Demonstration of improving the GW-sensitivity with a long signal recycling cavity

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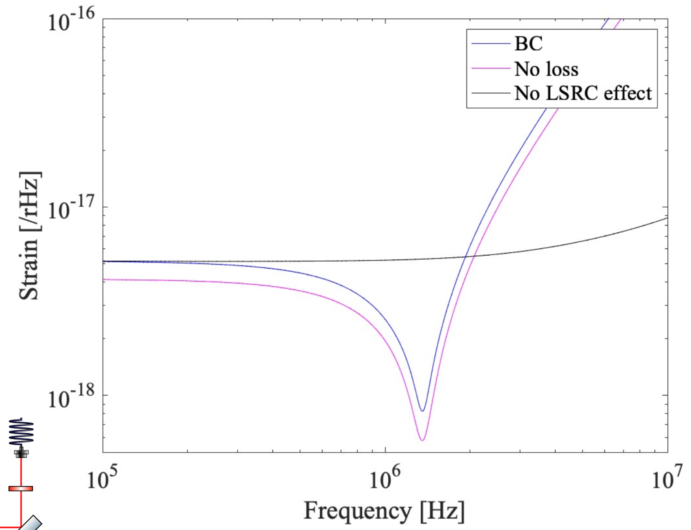
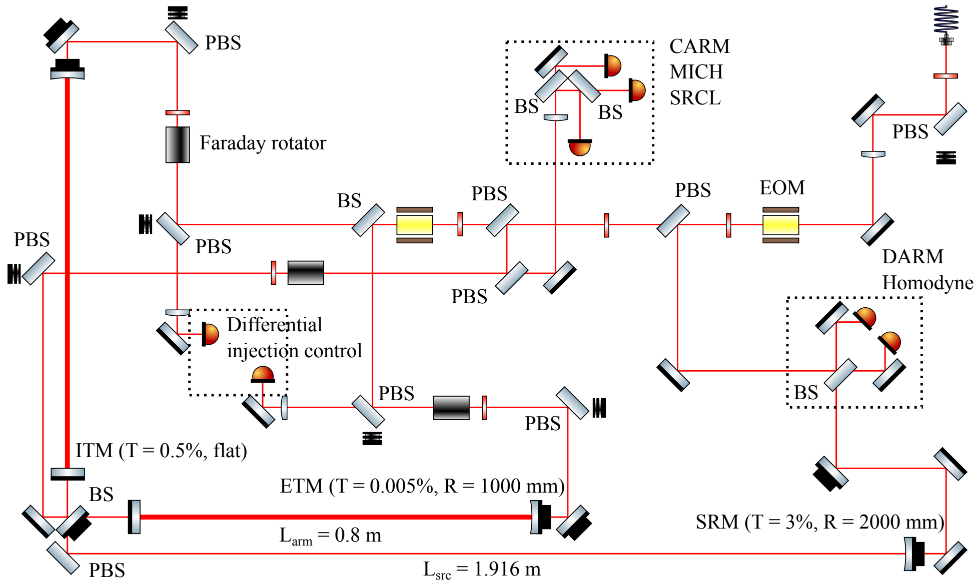
Summary

- ➢Motivation of detection of high frequency gravitational waves
- ➢Long signal recycling cavity effect
  - Theory
  - Demonstration at the table-top scale
  - Experimental design

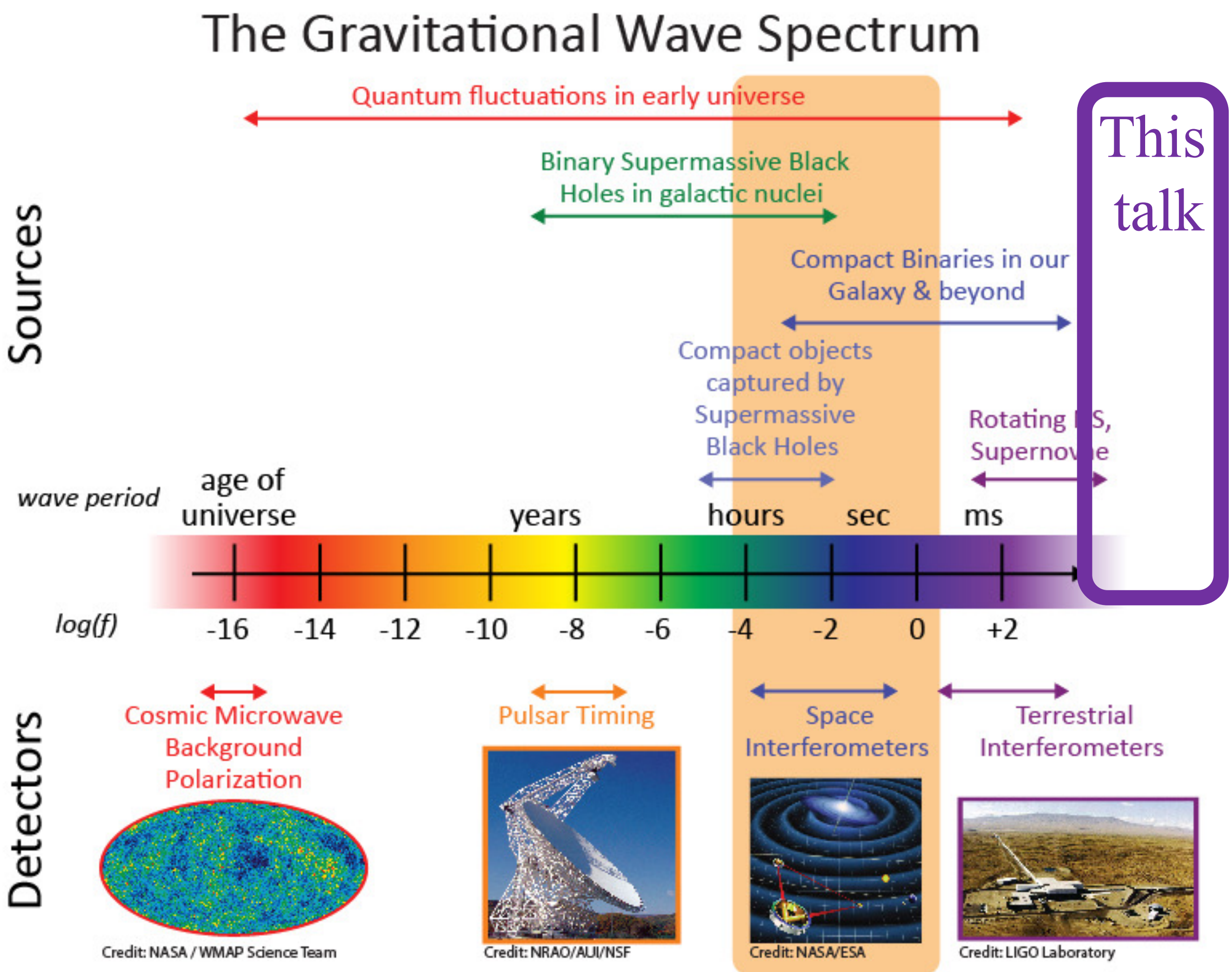




Introduction

- 90 events detected by LIGO-Virgo so far
  - Population of binary black holes
  - Binary neutron stars and multi-messenger astronomy
  - GR test
  - Hubble constant measurement

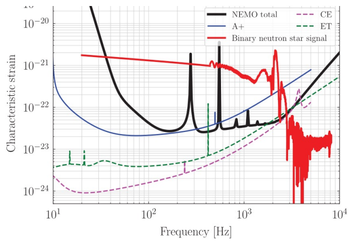
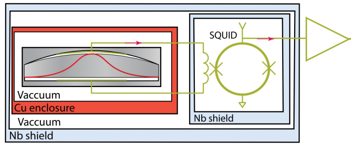
- Multi-wavelength GWs
  - Primordial GW (CMB)
  - Supermassive BH (PTA)
  - Massive BH (LISA)



Credit: NASA

Motivation

➢High frequency GWs

Frequency	~kHz	Above kHz
Science	• Equation of state of NS • Sky localization • Pulsar ellipticity • Harmonics of BBH ringdown	• Merger of primordial BHs • BH supper radiance • Phase transition in the early Universe
Detector	Conventional large detector • NEMO • LIGO-HF • KAGRA-HF 	New-type • Levitated sensors • Bulk acoustic wave • Interferometer 

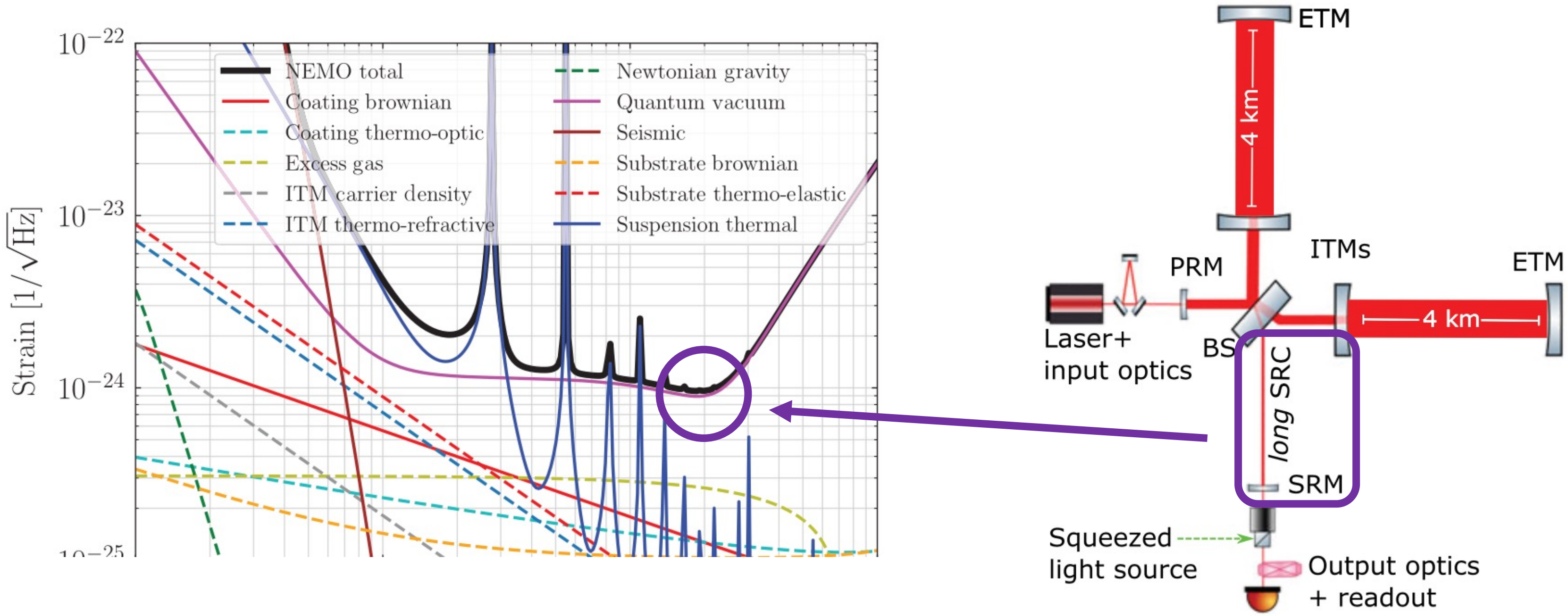
PASA 37, e047 (2020)

PRL 127, 071102 (2021)

Method

➢Long signal recycling cavity (LSRC)

- Planned to be used in future detectors targeting at BNS merger frequency (~kHz)
- No demonstration so far at a table-top scale experiment
- Useful technique for short interferometers towards various precise measurement



PASA 37, e047 (2020)

Sensitivity calculation

➢Quantum noise

h_{SQL}^2: SQL sensitivity

$$S_h = \frac{h_{SQL}^2}{2}\left(\mathcal{K} + \frac{1}{\mathcal{K}}\right) \qquad S_{h,shot} = \frac{h_{SQL}^2}{2\mathcal{K}} \qquad \mathcal{K} = \left(\frac{\omega_{SQL}}{\omega}\right)^2 K(\omega)$$

Radiation pressure noise

SRM amplitude reflectivity

Conventional $$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2}{(1+r)^2\gamma^2}\omega^2 \qquad (L_{src} \to 0)$$

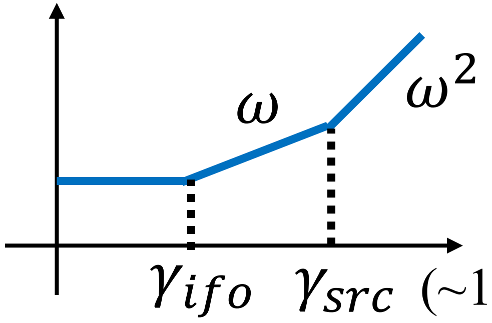
Arm cavity line width

Non-zero SRC length $$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2 - 8rL_{src}\gamma/c}{(1+r)^2\gamma^2}\omega^2 + \frac{4rL_{src}^2/c^2}{(1+r)^2\gamma^2}\omega^4$$

Amplitude sensitivity

➢Short SRC

- $\omega < \gamma_{ifo}$: flat
- $\gamma_{ifo} < \omega < \gamma_{src}$: $\sqrt{S_h} \propto \omega$
- $\gamma_{src} < \omega$: $\sqrt{S_h} \propto \omega^2$
  (through two cavities)

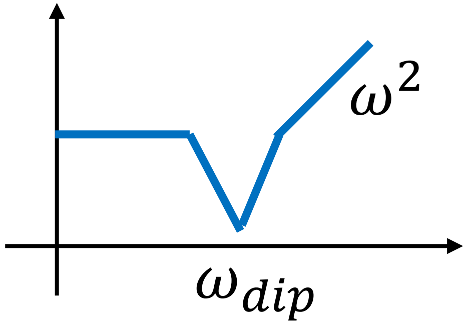


(~100 kHz in aLIGO)

positive

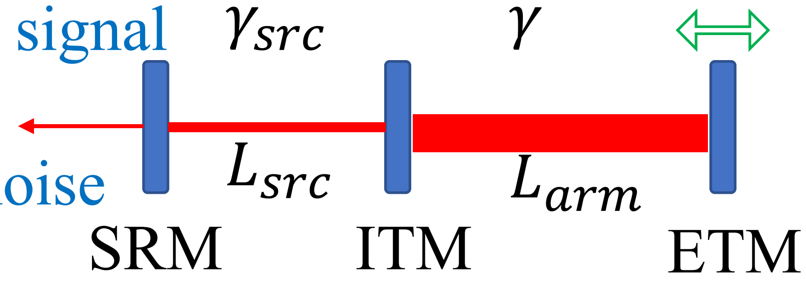
➢Long SRC

- $\omega < \omega_{dip}$: flat
- $\omega_{dip} < \omega$: $\sqrt{S_h} \propto \omega^2$



negative

Enhanced signal
v.s.
flat shot noise



Non-zero SRC length

$$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2 - 8rL_{src}\gamma/c}{(1+r)^2\gamma^2}\omega^2 + \frac{4rL_{src}^2/c^2}{(1+r)^2\gamma^2}\omega^4$$

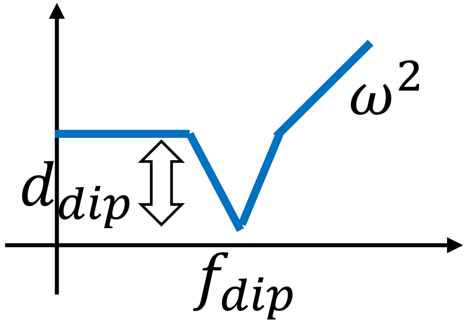
Dip in the sensitivity

- The negative ω^2 term generates the dip when $T_{srm}^2 < 8T_i L_{src}/L_{arm}$

Dip frequency: $f_{dip} = \frac{c}{8\pi}\sqrt{\frac{T_i}{L_{arm}L_{src}}}$

~kHz with km-scale arm

~MHz at table-top scale



Depth: $d_{dip} = \frac{T_{srm}}{2}\sqrt{\frac{L_{arm}}{T_i L_{src}}}$

T_i: ITM transmissivity

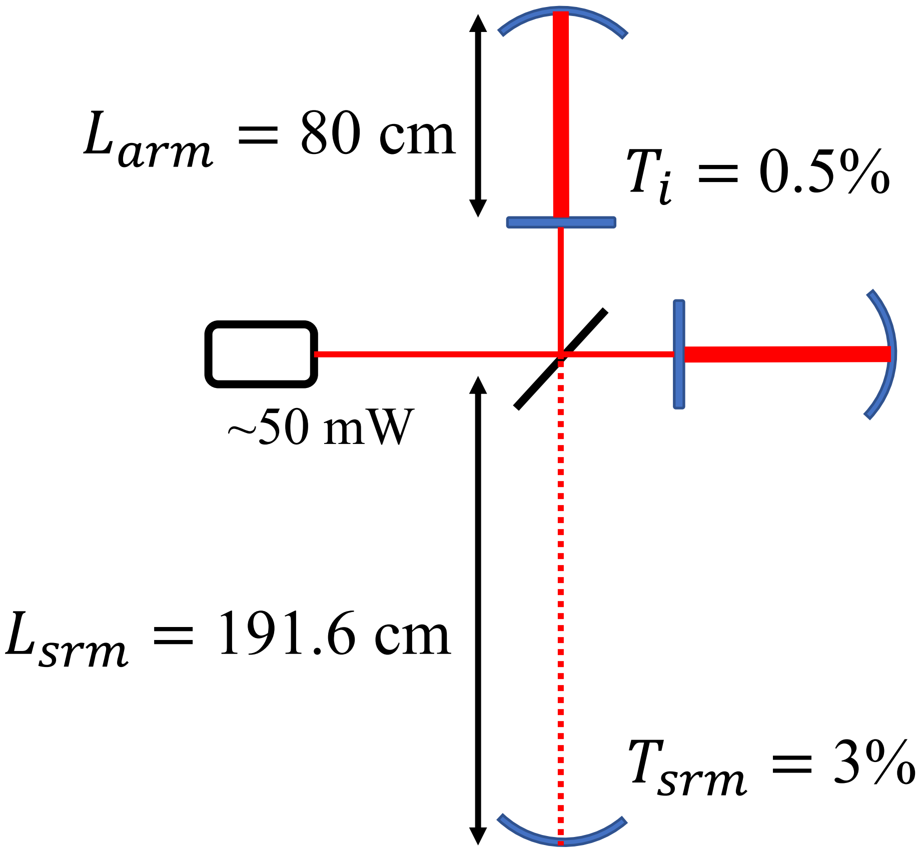
L_{arm}: arm length

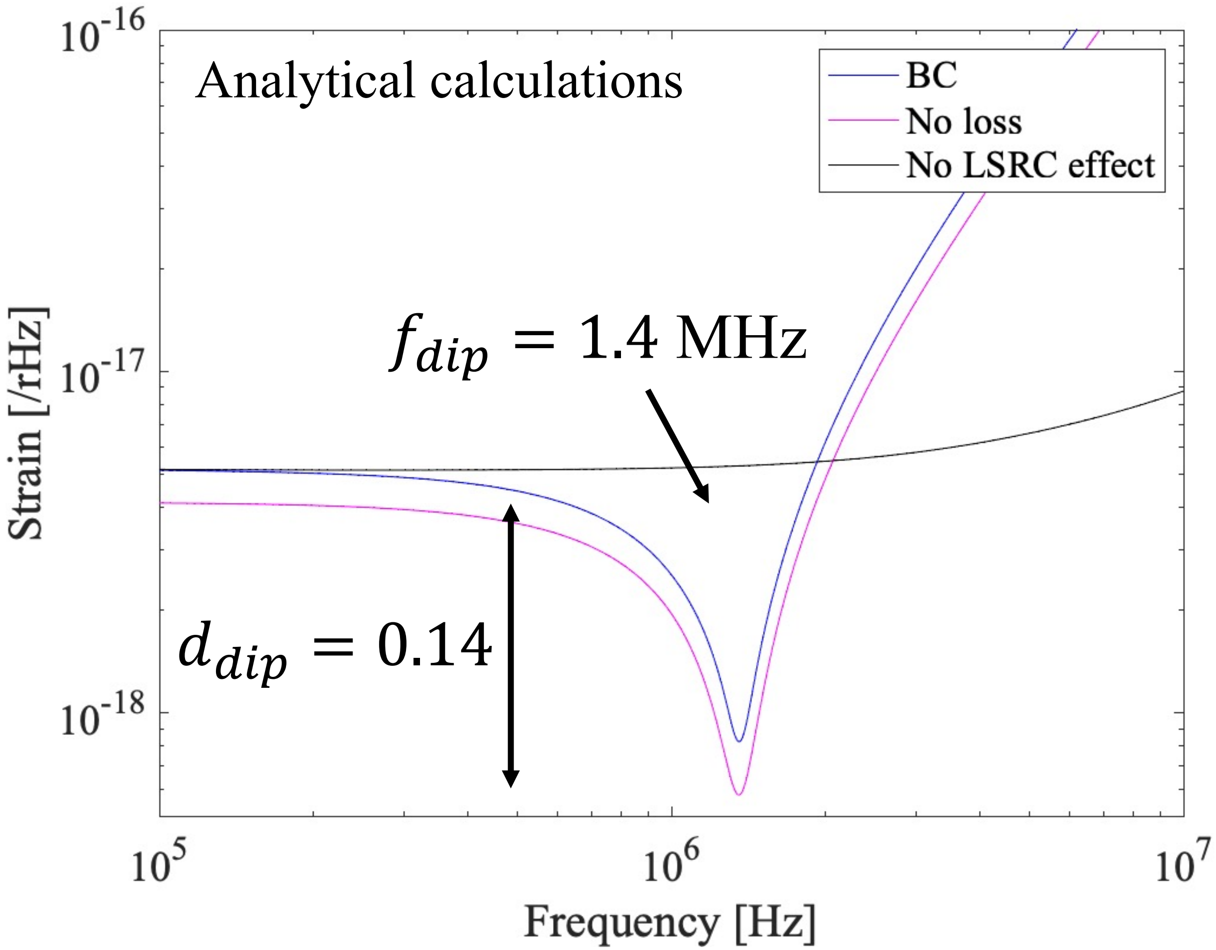
Non-zero SRC length

$$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2 - 8rL_{src}\gamma/c}{(1+r)^2\gamma^2}\omega^2 + \frac{4rL_{src}^2/c^2}{(1+r)^2\gamma^2}\omega^4$$

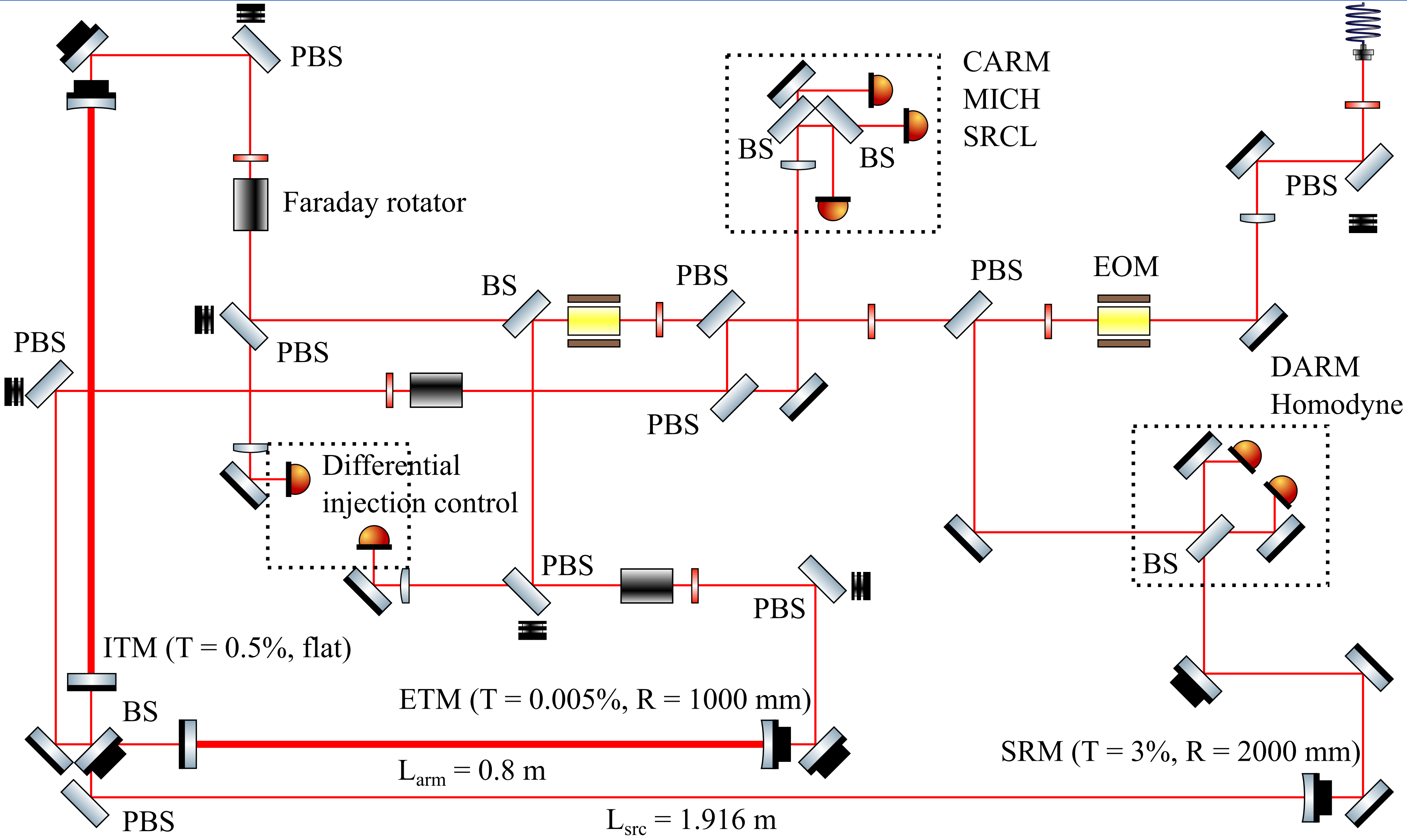
Experiment plan

- Demonstration of LSRC at the table-top scale with SRFPMI

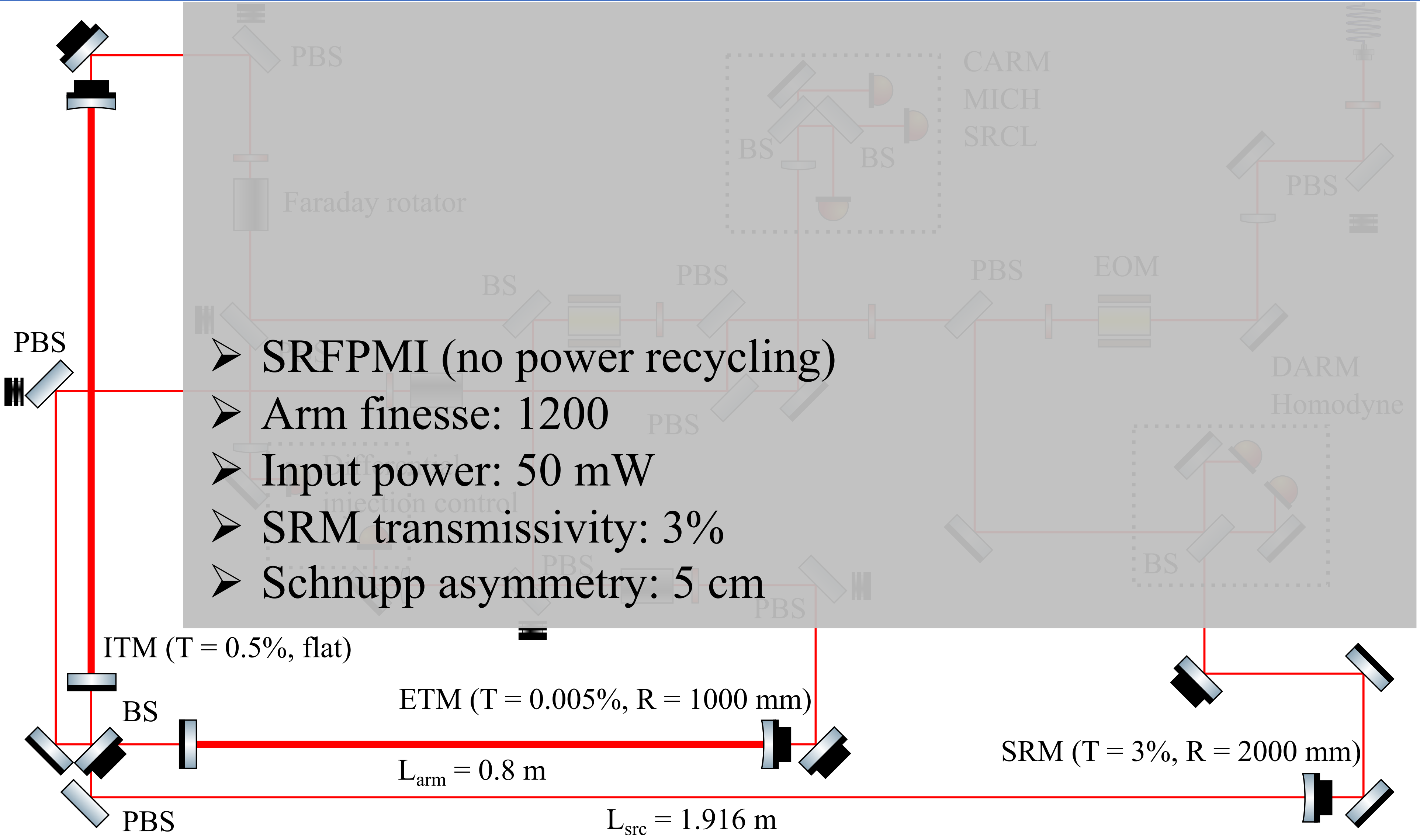




Optics layout

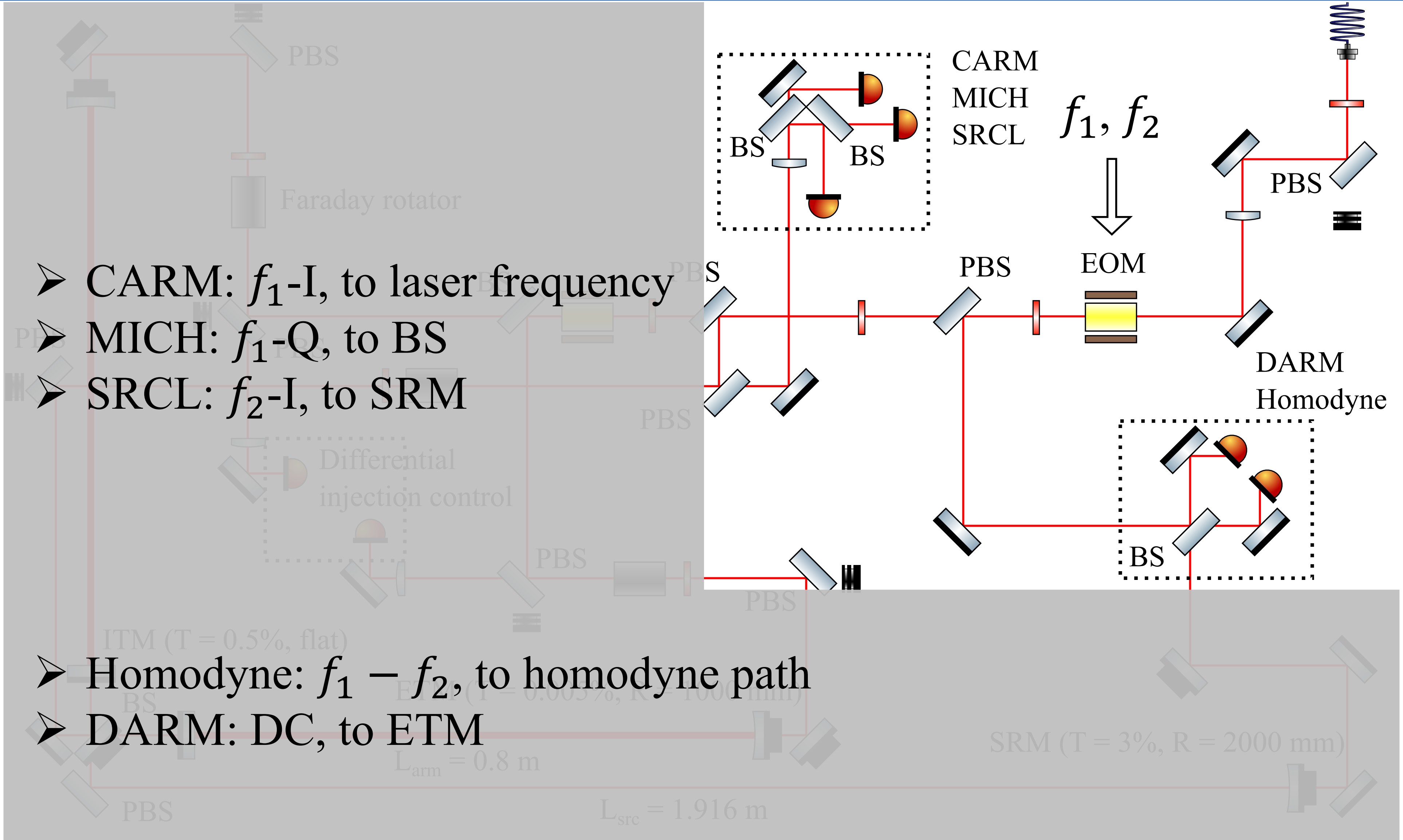


Interferometer



- SRFPMI (no power recycling)
- Arm finesse: 1200
- Input power: 50 mW
- SRM transmissivity: 3%
- Schnupp asymmetry: 5 cm

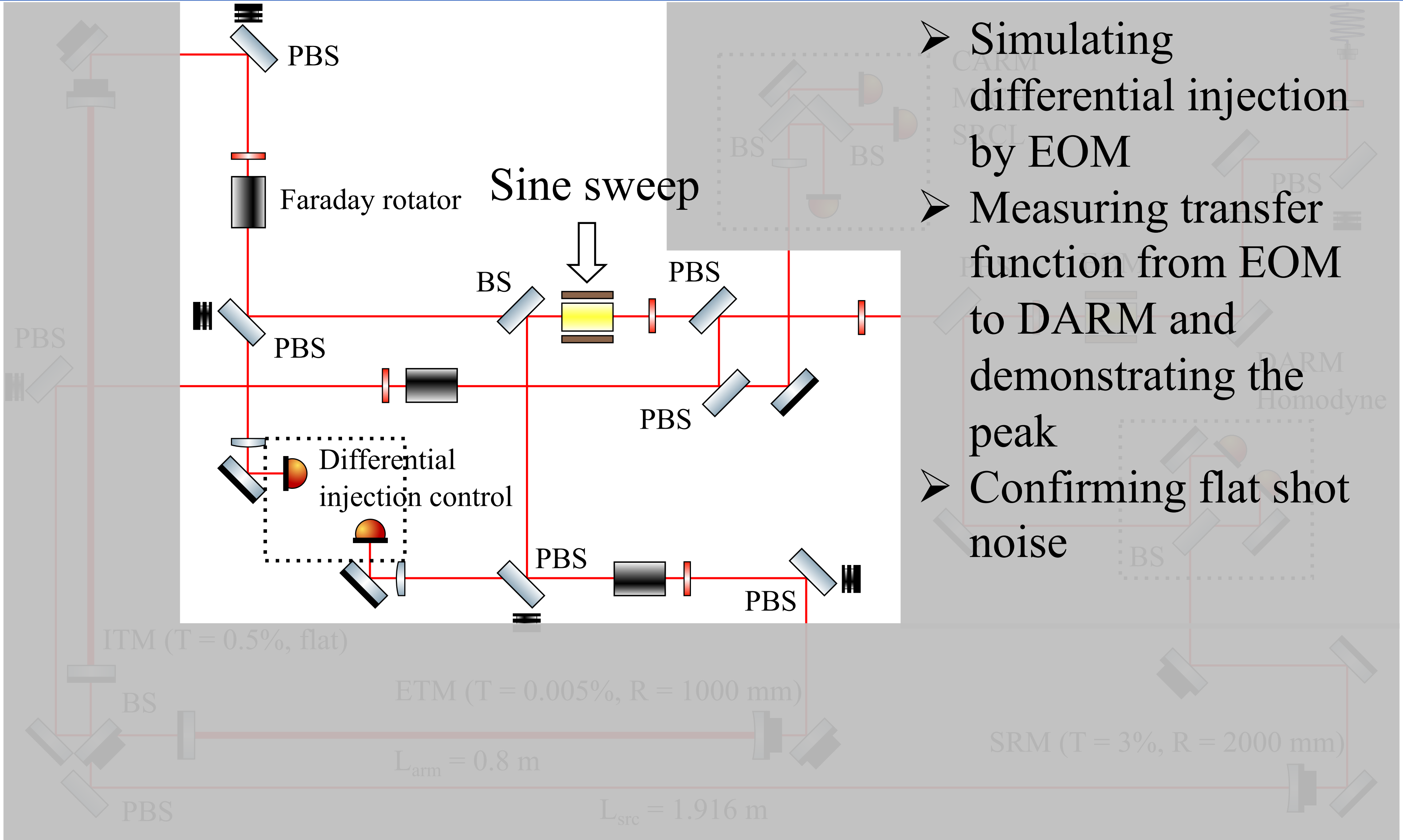
Modulation and detection



- CARM: f_1-I, to laser frequency
- MICH: f_1-Q, to BS
- SRCL: f_2-I, to SRM

- Homodyne: $f_1 - f_2$, to homodyne path
- DARM: DC, to ETM

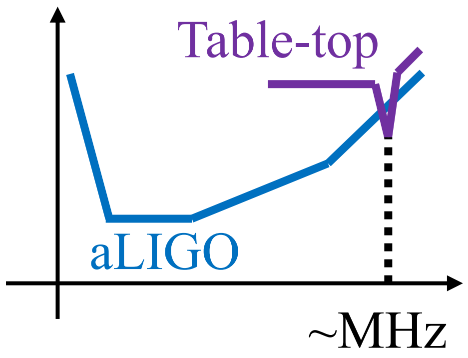
Transfer function measurement



- Simulating differential injection by EOM
- Measuring transfer function from EOM to DARM and demonstrating the peak
- Confirming flat shot noise

Future

- Demonstration of the signal enhancement and the sensitivity dip
  - Constructing the experimental setup
  - Transfer function measurement around MHz
  - Shot noise measurement
  - Squeezing



- Search for MHz GWs
  - Sensitivities are determined only by the input power at high frequencies
  - Increasing the input power with the power recycling up to O(100 W)

- Other applications
  - Holographic noise (holometer)
  - Axion and dark matter