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Sensitivity Optimization of Cryogenic Gravitational Wave Detectors

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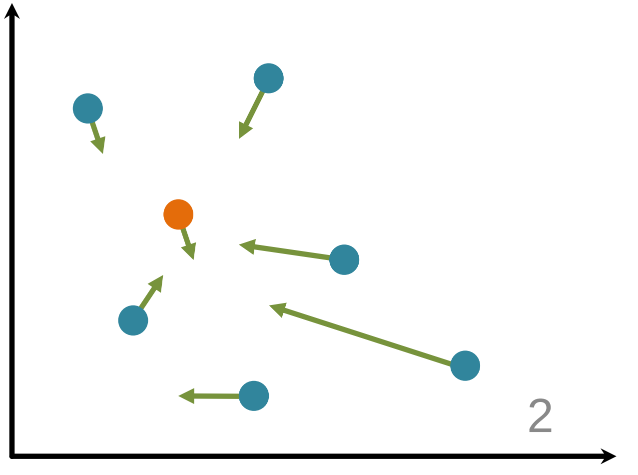
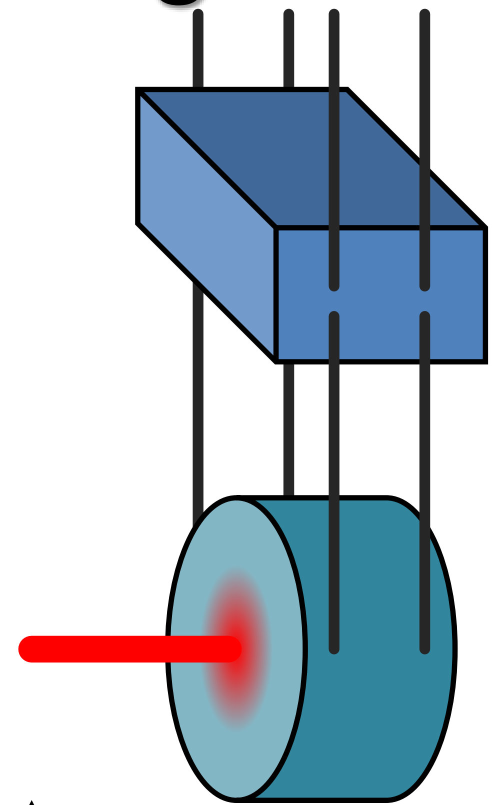
Overview

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

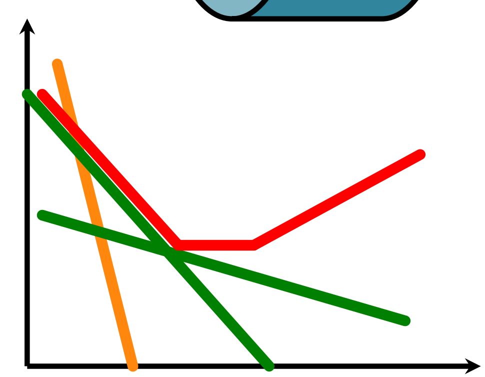


Room Temperature Design

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

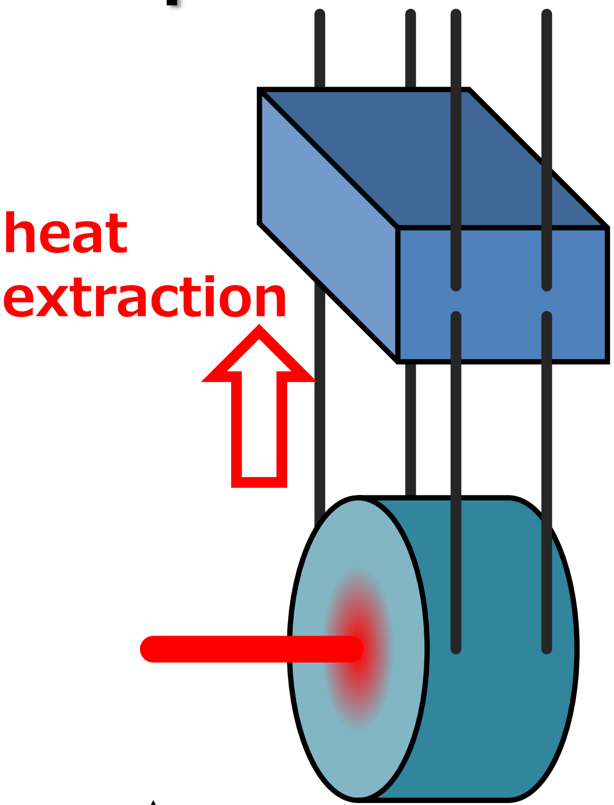


- Quantum noise: optimize the shape
  input laser power
  tune signal recycling parameters



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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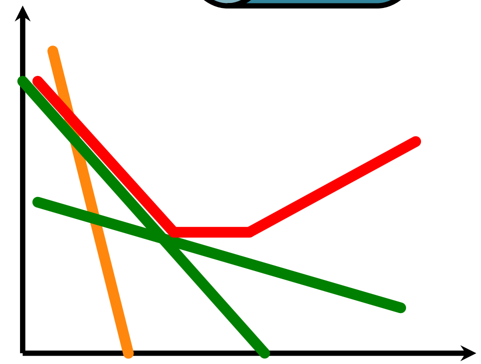

Cryogenic Design is Complicated

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  - multi-stage suspensions
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- Thermal noise: ~~reduce!~~ optimize
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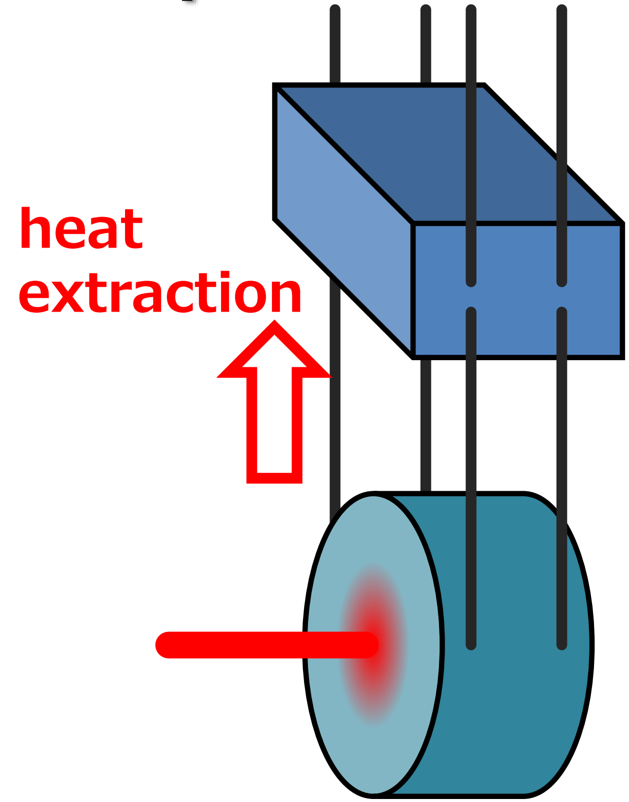


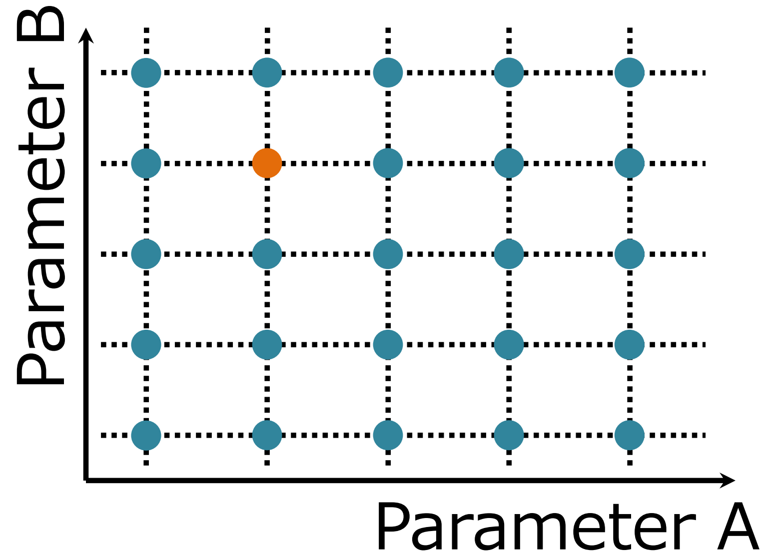
worse cooling power
mirror heating

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

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

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

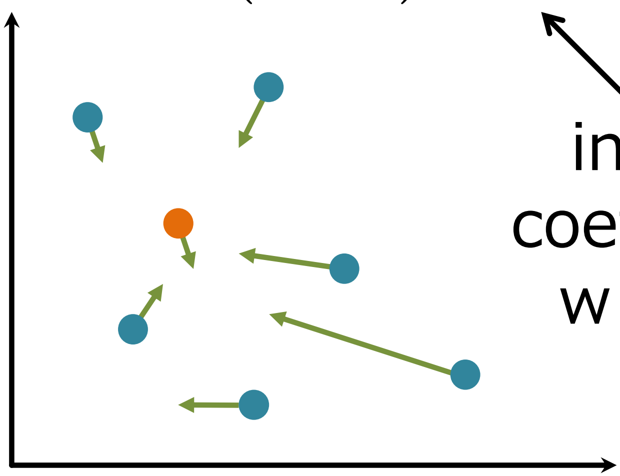
personal best position so far

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 (~1)

acceleration coefficient c (~1)
random number r ∊ [0,1]



Parameter space

Kennedy & Eberhart (1995)

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

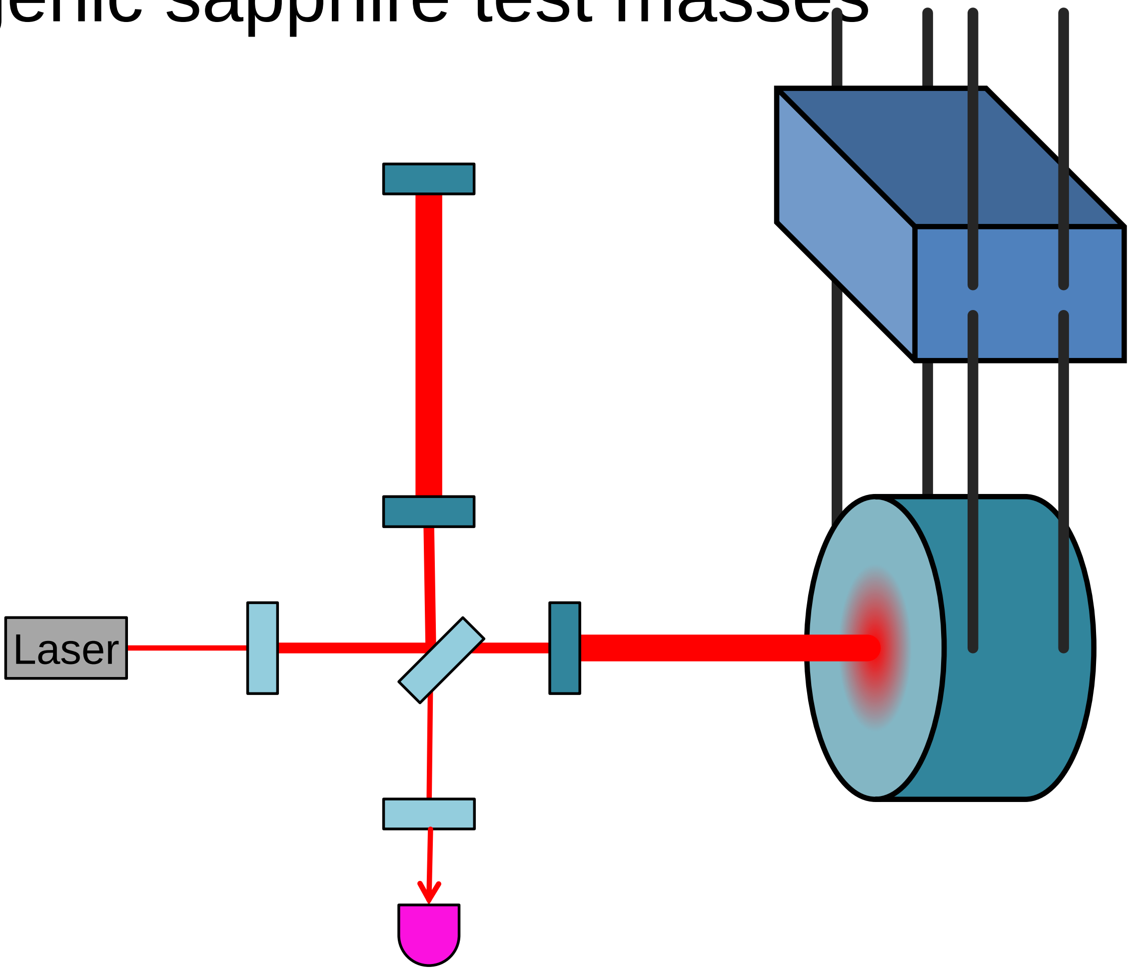
Pros and Cons of PSO

- 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

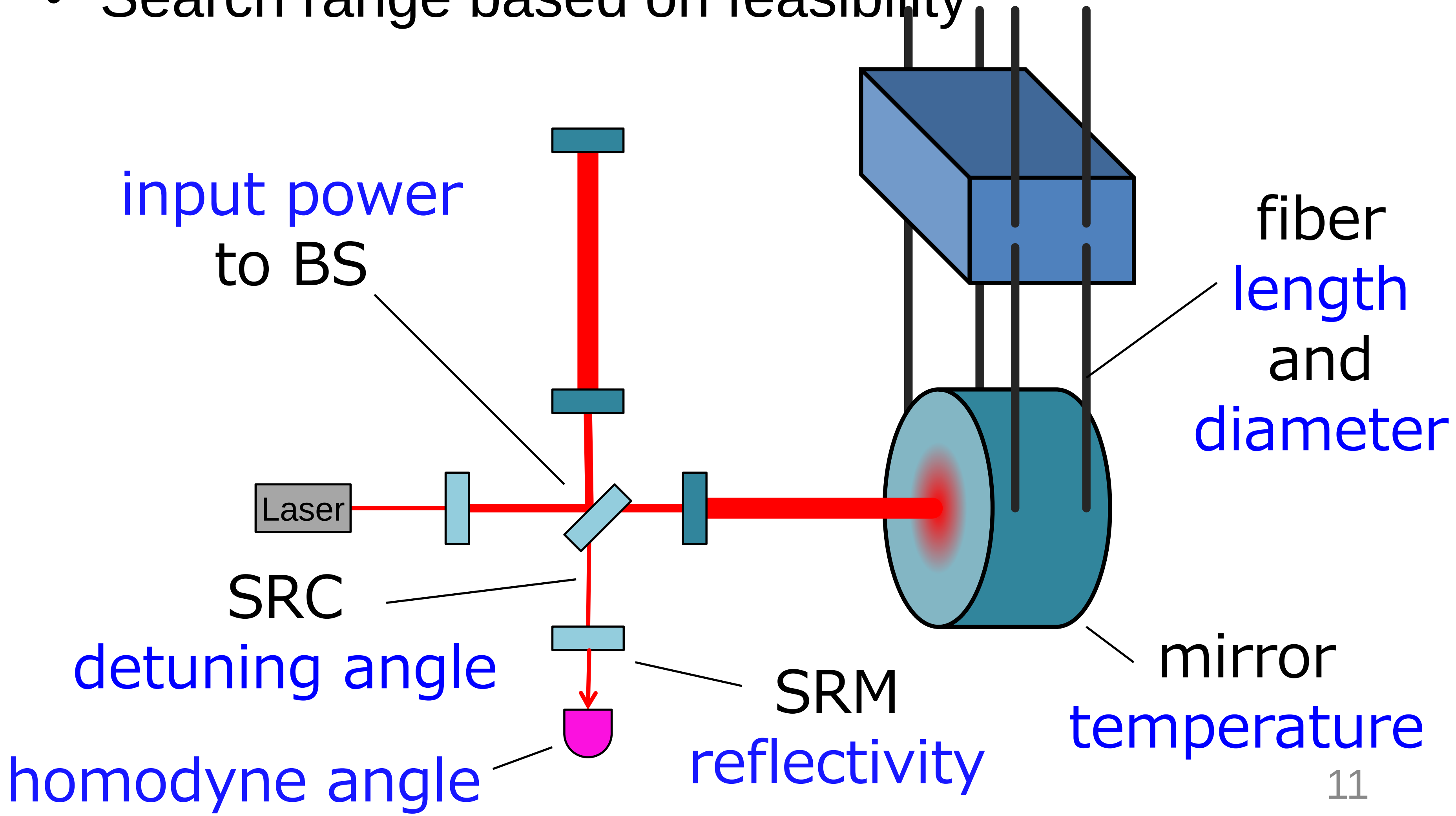
KAGRA

- RSE interferometer
- Cryogenic sapphire test masses



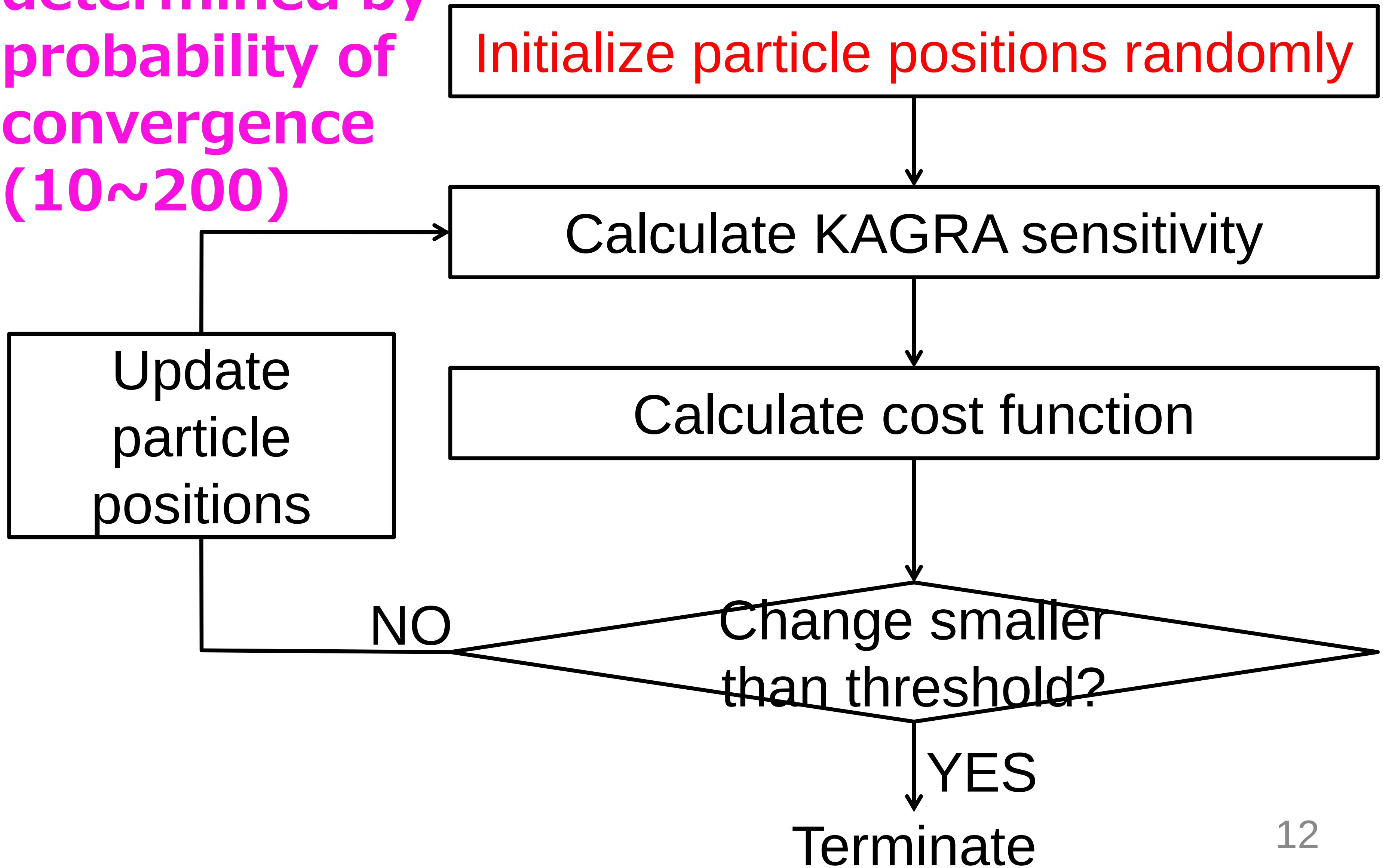
KAGRA Parameters to Optimize

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



PSO Algorithm

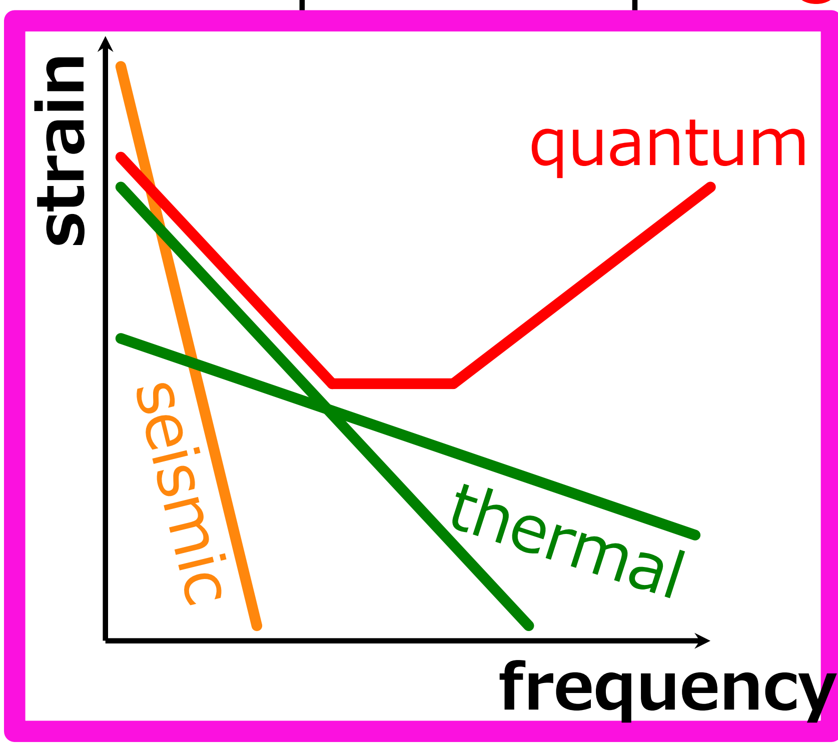
Swarm size determined by probability of convergence (10~200)



PSO Algorithm

Initialize particle positions randomly

Calculate KAGRA sensitivity



Calculate cost function

Change smaller than threshold?

YES

Terminate

PSO Algorithm

Initialize particle positions randomly

↓

Calculate KAGRA sensitivity

↓

Calculate cost function

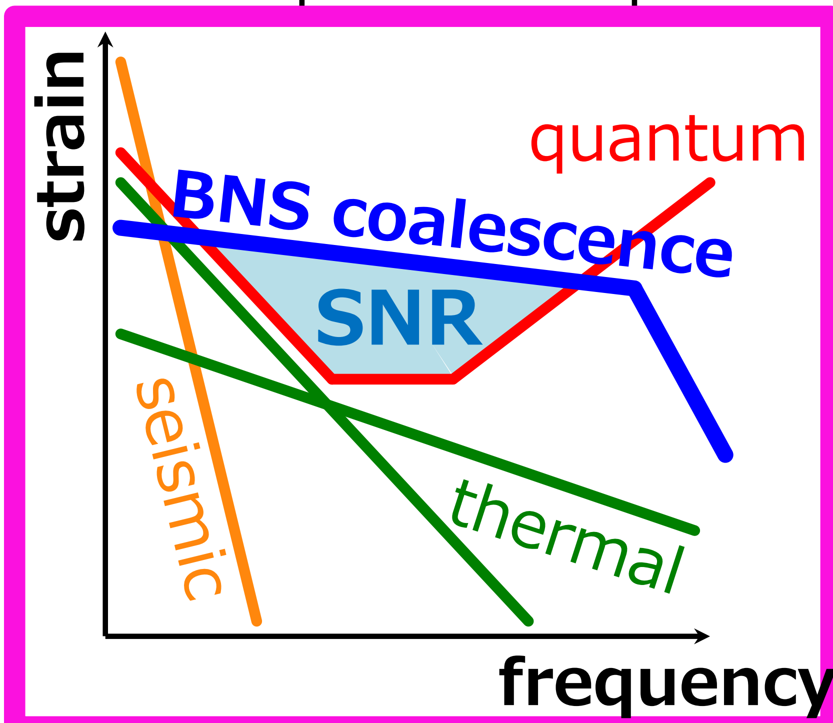
↓

Change smaller than threshold?

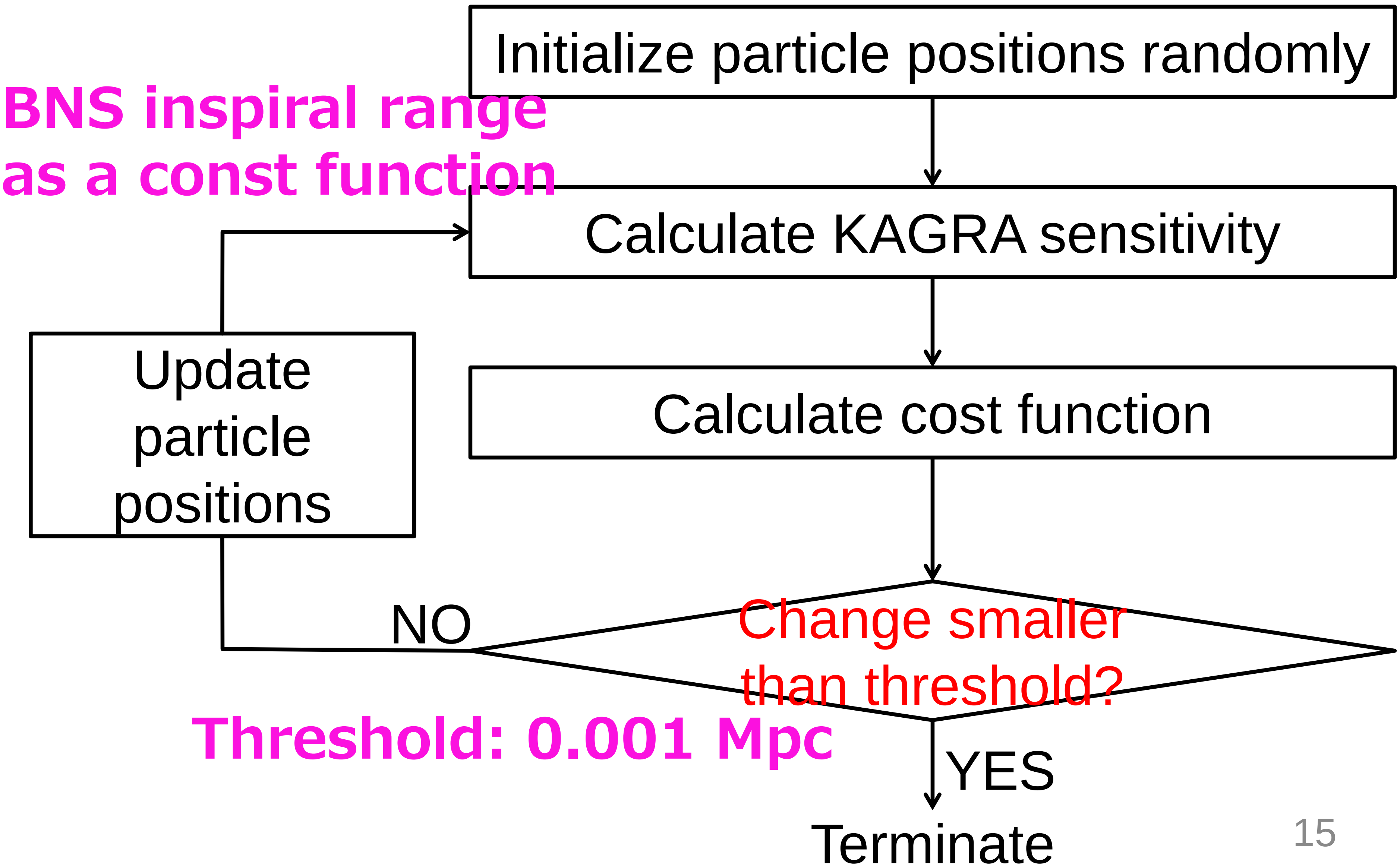
↓ YES

Terminate

BNS inspiral range as a const function



PSO Algorithm



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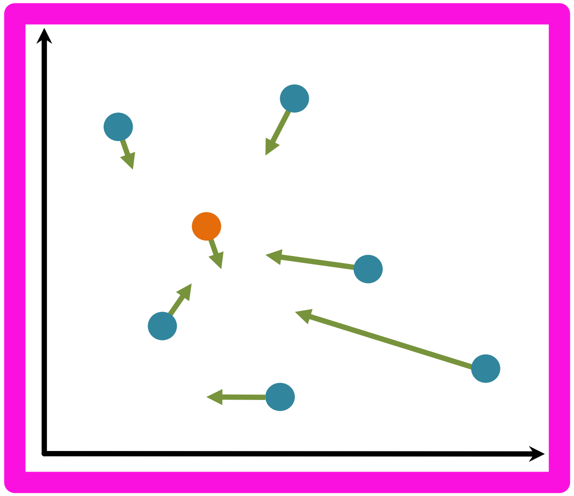


Initialize particle positions randomly

Calculate KAGRA sensitivity

Calculate cost function

Change smaller than threshold?

NO

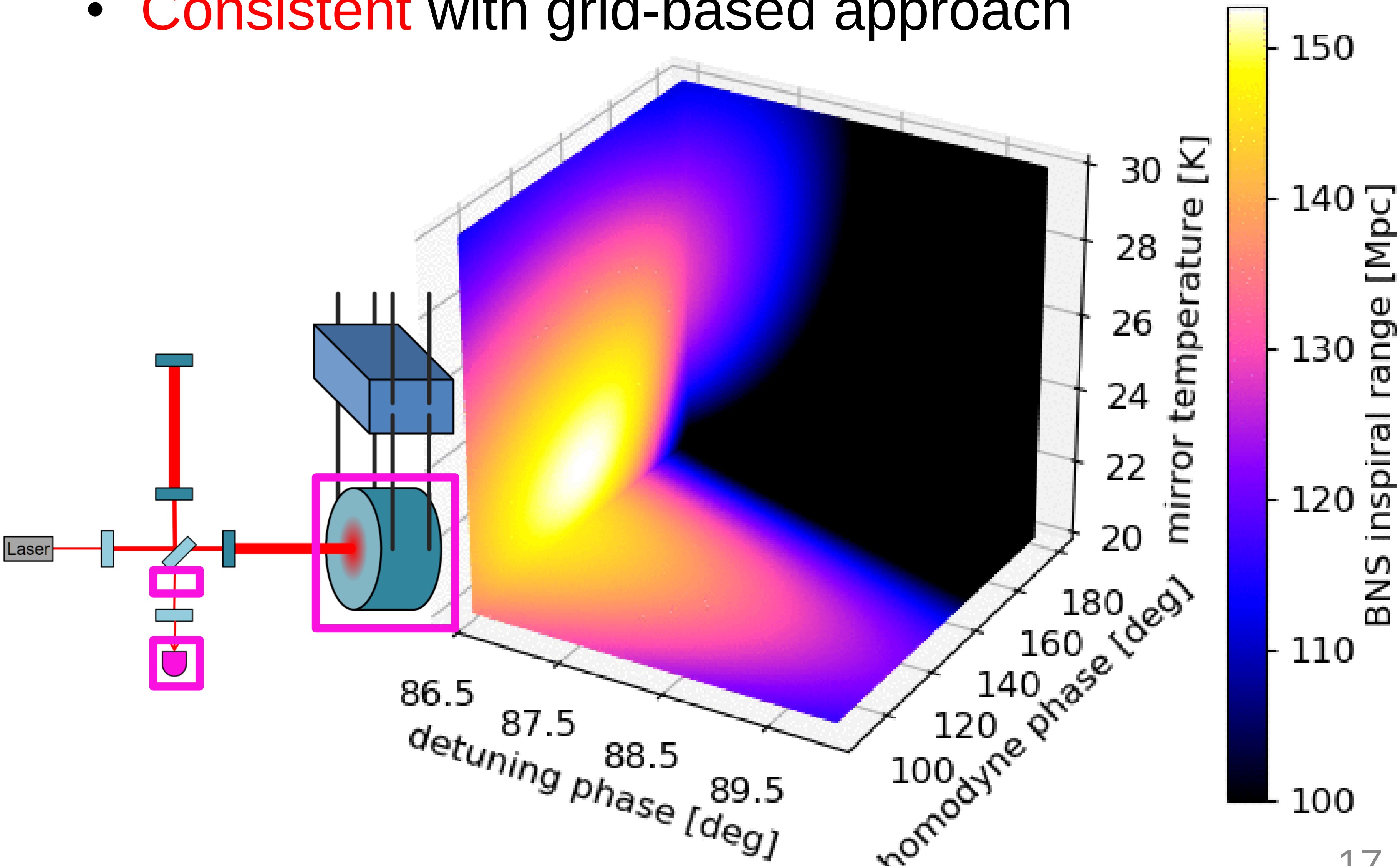
Update particle positions

YES

Terminate

3 Parameter Optimization

- Consistent with grid-based approach



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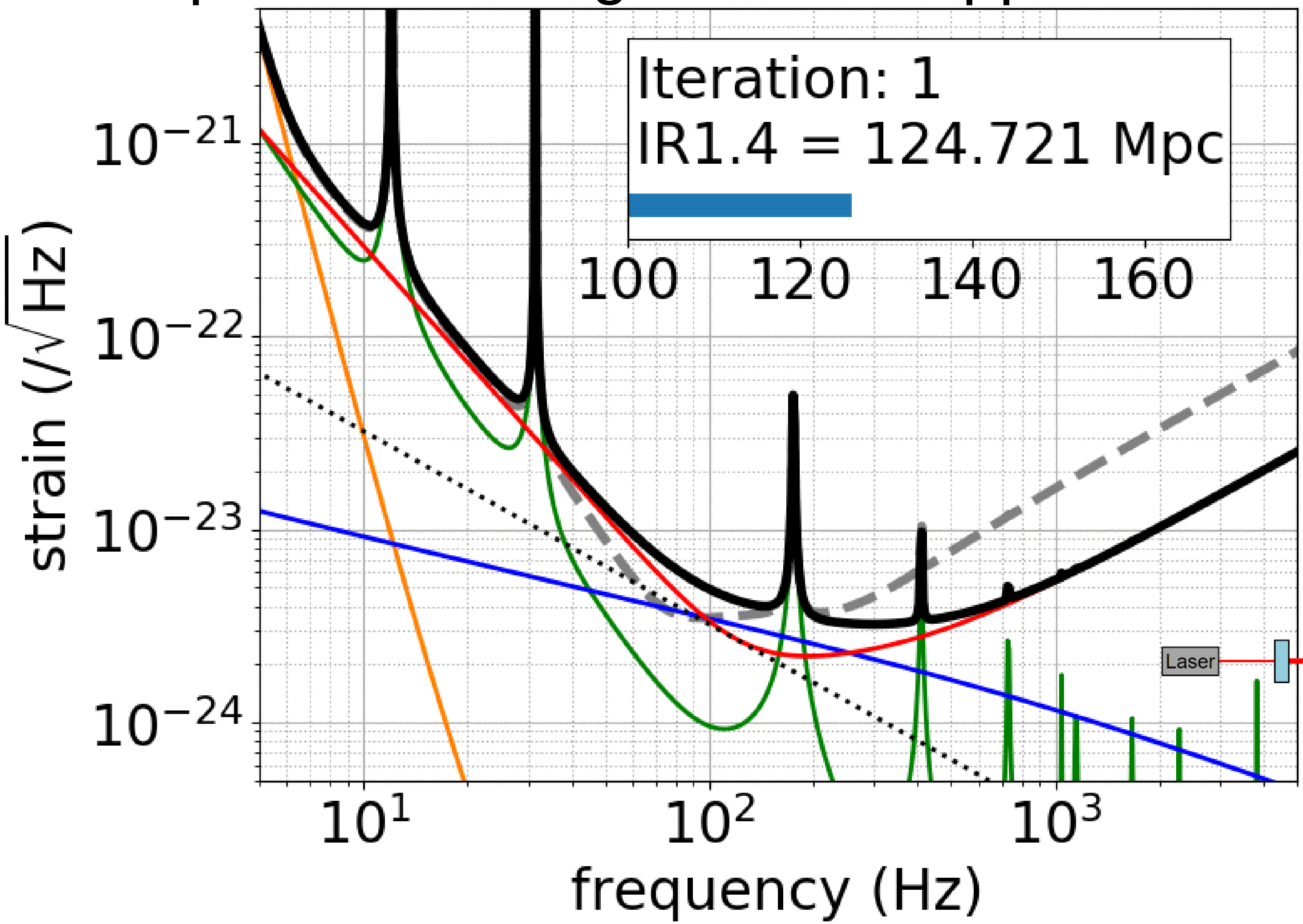

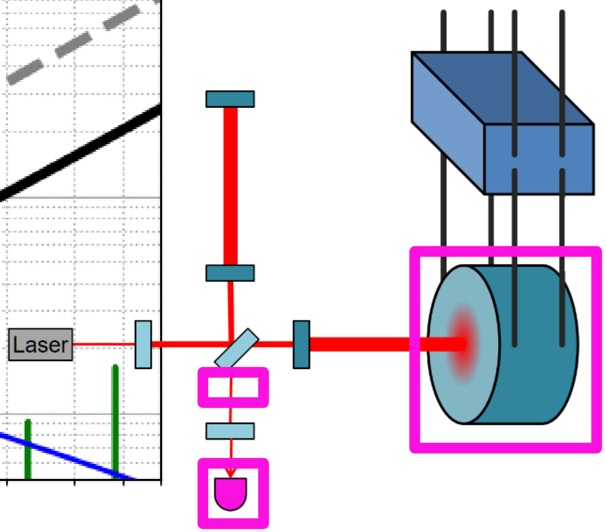

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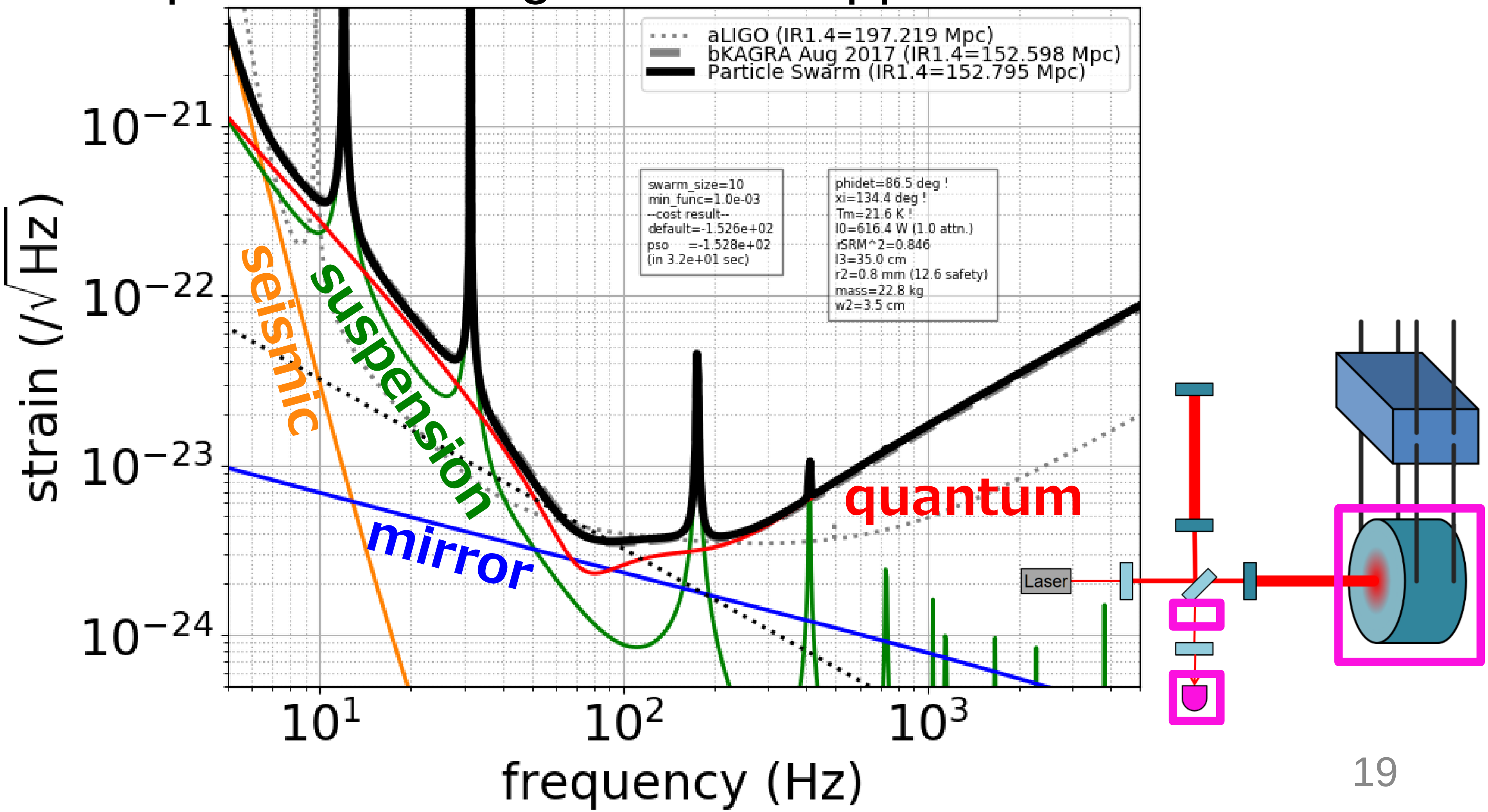
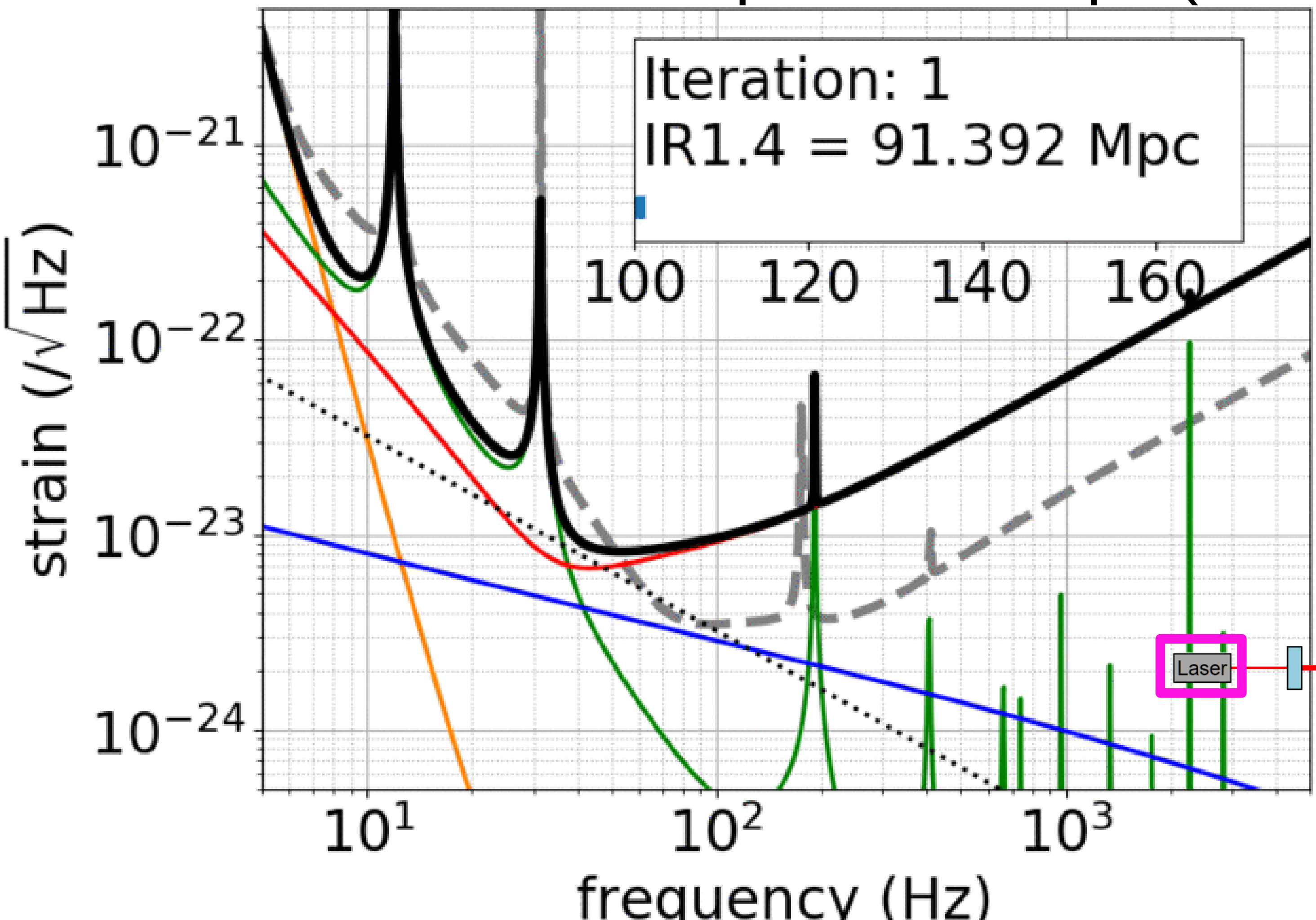
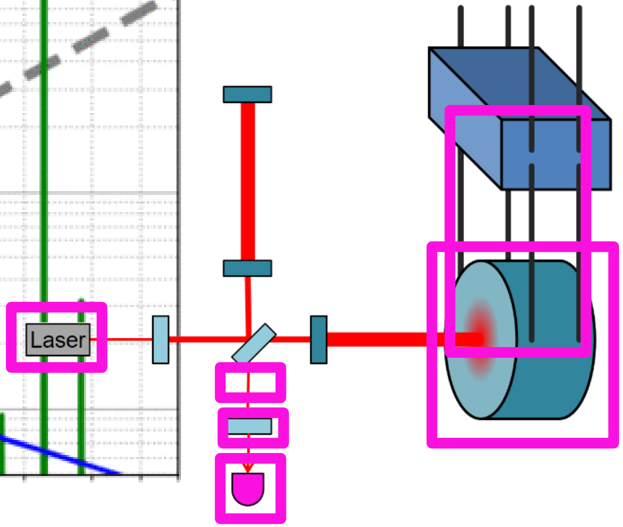


7 Parameter Optimization

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





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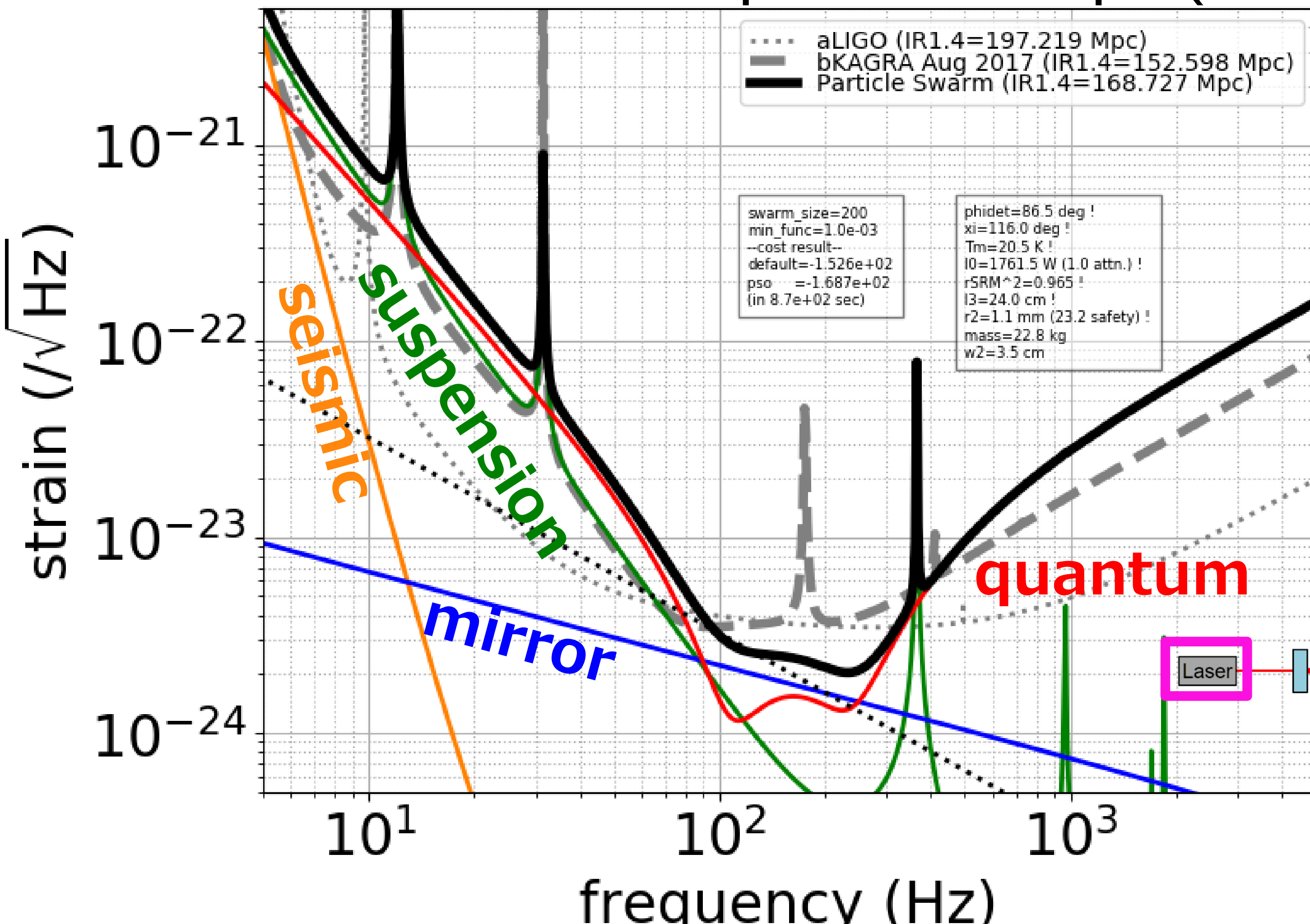
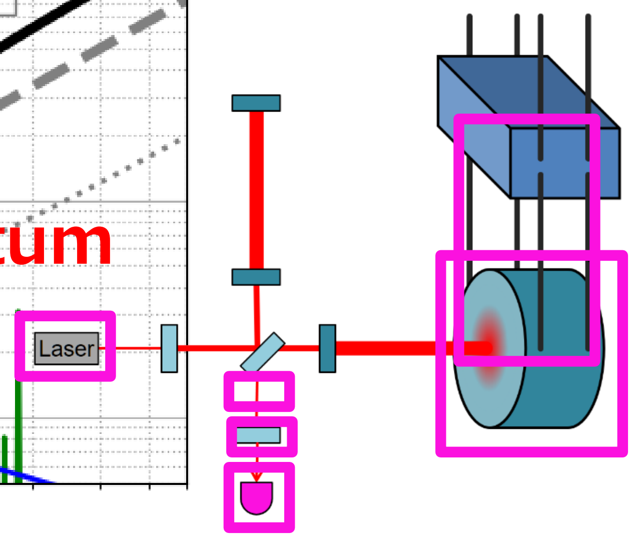


Shorter and thicker to put more power with 20 K



Computational Cost

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

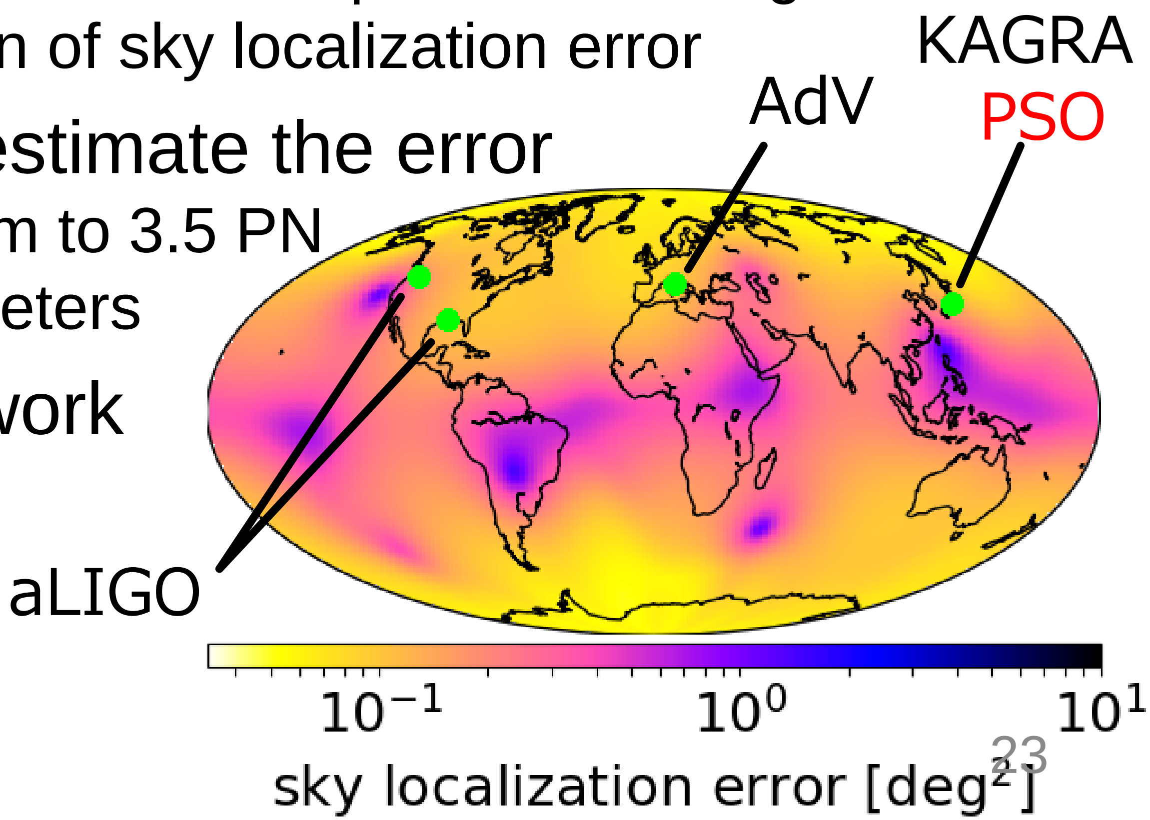
	Grid-based	PSO
3 params	10^5 回	10×(52±13) 回
5 params	10^9 回	20×(73±16) 回
7 params	10^{14} 回	200×(60±18) 回

* In case optimization is done within 0.1 Mpc

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

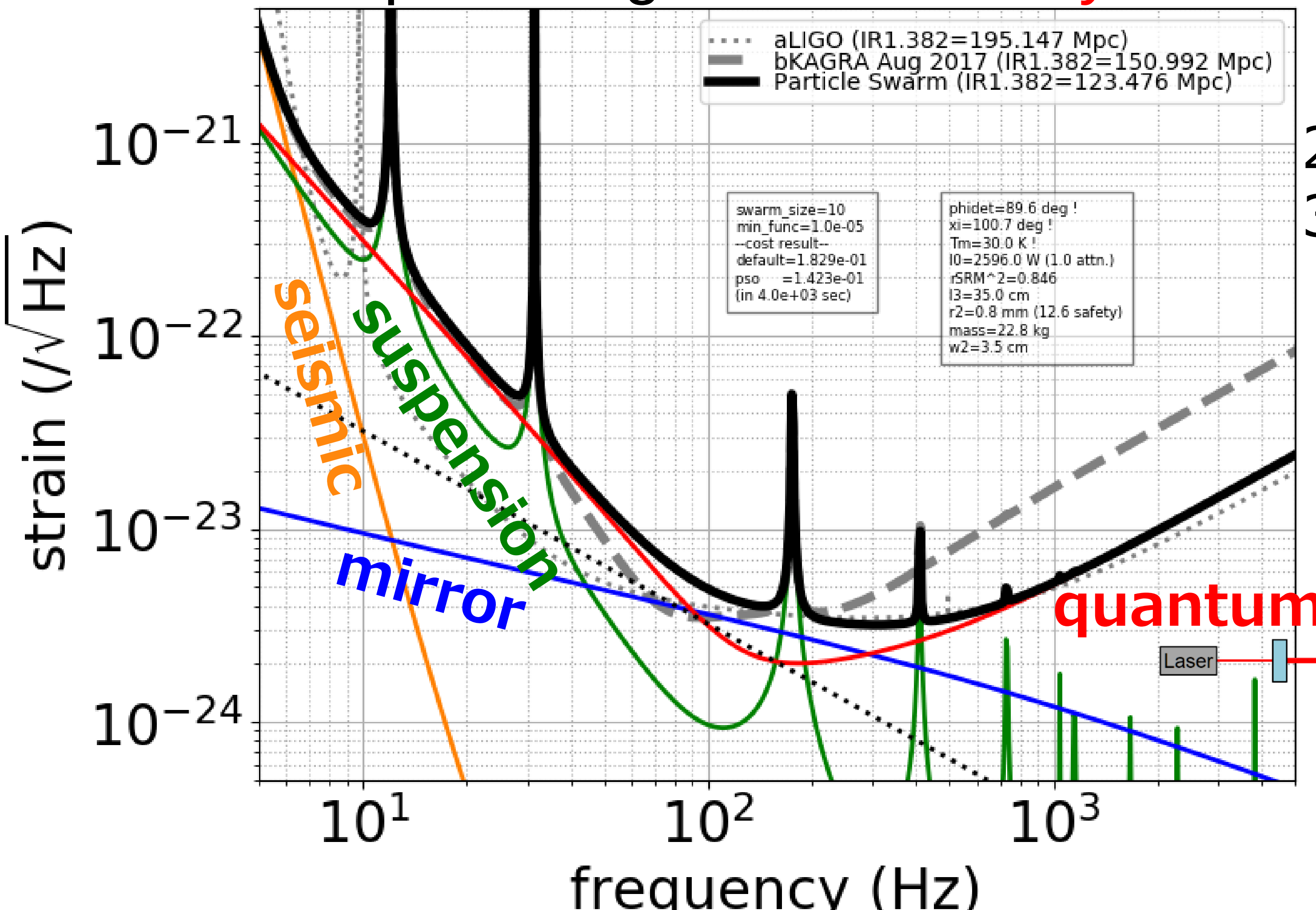
Sky Localization Optimization

- 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 3.5 PN
  - 11 binary parameters
- HLVK global network

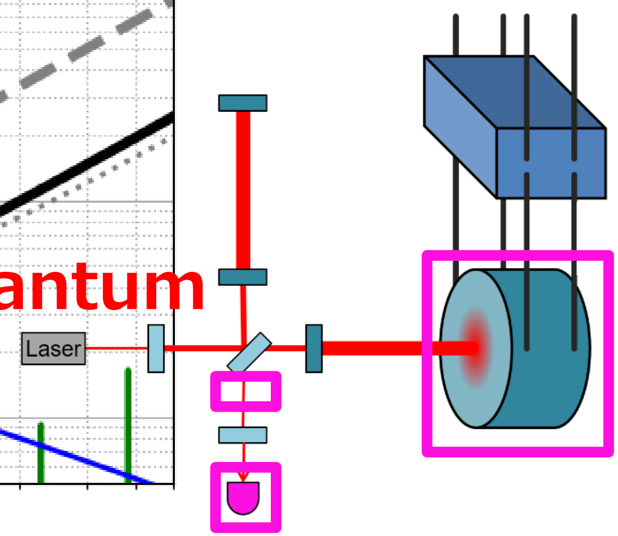


3 Parameter Optimization

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

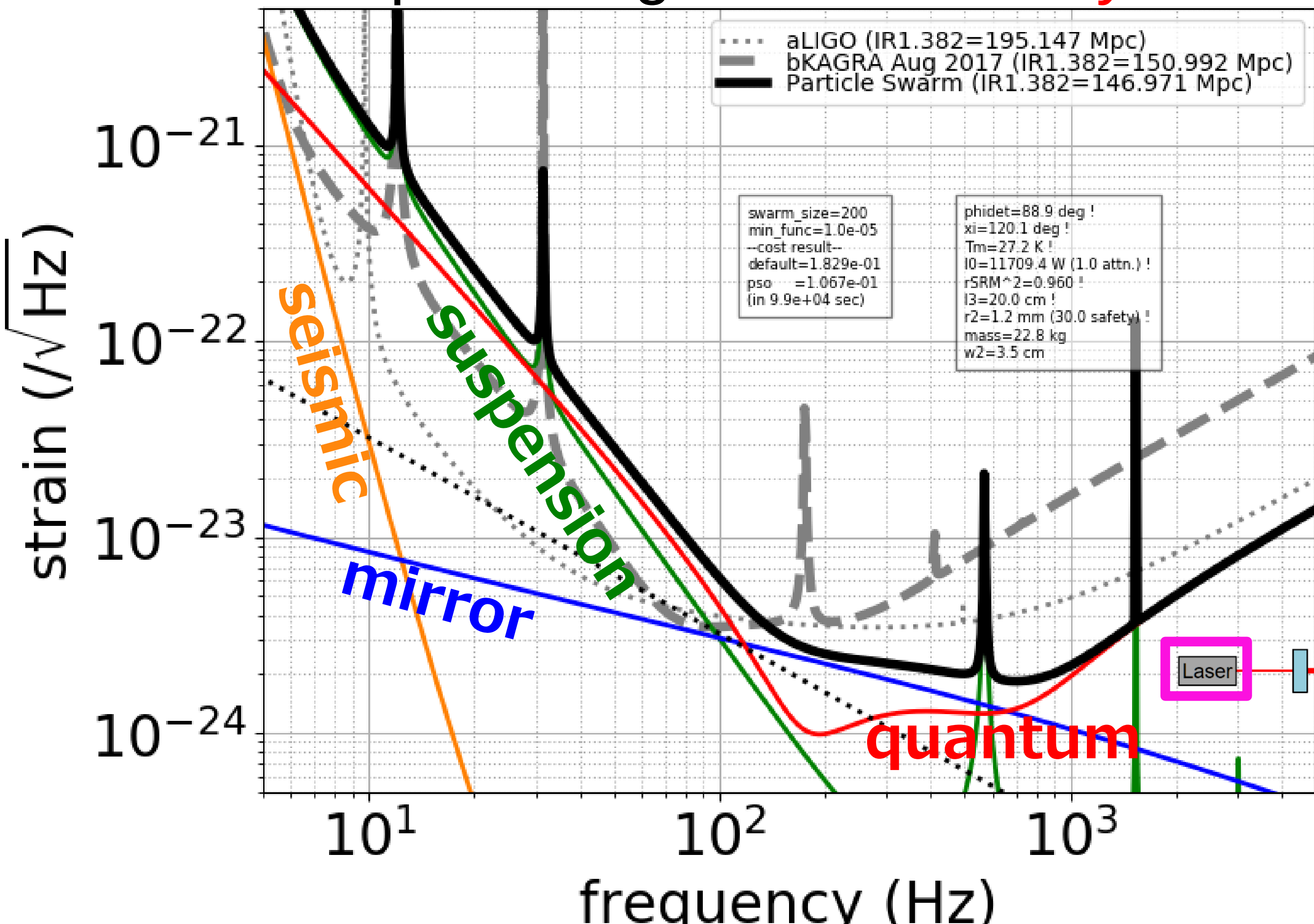


2600 W at BS
30 K

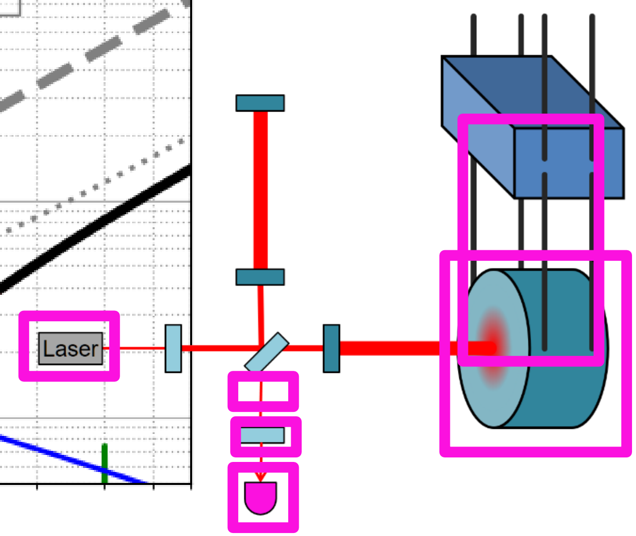


7 Parameter Optimization

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

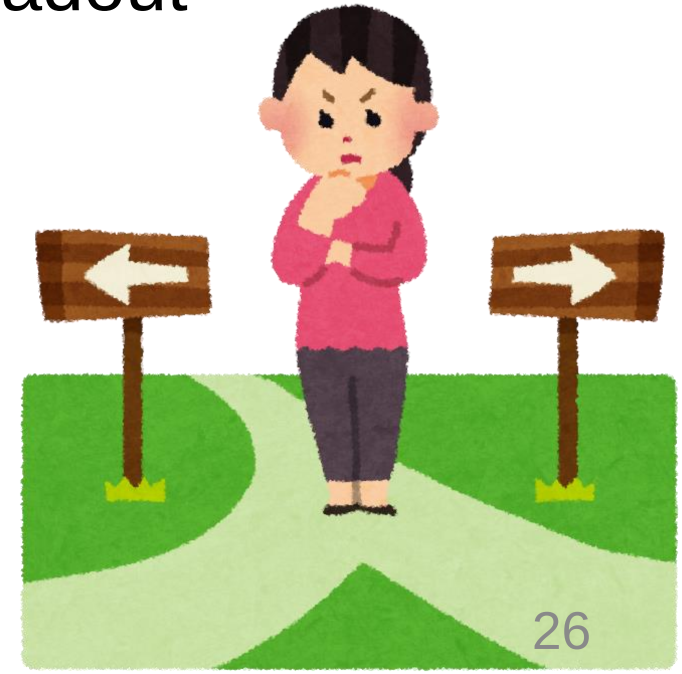


shorter and thicker fibers
1.1 kW at BS
27 K



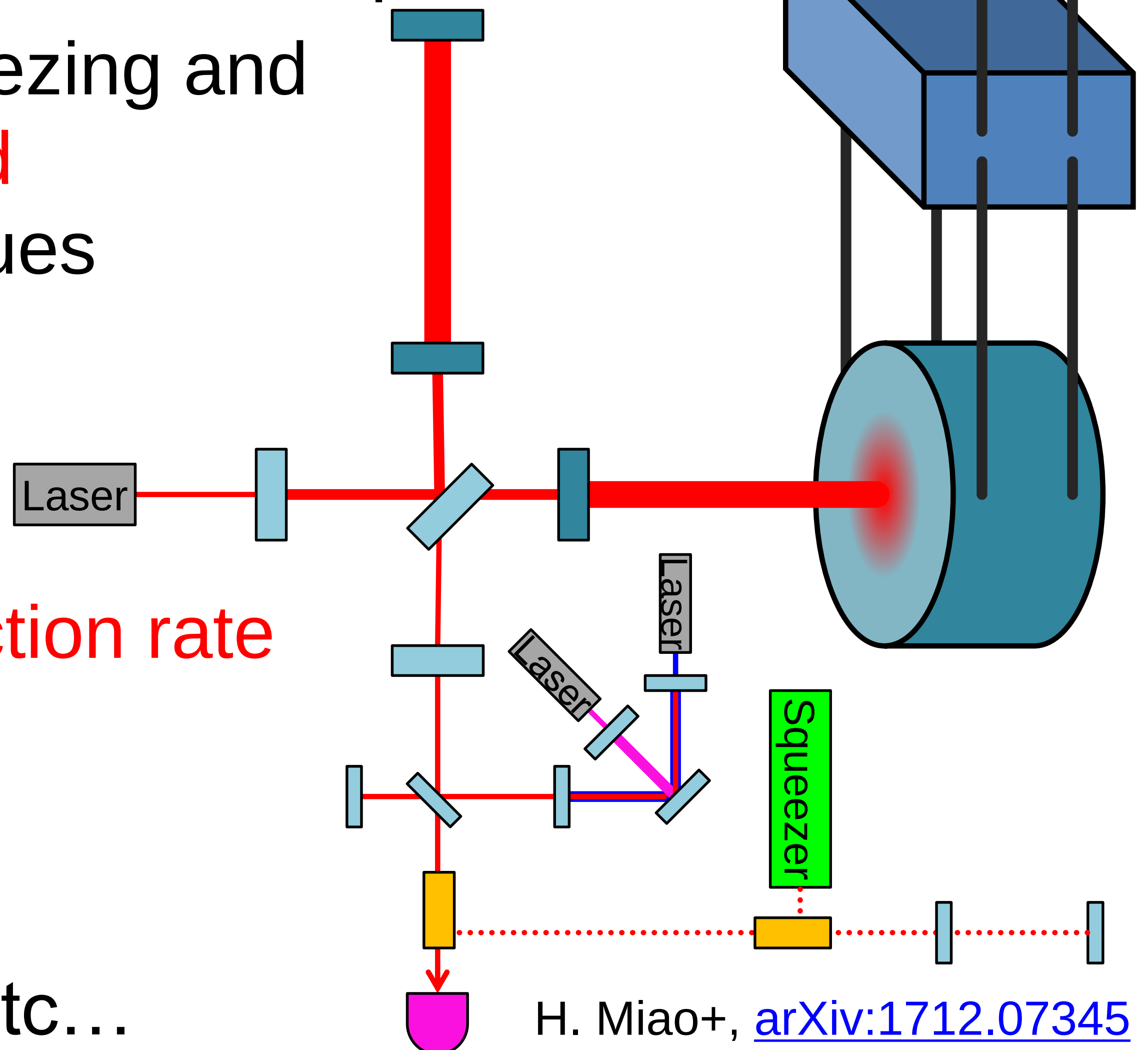
Summary of Strategy Difference

- Inspiral range optimization
  - high detuning, high SRM reflectivity
  - shorter and thicker fiber
  - lower temperature to keep mirror thermal low
- 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
- Optimization for
  - NS EoS
  - BH ringdown etc…

H. Miao+, [arXiv:1712.07345](https://arxiv.org/abs/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

- Yuta Michimura *et al.* arXiv:1804.09894

Supplementary Slides