GW Physics and Astronomy
Status and prospects

Yousuke Itoh (伊藤 洋介)

Research Center for the Early Universe,

the University of Tokyo

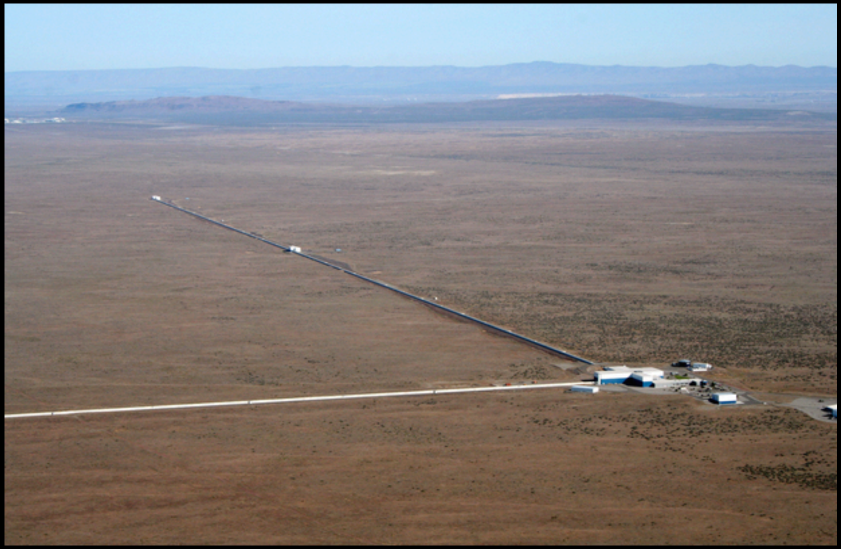
KAGRA Collaboration

LIGO Scientific Collaboration

First Workshop of the Young Researcher Association for Astroparticles, Chiba, 2016/10/29-31

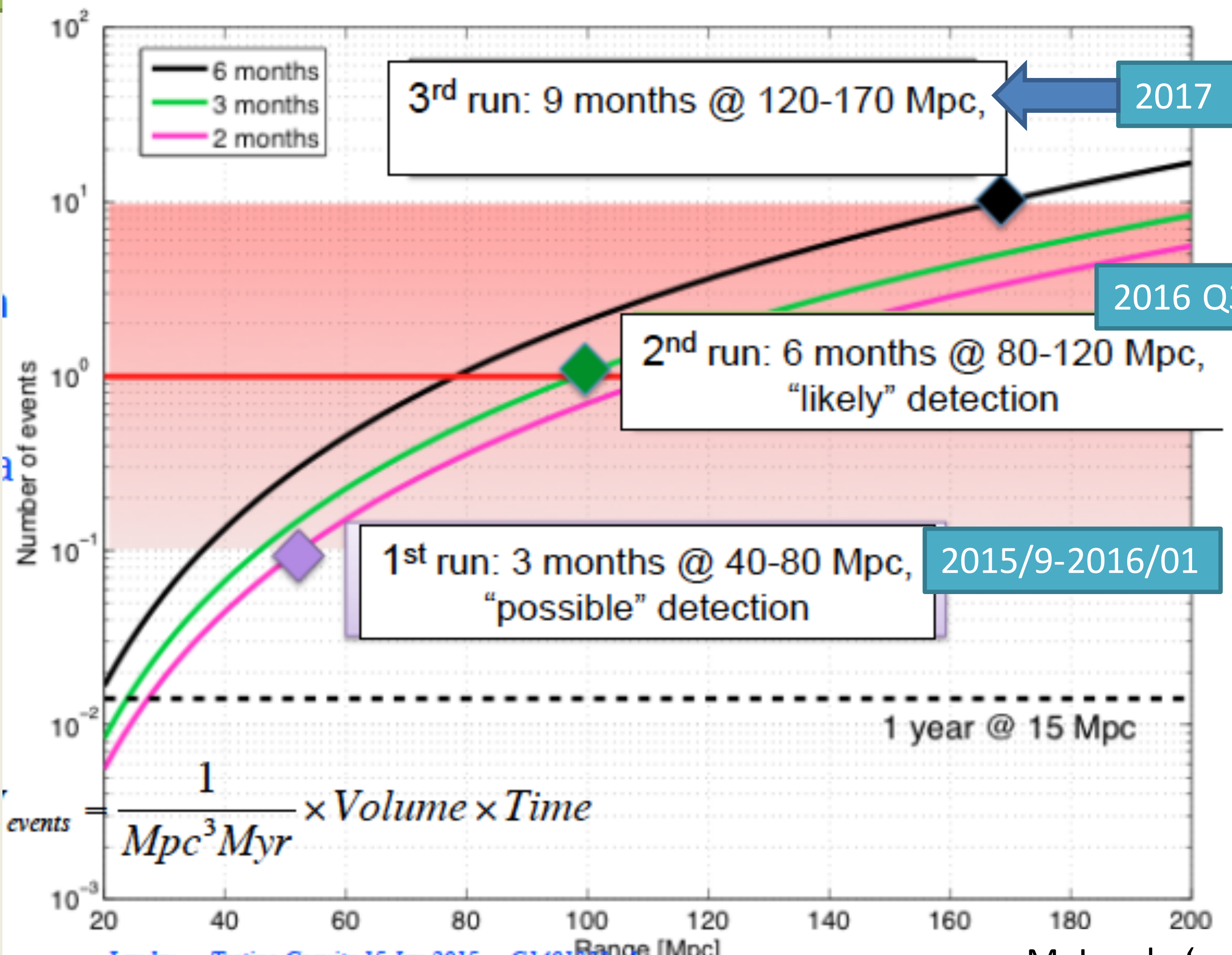
Yousuke Itoh

- post-Newtonian approximation (Tohoku Univ.) with T. Futamase, 2002
- GEO600 & LIGO data anlaysis at AEI, Potsdam & UWM (2002-2006)
- iKAGRA data analysis
  - Search for Continuous gravitational waves (pulsars)
  - Data analysis subsystem

GW150914 DISCOVERY BY LIGO

Expected NS/NS event rate for aLIGO 0.1 events in O1



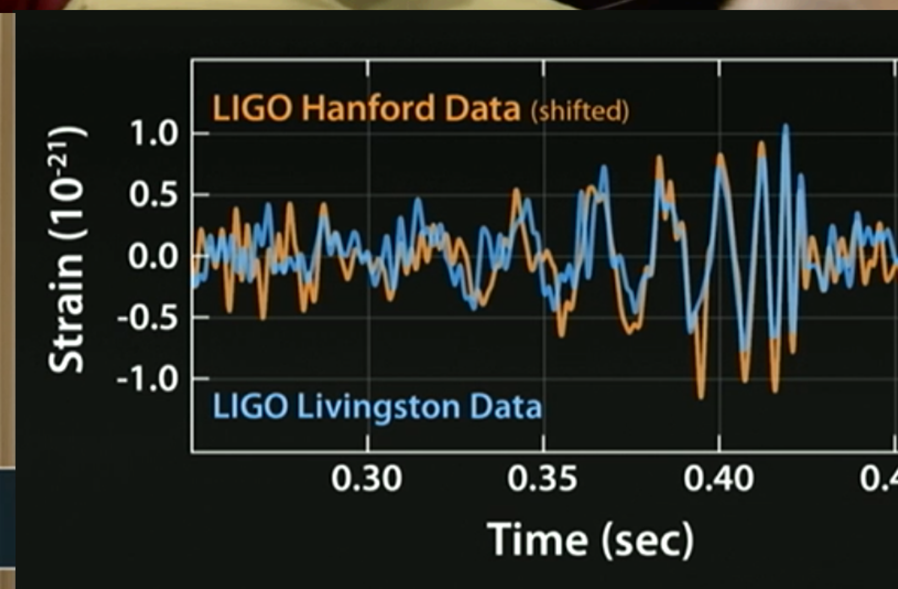
$$N_{events} = \frac{1}{Mpc^3 Myr} \times Volume \times Time$$

Landry – Testing Gravity 15 Jan 2015 - G1401

M. Landry's slide


National Science Foundation
NSF


David Reitze
LIGO Laboratory Executive Director, Caltech


LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
Time (sec)

GCN circular (access restricted at first)

TITLE: GCN CIRCULAR
NUMBER: 18330
SUBJECT: LIGO/Virgo G184098: Burst candidate in LIGO engineering run data

Dear colleagues,

We would like to bring to your attention a trigger identified by the online Burst analysis during the ongoing Engineering Run 8 (ER8).

1.3 Gyr

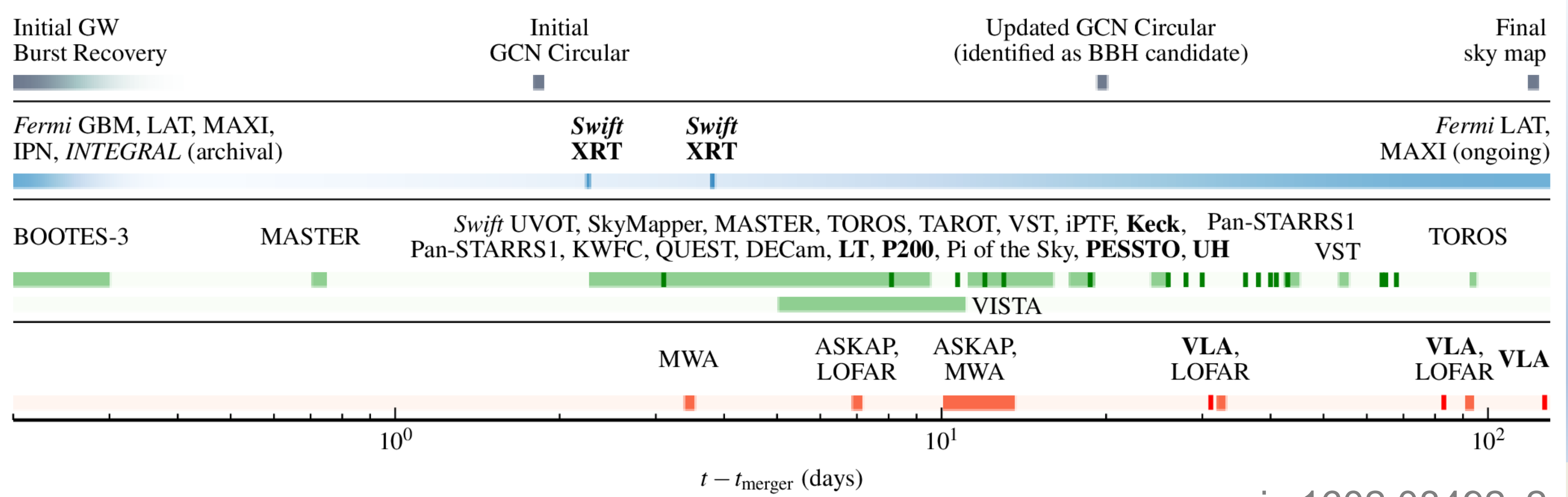
ER8 configuration:
(50 sec./a few min in O1)

2015-09-14 09:50:45 UTC

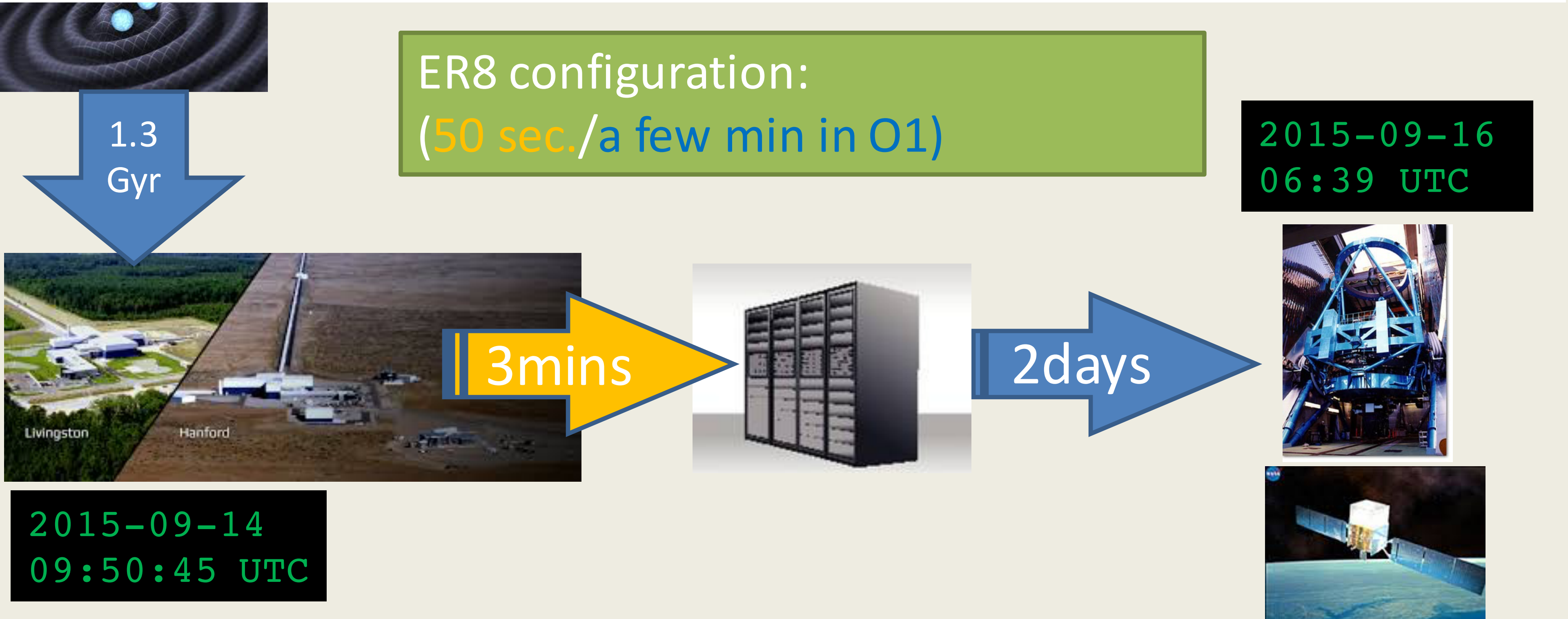
3mins

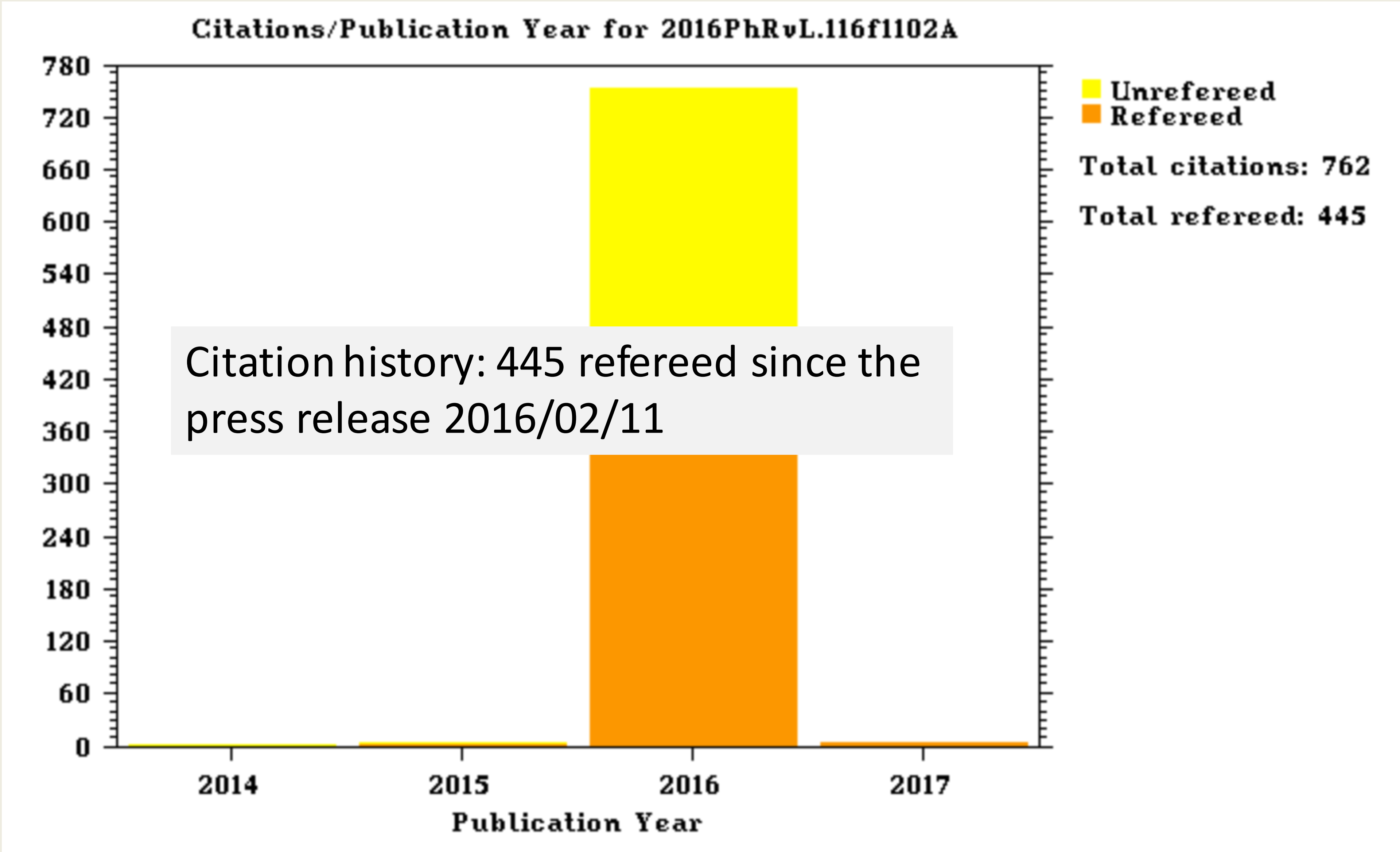
2days

2015-09-16 06:39 UTC



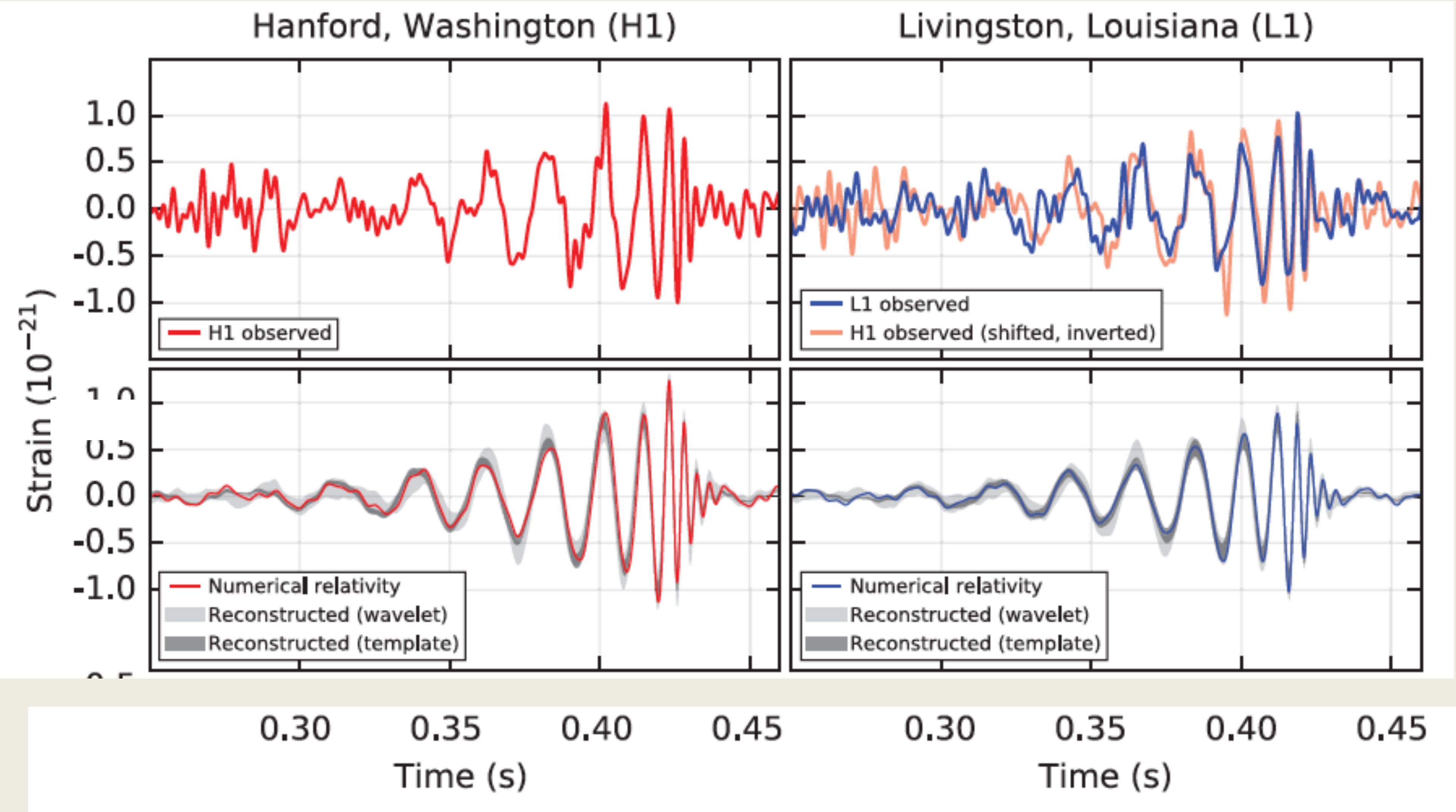
arxiv:1602.08492v2





Citation history: 445 refereed since the press release 2016/02/11

Observed GW



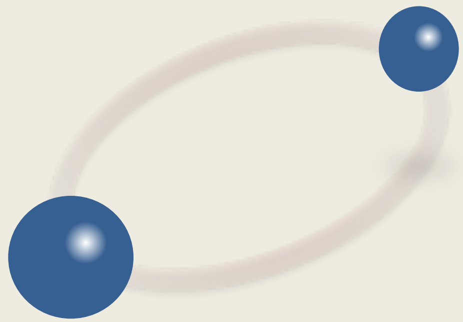
LSC 2016/2 PRL

Move from NS/NS to BBH

WHAT'S GW?

What emits gravitational wave (GW)?

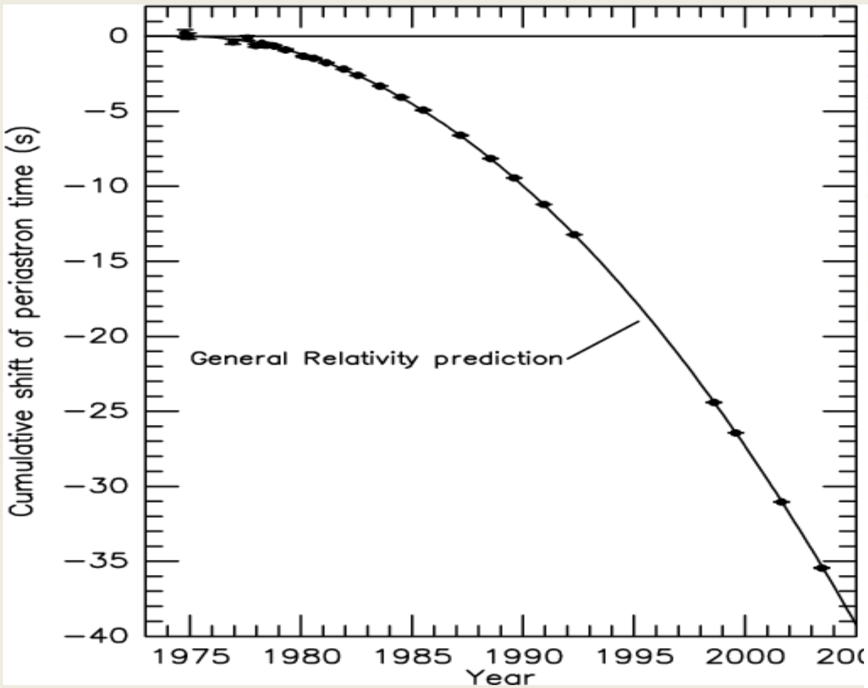
$$L_{GW} = \frac{G}{c^5}\left\langle \dddot{\hat{I}}_{ij}\dddot{\hat{I}}_{ij}\right\rangle \sim 4\times10^{50}\ \frac{\mathrm{erg}}{\mathrm{s}}\left(\frac{\varepsilon}{0.1}\right)\left(\frac{GM/c^2R}{0.1}\right)^2\left(\frac{v/c}{0.1}\right)^6$$



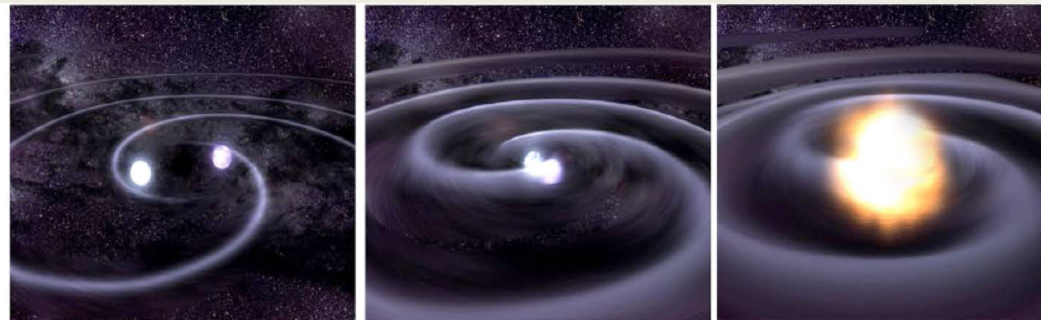
Non-Spherically symmetric (large ε),
Massive (large M),
Fast (large v)
systems will emit GWs most efficiently.
Astronomy!

Indirect evidence of GW existence: Double neutron star binary

- Known to exist: PSR B1913+16
- 1993 Nobel prize



Taylor & Weisberg (2004)



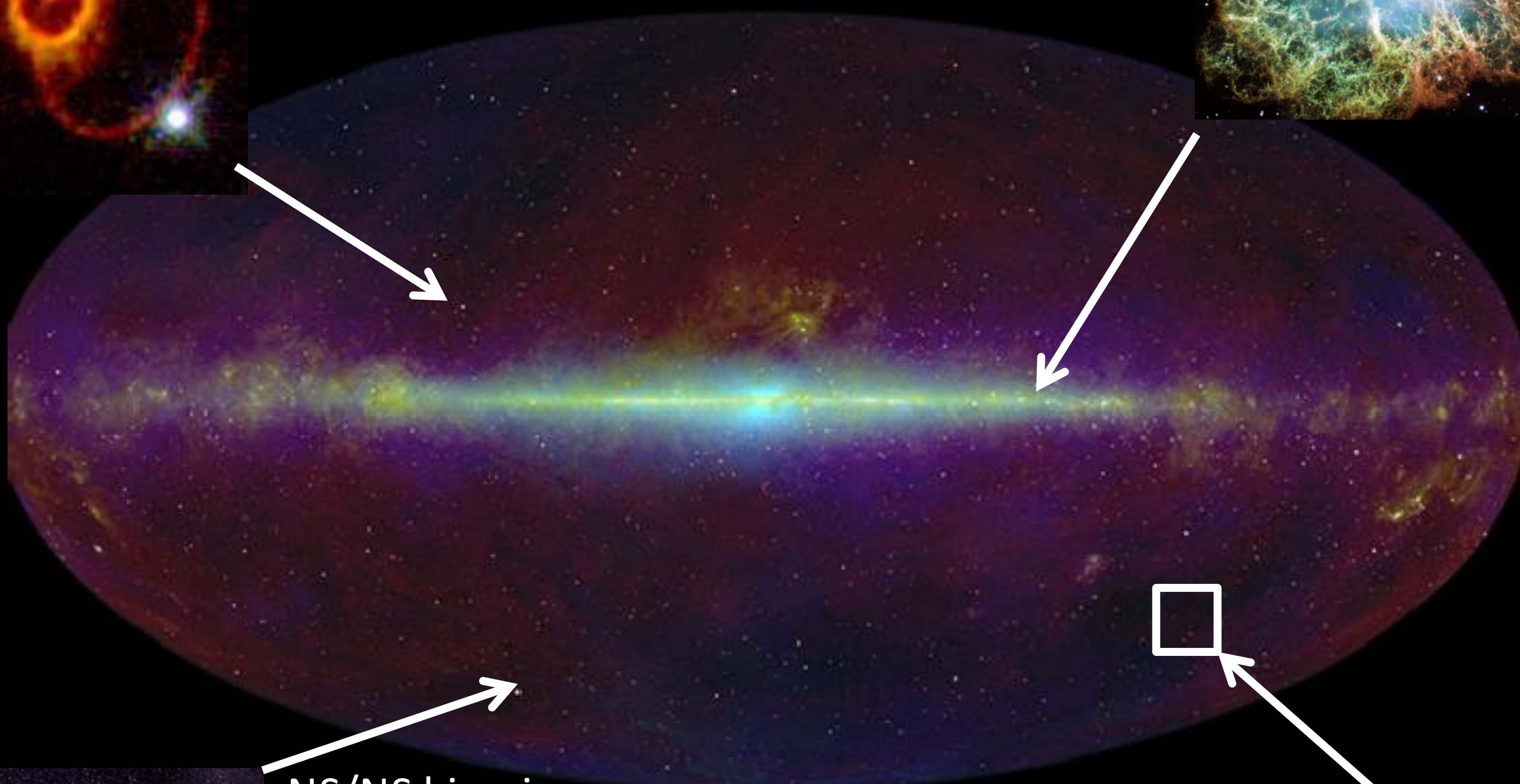
	P_b (days)	e	r (kpc)	$\tau_{\rm age}$ (Gyr)	$\tau_{\rm GW,c}$ (Gyr)	m_p ($M_\odot$)	m_c ($M_\odot$)
J0737-3039	0.102	0.088	1.2	0.2/0.05	0.08	1.34	1.25
J1518+4904	8.63	0.249	0.6	10	–	≤ 1.17	≥ 1.55
B1534+12	0.421	0.274	1.0	0.25	3.2	1.33	1.35
J1756-2251	0.320	0.181	2.5	0.4	1.6	1.40	1.18
J1811-1736	18.8	0.828	5.5	2	–	≤ 1.64	≥ 0.93
J1829+2456	1.18	0.139	0.74	10	–	≤ 1.34	≥ 1.26
J1906+0746	0.166	0.085	4.5	0.0001	0.32	1.25	1.37
B1913+16	0.323	0.617	7.1	0.1	0.32	1.44	1.39
B2127+11C	0.335	0.681	13	0.1	0.25	1.36	1.35

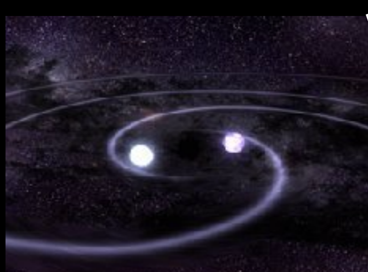
J0737-3039 (2003)
NEW: PSR J1913+1102 by E@H

Gravitational Wave sources for KAGRA/LIGO/VIRGO

SNe, GRBs in local universe.

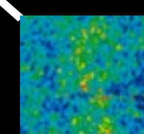
Nearby pulsars in Milkyway





NS/NS binaries coalescence within 200 Mpc. Steller mass BH/BH within z~ 0.1.

Stochastic background Probably not primordial one.

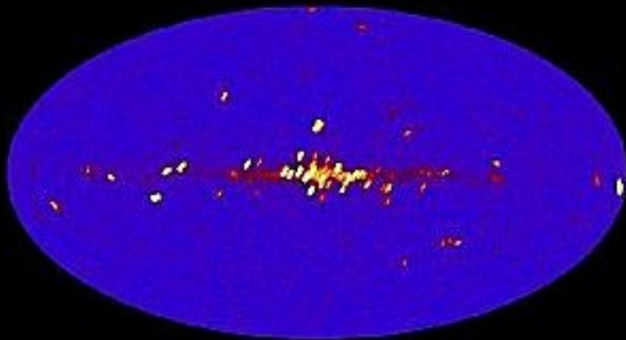


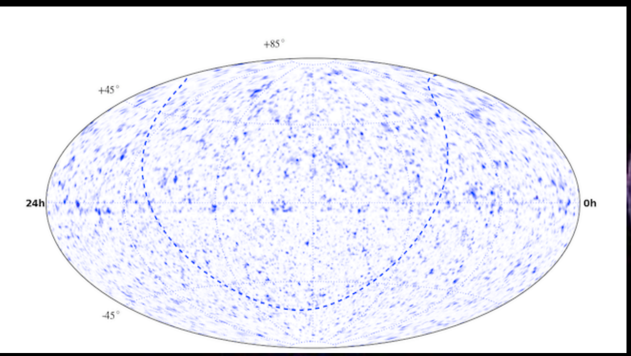
Images are taken from NASA and hubblesite.

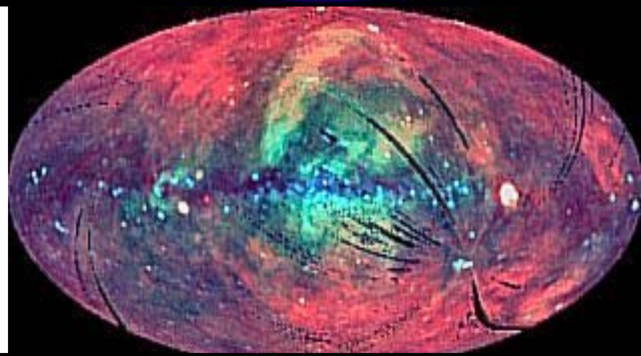
All sky maps:

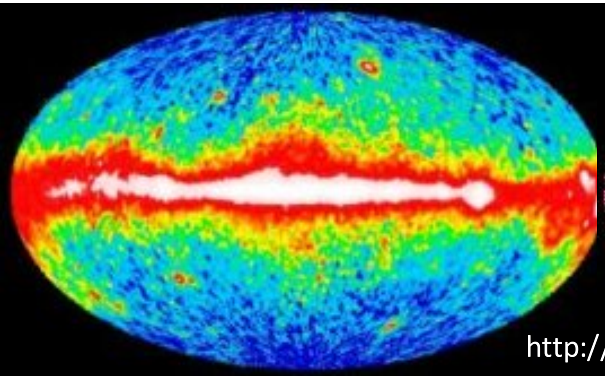
Neutrino (Icecube)
Gamma-Ray >100MeV (CGRO, NASA)
Gamma-Ray (N. Gehrels et.al. GSFC, EGRET, NASA)
X-Ray 2-10keV (HEAO-1, NASA)
X-Ray 0.25, 0.75, 1.5 keV (S. Digel et. al. GSFC, ROSAT, NASA)
Ultraviolet (J. Bonnell et.al.(GSFC), NASA)
Visible (Axel Mellinger)
Infrared (DIRBE Team, COBE, NASA)
Radio 1420MHz (J. Dickey et.al. UMn. NRAO SkyView)
Radio 408MHz (C. Haslam et al., MPIfR, SkyView)

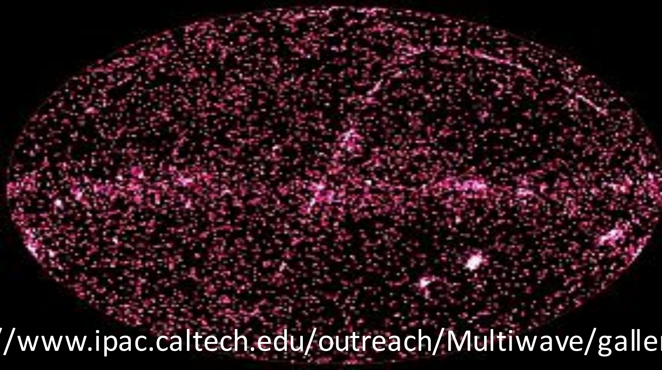
GW????

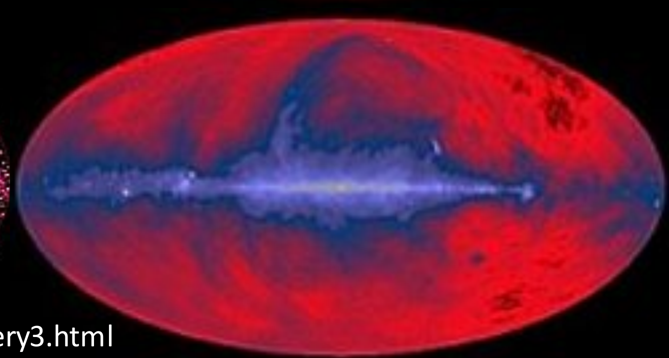












http://www.ipac.caltech.edu/outreach/Multiwave/gallery3.html

All sky maps:

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Gamma-Ray >100MeV (CGRO, NASA)
X-Ray 0.25, 0.75, 1.5 keV (S. Digel et. al. GSFC, ROSAT, NASA)
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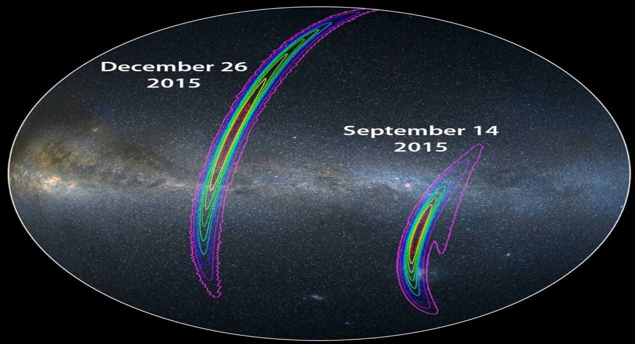
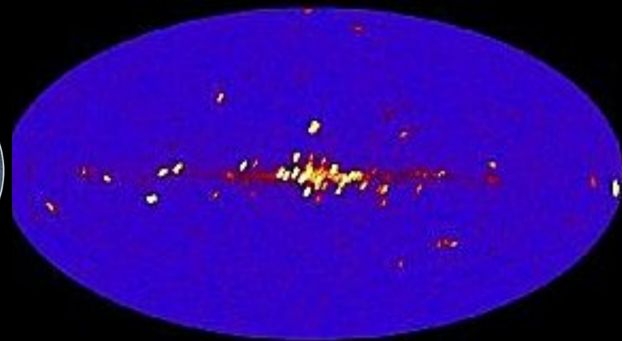
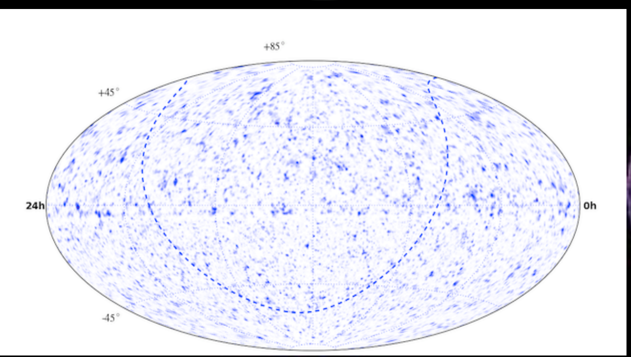
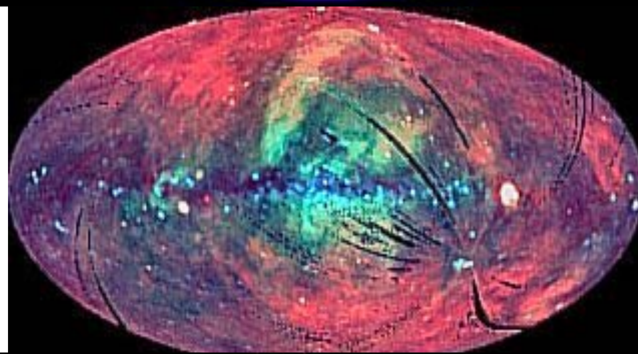
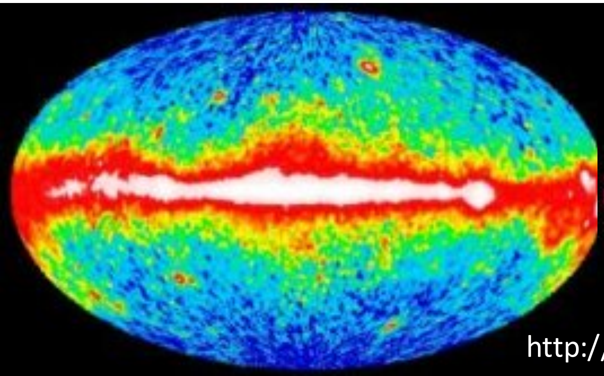
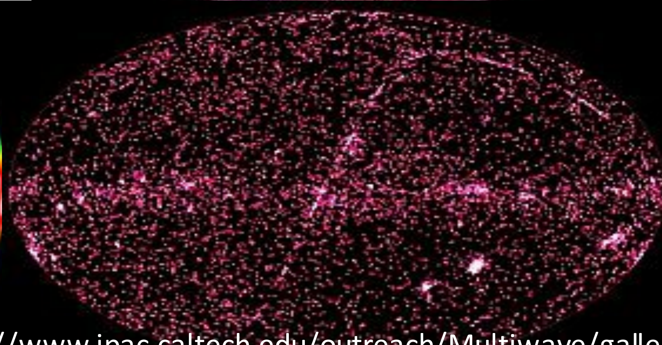
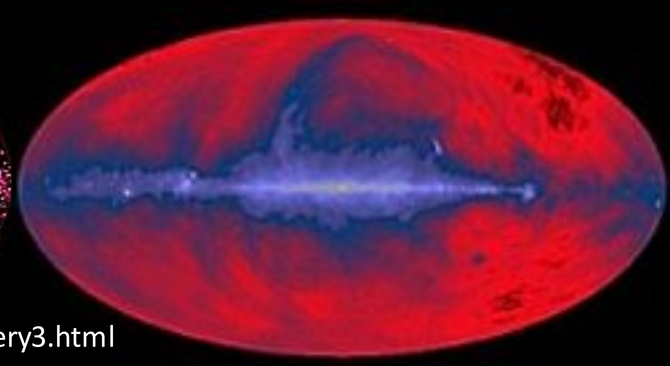






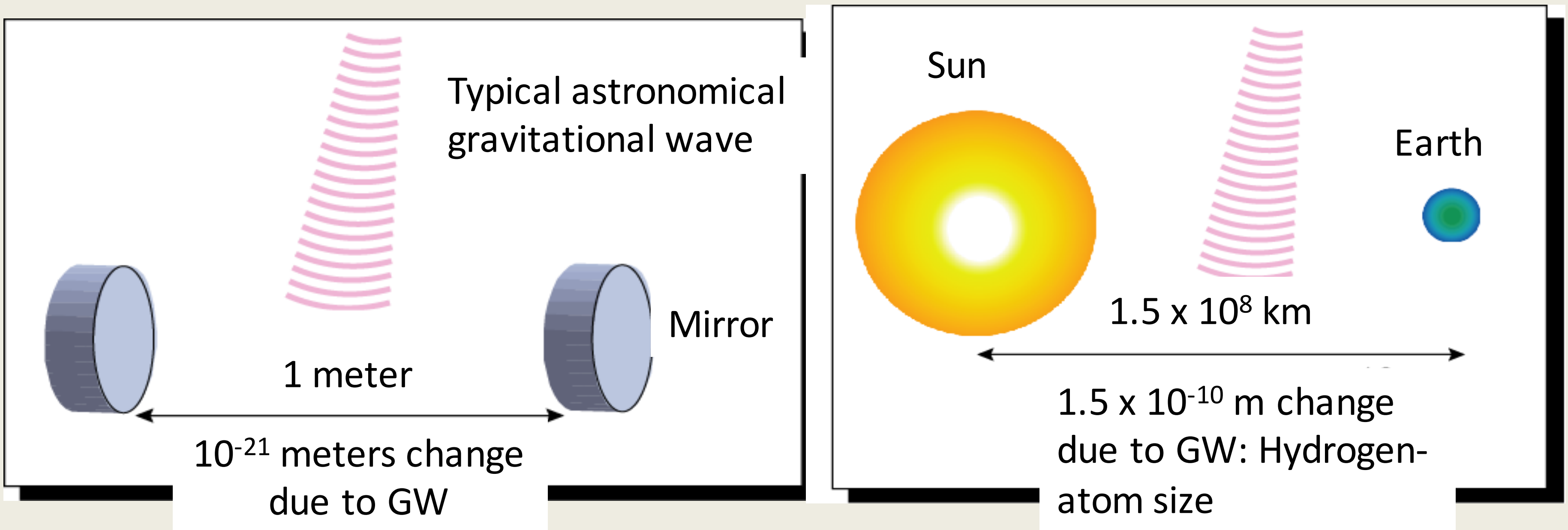


http://www.ipac.caltech.edu/outreach/Multiwave/gallery3.html

It's a tiny effect at the Earth.

In essence, we just measure change of distance between two freely falling objects….



But it is extraordinarily tiny tiny change in distance ….

$$\delta l = h(t) L$$

It’s a tiny effect at the Earth.

$$\delta l = h(t) L$$

重力波による
長さの変化

重力波振幅

「ベース」の
長さ

DETECTOR BASICS

km-class GW detectors in the world: 2015

LIGO Hanford 4 km, desert

GEO 600 600 m, university farm

LIGO Livingston 4 km, forest

Virgo Cascina 3 km

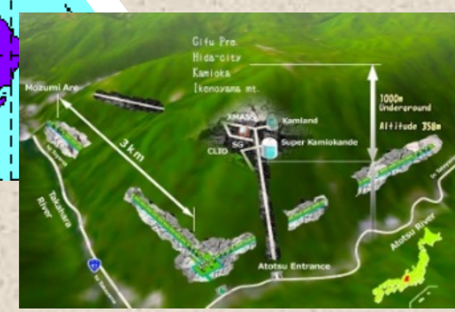
km-class GW detectors in the world: FY2015

LIGO Hanford 4 km, desert

GEO 600 600 m, university farm

LIGO Livingston 4 km, forest

Virgo Cascina 3 km



iKAGRA Kamioka, 3 km, Michelson underground

km-class GW detectors in the world: 2023 -

LIGO Hanford 4 km, desert

GEO 600 600 m, farm

LIGO India !
Approved by the Indian gov. on 2016/02/16
202x online??

LIGO Livingston 4 km, forest

Virgo Cascina 3 km

bKAGRA Kamioka, 3 km, DRFPM cryogenic, underground

Gravitational Wave Detectors

measure time variation of spatial distance

LIGO Hanford 2Km & 4Km
LIGO Livingston 4 Km
GEO Hannover 600m

http://www.ligo-wa.caltech.edu/

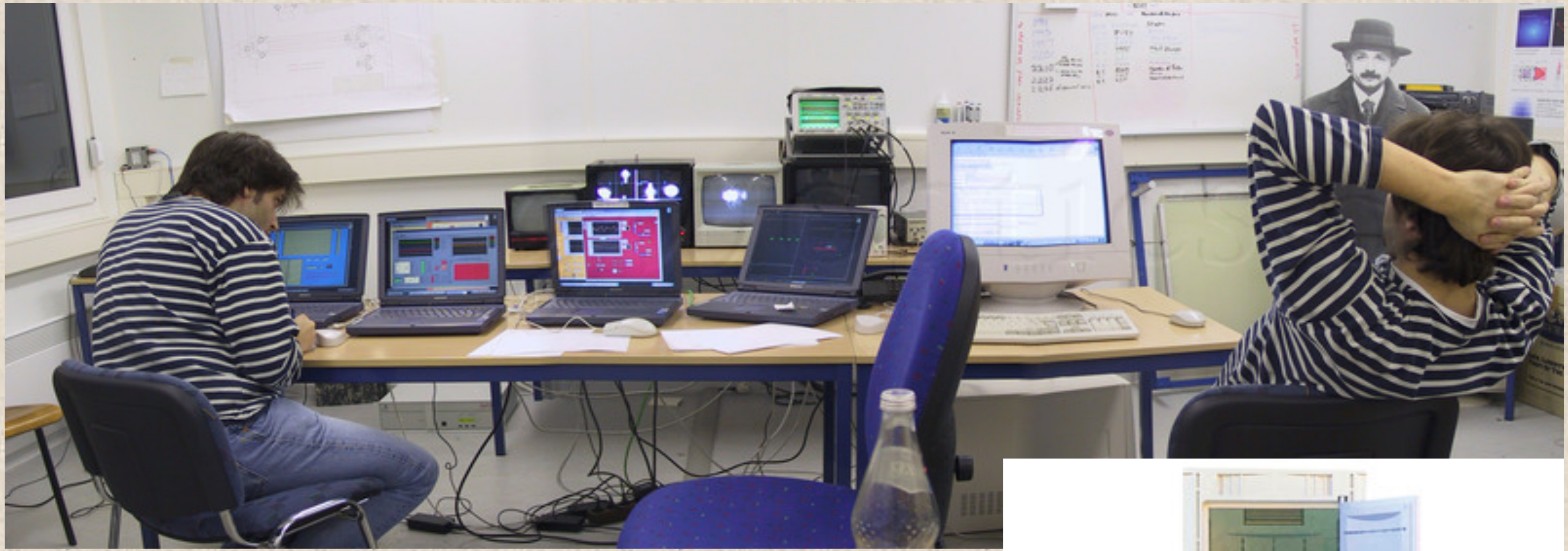
aLIGO (Hanford) Control room

Gravitational Wave Detectors

measure time variation of spatial distance

GEO 600 control room

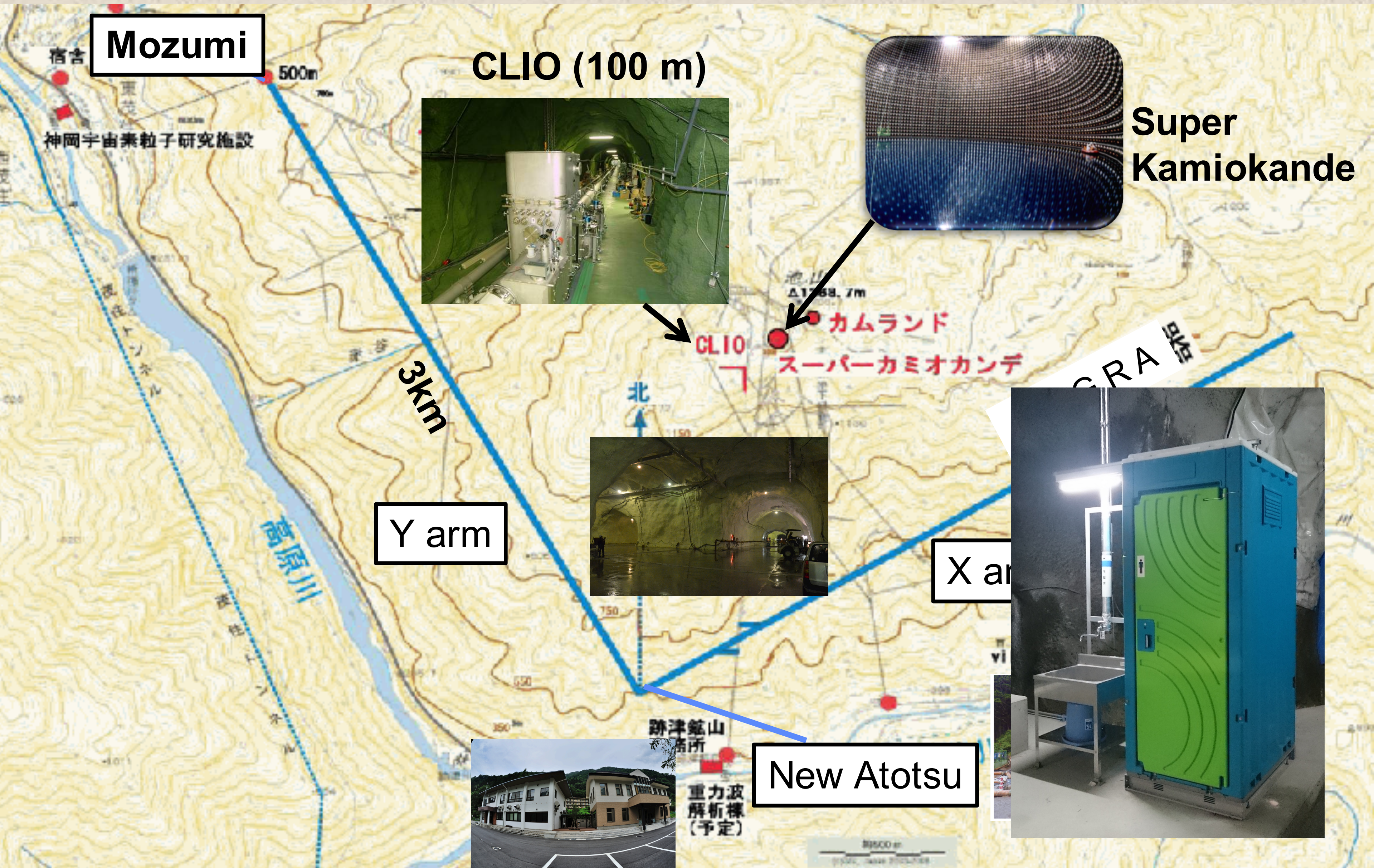
GEO 600 Control room around 2002



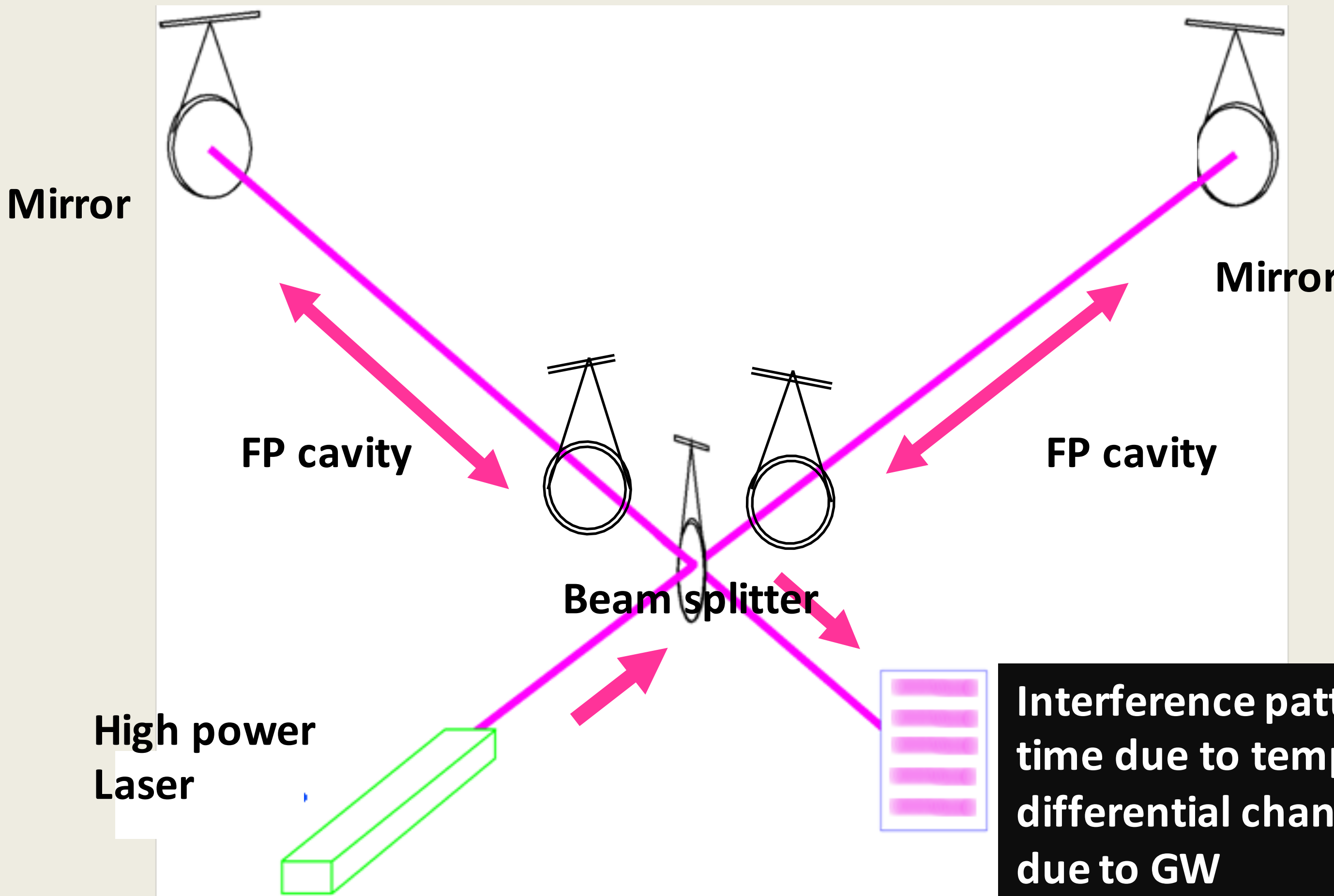
Toilets available (outside of the control room) →

KAGRA site

KAGRA site (Kamioka mine)



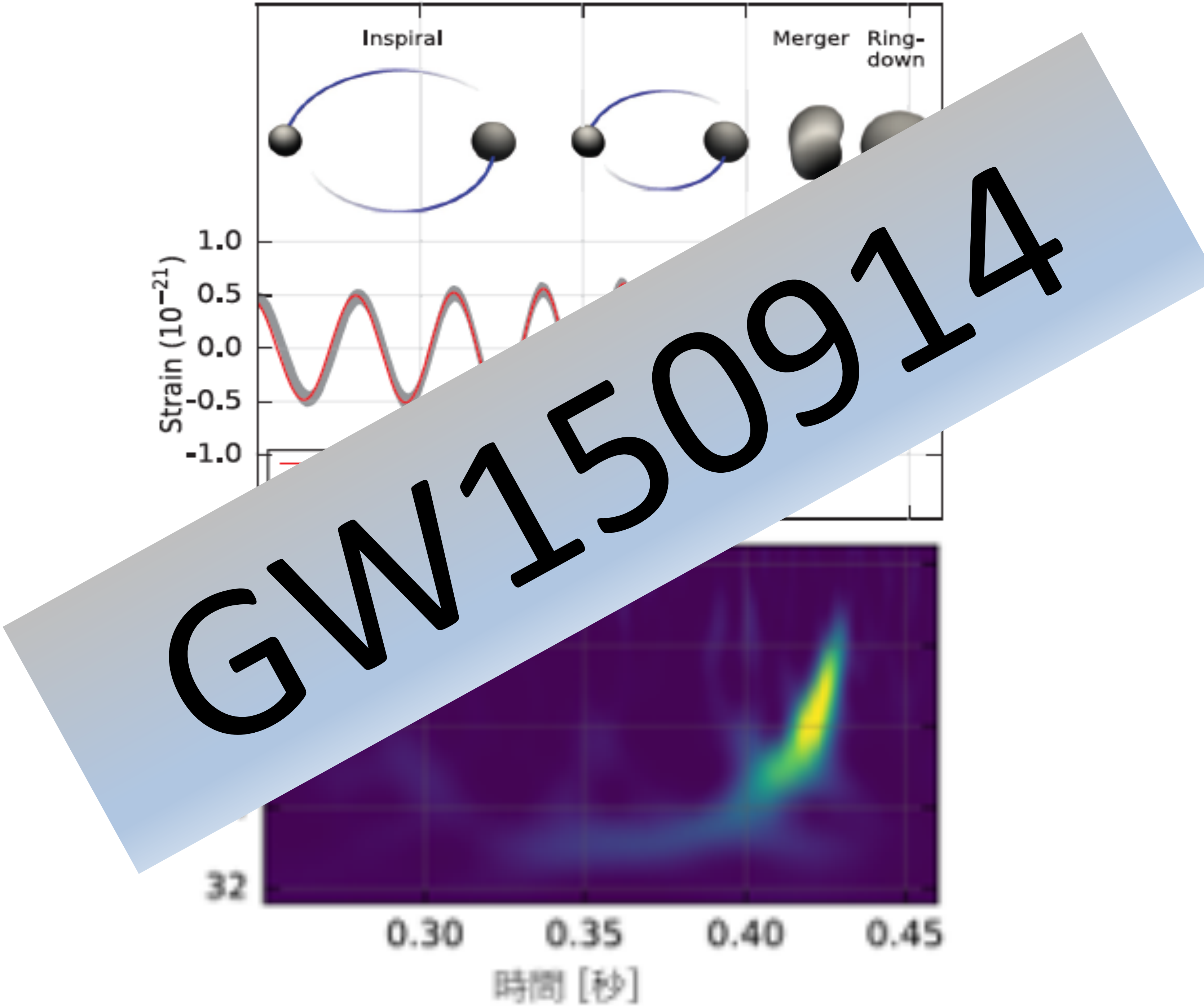
Use a Laser interferometer to detect GWs



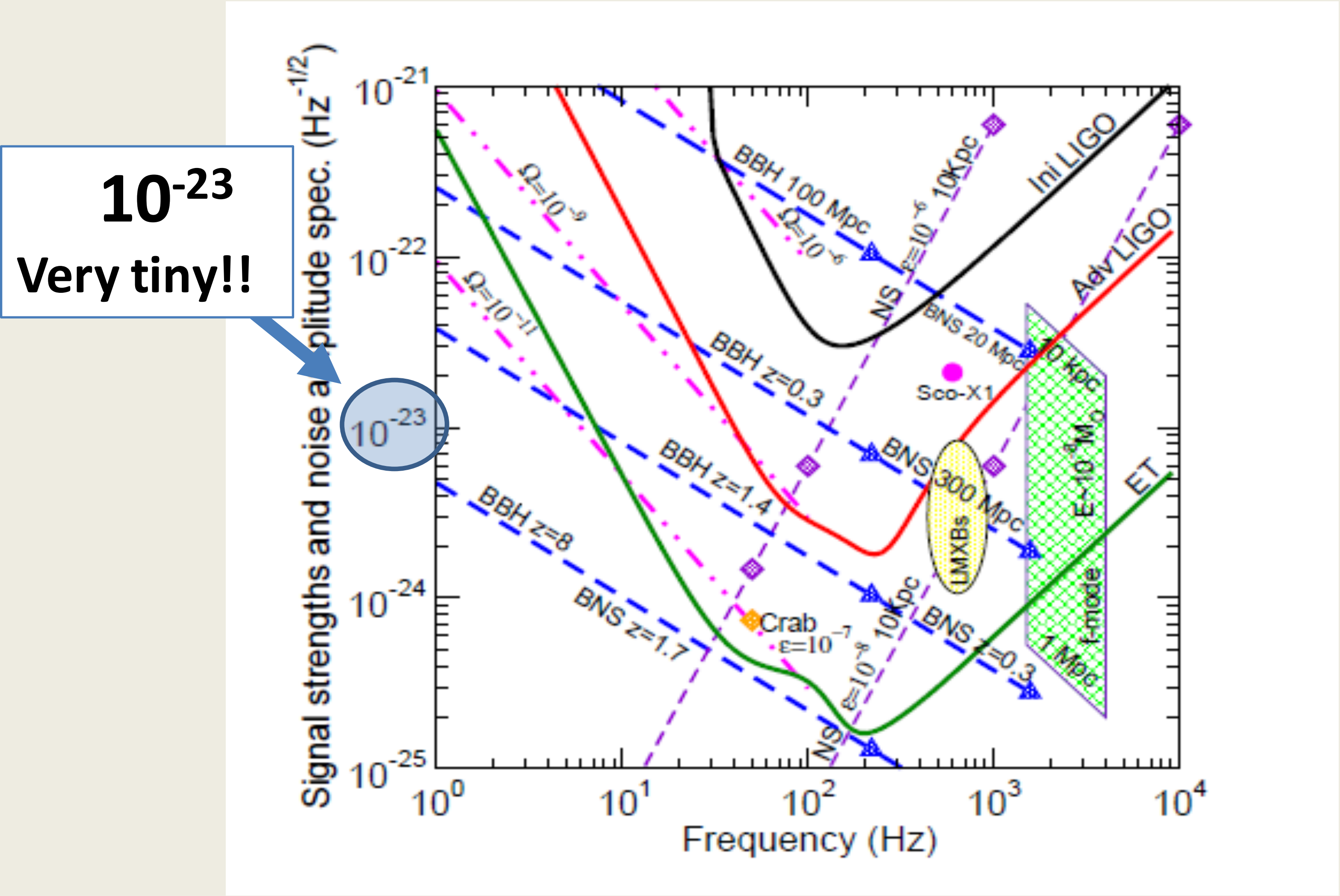
Interference pattern changes in time due to temporal differential change in distances due to GW

アニメーション(LIGO)

A Schematic figure of an interferometric GW detector: taken from Einstein@Home web page.

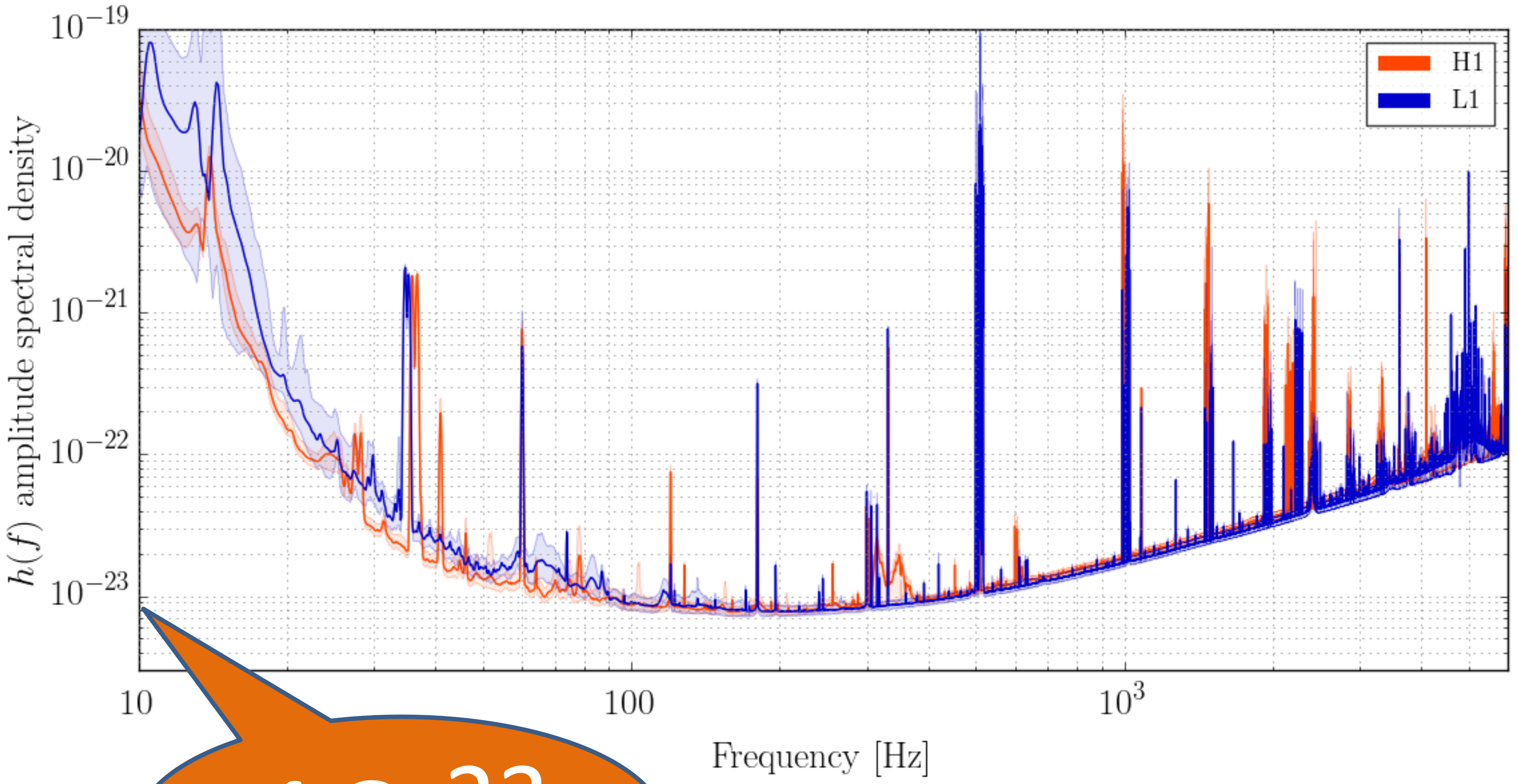

GW150914
Inspiral
Merger
Ring-down
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
32
0.30
0.35
0.40
0.45
時間 [秒]

Sensitivity curves of ground based detectors and expected GW sources



Sathyaprakash & Schutz Liv. Rev. Rel. (2009)

GW experimentalists had made it!!!



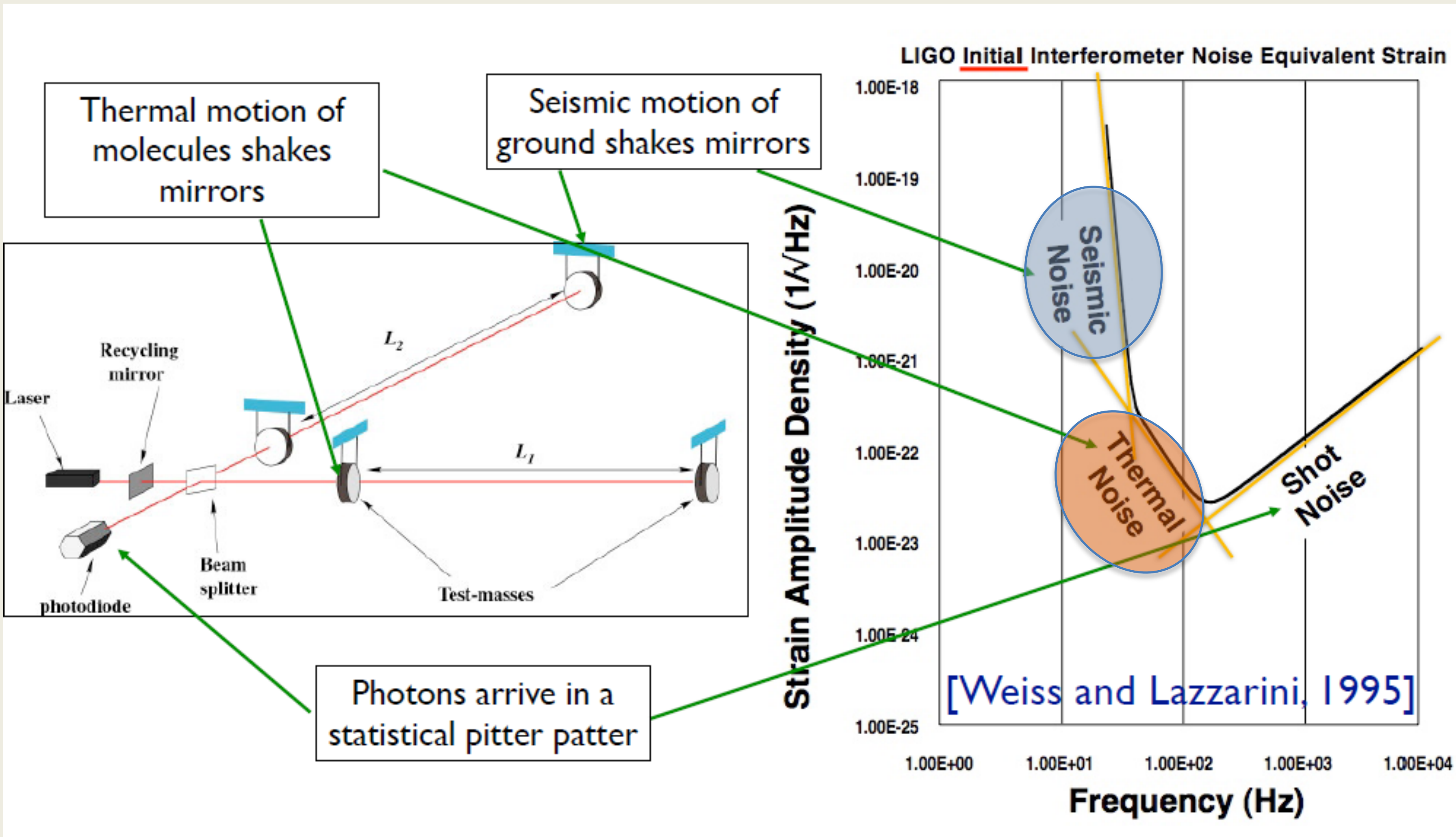
10^{-23}

https://losc.ligo.org/events/GW150914/

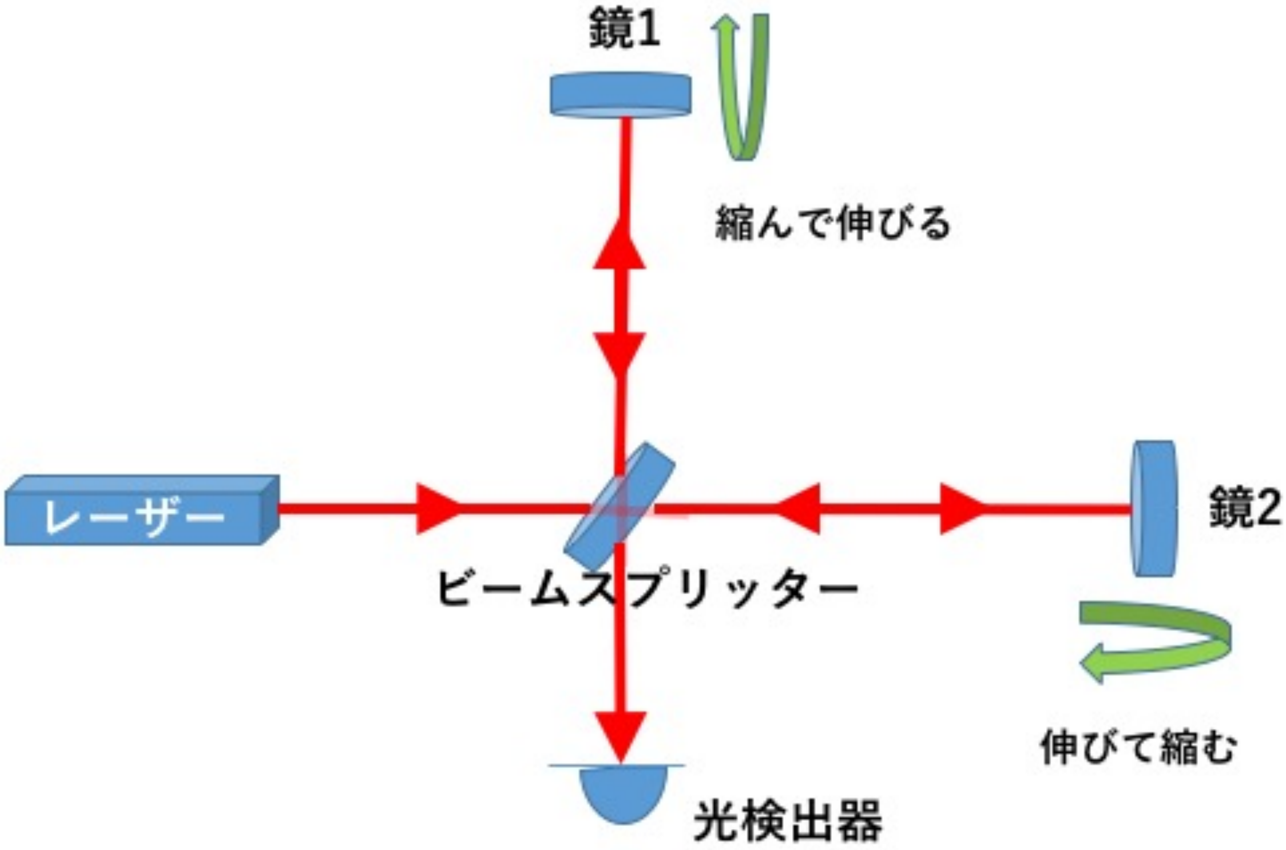
Sensitivity curve of the Ground based detectors

Lase interferometer → measure distance

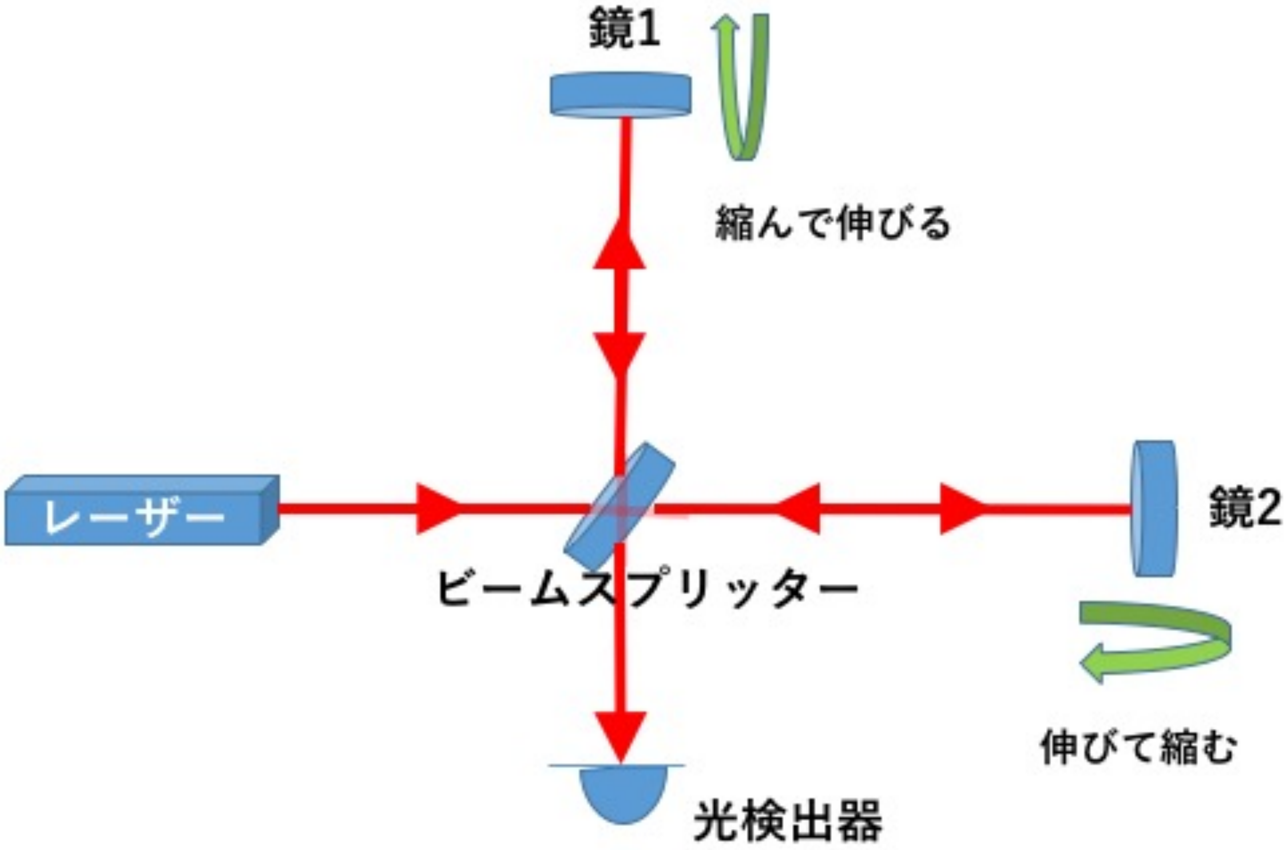
$$\delta l = h(t)L$$



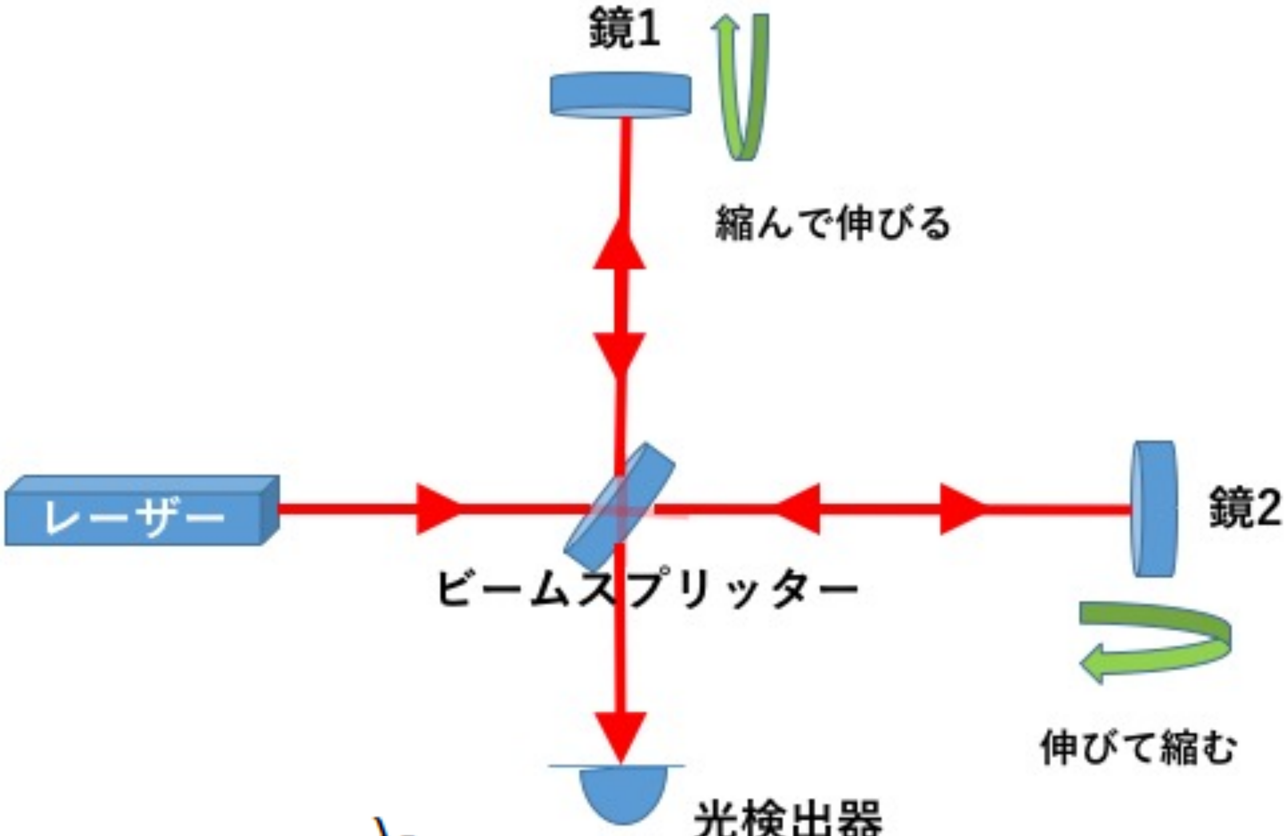
Joshua Smith Slide @ GWPAW2013



$$h \simeq \frac{\Delta l}{l} \sim \frac{\lambda_{laser}}{l} \sim \frac{10^{-6}m}{10^{3}m} \sim 10^{-9}$$

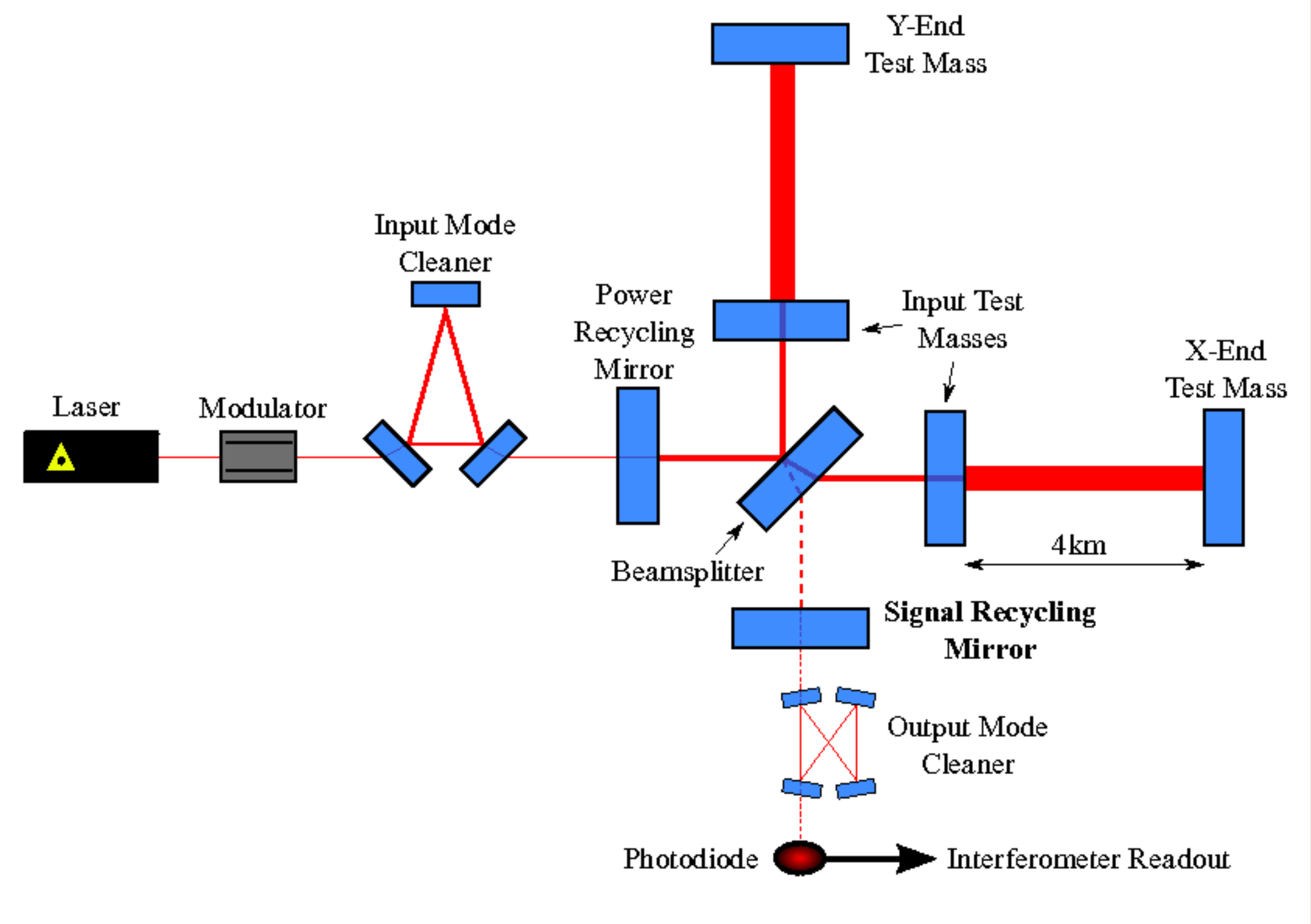


$$h \simeq \frac{\Delta l}{l_{eff}} \sim \frac{\lambda_{laser}}{\mathcal{F} l} \sim \frac{10^{-6} m}{10^{6} m} \sim 10^{-12}$$



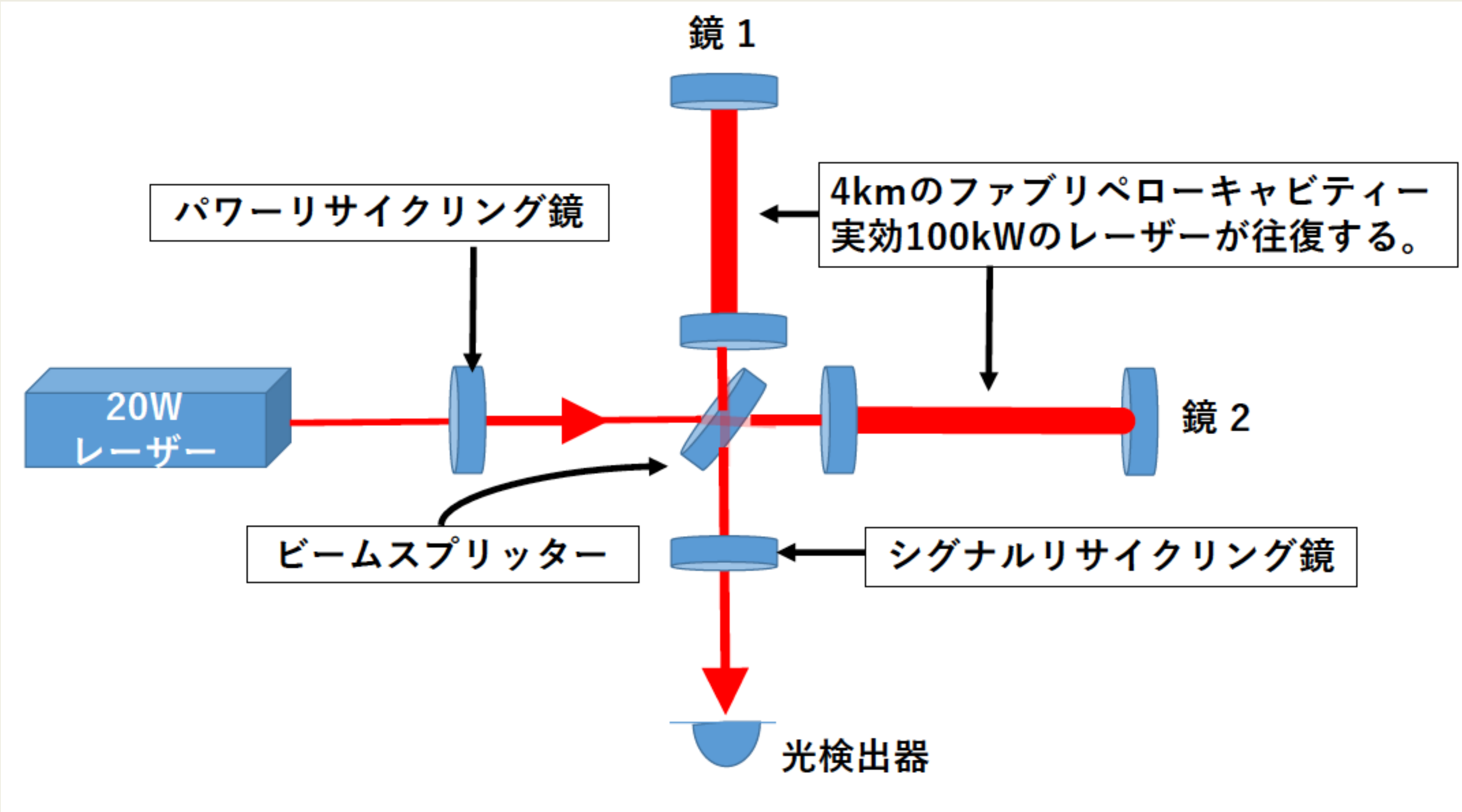
$$\Delta l = \frac{\lambda_{Laser}}{N_{photon}^{1/2}}$$

$$N_{photon} = \frac{P_{Laser}}{hc/\lambda_{Laser}} \frac{l_{eff}}{c} \sim 10^{18}$$



$$h \simeq \frac{\Delta l}{l_{eff}} \sim \frac{1}{N_{photon}^{1/2}} \frac{\lambda_{laser}}{\mathcal{F} l} \sim 10^{-21}$$

LSC: Class.Quant.Grav. 26 (2009

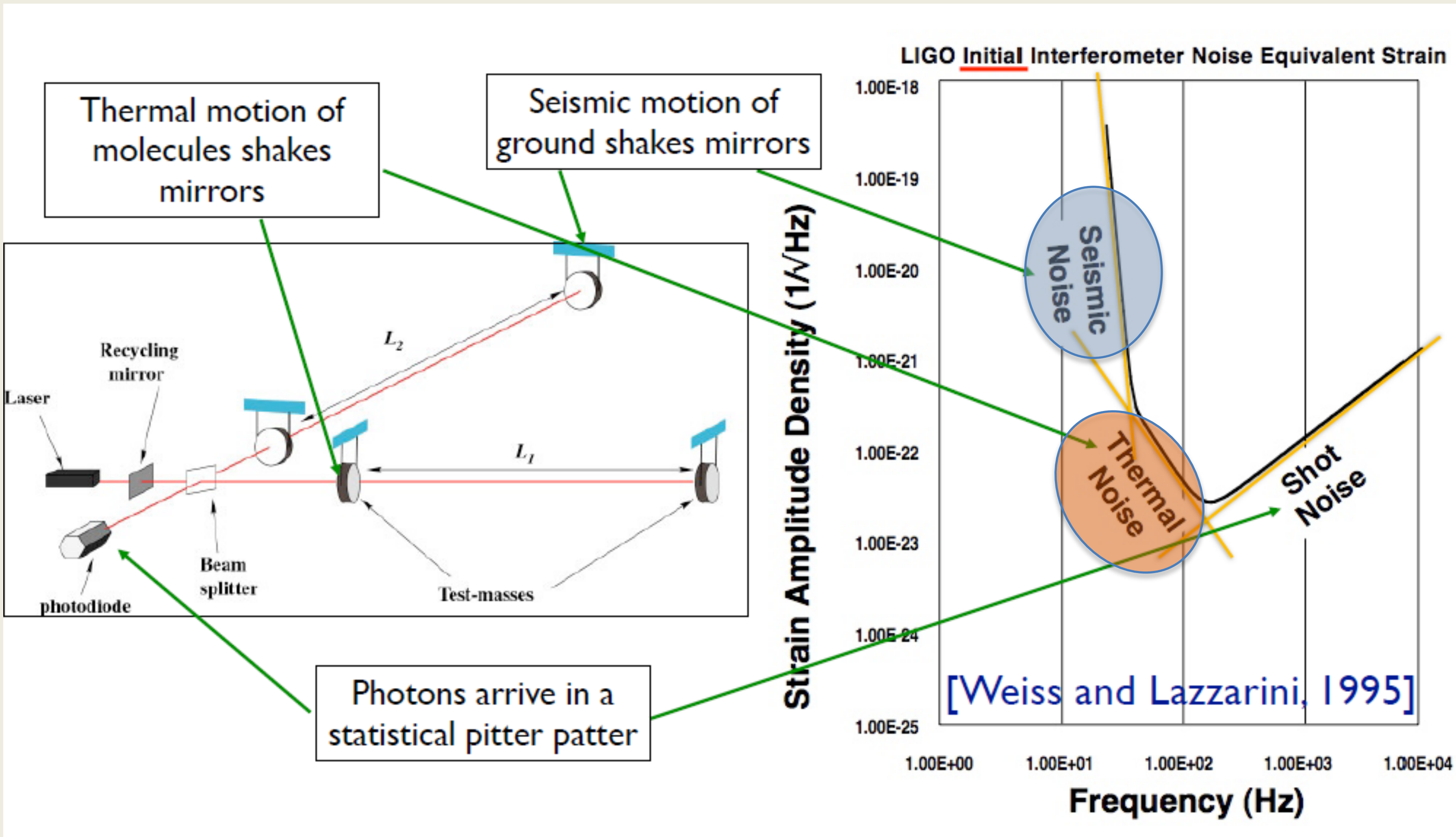


2015年9月から2016年1月までおこなわれた advanced LIGOの最初の観測時の光学的構成の簡略図。

Sensitivity curve of the Ground based detectors

Lase interferometer → measure distance

$$\delta l = h(t)L$$



Joshua Smith Slide @ GWPAW2013

KAGRA: World’s first 2.5 generation GW detector

- Japanese gravitational wave experiment.
- Fabry-Perot Michelson type Laser interferometer.
- Two 3km arms.
- Under Kamioka mine (same site as Super-Kamiokande), Gif pref. Japan to reduce seismic noise.
- 20 Kelvin mirror to reduce thermal noise.

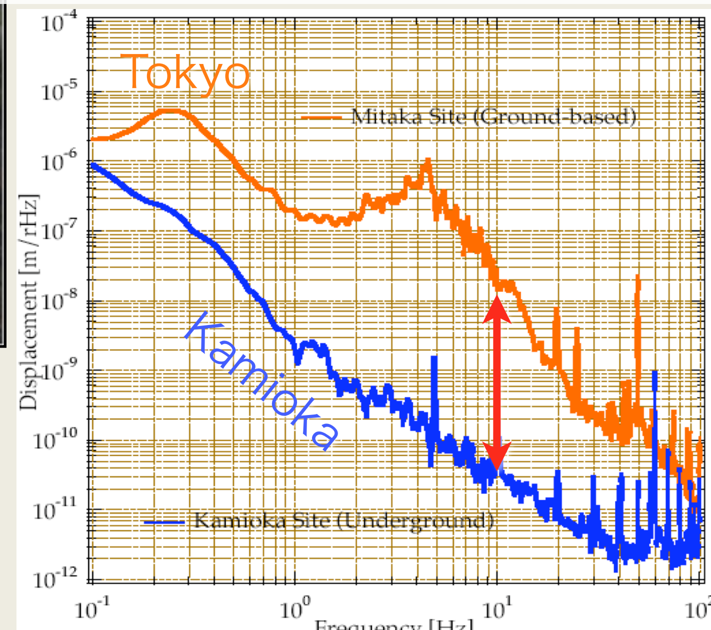
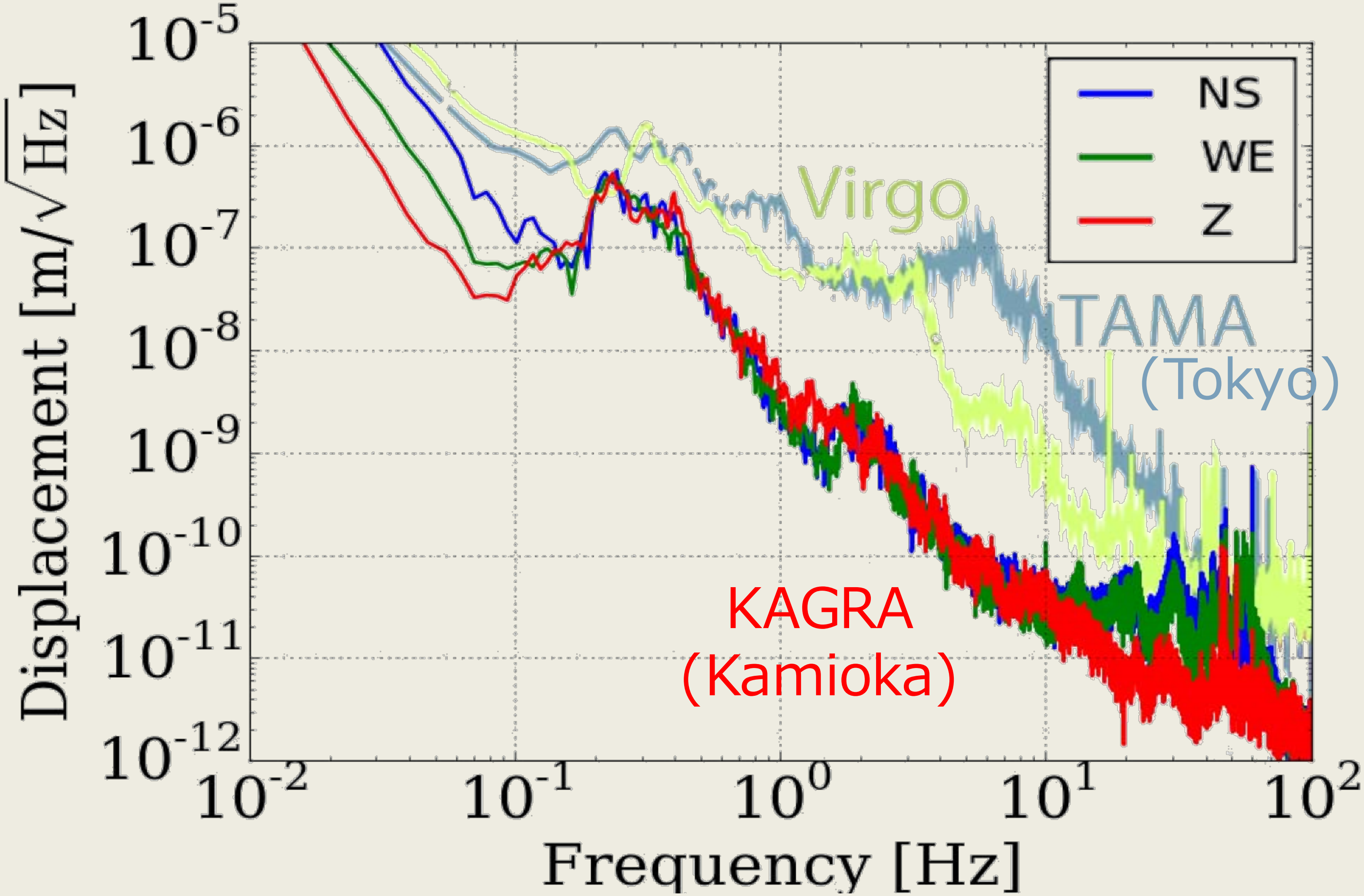


Image & seismic Data from
http://gwcenter.icrr.u-tokyo.ac.jp/en/

KAGRA underground



Plot by A. Shoda et al. (JGW-G1605219-v3)

KAGRA

KAGRA site location

KAGRA Collaboration

- **PI: Takaaki Kajita**
- **Host: ICRR, Univ. of Tokyo,Co-Hosts: KEK and NAOJ**
- **248 collaborators from more than 80 institutes**

75 researchers from ~ 38 oversea univ./inst.)

- **Japan Gravitational Wave Consortium (JGWC)**
- **ELiTES collaboration for R&D of ET-KAGRA**
- **Strong supports from LIGO-VIRGO collaboration**
- **Kipp Cannon, a new associate prof. @ RESCEU (2016/02)**

MEXT New Innovative Area: “New development in astrophysics through multimessenger observations of gravitational wave sources”
http://www.gw.hep.osaka-cu.ac.jp/gwastro/
PI: Takashi Nakamura (2012-2016)
X-ray (N. Kawai)
Optical Infrared (M. Yoshida)
Neutrino (M. Vagins)
GW data analysis (N. Kanda)
Theory (T. Tanaka)

Photos of the KAGRA site

Photo courtesy: N. Kanda, S. Miyoki, K. Yamamoto

KAGRA status

- iKAGRA finishes successfully
  - simple Michelson
  - stable data transfer, basic calibration
  - data analysis now undertaken
- bKAGRA: Cryogenic-DRFPM (2018-).
- Some issues: (other than money & manpower)

bear threats avoidance by loud music (Autumn/Spring)

man power for snow shoveling (Winter)

1000 t/h water flow by snow melting (April)

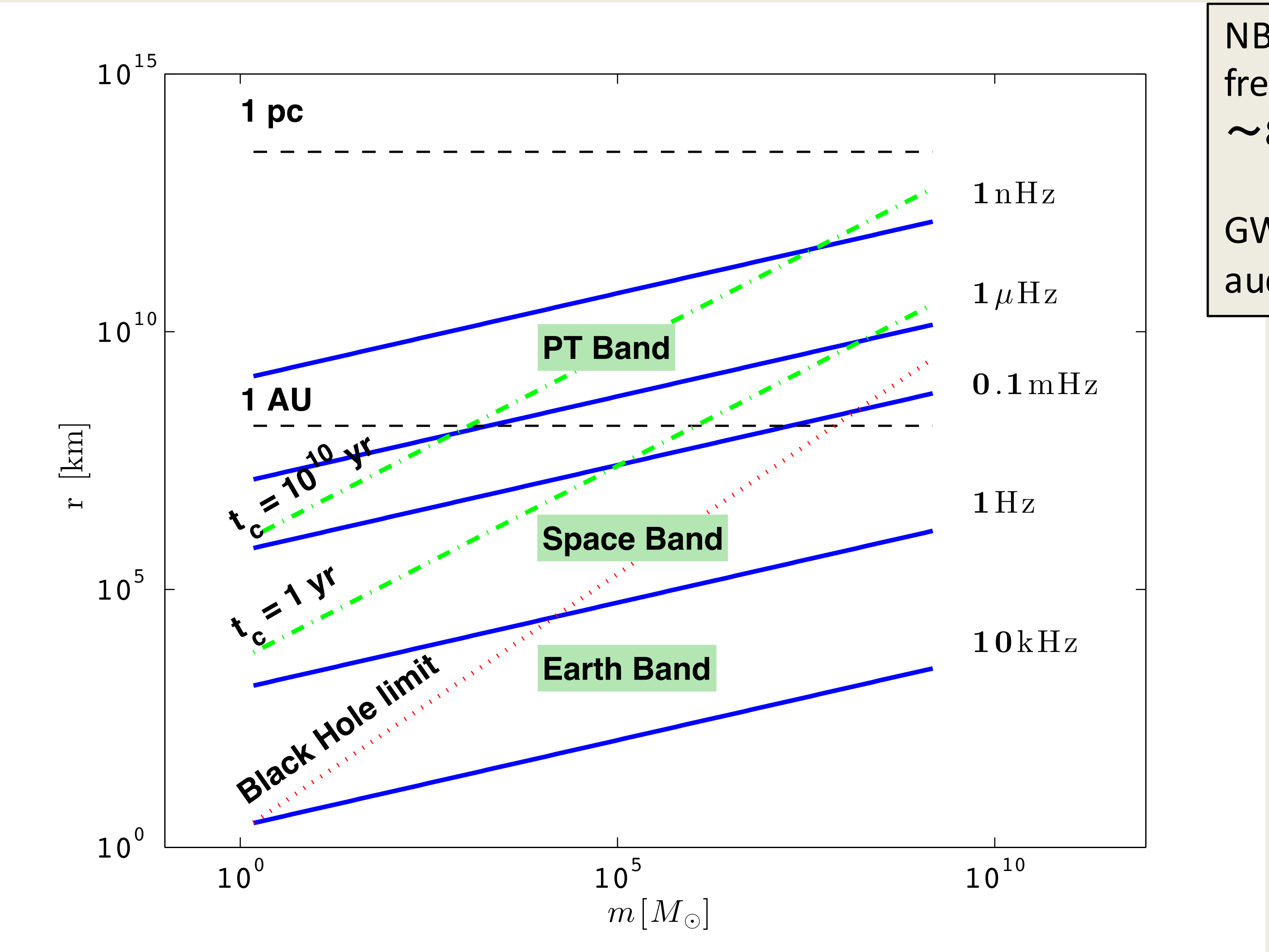
iKAGRA run

- March 26 – 31, April 11 – 25: 2 periods
- Simple Michelson configuration
- Observation shifts
- Stable data transfer, off-line calibration
- CBC Hardware injections
- Get experiences for bKAGRA 2018/03 & 2018/09

MULTIBAND GW ASTRONOMY

Characteristic GW freq.

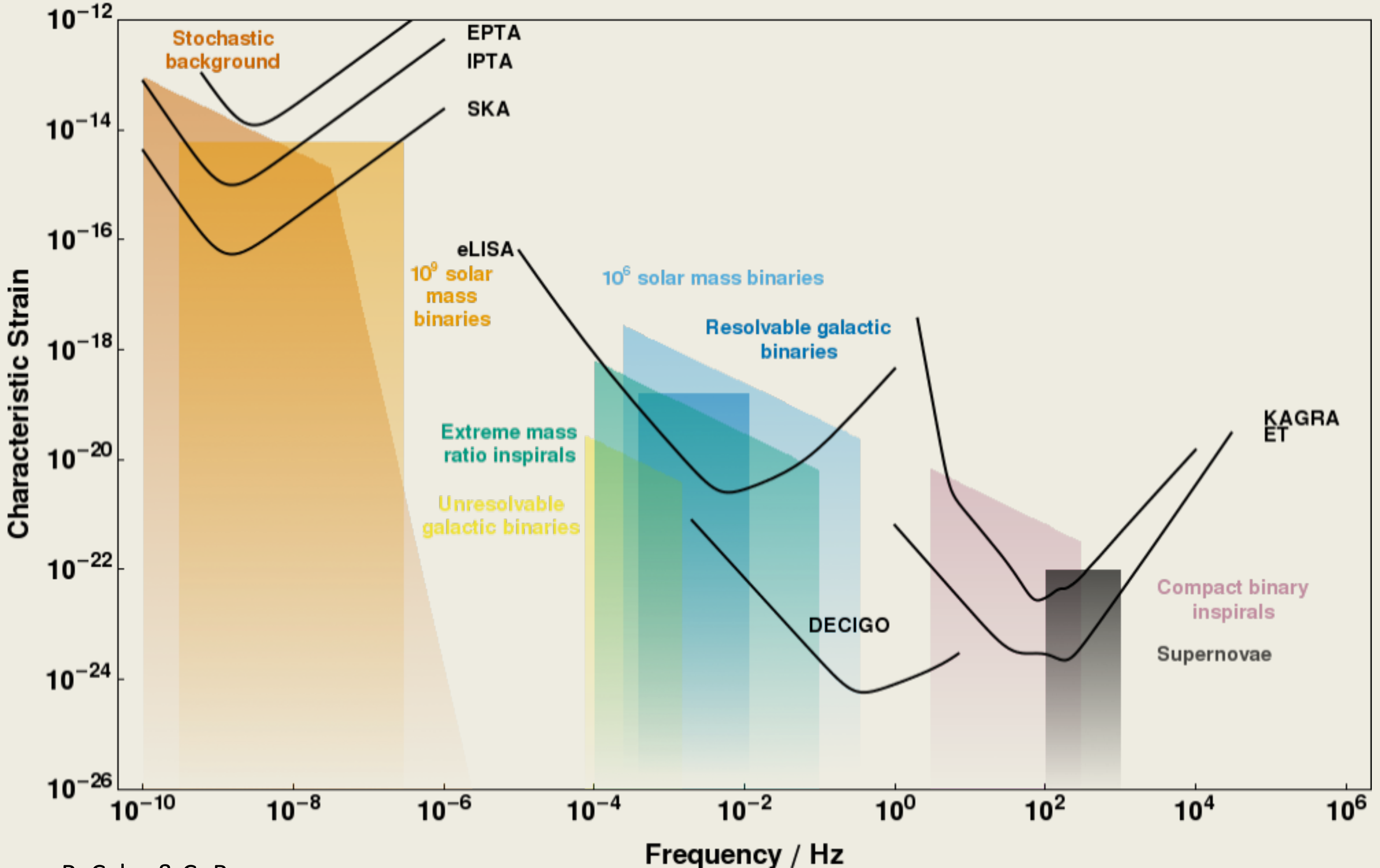
$$f_{\rm gw} \sim \frac{1}{2\pi}\sqrt{\pi G \rho} \sim \frac{1}{4\pi}\sqrt{\frac{3Gm}{R^3}}$$



NB: Visible light frequency: 400THz ～800THz

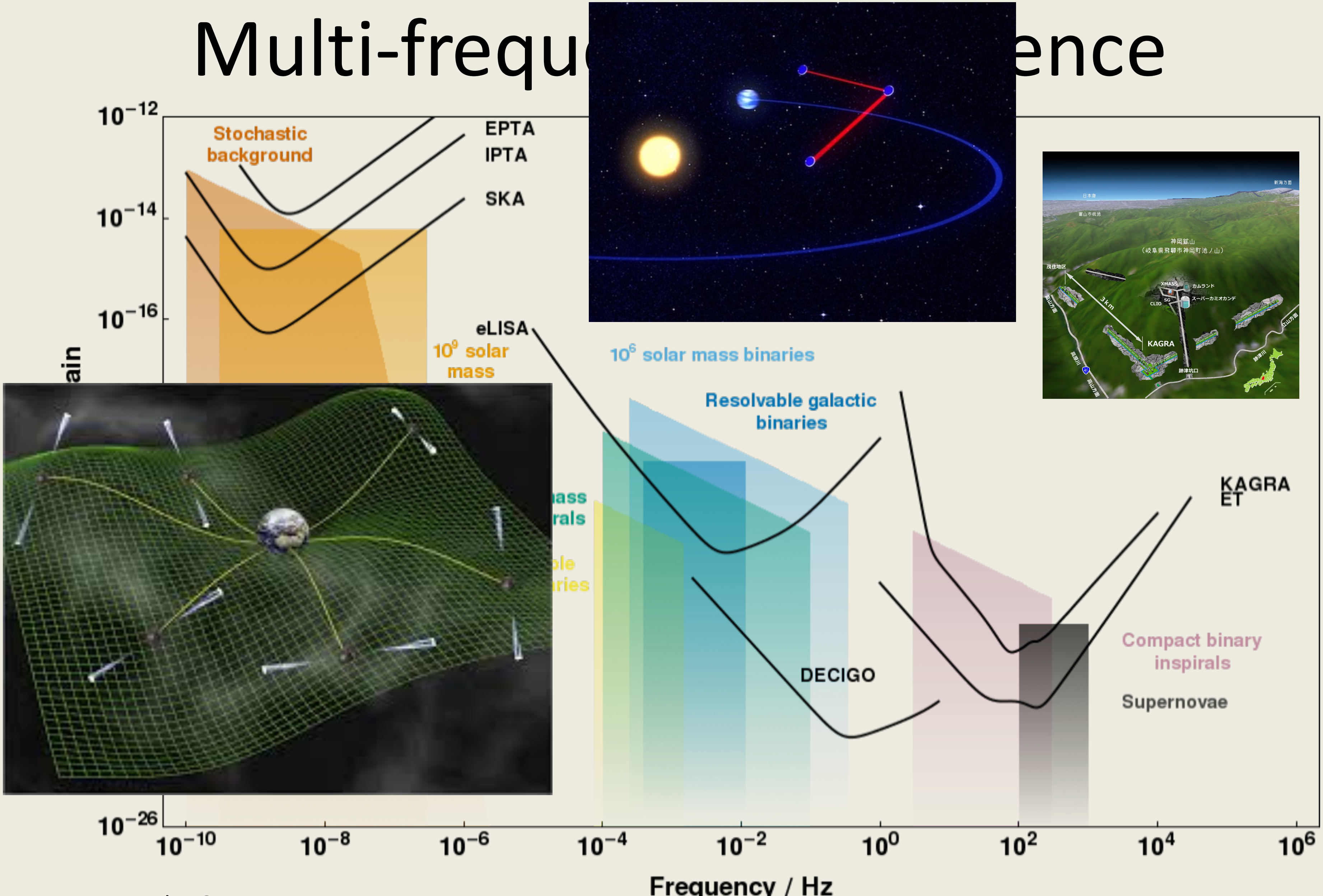
GW freq. is audible.

Multi-frequency GW Science



C. Moore R. Cole, & C. Berry
http://www.ast.cam.ac.uk/~rhc26/sources/

Multi-frequ ence



C. Moore R. Cole, & C. Berry
http://www.ast.cam.ac.uk/~rhc26/sources/

PTA: Background from SMBH Binaries

Sesana 2013 arxiv 1211.5375

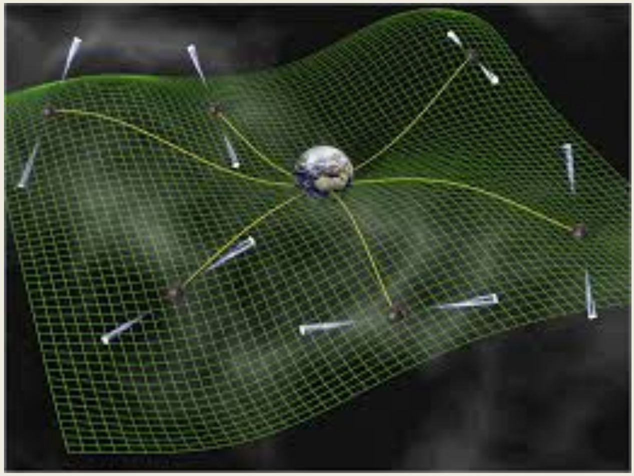
- Binary Stochastic BGGW

$$h_c(f) \simeq \left(\frac{1}{f^2}\int \frac{dz dM_{\bullet,1} dq_{\bullet}}{1+z} \frac{d^3 n}{dz dM_{\bullet,1} dq_{\bullet}} \frac{dE_{gw}(\mathcal{M})}{d\ln f_r}\right)^{1/2} \equiv A\left(\frac{f}{1\mathrm{yr}^{-1}}\right)^{-2/3}$$

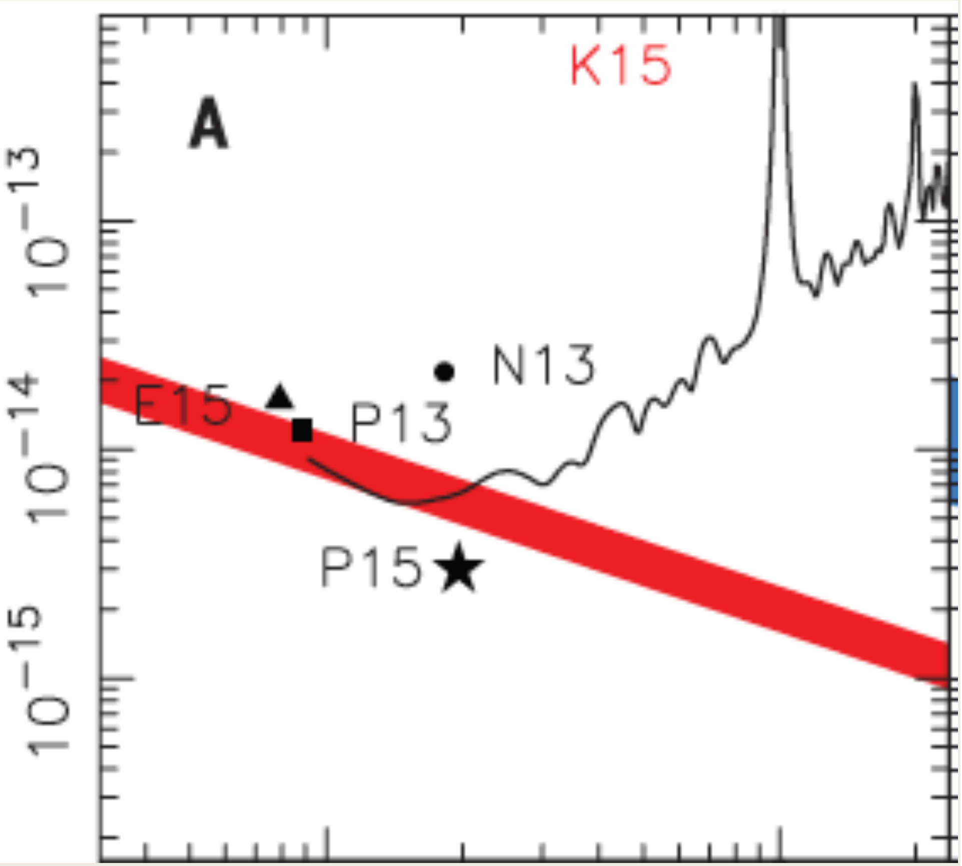
- Assuming SMBHB coalescence just after host galaxies merges. Find galaxy merger rate

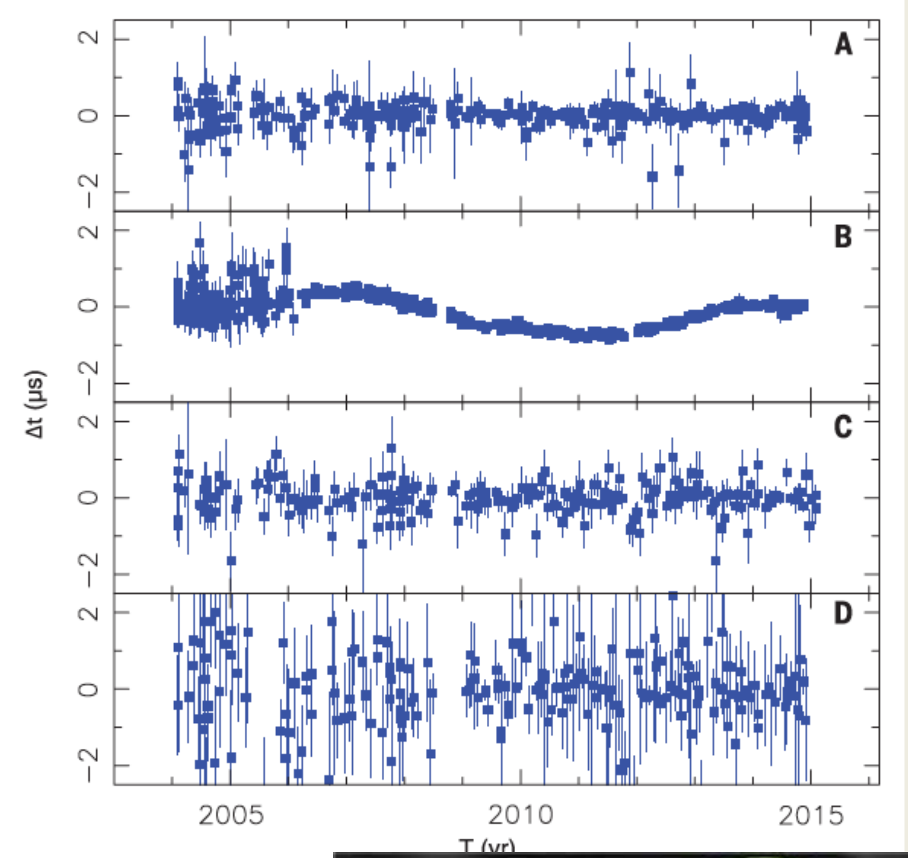
$$\frac{d^3 n_G}{dz dM dq} = \frac{\phi(M,z)}{M\ln 10} \frac{\mathcal{F}(z,M,q)}{\tau(z,M,q)} \frac{dt_r}{dz}$$

- Galactic mass function · number of galaxy pairs/volume from Observation
- Merger time scale from Millenium simulation (Kitzbichler & White (2008))
- SMBH mass from the Buldge-mass relation

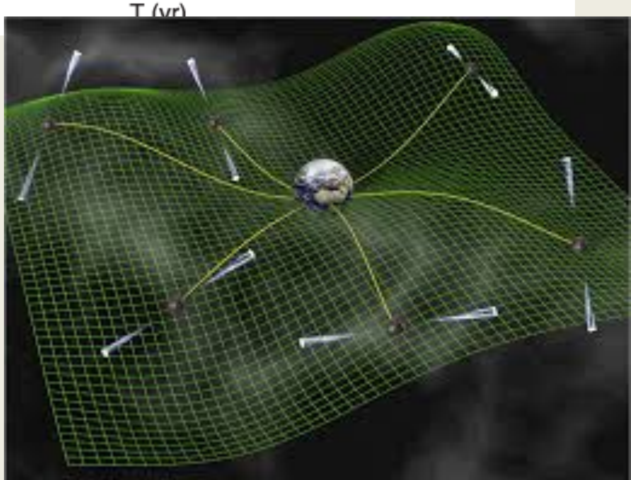


PTA: Background from SMBH Binaries



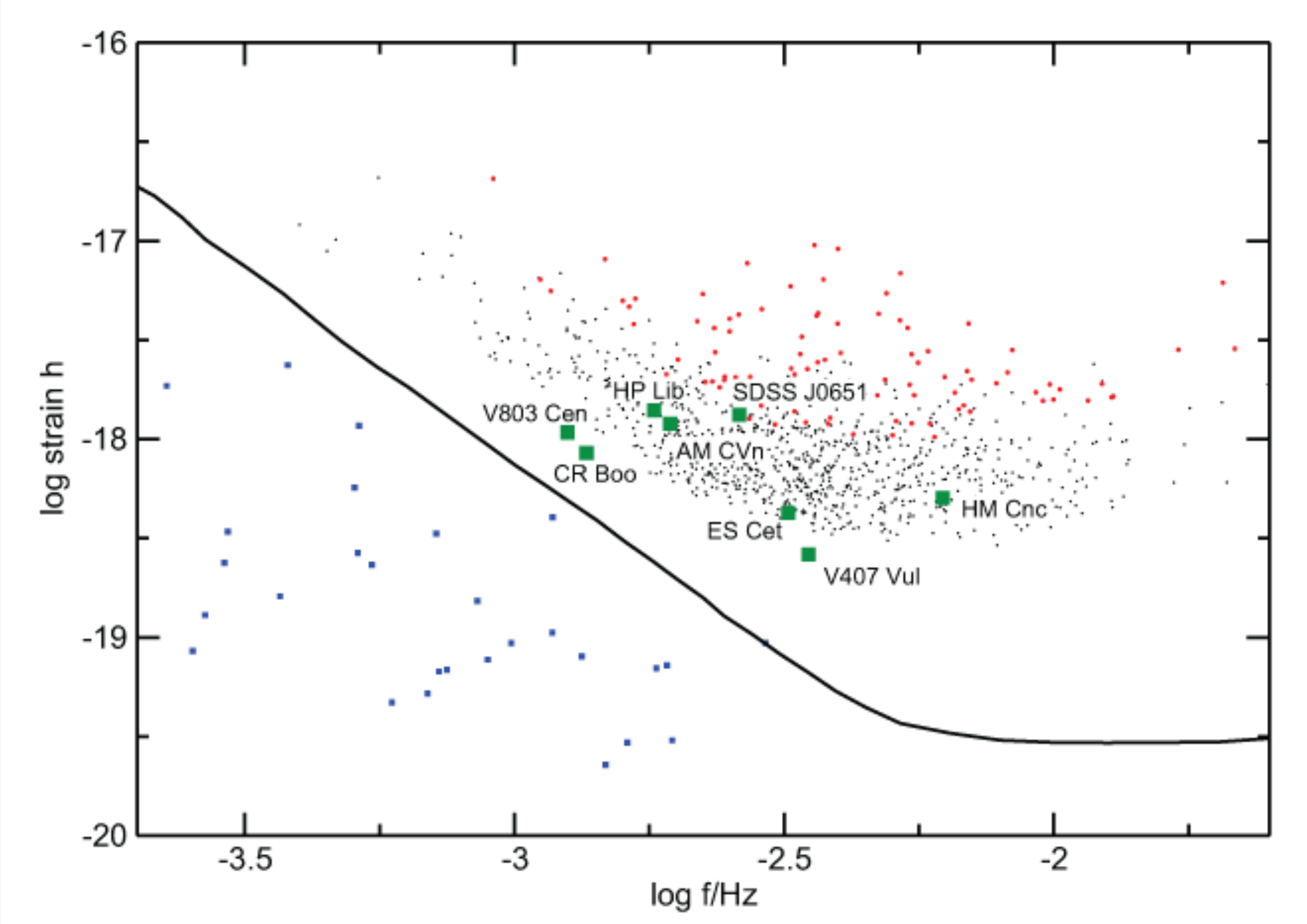


Shannon et al (2015)
PPTA



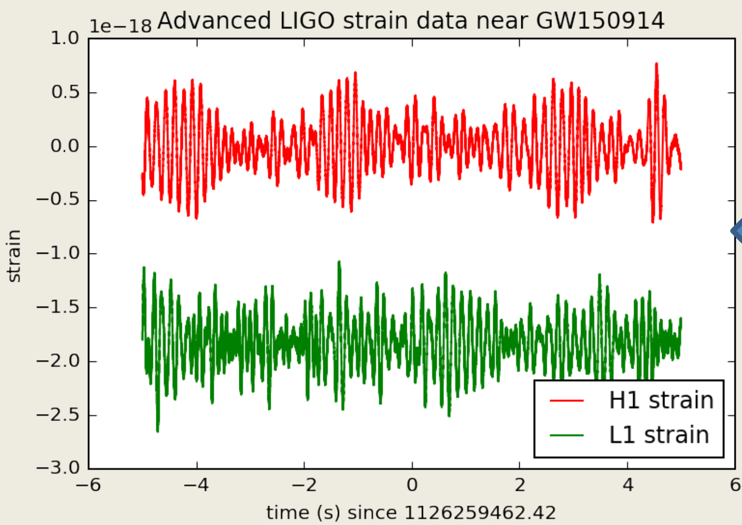
http://relativity.livingreviews.org/Articles/lrr-2014-3/articlese10.html

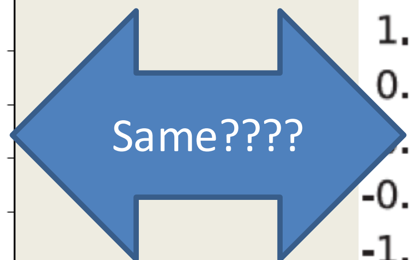
eLISA (2034?) verification binary

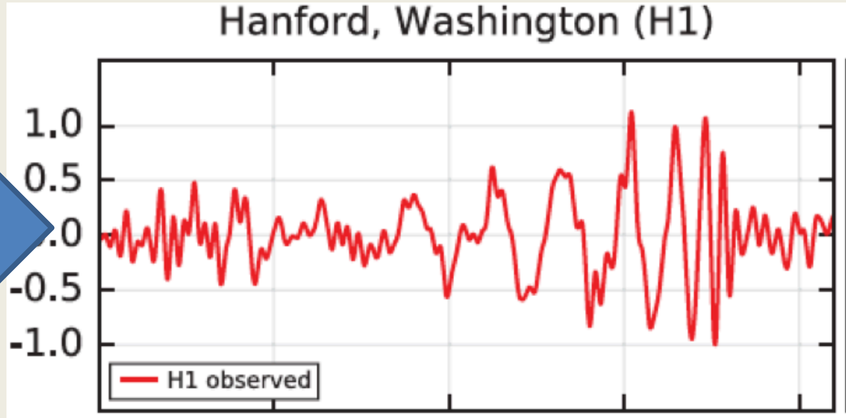


GW ASTRONOMY

Data analysis

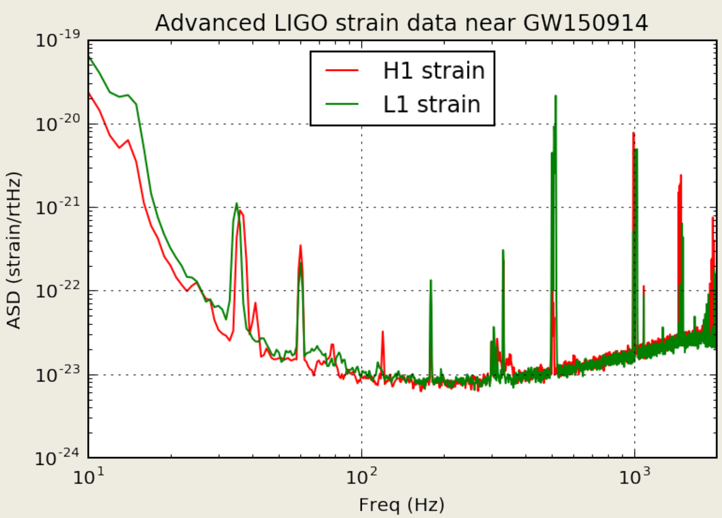






Reconstructed GW

Detector output time series



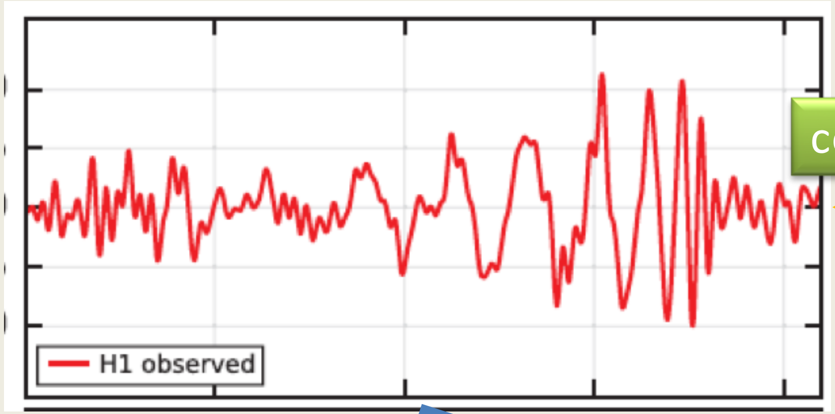
Detector power spectrum :

Huge power in low frequencies

- ✓ High-pass filter (typ. Hann)
- ✓ Whitening
- ✓ Line noise notch filter

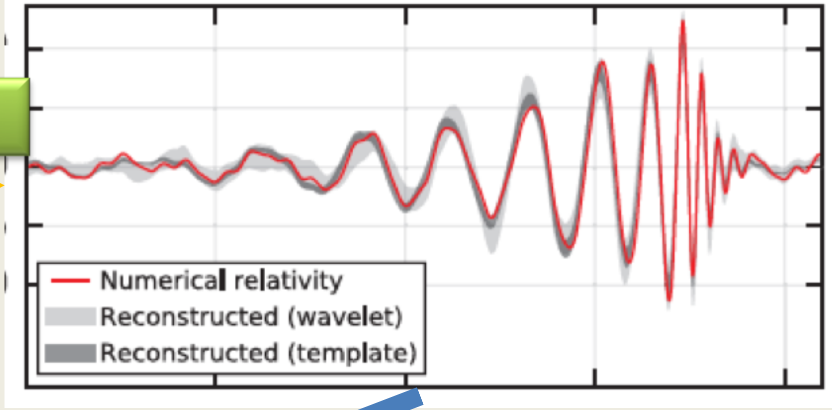
Data analysis

Reconstructed GW



compare

Theoretical expectations



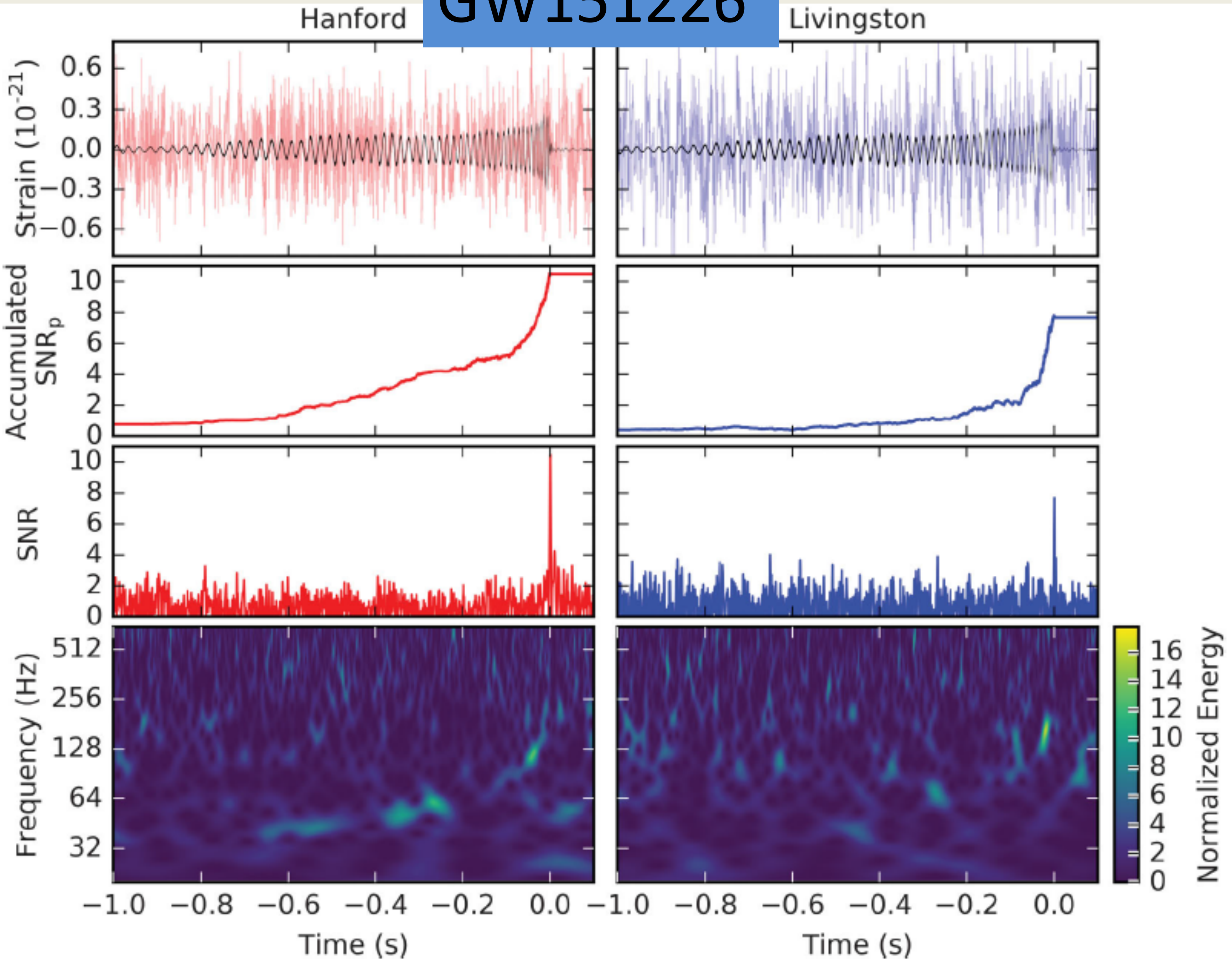
$$\langle s|h\rangle(t) = 4\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t}\, df$$

Want to extract physical information

Compute correlation with theoretical expectation

Find the model that maximizes the correlation

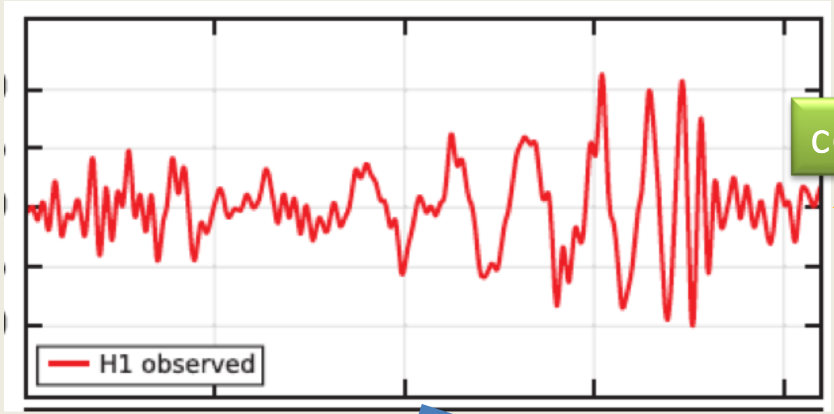
GW151226



Hanford
Livingston
Strain (10^{-21})
0.6
0.3
0.0
−0.3
−0.6
Accumulated SNR_p
10
8
6
4
2
0
SNR
Frequency (Hz)
512
256
128
64
32
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Time (s)
Normalized Energy
16
14
12
10
8
6
4
2
0

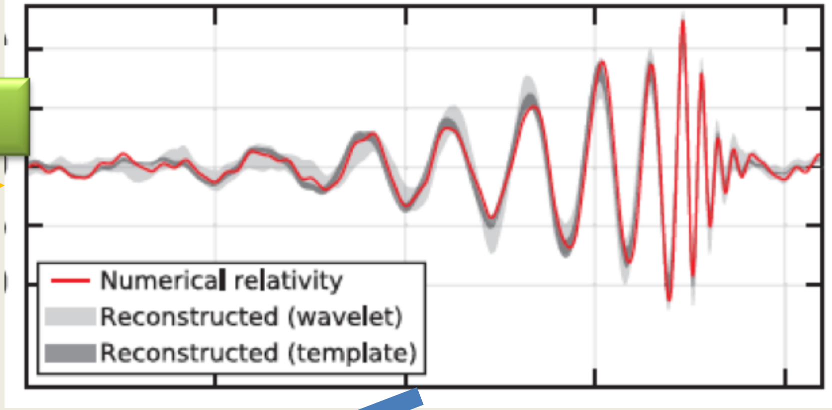
Data analysis

Reconstructed GW



compare

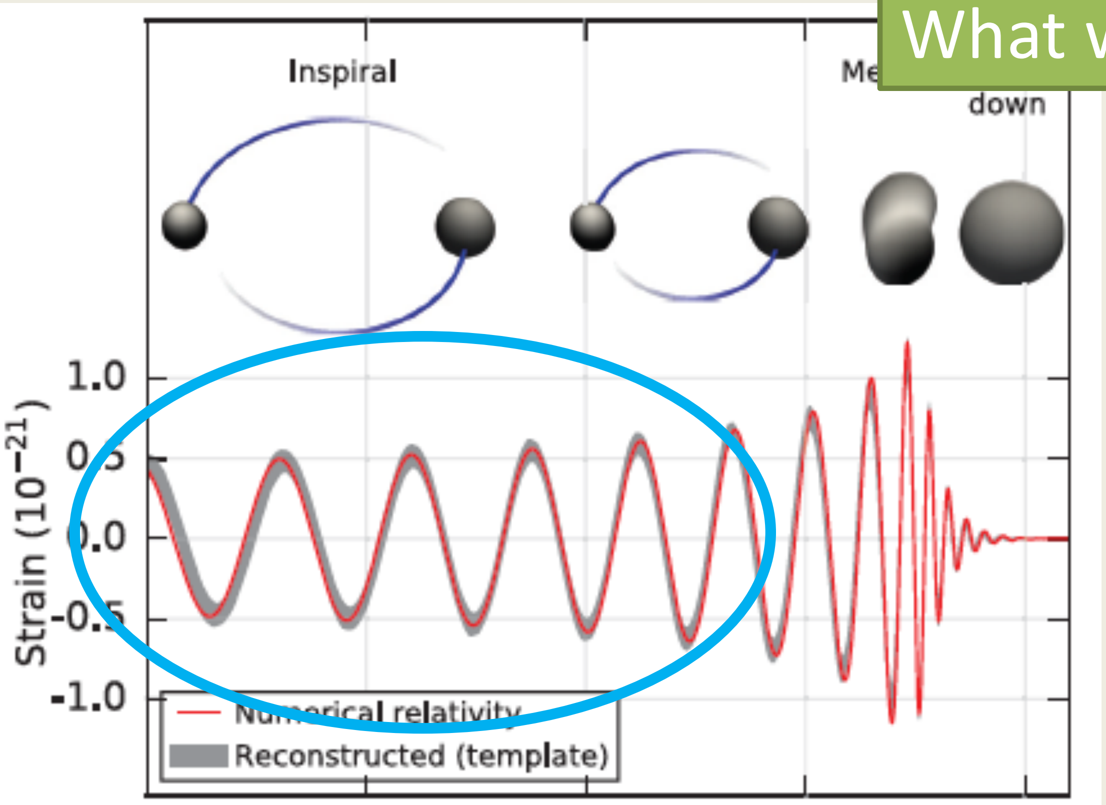
Theoretical expectations



$$\langle s|h\rangle(t) = 4\int_0^{\infty} \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t}\, \mathrm{d}f$$

Want to extract physical information
Compute correlation with theoretical expectation
Find the model that maximizes the correlation

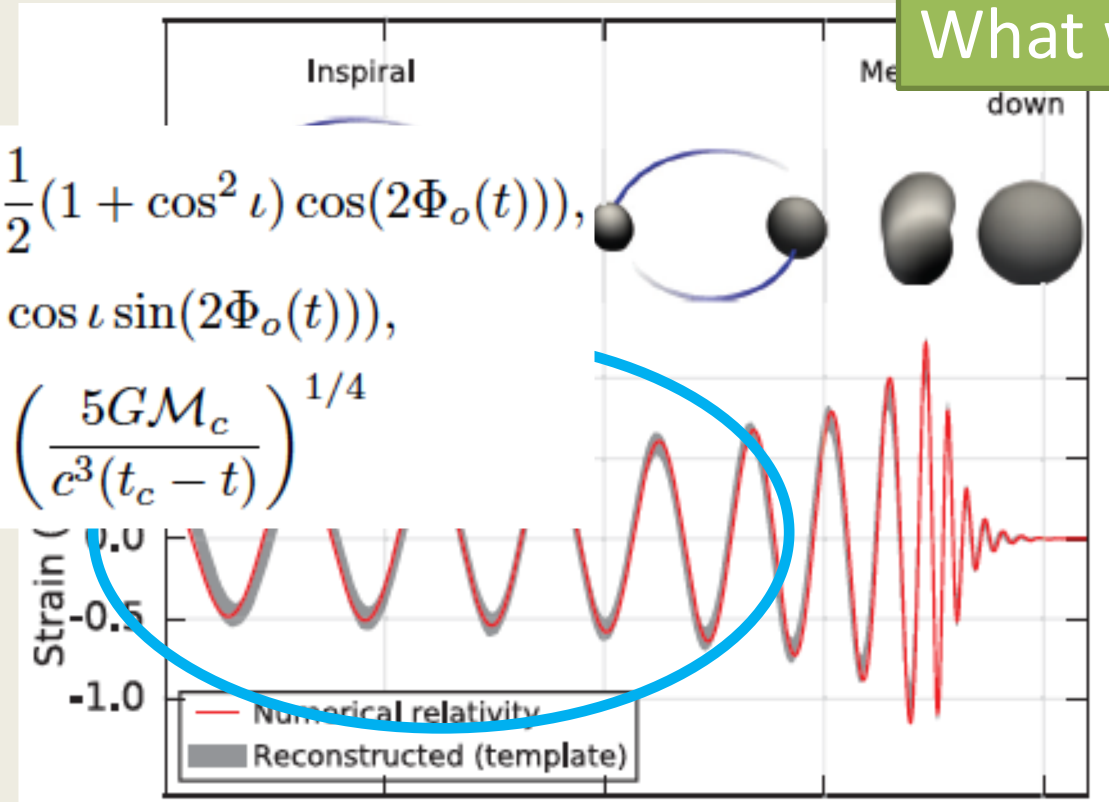
What we can learn



$$h(t) = \frac{G\mathcal{M}}{c^2 r} U(\vec{n}, \iota, \psi) \left(\frac{5G\mathcal{M}/c^3}{t_c - t} \right)^{1/4} \cos\left(\Phi_0 - \left(\frac{t_c - t}{5G\mathcal{M}/c^3} \right)^{5/8} + (\text{BH spins}) \right)$$

Luminosity distance, sky location $\vec{n}$,masses, spin angular momentums of the black holes of the binary

What we can learn



$$h_+(t) = -A(t)\frac{1}{2}(1+\cos^2\iota)\cos(2\Phi_o(t)),$$

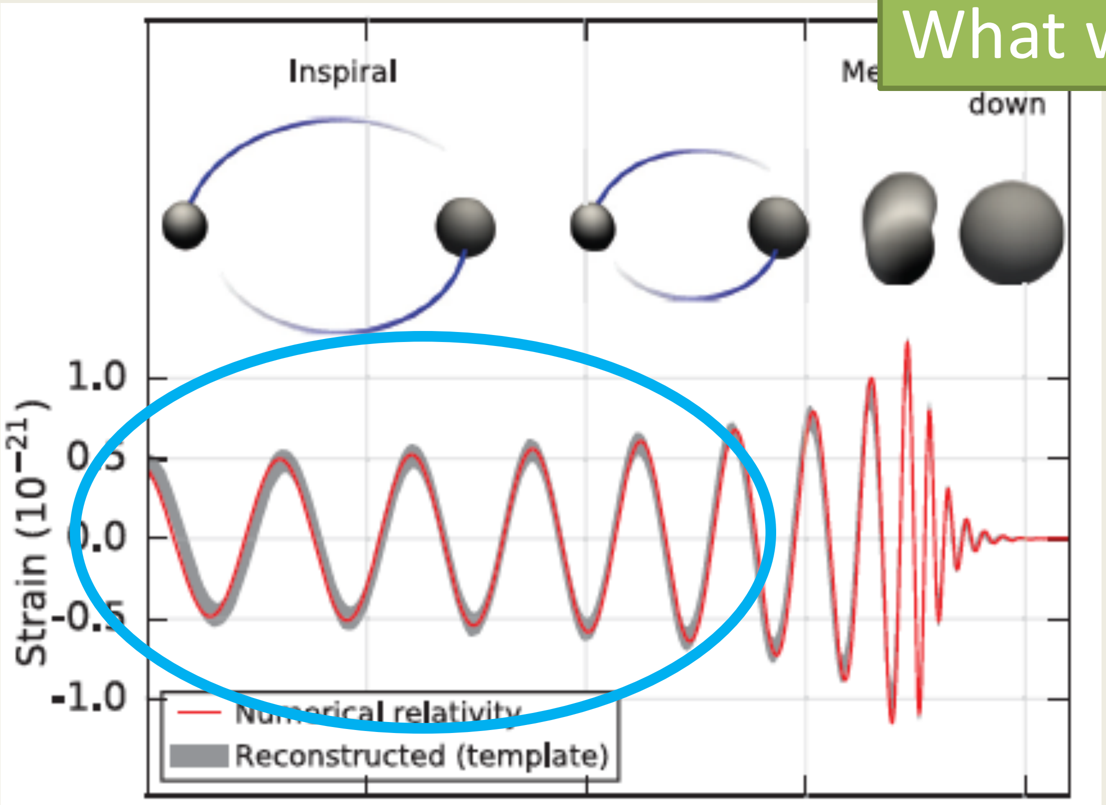
$$h_\times(t) = -A(t)\cos\iota\sin(2\Phi_o(t)),$$

$$A(t) = \frac{G\mathcal{M}_c}{c^2 r}\left(\frac{5G\mathcal{M}_c}{c^3(t_c - t)}\right)^{1/4}$$

$$h(t) = \frac{G\mathcal{M}}{c^2 r}U(\vec{n},\iota,\psi)\left(\frac{5G\mathcal{M}/c^3}{t_c - t}\right)^{1/4}\cos\left(\Phi_0 - \left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{5/8} + (\mathrm{BH\,spins})\right)$$

Luminosity distance, sky location $\vec{n}$,masses, spin angular momentums of the black holes of the binary

What we can learn



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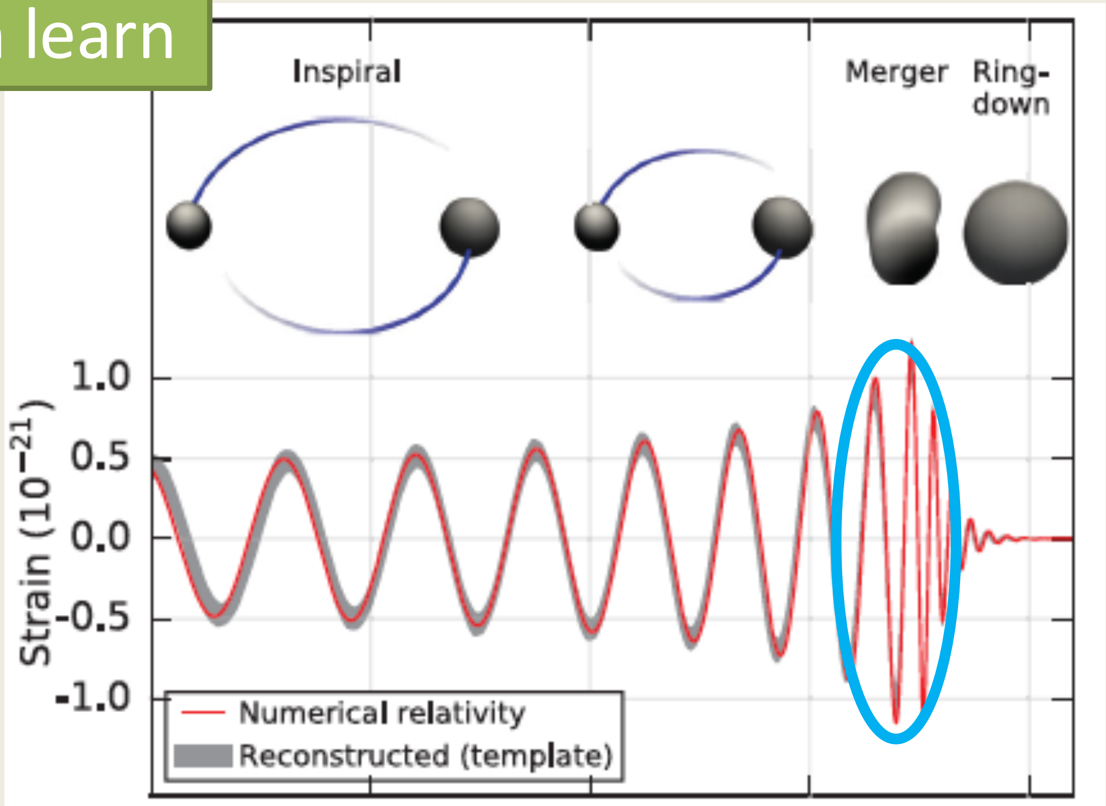
Luminosity distance, sky location $\vec{n}$,masses, spin angular momentums of the black holes of the binary

What we can learn

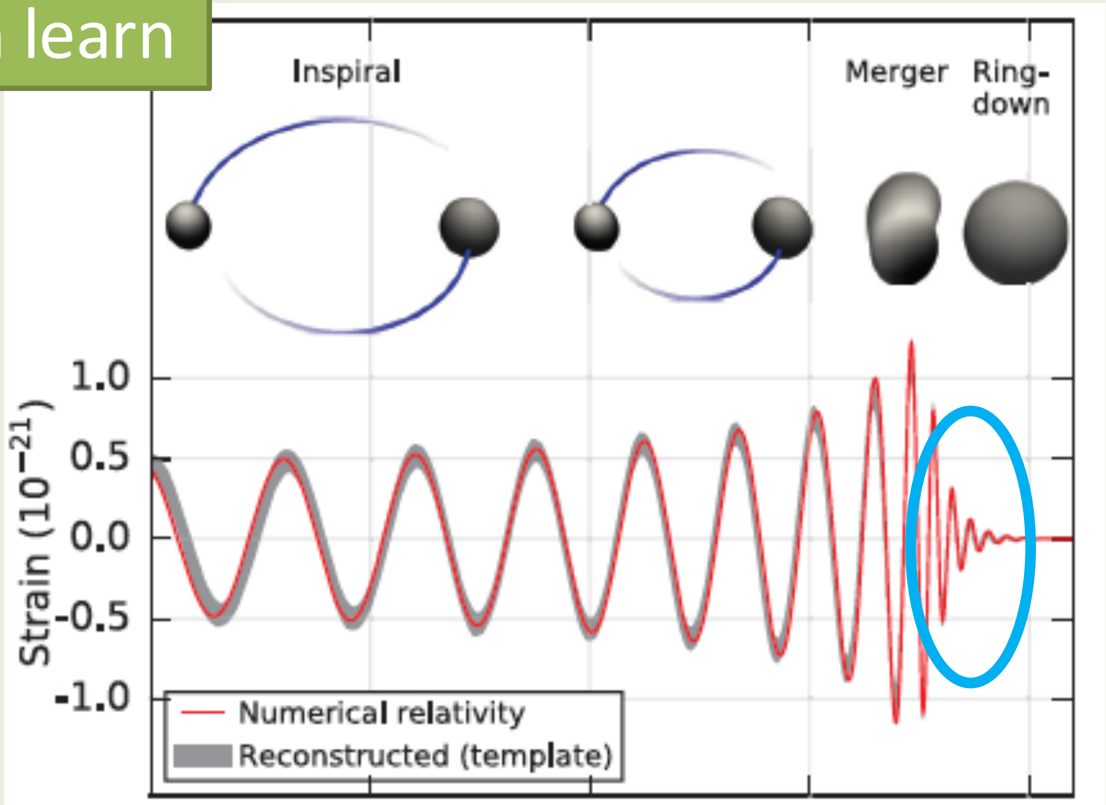


Numerical Relativity : Merger of two black holes

What happened to event horizons?

How much energy was radiated?

What we can learn



$$h(t) = \frac{GM}{c^2 r} V(\vec{n}, \psi) \mathrm{Re} \sum_{nlm} A_{nlm} V_{nlm}(\iota, \phi) \exp\left[i \frac{c^3 \Omega_{nlm} t}{CM} \right]$$

$$\Omega_{nlm} \equiv \frac{GM}{c^3} \left(\omega_{nlm} + \frac{i}{\tau_{nlm}} \right)$$

$$\omega_{nlm} = \omega_{nlm}(M, a),$$
$$\tau_{nlm} = \tau_{nlm}(M, a)$$

Mass (M), spin angular momentum (a) of the final black hole.
Kerrness: Test of GR

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

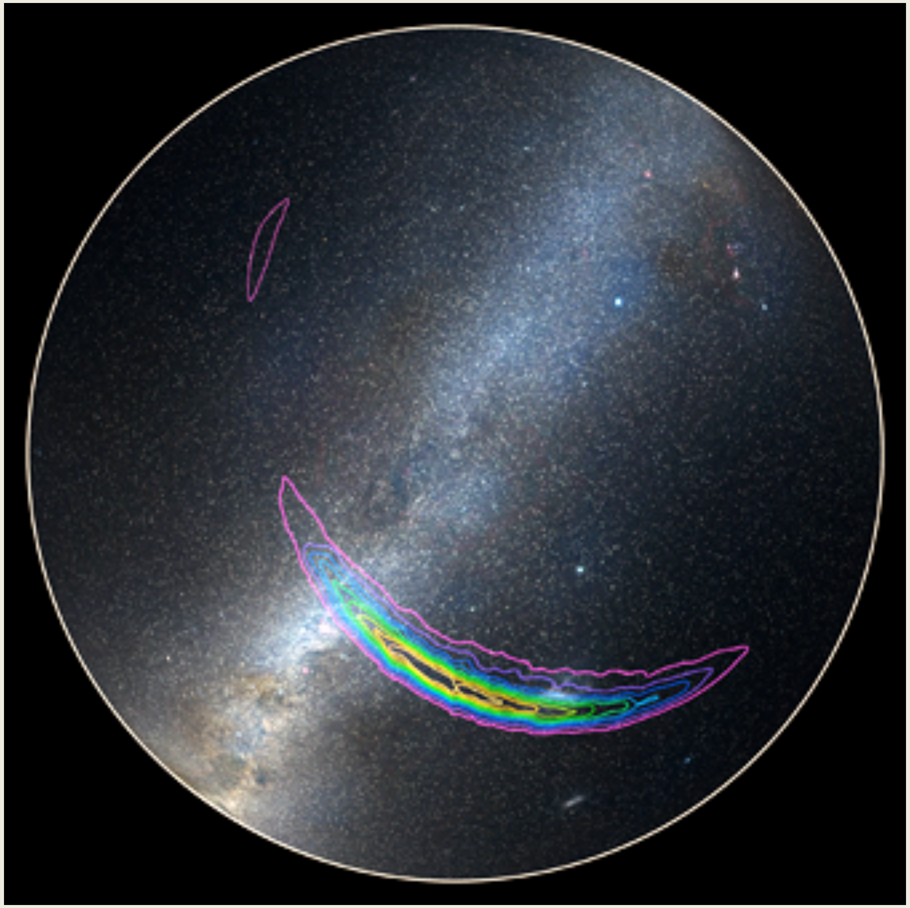
https://losc.ligo.org/events/GW150914/

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

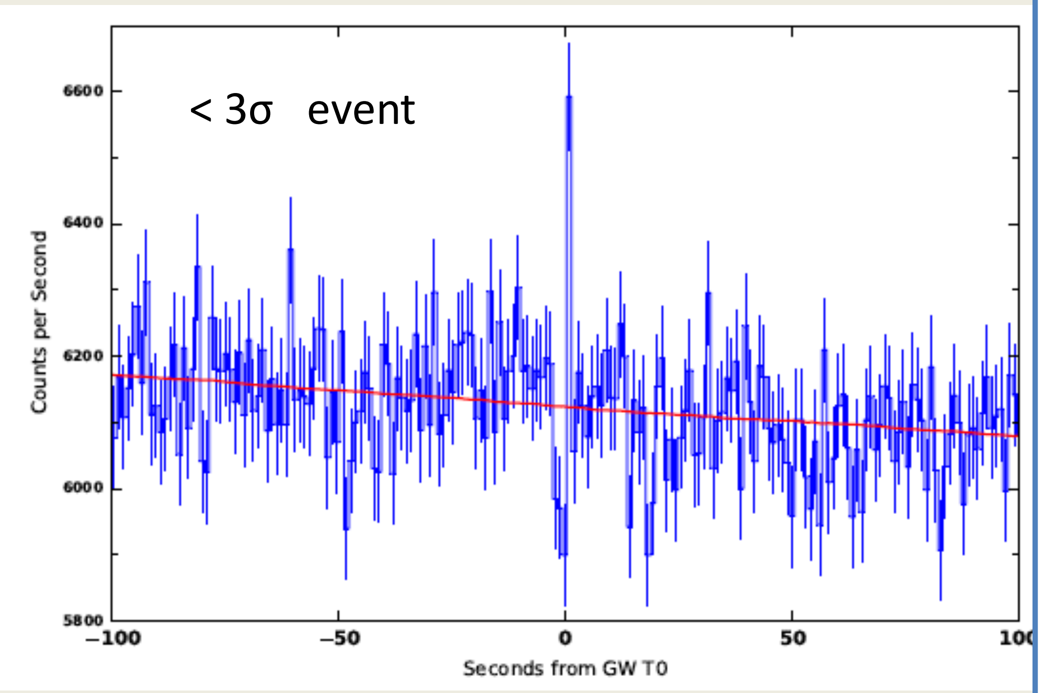
Localization



~ 600 square degrees

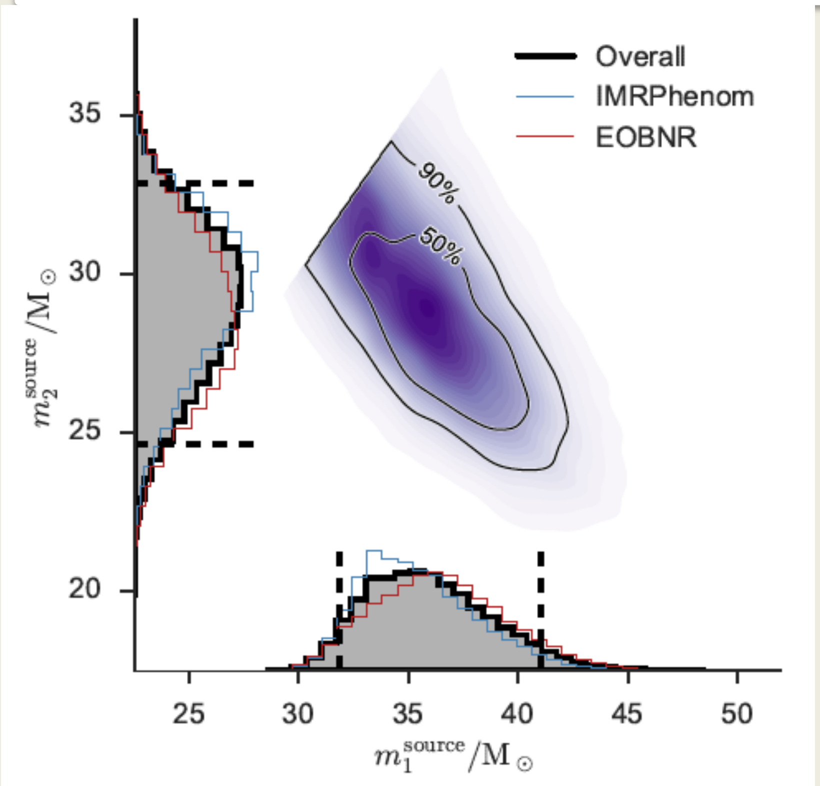
$$\delta\theta \sim \frac{0.3\ \mathrm{rad}}{\mathrm{SNR}} \left(\frac{f}{100\mathrm{Hz}}\right)^{-1} \left(\frac{D}{10,000\mathrm{km}}\right)^{-1}$$

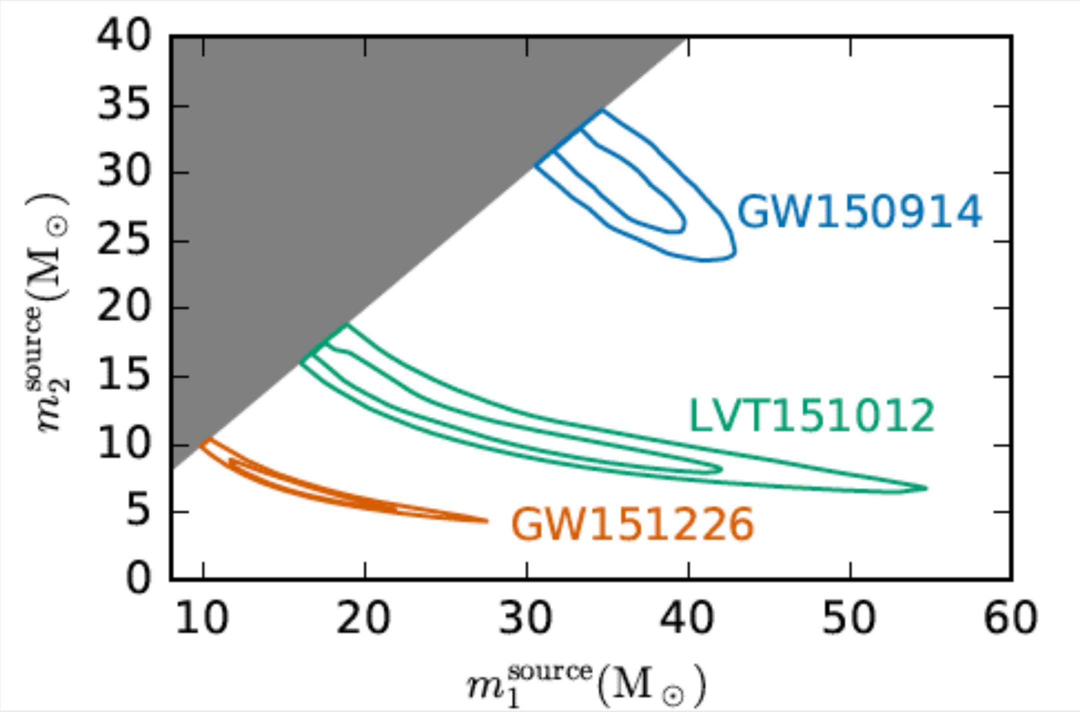
Gamma-ray detection by Fermi GBM



- ✓ 0.4sec after GW150914
- ✓ False alarm probability 0.002
- ✓ 1sec flash: SGRB?
- ✓ 2 x 10^{49} erg s^{-1} @410Mpc
  - one order dimmer?
- ✓ If SGRB we should find 10 events akin to GW150914 .
- ✓ NO detection by INTEGRAL/SWIFT
- ✓ Collaboration issues Arxiv: 1606.00314

Can find (1+z)M. No redshift info.

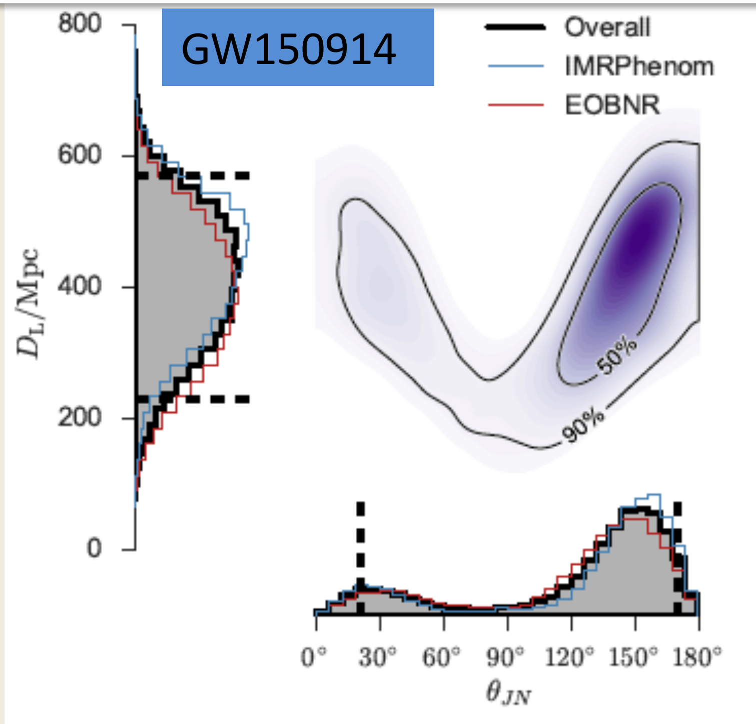


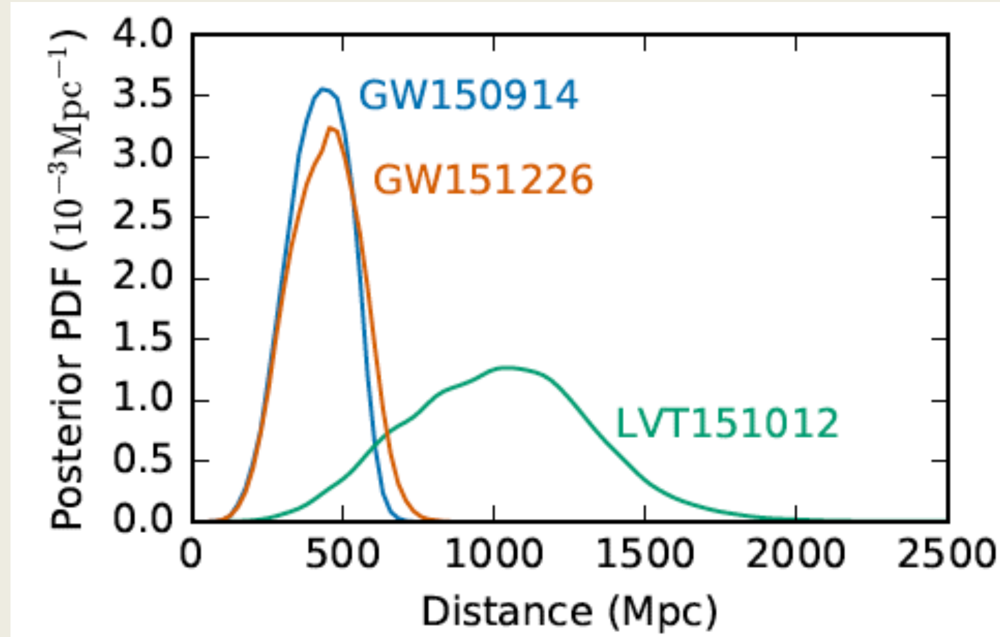


$$h_+(t) = -\frac{1+\cos^2\iota}{2}\frac{G\mathcal{M}}{c^2 r}\left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{-1/4}\cos\left[\varphi_c - \left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{5/8}\right]$$

$$h_\times(t) = -\cos\iota\frac{G\mathcal{M}}{c^2 r}\left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{-1/4}\sin\left[\varphi_c - \left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{5/8}\right]$$

degeneracy between distance & inclination





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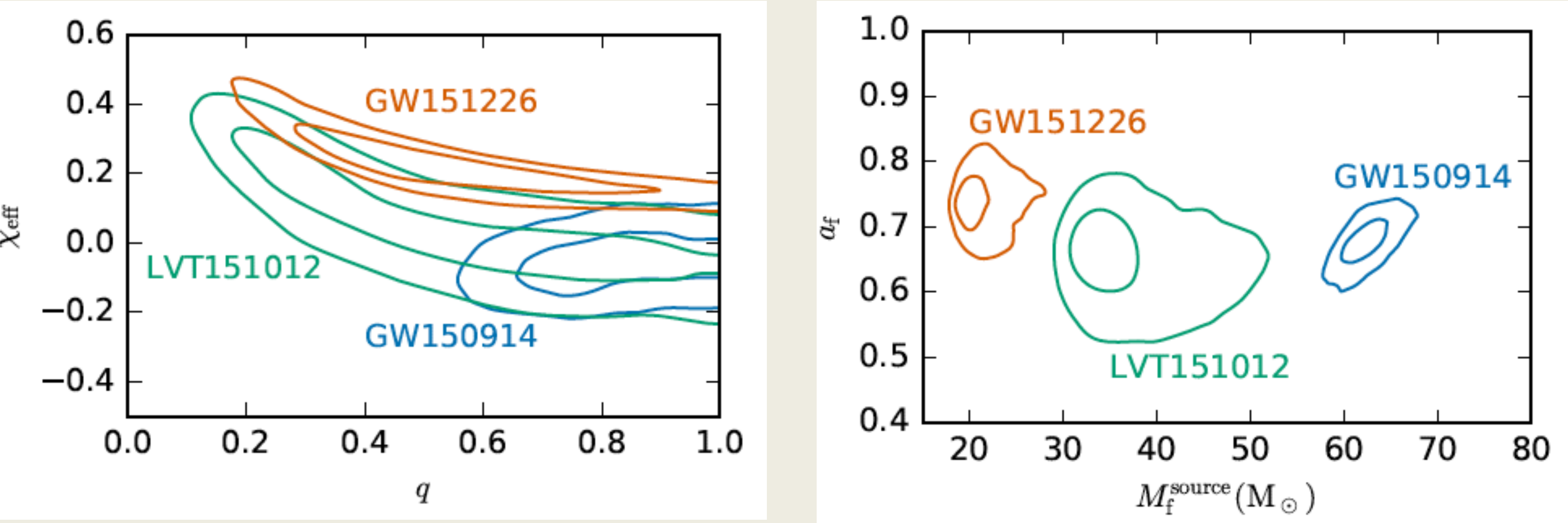
Spins

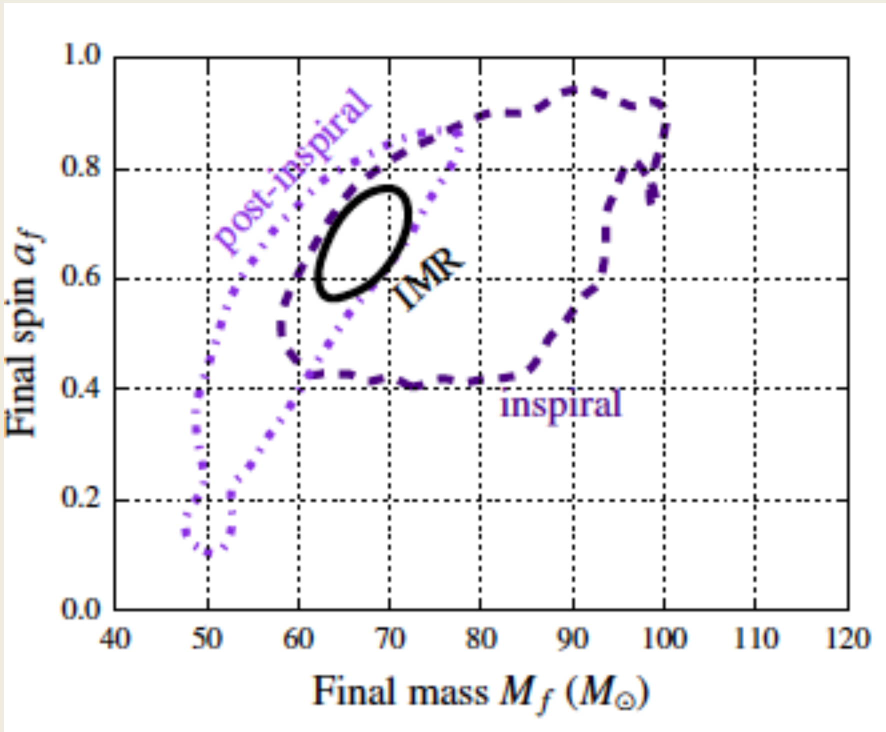


質量比 $q = m_2/m_1 < 1$

有効スピン $$\chi_{eff} = \frac{1}{m_1 + m_2}\hat{L} \cdot \left(\frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2} \right)$$

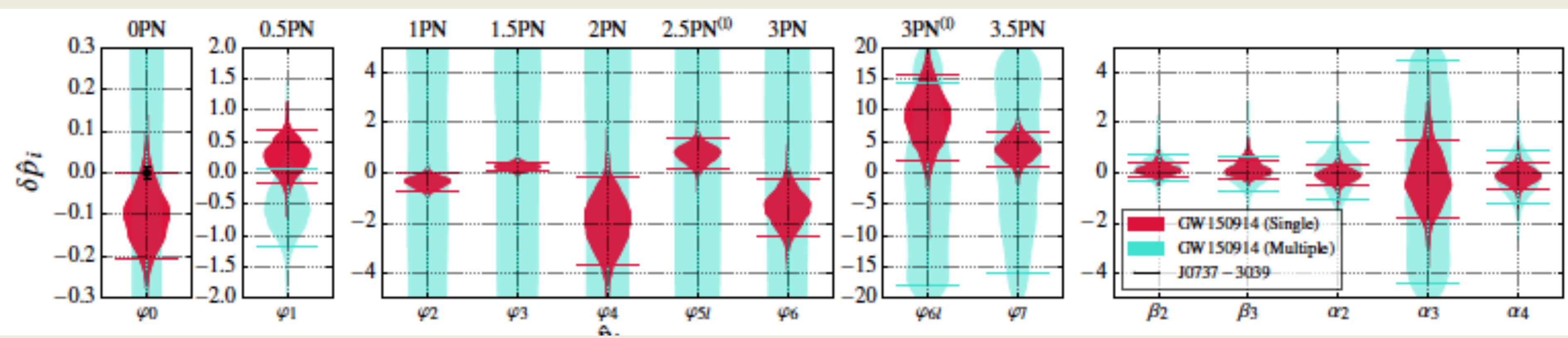
Aligned or intrinsically small.

Test of GR

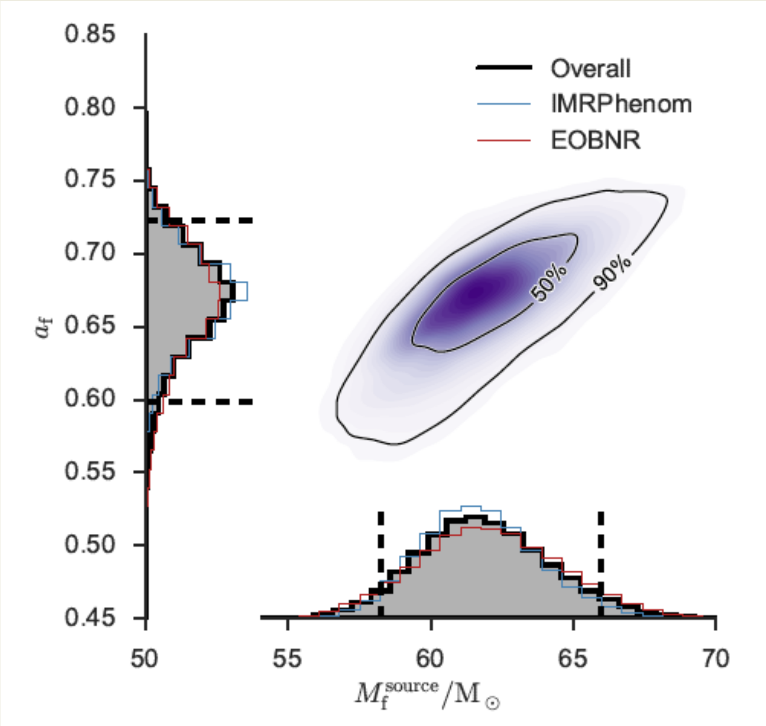


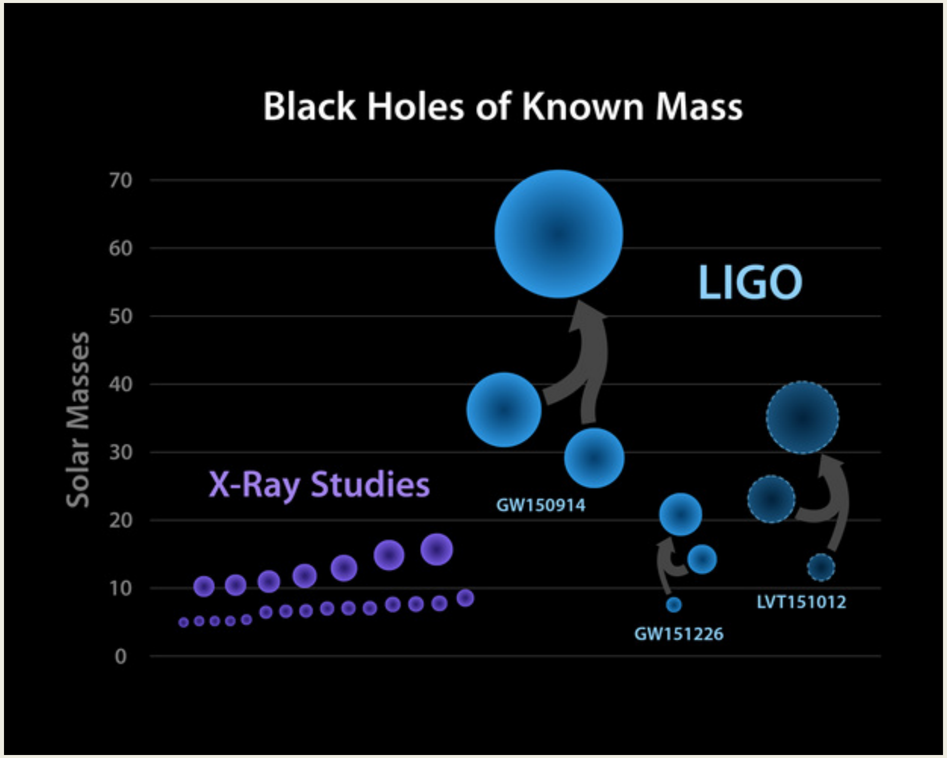
- Mass/spin of final BH estimated from pre-merger and during/after merger are consistent.
- Not contradictory to GR waveform

$$\tilde{h}^{\mathrm{M}}_k(f;\vec{\vartheta}) = \tilde{h}_k(f;\vec{\vartheta}) \left[1 + \delta A_k(f;\vec{\vartheta})\right] \times \exp\left[i\delta\phi_k(f;\vec{\vartheta})\right],$$



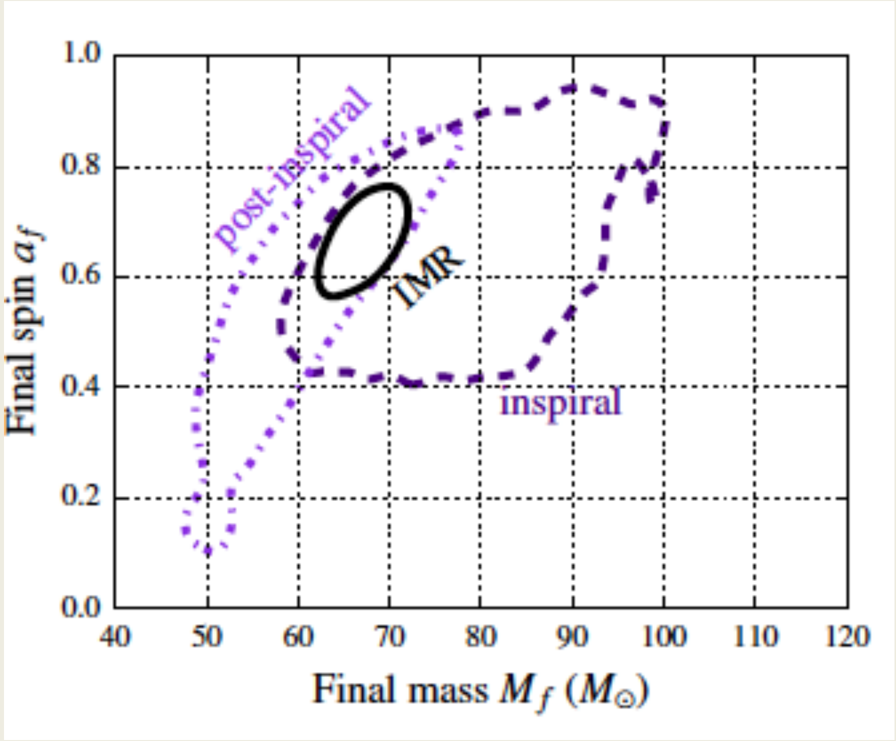
Final BH Mass and spin





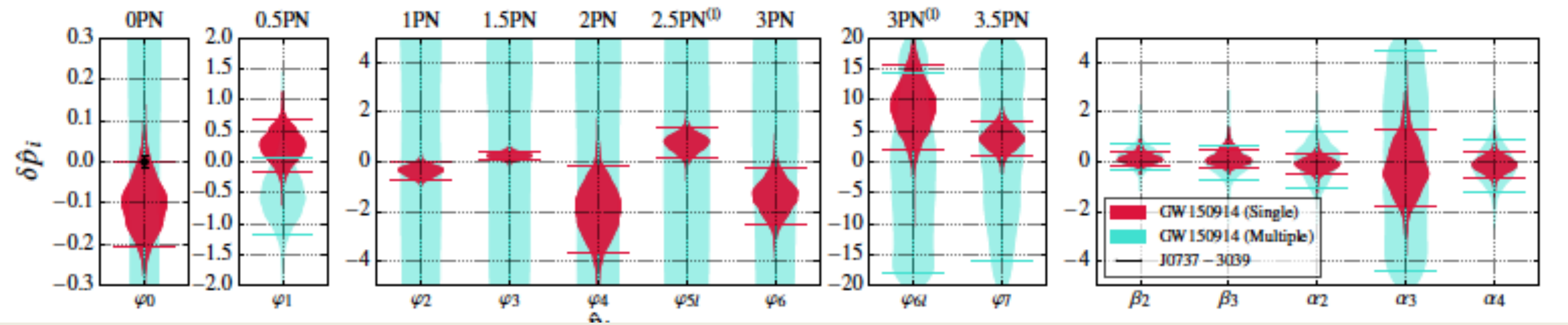
Relatively well-determined
Determination from X-ray obs may be controversial.

Test of GR

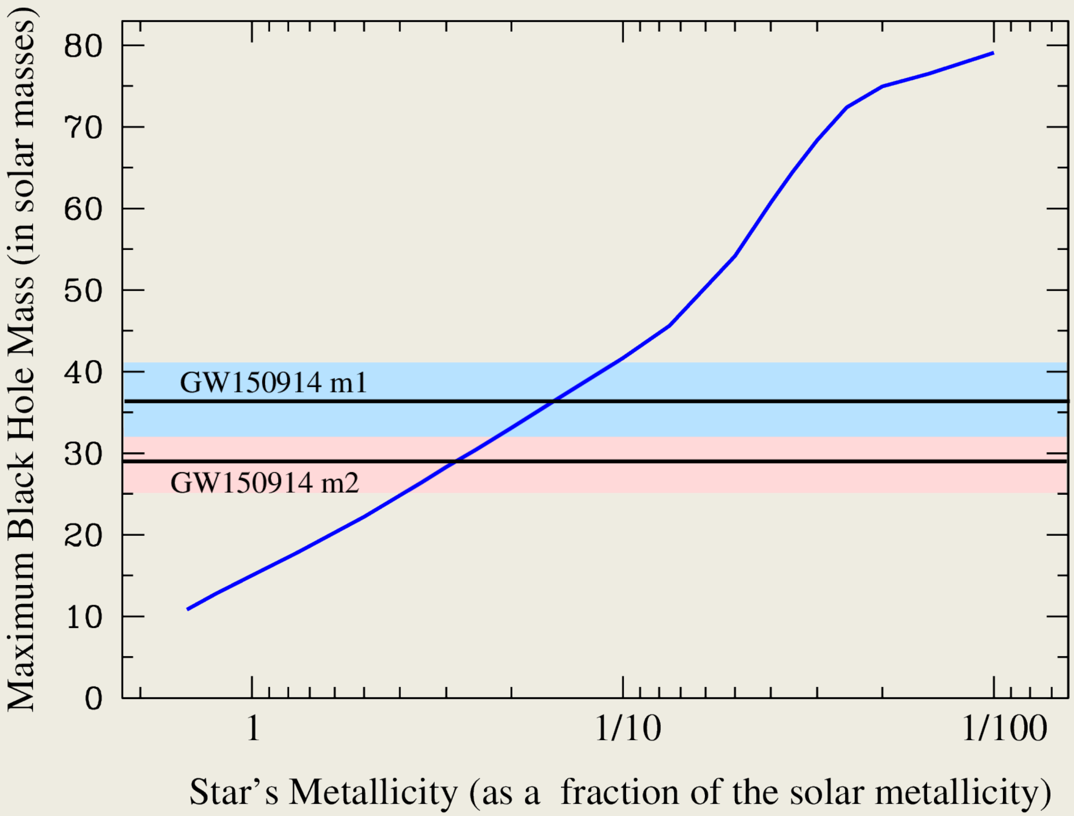


- Parameters from Inspiral and post-inspiral are consistent.
- No deviation from GR found

$$\tilde{h}^{\mathrm{M}}_k(f;\vec{\vartheta}) = \tilde{h}_k(f;\vec{\vartheta})\left[1+\delta A_k(f;\vec{\vartheta})\right] \times \exp\left[i\delta\phi_k(f;\vec{\vartheta})\right],$$



Progenitor



- ✓ Unknown
- ✓ may have much smaller metalicity

too much metals:

(a) interstellar gas cools
- cloud splits into small pieces
- small stars form

(b) Large opacity
- Large stellar wind
- Large mass loss

- ✓ May be Pop III ?? (Kinugawa et al. 2014)
  - ✓ B-DECIGO science target

http://ligo.org/science/Publication-GW150914Astro/index.php

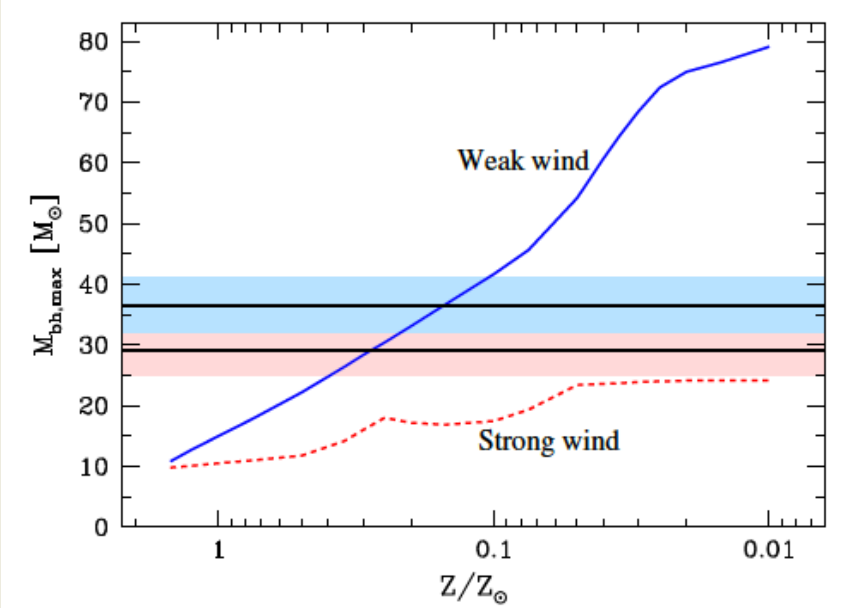
ASTROPHYSICAL IMPLICATIONS

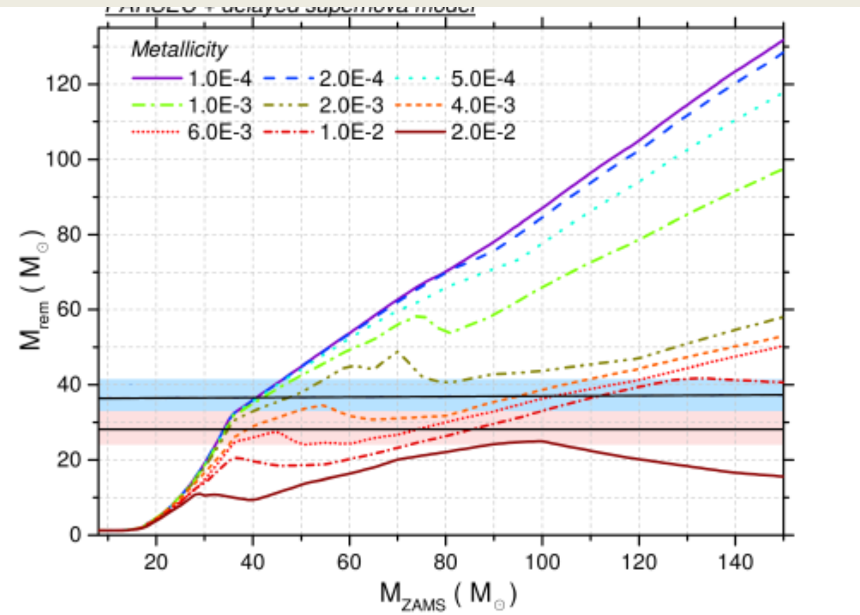
ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914

- Facts :
  - Existence of BH with mass larger than 25 M_{sun}
  - Nearly equal mass
  - Small spin or aligned spin
  - Event rate: 2-53 (400) $Gpc^{-3}\,yr^{-1}$
- Two scenario
  - Isolated BBH in galactic fields: isolated scenario
  - Young and/or old dense stellar environments: dynamical scenario
- Suggestions
  - Mass indicates low metalicity: $Z < 0.5\ Z_{sun}$
    - From old universe or low mass (low metal) galaxy
  - Cannot distinguish two scenarios

High mass indicates low metalicity

- Mass:
  - X-Ray Binary (XRB) 22 systems : M_{BH} ~ 5-20 M_{sun}
  - Stellar wind:
    - low metallicity -> weak wind -> low mass-loss -> high mass BH
    - But stellar wind from low metal star is not well-known: extraporation to Z_{sun} ~ 0.02

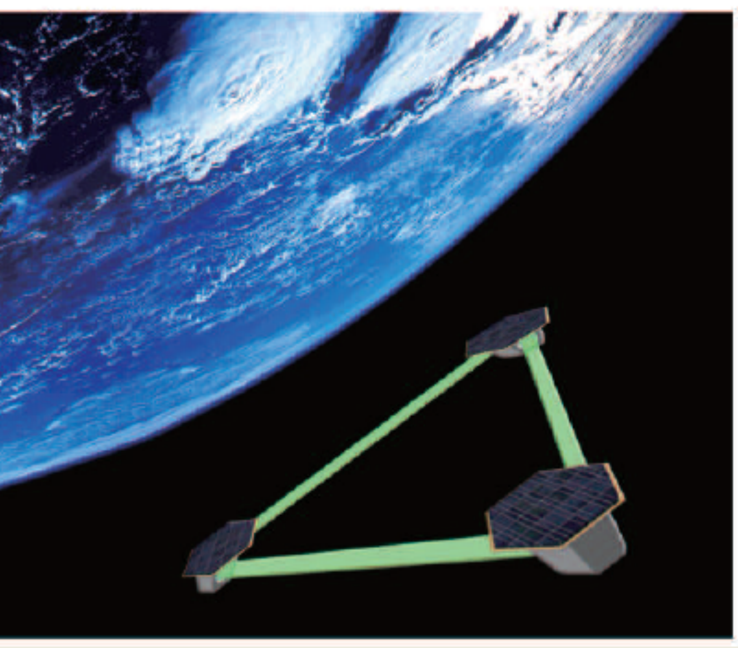


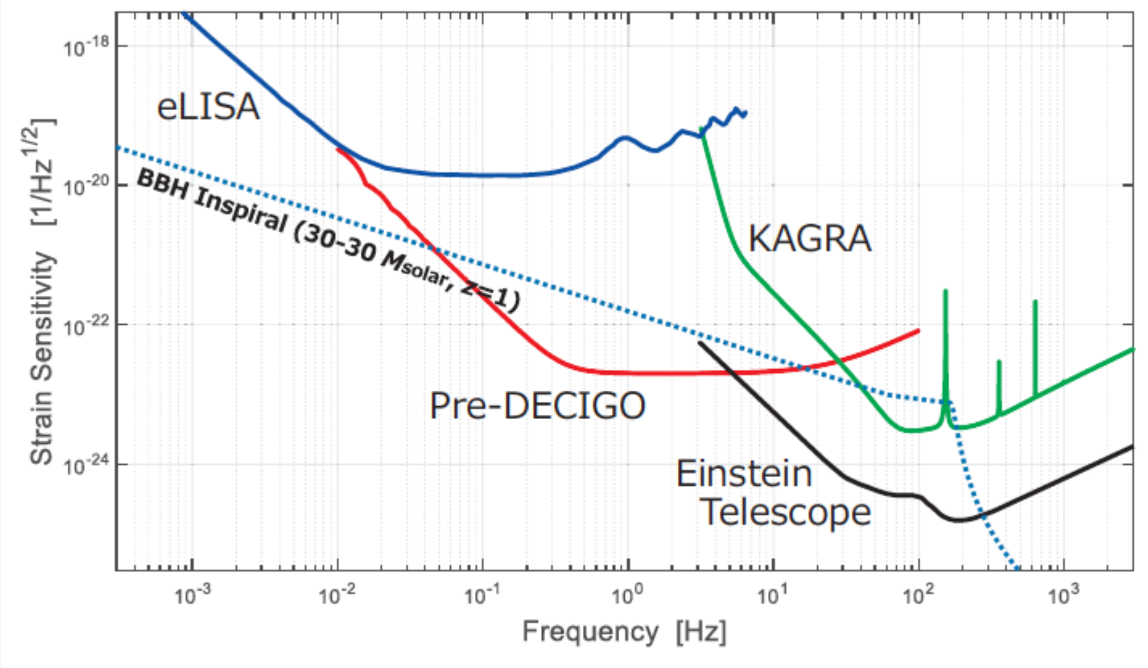


distinguish two scenarios

- Spin measurement
  - orbital angular momentum does not need to align with BH spins in dynamical scenarios
  - Could not constrain from the GW observation.
- Eccentricity
  - Eccentricity would be large in dynamical scenarios
  - But we cannot determine e if $e < 0.1$
  - Eccentricity is always small in the aLIGO band

Redshift distribution and B-DECIGO?



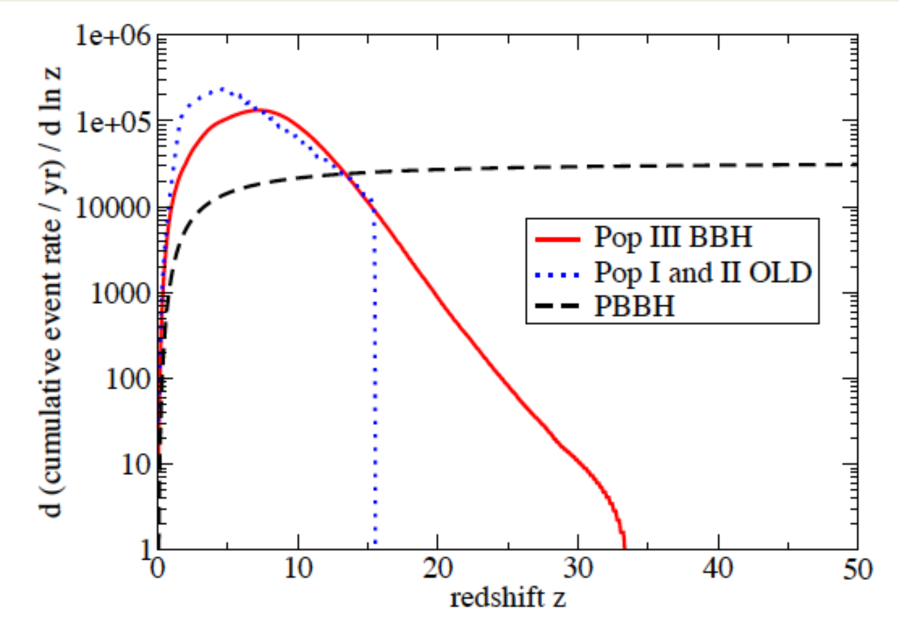


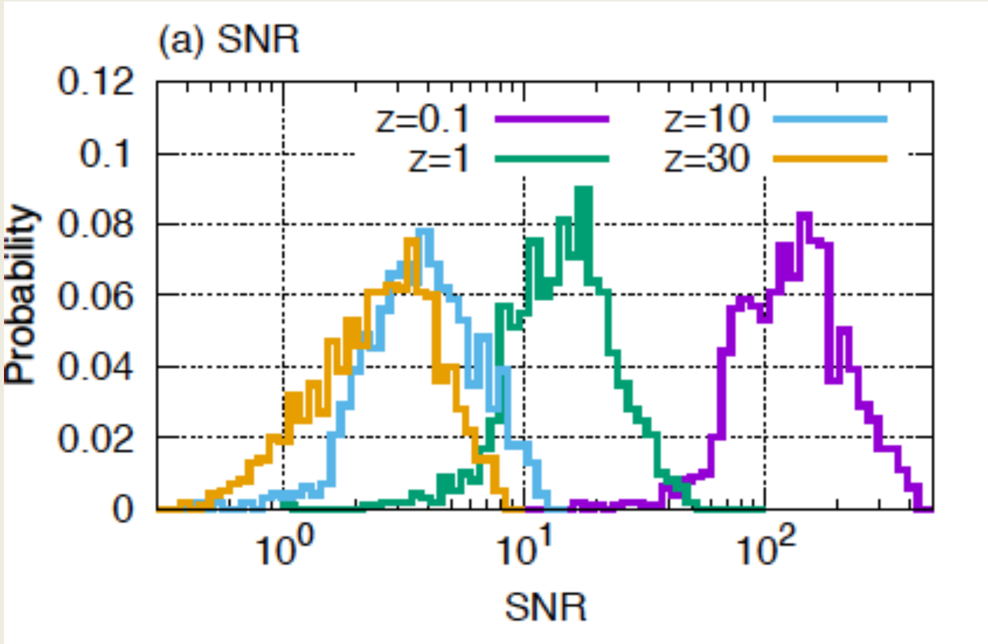
geocentric orbit

Maybe we will call it "B-DECIGO" instead of "Pre-DECIGO".

nakamura et al.
1607.00897

Redshift distribution and “B-DECIGO”?

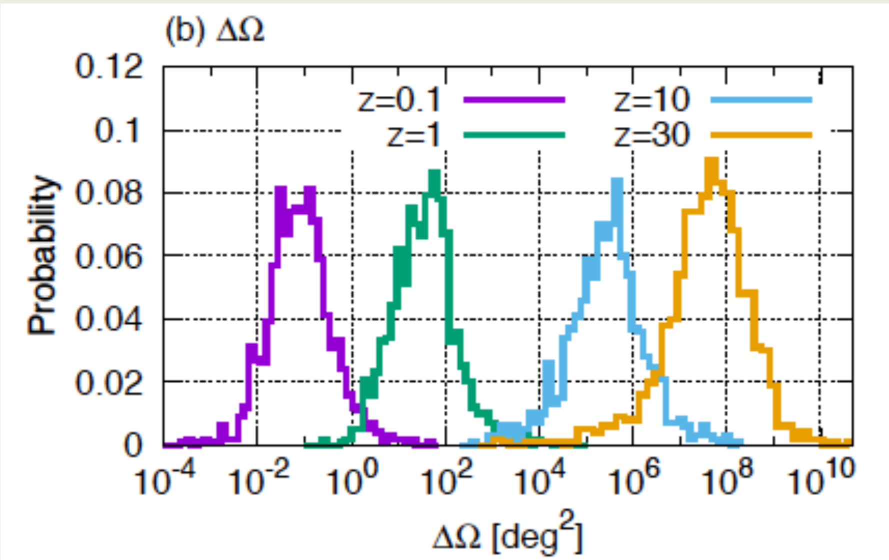


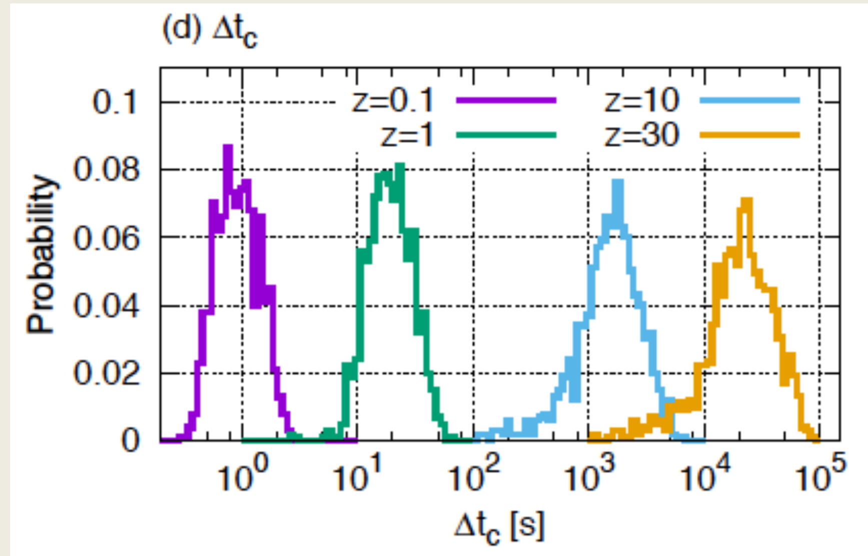


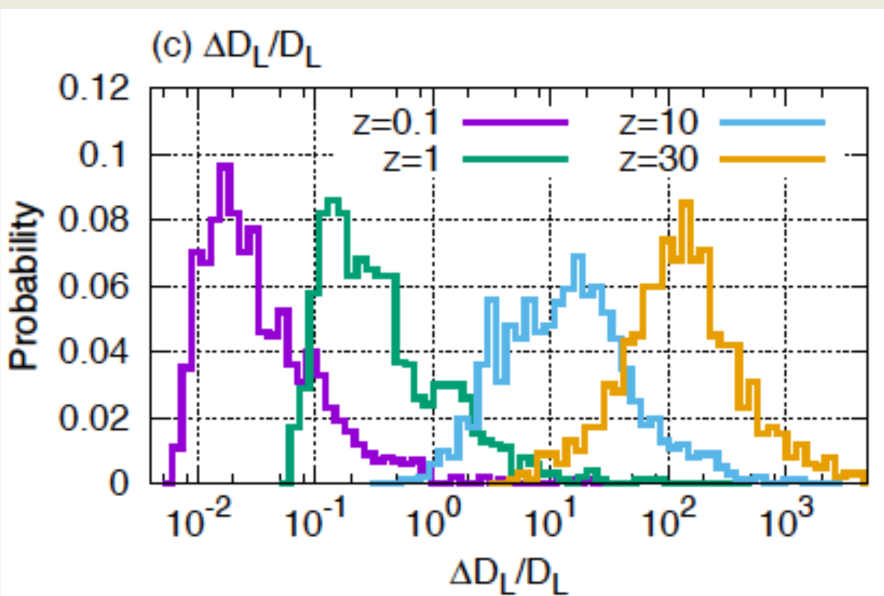
With “B-DECIGO”, we can distinguish three scenarios: PoP III, Pop I/II, and PBBH

nakamura et al.
1607.00897

"B-DECIGO" forecasts







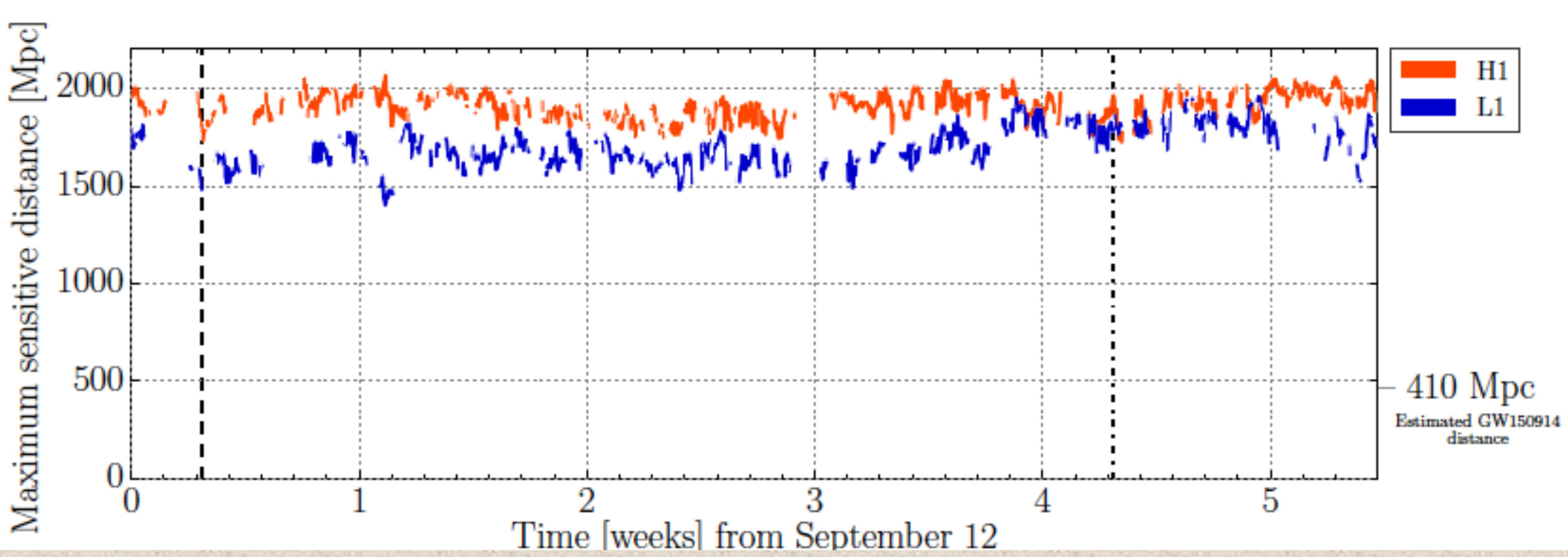
$$\Delta\Omega \simeq 35\,\mathrm{deg}^2 \left(\frac{0.1\,\mathrm{Hz}}{f}\right)^2 \left(\frac{10}{\mathrm{SNR}}\right)^2 \left(\frac{10^6\,\mathrm{s}}{T}\right)^3,$$

Prediction for KAGRA, aLIGO, & Virgo and other follow-up teams

nakamura et al.
1607.00897

DETAILS

Operation time-line and sensitivity



Kiwamu Izumi (和泉究)、天文学会誌6月号
http://www.asj.or.jp/geppou/archive_open/2016_109_06/109_381.pdf
Keiko Kokeyama (苔山圭子)、高エネルギーニュース
Cannon et al., 情報処理学会誌5月号

TITLE: GCN CIRCULAR
NUMBER: 18330
SUBJECT: LIGO/Virgo G184098: Burst candidate in LIGO engineering run data

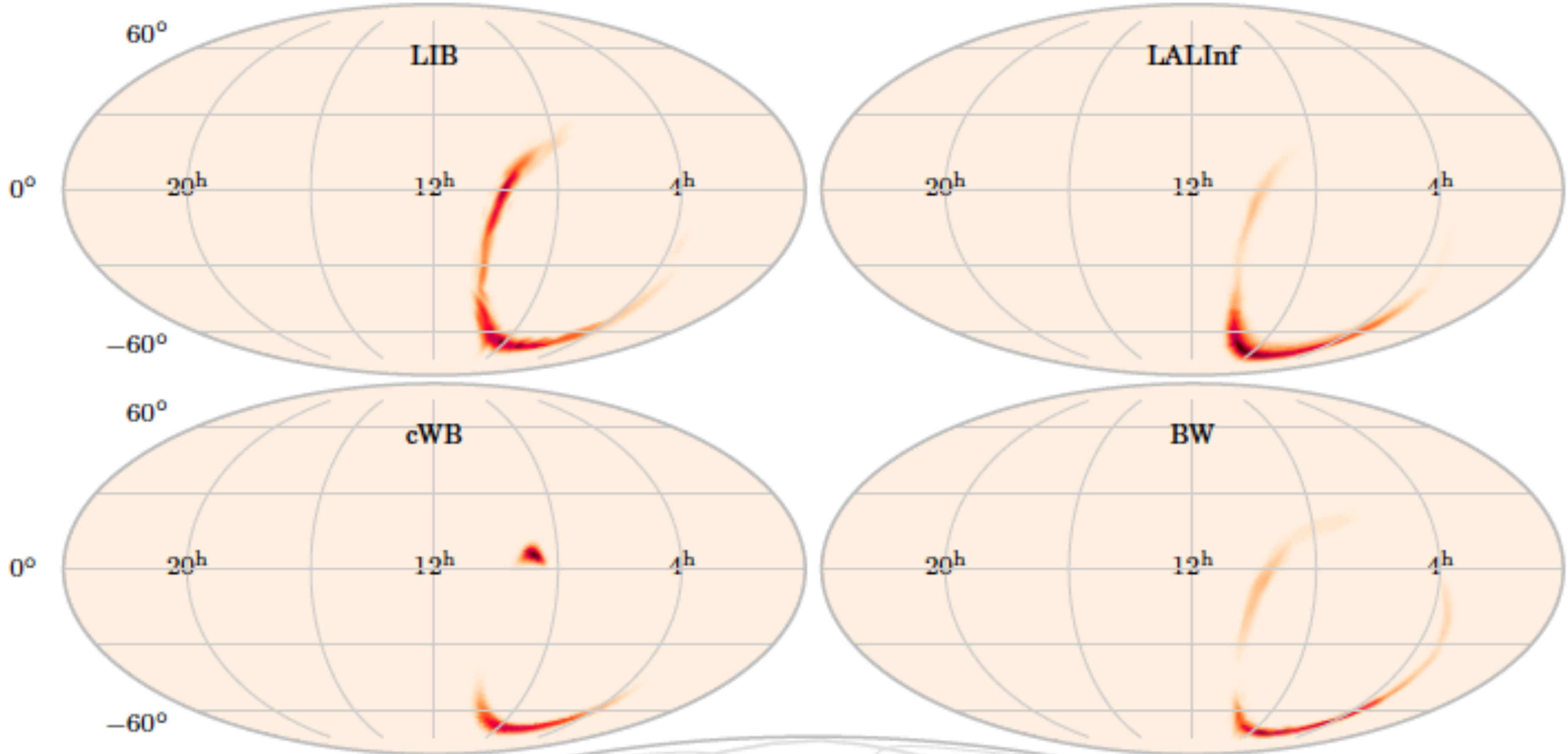
Dear colleagues,

We would like to bring to your attention a trigger identified by the online Burst analysis during the ongoing Engineering Run 8 (ER8).

G184098 (2015-09-16 06:39 UT)
2015-09-14 09:50:45 UTC

- FAR below ~1/month
  - < 1/(2.7yr) → < 1/(100yr) → < 1/(22500yr) → < 1/(203000yr)
- gstlal/pycbc pipeline were turned-off.
- ER8: O1 not yet started
  - Calibration not fixed.
  - Manual alert to EM follow-up within 3 mins of discovery.
- 200 deg^2 (50 % CL) or 750 deg^2 (90 % CL)
- Distance not announced.
- Mass not announced.

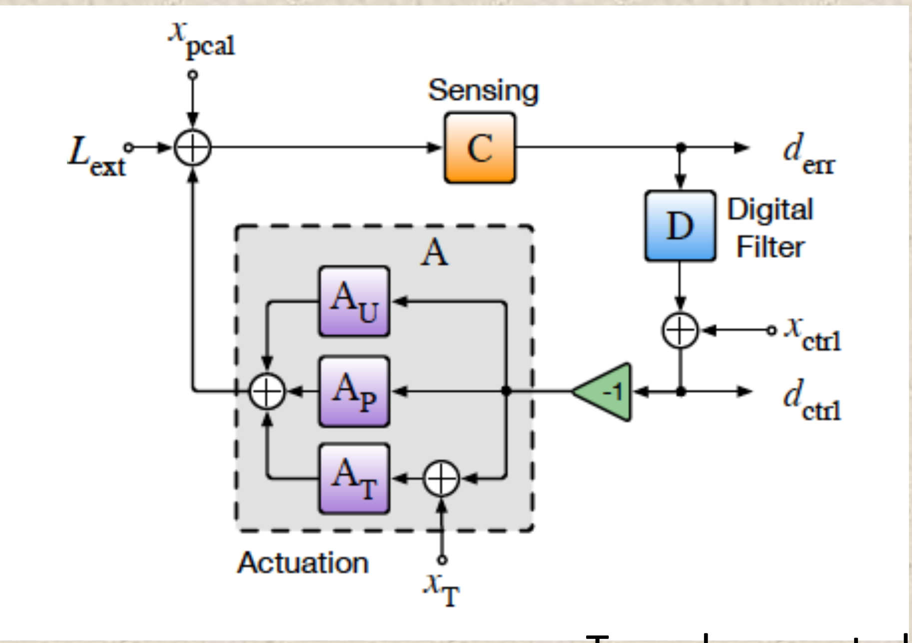
direction



	confidence regions		Fidelity			
	50%	90%	LIB	BW	LALInf	LALNoCE
cWB	98 deg^2	308 deg^2	0.55	0.55	0.51	0.50
LIB	208 deg^2	746 deg^2	-	0.45	0.68	0.28
BW	101 deg^2	634 deg^2	-	-	0.68	0.87
LALInf	140 deg^2	590 deg^2	-	-	-	0.81
LALNoCE	48 deg^2	150 deg^2	-	-	-	-

Calibration has a large impact.

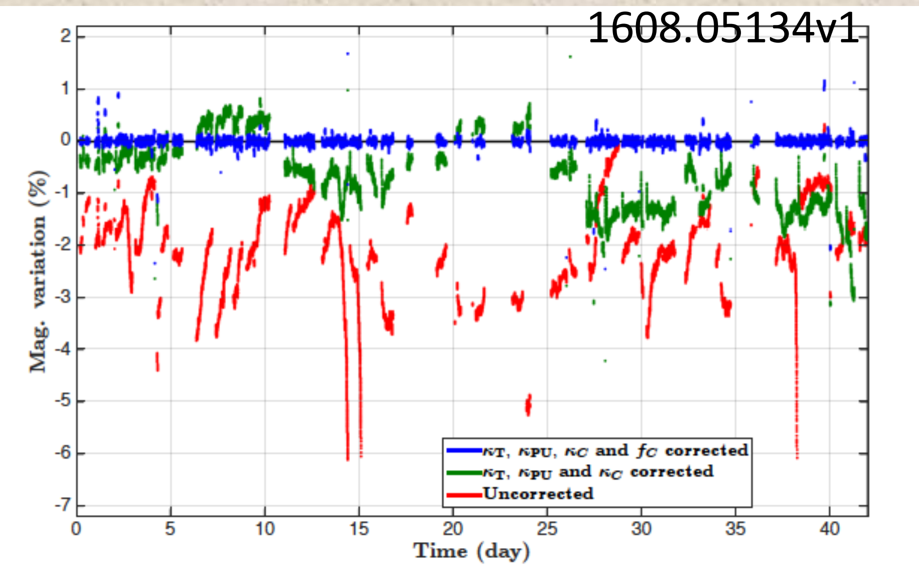
Calibration

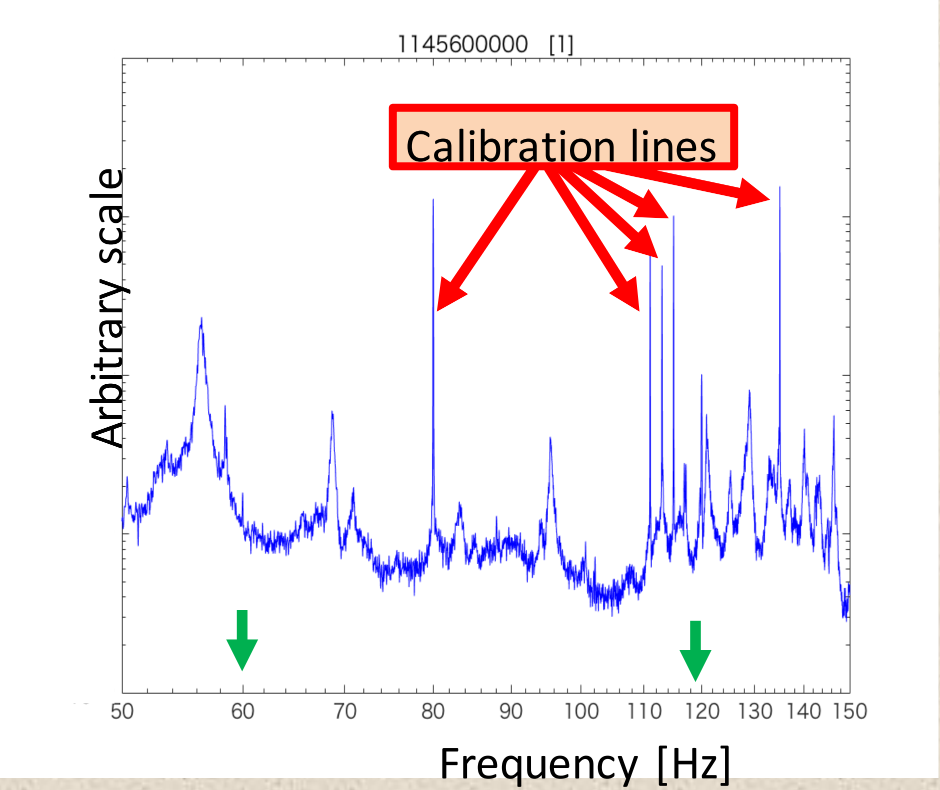


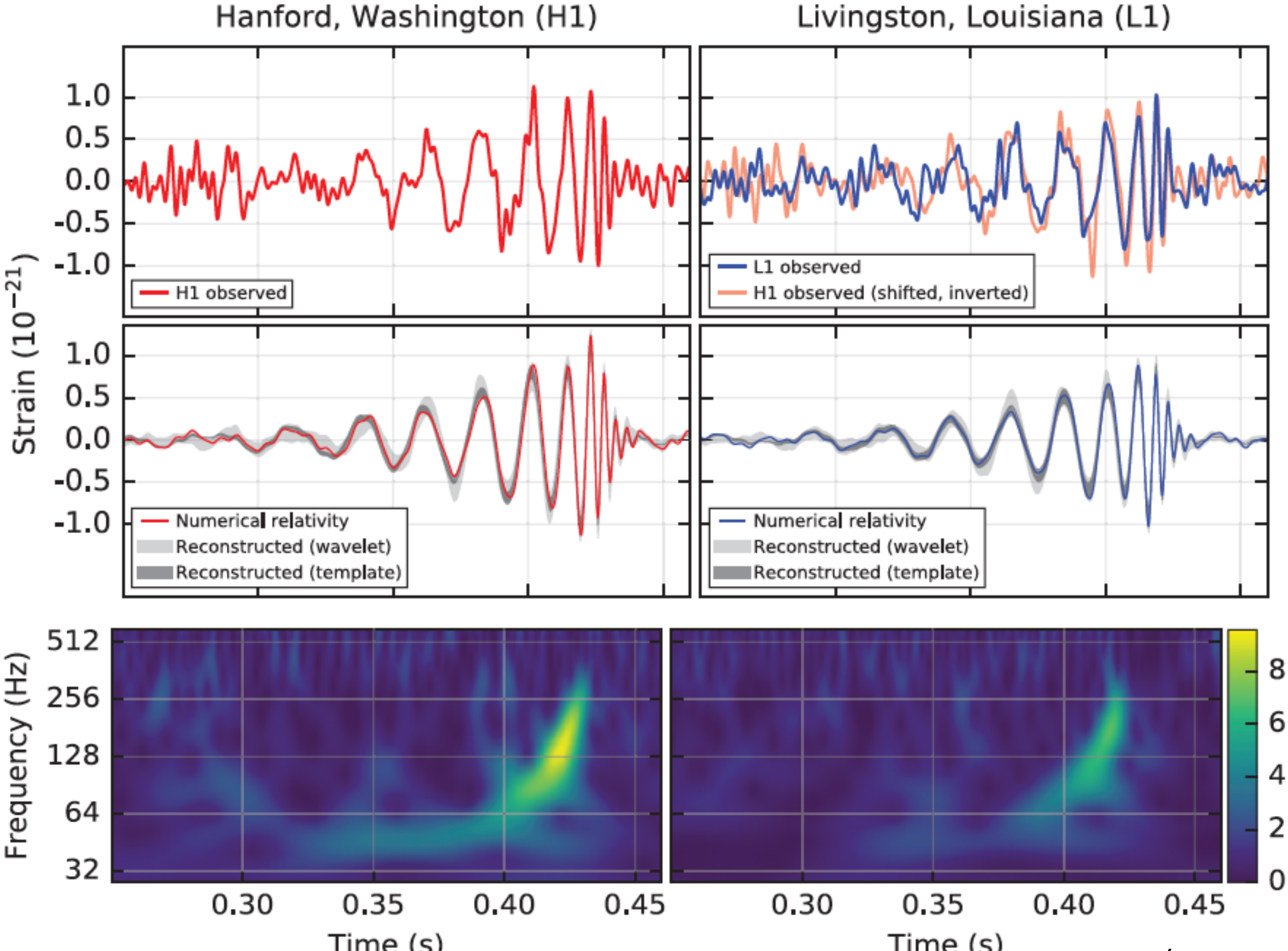
$$R(f) = \frac{1 + A(f)\,D(f)\,C(f)}{C(f)}$$

$$L_{ext}(f) = R(f) d_{err}(f)$$

Tuyenbayev et al. 1608.05134v1

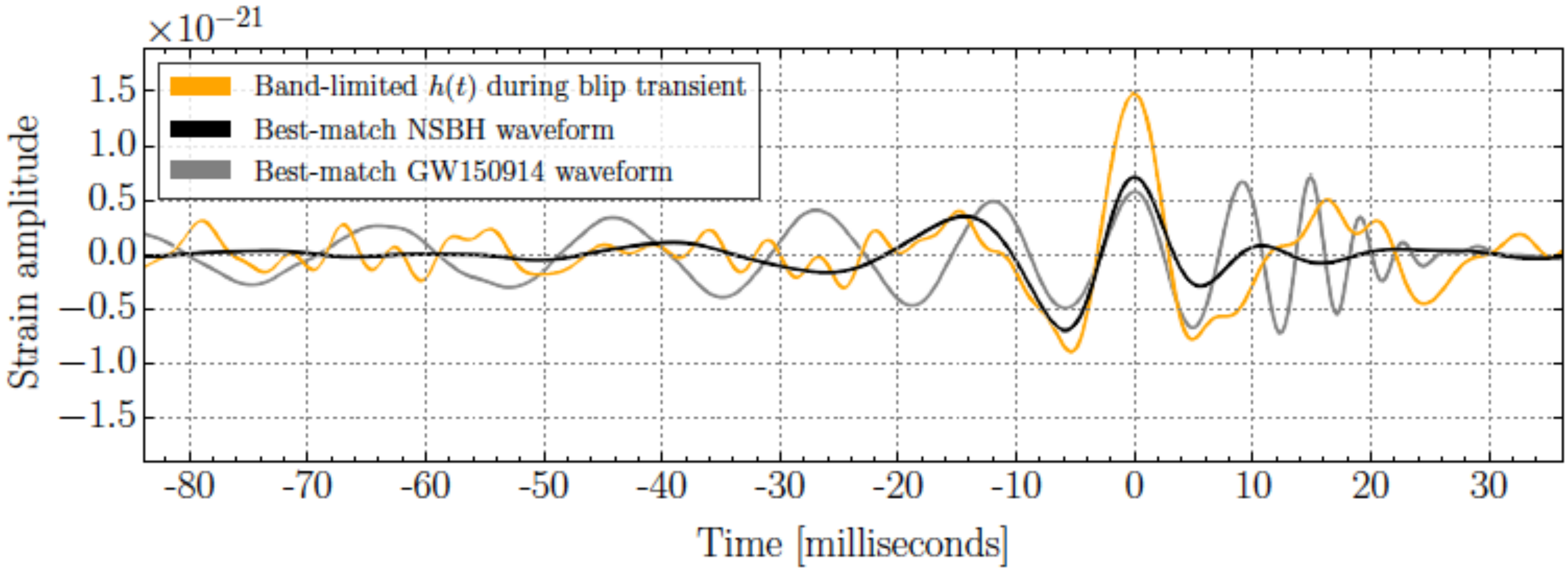




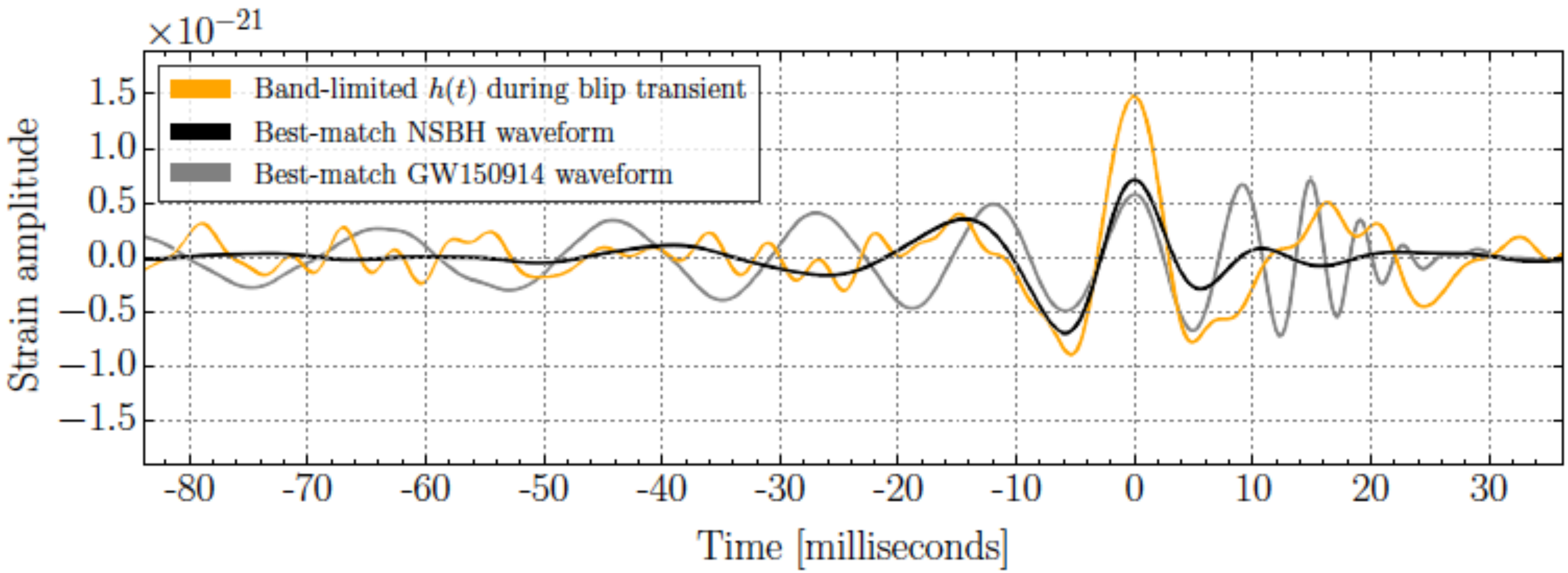


LSC 2016/2 PRL

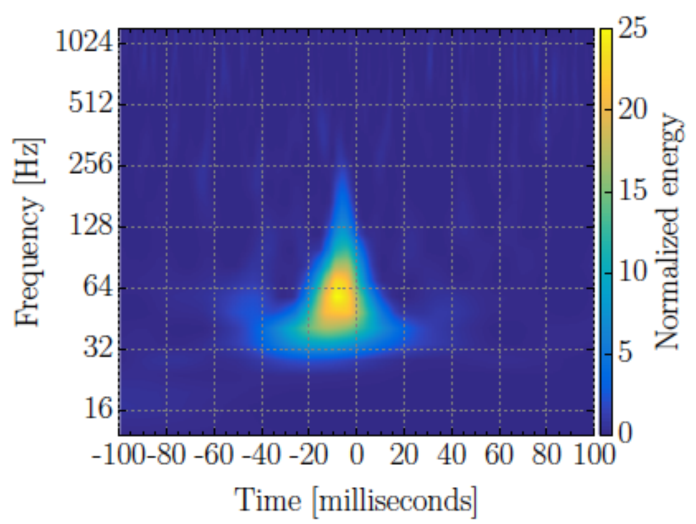
Another event?

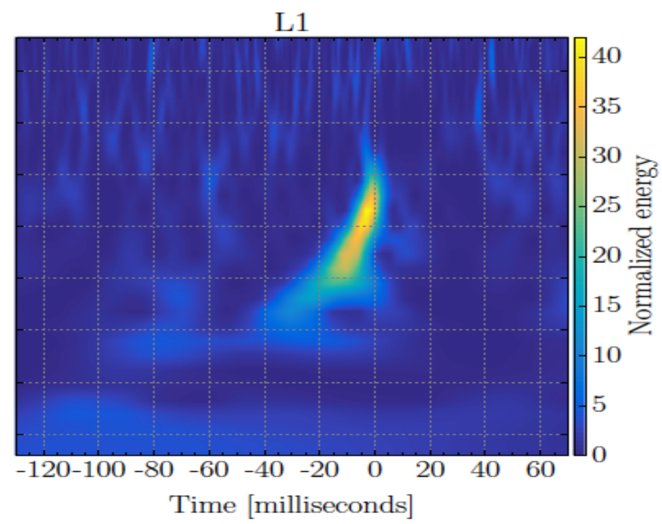


Another event? Not really



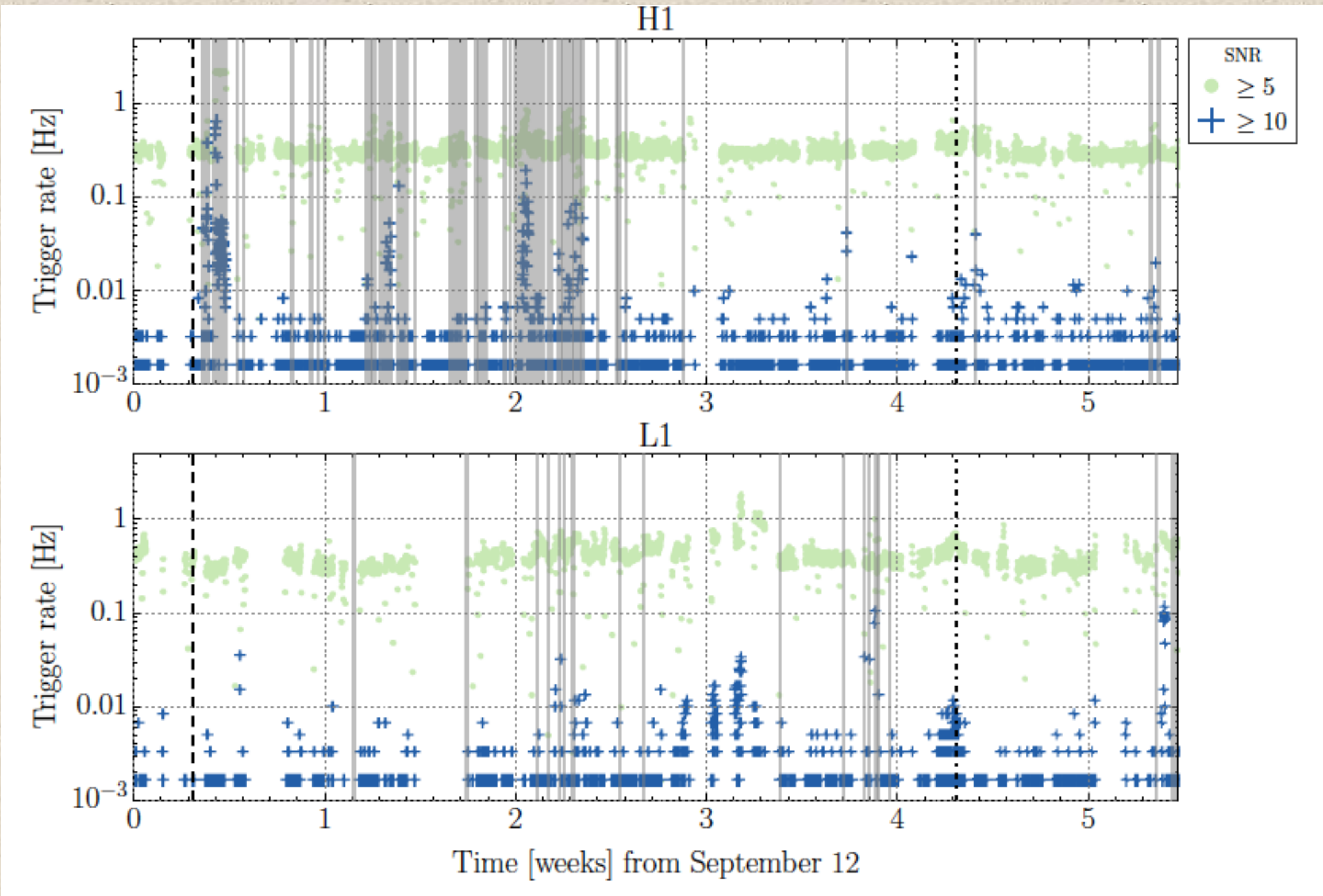
Blip noise





True signal

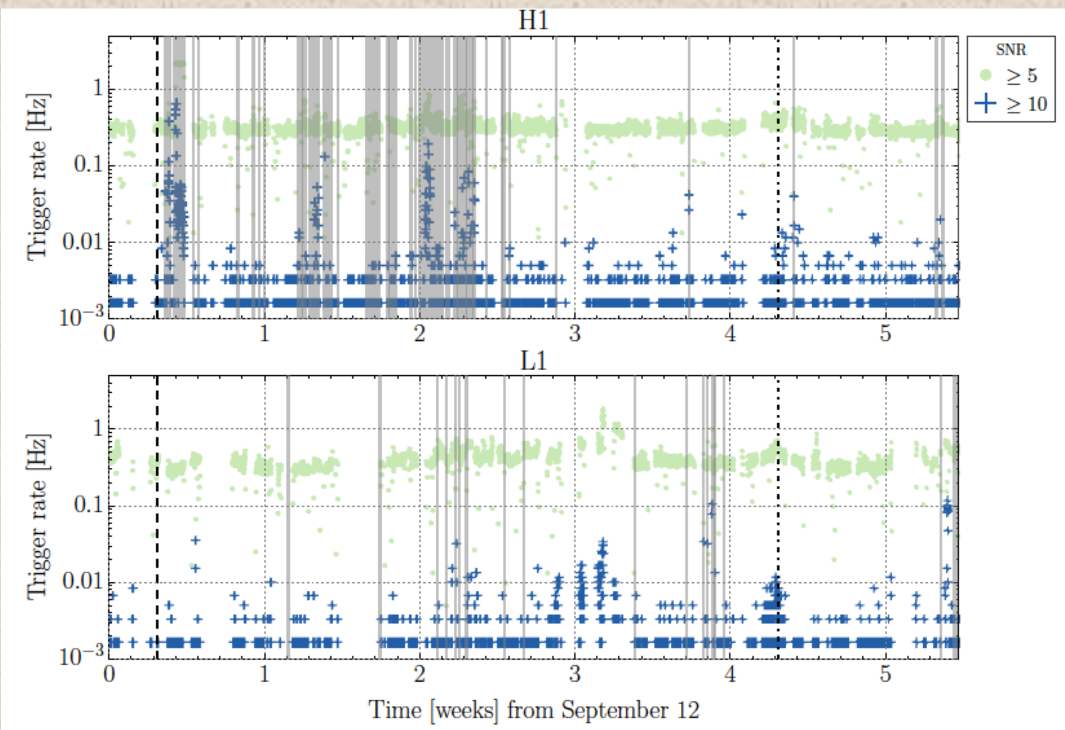
False alarms: Omicron

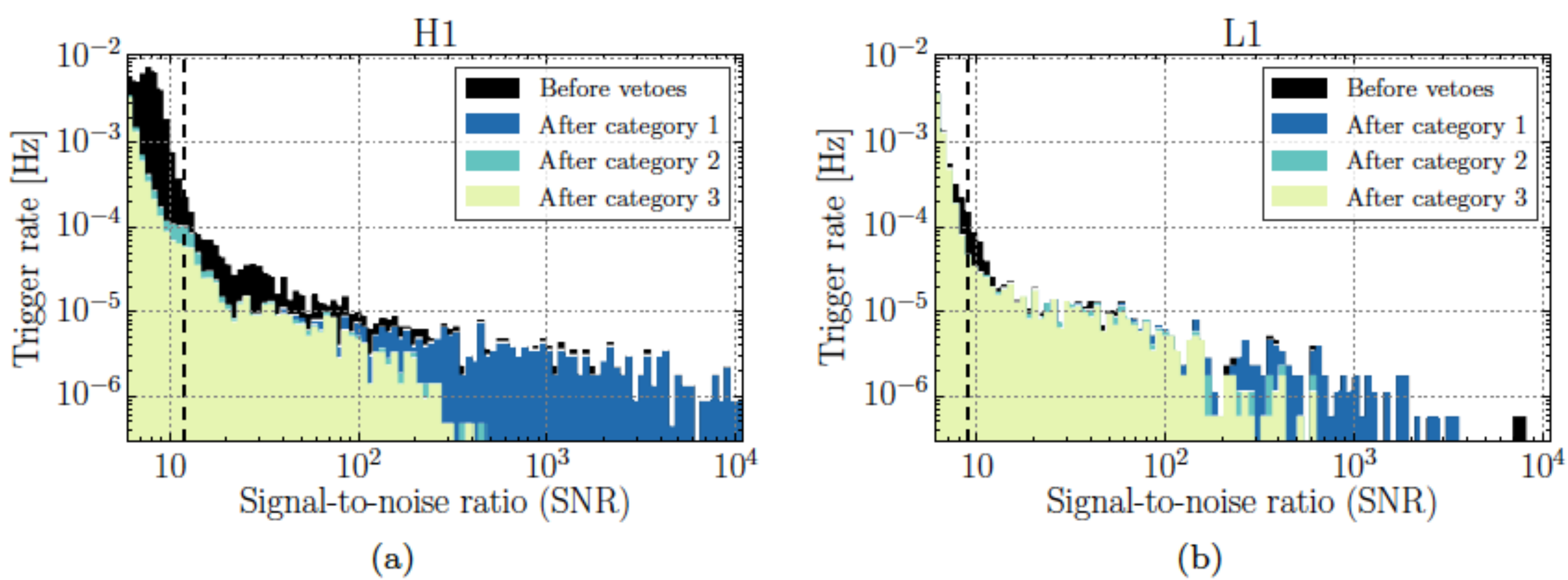


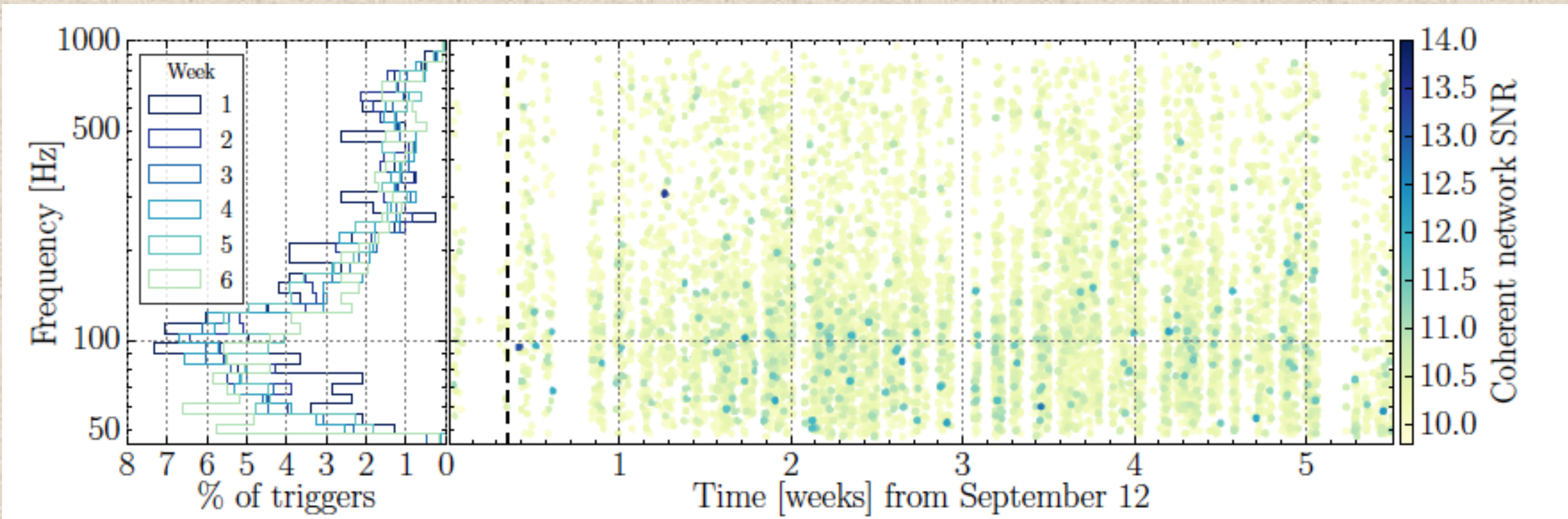
Abbott et al. P1500238

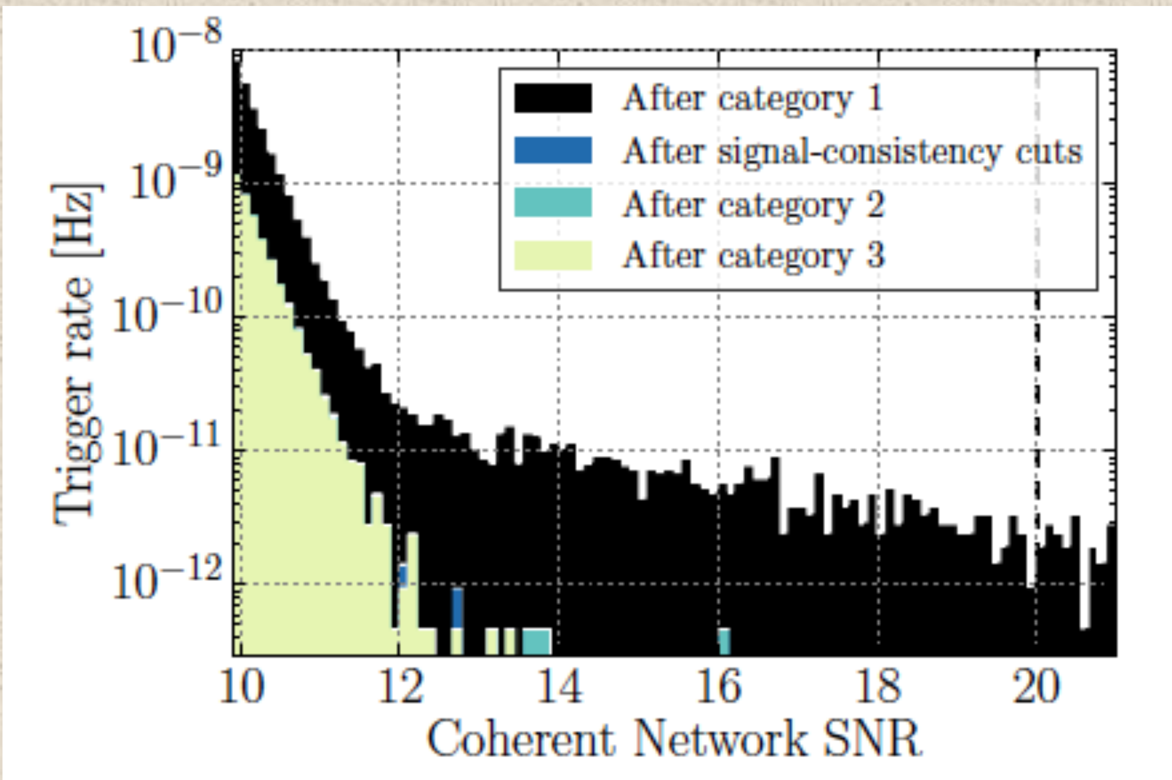
False alarms: Omicron

Abbott et al. P1500238





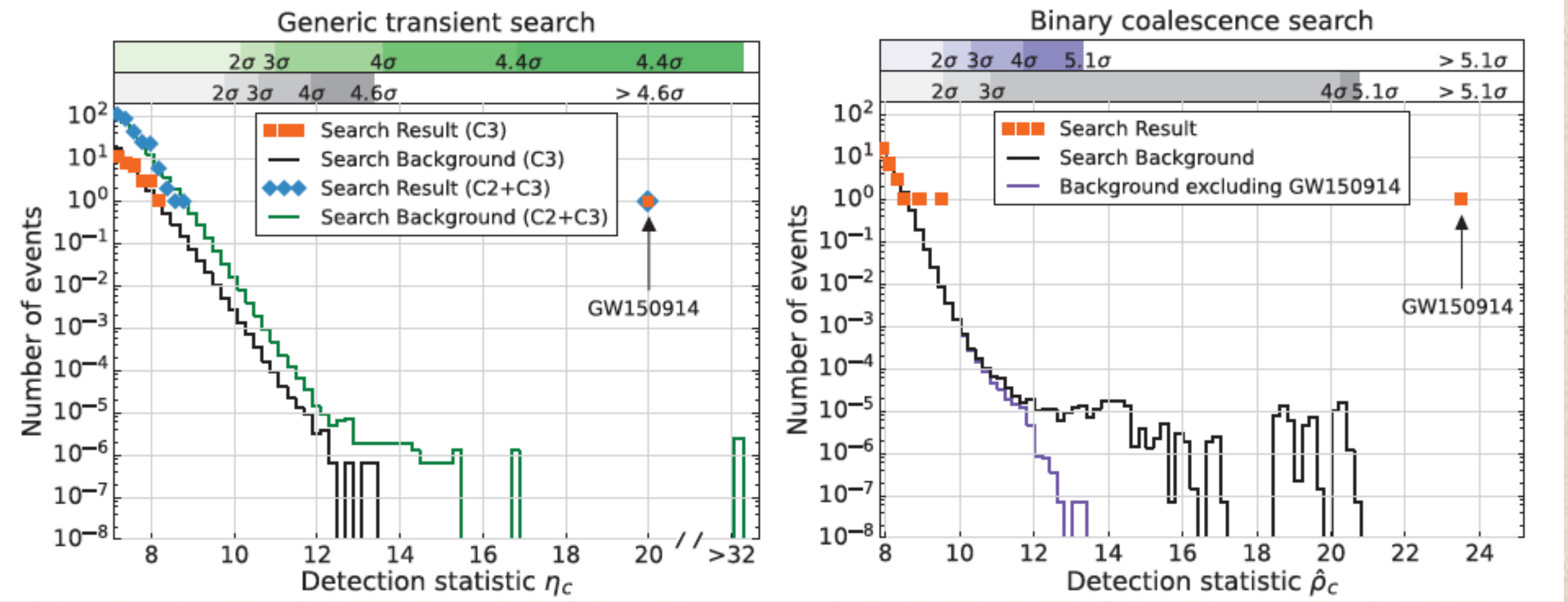




False alarms: Coherent WaveBurst

Abbott et al.
P1500238

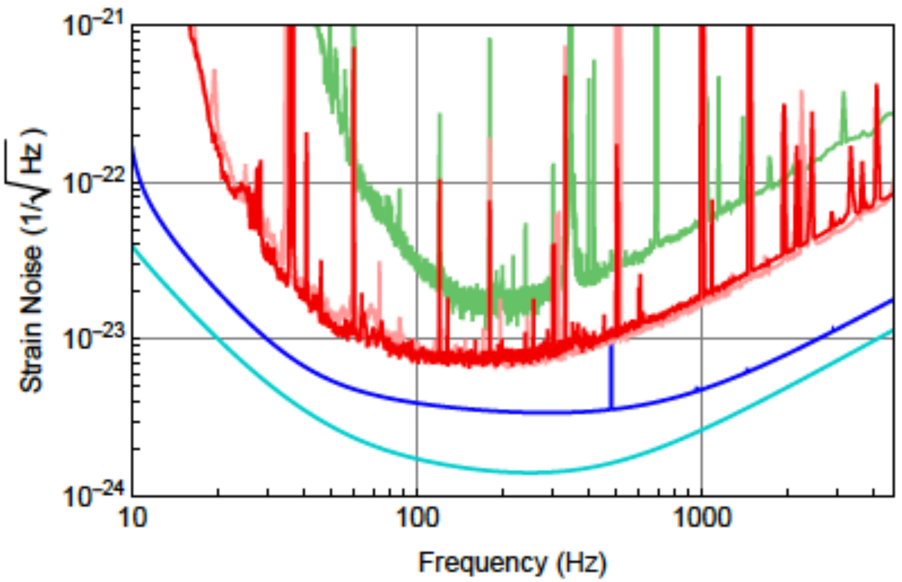
False alarm probability

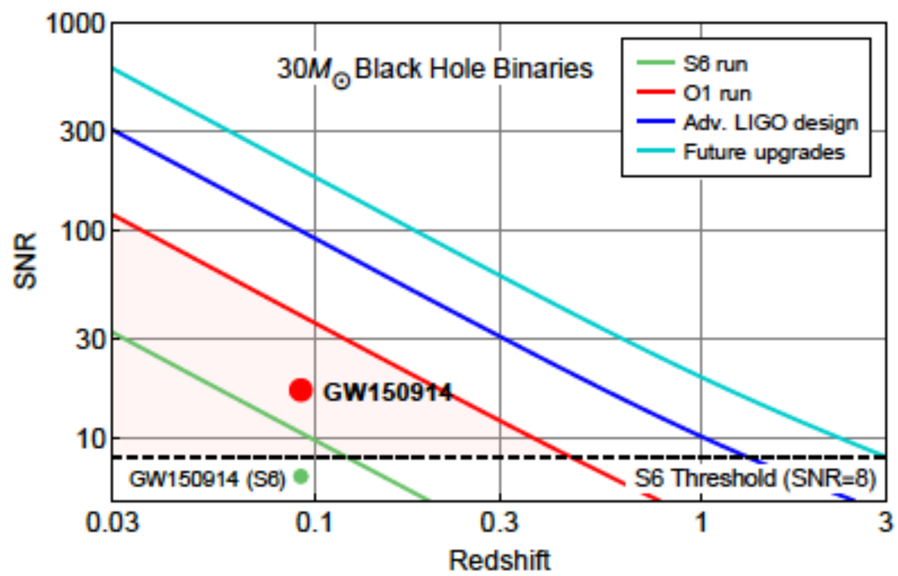


- Green (Right)/Black (Left) are assuming GW150914 were a noise: essentially one detector background.
- Scaled to 16 days
- Actually hard to see significance. Perhaps, much significant than "5.1 sigma"

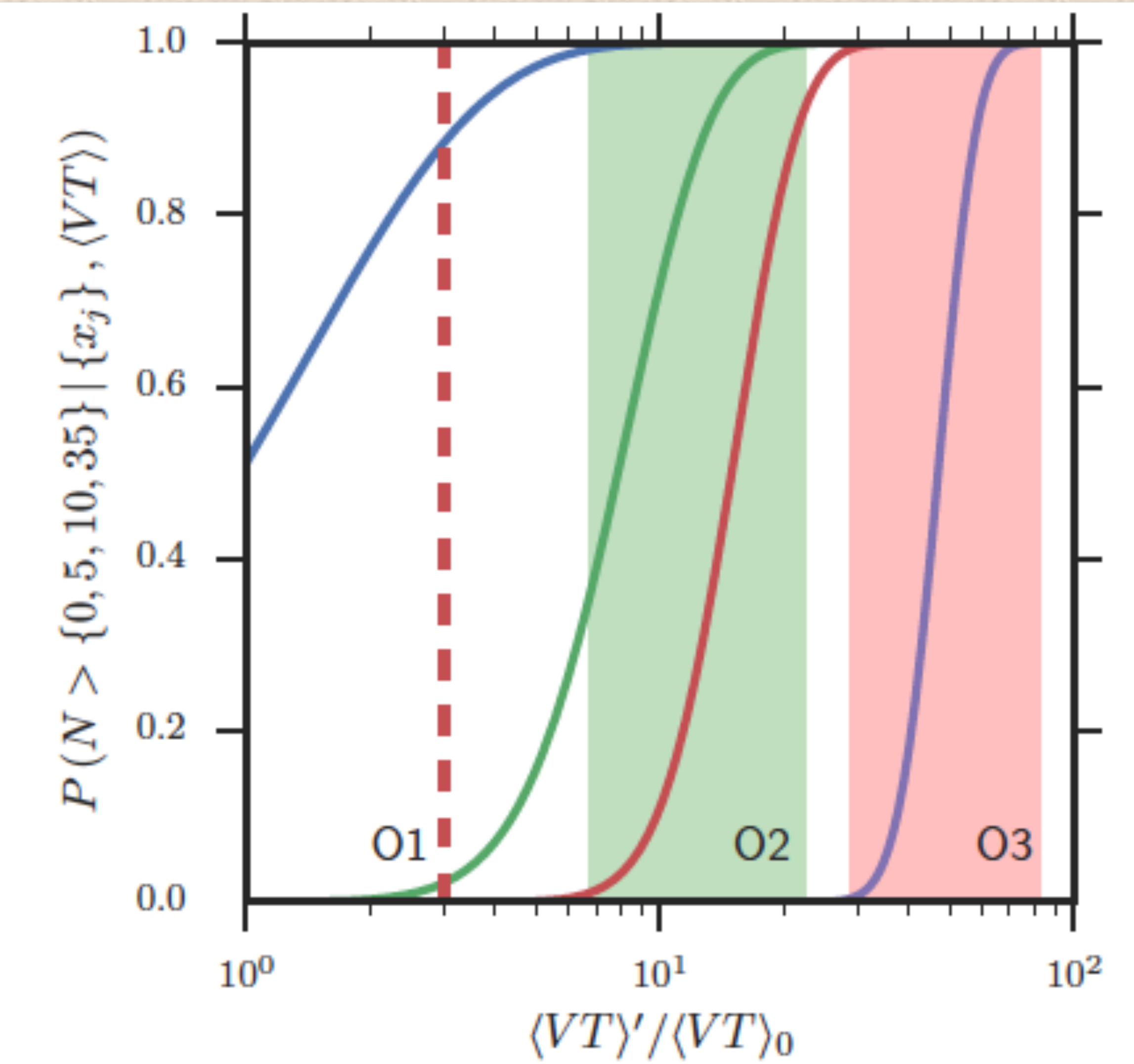
FUTURE

Plan and prospects





Prospects based on real events



Roughly,
1/(0.8^3Gpc^3 16/365 yr)
~ 45 events/Gpc^3/yr

O2:
2016/11-?, 2017/03-
(with Virgo)?
Likely have ~ 10 events

Why KAGRA useful in 2018?

<u>CBC/Burst Search: we do not know when it visits us.</u>

Importance is in not only the sensitivity, but also in the duty cycle.

Duty cycle in O1

LHO (windy desert)

LLO (forestry)

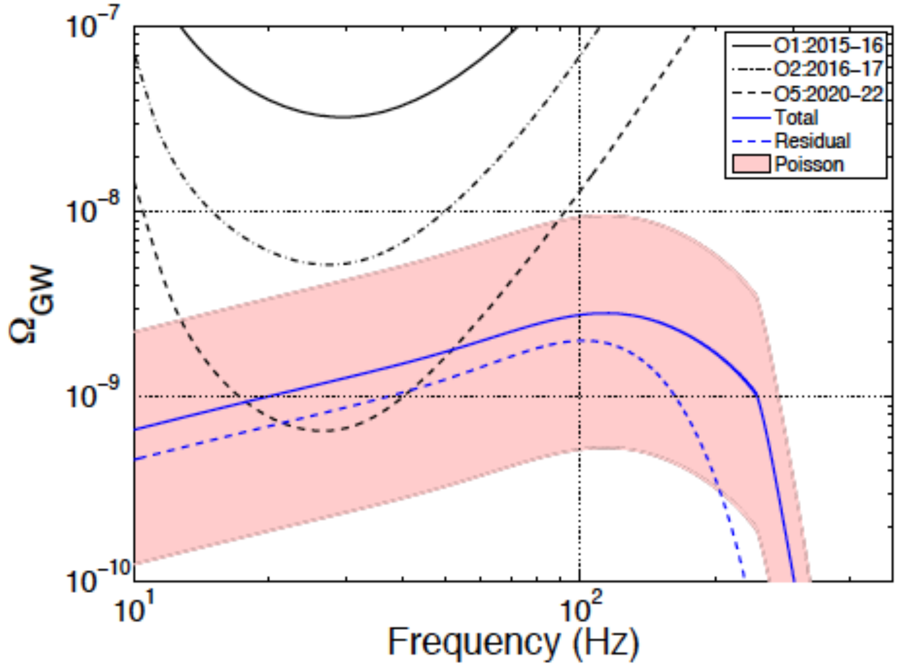
33 % coincidence

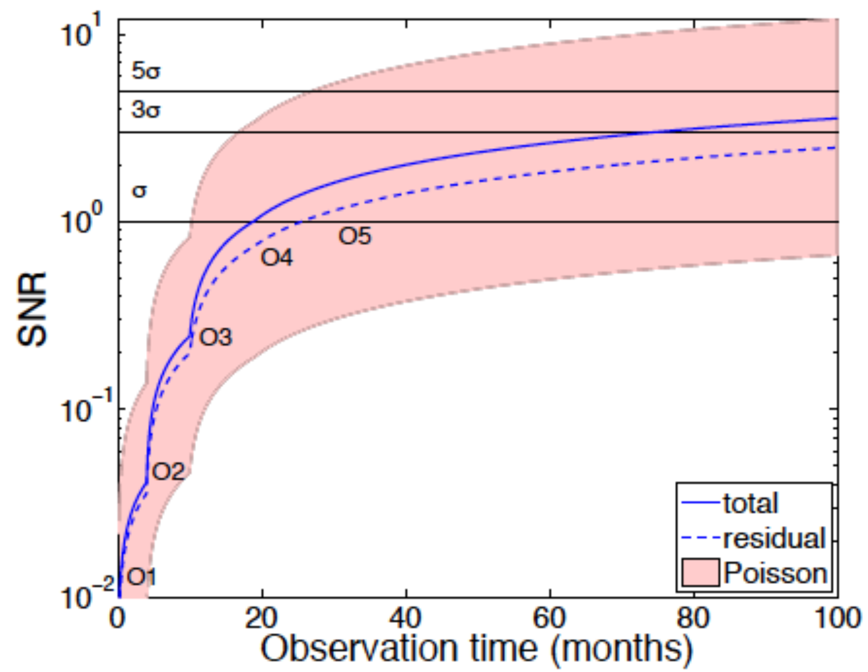
VIRGO (VSR2/4) 80%

KAGRA (expected) 80%

- ✓ We need as many detectors as possible that are **actually** running.
- ✓ Underground is ideal place (low seismic noise)

Stochastic foreground



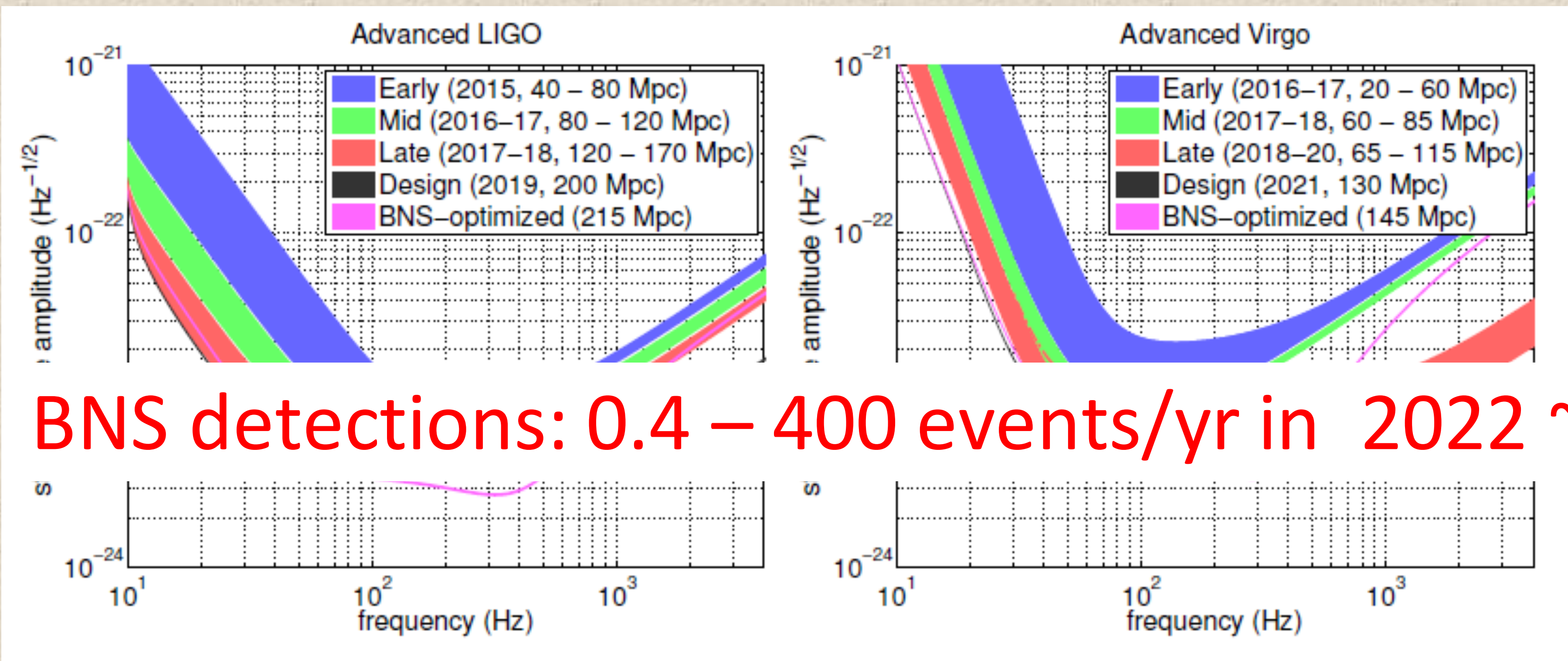


O5 (2022?) science

Obstacles to inflationary GWs?

BNS: Expected sensitivity curves & inspiral ranges of aLIGO/aVIRGO

Arxiv: 1304.0670

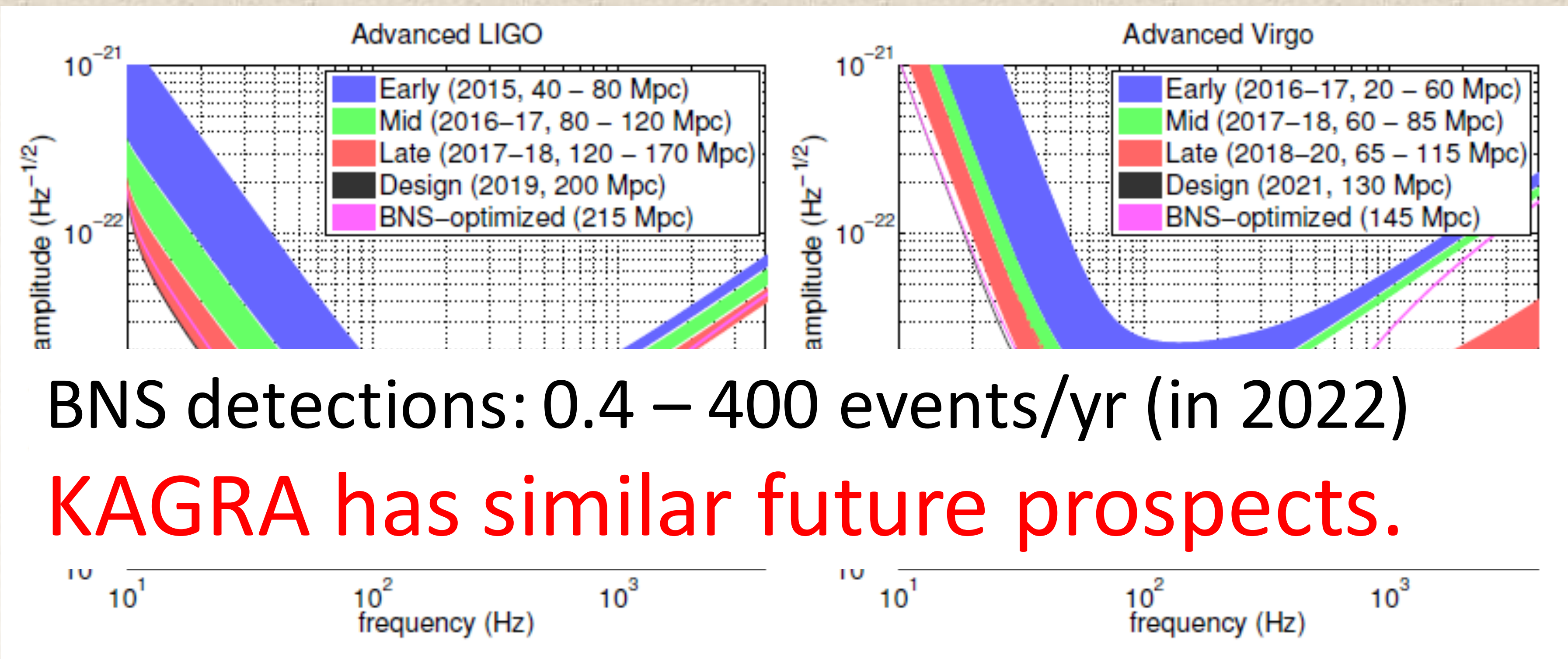


BNS detections: 0.4 – 400 events/yr in 2022 ~

Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Burst Range (Mpc) Virgo	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	% BNS Localized within 20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

BNS: Expected sensitivity curves & inspiral ranges of aLIGO/aVIRGO

Arxiv: 1304.0670



BNS detections: 0.4 – 400 events/yr (in 2022)

KAGRA has similar future prospects.

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Prospects

個人の感想です。

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
LIGO	GW150914 GW151226	O2a	O2b	O3?		O4?		A+ Commissioning?	A+ observation?	
Virgo	Virgo construction		aVirgo observation ?							
KAGRA	iKAGRA construction	iKAGRA Simple Michielson	bKAGRA construction	bKAGRA cryogenic	bKAGRA construction	bKAGRA cryogenic DRFPMI				
LIGO-India		governmental approval	LIGO India construction							Start as A+?
BNS		0.006-10		0.04-100		0.2-200			2-2000??	
BBH		- 30??		- 100???		-200???			3 events / day?	

Test of GR?

- Many events?
- Improvements in localization and duty cycle?
- NS-BH?

BBH dist.
BBH SB
Non CBC

Only KAGRA & Virgo ?
NS/NS, SNe …

Typical GW：Double Neutron star

minutes before

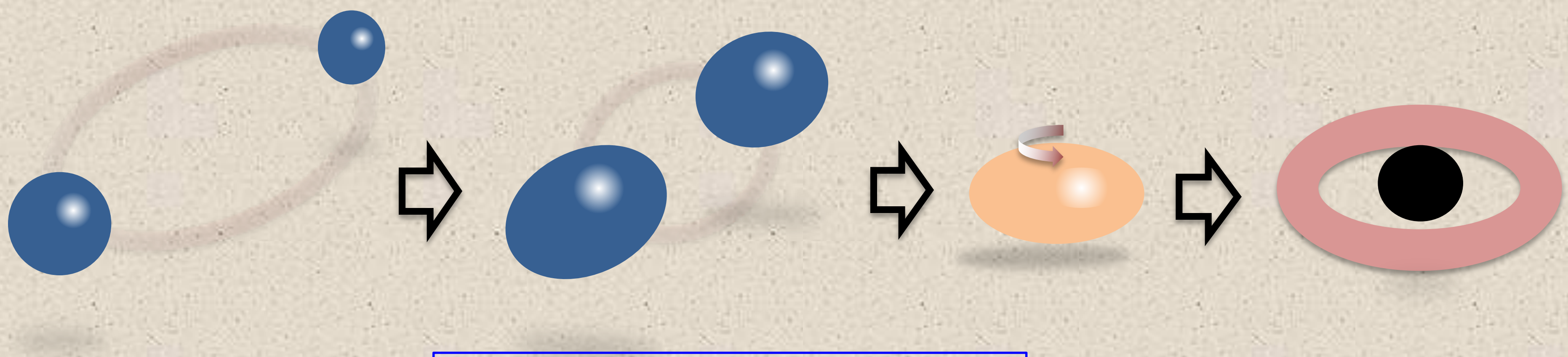
$r_{\mathrm{orb}} >> R_{\mathrm{NS}}$

milli-sec before

$r_{\mathrm{orb}} \le 5R_{\mathrm{NS}}$

Hypermassive NS

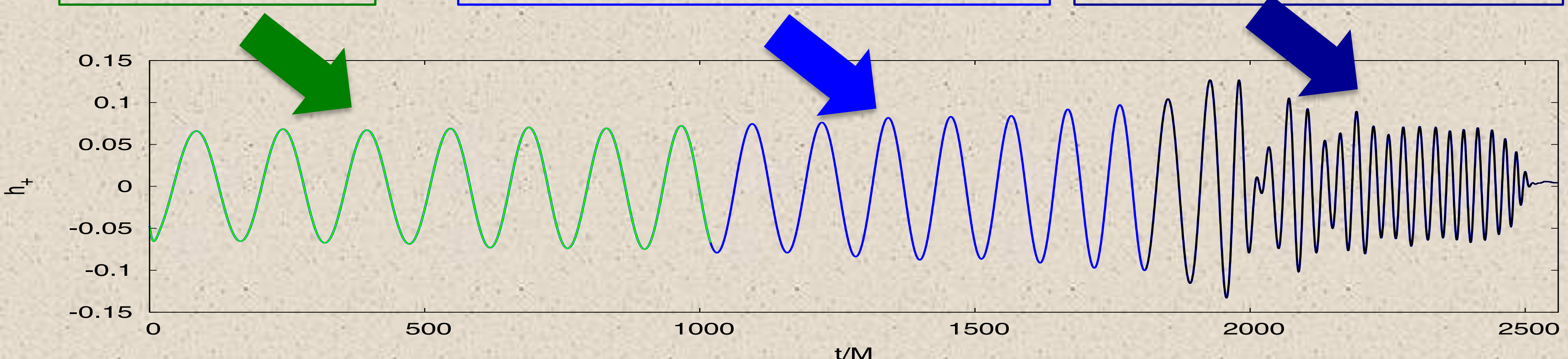
Collapose to BH & GRB?



Post-Newton

Post-Newton with tidal coupling or NR

Numerical relativity



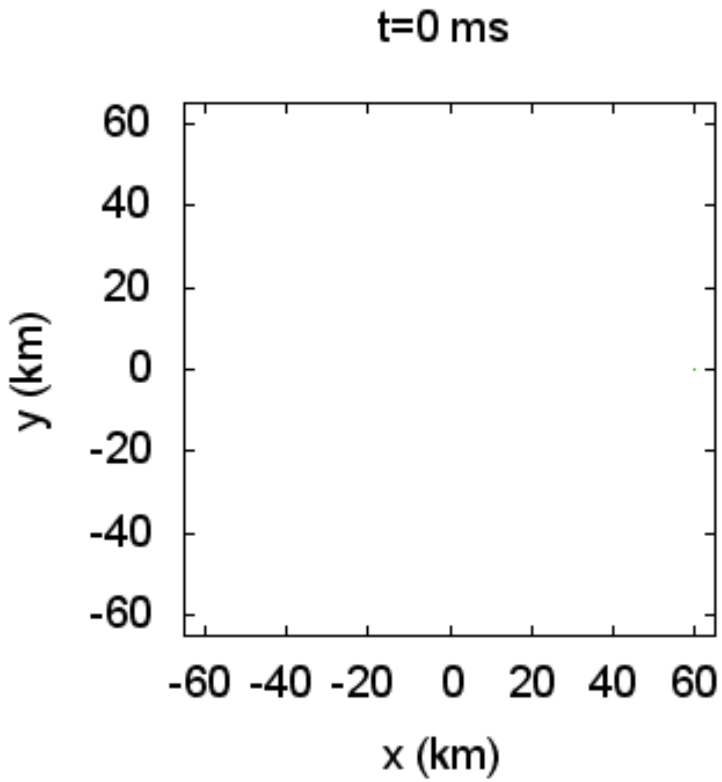
2014 April KAGRA Data analysis school “Numerical Relativity” (By Prof. Masaru Shibata)

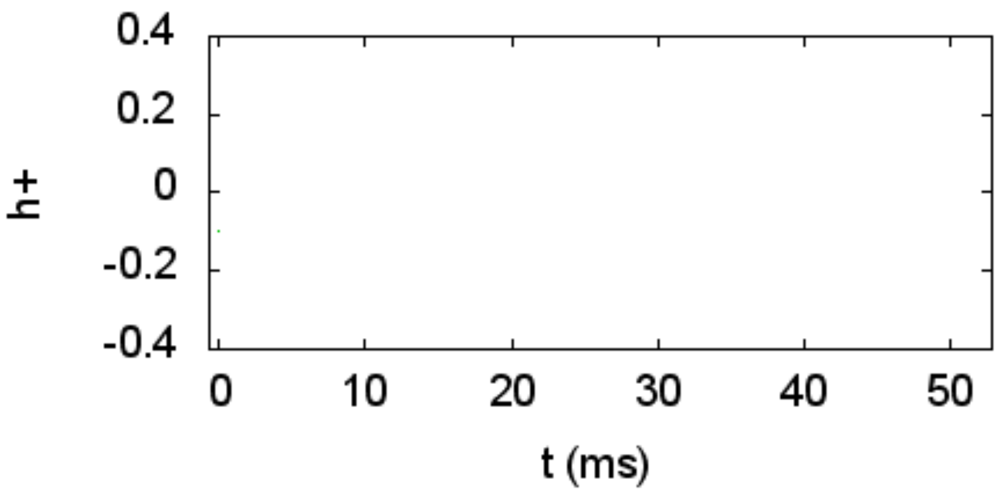
Including tidal effects

1.35-1.35 M_{sun}, EOS: MS1 (stiff)

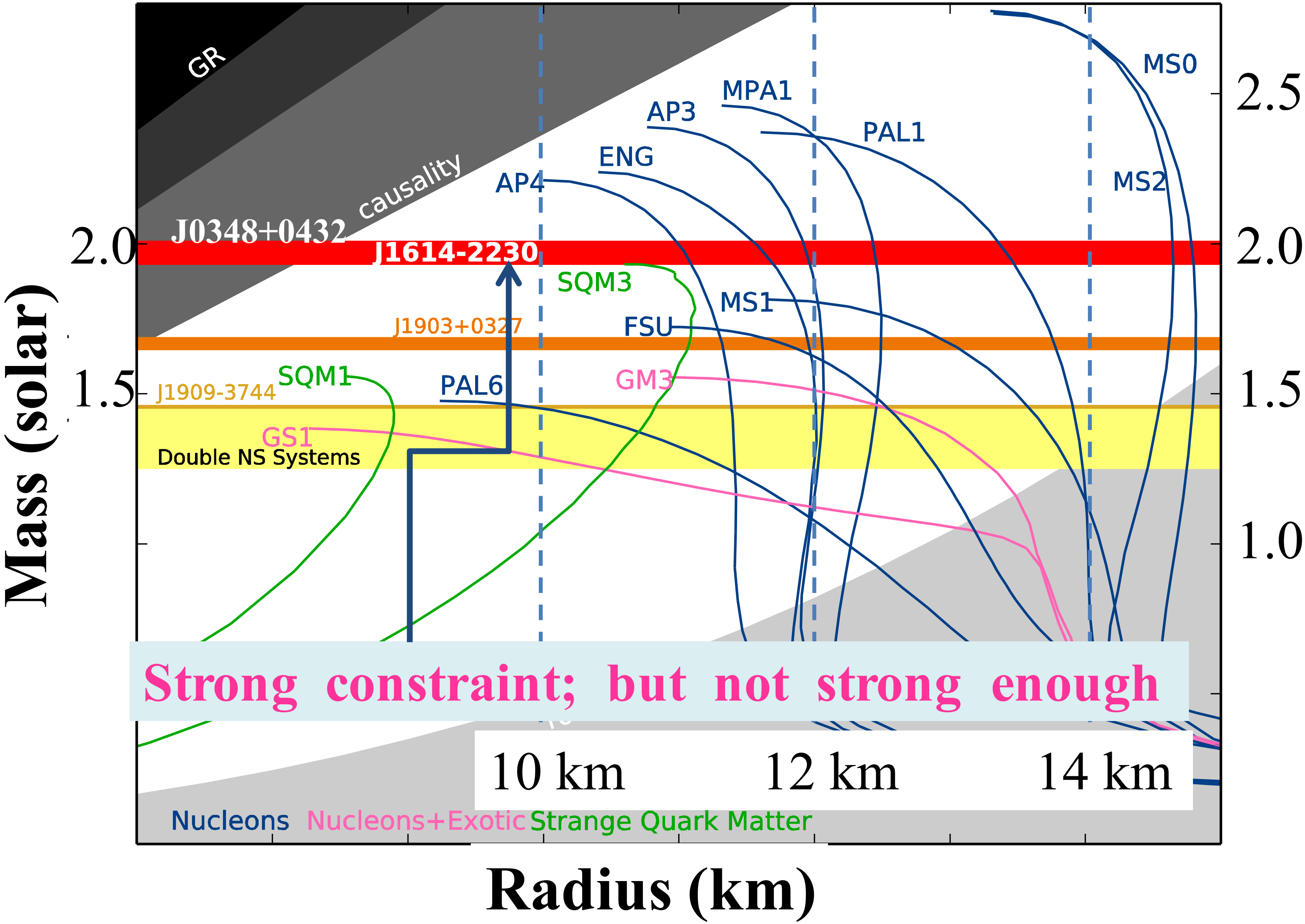
without tidal effects

with tidal effects

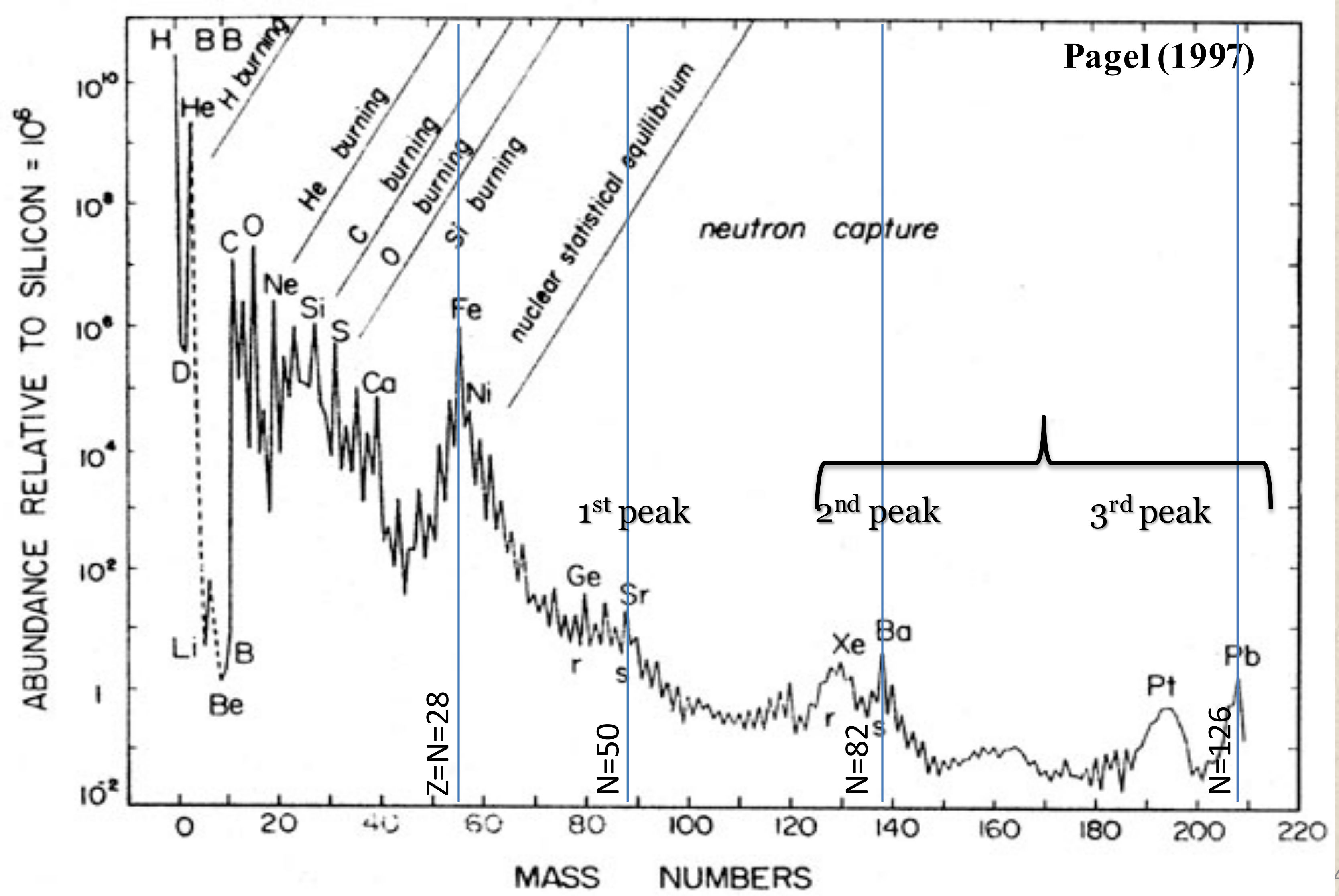




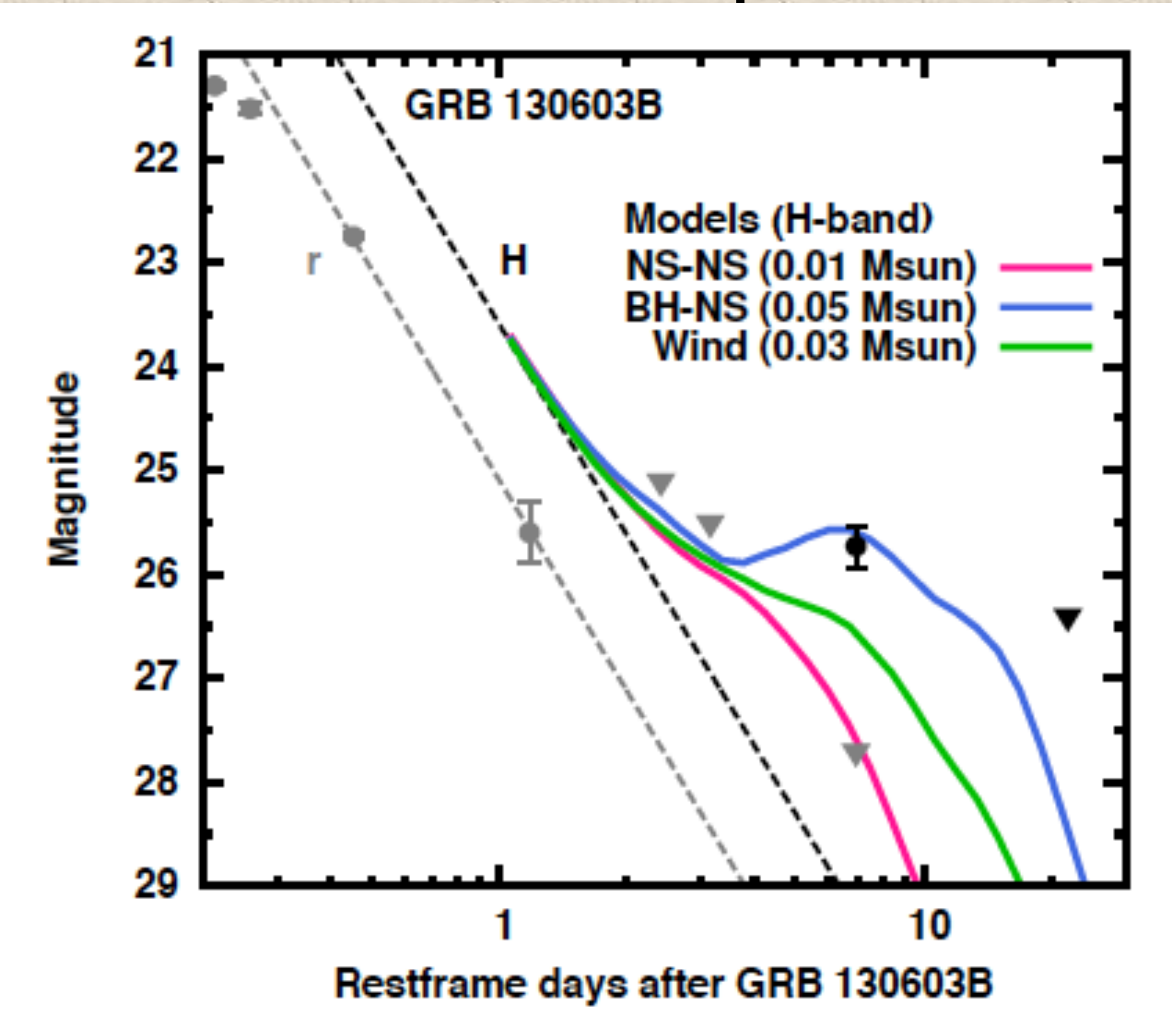
Neutron star mass-radius relation: EOS



- **Mystery of generation sites of the r-process elements**



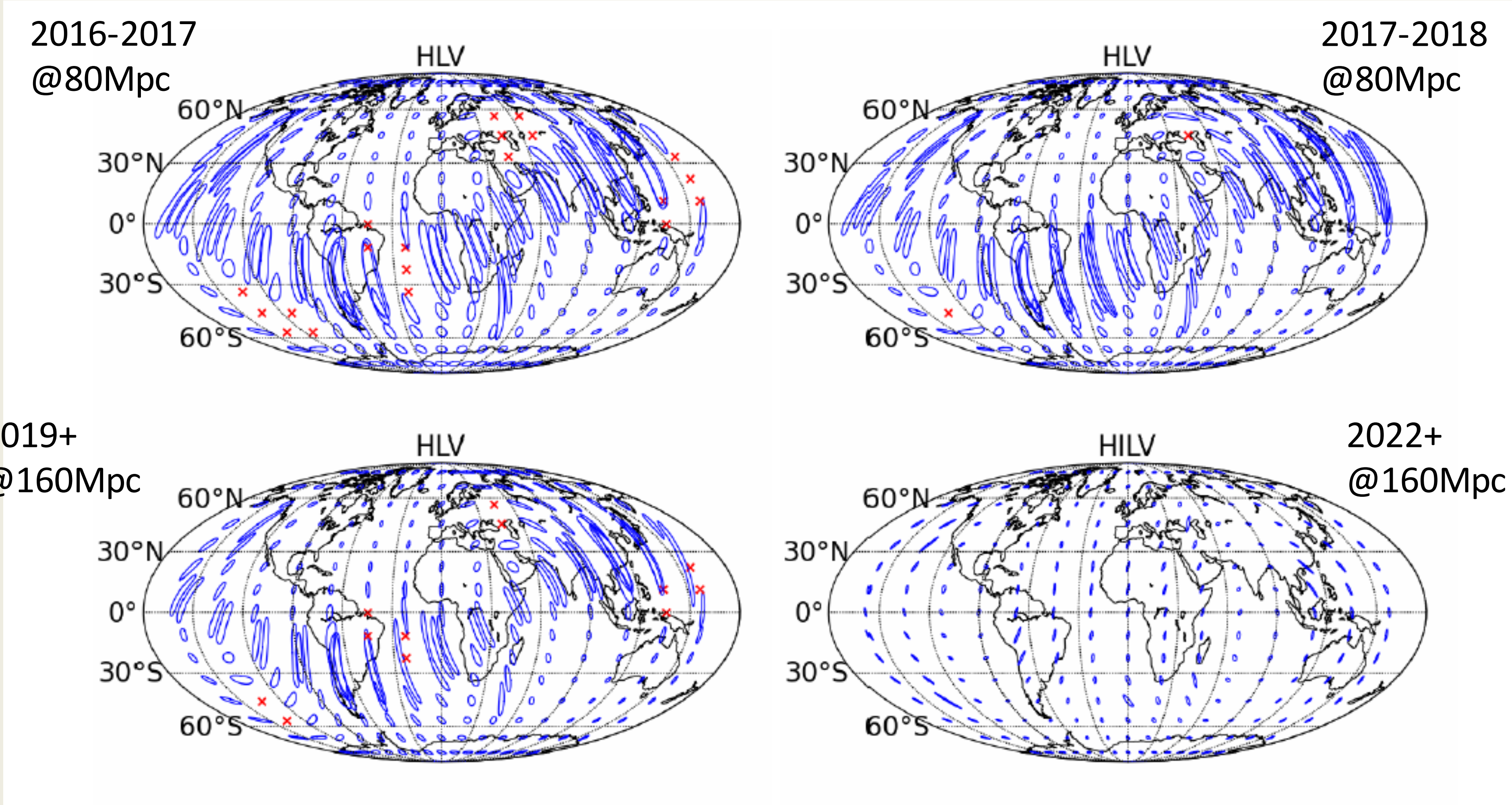
Follow up



M. Tanaka, 1605.07235

Angular resoluton (90 % CL)

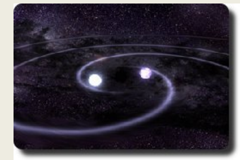
Arxiv: 1304.0670

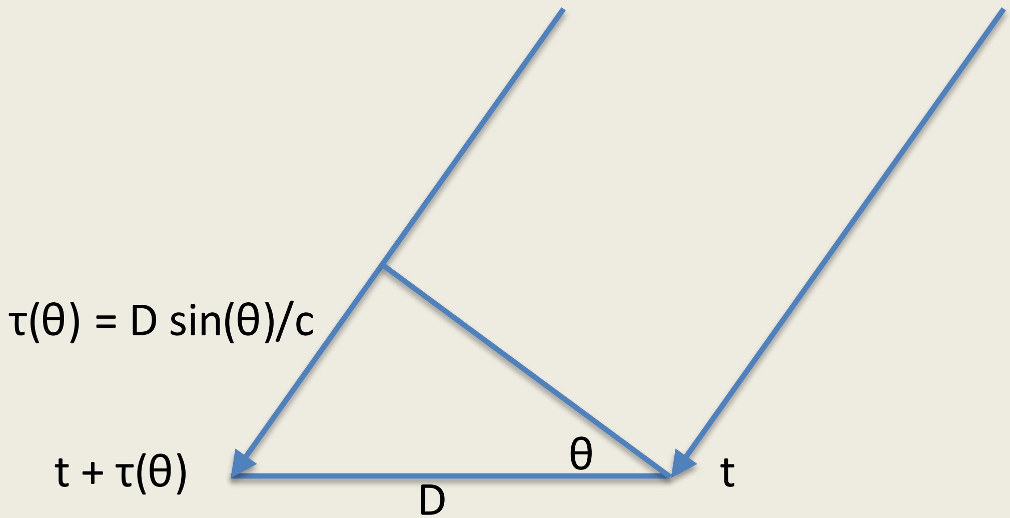


Virgo plans to join the LSC O2b from 2017 March.
Need more to test polization!!!

Localization

Difference in times of arrivals





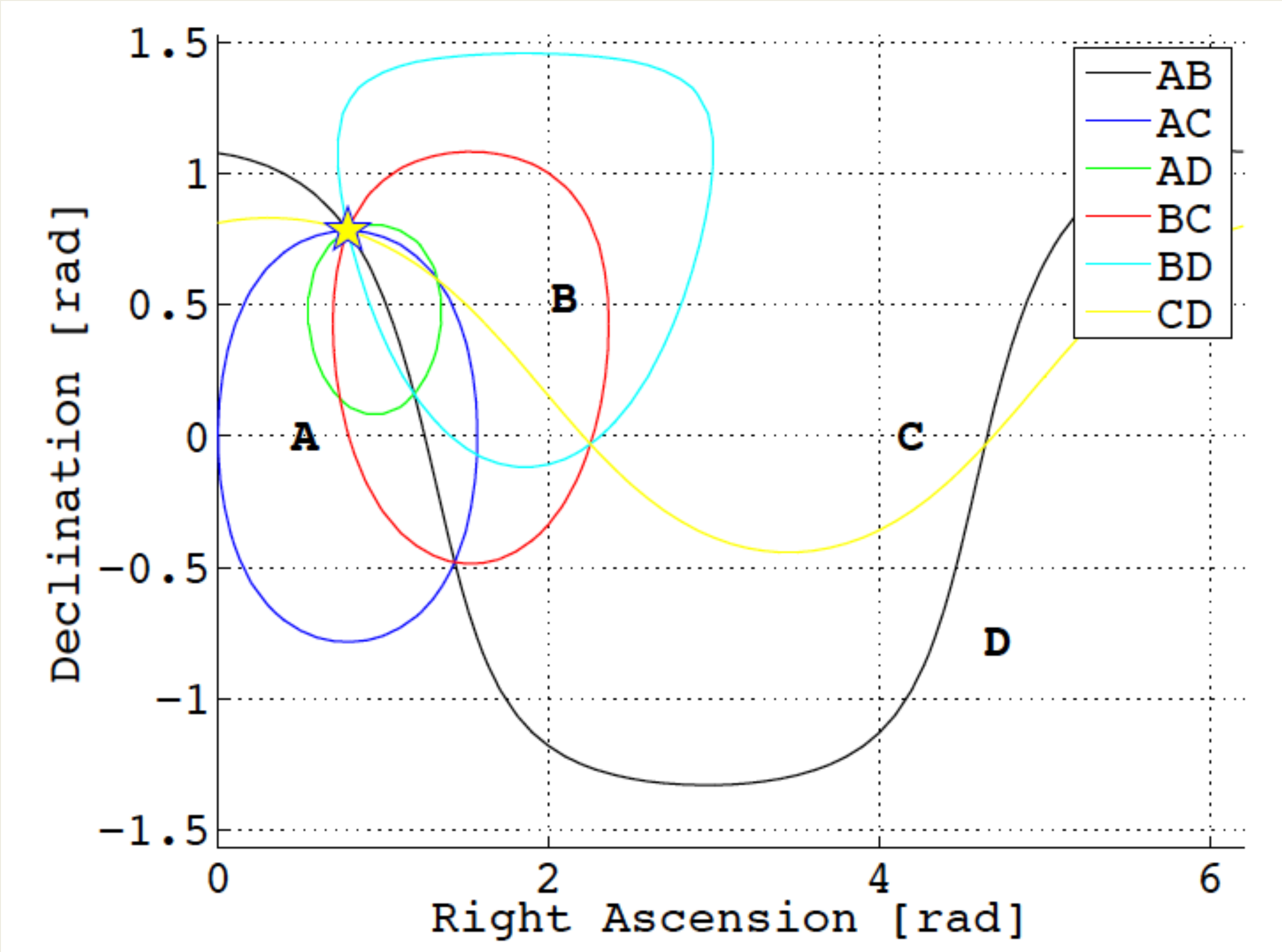
Need multiple detectors, better to have many.

Baseline D and arrival time determination are important

Diffraction limited angular localization is bad….

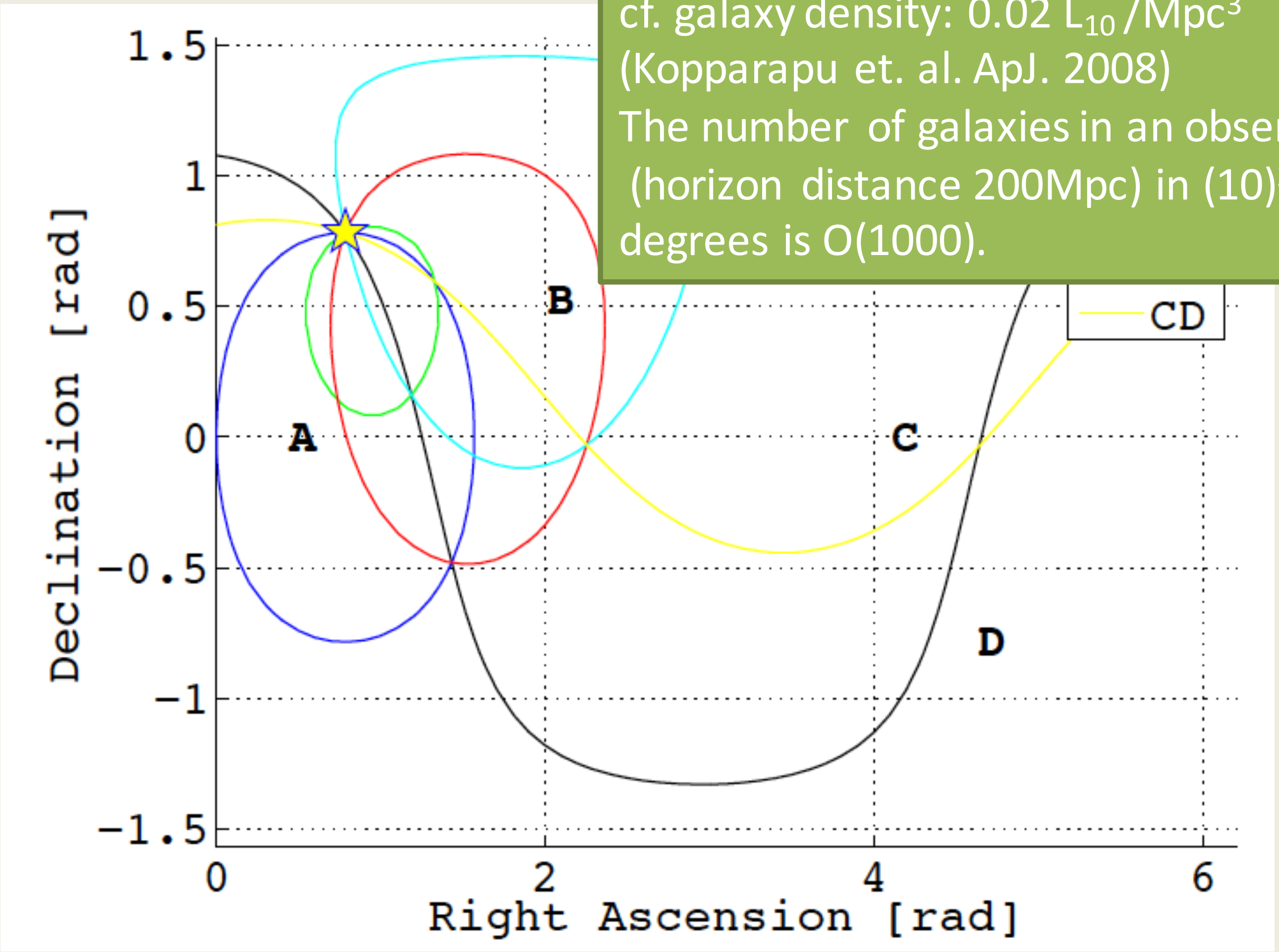
$$\delta\theta \sim \frac{0.3\ \mathrm{rad}}{\mathrm{SNR}} \left(\frac{f}{100\mathrm{Hz}}\right)^{-1} \left(\frac{D}{10,000\mathrm{km}}\right)^{-1}$$

Localization (simple time delay)



$$\delta\theta \sim \frac{0.3\ \mathrm{rad}}{\mathrm{SNR}} \left(\frac{f}{100\mathrm{Hz}}\right)^{-1} \left(\frac{D}{10,000\mathrm{km}}\right)^{-1}$$

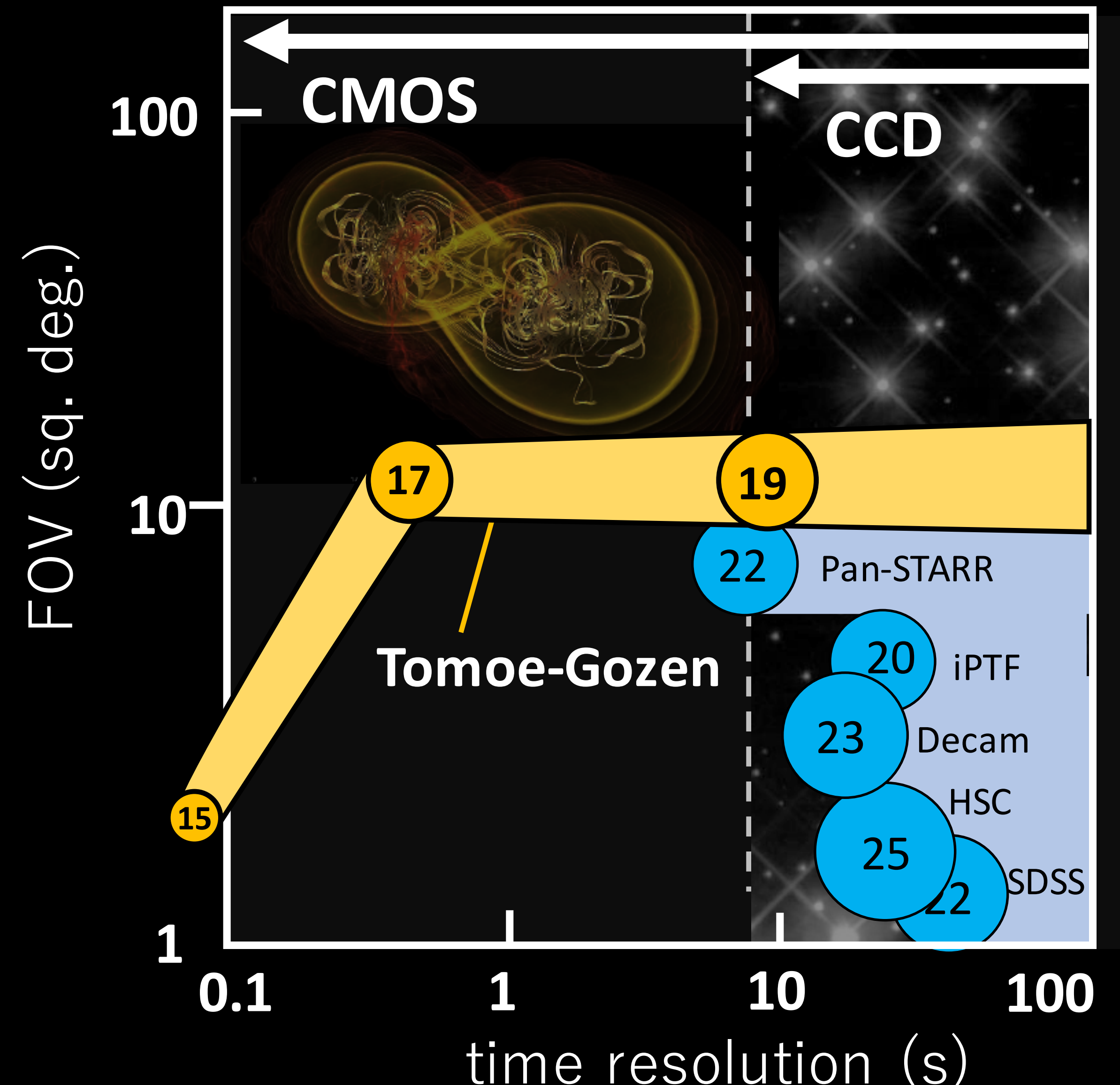
Localization (simple time delay)



cf. galaxy density: 0.02 L_{10} /Mpc^3
(Kopparapu et. al. ApJ. 2008)
The number of galaxies in an observable volume (horizon distance 200Mpc) in $(10)^2$ square degrees is O(1000).

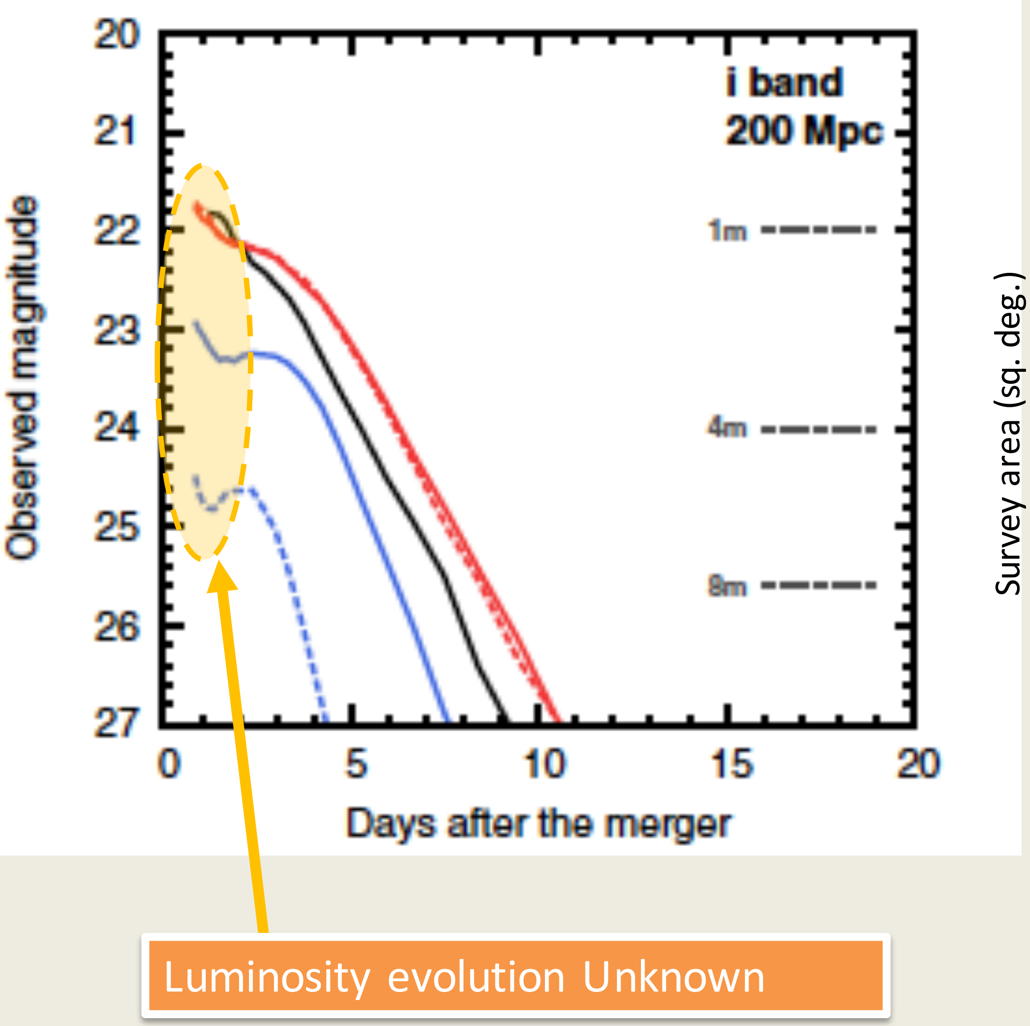
$$\delta\theta \sim \frac{0.3\ \mathrm{rad}}{\mathrm{SNR}} \left(\frac{f}{100\mathrm{Hz}}\right)^{-1} \left(\frac{D}{10,000\mathrm{km}}\right)^{-1}$$

Follow-up: time resolution & FOV



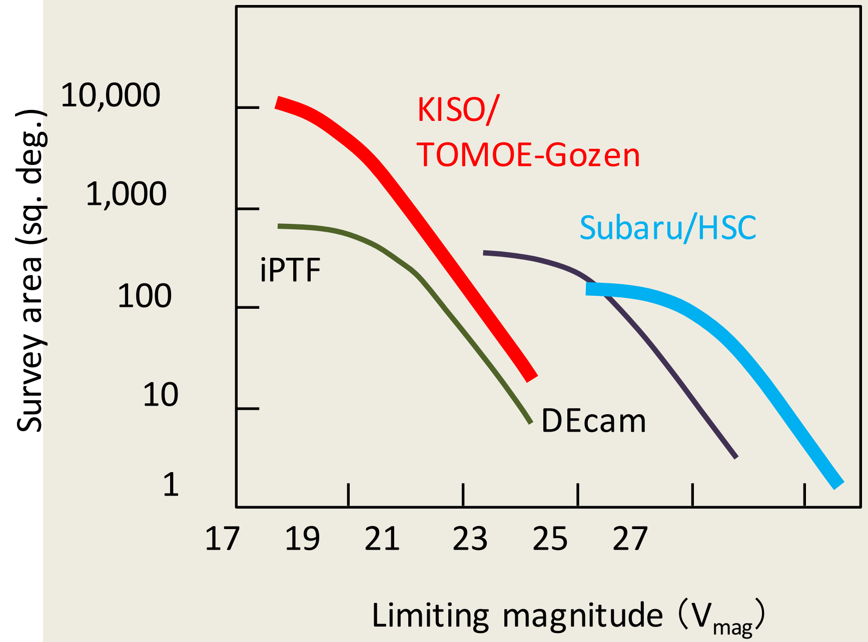
circle size: limiting magnitude

Follow-up: macronova



Tanaka & Hotokezaka (2013)

Area survayrable within 1 hour



SUMMARY

Summary: 2016

- Existence of stellar mass BBHs
  - GW150914, LVT151012, GW151226
  - Progenitors unknown
- Localization is important
  - KAGRA

Summary: 202x

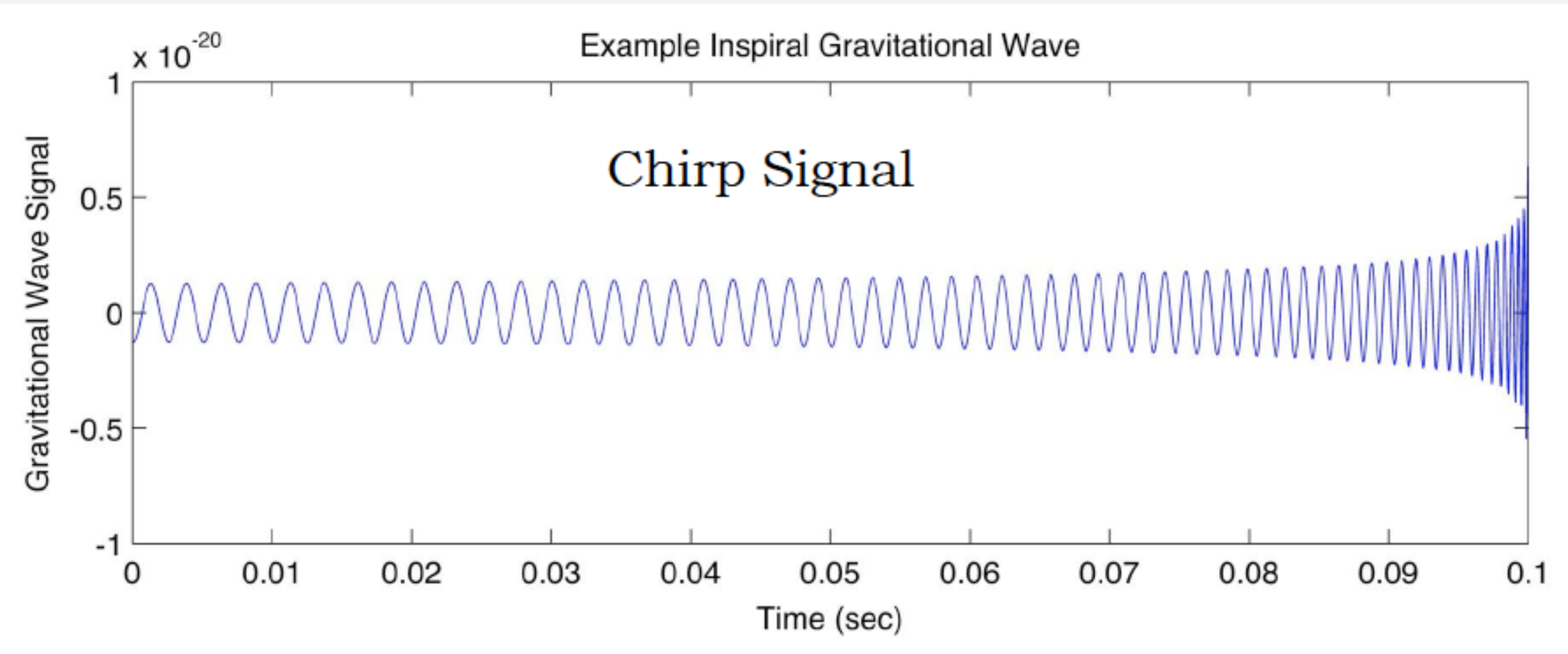
- Localization > 10 square degrees (With KAGRA,India)
- High event rate era: 1 event / day ?
  - Distributions : Mass, Spins, direction, redshift
  - Test of GR
  - Strange object?
  - RESCEU Symposium on GW science "High Event Rate Era", Dec. 5-6
- "Big(?)data ": 300k channels, 1PB/yr
- Detection of NS-BH (or NS/NS), NS EOS
- Non CBC

GW2016 RESCEUで検索！
http://www.resceu.s.u-tokyo.ac.jp/workshops/GW2016/index.php

BREAK

Let’s compute a GW from a binary

Want to draw the following curve.



Let's compute a GW from a binary

$$\vec{x}_1(t) = \frac{m_2}{m_1+m_2} a(\cos(\omega_o t), \sin(\omega_o t), 0),$$
$$\vec{x}_2(t) = -\frac{m_1}{m_1+m_2} a(\cos(\omega_o t), \sin(\omega_o t), 0),$$

Binary with orbital radius a , angular frequency ω_o

$$I_{xx} = \frac{1}{2}\mu a(1+\cos(2\omega_o t)),$$
$$I_{xy} = \frac{1}{2}\mu a\sin(2\omega_o t),$$
$$I_{yy} = \frac{1}{2}\mu a(1-\cos(2\omega_o t)),$$

Compute quadrupole moment. Let μ denote reduced mass

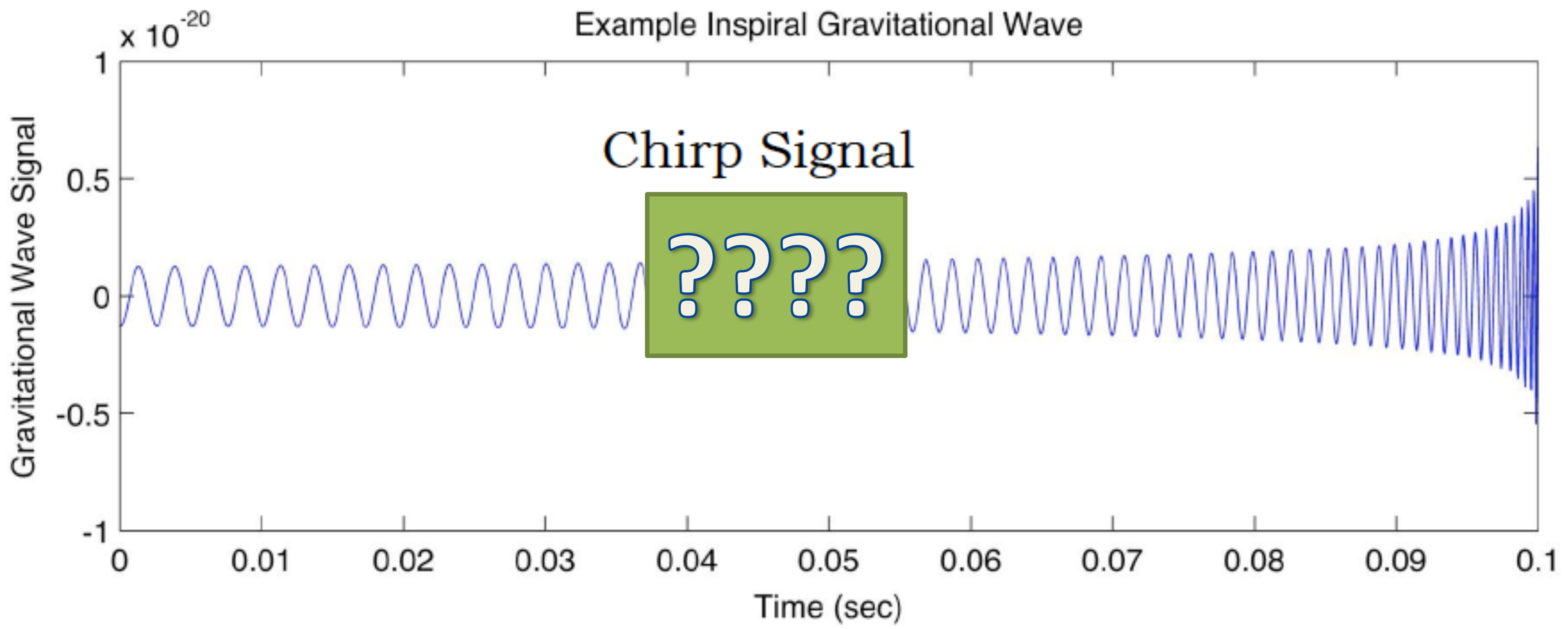
$$\mu = m_1 m_2/(m_1+m_2)$$

$$\ddot{I}_{xx} = -2\omega_o^2 \mu a\cos(2\omega_o t),$$
$$\ddot{I}_{xy} = -2\omega_o^2 \mu a\sin(2\omega_o t),$$
$$\ddot{I}_{yy} = 2\omega_o^2 \mu a\cos(2\omega_o t)),$$

Take temporal derivatives twice, compute transverse-traceless part.

Let's compute a GW from a binary

$$h_{ij}^{TT} = \frac{2G\ddot{I}_{ij}^{TT}}{c^4 r} = \frac{4G\mu a\omega_o^2}{c^4 r}\begin{pmatrix} -\cos(2\omega_o t) & -\sin(2\omega_o t) & 0 \\ -\sin(2\omega_o t) & \sin(2\omega_o t) & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



Let's compute a GW from a binary

$$h_{ij}^{TT} = \frac{2G\ddot{I}_{ij}^{TT}}{\ldots} = \frac{4G\mu a\omega_o^2}{\ldots}\begin{pmatrix} -\cos(2\omega_o t) & -\sin(2\omega_o t) & 0 \\ -\sin(2\omega_o t) & \sin(2\omega_o t) & 0 \\ \ldots \end{pmatrix}$$

How can we compute time series h(t) (scalar) from tensor $h^{TT}_{ij}(t)$?

Detector output time series

Linear perturbation solution to the Einstein equations

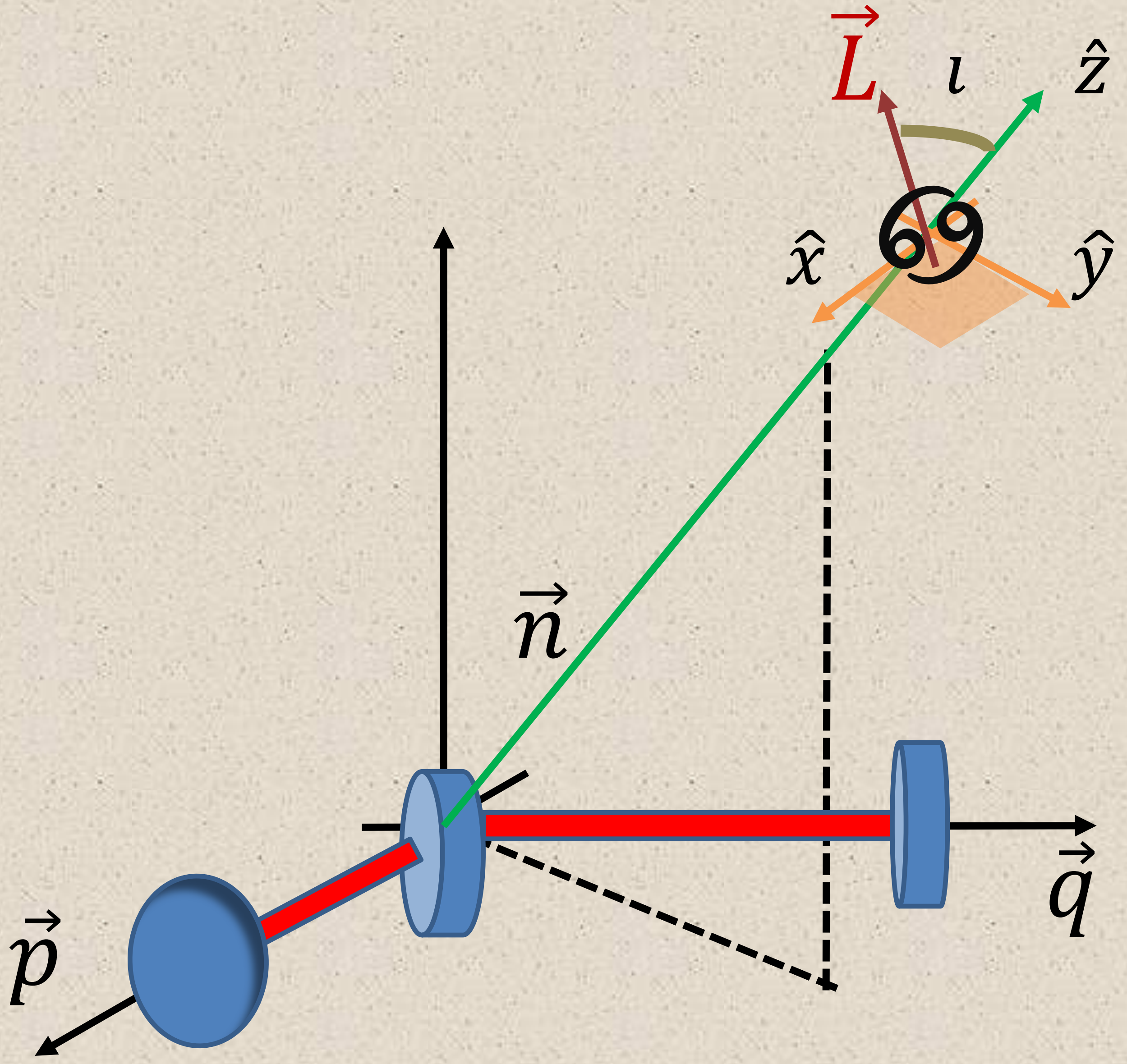
$$h_{ij}^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}_{ij} = e_{ij}^{+} h_+ + e_{ij}^{\times} h_\times$$

Polarization tensors

$$e_{ij}^{+} = \hat{x}_i \hat{x}_j - \hat{y}_i \hat{y}_j,$$
$$e_{ij}^{\times} = \hat{y}_i \hat{x}_j + \hat{x}_i \hat{y}_j$$

Detector arm vectors p & q, Antenna pattern function F_+、F_x

$$h(t) = \frac{1}{2}(\hat{p}^i \hat{p}^j - \hat{q}^i \hat{q}^j) h_{ij}^{TT}(t)$$
$$= F_+(\vec{n}, \psi) h_+(t) + F_\times(\vec{n}, \psi) h_+(t)$$


$\vec{L}$
ι
$\hat{z}$
♋
$\hat{x}$
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$\vec{n}$
$\vec{q}$
$\vec{p}$

Detector output time series

Linear perturbation solution to the Einstein equations

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

Polarization tensors

$$e_{ij}^{+} = \hat{x}_i \hat{x}_j - \hat{y}_i \hat{y}_j,$$
$$e_{ij}^{\times} = \hat{y}_i \hat{x}_j + \hat{x}_i \hat{y}_j$$

Detector arm vectors p & q, Antenna pattern function F_+、F_x

$$\begin{aligned} h(t) &= \frac{1}{2}(\hat{p}^i \hat{p}^j - \hat{q}^i \hat{q}^j) h_{ij}^{TT}(t) \\ &= F_+(\vec{n}, \psi) h_+(t) + F_\times(\vec{n}, \psi) h_+(t) \end{aligned}$$

Let's compute a GW from a binary

$$L_{\rm gw} = \frac{G}{5c^5}\langle \dddot{I}_{kl}\dddot{I}^{kl}\rangle = \frac{32c^5}{5G}\left(\frac{G\mathcal{M}_c\omega_o}{c^3}\right)^{10/3}$$

$$\mathcal{M}_c = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$$

Compute GW energy using the quadrupole formula. Mc is a chirp mass

$$E_{\rm orbit} = \frac{1}{2}\mu v^2 - \frac{G\mu m_t}{R} = -\frac{\mu c^2}{2}\left(\frac{G m_t \omega_o}{c^3}\right)^{2/3}$$

L_{gw} is from the orbital energy.

$$dE_{\rm orbit}/dt + L_{\rm gw} = 0$$

$$\dot{\omega}_o = \frac{96}{5}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{5/3}\omega_o^{11/3}$$

Get a differential equation for ω_o

$$\omega_o(t) = \frac{5^{3/8}}{8}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{-5/8}(t_c - t)^{-3/8},$$

$$\Phi_o(t) = -\int_t^{t_c}\omega_o(t)dt = -\left(\frac{5G\mathcal{M}_c}{c^3(t_c-t)}\right)^{-5/8}$$

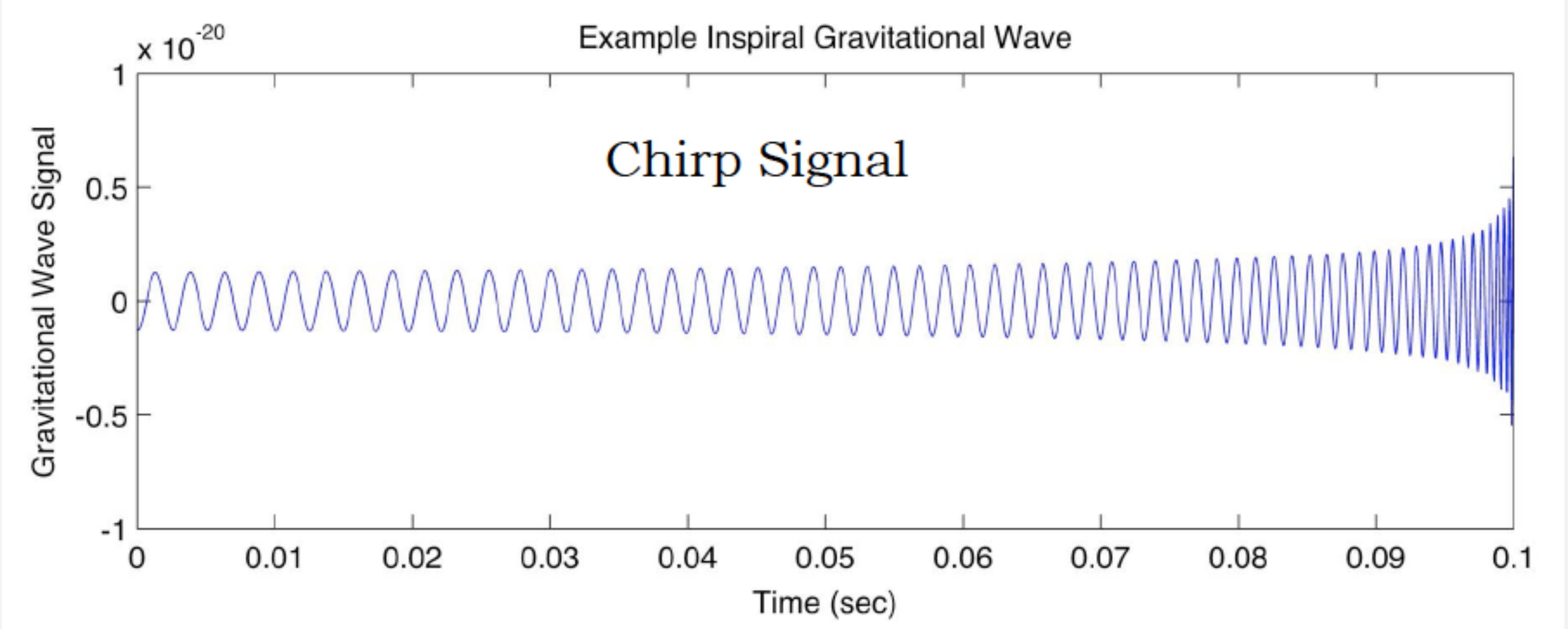
Solve it, find the phase evolution equation.

Let's compute a GW from a binary

$$h_+(t) = -A(t)\frac{1}{2}(1+\cos^2\iota)\cos(2\Phi_o(t))),$$

$$h_\times(t) = -A(t)\cos\iota\sin(2\Phi_o(t))),$$

$$A(t) = \frac{G\mathcal{M}_c}{c^2 r}\left(\frac{5G\mathcal{M}_c}{c^3(t_c - t)}\right)^{1/4}$$



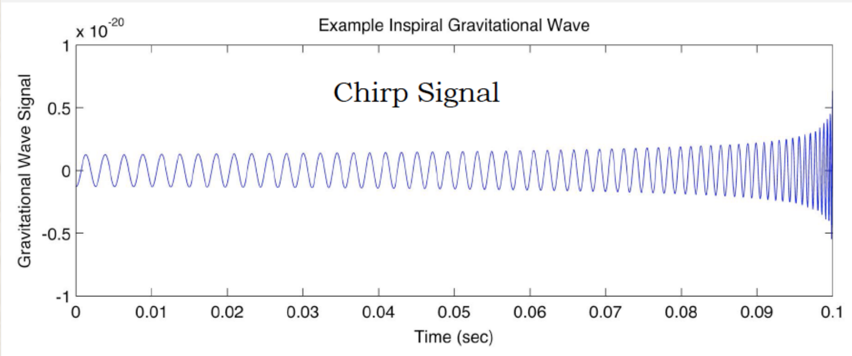
Let's compute a GW from a binary

$$\tilde{h}_+(f_{\rm gw}) = \int_{-\infty}^{\infty} dt e^{-2\pi i f_{\rm gw} t} h_+(t) = \frac{1}{2}\int_{-\infty}^{t_c} dt e^{-2\pi i f_{\rm gw} t} A_+(t) e^{i\Phi_{\rm gw}(t)}$$

Use stationary phase approximation. Note that the integrand oscillates so rapidly that it amounts to zero for any frequencies other than

$$d\Phi_{\rm gw}(t_f)/dt = f_{\rm gw}$$

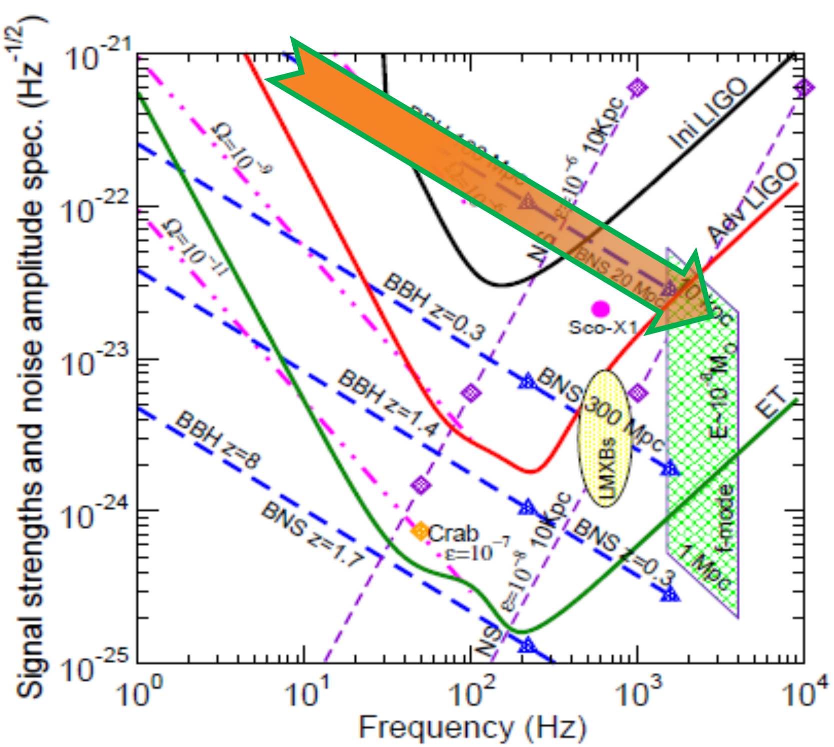
$$\begin{aligned}
\tilde{h}_+(f_{\rm gw}) &\simeq \frac{1}{2}\int_{-\eta}^{\eta} dt A_+(t) \exp\left[i\Phi_{\rm gw}(t_f) - 2\pi i f_{\rm gw} t_f + \frac{i}{2}\ddot{\Phi}_{\rm gw}(t_f)(t-t_f)^2\right] \\
&\simeq \frac{1}{2} A_+(t_f) e^{i\Phi_{\rm gw}(t_f) - 2\pi i f_{\rm gw} t_f} \int_{-\eta}^{\eta} dt \exp\left[\frac{i}{2}\ddot{\Phi}_{\rm gw}(t_f) t^2\right] \\
&\simeq \frac{1}{2}\sqrt{\frac{2\pi}{|\ddot{\Phi}_{\rm gw}(t_f)|}} A_+(t_f) e^{i\Phi_{\rm gw}(t_f) - 2\pi i f_{\rm gw} t_f + \frac{i\pi}{4}} \qquad (1.3.106)
\end{aligned}$$



$$h_+(t) = -A(t)\frac{1}{2}(1+\cos^2\iota)\cos(2\Phi_o(t))),$$

$$h_\times(t) = -A(t)\cos\iota\sin(2\Phi_o(t))),$$

$$A(t) = \frac{G\mathcal{M}_c}{c^2 r}\left(\frac{5G\mathcal{M}_c}{c^3(t_c - t)}\right)^{1/4}$$



$$\tilde{h}_+(f) = -A(f)\frac{1}{2}(1+\cos^2\iota)\,\exp\left[-i\Psi(f) - 2i\phi\right],$$

$$\tilde{h}_\times(f) = -A(f)\cos\iota\,\exp\left[-i\Psi(f) - \frac{i\pi}{2} - 2i\phi\right],$$

$$A(f) \equiv \left(\frac{5\pi}{24}\right)^{1/2}\frac{c}{r}\left(\frac{G\mathcal{M}_c}{c^3}\right)^2\left(\frac{\pi G\mathcal{M}_c f}{c^3}\right)^{-7/6},$$

$$\Psi(f) \equiv 2\pi f t_c - \frac{\pi}{4} - \phi_c + \frac{3}{128}\left(\frac{\pi G\mathcal{M}_c f}{c^3}\right)^{-5/3}$$

$$\text{Power} = \int f S_h(f)\,d\ln f,$$

$$\sqrt{f S_h(f)} = \sqrt{f|\tilde{h}(f)|^2} \propto f^{-2/3}$$

Sathyaprakash & Schutz Liv. Rev. Rel. (2009)

RESUME