Current Status of ASC Design for LCGT

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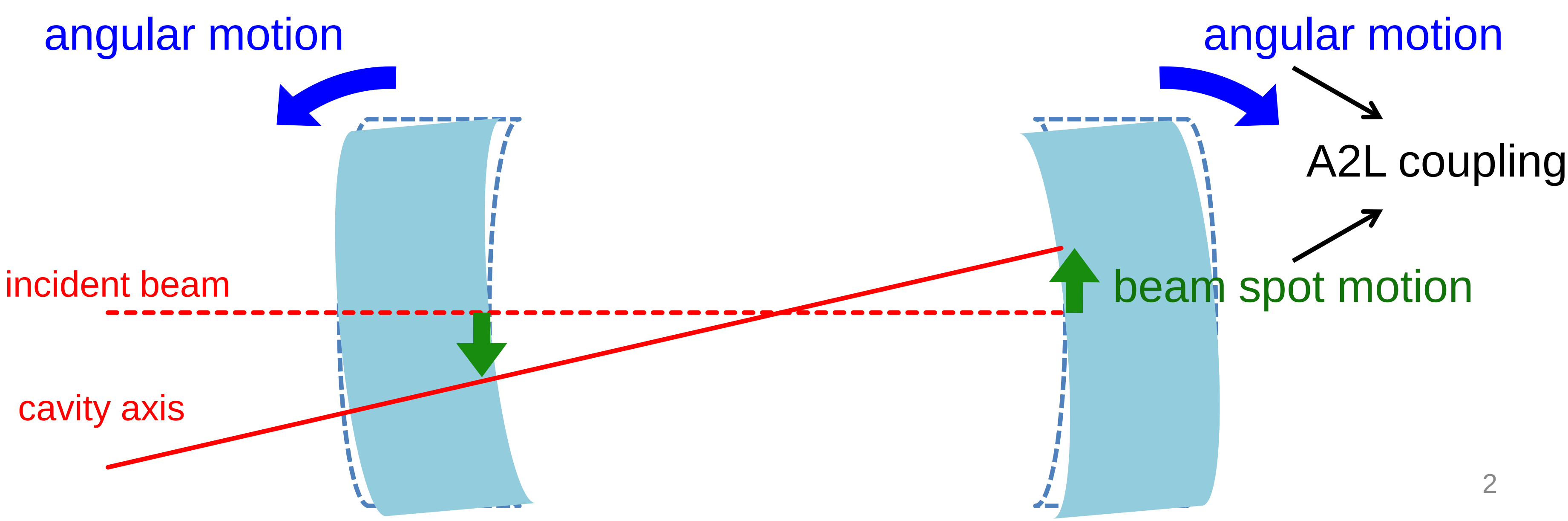
What is ASC?

- Alignment Sensing and Control
- angular motion makes beam spot motion and (angular motion)×(BSM) makes length fluctuation
  → angular motion must be controlled
- global control(WFS) and local control(OpLev etc)

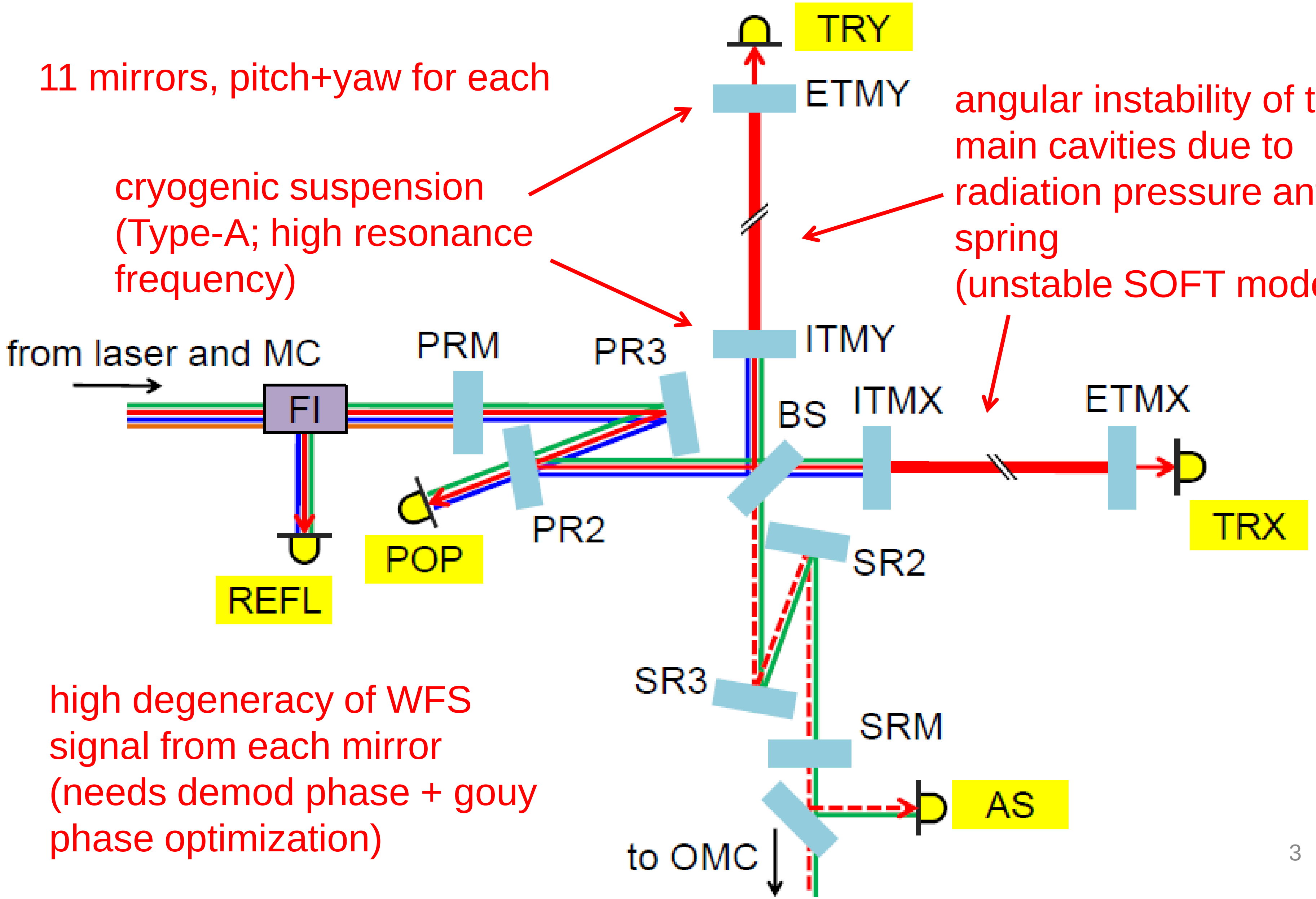


ASC is tough

11 mirrors, pitch+yaw for each

cryogenic suspension (Type-A; high resonance frequency)

angular instability of the main cavities due to radiation pressure anti-spring (unstable SOFT mode)



high degeneracy of WFS signal from each mirror (needs demod phase + gouy phase optimization)

What we have done

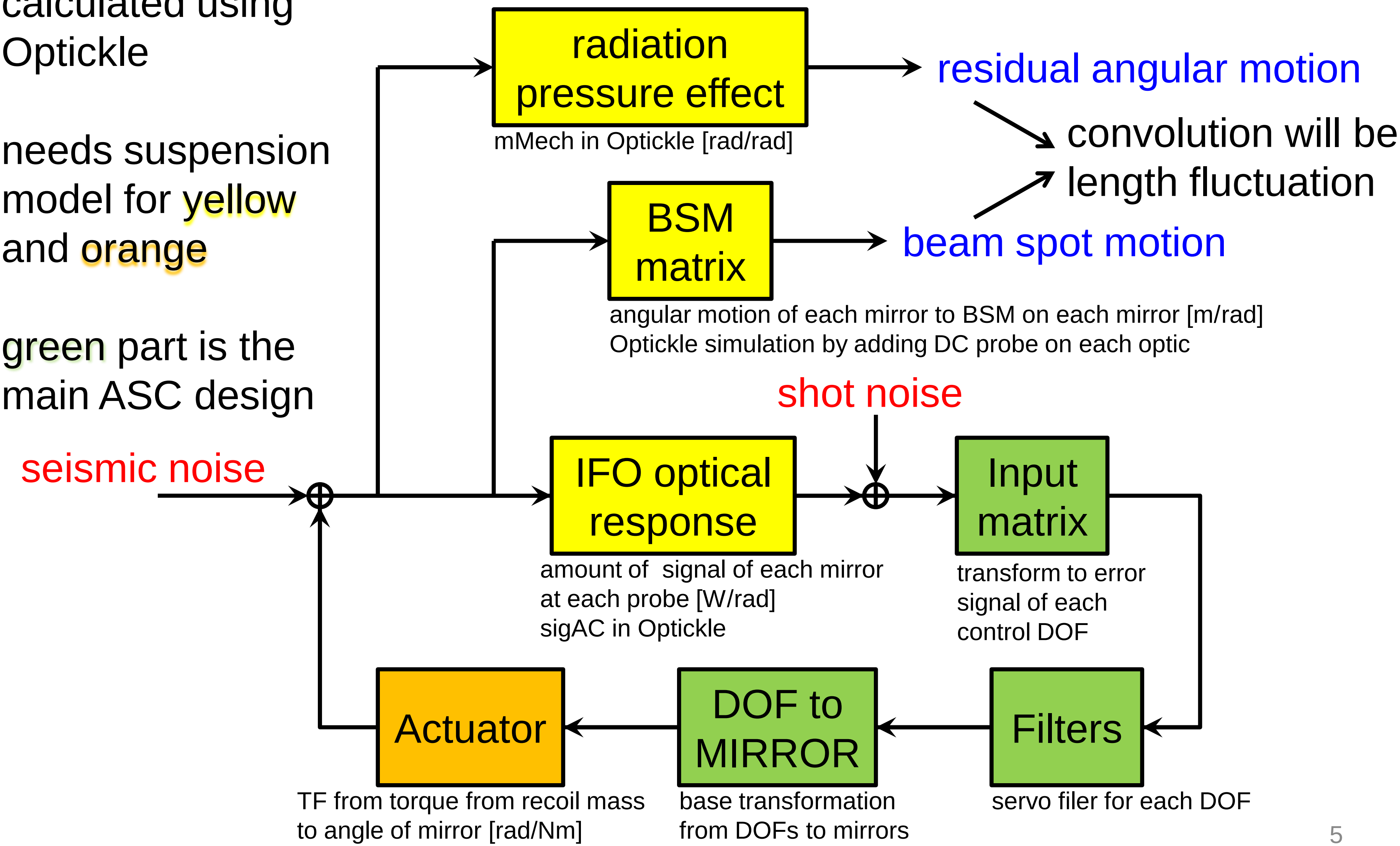
- developed 3D rigid body model for modeling suspension (by T. Sekiguchi)
- developed a tool for simulating/designing WFS servo loop (this talk)
  - optical response of IFO is simulated using *Optickle*
  - loop noise calculation similar to *pickle* (aLIGO ASC tool)
  - uses suspension TF, angular seismic noise as input
  - matrix based, frequency domain ($11 \times 11 \times$freq matrix)

Structure of ASC model

yellow matrices are calculated using Optickle

needs suspension model for yellow and orange

green part is the main ASC design



ASC design procedure

- step 0. choose control DOF
- step 1. select sensing ports
  demodulation/gouy phase optimization
- step 2. design servo filters (control loop)
- step 3. calculate residual angular motion
- step 4. calculate residual beam spot motion
- step 5. estimate A2L coupling

- step 6. do 0-5 for pitch and yaw
  → is total A2L noise below LCGT sensitivity?

1. Sensing port selection

Optimize demodulation phase + gouy phase and select sensing ports
I / Q is demod phase difference, A / B is gouy phase difference

POP DC

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	-19.4	-22.0	-24.7	-81.4	-44.3	-46.9	88.1	87.0	64.5	64.5	64.5
max ampl	-42003.1	-7661.3	-8.2	-0.5	-507.3	-1310.5	-3375.0	-1680.9	1.3	0.2	0.1
Gouy	-2	-2	NaN	NaN	71	71	70	70	NaN	NaN	NaN
ampl	-28338.6	-5091.0	NaN	NaN	153.3	433.5	-2268.6	-1136.5	NaN	NaN	NaN
contami	1.2	6.8	NaN	NaN	29.4	10.4	2.0	3.9	NaN	NaN	NaN
N big sig	1	2	NaN	NaN	6	3	1	2	NaN	NaN	NaN

POP_ADC (min CS)

REFL DC

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	-3.5	3.8	-0.8	-16.8	2.1	3.9	4.0	36.0	83.8	83.8	83.8
max ampl	-66522.5	-57318.2	-57.7	43.8	-28726.4	-81234.2	-9402.2	-3818.7	-2485.2	-297.9	-156.4
Gouy	-86	86	NaN	NaN	-6	86	86	-87	-86	-86	-86
ampl	-6172.3	-5533.9	NaN	NaN	-20108.3	-7887.1	-923.3	1472.1	1729.5	207.3	108.9
contami	1.7	3.7	NaN	NaN	8.6	2.6	22.4	7.3	6.1	50.9	96.9
N big sig	1	2	NaN	NaN	4	1	6	3	2	5	6

POP f1 demodulation

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	17.1	-32.9	51.8	51.8	39.3	-28.6	-27.3	19.6	-25.5	-25.5	-25.5
max demod	0.1	0.1	-89.9	-89.9	-71.0	-0.1	-0.1	0.5	-0.0	-0.0	-0.0
max ampl	118.7	-119.7	53.4	-65.5	48.4	-70.7	-8.2	-8.3	-164.2	-19.7	-10.3
Gouy	64	-73	-81	-81	-82	-73	-73	-38	-73	-73	-73
demod	0	-2	-89	-89	-89	-2	-2	-90	-2	-2	-2
ampl	81.1	-91.5	-36.3	44.5	-32.3	-50.5	-5.7	0.1	-110.7	-13.3	-7.0
contami	1.3	3.3	3.1	2.5	3.6	6.0	52.9	13.1	2.7	22.7	43.2
N big sig	1	2	2	1	3	3	7	6	1	5	6

POP_B1Q POP_B1I (min CS)

REFL f1 demodulation

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	89.9	85.9	71.8	71.1	-13.8	-22.3	-57.0	19.2	-6.2	-6.2	-6.2
max demod	0.0	0.0	77.6	-88.3	0.6	0.0	0.0	0.0	-0.1	-0.1	-0.1
max ampl	-161213.2	26218.0	-128.0	-153.4	-909.2	-3111.6	-620.1	6313.7	-384.4	-46.1	-24.2
Gouy	-71	0	0	0	0	0	0	0	0	NaN	NaN
demod	1	-3	-90	-90	-90	-3	-3	-3	-4	NaN	NaN
ampl	152357.5	-1858.0	40.5	-49.7	35.9	-2876.0	-337.4	5954.7	-381.3	NaN	NaN
contami	1.2	6.7	3.3	2.7	3.7	4.4	37.1	2.1	32.8	NaN	NaN
N big sig	1	3	2	1	3	2	6	1	5	NaN	NaN

REFL_B1I (min CS)

POP f2 demodulation

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	72.6	76.6	81.8	79.5	75.5	75.5	75.5	75.4	81.5	81.5	81.5
max demod	0.1	0.1	-26.9	-23.0	0.0	0.1	0.1	0.1	-90.0	-90.0	-90.0
max ampl	-5076.6	2282.9	2.8	-4.0	1947.9	5511.2	660.5	335.8	0.0	0.0	0.0
Gouy	-17	-20	70	70	68	-20	-20	-14	NaN	NaN	NaN
demod	-70	-70	90	90	90	-70	-70	75	NaN	NaN	NaN
ampl	-90.6	-55.7	-1.3	1.6	-2.6	-98.2	-11.6	-4.2	NaN	NaN	NaN
contami	1.2	3.7	6.7	5.6	4.9	2.1	17.8	36.2	NaN	NaN	NaN
N big sig	1	2	4	2	2	1	4	5	NaN	NaN	NaN

REFL f2 demodulation

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	-89.9	84.0	76.4	-86.7	-74.9	-75.4	-78.1	26.3	-79.3	-79.3	-79.3
max demod	0.1	0.2	8.5	-16.5	0.0	0.0	0.0	-0.0	89.8	89.8	89.8
max ampl	163972.4	-19501.2	-21.6	13.3	-4926.0	-14407.0	-2073.0	6213.0	0.0	0.0	0.0
Gouy	-78	40	NaN	-79	40	40	40	-1	NaN	NaN	NaN
demod	90	-90	NaN	-90	-90	-90	-90	-87	NaN	NaN	NaN
ampl	265.0	105.4	NaN	3.7	67.6	185.4	21.8	291.7	NaN	NaN	NaN
contami	1.2	3.7	NaN	87.6	5.7	2.1	17.8	1.2	NaN	NaN	NaN
N big sig	1	2	NaN	3	3	1	4	1	NaN	NaN	NaN

REFL_A2I (max CS)

AS DC

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	-16.9	-16.9	-87.3	-30.2	-6.2	-24.9	-26.6	83.7	-13.3	-12.9	23.8
max ampl	-7.5	9.2	-0.2	0.3	-2.7	5.7	0.6	0.9	12.7	1.6	1.1
Gouy	-66	-66	74	77	73	77	77	73	64	65	73
ampl	-3.5	4.3	0.1	-0.1	-0.4	-0.8	-0.1	0.6	2.0	0.2	0.5
contami	5.5	4.5	22.3	53.4	8.4	3.9	31.1	4.9	3.1	24.5	5.9
N big sig	3	2	6	9	5	1	8	1	1	7	4

AS_BDC (min CS/CH)

TRX DC

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	-25.6	74.8	-25.6	74.8	-10.4	0.5	0.4	-0.6	-36.3	-36.3	-36.3
max ampl	-43183.8	15641.0	-43183.3	15640.8	0.0	-43.4	-5.2	-2.6	0.0	0.0	0.0
Gouy	-15	64	-15	64	NaN	NaN	NaN	NaN	NaN	NaN	NaN
ampl	-30013.6	10865.5	-30013.4	10865.4	NaN	NaN	NaN	NaN	NaN	NaN	NaN
contami	2.0	2.0	2.0	2.0	NaN	NaN	NaN	NaN	NaN	NaN	NaN
N big sig	1	1	2	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN

TRX_ADC (min CS/DS)

AS f1 demodulation

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	84.8	81.4	89.5	86.2	-13.4	89.6	89.5	88.6	76.8	77.1	-67.5
max demod	-90.0	-90.0	-90.0	-90.0	-90.0	-90.0	-90.0	-90.0	-90.0	-90.0	89.3
max ampl	-0.3	-0.0	-1511.0	-245.9	9.2	0.5	0.1	0.0	-0.0	-0.0	-0.0
Gouy	NaN	NaN	-4	0	-1	NaN	NaN	NaN	NaN	NaN	NaN
demod	NaN	NaN	0	0	0	NaN	NaN	NaN	NaN	NaN	NaN
ampl	NaN	NaN	0.0	-0.0	0.0	NaN	NaN	NaN	NaN	NaN	NaN
contami	NaN	NaN	1.1	2.3	3.9	NaN	NaN	NaN	NaN	NaN	NaN
N big sig	NaN	NaN	1	1	3	NaN	NaN	NaN	NaN	NaN	NaN

AS_A1Q (max DS)

TRY DC

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
max Gouy	-25.6	74.8	-25.6	74.8	0.5	0.5	0.4	-0.6	-23.9	-23.9	-23.9
max ampl	-43183.8	15641.0	43183.4	-15640.8	-30.6	-43.4	-5.2	-2.6	-0.0	-0.0	-0.0
Gouy	-15	64	-15	64	NaN	NaN	NaN	NaN	NaN	NaN	NaN
ampl	30013.7	10865.5	30013.5	-10865.4	NaN	NaN	NaN	NaN	NaN	NaN	NaN
contami	2.0	2.0	2.0	2.0	NaN	NaN	NaN	NaN	NaN	NaN	NaN
N big sig	1	1	2	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN

TRY_ADC (min CS/DS)

positive g-factor

1. Sensing port selection

sensing ports

WFS Sensing Matrix [W/mrad/sqrt(2/pi)]

(Gouy phases at POP A:70.6, POP B:-72.9 REFL A:-89.9, REFL B:-0.1, AS A:89.5, AS B:73.1, TR A:64.4 deg)

control DOF

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
REFL_A2I	163.97	19.39	0.02	0.01	-4.76	-13.95	-2.03	-2.74	0.00	0.00	0.00
TRX_ADC	0.03	10.88	0.03	10.88	0.00	-0.01	-0.00	-0.00	-0.00	-0.00	-0.00
AS_A1Q	0.00	0.00	1.51	0.25	0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00
TRY_ADC	0.03	10.88	-0.03	-10.88	-0.01	-0.01	-0.00	-0.00	-0.00	-0.00	-0.00
POP_B1Q	-0.00	-0.00	0.03	-0.04	0.03	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
REFL_BDC	-46.95	-40.43	-0.04	0.03	-20.30	-57.30	-6.63	-2.18	-0.19	-0.02	-0.01
POP_ADC	0.03	0.24	0.00	0.00	0.15	0.43	-2.28	-1.14	0.00	0.00	0.00
REFL_B1I	0.27	-1.81	-0.00	-0.00	-0.88	-2.88	-0.34	5.96	-0.38	-0.05	-0.02
POP_B1I	-0.00	-0.09	0.00	-0.00	0.02	-0.05	-0.01	0.00	-0.11	-0.01	-0.01
AS_BDC	-0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00

barely diagonalized

reconstruct error signal for each DOF by combining signal from sensing ports (input matrix)

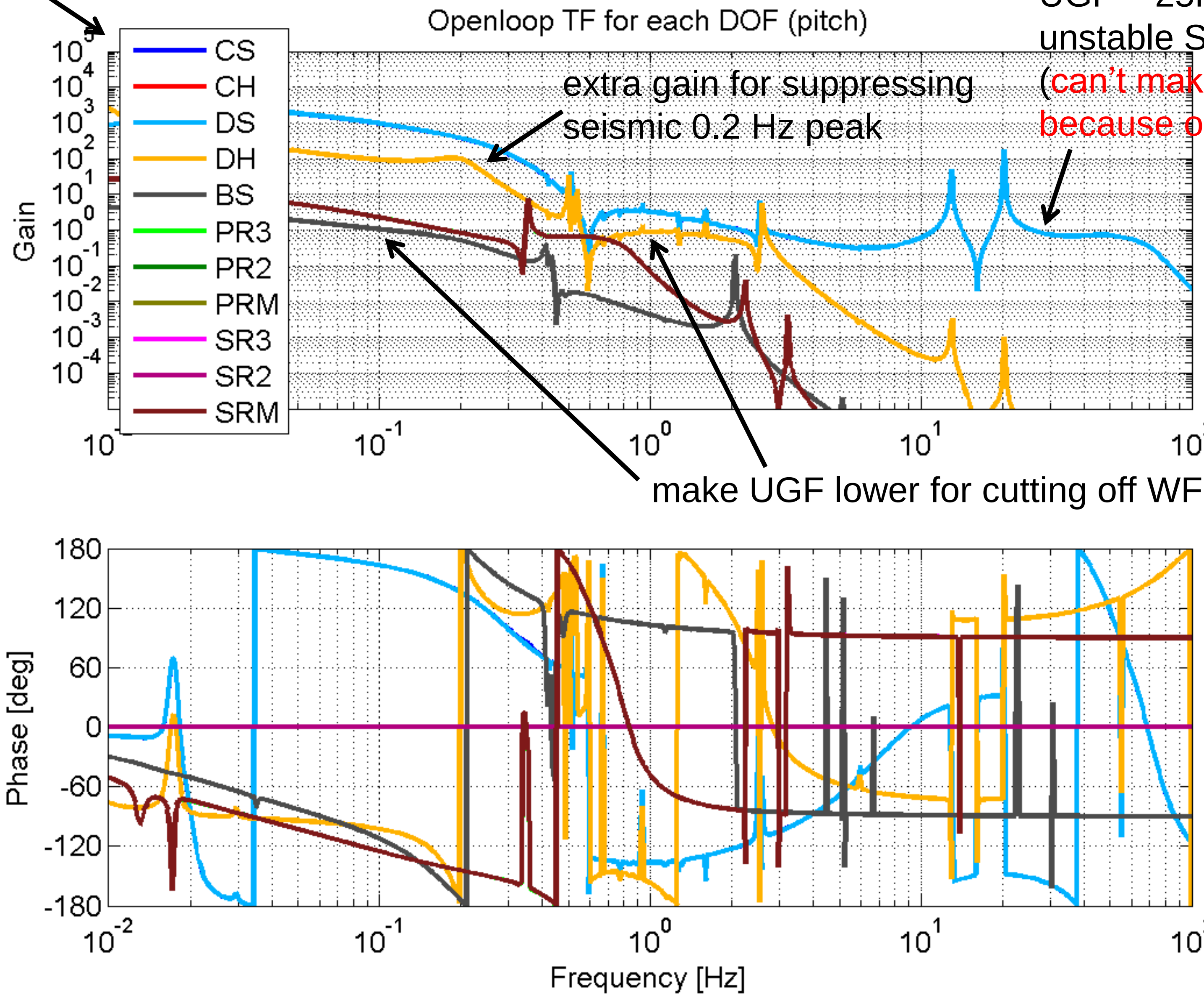
small WFS signal, so no WFS control for SR2

2. Design control loop

high gain at DC
for drift control

UGF ~ 25Hz for unstable SOFT mode (can't make UGF lower because of instability)

extra gain for suppressing seismic 0.2 Hz peak

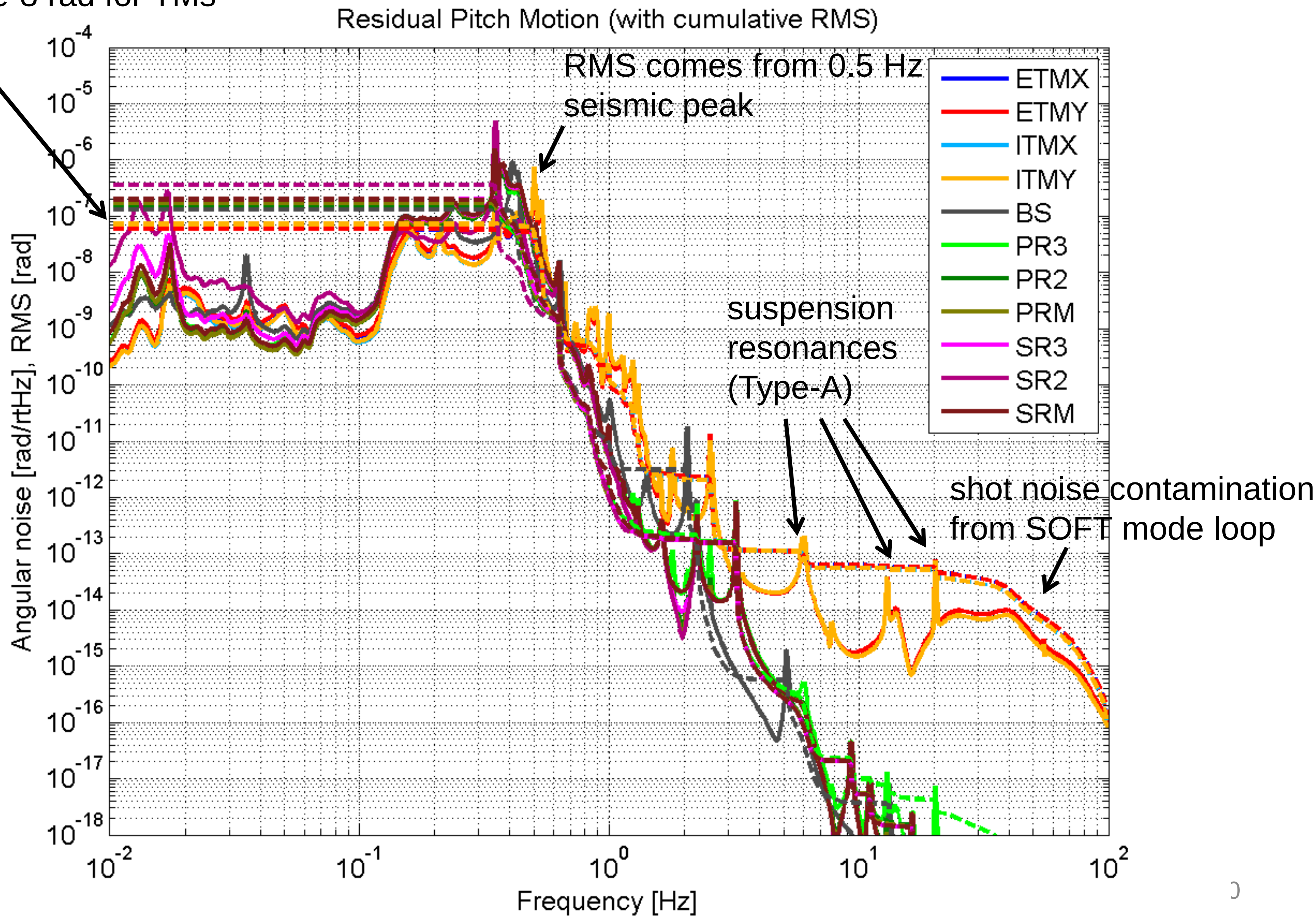


make UGF lower for cutting off WFS shot noise

positive g-factor
pitch

3. Residual angular motion

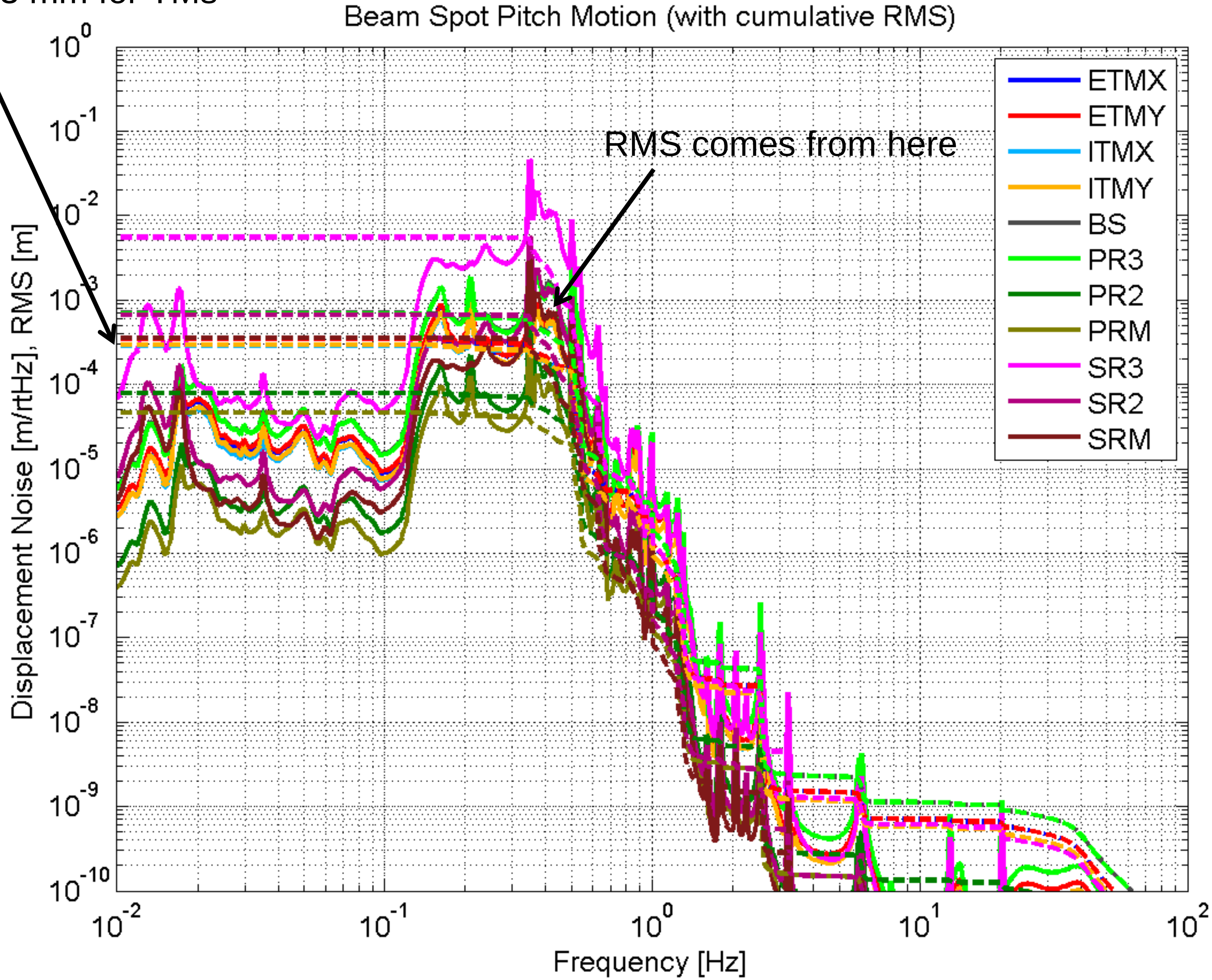
RMS ~ 6e-8 rad for TMs



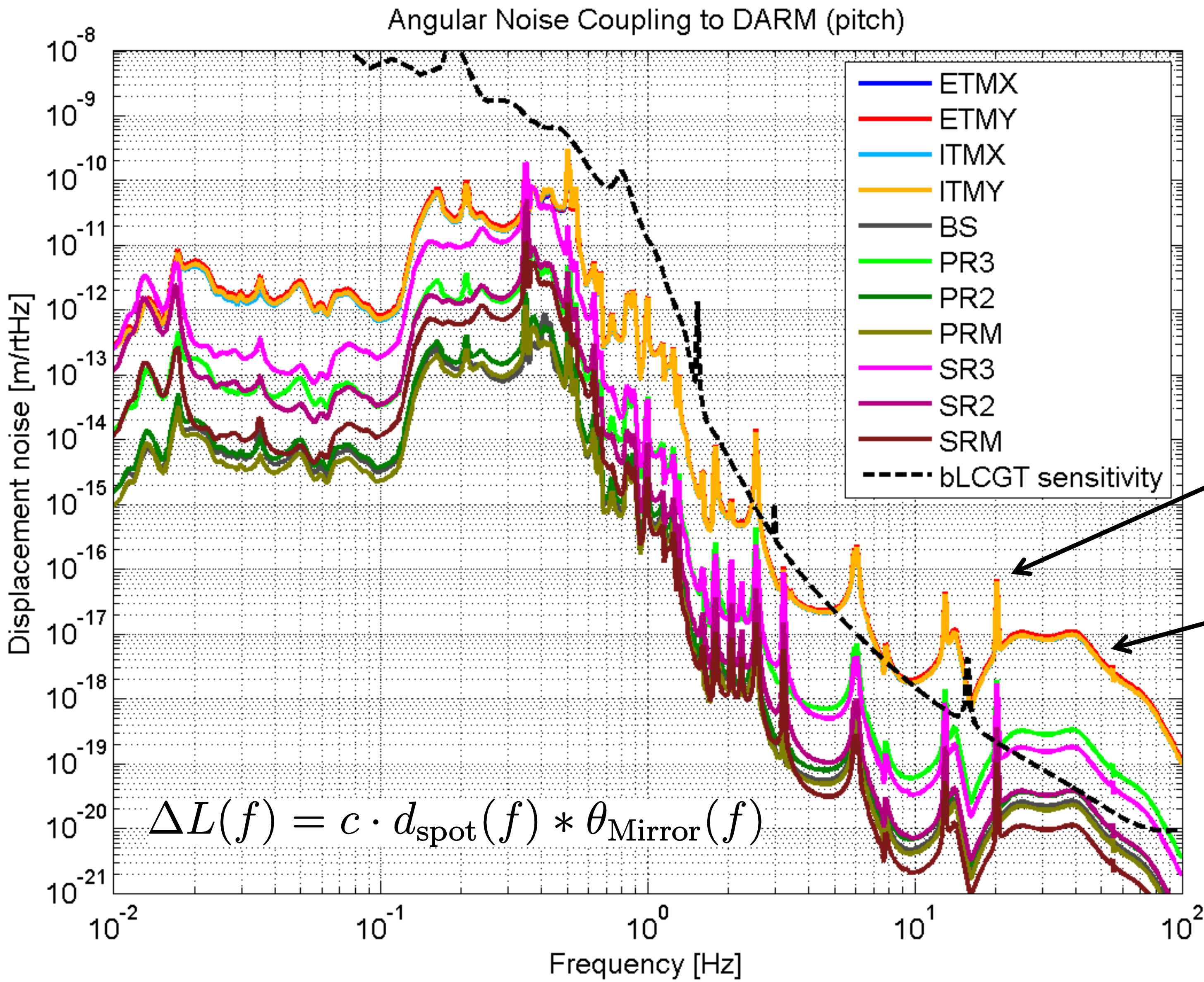
positive g-factor
pitch

4. Beam spot motion

RMS ~ 0.3 mm for TMs



5. A2DARM coupling



suspension resonances (Type-A, pitch)

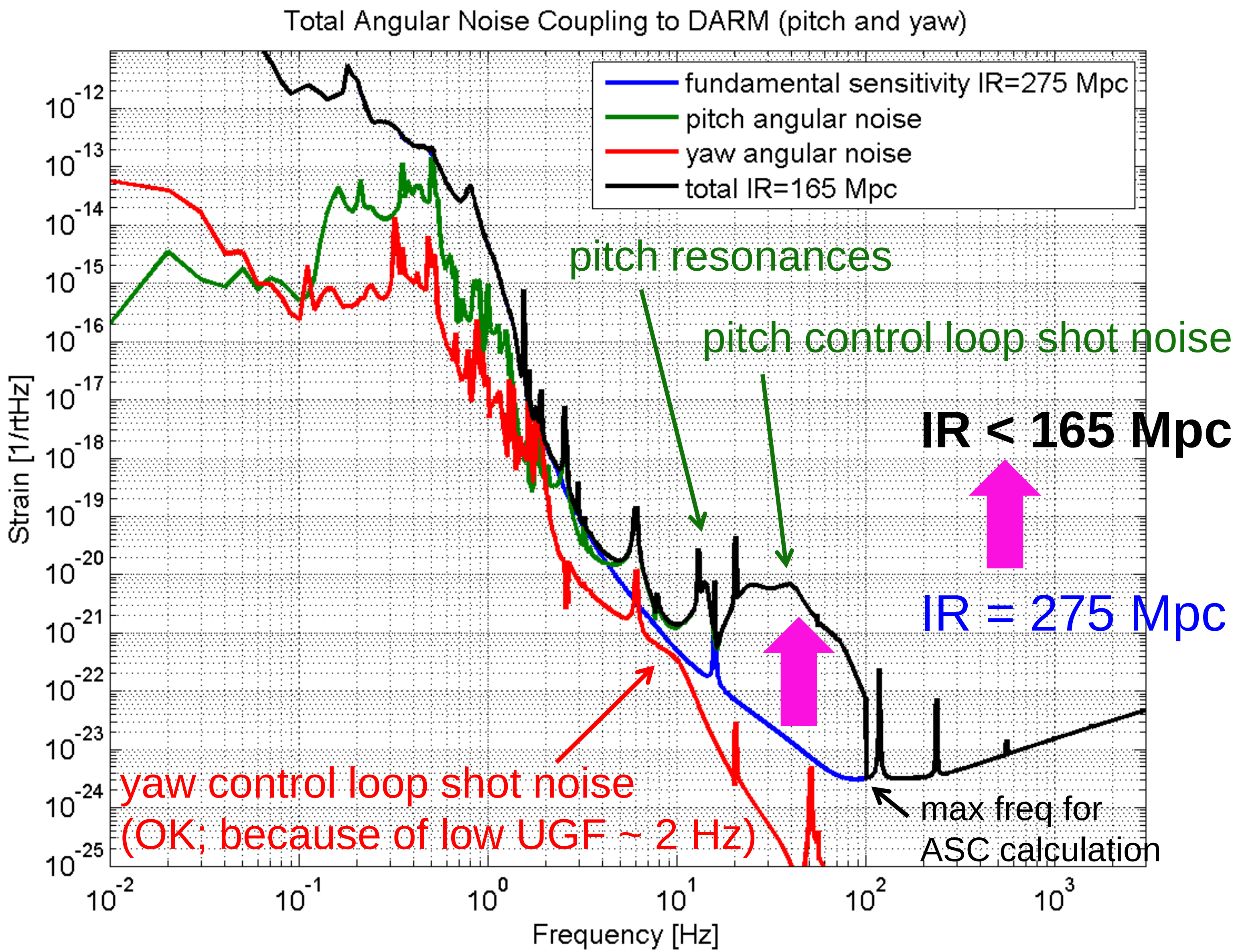
shot noise (very bad!!)

6. Pitch and yaw

- plots above are for pitch control loop
- do the same thing for yaw

→ total A2DARM coupling

Total A2DARM coupling



How to reduce A2DARM?

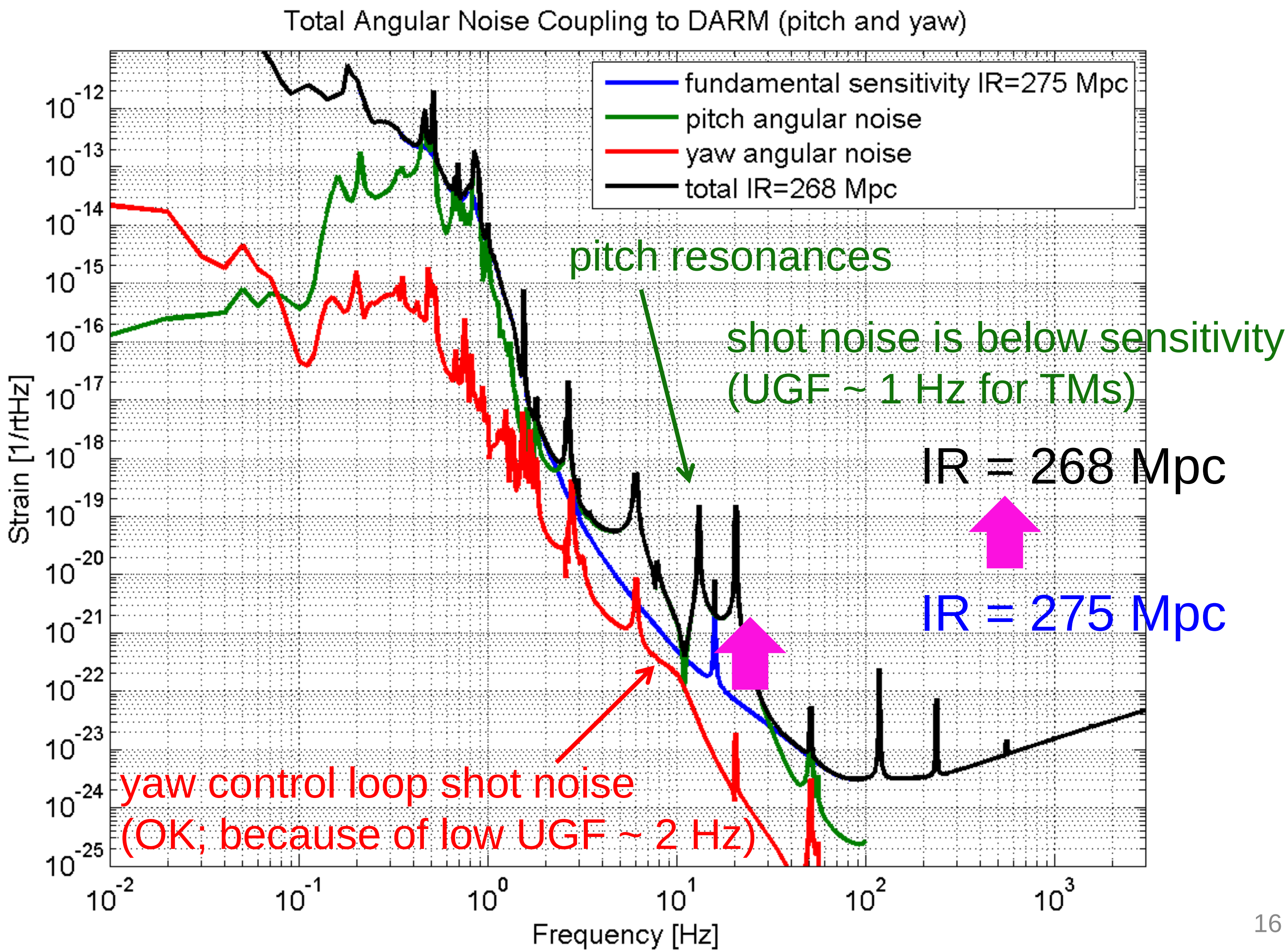
- make pitch SOFT mode stable
  - increase mechanical restoring torque of Type-A(TM) pitch by factor of ~20%
  - negative g-factor
    smaller radiation pressure anti-spring
    → we can lower UGF of TM control
    smaller beam spot motion

unstable if;

radiation pressure anti-spring(SOFT mode)	>	mechanical restoring torque

current default design is positive g (ITM: flat, ETM: R=7 km)
negative g candidate is ITM: R=1.5 km, ETM: R=1.6 km

If negative g-factor……



Reducing A2DARM even more

- employ local damping
  particularly, pitch 0.5 Hz peak
  (difficult to damp by WFS)
  passive + active
- refine suspension design
  somehow move / damp pitch ~ 20Hz peaks

→ work in progress

Future plans

- include strategic local damping
  cooperation with vibration isolation group
- geometrical study of beam in IFO
  for better DOF selection
- upgrade WFS tool
  - compare and check with aLIGO calculation
  - adopt AdVirgo method
  - include more noise
    AS shot noise, seismic noise on QPD, WFS broadband noise ……
    currently, only mirror seismic and QPD shot noise

Summary

- developed a tool for simulating / designing ASC
- evaluated A2DARM for current design
  IR will be < 165Mpc
- proposed negative g-factor solution
- we need better suspension (pitch)

- lots of things to do to make this tool more relevant to reality!