Gravitational Wave Cosmology
重力波宇宙学

— Dawn is Arriving! —
黎明即将到来!

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YITP, Kyoto University
LeCosPA, National Taiwan University

23 May, 2018

Gravitational Waves?

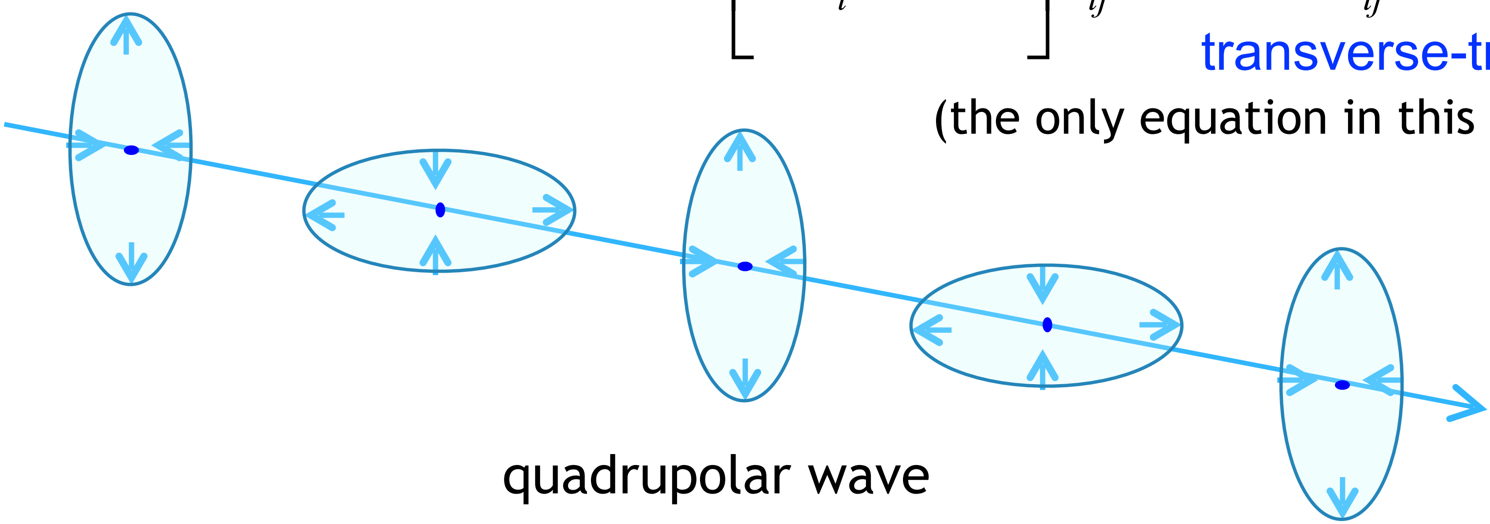
What are Gravitational Waves (GW)?

- GWs are ripples of spacetime, propagating at c, predicted by Einstein in 1916.
- Emitted when energy distribution fluctuates violently.
- GW propagates by stretching and contracting space perpendicular to the propagation direction (quadrupolar (spin=2) wave)

$$\left[-\partial_t^2 + c^2 \overset{(3)}{\Delta}\right] h_{ij} = 0, \quad \partial^i h_{ij} = h^i{}_i = 0$$

transverse-traceless

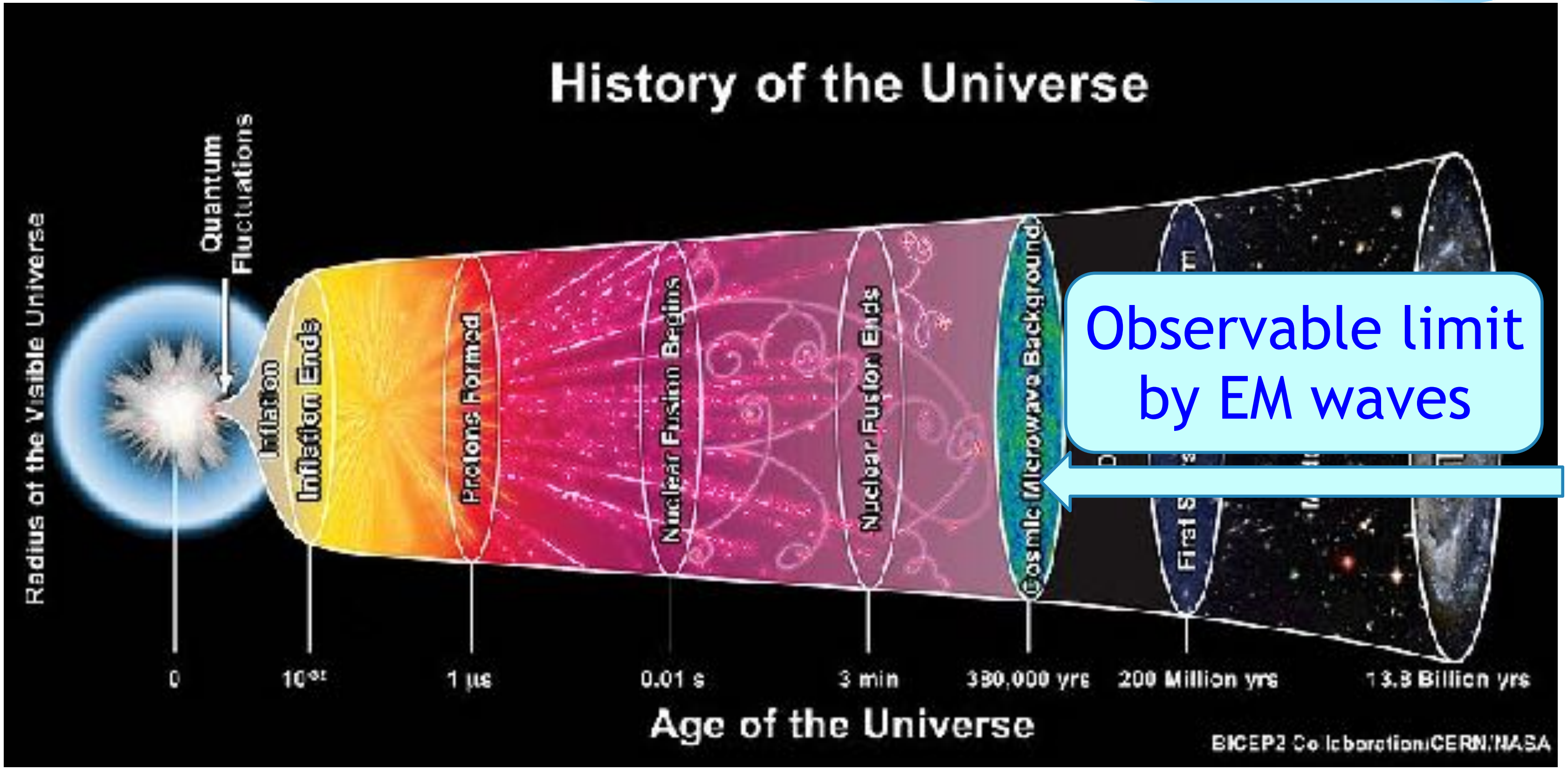
(the only equation in this lecture)



quadrupolar wave

GWs penetrate everything!

Beginning of the Universe may be probed!

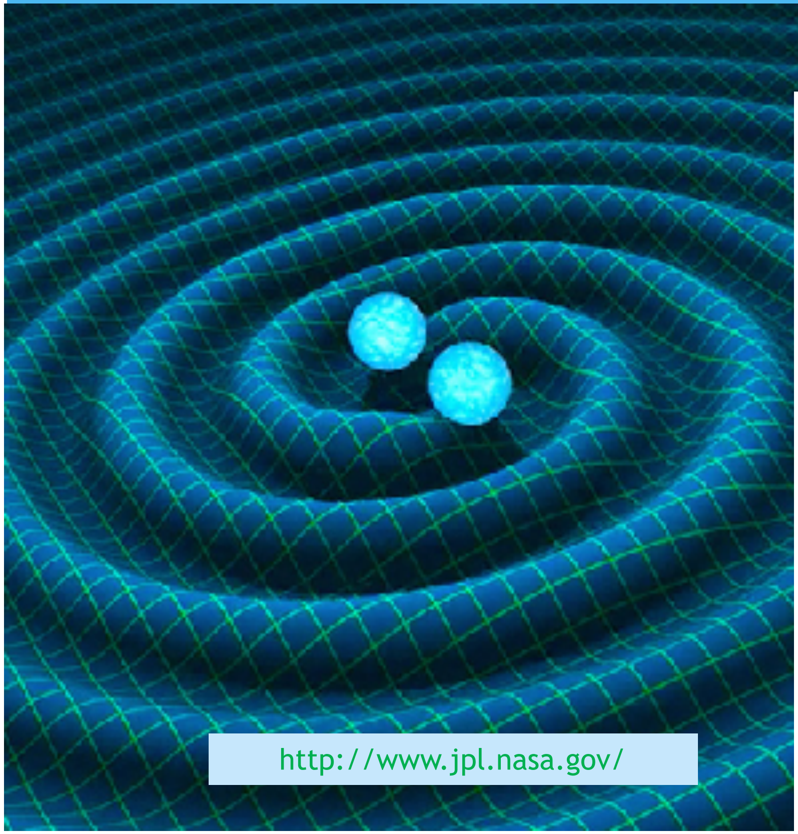


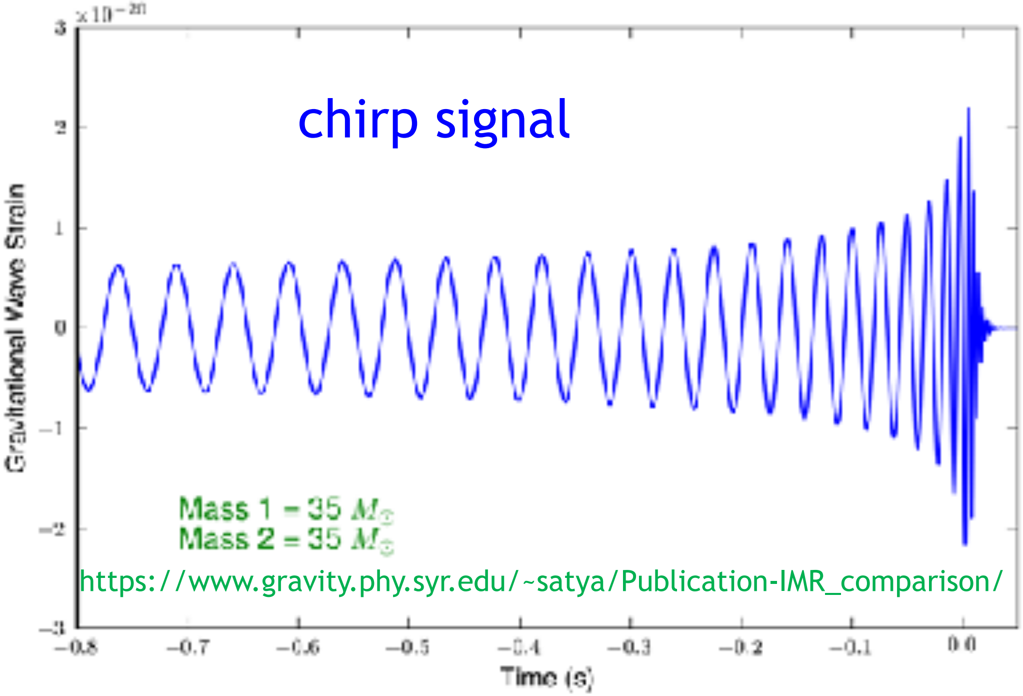
Observable limit by EM waves

Where do GWs come from?

GWs from binary NS/BHs

NS=Neutron Star
BH=Black Hole



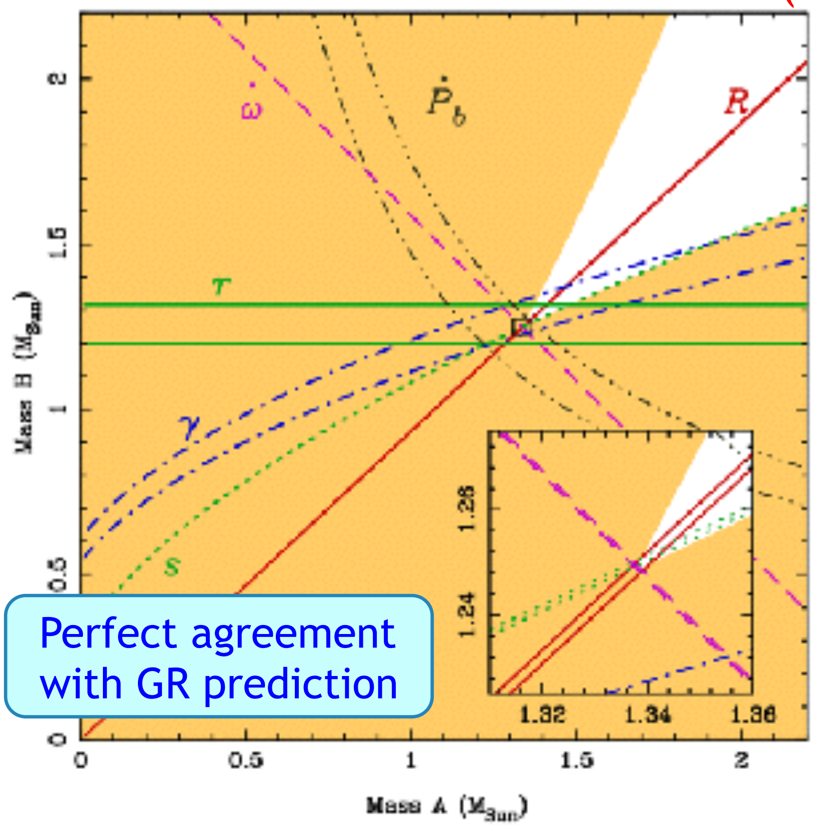


By observing emitted GWs, properties of
strongly curved spacetime and matter under extreme conditions

Indirect evidence of GWs

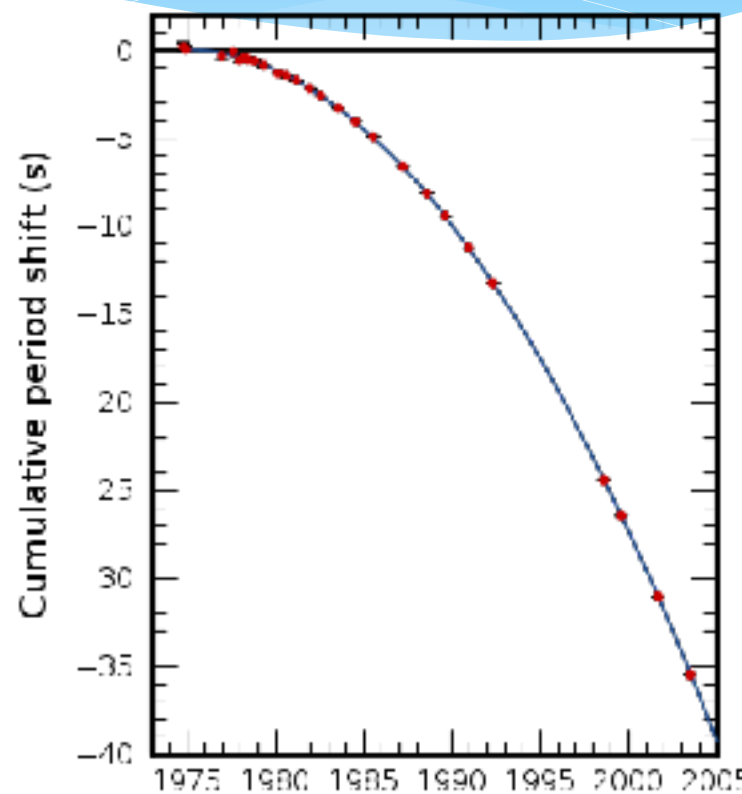
Situation until Sept 2015 (approx. 100 yrs after Einstein)

decrease of orbital period due to GW emission in binary pulsars (NS)



Perfect agreement with GR prediction

PSR J0737-3039：Kranmer et al. ‘06



PSR B1913+16/Hulse-Taylor Binary
1993 Nobel Prize in Physics

Direct Detection of GW Event!

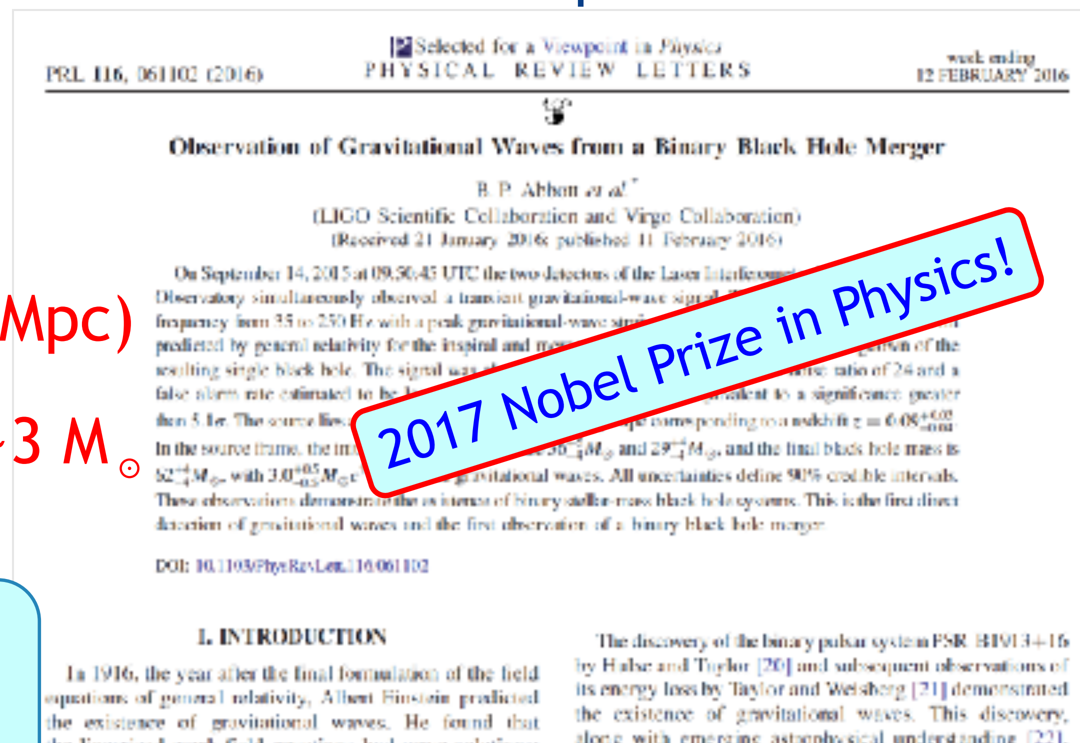
GW150914

- LIGO detected GWs from Binary BHs on 14 Sept, 2015
- only two days after the machine started to operate

very lucky!

- each BH mass~30 $M_{\odot}$
- distance~1.2 G lyr (400 Mpc)
- energy emitted as GWs~3 $M_{\odot}$

10,000 x (super nova explosion energy)!



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 ... 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

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions:

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22],

2017 Nobel Prize in Physics!

What is LIGO?

- LIGO=Laser Interferometric Gravitational wave Observatory

3000km = 10 ms

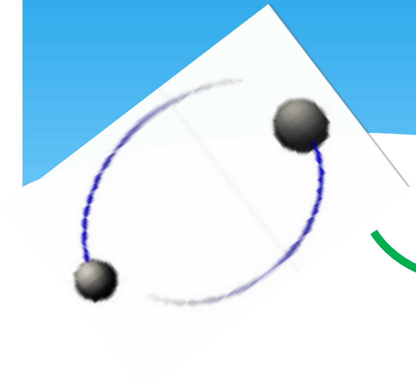
each arm = 4km

can detect GW amplitude of ~ 10^{-21} !

$$\frac{\delta L}{L} = 10^{-21} \Leftrightarrow \delta L = 4\times 10^{-16}\,\mathrm{cm}!$$

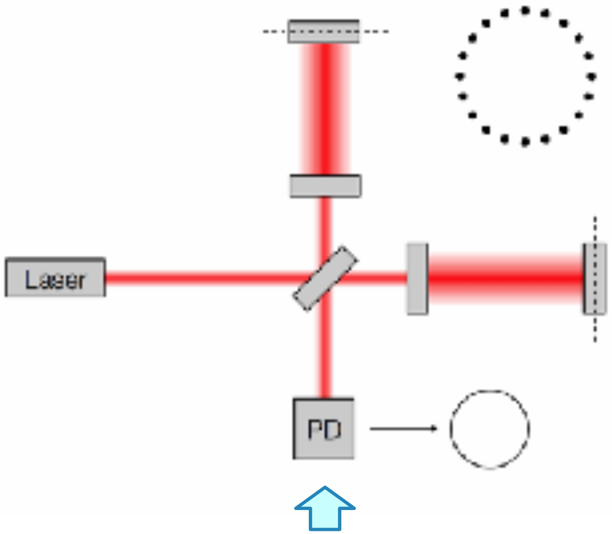
size of neucleon ~ 10^{-13}cm

Principle of Interferometer



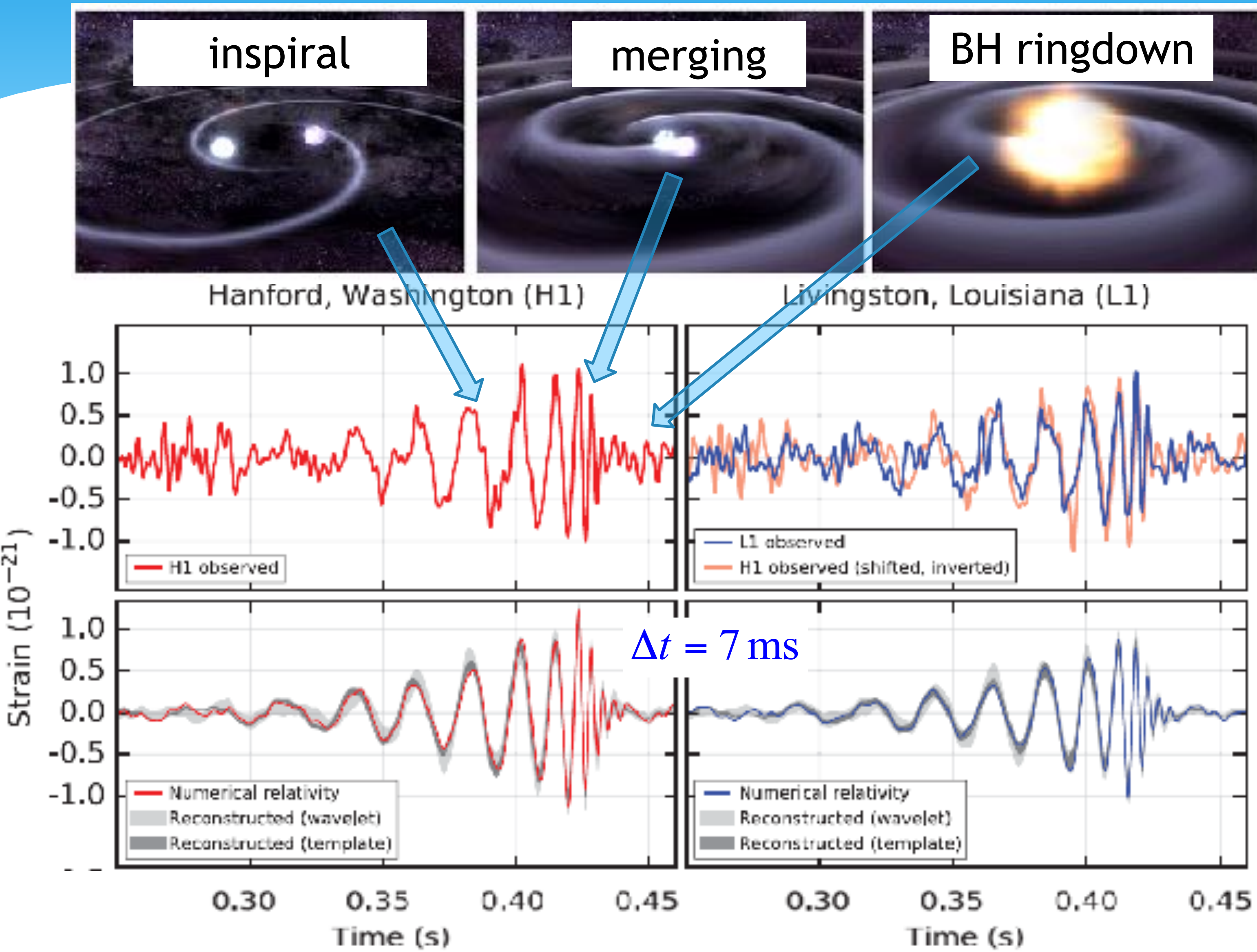
GWs from BBH, etc.

arm length oscillates
when GWs pass through



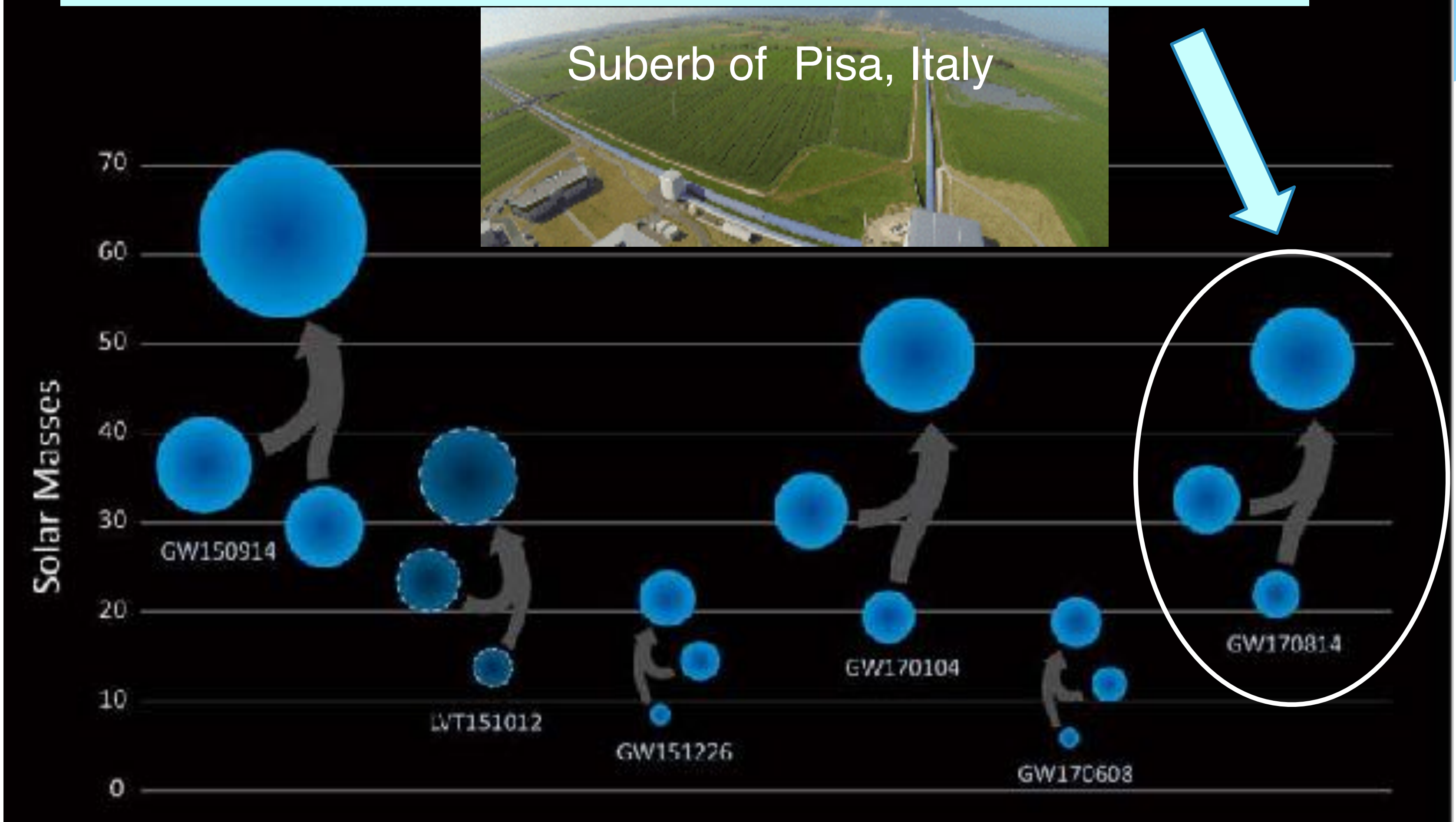
detector sees fluctuating light

observed GW signal



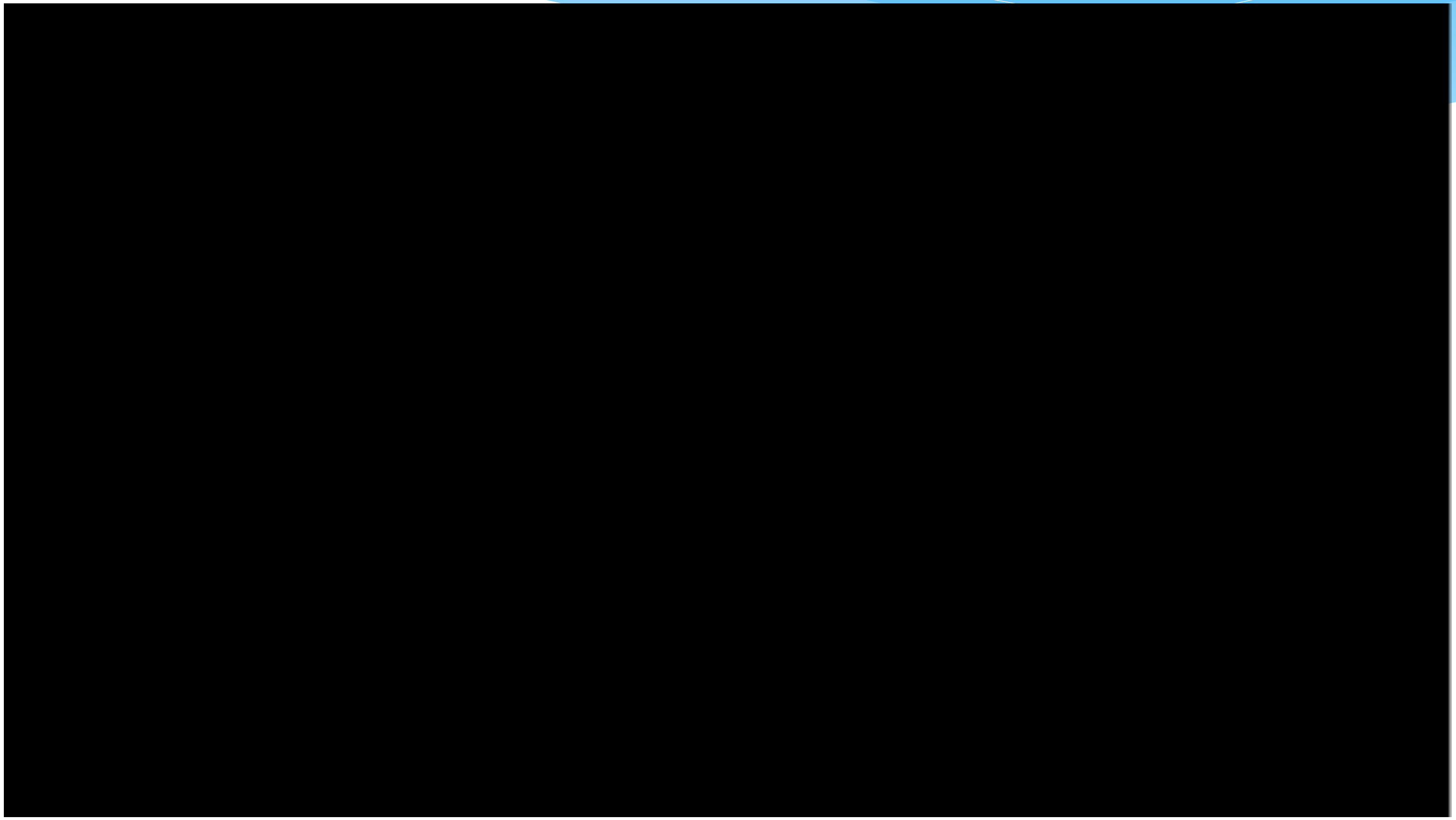
Already 5(+1) events observed

Co-observation with Virgo(France-Italy)



"Sound" of GWs

GW150914 and GW151226

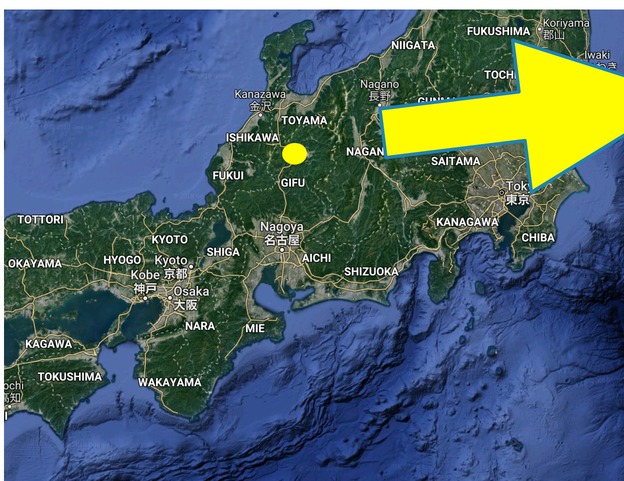


a bit about Japan

KAGRA ~ 神樂

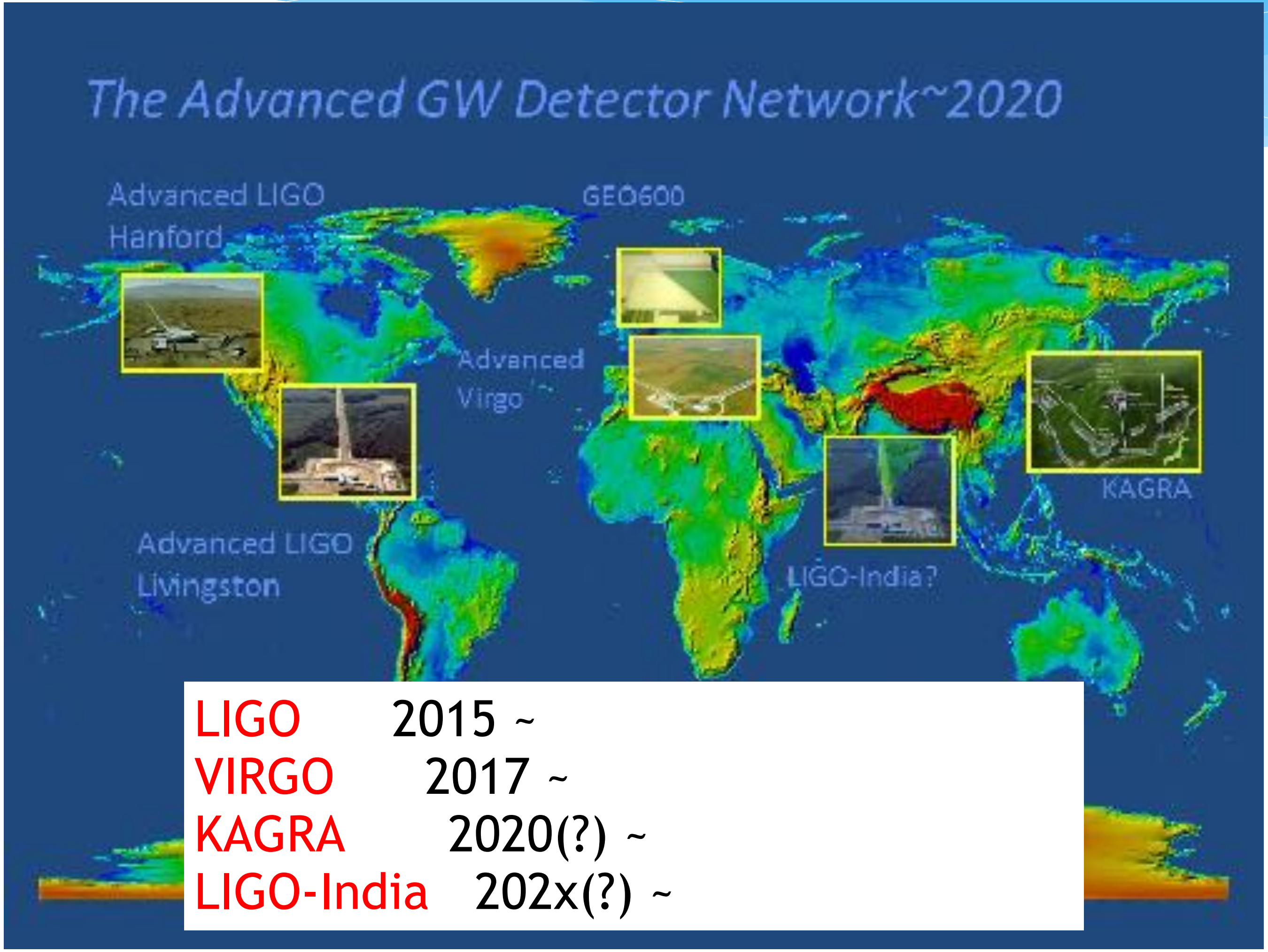
KAmioka GRAvitational wave detector

almost completed
full op by 2020



http://gwcenter.icrr.u-tokyo.ac.jp/en/

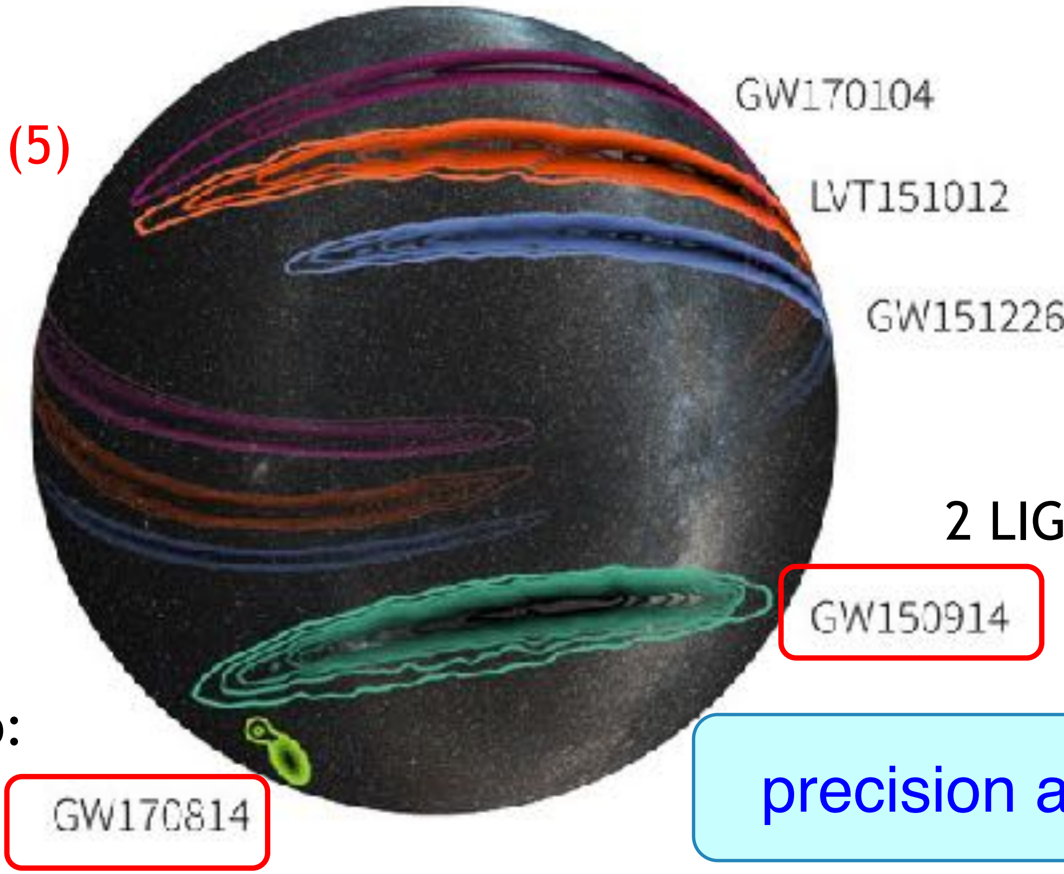
future GW detector network



LIGO 2015 ~
VIRGO 2017 ~
KAGRA 2020(?) ~
LIGO-India 202x(?) ~

angular reslution

- sustantial improvement in angular resolution by addition of Virgo: from 2 LIGO(2) to 2 LIGO+Virgo (3) detectors.
- +KAGRA (4)
- +LIGO-India (5)



2 LIGO: S/N=24

2 LIGO+Virgo: S/N=18

precision astronomy!

WHAT'S NEXT after BBHs?

Big News in last October

LIGO did it again!

PRL ... (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

announced right after Nobel Prize

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 ... with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estim... 8.0×10^4 year... 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 ... we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of ... $M_\odot$. 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 ... insight into astrophysics, dense matter, gravitation, and cosmology.

NS mass

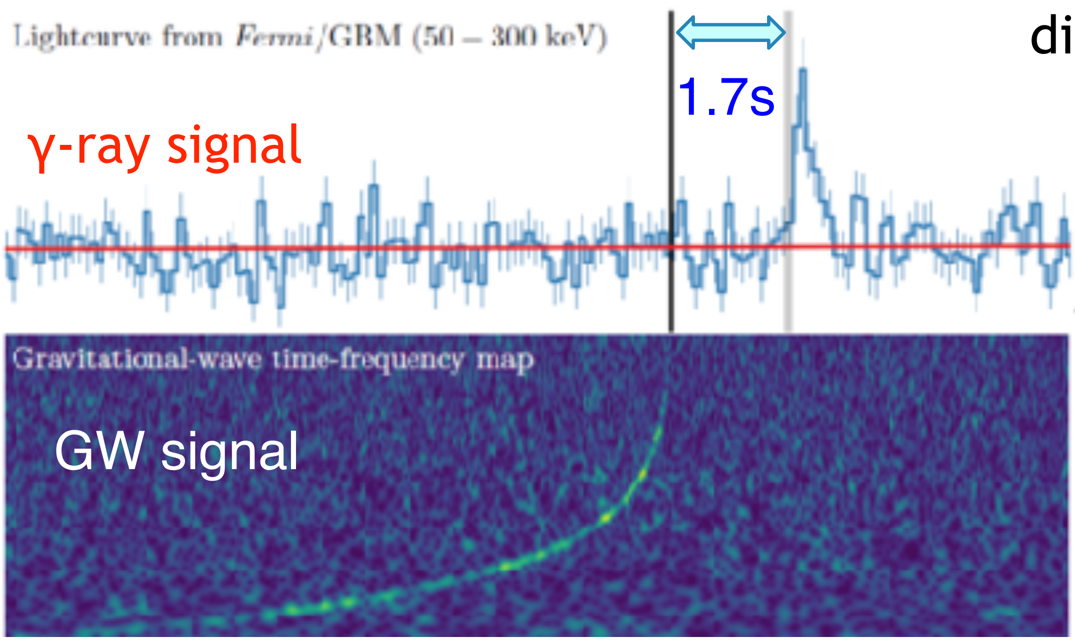
strong signal

also observed by EMWs!

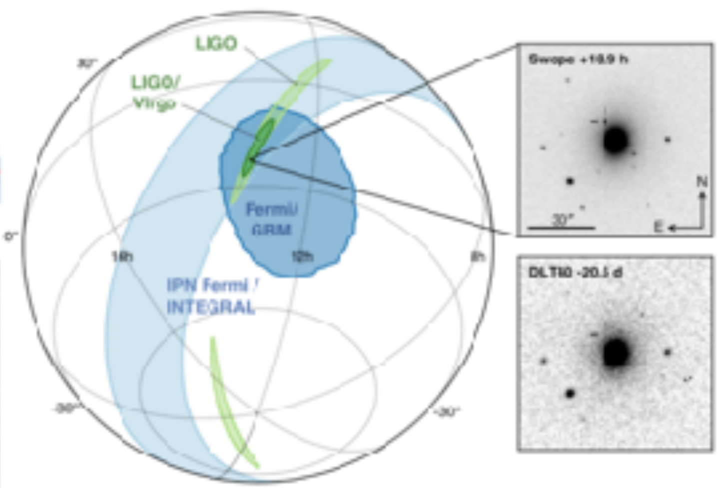
GW170817=GRB170817A

γ-ray burst

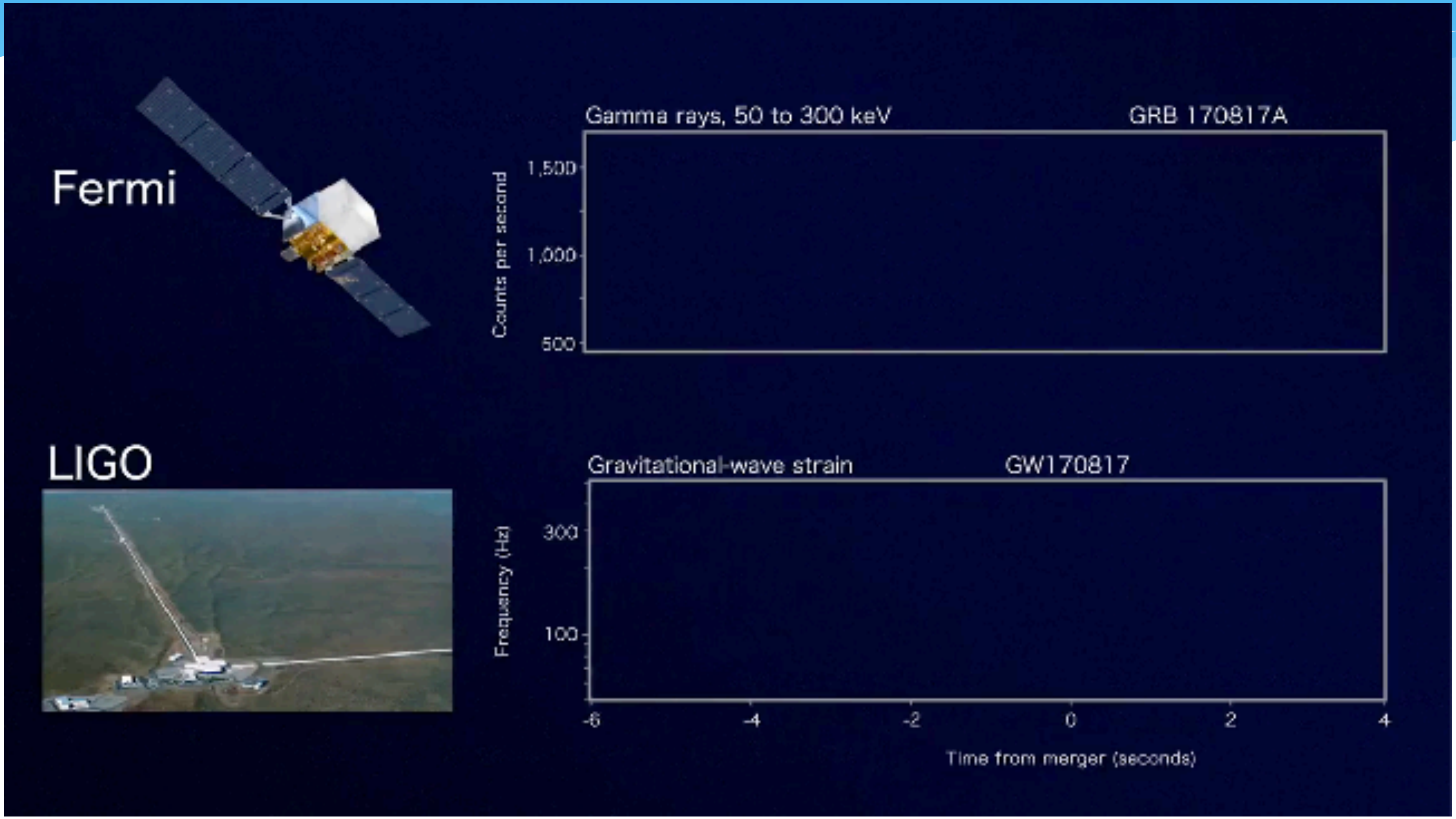
LIGO-Virgo + Fermi simultaneously detected GWs and γ-ray from Binary NS merger

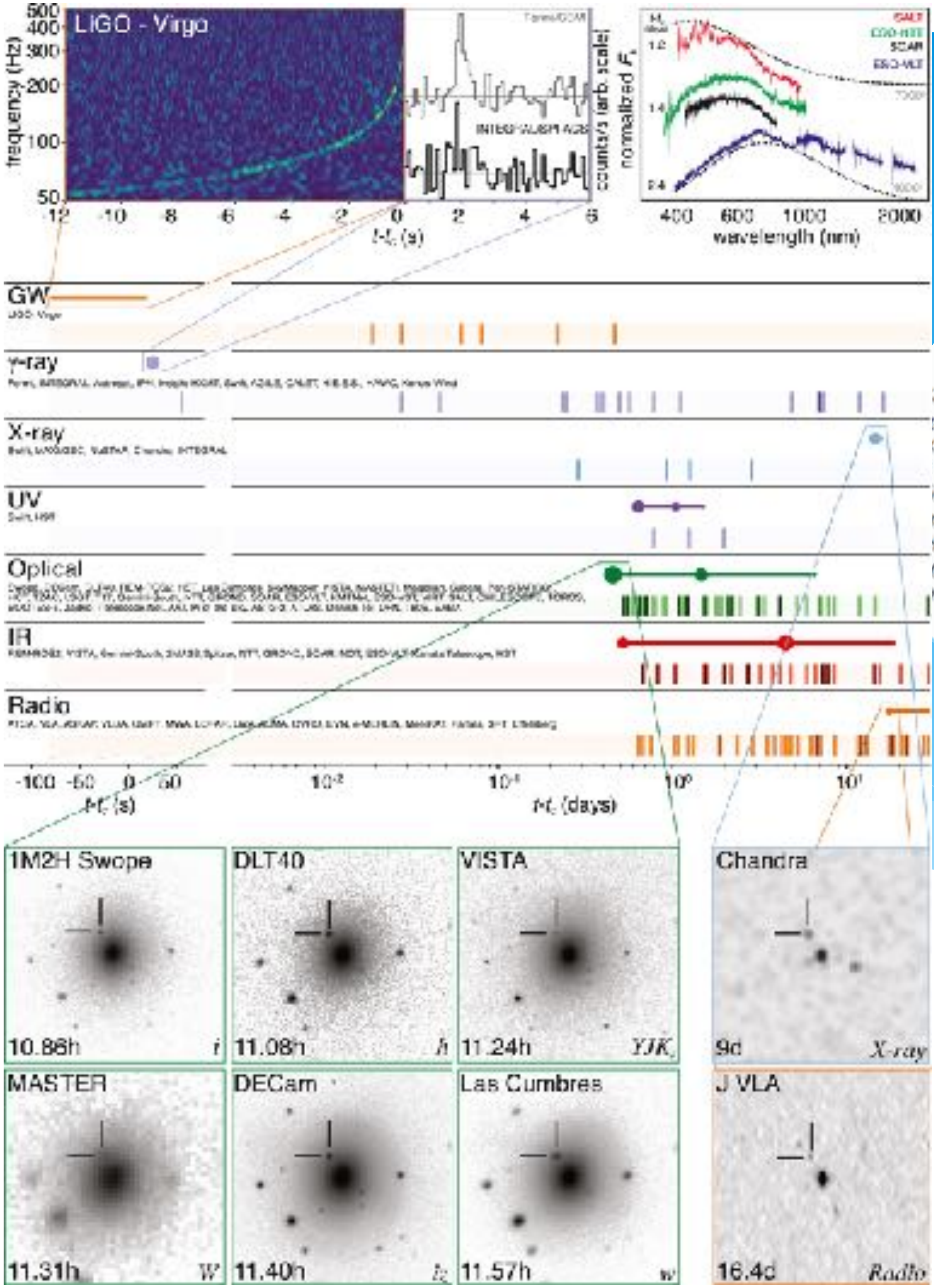


distance: 0.13 G lyr (~ 40 Mpc)

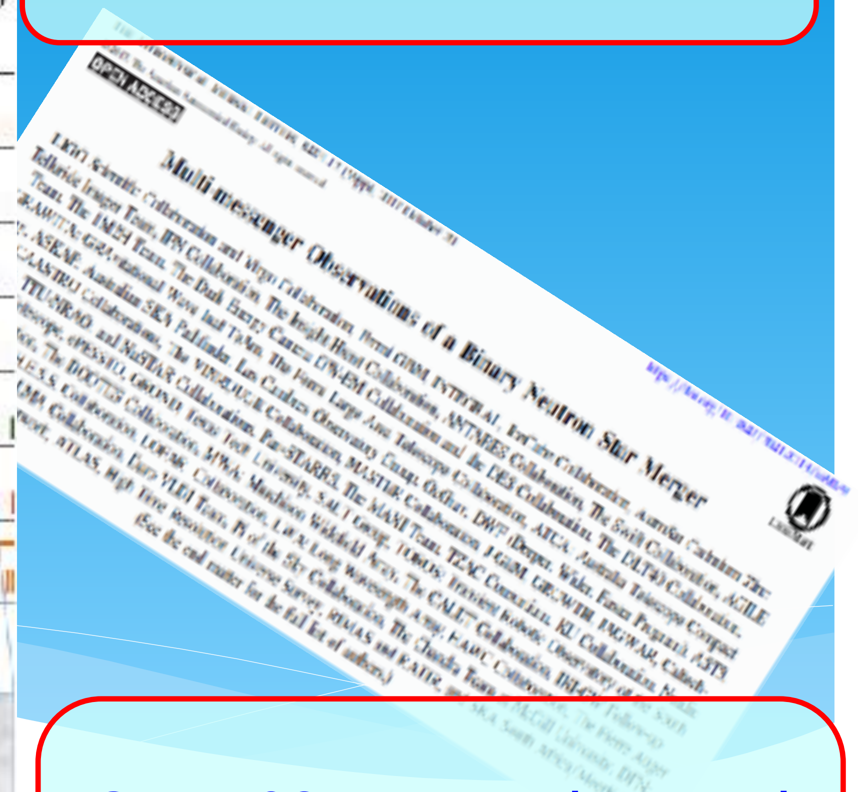


“Sound” of GWs and γ-ray





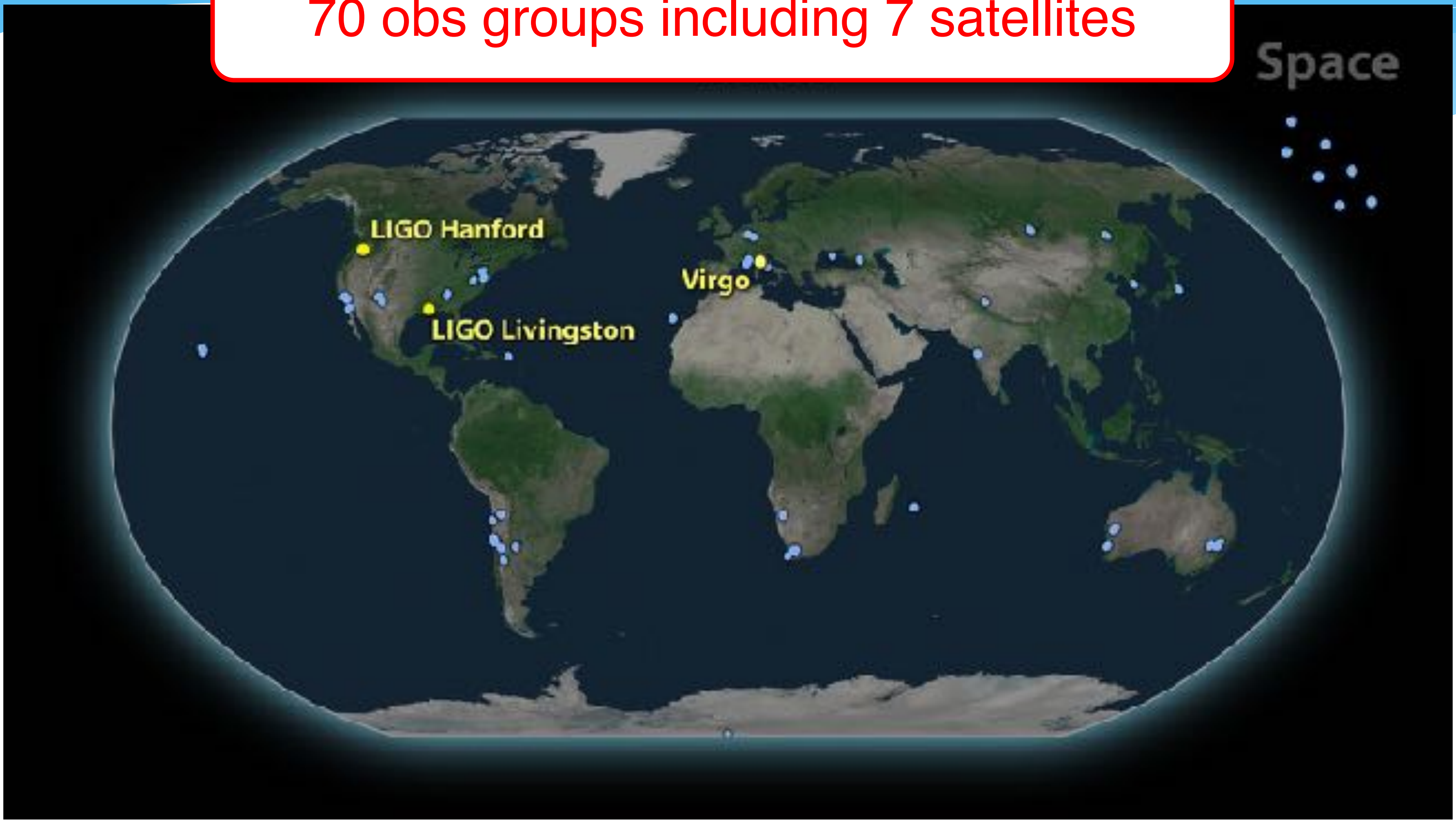
Not only GWs and γ-ray



GW170817 was observed at various wavelengths from γ-ray to radio

dawn of multi-messenger astronomy

70 obs groups including 7 satellites



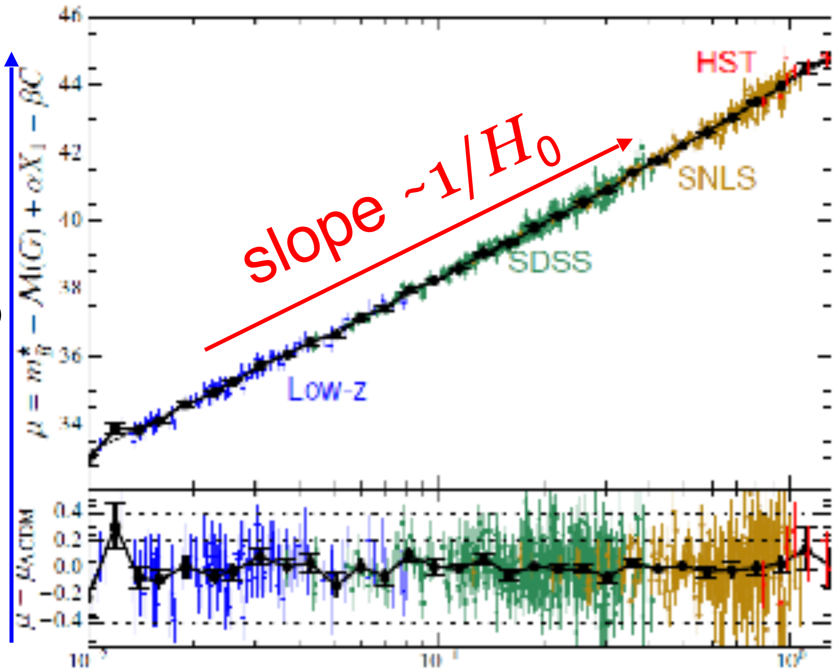
from Astronomy to Cosmology

Cosmoloical implication of GW170817

Hubble's law:

measured by redshift → $V = H_0 r$ ↑ estimated from magnitude

magnitude

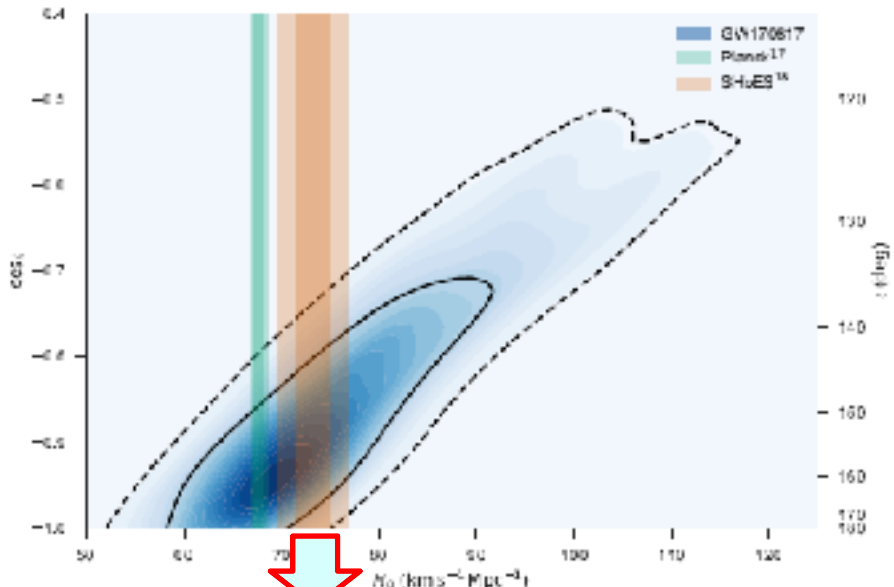


redshift

Betoule et al. arXiv:1401.46064

A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

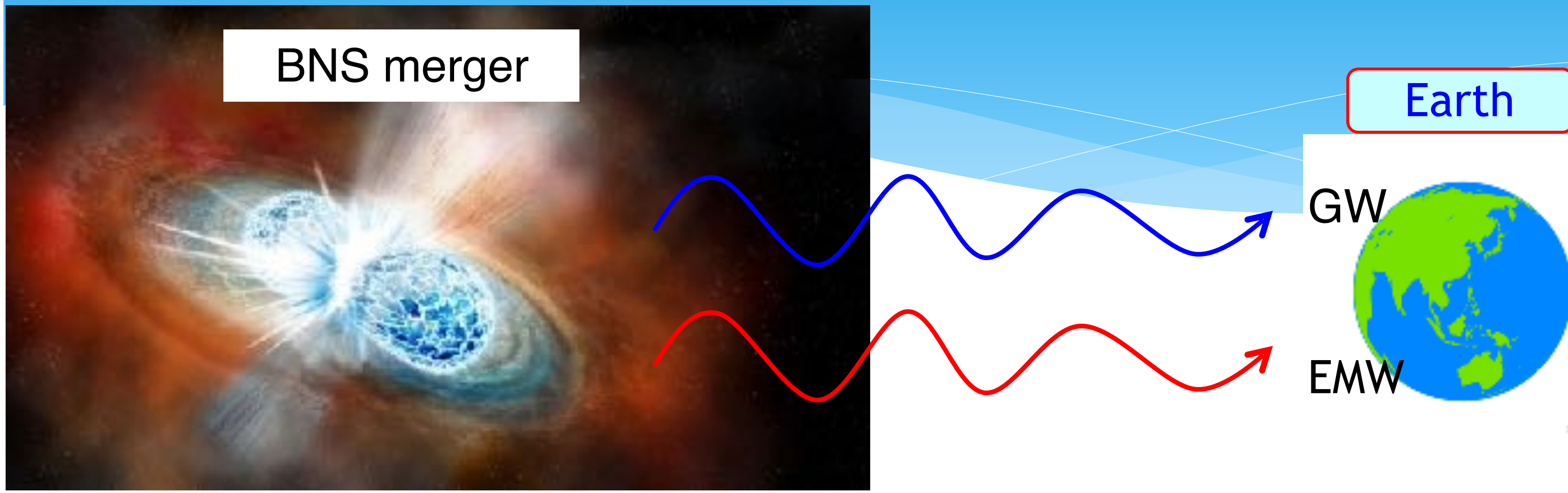
THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABORATION, THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION, THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION, THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.



$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}.$$

~10% accuracy by a single observation!

EMWs and GWs



http://natgeo.nikkeibp.co.jp/atcl/news/17/101800401/

distance = 0.13 G lyr

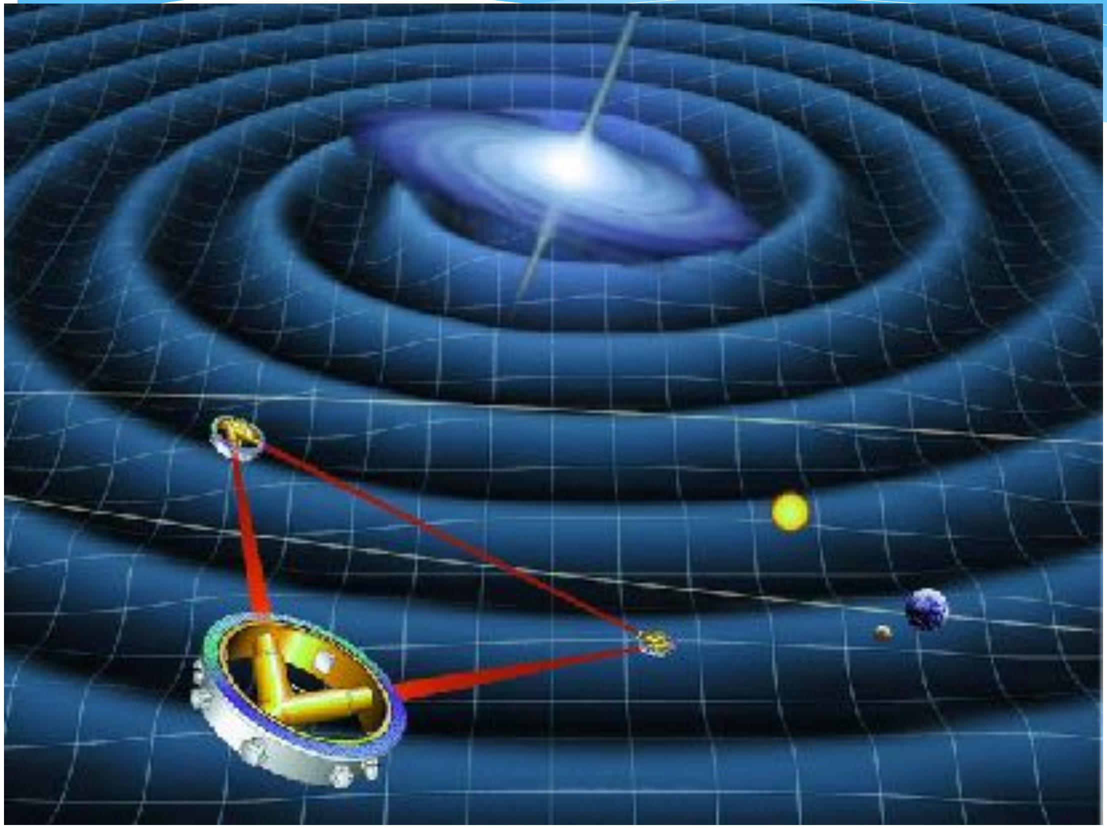
only 1.7s difference after traveled 0.13 Glyr (~4x10[15]s)

$c_{GW} - c_{EMW} < 10^{-5}$ cm/s

very strong constraint on Dark Energy models

future projects

Space GW Observatories



http://lisa.nasa.gov/

Japan +?

DECIGO

Deci-hertz Interferometer Gravitational wave Observatory

arm length 1,000 km

~203x?

freq:~ 0.1 Hz

Europe + US + ?

LISA

Laser Interferometer Space Antenna

arm length 5,000,000 km

~2035?

freq:~10^{-3}Hz

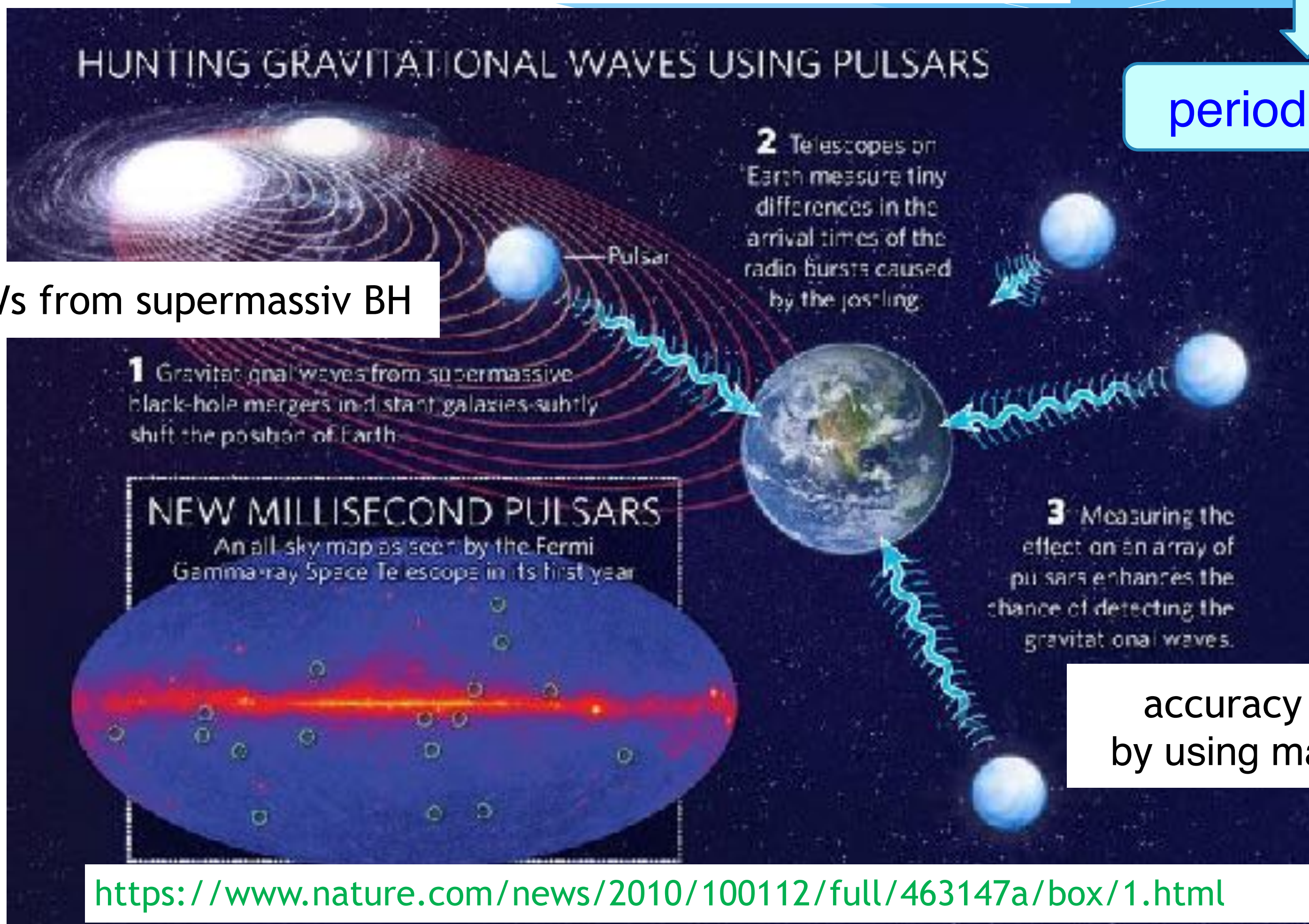
Pulsar Timing Array

Pulsar is an extremely accurate clock:
pulse arrival times fructuate when GWs pass through

freq: ~ 10^{-8}Hz

period ~ 10 yr

GWs from supermassiv BH

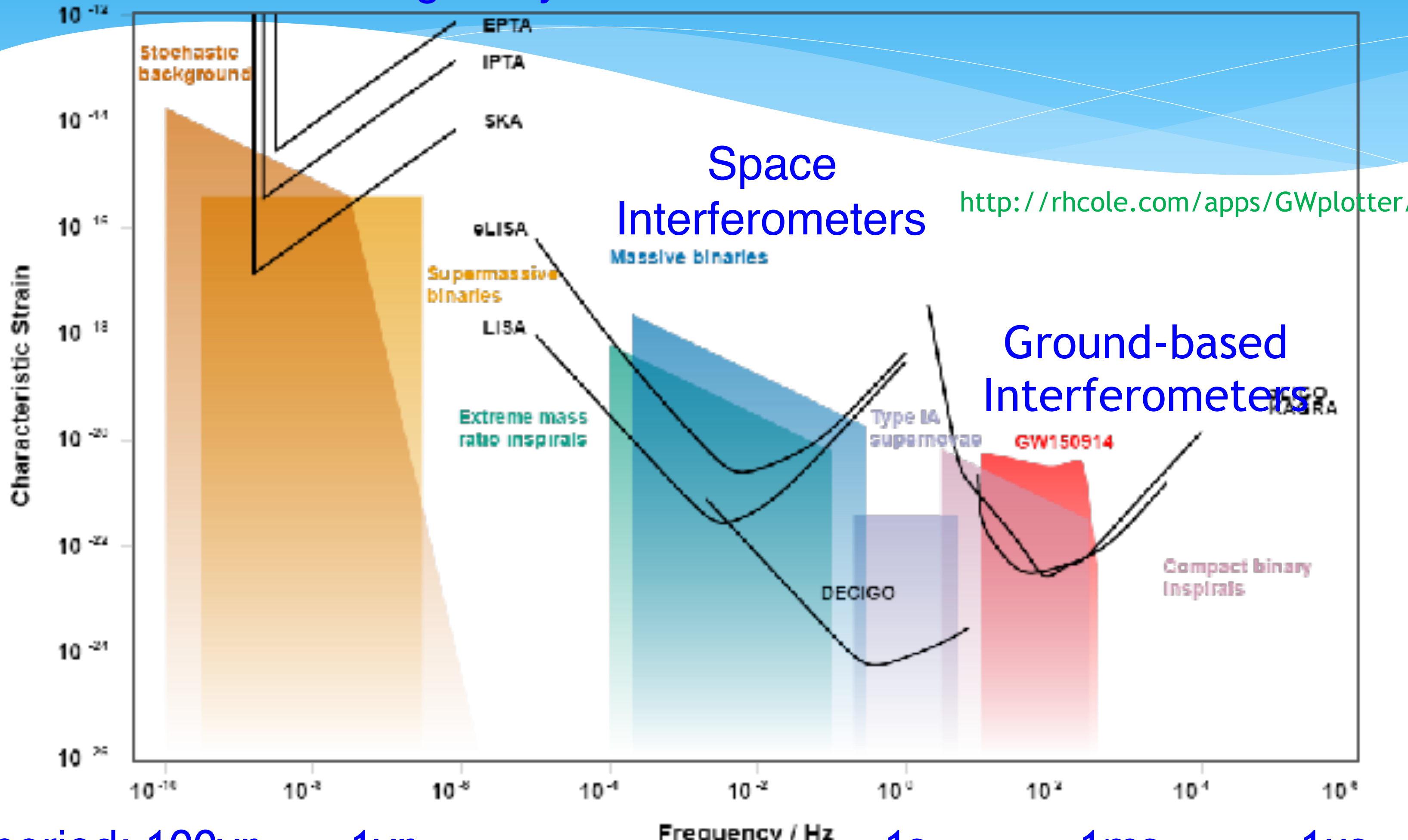


accuracy increases by using many pulsars

https://www.nature.com/news/2010/100112/full/463147a/box/1.html

Multi-band GW Astronomy

Pulsar Timing Array



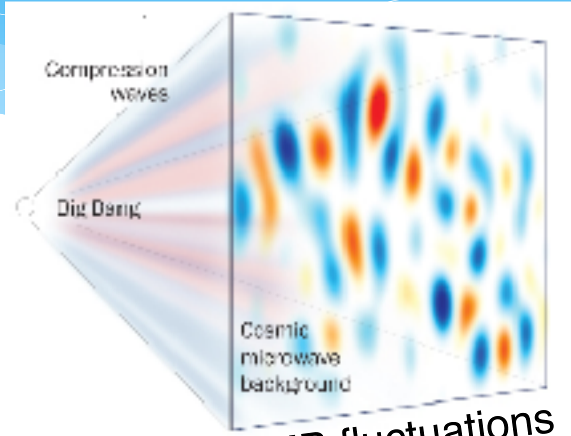
period: 100yr 1yr 1s 1ms 1μs

GW Cosmology

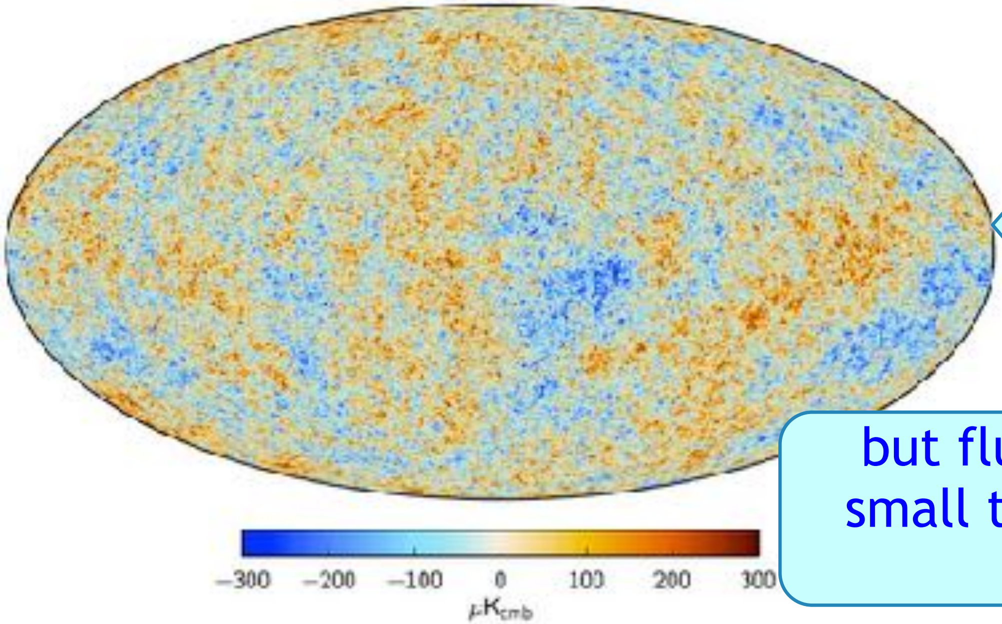
GWs from Inflation

quantum spacetime (tensor: spin 2) fluct'ns turn into Cosmological GW Background (CGWB)

- curvature (scalar) perturbations from inflation generate Cosmic Microwave Background (CMB) temperature fluctuations
- GW (tensor) perturbations also generate CMB temperature fluctuations



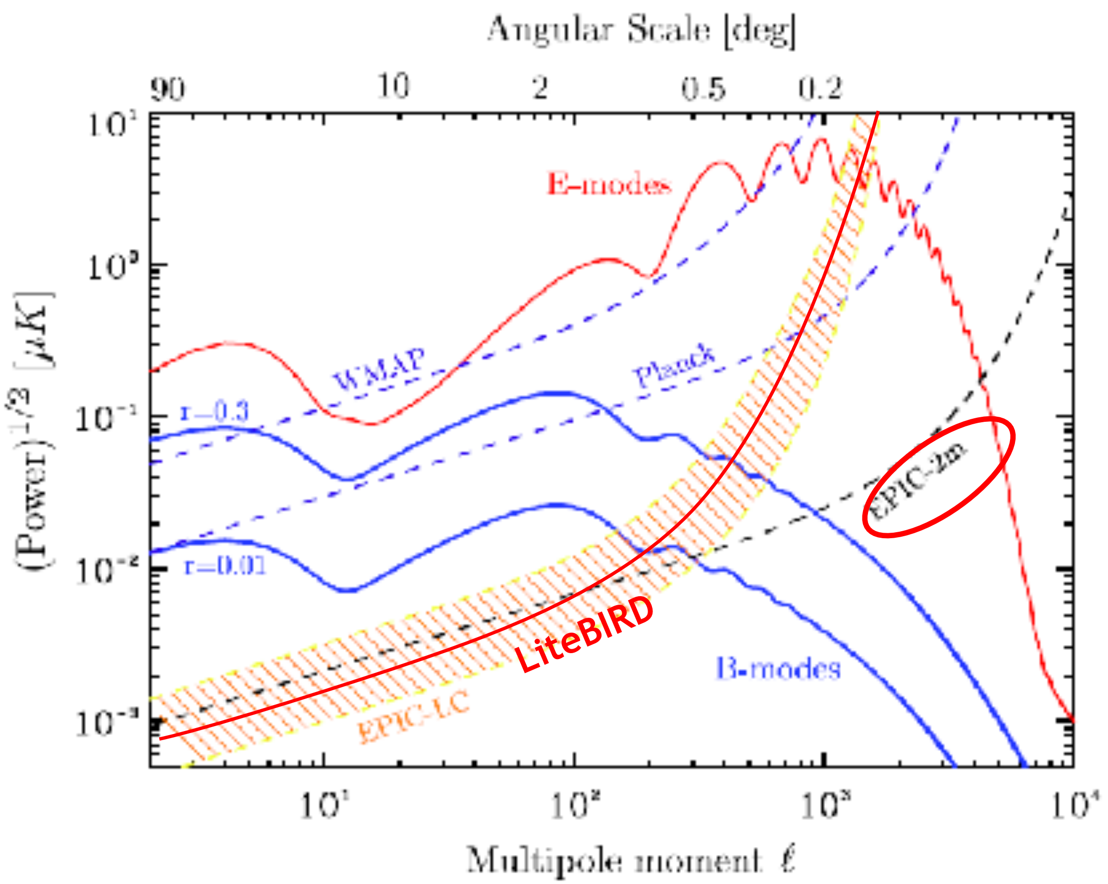
CMB fluctuations



CMB temp fluctuations observed by Planck Satellite

but fluct'ns generated by GW are too small to be seen compared to those by curvature pertrurbations

B-mode projects



http://arxiv.org/abs/0811.3911v1

LiteBIRD
2025 ~ 2030?

http://litebird.jp/eng/

Lite (light) Satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection

Kavli IPMU is in!

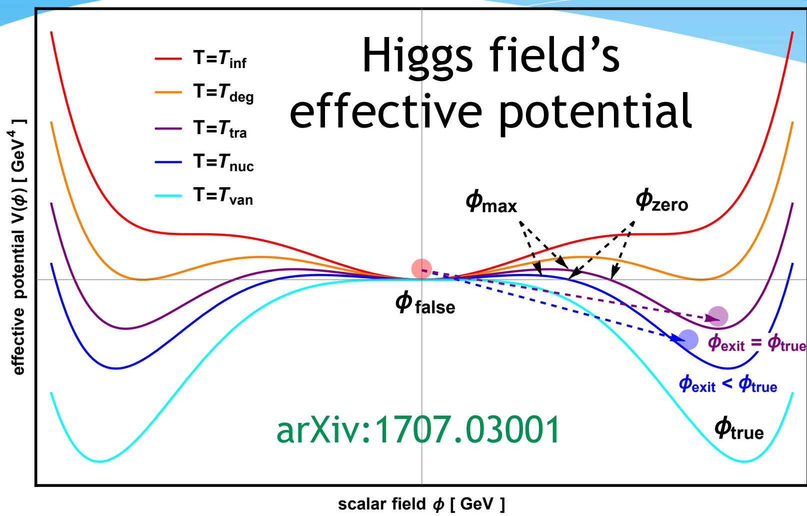
EPIC
2030 (??)

http://arxiv.org/abs/0906.1188

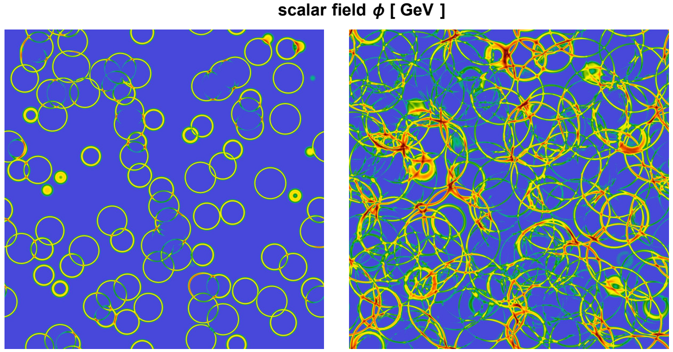
Experimental Probe of Inflationary Cosmology

GWs from Phase Transition

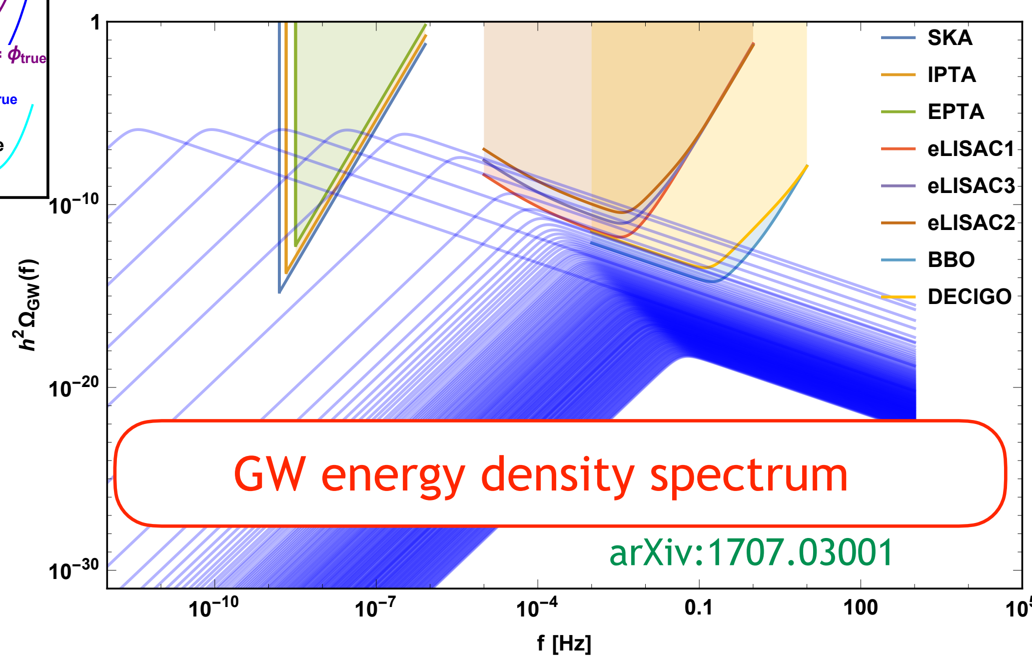
Electro-Weak transition may be strongly first order



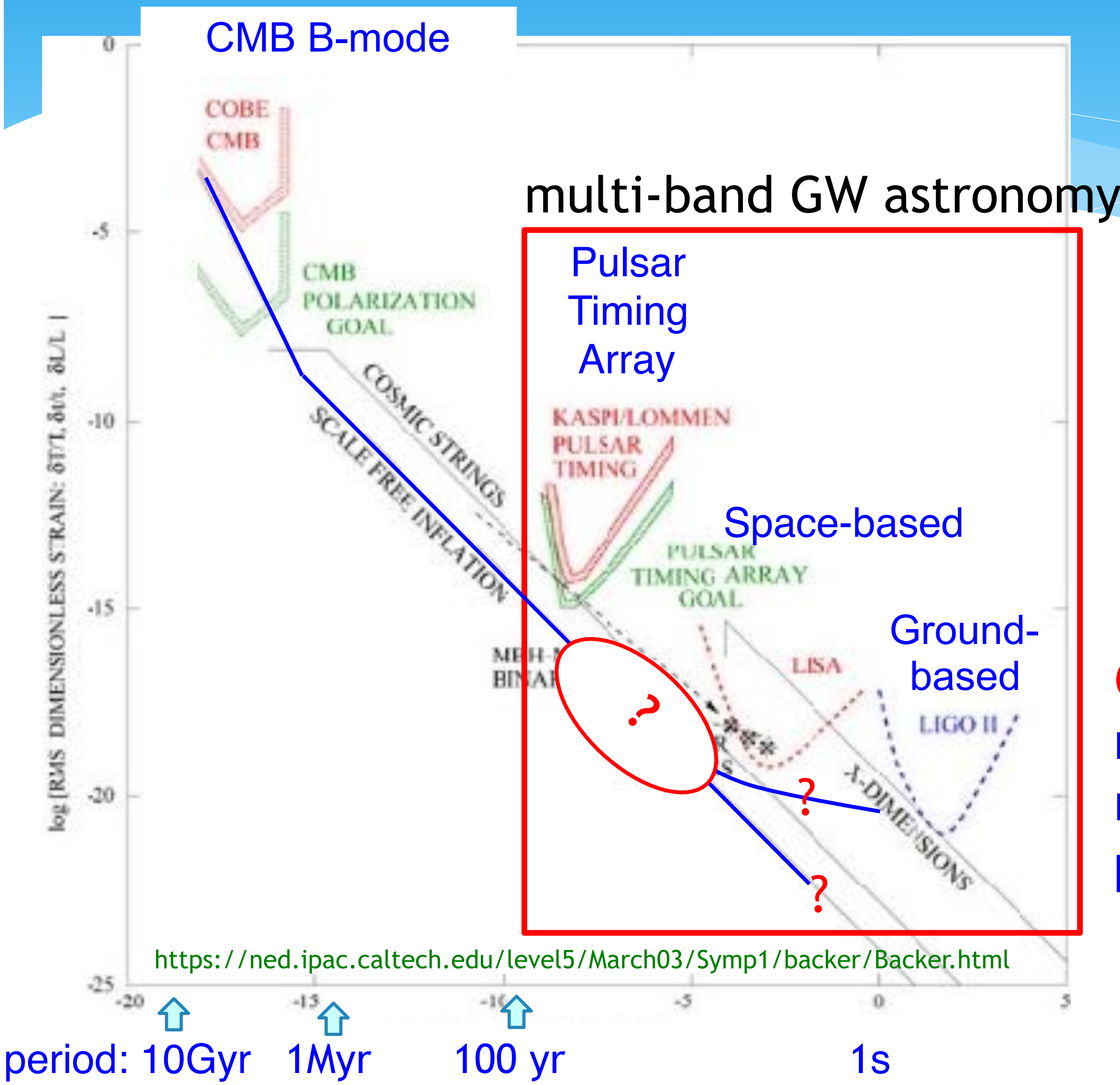
formation & collisions of bubbles generate GWs



bubble formation and collisions
arXiv:1511.04527



Dawn of GW “Cosmology”



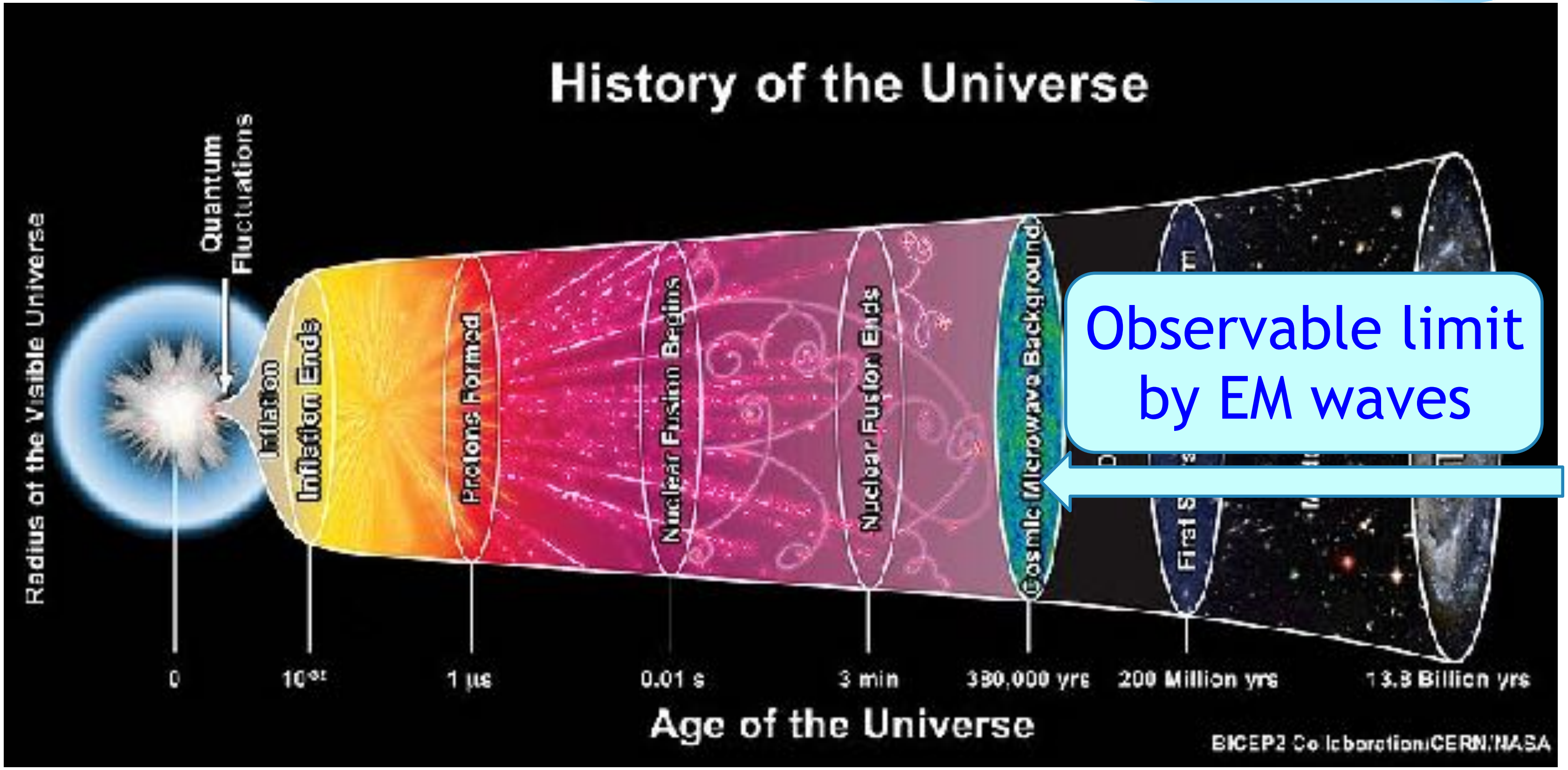
Era of GW astronomy
has arrived

Cosmology will undergo a revolutionary change!

GWs from early Universe may be detecte at any band, ranging over 20 digits from period of 10Gyr to 1ms !

GWs penetrate everything!

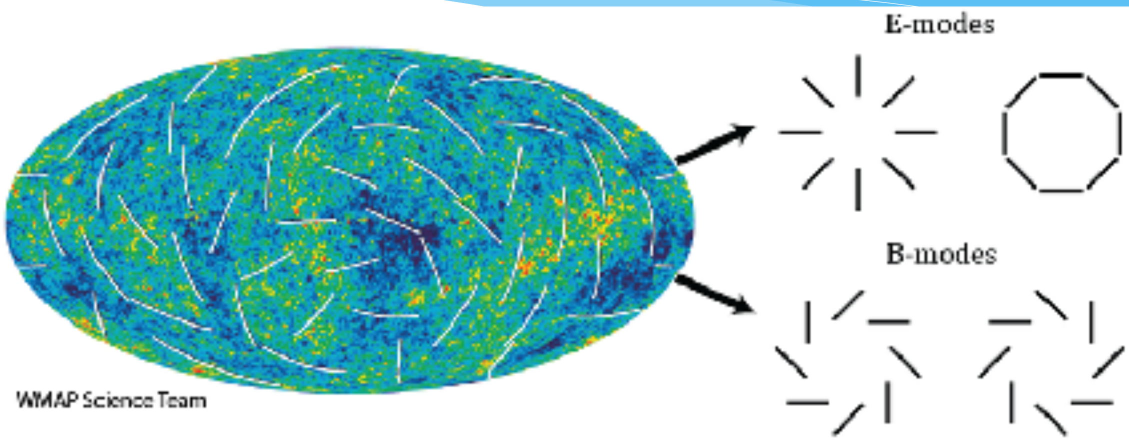
Beginning of the Universe may be probed!



Observable limit by EM waves

CMB B-mode polarization

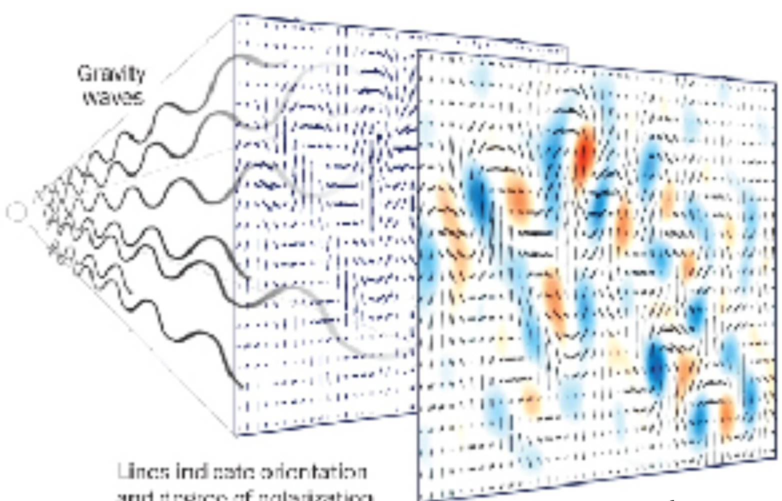
GWs produce B-mode fluctuations in CMB polarization



E-mode

⇕

B-mode
characteristic to
GW perturbations



Source: Harvard-Smithsonian Center for Astrophysics

B-mode

B-mode polarized light with osc period of 10 G yrs

⇕

GW detector with arm length of 10 G lyr !

GWs are an indespensable tool to explore the unknown Universe and discover new physics!

What will be discovered next?

Stay tuned!