TAMA300: current status and the joint observation with LIGO

National Astronomical Observatory of Japan

Koji Arai (TAMA project)

Overview of this talk

- **Introduction of TAMA300**
  a 300-m Fabry-Perot Michelson interferometer
  8 observations in past

- **The 6th observation: Data Taking 6**
  The observation for 50 days in the summber of 2001
  Analyses of the 1038-hours data

- **The 8th observation: Data Taking 8 (= LIGO S2)**
  LIGO-TAMA joint observation for 2 months
  Detector development for DT8
  Operational status

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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***

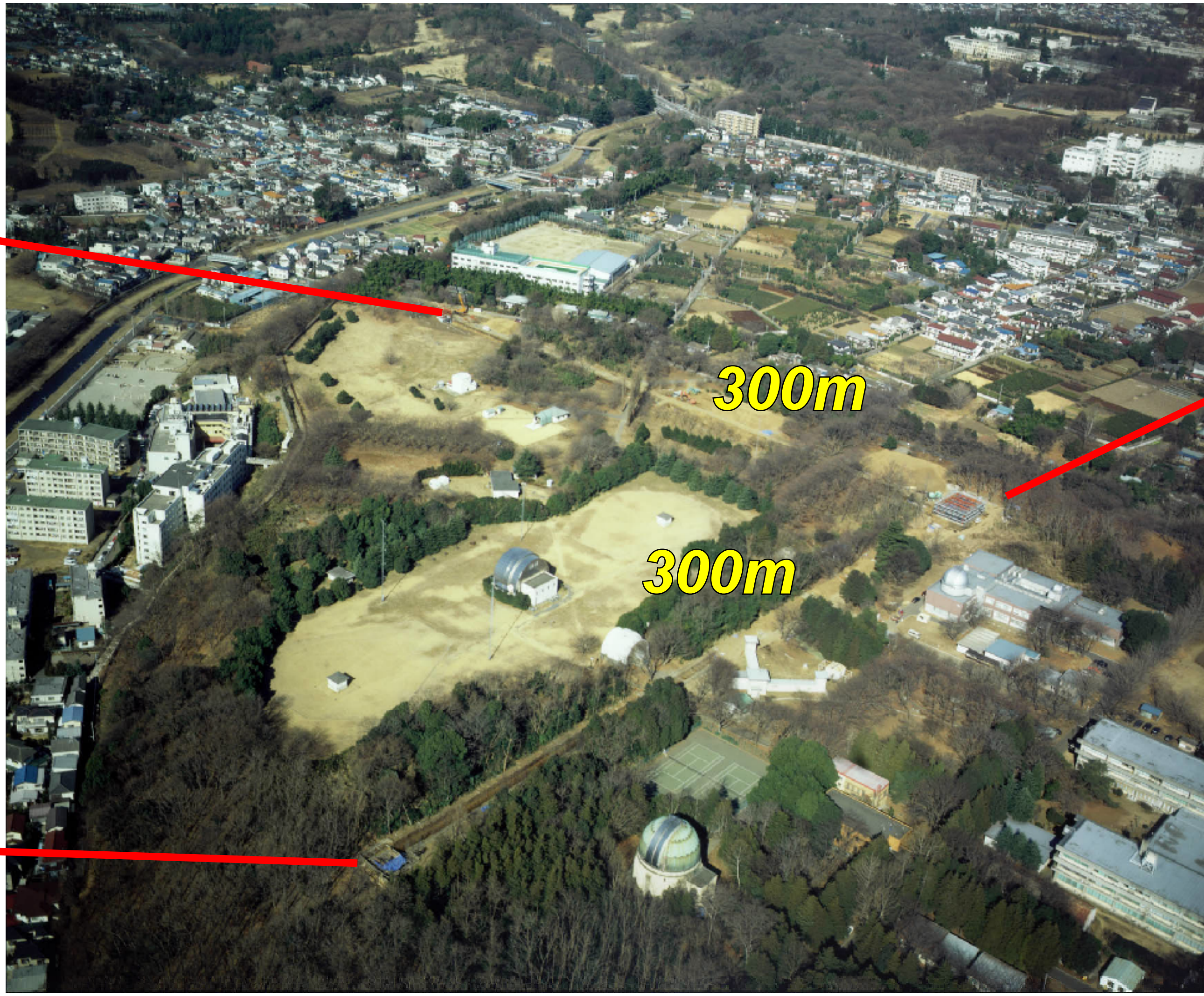
  To develop a detector capable to detect GW events
  □ □ □ □ □ □ □ □ □ □ □ □ □ □ in nearby galaxies.
  To establish techniques for a future km-class interferometer

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

Bird's view of the TAMA site

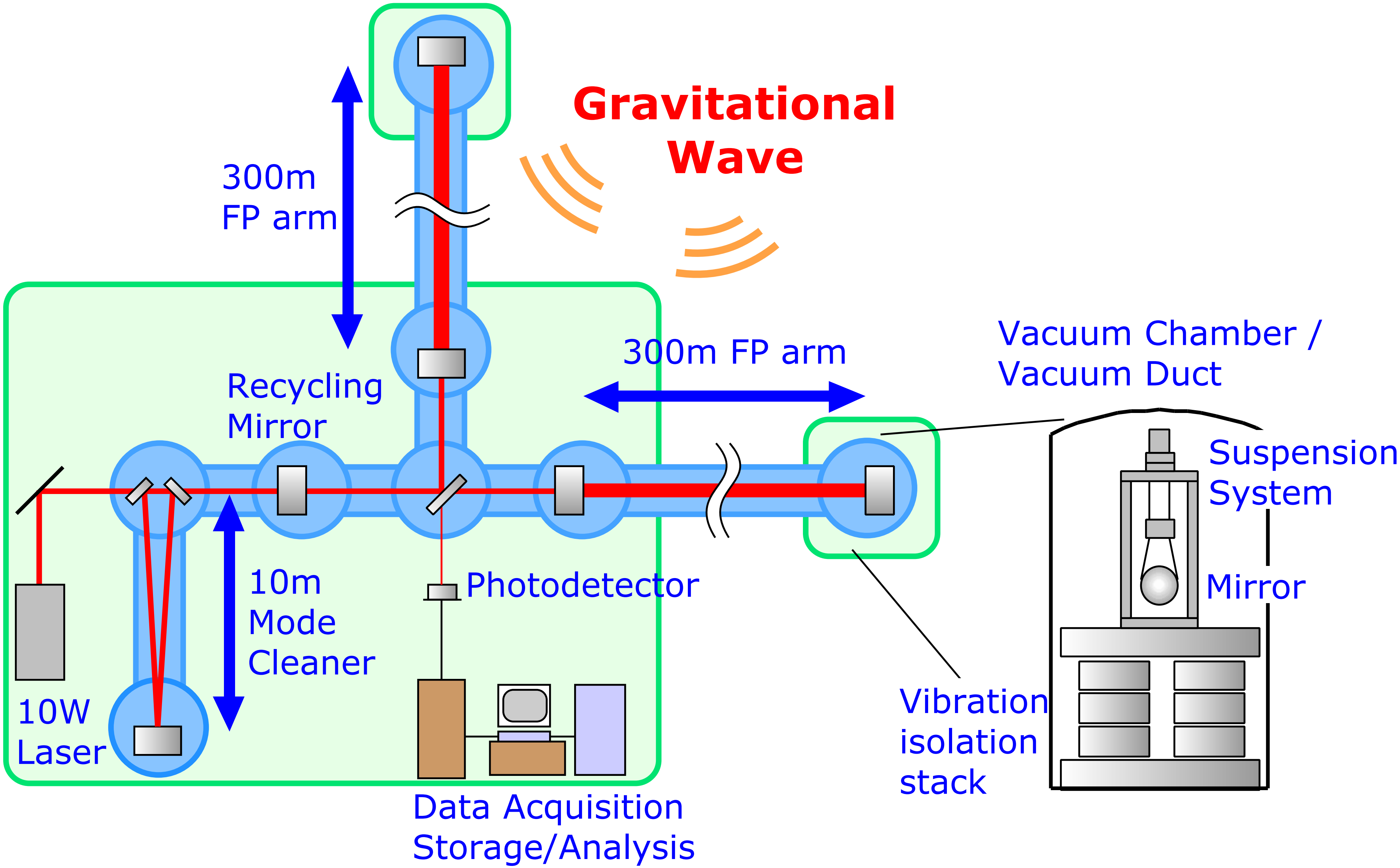
- **National Astronomical Observatory of Japan**

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

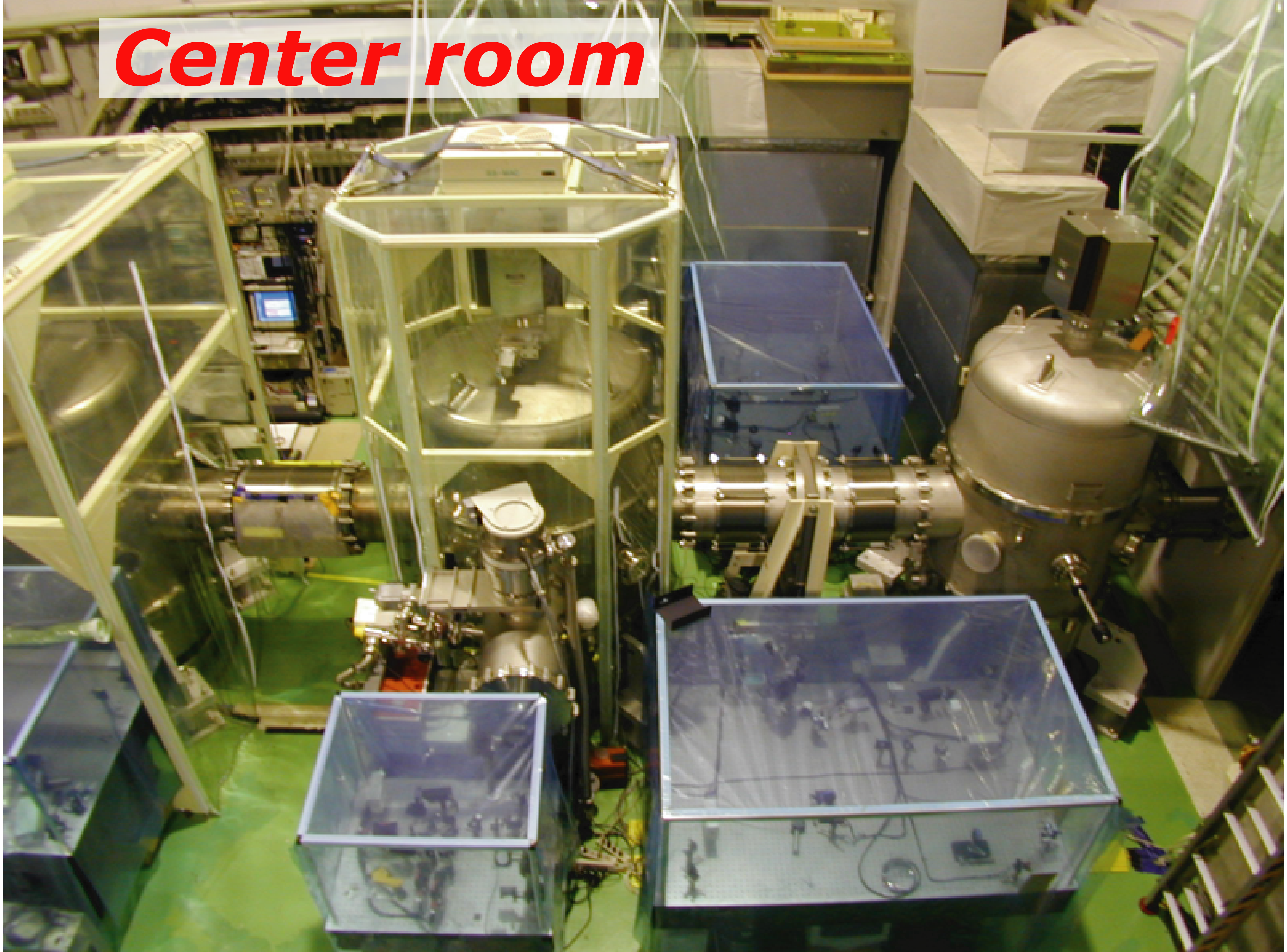


Middle of a city area ~ heavy traffic

TAMA300 detector ~ overview

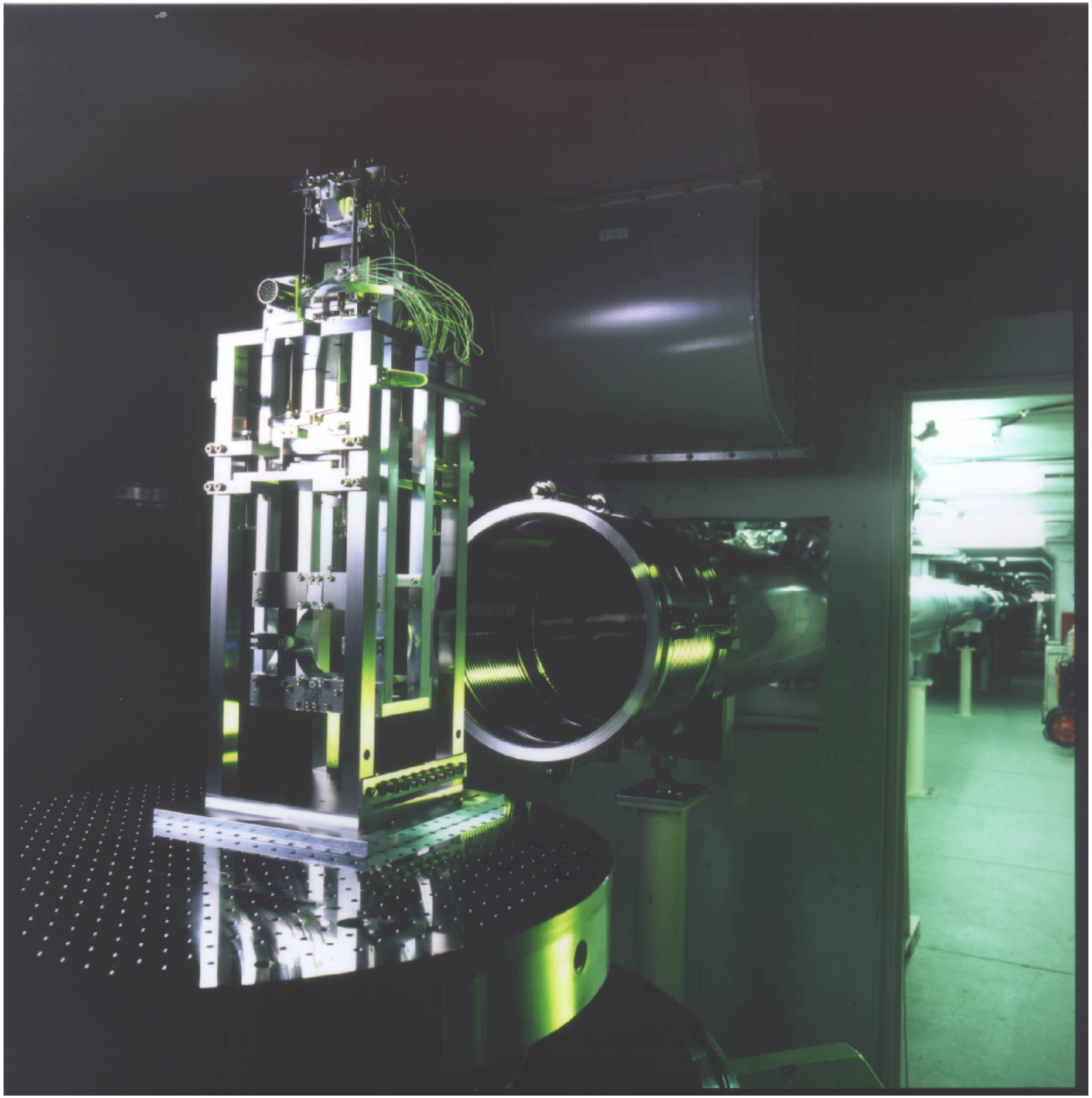


Center room



300m vacuum tube

Vibration Isolation System



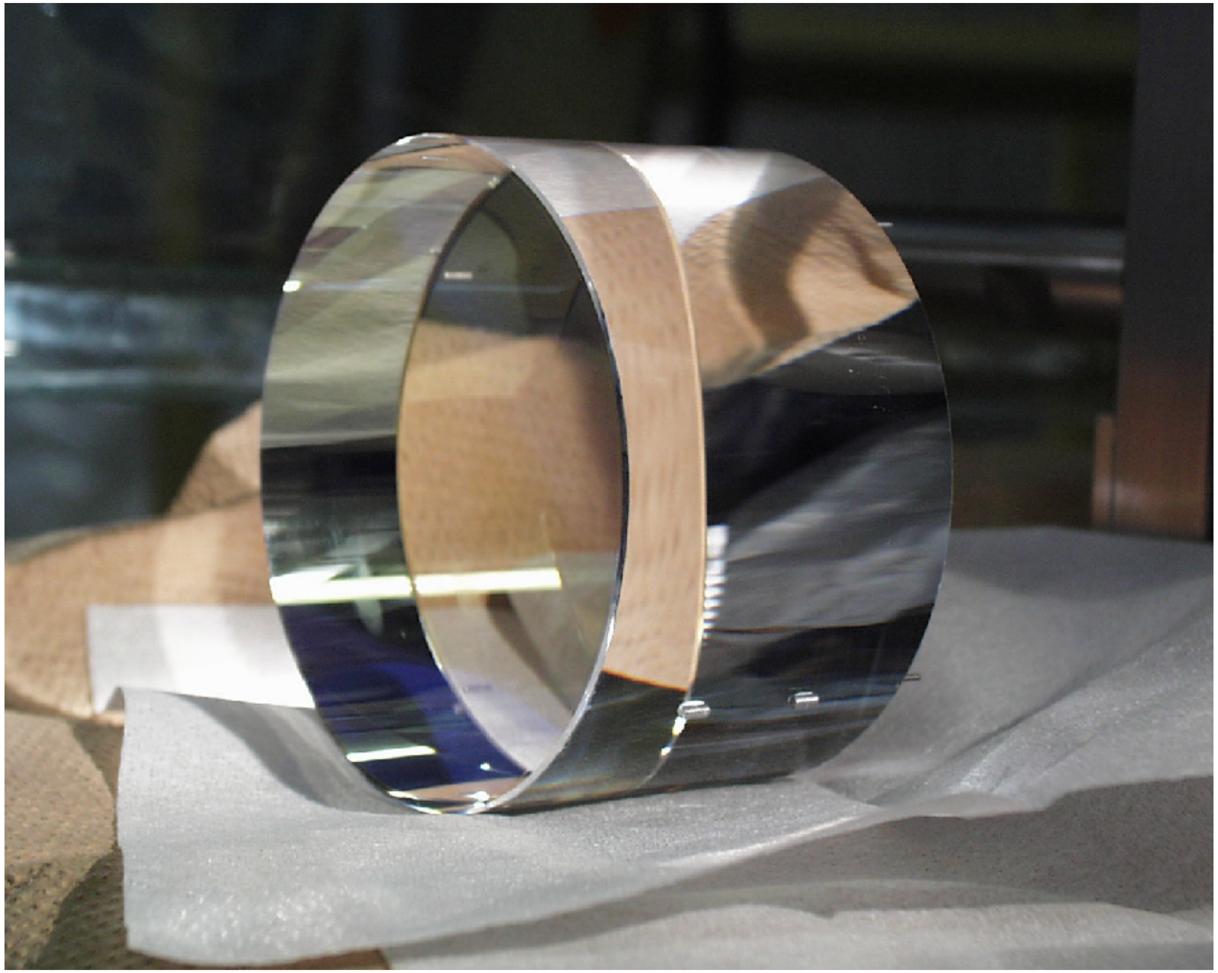
- **3 layer system**

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***



Mechanical quality

Intrinsic Q ~ 3×10^6

Optical quality

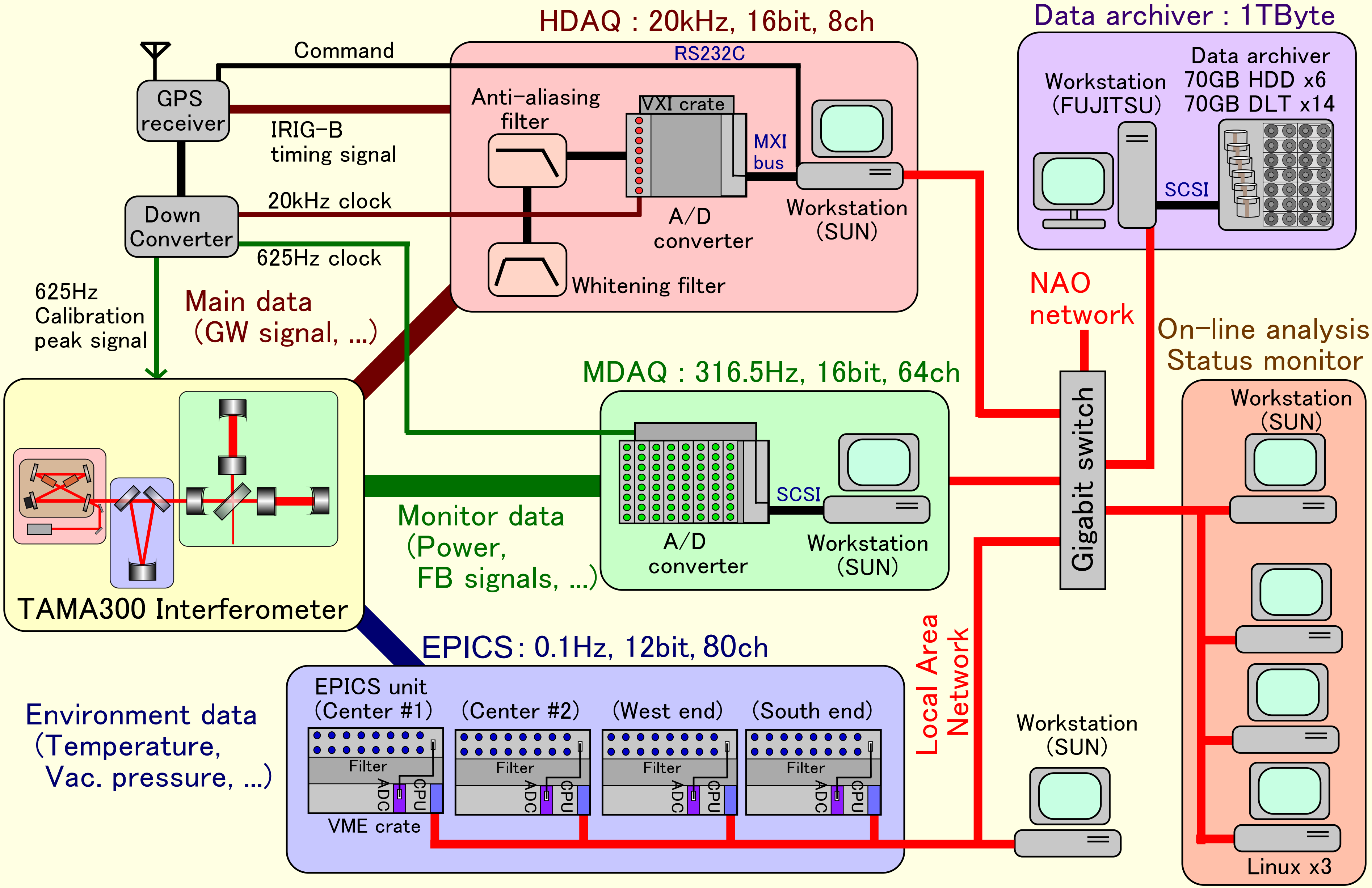
substrate absorption
□ 3ppm/cm
total loss in reflection
□ 30ppm
figure error
□ $<\lambda/40$
surface roughness
□ <1 Å

Control electronics

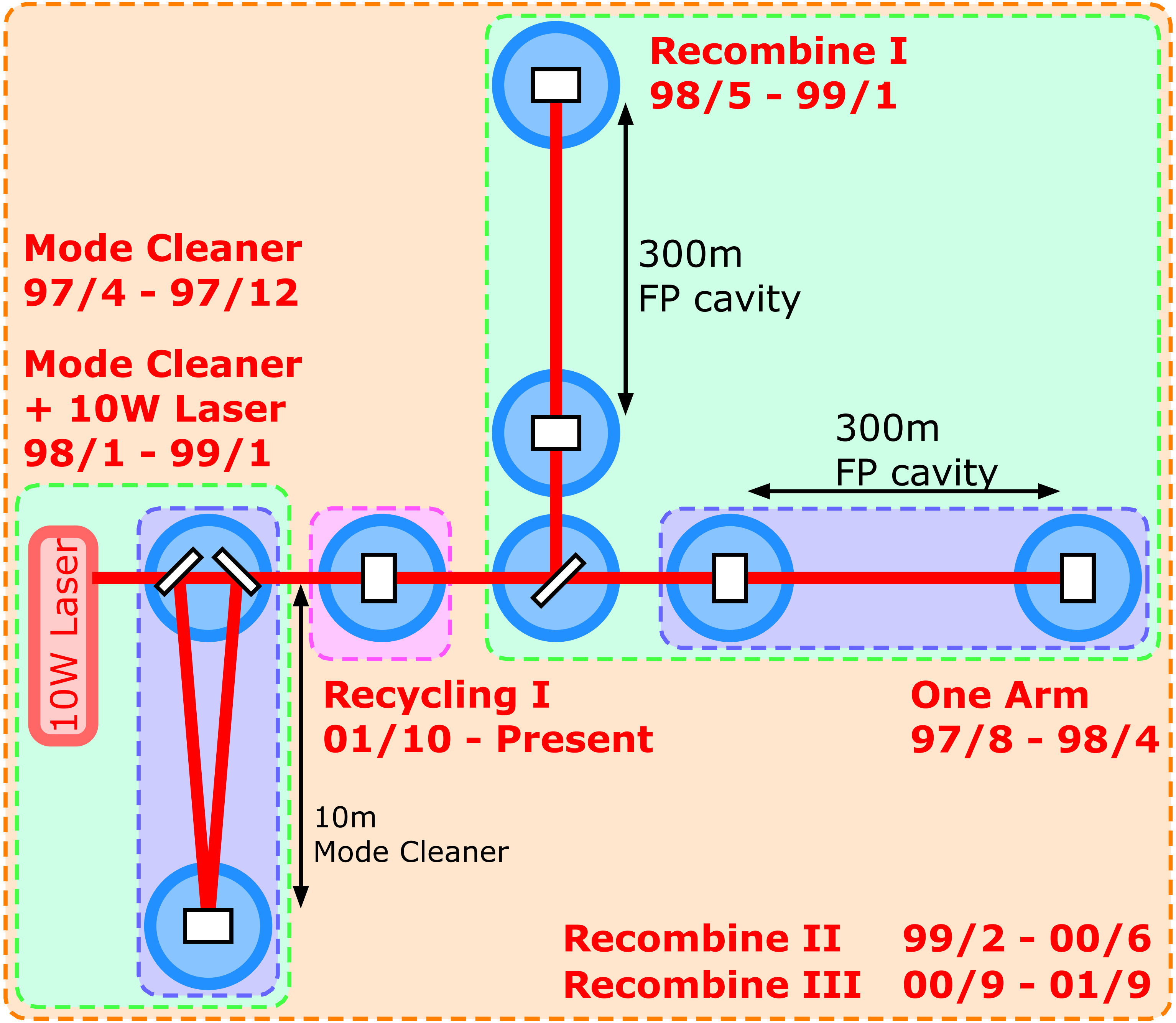
Control electronics

- o Analog servo circuits for the most systems
- o Digital control/switching capability
- □ of the analog circuits for automatic lock
- o Several digital servos

Data Acquisition System



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
2003/2-4	Data Taking 8	1158h

Data taking (DT) runs in past

6 observations without power recycling
2 observations with power recycling

[Without power recycling]

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	*LISM(20m)*

[With power recycling]

DT7	2002	Aug, 31~Sep. 2	1 day	25 hours	*LIGO & GEO*
DT8	2003	Feb. 14~Apr. 15	59 days	1158 hours	*LIGO*

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Interferometer on DT6

- DT6 ~ 50 days run (2001/8/1~9/20)
  - IFO configuration: Fabry-Perot Michelson (w/o power recycling)
  - Enough sensitivity to detect Galactic merger events
    Enough stability for long term operation

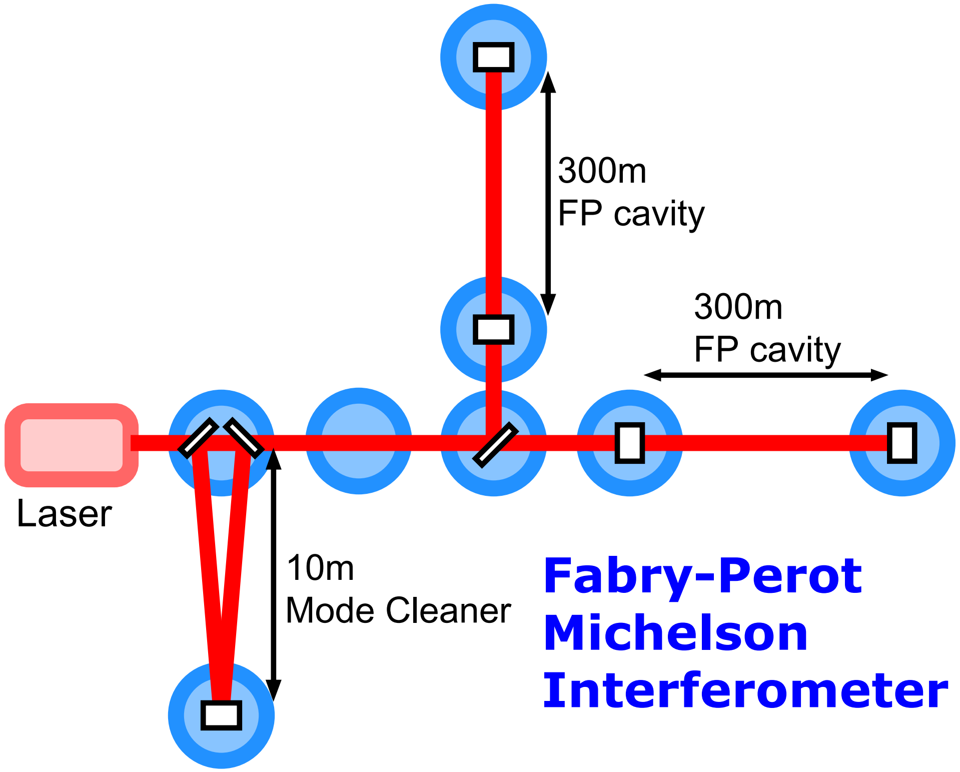
    ~ high duty ratio, auto lock-acquisition

    Total lock time 1107 h (92.3%)

    Total obs. data (excl. after-lock adj.)
    1038 h (86.5%)

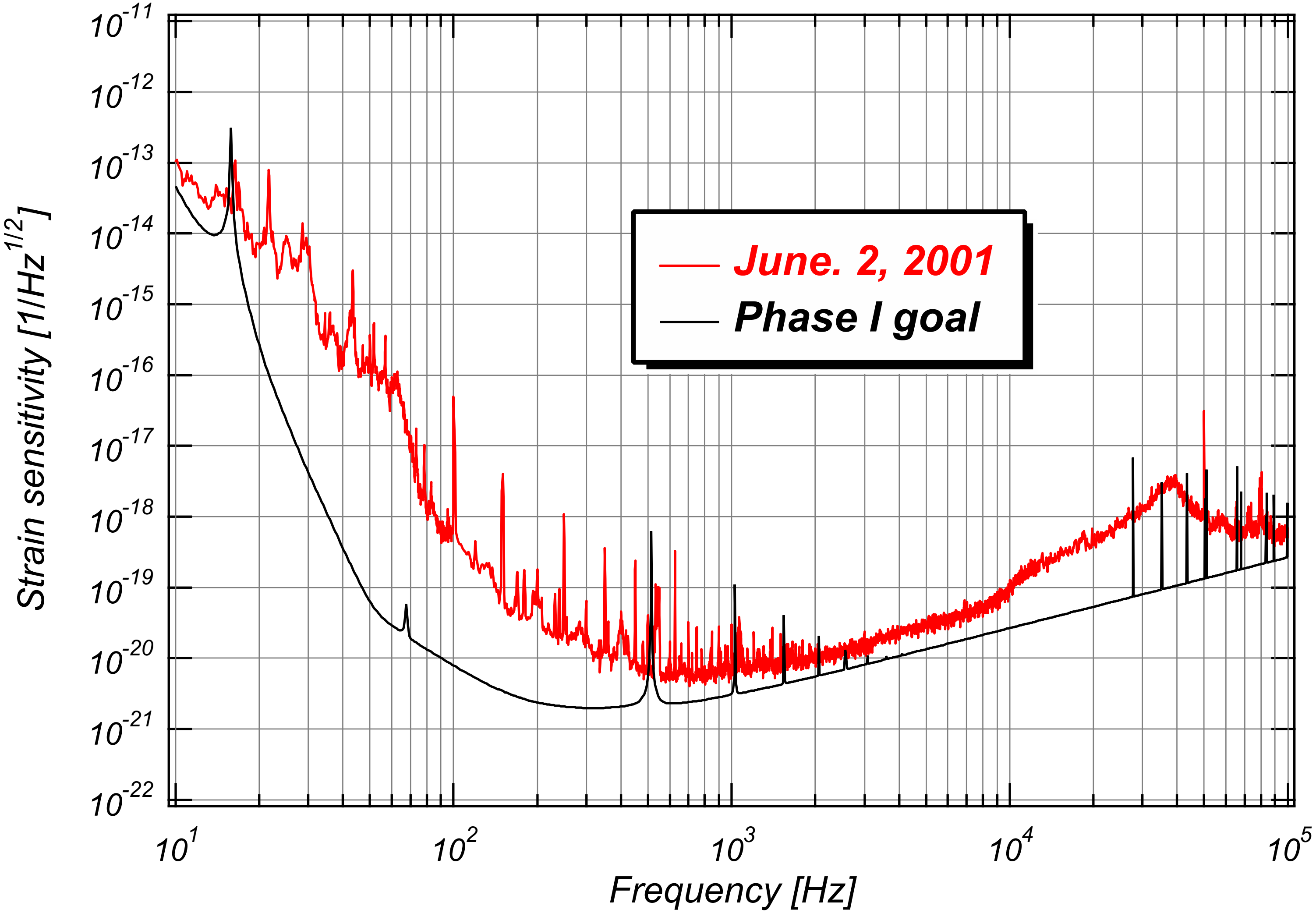
  - Coincidence with LISM 20m IFO at Kamioka mine

    Lock overlapping 709 h (59.1%)



Sensitivity of IFO at DT6

- Displacement noise $dx = 1.5 \times 10^{-18}$ m/Hz$^{1/2}$ (@700Hz)
  Strain sensitivity□ $h = dx/300$
  $= 5 \times 10^{-21}$ /Hz$^{1/2}$



Binary Range: 33kpc

(Distance to observe NS inspirals with SNR=10)

DT6 data analysis

- ***Binary inspiral search***

  Matched filtering search (1~2Msolar)

  Coincidence analysis

  between TAMA and LISM20m (1~2Msolar)

- ***Burst search***

  Non-Gaussianity detection using higher-order stat.

- ***Periodic GW search***

  Possible GW wave from SN1987a (@~935Hz)

GW search: compact binary inspirals

- ***Matched filtering analysis***

Upper limit to the galactic event rate:

□ □ □	Revent [/h]□	Revent [/y]□ □	Dobs□□	Tobs
□ DT2:	0.59□ /h□	$=5.2\times10^{3}$/year□	3.4kpc□	31h
□ DT4:	0.027□/h□	$=2.4\times10^{2}$/year□	17.9kpc□	167h
□ DT6:	0.0095/h□	$=8.3\times10^{1}$/year□	33.1kpc□	1038h

Matched Filtering analysis

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

  $h(t)$: known gravitational waveform (2.5PN template)

  $n(t)$: noise.

- Correlation of the detector output and the template in the frequency domain:

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

- Weighted by $S_n(f)$ noise spectrum density

- Signal to noise ratio $\mathrm{SNR} = \rho / \sqrt{2}$

- Find the optimal parameters

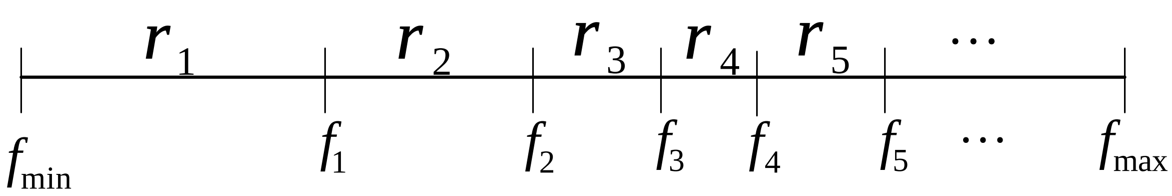
$$m_1, m_2, t_c, \ldots$$

  in a data chunk which maximizes ρ

c^2 test

Divide frequency region into bins.
Test whether the contribution to r from each bins agree with that expected from chirp signal

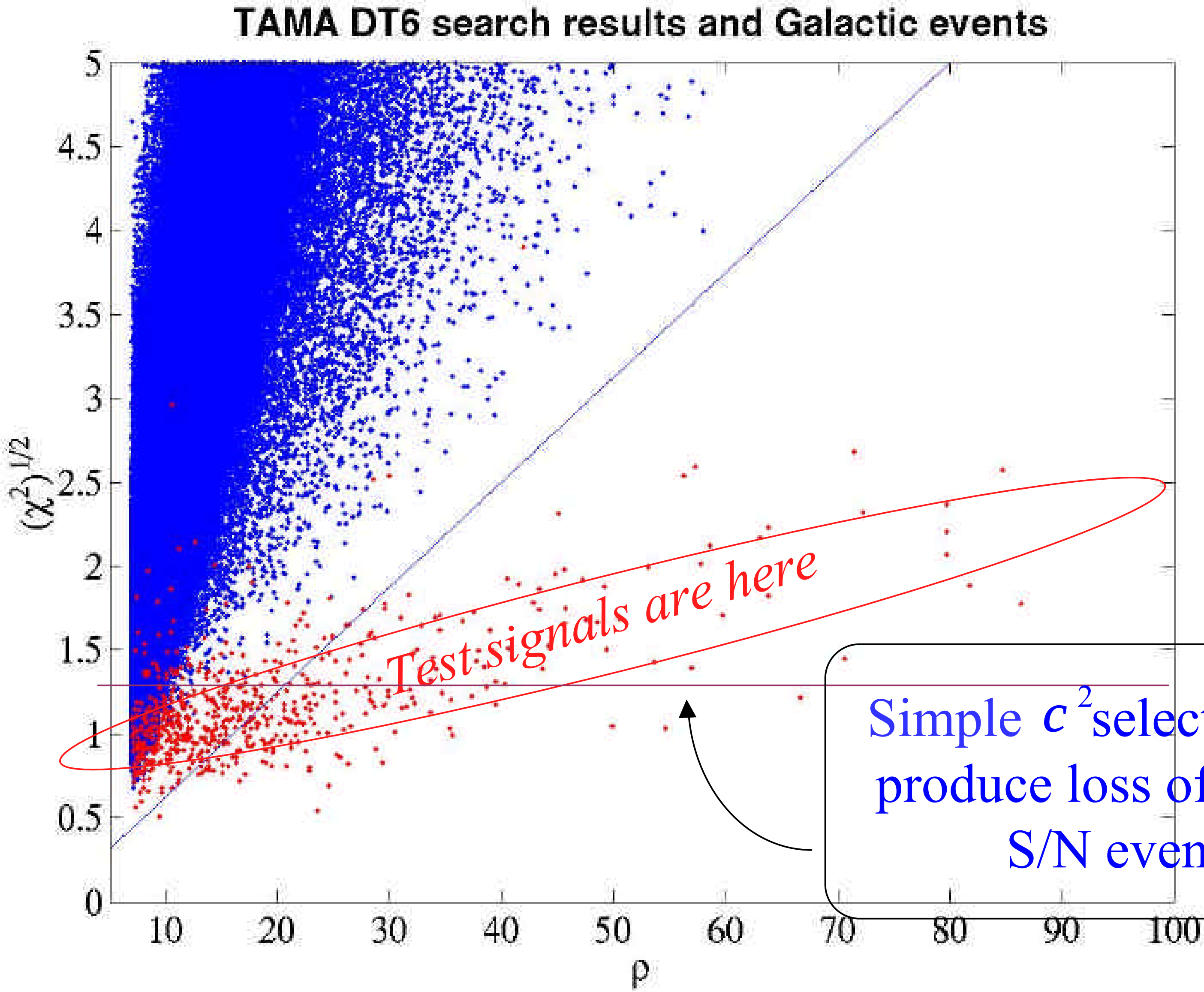
$$r \equiv (s, h) \quad \left(= 2 \int \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} df \right)$$



$$c^2 \equiv \sum \frac{1}{s_i^2} (r_i - \bar{r}_i)^2$$

$$s_i^2 \equiv \left\langle (r_i - \bar{r}_i)^2 \right\rangle, \quad \bar{r}_i = \left\langle r_i \right\rangle$$

Performance of $r/\sqrt{c^2}$ selection



Simple c^2 selection will produce loss of strong S/N events

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

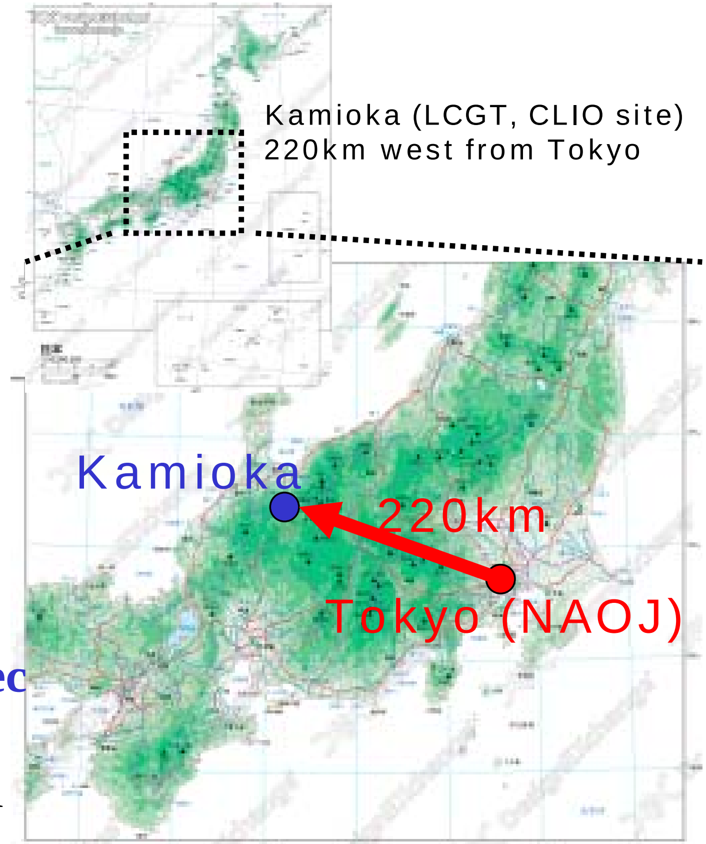
⇨ Upper limit to the Galactic event rate

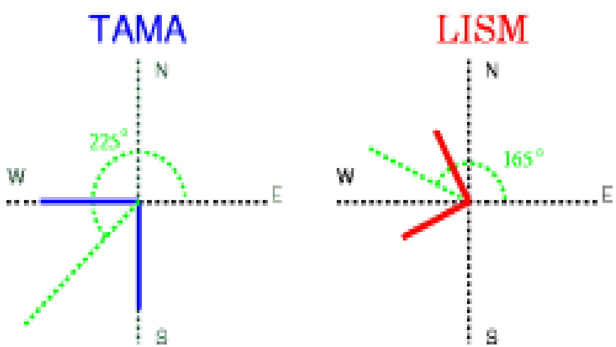
$$= \frac{\mathrm{N}}{T\varepsilon} = 0.0095 \ \ [1/\mathrm{hour}] \ \ (C.L. = 90\%)$$

Location of TAMA and LISM

	orientation	latitude	longitude
TAMA	225 °	35.68 ° N	139.54 ° E
LISM	165 °	36.25 ° N	137.18 ° E

- Distance between TAMA and LISM 〜 220km
- **Maximum delay of signal arrival time〜0.73msec**
- Relation between TAMA and LISM arms direction





Results of coincident event search

Results of onestep search for common lock parts

TAMA	LISM
158437 events	142465 events

↓

After t_c -coincidence

70 events

↓

After t_c, M, η -coincidence

18 events

↓

After t_c, M, η, ρ -coincidence

13 events

Results of coincident event search

Results of onestep search for common lock parts

TAMA	LISM
158437 events	142465 events

After t_c-coincidence — 70 events

accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$ — 70.45 ± 8.53

After t_c, M, η -coincidence — 18 events

accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$ — 17.55 ± 4.08

After t_c, M, η, ρ -coincidence — 13 event

accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$ — 12.76 ± 3.51

Coincident event search upper limit (4)

From above figure, we set threshold for each detector,

TAMA threshold : $\rho_{tama} / \sqrt{\chi^2_{tama}} = 6.2$

LISM threshold : $\rho_{lism} / \sqrt{\chi^2_{lism}} = 5.3$

Observed number of events over threshold: Nobs=0

Expected number of fake events over threshold : N_{bg}=0.72

We can obtain **the average number of events over threshold N=2.3 (C.L.=90%)**

- The second, we evaluated **detection efficiency ε**

we performed a Galactic event simulation (within 1kpc) .

Setting above thresholds, we can obtain the probability that we observe events over the each detector's threshold **(namely detection efficiency)** ⇒ **ε = 0.22**

- Length of data : **T=244 hours**

TAMA + LISM case

Upper limit to the Galactic (within 1kpc) event rate :

N/T ε = 0.042 events/hour (C.L. 90%)

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 (4)
--- DT6 data analysis ---

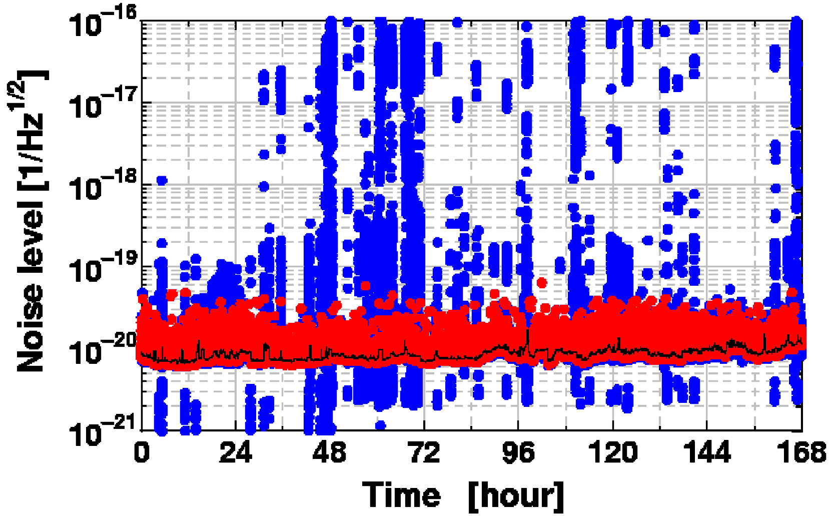
- **Data Taking 6 (Summer 2001)**
  -
  - **Bandwidth : 500Hz**
    Rejected data : 10%
    (False dismissal rate : 1ppm)

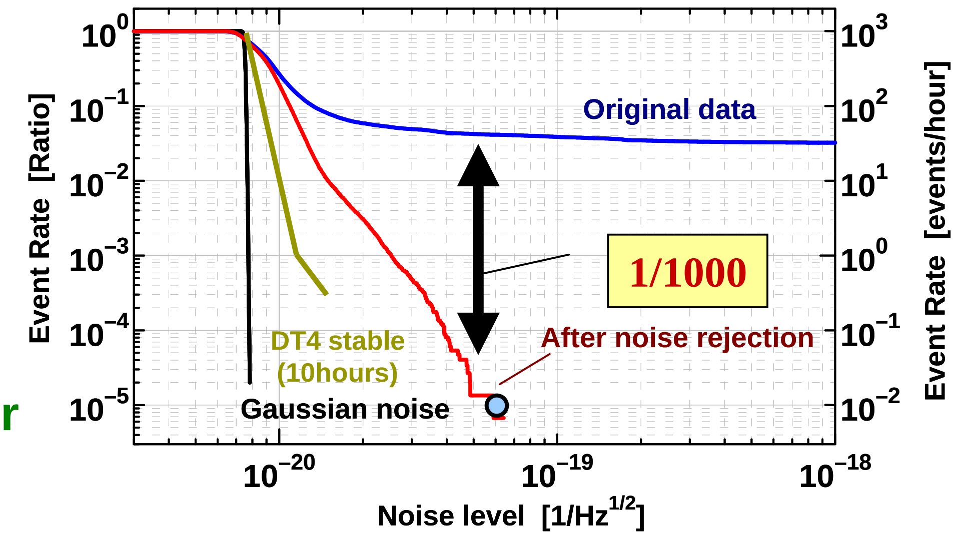
    ⇩

    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

- **Target: possible SN1987a remnant**

(Middleditch, et al. New Astronomy, 5 (2000) 243)

o **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: $2\sim3\times10^{-10}$ [Hz/s])

o **Search result: DT6 50days data**

Time-domain search: $h=3.8\times10^{-23}$ (False Alarm:1.8%)

Frequency domain search: $h=4.1\times10^{-23}$ (False Alarm:1.8%)

↕

($h_{upperlimit}$ from the spindown: $h=9.4\times10^{-27}$)

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Data Taking 8 (LIGO S2)

- **DT8 ~ 2 months run (2003/2/14~4/15)**

First full-time joint observation with LIGO S2

(c.f. DT7: partial participation of TAMA to S1)

First long-term observation with power recycling

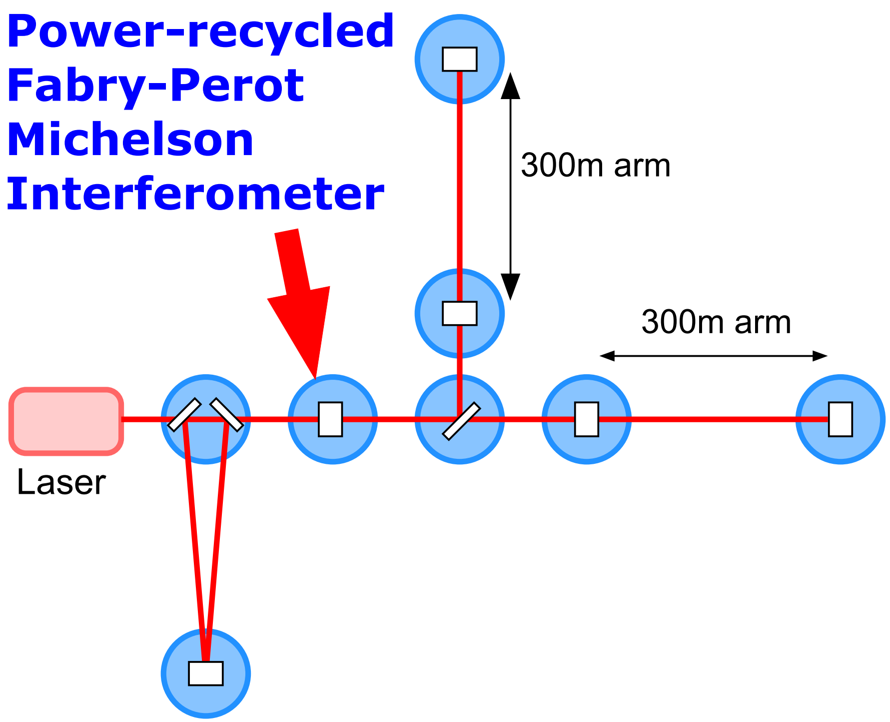
Power recycling of TAMA300 (2001/10~Present)

Power recycling gain of 4.5

Best sensitivity: 2.7×10^{-21} [$/\mathrm{Hz}^{1/2}$]

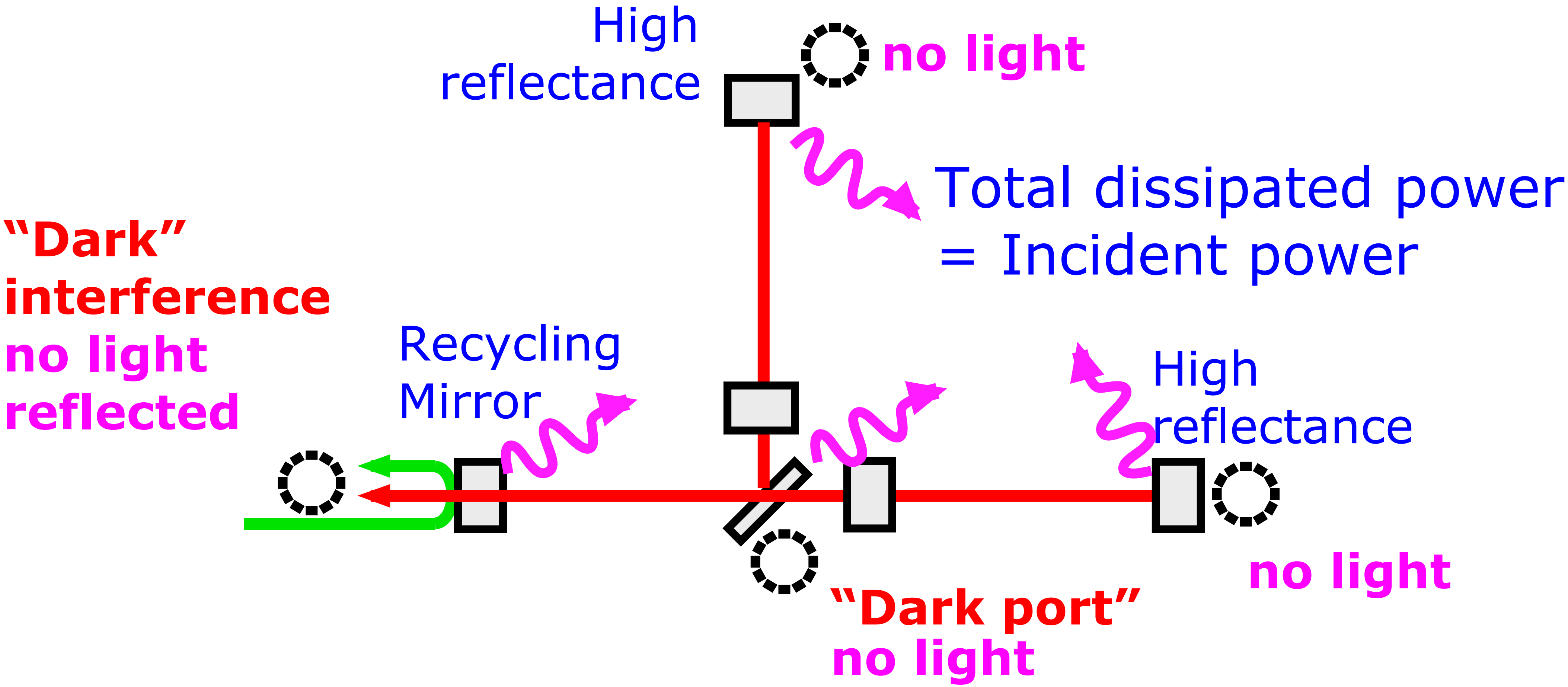
IFO operation

Accumulated data:	1158 hours
Duty cycle:	81.3 %
Longest lock:	20.5 hours



Principle of power recycling

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



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

DT8 ~ IFO development

l Fitting the IFO for DT8

Sensitivity

>> Improvement of the detection noise/shot noise level
by power recycling

>> Reduction of the frequency noise

Stability

>> Automatic lock system

>> Automatic alignment control for 4 test masses,
recycling mirror, and the mode cleaner mirrors

>> Optical axis control

Automatic lock acquisition

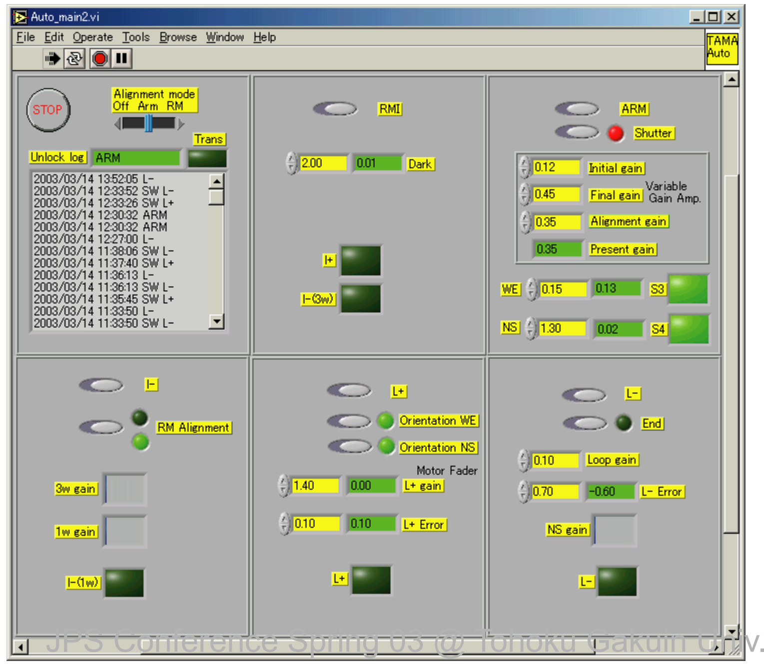
Self-switching sub-systems (Laser&MC)

MC frequency stabilization
MC alignment control
Laser intensity stabilization
Optical axis control
Injection lock servo of the laser

Digital switching using PC and Labview

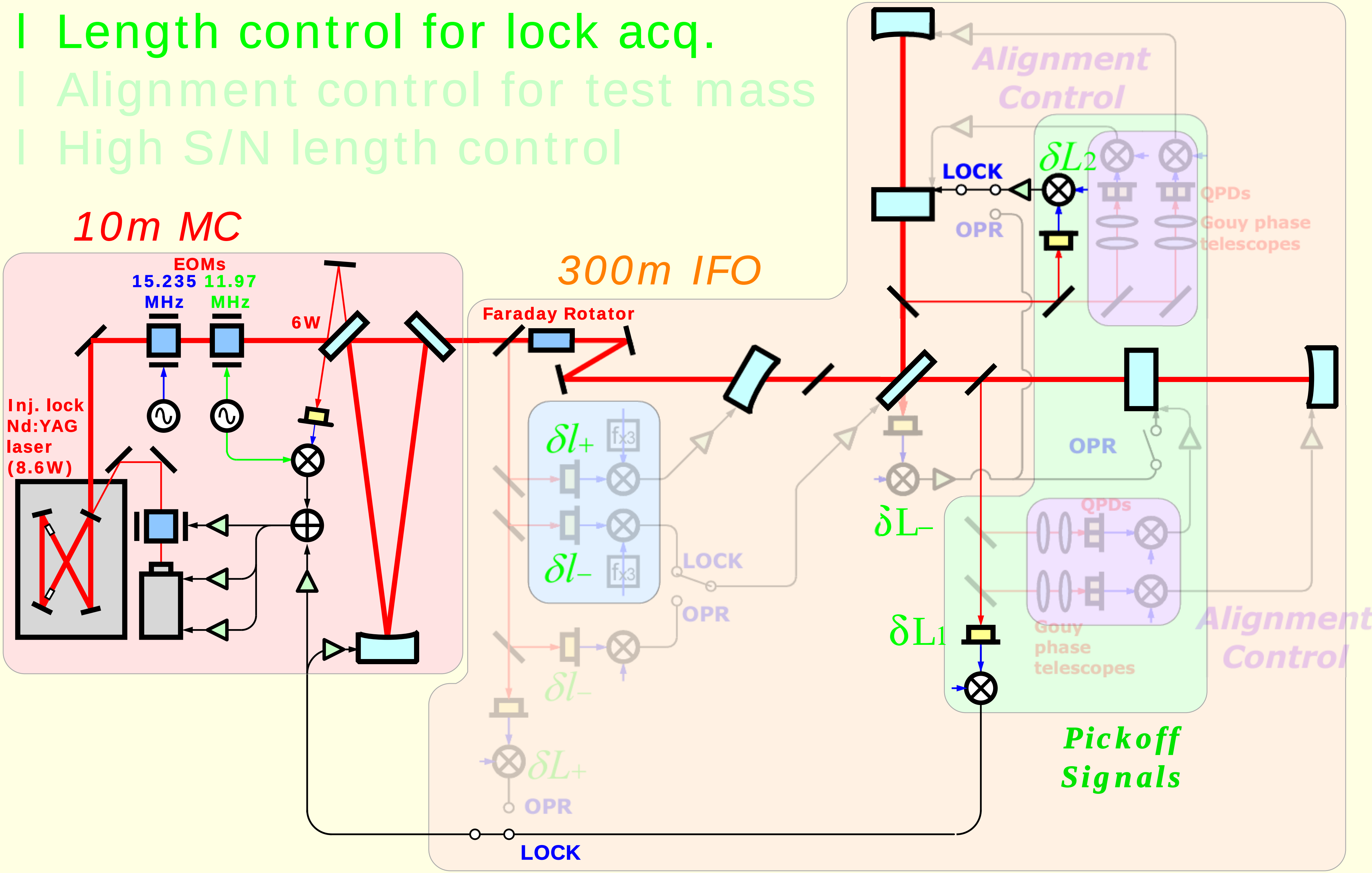
Lock acquisition
Manual mirror alignment
IFO Status monitoring

Hardware: PC + DAQ board
Software: National Instruments LabVIEW



Optical Config. and control system

- Length control for lock acq.
- Alignment control for test mass
- High S/N length control



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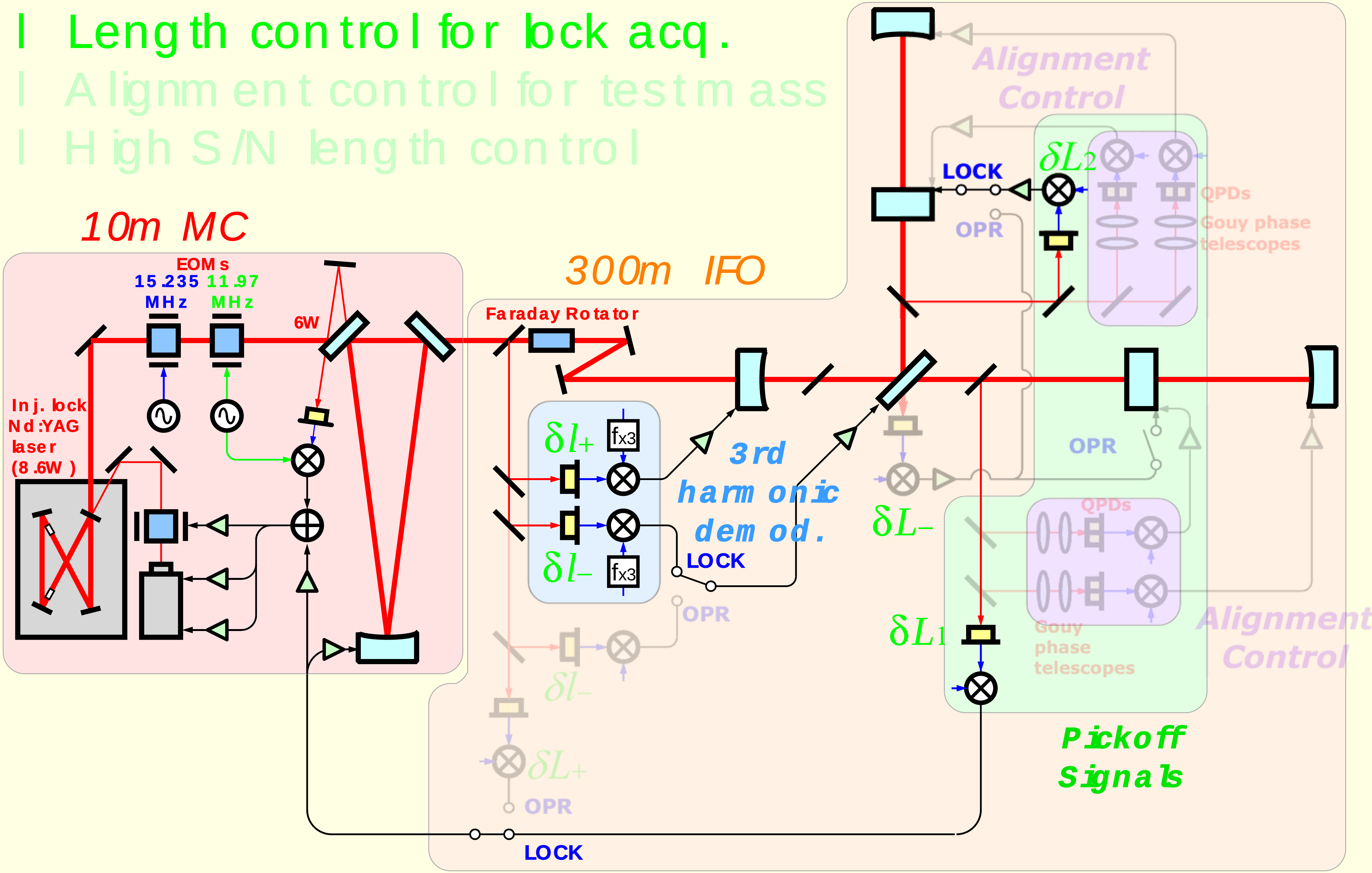

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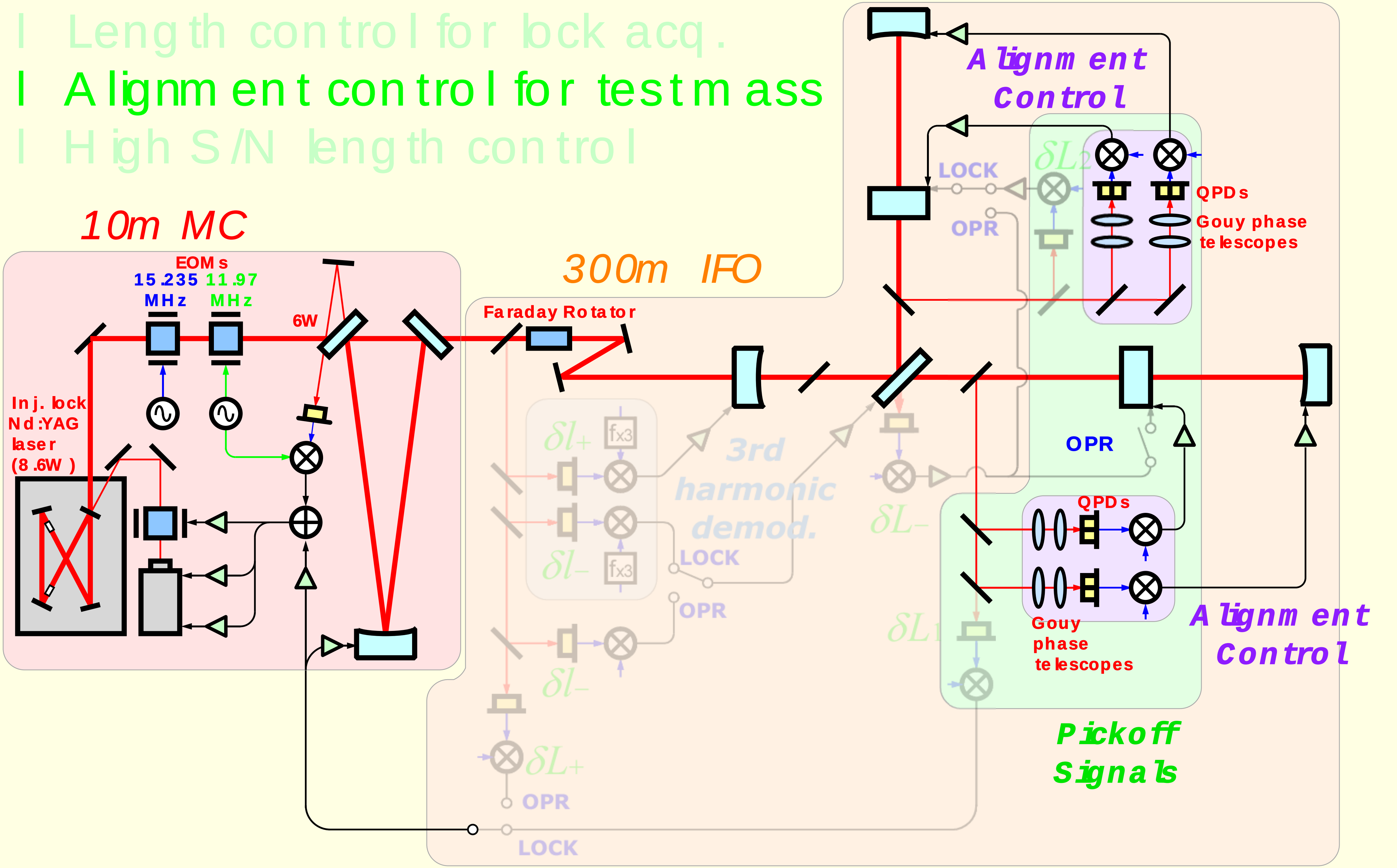

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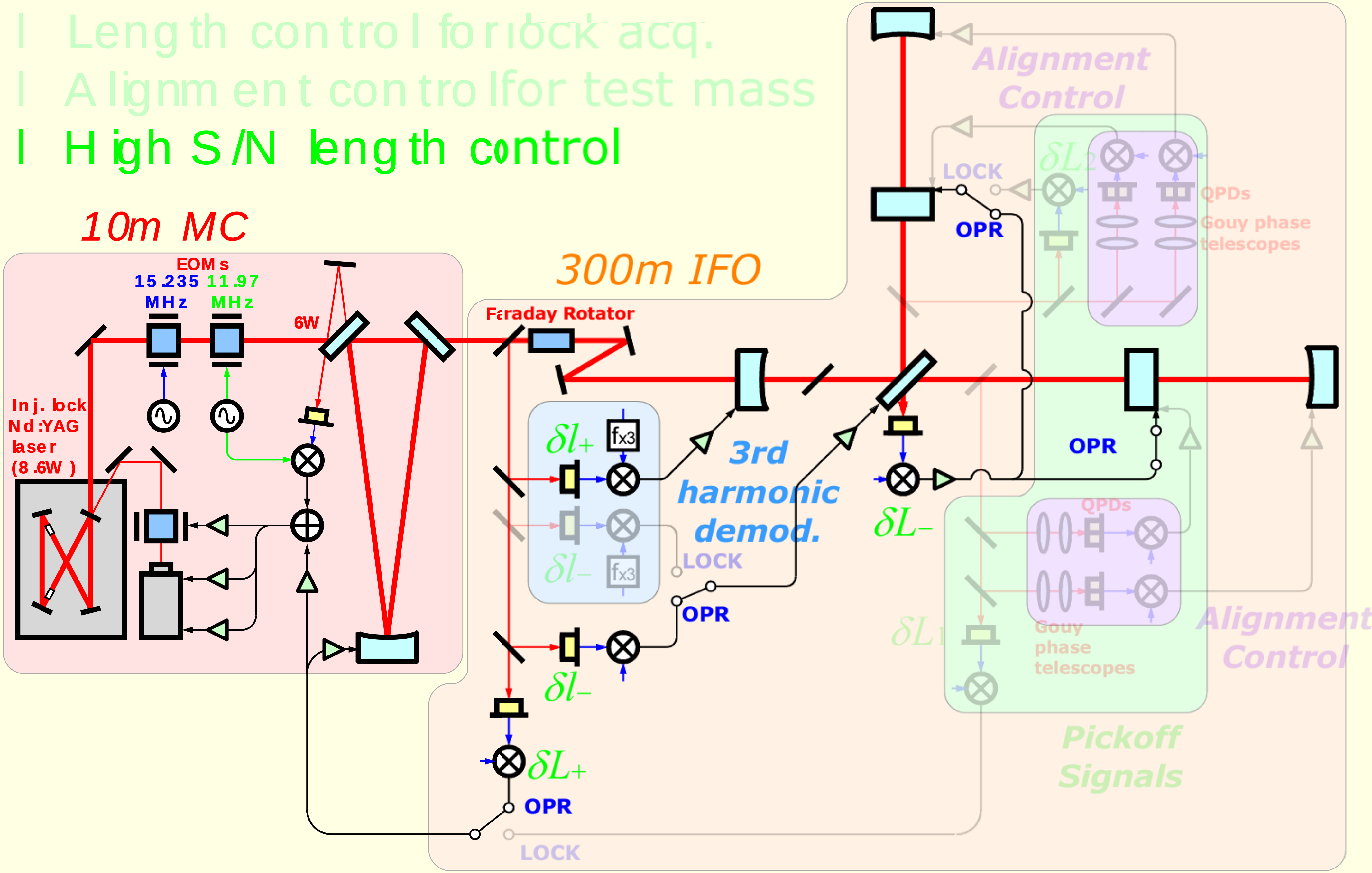
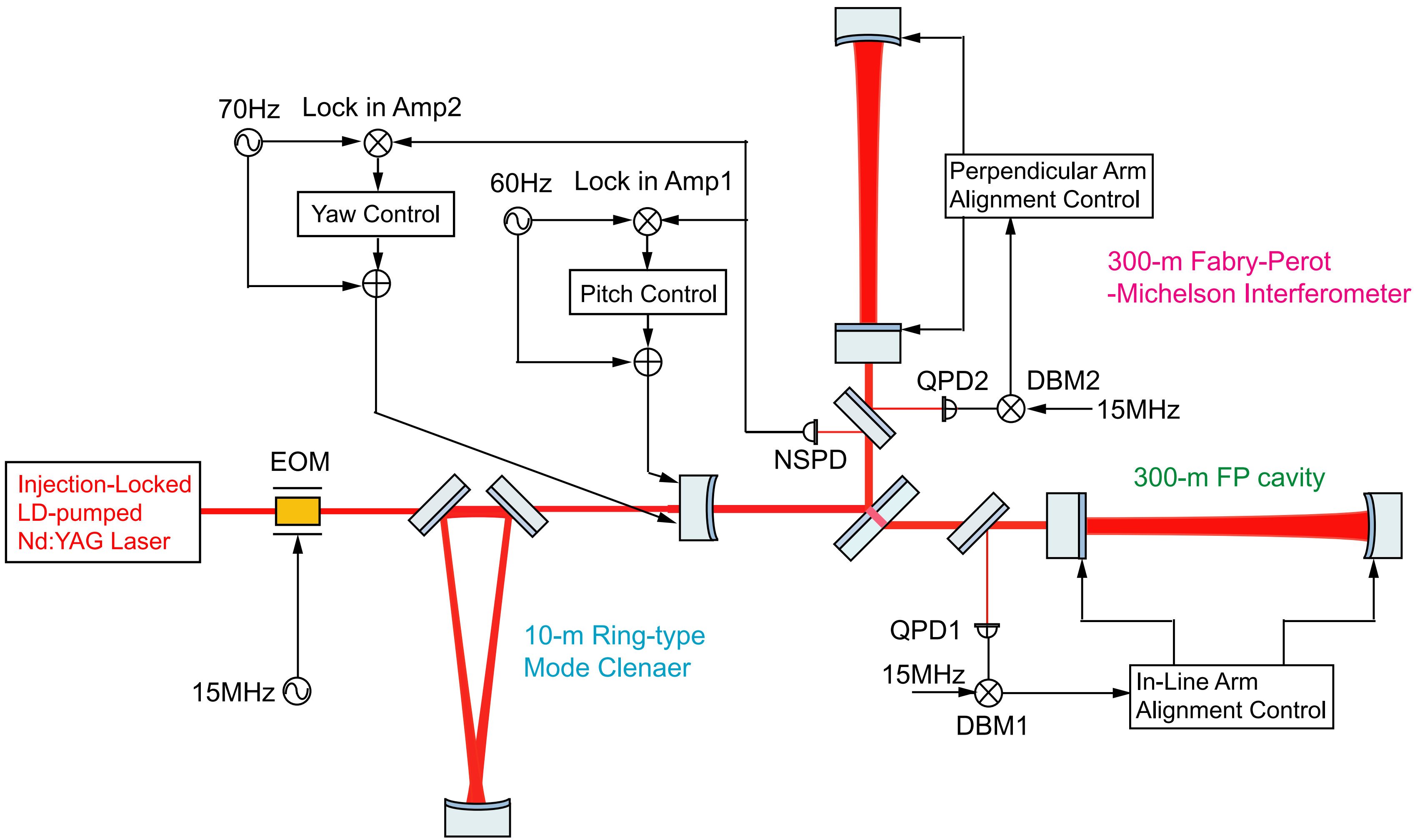


Alignment control

Alignment control servo for the recycling mirror

- ☐ Mechanical modulation technique (Pitch 60Hz, Yaw 70Hz)
- ☐ Suppress long-term drift => bandwidth < 1Hz

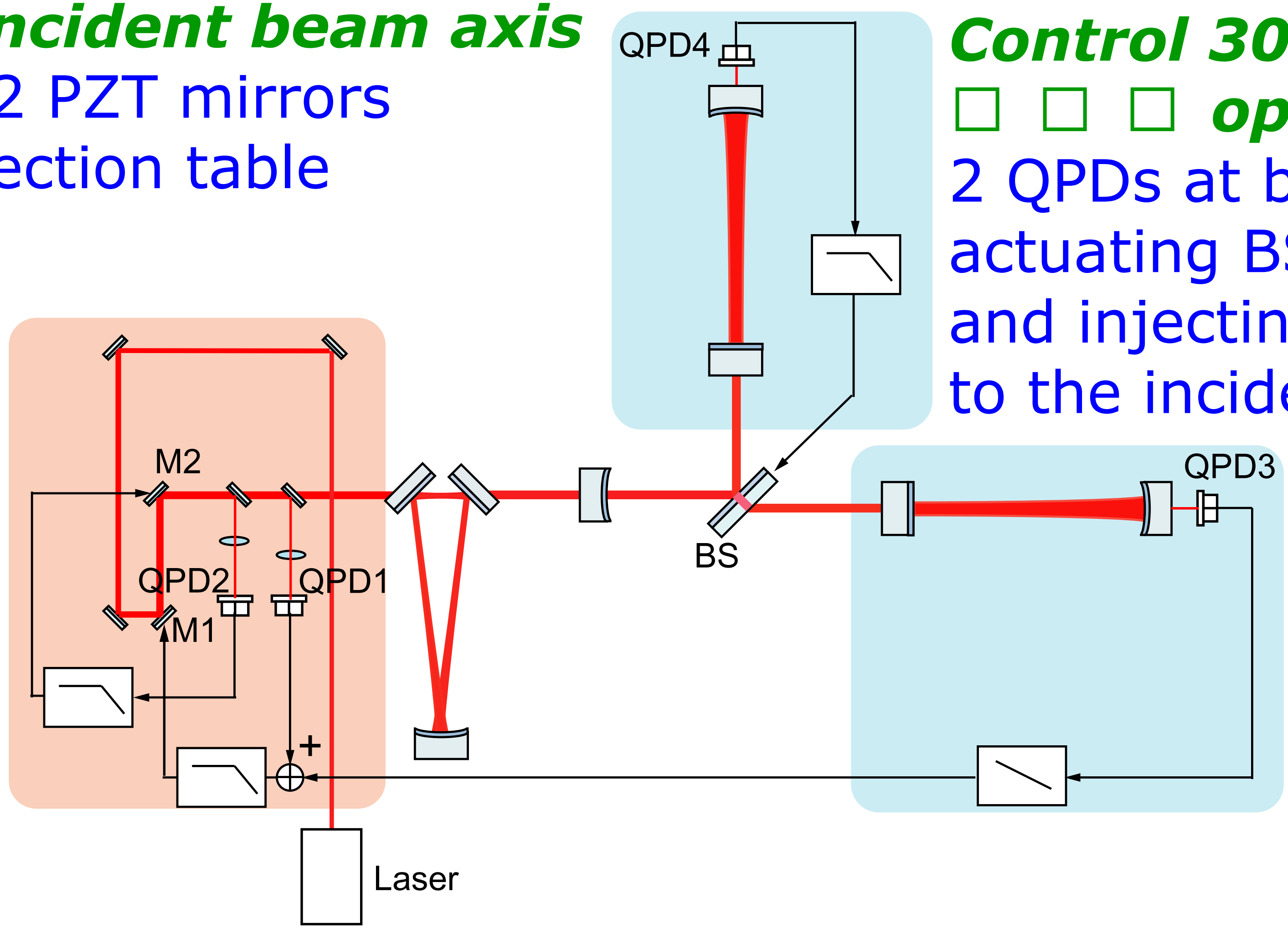
=> All of the five mirrors are controlled



Stabilizing optical axes

Control incident beam axis
2 QPDs / 2 PZT mirrors
on the injection table

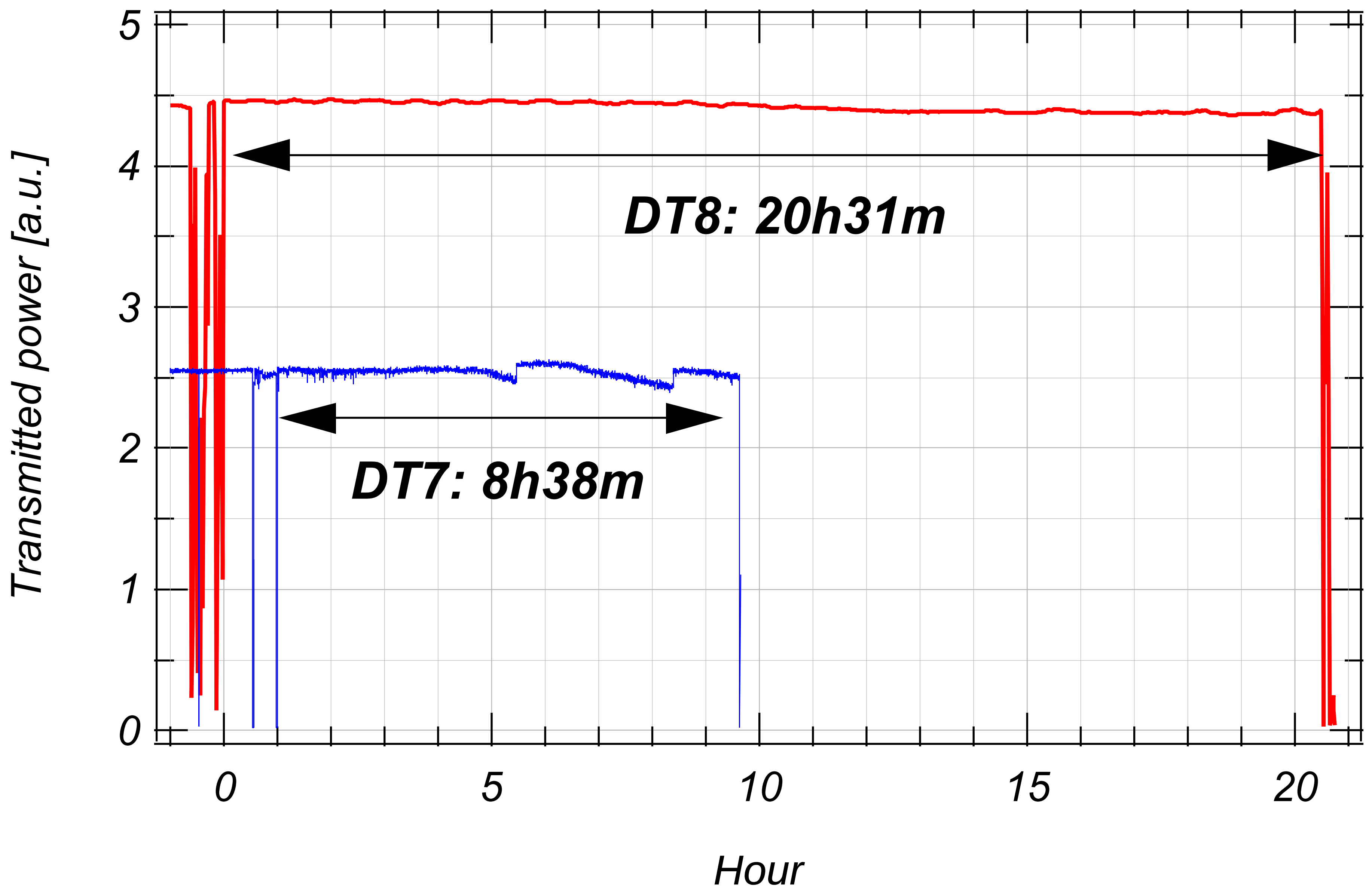
Control 300-m
□ □ □ optical axes
2 QPDs at both end
actuating BS
and injecting signal
to the incident axis servo



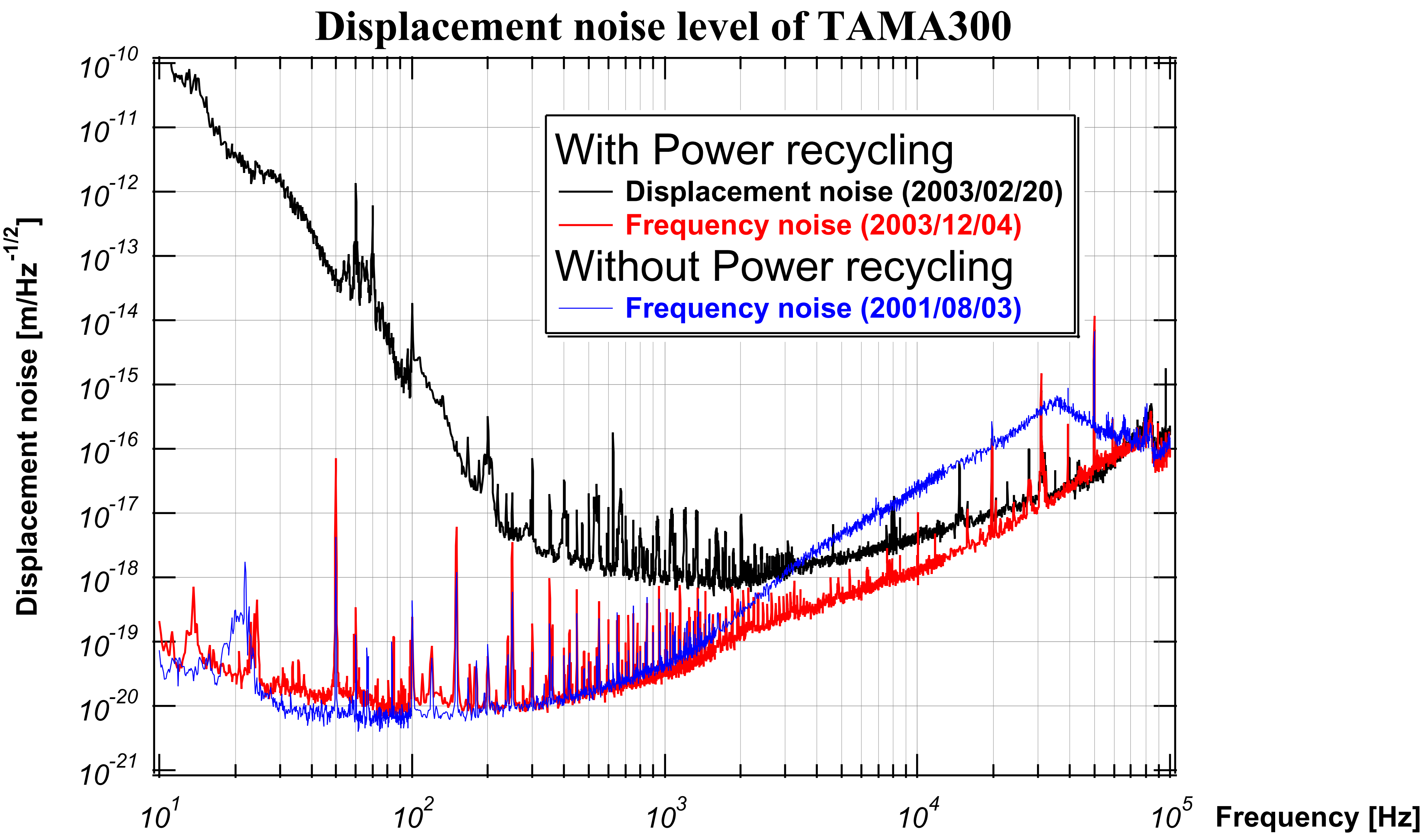
=> Minimizing the alignment noise coupling to dL-.
=> Improvement of the long-term stability of the main IFO,
□ □ as well as the long-term stability of the MC.

Improved long-term stability

Longest lock stretch in the observations



Frequency Stabilization

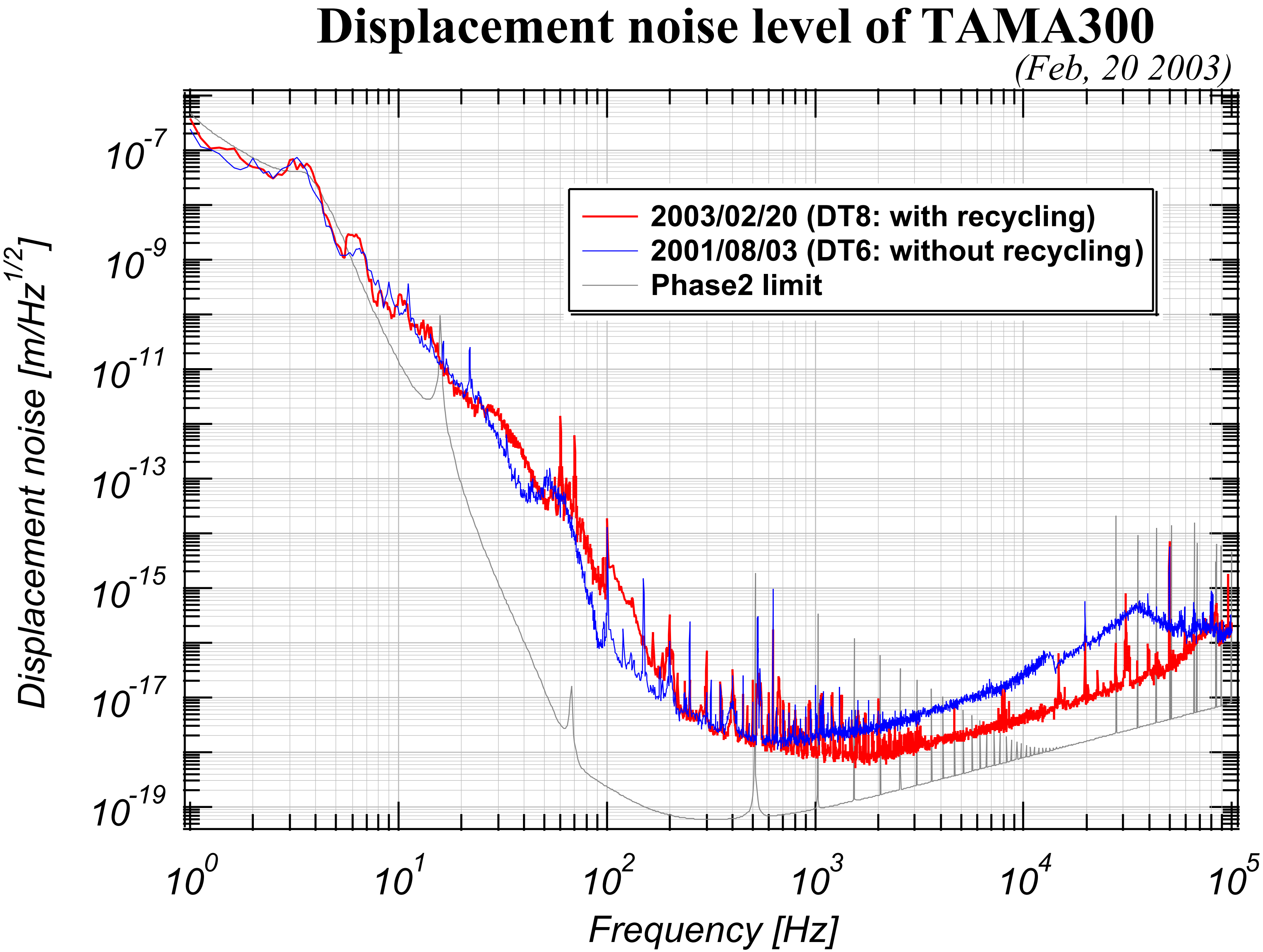


Control bandwidths extended:

□ □ MC servo□ □ □ □ □ (300kHz -> 600kHz)

□ □ Common-mode servo□ (□ 20kHz -> 40kHz)

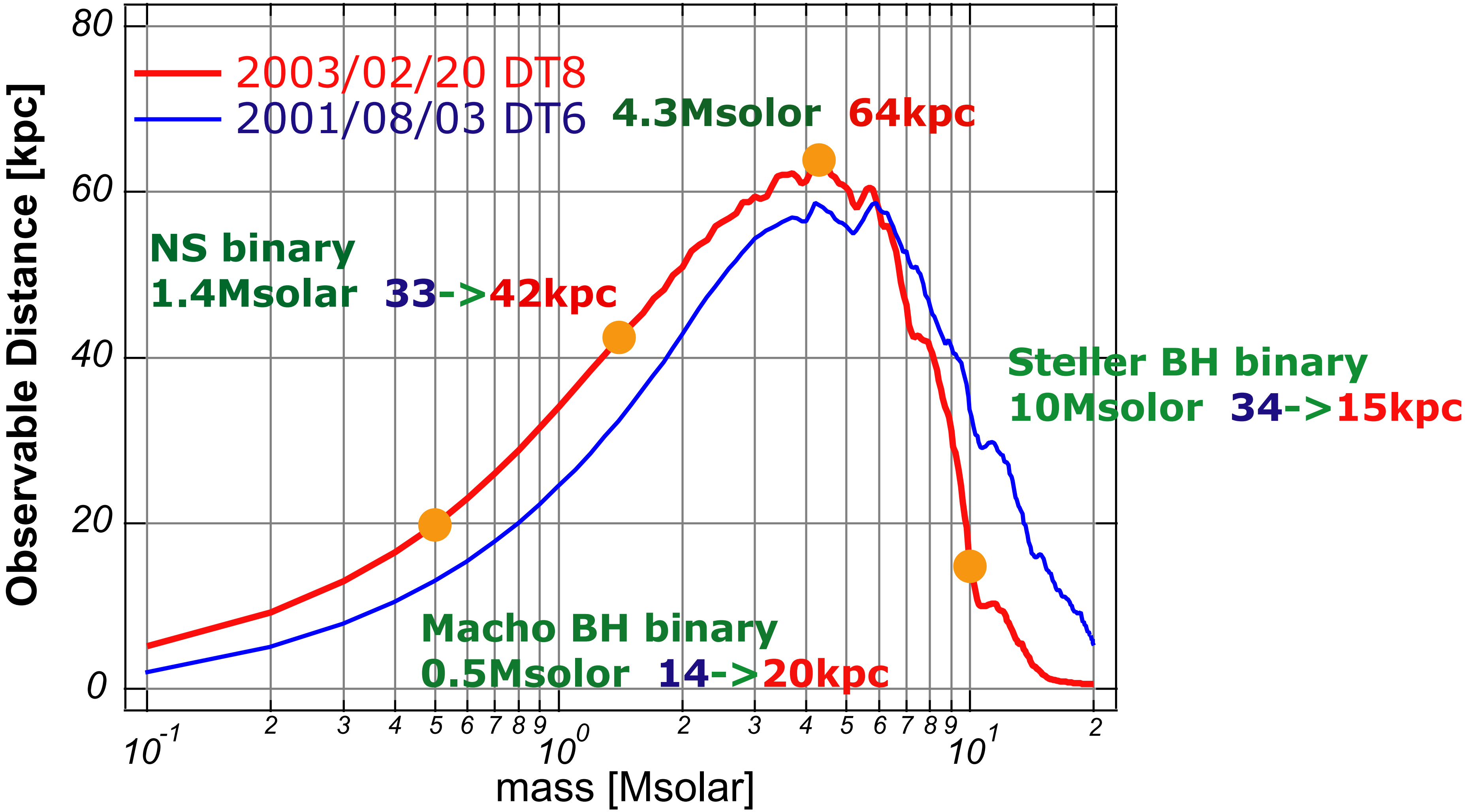
Sensitivty @ DT8



Floor level: 8×10^{-19} m/$Hz^{1/2}$□ (in displacement)

□ □ □ □ 2.7×10^{-21} /$Hz^{1/2}$□ (in strain)

Observable distance with SNR=10

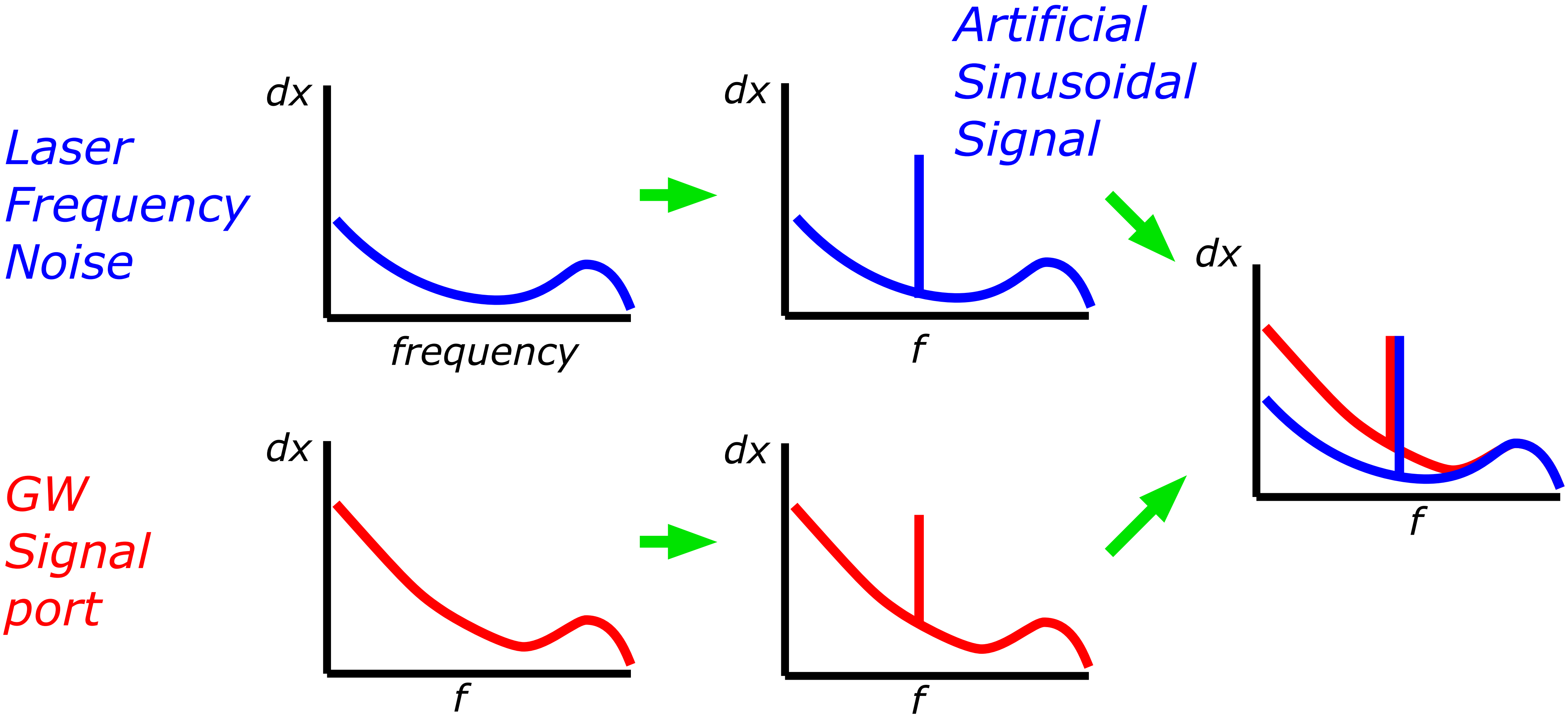


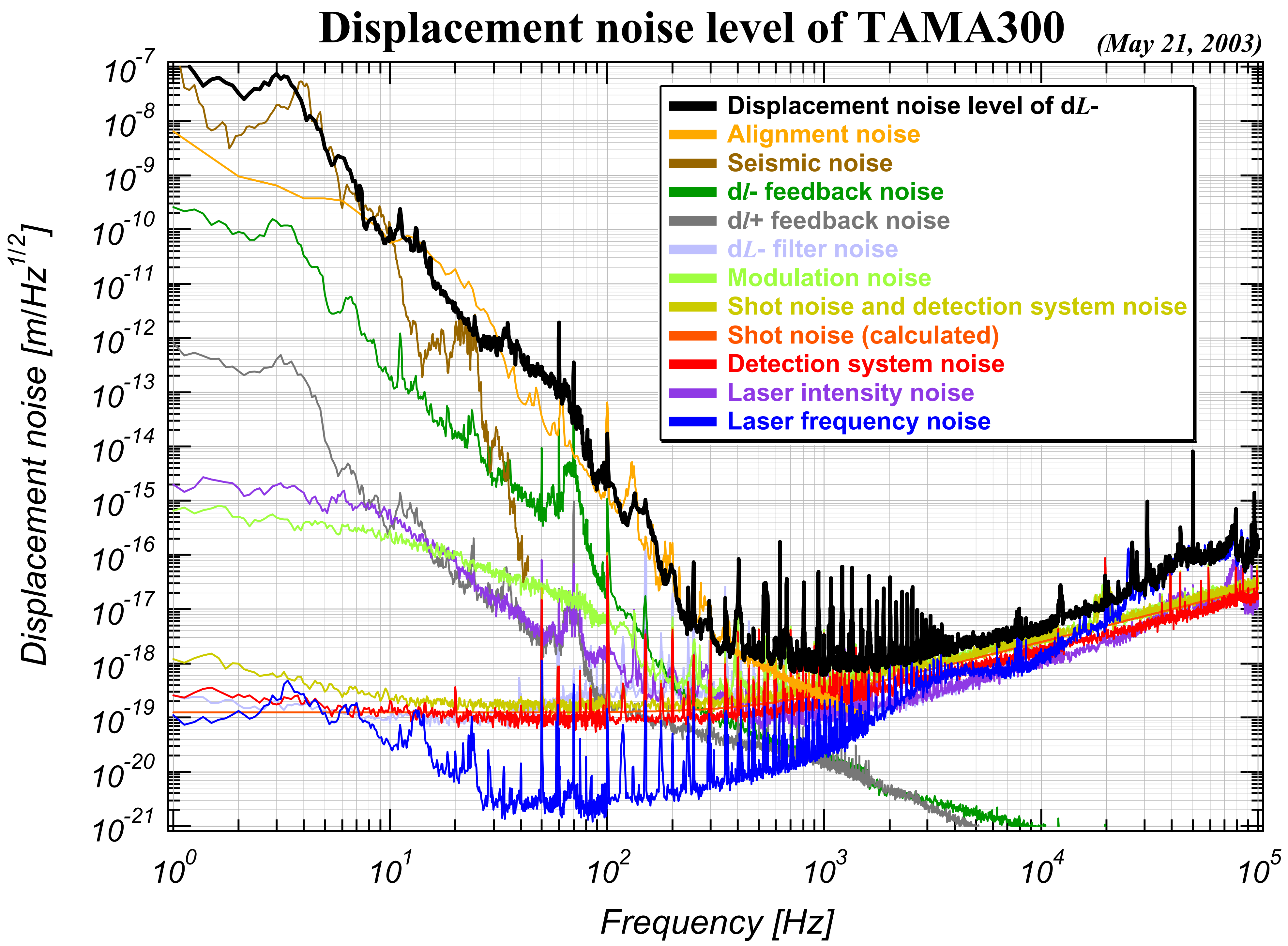
SNR improvement for 1.4-1.4Msolar and 0.5-0.5Msolar

Deterioration for 10-10Msolar caused by wideband alignment filters

Estimation of noise contributions

- **Noise estimation based on signal injection**

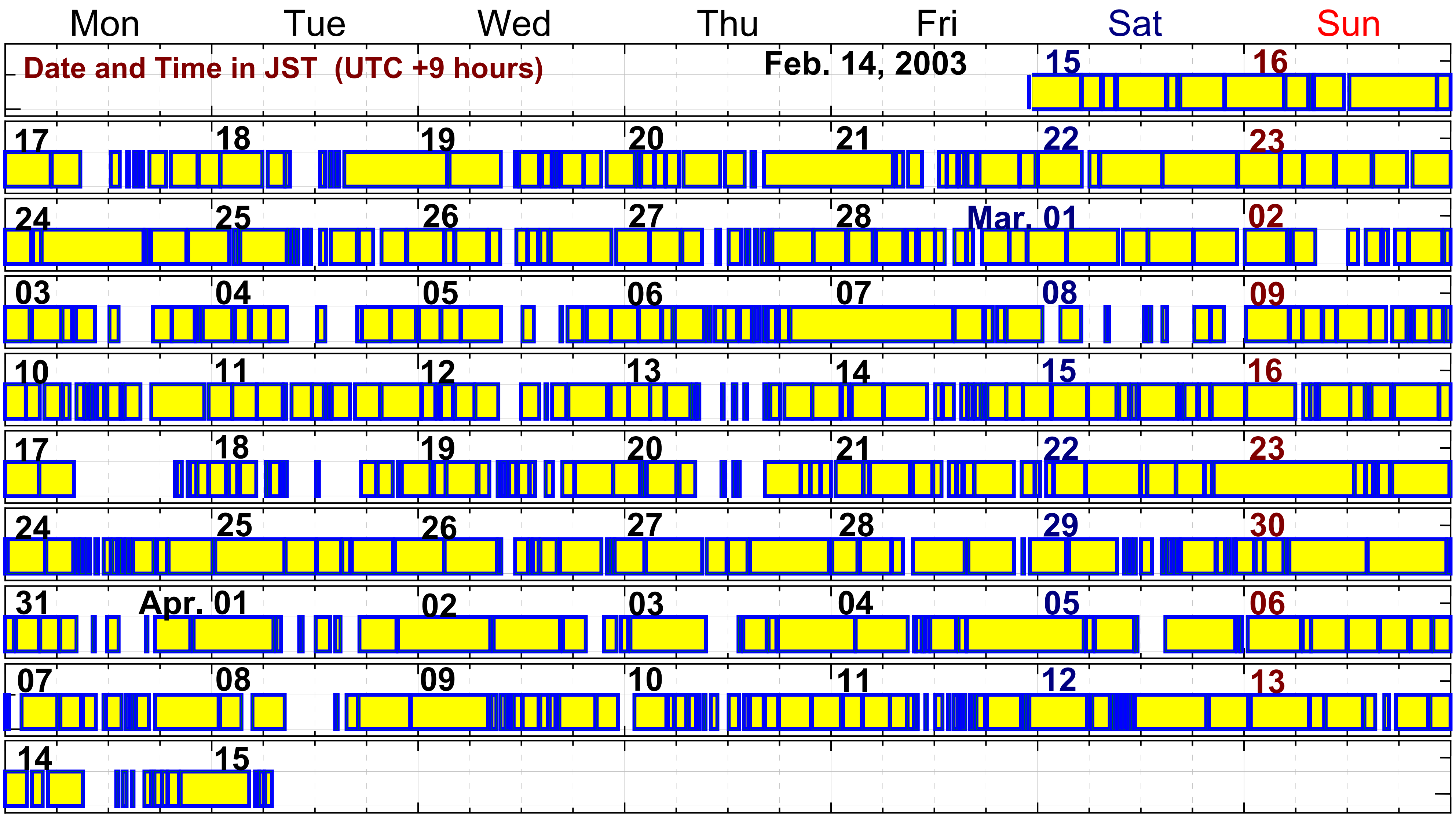




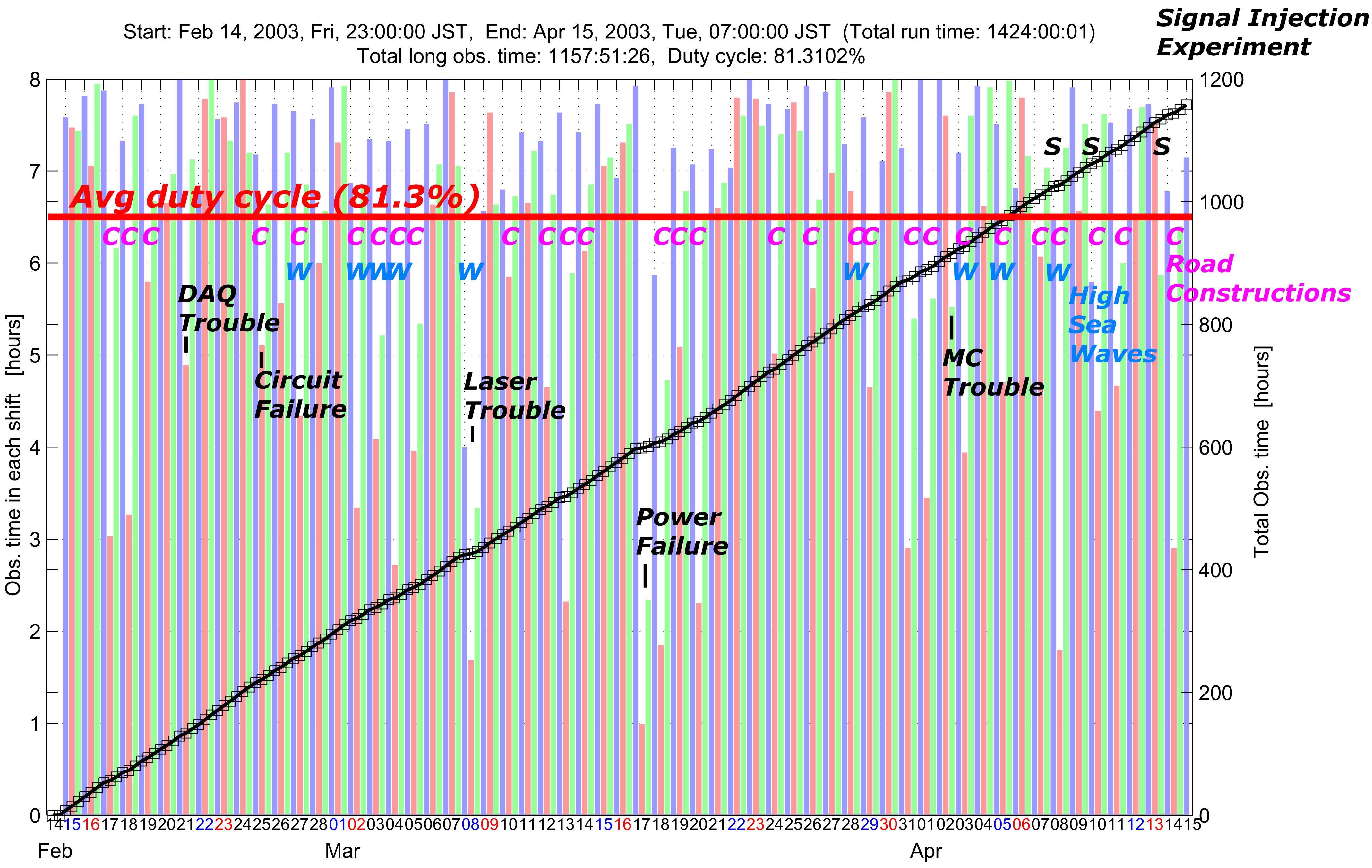
Displacement noise level of TAMA300
(May 21, 2003)
Displacement noise level of dL-
Alignment noise
Seismic noise
dl- feedback noise
dl+ feedback noise
dL- filter noise
Modulation noise
Shot noise and detection system noise
Shot noise (calculated)
Detection system noise
Laser intensity noise
Laser frequency noise
Displacement noise [m/Hz^1/2]
Frequency [Hz]

Observation calendar

- **1157h51m (out of 1424 hours, duty cycle 81.3%)**



Duty cycle



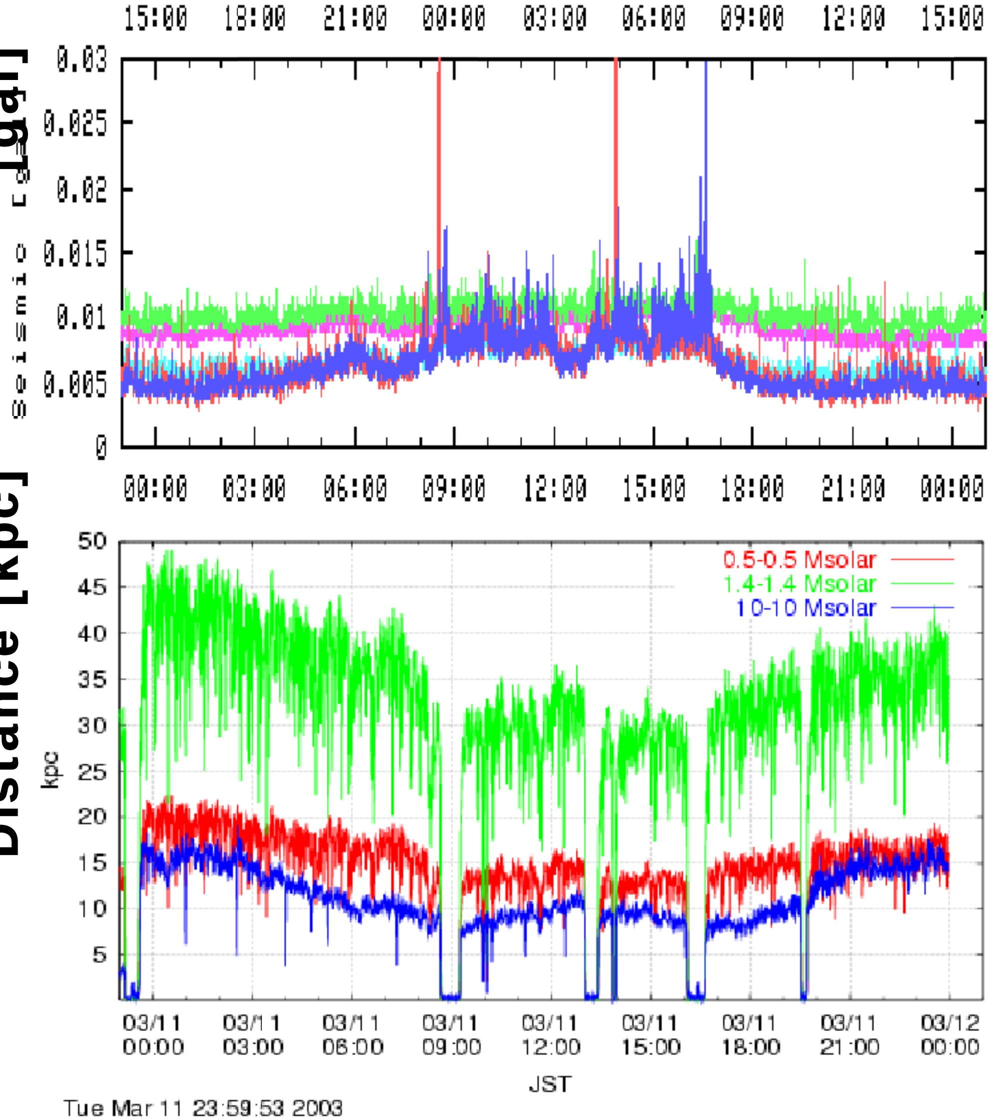
Signal Injection Experiment
Start: Feb 14, 2003, Fri, 23:00:00 JST, End: Apr 15, 2003, Tue, 07:00:00 JST (Total run time: 1424:00:01)
Total long obs. time: 1157:51:26, Duty cycle: 81.3102%
Avg duty cycle (81.3%)
DAQ Trouble
Circuit Failure
Laser Trouble
Power Failure
MC Trouble
Road Constructions
High Sea Waves
Obs. time in each shift [hours]
Total Obs. time [hours]
Feb
Mar
Apr

DT8 ~ Disturbance by construction

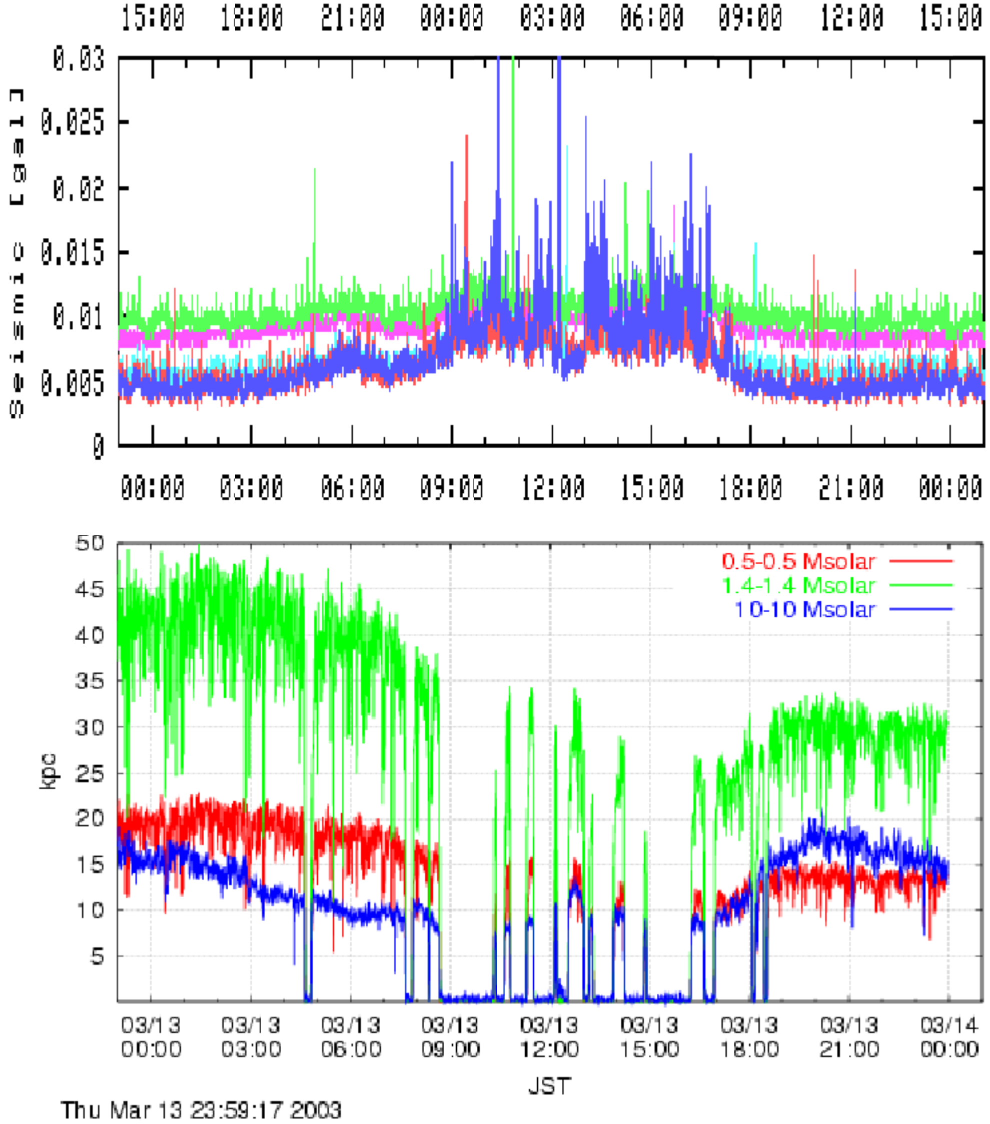
11th May, 2003 (Tue)
(Quiet weekday)

Seismic level [gal]

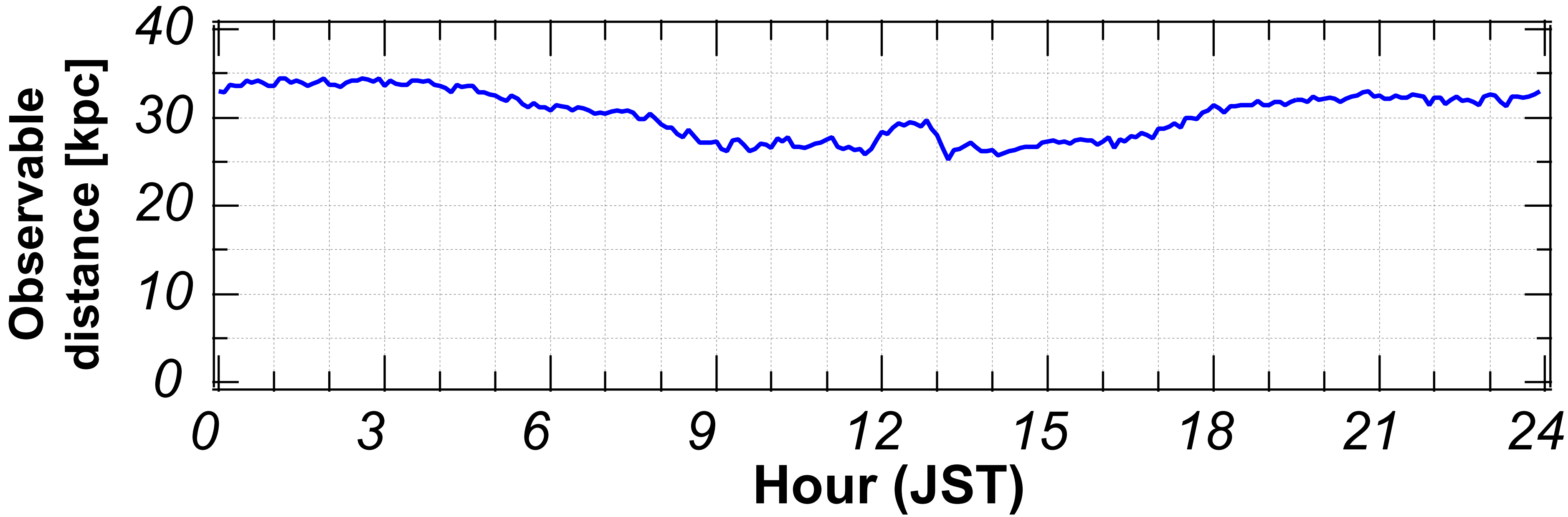
Observable Distance [kpc]

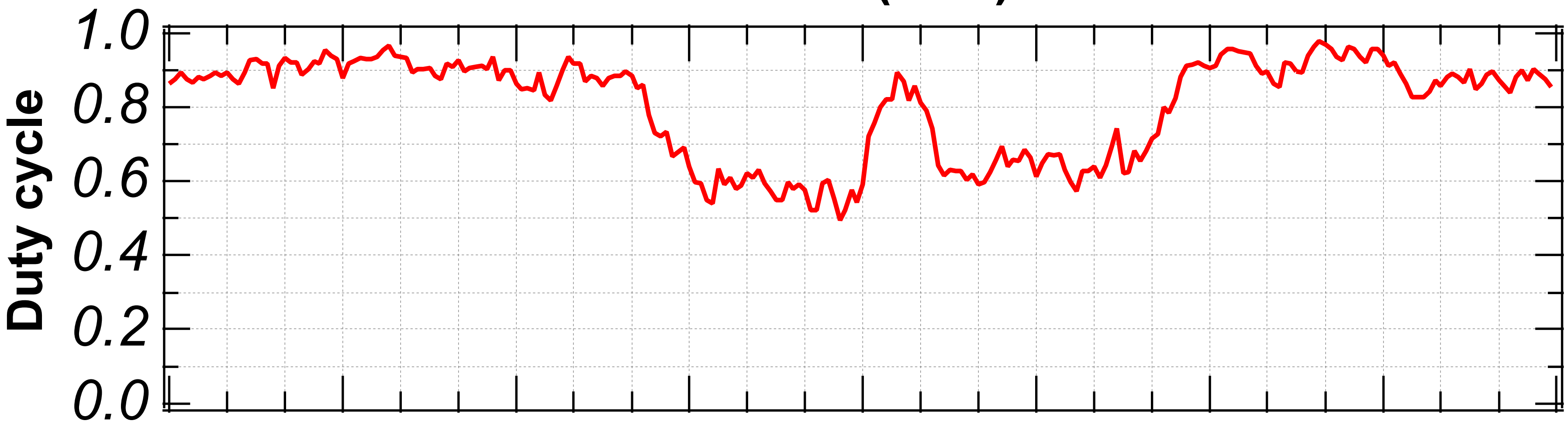


13rd May, 2003 (Thu)
(Noisy weekday)



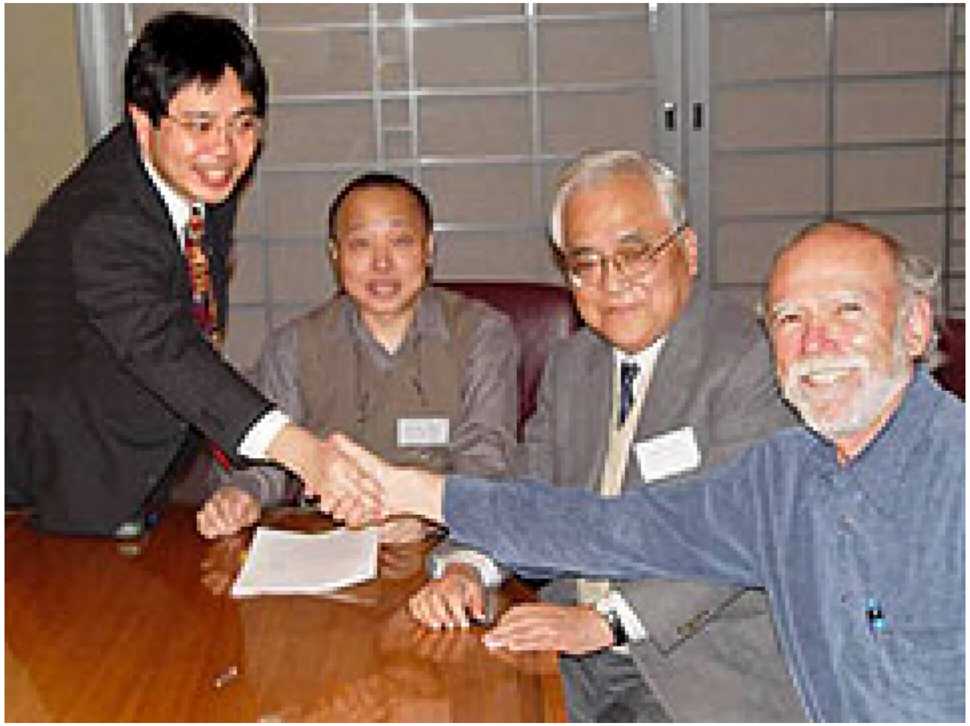
Daily trend of duty cycle/binary range





TAMA-LSC working group

- **Concluded the MOU between TAMA and LSC at GWDAW 2002 in Kyoto**



The photograph excerpted from LIGO News

Discussions for the joint data analysis are now underway!

WG members

- Masaki Ando (University of Tokyo)
- Patrick Brady (University of Wisconsin-Milwaukee)
- Sam Finn (Pennsylvania State University)
- Nobuyuki Kanda (Osaka City University)
- Erik Katsavounidis (MIT)
- Albert Lazzarini (Caltech)
- Hideyuki Tagoshi (Osaka University)
- Ryutaro Takahashi (National Astronomical Observatory of Japan)
- Daisuke Tatsumi (National Astronomical Observatory of Japan)
- Peter Saulson (Syracuse University)

Future Plan

- ***Data Analysis of the DT8 data***
  In progress

- ***IFO: sufficient stability for long-term obs.***
  Concentrate on the noise issues

- ***Further automation of the observation***
  To operate the interferometer with less
  numbers of the interferometer experts
  on the observations

  Ultimately toward a contiunuous observation

Summary

- ***Interferometric GW detector TAMA300***
- ***Data Analysis using DT6 data***

Binary ispirals: R_event<0.0095/hr
coincident search with LISM20m

Burst search: Reduction of the IFO related noise
R_event<0.01/hr for $h_{rms}=3x10^{-17}$

CW search: Possible 1987A pulsar ~935Hz
$h<4x10^{-23}$

- ***Data Taking 8***

Full-time observation with LIGO S2

Power recycling

Improvement of the sensitivity

$h = 2.7 x 10^{-21}$ /sqrtHz @1.5kHz

1158 hours of 1424 hours => duty cycle 81.3%