



Le onde gravitazionali, nuova voce dell'Universo

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per le Collaborazioni LIGO e Virgo

LIGO Livingston Observatory
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Virgo, Cascina, Italy

LIGO Hanford Observatory
Washington, USA



GEOMETRIA E GRAVITAZIONE: LA RELATIVITÀ GENERALE

L'universalità della caduta dei corpi

1638

Galileo:

e finalmente ho preso due palle, una di piombo ed una di sughero, quella ben più di cento volte più grave di questa, e ciascheduna di loro ho attaccata a due sottili spaghetti eguali, lunghi quattro o cinque braccia, ...

gli ho dato l'andare nell'istesso momento, ed esse, scendendo per le circonferenze de' cerchi descritti da gli spaghi eguali, hanno sensatamente mostrato, come la grave va talmente sotto il tempo della leggiera, che né in ben cento vibrazioni, né in mille, anticipa il tempo d'un minimo momento,

ma camminano con passo egualissimo



Spazio tempo

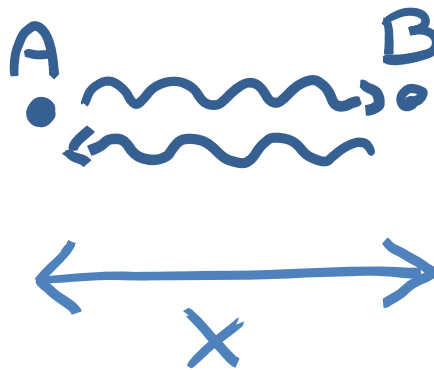
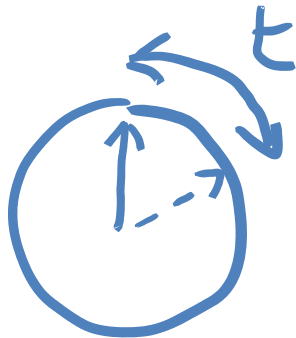
- Il moto di un corpo sottoposto alla forza di gravità non dipende dalla massa, forma, struttura
- Tutti i corpi si muovono con accelerazione di gravità ...
- ... nello spazio(-tempo) comune a tutti

Luce: Misura dello spazio tempo

Usiamo la luce:

per vedere quanto distano dei corpi nello spazio

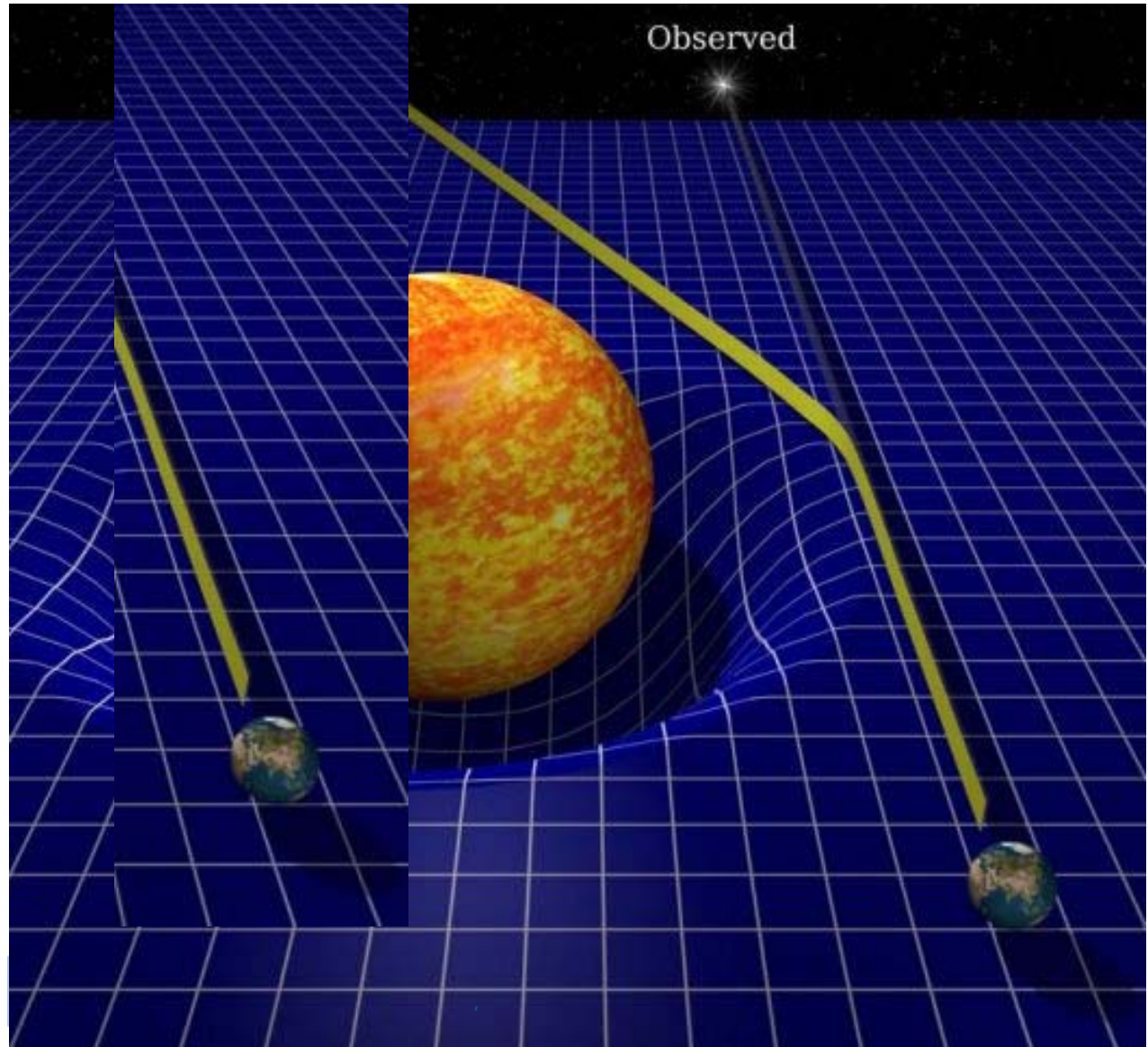
per vedere quanto tempo trascorre tra due eventi



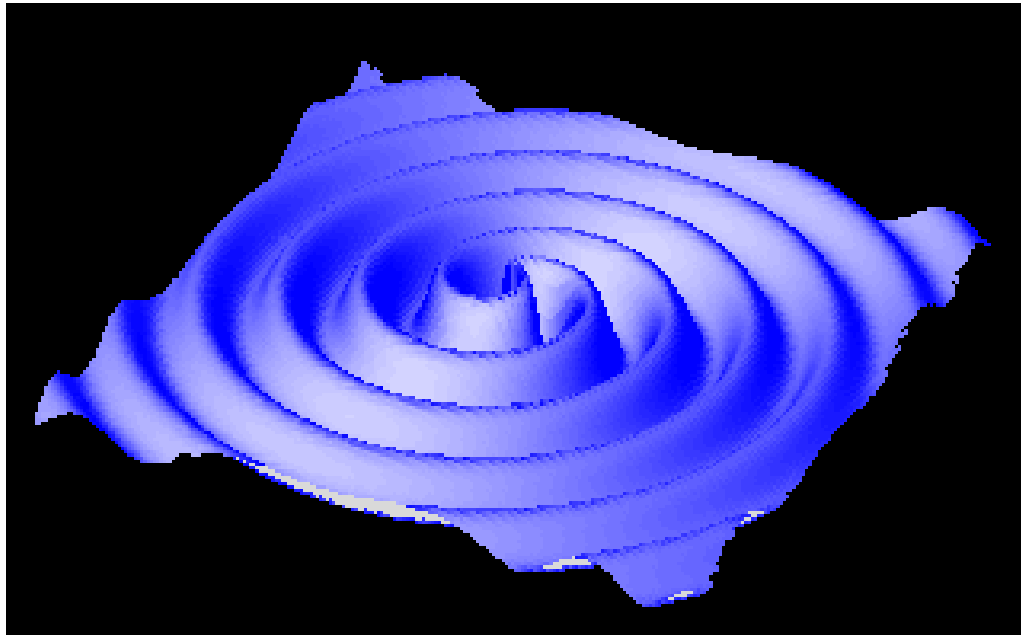
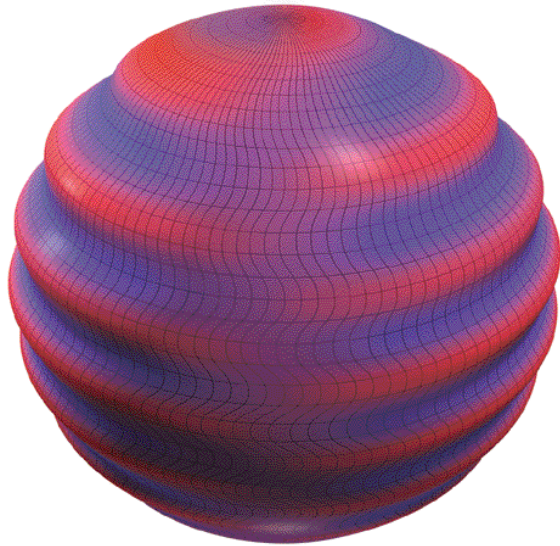
$$2x = c \cdot t$$

Geometria e gravitazione

- In assenza di gravità, la luce viaggia in linea retta a velocità costante
- Tesse la trama di uno spazio-tempo dove vale la geometria euclidea.
- La luce dice dove si trovano i corpi e quando avvengono gli eventi.
- Le masse modificano la trama, la luce curva, rallenta... è cambiata la geometria
- Vicino al Sole l'effetto è di qualche parte su un milione.



Propagazione della curvatura



La curvatura non si crea istantaneamente ovunque
Si propaga alla velocità della luce

L'onda gravitazionale è una grinza che viaggia sul tessuto dello spazio tempo
Mantiene la stessa forma

Trasporta energia

Ci indica il moto delle stelle anche se non le vediamo, è un segnale «diverso»



INTERFEROMETRI PER RIVELARE ONDE GRAVITAZIONALI

GW150914 - April 2016

Francesco Fidecaro

9

Un'antenna per onde gravitazionali

- Il passaggio di un'onda gravitazionale cambia la distanza tra due masse, altrimenti ferme
- Più le masse sono lontane, maggiore è l'effetto ...
- ... che è piccolissimo anche per masse distanti 3 km:

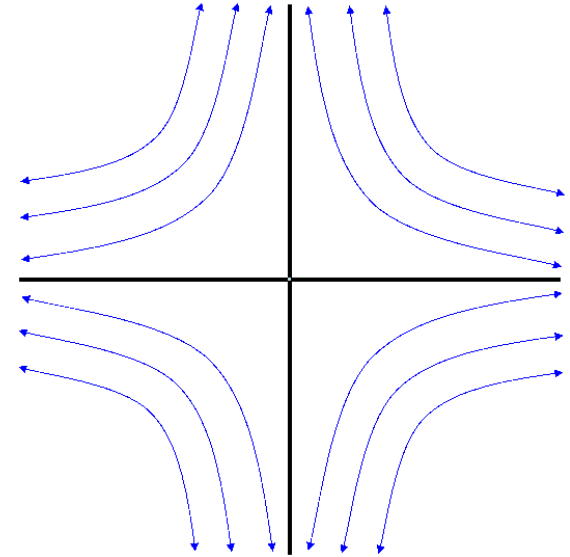
$$1/10^{20} \text{ m} = \frac{1}{\underbrace{1000 \dots 000}_{20 \text{ zeri}}} \text{ m}$$

- È un decimiliardesimo del raggio di un atomo, da misurarsi su oggetti di diametro 35 cm e spessi 20 cm.

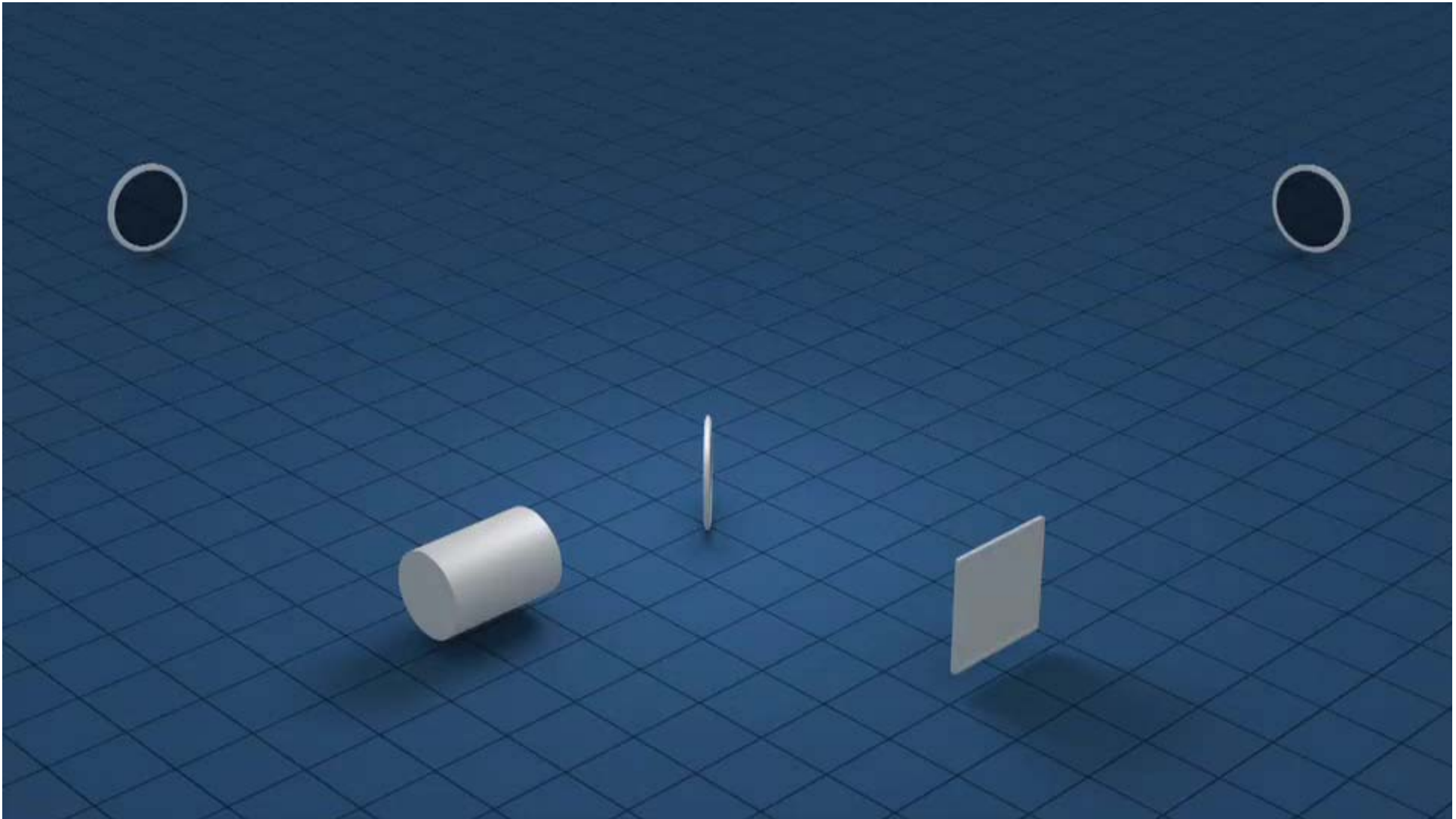
L'Interferometro

Un trasduttore per Onde Gravitazionali

- Un'onda che entra perpendicolarmente nello schermo muove le masse così:
- si usa la tecnica dell'interferenza tra due fasci di luce per vedere le variazioni di distanza.



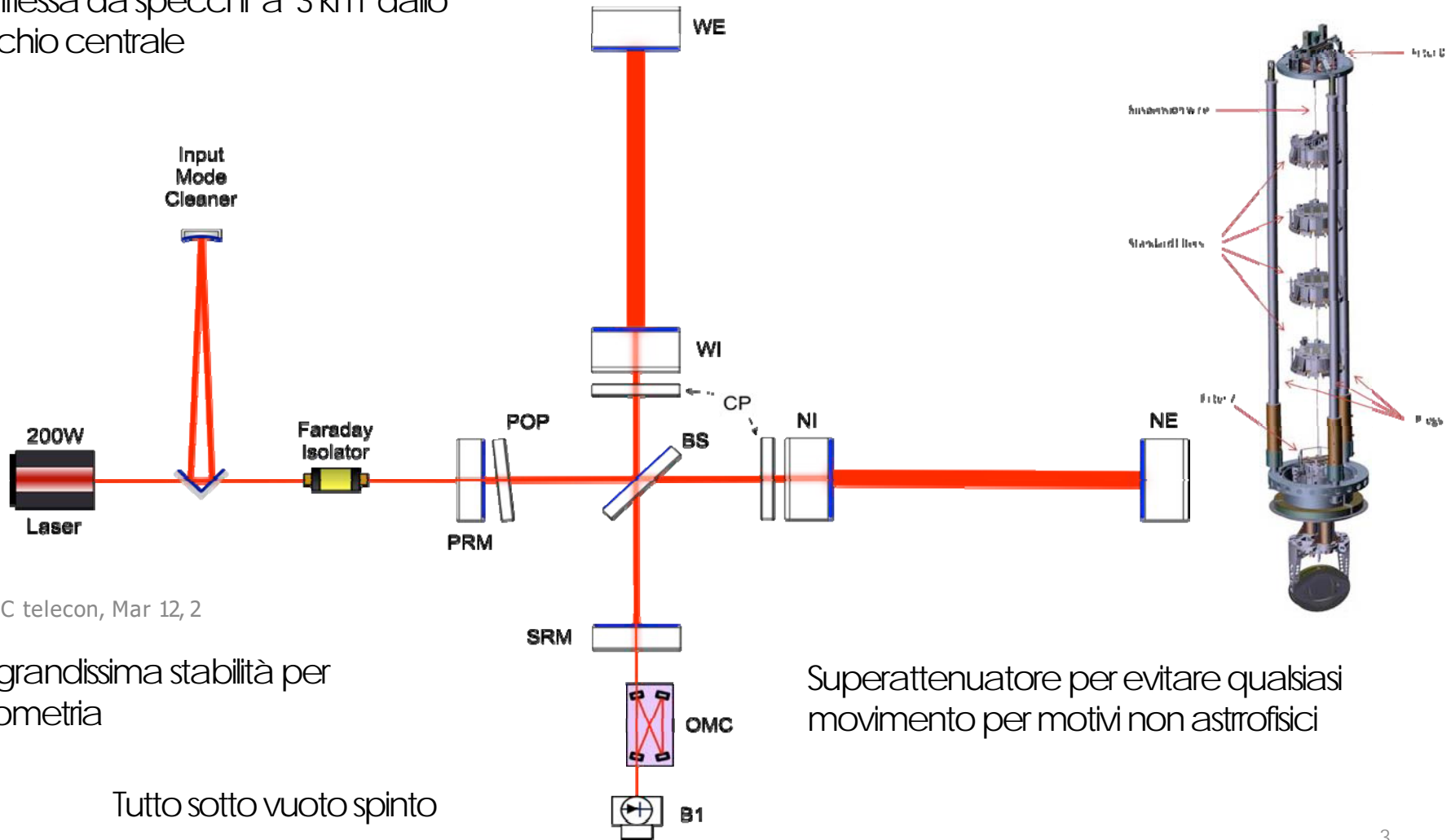
Interferometria con due bracci perpendicolari tra loro



PRINCIPALI COMPONENTI

Confronto della distanza percorsa dalla luce riflessa da specchi a 3 km dallo specchio centrale

Specchi lavorati al meglio per mantenere le caratteristiche del fascio laser



LVC telecon, Mar 12, 2

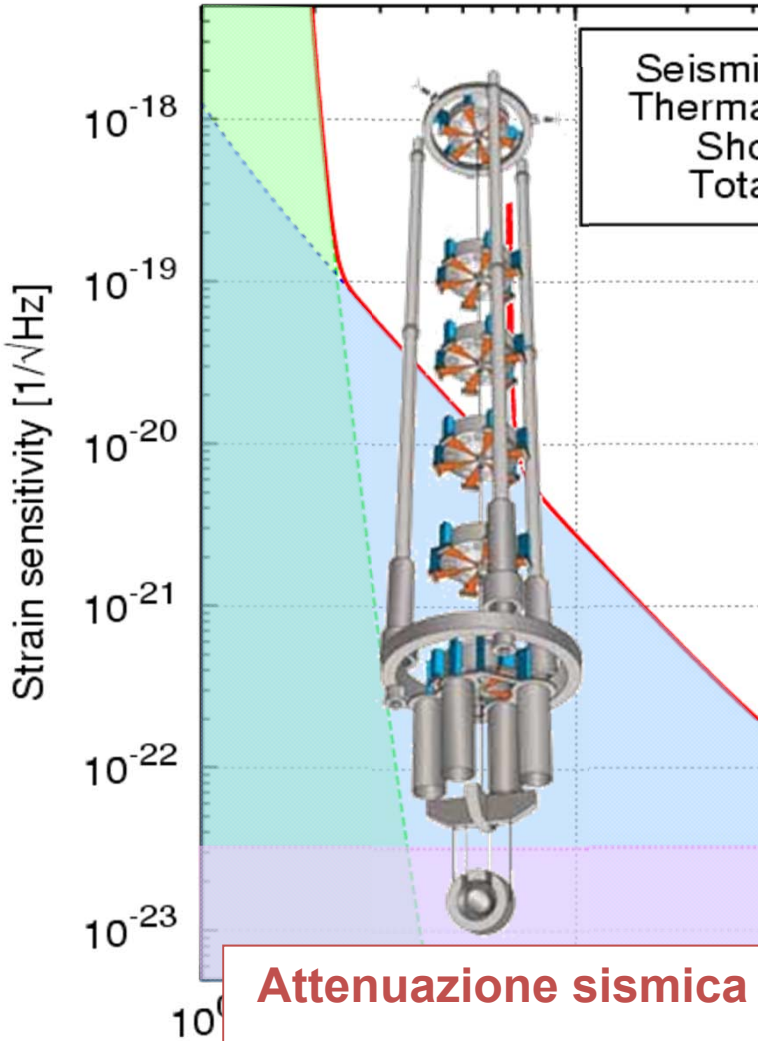
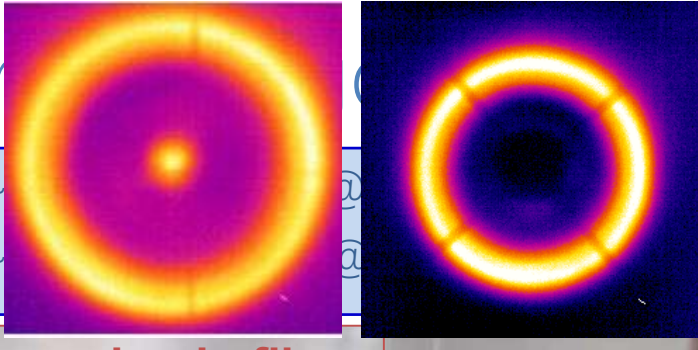
Laser di grandissima stabilità per l'interferometria

Tutto sotto vuoto spinto

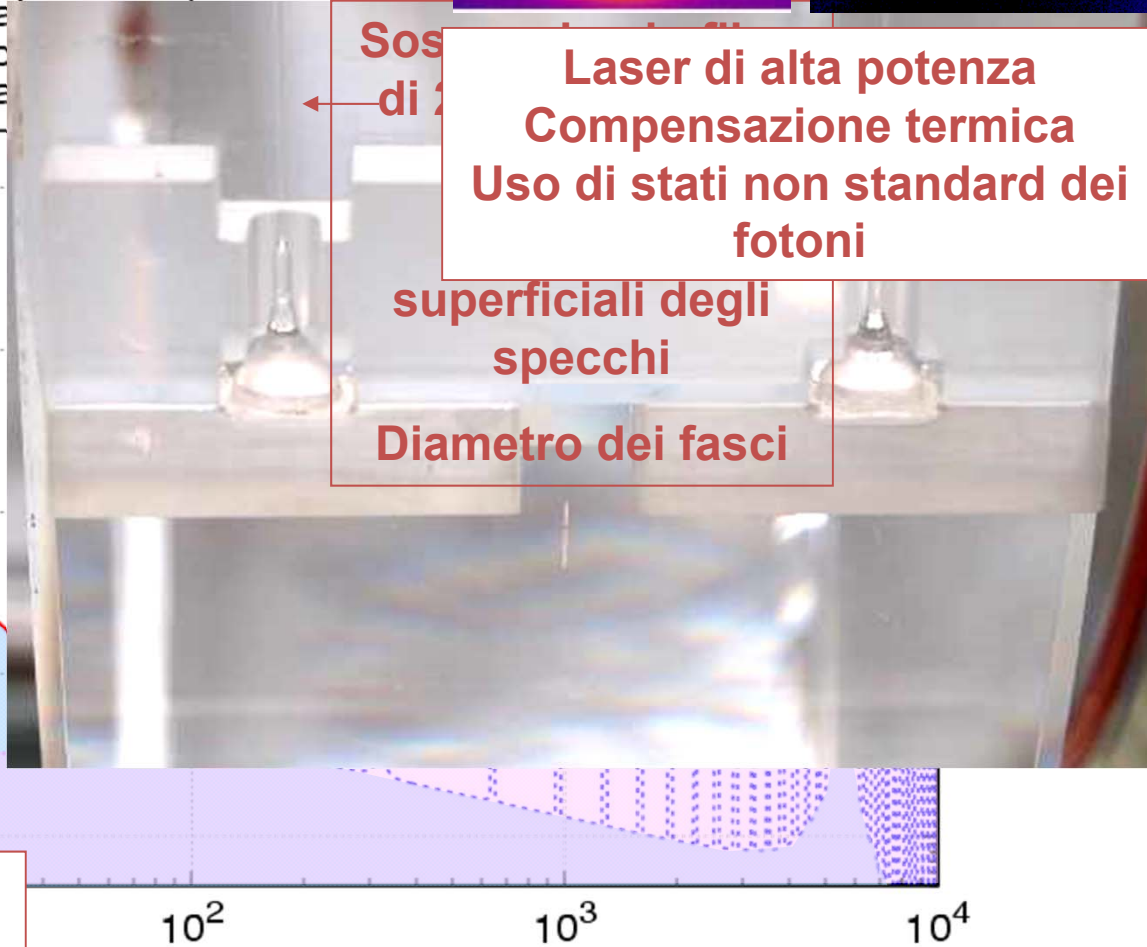
Superattenuatore per evitare qualsiasi movimento per motivi non astrofisici

Sorgenti di rumore

- $h \sim$
- $h \sim$



Attenuazione sismica
Fluttuazioni locali della gravità



Sost...
di 2

Laser di alta potenza
Compensazione termica
Uso di stati non standard dei fotoni

superficiali degli specchi

Diametro dei fasci



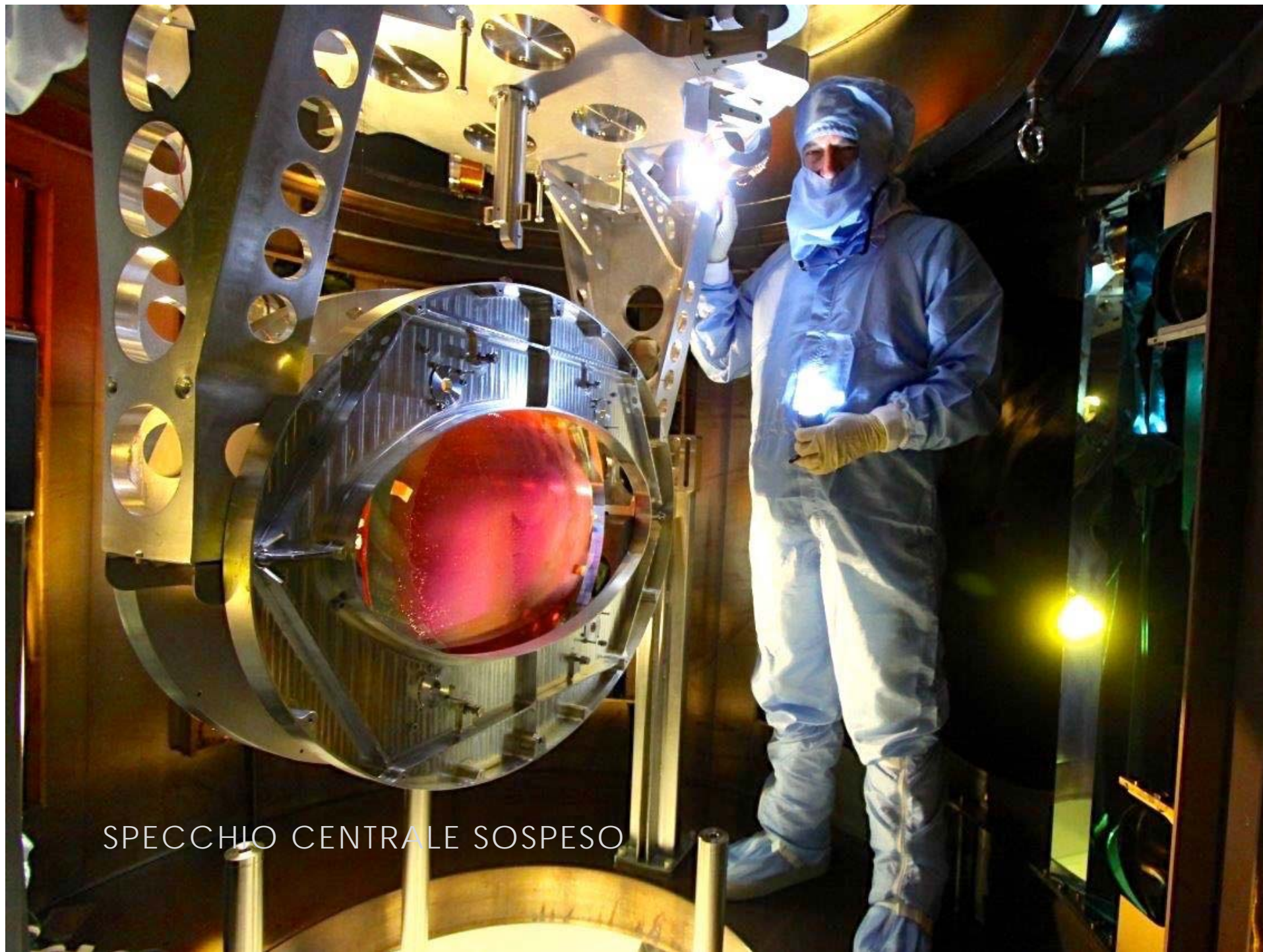
Il sito di Virgo a Cascina

- Prima generazione collaudata (1992-2009)
- Advanced Virgo: passaggio alla seconda generazione
- Obiettivi:
 - Aumentare il tasso di conteggio di ~1000
 - Partecipare alle prime rivelazioni
 - Iniziare l'astronomia gravitazionale
- Finanziamento da INFN, CNRS, EGO, Nikhef, deciso in Dic 2009: 23.8 ME
 - Con contributi dalla Polonia e dall'Ungheria
- "Prima luce" attesa in primavera 2016





Polishing terminato, deposizione strati riflettenti in corso



SPECCHIO CENTRALE SOSPESO



SUPERATTENUATORI

SA upgrade in progress.
BS completed, WI close to completion.

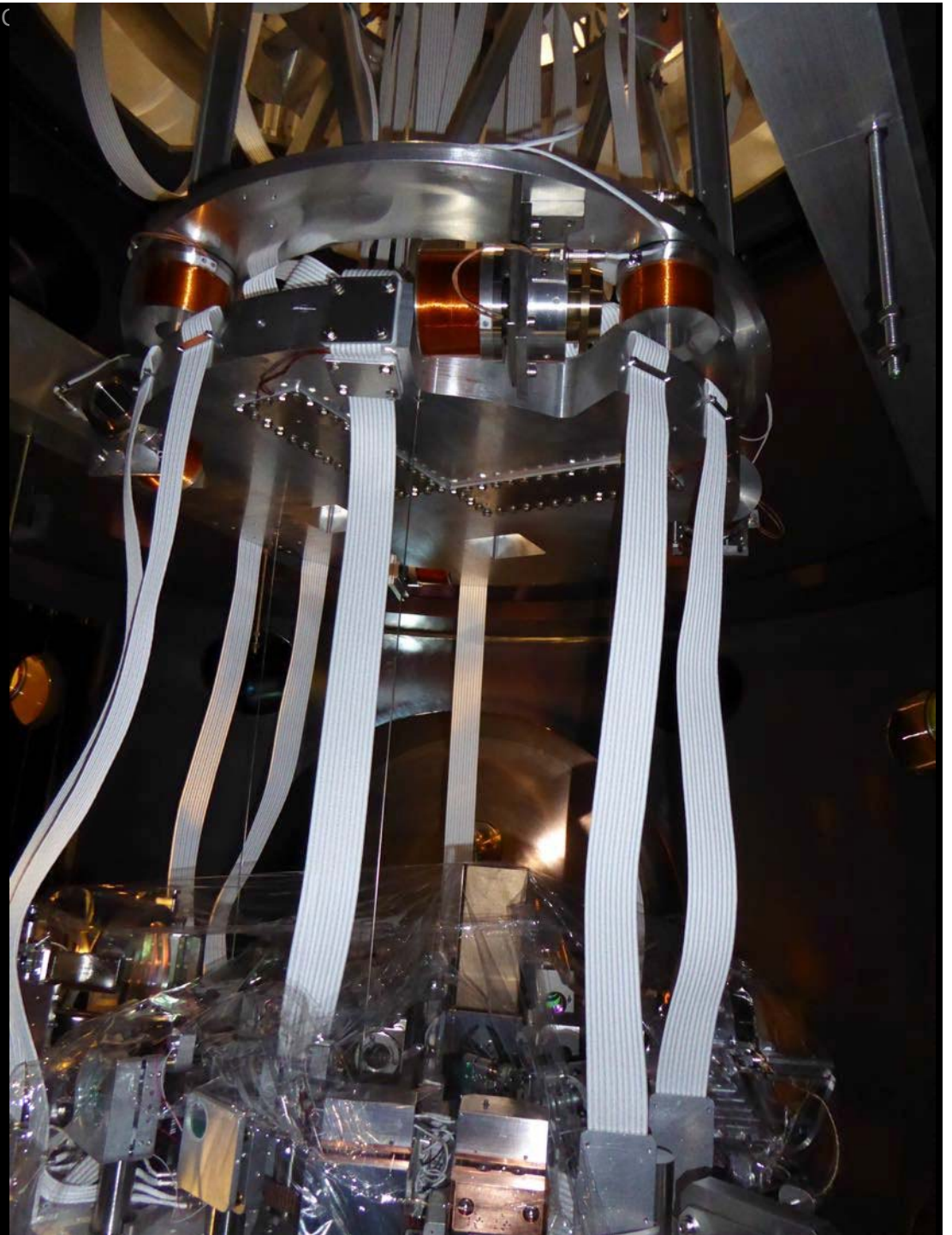


BANCO DI RIVELAZIONE



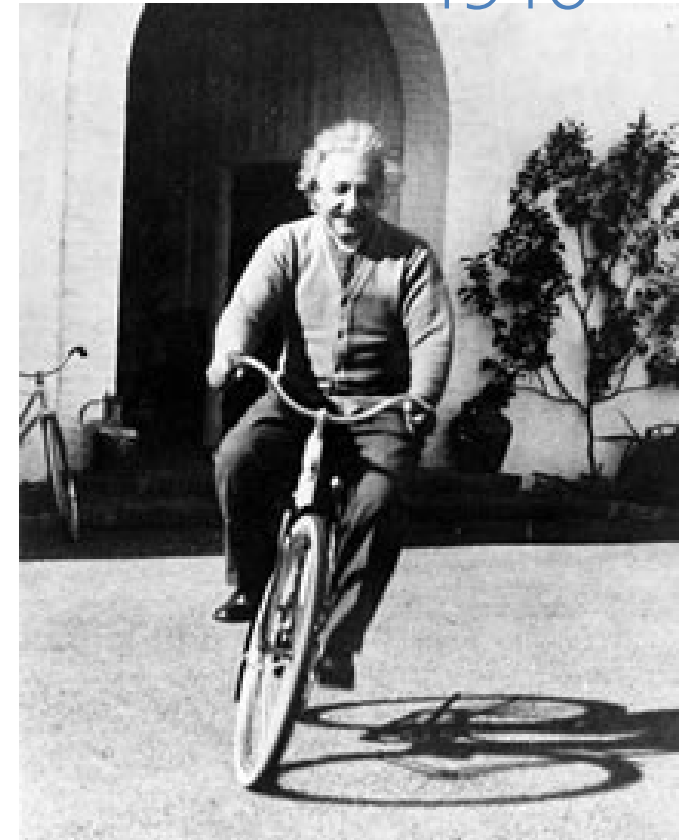
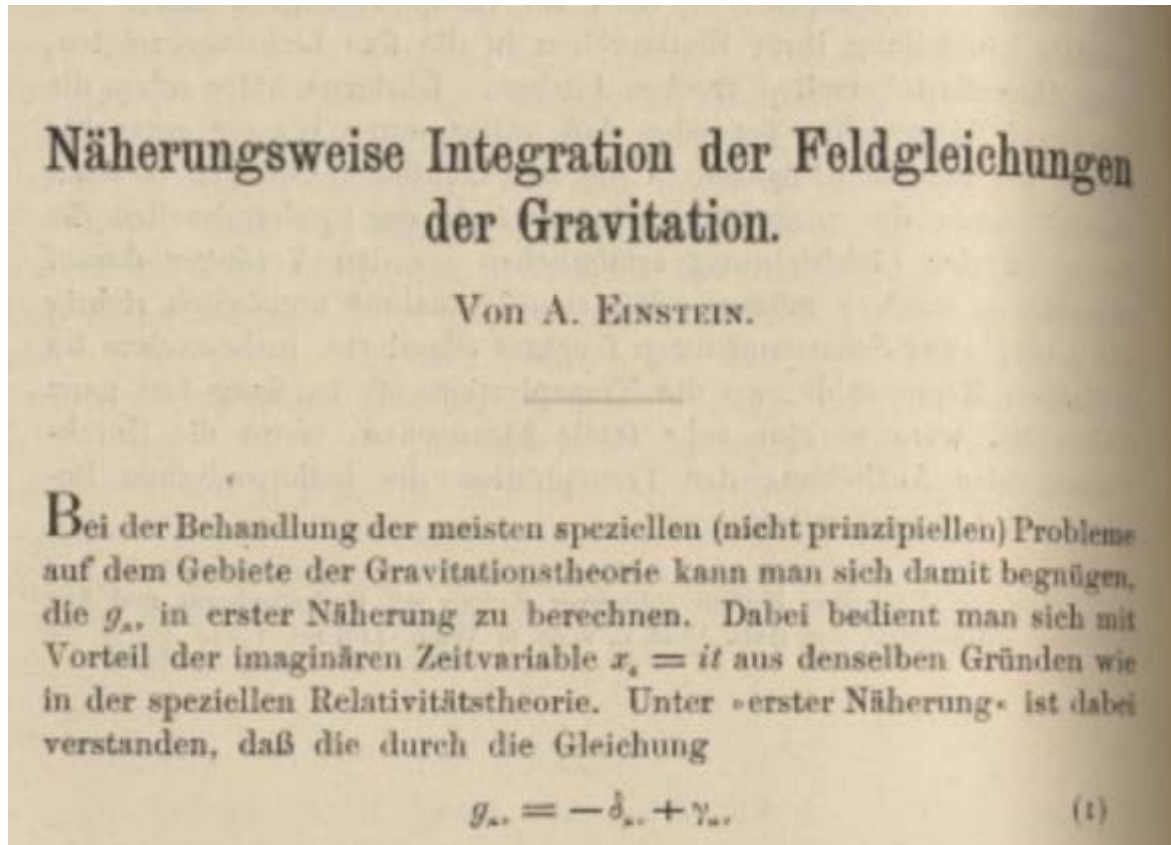


... SOSPESO IN TORRE



L'EVENTO

Cento anni fa
1916



Albert Einstein

Näherungsweise Integration der Feldgleichungen der Gravitation, Berlin 22.6.1916

Integrazione in modo approssimato delle equazioni di campo della gravitazione

Quest'anno 2016

PRL 116, 061102 (2016)

Selected for a Viewpoint in *Physics*
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 frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21} . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ . The source lies at a luminosity distance of 410_{-180}^{+160} Mpc corresponding to a redshift $z = 0.09_{-0.04}^{+0.03}$. In the source frame, the initial black hole masses are $36_{-4}^{+5} M_{\odot}$ and $29_{-4}^{+4} M_{\odot}$, and the final black hole mass is $62_{-4}^{+4} M_{\odot}$, with $3.0_{-0.5}^{+0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

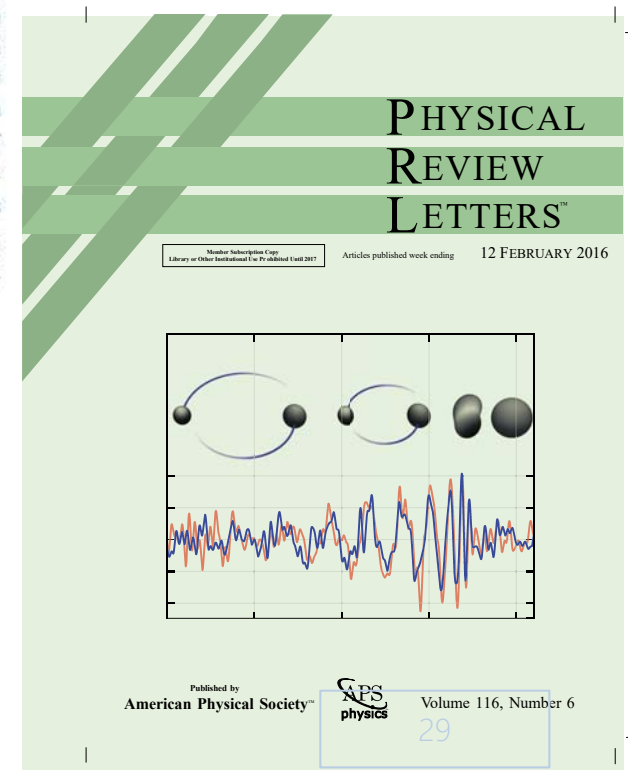
DOI: 10.1103/PhysRevLett.116.061102

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

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

GW150914 - April 2016

Francesco Fidecaro





THE EVENT GW150914 AT 2015-09-14 11:50:45 CEST

September 14, 2015 – 12:56 CEST

From: Marco Drago <marco.drago@aei.mpg.de>
Sent: lunedì 14 settembre 2015 12:56
To: burst@sympa.ligo.org
Cc: cbc@ligo.org; The LIGO Data Analysis Software Working Group; Calibration; dac@sympa.ligo.org; burst@ligo.org; detchar@sympa.ligo.org; losc-devel@ligo.org; lsc-all@ligo.org
Subject: [dac] Very interesting event on ER8

Hi all,

cWB has put on gracedb a very interesting event in the last hour.

<https://gracedb.ligo.org/events/view/G184098>

This is the CED:

https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

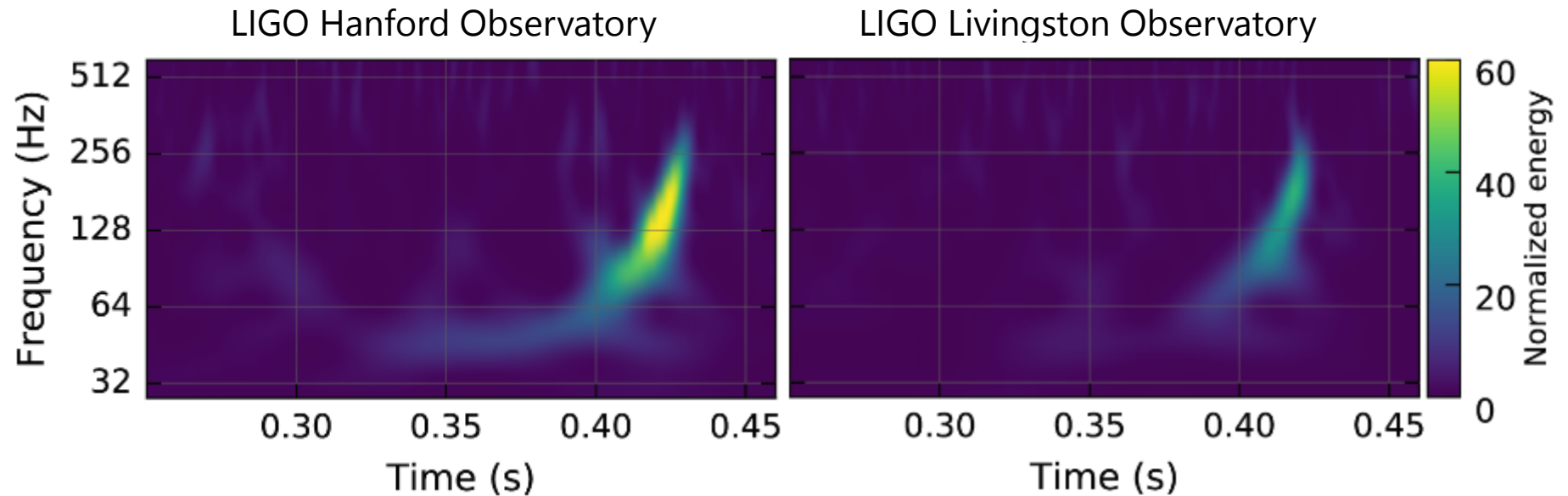
Qscan made by Andy:

https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/

https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/ It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

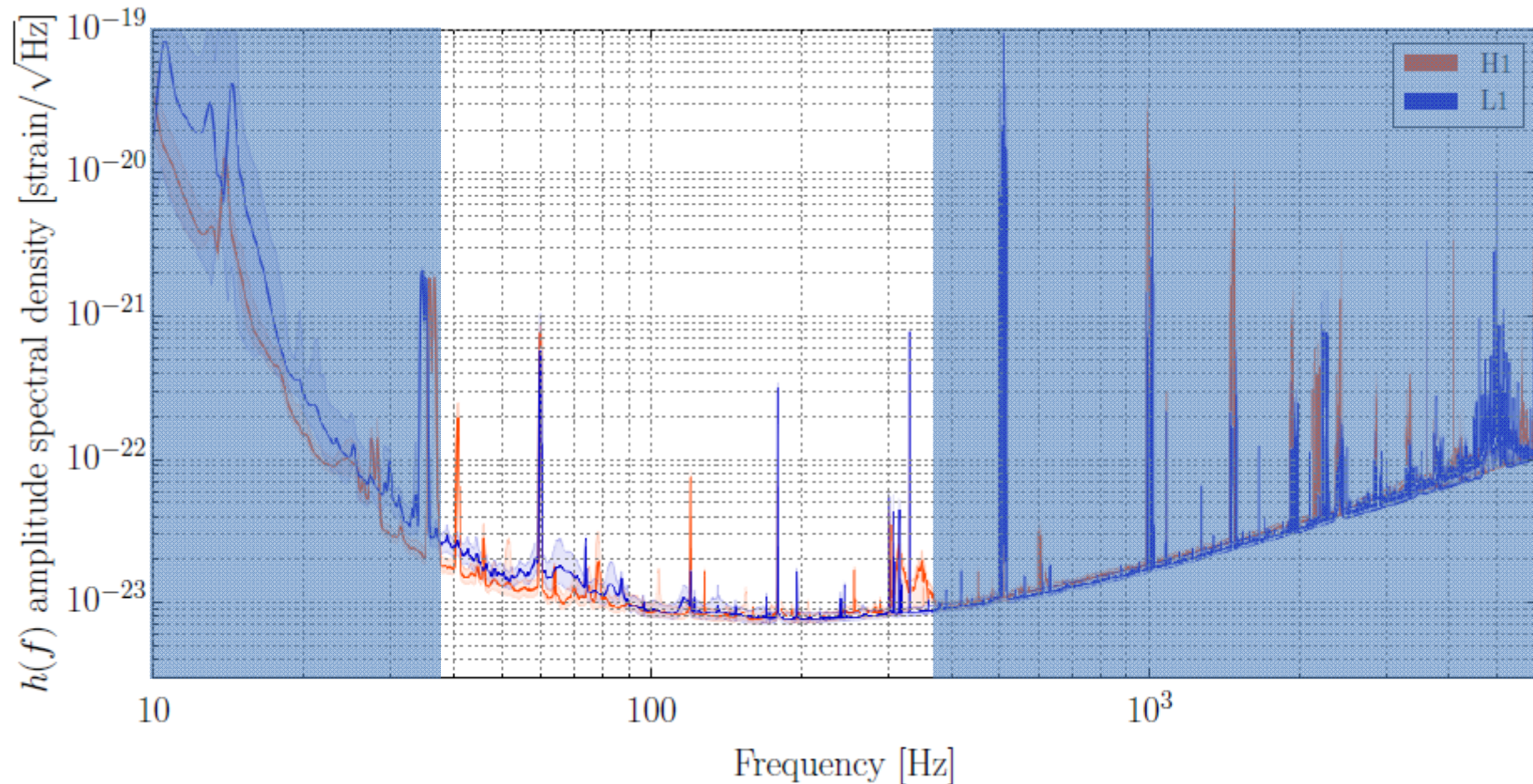
September 14, 2015 – 11:50:45 CEST



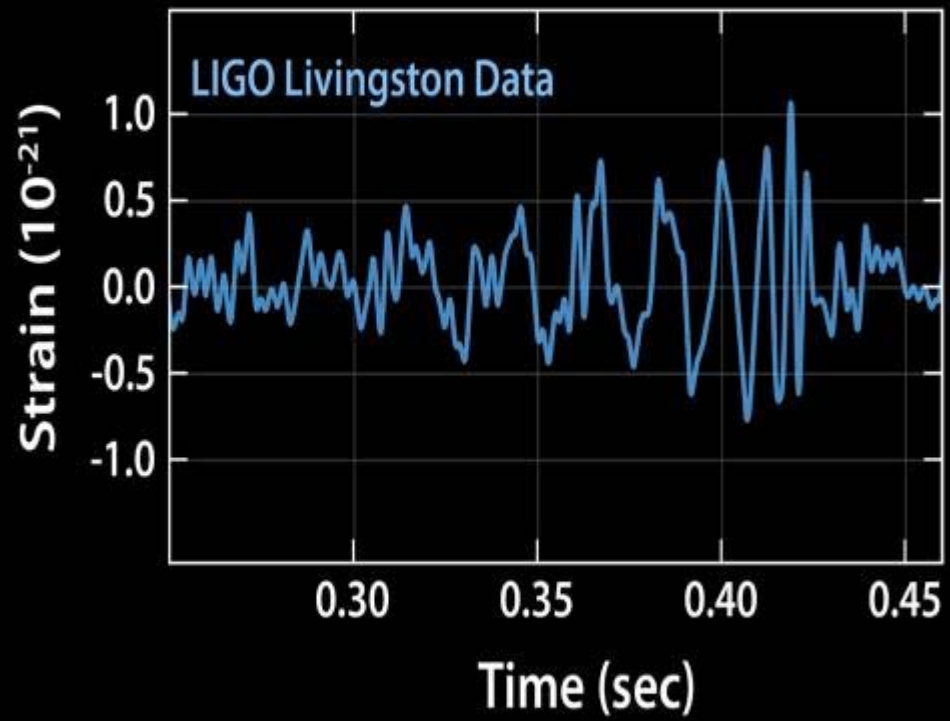
Initial detection made by a low latency searches for generic GW transients: **Coherent WaveBurst**

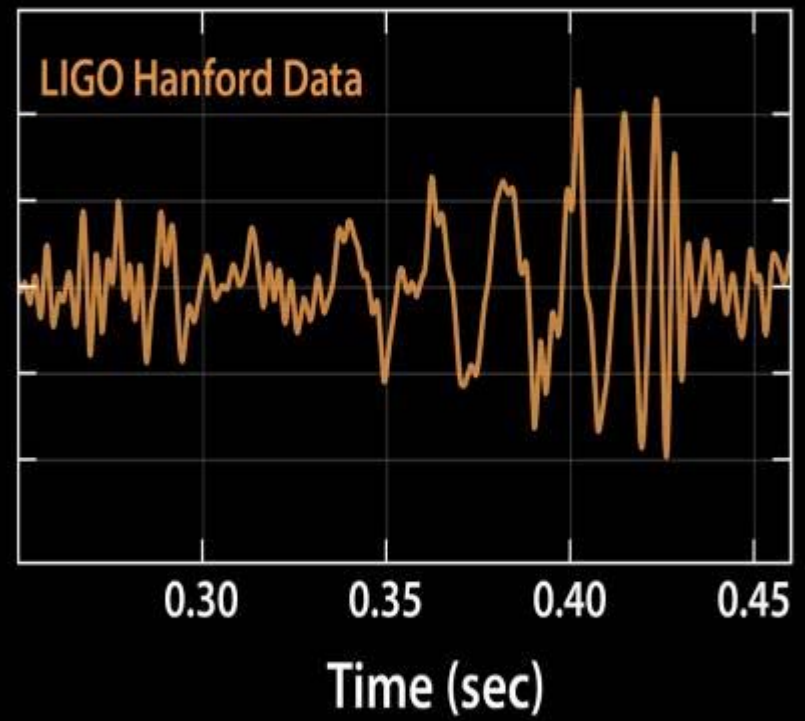
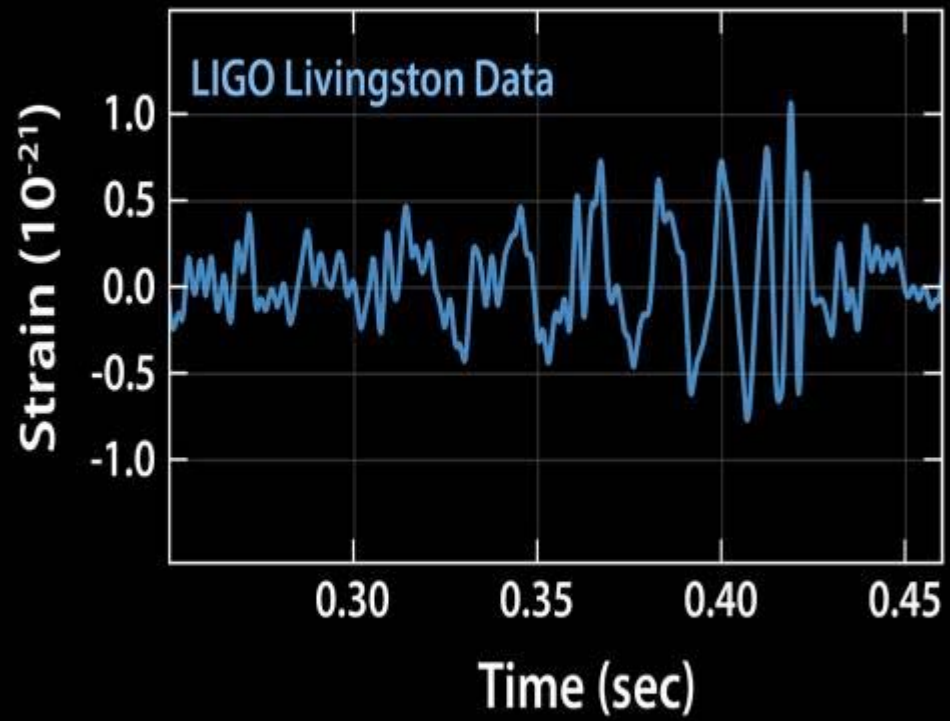
Reported within 3 minutes after data acquisition

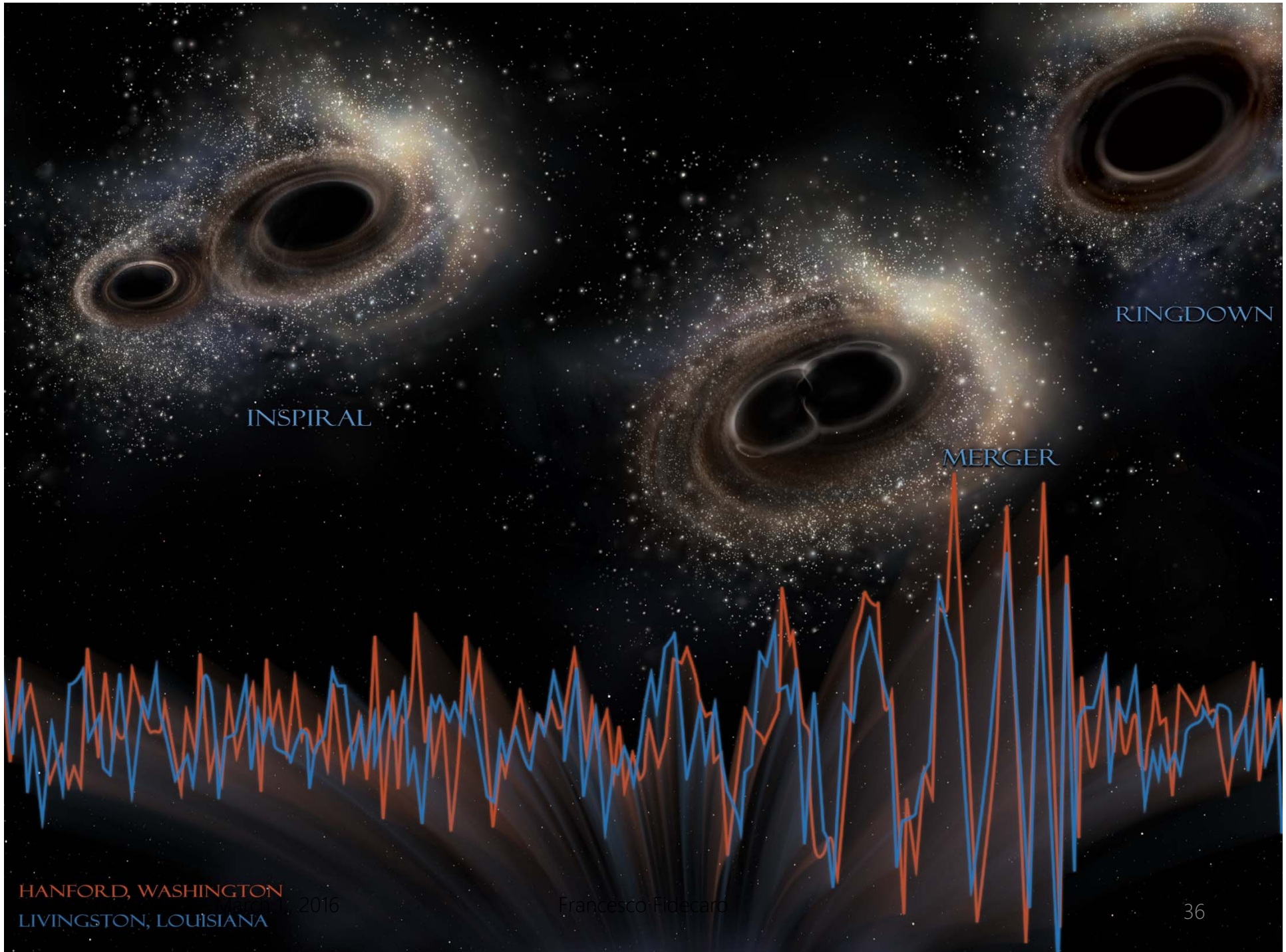
Rumore nei rivelatori



Si applica un filtro passabanda da 35-350 Hz e si eliminano le bande per le linee spettrali dovute allo strumento







INSPIRAL

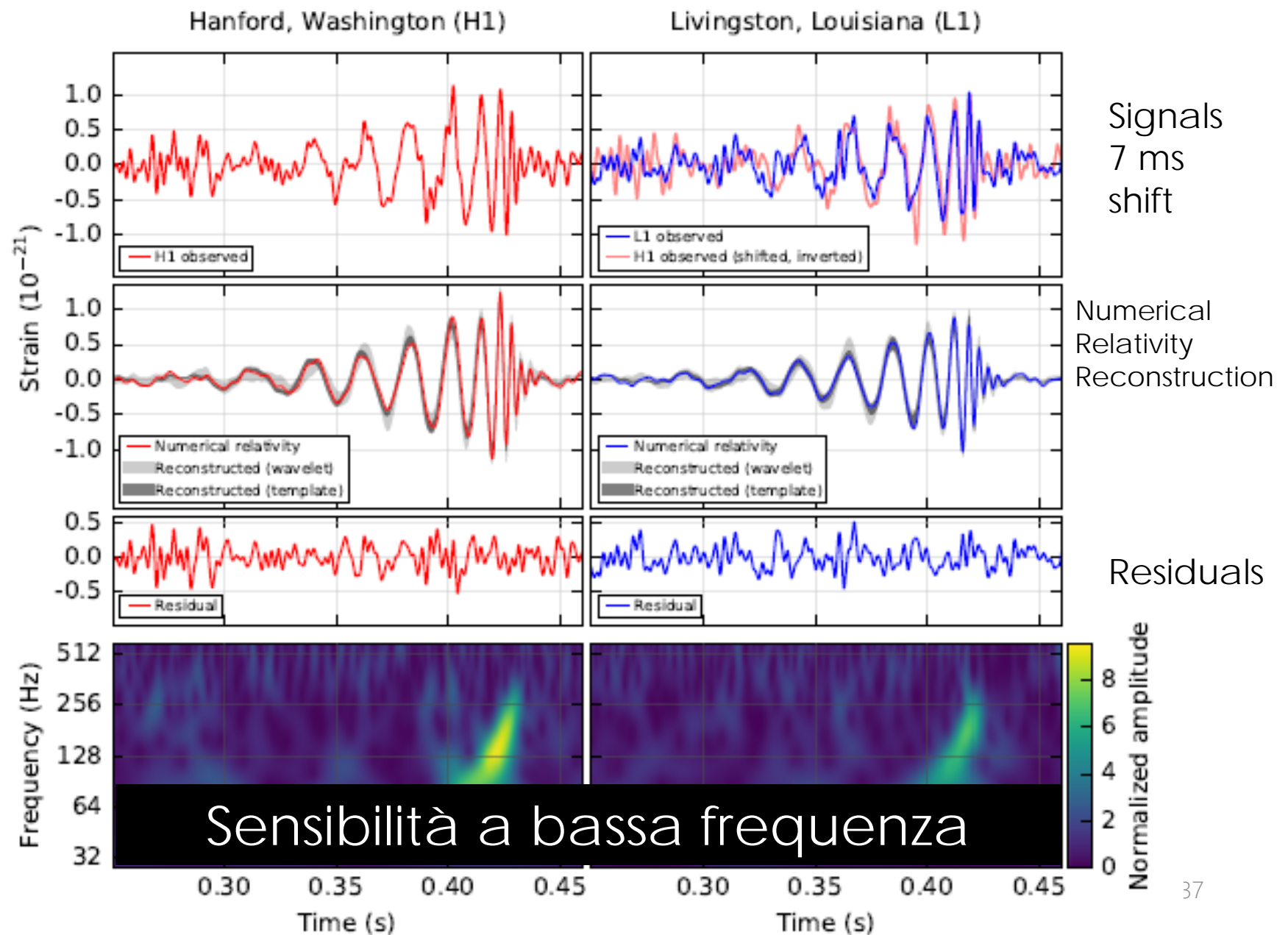
RINGDOWN

MERGER

HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA 2016

Francesco Pidecaro

Segnali, residui, grafici tempo frequenza



Potenziali sorgenti di rumore

- Nella stessa banda di frequenza dei segnali astrofisici c'è anche rumore stazionario e transienti
- Il livello di rumore stazionario, rappresentato dalla curva di sensibilità, è il risultato del progetto e realizzazione dell'interferometro.
- La maggior parte del tempo il segnale non c'è, ciò che si osserva è il rumore stazionario
- Rumori transitory possono essere identificati usando usando l'informazione proveniente da eventi locali o interni allo strumento stesso.
- 2×10^5 canali ausiliari sono costantemente monitorati per identificare sorgenti che potrebbero influenzare il segnale di onda gravitazionale

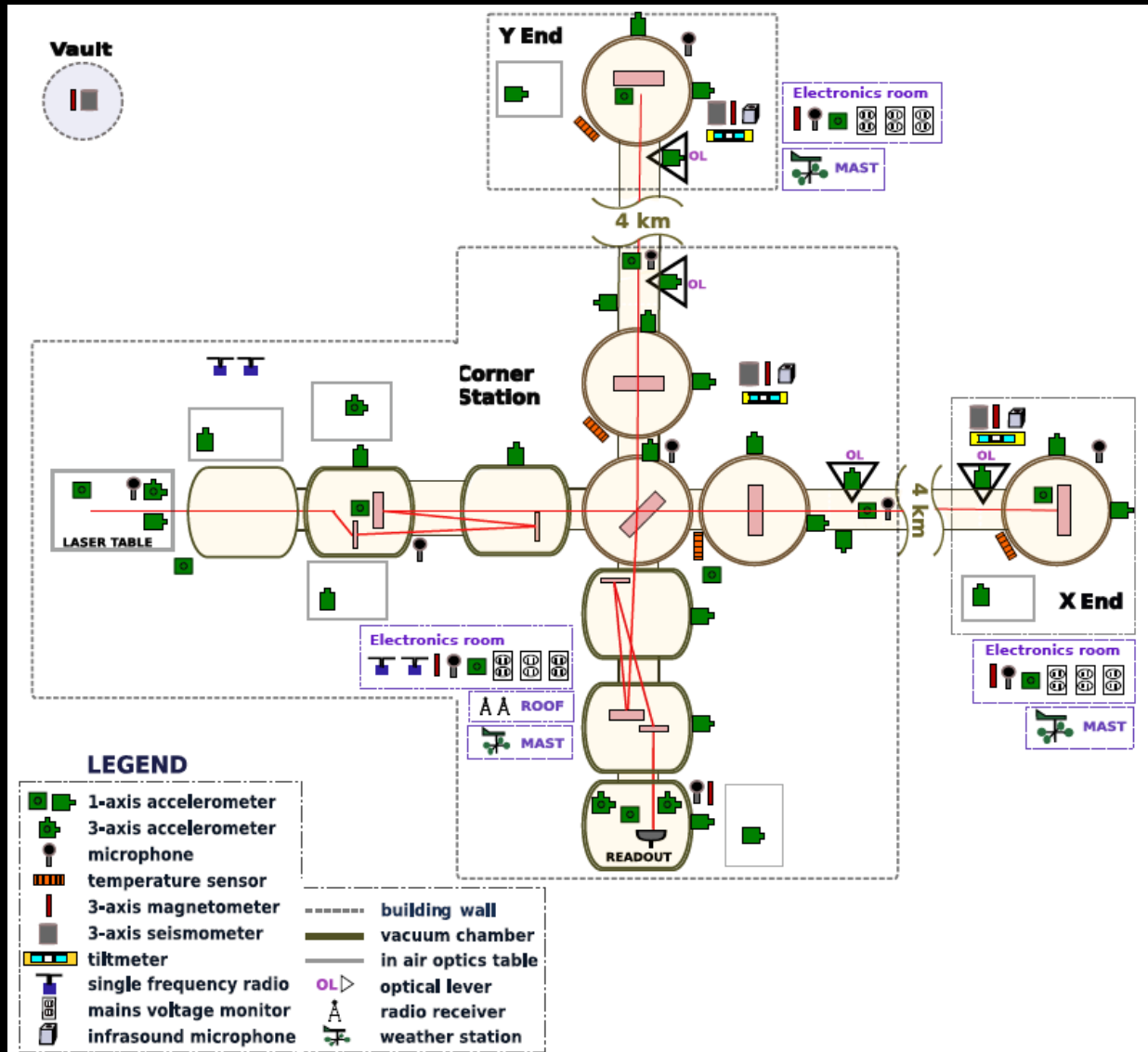
Sorgenti di rumore locali

Rumore non correlato

- Rumore di spostamento antropogenico:
Accelerometri, Sismometri, Microfoni
- Terremoti con frequenza 0.03 – 0.1 Hz più alta possono generare armoniche nello strumento:
Sismometri, Clinometri per il terreno
- Rumore magnetico: *Magnetometri*
- Inquinamento elettromagnetico: può interferire con segnali a radiofrequenza usati nello strumento:
antenne radio, registrazione dei segnali presenti
- Blip presenti nei circuiti di controllo: *verifica della forma d'onda e controlli di consistenza*

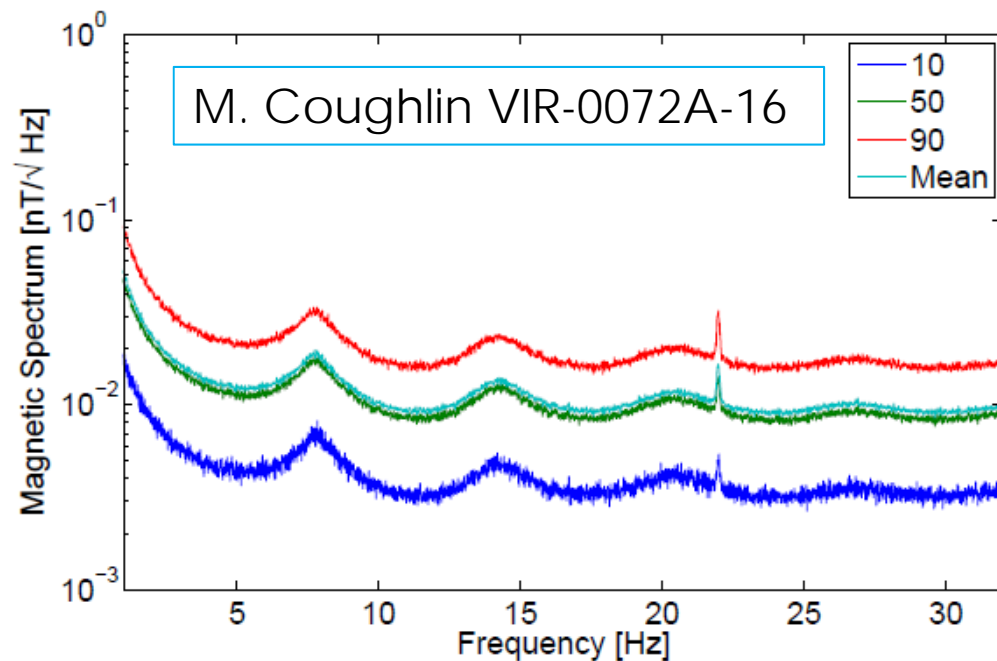
Sensori ambientali per LIGO

- Sisma e vibrazioni
- Inclinazione
- Suoni
- Infrasuoni
- Campi Magnetici
- Radiofrequenza
- Rete 115V 60Hz
- Meteo
- Fulmini
- Temperatura



Sorgenti di rumore globali: Rumore correlato

- Rumore globale (correlato): sorgenti di campo elettromagnetico:
 - Fulmini ed eccitazione delle risonanze di Schumann della ionosfera
 - Eventi solari
 - Vento solare
 - Comunicazioni radios
- Sorveglianza con antenne
- Sciami estesi di raggi



(a) PSD

Detection procedure

	Step 1 (2 weeks)	Step 2 (4 weeks)	Step 3 (4 weeks)	Step 4 (3 weeks)
Search Group	Notice, notify, launch studies of significance, PE	Organize info for paper; continue signif./PE studies	On call	Answer questions
DetChar + Instrumentalists	Evaluate DQ and instrument state	Present DQ / instrument to DC	On call	Answer questions
Reviewers	Review search procedure	Review search results	On call	Answer questions
Paper Coordinating Team		Assemble case for presentation to DC; Coordinate writing of paper	Present Detection Claim, paper to DC	Present to Collaborations
Detection Committee	Look in on	Review DQ	Review Detection Claim	Present to Collaborations
EM follow	Search for counterpart	Interpret observations	On call	Answer questions
DAC	Facilitate communication	Convene presentations, collect questions	Convene presentations, collect questions	Prepare Collaborations meetings
Collaborations	Ask questions	Ask questions	Ask questions	Make judgment
Spokespersons	Keep process moving	Appt. Paper Coordinating Team	Keep process moving	Plan publication, publicity

FAILURE

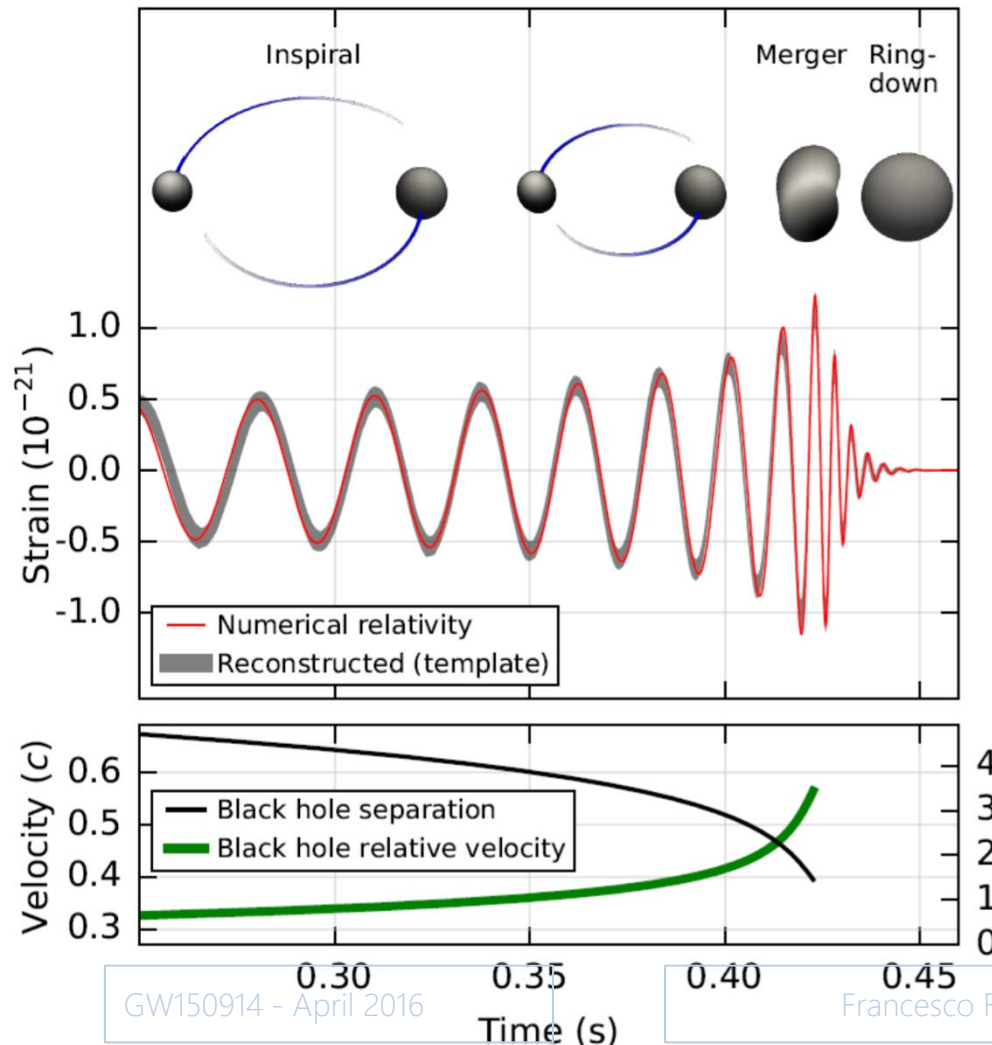
Conclusioni sulle misure

- Dopo anni di lavoro le collaborazioni LIGO e Virgo erano pronte per rivelare deboli segnali provenienti dai luoghi più remoti dell'Universo
- Il primo segnale è stato grande e il compito è stato più facile
- **Abbiamo rivelato le Onde Gravitazionali!**

Publicazioni su GW150914

- Detection Paper
[Phys. Rev. Lett. 116, 061102 \(2016\)](#)
[arXiv:1602.03837](#)
- Astrophysics implications
[ApJL, 818, L22, 2016](#)
[arXiv:1602.03846](#)
- Test of GR
[arXiv:1602.03841](#)
- Rates
[arXiv:1602.03842](#)
- Stochastic Background
[arXiv:1602.03847](#)
- EM follow-up
in preparation
- High Energy Neutrinos
in preparation
- CBC searches
[arXiv:1602.03839](#)
- Unmodeled searches
[arXiv:1602.03843](#)
- Parameter Estimation
[arXiv:1602.03840](#)
- Instrument
[arXiv:1602.03838](#)
- DetChar
[arXiv:1602.03844](#)
- Calibration
[arXiv:1602.03845](#)
- Public data release
<https://lsc.ligo.org/events/GW150914>

Perché sono buchi neri?



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

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

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

Stelle di neutroni escluse

Binaria buco nero e stella di neutron?
 M_{BH} dovrebbe essere molto grande
 \Rightarrow Coalescenza avviene a frequenza più bassa

NS: $\omega_{\text{Kepler-max}} \approx 2\pi \times 75 \text{ Hz}$

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

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

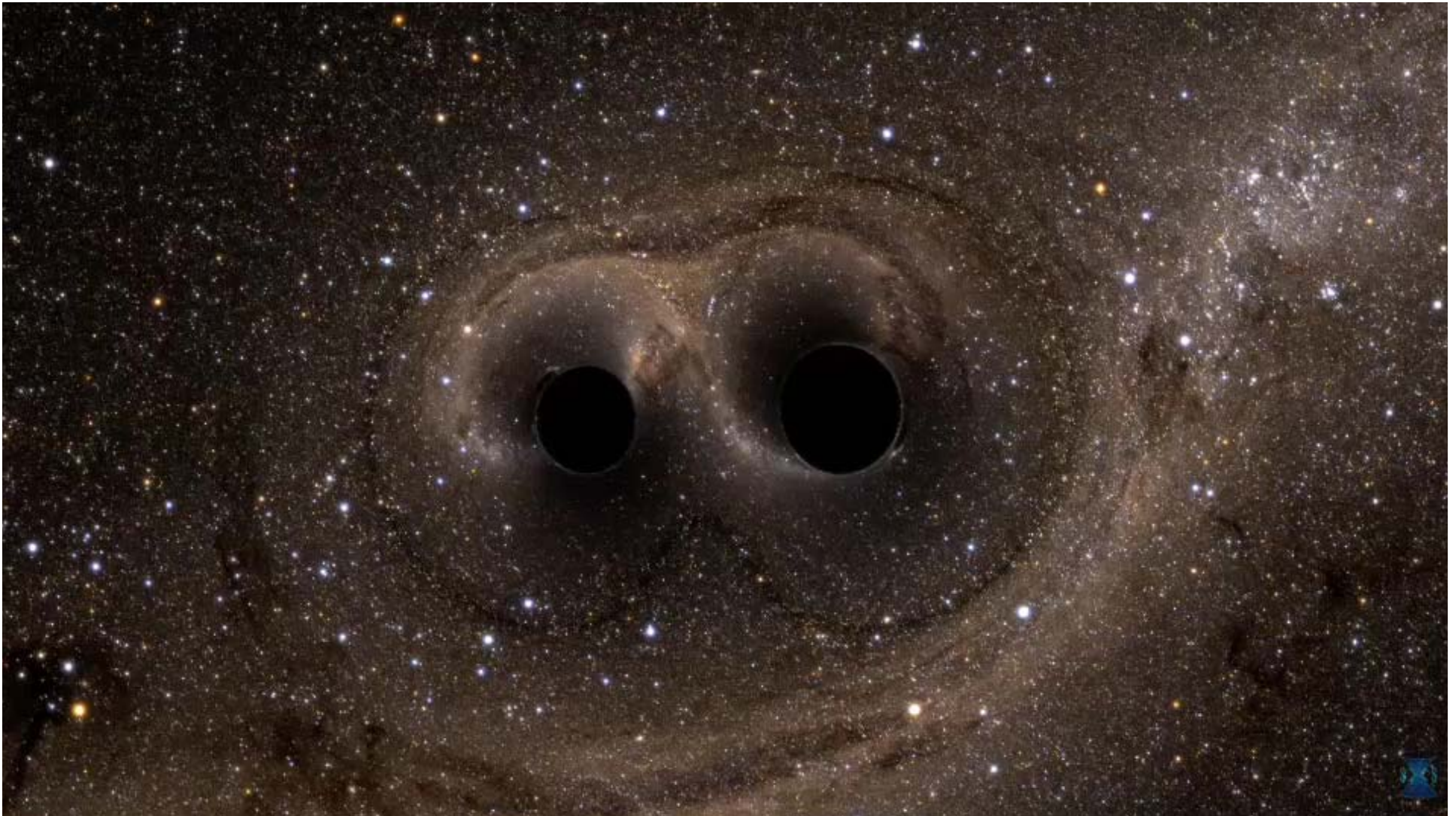
$$r_{\text{Schwarz}}(M) = \frac{2GM}{c^2} \sim 210 \text{ km}$$

Parametri della sorgente per GW150914

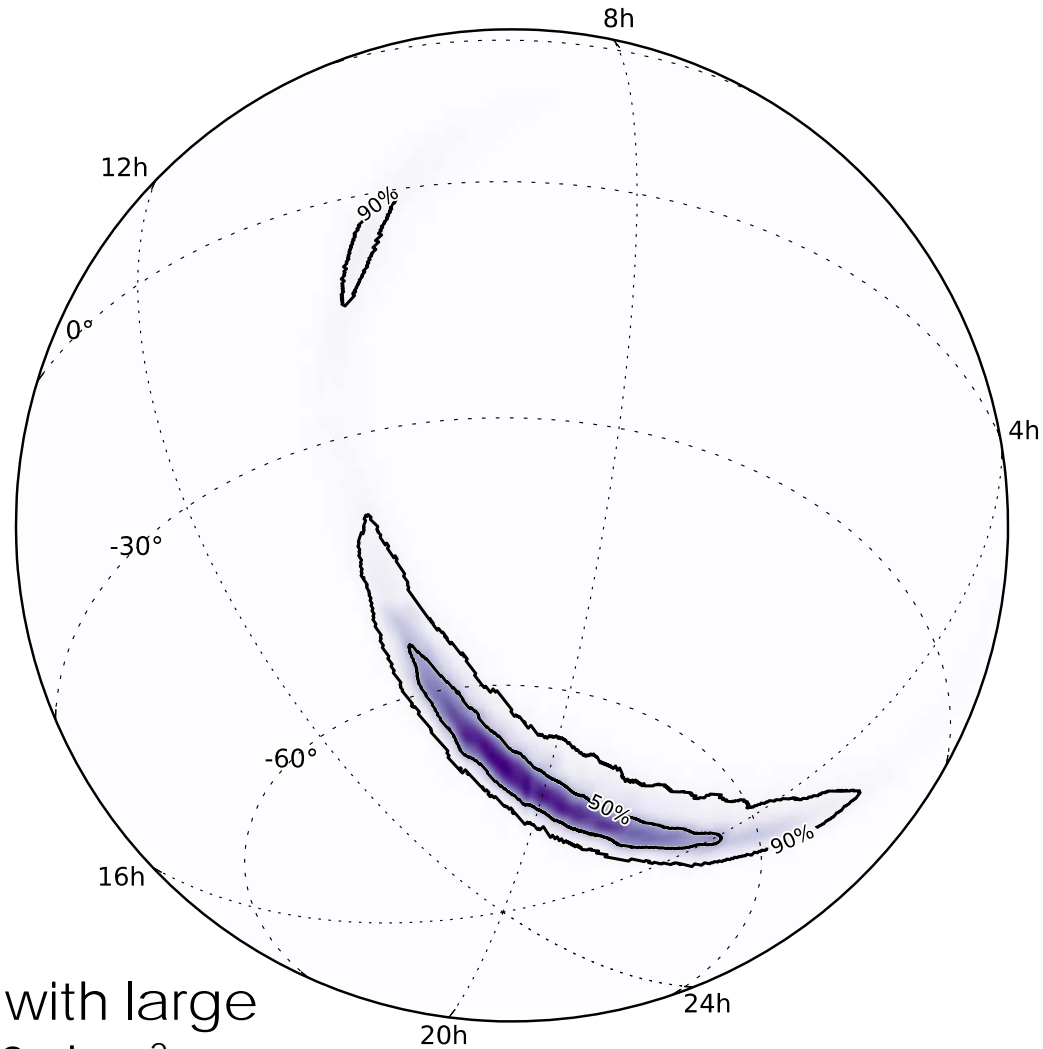
- Usando famiglie di segnali ottenute da simulazioni numeriche di coalescenze di buchi neri per determinare i parametri del Sistema si determina l'energia totale irraggiata sotto forma di onde gravitazionali, pari all'equivalente di 3.0 ± 0.5 masse solari
- Il sistema raggiunge un picco di potenza di $\sim 3.6 \times 10^{56}$ ergs, lo spin del buco nero finale < 0.7 (non è il massimo spin)

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

Due buchi neri su sfondo di cielo stellato



Posizione nel cielo



Source location with large uncertainty $\sim 600 \text{ deg}^2$

A visualization of a gravitational well, showing two black holes as dark circular regions. The well is depicted as a curved, funnel-like structure with a brownish-gold glow, set against a background of a starry field with various colored stars (white, blue, yellow, orange).

IMPLICAZIONI DI GW150914

GW150914 - April 2016

Francesco Fidecaro

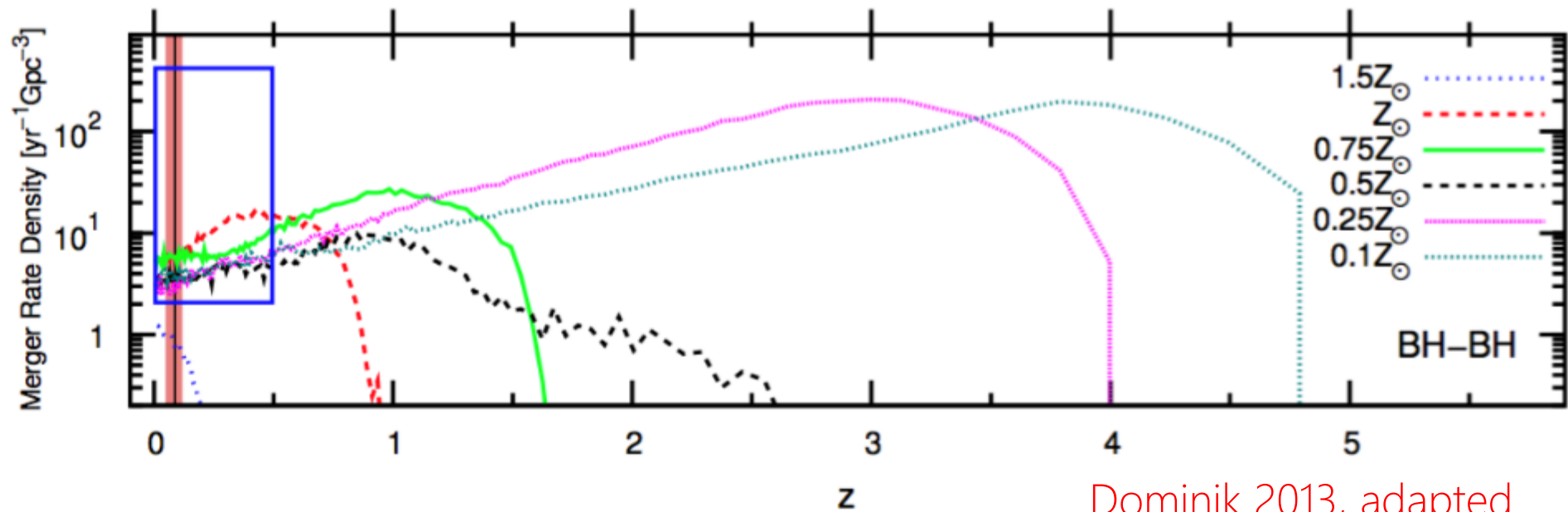
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Implicazioni per l'Astrofisica

Fatti principali

- I sistemi binary di buchi neri esistono!
 - Si formano e collassano su una scala di tempo a noi accessibile
 - In precedenza si prevedevano da 0 a 1000 eventi / Gpc³ / anno
 - Ora possiamo escludere l'estremità più bassa: tasso > 1 / Gpc³ / anno
 - Le masse ($M > 20 M_{\odot}$) sono grandi rispetto a quelle di buchi neri noti
- Progenitori sono
 - Presumibilmente **pesanti**, $M > 60 M_{\odot}$
 - Probabilmente con **bassa metallicità**, $Z < 0.25 Z_{\odot}$
- Il redshift misurato $z \sim 0.1$
- Modelli con bassa metallicità possono produrre coalescenze a basso z con frequenza consistente con le nostre osservazioni

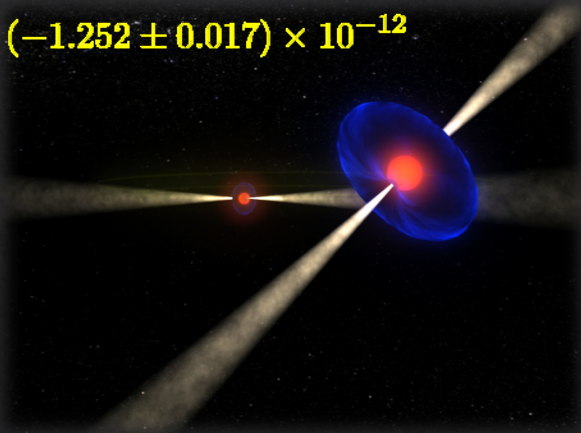
Un futuro luminoso?



- Il sistema GW150914 BBH può avere avuto origine sia
 - Recentemente, con un tempo di coalescenza piccolo
 - Più indietro nel tempo, con un tempo di coalescenza più lungo
 - Con una singola osservazione non è possibile capire quale caso si verifica
- Secondo i modelli, a redshift più alti il numero di eventi aumenta!
 - Potenzialmente un futuro *molto* luminoso per aLIGO, AdVirgo !

GW150914: una sonda per il regime di gravità forte

$$\dot{T}_b = (-1.252 \pm 0.017) \times 10^{-12}$$



Binaria più relativistica nota fino da oggi: J0737-3039

Raggio di Schwarzschild: $R_s \sim 4.8\text{km}$

Distanza tra le due pulsar: $d \sim 9 \times 10^5\text{km}$

Velocità orbitale: $\left(\frac{v}{c}\right)^2 \sim 4 \times 10^{-6} \sim \frac{R_s}{d}$

Coalescenza: tra $85 \times 10^6\text{yr}$

GW150914

Raggio di Schwarzschild: $R_s \sim 90\text{km}$

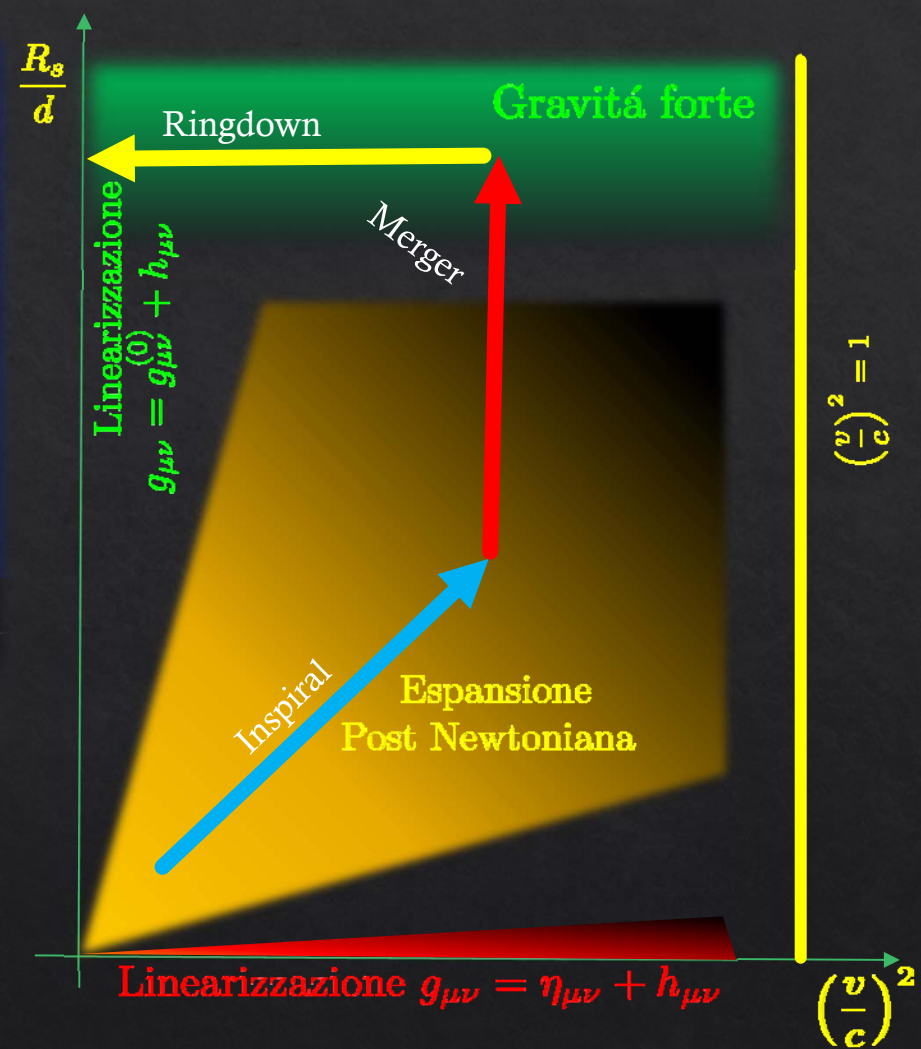
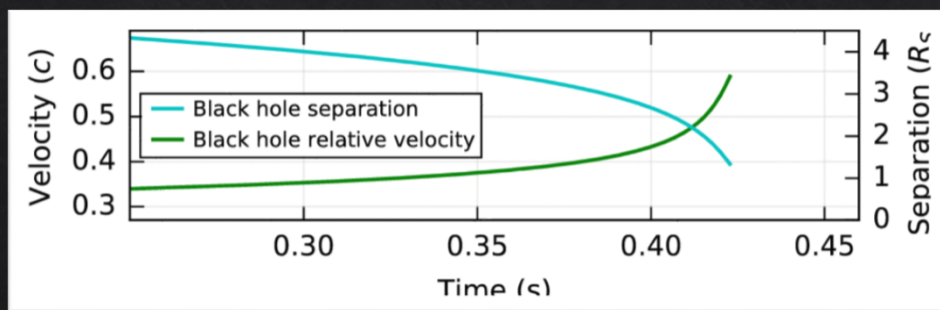
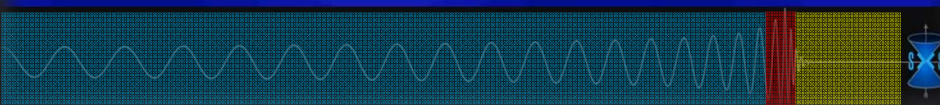
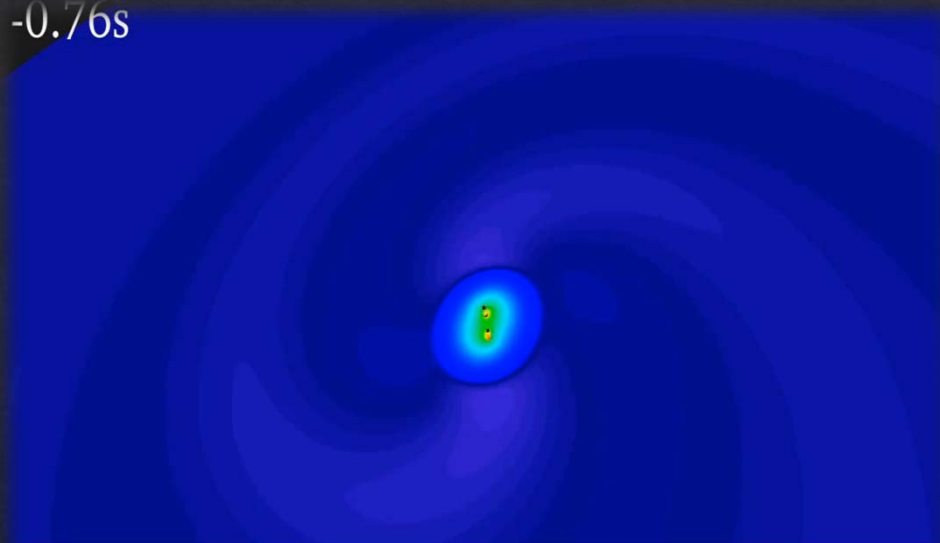
Distanza tra le due pulsar: $d \gtrsim 180\text{km}$

Velocità orbitale: $\left(\frac{v}{c}\right)^2 \lesssim 0.36$

$$-1 \lesssim \dot{T}_b \lesssim -0.1$$

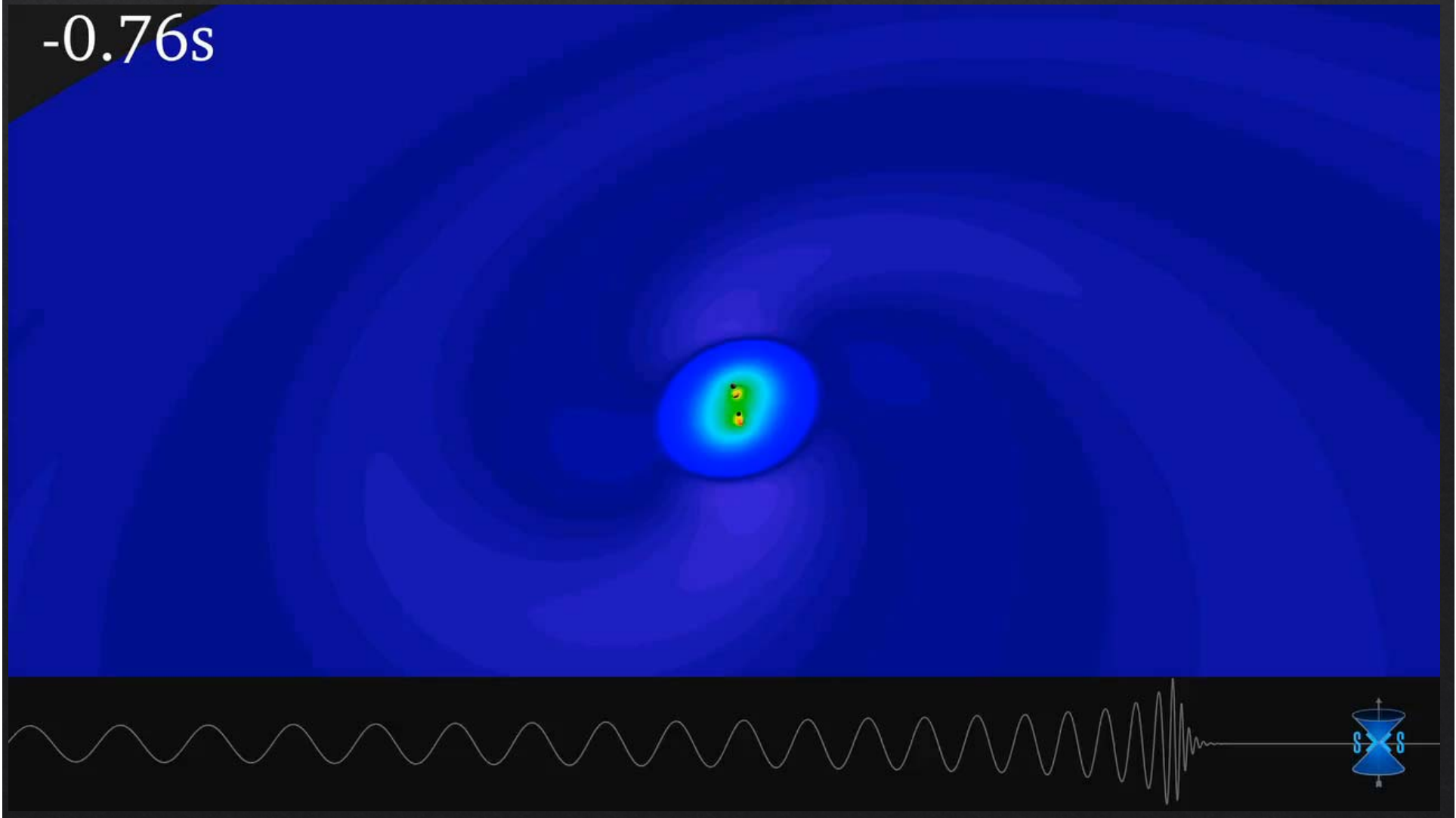


-0.76s



Lo spazio-tempo vicino ai due buchi neri

-0.76s



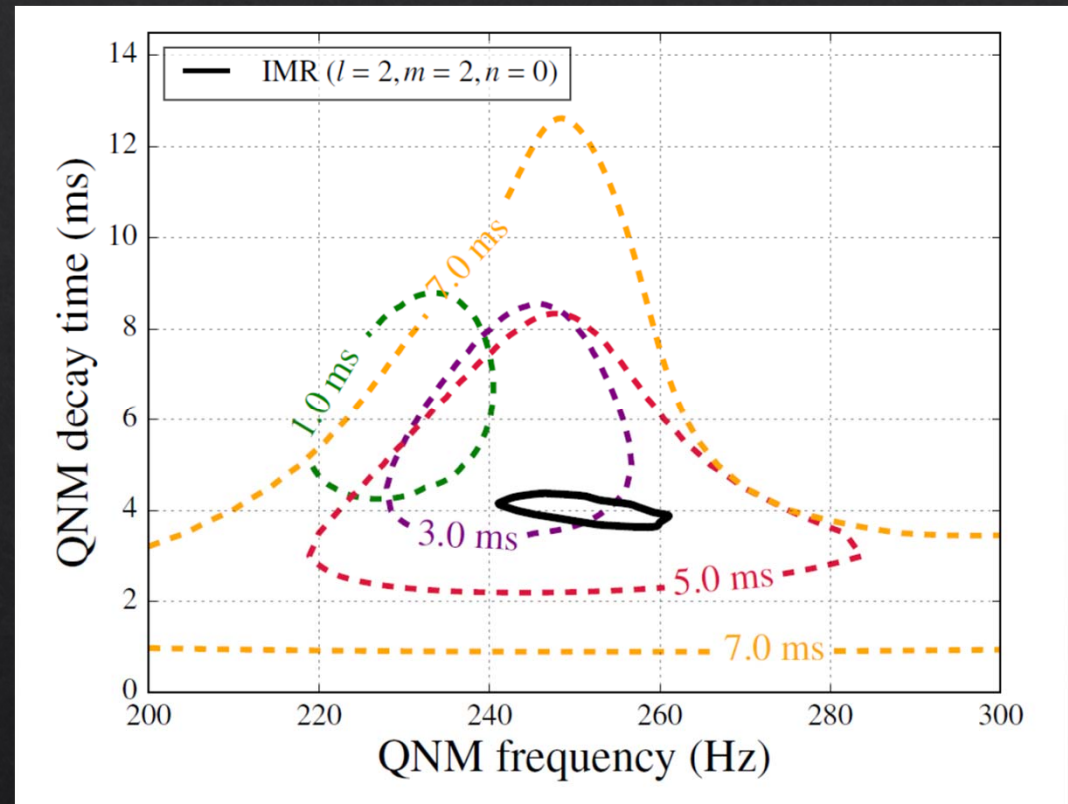
Quasi Normal Modes

Ricerca di 1 solo modo (quello con minore dissipazione)

$$h(t) = A\theta(t - t_0)e^{-(t-t_0)/\tau} \cos[\omega_0(t - t_0) + \phi_0]$$

$$t_0 = t_M + \Delta t$$

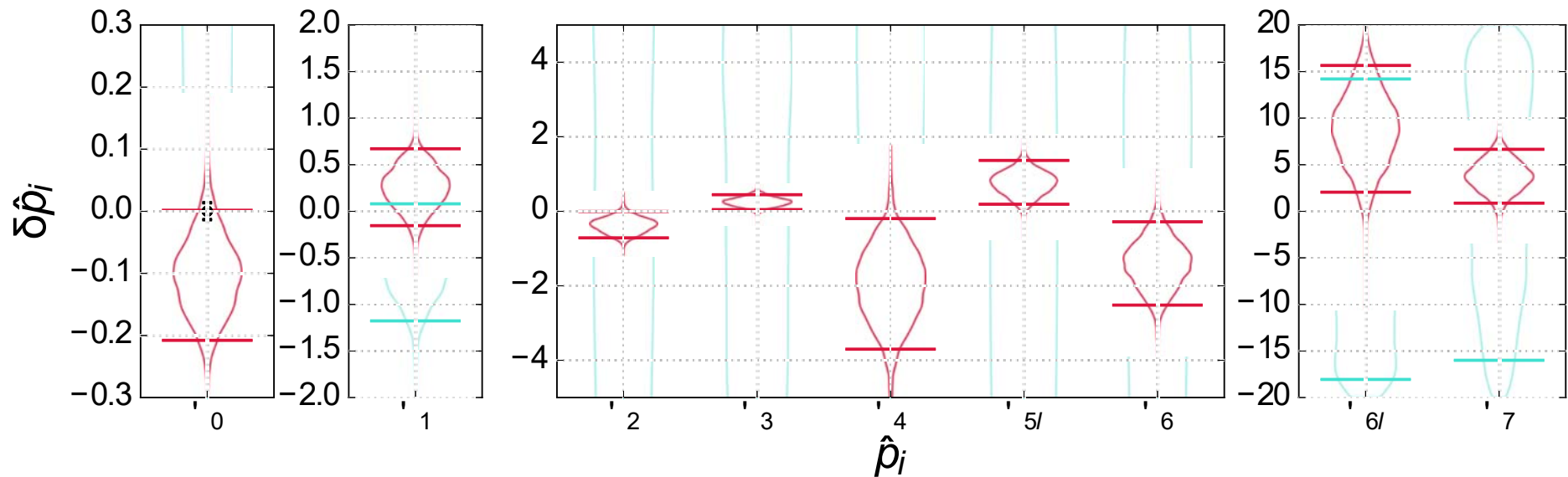
- I contorni corrispondono a una confidenza del 90%
- Viene variato Δt
- Il contorno scuro: la predizione basata sui parametri
Inspiral+Merger+Ringdown



Deviation of PN coefficients from GR ?

- Nominal value predicted by GR
- Allow variation of the coefficients
 - > Is the resulting waveform consistent with data ?

Red: vary one parameter at a time
Cyan: allow all parameters to vary



- Find no evidence for violations of GR

«Massa del gravitone»

- Supponendo una relazione di dispersione $E^2 = p^2 c^2 + m_g^2 c^4$

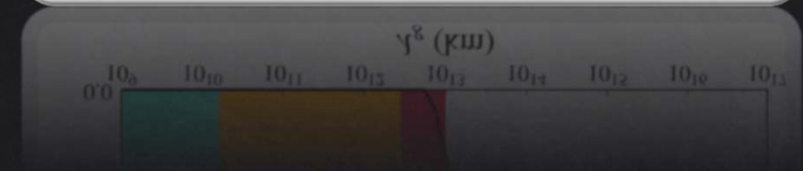
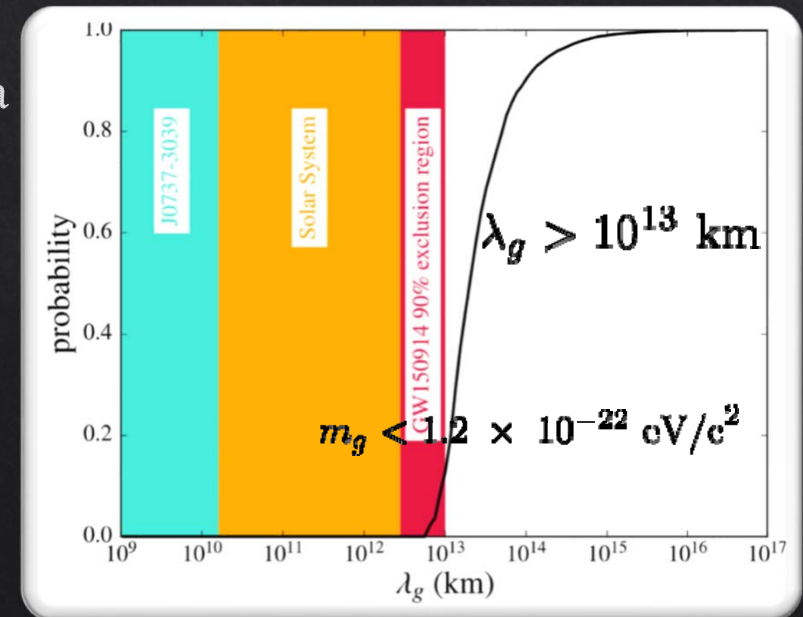
troviamo $\frac{v_g^2}{c^2} = 1 - \frac{c^2}{\lambda_g^2 f^2}$ $\varphi(r) = \frac{GM}{r} e^{-r/\lambda_g}$

- Miglioramento di un fattore 3 rispetto al limite da osservazioni del sistema solare:

$$\lambda_g > 10^{13} \text{ km}$$

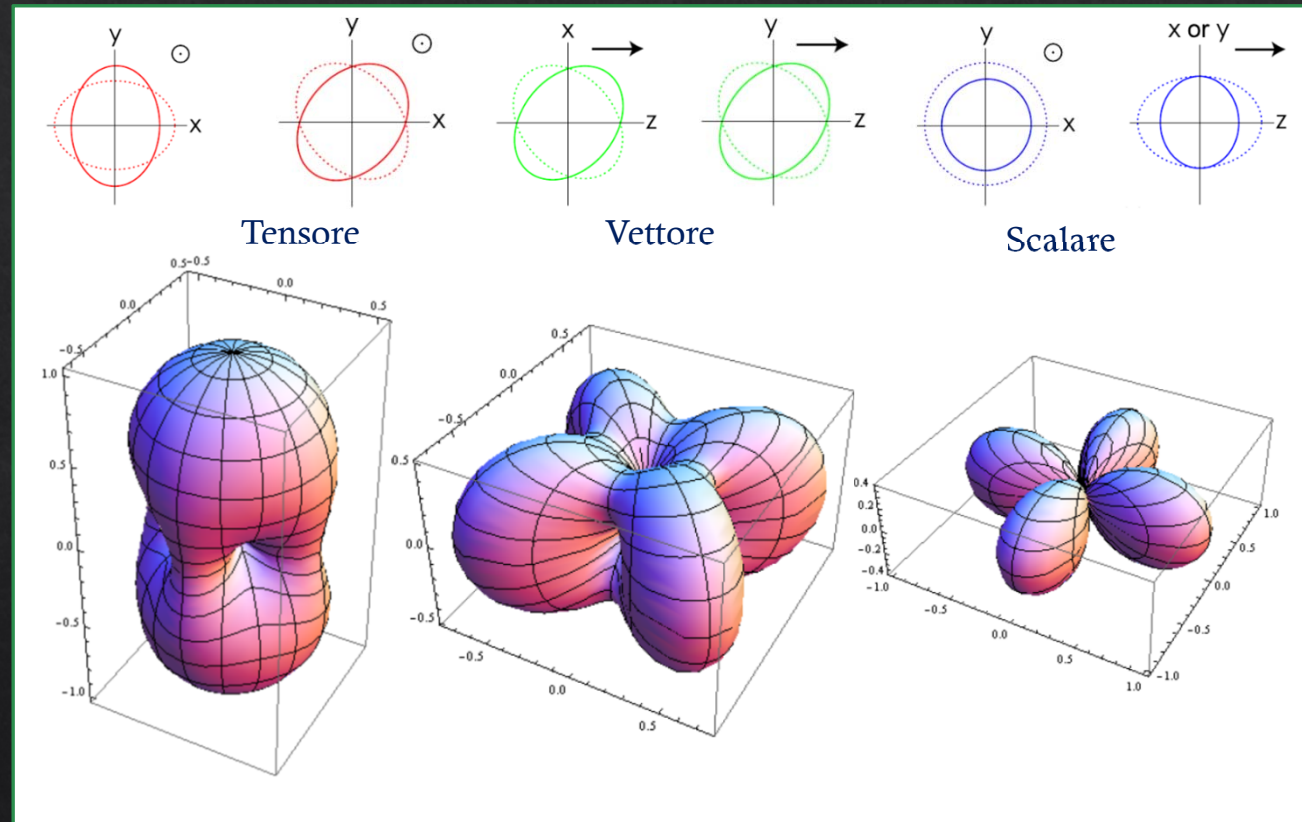
$$m_g < 1.2 \times 10^{-22} \text{ eV}/c^2$$

- Risultati basati su gravitational lensing e cluster di galassie sono migliori, ma dipendenti dal modello

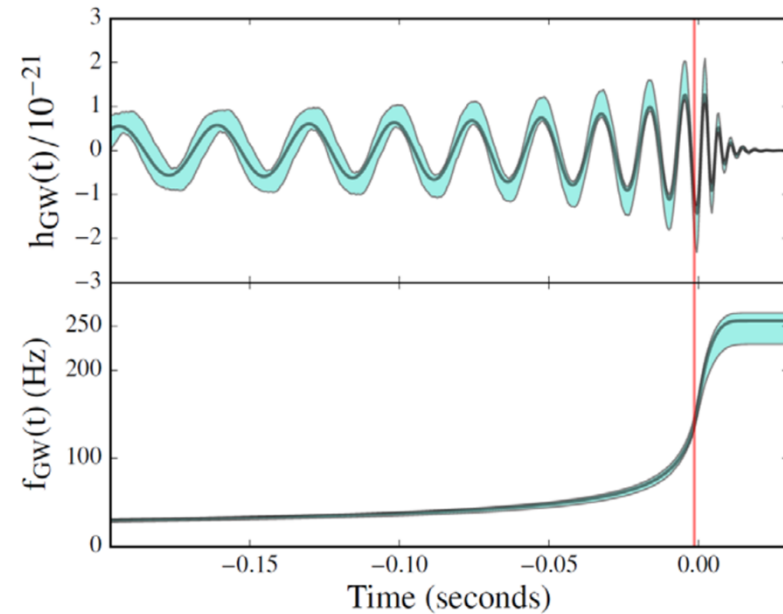
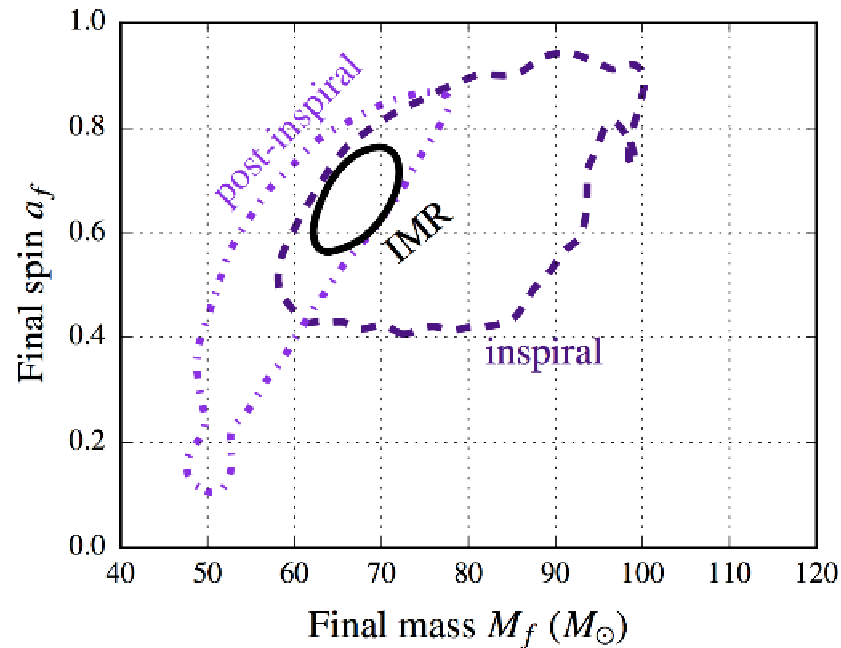


Studio delle polarizzazioni

- ◆ I due interferometri LIGO sono all'incirca allineati
- ◆ Impossibile usare la dipendenza della *angular pattern function* per discriminare diverse polarizzazioni
- ◆ Questo cambierà con Virgo in presa dati



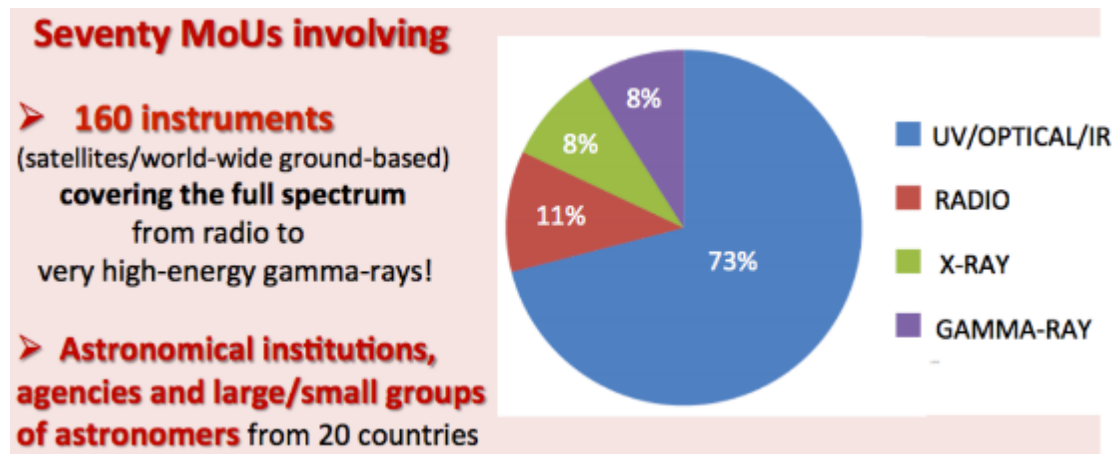
Waveform internal consistency



1. Predict final black hole mass and spin from the inspiral signal
2. Predict final black hole mass and spin from the ring-down phase
3. Compare to check consistency of GR in different regimes

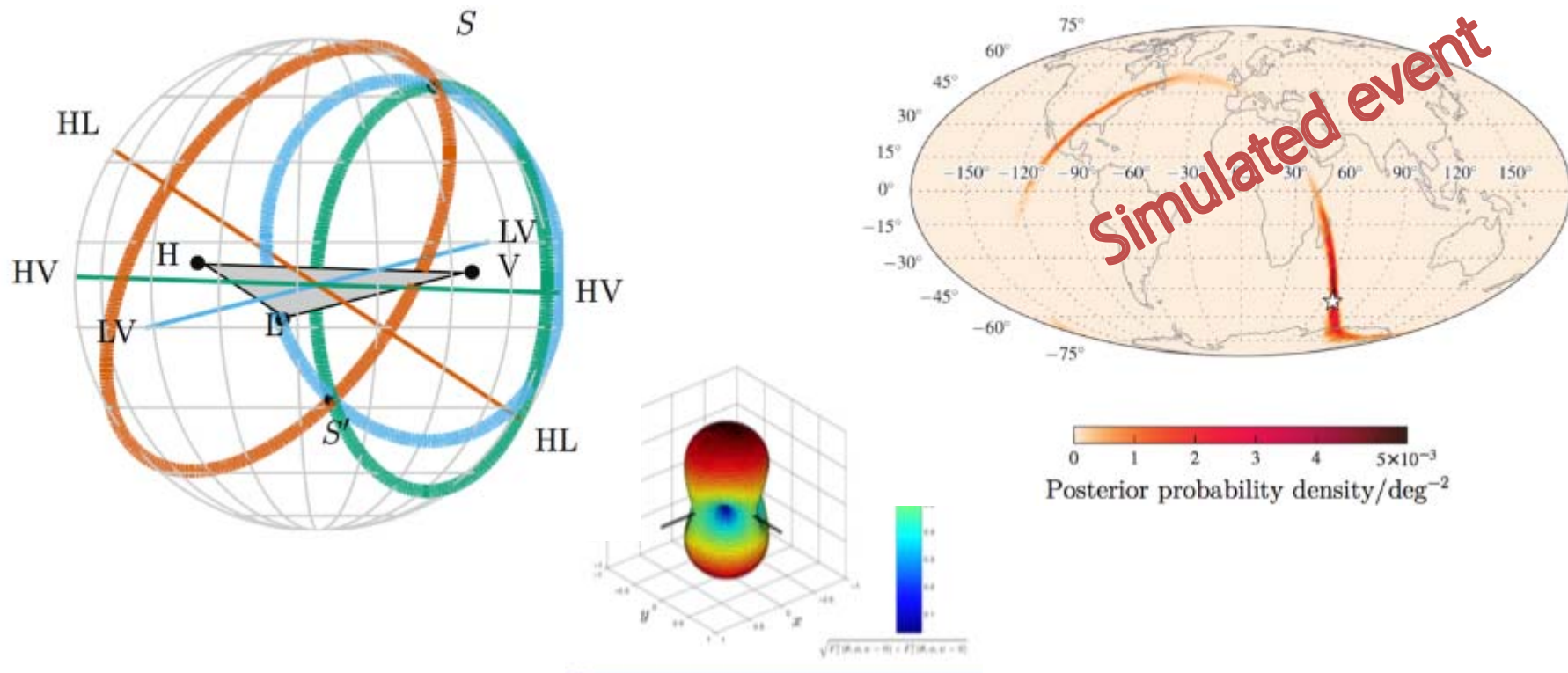
EM follow-up key facts

- LVC called for EM observers to join a follow-up program
 - LIGO and Virgo share *promptly* with astronomers interesting triggers; up to a few at current sensitivity
 - Provide limited directional information, promptly estimated



- Big participation to GW150914 observation:
 - 24 groups carried out observations
 - Challenging! Source location with large uncertainty $\sim 600 \text{ deg}^2$

Why is our error box so large?

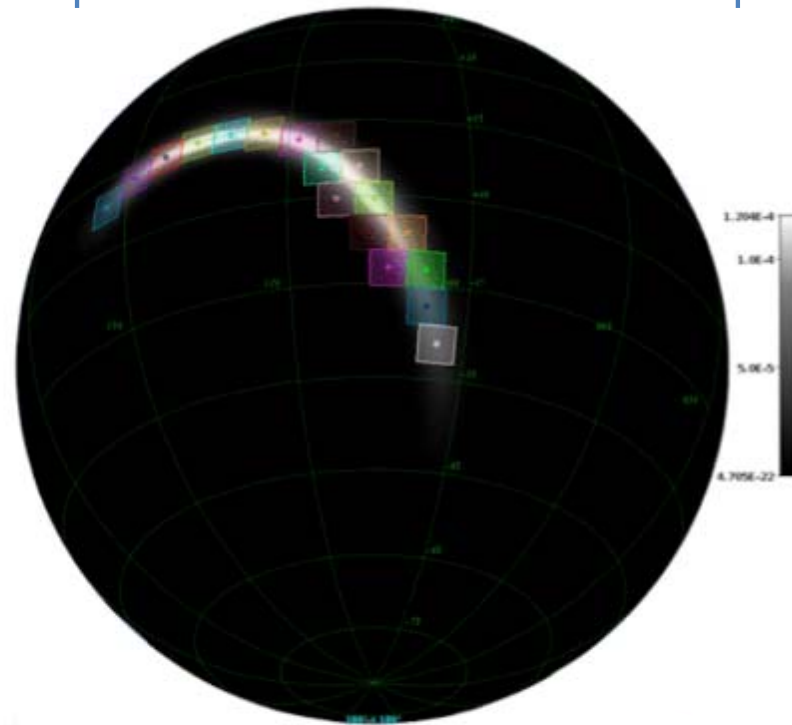


- Two interferometers (HL), each with poor directionality, determine by time delay an **annulus** in the sky
- Folding in also amplitude information, we can do a bit better (*in the RHS, a simulation with a BNS event*)

How do we cope? With telescope time..

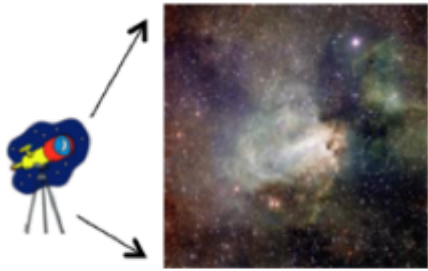
```
Python 2.7.6 Shell [Python 2.7.6 Shell]
Python 2.7.6 (default, Jun 22 2015, 17:54:13)
[GCC 4.8.2] on linux2
Type "copyright", "credits" or "license()" for more information.
>>> import GWsky
>>> GWsky.main()
Load a probability skymap
> bayestar.fits(11).gr
#####
Provide the probability value (r) to define the confidence region:
(e.g. 1 for all the sky, 0.5 to merge only the 50% confidence region)
: 0.50
The area confined in 95.0% of probability is 825.83 deg^2.

The table that contained those pixels is displayed in Aladin plane
= contour.ipix.out >
#####
Insert the size of your Field of View (FOV):
side(x), side(y) : }
```



- A *sky map* produced by LIGO and Virgo is tiled with **multiple** observations, searching for transients
- Looking for fading objects, repeat observations after days

.. and smart algorithms



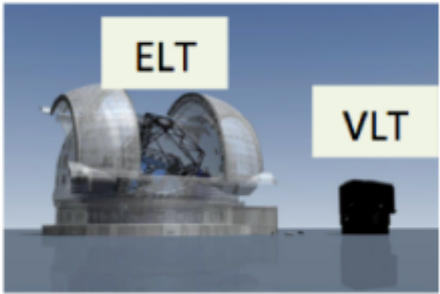
Wide-field telescope
FOV >1 sq.degree



"Fast" and "smart" software to select a sample of candidate counterparts

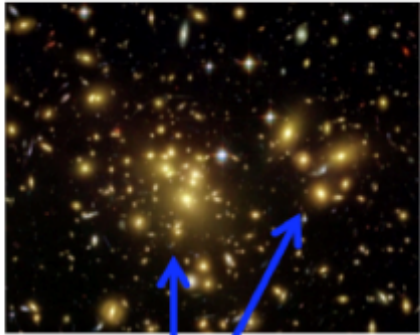


Larger telescope to characterize
the candidate nature

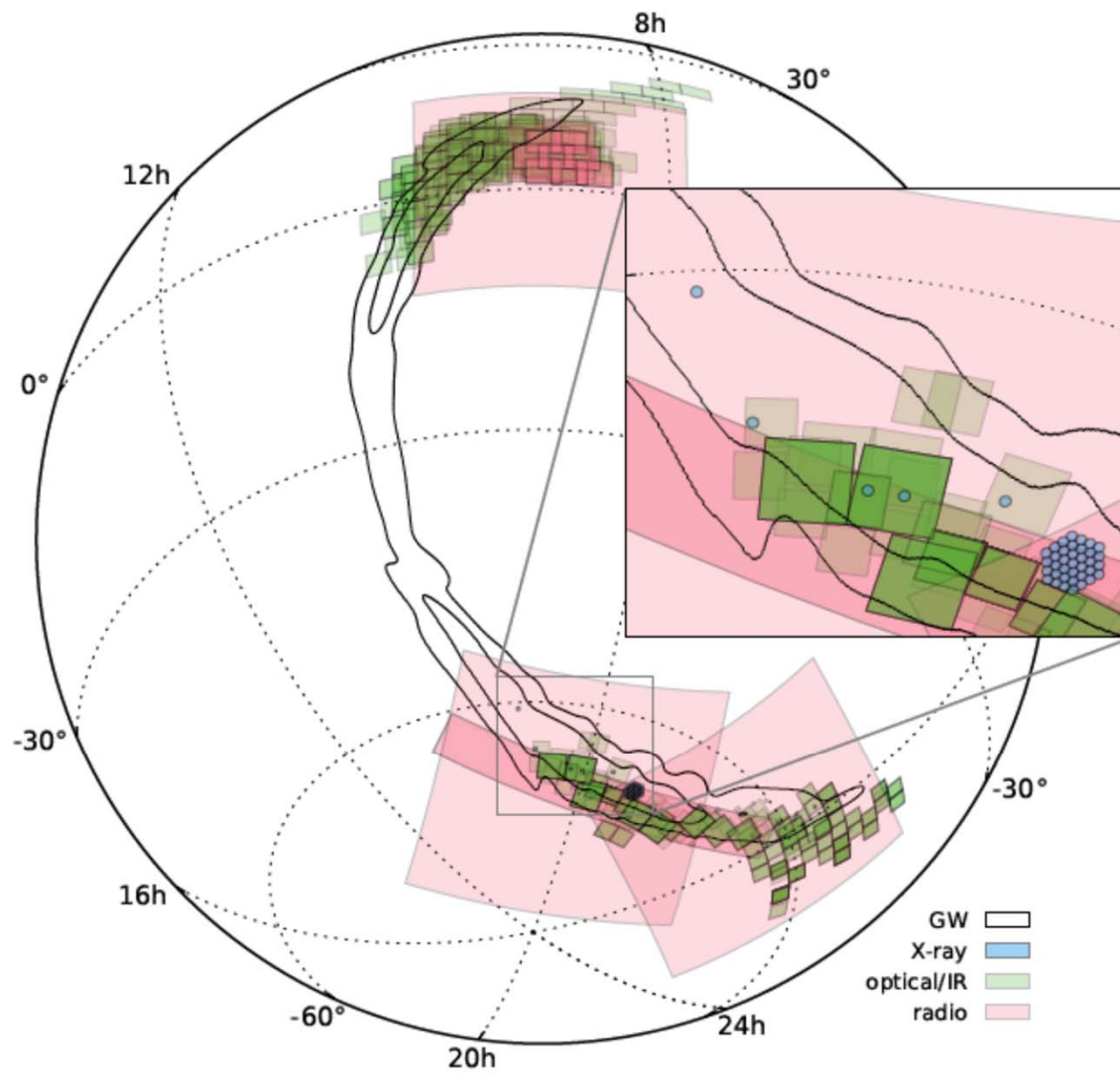


The EM Counterpart!

Aasi et al. 2014, ApJS, 211

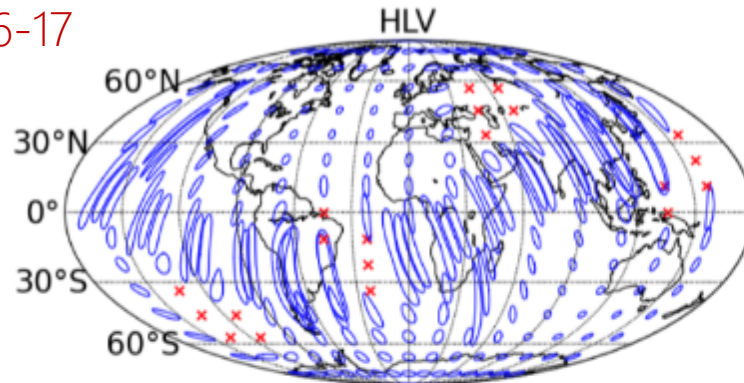


Galaxy targeting?

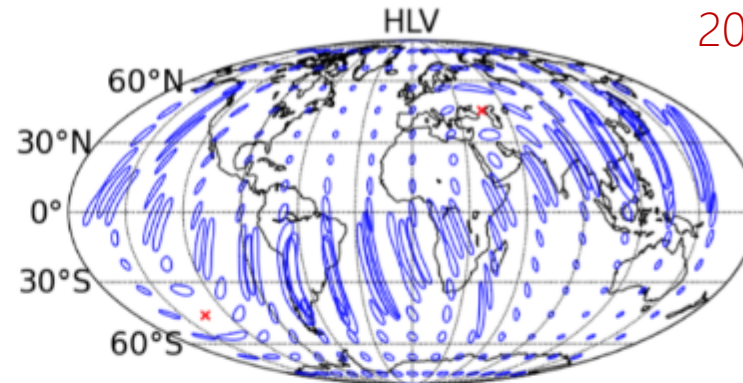


In the future, we'll be more precise

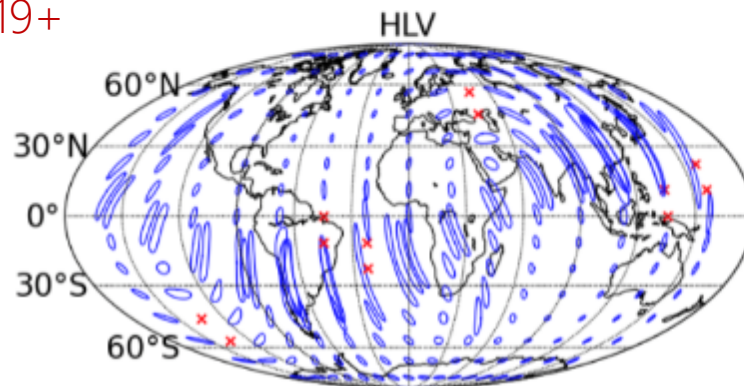
2016-17



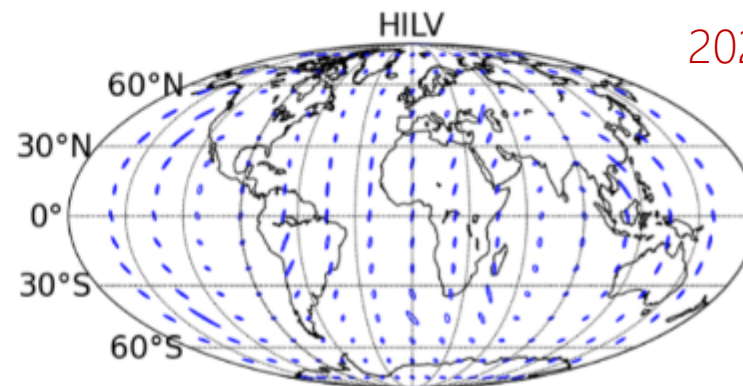
2017-18



2019+



2022+



- Adding Virgo will break the annulus
- As sensitivity progresses, so does the localization
- In the design LIGO-Virgo network, GW150914 could have been localized to less than 20 deg²

The advanced GW detector network: 2015-2025

Advanced LIGO
Hanford
2015



GEO600 (HF)
2011



KAGRA
2017

Advanced LIGO
Livingston
2015

Advanced
Virgo
2016



LIGO-India
2022



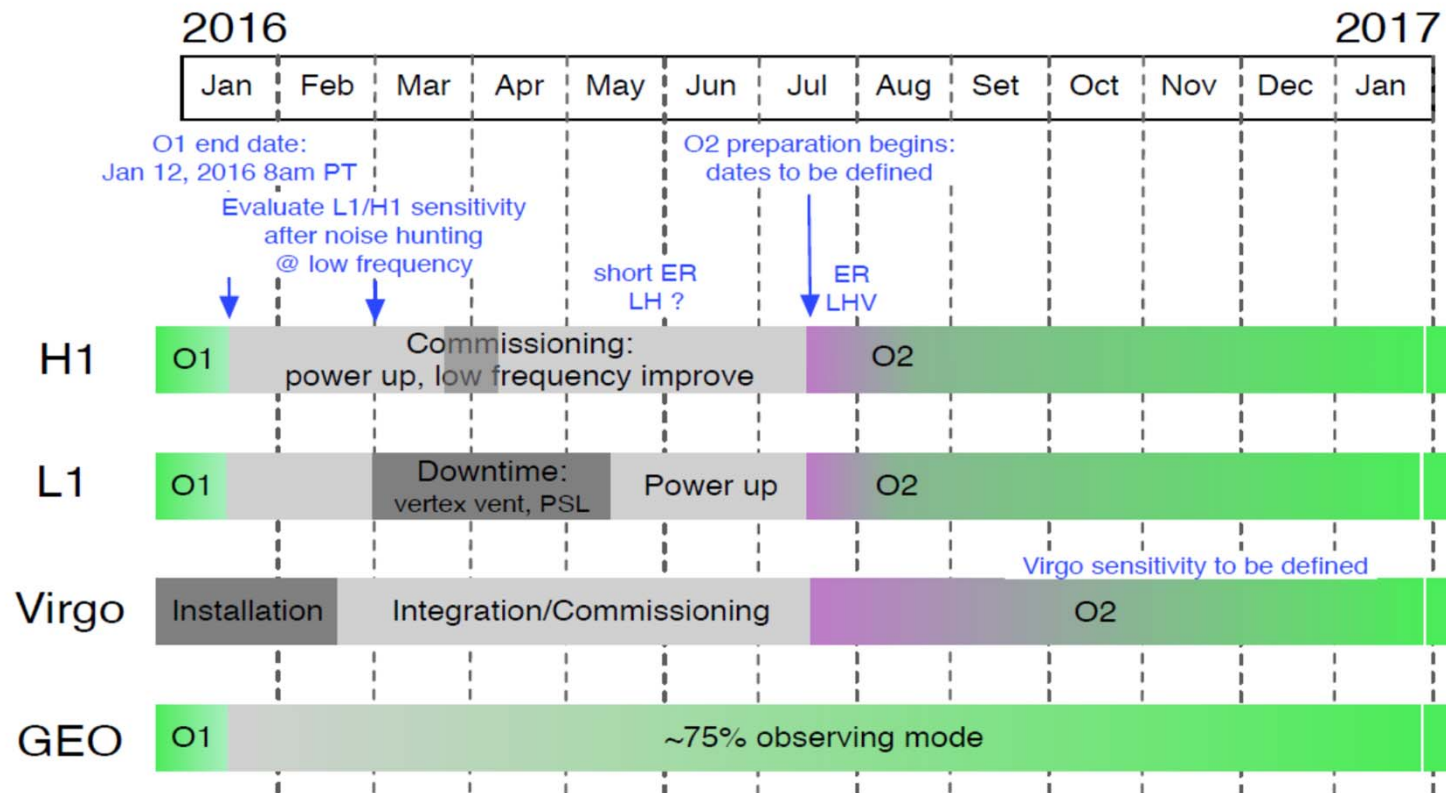
Stavi dicendo qualcosa, o erano due buchi neri?

CONCLUSIONI E PROSPETTIVE

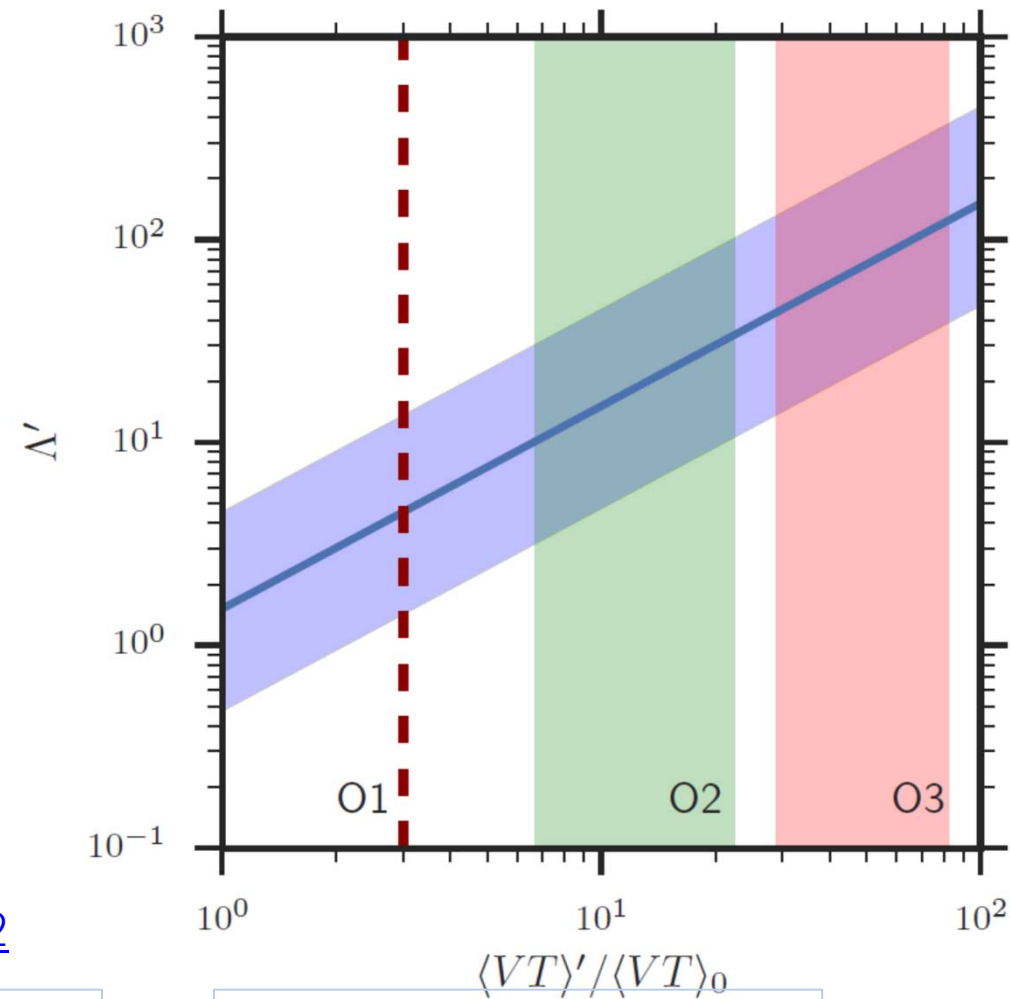


Towards O2

Joint Run Planning Committee
Working schedule toward O2



Quanti eventi di coalescenza di buchi neri in futuro?



[arXiv:1602.03842](https://arxiv.org/abs/1602.03842)

GW150914 - April 2016

Francesco Fidecaro

96

IN DEFINITIVA

- E' stato registrato il passaggio di onde gravitazionali dalla coalescenza di due buchi neri di massa stellare
- La forma del segnale e la previsione della relatività generale per riduzione delle dimensioni dell'orbita, coalescenza e "rimbombo" del buco nero finale sono in accordo
- Questa è la prima rivelazione diretta di onde gravitazionali e la prima osservazione della coalescenza di un sistema binario di buchi neri

GRAZIE !

SPARE SLIDES

GW150914 - April 2016

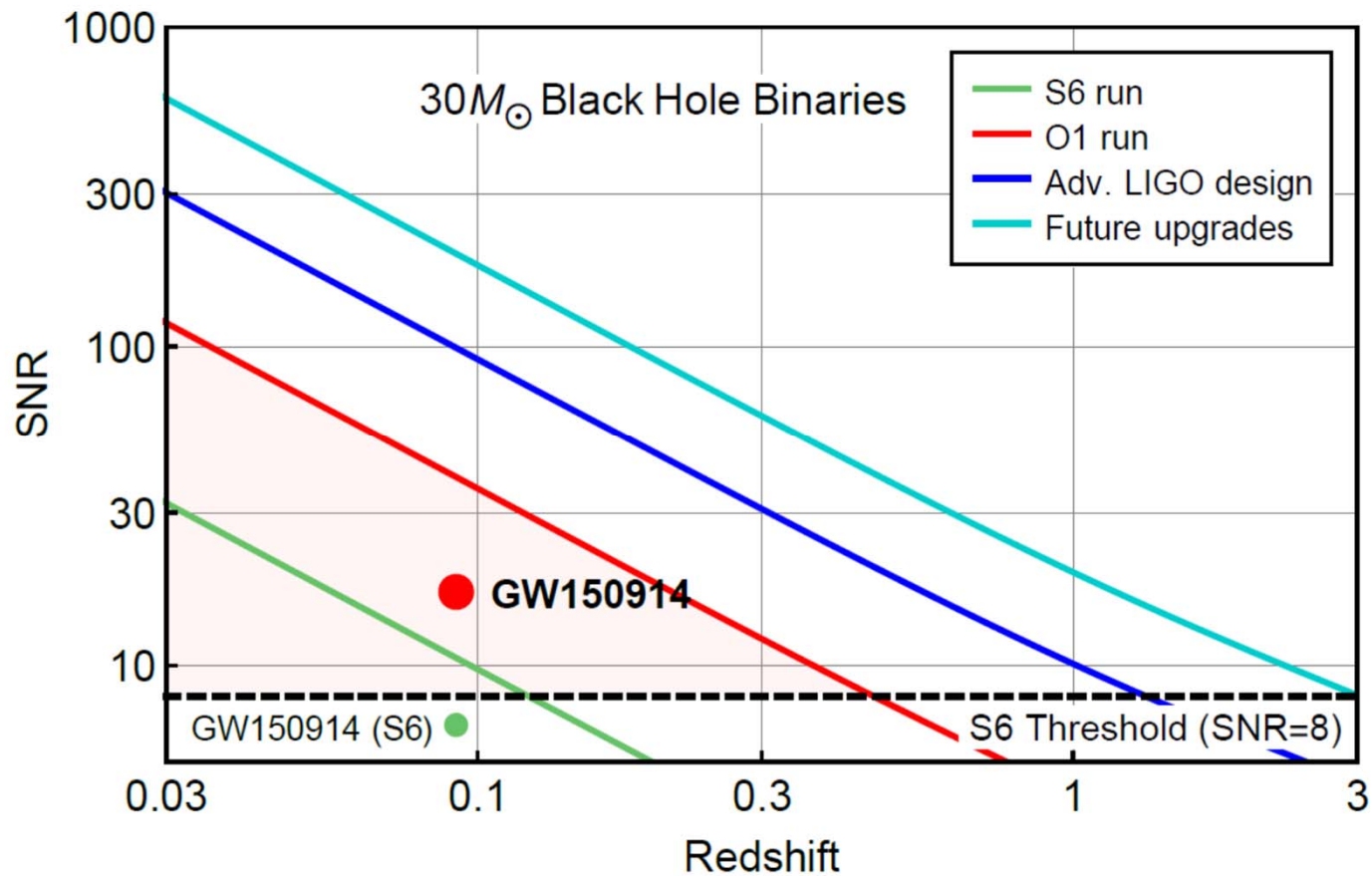
Francesco Fidecaro

100

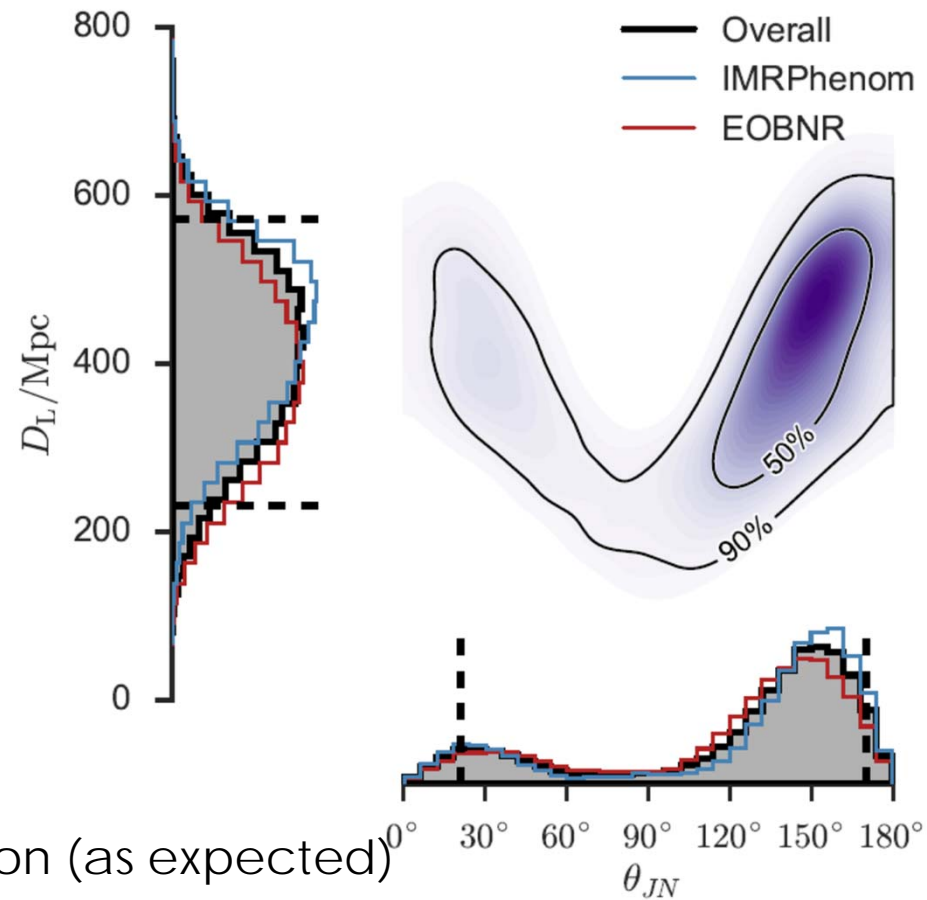
O1: Data analysis & Computing

- Several search 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/involvement of CNAF staff (bi-weekly meetings)

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



Distance and Inclination



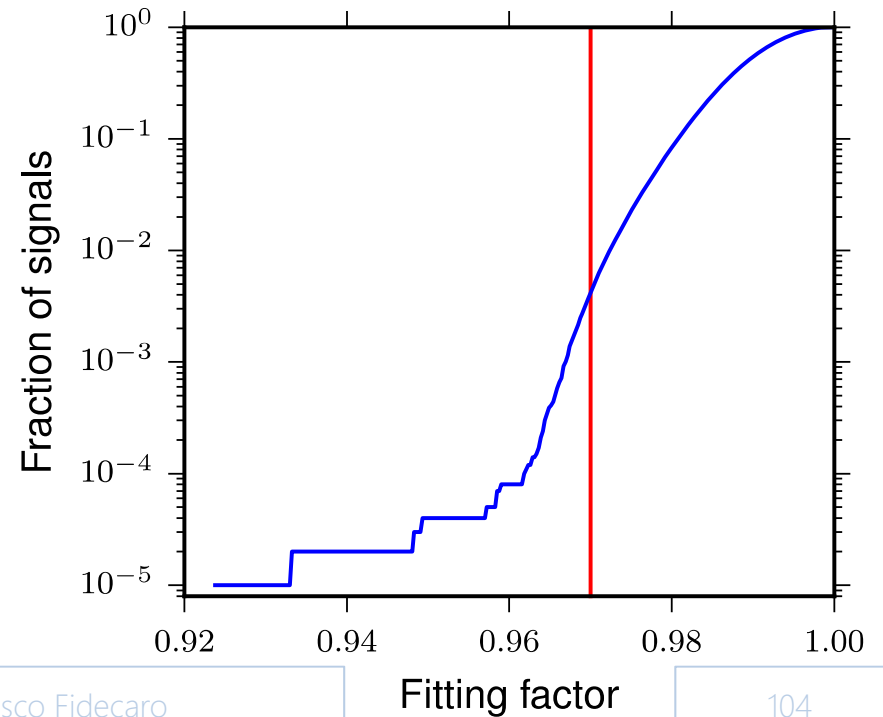
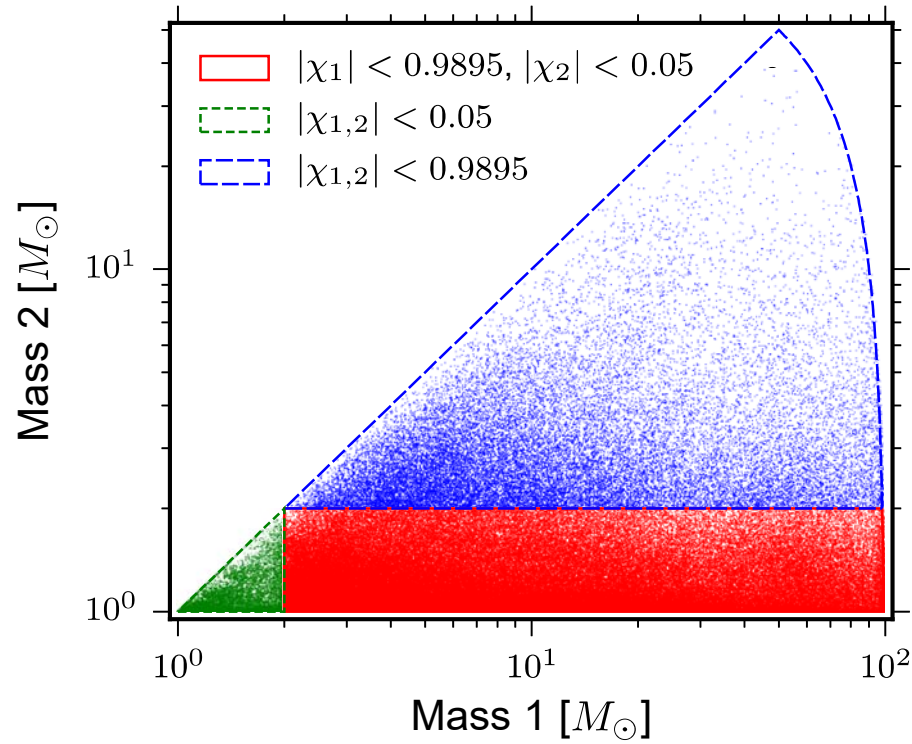
[arXiv:1602.03840](https://arxiv.org/abs/1602.03840)

GW150914 April 2016

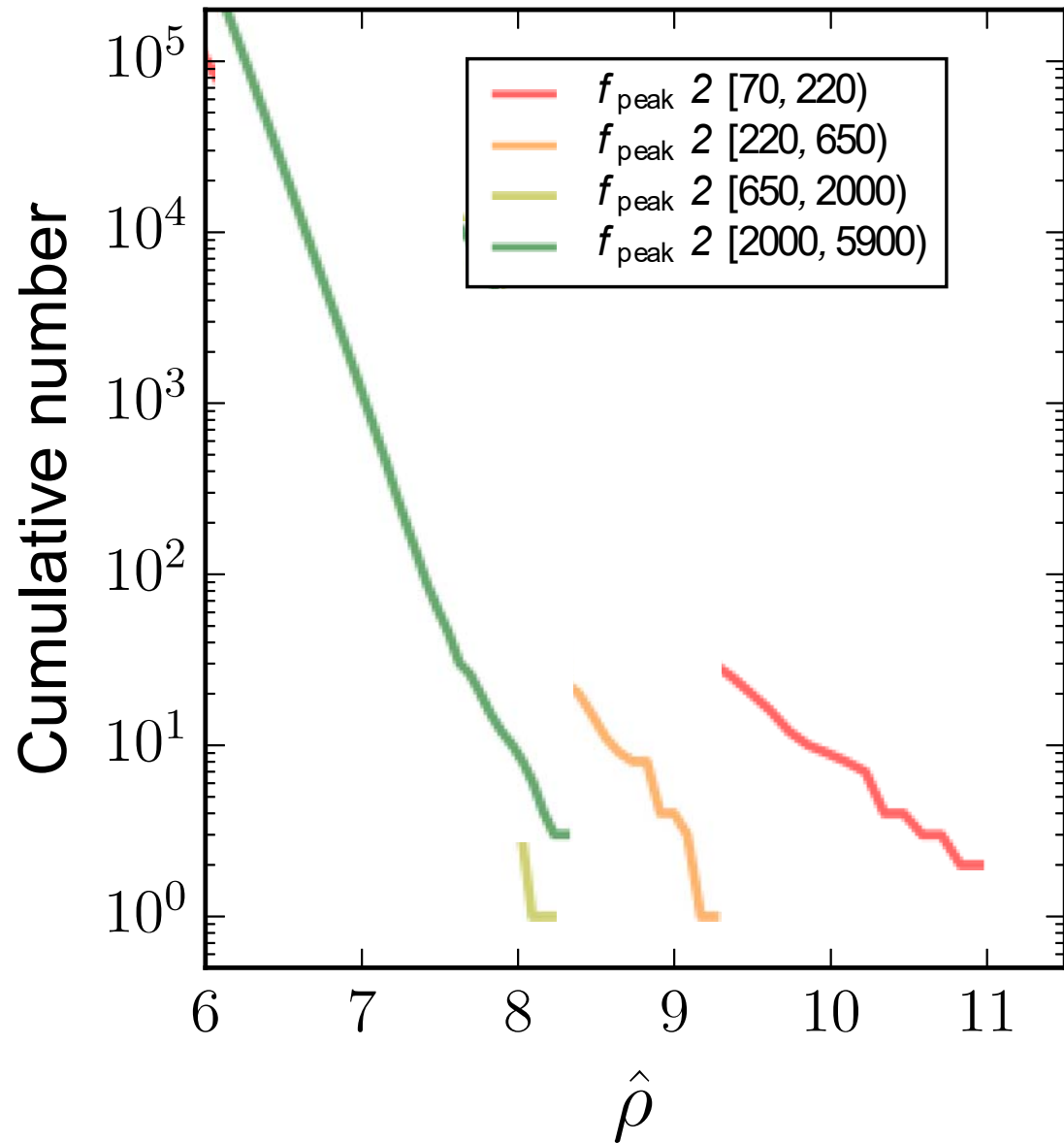
Francesco Fidecaro

103

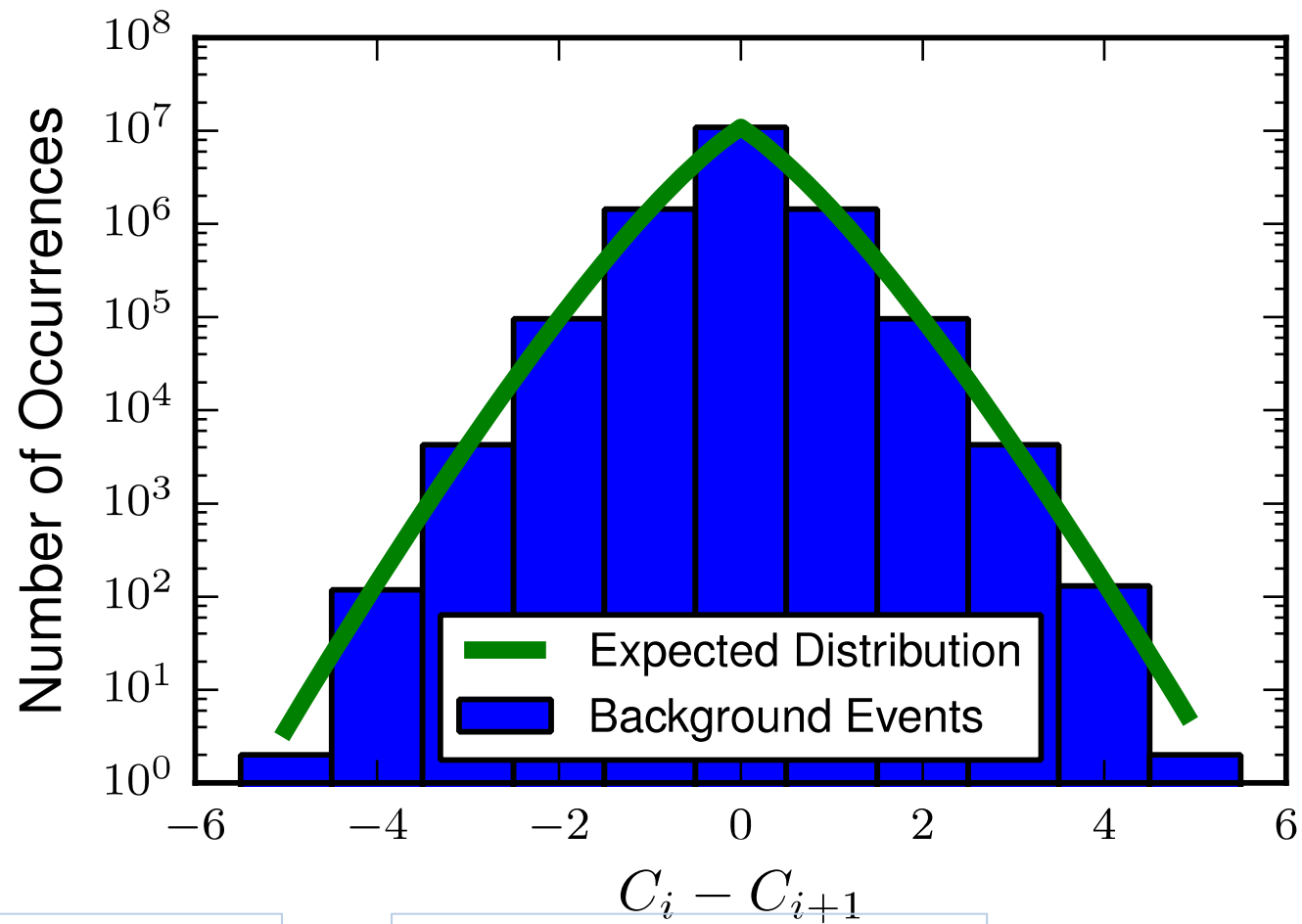
Template bank



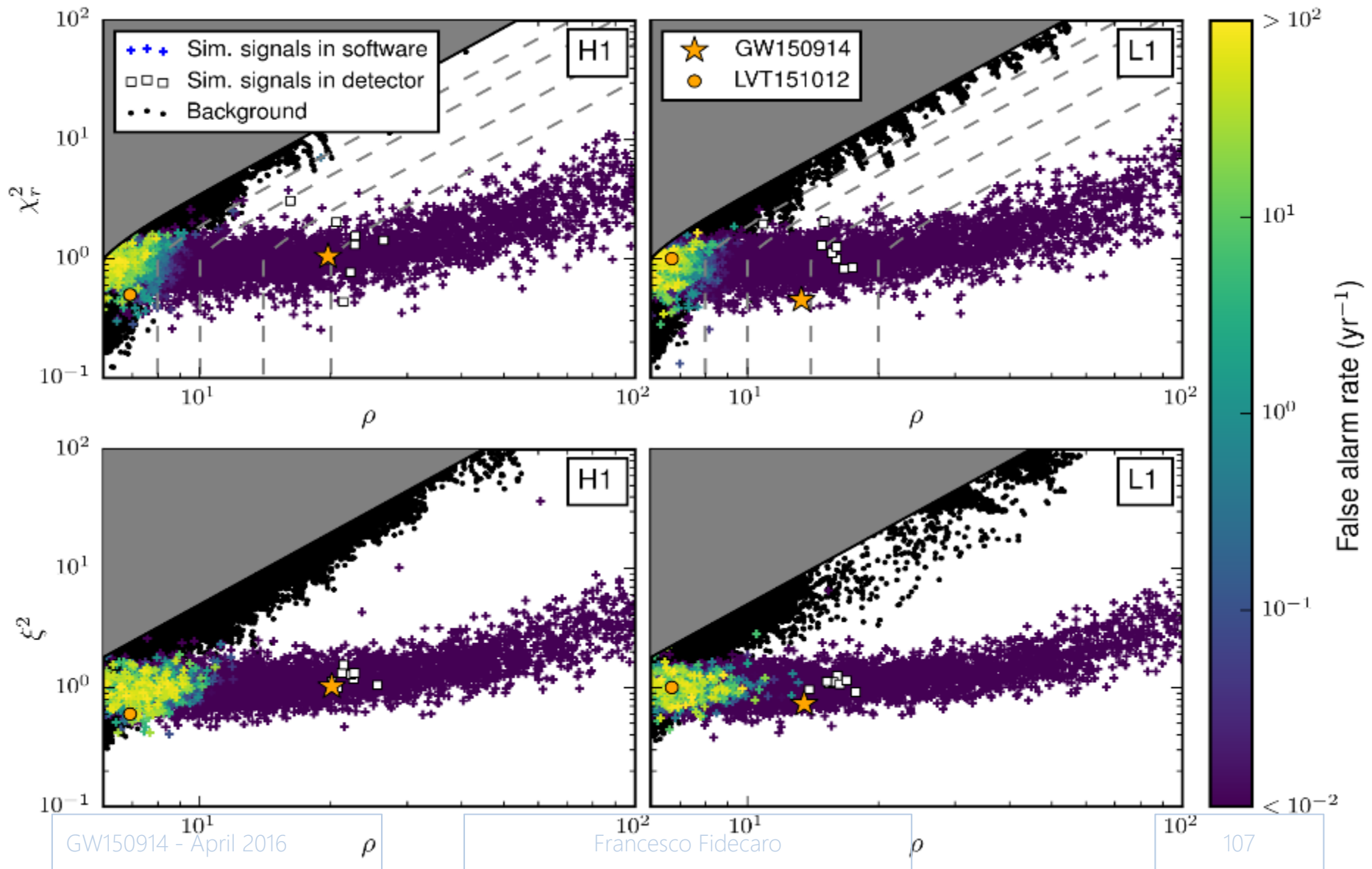
Template dependent background



Slide correlation

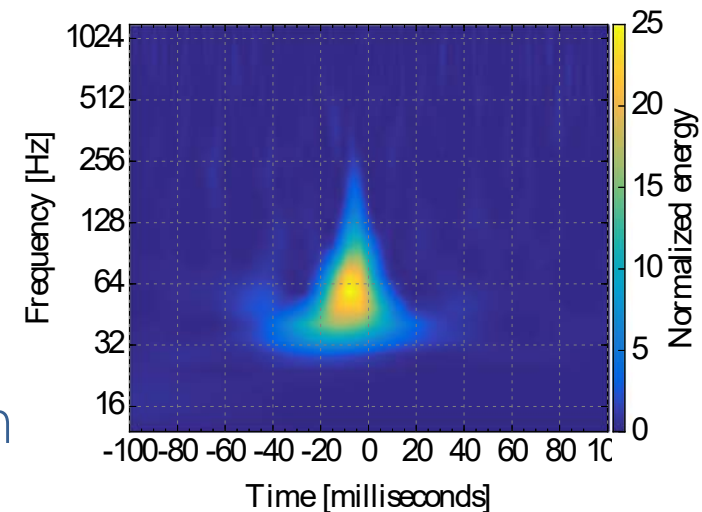


Simulated signals

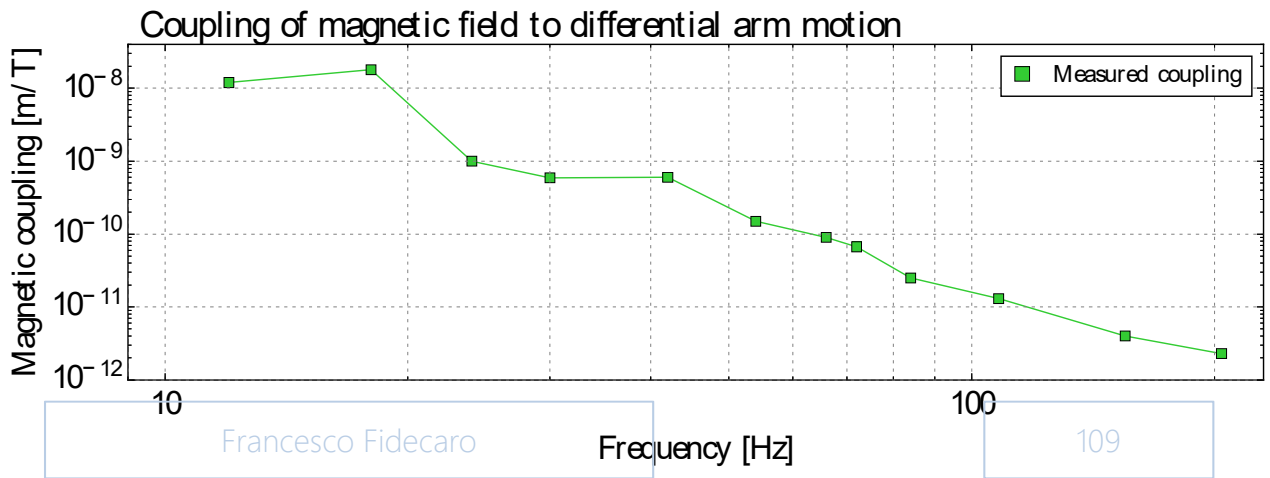
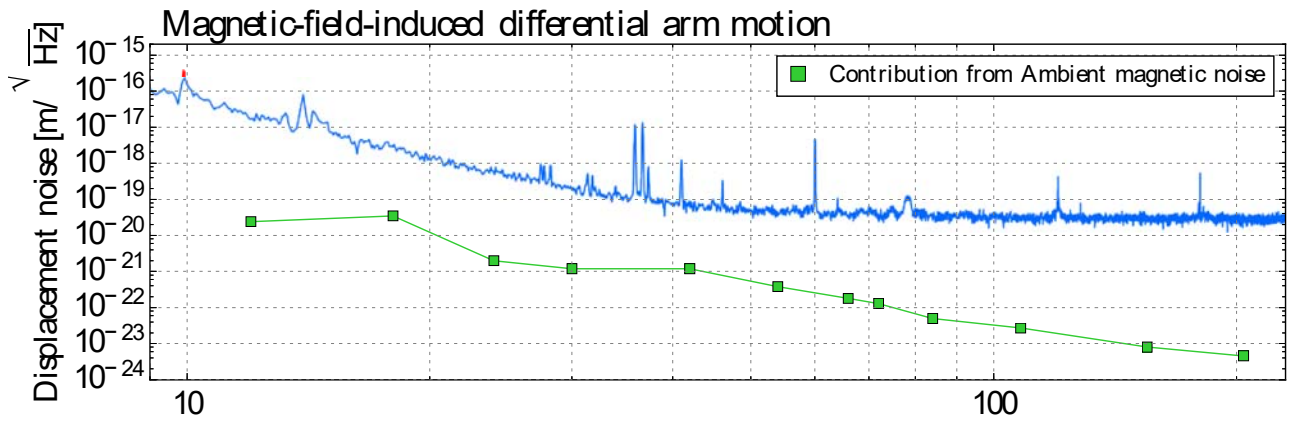
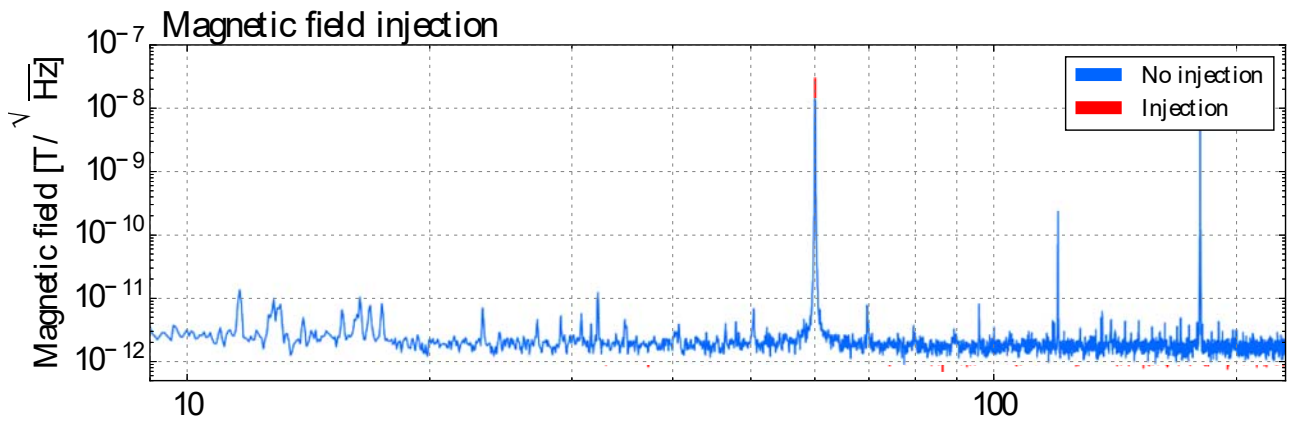


Transient noise

- Detectors were operating in their nominal state at the time of GW150914
- Still contain non-Gaussian transients, examples:
 - Anthropogenic noise
 - Seismic noise
 - “Blip” transients
- Mitigate noise by “vetoing” times of elevated noise, measured in auxiliary channels.
- Data are clean and stationary around



Noise coupling example: Magnetic fields



Correlated noise

- Possible electromagnetic noise sources
 - Lightning, solar events.
 - Would be picked up in radio receivers, magnetometers
 - Nothing at time of event
- Cosmic ray showers
 - Not correlated on 3,000 km scales
 - Cosmic ray detector at Hanford – no events

Monitoring channels

- Interferometer monitoring
 - Transmitted light beams, optics alignment sensors, feedback signal
- Environmental monitoring
 - Seismic sensors, microphones, magnetometers, radio-frequency antennas, cosmic rays detectors
- Detailed study of the couplings between auxiliary channels/environmental disturbances and detector output
 - Injections of external disturbances
- Potential noise sources
 - Anthropogenic noise, Earthquakes, Radio Frequency noise
 - Lightning, Cosmic rays

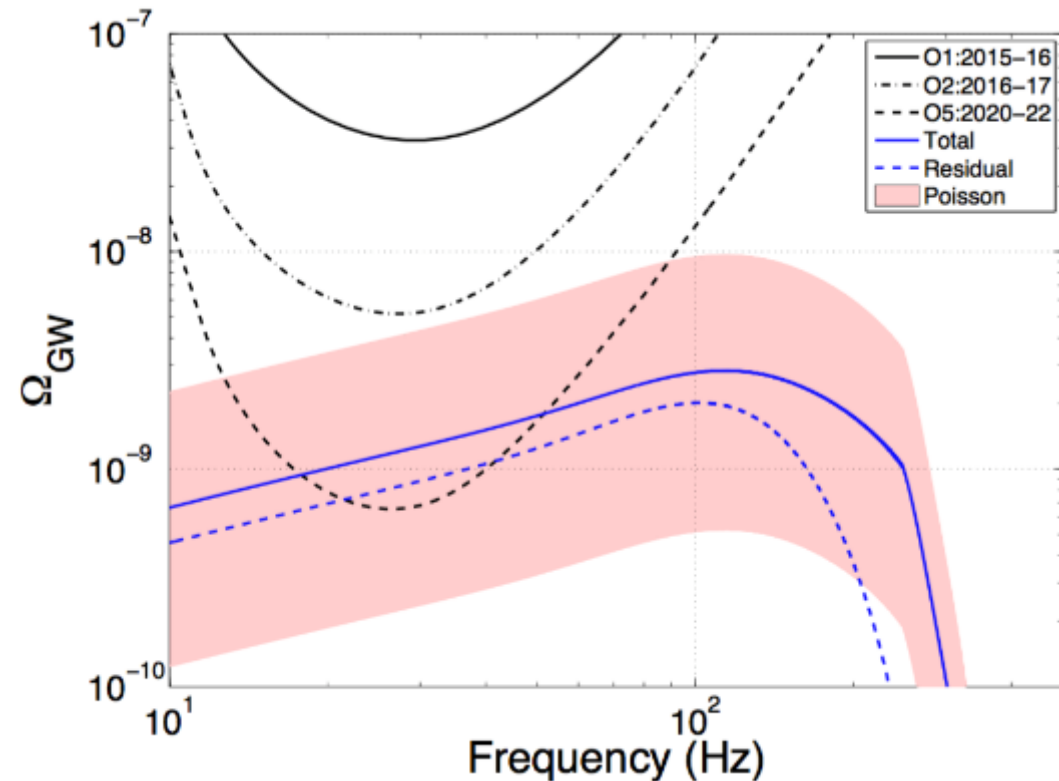
Calibration

- The detector output is calibrated in strain by measuring its response to test mass motion induced by photon pressure from a modulated calibration laser beam
- Calibration uncertainty (1σ) less than 10% in amplitude and 10 degrees in phase
- Continuously monitored with calibration laser excitations at selected frequencies.
 - Two alternative methods are used to validate the absolute calibration
 - main laser wavelength
 - radio-frequency oscillator

What could be seen?

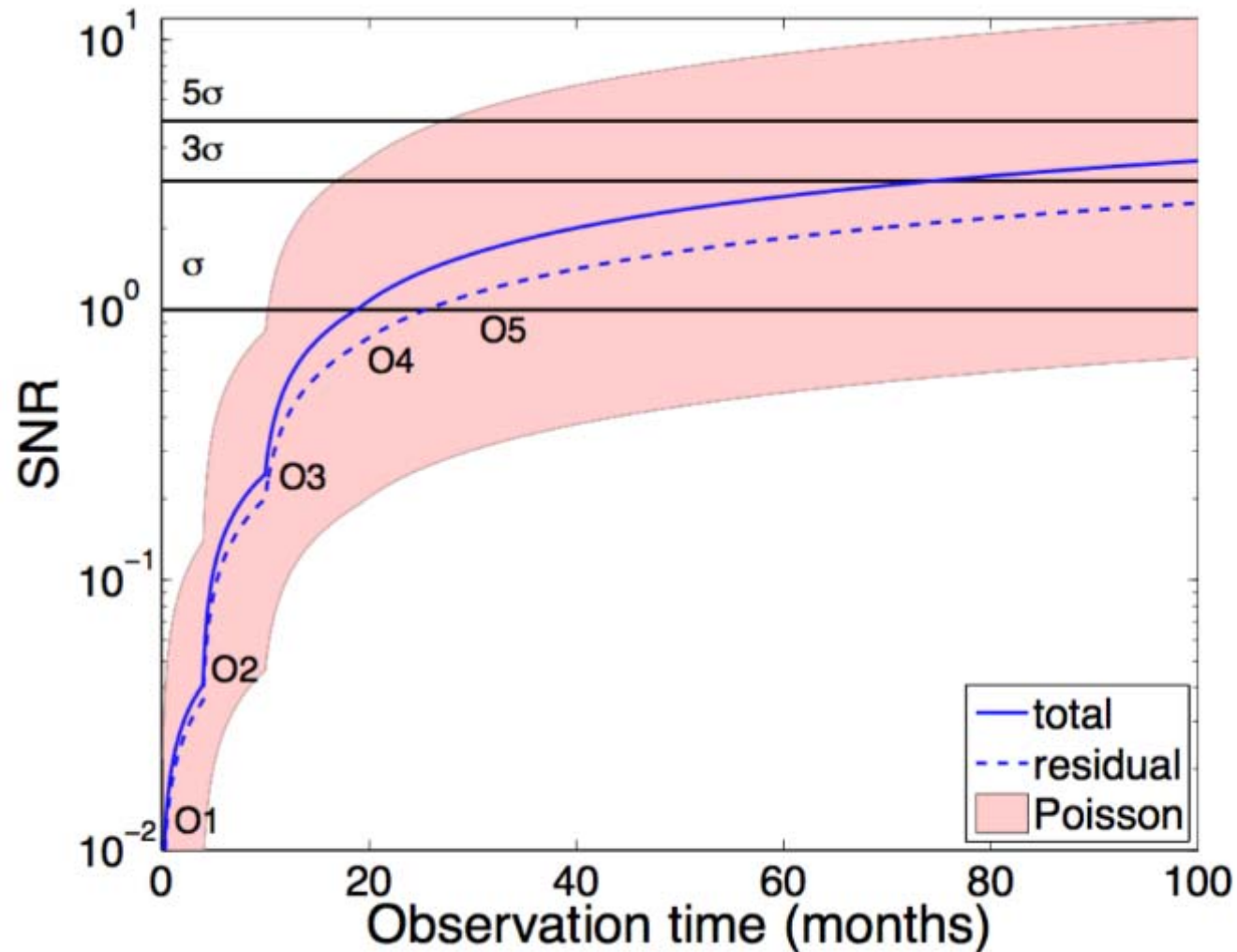
$$\Omega_{\text{GW}}(f) = \frac{f}{\rho_c} \frac{d\rho_{\text{GW}}}{df}$$

GW energy density per unit frequency, normalized to the density ρ_c to close the Universe



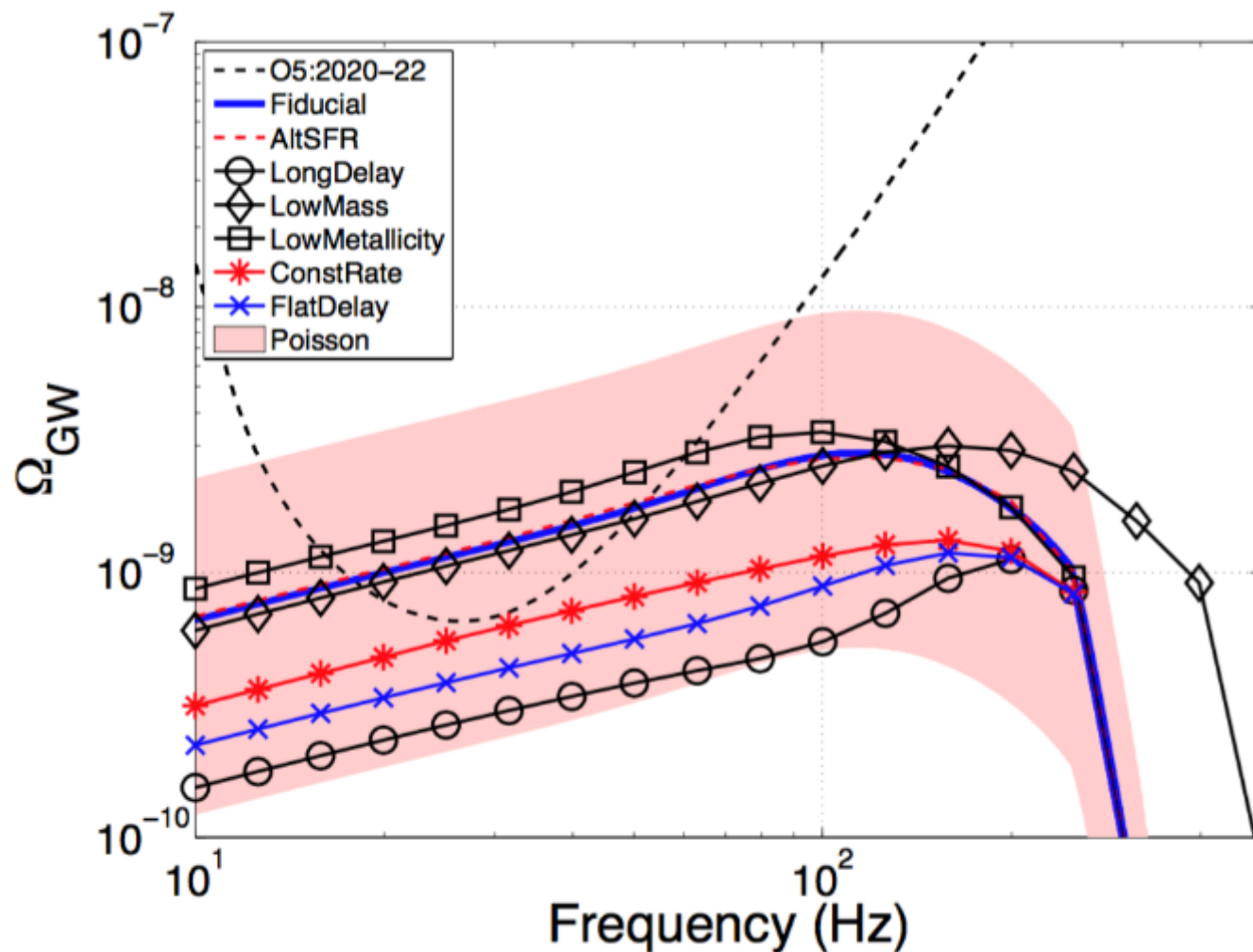
- For a given model prediction (blue curve) the pink region is due to the Poisson uncertainty on the measured BBH rate
- High uncertainty, with a single event: still, as sensitivity progresses from O1 to O5 the signal is *potentially* detectable

SNR accumulation



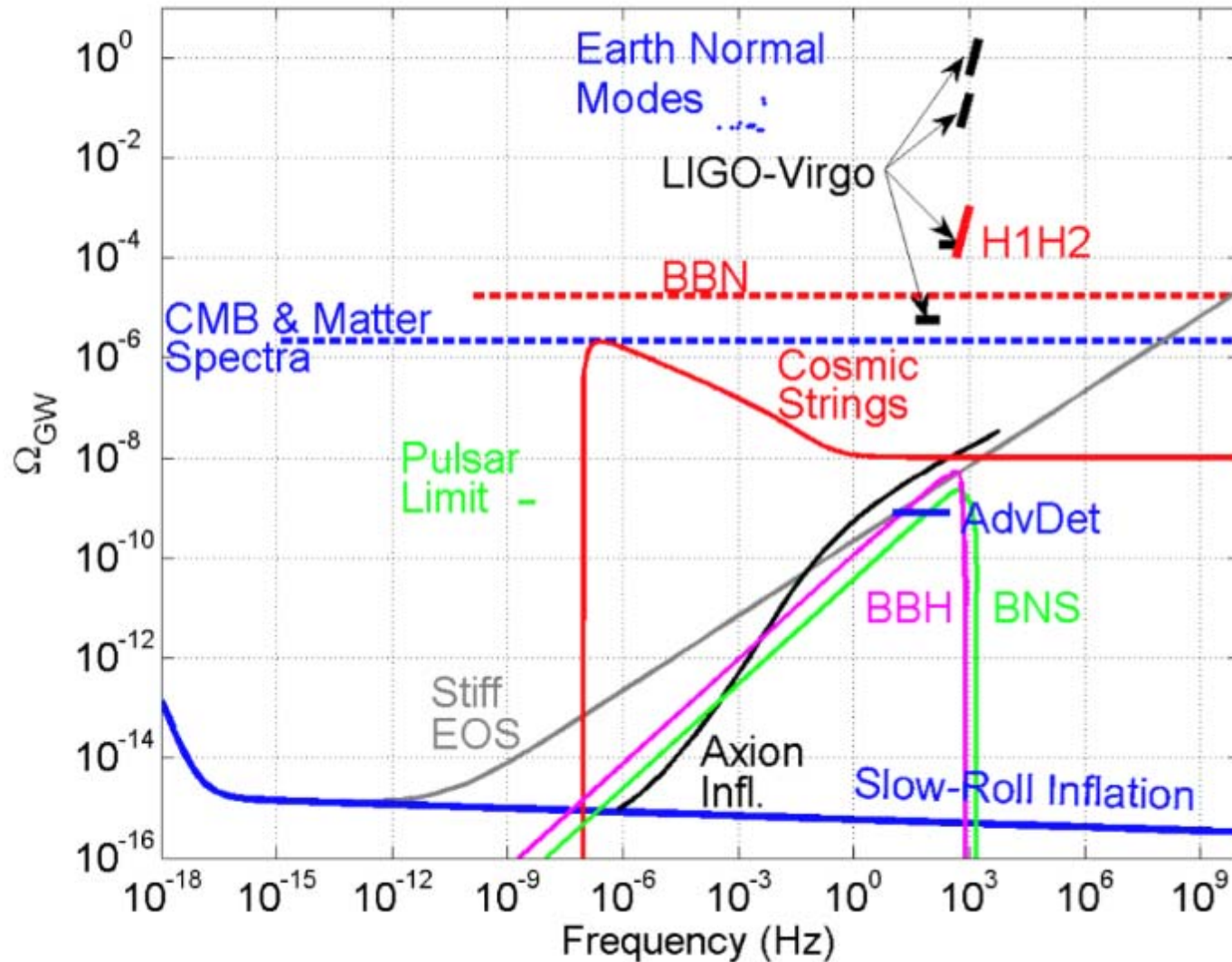
- Detectors' progress helps, but achieving high significance requires also to integrate observation time

Does model variation matter?



- Predictions still dominated by the rate uncertainty
- Pink region will shrink with future event detections

Which limits had we set already?



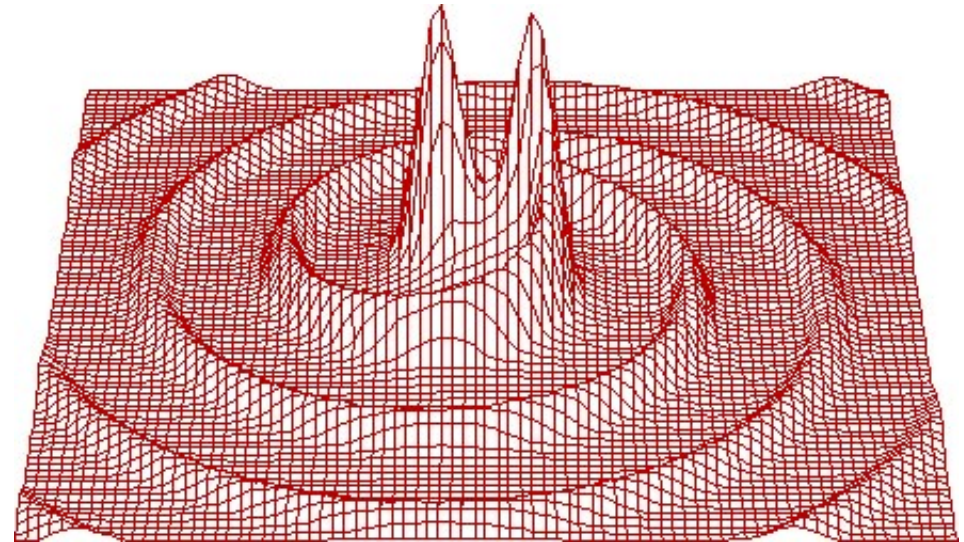
- Advanced Detectors see a small portion of the spectrum



GENERAL RELATIVITY & GRAVITATIONAL WAVES IN A NUTSHELL

Einstein's Theory of Gravitation

- a necessary consequence of Special Relativity with its finite speed for information transfer
- gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



gravitational radiation
binary inspiral of
compact objects

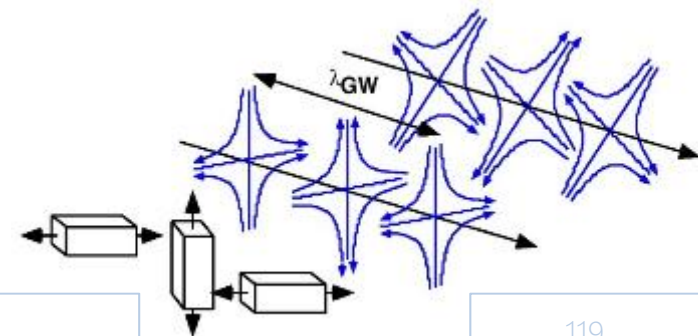
Einstein's Theory of Gravitation

gravitational waves

- Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, h_{mn} . In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the transverse traceless gauge the formulation becomes a familiar wave equation
- The strain h_{mn} takes the form of a plane wave propagating at the speed of light (c)
- Since gravity is spin 2, the waves have two components, but rotated by 45° instead of 90° from each other

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

$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$





$$h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

Indirect Evidence for Gravitational Waves

PSR 1913+16



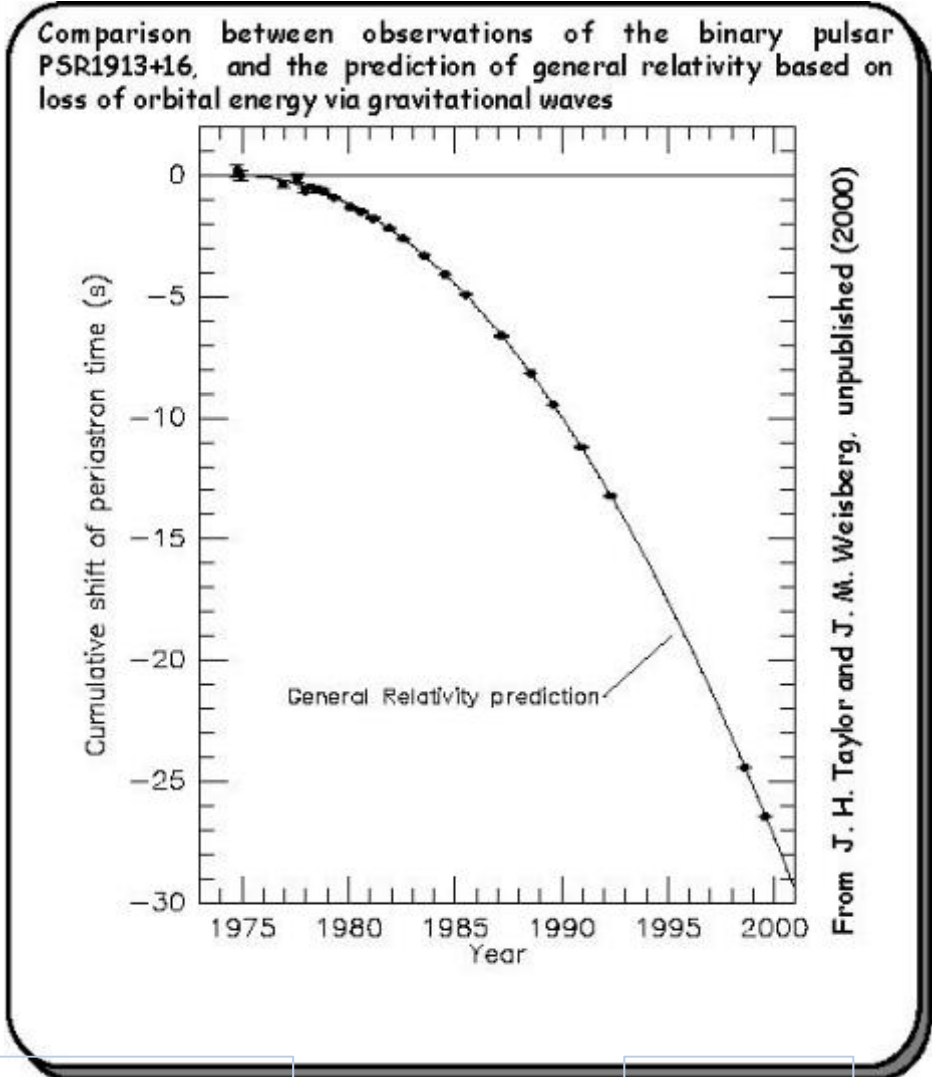
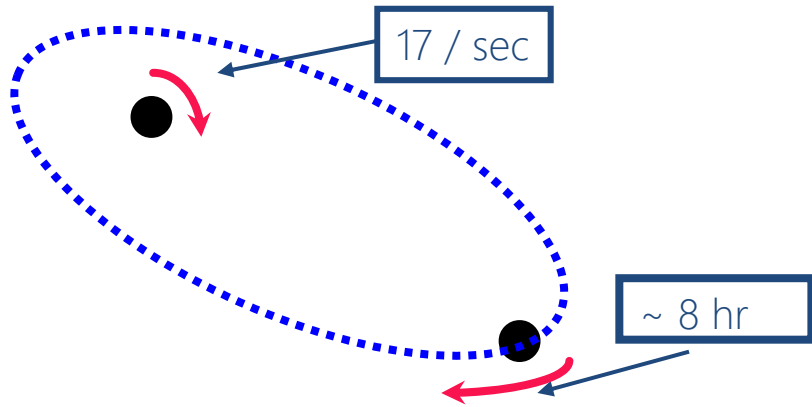
Joseph Taylor



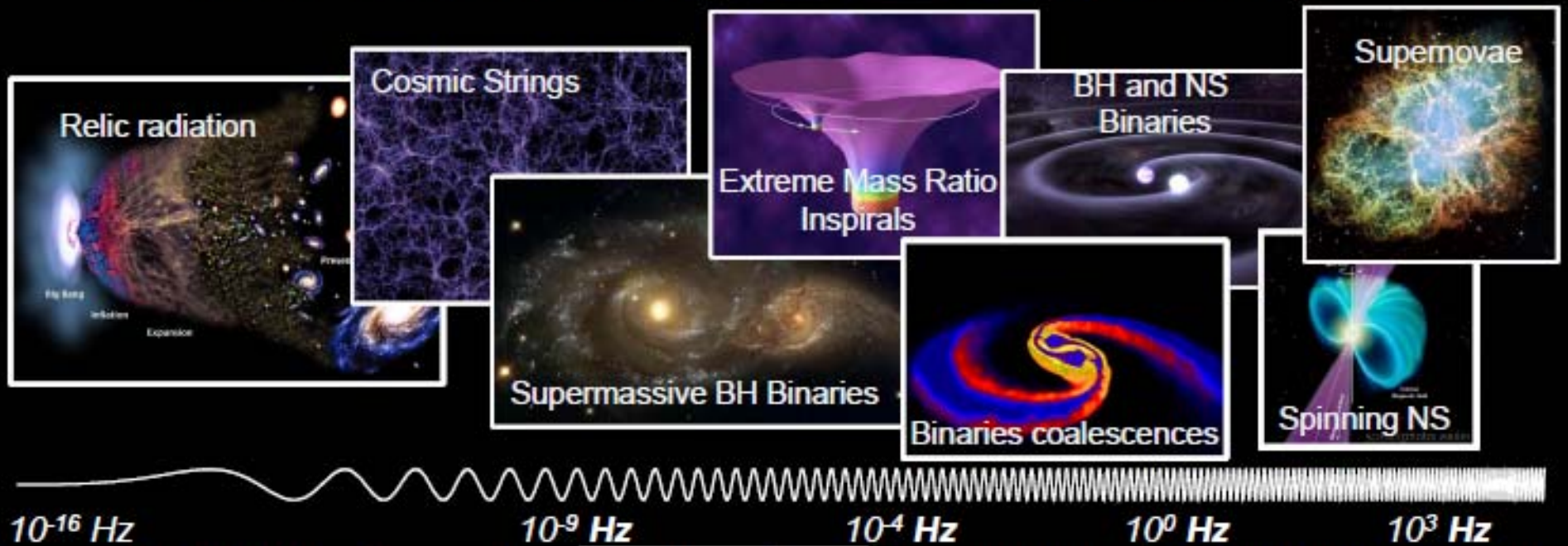
Russell Hulse



1993 Nobel Prize
In Physics

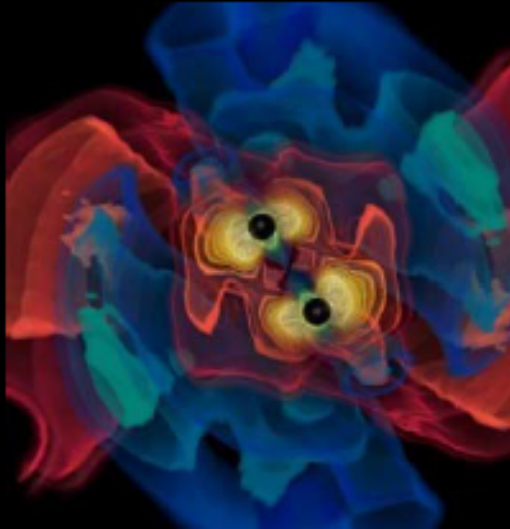


The Gravitational Wave Spectrum



Laser
Interferometer
Gravitational Wave
Observatory

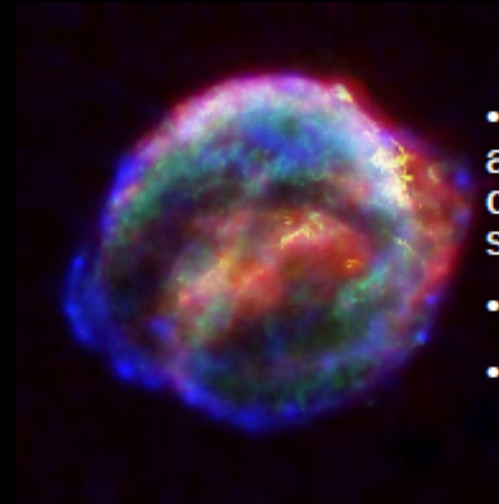
Astrophysical targets for ground-based detectors



Credit: AEI, CCT, LSU

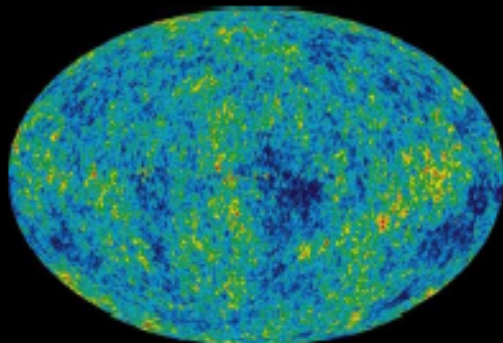
Coalescing Binary Systems

- Neutron stars, low mass black holes, and NS/BS systems



'Bursts'

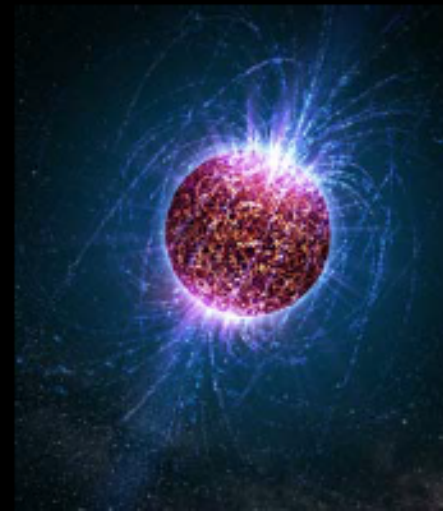
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Stochastic GWs

- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range



Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- probe crustal deformations, 'EOS, quarkiness'