KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

TDLI
26 July 2019

Gravitational Wave Cosmology

— the Dawn has Arrived! —

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YITP, Kyoto University
LeCosPA, National Taiwan University

YITP YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

LeCosPA

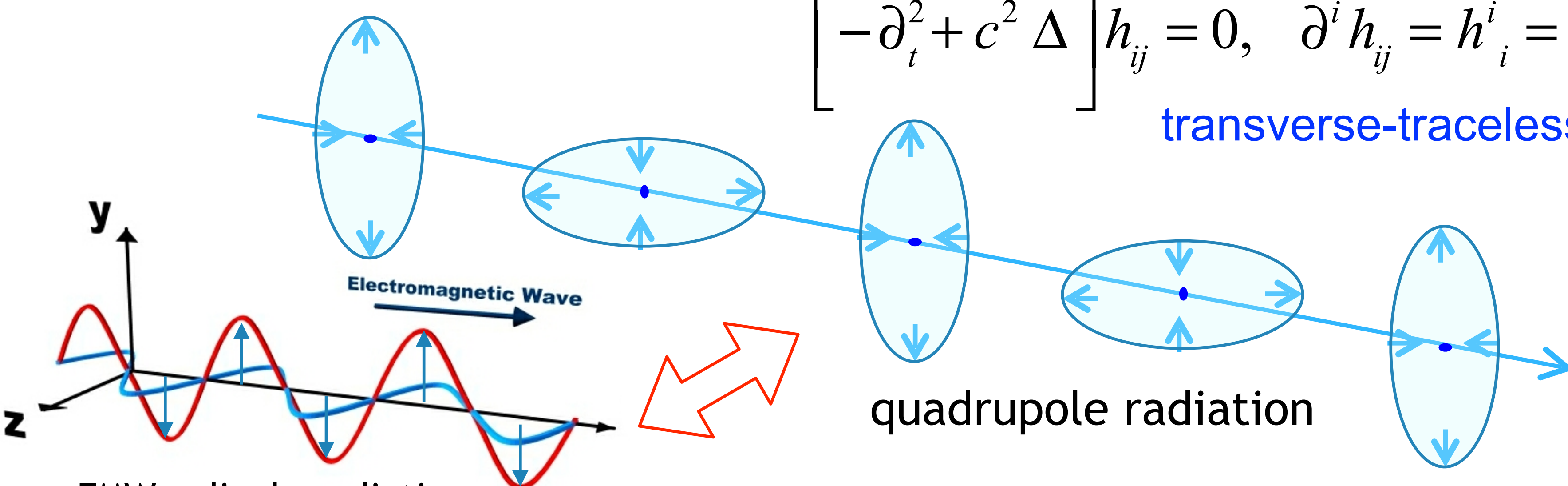
Gravitational Waves!

What are Gravitational Waves?

* GWs are ripples of spacetime, propagating at c, predicted by Einstein in 1916.
* Emitted when energy-momentm 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

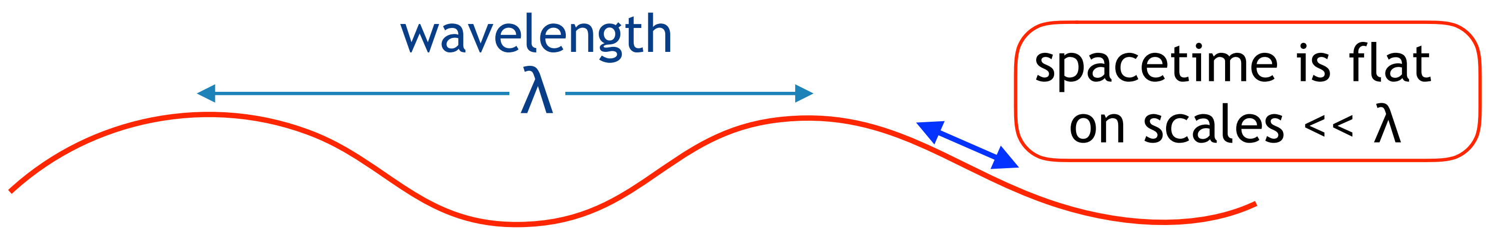


EMWs: dipole radiation

a bit more about GWs

* Equivalence Principle, encoded in Einstein's general relativity, states that spacetime is locally flat.
* GW carries energy, but not on scales smaller than its wavelength.
* Local energy-momentum tensor doesn't exist.

  (⟺ local energy-momentum exists for EMWs)



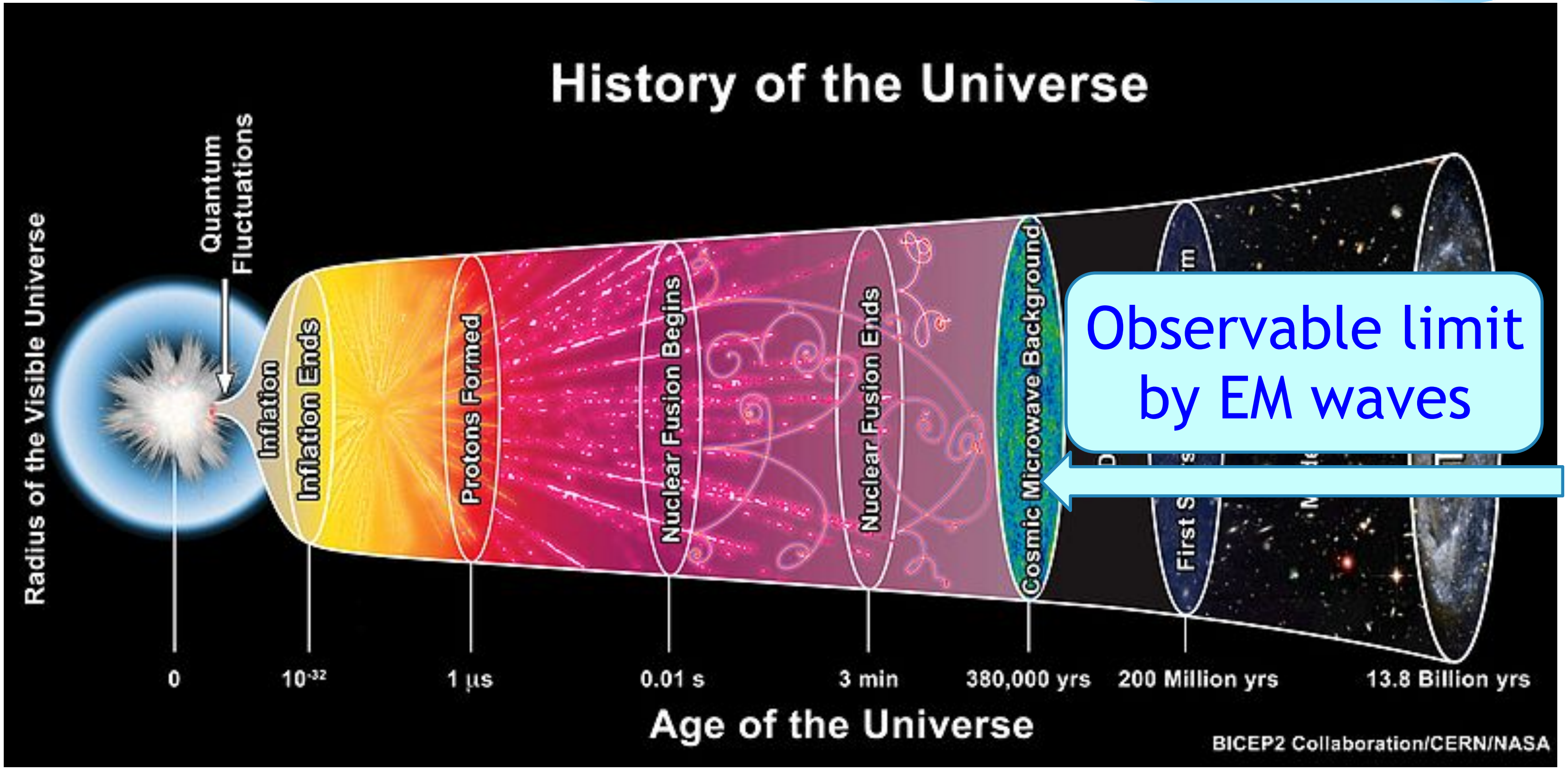
* A point mass (size<< λ) doesn't see GWs.

  ⟺ Gws don't lose energy when passing through space filled with free particles.

  (GWs interact with them only through gravity, ie, spacetime distortion caused by particles)

GWs penetrate everything!

Beginning of the Universe may be probed!

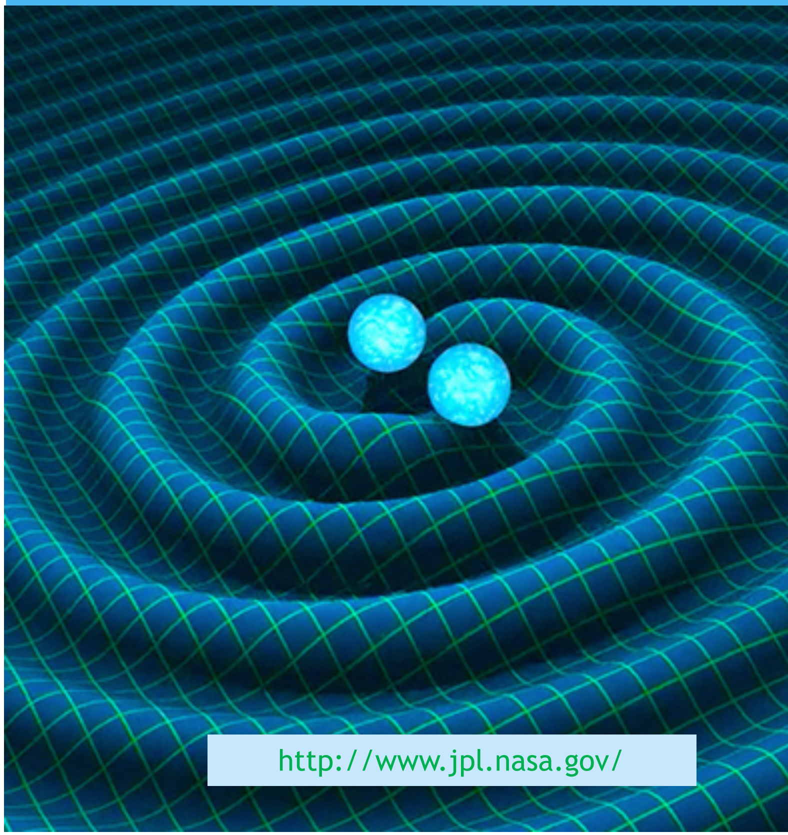


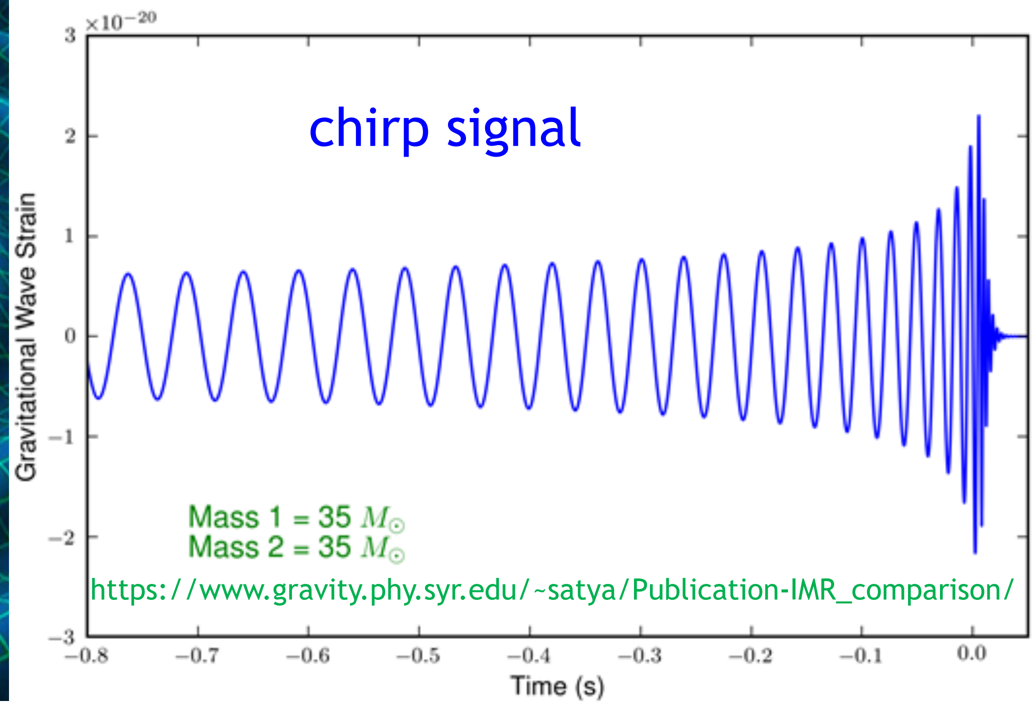
Observable limit by EM waves

Where do GWs come from?

GWs from binary NS/BHs

NS=Neutron Star
BH=Black Hole





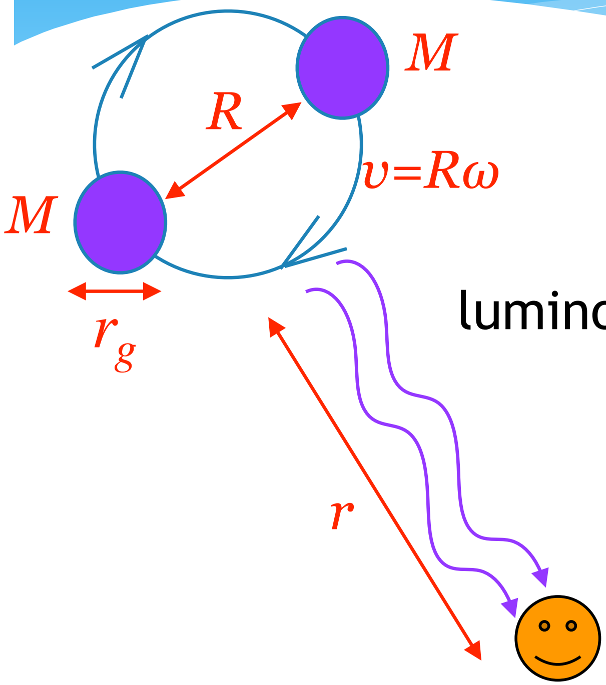
By observing emitted GWs, properties of strongly curved spacetime and matter under extreme conditions

Quadrupole Formula

GW amplitude: $h_{ij} \sim \frac{2G}{rc^4} \boxed{MR^2\omega^2} \leftarrow \sim \frac{d^2}{dt^2}(\text{Quadrupole})$

$\sim 10^{-19} \frac{M}{M_\odot} \boxed{\frac{\text{Mpc}}{r}} \frac{v^2}{c^2}$

Mpc ~distance to Andromeda



luminosity: $\frac{dE_{GW}}{dt} \sim 4\pi r^2 \left\langle \dot{h}_{ij}^{\,2} \right\rangle \sim \boxed{10^5 \left(\frac{r_g}{R}\right)^2 \left(\frac{v}{c}\right)^6 M_\odot c^2/\text{s}}$

$$\boxed{\Delta t \sim r_g/c = 10^{-5} \frac{M}{M_\odot} \text{ s}}$$

$r_g = \frac{2GM}{c^2} \sim 3\text{km} \frac{M}{M_\odot}$: Schwarzschild radius

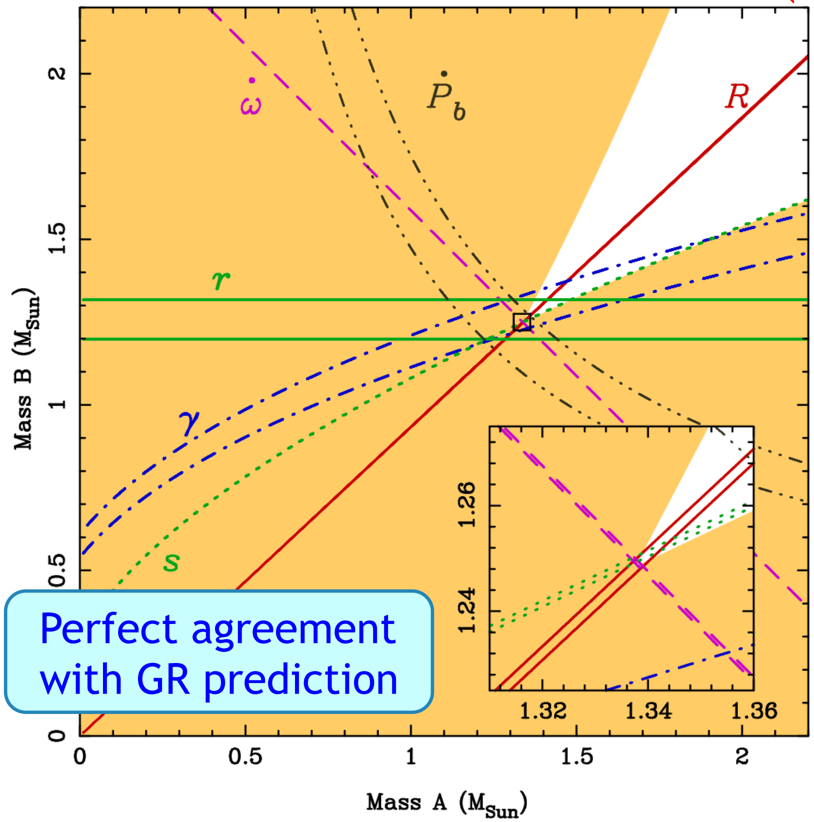
emitted energy: $\Delta E_{GW} = \frac{dE_{GW}}{dt} \Delta t \sim \boxed{\frac{M}{M_\odot} \left(\frac{r_g}{R}\right)^2 \left(\frac{v}{c}\right)^6 M_\odot c^2}$

>20% of rest mass can be converted to GWs!

Indirect evidence of GWs

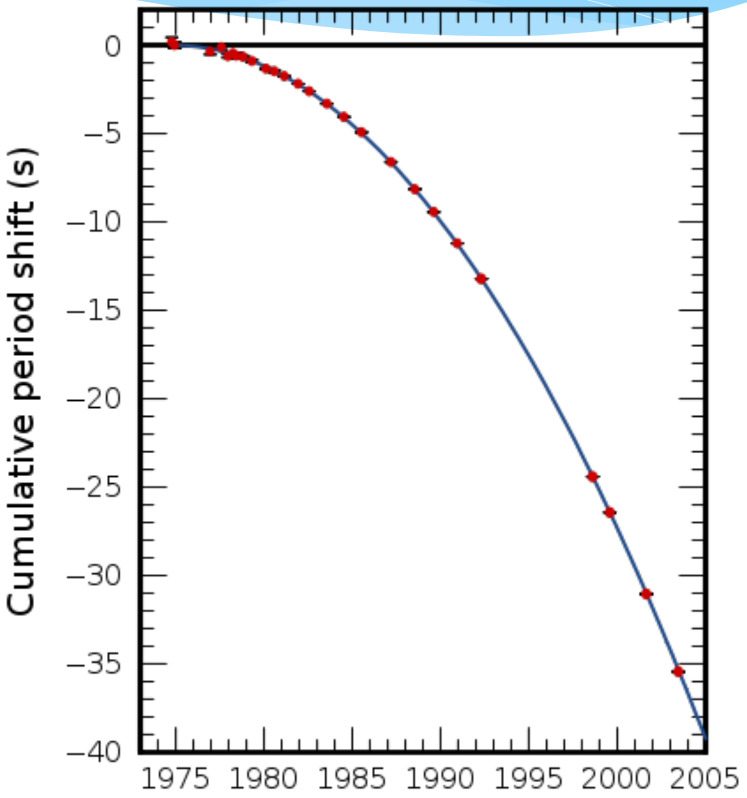
Situation until Sept 2015 (approx. 100 yrs after Einstein)

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!

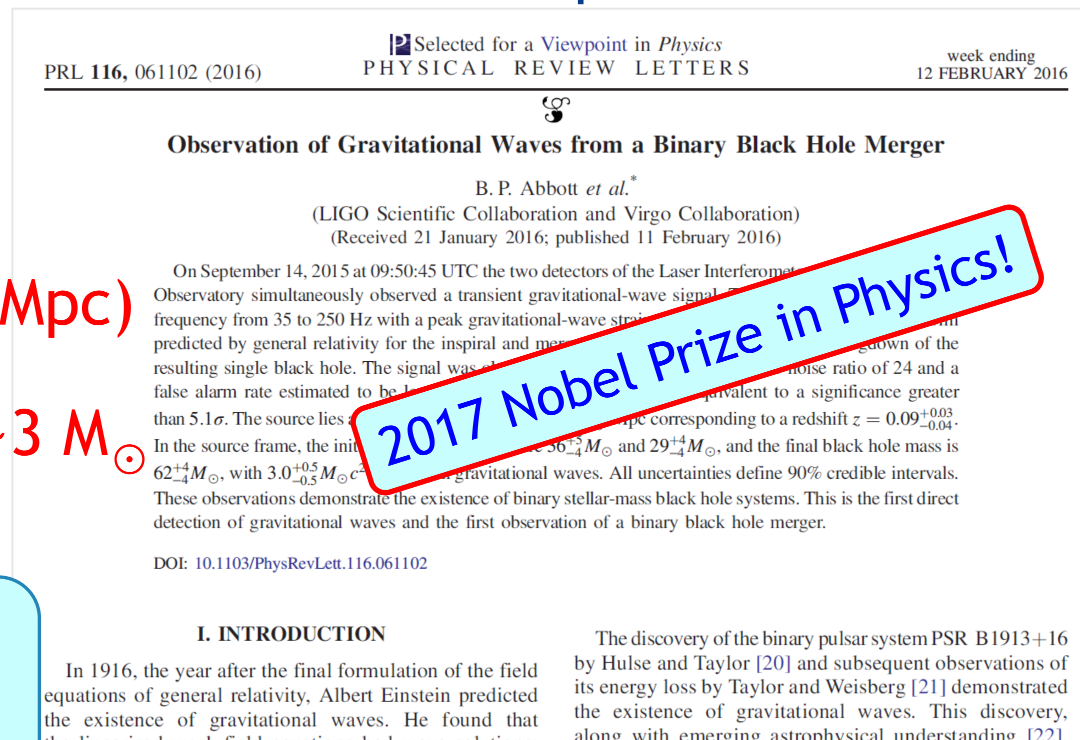
GW150914

- 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 $M_\odot$

10^4 x (SN energy)!



PRL **116,** 061102 (2016) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferomet
Observatory simultaneously observed a transient gravitational-wave signal
frequency from 35 to 250 Hz with a peak gravitational-wave strai
predicted by general relativity for the inspiral and mer … down of the
resulting single black hole. The signal was … noise ratio of 24 and a
false alarm rate estimated to be l … uivalent to a significance greater
than 5.1σ. The source lies … pc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$.
In the source frame, the init … $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is
$62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ … 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

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

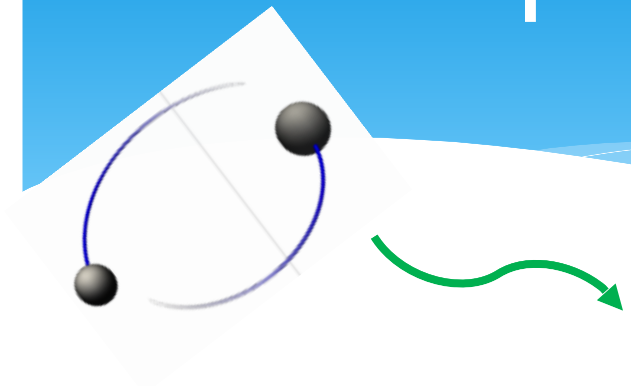
3000km = 10 ms

each arm = 4km
can detect GW amplitude of $\sim 10^{-21}$!

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

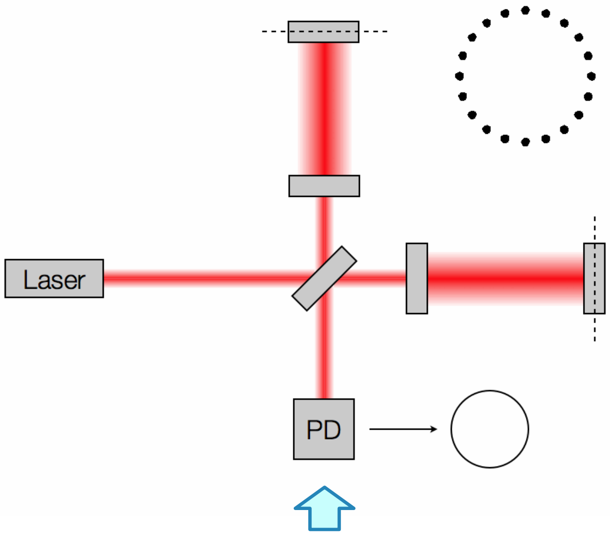
size of neucleon ~ 10^{-13}cm

Principle of Interferometer



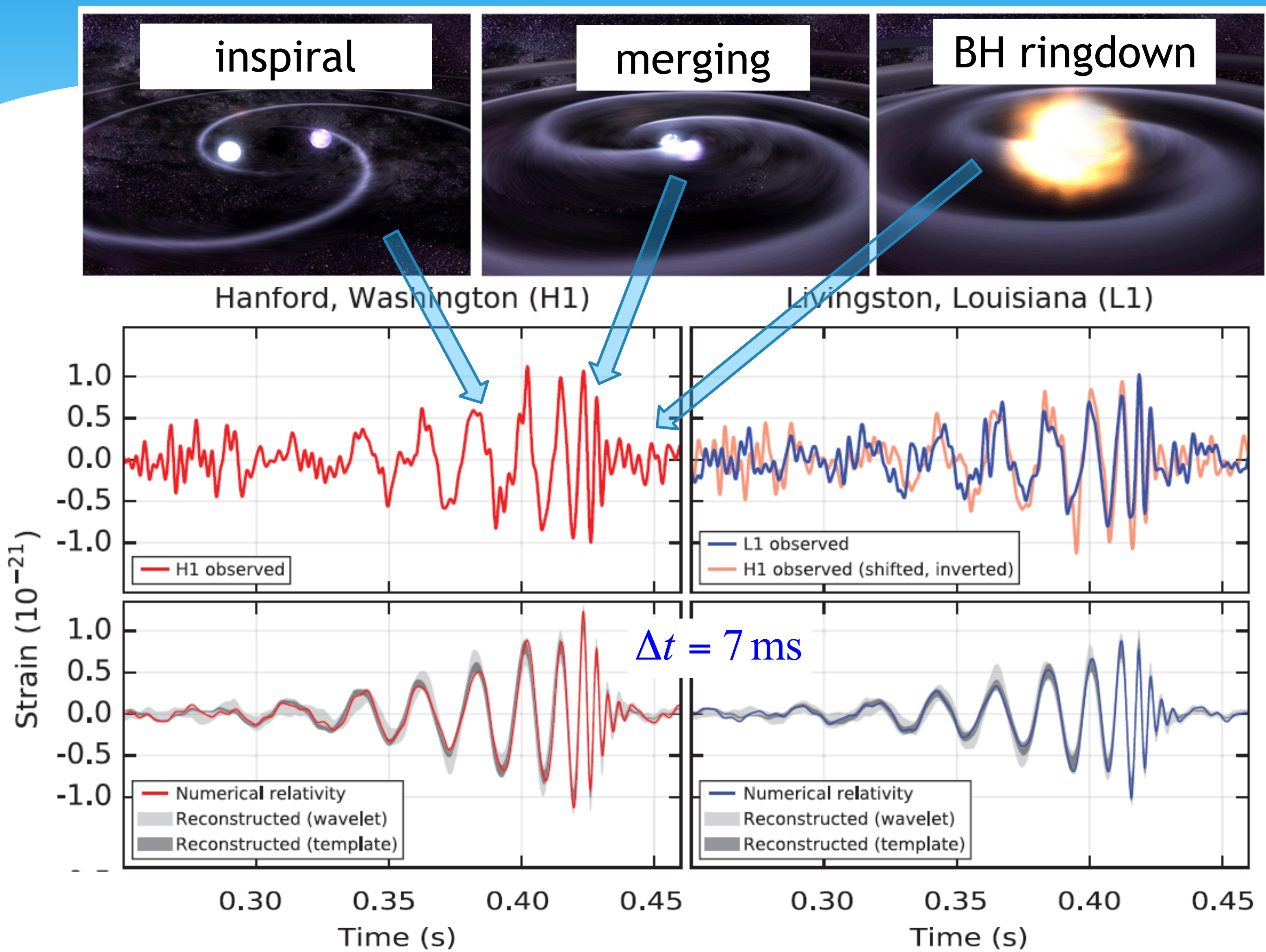
GWs from BBH, etc.

arm length oscillates
when GWs pass through



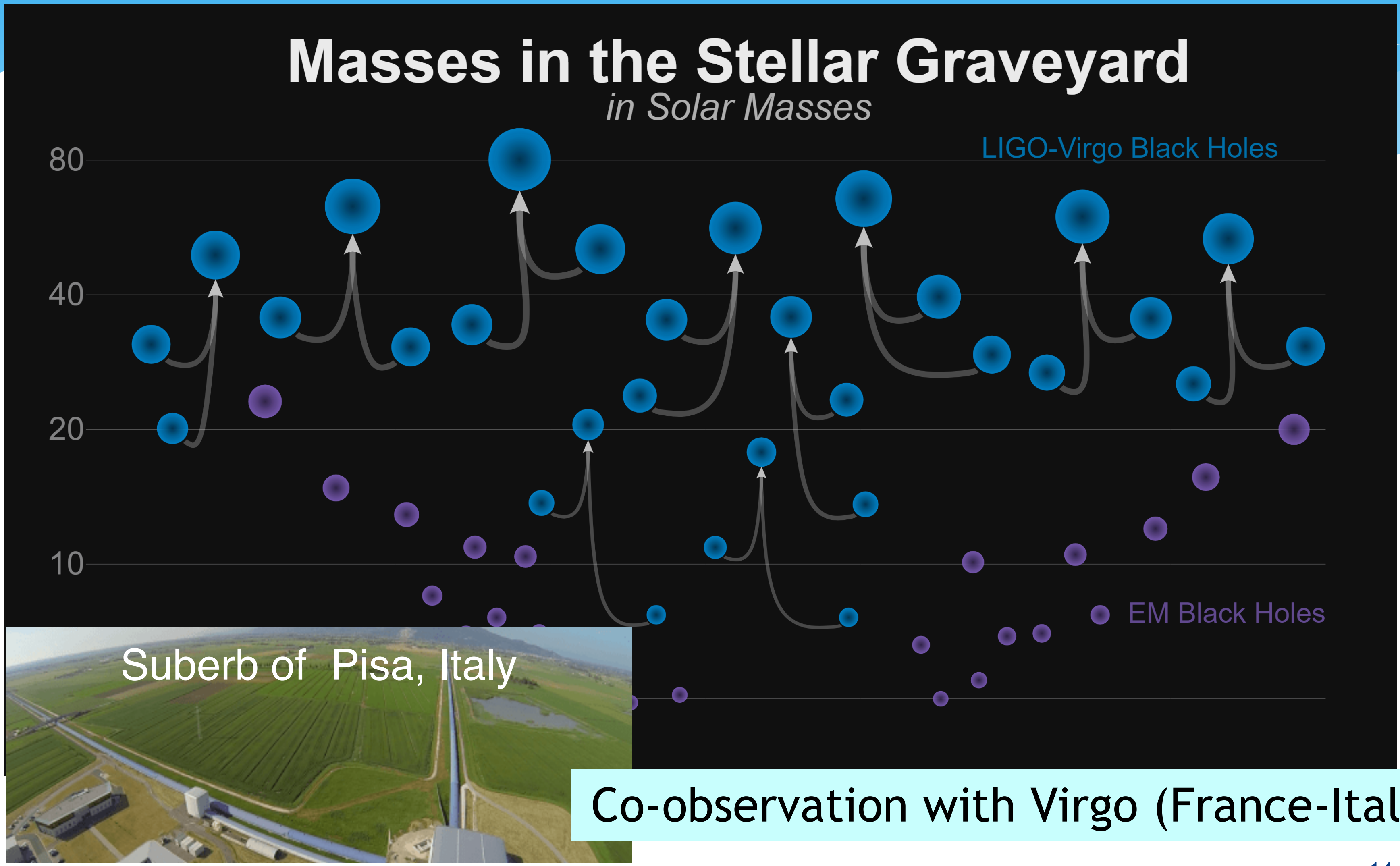
detector sees fluctuating light

observed GW signal



Already 10 BBH events detected!

(+3 more by LIGO-Virgo Observation 3 (O3), as of 2 May 2019)



Co-observation with Virgo (France-Italy)

"Sound" of GWs

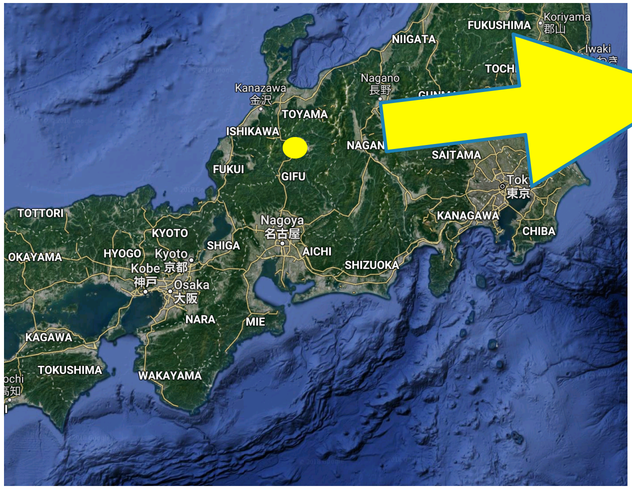
GW150914 and GW151226

a bit about Japan

KAGRA ~ 神樂

KAmioka GRAvitational wave detector

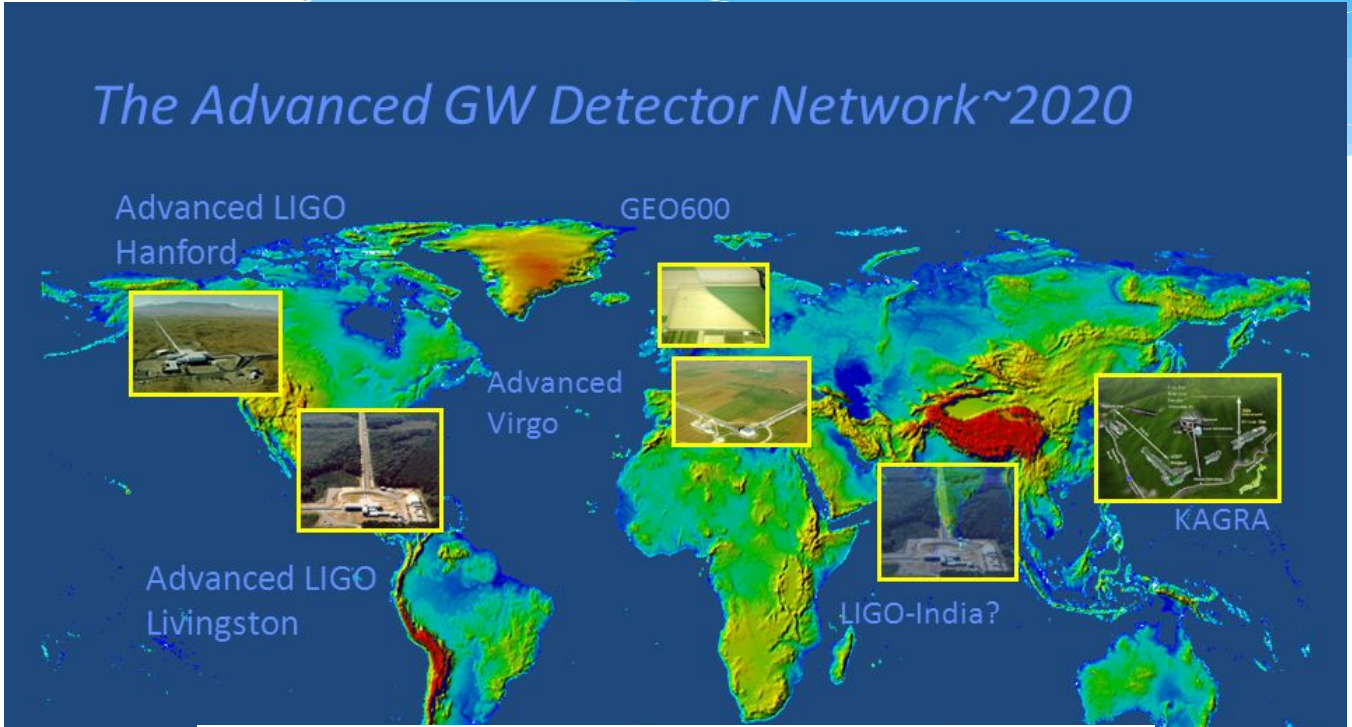
almost completed, plan to join LIGO-Virgo O3 by the end of 2019!



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

future

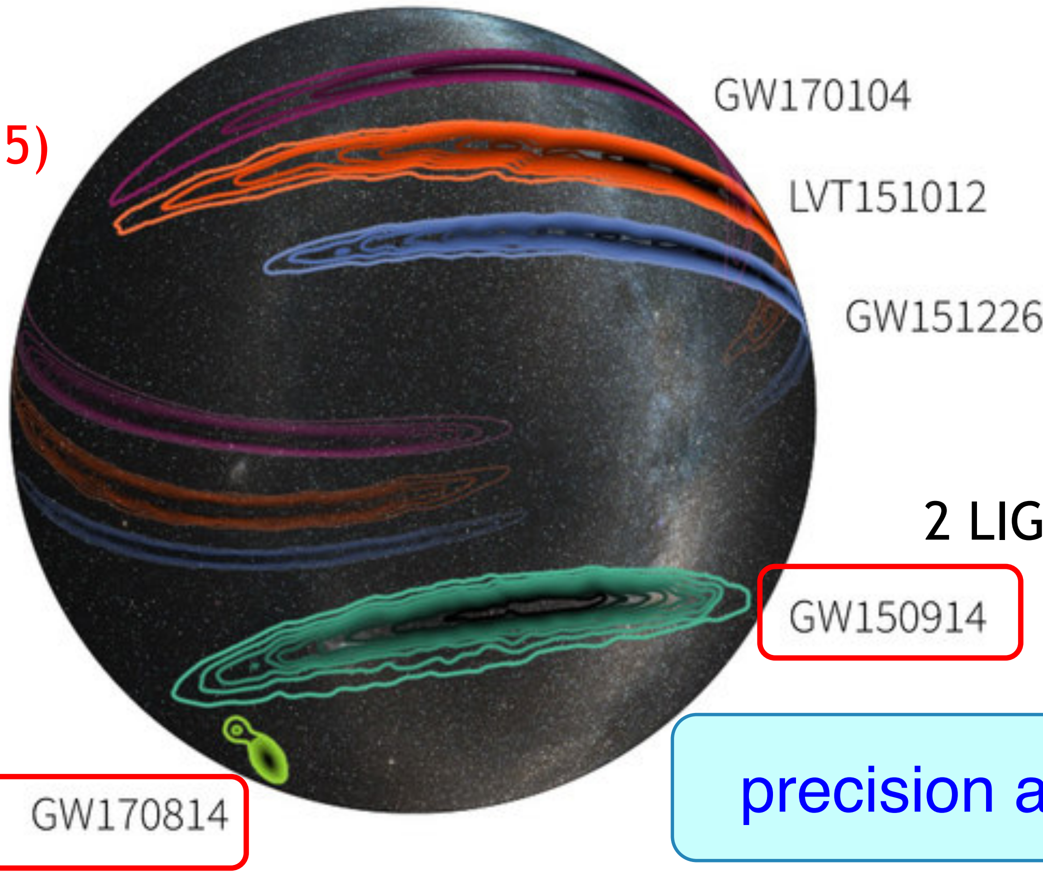
GW detector network



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 101 (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)

(Receive 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 betw n 0.86 and 2.26 $M_\odot$, in agreement masses of known neutron stars. Restricting the componen ins to the range inferred in e find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of $_\odot$. 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 an ovides the first direct evidence of a link between these mergers and short γ-ray bursts. bsequent ide fication of transient counterparts across the electromagnetic spectrum in the same location fu suppor the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and insight into astrophysics, dense matter, gravitation, and cosmolog

NS mass

strong signal

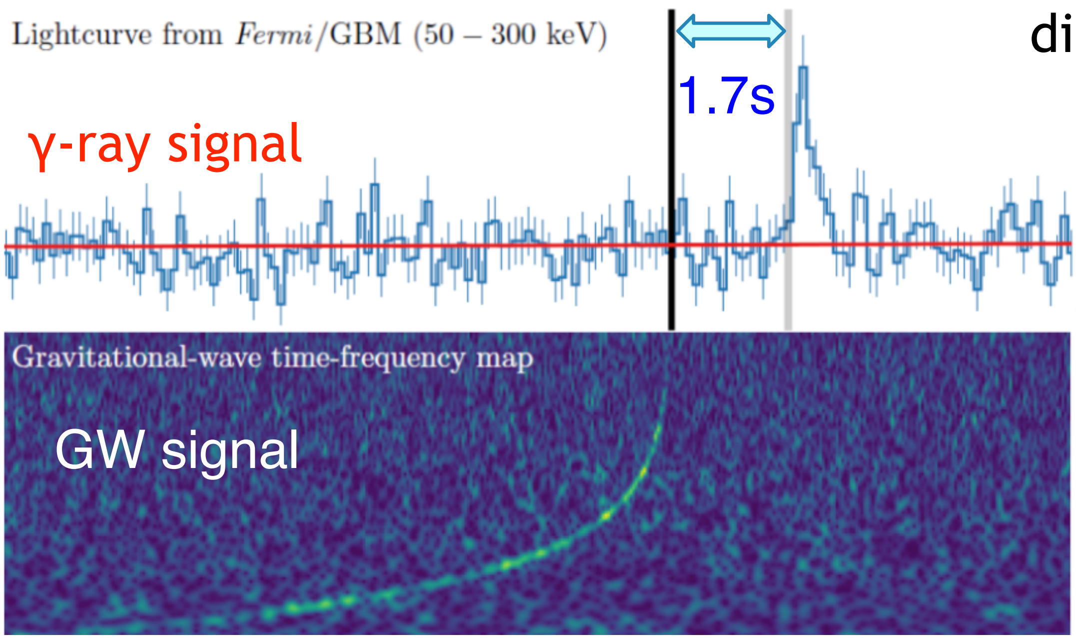
observed also by EMWs!

GW170817=GRB170817A

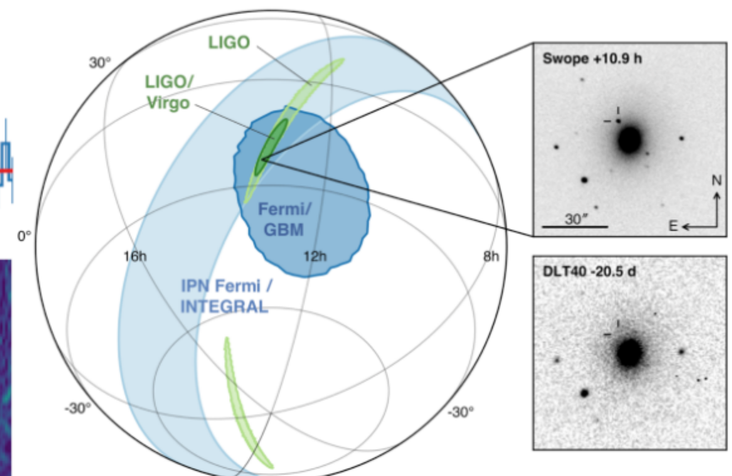
γ-ray burst

LIGO Scientific Collaboration

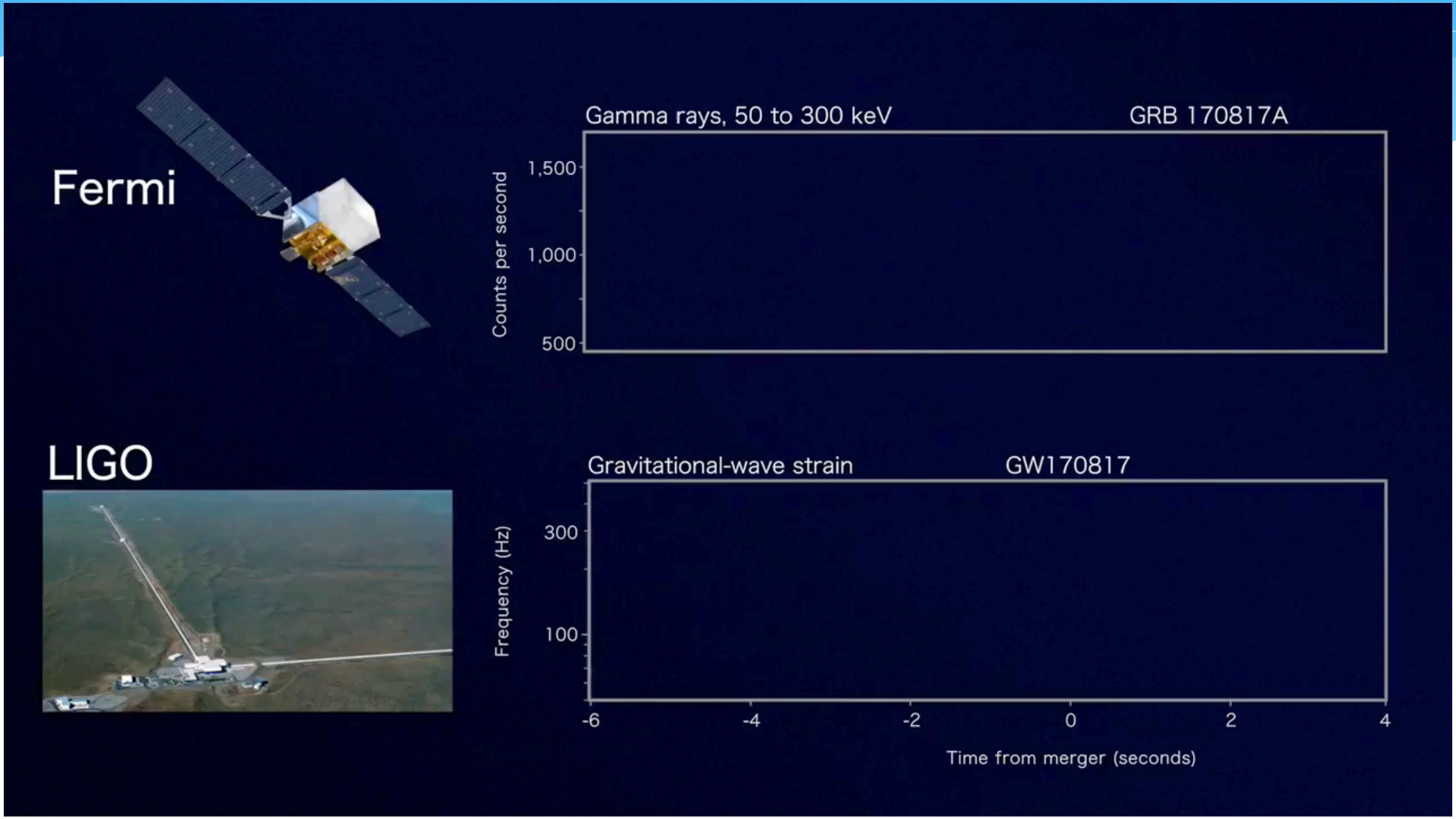
LIGO-Virgo + Fermi simultaneously detected GWs and γ-ray from Binary NS merger

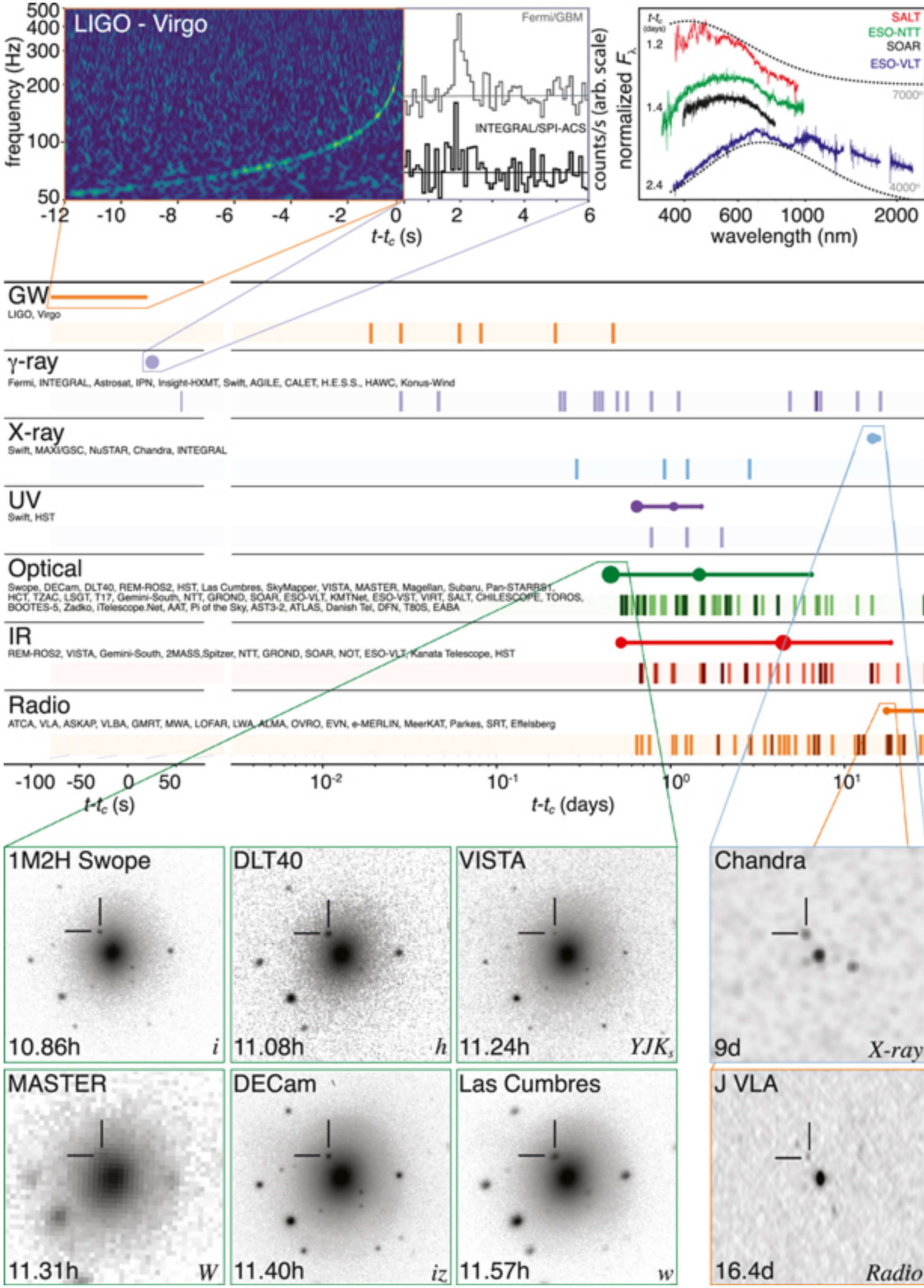


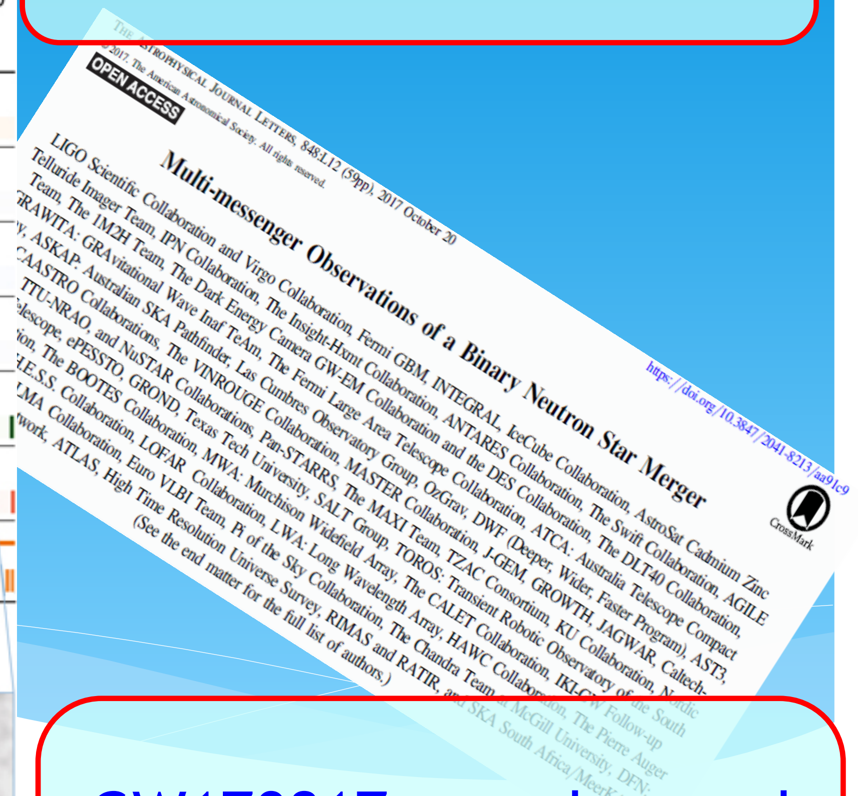
distance: 0.13 G lyr (~ 40 Mpc)



“Sound” of GWs and γ-ray






THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20
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OPEN ACCESS
https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

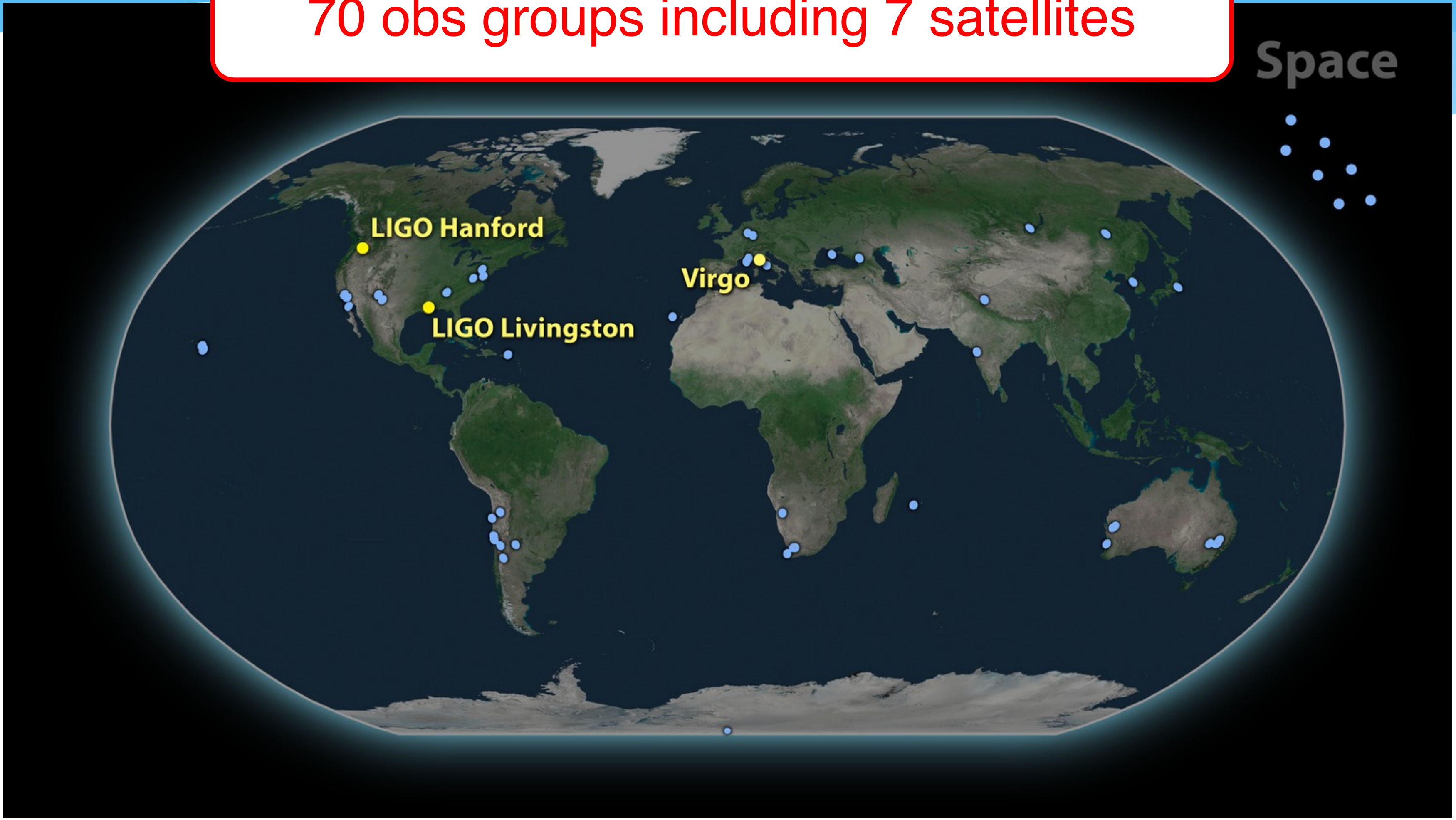
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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

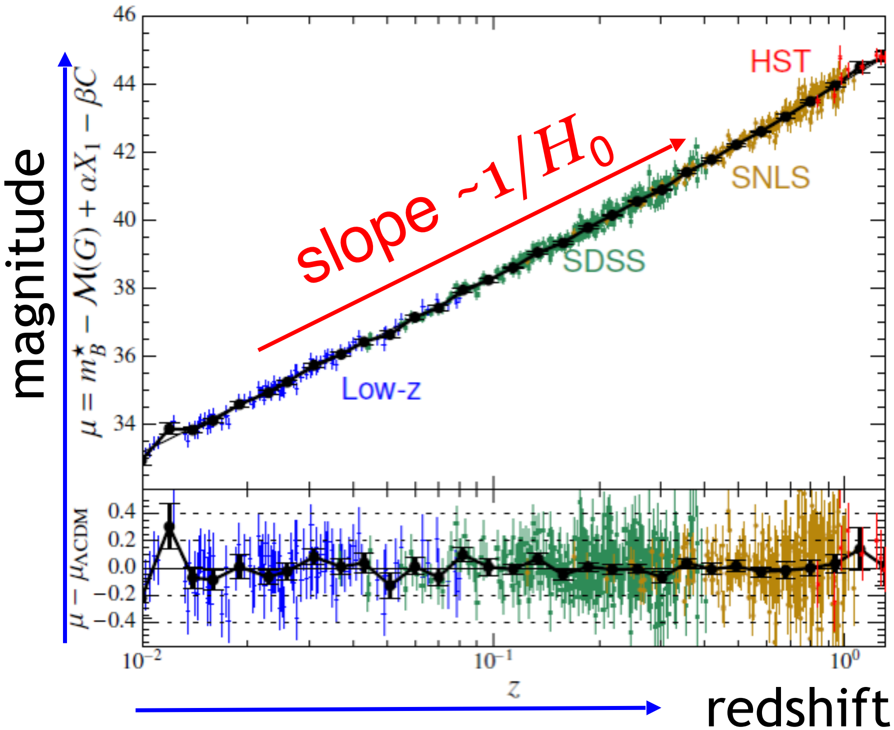


from Astronomy to Cosmology

Cosmoloical implication of GW170817

Hubble-Lemaitre law:

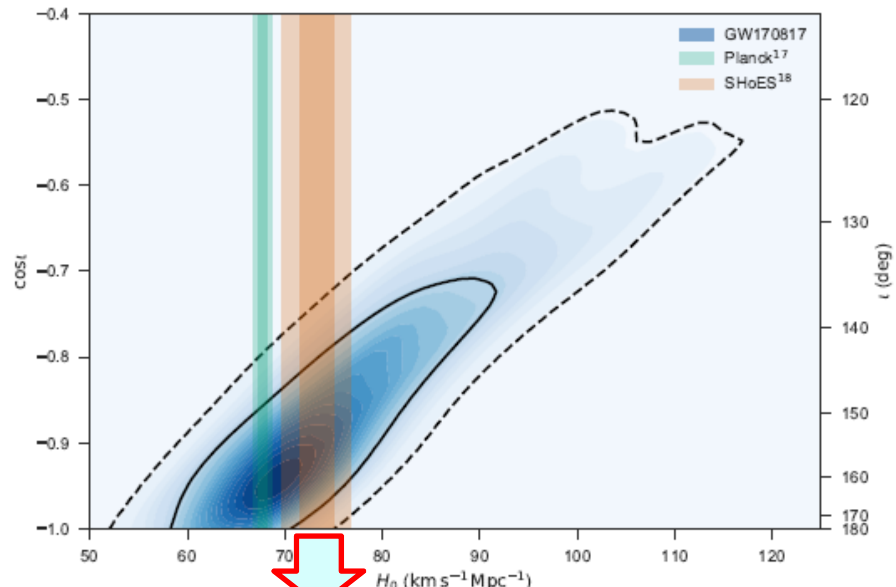
measured by redshift → $V = H_0 r$ ↑ estimated from magnitude



Betoule et al. arXiv:1401.46064

A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

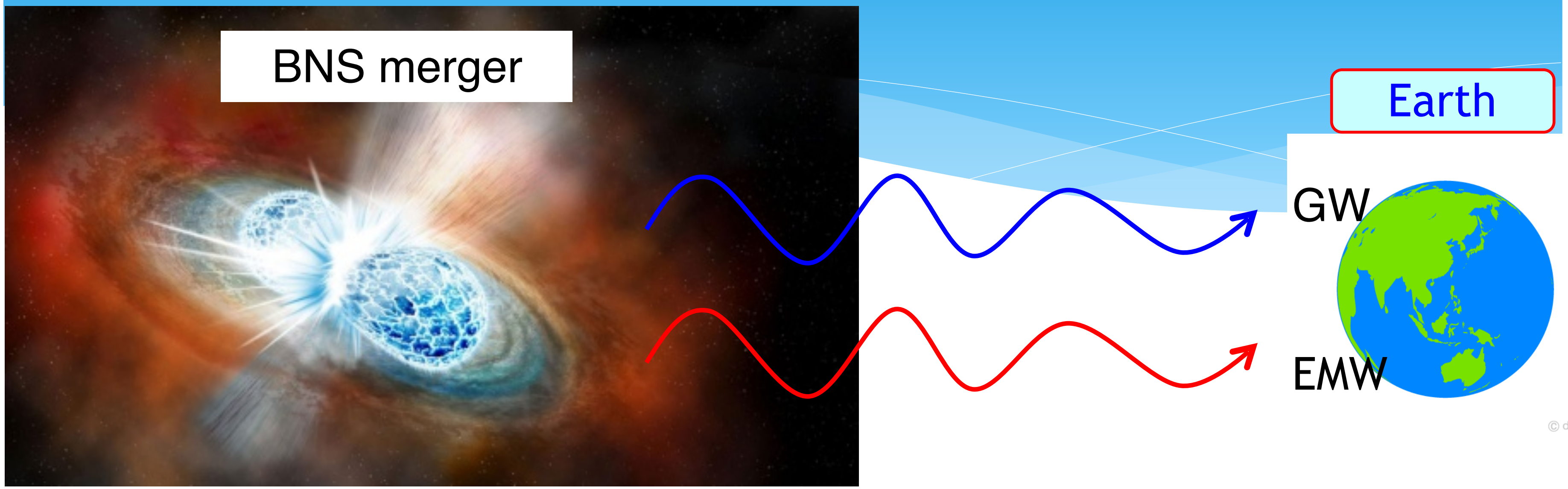
THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABORATION, THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION, THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION, THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.



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

~10% accuracy by a single observation!

EMWs and GWs



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

distance = 0.13 G lyr

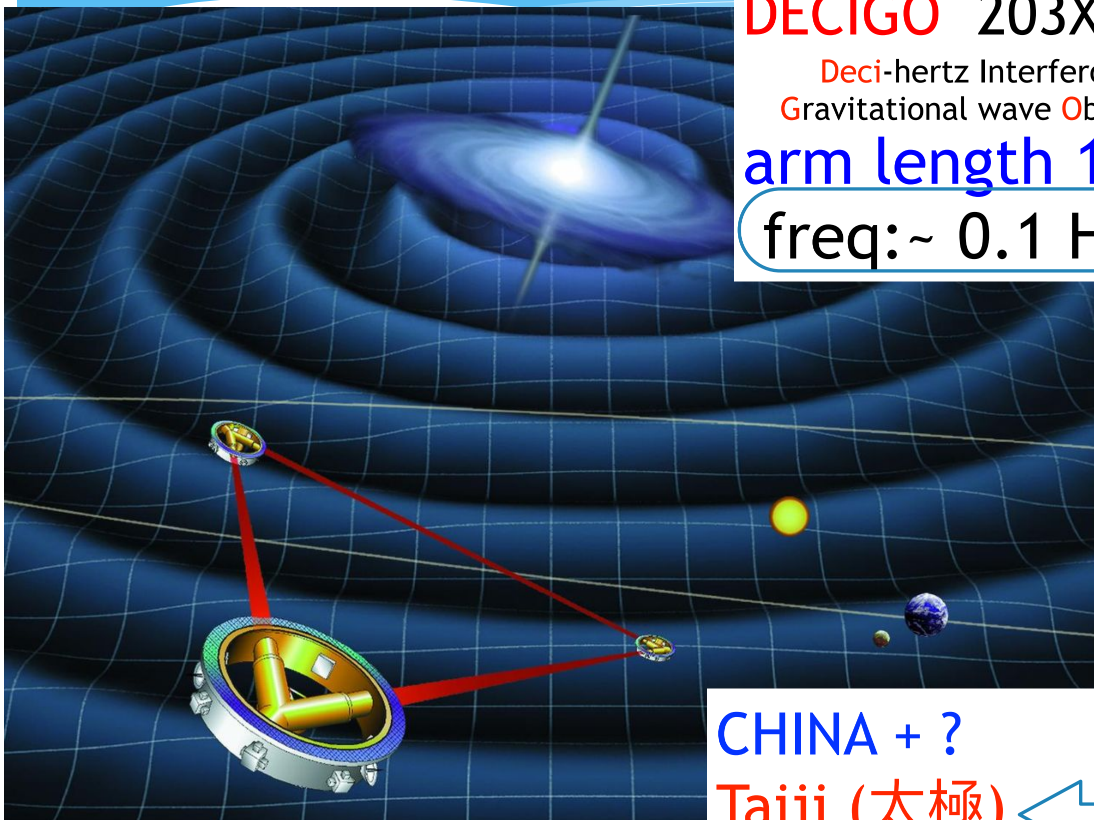
Δt=1.7s for L=0.13 Glyr
(L=4×10^{15}s x c)

⇨ $c_{GW} - c_{EMW} < 10^{-5}$ cm/s

strong constraint on Dark Energy models

future projects

Space GW Observatories



Japan +?

DECIGO 203X?

Deci-hertz Interferometer Gravitational wave Observatory

arm length 1,000 km

freq:~ 0.1 Hz

Europe + US + ?

LISA 2035?

Laser Interferometer Space Antenna

arm length 5,000,000 km

freq:~10^{-3}Hz

CHINA + ?

Taiji (太極) ⇔ TianQin (天琴) 203X?

3,000,000 km | 100,000 km

freq: ~10^{-3} Hz | ~10^{-2}Hz

http://lisa.nasa.gov/

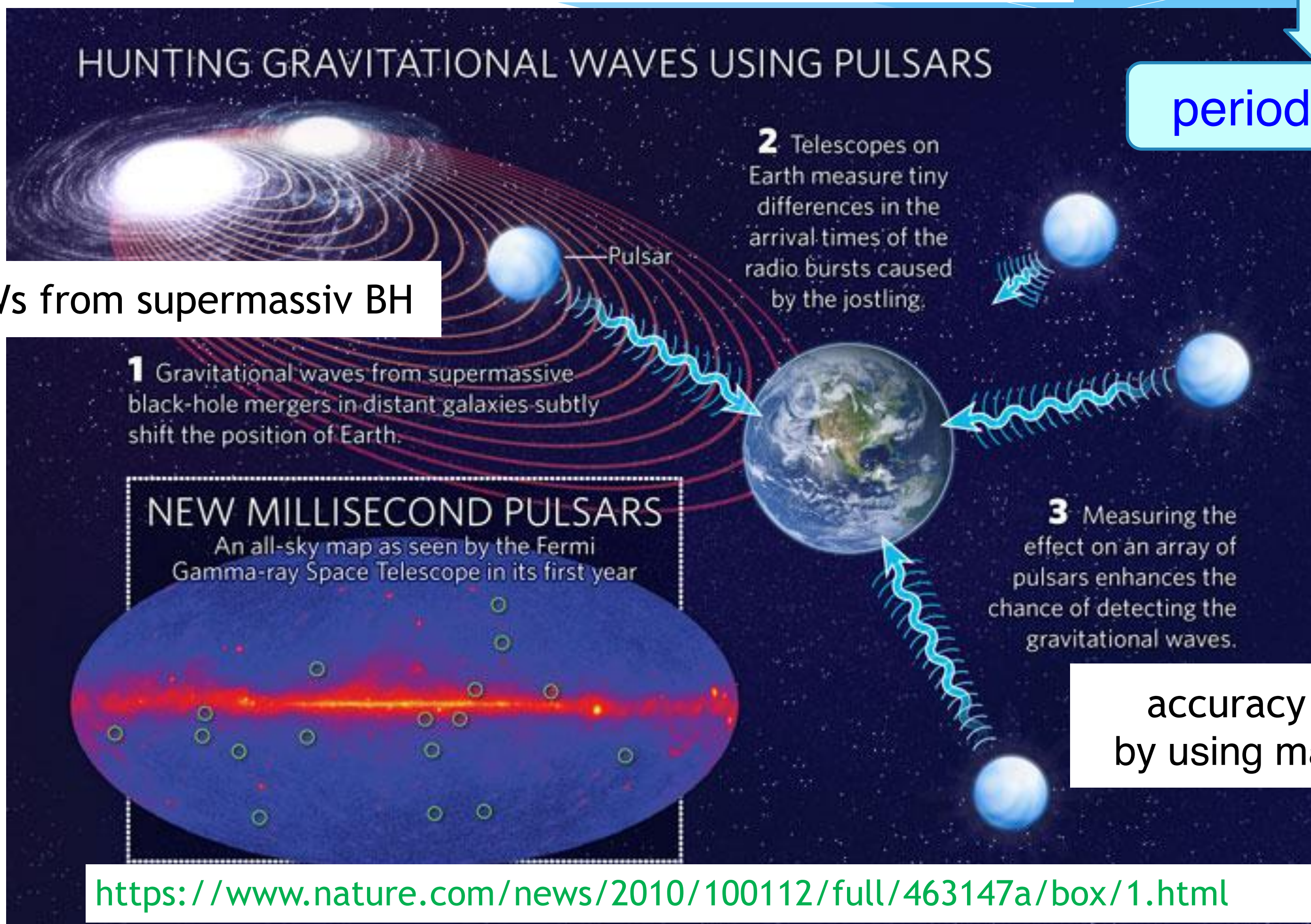
Pulsar Timing Array

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

freq: ~ 10^{-8}Hz

period ~ 10 yr

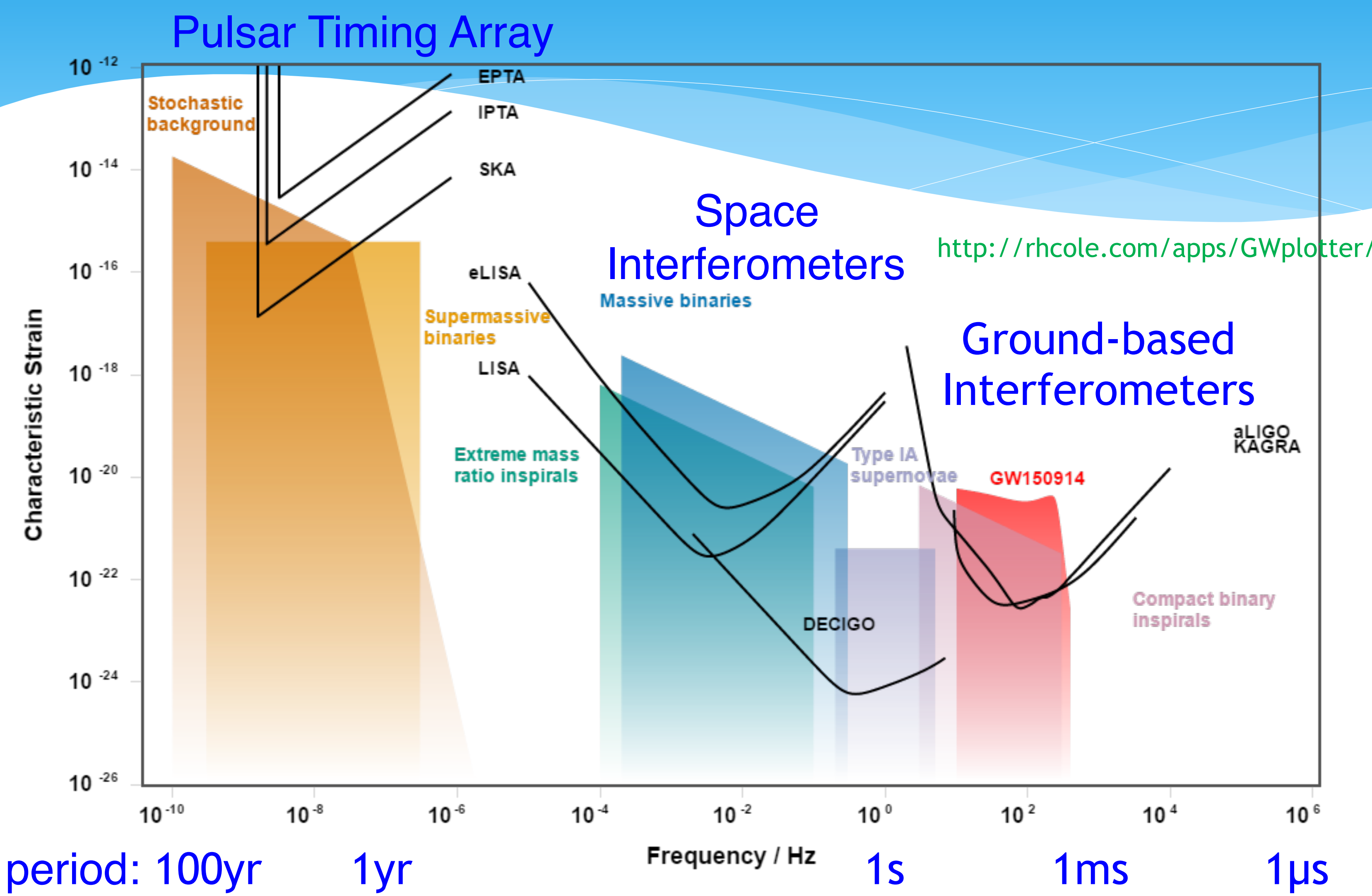
GWs from supermassiv BH



accuracy increases
by using many pulsars

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

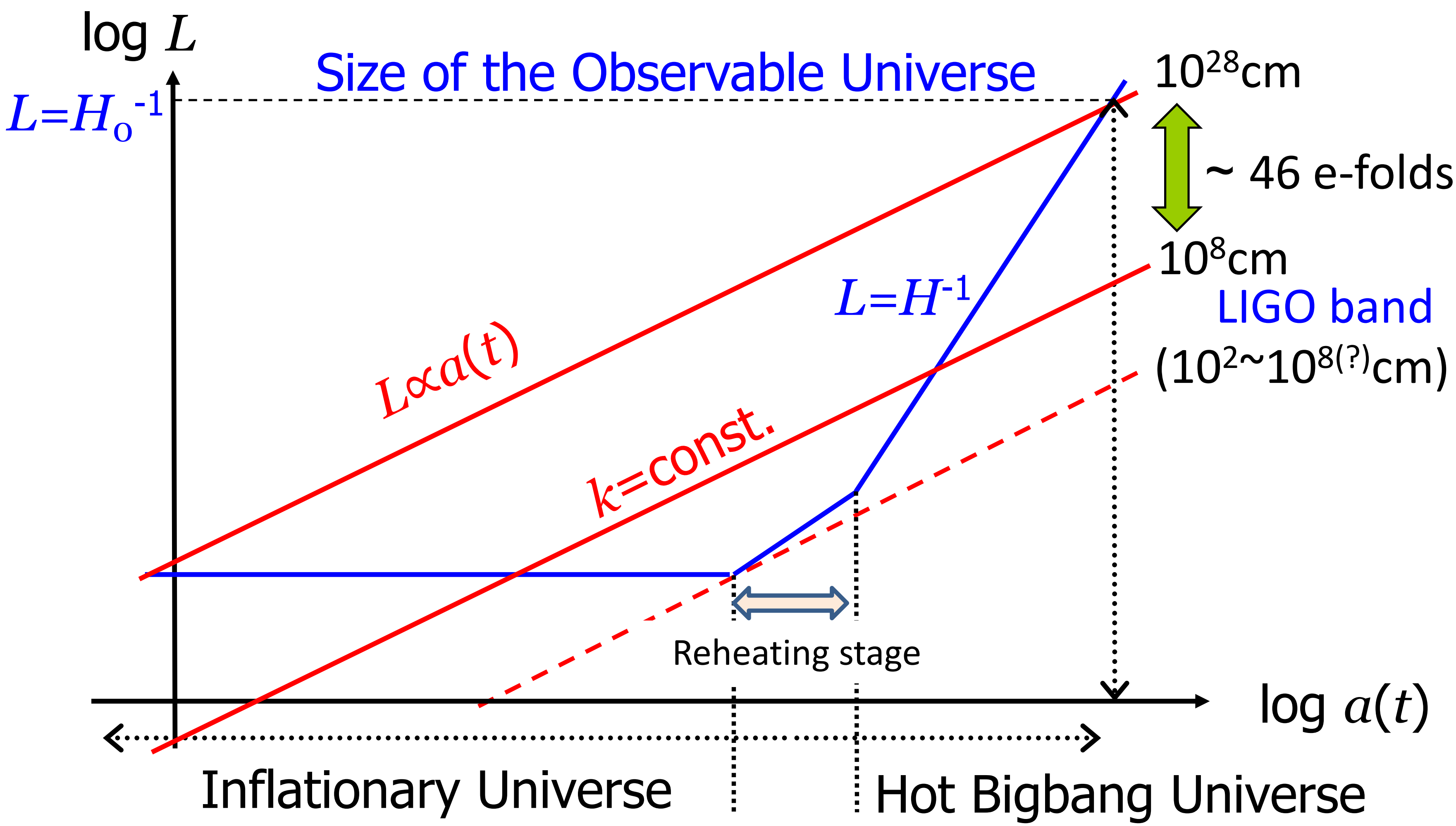
Multi-band GW Astronomy



GW Cosmology: Topics

length scales of the inflationary universe

⟺ targets for multi-frequency GW astronomy



GWs from Inflation

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

Starobinsky '79

$$ds^2 = -dt^2 + a^2(t)\,(\delta_{ij} + h_{ij})\,dx^i dx^j \qquad a(t) \sim \exp[Ht]$$

tensor (GW) perturbation

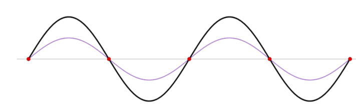
quasi-exponential expansion

"comoving" wavenumber

$$\Rightarrow \quad \ddot{h}_{ij} + 3H\dot{h}_{ij} + \frac{k^2}{a^2}h_{ij} = 0$$

effect of expansion

wavelength: $\lambda = \dfrac{2\pi a}{k}$



https://oceanservice.noaa.gov/facts/seiche.html

$$\Rightarrow \quad h_{ij} \to \text{constant}$$

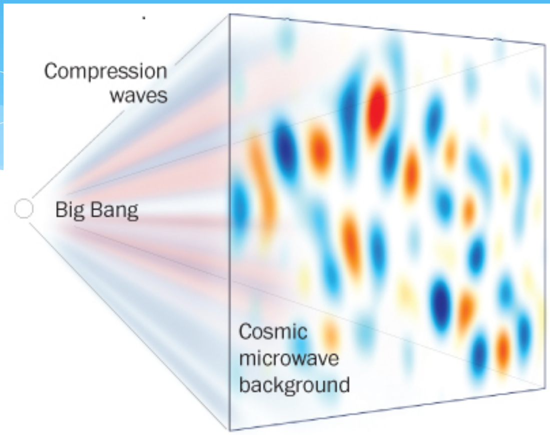
for $k^2/a^2 \ll H^2$

Vacuum fluct's freeze to a constant
on super Hubble horizon scale

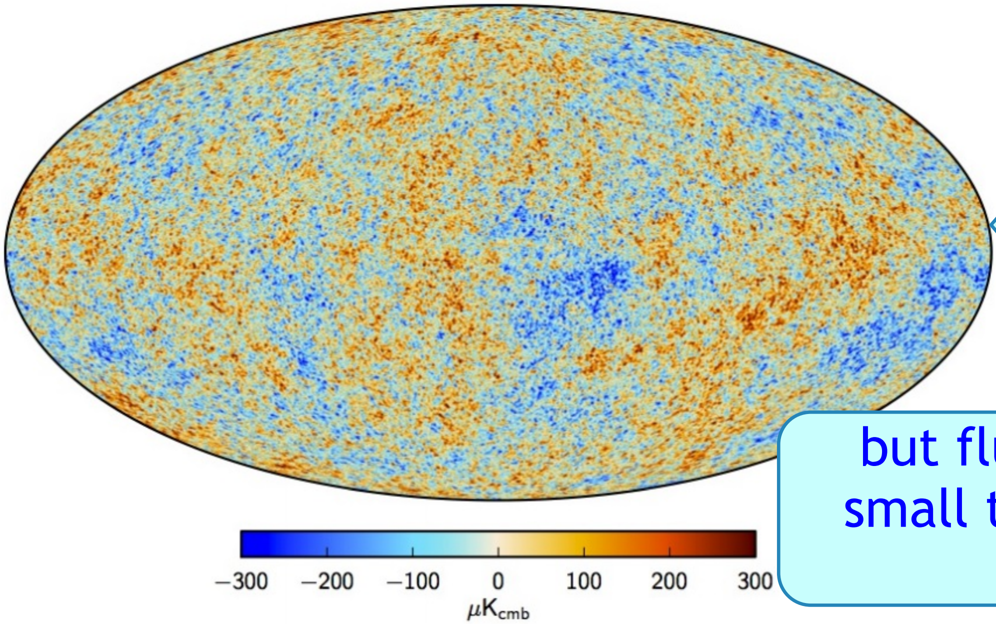
detecting GWs in CMB

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

- GW (tensor) perturbations also generate CMB temperature fluctuations



CMB fluctuations

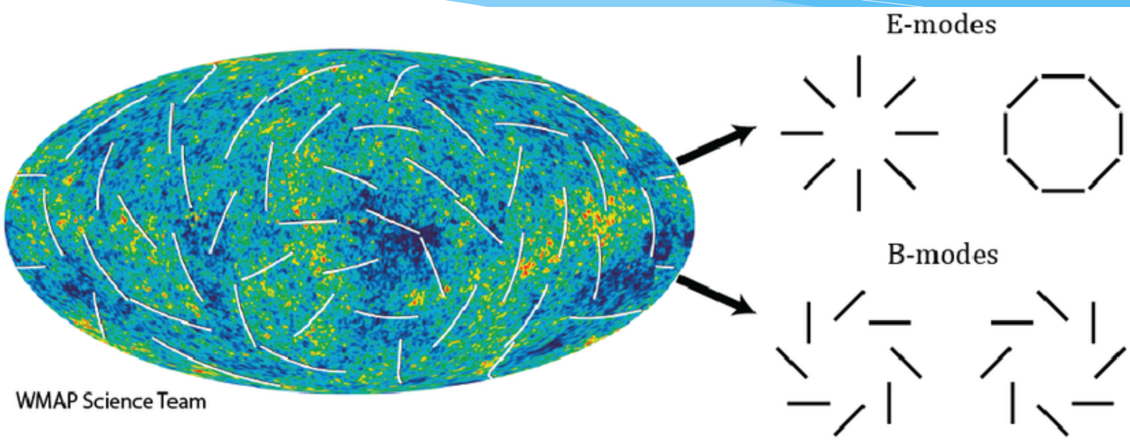


CMB temp fluctuations observed by Planck Satellite

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

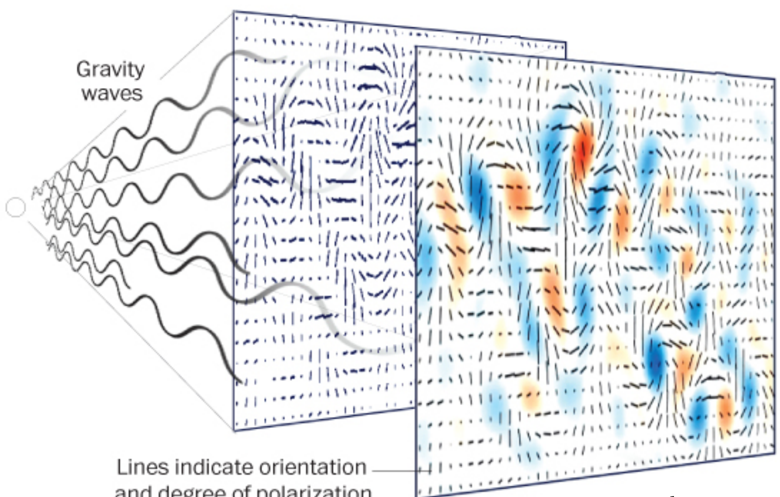
CMB B-mode polarization

GWs produce B-mode fluctuations in CMB polarization



E-mode

B-mode
characteristic to
GW perturbations



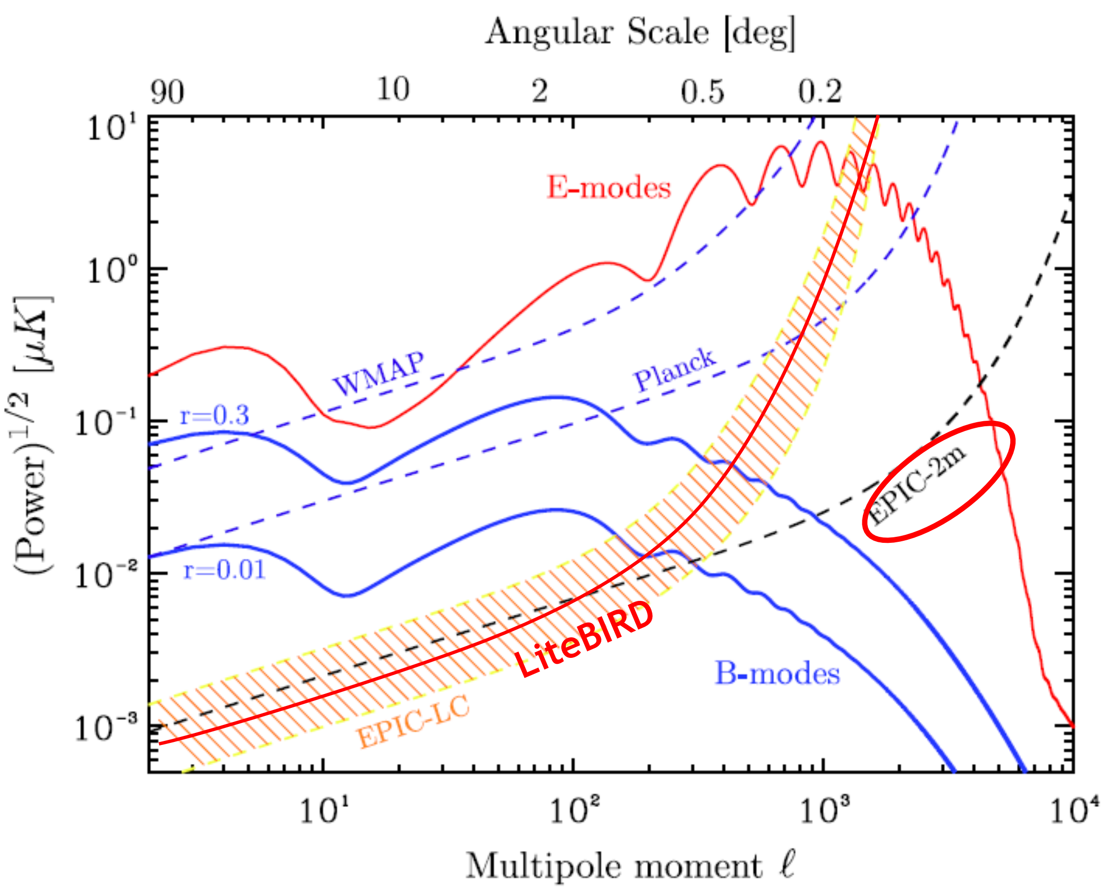
Source: Harvard-Smithsonian Center for Astrophysics

B-mode

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

GW detector with arm
length of 10 G lyr !

B-mode projects



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

LiteBIRD
2027 ~
http://litebird.jp/eng/

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

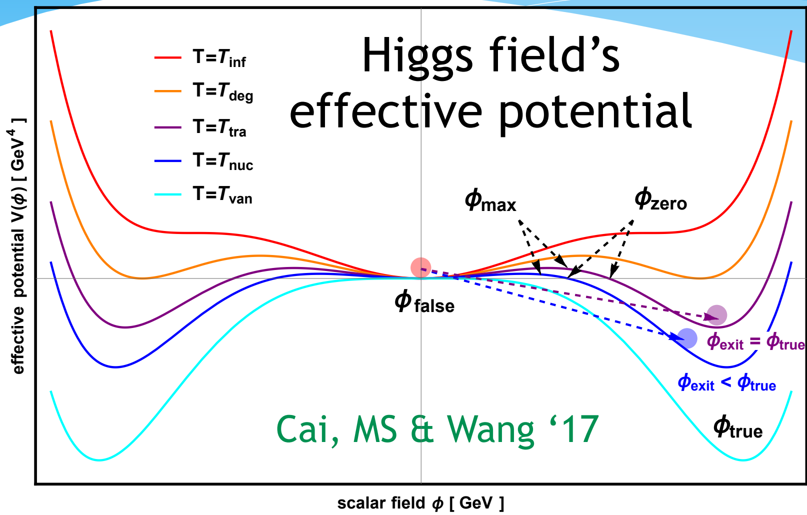
Phase A approved by JAXA!
Kavli IPMU is in!

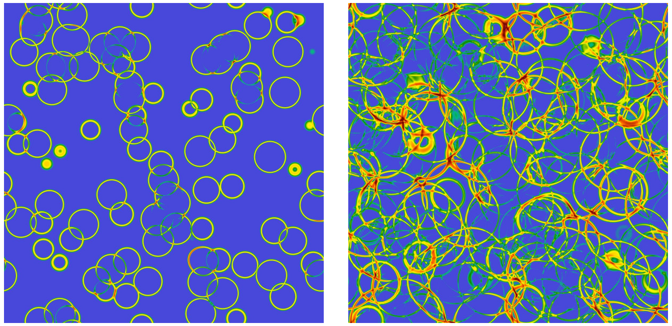
EPIC
203X (???)
http://arxiv.org/abs/0906.1188

Experimental Probe of Inflationary Cosmology

GWs from Phase Transition

Electro-Weak transition may be strongly first order

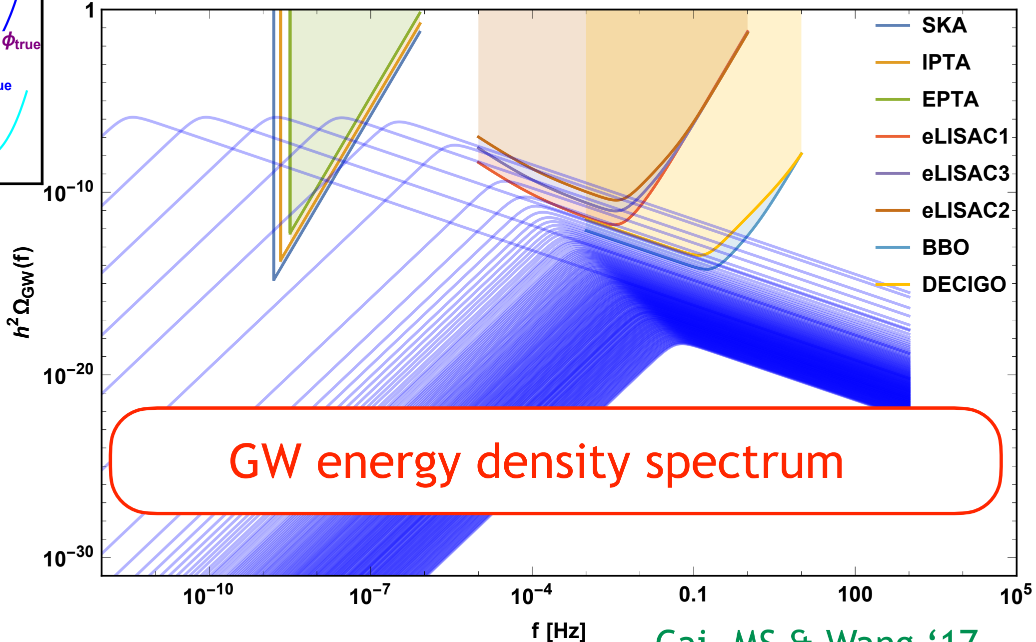




bubble formation and collisions

Hindmarsh et al. '15

formation & collisions of bubbles generate GWs

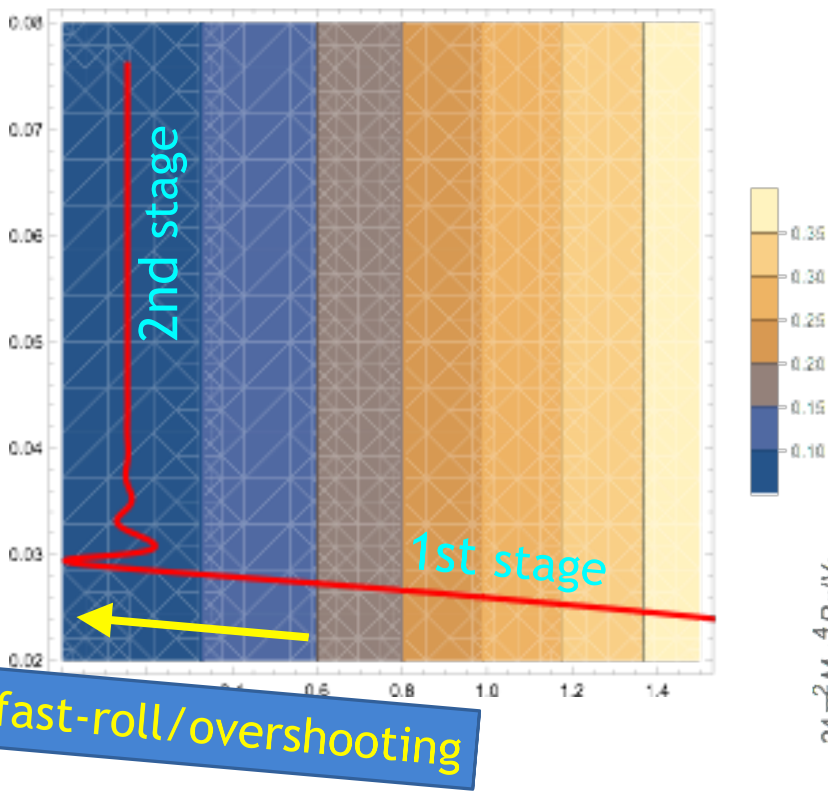


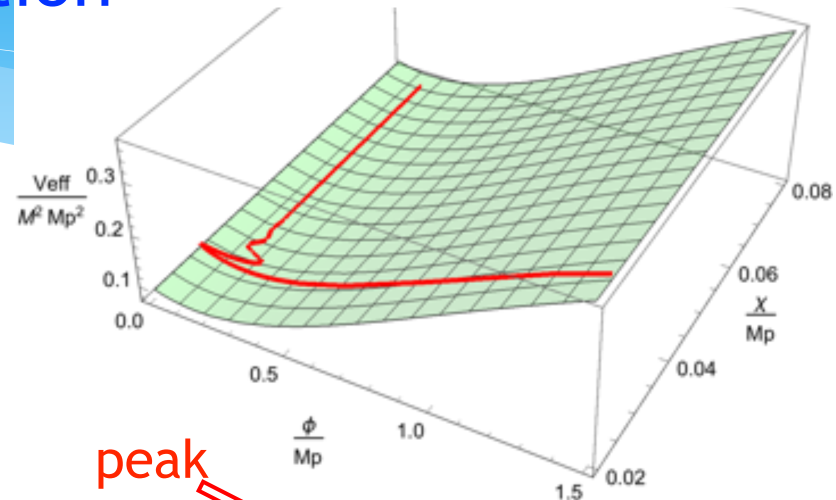
Cai, MS & Wang '17

PBH from Inflation

2-field inflation

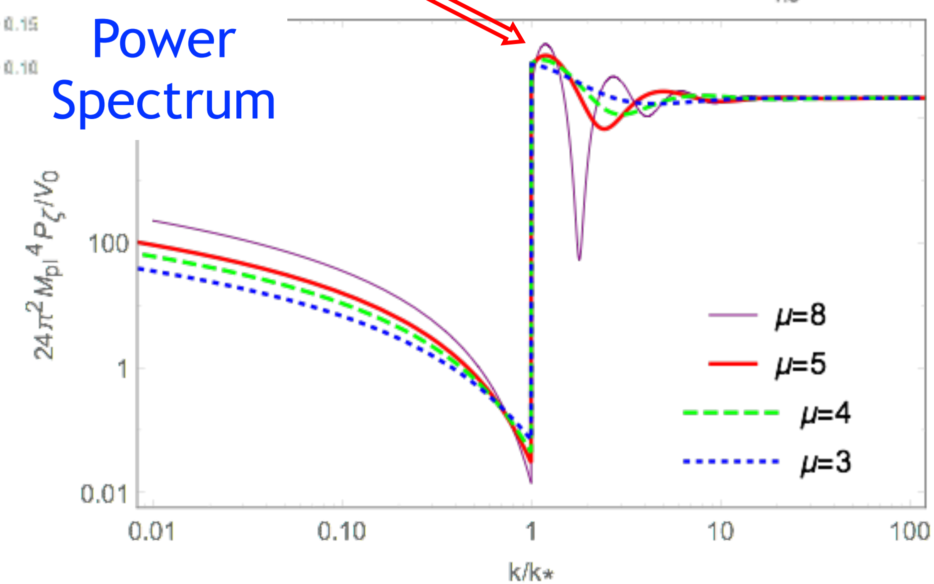
Pi, Zhang, Huang & MS '17



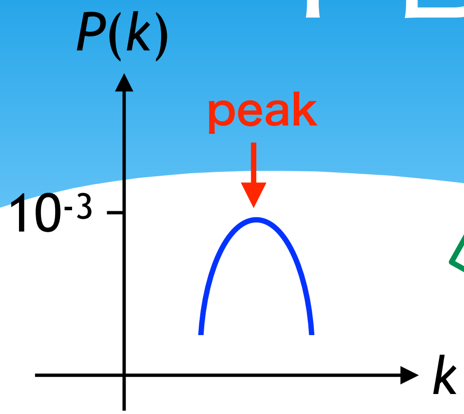


Power Spectrum

peak



PBH=DM model

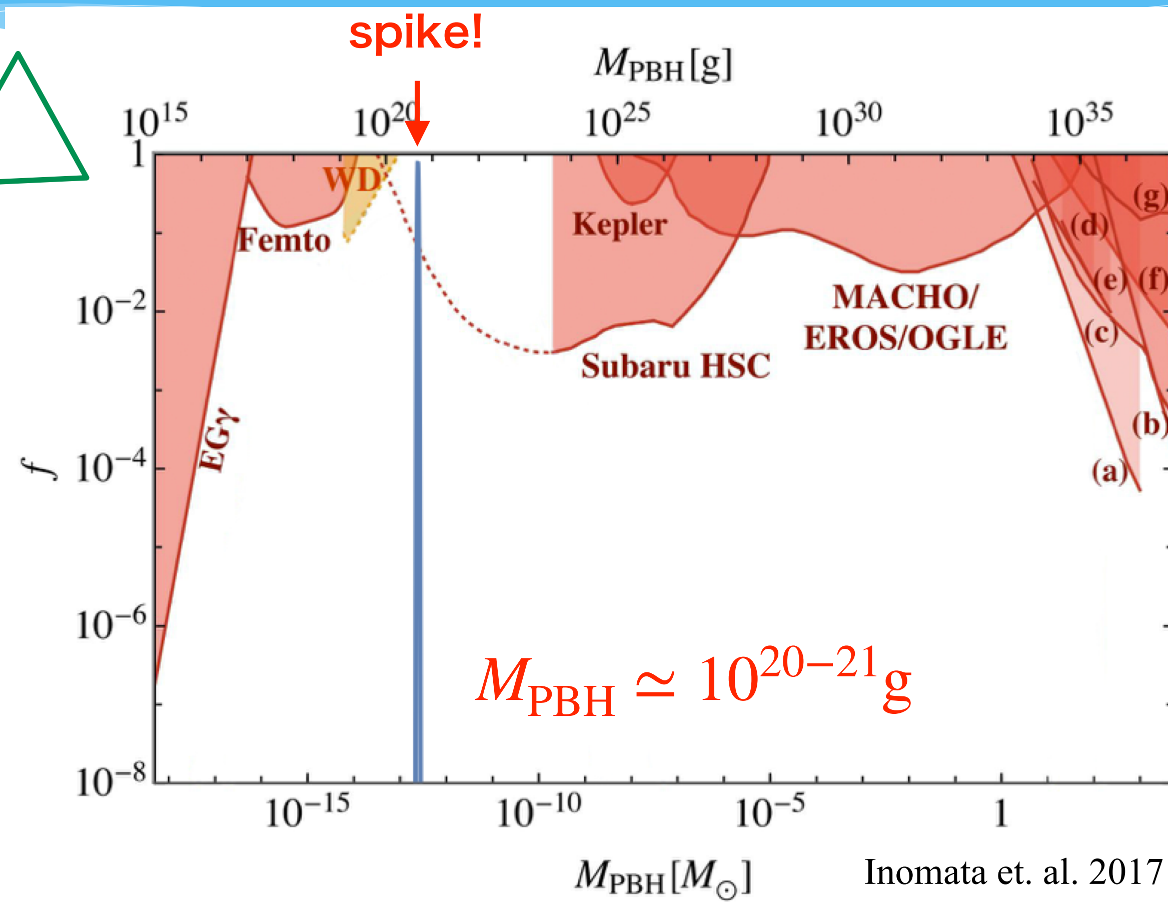


$$f(M) \propto \exp\left[-\frac{O(0.1)}{P(k)}\right]$$

a sharp peak in $P(k)$

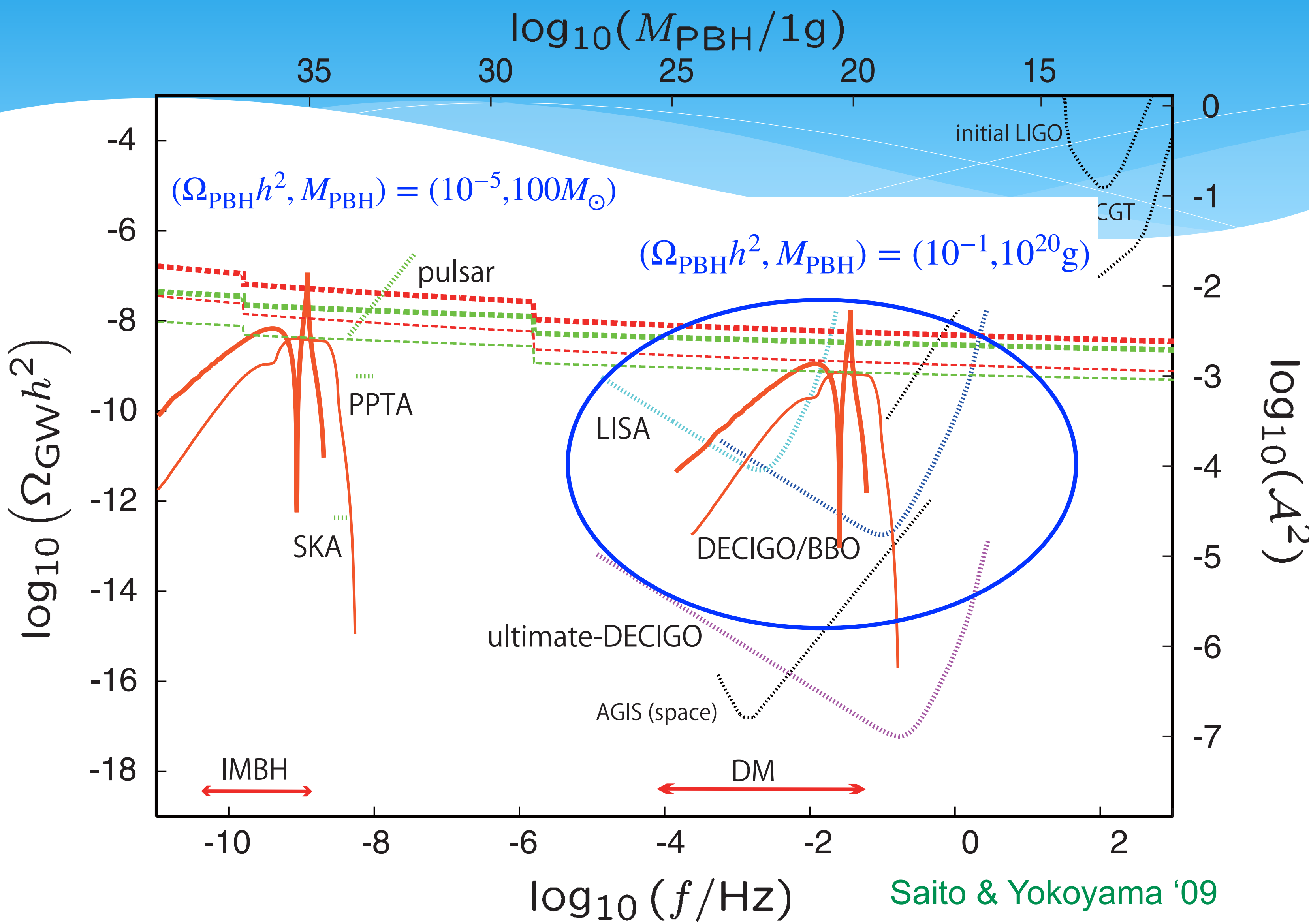
a spike in $f(M)$

monochromatic PBH mass fcn



Inomata et. al. 2017

GWs will test PBHs=DM!



Saito & Yokoyama '09

Recent Updates

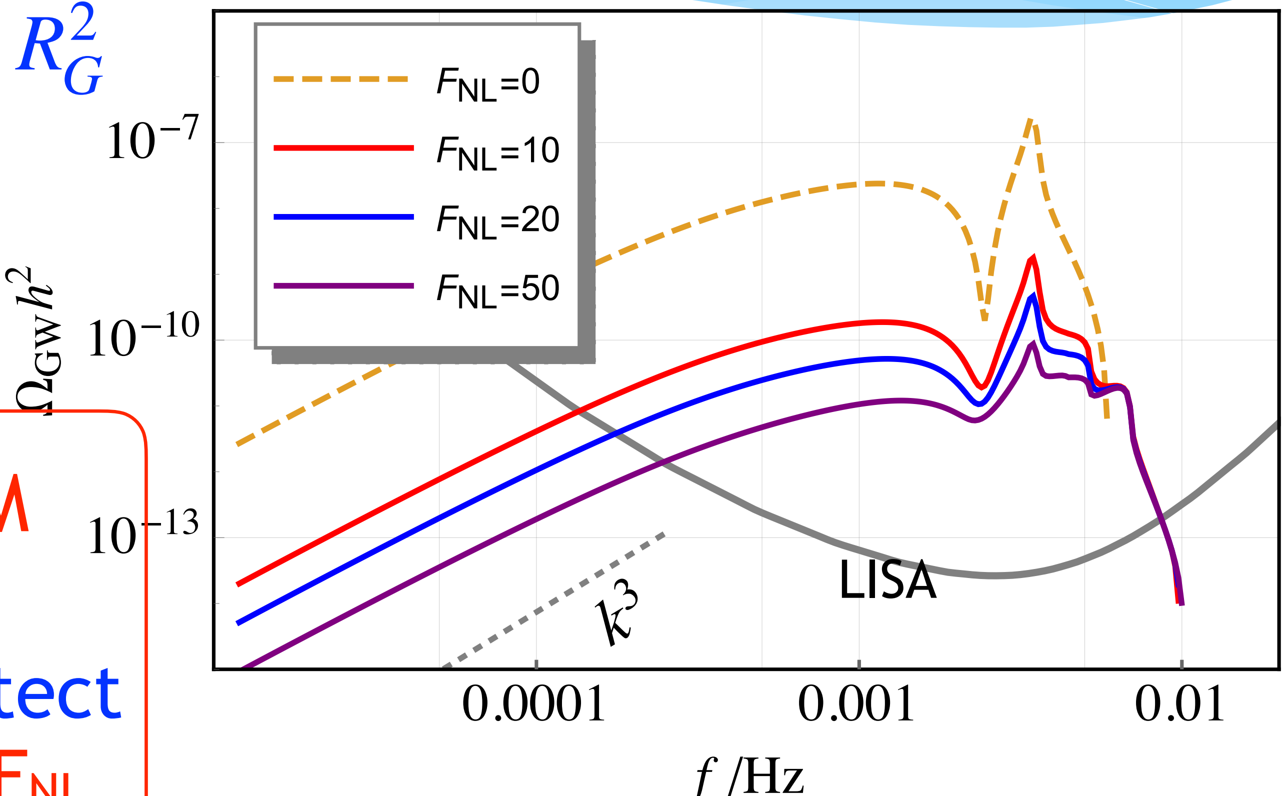
PBHs from Non-Gaussian fluctuations

Cai, Pi & MS '18

Non-Gaussianity parameter

$$\mathcal{R} = \mathcal{R}_G + F_{NL}\,\mathcal{R}_G^2$$

determines amount of PBHs

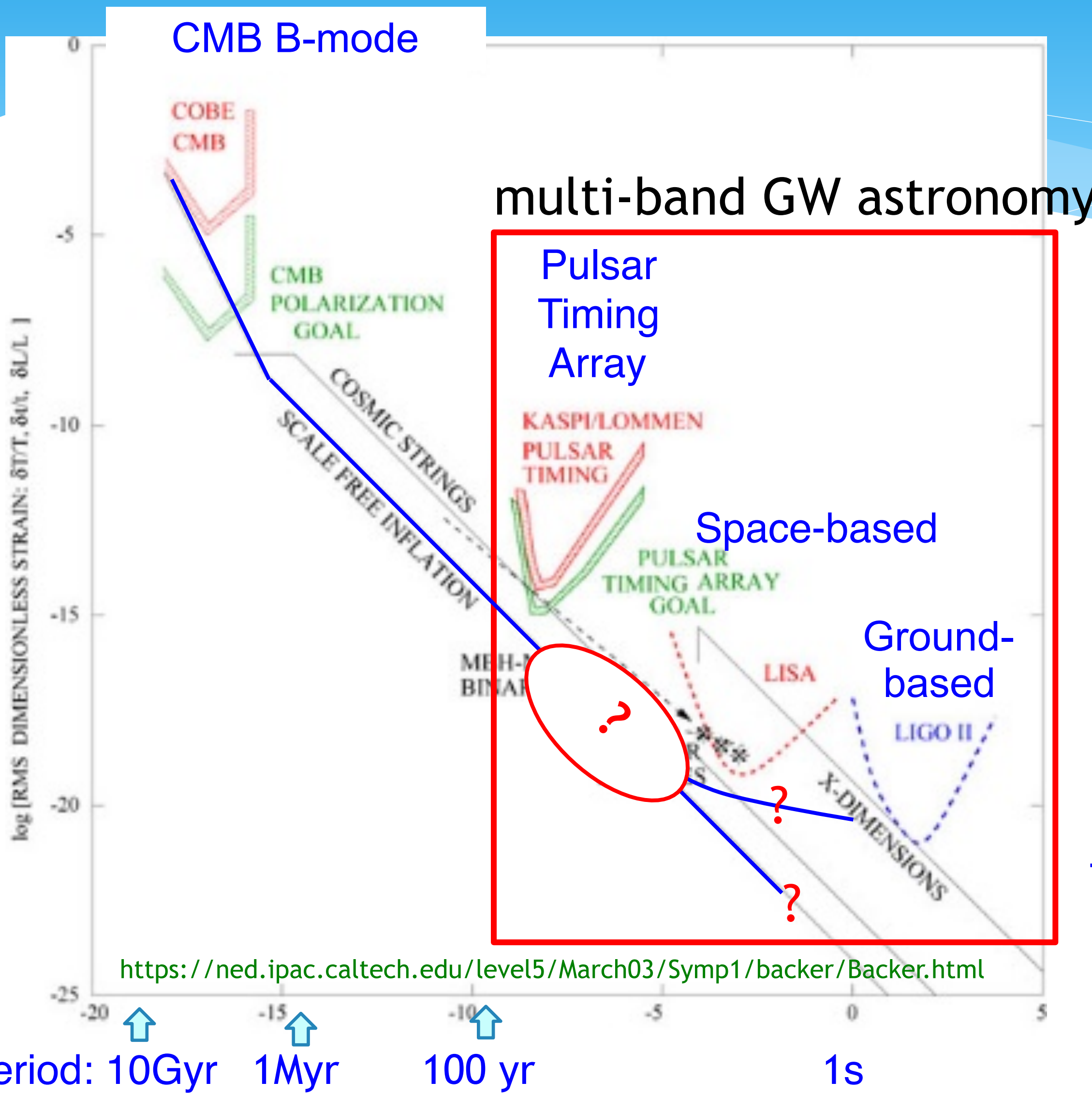


if PBHs = CDM

⬇

LISA "must" detect GWs indep of F_{NL}

Dawn of GW “Cosmology”



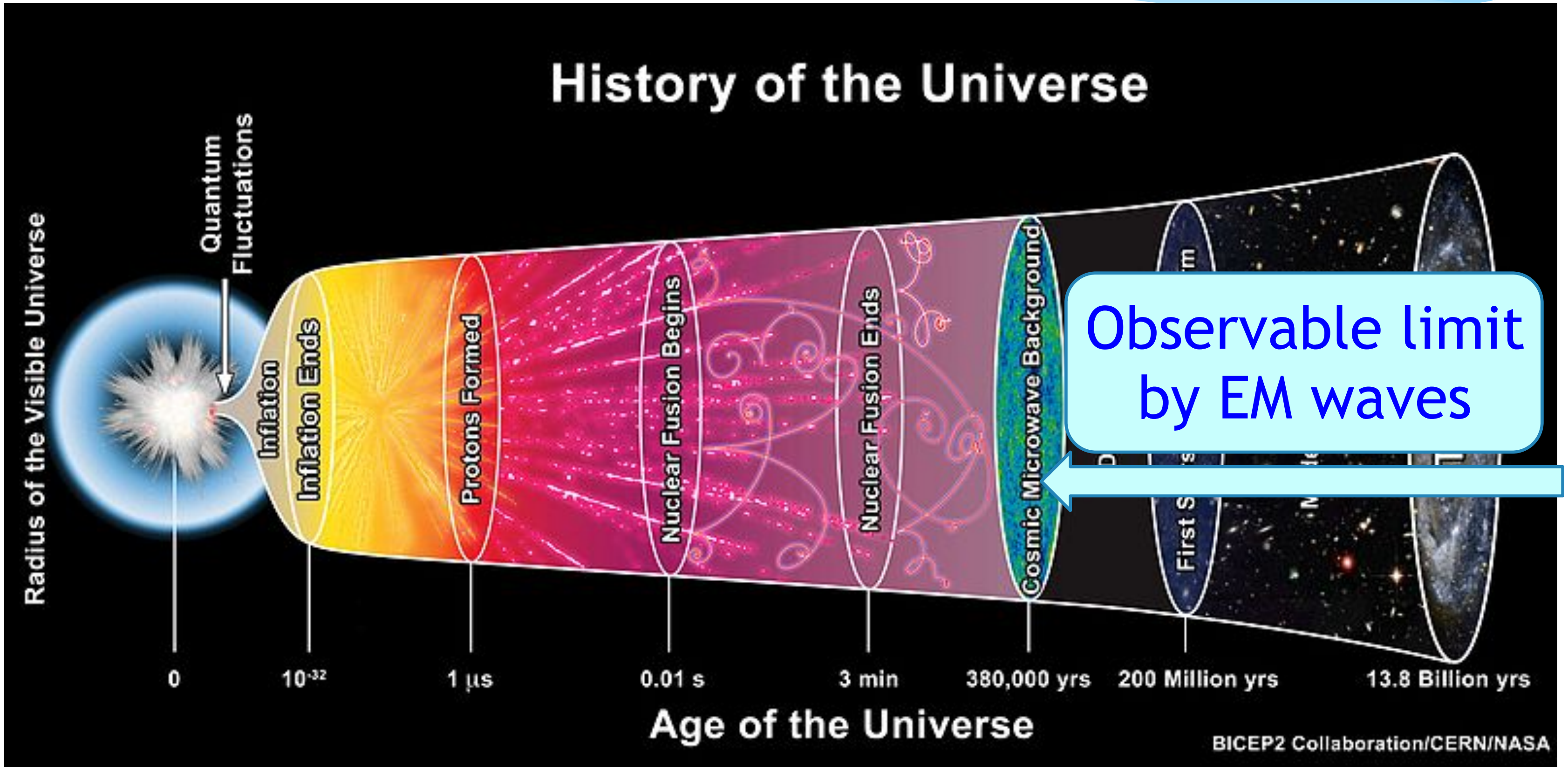
Era of GW astronomy has arrived

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

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

What will be discovered next?

Stay tuned!