Gravitational Waves Astronomy

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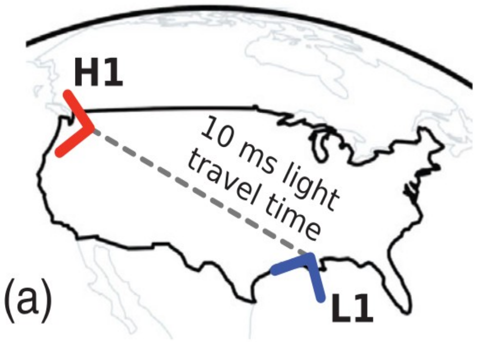
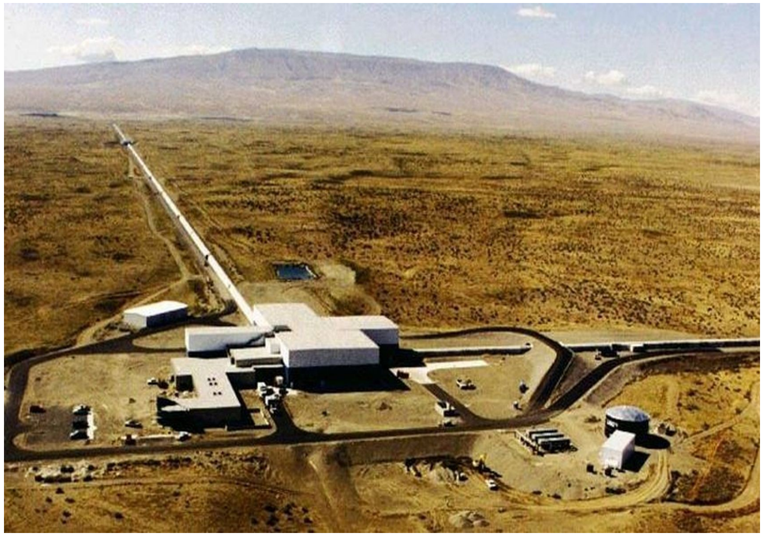


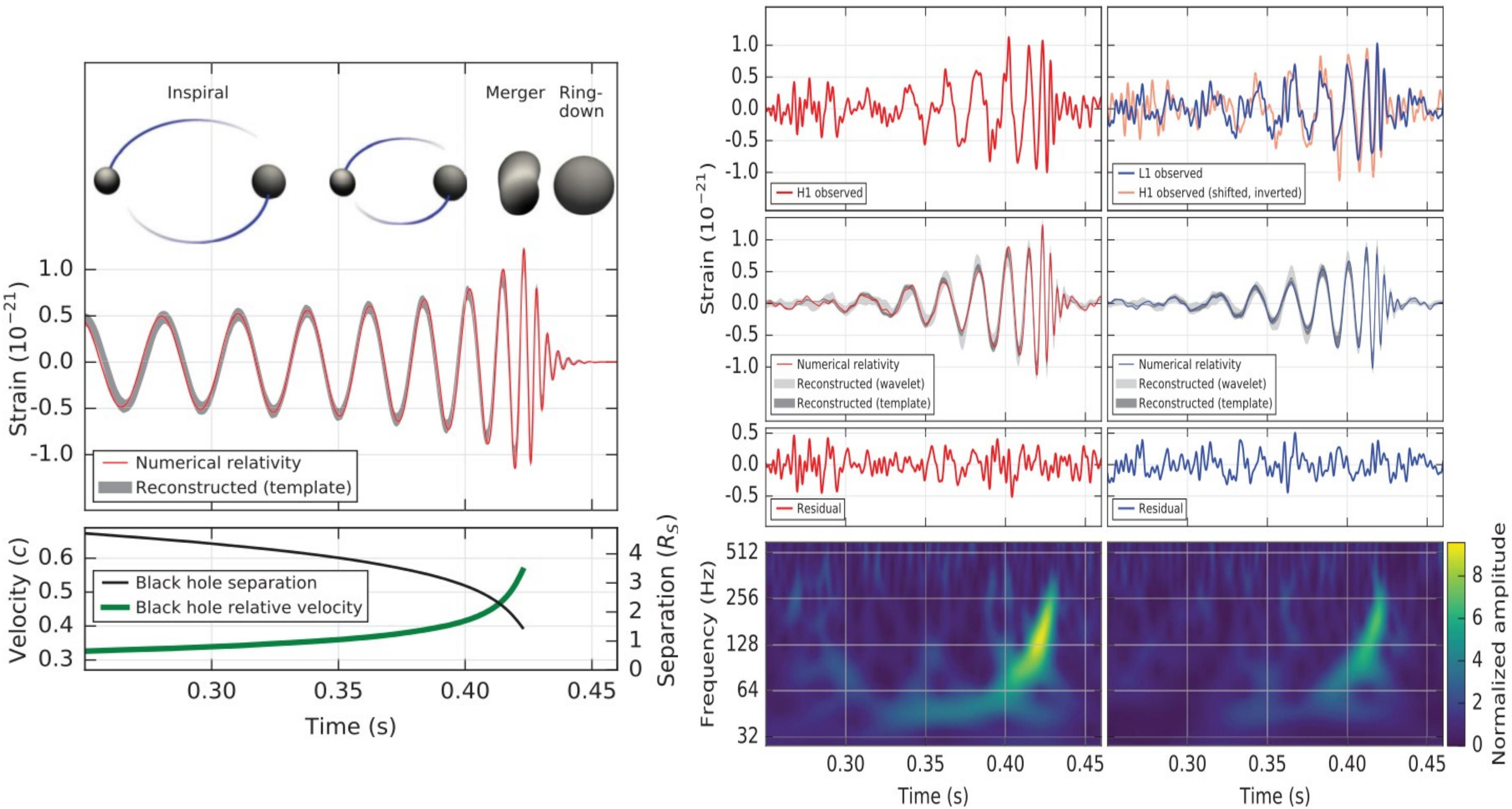


LSC LIGO Scientific Collaboration

VIRGO

FNP Fundacja na rzecz Nauki Polskiej

GW150914- the first LIGO gravitational wave detection from BBH with masses 29 M_{sun} and 36 M_{sun} all together < 200 ms (a chirp signal)



Burst search

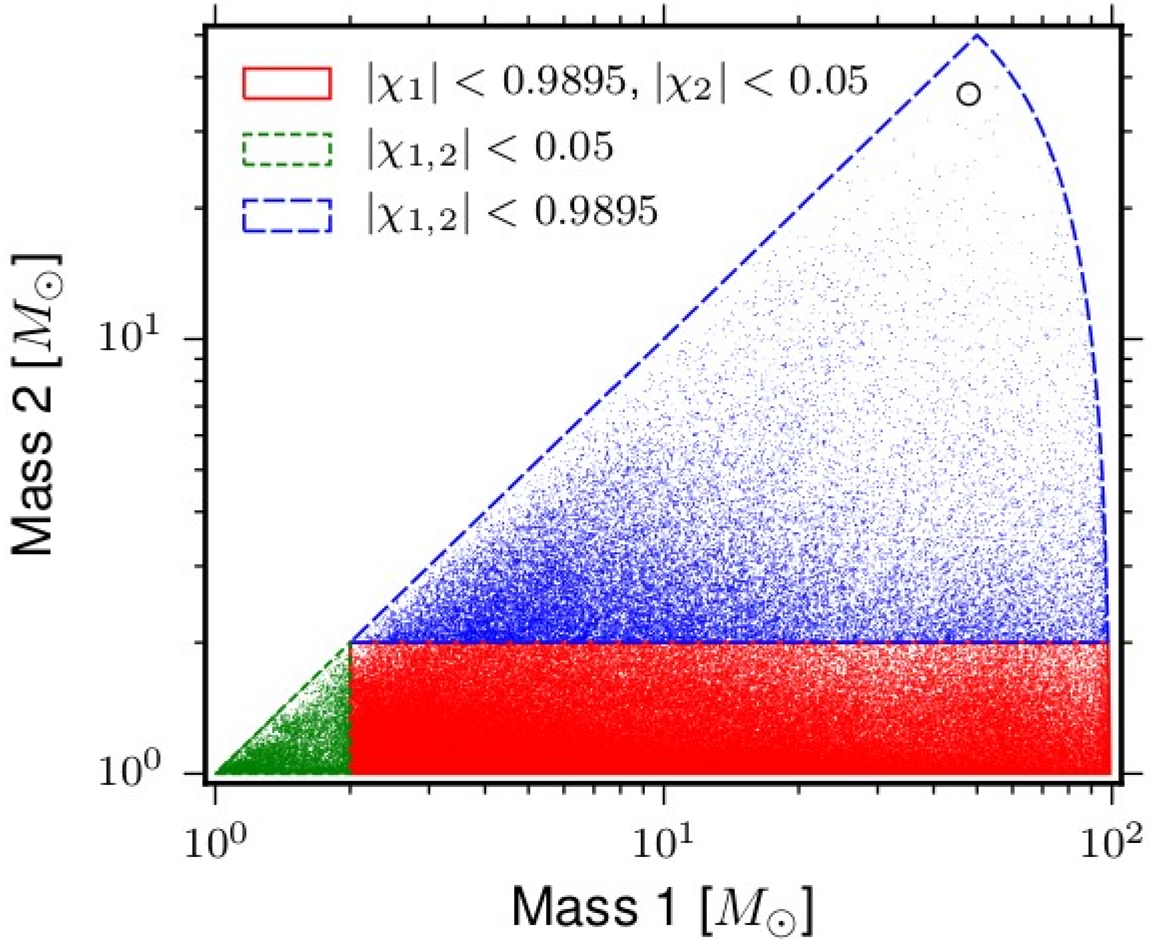
- No prior knowledge of the shape of the signal
- Search for coincident bursts
- Signal reconstruction
- Detection statistics based on similarity of waveforms in two (or more) detectors
- Low latency – less than 3 minutes
- Later off line detailed analysis with background estimates

Compact Binaries Coalescence search

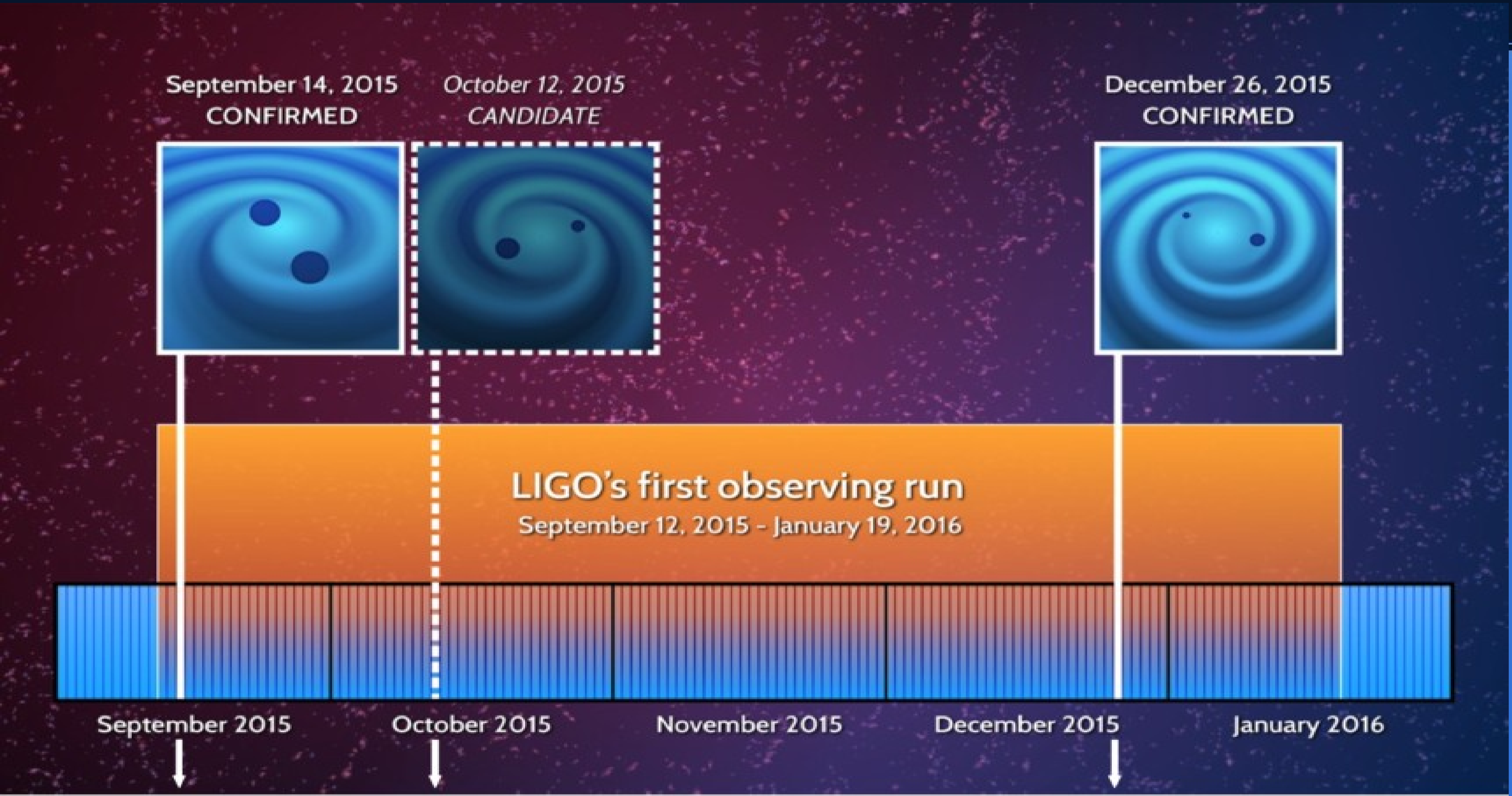
Search targeted at binary coalescence signals: NSNS, BHNS BHBH

Matched filtering
Template bank

Background estimate using time shifts



LIGO- the first observing run O1 (14.09.2015-19.01.2016).
The era of GW astronomy has begun

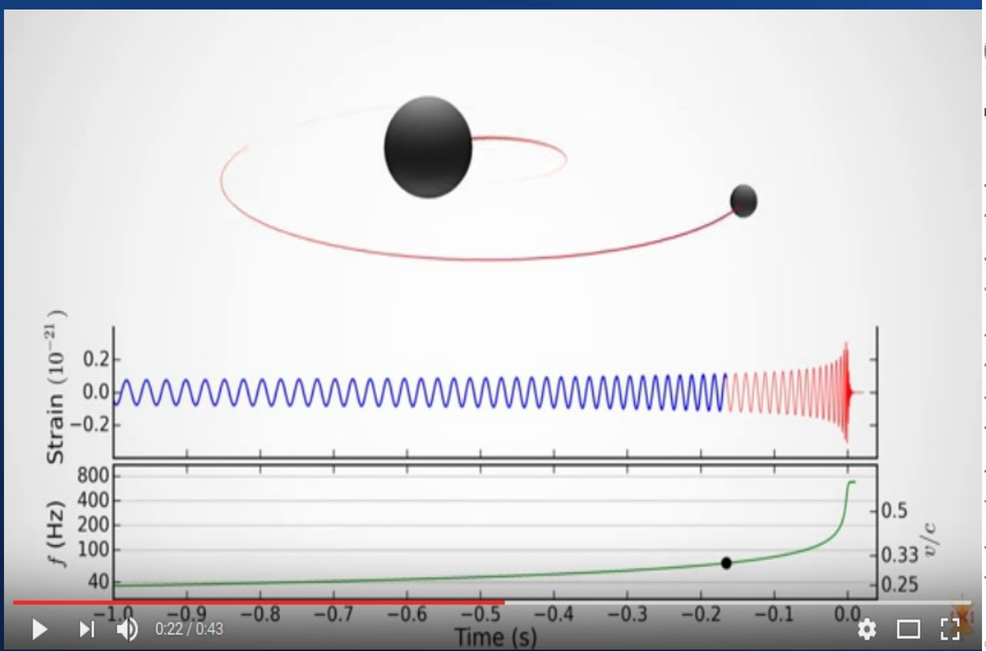


SNR=23.7
FAR < 6 10^{-7} yr^{-1}
Significance > 5.3 σ

SNR=9.7
FAR =0.37 yr^{-1}
Significance = 1.7 σ

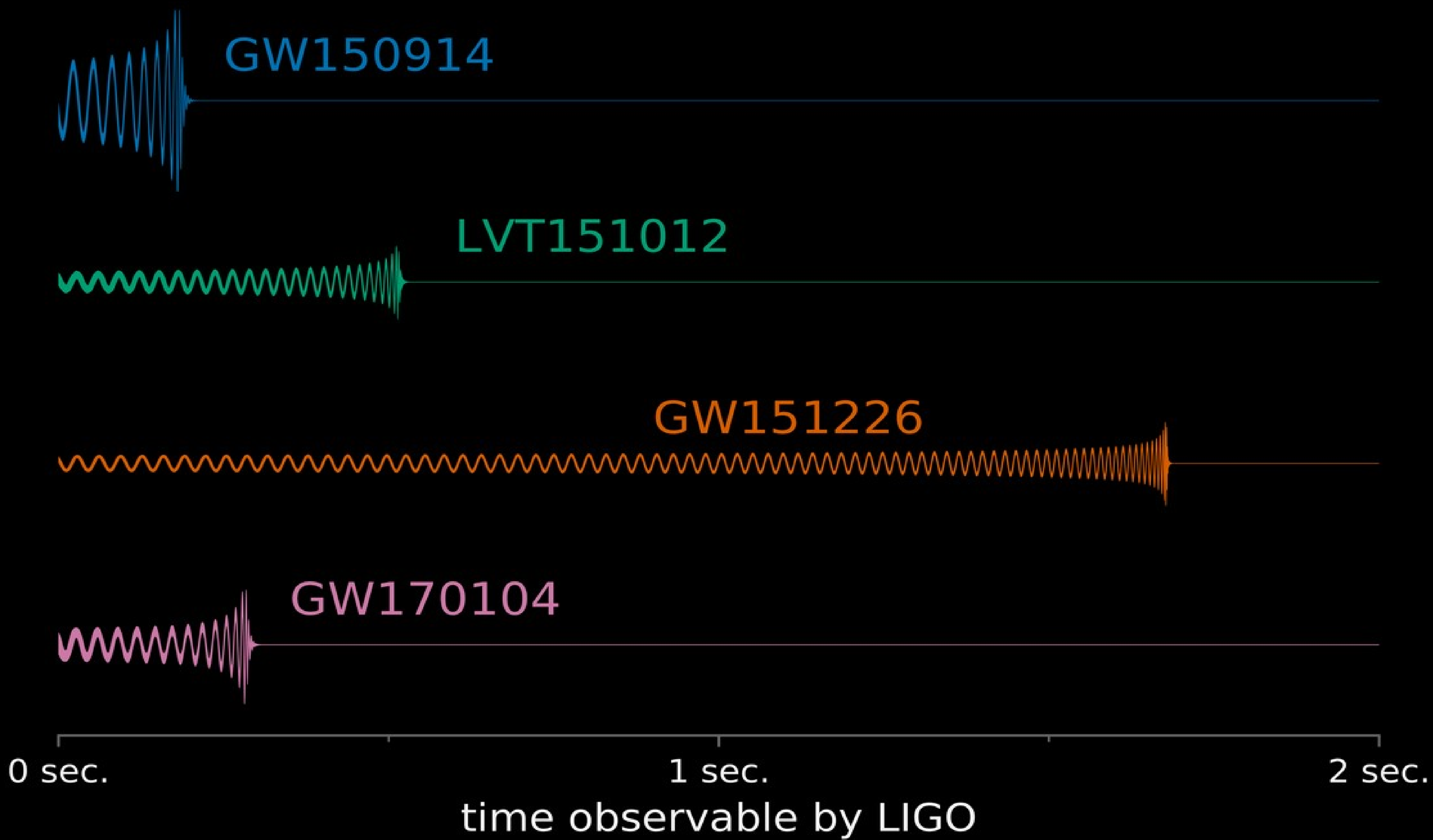
SNR=13.0
FAR < 6 10^{-7} yr^{-1}
Significance > 5.3 σ

GW170104: the first BBH from O2 LIGO
- the most distant observed BBH, the spin axes in a merging binary system could be misaligned

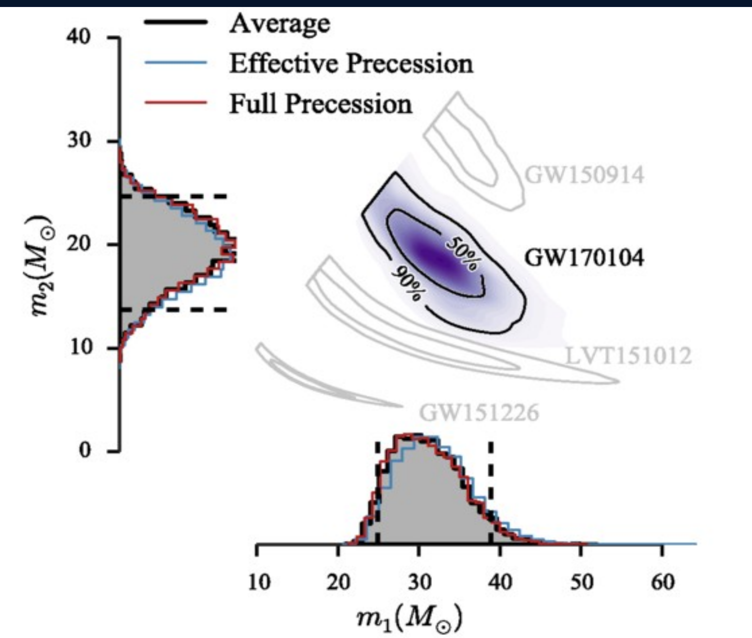


Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

Gravitational waves from coalescing binary black holes observational runs O1 (12.09.2015-19.01.2016) i O2 (30.11.2016- mid 2017)

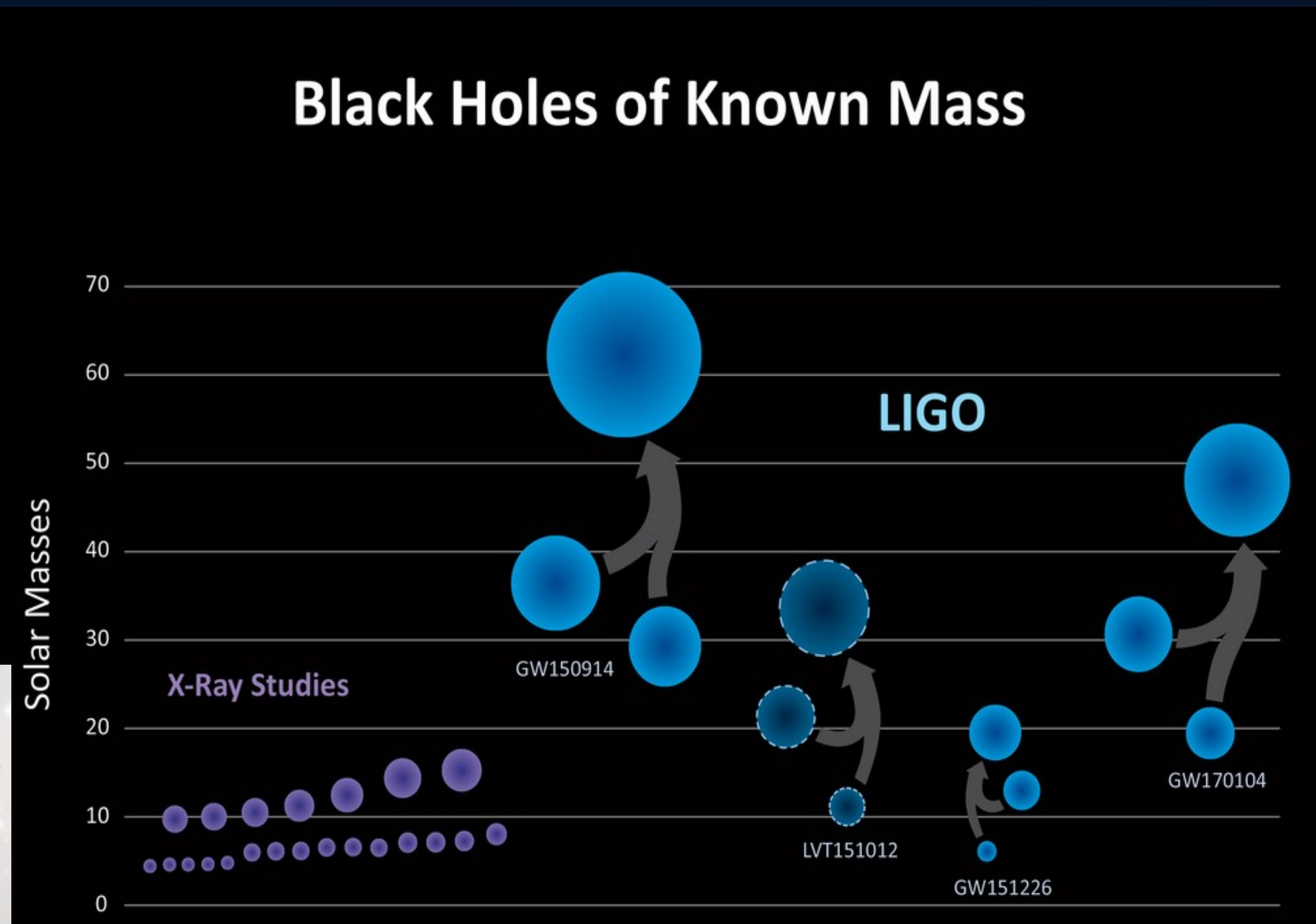


Evidence of existance of heavy masses stellar mass black holes > 20 Msun mass



Event	GW150914	GW151226	LVT151012
m_1 ($M_\odot$)	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
m_2 ($M_\odot$)	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}

Abbott et al. 2016, Phys. Rev. X, 6, 041015



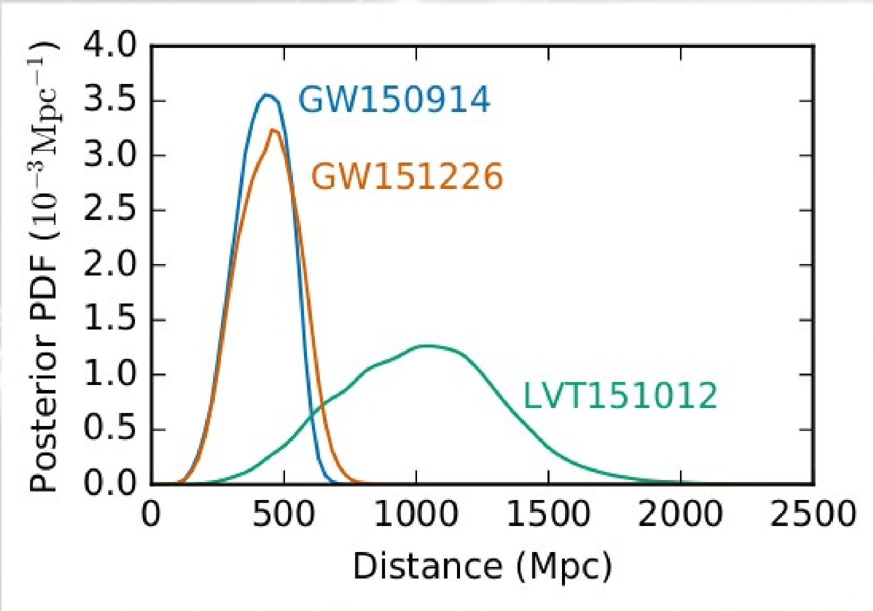
GW170104: $31.2^{+8.4}_{-6.0} M_\odot$ $19.4^{+5.3}_{-5.9} M_\odot$

B. P. Abbott *et al.**
(LIGO Scientific and Virgo Collaborati
PRL **118,** 221101 (2017)

Where the mergers of two black holes occured ?

with a aVirgo ~10 x better localization

Luminosity distance



Event	GW150914	GW151226	LVT151012
D_L (Mpc)	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}

Abbott et al. 2016, Phys. Rev. X, 6, 041015

Final sky localization

Event	GW150914	GW151226	LVT151012
$\Delta\Omega$ (deg^2)	230	850	1600

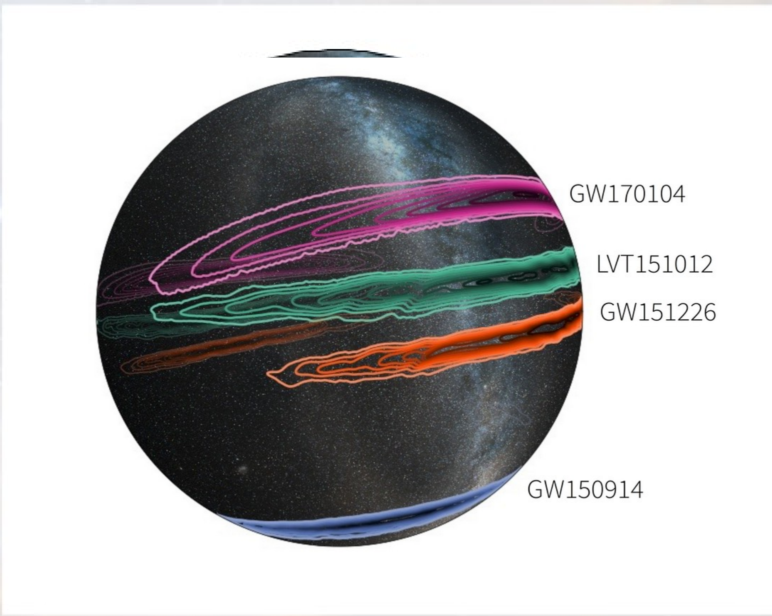


Image credit: LIGO/L. Singer/A. Mellinger

GW170104: 880^{+450}_{-390} Mpc

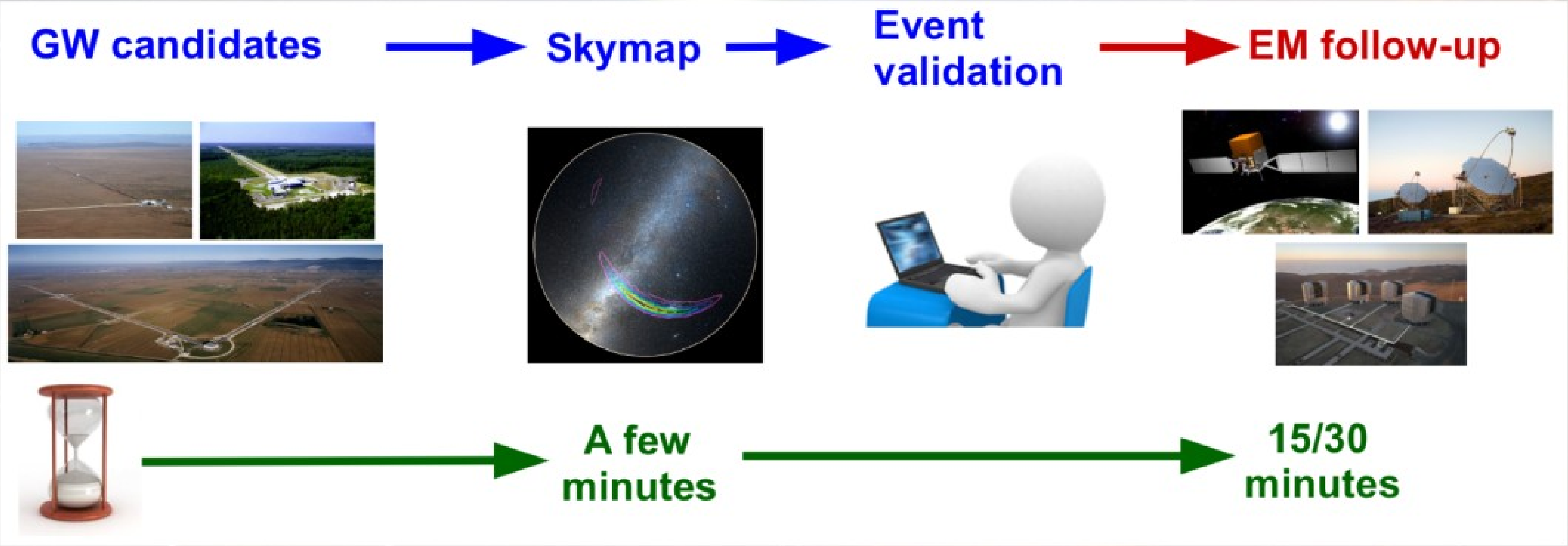
B. P. Abbott *et al.** (LIGO Scientific and Virgo Collaboration)

PRL **118,** 221101 (2017)

Gravitational waves and EM joint observations

Two possible scenarios:

- **EM follow-up:** low-latency GW data analysis pipelines promptly identify GW candidates and send GW alerts to trigger prompt EM observations and start archival searches



- **Externally-triggered GW searches:** an EM transient event is detected and GW data are analyzed to look for possible associated GW events.

Multi-messenger astronomy
GW and EM joint observations

80 MoUs* involving 170 instruments (satellites and ground-based telescopes) covering the full spectrum from radio to very high-energy γ-rays

65 teams of astronomers were ready to observe during O1!

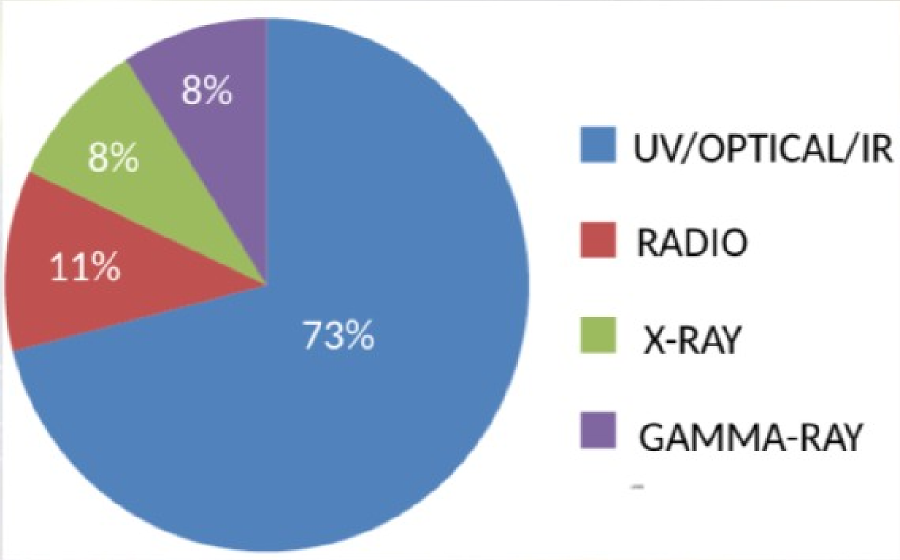
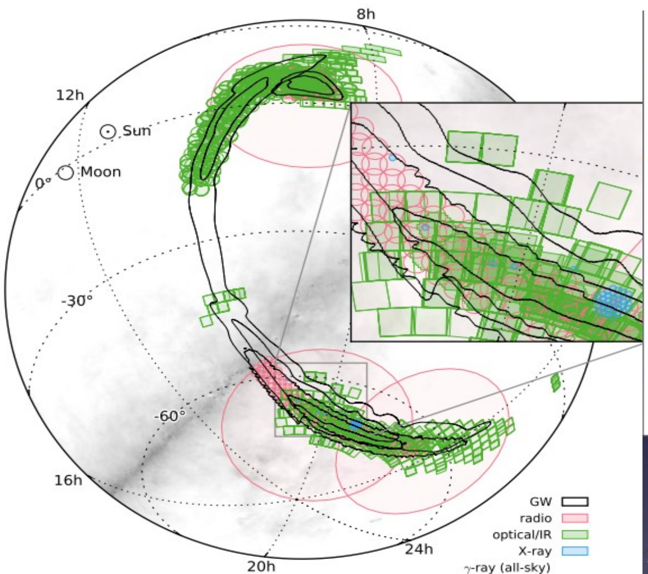
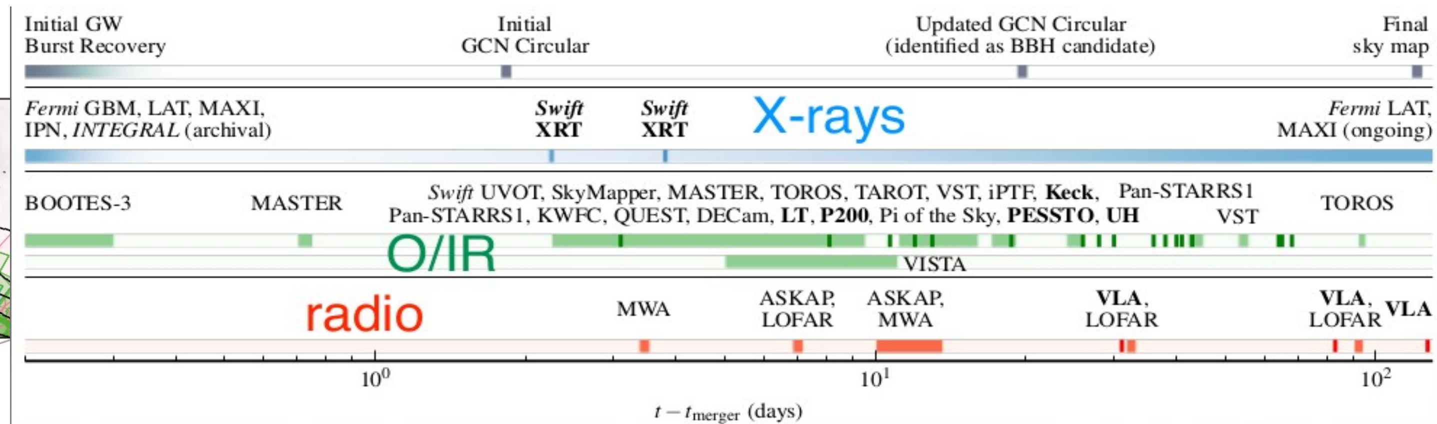


Image credit: M. Branchesi

Although no EM emission was expected from stellar mass BBH mergers due to the absence of matter around them, an intensive EM follow-up campaign has been performed to look for a possible EM counterpart to GW150914 and GW151226

GW150914 - EM Follow-up





The LVC, EM Collabs, ApJL, arxiv/1602.08492

All upper limits

except potential Fermi GBM gamma-ray burst counterpart?

Flurry of theoretical ideas for how a BBH could produce a GRB:

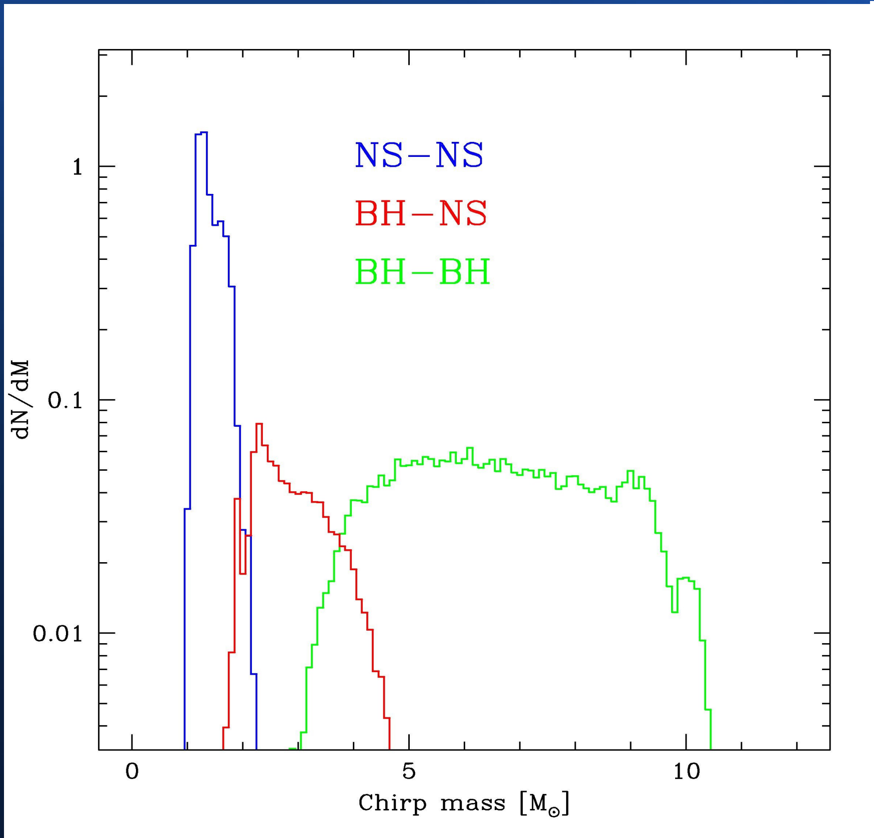
Loeb 2016, ApJL, arXiv:1602.04735
Perna et al. 2016, ApJL, arXiv:1602.05140
Stone et al. 2016, arXiv:1602.04226

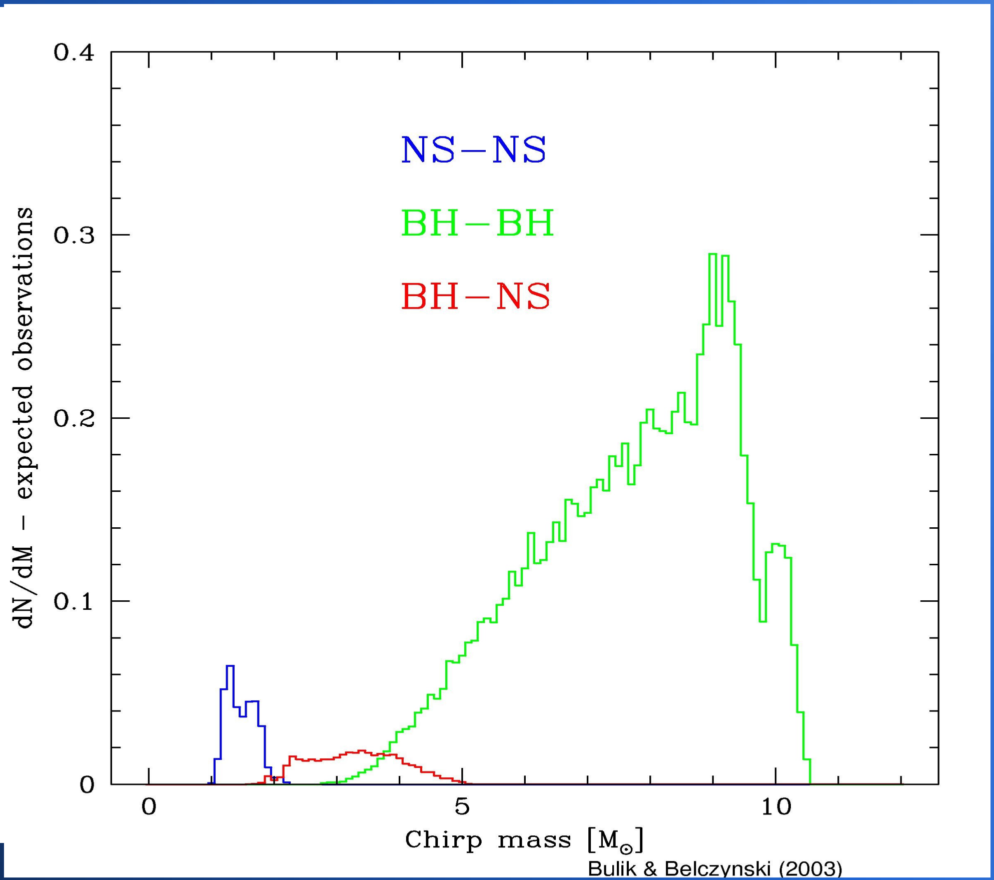
Archive data search → Fermi/GBM → possible **sub-threshold candidate**?

- ➢ a hard event 0.4 s after the GW event, lasted 1 s → rate 10^{-3} Hz, no sky-localization

Not detected by INTEGRAL, but not ruled out as a possible counterpart, though unexpected for a BBH!!

First detection- BBH



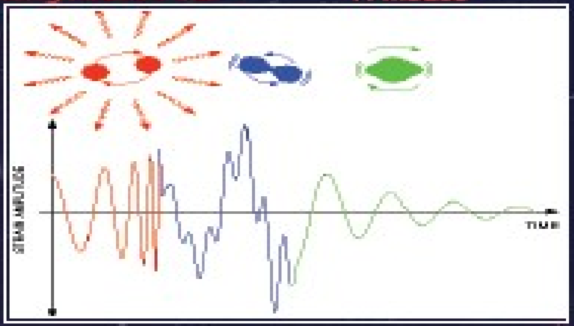


Bulik & Belczynski et al 2010

Astrophysical Sources of GW
10 Hz – 10 kHz

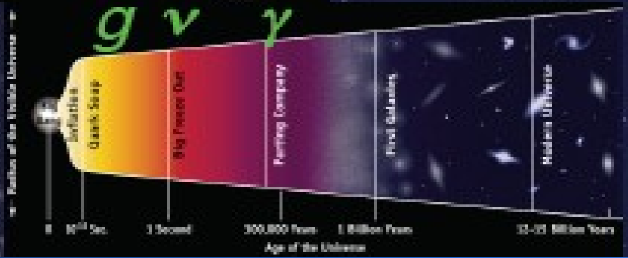
- Periodic sources
  - Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries

- Coalescing compact binaries
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW
  - waveforms

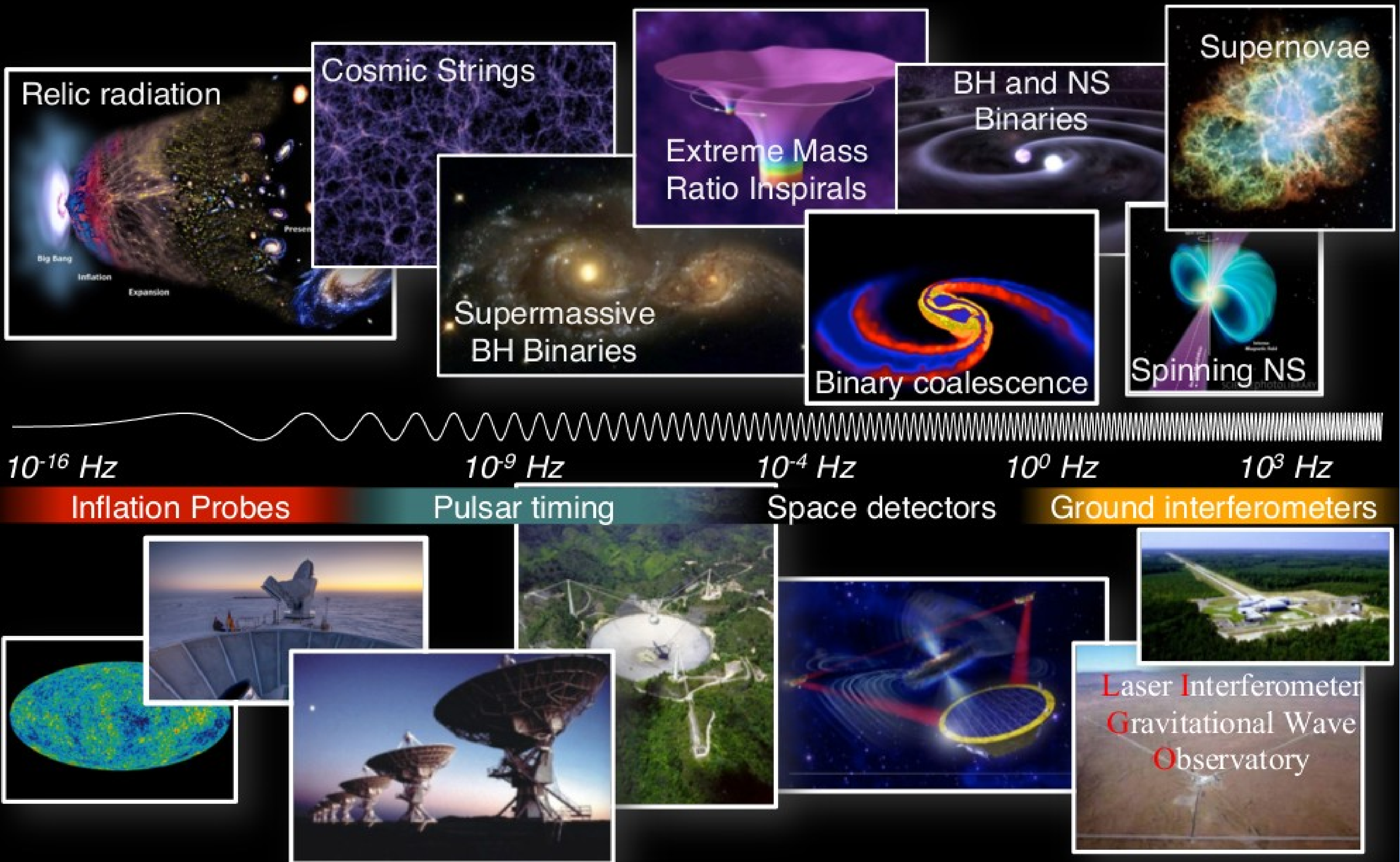


- Burst events
  - e.g. Supernovae with asymmetric collapse

- Stochastic background
  - Primordial Big Bang ($t = 10^{-22}$ sec)
  - Continuum of sources
- *The Unexpected !*



So much to look forward in GW astrophysics!



Slide: Matt Evans (MIT)

Goals of Gravitational Waves Observations

- Fundamental Physics
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Is Einstein theory the correct theory of gravity?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Astrophysics
  - What is the nature of gravitational collapse?
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - How did massive black holes at galactic nuclei form and evolve?
  - What is dark energy?
  - What phase transitions took place in the early Universe?
  - What were the physical conditions at the big bang?

Gravitational Wave Astronomy

open a new Window on the Universe

test GR and GR instabilities

Solving the enigma of GRBs and resolving their different classes

Measuring the cosmological parameters with GW standard sirens.

Understanding the mass-spectrum of compact stars and their populations – constraints on evolution

Measuring masses, spins,..of compact objects in binaries (constraints on NS EOS)

....

Gravitational wave sources

Requirements: compact M/R, relativistic and highly asymmetric

$-16 < \log f_{GW}$ [Hz] < 6

(sensitivity of terrestial detectors 10 Hz to 10 kHz)

- unknown sources
- known sources:

$$h \propto \mathcal{M}^{5/3} \times f^{2/3} \times r^{-1}$$

–- rotating and oscillating neutron stars

–- **binaries** **S/N~Mchirp/Distance,**

– **f_{GW}=2 forb,**

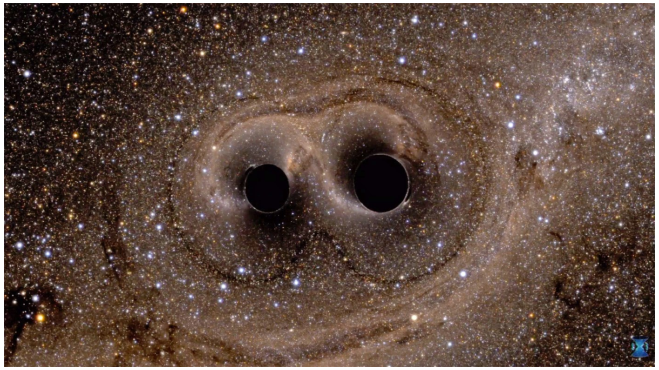
– **fmerger~ 2kHz/M_{tot}**

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

–- supernovae

•- stochastic background (primordial and originating from cosmic sources)

GW150914 - our firsts:



- Detection of gravitational waves
- Detection of a black hole
- Detection of a black hole binary
- The brightest source ever seen in the sky:

$$L_{GW} = 200^{+30}_{-20} \mathrm{M}_{\odot} s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\ s}^{-1}$$

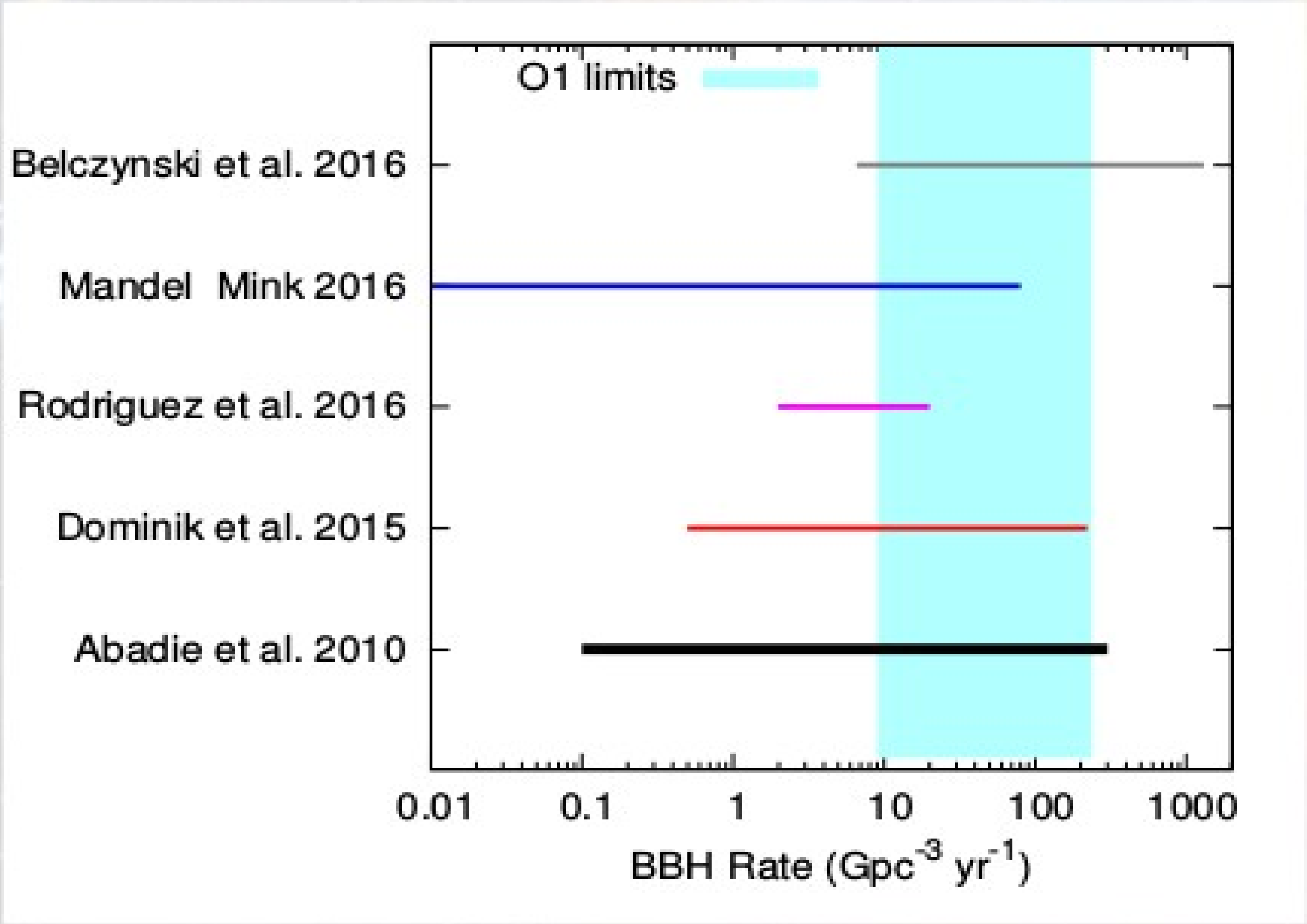
- Evidence for heavy BHs with masses of 30 and and up to 60 solar masses
- Their formation requires an origin from low-metallicity environments
- Such BBH can form both dynamical processes or isolated binaries

From Initial to Advanced GW detectors

Network	Source	$\dot{N}_{\rm low}$ $({\rm yr}^{-1})$	$\dot{N}_{\rm re}$ $({\rm yr}^{-1})$	$\dot{N}_{\rm high}$ $({\rm yr}^{-1})$
Initial	NS-NS	2×10^{-4}	0.02	0.2
	NS-BH	7×10^{-5}	0.0004	0.1
	BH-BH	2×10^{-4}	0.007	0.5
Advanced	NS-NS	0.4	40	400
	NS-BH	0.2	10	300
	BH-BH	0.4	20	1000

- Initial LIGO, initial Virgo
  - Active 2002-2011
  - No detections
  - Design sensitivity reached
    - Proof of the technology!
- Advanced detectors
  - O1: September-December 2015
    Advanced LIGO, limited sensitivity
  - O2: 2016-2017
    Advanced LIGO + Advanced Virgo
  - O3: 2017-2018
    Advanced LIGO + Advanced Virgo
    (+ KAGRA?)
  - Design sensitivity: 2019+

BBH merger rate:
9 - 240 Gpc^{-3} yr^{-1}



Supernovae and the core collapse

Core collapse of massive stars

- supernovae:
  - SBO X-rays, UV (minutes, days)
  - optical (week, months)
  - radio (years)

Image Credit: Avishay Gal-Yam

- long GRBs

Isolated neutron stars

- soft γ-ray repeaters
- radio/X-ray pulsar glitches

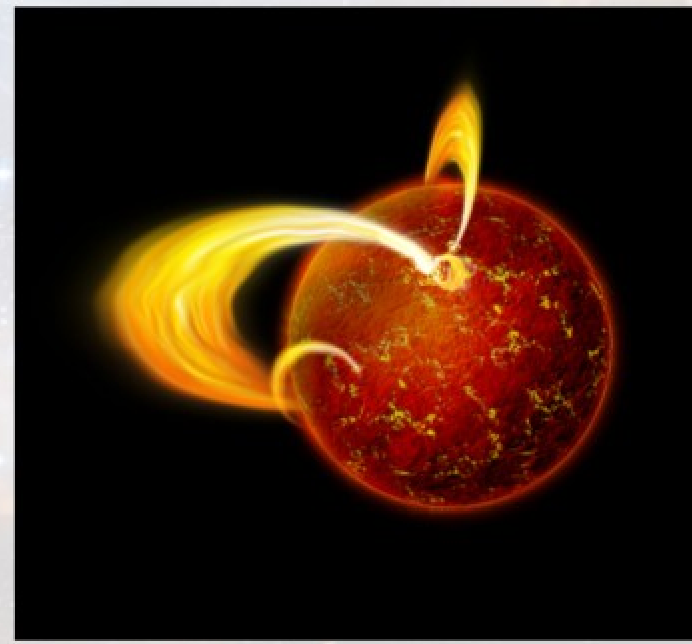


Image Credit: NASA, CXC, M. Weiss

Dzwięk - 2SN

The merger of a NS with NS or BH

NS-NS and NS-BH mergers

- Short GRBs:
  - *Prompt* γ-ray emission (< 2 s).
  - Multiwavelegth *afterglow* emission: X-ray, optical and radio (minutes, hours, days, months).
- Kilonova: optical and NIR (days-weeks).
- Late blast wave emission: radio ($\sim$ months, years).

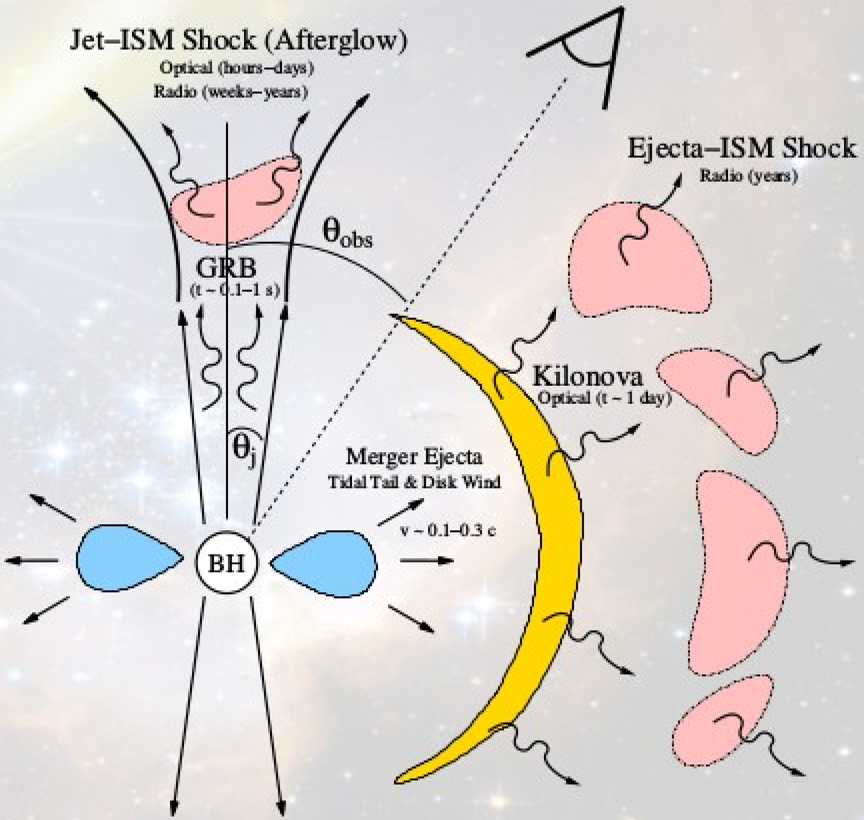
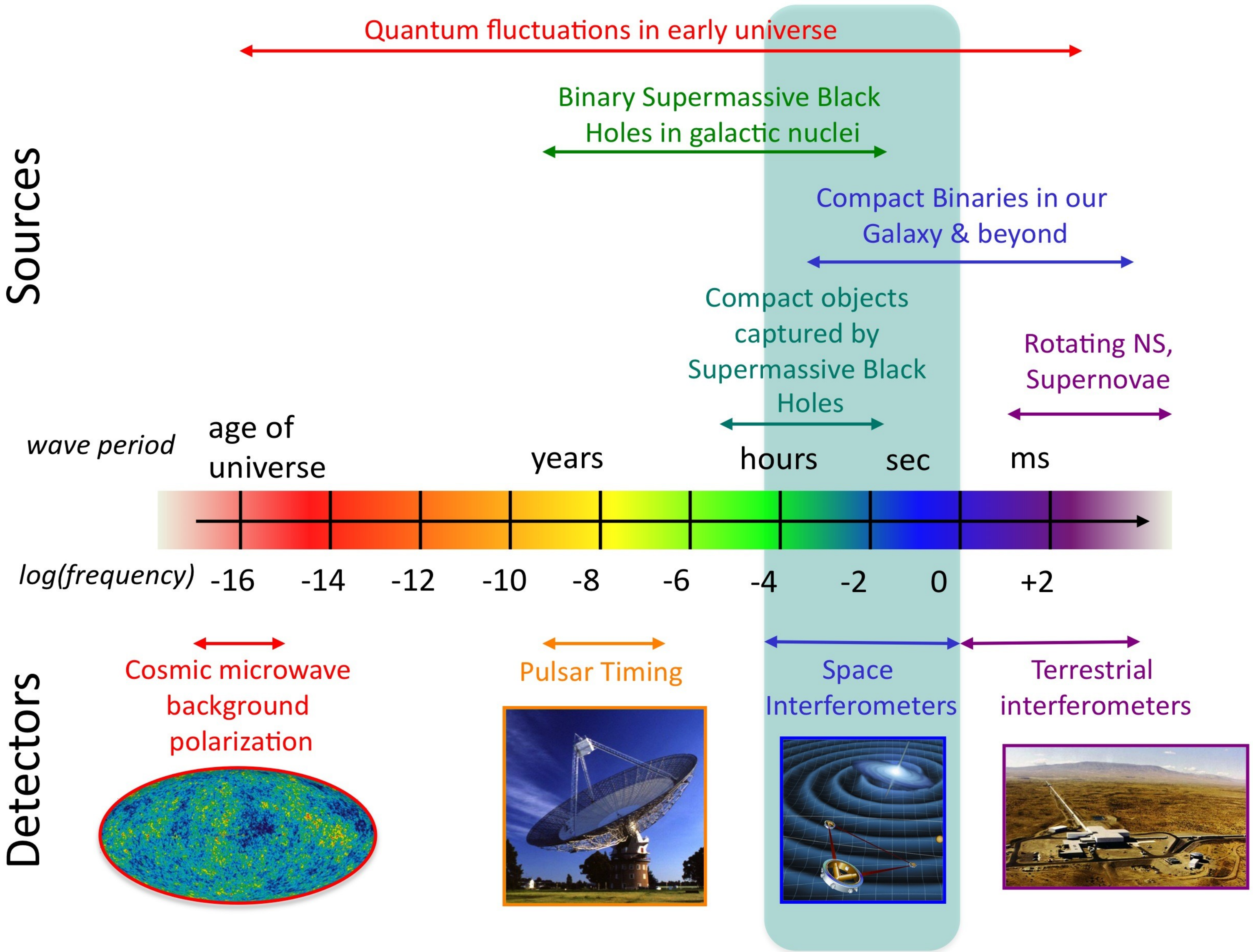


Image credit: Metzger & Berger 2012

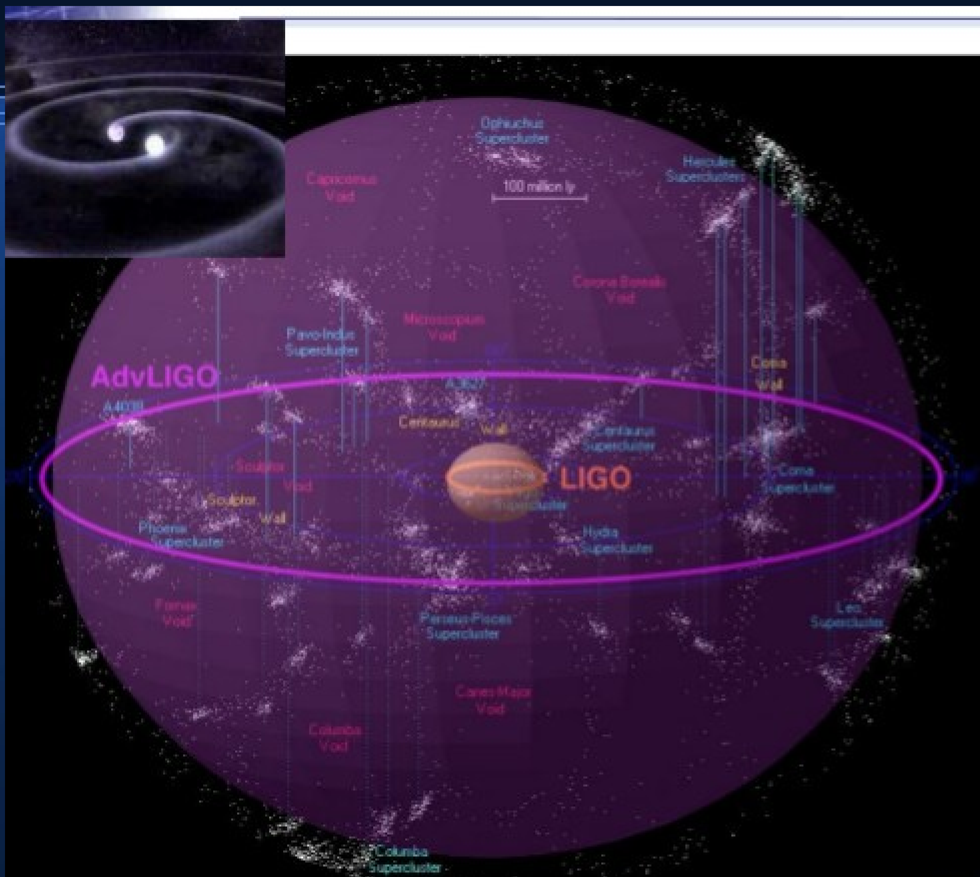
GW150914 -a binary black hole !

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

The Gravitational Wave Spectrum



From Initial to Advanced GW detectors



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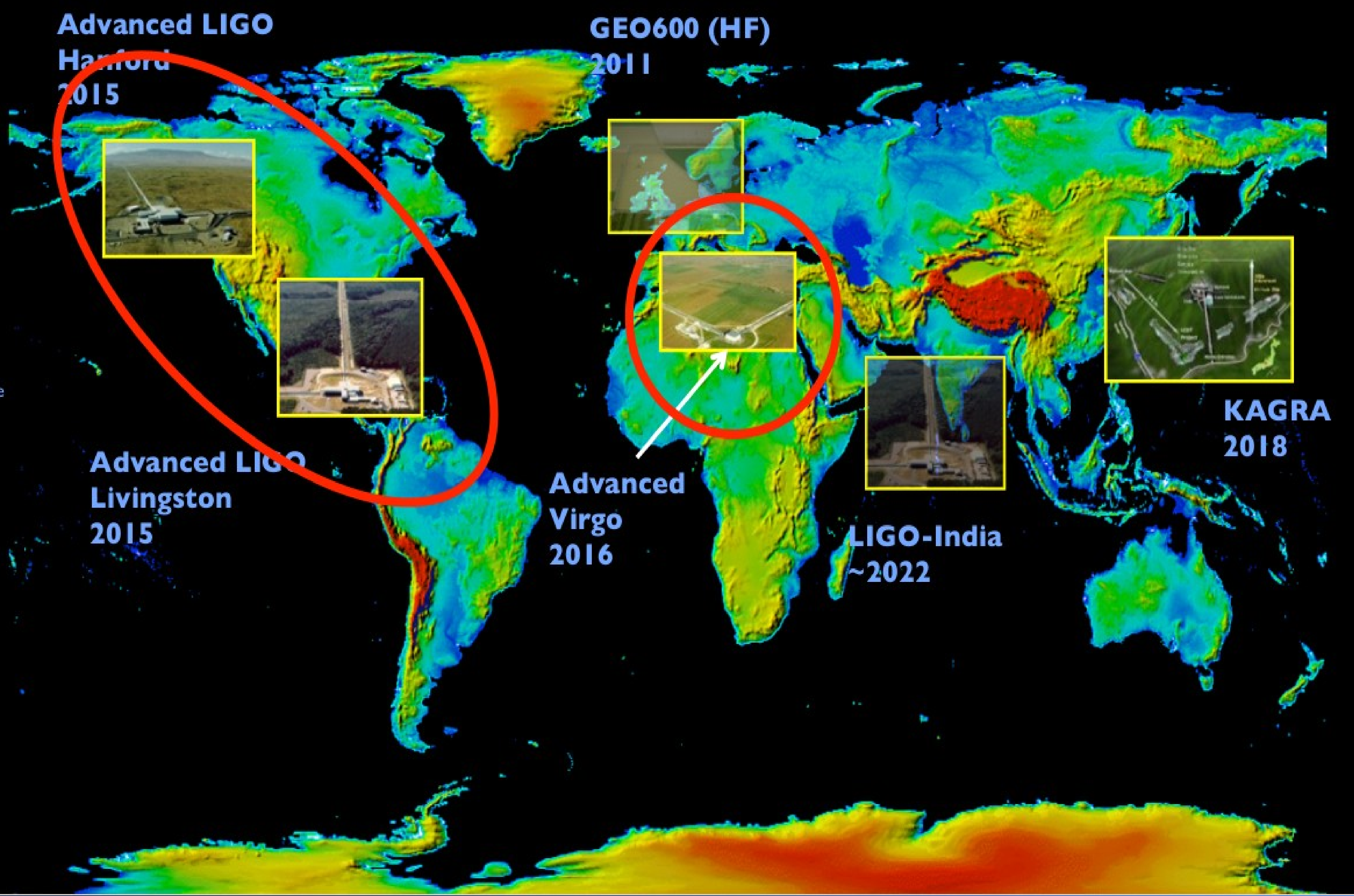
Advanced Gravitational Wave Detector Network

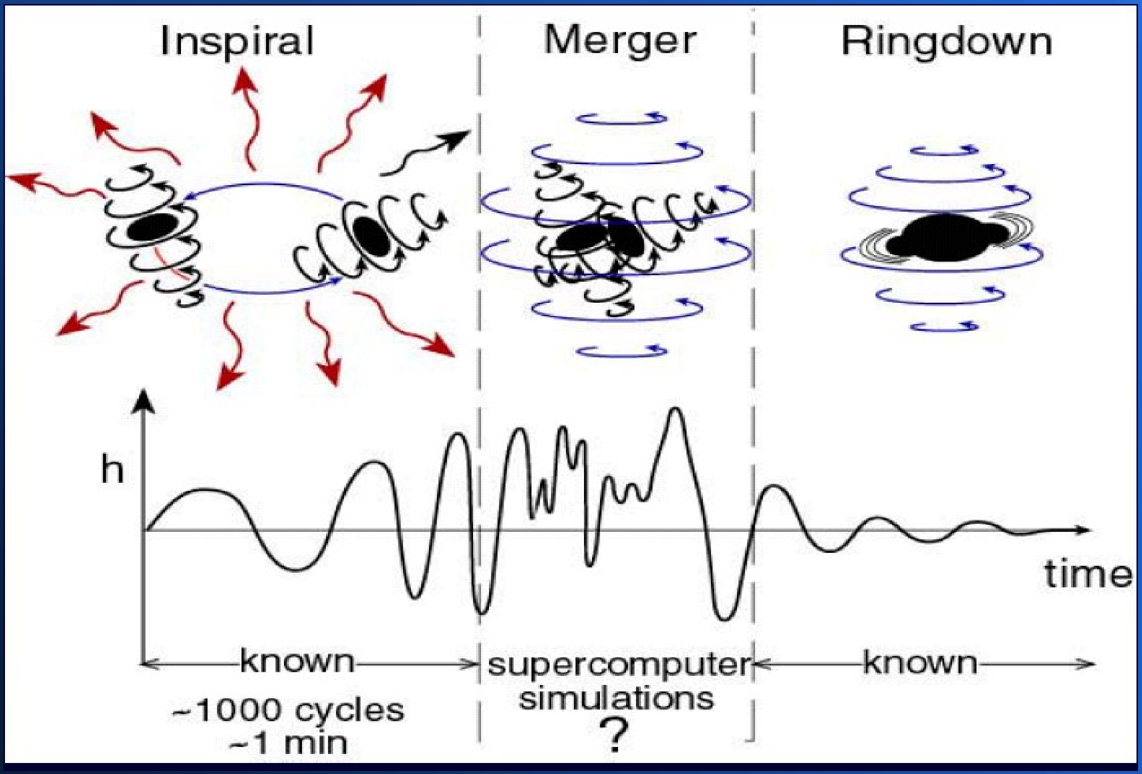


EXTRA SLIDES

EXTRA SLIDES

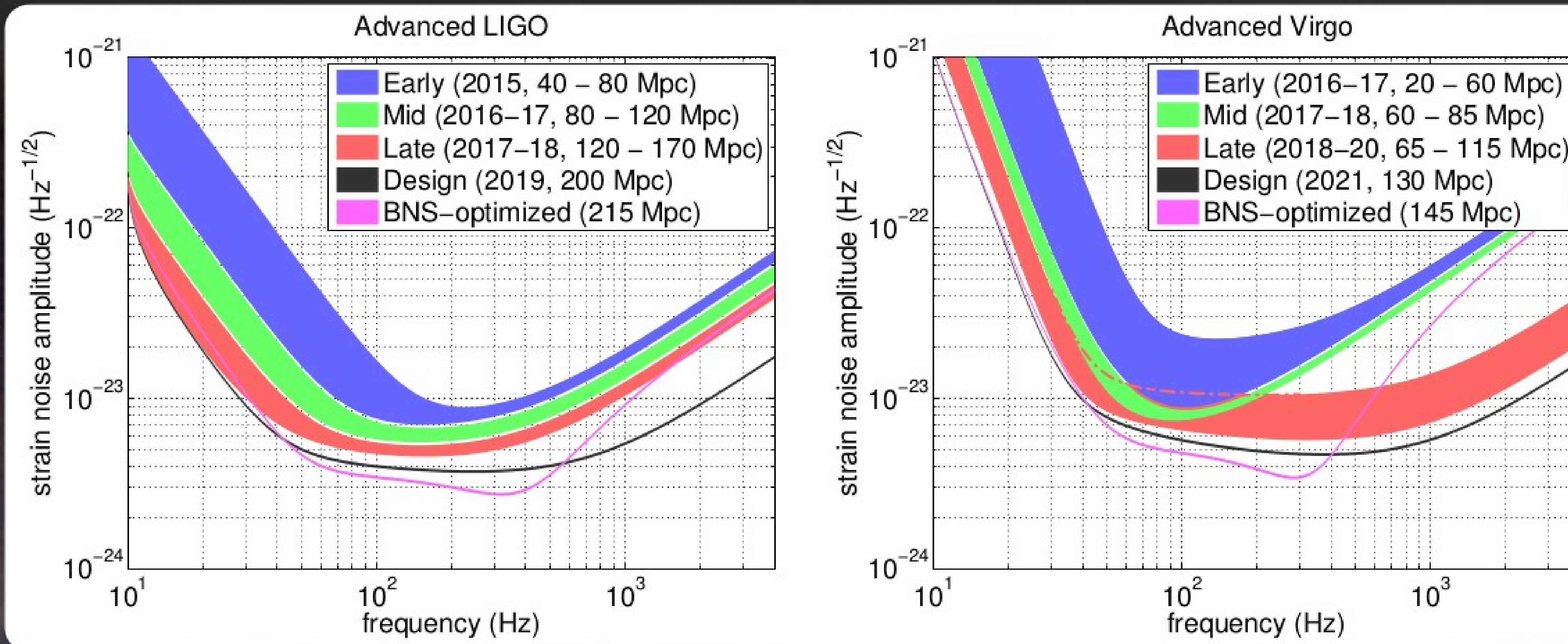
Compact binaries- three phases of coalescence

inspiral” - until marginally stable orbit
“merger” - until the common horizon
“ringdown” - black hole oscillations



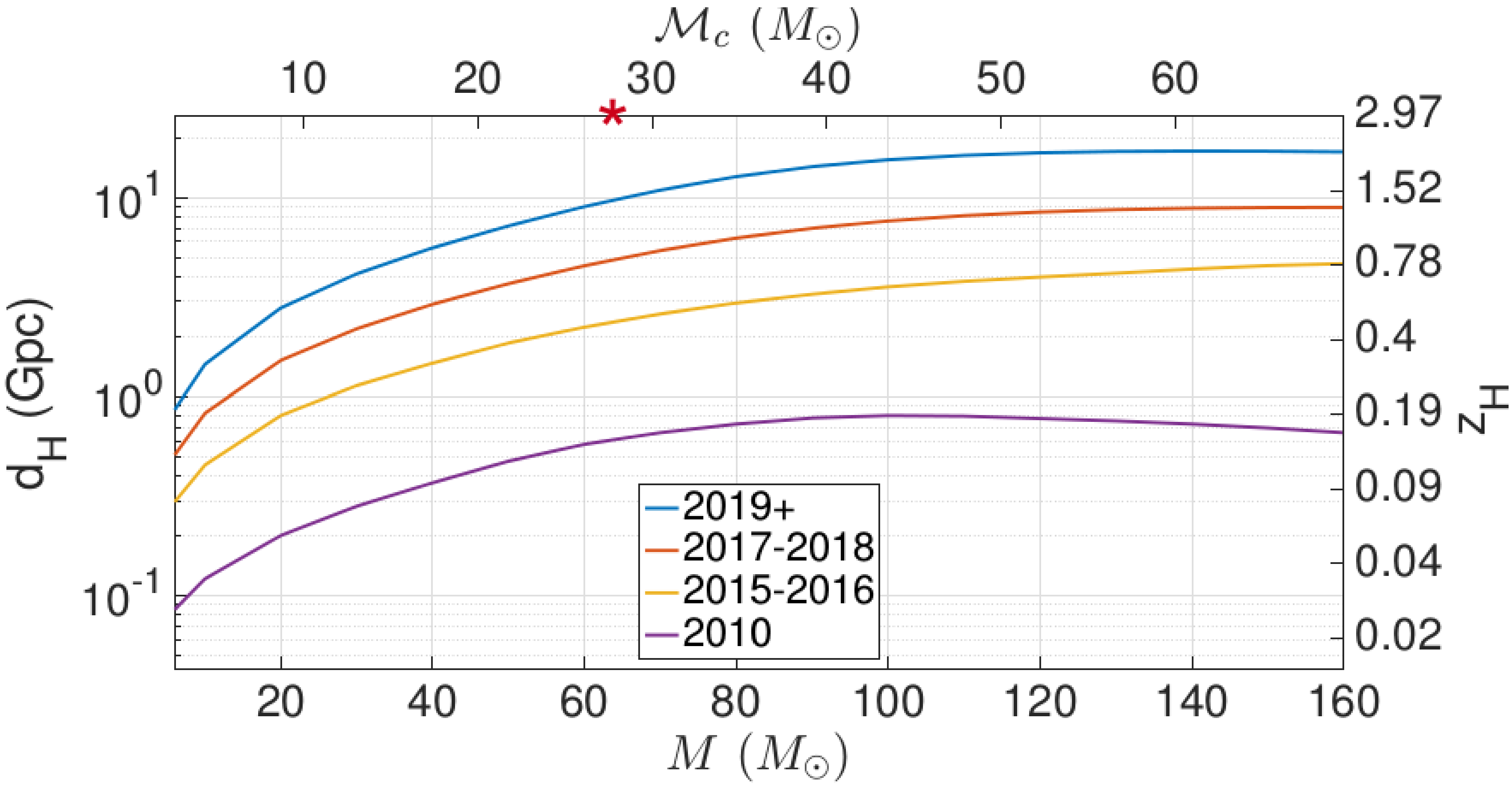
$$\mathcal{M} = \frac{c}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

Advanced LIGO+Virgo 2015-2022

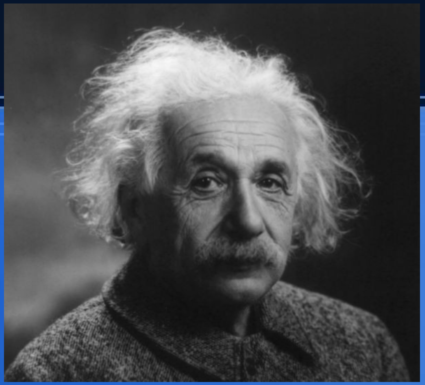


Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

How far we can go ?

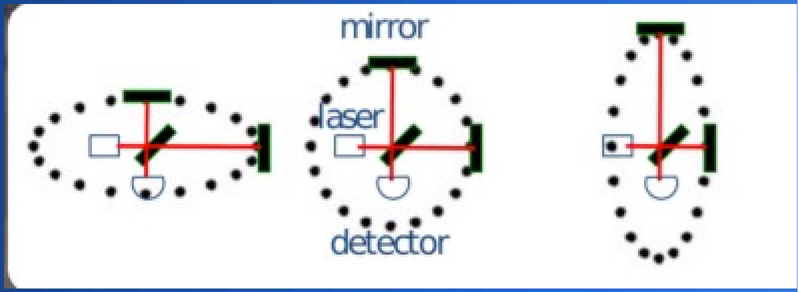


Gravitational Waves



- predicted by A. Einstein in 1916, consequence of GR 1915
- they carry energy (Trautman 1958)
- exact sollution for spherical gravitational waves(Robinson & Trautman,1960)
- GW propagates if concentration of mass (energy) moves/changes shape
- spacetime oscilations that travel at velocity v = c
- interact weakly with matter (we can see objects that cannot be seen in any other way)
- new sort of radiation --> new discoveries
- the efect of a wave on 2 test particles dL~ h L

GW amplitude h~1/10^21

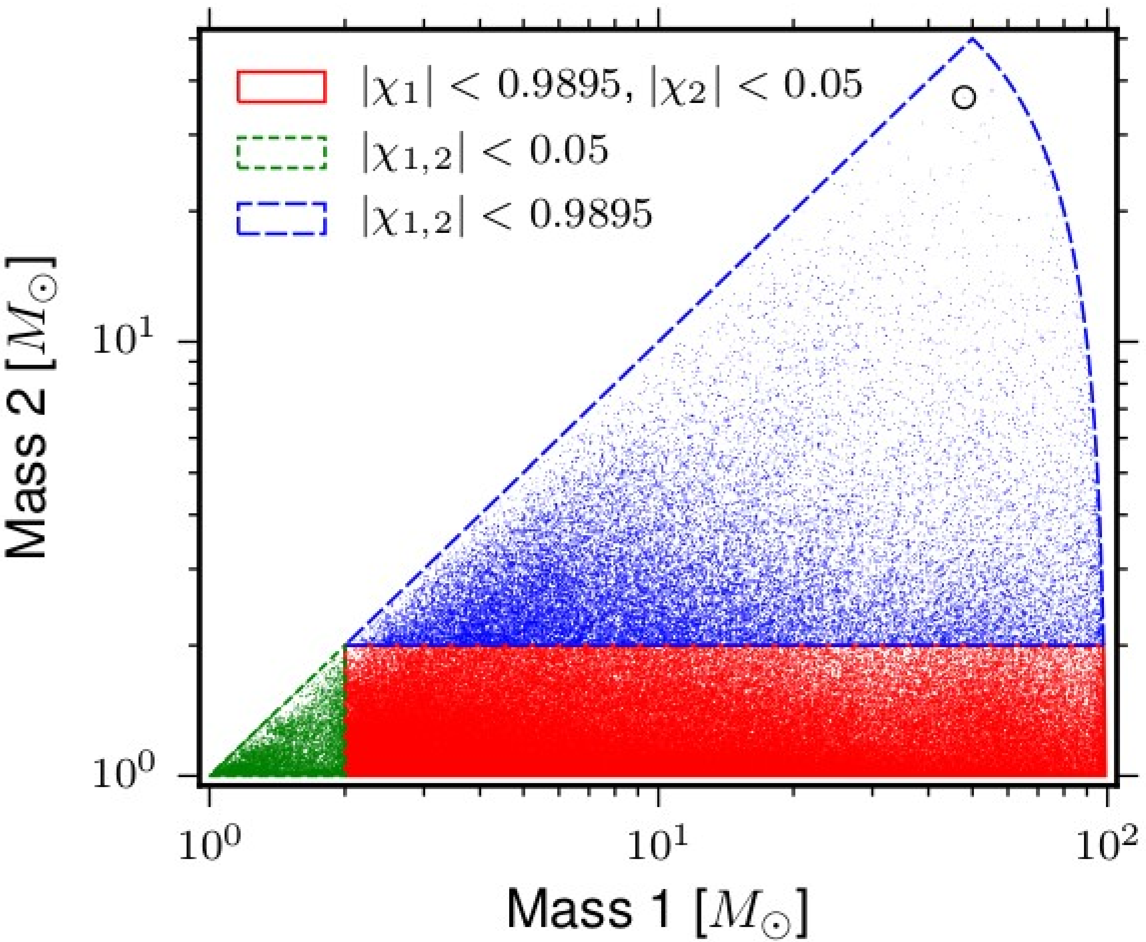


CBC search

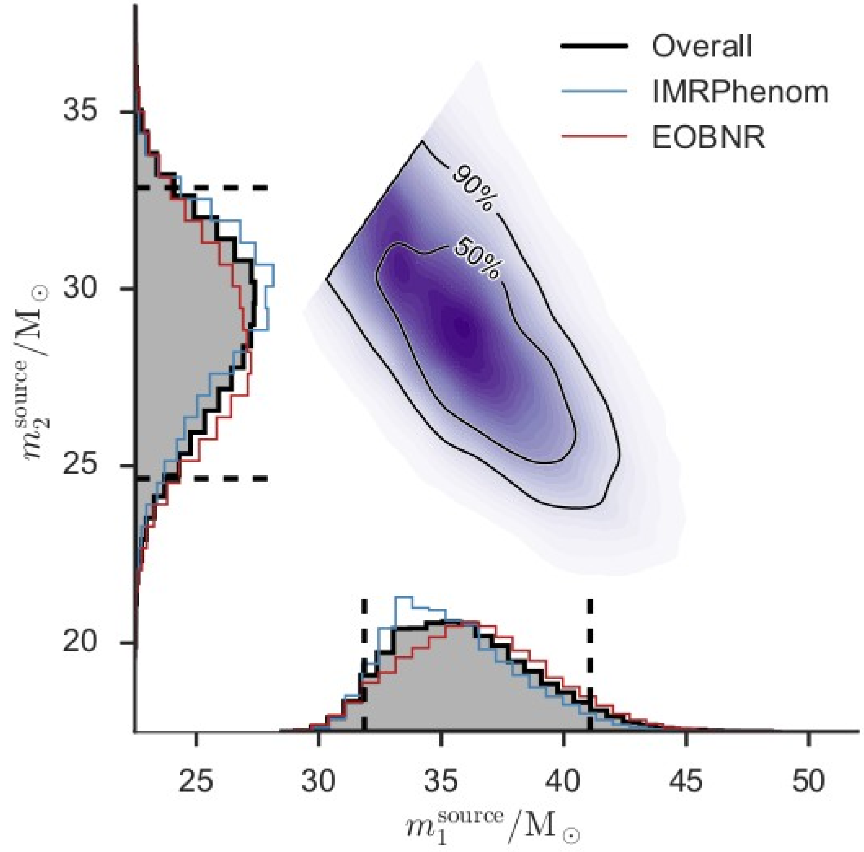
Seach targeted at binary coalescence signals:
NSNS, BHNS
BHBH

Template bank

Background estimate using time shifts



Masses



Overall
IMRPhenom
EOBNR
90%
50%
35
30
25
20
$m_2^{\rm source}/{\rm M}_\odot$
25
30
35
40
45
50
$m_1^{\rm source}/{\rm M}_\odot$

Gravitational Waves

predicted by GR, 1916

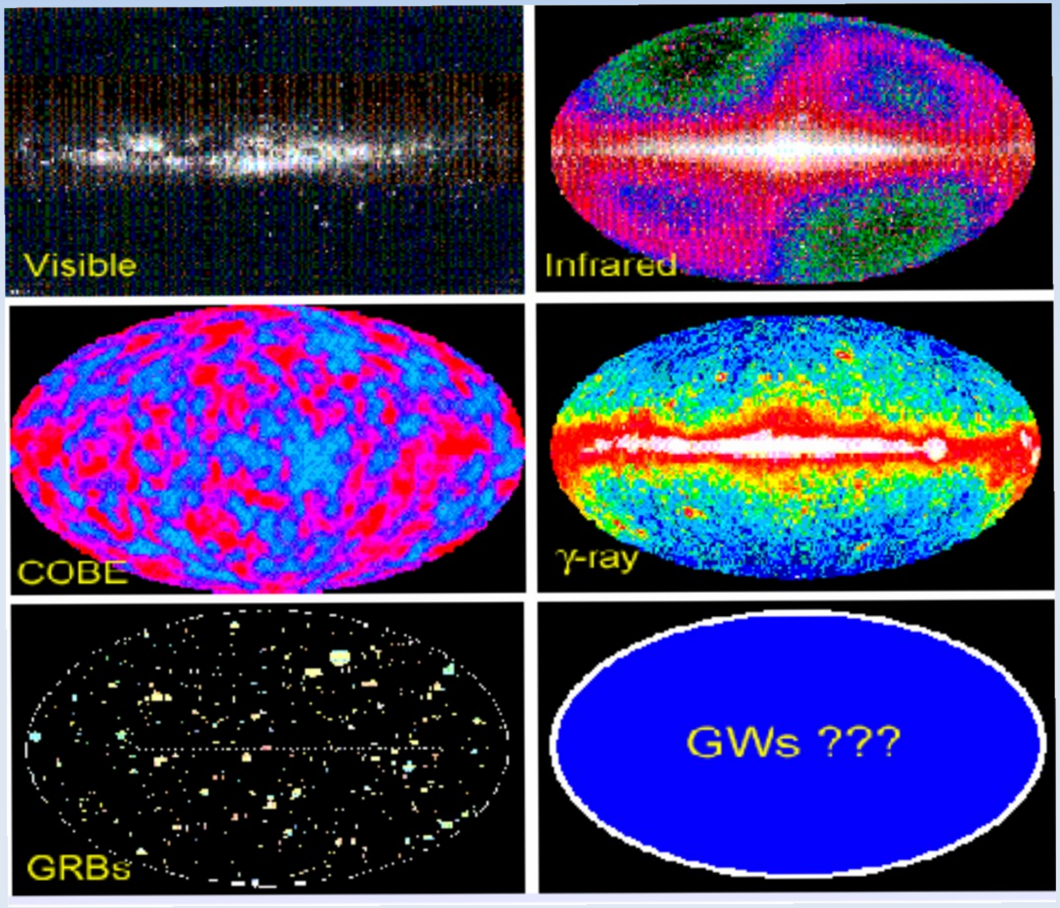
spacetime oscilations

new sort of radiation

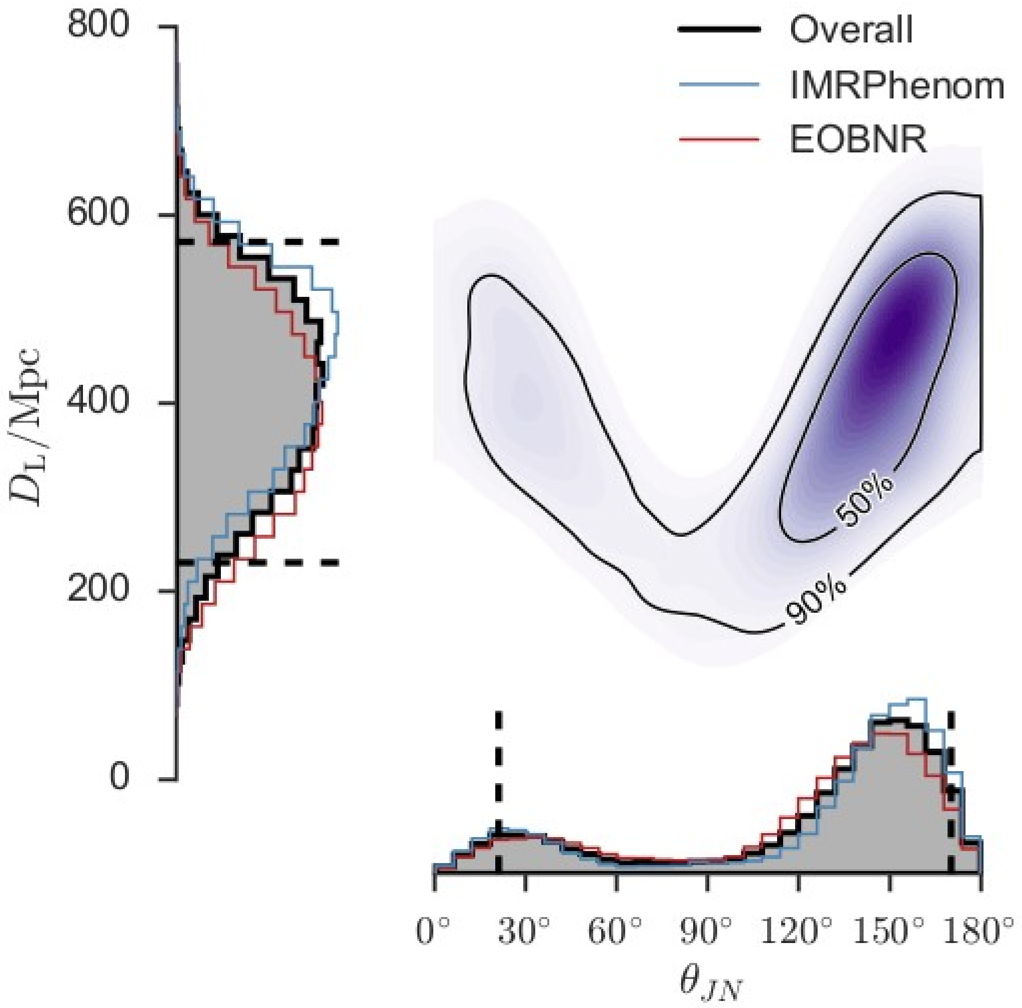
--> new discoveries

we can see objects
that cannot be seen
in any other way

a new test of GR



Distance and inclination



Burst search

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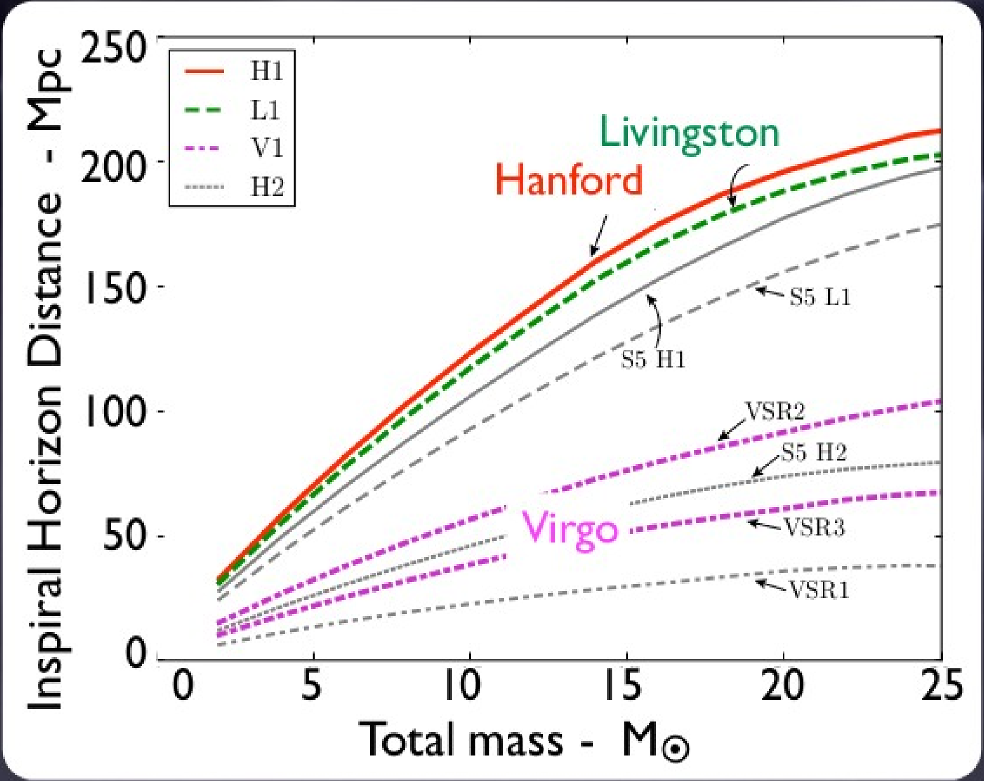
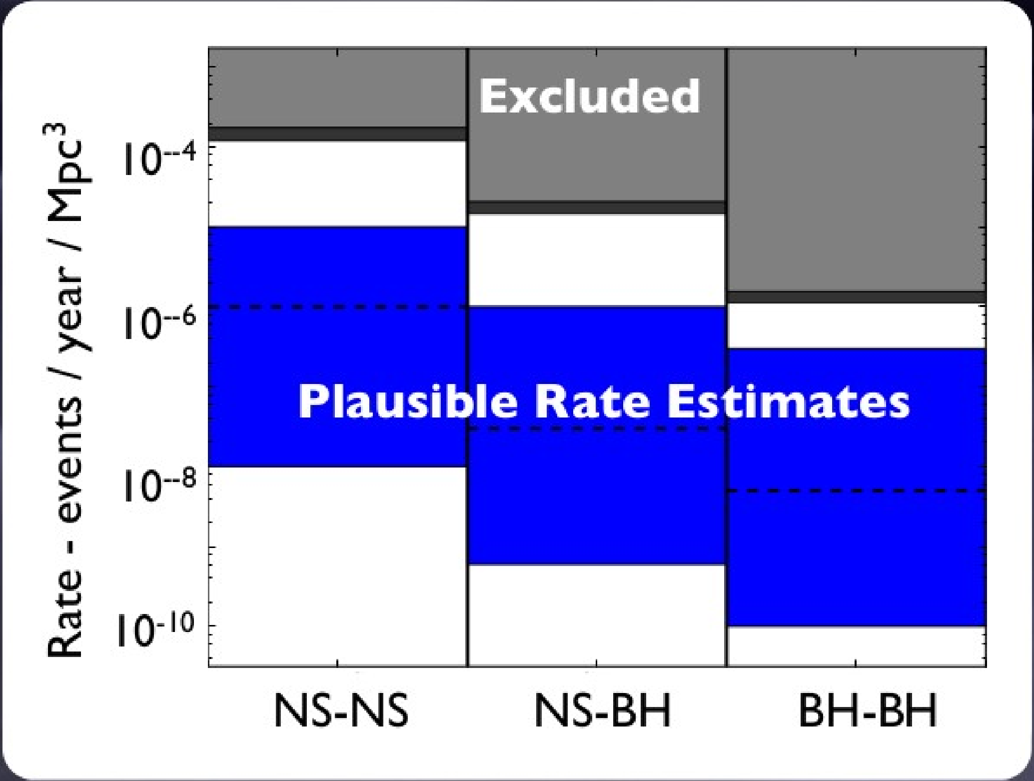
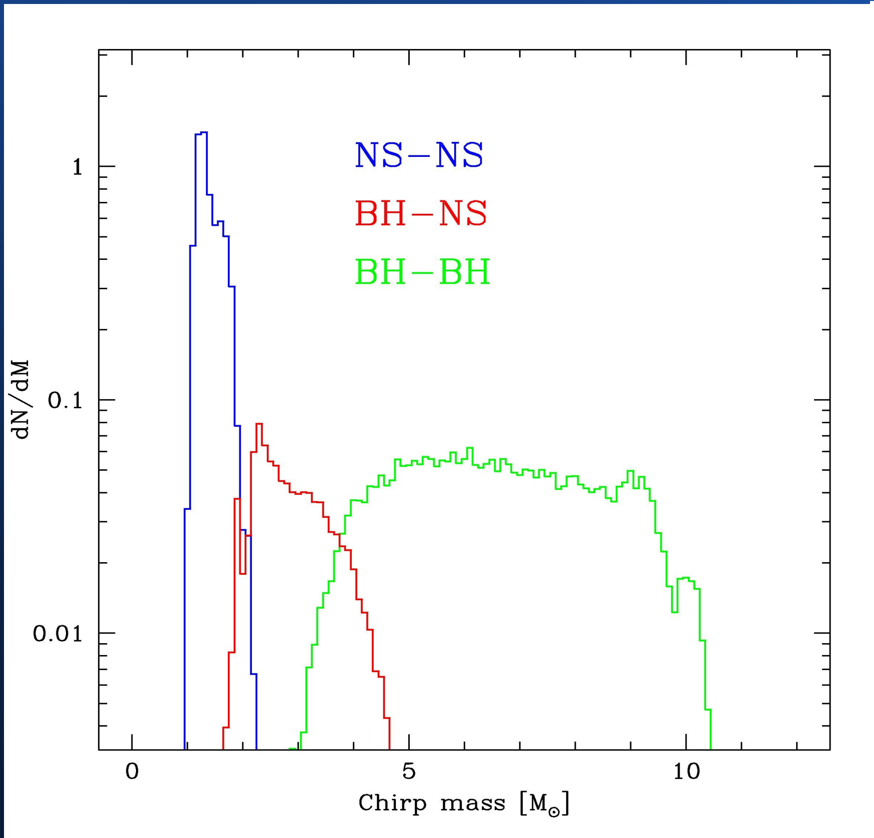
GW Science From First Generation (2005-2010)

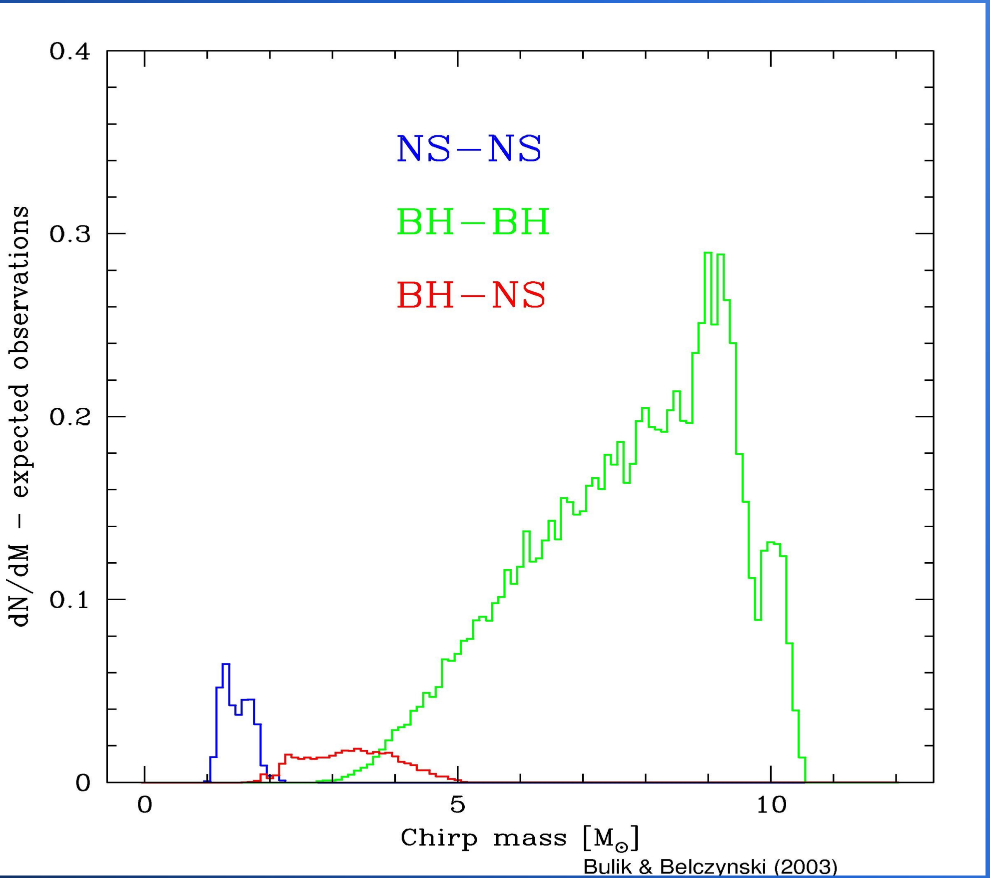




PRD 85 (2012) 08202

First detection- BBH





Bulik & Belczynski et al 2010

From Initial to Advanced GW detectors

Network	Source	$\dot{N}_{\mathrm{low}}$ (yr^{-1})	$\dot{N}_{\mathrm{re}}$ (yr^{-1})	$\dot{N}_{\mathrm{high}}$ (yr^{-1})
Initial	NS-NS	2×10^{-4}	0.02	0.2
	NS-BH	7×10^{-5}	0.0004	0.1
	BH-BH	2×10^{-4}	0.007	0.5
Advanced	NS-NS	0.4	40	400
	NS-BH	0.2	10	300
	BH-BH	0.4	20	1000

- Initial LIGO, initial Virgo
  - Active 2002-2011
  - No detections
  - Design sensitivity reached
    - Proof of the technology!
- Advanced detectors
  - O1: September-December 2015 Advanced LIGO, limited sensitivity
  - O2: 2016-2017 Advanced LIGO + Advanced Virgo
  - O3: 2017-2018 Advanced LIGO + Advanced Virgo (+ KAGRA?)
  - Design sensitivity: 2019+

Gravitational wave astronomy

•Initial GW detectors -no detection but lower limits on distances to GRBs, upper limits on GW from PSRs, on event rates (Abadie, J. Abbot,et al.2009, 2010)

• Advanced GW – GW150914 - first direct detections, Robust data analysis techniques are in place, 4 working groups: Burst, Stochastic Backgrounds, Coalescing Binaries, Continuous Waves

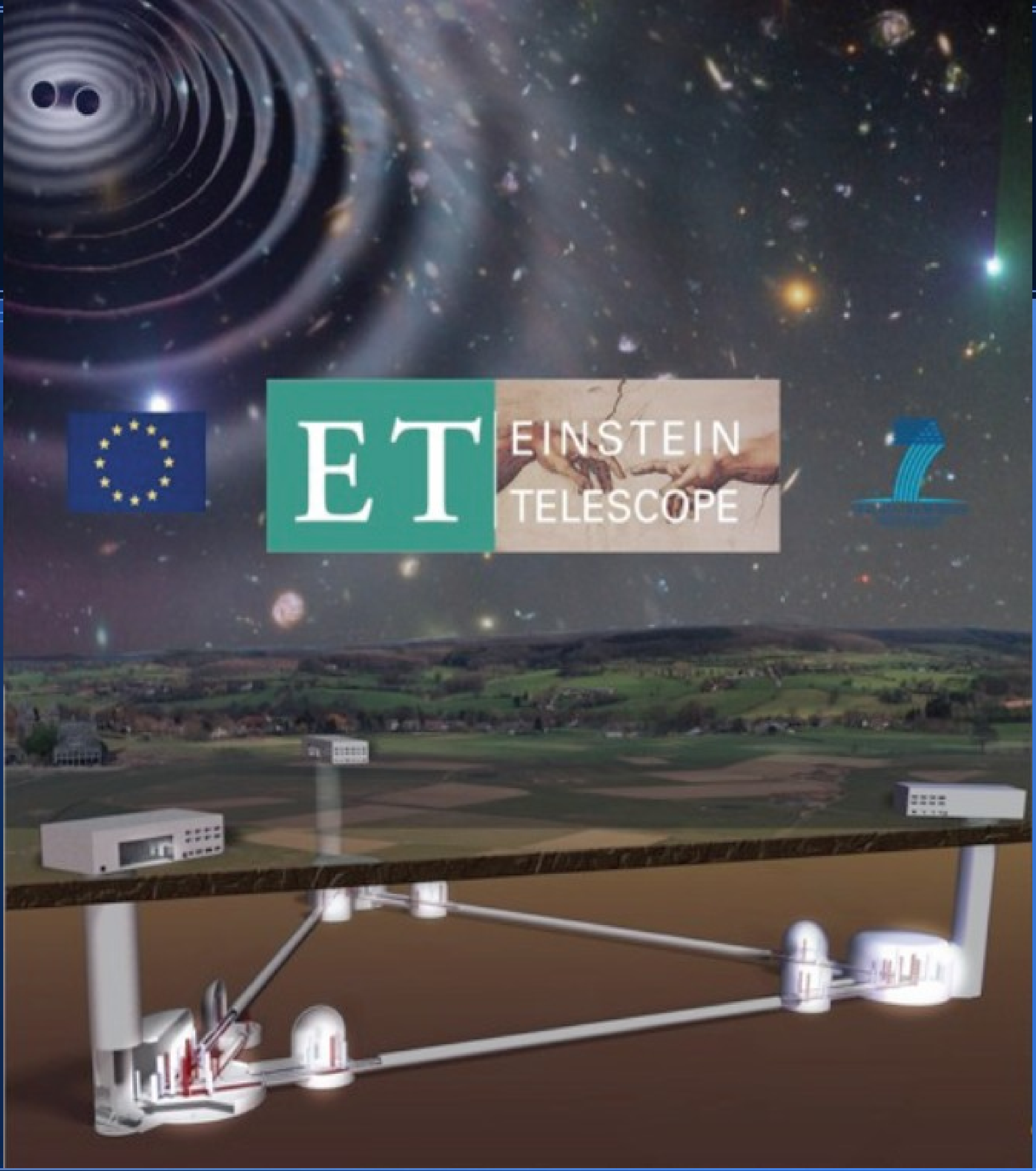
•Detector development:

–2015-2022: 2nd :**Adv LIGO/VIRGO +KAGRA+India-LIGO** ~10 times more sensitive (10^3 times more events/yr), NS-NS (200 Mpc), NS-BH (1Gpc),BH-BH (2Gpc); *10Hz-10kHz*

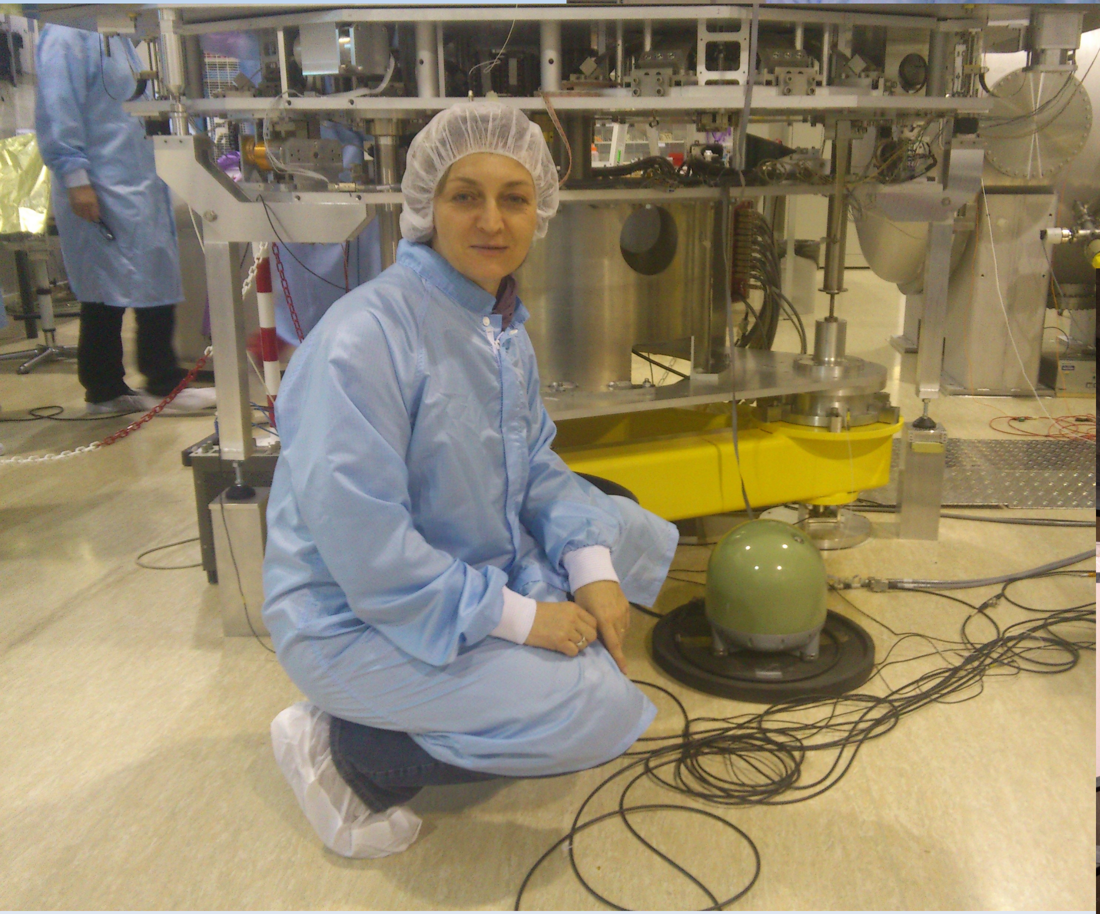
–2030 ?: 3rd : **ET** ~ 100 (10^6 events/yr), *1 Hz-10 kHz*

–2034 ?: space detectors: **eLISA/NGO** (*0.003-0.01 Hz)*, **DECIGO** (*0.1-1Hz*)

- **sensitivity (h~dL/L)**
  10 km arms
  instead of 3-4 km
- **sensitivity below 10 Hz**
  (seismic noise)
  150 m underground
- **> 1 kHz thermal noise**
  cryogenic mirrors
  cooled down to 10 K

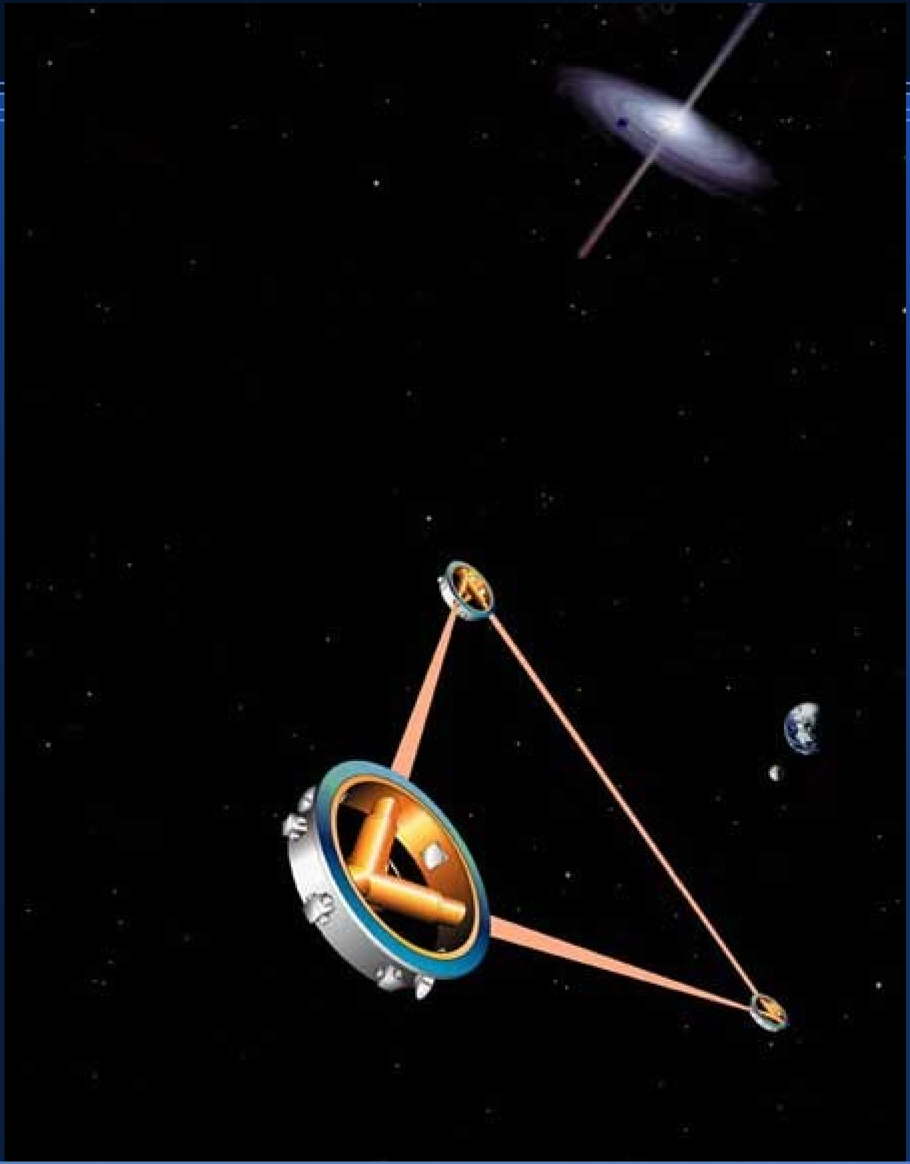


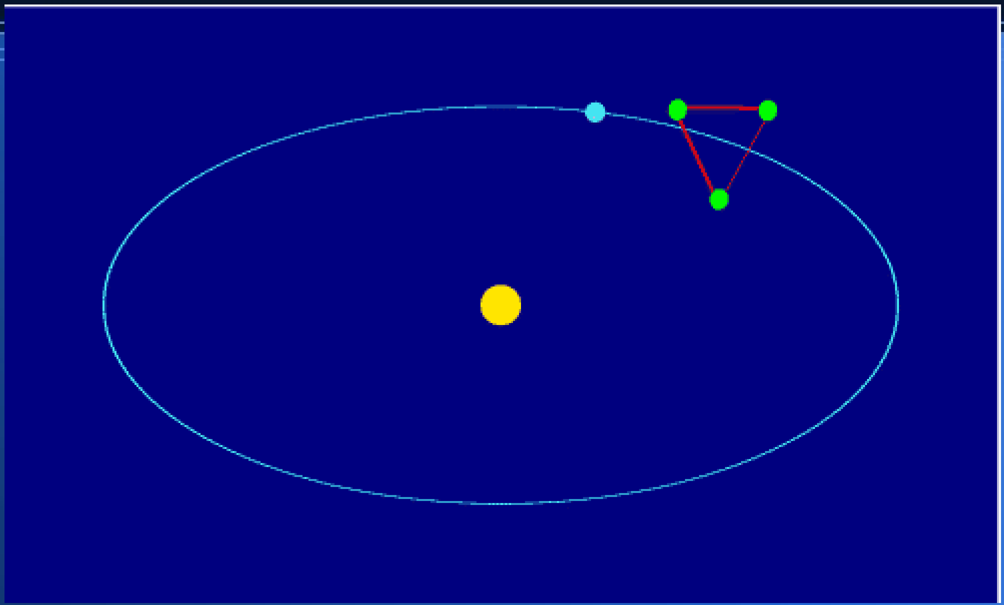
ET (1Hz-10kHz)



kubuntu

LISA – cosmic mission

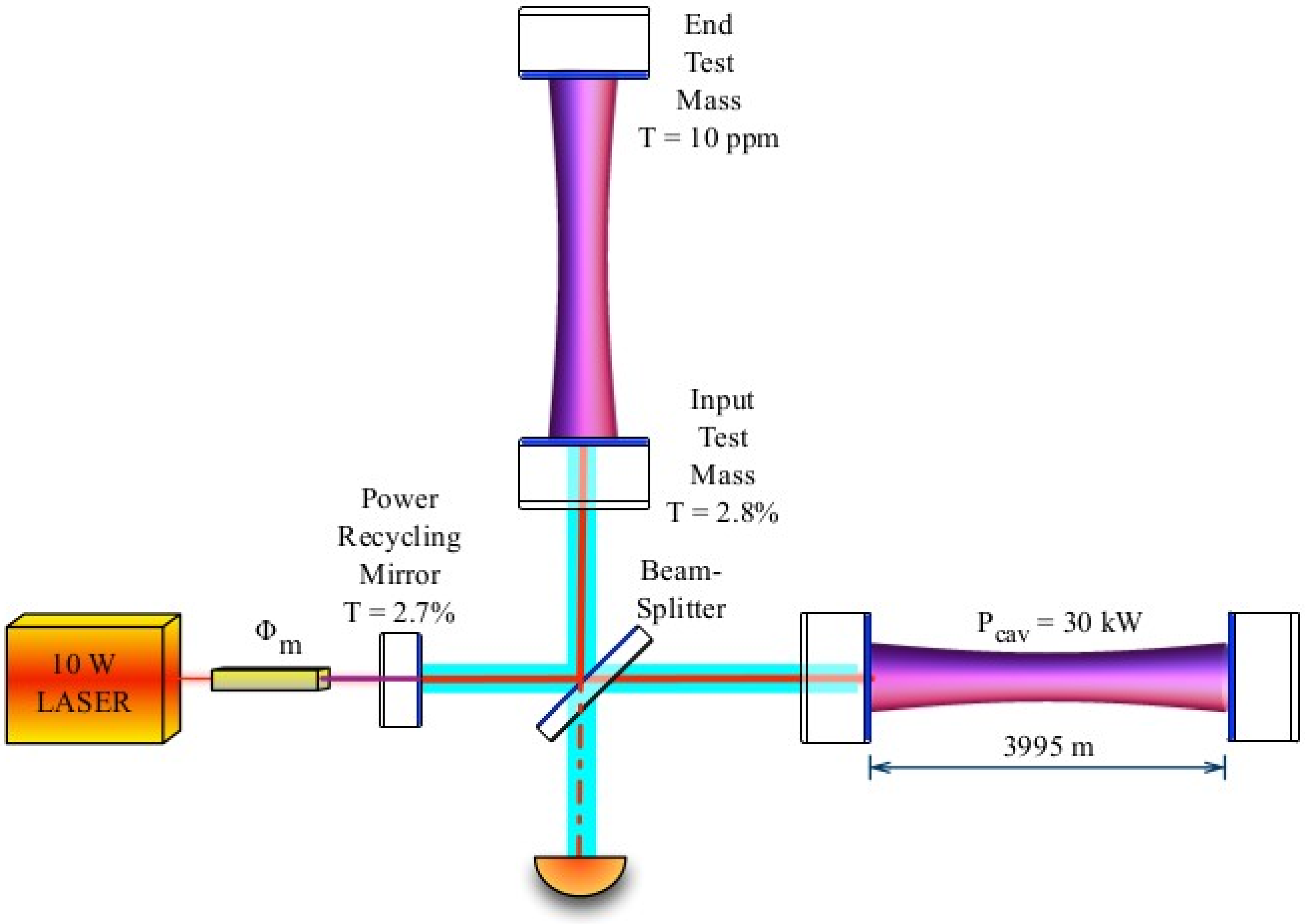




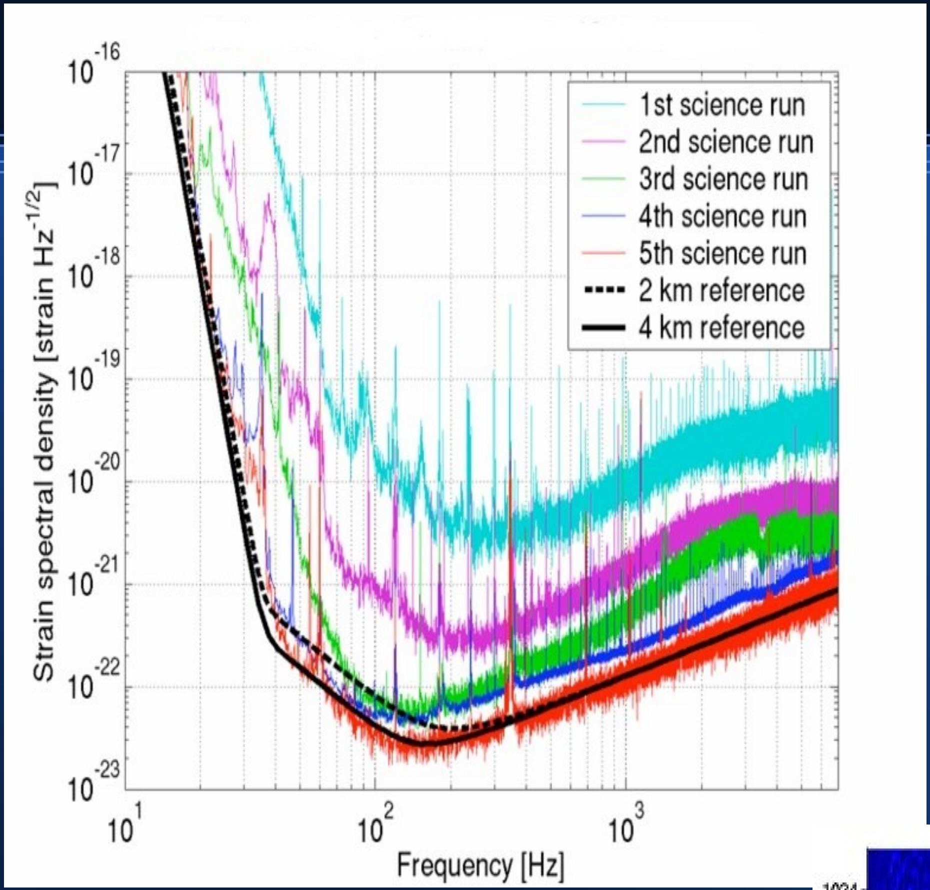
3 detectors - 5 mln km
-->1 detector, 1 mln km

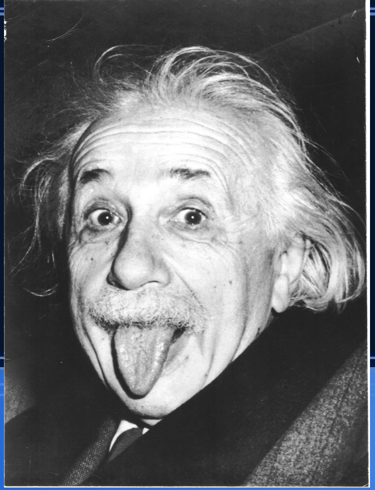
f_{GW}~ 0.001 - 0. 01 Hz

Interferometers: initial



1st generation – summary





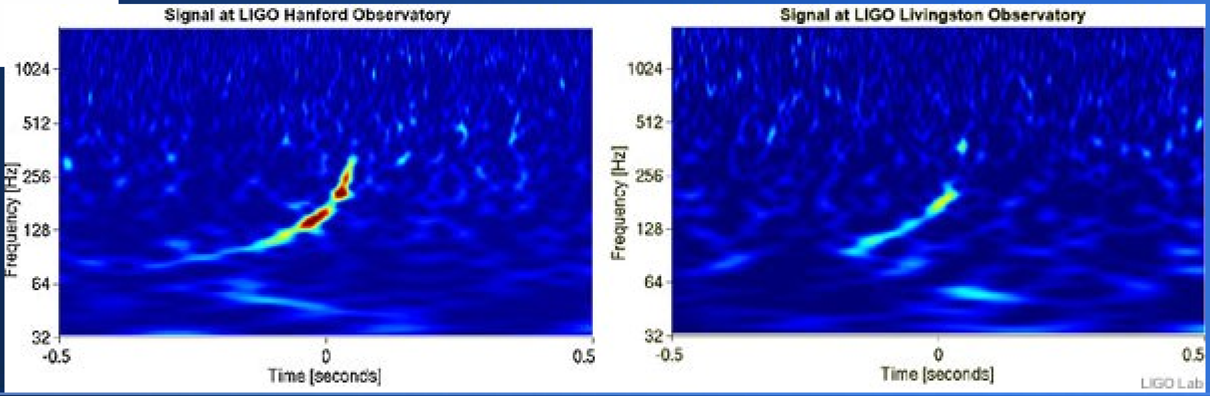
-
- - no detection :(
- - obtained required S/N :)
- - common scientific runs :)

S5-VSR1 (4 months, 2007),

S6-VSR2/ VSR3 (6/2months, 2009/2010:)

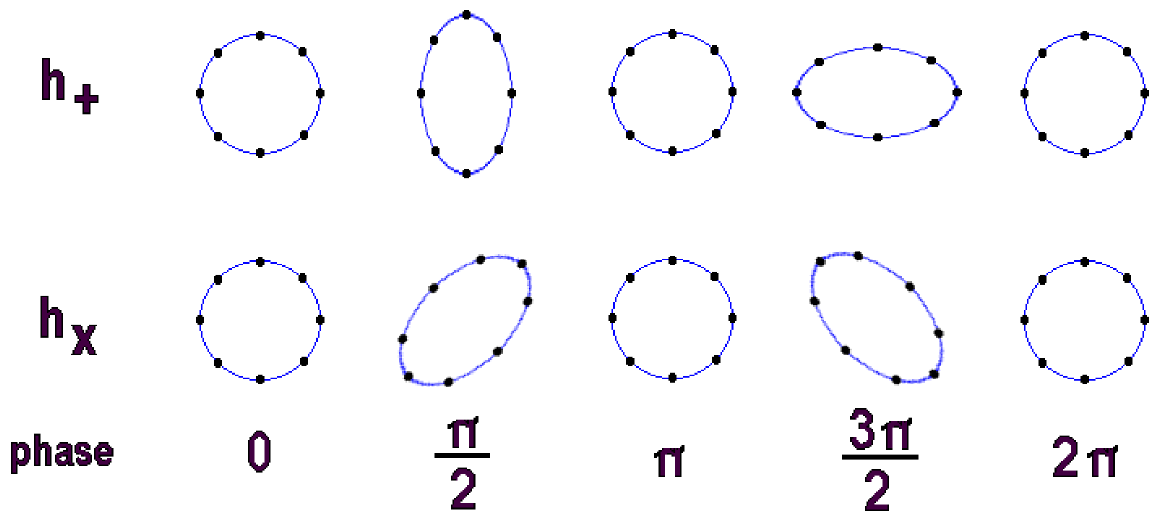
- - blind injection test – Big Dog event, NS-BH :)

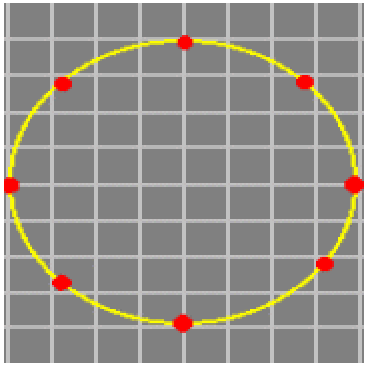
..but lower limits on distances to GRBs, upper limits on GW from PSRs, on event rates (Abadie, J. Abbot,et al.2009, 2010)

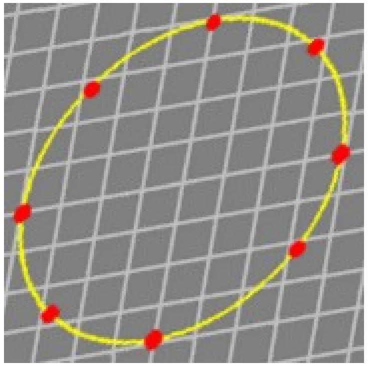


The principle of detection

Two polarizations: h+, hx, 45 degree,quadrupole transverse wave, interaction with matter:



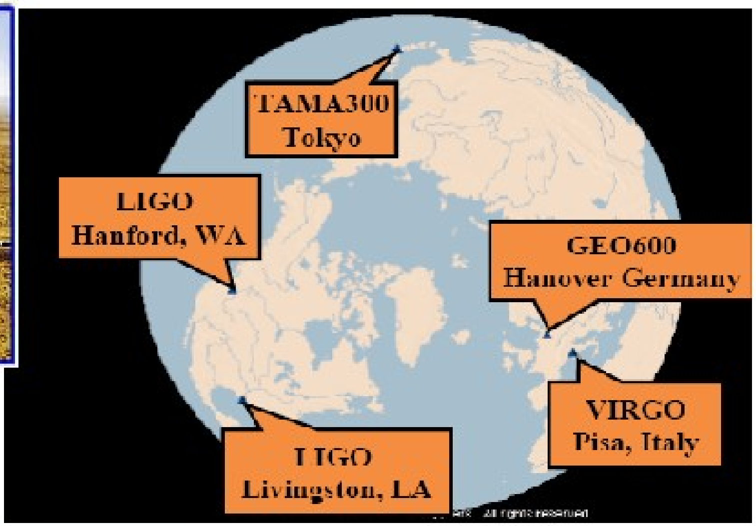




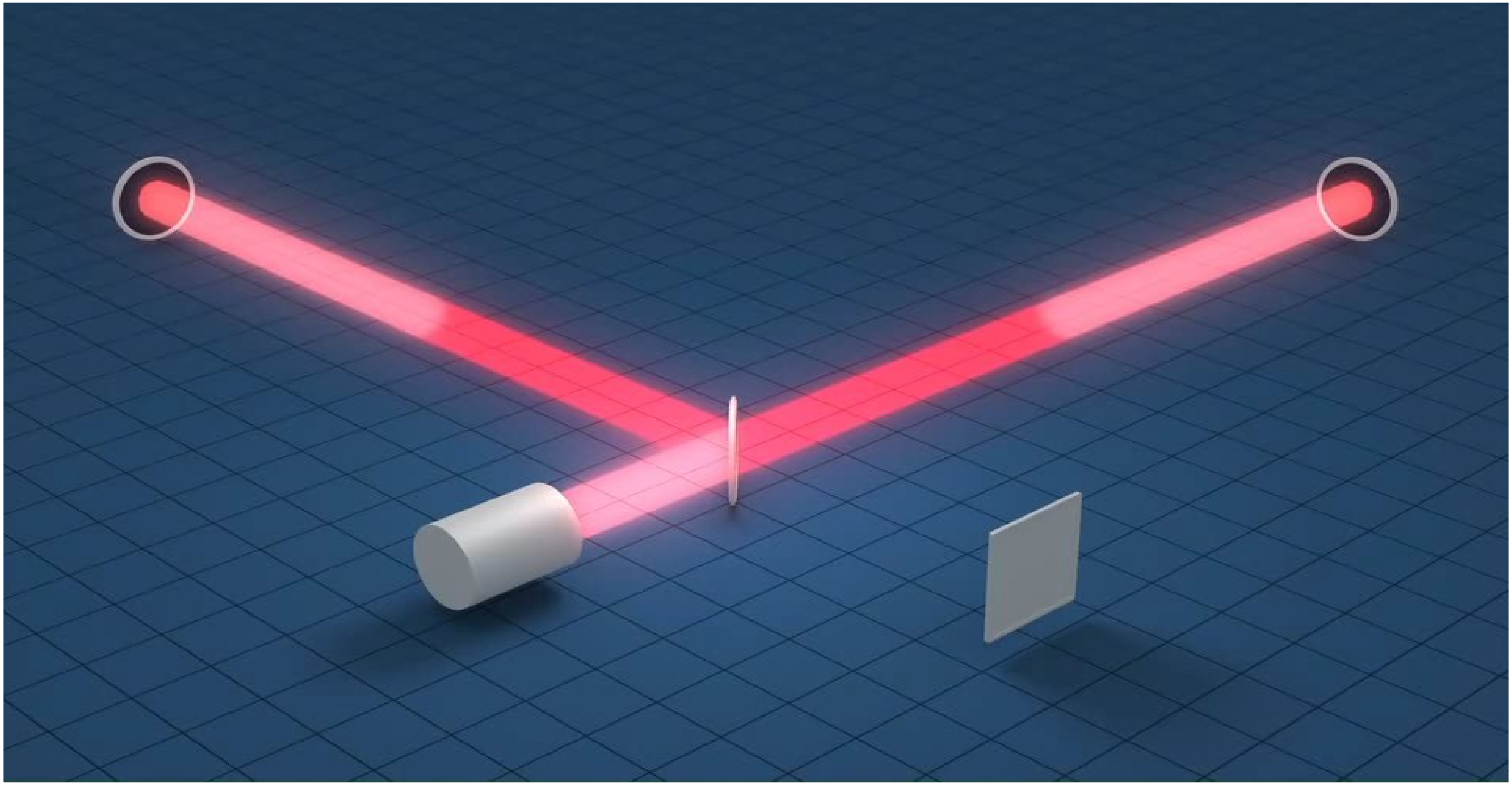
$$h \approx \frac{R_g}{D}\frac{v^2}{c^2} \approx 2 \times 10^{-21}$$

$$M = 60M_\odot \quad D = 400Mpc\ v = 0.2c$$

1^{st} detectors: LIGO,VIRGO, GEO600, TAMA f_{GW} ~10Hz-1kHz



Detection principle



Order of magnitude estimates

$$\Delta L \approx 10^{-18} m$$

500 round trips, expected delay:

$$\Delta L_{eff} = 500 \times 10^{-18}\mathrm{m} \approx 5 \times 10^{-16}\mathrm{m}$$

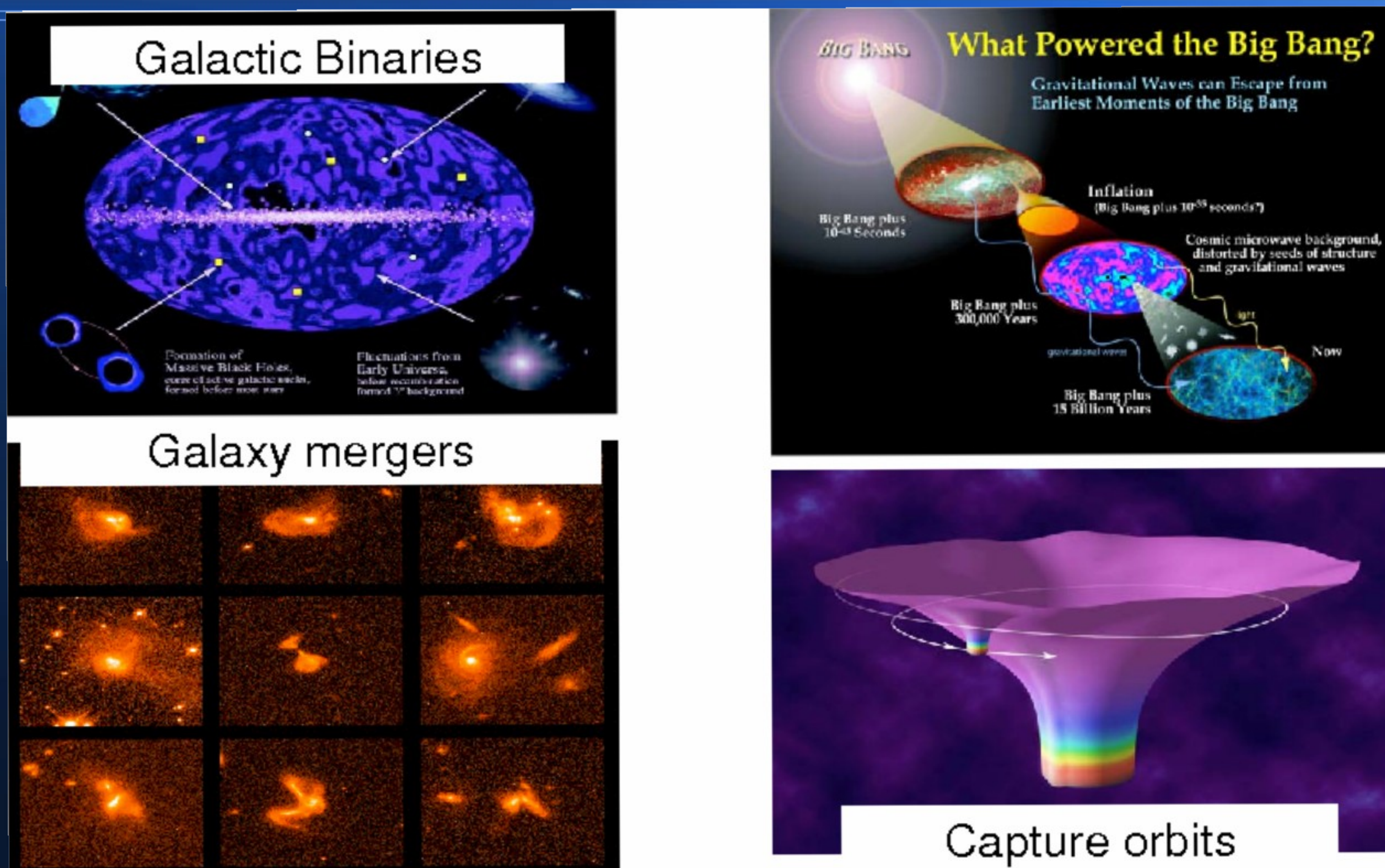
The laser wavelength is 1064nm. Expected phase amplitude:

$$\Delta\phi \approx 5 \times 10^{-16}/10^{-6} = 5 \times 10^{-10}$$

With 100kW power the Poisson noise fluctuations are

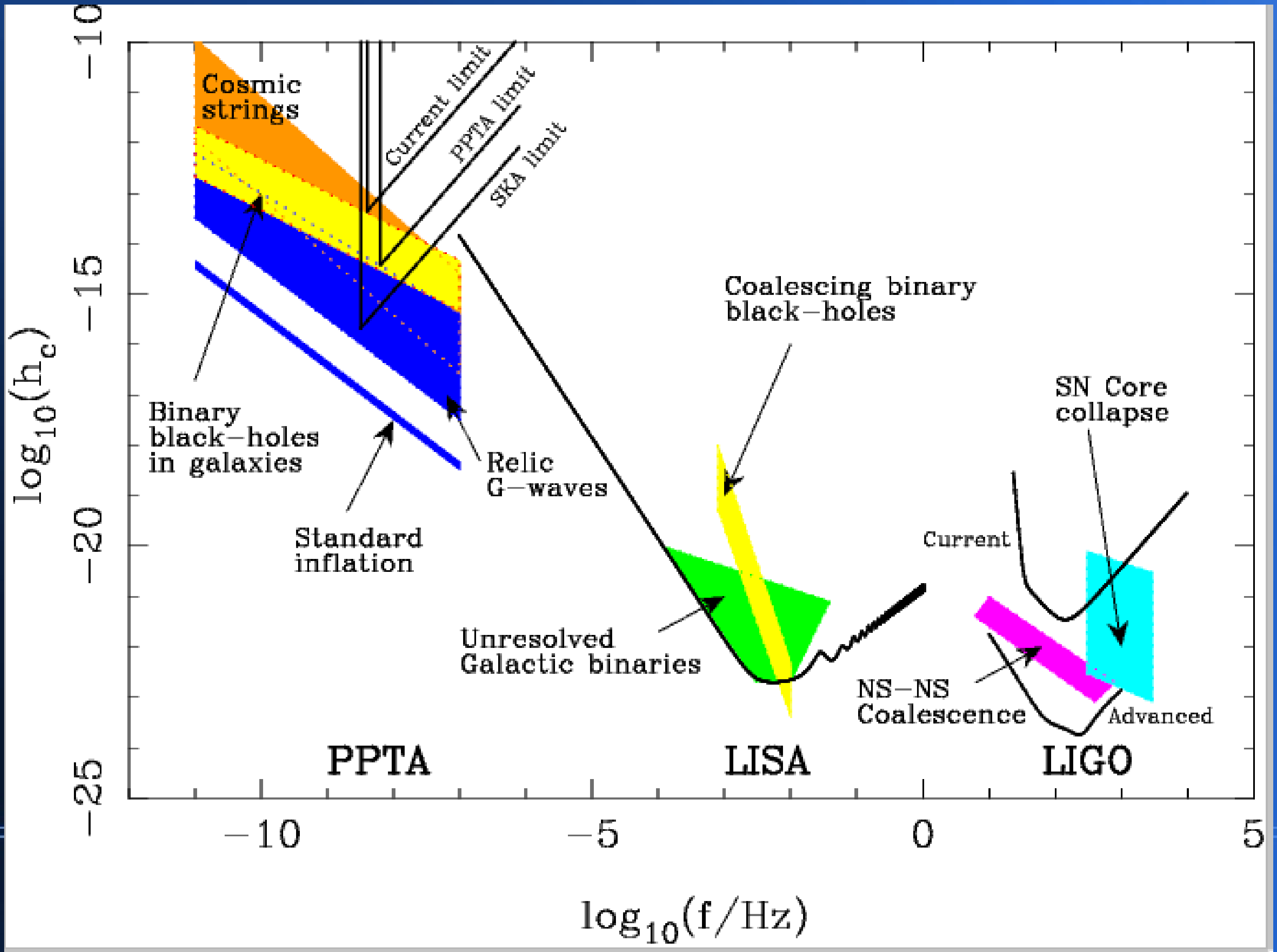
$$\delta\phi = N^{-1/2} = \sqrt{\frac{hc}{\lambda P \Delta T}} = \sqrt{\frac{10^{-19}\mathrm{J}}{10^{5}\mathrm{W}10^{-2}\mathrm{s}}} \approx 10^{-11}$$

Astrophysical sources for LISA



GW Astronomy

ELF log f = -16 to -10, VLF log f= -10 to -6, LF log f = -6 to 0, HF log f = 0 to 6



Polish participation in GW searches

Konsorcjum VIRGO (POLGRAW) - 1szej i 2giej generacji detektory fal grawitacyjnych(od 2008),lider- A. Królak

Instytut Matematyki PAN (IMPAN), Uniwersytet Zielonogórski (UZ) Uniwersytet Warszawski (UW), Uniwersytet Białostocki (UwB), Narodowe Centrum Badań Jądrowych (NCBJ), Uniwersytet M. Kopernika(UMK) Instytut Matematyki PAN (IMPAN), Centrum Astronomiczne PAN

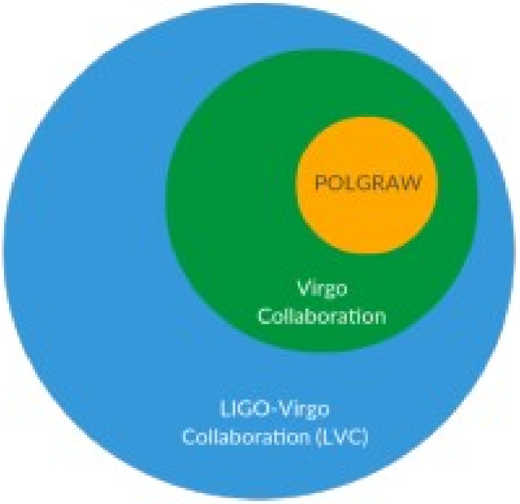
Kontrybucje :**Analiza danych, Budowa części detektora Advanced VIRGO, Badania teoretyczne, Symulacje numeryczne sygnału z astrofizycznych źródeł** (MNiSW, FNP)

Konsorcjum EINSTEIN TELESCOPE -3ciej generacji (od 2013), lider-T.Bulik UZ , UW, PW, UwB, IMPAN, CAMK **Kontrybucje:** **Badania teoretyczne astrofizycznych źródeł, poszukiwanie miejsca na budowę ET (budowa sejsmometrów)** **(NCN, EU „Aspera")**

Konsorcjum KAGRA -**współpraca z Japonią**, UZ, PW, UW (od 2014)

Virgo-POLGRAW

- prof. dr hab. Andrzej Królak (IM PAN), lider grupy
- dr hab. Michał Bejger (CAMK PAN)
- prof. dr hab. Krzysztof Belczyński (OAUW)
- dr Arkadiusz Błaut (IFT UWr)
- dr Kazimierz Borkowski (CA UMK)
- prof. dr hab. Tomasz Bulik (OAUW)
- dr Paweł Ciecieląg (CAMK PAN)
- dr Orest Dorosh (NCBJ)
- prof. dr hab. Piotr Jaranowski (WF UwB)
- dr Izabela Kowalska-Leszczyńska (OAUW)
- mgr inż. Adam Kutynia (WE PWr)
- dr Maciej Piętka (kiedyś WF UwB)
- dr hab. Dorota Rosińska (IA UZ)
- mgr Magdalena Sieniawska (CAMK PAN)
- dr Adam Zadrożny (NCBJ)



- Virgo-POLGRAW: 15 członków grupy (9 na liście autorów).
- Współpraca Virgo: 250.
- LIGO Scientfic Collaboration: >1000.

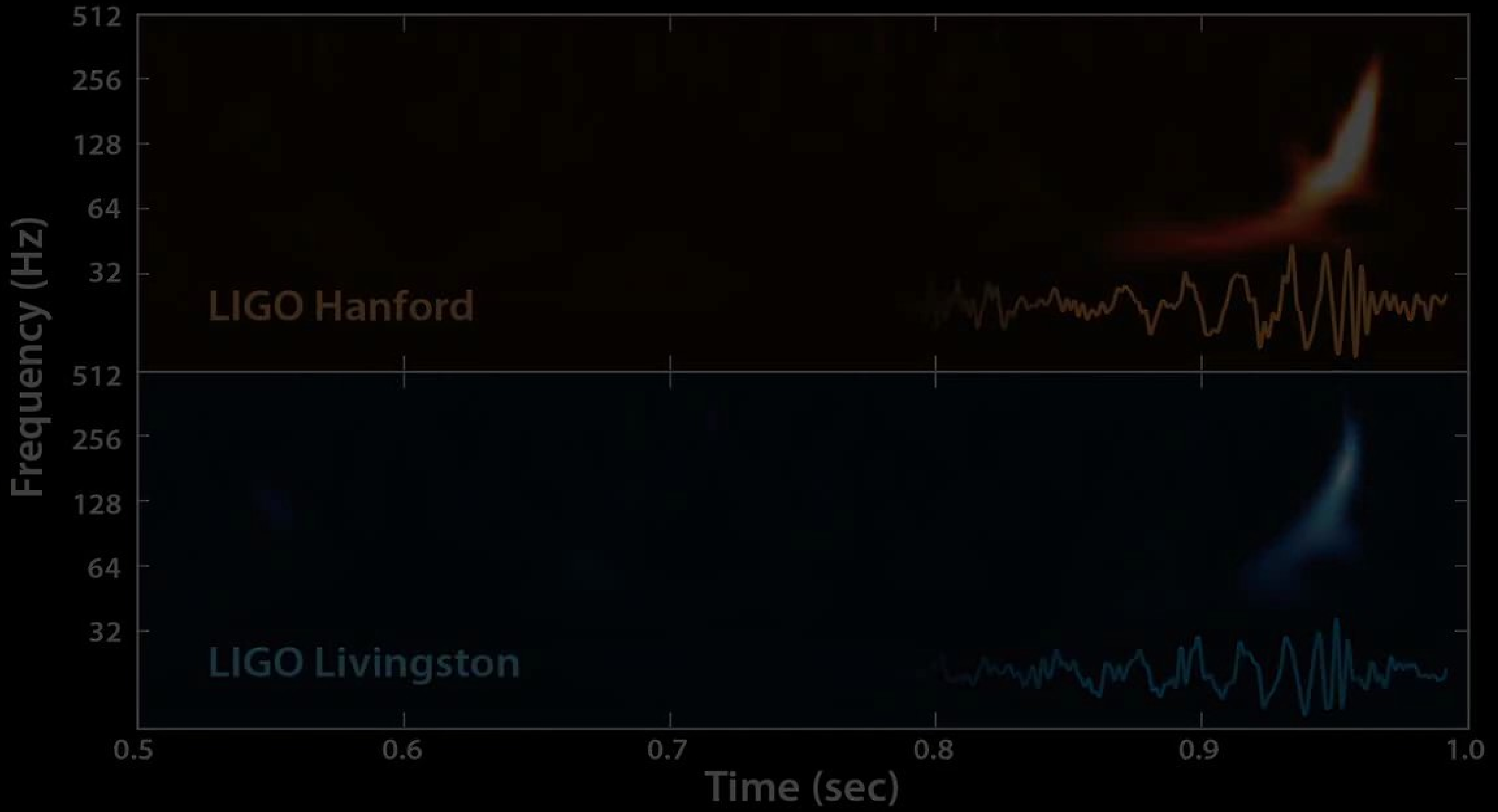
GW150914: parametry

- $M_1 = 36^{+5}_{-4}\ \mathrm{M_\odot}$, $M_2 = 29^{+4}_{-4}\ \mathrm{M_\odot}$,
- Parametry finalnej czarnej dziury:
  - masa $M_f = 62^{+4}_{-4}\ \mathrm{M_\odot}$,
  - spin $a_f = 0.67^{+0.05}_{-0.07}$,
- Odległość: $410^{+160}_{-180}\ \mathrm{Mpc}$ (1 miliard 300 milionów lat świetlnych, przesunięcie ku czerwieni $z = 0.09^{+0.03}_{-0.04}$).
- Czas trwania zdarzenia: 0.12 s,
- Końcowa prędkość orbitalna: 0.5 c,
- Energia wyemitowana w falach: $3\ \mathrm{M_\odot c^2}$,
- W momencie największej „jasności”: $3.6 \times 10^{49}\ \mathrm{W}$ ($200\ \mathrm{M_\odot c^2/s}$),
  $\rightarrow$ 100 razy więcej mocy niż cały wszechświat!

GW150914: najjaśniejsze kosmiczne wydarzenie kiedykolwiek zaobserwowane

- Pierwsza bezpośrednia detekcja fal grawitacyjnych
- Pierwsza detekcja dynamicznie zmiennego horyzontu
- Nowy sposób pomiaru masy i tempa rotacji (spinu) czarnych dziur
- Pierwsza obserwacja układu podwójnego czarnych dziur
- Najbardziej energetyczne zjawisko obserwowane w historii
- Nowe ograniczenie na masę grawitonu
- Nowe Okno na Wszechświat

The detection on Sep 14th, 2015



Gravitational wave astronomy

•1st: Virgo/Ligo - no detection yet, but lower limits on distances to GRBs, upper limits on GW from PSRs, on event rates (Abadie, J. Abbot,et al.2009, 2010) **required S/N,common runs : S5-VSR1 (4 months, 2007), S6-VSR2/ VSR3 (6/2months, 2009/2010),blind injection**

Detector development:

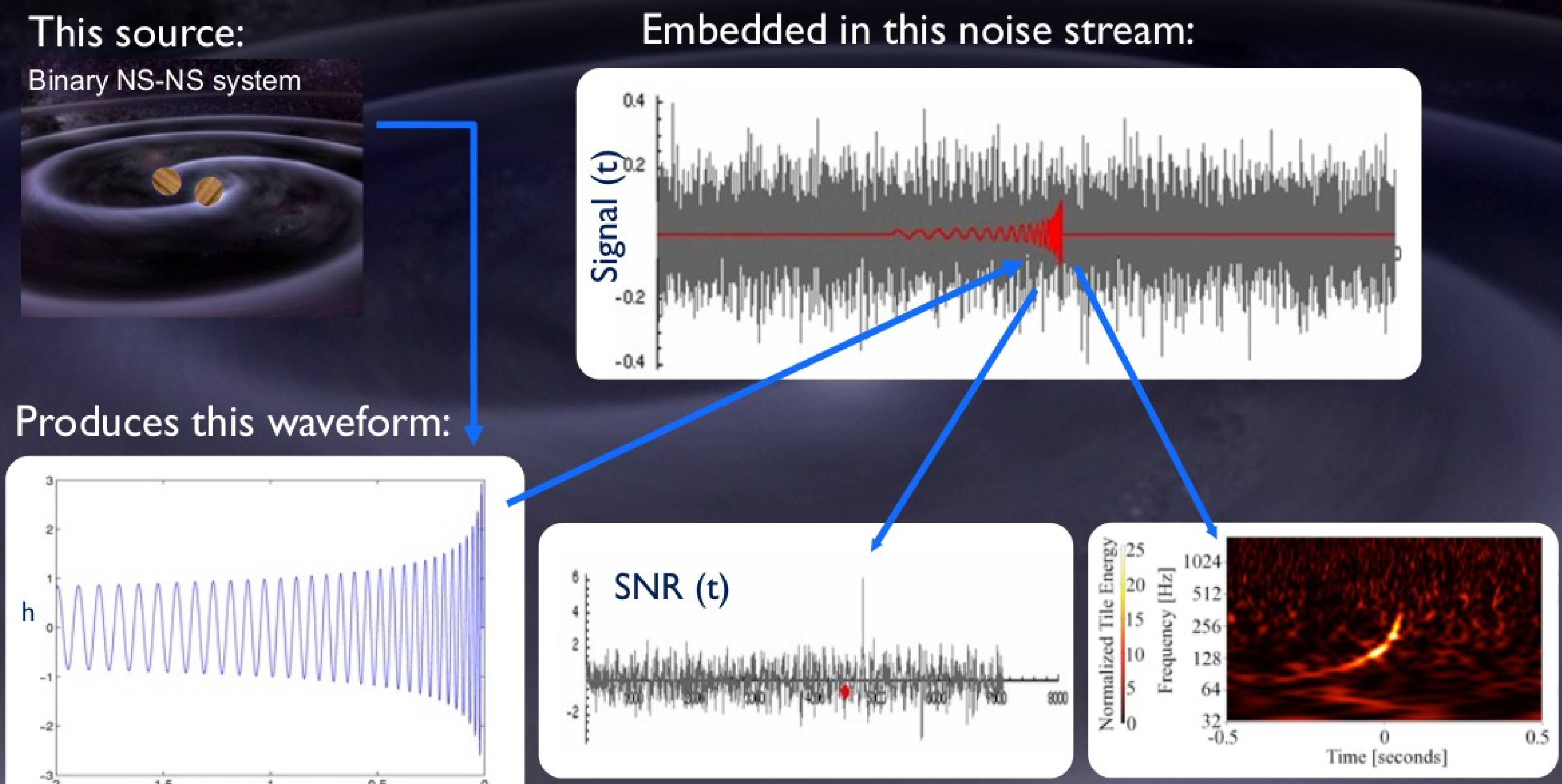
- 2015: **2nd** :Adv LIGO/VIRGO (10Hz-10kHz) ~10 x more sensitive (10^3 times more events/yr),
- NS-NS (450 Mpc), NS-BH (1Gpc),BH-BH (2Gpc),
- 2030 ?: **3rd** : ET (1 Hz-10 kHz) ~ 100 (10^6 events/yr)

	BNS	NS-BH	BBH
Initial LIGO (2002-06)	0.02	0.006	0.01
Adv. LIGO (2014+)	40	10	20
ET	Millions	100,000	Millions

Advanced LIGO

- **Funded by NSF in April 2008**
- **Cost of the upgrade: $205M (NSF) and $30M from partners in Germany (Max Planck Albert Einstein Institute), UK (STFC), and Australia (ARC)**
  - Cost comparison: 1 Advanced LIGO = 0.03 Large Hadron Colliders
- **Design goals:**
  - Complete upgrade of three LIGO interferometers
  - Sensitivity to binary neutron star inspirals to 200 MPc*
    - 10X the range of initial LIGO, 1000X the volume (and event rate)
- **Planned 7 year construction phase scheduled for completion in March 2015**
- **Current Status: Advanced LIGO Project FINISHED as of March 31!**
  - *LIGO Livingston interferometer*: completed installation in April 2014, first lock in May, currently being commissioned
  - *LIGO Hanford interferometer*: completed installation in September 2014, first lock in December, currently being commissioned
  - *Third interferometer*: components assembled and in storage for future installation in LIGO-India

What Might the First Direct GW Detection Look Like?



Astrophysical sources of GW

- ELF log f = -16 to -10, VLF log f= -10 to -6, LF log f = -6 to 0, HF log f = 0 to 6

f (Hz)	wavelength	method	source
~ 10^-16	~ 10^9 ly	anisotropy of microwave background	primordial
~ 10^-9	~ 10 ly	timing of millisecond pulsars	primordial, cosmic strings
~ 10^-4 to 10^-1	~ 0.01 AU to 10 AU	Doppler tracking of spacecraft, laser interferometer in space (**LISA**)	binary stars, supermassive black holes
~ 10 to 10^3	~ 300 km to 30,000 km	laser interferometers on earth (**LIGO**, VIRGO, GEO, TAMA)	inspirals: NS+NS, BH+BH, NS+BH
~ 10^3	~ 300 km	Cryogenic resonant bar detectors	supernovae, spinning neutron stars

Detection rate

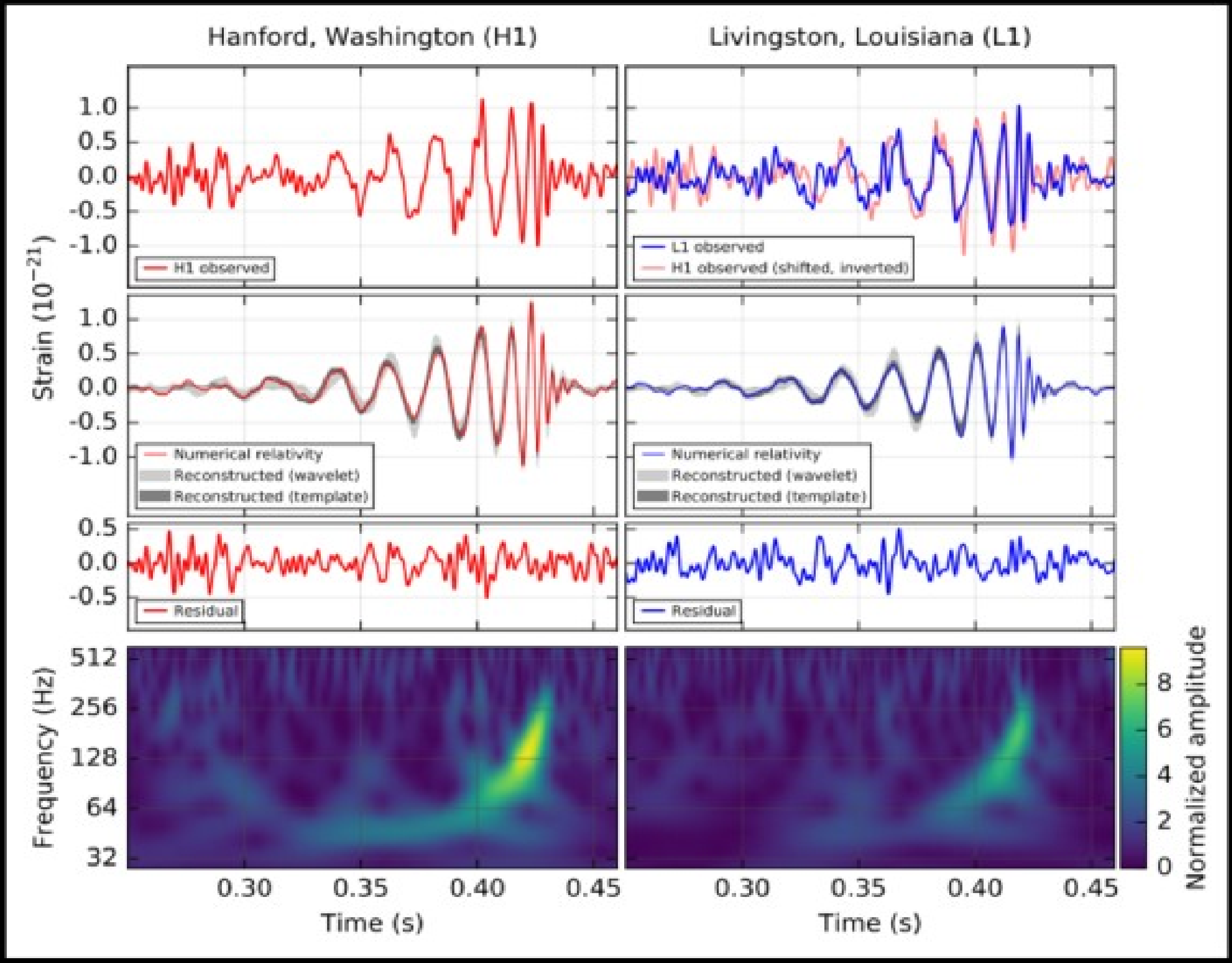
Future evolution: stable mass transfer
Formation of BBH

$$R = 0.63 \left(\frac{4\pi}{\Omega_s}\right) \left(\frac{M_{chirp}}{18 M_\odot}\right)^{5/2} \left(\frac{r_{BNS}}{18\mathrm{Mpc}}\right)^3 \left(\frac{2\mathrm{Mpc}}{r_s}\right)^3 \left(\frac{10^6\,\mathrm{yr}}{t_{obs}}\right) \mathrm{yr}^{-1}$$

May already be detected in current LIGO/VIRGO data!

GW150914: układ podwójny czarnych dziur

14 września 2015 r. oba detektory LIGO (Livingston i Hanford) zarejestrowały, z przesunięciem 7 ms, ten sam sygnał:

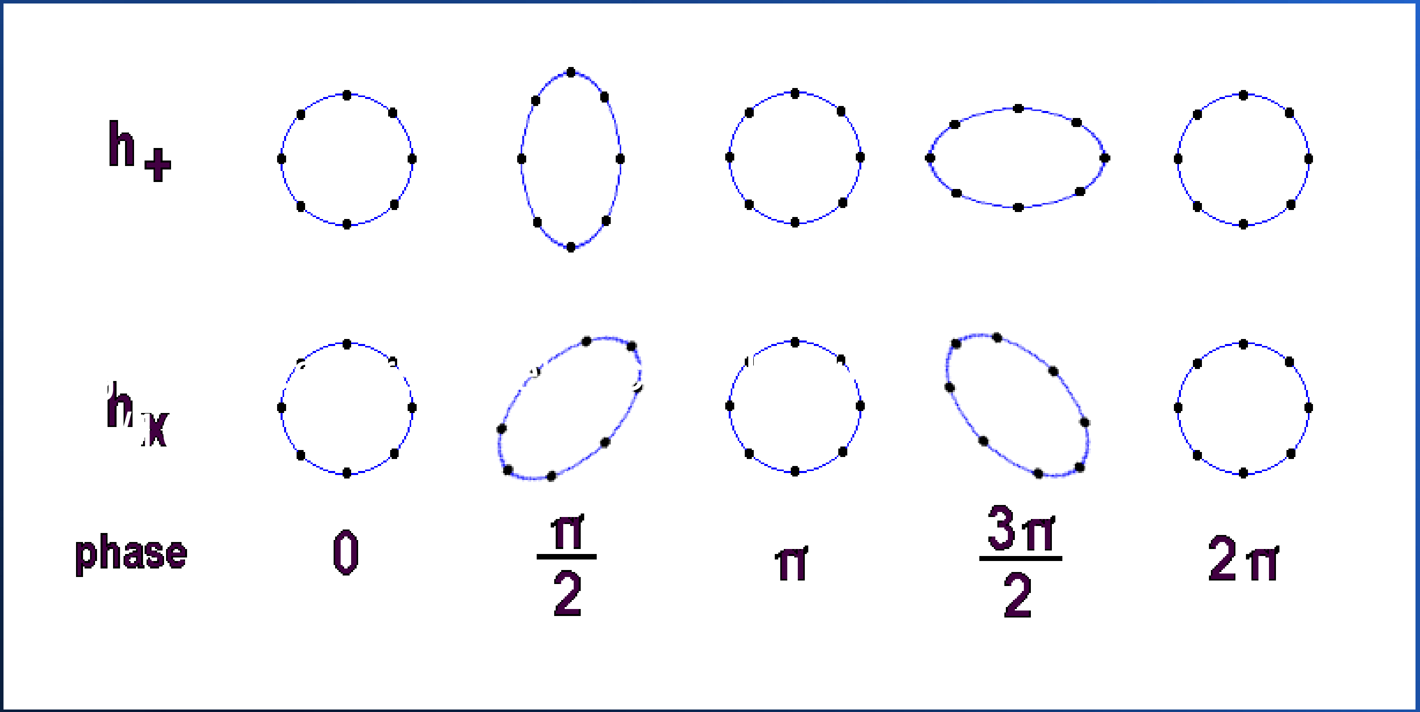


Parametry źródła sygnału i odległość zostały obliczone metodami statystycznymi (*metoda filtru dopasowanego*).

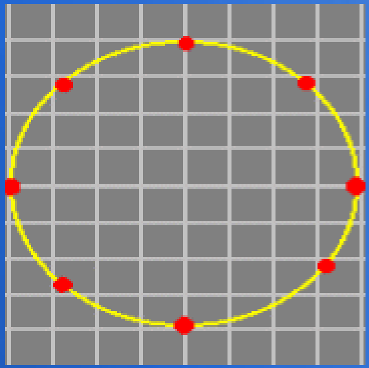
Gravitational wave polarisations

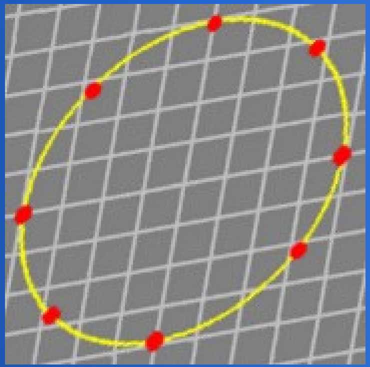
Gravitational waves are transverse

- Two polarisations: EM 90 deg; GW 45 deg



linear



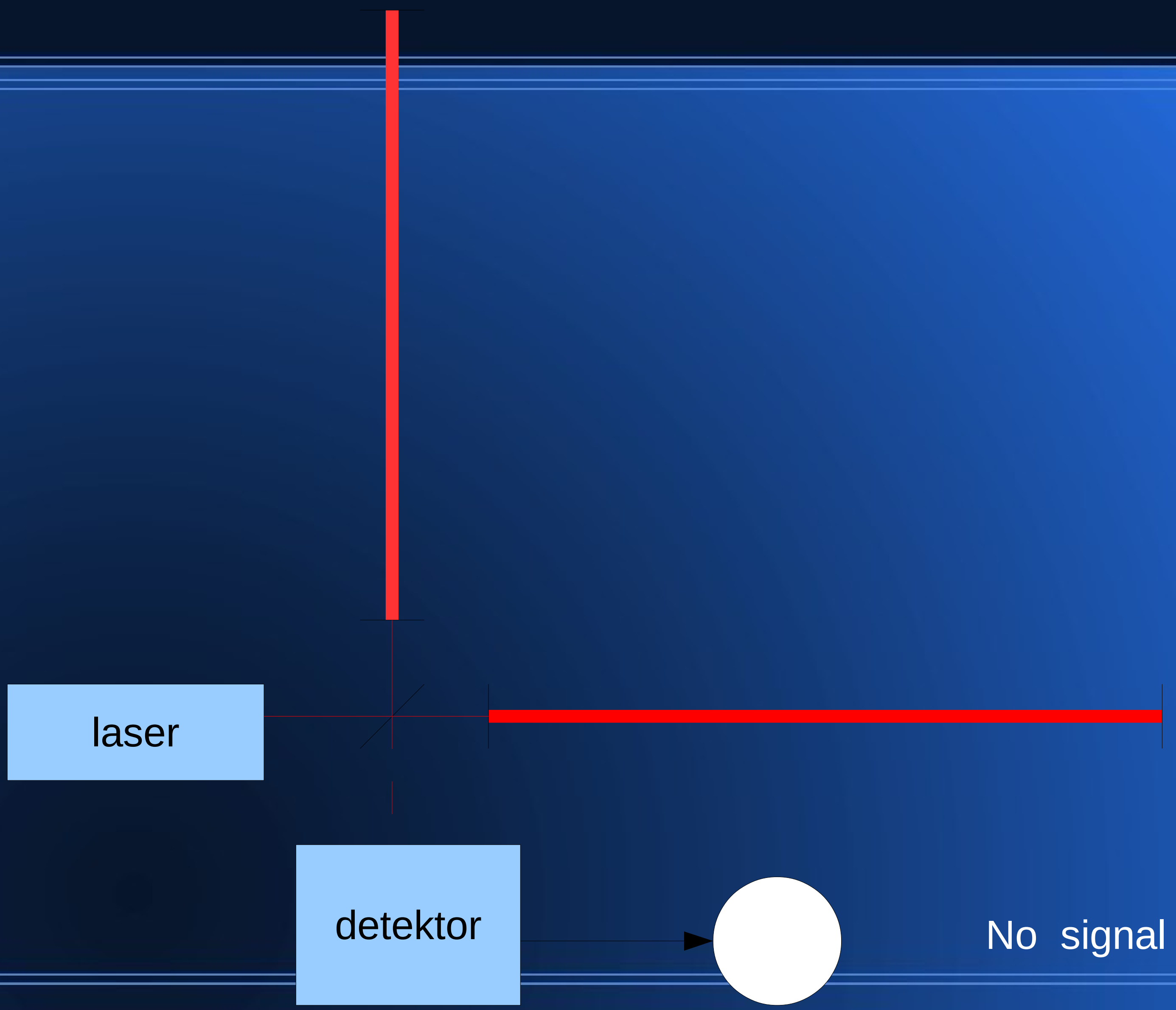


Estimate of the amplitude

-

- Source: mass M, size L, variability P
- Quadrupole moment ML^2
- $$h=(G/c^4)(ML^2/P^2)/r$$
- h ~ second derivative of quadrupole moment
- Higher moments – factors (v/c)
- Maximally:

$$h \approx \frac{r_g}{r}\left(\frac{v}{c}\right)^2$$


laser
detektor
No signal

$dL = h\,L$

Gravitational wave

SIGNAL !

4km Beam Tubes

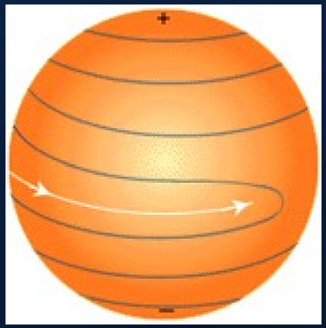
- Light must travel in an excellent vacuum
  - » Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs!
  - » 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters' bullets and the stray car
- Tube is straight to a fraction of a cm…not like the earth's curved surface

Gravitational wave

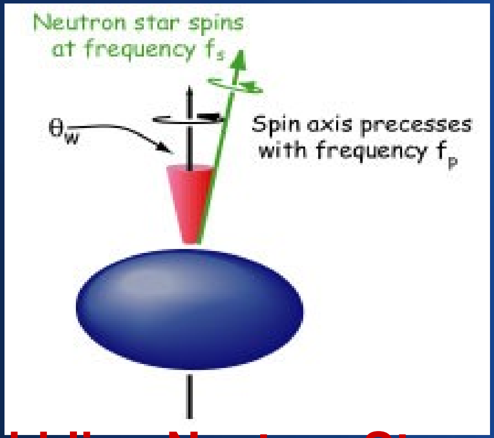
SIGNAL !

Rotating Neutron Stars

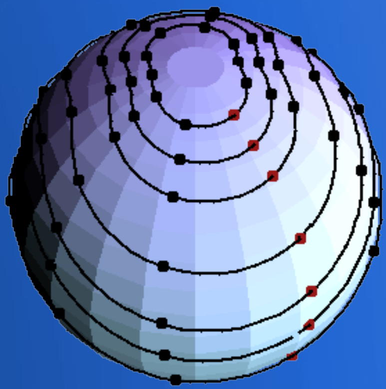
- GW if NS non-axisymmetric ~10^9 NS in the Galaxy f_{GW} frequency depeds on a mechanism:
  - r-modes ~ 4/3*f_{rot} ~10^3 identyfied
  - spin precession~ f_{rot}
  - bar shape ~2 f_{rot}
- Upper limits: spin down luminosity
-
-



Magnetic mountains



Wobbling Neutron Star



R-modes in accreting stars

Supernovae

Asymmetry

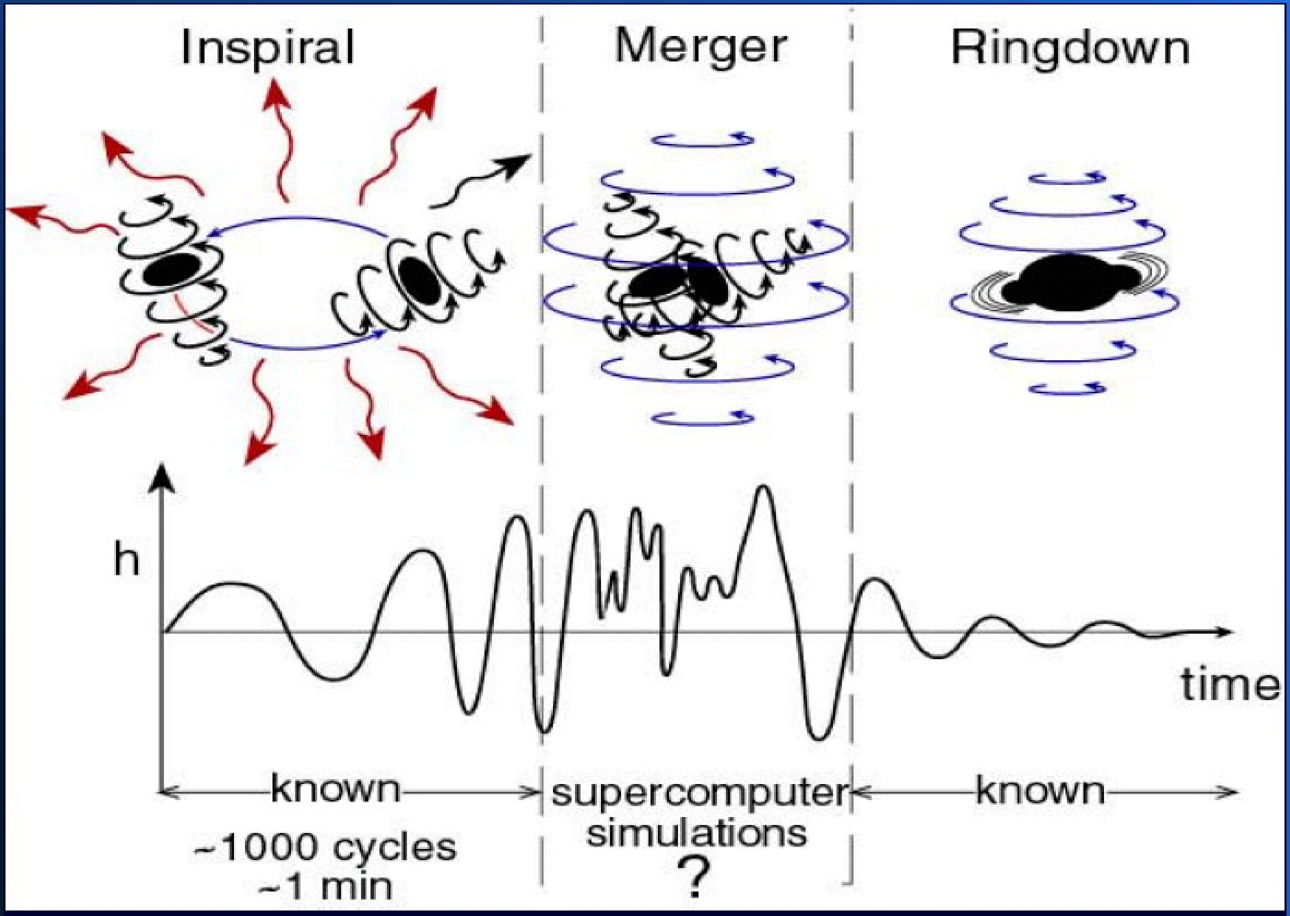
Graviational wave amplitude

Detectability

Galactic rate

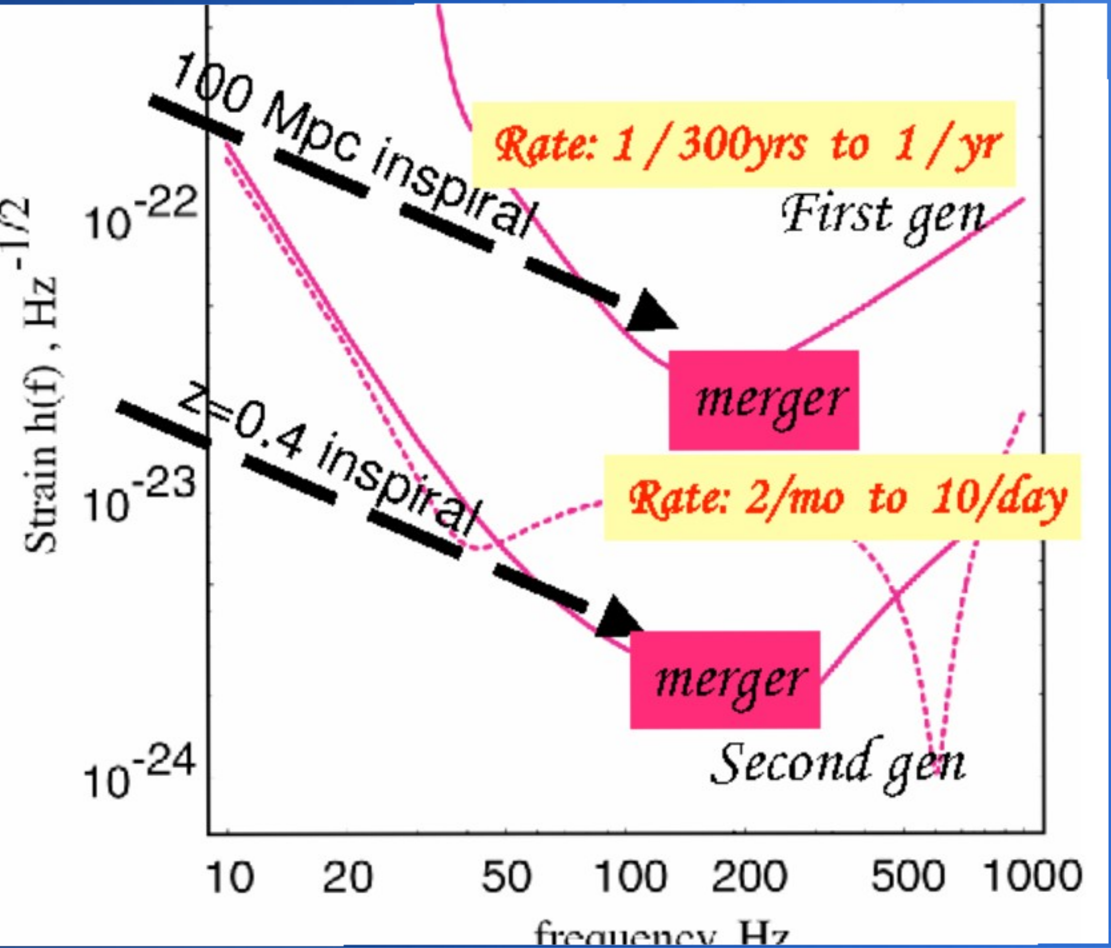
Compact binaries- three phases of coalescence

inspiral” - until marginally stable orbit
“merger” - until the common horizon
“ringdown” - black hole oscillations



Coalescing BBH

- $10M_\odot + 10\ M_\odot$ BH/BH binary
- Event rates based on population synthesis,
- mostly globular cluster binaries.
- Totally quiet!!



Coalescing BH-NS

NS-BH Event rates

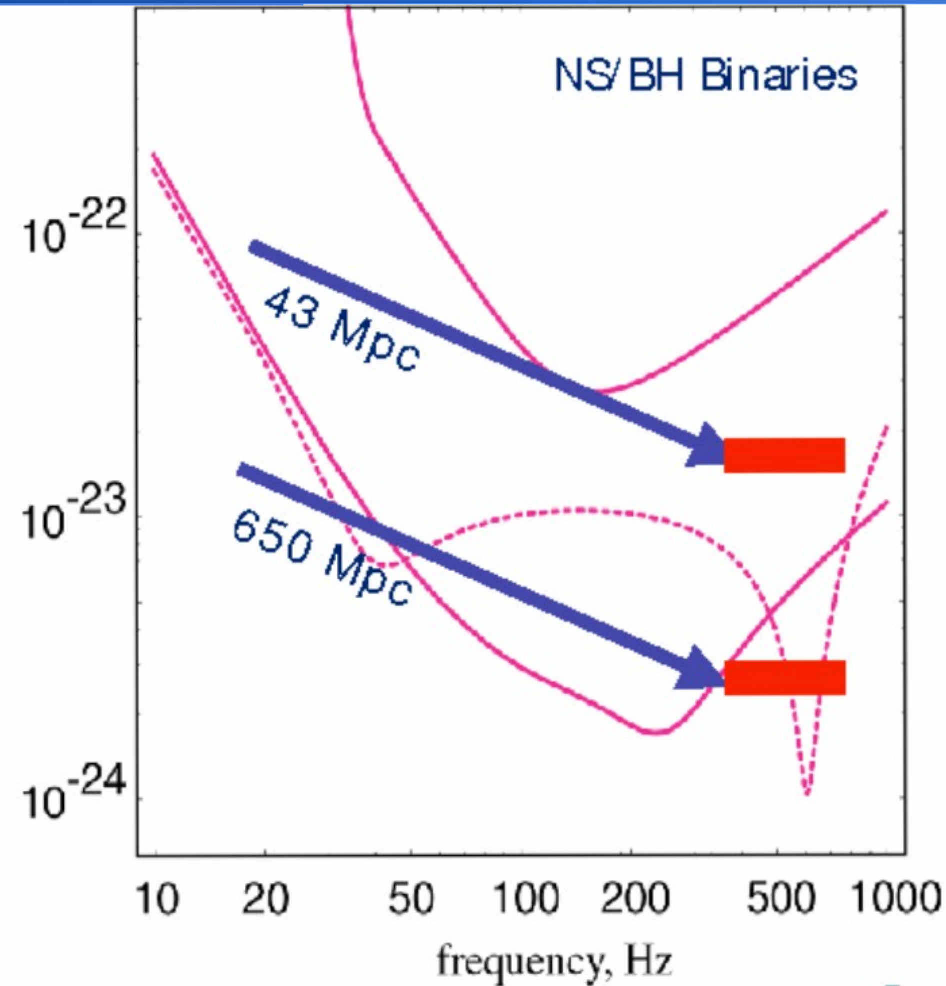
Based on *Population Synthesis*

Initial interferometers

- Range: 43 Mpc
- 1/1000 yrs to 1 per yr

Advanced interferometers

- Range: 650 Mpc
- 2 per yr to several per day

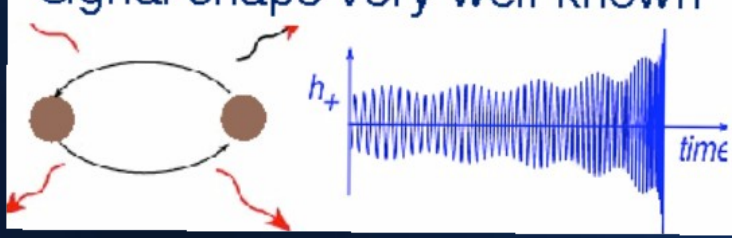


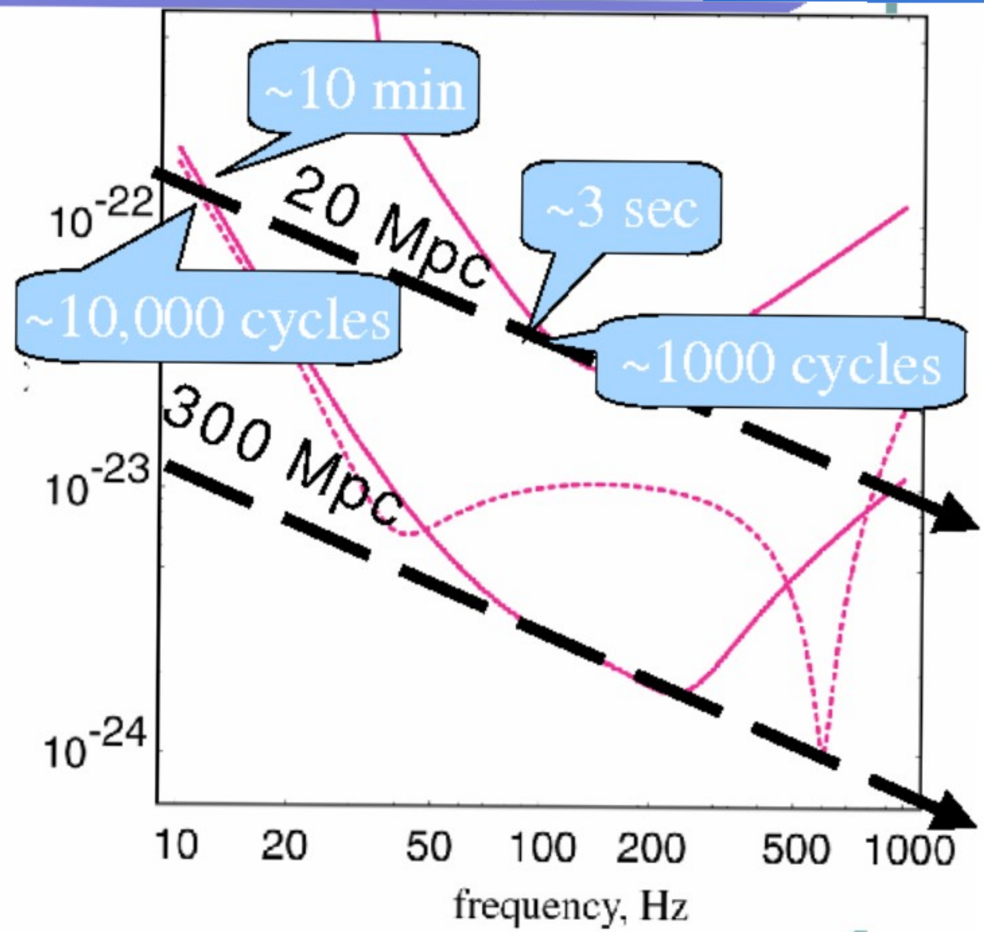
Coalescing BNS

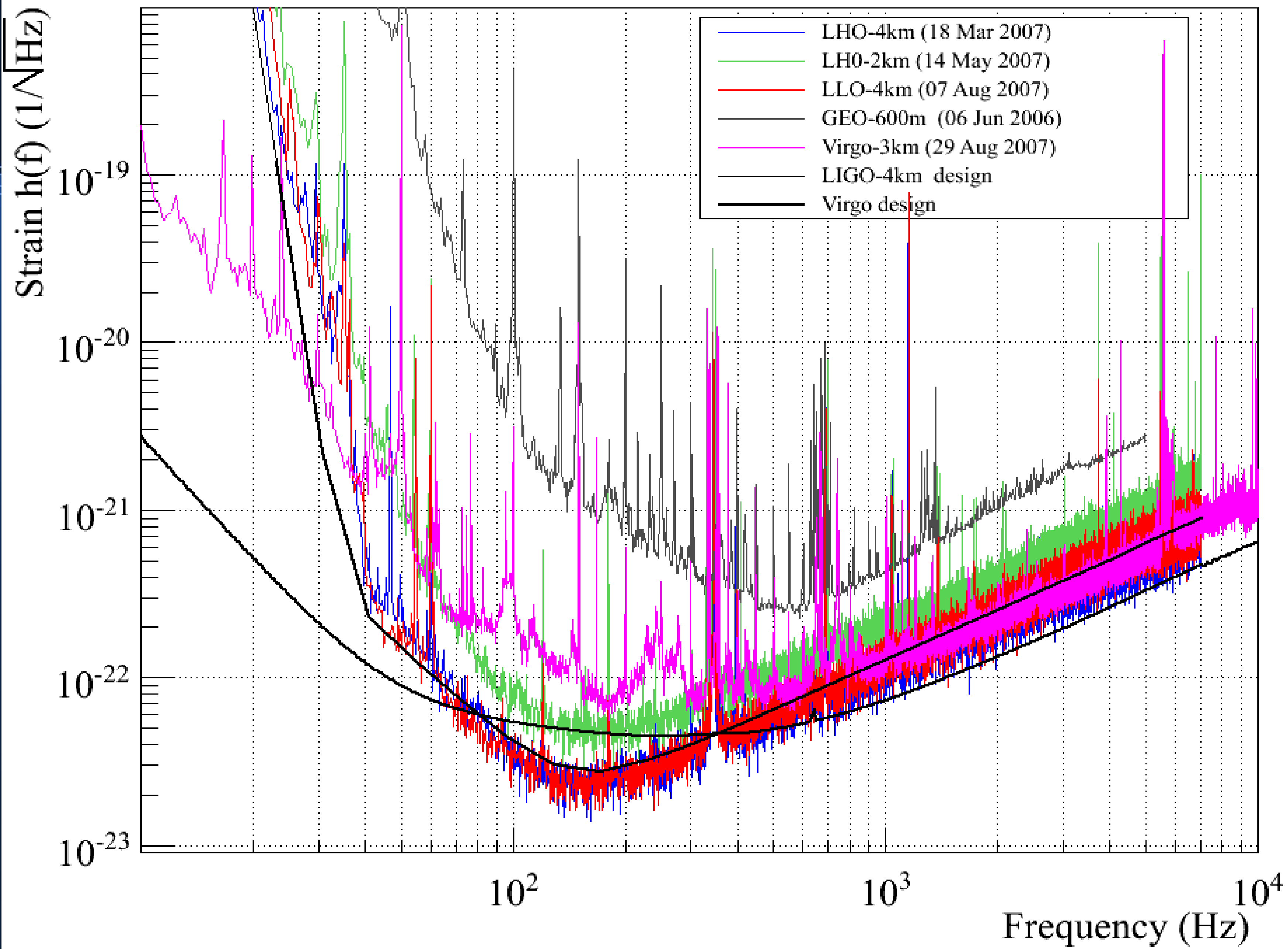
NS-NS coalescence event rates

- Initial interferometers
  - Range: 20 Mpc
  - 1 per 40 yrs to 1 per 2 yrs
- Advanced interferometers
  - Range: 300Mpc
  - few per yr to several per day
- The discovery of a new binary pulsar have increased the rate upwards by an order of magnitude

Signal shape very well known







LHO-4km (18 Mar 2007)
LH0-2km (14 May 2007)
LLO-4km (07 Aug 2007)
GEO-600m (06 Jun 2006)
Virgo-3km (29 Aug 2007)
LIGO-4km design
Virgo design
Strain h(f) (1/√Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^2
10^3
10^4
Frequency (Hz)

Detection of gravitational waves

- Test masses
- A network of detectors needed: to confirm detections independently and open a new window on the Universe
- narrow bandwidth: resonance detectors (~1 kHz)
- large bandwidth: laser interferometers (~10Hz-1kHz)
- Measurement of distances between them using light beams
- dL~ h L

Pulsar timing

- PPTA, EPTA, NanoGrav
- Sensitivity: wave amplitude – 10^{-13}, 10^{-14}
- Frequency range: below 10^{-7} Hz
- Directional sensitivity – important to monitor many pulsars
- Timescale for detection
- vs. frequency range

Animacja

Coalescing compact binaries

During the frequency change from 100-200Hz GWs carry away $5\times10^{-3}M_{\odot}c^2$.

In LIGOs band

- NS/NS (~16000 cycles)
- NS/BH(~3500 cycles)
- BH/BH(~600 cycles)

events/year	LIGO-I	LIGO-II
NS/NS	~0.05	~60-500
BH/NS	~0.02	~80
BH/BH	~0.8	~2000
Total	0.8	2000

The GW amplitude is:

$$h \approx 7.5\times10^{-23}\left(\frac{M}{2.8M_{\odot}}\right)^{2/3}\left(\frac{\mu}{0.7M_{\odot}}\right)\left(\frac{f}{100Hz}\right)^{2/3}\left(\frac{100Mp}{r}\right.$$

Larger total mass improves detection probability.

- Phase effects are important, if the signal and the template get out of phase their cross correlation will be reduced.
- High accuracy templates are needed for accurate detection.

- but Bulik et al. 2011, IC10 X-1/NGC300 X-1: THE VERY IMMEDIATE PROGENITORS OF BH-BH BINARIES (BH-WR) will form BH-BH system with Mtot~40 Msol in < 0.3 Myr, d< 2 Mpc => 1-3 events/yr for Initial VIRGO/LIGO

Coalescing compact binaries

During the frequency change from 100-200Hz GWs carry away $5 \times 10^{-3} M_{\odot} c^2$.

In LIGOs band

- NS/NS (~16000 cycles)
- NS/BH(~3500 cycles)
- BH/BH(~600 cycles)

events/year	LIGO-I	LIGO-II
NS/NS	~0.05	~60-500
BH/NS	~0.02	~80
BH/BH	~0.8	~2000
Total	0.8	2000

The GW amplitude is: $h \approx 7.5 \times 10^{-23} \left(\frac{M}{2.8 M_{\odot}}\right)^{2/3} \left(\frac{\mu}{0.7 M_{\odot}}\right) \left(\frac{f}{100 Hz}\right)^{2/3} \left(\frac{100Mp}{r}\right.$

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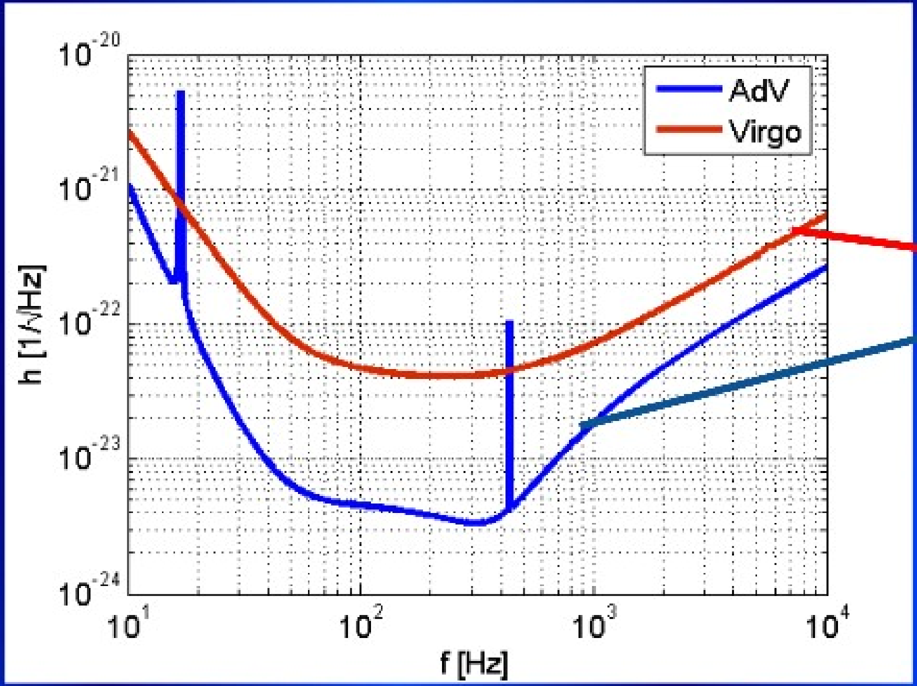
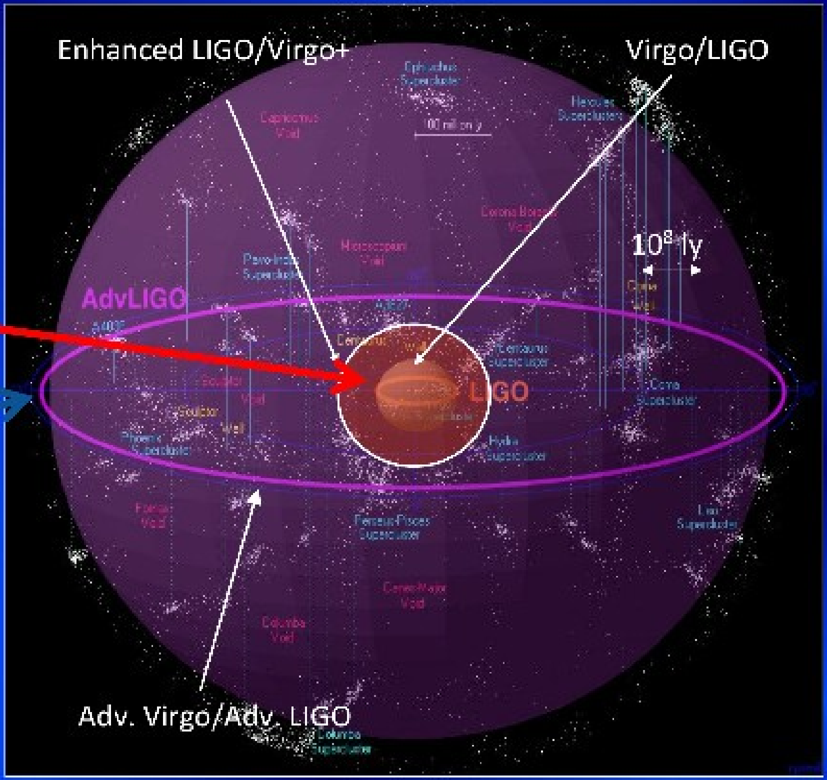
2nd generation: Adv Virgo/LIGO

- The upgrade to the advanced phase (2nd generation) is just started (LIGO) or will start within this year (Virgo). The detectors should be back in commissioning in 2014
- Advanced are promising roughly a factor 10 in sensitivity improvement:





Observational proof – PSR 1913+16

Nobel 1993 - Hulse & Taylor

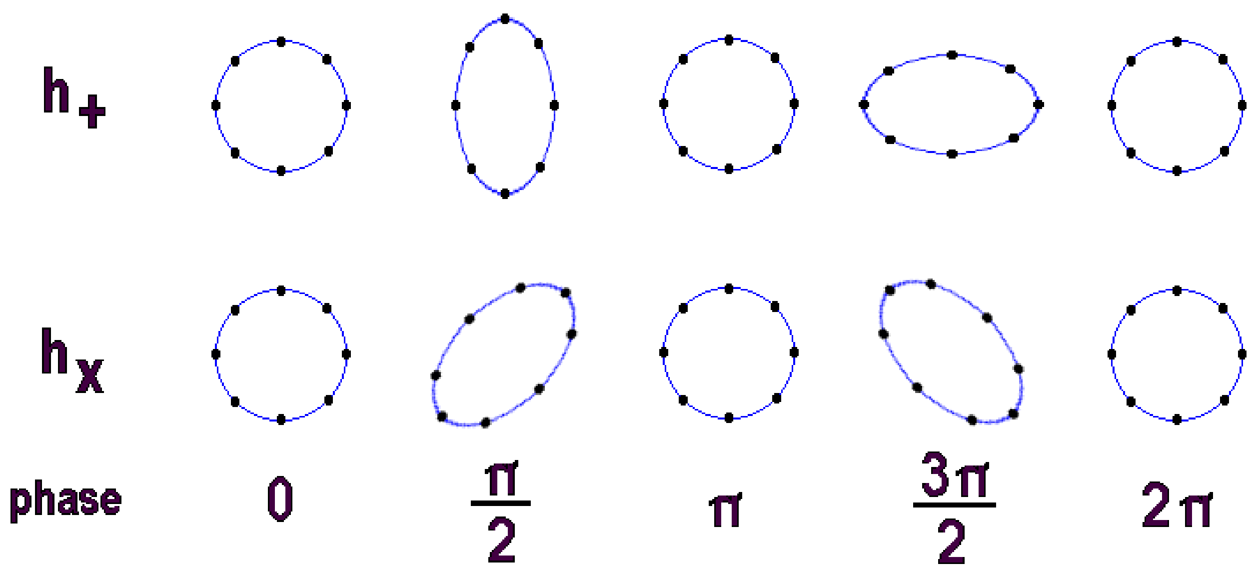
<-- observed decay of P = 7 h 45 min (75 microsekund/yr) due to gravitational radiation ---> merger in 140 Myr

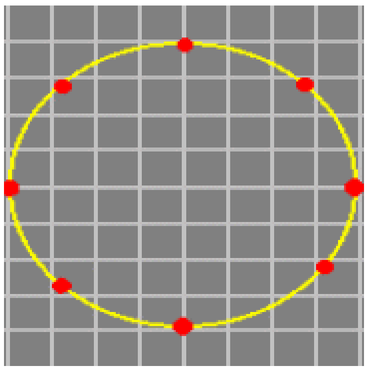
$\dot{P}$obs/$\dot{P}$teo =1.0025 +/-0.0022

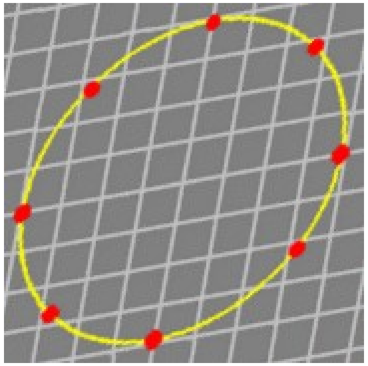
Gravitational wave polarisations

Gravitational waves are transverse
Two polarisations: EM 90 deg; GW 45 deg

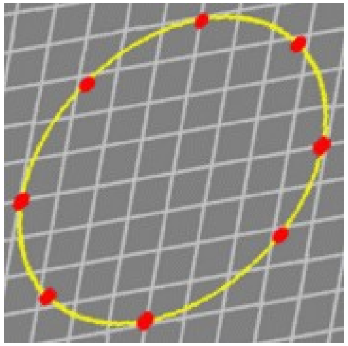
linear



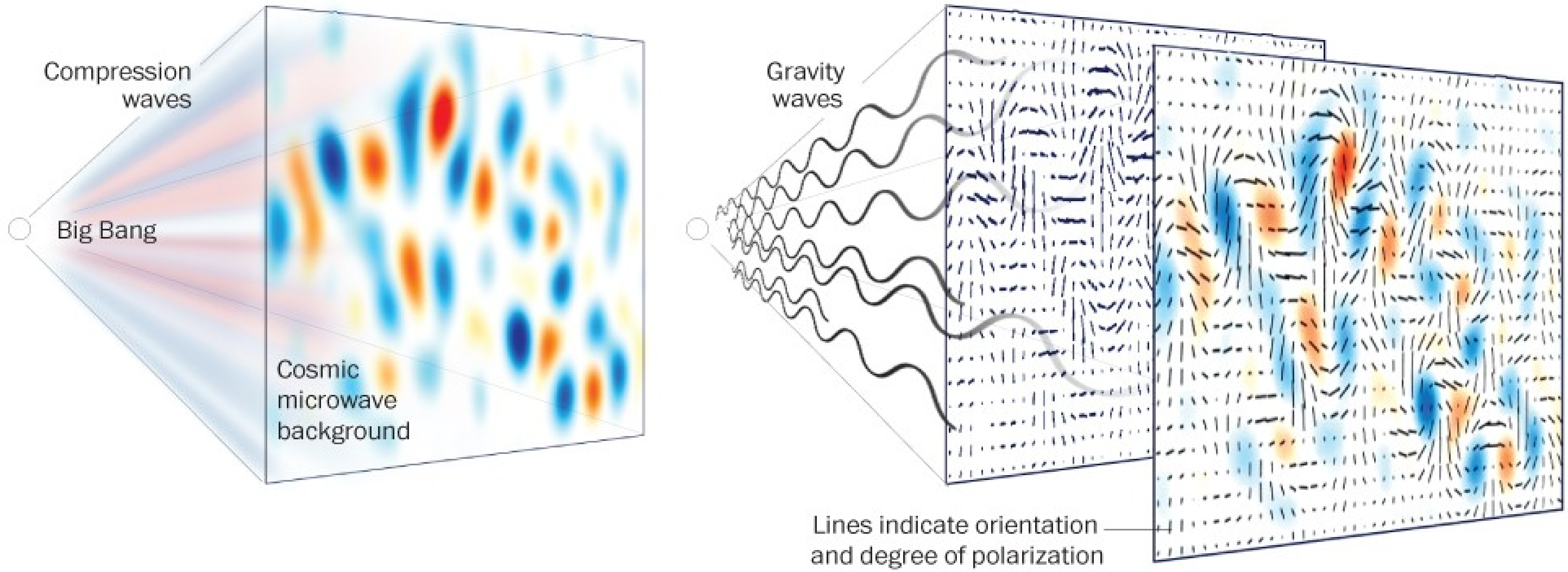




Curcular



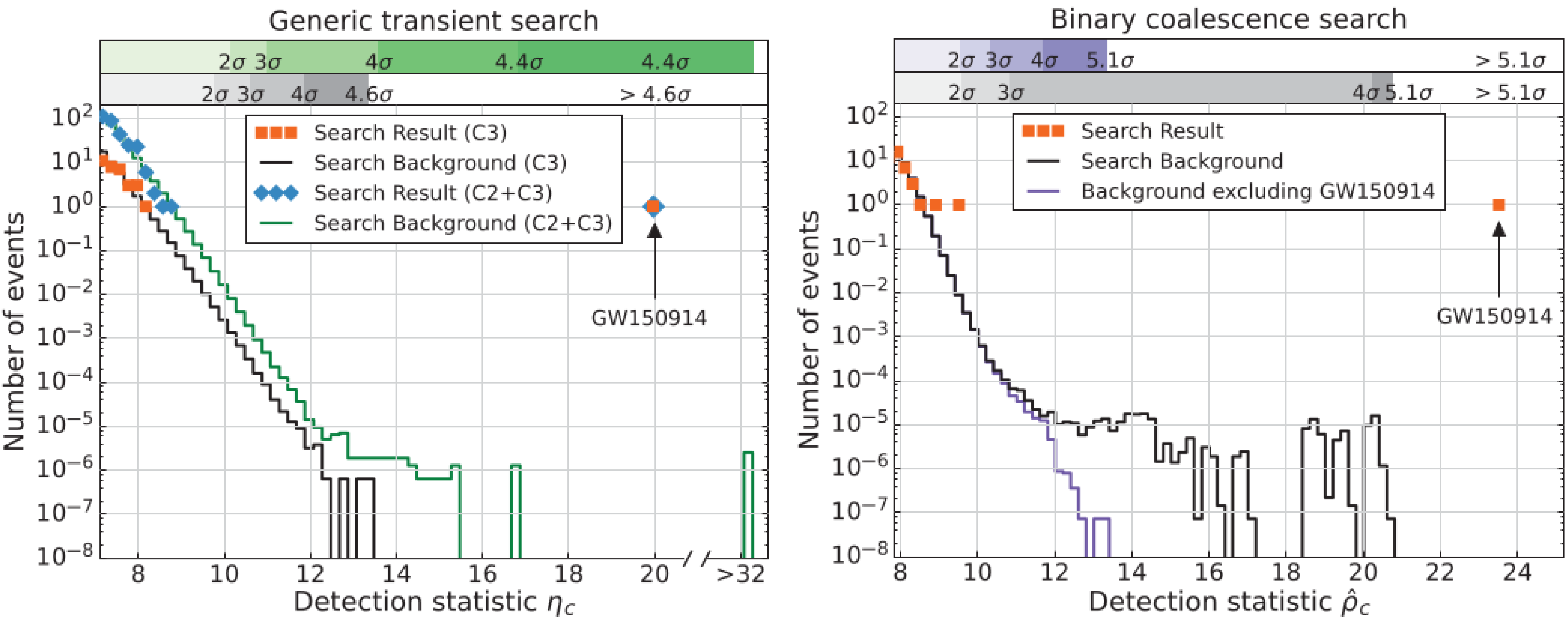
BICEP2 polarization of the B-mode polarization of CMB – GW fingerprint?



Within a tiny fraction of a second, the big bang inflated the universe. **Compression waves** created a pattern in the afterglow of the expansion, known as the **cosmic microwave background**, which scientists have studied and mapped since the 1960s.

In the 1990s, physicists theorized that rapid inflation during the big bang would also generate **gravity waves**, which would leave their mark by polarizing light in the cosmic afterglow. Extremely sensitive telescopes at the South Pole have detected such skewed light waves, but scientists have spent almost a decade ensuring that the phenomenon was not the result of other factors.

GW150914 – found by both BURST and CBC team



Waited to acquire 16 days background data to estimate properly the significance.

False alarm probability – better than 1 event in 203000 years.

Detection principle