21st International Conference on Computing in High Energy and Nuclear Physics **CHEP2015** Okinawa Japan

KAGRA and the Global Network of Gravitational Wave Detectors

- Construction Status and Prospects for GW Astronomy with Data Sharing Era -

Nobuyuki Kanda (Osaka City U.)
KAGRA collaboration

at CHPE2015, Okinawa, April 14th 2015.

Gravitational Wave as the frontier of fundamental physics

KAGRA

$$f = -G\frac{m_1 m_2}{r^2}$$

"action at a distance"
by Newton

"distortion of space-time"
by Einstein

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

$R_{\mu\nu}$: Riemann curvature tensor
R : Scalar curvature
$g_{\mu\nu}$: metric tensor
$T_{\mu\nu}$: Energy-Momentum tensor

Gravity

- is the interaction that we know from the most older.
- However, we know less about it.

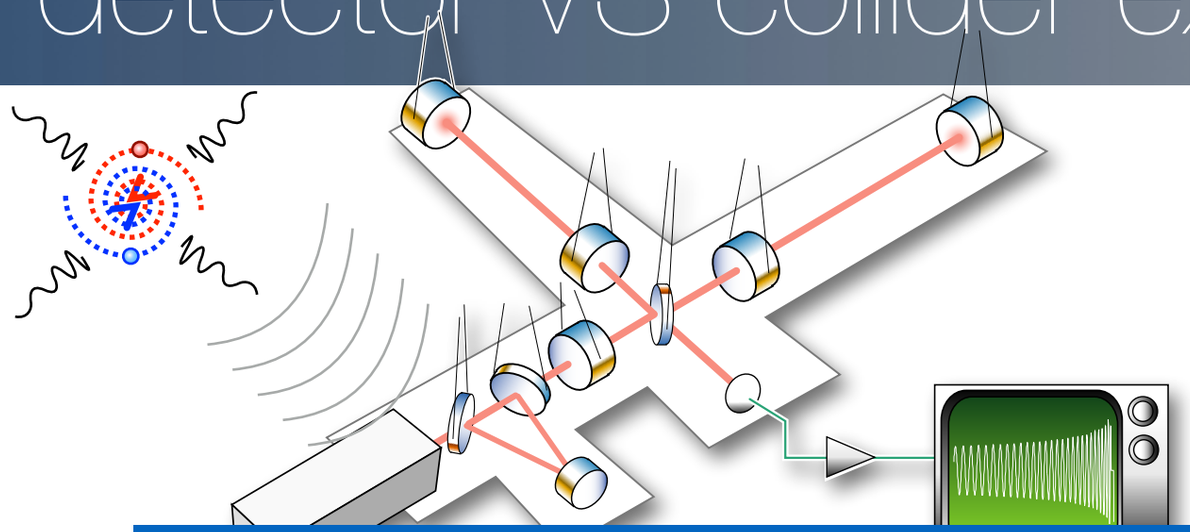
100 years ago, Einstein predicted the wave solution in his equation of General Relativity,

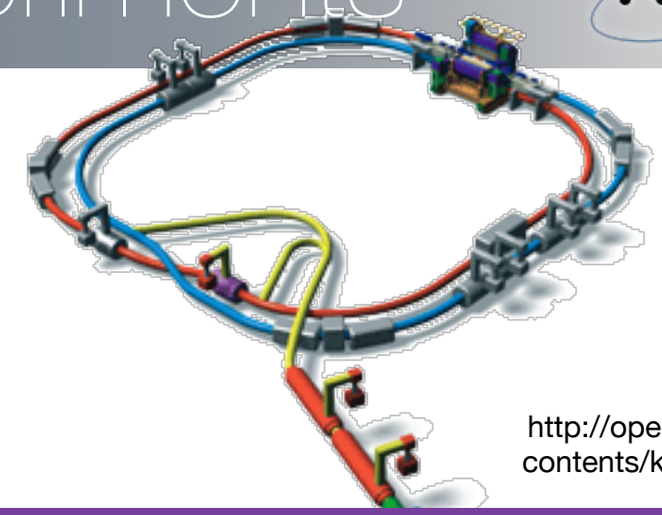
- which is called as "***gravitational wave (GW)***".
- This is important prediction of the general relativity.
- However, we humankind did not measure the gravitational wave directly.

There is 'in-direct' proof of GW. Also, many experimental tests support the general relativity.

However, we never detect GW directly yet (in early 2015), and these GR tests are in weak gravity field.

GW detector VS collider experiments





http://openhouse.kek.jp/contents/kekbtunnel.html

	Laser Interferometric GW detector	Collider
Target Sources	GW from Super-novae, Blackholes, Neutron stars, etc. ('High-energy" phenomena in the universe.)	High-energy particles
Resemblance	Long base-line apparatus	
	Controls are distributed, but have to be integrated.	
	World highest class techniques : highest energy /highest sensitivity	
	Stableness of the system is important.	
	We often choose the sites out of the way (underground, desert, etc.).	
	Large amount of data : Many channels including environmental monitors.	
Difference	Main signal is in single channel.	**Huge # of multi-channels** for event reconstruction
	Signals are embedded in the time series	Triggered events
	Various waveform (**variations in raw signal extraction**)	Each channel calibration is more simple.

Plan of Talk

KAGRA

Gravitational Wave : prediction, detection and science

How to detect

Global Network of GW Detectors

- and Status of KAGRA

Computing in GW detectors (in KAGRA)

- Digital control of the laster interferometer
- Data transfer and storage
- Data Analysis (GW Event Search)

Follow-up / Coincidence observations

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Follow-up / Coincidence observations

- Full data have to be recorded without trigger or front-end level selection
- **Dead time less!**
- Data **processing must be faster than real data .**

What is Gravitational Wave ?

KAGRA

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)

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

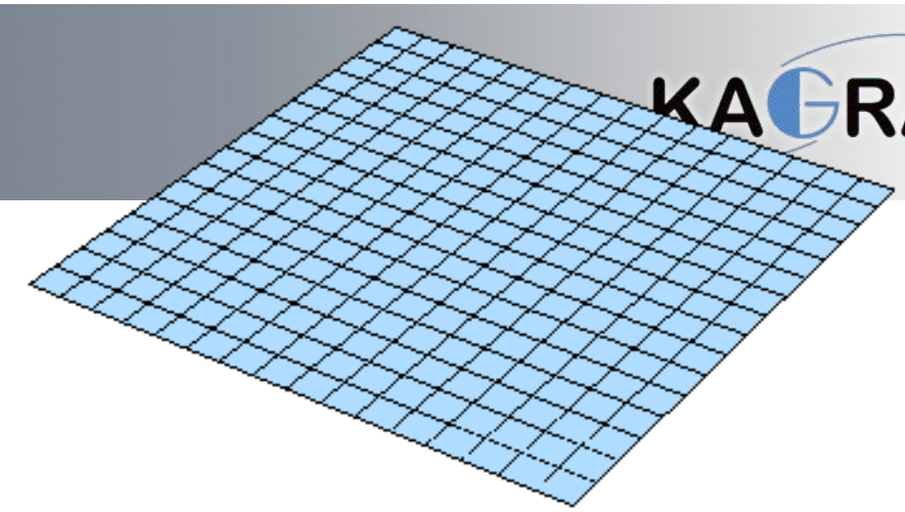
"curved (distorted)" space-time

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

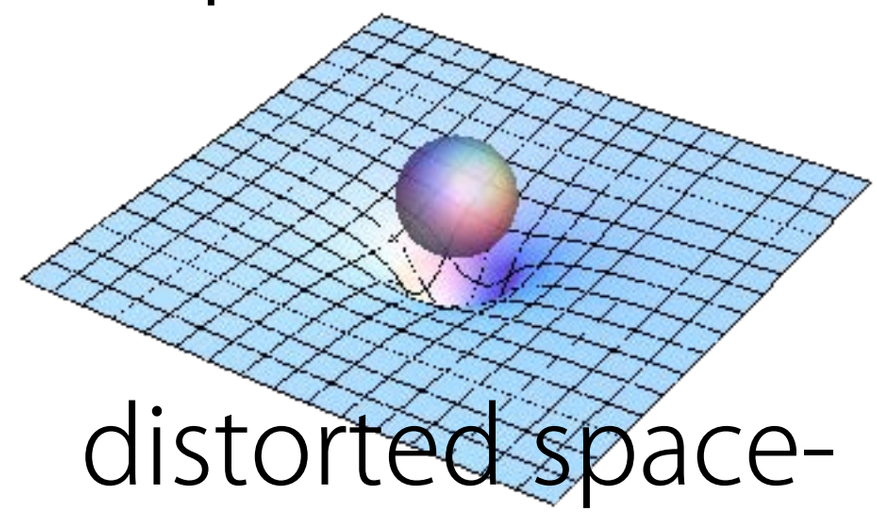
small perturbation 'h' --> Waves

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

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

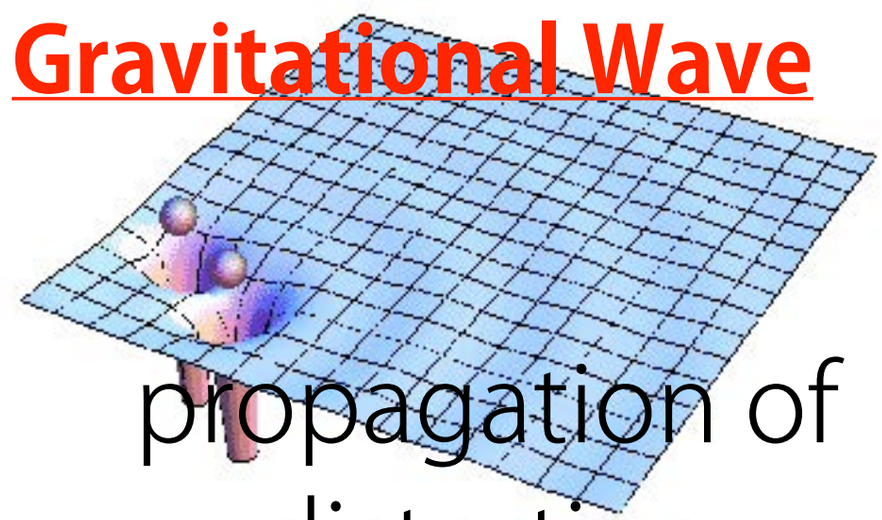


flat space-time



distorted space-time = gravity

Gravitational Wave



propagation of distortion

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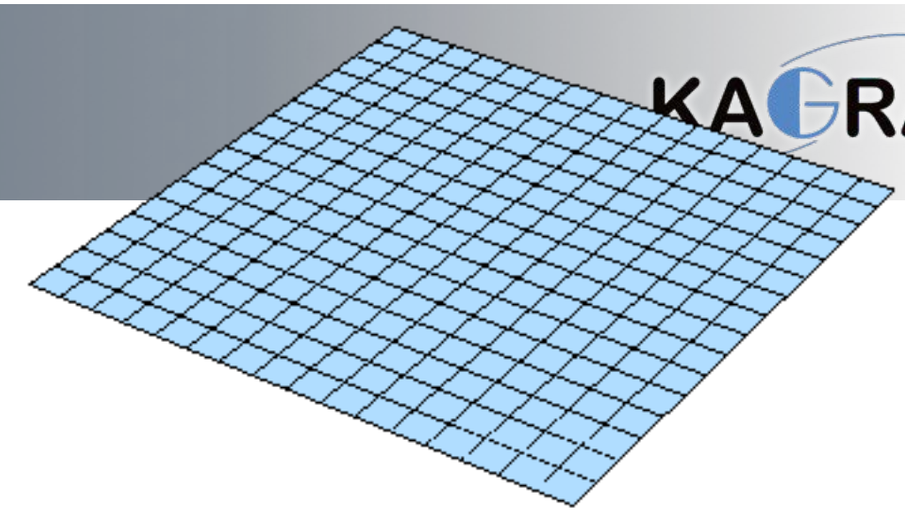

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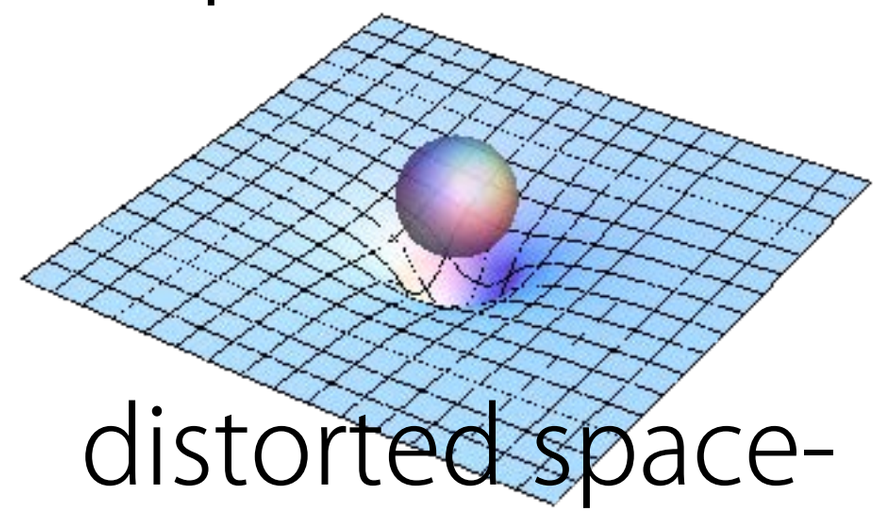

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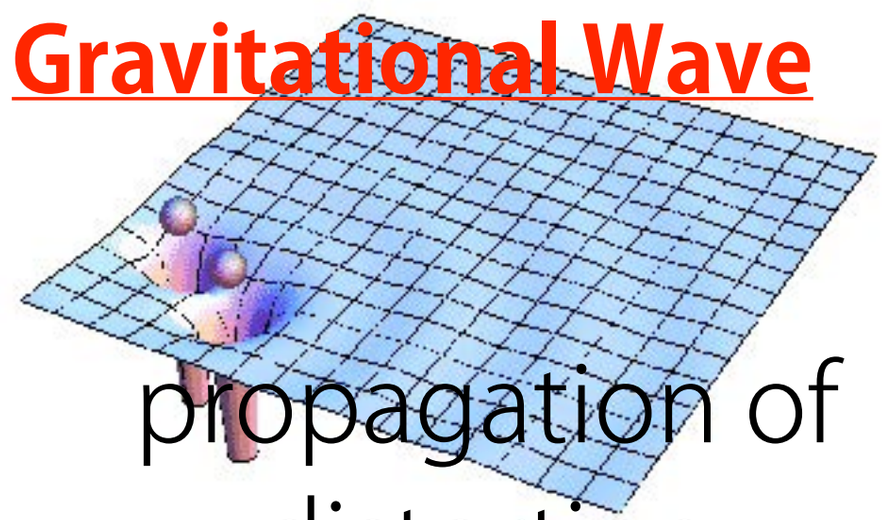
Gravitational Wave

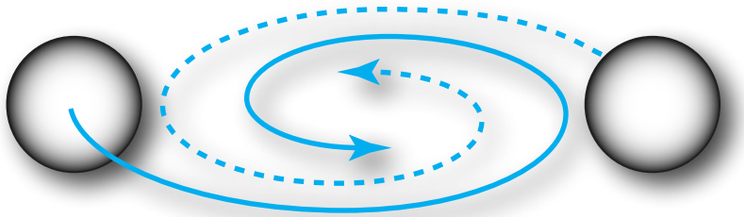


propagation of distortion

GW Sources

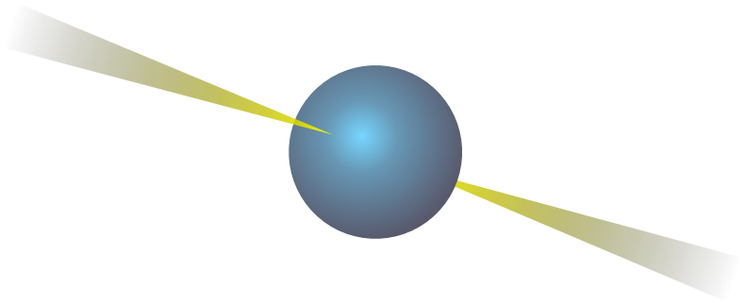
Occasional events:

- **C**ompact **B**inary **C**oalescence (NS-NS, NS-BH, BH-BH)
  NS: neutron star , BH: black-hole
- Supernovae
- BH ringdown
- Pulsar glitch



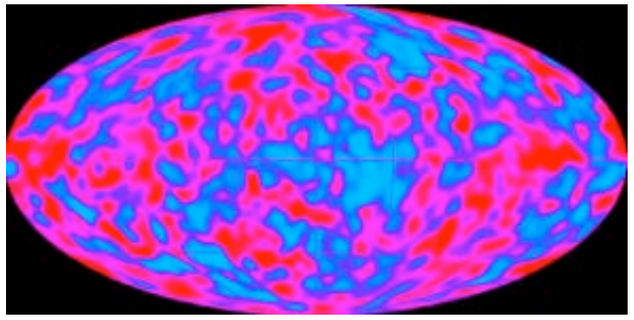
Continuous waves:

- Pulsar rotation
- Binaries



Stochastic Background

- Early universe (i.e. Inflation)
- Cosmic string
- Astronomical origin
  (e.g. many NS in galaxy cluster)



(& Unknown sources...)

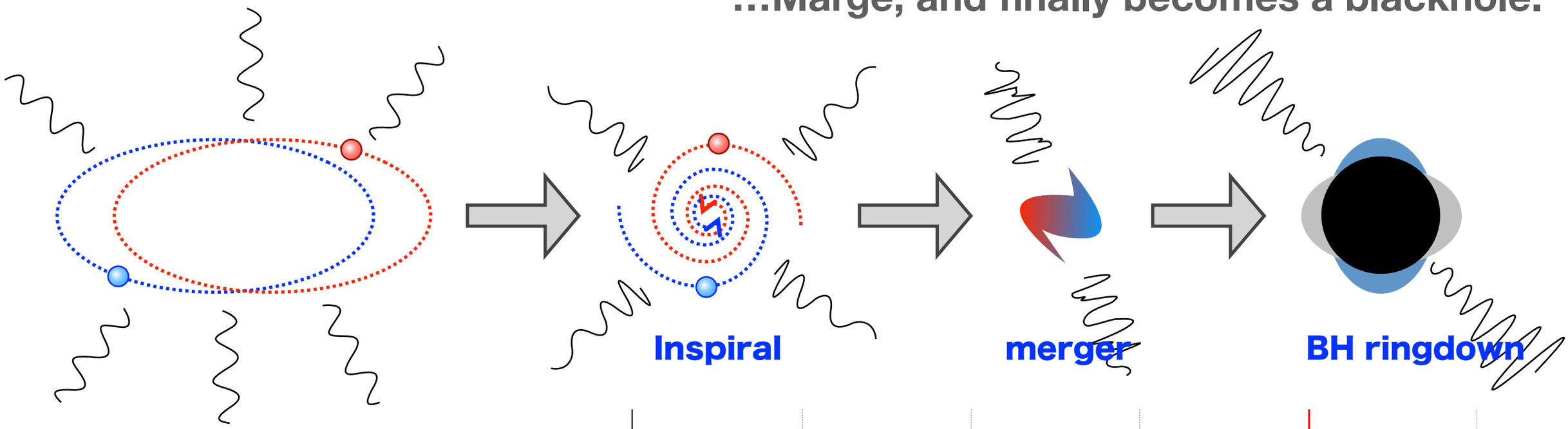
typical target : $h \lesssim 10^{-22} - 10^{-24}$

h is strain, non-dimensional. $h = \frac{\delta \ell}{\ell}$

Typical Source : Compact Binary Coalescence

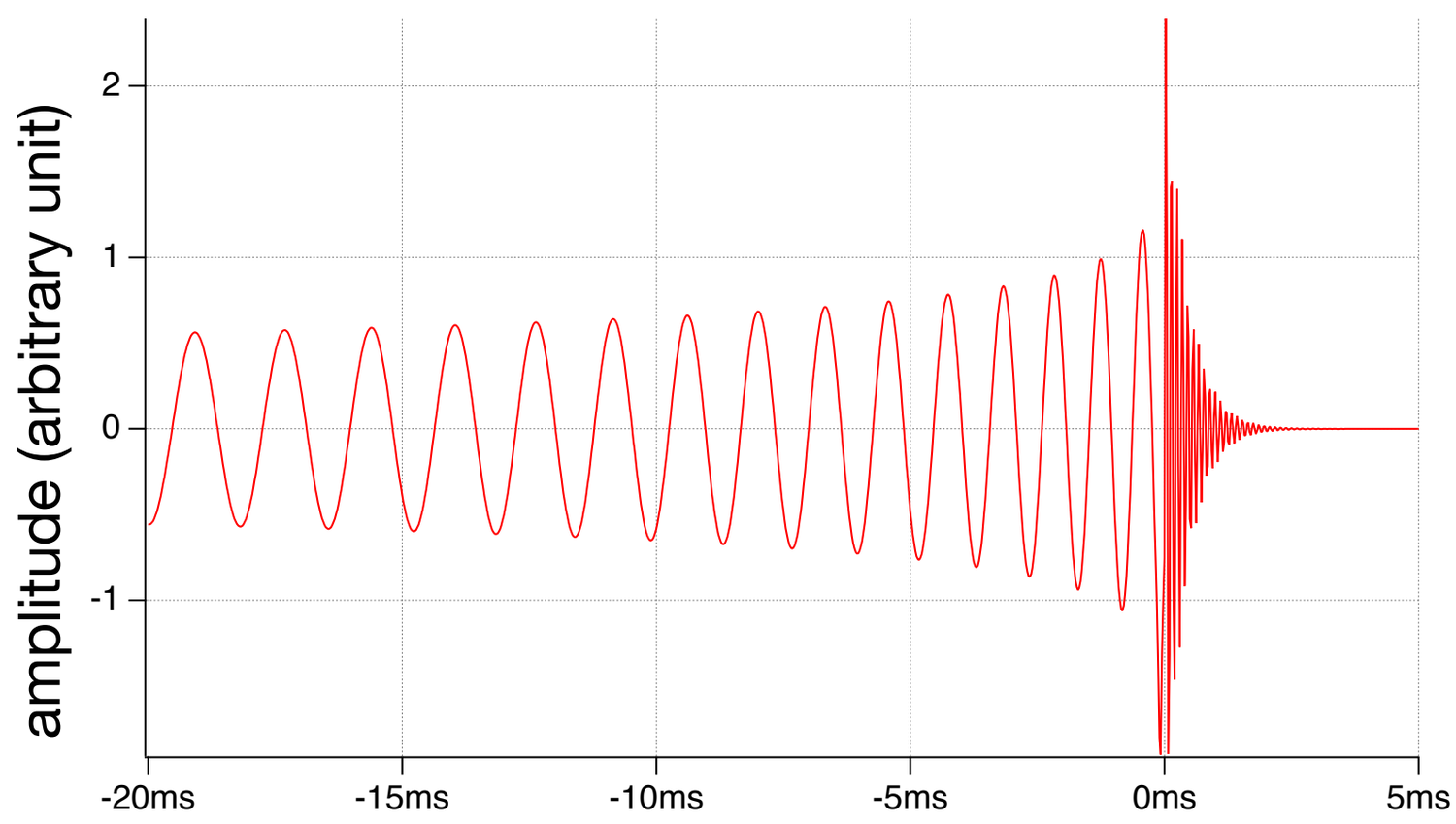
Binary radiates GW, shrink the orbit, going to coalescence…

…Marge, and finally becomes a blackhole.



time series

h **~10^{-24}** for NS-NS at 200Mpc away!



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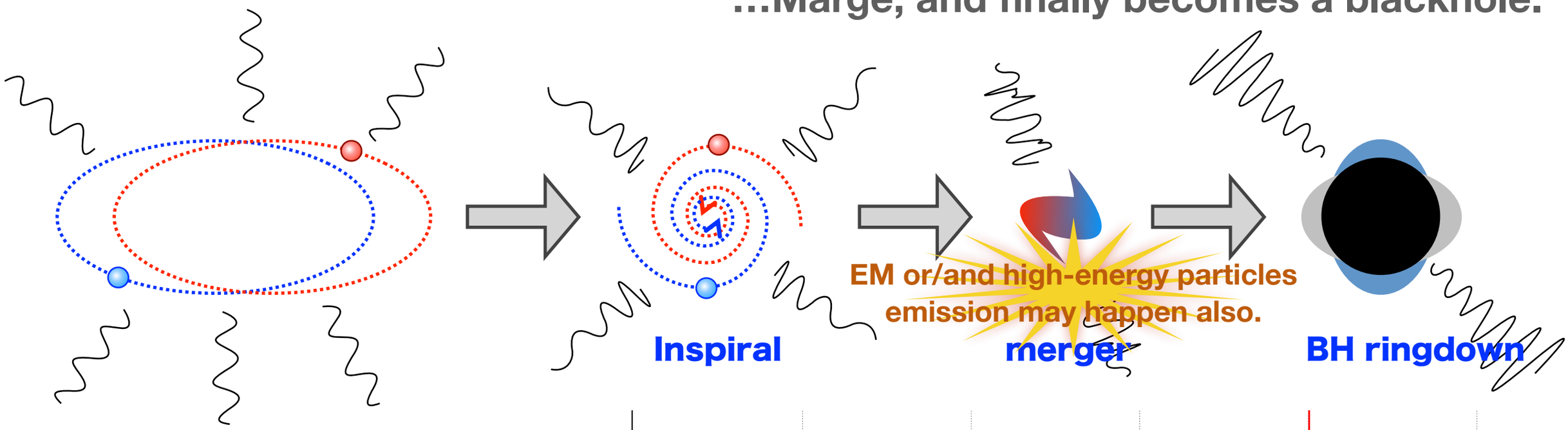

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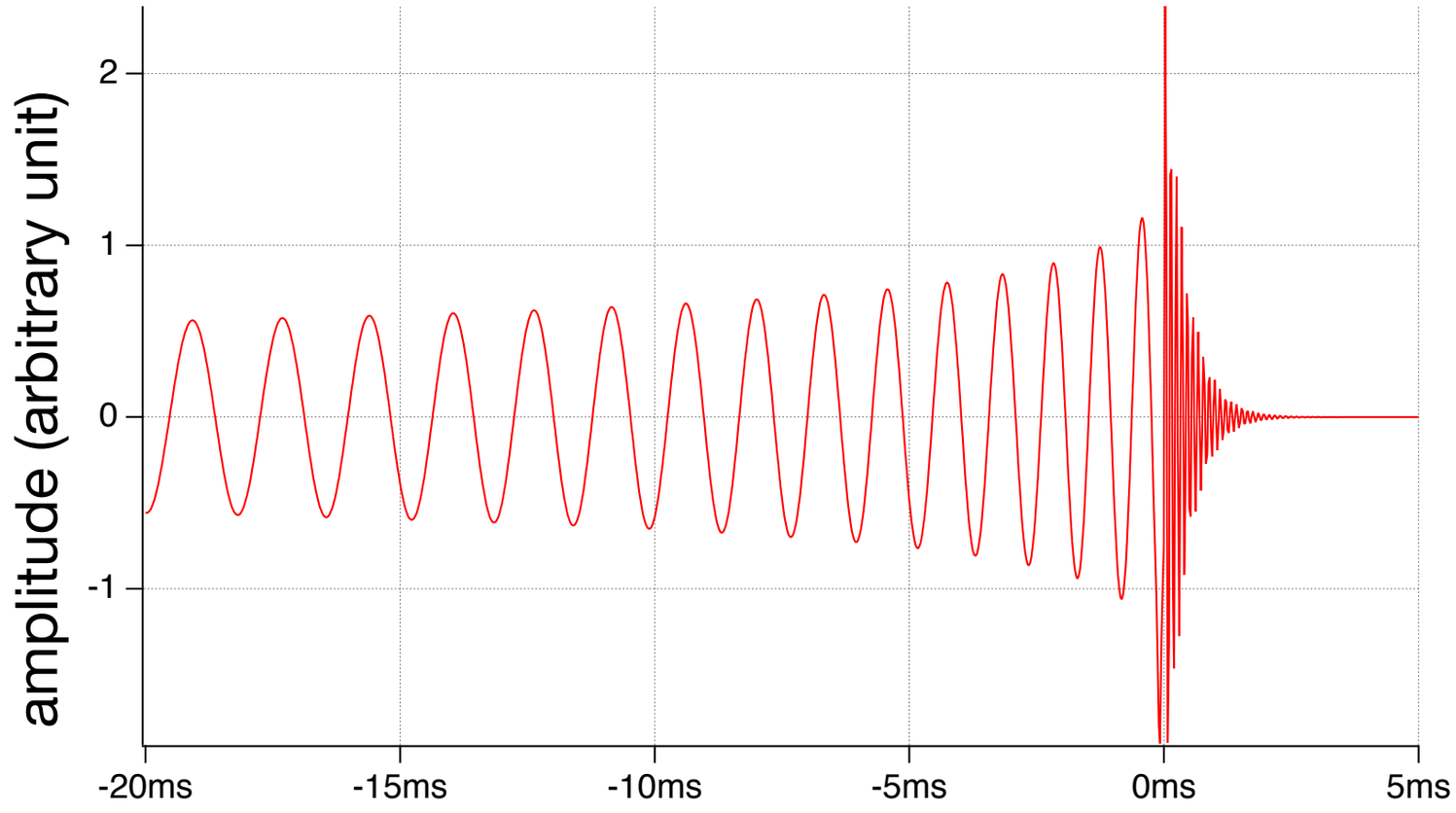
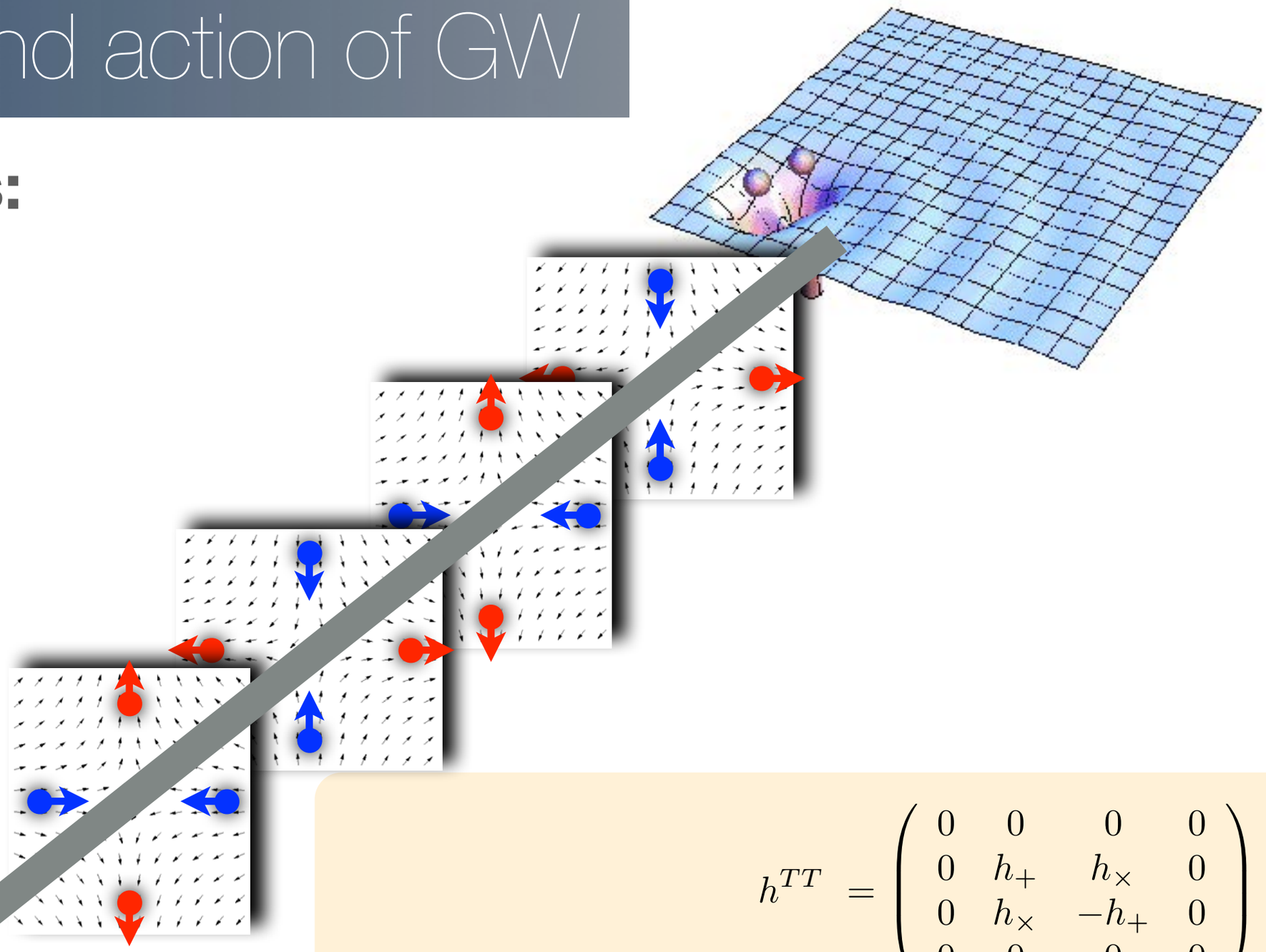


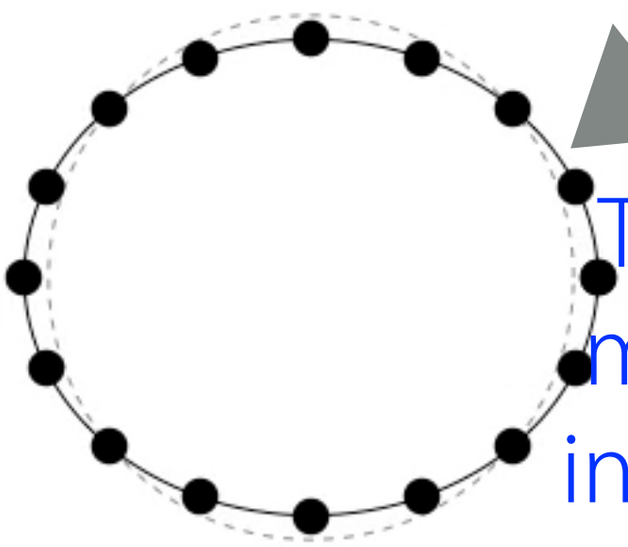
Propagation and action of GW

Characteristics:

- light speed
- transverse
- quadrupole
- (tidal force)



$$h_+ \cos(\vec{k} \cdot \vec{x} - 2\pi f_{GW} t)$$



Tidal force on masses will be induced by GW incident.

$$h^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$h_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \hat{h}_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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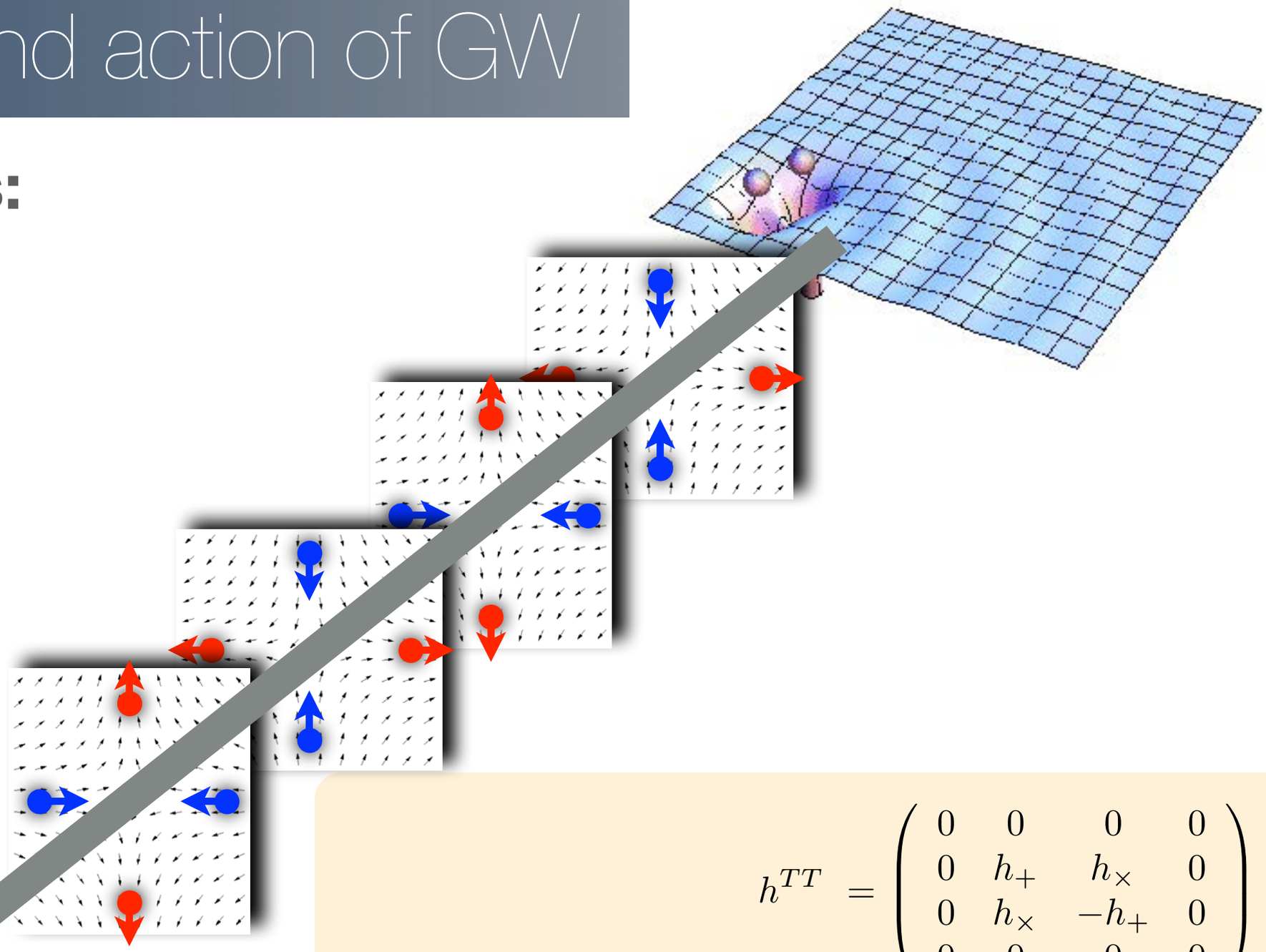

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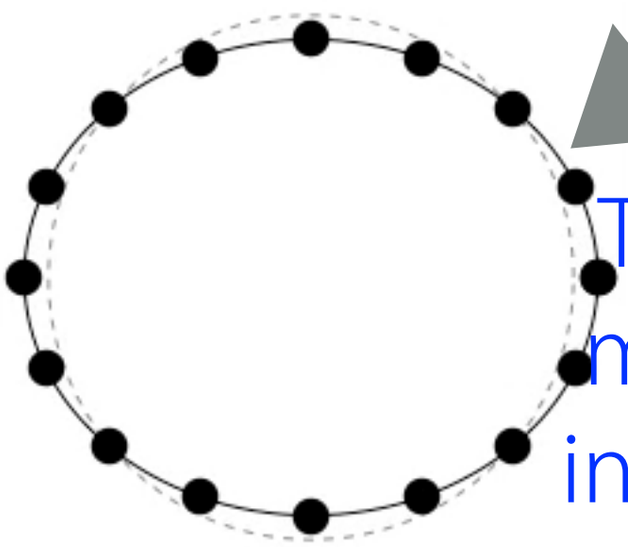

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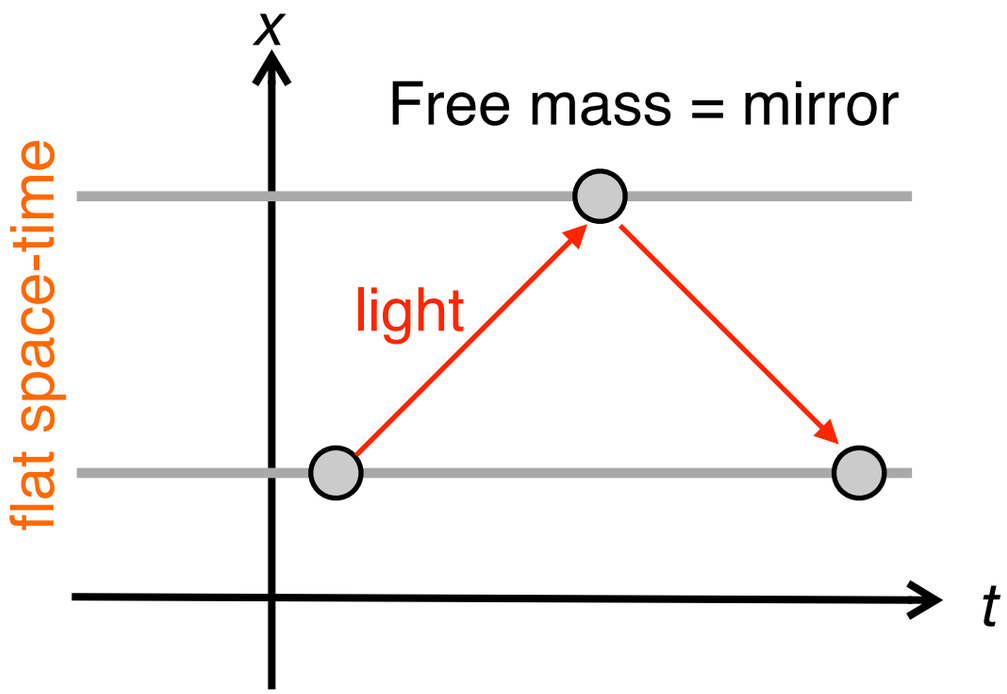
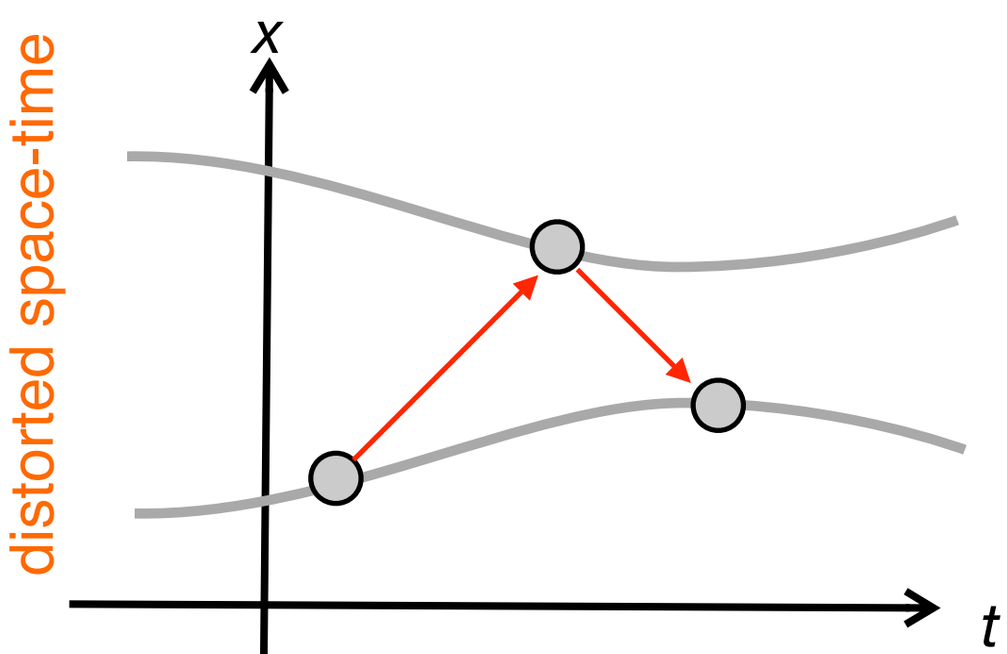
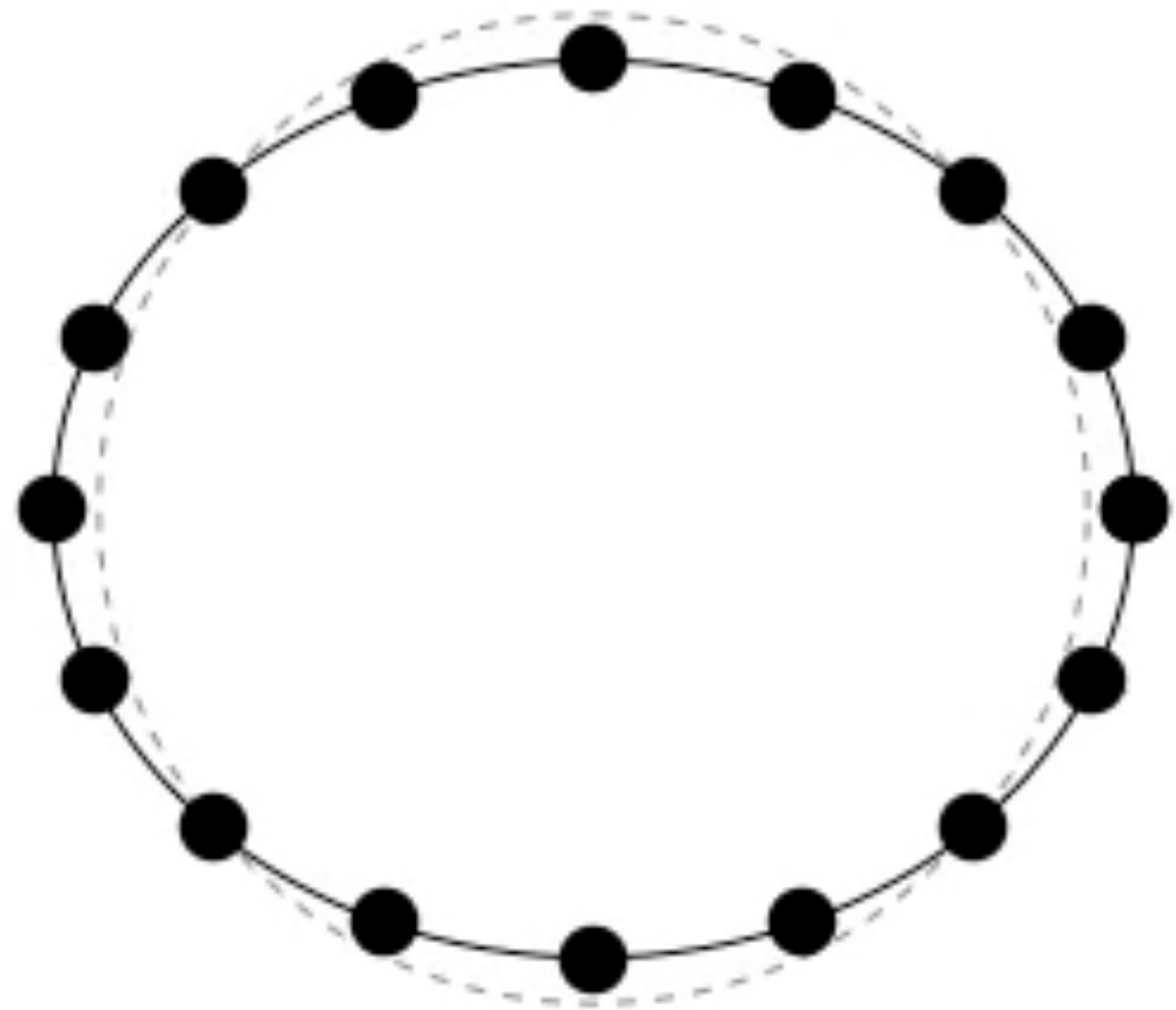
Free Test Masses & Laser interferometer







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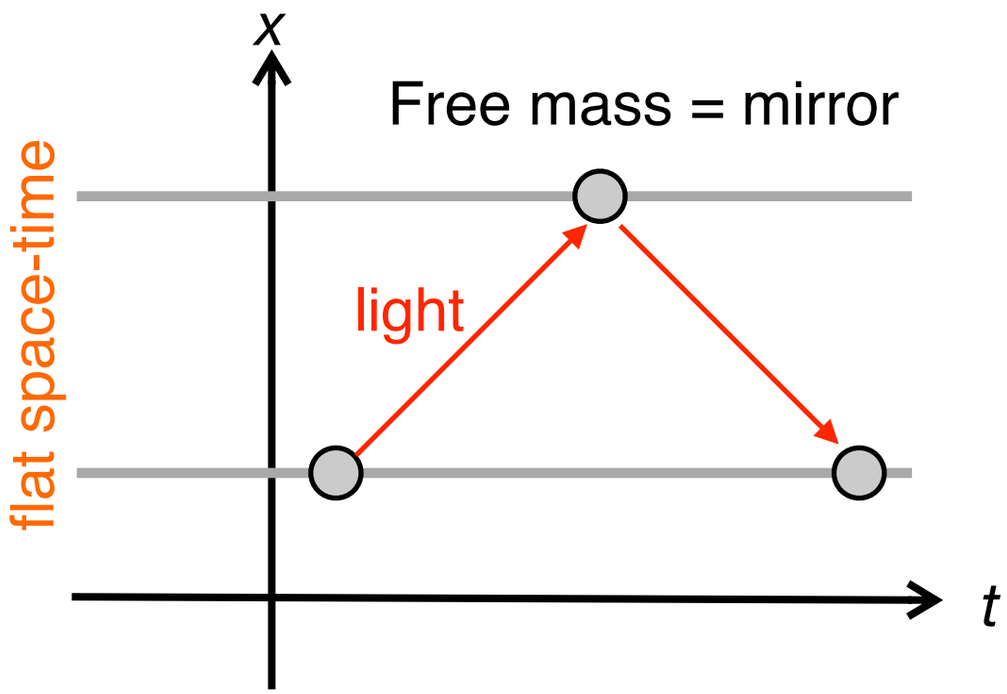

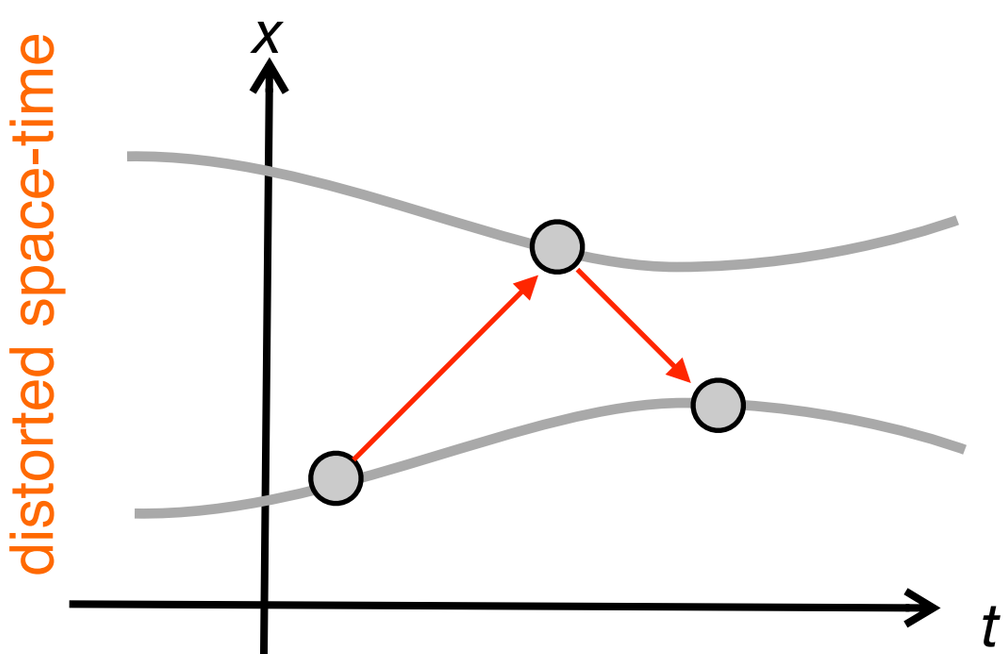

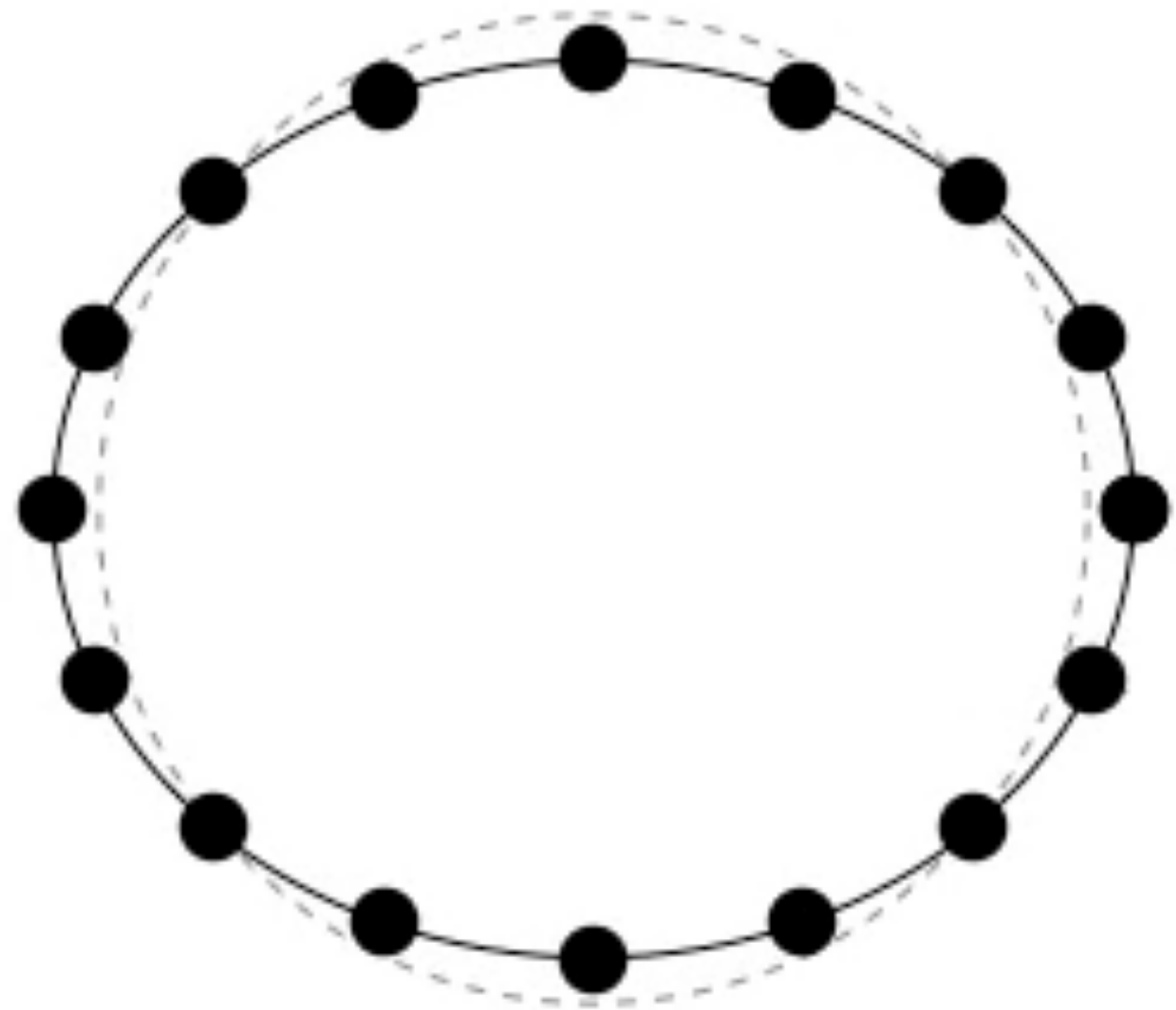

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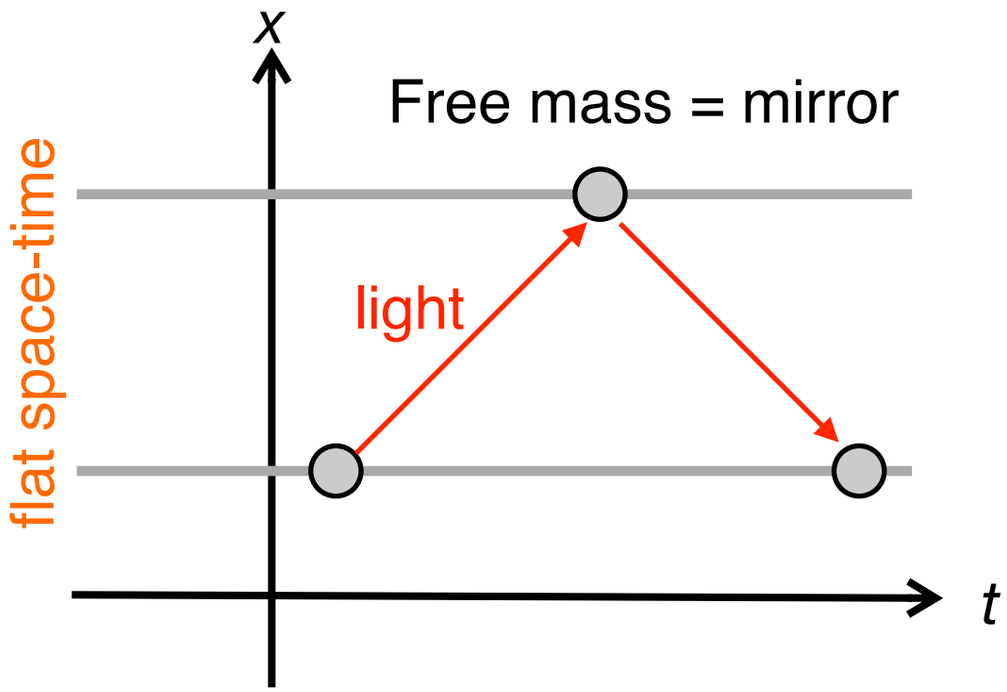
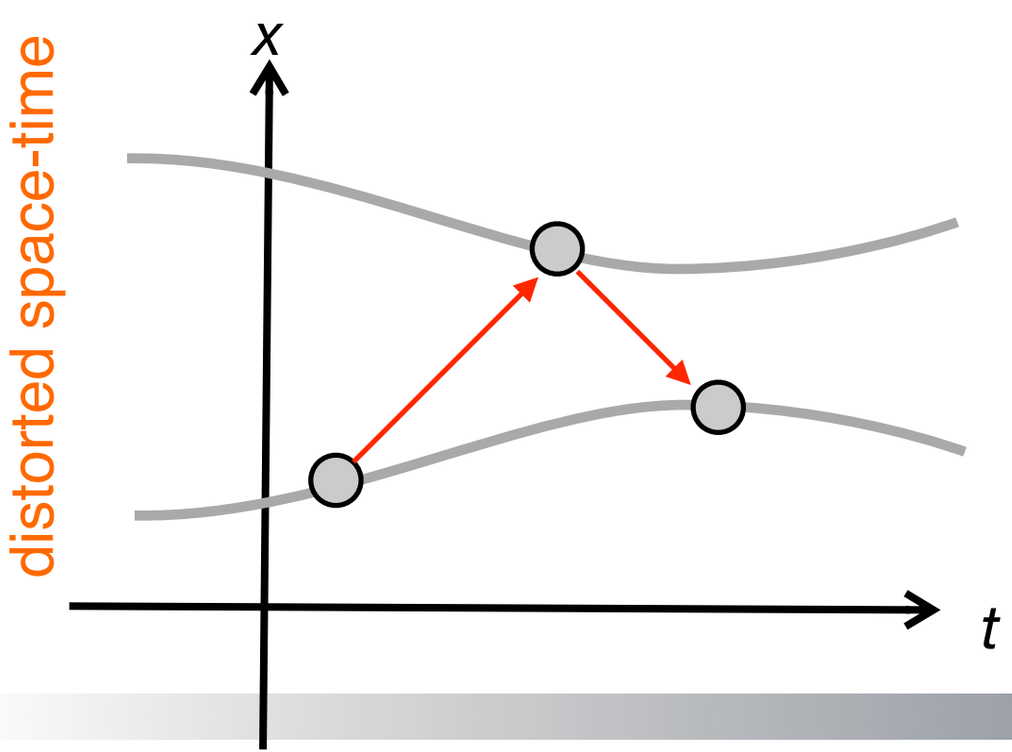
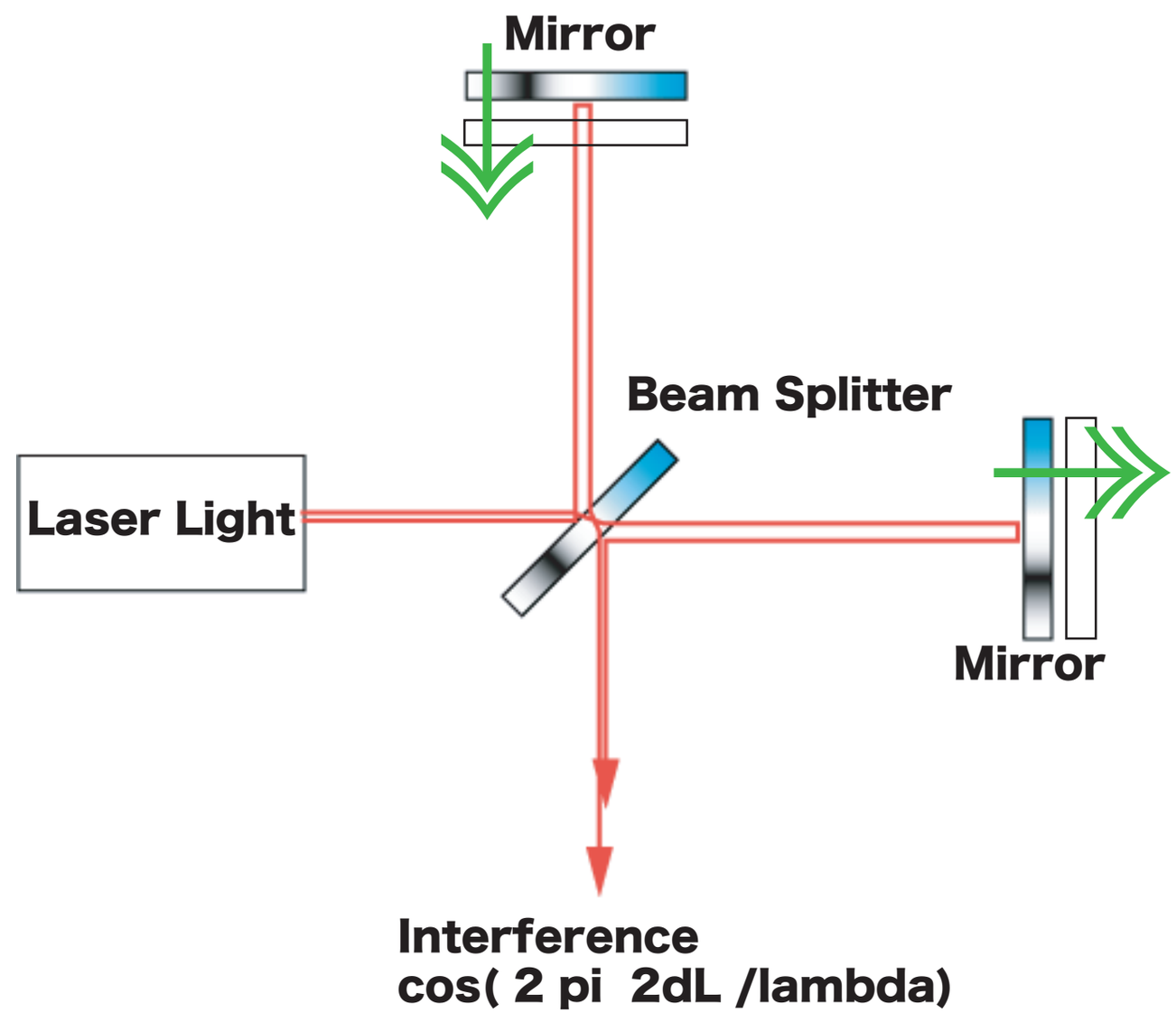






Michelson Interferometer

Schematic Figure

KAGRA

Free mass

- --> suspended mirror

To integrate strain 'h'

- --> long baseline arms.

Limited size

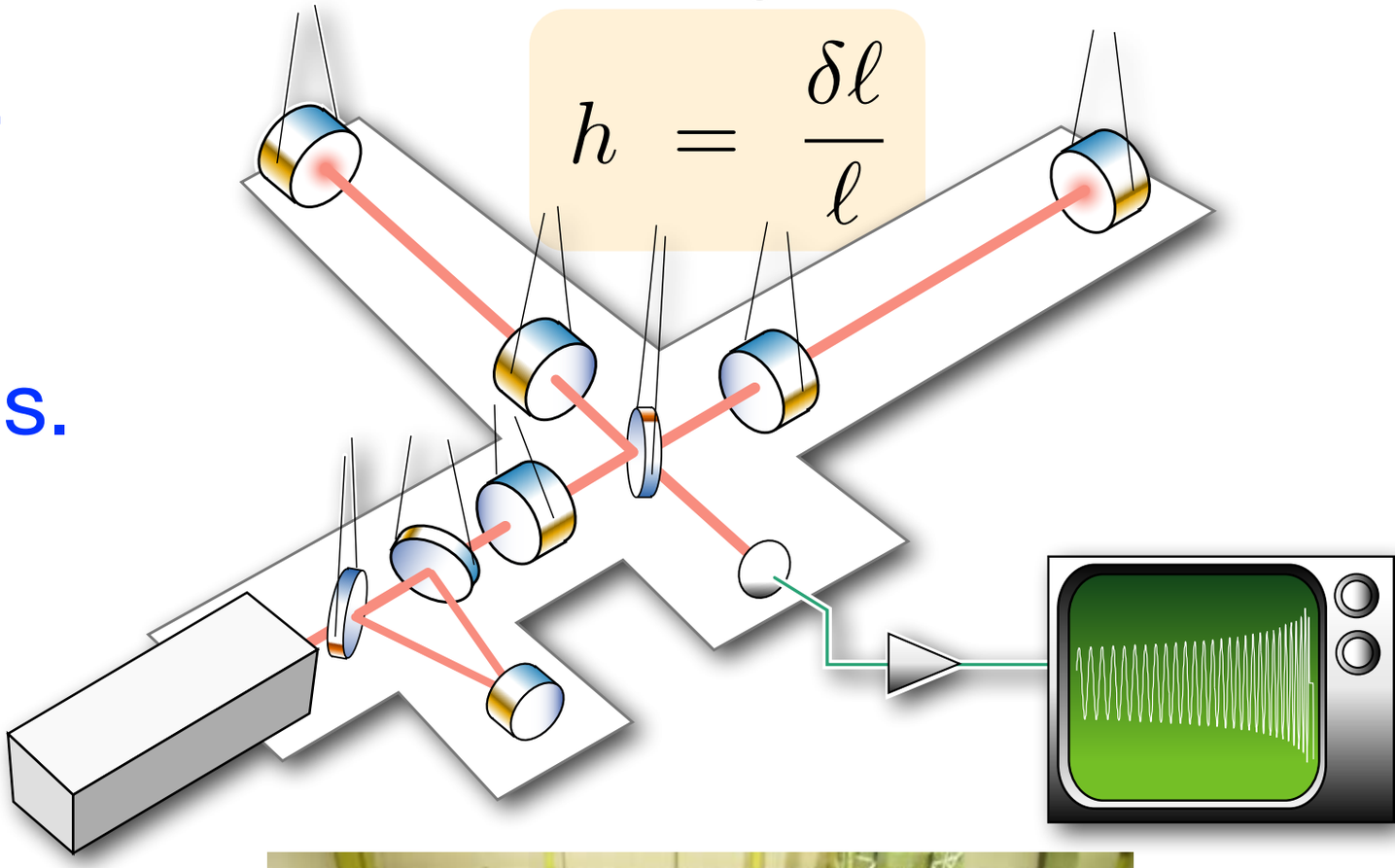
- --> Folding arms / Storage cavity

Against noises -->

- high power laser
- Cooling
- etc..

merit on long base-line

$$h = \frac{\delta \ell}{\ell}$$



CBC simulated signal

observed signal = instrumental noise + GW

The simulation is TAMA detectors real data + theoretical waveform embedded.
This is the event near near by our earth as like a few pc…

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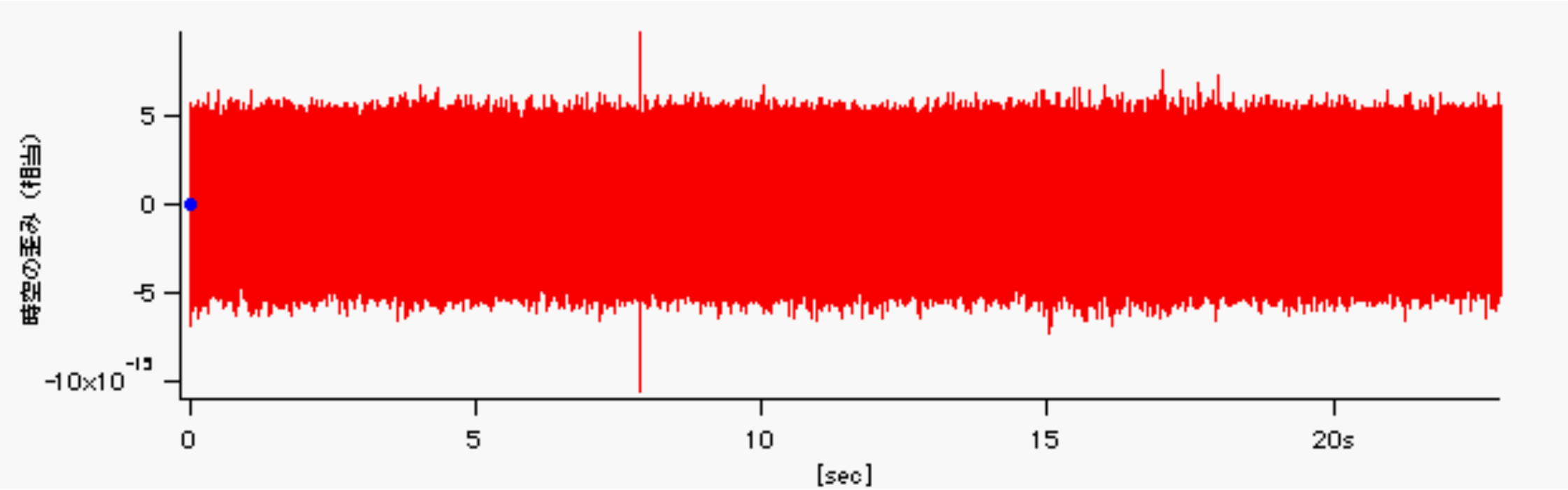

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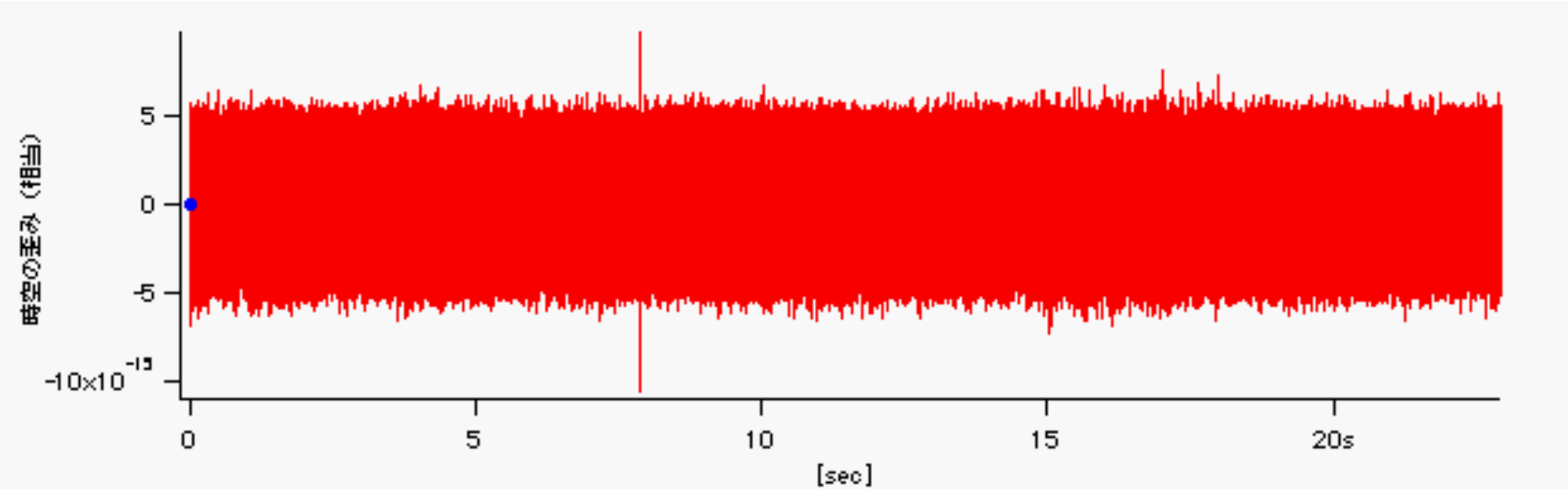

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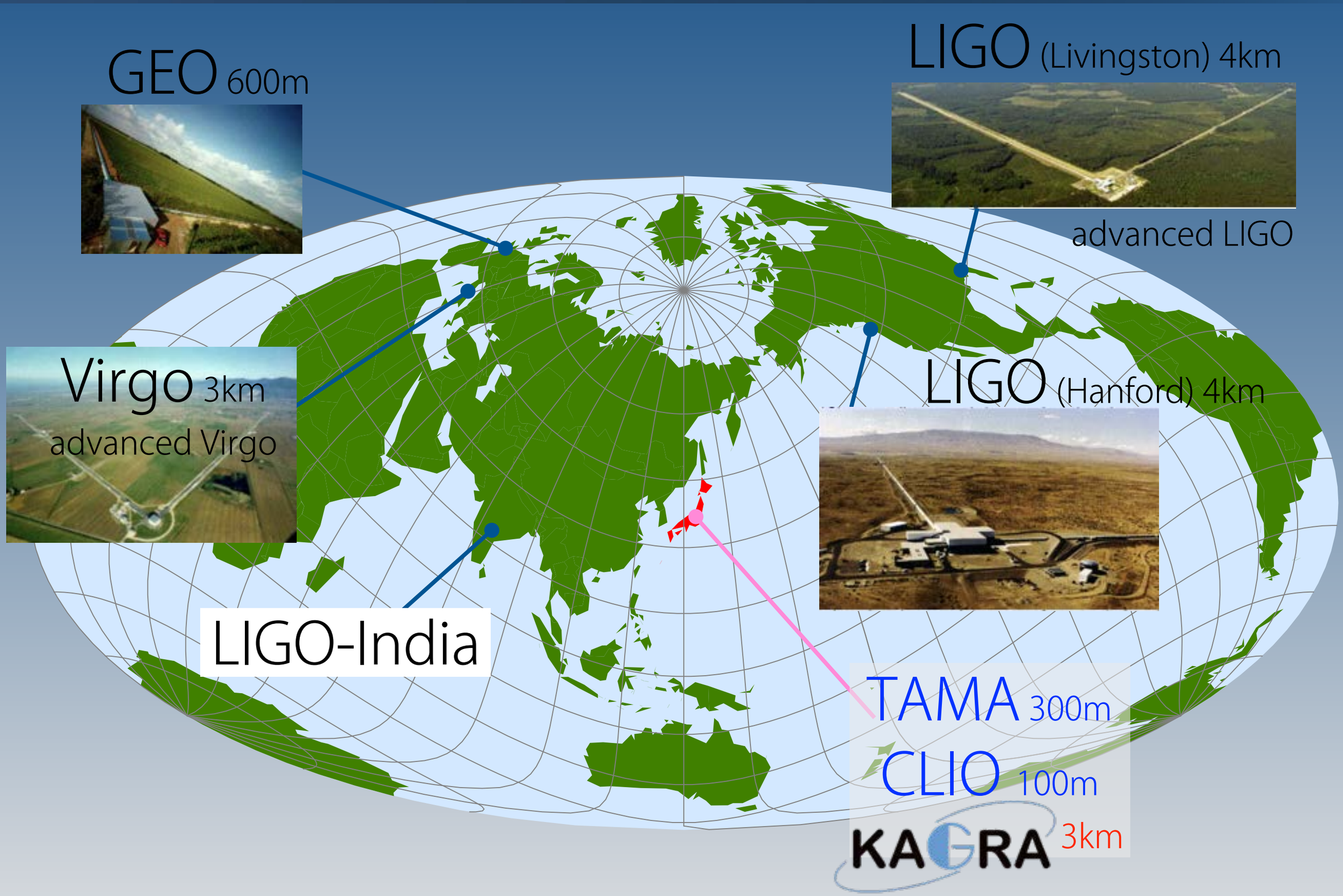
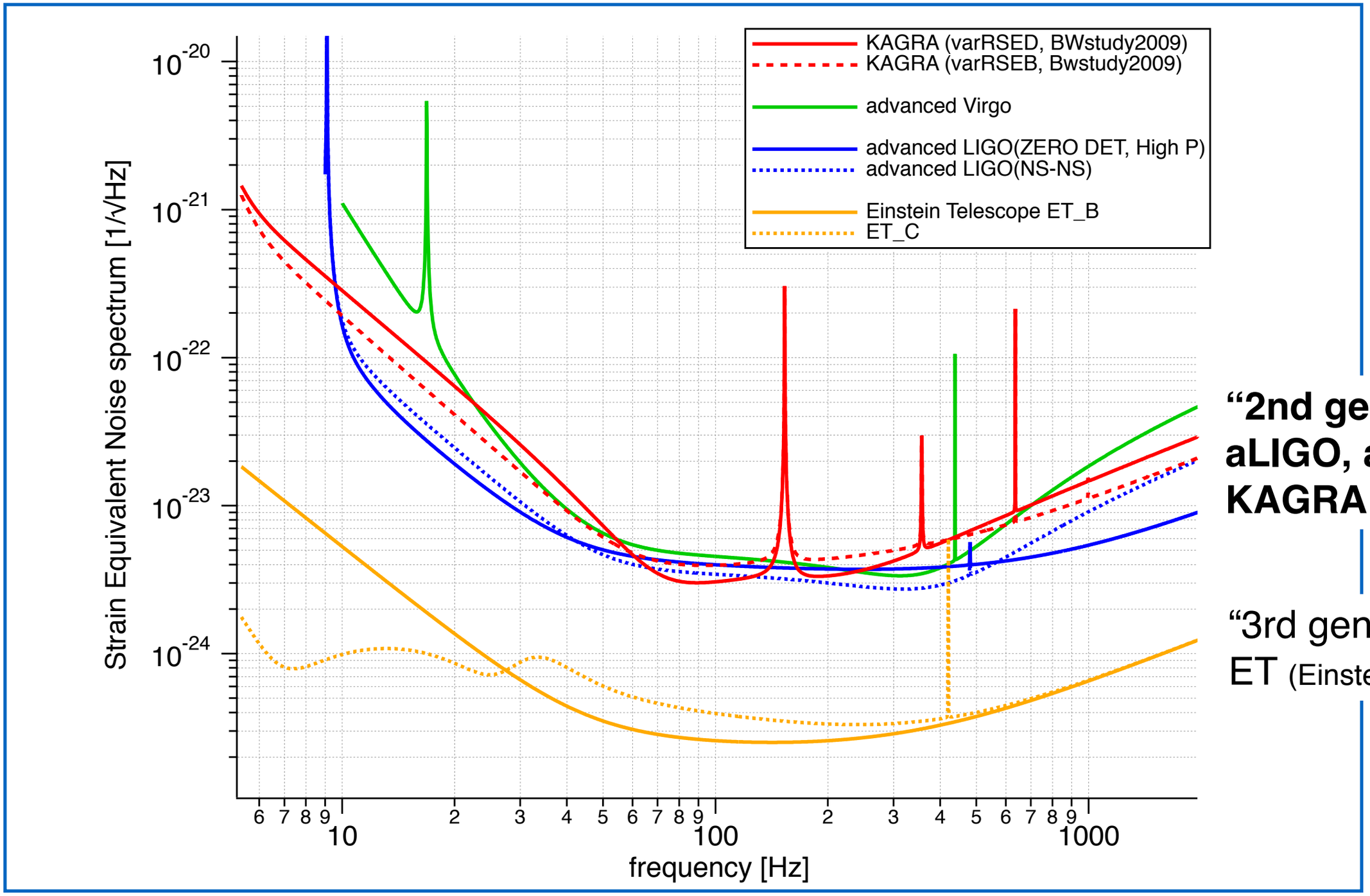
World Wide Projects



Sensitivity target of GW detectors



"2nd generation"
aLIGO, aVirgo, KAGRA

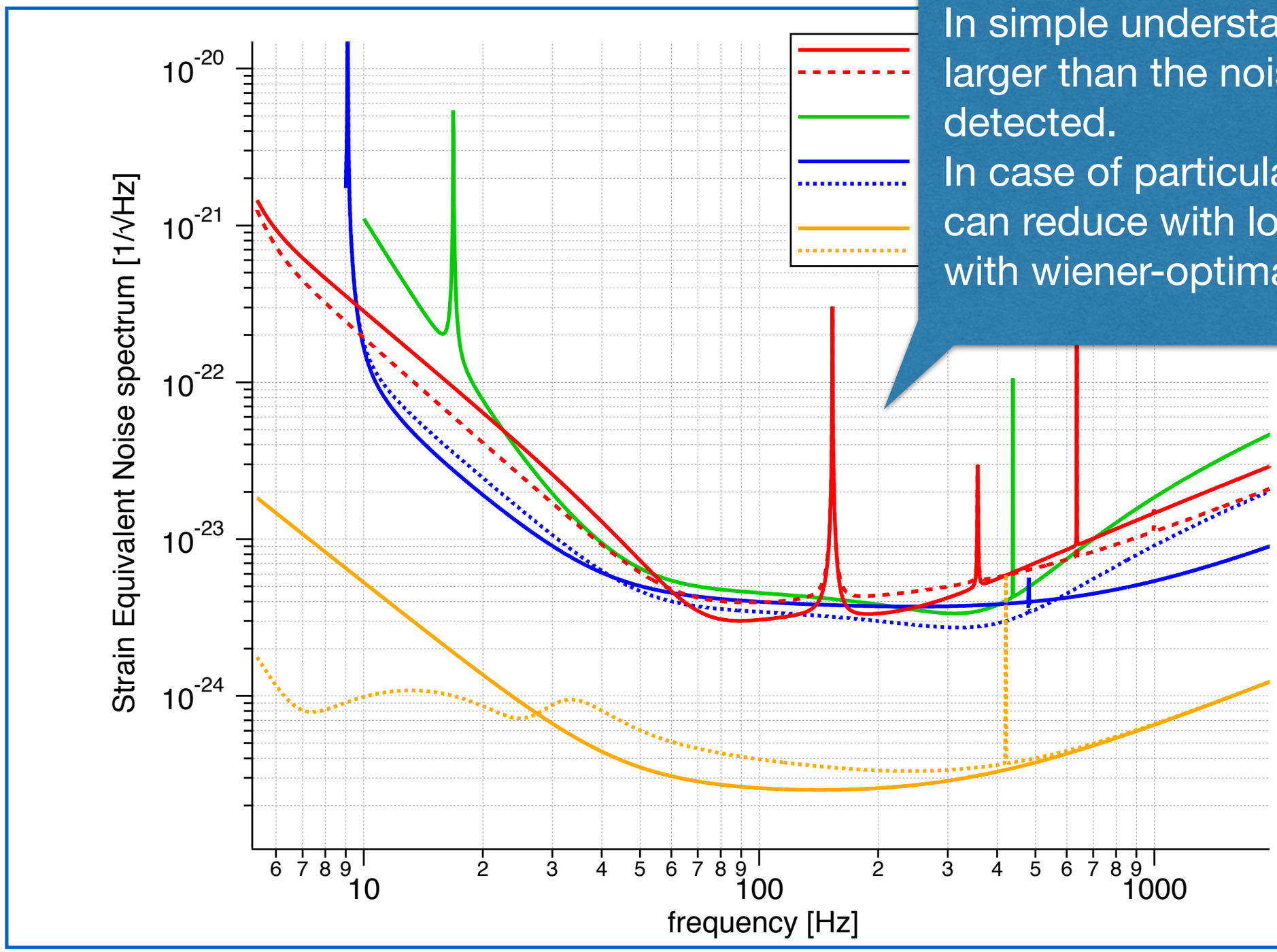
"3rd generation"
ET (Einstein Telescope)

Advanced LIGO will start in 2015, and will continuously upgrade its sensitivity.
Virgo has similar schedule.
bKAGRA operation (cryogenic) will be start in late 2017 or early 2018.

Sensitivity target of GW det

Note: Sensitivity = Noise level

In simple understanding, GW which larger than the noise level can be detected.
In case of particular waveform, noise can reduce with long time integration, with wiener-optimal filter etc.



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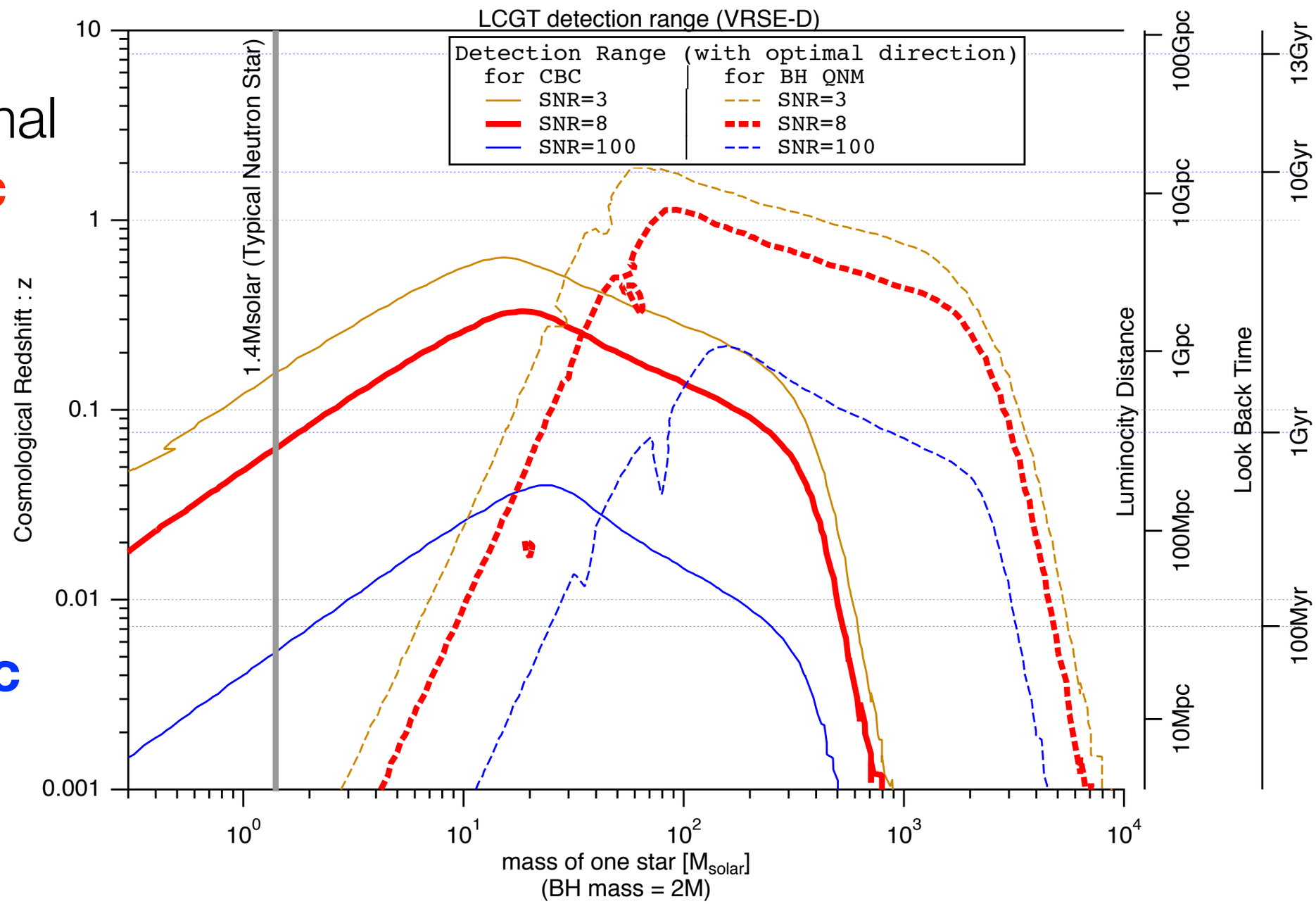
Detection Range

KAGRA's **NS-NS** detection range is **280 Mpc** for optimal direction, **173Mpc for all sky average**

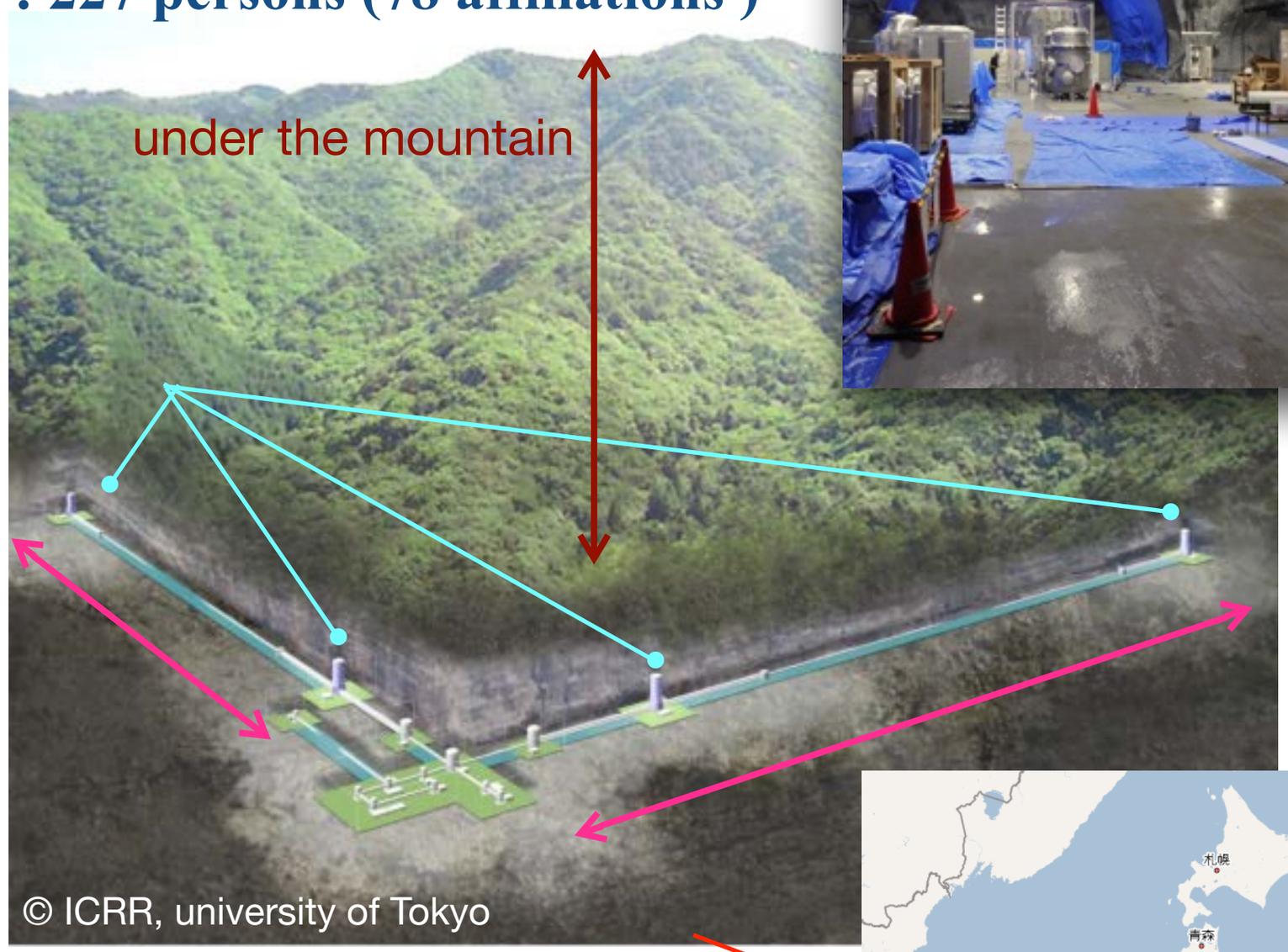
-> 10 event/yr

For **supernovae**, the range may be **typically ~100kpc ~1Mpc** or as like, depending on the SNe model.



KAGRA

KAGRA collaboration : 227 persons (78 affiliations)



Underground

- in Kamioka, Japan
- Silent & Stable environment

Cryogenic Mirror

- 20K
- sapphire substrate

3km baseline

Plan

- 2010 : construction started
- **2015 : first run in normal temperature at December**
- 2017- : observation with cryogenic mirror

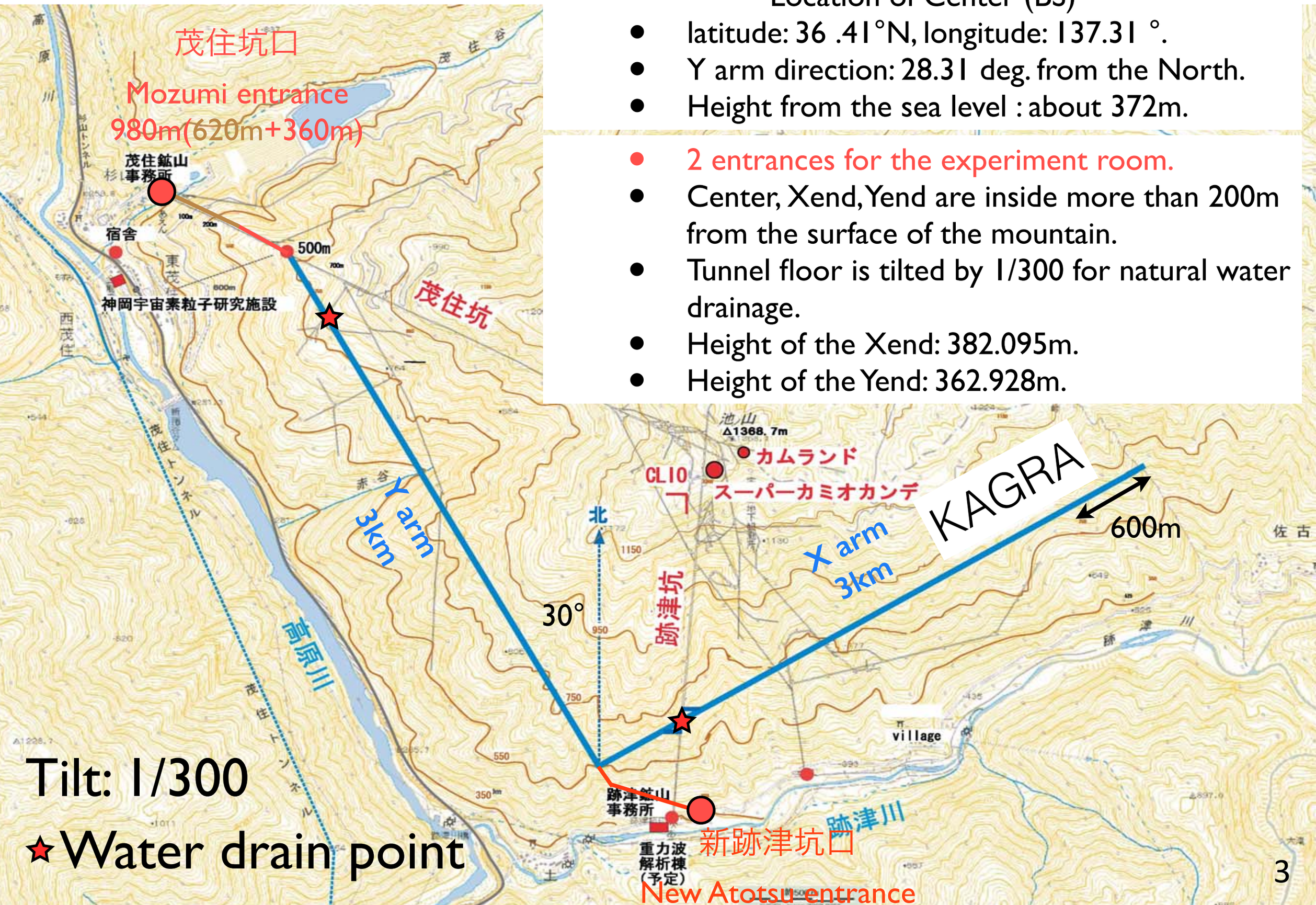
Tunnel excavation completed at March 2014

(4th July, 2014)

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

Cryostat

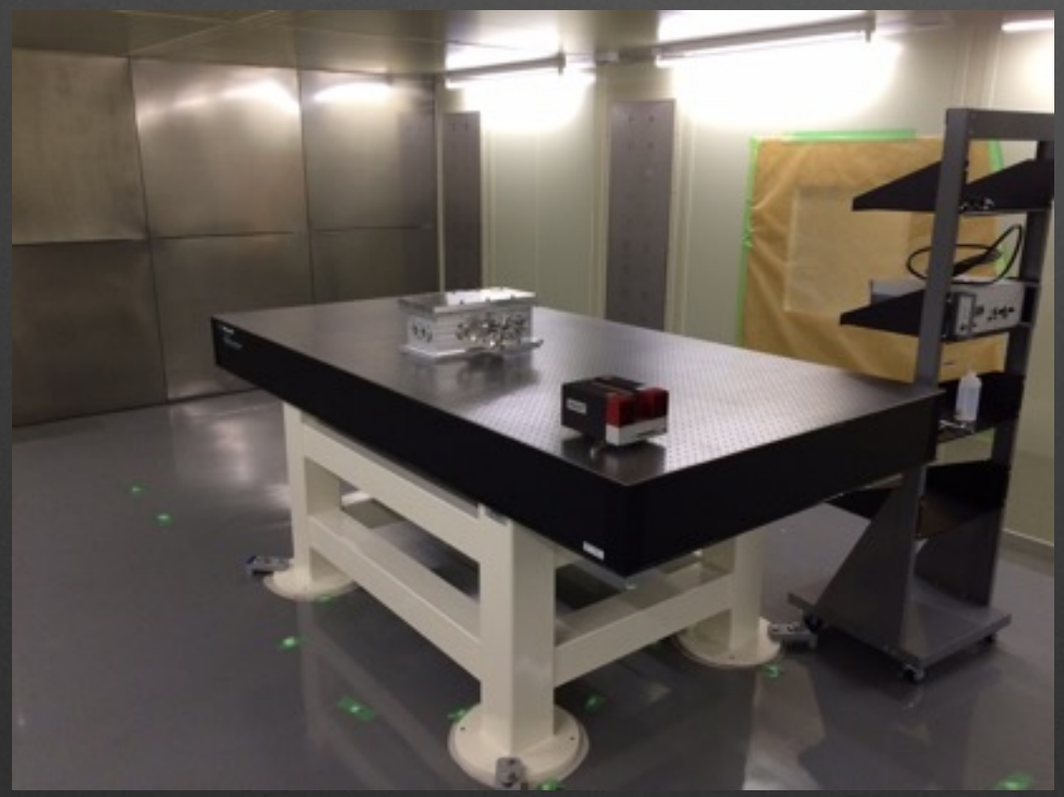
MC chambers and cryostats installation

Transportation of cryostat in Y arm

Installation of MC chambers
(center area)

viewgraph by T.Uchiyama

construction of the clean booths



X-end

Hardware of iKAGRA data system

@Kamioka surface bilding

- 200TiB lustre storage system (FEFS), separate MDT and OSS
- 1 data server
- 4 calculation nodes (8cores x 2CPUs) = 64cores
- 2 job management servers

VPN switch

@Kashiwa (ICRR building 6th floor

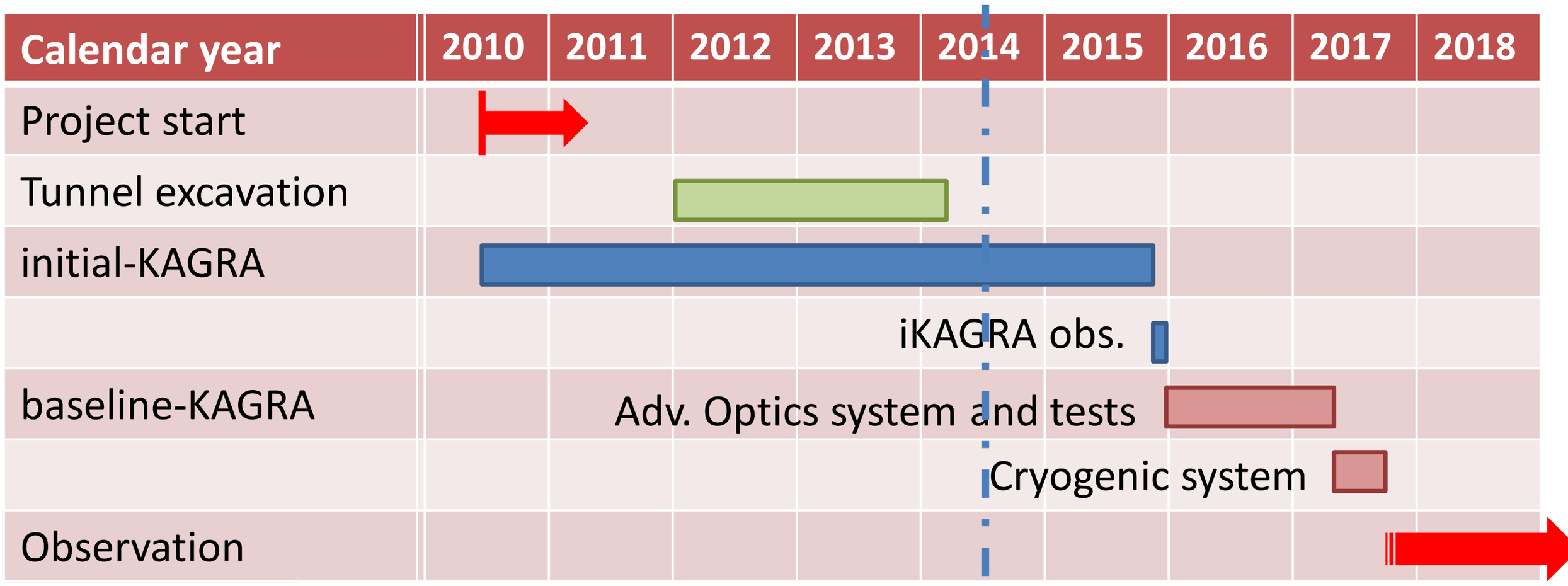
- 100 TiB lustre storage system (FEFS), single storage for MDT +OSS
- 2 login server
- VPN switch

placed at computer area beside the control room, 1st floor of analysis build.

200 TiB 'lustre' file system

Schedule to the observation era

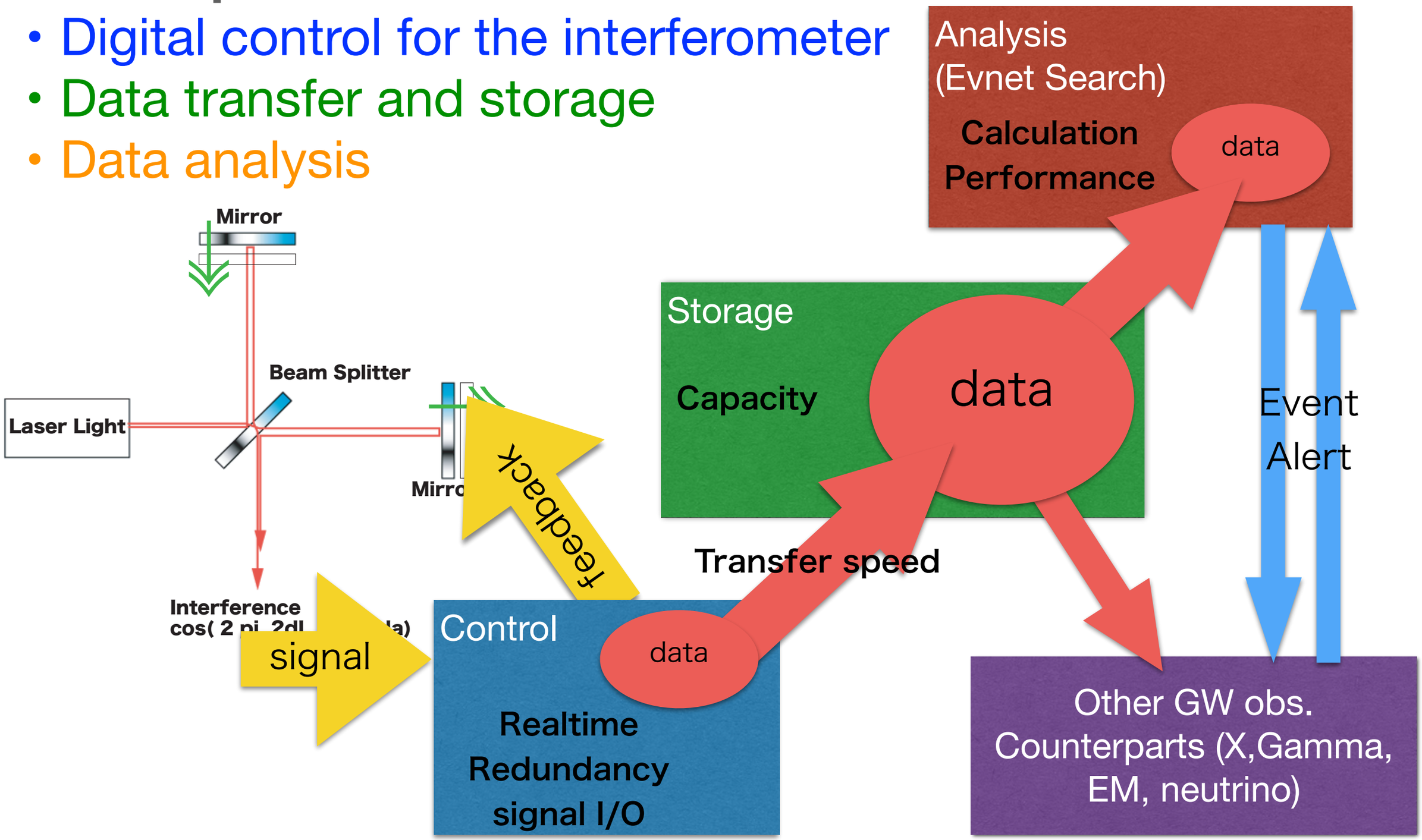
drawn by T.Kajita



Computing in GW detector

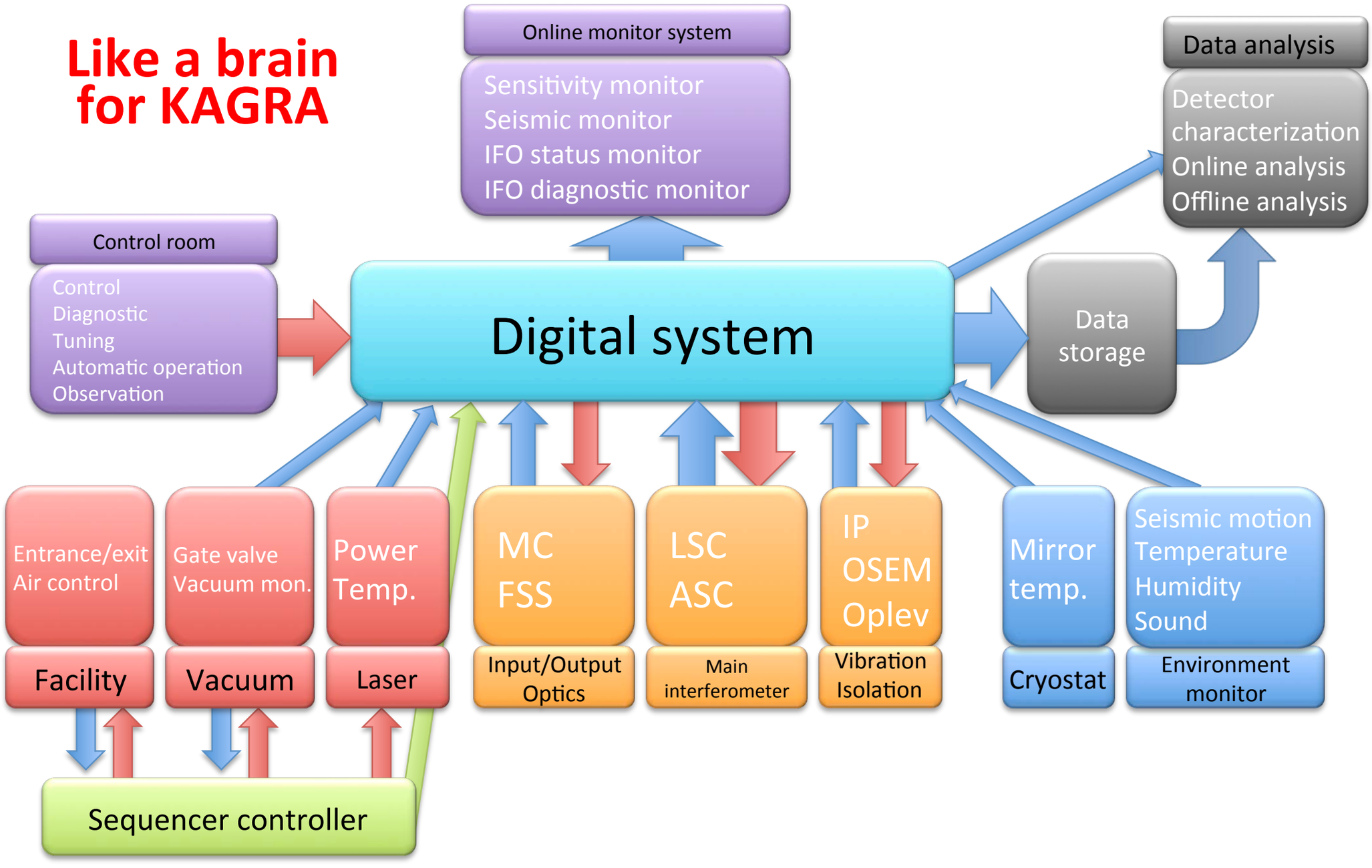
Various layers computings are necessary for KAGRA operation.

- Digital control for the interferometer
- Data transfer and storage
- Data analysis



Important role as interface to subsystems

Like a brain for KAGRA

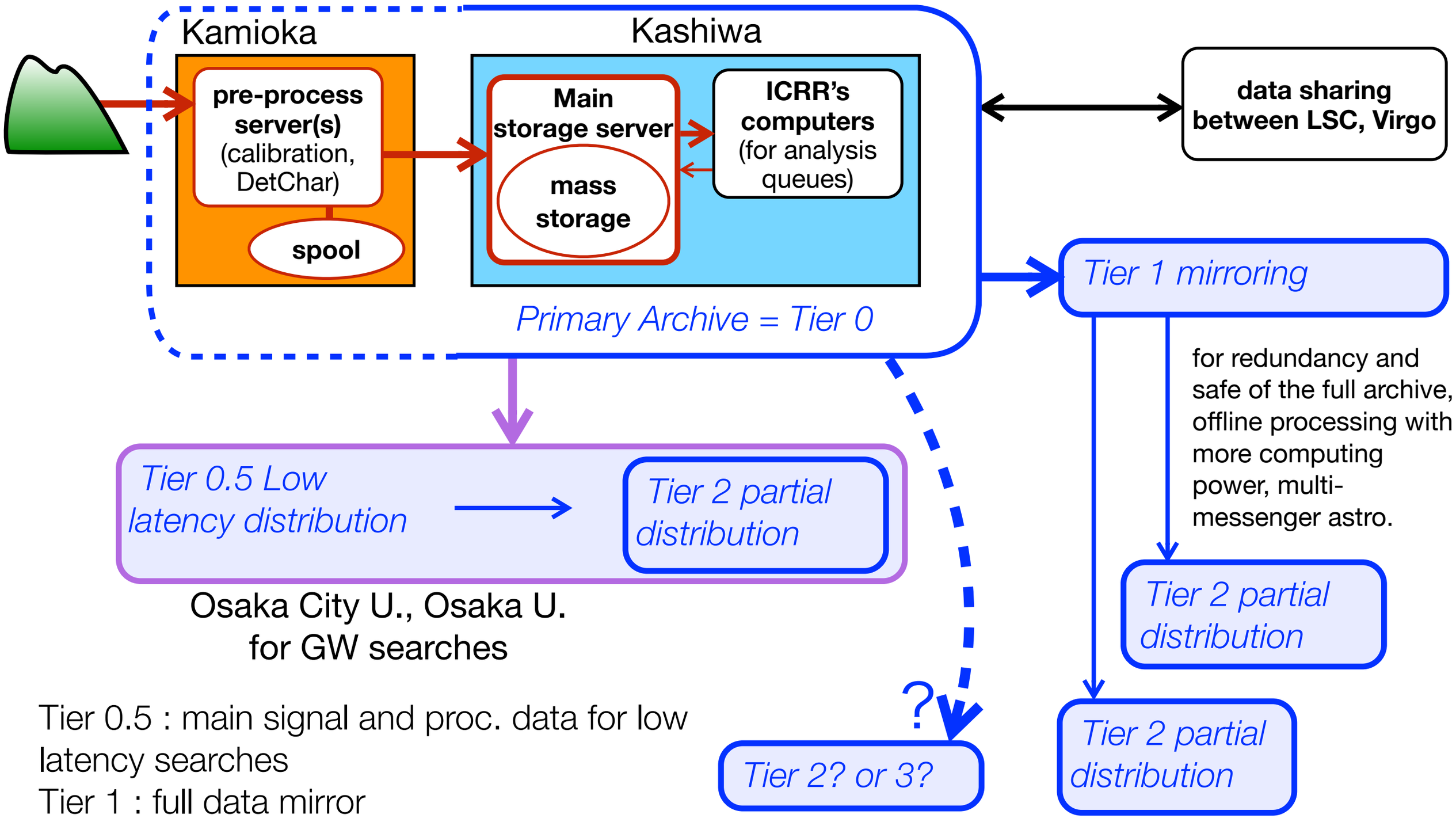


JGW-G1503284

2015/2/5 KAGRA f2f meeting

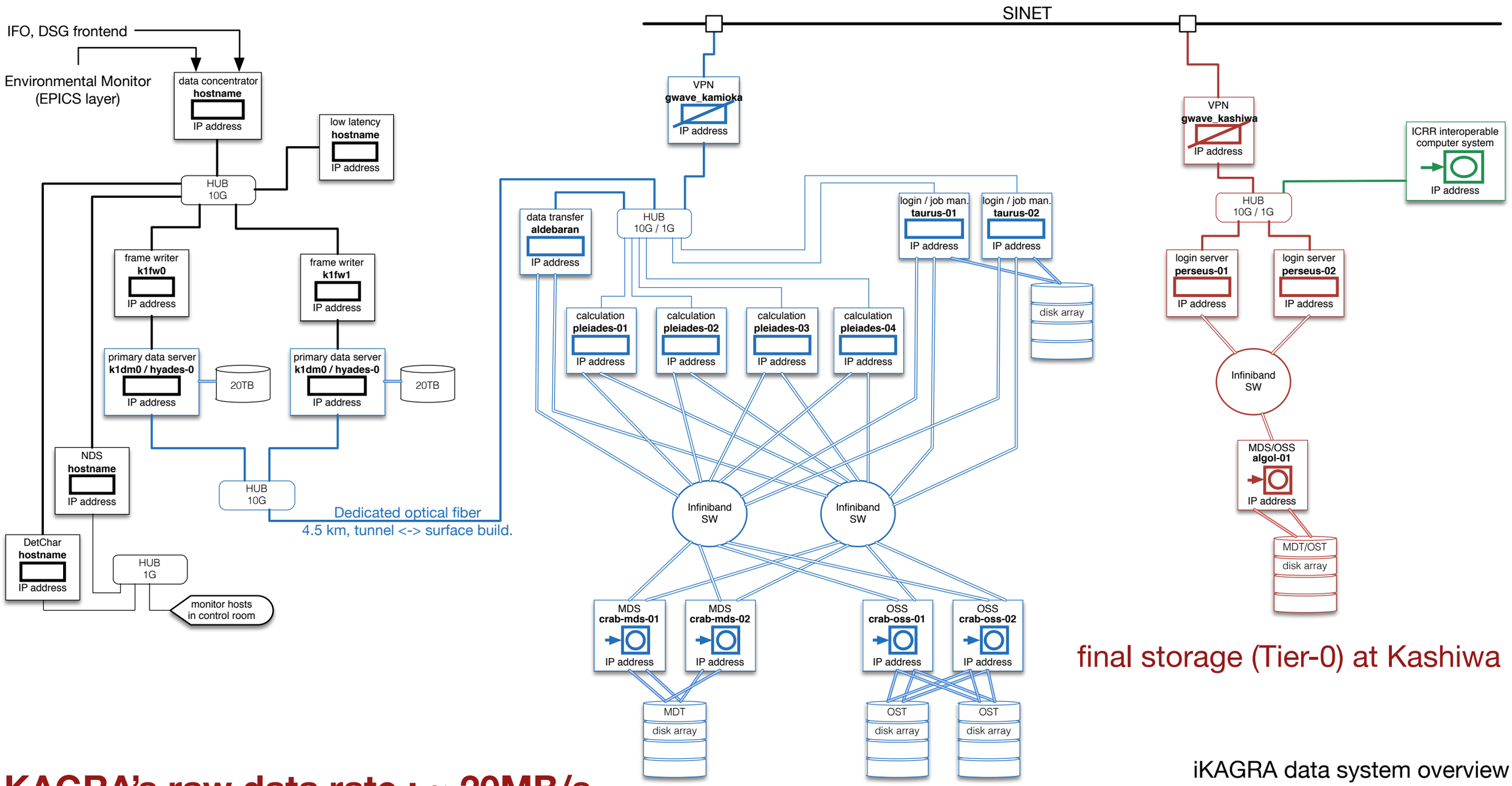
by O.Miyakawa

Data flow overview



Tier 0.5 : main signal and proc. data for low latency searches
Tier 1 : full data mirror
Tier 2 : proc. data
Tier 3 : partial cache of proc. data

Main Stream of KAGRA Data



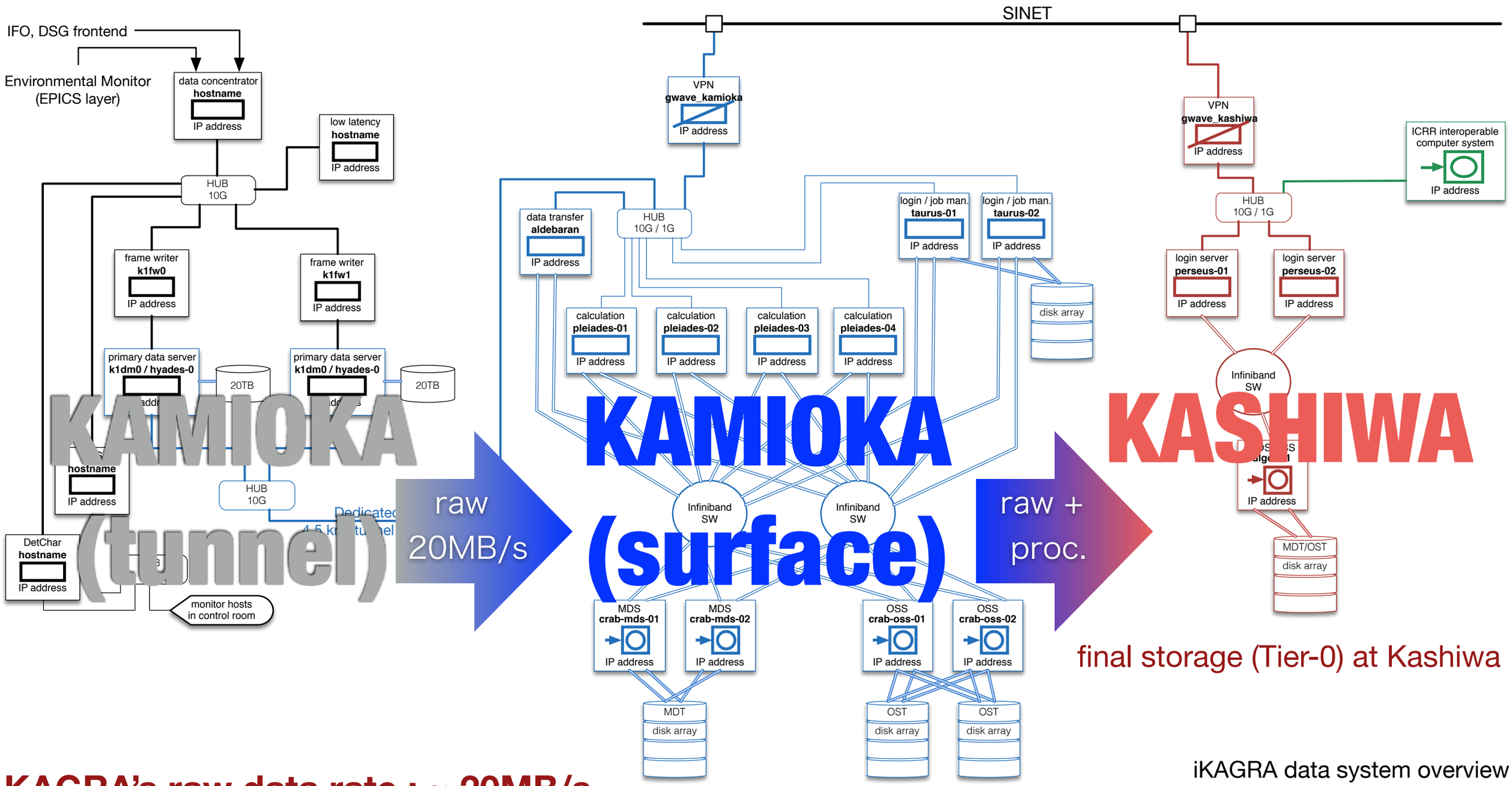
KAGRA's raw data rate : ~ 20MB/s (~630 TB/yr)

surface building at Kamioka

final storage (Tier-0) at Kashiwa

iKAGRA data system overview

Main Stream of KAGRA Data



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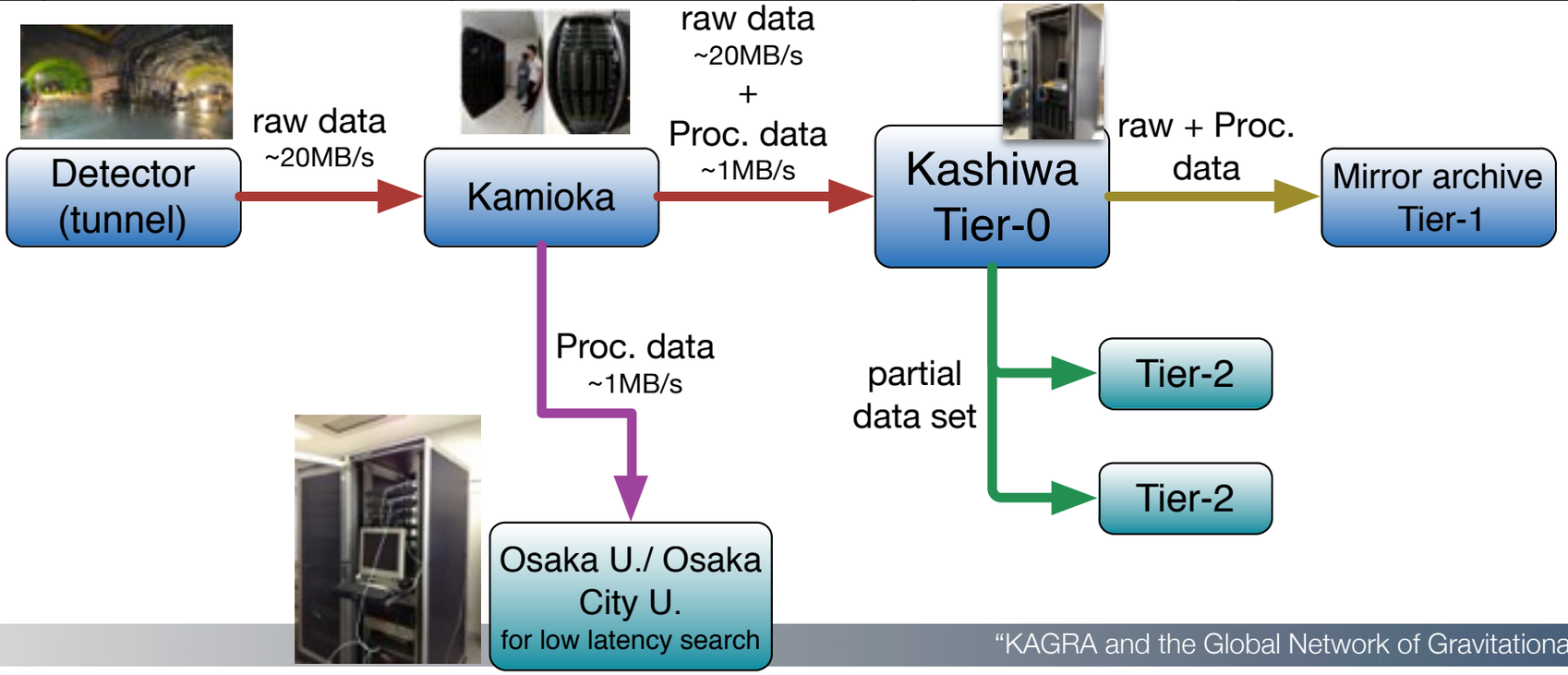
surface building at Kamioka

final storage (Tier-0) at Kashiwa

iKAGRA data system overview

Amount of Data

phase	duration	data rate / duty	total expected amount	from -> to
iKAGRA	about 1 month at **December 2015**	**20MB/s / 100%**	**100 TiB**	**Kamioka -> Kashiwa**
		1MB/s / 100%	**5TiB**	**Kamioka -> Osaka City U./Osaka U.**
commissioning	**2016-2017**	**20MB/s / ?(5~10%)**	**?**	**Kamioka -> Kashiwa**
		1MB/s / ?(5~10%)	**?**	**Kamioka -> Osaka City U./Osaka U.**
bKAGRA	**2017 -**	**20MB/s / 100%**	**3PB / 5yrs**	**Kamioka -> Kashiwa**
		1MB/s / 100%	**150 TiB / 5yrs**	**Kamioka -> Osaka City U./Osaka U.**

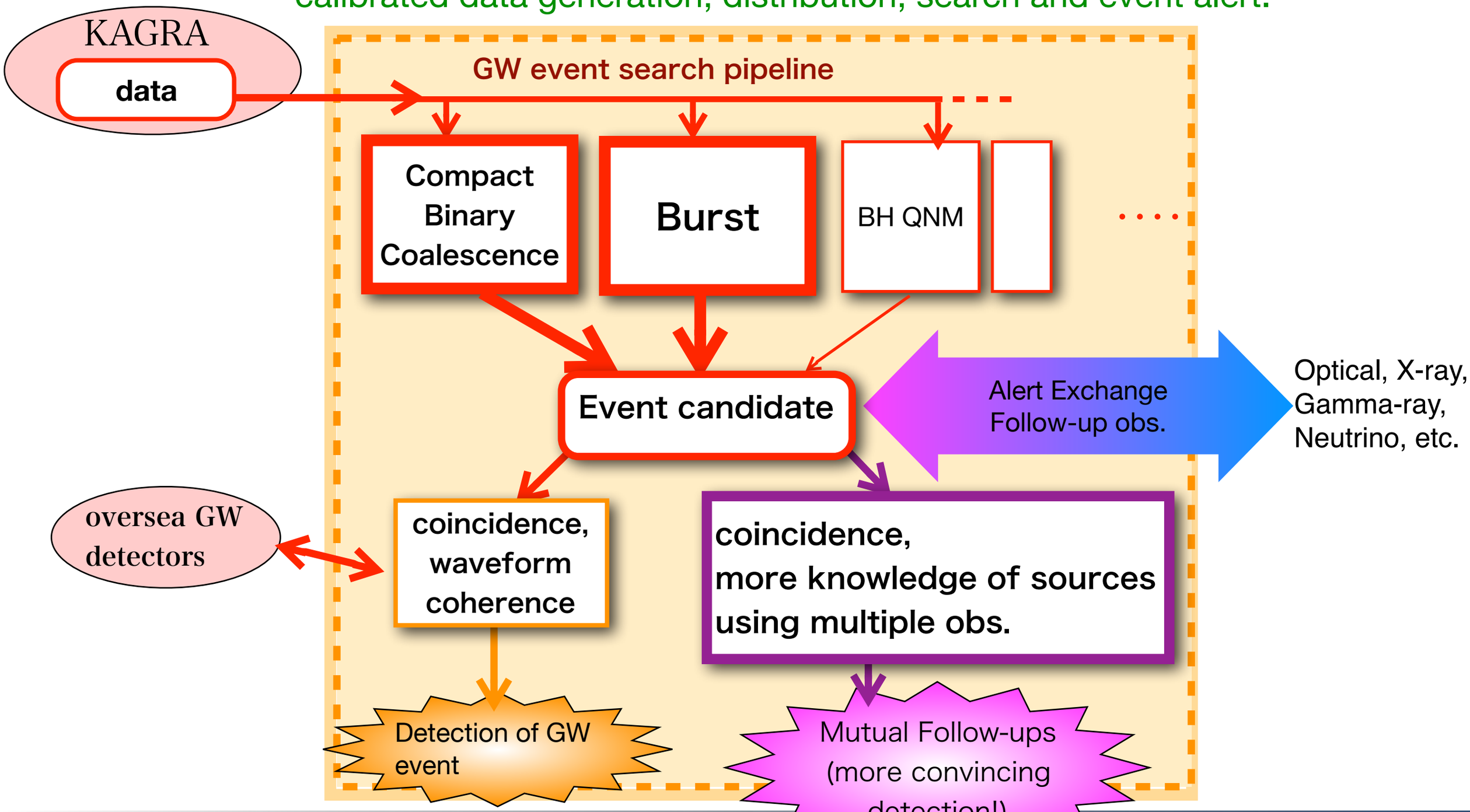


Data analysis (GW event searches)

KAGRA

Search for various GW waveforms in data stream

- Fast processing pipeline (calculation > observation)
- Low latency for end-to-end of the system : Tier-0 data transfer, storage, calibrated data generation, distribution, search and event alert.



Challenge in GW data analysis

KAGRA

We don't know where, when GW events will arrive.

- →search with a fine tooth comb for all data of long observation period.

Waveform and amplitudes depend on various parameters of progenitors **(e.g. distance, mass of star, spins, EOS(equation of state), direction, alignment, initial condition of the orbit, etc.)**

(We will get different waves event by event. Therefore, the identification of signals is quite different from the case of photo-multiplier tube.)

- →search for all possible parameter spaces.

We don't know 'real' signal yet.

Also, some kind of GW may be always present. (Continuous, Stochastic GW.)

- →It is difficult to adopt triggers or to reduce in DAQ level.

Computing cost for CBC

KAGRA

- For CBC search, it requires ~1TFlops for minimal requirement. (Several ~ ten times more for complete search)
- Continuous and Burst searches also require ~1TFlops respectively.
- Stochastic require less than above.

At least, a few~several Tflops is necessary for GW data analysis.

KAGRA sensitivity | mass search region | necessary numbers of templates | calculation costs.

noise model	$m_{\rm min}[M_\odot]$	$m_{\rm max}[M_\odot]$	$N_{\rm temp}$	$P_{\rm comp}$(no χ^2)[flops]	$P_{\rm comp}$(with χ^2)[flops]
VRSE-B	1	3	1.4×10^5	2.3×10^{10}	1.8×10^{11}
VRSE-B	1	100	7.0×10^5	1.1×10^{11}	8.8×10^{11}
VRSE-B	0.2	3	1.8×10^7	3.4×10^{12}	2.7×10^{13}
VRSE-B	0.2	100	3.1×10^7	5.8×10^{12}	4.6×10^{13}
VRSE-D	1	3	1.2×10^5	1.9×10^{10}	1.5×10^{11}
VRSE-D	1	100	5.9×10^5	1.0×10^{11}	8.0×10^{11}
VRSE-D	0.2	3	1.6×10^7	3.0×10^{12}	2.4×10^{13}
VRSE-D	0.2	100	2.7×10^7	5.0×10^{12}	4.0×10^{13}

Estimation of calculation costs for CBC (by Tagoshi)

Effective performance of FFT

KAGRA

Dominant calculation cost is FFT (Fast Fourier Transform).

- One of the problem is the length of the data(>2^20)

FFT performance will be drastically reduced with data exceeds cache size.

Key technique:

→ parallel computing

→ GPGPU

etc.

Effective performance of FFT

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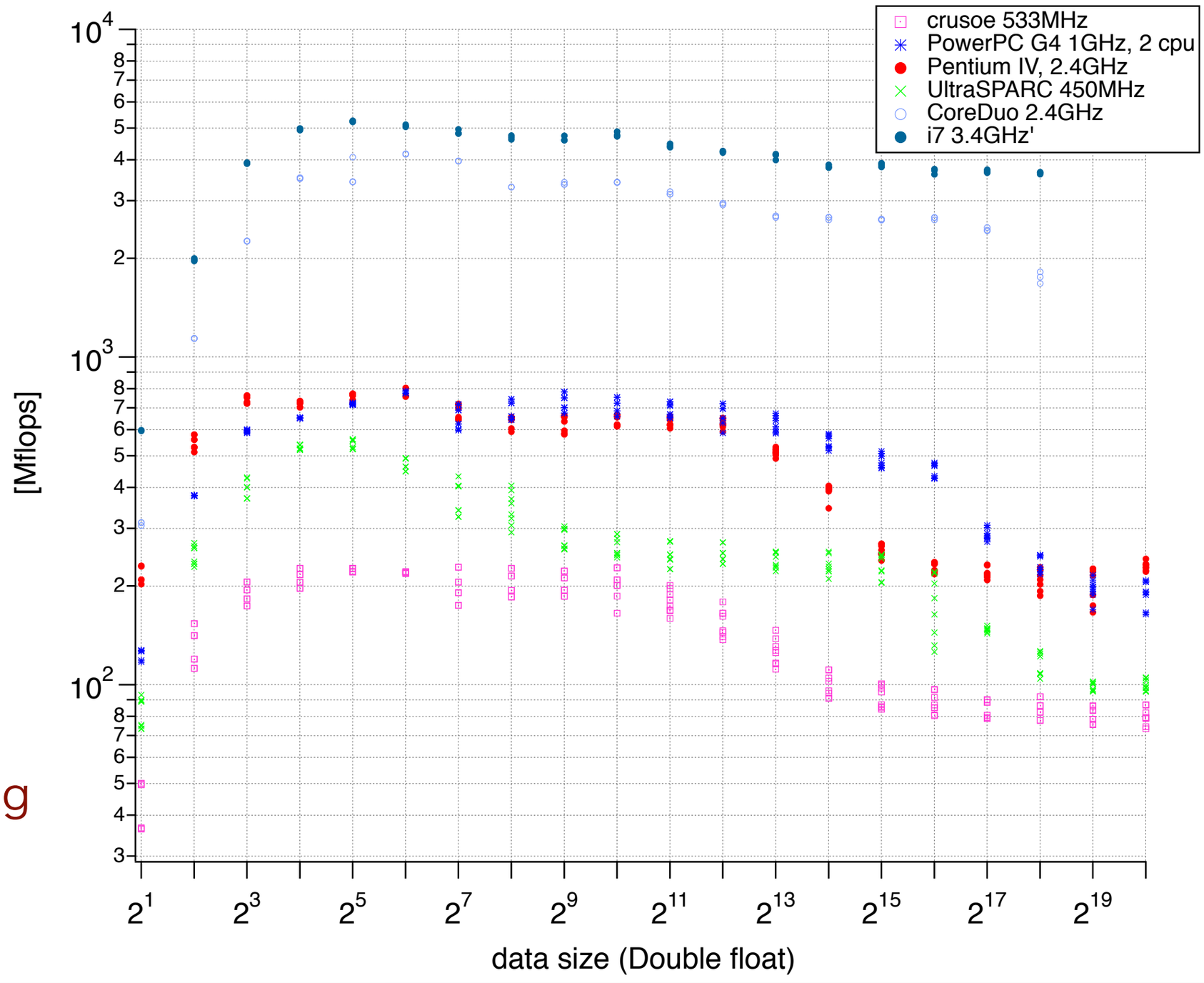

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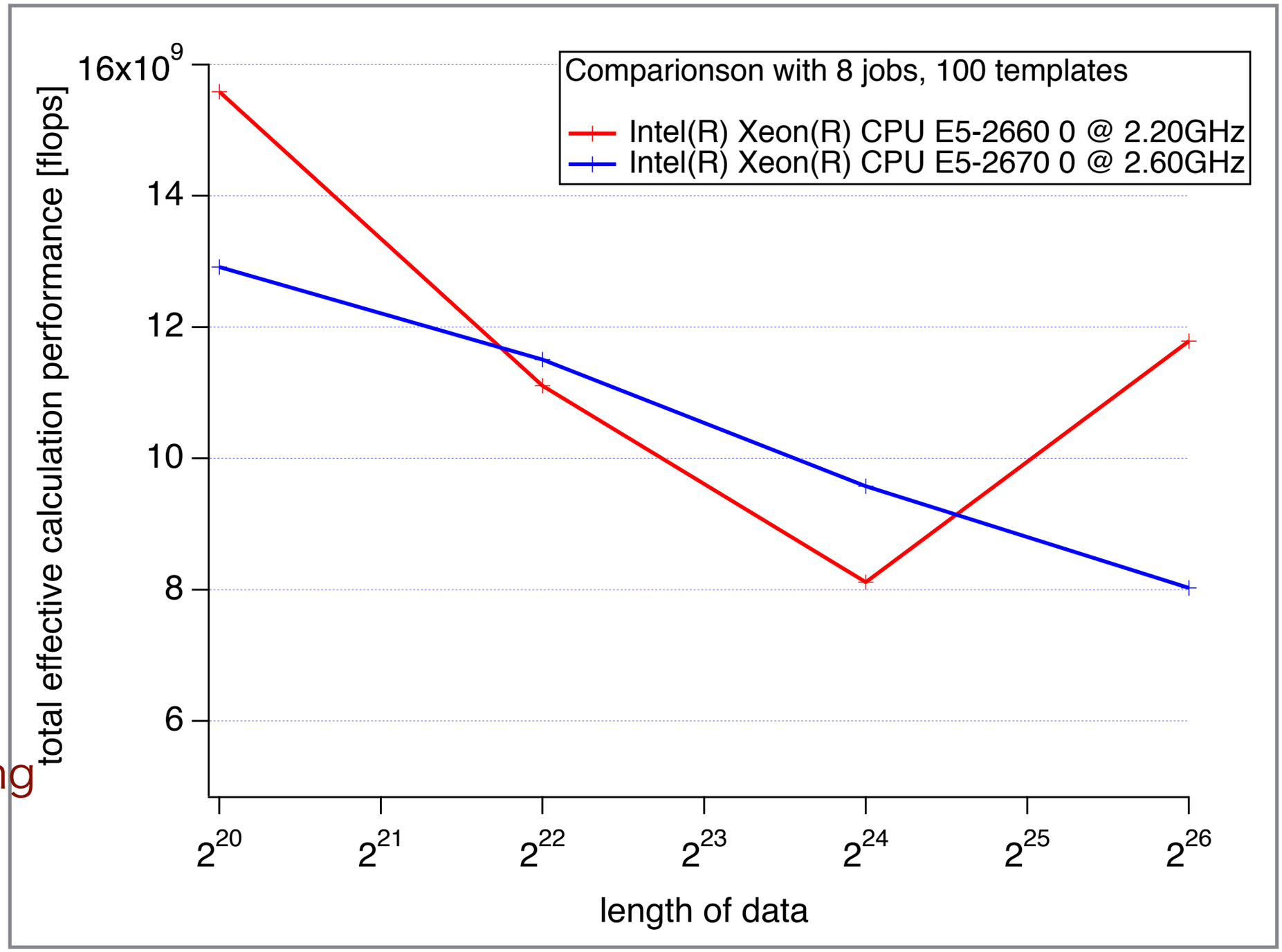


Key technique:

→ parallel computing

→ GPGPU

etc.

Data Analysis Software in KAGRA

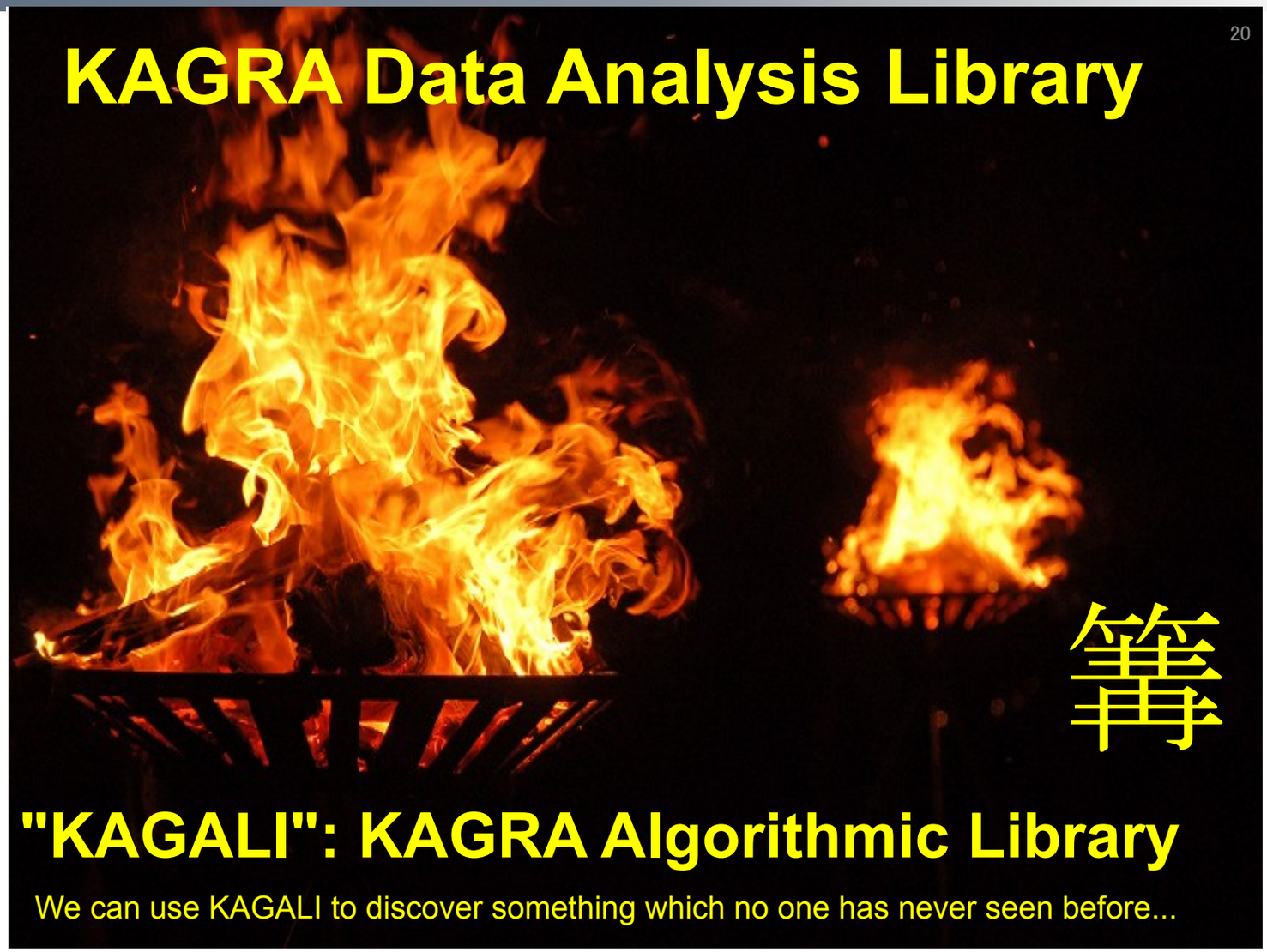
KAGRA

KAGALI

- We are using LIGO,Virgo software. However to add more KAGRA original functions, we are developing own library (KAGALI).

KAGRA coding rule

by Y.Itoh



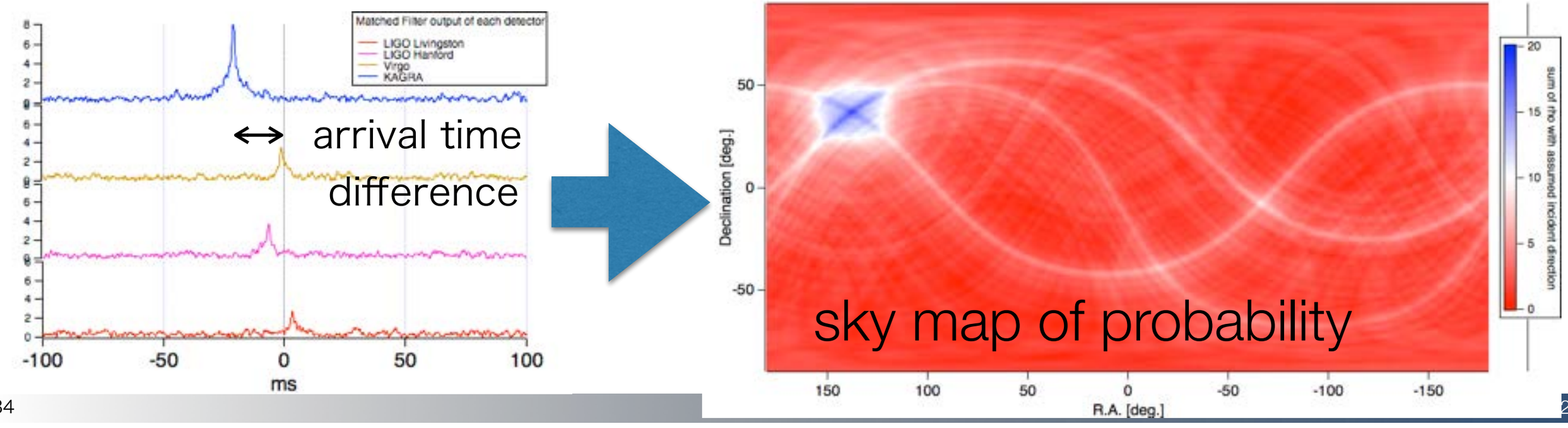
KAGALI Apps layer	LVApps
KAGALI (Lib. layer)	LAL, VIRGO
LAL, VIRGO (+KAGALI) tools	
KAGALI I/O	LAL, VIRGO I/O

Global network with data sharing

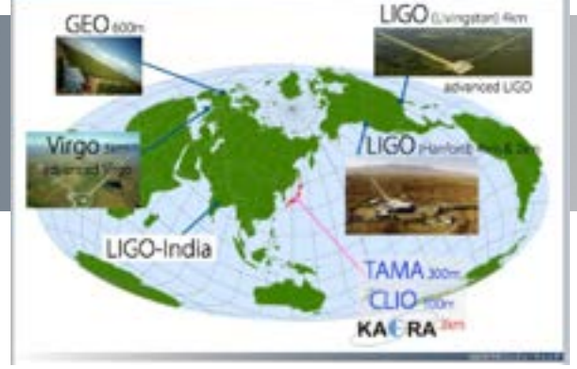
To determine the direction of GW sources,

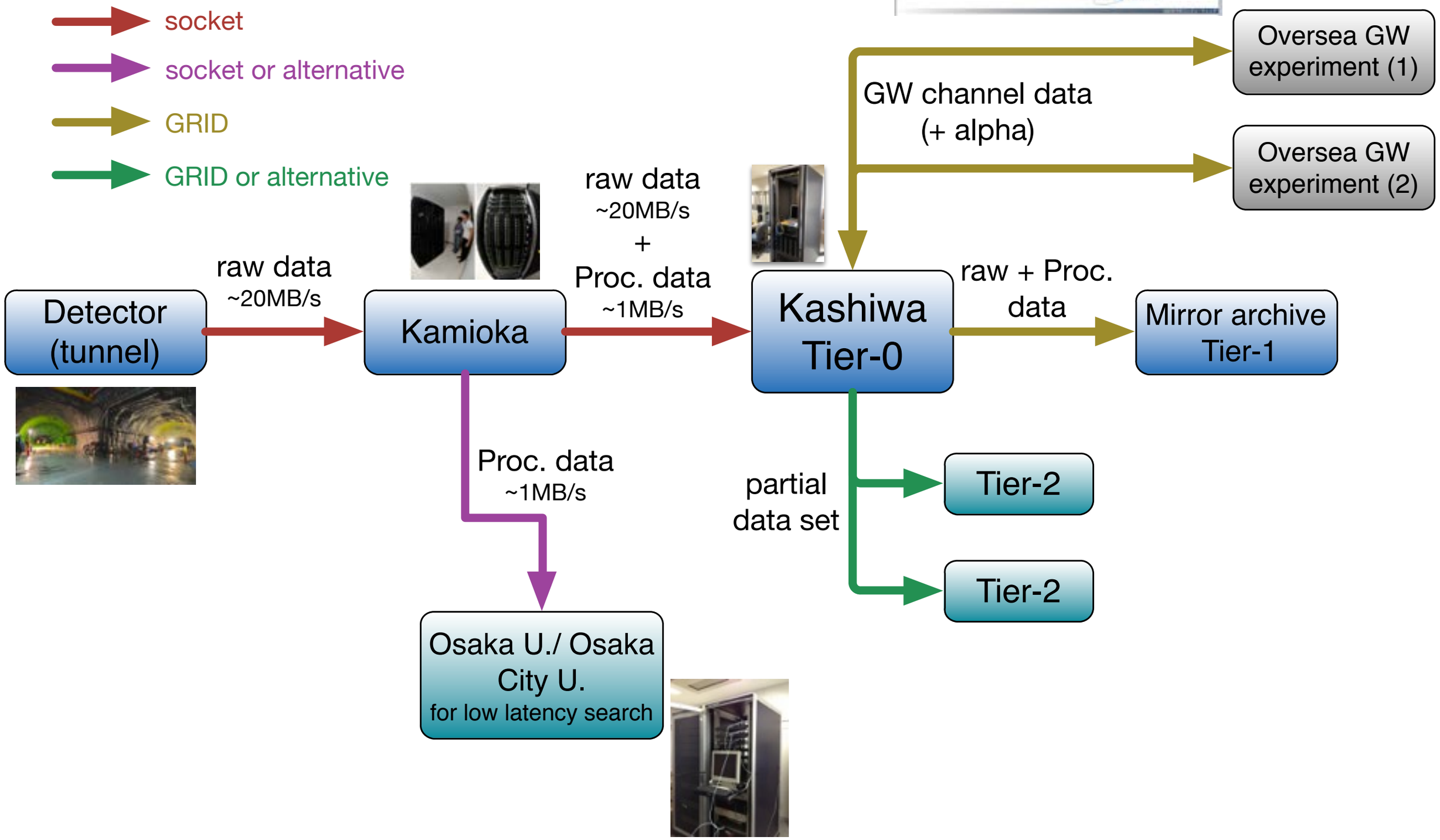
- Triangulation with arrival time difference
- +constraints : amplitude ratio, polarization etc.

cf: diffraction limit λ/D
*Since λ is order of 100km or longer, we have to use detectors of **global** distributed network.*



Data Transfer





Alert and follow-ups/counterparts

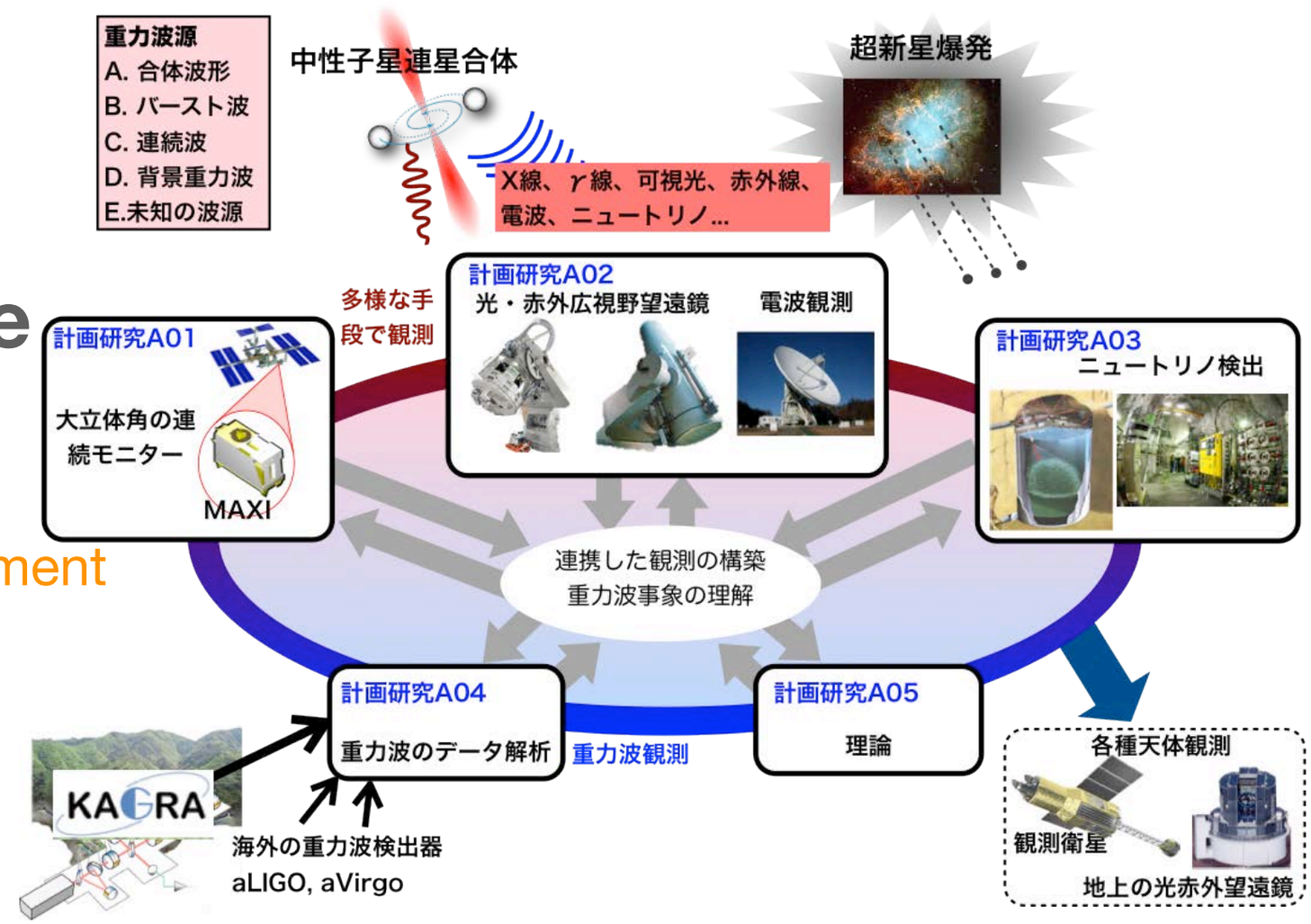
cooperation in KAKENHI (科研費新学術領域)

1. Fast processing of KAGRA data

- Search GW, especially in “low latency analysis”.

2. Mutually follow-ups with EM and neutrino

- Generate, validate and distribute GW event alert from KAGRA
- Search GW with external trigger



3. Further more science on GW data analysis

- Try new physics possibility or new methodological improvement with the theory researches

Summary

KAGRA

We are targeting first gravitational wave detection.

- International competition and cooperation are important.

To convince the GW detection, we need coincidence and follow-up observations.

- The low latency event searches are necessary to realize it.
  A computing is one of a key of the project success.
- ***Multi-messanger observation of GW objects will open new era.***

KAGRA will have its first operation in this year !

- We also expect the operation of advanced LIGO, advanced Virgo.

We hope that GW detection and astronomy will be realized with enough computing power.

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Notice:

http://www.gw.hep.osaka-cu.ac.jp/GWPAW2015/

Reserved Viewgraphs

Direct measurement of GW

KAGRA

Aim of direct detection / measurement of GW!

- We have to test in '**strong**' gravity field !

  Past experimental GR (General Relativity) tests had been done in weak gravity field (in Solar system)

  Direct measurement of wave property is important as the test of a fundamental interaction .

- GW waveform carry information of its sources

  New probe for astrophysics and cosmology

- Tagging GW events = seeing sources

  Gravitational Wave Astronomy

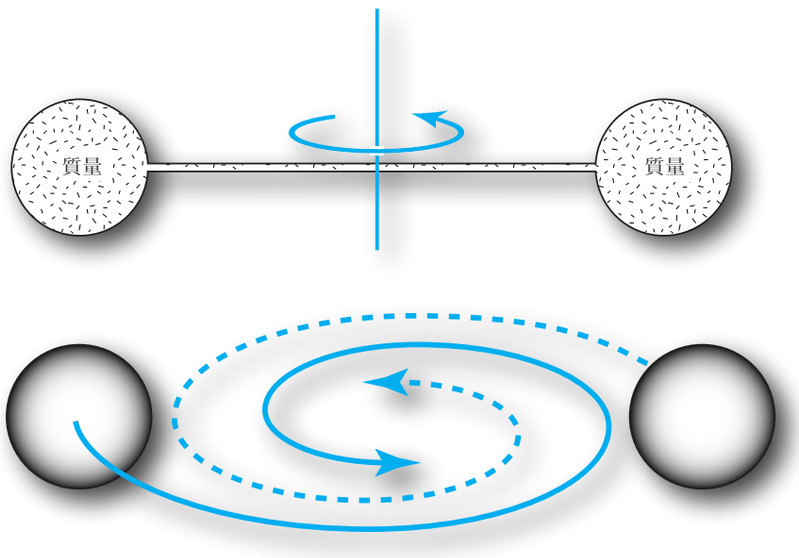
- There will be many interesting sources of GW, which can be observed with counterparts : e.g. EM emission, particles.

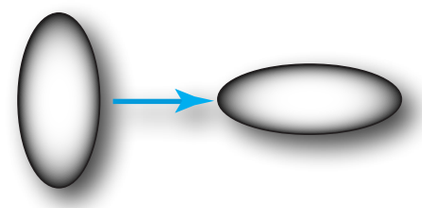
With what can we be convinced of detection of GW?

Need Counterparts !

Quadrupole radiation

Mass quadrupole moment is lowest order of GW radiation.





$$I_{\mu\nu} = \int dV (x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu} r^2)\rho(\vec{r})$$

Amplitude $h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}$

Energy (Luminosity) $E_{GW} \sim \frac{G}{5c^5} < \dddot{I}_{\mu\nu}\dddot{I}^{\mu\nu} >$

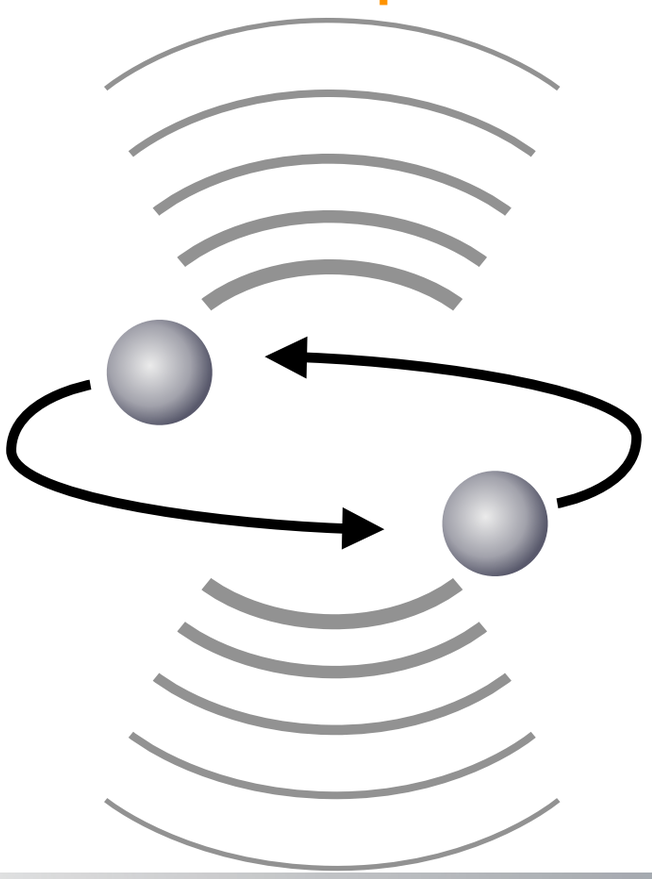
Indirect proof of GW

KAGRA

Binary Pulsar PSR1913+16

by Hulse & Taylor

- Kepler orbital period of
  to the GW emission, th
  angular momentum of
- Measurement agree ve
  theoretical prediction.



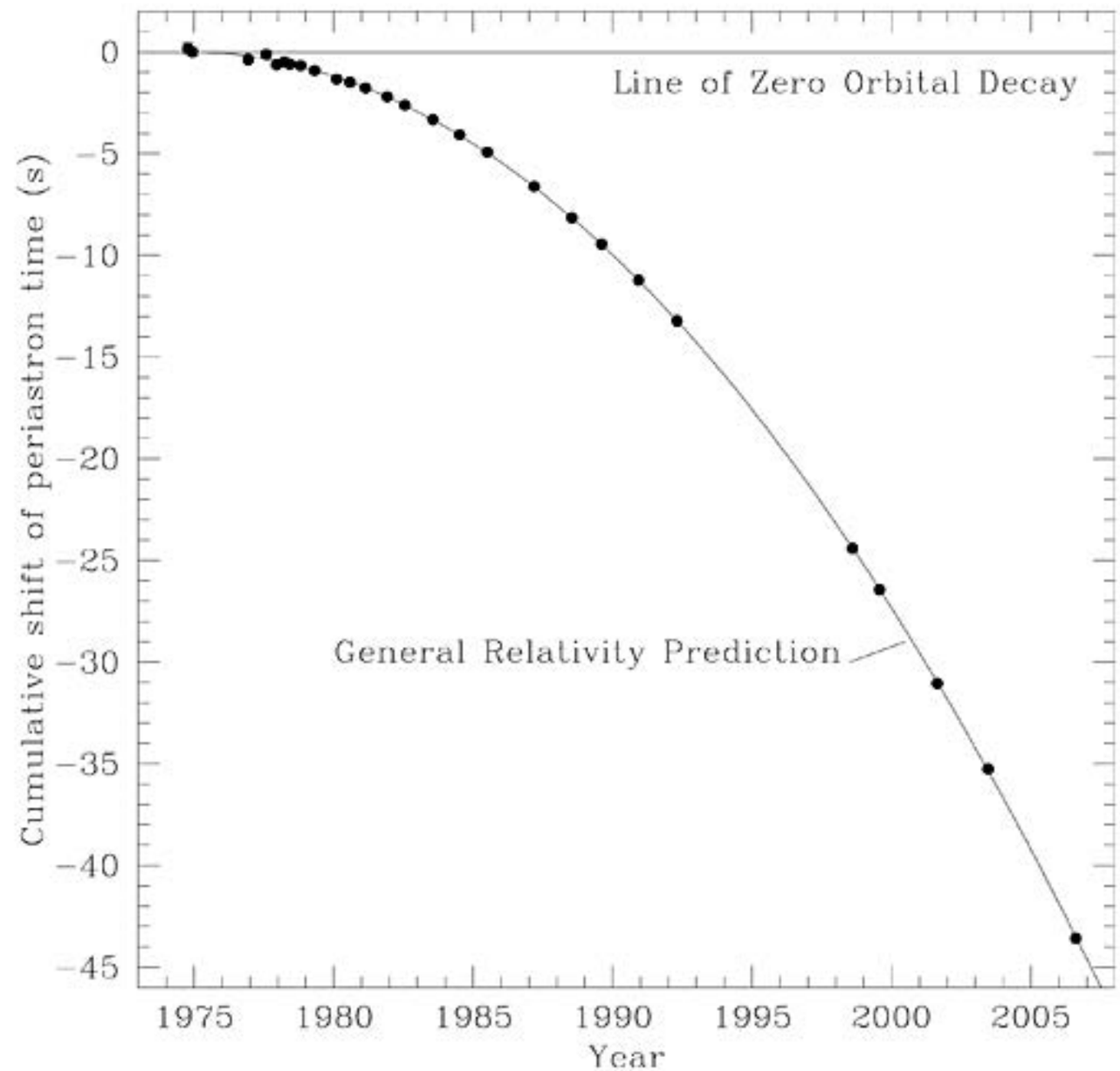
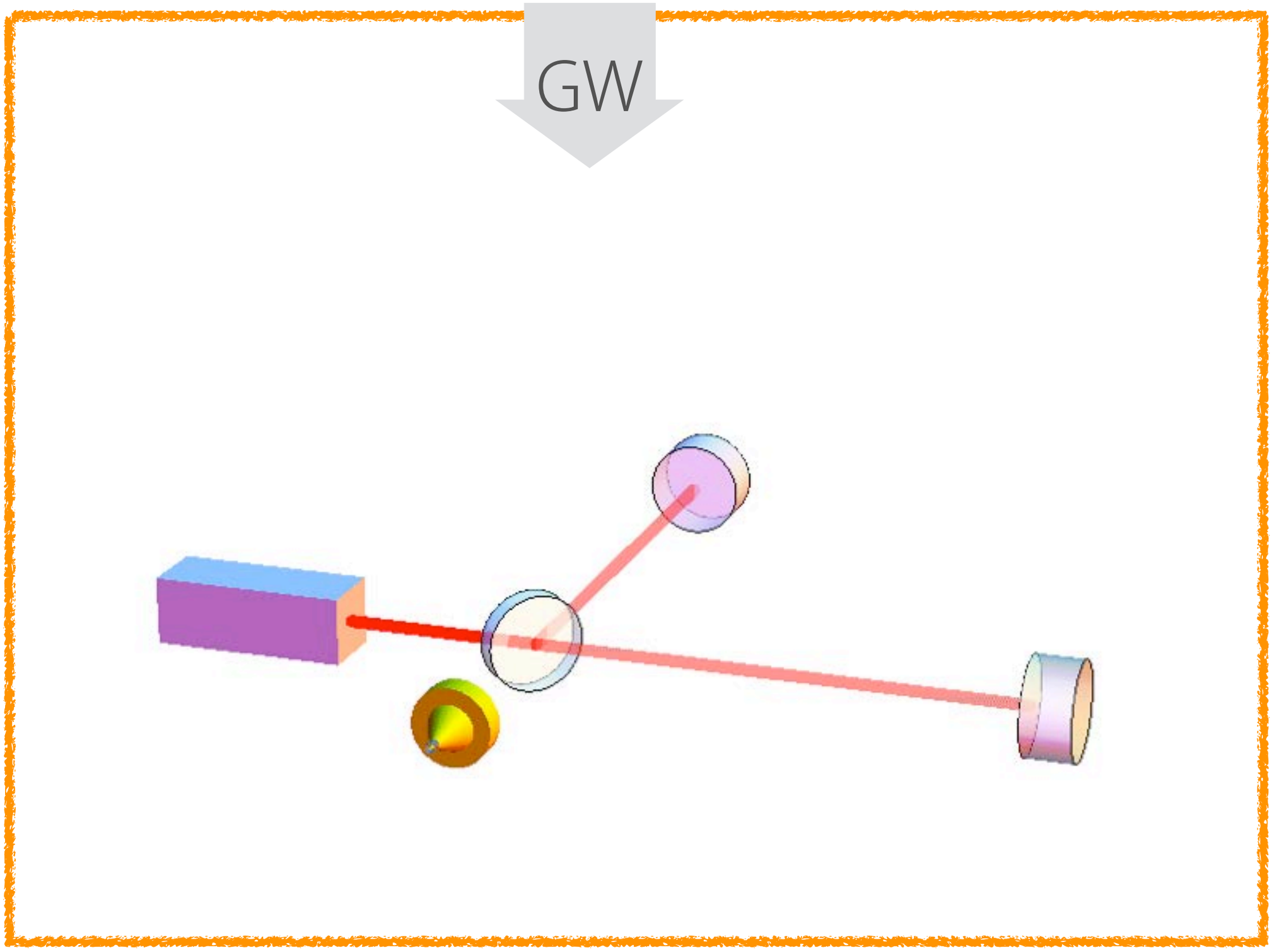


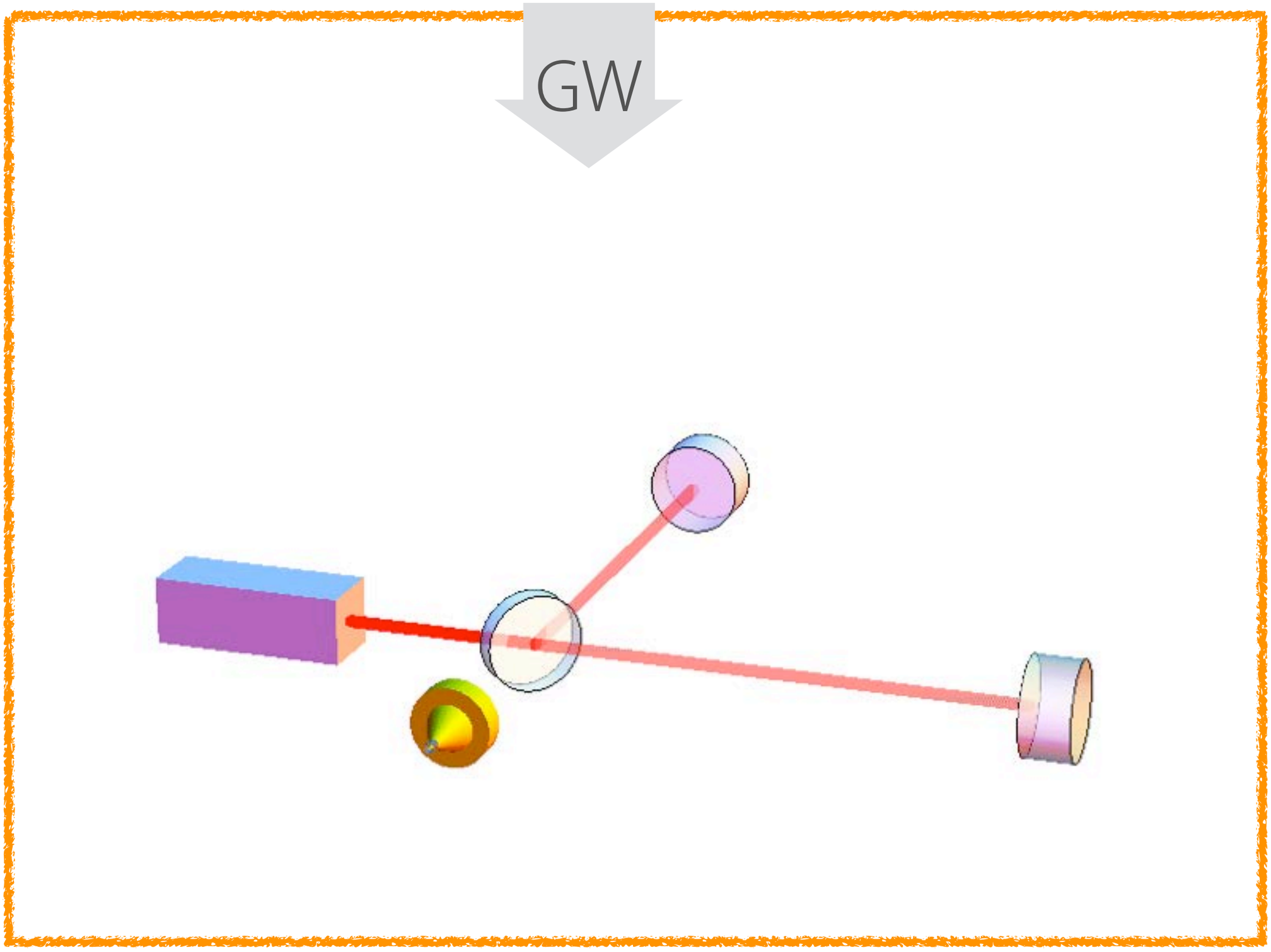
Figure 26: Orbital decay in the binary pulsar B1913+16 system demonstrated as an increasing orbital phase shift for periastron passages with time. The GR prediction due entirely to the emission of gravitational radiation is shown by the parabola. Figure provided by Joel Weisberg.

Duncan R. Lorimer, "Binary and Millisecond Pulsars", Living Reviews in Relativity

Schematic figure & Antenna Pattern

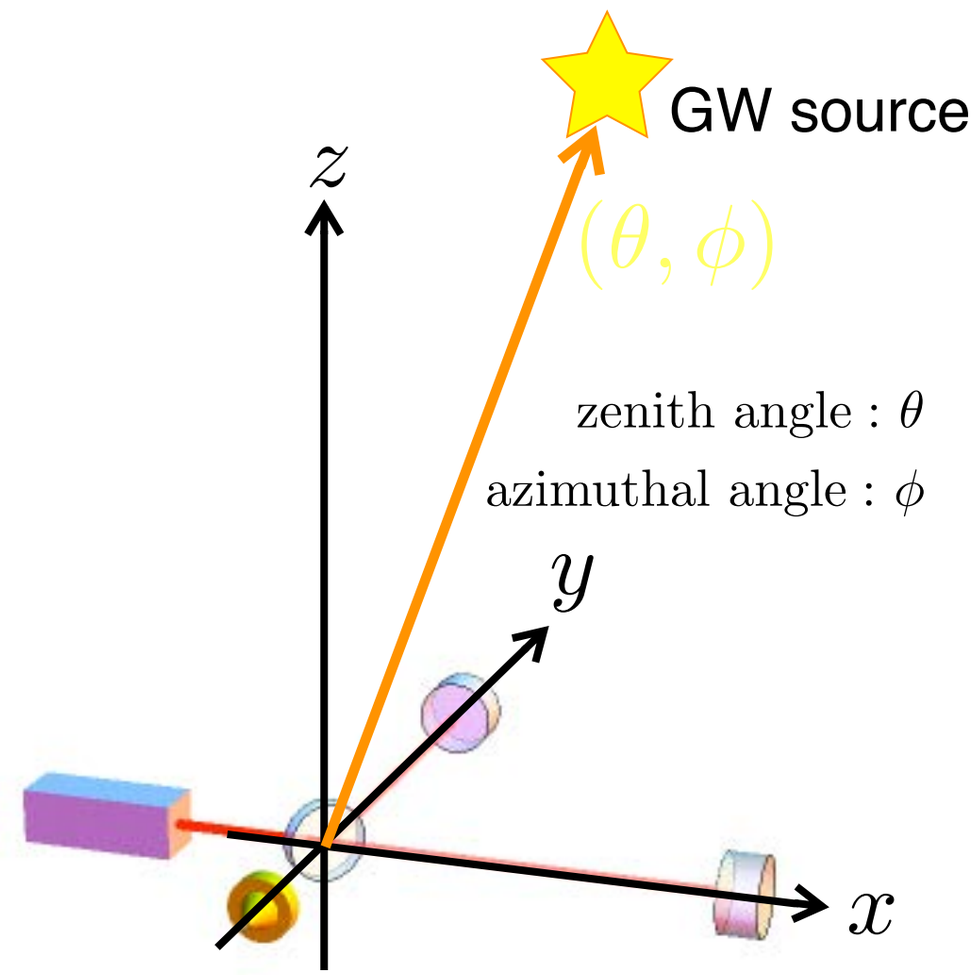


Schematic figure & Antenna Pattern



Antenna Pattern
(Response for source direction and polarization)

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



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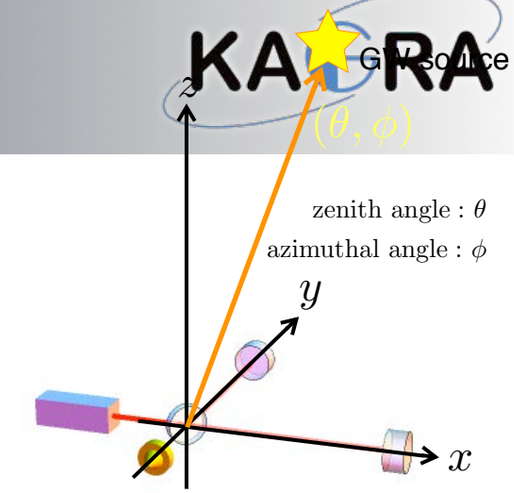

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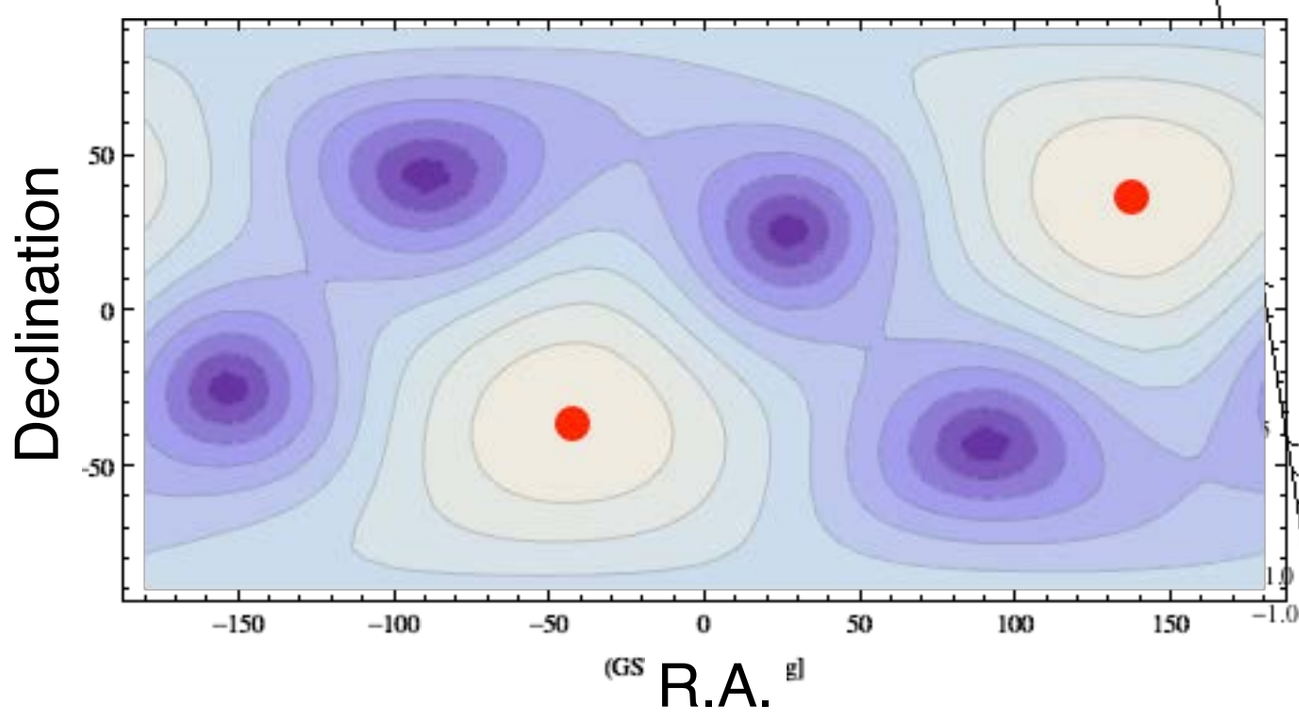
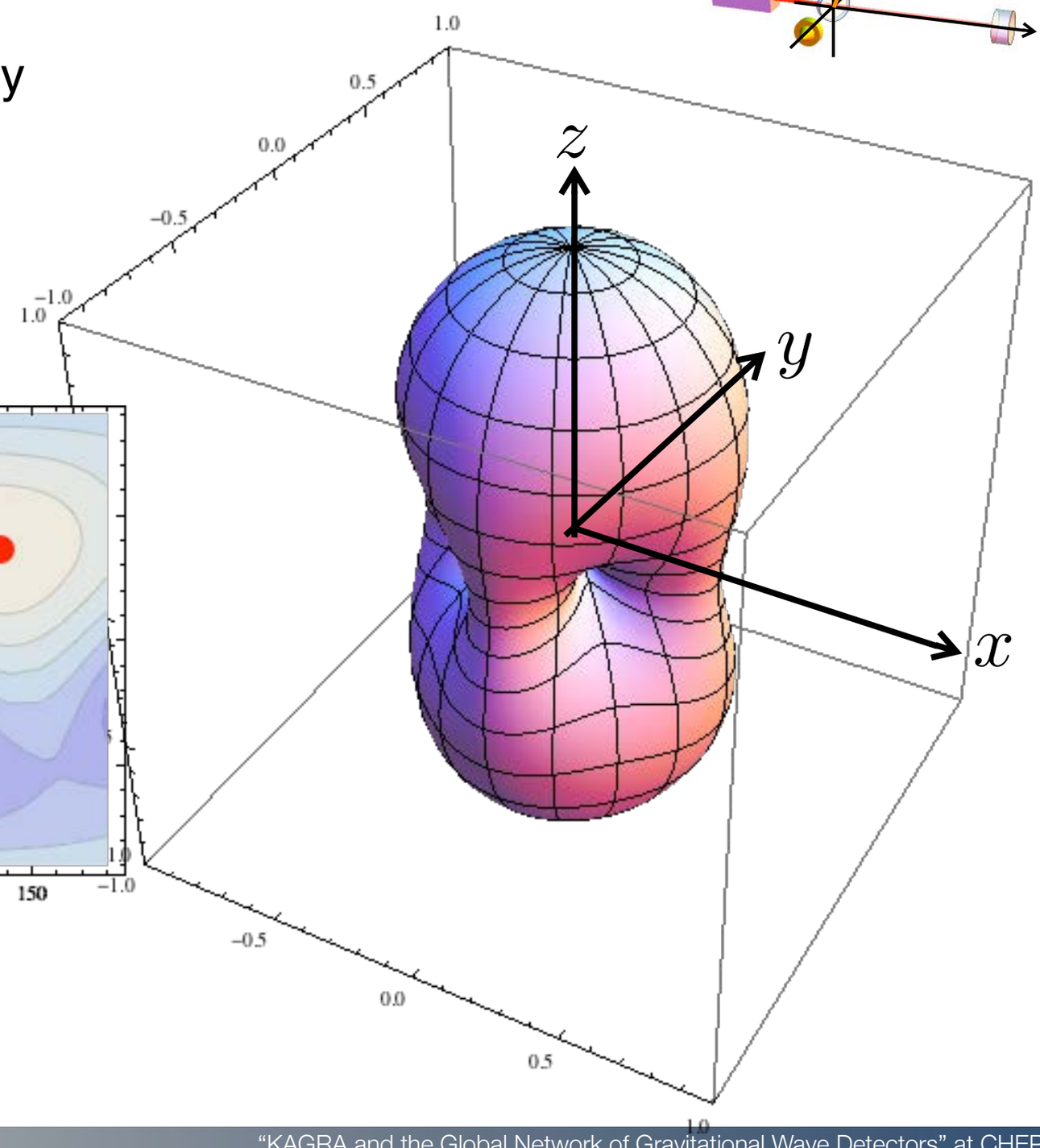
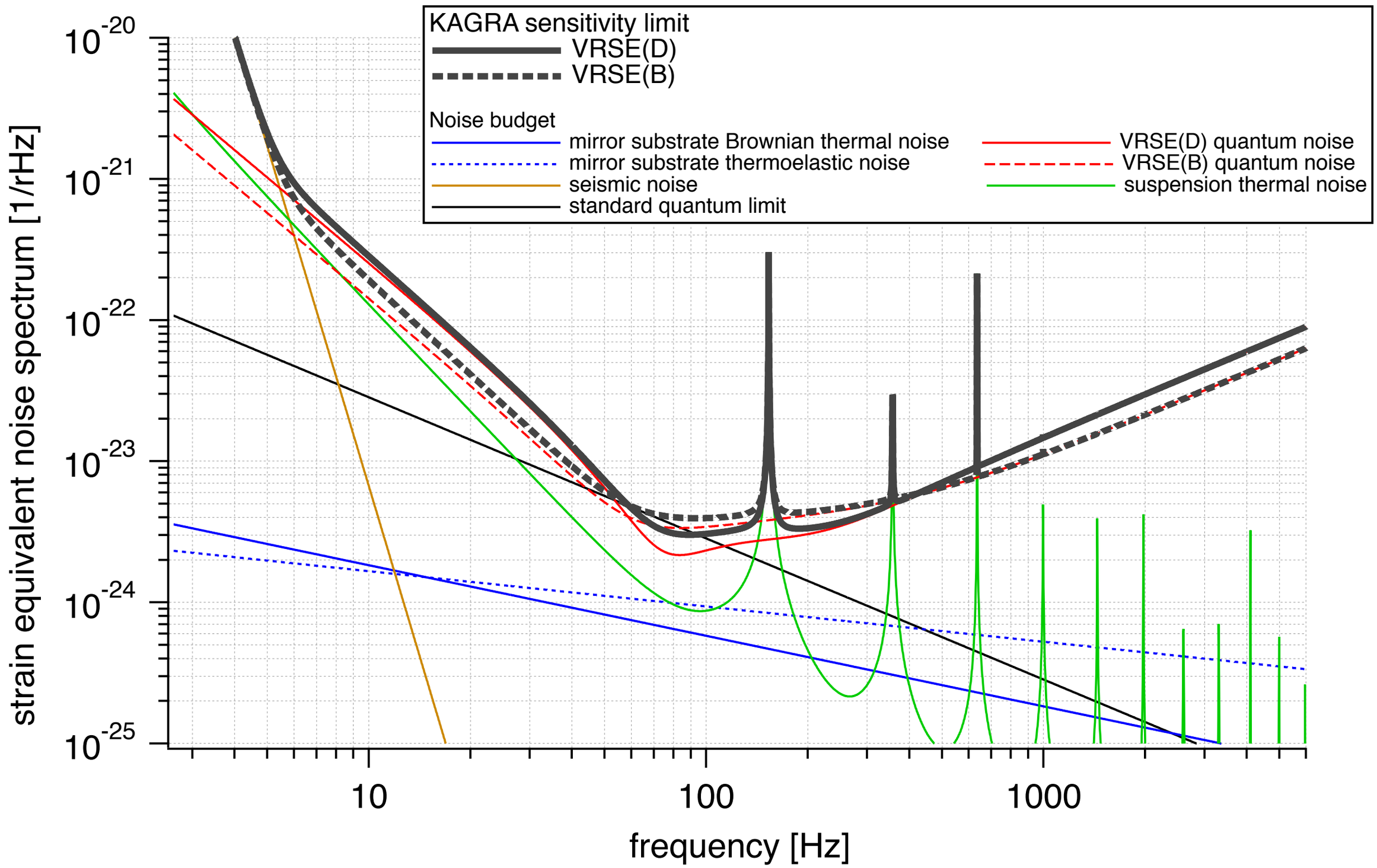




Design Sensitivity of KAGRA (bKAGRA)

KAGRA

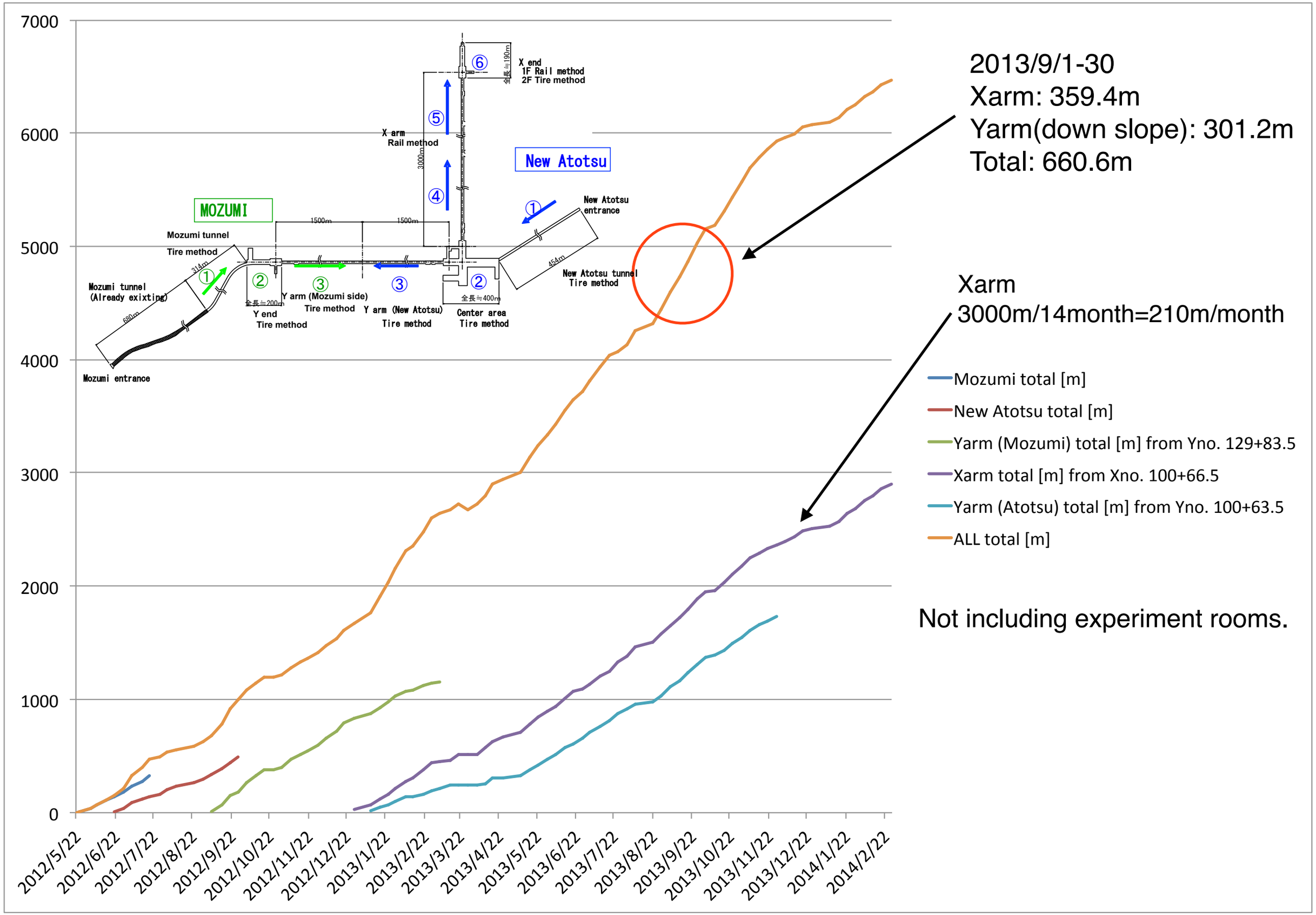
h ~ factor x 10^{-24} [/√Hz] for observation band



KAGRA Collaboration in the world

- Research organizations of laboratories and faculties of universities are 41 in Japan and 37 in overseas
- 158 researchers in Japan and 69 in abroad, 227 members in total

viewgraph by K.Kuroda

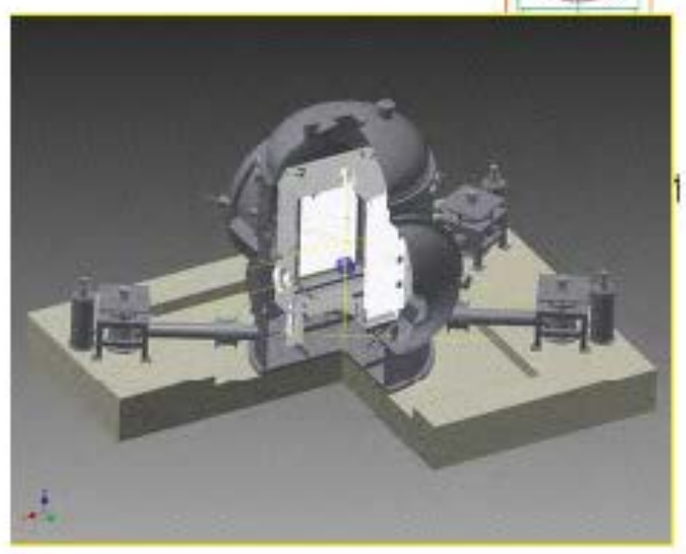


by T.Uchiyama

Vibration isolation and cryostat

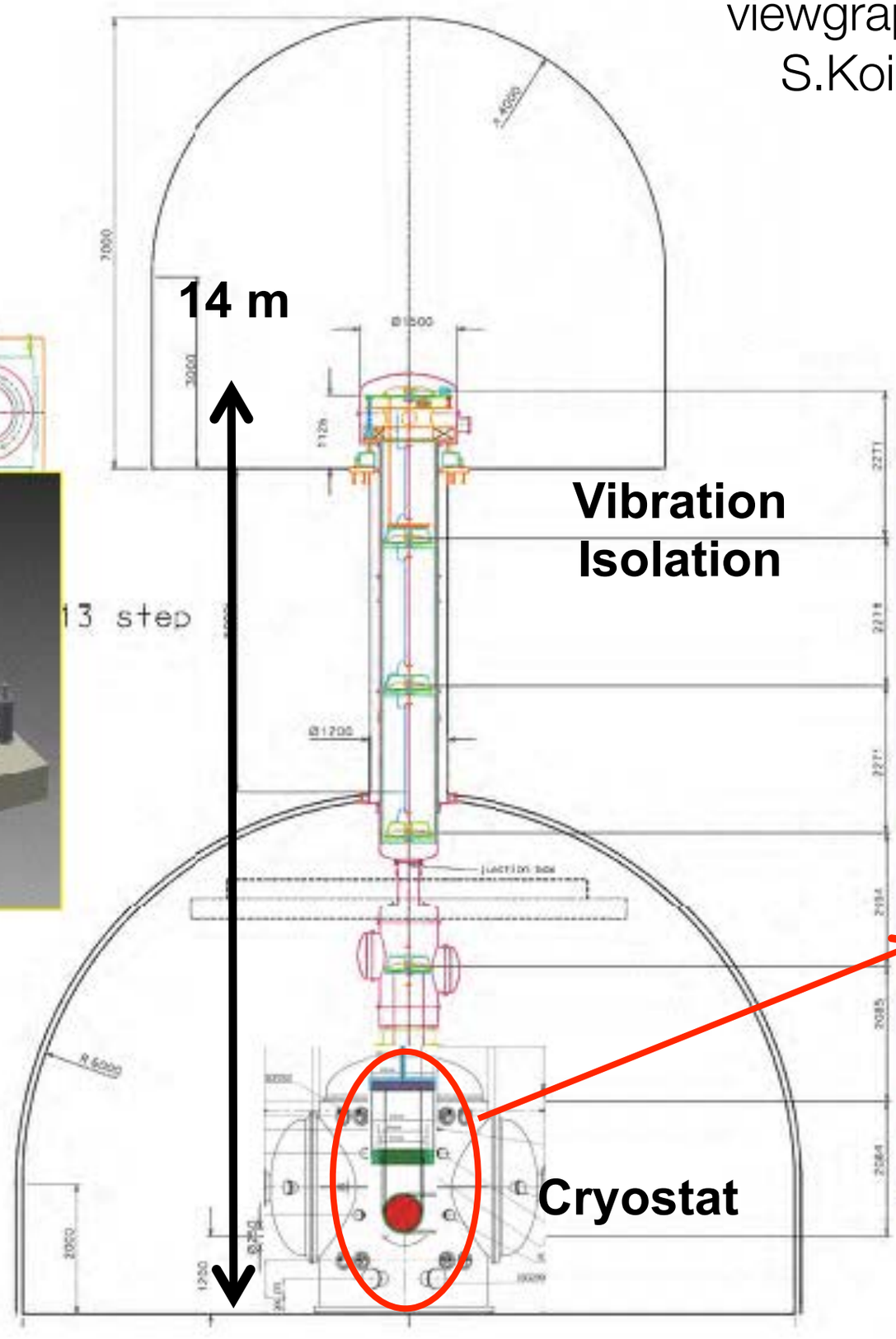
KAGRA

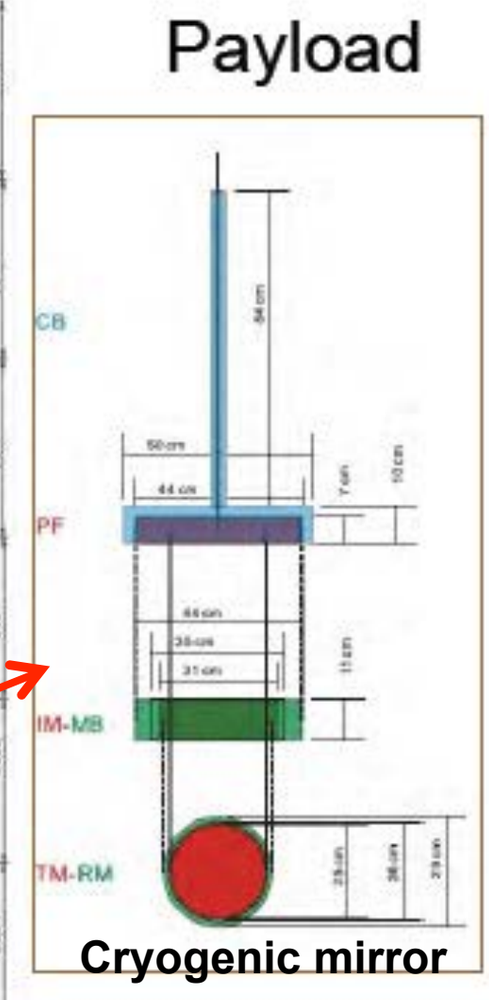
viewgraph by K.Yamamoto, S.Koike & R.Takahashi



Cryostat
PTC units

S.Koike



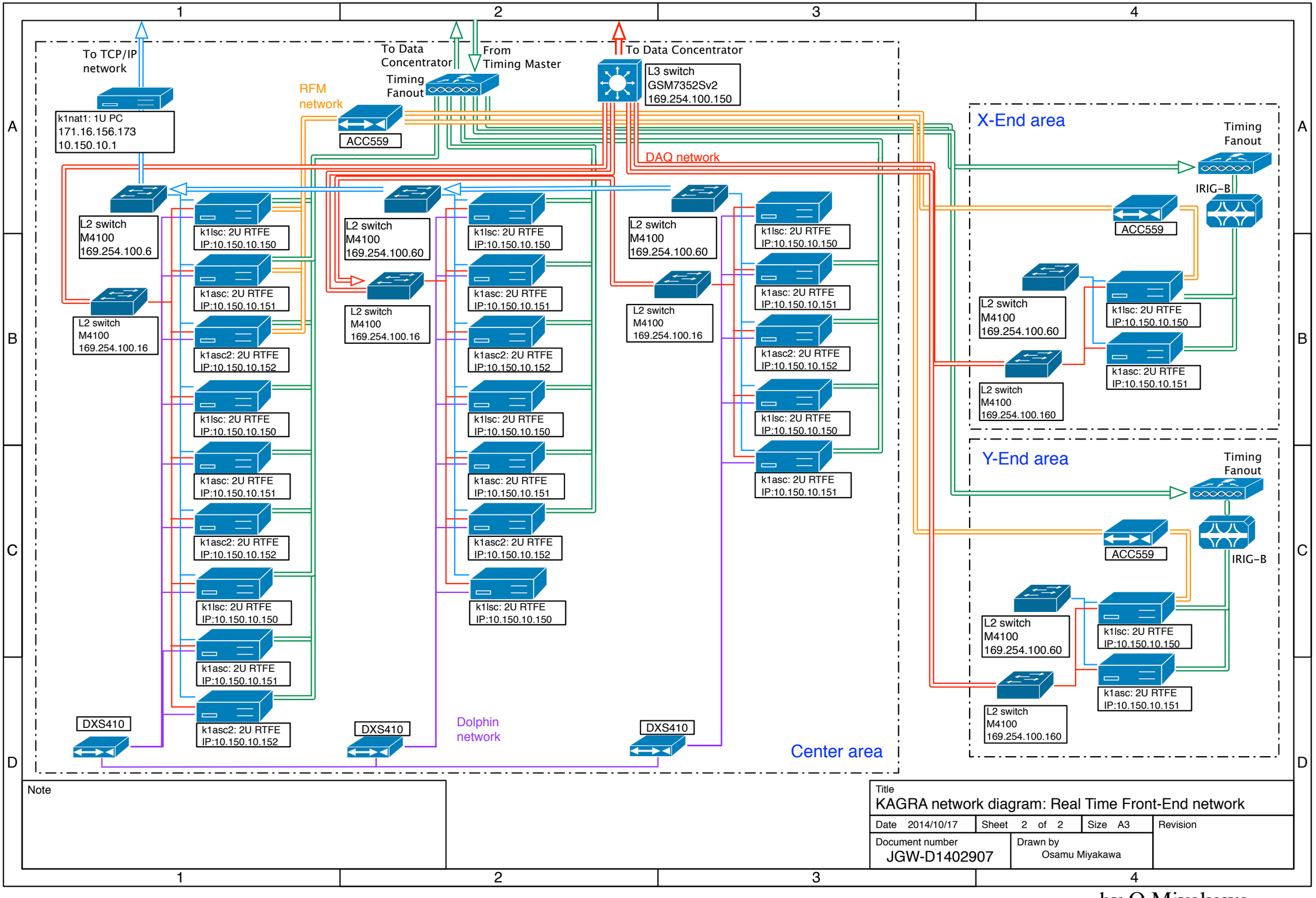


R.Takahashi

New building (“Analysis build.”)

New building ("Analysis build.")

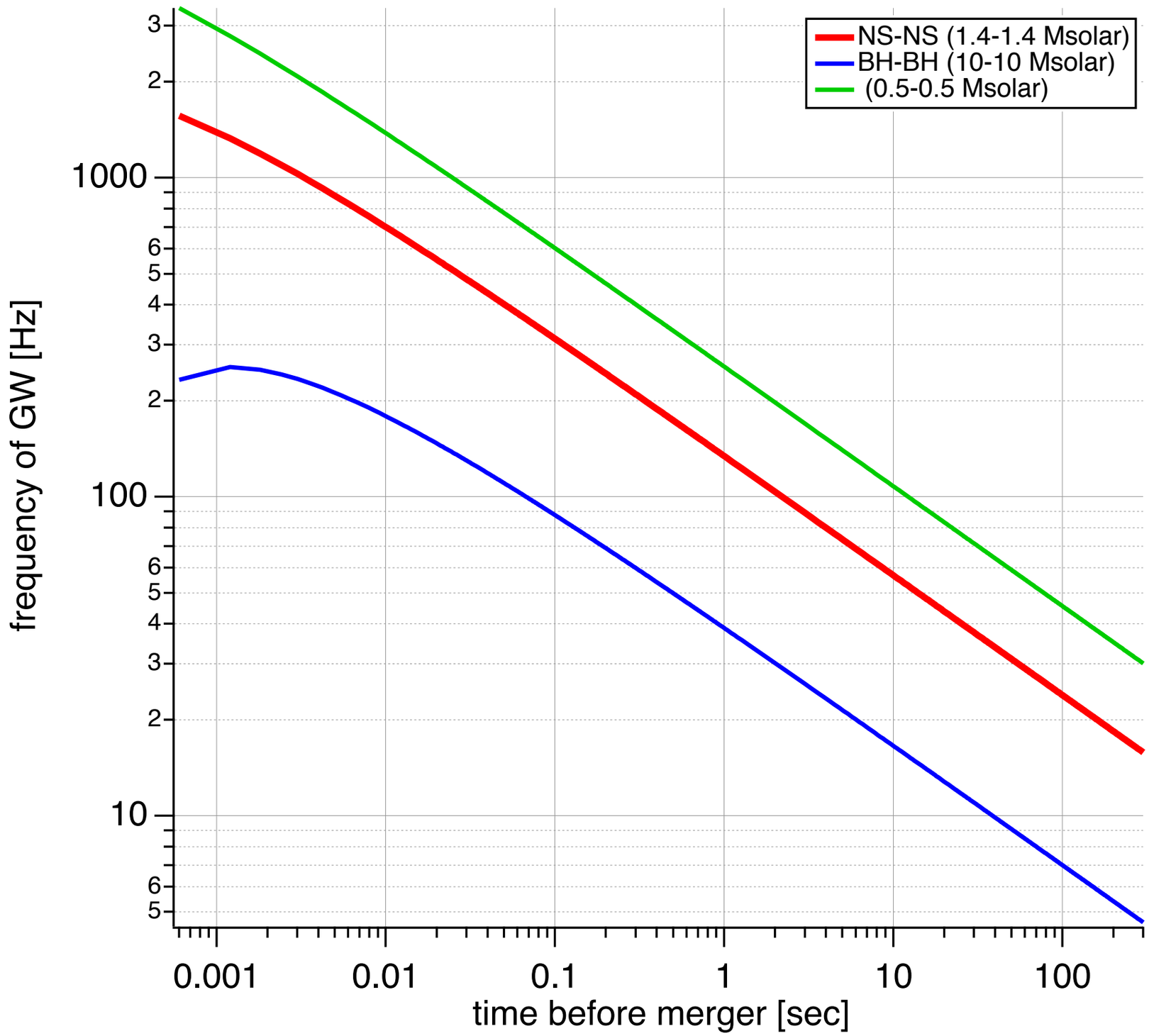
Network inside the tunnel



by O.Miyakawa

(1) NS-NS連星合体１分前に検出（アラート発信）できるか？

チャープ波の周波数発展



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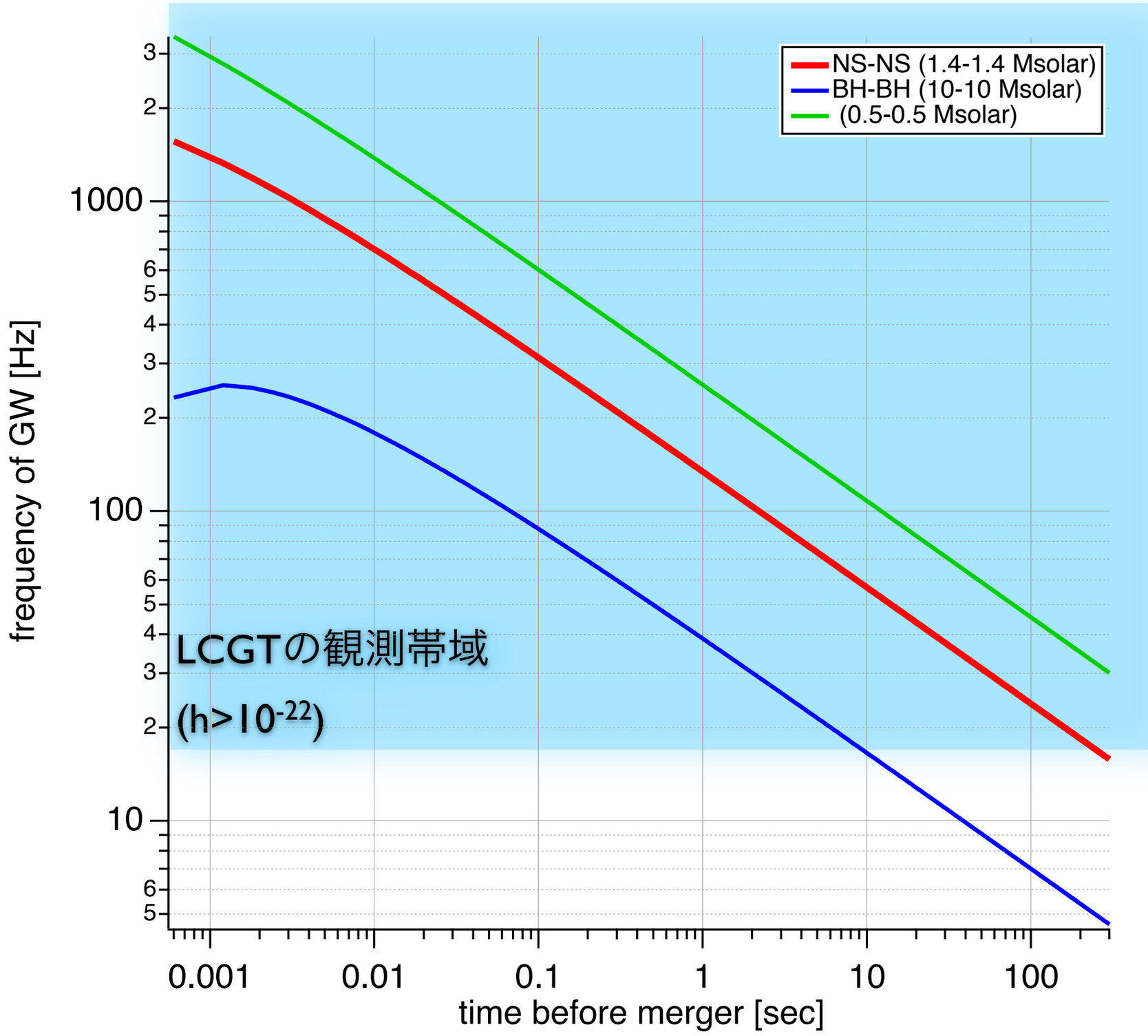


(1) NS-NS連星合体１分前に検出（アラート発信）できるか？

合体前XX秒までの積分で得られるS/N（最終的にえられるS/Nで規格化）

•NS-NSの場合、

１分前だと１割くらい

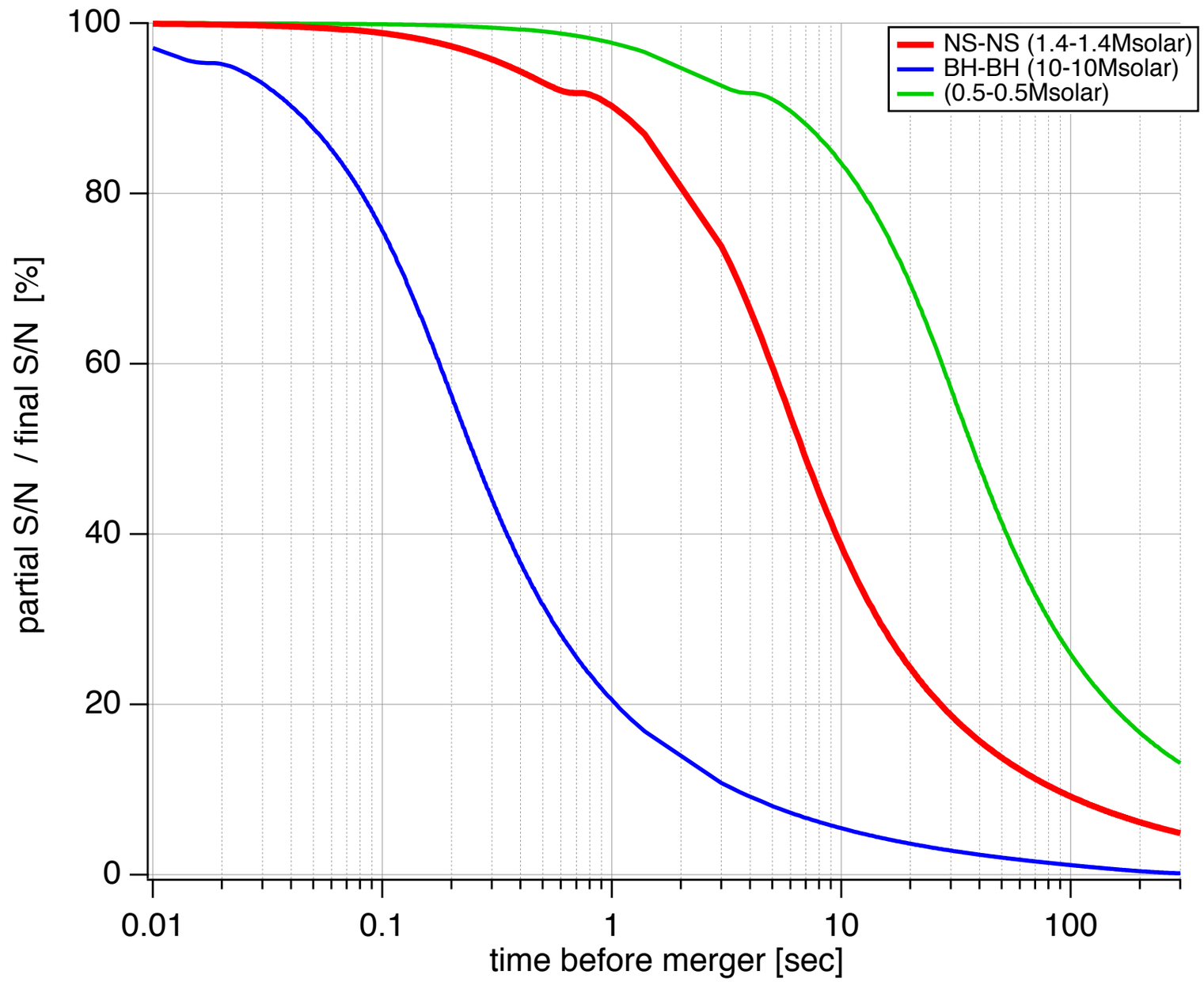
10秒前でも４割

検出するのにS/N>8とすると、予報が可能な連星までの距離は

１分前：25Mpc

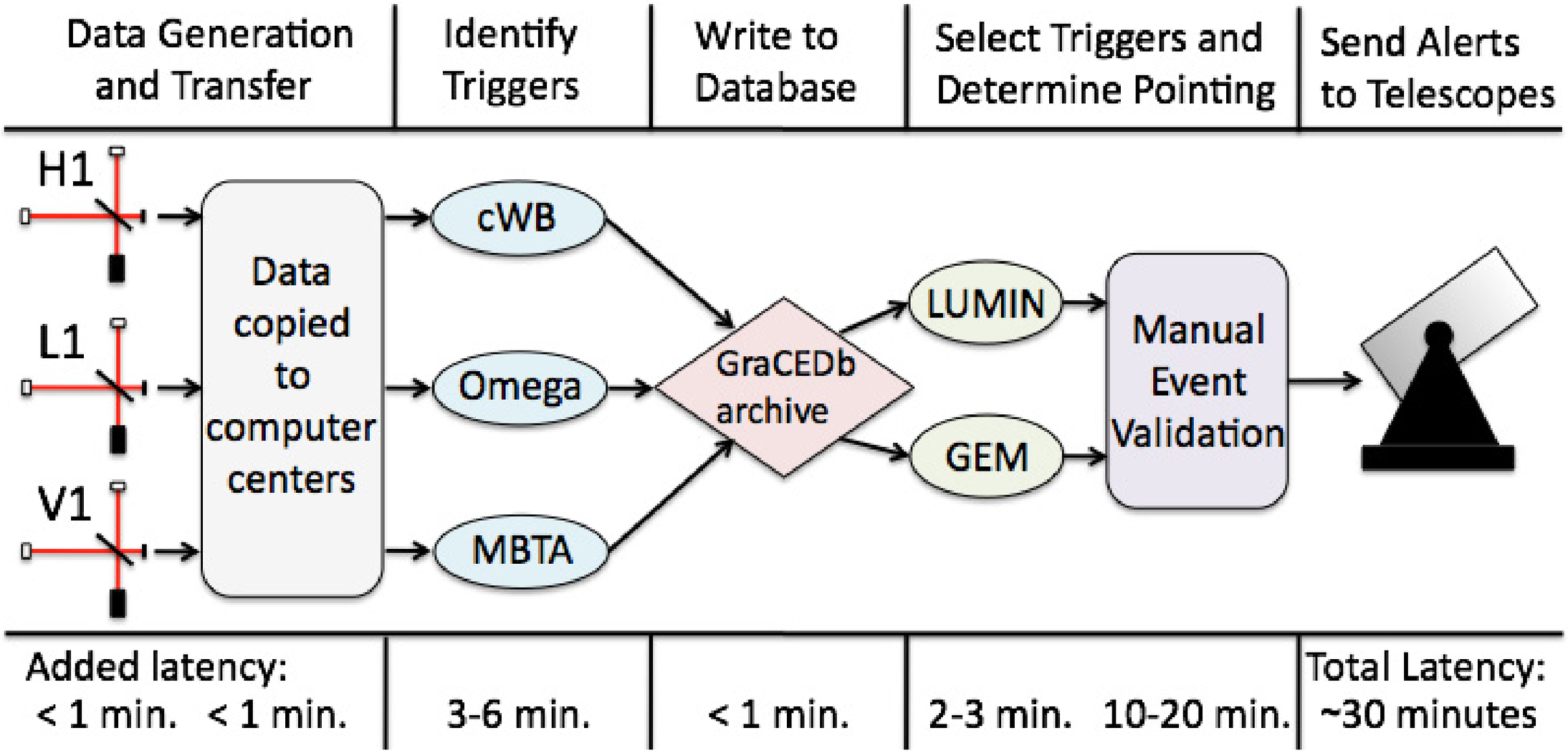
10秒前：80Mpc

（＊ただし最適方向。平均の目安は×0.59）



LIGO, Virgo @2009-2010

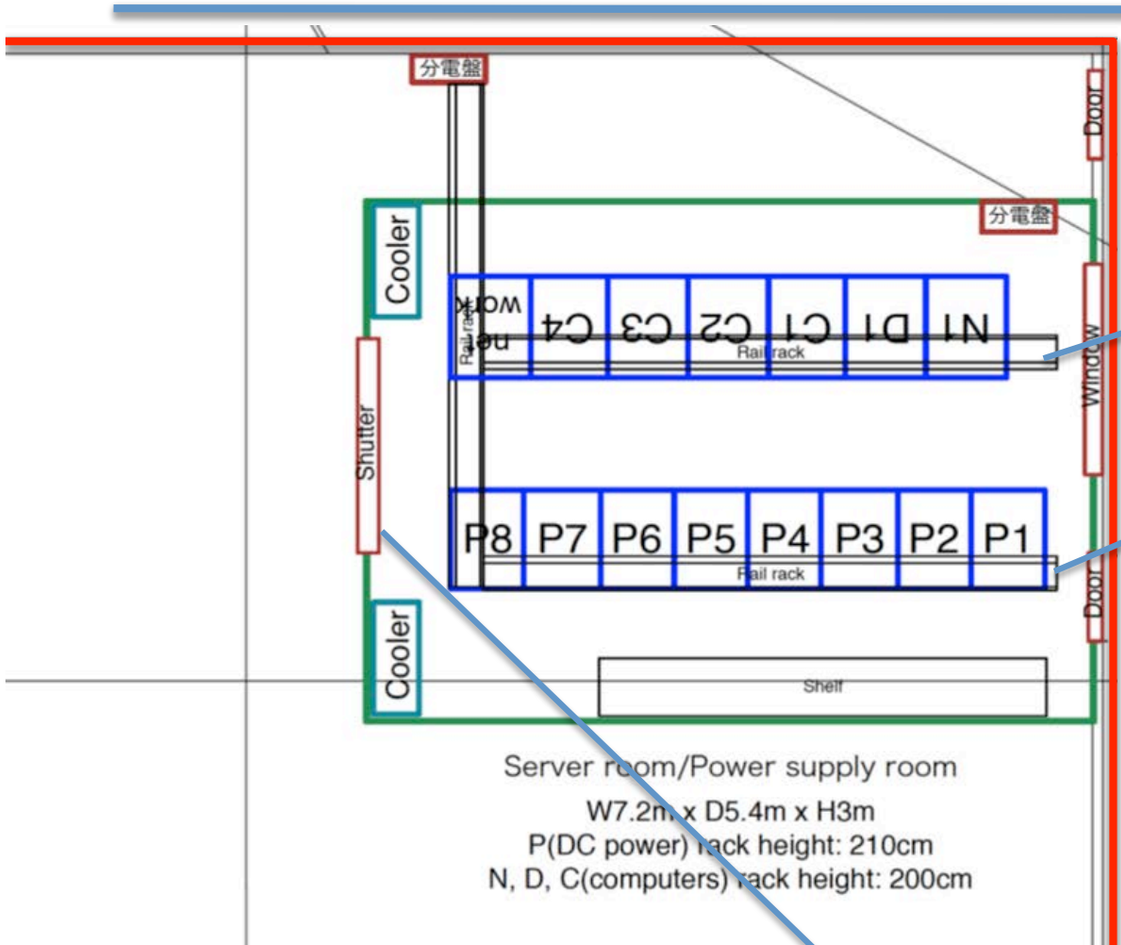
A&A 539, A124 (2012)



⇧ 現状(@2015)、探索
部分は高速化している

Control computers (installation)

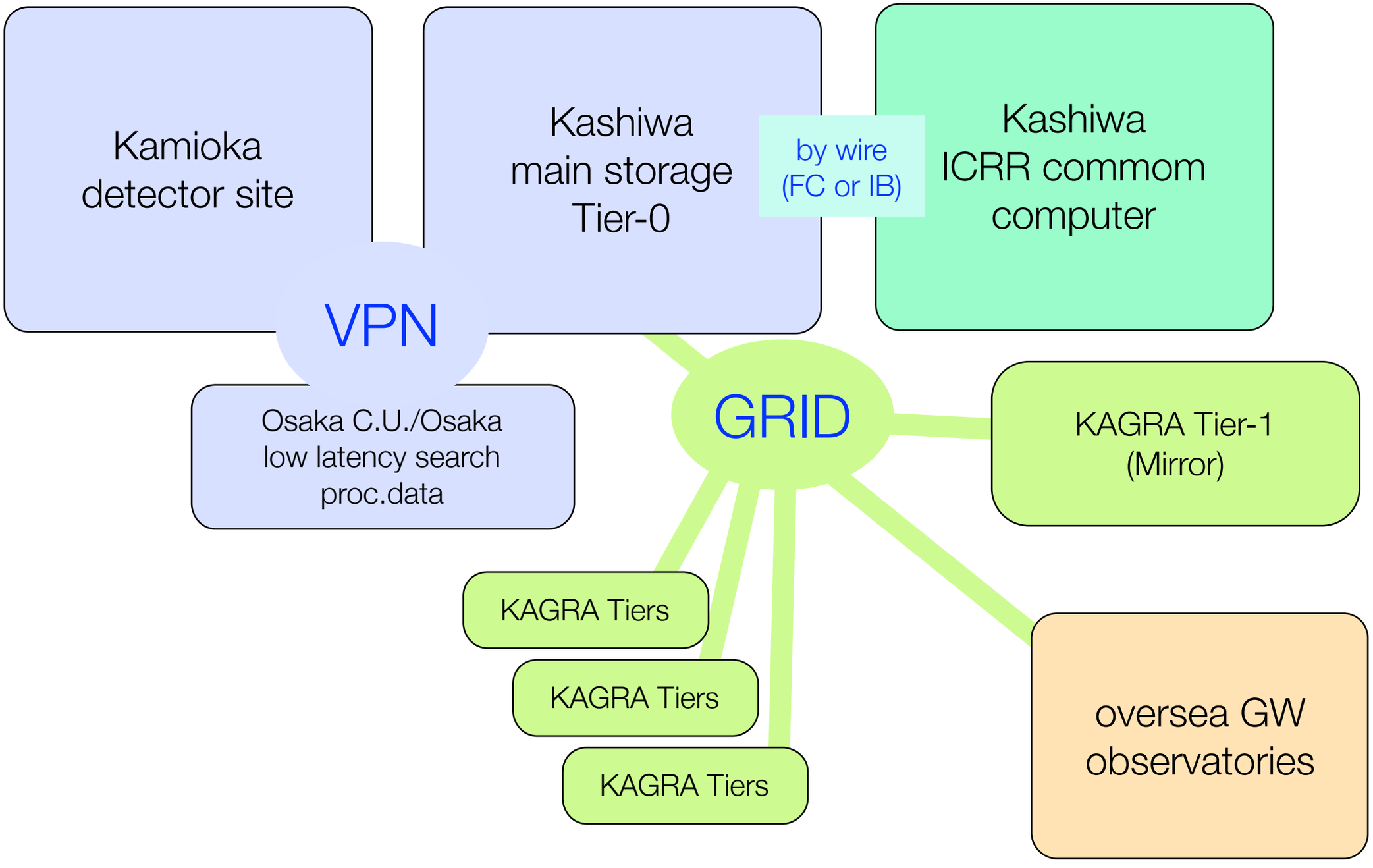
Inside of Front room



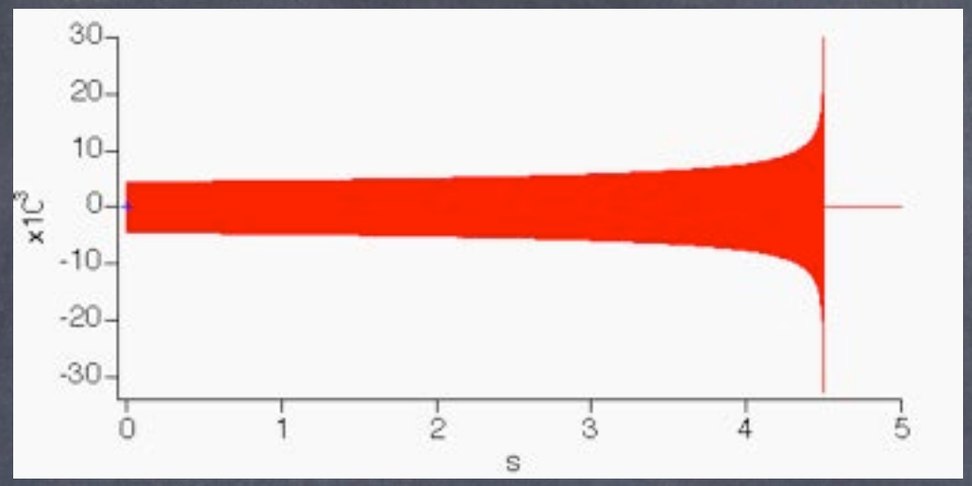
by O.Miyakawa

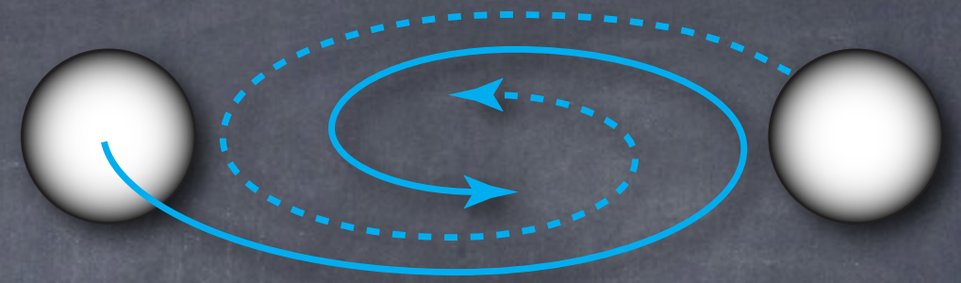
VPN and GRID

Tentative Plan

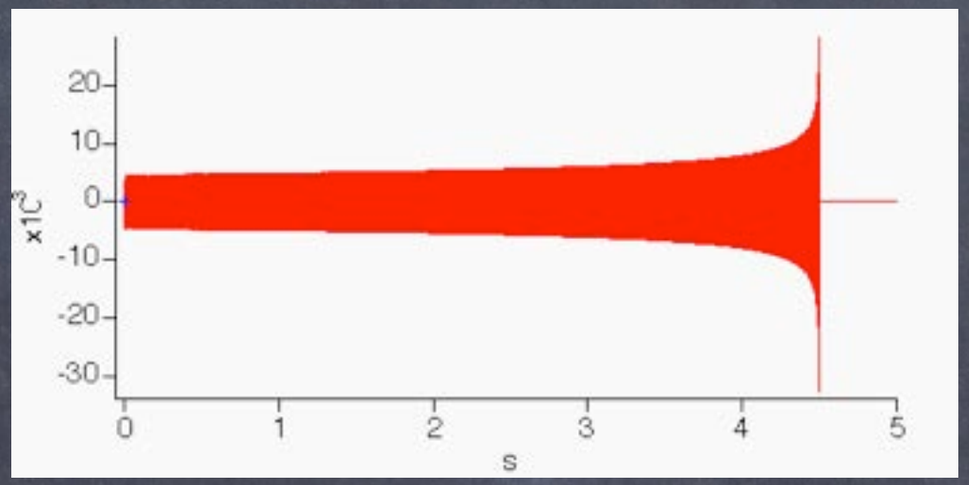


"Chirp" of mass

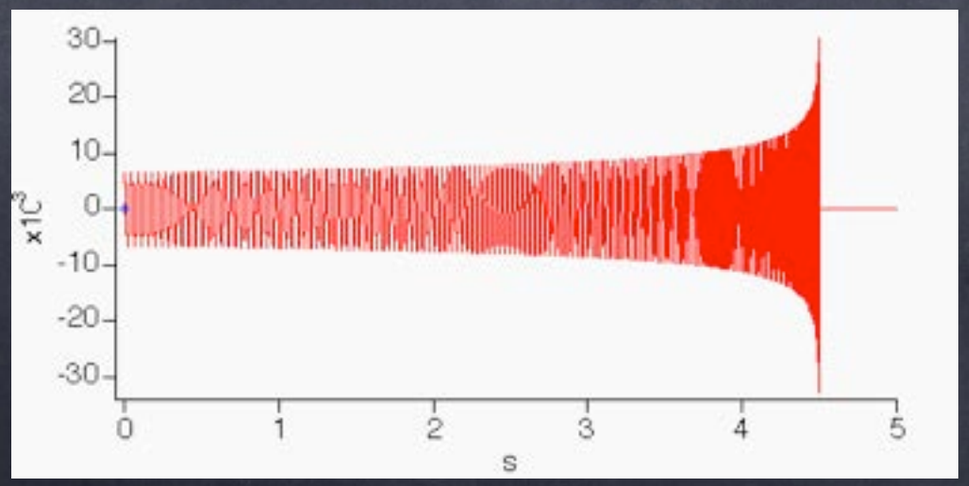




0.5-0.5 M_{solar}



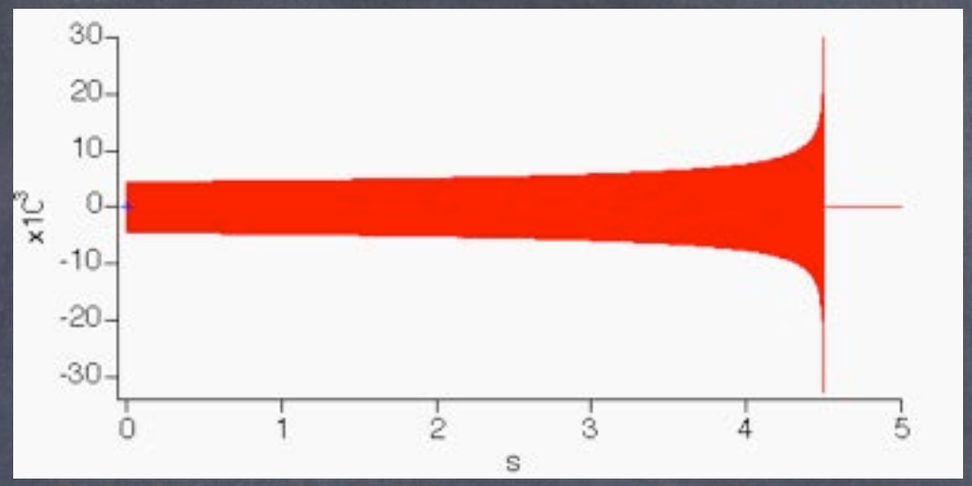
1.4-1.4 M_{solar}

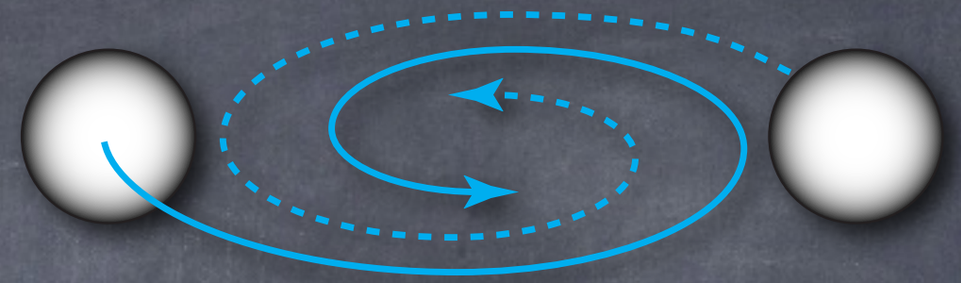


10-10 M_{solar}

frequency development --> mass of stars

"Chirp" of mass





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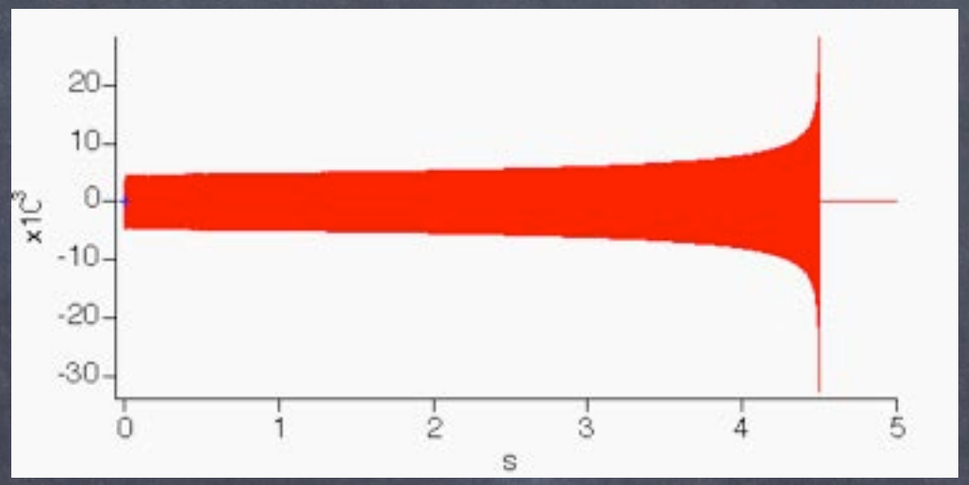

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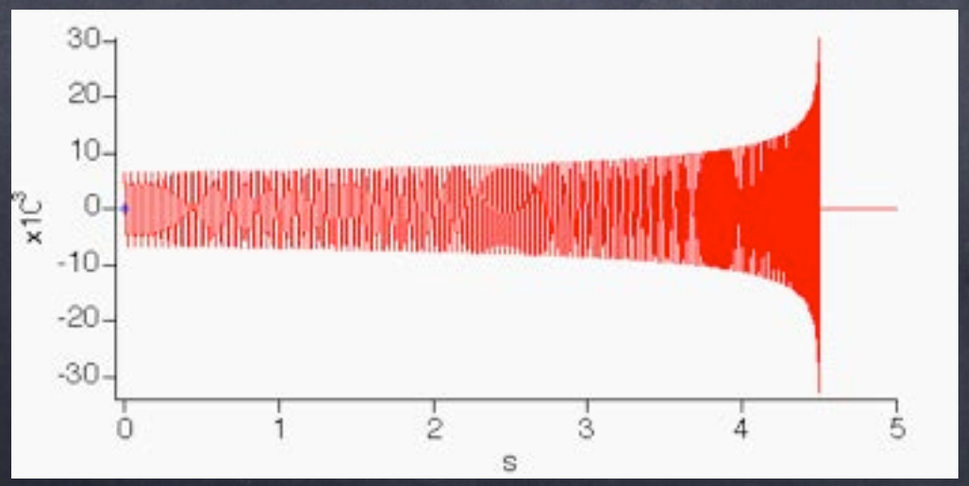
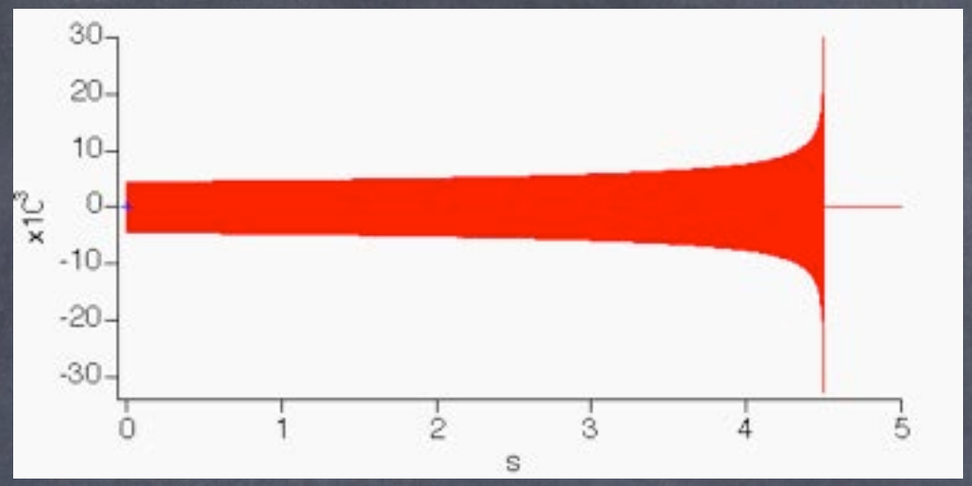
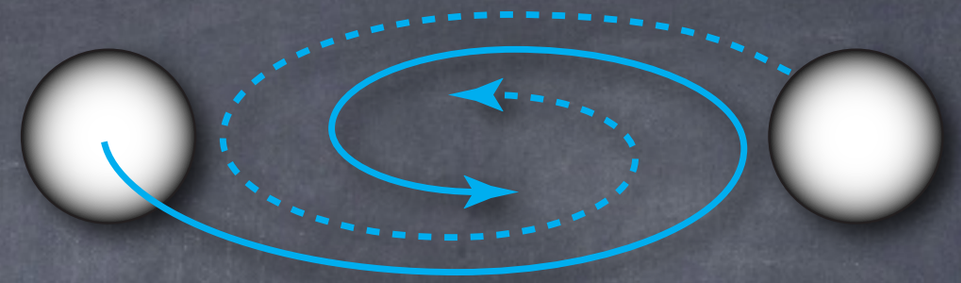


10-10 M_{solar}

frequency development --> mass of stars

"Chirp" of mass





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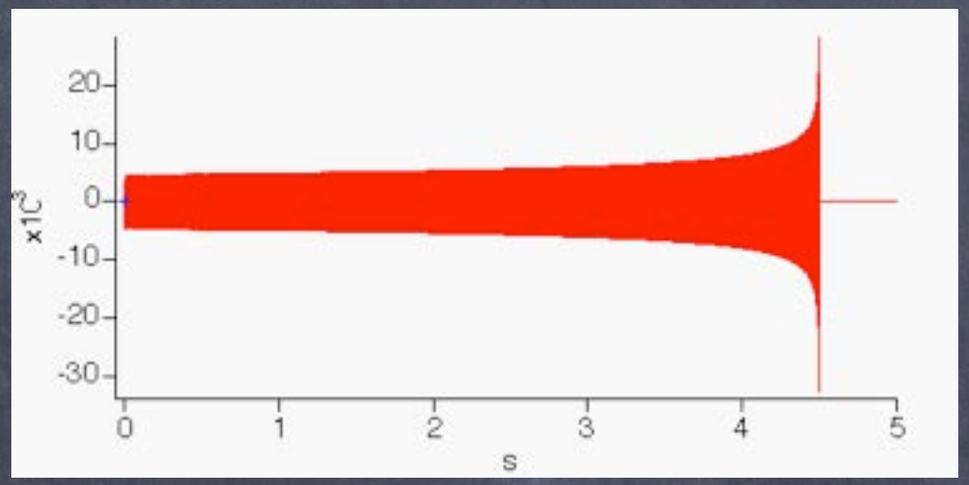

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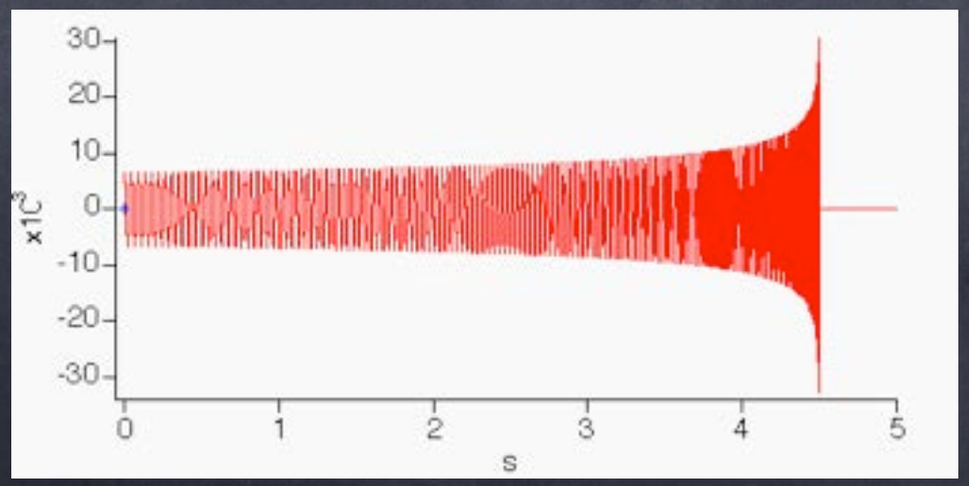

10-10 M_{solar}

frequency development --> mass of stars

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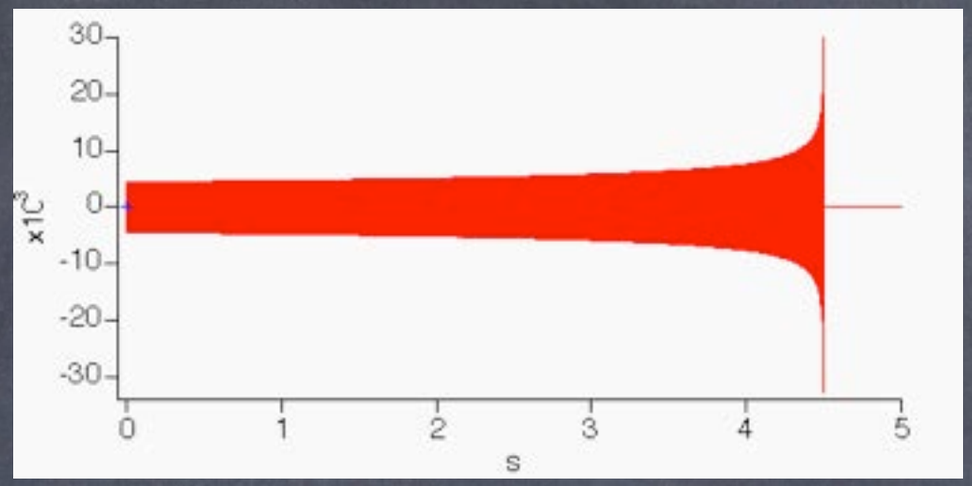
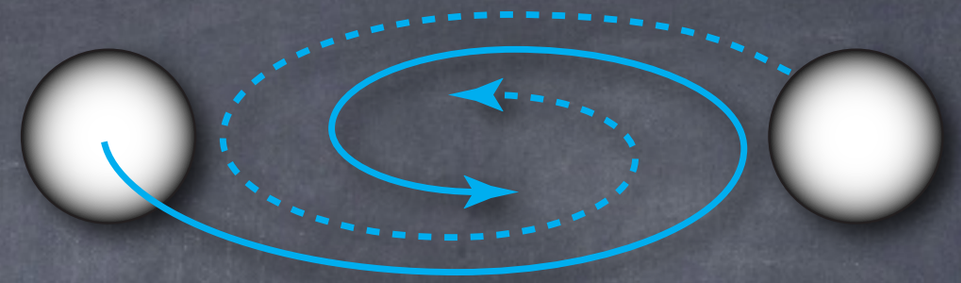
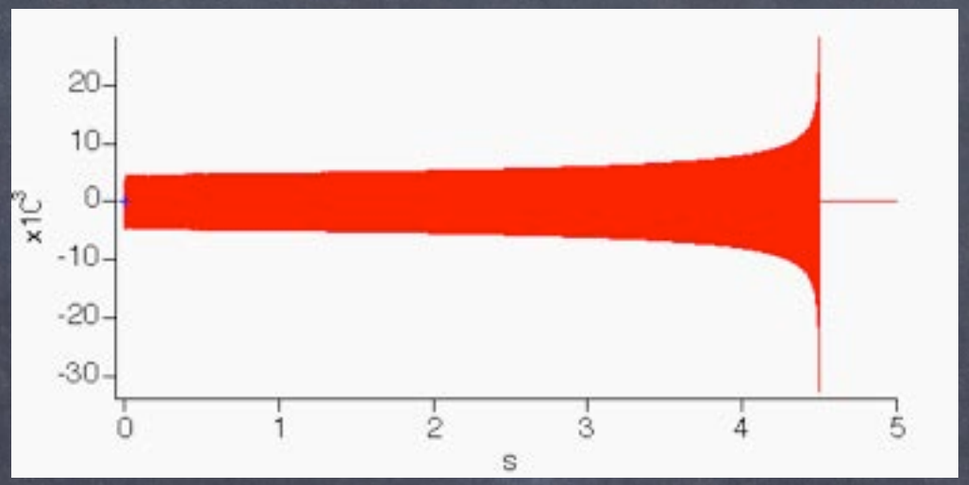




0.5-0.5 M_{solar}



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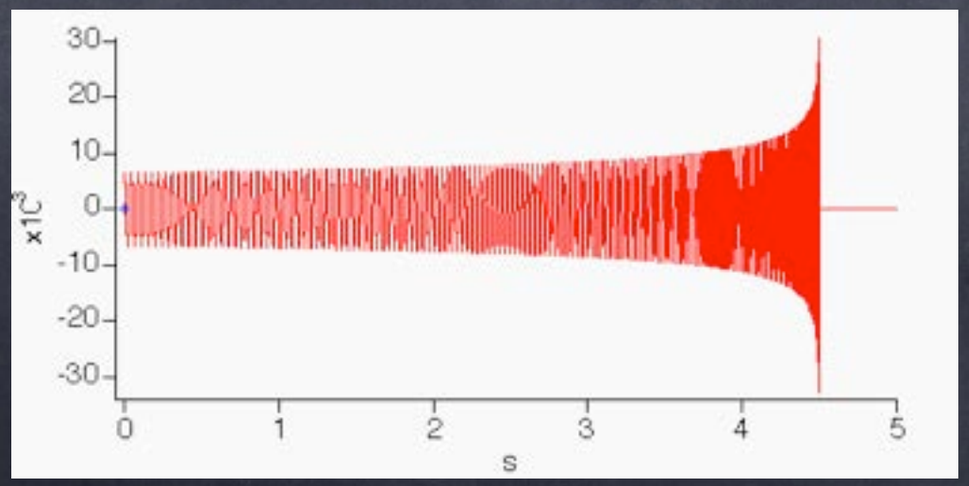

10-10 M_{solar}

frequency development --> mass of stars