Status of TAMA

National Astronomical Observatory
of
Japan

Koji Arai (TAMA project)

Overview of this talk

- ***Introduction***

  Laser interferometric gravitational-wave detector

  Worldwide status

- ***TAMA300 detector***

  Overview of the detector

  Activity1: 1000hours observation (2001/8-9)
  Activity2: Recycling experiment (2001/12~)

- ***Analysis of TAMA300 data***

  Inspiral search, burst search, and pulsar search

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Gravitational wave detection (1)

- ***Direct detection of GW***

  Binary pulsar observation

  ⇨ *Indirect proof of GWs*

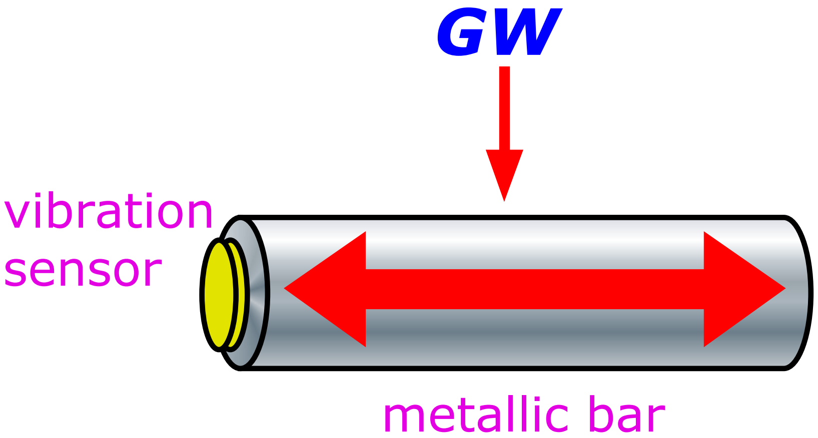
  Direct observation of GWs

  ⇨ *Confirmation of General Relativity in a strong gravitational field*

  ⇨ *Information of astrophysical objects which is different from that with EM observation*

Gravitational wave detection (2)

- **Resonant mass detector**

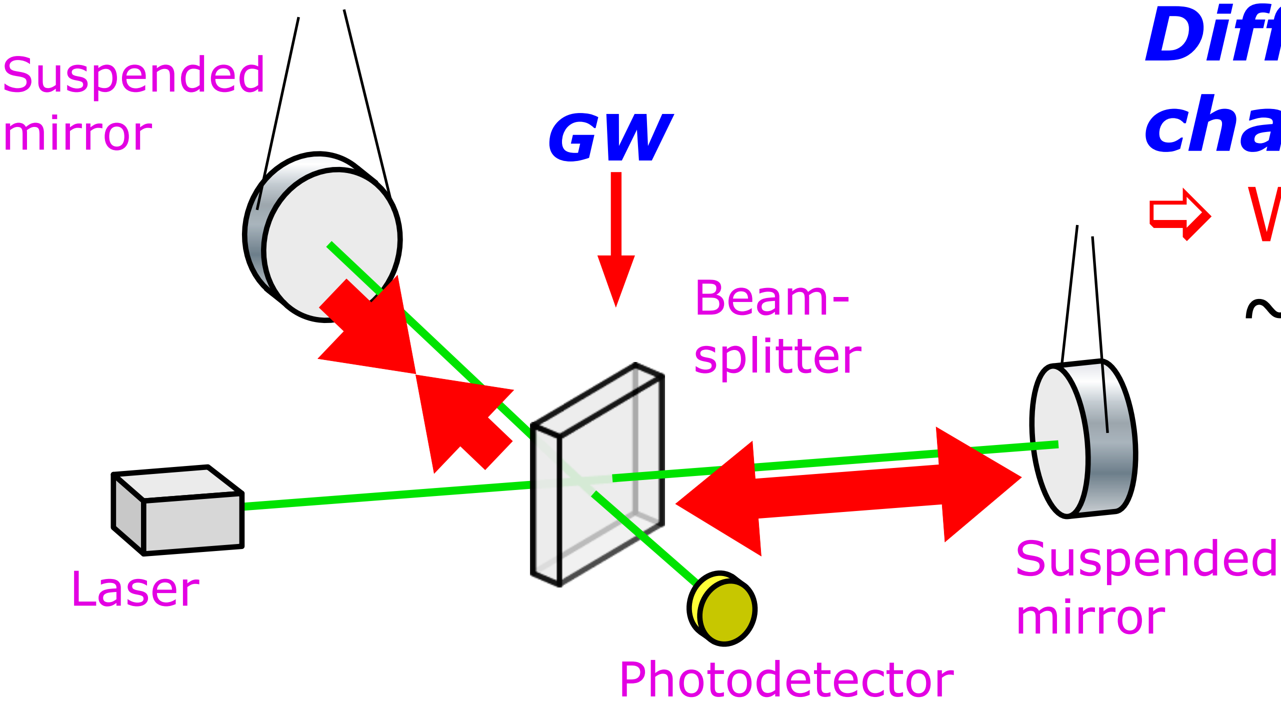


Excitation of quadrupole modes of the bar

⇨ Narrow-band detection

~ only at the resonant frequency

- **Interferometric detector**



Differential pathlength change of two arms

⇨ Wide-band detection

~ waveform is preserved

Interferometric GW detector throughout the world

- ***4 projects, 6 large-scale interferometers***

VIRGO
(Italy & France)

Site: Pisa
L=3km

GEO
Germany & Great Britain

Site: Hannover
L=600m

TAMA
Japan

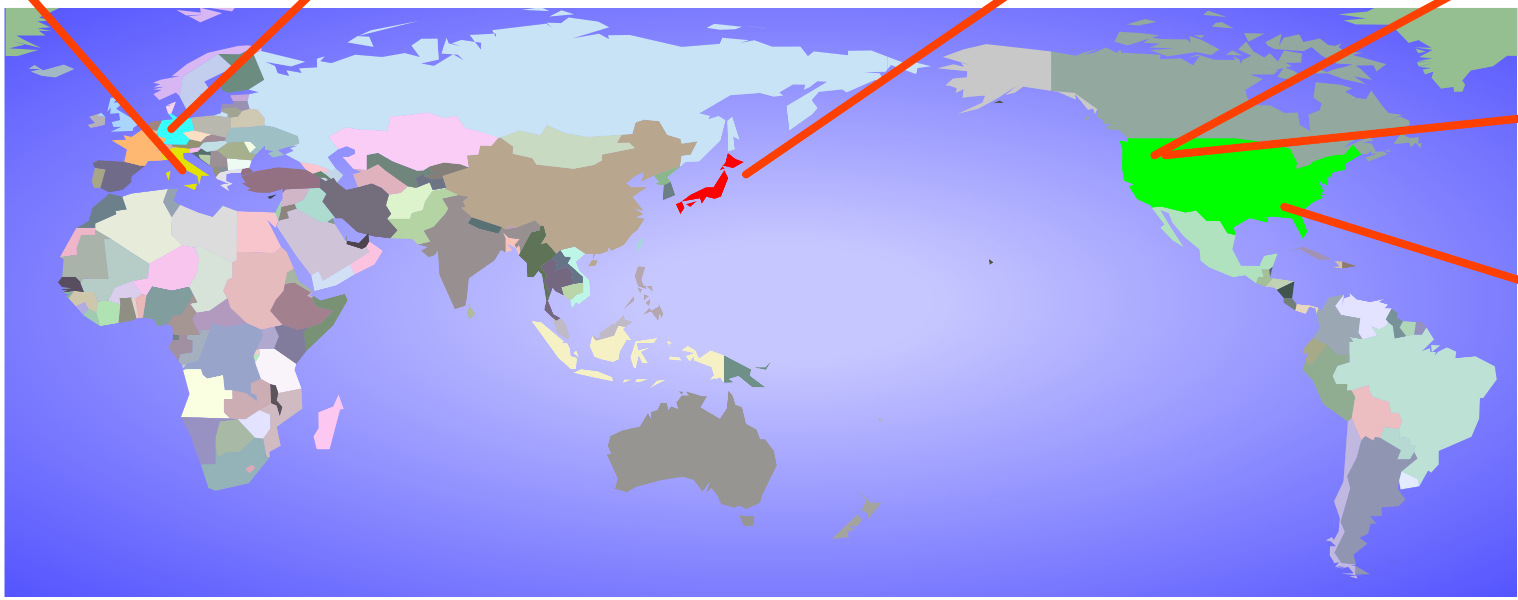
Site: Tokyo
L=300m

LIGO
U.S.A.

Site:
Hanford 1
L=2km

Hanford 2
L=4km

Louisiana
L=4km



LIGO

First light 1999
Improving the sensitivity
and the stability
8 engineering runs
Run into Scientific runs from 2002

GEO

Engneering and Science runs from 2002
Changing the optical configuration (Signal Recycling)

VIRGO

5 engneering runs
End commissioning of CITF (Short interferometer),
Arm construction finished
Move to Full 3k IFO

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TAMA300

- ***Laser interferometric GW detector***
  □ □ □ □ □ □ □ □ □ □ □ with arm length of 300m

  Site: National Astronomical Observatory of Japan,
  □ □ (Mitaka, Tokyo)

- ***Object of the project***

  To develop a detector capable to detect GW events
  □ □ □ □ □ □ □ □ □ □ □ □ □ □ in nearby galaxies.
  To establish techniques for a future km-class interferometer

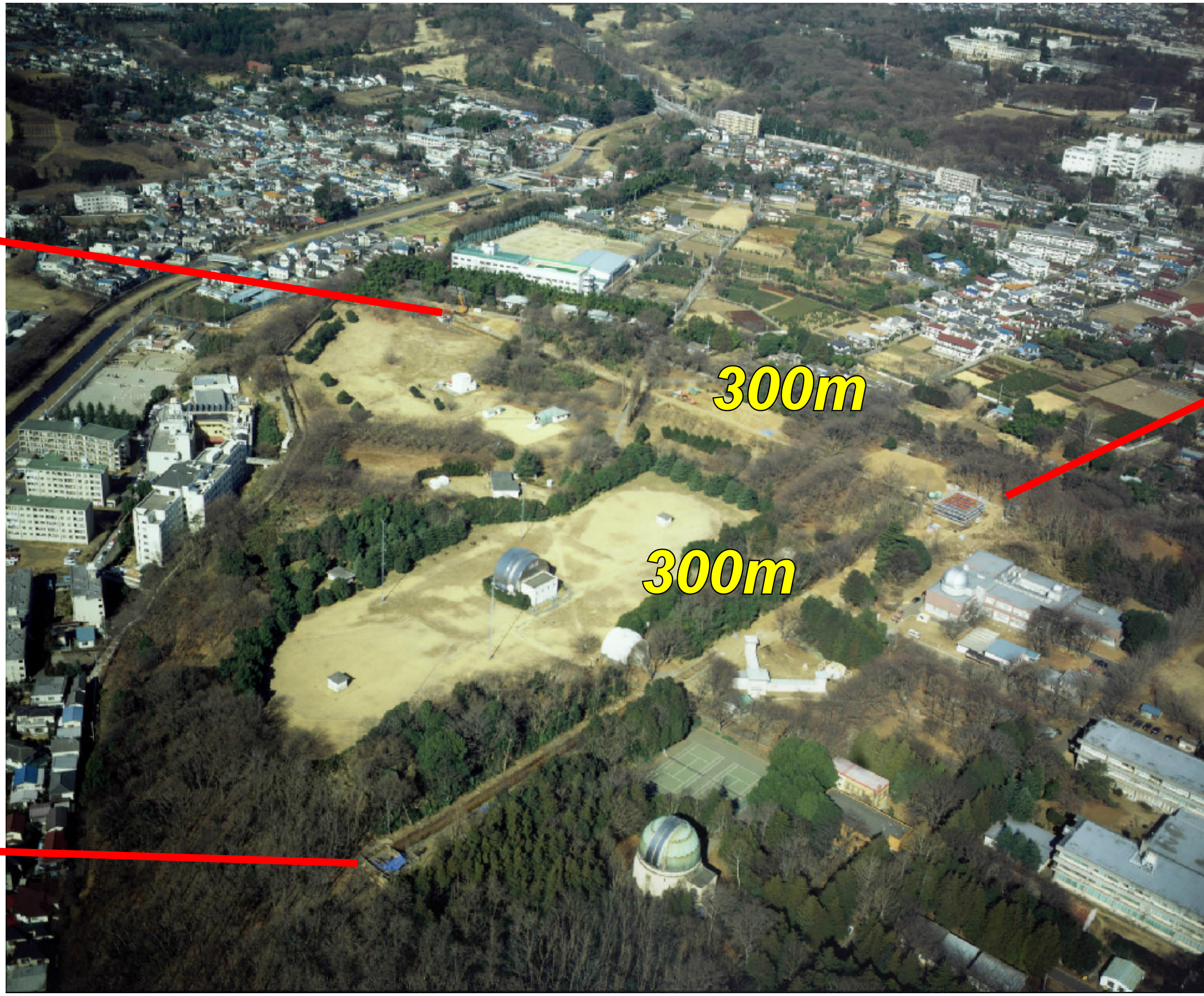
Designed sensitivity ~ $h_{RMS} = 3 \times 10^{-21}$ @300Hz (BW300Hz)

Bird's view of the TAMA site

- **National Astronomical Observatory of Japan**

Tokyo, Mitaka Campus (E139.32.21 N35.40.25)

West End Room

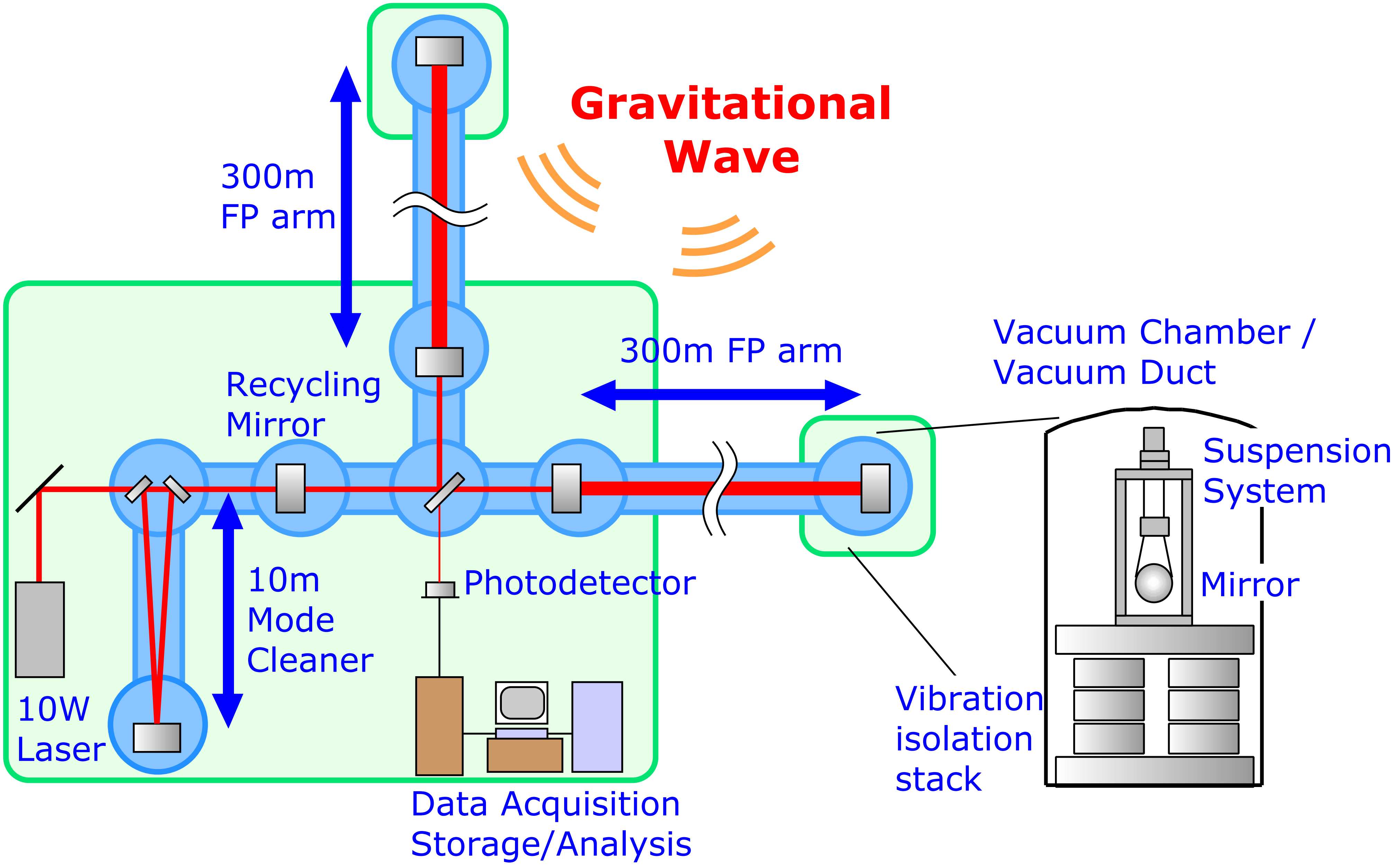


Center Room

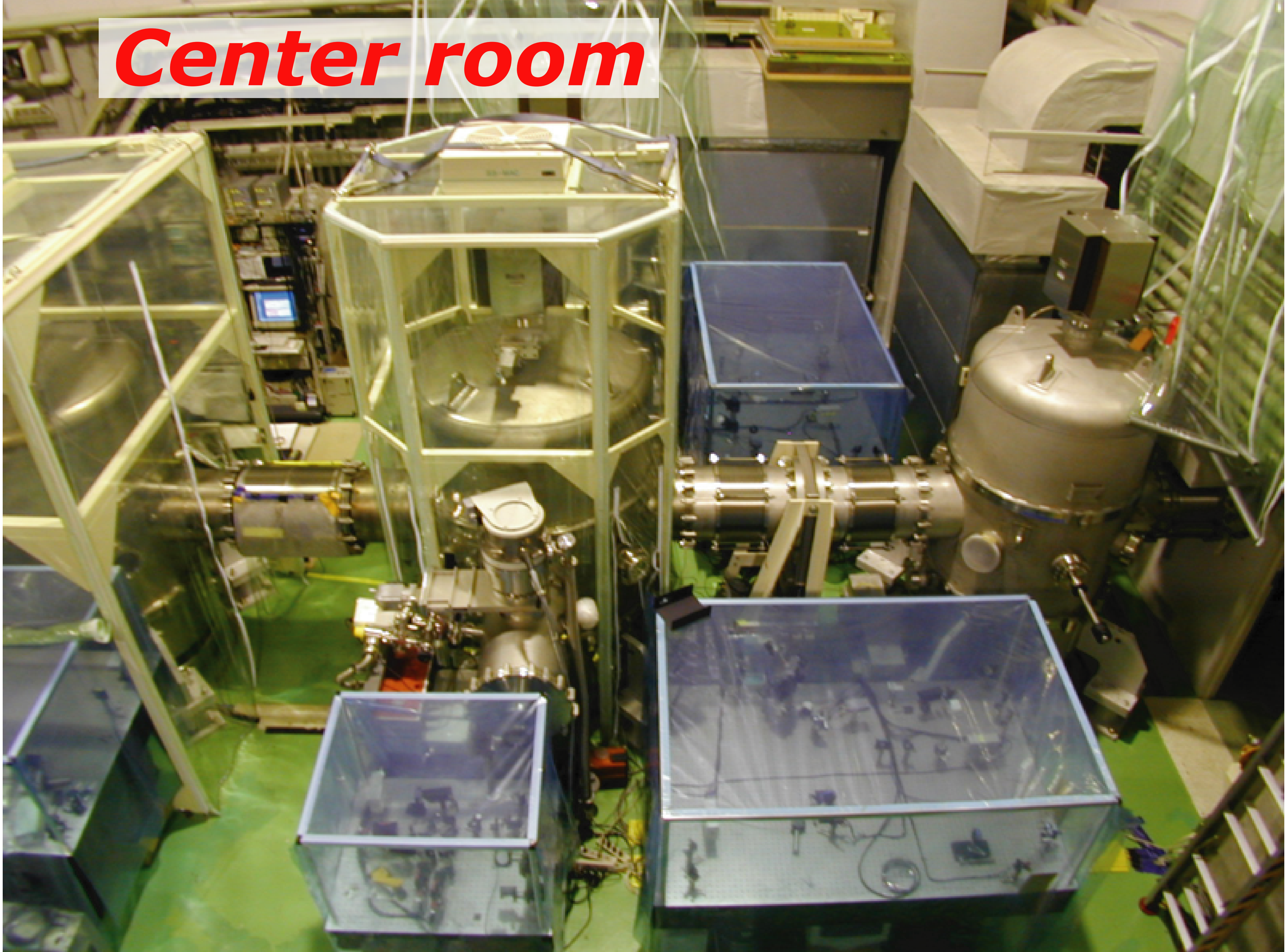
South End Room

Middle of a city area ~ heavy traffic

TAMA300 detector ~ overview

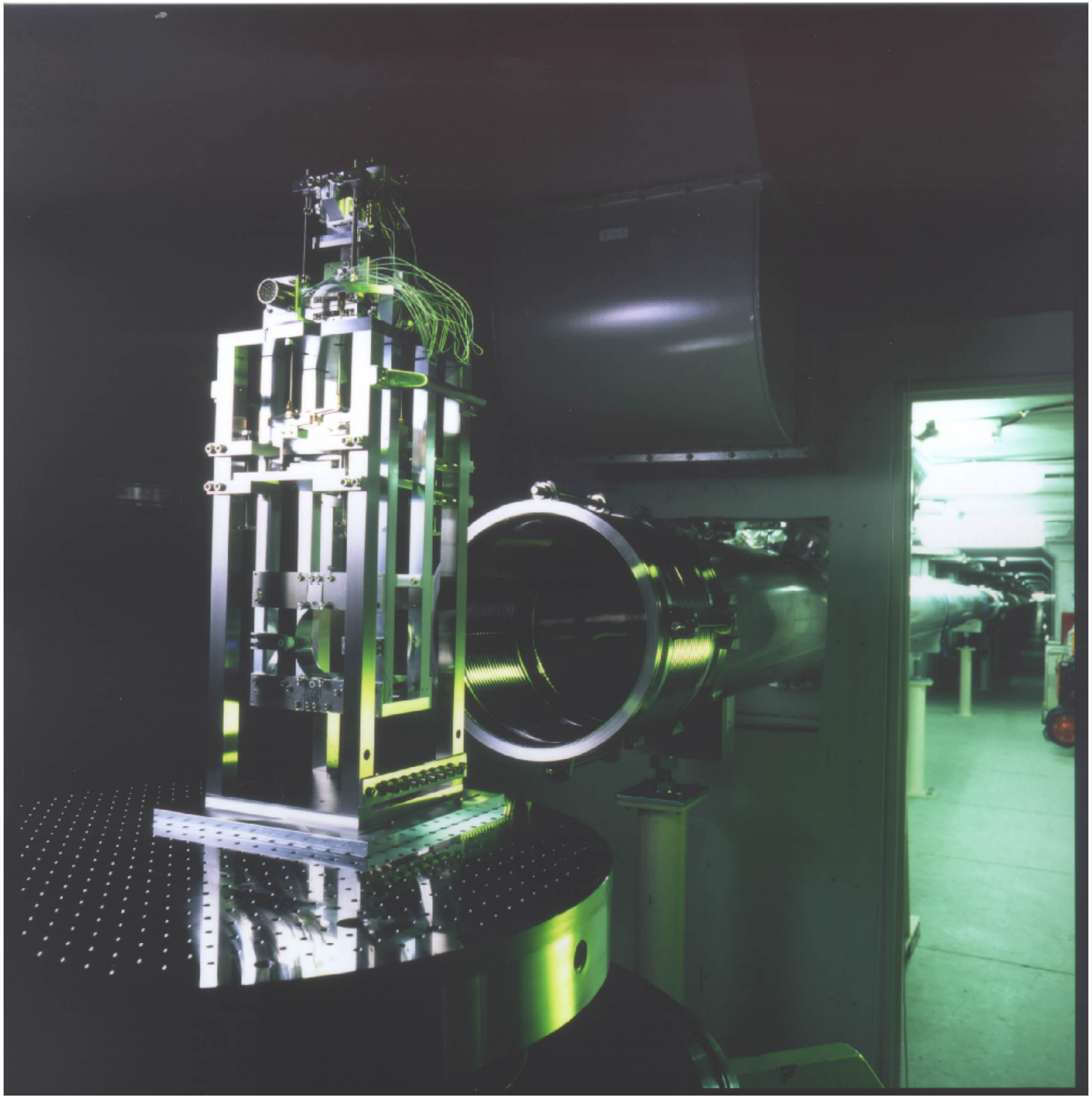


Center room



300m vacuum tube

Vibration Isolation System



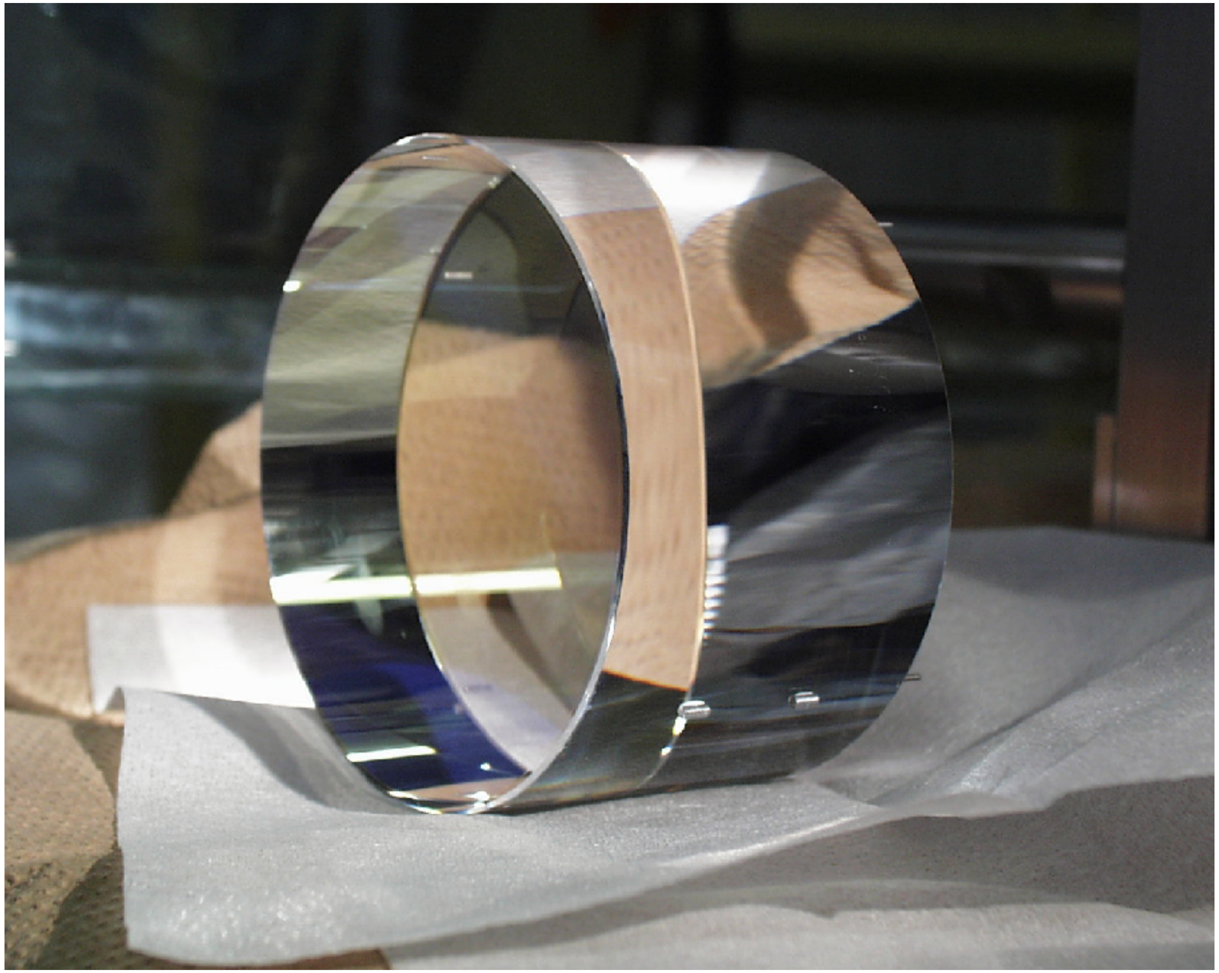
- **3 layer system**

Actively-controlled
air spring
+
Stack
(Sandwitches of rubbers
and metal blocks)
+
Double pendulum
suspension

Achieved performance
~ better than 10^{-8}
at 150Hz

Mirror

- **Fused silica (SiO_2) ϕ *100mm x 60mm***



High mechanical quality

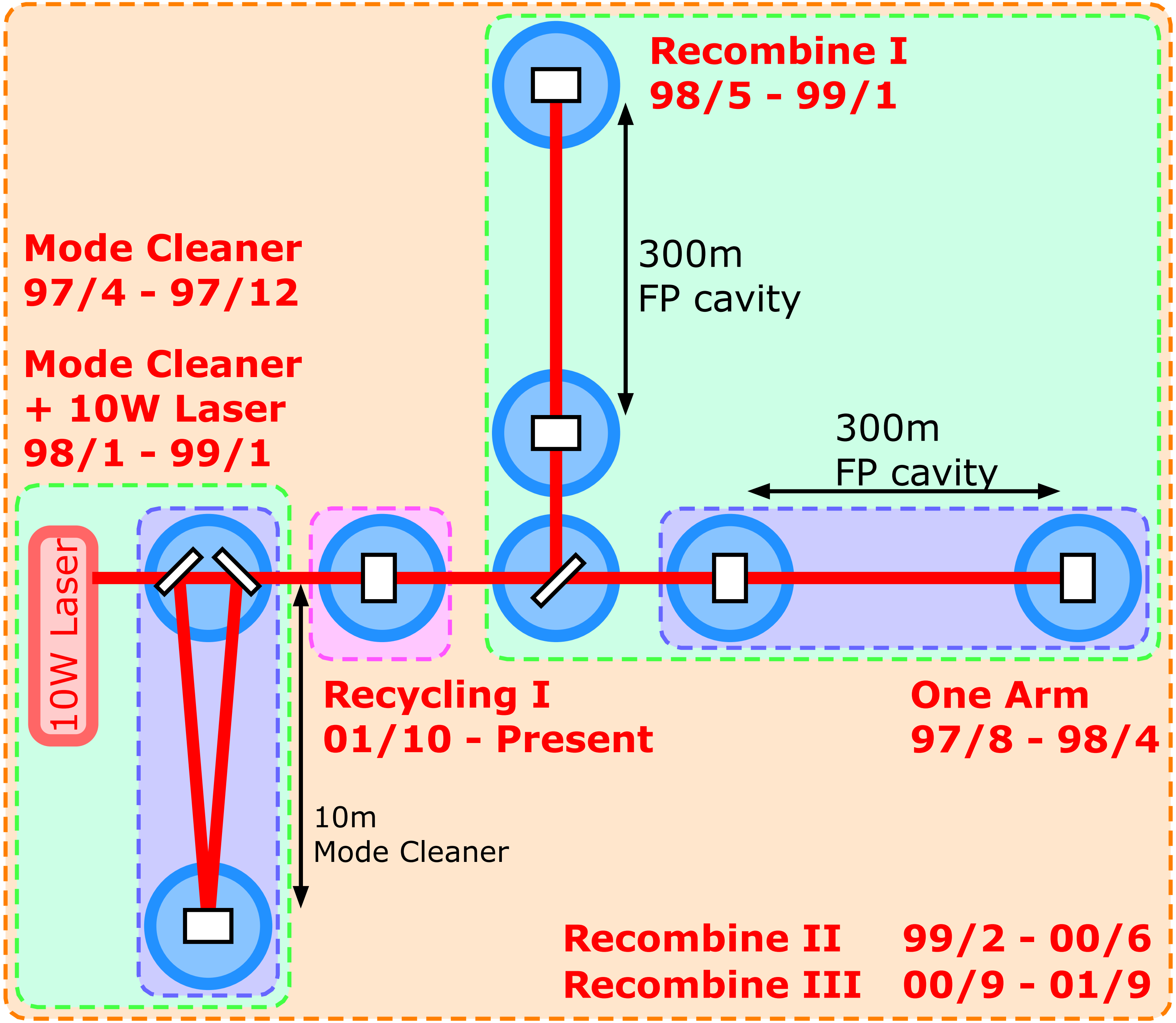
~ to suppress thermal vibration in the observation band

High optical quality

~ ultra low loss (~30ppm) in reflection.

Control electronics

History of TAMA development



1995	Project started	
1996	Facility construction completed	
1997	Vacuum system completed	
1999/8	Data Taking 1	11h
1999/9	Data Taking 2	31h
2000/4	Data Taking 3	13h
2000/8, 9	Data Taking 4	167h
2001/3	Data Taking 5	111h
2001/8,9	Data Taking 6	1038h
2001/10-	Recycling experiment	
2002/8-9	Data Taking 7	25h

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Past data taking (DT) runs

[Without power reycycling]

DT1	1999 Aug. 6-7	1 night	11 hours
DT2	1999 Sep. 17~20	3 nights	31 hours
DT3	2000 Apr. 20~23	3 nights	13 hours
DT4	2000 Aug. 21~Sep. 4	13 nights	167 hours
DT5	2001 Mar. 2~8	6 days	111 hours
DT6	2001 Aug. 1~Sep. 20	50 days	1038 hours

[With power recycling]

DT7	2002 Aug, 31~Sep. 2	1 day	25 hours

Data runs have been held prior to the other projects.

Achievements on DT6

- **Sensitivity enough to detect Galactic GW events**

  Strain sensitivity: $h = 5 \times 10^{-21}$ /sqrtHz

  NS ispirals with SNR=10: 33kpc

- **Stable operation ~ high duty ratio**

  Total amount of observation data: 1038 h (86.5%)

  (adjustment period excluded)

- **Coincident run with Kamioka 20m prototype**

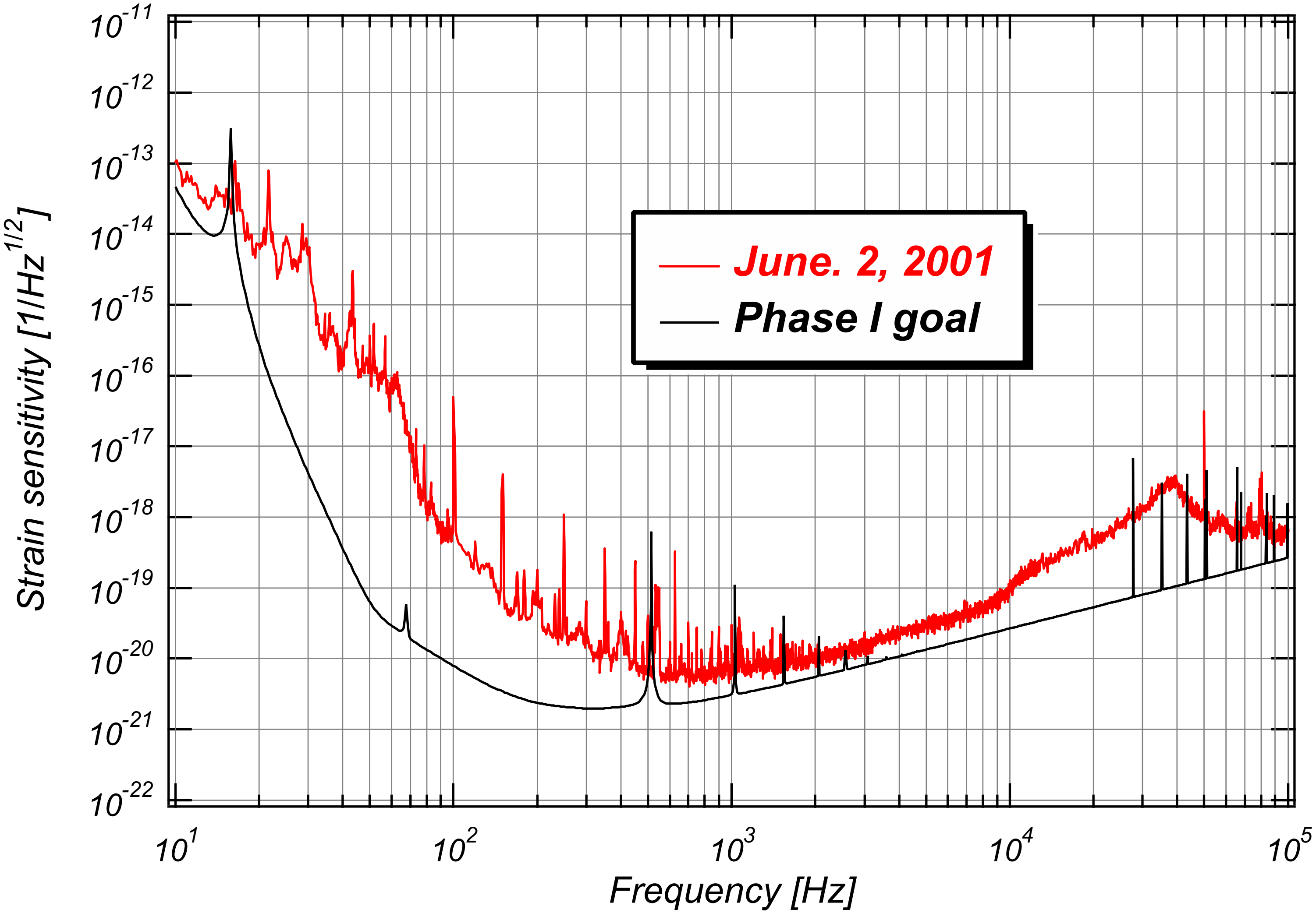
  Total amount of coincident operation: 709 h (59.1%)

Achieved sensitivity (at DT6)

- Displacement noise dx□= 1.5 x 10^{-18} m/$Hz^{1/2}$

Strain sensitivity□ □ h□= dx/300□ □ (@700Hz)

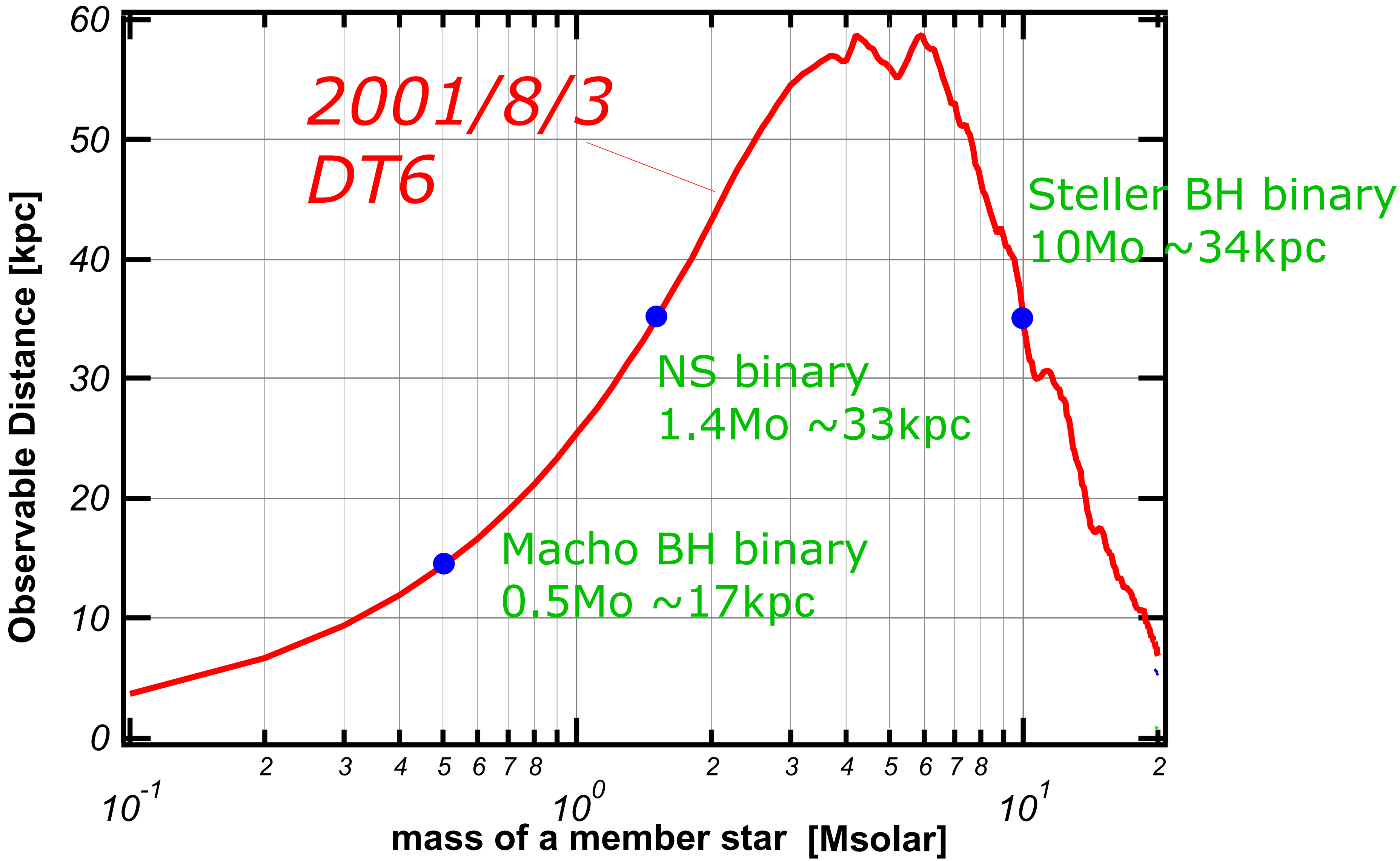
□ □ □ □ □ □ □ □ □ □= $5x10^{-21}$ /$Hz^{1/2}$



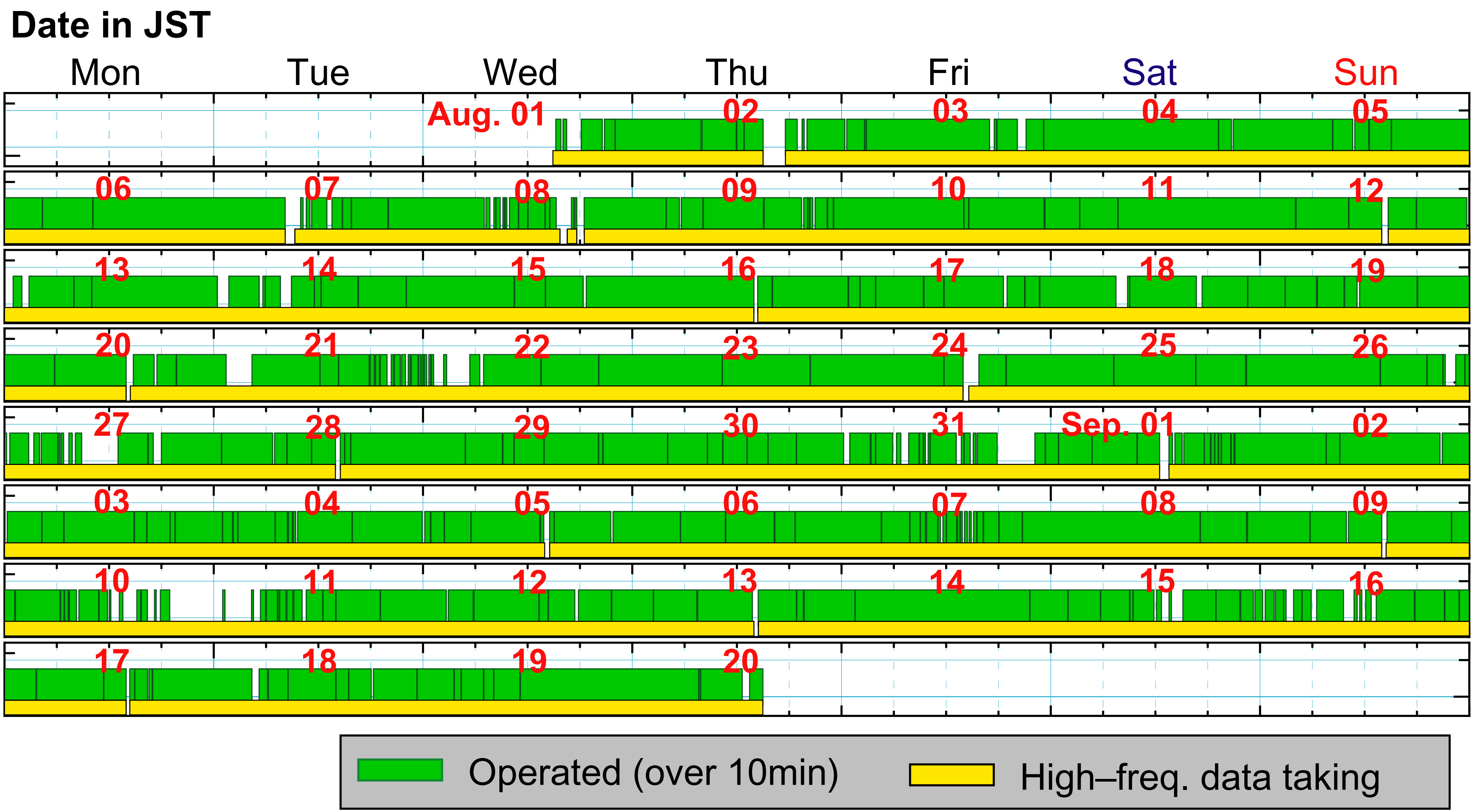
DT6: SNR to compact binaries

- Observable distance with SNR=10

□ □ □ □ using matched filtering



Observation calendar

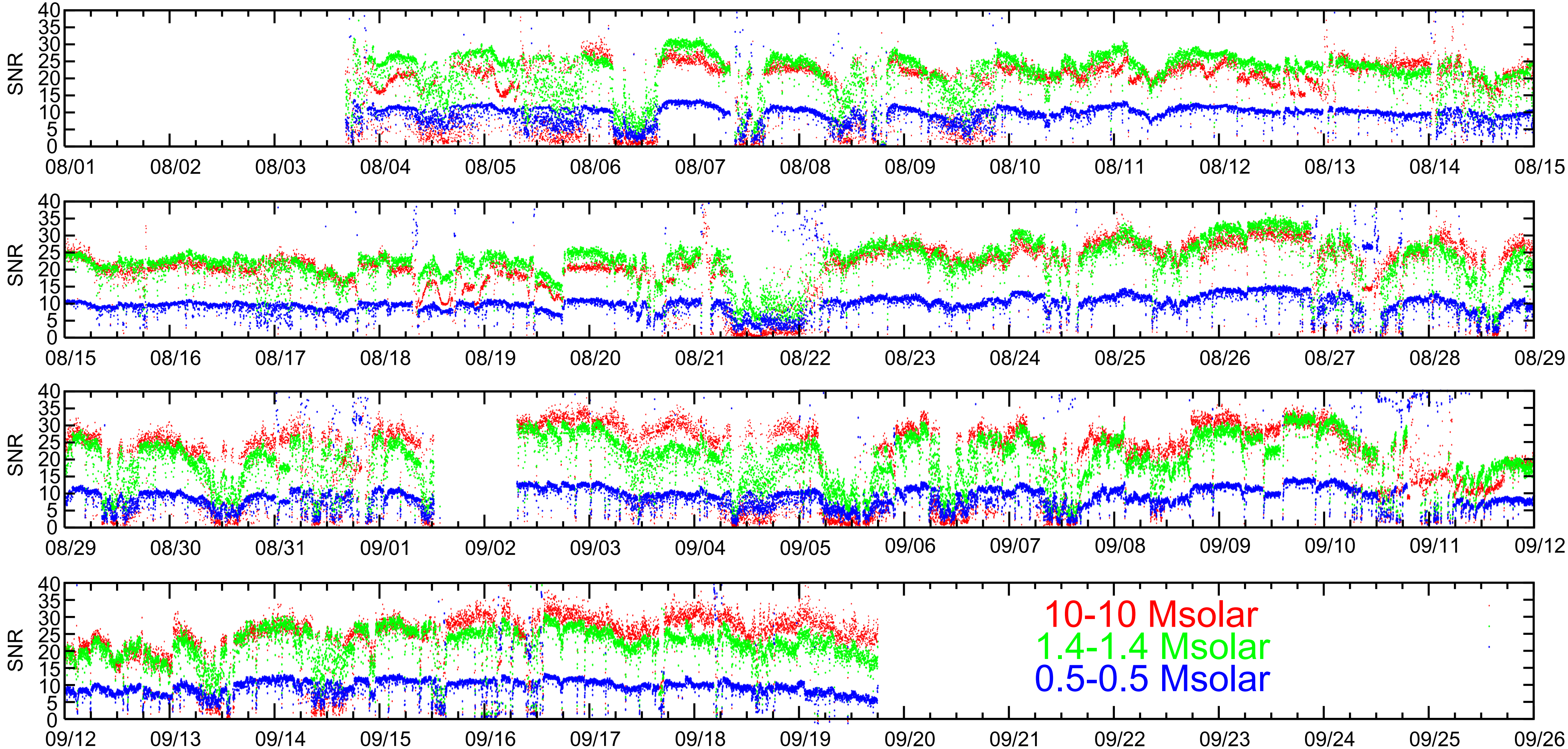


Causes of obs. time loss

Total obs. time: 1038:07:35, Duty cycle: 86.5105%

SNR trend during DT6

- About 80% is adequate to analyses



=> To data analysis

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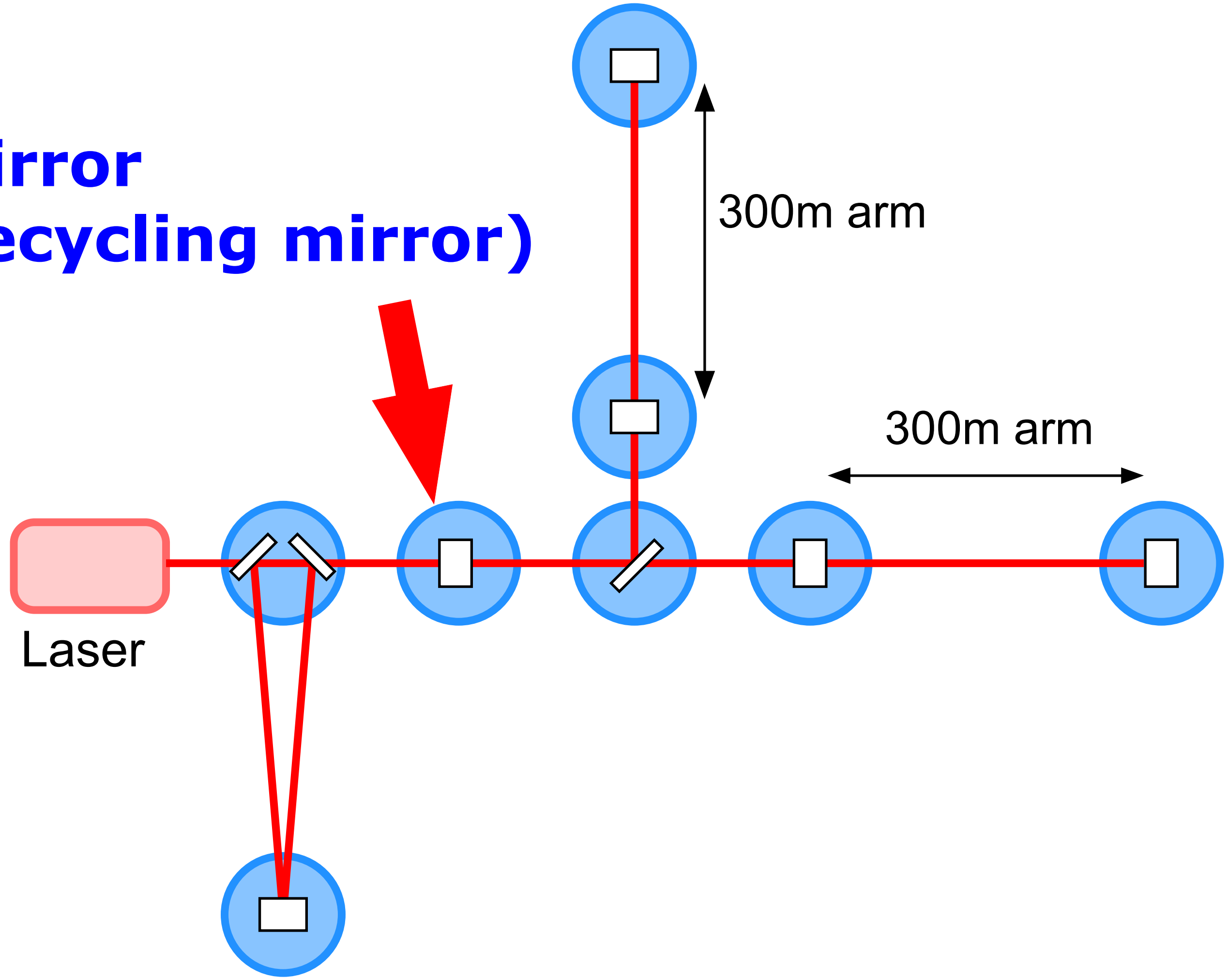
Power recycling

- **Enhancing light power in the interferometer**

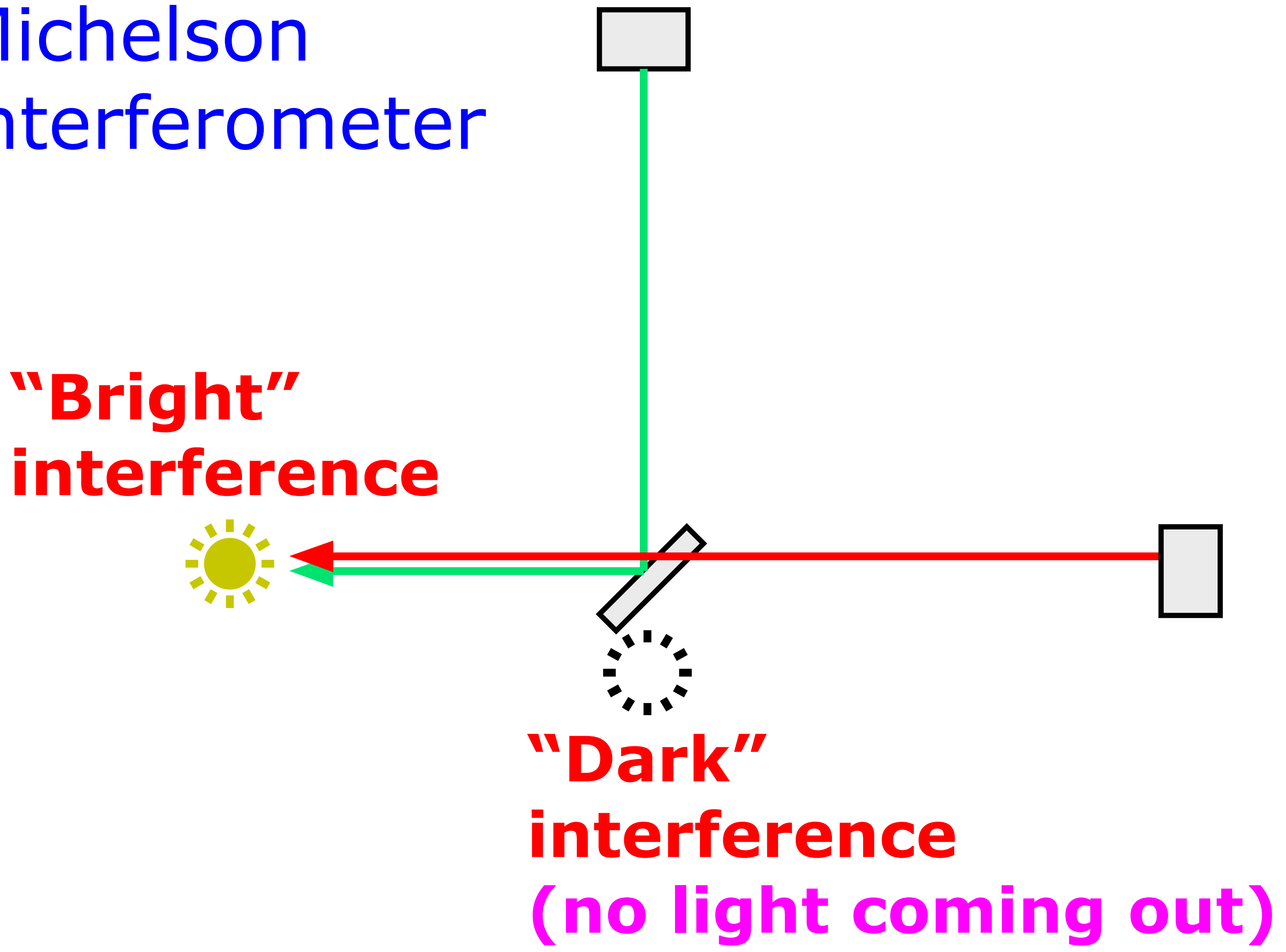
Partial mirror
(Power recycling mirror)



Principle of power recycling

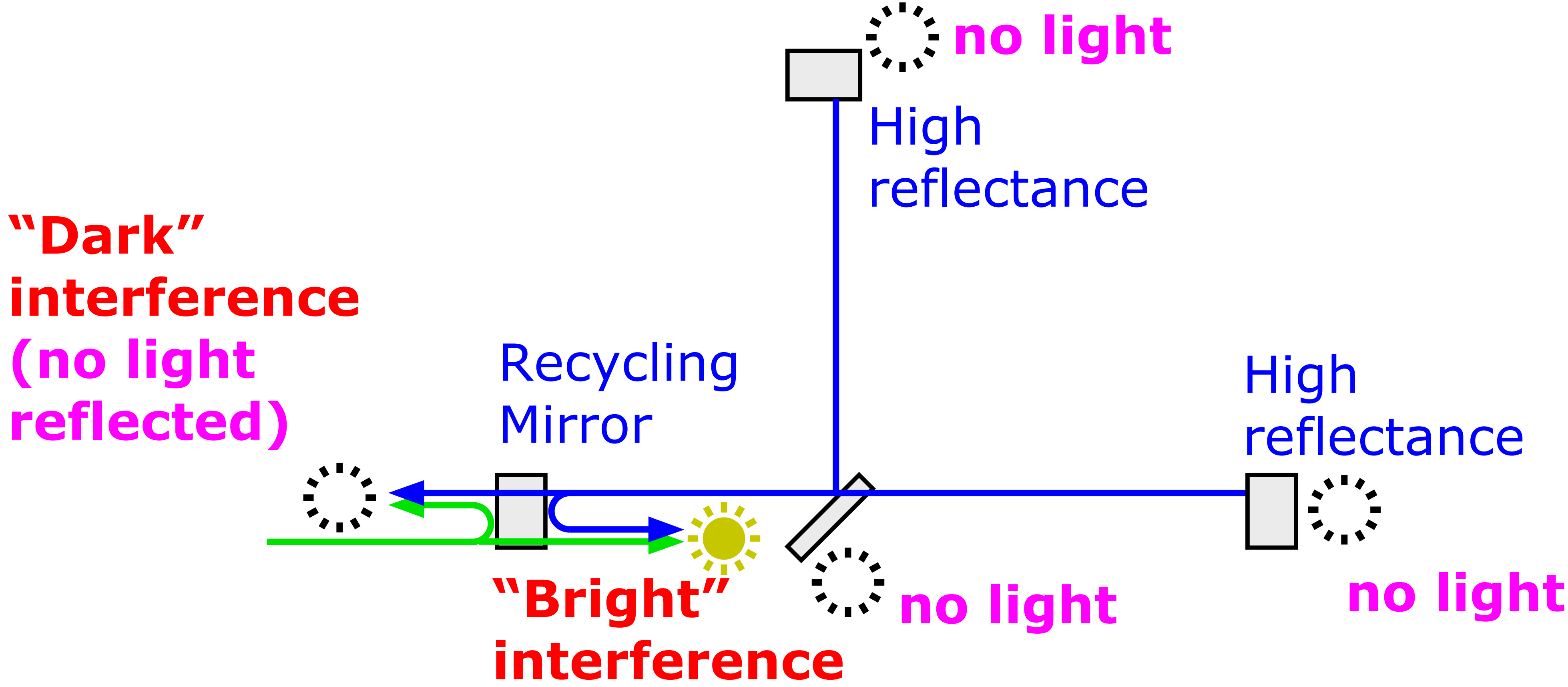
- **Why recycling mirror increases the light power in the interferometer?**

e.g. Michelson interferometer



Principle of power recycling

- **Why recycling mirror increases the light power in the interferometer?**

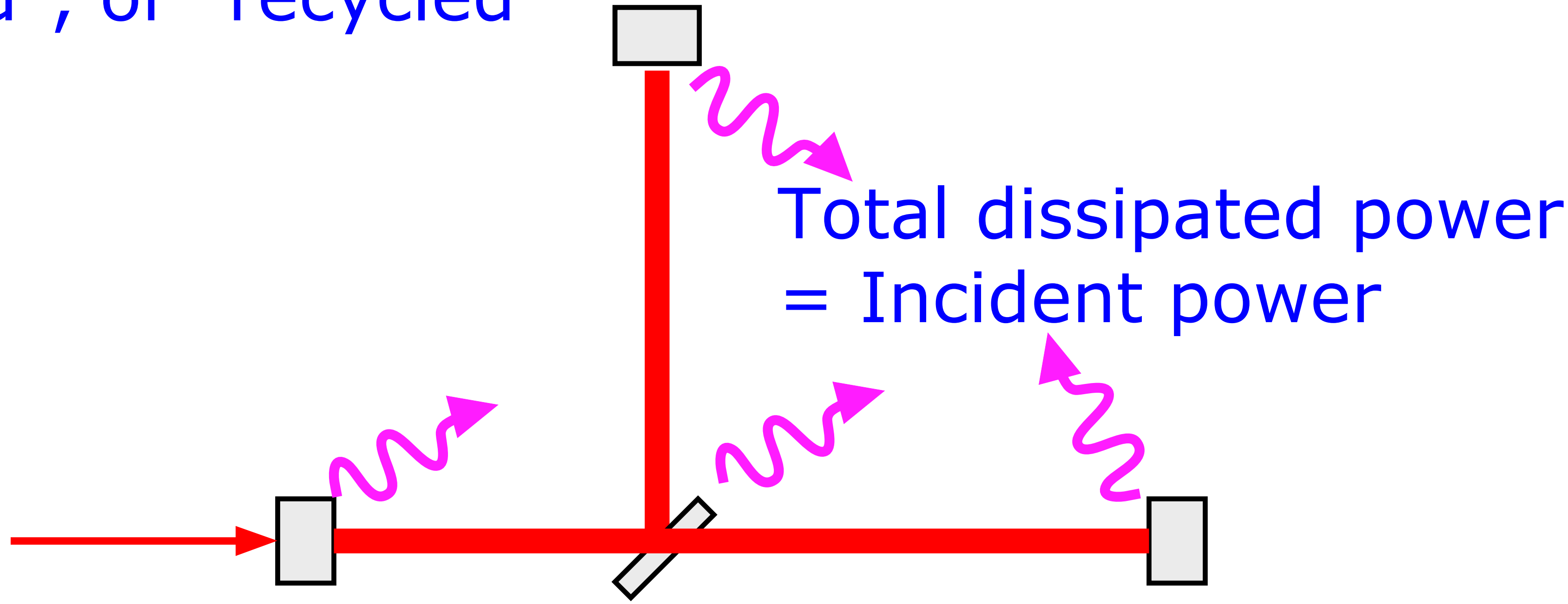


Q. The light has no way out from the interferometer.
Where does the light go?

Principle of power recycling

- **Laser light is enclosed in the interferometer**

  This condition is so-called "resonant", "impedance matched", or "recycled"



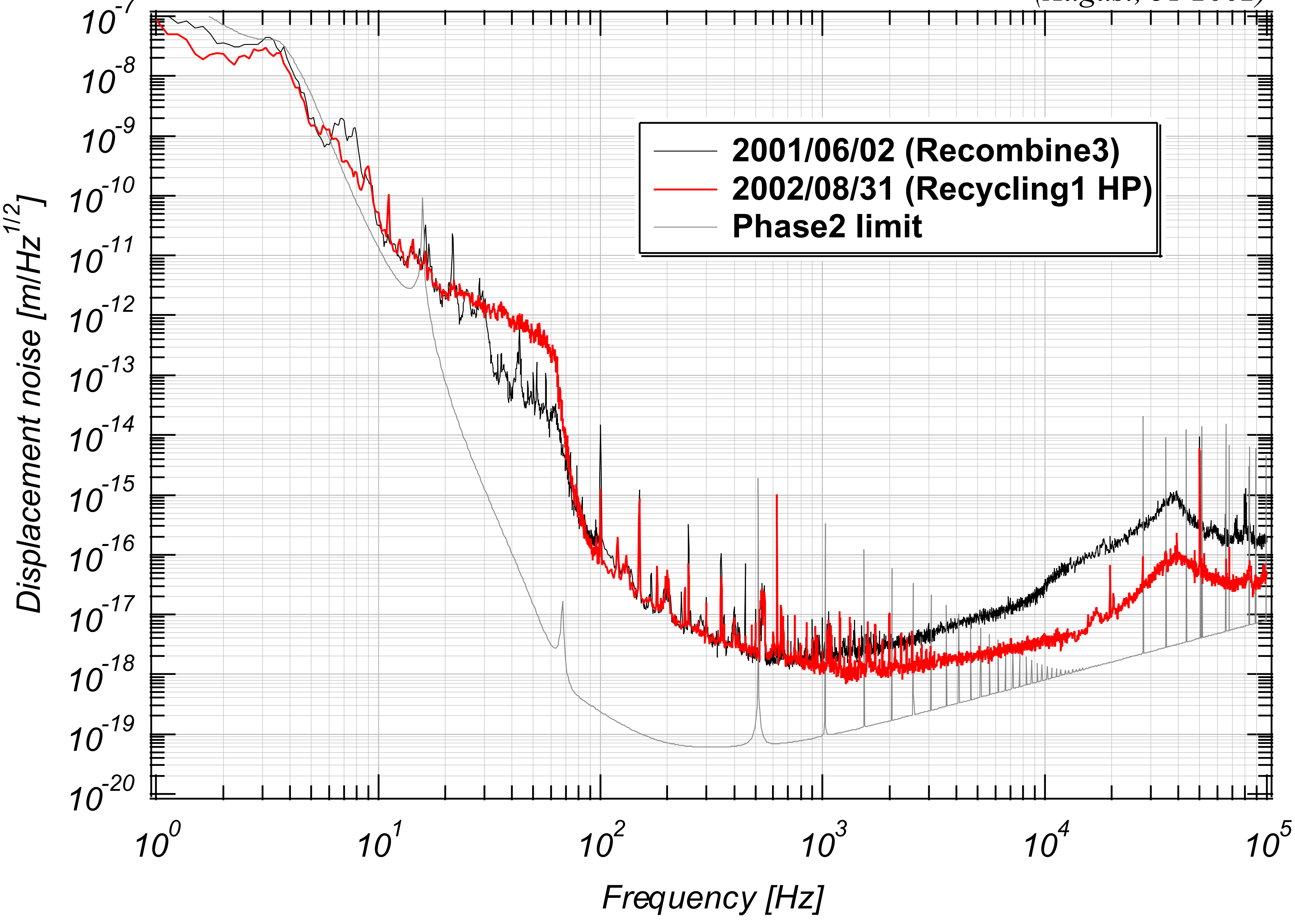
$$P_{\mathrm{inc}} = \varepsilon_{\mathrm{loss}} P_{\mathrm{internal}} \rightarrow P_{\mathrm{internal}} = \frac{P_{\mathrm{inc}}}{\varepsilon_{\mathrm{loss}}} \equiv g\, P_{\mathrm{inc}}$$

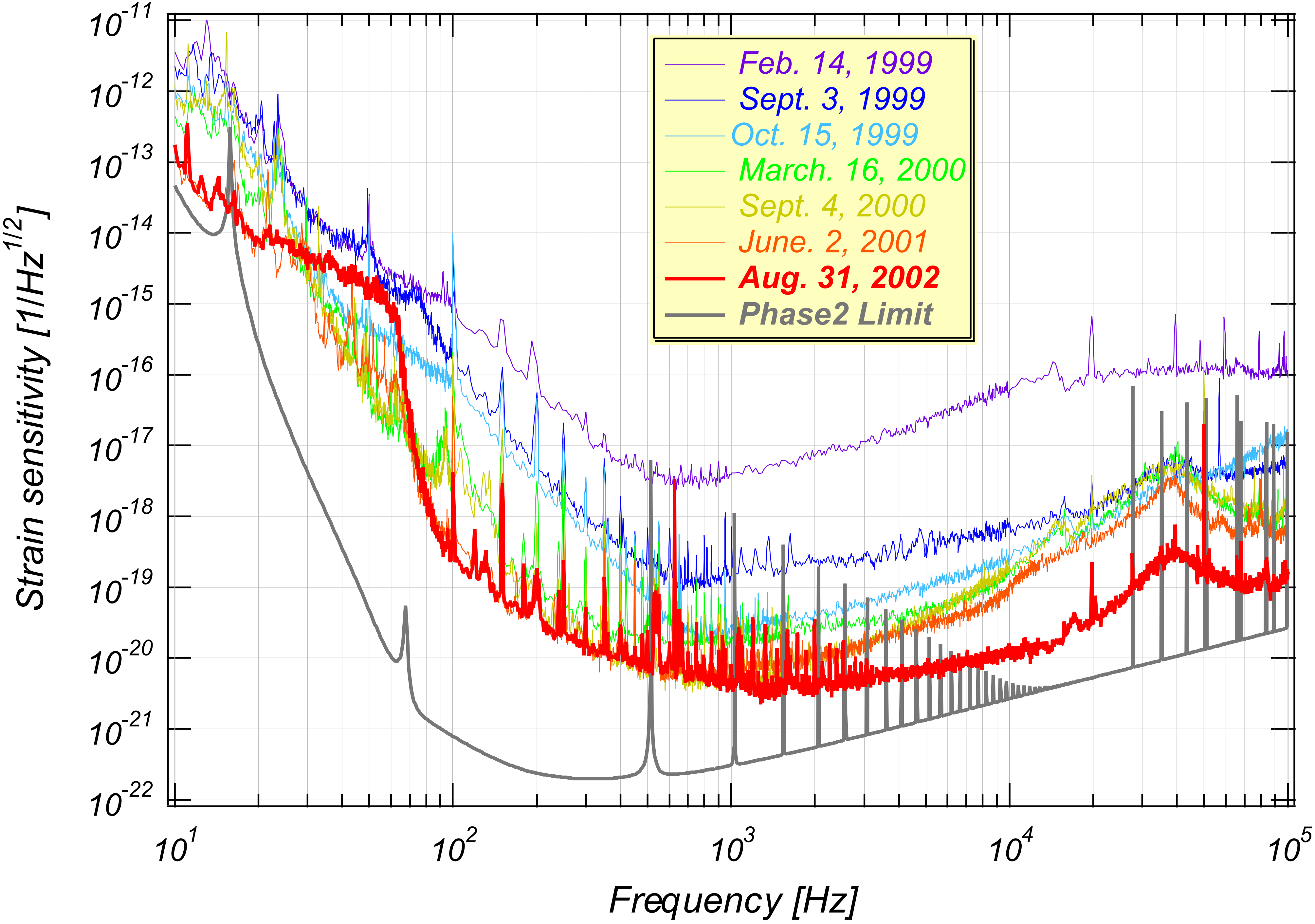
Power in the arms → enhanced

Low loss optics → High recycling gain

Displacement noise level of TAMA300

(August, 31 2002)

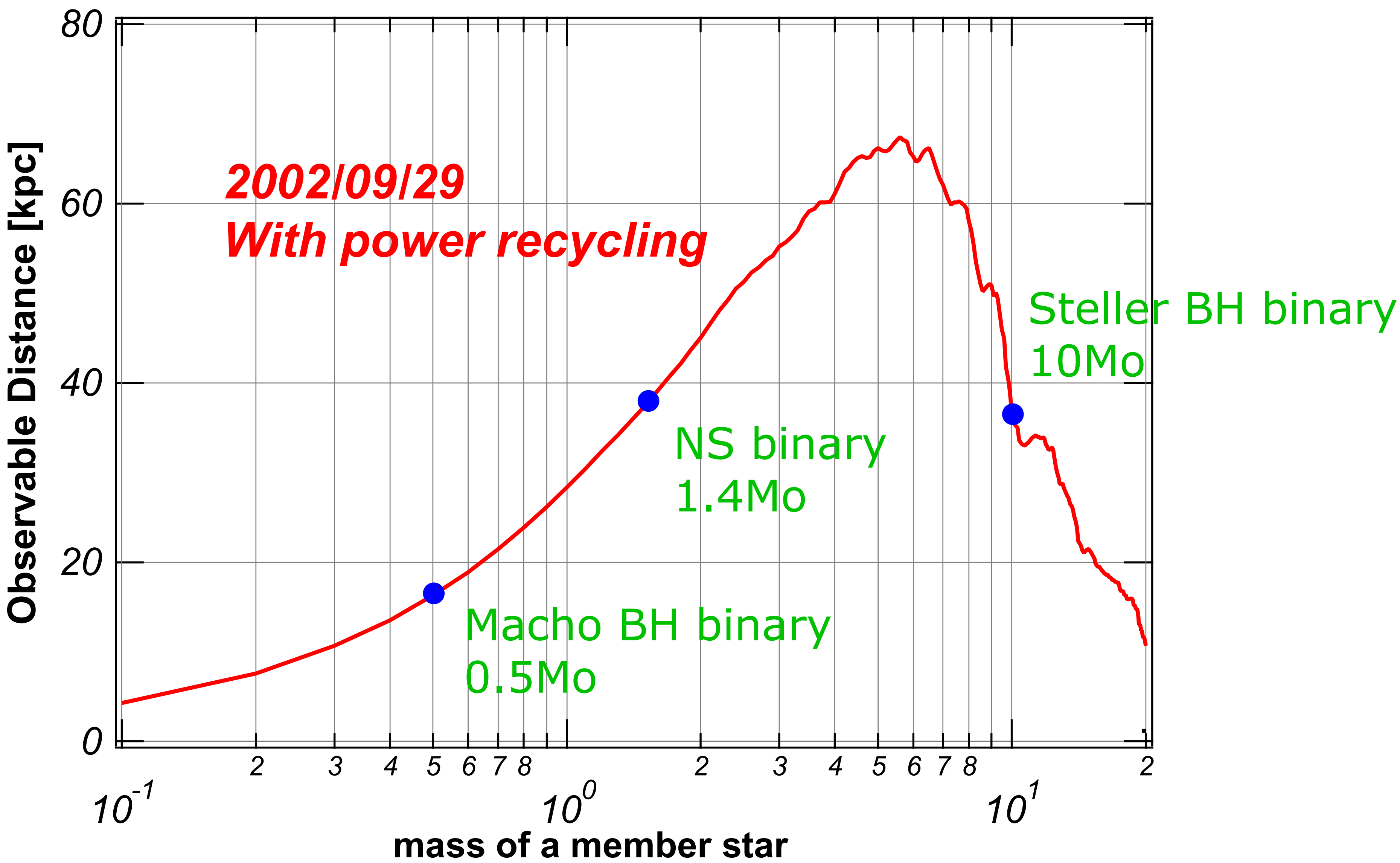




Feb. 14, 1999
Sept. 3, 1999
Oct. 15, 1999
March. 16, 2000
Sept. 4, 2000
June. 2, 2001
Aug. 31, 2002
Phase2 Limit
Strain sensitivity [1/Hz^1/2]
Frequency [Hz]
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^1
10^2
10^3
10^4
10^5

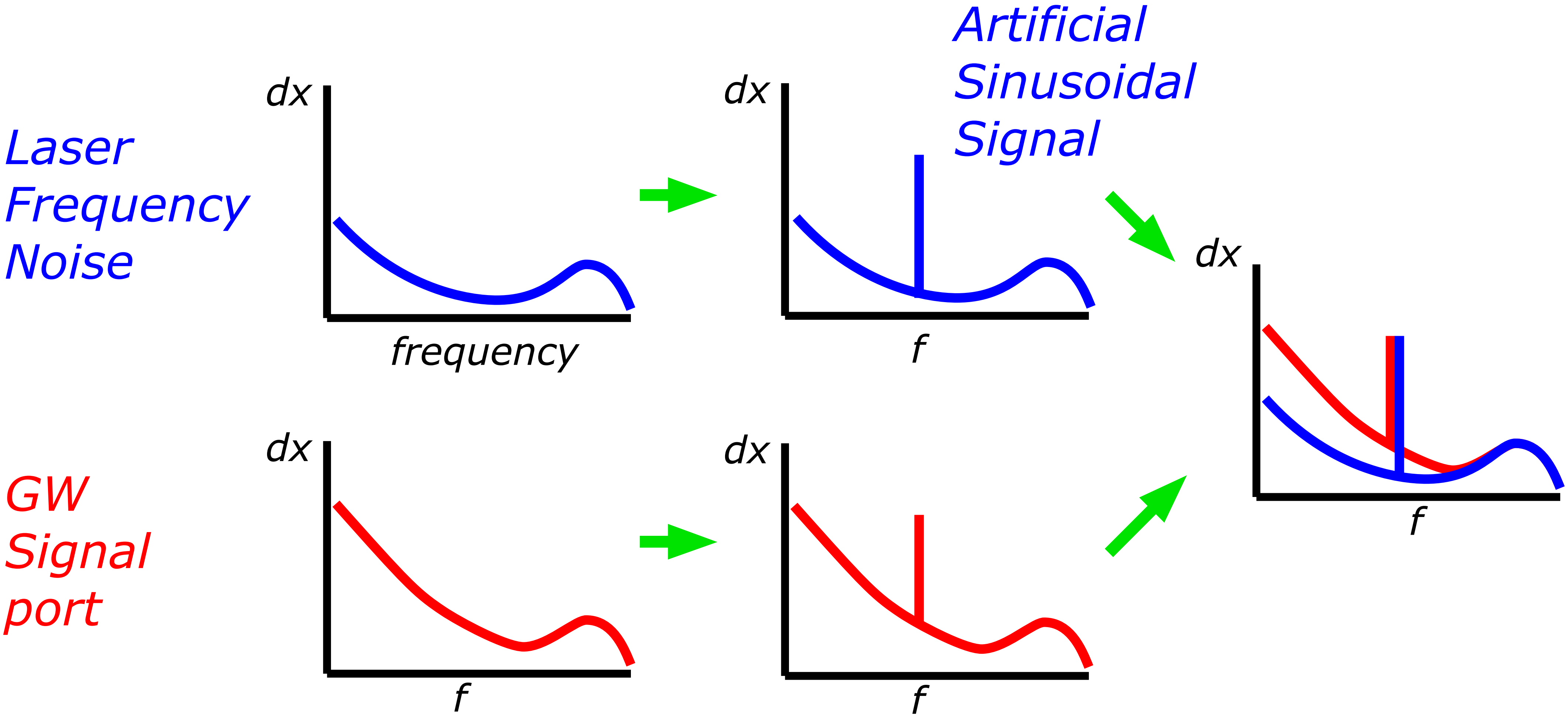
Expected SNR to inspirals

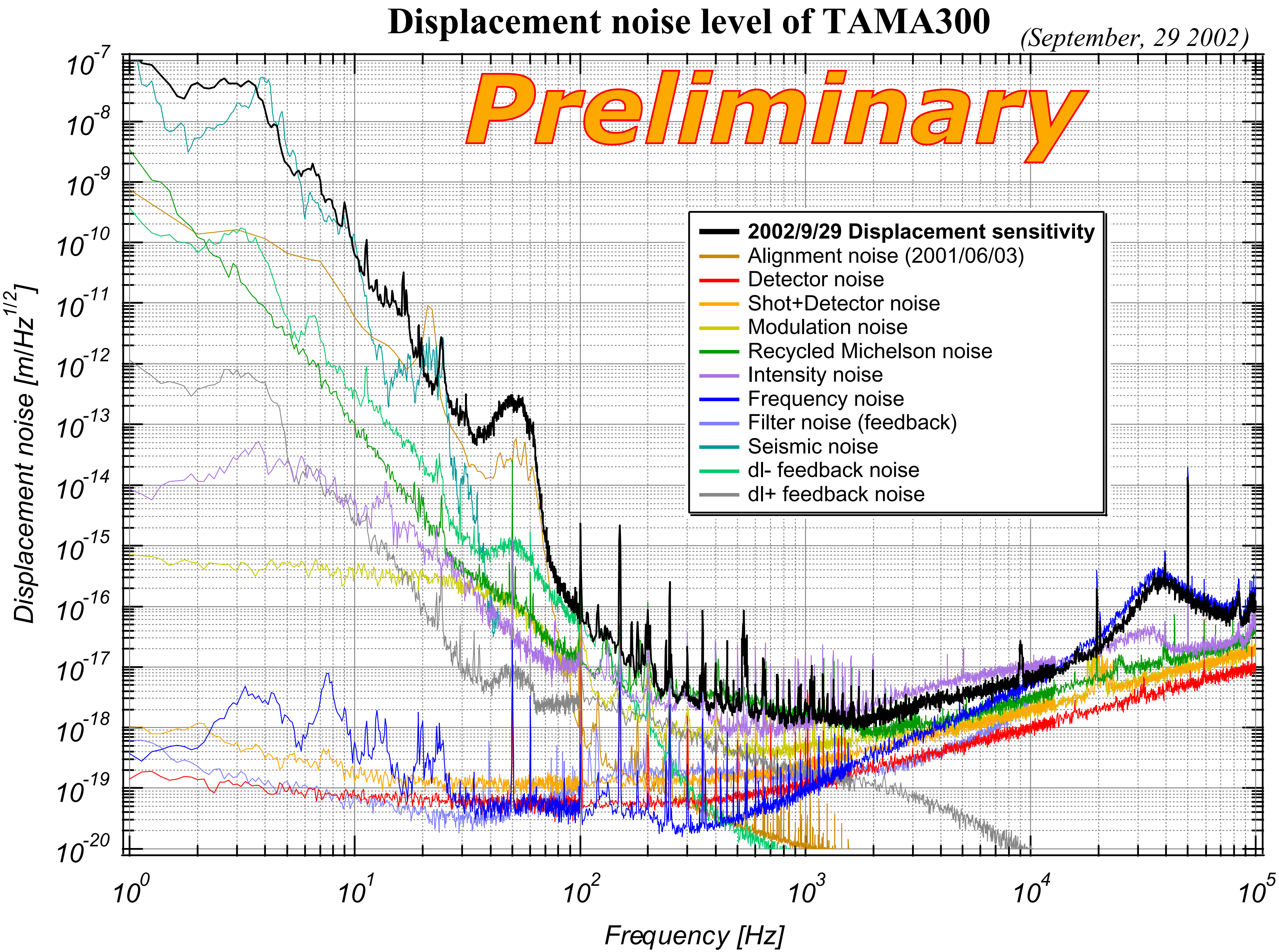
- Observable distance with SNR=10
  □ □ □ □ using matched filtering



Estimation of noise contributions

- Noise estimation based on signal injection



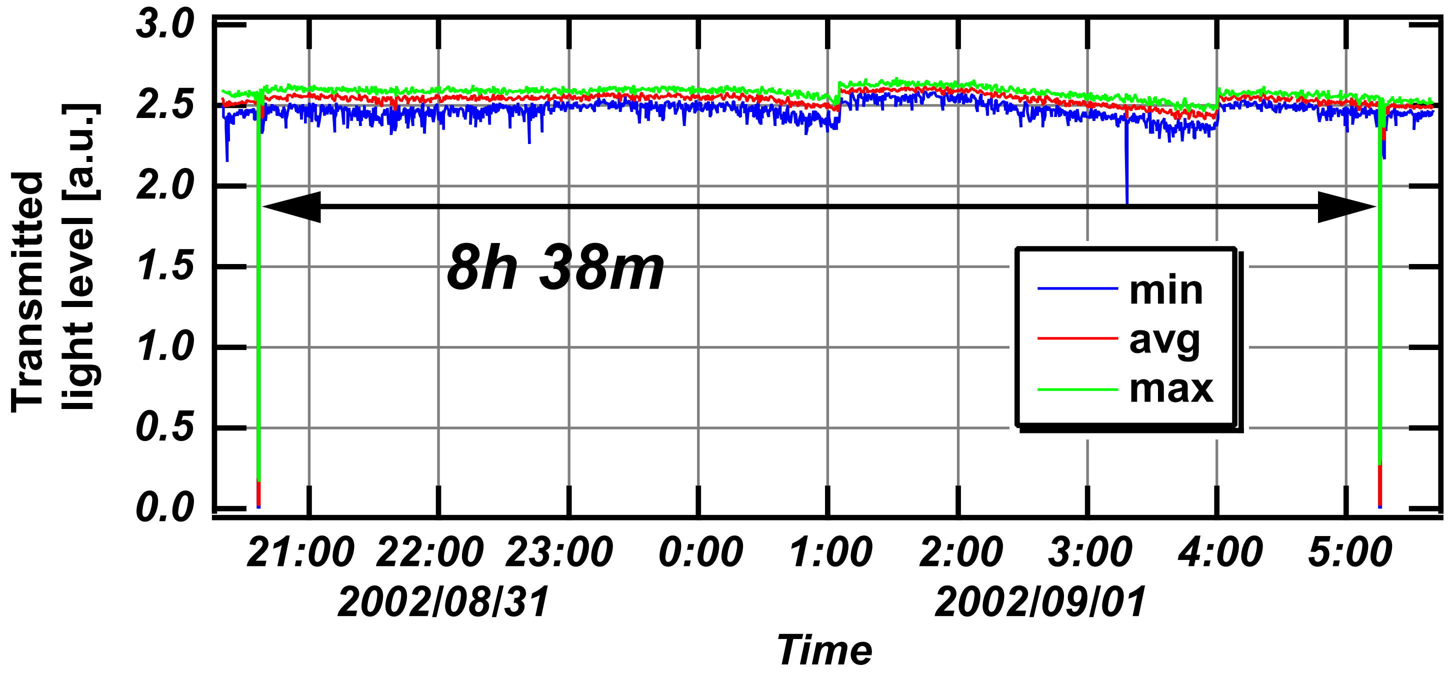


Displacement noise level of TAMA300
(September, 29 2002)
Preliminary
2002/9/29 Displacement sensitivity
Alignment noise (2001/06/03)
Detector noise
Shot+Detector noise
Modulation noise
Recycled Michelson noise
Intensity noise
Frequency noise
Filter noise (feedback)
Seismic noise
dl- feedback noise
dl+ feedback noise
Displacement noise [m/Hz^1/2]
Frequency [Hz]

Stability

- **Recycling also increases complication □ of the system**

Internal power becomes sensitive to mirror motions



Longest continuous operation

□ with power recycling:□ □ 8h 38m

□ (without power recycling:□24h 50m)

Concident observations

- ***large-scale interferometers in operation***

  - **S1 (Scientific run 1)**

    2002/8/22-2002/9/9

    Coincident run by LIGO and GEO

    Partial participation of TAMA

  - **S2 (Scientific run 2)**

    2003/2/14-2002/4/14

    Full coincident run by LIGO, GEO and TAMA

TAMA, LIGO (and GEO) detectors enter the observation phase in 2002 - 2003.

- 5 detectors are operating in Comparable Sensitivity

  TAMA: 300m at Mitaka Tokyo

  LIGO: Livingston 4km, Hanford 4km, 2km

  GEO: 600m
- Benefit

  Increase of whole sky coverage

  Statistical Treatment

  - More strict rejection for fake events
  - Efficient criteria with same fake rate of single detector analysis
- Stable run scheduling

  LIGO(+GEO) S1<-> TAMA DT7

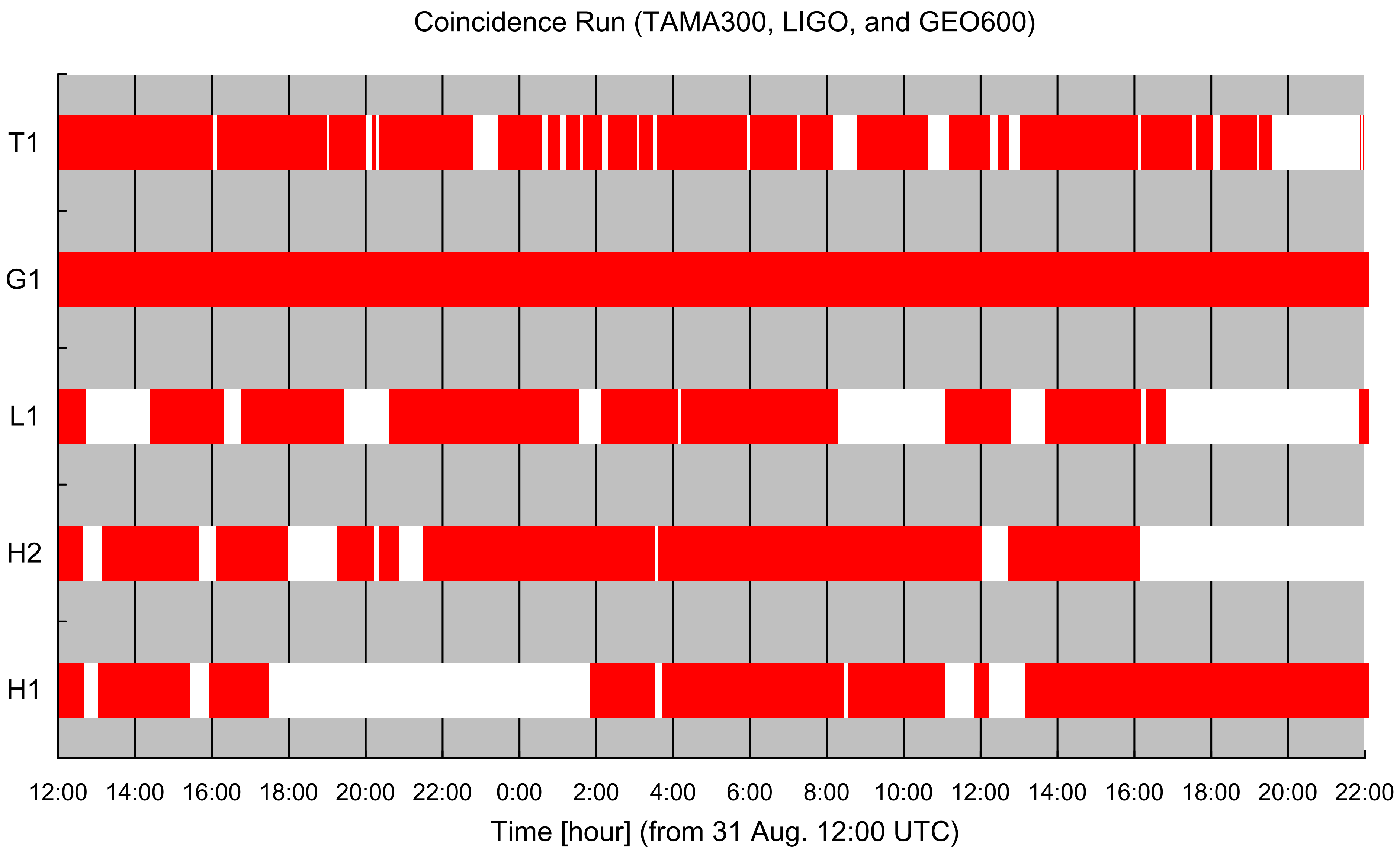
  - 2002, summer. 2 weeks <-> 3 days
  - Actual 9hrs 50min. common locking data

  LIGO(+GEO) S2 run <-> TAMA DT8

  - Duration: 2/14/2002 - 4/14/2002

S1 & DT7

Common Lock of 5 interferometers: 9hrs 50min
Longest Common Lock stretch: 2hrs 24min



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☞ - ***Analysis of TAMA300 data***

  Inspiral search, burst search, and pulsar search

Gravitational wave search: Compact binary Inspiral

Matched filtering analysis （Tagoshi, et al.)

We analyzed 1000 hours data of DT6 by matched filtering to search for compact binary inspirals

Upper limit to the event rate:

- DT2: 0.59/hours (0.3-10Msolar) (Phys.Rev.D63,062001(2001))
- DT4: 0.027/hours (0.3-4.7Msolar)
- DT6: Upper limit to Galactic event rate:

0.0095/hours (1-2Msolar)

TAMA-LISM coincidence analysis (Takahashi's talk) is also done

Matched filter

- Detector outputs: $s(t) = Ah(t) + n(t)$

  $h(t)$: known gravitational waveform (template) → Post-Newtonian approximation

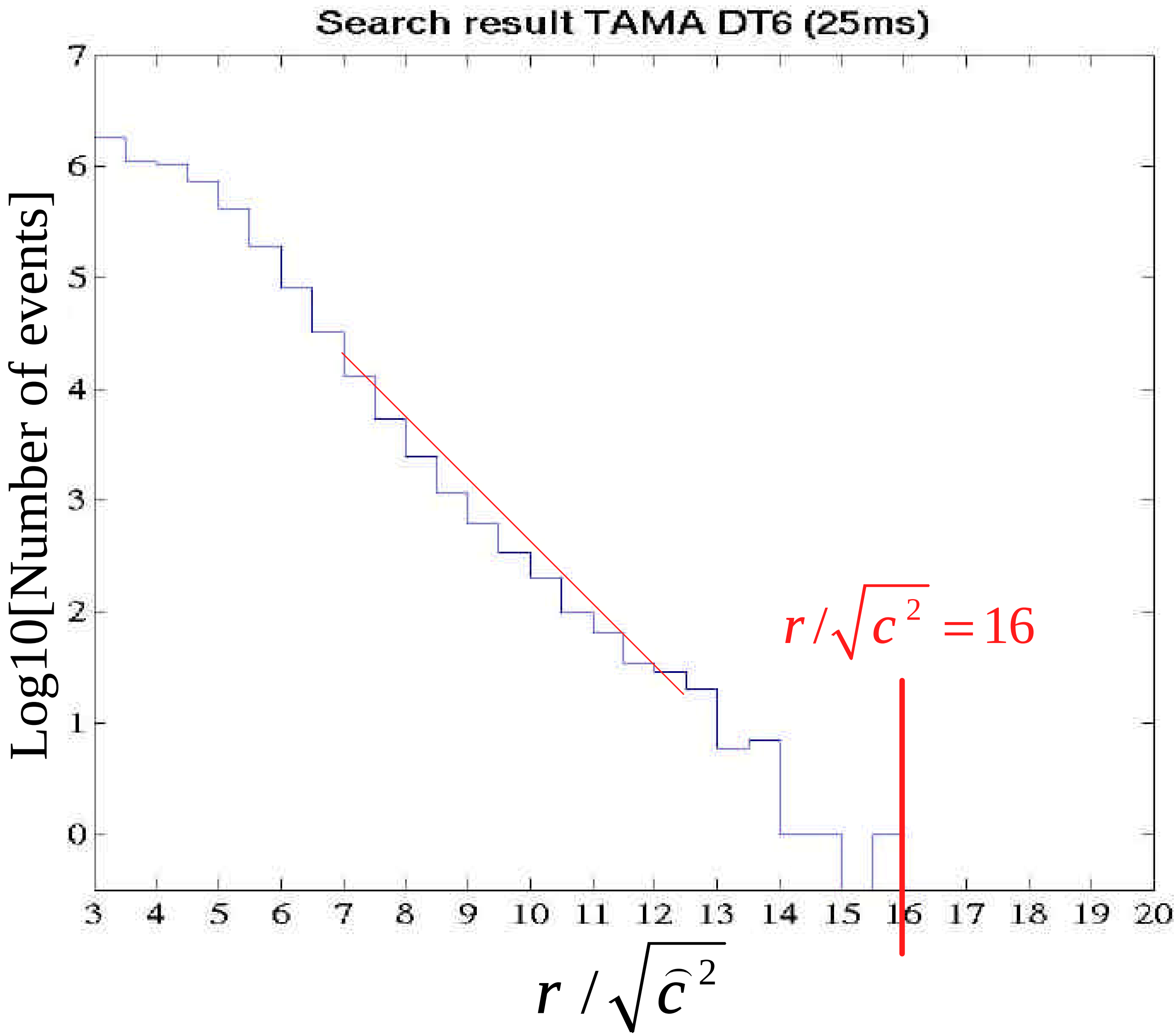
  $n(t)$: noise.

- Outputs of matched filter:

$$r(m_1, m_2, t_c, \ldots) = 2\int \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} df$$

- $S_n(f)$ noise spectrum density

- signal to noise ratio $\mathrm{SNR} = r/\sqrt{2}$
- Matched filtering is the process to find optimal parameters which realize $\left(\max_{m_1, m_2, t_c, \ldots} r(m_1, m_2, t_c, \ldots) \right)$



Search result TAMA DT6 (25ms)
Log10[Number of events]
$r/\sqrt{c^2} = 16$
$r/\sqrt{\hat{c}^2}$
0
1
2
3
4
5
6
7
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Upper limit to the Galactic event rate

threshold=16 (～S/N=11) (fake event rate=0.8/year)

Efficiency for Galactic events $\varepsilon = 0.23$ (from simulation)

•We also obtain upper limit to the average number of events over threshold by standard poisson statistics analysis

⇨ N=2.3 (C.L.=90%)

•Data length used : T＝1039 hours

⇨ Upper limit to the Galactic event rate

$$= \frac{N}{T\varepsilon} = 0.0095 \ [1/\text{hour}] \ (C.L. = 90\%)$$

c.f. Caltech 40m : 0.5/hour (*C.L.*=90%)

Allen et al. Phys. Rev. Lett. 83, 1498 (1999).

Burst wave analysis (1)   (Ando, et al.)

--- Burst gravitational wave search ---

- **Burst gravitational wave analysis (Super novae, etc.)**
  - **Waveforms are poorly predicted**
    - **Cannot use matched filtering method**
    - **Look for ‘something unusual’ events**
    - **Detection efficiency is limited by**
      non-Gaussian noises in a GW detector

Rejection of non-Gaussian noise is indispensable

- **Single detector**
  - **Detector improvement**
  - **Data processing**
- **Correlation with other detectors**
  - **Other GW detectors**
  - **Other astronomical channels**
    (Super novae, Gamma-ray burst, etc.)

Burst wave analysis (2)
--- Reduction of non-stationary noise ---

- **Non-Gaussian noise reduction**

Distinguish GW signal from non-Gaussian noises

with time-scale of the 'unusual signals'

GW from gravitational core collapse < 100 msec,

Noise caused by IFO instability > a few sec

- **2 statistics in detector output**
  - **Averaged noise power**
  - **2nd-order moment of noise power**

$$C_1 = \langle P_j \rangle$$

$$C_2 = \frac{1}{2}\left(\frac{\langle P_j^2 \rangle}{\langle P_j \rangle^2} - 2 \right)$$

Estimate parameter : 'GW likelihood'

Reduce non-stationary and non-Gaussian noises

without rejecting GW signals

Burst wave analysis (3)
--- Data processing ---

- **Data Processing**
  1. Calculate Spectrogram by FFT
  2. Extract a certain time-frequency region
     to be evaluated
  3. Evaluate GW likelihood at each frequency
  4. Reject given time region
     if it has large 'non-GW like' ratio
  5. Calculate total power for given T-F region

- **'Filter' outputs**

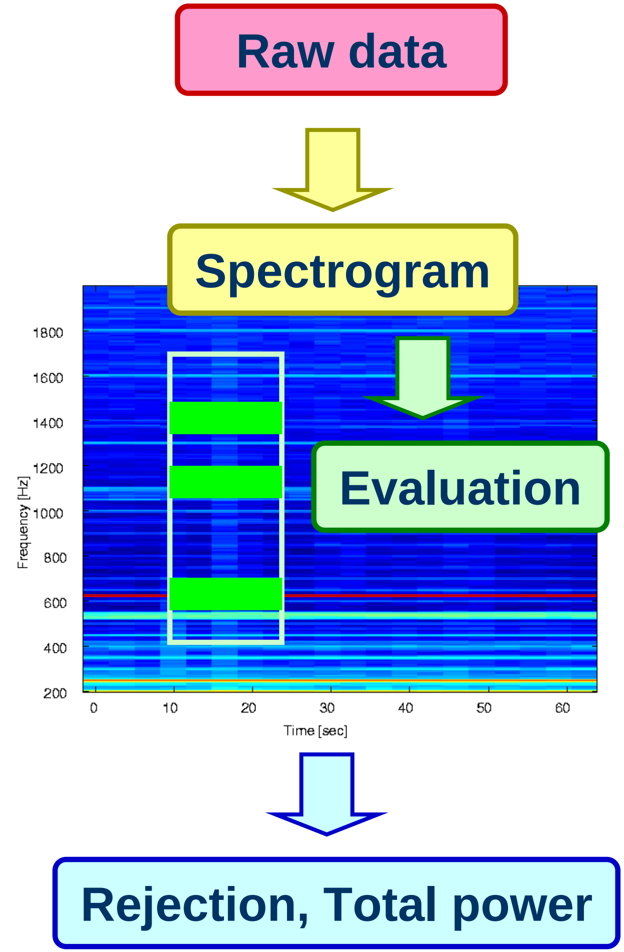
  Survived --- Stable detector operation

  Data may be used for GW search

  Large power : event candidates

  Rejected --- Detector instability

  Detector 'dead time'



Burst wave analysis (4)
--- DT6 data analysis ---

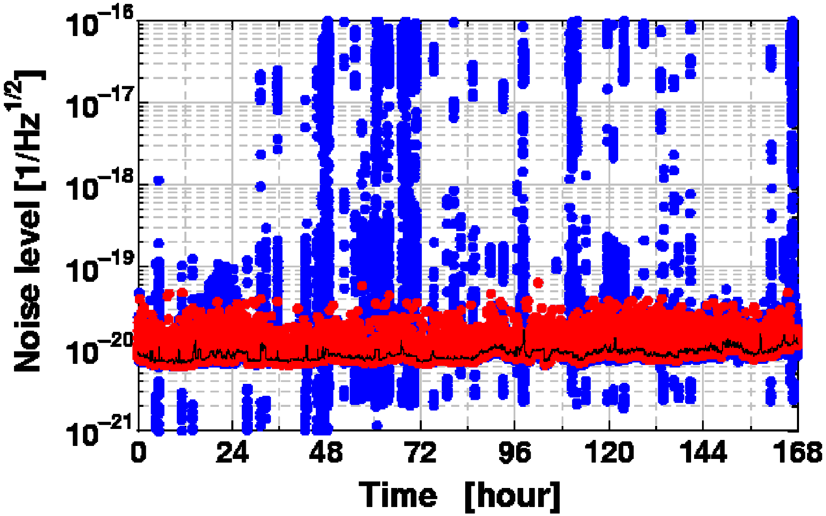
- **Data Taking 6 (Summer 2001)**
  - **Analyze last 1-week data**
  - **Bandwidth : 500Hz**

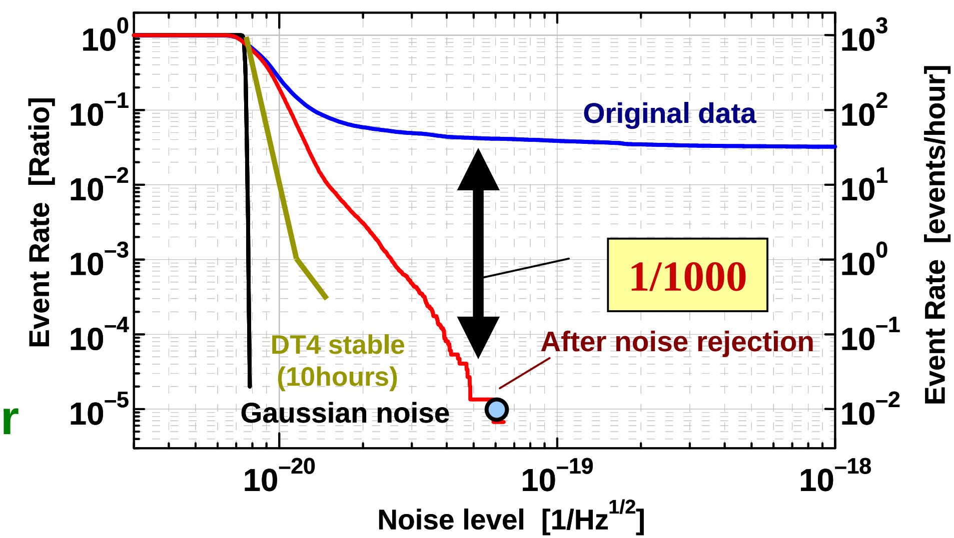
    Rejected data : 20%

    (False dismissal rate : 1ppm)

    Improvement of

    false event rate : 1/1000
  - **Still worse than stable hours in DT4, and Gaussian noise level**
- **Event rate for 10msec GWs**
  - **$h_{rms} \sim 1\times10^{-17}$: 1 events/hour**
  - **$h_{rms} \sim 3\times10^{-17}$: 10^{-2} events/hour**





Continuous wave from SN1987A

- **Continuous GW wave search at around 935Hz from SN1987a remnant (Soida, et al.)**

Expected Waveform: Sinusoidal

(f=934.908Hz +/- 0.05Hz)

+ time dependence of the sensitivity
+ doppler correction

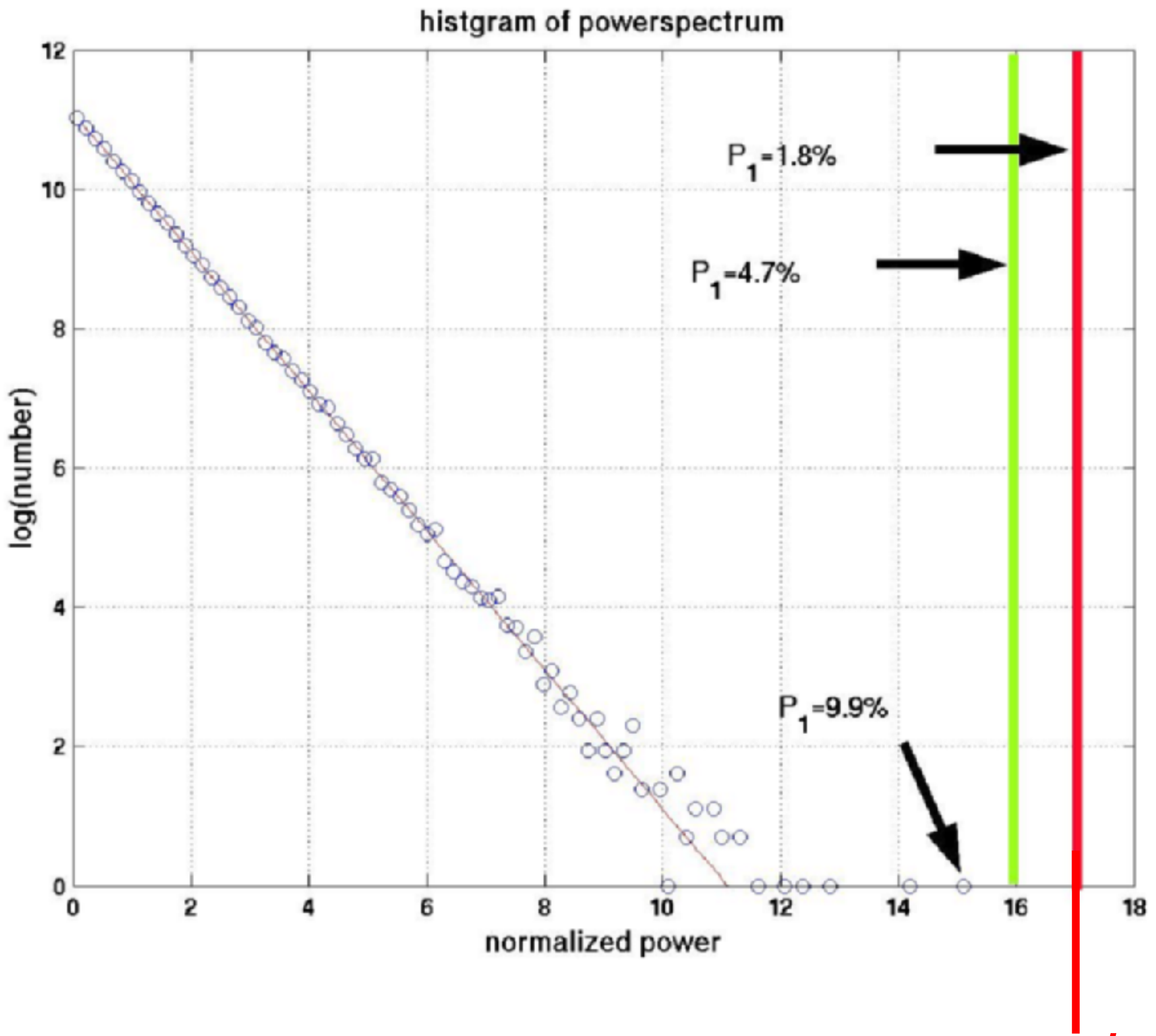
(the earth's daily/yearly round)

+ spindown correction

(assume spindown rate: 2.5×10^{-10} [Hz/s])

Search: DT6 50days data

Search result



h=3.8x10^{-23}
(False alarm rate 1.8%)

Theoretical upper limit from spindown rate: h=9.4x10^{-27}

Online analysis

- **Further development on data analysis system**

Requirement for long / coincident observation

Real-time/online GW event search

-> PC clusters on each institute

(NAO, Osaka Univ, Osaka City Univ., Univ. of Tokyo, ICRR)

Systematic search

-> Use of unified software

Network data distribution

-> connect each institute with Super SINET (>10Gbps)

Summary

- ***Interferometric GW detector TAMA300***

  Observation: 50 days, more than 1000 hours

  Power recycling: Improvement of the sensitivity

  $h = 3.3 \times 10^{-21}$ /sqrtHz @1.5kHz

- ***Data Analysis using DT6 data***

  Binary ispirals

  Burst search

  Continuous wave search

- ***Future plan***

  Continue to improve the performance

  Online/real-time analysis

  Coincident observation with LIGO and GEO