CREDO Week
Institute of Nuclear Physics,
Polish Academy of Sciences
Cracow

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Gravitational Waves – new dimension of multimessenger astronomy

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im. Augusta Chełkowskiego

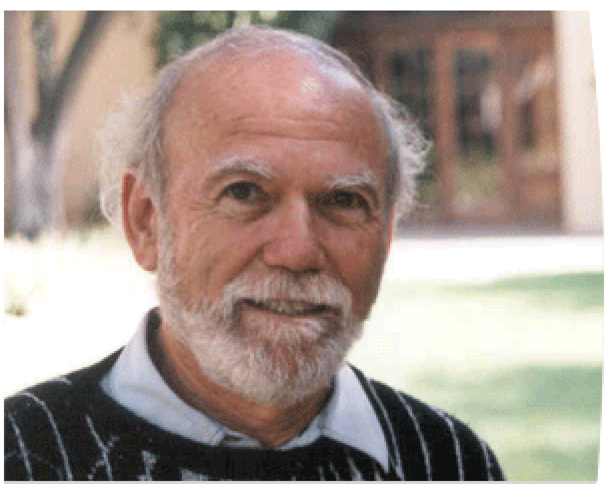
UNIVERSITY OF SILESIA
IN KATOWICE

2017 Nobel Prize in Physics

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

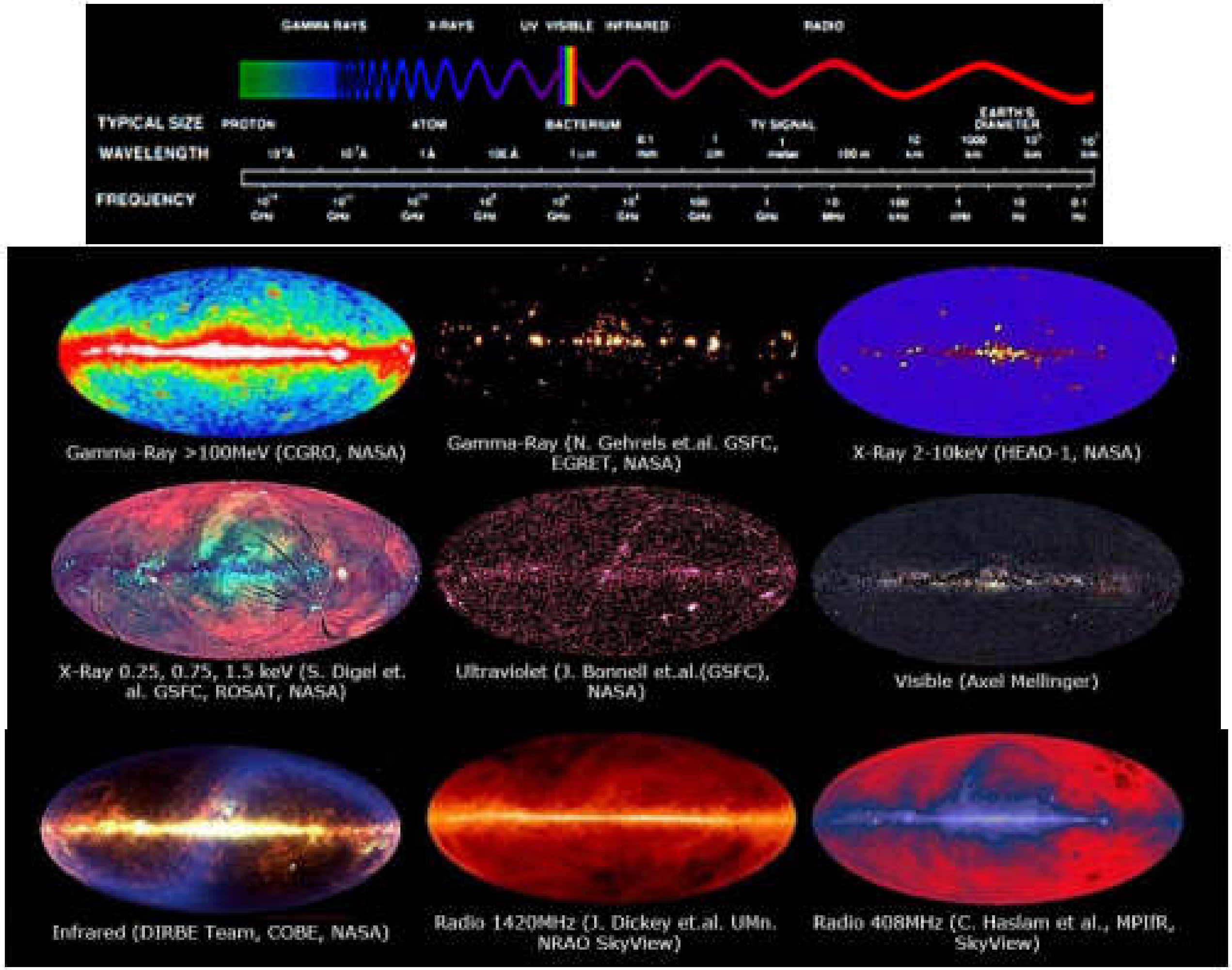
Rainer Weiss
1/2

Kip Thorne
1/4

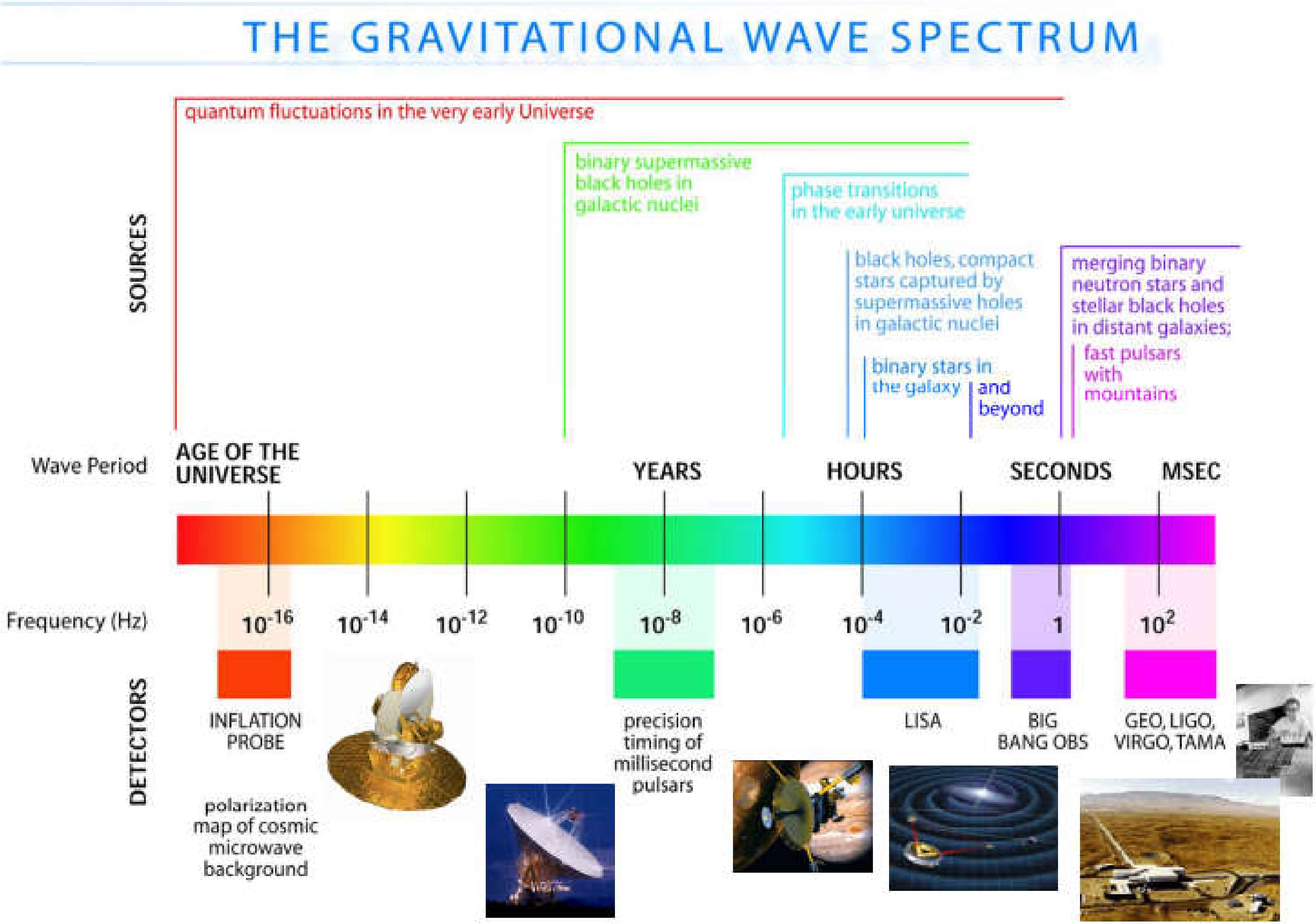


Barry Barish
1/4

Opening a new window on the Universe



Credits: Martin Hendry



Credits: Martin Hendry

How can we observe sources?

- For the majority of sources, some knowledge of the nature of the source is required for detection of a signal
- Matched filtering will be the primary tool for extracting tiny, quasi-periodic signals from the data stream
- Techniques such as the excess power method can be used for other sources, or if less is known about the exact nature of the source

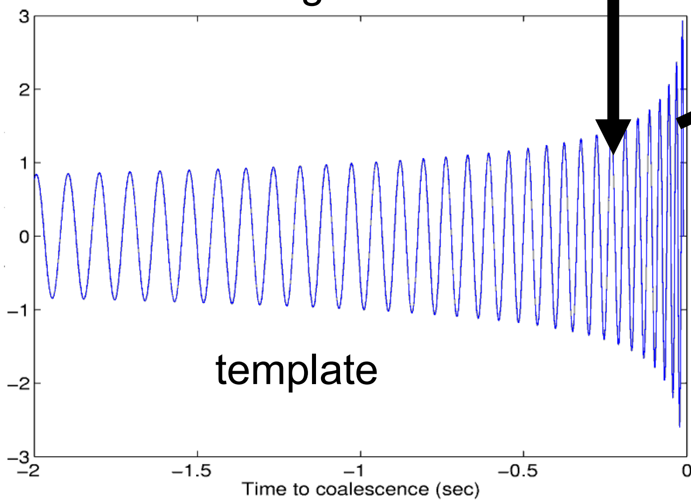
Eventually the most interesting road to discover NEW unexpected sources

i.e. we need to understand the detector’s noise perfectly

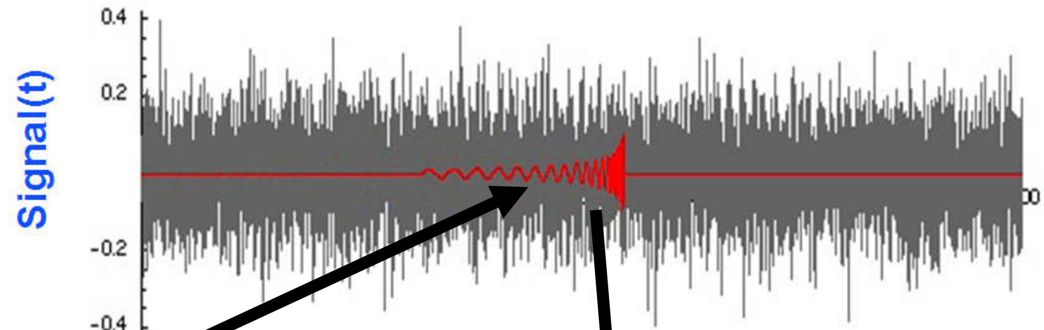
Search of compact binary coalescence

Source

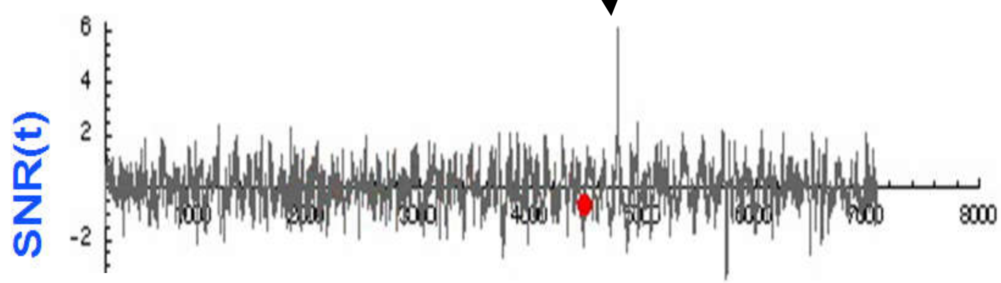
Produces a signal



Hidden in the detector noise



Matched template filtering
(optimal Wiener filter)

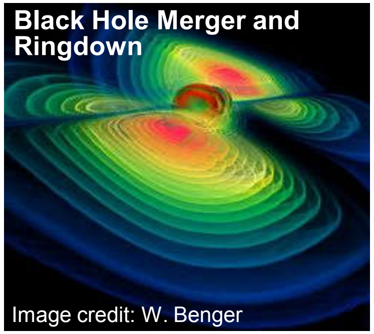


$$\rho^2 := (h|h) = 4\Re \int_0^\infty \frac{|\tilde{h}(f)|^2}{\tilde{S}(f)} \mathrm{d}f$$

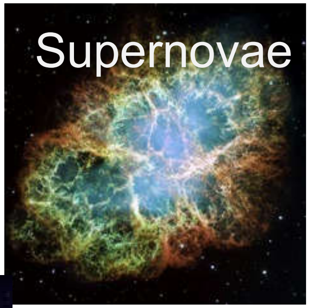
Credits: David Reitze

Gravitational wave sources

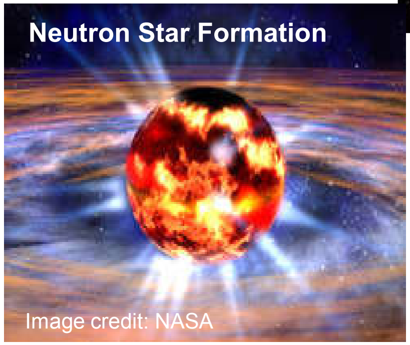
different frequencies, different temporal patterns, different data analysis methods:

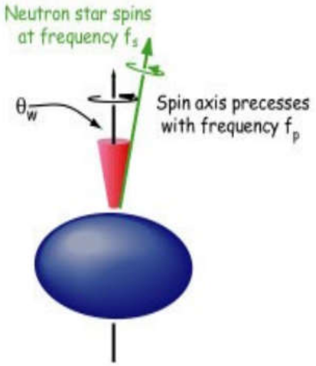


• **inspiraling sources**: compact binary systems (NS-NS, NS-BH, BH-BH)



• **burst sources** supernovae, collisions, black hole formations, **gamma ray bursts**… **cosmic strings cusps**





• **periodic sources**
rotating stars (pulsars), small „mountains", non-uniform density , dynamical instabilities

• **stochastic sources** early universe, unresolved sources...

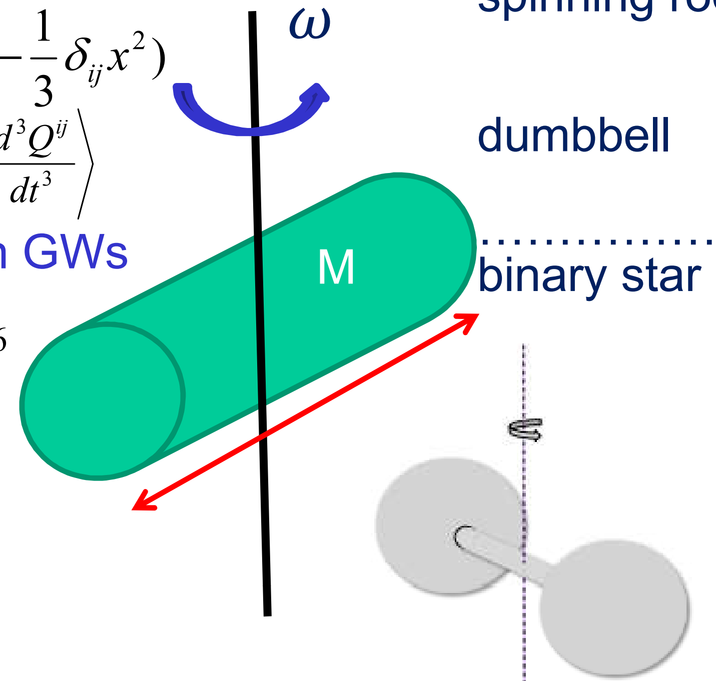
Quadrupole formula

$$h_{ij}(x,t) = \frac{2}{r}\frac{G}{c^4}\frac{d^2}{dt^2}Q_{ij}(ct-r) \qquad Q_{ij}(t) = \int d^3x\, \rho(x,t)(x_i x_j - \frac{1}{3}\delta_{ij}x^2)$$

$$L_{GW} = \frac{1}{5}\frac{G}{c^5}\left\langle \frac{d^3Q_{ij}}{dt^3}\frac{d^3Q^{ij}}{dt^3}\right\rangle$$

$$\frac{c^5}{G} = 3.6\times10^{52}W = 2.\times10^5\frac{M_O c^2}{s}$$

Power radiated in GWs



GW generation is effective for the systems with characteristic: dimensions of order r_s velocities of order c

$$L_{GW} \propto \frac{G}{c^5}M^2L^4\omega^6$$

$$L_G \propto 4\left(\frac{r_s}{r}\right)^2\left(\frac{v}{c}\right)^6\frac{c^5}{G}$$

Other parametrization very strong dependence on the compactness

$$L_G \propto \frac{c^5}{G}\left(\frac{GM}{rc^2}\right)^5$$

$$f_{GW} = \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$$

Kepler's 3rd law

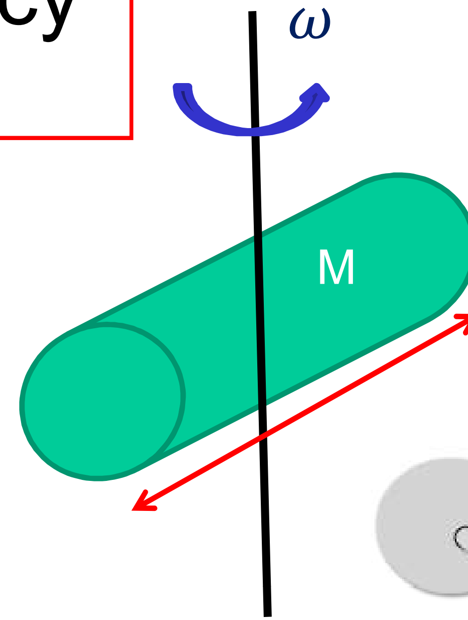
Upper bound for the frequency

$$R \geq R_s = \frac{2GM}{c^2}$$

$$f_{GW}(M) < \frac{1}{4\sqrt{2\pi}}\frac{c^3}{GM} \approx 10^4\ Hz\left(\frac{M_0}{M}\right)$$

Upper bound for the frequency

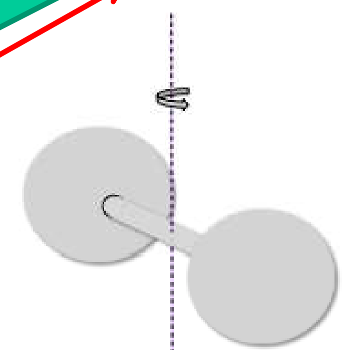
$$\boxed{f_{GW}(M) < \frac{1}{4\sqrt{2\pi}}\frac{c^3}{GM} \approx 10^4\ Hz\left(\frac{M_0}{M}\right)}$$



spinning rod

dumbbell

binary star



1 M_0	10^4 Hz (10 kHz)	NS
10 M_0	10^3 Hz (1 kHz)	stellar mass BH
100 M_0	10^2 Hz (0.1 kHz)	stellar mass BH
10^3 M_0	10 Hz	intermediate mass BH IMBH (in globular clusters)
10^6 M_0	10^{-2} Hz (10 mHz)	supermassive BH SMBH (in centers of galaxies)
10^9 M_0	10^{-5} Hz (10 μHz)	supermassive BH SMBH (in centers of galaxies)

$$f_{GW} = \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$$ Kepler's 3rd law

$$R \geq R_s = \frac{2GM}{c^2}$$

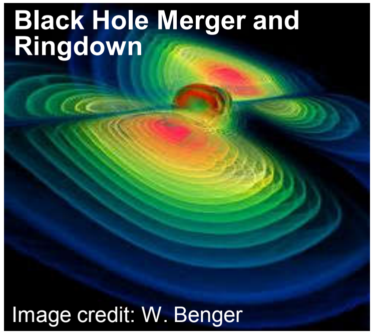
LIGO band 10 Hz – 100 kHz

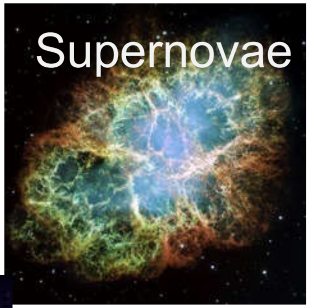
Gravitational wave sources

different frequencies, different temporal patterns,
different data analysis methods:

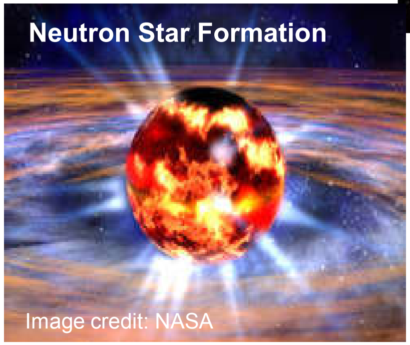
exceptional

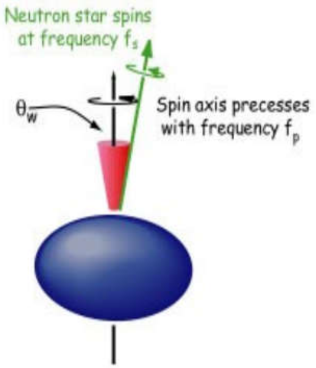
• **inspiraling sources**: compact binary systems
(NS-NS, NS-BH, BH-BH)





• **burst sources** supernovae, collisions,
black hole formations, **(long) gamma ray bursts**…
cosmic strings cusps



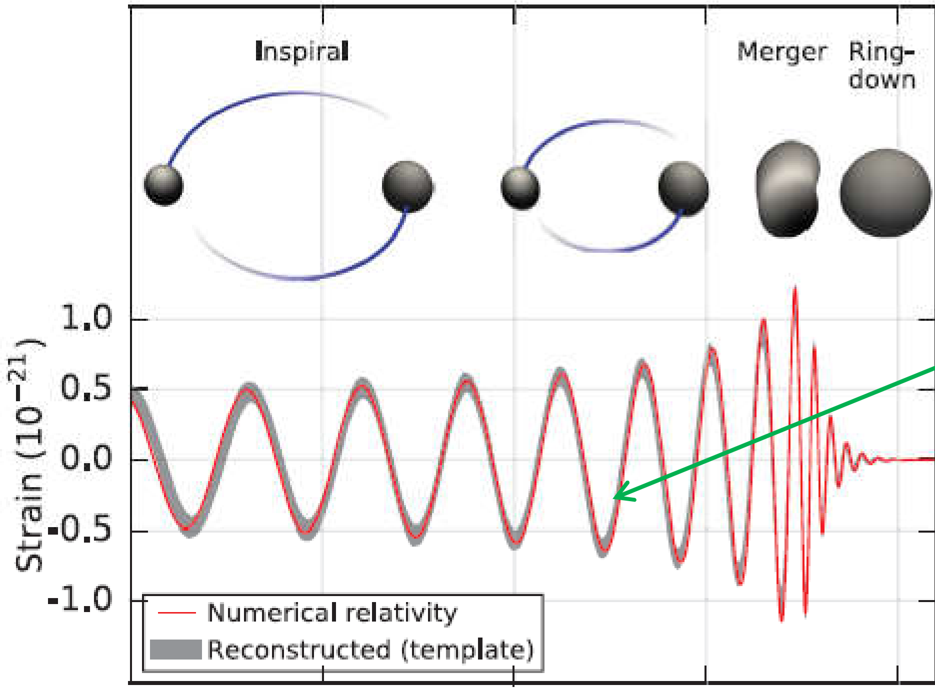


• **periodic sources**
rotating stars (pulsars), small „mountains”,
non-uniform density , dynamical instabilities

• **stochastic sources** early universe, unresolved sources...

The idea of „standard sirens”

B. Schutz 1986
B.Schutz, A. Królak 1987



Measure the strain h(t)
and frequency drift df/dt

$$h = \frac{4\pi^{2/3}(G\mathcal{M})^{5/3}}{c^4 D} f(t)^{2/3} \cos\left[\int_0^t f(t')\,dt'\right]$$

$$\frac{df}{dt} = \frac{96\pi^{8/3}}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

2 equations for 2 unknowns:
„chirp mass” *M* & distance D

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96\pi^{8/3}}\frac{df}{dt}\right)^{3/5} f^{-11/5}$$

$$D = \frac{4c}{\pi^2 h}\frac{df(t)}{dt} f^{-3} \cos\left(\int_0^t f(t')dt'\right)$$

for cosmological sources

$$t \to (1+z)t$$

$$f \to \frac{1}{1+z} f$$

$$\frac{df}{dt} \to \frac{1}{(1+z)^2}\frac{df}{dt}$$

$$M_c \to (1+z)M_c$$

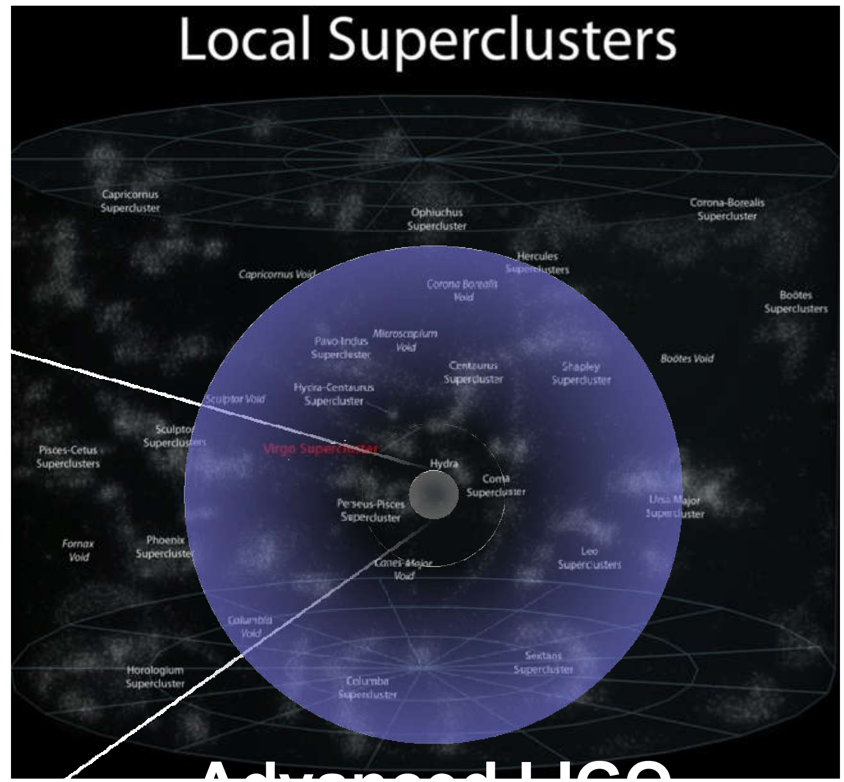
The distance inferred is the **luminosty distance**
*Unfortunately **redshift** cannot be easily measured !*

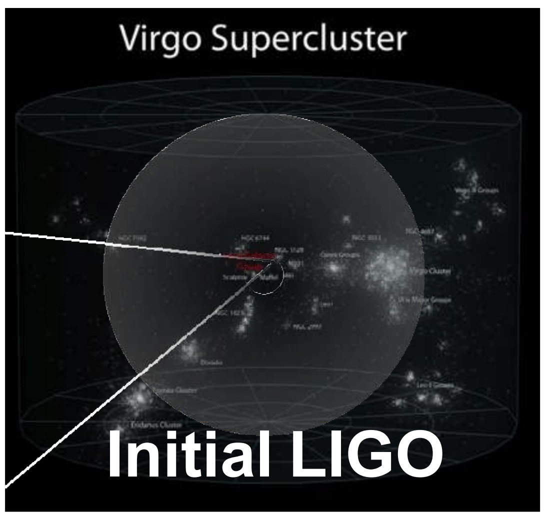
$$D_L = (1+z)\, D$$

Advanced LIGO

- A complete redesign and rebuild of the LIGO interferometers
  - 10x more sensitive, 1000x more of the universe probed
- A discovery machine - expect 10s of detections per year at design sensitivity for binary neutron stars
- An astronomical observatory – gravitational waveforms encode information about the dynamics of cataclysmic events
  - Reveals the universe in ways that electromagnetic astronomy cannot!

Comparison: For NS-NS systems –
- O(100) galaxies in initial LIGO range
- O(100,000) galaxies in Advanced LIGO range

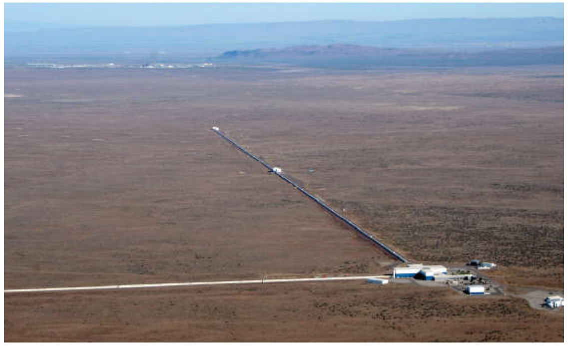


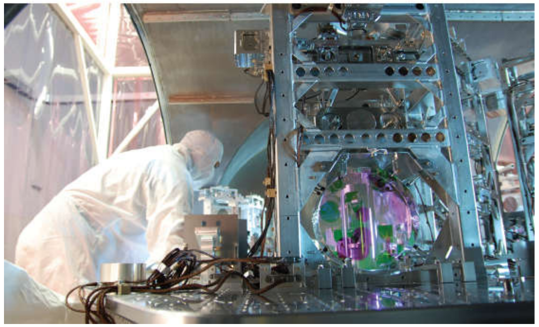


Slide: M. Evans

LIGO PRESS RELEASE

LIGO opens new window on the universe with observation of gravitational waves from colliding black holes





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

+ LVT 151012 !

PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

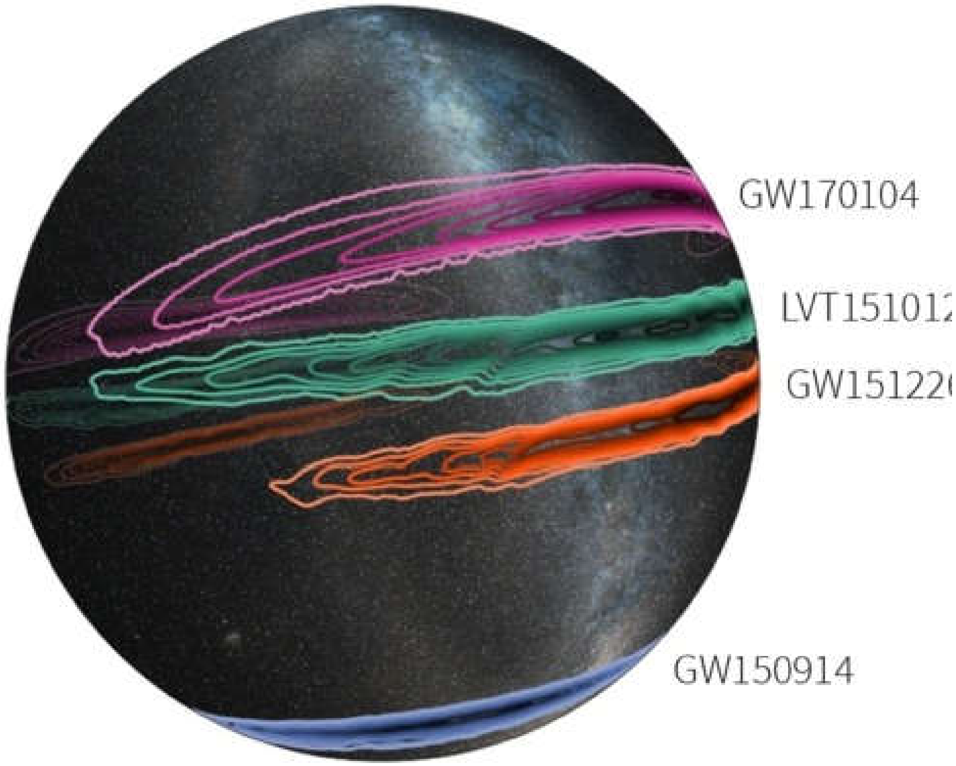
PRL **118,** 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

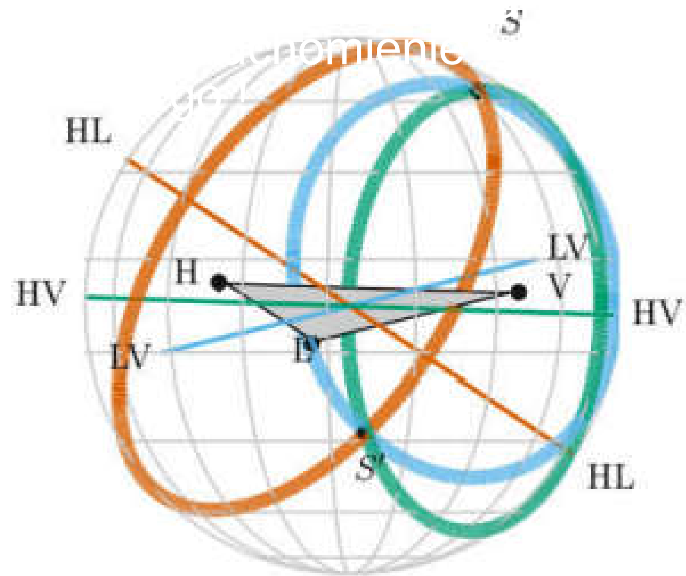
GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

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

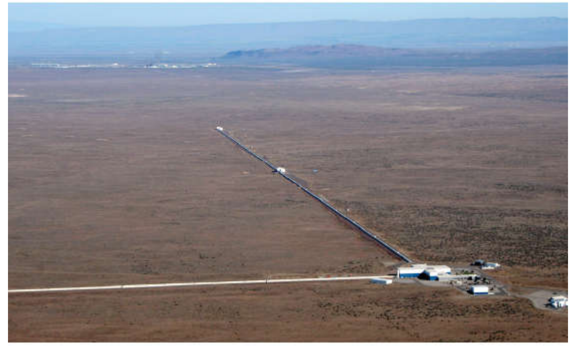
(Received 9 May 2017; published 1 June 2017)

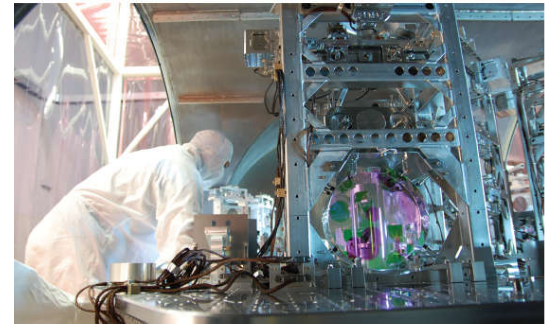
Poor localization for LIGO alone





LIGO opens new window on the universe with observation of gravitational waves from colliding black holes





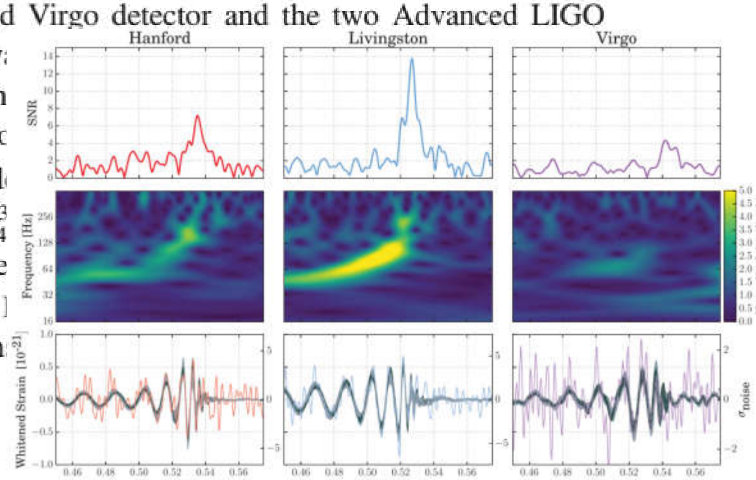
PRL **119,** 141101 (2017) PHYSICAL REVIEW LETTERS week ending 6 OCTOBER 2017

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

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

(Received 23 September 2017; published 6 October 2017)

On August 14, 2017 at 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-w stellar mass black holes, with a false-alarm rate of $\lesssim 1$ in three-detector network matched-filter signal-to-noise ratic holes are $30.5^{+5.7}_{-3.0} M_\odot$ and $25.3^{+2.8}_{-4.2} M_\odot$ (at the 90% credibl 540^{+130}_{-210} Mpc, corresponding to a redshift of $z = 0.11^{+0.03}_{-0.04}$ localization of the source, reducing the area of the 90% cre LIGO detectors to 60 deg^2 using all three detectors. gravitational-wave polarizations from the antenna respon new class of phenomenological tests of gravity.



DOI: 10.1103/PhysRevLett.119.141101

Electromagnetic emission

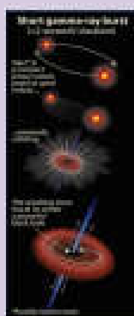
Merger of NS-NS / NS-BH

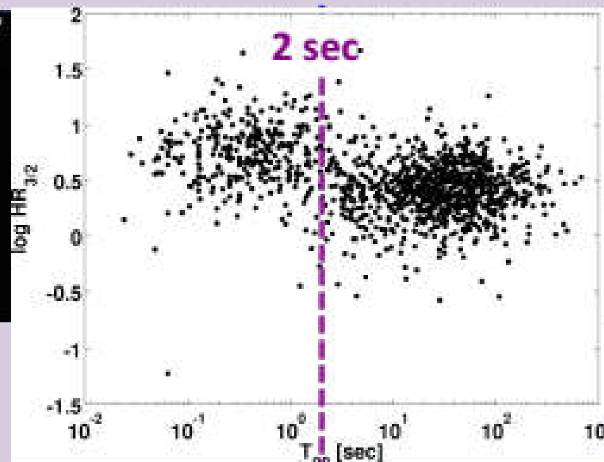
Core collapse of massive star

Gamma-Ray Burst

Short Hard GRB

Progenitor indications:
- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)



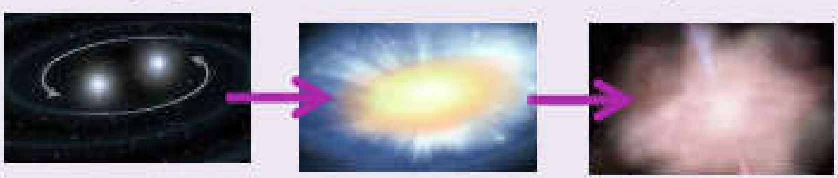


Long Soft GRB

Progenitor strong evidence: observed Type Ic SN spectrum

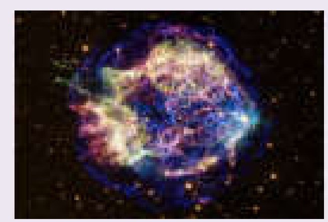
Kilonovae

(Optical/IR, radio remnant)



Supernovae

Type II, Ib/c



GW 170817 – New era of multimessenger astronomy

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

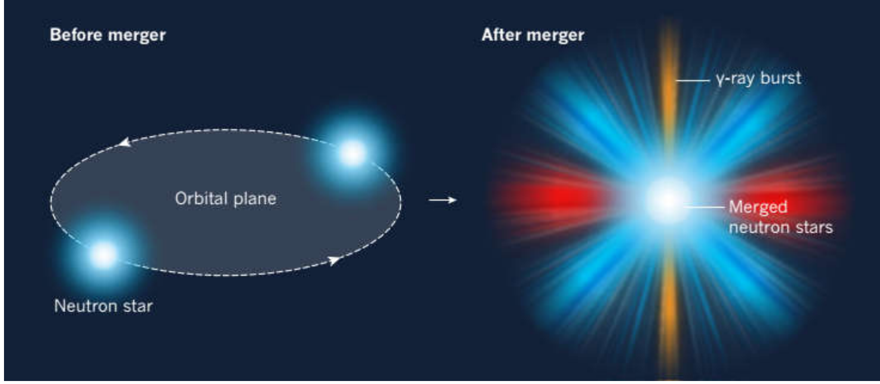
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101

GW170817 –
new dimension of multimessenger astronomy

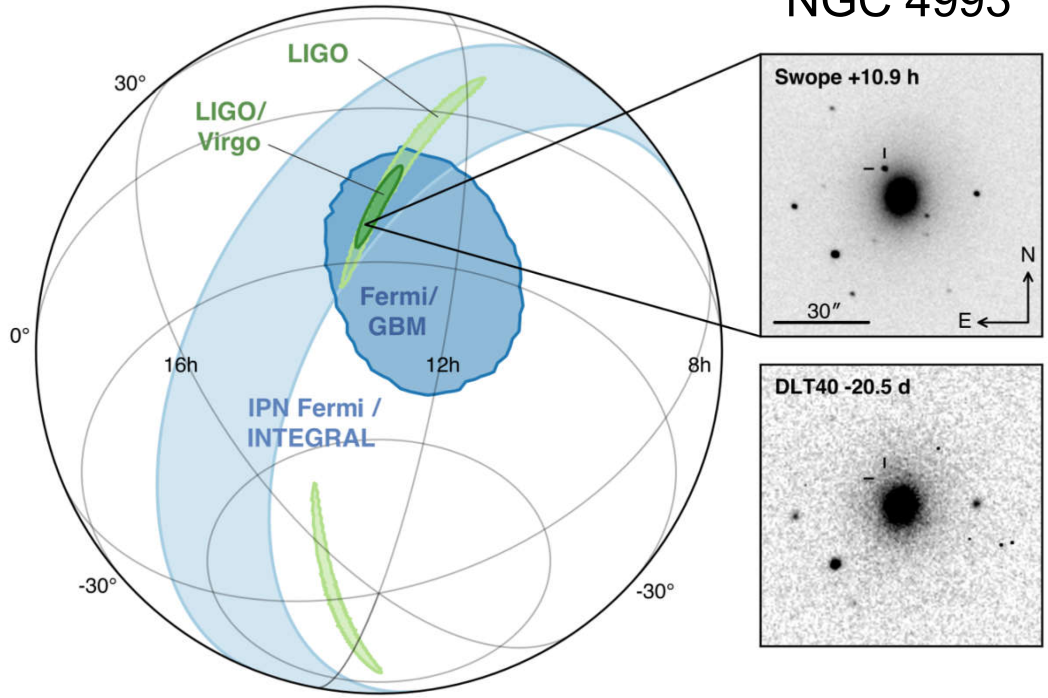


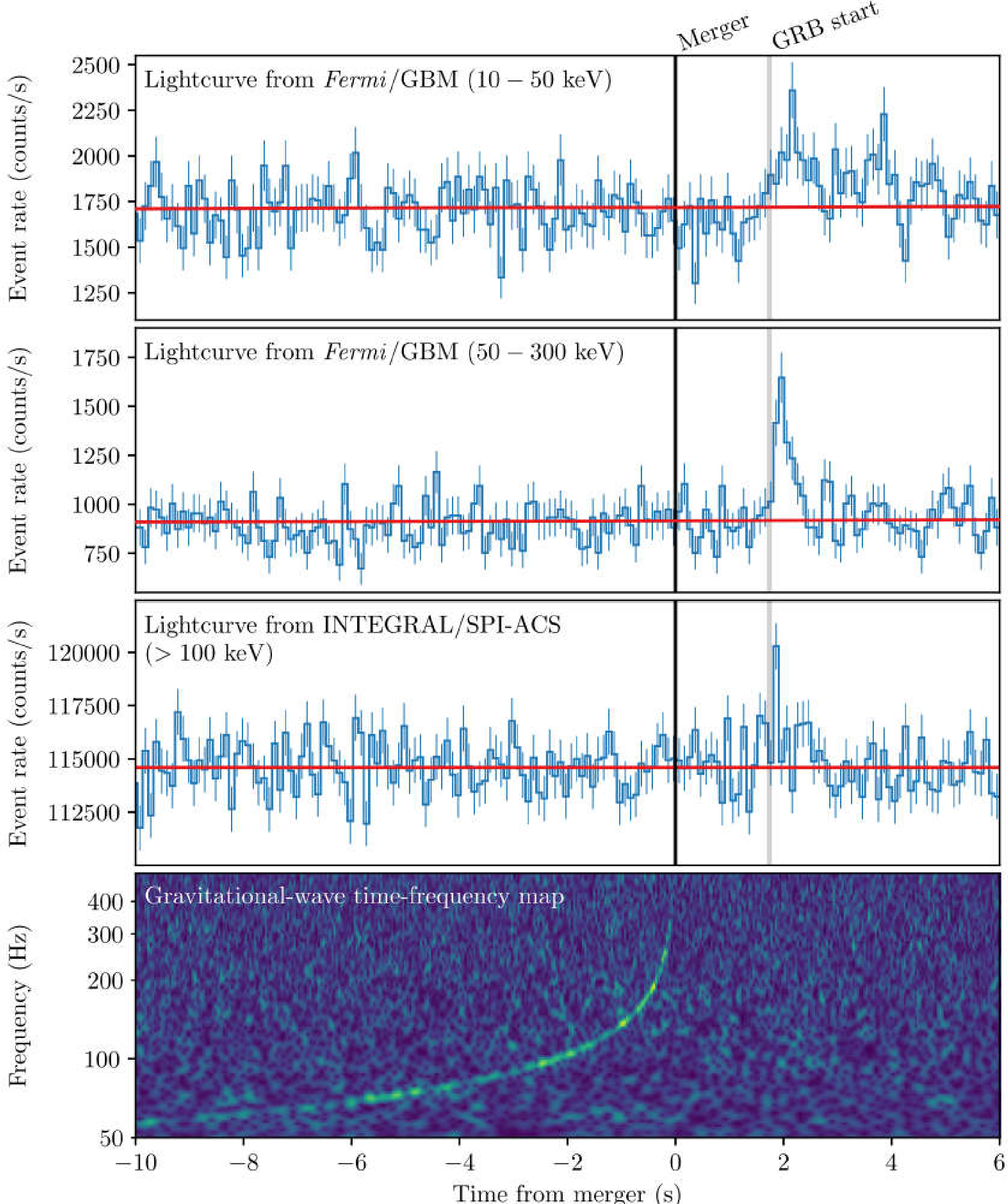
On August 17 2017 at 12:41:04 UTC
Advanced LIGO/Virgo detectors registered for the first time NS-NS coalescence signal

Electromagnetic counterpart signal registered also
- in gamma-rays (Fermi gamma-ray :
1.7 s after coalescence
- X-rays
- in optical
- infrared

- 5 papers in Nature
- dedicated issue of the ApJ
- more than 100 papers released Oct. 17

NGC 4993





Joint
multi-messenger
detection of
GW170817
and
GRB170817A

This single detection allowed us to test

- Theory of gravity
- Theory of NS (E.O.S.)
- Theory of gamma-ray bursts
- Nucleosynthesis of elements heavier than Fe
- Determine the Hubble constant

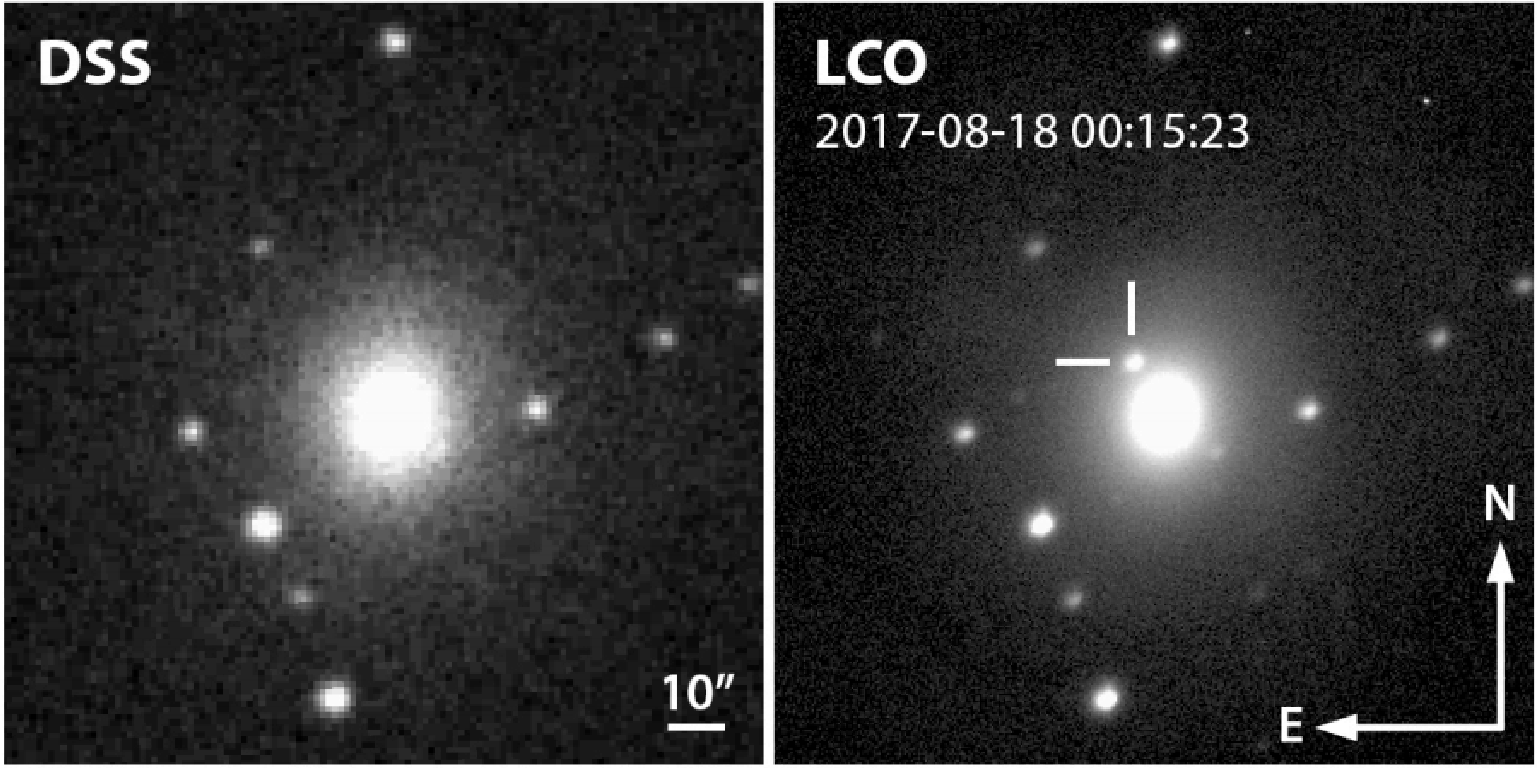


Figure 2 | LCO discovery image of the kilonova AT 2017gfo in the galaxy NGC 4993. The *w*-band LCO image (right), centered on NGC 4993, clearly shows a new source (marked with white ticks) compared to an archival image (left) taken on 1992 April 9 with the RG610 filter as part of the AAO-SES survey, retrieved via the Digitized Sky Survey (DSS).

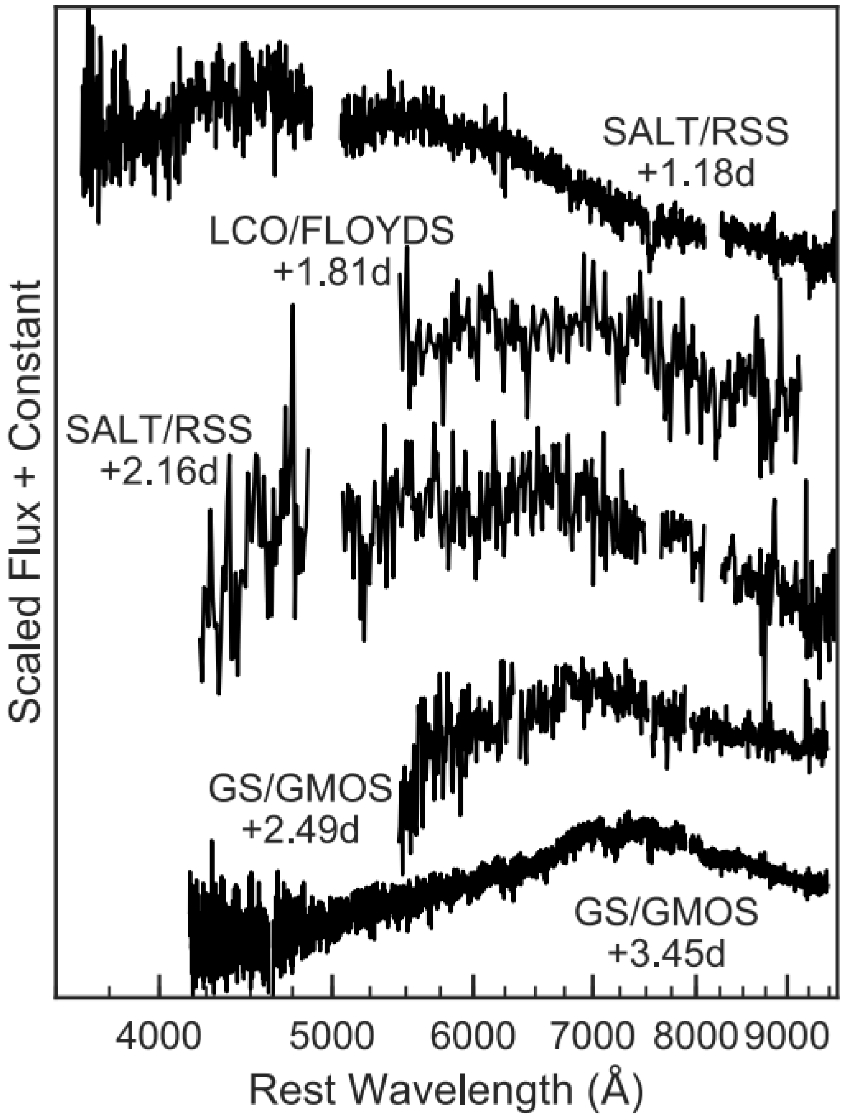
LCO – Las Cumbres Observatory; CTIO – Cerro Tololo Inter-American Observatory

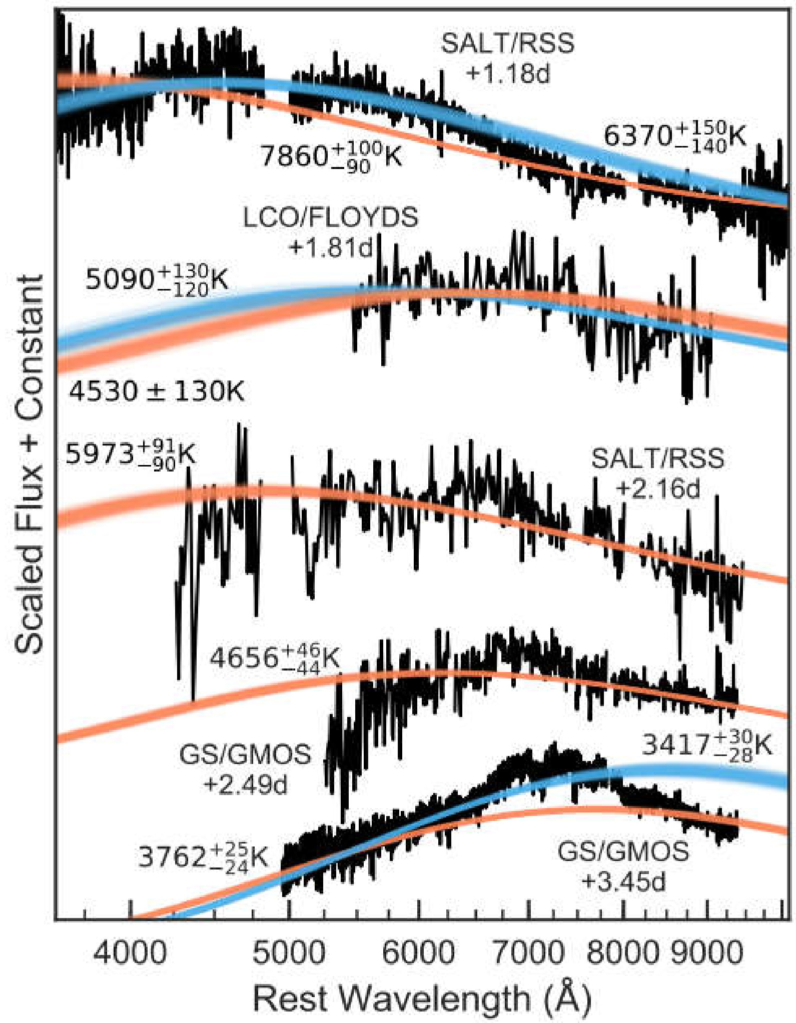
The Astrophysical Journal Letters, 848:L32 (8pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa9111

Spectroscopic evolution of the KN optical counterpart – from blue to red

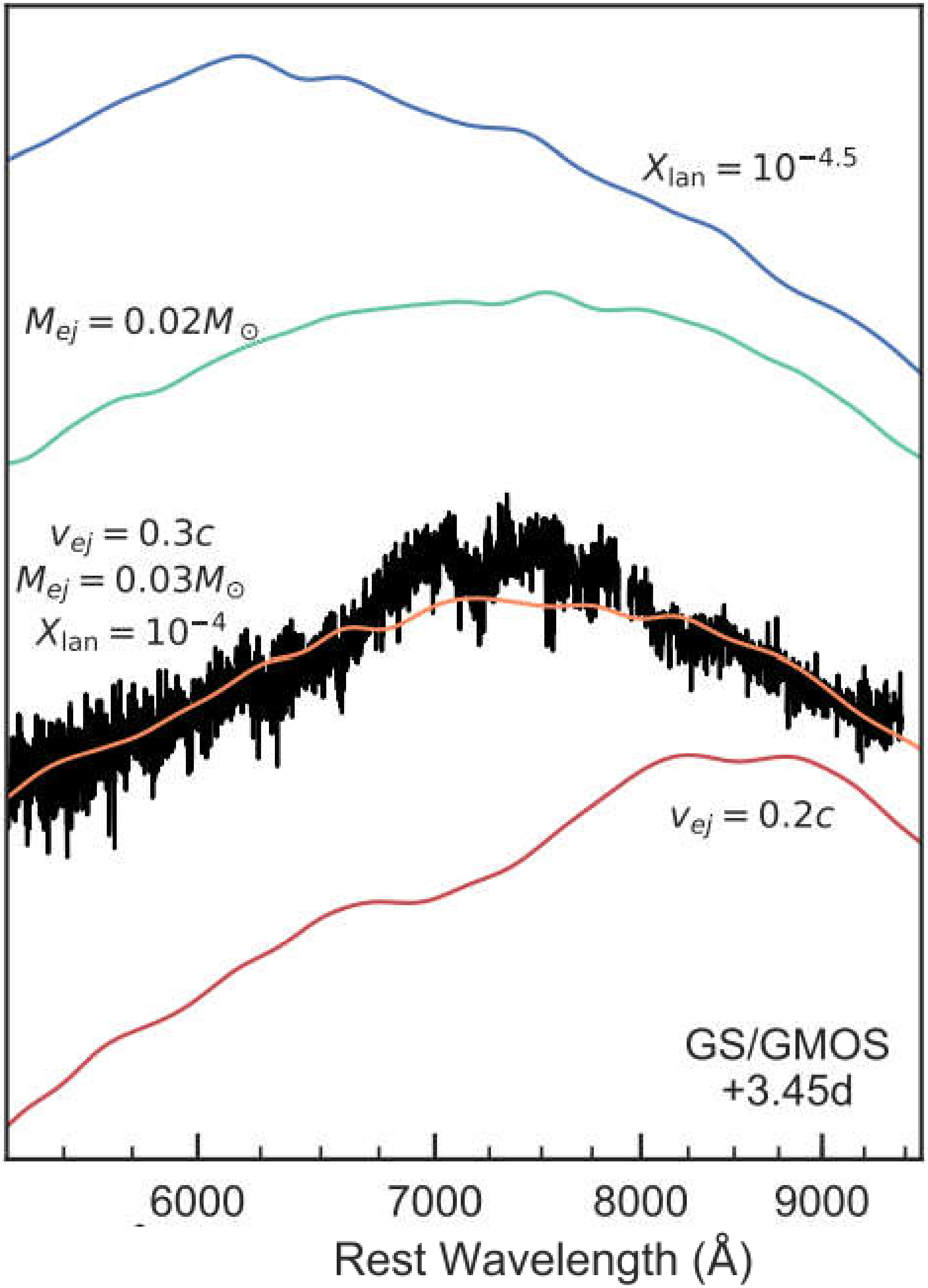
The Rapid Reddening and Featureless Optical Spectra of the Optical Counterpart of GW170817, AT 2017gfo, during the First Four Days

Curtis McCully[1,2], Daichi Hiramatsu[1,2], D. Andrew Howell[1,2], Griffin Hosseinzadeh[1,2], Iair Arcavi[1,2,19], Daniel Kasen[3,4,5], Jennifer Barnes[6,19], Michael M. Shara[7,8], Ted B. Williams[9], Petri Väisänen[9,10], Stephen B. Potter[9], Encarni Romero-Colmenero[9,10], Steven M. Crawford[9,10], David A. H. Buckley[9,10], Jeffery Cooke[11,12,13], Igor Andreoni[11,13,14], Tyler A. Pritchard[11], Jirong Mao[15,16,17], Mariusz Gromadzki[18], and Jamison Burke[1,2]





BB fits



KN models predict opacity driven by r-processes elements:

Sensitive to lanthanides/actinides abundance

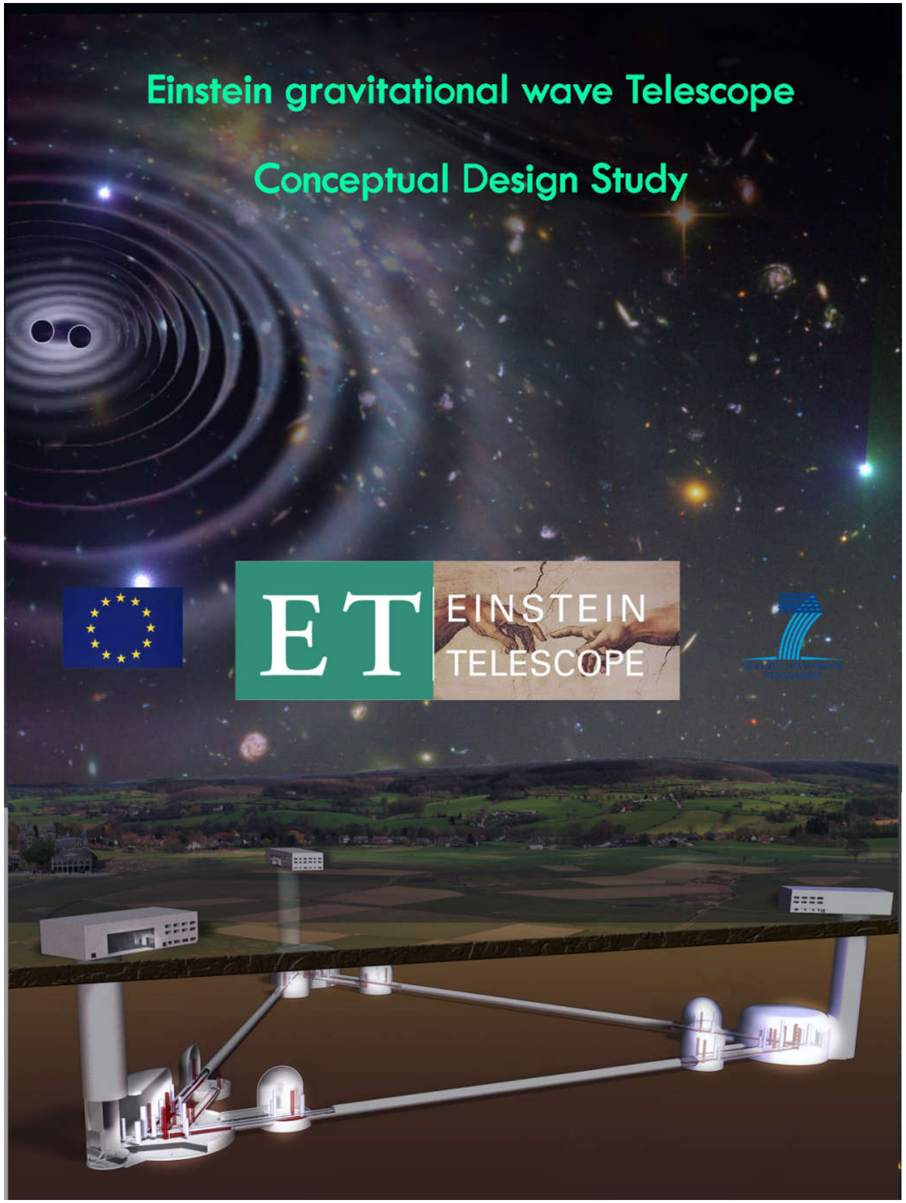
Table 1: Key Properties of GW170817

Property	Value	Reference
Chirp mass, $\mathcal{M}$ (rest frame)	$1.188^{+0.004}_{-0.002} M_\odot$	1
First NS mass, M_1	$1.36 - 1.60 M_\odot$ (90%, low spin prior)	1
Second NS mass, M_2	$1.17 - 1.36 M_\odot$ (90%, low spin prior)	1
Total binary mass, $M_{\rm tot} = M_1 + M_2$	$\approx 2.74^{0.04}_{-0.01} M_\odot$	1
Observer angle relative to binary axis, $\theta_{\rm obs}$	$11 - 33°$ (68.3%)	2
Blue KN ejecta ($A_{\rm max} \lesssim 140$)	$\approx 0.01 - 0.02 M_\odot$	e.g., 3,4,5
Red KN ejecta ($A_{\rm max} \gtrsim 140$)	$\approx 0.04 M_\odot$	e.g., 3,5,6
Light r-process yield ($A \lesssim 140$)	$\approx 0.05 - 0.06 M_\odot$	
Heavy r-process yield ($A \gtrsim 140$)	$\approx 0.01 M_\odot$	
Gold yield	$\sim 100 - 200 M_\oplus$	8
Uranium yield	$\sim 30 - 60 M_\oplus$	8
Kinetic energy of off-axis GRB jet	$10^{49} - 10^{50}$ erg	e.g., 9, 10, 11, 12
ISM density	$10^{-4} - 10^{-2}$ cm^{-3}	e.g., 9, 10, 11, 12

(1) LIGO Scientific Collaboration et al. 2017c; (2) depends on Hubble Constant, LIGO Scientific Collaboration et al. 2017d; (3) Cowperthwaite et al. 2017; (4) Nicholl et al. 2017; (5) Kasen et al. 2017; (6) Chornock et al. 2017; (8) assuming heavy r-process ($A > 140$) yields distributed as solar abundances (Arnould et al., 2007); (9)Margutti et al. 2017; (10) Troja et al. 2017; (11) Fong et al. 2017; (12) Hallinan et al. 2017

ET Design Study

Einstein Telescope



- Increased sensitivity
  great expectations
- Big catalogs of inspiral events at cosmological distances

10^3 - 10^8 events per yr
distances up to 2 Gpc (z=17)

- Some of them would be gravitationally lensed

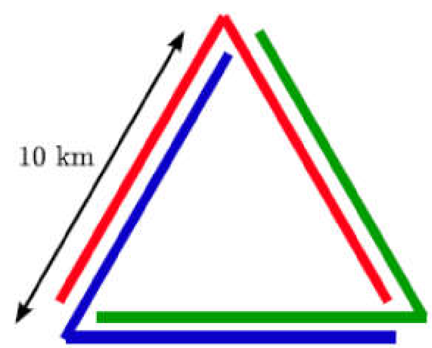
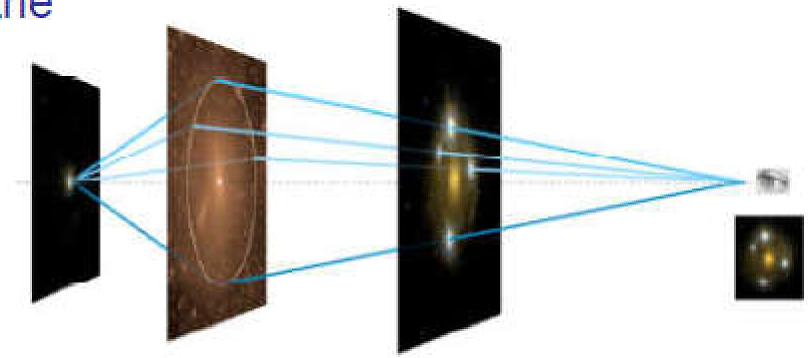


Figure 6: Three nested detectors in a triangular arrangement will form the final Einstein Telescope geometry.

Gravitational Lensing

Spherically symmetric lens model – the simplest realistic case



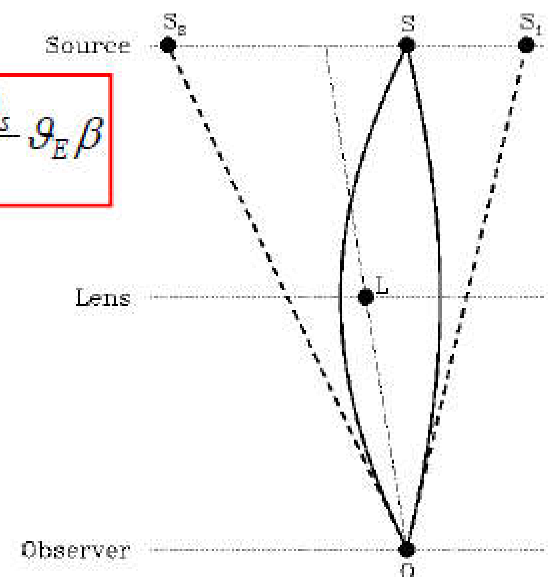
Einstein radius (determined by **mass** !)
- defines **characteristic angular scale**

$$\boxed{\vartheta_E = \sqrt{\frac{4GM_E}{c^2}\frac{D_{ls}}{D_s D_l}}}$$

Two images form on the opposite side of the lens

Time delay between images

$$\boxed{\Delta t = \frac{2(1+z_l)}{c}\frac{D_l D_s}{D_{ls}}\vartheta_E \beta}$$



Two lensing regimes:

Strong:
•multiple images
•time delays between images – (a method to measure H_0)

Weak: image distortion

7

Discussed in papers

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Strong gravitational lensing of gravitational waves in Einstein Telescope

Aleksandra Piórkowska,[a] Marek Biesiada[a] and Zong-Hong Zhu[b]

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[b]Department of Astronomy, Beijing Normal University, Beijing 100875, China

A. Piórkowska *et al.* JCAP10(2013)022

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Strong gravitational lensing of gravitational waves from double compact binaries — perspectives for the Einstein Telescope

Marek Biesiada,[a,b] Xuheng Ding,[a] Aleksandra Piórkowska[b] and Zong-Hong Zhu[a]

M. Biesiada *et al.* JCAP10(2014)080

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Strongly lensed gravitational waves from intrinsically faint double compact binaries — prediction for the Einstein Telescope

Xuheng Ding,[a] Marek Biesiada[a,b,c] and Zong-Hong Zhu[a]

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X. Ding *et al.* JCAP12(2015)006

50 – 100 lensed events per yr

Benefits from just a dozen of lensed EM + GW signals

ARTICLE

DOI: 10.1038/s41467-017-01152-9 OPEN

Precision cosmology from future lensed gravitational wave and electromagnetic signals

Kai Liao[1,2], Xi-Long Fan[3], Xuheng Ding[1,4,5], Marek Biesiada[4,6] & Zong-Hong Zhu[1,4]

The standard siren approach of gravitational wave cosmology appeals to the direct luminosity distance estimation through the waveform signals from inspiralling double compact binaries, especially those with electromagnetic counterparts providing redshifts. It is limited by the calibration uncertainties in strain amplitude and relies on the fine details of the waveform. The Einstein telescope is expected to produce 10^4–10^5 gravitational wave detections per year, 50–100 of which will be lensed. Here, we report a waveform-independent strategy to achieve precise cosmography by combining the accurately measured time delays from strongly lensed gravitational wave signals with the images and redshifts observed in the electromagnetic domain. We demonstrate that just 10 such systems can provide a Hubble constant uncertainty of 0.68% for a flat lambda cold dark matter universe in the era of third-generation ground-based detectors.

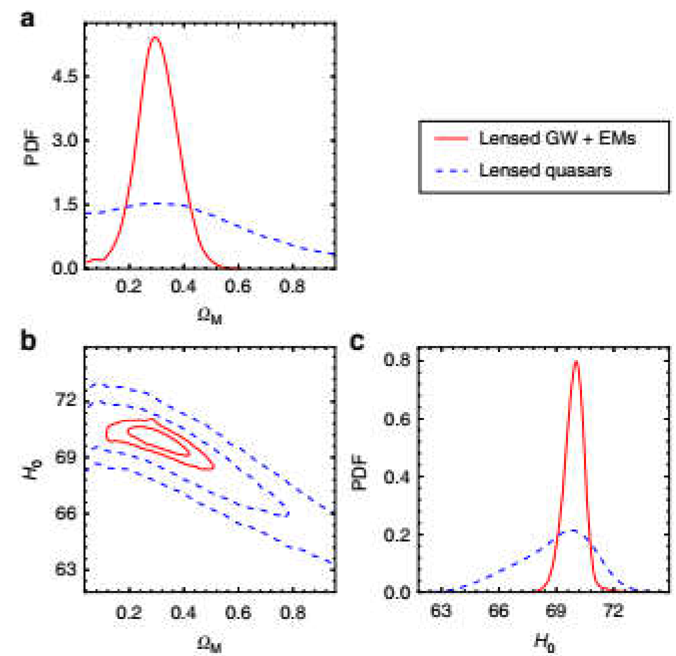

Table 2 The average constraining power of 10 lensed gravitational wave + electromagnetic systems

	Flat ΛCDM (Ω_M fixed)	Flat ΛCDM		Flat ωCDM			Open ΛCDM		
	H_0	H_0	Ω_M	H_0	Ω_M	w	H_0	Ω_M	Ω_k
Uncertainty	0.37%	0.68%	27%	2.2%	36%	25%	1%	38%	±0.18

We concerns cosmological parameters in different scenarios: flat lambda cold dark matter (Flat ΛCDM) with or without dimensionless matter density Ω_M fixed, flat ωCDM where the dark energy equation of state ω is a free parameter, and open ΛCDM where cosmic curvature Ω_k is a free parameter. For the same number of lensed quasars, the power is weaker by a factor of ~4 according to the uncertainty propagation using Eq. (1) and Table 1

Interesting application of lensed GW signals

PRL **118,** 091102 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

Speed of Gravitational Waves from Strongly Lensed Gravitational Waves and Electromagnetic Signals

Xi-Long Fan,[1,2,*] Kai Liao,[3] Marek Biesiada,[4,5] Aleksandra Piórkowska-Kurpas,[4] and Zong-Hong Zhu[1,5,†]
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[2]*Departments of Physics and Mechanical & Electrical Engineering, Hubei University of Education, Wuhan 430205, China*
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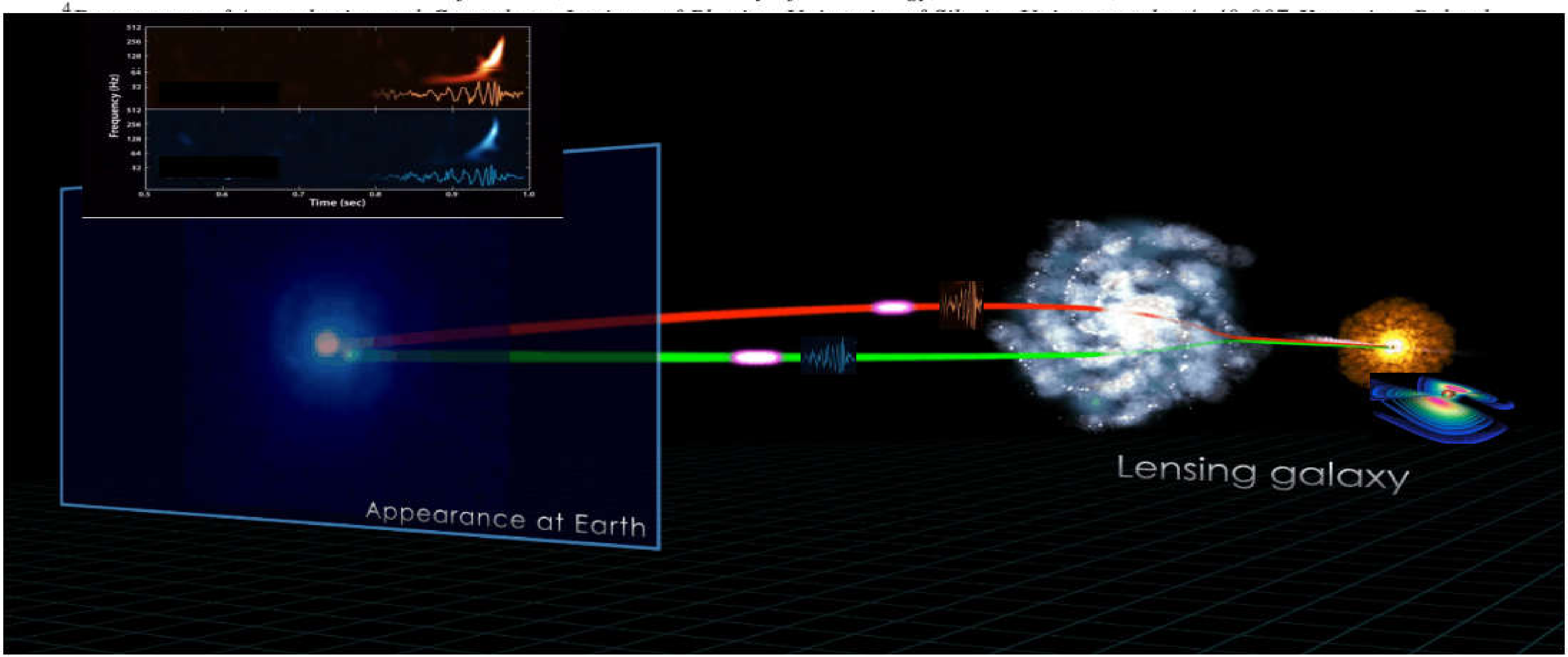


General Idea

Classically GW propagates with the speed of light c, but in some theories of modified gravity it can propagate with v_{GW} different from c

In a strongly lensed event time delays between images in GW Δt_{GW} and in EM Δt_γ would be different.

$$\Delta t_{\mathrm{SIS,GW}} - \Delta t_{\mathrm{SIS},\gamma} = \Delta t_{\mathrm{SIS},\gamma} \frac{m_{\mathrm{GW}}^2 c^4}{E^2} F_{\mathrm{lens}}(z_l, z_s),$$

where

$$F_{\mathrm{lens}}(z_l,z_s) = 1 + \frac{(1+z_s) I_2(0,z_s)}{2\tilde{r}(z_l,z_s)} - \frac{(1+z_l) I_2(0,z_l)}{2\tilde{r}(z_l)} - \frac{(1+z_l) I_2(0,z_l)}{\tilde{r}(z_l,r_s)}.$$

with the notation

$$I_n(z_1,z_2) := \int_{z_1}^{z_2} \frac{dz'}{(1+z')^n h(z')},$$

timing accuracy

$$1 - \left(\frac{v_{GW}}{c}\right)^2 \le \frac{\delta T}{\Delta t_\gamma F_{\mathrm{lens}}(z_l, z_s)}$$

time delay in EM

$$\boxed{1 - \left(\frac{v_{\mathrm{GW}}}{c}\right)^2 \le 4.26 \times 10^{-10} \left(\frac{\delta T}{1\ \mathrm{ms}}\right) \left(\frac{\sigma}{250\ \mathrm{km/s}}\right)^{-4} \times \left(\frac{y}{0.1}\right)^{-1}, \quad (20)}$$

$$\Delta t_{\mathrm{SIS,GW}} - \Delta t_{\mathrm{SIS},\gamma} = \Delta t_{\mathrm{SIS},\gamma} \frac{m_{\mathrm{GW}}^2 c^4}{E^2} F_{\mathrm{lens}}(z_l, z_s),$$

where

$$F_{\mathrm{lens}}(z_l,z_s)=1+\frac{(1+z_s)I_2(0,z_s)}{2\tilde{r}(z_l,z_s)} - \frac{(1+z_l)I_2(0,z_l)}{2\tilde{r}(z_l)} - \frac{(1+z_l)I_2(0,z_l)}{\tilde{r}(z_l,r_s)}.$$

with the notation

$$I_n(z_1,z_2) := \int_{z_1}^{z_2} \frac{dz'}{(1+z')^n h(z')},$$

General bound:

timing accuracy

$$1 - \left(\frac{v_{GW}}{c}\right)^2 \leq \frac{\delta T}{\Delta t_\gamma F_{\mathrm{lens}}(z_l, z_s)}$$

time delay in EM

$$\boxed{1 - \left(\frac{v_{\mathrm{GW}}}{c}\right)^2 \leq 4.26 \times 10^{-10} \left(\frac{\delta T}{1\ \mathrm{ms}}\right)\left(\frac{\sigma}{250\ \mathrm{km/s}}\right)^{-4} \times \left(\frac{y}{0.1}\right)^{-1}, \qquad (20)}$$

Lorentz Invariance Violating theories

Long searched-for Quantum Gravity is often expected to provide „foamy space-time” at short distances

i.e. a possible breakdown of Lorentz invariance could be expected

The simplest manifestation of QG phenomenology – energy dependent
relativistic dispersion relation, e.g.

$$E^2 - p^2c^2 = \epsilon E^2 \left(\frac{E}{\xi_n E_{QG}}\right)^n$$

for photons

$$E_\nu^2 - p_\nu^2 c^2 - m_\nu^2 c^4 = \epsilon E_\nu^2 \left(\frac{E_\nu}{\xi_n E_{\mathrm{QG}}}\right)^n$$

for massive particles

„sign parameter”

$$\varepsilon = \pm 1$$

„Quantum Gravity” energy scale

Time of flight approach: (Amelino-Camelia, Ellis, Sarkar, Piran …)
Measure energy dependent time delays from astrophysical sources

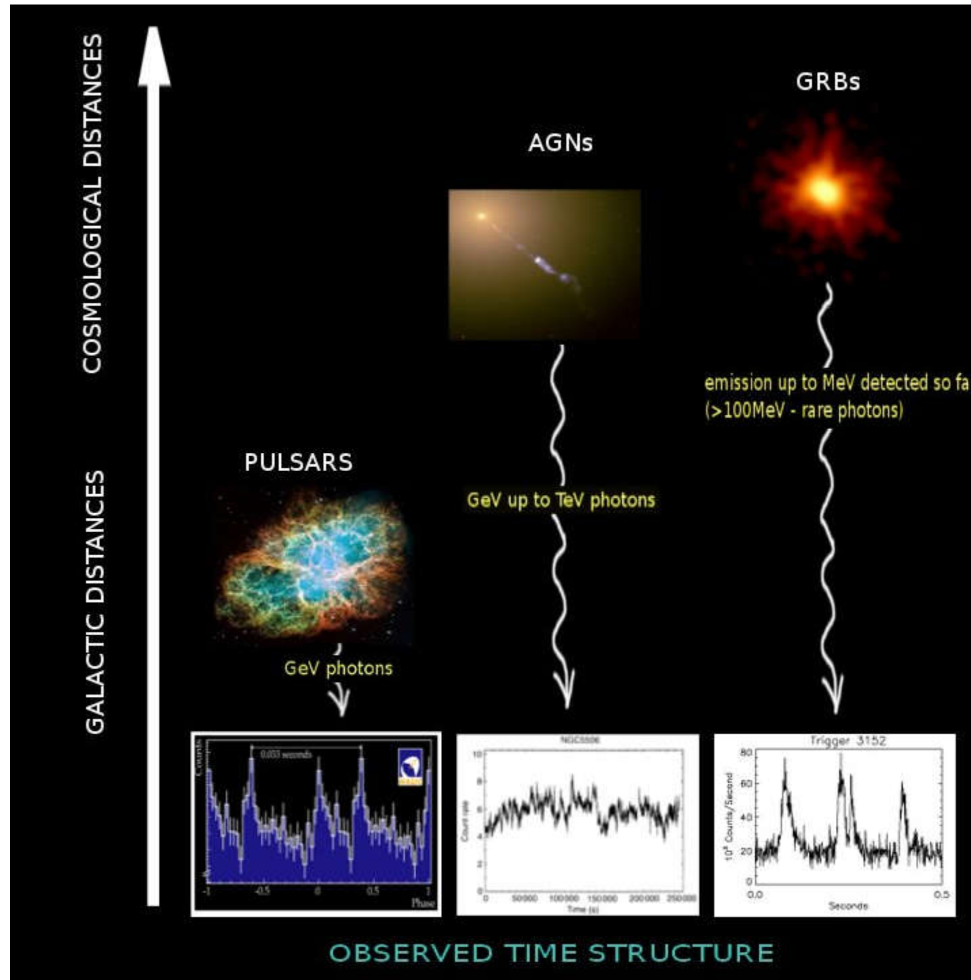
bonus: astronomical / cosmological distances compensate for weakness of the LIV effect – time delay is a cumulative (integral) effect

problems: intrinsic E-dependent time delays in emission, transparency of the Universe to high E photons

<u>sources:</u>

Blazars (BL Lac AGNs)
– e.g. Mkn 501 –
20 TeV photons detected
(rather close extragalactic sources)

Gamma Ray Bursts
highly energetic events,
TeV photons and neutrinos expected to be produced
(visible from much higher distances)
$0.5 < z < 6$ cosmological background has to be taken into account



How to get rid of intrinsic time lags ?

Mon. Not. R. Astron. Soc. 396, 946–950 (2009)
doi:10.1111/j.1365-2966.2009.14748.x

Gravitational lensing time delays as a tool for testing Lorentz-invariance violation

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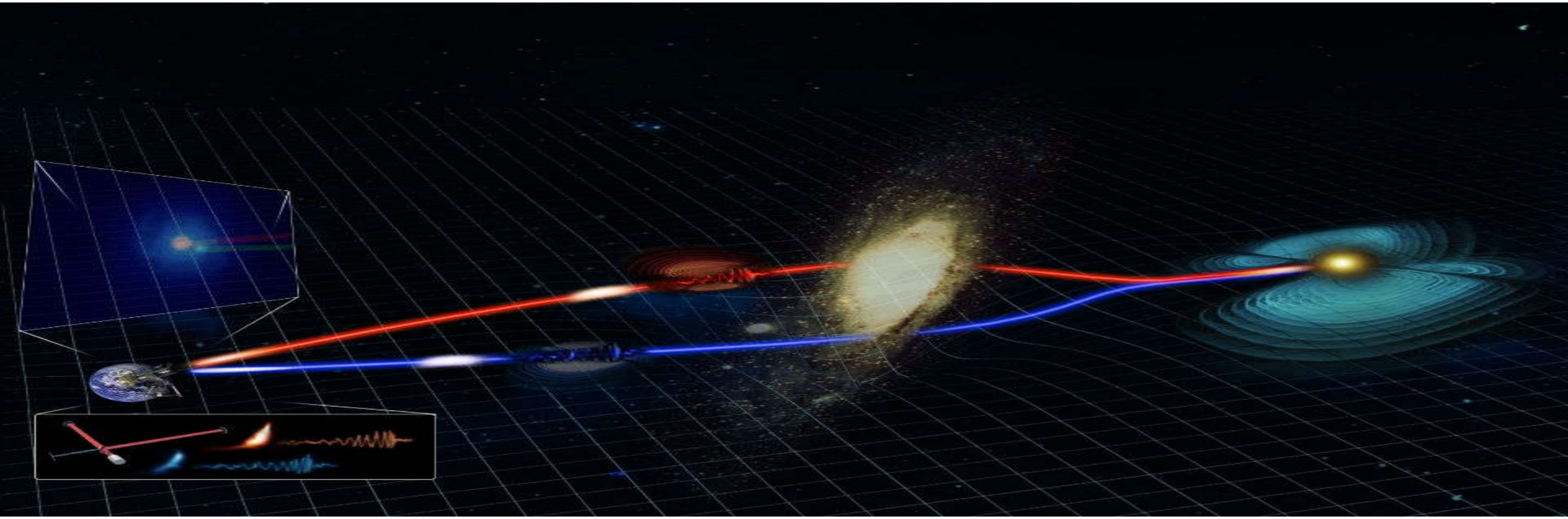

Observing time delays between images in two energy bands

low-energy (classic) vs. VHE photons,

we would see a difference in time delays

$$\boxed{\Delta t_{LIV,SIS} - \Delta t_{SIS} = \frac{8\pi}{H_0}\beta\frac{\sigma^2}{c^2}\frac{E}{E_{QG}}\int_0^z \frac{(1+z')dz'}{H(z')}}$$

$3.7 \times 10^{-9}\ s$ for $5\ TeV$

$1.5 \times 10^{-8}\ s$ for $20\ TeV$

Advantages:

- it gets rid of the intrinsic time delay effect (differential setting)
- it could be assessed in two completely independent (although coordinated !) observational campaigns – one at low energy and the other at high energy

Conclusion:

Era of GW astronomy has begun

This creates great opportunities for multimessenger astronomy

New perspectives for gravitational lensing

Stay tuned !