Astrophysics and detection of gravitational wave sources

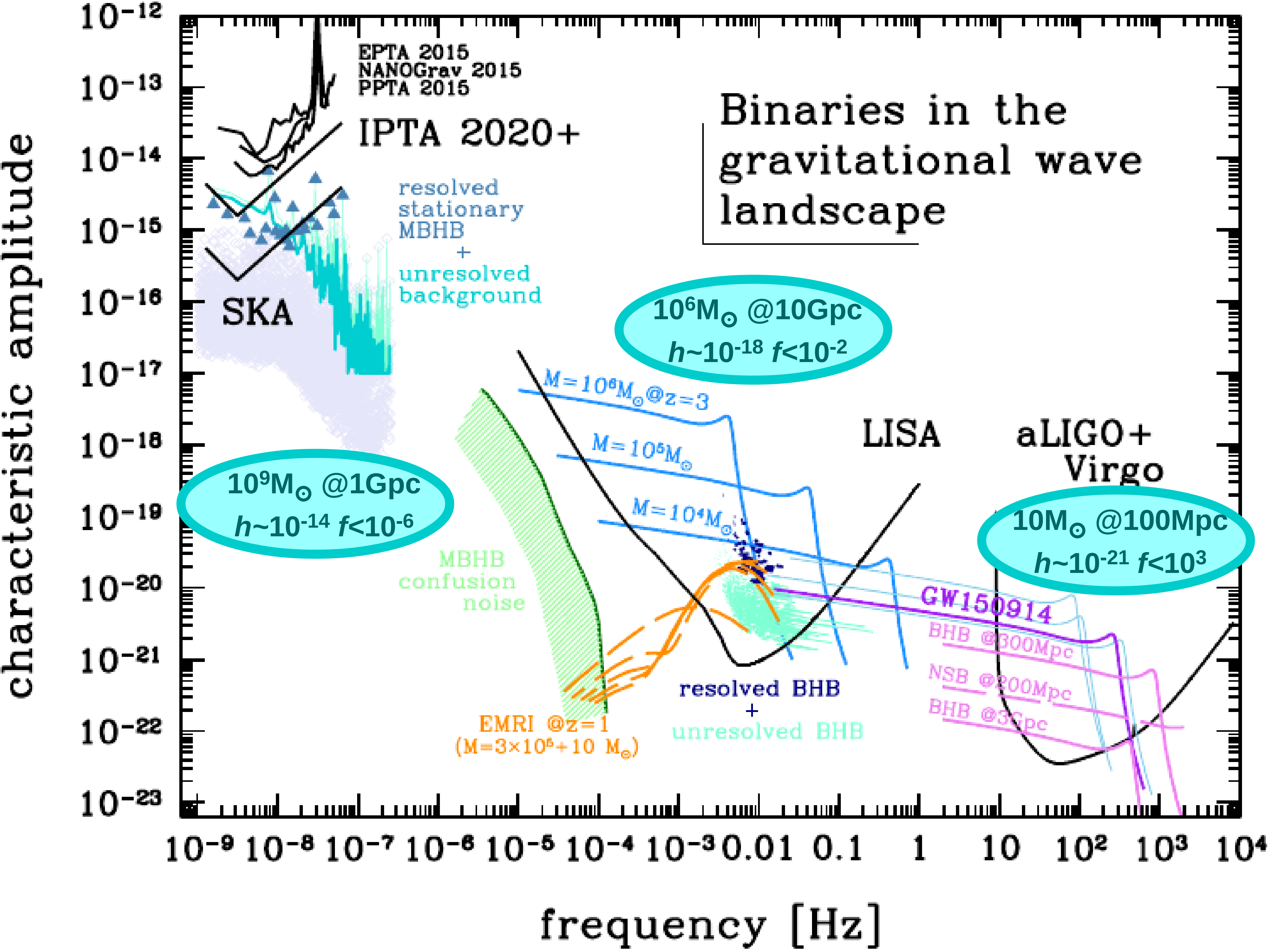
Alberto Sesana
(Universita` di Milano Bicocca)

OUTLINE

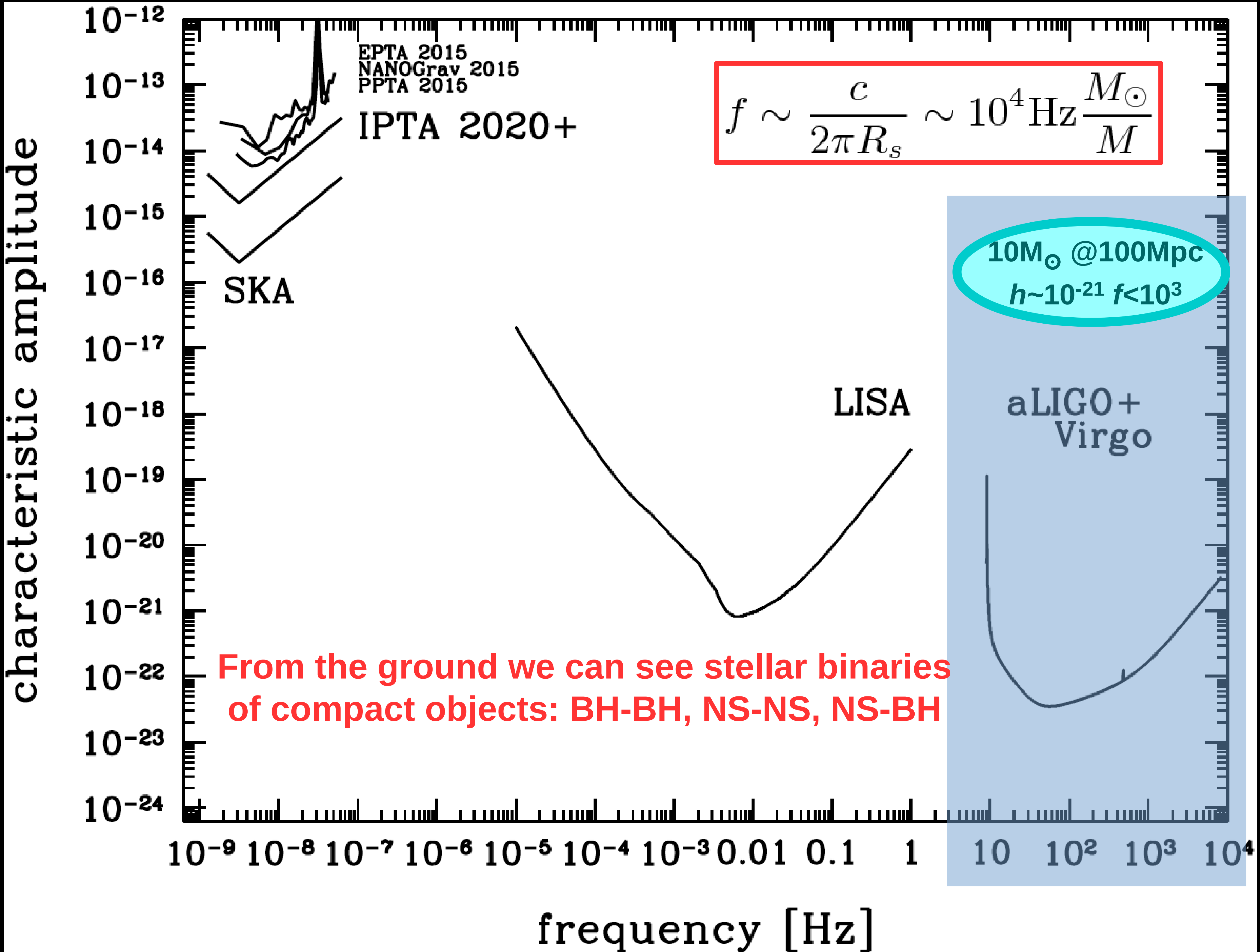
LECTURE 1 (NOW): Setting the stage
-Gravitational waves (GWs): theory and general considerations
-GWs from binary systems, relevant scalings

LECTURES 2/3 (Monday afternoon): ground based
-Detection of GW with ground based interferometers
-Black hole binaries (BHBs) detected by LIGO/Virgo
-GW170817 a neutron star binary (NSB)
-Astrophysics of ground based GW sources: formation scenarios
-Future from the ground: 3G detectors

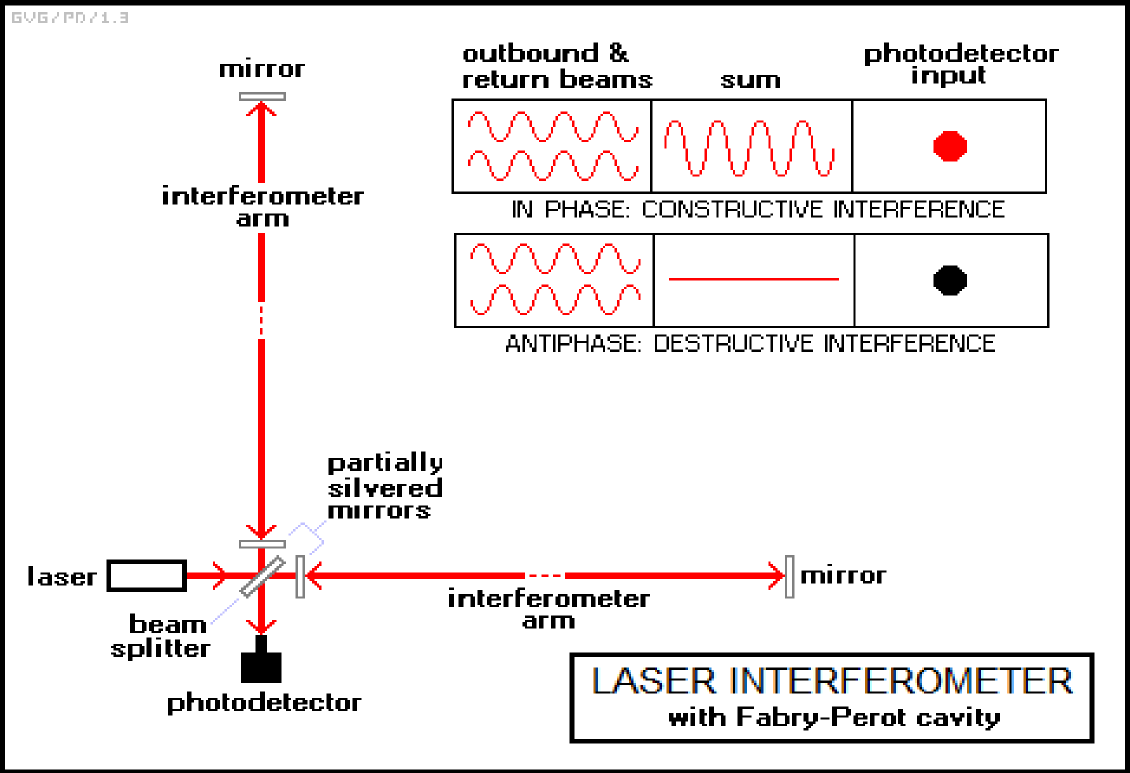
LECTURE 4/5 (Tuesday morning): space based
-Beyond the ground: GW detection from space
-Laser interferometer space antenna and its sources
-Galactic binaries
-Extreme mass ratio inspirals (EMRIs)
-Massive black hole (MBH) formation and evolution



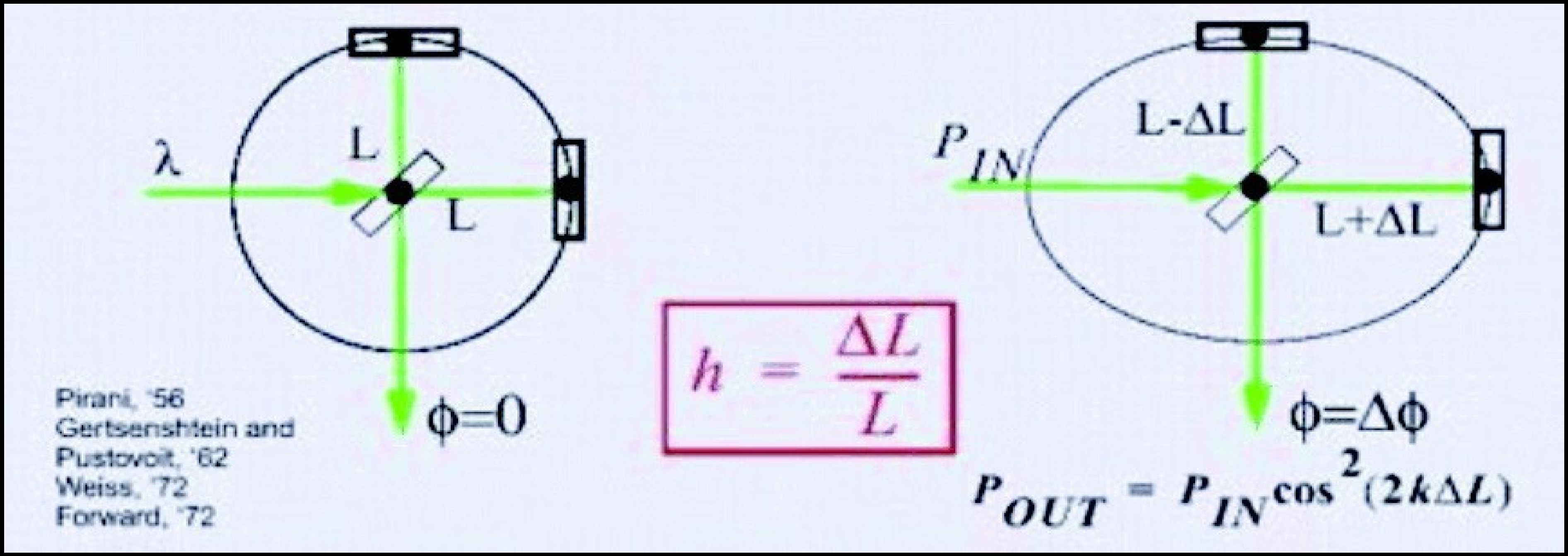
Binaries in the gravitational wave landscape
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
10^6M⊙ @10Gpc
h~10^-18 f<10^-2
10^9M⊙ @1Gpc
h~10^-14 f<10^-6
10M⊙ @100Mpc
h~10^-21 f<10^3
M=10^6M⊙@z=3
M=10^5M⊙
M=10^4M⊙
LISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB
+
unresolved BHB
EMRI @z=1
(M=3×10^5+10 M⊙)
characteristic amplitude
frequency [Hz]


EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
LISA
aLIGO+ Virgo
$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$
$10M_\odot$ @100Mpc
h~10^{-21} f<10^3
From the ground we can see stellar binaries of compact objects: BH-BH, NS-NS, NS-BH
characteristic amplitude
frequency [Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 10^2 10^3 10^4

Observation technique: laser interferometry

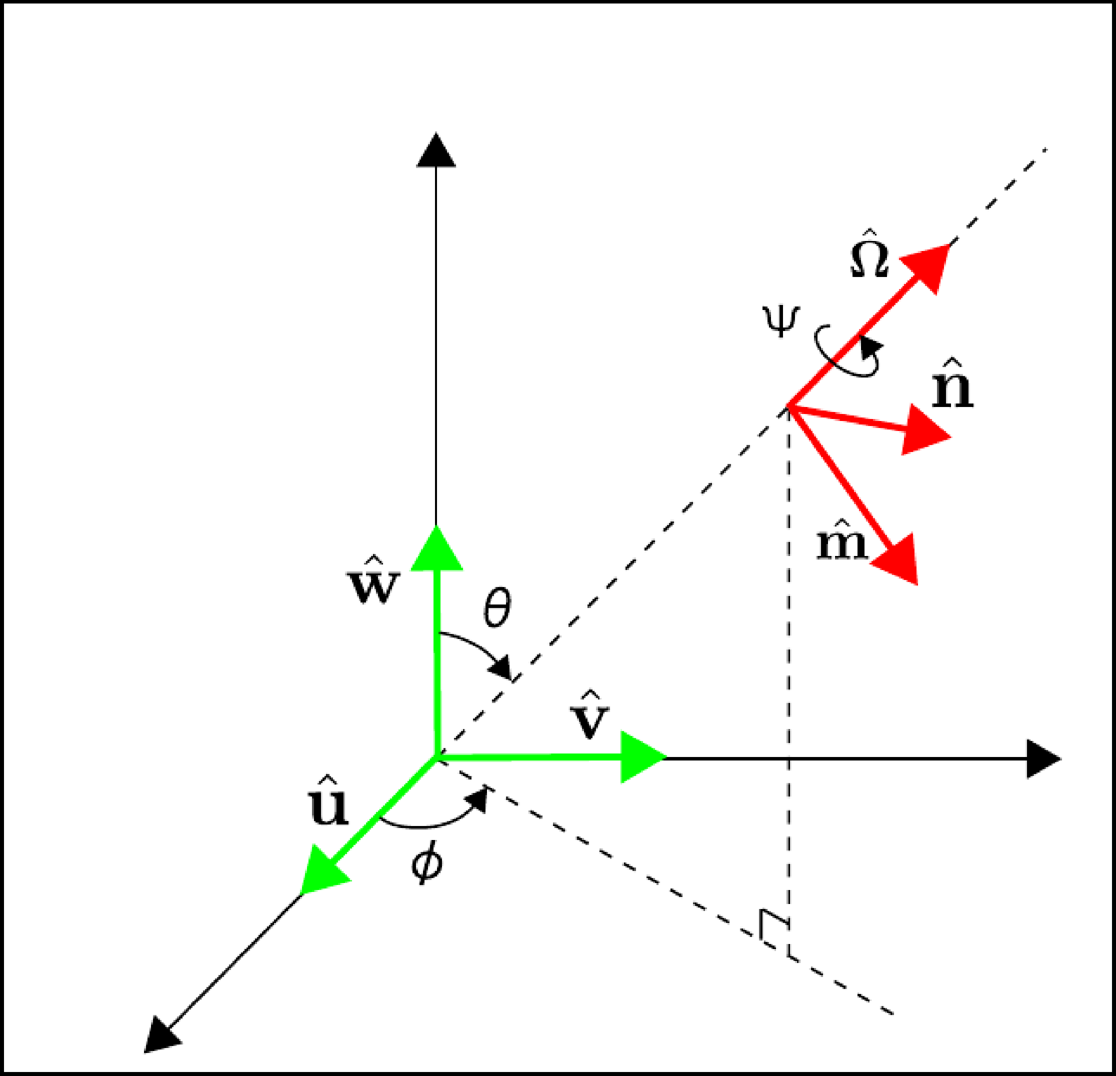


The wave passage changes the length of the path covered by the light in the two arms. The result is a de-phasing in the recombination of the two laser beams.



$$h_+(t) = \frac{4}{r}\left(\frac{GM_C}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f_{gw}}{c}\right)^{\frac{2}{3}}\left(\frac{1+\cos^2\theta}{2}\right)\cos(2\pi f_{gw}t + 2\phi)$$

$$h_\times(t) = \frac{4}{r}\left(\frac{GM_C}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f_{gw}}{c}\right)^{\frac{2}{3}}\cos\theta\sin(2\pi f_{gw}t + 2\phi)$$



The response of a detector to the two polarization waves depends on relative orientation of the detector and the incoming wave.

$$h_{ij}(t-\hat{\Omega}\cdot\vec{x}) = \sum_A h^A(t-\hat{\Omega}\cdot\vec{x})\epsilon_{ij}^A(\hat{\Omega})$$

$$\epsilon_{ij}^+ = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \epsilon_{ij}^\times = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

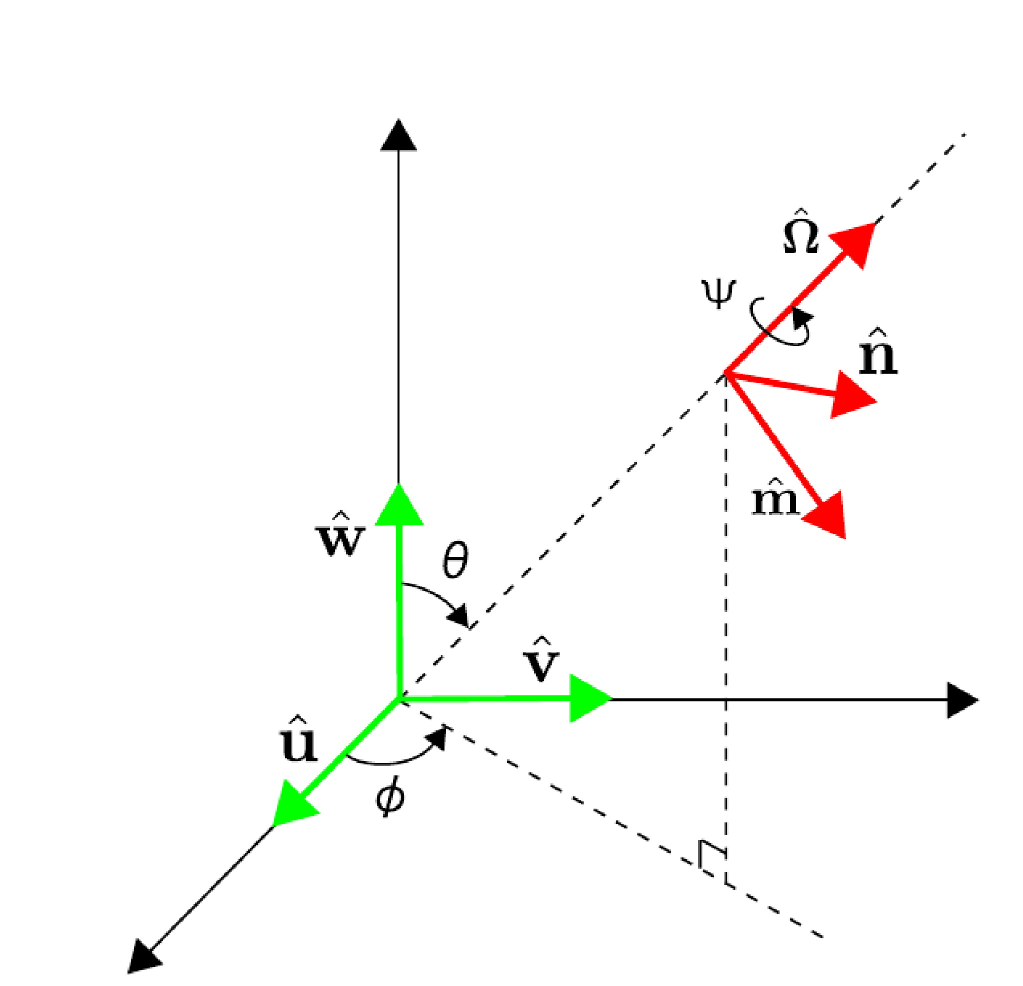
$$\epsilon_{ij}^x = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \epsilon_{ij}^y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$\epsilon_{ij}^b = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \epsilon_{ij}^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$\hat{x} = (1,0,0), \hat{y} = (0,1,0), \hat{z} = (0,0,1)$$

$$\hat{x}' = (\cos\theta\cos\phi, \cos\theta\sin\phi, -\sin\theta)$$
$$\hat{y}' = (-\sin\phi, \cos\phi, 0)$$
$$\hat{z}' = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$\hat{m} = \hat{x}'\cos\psi + \hat{y}'\sin\psi\,,$$
$$\hat{n} = -\hat{x}'\sin\psi + \hat{y}'\cos\psi\,,$$
$$\hat{\Omega} = \hat{z}'\,.$$



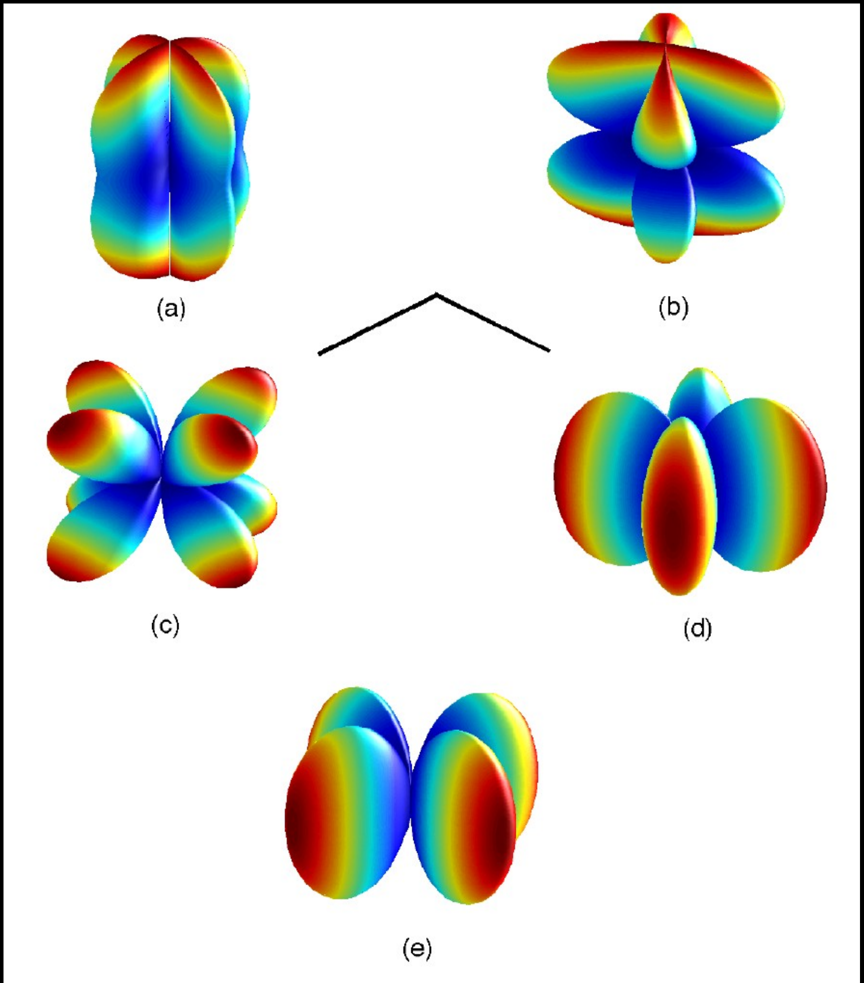
Ψ is the polarization angle. Defining the relative orientation of the polarization axis with respect to the tirection of the interferometer

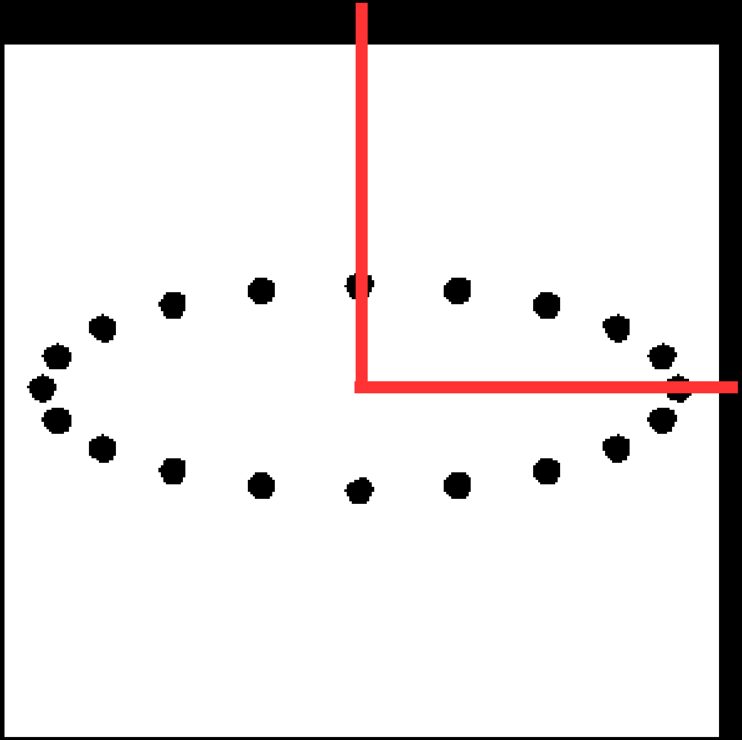
$$\begin{aligned}
\epsilon^+ &= \hat{m}\otimes\hat{m} - \hat{n}\otimes\hat{n}, \\
\epsilon^\times &= \hat{m}\otimes\hat{n} + \hat{n}\otimes\hat{m}, \\
\epsilon^x &= \hat{m}\otimes\hat{\Omega} + \hat{\Omega}\otimes\hat{m}, \\
\epsilon^y &= \hat{n}\otimes\hat{\Omega} + \hat{\Omega}\otimes\hat{n}, \\
\epsilon^b &= \hat{m}\otimes\hat{m} + \hat{n}\otimes\hat{n}, \\
\epsilon^\ell &= \hat{\Omega}\otimes\hat{\Omega}.
\end{aligned}$$

$$h(t) = \sum_A h_A(t - \hat{\Omega} \cdot x) F^A(\hat{\Omega}, \psi)$$

$$F^A(\hat{\Omega}, \psi) = \frac{1}{2} \left(\hat{x}^i \hat{x}^j - \hat{y}^i \hat{y}^j \right) \epsilon^A_{ij}(\hat{\Omega}, \psi)$$

$$\begin{aligned}
F^+(\theta, \phi, \psi) &= \frac{1}{2}(1 + \cos^2\theta) \cos 2\phi \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi, \\
F^\times(\theta, \phi, \psi) &= -\frac{1}{2}(1 + \cos^2\theta) \cos 2\phi \sin 2\psi - \cos\theta \sin 2\phi \cos 2\psi, \\
F^x(\theta, \phi, \psi) &= \sin\theta \left(\cos\theta \cos 2\phi \cos\psi - \sin 2\phi \sin\psi \right), \\
F^y(\theta, \phi, \psi) &= -\sin\theta \left(\cos\theta \cos 2\phi \sin\psi + \sin 2\phi \cos\psi \right), \\
F^b(\theta, \phi) &= -\frac{1}{2} \sin^2\theta \cos 2\phi, \\
F^\ell(\theta, \phi) &= \frac{1}{2} \sin^2\theta \cos 2\phi.
\end{aligned}$$



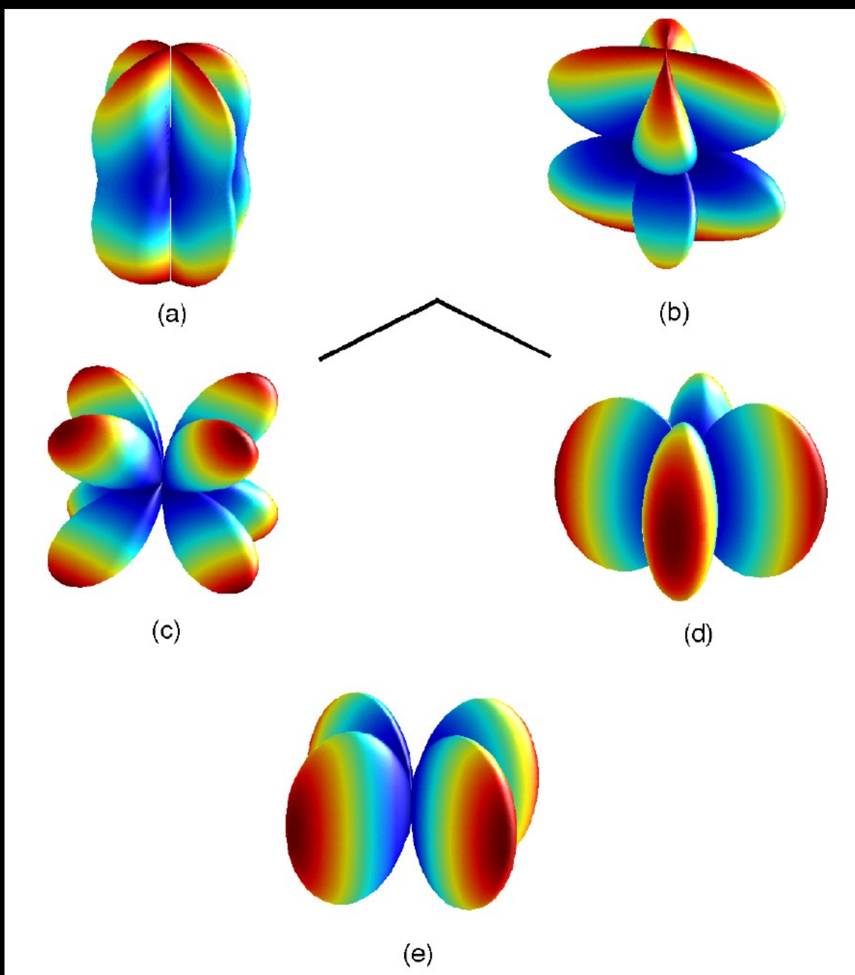


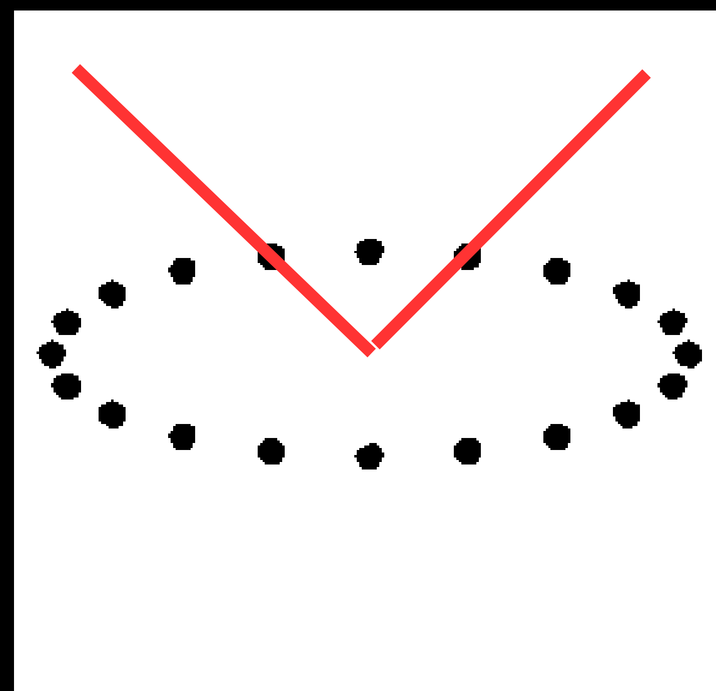
ΔL is maximum: the response of the detector to the wave is maximum

$$h(t) = \sum_A h_A(t - \hat{\Omega} \cdot x) F^A(\hat{\Omega}, \psi)$$

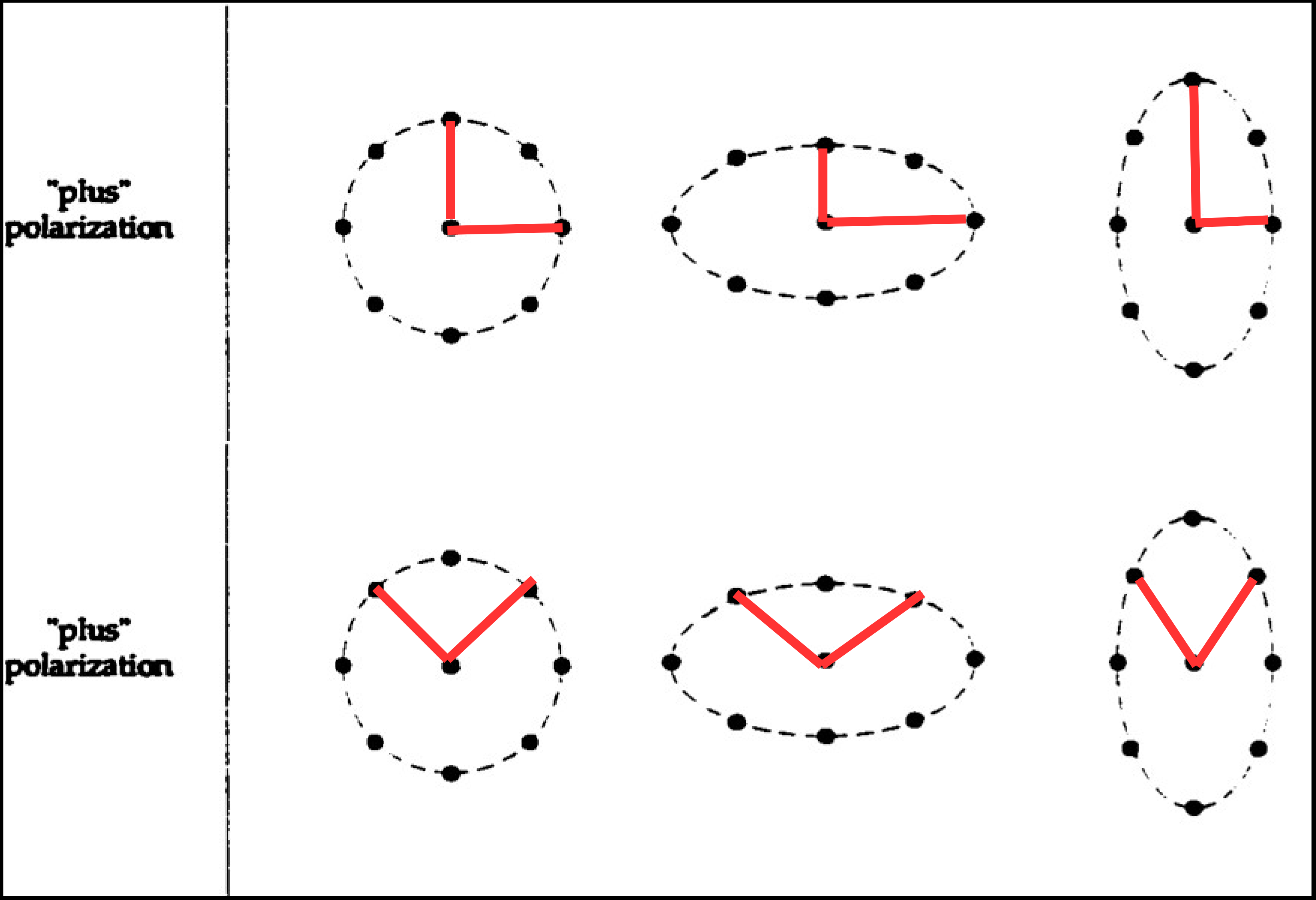
$$F^A(\hat{\Omega}, \psi) = \frac{1}{2} \left(\hat{x}^i \hat{x}^j - \hat{y}^i \hat{y}^j \right) \epsilon^A_{ij}(\hat{\Omega}, \psi)$$

$$\begin{aligned}
F^+(\theta, \phi, \psi) &= \frac{1}{2}(1 + \cos^2\theta)\cos 2\phi \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi, \\
F^\times(\theta, \phi, \psi) &= -\frac{1}{2}(1 + \cos^2\theta)\cos 2\phi \sin 2\psi - \cos\theta \sin 2\phi \cos 2\psi, \\
F^x(\theta, \phi, \psi) &= \sin\theta \left(\cos\theta \cos 2\phi \cos\psi - \sin 2\phi \sin\psi\right), \\
F^y(\theta, \phi, \psi) &= -\sin\theta \left(\cos\theta \cos 2\phi \sin\psi + \sin 2\phi \cos\psi\right), \\
F^b(\theta, \phi) &= -\frac{1}{2}\sin^2\theta \cos 2\phi, \\
F^\ell(\theta, \phi) &= \frac{1}{2}\sin^2\theta \cos 2\phi.
\end{aligned}$$



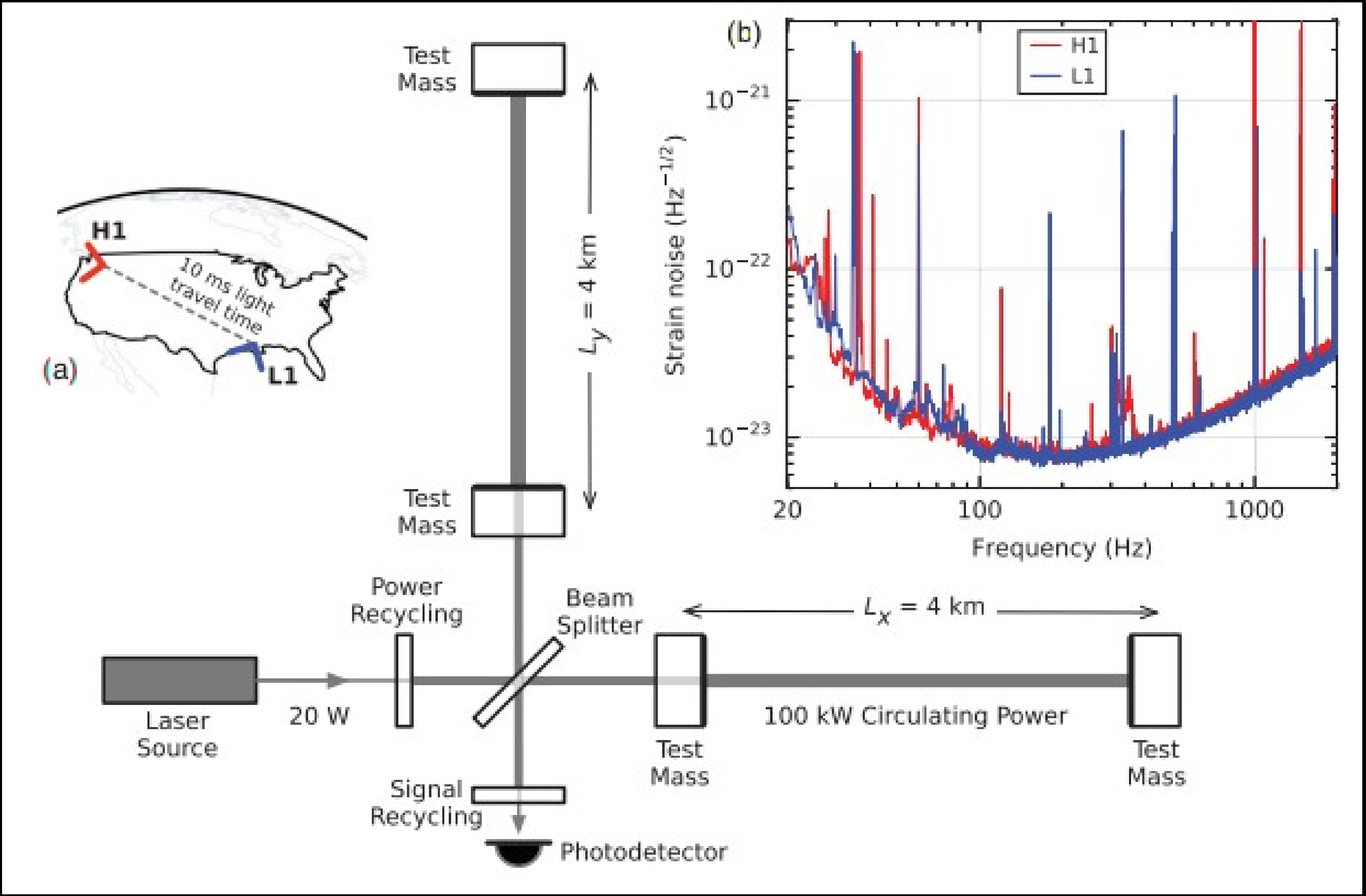


ΔL is null, so is the response of the detector to the wave


"plus" polarization
"plus" polarization

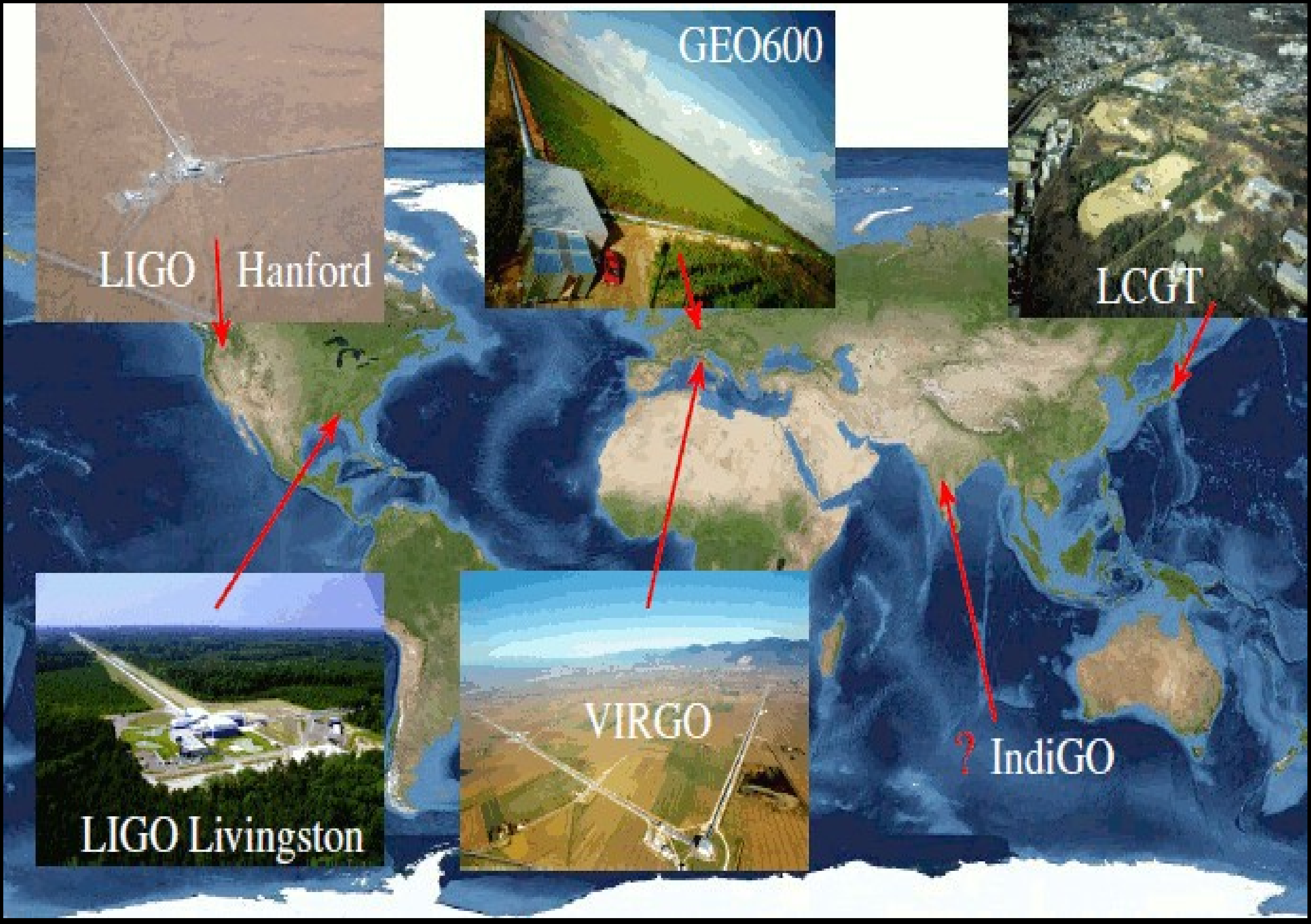
To see relative variations of 10^{-22}, we need a long interferometer…
a really long one!


SS12
SS12
Pisa
Chiesa di Santa
Maria della Spina
Safestay Pisa Ho
Via Bonanno Pisano
SS1
SS1



Interferometers are huge microphones. Contrary to telescopes, that are the equivalent to eyes and are pointed in the deserved direction, interferometers are huge ears, sensitive in all directions.

Network of ground based interferometers



What did LIGO see on September 14 2015?

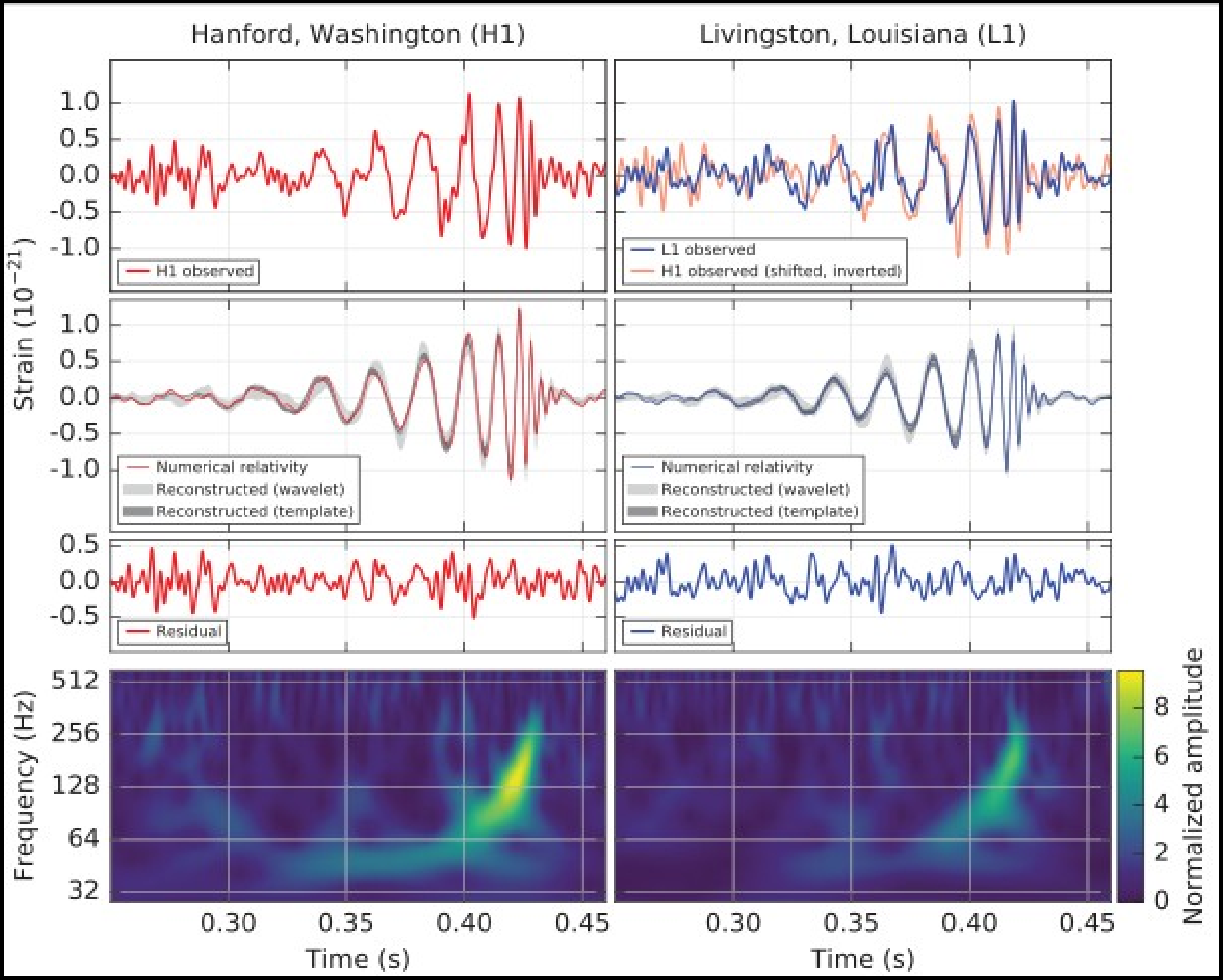
Long time ago (~1 billion years) in a galaxy far away (~1 billion light years) …

One billion years later on Earth….

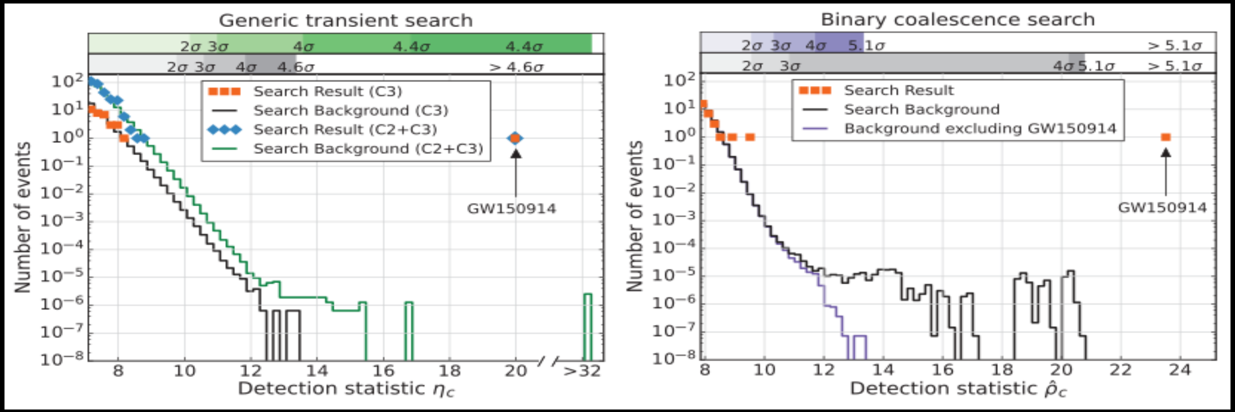
As the signal passes through the LIGO arms...

This is what LIGO saw, or I should say heard

Making history: 14 September 2015



On September 14 2015, the two LIGO detectors observed a coincident signal of 0.2 seconds



The signal was so strong that it was immediately recognized by the 'detection pipelines'

Nominal S/N: 24
Significance: 5.1σ

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 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^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ 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

The Physical Review Letters server registered more than 100000 accesses following the announcement.

Server crashed!

la Repubblica

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ANNO 41 - N. 36 · IN ITALIA € 2,00 con il Venerdì · VENERDÌ 12 FEBBRAIO 2016

R2/LA COPERTINA
Parigi ore 8, lezione di laicità a scuola per combattere fanatismo e terrore
ANAIS GINORI E EDGAR MORIN

R2/LA CULTURA
City on fire, lo strano caso del bestseller mancato
SARA GRATTOGGI

R2/GLI SPETTACOLI
L'annunciatrice diventa avatar addio ai mezzibusti del tiggì
ALDO FONTANAROSA E CARLO PICOZZA

Il grande caos delle Borse Ue, Juncker gela Renzi

> Milano perde il 5,6 %. Fed: pronti a tassi negativi. Petrolio, l'Opec si muove

ROMA. Una ondata di vendite travolge le Borse mondiali. In Asia, in Europa, negli Stati Uniti domina il segno meno. I mercati europei soffrono più degli altri. A Milano Piazza Affari chiude in rosso, a -5,63%. I titoli bancari sono bersagliati. Il petrolio cala, ai minimi da dodici anni. Lo spread tocca quota 160, prima di ripiegare. Janet Yellen, presidente della Federal Reserve, la banca centrale americana, annuncia che l'ipotesi «di tassi negativi» non è da escludere. Intanto, il giorno dopo la lettera del premier Matteo Renzi a *Repubblica*, il presidente della Commissione europea Jean-Claude Juncker risponde: non ci chieda altro, Bruxelles non intende cambiare rotta.

D'ARGENIO, GRECO, MASTROBUONI, POLIDORI E PULEDDA DA PAGINA 2 A PAGINA 6

IL VERTICE
"Cessate il fuoco in una settimana" Siria, prima intesa

ROMA. Primo accordo sulla Siria raggiunto nella notte al vertice di Monaco di Baviera. L'intesa prevede la cessazione delle ostilità entro una settimana e aiuti umanitari da subito. Resta il clima teso. Intanto, contro la lotta ai trafficanti sulle coste turche si mobilita anche la Nato.

BADUEL, DEL RE E NIGRO ALLE PAGINE 10 E 11

L'ANALISI
Il dilemma di Usa e Russia

BERNARDO VALLI

NULLA è definitivo nell'affollata guerra siriana, come non lo è attorno a un tavolo di giocatori incalliti. Dove, a tratti, i prepotenti, i virtuosi del bluff, hanno la meglio, nell'attesa che si concluda la partita. Quella in corso nella valle del Tigri e dell'Eufrate non è certo finita. La Russia di Putin è tuttavia al momento in grande vantaggio. È una svolta nel conflitto. Scesa in campo non ultima, ma soltanto di recente con un grande dispiegamento di forze, essa umilia in questa fase la coalizione guidata dalla super potenza americana, esitante e quindi nella scomoda posizione di chi subisce.

SEGUE A PAGINA 31

L'INTERVISTA

Parla Schulz "Bene la spinta di Matteo all'Europa serve più ambizione"

ANDREA BONANNI

A PAGINA 6

LO SCENARIO
Deflazione, il mondo sotto zero

DAL NOSTRO CORRISPONDENTE FEDERICO RAMPINI

NEW YORK

NELL'ELENCO di tutte le cose che vanno giù — le Borse, il petrolio, la fiducia degli investitori — oggi bisogna aggiungerne un'altra: il morale dei banchieri centrali. Dalla Federal Reserve alla Bce, dalla banca centrale del Giappone a quella della Cina, l'impotenza è il dato comune.

SEGUE A PAGINA 4

L'INTERVENTO DI BAGNASCO. BAGARRE AL SENATO PER UN BACIO GAY
I vescovi: voto segreto sulle unioni Il governo: non è la Cei a decidere

ROMA. Nuove tensioni sulla legge sulle unioni civili, in discussione al Senato. Il cardinale Angelo Bagnasco, presidente della Cei, interviene a favore del voto segreto. «Ci auguriamo che la libertà di coscienza su temi fondamentali per la vita della società e delle persone sia non solo rispettata, ma anche promossa con una votazione a scrutinio segreto», dichiara. Replica il sottosegretario ai Rapporti con il Parlamento, Luciano Pizzetti: «Le esortazioni sono giuste, ma come regolare il dibattito del Senato lo decide il presidente del Senato. Non il presidente della Cei». Bagarre a Palazzo Madama per un bacio gay.

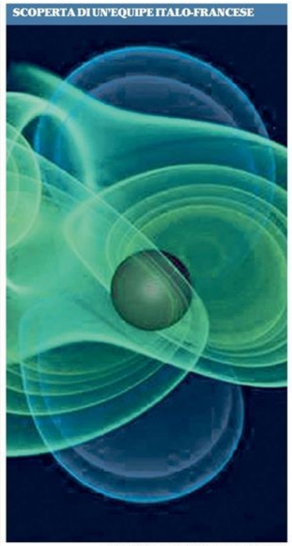
CASADIO, CIRIACO E DE MARCHIS ALLE PAGINE 8 E 9

IL PUNTO
STEFANO FOLLI
Un confine da rispettare

Il presidente della Cei, cardinale Bagnasco, ha superato la linea sottile che separa il diritto della Chiesa di esprimere valutazioni, esortazioni e moniti in assoluta libertà, specie su questioni etiche, dalla vera e propria ingerenza in questioni che riguardano solo il Parlamento.

SEGUE A PAGINA 31

SCOPERTA DI UN'EQUIPE ITALO-FRANCESE



AMELINO-CAMELIA E FRAIOLI ALLE PAGINE 22 E 23

Ecco lo tsunami della gravità Einstein vince 100 anni dopo

GIOVANNI BIGNAMI

L'AFFASCINANTE paradosso dell'Universo è che è tenuto insieme, anzi dominato, dalla forza più debole che ci sia: la gravità.

SEGUE A PAGINA 31

IL REPORTAGE
Nel cuore di Virgo a caccia di onde

ELENA DUSI A PAGINA 23

BIANCO STILE LAUDA
I colori della Ferrari tornano alla leggenda

MARCO MENSURATI

REPUBBLICA è in grado di pubblicare le bozze ufficiali — made in Maranello — della livrea che la Ferrari presenterà al mondo intero il prossimo 19 febbraio in un evento molto atteso.

SEGUE A PAGINA 50

PASTICCIO SUI RISULTATI
Ma che bel Sanremo se ci fossero le canzoni

NATALIA ASPESI

UN festival della Canzone dovrebbe essere fatto di canzoni, e magari di cantanti, non di vestiti, di stranezze, di pietismi e di comiche (in questo caso la Raffaele è simpatica).

SEGUE A PAGINA 30. SERVIZI ALLE PAGINE 46 E 47

SEDE: 00147 ROMA, VIA CRISTOFORO COLOMBO, 90 - TEL. 06/49821, FAX 06/49822923. SPED. ABB. POST., ART. 1, LEGGE 46/04 DEL 27 FEBBRAIO 2004 - ROMA. CONCESSIONARIA DI PUBBLICITÀ: A. MANZONI & C. MILANO - VIA NERVESA, 21 - TEL. 02/574941. PREZZI DI VENDITA: AUSTRIA BELGIO FRANCIA GERMANIA LUSSEMBURGO MONACO P. OLANDA PORTOGALLO SLOVENIA SPAGNA € 2,00 MALTA € 2,20 GRECIA € 2,50 CROAZIA KN 15 REGNO UNITO LST 1,80 REPUBBLICA CECA CZK 64 SLOVACCHIA SKK 80/€ 2,66 SVIZZERA FR 3,00 UNGHERIA FT 650

"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXV . . . No. 57,140 + · © 2016 The New York Times · NEW YORK, FRIDAY, FEBRUARY 12, 2016 · $2.50

Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by bashing his past criticism of President Obama — a remark that Mr. Sanders called a "low blow."

With tensions between the two Democrats becoming increasingly obvious, the debate was full of new lines of attack from Mrs. Clinton, who faces pressure to puncture Mr. Sanders's growing popularity before the next nominating contests in Nevada and South Carolina.

She is wagering that even voters excited by Mr. Sanders's inspiring message will reconsider their support when they learn of his lack of experience in foreign policy and his vague explanations for how he will pay for his expansive government programs.

Mrs. Clinton pounced from the start, after Mr. Sanders demurred in saying how much his proposals would increase the size of the federal government. She stepped in and said that by economists' estimates, the government would grow 40 percent under Mr. Sanders.

And rather than bashing him as she did at their debate last Thursday, she appeared to try to get under his skin by implying that he had not been transparent about the cost of his programs, such as his proposed expansion of government health care.

"This is not about math. This is

Continued on Page A16

Going Back to Trenton

Gov. Chris Christie has returned to New Jersey to tend to a state he at times abandoned in his run for president. Page A21.

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

Long in Clinton's Corner, Blacks Notice Sanders

Courted Hard in South Carolina, Loyalists Listen Closely

By RICHARD FAUSSET

ORANGEBURG, S.C. — When Helen Duley was asked whom she would vote for in the South Carolina primary, she answered as if the very question were absurd.

"What I'm seeing is a bunch of confusion, hearsay and foolishness," said Ms. Duley, 60, a retired nursing assistant who is African-American, shortly after finishing breakfast at the downtown McDonald's. "What I also see is a veteran who's already been in the White House eight years. A veteran: Hillary Clinton."

But that was late January. Interviewed again Tuesday as Mrs. Clinton's rival, Senator Bernie Sanders of Vermont, was surging toward an overwhelming victory in the New Hampshire Democratic primary, Ms. Duley found herself suddenly intrigued by a candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an undecided voter and planned to do some homework on Mr. Sanders.

Mrs. Clinton has long looked forward to the Feb. 27 Democratic contest in South Carolina, the first state where blacks will make up a dominant part of the primary vote. African-Americans accounted for more than half the voters in the 2008 Democratic primary, and she has been counting on them as a bulwark, not just

Continued on Page A18

Reginald Abraham, left, an organizer for Hillary Clinton, at a barbershop in Orangeburg, S.C.

Last Occupier In Rural Oregon Is Coaxed Out

This article is by Dave Seminara, Richard Pérez-Peña and Kirk Johnson.

PRINCETON, Ore. — They implored the last holdout in the armed occupation of a wildlife refuge here to think about the Holy Spirit. They explained that the First Amendment was about freedom of speech and the Second was about the right to bear arms, and said that they were in that order for a reason. They asked him what he thought Jesus would have done in his situation.

He, in turn, asked for pizza and marijuana, criticized a government that condoned abortion and drone strikes, and talked about U.F.O.s and dying rather than going to prison.

In the final moments, a standoff fed by big ideas about the role of government came down Thursday morning to the grievances and fears of one troubled young man, and the tense but successful efforts of his sympathizers and F.B.I. agents to coax him to surrender, ending the occupation of Malheur National Wildlife Refuge in southeastern Oregon.

"I'm actually feeling suicidal right now," said David Fry, 27, of Blanchester, Ohio, the last of the

Continued on Page A21

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most foreboding (and unwelcome) part of his theory.

More generally, it means that a century of innovation, testing, questioning and plain hard work after Einstein imagined it on paper, scientists have tapped into the deepest register of physical reality, where the weirdest and wildest implications of Einstein's universe become manifest.

Conveyed by these gravitational waves, power 50 times greater than the output of all the stars in the universe combined vibrated a pair of L-shaped antennas in Washington State and Louisiana known as LIGO on Sept. 14.

If replicated by future experiments, that simple chirp, which rose to the note of middle C before abruptly stopping, seems destined to take its place among the great sound bites of science, ranking with Alexander Graham Bell's "Mr. Watson — come here" and Sputnik's first beeps from orbit.

"We are all over the moon and back," said Gabriela González of Louisiana State University, a spokeswoman for the LIGO Scientific Collaboration, short for Laser Interferometer Gravitational-Wave Observatory. "Einstein would be very happy, I think."

Members of the LIGO group, a

Continued on Page A12

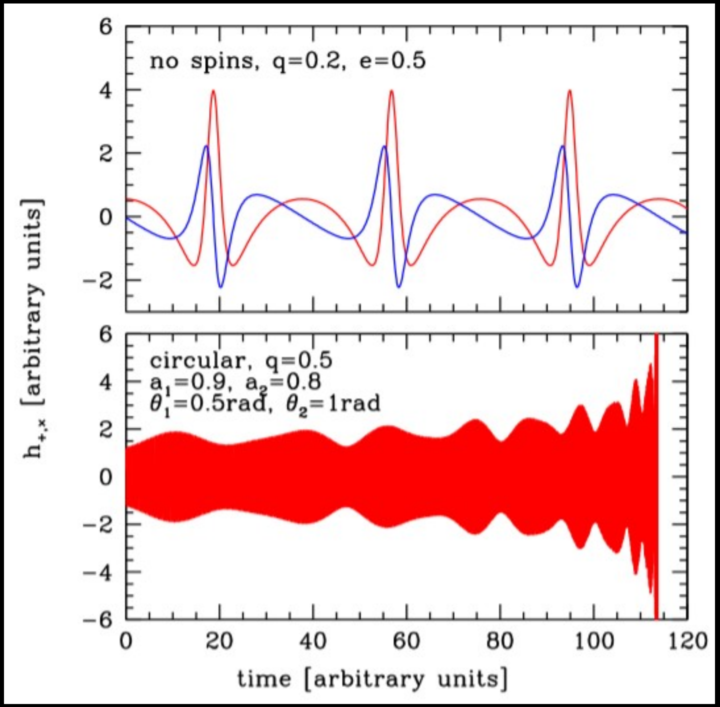
What information do we extract from the signal?

>Masses have great impact and the phase modulation and amplitude of the signal

>Eccentricity has a great impact on the waveform shape and phase modulation

>Spins have an impact on the waveform amplitude (precession) and phase

The precision of the measurement depends on the S/N and on the number of observed cycles



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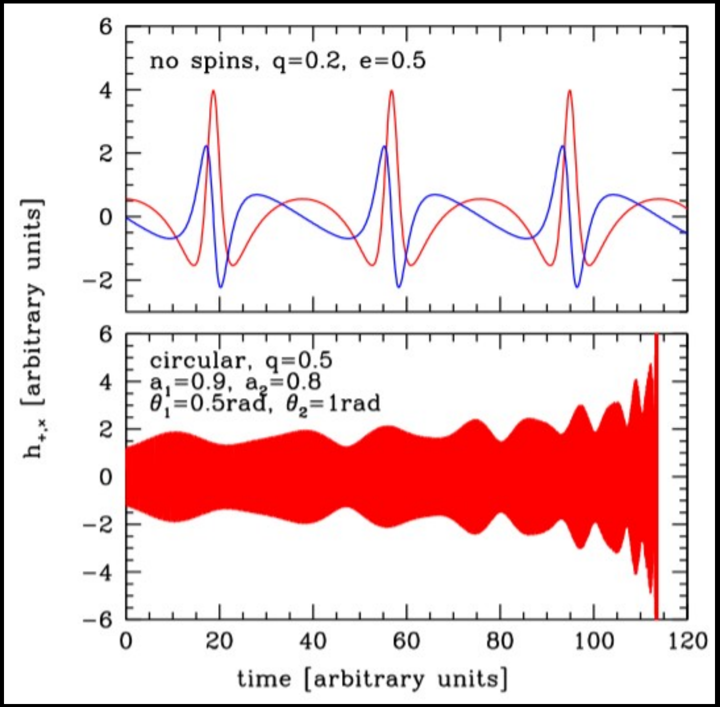

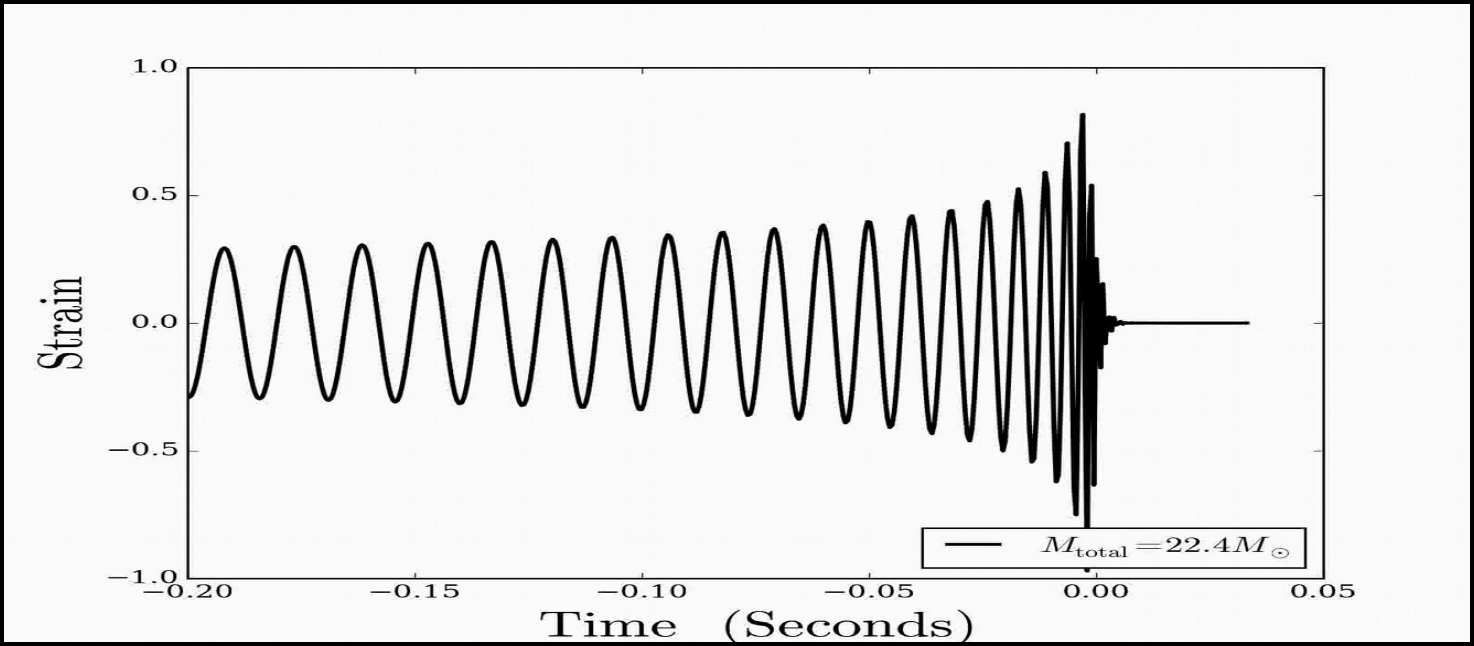

(Courtesy W. del Pozzo)

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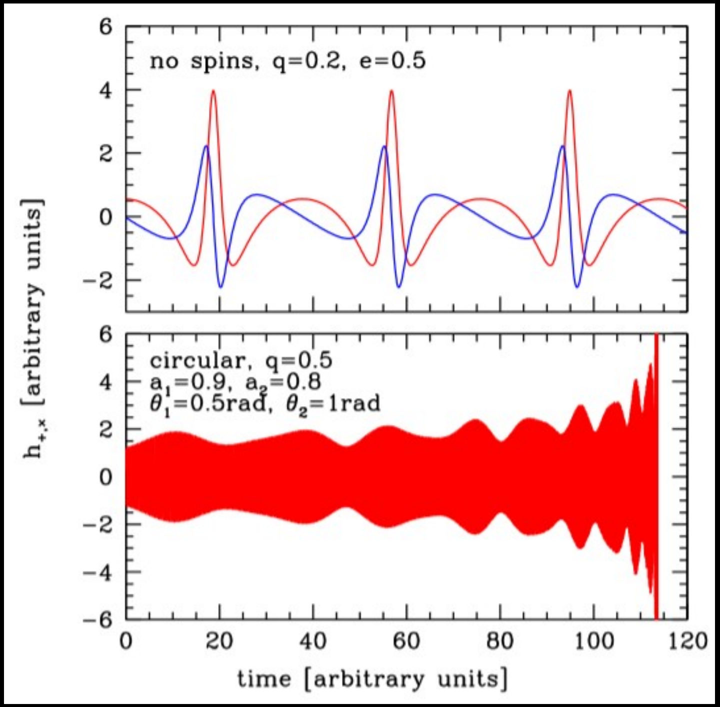

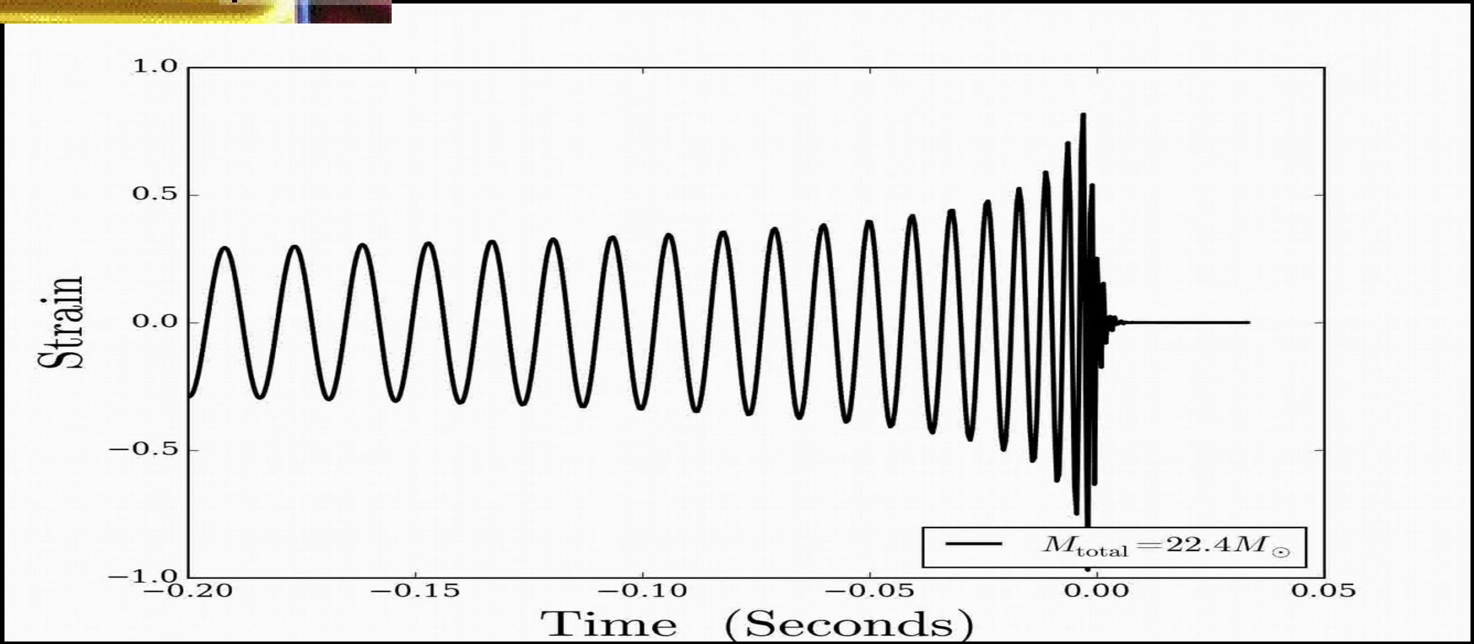

(Courtesy W. del Pozzo)

Source parameter extraction

$$h^{(\iota)}(t) = \frac{\sqrt{3}}{2}\left[F_+^{(\iota)}(t)h_+(t) + F_\times^{(\iota)}(t)h_\times(t)\right]$$

Detected signal: combination of the two wave *polarization amplitude* and the *antenna beam pattern*

$$h_+ = 2\frac{\mathcal{M}^{5/3}}{D_L}\left[1 + \left(\hat{\mathbf{L}}\cdot\hat{\mathbf{N}}\right)^2\right](\pi f)^{2/3}\cos\phi(t),$$

$$h_\times = -4\frac{\mathcal{M}^{5/3}}{D_L}\left(\hat{\mathbf{L}}\cdot\hat{\mathbf{N}}\right)(\pi f)^{2/3}\sin\phi(t),$$

polarization amplitude:
function of the source intrinsic parameters (*M*, *f*), of the source distance D_L, and of the source inclination *i=L•N*

$$F_+(\theta'_N, \phi'_N \psi'_N) = \frac{1}{2}(1+\cos\theta'^2_N)\cos 2\phi'_N\cos 2\psi'_N - \cos\theta'_N\sin 2\phi'_N\sin 2\psi'_N$$

$$F_\times(\theta'_N, \phi'_N \psi'_N) = \frac{1}{2}(1+\cos\theta'^2_N)\cos 2\phi'_N\sin 2\psi'_N + \cos\theta'_N\sin 2\phi'_N\cos 2\psi'_N$$

Antenna pattern:
function of the relative source-detector orientation. Depends on: souce sky location and polarization (θ φ ψ)

$$\phi(f) = \phi_c - \frac{1}{16}(\pi f\mathcal{M})^{-5/3}\left[1 + \frac{5}{3}\left(\frac{743}{336} + \frac{11}{4}\eta\right)(\pi M f)^{2/3} - \frac{5}{2}(4\pi - \beta)(\pi M f) + 5\left(\frac{3058673}{1016064} + \frac{5429}{1008}\eta + \frac{617}{144}\eta^2 - \sigma\right)(\pi M f)^{4/3}\right];$$

Phase evolution:
depends on the system masses and spins and eccentricity (M_1,M_2,a_1,a_2,e)

The full waveform for an eccentric spinning binary depends on *17 parameters*. Each of them leave a peculiar imprint in the waveform amplitude and phase.

>The position in the sky is essentially measured via triangulation
two interferometers → poor performance

>Distance is measured from the waveform amplitude (but is degenerate with sky position and orbit inclination)

The accuracy of the measurement depends on the number of interferometers and on the possibility of disentangle the two wave polarizations

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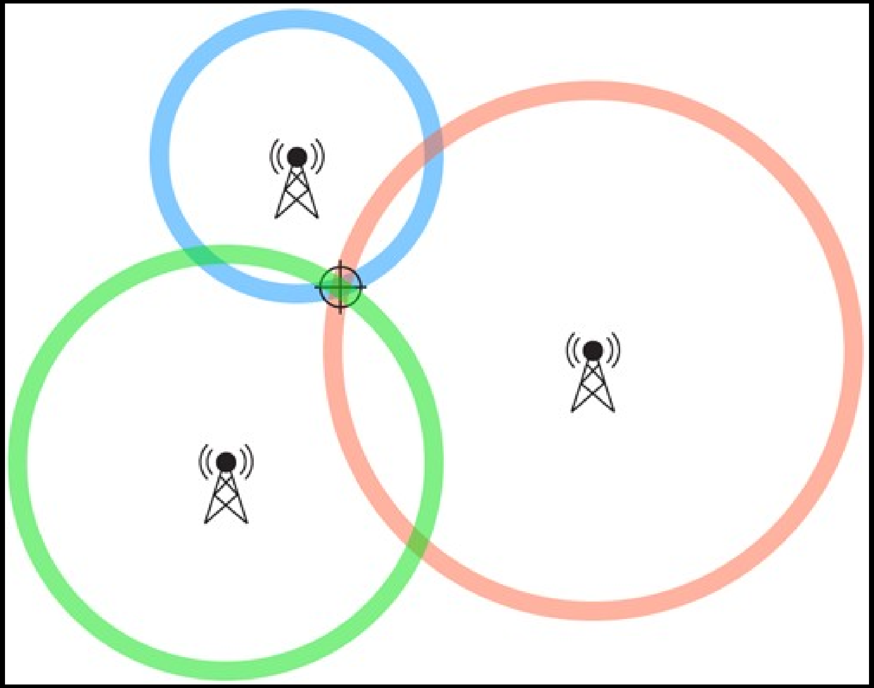

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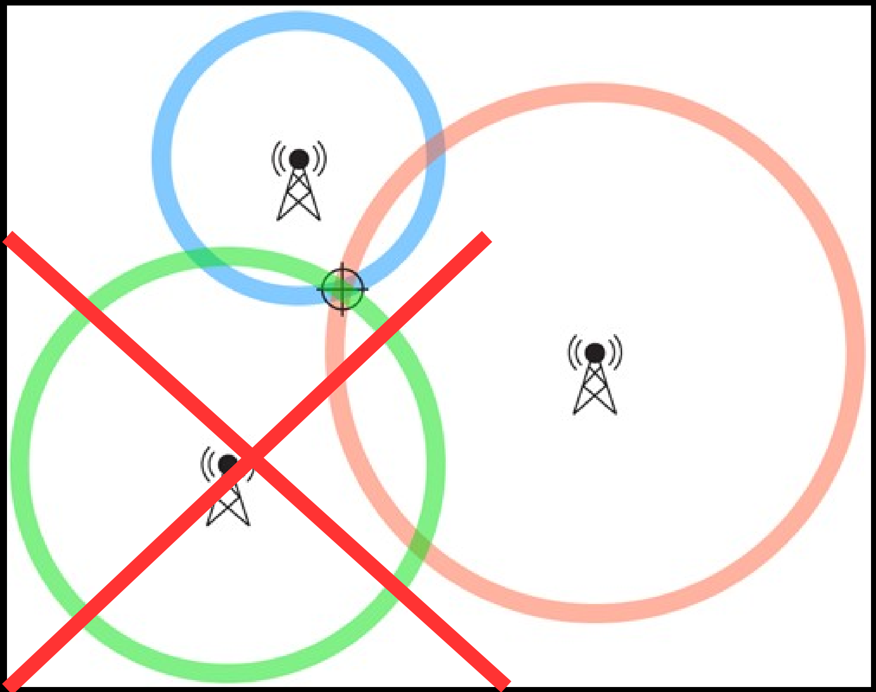
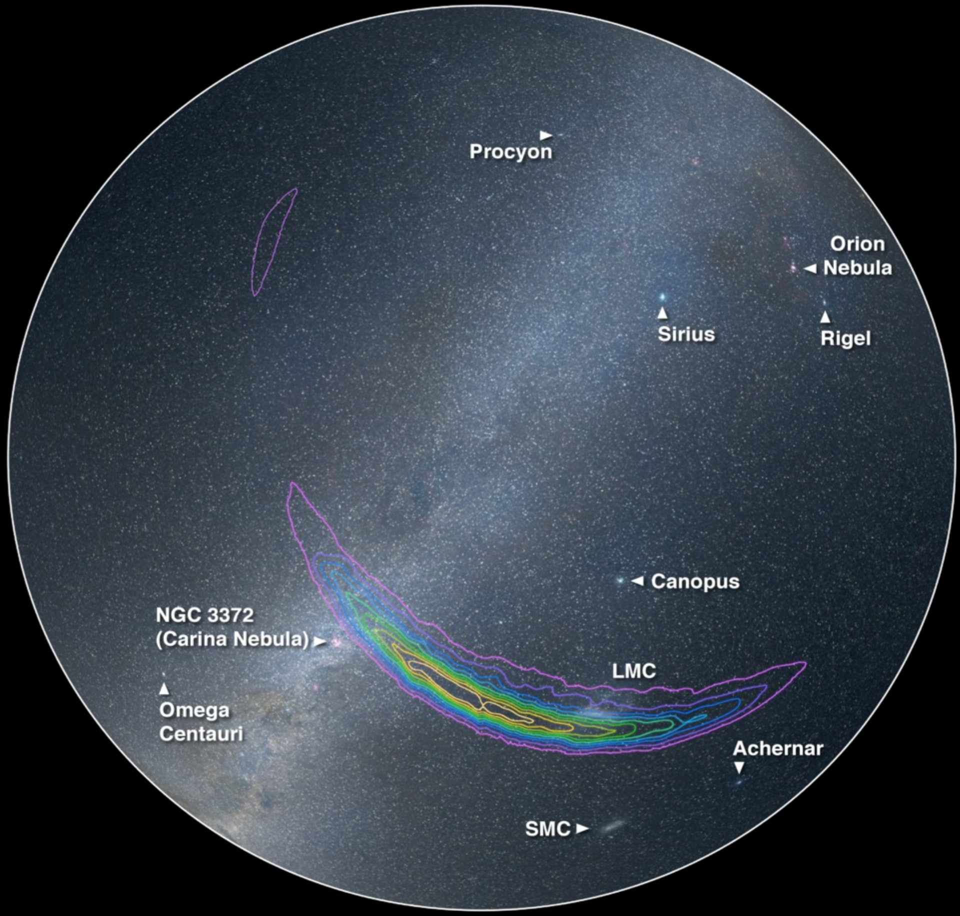
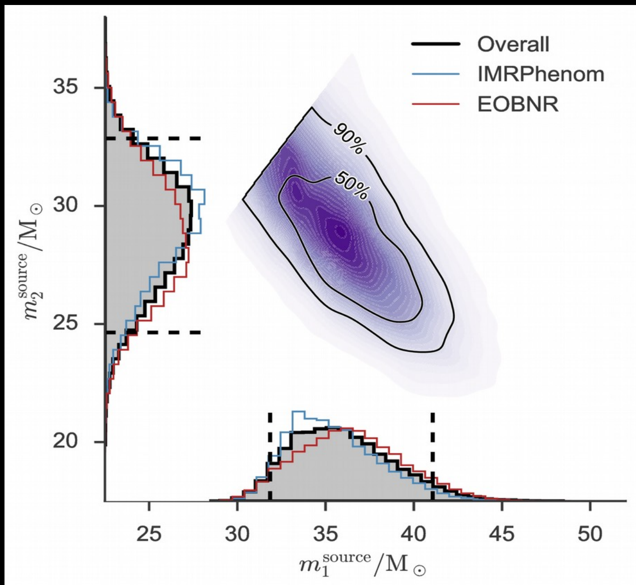
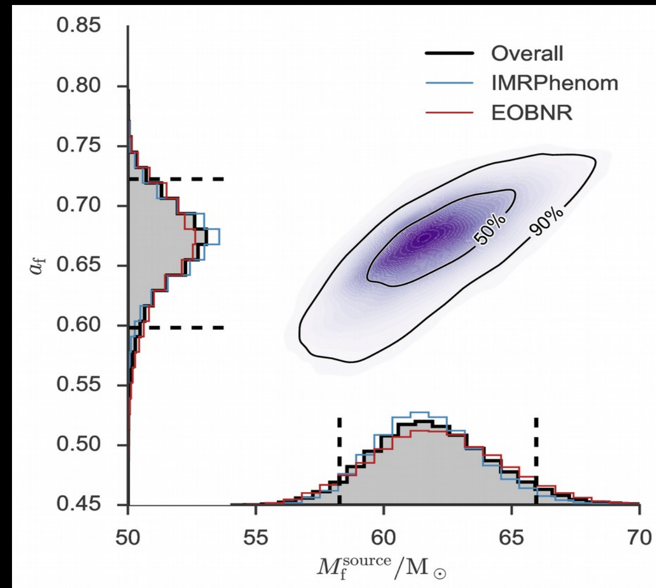
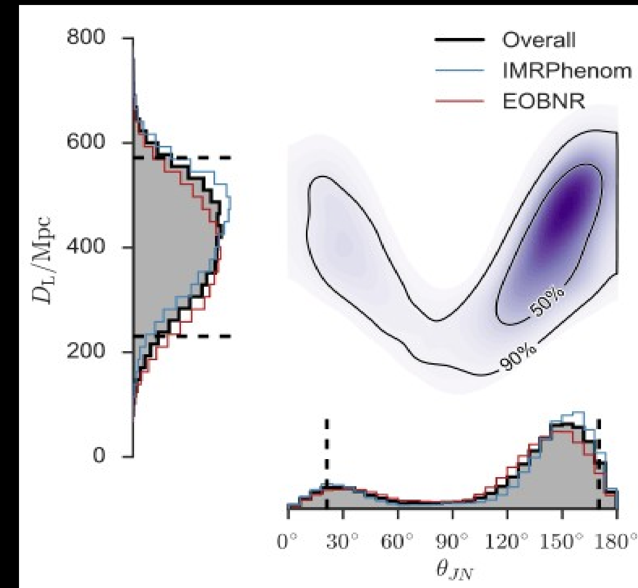


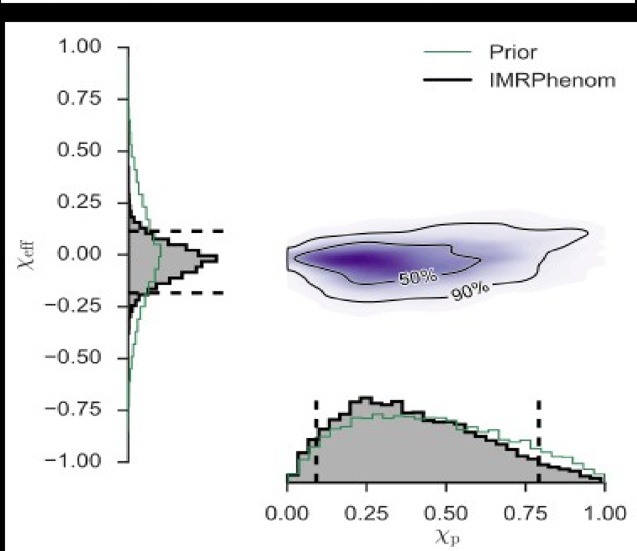


GW150914 (astro)physical properties









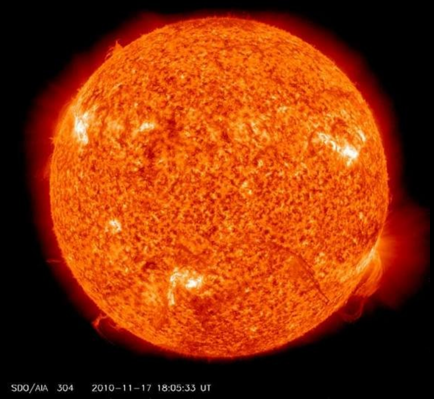
$$\chi_{\rm p} = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0$$

$$\chi_{\rm eff} = \frac{c}{G}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\hat{\boldsymbol{L}}}{M},$$

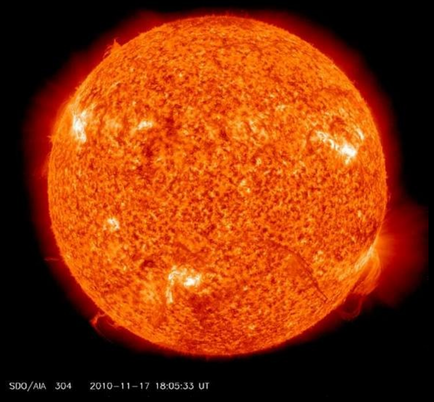
The signal comes from the coalescence of two black holes

-Masses M_1=36M$_\odot$ M_2=29M$_\odot$ M_f=62M$_\odot$
-Distances D=400Mpc, z=0.09
-Small spins
-Small eccentricity

The system irradiated 3 solar masses worth of energy in gravitational waves with a peak luminosity of L~3x10^{56}erg/s



x30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x30


Lago
Maggiore
Chiavenna
Varese
Lecco
Como
Cantù
Milano
Monza
Novara
Crema
Vigevano
Lodi
Pavia
Voghera
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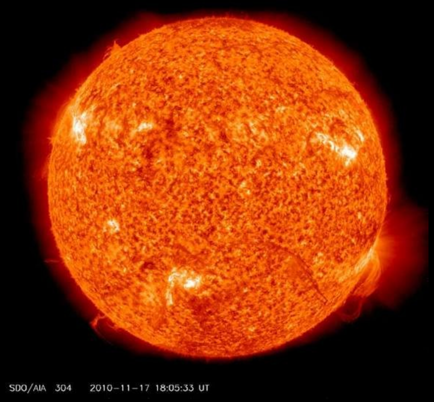
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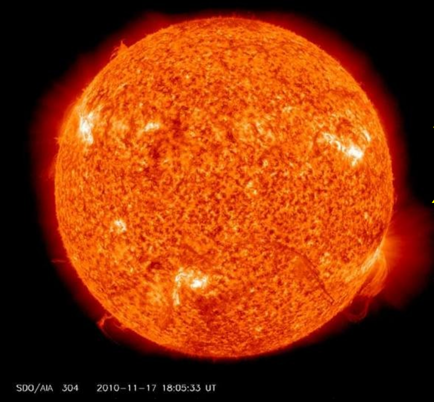
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Lodi
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Piacenza
Alessandria


Livigno
Bormio
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Temù
Iseo
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Lago di Garda
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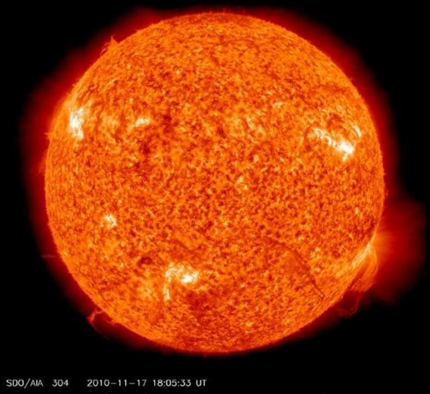
Sirmione
Verona
Cremona
Mantova
Gonzaga



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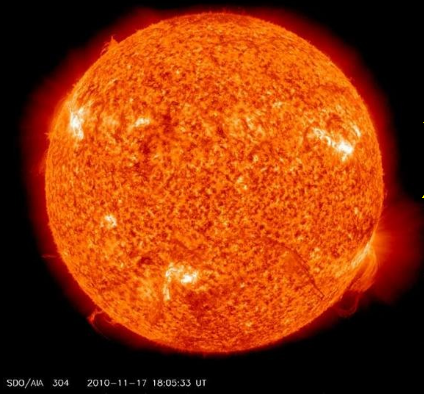


x30

v~200000 km/s

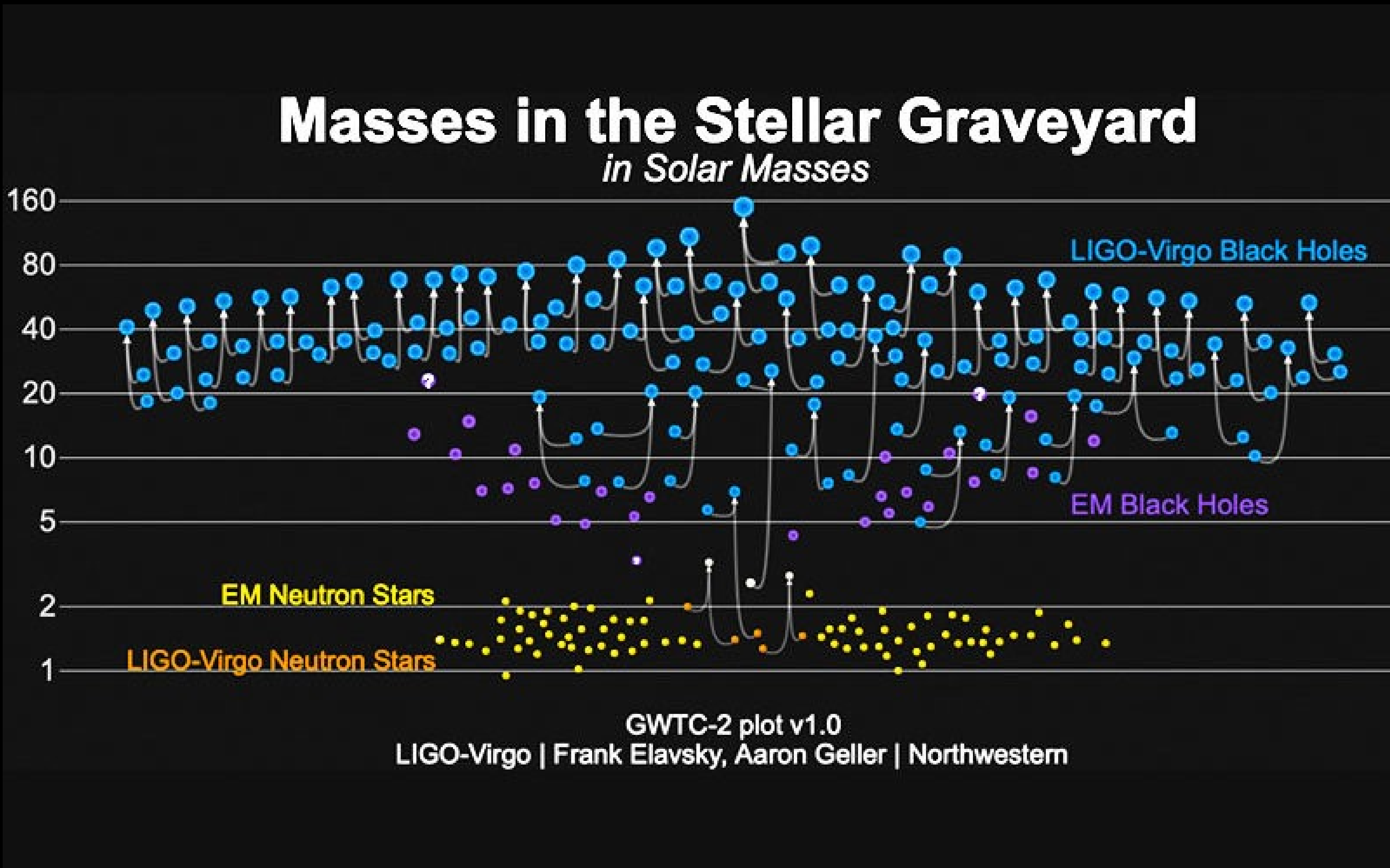
GW150914

First direct observation of gravitational waves

First direct observation of black holes

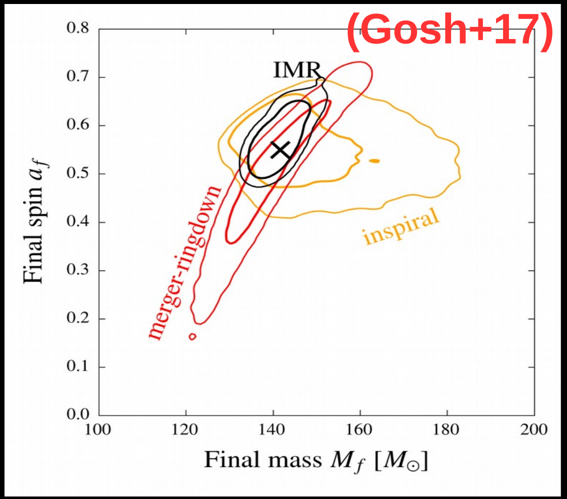
First direct observation of a black hole binary

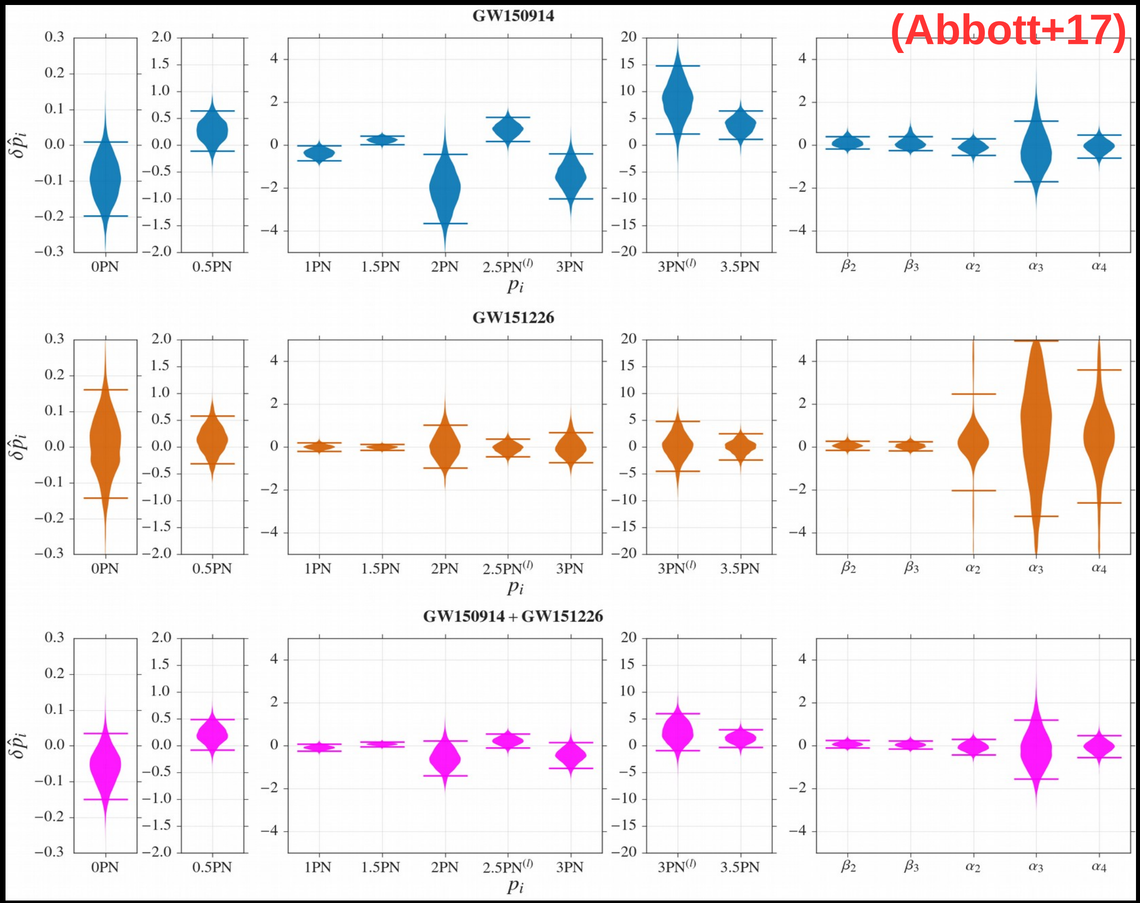
First test of General Relativity in the strong field regime

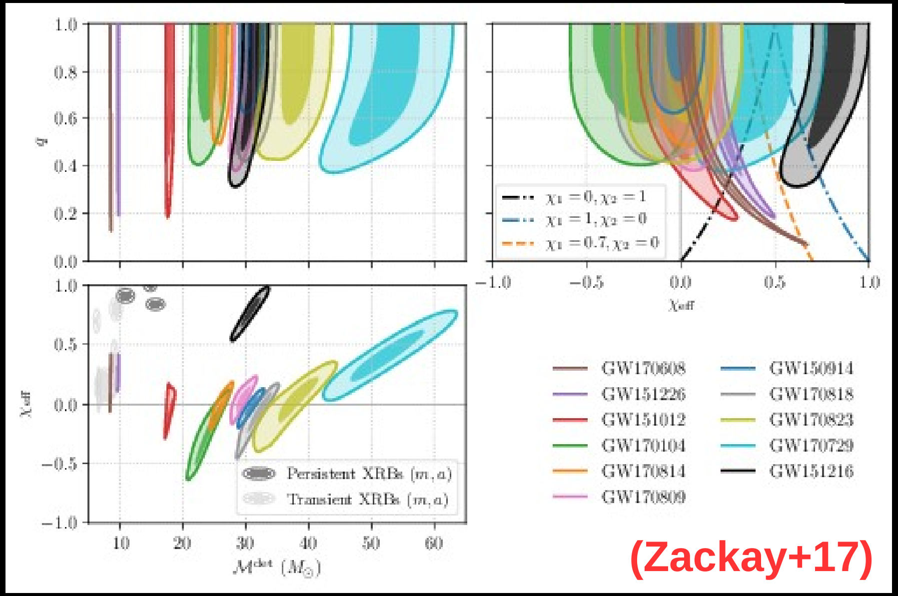

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Learning from BHBs

We'we seen black hole binaries (BHBs) coalescing for the first time (Abbott+ 2016 2017...)







- -First tests of GR in the strong field regime
- -Interesting astrophysical information (masses, spins)

→ Formation scenario?

2017 NOBEL PRIZE IN PHYSICS

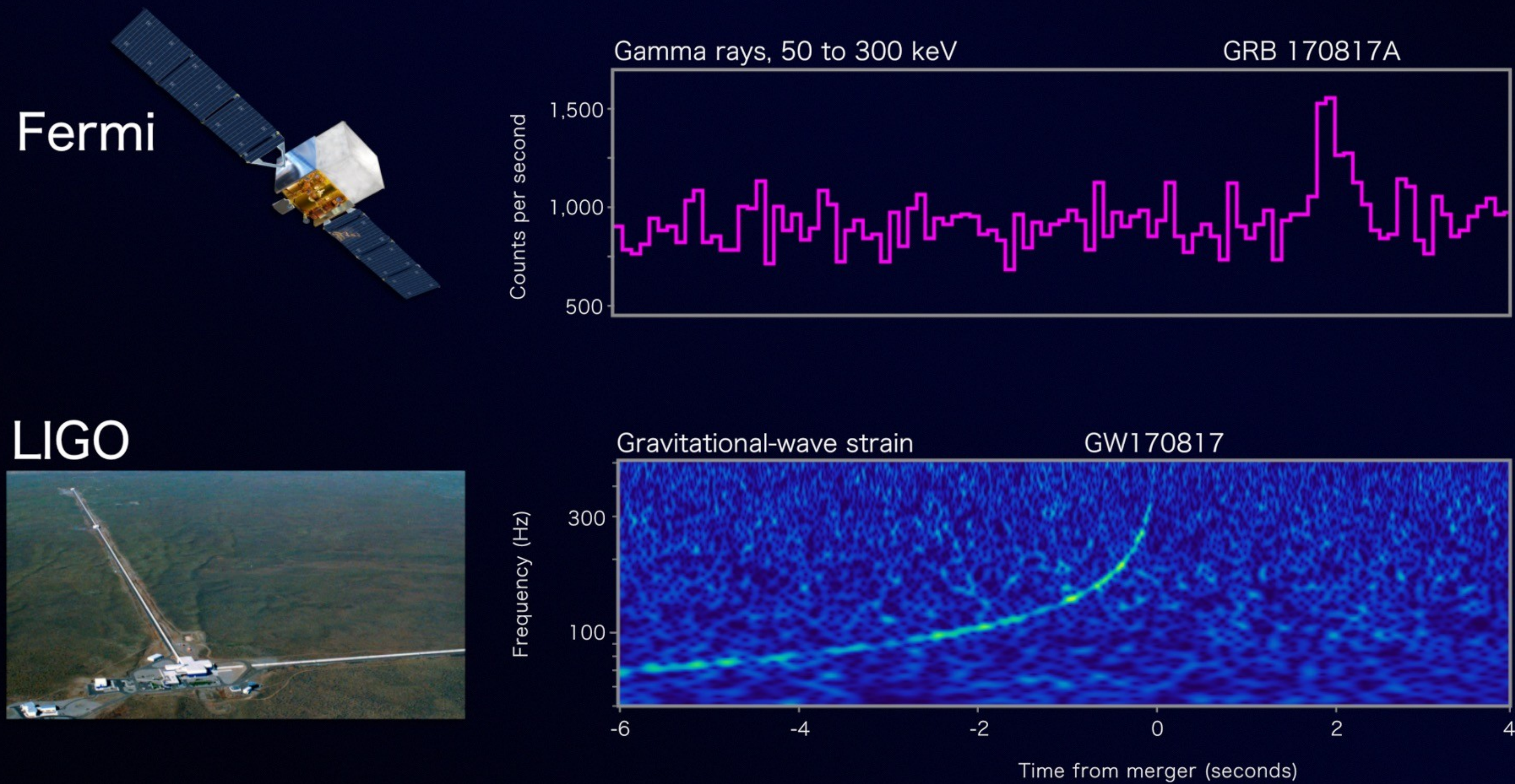
Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

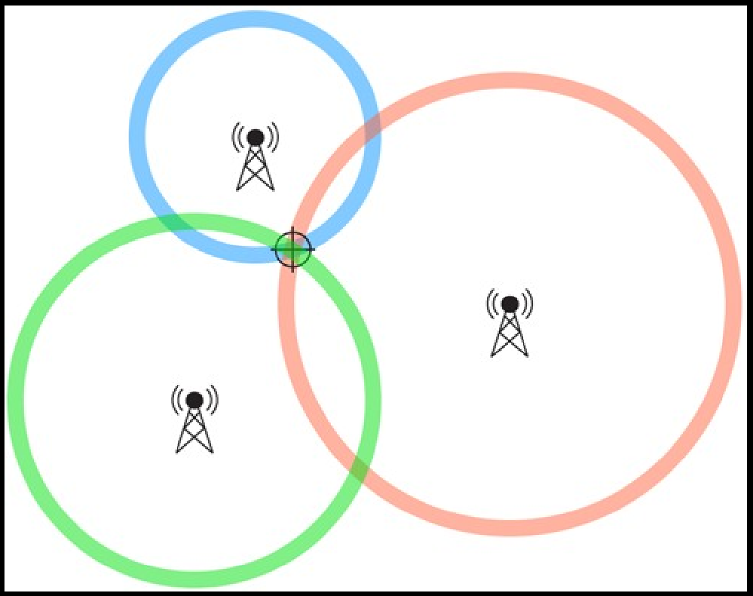
August 17 2017….

Both LIGO detectors observed a clear signal

The Gamma-ray detector Fermi, independently observed a burst 1.7 seconds after the end of the LIGO signal

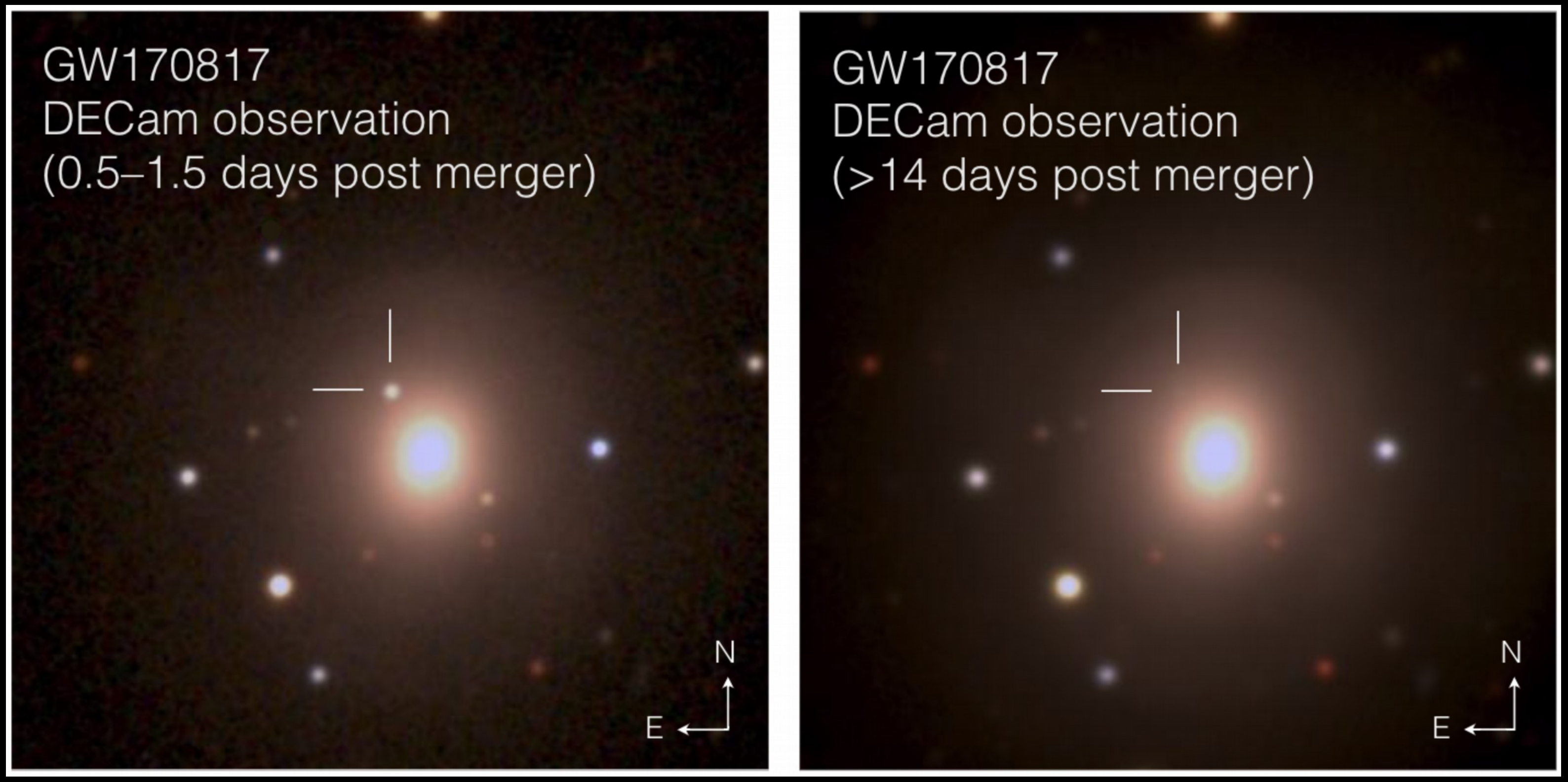


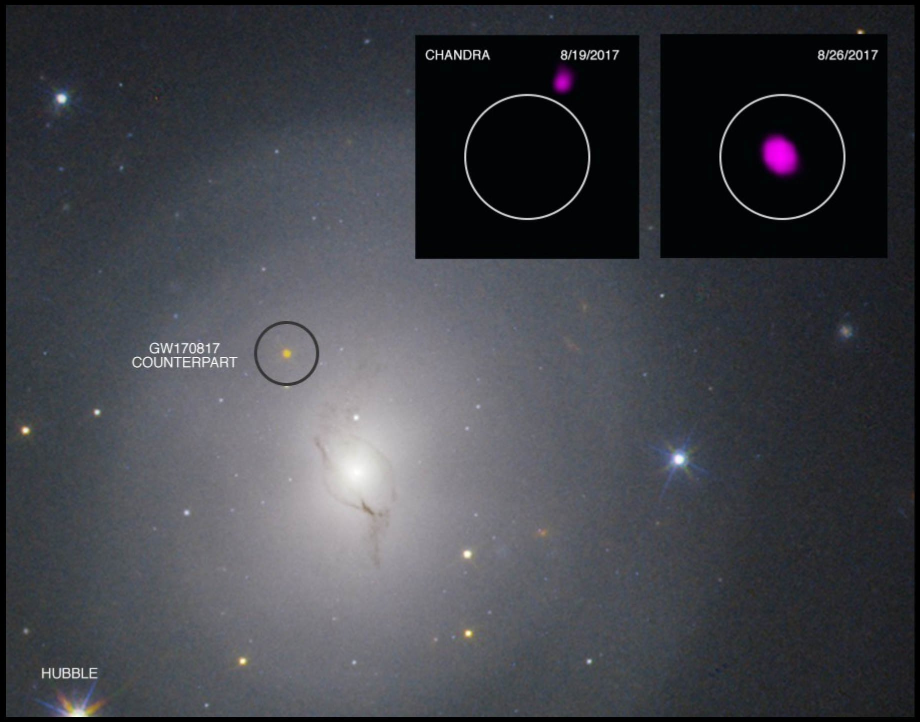
Triangulation using the LIGO-Virgo detectors allowed a decent sky localization of the signal



Alerts are sent out to observatories around the world: the hunt begins!

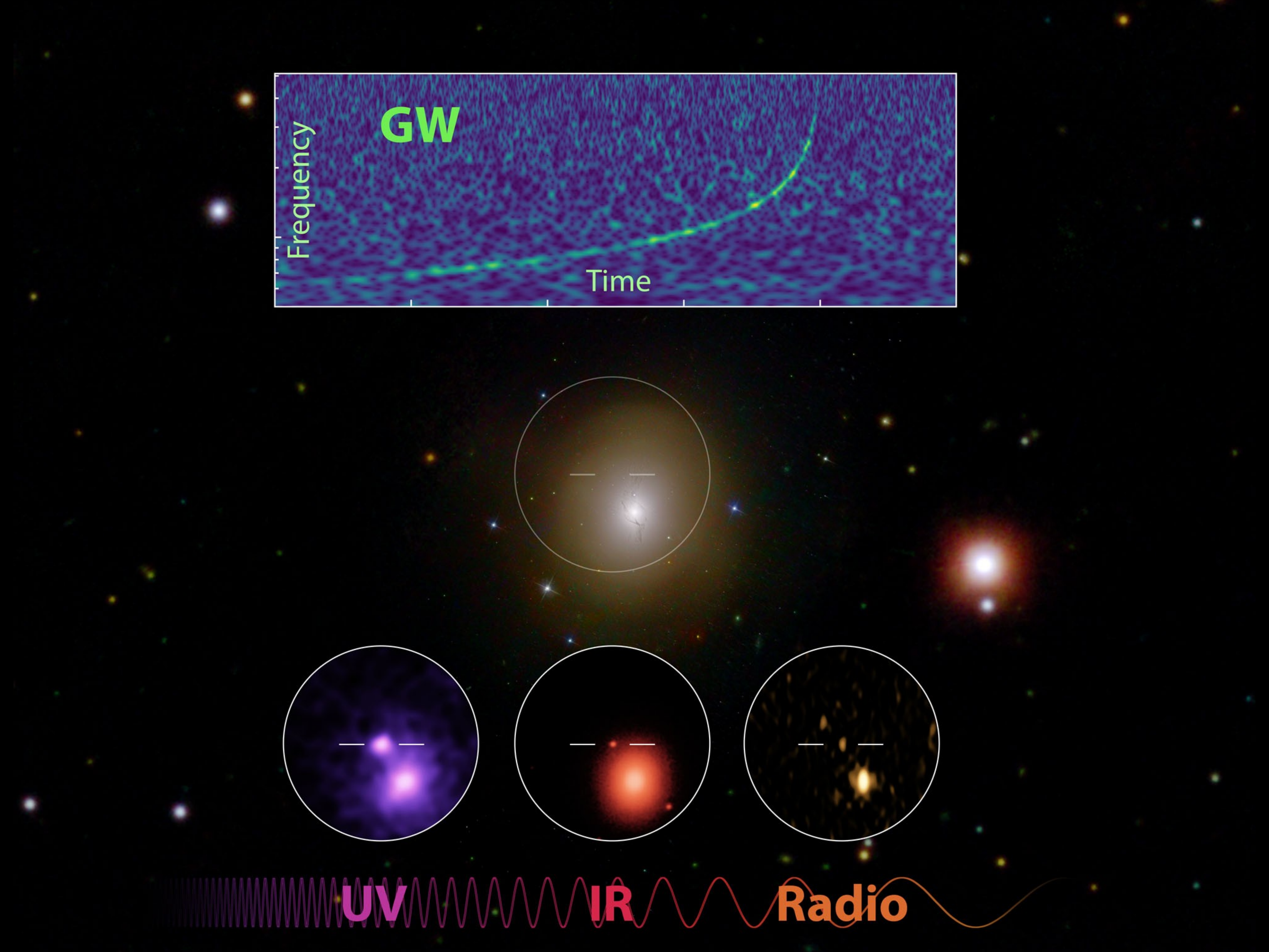
Credit: LIGO/Virgo/NASA/Leo Singer





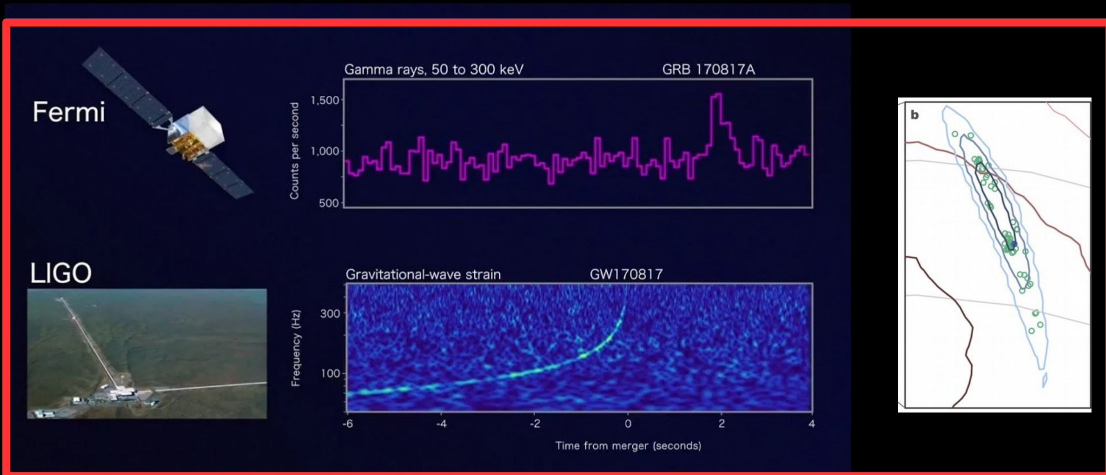
12 h later a counterpart was found! First in optical, then at all wavelengths.

The event occurred in the outskirts of NGC4993, an otherwise boring galaxy at 40 megaparsecs from us.


GW
Frequency
Time
UV
IR
Radio

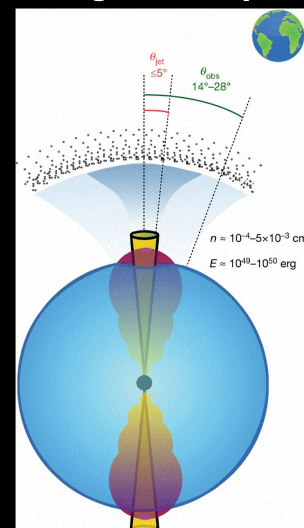
A unique event

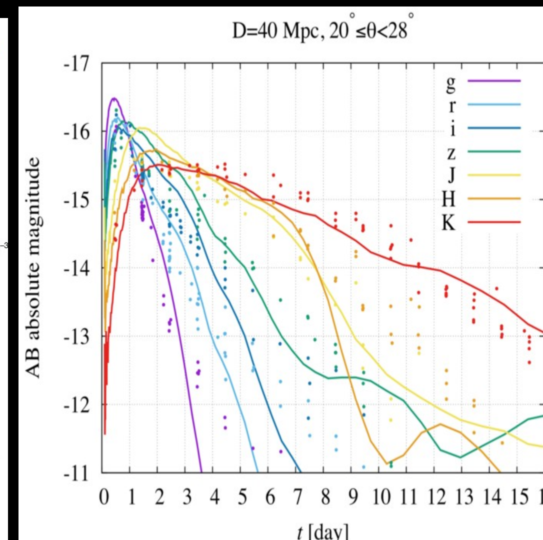
We've seen a merging neutron star (NS) binary GW170817 (Abbott+ 2017 2018)

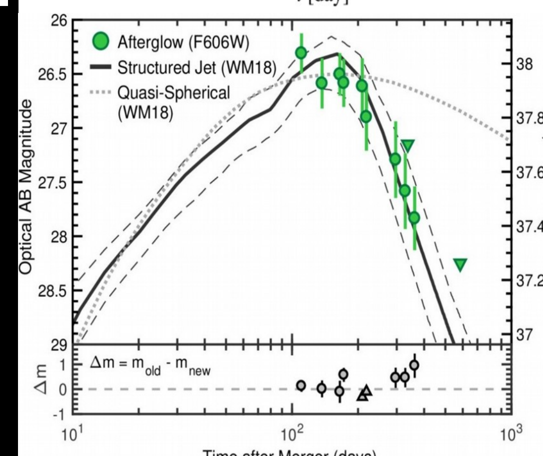


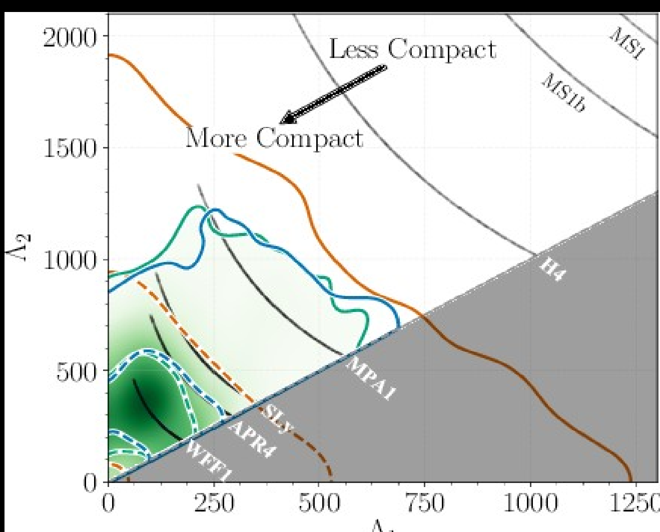
- -Confirm GRB – BNS merger connection
- -Kilonova from radioactive decay
- -Heavy element production
- -Structured jet launching and emergence

(Kawaguchi+18, Mooley+19, Ghirlanda+19, Fong+19, ….)





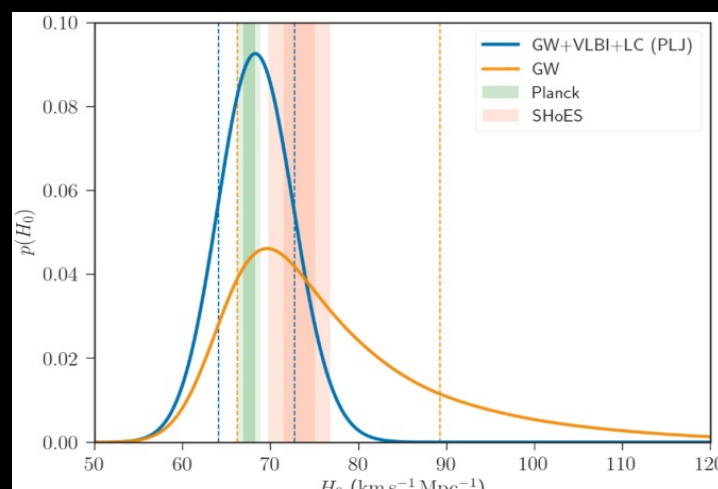




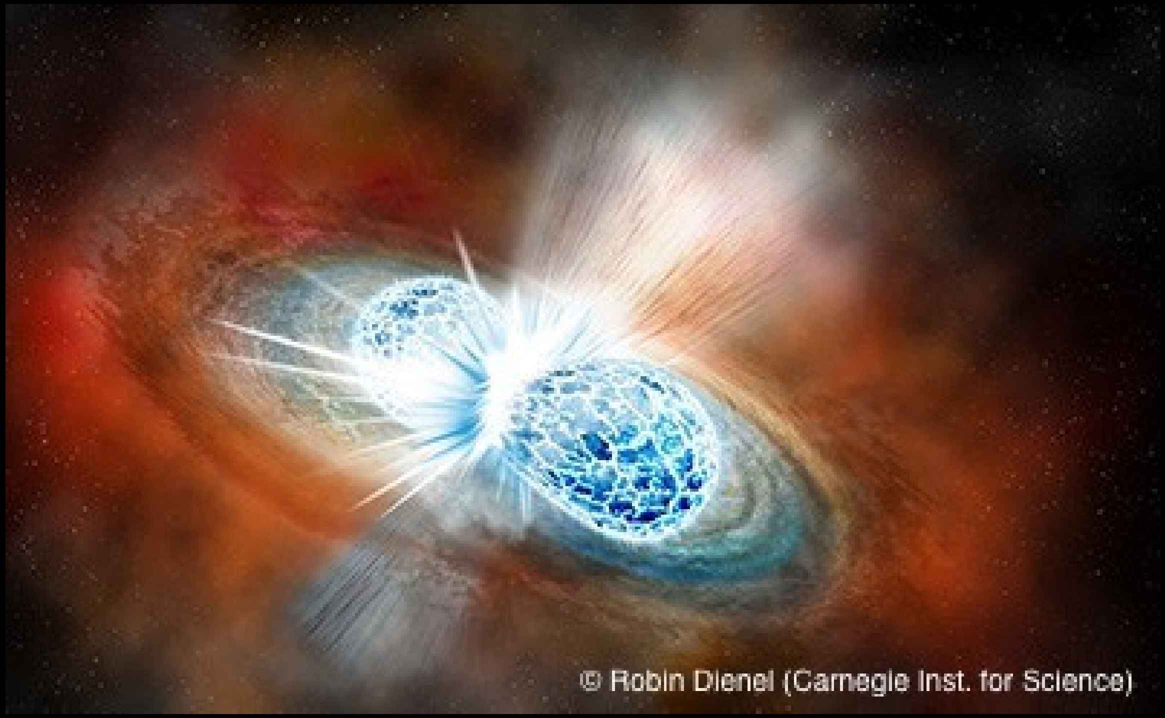
Constraints on the NS EoS from tidal deformability

(Abbott+18, ...)

First GW measurement of the Hubble constant



(Abbott+18, Hotokezaka+18...)



For the first time we observed an astrophysical event both in gravitational and electromagnetic waves

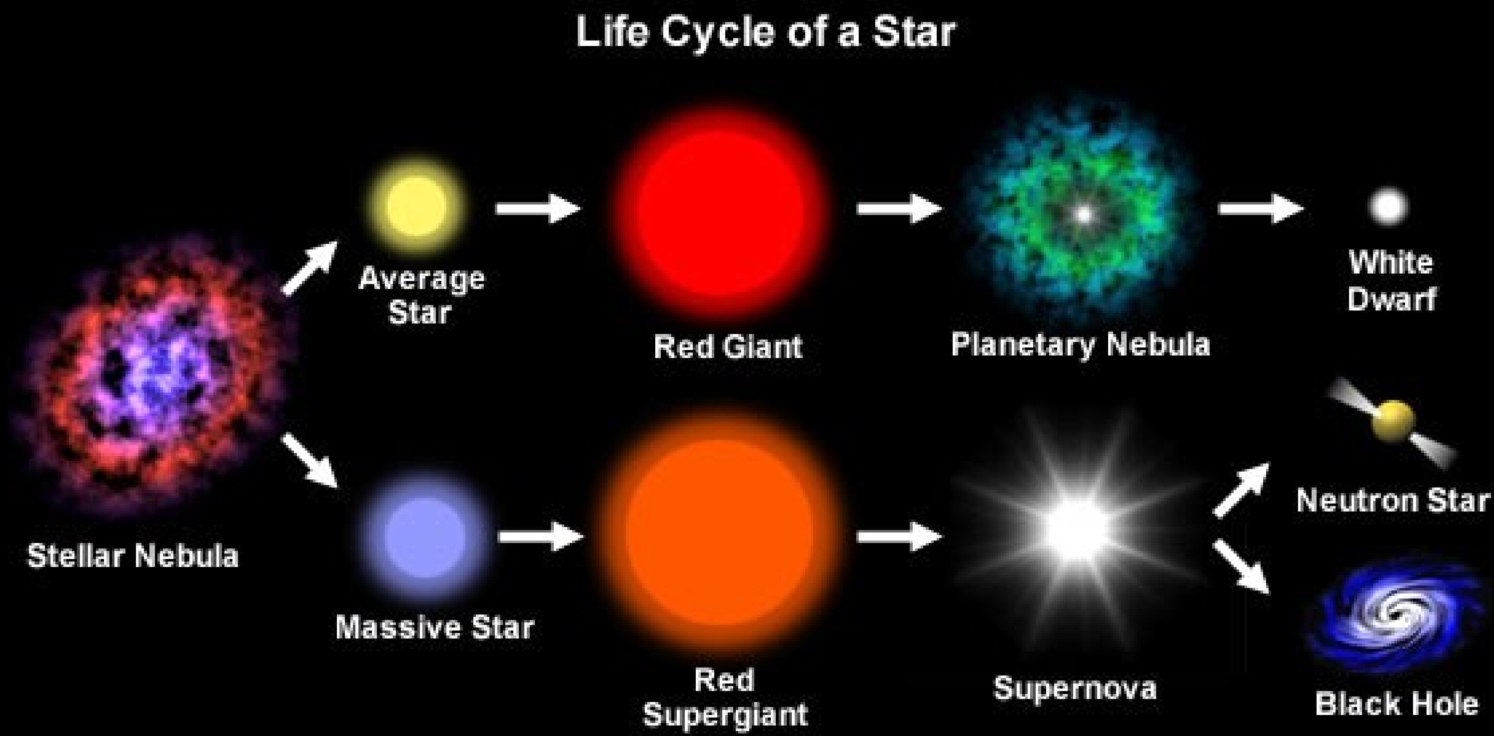
The event was a merger of two neutron stars

The merger prompt the formation of relativistic jet, thus generating a short gamma ray burst

Neutron rich material congregates in nulcei via r-processes

It is estimated that ~10 Earth masses of gold were produced in the event.

Formation of compact binaries

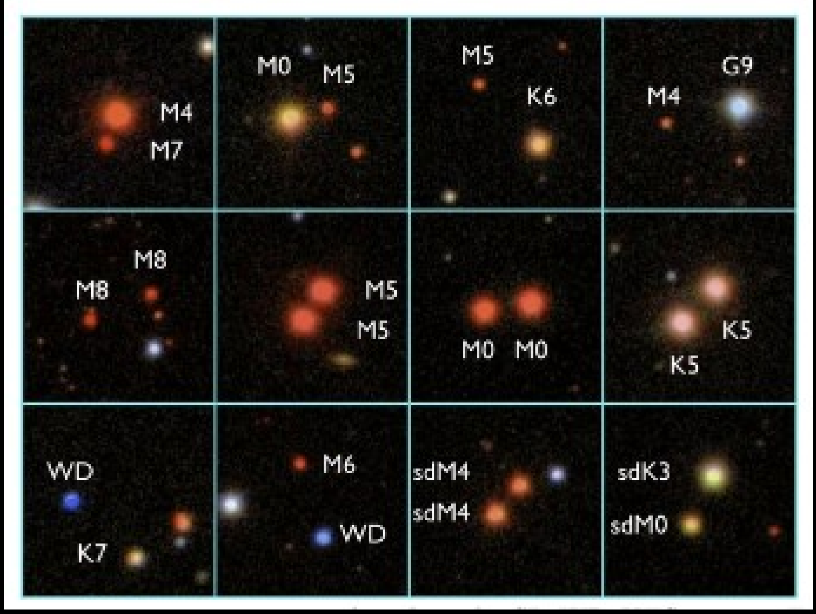


Mi<8Msun

8Msun<Mi<20Msun

MI>20Msun

Mass (solar masses)	Time (years)	Spectral type
60	3 million	O3
30	11 million	O7
10	32 million	B4
3	370 million	A5
1.5	3 billion	F5
1	10 billion	G2 (Sun)
0.1	1000s billions	M7



-Massive stars: burn fast and die young

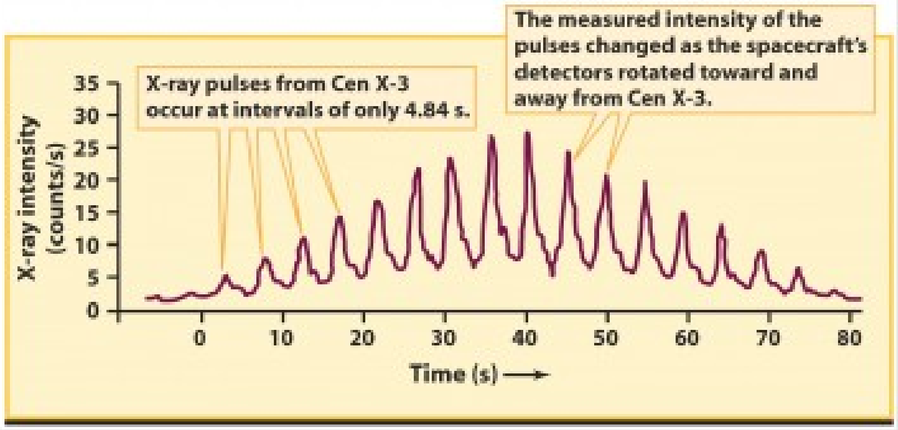
-Most massive stars (70%) are in binaries

(e.g. Sana et al 2012)

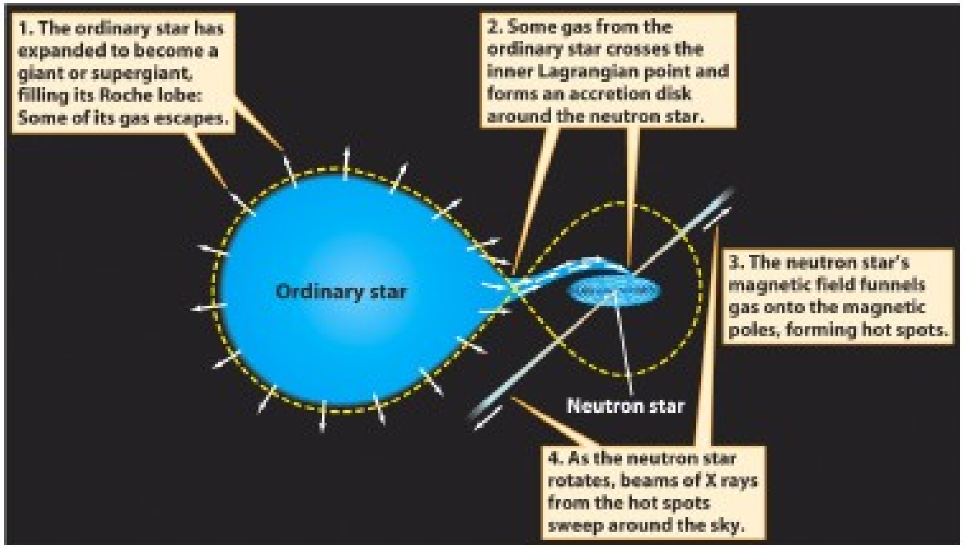
X-ray binaries: some pulsating X-ray sources are neutron stars in close binaries

- Cen X-3 is an example of a bright pulsating X-ray source which also varies substantially on longer timescales.

- Magnetic forces funnel gas accreting from a companion star onto the neutron star's magnetic poles, producing hot (~10^8 K) spots.
- These hot spots radiate intense beams of X rays.
- As the neutron star rotates, the X-ray beams appear to flash on and off.
- Periodic variations at the orbital period (typically days) may also be seen.

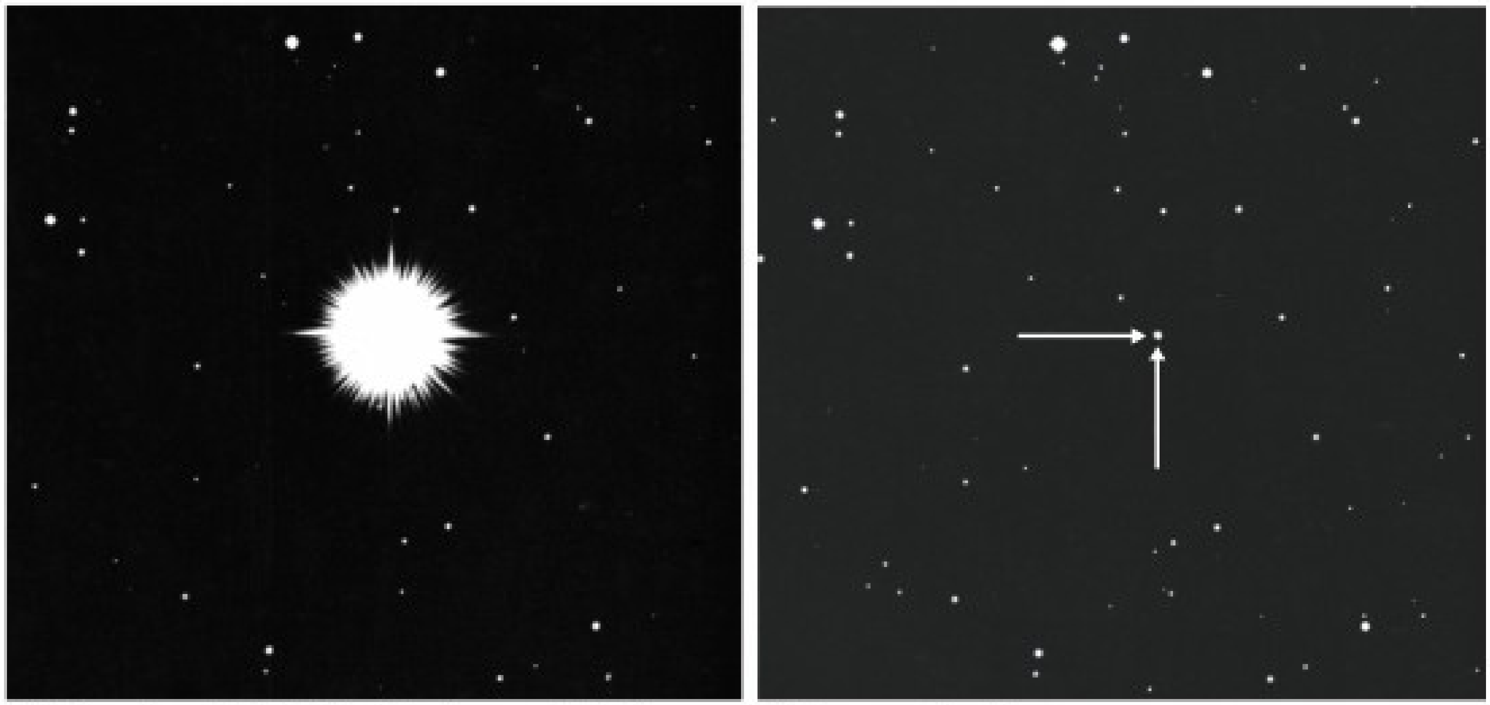


Longer term variations can arise due to the orbital motion of the binary

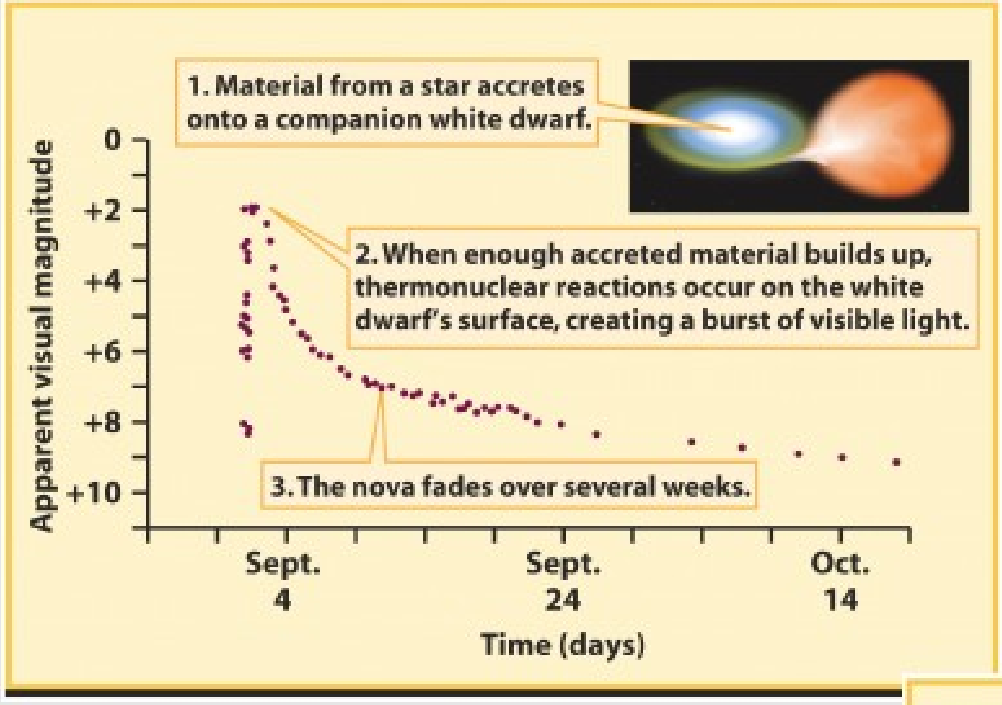


More binaries: novae and X-ray bursters

- Some stars which have high energy radiation (e.g. X-rays) also show remarkable outbursts.
- For example, novae exhibit a rise in optical brightness by a factor of 1000 or more, which then decays away on a timescale of weeks.
- The peak optical luminosity is ~10^{-4} of that observed in a supernova.
- Detailed studies have shown that a nova results from a thermonuclear explosion on the surface of a white dwarf, which is accreting material from a companion star in a close binary.



(a) Nova Herculis 1934 shortly after peak brightness (b) Two months later



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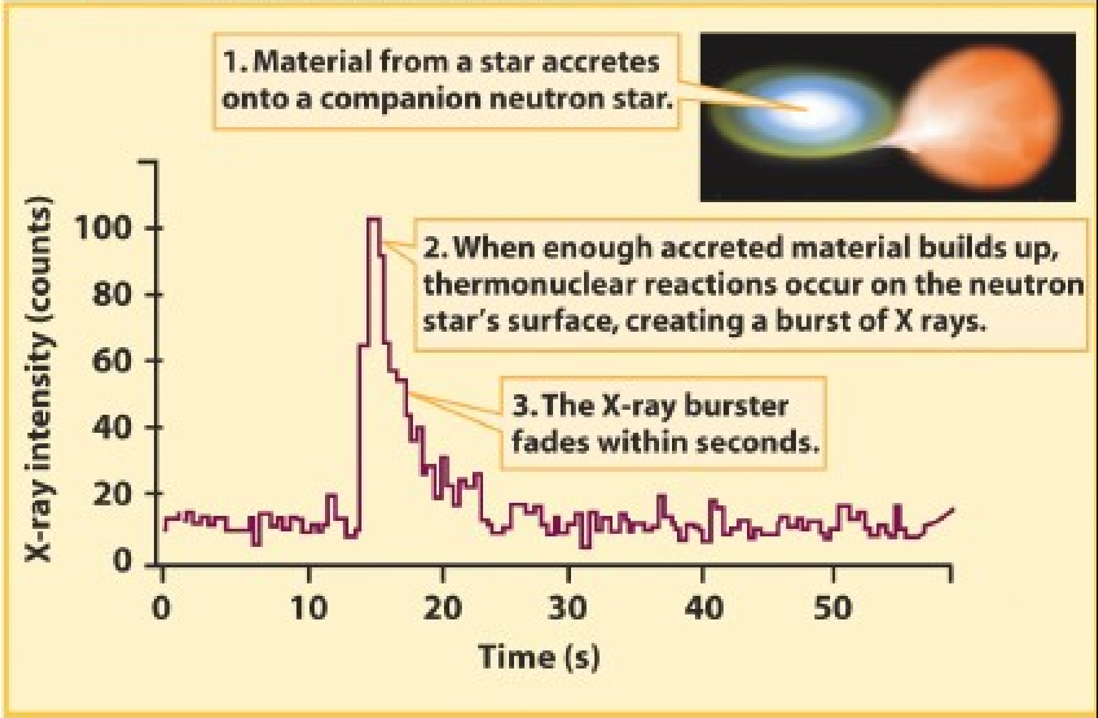
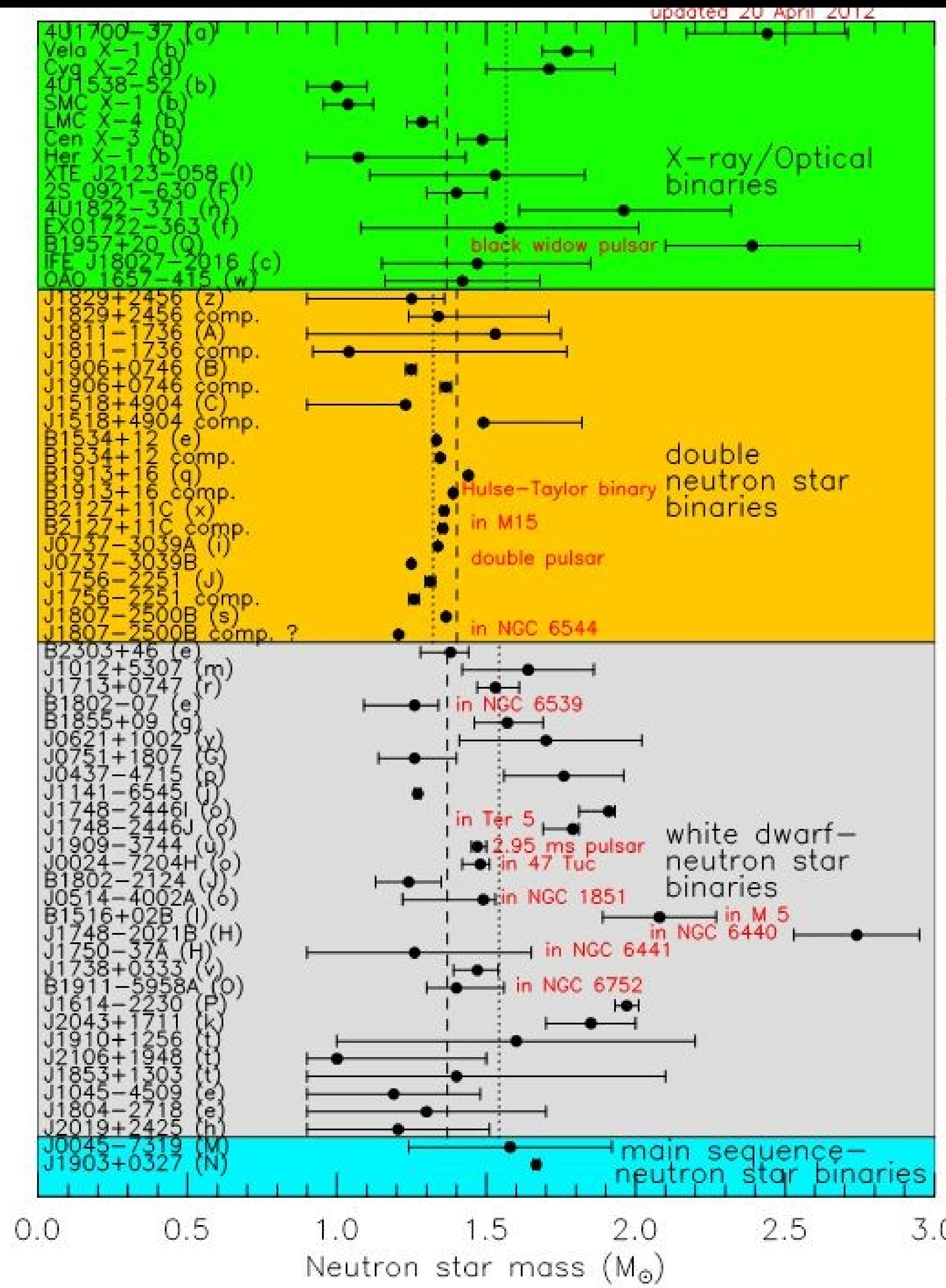
- A similar phenomenon, happening at higher energies and on shorter timescales, is seen the the X-ray burst sources.
- These emit flashes of bright X-ray emission lasting less than 1 minute.
- This is believed to occur due to a thermonuclear flash on the surface of an accreting <u>neutron star</u>.



Neutron Star Masses

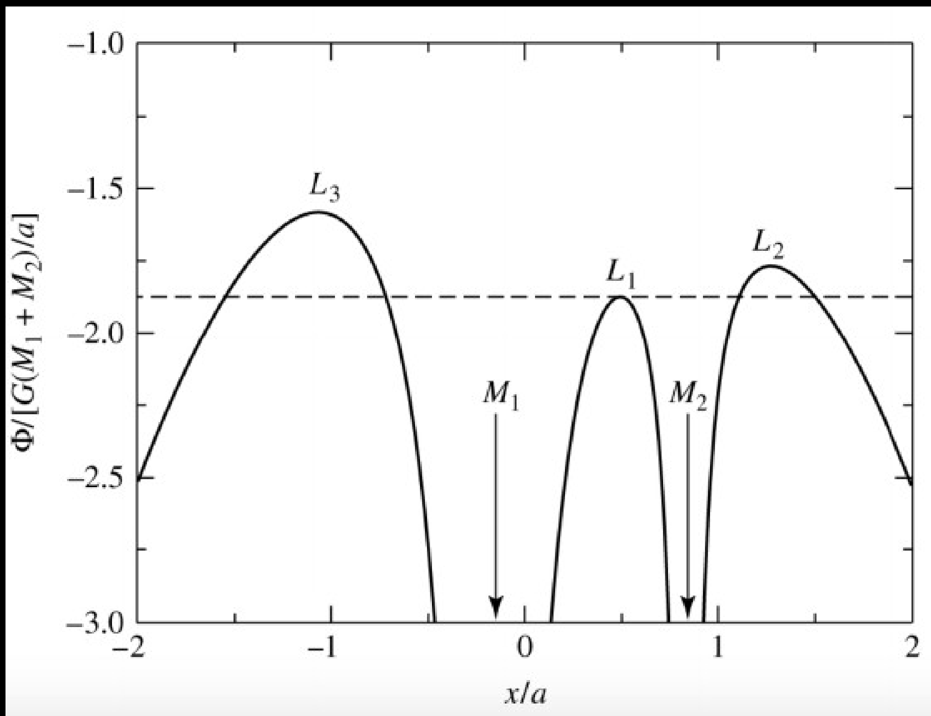
- Observations of neutron star binaries provide a growing list of neutron star mass estimates.
- Current observations predict a range of NS masses from 1.0 to >2 solar masses.
- Can we explain these masses?

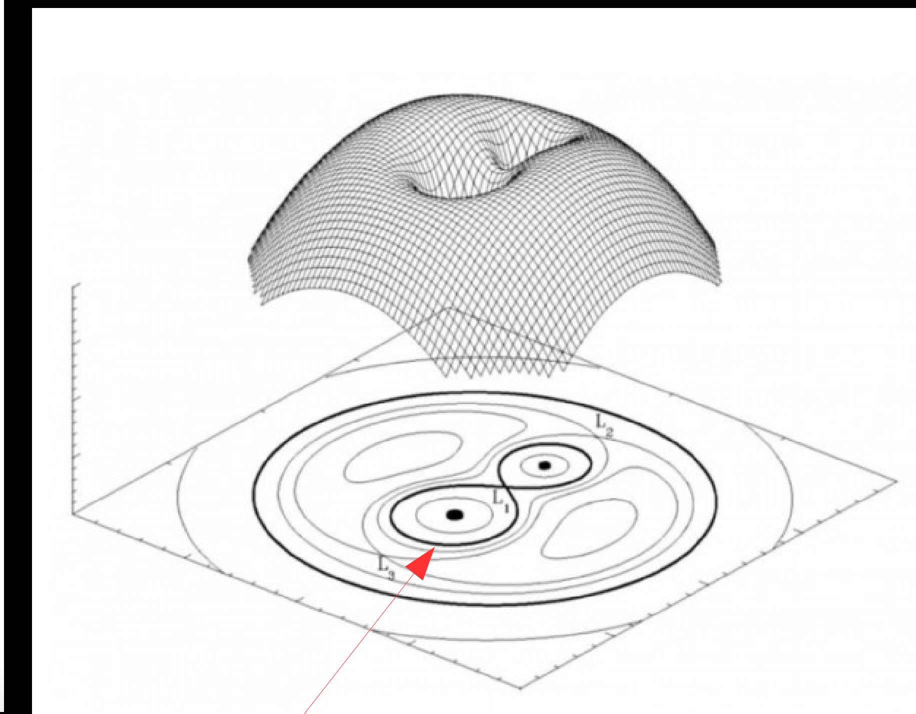


Lattimer 2013

Evolution of binaries: effective potential

$$U = -\frac{Gm(M_1 + M_2)}{r_{\rm CM}} - \frac{1}{2}m\omega^2 r_{\rm CM}^2 = -Gm\left(\frac{M_1}{s_1} + \frac{M_2}{s_2}\right) - \frac{1}{2}m\omega^2 r_{\rm CM}^2.$$





The region over which each component of the binary exerts its influence is called **Roche Lobe.**

The RL are connected by the unstable **Lagrangian point L1.**

$$\frac{R_1}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

Mass transfer

Assuming a circular binary, the angular momentum can be written as

$$J = \mu\sqrt{GMa}$$

Suppose that the secondary loses mass that is partly accreted by the primary, passing through L1

$$\dot{M}_2 < 0 \qquad \dot{M}_1 = -(1-\beta)\dot{M}_2 \qquad \beta \in [0,1]$$

By differentiating the J equation one can easily show that

$$\begin{aligned}\frac{\dot{a}}{a} &= 2\frac{\dot{J}}{J} - 2\frac{\dot{\mu}}{\mu} - \frac{\beta\dot{M}_2}{M} \\ &= 2\frac{\dot{J}}{J} - 2\left[(\beta-1)\frac{M_2}{M_1} + 1\right]\frac{\dot{M}_2}{M_2}\end{aligned}$$

If the mass transfer is conservative then

$$\frac{\dot{a}}{a} = -2\left(1 - \frac{M_2}{M_1}\right)\frac{\dot{M}_2}{M_2}$$

So the binary shrinks if M2>M1. This is important because the most massive star in the binary it is the first to evolve

Supernova kick

The binary can be described as the motion of **μ** in the potential of M

$$v_i = \sqrt{\frac{G(M_2 + M_1)}{a_i}}$$

M1 goes boom (SN) $M_c < M_1$, and $\Delta M = M_1 - M_c$

The explosion generates a kick

$$\mu_f = M_c M_2/(M_c + M_2) \qquad \vec{v}_f = \vec{v}_i + \vec{v}_{\rm kick}$$

$$E_f = \frac{1}{2}\mu_f v_f^2 - \frac{G M_c M_2}{a_i}$$

If the final velocity is larger then the escape velocity (calculated from Ef) then the binary gets unbound

$$v_f \leq v_e = \sqrt{\frac{2G(M_2 + M_c)}{a_i}}$$

If vkick is null the binary stays bound unbound if

$$\Delta M \leq \frac{M_1 + M_2}{2}$$

The kick velocity depends on the nature of the object

Neutron stars: bounce of the imploding layers onto the hard NS core can produce large kick if the overall process is asymmetric

The NS kick distribution is estimated to follow

$$f(v_{\rm kick}) = \sqrt{\frac{1}{\pi}}\frac{v_{\rm kick}^2}{\sigma_v^3}e^{-\frac{v_{\rm kick}^2}{2\sigma_v^2}}$$

with σ~190 km/s (estimated from the distribution of peculiar velocities of PSR wrt their local ref frame.

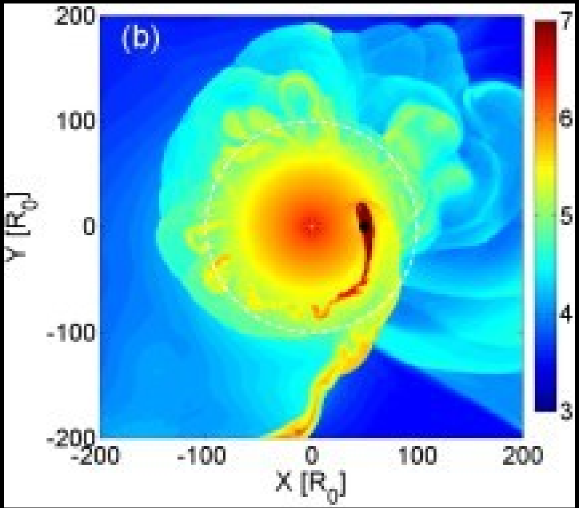
A binary with masses of ~10Msun @5AU separation has an escape speed of <100km/s.

So the first SN kick is expected to destroy many NS binaries (but obviously a fraction does survive since we do see NS binaries (e.g. Hulse & Taylor binary, Double Pulsar and many more…

Black holes: estimates are way more uncertain:
-theoretically since the horizon forms, we do not expect any bounce, so the kick velocity should be small

-observationally we cannot estimate vkick from lone BHs in the MW

Common envelope evolution



Compact object (CO) inspiralling into an envelope of a giant star. The inspiral of the CO 'heats up' the envelope eventually unbinding it:

$$\Delta E_{\rm env} = -E_{\rm env,i} = \frac{G M_{\rm gs} M_{\rm env}}{\lambda R_L}$$

By equating this to the change in energy of the compact object, one finds a relation between the initial and final separation of the binary:

$$\frac{a_f}{a_i} = \frac{M_{\rm core}}{M_{\rm gs}} \left(1 + \frac{2}{\lambda \alpha_{\rm ce}} \frac{a_i}{R_L} \frac{M_{\rm env}}{M_{\rm BH}}\right)^{-1} = \frac{M_{\rm core}}{M_{\rm gs}} \left(\frac{M_{\rm BH}}{M_{\rm BH} + \frac{2 M_{\rm env}}{\lambda \alpha_{\rm ce}} \frac{a_i}{R_L}}\right)$$

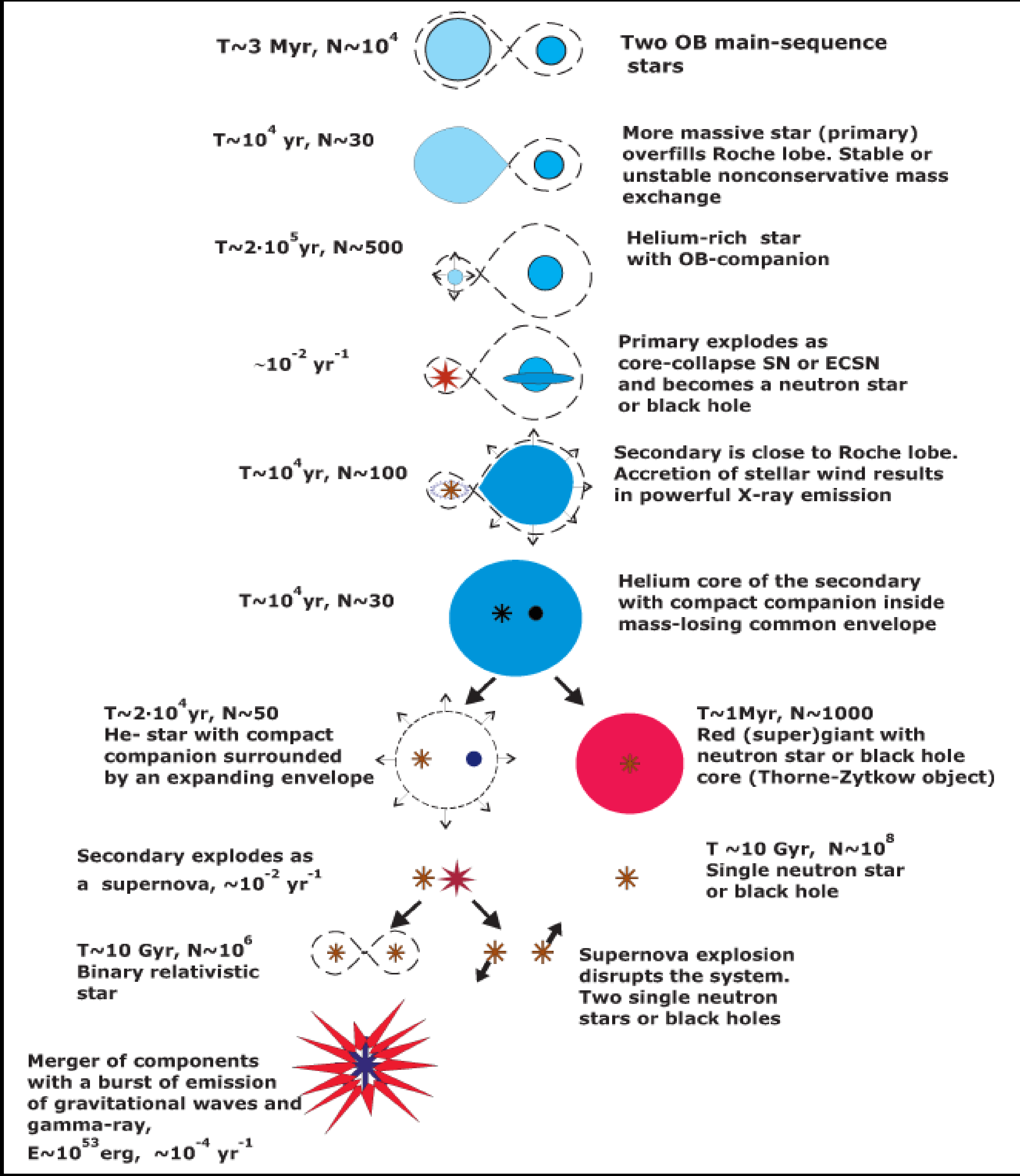
For typical massive star values:

$$\frac{M_{\rm core}}{M_{\rm gs}} \approx 0.2 - 0.3, \qquad \frac{M_{\rm BH}}{M_{\rm BH} + \frac{2 M_{\rm env}}{\lambda \alpha_{\rm ce}} \frac{a_i}{R_L}} \approx 0.05 - 0.01.$$

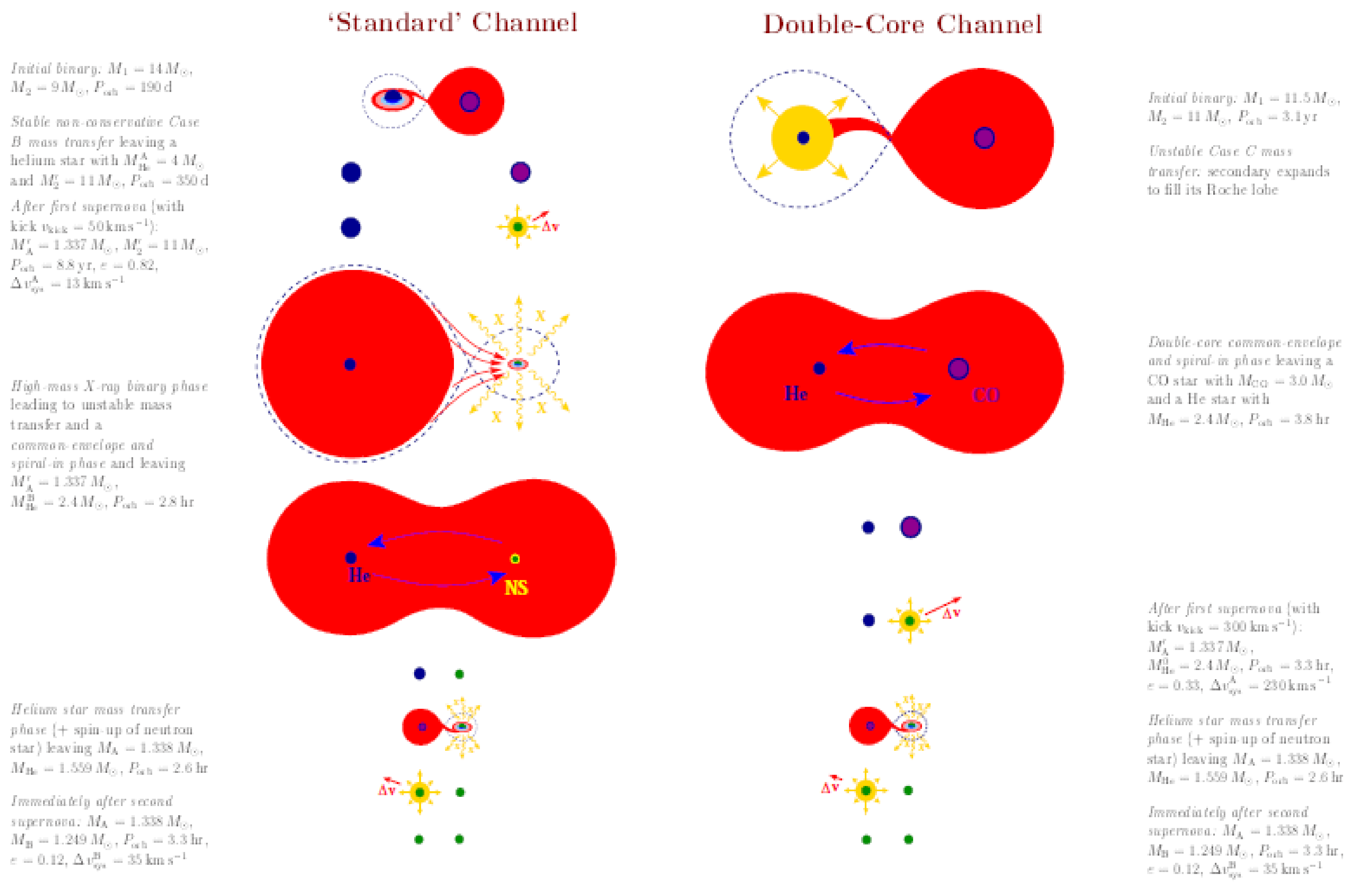
One gets a_f/a_i~0.01-0.001.

So, in principle the system can shrink from ~AU to ~solar radii.

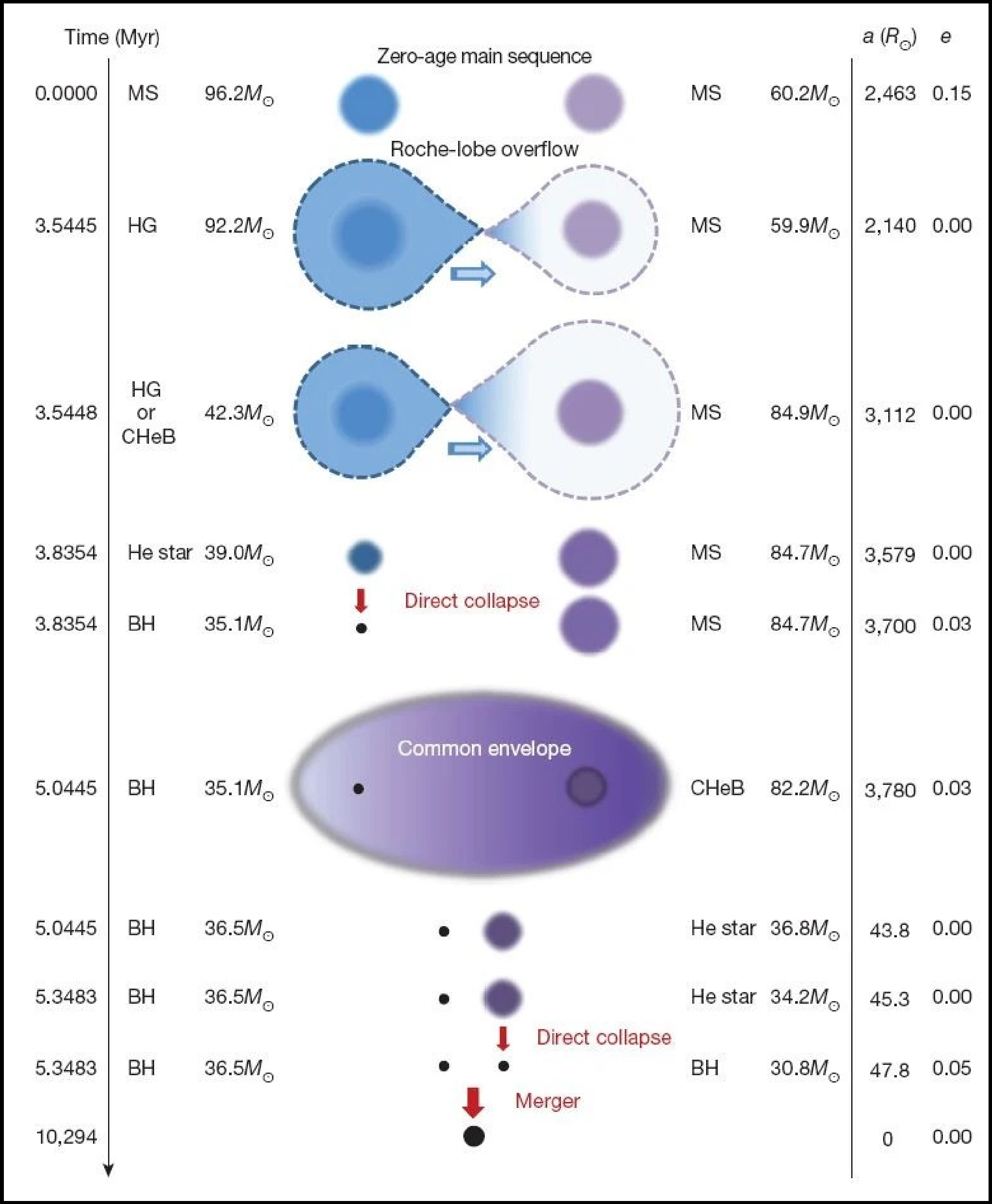
Evolution channels of massive binaries



Evolution channels of massive binaries



GW150914: an example scenario



(Belczynski et al. 2016)

$$a_0 = 1.6\ R_\odot \left(\frac{M_1}{M_\odot}\right)^{3/4} \left[q(1+q)F(e)\left(\frac{t_{\rm coal}}{1{\rm Gyr}}\right)\right]^{1/4}$$

Evolution of massive Binaries

Complications
-common envelope
-kicks
-metallicity
-rotation

Features:
-Preferentially high, aligned spins?
-small formation eccentricity

A back of the envelope estimate of the rate:

-stellar density in the universe $\rho=3\times10^8$ Msun/Mpc^3

-assuming 1Msun average mass this means 3×10^8 stars/Mpc^3

-for a Salpeter IMF, $N(m)\propto m^{-2.35}$ ~0.3% have m>30Msun (thus leading to a BH)

-70% of those stars are in binaries

-so we can estimate ~3×10^5 binaries/Mpc^3

-if they form steadily over an Hubble time we get a formation rate of ~2×10^4 binaries/Gpc^3/yr

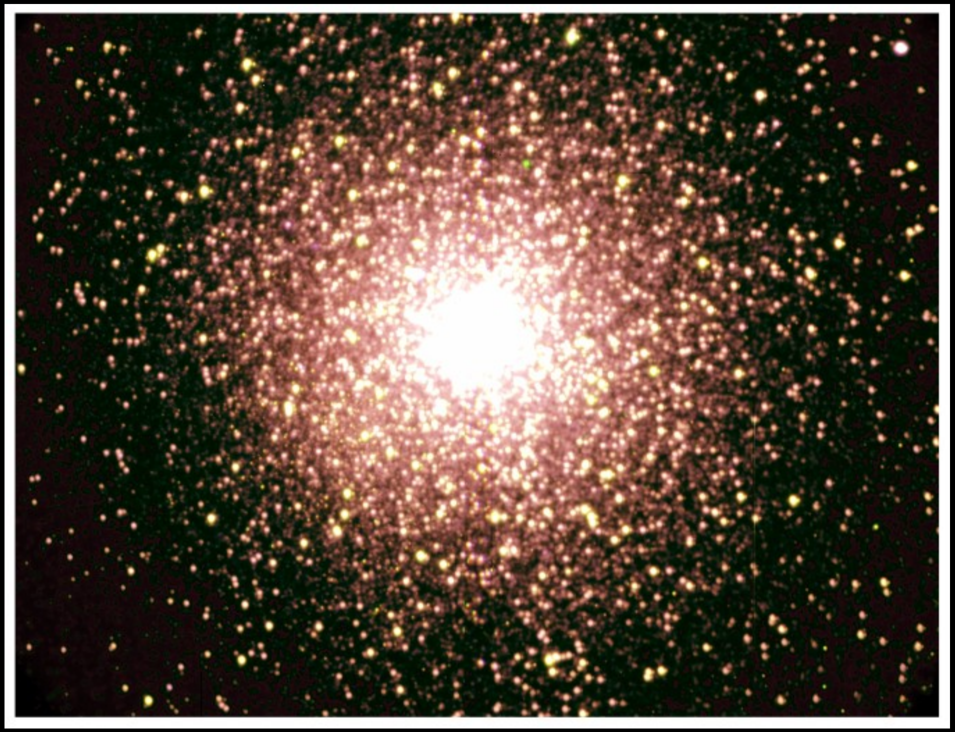
-if those binaries all merge in $t \ll t_{Hubble}$ then this is also the merger rate.

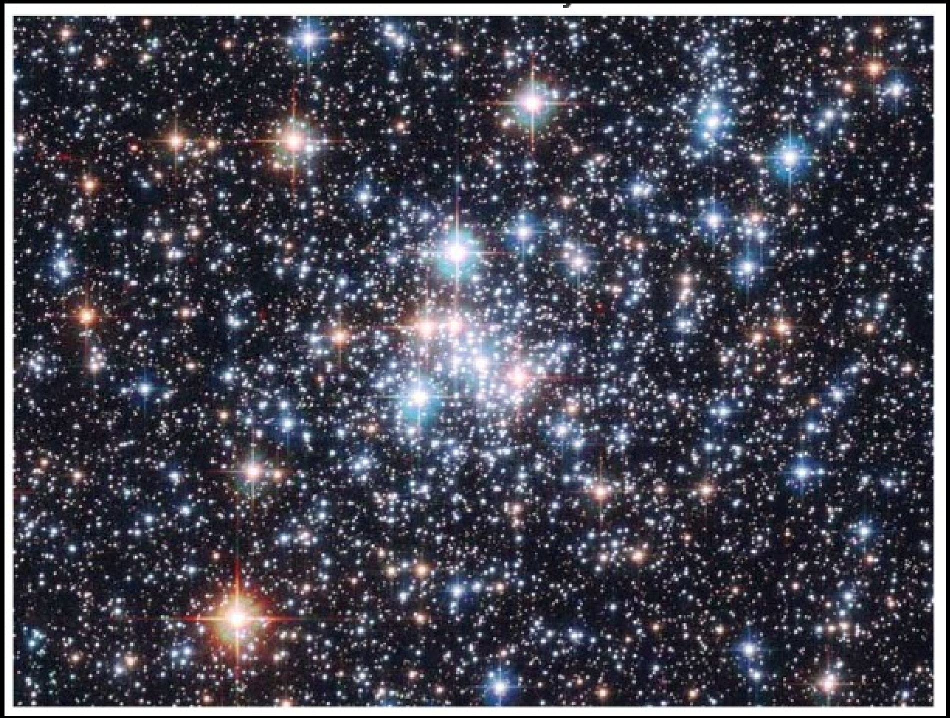
This is an upper limit and is 2-3 orders of magnitude larger then the measured LIGO/Virgo rate

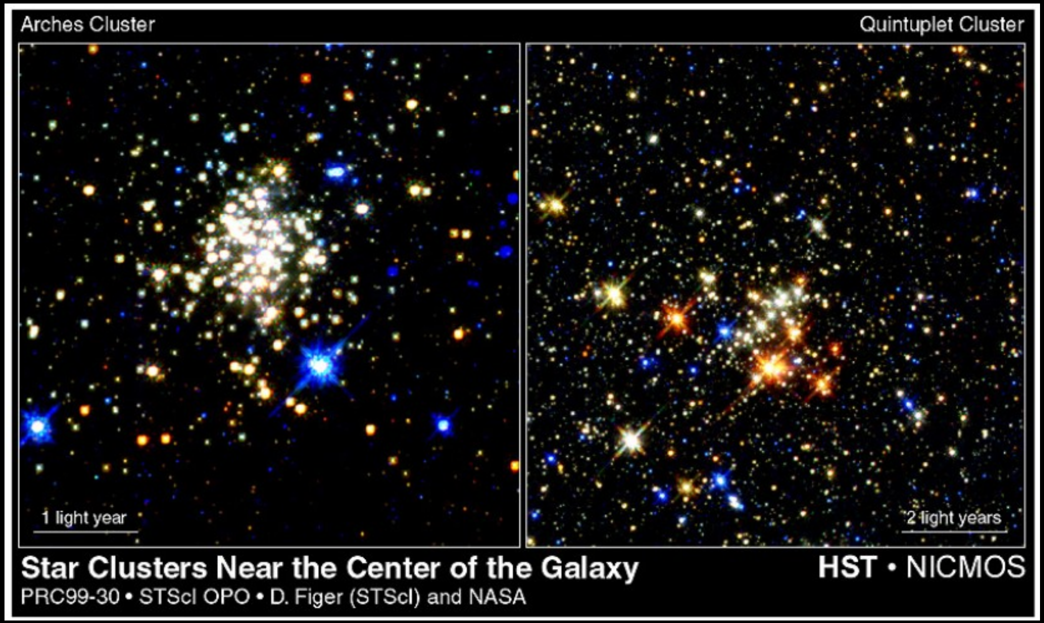
- -SN kicks can easily disrupt the vast majority of those binaries
- -Efficiency of CE unknown, it might be not efficiente enough or way too efficient

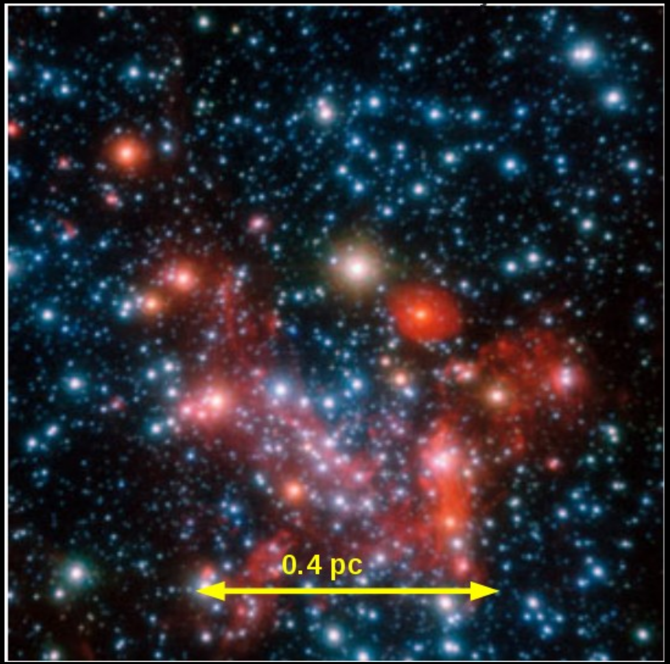
(one can do a similar calculation with NS binaries)

BHB origin: dynamical formation







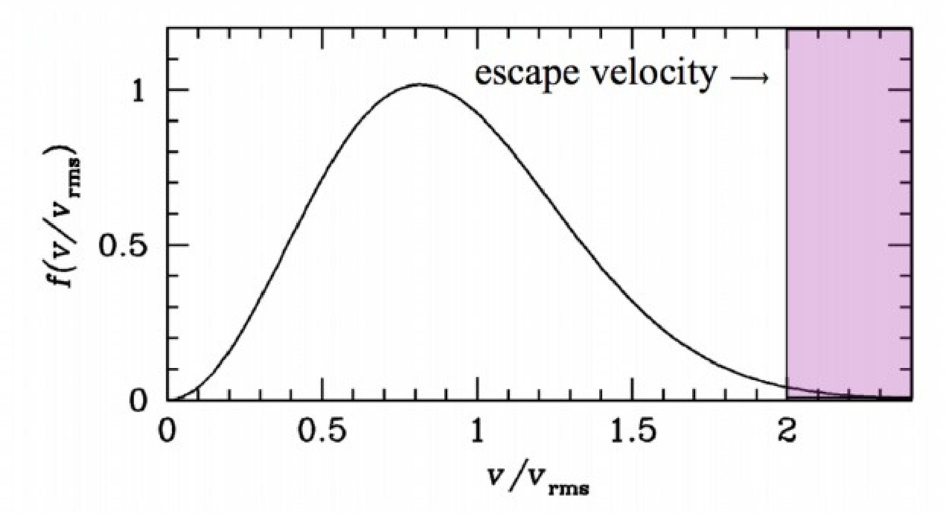


Dynamics of clusters (Celoria+ 2018)

Two body relaxation

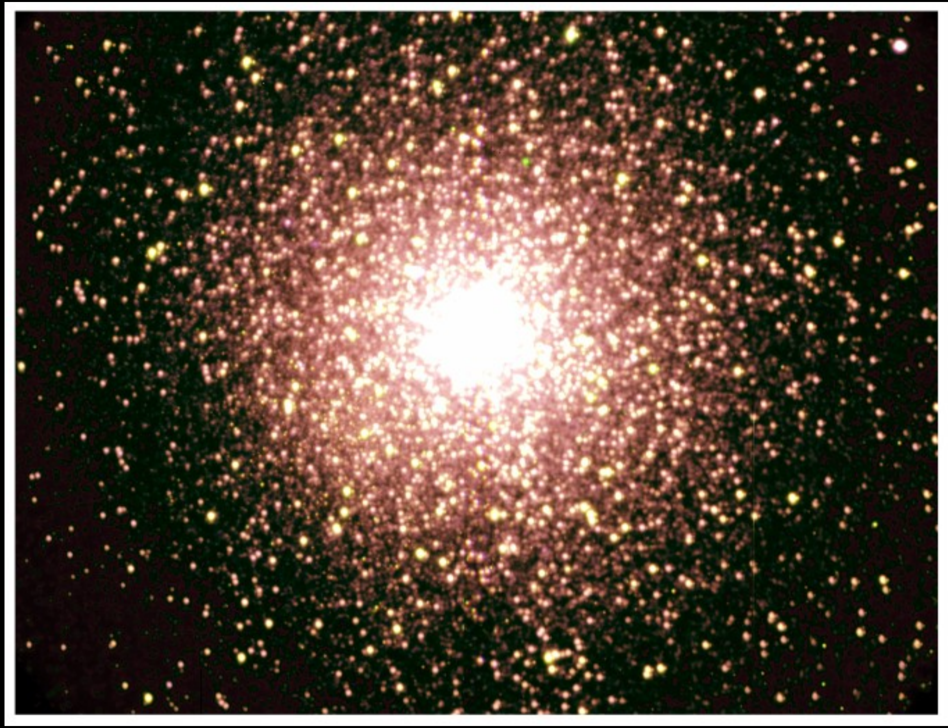
$$t_{\rm rlx} \approx \frac{10^8 \text{ yr}}{\log N}\left(\frac{M}{10^5 M_\odot}\right)\left(\frac{R}{1 \text{ pc}}\right)^{3/2}\left(\frac{1\ M_\odot}{m}\right)$$

Leads to evaporation



Leads to core collapse

$$\frac{\rho(t)}{\rho(0)} \propto \left(\frac{M(t)}{M(0)}\right)^{3\zeta-5}$$



Because of equipartition

$$\frac{1}{2}m_i\left\langle v_i^2\right\rangle = \frac{1}{2}m_j\left\langle v_j^2\right\rangle$$

Massive stars tend to segregate to the center of the cluster

$$t_{\rm segr}(M) = \frac{\langle m\rangle}{M}t_{\rm rlx}$$

For typical clusters this migration/evolution timescale is >3Myr which is the lifetime of the most massive stars.

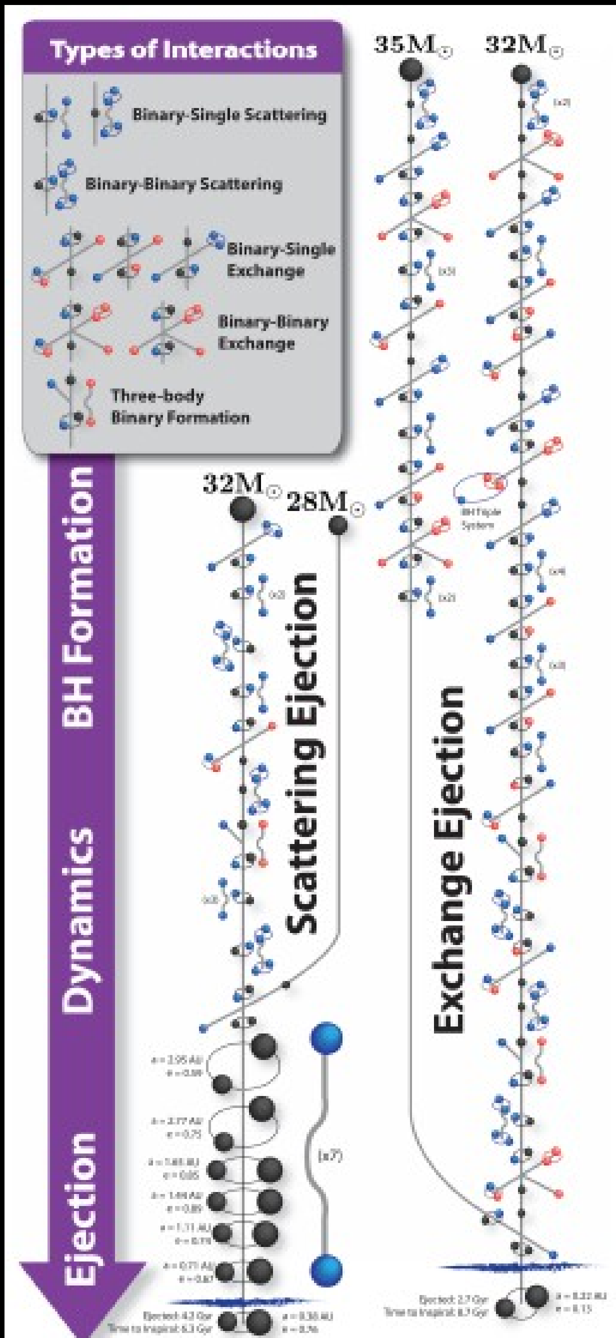
Therefore BHs tend to migrate through the centre where they form binaries either via direct GW capture or via triple interactions.

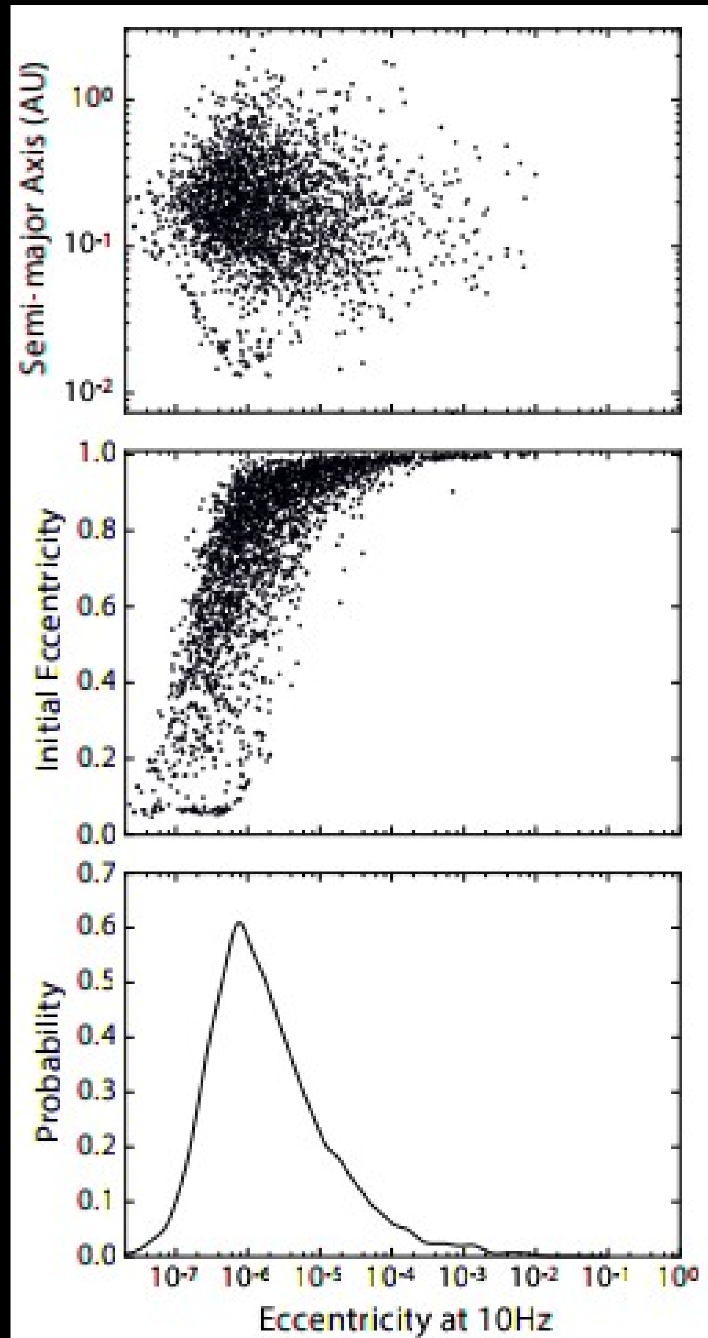
A variety of mechanisms then can lead to the merger of the binary:

- **-exchanges**
- **-Kozai-Lidov oscillations**
- **-Hardening**
- **…….**

Estimated rates through this channel are ~10/Gpc^3/yr (Rodriguez+2016...)

BHB origin: dynamical formation





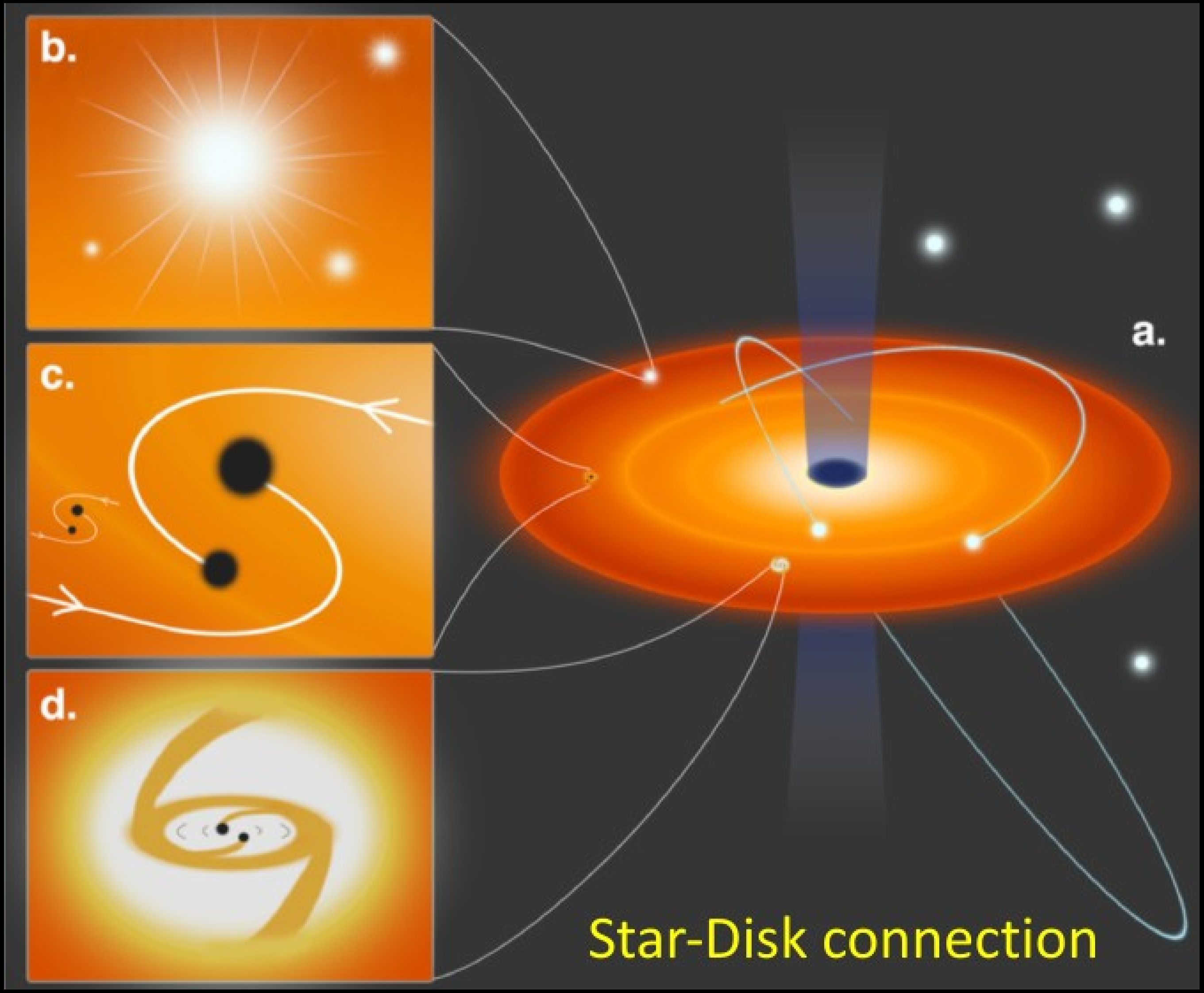
(Rodriguez et al. 2016)

Dynamical capture

Complications
- **mass segregation**
- **winds**
- **ejections**
- **multiple interactions**
- **resonant dynamics (Kozai-Lidov)**

Features:
- **randomly oriented spins?**
- **high formation eccentricities**

BHB origin: AGN disks



(Ford, McKernan, Haiman, Lin, Antonini….)

GALACTIC NUCLEI

AGN disks

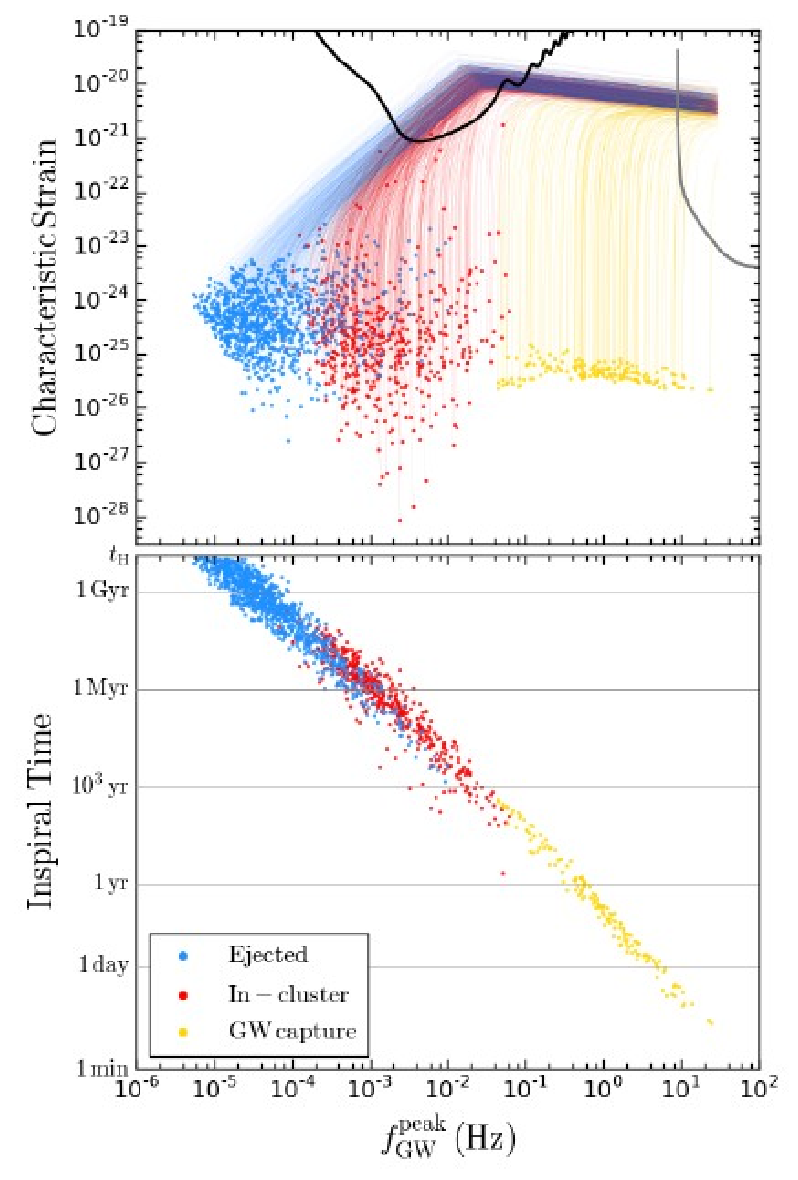
Complications
- capture
- evolution
- migration traps
- multiple interactions

Features:
- accelerated by large MBH potential
- EM counterparts?
- essociated to galactic centers

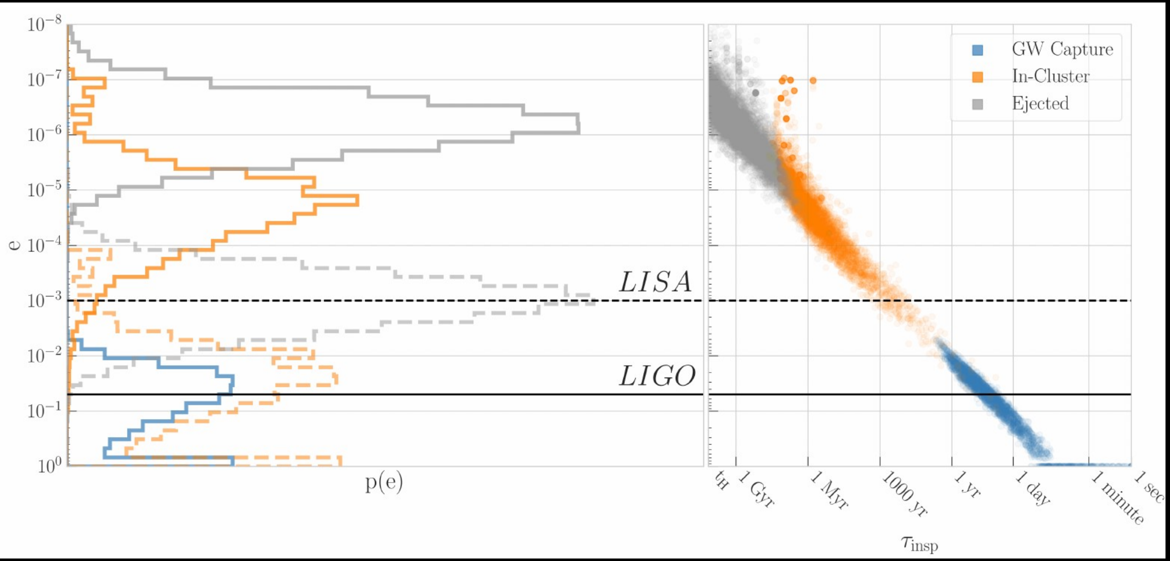
Kozai by SMBH

- very eccentric

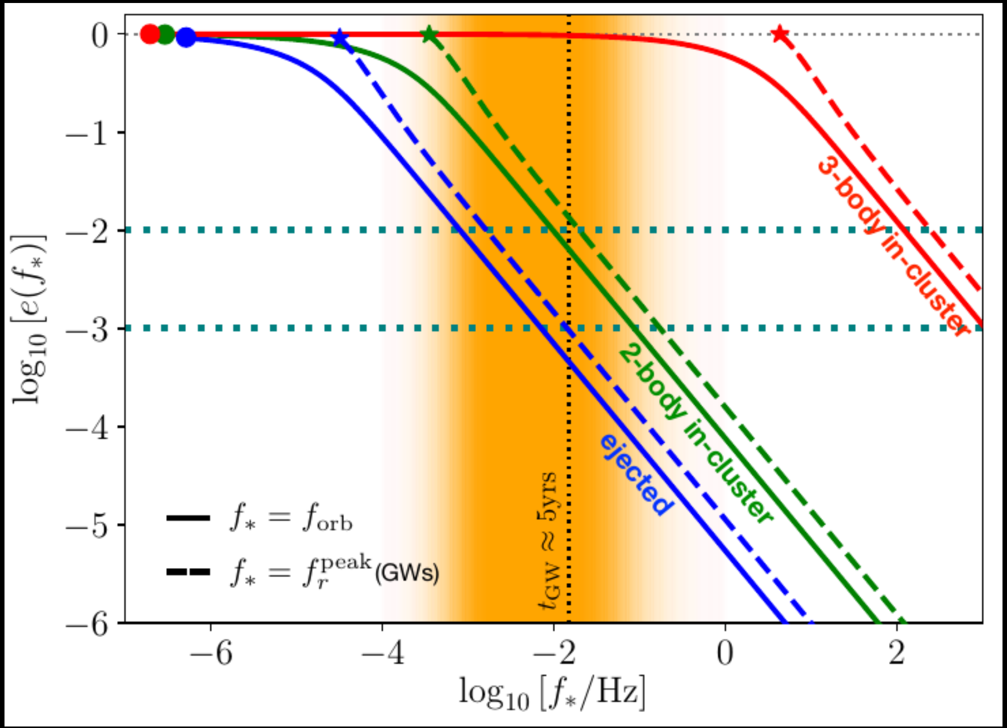
BHB formation triplets quadruplets...



(Kramer+)

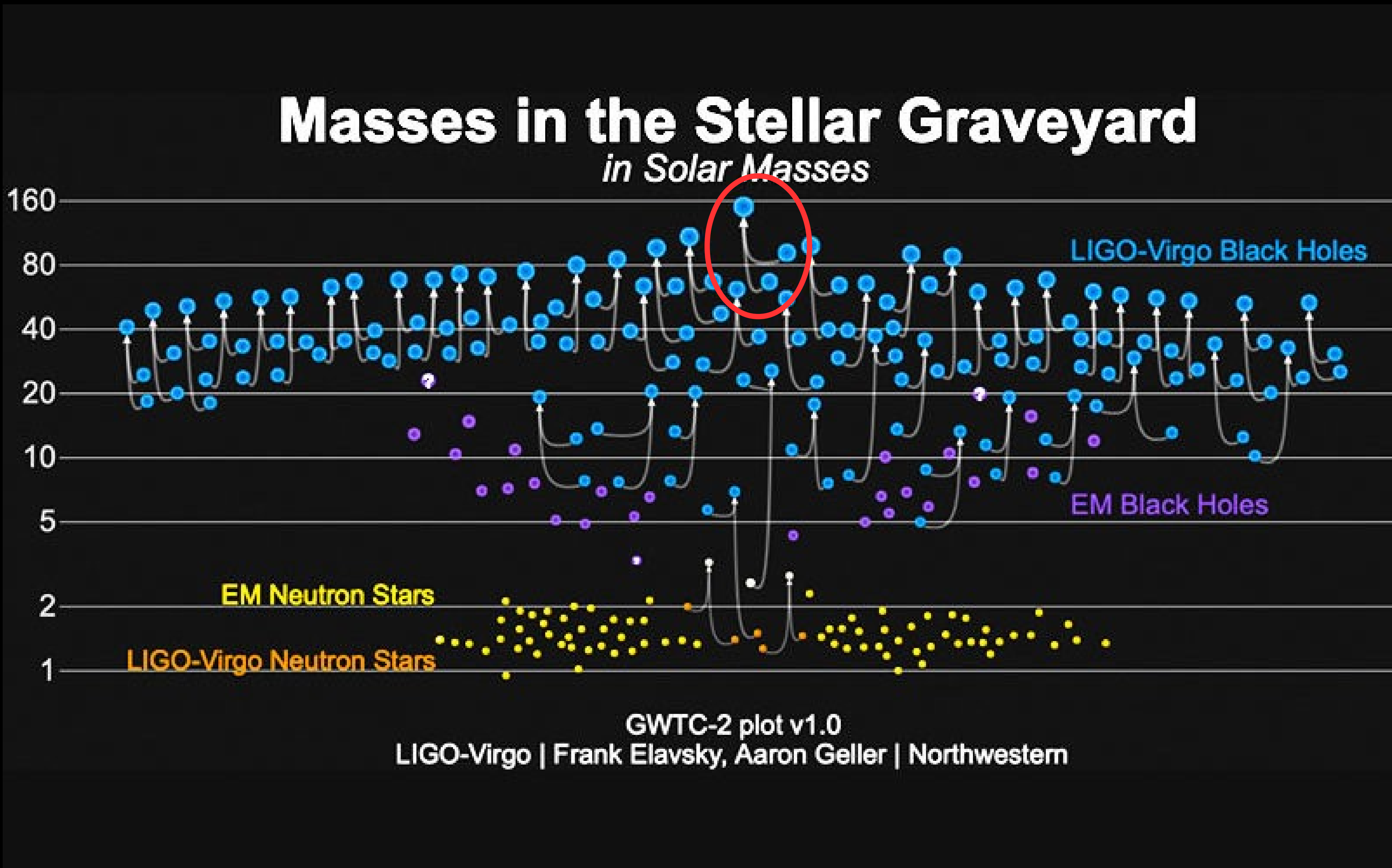


(Zevin+)



(D'Orazio & Samsing)

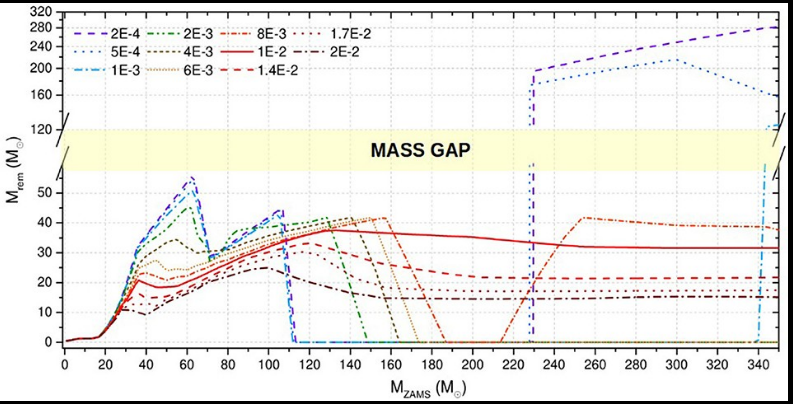
Those channels might be relatively rare!


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190521

~70+90 solar masses → 160Msun remnant: IMBH!!!!

The two progenitors are in the pair instability supernova gap



Route to formation:

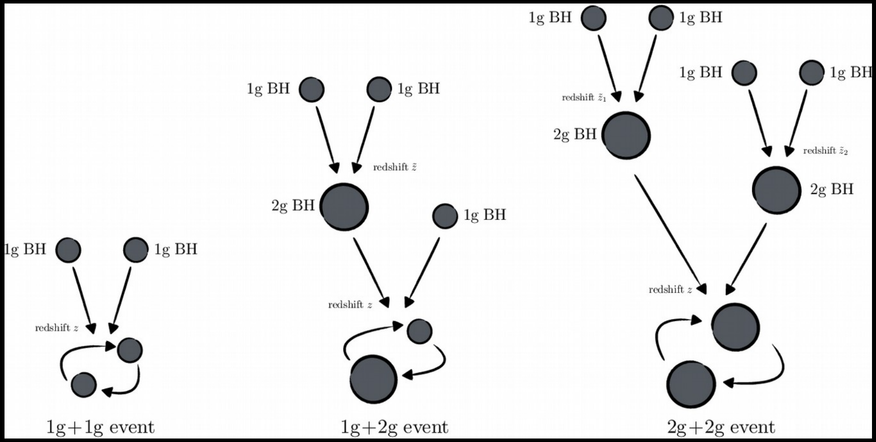
-very low metallicity popIII progenitors (Kinugawa+20, Farrell+20, Liu+20)

-primordial BHs

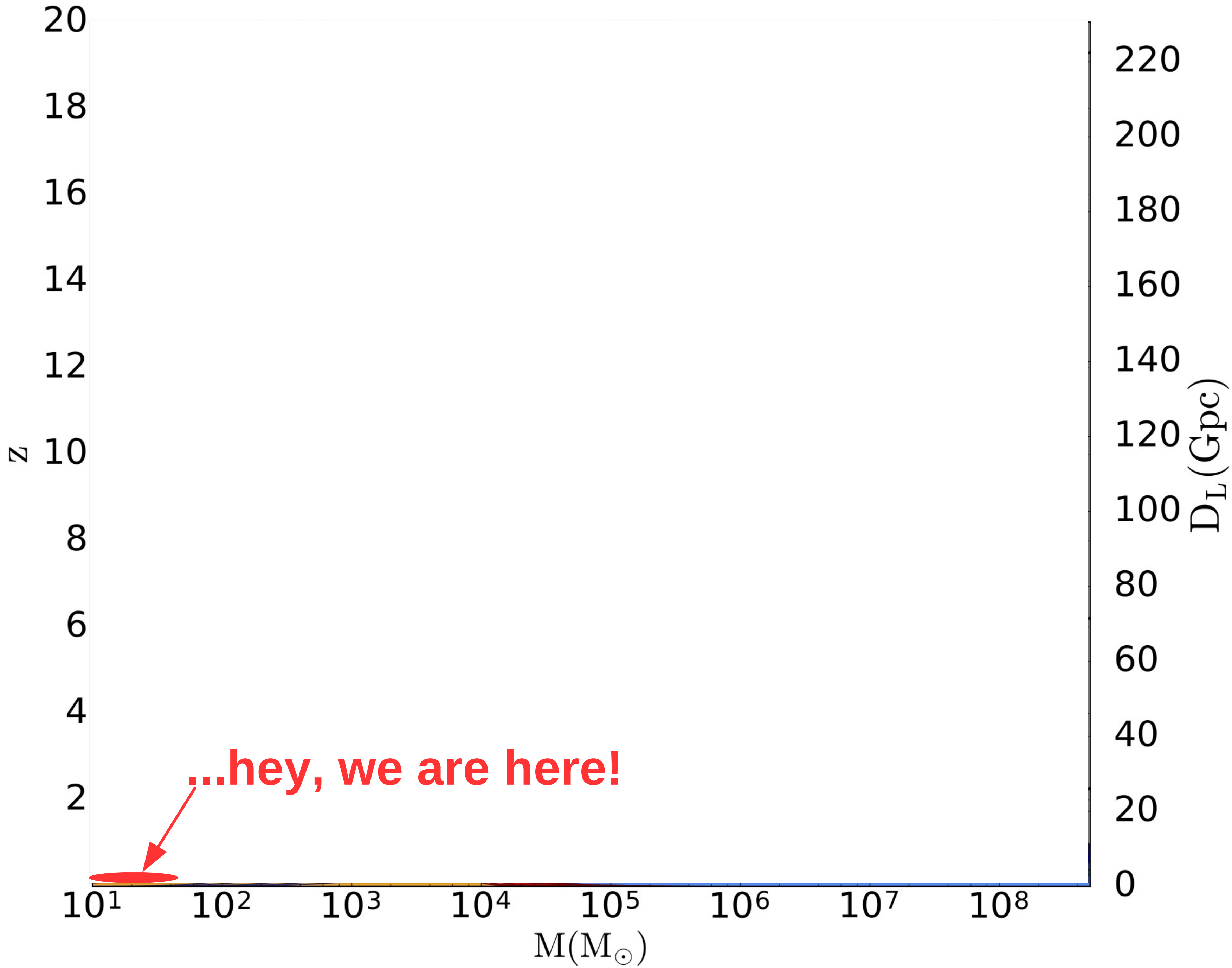
-’across gap binary’ (Mangiagli+2019, Fishback+20)

-Accretion in AGN disks (Graham+20, also proposing a counterpart)

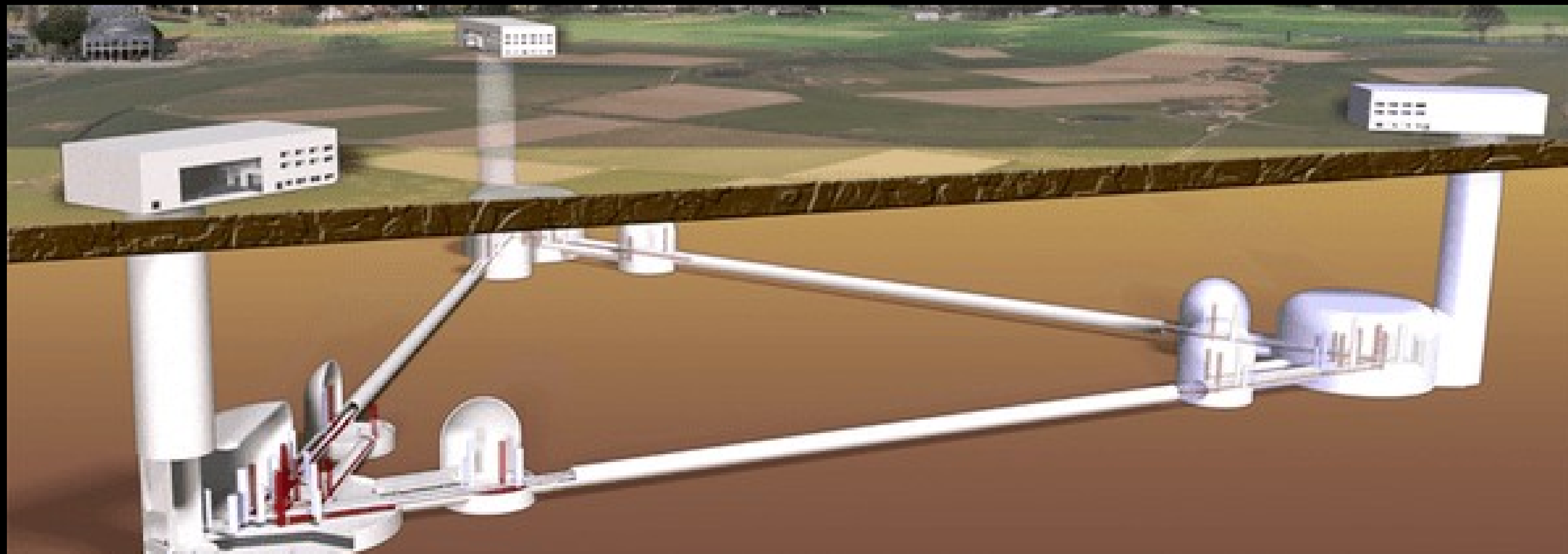
-2nd Generation (Gerosa+2017, Rordiguez+2020, Bin+20)

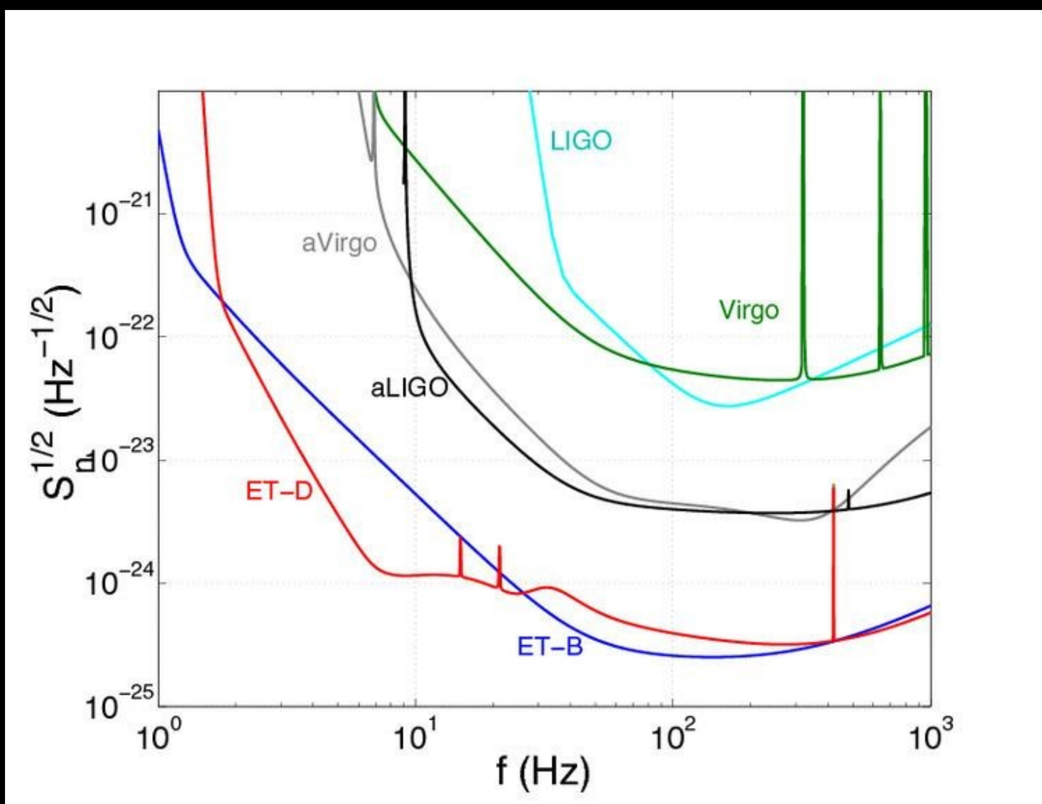


Binaries in the z-mass parameter space



3G detectors: ET and CE

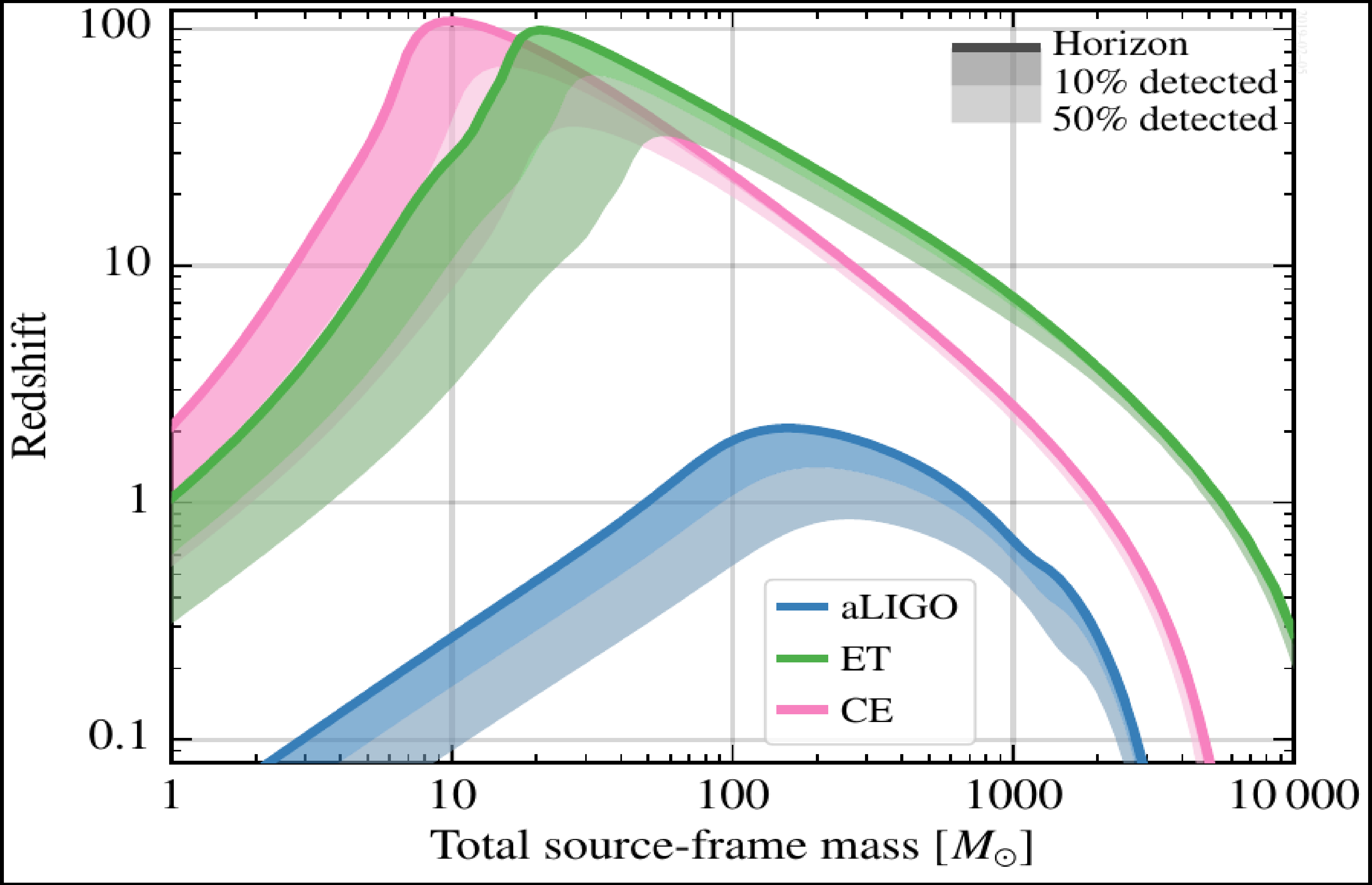




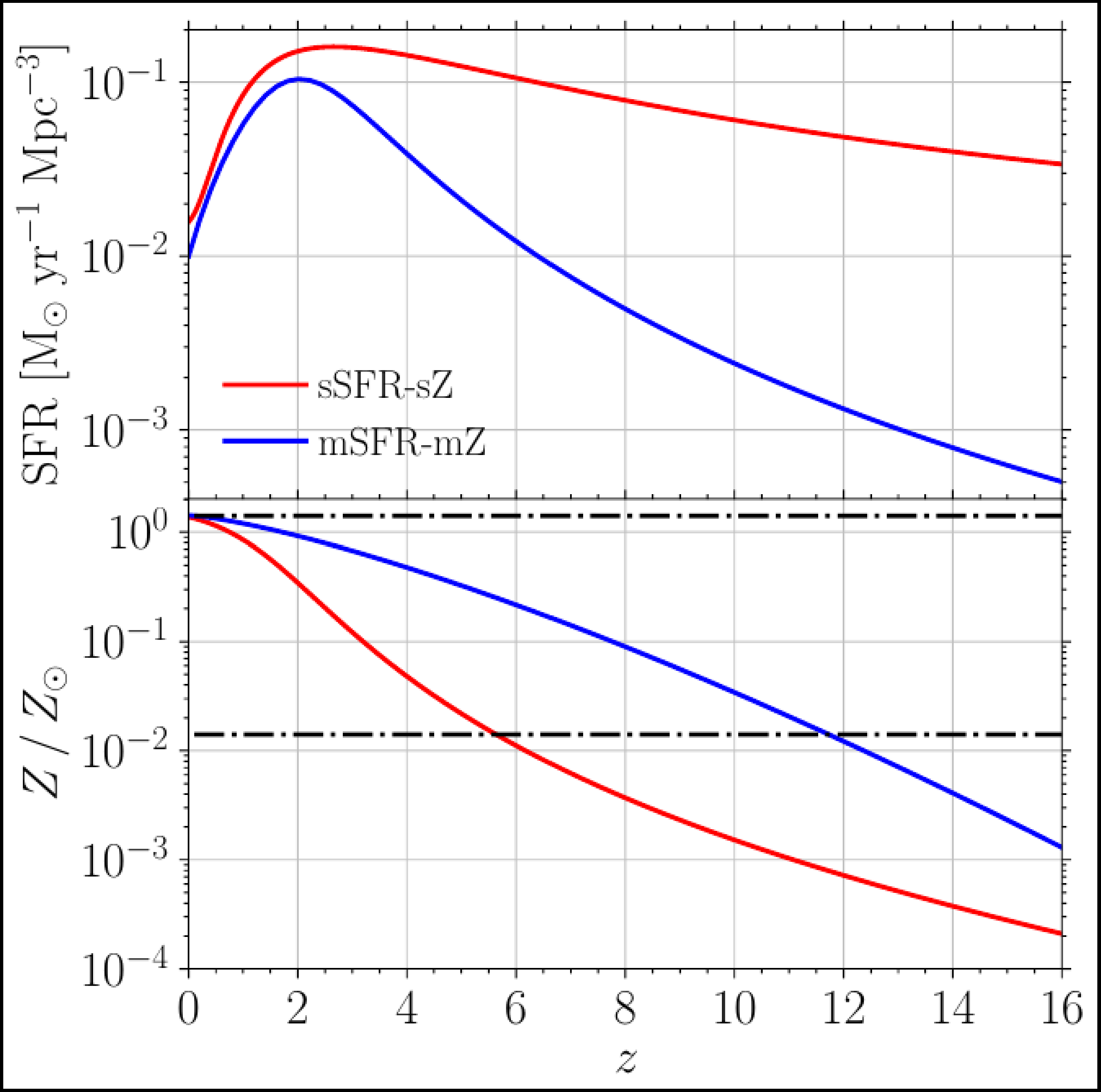
Einstein Telescope (ET)

- -underground facility (suppress noise)
- -triangular configuration
- -10 km long armlength
- -2030s'?
- -Netherlands? Sardinia?

3G detectors: ET and CE



- -All LIGO/Virgo-like BHBs in the Universe up to *z*~20 (~10^5/yr)
- -All neutron star binaries (NSBs) to *z*~2-3 (~10^4/yr)
- -intermediate mass BHs (IMBHs) up to *z*~2 (???)
- -~100 solar mass seed BHs to z~20



The cosmic merger rate depends on many things:

- -mass function
- -cosmic star formation rate
- -metallicity evolution
- -detailed binary evolution
- -time delay distribution (from formation to merger)

(Vitale 2018, Mangiagli+ 2019)

3G will truly probe the cosmic history of star formation and evolution, possibly beyond the epoch of reionization

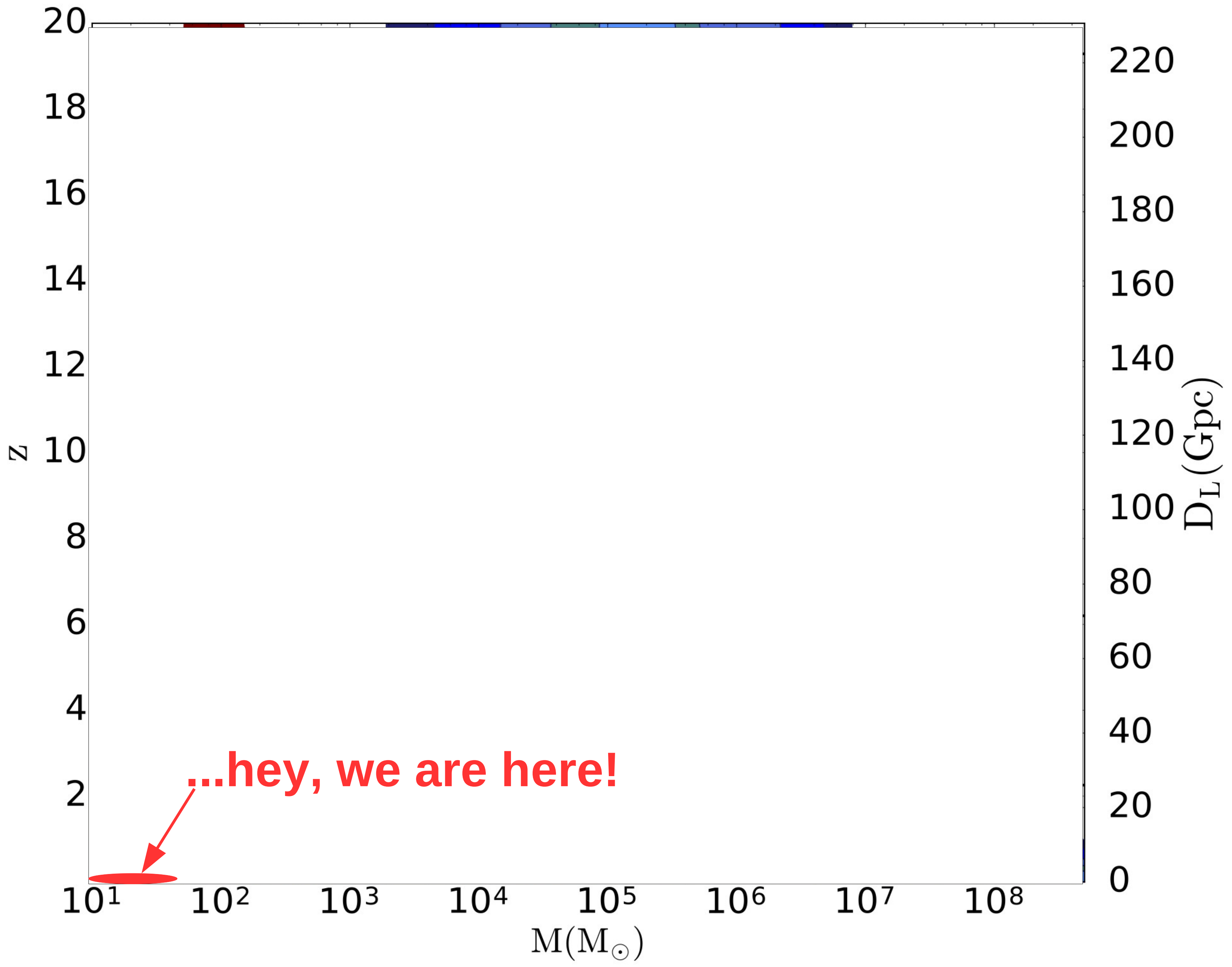
2G detectors are detecting many BHBs (and many more will come) however:

- -3G will increase the sample by at least 2 orders of magnitudes
- -Detailed distribution, can easily separate subpop
- -AGN channel: cross correlation with AGN catalogues?
- -exotic channels: might be too rare for 2G, identifiable in 3G via eccentricity measurement?

MOST IMPORTANTLY:

- -3G have higher redshift reach
- -3G have higher mass reach

Binaries in the z-mass parameter space



3G detectors reach