
  - especially important if we do find high event rate
- **Improved understanding of “detector” noise and false alarm rate**

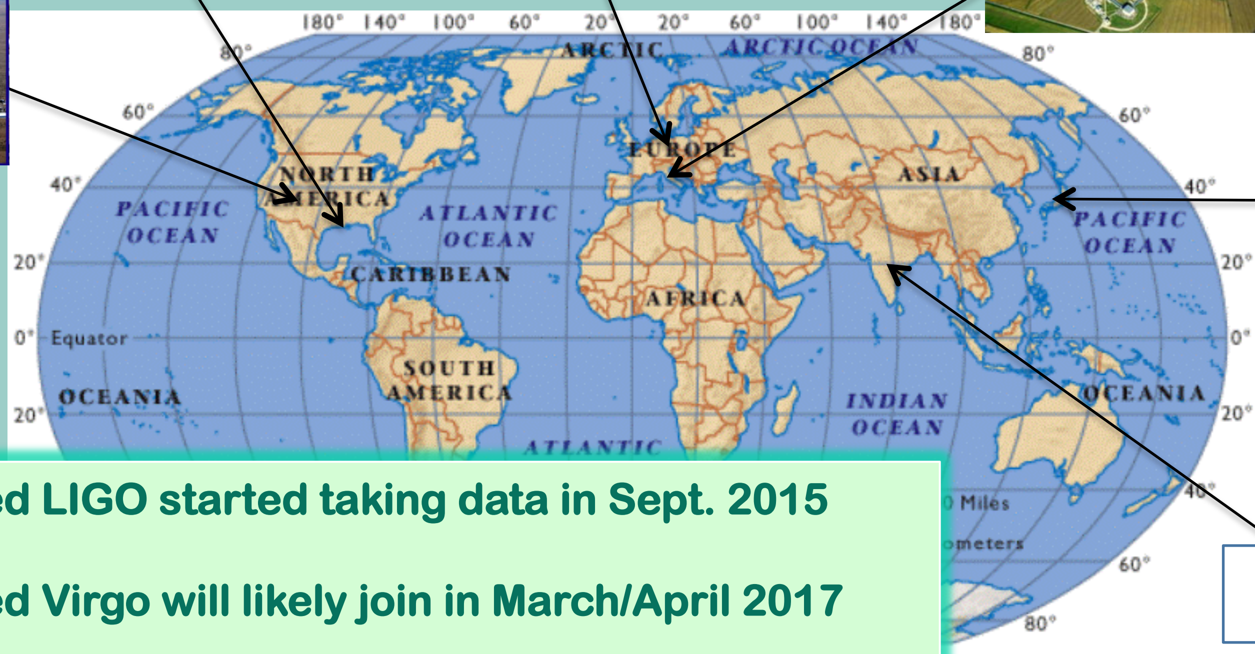
Global GW detector network

LIGO Livingston (LA, USA): 4 km dual recycled Fabry-Perot Michelson IFO

GEO600 (Hanover, GE):
600 m folded arms dual recycled Michelson triple pendulum suspensions

VIRGO (Cascina, IT):
3 km power recycled Fabry-Perot Michelson super-attenuator seismic isolation

LIGO Hanford (WA, USA):
4 km dual recycled Fabry-Perot Michelson IFO

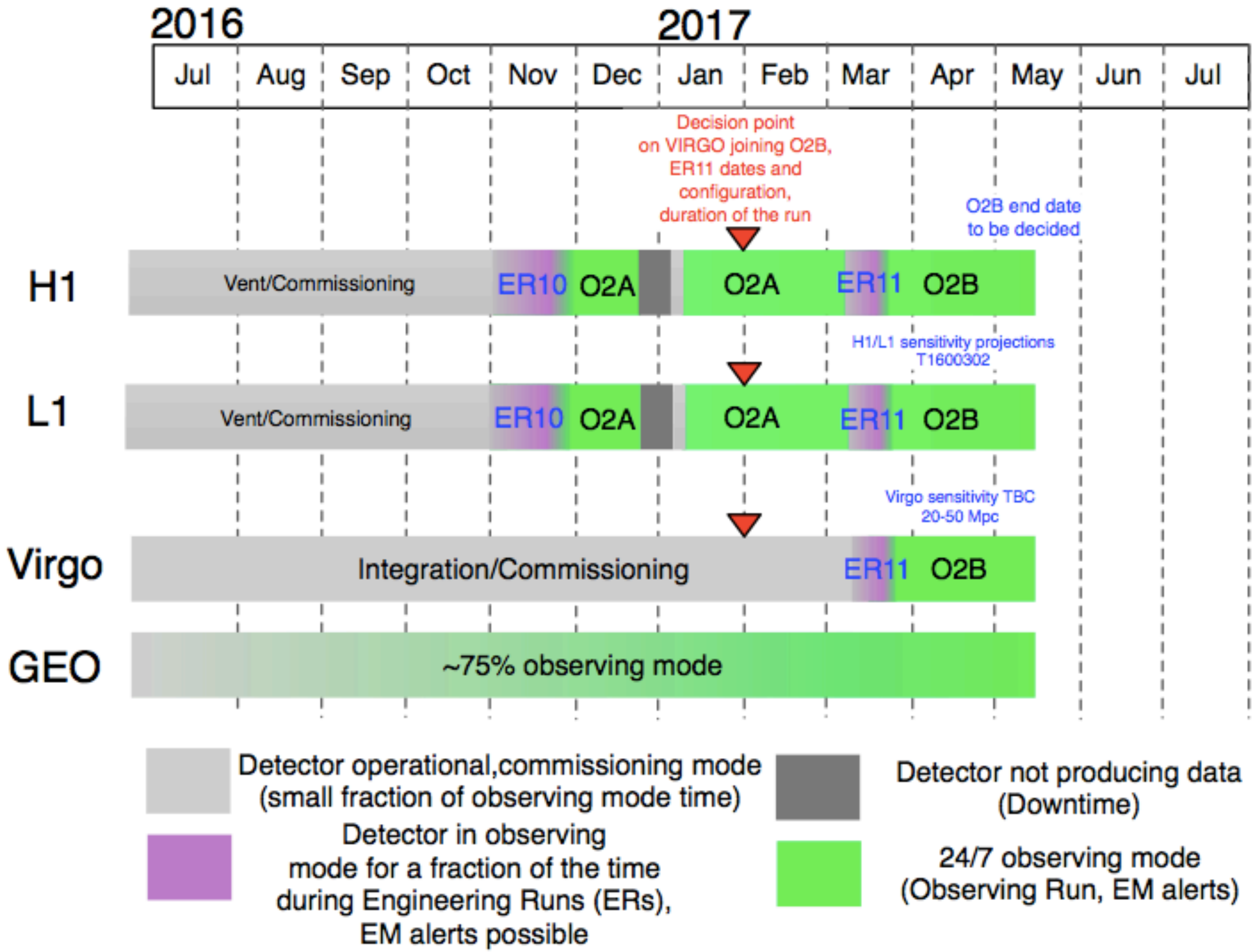


KAGRA (Hida-city, JP):
UNDER CONSTRUCTION (2019+)

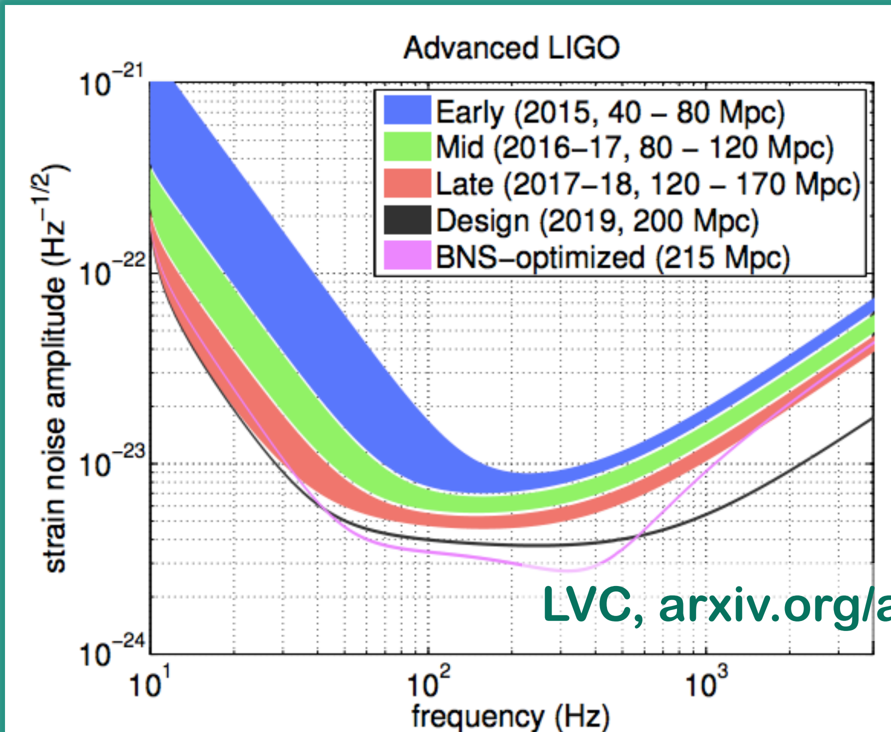
LIGO-India (IndIGO):
PLANNED (2022+)

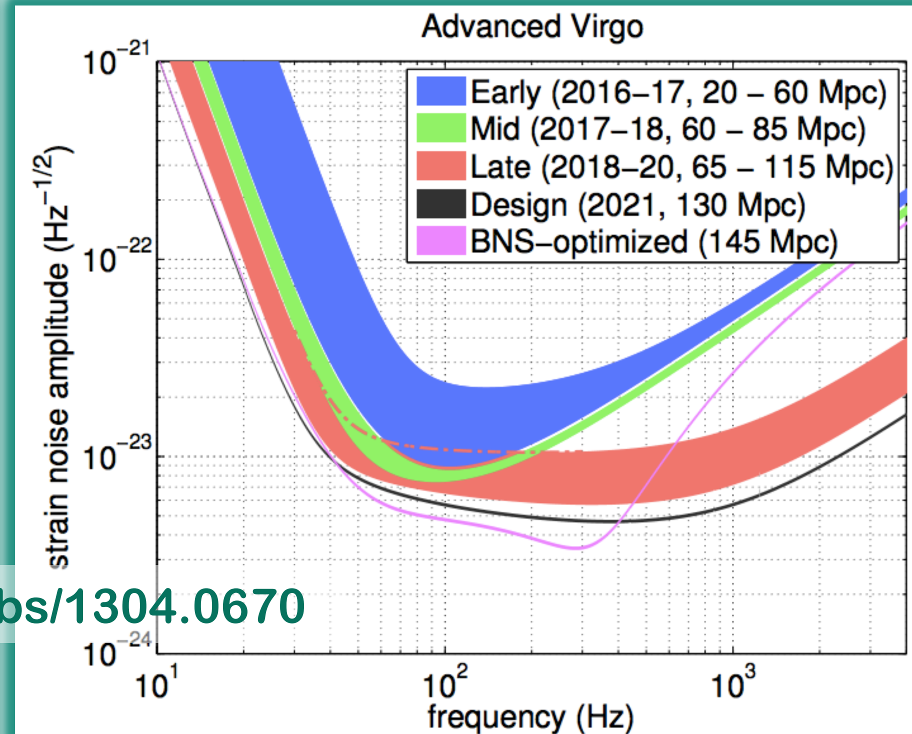
- **Advanced LIGO started taking data in Sept. 2015**
- **Advanced Virgo will likely join in March/April 2017**
- **By 2018, sensitivity expected to improve by a factor of 10 relative to Initial detectors**

Preliminary *Joint* ***LVC*** *Plan for the Second Observation period O2*



Advanced LIGO and Virgo expected sensitivity progression





LVC, arxiv.org/abs/1304.0670

- 2015: A 4 month run with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range).
- 2016–17: A 6 month run with H1L1 at 80 – 120 Mpc and Virgo at 20 – 60 Mpc.
- 2017–18: A 9 month run with H1L1 at 120 – 170 Mpc and Virgo at 60 – 85 Mpc.
- 2019+: Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 130 Mpc.
- 2022+: Four-detector H1L1V1+LIGO-India network at full sensitivity (aLIGO at 200 Mpc, AdV at 130 Mpc).

Beyond Advanced LIGO & Virgo

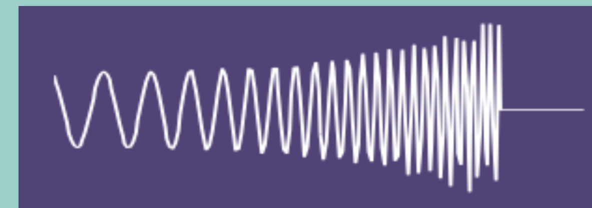
- **2006-2010:** ***detectors took 2 years worth of data at unprecedented sensitivity levels***
- **2015-2022:** ***five large detectors will become operational***
- **Advanced LIGO detectors both installed and locked, Advanced Virgo will come soon online, commissioning over the next <=3 years has the potential to see first and several detections**

- **Einstein Telescope (2018-2020):** 10 km arm length, triangular underground cryogenic detector
- **LIGO Voyager (2025-2030):** cryogenic (120 K) high power; x 3 improvement in aLIGO strain sensitivity
- **LIGO Cosmic Explorer (2030+):** new 40 km arm length interferometer

GW sources

TRANSIENT SIGNALS

- **Compact Binary Coalescing systems *(CBC)***, well modeled waveforms.
  The inspiral, merger and ring-down of binary NSs and Black Holes



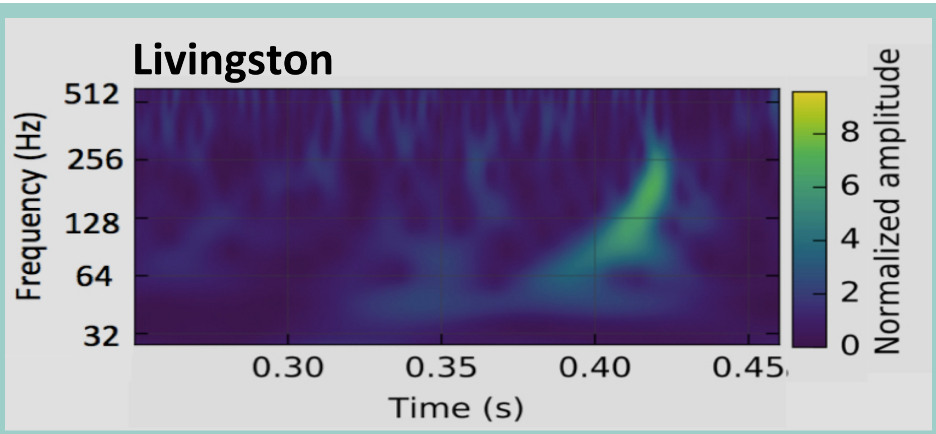
- **Supernovae, GRBs (*bursts*)**, unmodeled waveforms
  Short-duration GW events in coincidence (ideally) with signals in electromagnetic radiation/neutrinos

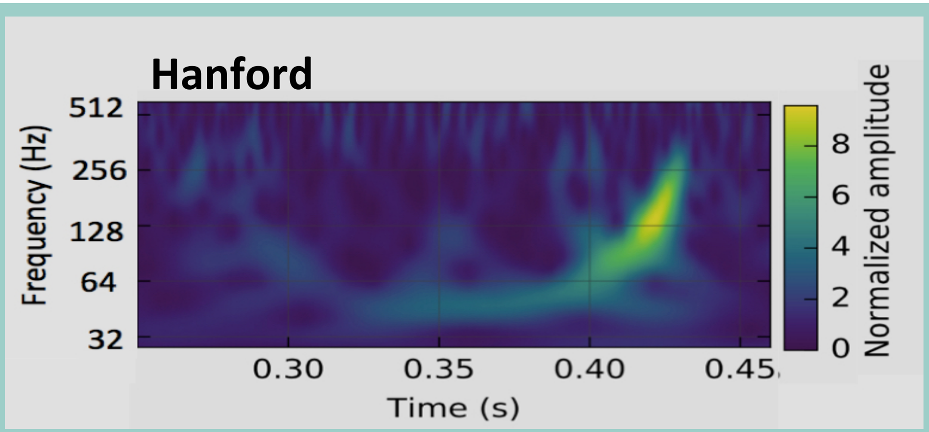
CONTINUOUS SIGNALS

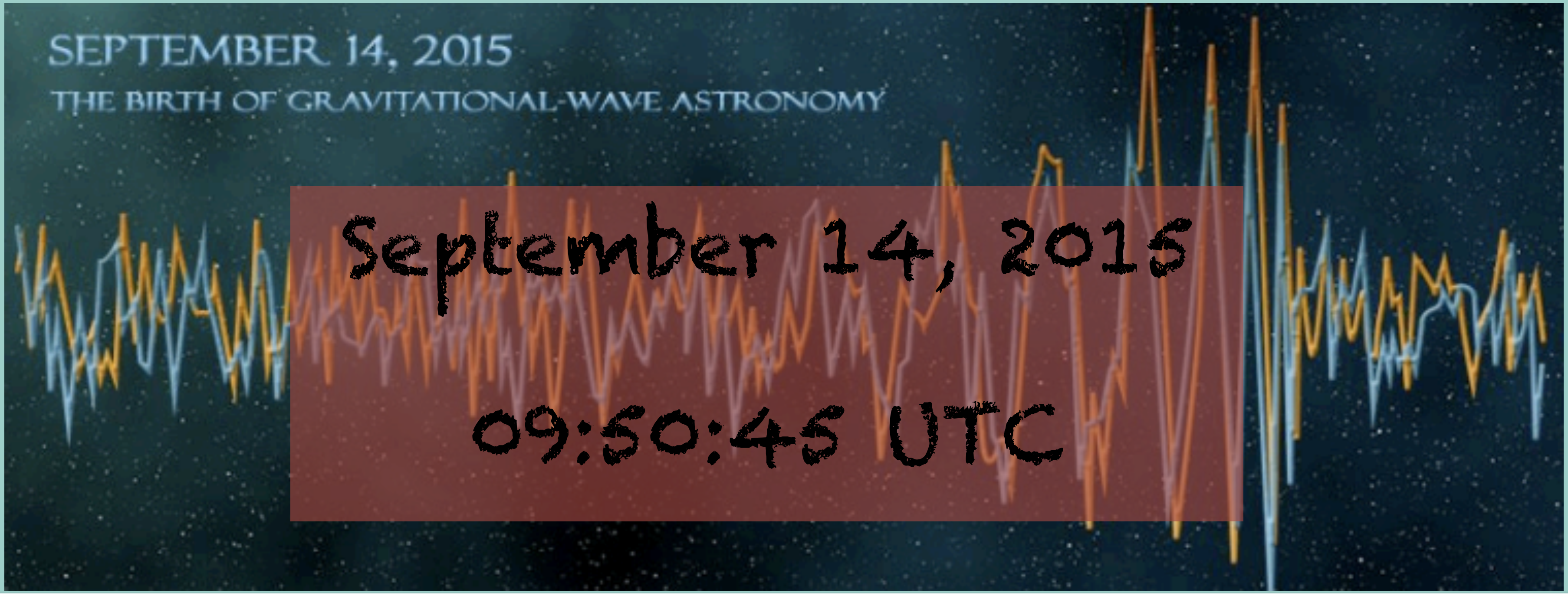
- **Cosmological GW (*stochastic background*)**
  A background of primordial and/or astrophysical GWs

- **Fast-spinning NSs in our galaxy (CWs)**
  e.g. non-axisymmetric spinning NSs

The 1st direct GW observation (PRL 116, 061102, 2016)





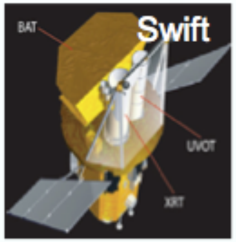


Multi-messenger Astronomy with GW searches

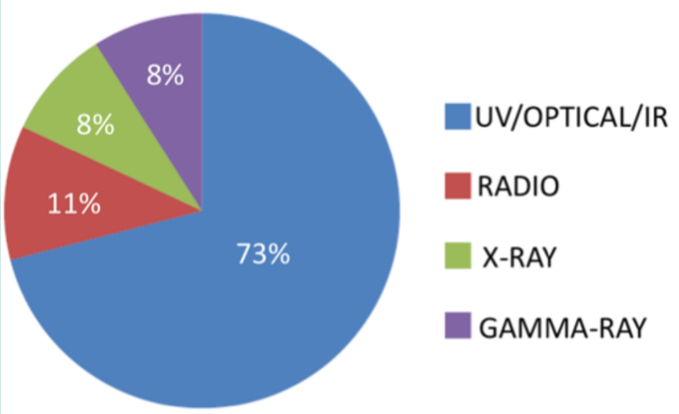
The GW-EM follow-up program

- More than 60 Partners from 19 countries
- About 150 instruments, covering the full spectrum from radio to very high-energy gamma rays

Policy for releasing GW triggers : *"Until first 4 GW events have been published, triggers will be shared promptly only with astronomy partners who have signed an MoU with LIGO–Virgo collaborations"*



X-ray, γ-ray follow-up



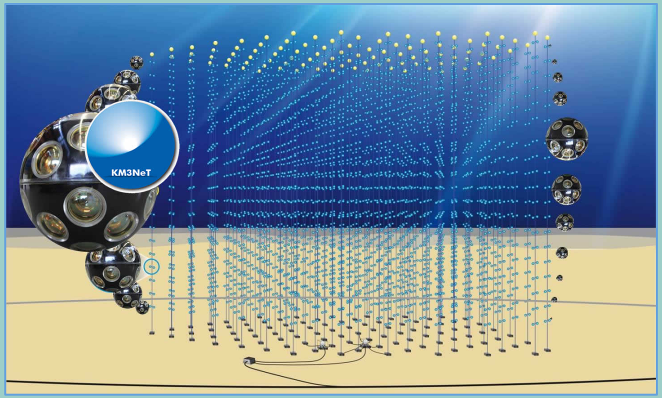
Optical follow-up

Multi-messenger Astronomy with GW searches

II

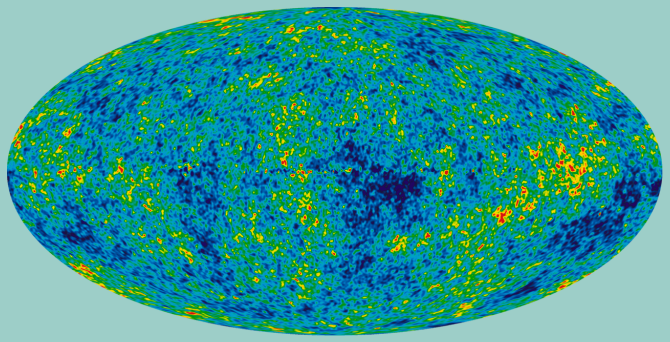
- Thanks to EM observations we can know (with high accuracy) the rotational parameters of several NSs, in particular radio pulsar (=> useful for both DIRECTED and TARGETED searches)

- GW searches in coincidence with neutrinos (ANTARES, IceCub and future KM3NeT): useful to improve SOURCE SKY LOCALIZATION



COSMIC MICROWAVE BACKGROUND (CMB)

- **Residual EM radiation -> remnant of the Big Bang**
- **Discovered by Penzias & Wilson in 1964**



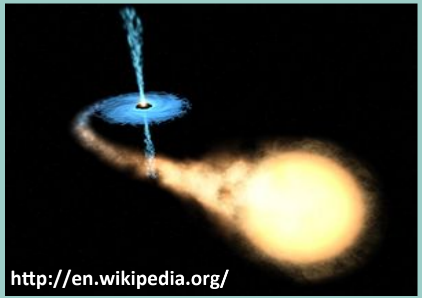
- The **B-modes** (one of the polarizations of such a radiation) are a type of signal **coming from the cosmic inflation,** and are determined by the **primordial GW density**
- **LSPE (Large-Scale Polarization Explorer) --- >** http://planck.roma1.infn.it/lspe/ **(LSPE is a mm-wave polarimeter aboard of a stratospheric balloon, aimed at measuring the polarization of the CMB at large angular scales)**

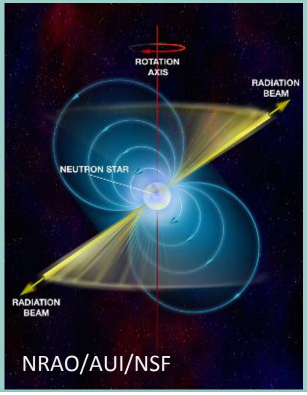
CW SIGNALS

- More than 2500 observed NSs (mostly pulsars) and $\mathcal{O}(10^8 - 10^9)$ expected to exist in the Galaxy

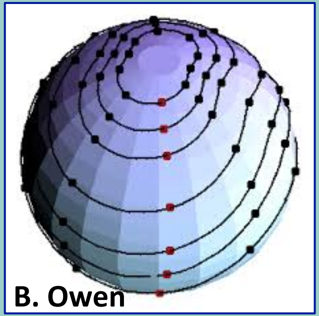
- To emit CWs a NS must have some degree of non-axisymmetry originating from
  - deformation due to elastic stresses or magnetic field
  - deformation due to matter accretion (*e.g.* LMXB)
  - free precession around rotation axis
  - excitation of long-lasting oscillations (*e.g.* r-modes)


http://www.indiana.edu/


http://en.wikipedia.org/



NRAO/AUI/NSF


B. Owen

CWs from rotating neutron stars

- Spinning neutron stars (NSs) with rotation rate f_r, equatorial non-axisymmetry $\varepsilon = (I_{xx}-I_{yy})/I_{zz}$ (with I_{ab} moments of inertia) are expected to emit CWs with frequency $f = 2 f_r$.

- The measured strain amplitude h_0 on Earth is given by

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

with d distance to the source.

[See C. Palomba's talk]

MAXIMUM DEFORMATION

- Normal NS ⟶ $\varepsilon \leq 10^{-5}$
- Hybrid (hadron-quark core) ⟶ $\varepsilon \leq 10^{-3}$
- Extreme quark stars ⟶ $\varepsilon \leq 10^{-1}$

[Johnson-McDaniel & Owen, PRD 87, 129903 (2013)]

CW SEARCH-TYPES

❑ **The way to search for CW signals depends on how much about the source is known. There are different types of searches:**

* **TARGETED** **searches for observed NSs.** **The source parameters (sky location, frequency & frequency derivatives) are assumed to be known with great accuracy (*e.g.* the Crab and Vela pulsars) => *O*(laptop)**

* **DIRECTED** **searches, where sky location is known while frequency and frequency derivatives are unknown (*e.g.* Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters) => *O*(cluster)**

* **ALL-SKY** **searches for unknown pulsars => computing challenge**
(Einstein@Home – Cloud – Grid Infrastructures)

CW searches from spinning NSs in binary systems

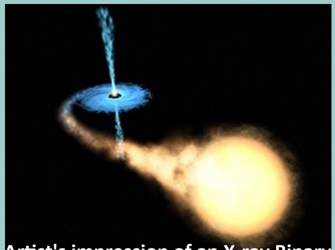
CWs from spinning NSs in binary systems

- More than half of the observed radio pulsars (with rotation rates that can plausibly emit CWs in the most sensitive band of the Virgo-LIGO detectors) are located in binary systems

- Accretion from a companion may cause an asymmetrical quadrupole moment of inertia of the spinning NS

- The CW signal from a source in a binary system is frequency-modulated by the source's orbital motion, which in general is described by five unknown *Keplerian parameters*

- Best candidate: Scorpius X-1 (the brightest low-mass X-ray binary), typically used as a *test bench* for all algorithms, as sky-position and binary orbital parameters are known with high accuracy



Artist's impression of an X-ray Binary

- All current methods to search for CWs emitted by NSs in binary systems are incomplete!

Novel (directed) search strategy to detect continuous gravitational waves from neutron stars in low- and high-eccentricity binary systems; *P. Leaci and the Rome Virgo group (submitted to PRD)*

The Novel method

http://arxiv.org/abs/1607.08751

- Very fast and robust directed search incoherent method exploiting the peak-amplitude related statistic (PRD 90, 042002, 2014)
- Algorithm validation performed by adding 131 artificial CW signals from pulsars in binary systems to simulated detector Gaussian noise ($S_h = 4 \times 10^{-24}$ Hz$^{1/2}$ in [70, 200] Hz)
- SEARCH PARAMETER SPACE

  $T_{obs} = 1$ month; $T_{FFT} = 512$ s;
  Single IFO

$$(\alpha_s, \delta_s) = (4.276, -0.273)\,\text{rad}$$

$$h_0^s \in [1, 5] \times 10^{-24}$$

$$\begin{aligned}
f_s &\in [70, 200]\,\text{Hz} \\
a_{p_s} &\equiv \frac{a\,\sin i}{c} \in [1,\,3]\,\text{s}, \\
P_s &\in [10,\,48]\,\text{h}, \\
t_{p_s} &\in \left[t_{\text{mid}} - \frac{P}{2},\, t_{\text{mid}} + \frac{P}{2}\right], \\
\log_{10} e_s &\in [-6,\, \log_{10}(0.9)]\,, \\
\omega_s &\in [0,\, 2\pi]\,\text{rad}\,,
\end{aligned}$$

- Total Computing Cost: 2.4 CPU hours
- The pipeline detected 128 signals
- The smallest GW amplitude detected is $h_0 \sim 7 \times 10^{-25}$
- By using 3 IFOs, and $T_{obs} = 1$ year, we gain more than a factor 3 in sensitivity!

RESULTS

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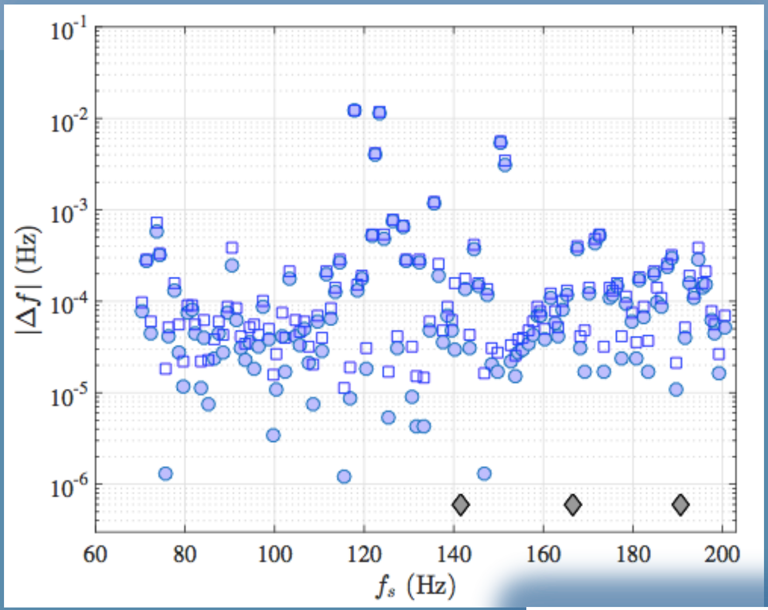
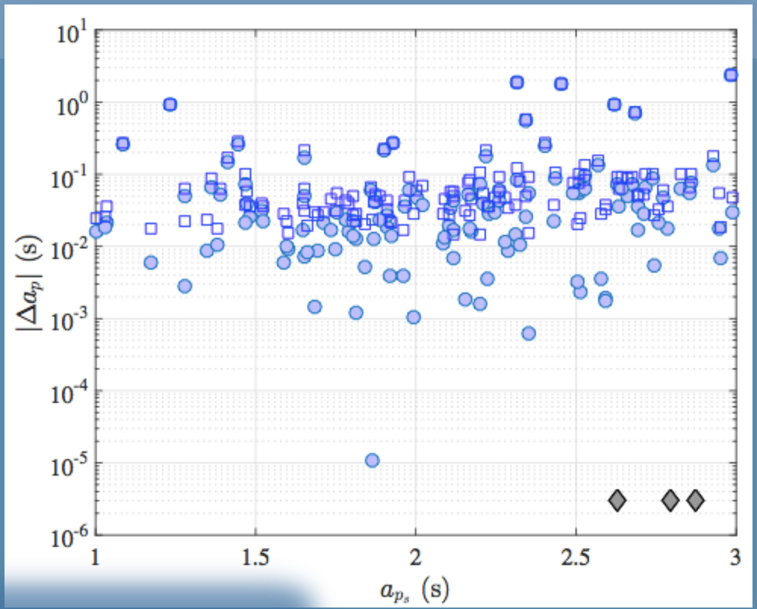
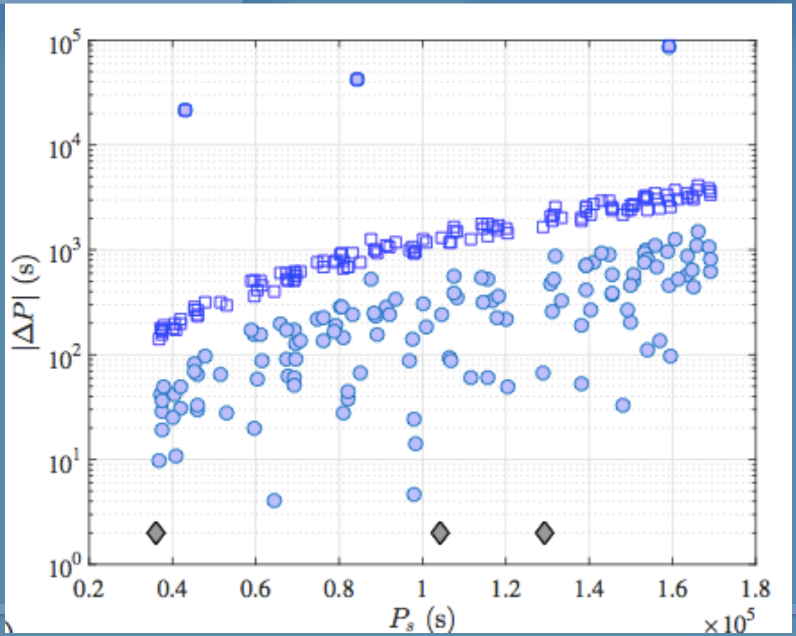


Frequency

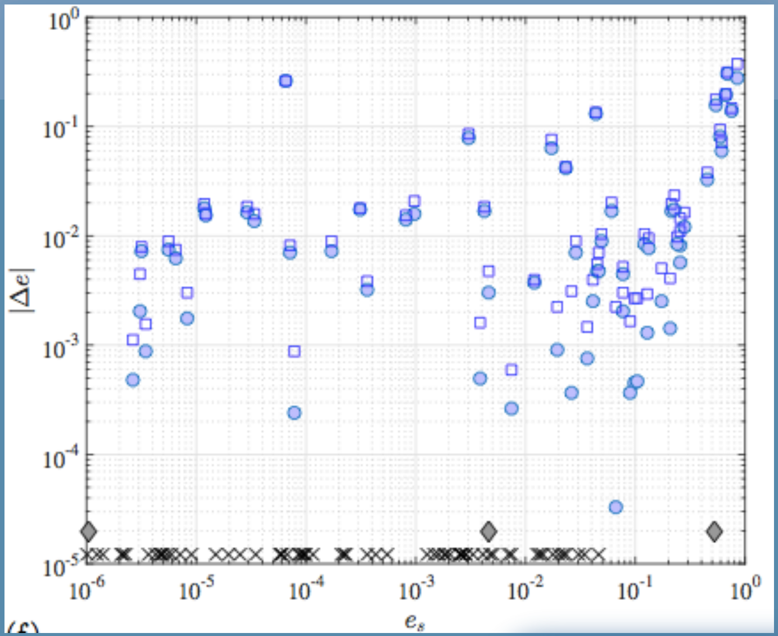


Orbital semi-major axis

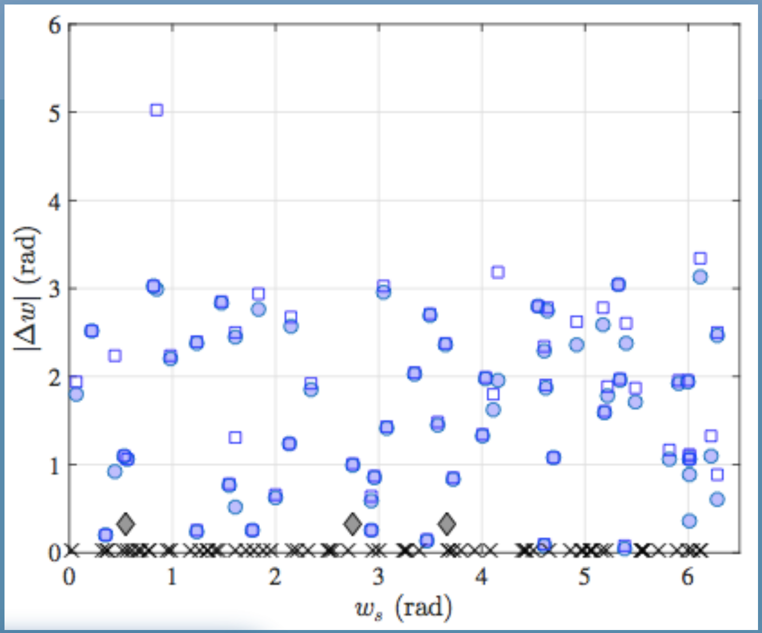


Orbital Period

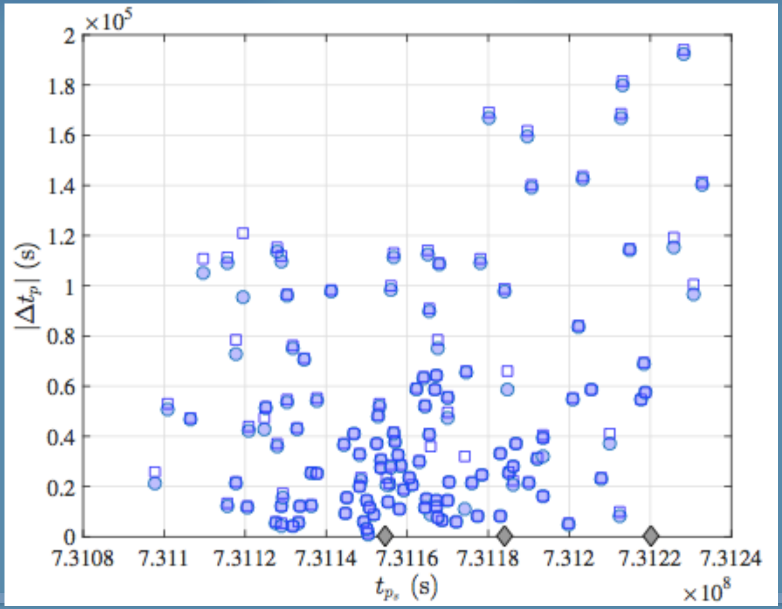
RESULTS



Eccentricity



Argument of periapse



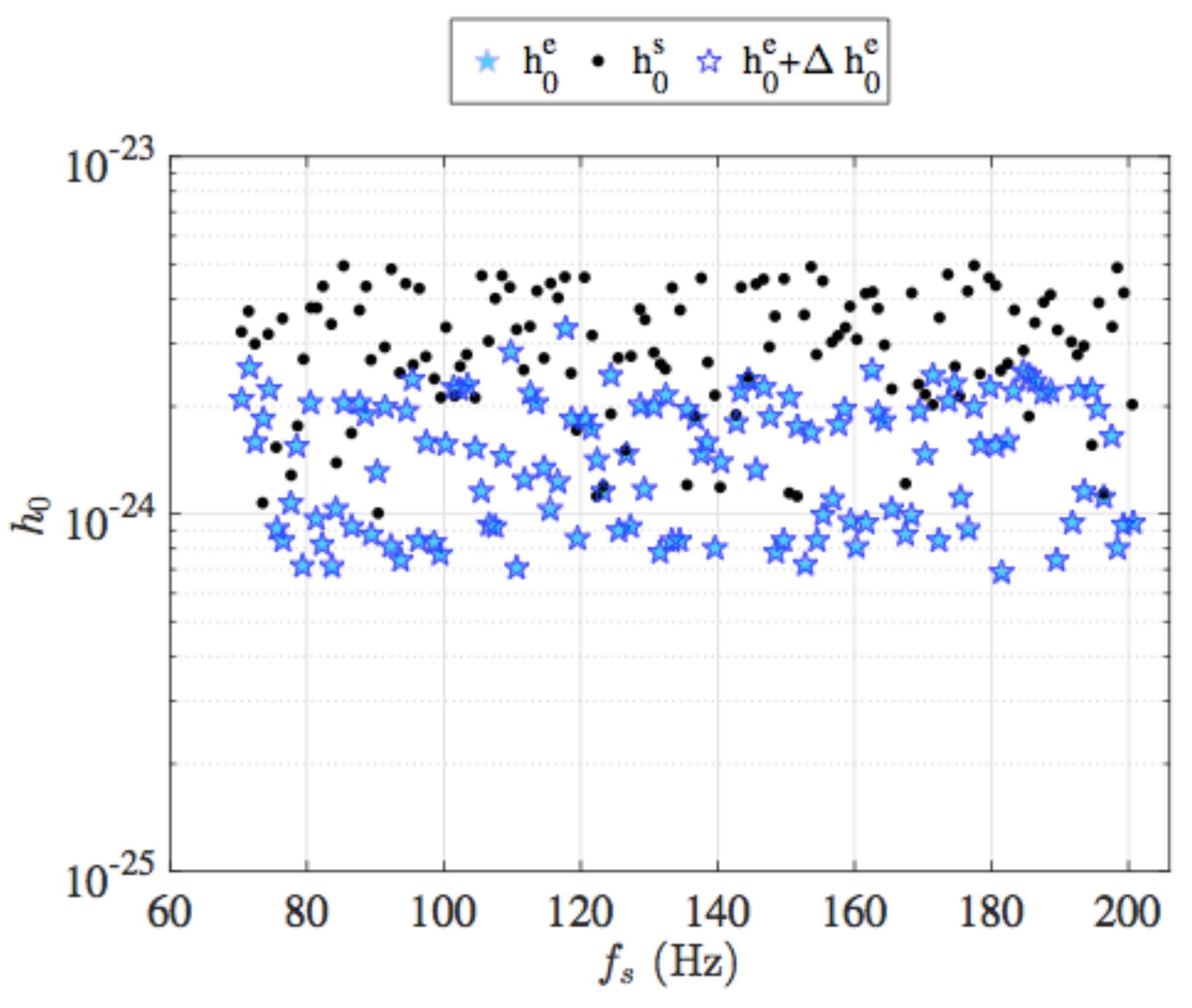
Time of periapse passage

Sensitivity Estimation

- Injected Amplitude

★ Detected if the injected amplitude would have been scaled up to the starred value

$T_{obs} \approx 1$ month
Single IFO



Concluding Remarks and Future Prospects

I

- The novel presented algorithm is the first one in the literature able to provide estimates for orbital eccentricity and argument of periapse.

- Performance comparison *wrt* pipelines used in *Messenger et al., PRD 92, 023006 (2015) and Leaci & Prix, PRD 91, 102003 (2015) and S. Suvorova et al., PRD 93, 123009 (2016)*

- The usage of different pipelines, searching for the same class of sources, and implemented with independent software, is crucial for robust vetting and accurate validation of results.

Concluding Remarks and Future Prospects *II*

✧ There are a plethora of ongoing and upcoming GW searches

✧ Several efforts actually ongoing:

- Improving sensitivity of all-sky/directed/targeted searches for CWs from isolated AND binary systems
- Analysis speedup (GPU technology)
- Prioritization of scientific goals for GW searches in observing runs (based on discovery potential, computing cost)
- Establishing a tighter link with EM observatories

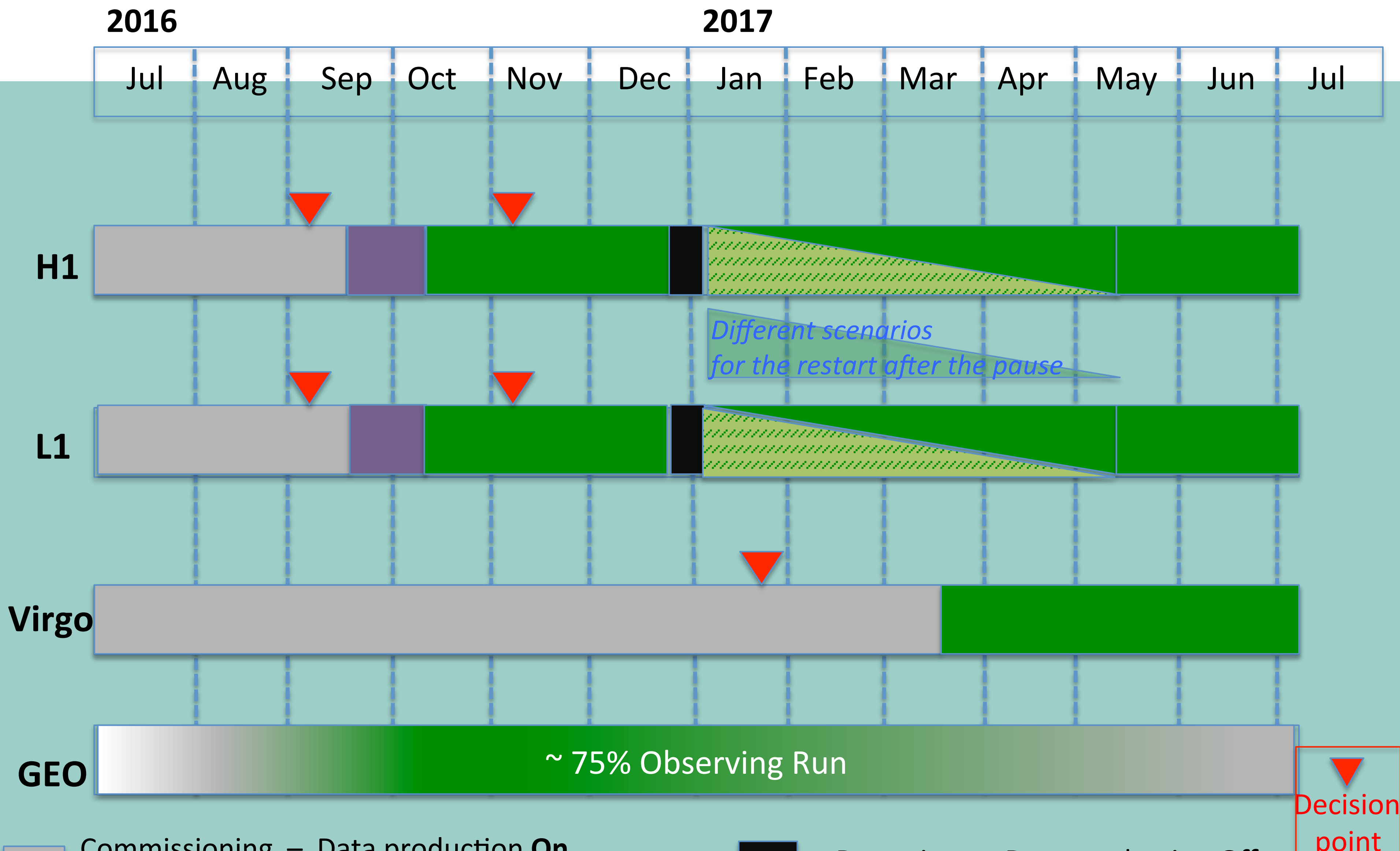
✧ We are looking forward to other GW detections!

CW signals might be the next detection!!!

THANKS FOR LISTENING!

BACKUP slides

Preliminary *Joint* ***LVC*** *Plan for the Second Observation period O2*



Commissioning – Data production **On**
Small fraction of time in observing mode

Engineering Run – Data production **On**
Detector in observing mode for a fraction of time

Downtime – Data production **Off**

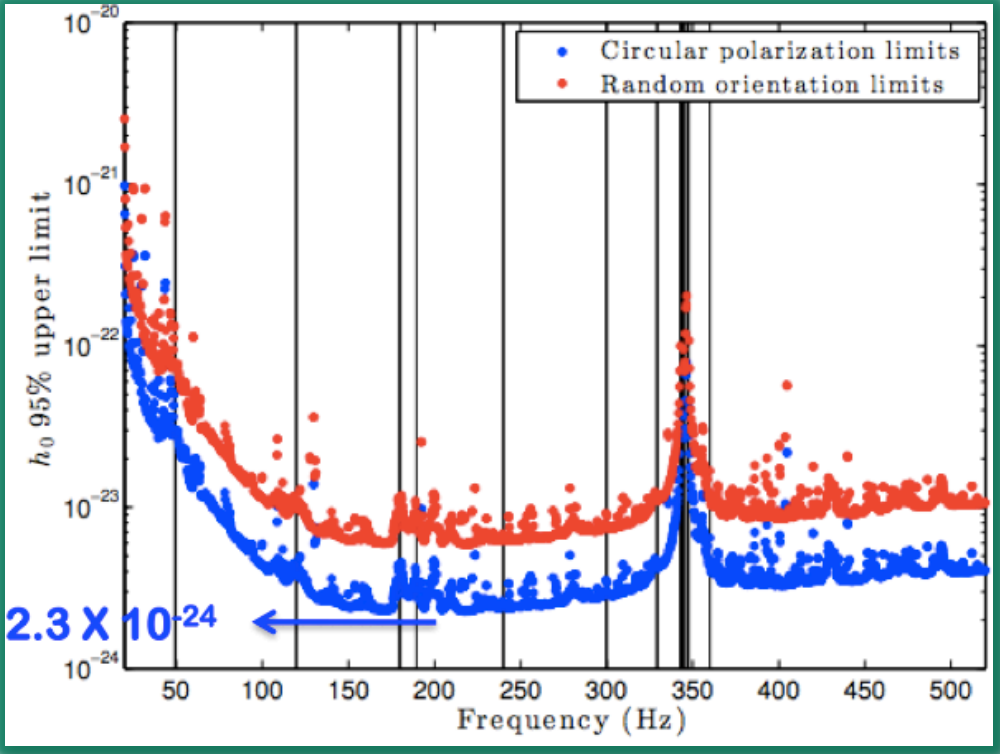
Observing Run – Data production **On**
Detector in observing mode 24/7 – EM alerts

All-sky search for CWs from spinning NSs in binary systems

- 1st All-Sky search for continuous unknown GW sources in binary systems that analyzed LIGO S6 and Virgo VSR2-R3 data; **LVC PRD 90,062010 (2014)**

- Algorithm based on doubly-Fourier-transformed data

- f: [20 - 520] Hz; P: [2 - 2254] h; a: [6x10^{-4} - 6500] ls; e = 0



- ULs on Scorpius X-1 also put, **from 20 to 57.25 Hz** -> a factor of 3 better than the all-sky upper limits

ALL-SKY SEARCHES

- Need to search for unknown sources located everywhere in the sky, with signal frequency as high as ~ 2 KHz and with values of spin-down as large as possible =>

COMPUTATIONALLY LIMITED!!

- Optimal coherent strategies (PRD 58, 063001, 1998) with long observations time T become computationally undoable

$$SNR \sim \frac{h_0}{\sqrt{S_n}}\sqrt{T}$$

Computing cost ~ T^{6+}

- Need to resort to SEMICOHERENT METHODS, where the entire data set is split into *N* shorter segments. Each segment is analyzed coherently, and afterwards the information from the different segments is combined incoherently:

$$SNR \sim \frac{h_0}{\sqrt{S_n}}\sqrt{T}\,N^{1/4}$$

- Fully coherent FOLLOW-UP happens only for the most promising candidates!
  [Shaltev, Leaci, Papa, Prix, PRD 89, 124030, (2014)]