Optimization of the KAGRA sensitivity

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Overview

- Developed a new way to optimize the KAGRA sensitivity design based on
  - CBC inspiral range
  - CBC parameter estimation

- Optimization done by Particle Swarm Optimizer YM+, [Phys. Rev. D 97, 122003 (2018)](#)

- Studied possible KAGRA+ candidates with budget constraints
  - 40 kg mirror
    with better coating
  - 400 W laser with squeezing
  - Frequency dependent
    squeezing

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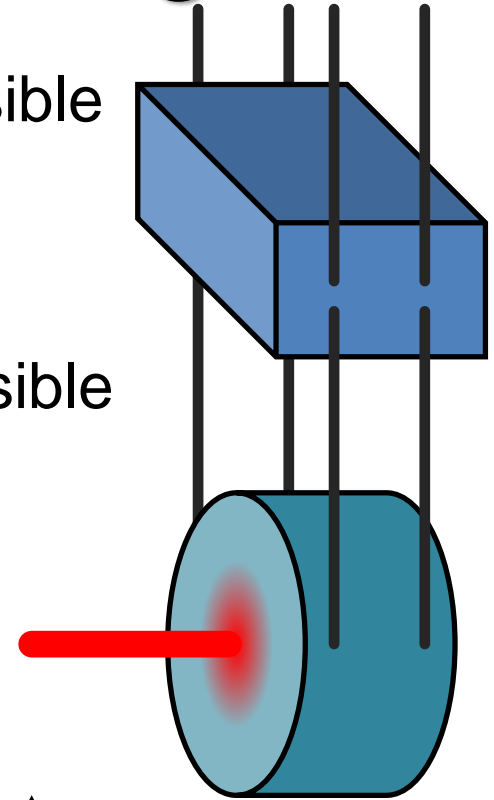
- Quantum noise: optimize the shape
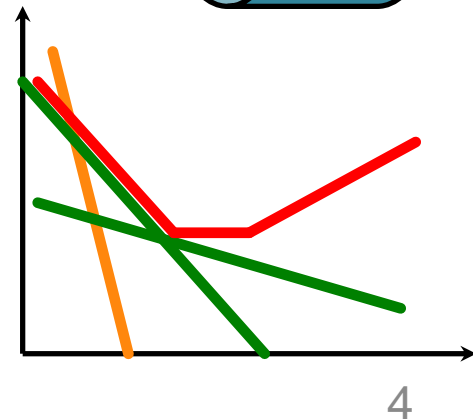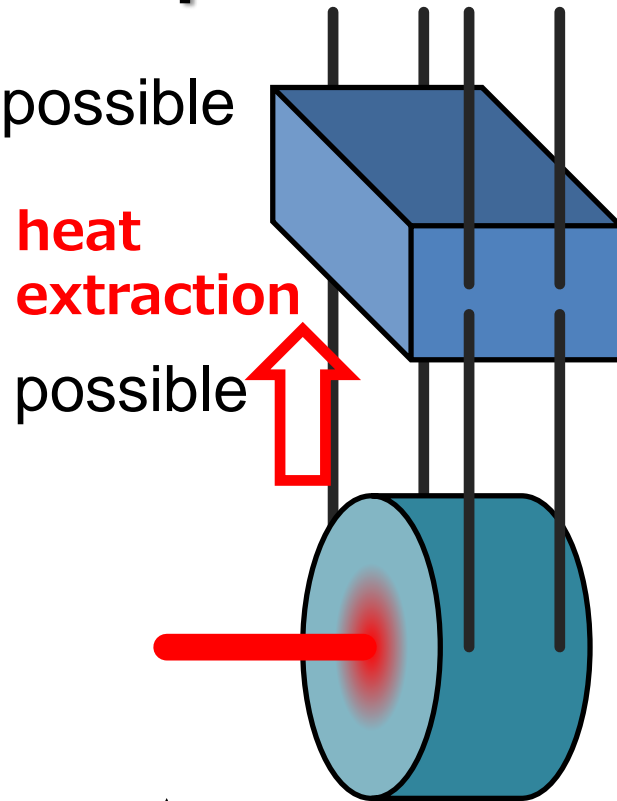 - input laser power
  - tune signal recycling parameters

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 fibers

  cryogenic cooling

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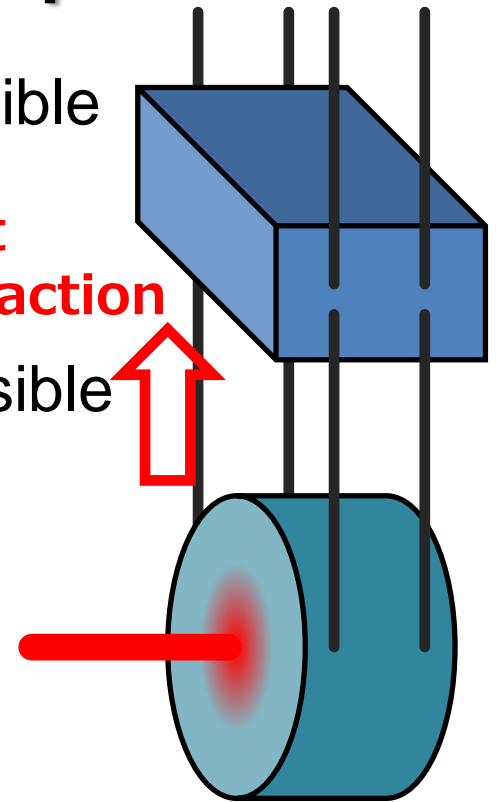
heat extraction

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 fibers

  cryogenic cooling

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

heat extraction

optimize

worse cooling power
mirror heating

Grid-based Search 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 (like KAGRA+) require more parameters to be optimized

- Almost impossible with grid-based approach

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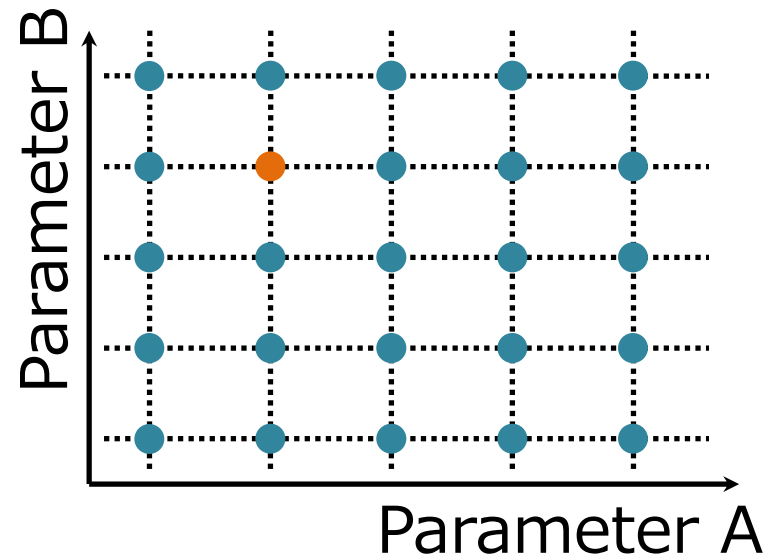
Particle Swarm Optimization!

- Particles search the parameter space based on own best position and entire swarm's best known position
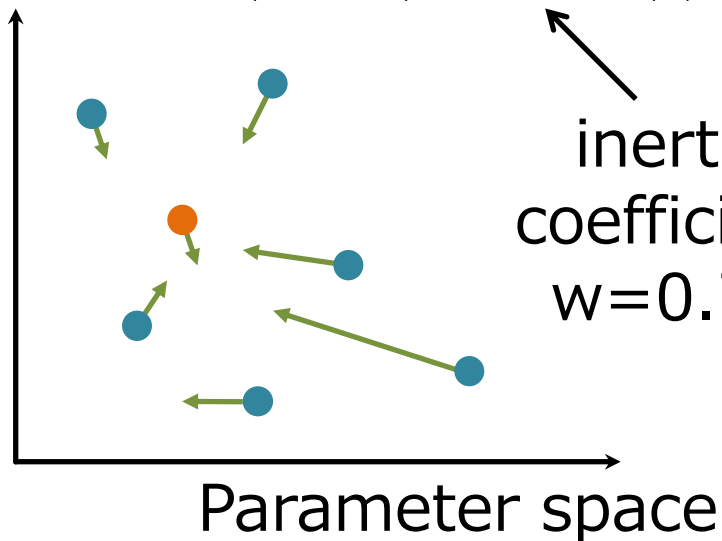
$$x_k(t+1) = x_k(t) + v_k(t)$$

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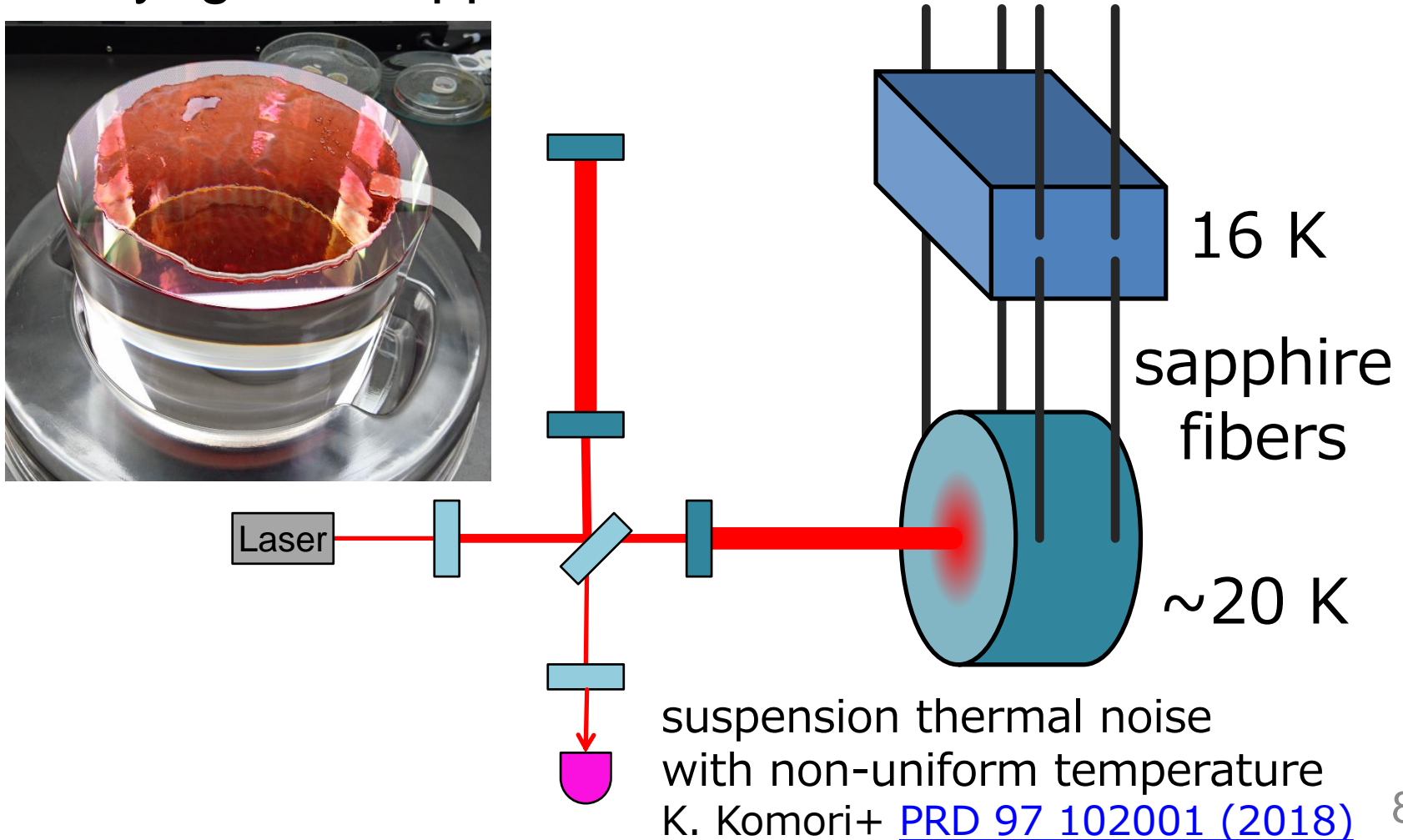
acceleration coefficient c=1.19
random number r ∈ [0,1]

Parameter space

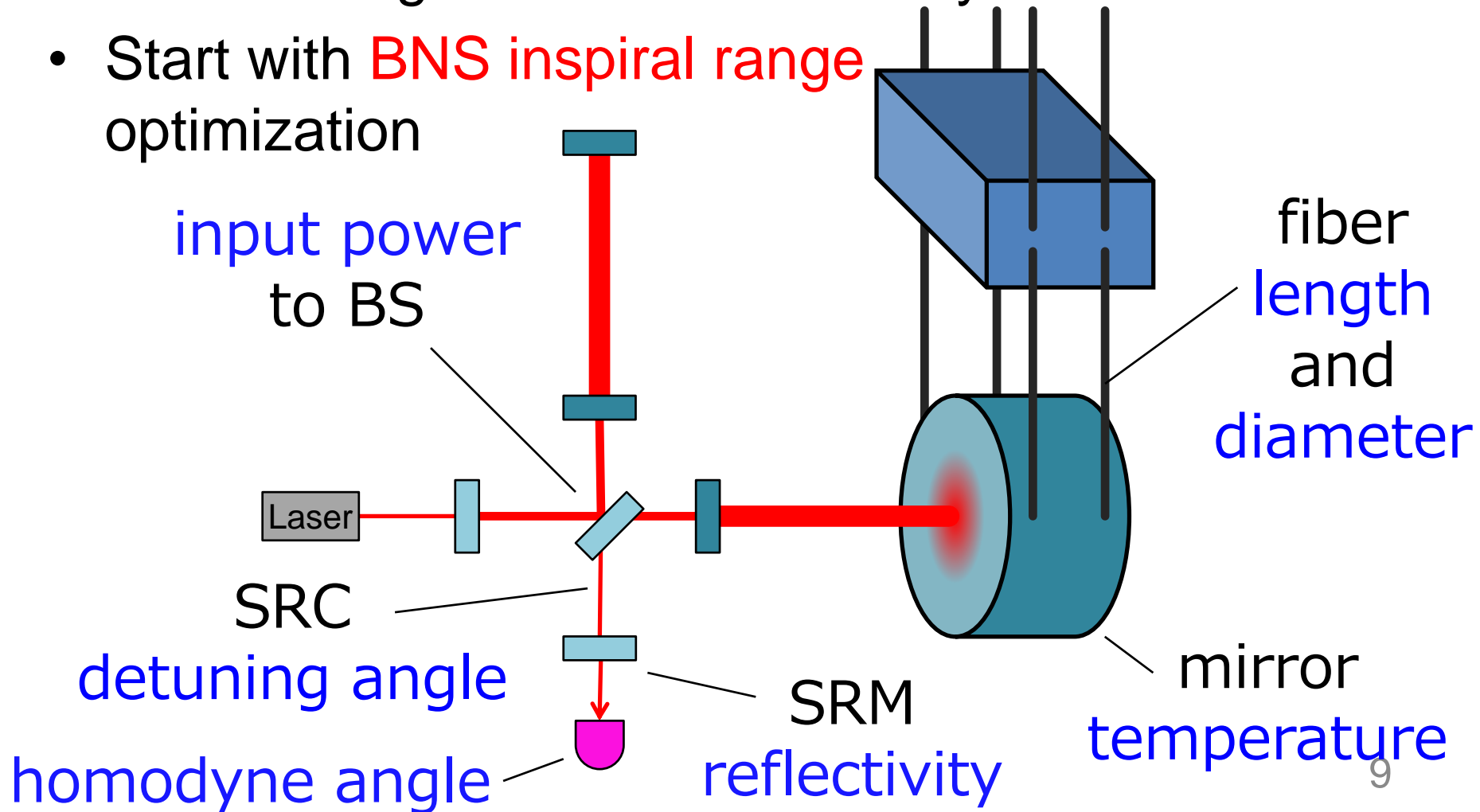Kennedy & Eberhart (1995)
values for w and c are from Standard PSO 2006

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Apply PSO for KAGRA Design

- RSE interferometer
- Cryogenic sapphire test masses

16 K

sapphire
fibers

~20 K

Laser

suspension thermal noise
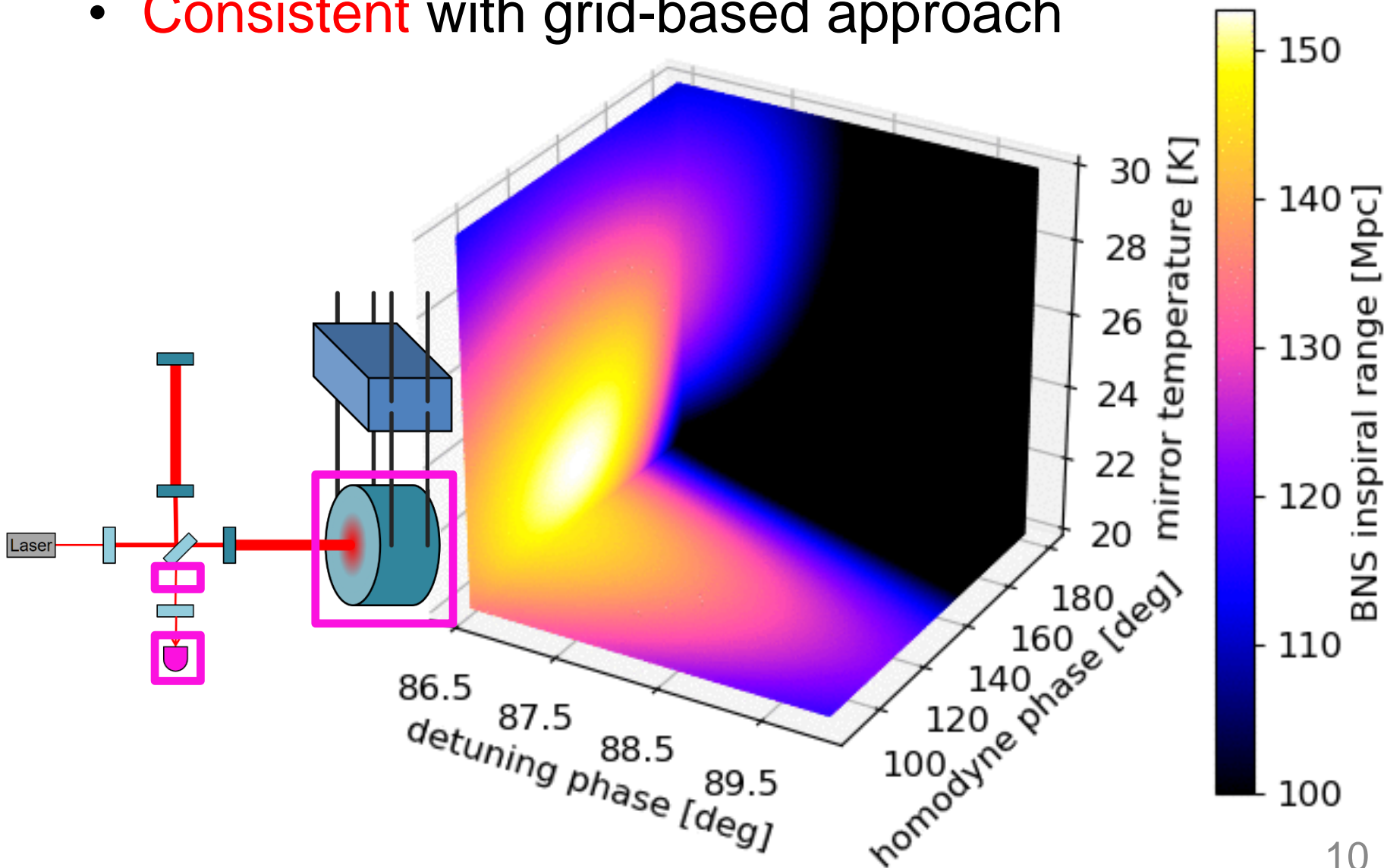with non-uniform temperature
K. Komori+ PRD 97 102001 (2018)

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Parameters of Interest

- 7 parameters are relatively easy to be retuned
- Search range based on feasibility
- Start with BNS inspiral range optimization

input power to BS

fiber length and diameter

Laser

SRC

detuning angle
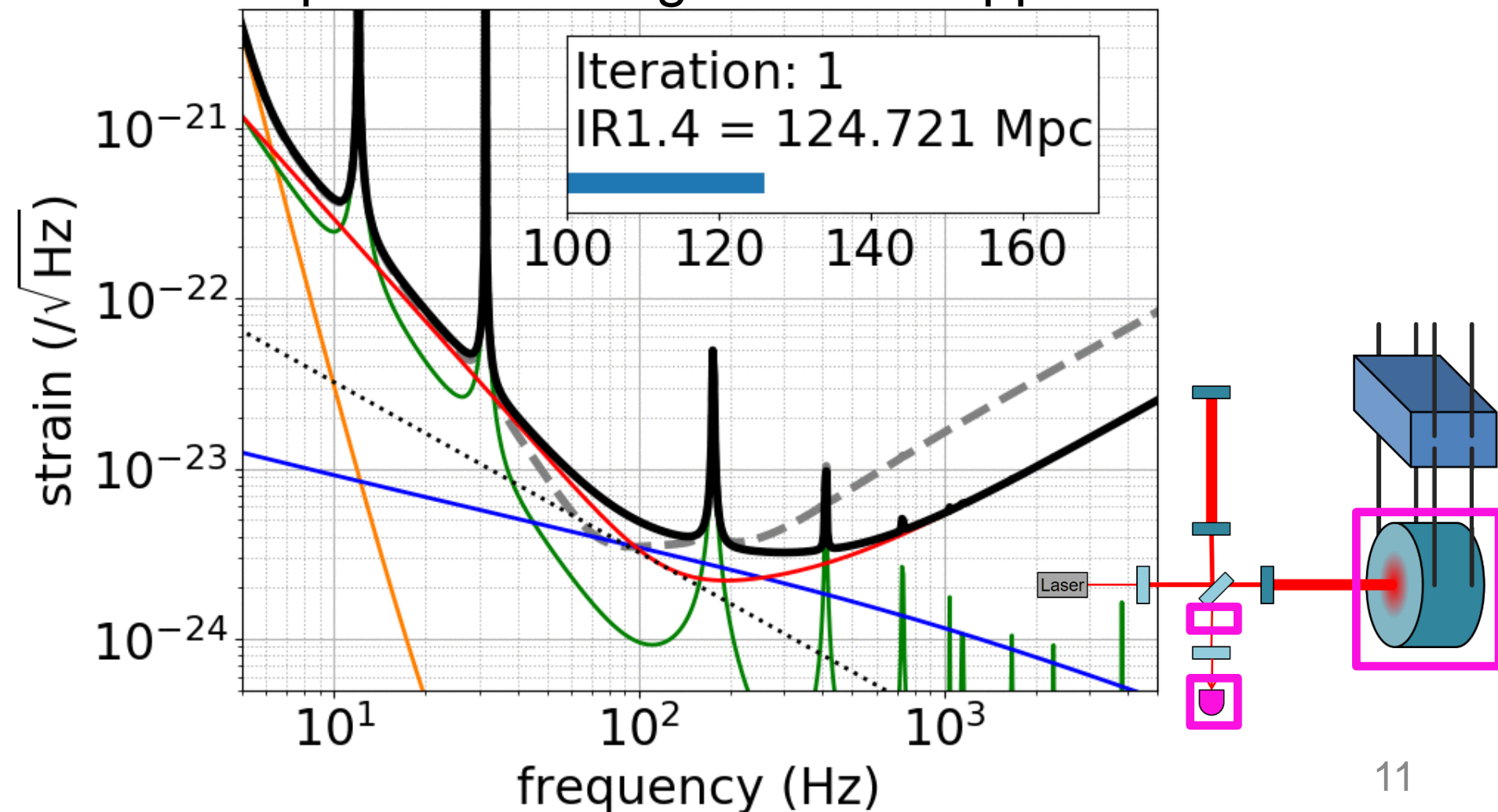
homodyne angle

SRM reflectivity

mirror temperature

3 Parameter Optimization

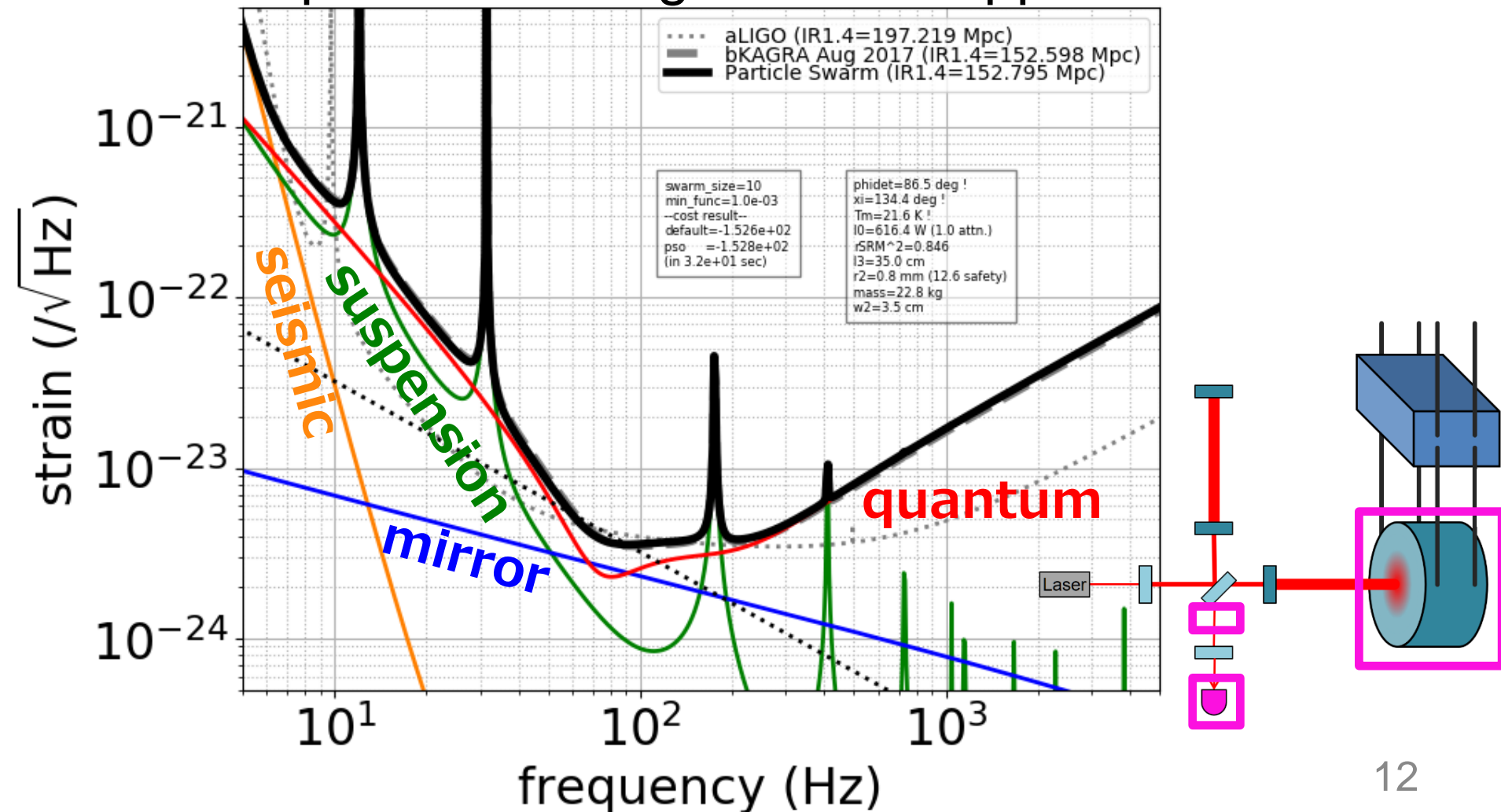- Consistent with grid-based approach

3 Parameter Optimization

- Consistent with current designed sensitivity which was optimized with grid-based approach
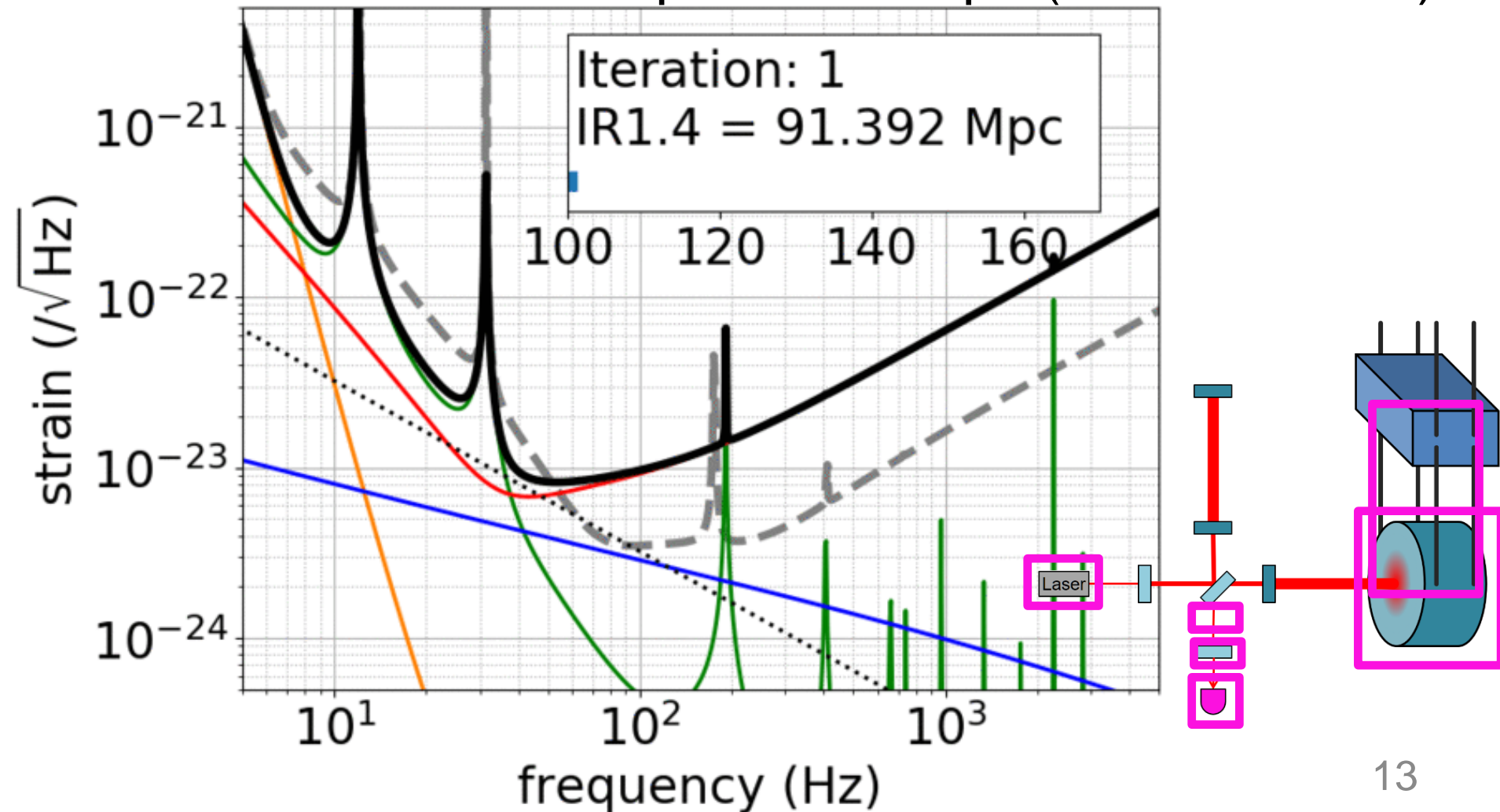
3 Parameter Optimization

- Consistent with current designed sensitivity which was optimized with grid-based approach
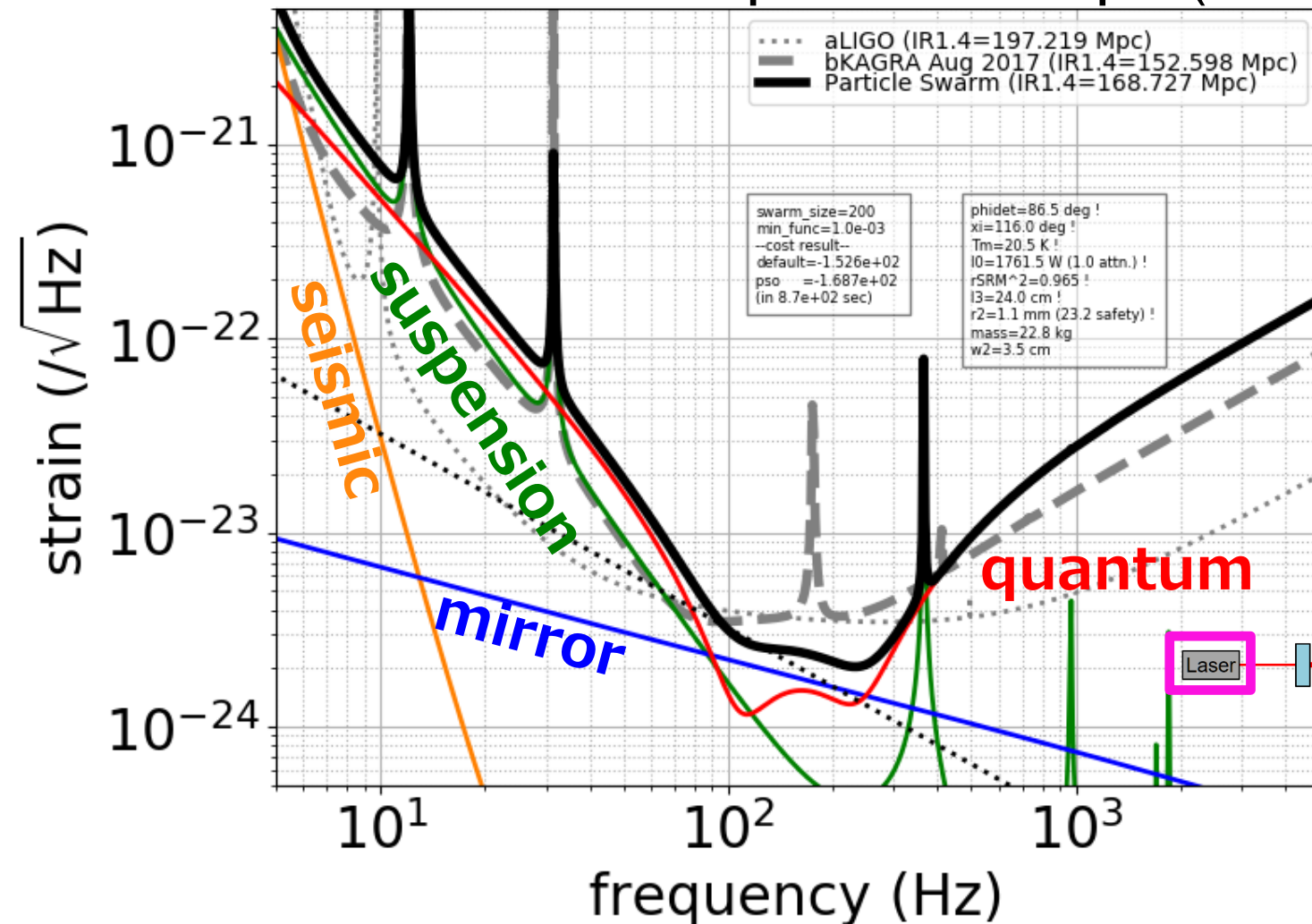
7 Parameter Optimization

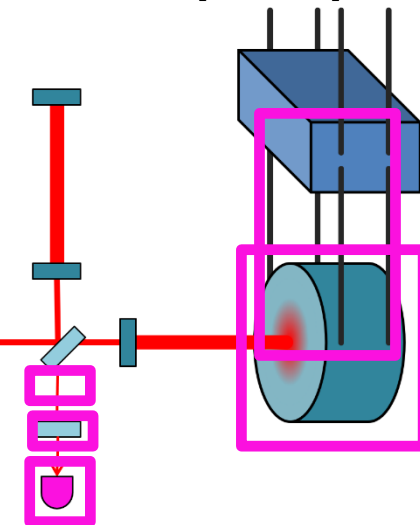- Changing suspension fibers and SRM increases BNS IR from 153 Mpc to 169 Mpc (10% increase)

7 Parameter Optimization

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

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	$10\times(52\pm13)$
5 params	~10^9	$20\times(73\pm16)$
7 params	~10^{14}	$200\times(60\pm18)$

* 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
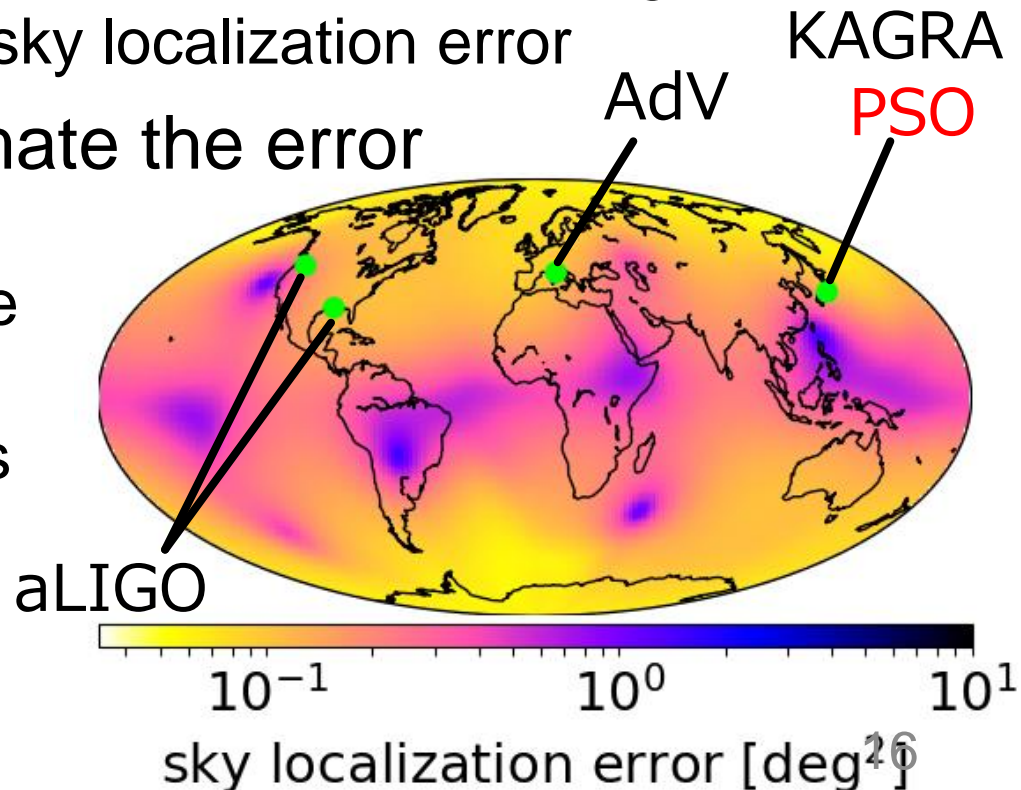
Sky Localization Optimization

- 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
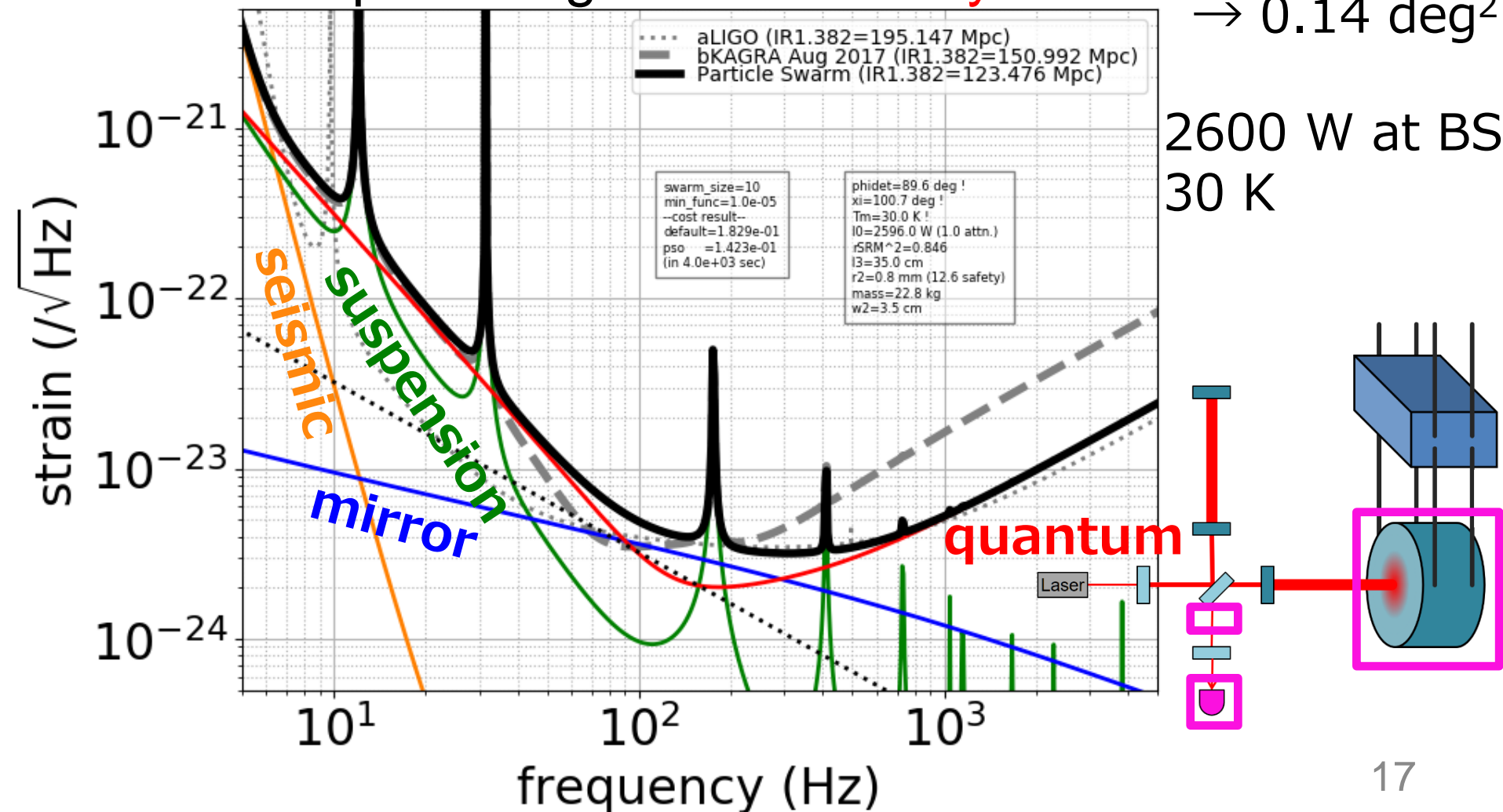
KAGRA

AdV

PSO

aLIGO

10^{-1} 10^0 10^1

sky localization error [deg^2]

3 Parameter Optimization

- Sky localization improved by a factor of 1.3 but inspiral range is reduced by 20%
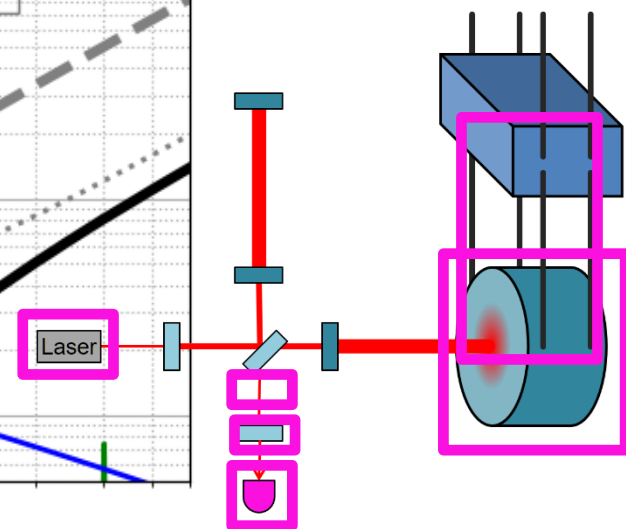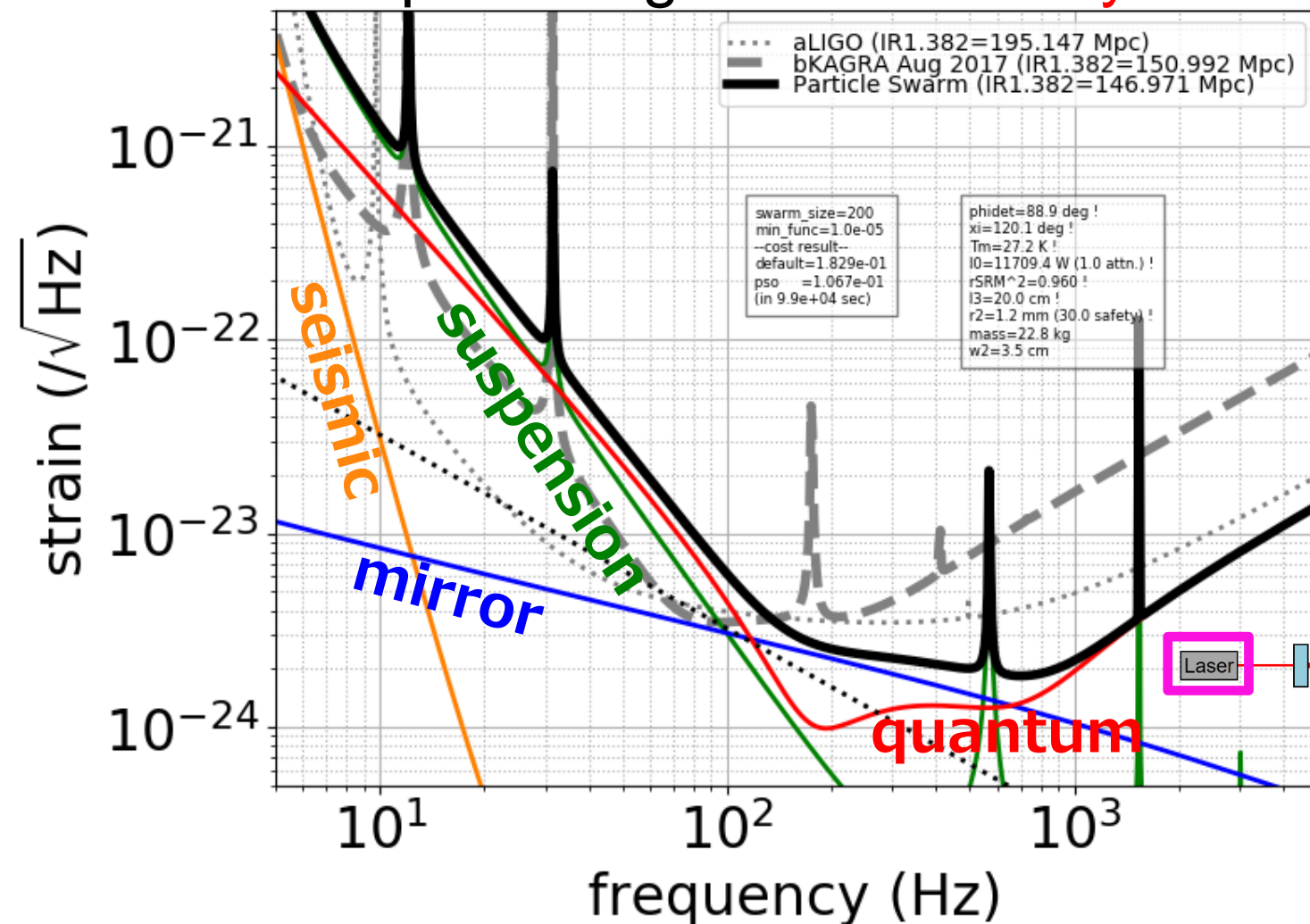
0.18 deg^2
→ 0.14 deg^2

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 deg^2 → 0.11 deg^2

shortest and thickest fibers 12 kW at BS 27 K

aLIGO (IR1.382=195.147 Mpc)
bKAGRA Aug 2017 (IR1.382=150.992 Mpc)
Particle Swarm (IR1.382=146.971 Mpc)

swarm_size=200
min_func=1.0e-05
--cost result--
default=1.829e-01
pso   =1.067e-01
(in 9.9e+04 sec)

phidet=88.9 deg !
xi=120.1 deg !
Tm=27.2 K !
I0=11709.4 W (1.0 attn.) !
rSRM^2=0.960 !
l3=20.0 cm !
r2=1.2 mm (30.0 safety) !
mass=22.8 kg
w2=3.5 cm

seismic

suspension

mirror

quantum

Laser

KAGRA+ with Budget Constraints

- Let's consider a bit more realistic upgrades
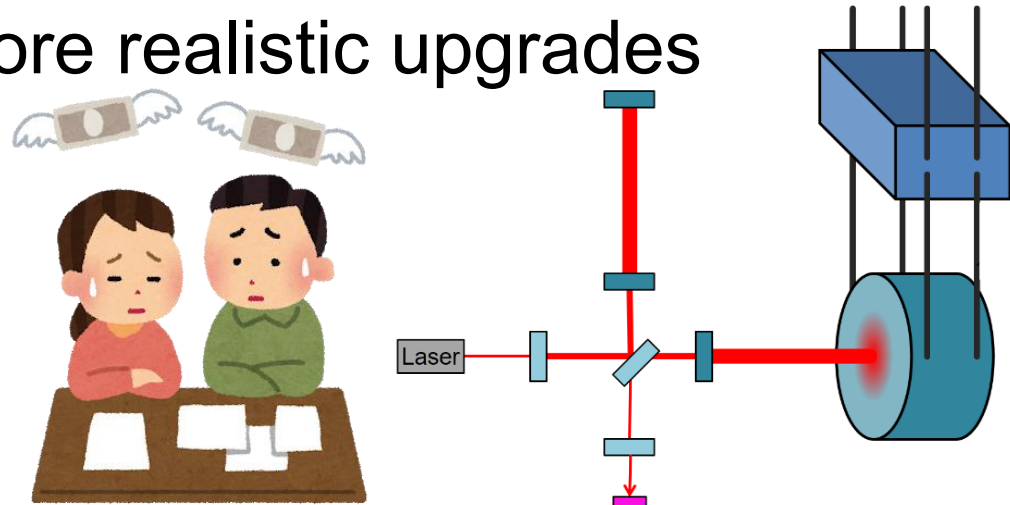
- Suppose you have $5M for KAGRA+

- Candidates would be

  A. 40 kg mirror with better coating (>$4M?)

  and new sapphire fibers ($1M?)
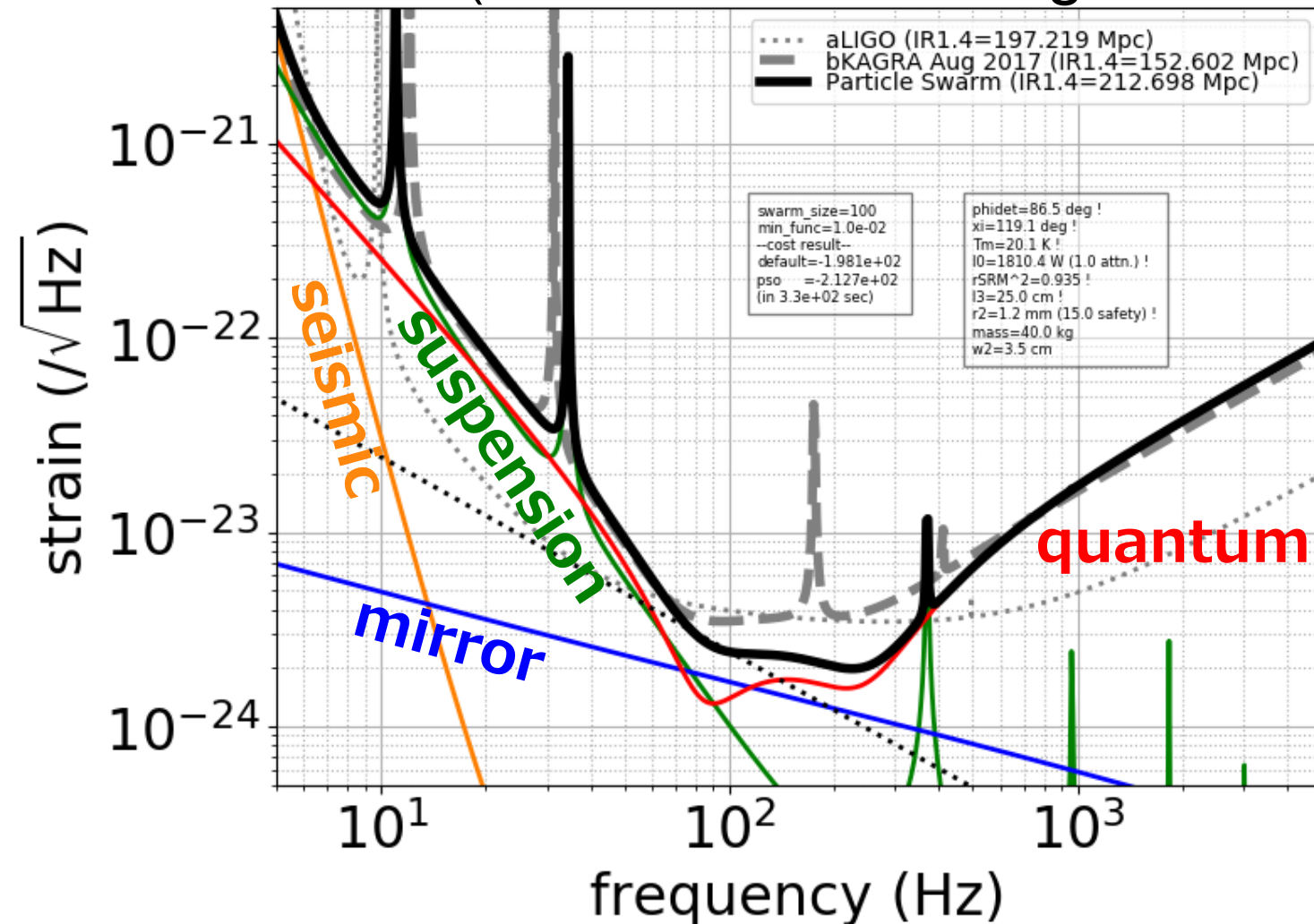
  (use existing cryostat and Type-A tower)

  B. 400 W laser ($3M?) with squeezing ($1M?)

  and new sapphire fibers ($1M?)

  C. Frequency dependent squeezing ($3M?)
  and new sapphire fibers ($1M?)

Plan A: 40 kg Mirror

- Also assumes factor of 2 coating thermal noise reduction (no beam size change assumed)
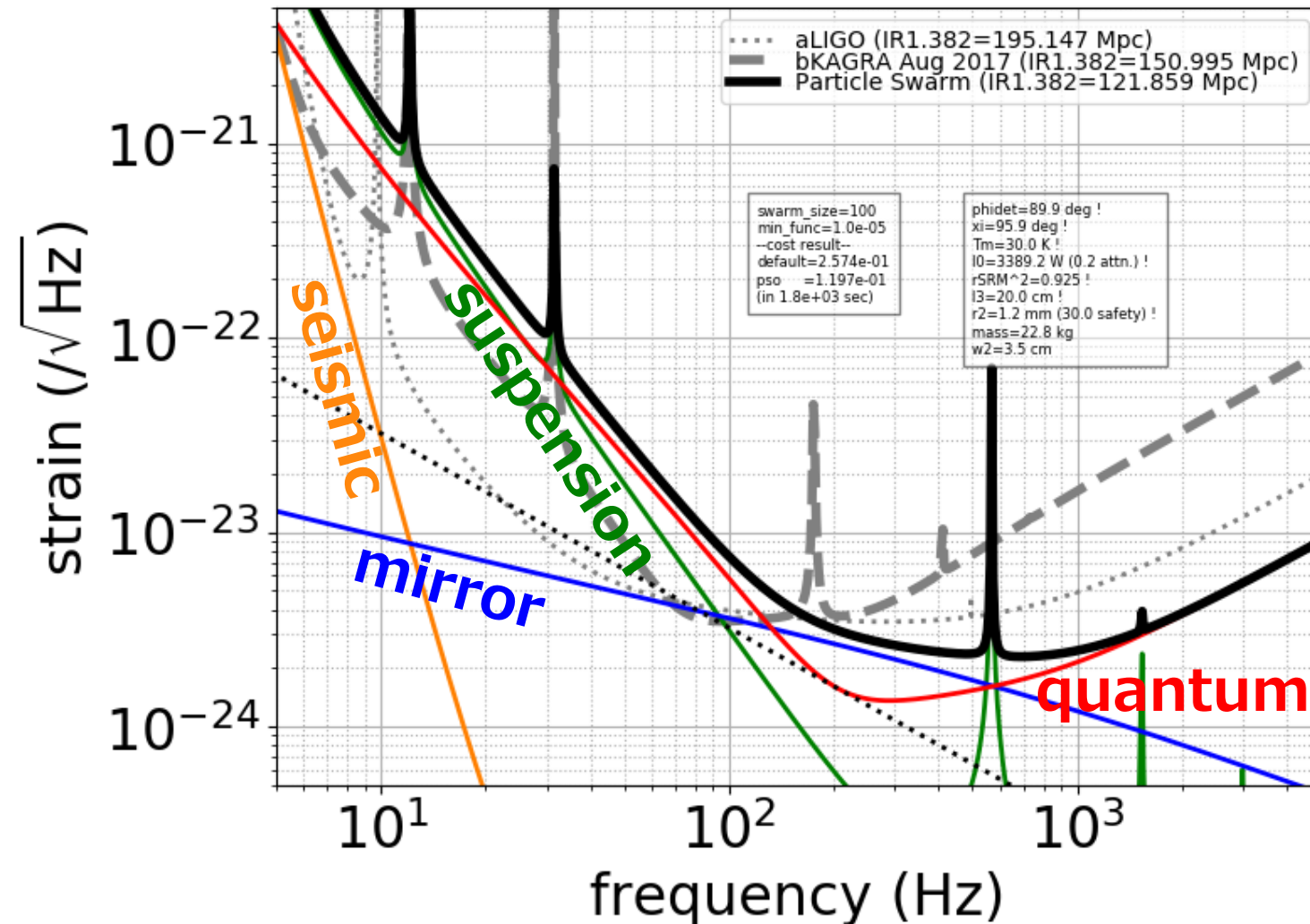

Good for mid frequency improvement → BNS range optimized

T=20.1 K
181 W input
thicker fiber
25.0 cm
φ2.4 mm
(thicker to allow for higher power)

Plan B: 400 W Laser with SQZ

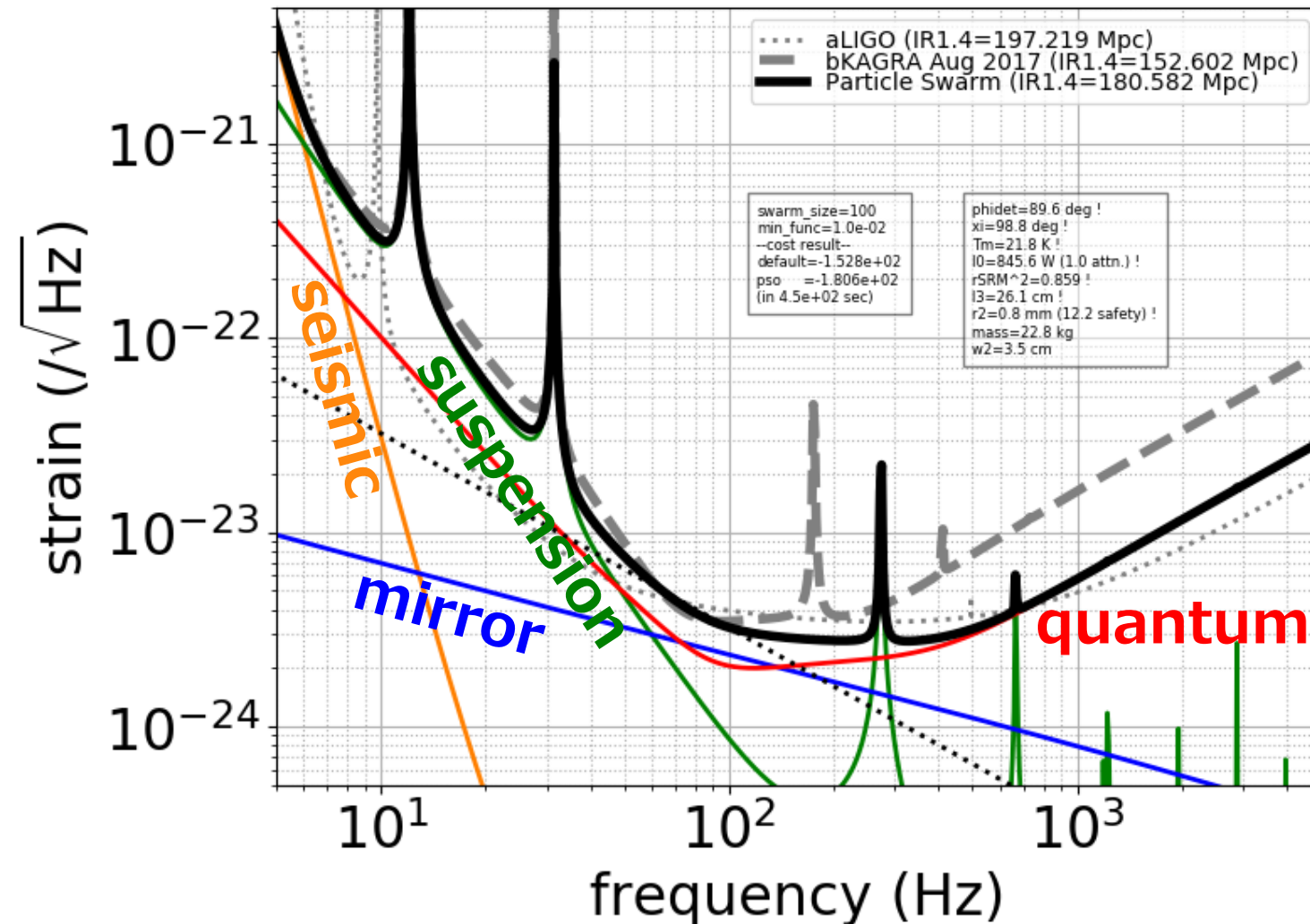- Assumes 10dB input SQZ (4.4 dB detected SQZ)

Good for high frequency improvement → BNS range optimized

T=29.8 K
330 W input
shorter and thicker fiber
20.1 cm
φ2.4 mm
(high power with high temperature)

Plan C: Freq. Dependent SQZ

- Assumes 10dB input SQZ and 100 m filter cavity

Broadband improvement → BNS range optimized

T=21.8 K
85 W input
similar fiber
26.1 cm
φ1.6 mm

Summary of $5M Plans

- A. New mirror takes time to fabricate
- B. High power operation is tough
- C. Does it fit in the facility?

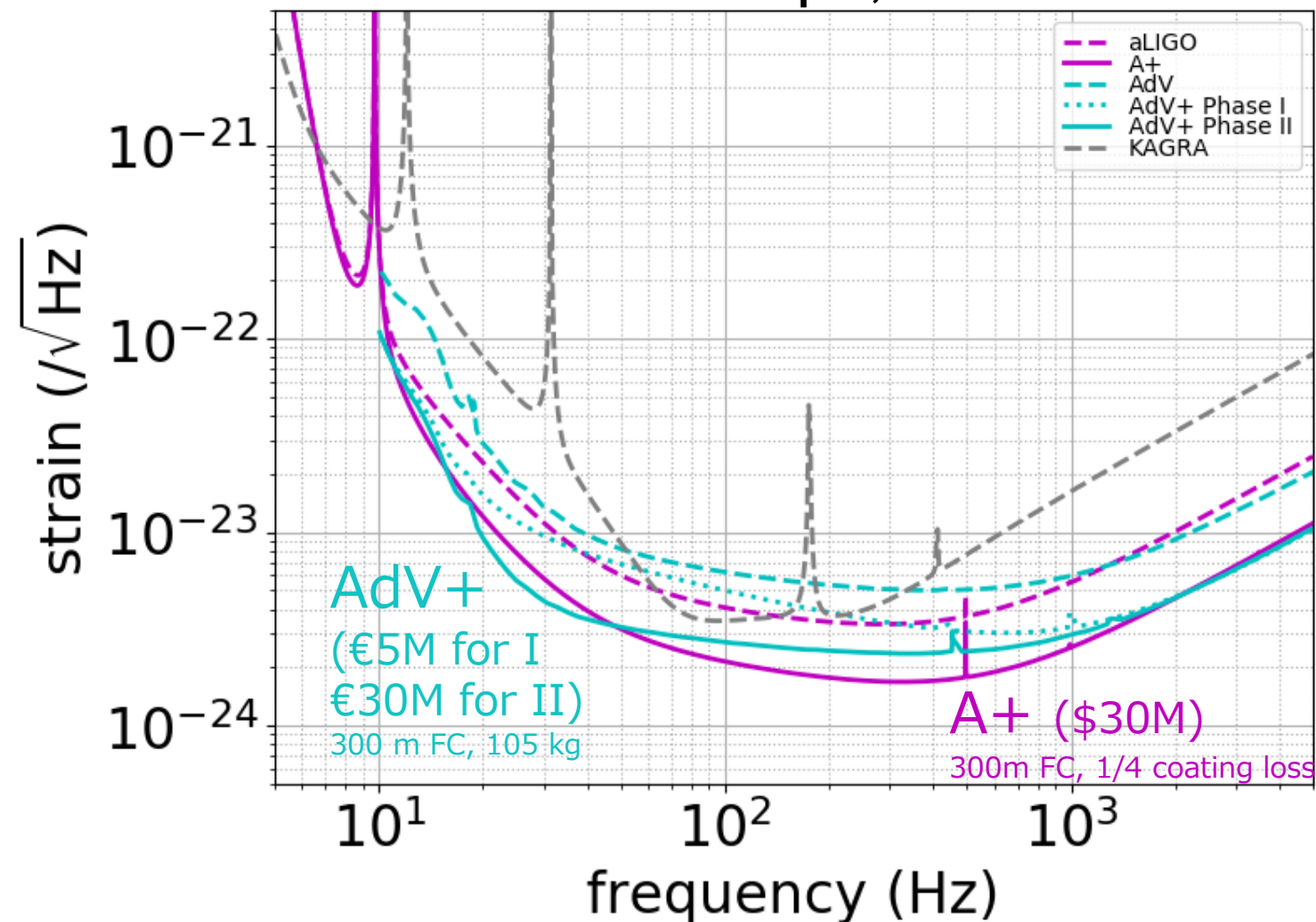|	Inspiral range (Mpc)			BNS localize (deg^2)
	BBH100	BBH30	BNS	
bKAGRA	353	1095	153	0.183
A. 40 kg mirror	339	1096	**213**	0.151
B. 400 W laser sqz	117	314	123	**0.114**
C. Freq. dep. sqz	**470**	**1177**	181	0.135

- I like A because of simplicity, but if fabrication of heavier mirrors cannot be done on time, go for C?

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Comparison Between 2G and 2G+

- **A+**: 325 Mpc
  AdV+ Phase I: 160 Mpc, **Phase II**: 300 Mpc

aLIGO curve from
LIGO-T1800044
(updated ver)

A+ curve from
LIGO-T1800042

AdV and AdV+
curves from
VIR-0325B-18

KAGRA curve
from
JGW-T1707038

Comparison Between 2G and 2G+

- Only Plan B (400W laser with squeezing) can beat A+ (but only slightly)
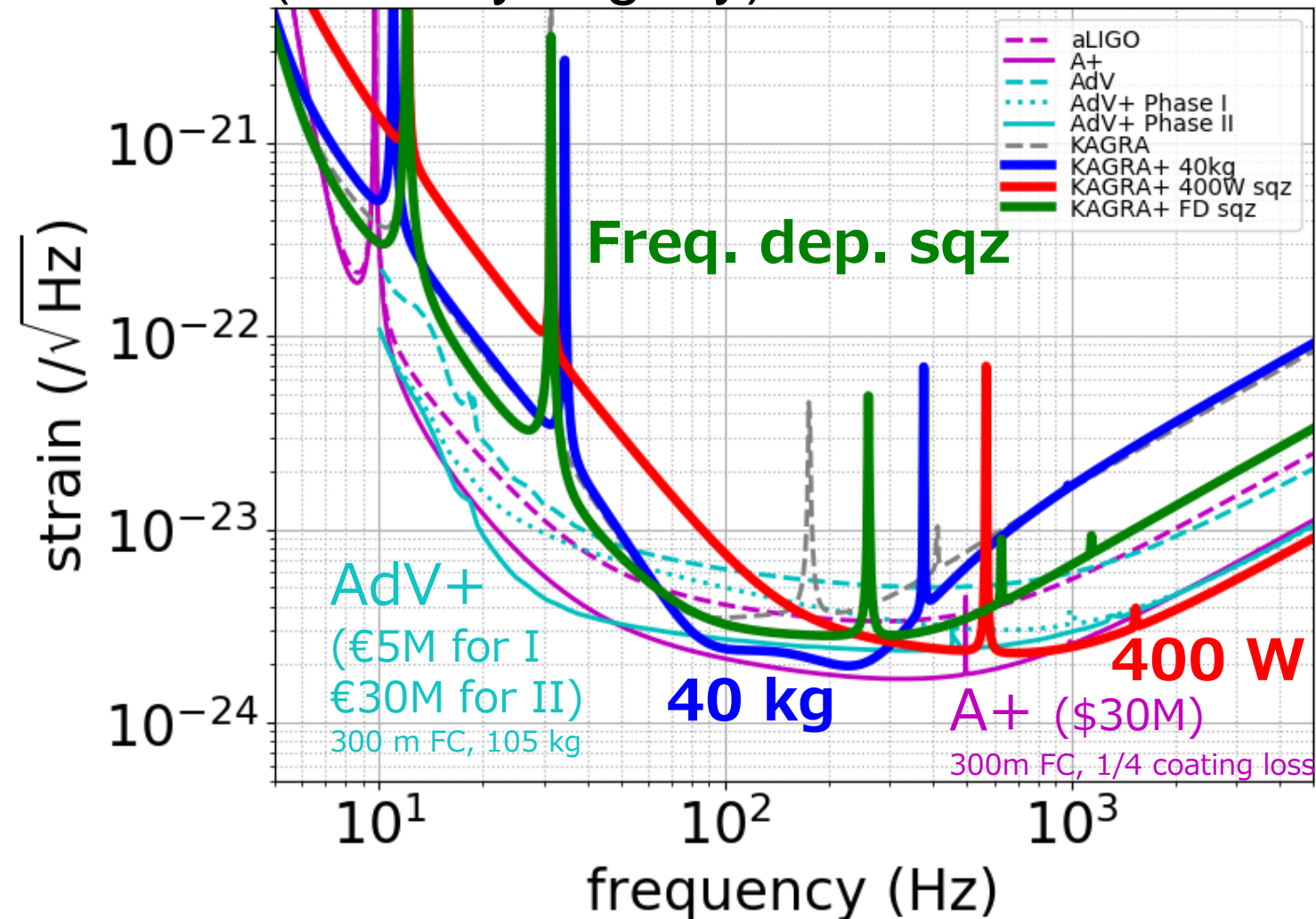
aLIGO curve from [LIGO-T1800044](#) (updated ver)

A+ curve from [LIGO-T1800042](#)

AdV and AdV+ curves from [VIR-0325B-18](#)

KAGRA curve from [JGW-T1707038](#)

Be Optimistic, Combine Them!

- 100 kg mirror with 1/4 coating loss (and larger beam size), 320 W, 10dB input sqz with 100 m filter cavity

355 Mpc

~ 10 yrs ?
~$20M ?

Legend:
- aLIGO
- A+
- AdV
- AdV+ Phase I
- AdV+ Phase II
- KAGRA
- KAGRA+ 40kg
- KAGRA+ 400W sqz
- KAGRA+ FD sqz
- KAGRA++

AdV+
(€5M for I
€30M for II)
300 m FC, 105 kg

KAGRA++

A+ ($30M)
300m FC, 1/4 coating loss
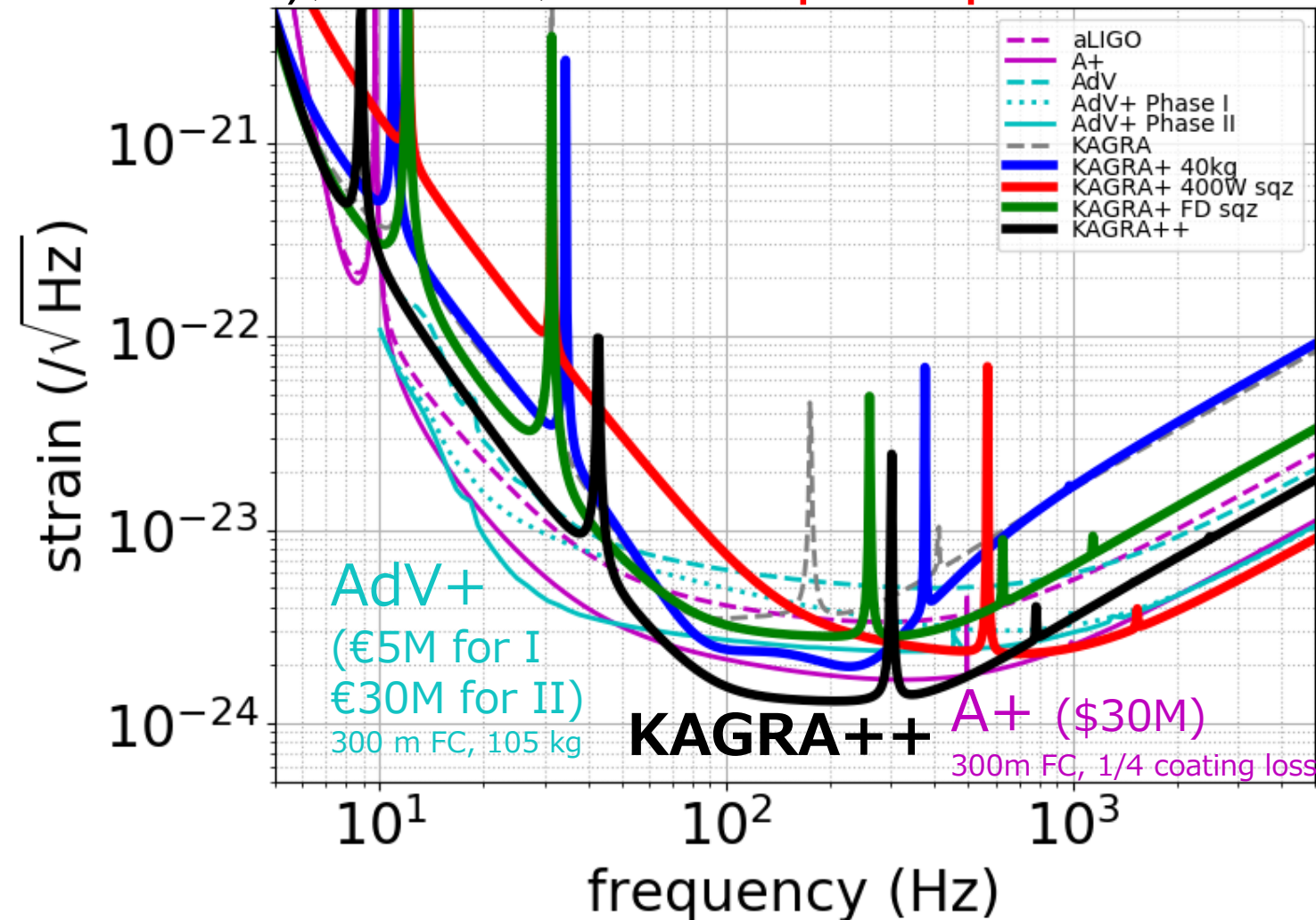
Summary

- Demonstrated sensitivity design with PSO

- Application to KAGRA shows both
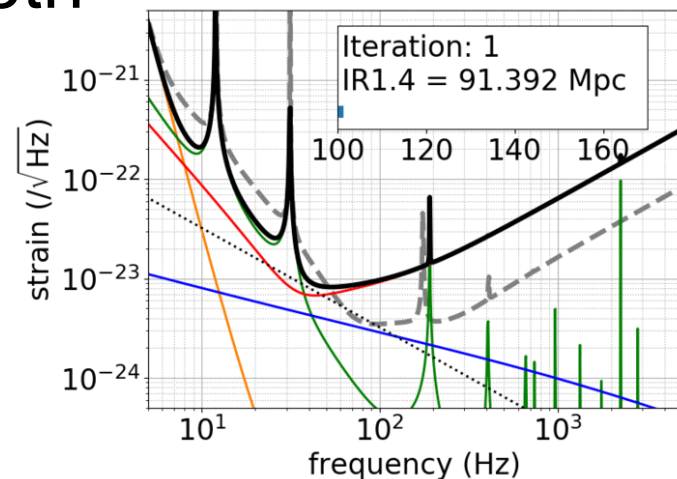   - BNS inspiral range
    - BNS sky localization
  can be improved by retuning
  7 parameters of
  existing components
    YM+, Phys. Rev. D 97, 122003 (2018)

- Also applied to KAGRA+ study and showed
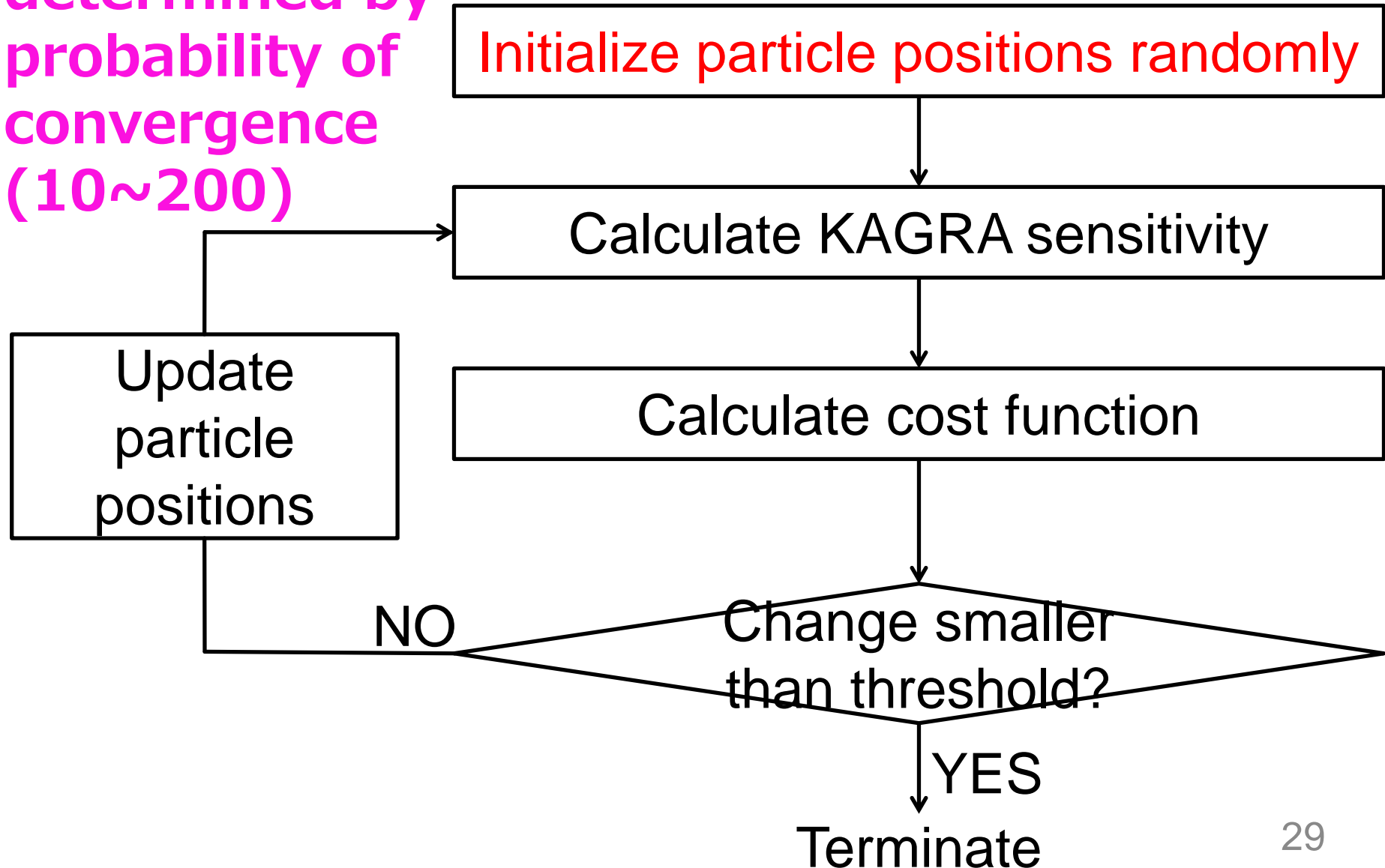 optimized sensitivity for 3+1 candidates
    Sensitivity data available at JGW-G1808426

Supplementary Slides

PSO Algorithm

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

Initialize particle positions randomly

↓

Calculate KAGRA sensitivity

↓

Calculate cost function

↓

Update particle positions

NO ← Change smaller than threshold?

YES ↓

Terminate

PSO Algorithm

Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

Change smaller than threshold?

YES

Terminate

strain

quantum

seismic

thermal

frequency

PSO Algorithm

BNS inspiral range as a cost function
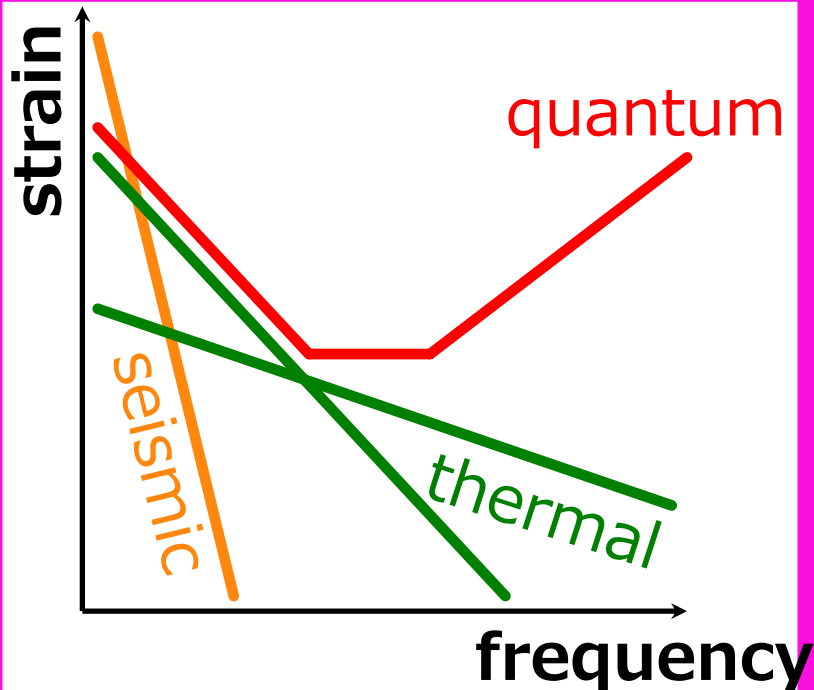

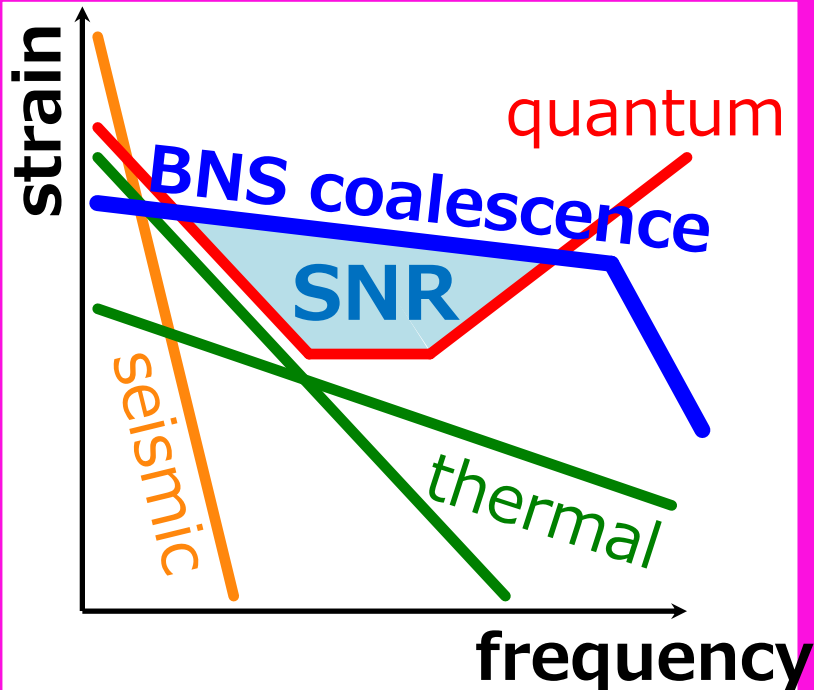Initialize particle positions randomly

Calculate KAGRA sensitivity

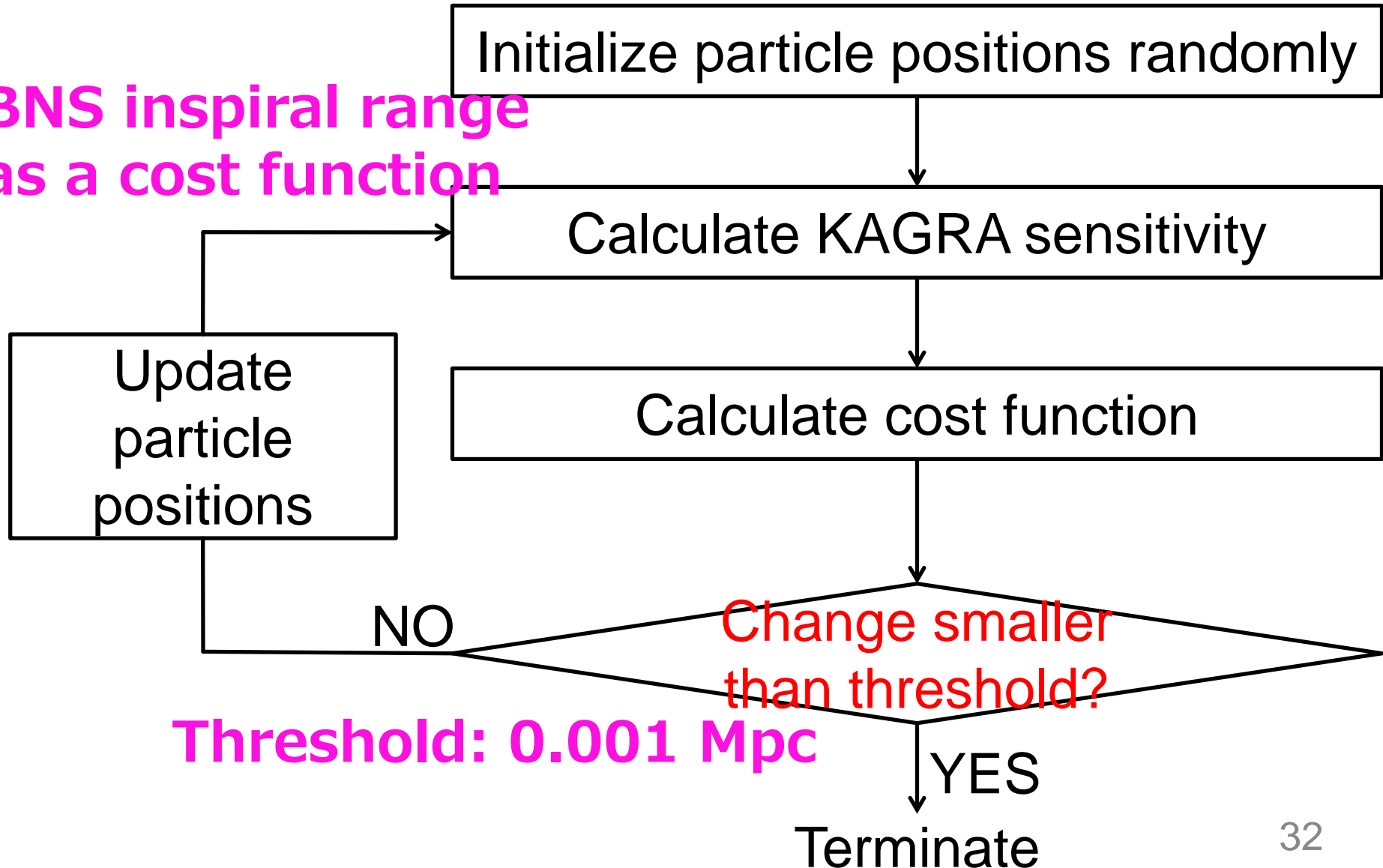Calculate cost function

Change smaller than threshold?

YES

Terminate

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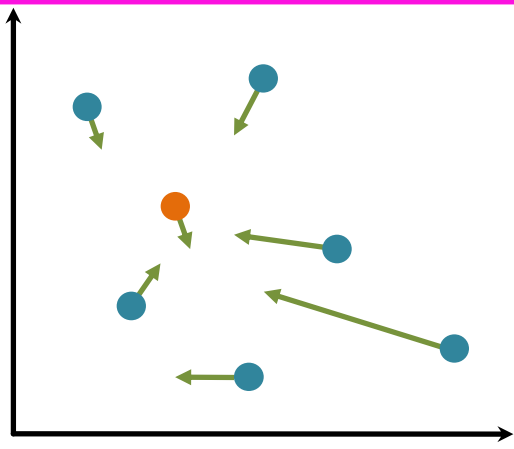# PSO Algorithm

BNS inspiral range as a cost function

Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

Update particle positions

NO

Change smaller than threshold?

Threshold: 0.001 Mpc

YES

Terminate

PSO Algorithm

Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

Change smaller than threshold?

NO

YES

Update particle positions

Terminate

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

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

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

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](#)

- ## Voyager quantum noise optimization
  input power, arm finesse, SRM transmissivity, homodyne, filter cavity

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

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 additionally require test mass suspension design change at ~0.1 Million USD/mirror

- Change in the test mass require ~0.6 Million USD/mirror (more for heavier ones)

Fiber Length and Diameter

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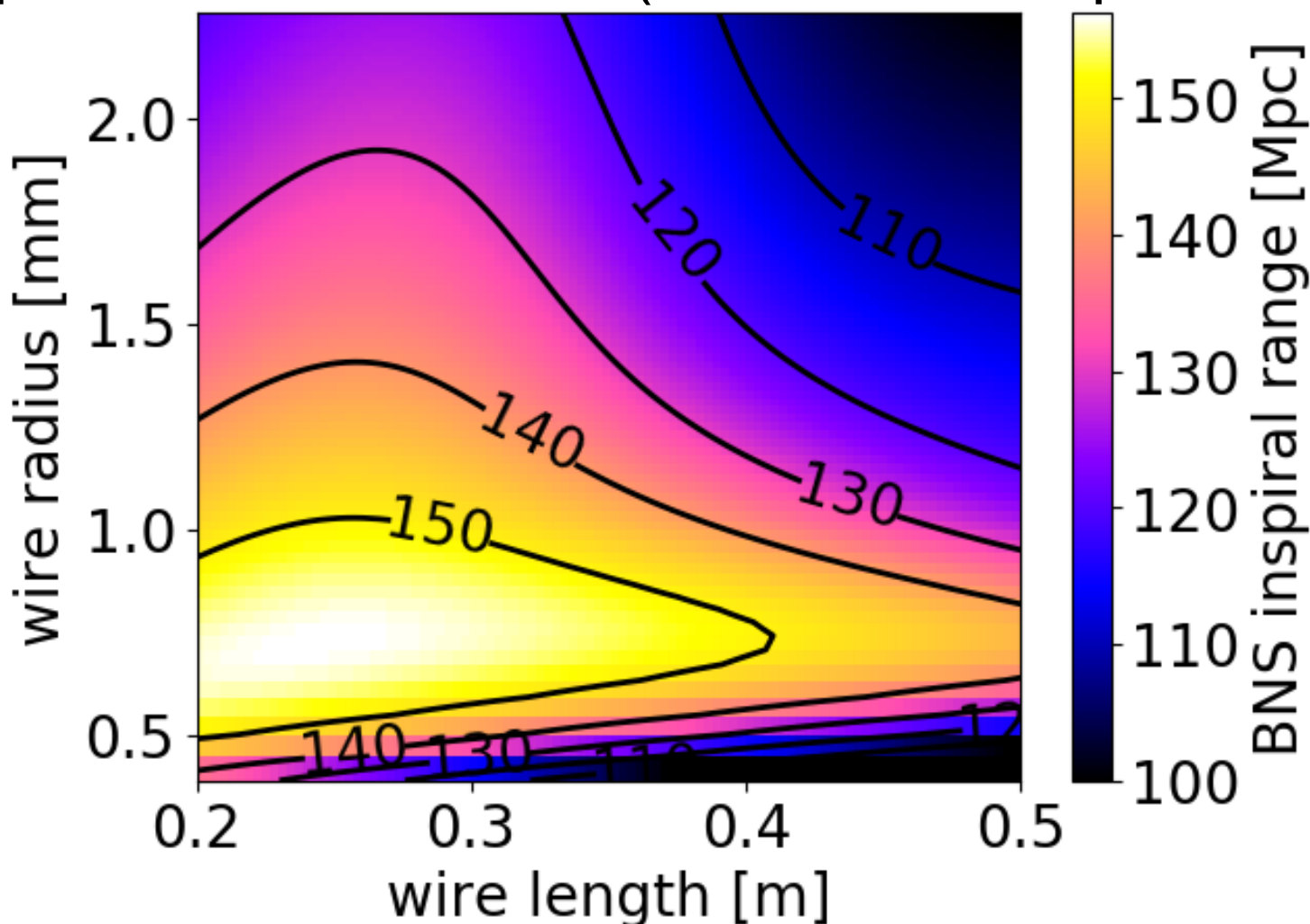
Fisher Matrix Analysis

- 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

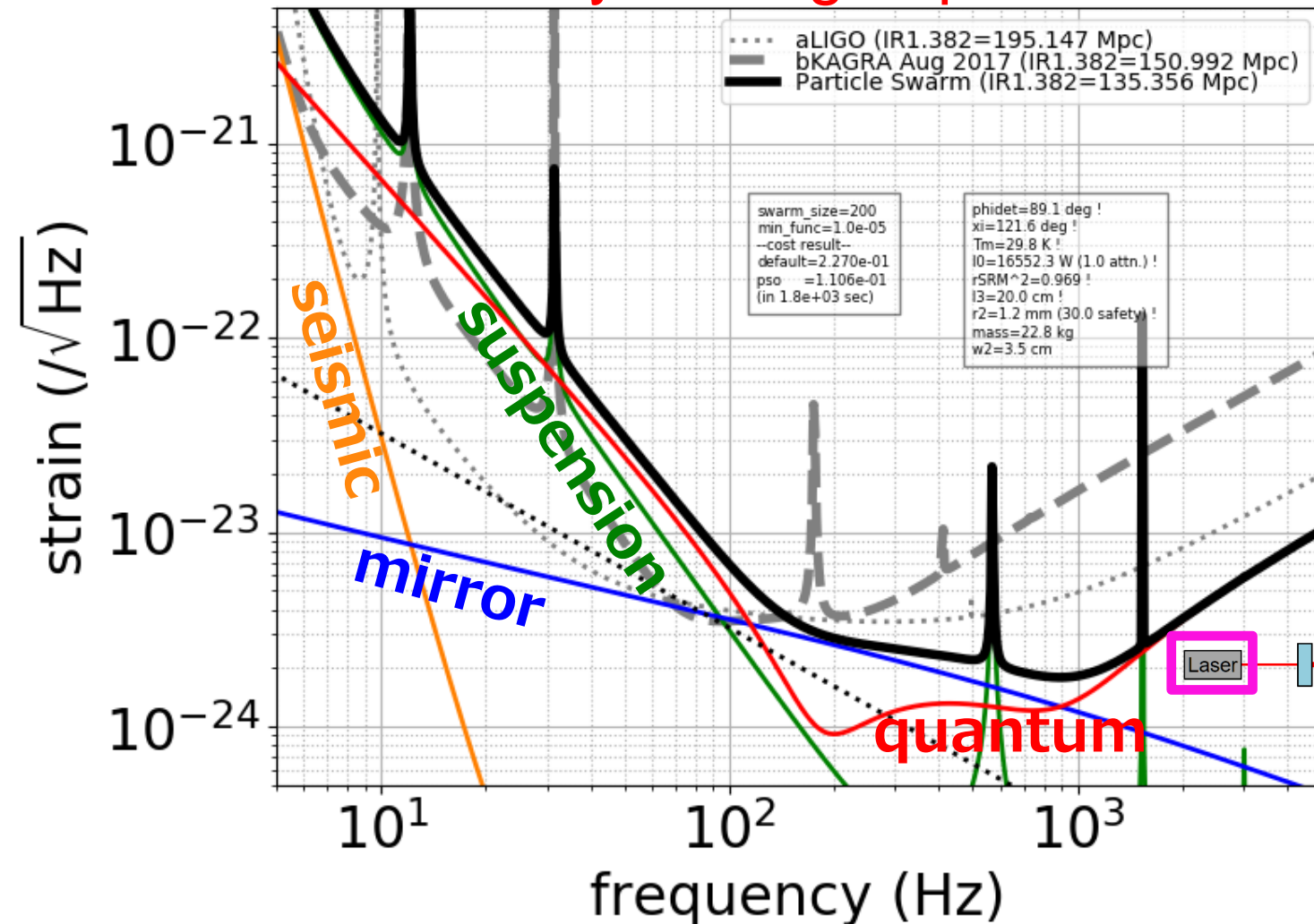chis, chia: symmetric/asymmetric spin $\quad \chi_{\mathrm{s/a}} = (\chi_1 \pm \chi_2)/2$

thetas, phis: colatitude / longitude of source

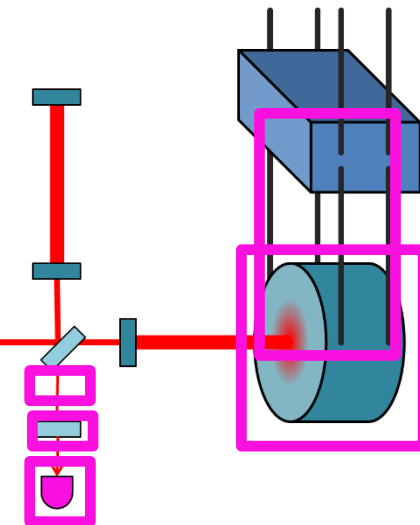cthetai: inclination angle

psip: polarization angle

Optimization for Fixed Sky Location

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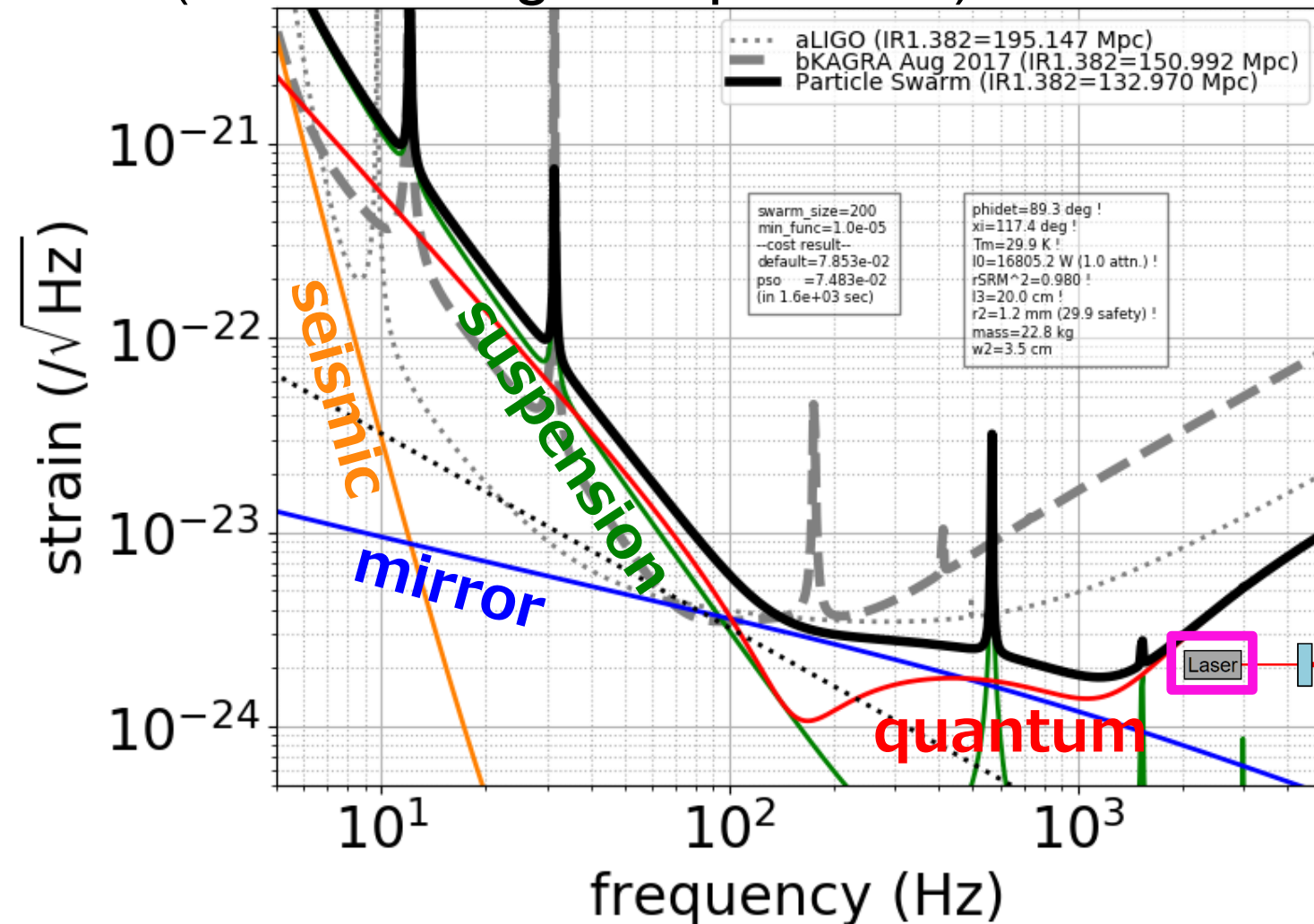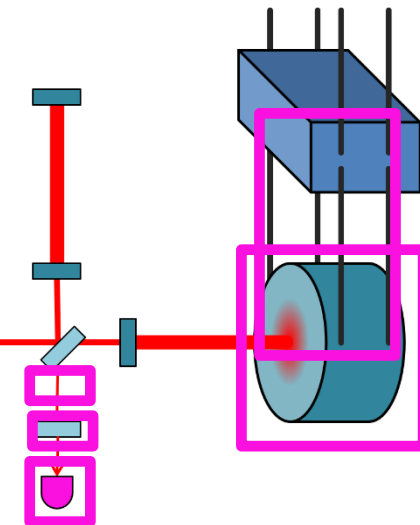

shortest and thickest fibers
1.7 kW at BS
30 K (max)

Symmetric Spin Optimization

- Similar to sky localization optimization (focus on high frequencies)
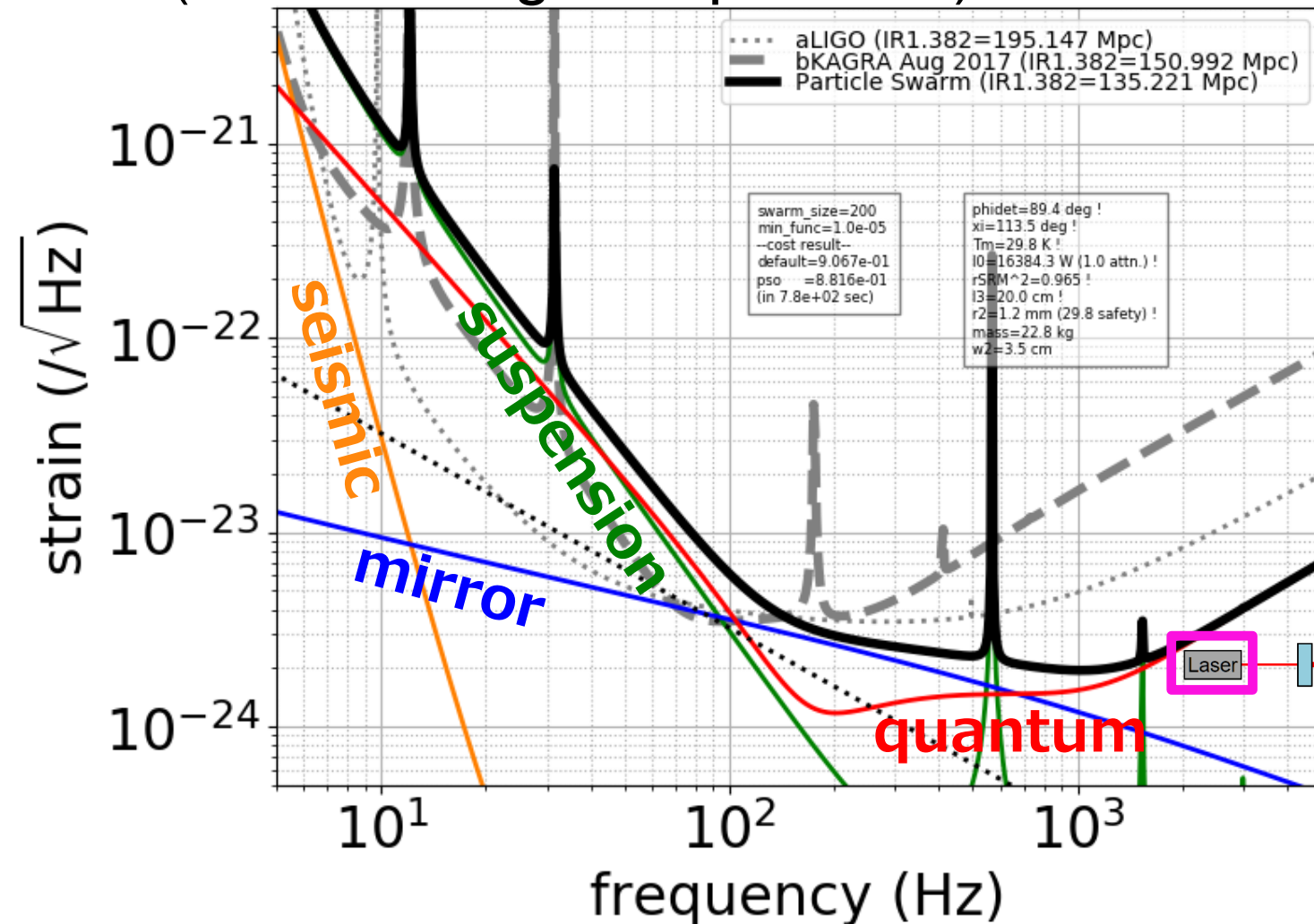
$$\chi_{\mathrm{s}} = \frac{\chi_1 + \chi_2}{2}$$
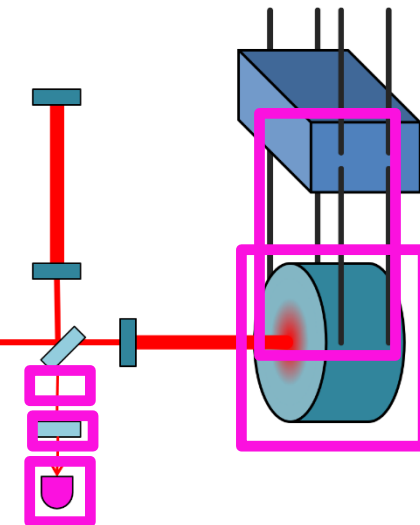
shortest and thickest fibers
1.7 kW at BS
30 K (max)

Asymmetric Spin Optimization

- Similar to sky localization optimization (focus on high frequencies)
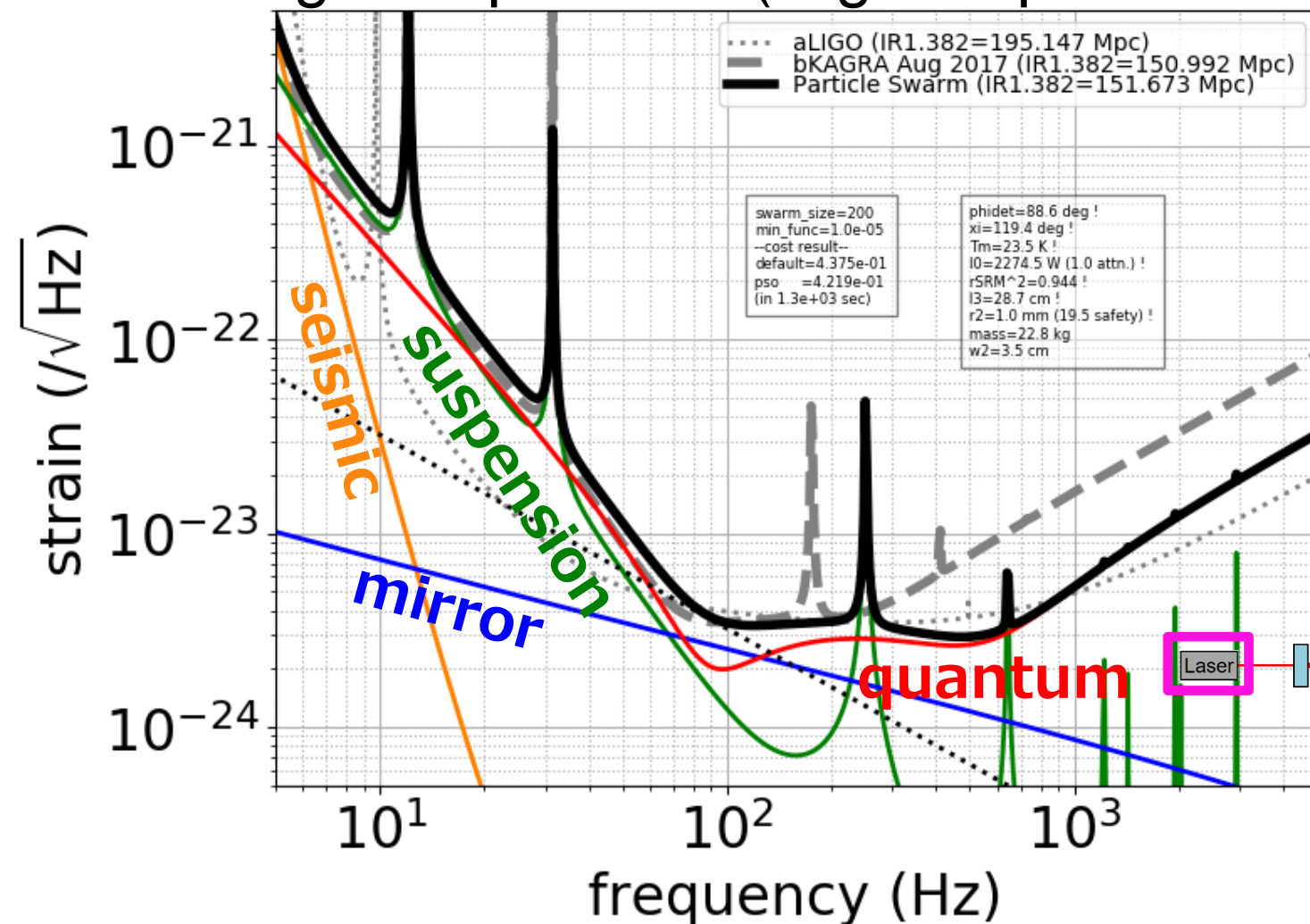
$$\chi_a = \frac{\chi_1 - \chi_2}{2}$$

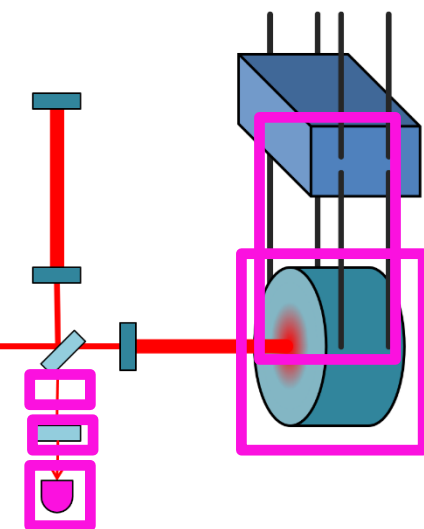shortest and thickest fibers 1.7 kW at BS 30 K (max)

Distance Optimization

- Similar to inspiral range optimization, but slight shift to high frequencies (slight improvement by 2%)
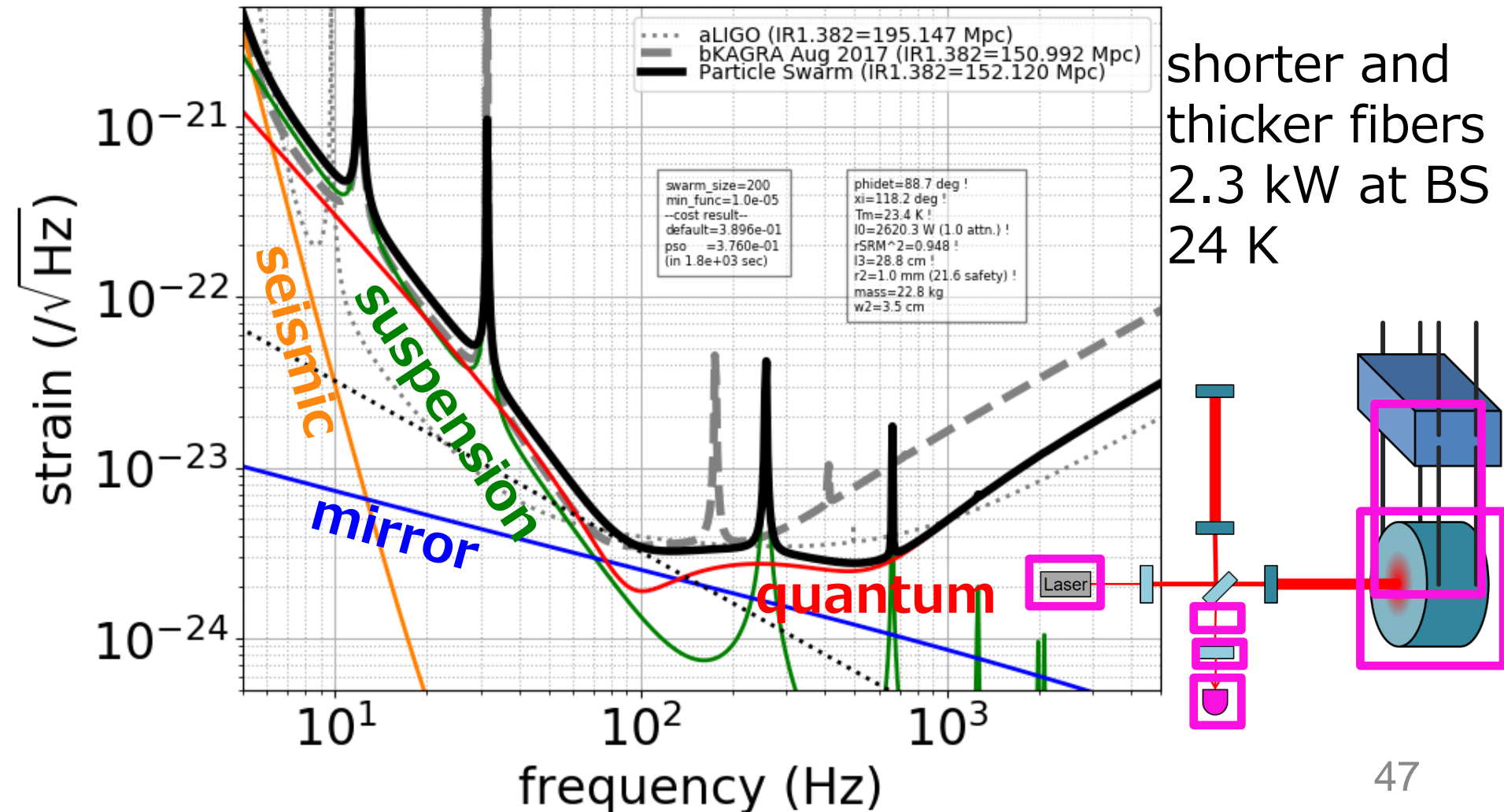
shorter and thicker fibers
2.3 kW at BS
24 K

Legend:
- aLIGO (IR1.382=195.147 Mpc)
- bKAGRA Aug 2017 (IR1.382=150.992 Mpc)
- Particle Swarm (IR1.382=151.673 Mpc)

swarm_size=200
min_func=1.0e-05
--cost result--
default=4.375e-01
pso   =4.219e-01
(in 1.3e+03 sec)

phidet=88.6 deg !
xi=119.4 deg !
Tm=23.5 K !
I0=2274.5 W (1.0 attn.) !
rSRM^2=0.944 !
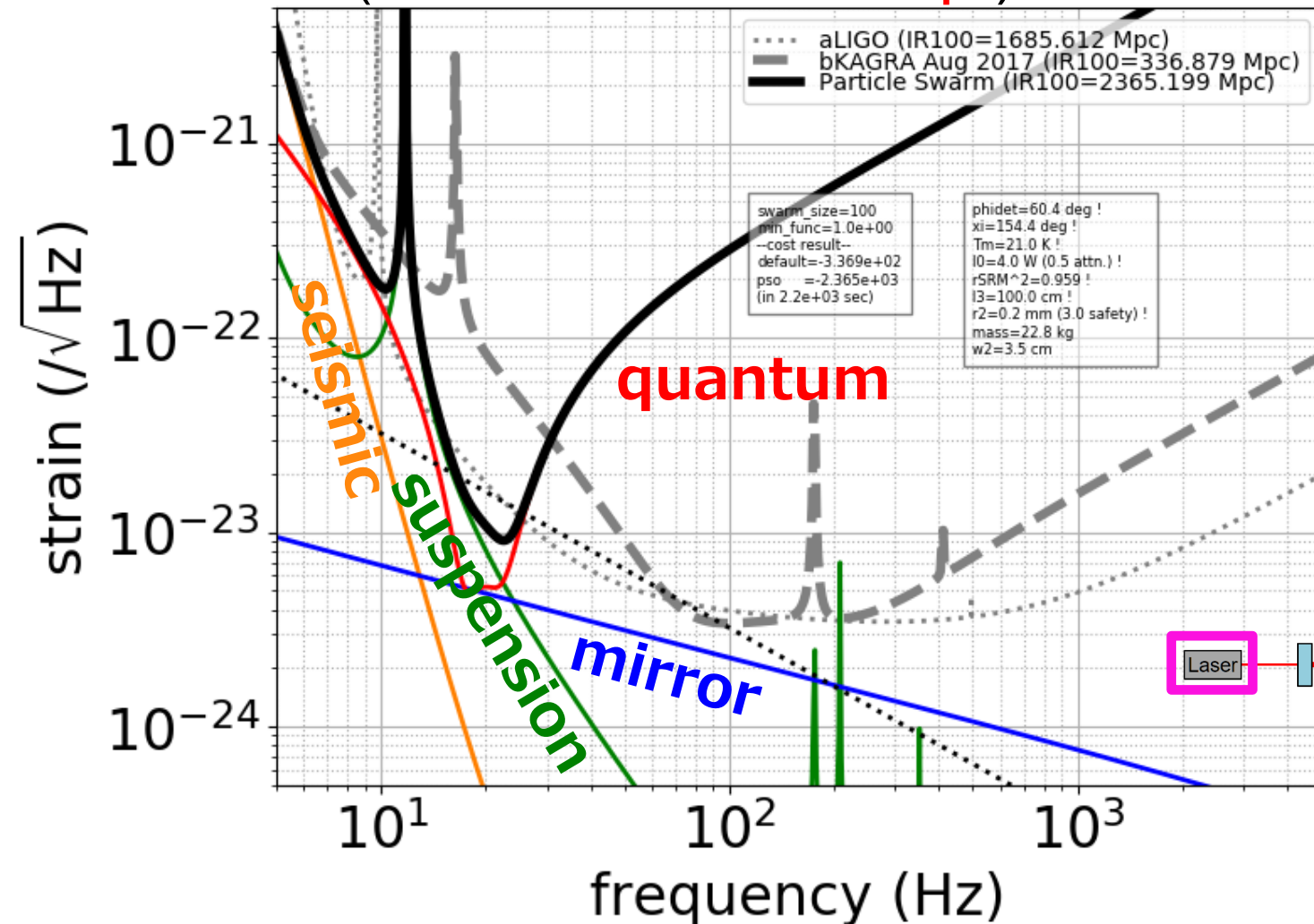l3=28.7 cm !
r2=1.0 mm (19.5 safety) !
mass=22.8 kg
w2=3.5 cm

Inclination Angle Optimization
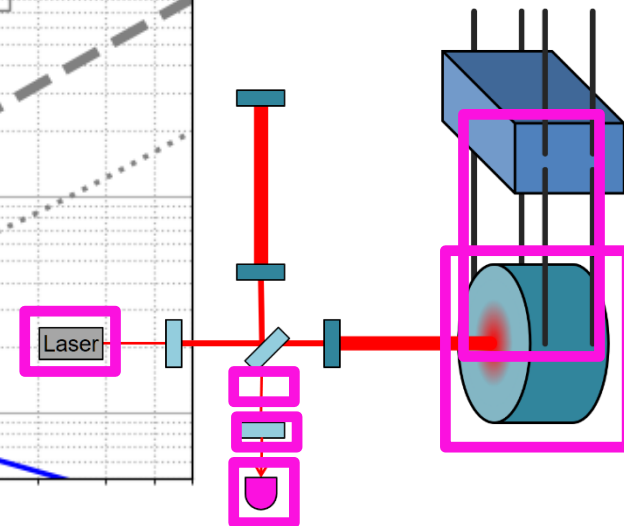
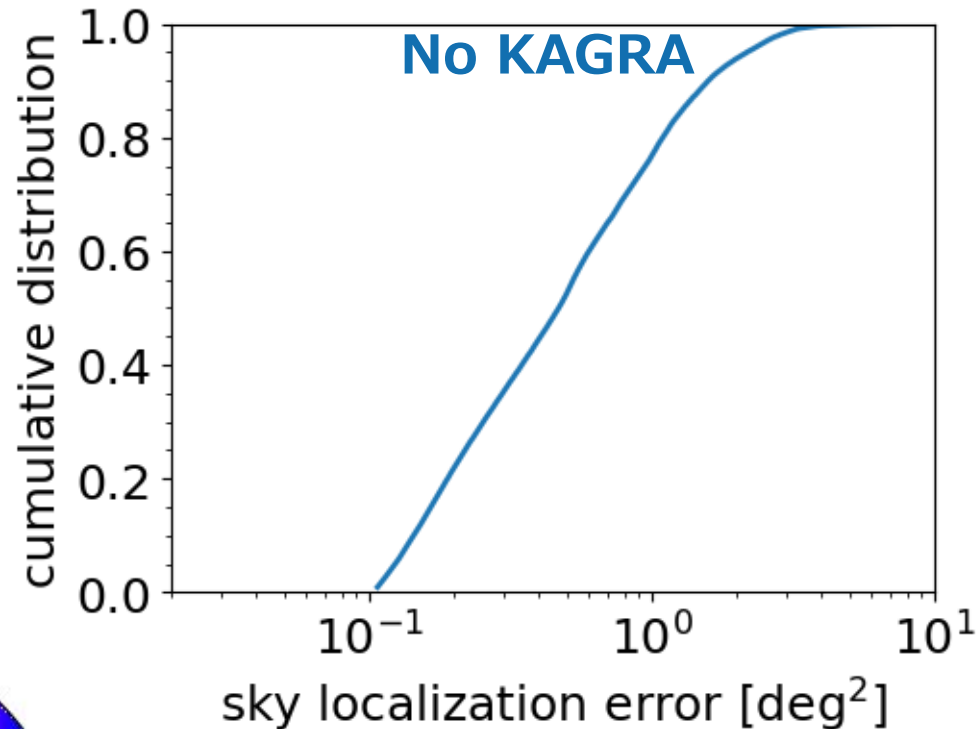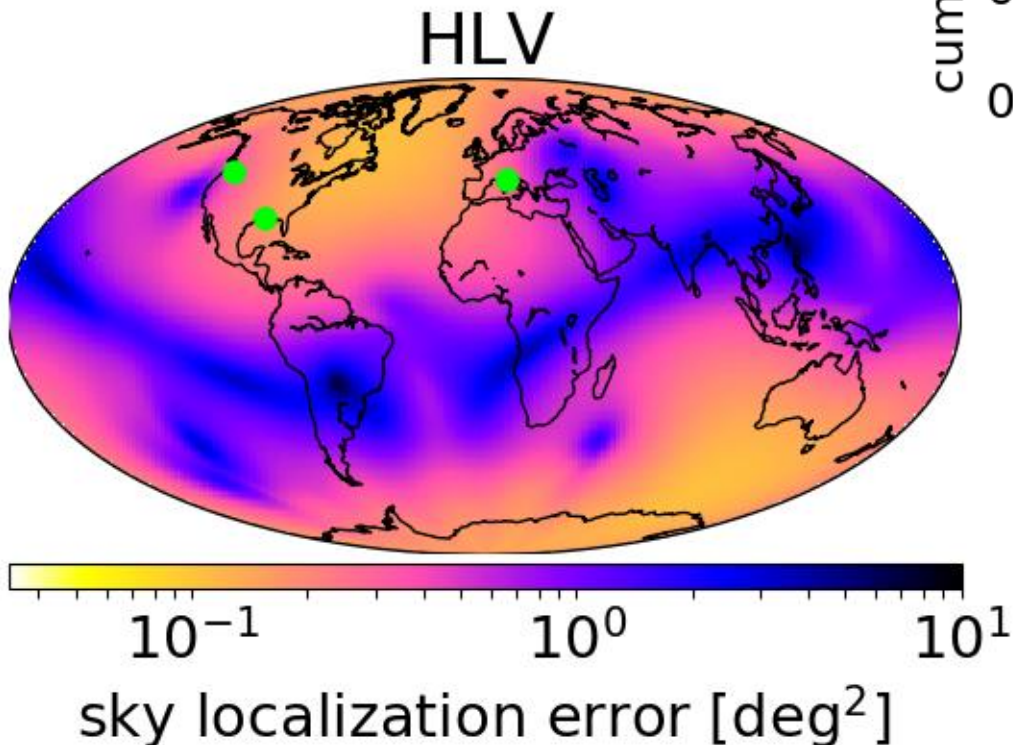- Similar to distance optimization (PE degeneracy)

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

No KAGRA

cumulative distribution vs sky localization error [deg^2]

HLV

sky localization error [deg^2]

	median
HLV	0.472 deg^2
HLVK	
HLVK+	

Sky Localization with HLVK

cumulative distribution

Default KAGRA

sky localization error [deg^2]

HLVK

sky localization error [deg^2]
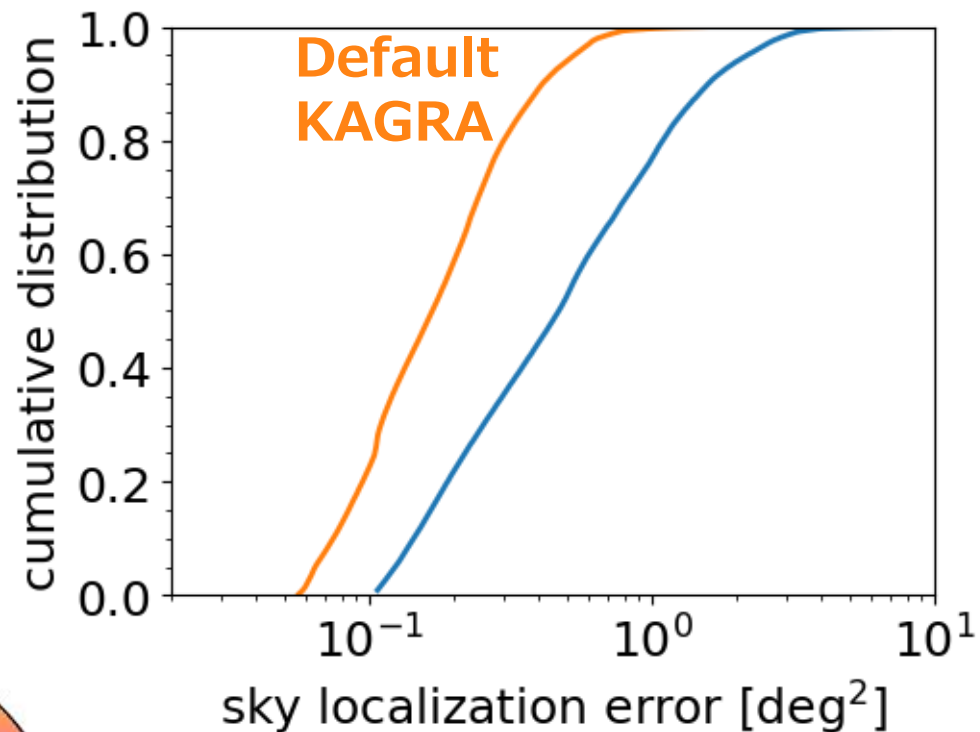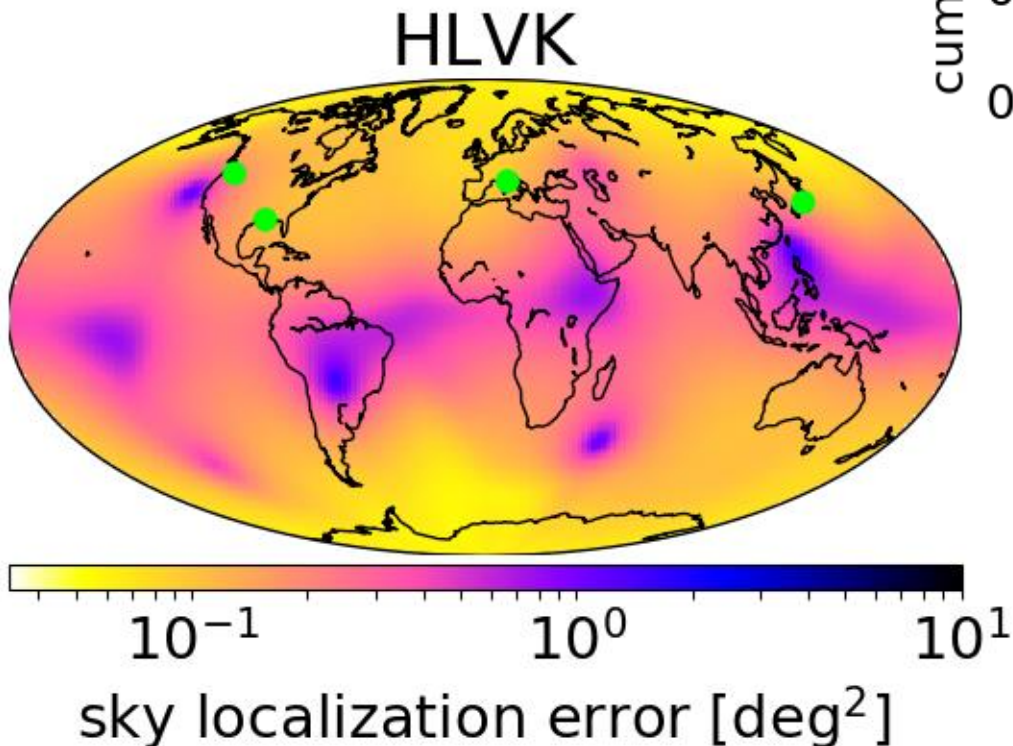
	median
HLV	0.472 deg^2
HLVK	0.168 deg^2
HLVK+	

Sky Localization with HLVK+

PSO KAGRA

cumulative distribution vs sky localization error [deg^2]

HLVK+

sky localization error [deg^2]
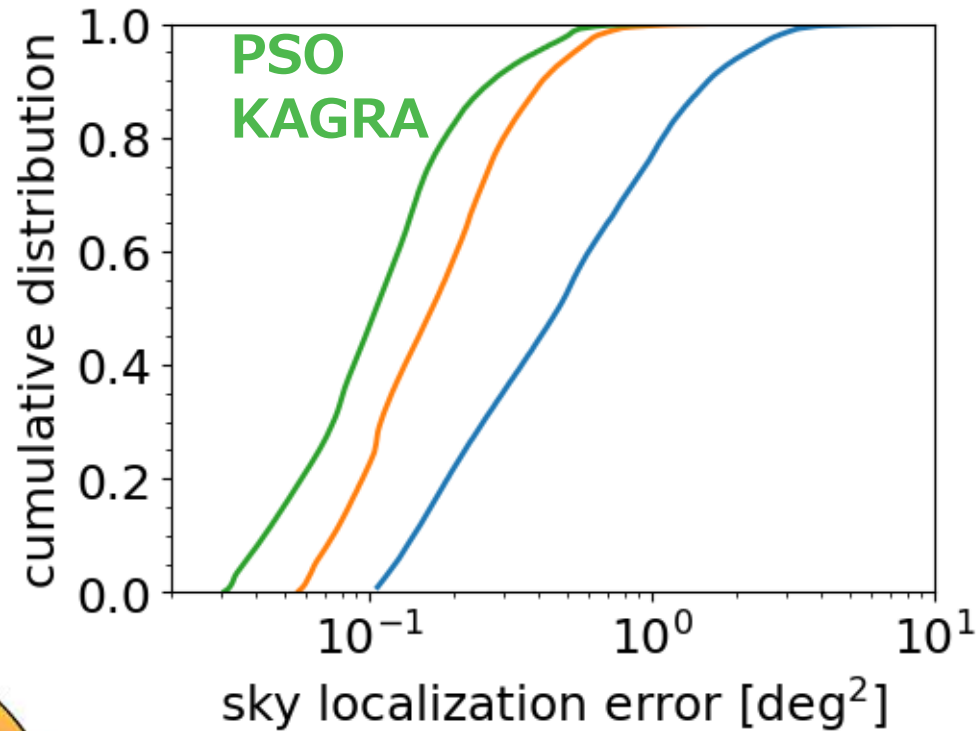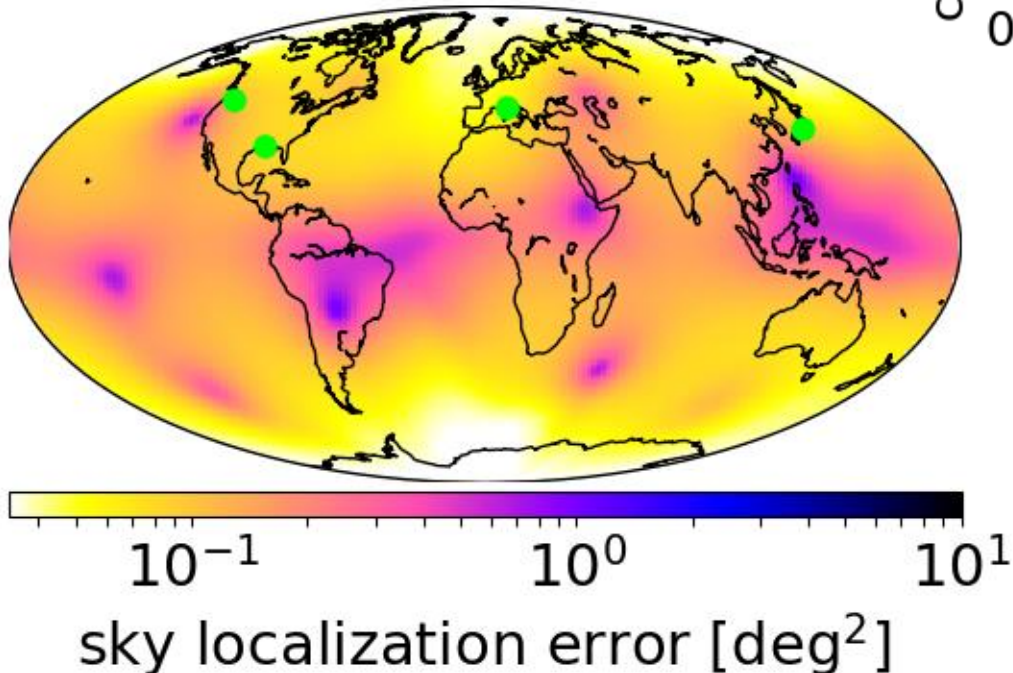
	median
HLV	0.472 deg^2
HLVK	0.168 deg^2
HLVK+	0.107 deg^2
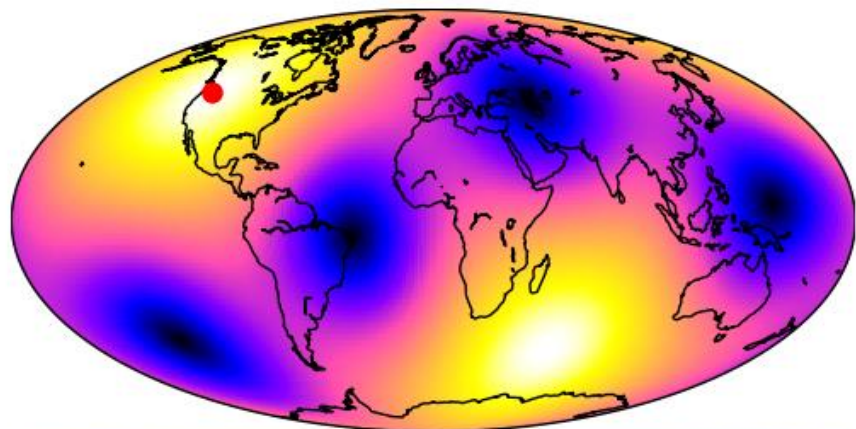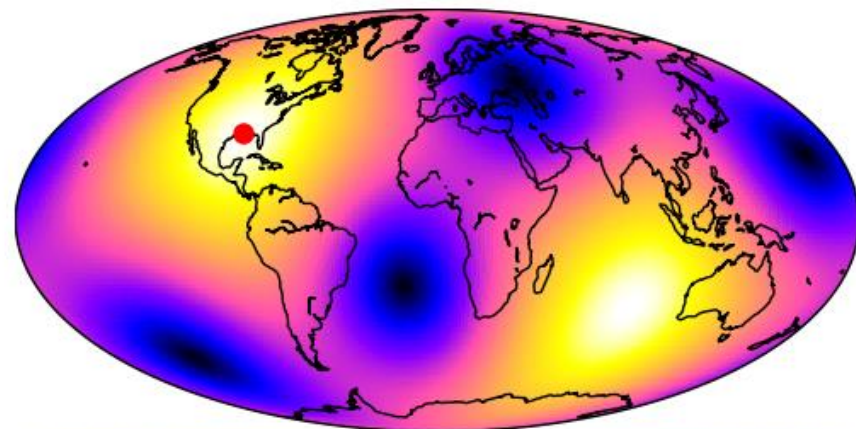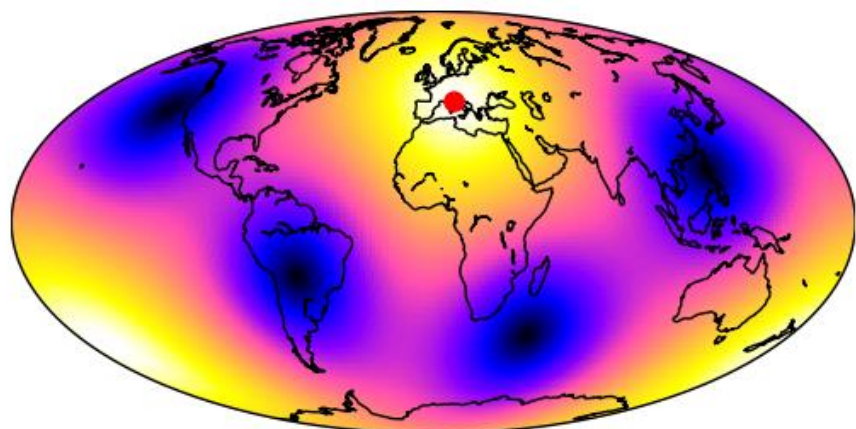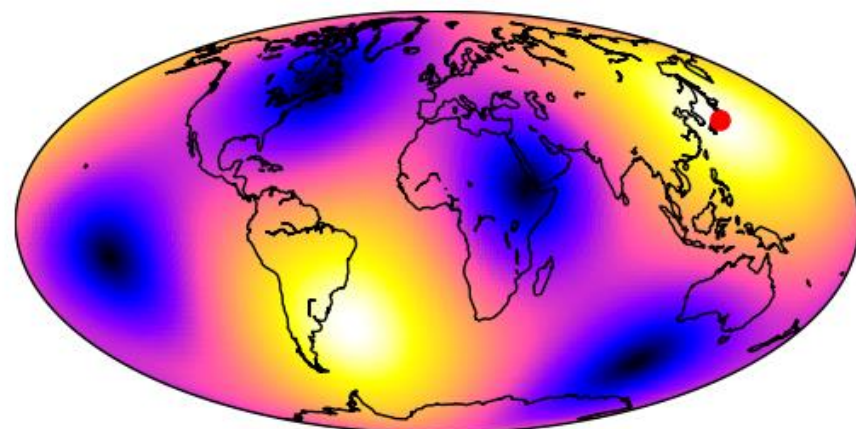
Antenna Pattern

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

KAGRA Cryostat Schematic

arXiv:1710.04823