Alignment Sensing and Control for KAGRA

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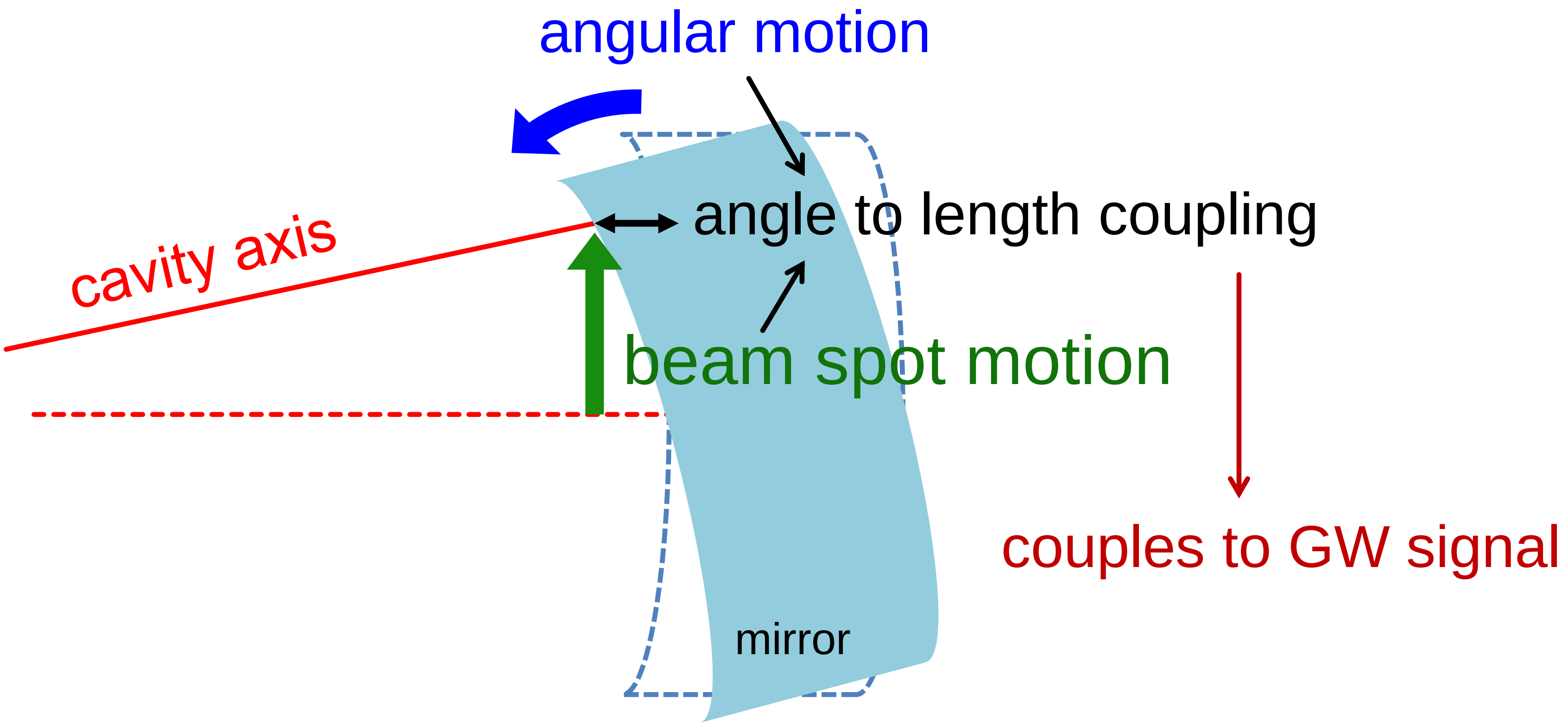
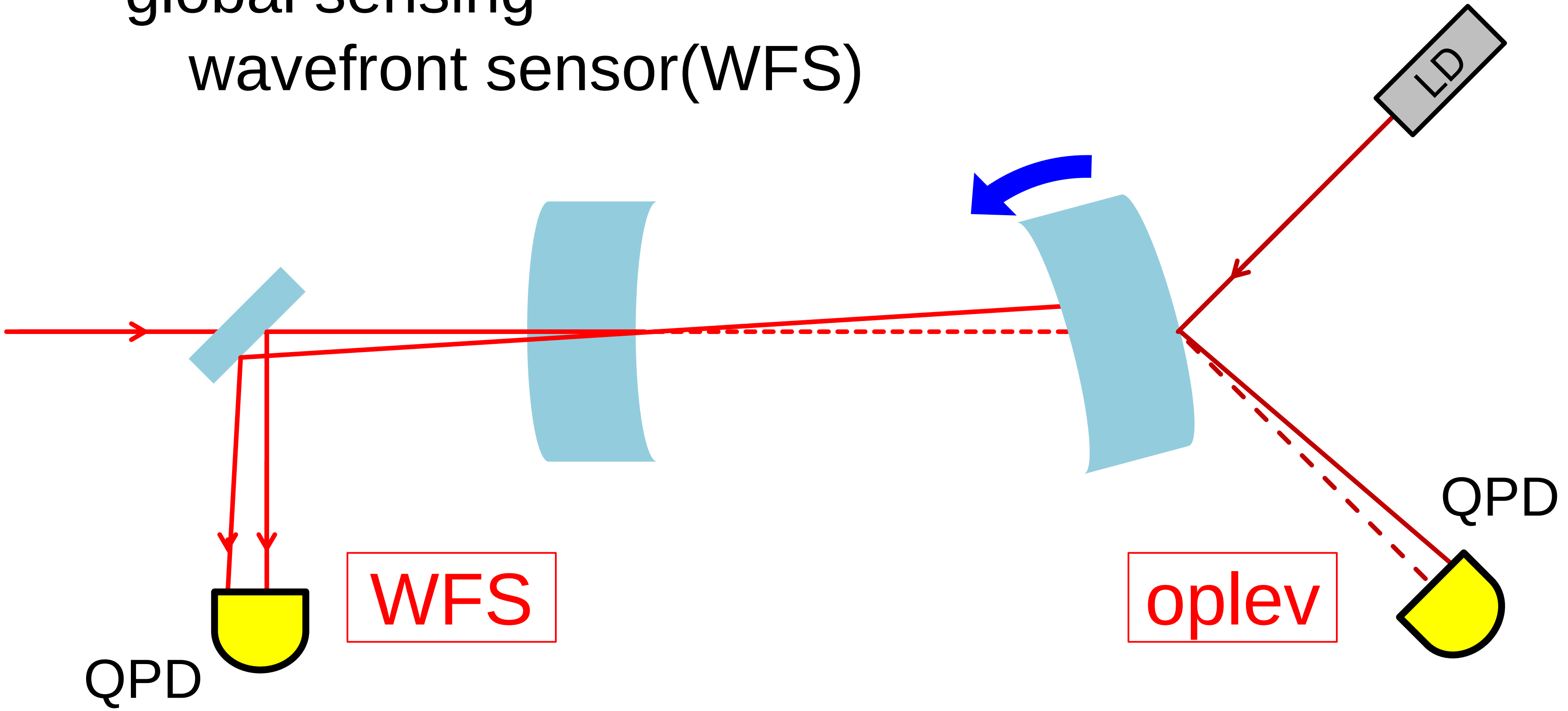
What is ASC?

- Alignment Sensing and Control
- angular motion is a noise source to IFO
  → must be controlled



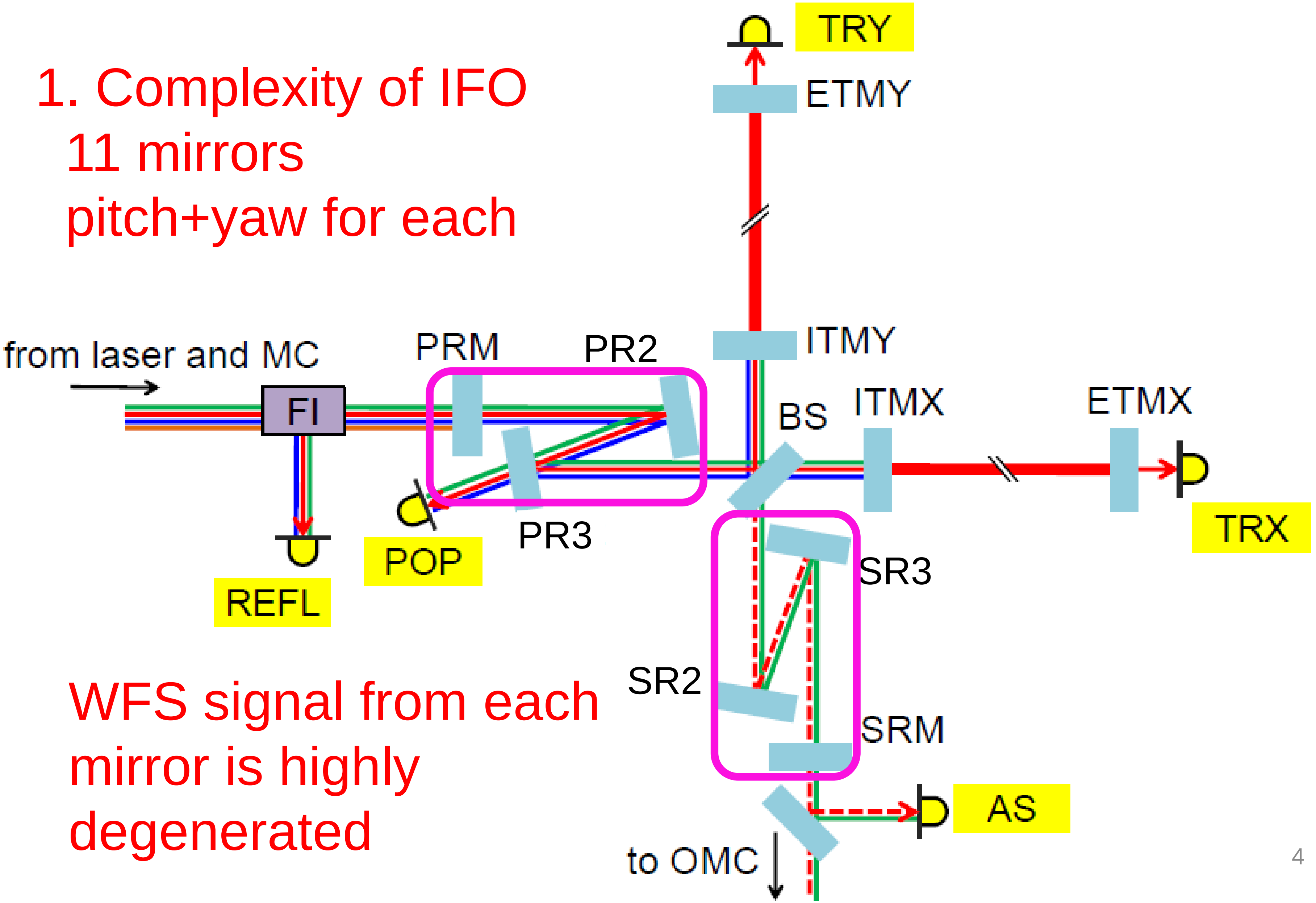
Alignment Sensing

- local sensing
  optical levers, OSEMs, ……
- global sensing
  wavefront sensor(WFS)



ASC is tough

1. Complexity of IFO
   11 mirrors
   pitch+yaw for each

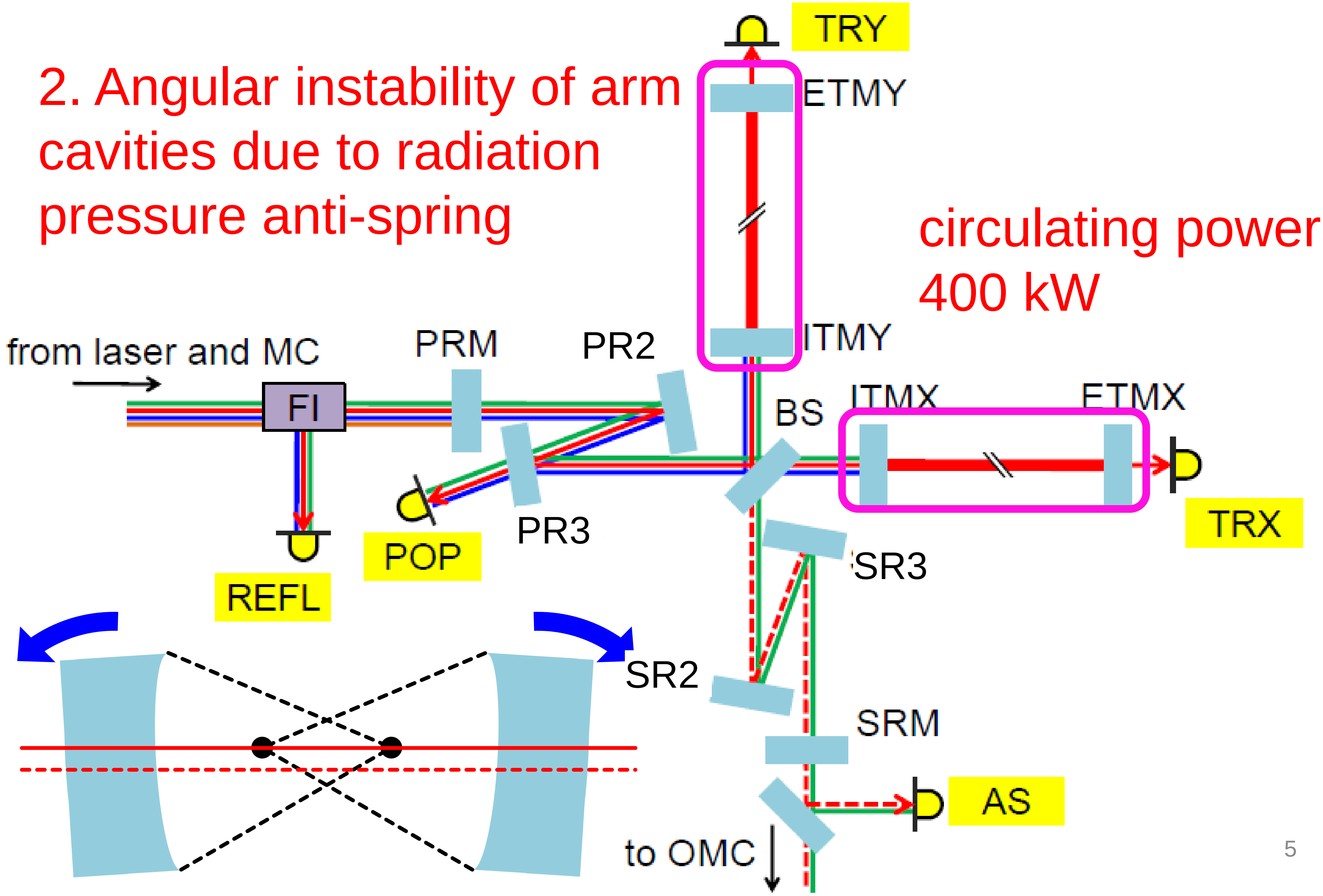


WFS signal from each mirror is highly degenerated

ASC is tough

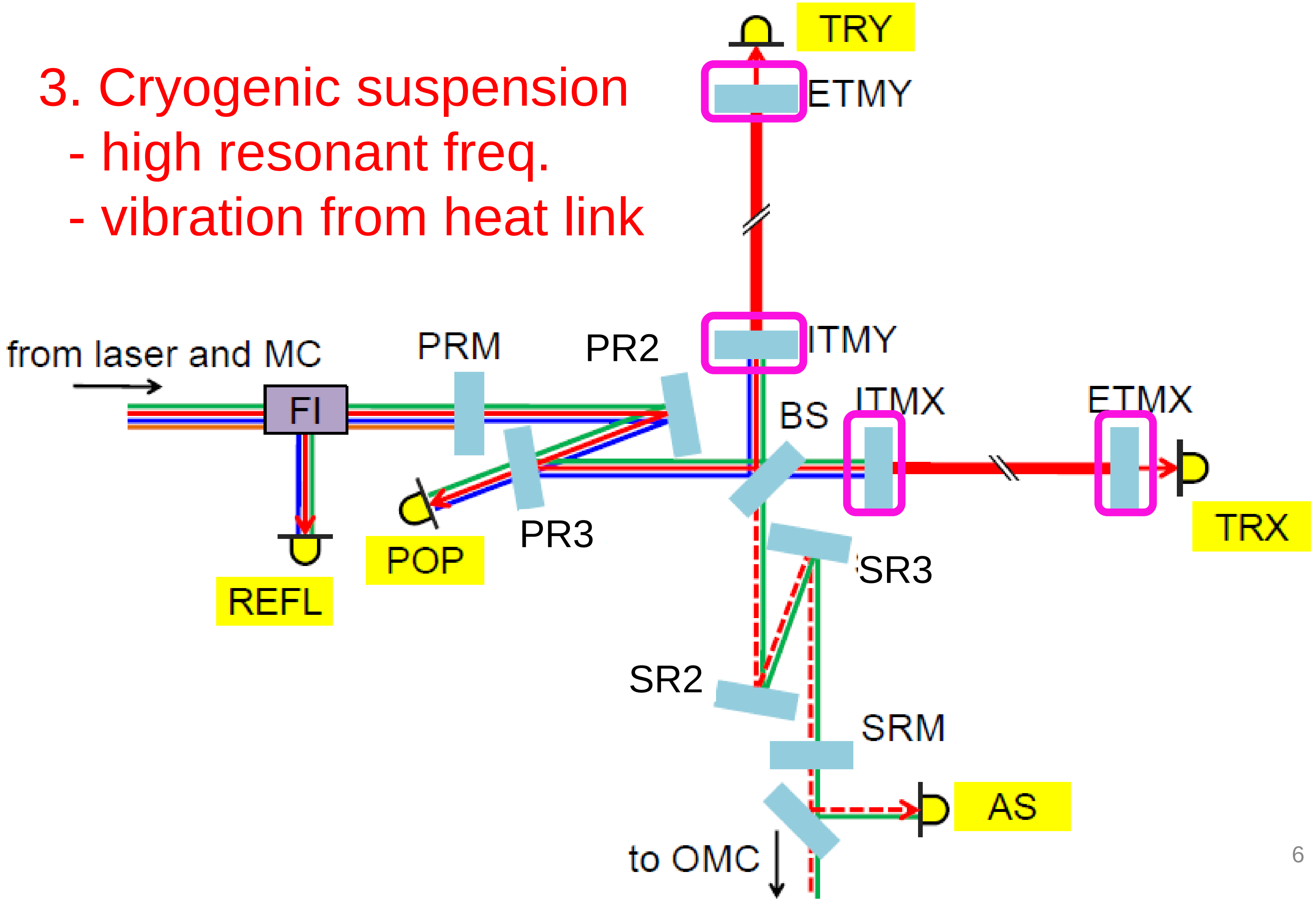
2. Angular instability of arm cavities due to radiation pressure anti-spring

circulating power 400 kW



ASC is tough

3. Cryogenic suspension
- high resonant freq.
- vibration from heat link



What we have done

- developed 3D rigid body model for modeling suspension (by T. Sekiguchi)
- developed a tool for simulating/designing WFS servo loop
- finalized IFO design based on many considerations including ASC

WFS servo modeling

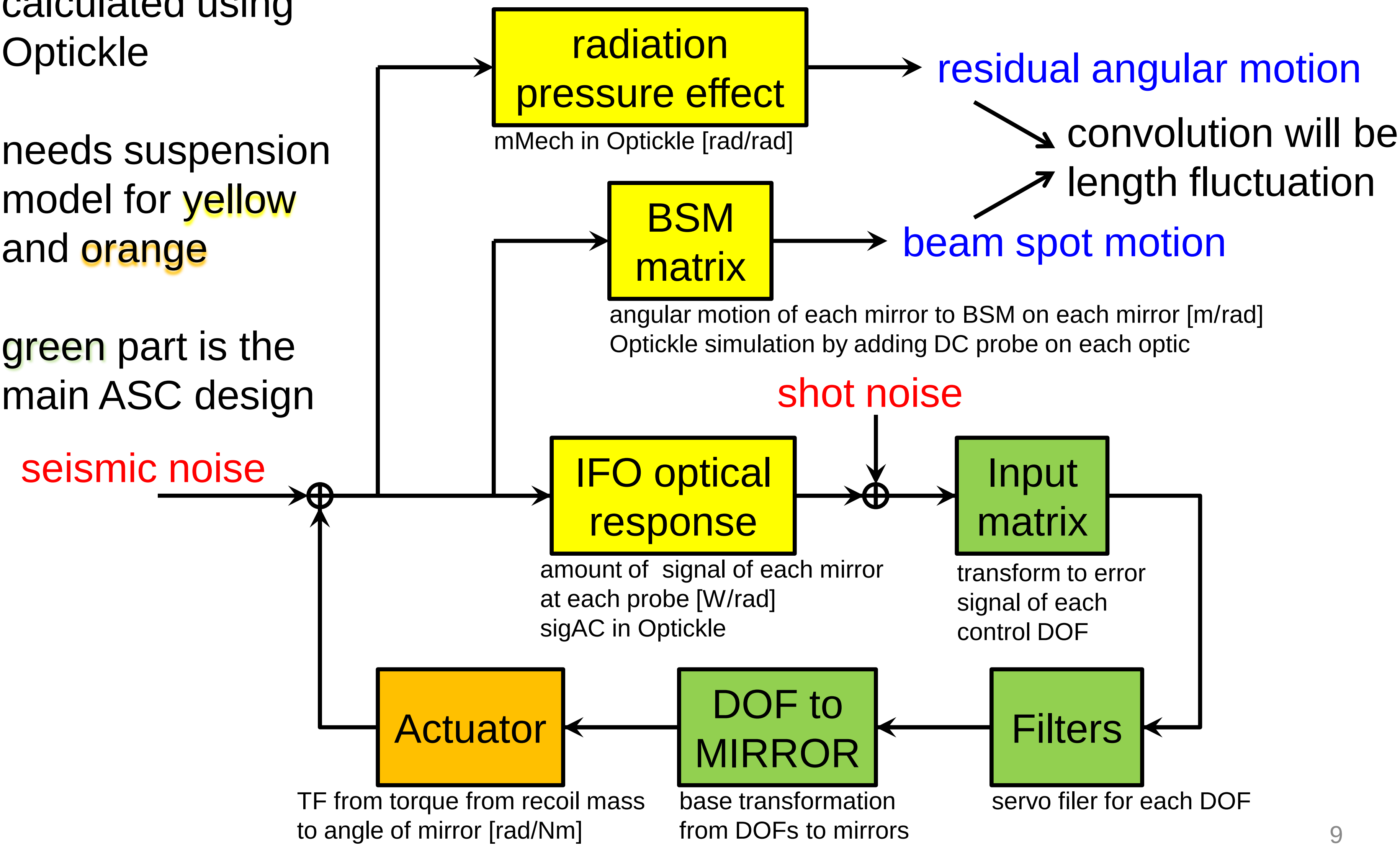
- optical response of IFO is simulated using *Optickle*
- loop noise calculation similar to *pickle* (aLIGO ASC tool)
- uses suspension TF, angular seismic noise as input
- matrix based, frequency domain
  (11×11×freq matrix)

Structure of WFS servo model

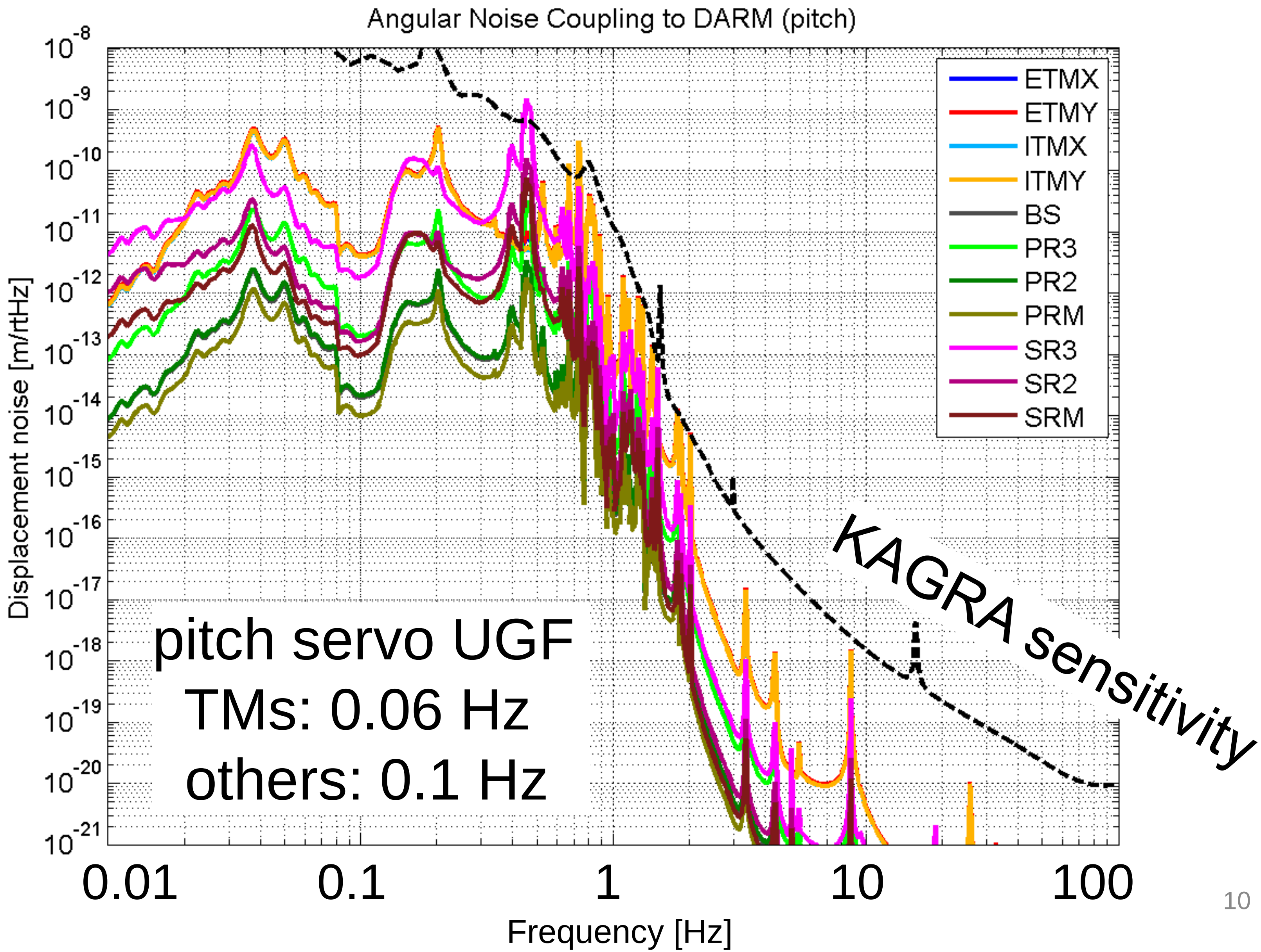
yellow matrices are calculated using Optickle

needs suspension model for yellow and orange

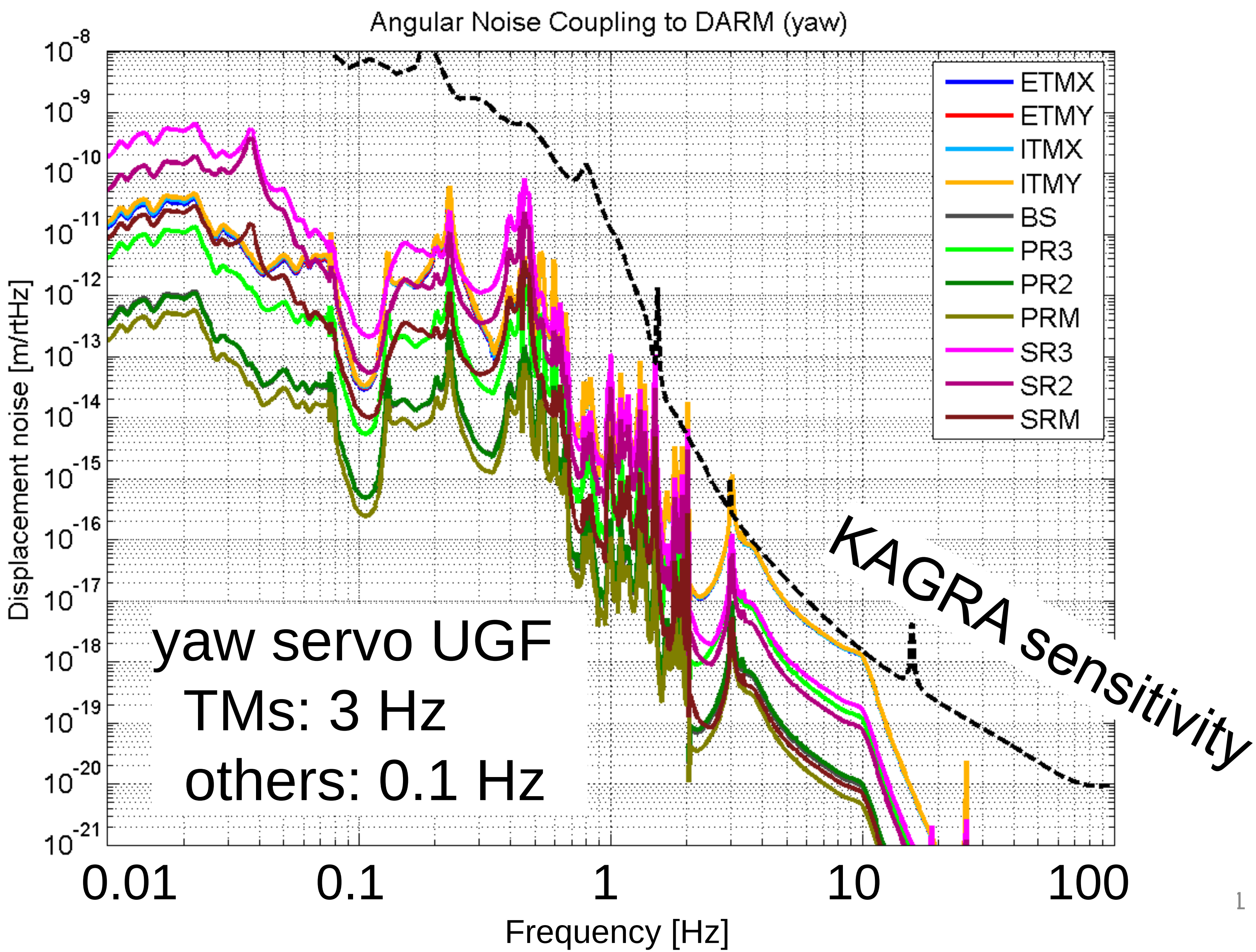
green part is the main ASC design



Angular noise coupling

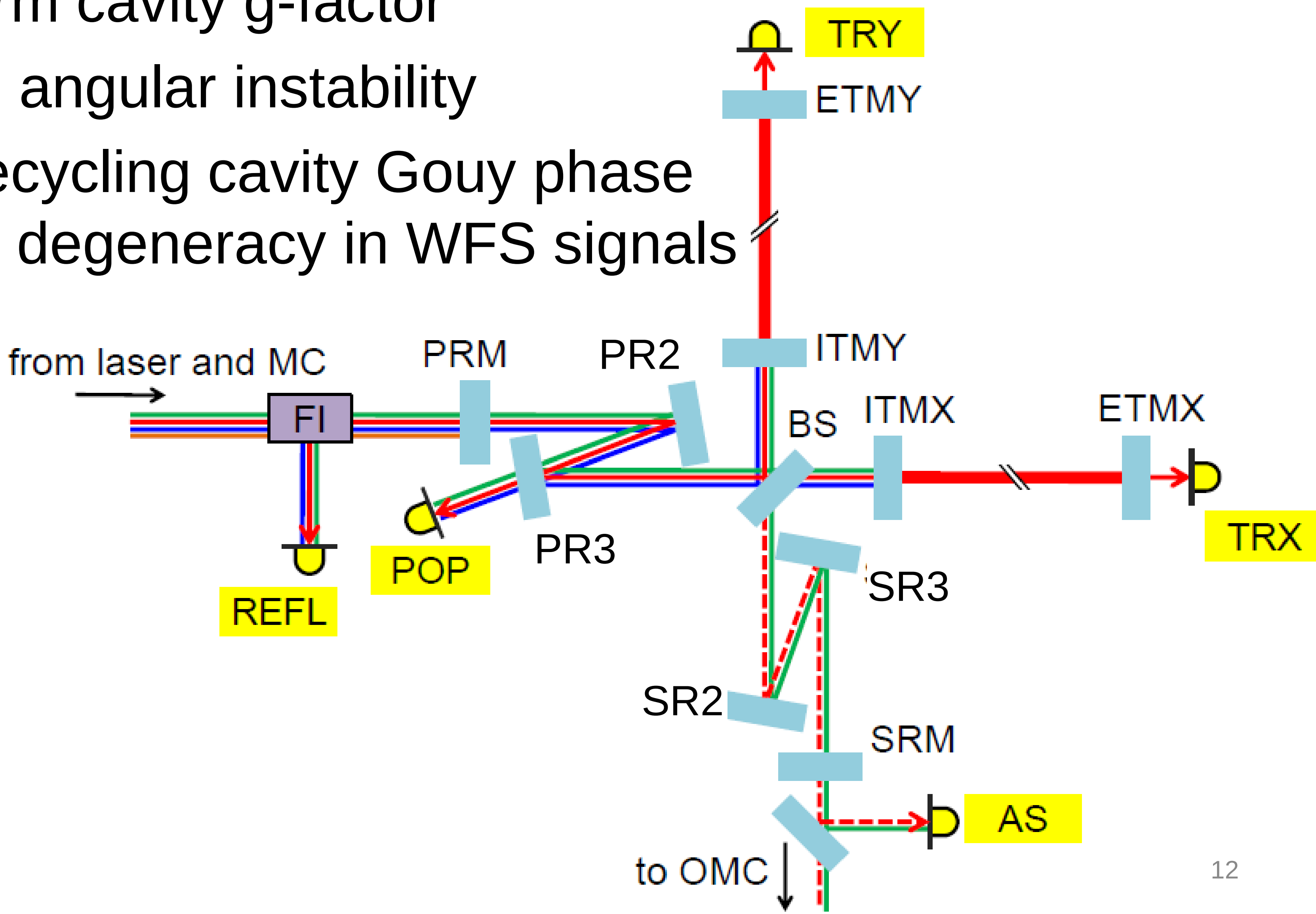


Angular noise coupling



IFO design and ASC

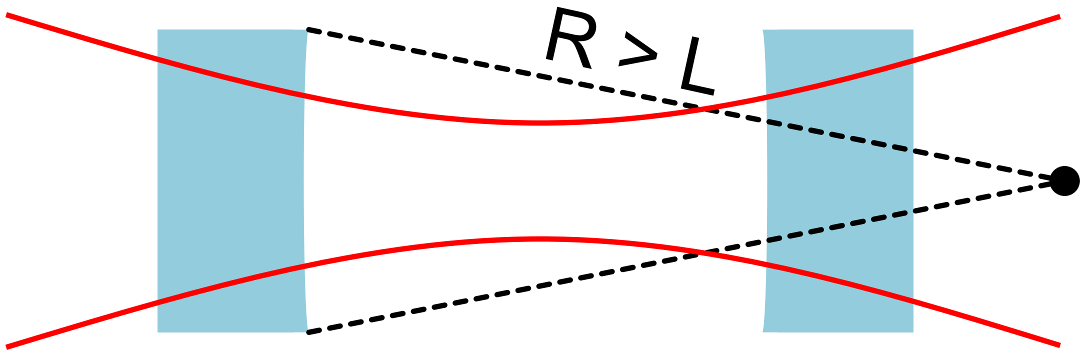
- arm cavity g-factor
  angular instability
- recycling cavity Gouy phase
  degeneracy in WFS signals



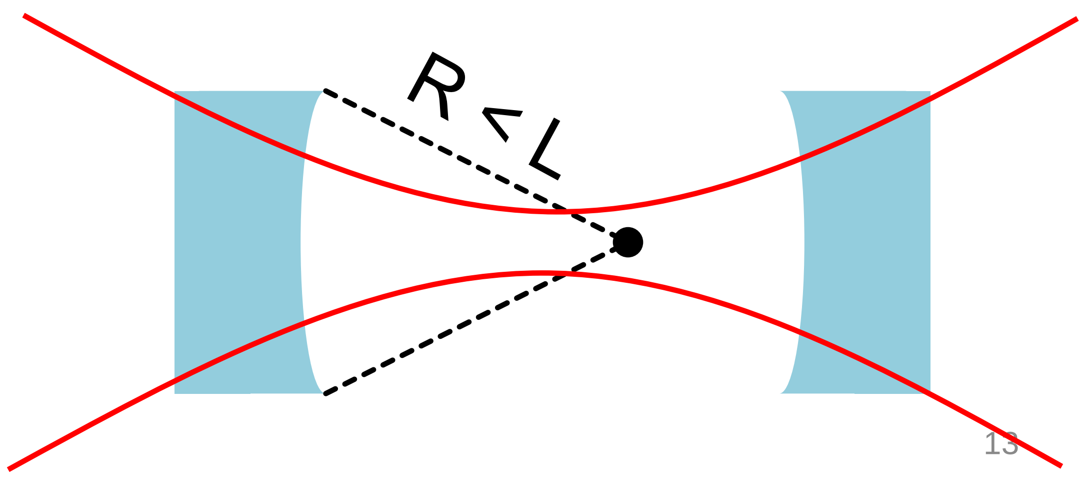
Arm cavity g-factor

- g-factor ← beam spot size ← mirror thermal noise
- two solutions for the same spot size

positive g-factor



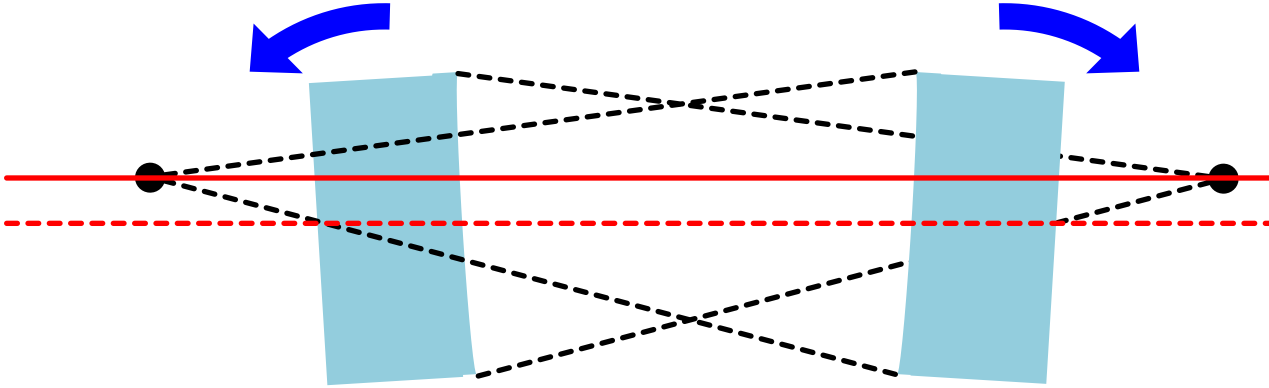
negative g-factor



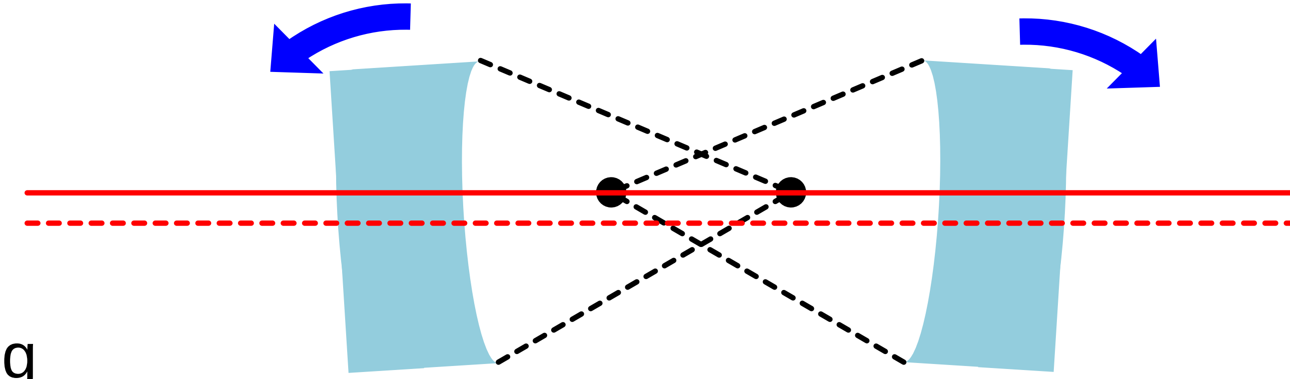
Sidles-Sigg instability

- angular instability due to radiation pressure anti-spring

positive g-factor
- larger beam displacement
- larger anti-spring

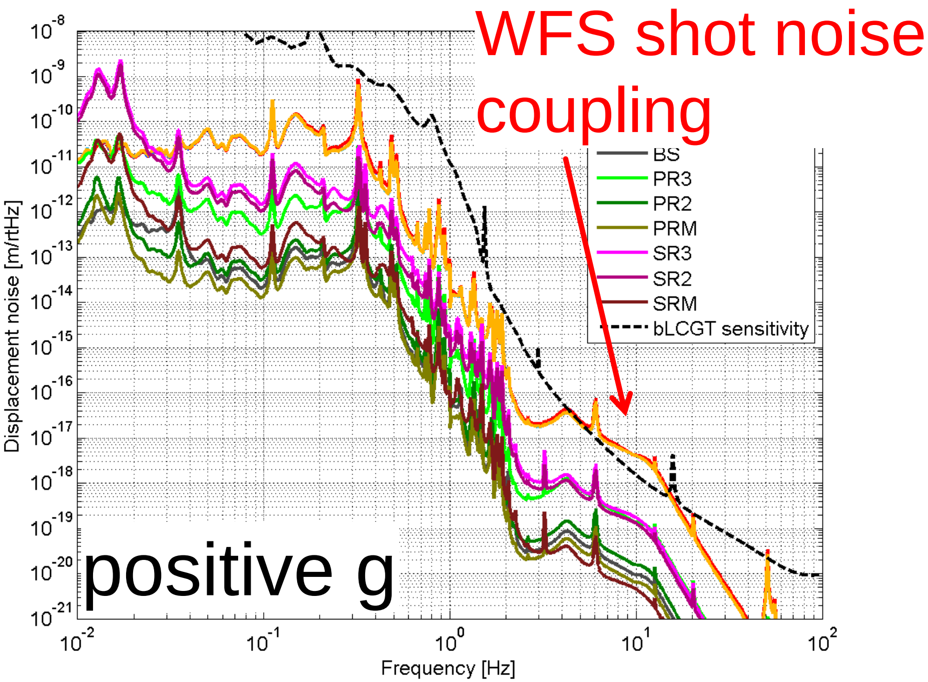


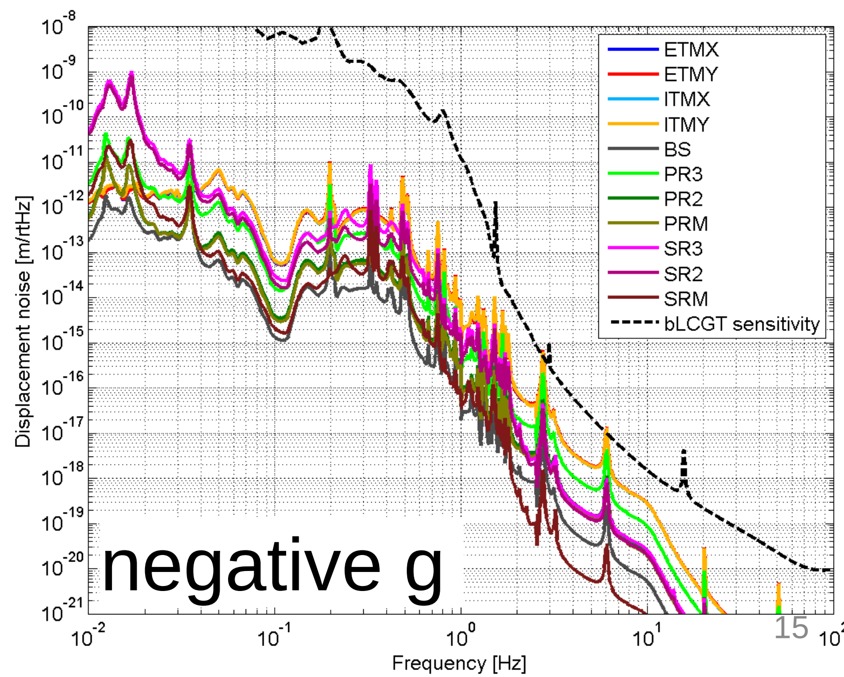
negative g-factor
- smaller beam displacement
- smaller anti-spring



Positive or negative

- positive g-factor gives larger anti-spring
  → needs to be controlled with high UGF
  → strong coupling of WFS shot noise
  → worse IFO sensitivity
- decided to use negative g-factor





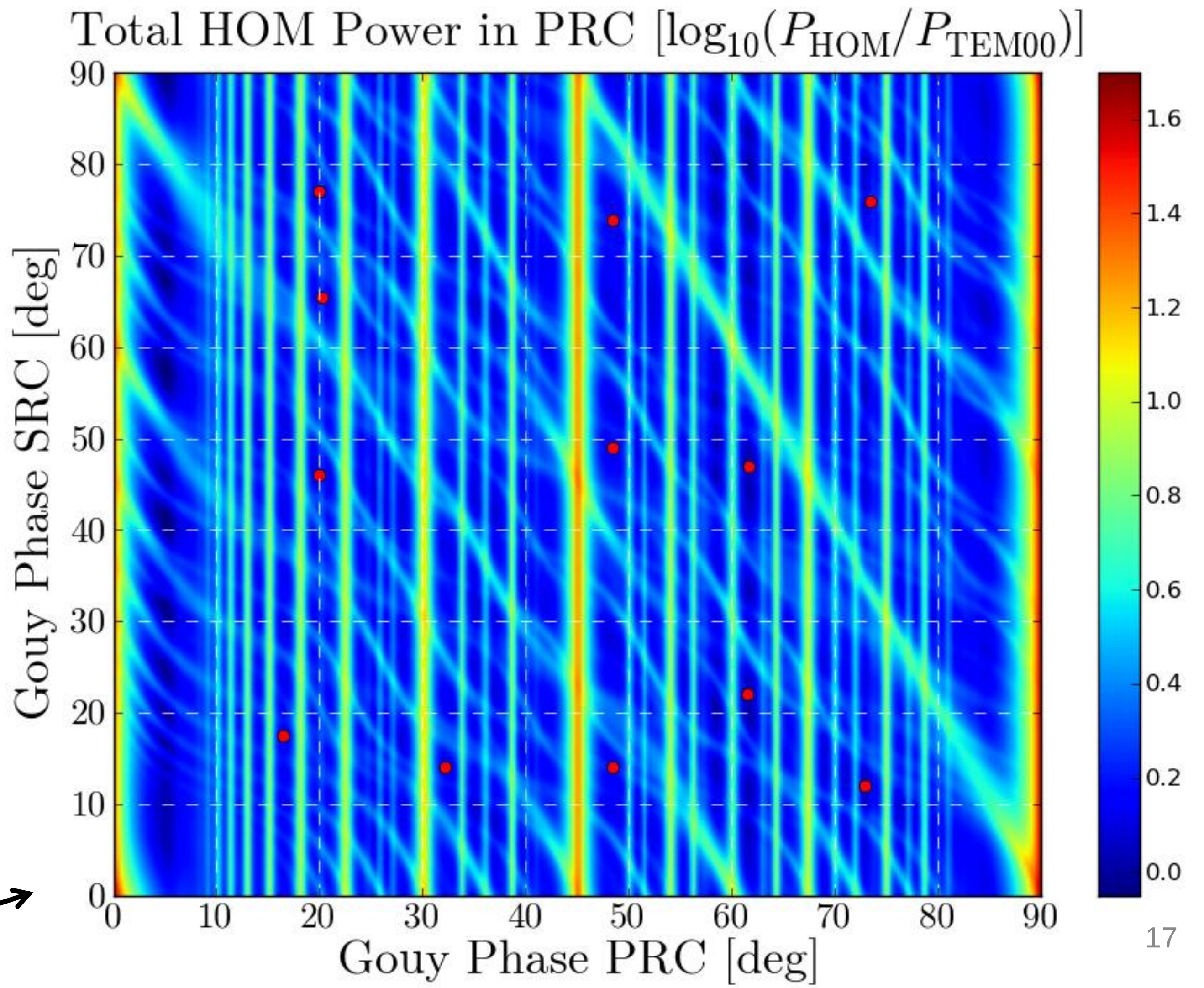
Recycling cavity Gouy phase

- RC Gouy phase suppresses HOMs in RC
- too much suppression of TEM10/01 suppresses WFS signal (especially of RC mirrors)

- design procedure we took
  1. Pick PRC/SRC Gouy phase pairs based on HOM suppression
  2. Calculate level of WFS signal degeneracy for each candidates
- how can we estimate “level of degeneracy” ?

HOM power and RC Gouy phase

- red dots are the candidates



by Y. Aso

WFS sensing matrix

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

(Gouy phases at POP A:-13.0, POP B:-76.3 REFL A:88.7, REFL B:-85.6, AS A:6.8, AS B:-84.1, TR A:-64.1 deg)

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
TRX_ADC	-12.37	-0.03	-12.38	-0.07	0.00	-0.01	-0.00	-0.00	-0.00	-0.00	-0.00
REFL_A2I	-37.31	-136.45	0.04	0.20	5.93	17.57	2.46	2.92	-0.00	-0.00	-0.00
TRY_ADC	-12.37	-0.03	12.38	0.07	-0.01	-0.01	-0.00	-0.00	0.00	0.00	0.00
AS_A1Q	0.00	0.01	8.70	43.63	0.08	-0.01	-0.00	-0.00	-0.00	-0.00	-0.00
POP_A1Q	0.03	-0.00	0.48	-0.44	0.31	-0.03	-0.00	-0.00	-0.01	-0.00	-0.00
POP_A2Q	-2.44	0.65	0.00	0.00	1.44	4.15	0.51	0.25	-0.00	-0.00	-0.00
POP_BDC	0.22	-0.03	-0.00	-0.01	-0.15	-0.38	-2.62	-1.28	0.02	0.00	0.00
REFL_BDC	-1.01	-5.47	0.02	-0.02	-0.07	-0.11	-0.00	2.97	0.03	0.00	0.00
POP_B1I	2.64	-0.38	0.00	0.00	-0.58	-3.04	-0.37	-0.18	-1.36	-0.16	-0.08
AS_BDC	-0.01	0.01	0.00	-0.00	-0.01	0.00	-0.00	-0.00	0.02	0.00	-0.04

Sensing matrix diagonalization

- we use input matrix to extract error signal for each mirror from sensing matrix

$$\begin{pmatrix} \mathbf{S}^{-1} \end{pmatrix} \times \begin{pmatrix} \mathbf{S} \end{pmatrix} = \begin{pmatrix} \mathbf{I} \end{pmatrix}$$

$\mathbf{S}^{-1}$: rows — error signal for each mirror; columns — signal at each port

↑ input matrix [rad/W]

$\mathbf{S}$: rows — signal at each port; columns — each mirror motion

↑ sensing matrix [W/rad]

$\mathbf{I}$: rows — error signal for each mirror; columns — each mirror motion

↑ ideally, identity matrix

Estimation for degeneracy level

- in reality, WFS shot noise contaminates

$$\left(\mathbf{S}^{-1} \right) \times \left(\mathbf{S} \;\vdots\; \mathbf{N} \right) = \left(\mathbf{I} \;\vdots\; \mathbf{S}^{-1}\mathbf{N} \right)$$

error signal for each mirror

signal at each port

each mirror motion

WFS shot noise

signal at each port

error signal for each mirror

each mirror motion

WFS shot noise

input matrix [rad/W]

sensing matrix [W/rad]

ideally, identity matrix

shot noise matrix [W/rtHz]

equivalent shot noise [rad/rtHz]

Equivalent shot noise

- PRC 16.5 deg, SRC 17.5 deg was the best
- basically larger Gouy phase gives worse SNR

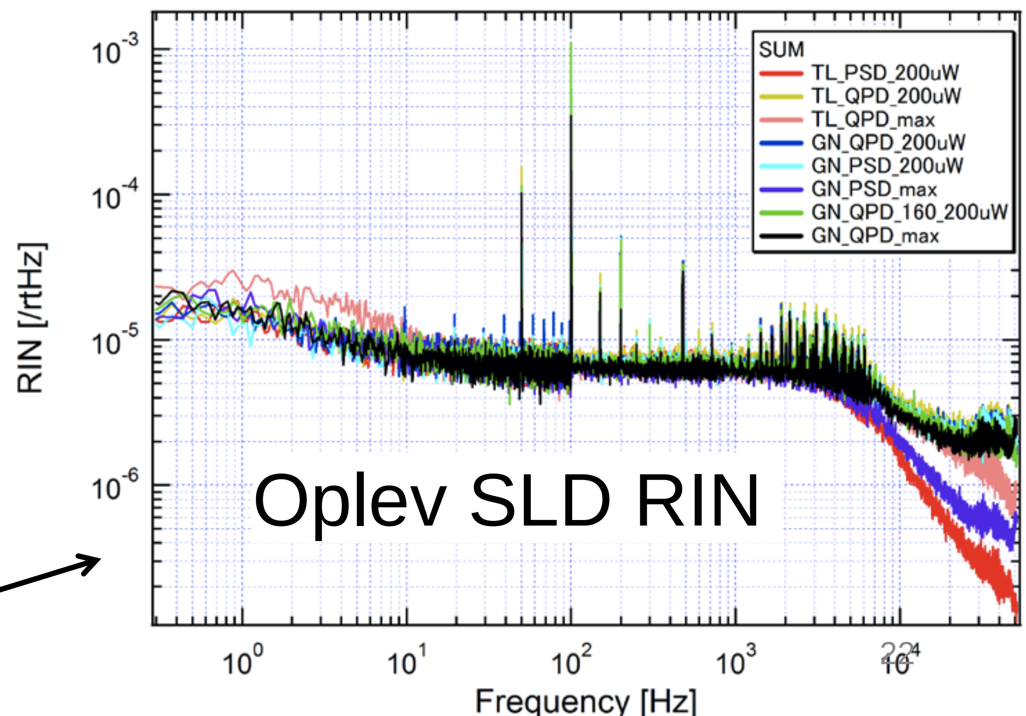
	P195_S195	P615_S220	P200_S770	P735_S760	P165_S175	P350_S250
CS:	7.75	7.75	7.76	7.76	7.75	7.76
CH:	4.27	6.48	21.35	9.55	4.61	5.85
DS:	7.76	7.76	7.75	7.76	7.76	7.76
DH:	1.92	2.3	2.47	2.46	1.87	2.04
BS:	457.18	743.18	160.78	125.74	431.02	511.87
PR3:	162.78	320.06	194.93	326.1	153.1	199.67
PR2:	62.55	347.09	128.62	1114.51	55.78	104.97
PRM:	29.75	106.14	159.81	292.25	27.53	48.83
SR3:	214.27	496.29	515.94	412.98	196.14	312.74
SR2:	0	0	0	0	0	0
SRM:	627.87	719.27	1142.56	2142.45	579.1	712.03

(all in 10^{-15} rad/rtHz)

SR2 is not controlled by WFS
because of too much degeneracy

Optical levers?

- for some mirrors, WFS equivalent shot noise is ~10^{-13} rad/rtHz
- but optical levers are worse
  - shot noise: ~10^{-12} rad/rtHz (5 mW)
  - intensity noise: ~10^{-10} rad/rtHz (RIN 10^{-5} /rtHz)
- optical levers can be used only for local damping



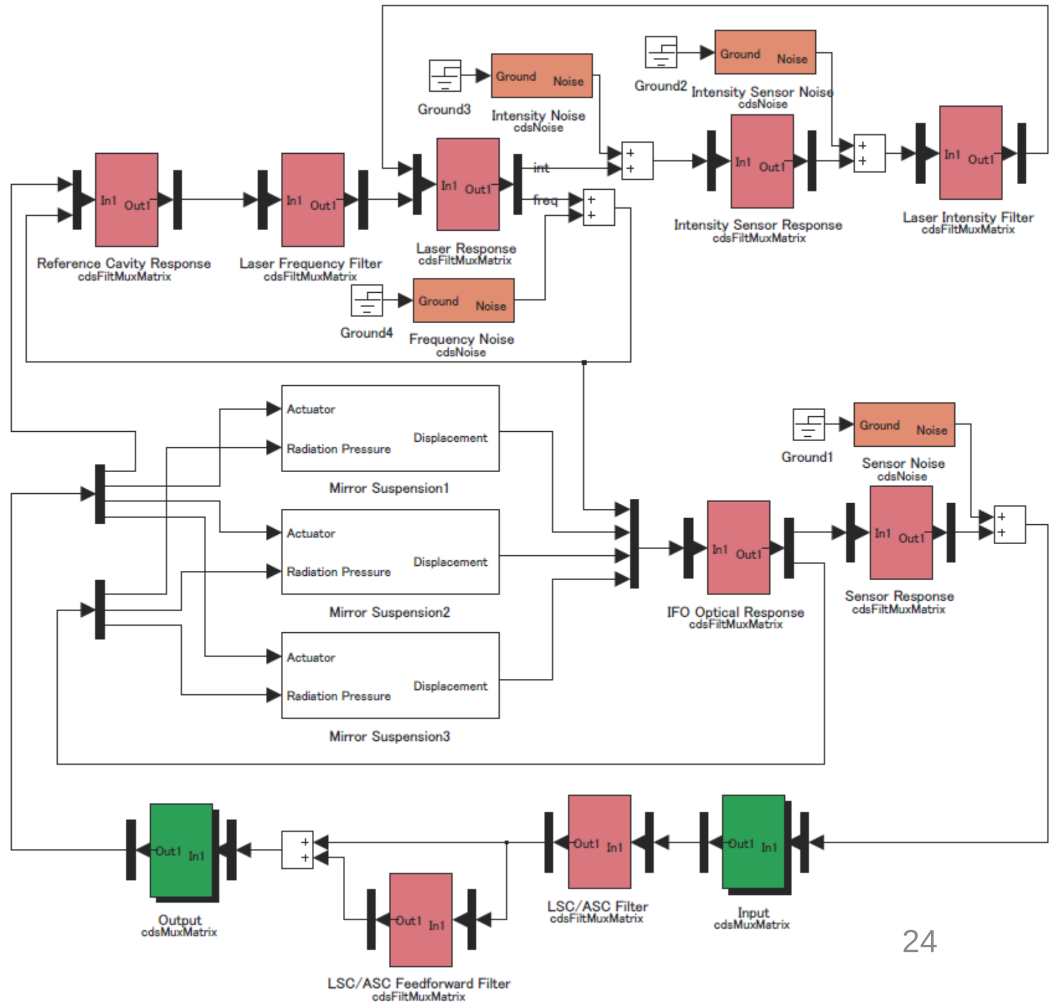
by K. Agatsuma
JGW-G1201388

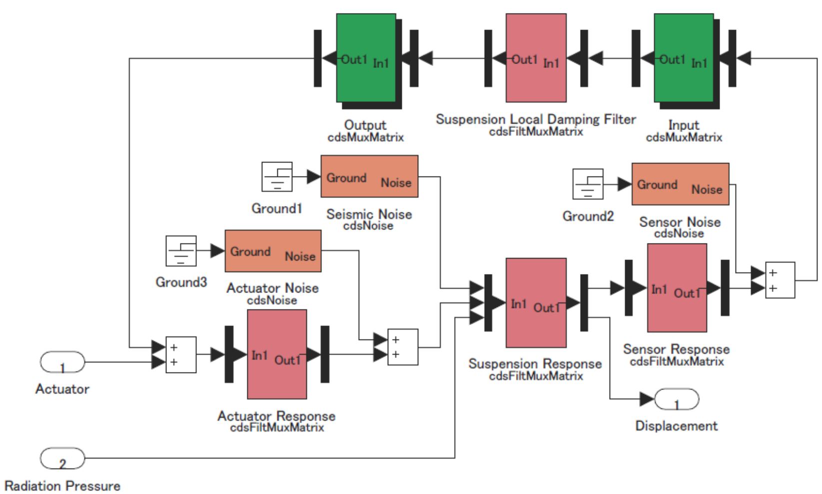
Future plans

- modeling of suspension local damping
  no local damping is included yet
- geometrical study of IFO beam
  for better DOF selection
- include seismic/electrical noise on QPDs etc
  for more realistic modeling
- estimate thermal effect on ASC
  thermal lensing changes Gouy phase
- initial alignment scheme
  lock acquisition mode / science mode

Overall modeling of ISC

- including all LSC/ASC, suspension local damping, laser intensity/frequency servo ……
- can be used for
  - servo design
  - loop noise calc.
  - noise budgeting
  - PD/circuit range





Summary

- developed a tool for simulating / designing ASC
- finalized IFO designing
- needs modeling of suspension local damping
- work for ISC modeling has started

Optickle model

- as of June 2012