Strategy to Detect GW

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LCGT collaboration

at LCGT TAC, 08/22/2005

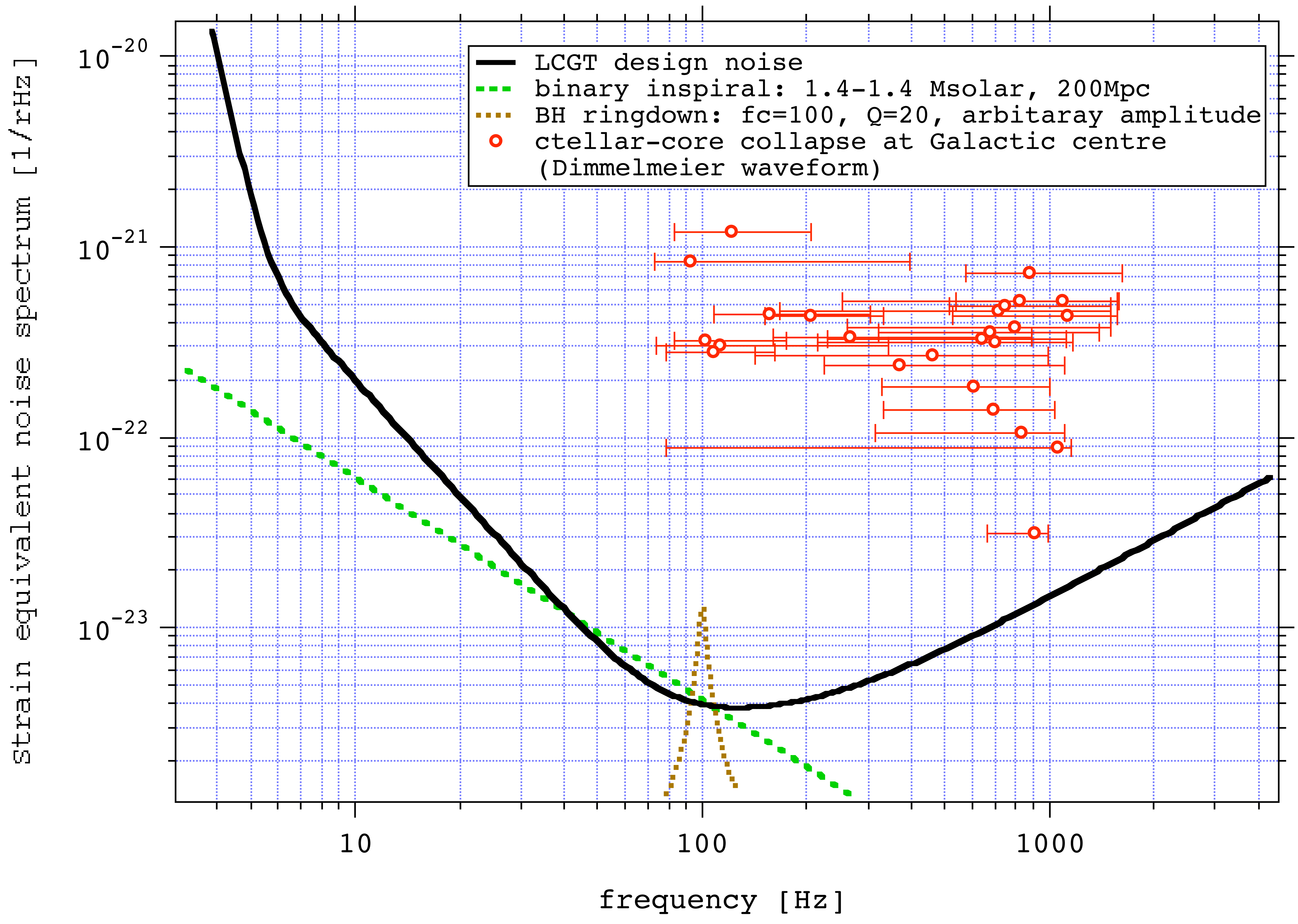
神岡地下
Kamioka underground
長基線
Long base-line
低温鏡
Cryogenic mirror

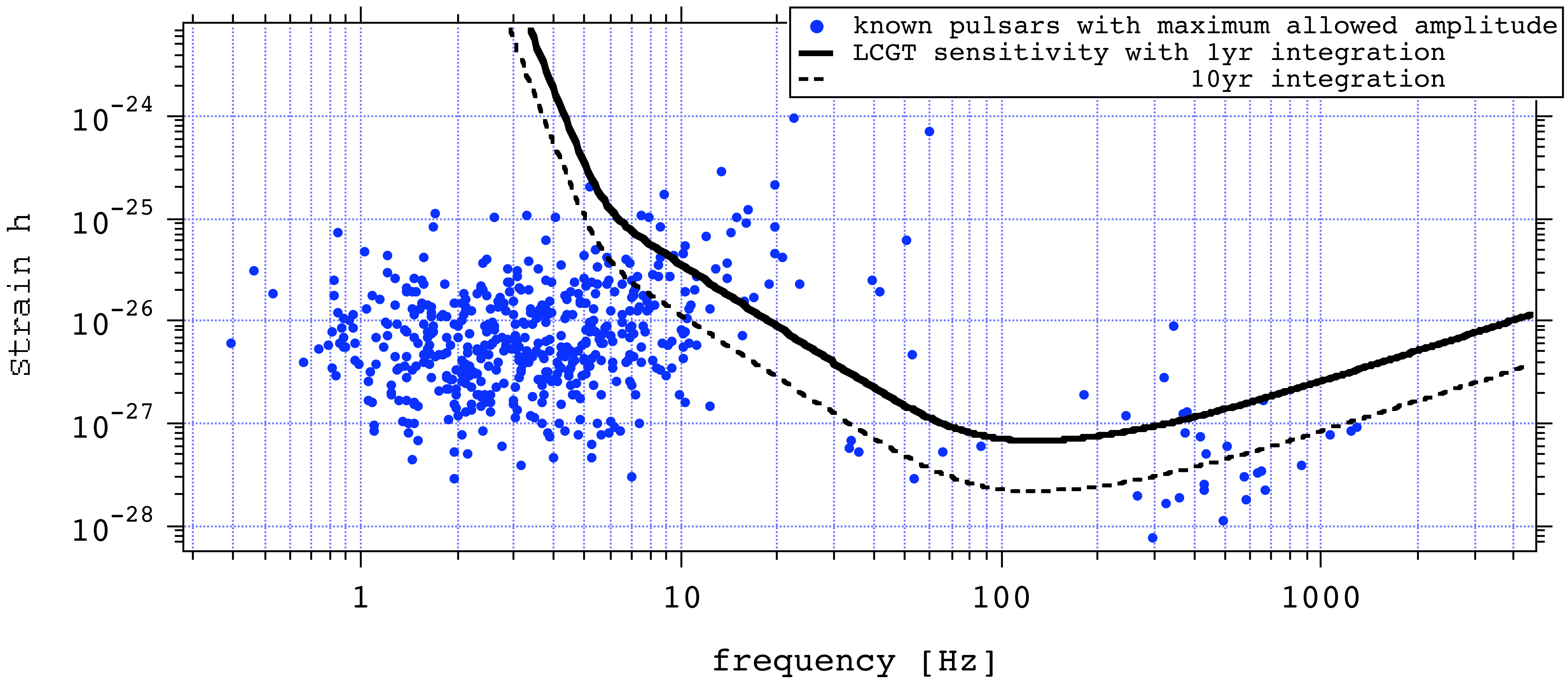
Gravitational Wave Sources; Feasibility and Physics on Detections

Source study started during TAMA analysis...

source	*waveform*	*feasibility study* *detection*	*extract info.*	*Physics / Astro.Phys.*
NS (BH) binary	Inspiral	Range : 240 Mpc (max) Rate (# of events/3yr) : ?	Arrival time : Δt < 1msec direction : $\Delta\theta$ ~ 1-2 degree Mass resolution : $\Delta M/M$ < ? %	population host galaxy ? formation of NS binary
	Merger		waveform : h(t) or h(f) with accuracy of $\Delta h/h$ ISCO : $\Delta f/f$ <?%	viscosity,density,etc. of NS -> Equation of State
Black-Hole	ringdown	3% energy loss -> Range : Mass Region : 10? –1000 Msol	$\Delta M/M$ < 10% $\Delta a/a$ < ...	excitation of BH Intermediate mass BH mass spectroscopy formation of BH
Supernovae (GRB? etc.)	Burst	Range : Rate (=SNR in our galaxy x Range x SII rate)	waveform, : h(t), h(f) Arrival time : Δt	numerical model of core core structure EOS
(background)	Stochastic	Ωgw (<- power spectrum, cross talk of two LCGT detector)		string cosmology, nuclear synthesis, etc.
Pulsar	continuous	max SNR (<- know pulsars)	accuracy of dP/dt /P	model of spindown of NS

Target GW Sources





known pulsars with maximum allowed amplitude
LCGT sensitivity with 1yr integration
10yr integration
Strain h
frequency [Hz]
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
1
10
100
1000

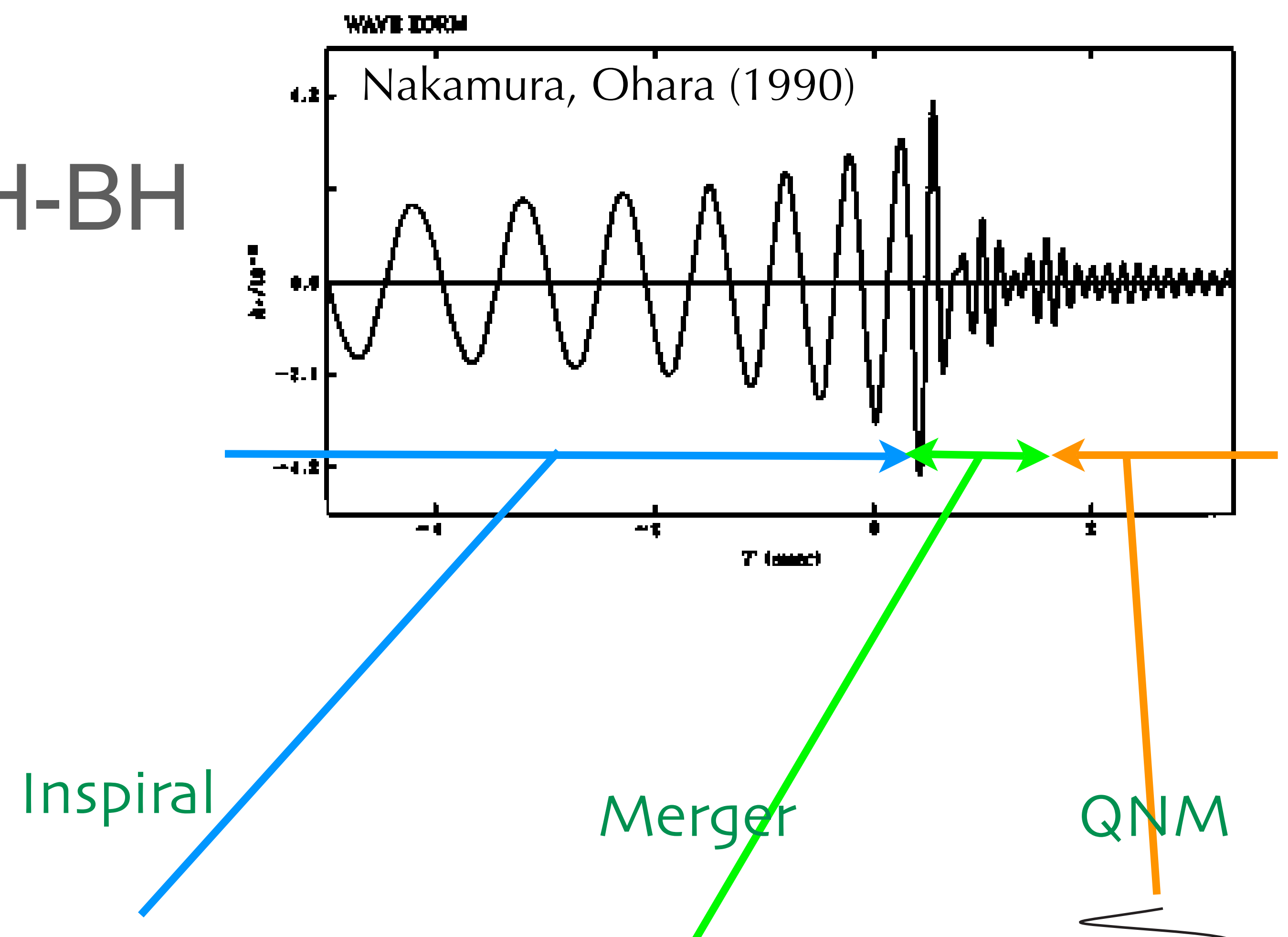
Binary Coalescence : Most Promised Source

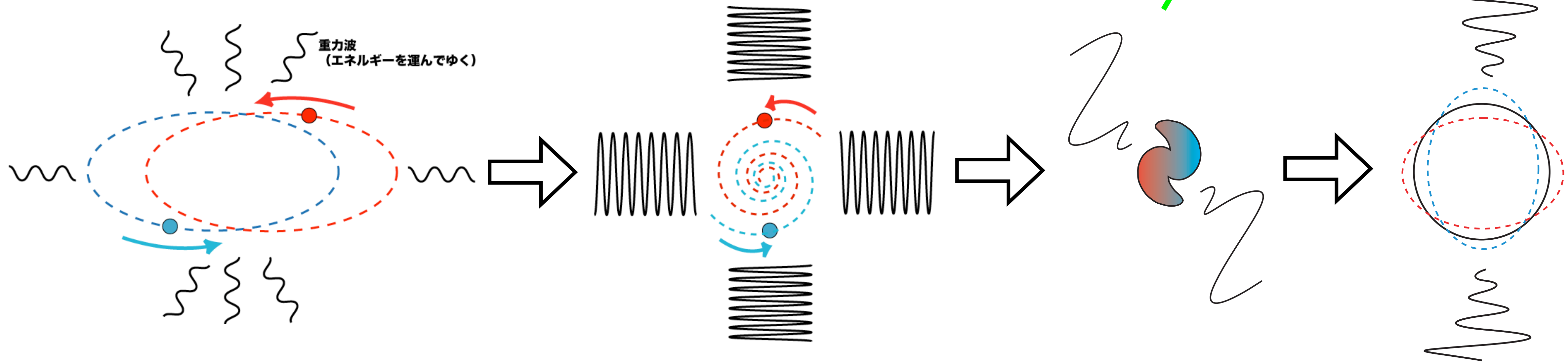
Compact Binary

- NS-NS, NS-BH, BH-BH

Waveform

- Inspiral
- Merger
- QNM of BH



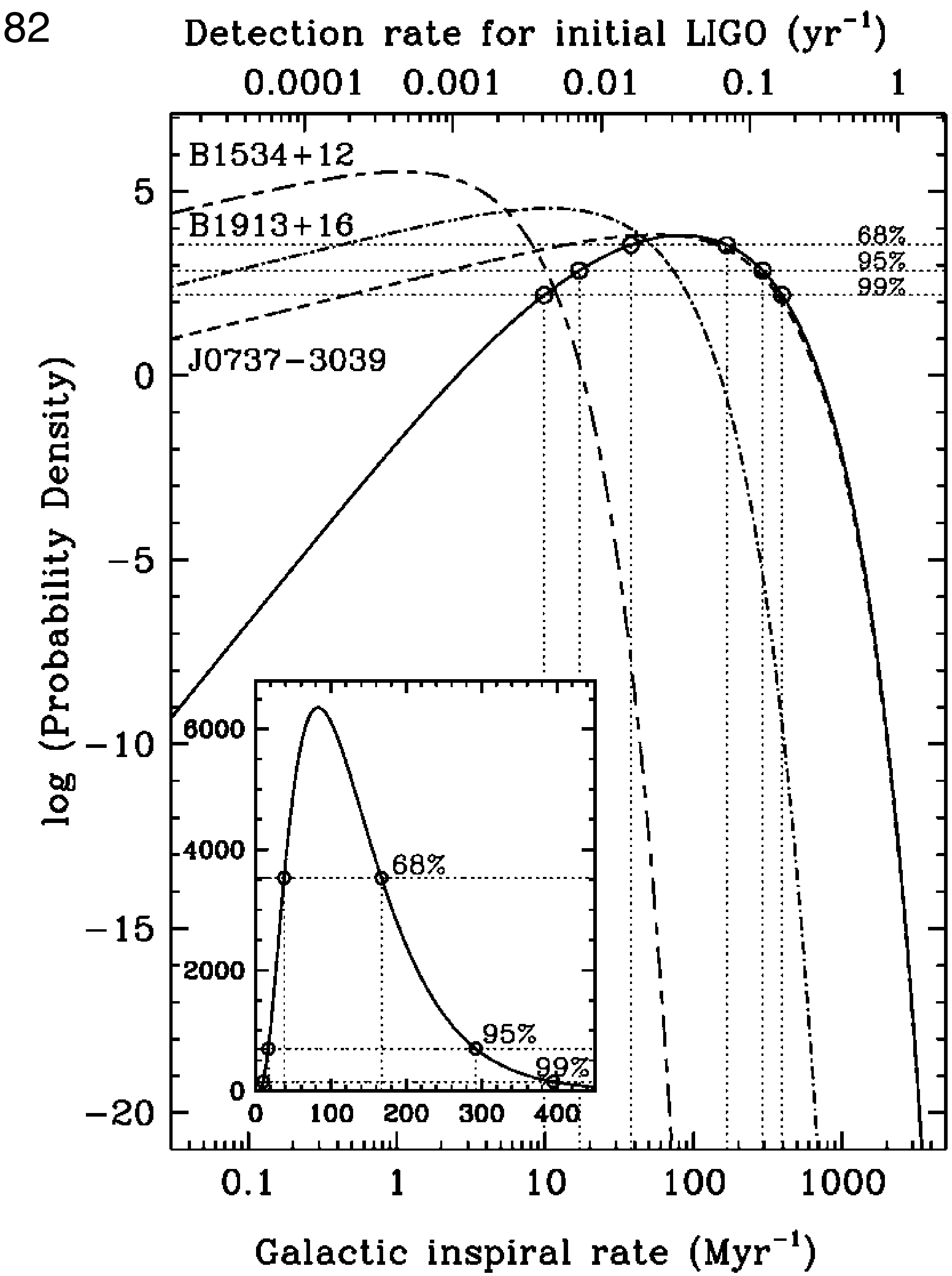


Rate of Binary Coalescence

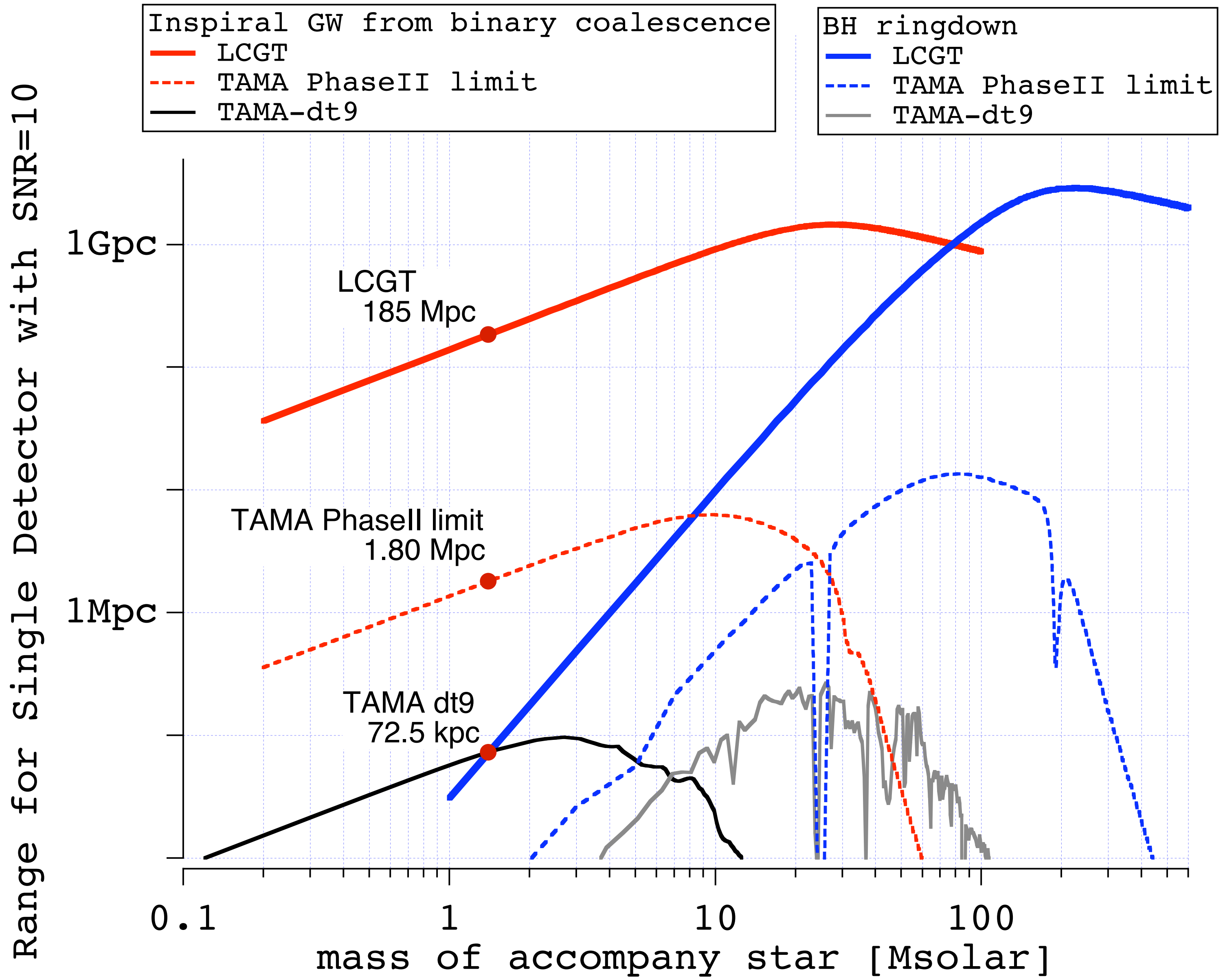
Kalogera et.al., ApJL. 601 (2004) L179-L182
Kim et.al., astro-ph/0405564
ApJ.614:L137-138

Model[a]	$\mathcal{R}_{\rm tot}$ ($\rm Myr^{-1}$)
1	$23.2^{+59.4}_{-18.5}$
6	$83.0^{+209.1}_{-66.1}$
9	$7.9^{+20.2}_{-6.3}$
10	$23.3^{+57.0}_{-18.4}$
12	$9.0^{+21.9}_{-7.1}$
14	$3.8^{+9.4}_{-2.8}$
15	$223.7^{+593.8}_{-180.6}$
17	$51.6^{+135.3}_{-41.5}$
19	$14.6^{+38.2}_{-11.7}$
20	$89.0^{+217.9}_{-70.8}$

[a] Model numbers correspond to KKL. Mode
reference model in this study.
[b] Increase rate factor compared to previous



Detection Range & Event Rate of Binary Inspiral GW



	Range (SNR$\geq$ 10, 1.4-1.4$M_{\odot}$, optimal incident) [Mpc]	Expected Rate of Detection [events/yr]
single LCGT	185	$2.8\ ^{+7.2}_{-2.3}$
two LCGT	257	$7.9\ ^{+20.4}_{-6.5}$

Detection Scheme : Matched Filter

Known wave form

- coalescence of compact binaries ;
- NS-NS, NS-BH, BH-BH, PBMACHO

Known noise spectrum in Fourier domain

Linear system

- signal: s(t) = n(t) + a h(t)
- noise component :n(t), GW signal: a h(t)
- average noise power spectrum: Sh(f)
- template waveform: h(t)
- signal-to-noise ratio:
- chi^2 test

Require 10^5 templates and 10^{11} flops at least

The method was well implemented in previous experiments: i.e. TAMA, LIGO

$$\langle h, s \rangle = 2 \int \frac{\tilde{h}^* \cdot \tilde{s}}{S_h} df$$

$$\mathrm{SNR} = \sqrt{\langle h_+, s \rangle^2 + \langle h_\times, s \rangle^2} \,/\sqrt{2}$$

Physics on Binary Inspiral GW

With LCGT:

- mass
- neutron star raduius, viscosity, etc.
- BH? or hyper massive neutron star ?

  (Physics on merger phase & after)

With International GW detector network:

- direction
- distance

Black-hole Quasi-Normal Mode : Ringdown GW

Binary,
SN expl.

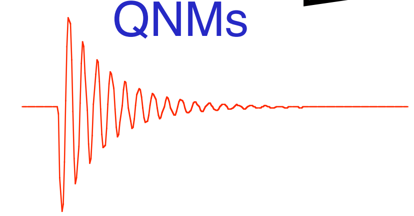
inspiral-merger

core collapse

BH formation
perturbed BH

Ringdown

QNMs



Kerr BH

Waveform: Damped sinusoid (Quasi-normal modes)

$$h(t) = \exp(-\pi f_c t/Q) \sin(2\pi f_c t)$$

central frequency

Quality factor

$$f_c = \frac{3.2 \times 10^4 [\mathrm{Hz}]}{M/M_\odot} \left[1 - (1-a)^{0.3}\right]$$

Echeverria (1989)

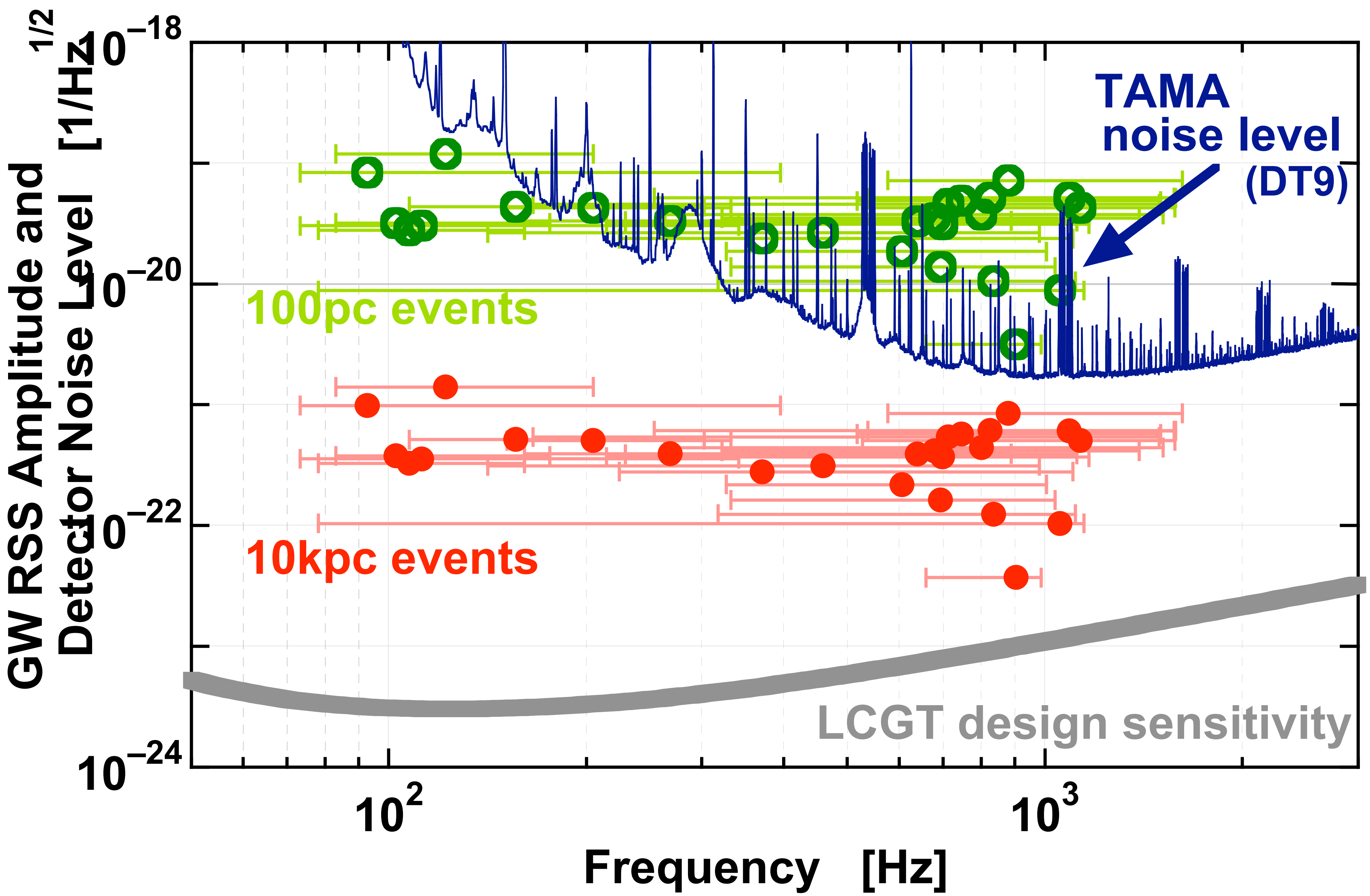
$$Q = 2.0(1-a)^{-0.45}$$

M: Mass
a: Spin

* Probe for BH direct observation
* BH physics in inspiral-merger, core collapses, ...

-> BH mass & Kerr parameters

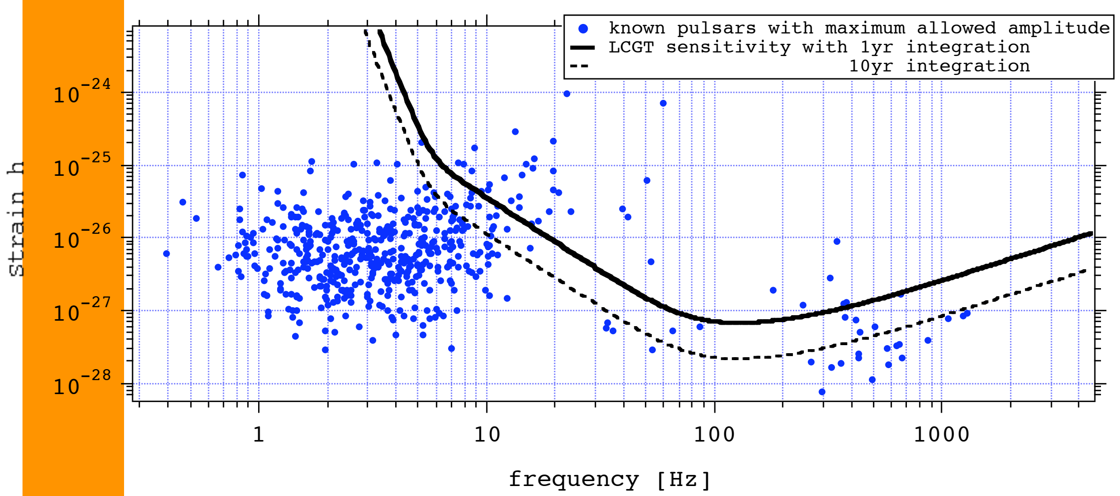
Stellar-core collapse : Burst GW



cf: Dimmelmeier, et al. (2002)

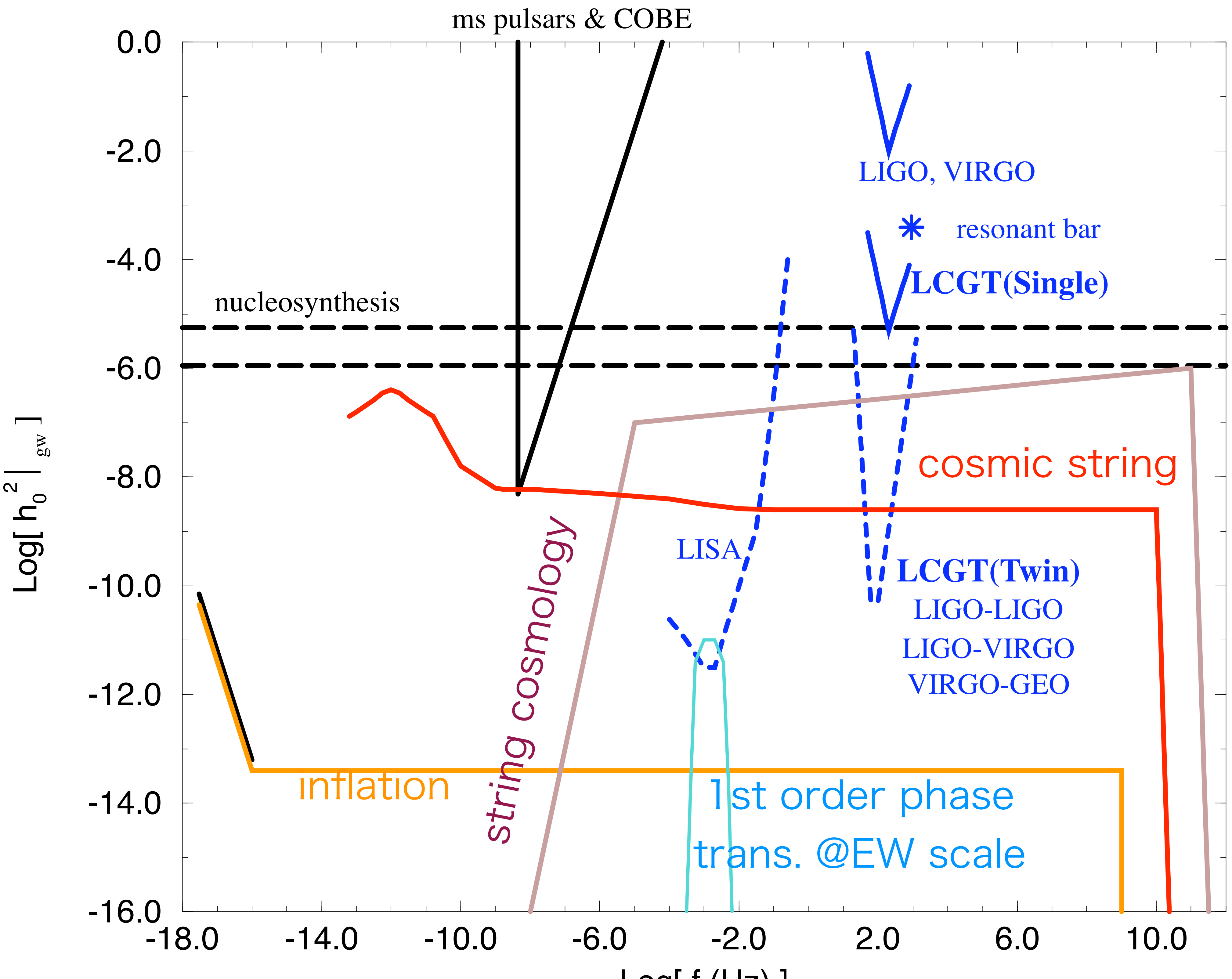
Pulsars : Continuous GW

Some known pulsars expected to detect or to give upper limit which better than theoretical arrowed.



Pulsar	dist. [kpc]	freq [Hz]	h upper limit with 1 year of LCGT
Crab	2.0	60	1.1×10^{-27}
Vela	0.5	22	7.3×10^{-27}
1951+32	2.5	50	1.5×10^{-27}
1706-44	1.8	20	8.8×10^{-27}
1509-58	4.4	13	2.1×10^{-26}
0540-69	4.9	40	2.2×10^{-27}
1823-13	4.1	20	8.8×10^{-27}
1046-58	3.0	16	1.4×10^{-26}
1259-63	4.6	42	2.0×10^{-27}
1800-21	3.9	15	1.6×10^{-26}
	0.15	347	1.0×10^{-27}
1757-24	4.6	16	1.4×10^{-26}

Stochastic GW



M.Maggiore, gr-qc/0008027

$$h^{1d}_{min} = (2 f S_n(f)/F)^{1/2}$$

$$h^{2d}_{min} \simeq 1.12 \times 10^{-2} h^{1d}_{min}(f) \left(\frac{1\mathrm{Hz}}{\Delta f}\right)^{1/2} \left(\frac{1\mathrm{yr}}{T}\right)^{1/4}$$

Sensitivity : $h_f(100\mathrm{Hz}) \sim 4.4 \times 10^{-24}$ [/rHz]

Single interferometer

- $h^{1d}_{min}(100\ \mathrm{Hz}) = 3.9 \times 10^{-23}$
- **$h_0^2\ \Omega_{gw}^{1d}\ (100\mathrm{Hz}) \sim 3.8 \times 10^{-5}$**

Twin interferometers

- 1yr integration, freq. band: 100Hz
- $h^{2d}_{min}(100\ \mathrm{Hz}) = 1.4 \times 10^{-25}$
- **$h_0^2\ \Omega_{gw}^{2d}\ (100\mathrm{Hz}) \sim 4.8 \times 10^{-10}$**

Sources Remarks

Target Sorces:

- **Binary Coalescence (Typically, Search with Inspiral)**

  most promising. We expect several events/year.

- **BH Ringdown**

  interest probe for Black-hole.

- **Burst**

  promising sources with other observations

- **Continuous**

  Know pulsars be a candidates.

- **Stochastic**

  The results will have enough meaning comparing with theories.

How does the Twin Interferometers behave?

Why we need twin interferometes ?

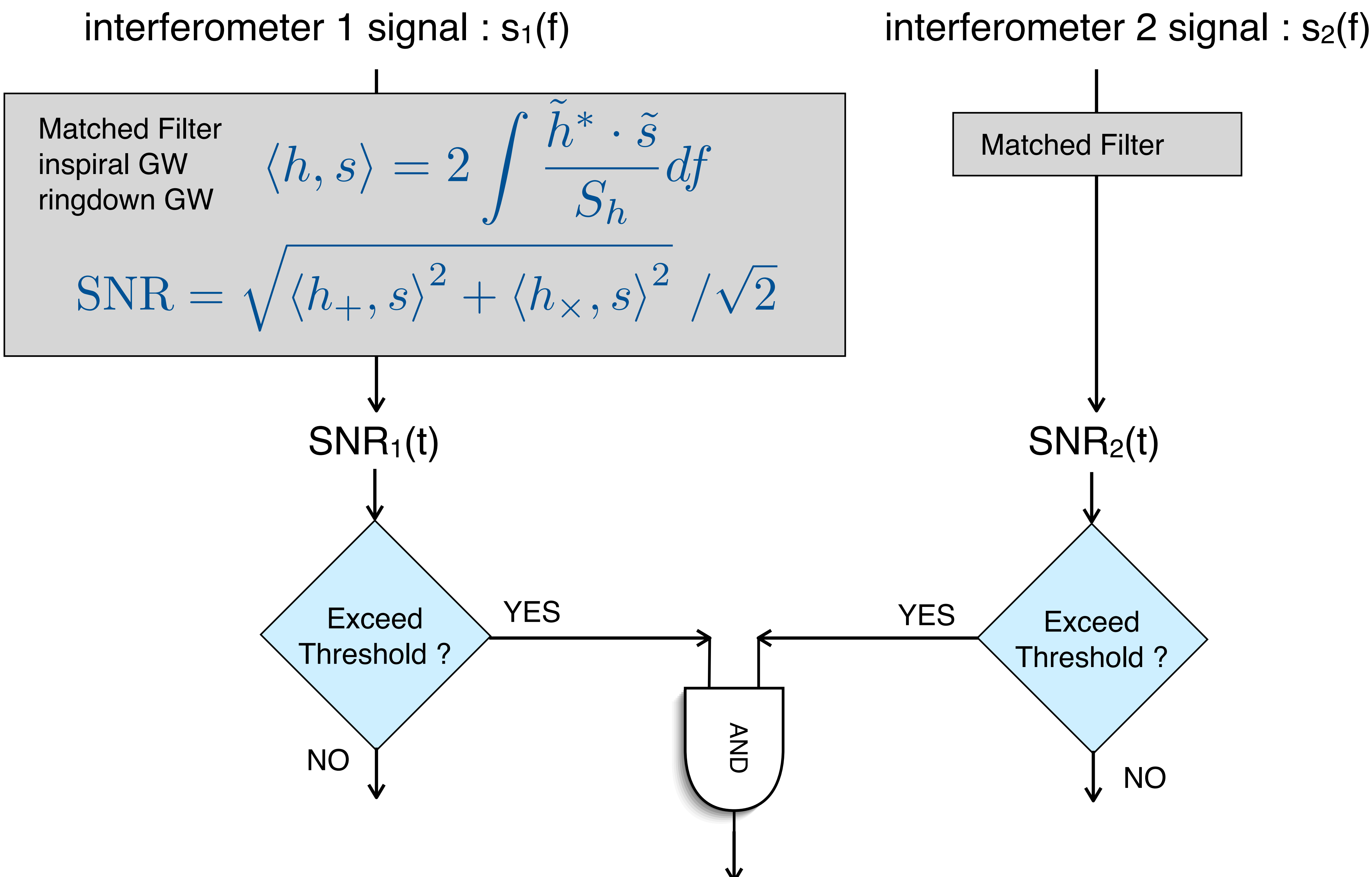
Redundancy of GW evidence

- Both Interferometers should detect at same;
  - arrival time
  - amplitude
  - waveform

Stochastic GW Search(,also for any GW sources)

- Correlation of two interferometer give different order of search performance
- Closed placed detectors have a wider frequency band

Coincidence Strategy



True events can survive.
(+fakes due to accidental coincidence, &noise cross talks)

More strategies:
Coherence, Correlation

Coherence

- log likely-hood sum of two outputs

$$\sum_{I=1}^{N} \ln \lambda_{(I)} = \sum \left\{ \left\langle h^{(I)}, s^I \right\rangle_{(I)} - \frac{1}{2} \left\langle s^I, s^I \right\rangle_{(I)} \right\}$$

- signal addition

will gain SNR by √2

Correlation

$$\int s_1(t) s_2(t) dt$$

Redundancy : Statistical Advantage

If noises are complete gaussian, we can estimate the amount of fake events due to noises. However, ...

Reduce fake due to noise

- fake rate of each interferometers: R_1, R_2
- time window: ΔT

  (<- arrival time resolution for GW events + T.O.F)

- accidental coincidence rate:

  $R_{acc} = R_1 R_2 \Delta T$

reduction ~ $R \Delta T$

example:
LISM-TAMA ~10^{-4}
LIGO-TAMA

TAMA300	LISM
1,868,388	1,292,630
Results of coincidence analysis	
n_{obs}	$\bar{n}_{acc} \pm \bar{\sigma}_{acc}$
4706	$(4.2 \pm 0.5) \times 10^3$
804	$(7.1 \pm 0.8) \times 10^2$
761	$(6.7 \pm 0.8) \times 10^2$
N_{obs}	N_{bg}
0	0.063

H.Takahashi et. al., PRD70, 042003

This is a big advantage!

The correlation make possible to search the stochastic GW.

Sensitivity：$h_f(100Hz) \sim 4.4 \times 10^{-24}$ [/rHz]

Single interferometer

- $h_0^2\ \Omega_{gw}^{1d}\ (100Hz) \sim 3.8 \times 10^{-5}$

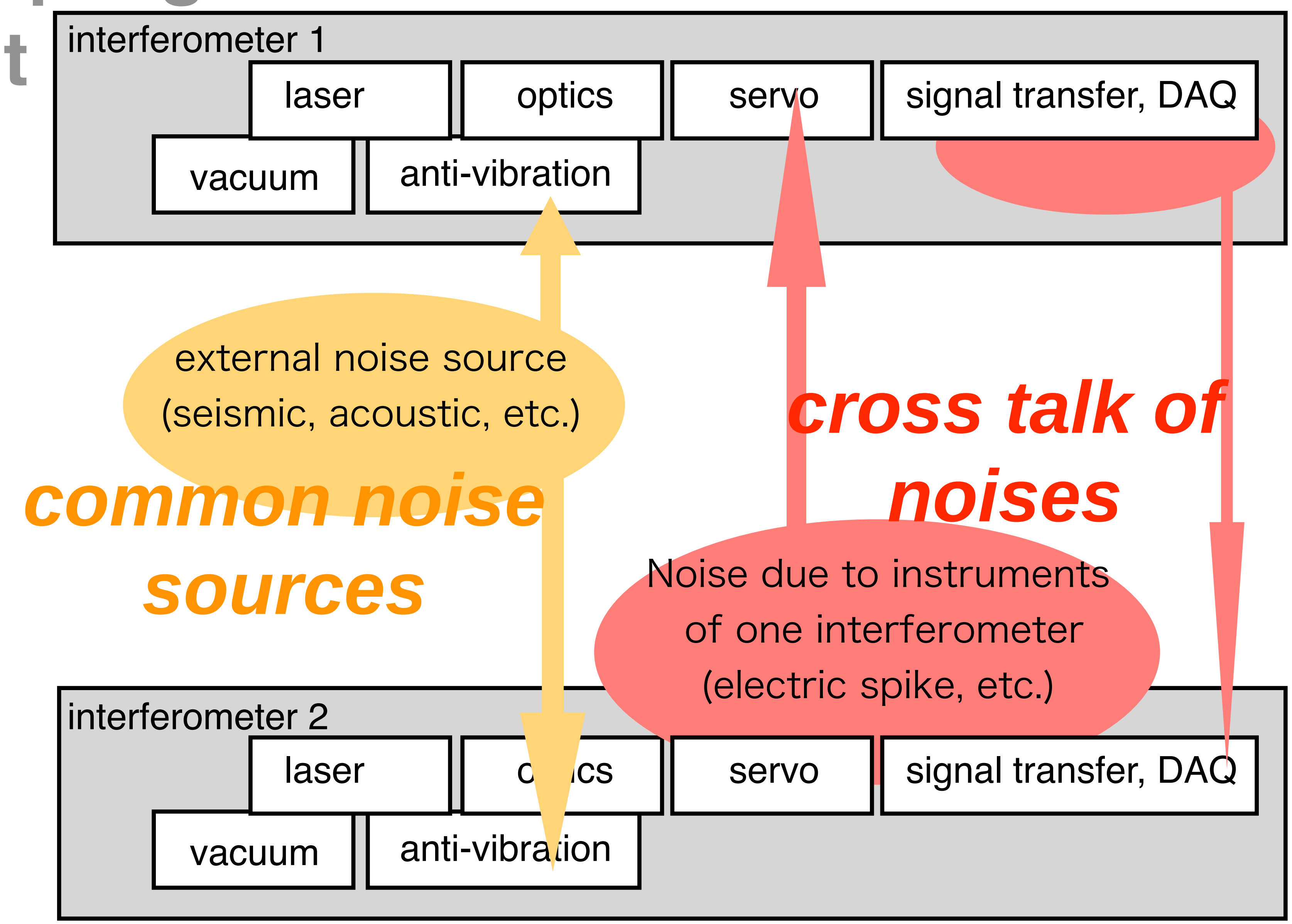
Twin interferometers

- 1yr integration, freq. band : 100Hz
- $h_0^2\ \Omega_{gw}^{2d}\ (100Hz) \sim 4.8 \times 10^{-10}$

Pragmatic Problems

Noise cross talk & common components

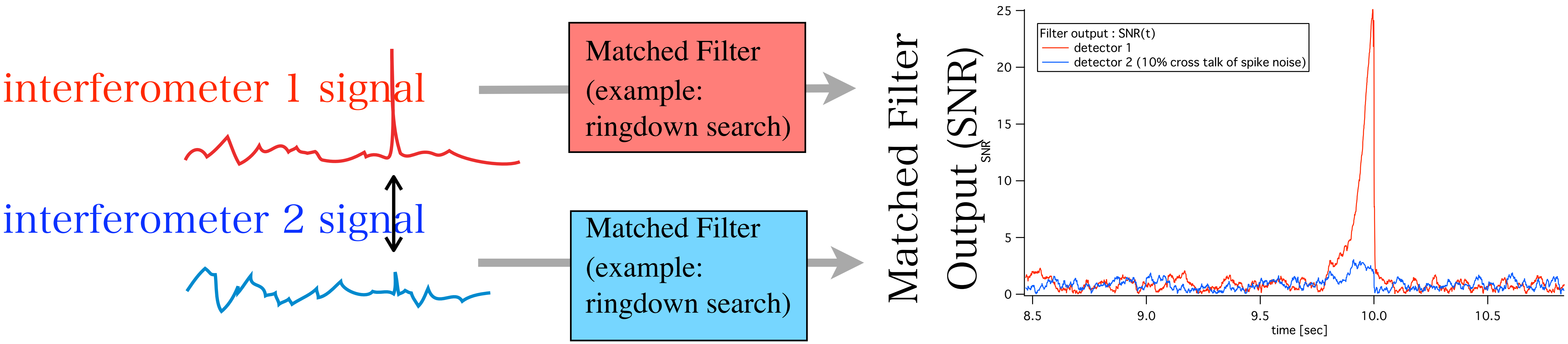
- seismic motion
- electric coupling
- mechanical coupling
- gravity gradient



Solution 1 : Consistency in strain calibrated data

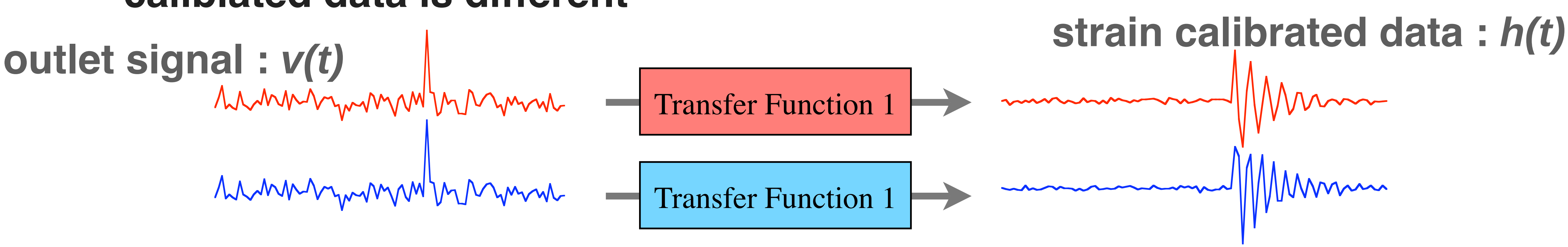
- **The fake's amplitude is different.**

  propotional to the coupling factor



- **Waveforms are similar in *v(t)*, but different in *h(t)* or *h(f)***

  Transfer functions are different. Thus, the behaivor in strain caliblated data is different

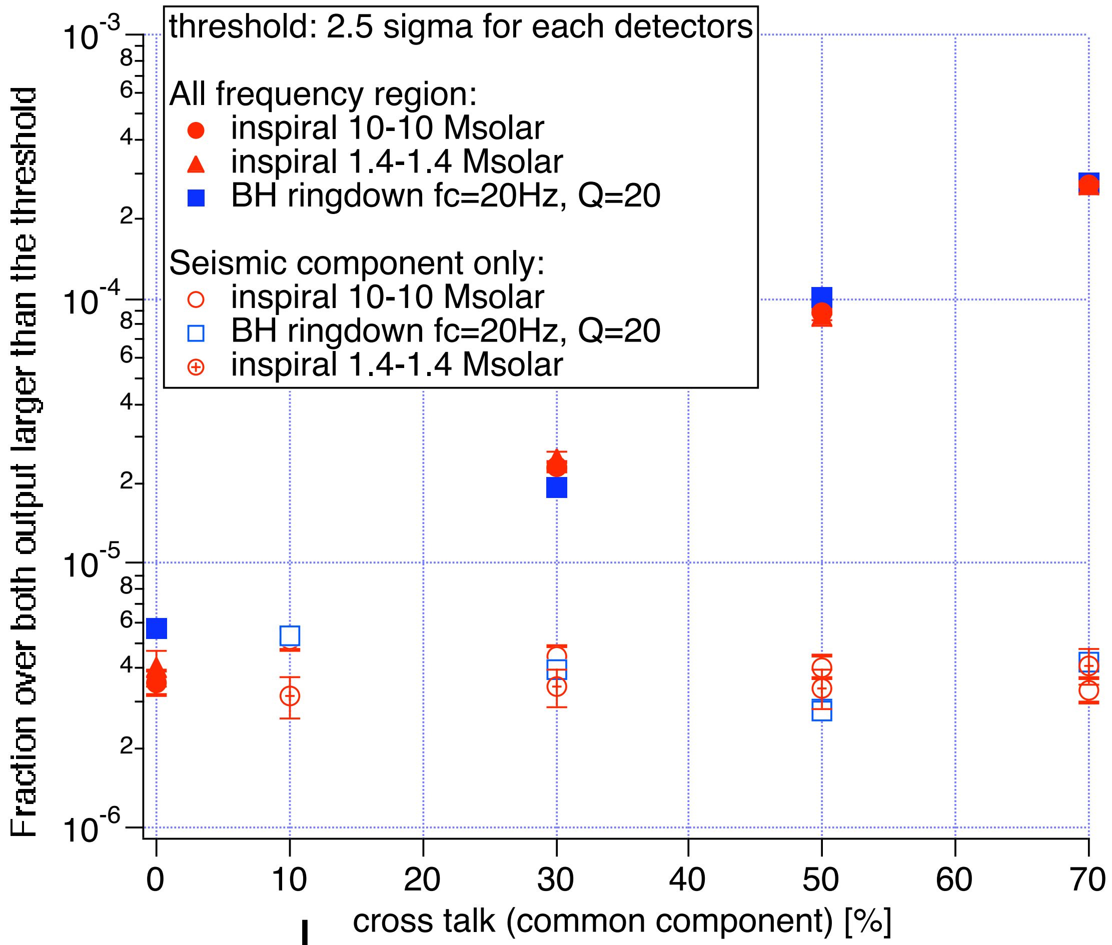


Solution 2 : Analysis can be insensitive to the noisy frequency band.

Coincidence of Fakes with Cross Talk Noise (Simulation)

Cases for:

- Whole frequency band
- Seismic component only



		inspiral 1.4-1.4 Msol	inspiral 10-10 Msol	BH ringdown (20Hz,Q2=0)
cross talk model	all frequency band	30% -> x 10	30% -> x 10	30% -> x 10
	seismic component only	no effect	no effect	no effect
	spike	proportional to cross talk	proportional to cross talk	proportional to cross talk

for Stochastic GW: 5% cross talk -> $h_0^2\ \Omega_{gw}^{2d} \sim 10^{-8}$

Brief Summary for Twin Interferometers

Twin interferometers will drastically improve

- noise reduction (=range of search),
- utility of LCGT.

Problem is ‘cross talk of noises’.

The problem can escape with

- different tuning of IFO,
- keep independency in observation band.