Search for Gravitational Wave Events and Data Quality Evaluation on TAMA300

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Osaka City University
&
the TAMA collaboration

Plan of This Talk

1. Introduction for Laser Interferometric Gravitational Wave Detector
2. Brief History and Progress of TAMA Project
3. Evaluation of Data Quality
    - Sensitivity
    - Calibration
    - Stability
4. GW Event Search in TAMA
    - How to Extract GW signals
    - Binary Inspiral
    - BH Quasi-Normal Mode Ringdown
    - Burst

1. Introduction

Target Sources for Ground-based Laser Interferometric GW Detector

1. Coalescence of Compact Binaries:

   Neutron star-NS, Balckhole-BH, NS-BH, MACHO binaries

   - Precise Prediction of Waveform for Inspiral (Chirp) wave

2. Burst GW (Supernovae)
3. Continuous Wave (Pulsar)

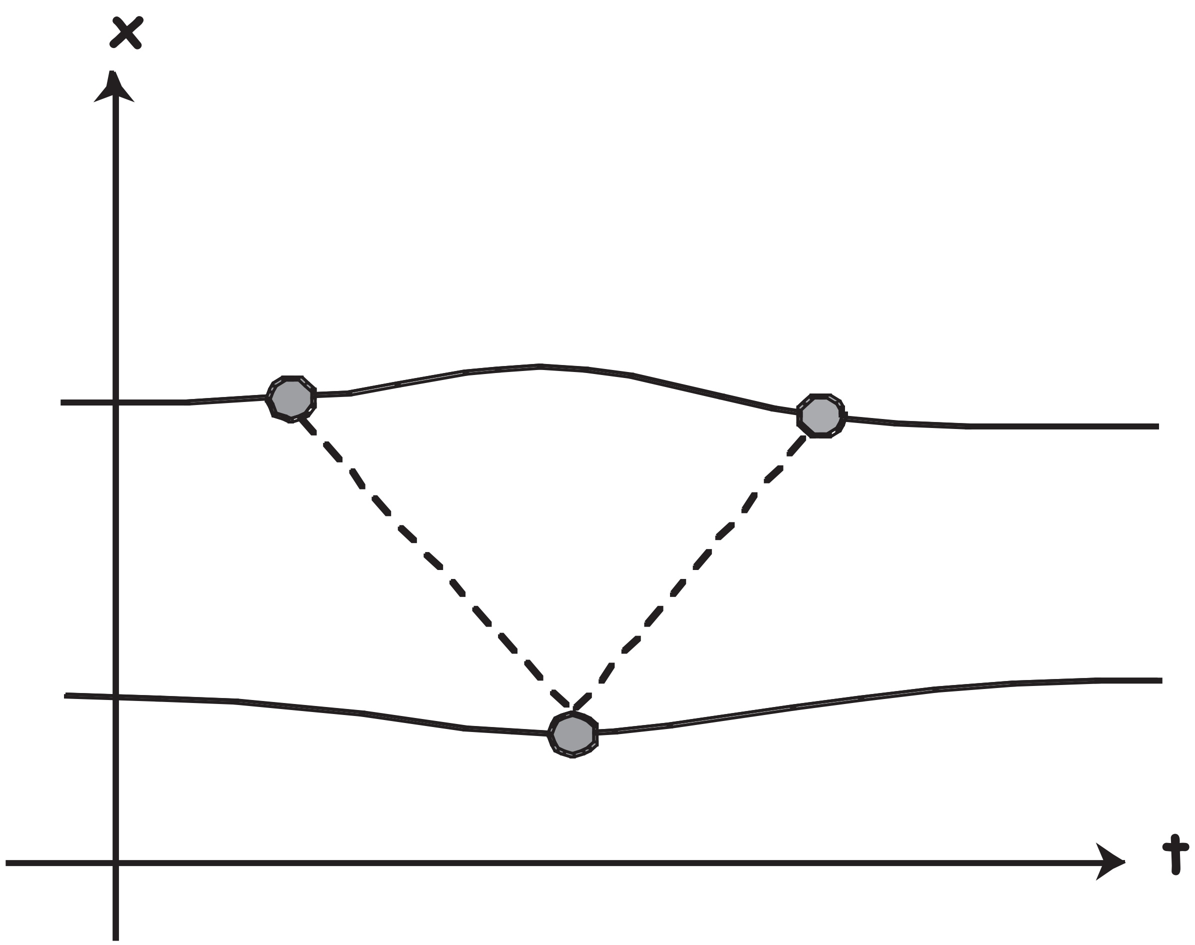
Typical Frequency band : 10Hz – 10kHz

(in TAMA; several 10Hz – 5kHz)

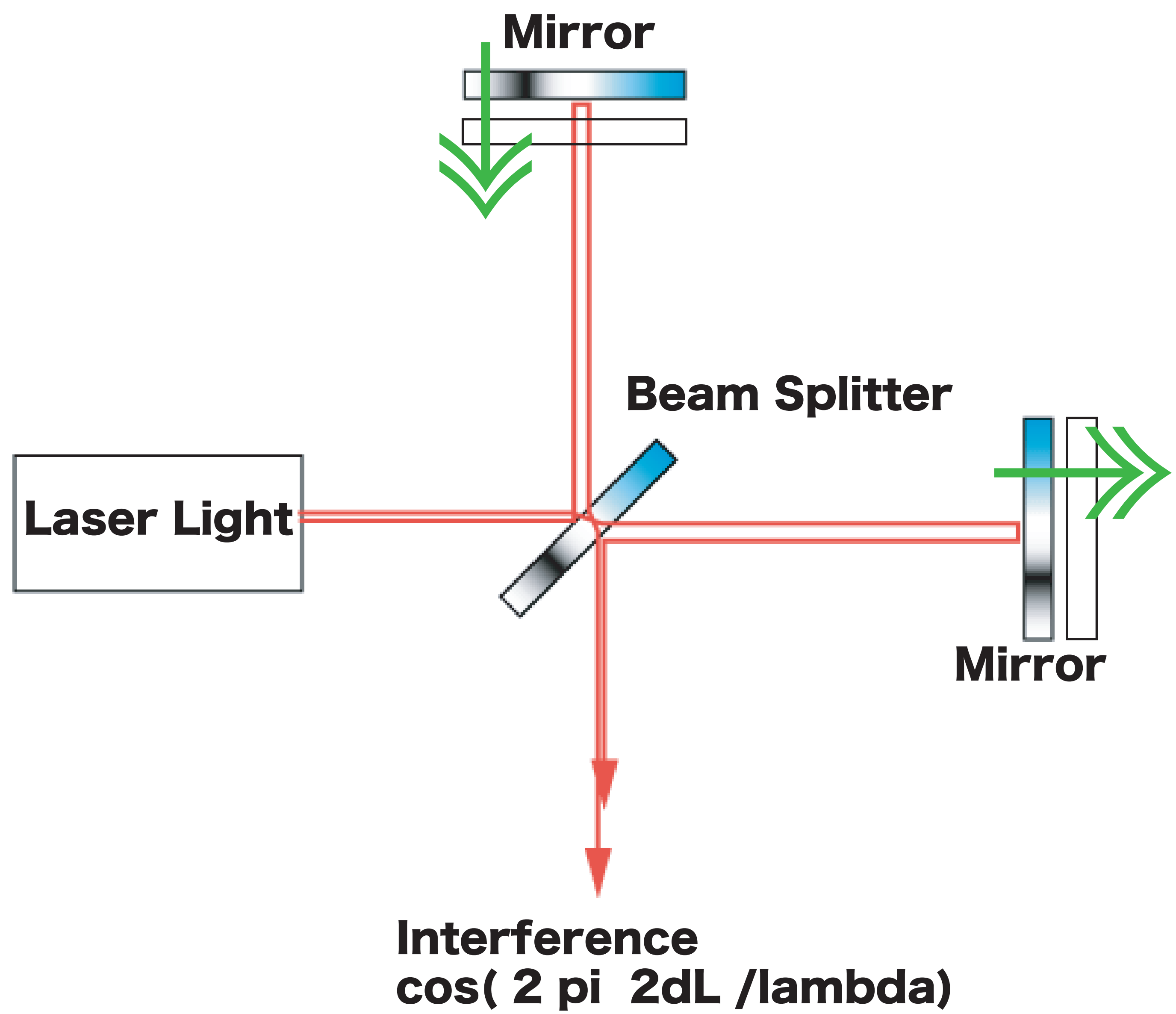
Sensitivity in strain $h > 10^{-21} - 10^{-24}$

(inTAMA; 3×10^{-22}*)*

Laser Interferometric GW Detector



Free Mass
in space-time

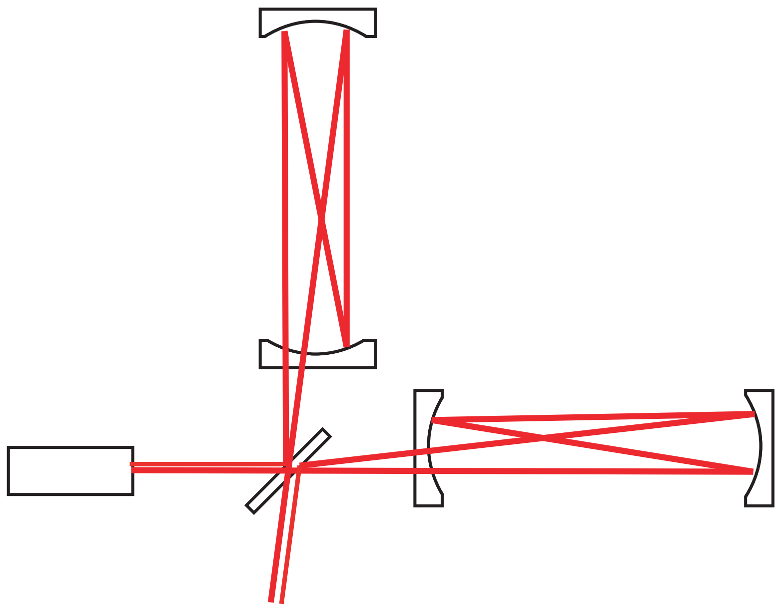


Michelson IF !

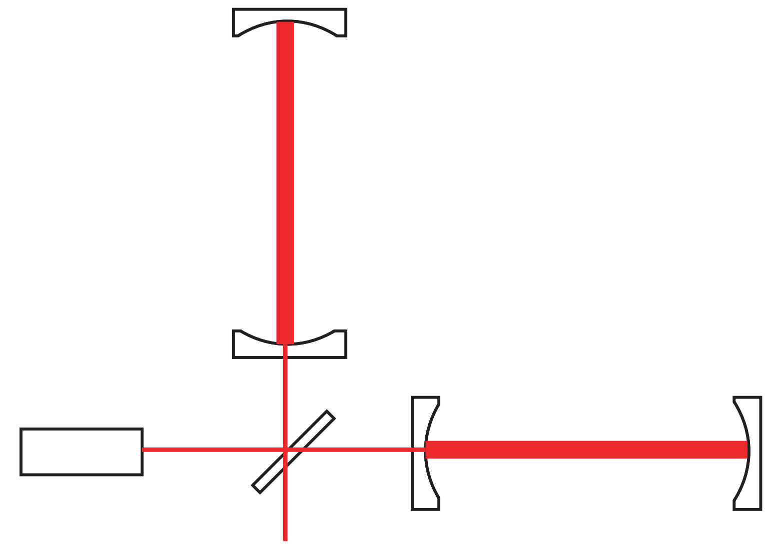
with Suspended Mirror

Folding Arms & get more Power

1kHz GW --> Optimal arm length = 75 km !

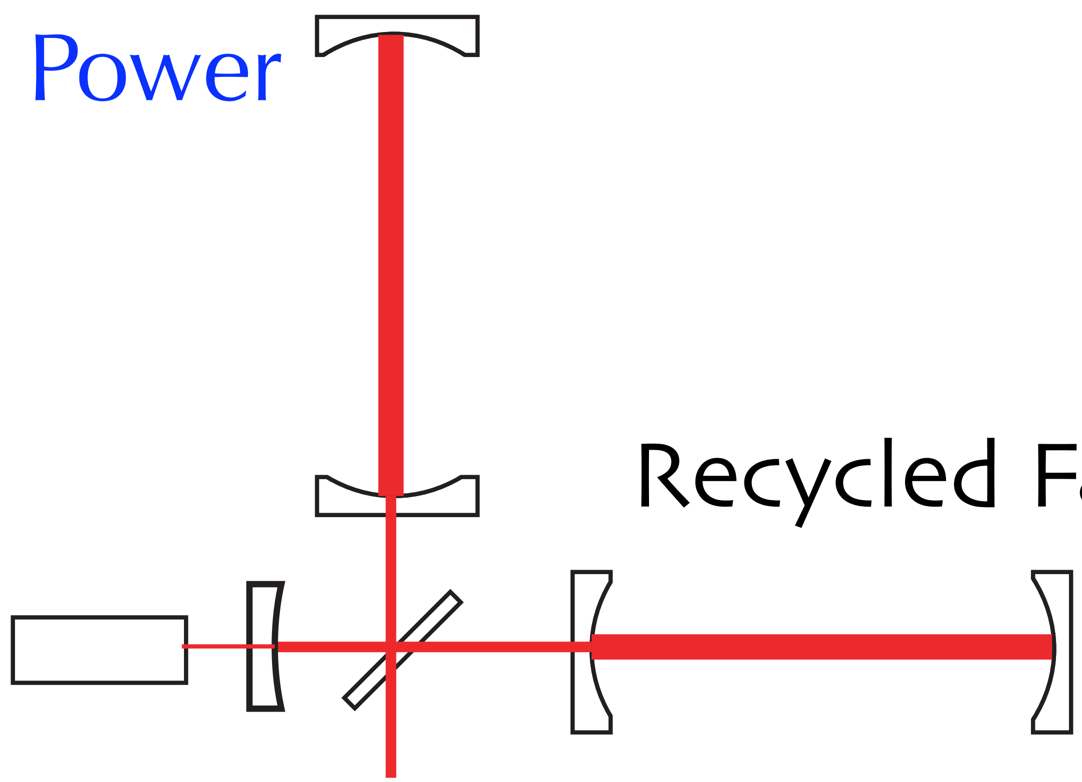


Delay Line



Fabry=Perot

More Laser Power

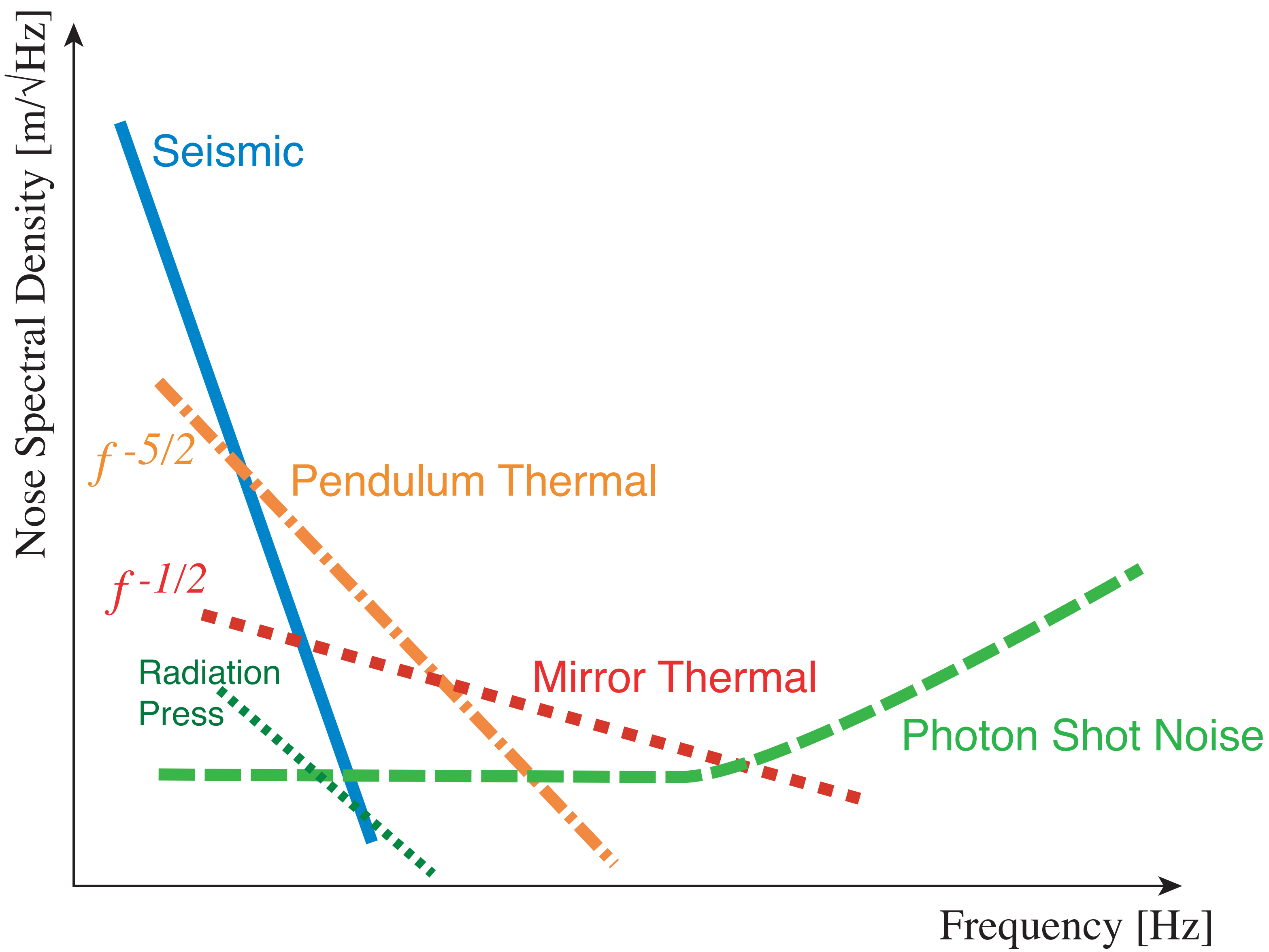


Recycled Fabry=Perot

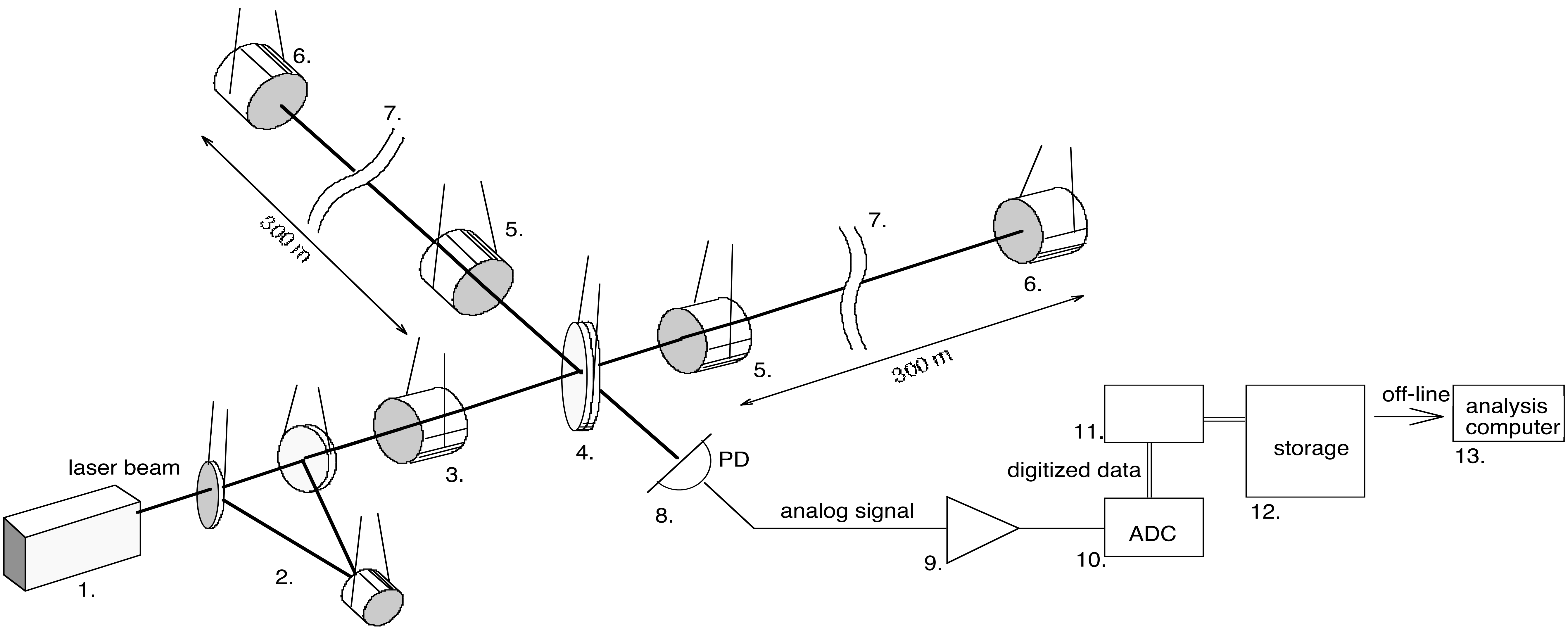
Detector design

– Competition with Noises –

1. Seismic Noise
2. Thermal Noise
3. Photon Shot Noise & Radiation Pressure Noise



Skematic View



2. Overview of TAMA Project

TAMA 300

Target:

- Achieve a Sensitivity for GW from Compact Binary in our Galaxy
  -> Research and Shakedown the Interferometer Tech
- Establish the Detector System for Realistic "Observation"

Construction Site:

- NAOJ, Mitaka, Tokyo

Collaboration:

- 20 institutes with more than 70 persons

The First Search for Gravitational Waves from Inspiraling Compact Binaries using TAMA300 data

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(The TAMA Collaboration)

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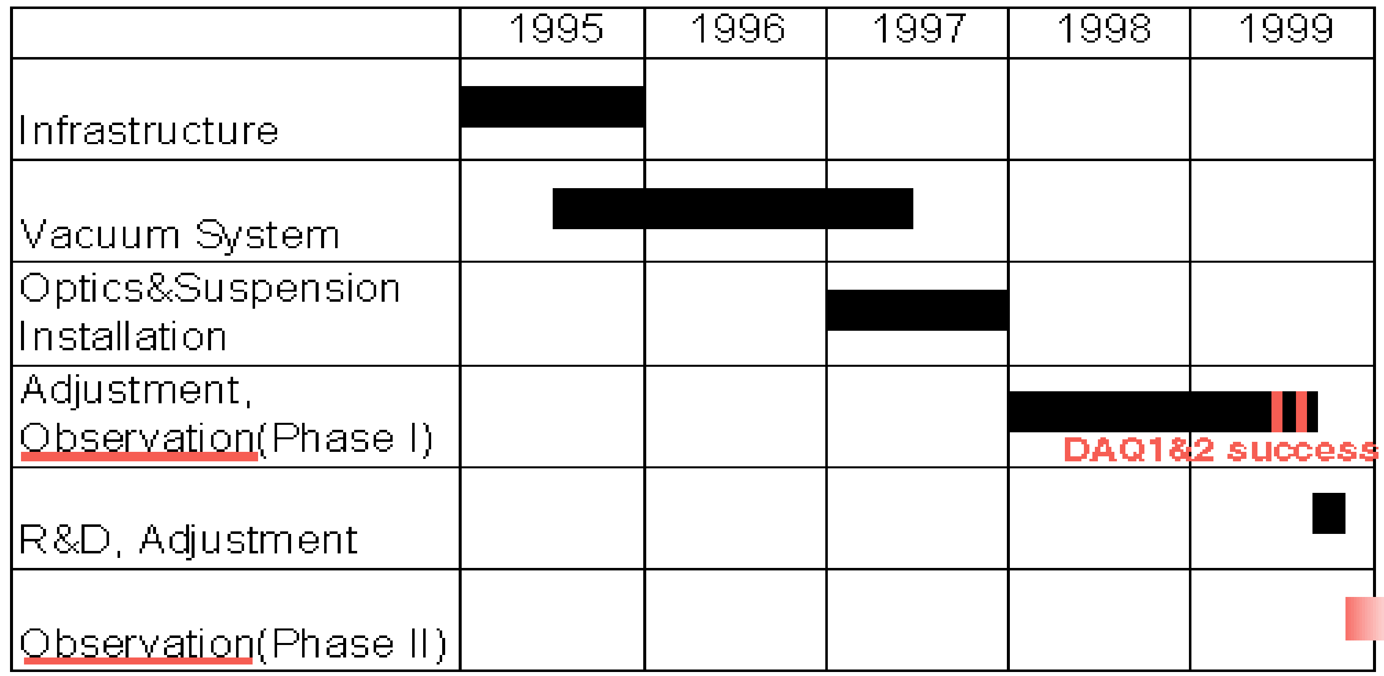
[19] *Precision Engineering Division, Faculty of Engineering, Tokai University*

Project History

1. 1995: start to construction
2.
3.
4.
5.

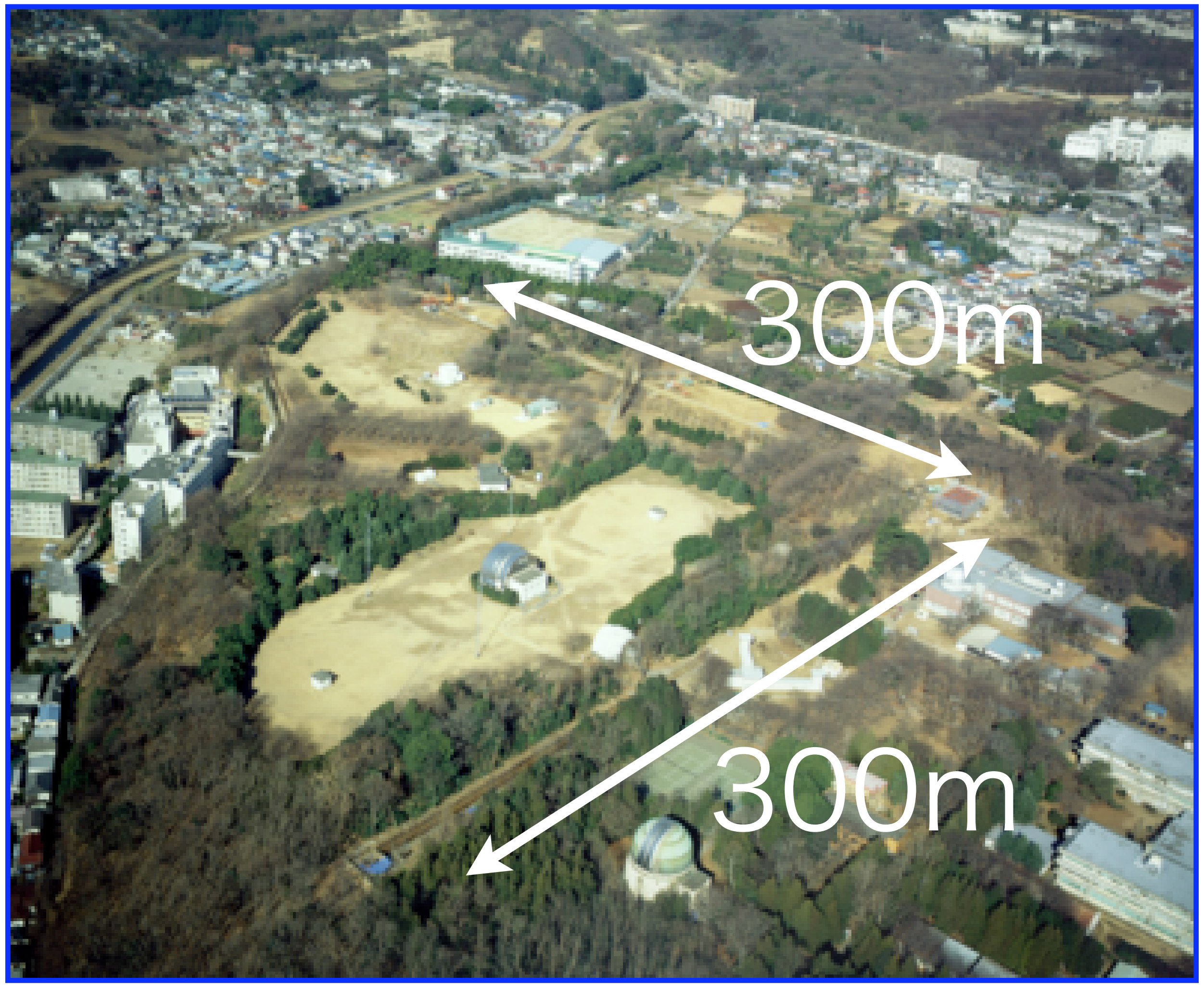


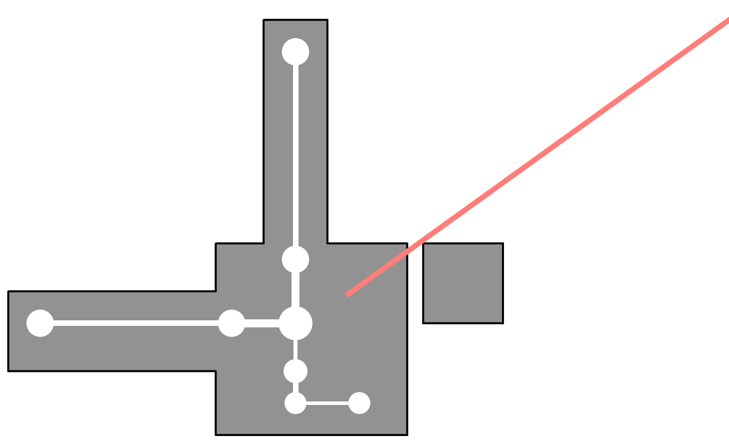
6. 1999: first physics run
7. 2001: 2 months observation
8. 2002: get new fund
9. 2003: Coincidence run with LIGO, GEO

Specification

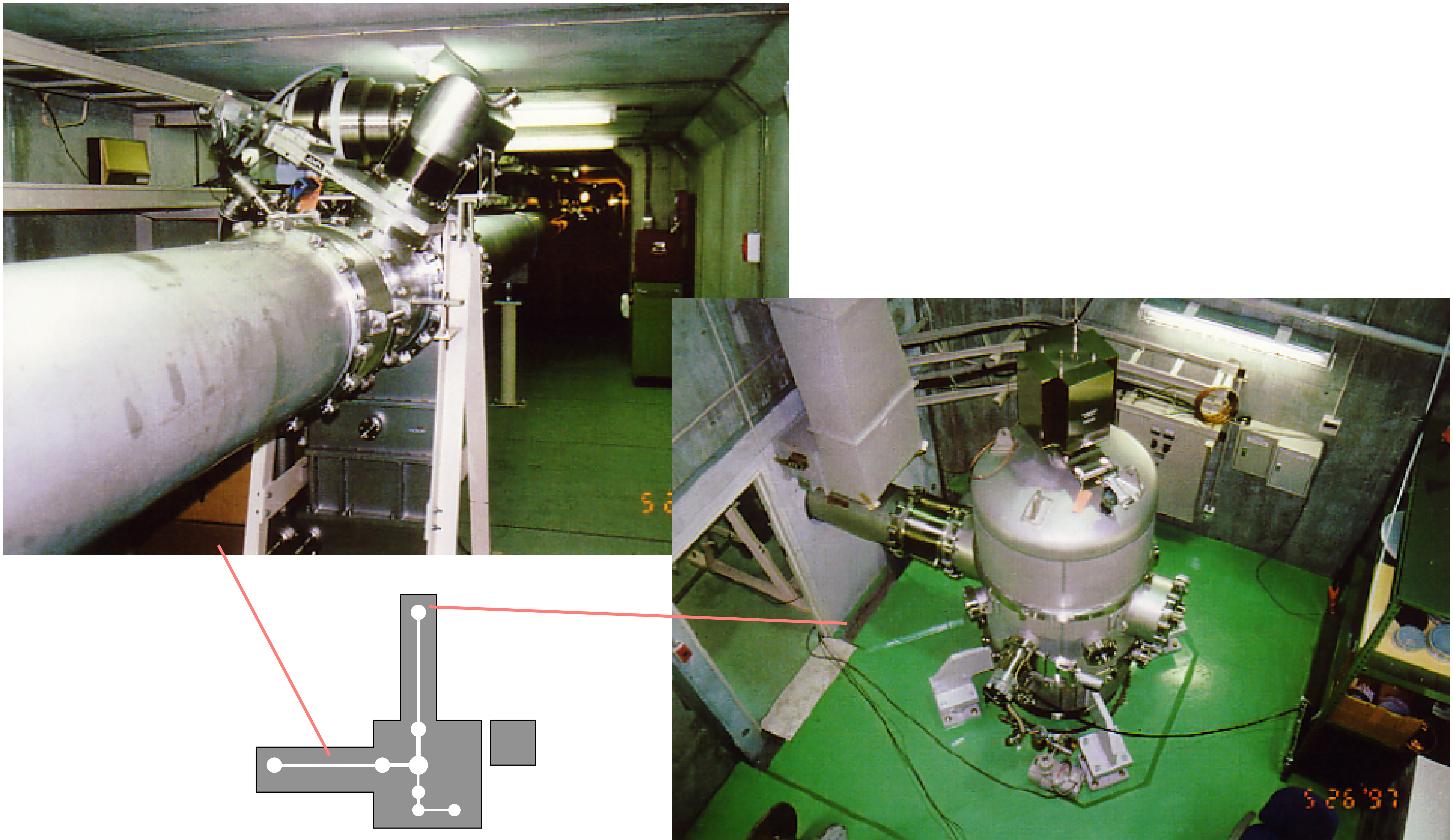
1. Location : NAOJ, Mitaka, Tokyo (E139.32.21 N35.40.25)
2. Target Sensitivity : $h_{r.m.s.} = 3 \times 10^{-21}$ at 300Hz with BW=300Hz
3. Baseline : 300m
4. Type : Fabry-Perot-Michelson with Power Recycling
5. Finesse of Arm Cavity : 520
6. Laser : Injection-lock Nd:YAG, 10W, 1064nm
7. Power Recycling Gain : 10

TAMA Photograph
Bird view, Center Room

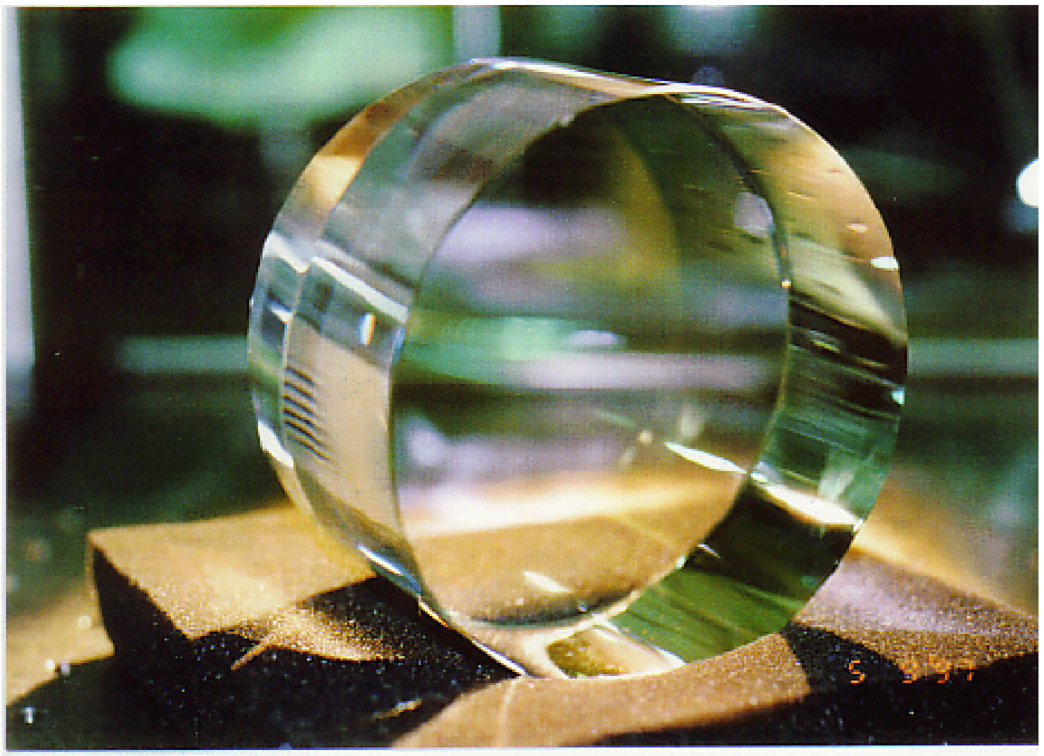


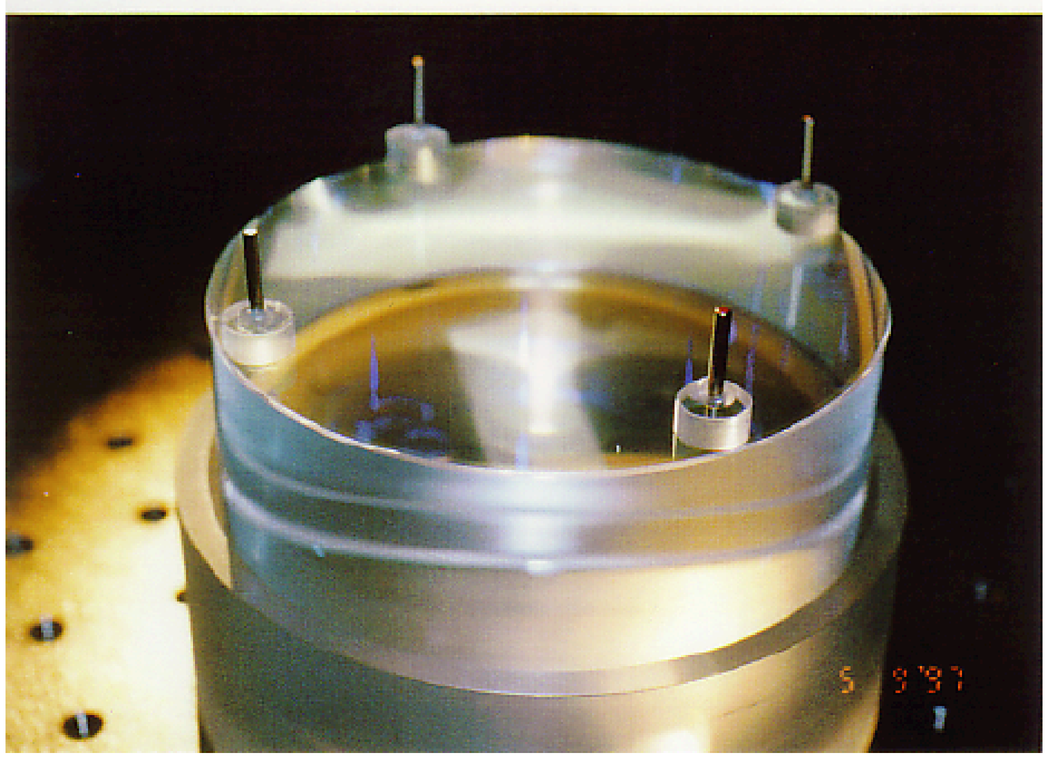


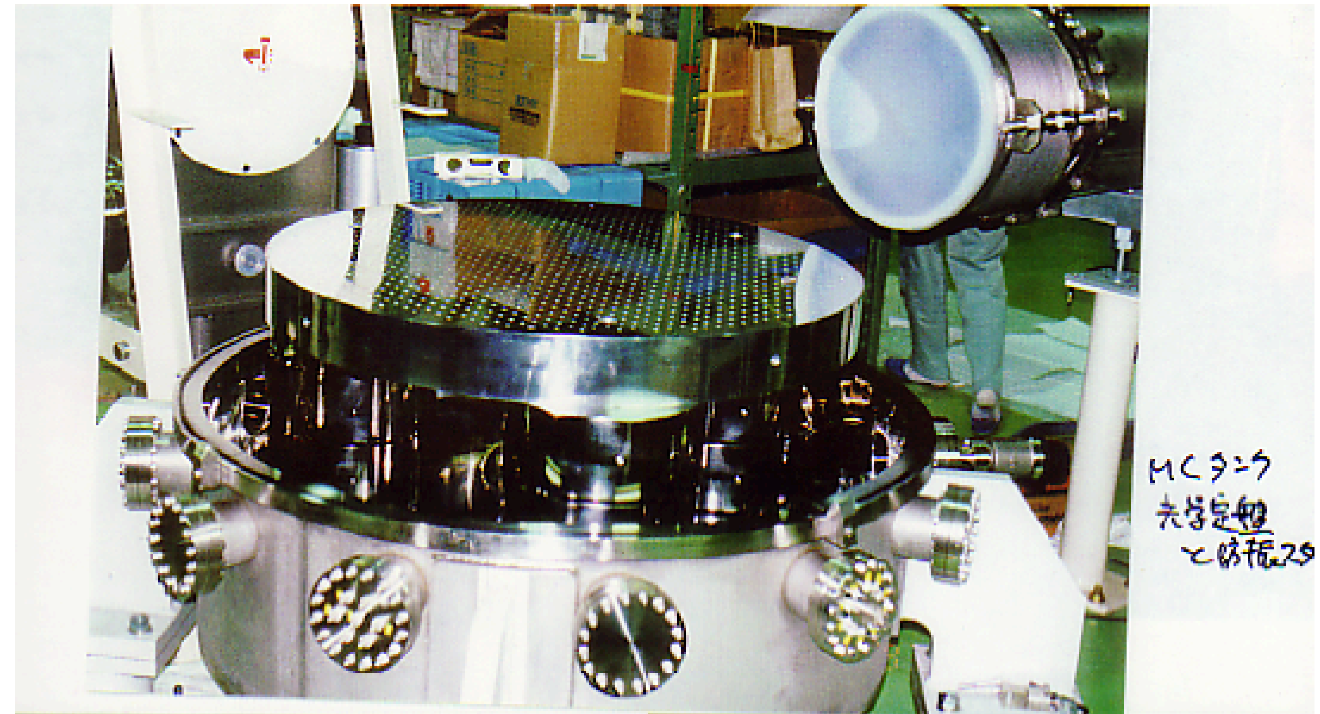
TAMA Photograph
Vacuum, Arm, End Room

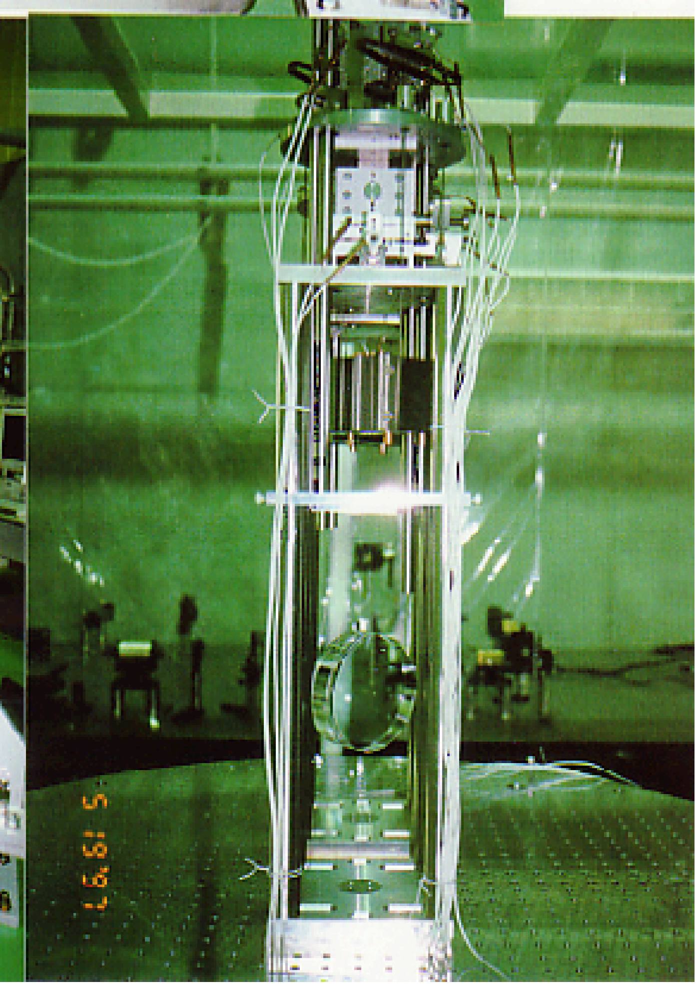


TAMA Photograph
Mirrors, Vibration Isorations

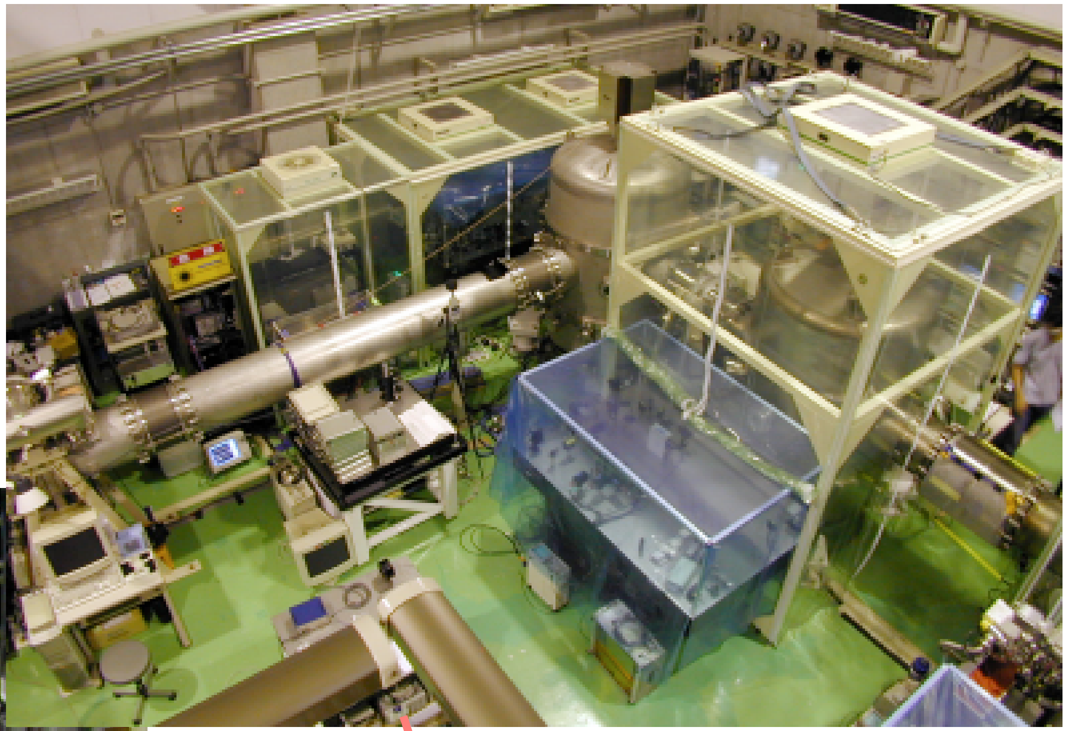


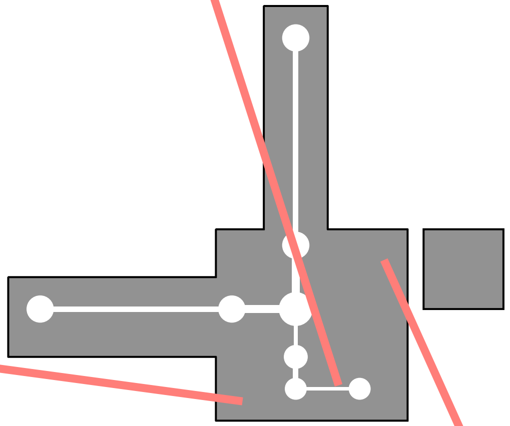






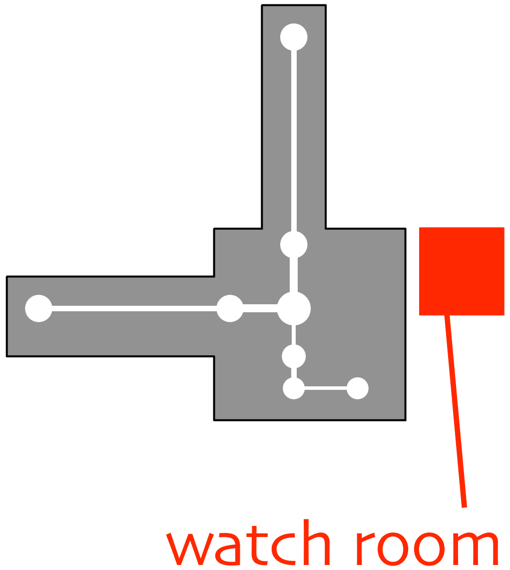
TAMA Photograph
Electronics *and hard worker...*

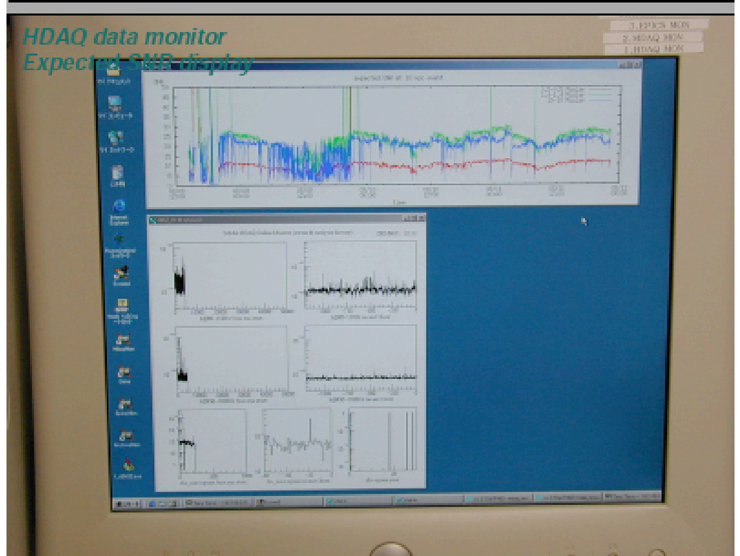


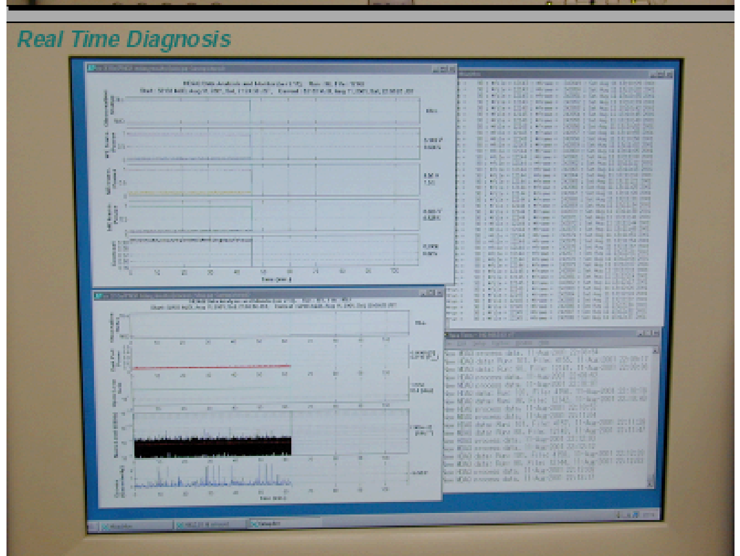


DAQ front-end
Workstations

TAMA Photograph
Online Monitors





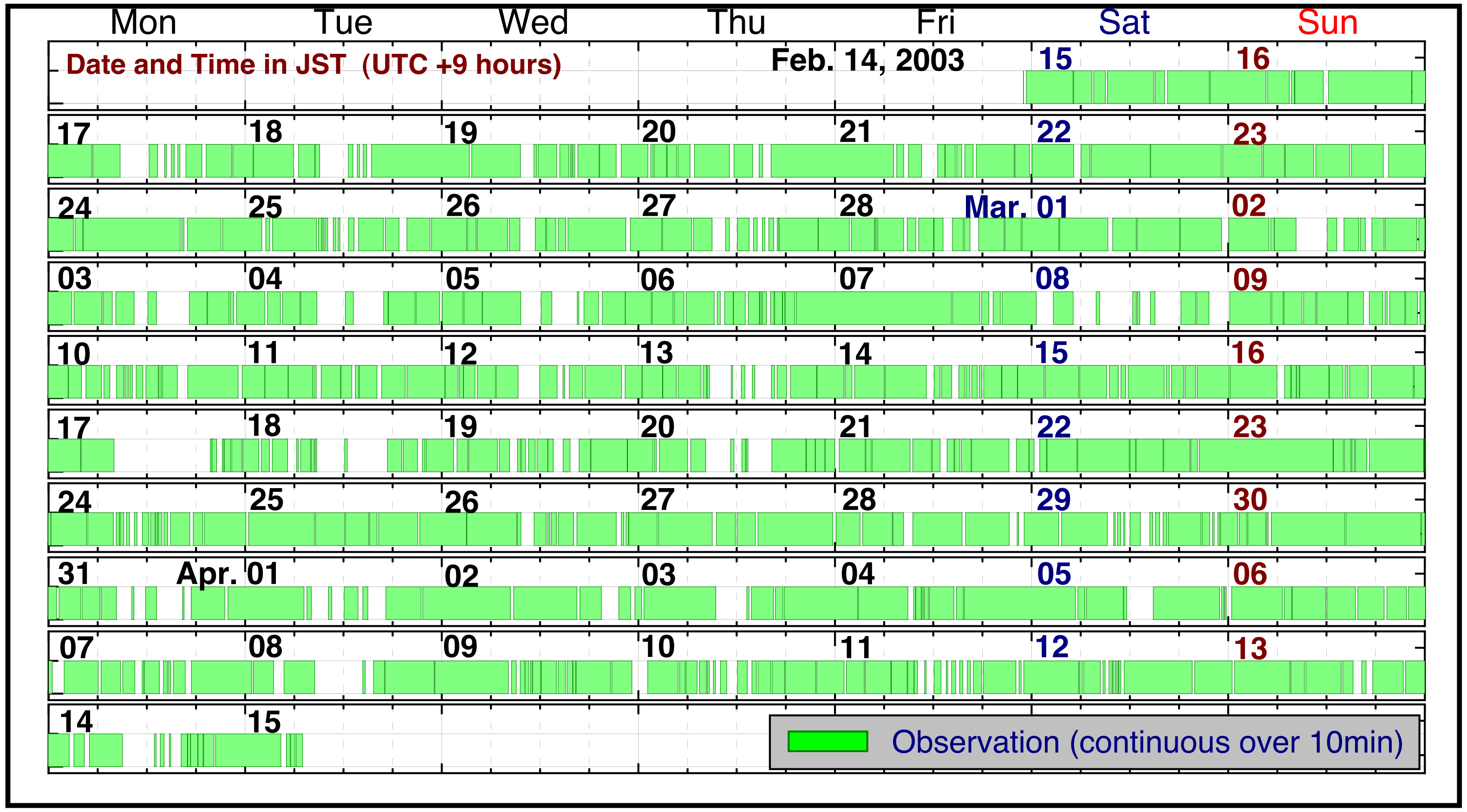


and comfortable(?) workers...

Epoch Data Takings (DT#)
- major test run, observational run -

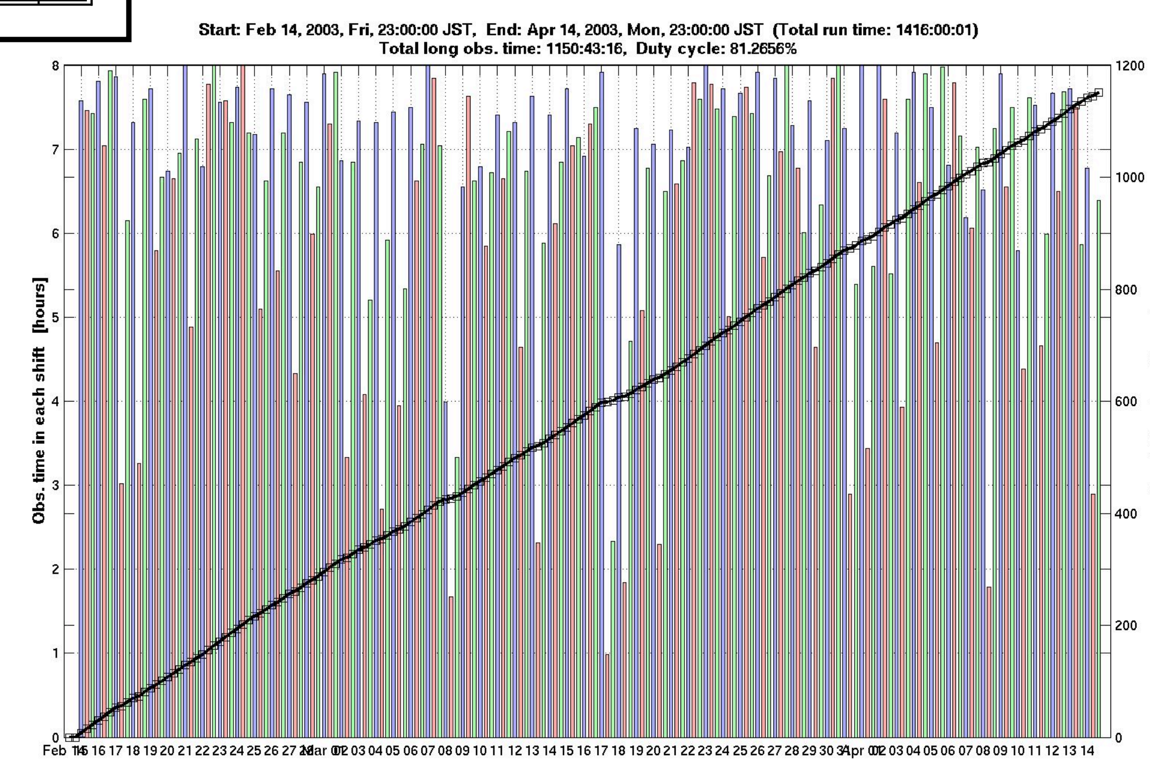
Data Taking	period	actual data amount	take note
DT1	8/6 - 7/1999	~3 + ~7 hours continuous lock	first whole system test
DT2	9/17 - 20/1999	31 hours	first Physics run
DT3	4/20 - 23/2000	13 hours	
--	8/14/2000	World best sensitivity	$h \sim 5\mathrm{x}10^{-21}$ [1/√Hz]
DT4	8/21 - 9/3/2000	167 hours	stable long run
DT5	3/1 - 3/8/2001	111 hours	
Test Run 1	6/4 - 6/6/2001	Longest stretch of continuous lock is 24:50	keep running all day
DT6	8/1 - 9/20/2001	1038 hours duty cycle 86%	full-dressed run
DT7	8/31 - 9/2/2002	24 hours with duty cycle 76.7%	Recycling, $h \sim 3\mathrm{x}10^{-21}$ [1/√Hz], Simultaneous obs with LIGO & GEO
DT8	2/14 – 4/14/2003	1168 hours, duty cycle 81.1%	coincidence obs with LIGO S2

DT8 Observation

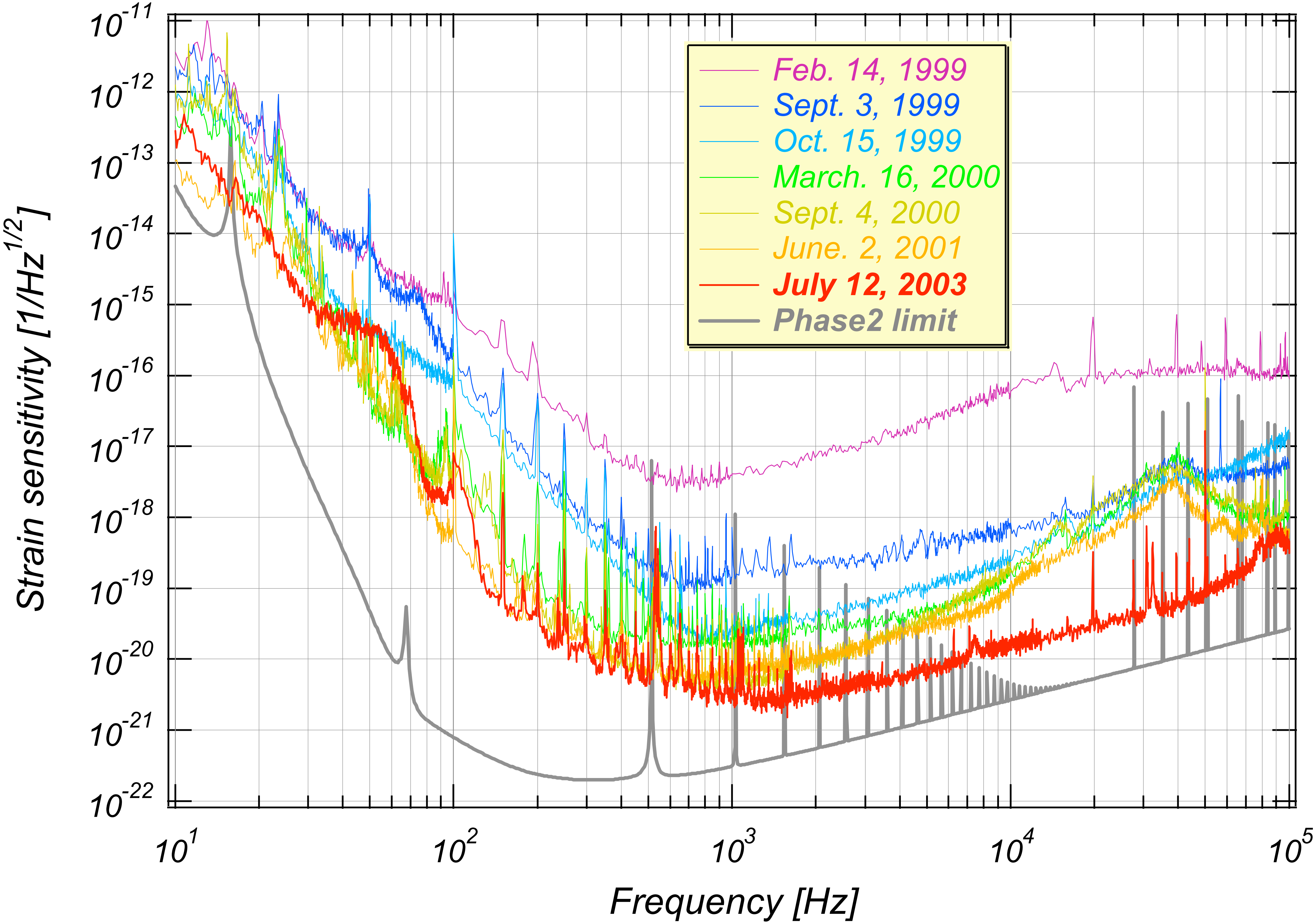


lock time table

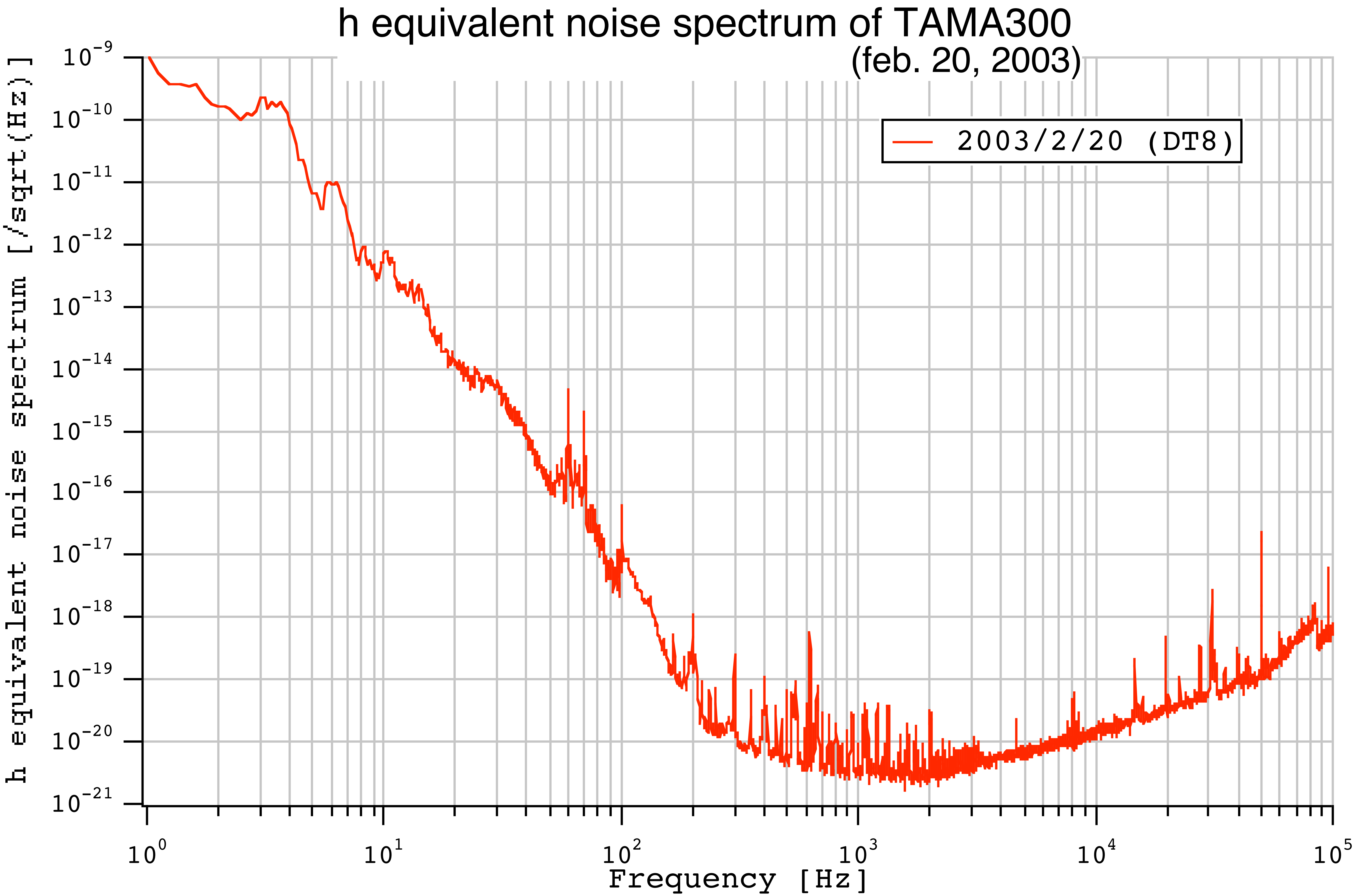
duty cycle & Integration



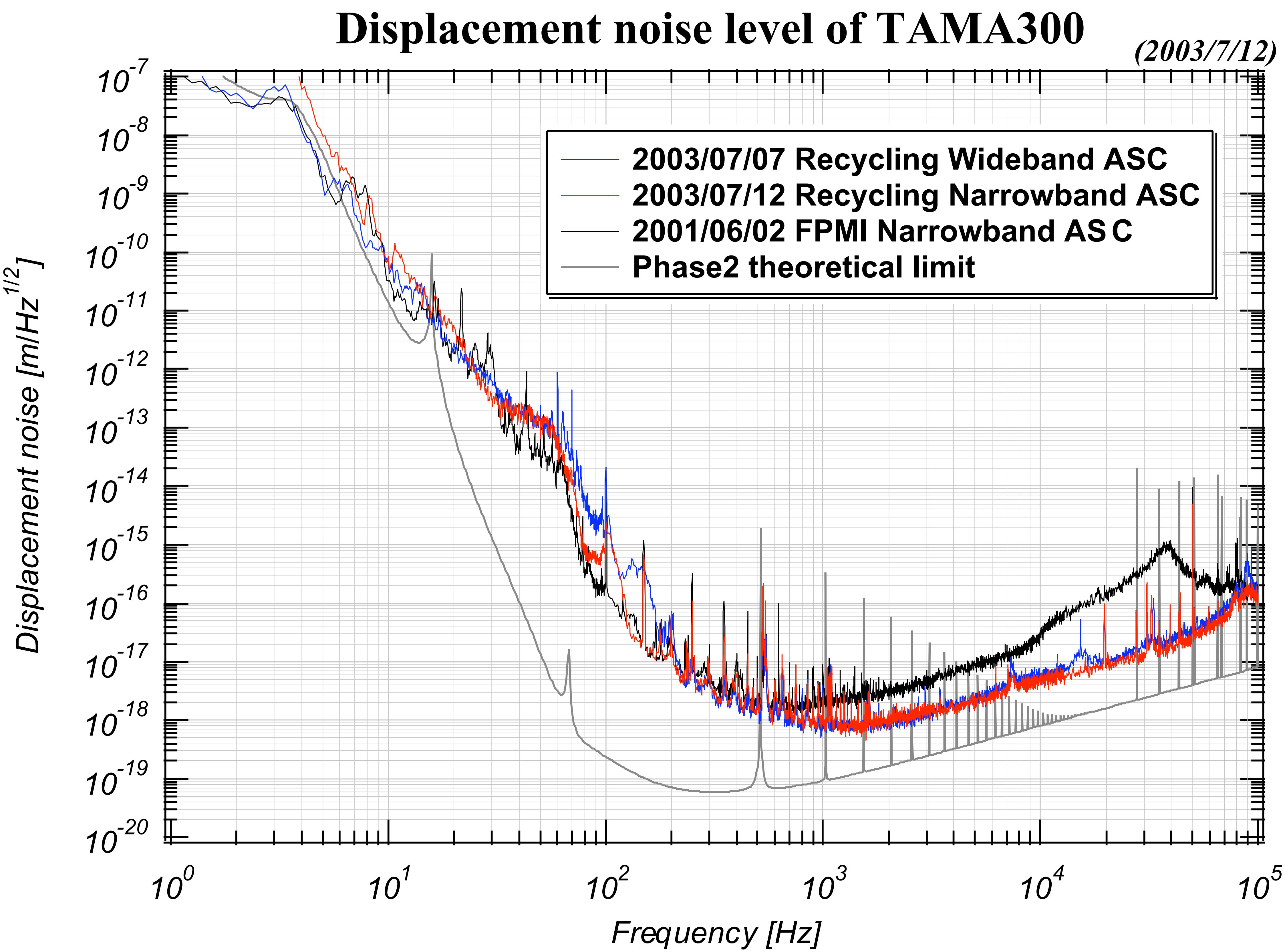
Strain Equivalent Noise Spectrum of TAMA



Strain Equivalent Noise Spectrum of TAMA at **DT8 (Feb.-Mar.2003)**



Strain Equivalent Noise Spectrum of TAMA (latest)



cf: 2003/07/12 preserving the floor level of 8x10 -19 m/Hz 1/2 @1.5kHz.

Observational Range (distance with SNR=10)

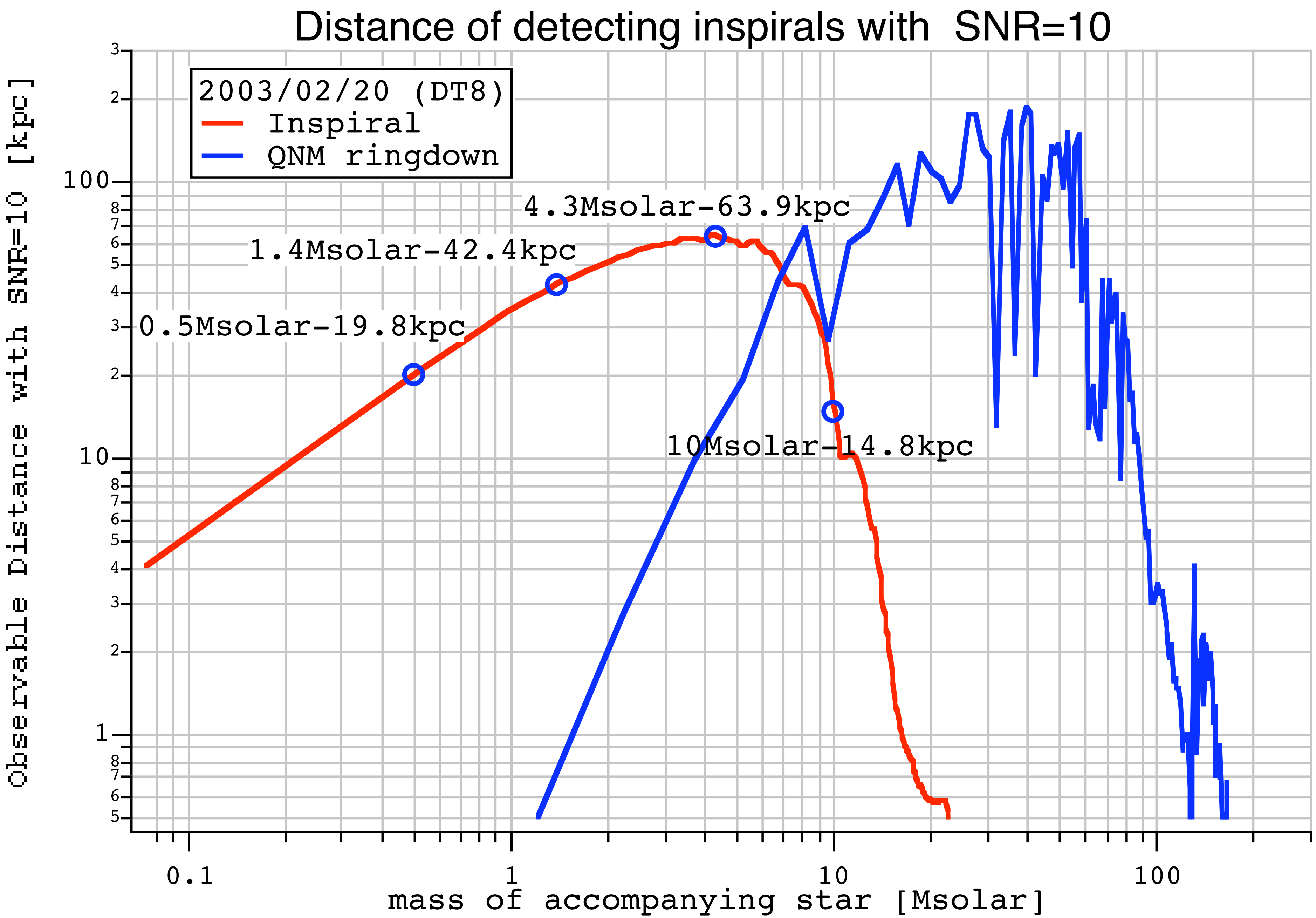
- Inspiral

$$\mathrm{SNR} = \sqrt{2}\,A\left[4\int \frac{f^{-\frac{7}{3}}}{S_n(f)}df\right]^{\frac{1}{2}} \qquad A = T_\odot \frac{c}{d}\left(\frac{5\mu}{96M_\odot}\right)^{\frac{1}{2}}\left(\frac{M}{\pi^2 M_\odot}\right)^{\frac{1}{3}} T_\odot^{-\frac{1}{6}}$$

$$T_\odot = \left(\frac{G}{c^3}\right) M_\odot$$

- BH QNM

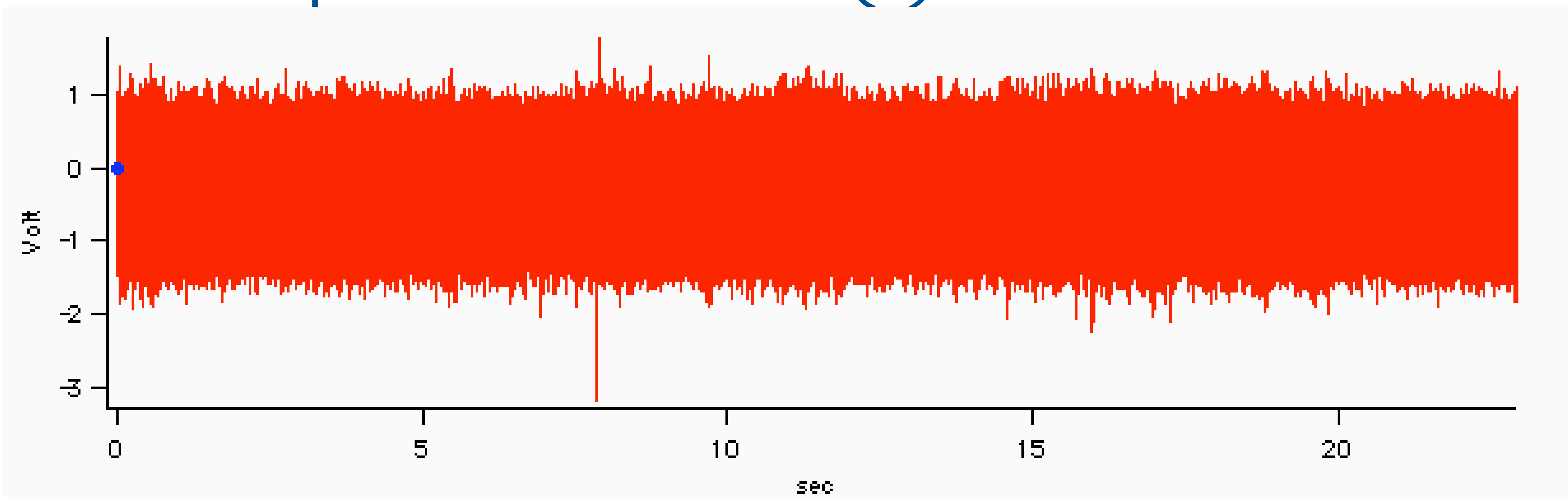
Assuming the BHs formed from binary coalescence (Flanagan & Hughes, Phys.Rev.D57)



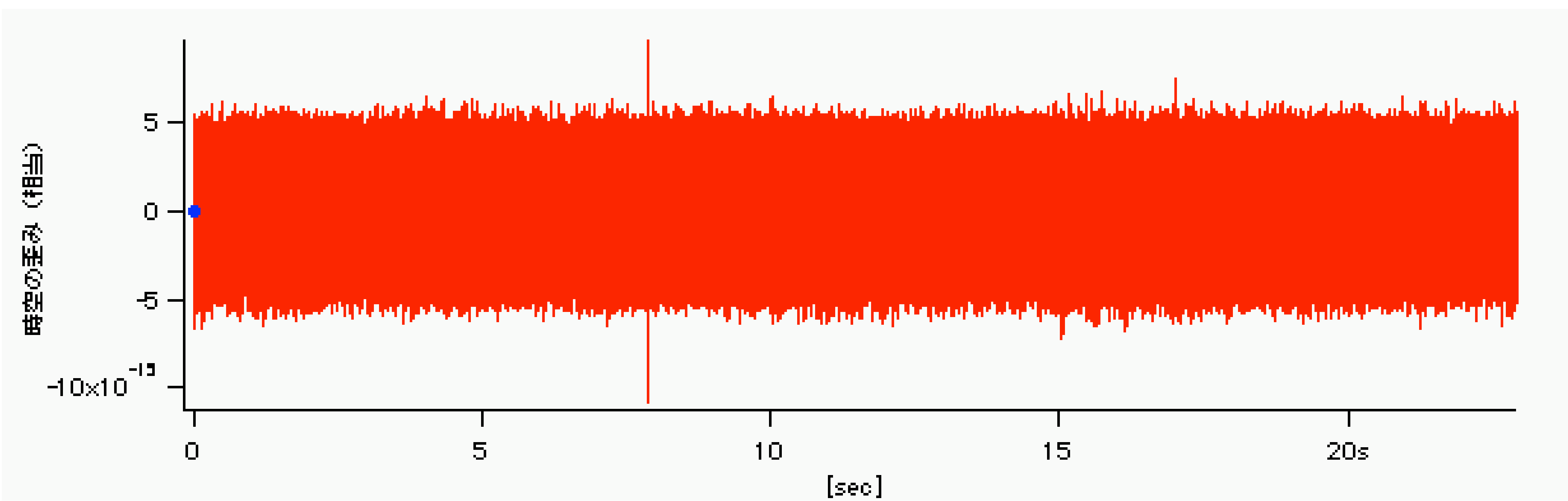
Sound of TAMA...

"sound" of TAMA interferometer (at dt6)

Sample of raw data v(t) sound.



h(t) converted signal. (100-5000Hz)



3. Evaluation of Data Quality

What are required for realistic observatory ?

We get it ! $\text{raw data (time series)} : v(t)$

Key technique !

to establish the detector as "observatory"

Transfer Function (Open loop Gain of the interferometer feedback system)

$\text{calibration} : \dfrac{\Delta h}{h}$

We need this ! $\text{obs. signal} : s(t) = h(t) + n(t)$

$\text{GW} : h(t)$

$\text{noises} : n(t)$

characterization of noise
(n(f), <n>, gaussianity, stability, etc..)

3. Evaluation of Data Quality

What are required for realistic observatory ?

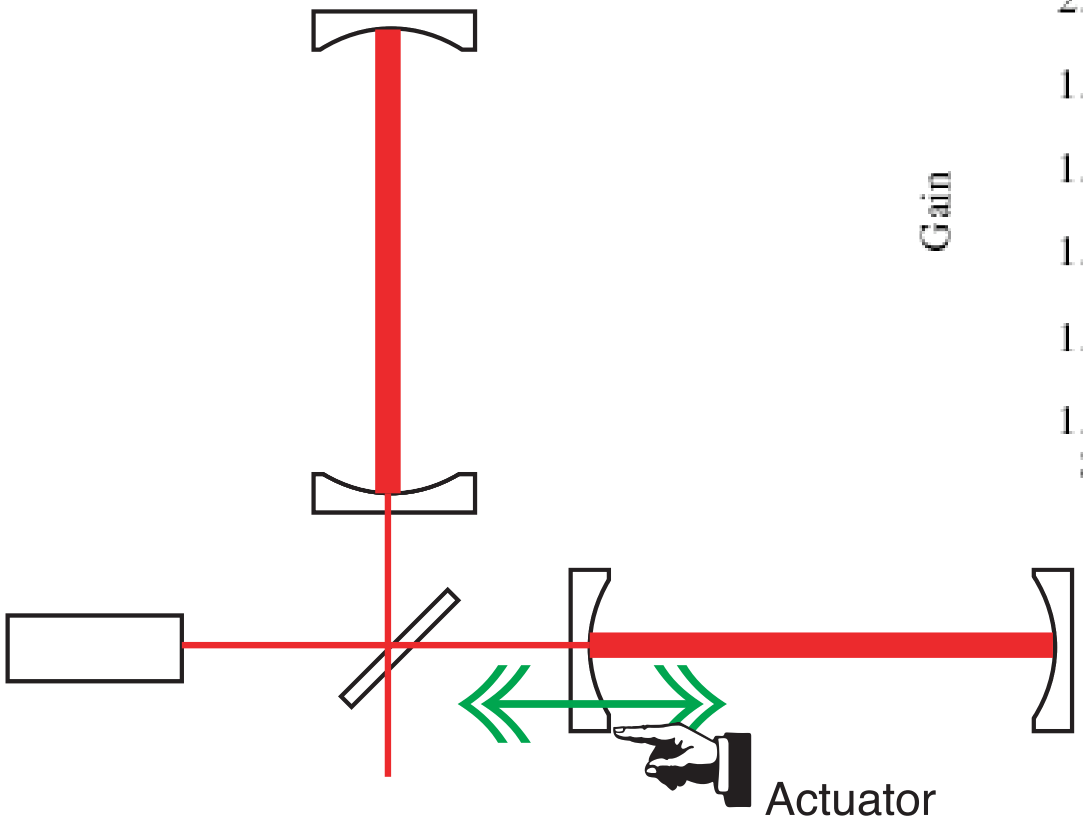
1. Calibration
   - Accuracy of Amplitude of GW (in strain *h*)

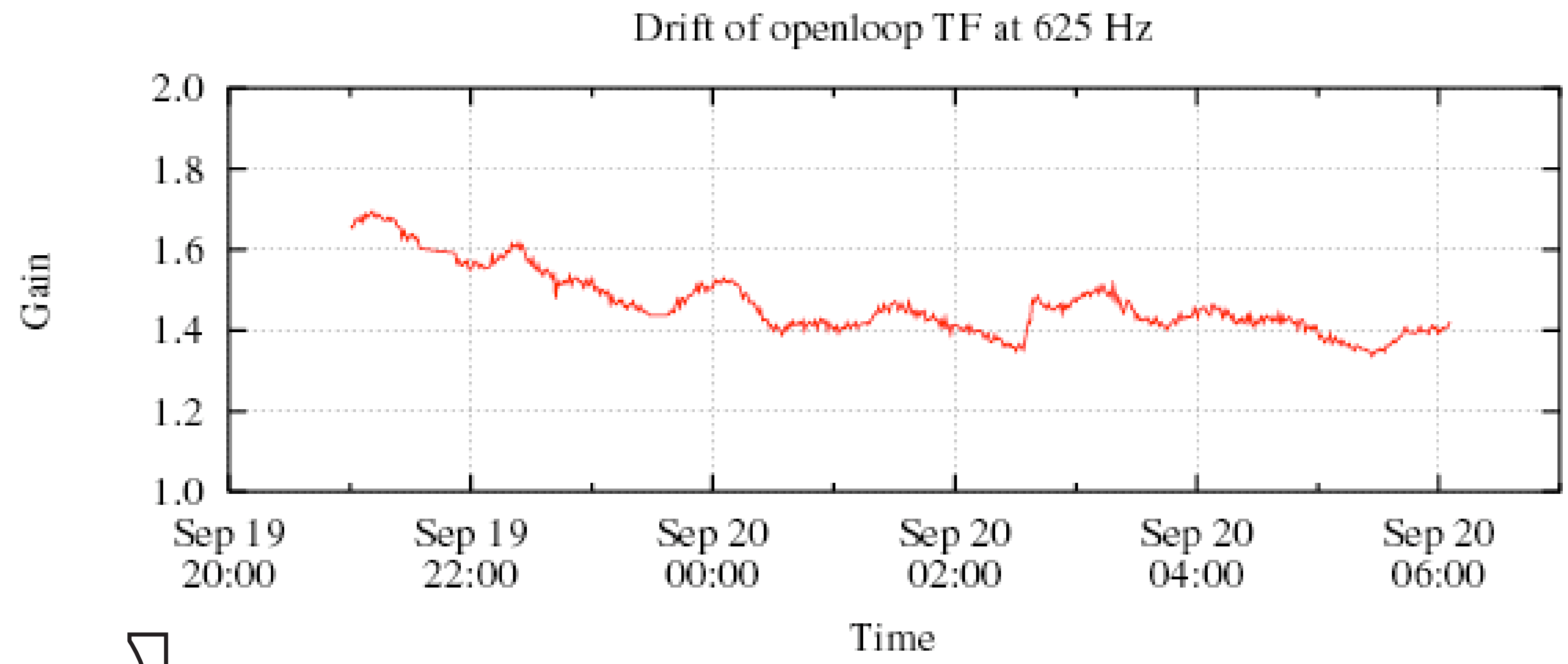
     These will change due to IF optical conditions during long operation.
2. Stability of Noises, or its Evaluation
   - Various Component of Noises
   - Unstable (non-stational) Noise Sources

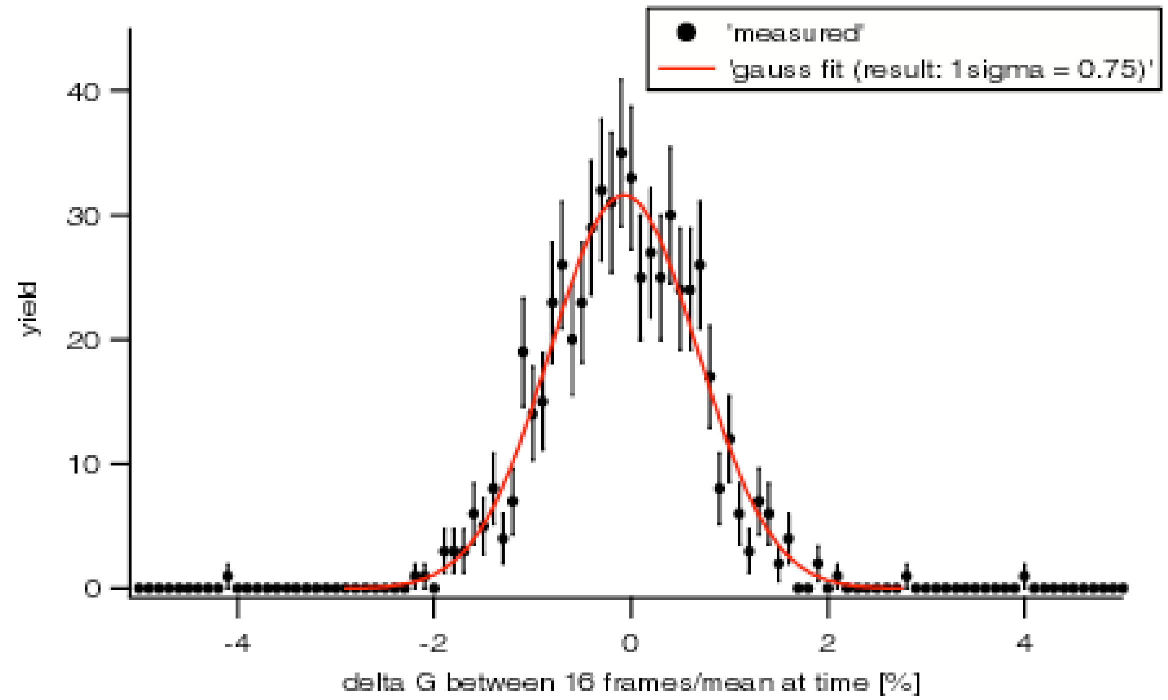
     Noise source inside the detector

     Disturbances from outside

Calibration Signal Injection







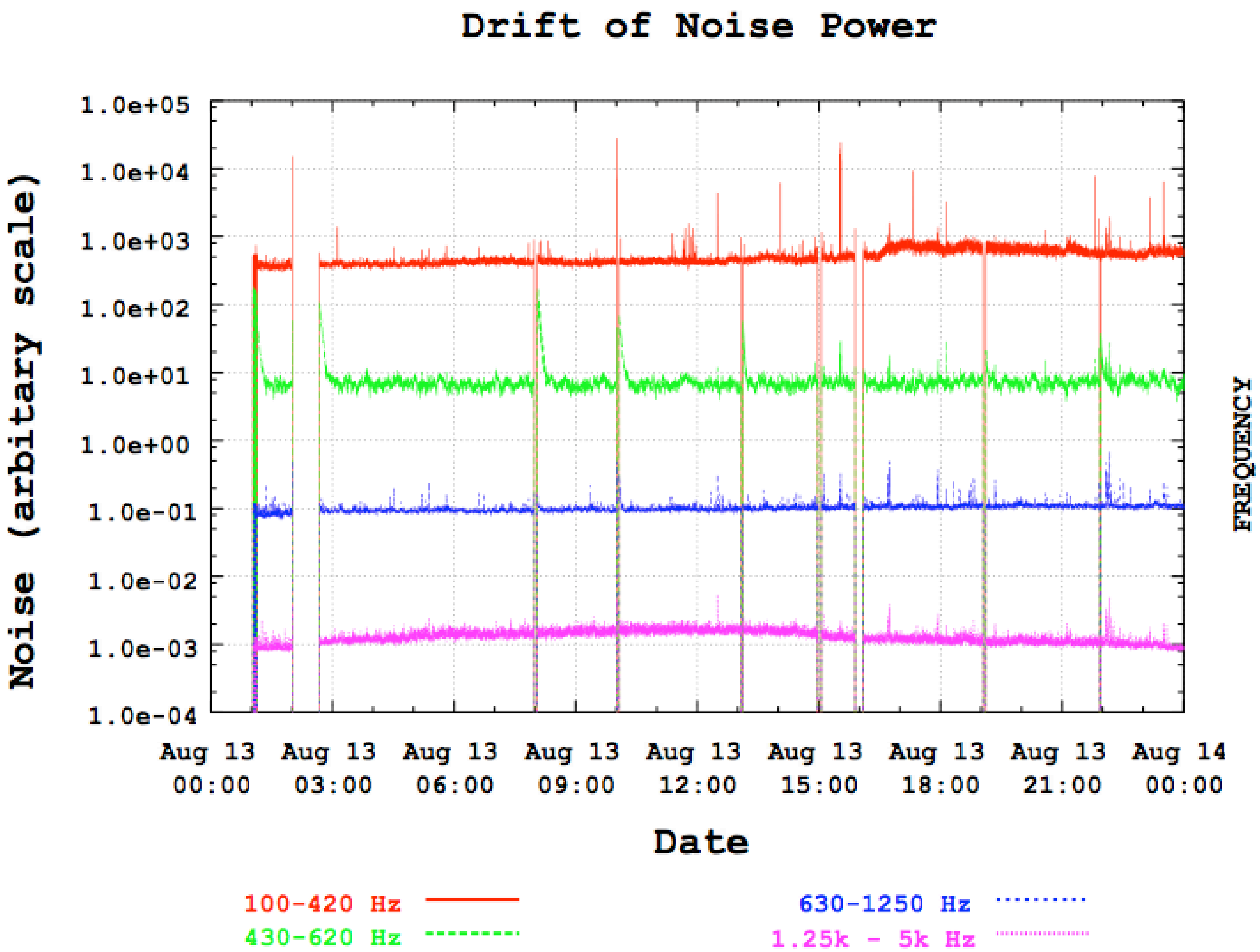
Gain drift for night ~ 30% (dt2)

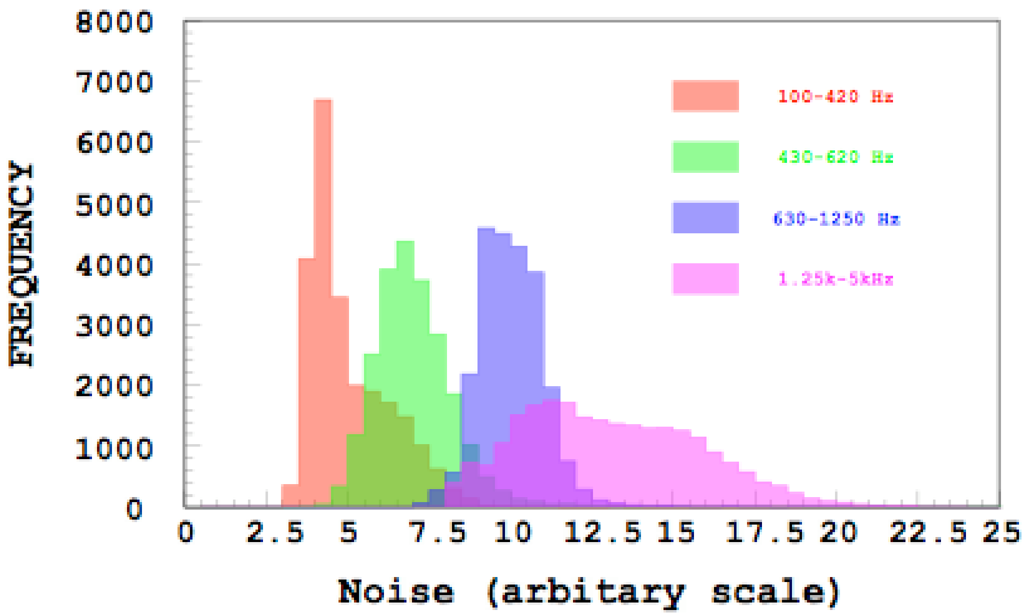
Calibration accuracy ：

$\Delta h/h$ ~ 1% @625Hz

Noise Stability

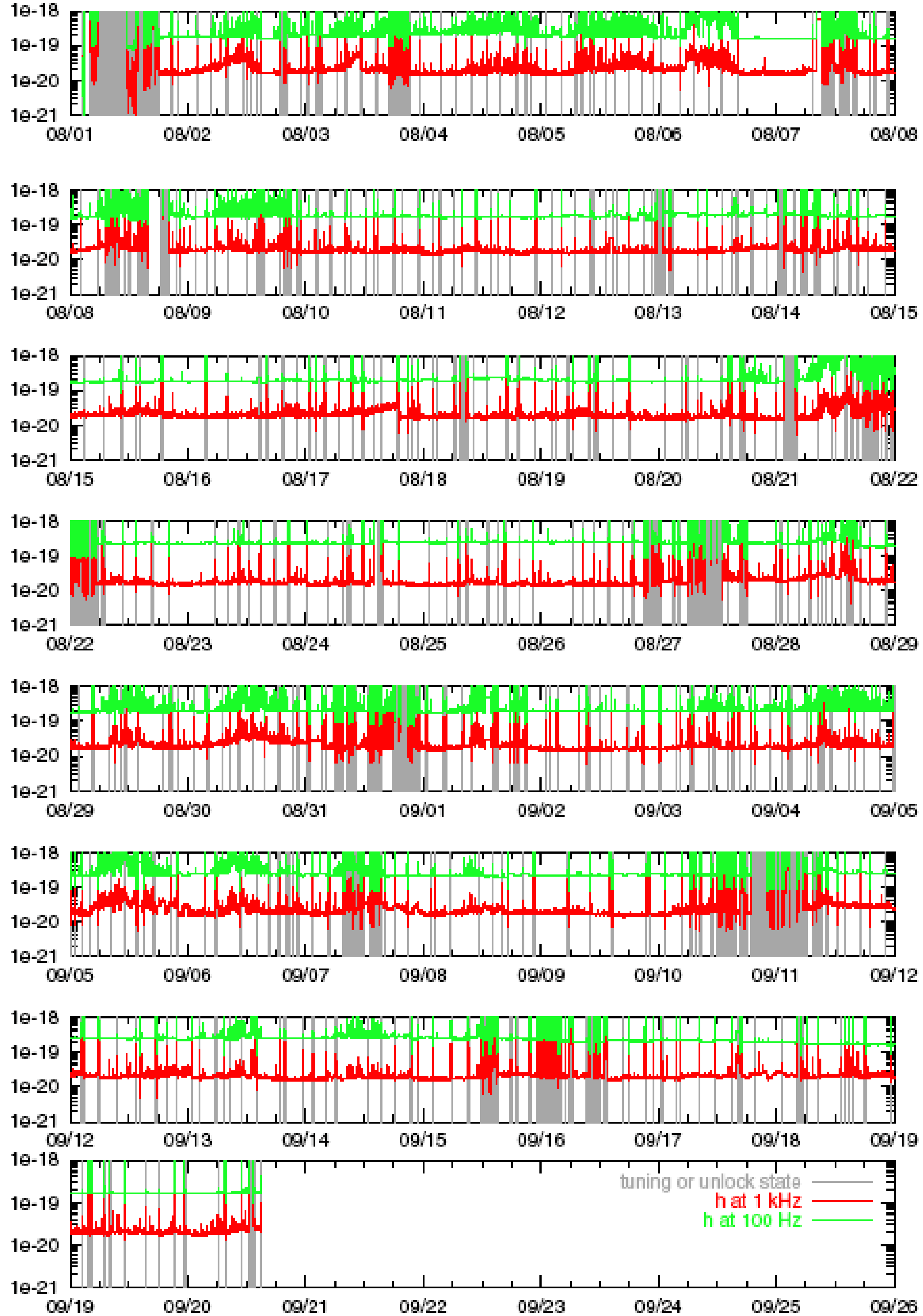
Typical Noise Drift at dt8





Sensitivity History of dt6

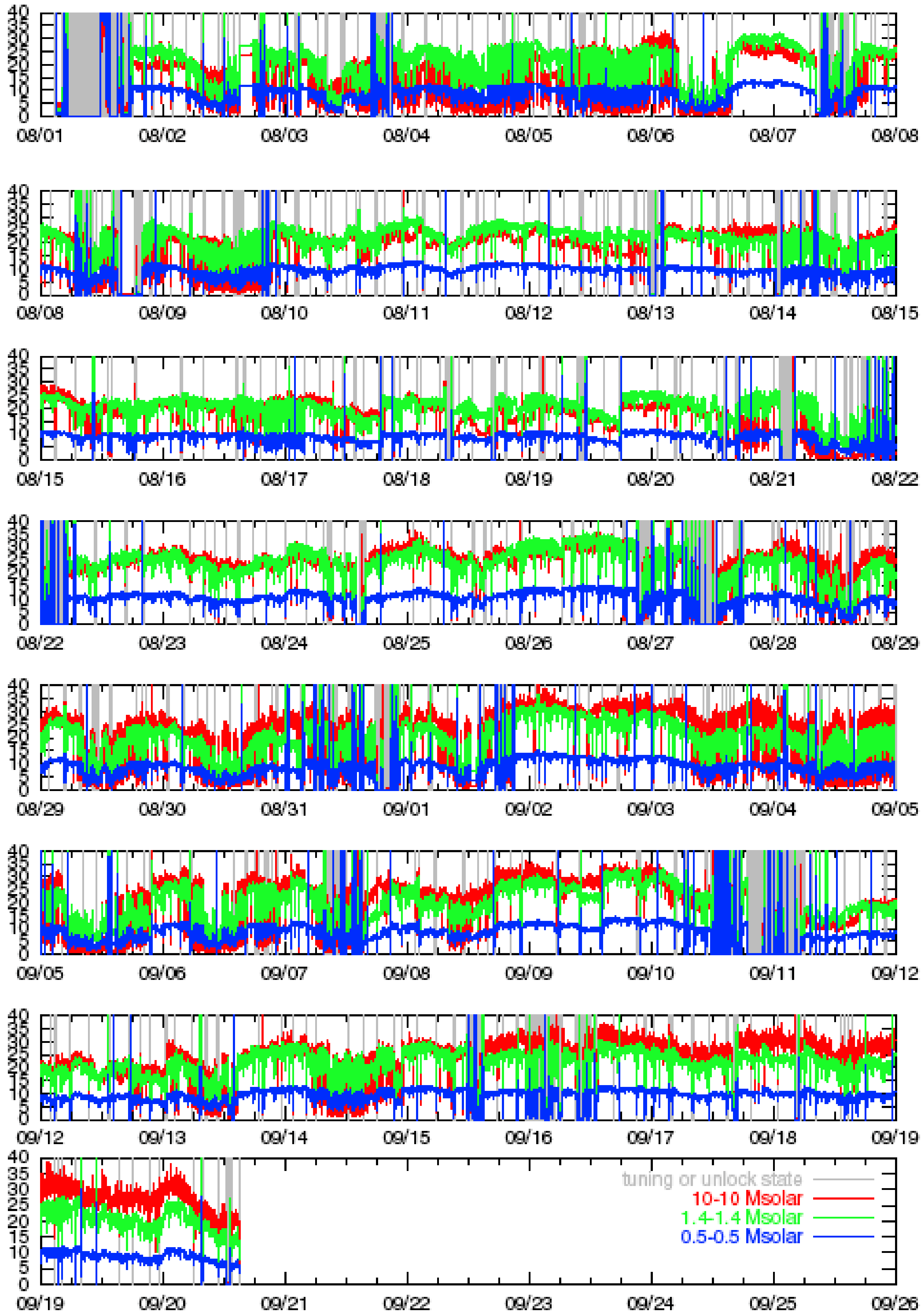
[/√Hz]



date

Observable Range History of dt6

[kpc]



date

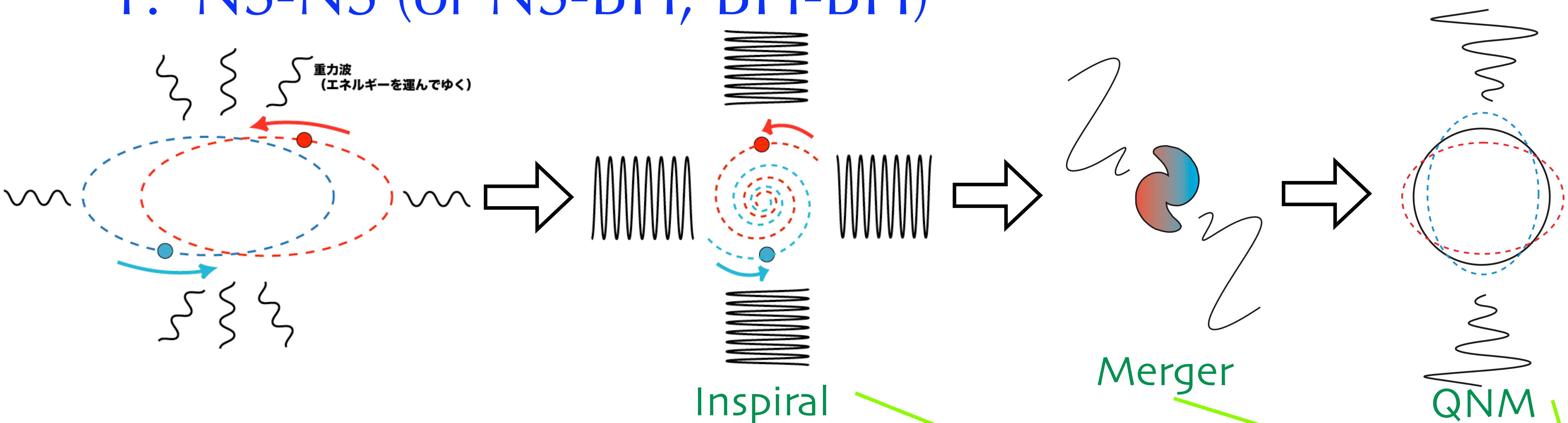
4. GW Event Search in TAMA300

Strategy

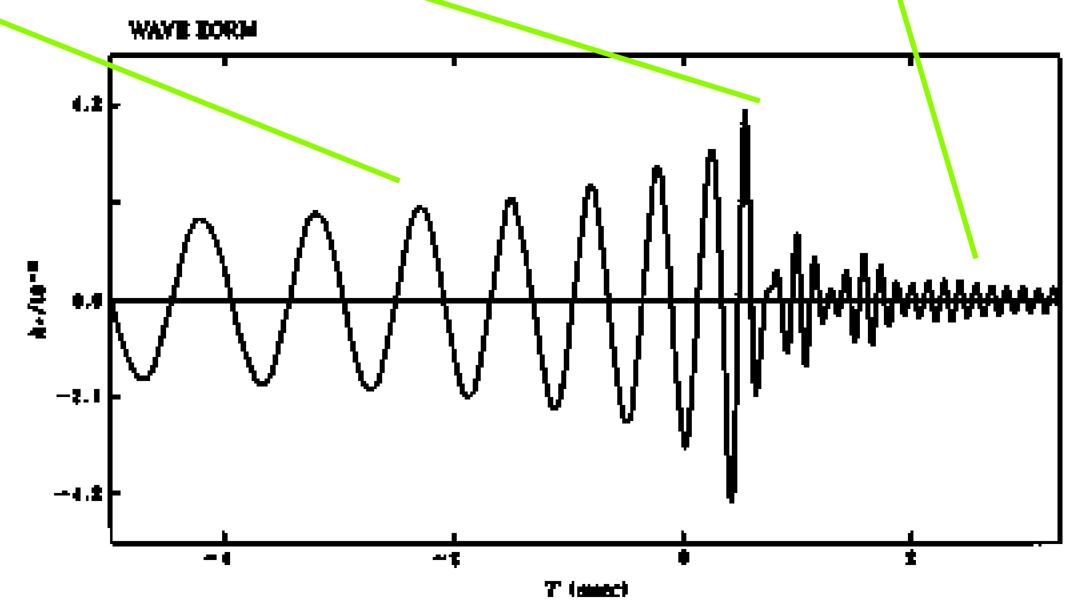
1. Compact Binary Coalescence
    - **Inspiral GW search**
    - Online implementation of inspiral GW search
    - ringdown GW from BH quasi-normal mode
2. Burst
    - Burst GW behavior
3. Continuous
    - SN1987a remnant pulsar

Coalescence of Compact Binaries

1. NS-NS (or NS-BH, BH-BH)



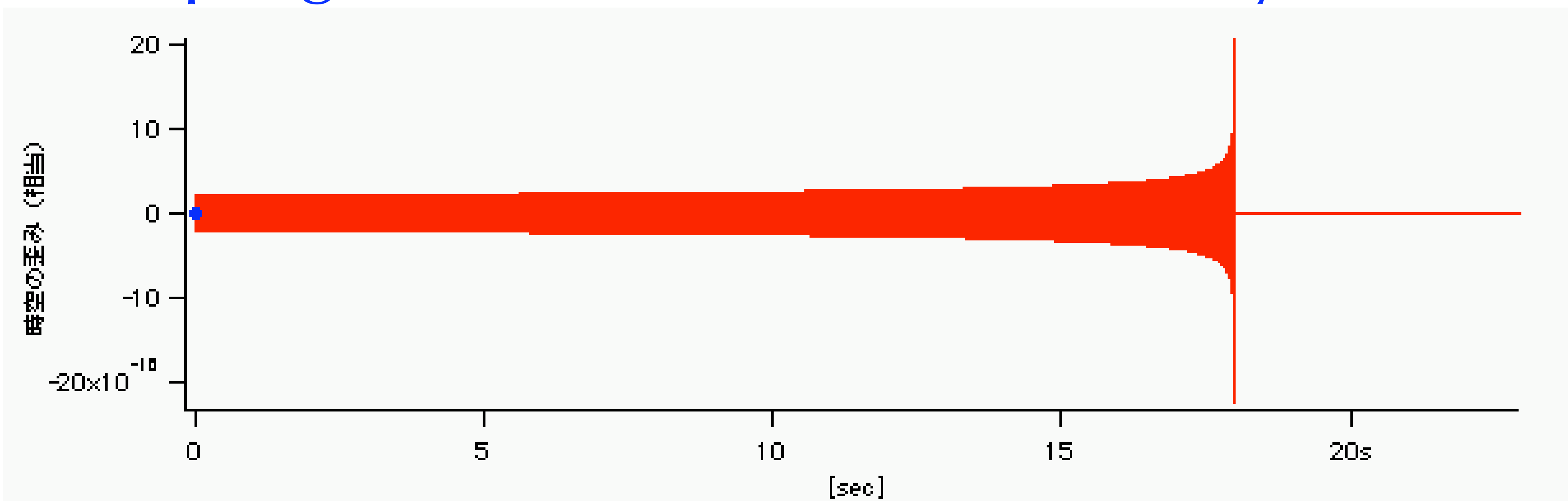
2. Expected Rate (Population)
   - 1 event/10^6yr/galaxy
3. Prediction of Waveform
   - 1. Inspiral
     - Post-Newton Approxmation
     - Parameters : mass of starts, arrival time, polarization
   - 2. Merger <- The analytical calculation is a hard. There are some numerical expectation
   - 3. BH quasi-normal mode
     - Perturbation
     - Parameters : mass, Kerr parameter



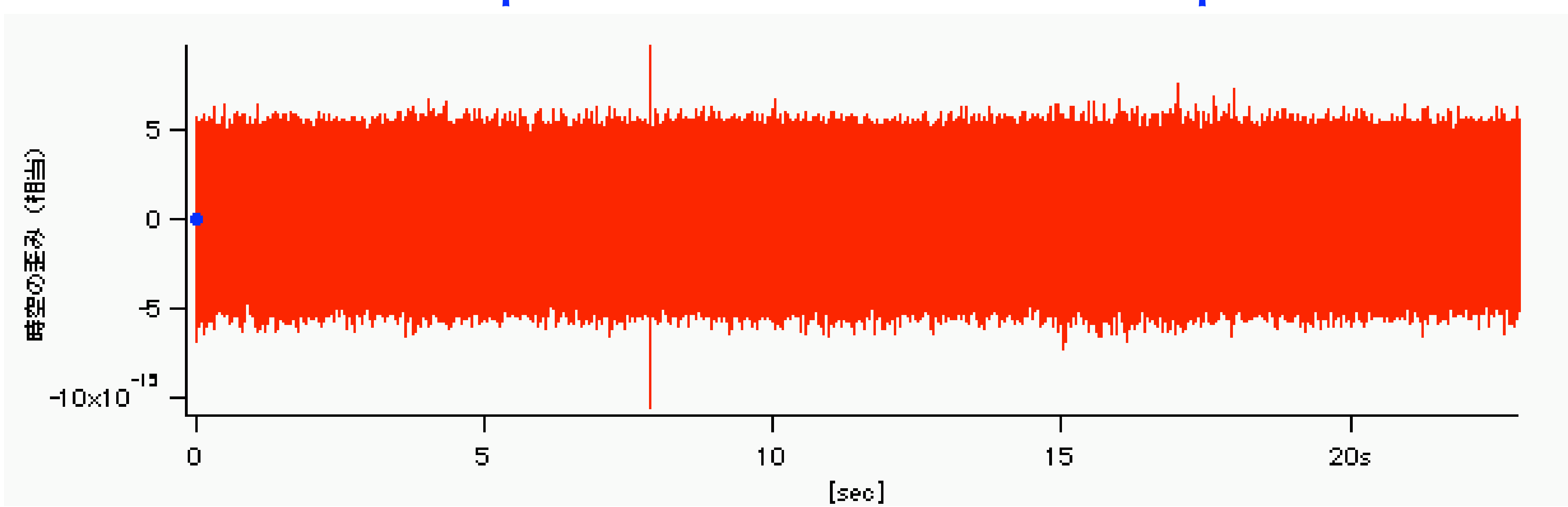
Nakamura, Ohara (1990)

demonstration: Is it hard to hear the GW sound ?

Chirp signal (1.4-1.4 Msolar, Arbitrary)



Embeded chirp in TAMA noise (10 pc!)



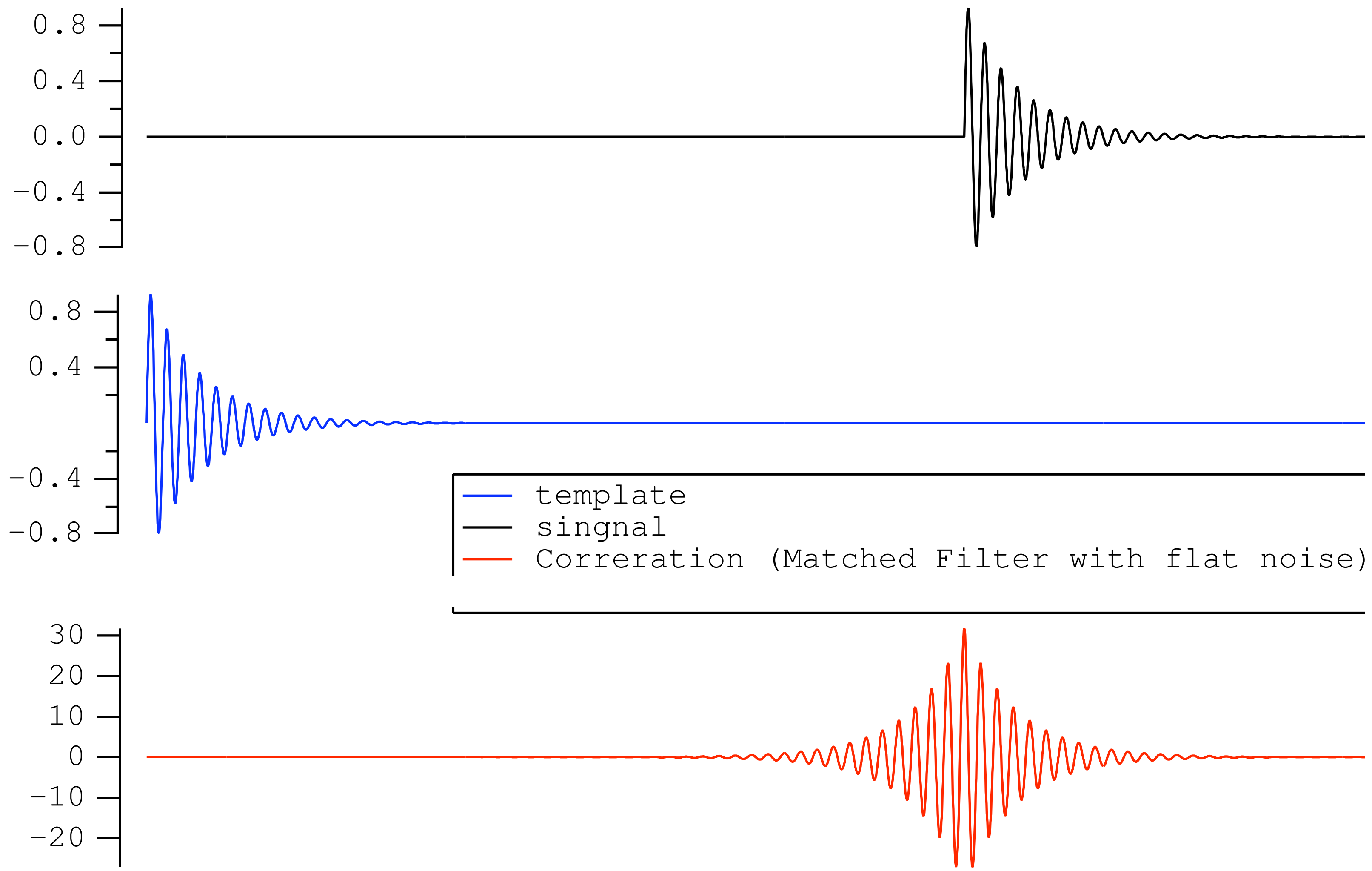
-> We need powerful tool for kpc sources !

Matched Filter (Wiener Optimal Filter)

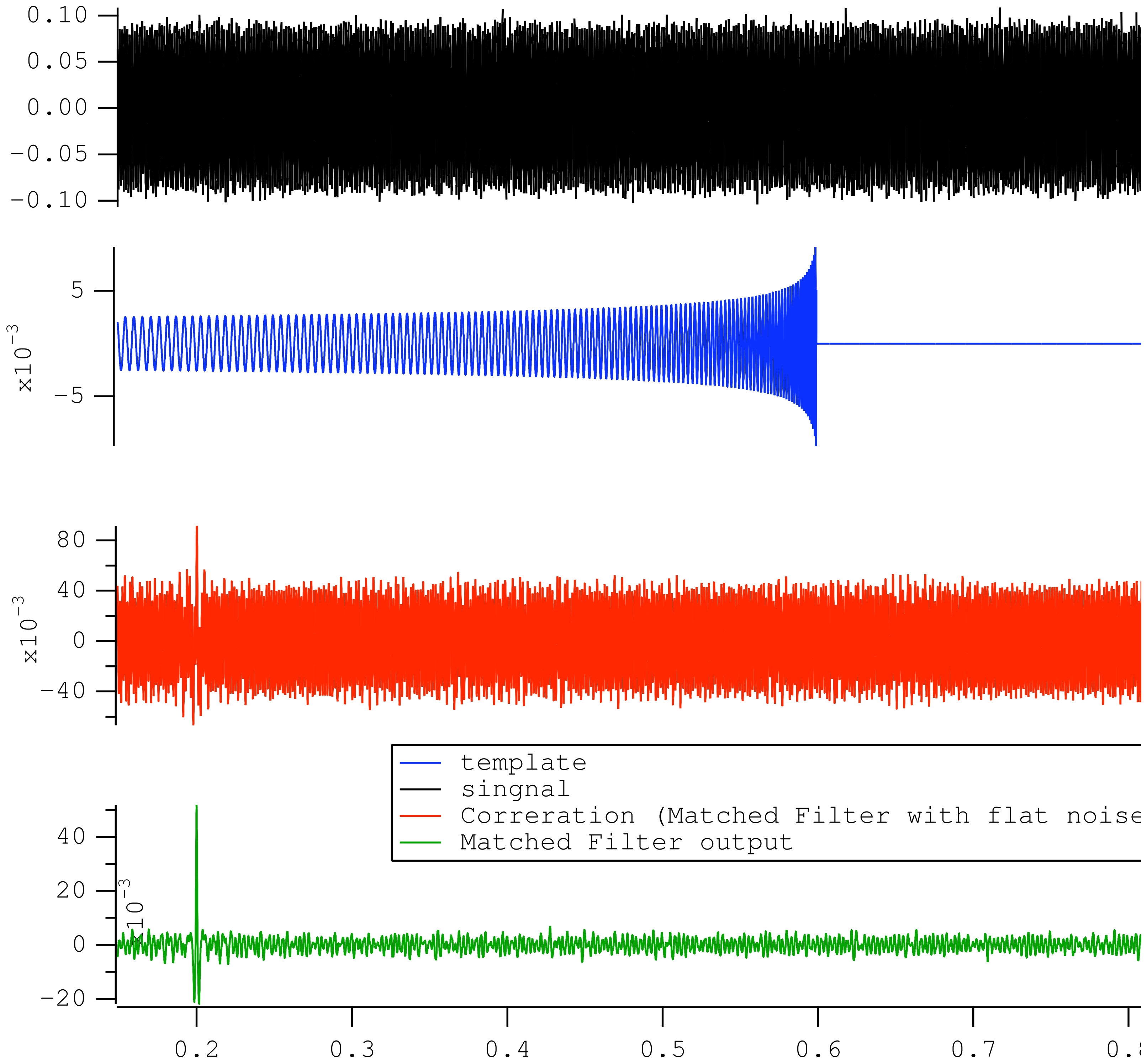
1. Known wave form
2. Known noise spectrum in Fourier domain
3. Linear system

- signal: $s(t) = n(t) + a\,h(t)$
- noise component : $n(t)$, GW signal: $a\,h(t)$
- average noise power spectrum: $S_h(f)$
- template waveform: $h(t)$
- signal-to-noise ratio: $\mathrm{SNR} = \rho/\sqrt{2}$

$$\rho(\tau;\mathrm{parameters}) = 2\int_{f_1}^{f_2} \frac{\tilde{h}^*(f)\cdot\tilde{s}(f)}{S_h(f)} e^{-i2\pi f\tau}\,df$$



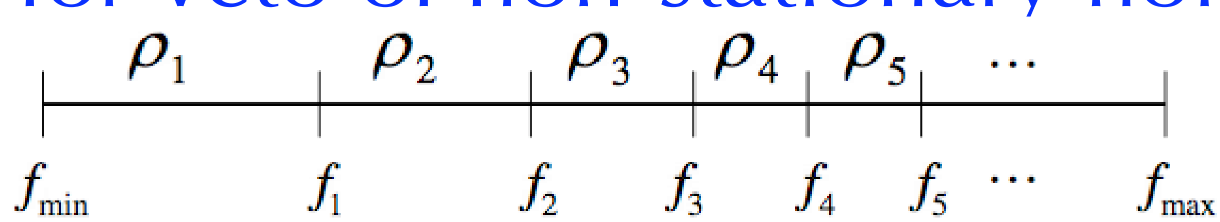
Simulation example of matched filter: QNM ringdown



simulation example
(TAMA real data + embedded inspiral signal)

Inspiral GW

1. SNR with Matched Filter
2. Search mass region
   - DT2: 0.3 - 10 M_{solar} (Hierarchic Search)
   - DT6: 1 - 2 M_{solar}
   - DT8: 1 - 3 M_{solar}
3. χ^2 test for veto of non-stationary noises



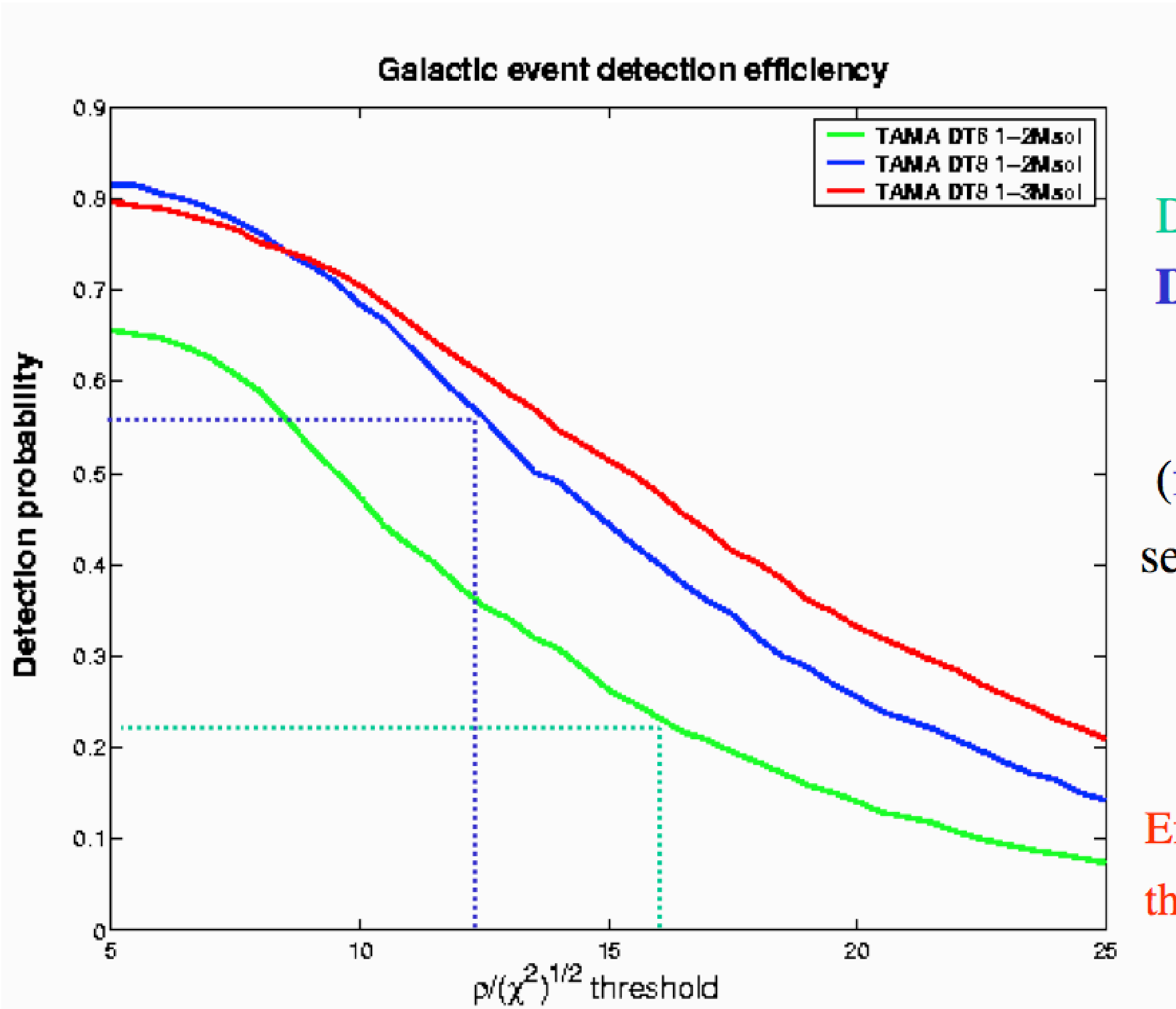
$$\chi^2 \equiv n \sum (\rho_i - \bar{\rho}_i)^2$$

$$, \bar{\rho}_i = \langle \rho_i \rangle$$

$$\hat{\chi}^2 = \chi^2 / (2n-2)$$

Galactic event detection efficiency

To estimate detection efficiency, we perform **Galactic event simulation**



	Threshold	efficiency
DT6	16	0.23
DT8	**12**	**0.58**

⇩

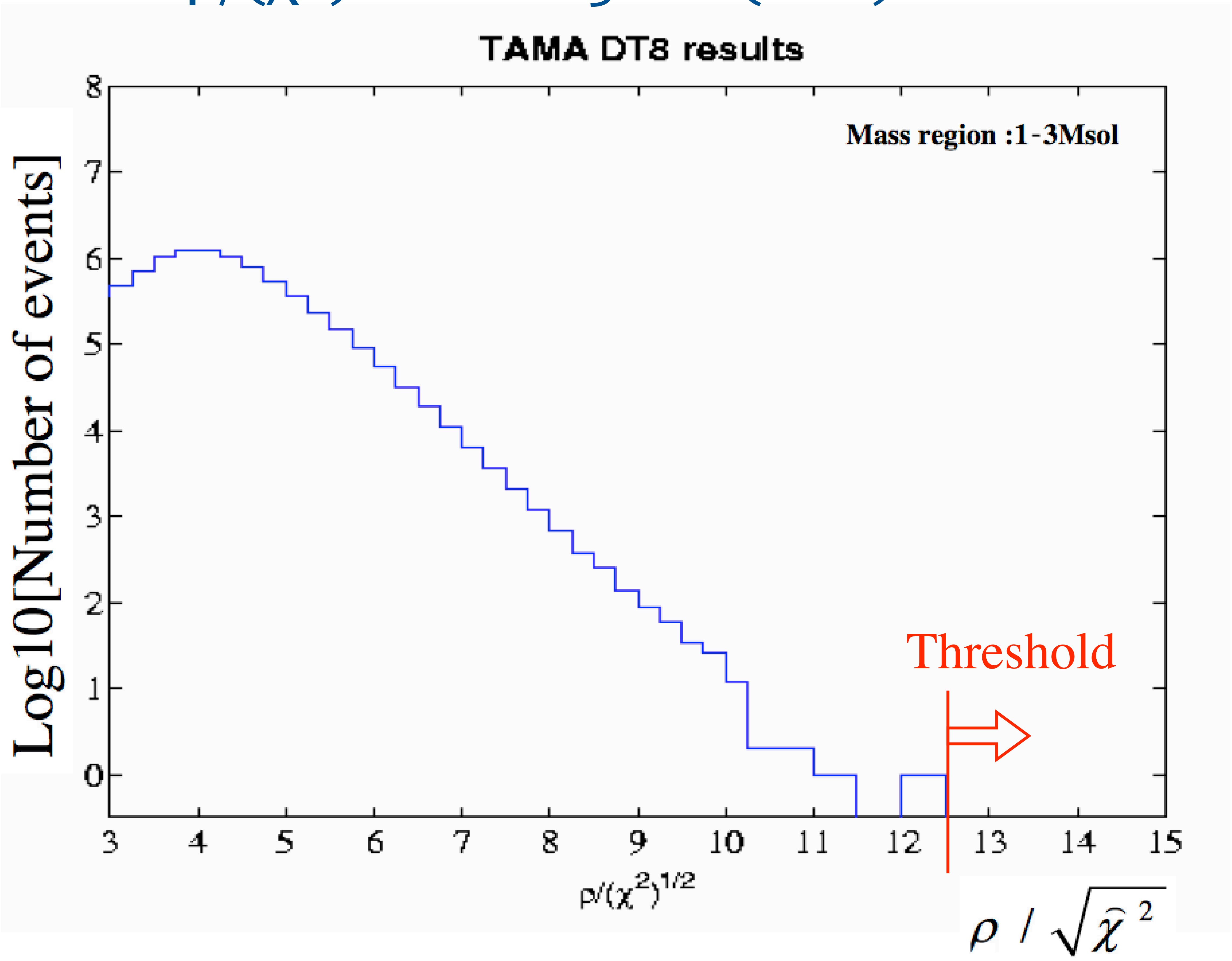
(fake event rate = 0.8 / year)

search mass region:

$$1.0M_{solar} \le m_1, m_2 \le 2.0M_{solar}$$

Efficiency of DT8 becomes three times better than that of DT6

$\rho/(\chi^2)^{1/2}$histrogram (DT8)



Upper Limit

In case for DT8;

1. Search Mass Region : 1 - 3 M_{solar}
2. Threshold = 12.5
   - (S/N ~ 9)
   - Fake event rate ~ 0.8 event/yr
   - Efficiency for Galactic Event : 61%
3. Observed event candidates : N_{obs} =0
4. Expected Background contamination : N_{BG} =0.1
5. Poisson statistics: N=2.3 (C.L.=90%)

$$\mathrm{DT8}: \frac{N}{Te} = 3.3 \times 10^{-3}[\mathrm{event/hour}](\mathrm{C.L.} = 90\%)$$

Upper limit (Summary)

1. DT2
   - Range (SNR=10): 3.4 kpc
   - Mass region: 0.3 - 10 M_{solar} , Upper limit: 0.59 event/hour (C.L.90%)
2. DT4
   - Range (SNR=10): 17.9 kpc
   - Mass region: 1-2 M_{solar} ,Upper limit: 0.027 event/hour (C.L.90%)
3. DT6
   - Range (SNR=10): 33.1 kpc
   - Mass region: 1-2 M_{solar} ,Upper limit: 0.0095 event/hour (C.L.90%)
4. DT8
   - Range (SNR=10): 42.2 kpc
   - Mass region: 1-2 M_{solar} ,Upper limit: 0.0056 event/hour (C.L.90%)
   - 1-3 M_{solar} ,Upper limit: 0.0033 event/hour (C.L.90%)

Ringdown

1. BH formation (by compact binary, etc.)
   - -> quasi-normal mode GW
     - dumped sinusoidal waveform “ringdown”
     - mass and Kerr parameter determine the waveform

$$h(t) = Ae^{-\pi \frac{f_c t}{Q}} \sin(2\pi f_c t)$$

$$f_c t \sim \frac{3.2 \times 10^4}{M}[1 - 0.63(1-a)^{0.3}][\mathrm{Hz}]$$

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

Ringdown

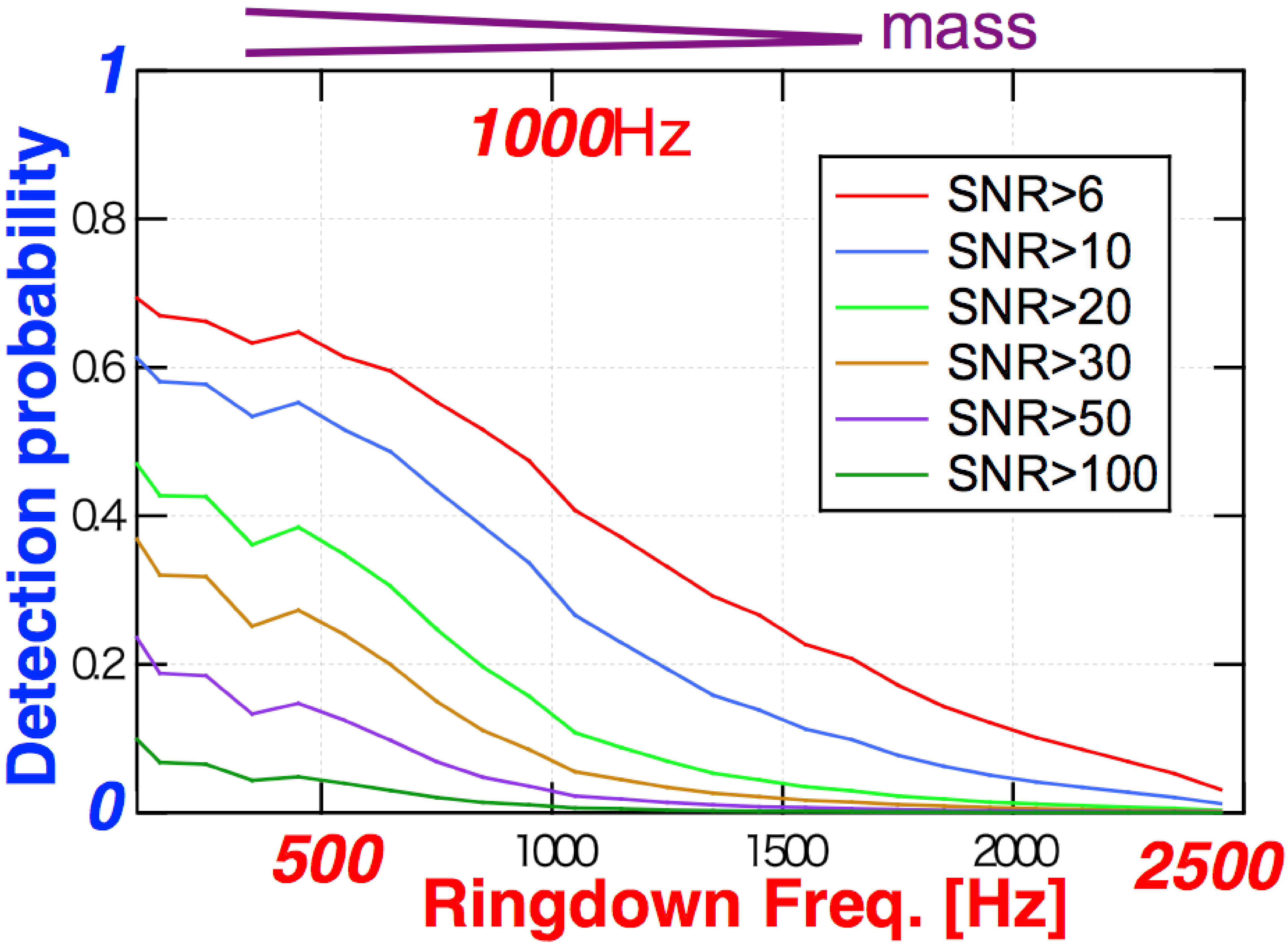
1. Templates
   - Optimized by Nakano et al. (gr-qc/0306082, submitted to PRD.)
   - Implementation on TAMA data with minimal match 98%
   - # of template ~800
2. Efficiency for Galactic Event by MC simulation
   - Monte-Carlo simulation with Galactic distribution
   - Eff ~ 60%

$$dN = e^{-\frac{R^2}{2R_0^2}} e^{-\frac{z}{h}} R \, dRdz$$

$$R_0 = 4.8[kpc], h = 1[kpc]$$

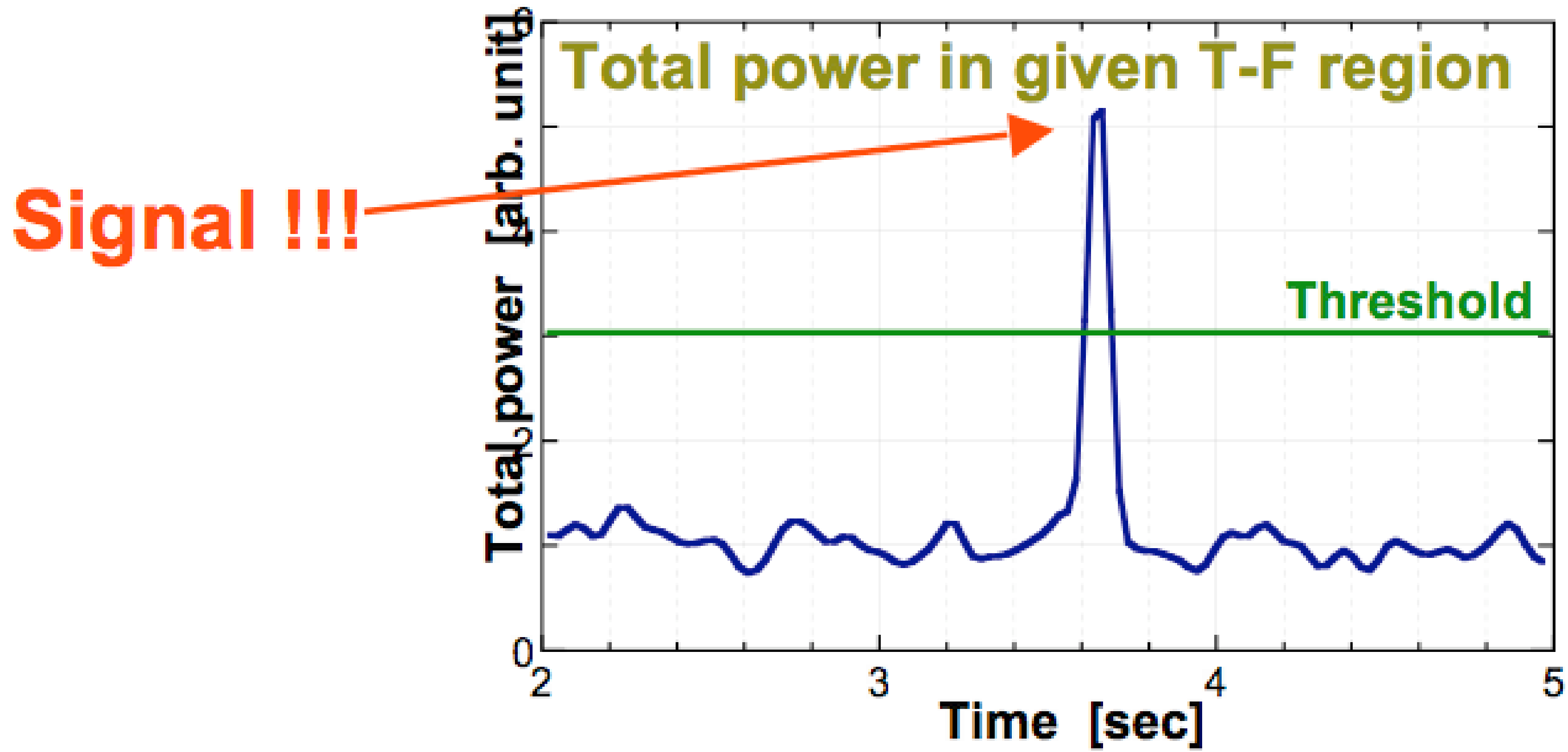
3. More powerful veto logic is required to exclude the fake event due to non-stationary noises.
4. Search is on going...

Efficiency for galactic event of QNM ringdown (MC simulation)



Burst

1. Excess Power Filter



2. Non-Gaussian noise Rejection (c1-c2)
   - rejection of non-gauss excess ~1/30
   - Integrated sensitivity: h_{rms} ~ 3 x 10^{-17} for 1 msec spike

Summary

1. TAMA progressed steadily, and established "observatory" key issues.
   - long&continuous operation (two months, with 80% duty time)
2. Data Calibration is well done.
   - Accuracy: Δh/h ~ 1%
3. Noise charaterestics are traced in real time for long operation.
4. Event Search
   - Inspiral GW from Compact Binary
     - Upper limit for Galactic Event $\mathrm{DT8}: \frac{N}{Te} = 3.3 \times 10^{-3} [\mathrm{event/hour}] (\mathrm{C.L.} = 90\%)$
     - DT8 (2003) result is two times better than DT6(2001)'s.
   - Quasi-Normal Ringdown
     - Matched Filter with an efficient template design
     - Eff. ~ 60% for Galactic event (assuming merger forms BH)
   - Burst
     - Excess power filter & Spectrogram filter
     - Non-Gaussian noise rejected by time-scale selection
   - Continuous
     - Upper limit for SN1987a remnant $h \sim 5 \times 10^{-23} (\mathrm{C.L.} = 99\%)$

Now, the interferometric detectors growing as a r observatory.