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***

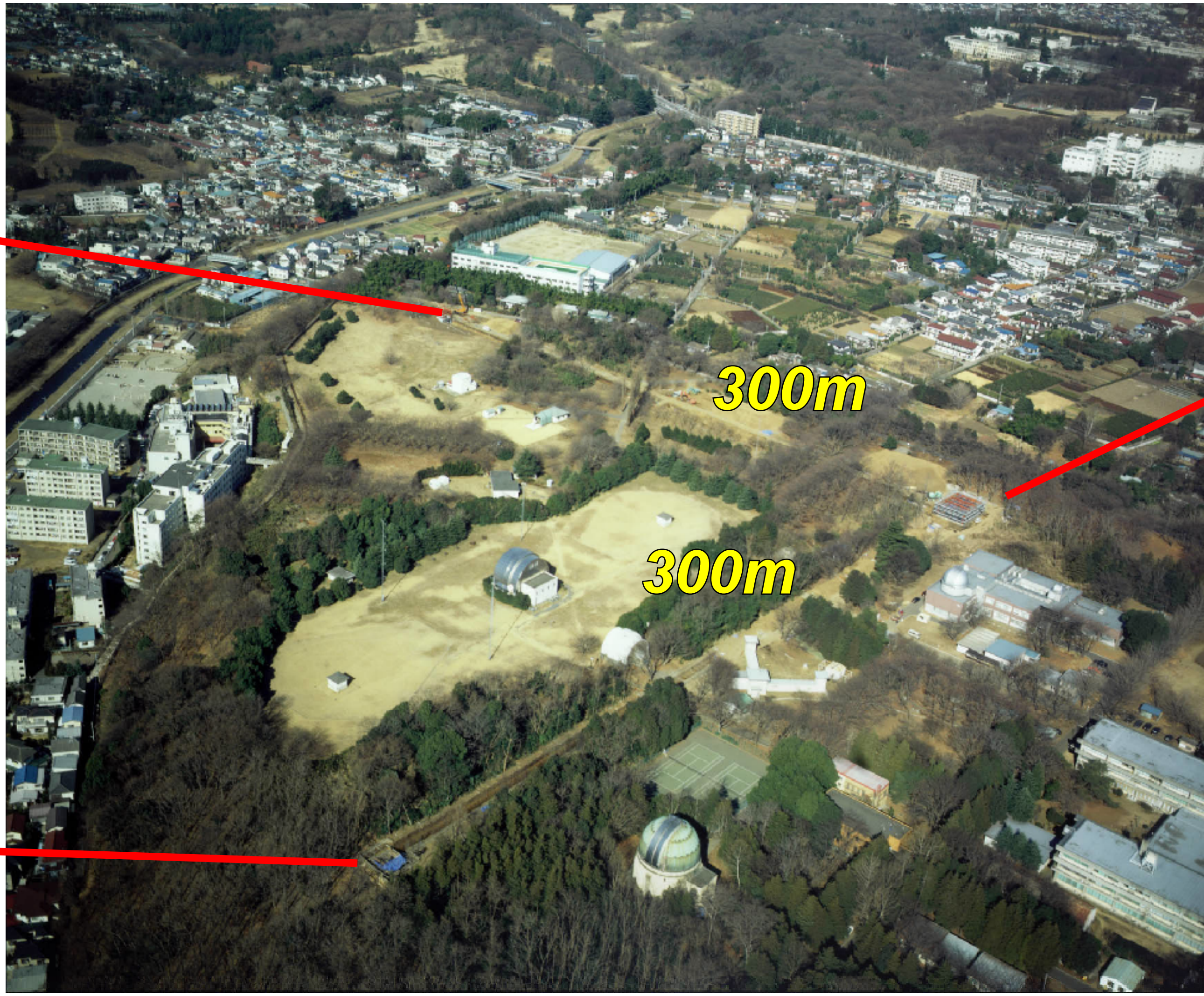
  To develop a detector capable to detect GW events
  □ □ □ □ □ □ □ □ □ □ □ □ □ □ in nearby galaxies.
  To establish techniques for a future km-class interferometer

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

Bird's view of the TAMA site

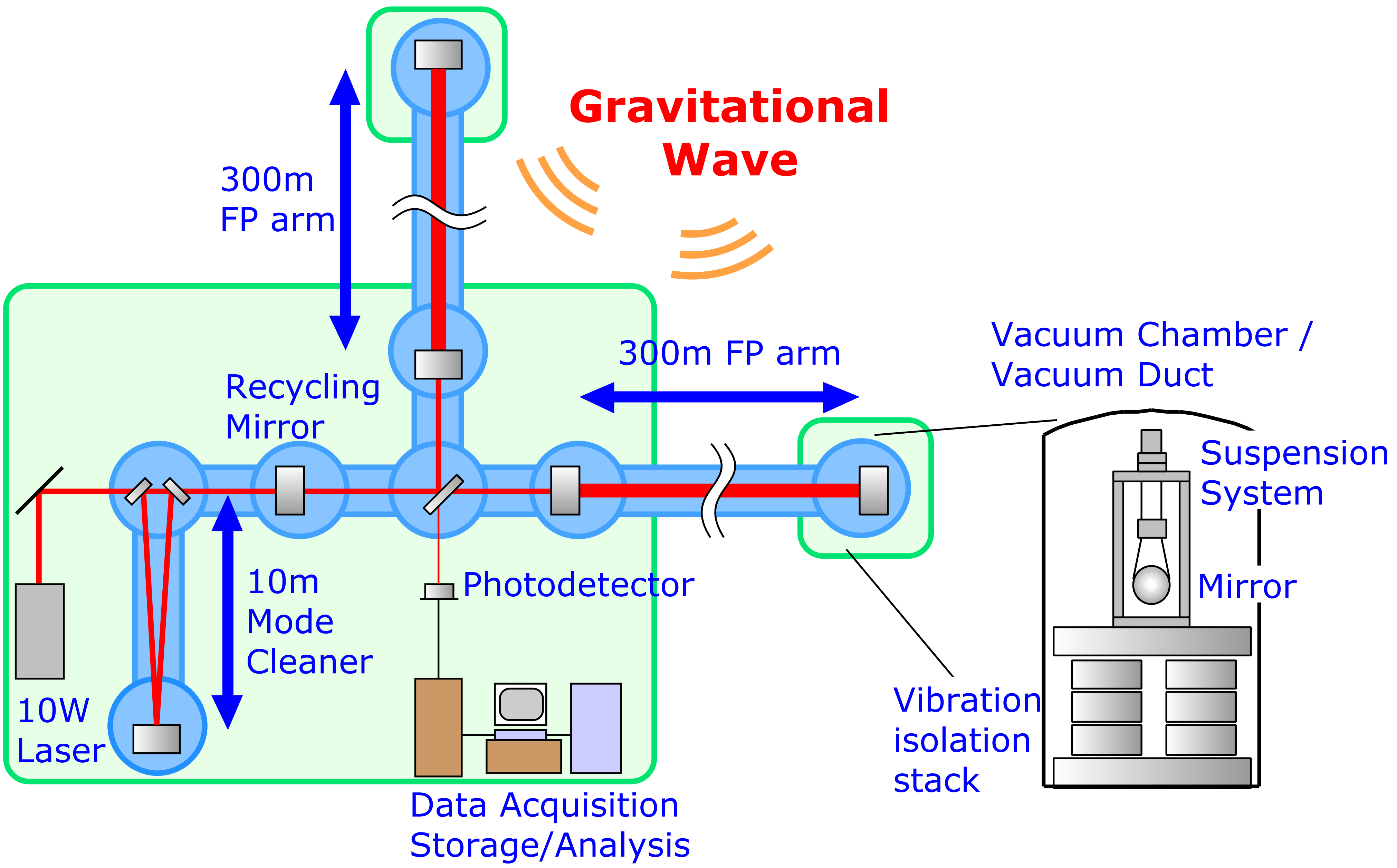
- **National Astronomical Observatory of Japan**

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

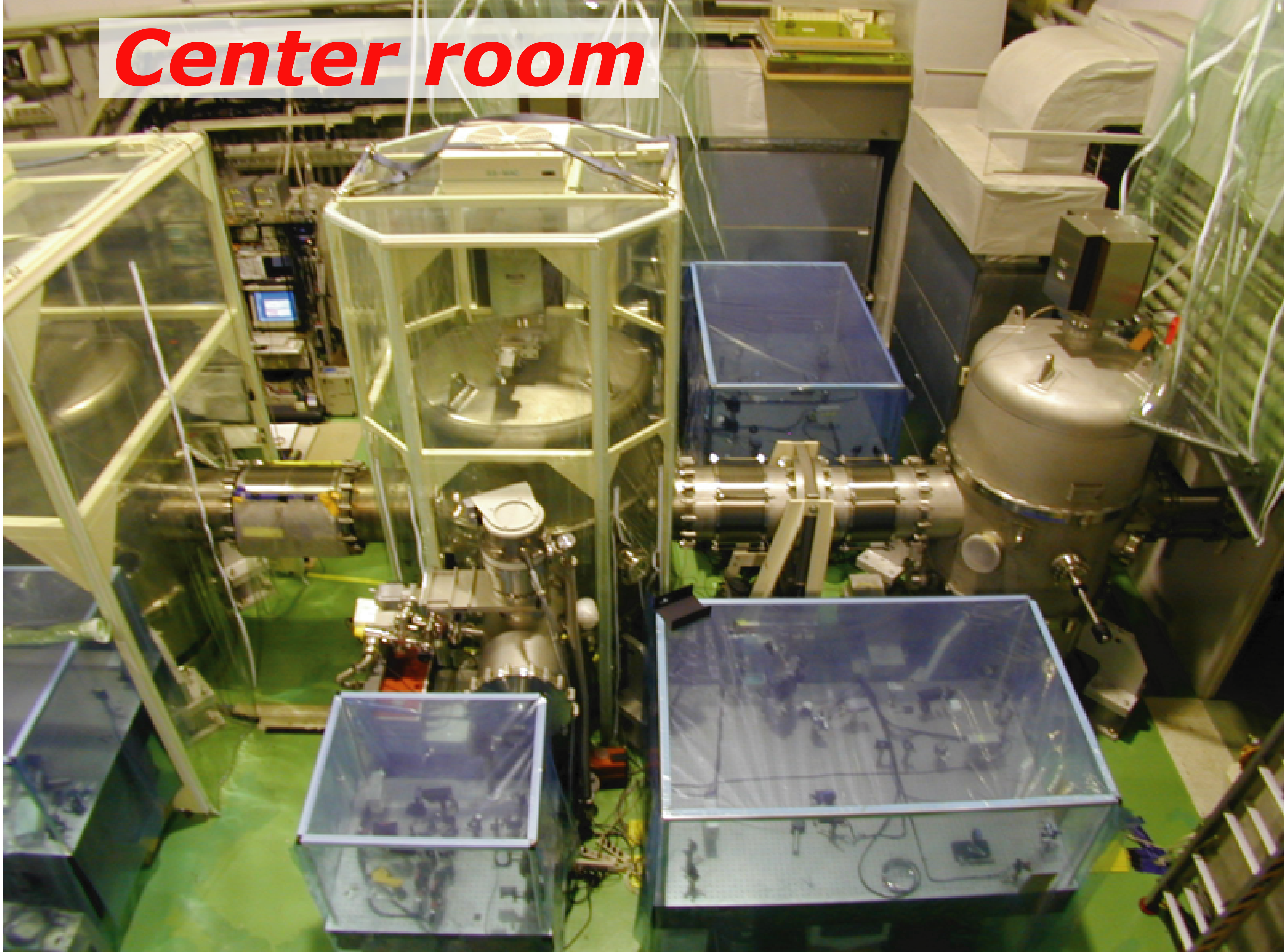


Middle of a city area ~ heavy traffic

TAMA300 detector ~ overview

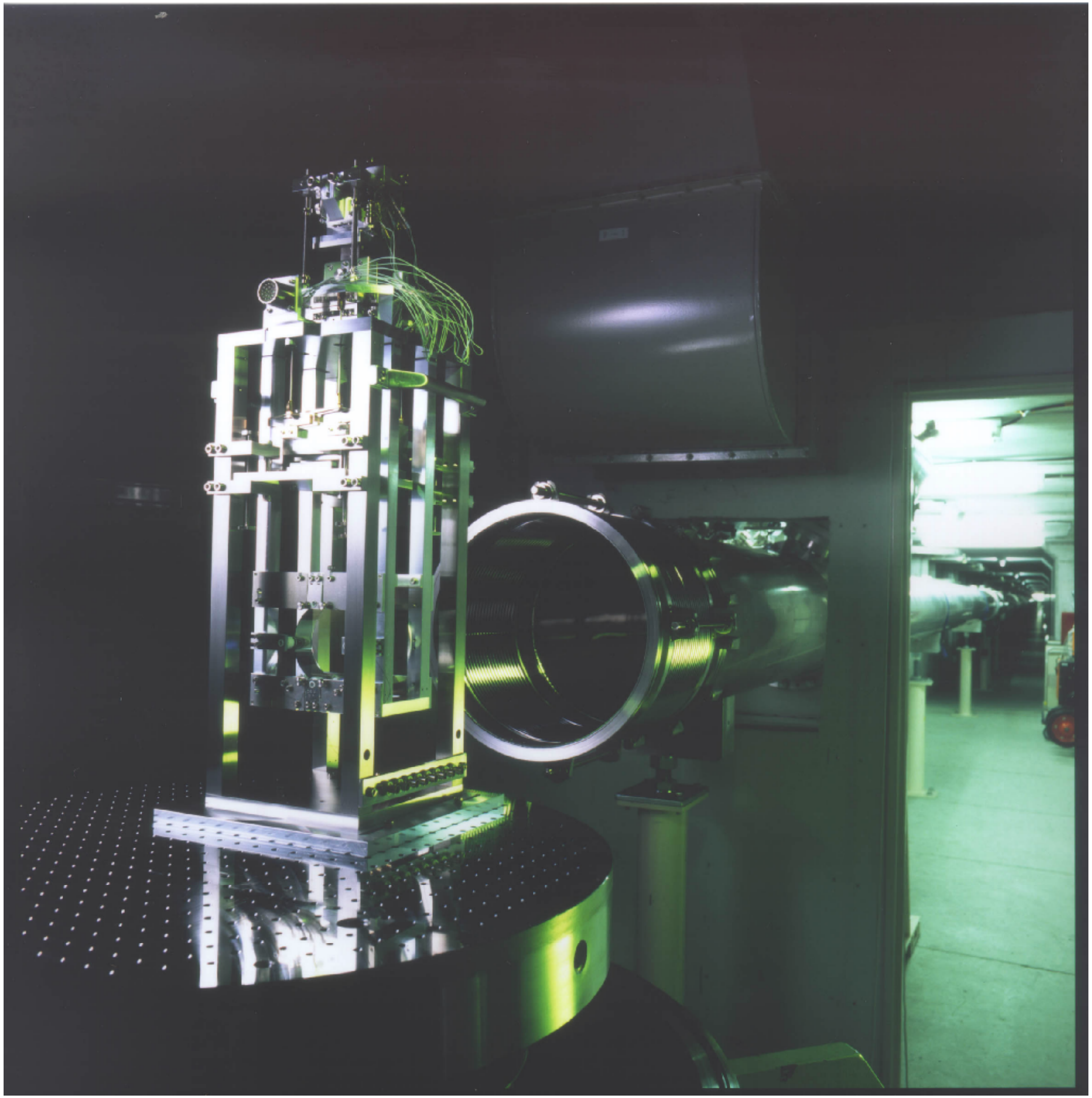


Center room



300m vacuum tube

Vibration Isolation System



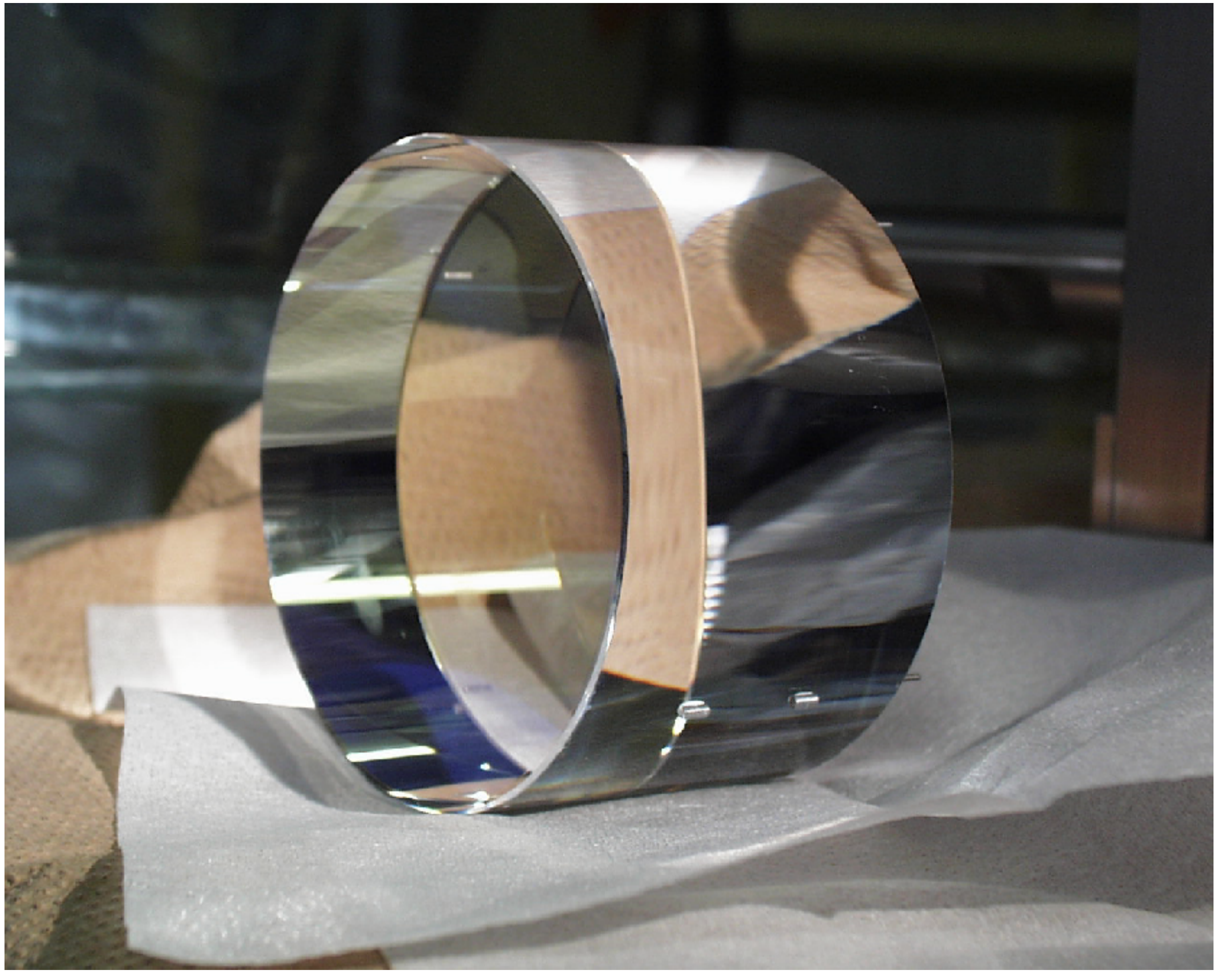
- **3 layer system**

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

□ <λ/40

surface roughness

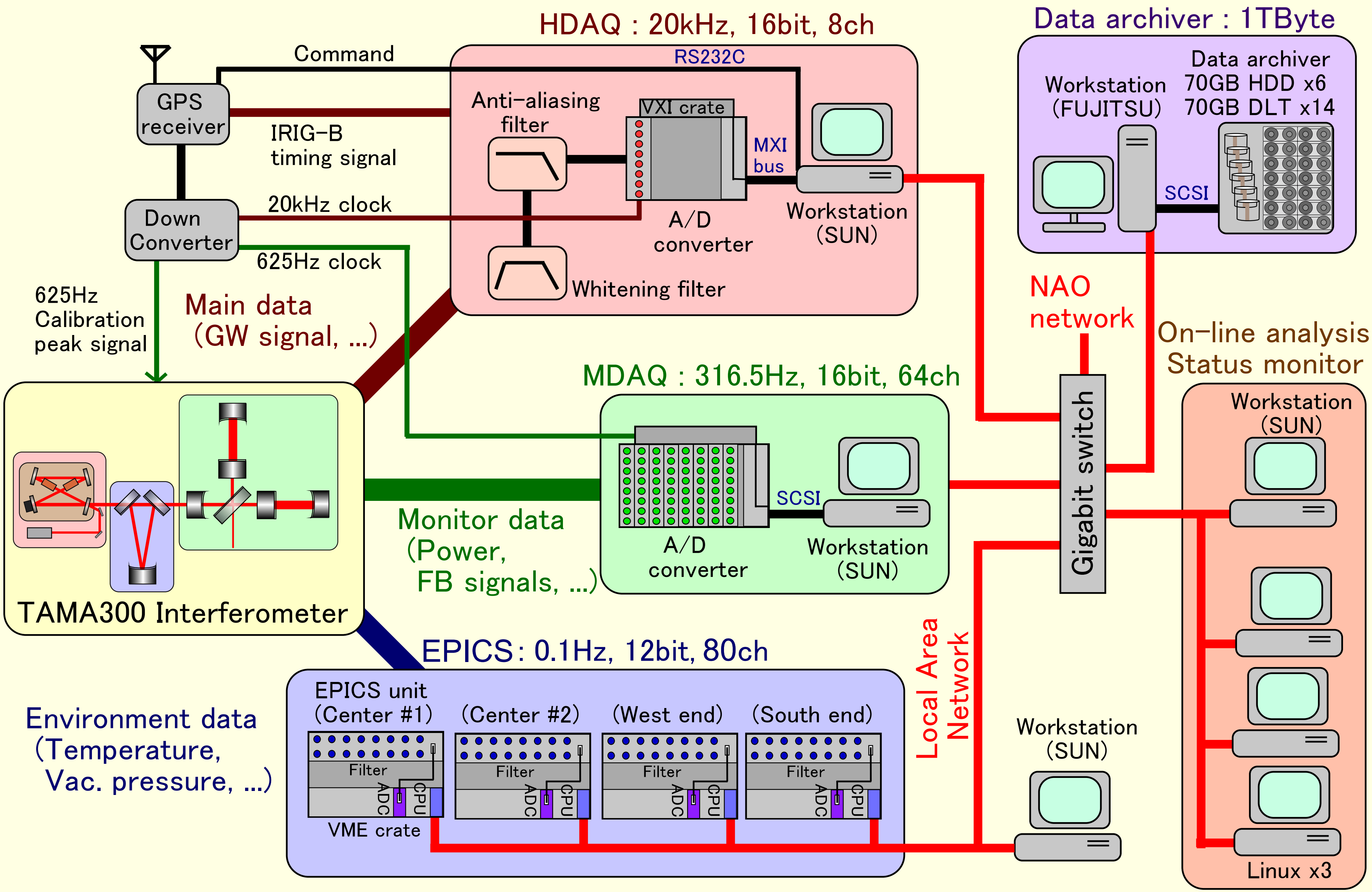
□ <1 Å

Control electronics

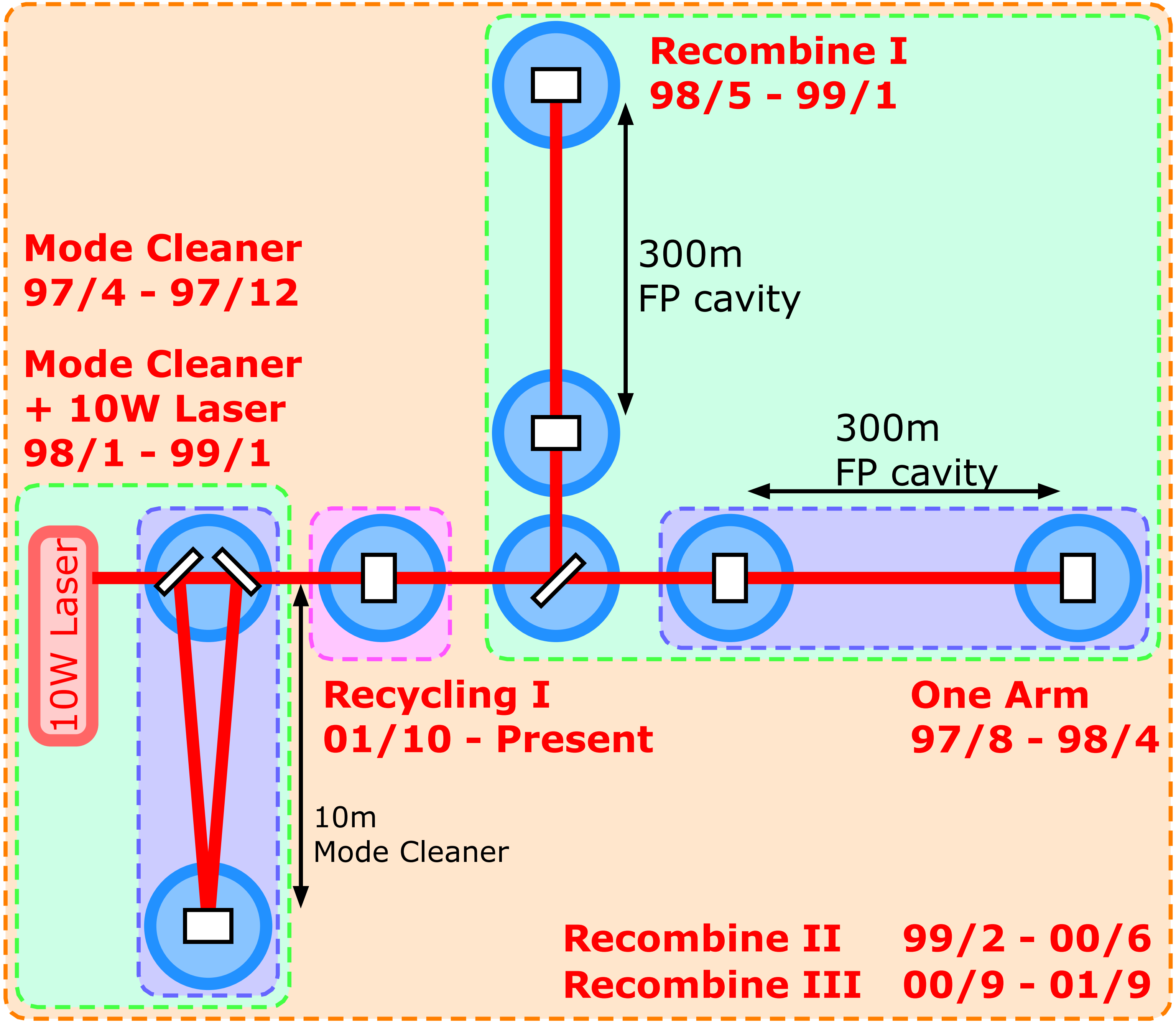
Control electronics

- 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

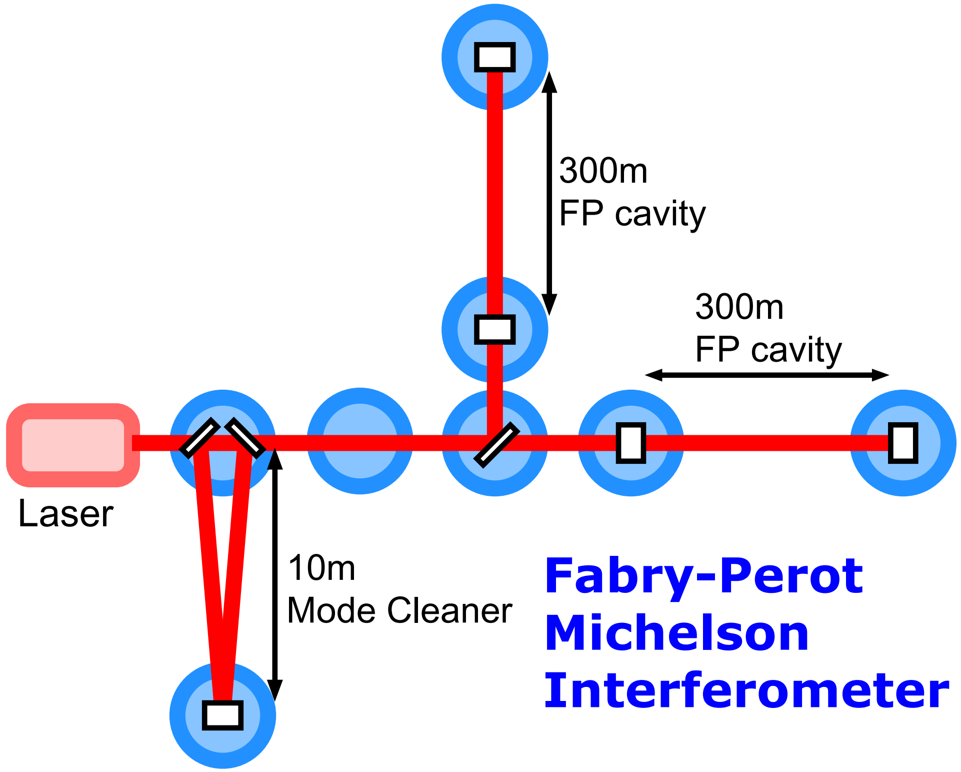
    ~ high duty ratio, auto lock-acquisition

    Total lock time 1107 h (92.3%)

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

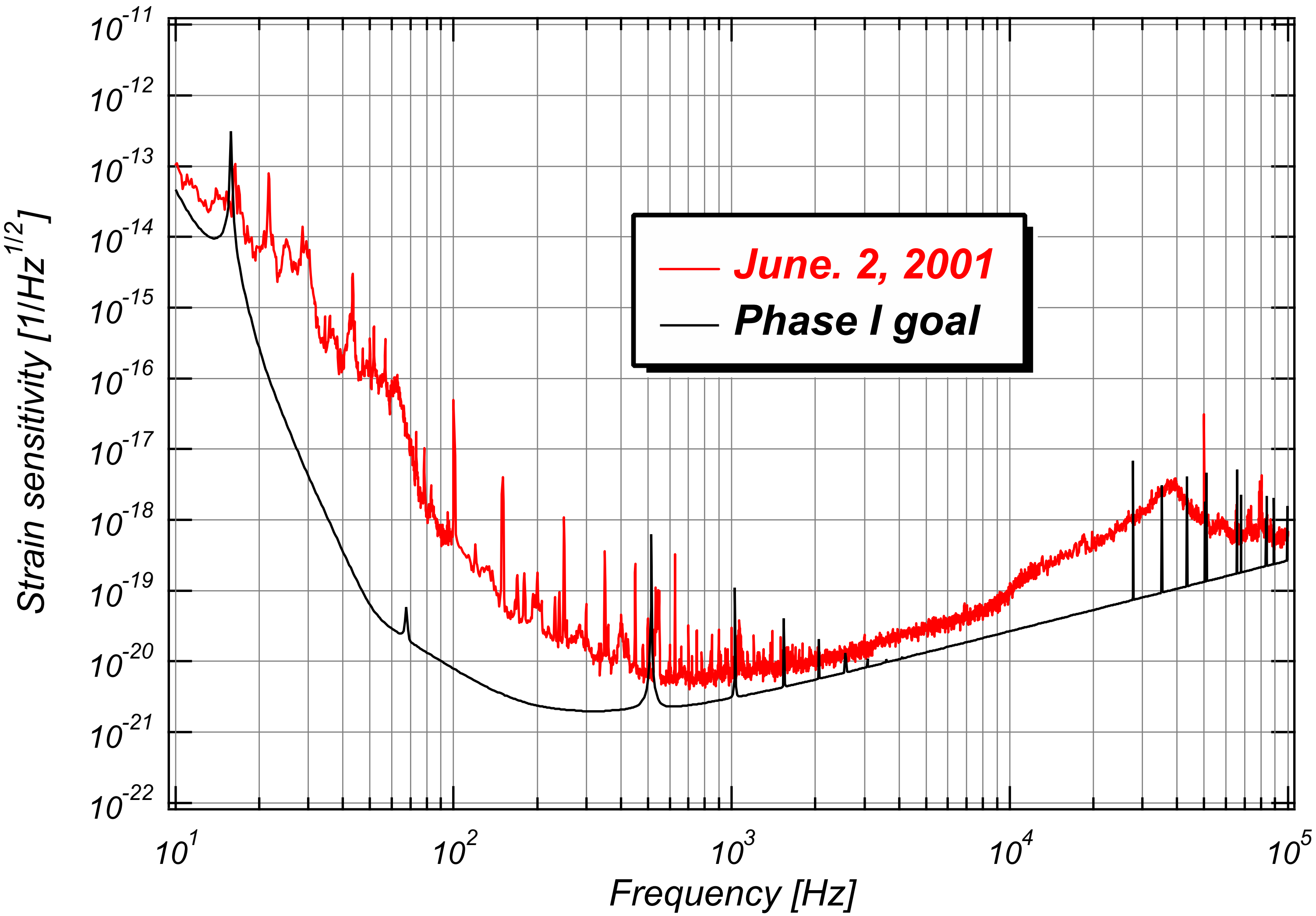
  - Coincidence with LISM 20m IFO at Kamioka mine

    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	$=5.2\text{x}10^{3}$/year	3.4kpc	31h
DT4:	0.027/h	$=2.4\text{x}10^{2}$/year	17.9kpc	167h
DT6:	0.0095/h	$=8.3\text{x}10^{1}$/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

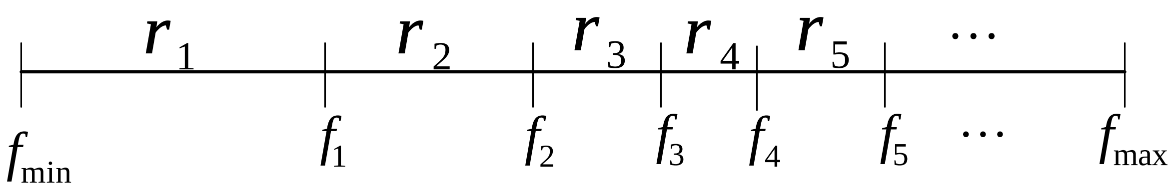
$$m_1, m_2, t_c, \ldots$$

  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

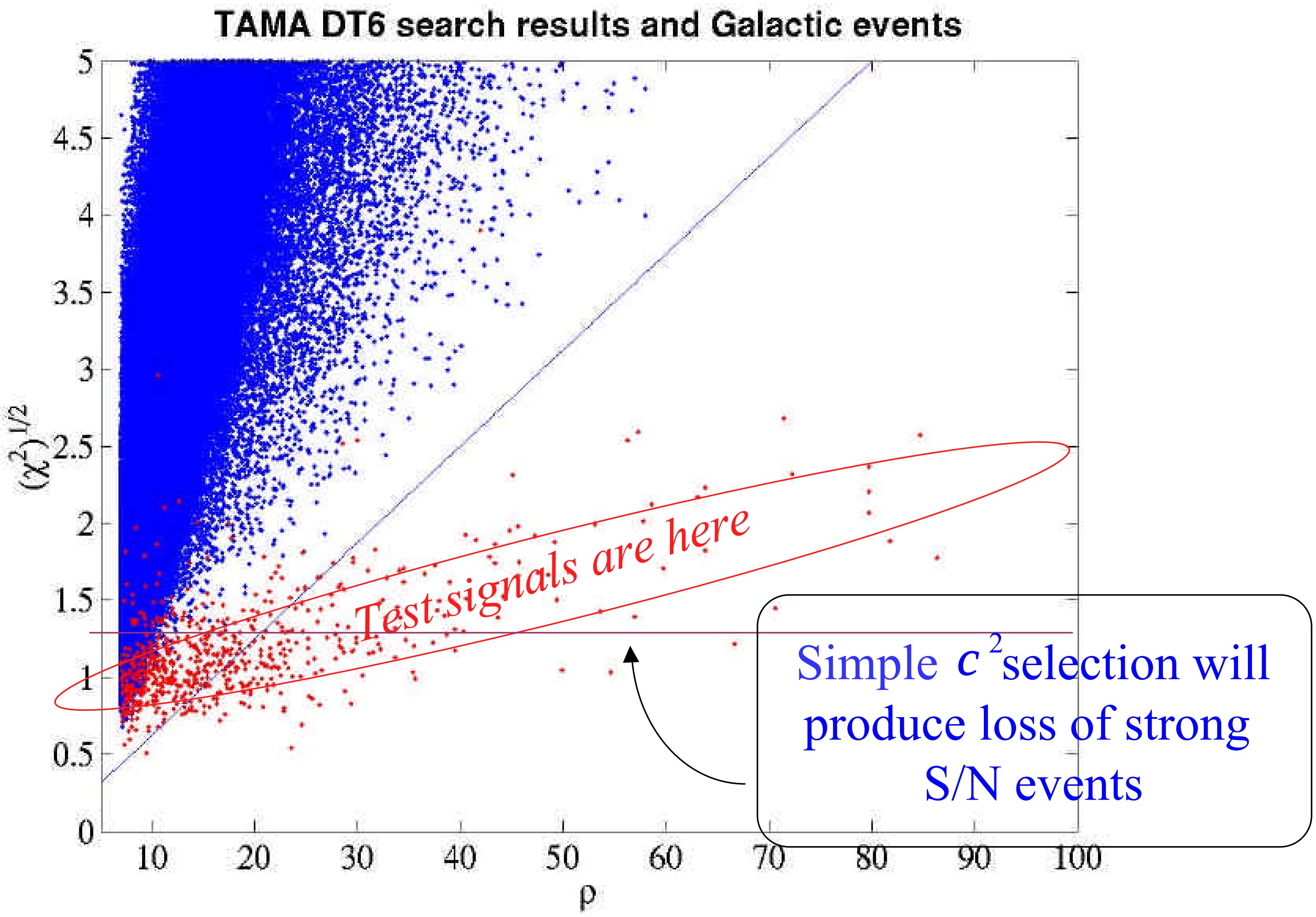
$$r \equiv (s, h) \quad \left(= 2\int \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)}\, df \right)$$



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

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

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



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

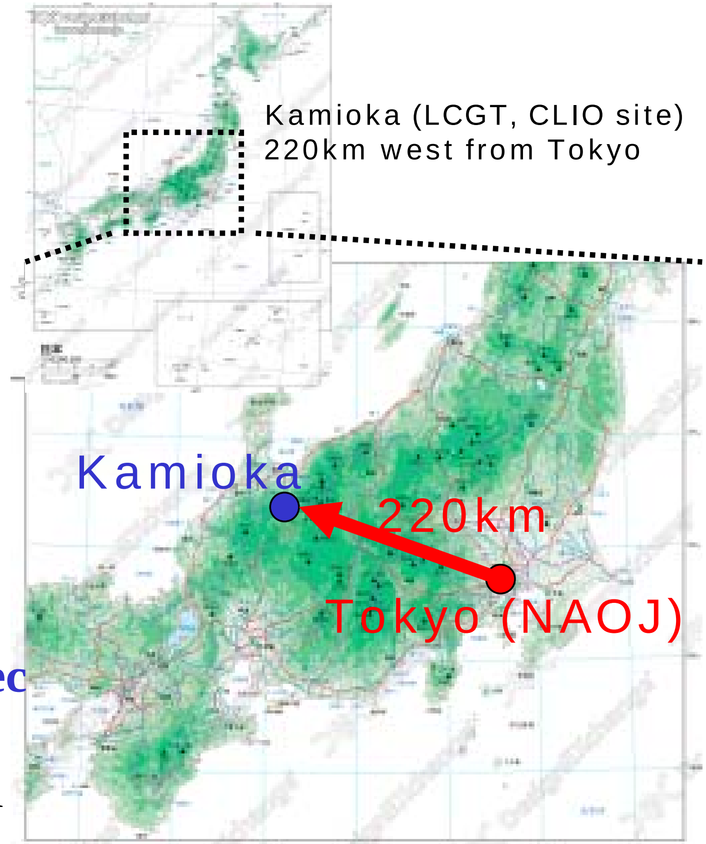
⇨ Upper limit to the Galactic event rate

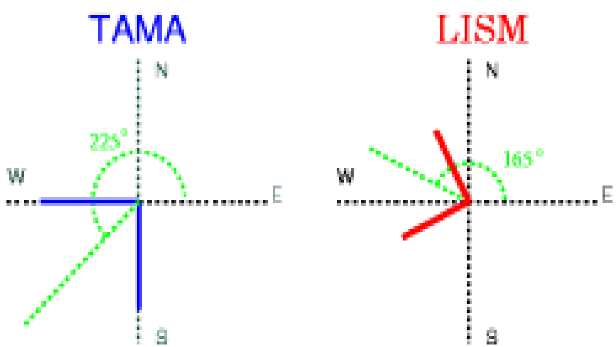
$$= \frac{N}{T\varepsilon} = 0.0095 \ [1/\text{hour}] \ (C.L. = 90\%)$$

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

70 events — 70.45 ± 8.53

After t_c, M, η-coincidence — accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$

18 events — 17.55 ± 4.08

After t_c, M, η, ρ-coincidence — accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$

13 event — 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

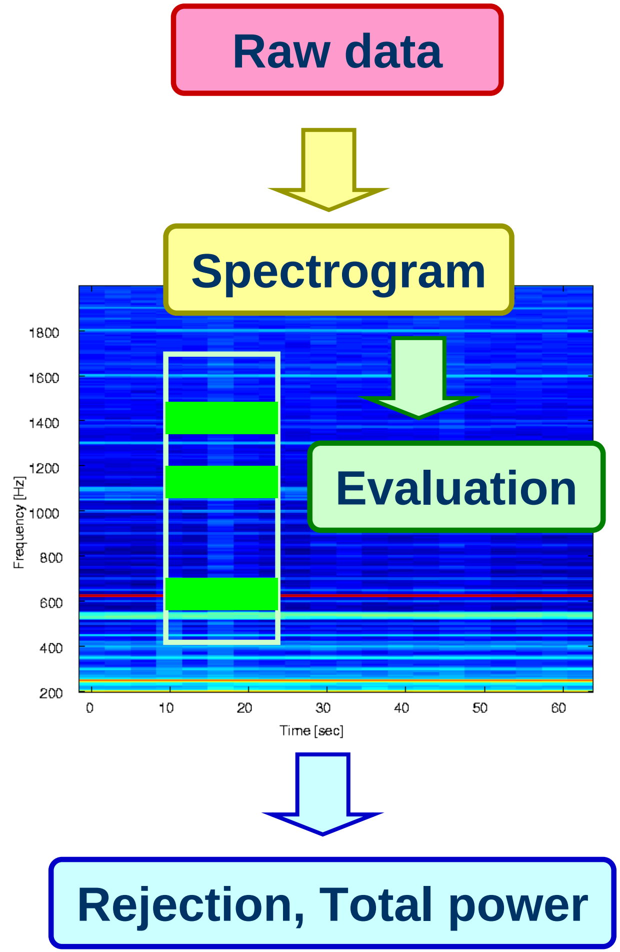
Burst wave analysis (3)
--- Data processing ---

- **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

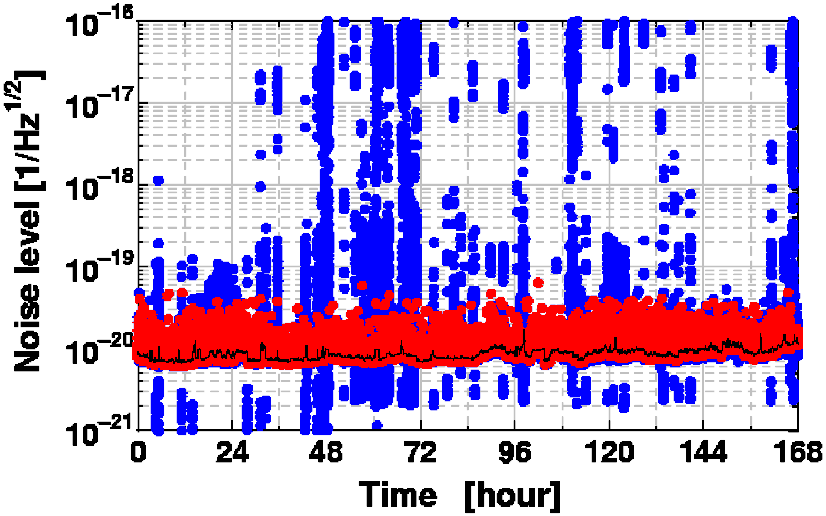
  Rejected --- Detector instability
  Detector 'dead time'

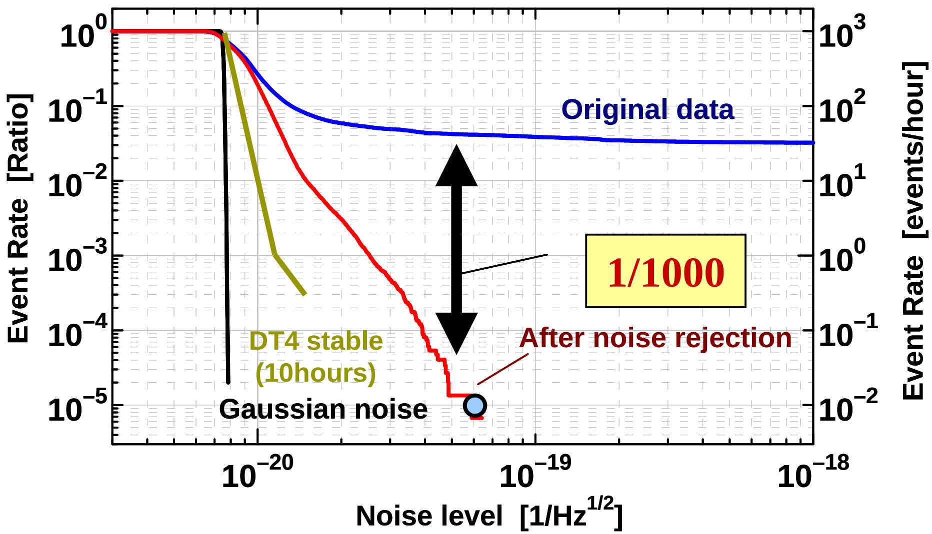


Burst wave analysis (4)
--- DT6 data analysis ---

- Data Taking 6 (Summer 2001)
  -
  - 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

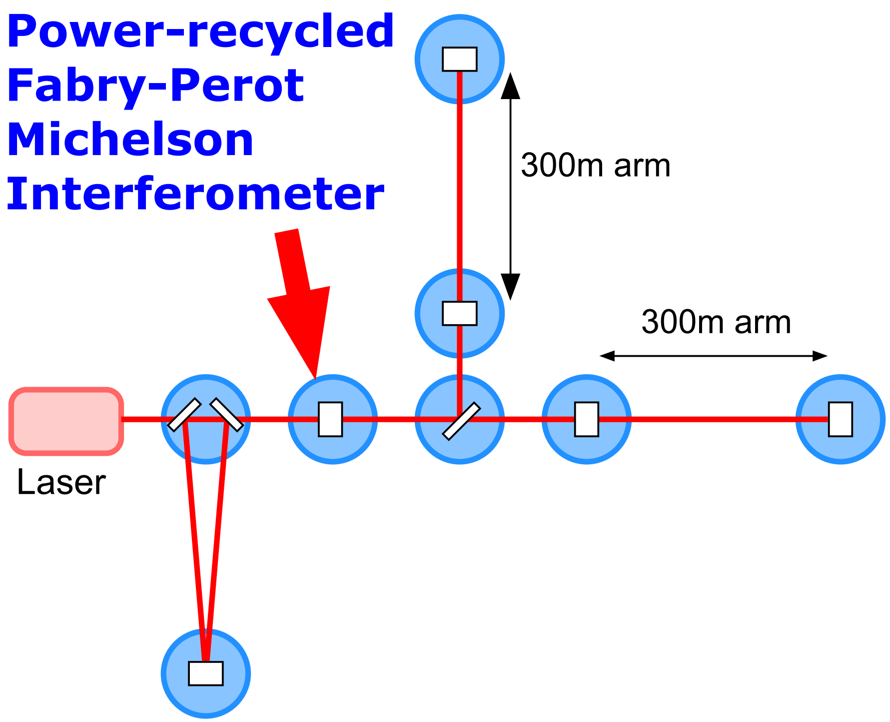
Power recycling of TAMA300 (2001/10~Present)

Power recycling gain of 4.5

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

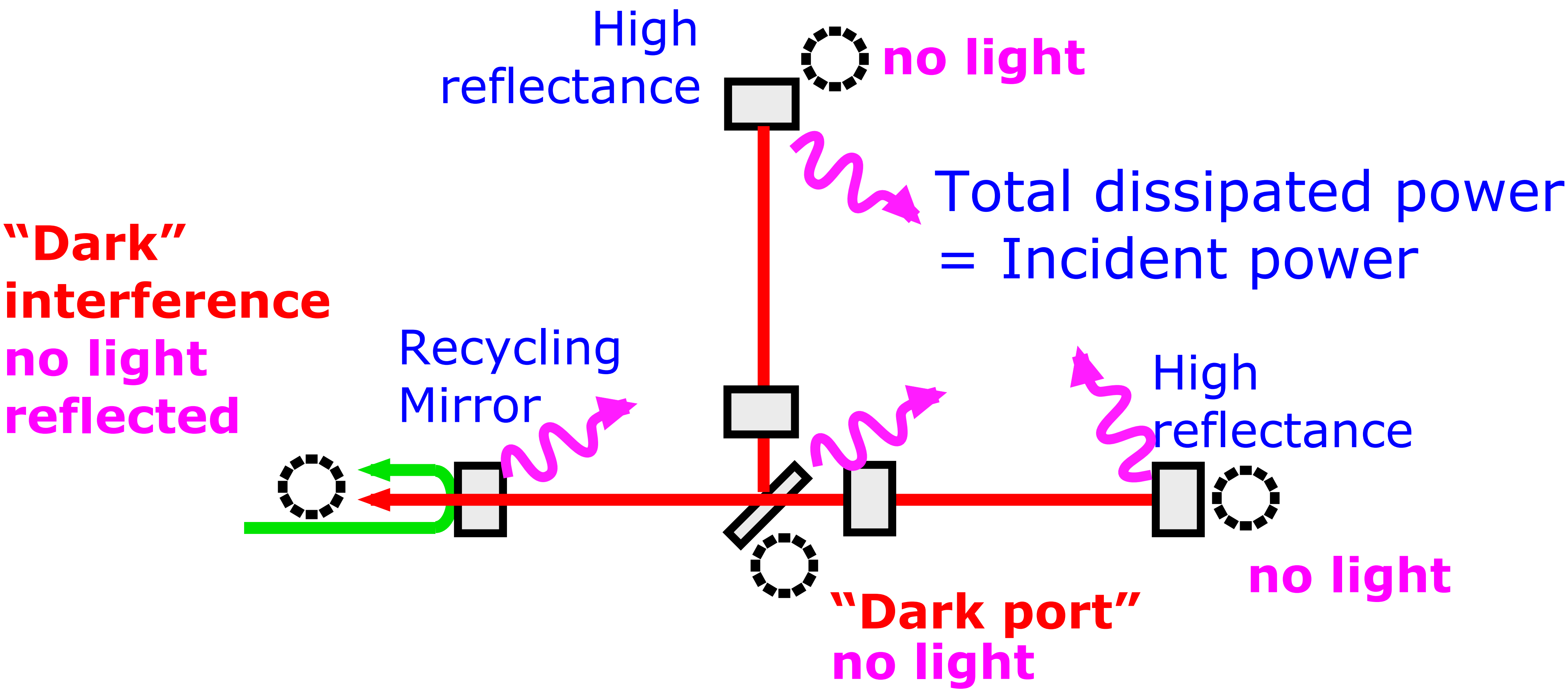
IFO operation

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

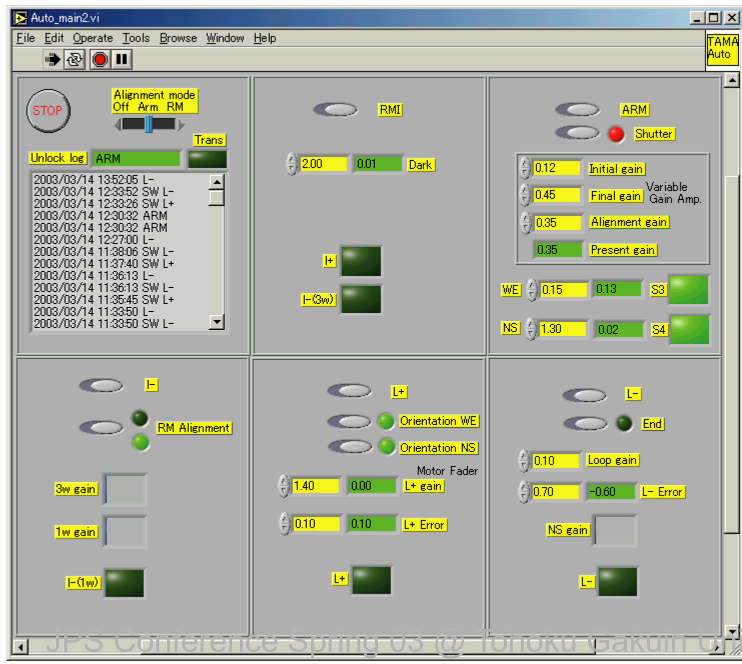
Self-switching sub-systems (Laser&MC)

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

Digital switching using PC and Labview

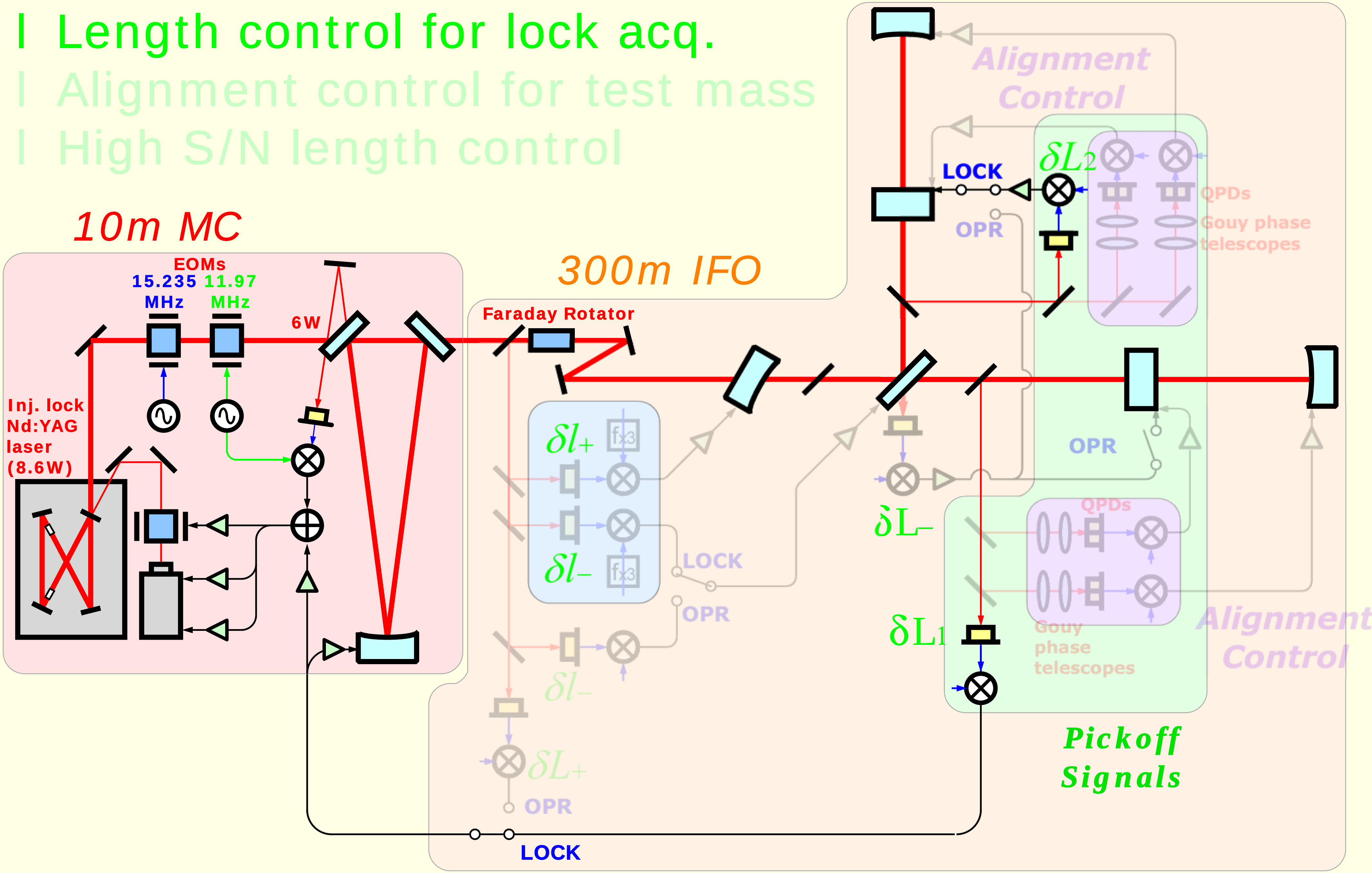
- Lock acquisition
- Manual mirror alignment
- IFO Status monitoring

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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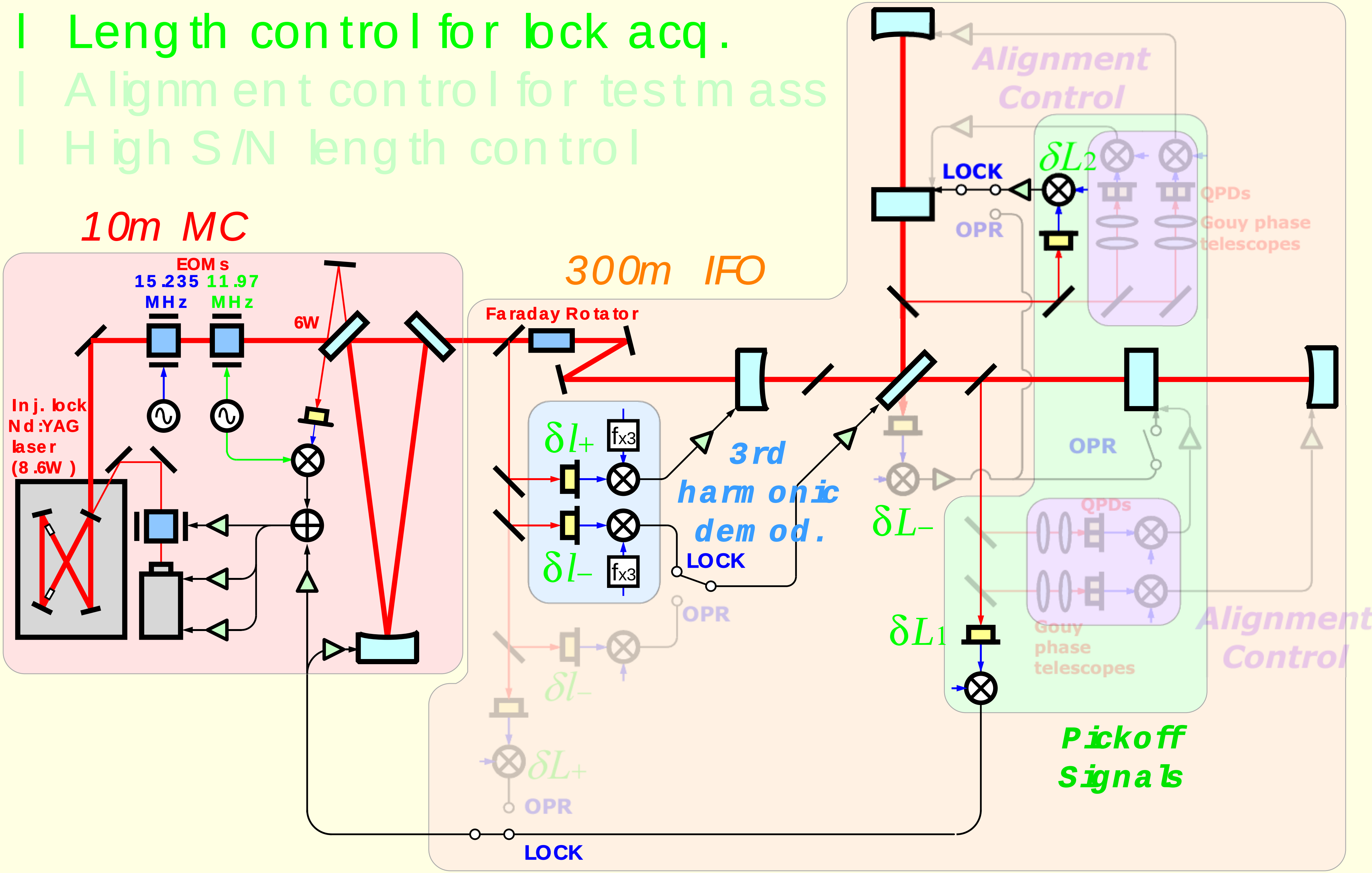

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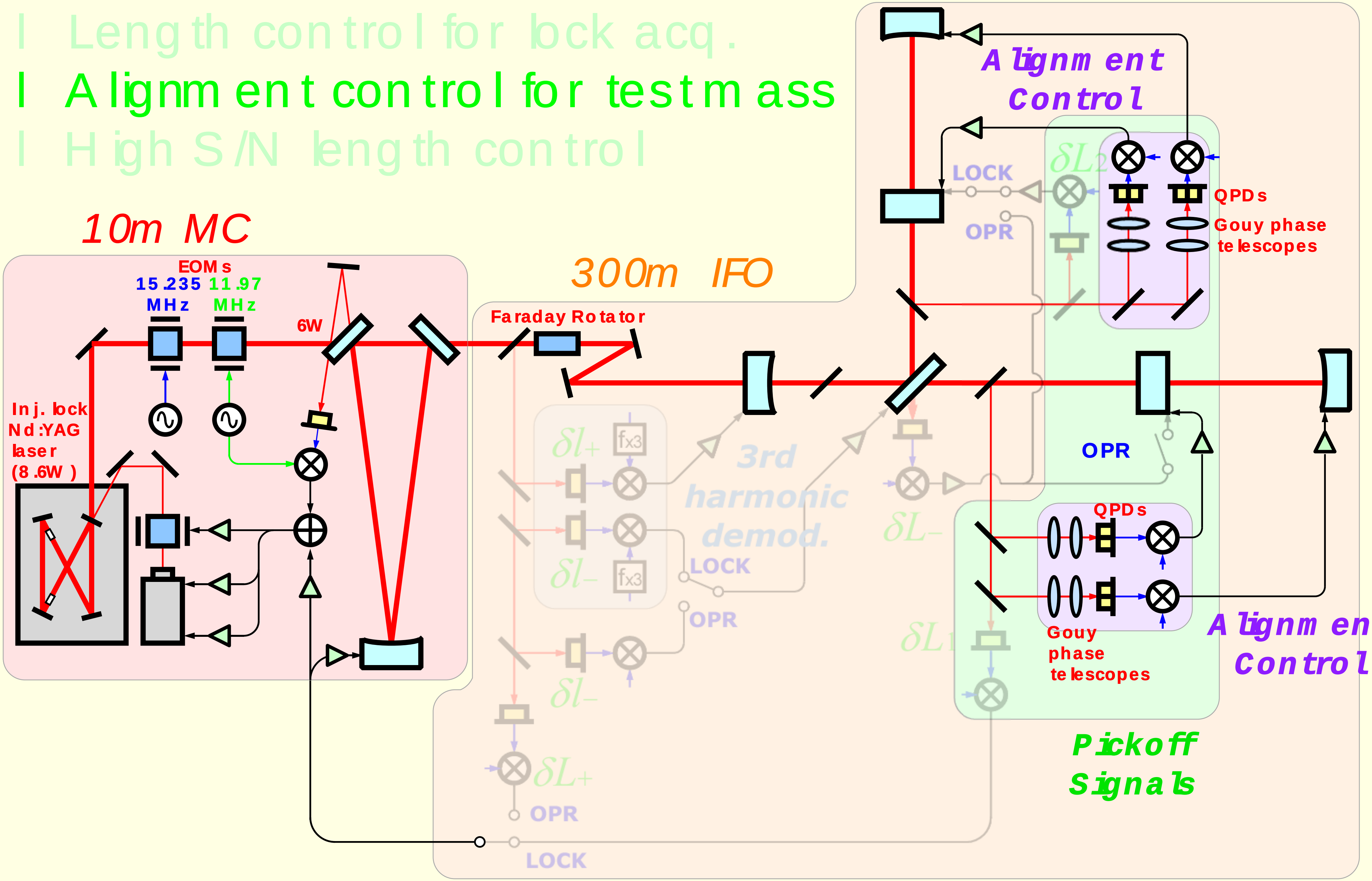

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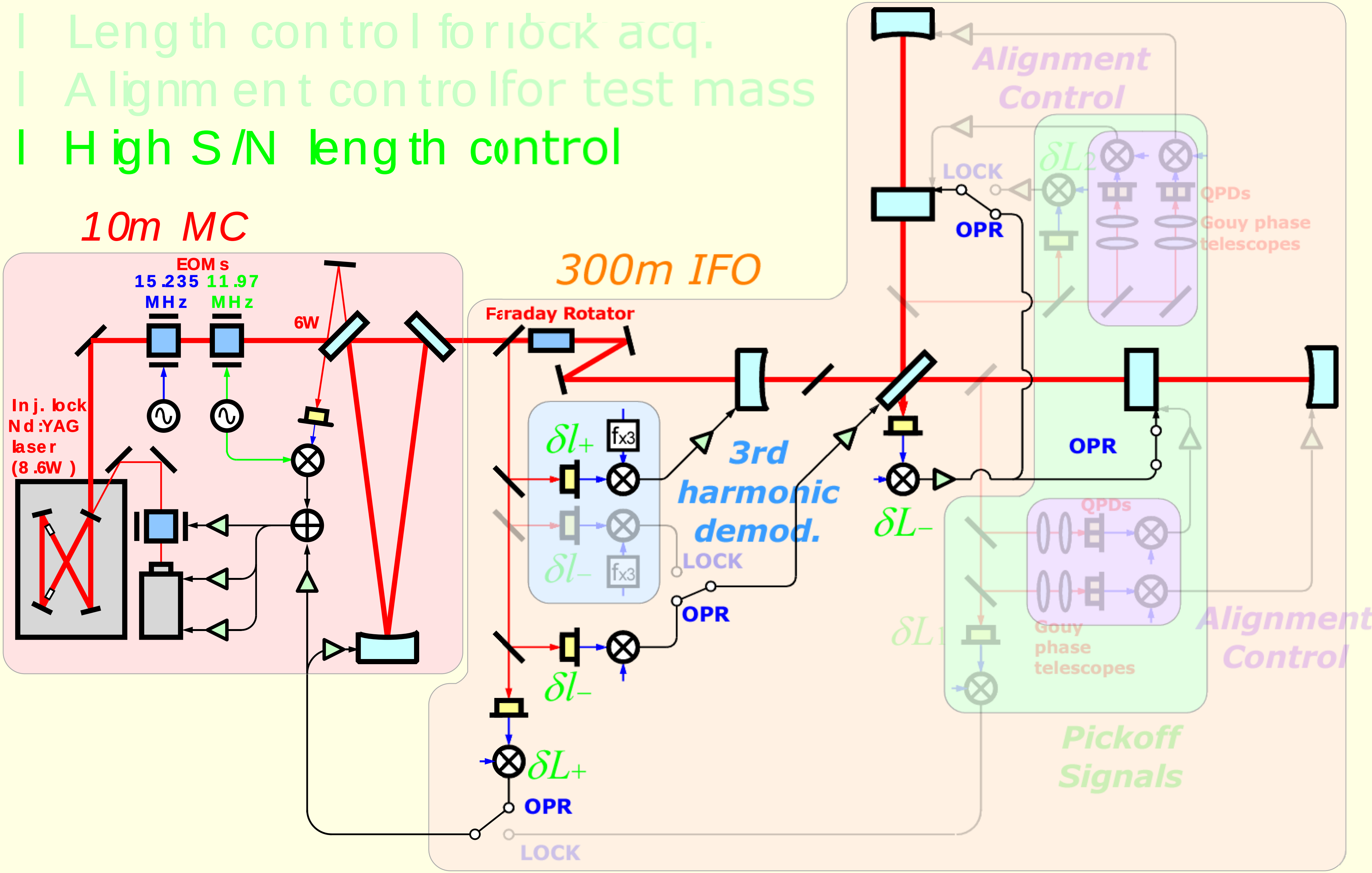
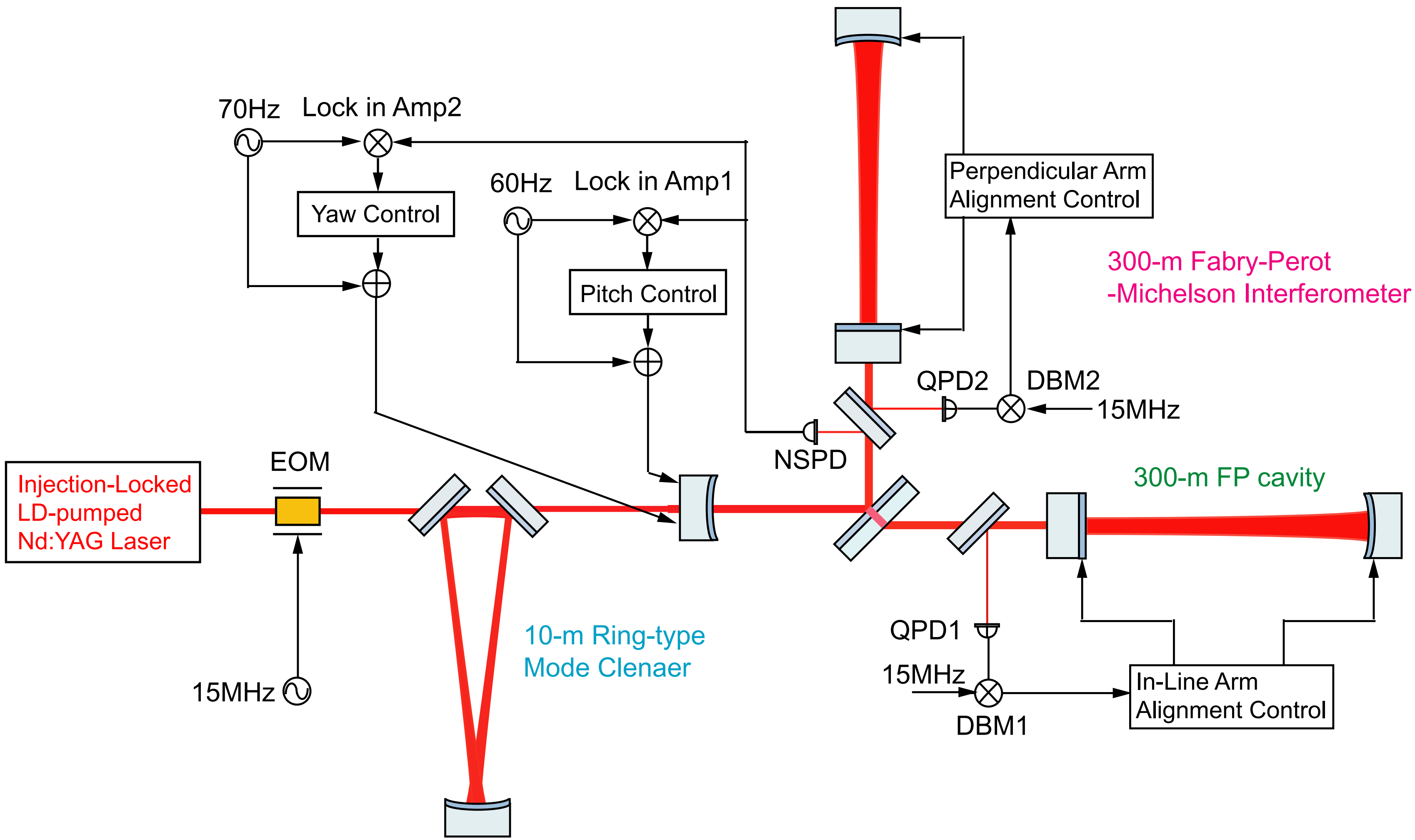


Alignment control

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



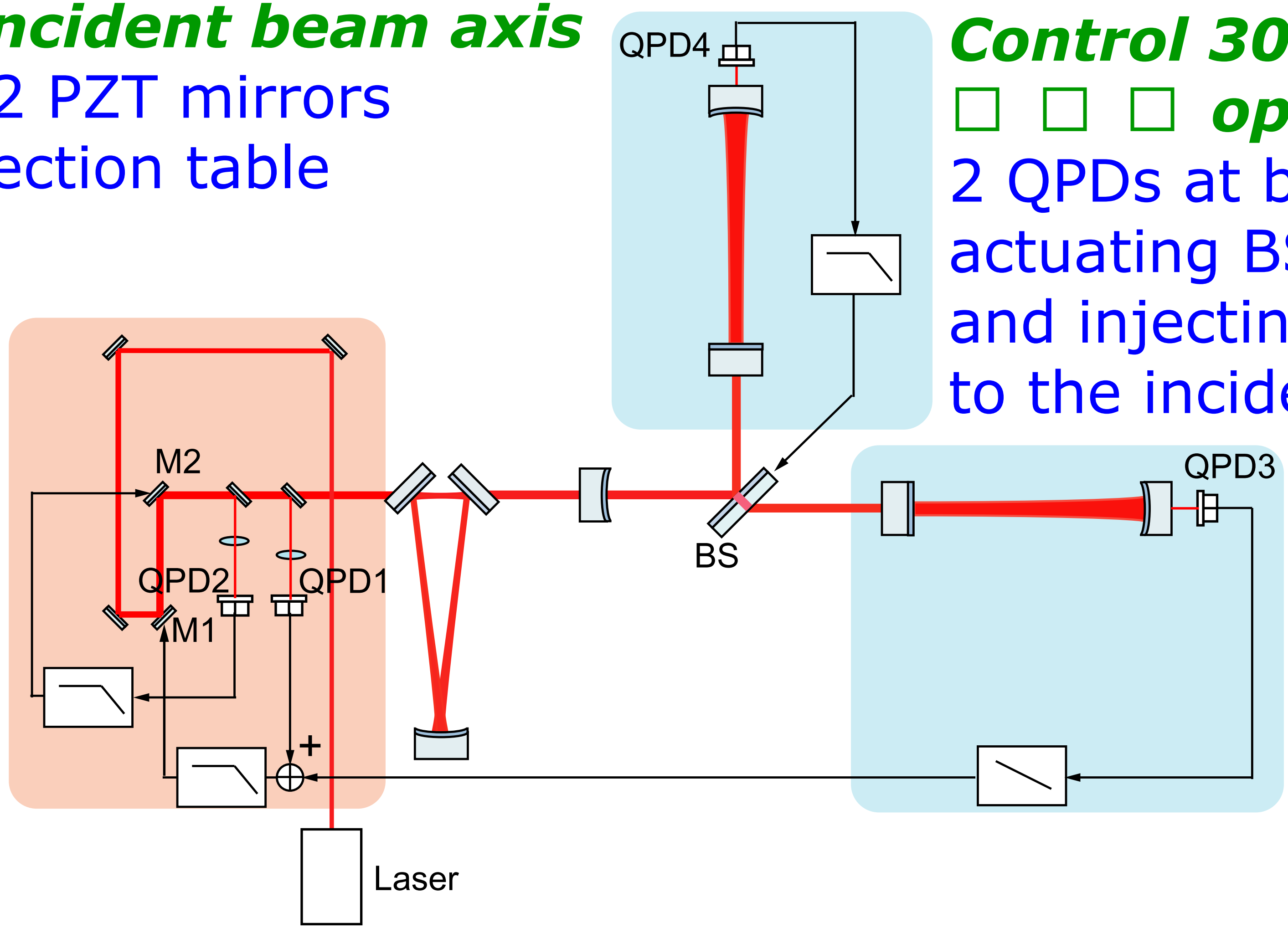
Stabilizing optical axes

Control incident beam axis

2 QPDs / 2 PZT mirrors
on the injection table

Control 300-m
□ □ □ optical axes

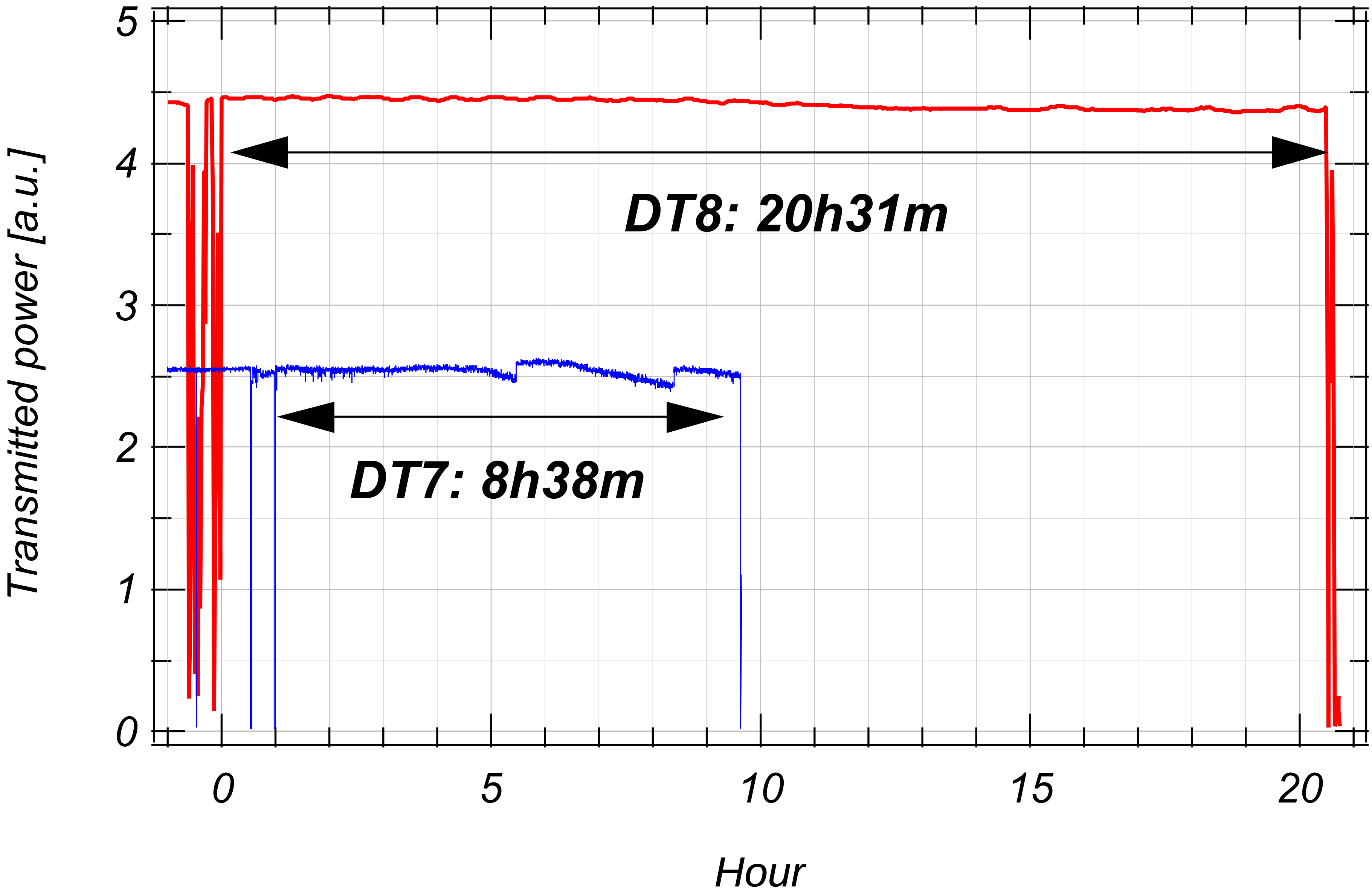
2 QPDs at both end
actuating BS
and injecting signal
to the incident axis servo



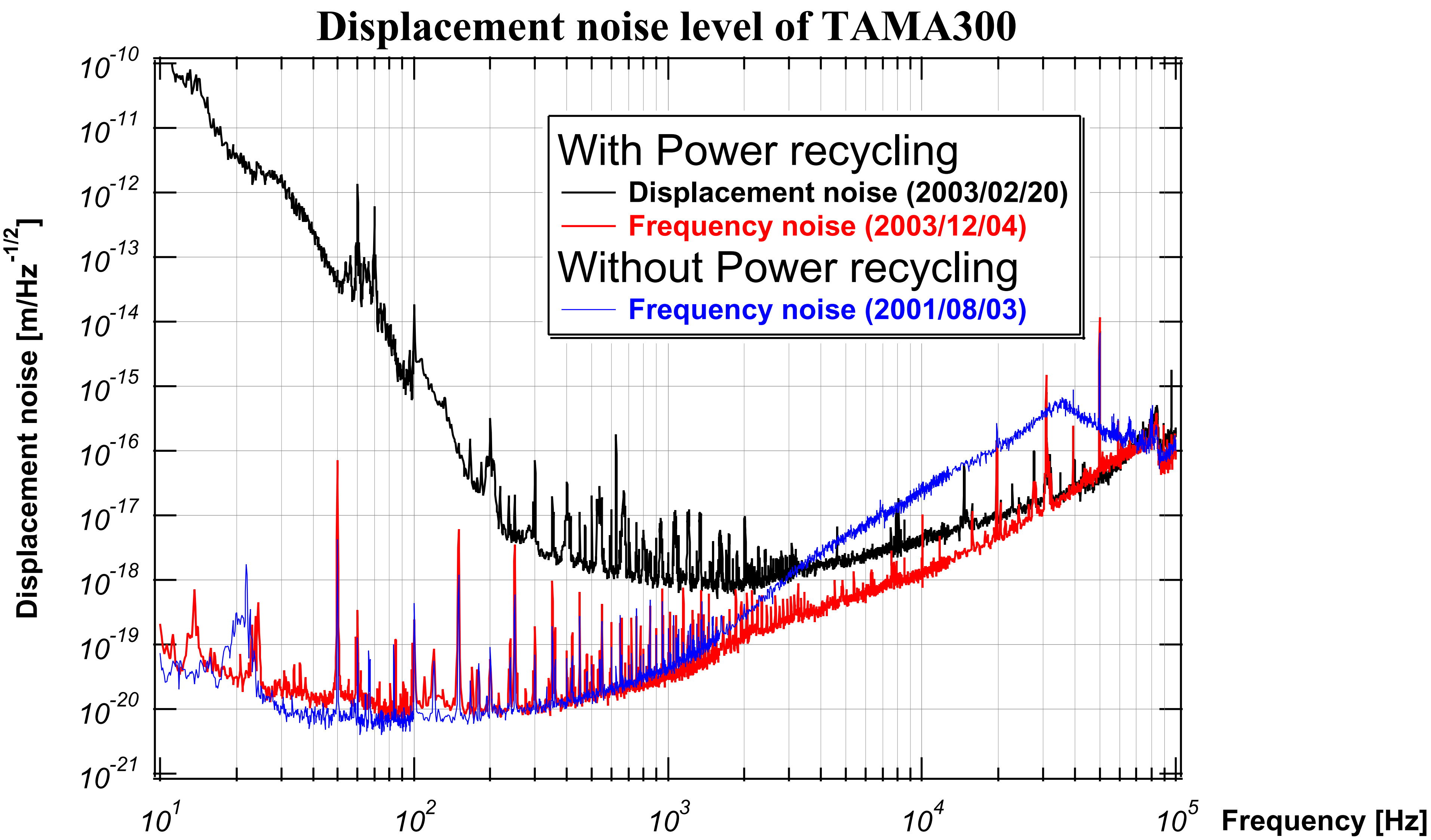
=> Minimizing the alignment noise coupling to dL-.
=> Improvement of the long-term stability of the main IFO,
□ □ as well as the long-term stability of the MC.

Improved long-term stability

Longest lock stretch in the observations



Frequency Stabilization

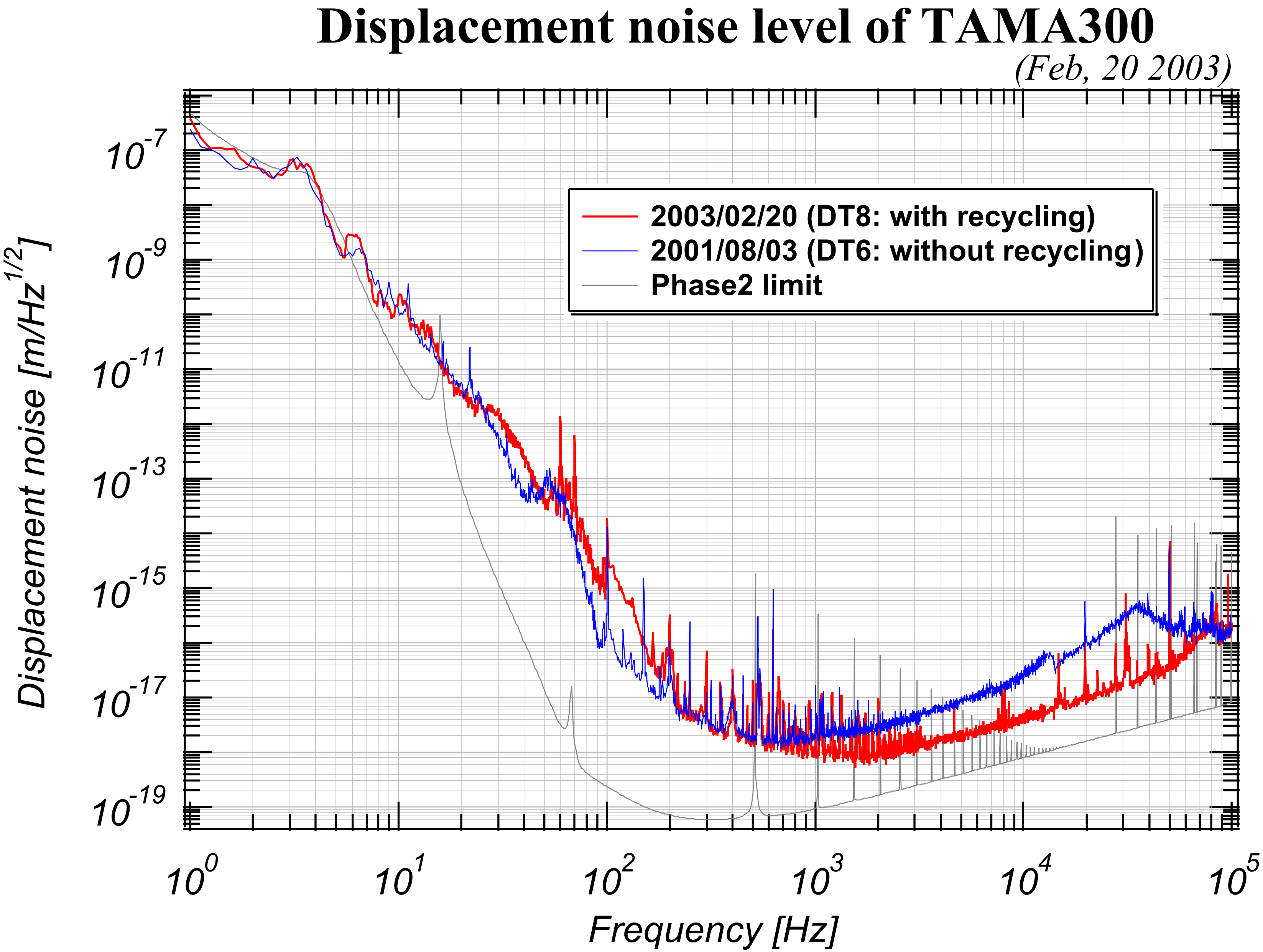


Control bandwidths extended:

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

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

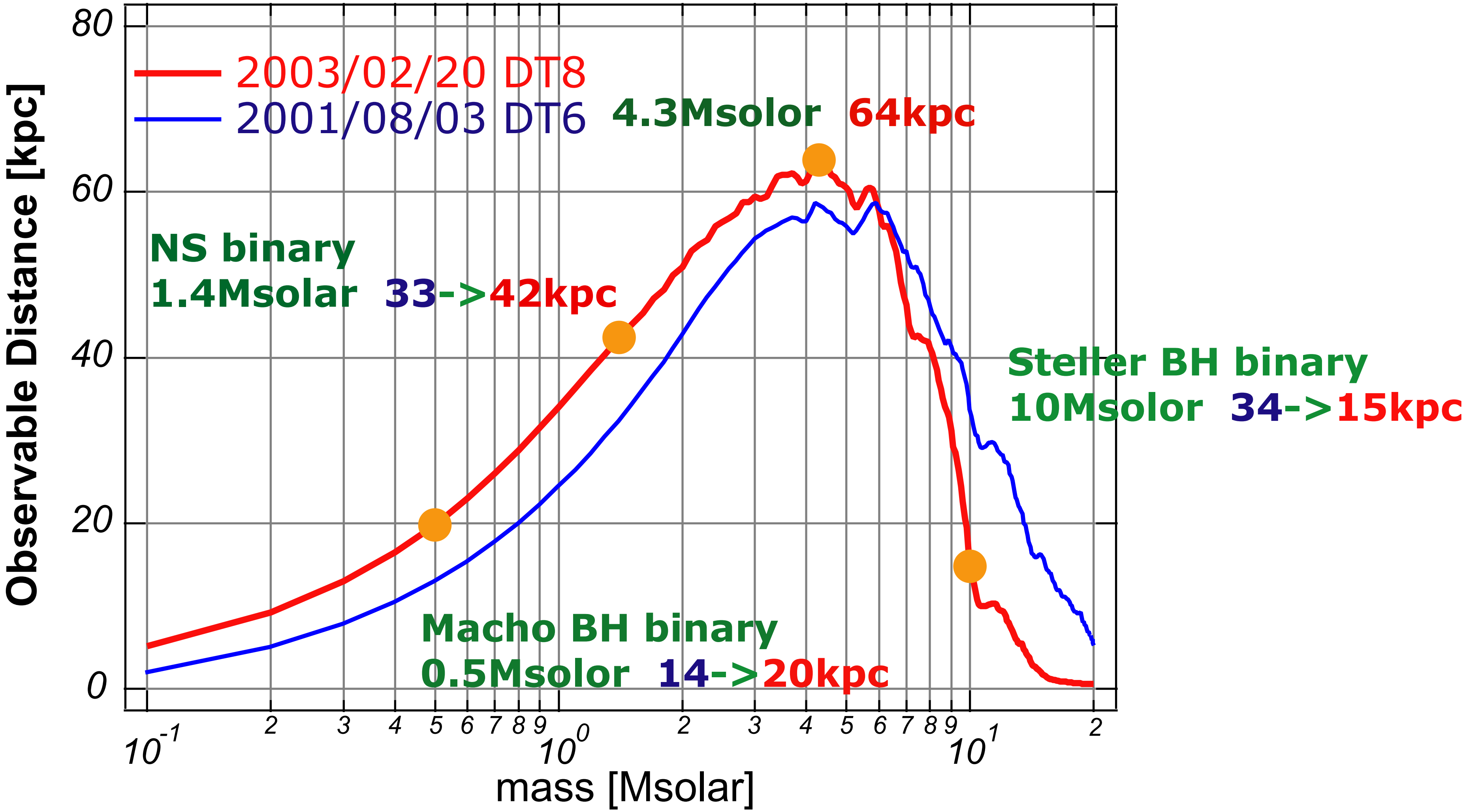
Sensitivty @ DT8



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

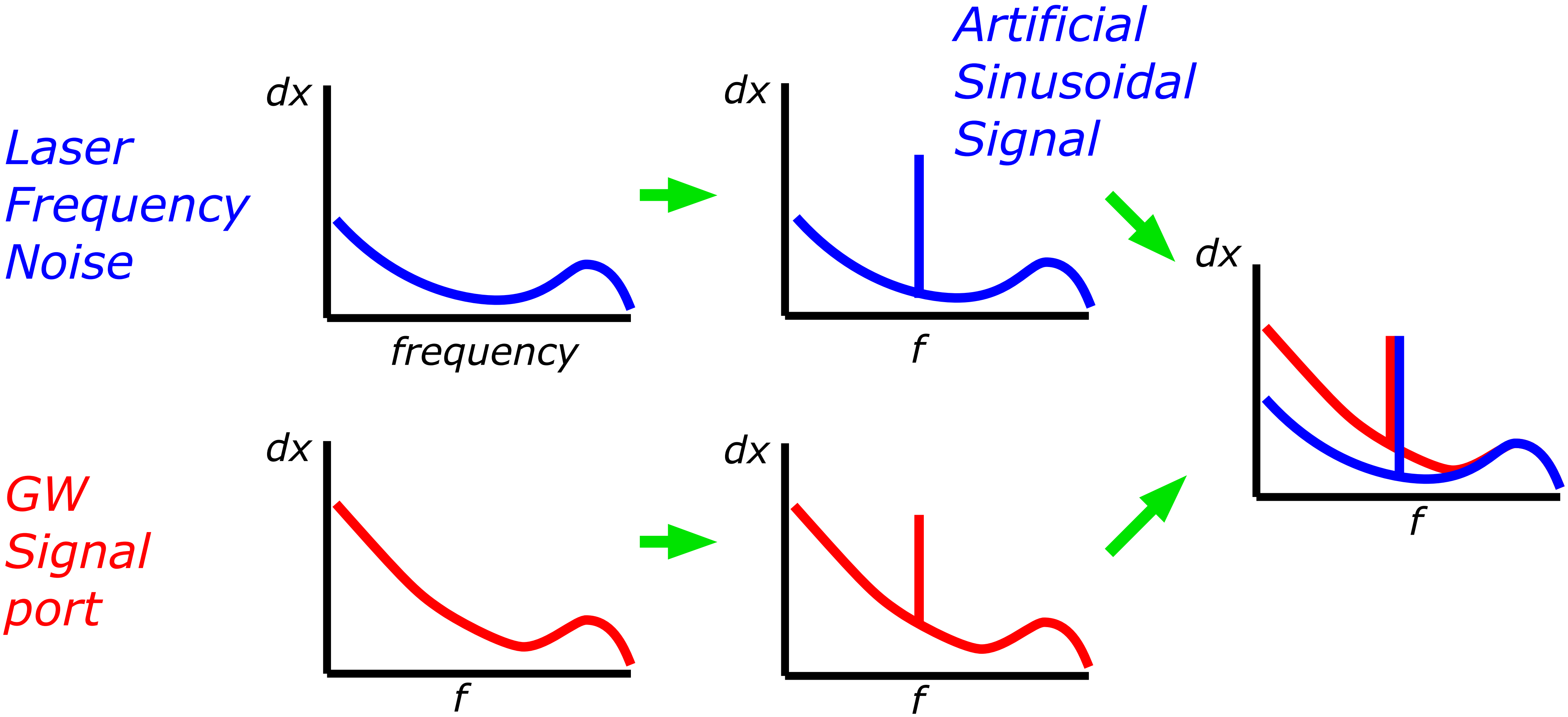


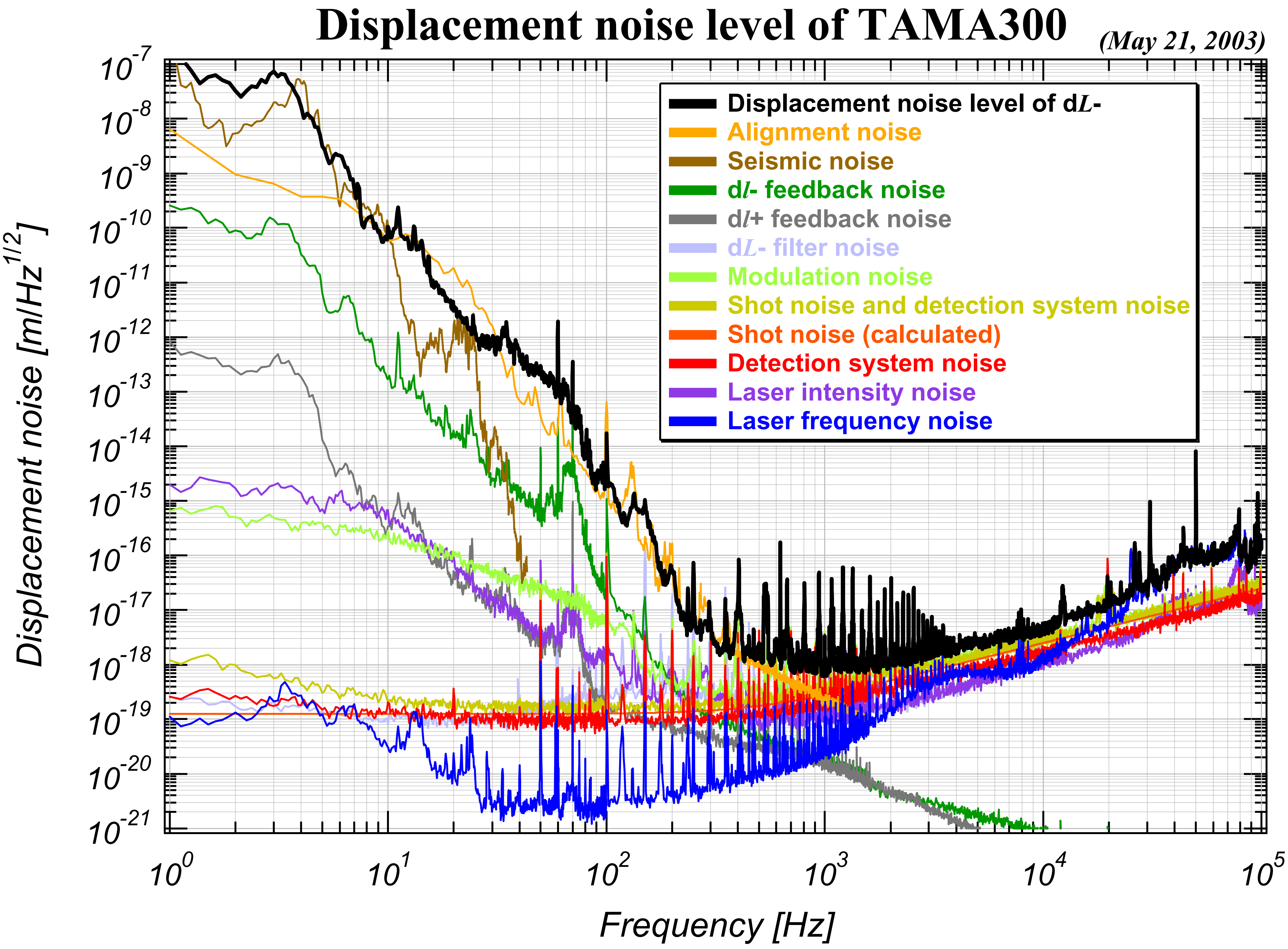
SNR improvement for 1.4-1.4Msolar and 0.5-0.5Msolar

Deterioration for 10-10Msolar caused by wideband alignment filters

Estimation of noise contributions

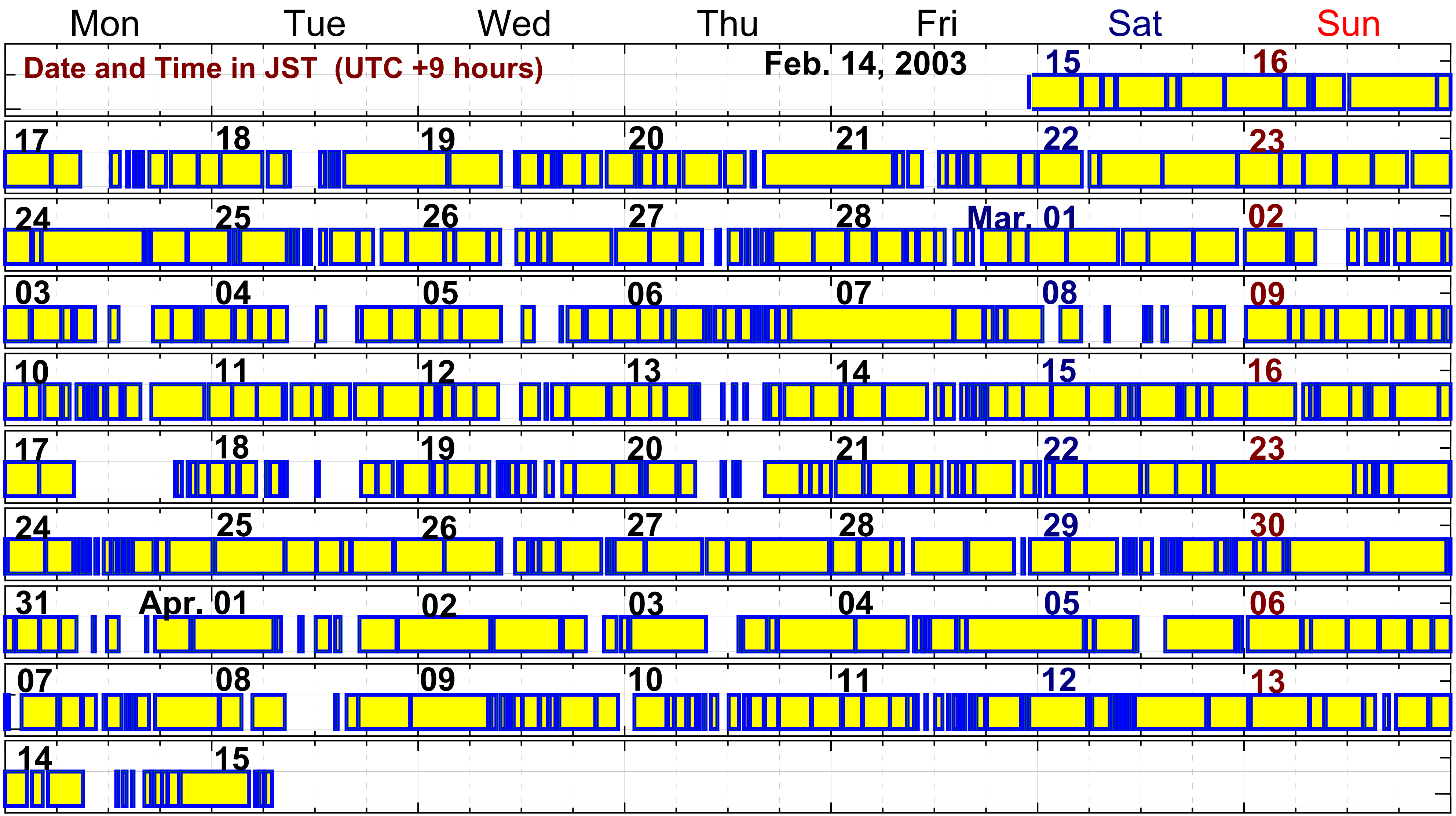
- **Noise estimation based on signal injection**



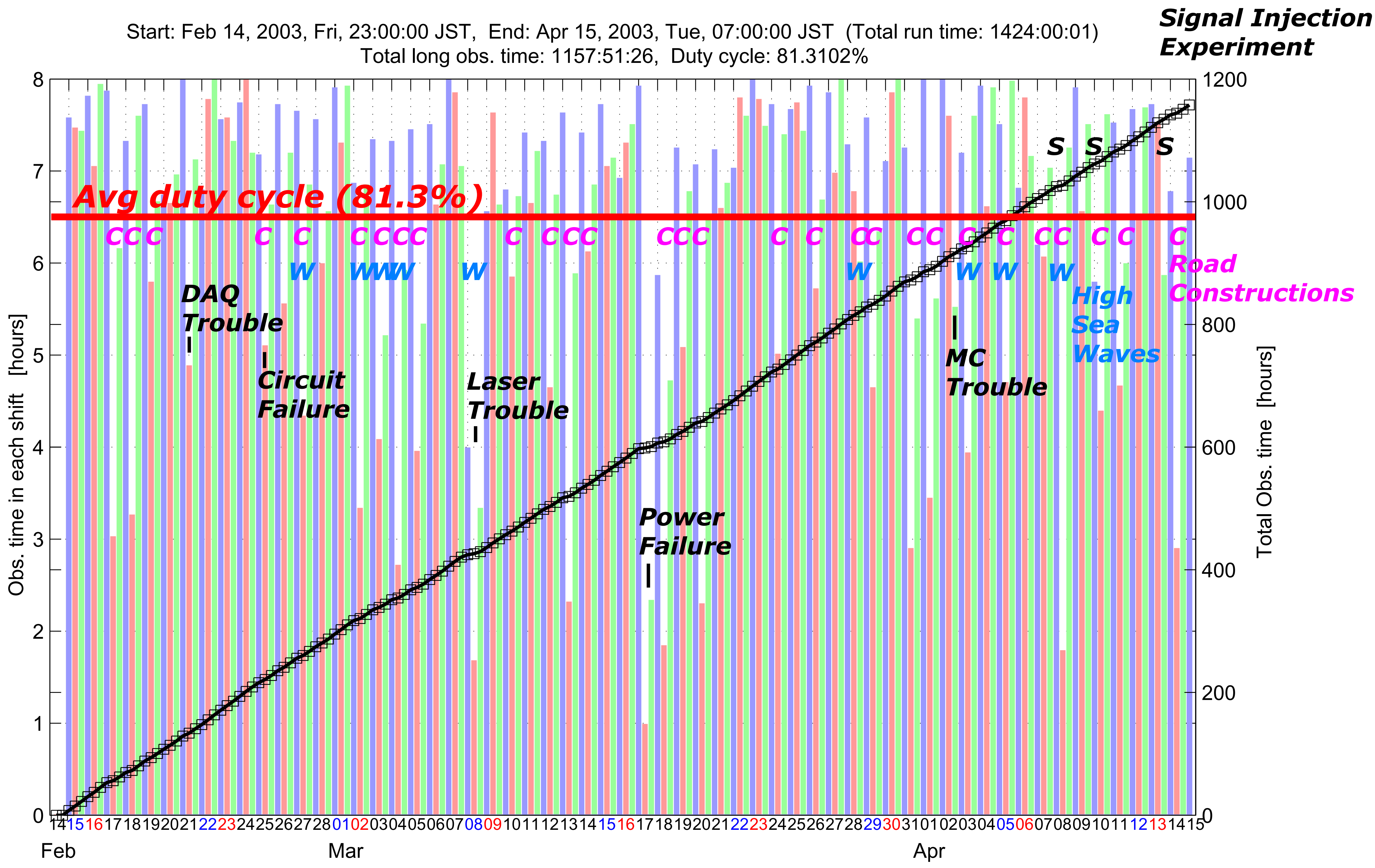

Displacement noise level of TAMA300
(May 21, 2003)
Displacement noise level of dL-
Alignment noise
Seismic noise
dl- feedback noise
dl+ feedback noise
dL- filter noise
Modulation noise
Shot noise and detection system noise
Shot noise (calculated)
Detection system noise
Laser intensity noise
Laser frequency 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

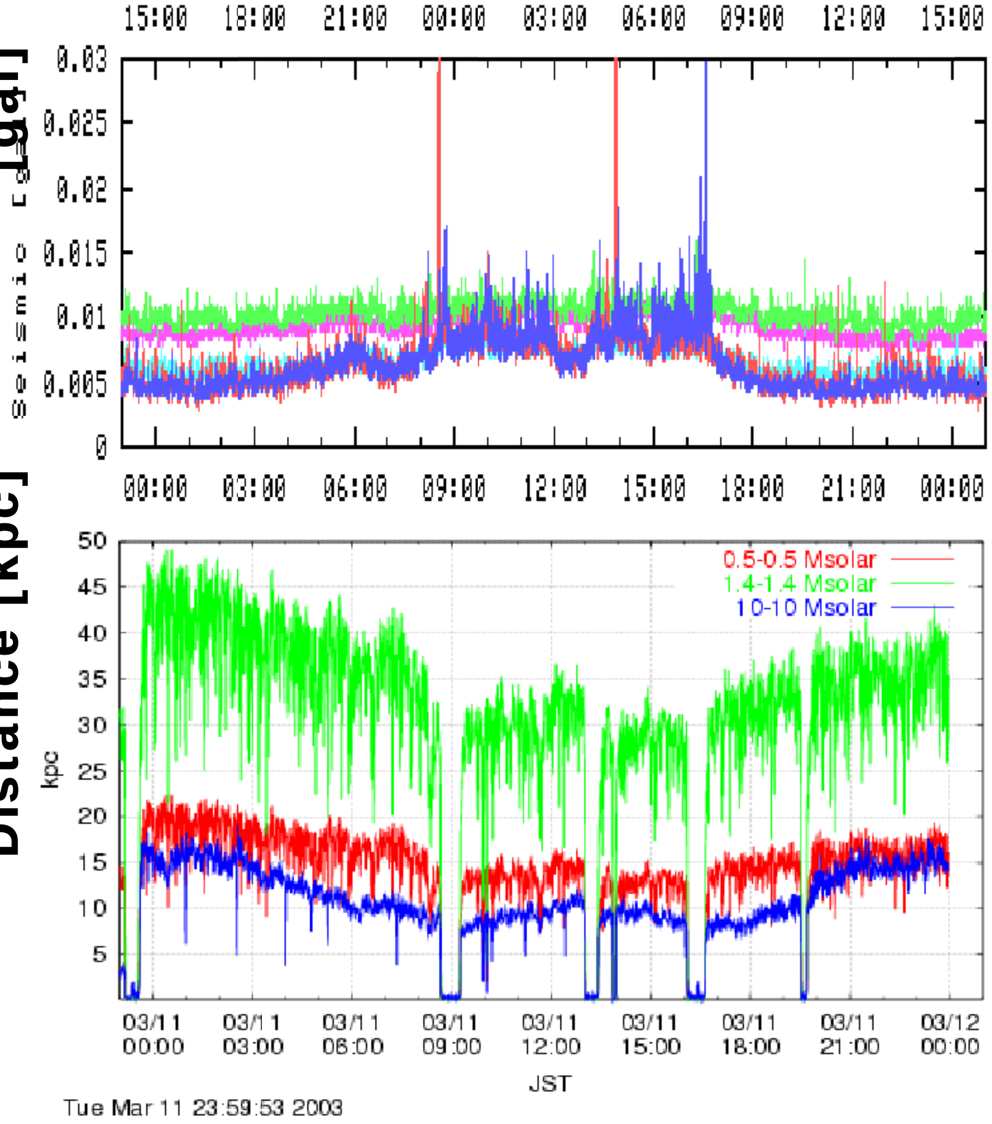
DT8 ~ Disturbance by construction

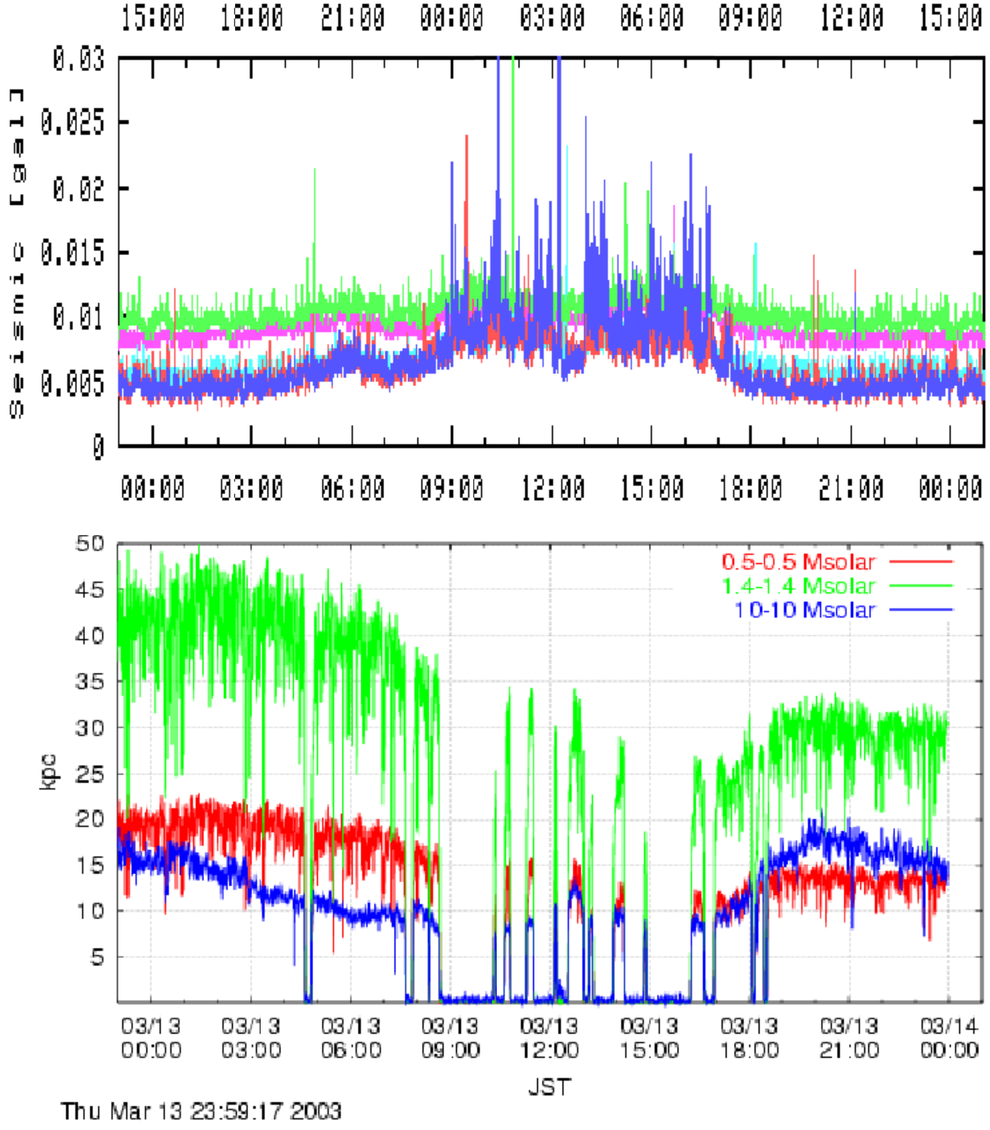
11th May, 2003 (Tue) (Quiet weekday)

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

Seismic level [gal]

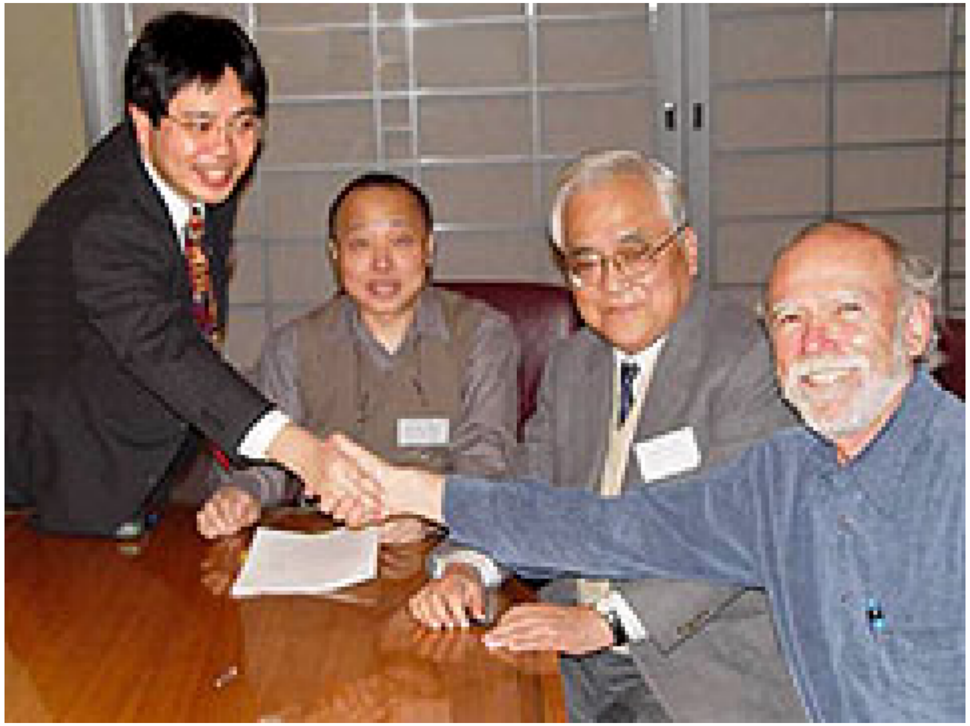
Observable Distance [kpc]





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

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

1158 hours of 1424 hours => duty cycle 81.3%