

Optimization of the KAGRA sensitivity

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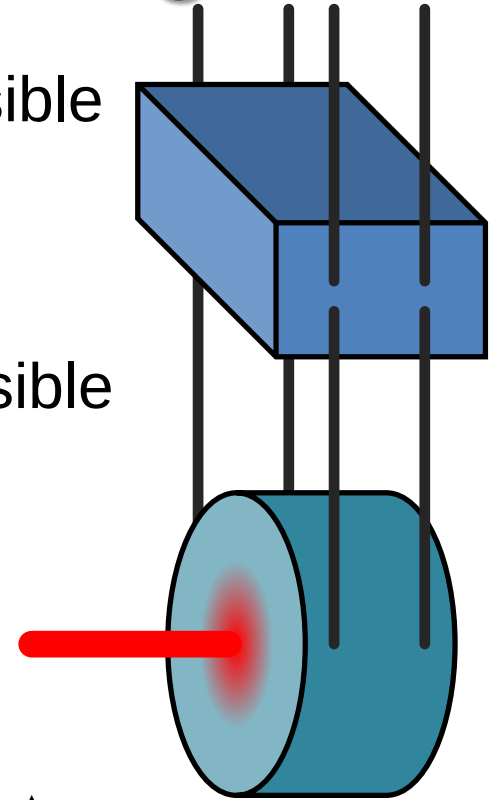
Overview

- 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



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



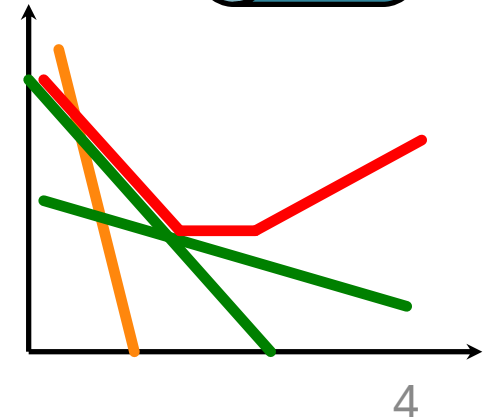
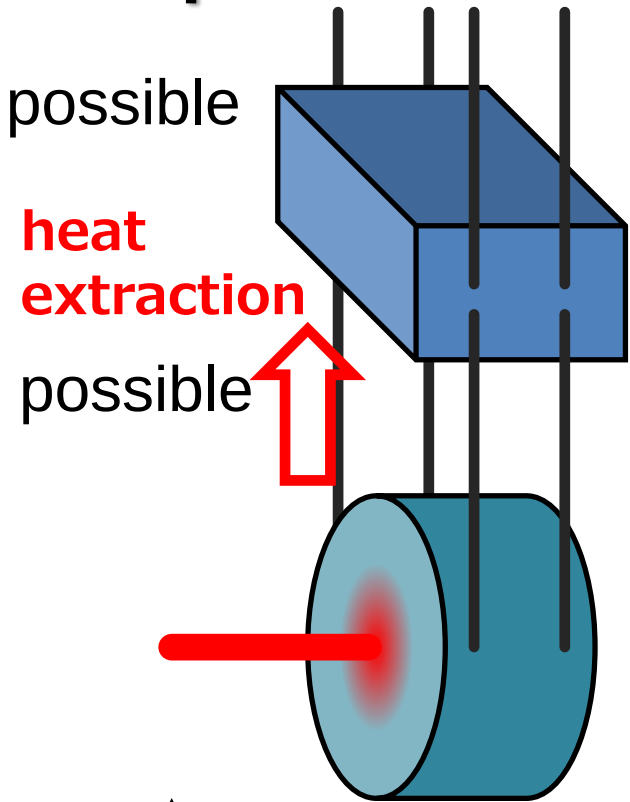
Cryogenic Design is Complicated

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

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

cryogenic cooling

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



Cryogenic Design is Complicated

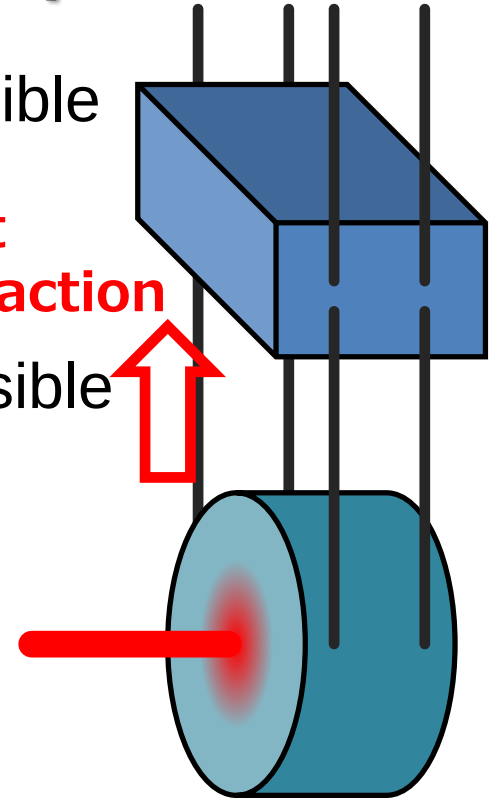
- **Seismic noise**: reduce as much as possible
multi-stage suspensions
underground

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

cryogenic cooling

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

heat
extraction

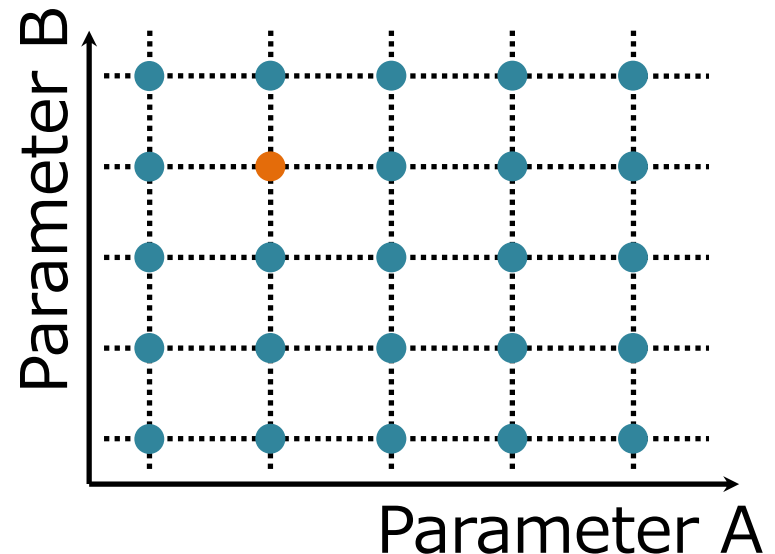


worse cooling power
mirror heating

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



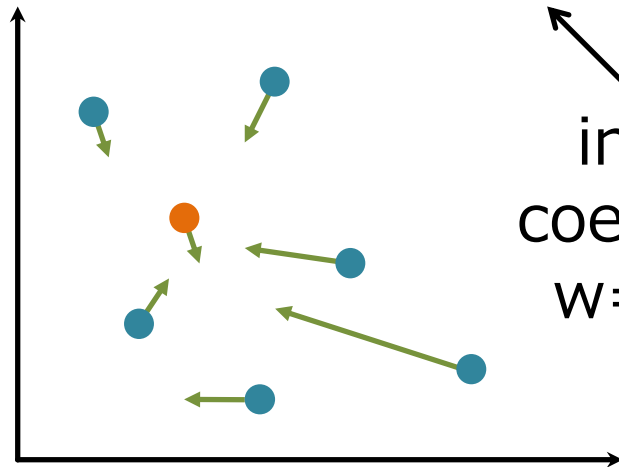
Particle Swarm Optimization!

- 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

$$v_k(t+1) = wv_k(t) + c_1r_1(\hat{x}_k - x_k(t)) + c_2r_2(\hat{x}_g - x_k(t))$$



inertia
coefficient
 $w=0.72$

acceleration coefficient $c=1.19$
random number $r \in [0,1]$

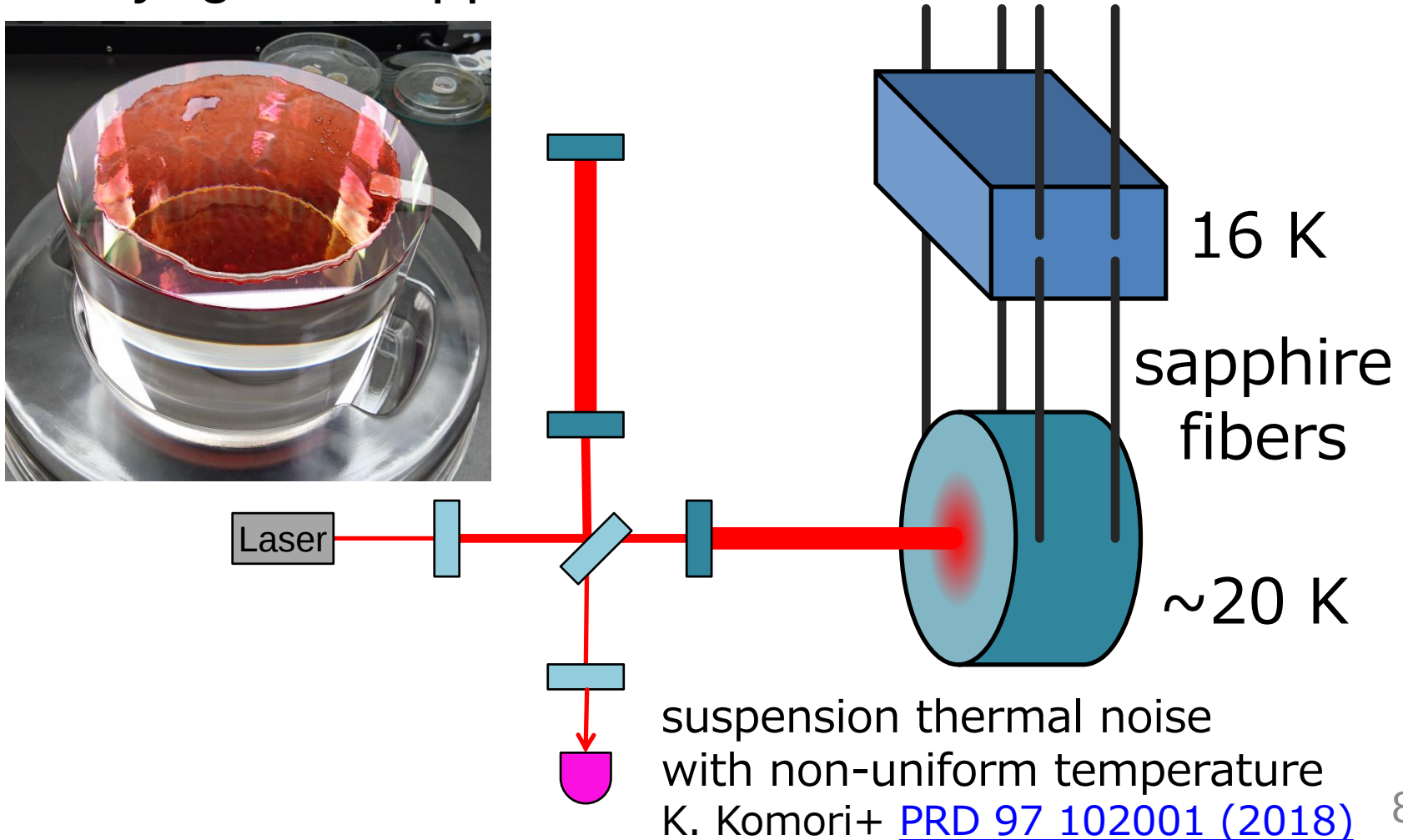
Parameter space

[Kennedy & Eberhart \(1995\)](#)

values for w and c are from [Standard PSO 2006](#)

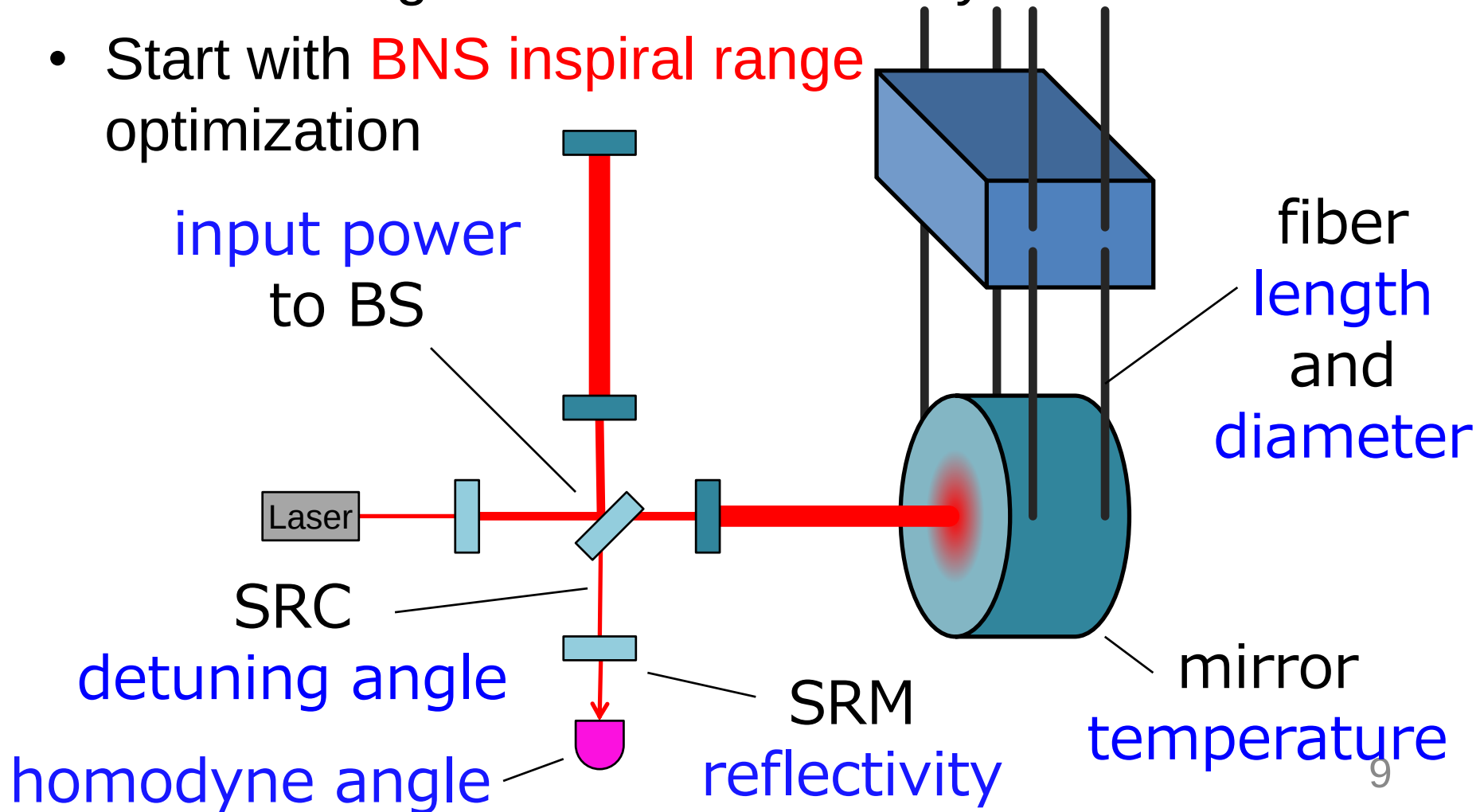
Apply PSO for KAGRA Design

- RSE interferometer
- Cryogenic sapphire test masses



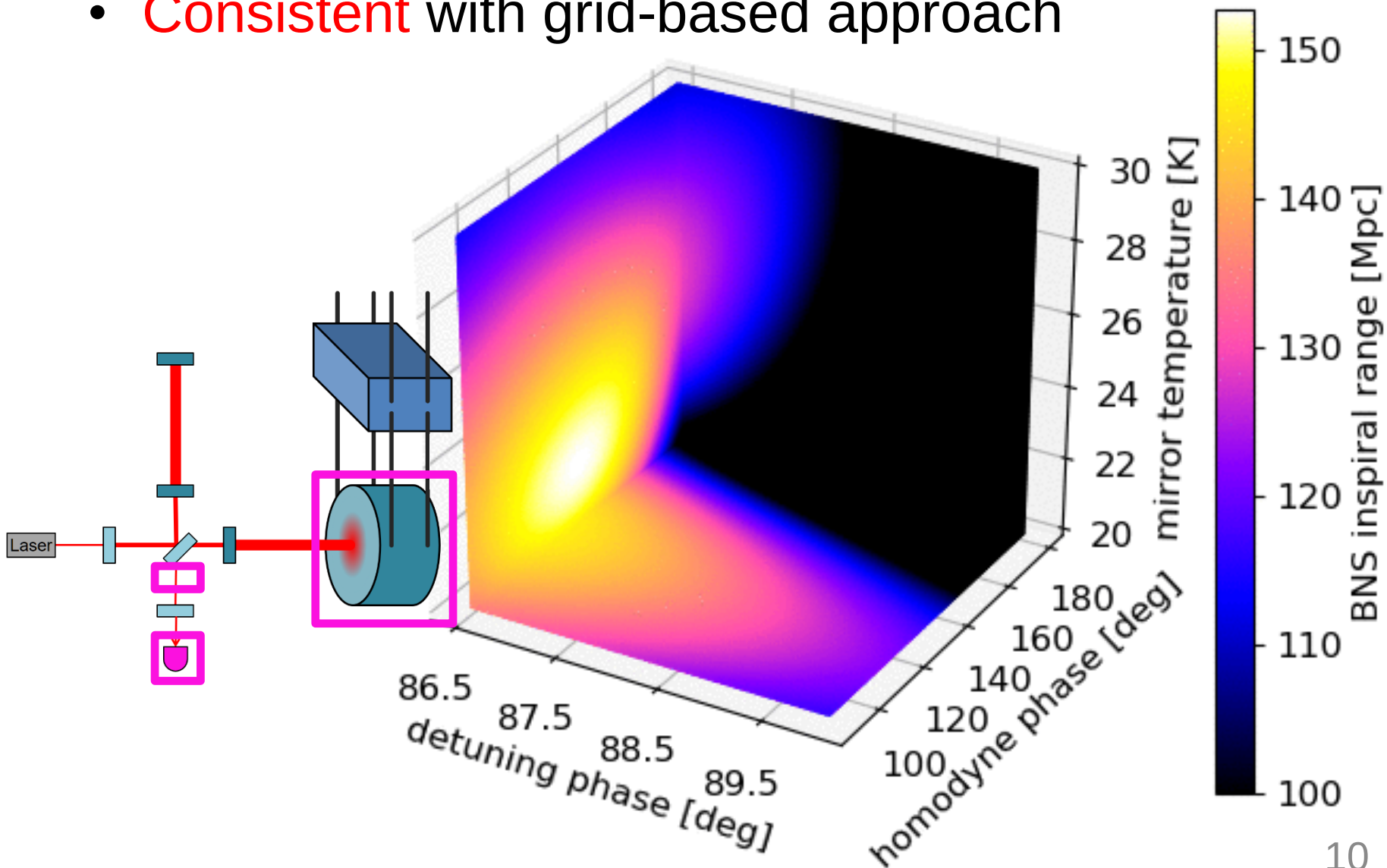
Parameters of Interest

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



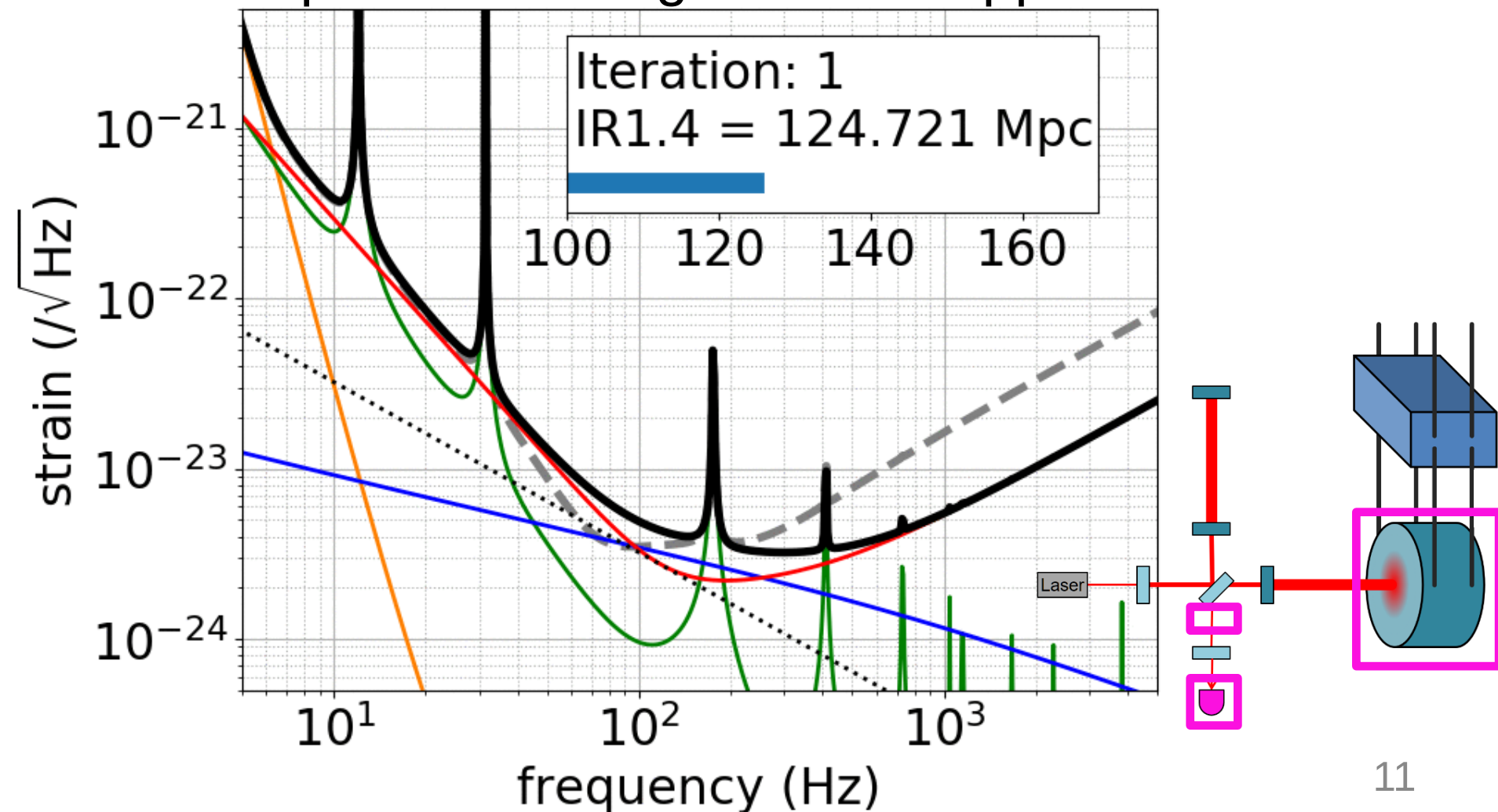
3 Parameter Optimization

- **Consistent** with grid-based approach



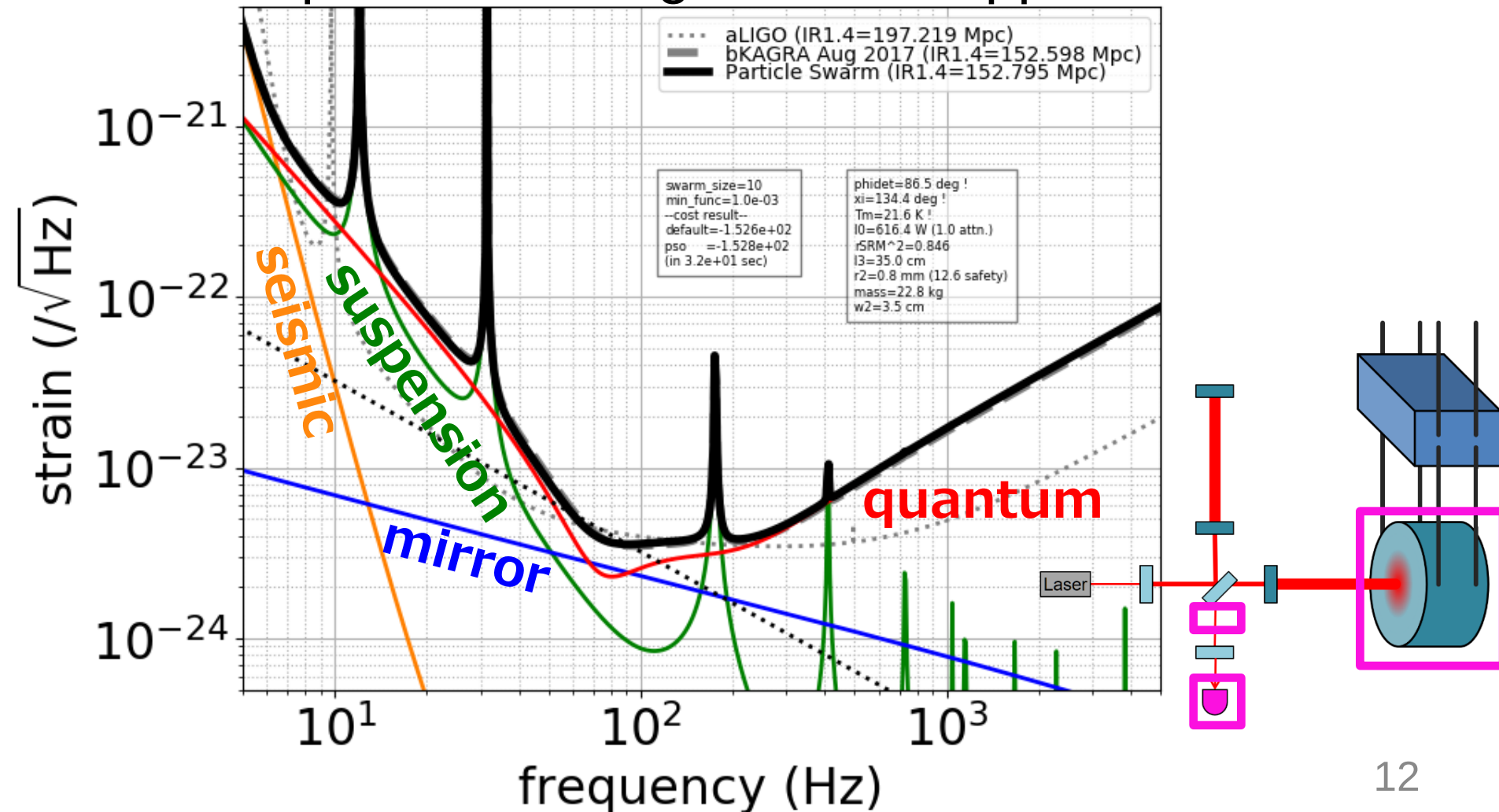
3 Parameter Optimization

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



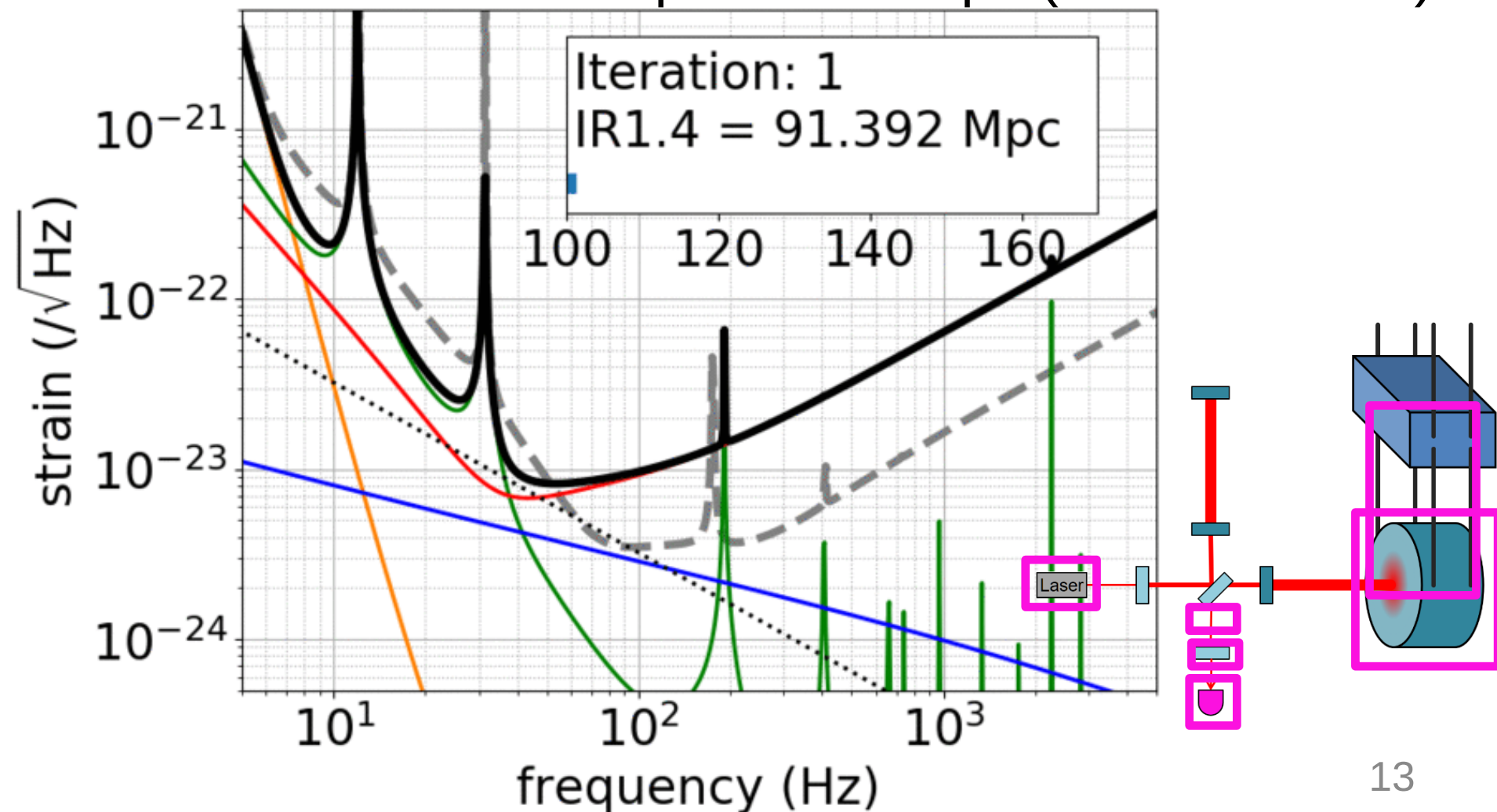
3 Parameter Optimization

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



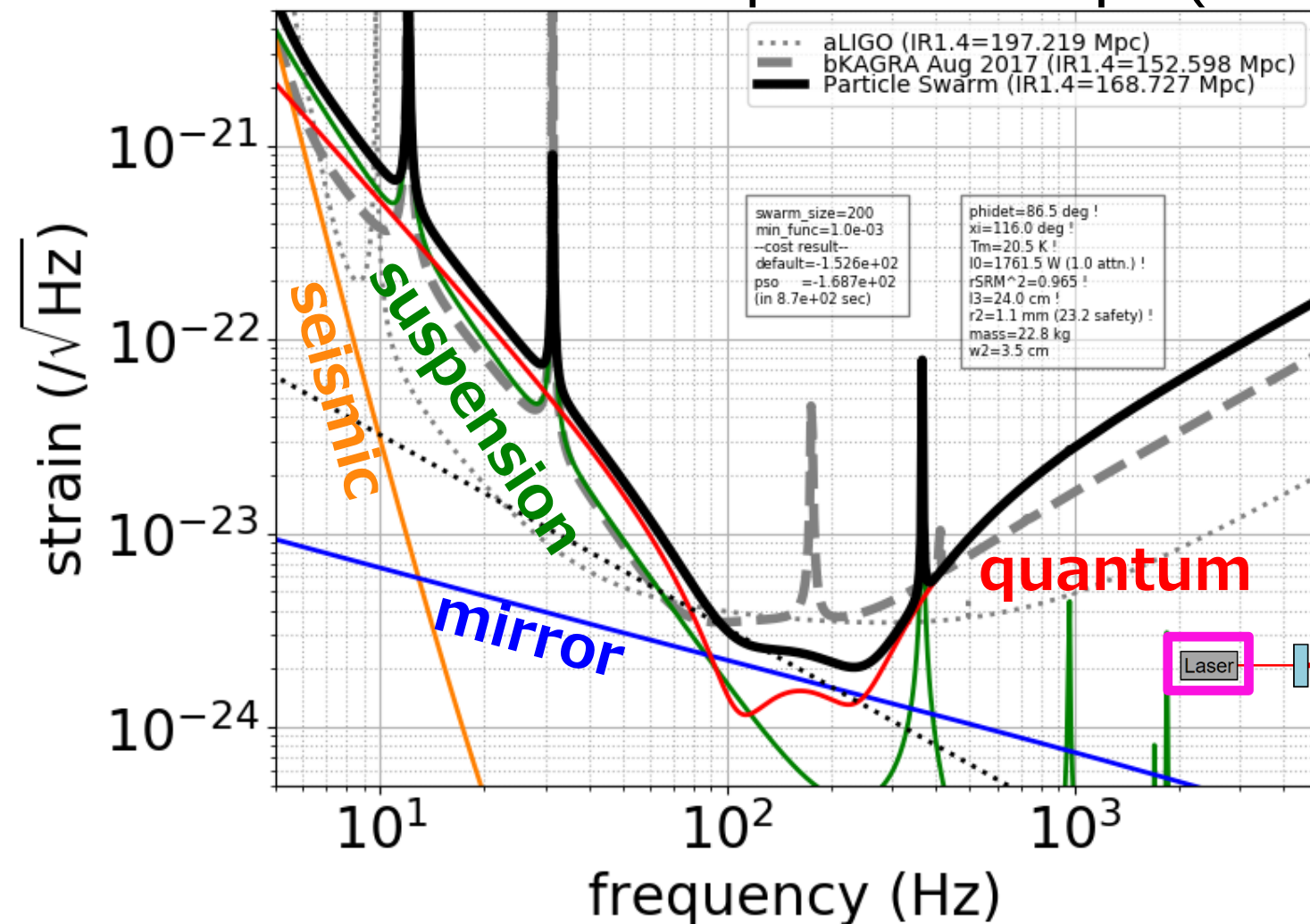
7 Parameter Optimization

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

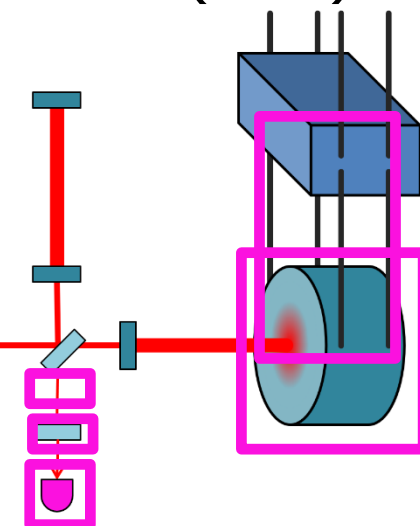


7 Parameter Optimization

- 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	$\sim 10^5$	$10 \times (52 \pm 13)$
5 params	$\sim 10^9$	$20 \times (73 \pm 16)$
7 params	$\sim 10^{14}$	$200 \times (60 \pm 18)$

* 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

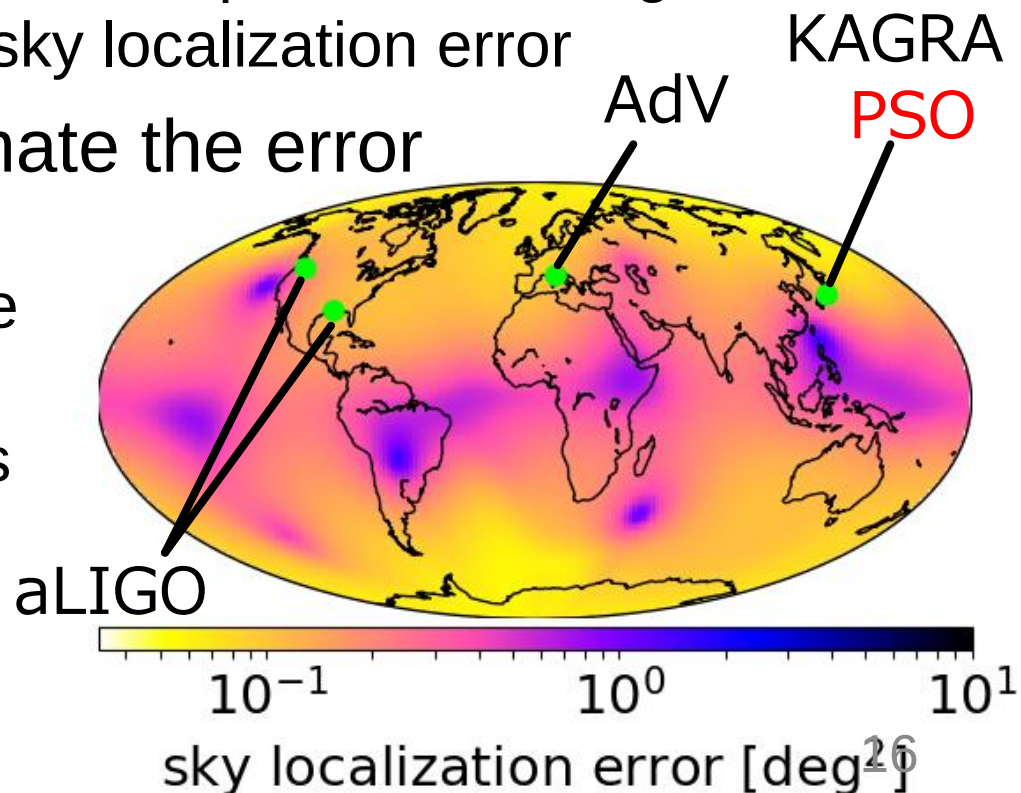
Sky Localization Optimization

- 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

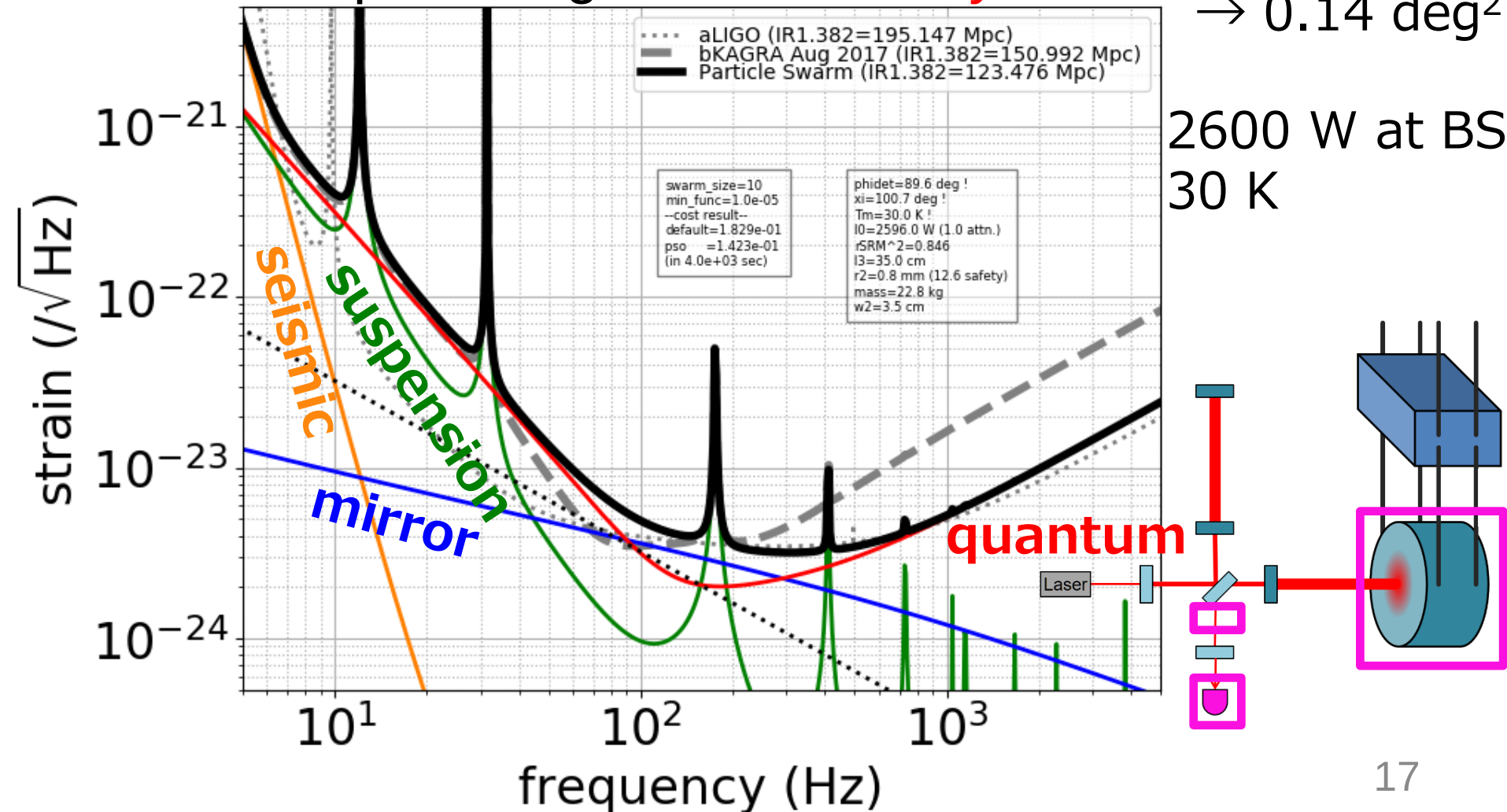


3 Parameter Optimization

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

0.18 deg²
→ 0.14 deg²

2600 W at BS
30 K

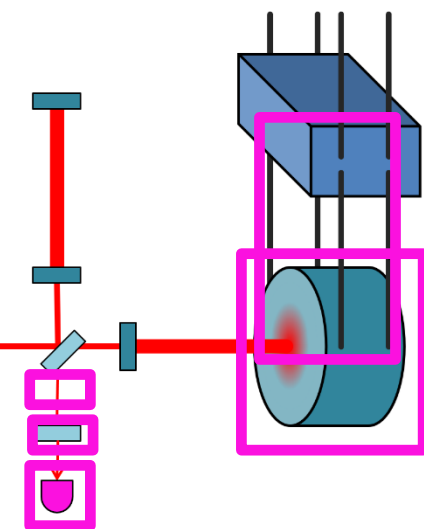
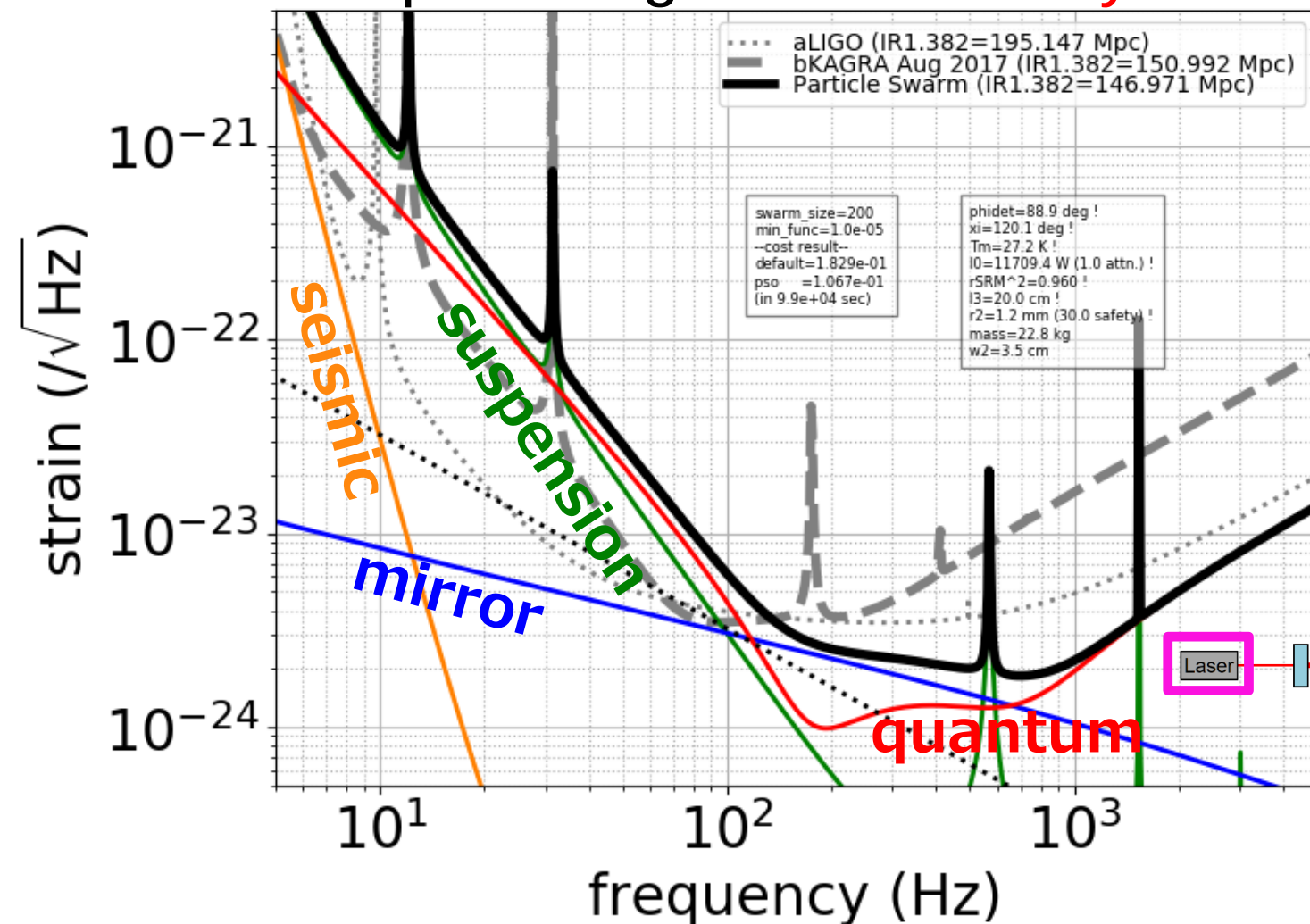


7 Parameter Optimization

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

0.18 deg²
→ 0.11 deg²

shortest and
thickest fibers
12 kW at BS
27 K



KAGRA+ with Budget Constraints

- Let's consider a bit more realistic upgrades

- Suppose you have
\$5M for KAGRA+

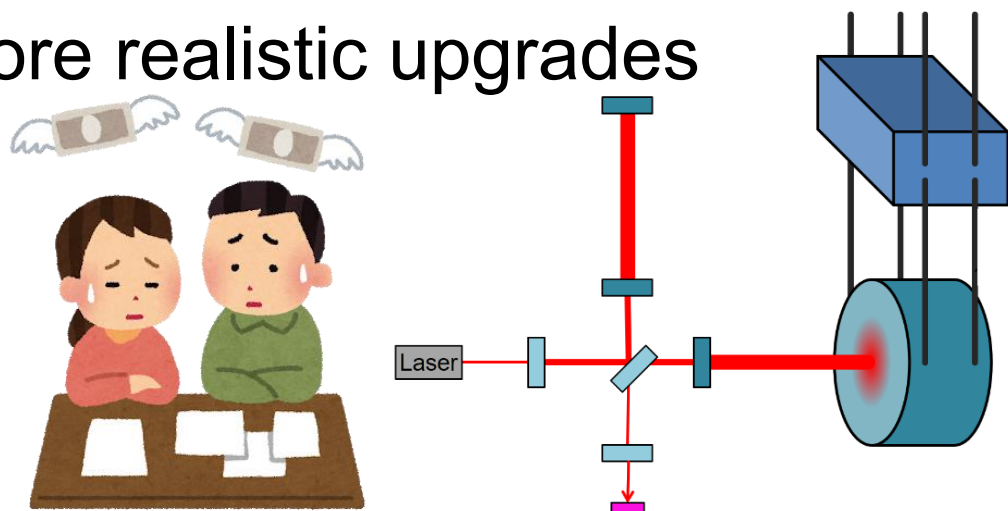
- Candidates would be

A. 40 kg mirror with better coating (>\$4M?)
and new sapphire fibers (\$1M?)

(use existing cryostat and Type-A tower)

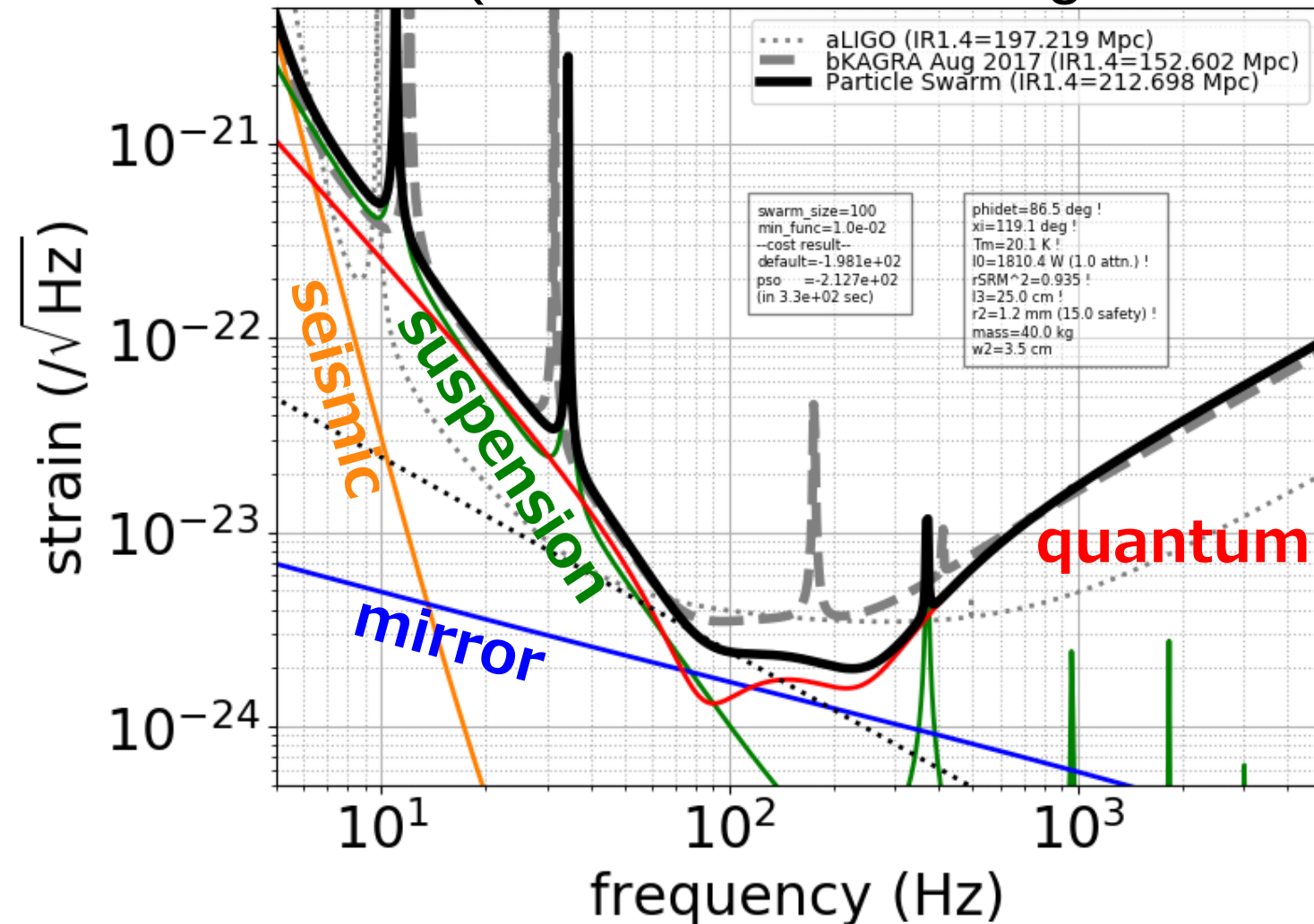
B. 400 W laser (\$3M?) with squeezing (\$1M?)
and new sapphire fibers (\$1M?)

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



Plan A: 40 kg Mirror

- Also assumes factor of 2 coating loss angle reduction (no beam size change assumed)

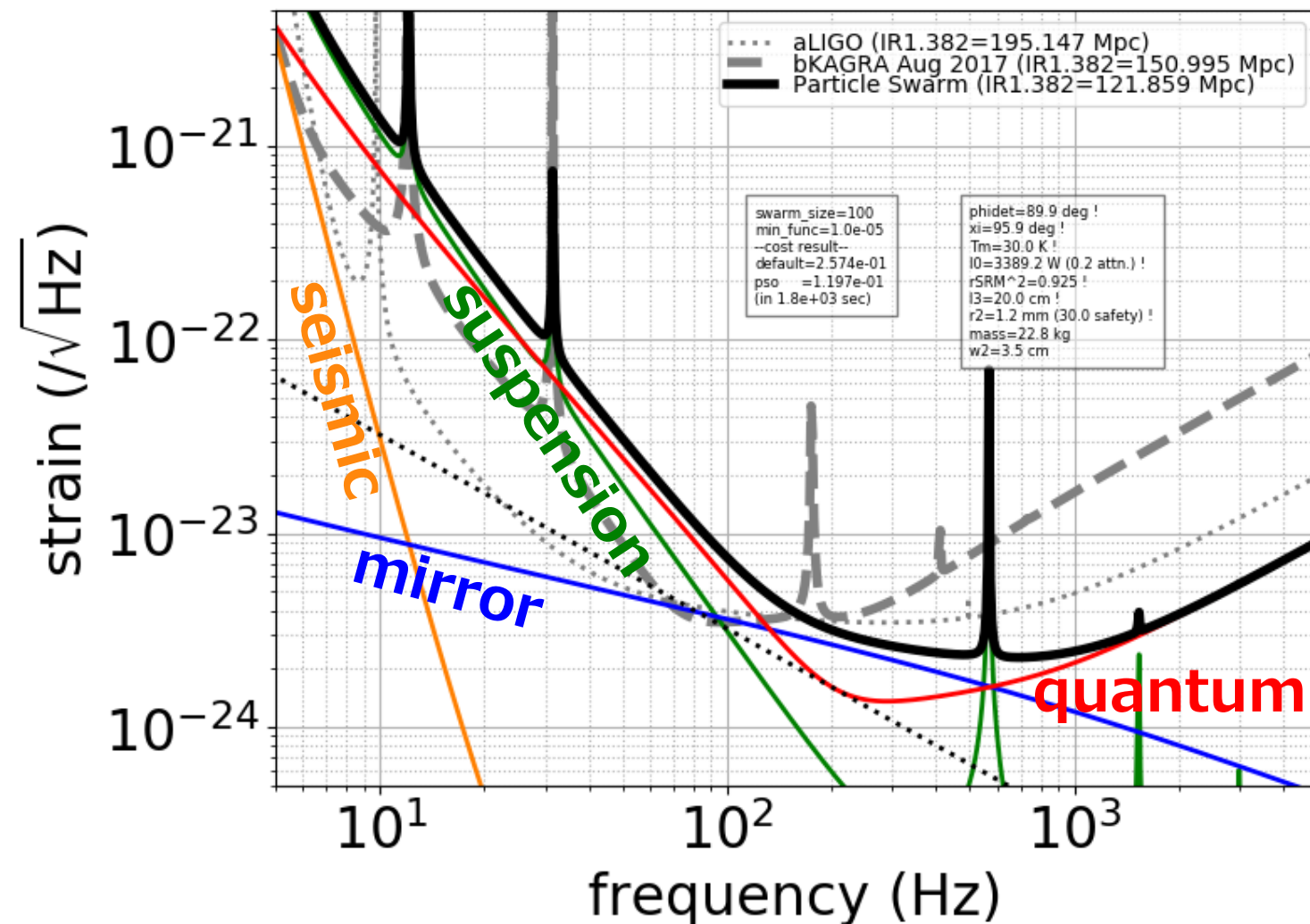


Good for mid frequency improvement
→ BNS range optimized

T=20.1 K
181 W input
thicker fiber
25.0 cm
 $\phi 2.4$ mm
(thicker to allow for higher power)

Plan B: 400 W Laser with SQZ

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

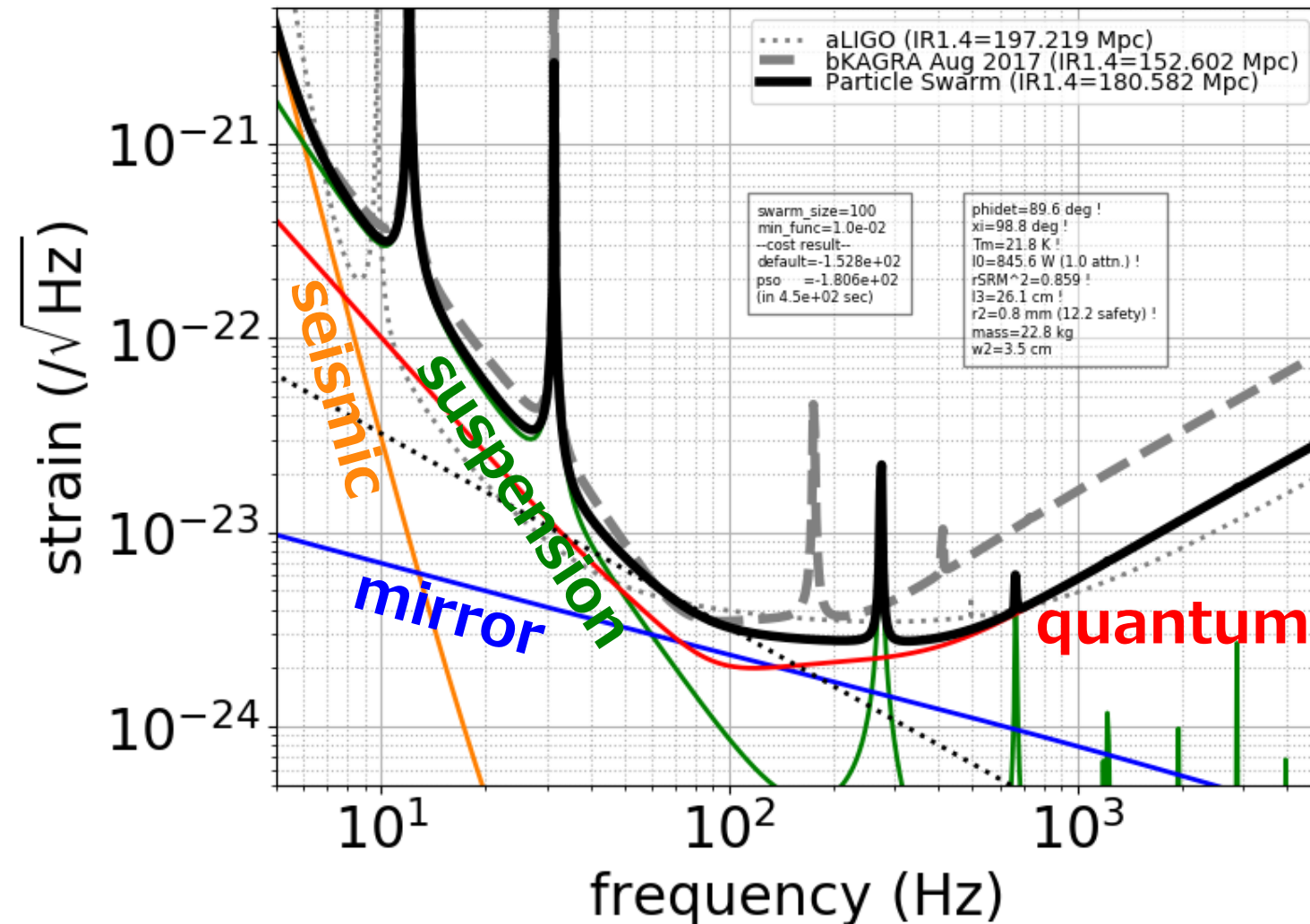


Good for high frequency improvement
→ BNS range optimized

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?



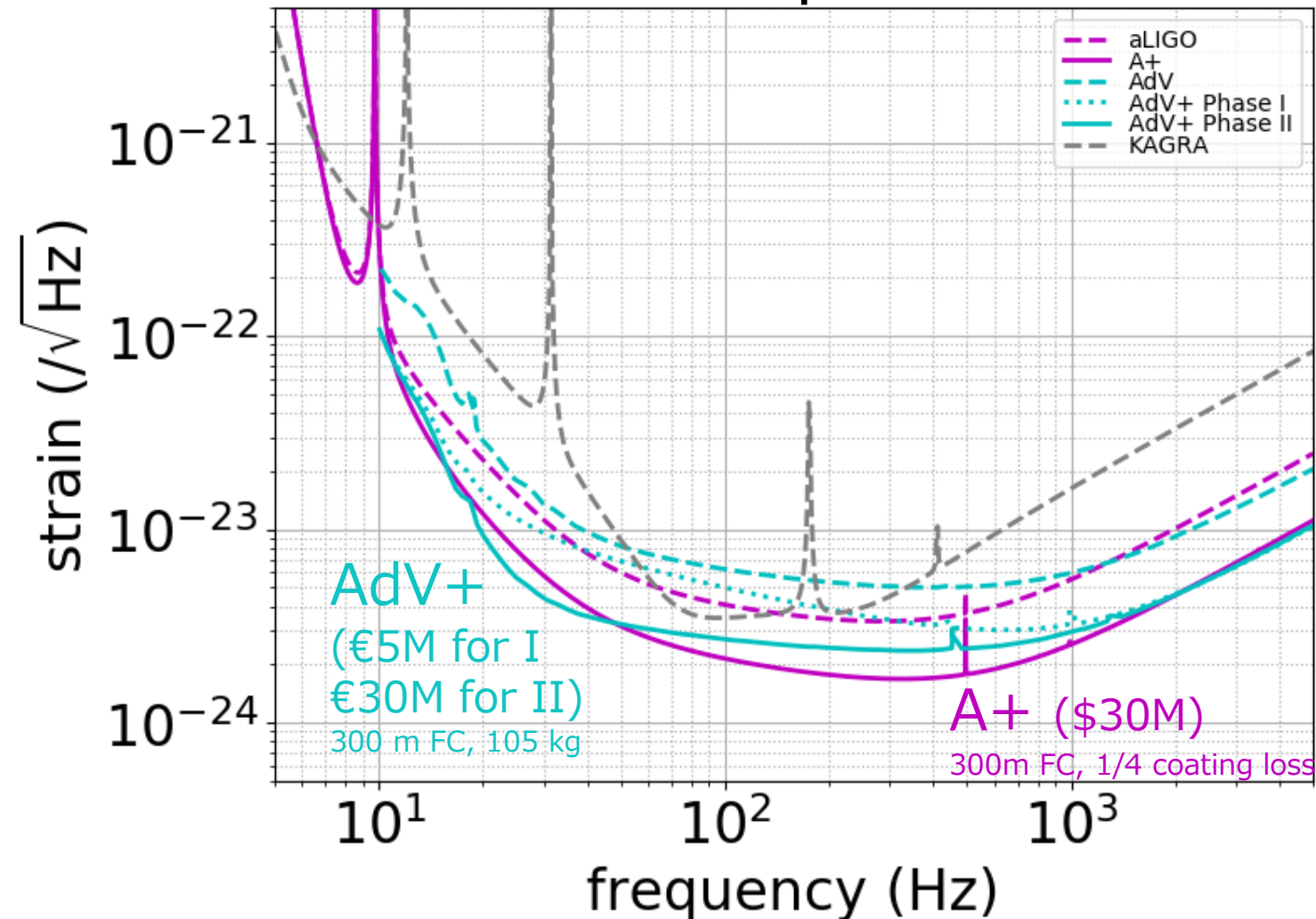
	Inspiral range (Mpc)			BNS localize (deg ²)
	BBH100	BBH30	BNS	
bKAGRA	353	1095	153	0.183
A. 40 kg mirror	339	1096	213	0.151
B. 400 W laser sqz	117	314	123	0.114
C. Freq. dep. sqz	470	1177	181	0.135

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

Comparison Between 2G and 2G+

- A+: 325 Mpc

AdV+ Phase I: 160 Mpc, Phase II: 300 Mpc



aLIGO curve
from

[LIGO-T1800044](https://arxiv.org/abs/LIGO-T1800044)
(updated ver)

A+ curve from

[LIGO-T1800042](https://arxiv.org/abs/LIGO-T1800042)

AdV and AdV+
curves from

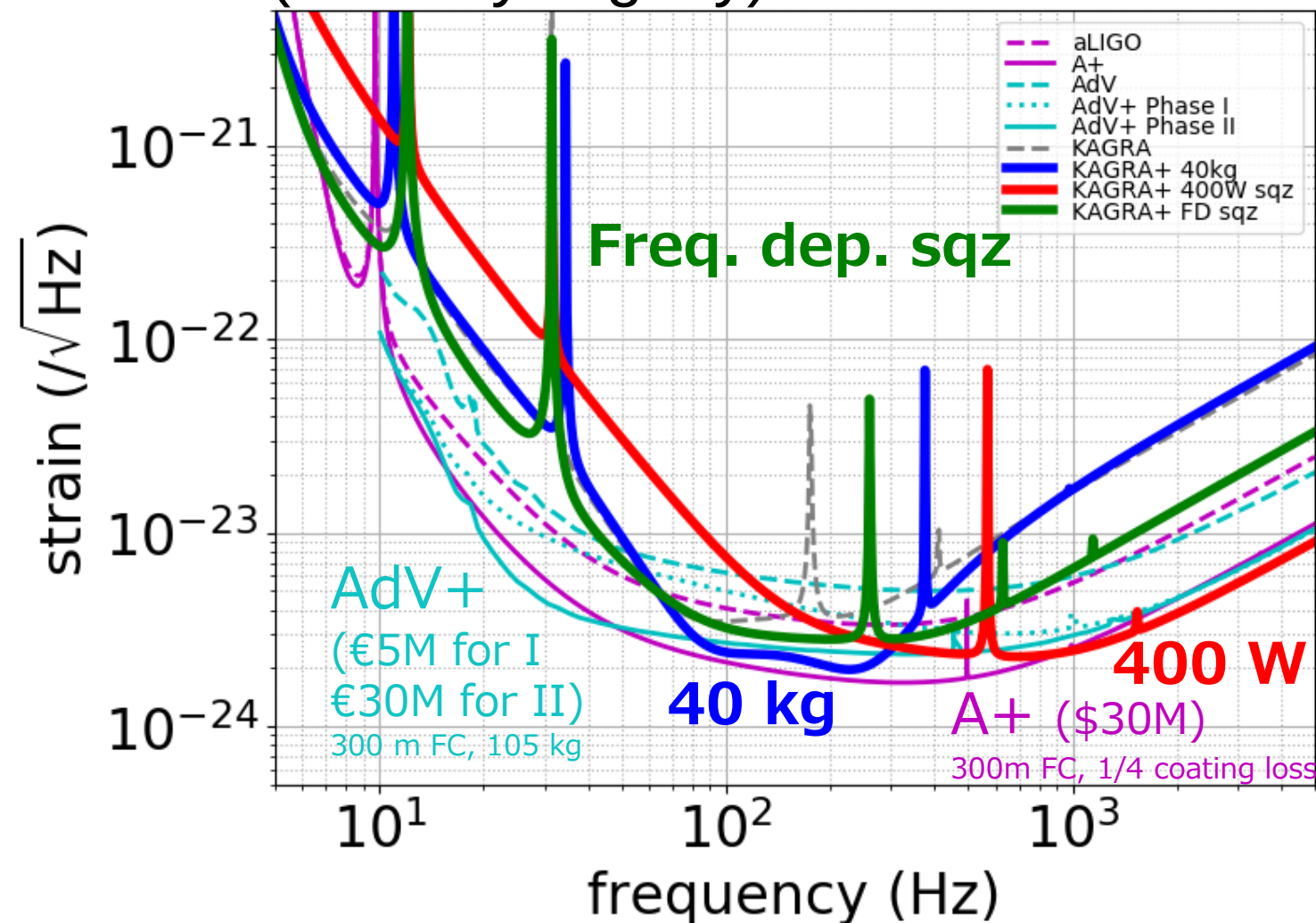
[VIR-0325B-18](https://arxiv.org/abs/VIR-0325B-18)

KAGRA curve
from

[JGW-T1707038](https://arxiv.org/abs/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](https://www.ligo.caltech.edu/publications/LIGO-T1800044) (updated ver)

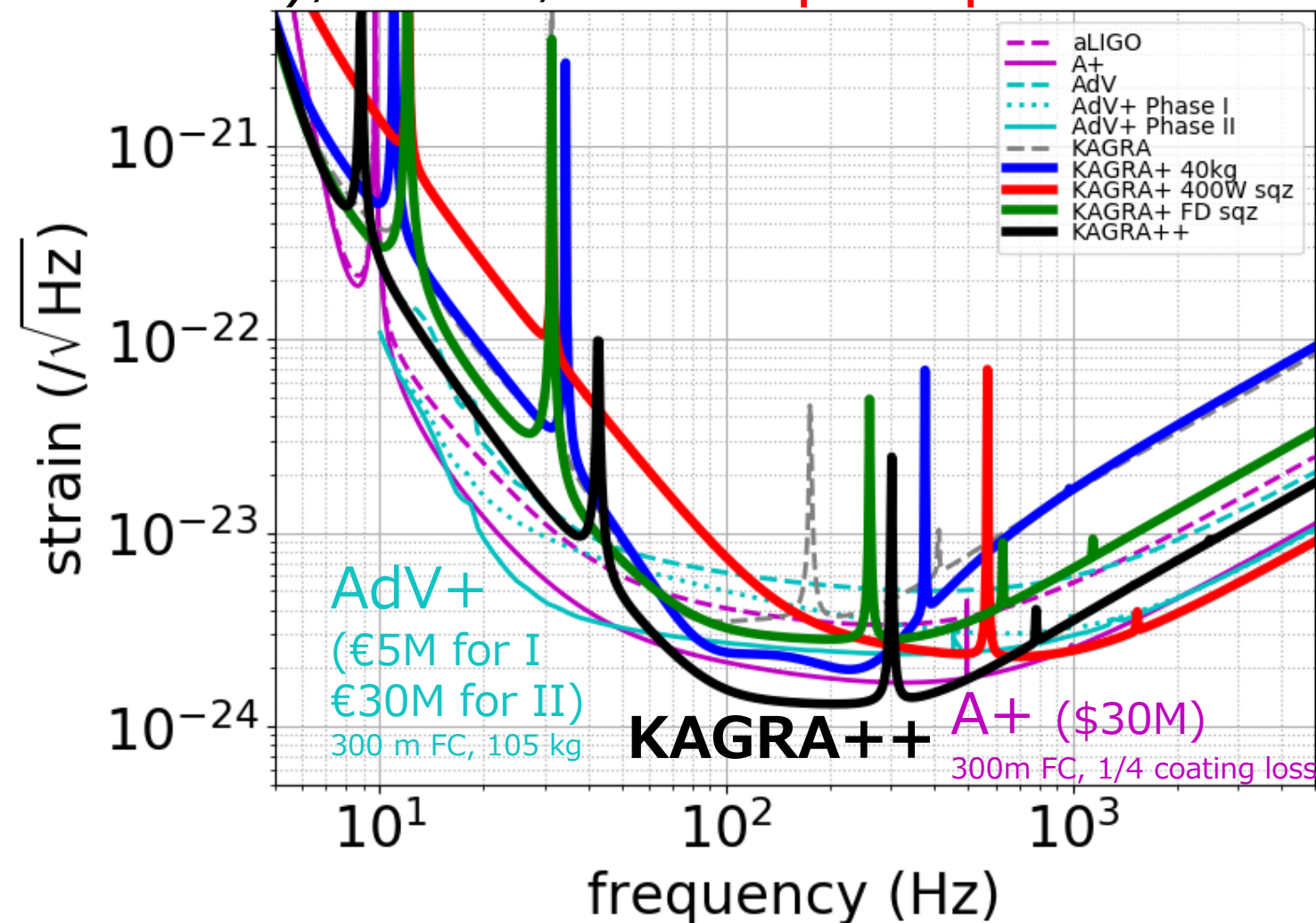
A+ curve from [LIGO-T1800042](https://www.ligo.caltech.edu/publications/LIGO-T1800042)

AdV and AdV+ curves from [VIR-0325B-18](https://www.ligo.caltech.edu/publications/VIR-0325B-18)

KAGRA curve from [JGW-T1707038](https://www.ligo.caltech.edu/publications/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 ?



Summary

- Demonstrated sensitivity design with **PSO**
- Application to KAGRA shows both

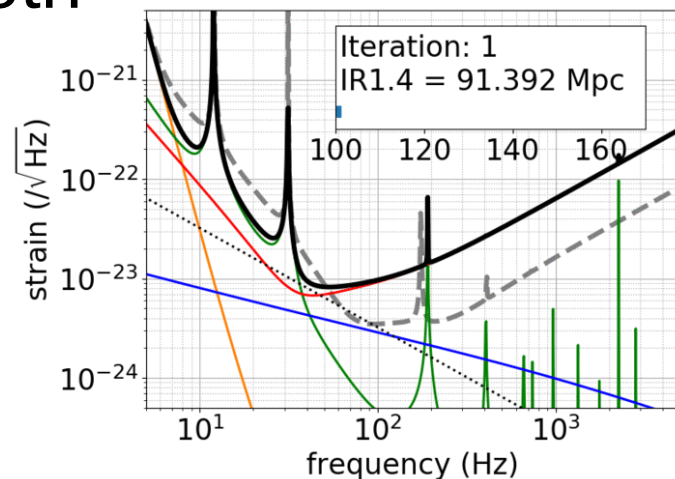
- BNS **inspiral range**
- BNS **sky localization**

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

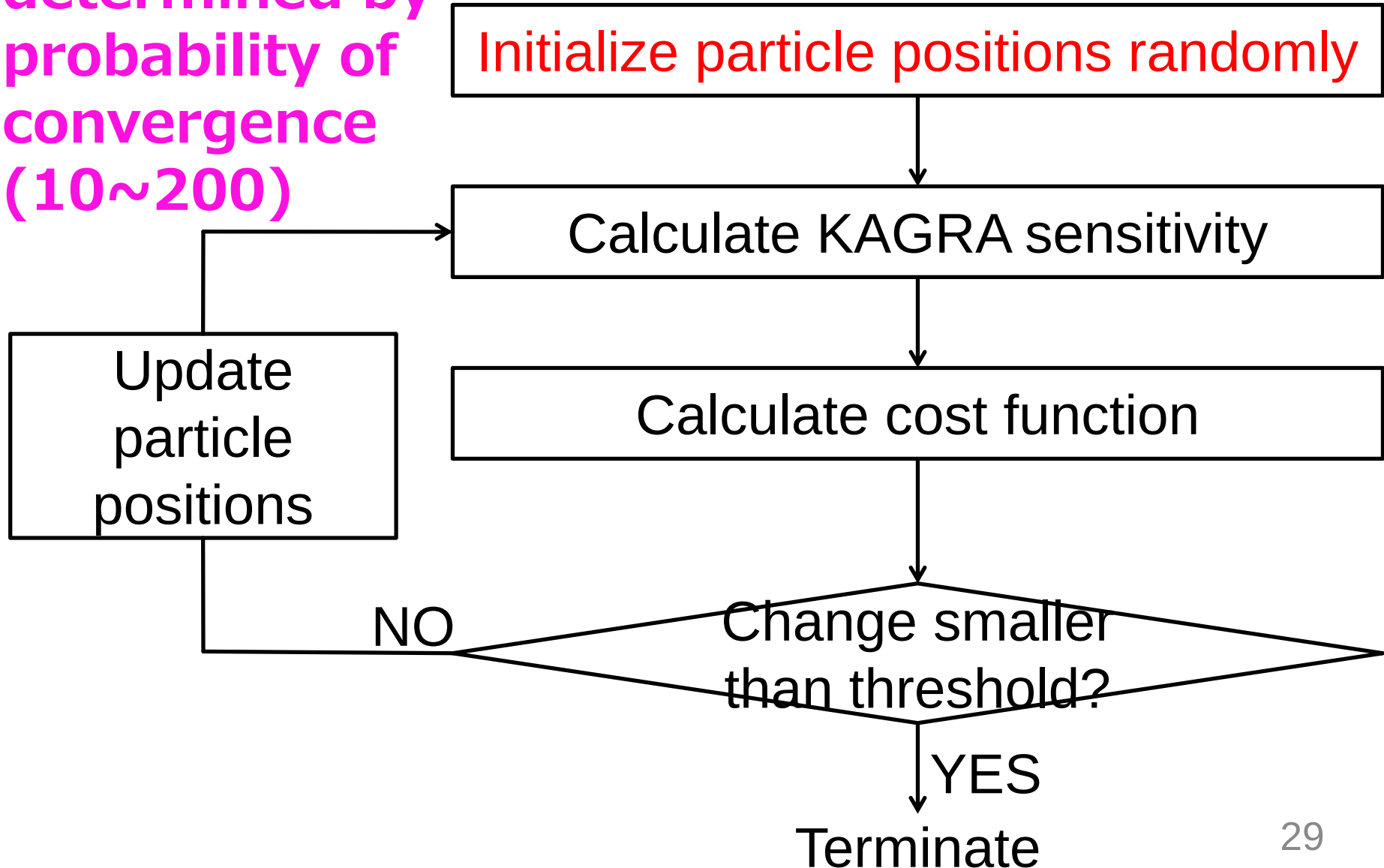
Sensitivity data available at [JGW-G1808426](#)



Supplementary Slides

PSO Algorithm

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



PSO Algorithm

Initialize particle positions randomly

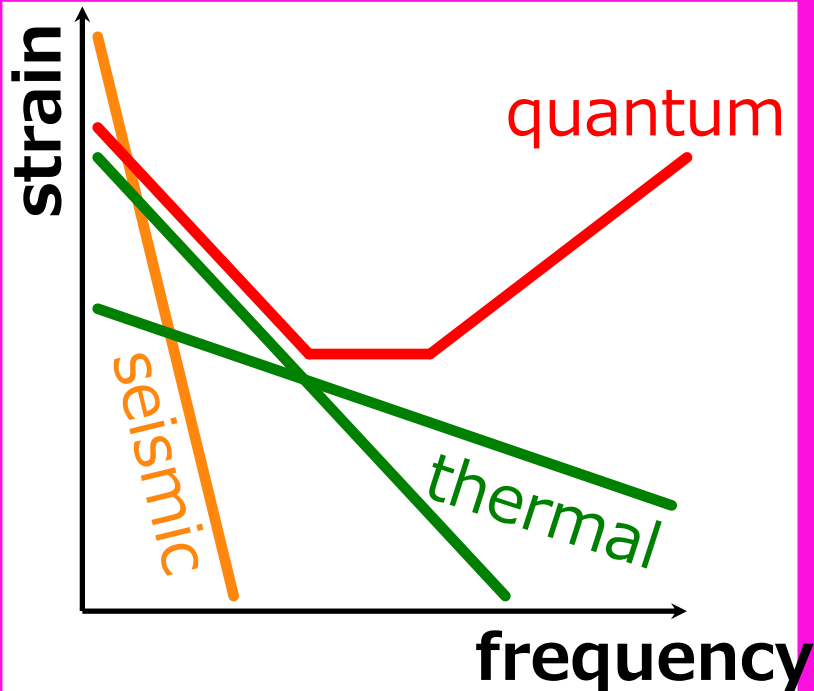
Calculate KAGRA sensitivity

Calculate cost function

Change smaller
than threshold?

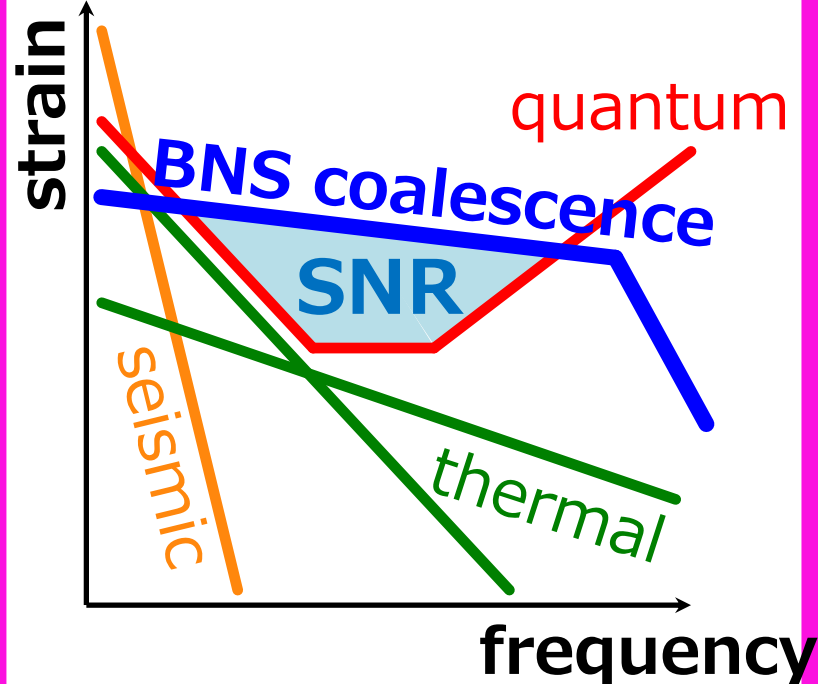
YES

Terminate



PSO Algorithm

BNS inspiral range
as a cost function



Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

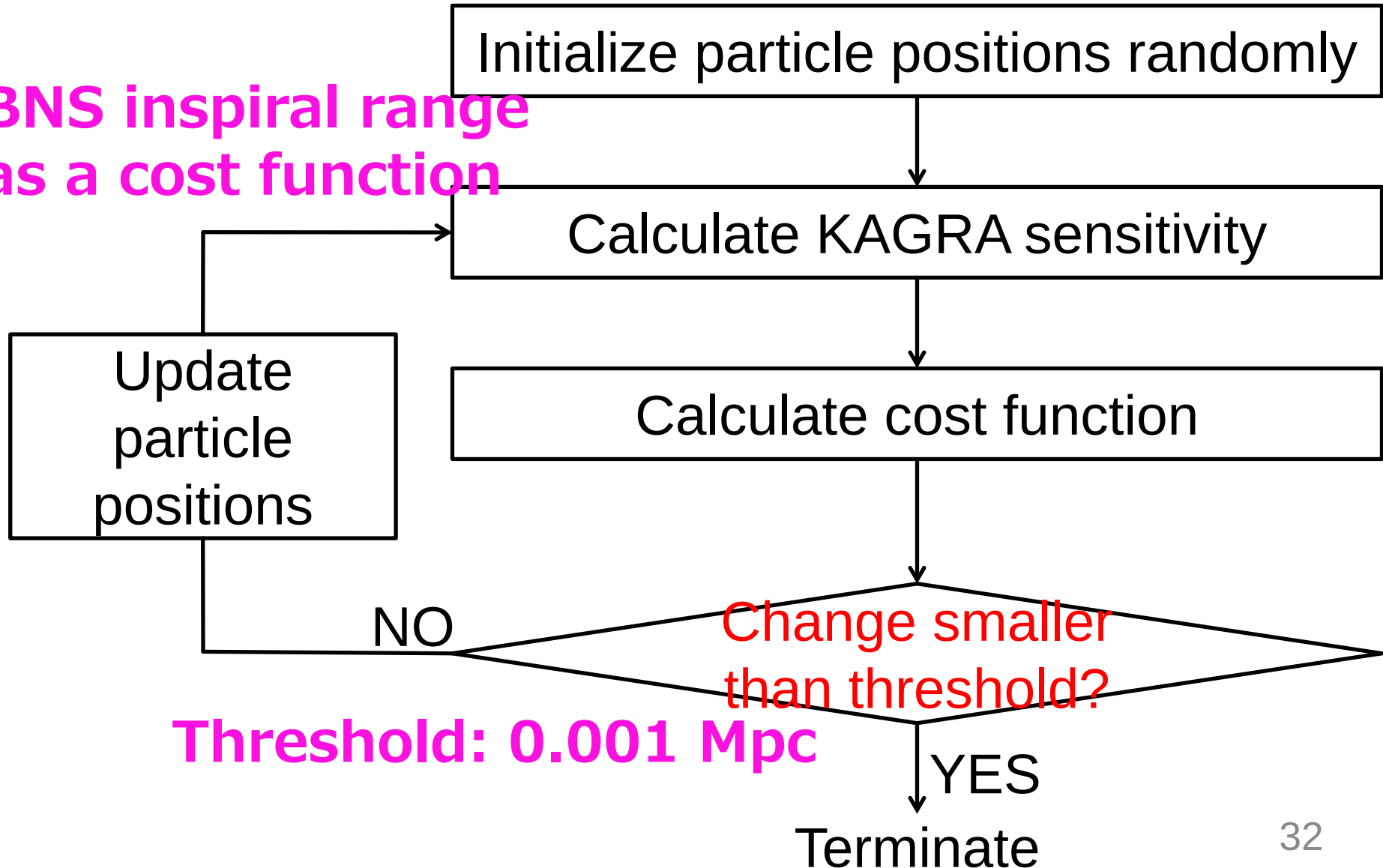
Change smaller
than threshold?

YES

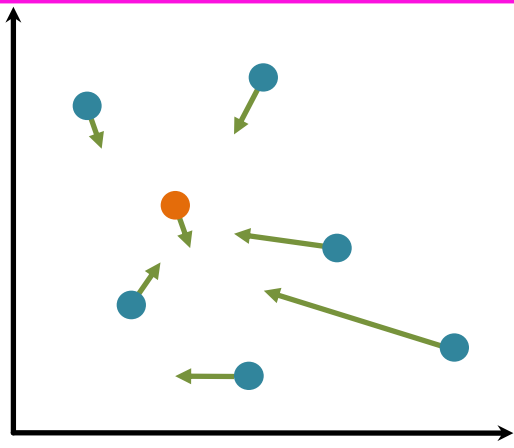
Terminate

PSO Algorithm

**BNS inspiral range
as a cost function**



PSO Algorithm



Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

Update
particle
positions

NO

Change smaller
than threshold?

YES

Terminate

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

$$v_k(t+1) = wv_k(t) + c_1r_1(\hat{x}_k - x_k(t)) + c_2r_2(\hat{x}_g - x_k(t))$$

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



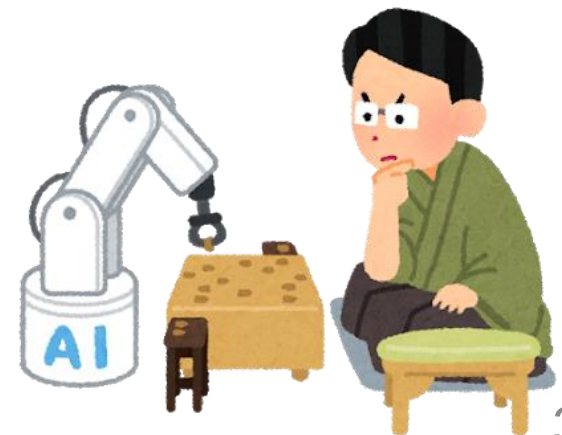
Pros and Cons of PSO

- **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} deg²
- 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](#))

- *Reflecting wall* boundary:
 $x = x_{\max}, v = -v$ if $x > x_{\max}$
 $x = x_{\min}, v = -v$ if $x < x_{\min}$

step size which changes
BNS inspiral range by 0.1 Mpc

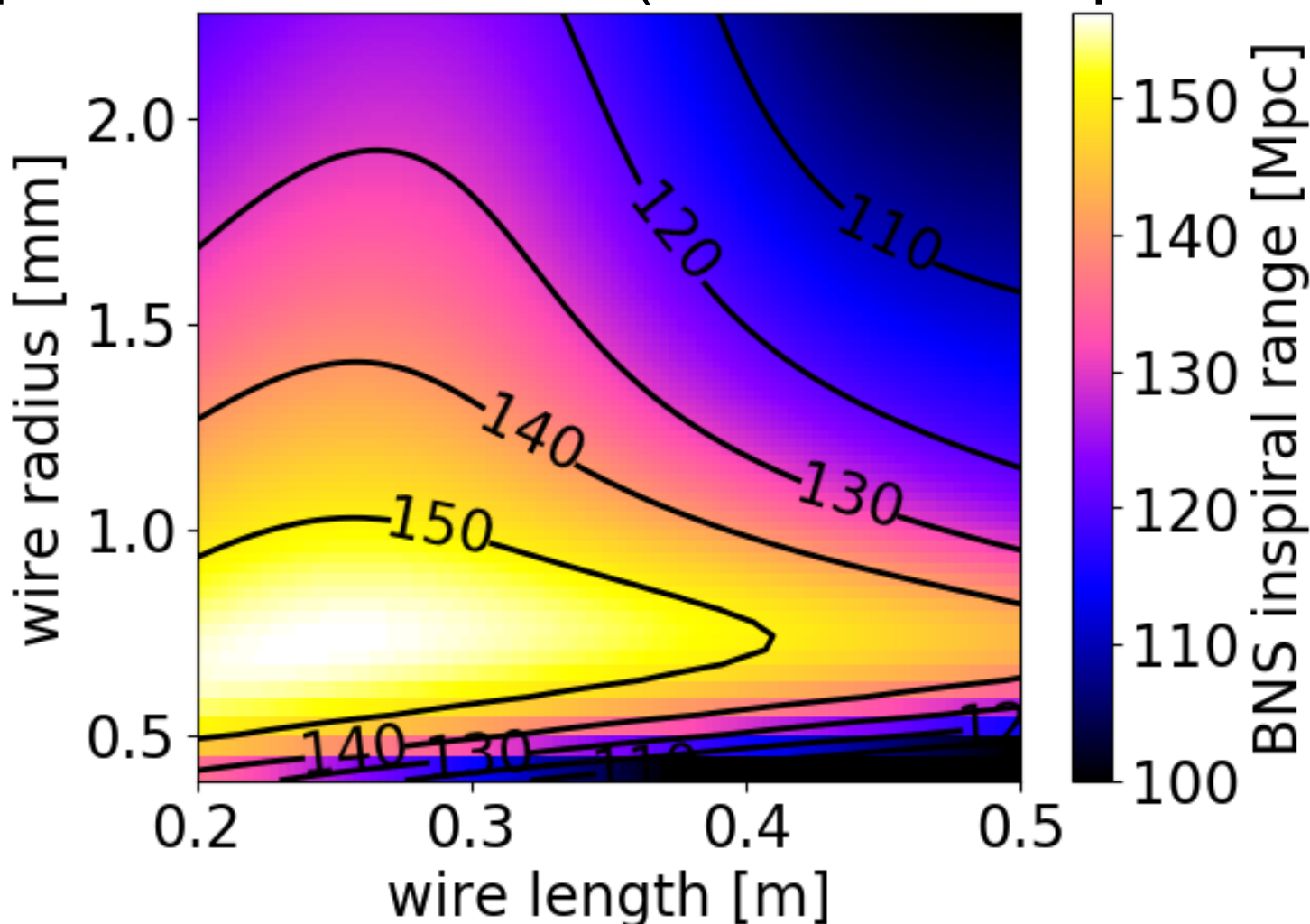


Money

- 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/ ϕ 1.4mm is optimum for BNS IR if other parameters are fixed (default: 35cm/ ϕ 1.6mm)



Fisher Matrix Analysis

- Fisher matrix

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

- 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 $\chi_{s/a} = (\chi_1 \pm \chi_2)/2$

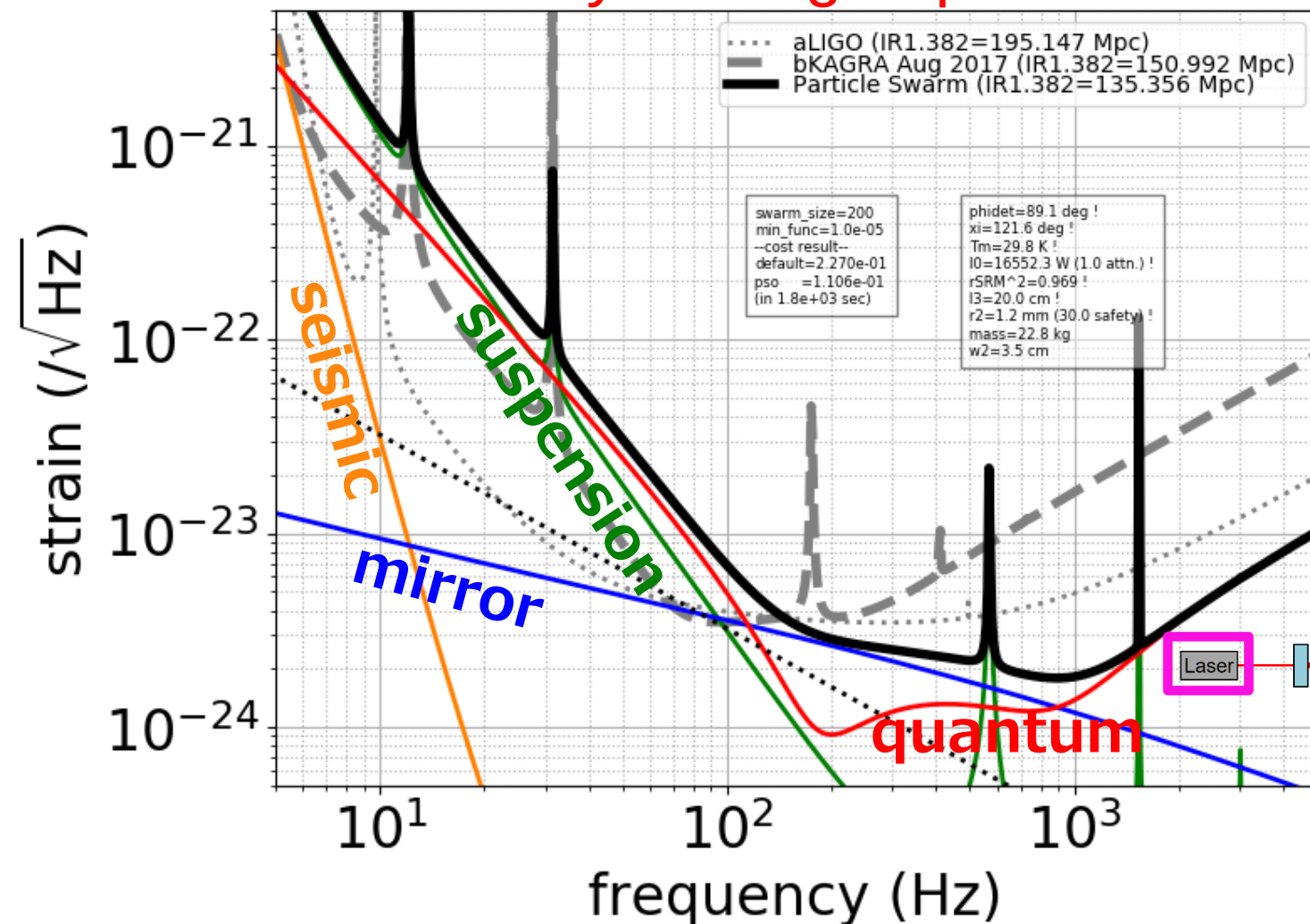
thetas, **phis**: colatitude / longitude of source

cthetai: inclination angle

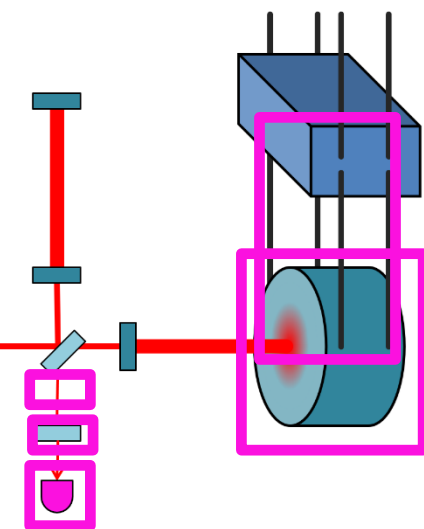
psip: polarization angle

Optimization for Fixed Sky Location

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



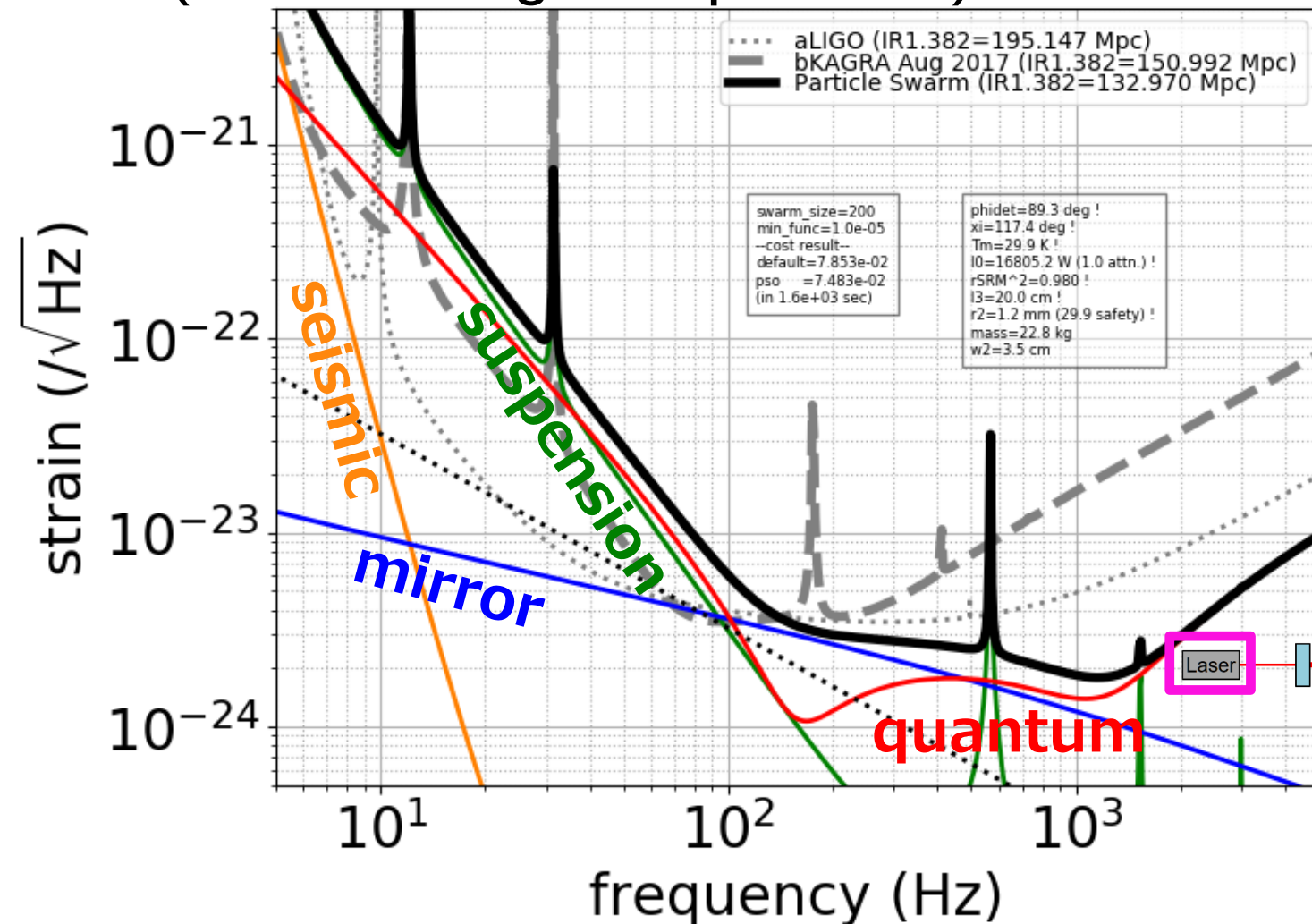
shortest and
thickest fibers
1.7 kW at BS
30 K (max)



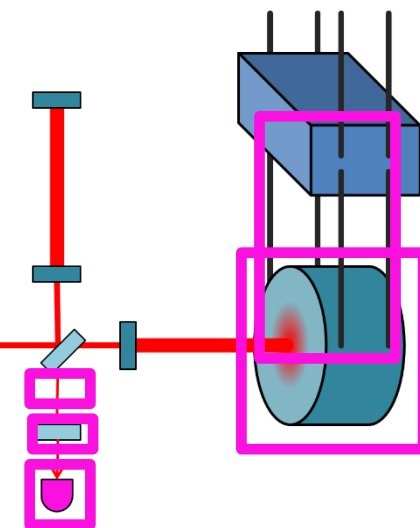
Symmetric Spin Optimization

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

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



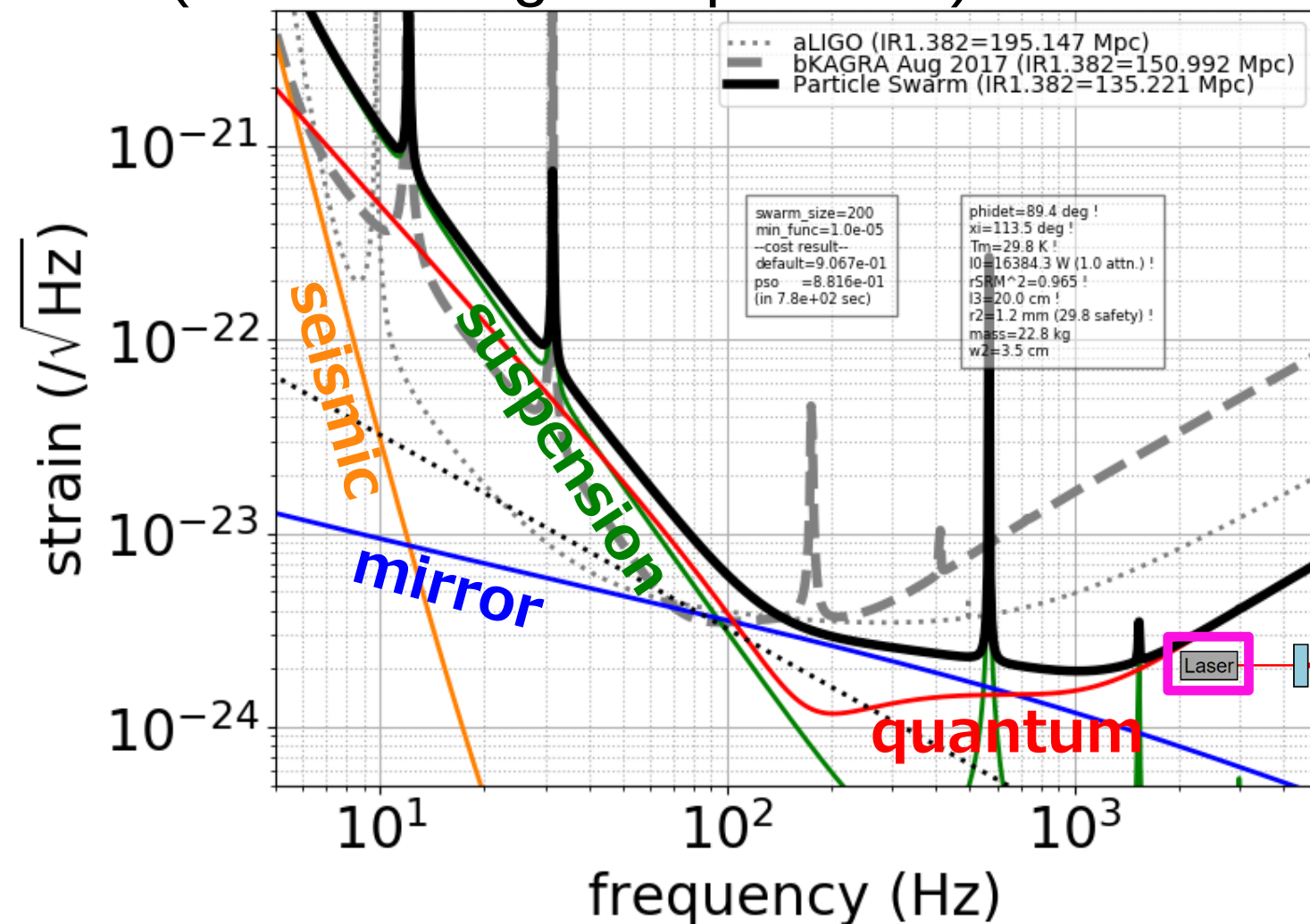
shortest and
thickest fibers
1.7 kW at BS
30 K (max)



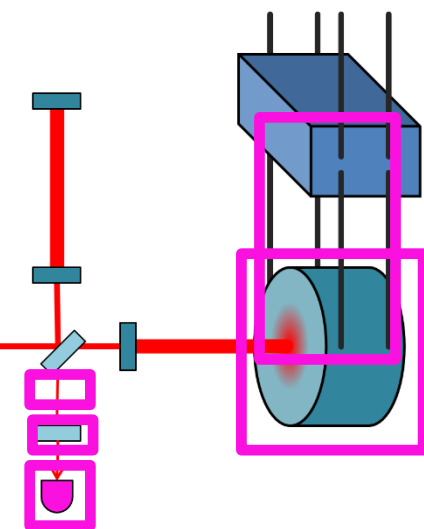
Asymmetric Spin Optimization

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

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

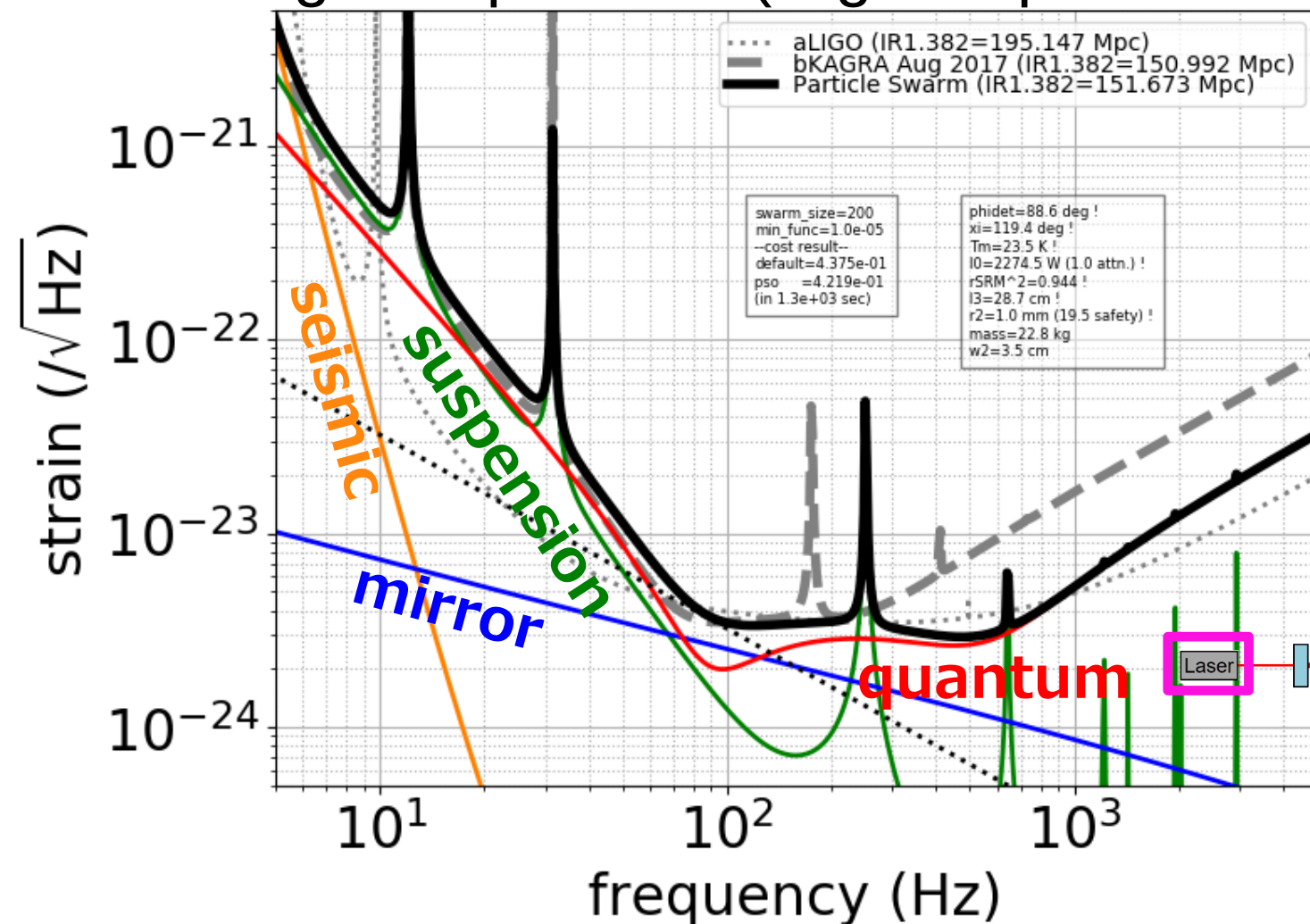


shortest and
thickest fibers
1.7 kW at BS
30 K (max)

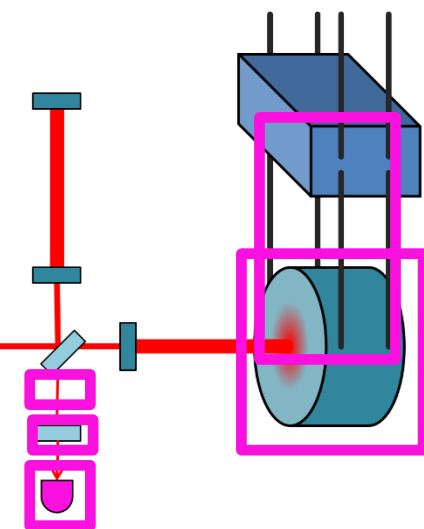


Distance Optimization

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

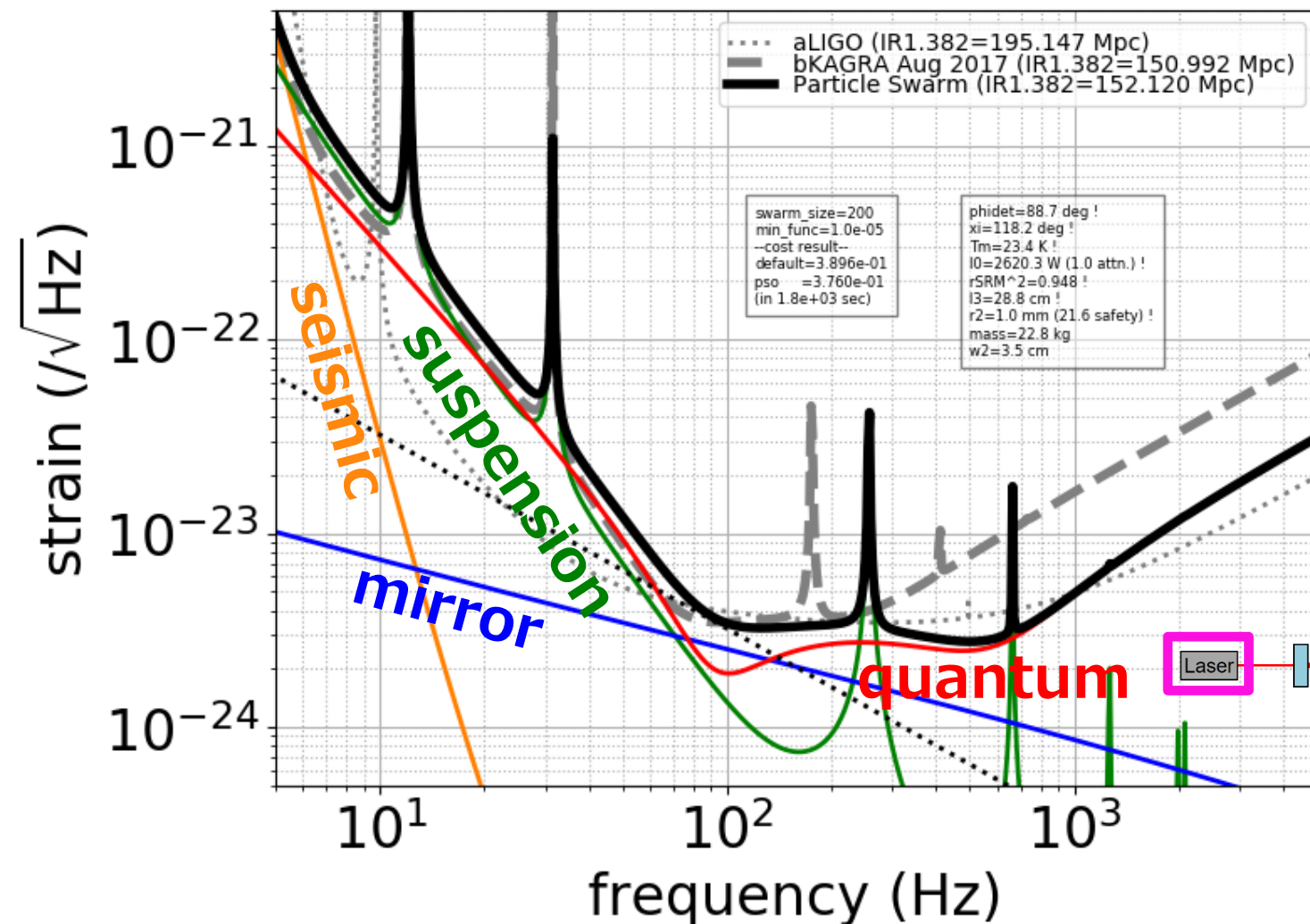


shorter and
thicker fibers
2.3 kW at BS
24 K

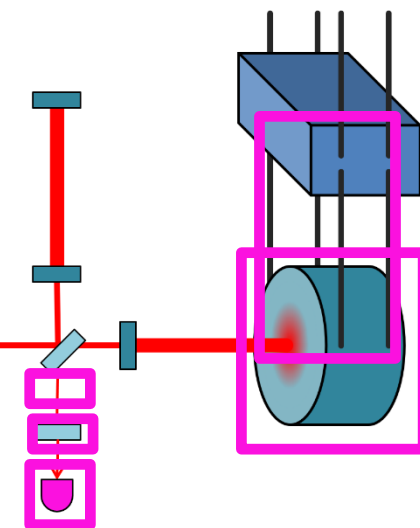


Inclination Angle Optimization

- Similar to distance optimization (PE degeneracy)

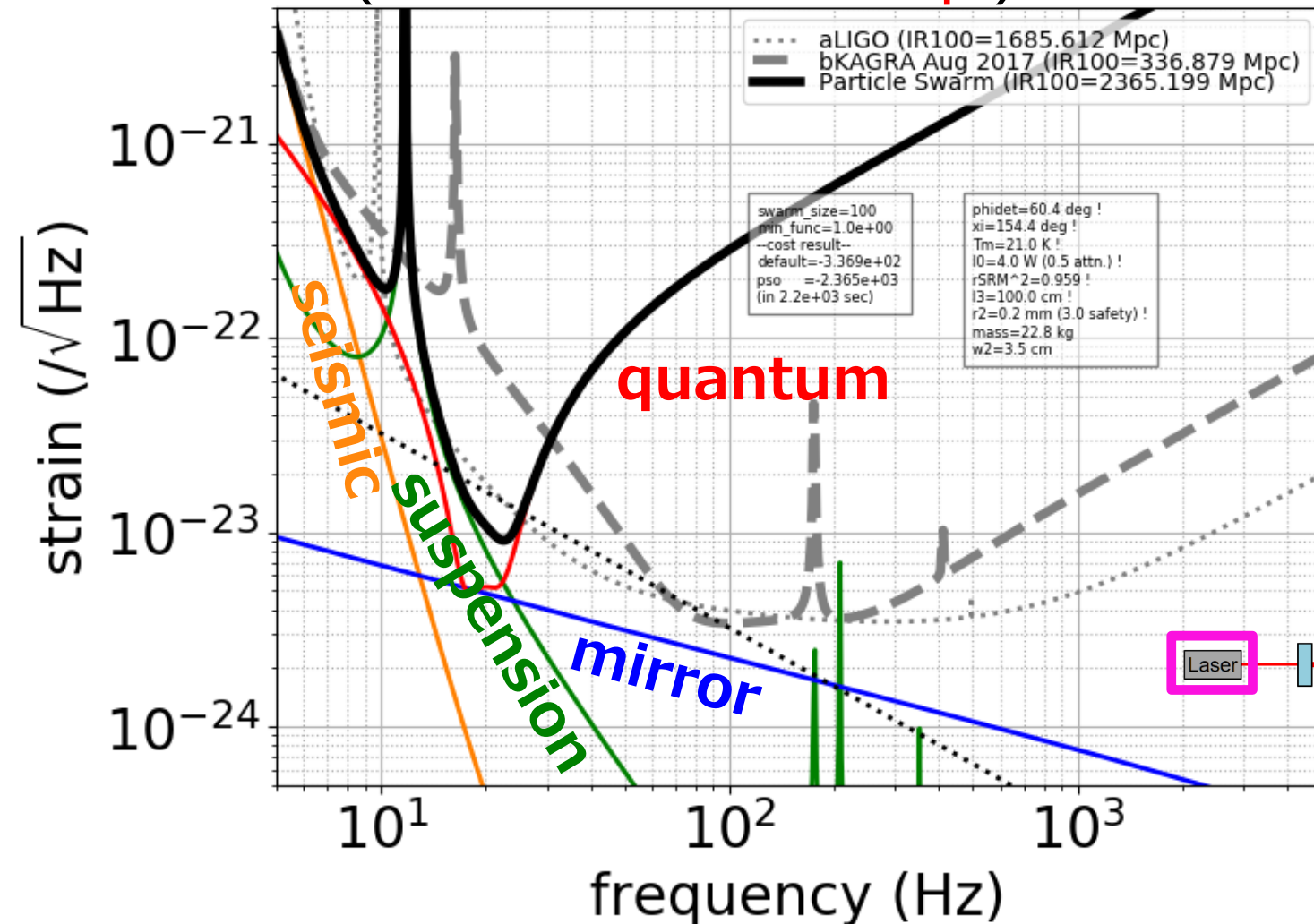


shorter and
thicker fibers
2.3 kW at BS
24 K

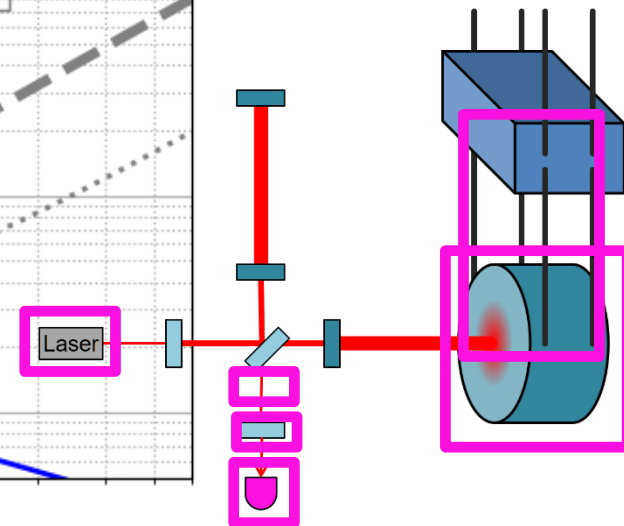


BBH100 IR Optimization

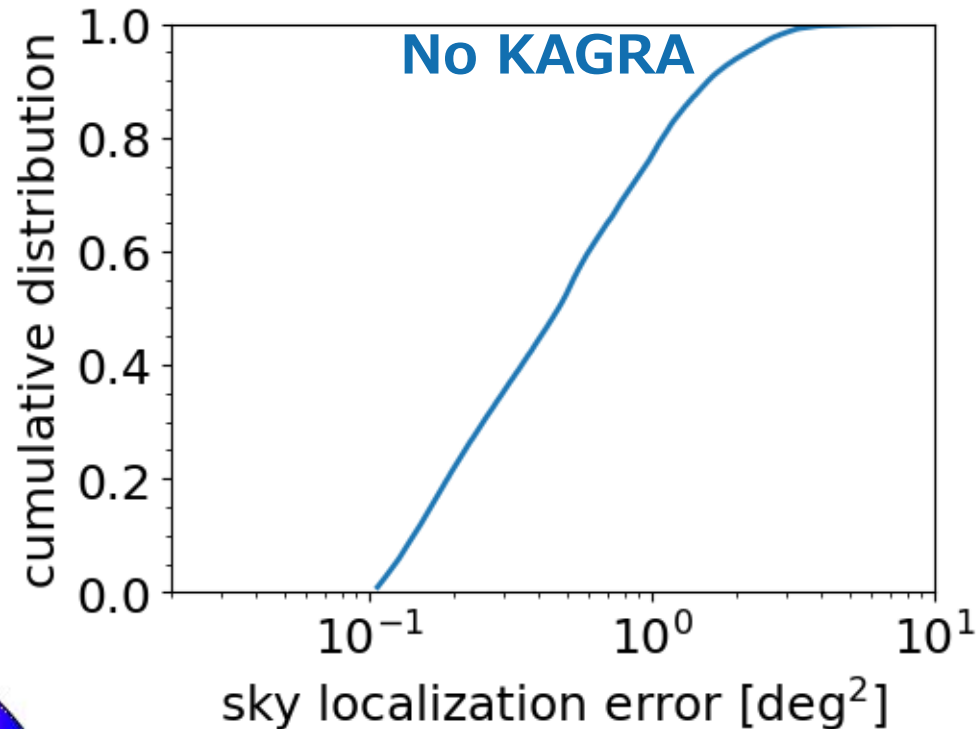
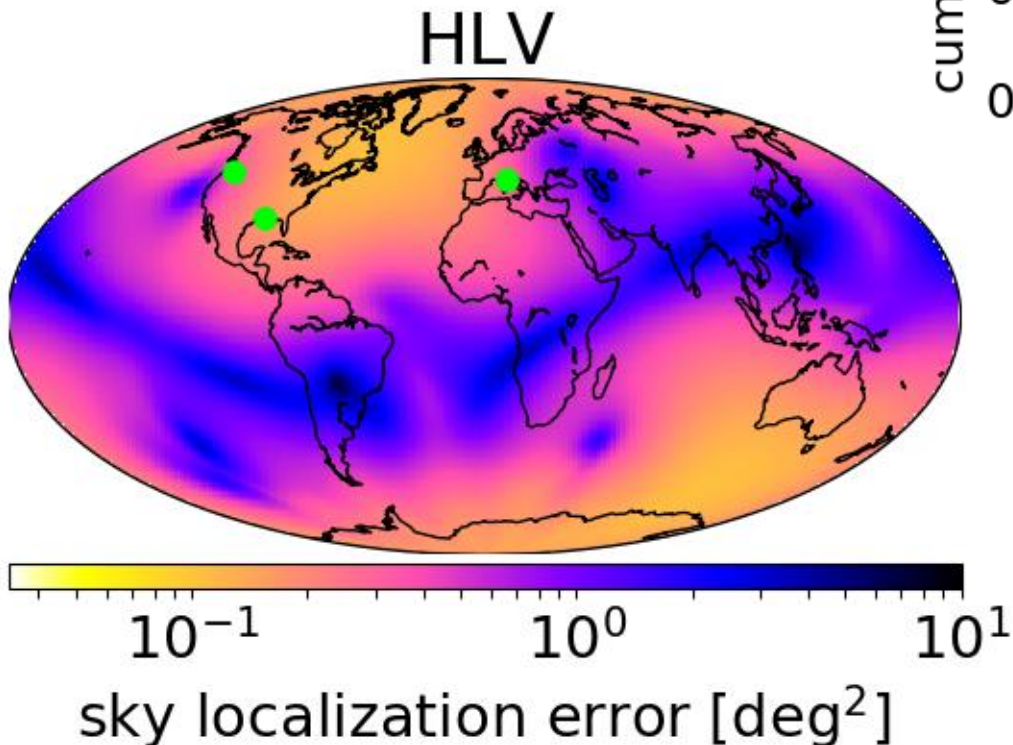
- Low power, low temperature with thin and longer fibers (KAGRA+ **LF concept**)



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

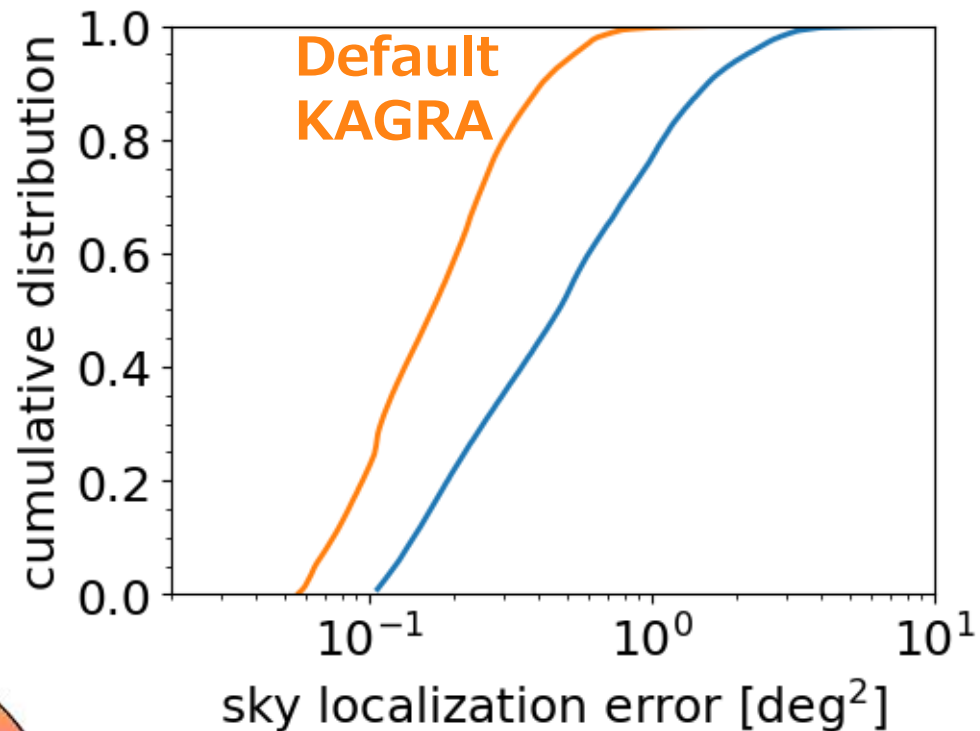
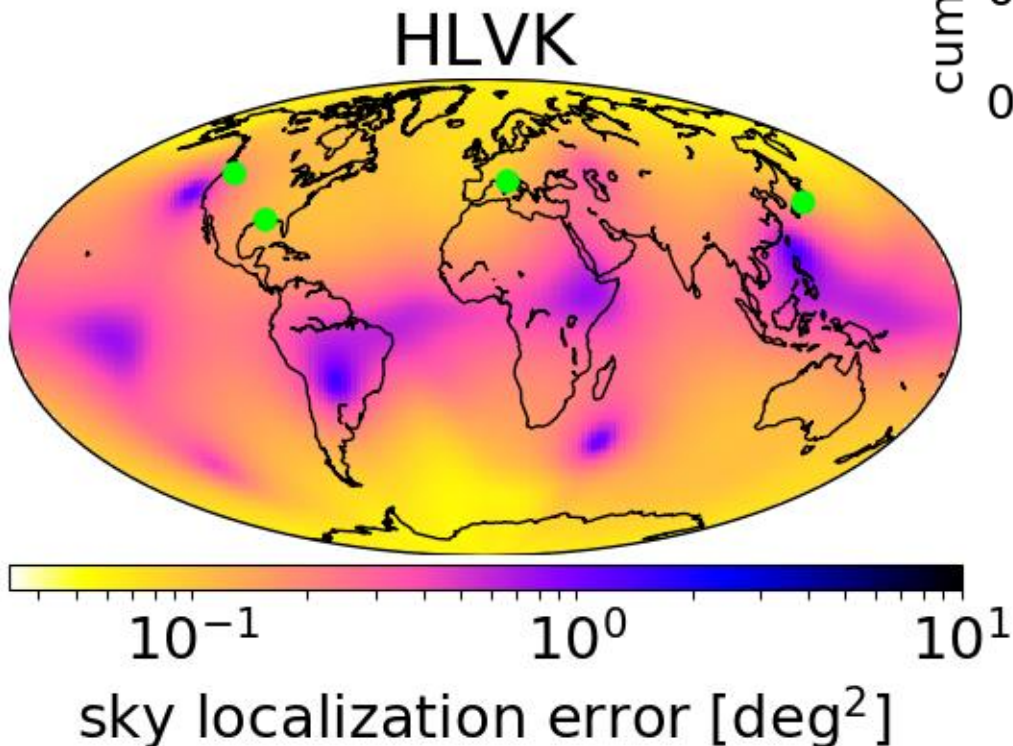


Sky Localization with HLV



	median
HLV	0.472 deg^2
HLVK	
HLVK+	

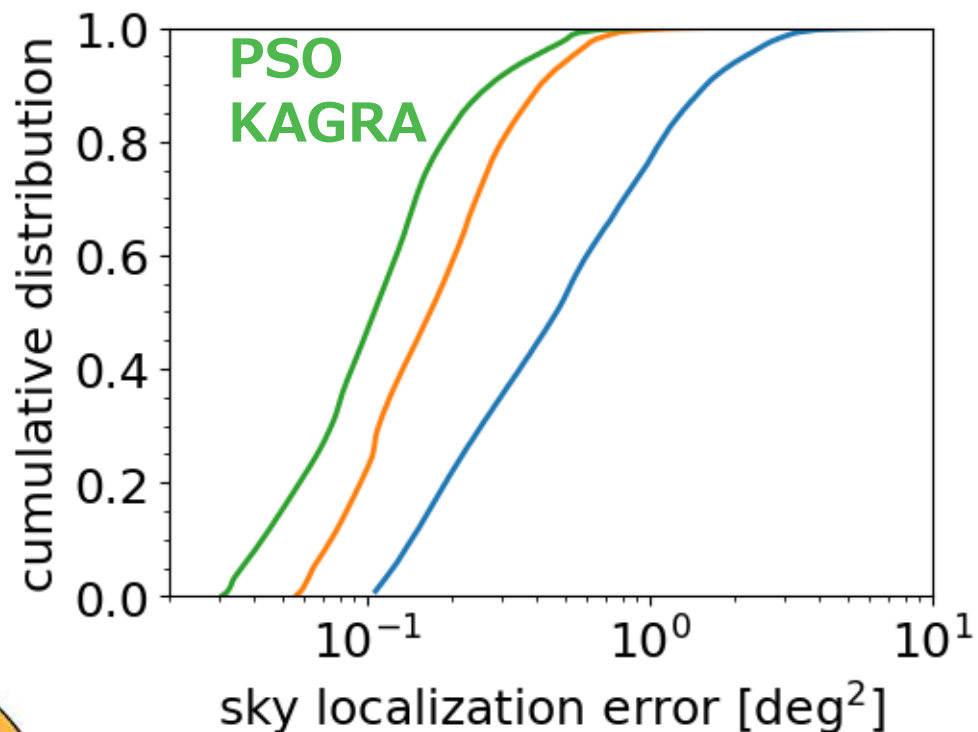
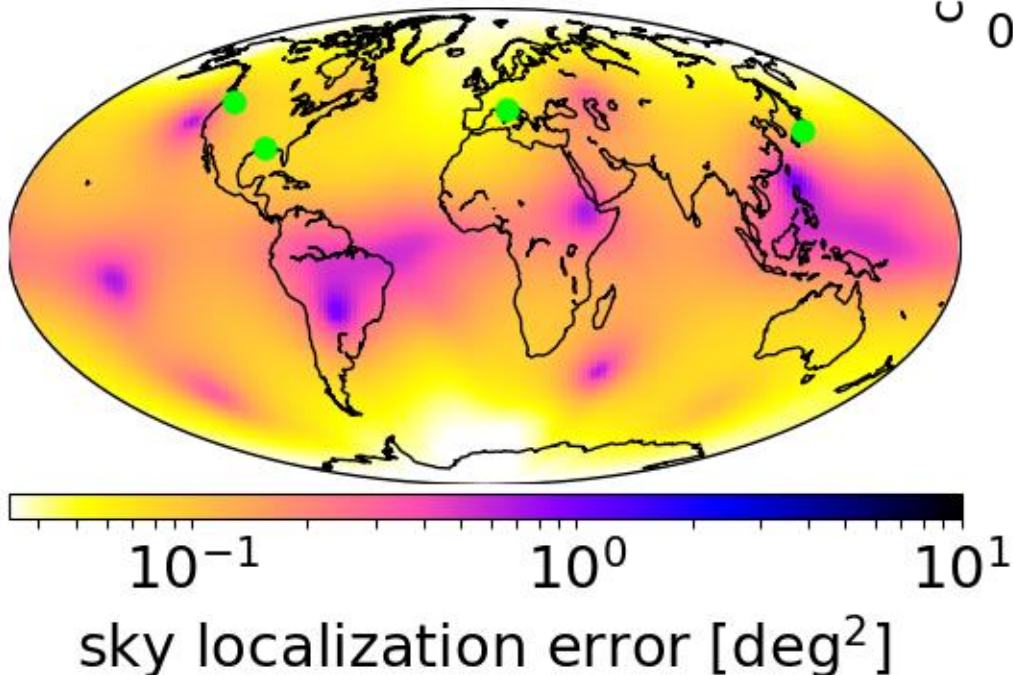
Sky Localization with HLVK



	median
HLV	0.472 deg ²
HLVK	0.168 deg ²
HLVK+	

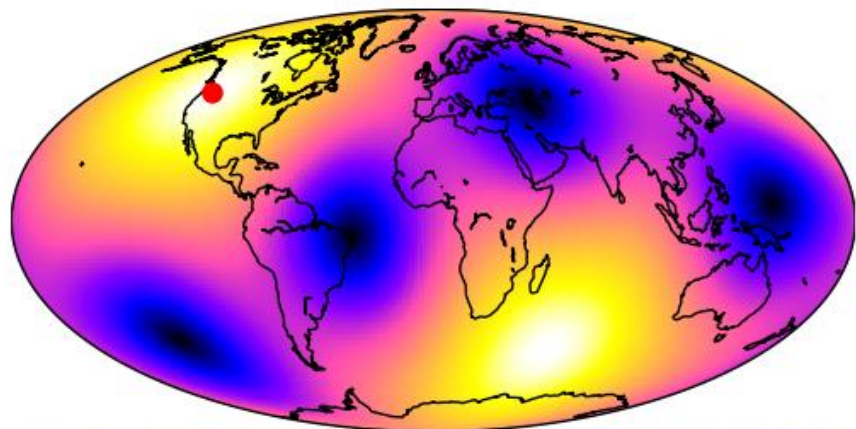
Sky Localization with HLVK+

HLVK+

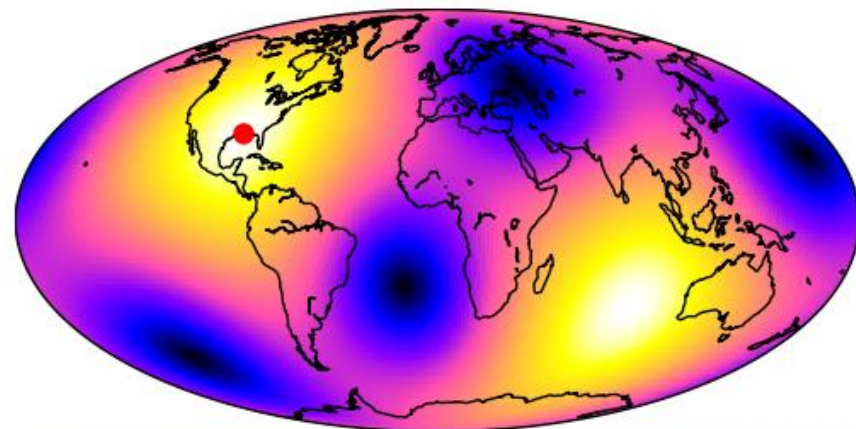


	median
HLV	0.472 deg^2
HLVK	0.168 deg^2
HLVK+	0.107 deg^2

H Antenna Pattern L

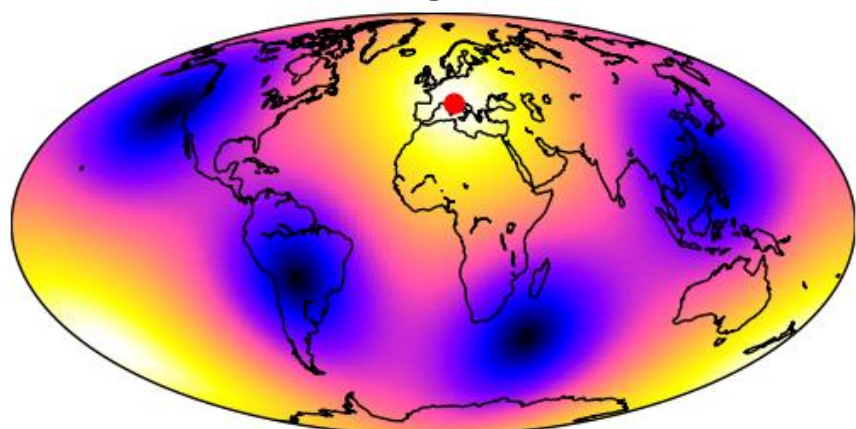


0.0 0.2 0.4 0.6 0.8 1.0
antenna pattern



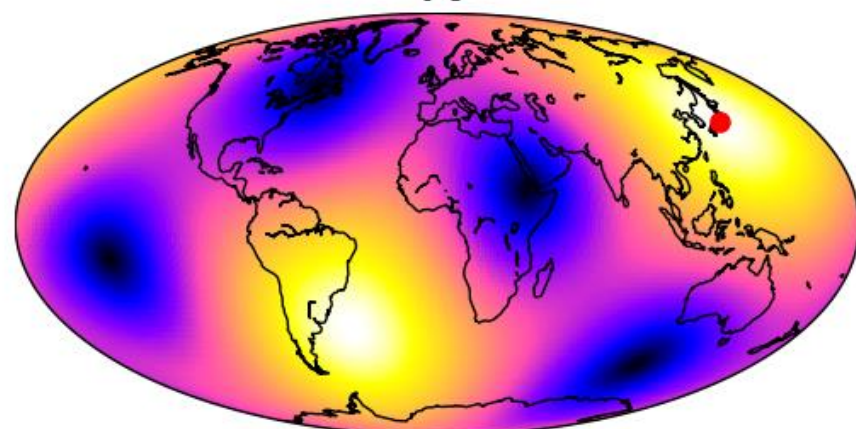
0.0 0.2 0.4 0.6 0.8 1.0
antenna pattern

V



0.0 0.2 0.4 0.6 0.8 1.0
antenna pattern

K



0.0 0.2 0.4 0.6 0.8 1.0
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

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
- **Inspirial range calculation**
 - SNR=8, $f_{min}=10$ 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

KAGRA Cryostat Schematic

