Onde gravitazionali

Come le ascoltiamo? Cosa ci raccontano?

Gianluca Gemme - *INFN Genova*

on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO Livingston Observatory
Louisiana, USA

Virgo, Cascina, Italy

LIGO Hanford Observatory
Washington, USA

New Era in Astronomy!

14 Sep 2015: First detection of Gravitational Waves!

229,000 paper downloads from
APS in the first 24 hours,
servers down!

[Phys. Rev. Lett. 116, 061102 (2016)]

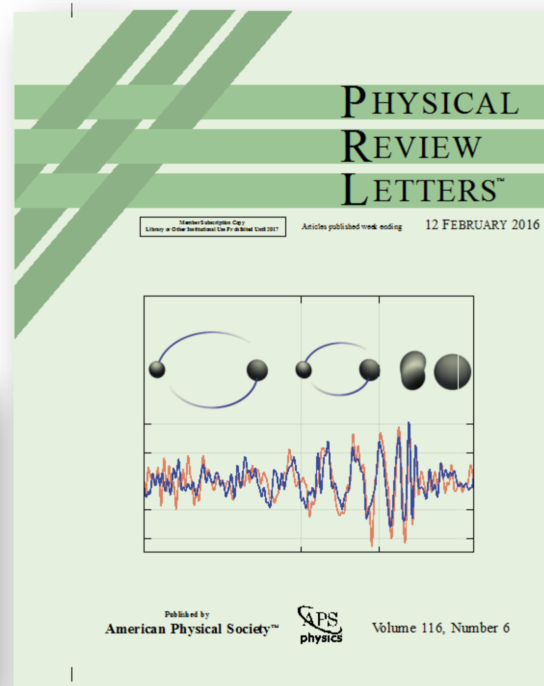
Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

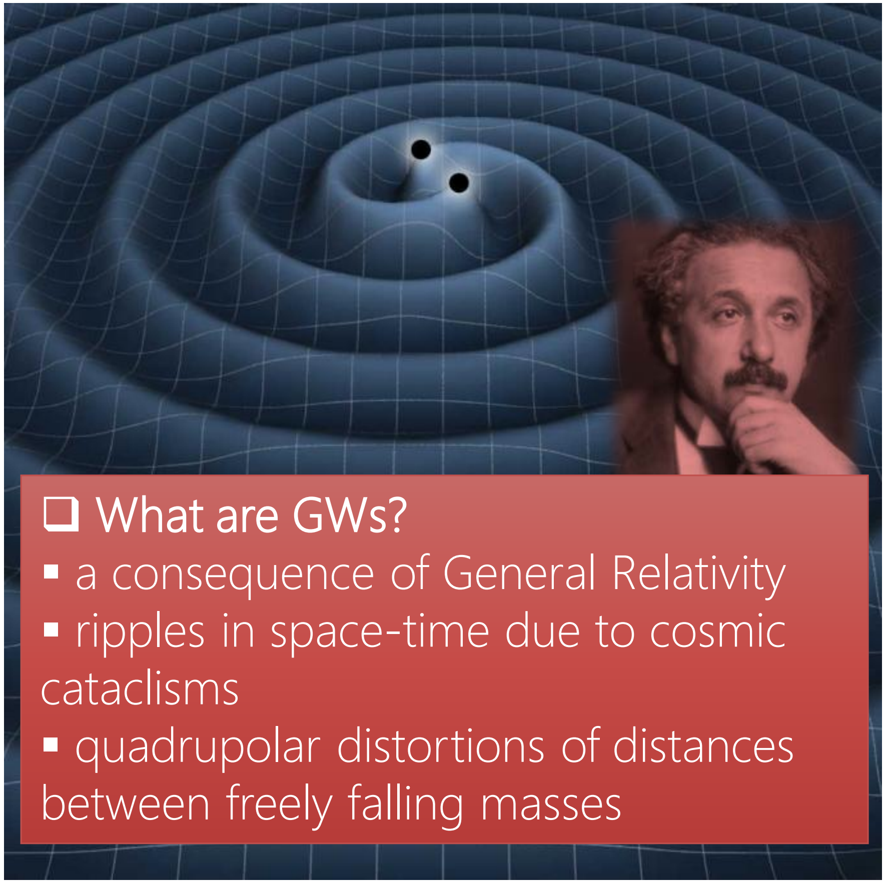
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in



Binary black holes do exist!
and **we can listen to them** coalesce

This is the birth of gravitational wave astronomy

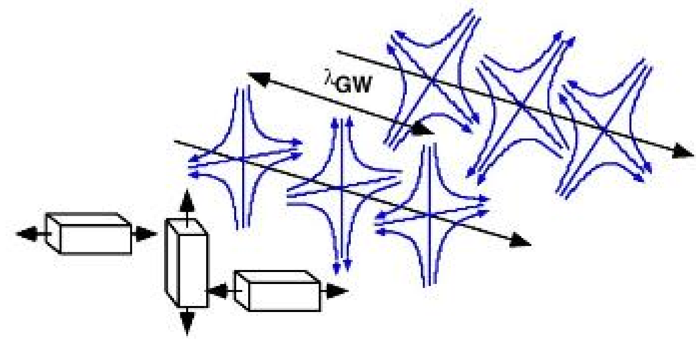
Gravitational Waves



❑ What are GWs?

- a consequence of General Relativity
- ripples in space-time due to cosmic cataclisms
- quadrupolar distortions of distances between freely falling masses

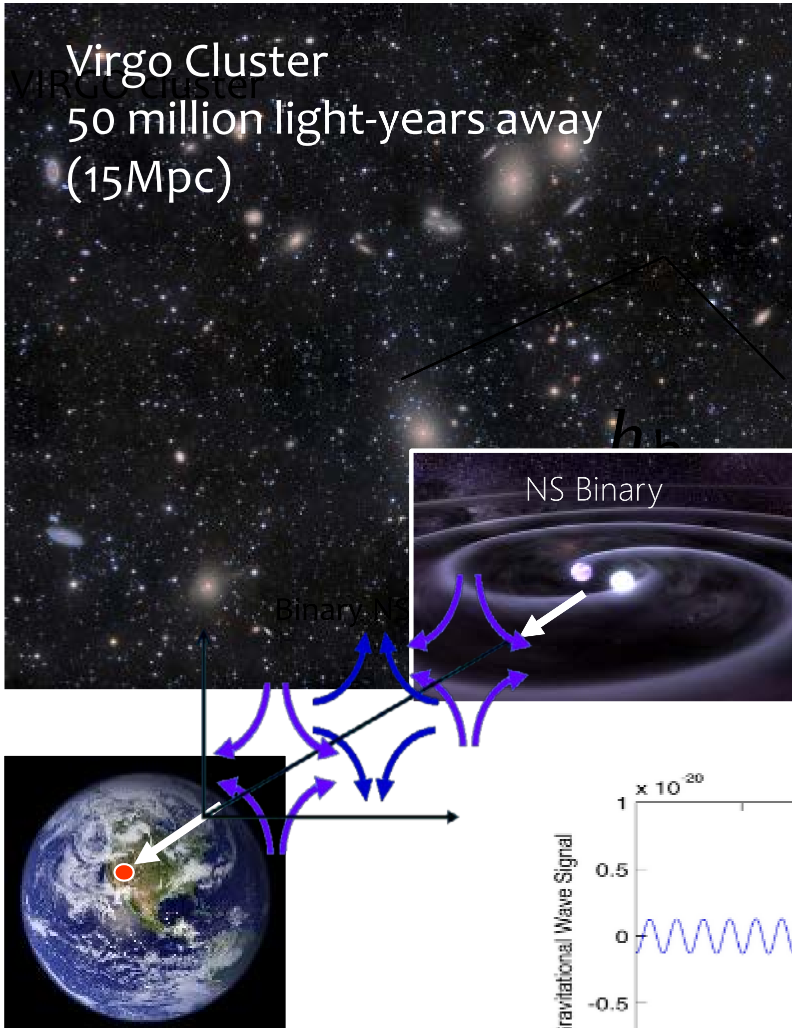
the waves have two components, rotated by 45º from each other



$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

strain $h = \Delta L / L$

Gravitational waves are hard to measure, they are small…

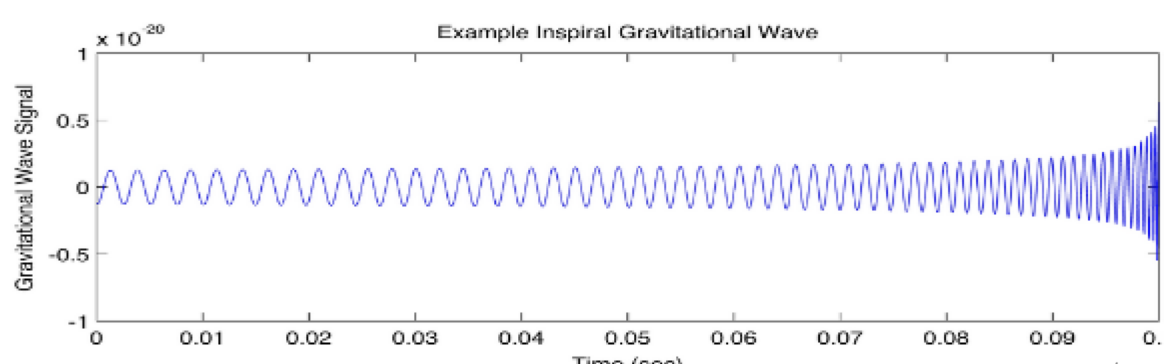


Tiny interaction with matter:

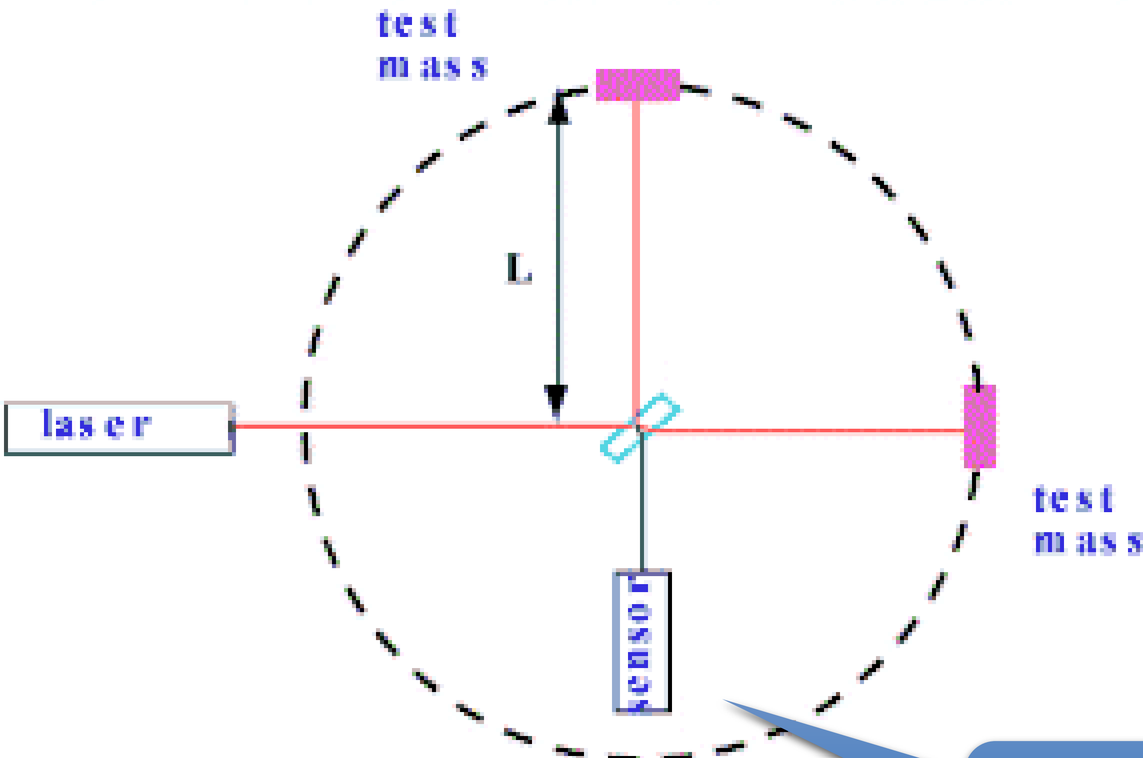
- Extremely difficult to detect
- Ideal messengers from remote space-time regions
- *Can bring a whole new view of the Universe*

$h = \Delta L/L \sim 10^{-21}$

- even with test masses L~km far apart,
- displacement is $\Delta L \sim 10^{-18}$ m



Interferometer:
a Gravitational Wave Transducer



Laser used to measure relative lengths of two orthogonal arms

…causing the interference pattern to change at the photodiode

How to improve sensitivity?

- Very long arms to get a larger displacement

Measure difference in length
to one part in 10^{21} or 10^{-18} meters

- Fabry-Perot cavity in each arm

To increase phase change

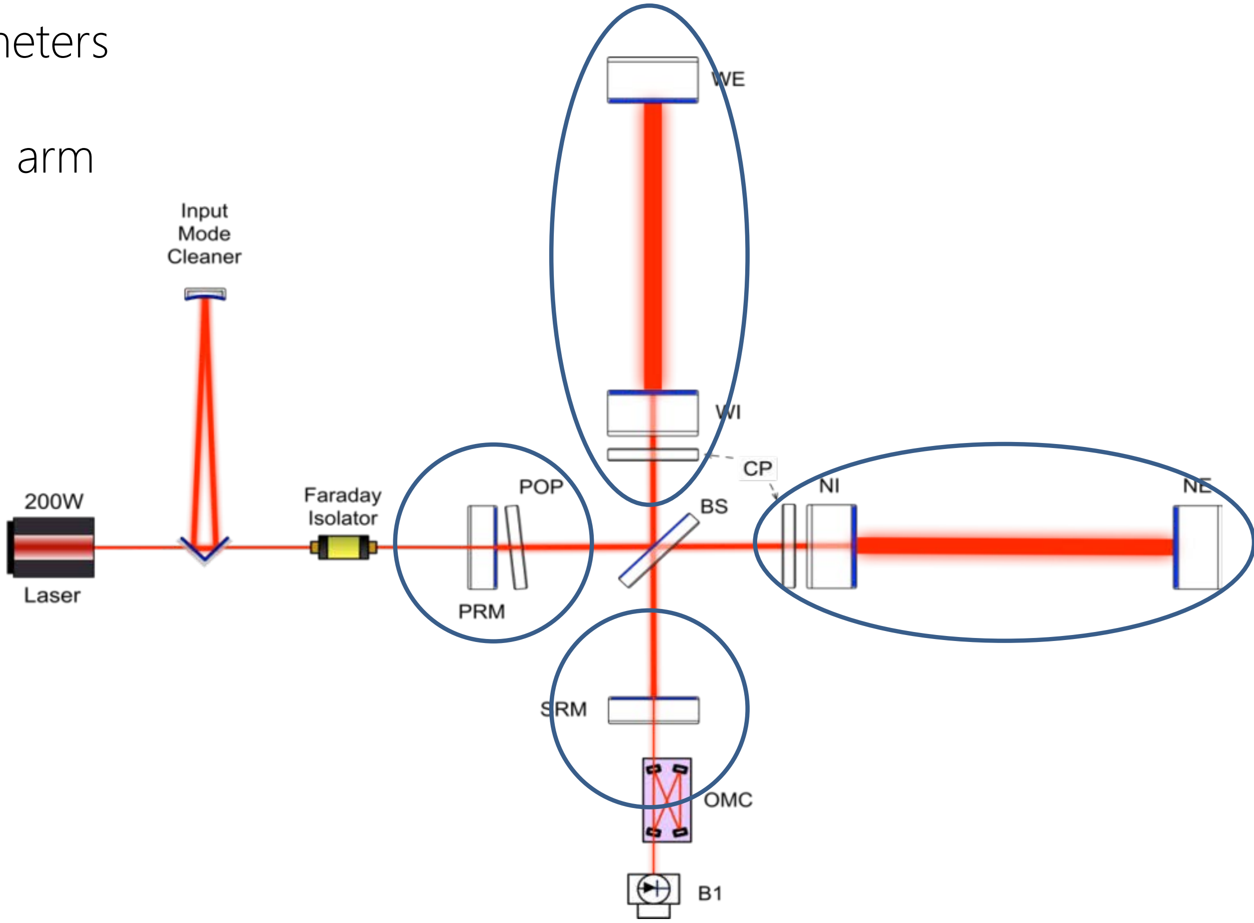
$$\Delta\varphi_{FP} \sim \mathcal{F}\Delta\varphi_M$$

- Recycle injected power

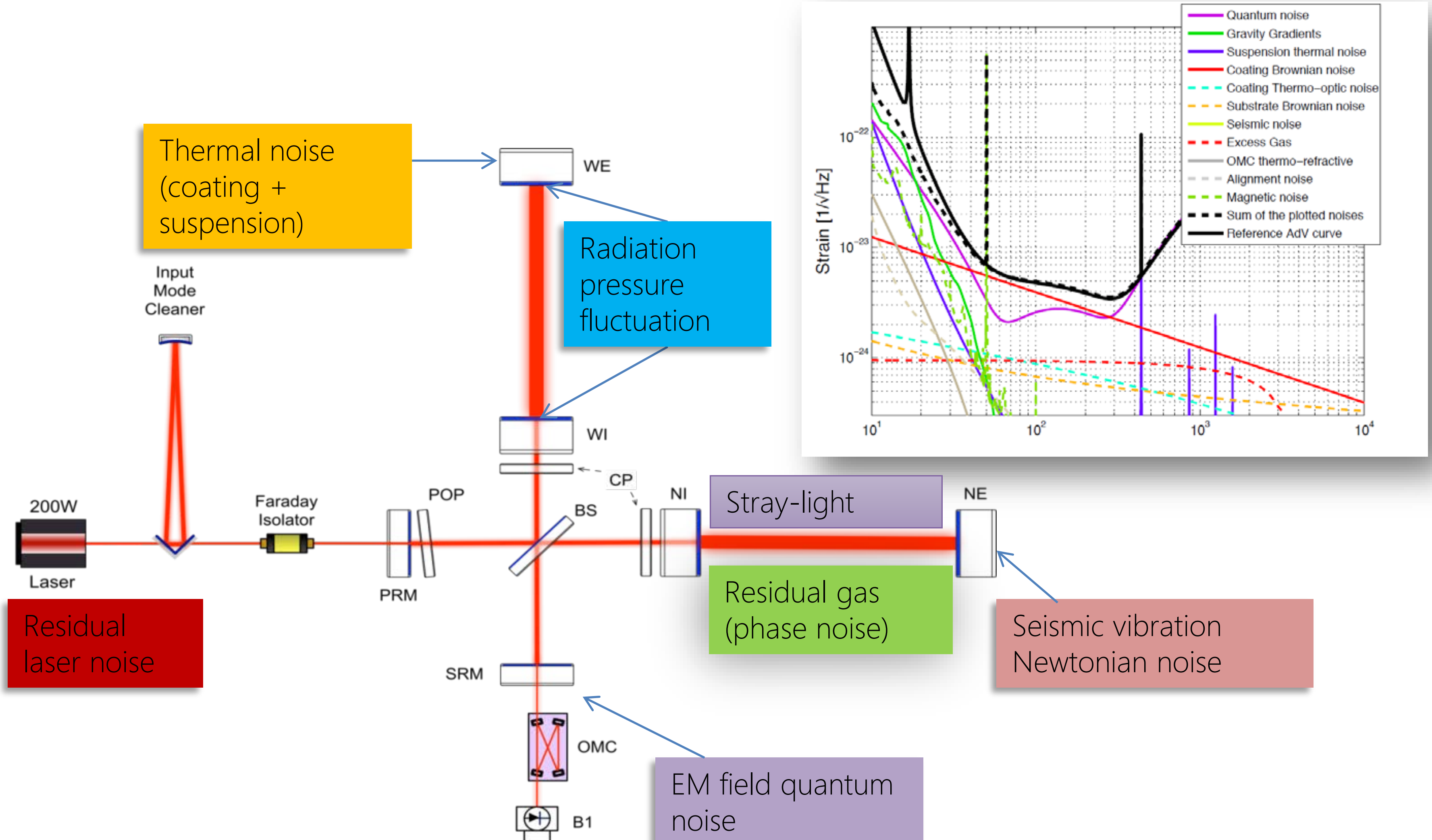
To increase input power

- Recycle outgoing signal

To amplify the output



GW Detectors - Noise



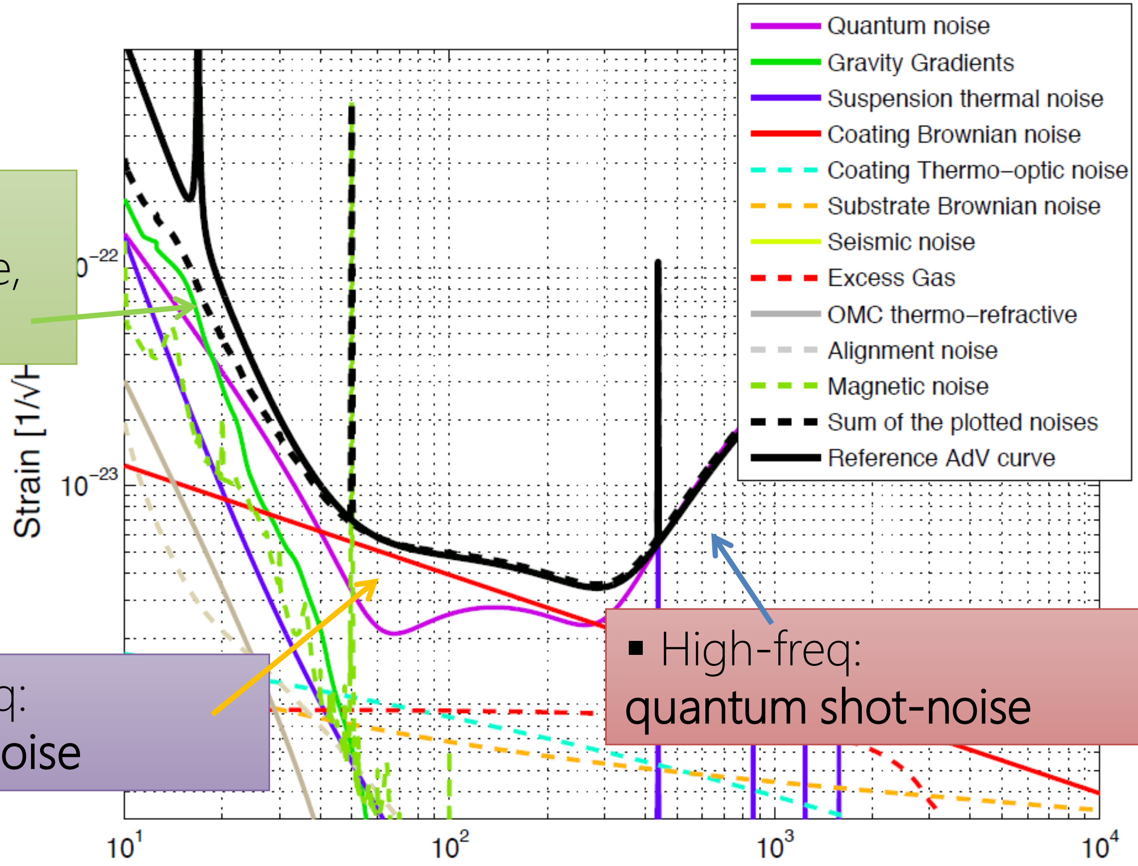
GW Detectors - Noise

Limiting noises at different frequency ranges:

- Low-freq:
newtonian noise, seismic noise, residual technical noises

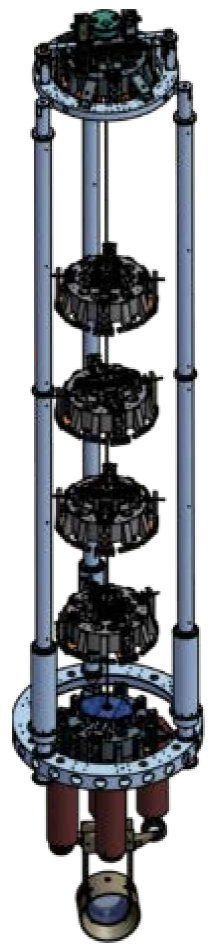
- Mid-freq:
thermal noise

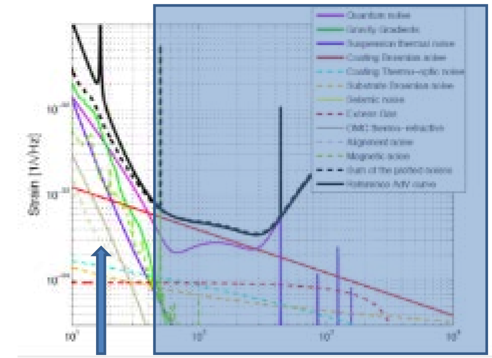
- High-freq:
quantum shot-noise



Low frequency noise

- Dominated by *seismic noise*
- Managed by suspending the mirrors from extreme vibration isolators (attenuation > 10^{12})
- Technical noises of different nature are the real challenge in this range
- Ultimate limit for ground-based detectors:
  gravity gradient noise

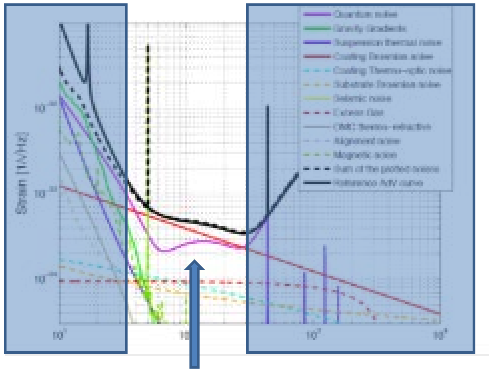


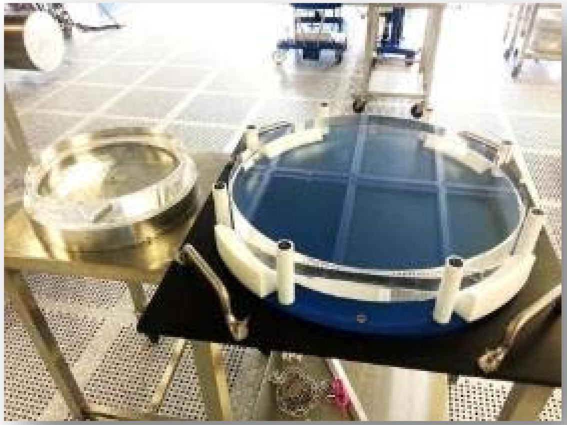


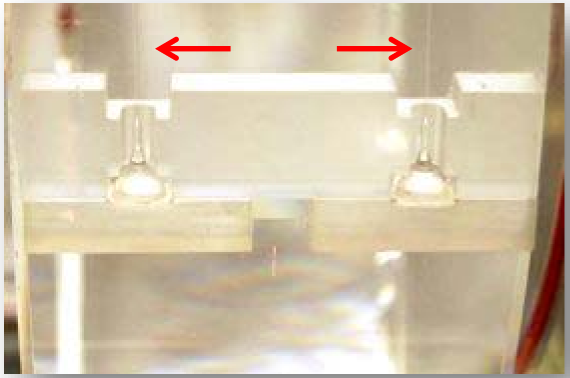
Intermediate frequency noise

- Mid frequency range:
  - Dominated by thermal noise of mirror coatings and suspensions

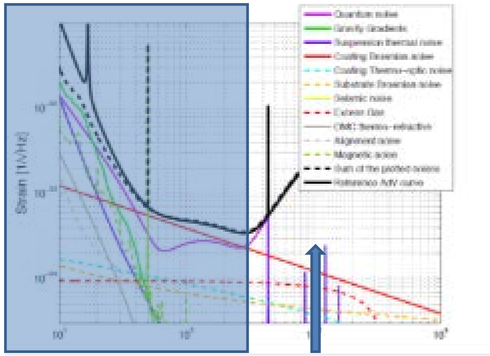
- Reduced by:
  - *Larger beam spot* (sample larger mirror surface)
  - Test masses suspended by fused silica fibers (low mechanical losses)
  - Mirror coatings engineered for low losses



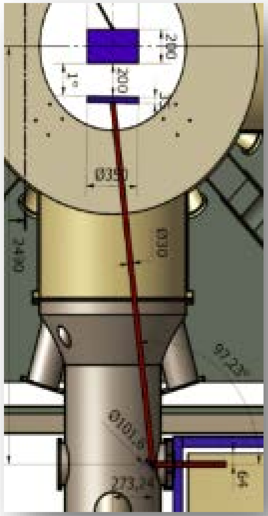


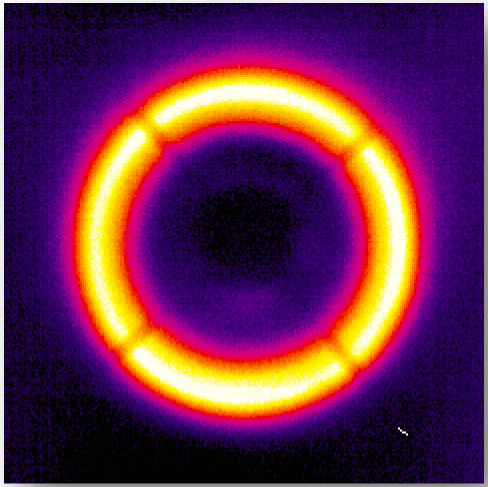


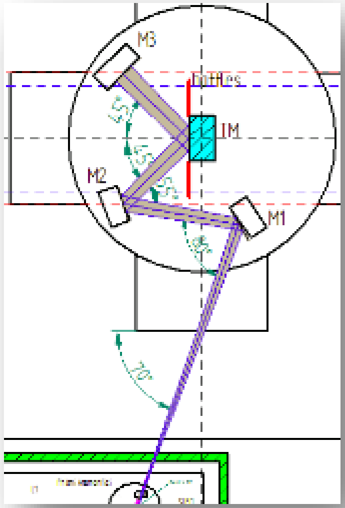
High frequency noise



- High frequency range:
  - Dominated by laser shot noise. Improved by increasing the power: *>100W input*, ~1 MW in the cavities
- Requires:
  - New laser amplifiers (solid state, fiber)
  - Heavy, low absorption optics (substrates, coatings)
  - Sophisticated systems to correct for thermal aberrations







Advanced Virgo in a nutshell

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009
- First science data scheduled in 2016

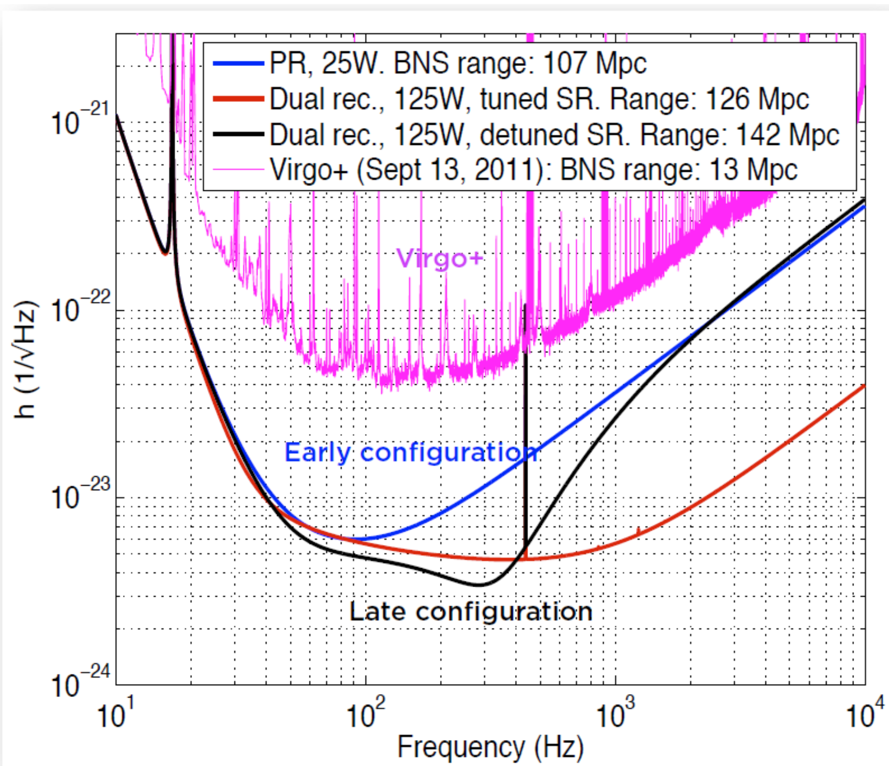
5 European countries
19 labs, ~200 authors

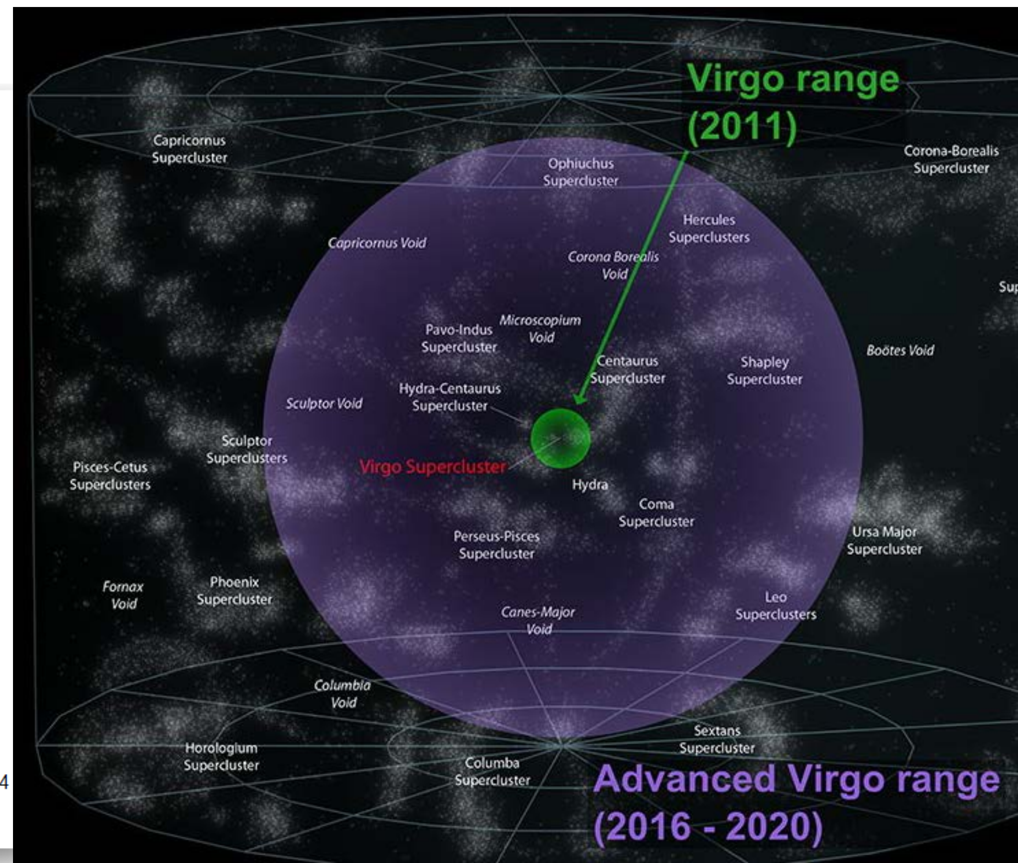
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

http://public.virgo-gw.eu/)

Advanced detectors

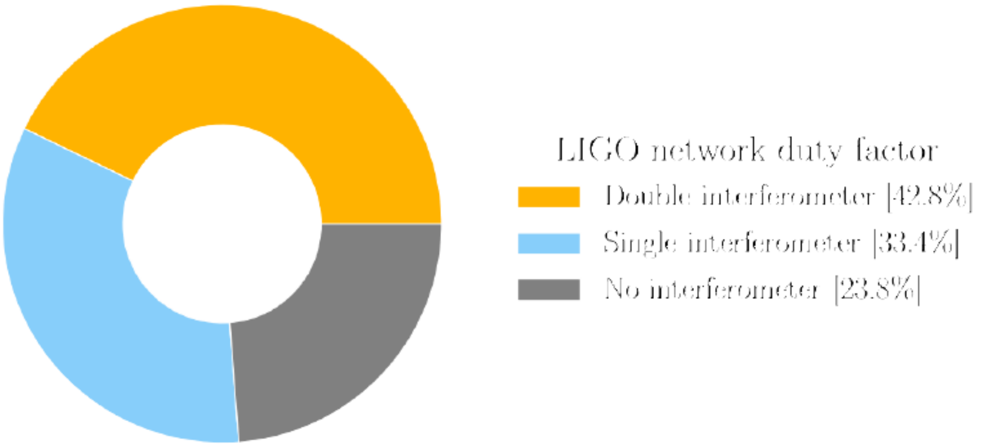
- 10X better amplitude sensitivity
  - Event rate ∝ (reach)^3 ~ 1000X greater
    - 1 day of observation with Advanced detectors ≫ 1 year with Initial detectors



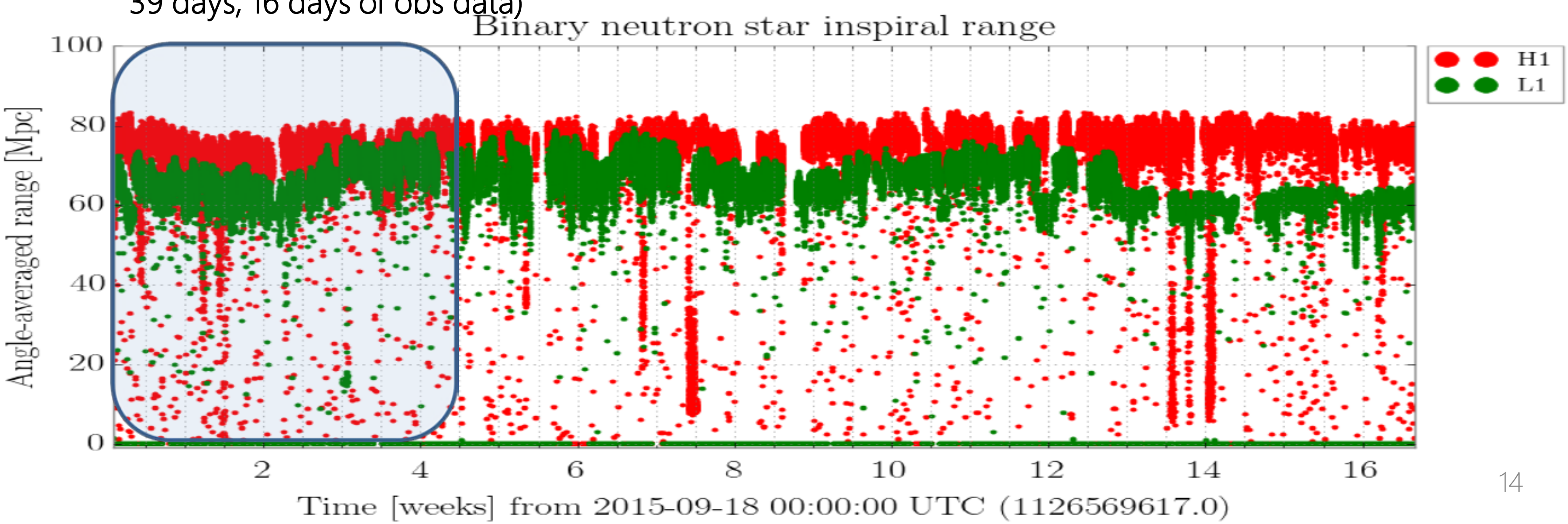


O1 in a nutshell

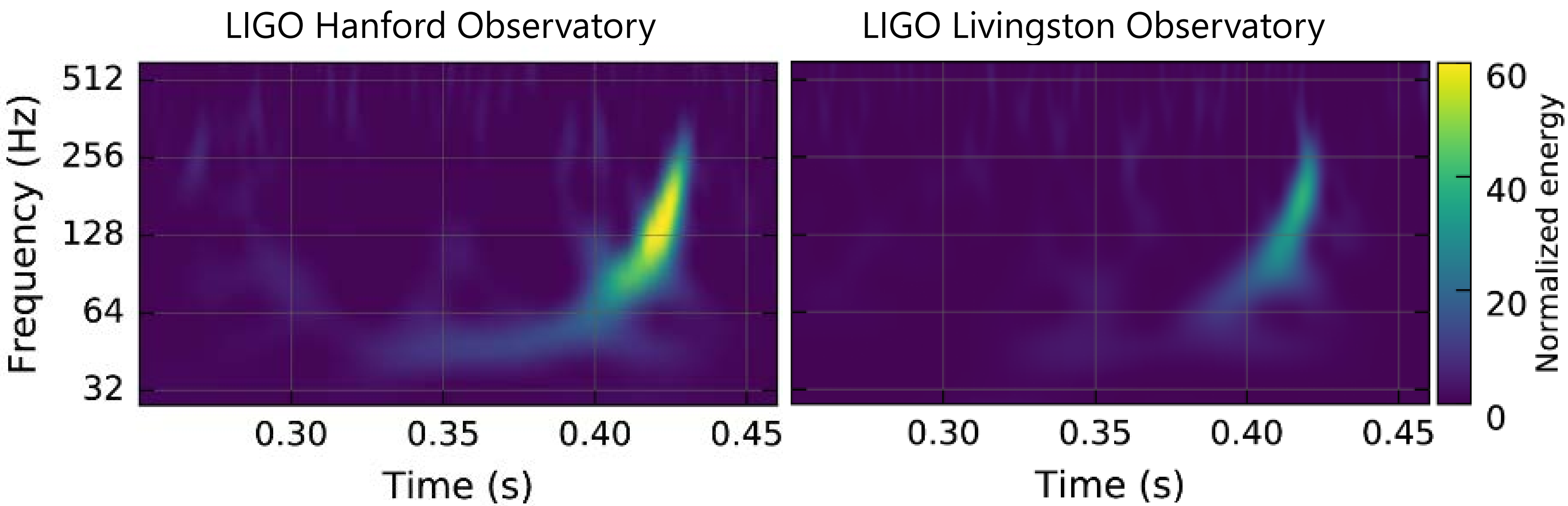
- Official dates : 18th of September 2015 to 12th of January 2016
- Dates with very good confidence : from the 12th of September to the 15th of January 2016
- H1 livetime : 62.6 %
- L1 livetime : 55.3 %



Data jointly analyzed to determine the significance of GW150914
(Sept 12 - Oct 20, 2015,
39 days, 16 days of obs data)



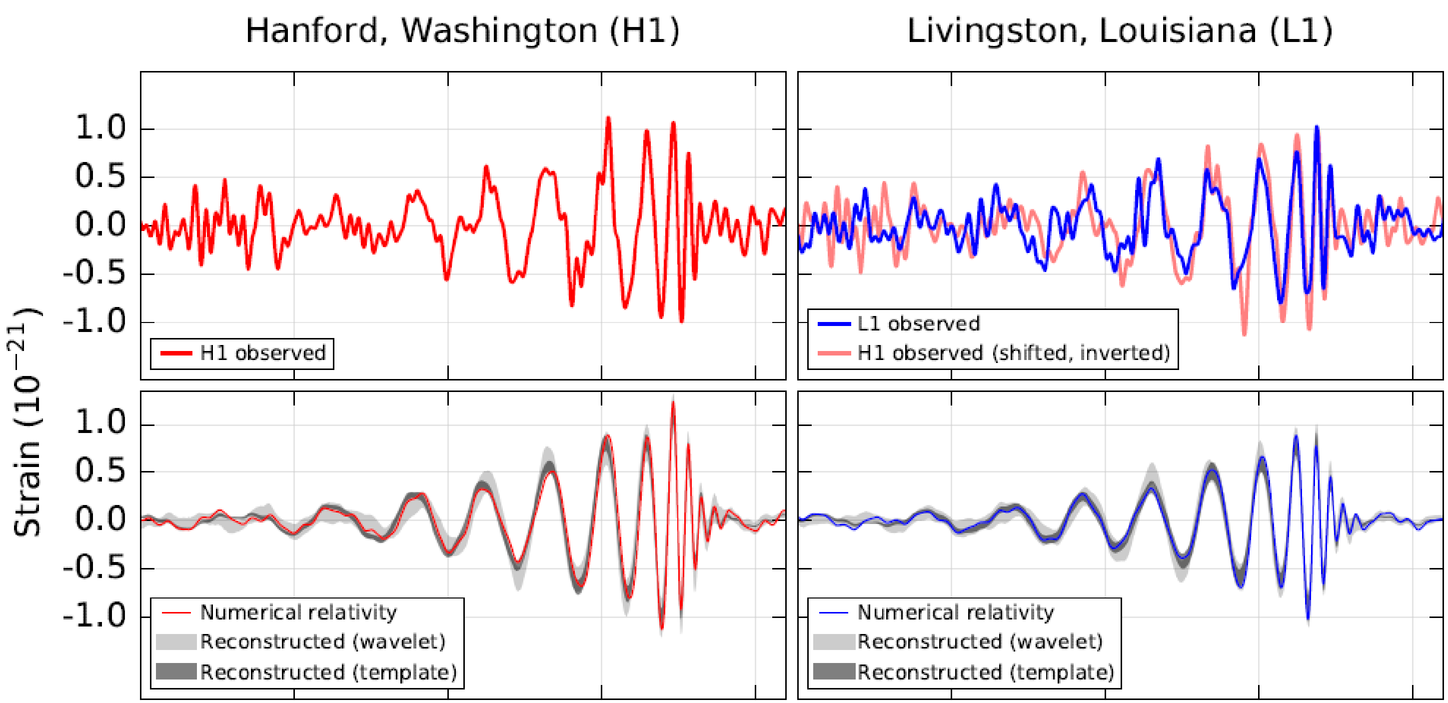
September 14, 2015 – 11:50:45 CET



Initial detection made by a low latency searches for generic GW transients: Coherent WaveBurst

Reported within 3 minutes after data acquisition

GW150914: the signal



- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

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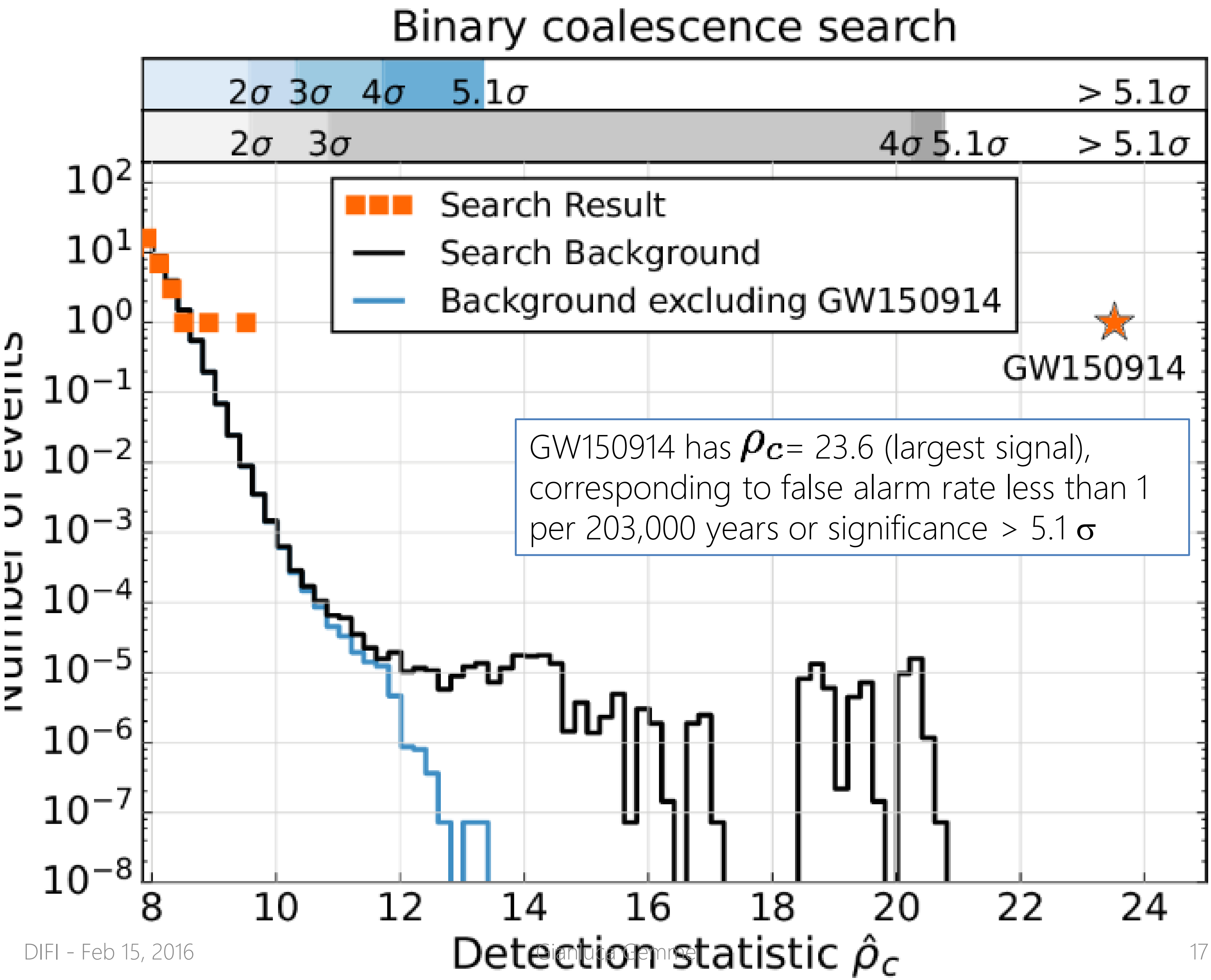
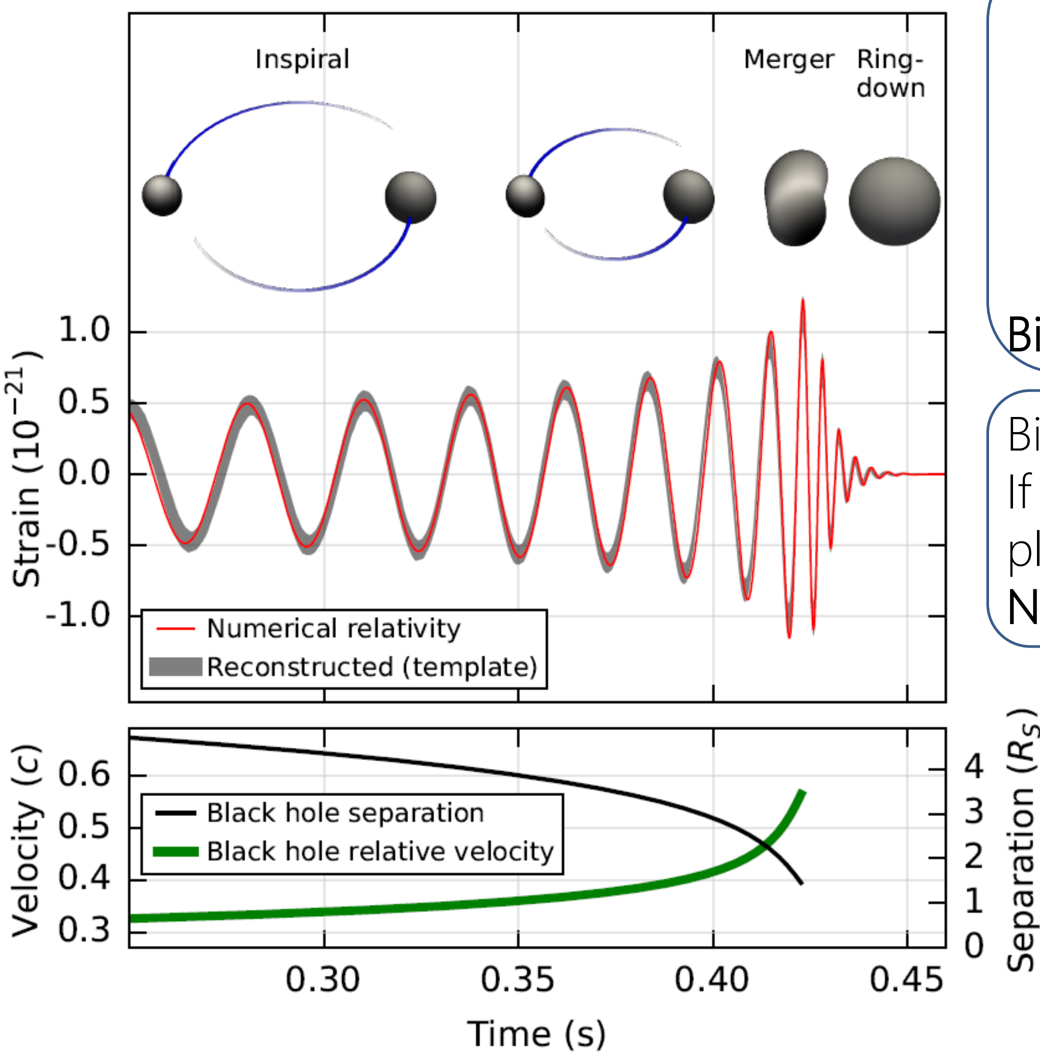


GW150914 has ρ_c= 23.6 (largest signal), corresponding to false alarm rate less than 1 per 203,000 years or significance > 5.1 σ

Why black holes?



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

$$\mathcal{M} \simeq 30 M_\odot$$

$$M = m_1 + m_2 \text{ is } \gtrsim 70 M_\odot$$

Binary neutron stars excluded

Binary made by one BH and one NS?
If so, M_{BH} very large ⇒Coalescence takes place at lower frequencies
NS-BH binary excluded

$$\omega_{\mathrm{Kepler-max}} = 2\pi f_{\mathrm{GW-max}}/2 = 2\pi \times 75 \text{ Hz.}$$

$$R = \left[\frac{GM}{\omega^2_{\mathrm{Kepler-max}}}\right]^{1/3} \sim 350 \text{ km.}$$

$$r_{\mathrm{Schwarz}}(M) = \frac{2GM}{c^2} \sim 210 \text{ km}$$

Source Parameters for GW150914

- Median values with 90% credible intervals, including statistical errors from averaging the results of different waveform models. Masses are given in the source frame: to convert in the detector frame multiply by (1 + *z*)
- Source redshift assumes standard cosmology
- Total energy radiated in gravitational waves is 3.0±0.5 $M_o\ c^2$
  The system reached a peak ~3.6 x10^{56} ergs, and the spin of the final black hole < 0.7

Primary black hole mass	$36^{+5}_{-4}\ \mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180}\ \mathrm{Mpc}$
Source redshift, z	$0.09^{+0.03}_{-0.04}$

Testing GR

- Most relativistic binary know today : J0737-3039
  - Orbital velocity $v/c \sim 2 \times 10^{-3}$
- GW150914 : Higly disturbed black holes
  - Non linear dynamics
- Access to the properties of space-time
  - Strong field, high velocity regime testable for the first time

$$v/c \sim 0.6$$

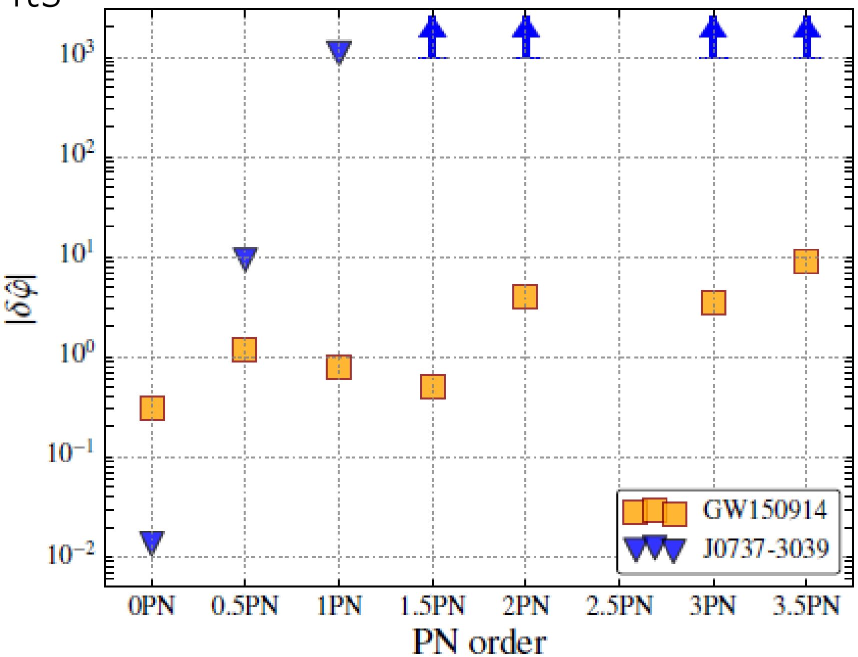
- Tests :
  - Waveform internal consistency check
  - Deviation of PN coefficients from General Relativity
  - Bound on graviton mass
- All tests are consistent with predictions of General Relativity

arXiv:1602.03841

Deviation of PN coefficients from GR

- Post Newtonian formalism
- Phase of the inspiral waveform -> power series in $f^{1/3}$
- Nominal value predicted by GR
- Allow variation of the coefficients

  -> Is the resulting waveform consistent with data ?



- No evidence for violations of GR

arXiv:1602.03841

Upper bound on the graviton mass

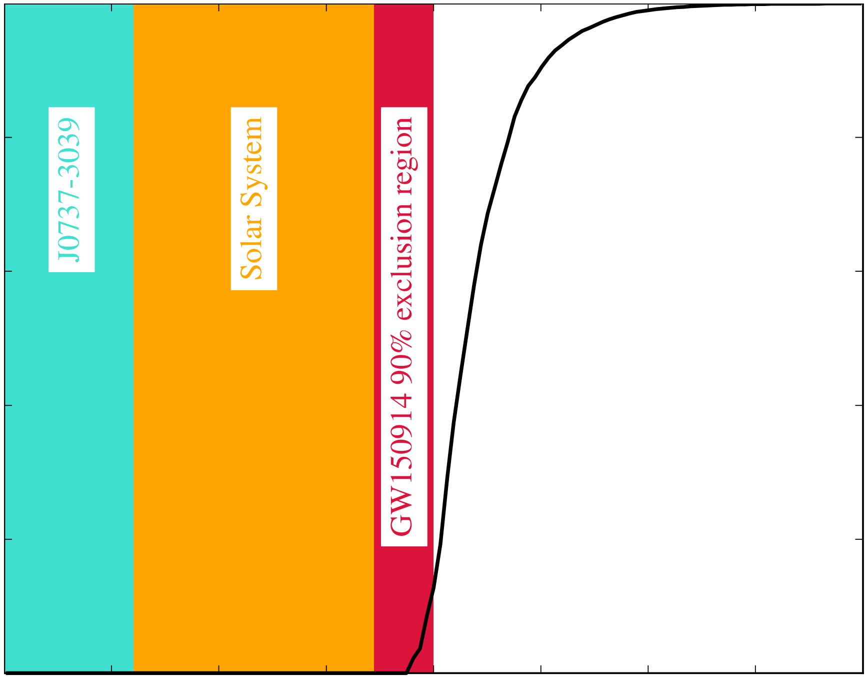
- If $c_{GW} < c$

⇔ gravitational waves have a modified dispersion relation

- Findings : at 90 % confidence, $\lambda_g > 10^{13}$ km

or equivalently

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



arXiv:1602.03841

Conclusions

Binary black holes do exist!
Form and merge in time scales accessible to us
and **we can listen to them** coalesce

We built *audio telescopes* to sense the vibrations of spacetime that these events send out

this is the birth of gravitational wave astronomy

We look forward to upcoming science runs with Advanced Virgo online!

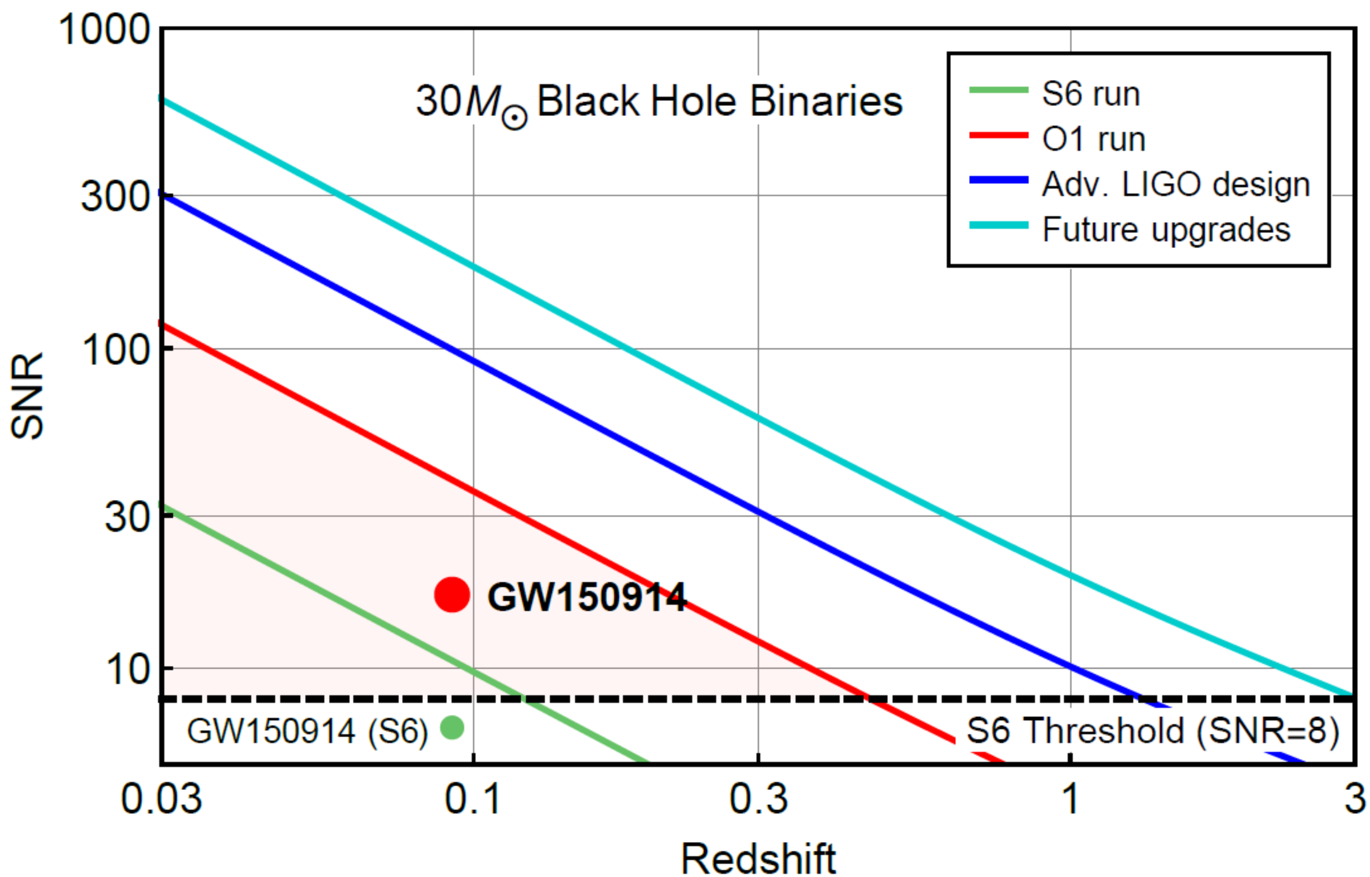
For further details:
talk by G. Stratta this afternoon (15:40) - EM follow-up
poster by D. Bersanetti – Locking strategy

SPARES

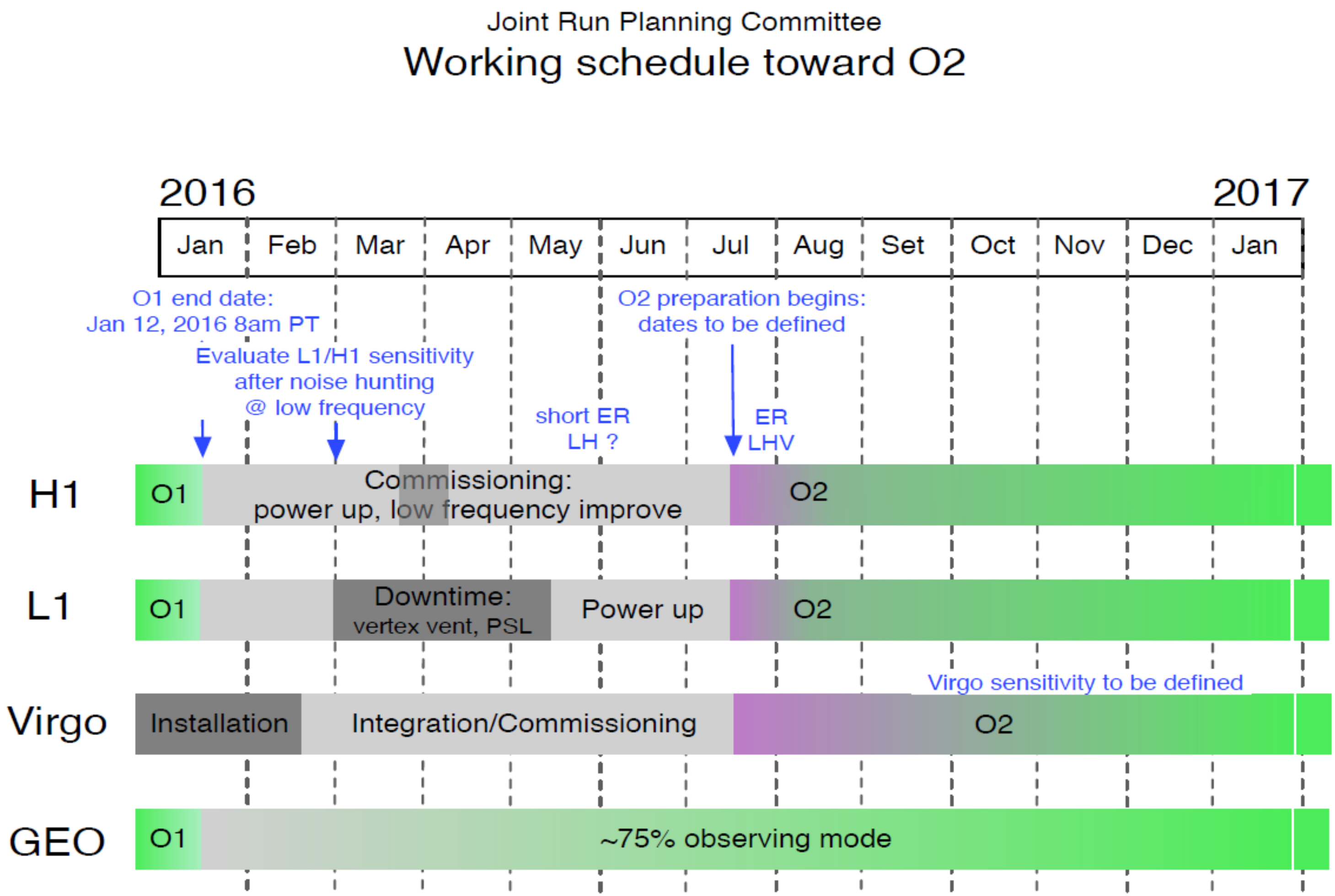
O1: Data analysis & Computing

- Several seach pipelines with crucial contribution from Virgo
  - BURST: cWB, oLIB, STAMP (long duration transients), GRB-triggered search, Cosmic Strings
  - EM FOLLOW-UP: low-latency searches, SkyMaps, GW alert production and transmission
  - CBC: MBTA (low latency searches, sky localization), TIGER (test of strong-field dynamics of GR)
  - CW: NoEMI (noise line identification), All-sky searches (time domain F-stat, Frequency Hough, polynomial search), targeted and directed searches (time domain F-stat, 5-vector)
  - SGWB: Isotropic and directional searches (Schumann resonances, polarization states)
- Computing
  - Continuous data transfer of O1 data to CNAF (almost in real time)
  - Ongoing tests to improve the compatibility with LDG
  - Strong support/involvment of CNAF staff (bi-weekly meetings)

Signal-to-noise ratio vs z for 30 $M_\odot$ BBH



Towards O2


Joint Run Planning Committee
Working schedule toward O2
2016
2017
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Set
Oct
Nov
Dec
Jan
O1 end date:
Jan 12, 2016 8am PT
Evaluate L1/H1 sensitivity
after noise hunting
@ low frequency
short ER
LH ?
O2 preparation begins:
dates to be defined
ER
LHV
H1
O1
Commissioning:
power up, low frequency improve
O2
L1
O1
Downtime:
vertex vent, PSL
Power up
O2
Virgo sensitivity to be defined
Virgo
Installation
Integration/Commissioning
O2
GEO
O1
~75% observing mode

BBH rates

- GW150914 observation → interesting rate of BBH events
  - Range within 2 – 400 / Gpc^3 / yr
  - High mass binary→ loud signal → visible far away
- At high redshifts, could be many more sub-threshold
  - Not detectable as individual signals
  - Potentially detectable as a correlated noise among detectors
- Predictions *in principle* model dependent
  - Depend on Star Formation Rate
  - Depend on **delay between formation and merger**, in turn depending on initial eccentricity, spin ….
  - We've got just one observation, hard to constrain models

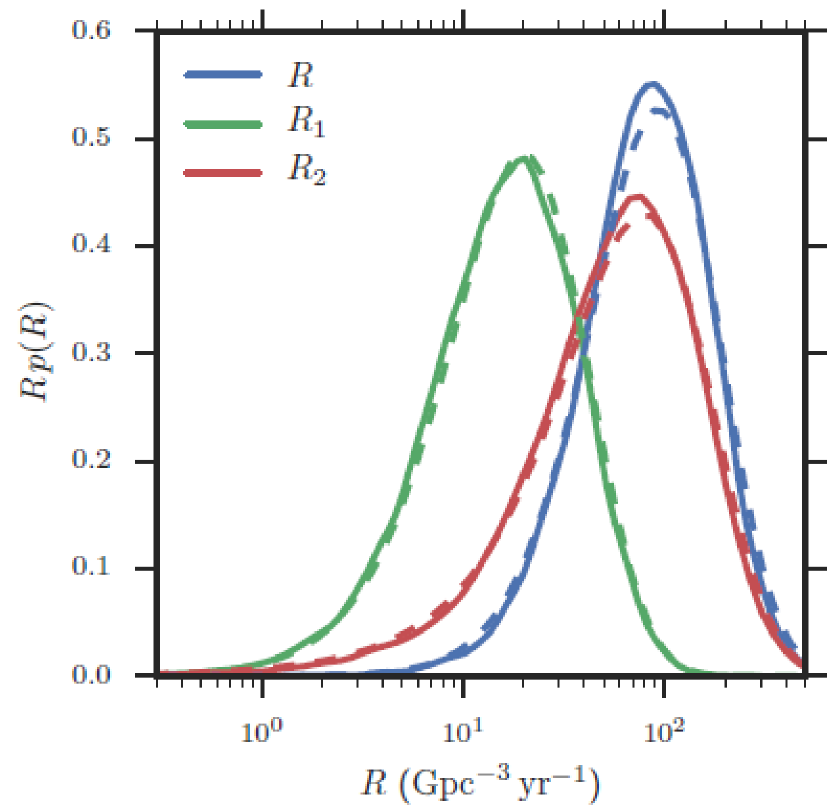
Rate estimates

- With only one event, can't measure rates accurately
- Estimates also depend upon astrophysical assumptions

- Rate: 4 - 53 $Gpc^{-3}yr^{-1}$
- Consistent with former predictions: 0.1 -300 $Gpc^{-3}yr^{-1}$ (Abadie et al. 2010 arXiv:1003.2480)

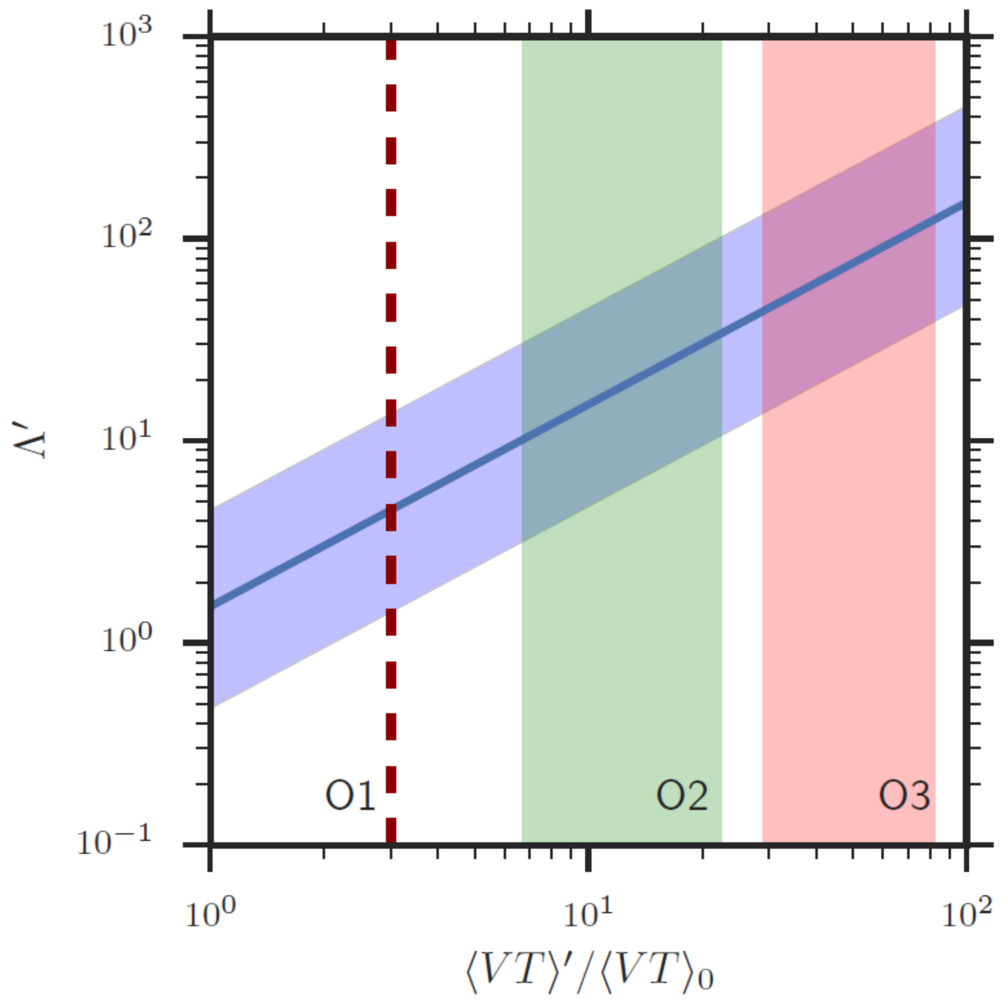
- Including LVT151012
  6 – 400 $Gpc^{-3}yr^{-1}$

- Overall 4 – 600 $Gpc^{-3}yr^{-1}$



arXiv:1602.03842

How many BBH merger in future data?



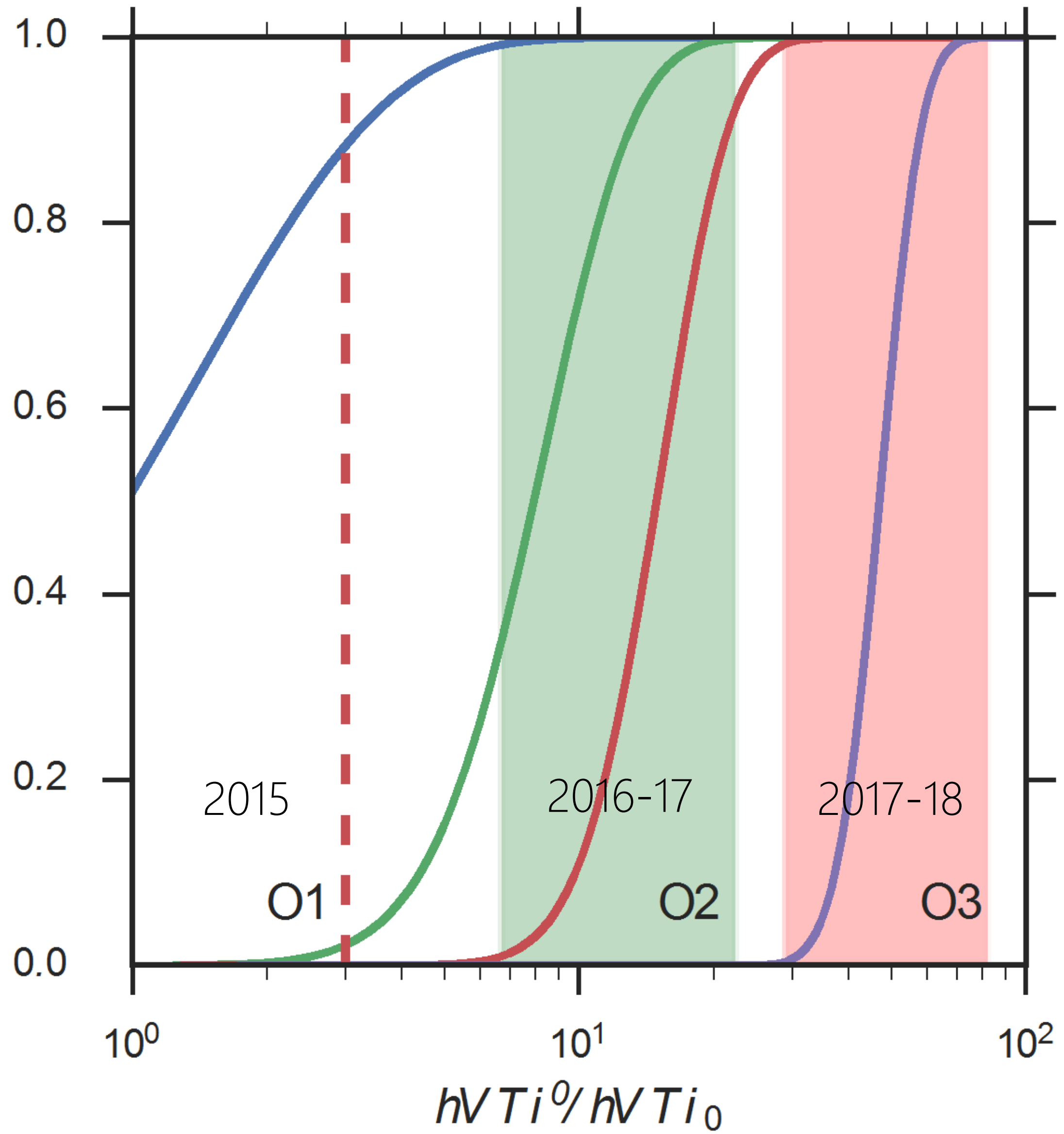
arXiv:1602.03842

Expectations for future runs

Probability of observing

- N > 0 (blue)
- N > 5 (green)
- N > 10 (red)
- N > 35 (purple)

highly significant events, (FARs <1/century) as a function of surveyed time-volume.



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