GWADW 2018 @ Alyeska Resort, Alaska

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# Sensitivity Optimization of Cryogenic Gravitational Wave Detectors

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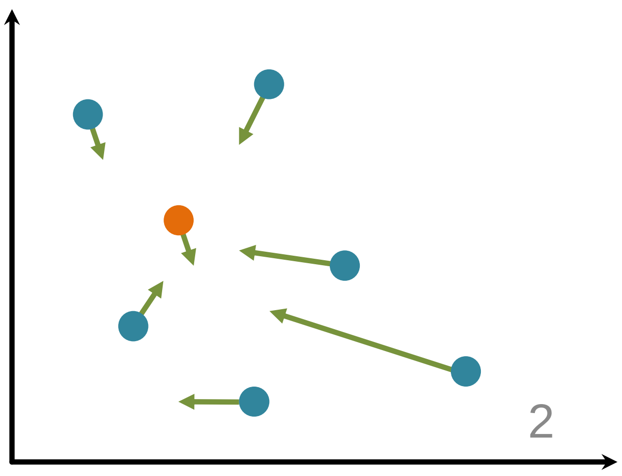
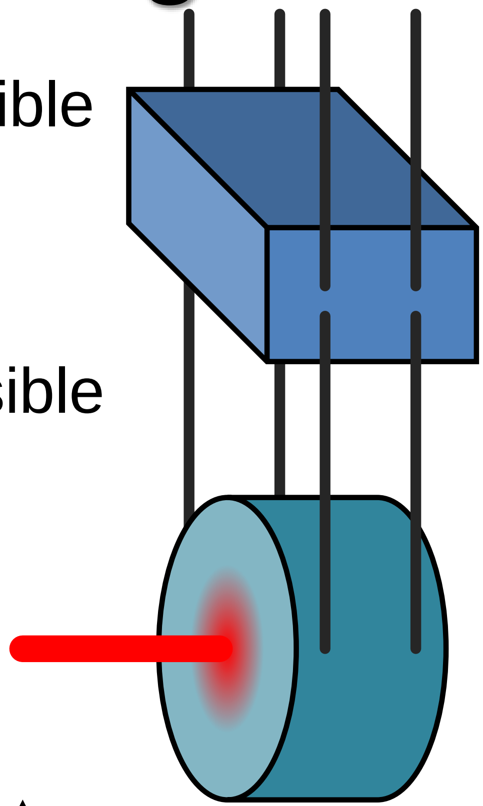
# Overview

- 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 even with many parameters
- Applied for KAGRA sensitivity design
  - re-tuned 7 parameters
  - inspiral range optimization
  - sky localization optimization

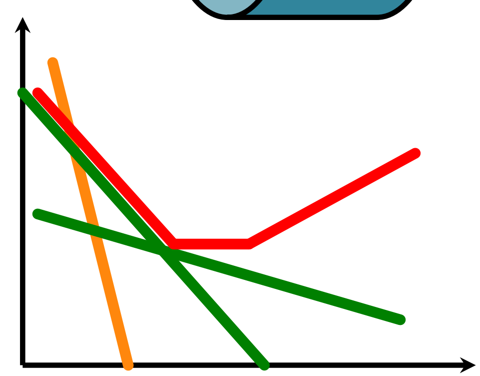


- YM+ arXiv:1804.09894

# Room Temperature Design



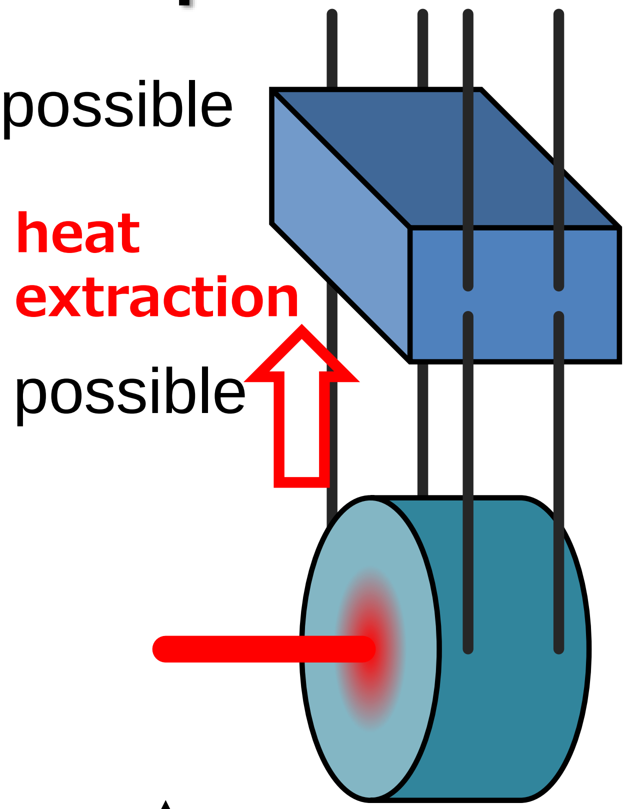
- Seismic noise: reduce as much as possible
  - multi-stage suspensions
  - underground
- Thermal noise: reduce as much as possible
  - larger mirror
  - thinner and longer wires



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

# Cryogenic Design is Complicated

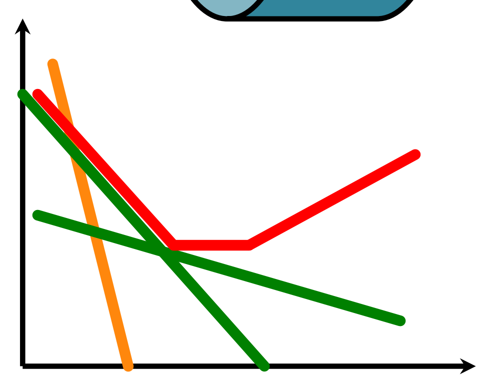
- Seismic noise: reduce as much as possible
  multi-stage suspensions
  underground




- Thermal noise: reduce as much as possible
  larger mirror
  thinner and longer wires

  cryogenic cooling

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



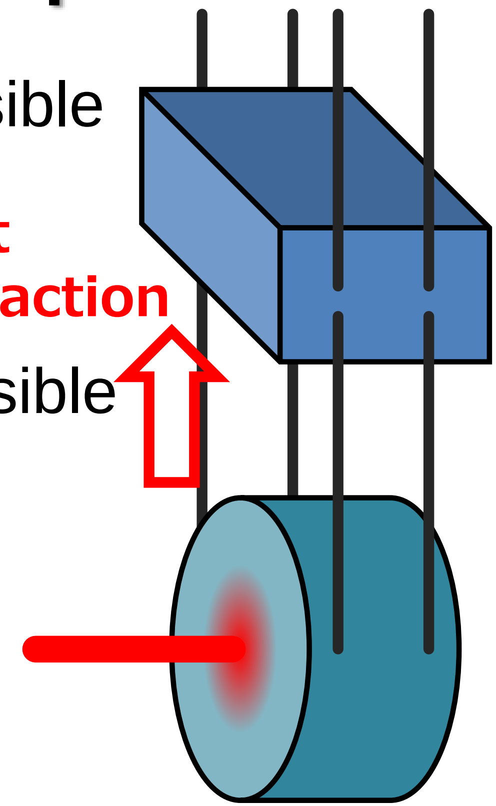
# Cryogenic Design is Complicated

- Seismic noise: reduce as much as possible
  - multi-stage suspensions
  - underground
- Thermal noise: ~~reduce~~ as much as possible
  optimize
  - larger mirror
  - thinner and longer wires

  cryogenic cooling

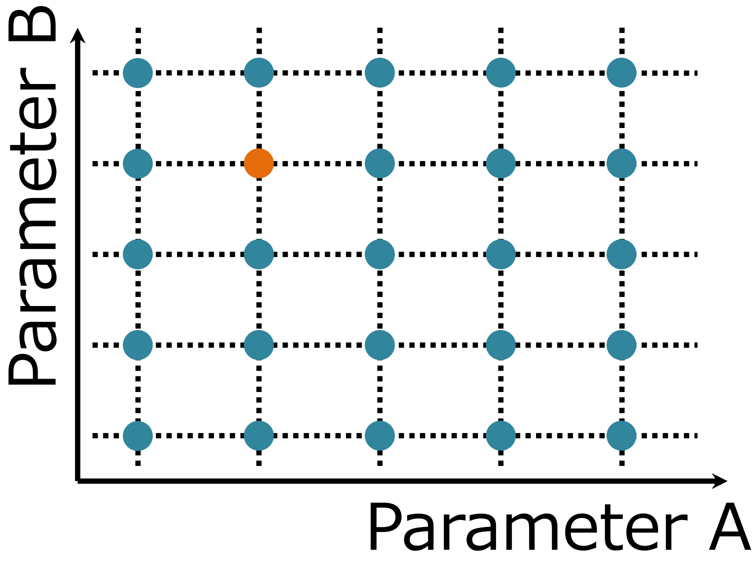
worse cooling power
mirror heating

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


heat extraction

# 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

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

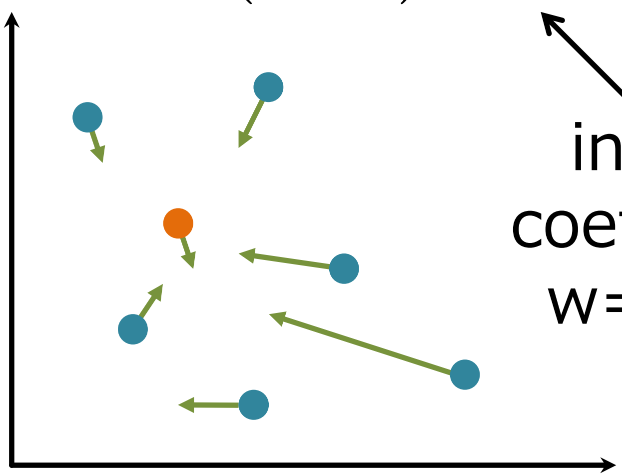
personal best position so far

global best position so far

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

inertia coefficient w=0.72

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



Parameter space

[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

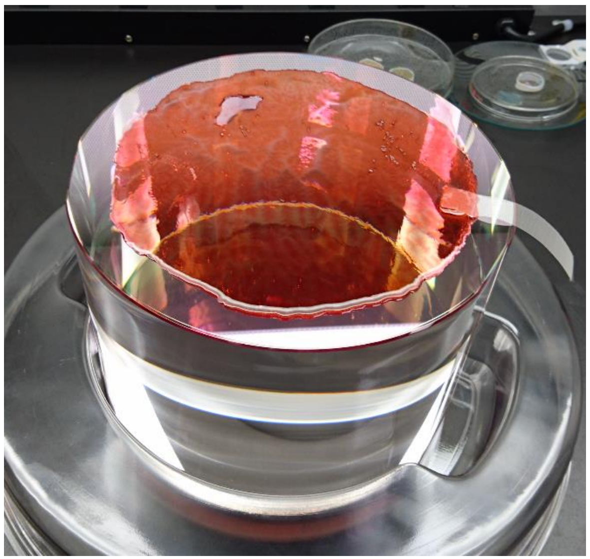
# Pros and Cons of PSO

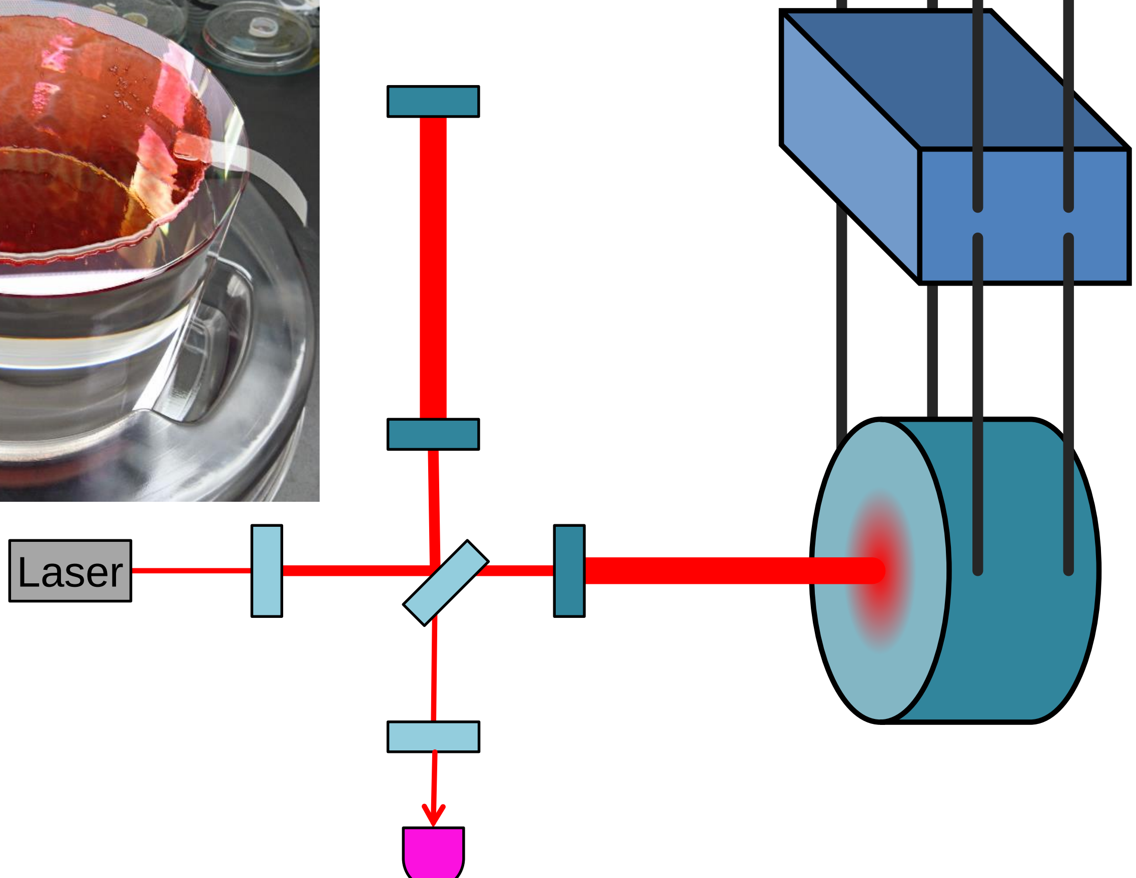
- Fast even for highly multidimensional parameter space ☺
  - uses entire swarm's information to search
- Requires small number of design variables and little prior information ☺
  - basically only swarm size and termination criterion
  - prior information is only search range
- No guarantee for convergence 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

# Apply PSO for KAGRA Design

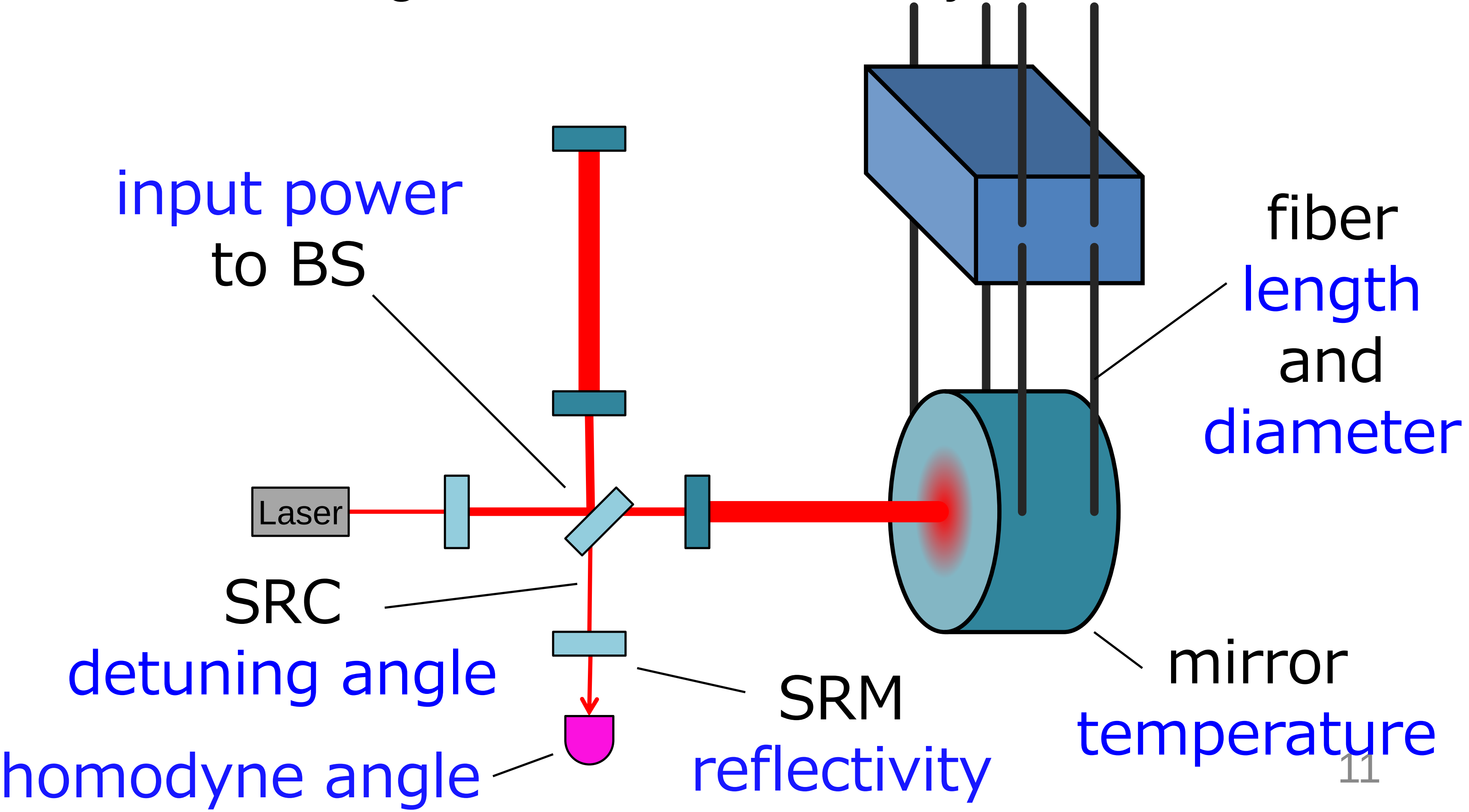
- RSE interferometer
- Cryogenic sapphire test masses





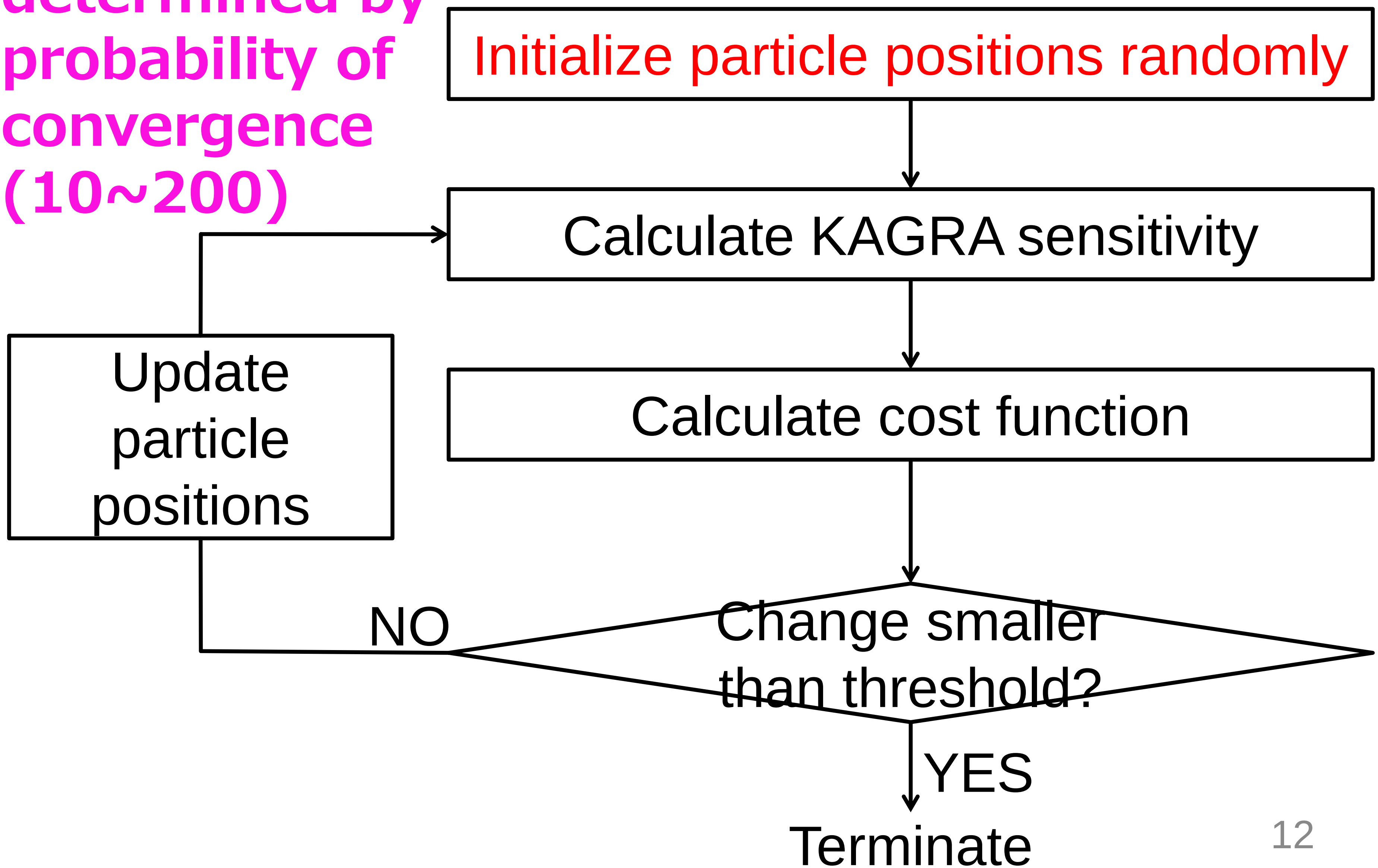
# KAGRA Parameters to Optimize

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

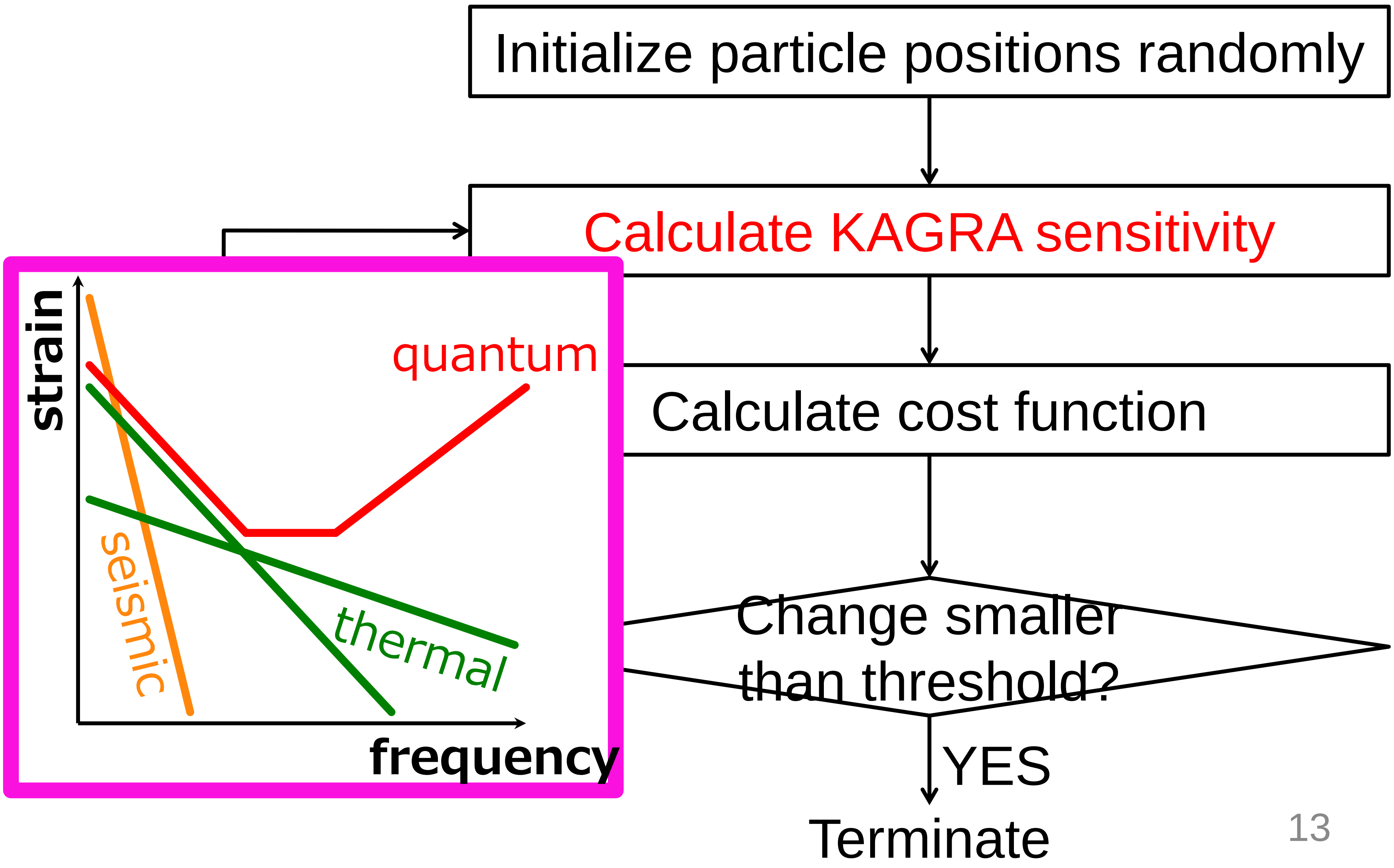


# PSO Algorithm

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

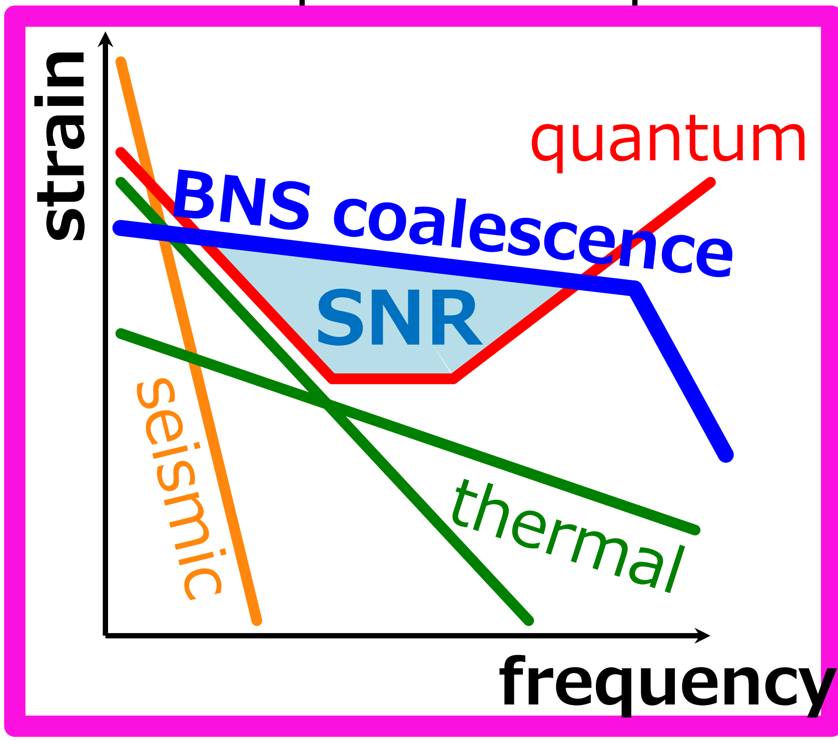


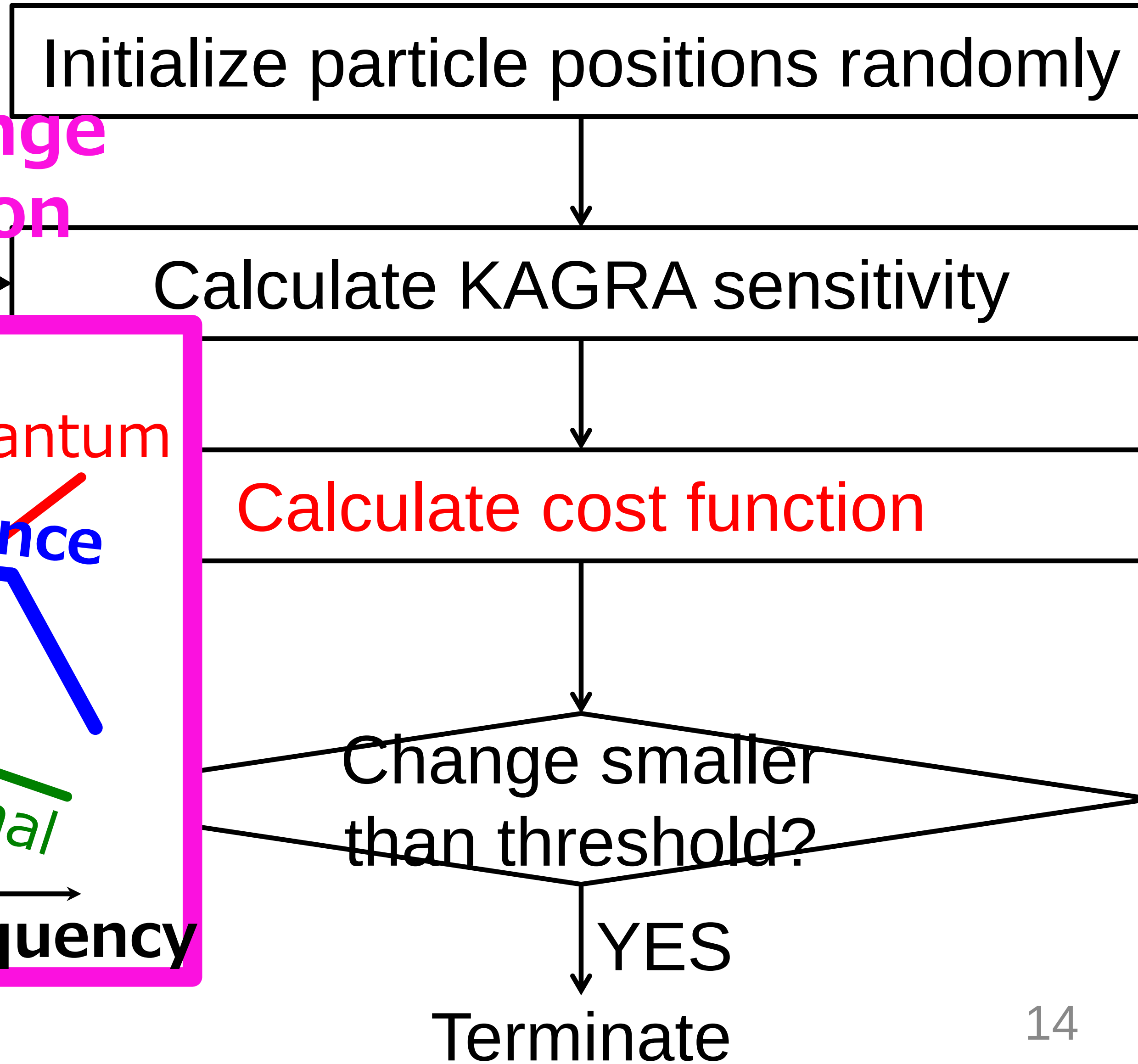
# PSO Algorithm



# PSO Algorithm

**BNS inspiral range as a cost function**



# PSO Algorithm

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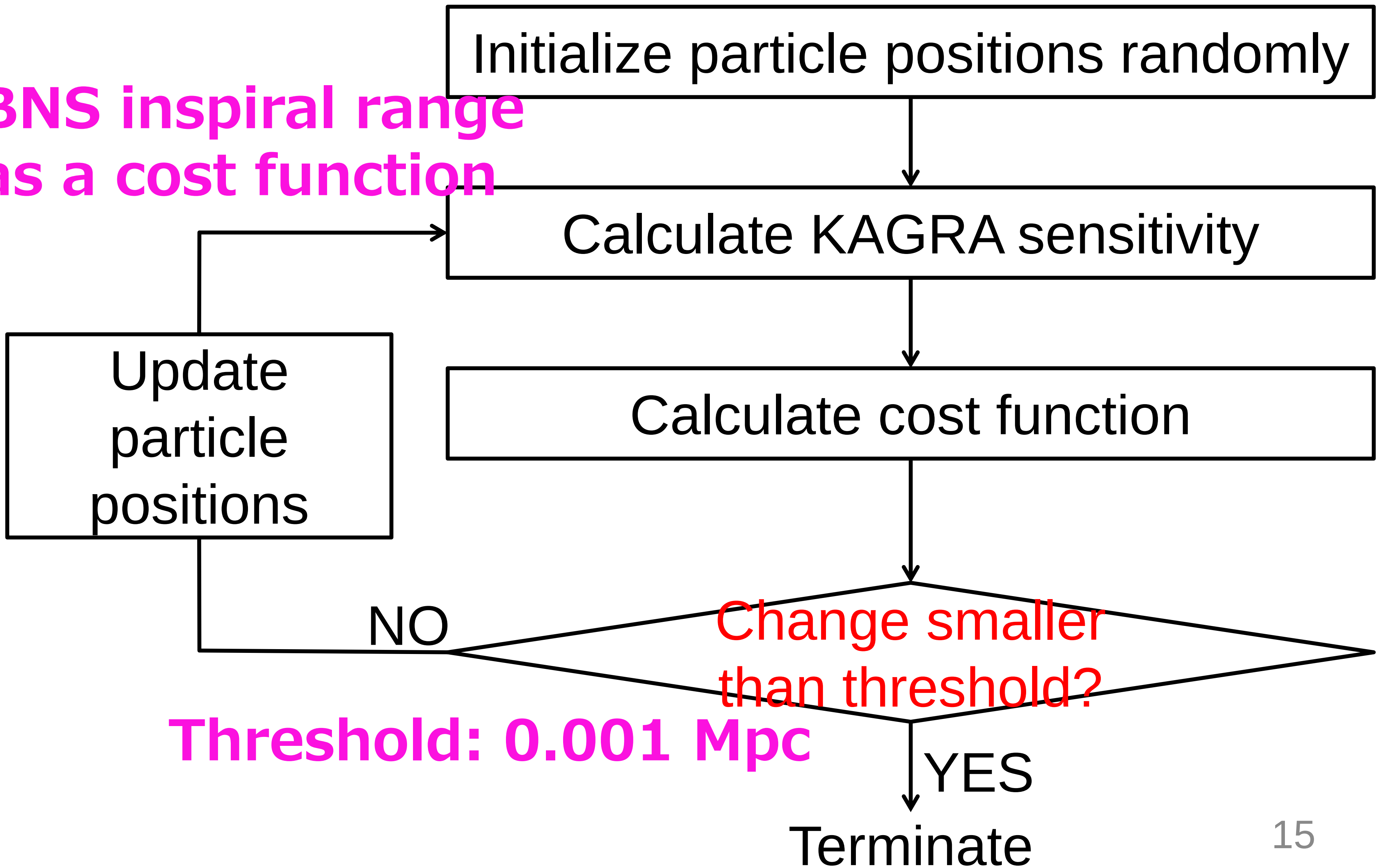
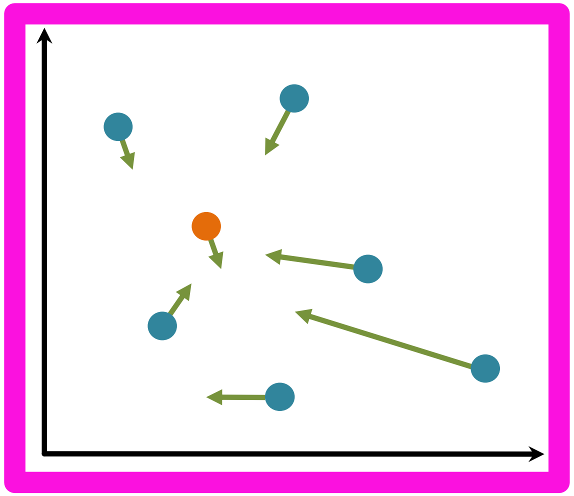



**Threshold: 0.001 Mpc**

# PSO Algorithm



Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

Change smaller than threshold?

NO

Update particle positions

YES

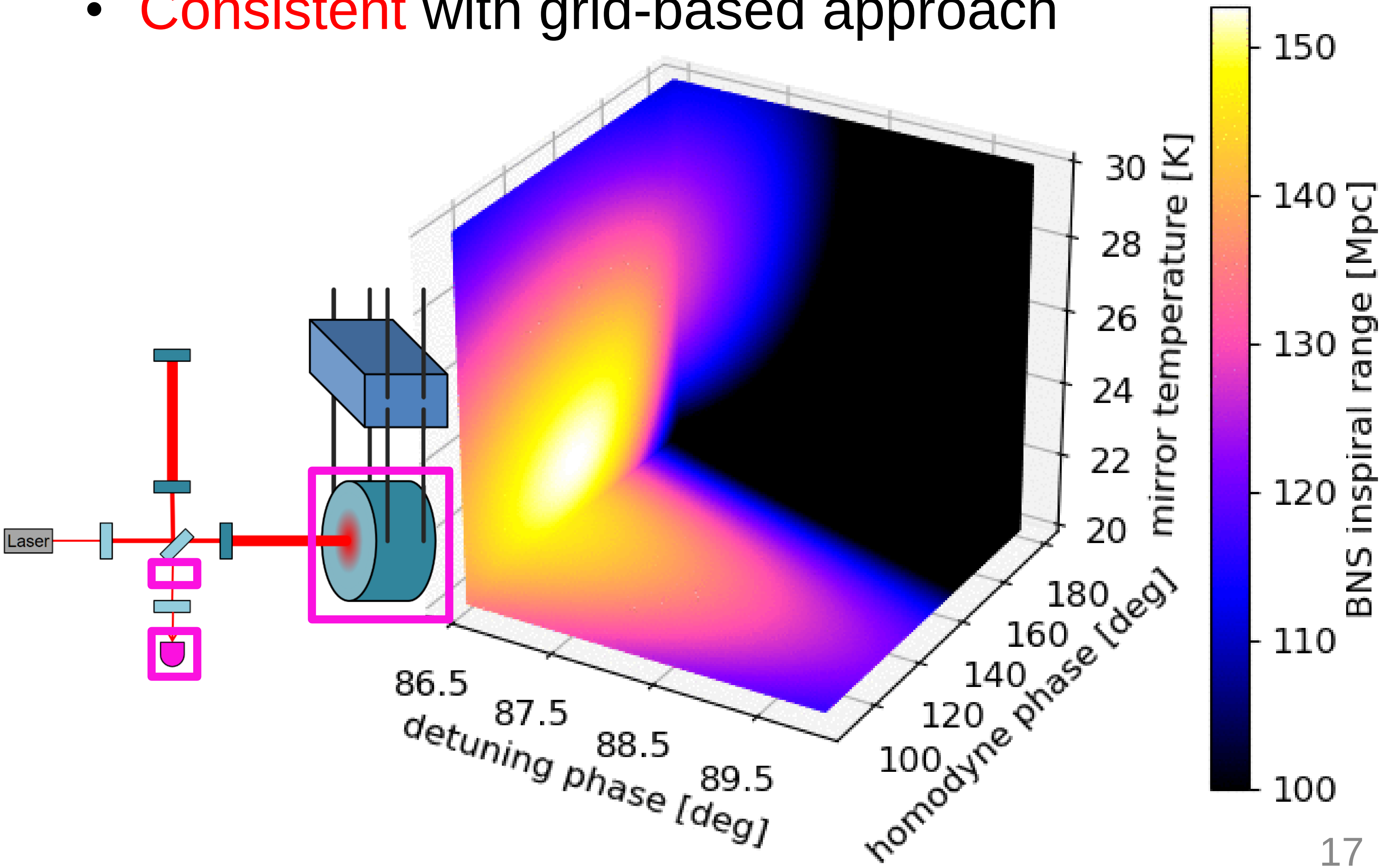
Terminate

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

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

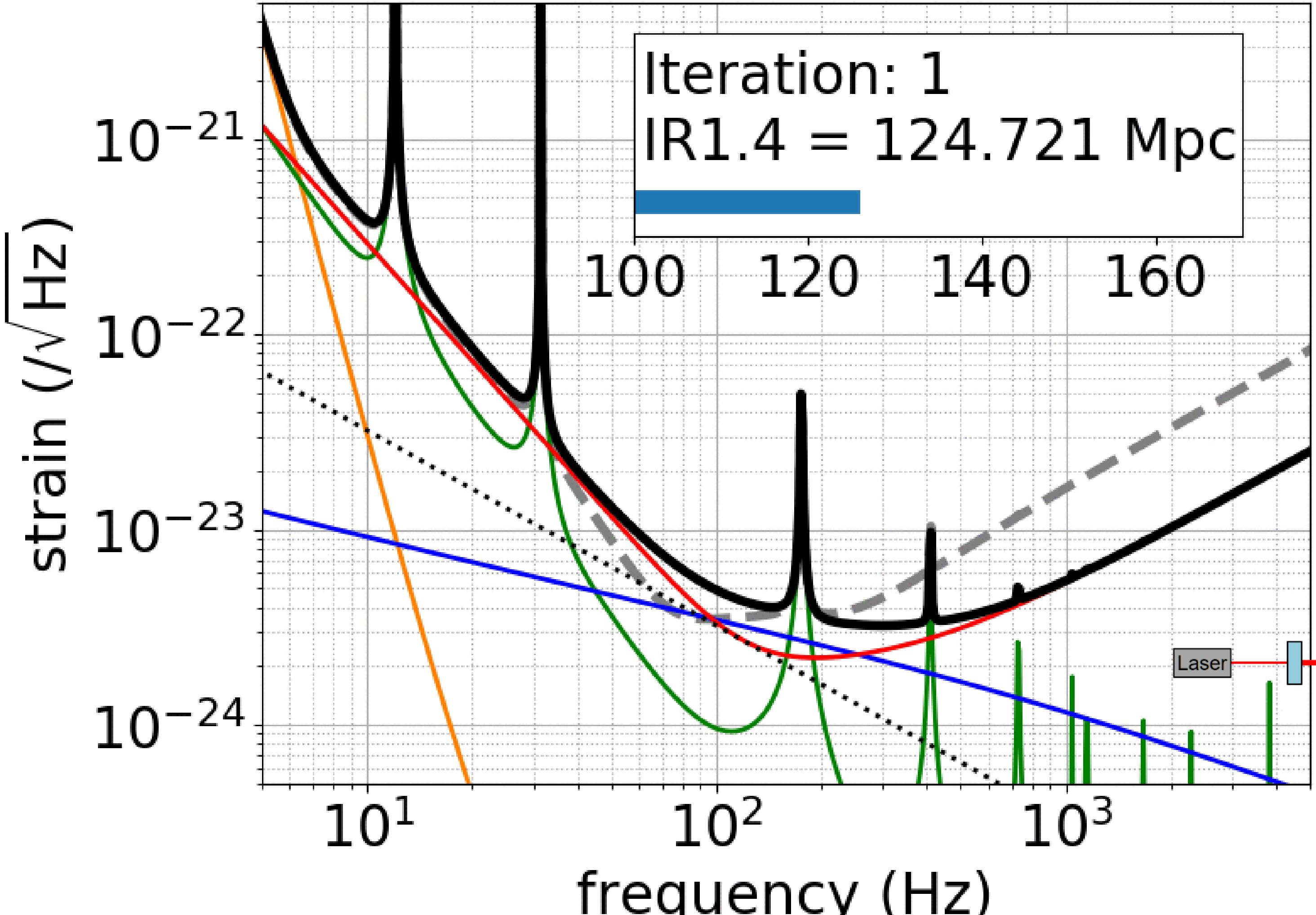
# 3 Parameter Optimization

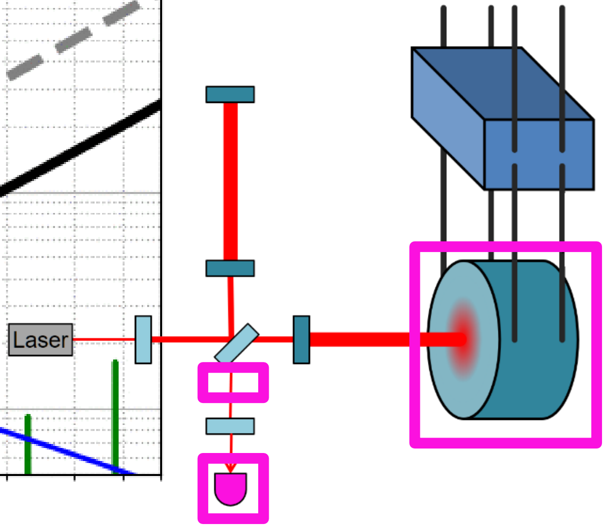
- Consistent with grid-based approach



# 3 Parameter Optimization

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



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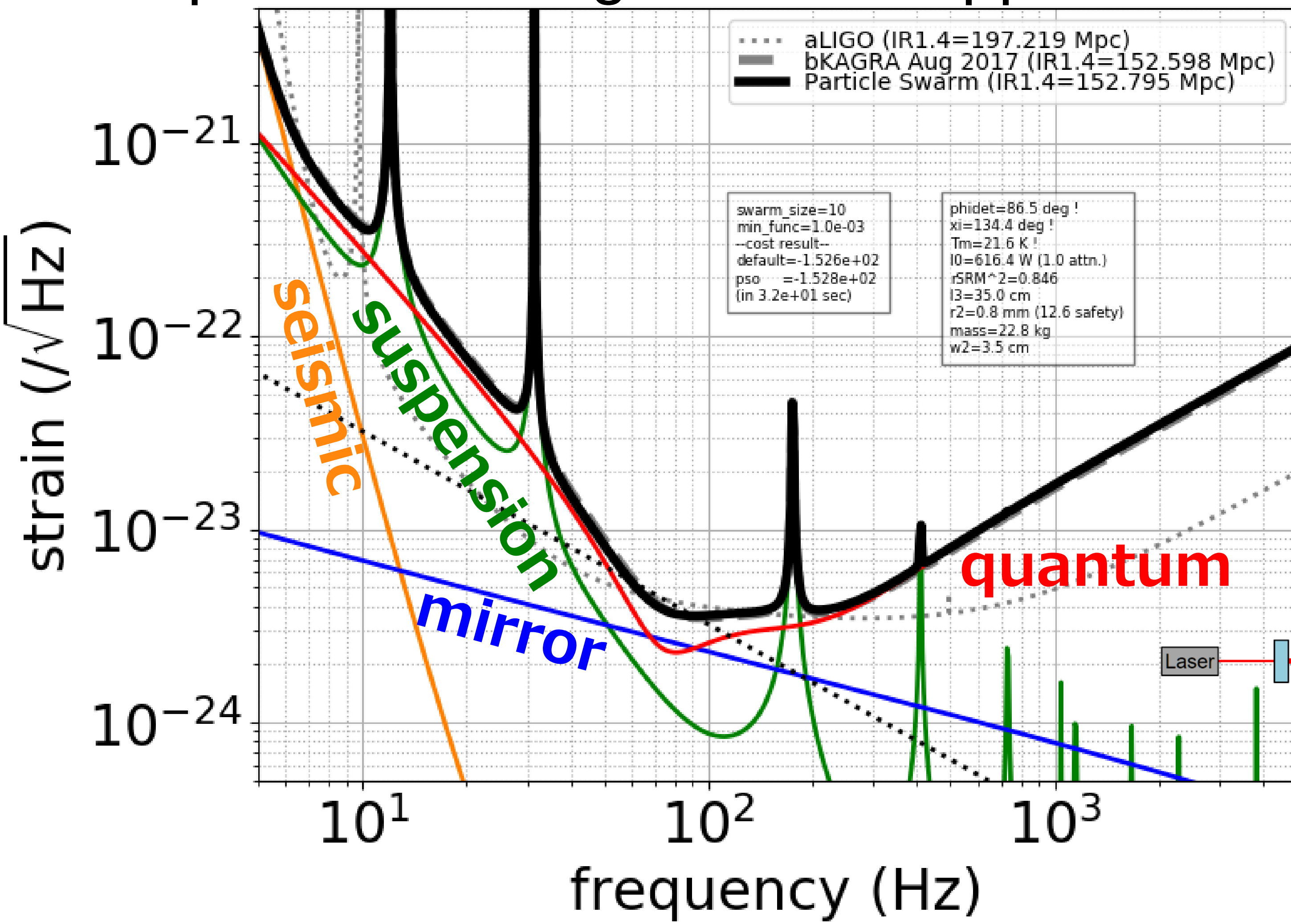
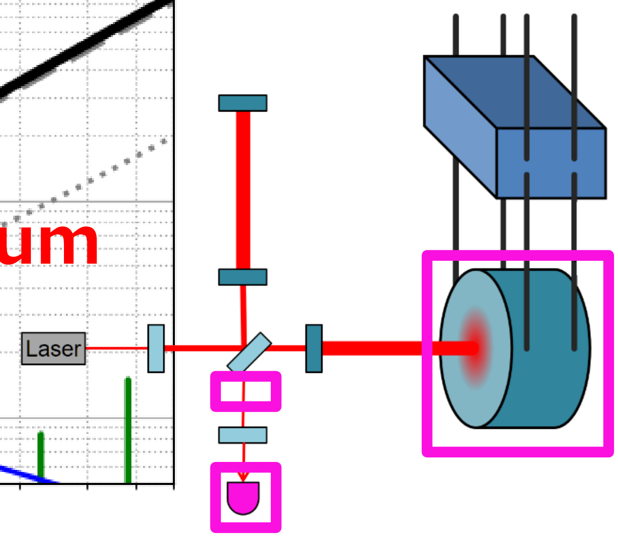
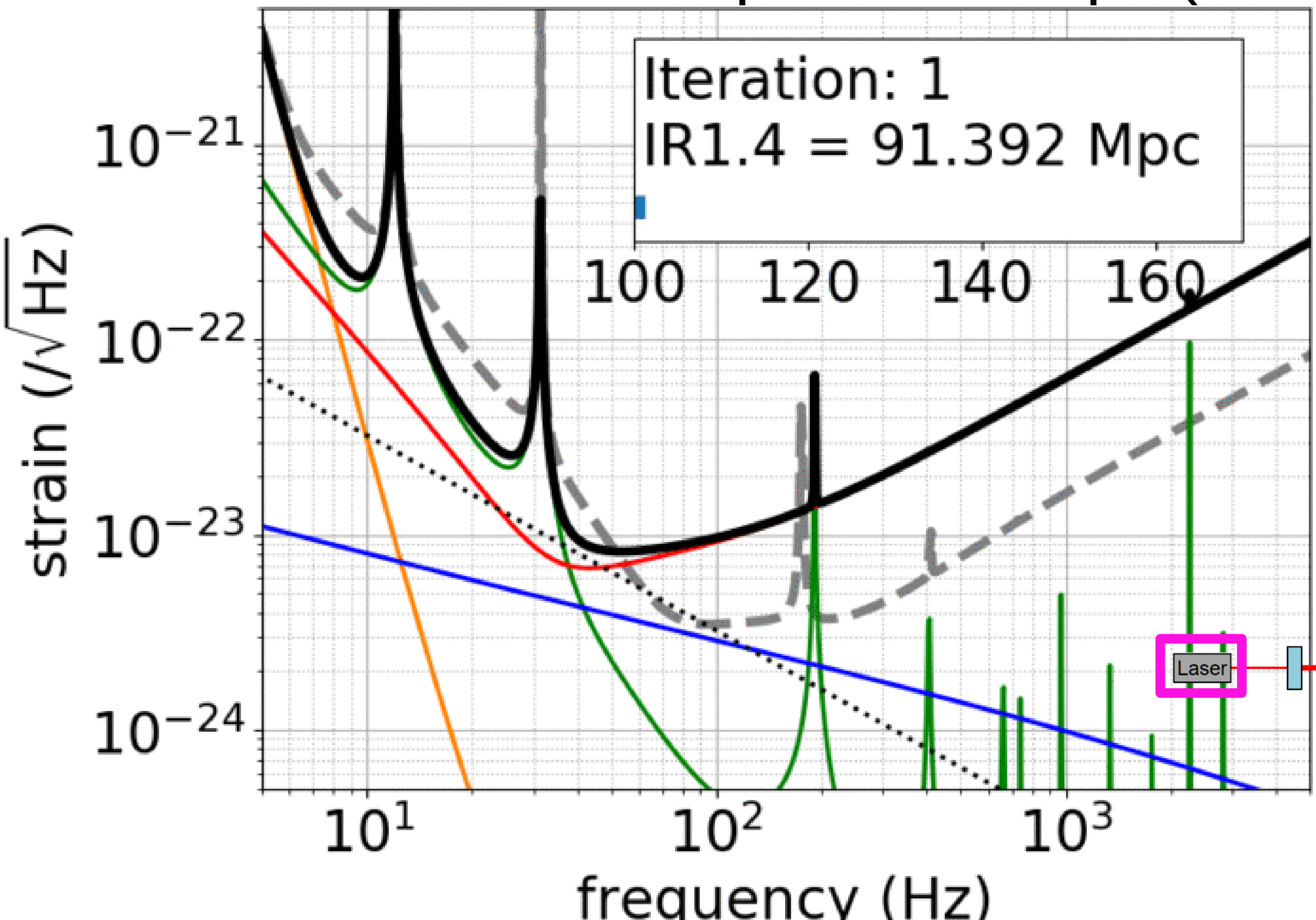
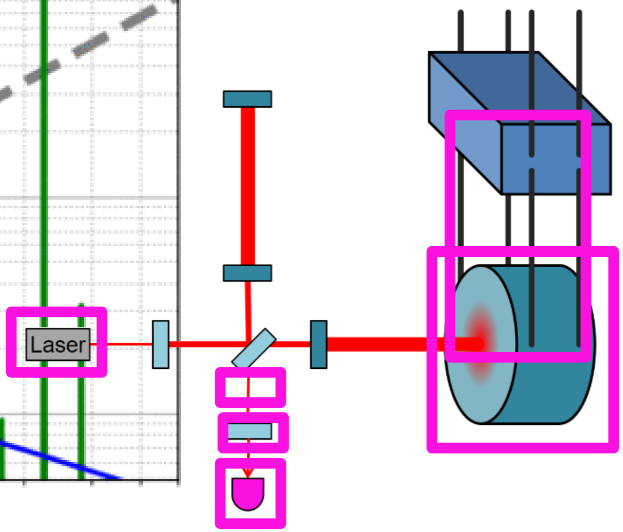


# 7 Parameter Optimization

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



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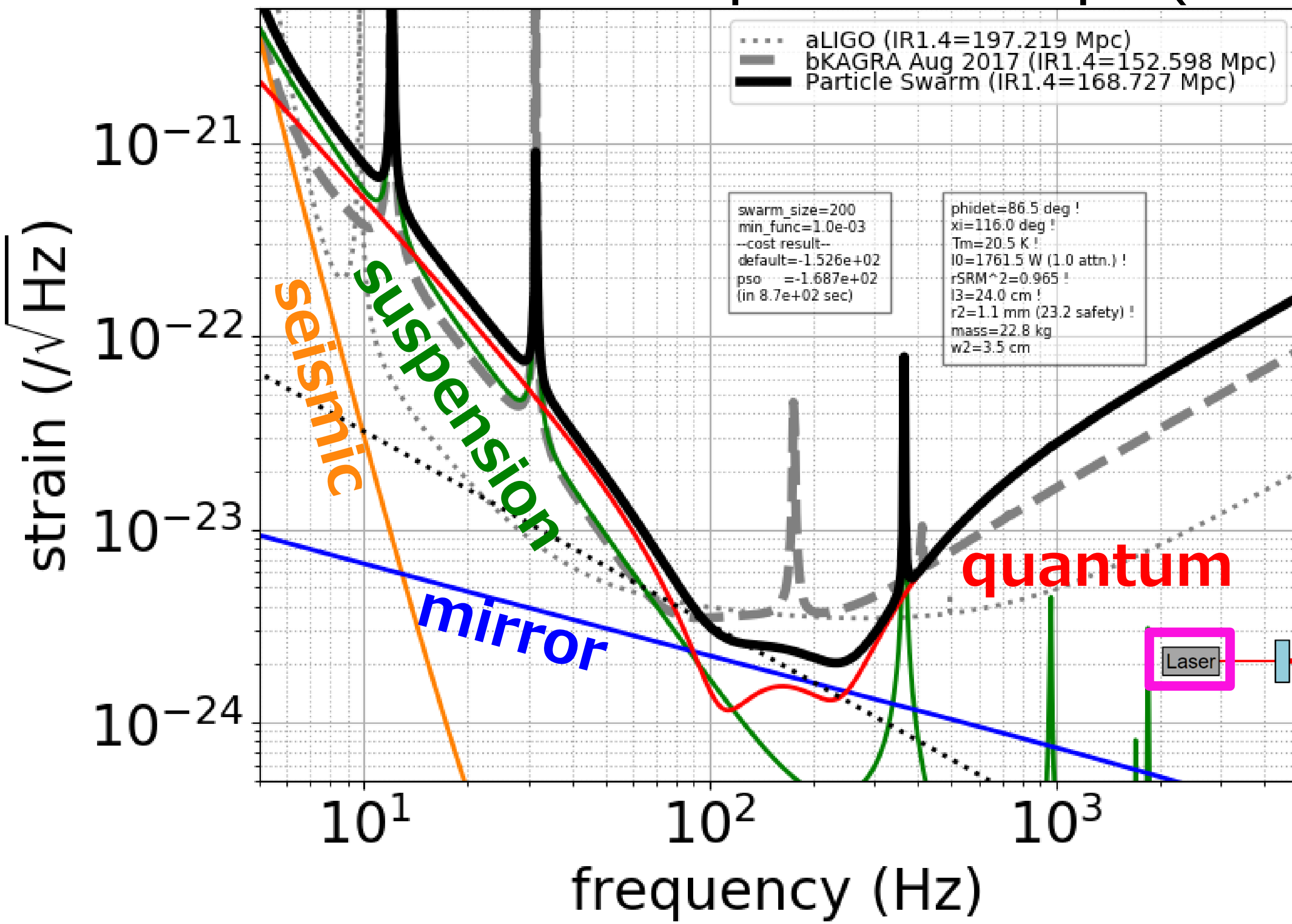
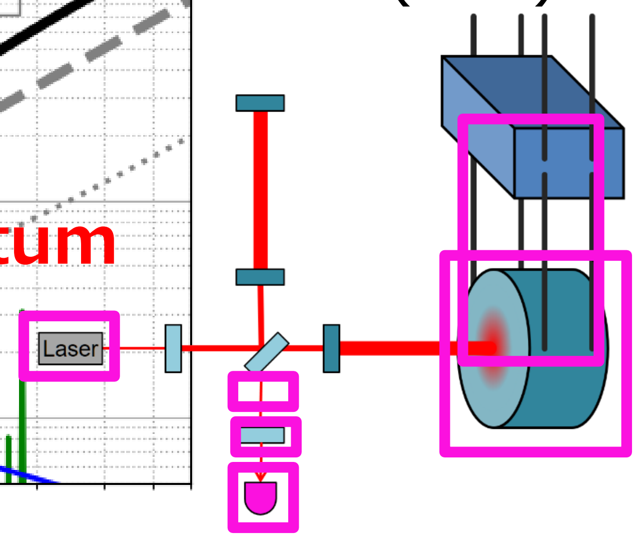



shorter and thicker to put more power with 20 K (min)



# Sensitivity Design with PSO is Fast

- Optimization done in O(10) minutes with my laptop
- Number of cost function evaluations

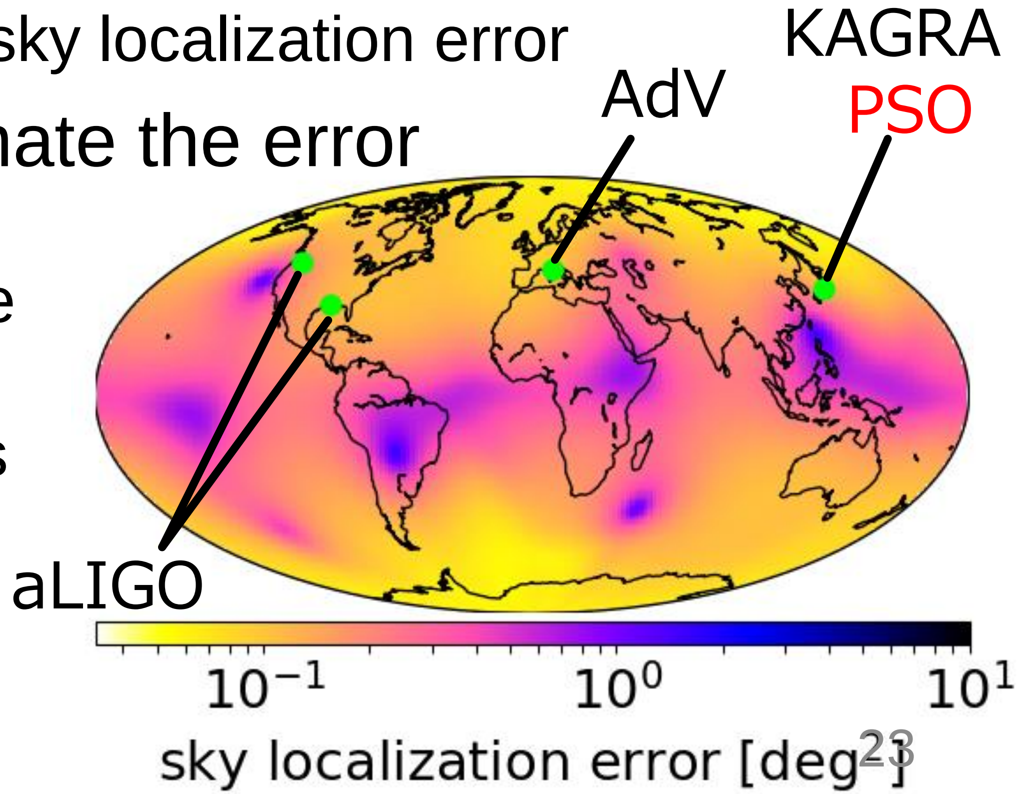
| | Grid-based | PSO |
|---|---|---|
| 3 params | ~$10^5$ □ | 10×(52±13) □ |
| 5 params | ~$10^9$ □ | 20×(73±16) □ |
| 7 params | ~$10^{14}$ □ | 200×(60±18) □ |

* 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

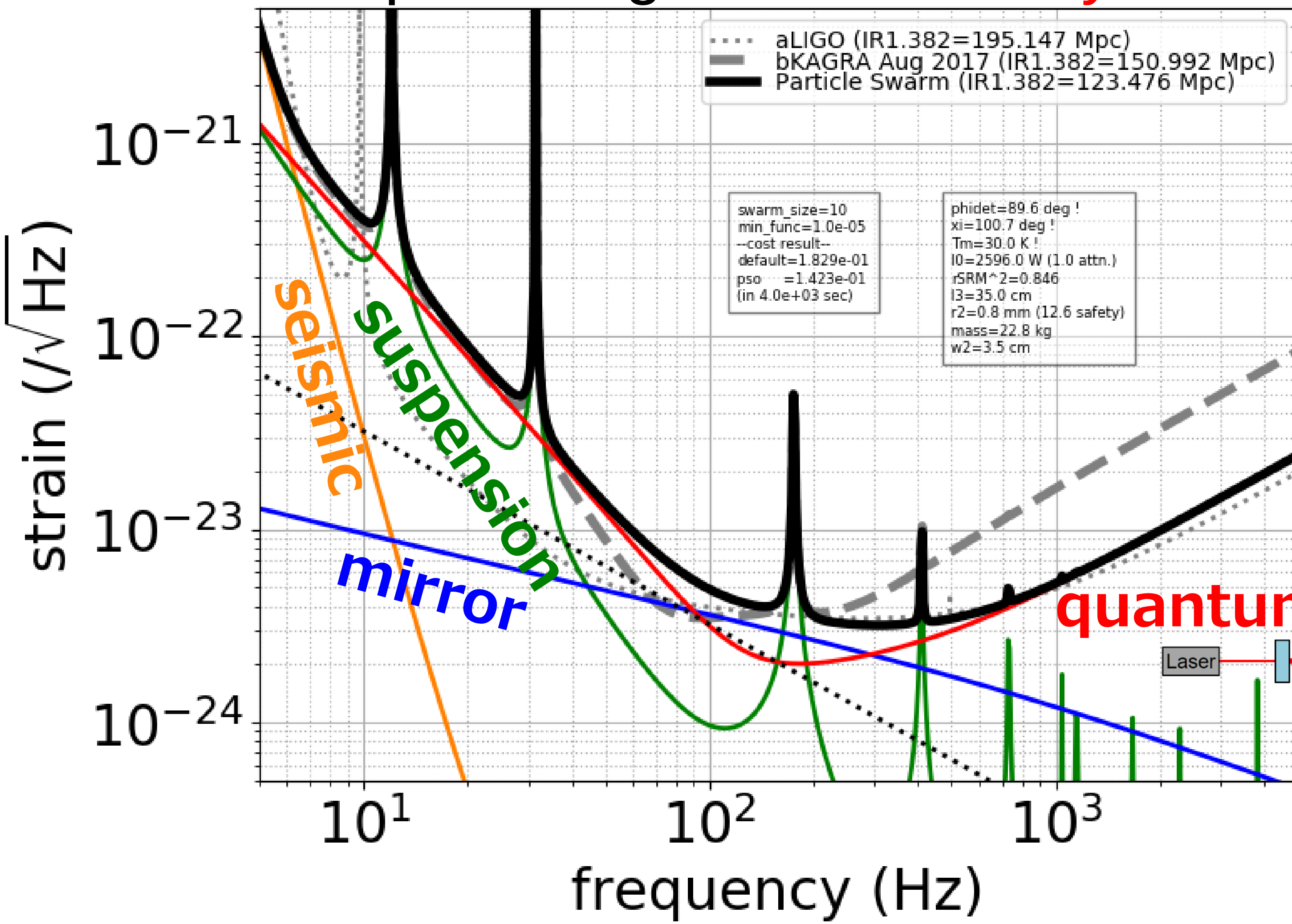
- Cost function:
  sky localization of GW170817-like binary
  - 1.25-1.5 Msun at 40 Mpc, inclination 28 deg
  - zero spins, no precession
  - 108 sets of sky location and polarization angle to derive median of sky localization error
- Fisher matrix to estimate the error
  - inspiral waveform to
    3.0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



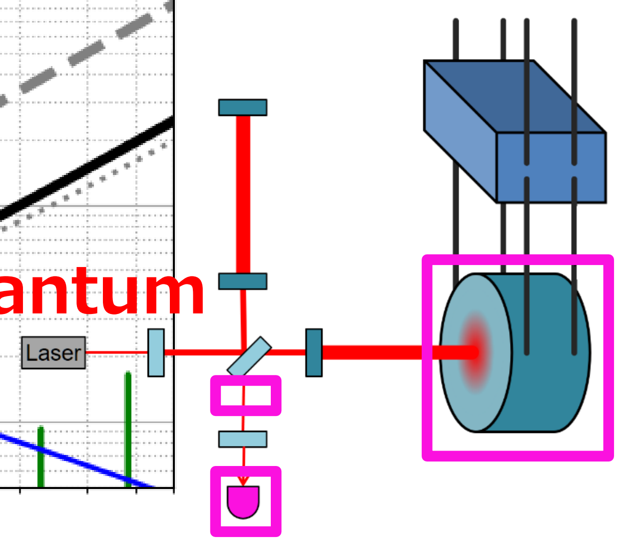
# 3 Parameter Optimization

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

0.18 $\text{deg}^2$
$\rightarrow$ 0.14 $\text{deg}^2$

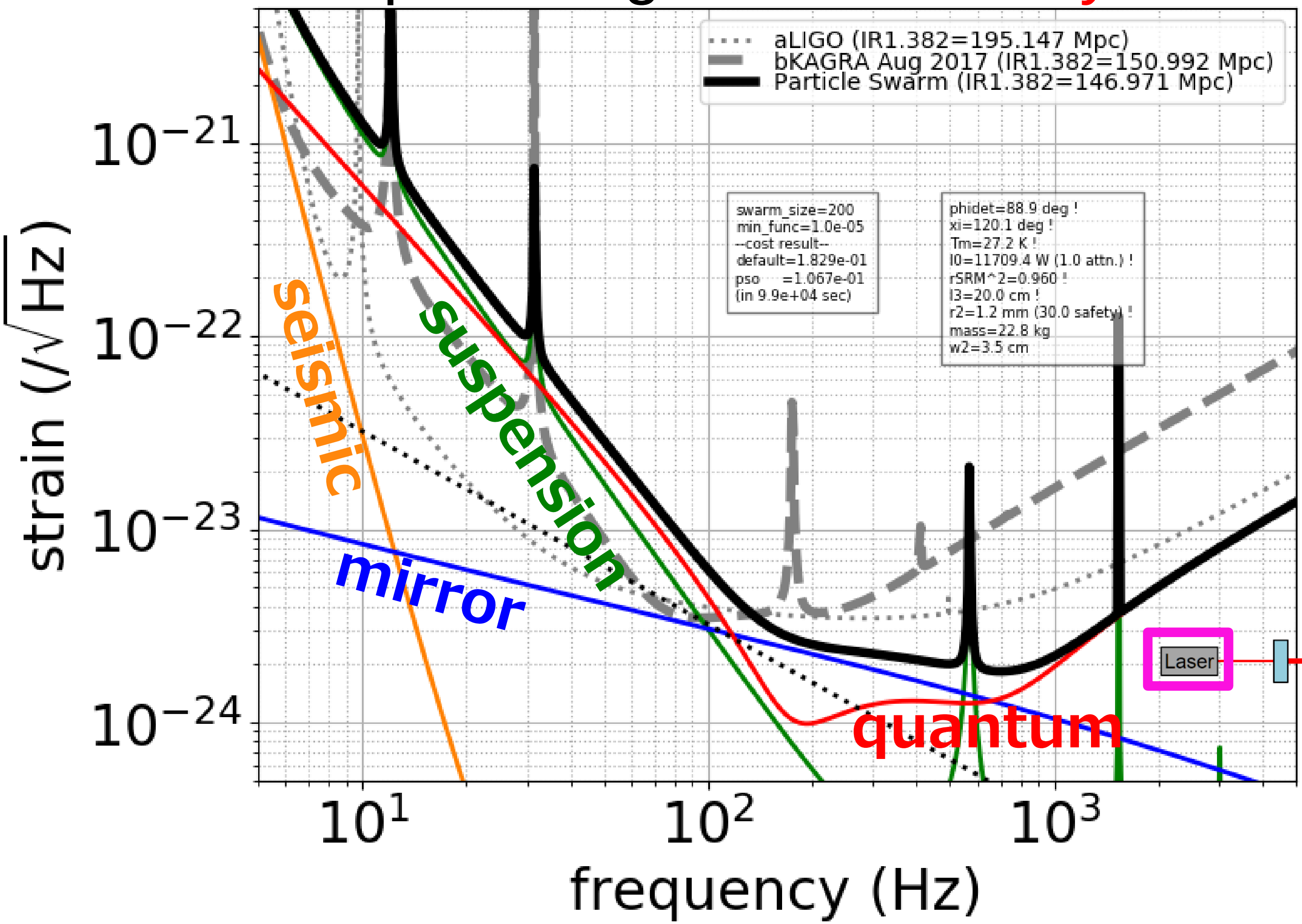



2600 W at BS
30 K



# 7 Parameter Optimization

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



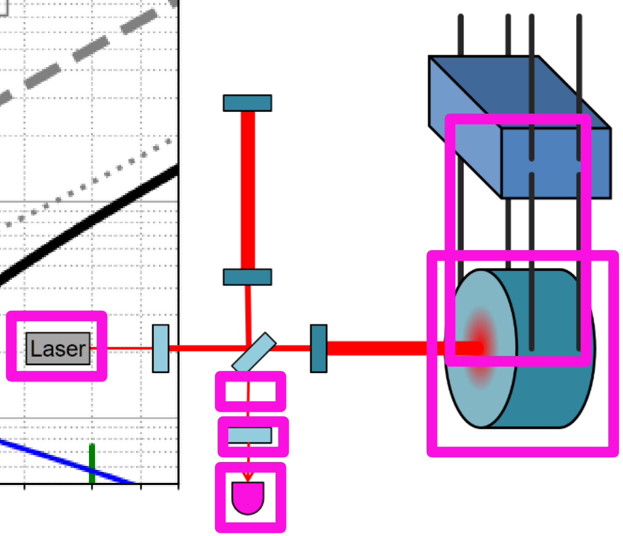

$0.18\ \text{deg}^2$

$\rightarrow 0.11\ \text{deg}^2$

shortest and thickest fibers

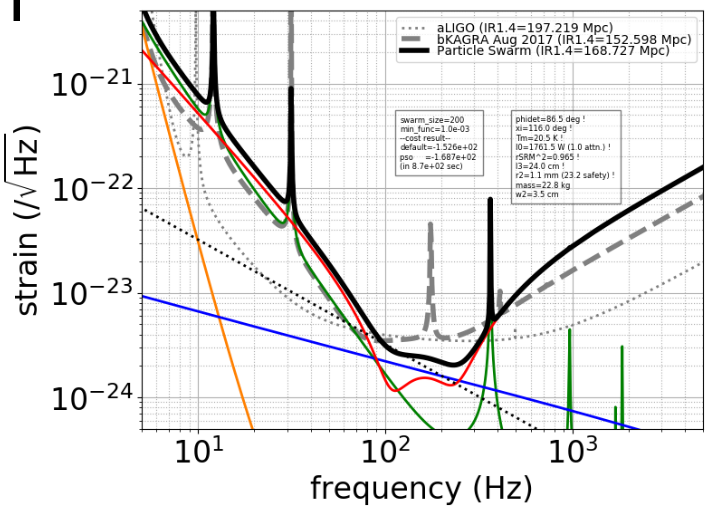
1.1 kW at BS

27 K

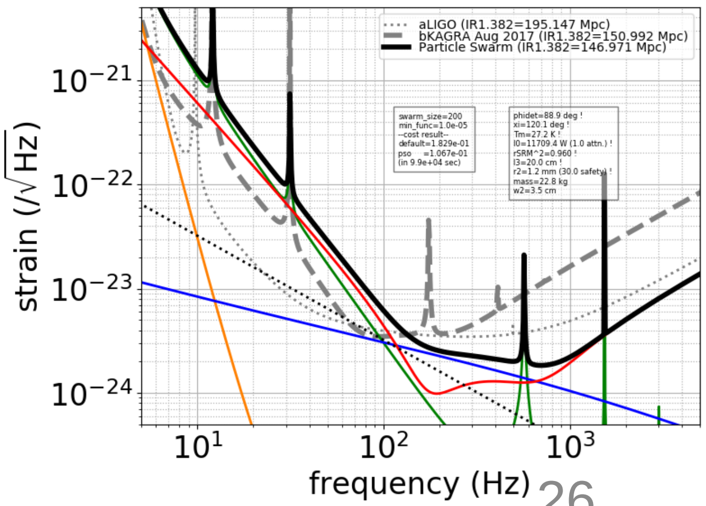


# Summary of Strategy Difference

- BNS inspiral range optimization
  - high detuning, high SRM reflectivity
  - shorter and thicker fiber
  - lower temperature to keep mirror thermal low

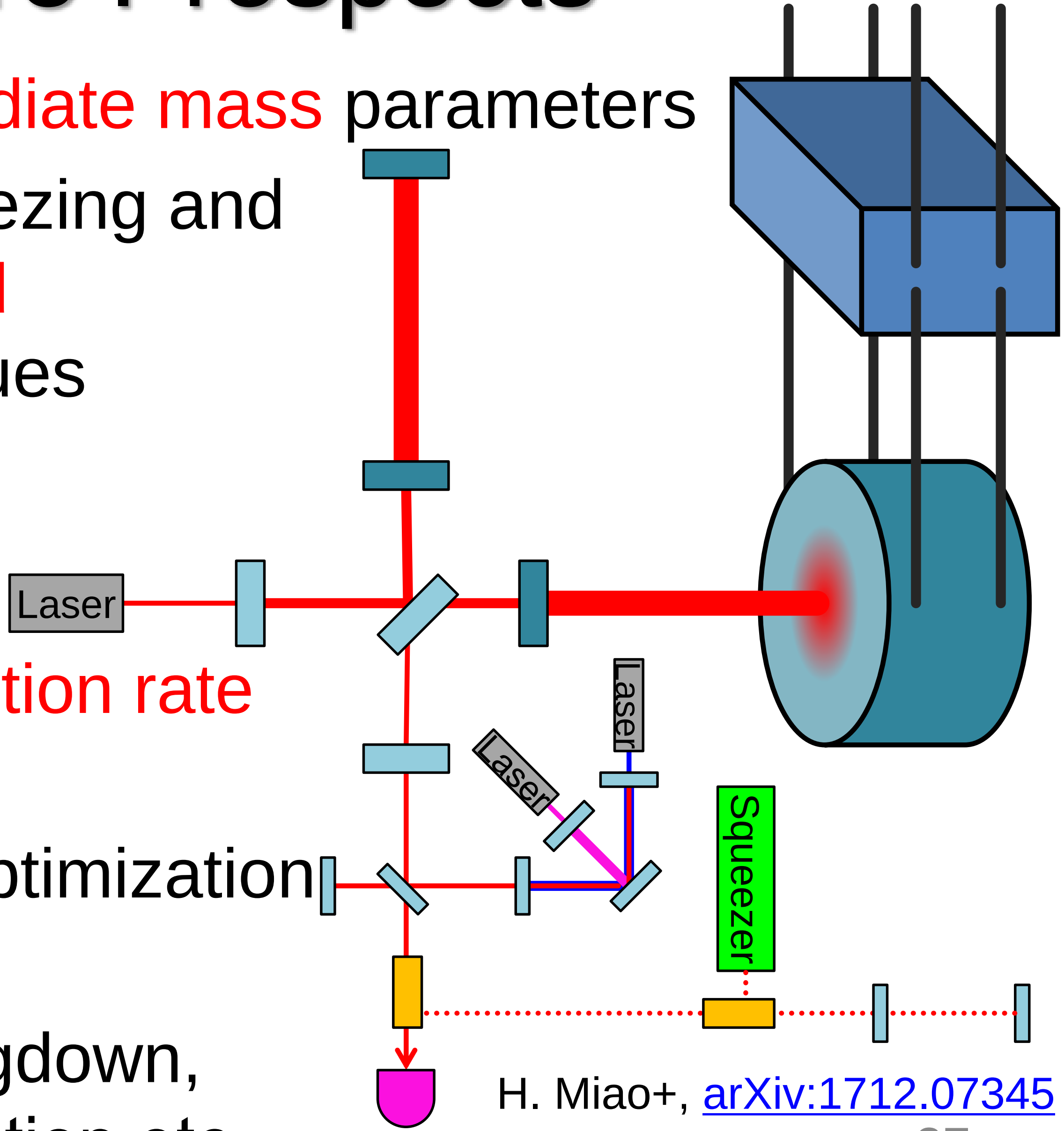



- BNS sky localization optimization
  - no detuning, conventional readout
  - shorter and thicker fiber
  - higher temperature to put more laser power



# 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, non-GR polarization 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)
```

xopt ↑ optimal parameter set

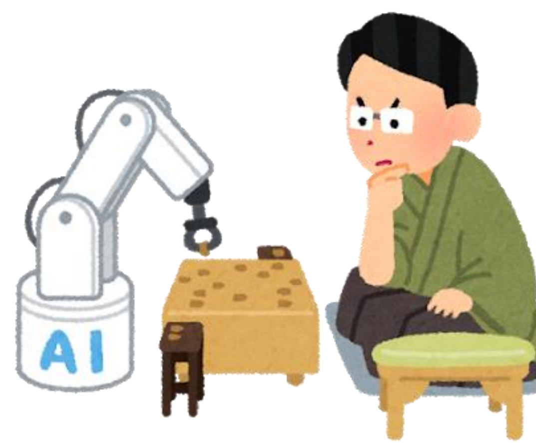
fopt ↑ optimal cost function

func ↑ cost function

lb, ub ↑ 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

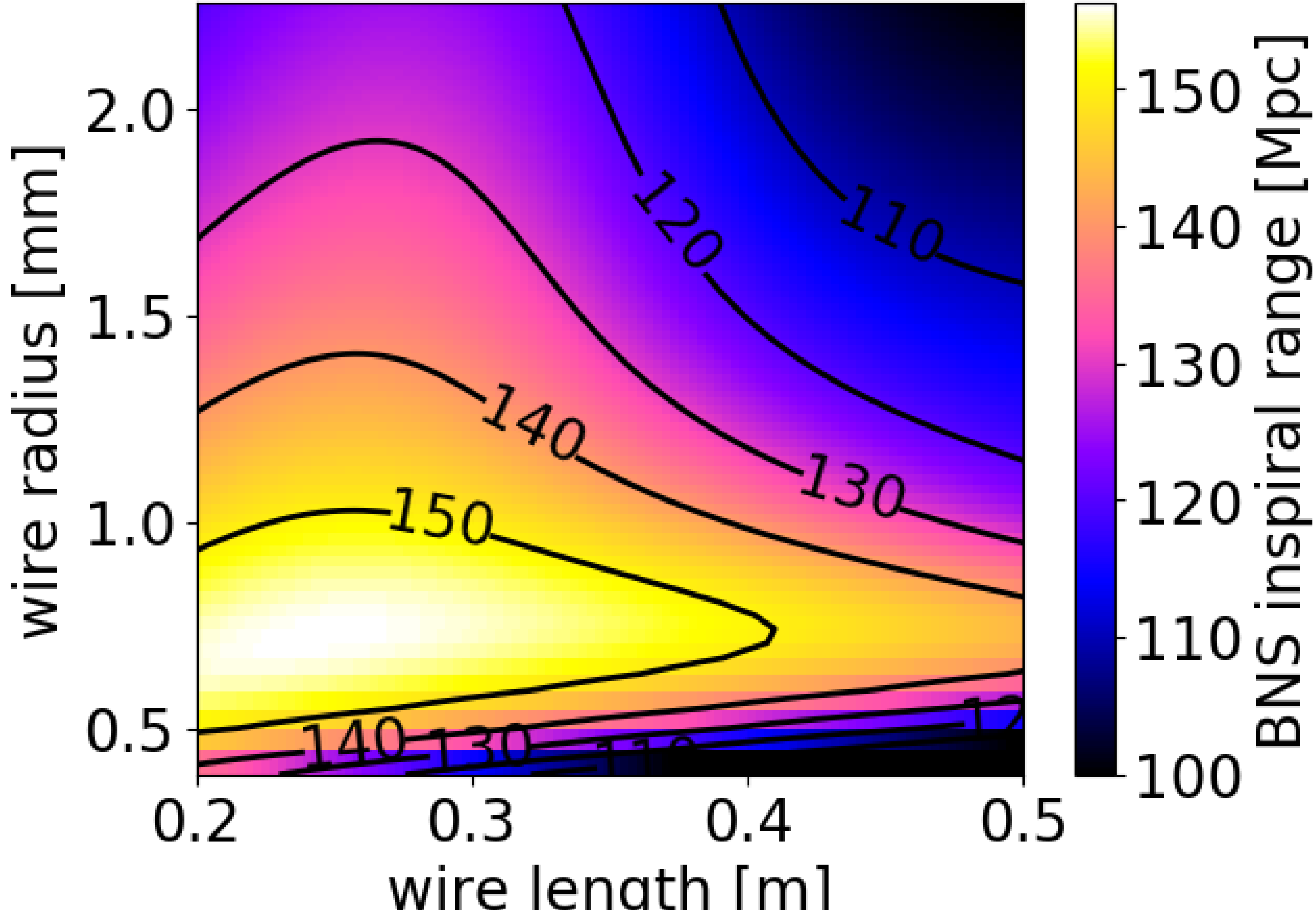
- *Reflecting wall* boundary:
  x=xmax, v=-v if x>xmax
  x=xmin, v=-v if x<xmin

# 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

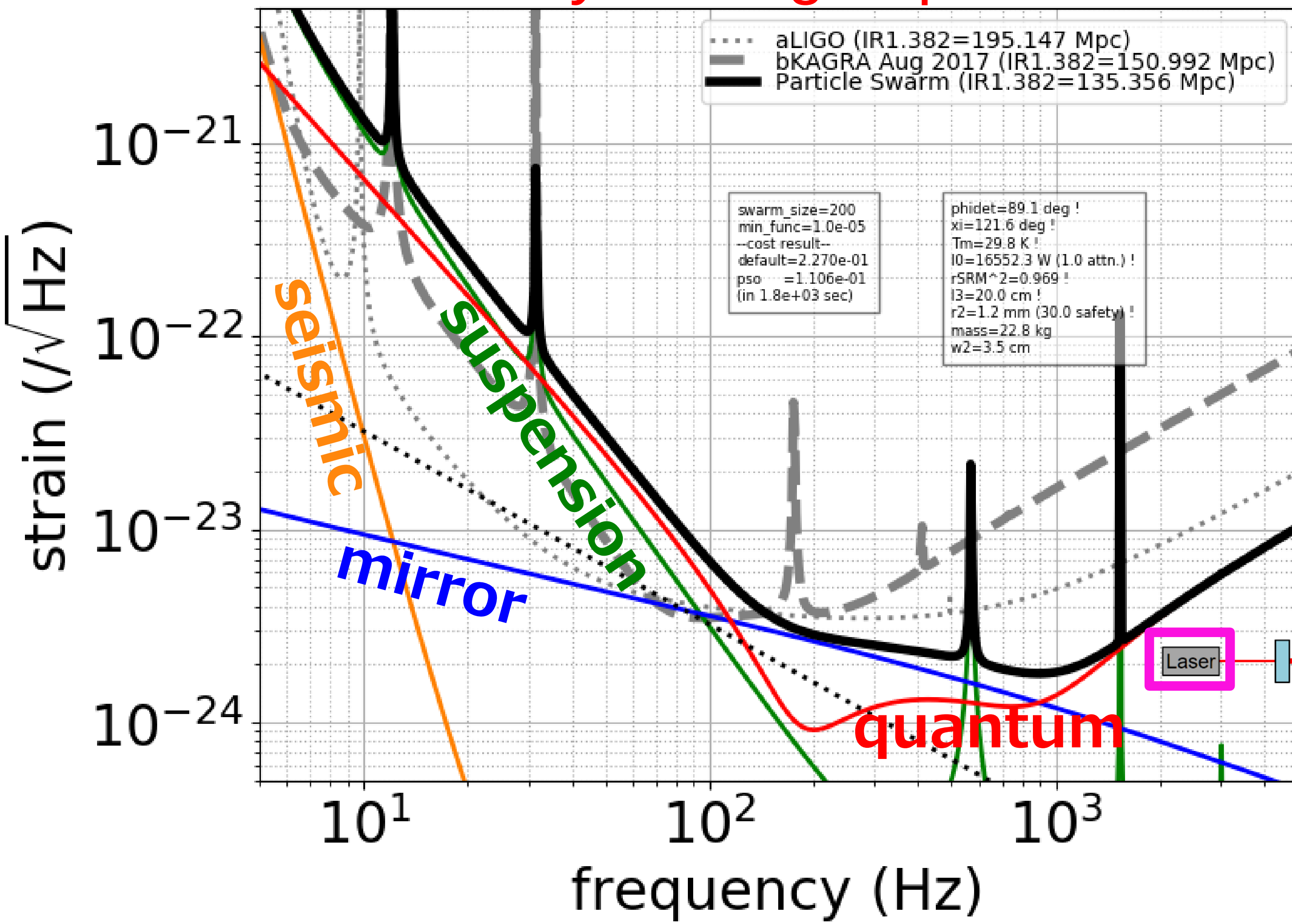
$$\sqrt{\langle(\delta\lambda^i \delta\lambda^j)\rangle} = \sqrt{(\Gamma^{-1})^{ij}}$$

- 11 binary parameters considered

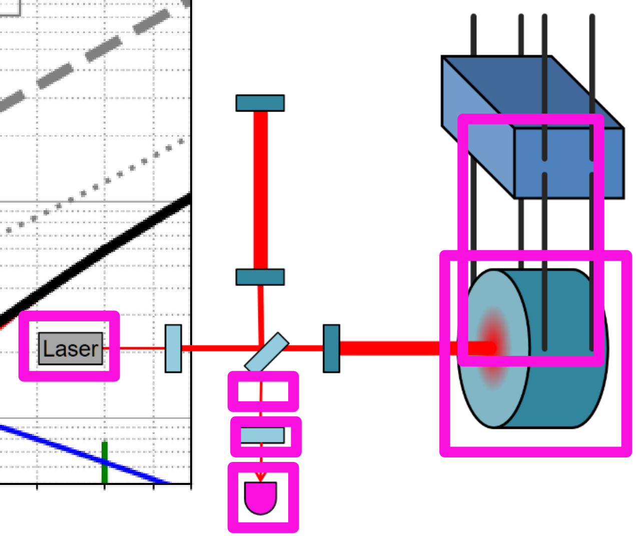
mc: chirp mass
eta: symmetric mass ratio
tc, phic: time and phase for coalescence
dL: luminosity distance
chis, chia: symmetric/asymmetric spin $\chi_{\mathrm{s/a}} = (\chi_1 \pm \chi_2)/2$
thetas, phis: colatitude / longitude of source
cthetai: inclination angle
psip: polarization angle

# Optimization for Fixed Sky Location

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



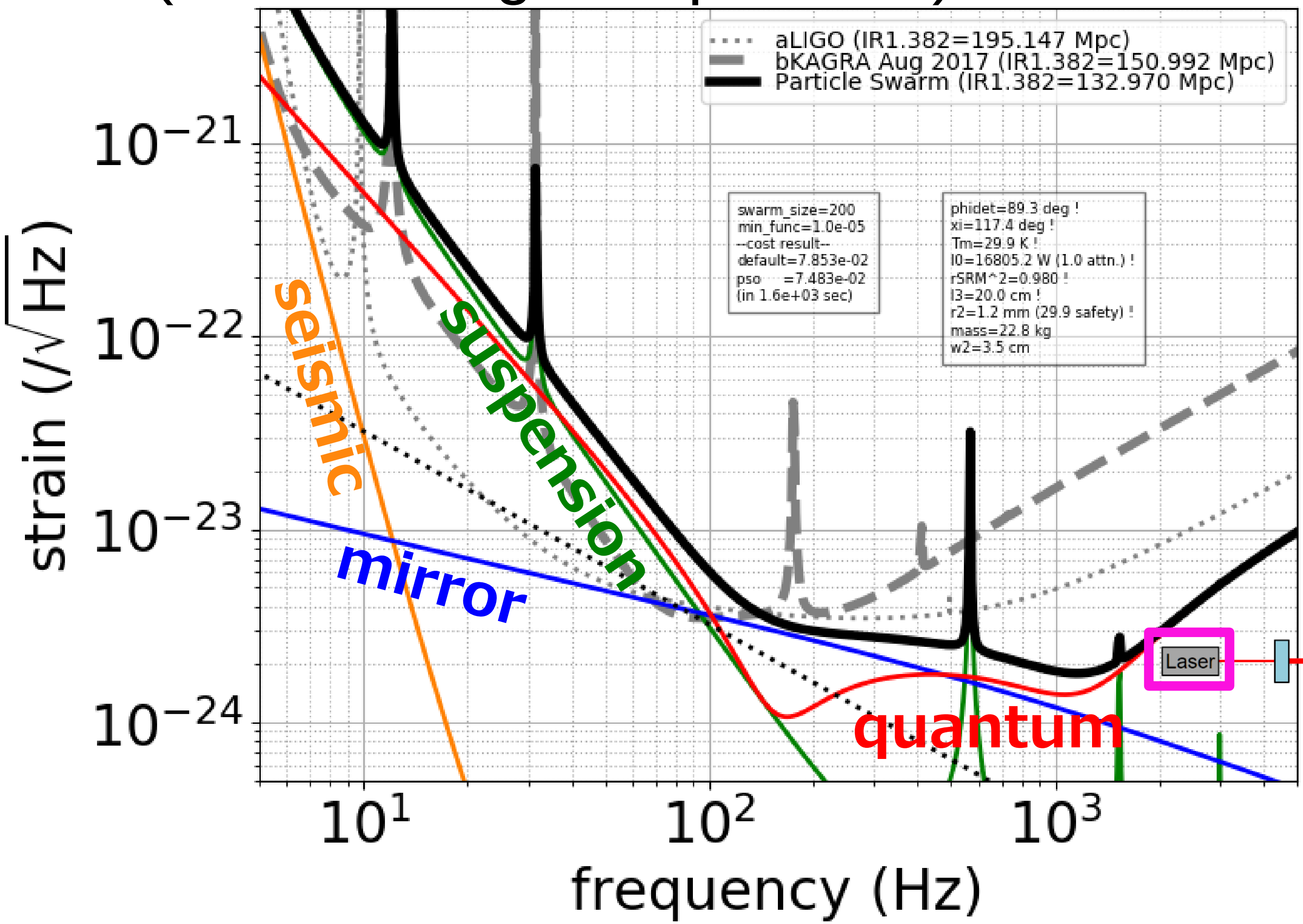

shortest and thickest fibers
1.7 kW at BS
30 K (max)



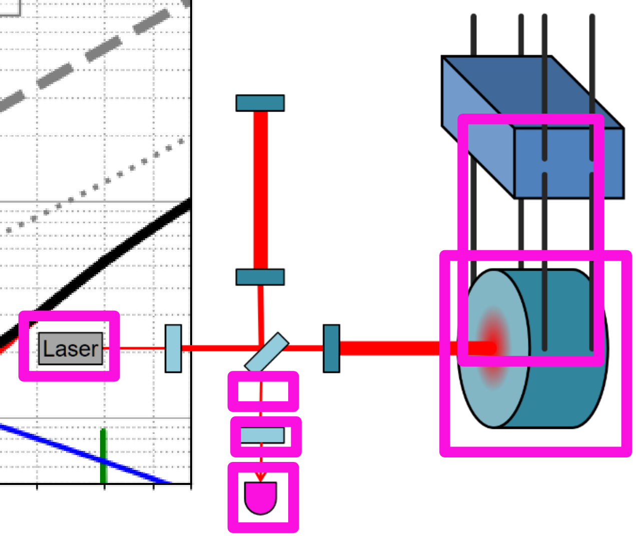
# Symmetric Spin Optimization

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

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



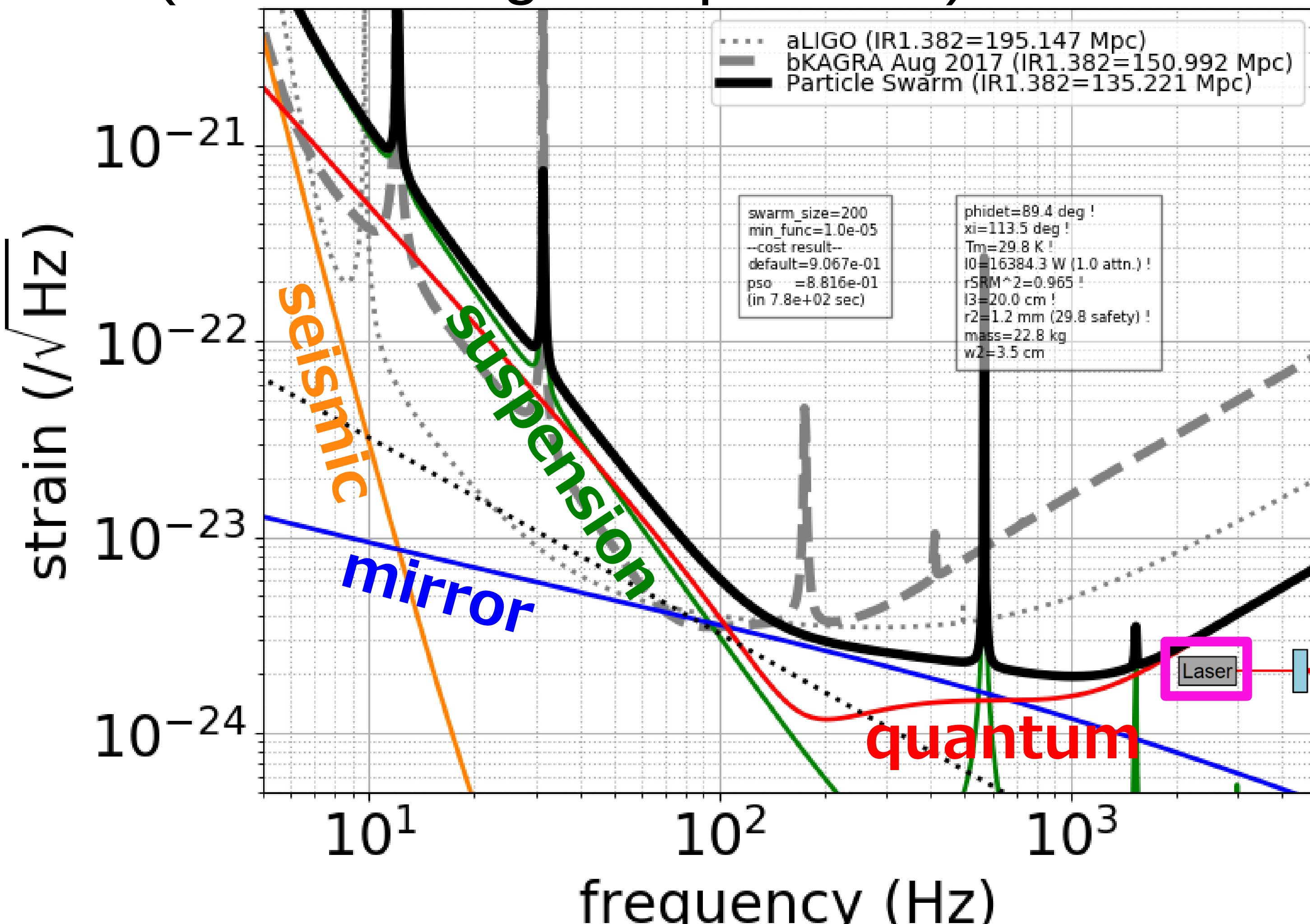

shortest and thickest fibers
1.7 kW at BS
30 K (max)



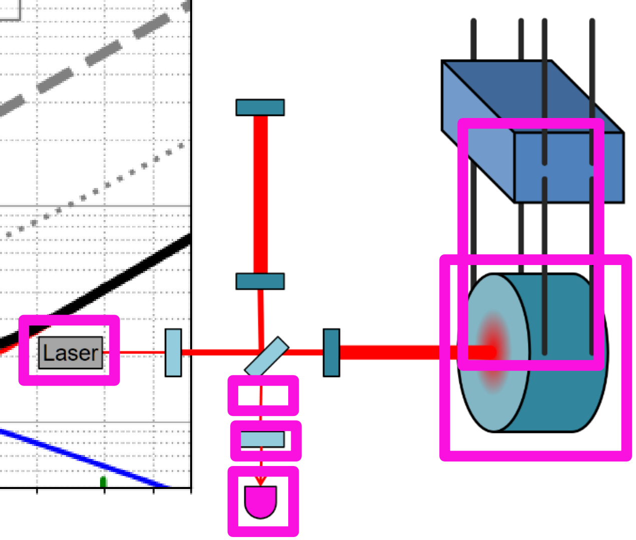
# Asymmetric Spin Optimization

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

$$\chi_a = \frac{\chi_1 - \chi_2}{2}$$

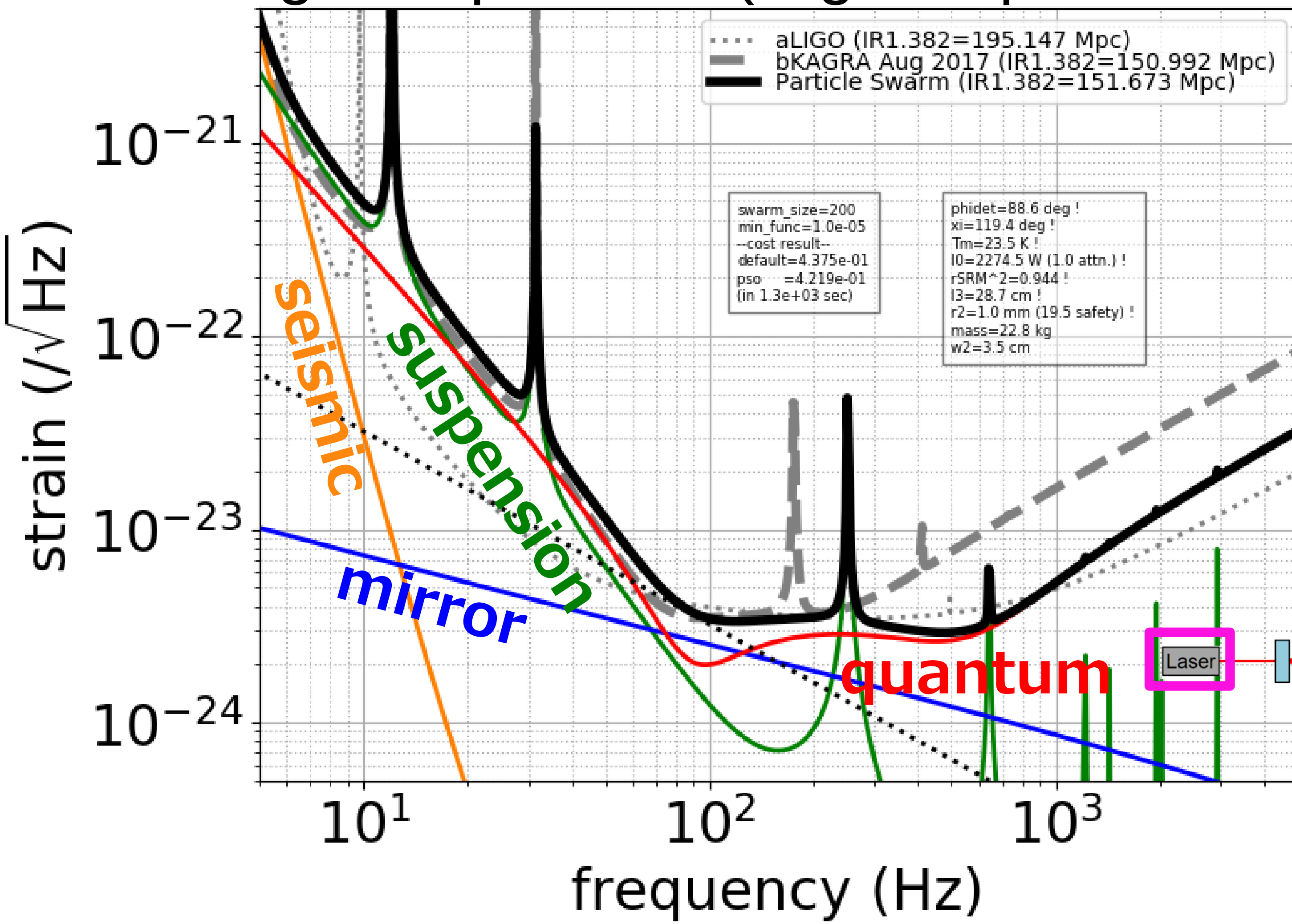



shortest and thickest fibers
1.7 kW at BS
30 K (max)

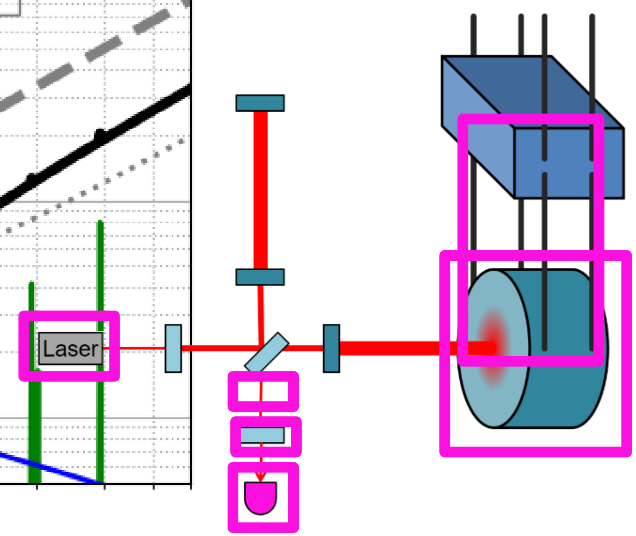


# Distance Optimization

- Similar to inspiral range optimization, but slight shift to high frequencies (slight improvement by 2%)

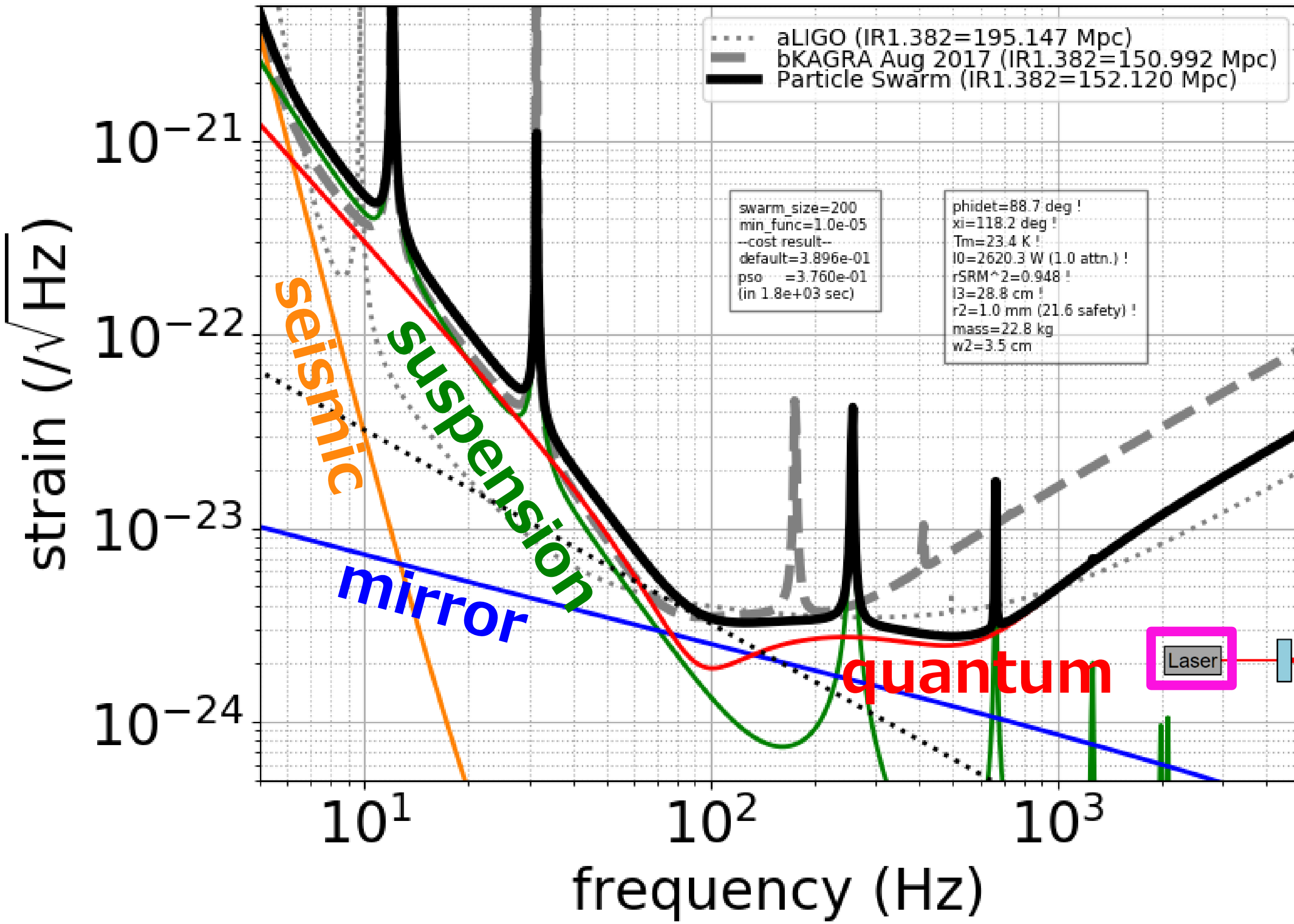



shorter and thicker fibers
2.3 kW at BS
24 K

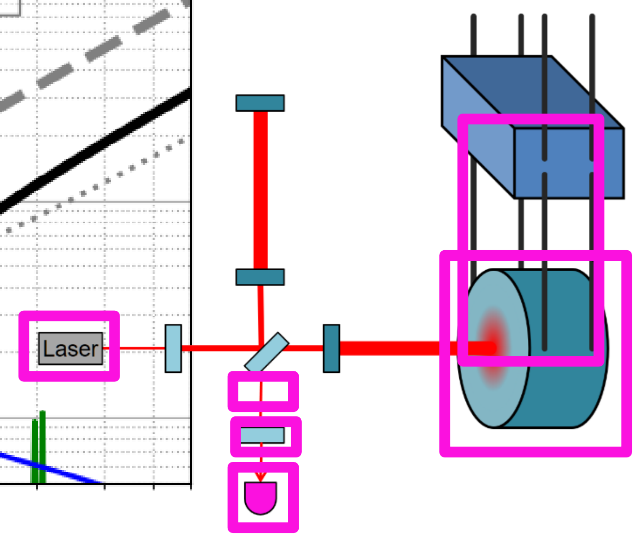


# Inclination Angle Optimization

- Similar to distance optimization (PE degeneracy)

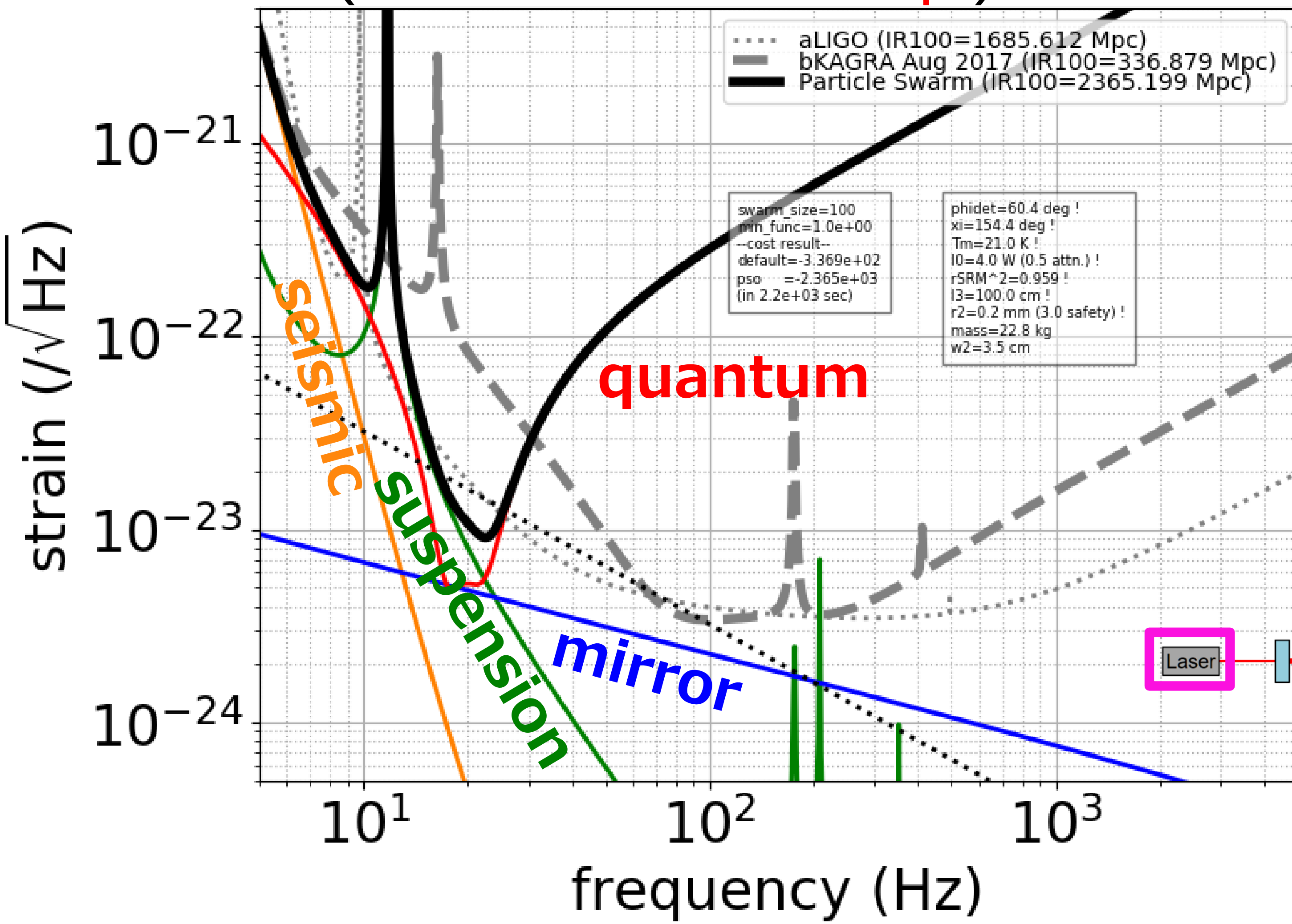



shorter and thicker fibers
2.3 kW at BS
24 K



# BBH100 IR Optimization

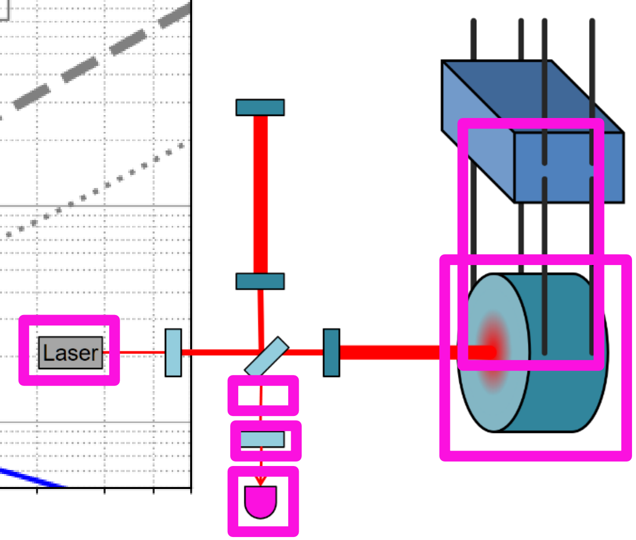
- Low power, low temperature with thin and longer fibers (KAGRA+ LF concept)



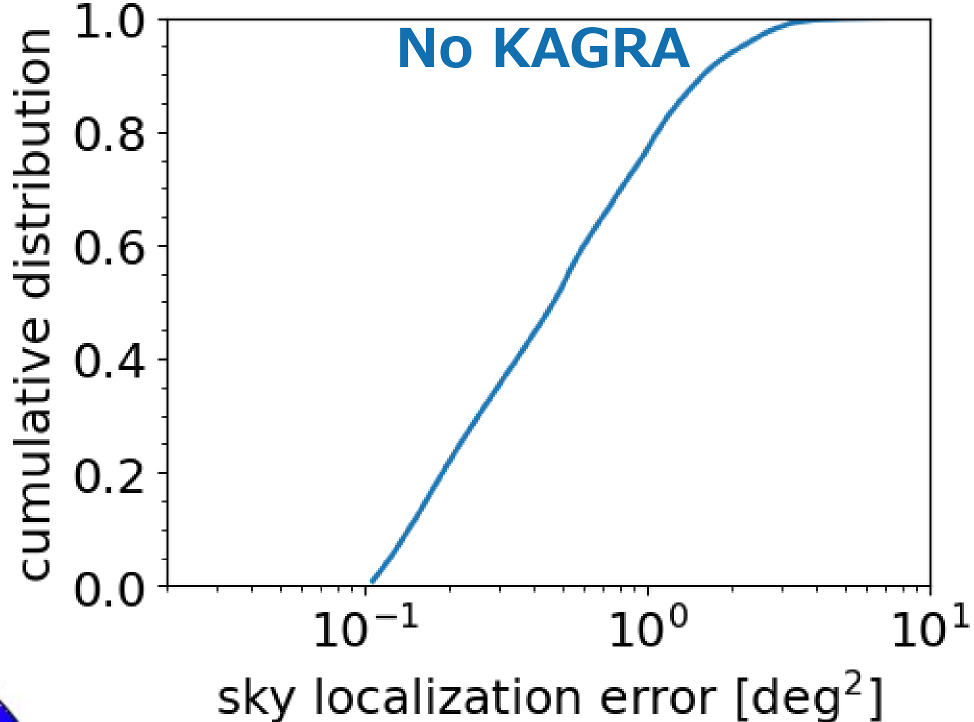

x4 heavier IM with thinner IM suspension

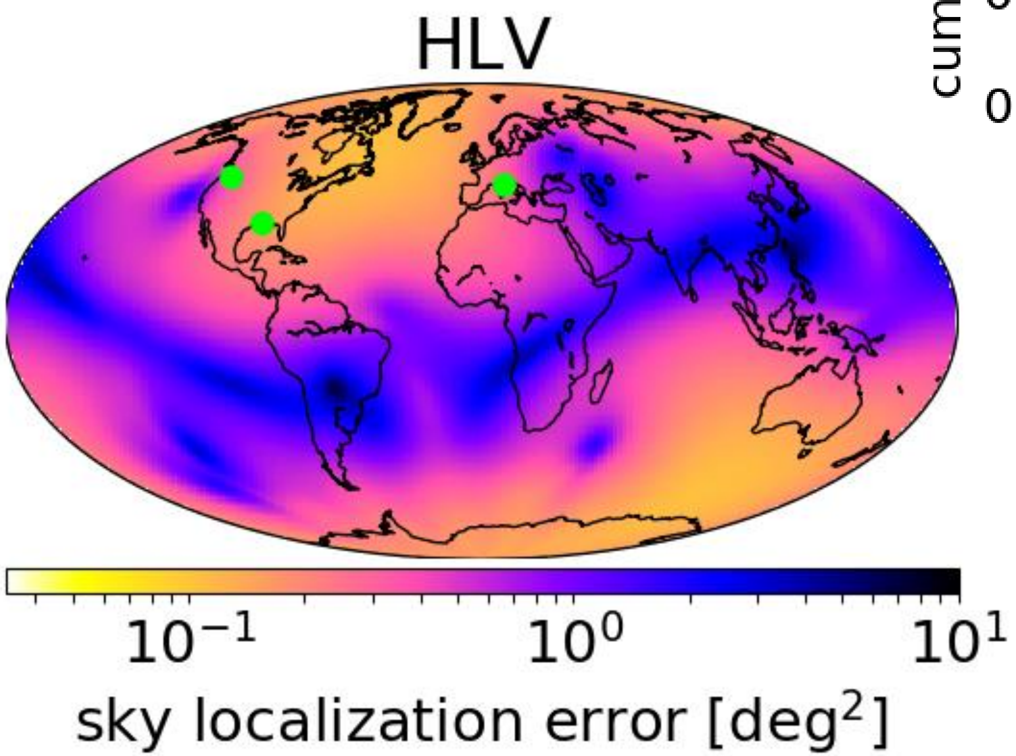
Less ambient heat

Allowed higher detuning



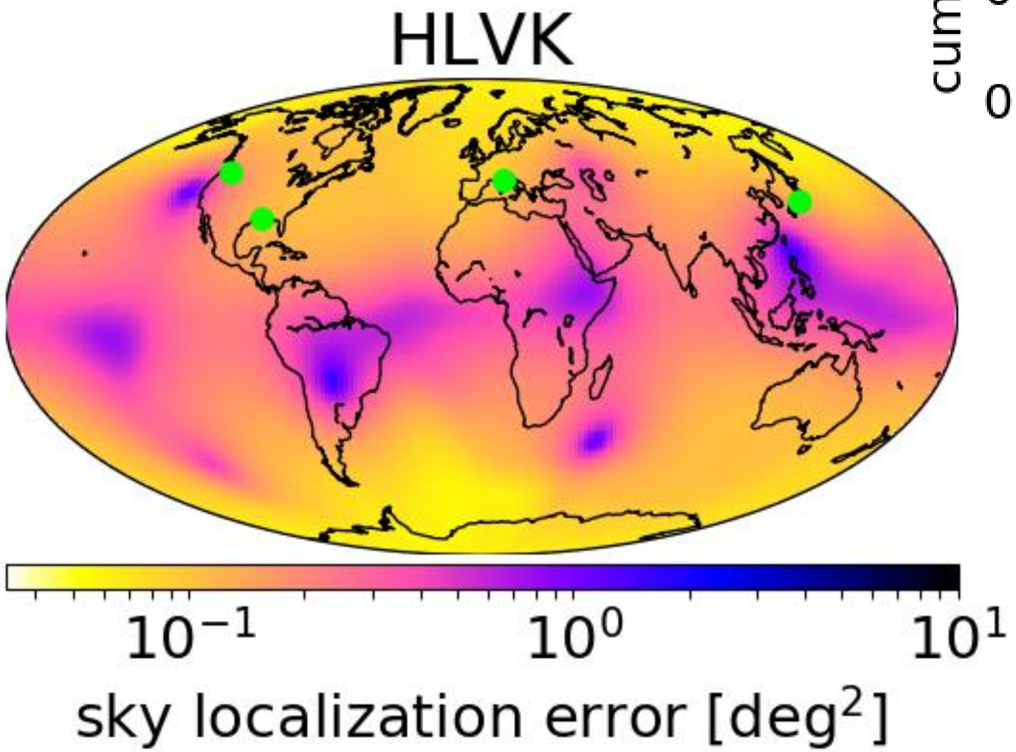
# Sky Localization with HLV

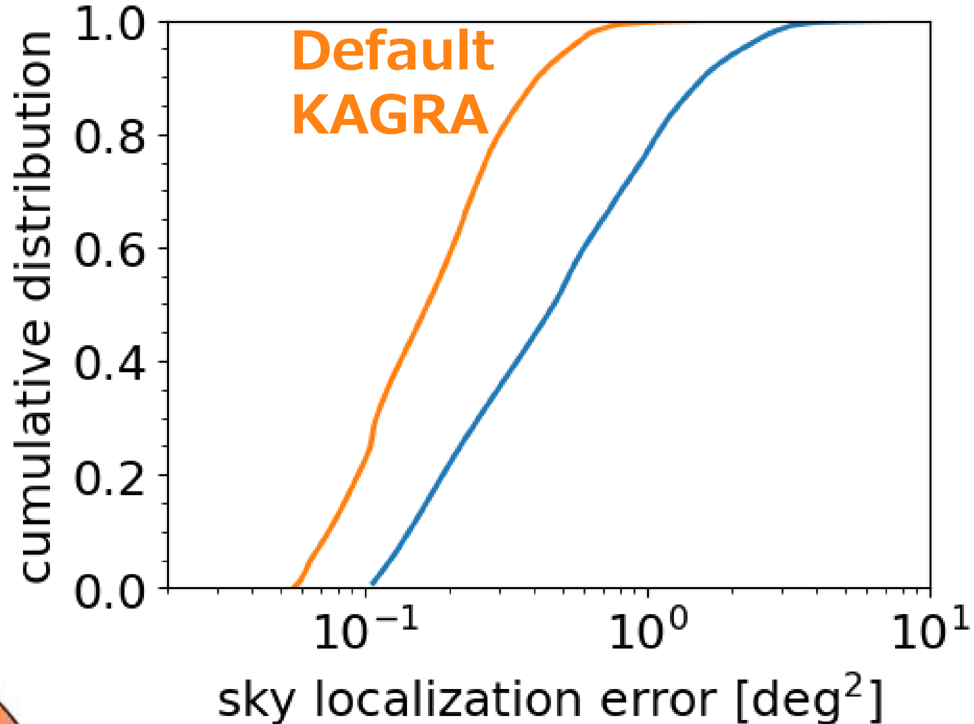



| | median |
|---|---|
| HLV | 0.472 deg$^2$ |
| HLVK | |
| HLVK+ | |

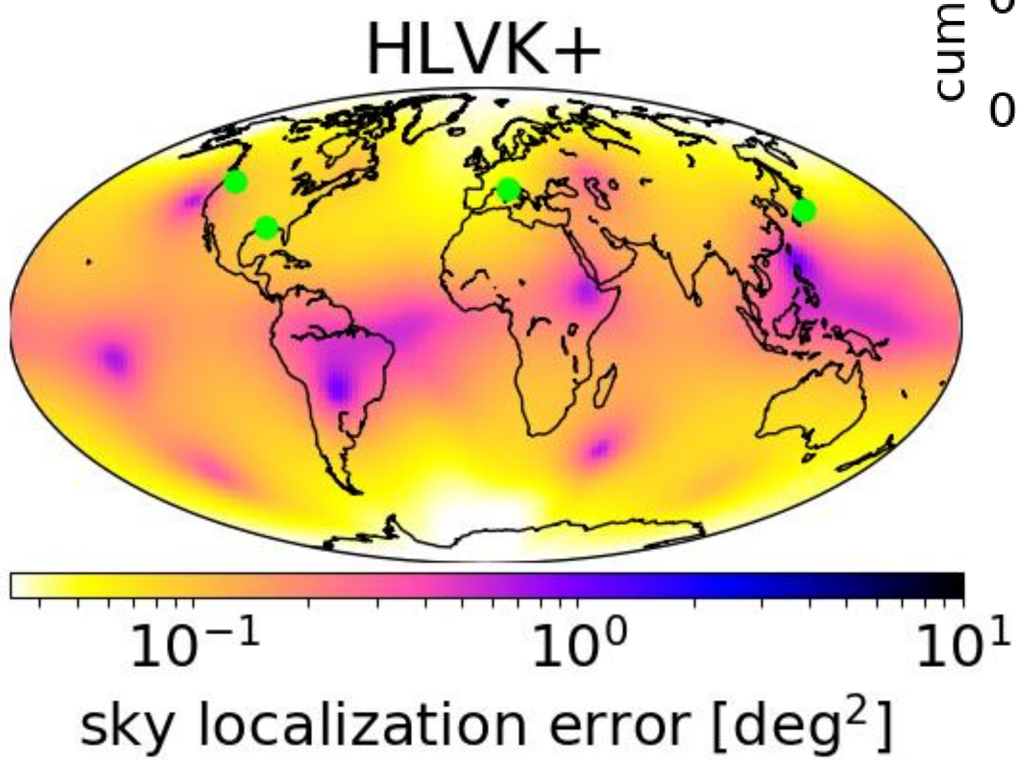
# Sky Localization with HLVK

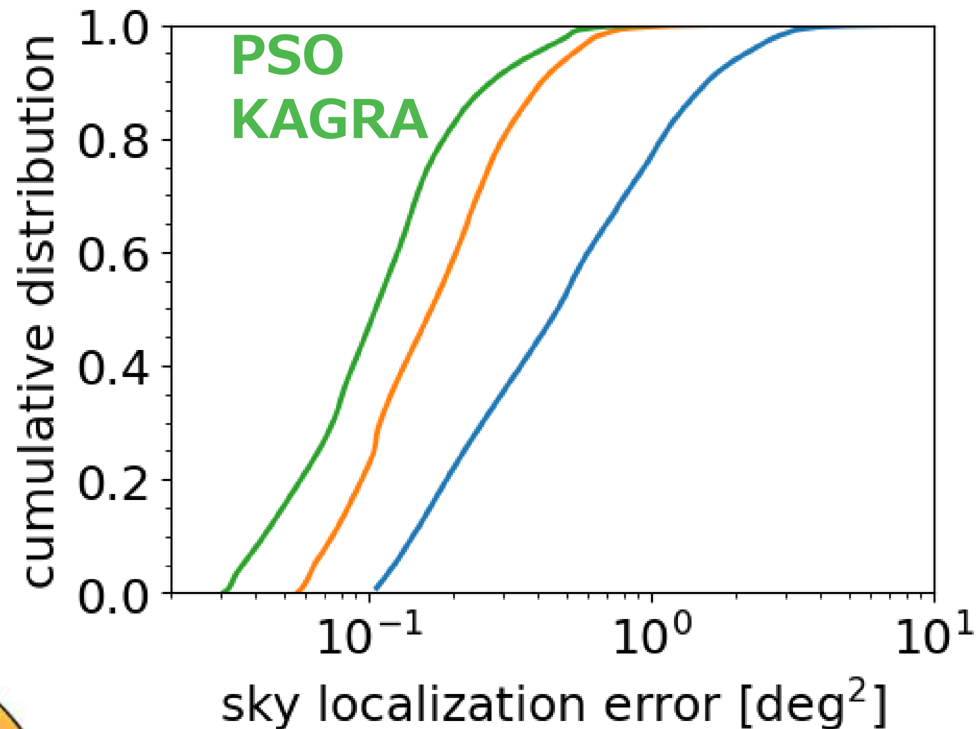



| | median |
|---|---|
| HLV | 0.472 deg$^2$ |
| HLVK | 0.168 deg$^2$ |
| HLVK+ | |

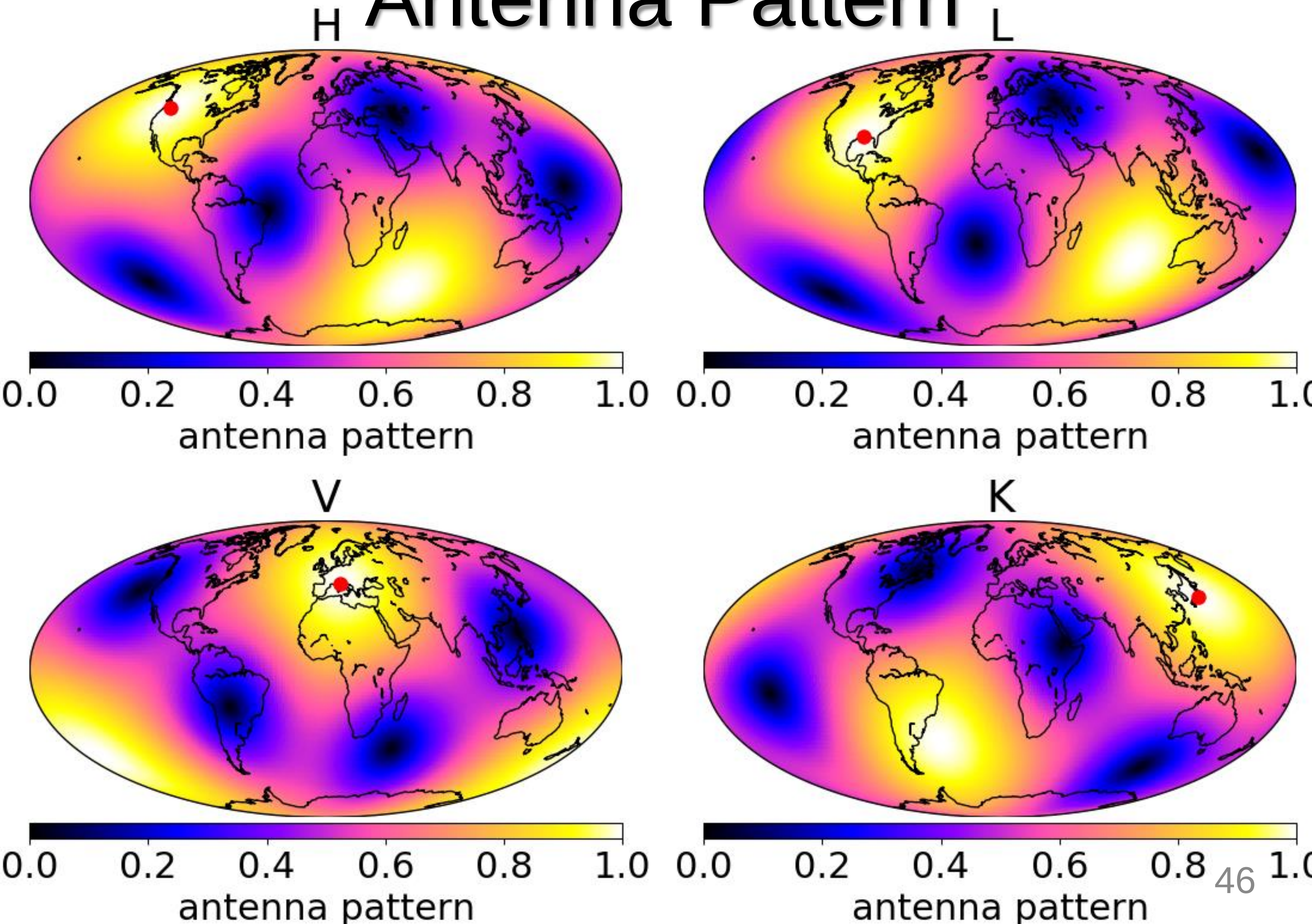
# Sky Localization with HLVK+




| | 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)

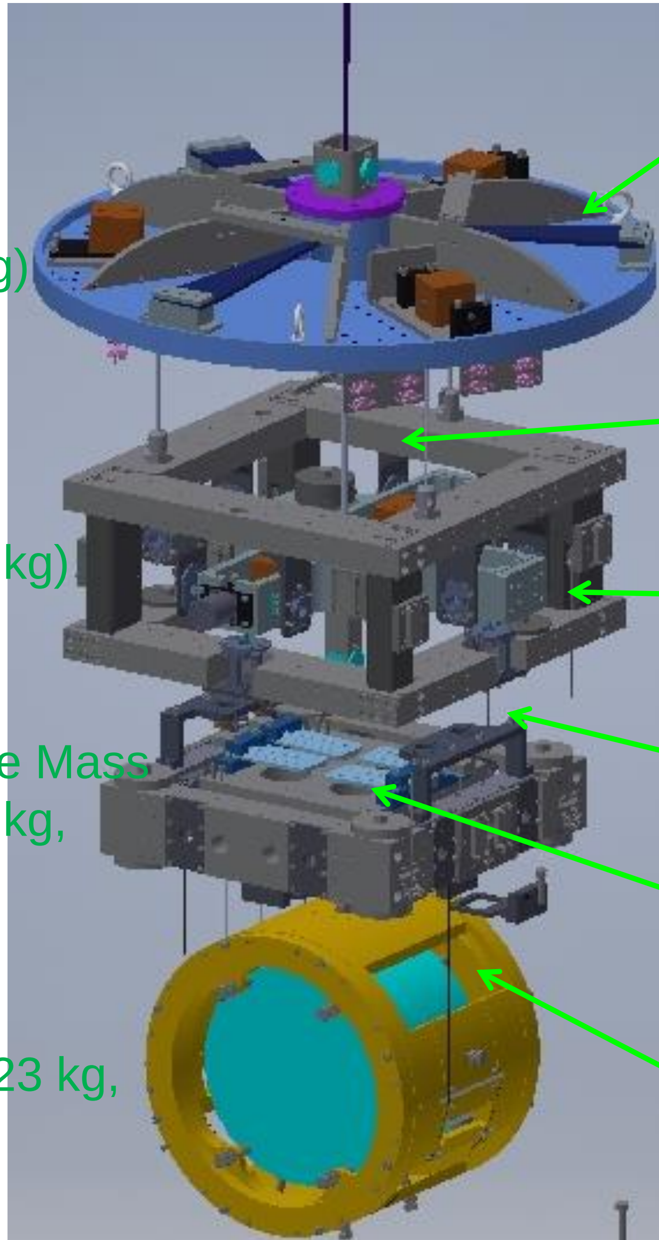
# KAGRA Detailed Parameters

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



Platform
(SUS, 65 kg)

Marionette
(SUS, 22.5 kg)

Intermediate Mass
(SUS, 20.1 kg,
16 K)

Test Mass
(Sapphire, 23 kg,
22 K)

3 CuBe blade springs

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

Heat link attached to MN

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

4 sapphire blades

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