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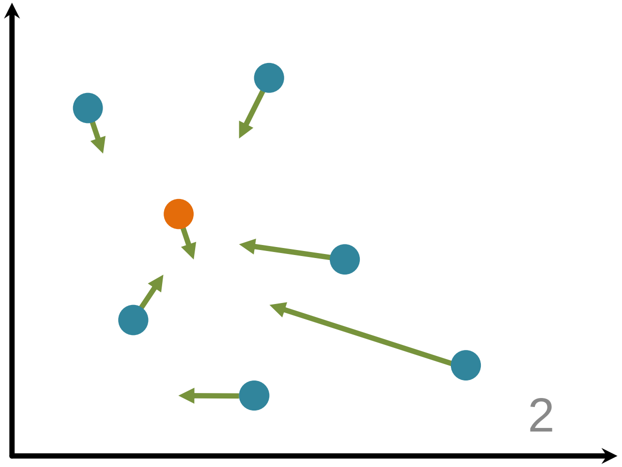
Sensitivity Optimization of Cryogenic Gravitational Wave Detectors

Yuta Michimura
Department of Physics, University of Tokyo

Kentaro Komori, Atsushi Nishizawa, Hiroki Takeda,
Koji Nagano, Yutaro Enomoto, Kazuhiro Hayama,
Kentaro Somiya, Masaki Ando

Overview

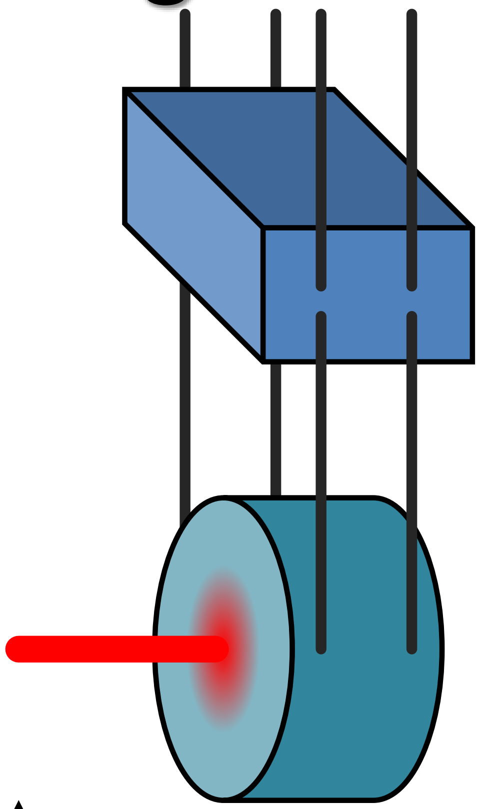
- Cryogenic GW detectors require careful design
  - tradeoff between laser power and temperature
  - simultaneous tuning of multiple parameters
- Particle swarm optimization
  - simple algorithm, few design variables
  - fast
- Applied for KAGRA sensitivity design
  - re-tuned 7 parameters
  - inspiral range optimization
  - sky localization optimization



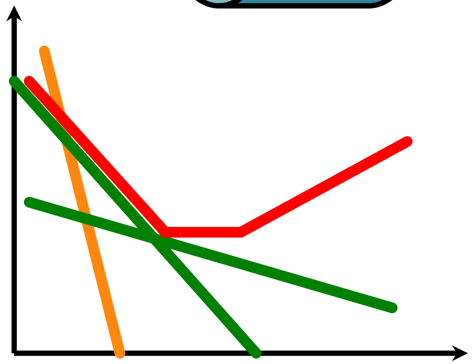
- YM+ [arXiv:1804.09894]

Room Temperature Design

- Seismic noise: reduce!
  multi-stage suspensions
  underground
- Thermal noise: reduce!
  larger mirror
  thinner and longer wires

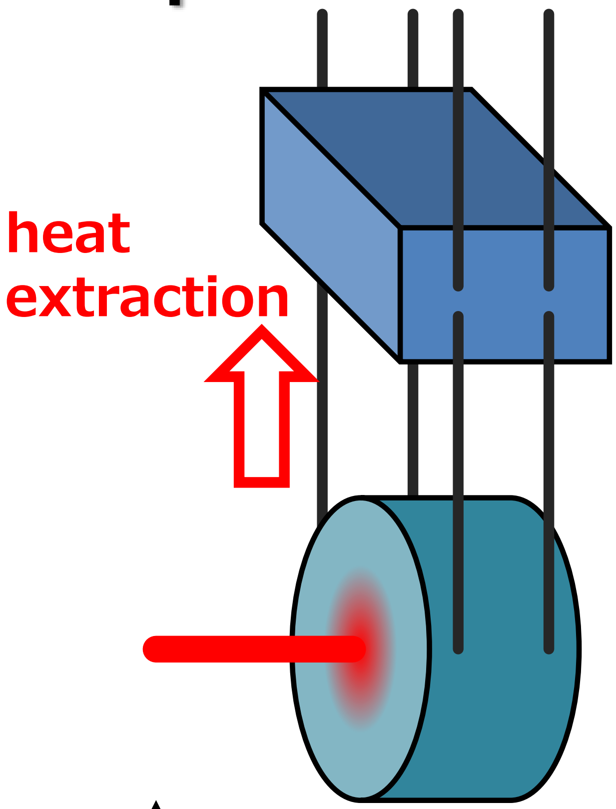


- Quantum noise: optimize the shape
  input laser power
  tune signal recycling parameters



Cryogenic Design is Complicated

- Seismic noise: reduce!
  - multi-stage suspensions
  - underground
- Thermal noise: reduce!
  - larger mirror
  - thinner and longer wires
  - cryogenic cooling



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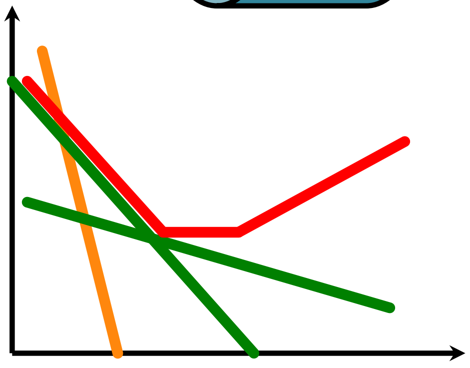
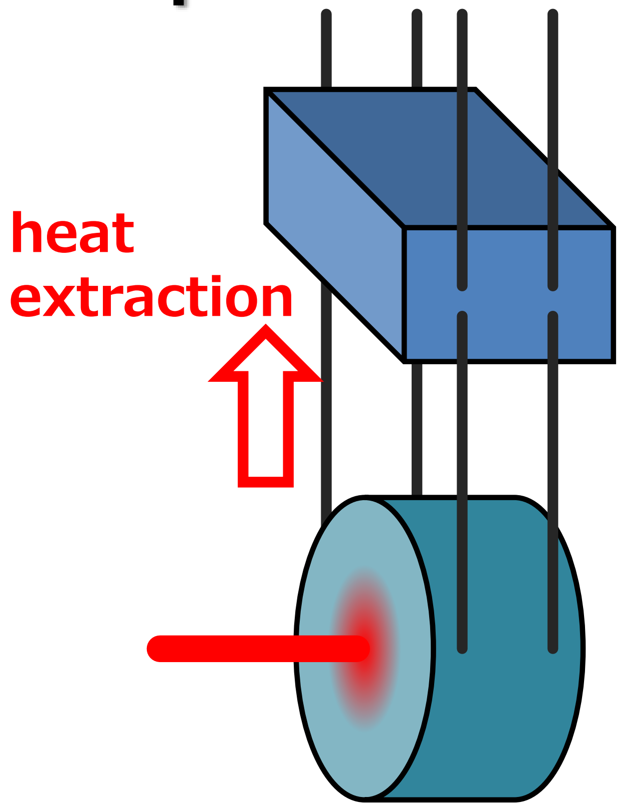


Cryogenic Design is Complicated

- Seismic noise: reduce!
  - multi-stage suspensions
  - underground
- Thermal noise: reduce! optimize
  - larger mirror
  - thinner and longer wires
  - cryogenic cooling
- Quantum noise: optimize the shape
  - input laser power
  - tune signal recycling parameters

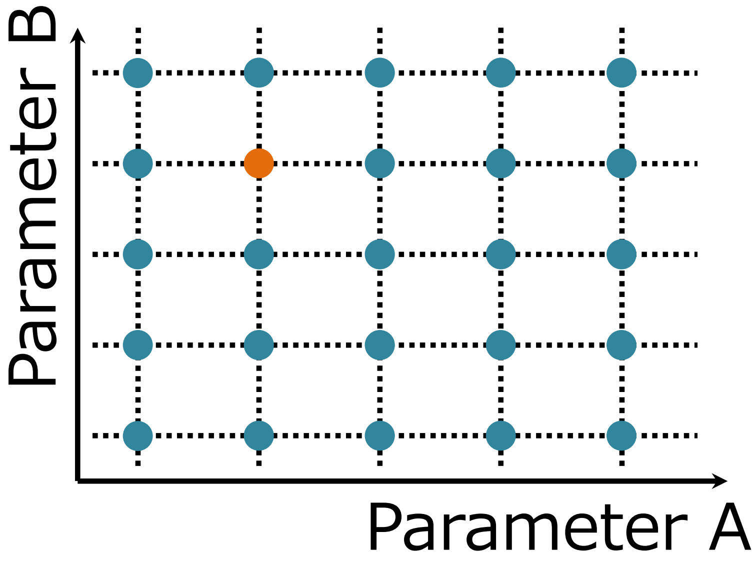
worse cooling power
mirror heating



Ancient Method is not Scalable

- Sensitivity design is an optimization problem
- Grid-based parameter search
  - deterministic
  - computational cost grows exponentially with number of parameters

- Future GW detectors (with crazy quantum ideas) require more parameters to be optimized
- Almost impossible with grid-based approach



Particle Swarm Optimization!

- Particles search the parameter space based on own best position and entire swarm's best known position

$$x_k(t+1) = x_k(t) + v_k(t)$$

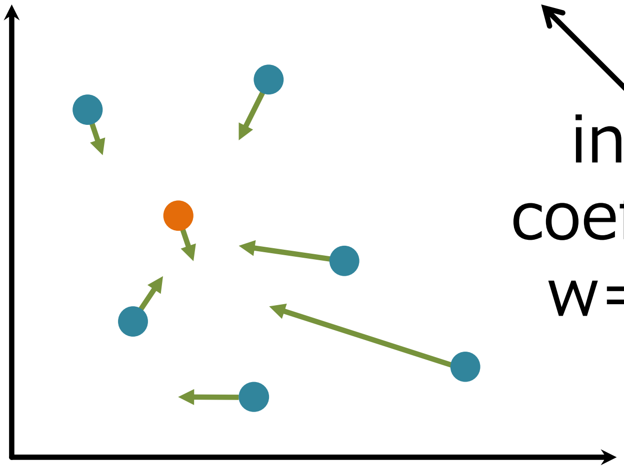
$$v_k(t+1) = wv_k(t) + c_1 r_1(\hat{x}_k - x_k(t)) + c_2 r_2(\hat{x}_g - x_k(t))$$

personal best position so far

global best position so far

inertia coefficient w=0.72

acceleration coefficient c=1.19
random number r ∈ [0,1]



Kennedy & Eberhart (1995)
values for w and c are from Standard PSO 2006

PSO for GW Related Research

- CBC search
  Weerathunga & Mohanty, PRD 95, 124030 (2017)
  Wang & Mohanty, PRD 81, 063002 (2010)
  Bouffanais & Porter, PRD 93, 064020 (2016)
- Continuous GW search using pulsar timing array
  Wang, Mohanty & Jenet, ApJ 795, 96 (2014)
- Cosmological parameter estimation using CMB
  Prasad & Souradeep, PRD 85, 123008 (2012)
- Gravitational lens modeling
  Rogers & Fiege, ApJ 727, 80 (2011)
- Sensor correction filter design
  Conor Mow-Lowry, LIGO-G1700841 LIGO-T1700541

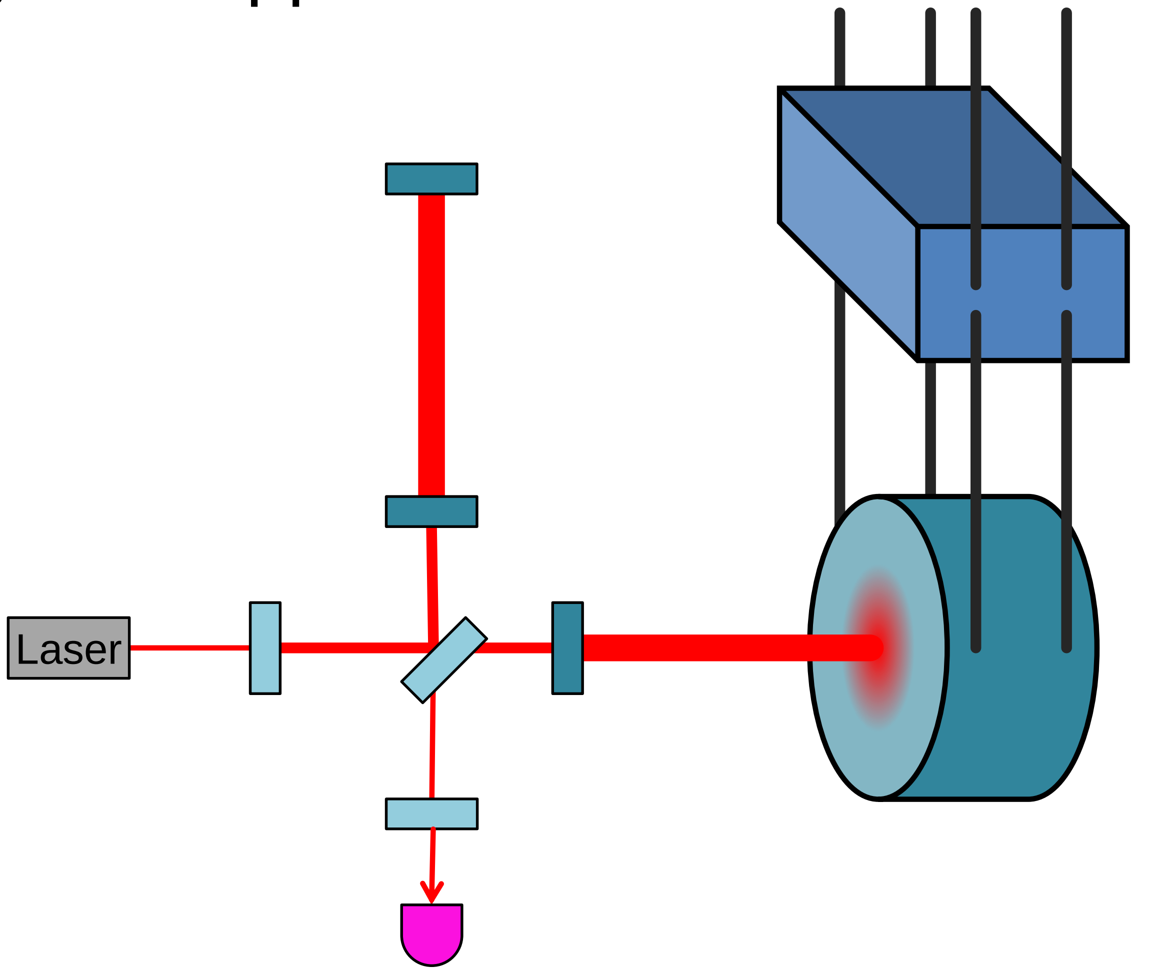
Pros and Cons of PSO

- Fast even for highly multidimensional parameter space ☺
  - uses entire swarm's information to search
- Requires small number of design variables and little prior information ☺
  - basically only swarm size and termination criterion
  - prior information is only search range
- No guarantee for convergence to global maximum ☹
  - stochastic method
- Do not give error of the parameters ☹
  - no direct information on stability of the solution

→ Sounds great for detector design

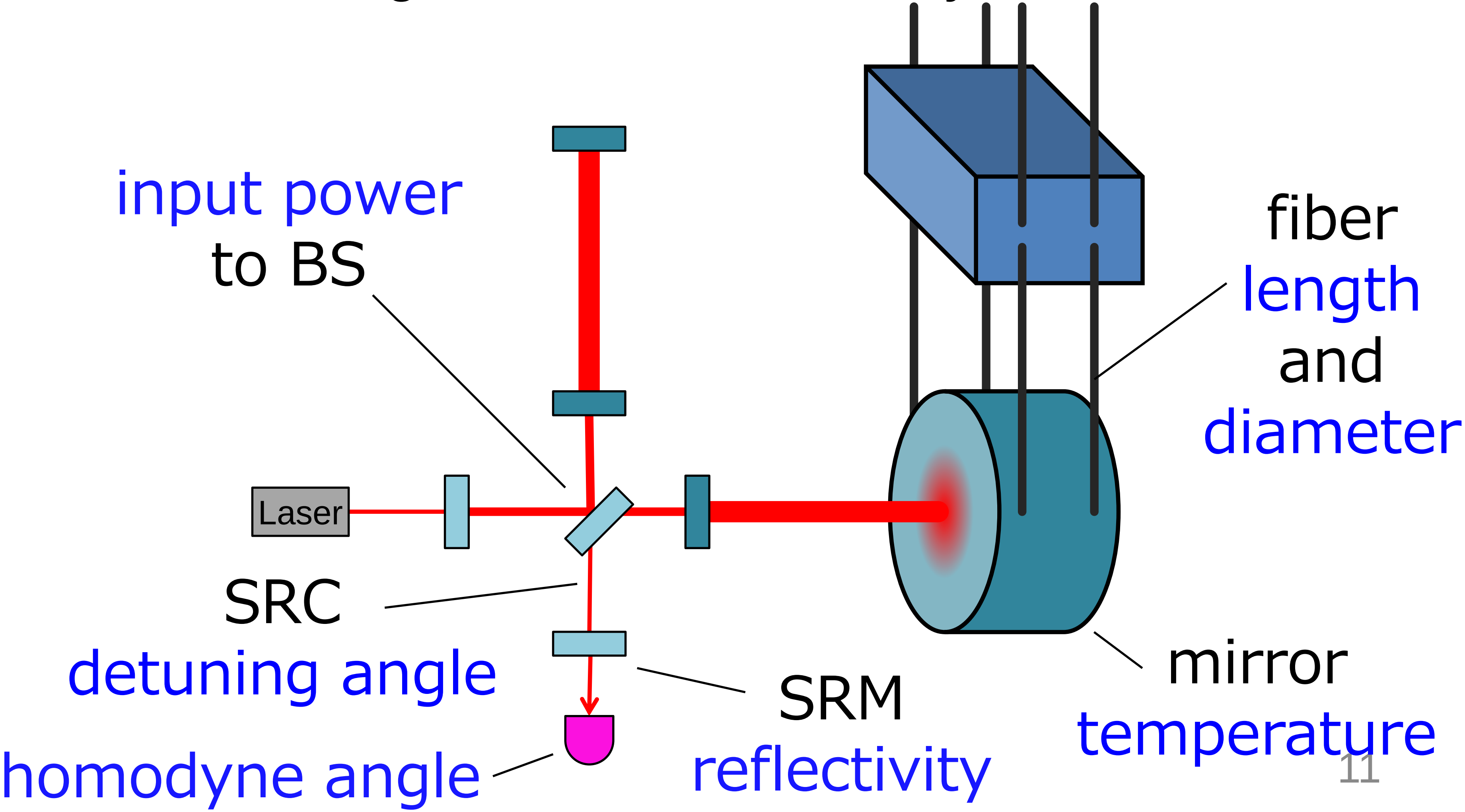
KAGRA

- RSE interferometer
- Cryogenic sapphire test masses



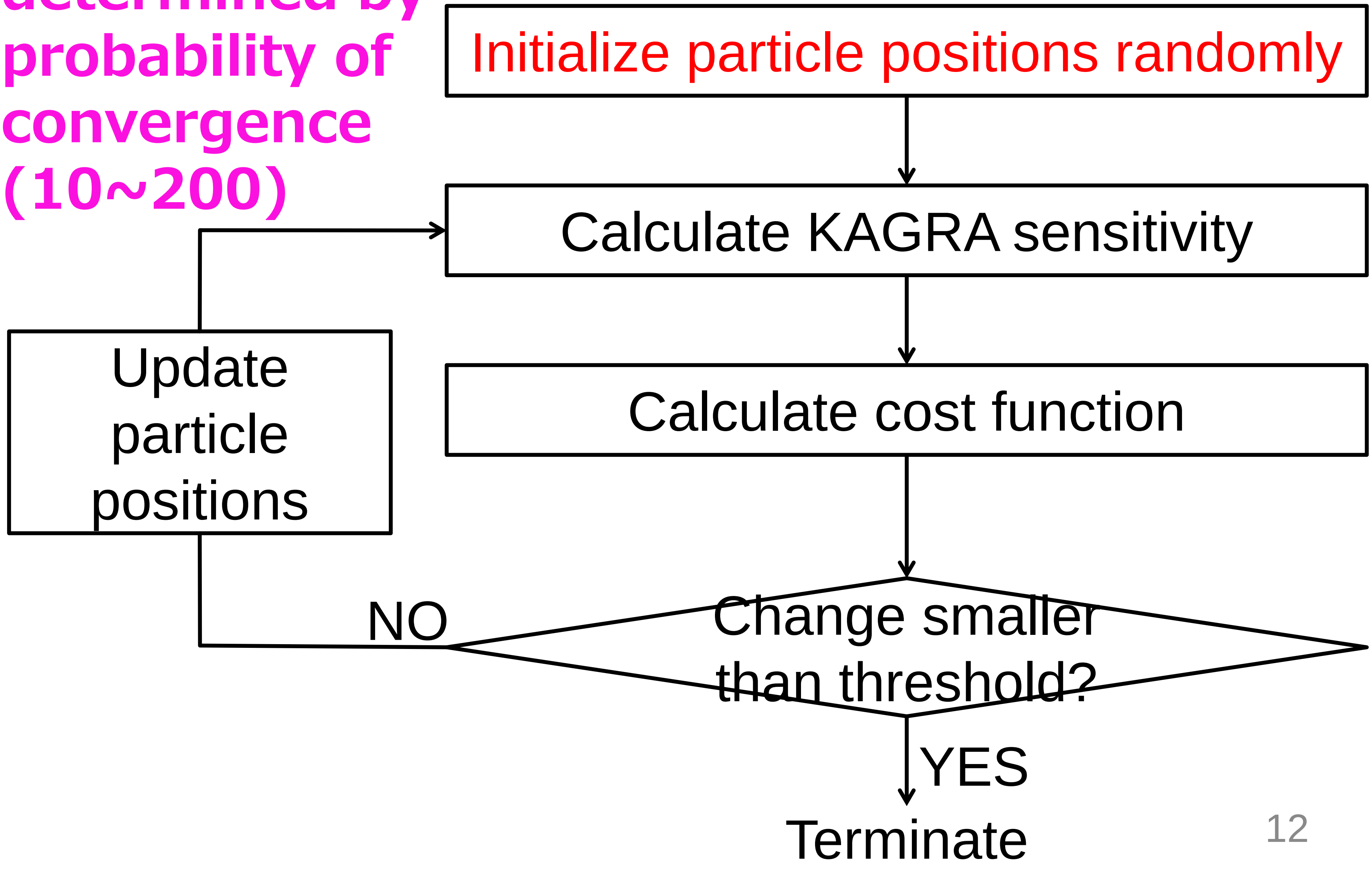
KAGRA Parameters to Optimize

- 7 parameters relatively easy to be retuned
- Search range based on feasibility

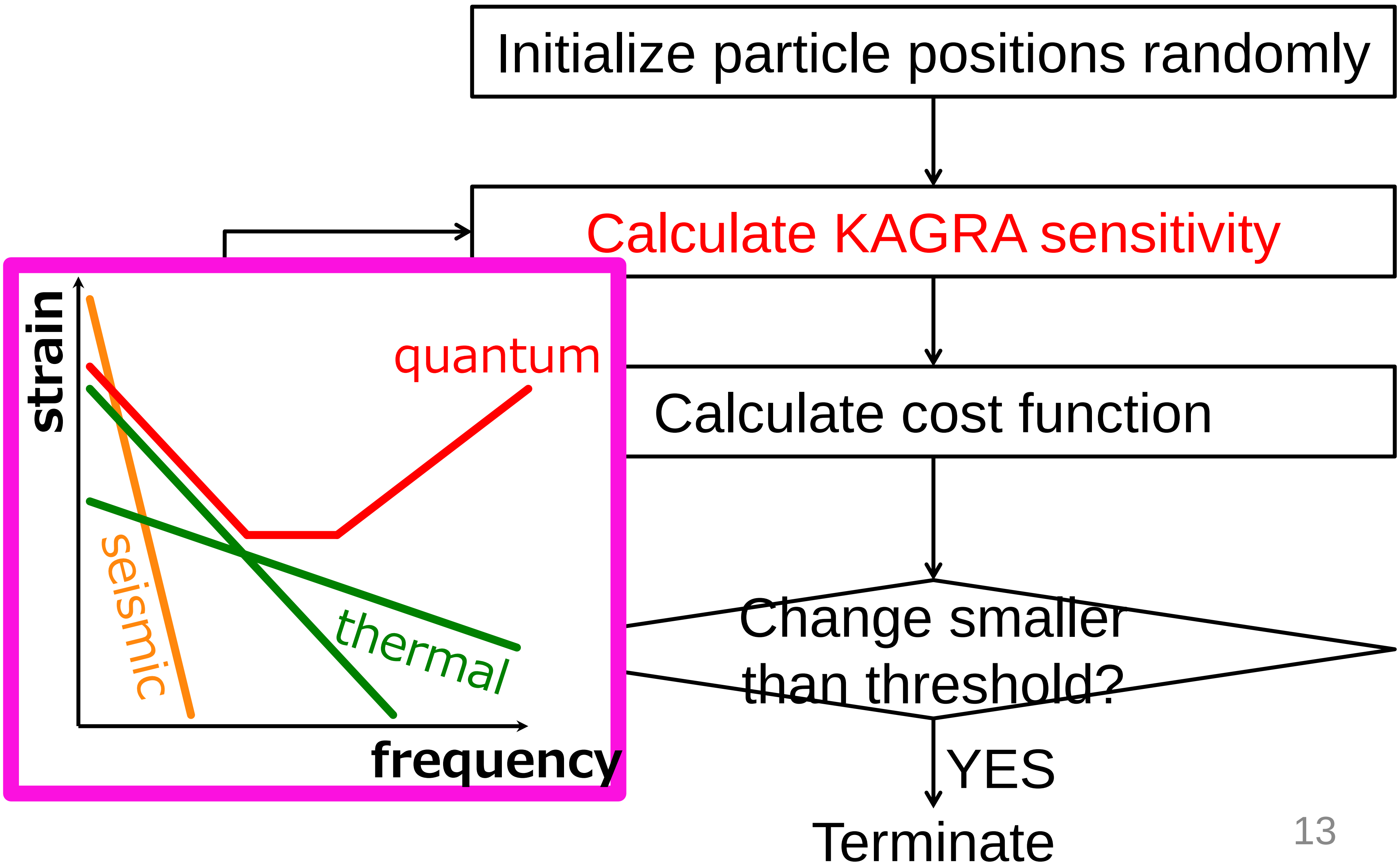


PSO Algorithm

Swarm size determined by probability of convergence (10~200)

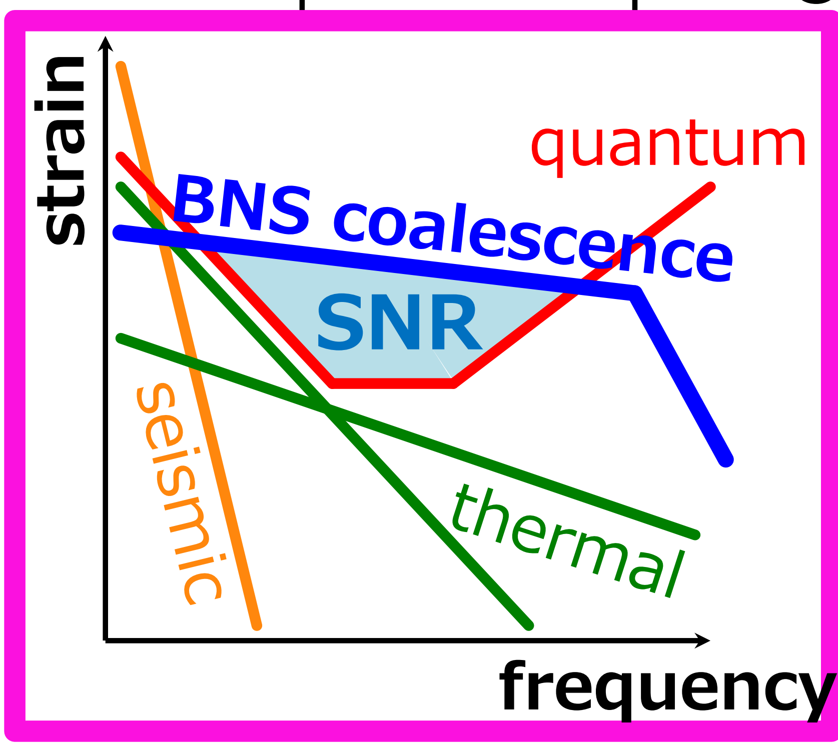


PSO Algorithm



PSO Algorithm

BNS inspiral range as a cost function



Initialize particle positions randomly

↓

Calculate KAGRA sensitivity

↓

Calculate cost function

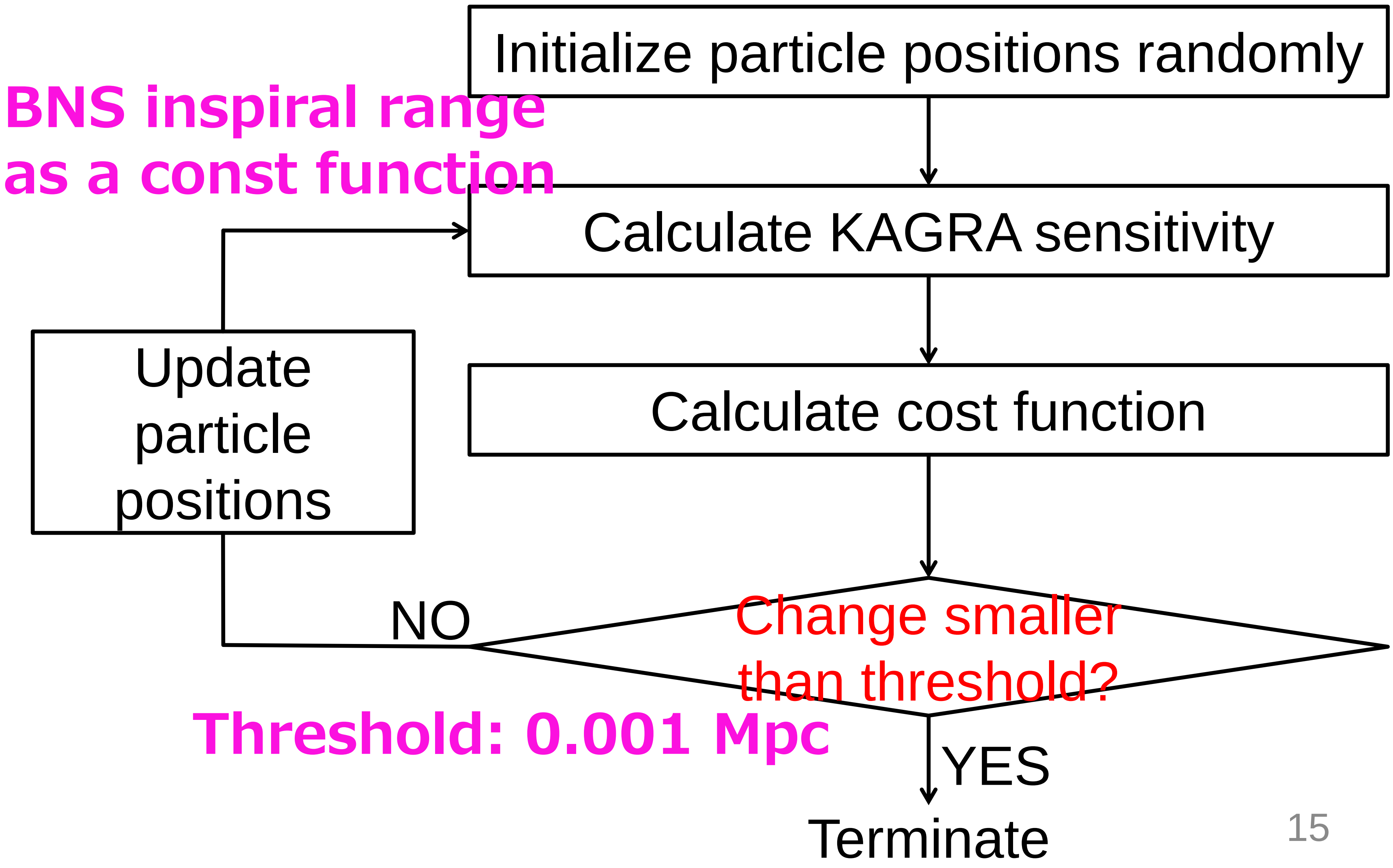
↓

Change smaller than threshold?

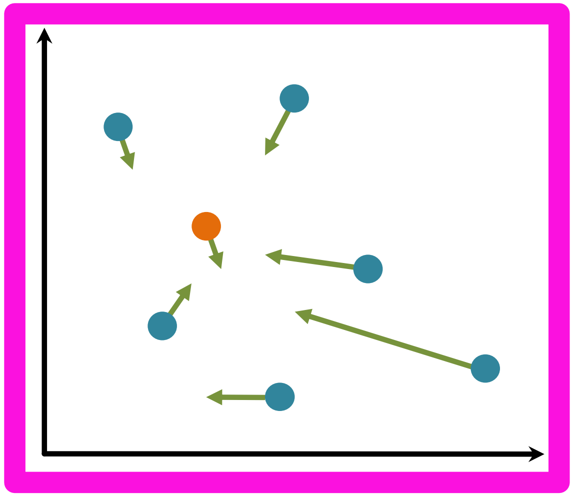
↓ YES

Terminate

PSO Algorithm



PSO Algorithm



Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

Change smaller than threshold?

NO

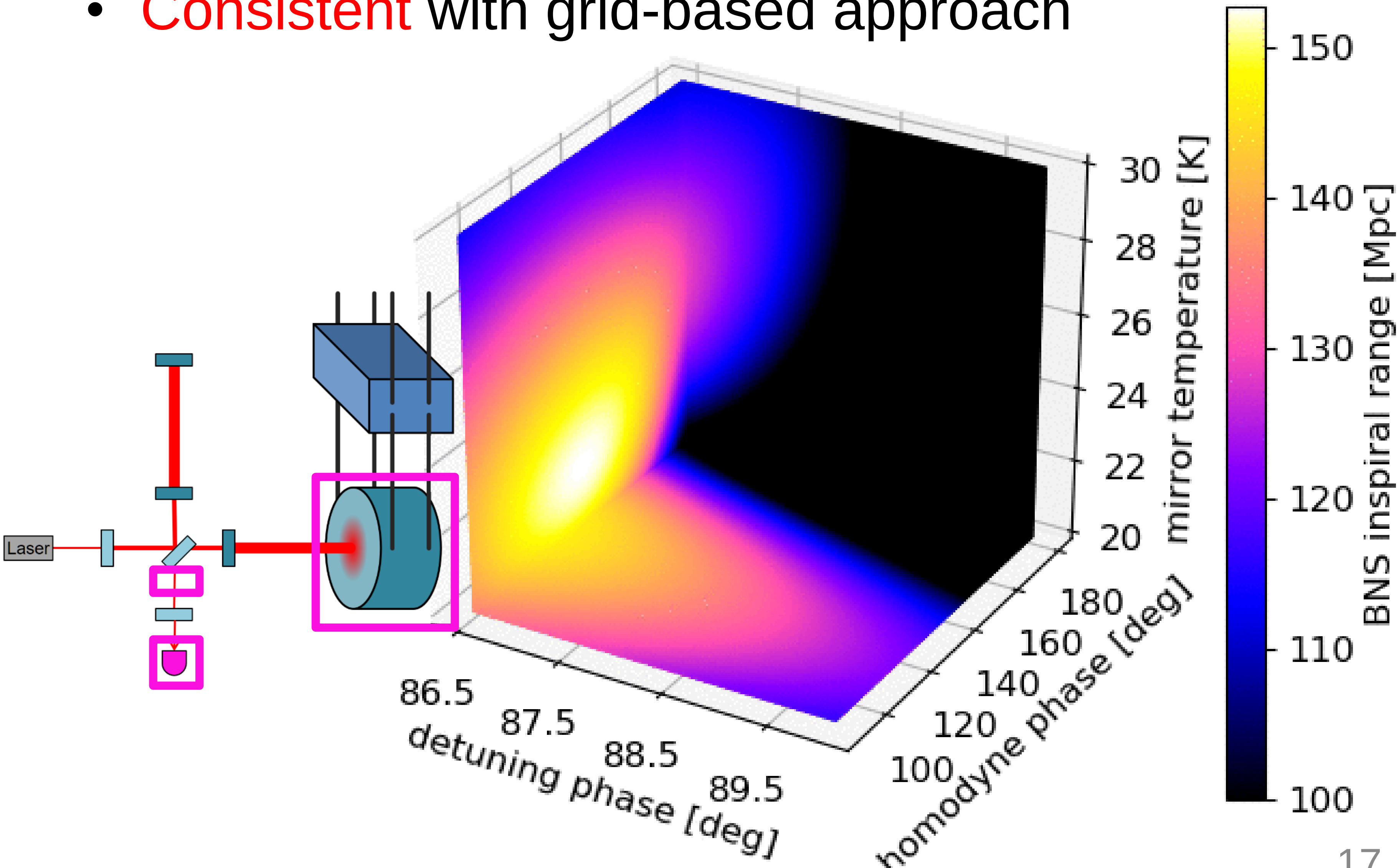
Update particle positions

YES

Terminate

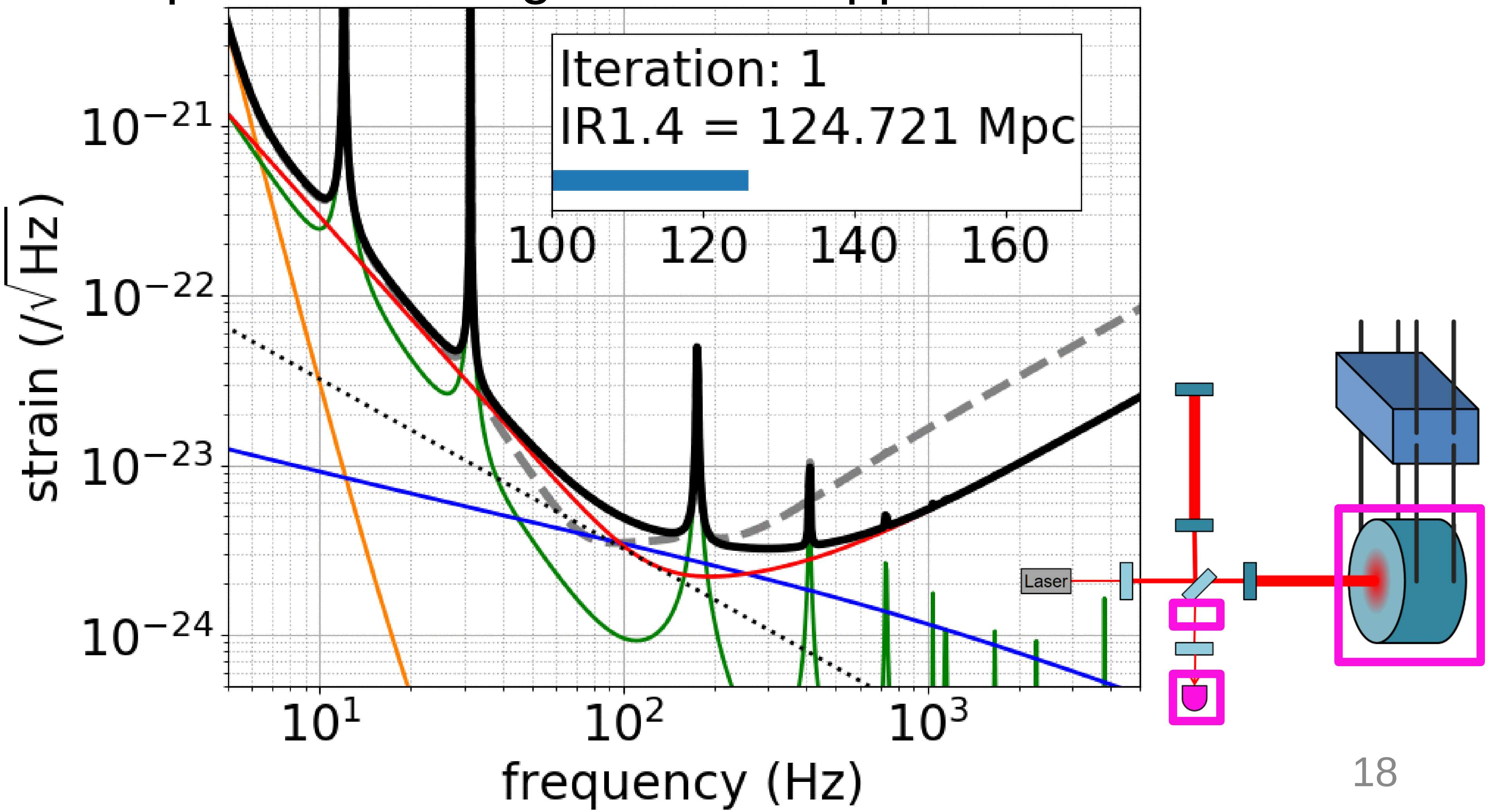
3 Parameter Optimization

- Consistent with grid-based approach



3 Parameter Optimization

- Consistent with current designed sensitivity optimized with grid-based approach



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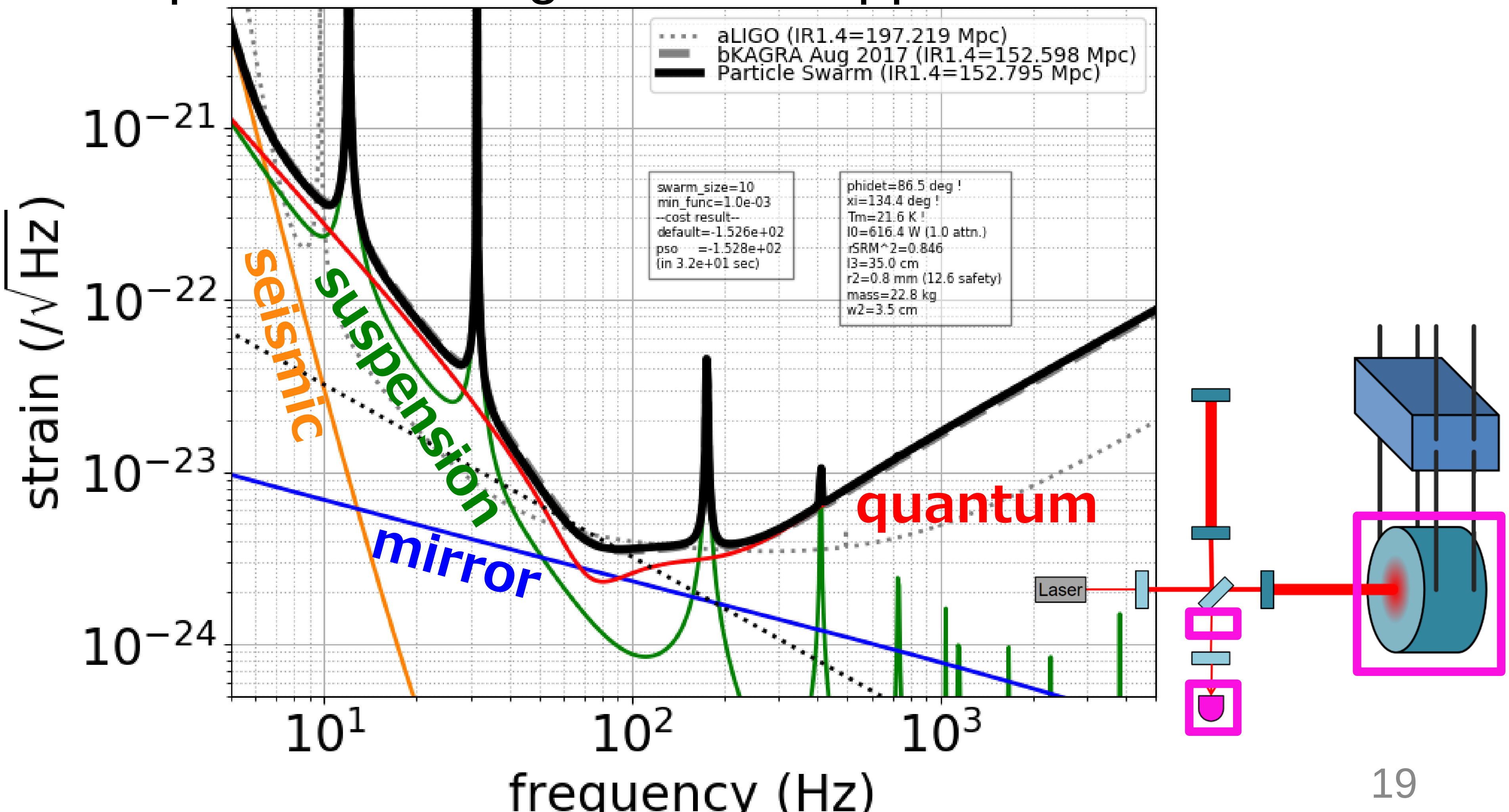
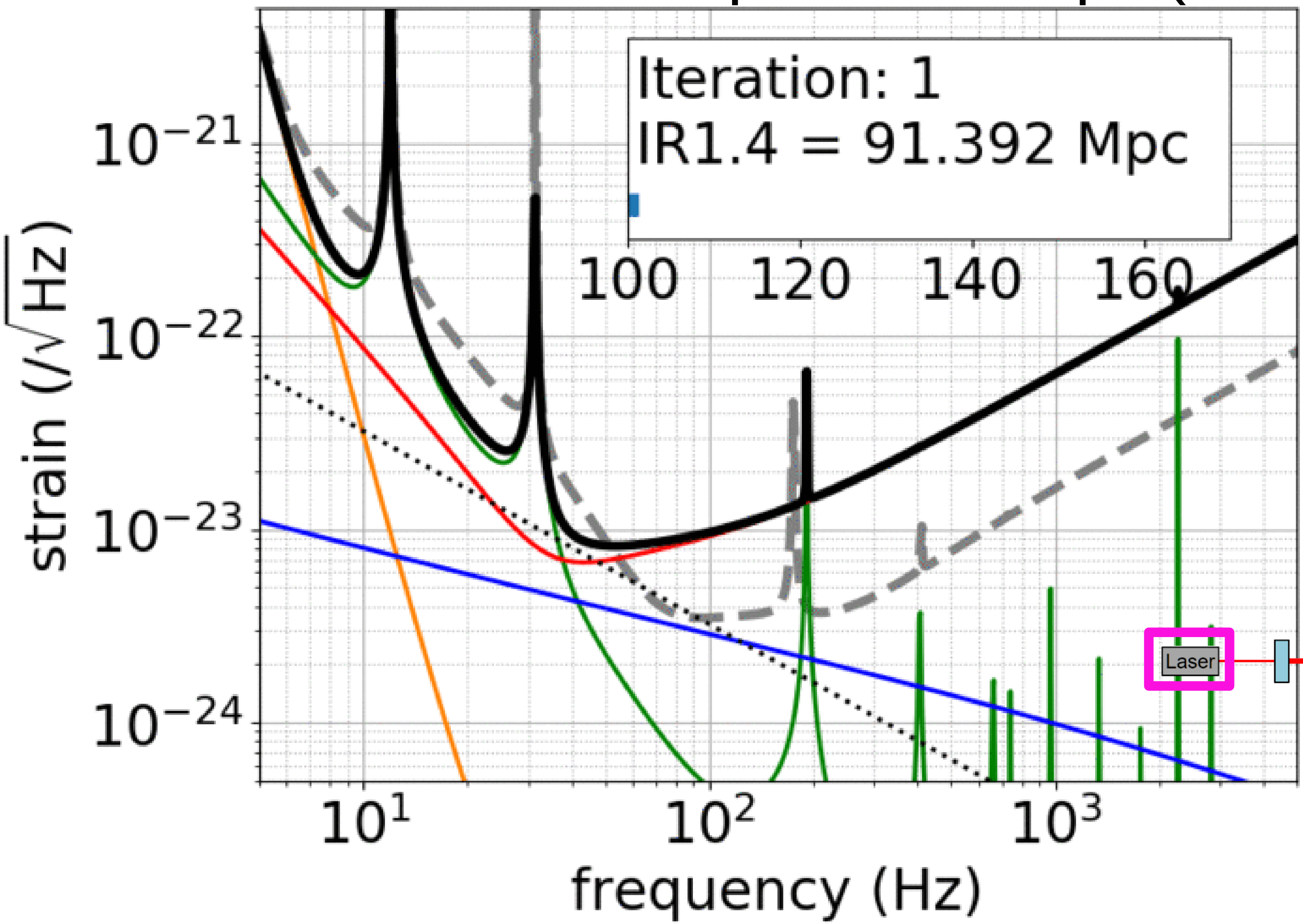
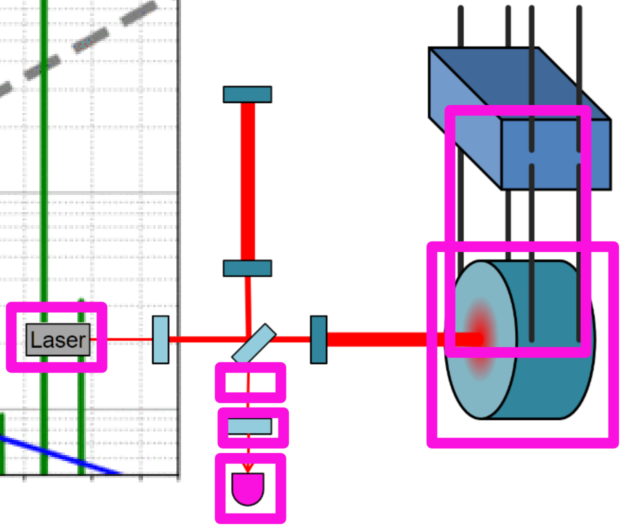


7 Parameter Optimization

- Changing suspension fibers and SRM increases BNS IR from 153 Mpc to 169 Mpc (10% increase)





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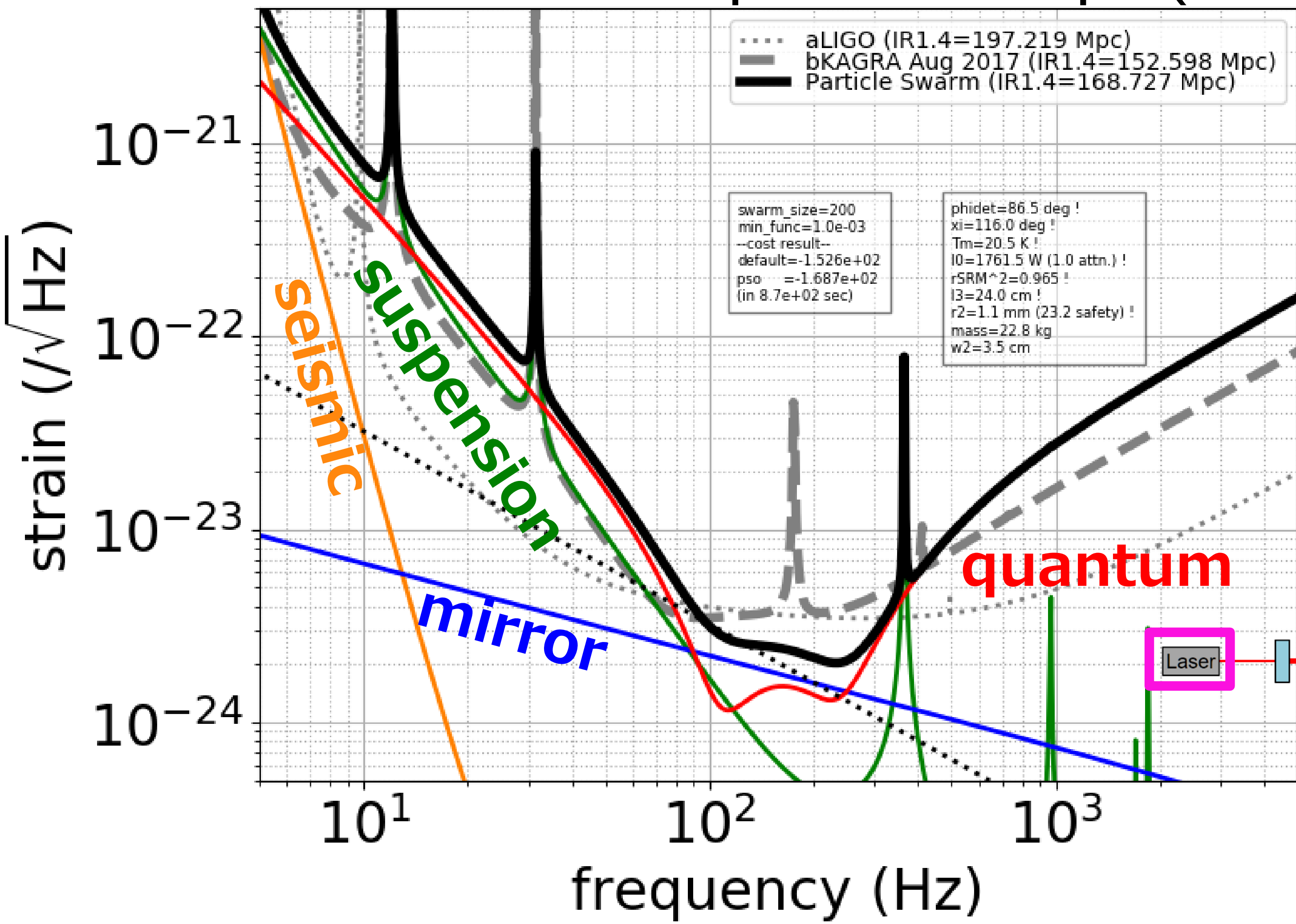
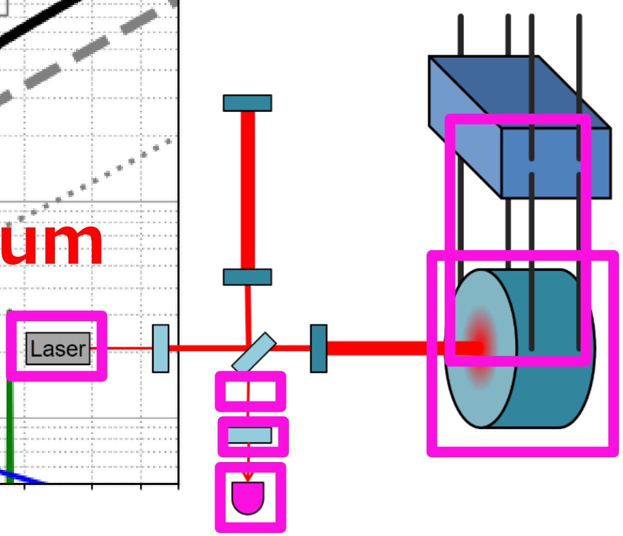


Shorter and thicker to put more power with 20 K



Sensitivity Design with PSO is Fast

- Optimization done in O(100) sec with this laptop
- Number of cost function evaluations

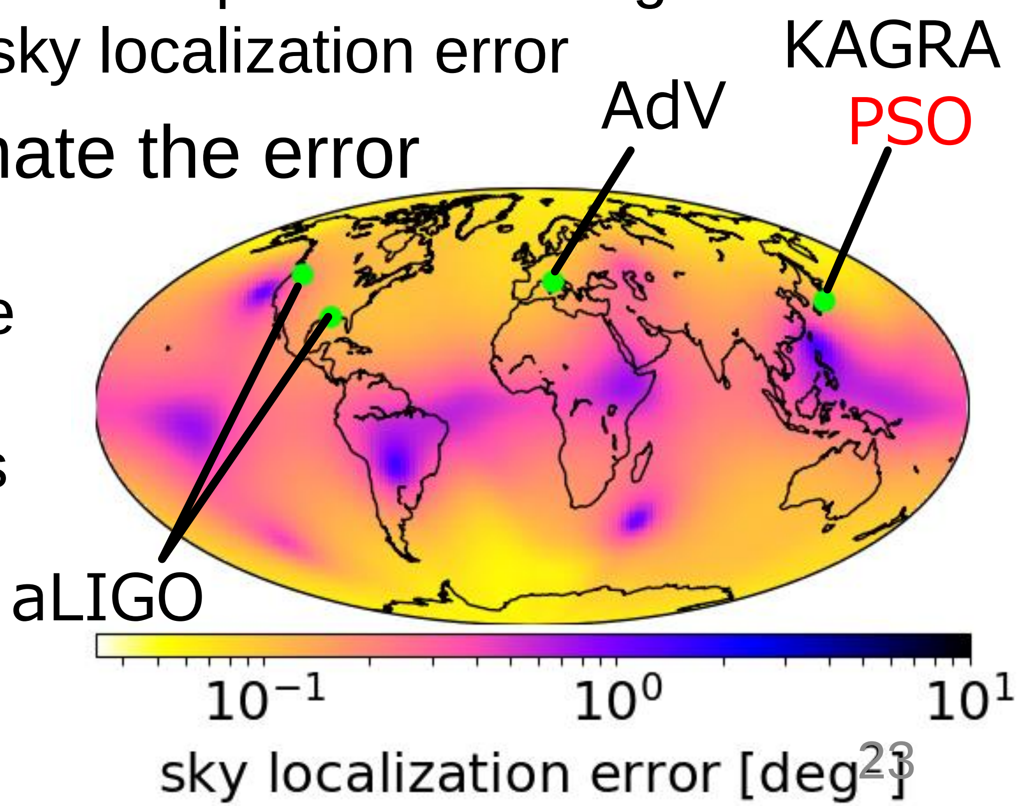
	Grid-based	PSO
3 params	10^5 □	10×(52±13) □
5 params	10^9 □	20×(73±16) □
7 params	10^{14} □	200×(60±18) □

* In case optimization is done at precision of 0.1 Mpc

- Computational cost do not grow exponentially with dimensionality of parameter space
- Useful for optimization with many parameters, computationally expensive cost function

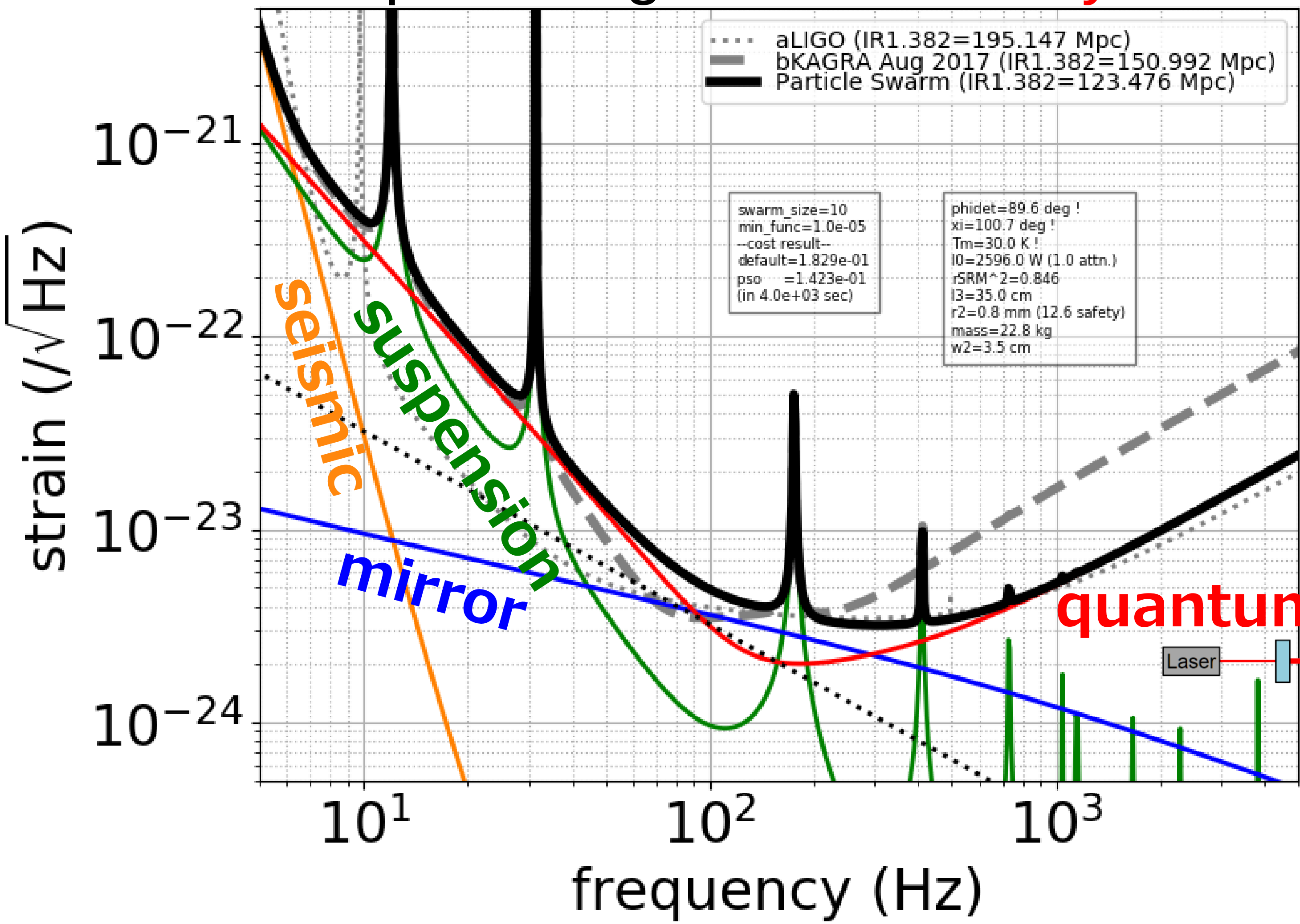
Sky Localization Optimization

- Cost function:
  sky localization of GW170817-like binary
  - 1.25-1.5 Msun at 40 Mpc, inclination 28 deg
  - no spins
  - 108 sets of sky location and polarization angle to derive median of sky localization error
- Fisher matrix to estimate the error
  - inspiral waveform to
    3.0 PN in amplitude
    3.5 PN in phase
  - 11 binary parameters
- HLVK global network

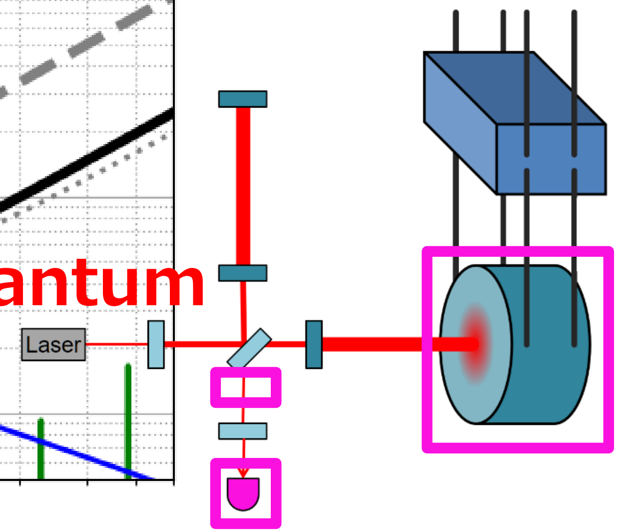


3 Parameter Optimization

- Sky localization improved by a factor of 1.3 but inspiral range is reduced by 20%

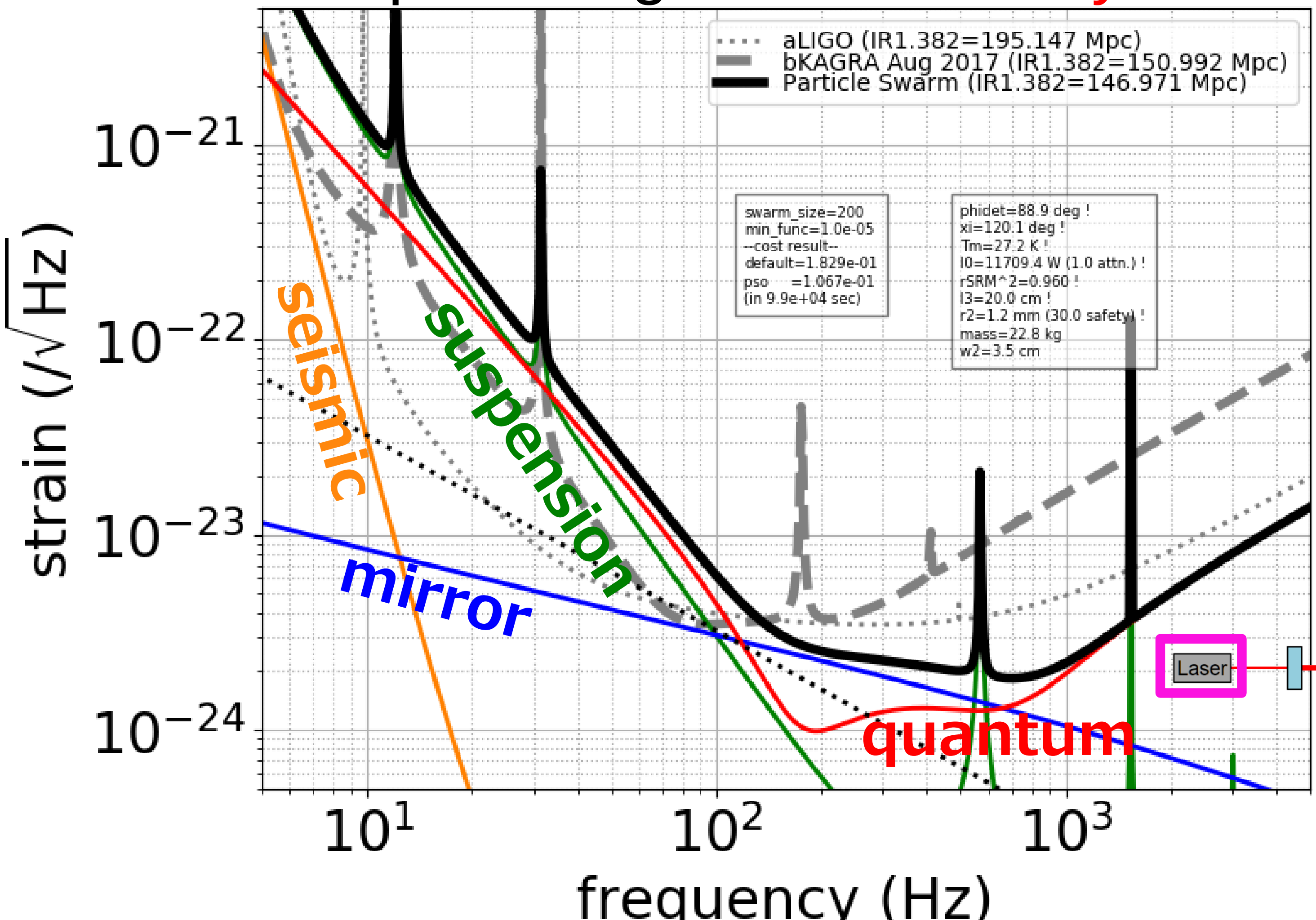


2600 W at BS
30 K

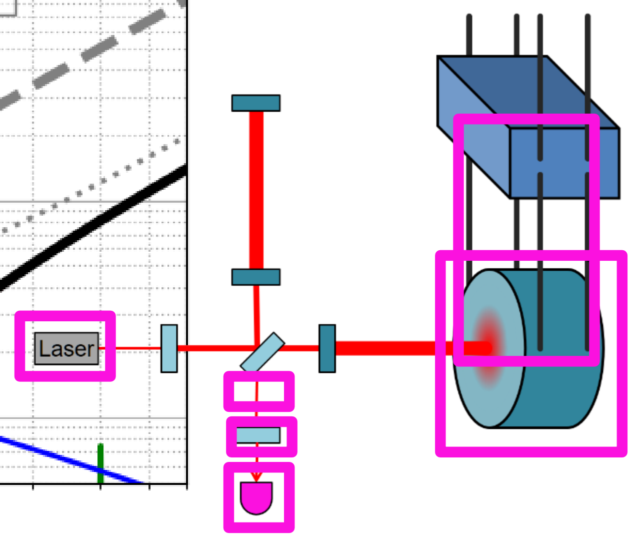


7 Parameter Optimization

- Sky localization improved by a factor of 1.6 but inspiral range is reduced by 2%

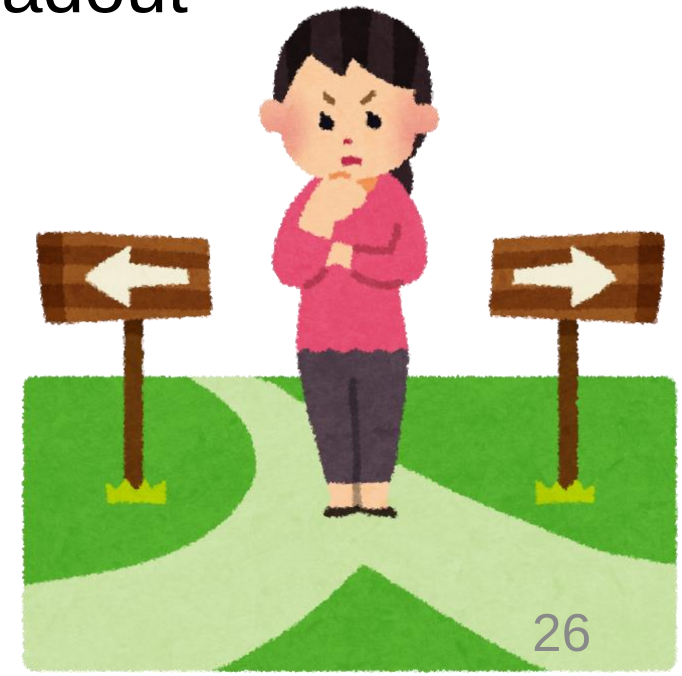


shorter and thicker fibers
1.1 kW at BS
27 K



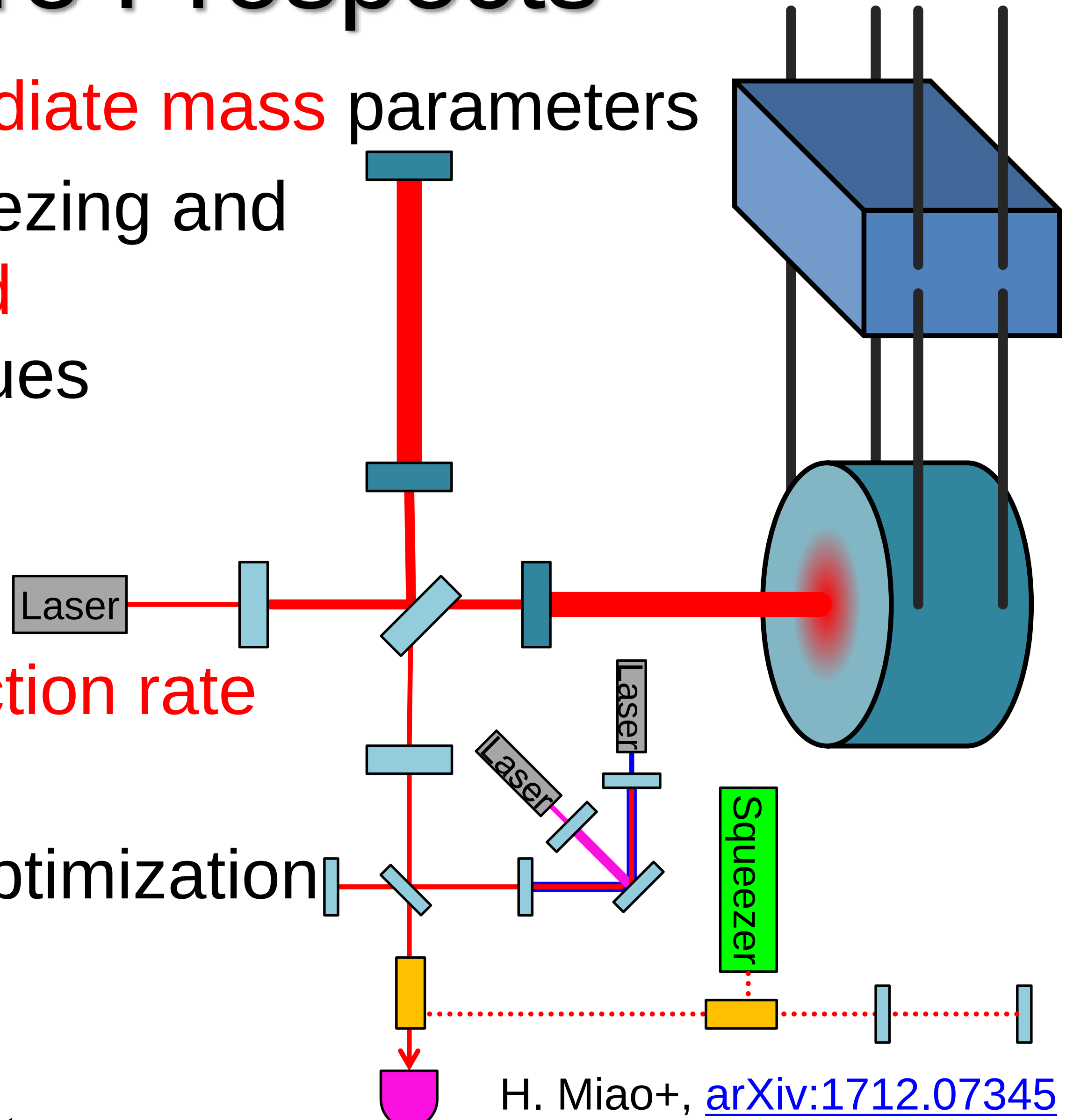
Summary of Strategy Difference

- BNS inspiral range optimization
  - high detuning, high SRM reflectivity
  - shorter and thicker fiber
  - lower temperature to keep mirror thermal low
- BNS sky localization optimization
  - no detuning, conventional readout
  - shorter and thicker fiber
  - higher temperature to put more laser power



Future Prospects

- Optimize intermediate mass parameters
- Incorporate squeezing and more complicated quantum techniques



- Incorporate detection rate into cost function
- Global network optimization
- Optimization for
  - NS EoS
  - BH ringdown etc…

H. Miao+, arXiv:1712.07345

Summary

- Demonstrated sensitivity design with PSO
- Application to KAGRA shows
  - BNS inspiral range can be increased by 10 %
  - BNS sky localization can be improved by 1.6

  by retuning 7 parameters of existing components

- Showed that PSO is useful for future GW detectors
  - low computational cost
  - little prior information necessary
  - allows more sophisticated cost function

- YM+ arXiv:1804.09894

Supplementary Slides

Pyswarm

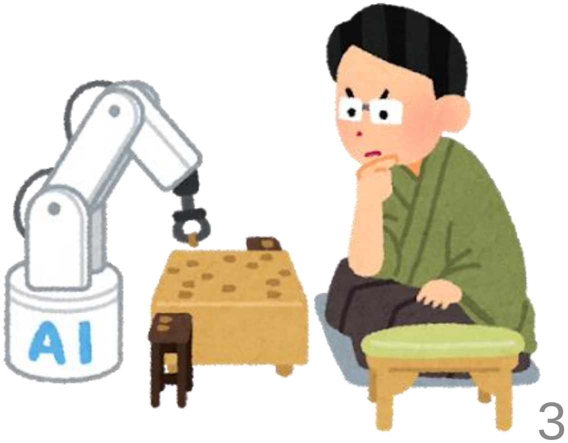
- Python package Pyswarm was used for this work
  https://pythonhosted.org/pyswarm/
  https://github.com/tisimst/pyswarm/
- PSO as easy as

```
xopt, fopt = pso(func, lb, ub)
```

optimal parameter set — optimal cost function — cost function — lower and upper bounds

Other Optimization Methods

- Simulated annealing
  tuning cooling schedule is troublesome
- Genetic algorithm
  too many design variables
- Markov chain Monte Carlo
  tend to be dependent on prior distribution
  gives error from posterior distribution
  takes time
- Machine learning
  if the problem well-modeled,
  you don’t need ML



Swarm Size Determination

- Probability of convergence: ratio of PSO trials resulted within 0.1 Mpc or 10^{-3} deg^2
- Increased swarm size until probability of convergence is larger than 90%

number of params	3	5	7
number of particles	10	20	200
number of iterations	52 ± 13	73 ± 16	60 ± 18
probability of convergence	98 %	96 %	91 %

* From 100 PSO trials

IFO Parameter Search Range

	Lower bound	Upper bound	KAGRA Default	Precision
Detuning angle [deg]	86.5 (or 60) *	90	86.5	0.1
Homodyne angle [deg]	90	180	135.1	3
Mirror temperature [K]	20	30	22	0.09
Power attenuation	0.01	1	1	0.02
SRM reflectivity	0.5	1	0.92 (85%)	6e-4
Wire length [cm]	20	100	35	0.02
Wire safety factor	3	30	12.57 (0.8 mm)	0.07

* Considering SRC nonlinearity, maximum detuning is 3.5 deg
(see Y. Aso+ CQG 29, 124008)

step size which changes BNS inspiral range by 0.1 Mpc

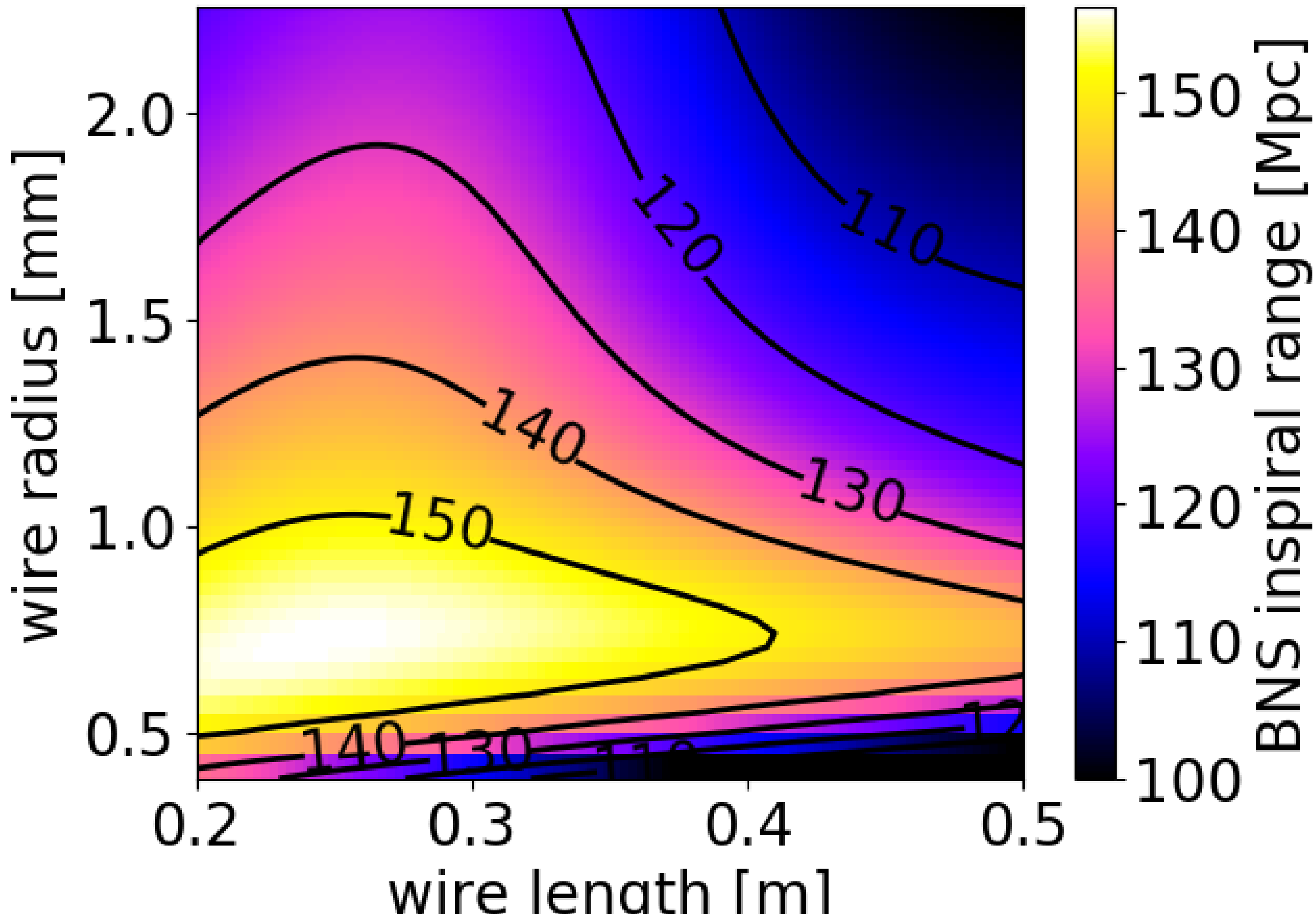
- *Reflecting wall* boundary:
  x=xmax, v=-v if x>xmax
  x=xmin, v=-v if x<xmin

Money

- Detuning angle and homodyne angle can be retuned without additional cost
- Mirror temperature and input power can be retuned without additional cost if power at BS is less than ~1 kW (~100 W entering PRM)
- Change in SRM reflectivity require ~0.1 Million USD
- Change in wire parameters require ~0.01 Million USD/fiber
- Change in wire length require test mass suspension design change at ~0.1 Million USD/mirror
- Change in the test mass require ~0.5 Million USD/mirror

Fiber Length and Diameter

- 25cm/φ1.4mm is optimum for BNS IR if other parameters are fixed (default: 35cm/φ1.6mm)



Fisher Matrix Analysis

- Fisher matrix

$$\Gamma_{ij} = 4\Re \int_{f_{\min}}^{f_{\max}} \sum_k \frac{\partial h_k^*(f)}{\partial \lambda^i} \frac{\partial h_k(f)}{\partial \lambda^j} \frac{\mathrm{d}f}{S_{\mathrm{n,k}}(f)}$$

- Covariance

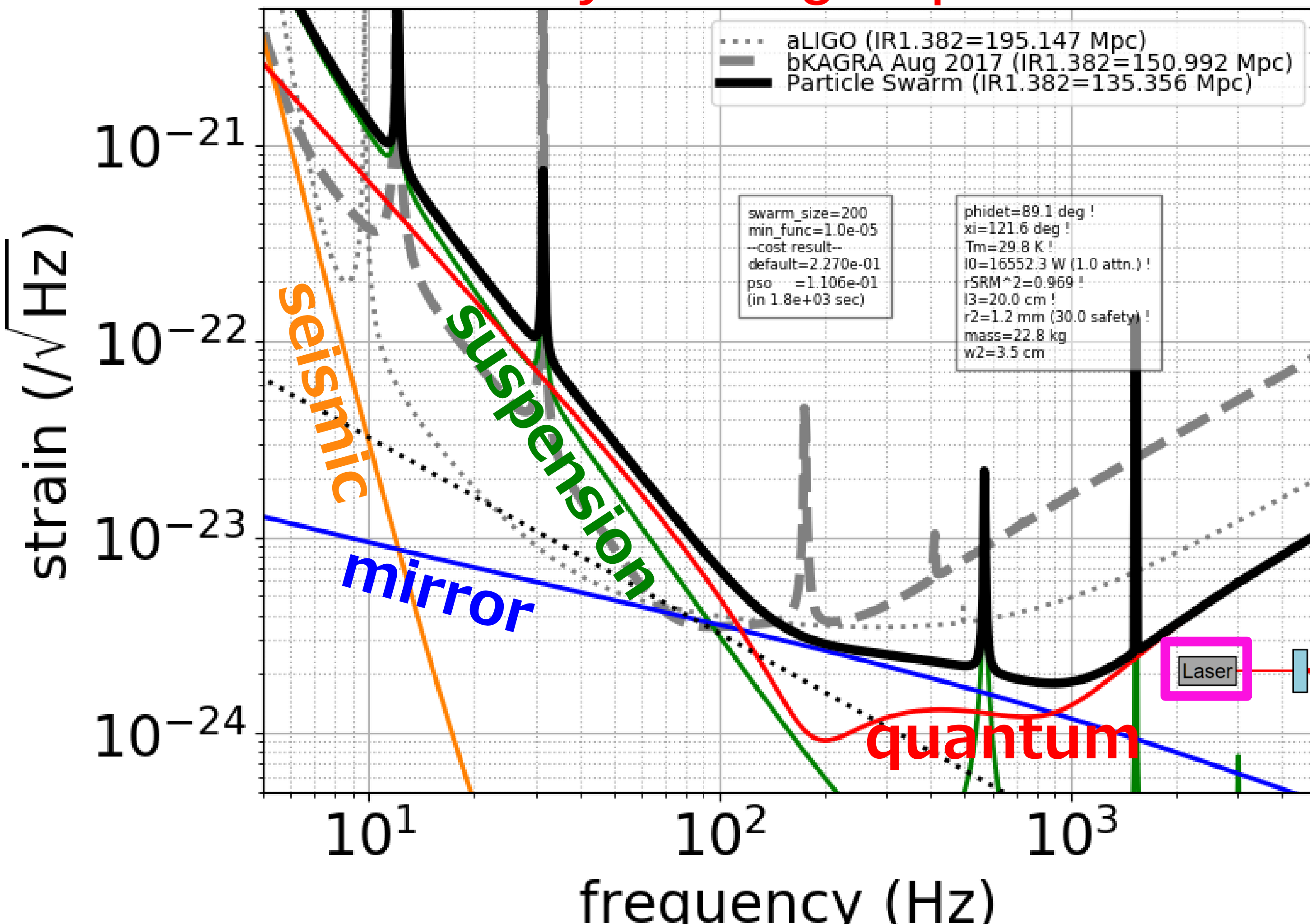
$$\sqrt{\langle(\delta\lambda^i \delta\lambda^j)\rangle} = \sqrt{(\Gamma^{-1})^{ij}}$$

- 11 binary parameters considered

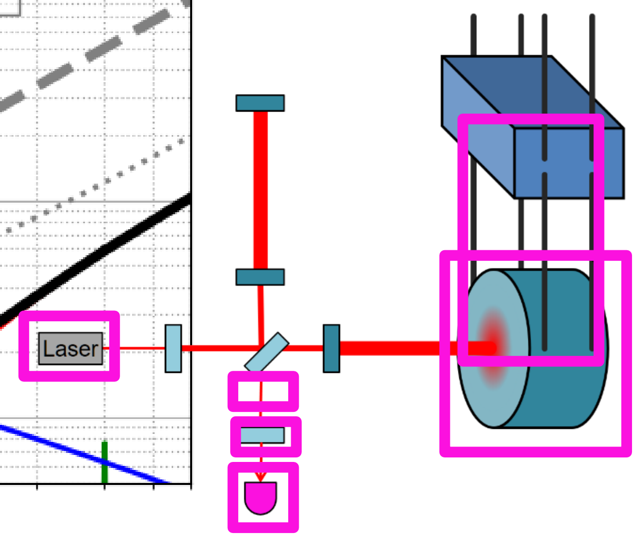
mc: chirp mass
eta: symmetric mass ratio
tc, phic: time and phase for coalescence
dL: luminosity distance
chis, chia: symmetric/asymmetric spin $\chi_{\mathrm{s/a}} = (\chi_1 \pm \chi_2)/2$
thetas, phis: colatitude / longitude of source
cthetai: inclination angle
psip: polarization angle

Optimization for Fixed Sky Location

- Result for fixed sky location and polarization angle is similar to sky average optimization



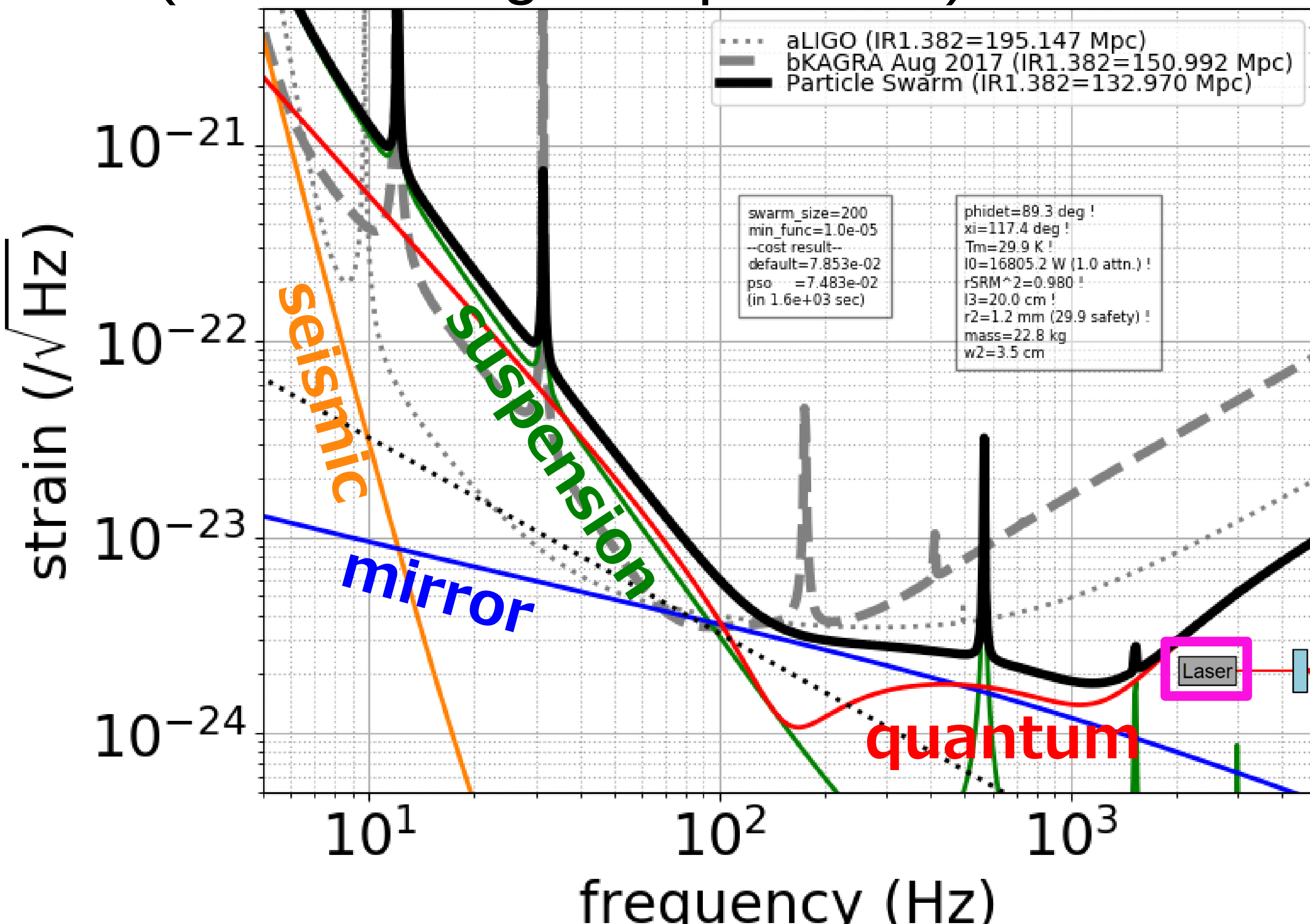
shorter and thicker fibers
1.7 kW at BS
30 K



Symmetric Spin Optimization

- Similar to sky localization optimization (focus on high frequencies)

$$\chi_s = \frac{\chi_1 + \chi_2}{2}$$



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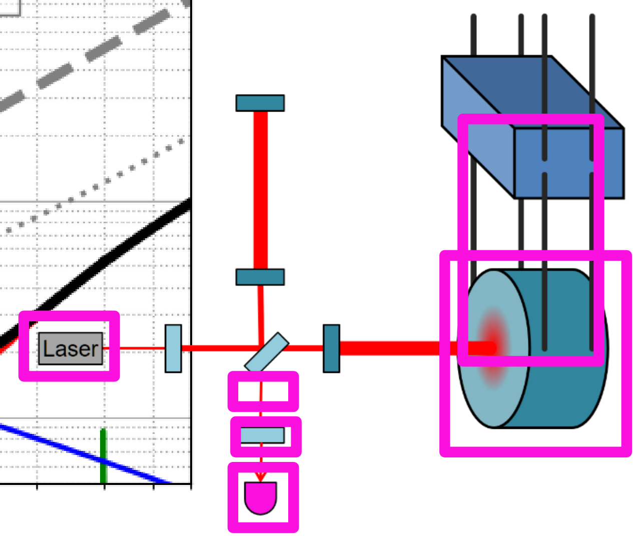
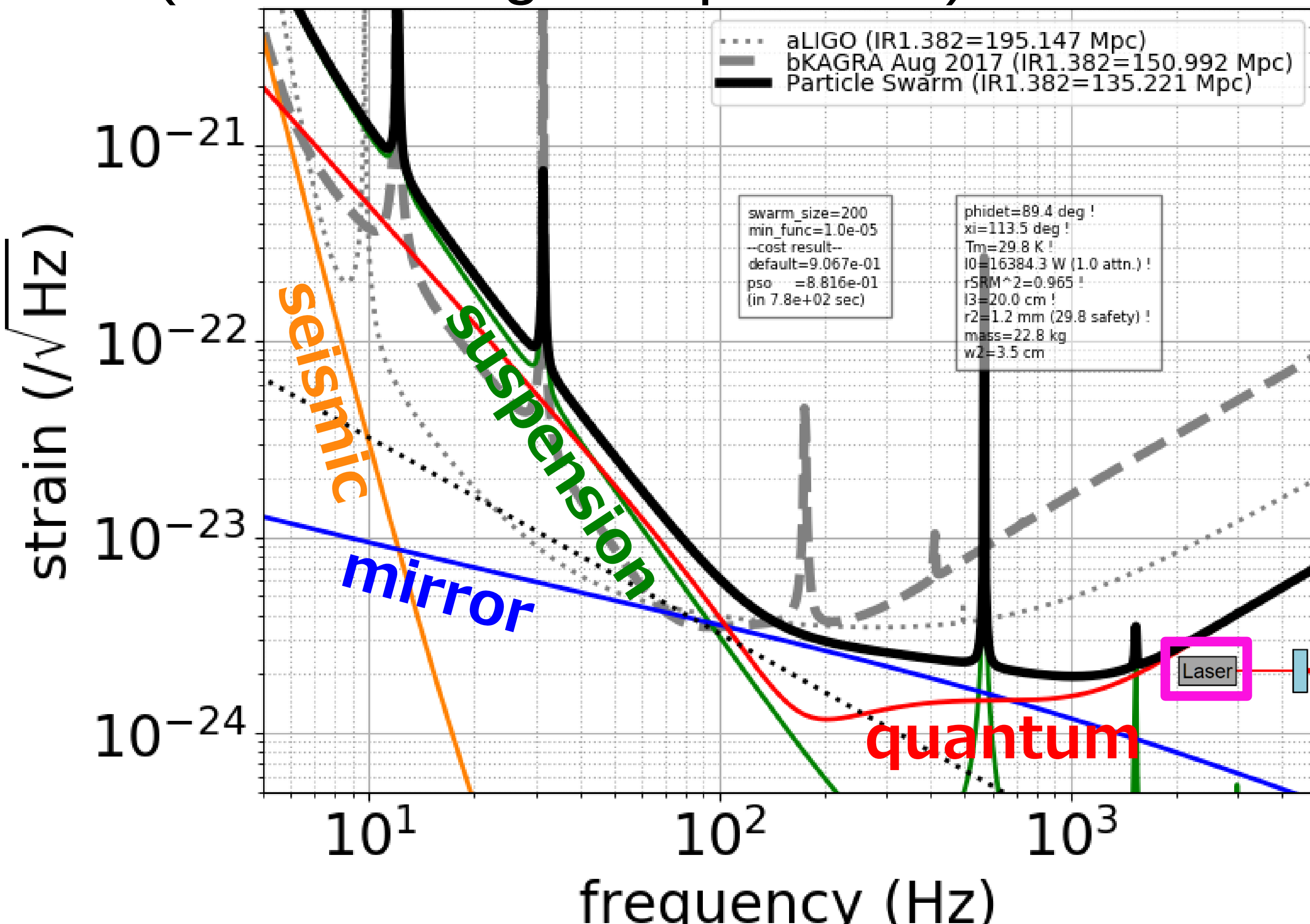


Asymmetric Spin Optimization

- Similar to sky localization optimization (focus on high frequencies)

$$\chi_{\mathrm{a}} = \frac{\chi_1 - \chi_2}{2}$$



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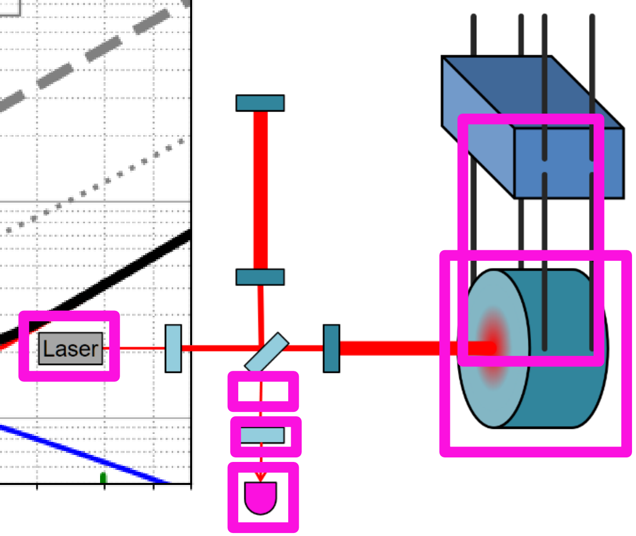
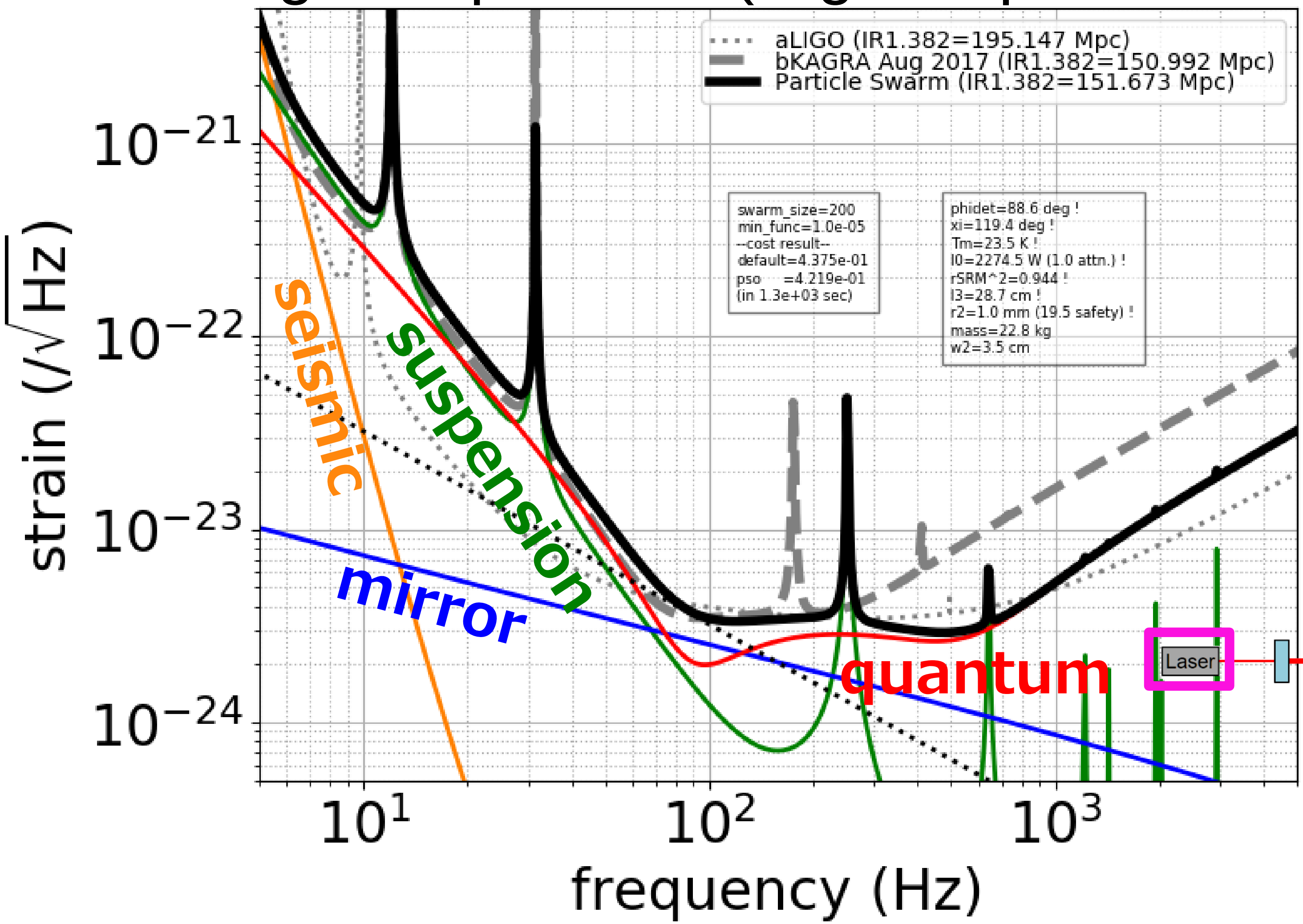
30 K

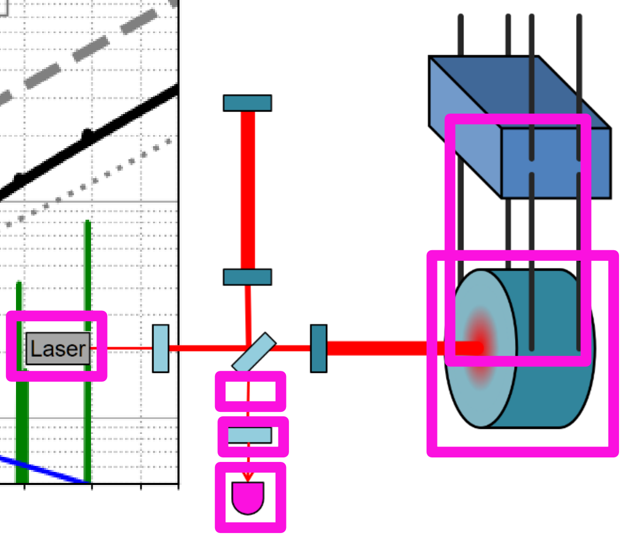


Distance Optimization

- Similar to inspiral range optimization, but slight shift to high frequencies (slight improvement by 4%)

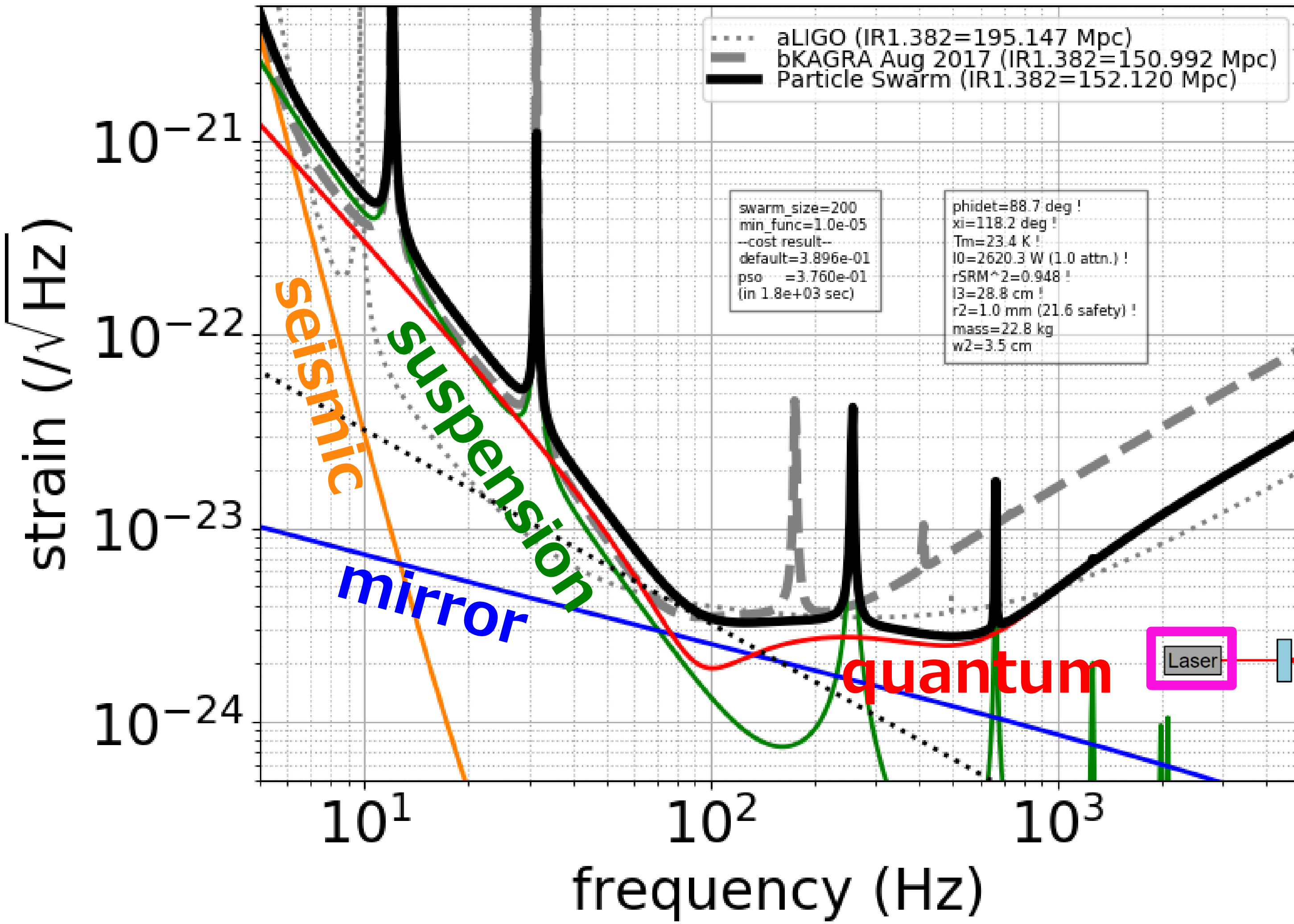


bit shorter and thicker fibers
2.3 kW at BS
24 K



Inclination Angle Optimization

- Similar to distance optimization (PE degeneracy)



bit shorter and thicker fibers
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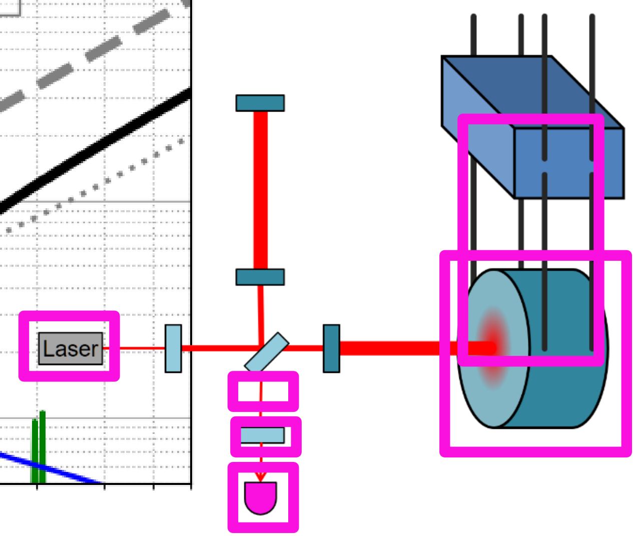
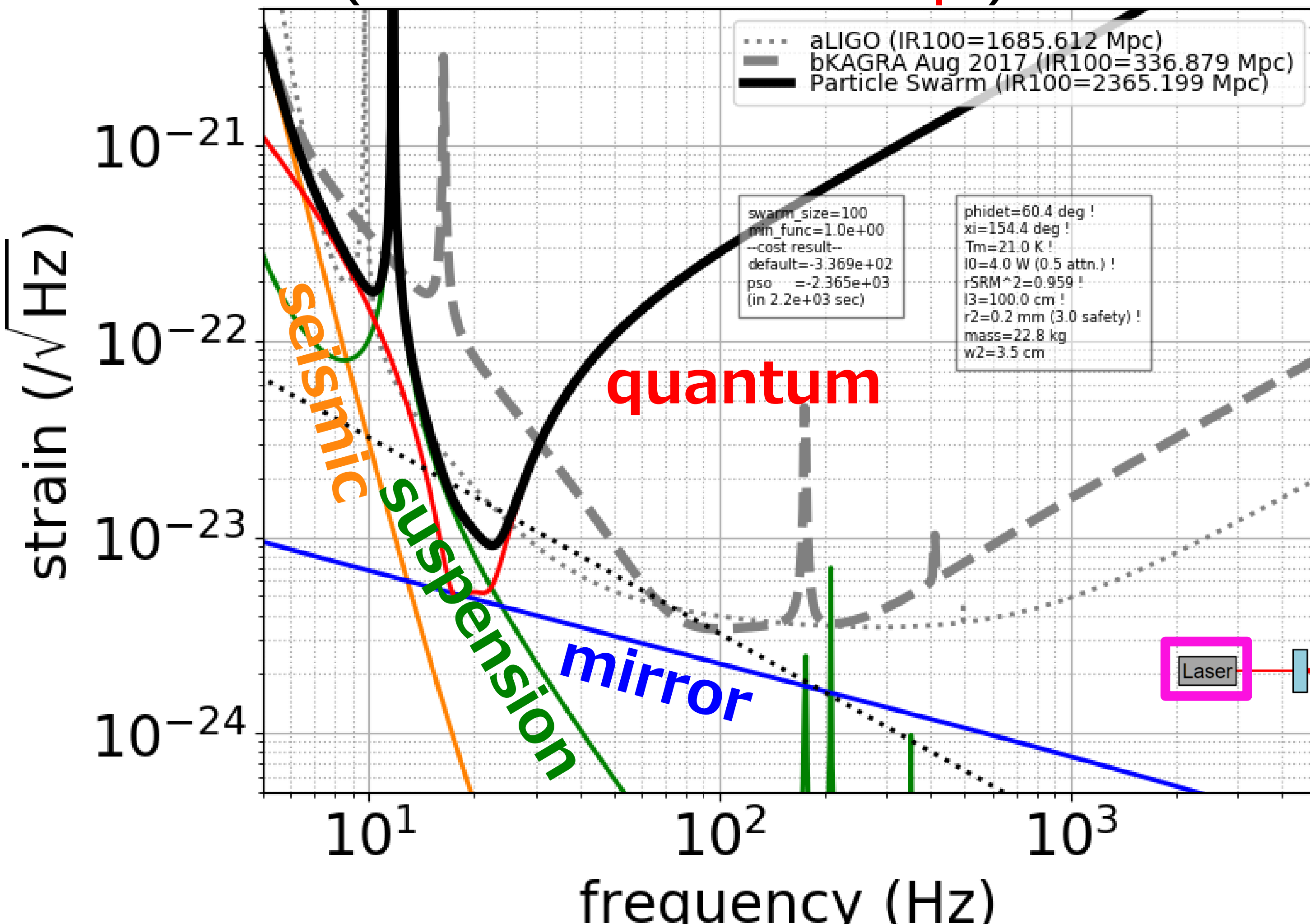
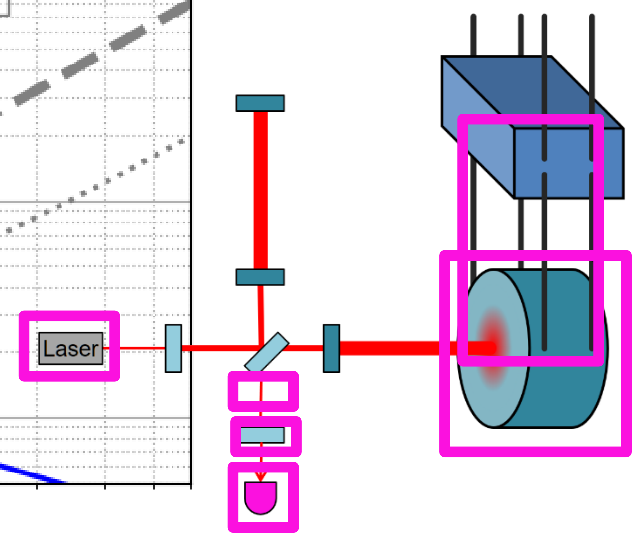


BBH100 IR Optimization

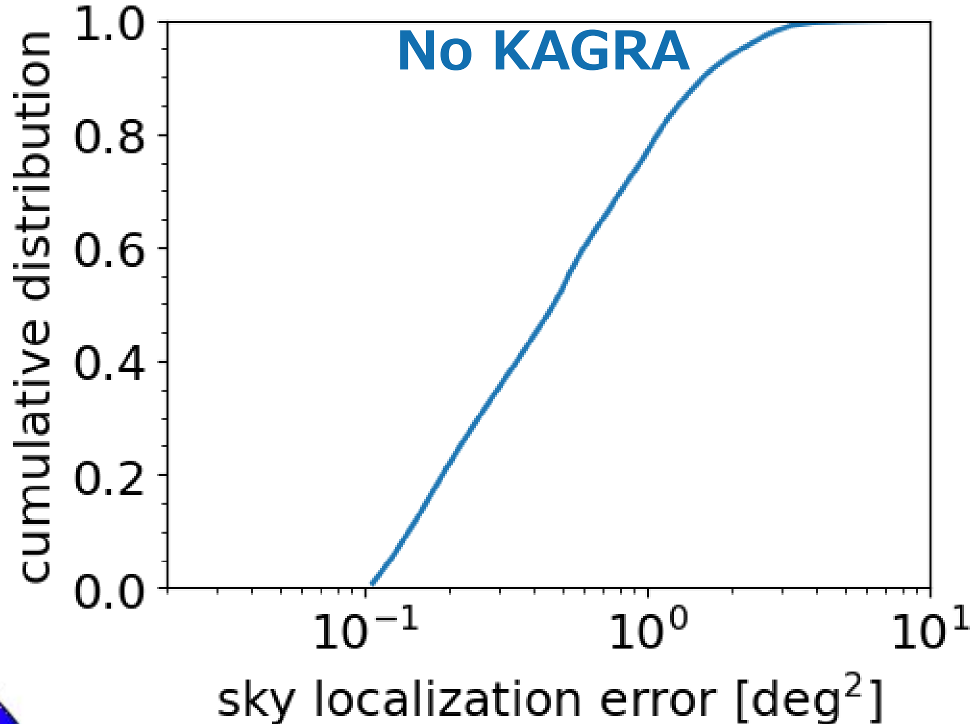
- Low power, low temperature with thin and longer fibers (KAGRA+ LF concept)

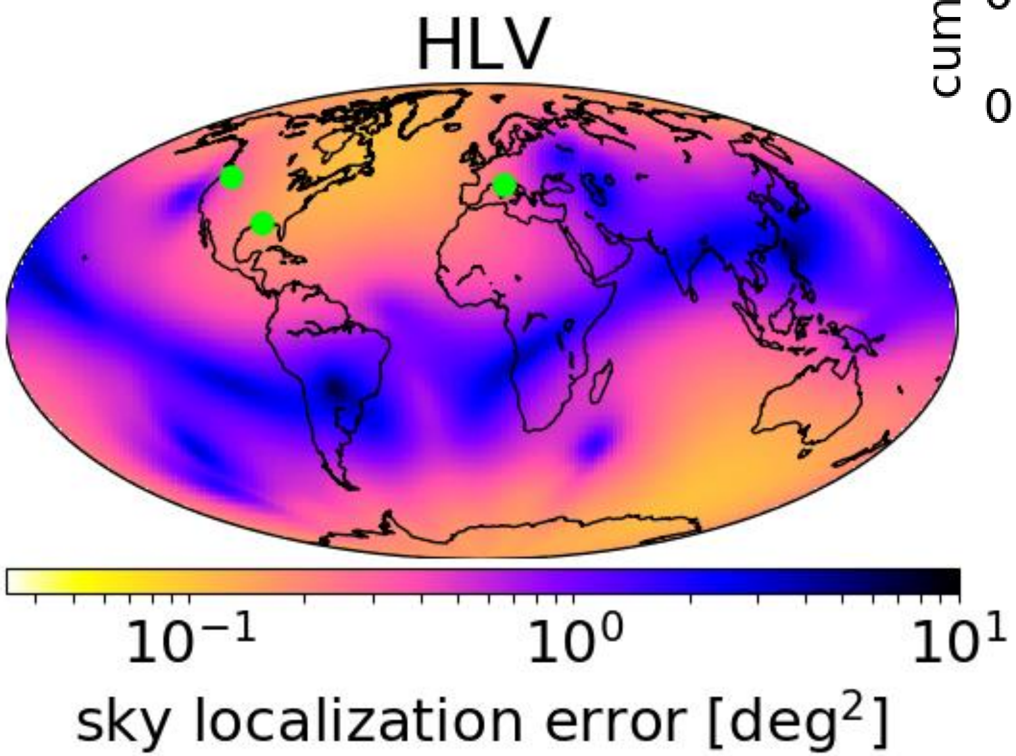


x4 heavier IM with thinner IM suspension
Less ambient heat
Allowed higher detuning



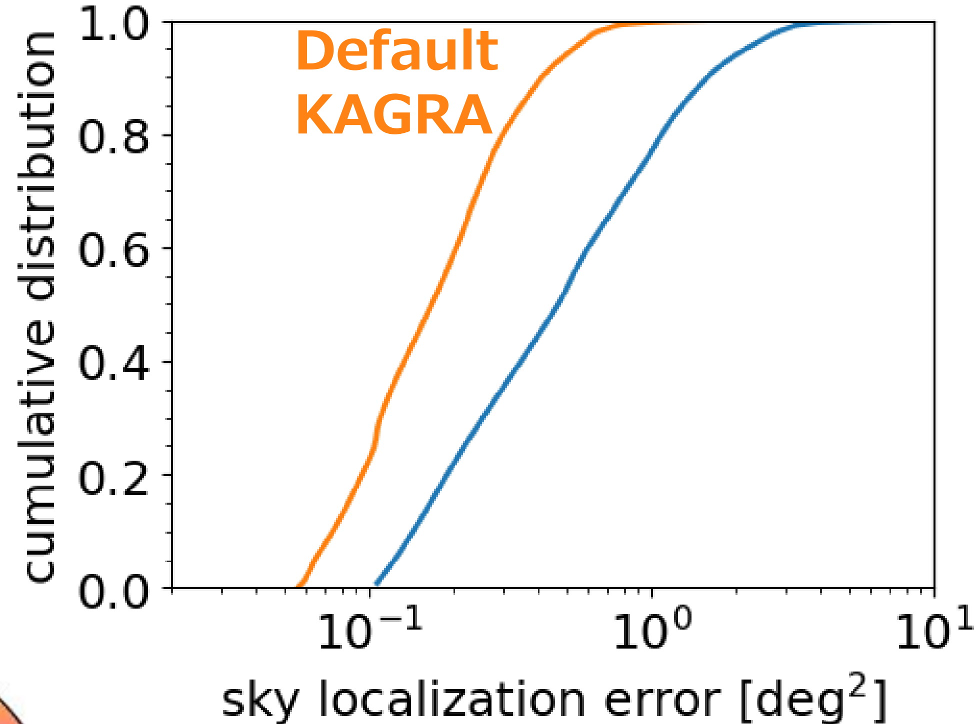
Sky Localization with HLV

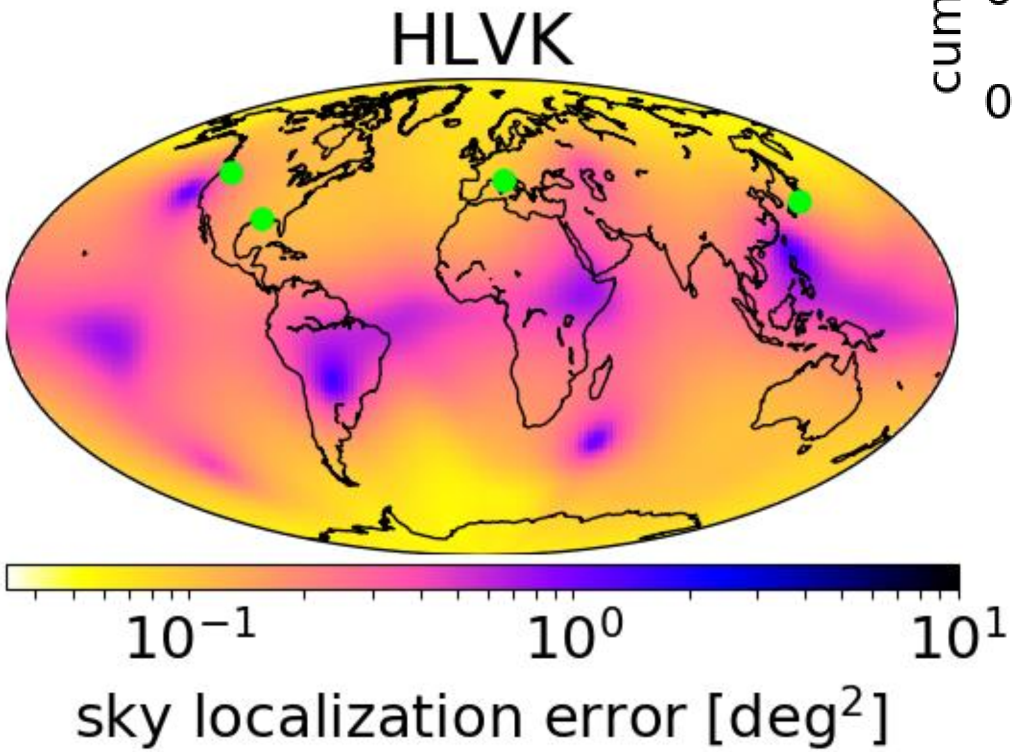




	median
HLV	0.472 deg^2
HLVK	
HLVK+	

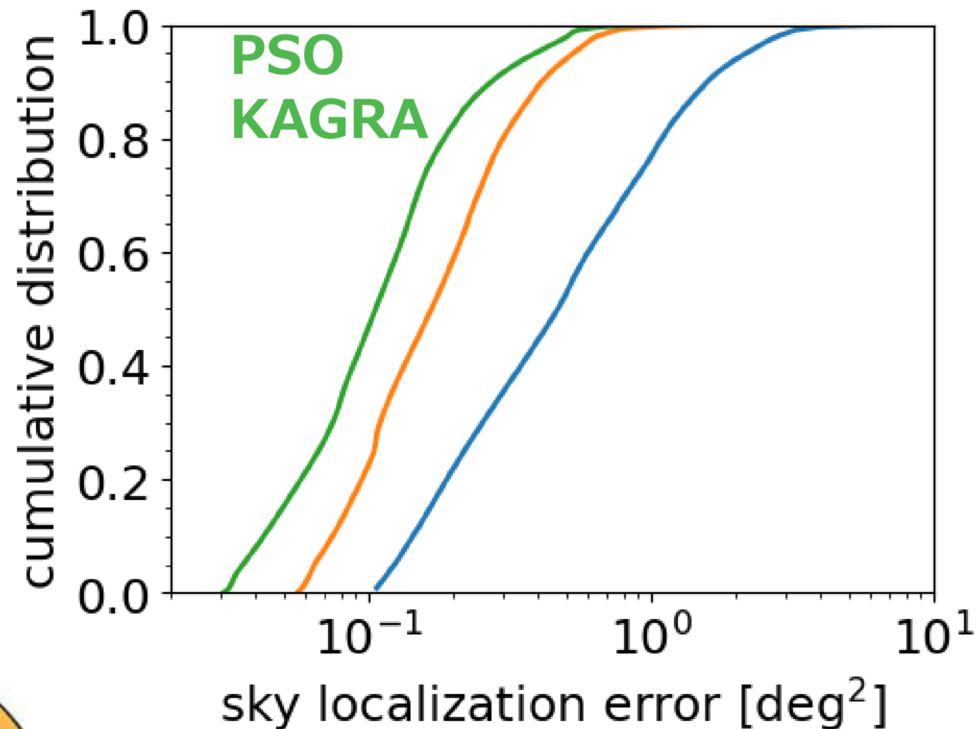
Sky Localization with HLVK

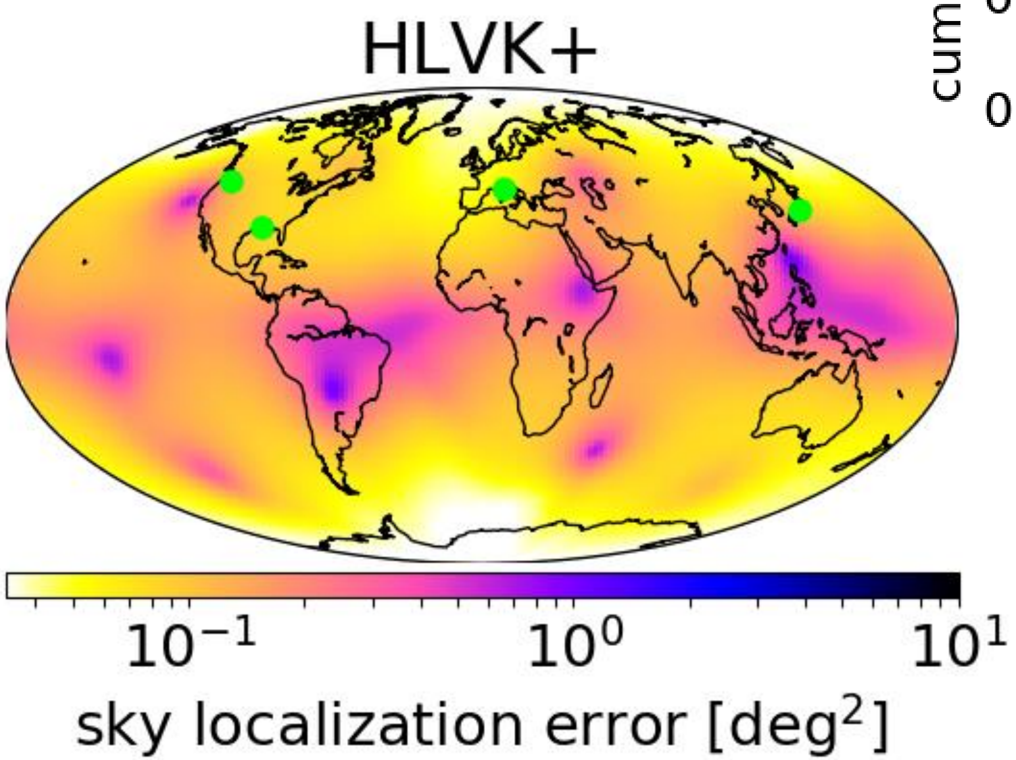




	median
HLV	0.472 deg^2
HLVK	0.168 deg^2
HLVK+	

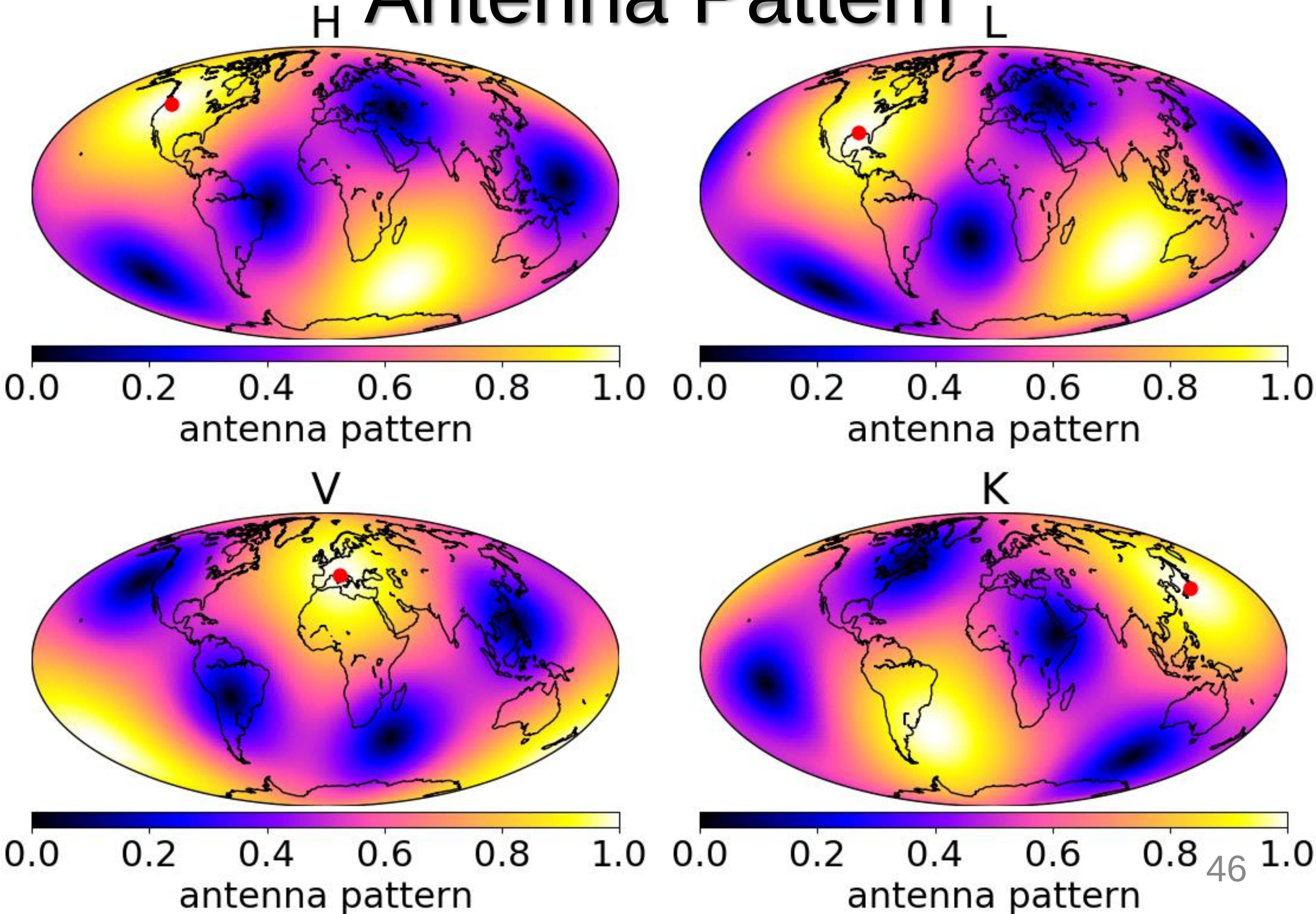
Sky Localization with HLVK+





	median
HLV	0.472 deg^2
HLVK	0.168 deg^2
HLVK+	0.107 deg^2

Antenna Pattern



2G/2G+ Parameter Comparison

	KAGRA	AdVirgo	aLIGO	A+	Voyager
Arm length [km]	3	3	4	4	4
Mirror mass [kg]	23	42	40	80	200
Mirror material	Sapphire	Silica	Silica	Silica	Silicon
Mirror temp [K]	22	295	295	295	123
Sus fiber	35cm Sap.	70cm SiO_2	60cm SiO_2	60cm SiO_2	60cm Si
Fiber type	Fiber	Fiber	Fiber	Fiber	Ribbon
Input power [W]	67	125	125	125	140
Arm power [kW]	340	700	710	1150	3000
Wavelength [nm]	1064	1064	1064	1064	2000
Beam size [cm]	3.5 / 3.5	4.9 / 5.8	5.5 / 6.2	5.5 / 6.2	5.8 / 6.2
SQZ factor	0	0	0	6	8
F. C. length [m]	none	none	none	16	300

LIGO parameters from LIGO-T1600119, AdVirgo parameters from JPCS 610, 01201 (2015)

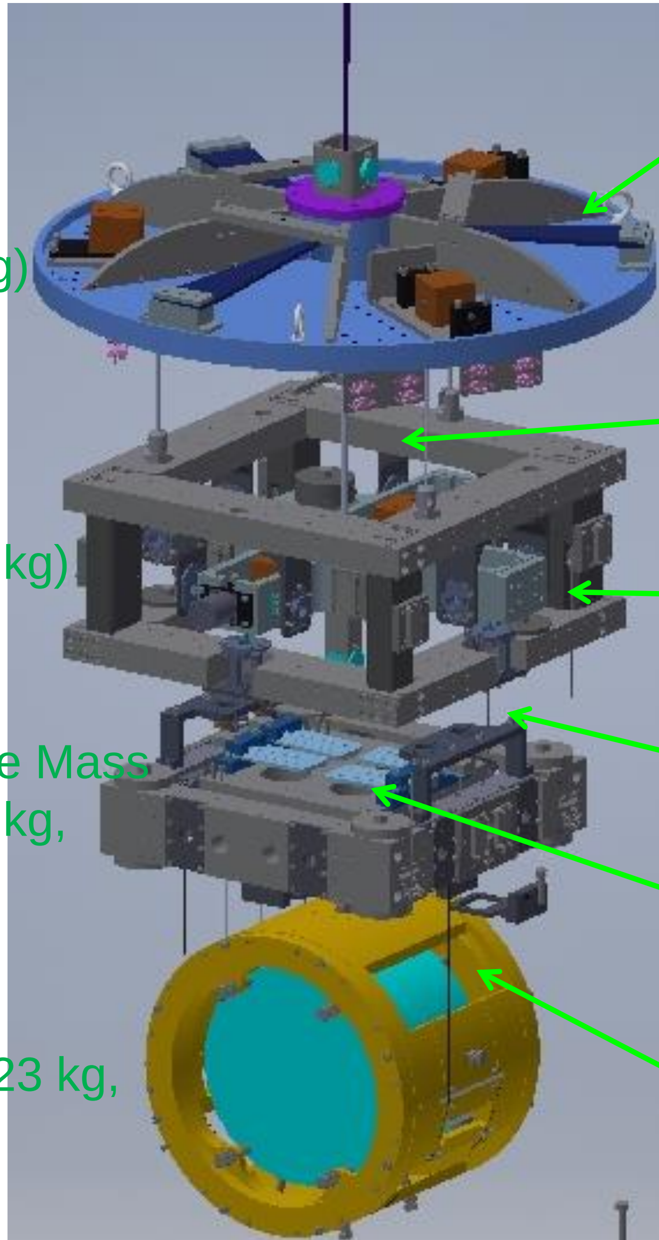
KAGRA Detailed Parameters

K. Komori *et al.*, JGW-T1707038

- **Optical parameters**
  - Mirror transmission: 0.4 % for ITM, 10 % for PRM, 15.36 % for SRM
  - Power at BS: 674 W
  - Detune phase: 3.5 deg (DRSE case)
  - Homodyne phase: 135.1 deg (DRSE case)
- **Sapphire mirror parameters**
  - TM size: 220 mm dia., 150 mm thick
  - TM mass: 22.8 kg
  - TM temperature: 22 K
  - Beam radius at ITM: 3.5 cm
  - Beam radius at ETM: 3.5 cm
  - Q of mirror substrate: 1e8
  - Coating: tantala/silica
  - Coating loss angle: 3e-4 for silica, 5e-4 for tantala
  - Number of layers: 22 for ITM, 40 for ETM
  - Coating absorption: 0.5 ppm
  - Substrate absorption: 50 ppm/cm
- **Suspension parameters**
  - TM-IM fiber: 35 cm long, 1.6 mm dia.
  - IM temperature: 16 K
  - Heat extraction: 5800 W/m/K at 20 K
  - Loss angle: 5e-6/2e-7/7e-7 for CuBe fiber/sapphire fiber/sapphire blade
- **Inspiral range calculation**
  - SNR=8, fmin=10 Hz, sky average constant 0.442478
- Seismic noise curve includes vertical coupling, vibration from heatlinks and Newtonian noise from surface and bulk

KAGRA Cryopayload

Provided by T. Ushiba and T. Miyamoto



3 CuBe blade springs

Platform
(SUS, 65 kg)

MN suspended by 1 Maraging steel fiber
(35 cm long, 2-7mm dia.)
MRM suspended by 3 CuBe fibers

Marionette
(SUS, 22.5 kg)

Heat link attached to MN

IM suspended by 4 CuBe fibers
(24 cm long, 0.6 mm dia)
IRM suspended by 4 CuBe fibers

Intermediate Mass
(SUS, 20.1 kg,
16 K)

4 sapphire blades

Test Mass
(Sapphire, 23 kg,
22 K)

TM suspended by 4 sapphire fibers
(35 cm long, 1.6 mm dia.)
RM suspended by 4 CuBe fibers