重力波観測の現状と

マルチメッセンジャーで探る重力波天体の物理

Status of Gravitational Wave Observations and Physics of GW Sources with Multi-messenger

Nobuyuki Kanda / Osaka City Univ.
KAGRA collaboration
3/2/2017, Chiba University

JGW-G1706300-v2

Basics of Gravitational Wave

Gravitational Wave (GW) is

- distortion of Space-Time
- predicted by General Relativity (GR) at 1915-1916
- directly measured at 2015

Detection / Observation of GWs

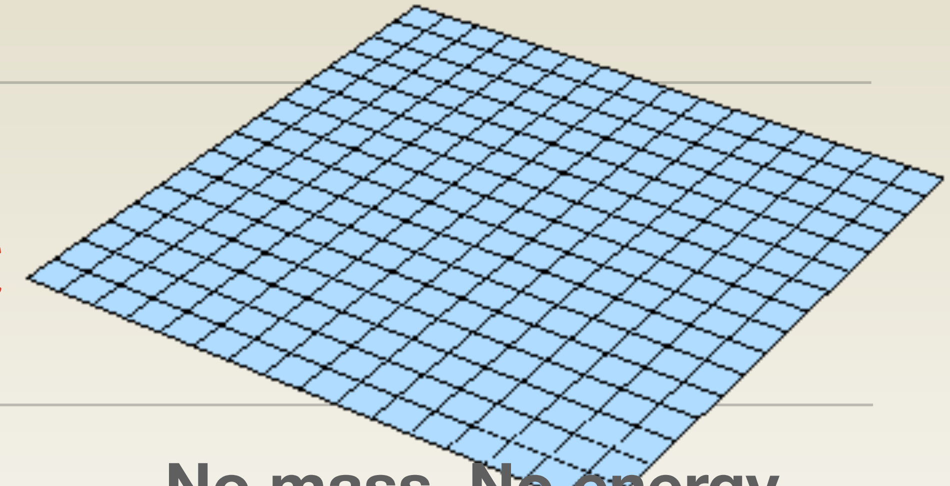
- by large base-length laser interferometer
- with **multi-detectors : two LIGOs +Virgo, KAGRA** in near future
- can extract **information of source's dynamical motion.**

GW sources are

- massive and compact objects : neutron star (NS), black-hole (BH)
- energetic motion : compact binary coalescence (CBC), supernova (SN)

  ==> These events **inevitably lead to high-energy astronomical phenomena**. Therefore, transient GWs may have multi-messenger counterpart.
- Pulsar
- Stochastic background (cosmological origin, astronomical origin, string, etc..)
- unknown

Space-time and its wave



No mass, No energy
=> Flat space-time

Gravity distorts the space-time !

Einstein Eq.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$

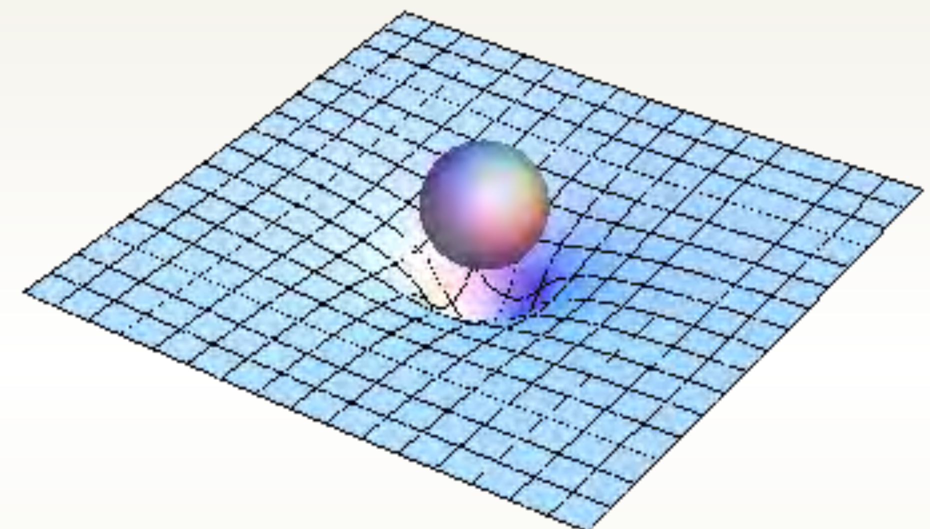
metric tensor

"flat" space-time (Minkowski)

$$g_{\mu\nu} = \eta_{\mu\nu} = \begin{array}{c} \begin{array}{cccc} ct & x & y & z \end{array} \\ \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \begin{array}{c} ct \\ x \\ y \\ z \end{array}$$

"curved (distorted)" space-time

$$g_{\mu\nu} \neq \eta_{\mu\nu}$$

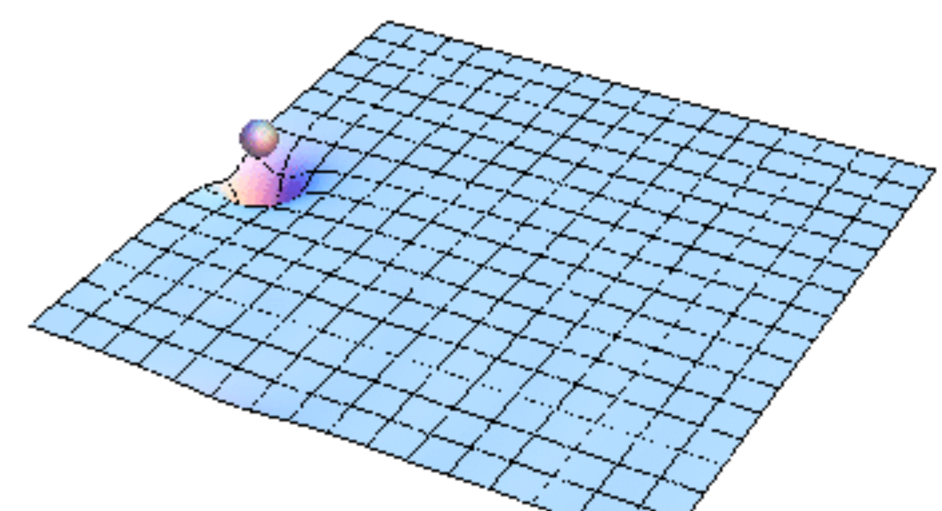


Gravity caused by mass
=> Distorted space-time

small perturbation 'h' --> Waves

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$



Mass motion (non-spherical)
=> Propagation of the distortion
"Gravitational Wave"

GW radiation

Source

- change (time derivative) of quadrupole moment of mass distribution $$I_{\mu\nu} = \int dV(x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu} r^2)\rho(\vec{r})$$

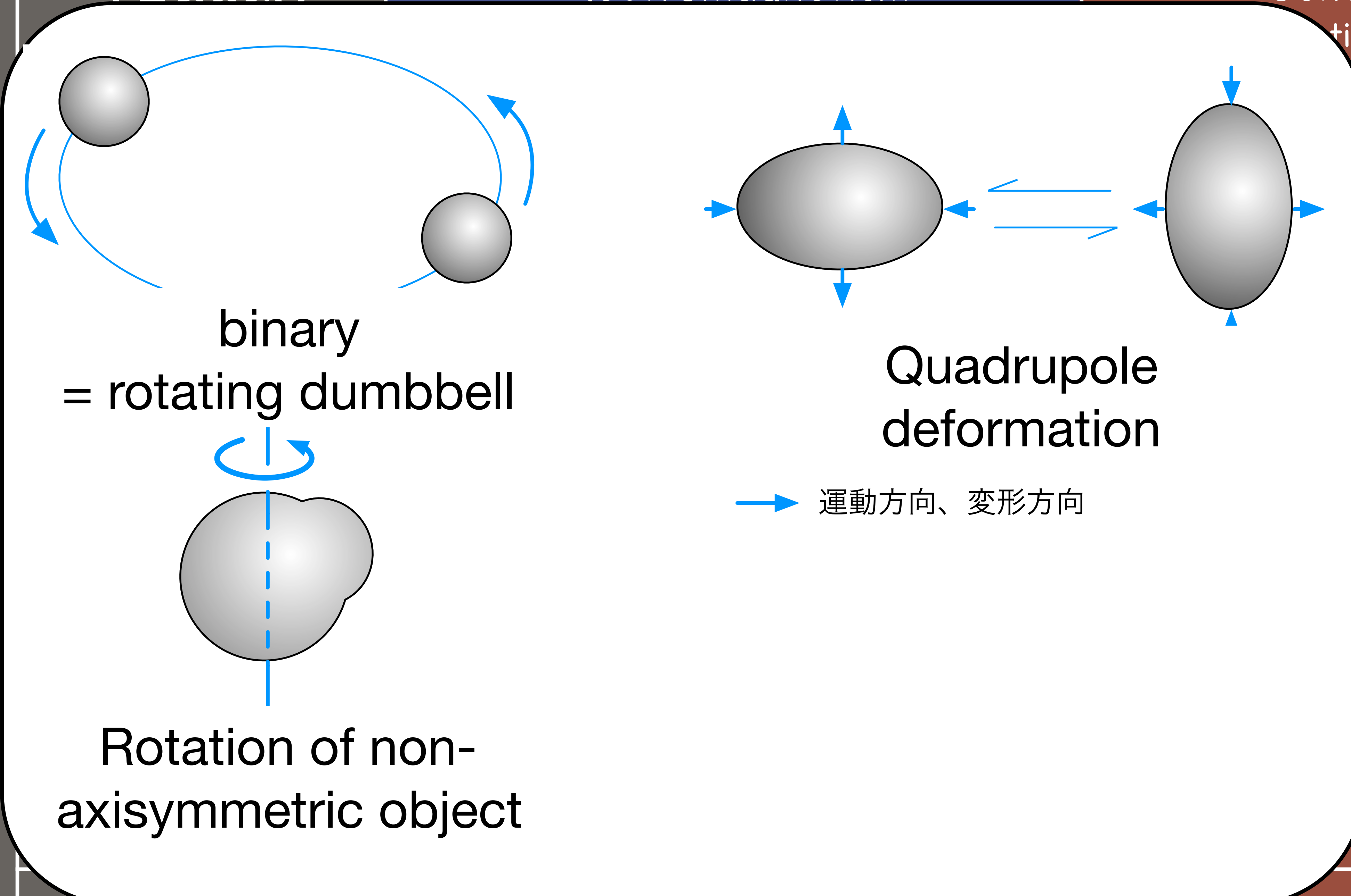
Amplitude

- inversely proportional to the distance between source and observer $$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}$$

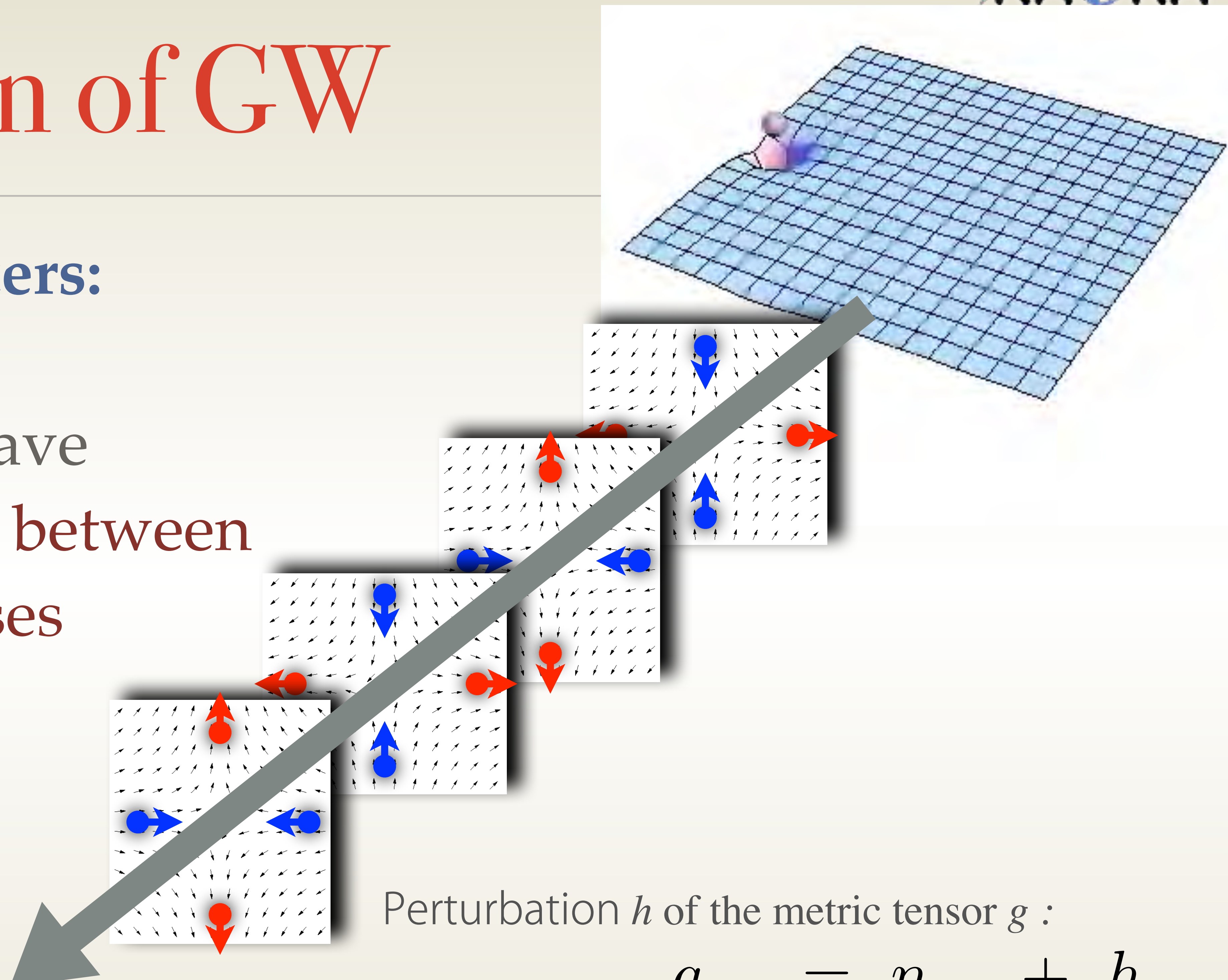
Energy

- total energy is given as : $$E_{GW} \sim \frac{G}{5c^5} < \dddot{I}_{\mu\nu} \dddot{I}^{\mu\nu} >$$

	Electromagnetic Wave	Gravitational Wave
Theory	Electromagnetism	General Relativity (…tion of Einstein Equation)
		Metric (… of the space-time)
		$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$.
		(…adrupole moment) $(\ddot{I}_{\mu\nu})$
		10^{-39} for protons .
Character	speed of light	speed of light
	transverse	transverse
Note:	easily interact with materials, can shield	very small loss passing the materials, cannot shield



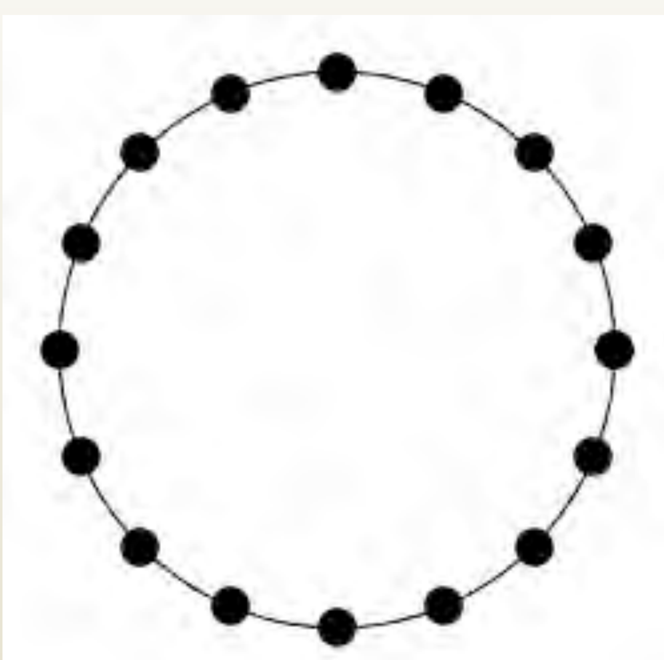
Propagation of GW



Important characters:

- Light speed
- Transverse wave

  Tidal force between point masses



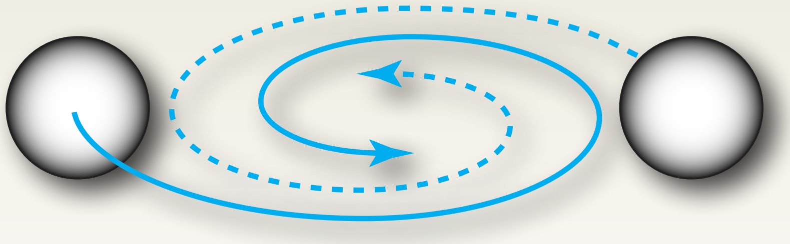
Perturbation *h* of the metric tensor *g* :

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

h is the strain of the spacetime.

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

Typical Sources of GW



Occasionally events :

- Compact binary coalescence (**CBC**):

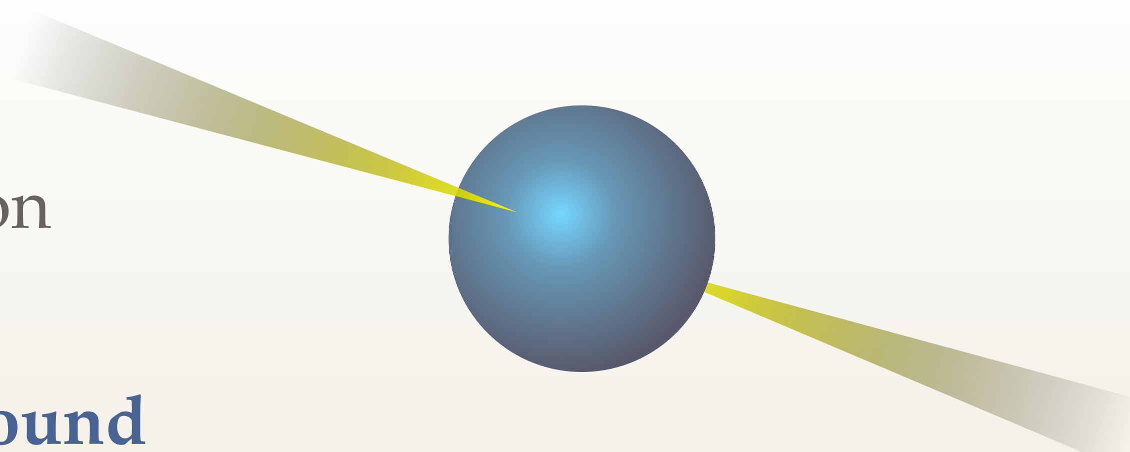
  NS-NS, NS-BH, BH-BH

  Neutron star : NS, Blackhole : BH

- **Supernovae**

  BH Quasi-normal mode oscillation

- Pulsar glitch



Continuous :

- Pulsar rotation

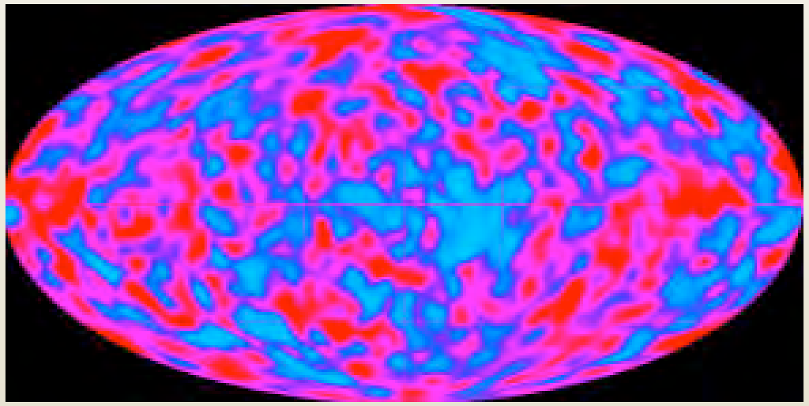
  Binary

Stochastic Background

- Early Universe

  Cosmic string

- Unresolvable astronomical origins



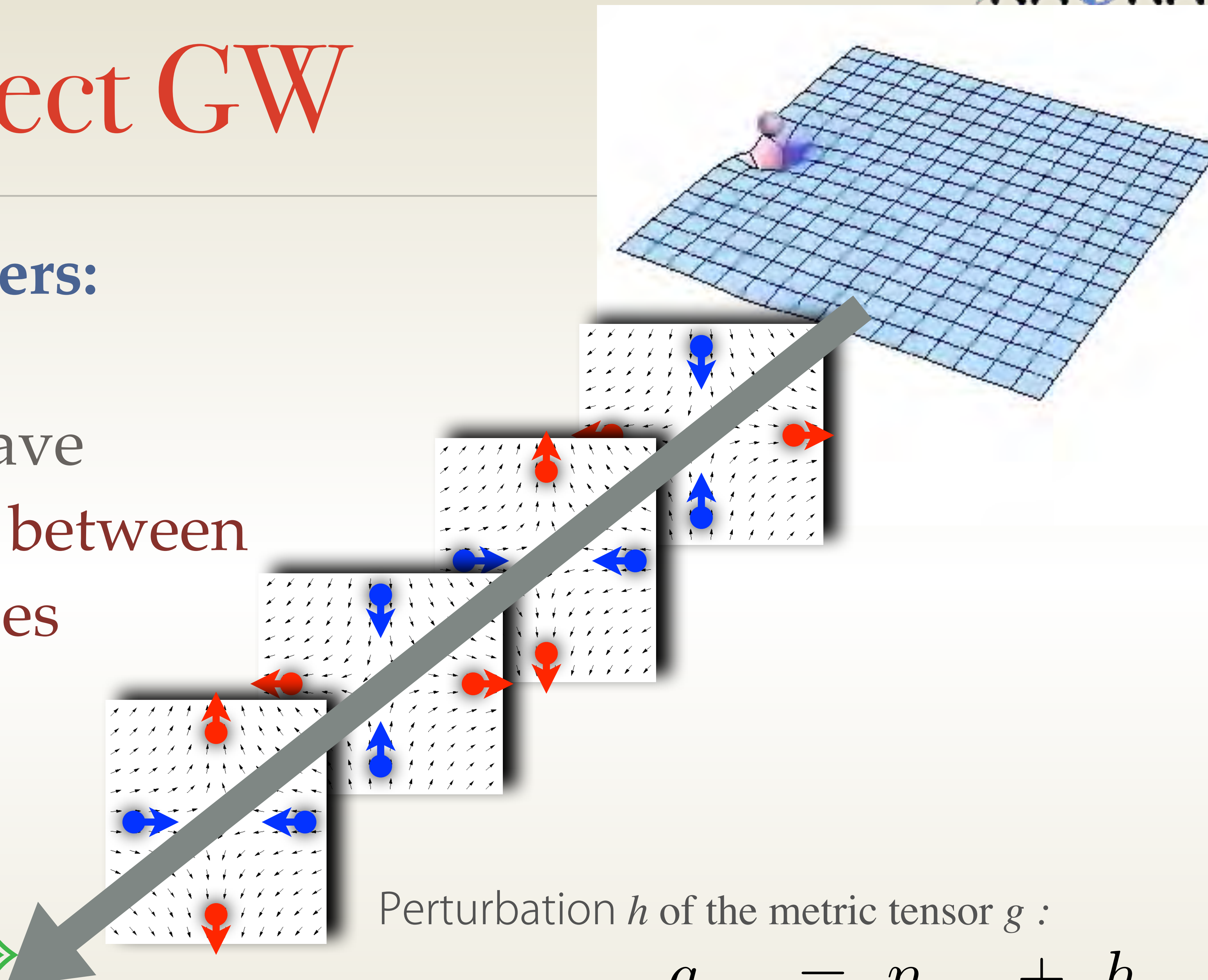
(& Unknown...)

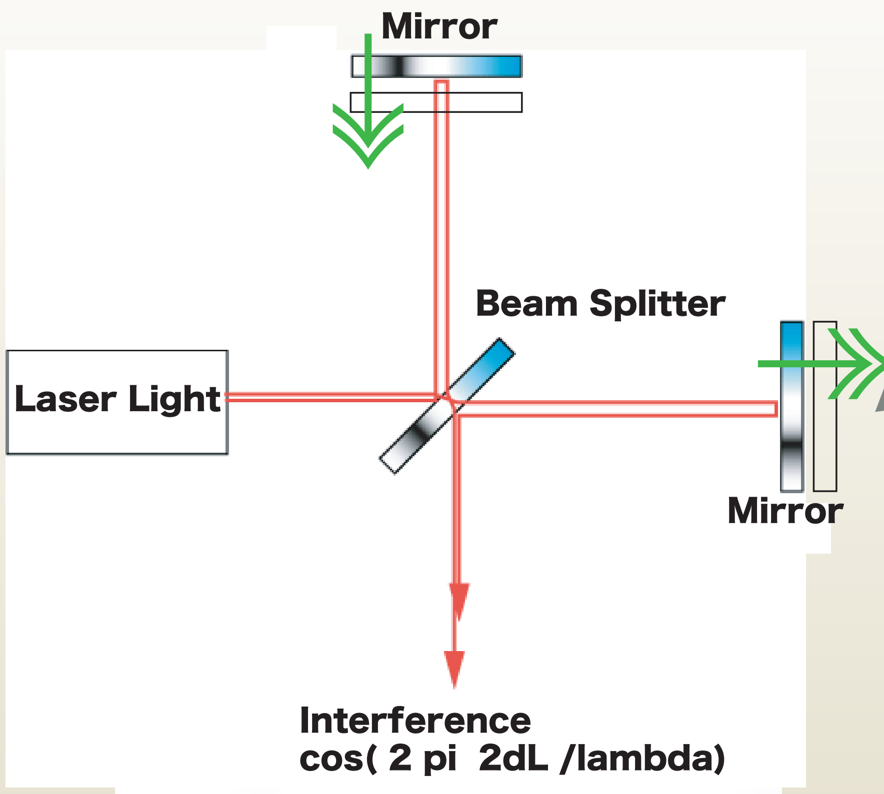
How to detect GW

Important characters:

- Light speed
- Transverse wave

  Tidal force between point masses





Perturbation h of the metric tensor g :

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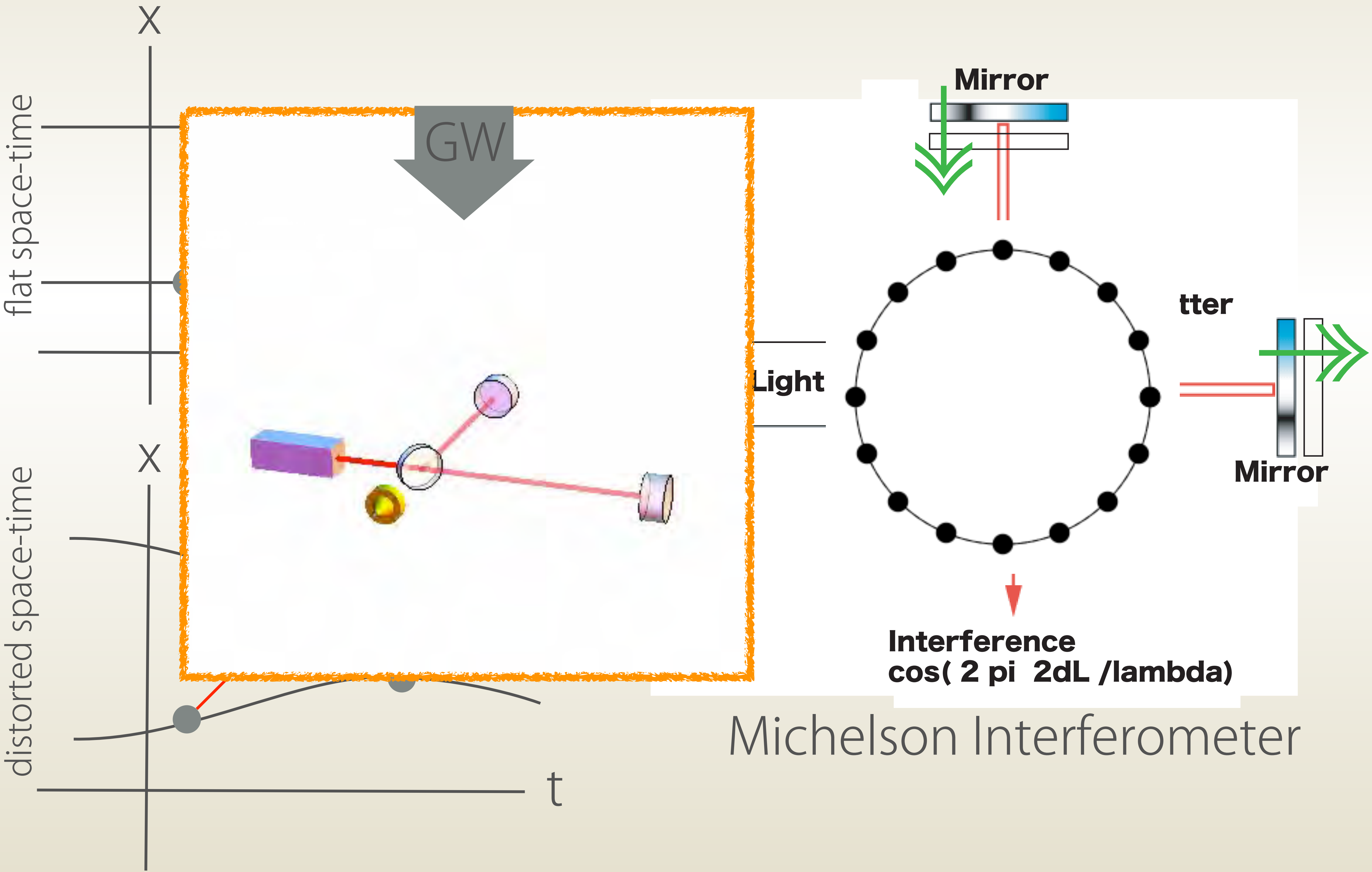
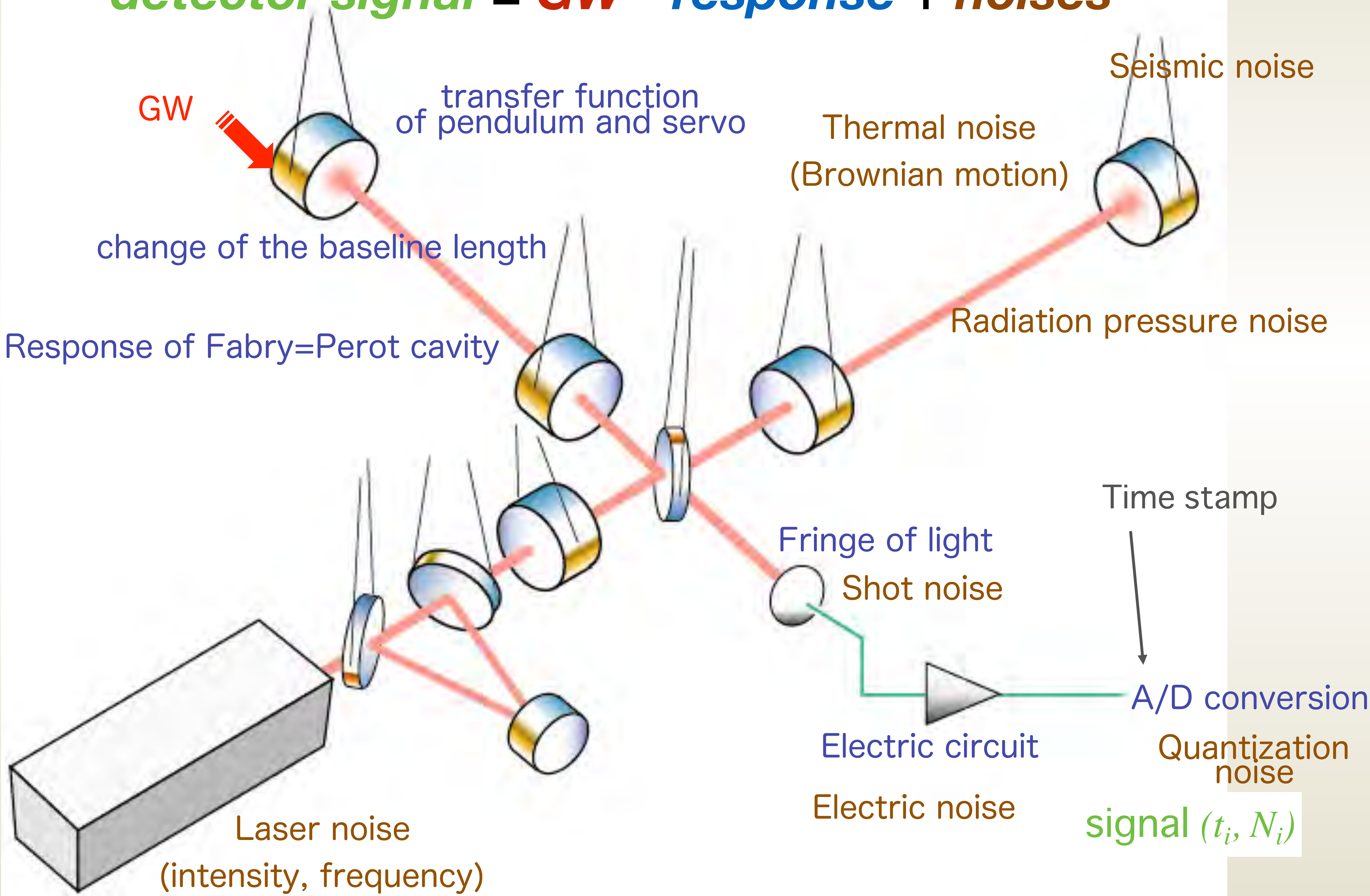
Fundamental of the detection

Free mass = suspended mirror

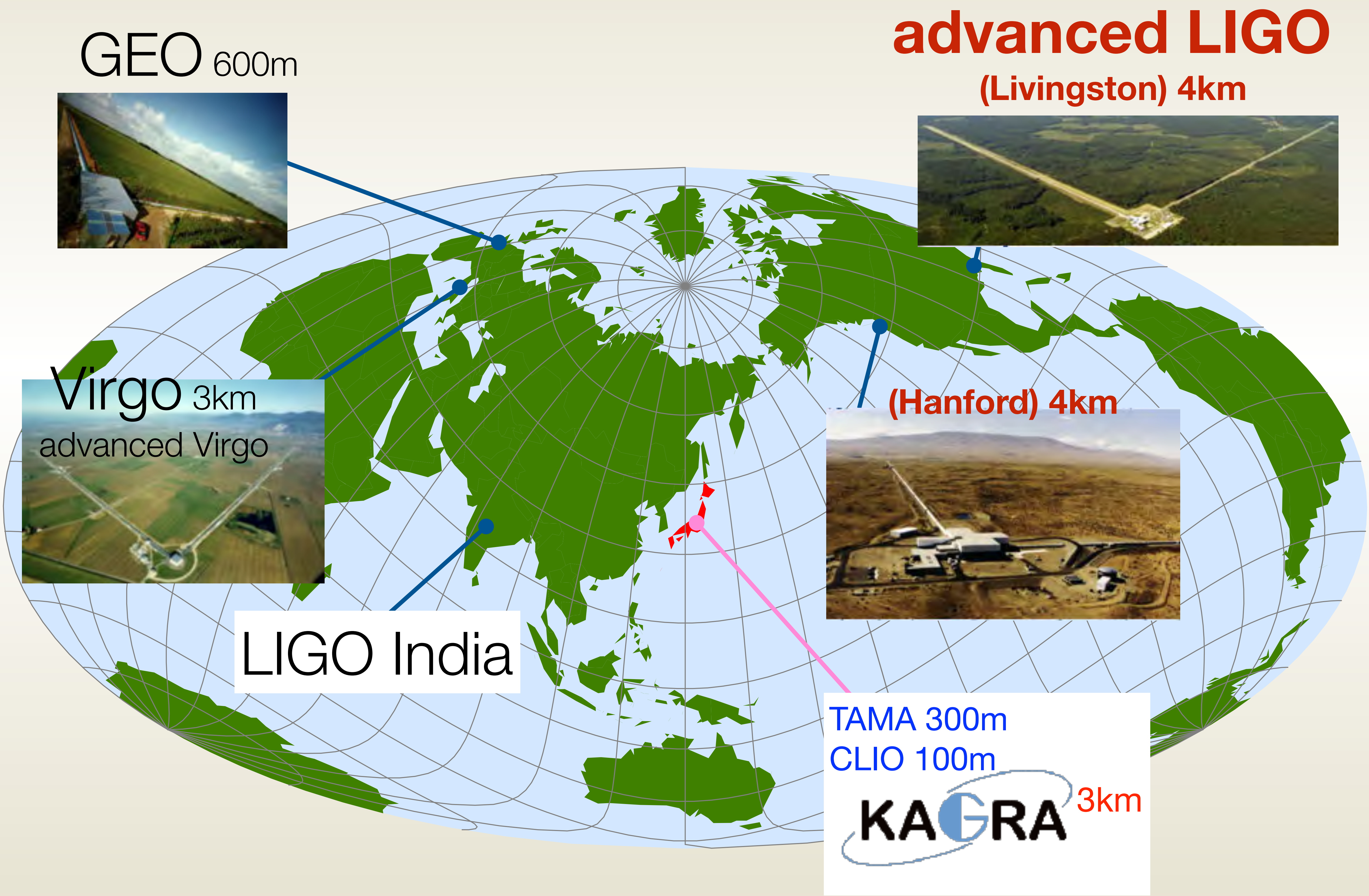


Schematics of Laser Interferometric Detector

detector signal = GW * response + noises



Global Network of GW detectors



Why we need many GW detectors ?

1. Localization of GW source direction

At least, Four or three detectors are necessary.

(depend on the relative direction and polarization of GW.)

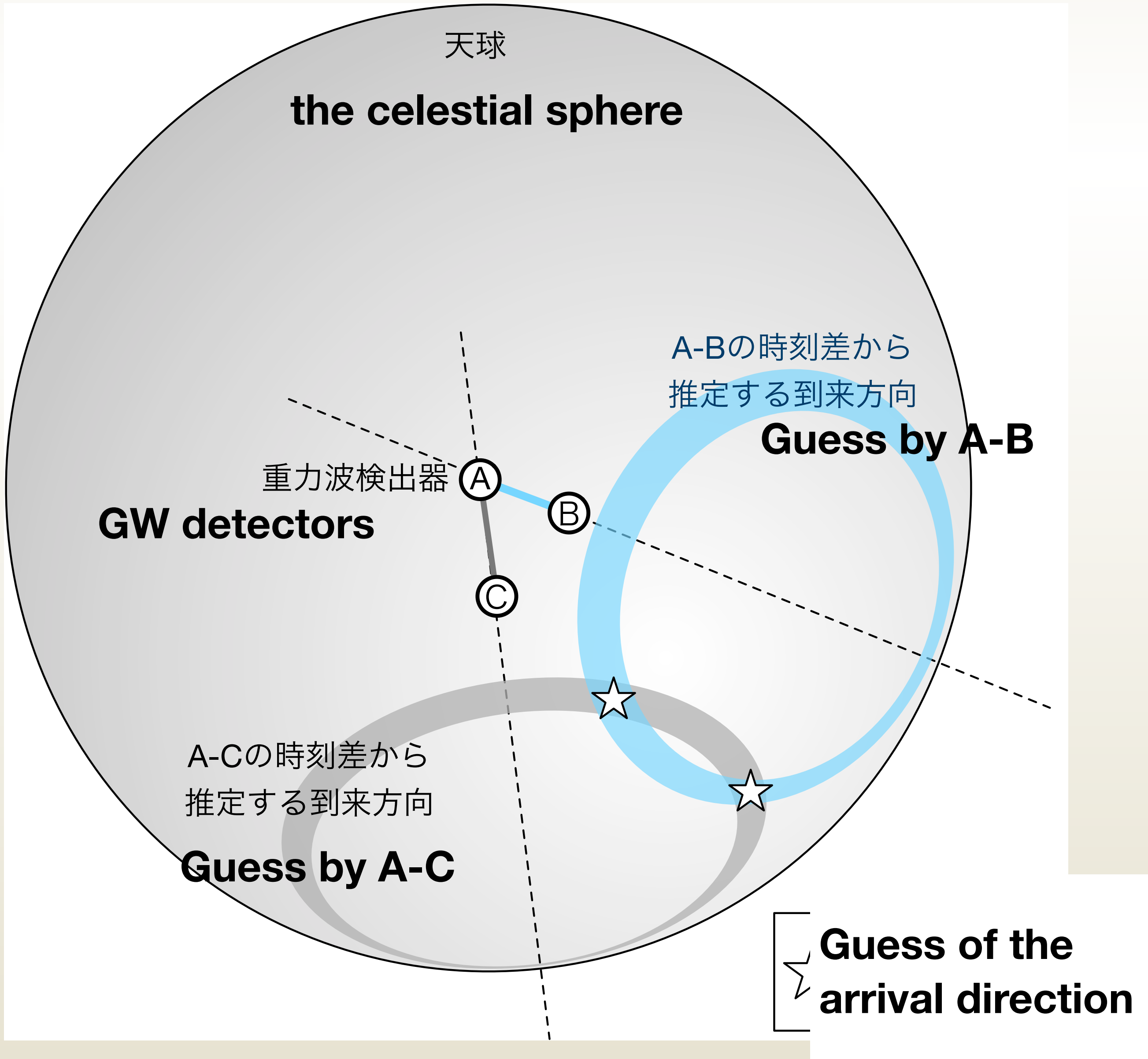
We will use :

- - arrival time difference
- - amplitude ratio of detectors

GW150914 : ~600 deg^2

Average using

4 detectors : ~5 deg^2



2. Sky coverage

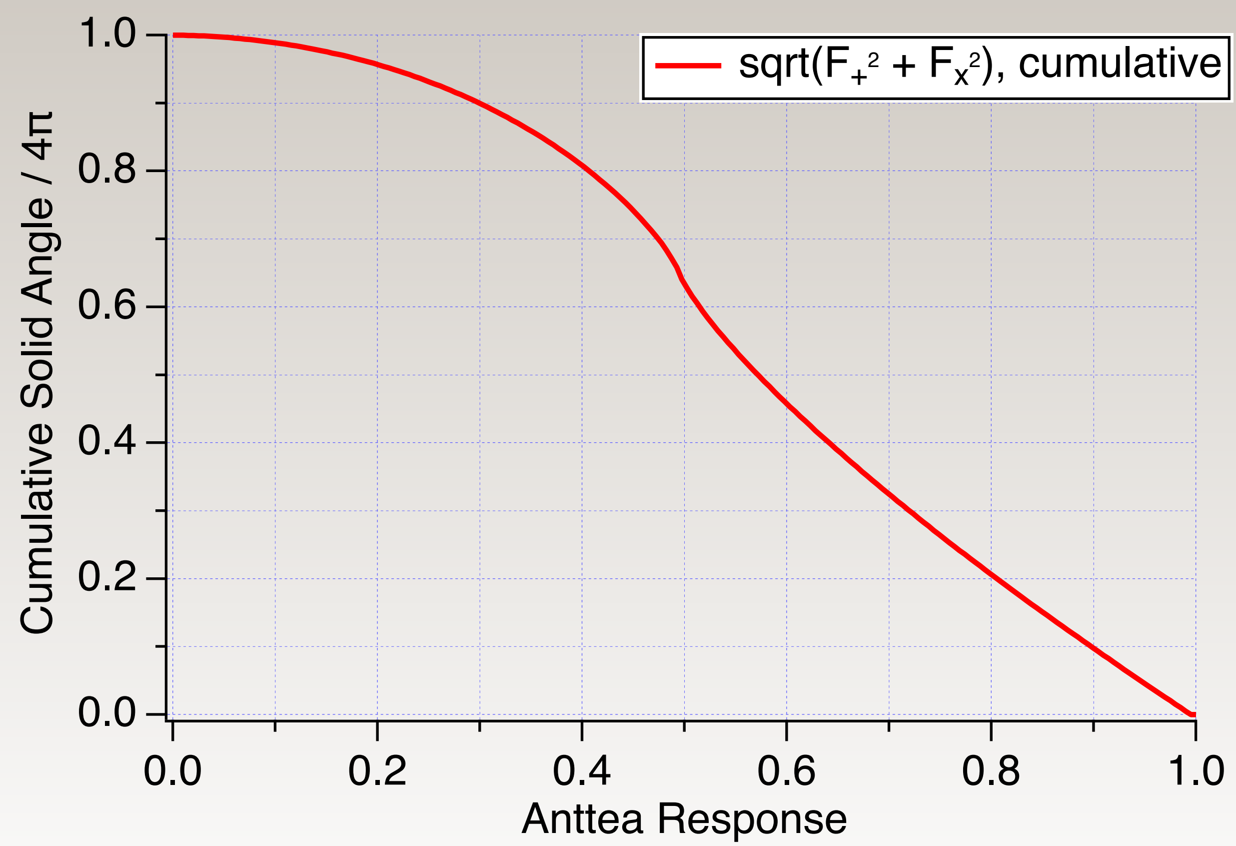
3. Survey volume

4. Duty time for operation

Antenna Pattern (Response for source direction and polarization)

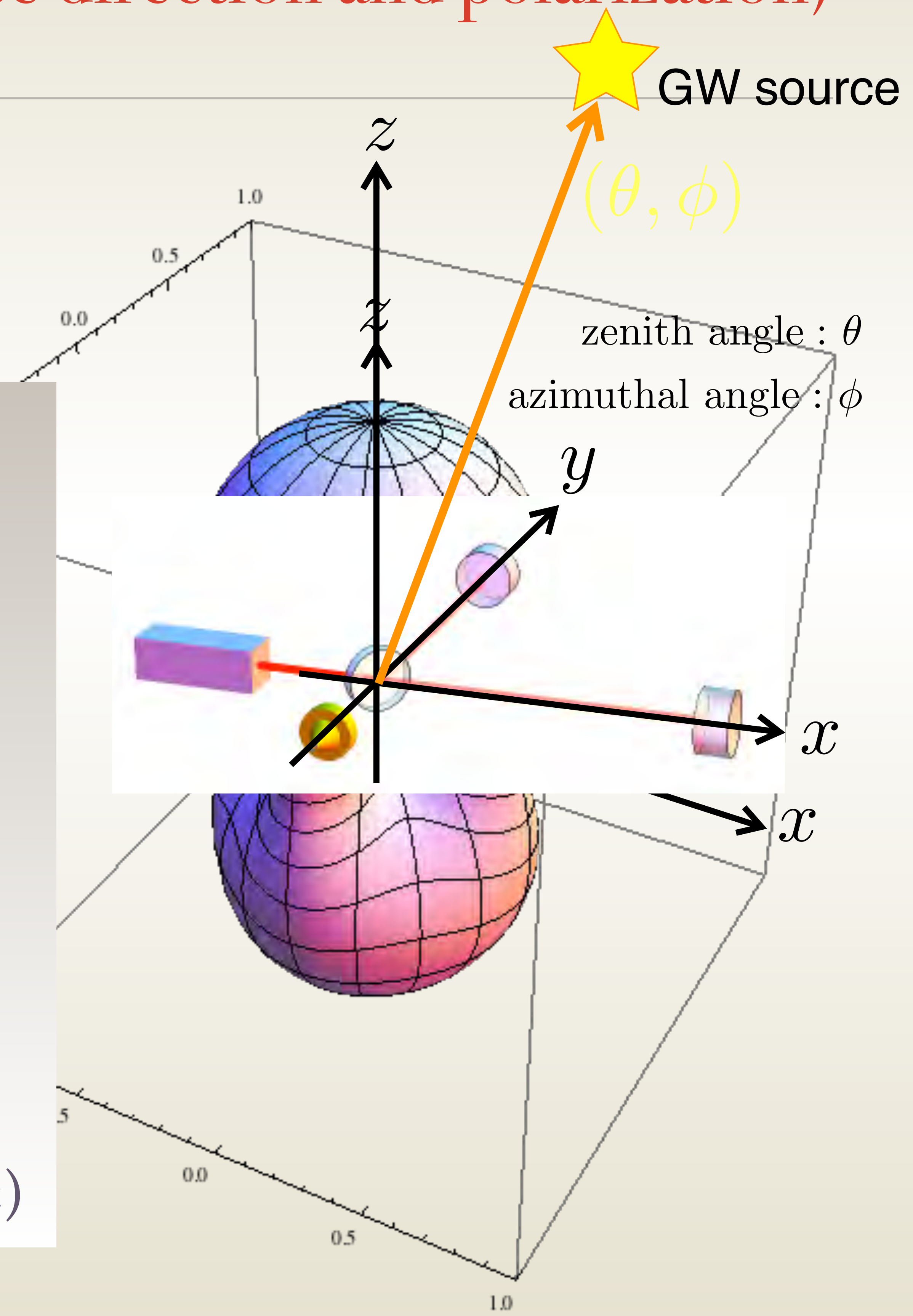
Interferometer's antenna pattern is widely spread as almost '**omni-directional**'.

~70% sky coverage by response > 0.5

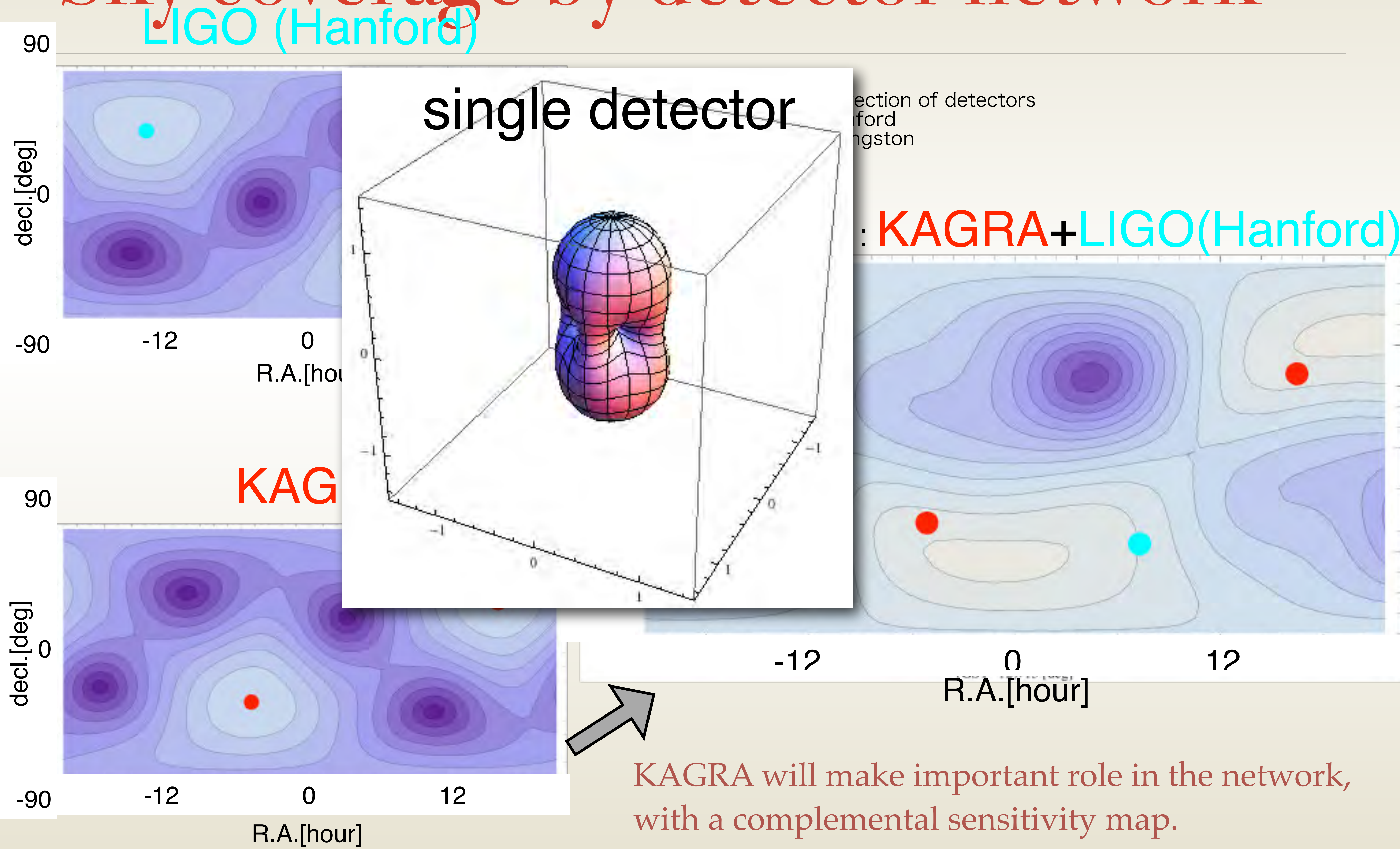


(目は悪いが、耳が悪いわけじゃ無い…^^;)

multi-detectors.

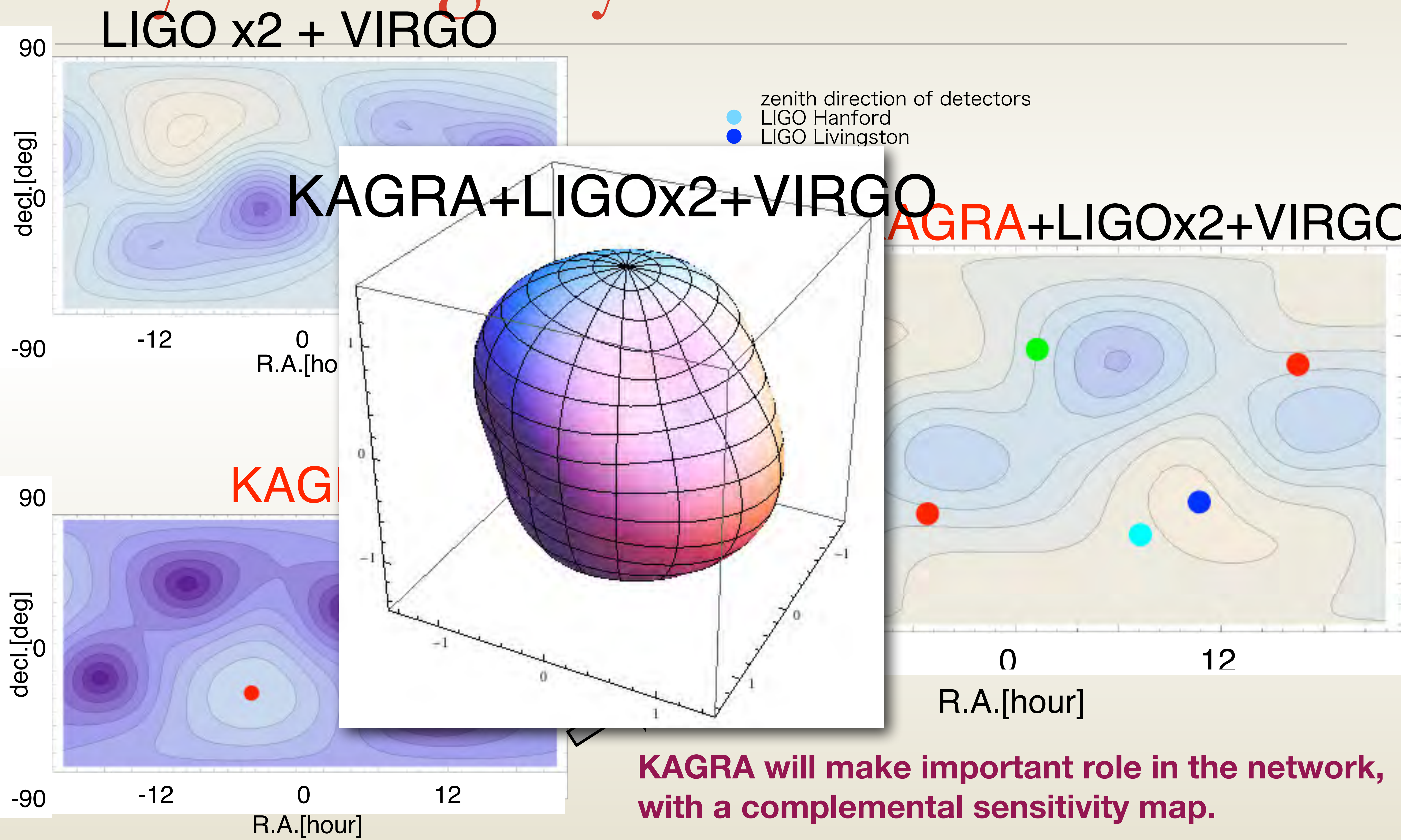


Sky coverage by detector network



KAGRA will make important role in the network, with a complemental sensitivity map.

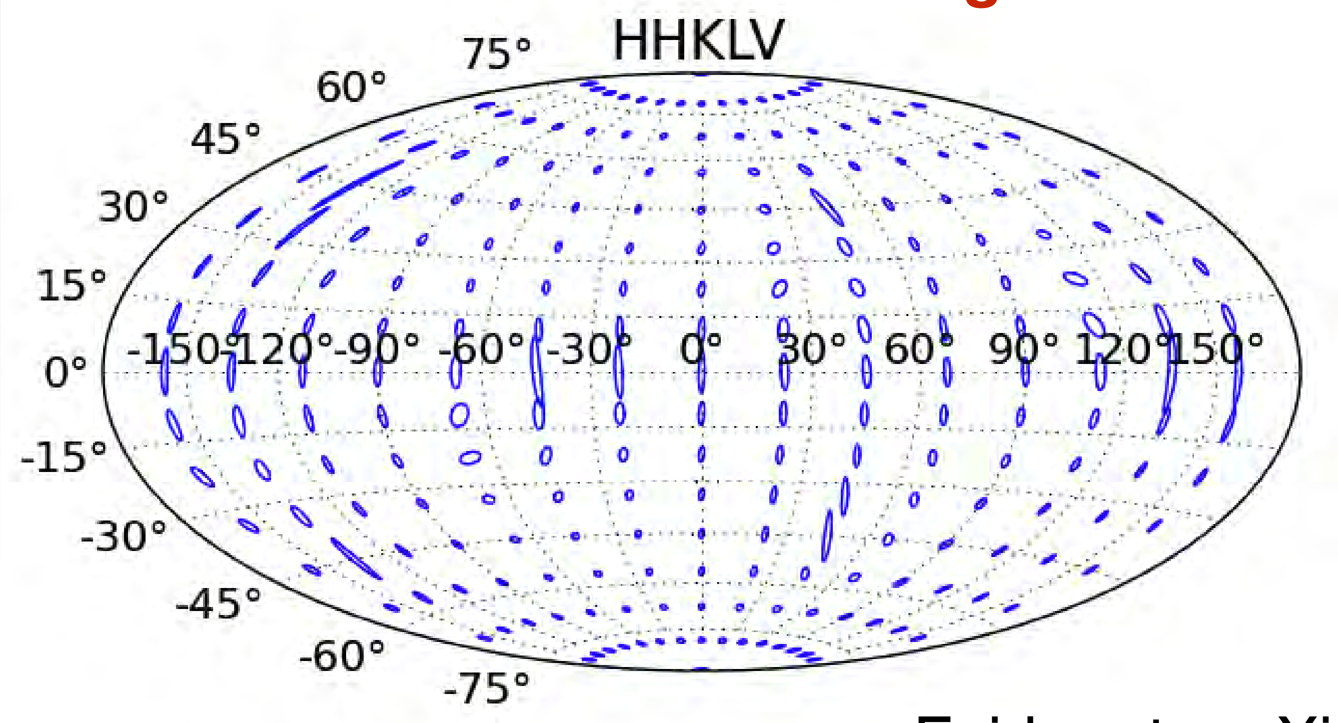
Sky coverage by detector network

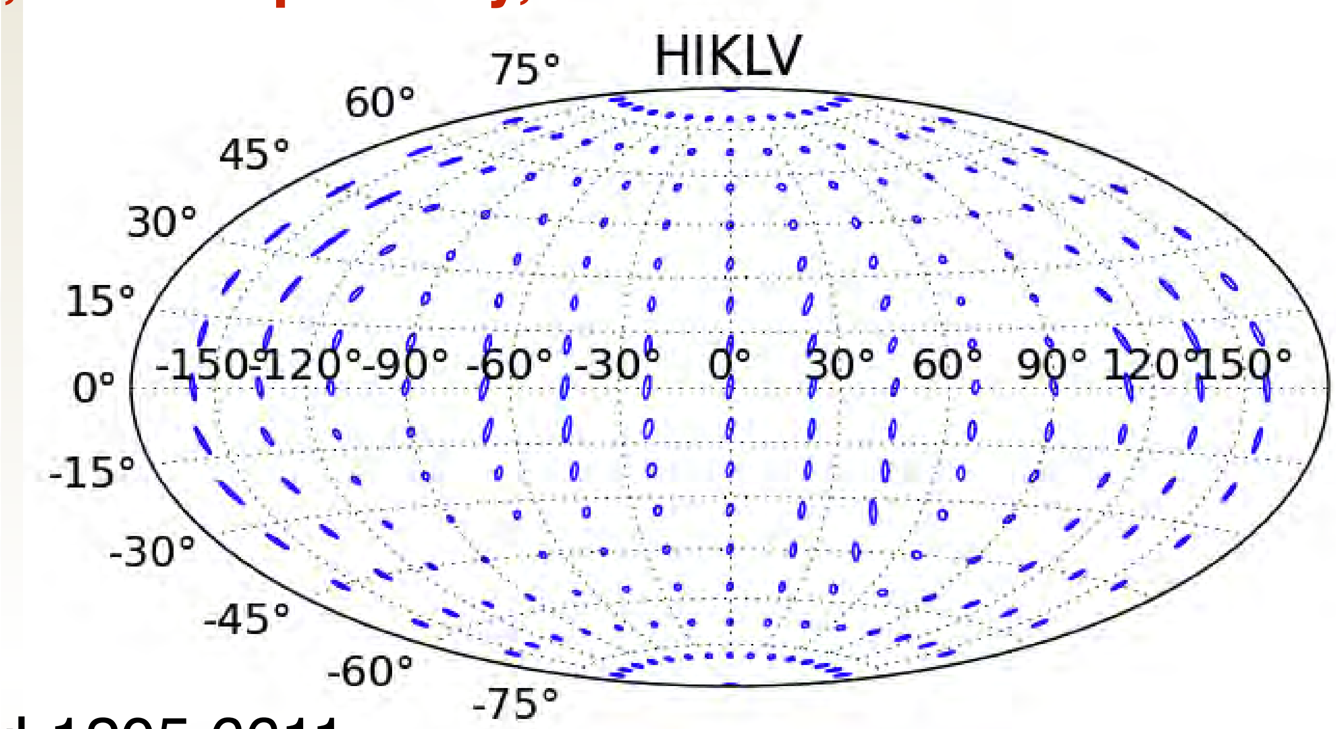


KAGRA will make important role in the network, with a complemental sensitivity map.

Arrival Direction

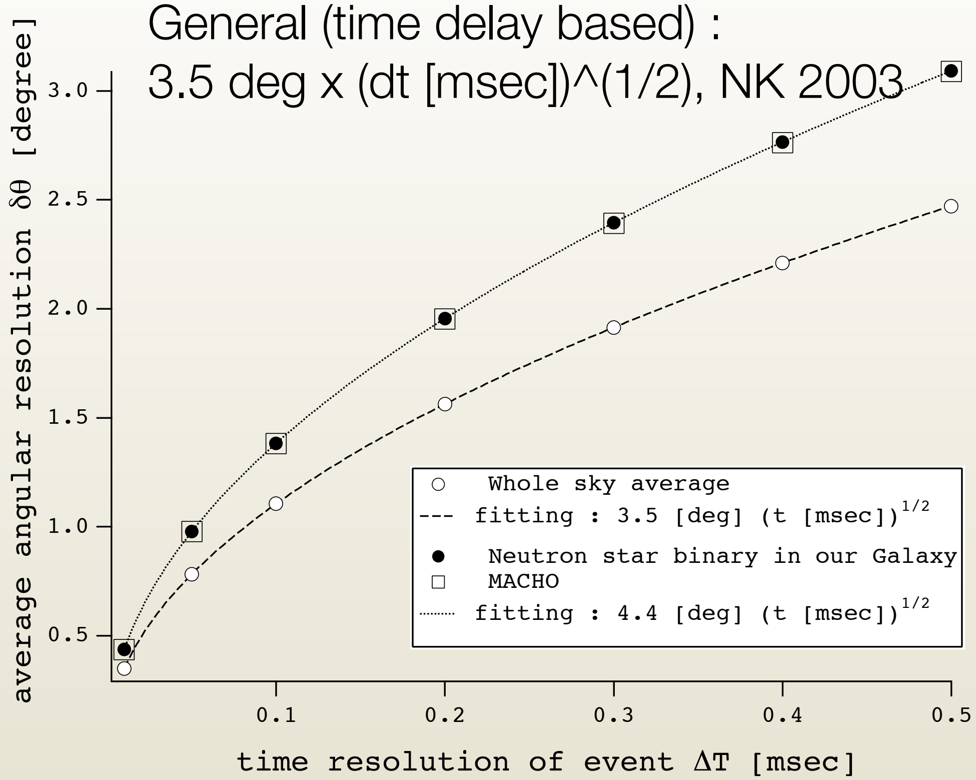
CBC : ~10 deg² resolution, at 160Mpc away, 5 detectors.



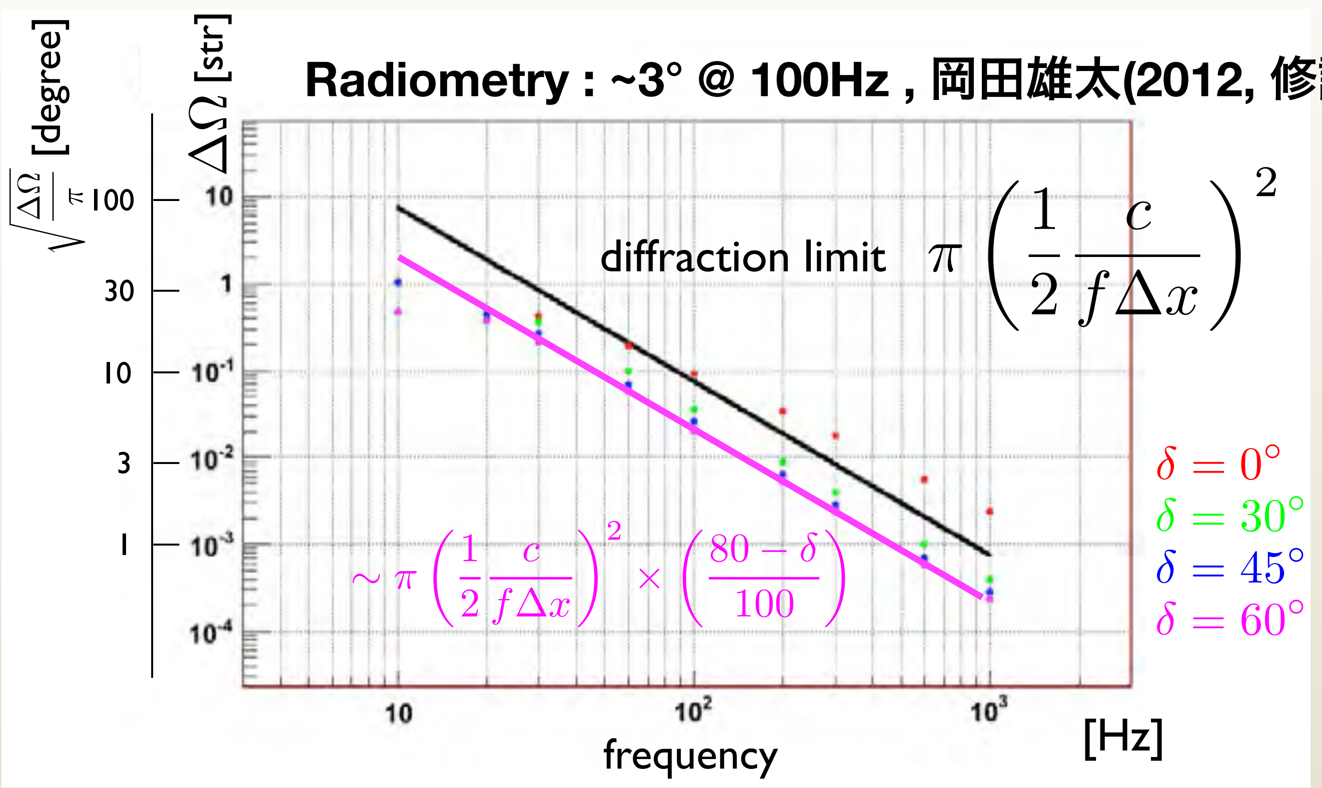


Fairhurst, arXivL1205.6611

General (time delay based) :
3.5 deg x (dt [msec])^(1/2), NK 2003

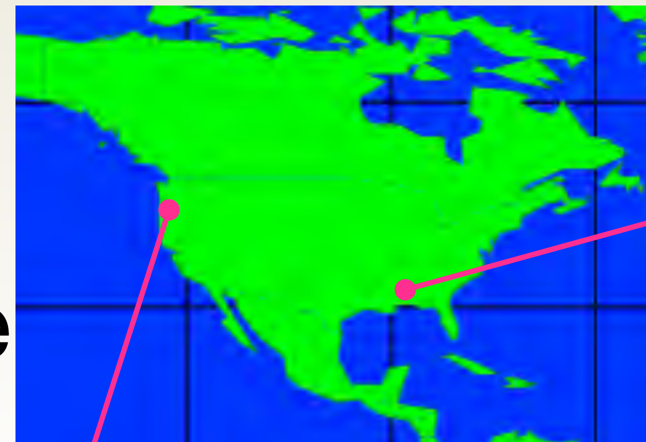


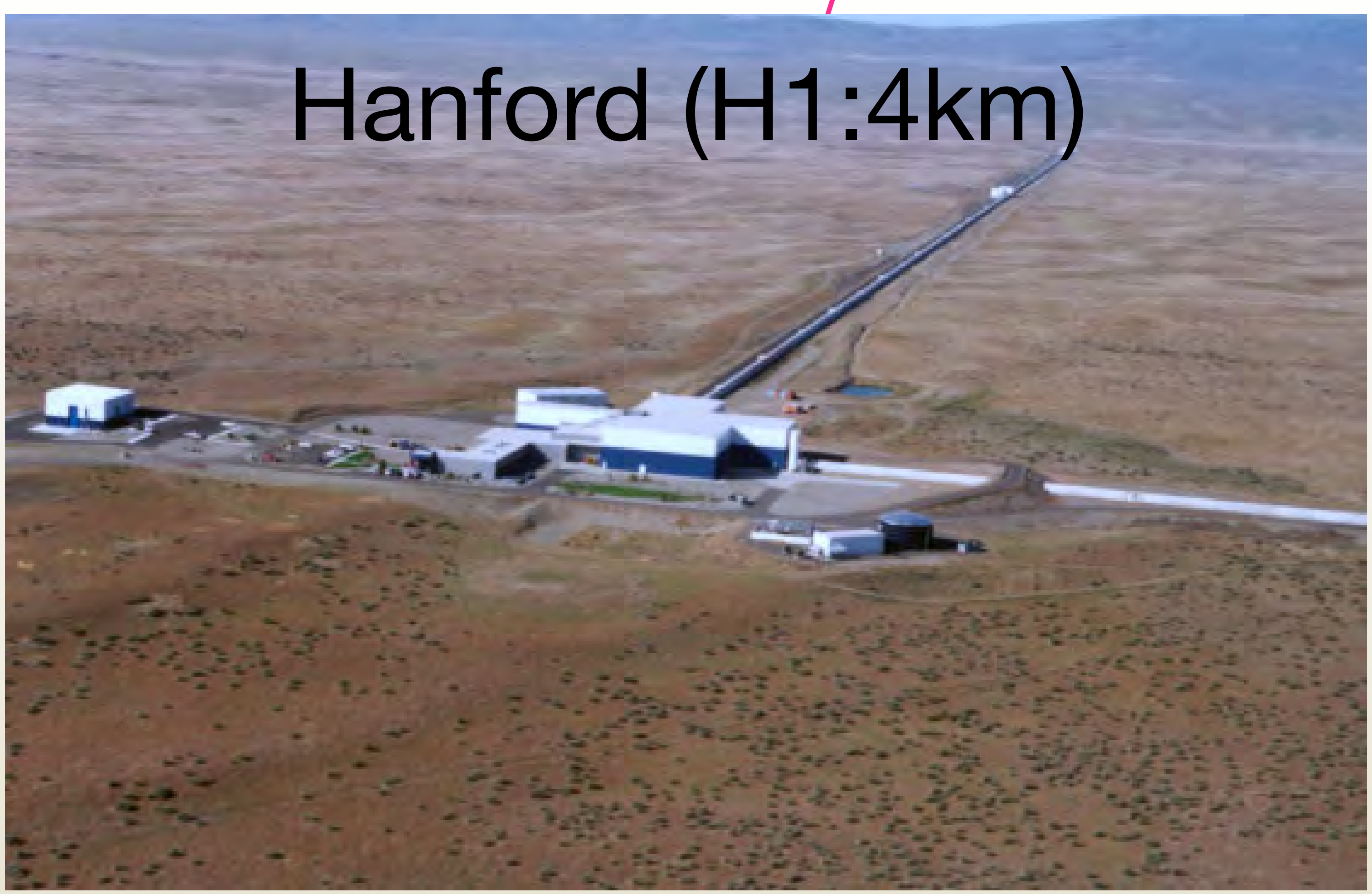
Radiometry : ~3° @ 100Hz , 岡田雄太(2012, 修論)



LIGO and 1st GW observation

Laser
Interferometric
Gravitational-Wave
Observatory





O1 (Observation 1)
2015/9/18 – 2016/1/12
1100 hours

http://www.ligo.org/

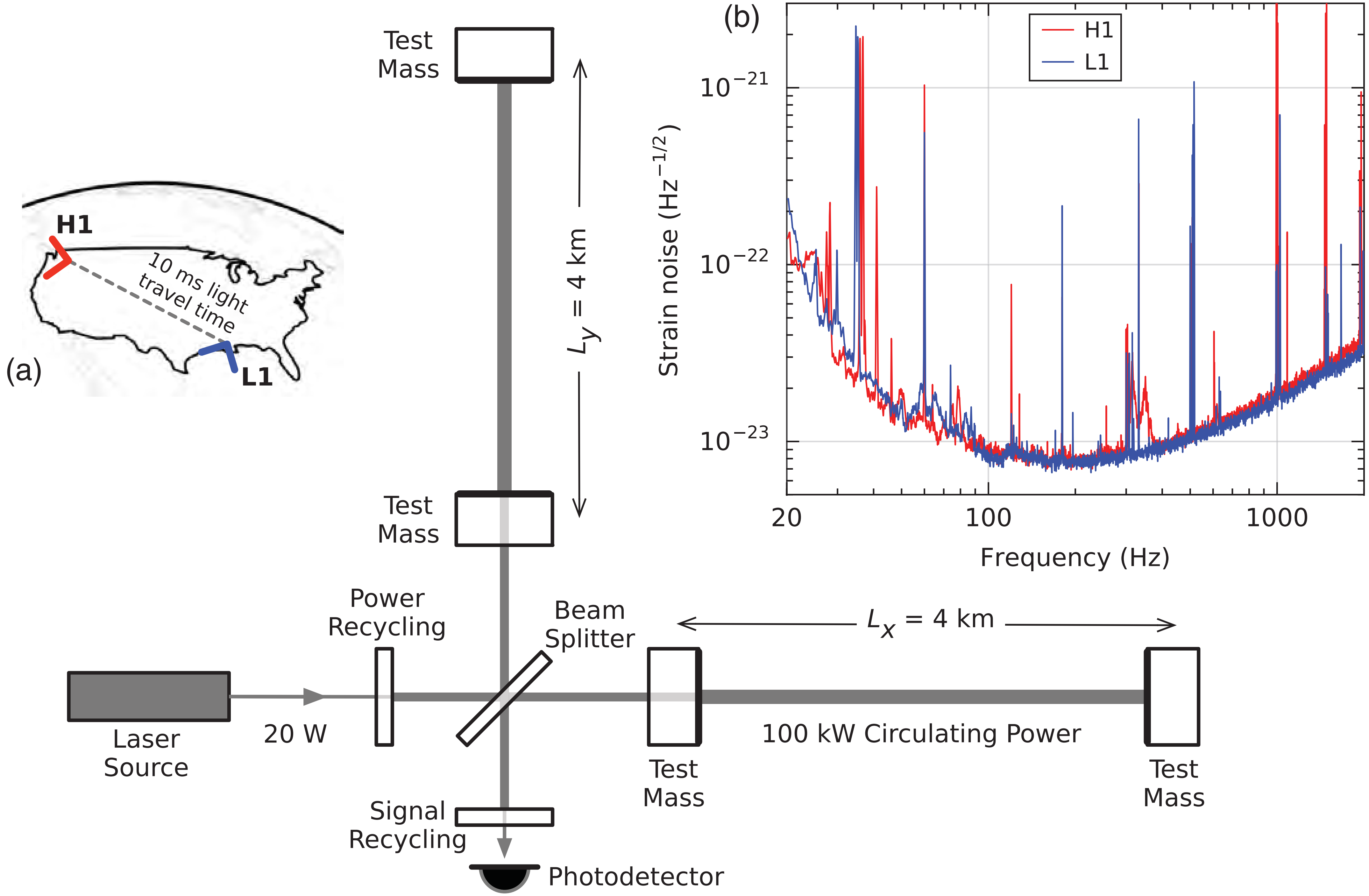
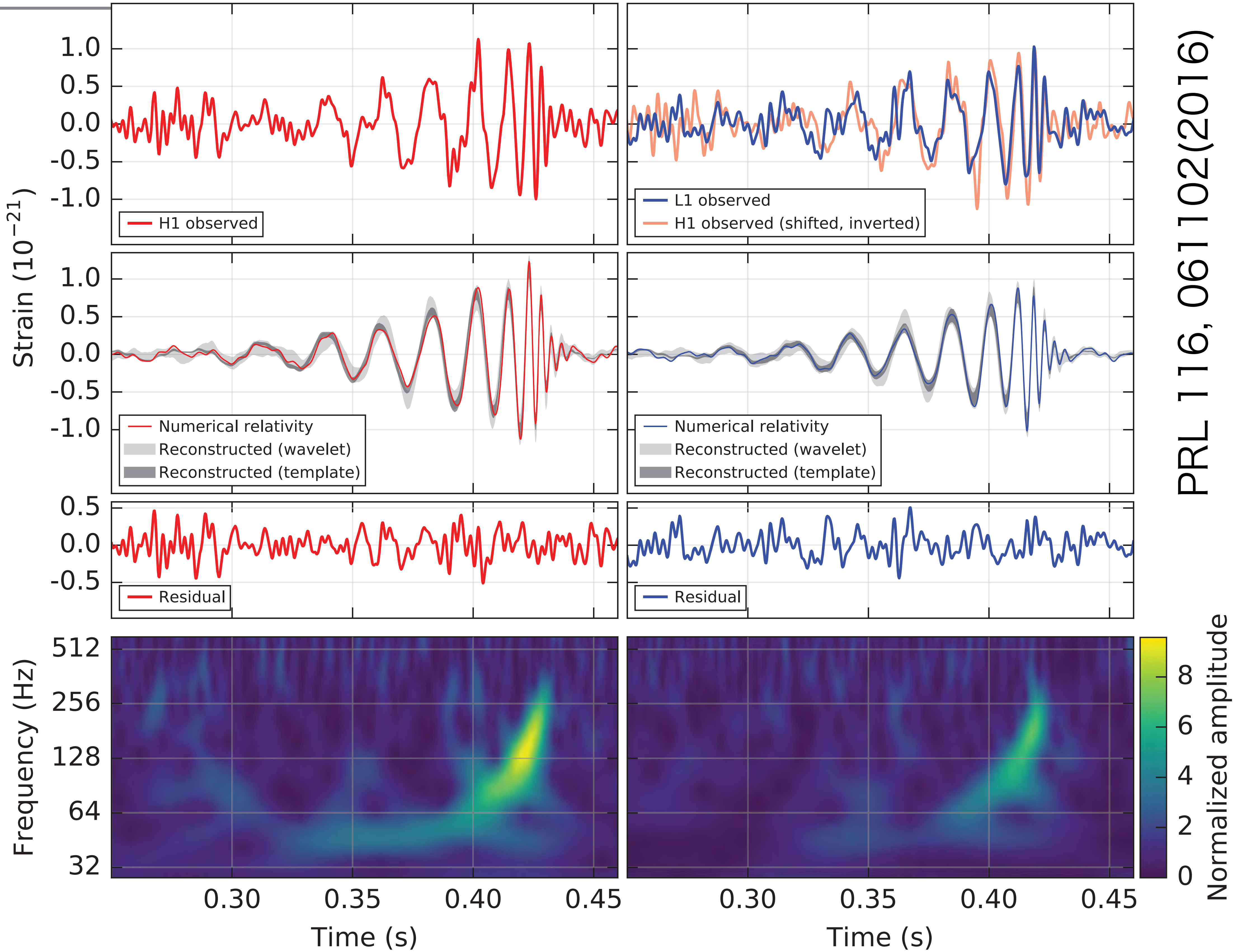


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). *Inset (b):* The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain

GW150914



PRL 116, 061102(2016)

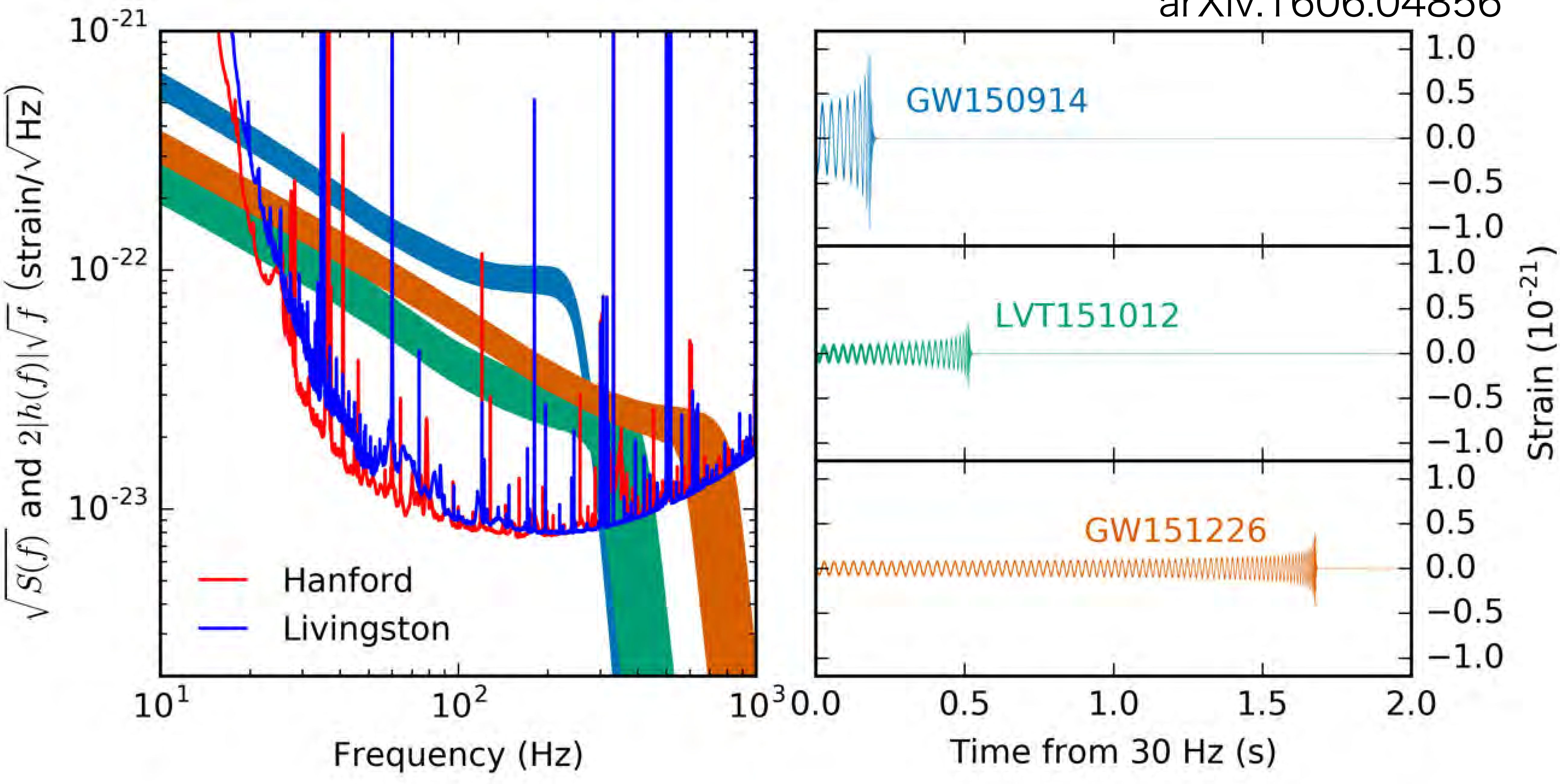
FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject

BH-BH in LIGO O1

- O1 (Observational run 1) : Sep.18, 2015 - Jan. 12, 2016

GW150914, GW151226 : BBH (Binary Black Hole) mergers

arXiv:1606.04856



Remarks : the observed GW events in LIGO O1

GW150914

GW151226

LVT150120

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

arXiv:1606.04856

Note : GW150914 in [Jy]

Using the fits to numerical simulations of binary black hole mergers in [92,93], we provide estimates of the mass and spin of the final black hole, the total energy radiated in gravitational waves, and the peak gravitational-wave luminosity [39]. The estimated total energy radiated in gravitational waves is $3.0^{+0.5}_{-0.5} M_\odot c^2$. The system reached a peak gravitational-wave luminosity of $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s, equivalent to $200^{+30}_{-20} M_\odot c^2/\mathrm{s}$.

PRL.116.061102

energy flux : 3.6×10^{56} erg/s

(cf: total energy : ~ 3 Msolar ~ 5.4×10^{54} erg)

luminosity distance : 420 Mpc = 1.3×10^{27} cm

bandwidth : ~ 300Hz

~ 5.7×10^{21} Jy

LIGO O2 run started

https://www.ligo.caltech.edu/news/2016-11-30

from Nov.30, 2016.

Scheduled as 6 months

LIGO Hanford and LIGO Livingston Observatories. Credit: Caltech/MIT/LIGO Lab.

LIGO Resumes Search for Gravitational Waves

News Release • November 30, 2016

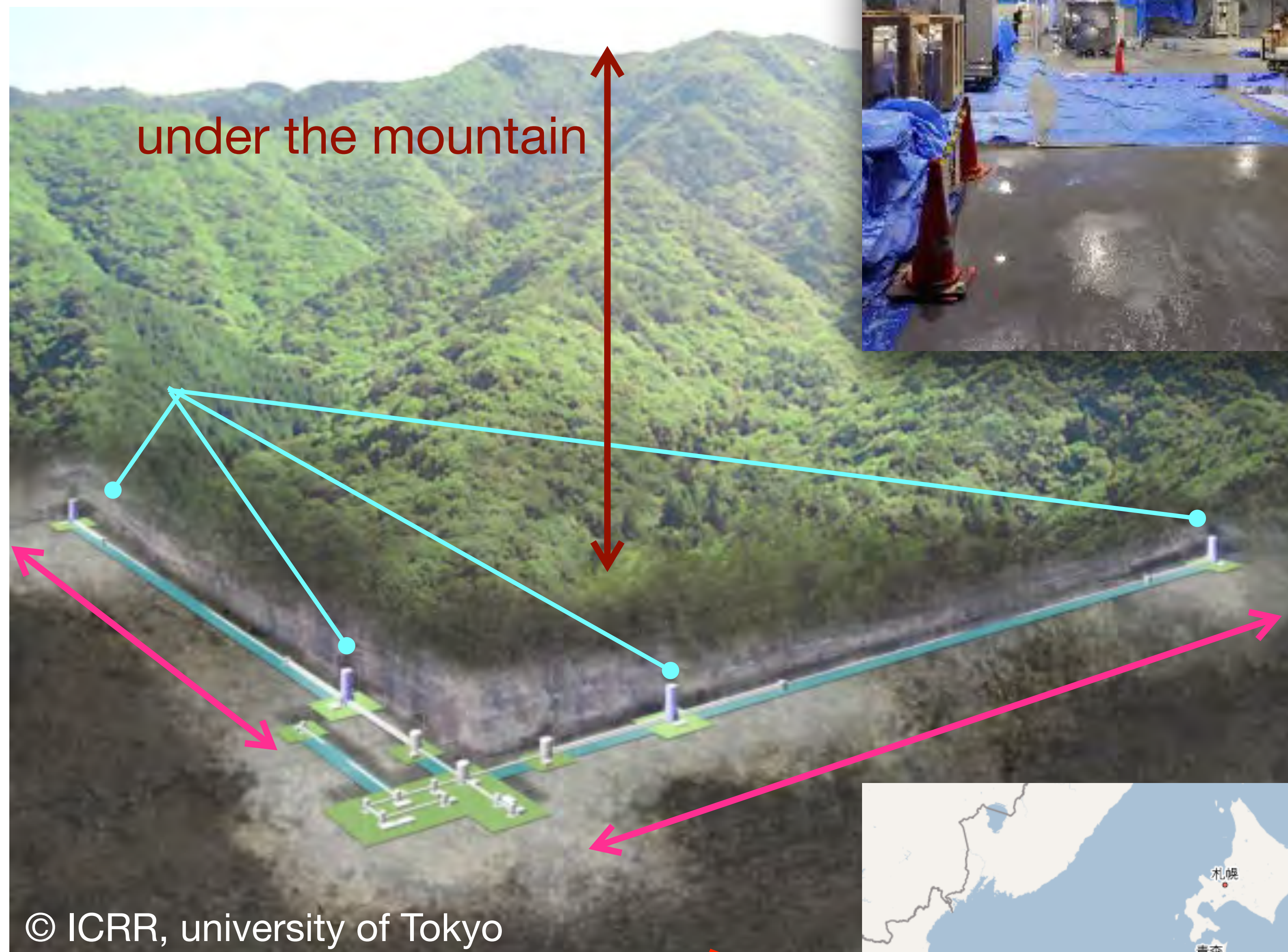
After a series of upgrades, the twin detectors of LIGO, the Laser Interferometer Gravitational-wave Observatory, have turned back on and resumed their search for ripples in the fabric of space and time known as gravitational waves. LIGO transitioned from engineering test runs to science observations at 8 a.m. Pacific Standard Time on November 30.

Mine Work Style

- Work cloths, work gloves, work boots
- Helmets
- Head ligts
- Reflect vests
- Oxygen sensors
- Electric bicycles

KAGRA

~280 persons (>80 affiliations)

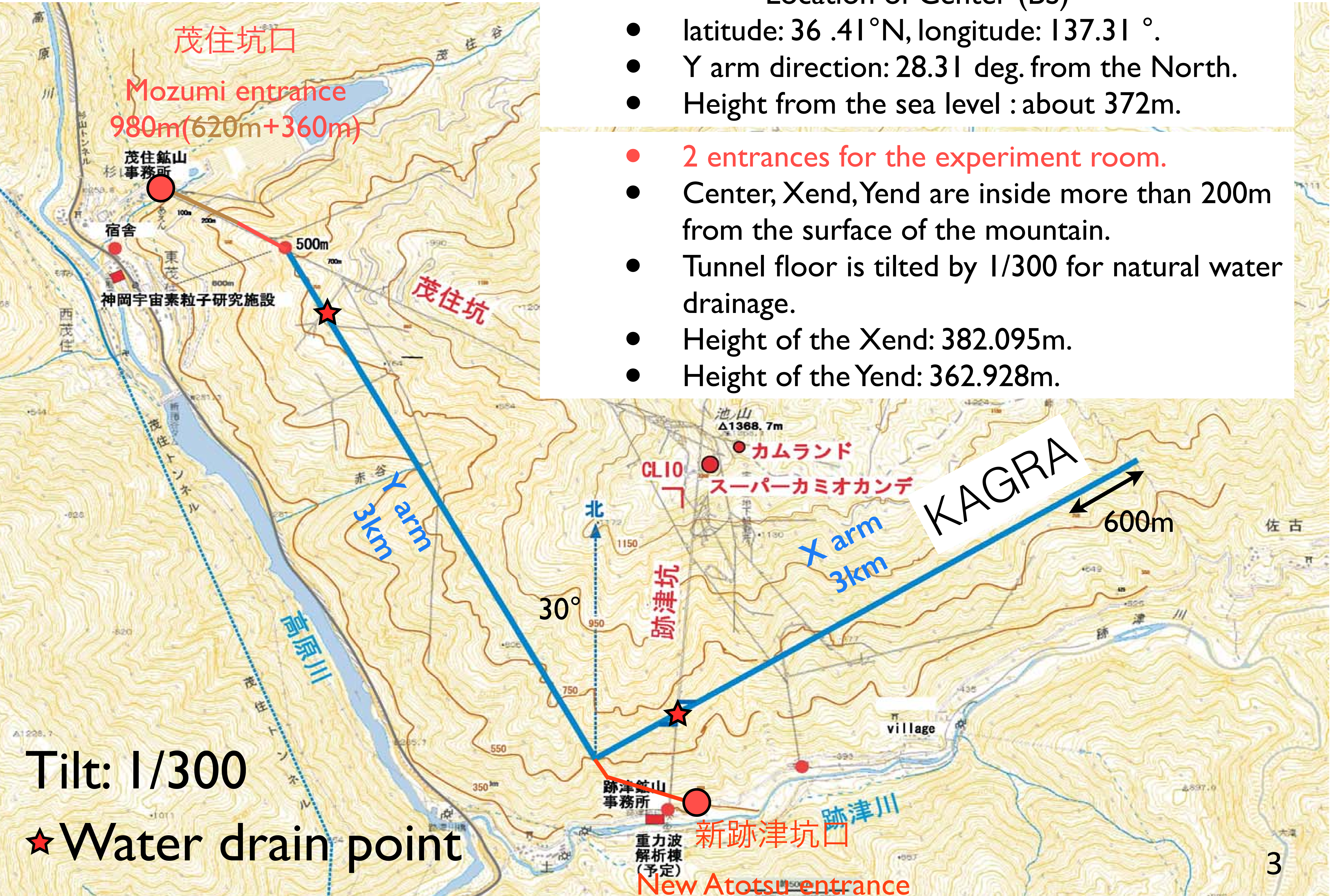


- Underground
  - Kamioka mine
  - Silent and Stable
- Cryogenic mirror
  - 20K
  - Sapphire substrate
- 3km baseline
- Schedule
  - 2010 : Construction start
  - early 2016 : 1st operation in normal temperature
  - early 2018 : cryogenic operation

Location of Center (BS)

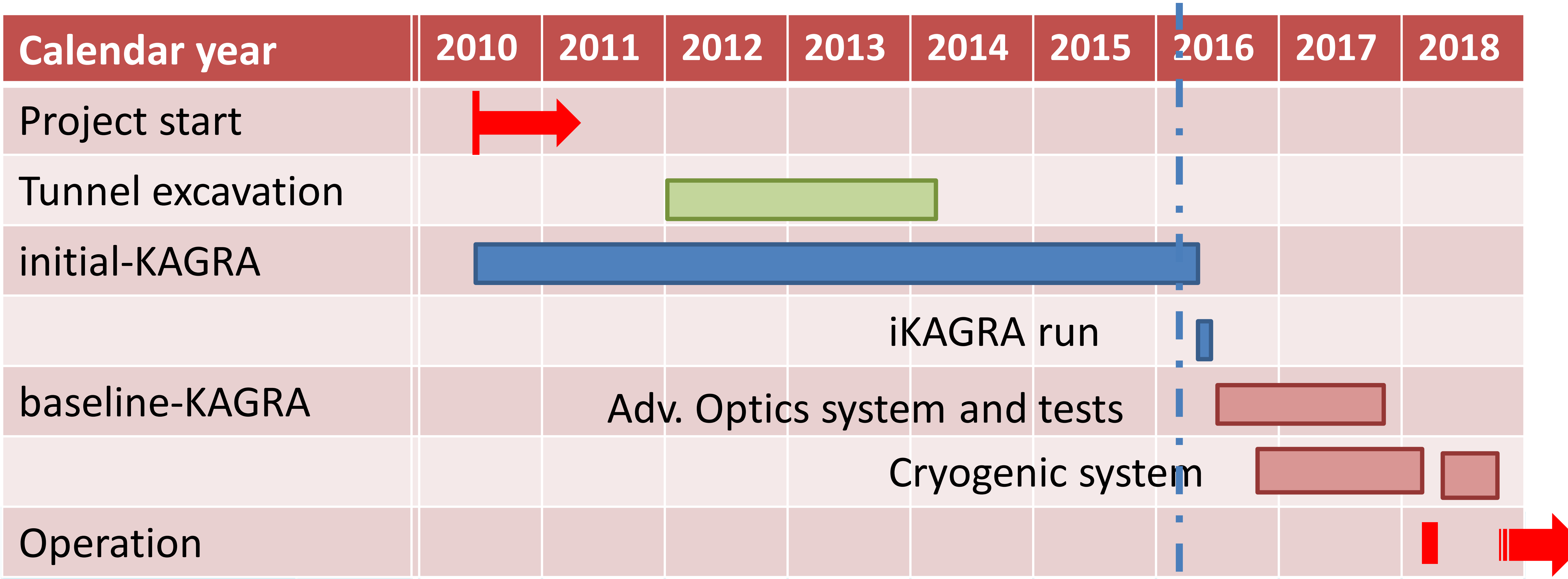
- latitude: 36 .41°N, longitude: 137.31 °.
- Y arm direction: 28.31 deg. from the North.
- Height from the sea level : about 372m.

- 2 entrances for the experiment room.
- Center, Xend, Yend are inside more than 200m from the surface of the mountain.
- Tunnel floor is tilted by 1/300 for natural water drainage.
- Height of the Xend: 382.095m.
- Height of the Yend: 362.928m.



by T.Uchiyama

Schedule



iKAGRA

- We had test run at March and April 2016.

bKAGRA

- Advanced optics and cryogenic system are in progress.
- Cryogenic operation ~end of FY2017

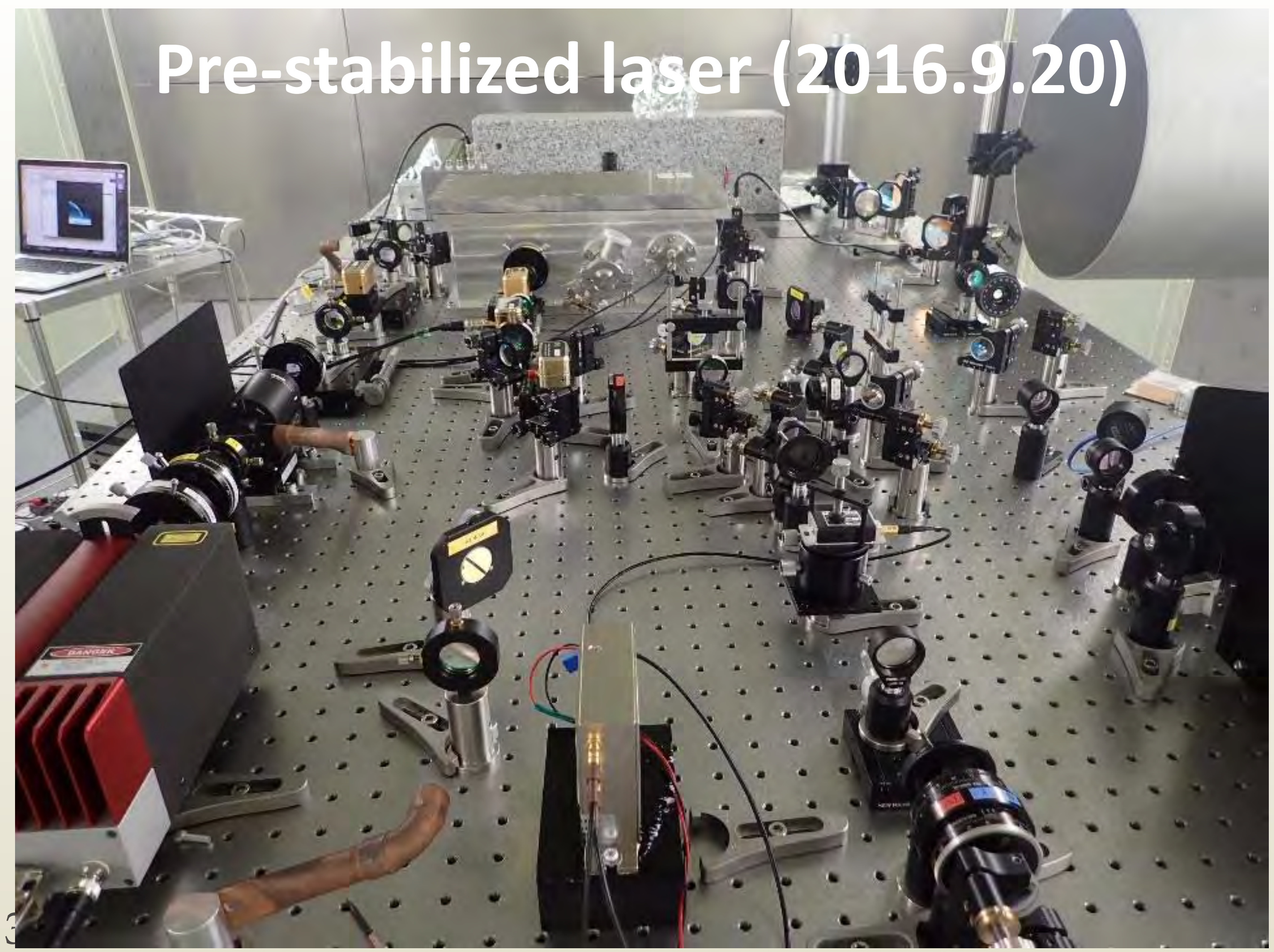
Shin-Atotsu entrance
(2017.1.7)

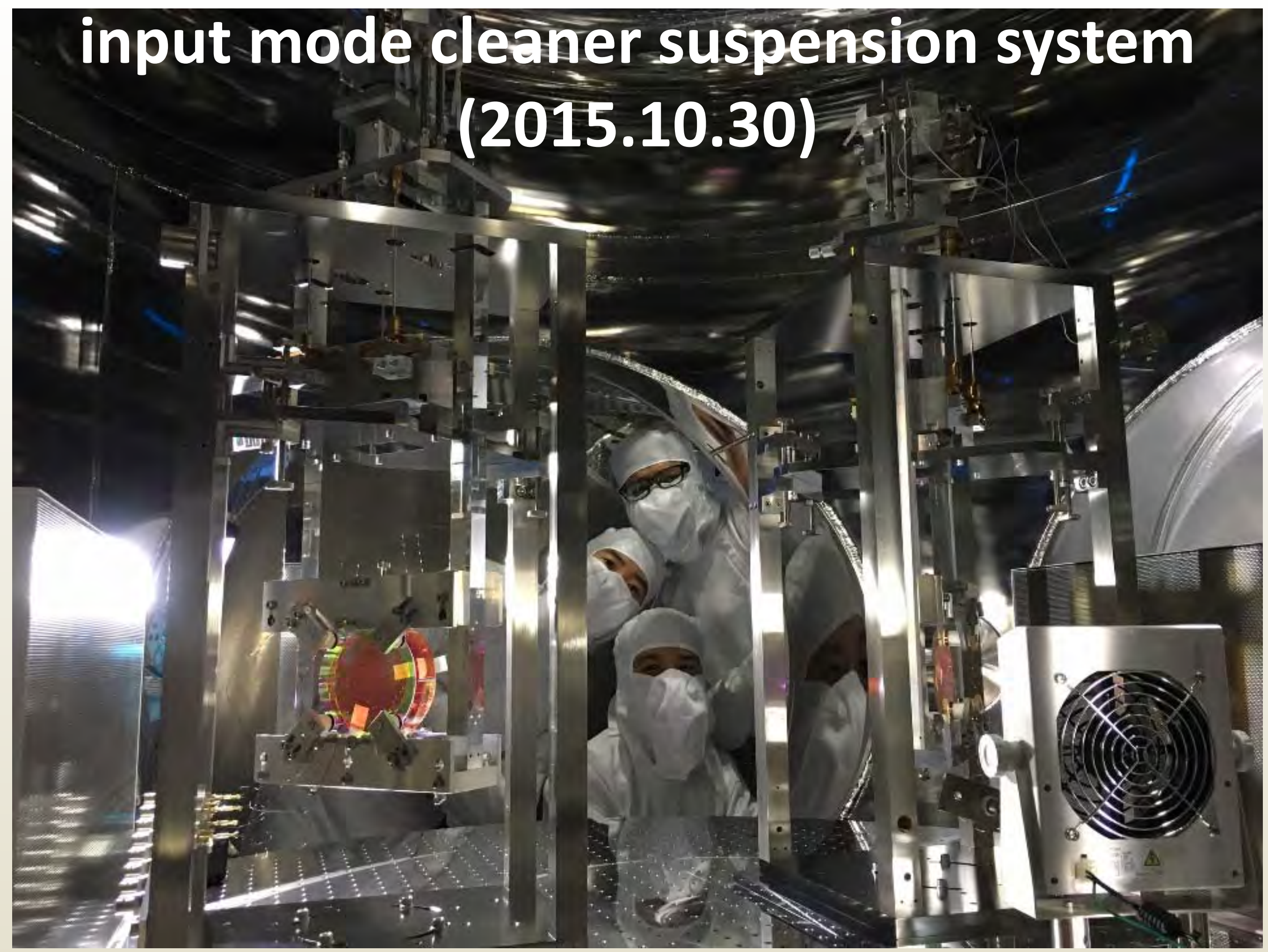
Tunnel excavation completed at March, 2014.

Photo : KAGRA tunnel, center corner

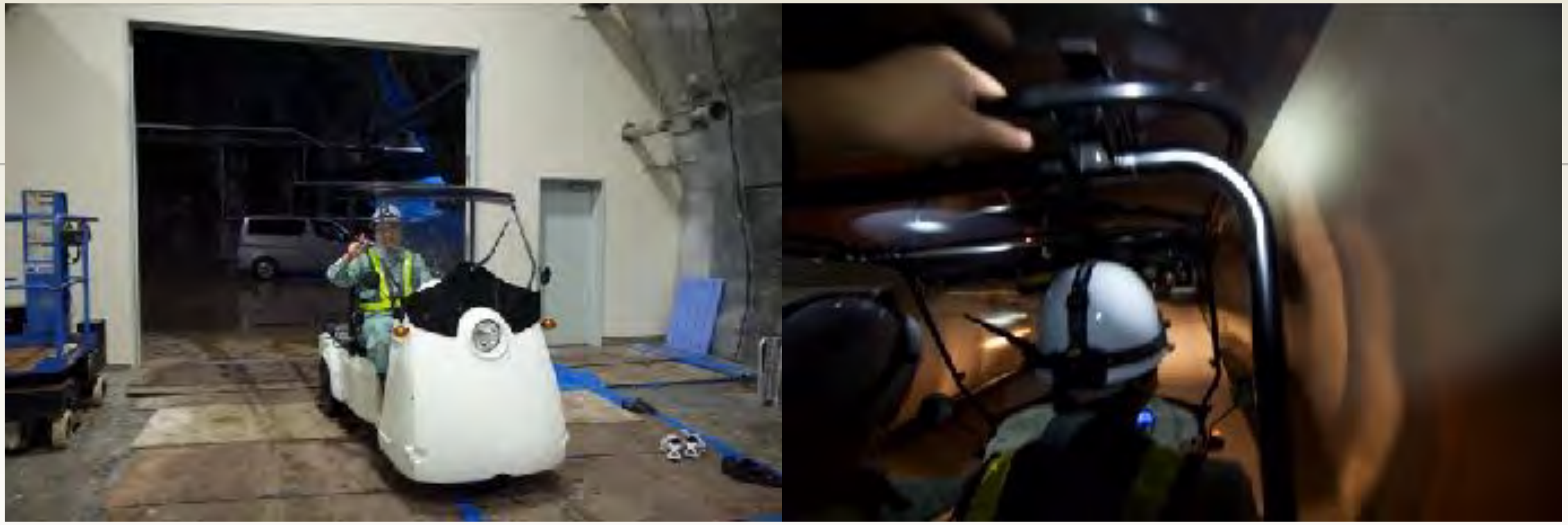

Central area (2017.1.7)


Cryostat for input test mass (2016.9.20)


Pre-stabilized laser (2016.9.20)


input mode cleaner suspension system (2015.10.30)

Tunnel



Drive by Electric car

mid of the X-arm

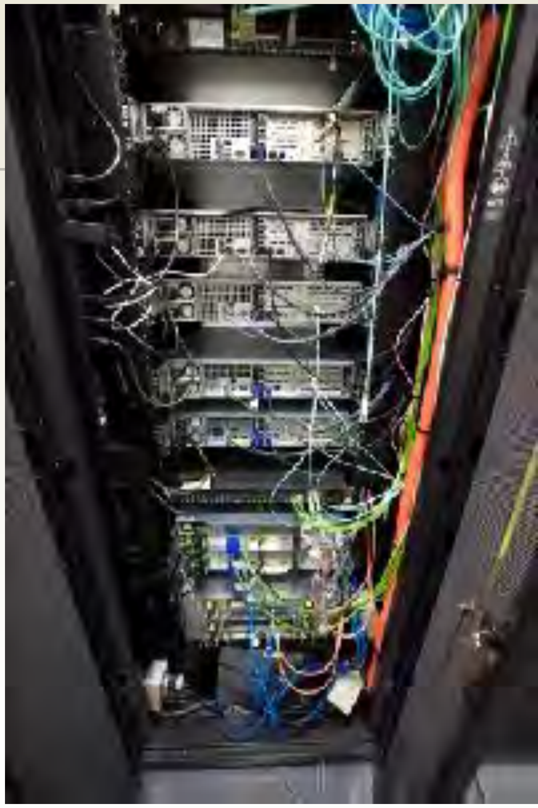
(almost) end of X-arm

KAGRA

Electronics hut

The electronics and computer hut
inside the KAGRA tunnel

DC power supply



frame writer -> transfer

I/O interface

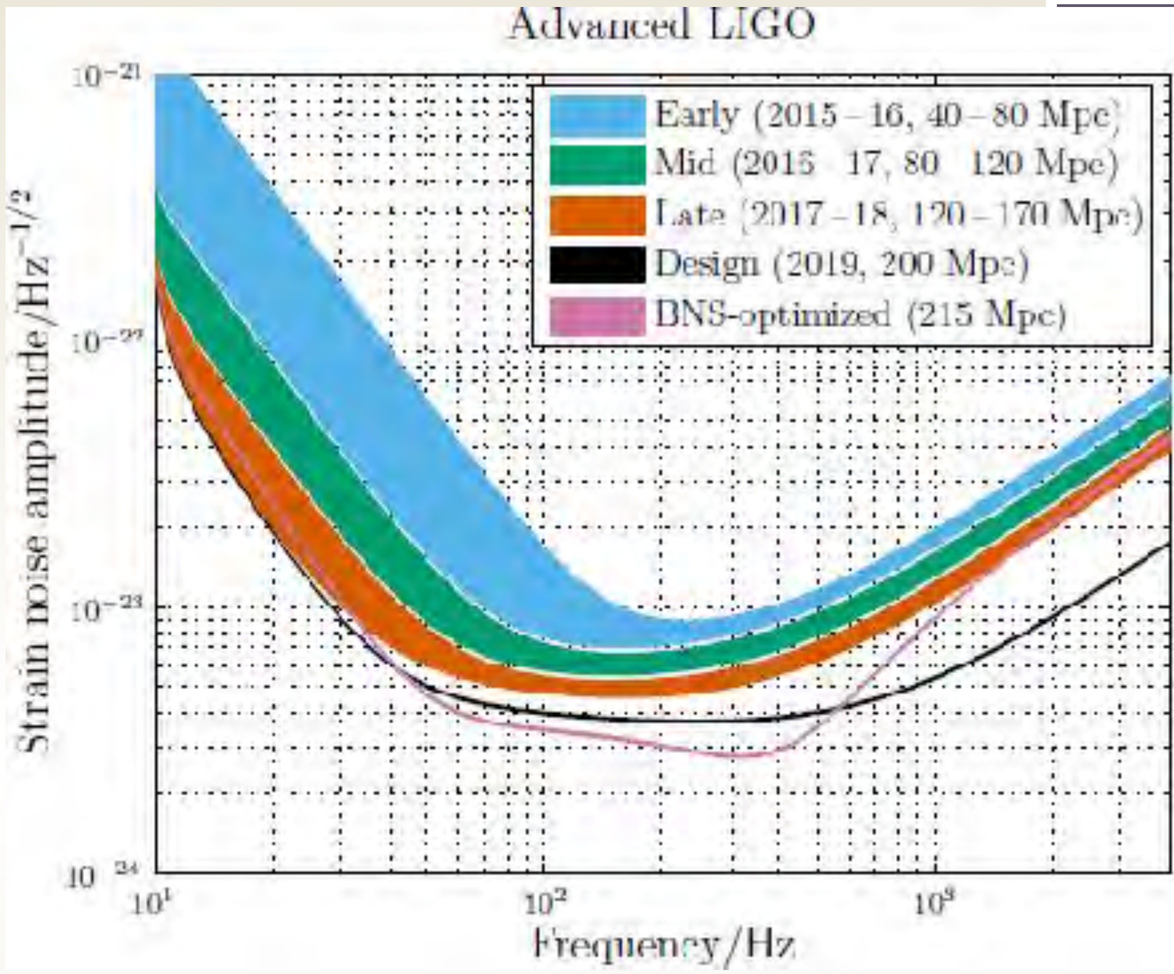
Fiber connection
from/to the surface

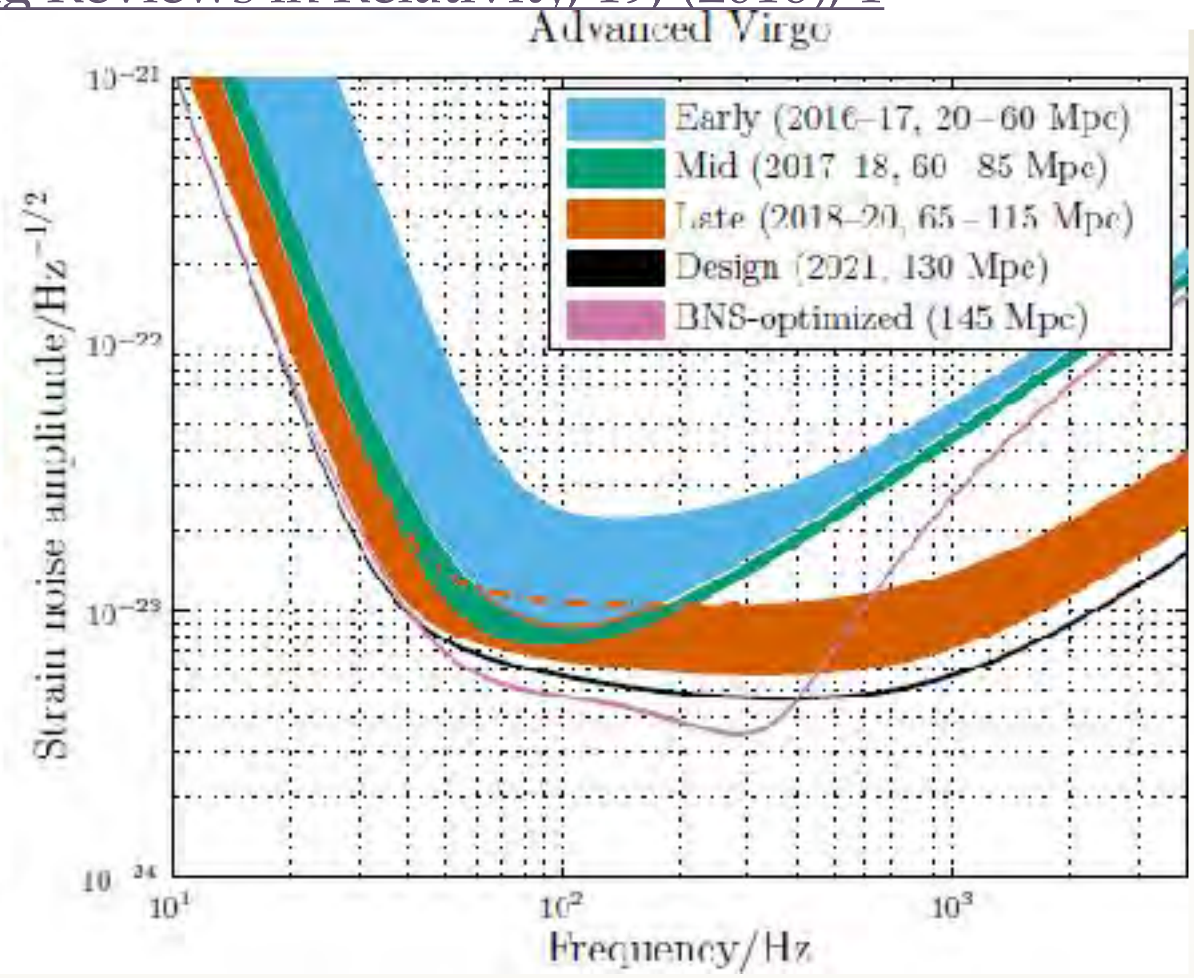
Control room

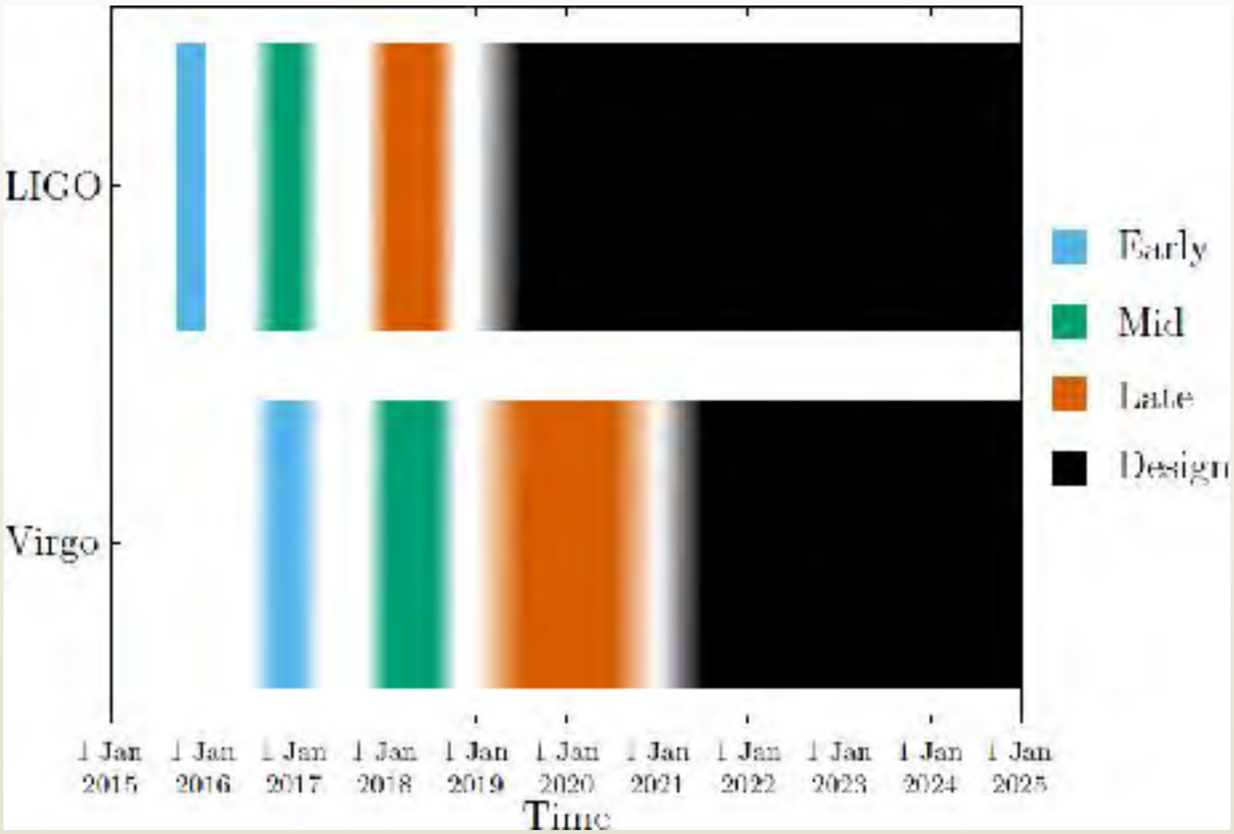
Control room, surface building at Kamioka

Observation Scenario

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo
Living Reviews in Relativity, 19, (2016), 1

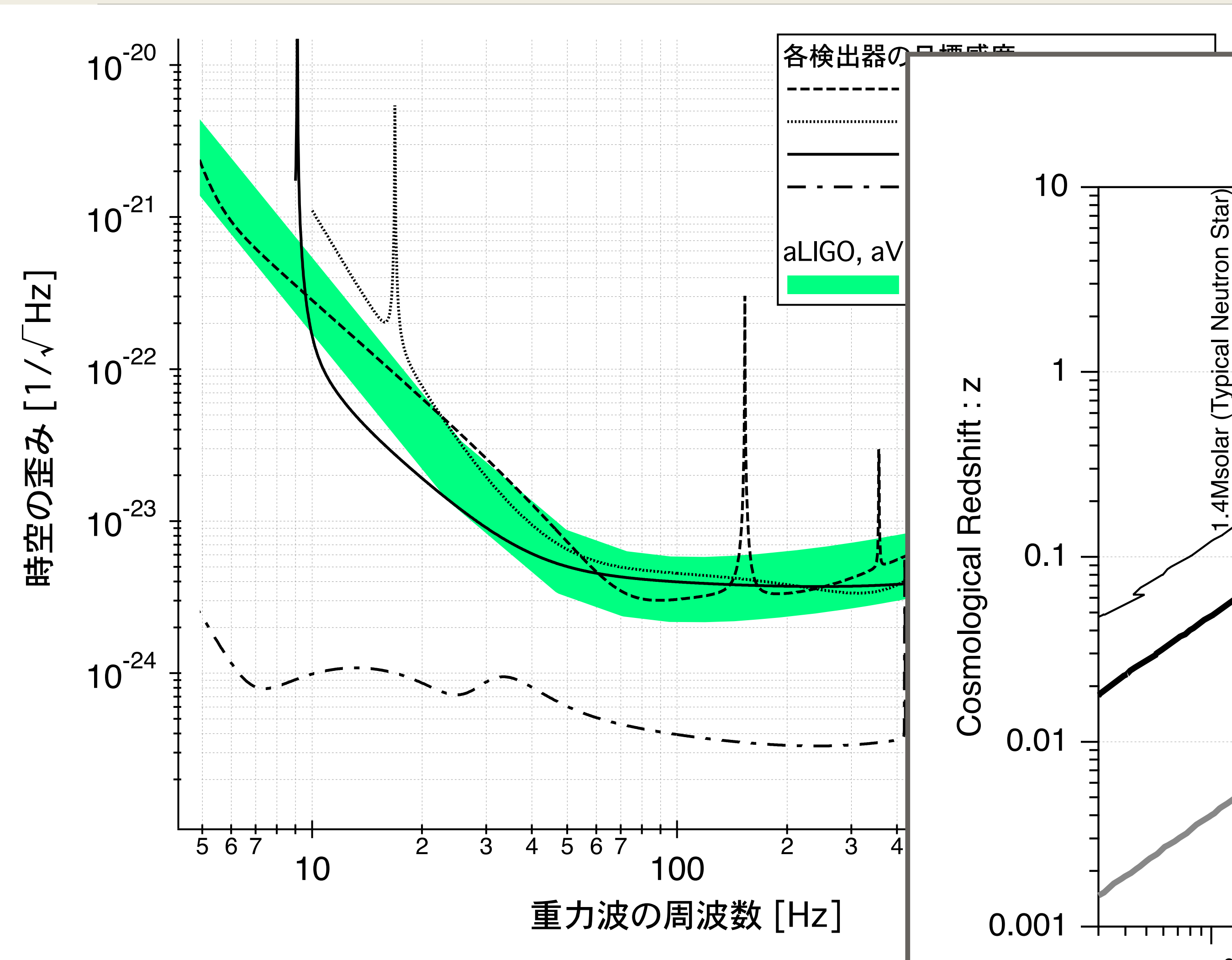


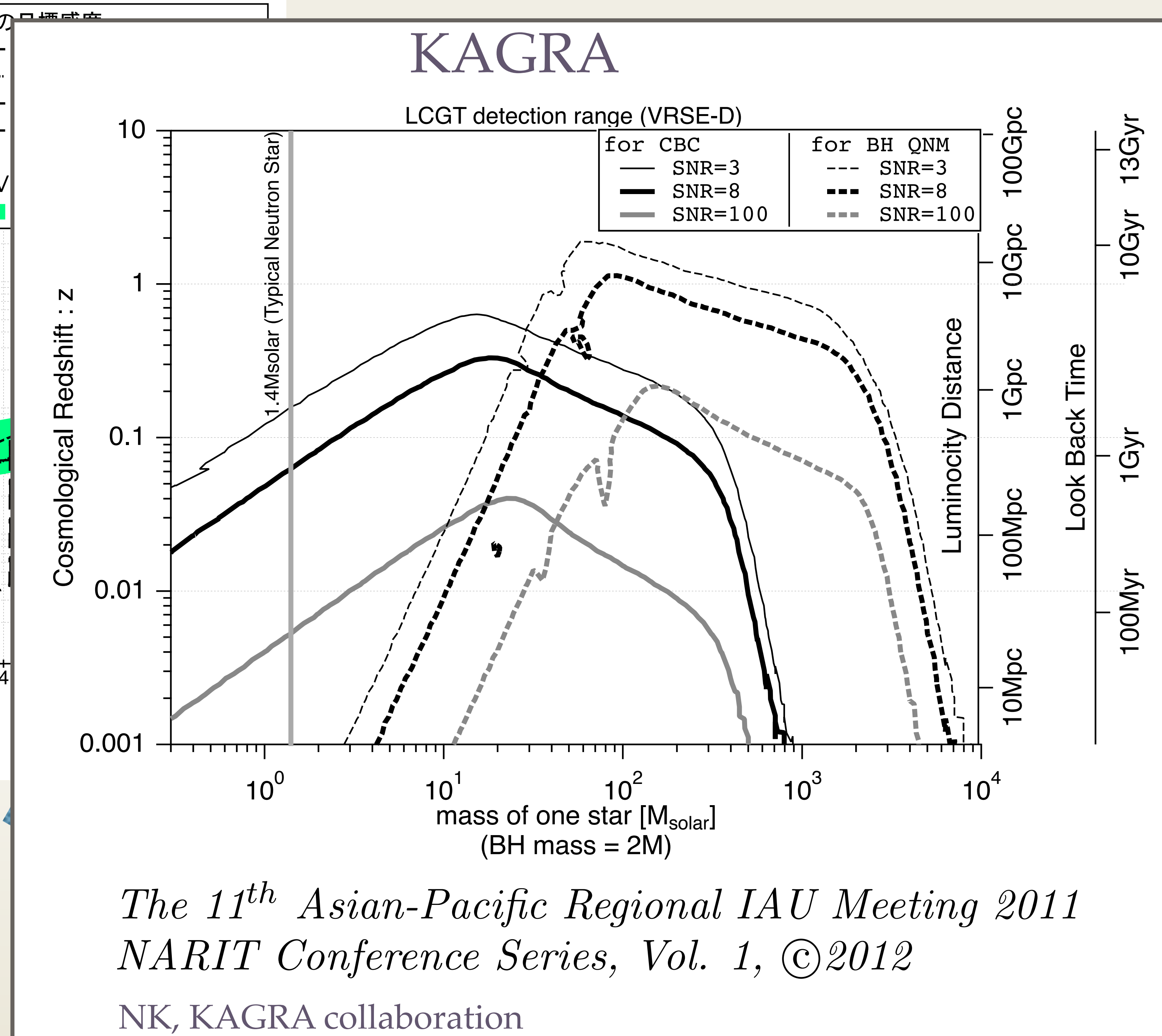


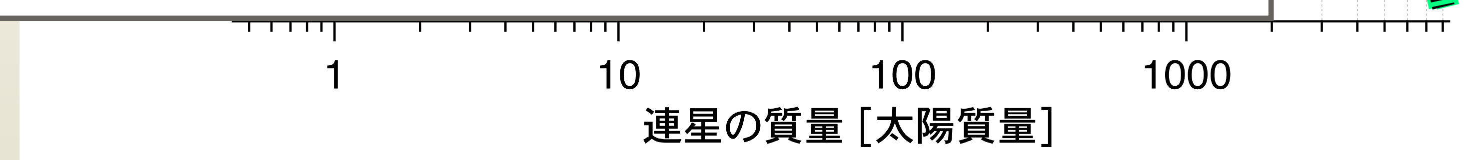


(In next update of this documents. KAGRA will appear in these figures.)

Sensitivity → Range







nce)

Remark : GW sources

Occasionally events :

- Compact binary coalescence (**CBC**):

  NS-NS, NS-BH, BH-BH

  Neutron star : NS, Blackhole : BH

- **Supernovae**

  BH Quasi-normal mode oscillation

- Pulsar glitch

Continuous :

- Pulsar rotation

  Binary

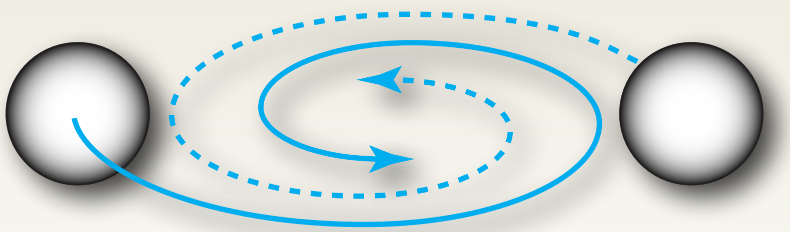
Stochastic Background

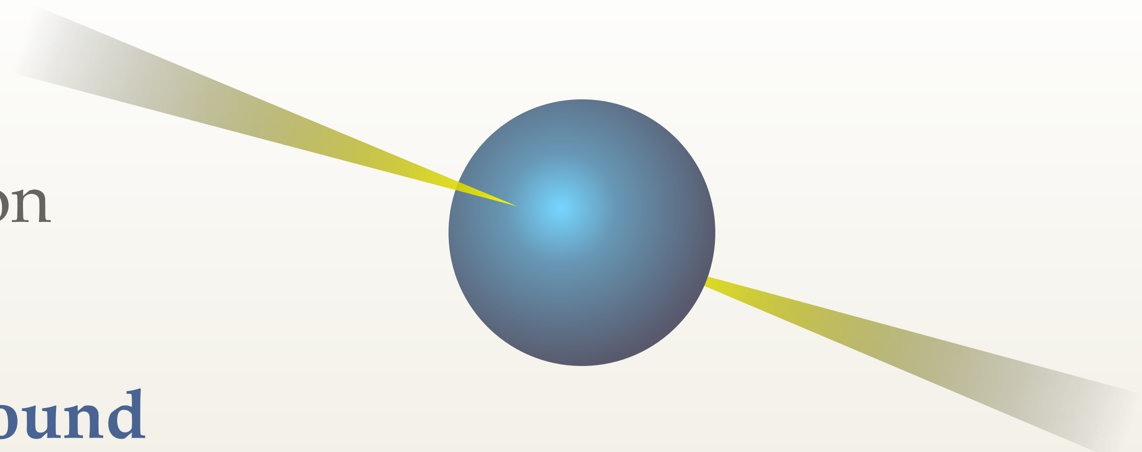
- Early Universe

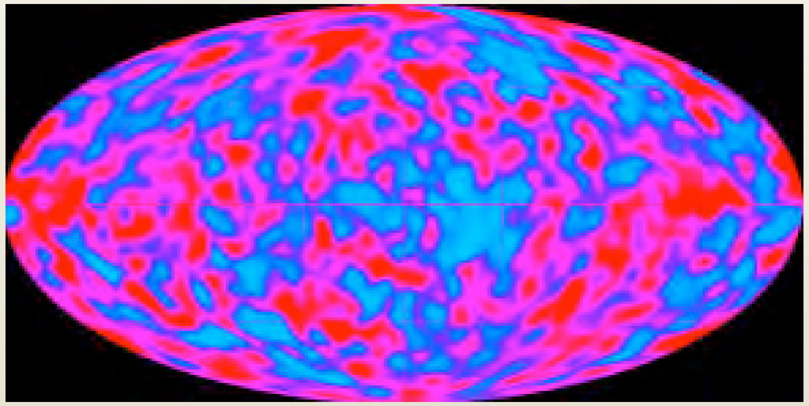
  Cosmic string

- Unresolvable astronomical origins

(& Unknown...)







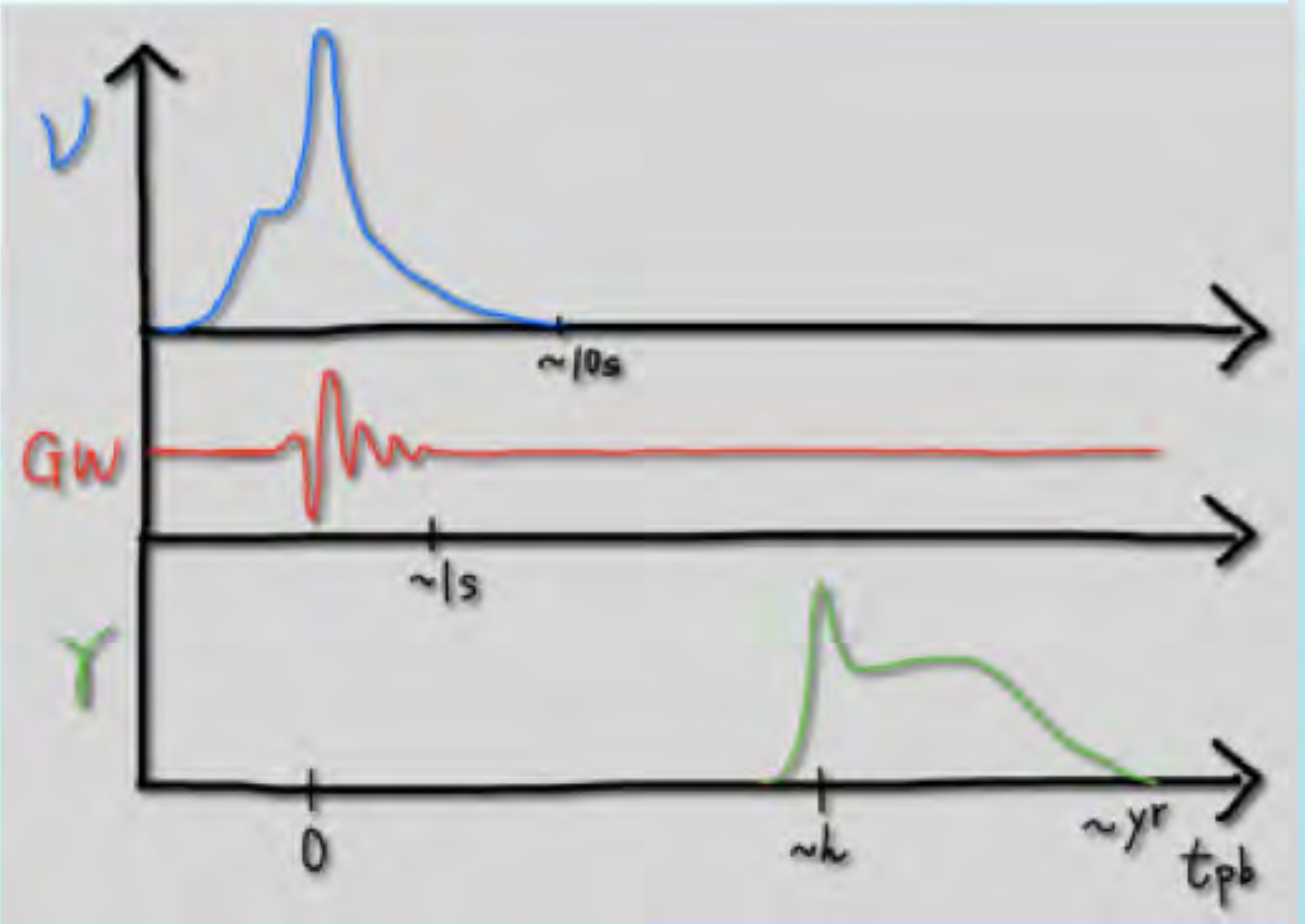
Supernova (SN)

Many process of SN possibly radiate GWs

- core bounce
- convection
- SASI
- Jet

Neutrino, GW, EM will be emitted.

- Fruitful scenario of 'coincidence detection'
- Multi-probes make it possible to get newer knowledge and deep understand of SN mechanism.

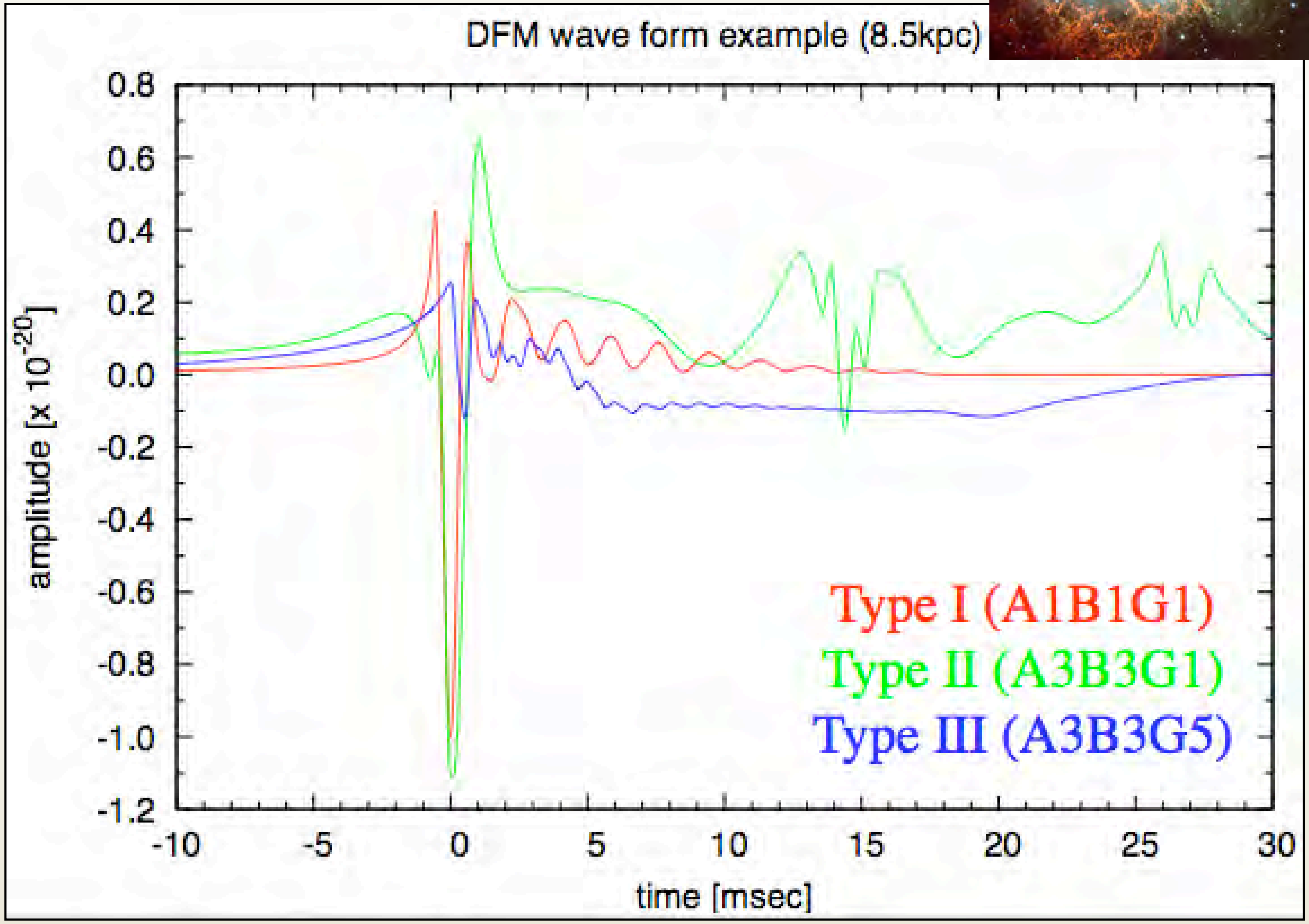


Drawn by Y.Suwa

GW signal (example : Supernova)

Supernova (type II) will emit short duration GW (Burst wave) according to various processes in it.

- Rotational Core collapse (Bounce)
- Convection
- Proto-neutron star formation and g-mode instability
- Standing-Accretion-Shock Instability
- ...



Dimmermeier at al.

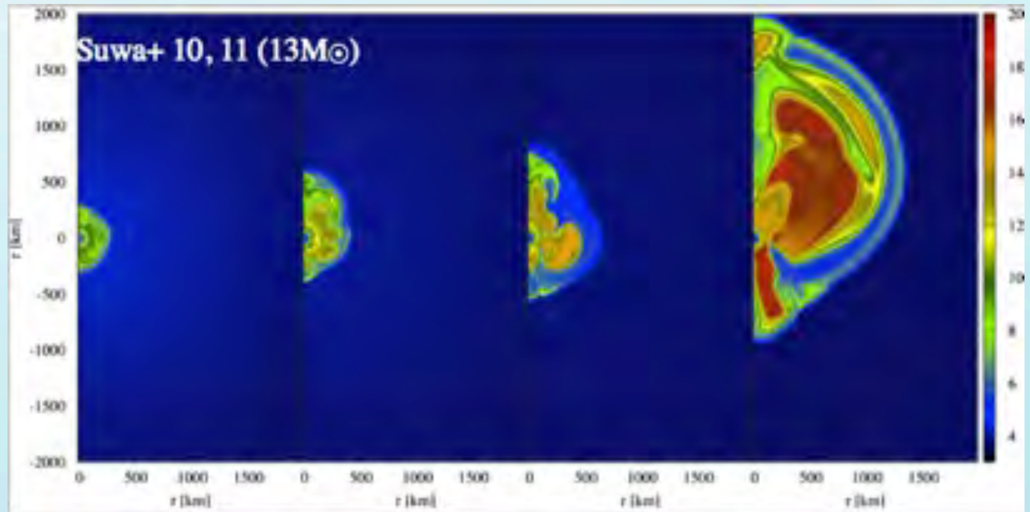
Team SKE

at Kakenhi New innovative area 「重力波天体」

SNe Theory(A05)

Y. Suwa

- **Provide time correlated data, GW and neutrino**
- **Suggest signature signals physical phenomenon**



Neutrino analysis(A03)

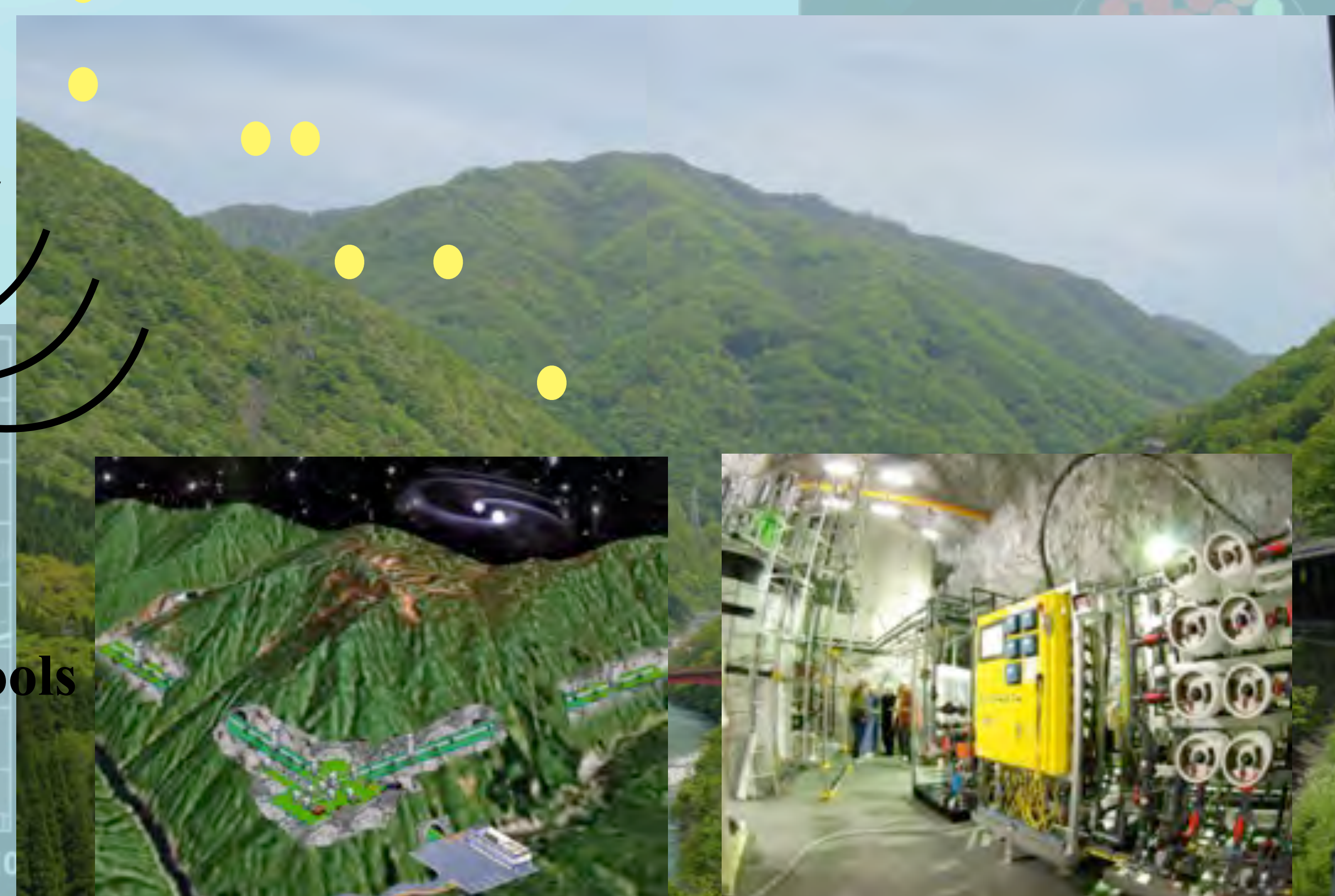
T. Kayano, Y. Koshio
M. Vagins

- **R&D of EGADS detector**
- **Signal simulations with EGADS and SK**

GW analysis(A04)

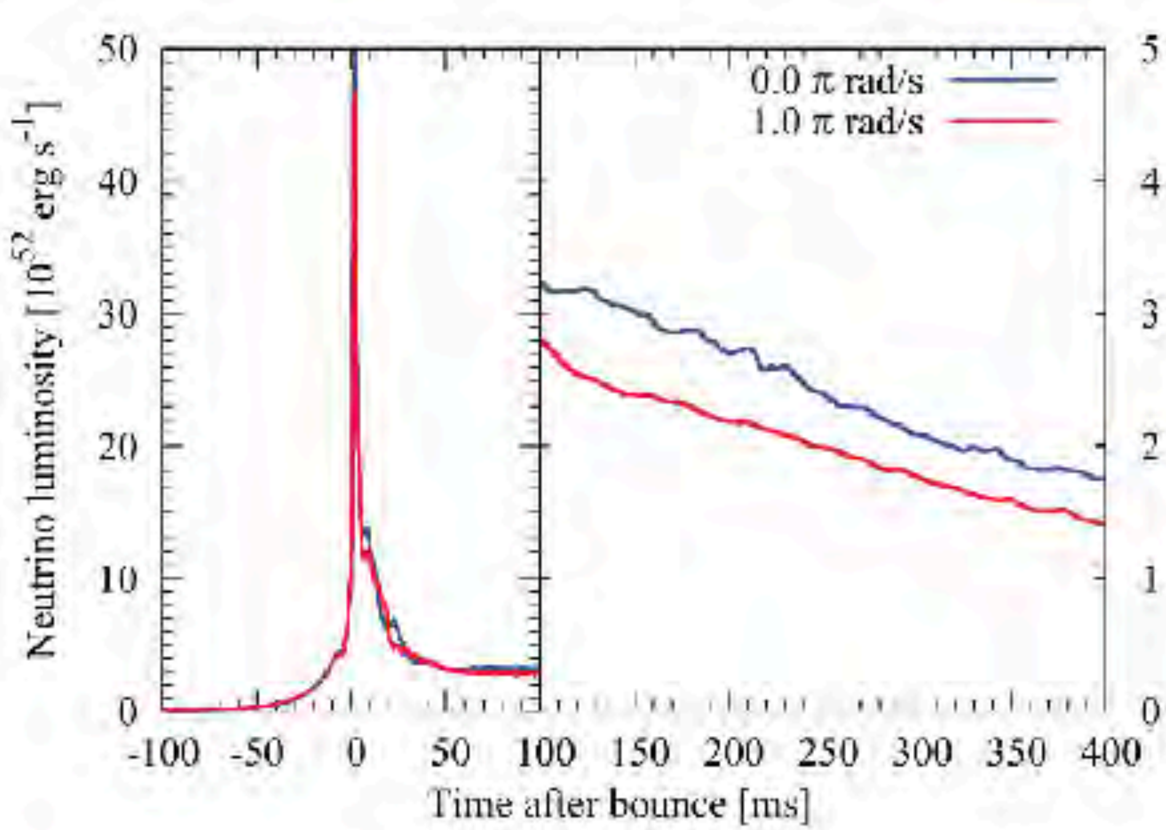
T. Yokozawa, M. Asano
N. Kanda

- **KAGRA detector simulations**
- **Develop/Optimize GW analysis tools**
- **Prepare for realtime observation**

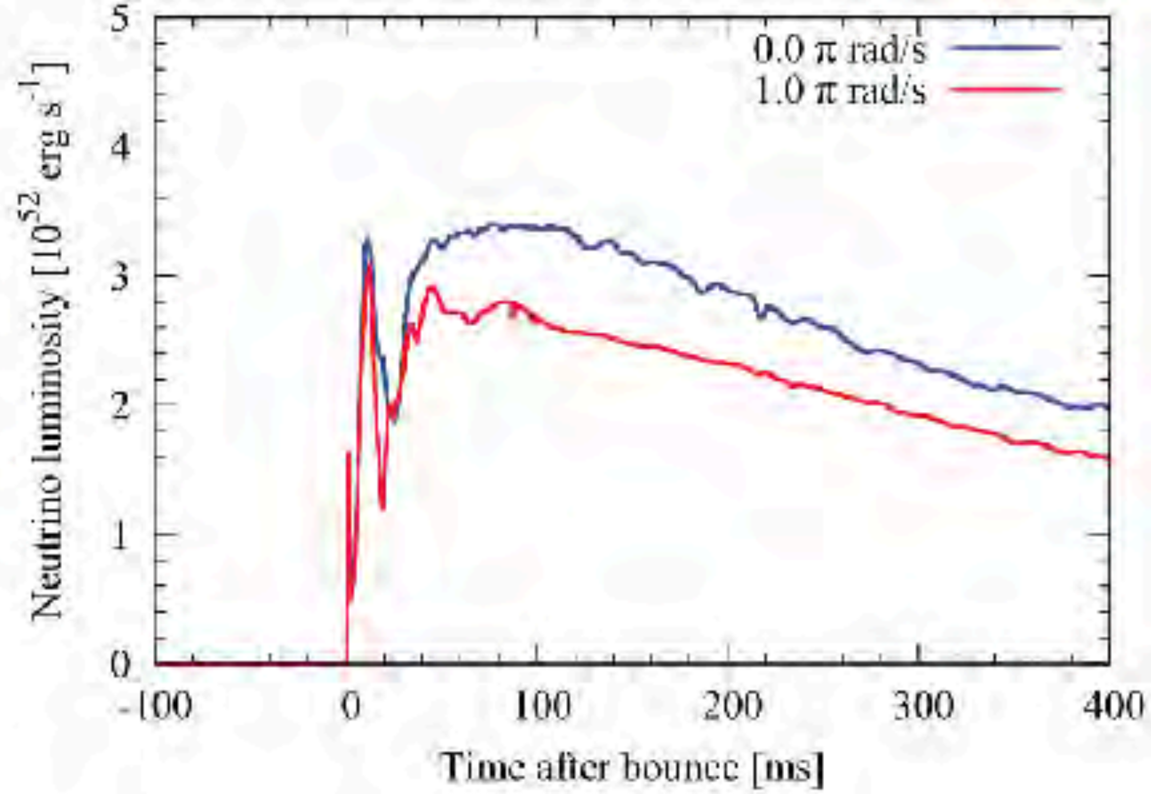


12

neutrino



(a) L_{ν_e}



(b) L_{ν_e}

GW

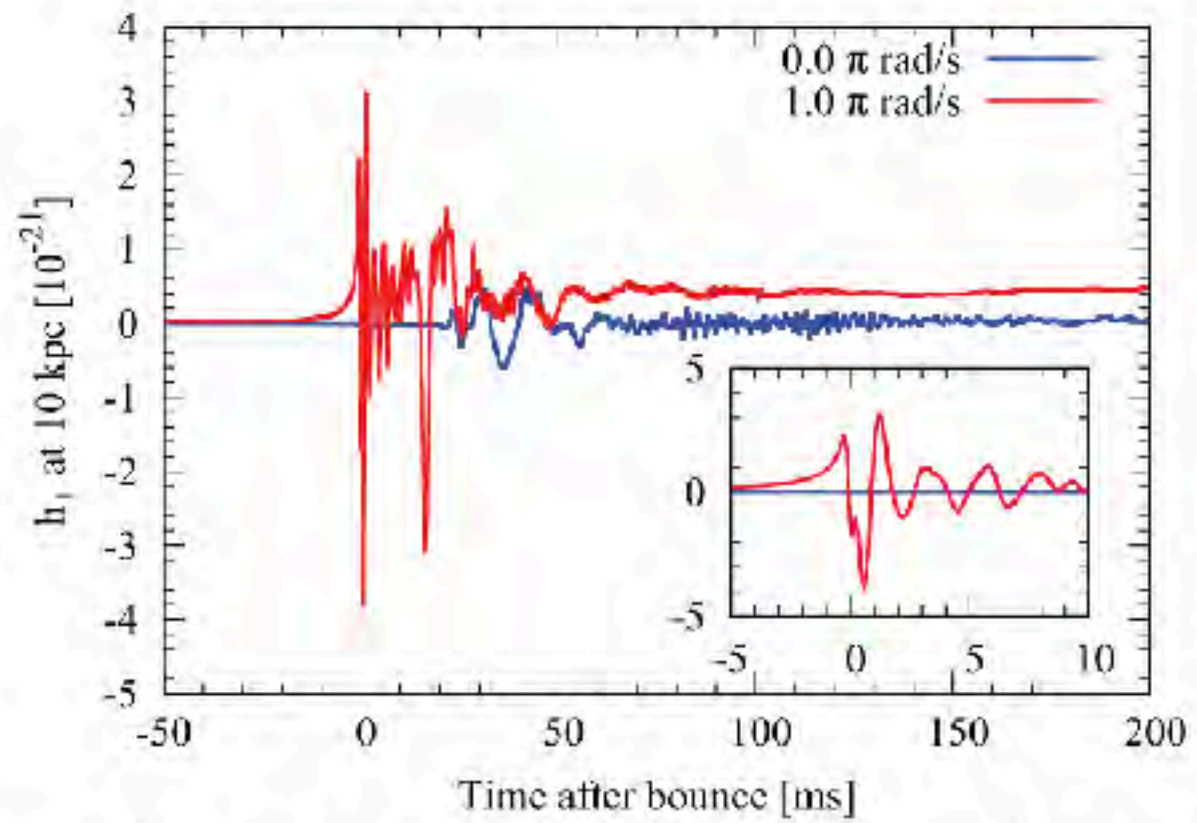


Figure 2. GW amplitude as a function of time for a core-collapse supernova occurring 10 kpc from the observer. Each line represents models with different initial rotation rates, i.e., no rotation ($\Omega_0 = 0.0\pi$) (blue) and strong rotation $\Omega_0 = 1.0\pi$ rad s^{-1} (red). The small panel shows features around the bounce time. The fast rotation model exhibits a large amplitude GW at the

T.Yokozawa et al.,
ApJ., 811, 86 (12pp) 2015

GW and neutrino analysis for the dynamics of SNe timing analysis <u>could suggests that the core is strongly rotating or not.</u>

Table 2
The Various Scenarios' GW Detection Efficiencies (GW eff.), Neutronization Neutrino Detection Efficiencies (Neutrino Eff.) for (1) EGADS or (2) GADZOOKS!, Their Product, and the P_r Value for the 0.0π rad s^{-1} Model

Scenario	GW Eff.(%)	Neutrino Eff.(%)	Detection Eff.(%)	P_r(%)
0.2 kpc, uniform	74.8	100.0(1)	74.8	0.0
1.0 kpc, uniform	46.5	46.8(1)	21.9	20.8
Galactic Center	0.0	97.5(2)	0.0	…
Galaxy Dist.	1.5	84.6(2)	1.5	0.2

Table 3
The Various Scenarios' GW Detection Efficiencies(GW eff.), Neutronization Neutrino Detection Efficiencies (Neutrino Eff.) for (1) EGADS or (2) GADZOOKS!, Their Product, and the P_r Value for the 1.0π rad s^{-1} Model

Scenario	GW Eff.(%)	Neutrino Eff.(%)	Detection Eff.(%)	P_r(%)
0.2 kpc, uniform	88.0	100.0(1)	88.0	98.4
1.0 kpc, uniform	73.6	40.2(1)	29.5	80.0
Galactic Center	21.5	94.8(2)	20.4	75.3
Galaxy Dist.	26.7	81.7(2)	24.7	76.2

Observational Strategy for GW and Neutrino

Problems/Concerns:

- Event must be near !

  Typical range of GW and Neutrino detector for SN is a few-several 100Mpc.
- Our galaxy might be optical thick.

Therefore, …

- Keep duty time!

  GW detectors may be key.

  Never lose the chance of golden event !
- Inference of the direction by each detection is essential.
- We must develop the data analysis that can be done with a single event.

Advantages

- omni-directional
- ‘time machine’ like

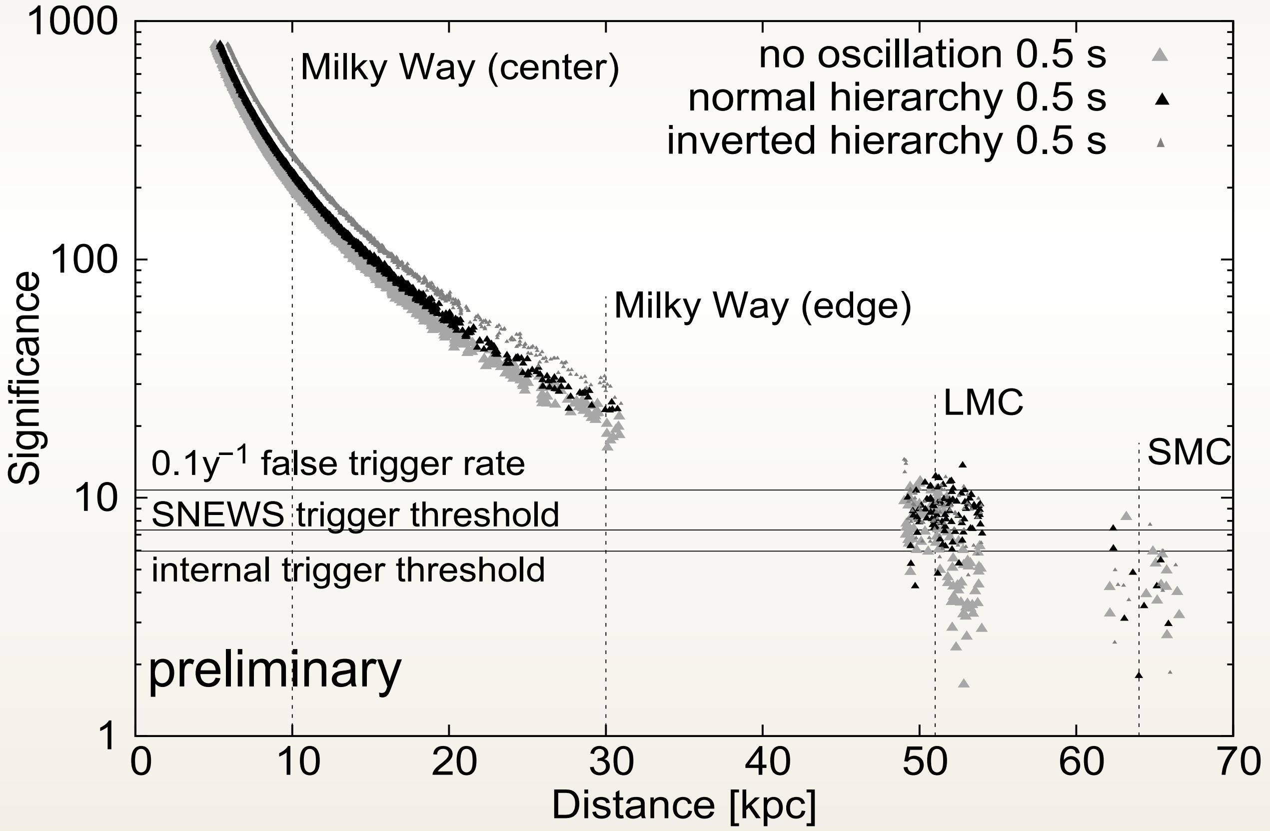
  In both detector cases, we can analyze past records of event triggers/signals.
- (In Japan) SK and KAGRA has less uncertainty of arrival time difference.

Key issues

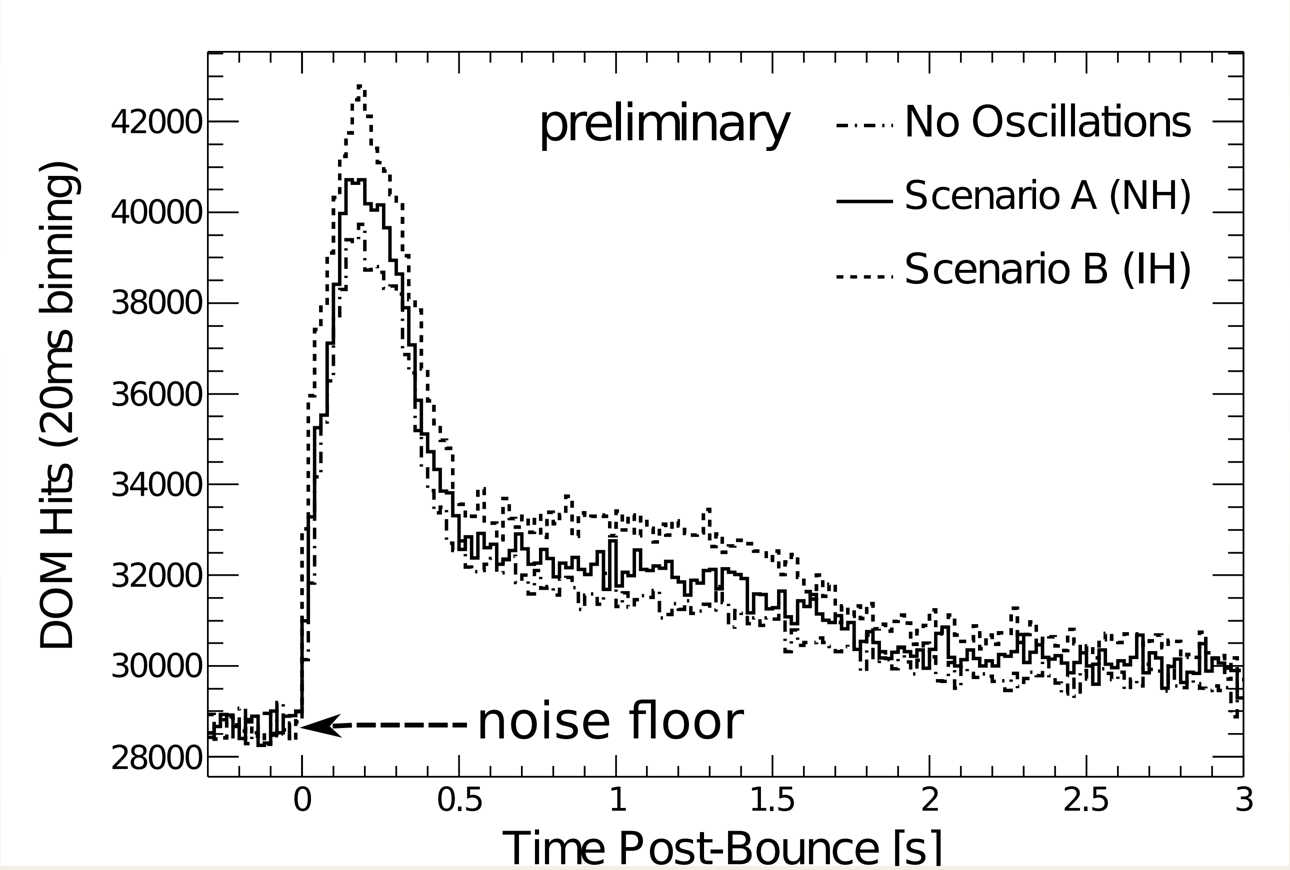
- time series (time profile) of both GW and neutrino flux
- infer the SN direction

一期一会

Personal question : How about IceCube for SN?

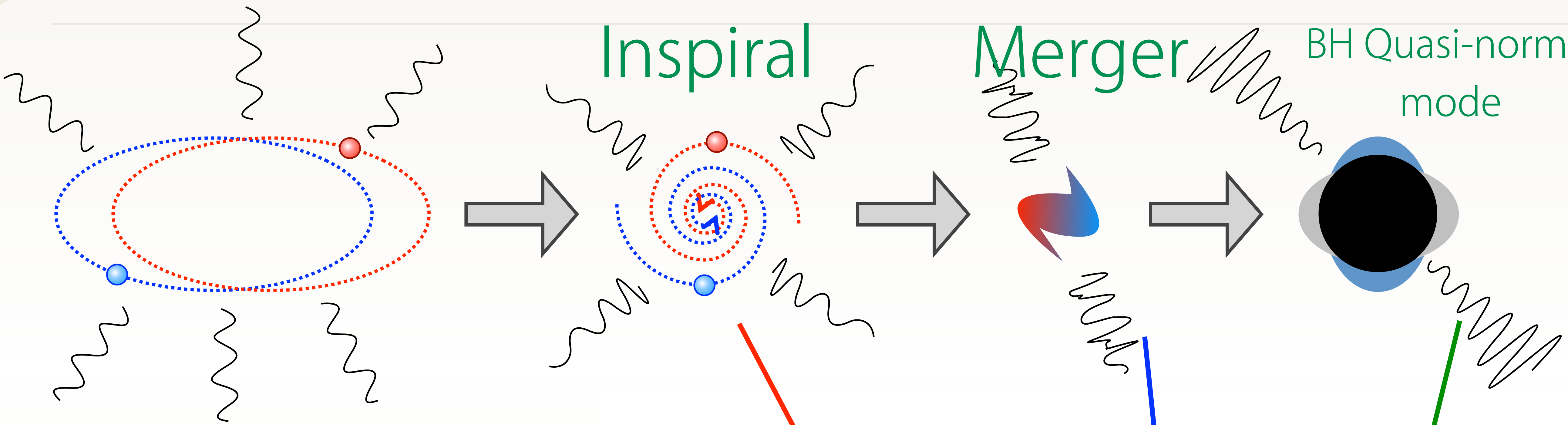


SN @10kpc away



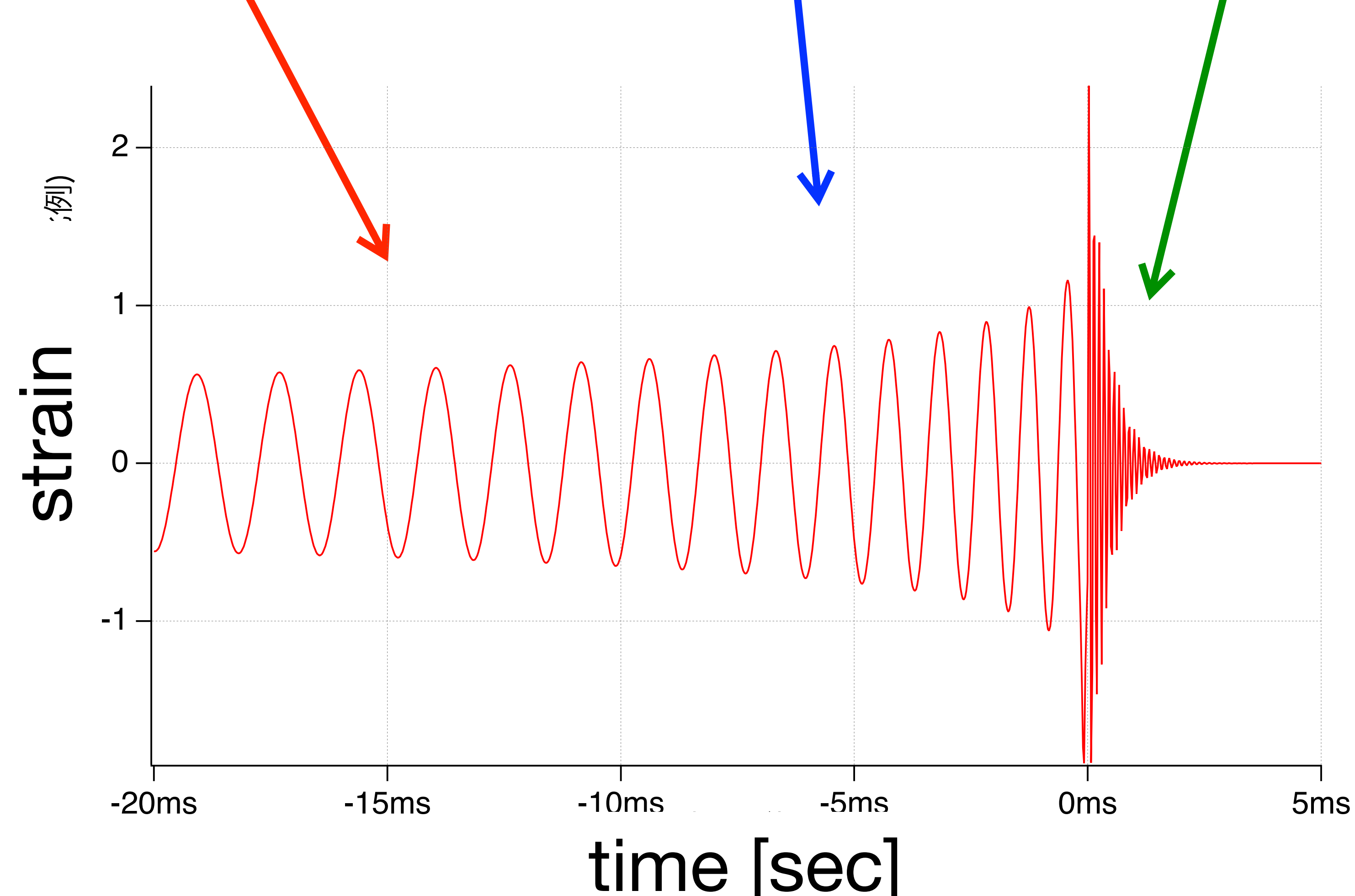
arXiv:1111.2731 (Proceedings of ICRC2011)

CBC (Compact Binary Coalescence)

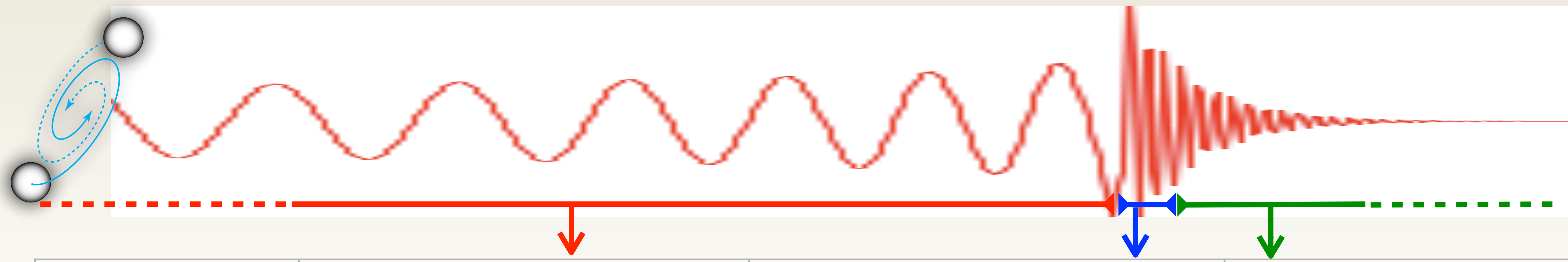


Compact Stars :

- Black-holes
- Neutron Stars



CBC Waveform and Physics



<table>
<tr><td>phase</td><td>Inspiral
(a few~1000sec,
depend on mass)</td><td colspan="2">merger
(~10msec)</td><td colspan="2">ringdown
(~100msec)</td></tr>
<tr><td>waveform</td><td>Post-Newton approx.
analytic waveform</td><td colspan="2">Numerical relativity</td><td colspan="2">Perturbation theory
of BH space-time</td></tr>
<tr><td>frequency</td><td>(10Hz) ~ 1.5 kHz</td><td colspan="2">a few kHz</td><td colspan="2">several kHz</td></tr>
<tr><td>Physics</td><td>mass of stars,
luminosity,
arrival time
(with multi-detectors,
direction, polarization,
phase, orbit
inclination, distance)</td><td>Tidal effects,
Viscosity,
…

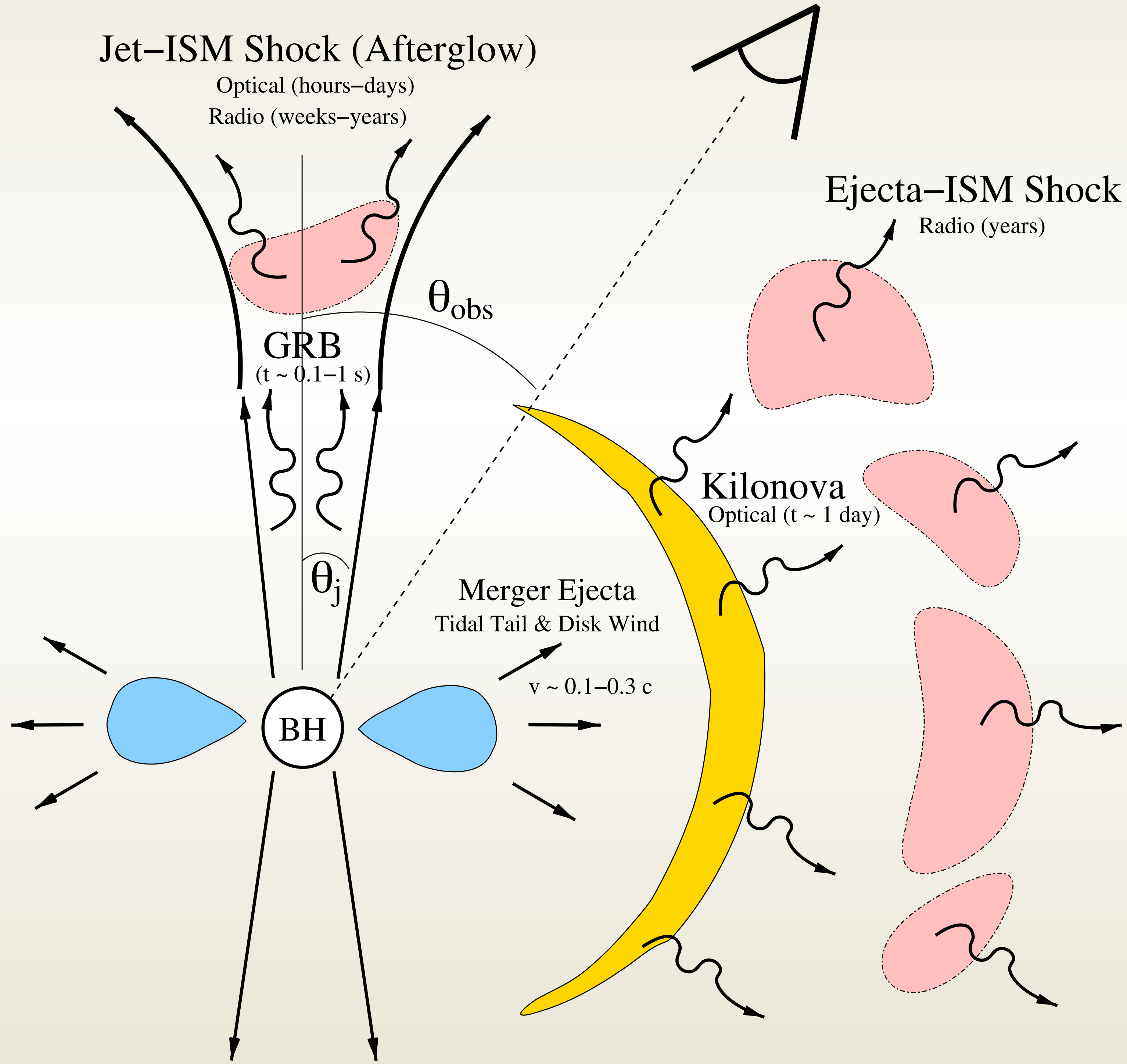
-> NS’s E.O.S.</td><td colspan="2">(In case of
Hyper-massive
NS is formed,)
EOS,
hyperon,
…</td><td>BH mass
BH spin

Testing GR</td></tr>
</table>

After merger of NS-NS, NS-BH

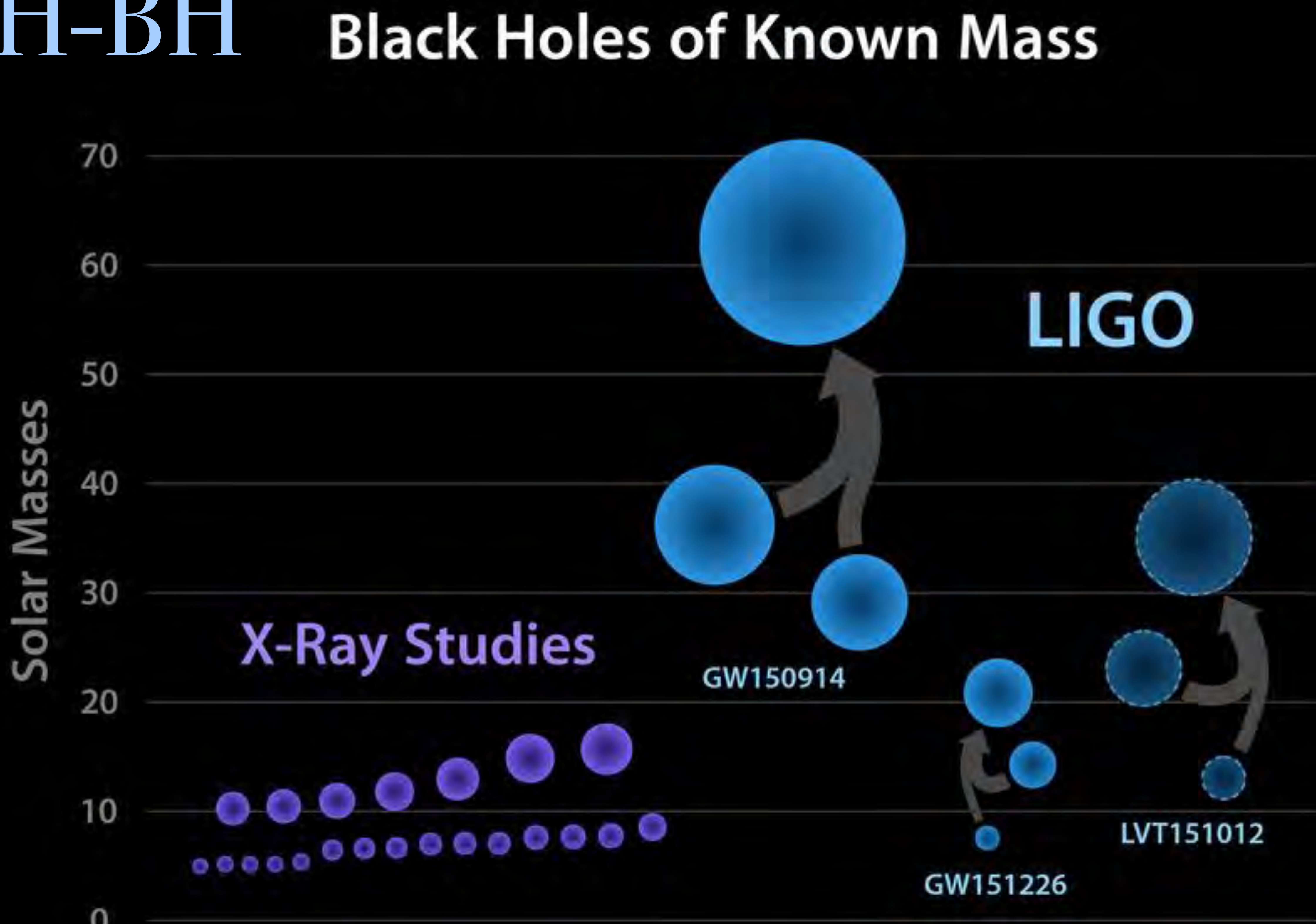
EM follow-ups

In cases of NS-NS and NS-BH, Electro-magnetic radiation can be expected.



Metzger & Berger, ApJ 746:48(2012)

BH-BH


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
LIGO
X-Ray Studies
GW150914
GW151226
LVT151012

Origin of Massive Black-holes ?

Stars as like our sun cannot form such heavy BH…

- Population III stars ?

    Metal less stars that may be the 'first stars' of the universe

- Dynamical formation ?

    runaway merger of BHs

- Primordial BH?

    BH formed directly at early universe

30 + 30 solar mass BHs

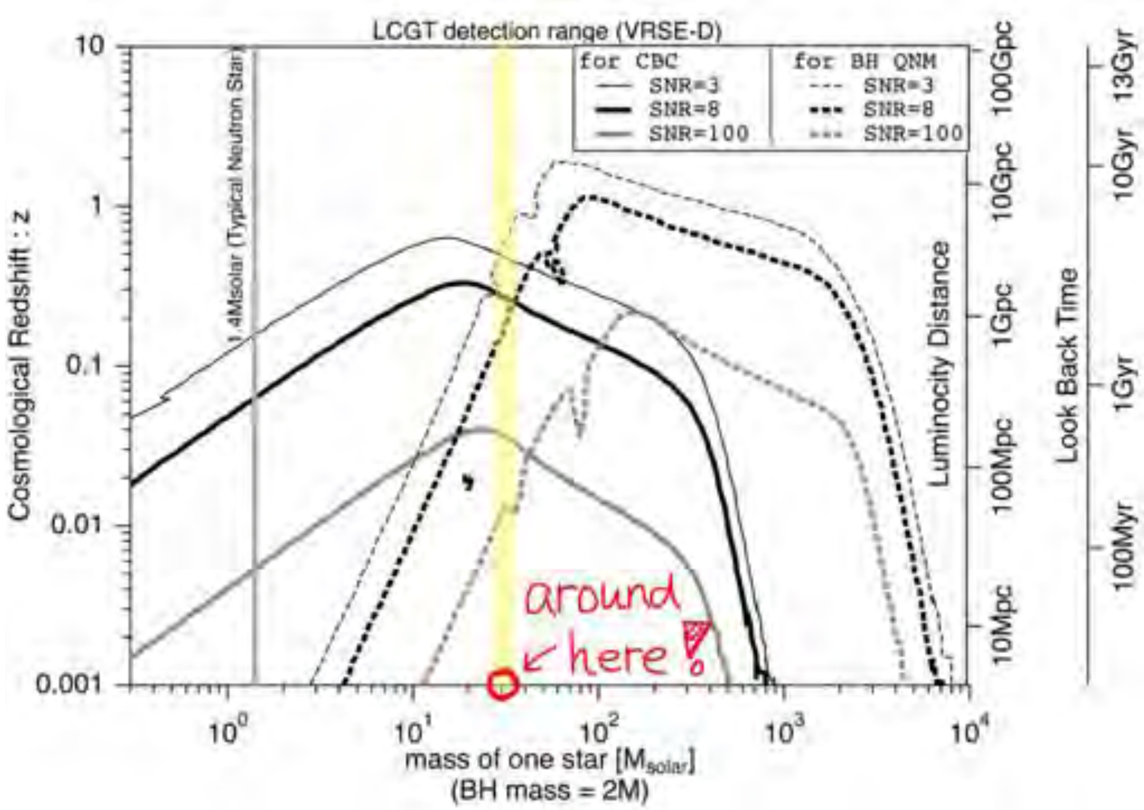
Interesting target for three reasons:

Inspiral and ringdown phases have roughly equal SNRs, so provides good test of GR

If population III stars (formed at redshifts 5-10) exist, these might be a substantial fraction.

Perhaps we will detect several of them in the first aLIGO data run O1, this September!

Nakano Talk



Osaka 20.6.2015

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viewgraph edited by Bruce Allen : (Personal) summary of new, novel, and interesting results presented at this workshop at GWPAW2015 Osaka, June 2015

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ROYAL ASTRONOMICAL SOCIETY

MNRAS **456,** 1093–1114 (2016) doi:10.1093/mnras/stv2624

The detection rate of inspiral and quasi-normal modes of Population III binary black holes which can confirm or refute the general relativity in the strong gravity region

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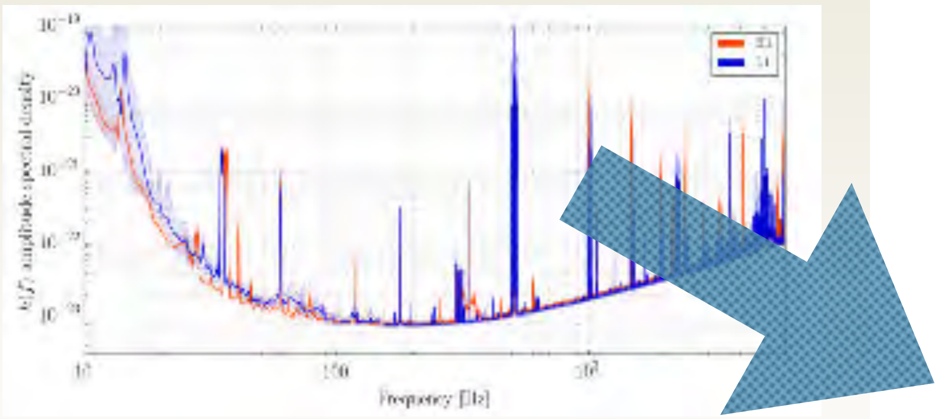
ABSTRACT

Using our population synthesis code, we found that the typical chirp mass defined by $(m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ of Population III (Pop III) binary black holes (BH–BHs) is $\sim 30\,M_\odot$ with the total mass of $\sim 60\,M_\odot$ so that the inspiral chirp signal as well as quasi-normal mode (QNM) of the merging black hole (BH) are interesting targets of KAGRA. The detection rate of the coalescing Pop III BH–BHs is ~ 180 events yr^{-1} $(SFR_p/(10^{-2.5}\,M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}))([f_b/(1 + f_b)]/0.33)Err_{sys}$ in our standard model, where SFR_p, f_b and Err_{sys} are the peak value of the Pop III star formation rate, the binary fraction and the systematic error with $Err_{sys} = 1$ for our standard model, respectively. To evaluate the robustness of chirp mass distribution and the range of Err_{sys}, we examine the dependence of the results on the unknown parameters and the distribution functions in the population synthesis code. We found that the chirp mass has a peak at $\sim 30\,M_\odot$ in most of parameters and distribution functions as well as Err_{sys} ranges from 0.046 to 4. Therefore, the detection rate of the coalescing Pop III BH–BHs ranges about 8.3-720 events yr$^{-1}(SFR_p/(10^{-2.5}\,M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}))([f_b/(1 + f_b)]/0.33)$. The minimum rate corresponds to the worst model which we think unlikely so that unless $(SFR_p/(10^{-2.5}\,M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}))([f_b/(1 + f_b)]/0.33) \ll 0.1$, we expect the Pop III BH–BHs merger rate of at least one event per year by KAGRA. Nakano, Tanaka & Nakamura show that if signal-to-noise ratio (S/N) of QNM is larger than 35, we can confirm or refute the general relativity (GR) more than 5σ level. In our standard model, the detection rate of Pop III BH–BHs whose S/N is larger than 35 is 3.2 events yr^{-1} $(SFR_p/(10^{-2.5}\,M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}))([f_b/(1 +$

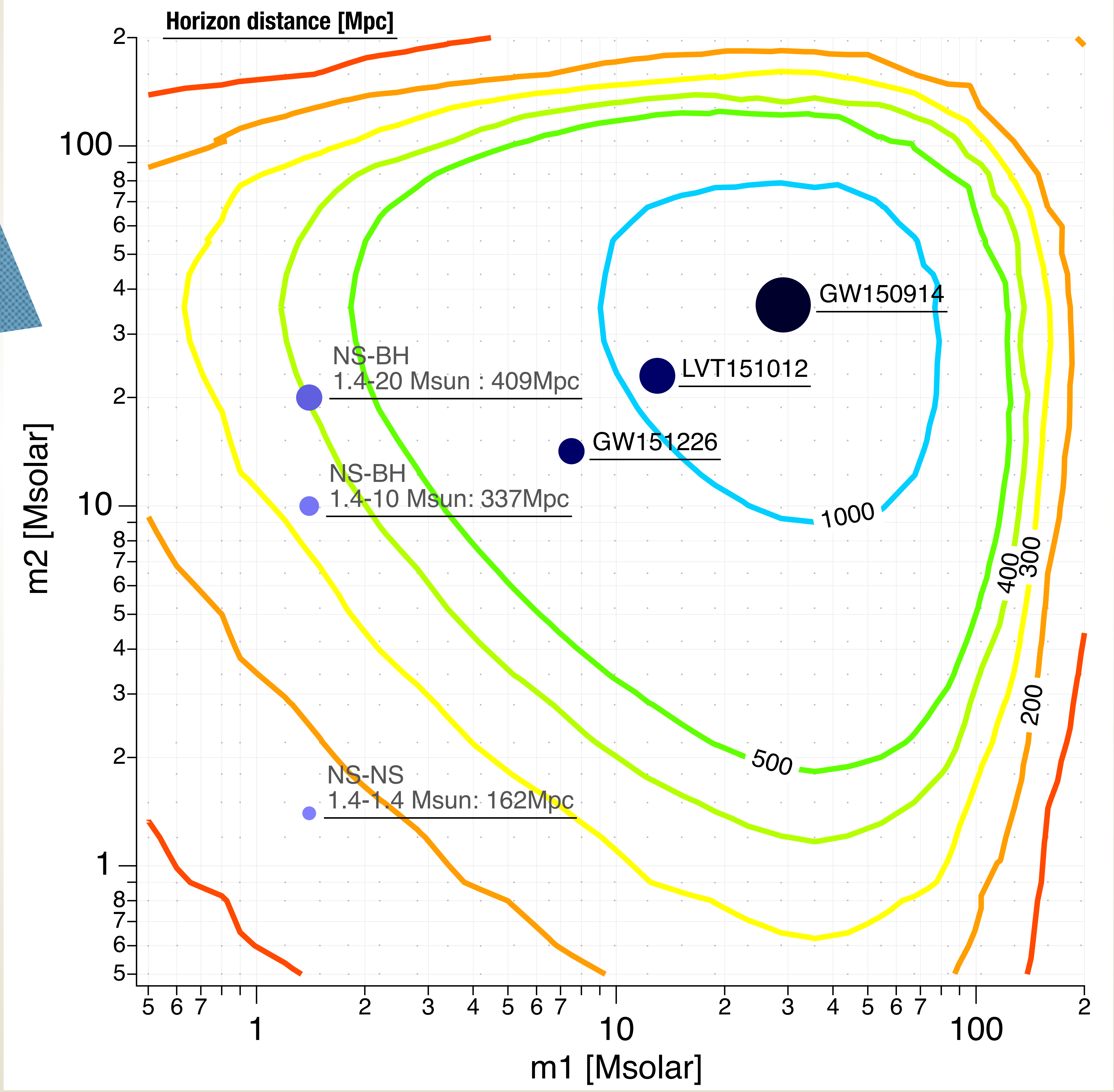
Window as a function of binary masses

Example : LIGO O1



Detector opens window for particular mass ranges.

(In another word, this might be a ‘**bias**’…)



Summary

Welcome to the observational era!

We need more more more events !!!

Multi-messenger observation

for deep understanding of GW sources.

i.e. dynamical motion and mechanism, origin, etc.

GW observation itself still attractive for the study of fundamental physics.