Noise coupling due to scattered light from output optics

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Contents of the talk

- Brief introduction of simulation activities in TAMA/LCGT collaborations

- Scattered light noise

  Motivation

  Principle of the noise

  Approach used in this study

  Simulation and interpretation of the result

  Michelson/Recycled MI/Recyceld FPMI

  Discussion/Conclusion

Simulation activities in TAMA/LCGT

- No comprehensive work to construct our own simulation environment / tool

- As users of the simulation softwares

  E2E: (ICRR - Hayakawa, et al, with LIGO E2E team)

    Modeling of CLIO (100-m cryogenic prototype in Kamioka)

    h(t) injection module

  Finesse: (NAOJ - Kawamura, et al with LIGO 40m team)

    Lock acquisition study for Caltech 40m

    Sensing design for an RSE interferometer (NAOJ - Kokeyama, et al)

    Scattered light noise estimation (NAOJ - Arai, et al)

  LISO:

    Linear circuit simulations (NAOJ, U-Tokyo. etc)

- Analysis related simulations

  Software signal injection of galactic GW events

  Crosstalk study of two co-located interferometer

  (Osaka City Univ - Kanda, et al)

Scattered light ~ introduction

- Demand of simulations from the site

Commissioning work

> Various kind of problems day by day

> Always confused by the complicated “real world”

To grasp what is happening in the real detector

> Even a simple model is often sufficient

if it reflects the physics we want.

> No need to be too exact

--- actual values will be obtained from experiments

Feedback to experiments

> Suggestions to the experiment

> Suggestions of experimental methods

Scattered light ~ motivation

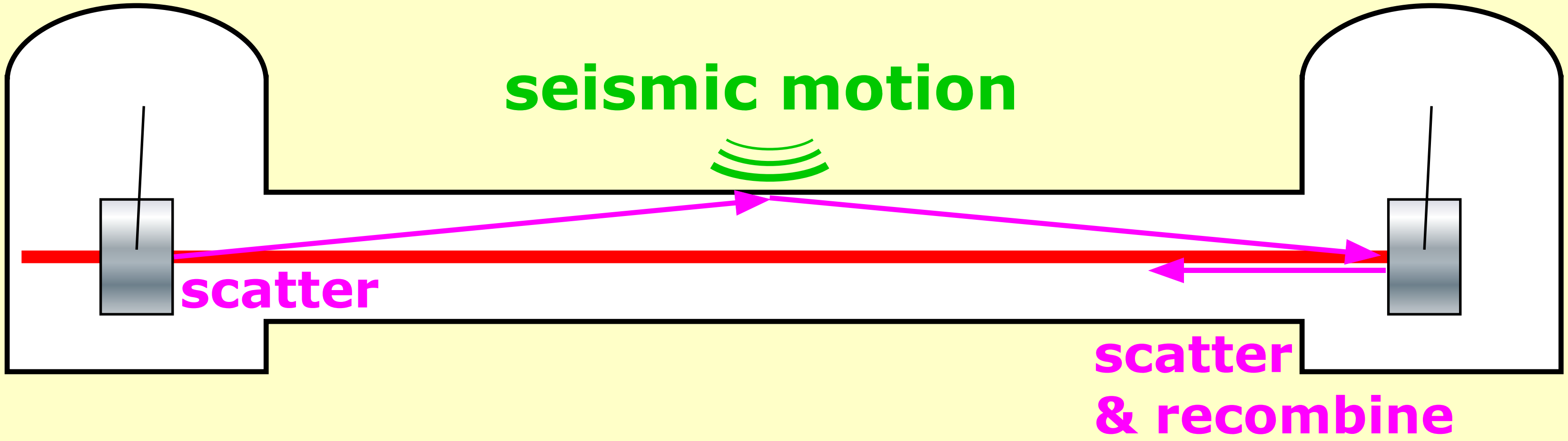
- Scattered light noise

A) Scattered light in the beam tube

B) Scattered light at the optical ports

A) Scattered light in the beam tube

> For the design of the long vacuum tubes and the buffles



> Experiment in TAMA

Excitation of a tube resonance: 5.6um@ 776.5Hz => $1\mathrm{x}10^{-17}$ m in the sensitivity

i.e. Seismic motion $dx = 1\mathrm{x}10^{-7} / f^{2}$ m/sqrtHz => ~ $2 \mathrm{~x}~ 10^{-19} / f^{2}$ m/sqrtHz

=> Negligible

PRD, Vol.70, 062003

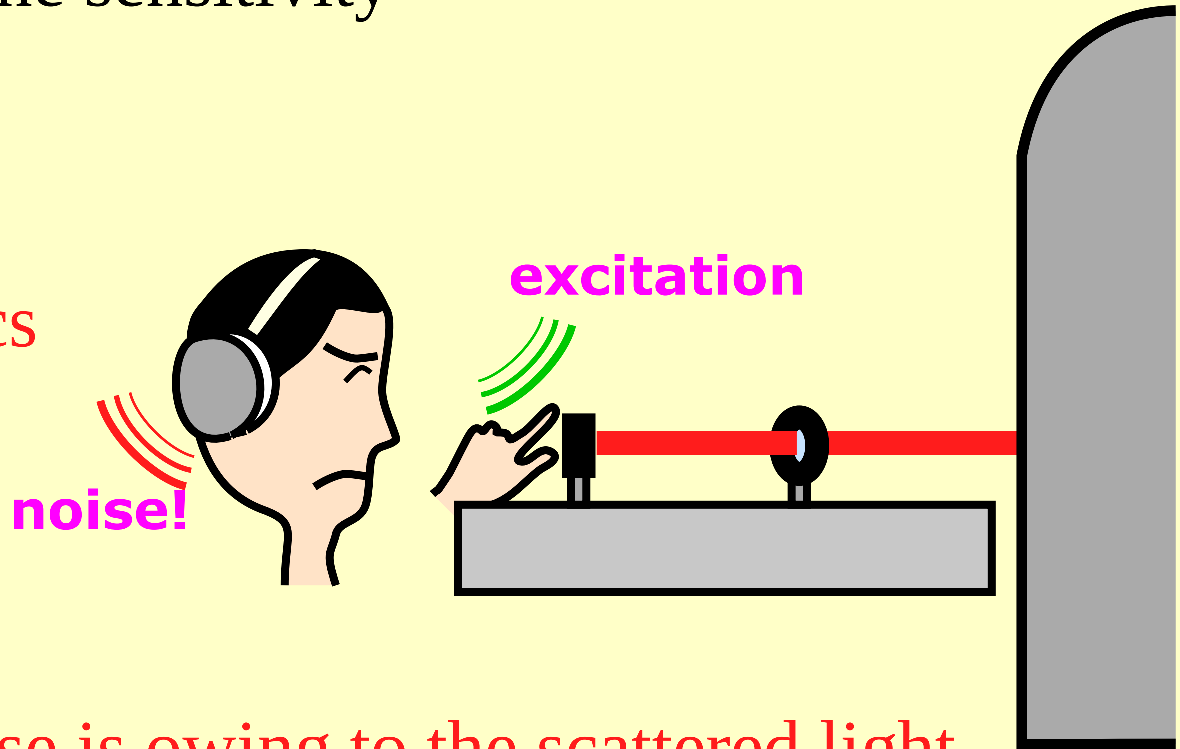
R. Takahashi, K. Arai, S. Kawamura, and M. R. Smith

Scattered light ~ motivation

B) Scattered light at the optical ports

Fact: touching of the output optics
=> mechanical peaks in the sensitivity

e.g.
> Tapping of the dark port optics
=> huge noise
> Bright port
=> moderate noise



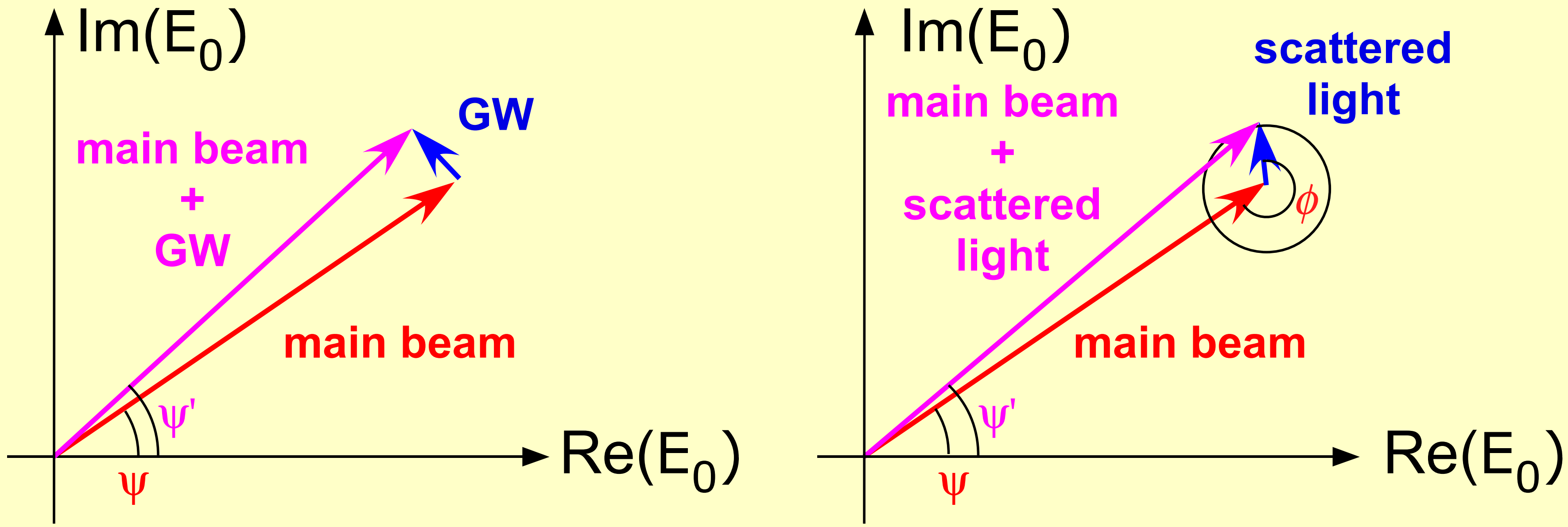
Expect some fraction of the noise is owing to the scattered light
Q. Which optical port is dangerous? How much?
> Tapping every optics
> More systematic estimation?

Scattered light ~ principle

- Coupling of scattered light to the output signal

GW detector ＝ optical phase sensor

Electric field of the main beam $E=E_0\,e^{i\,\Omega\,t}$



Scattered light recombined to the main beam

Motion of the scattering body

=> perturbation of the optical phase

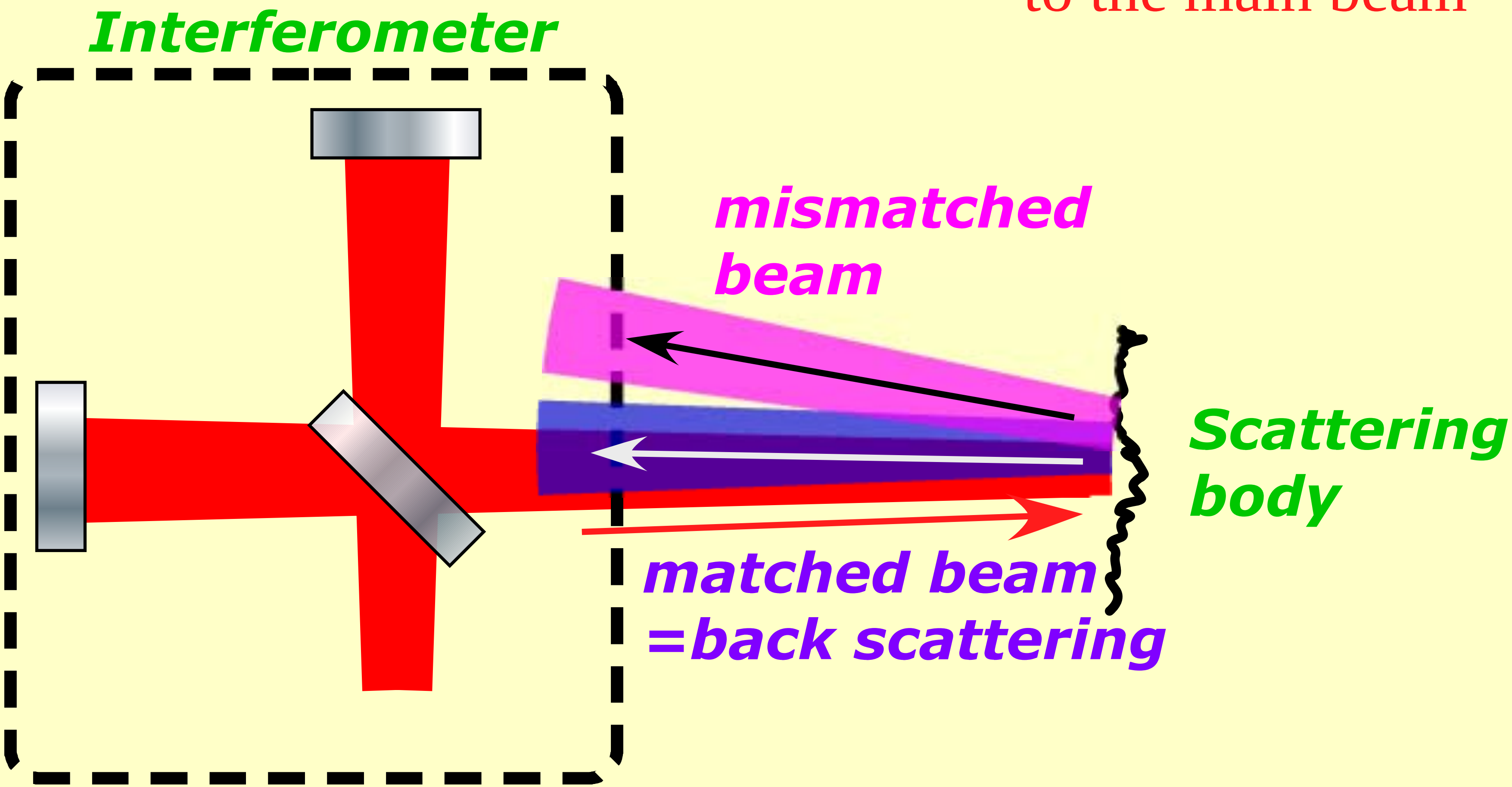
=> Appear in the output signal

Scattered light ~ back scattering

- Only back scattering is considered

In order to couple to the output signal

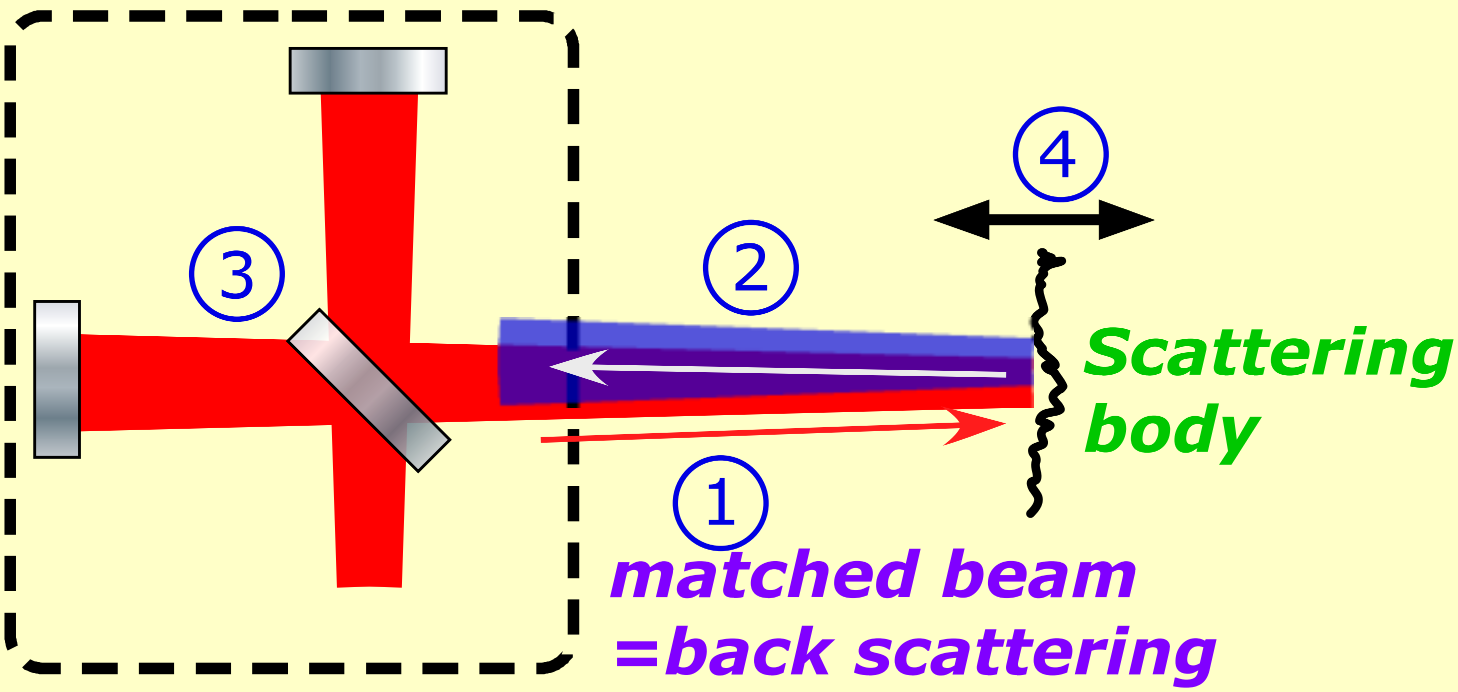
=> The scattered light should be spatially matched
to the main beam



=> Only consideration of TEM_{00} is enough

Scattered light ~ factors

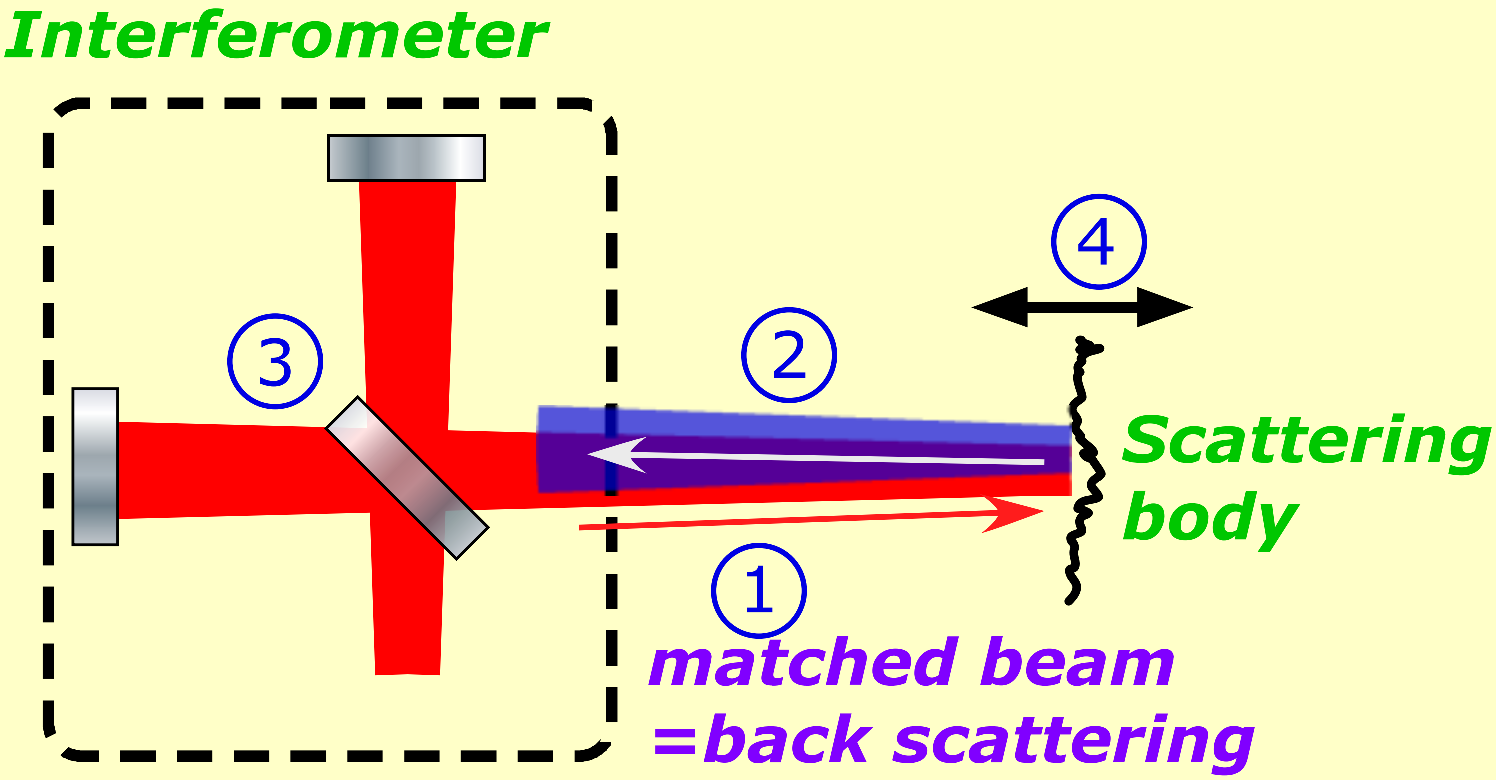
- Factors to determine the amount of the noise



1. Amount of the light power arrives on the scattering body. P_{out}
2. Efficiency of effective back scattering η_{scat}
3. Sensitivity of the signal to the scattering α
4. Amount of the scattering body's motion δx_{scat}

Scattered light ~ factors

- Factors to determine the amount of the noise



1. Amount of the light power arrives on the scattering body. => Easy to simulate
2. Efficiency of effective back scattering => Experiment
3. Sensitivity of the signal to the scattering => Easy to simulate
4. Amount of the scattering body's motion => Experiment

Simulation ~ Using Finesse

- “Finesse" is selected for the tool

  Reason: It looked the easiest tool for the purpose

  Any kind of length sensing tool does fit

- Use Finesse at the most basic level

  Modulation sideband: up to 1st order

  Spatial mode: only TEM_{00}

  Frequency range: only at DC

- Based on the TAMA300 parameters

  Michelson (MI) / Recycled Michelson (RMI) model

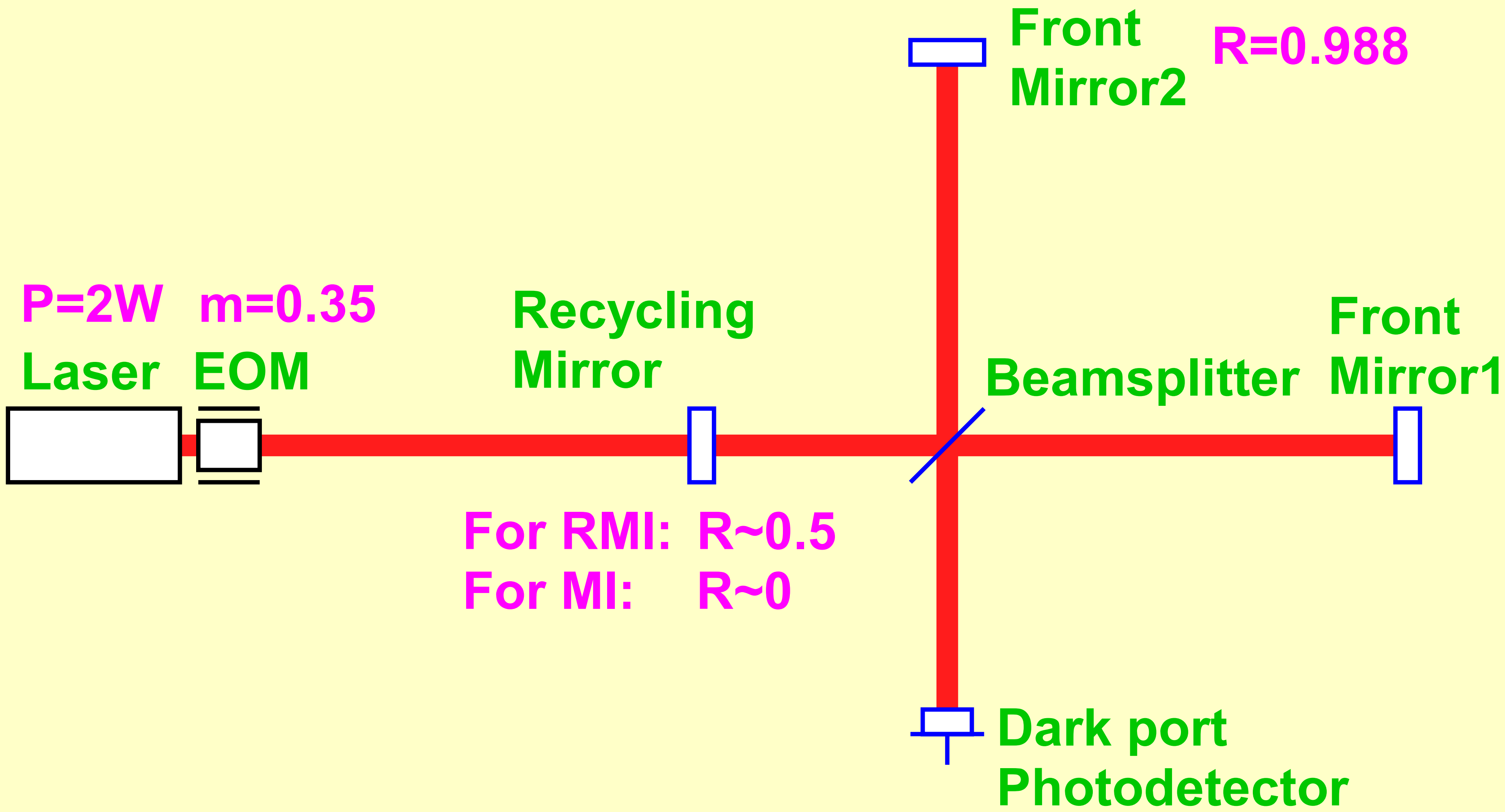
  => To understand nature of the scattered light noise

  Recycled Fabry-Perot Michelson (RFPMI) model

  => To acquire the applicable knowledge to TAMA300

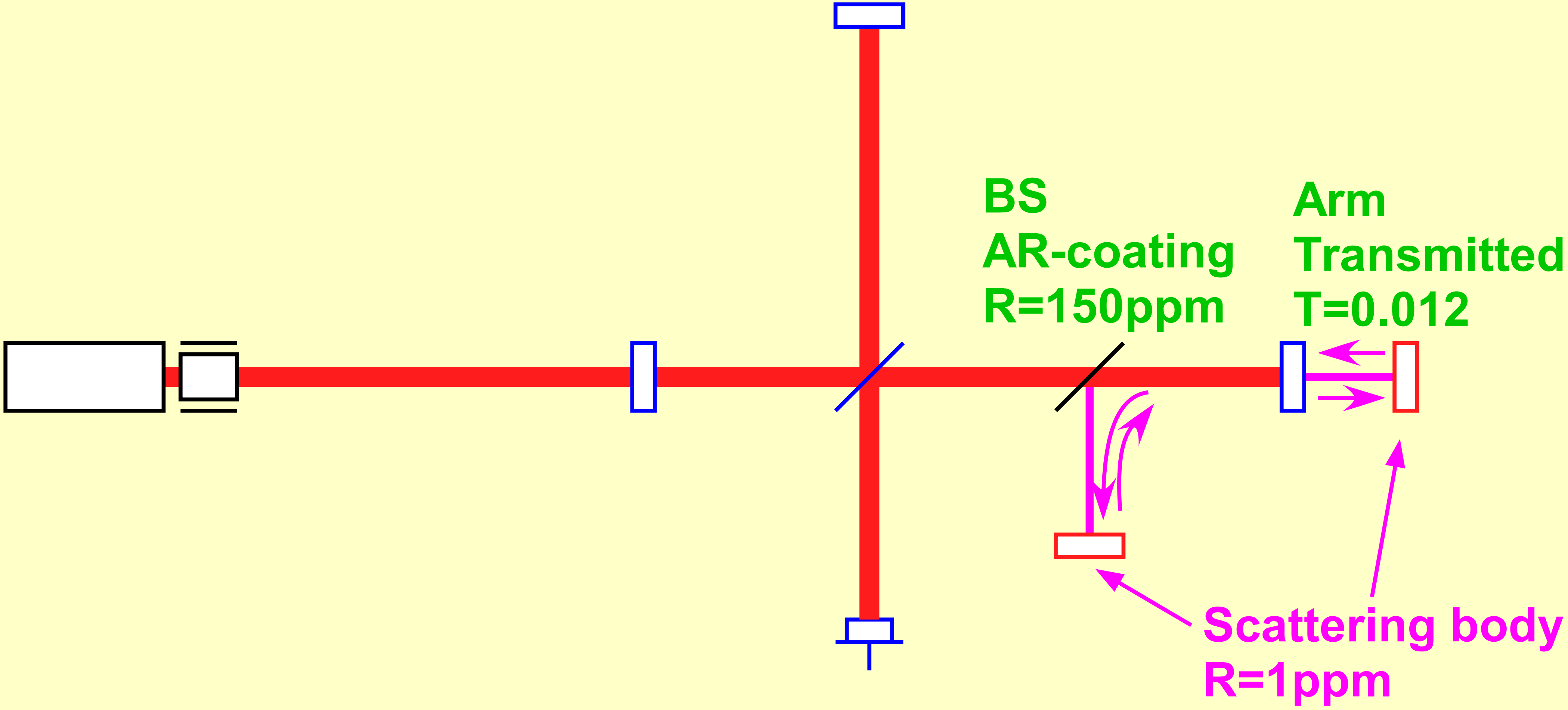
Simulation ~ MI/RMI model

RMI:
The carrier is resonant
The sidebands are not resonant



Simulation ~ MI/RMI model

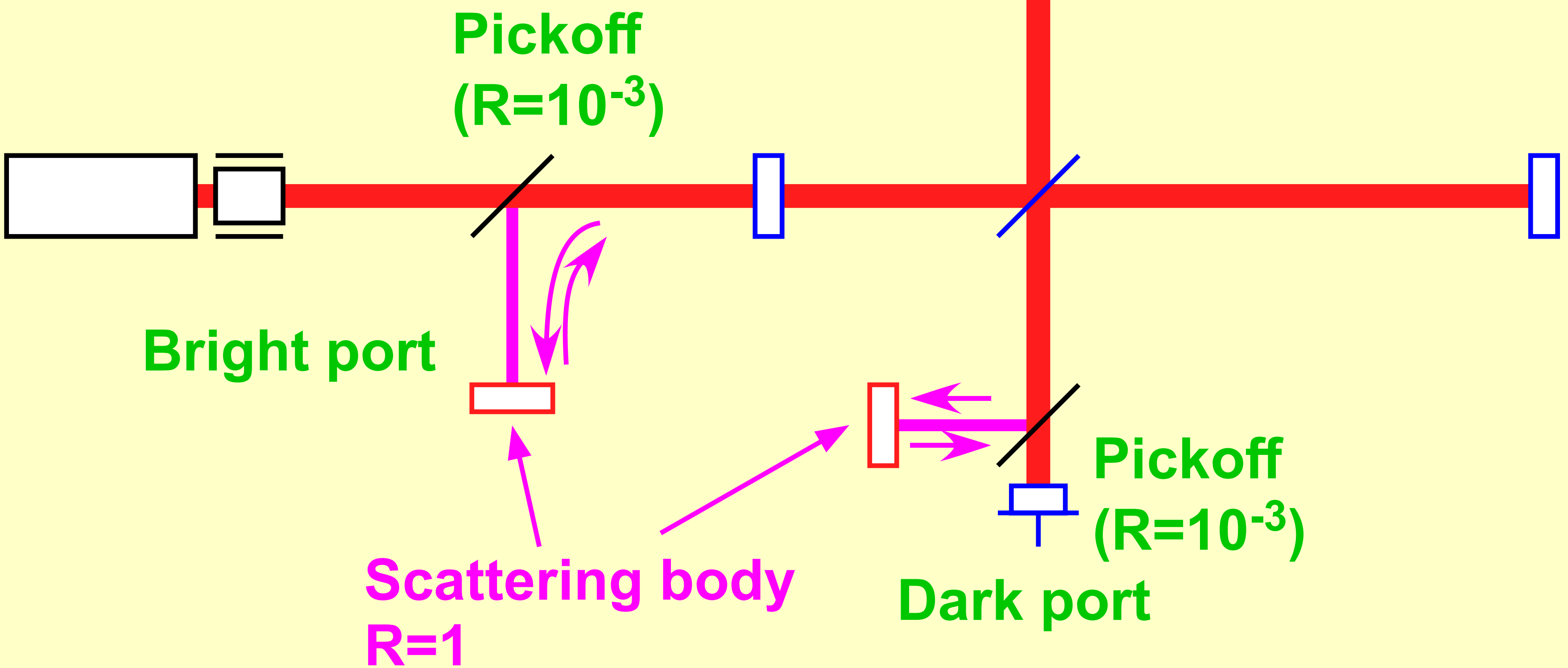
Placing scattering bodies with effective reflectivity of 1ppm



Simulation ~ MI/RMI model

Pickoff mirrors ($R=10^{-3}$) are inserted at several places

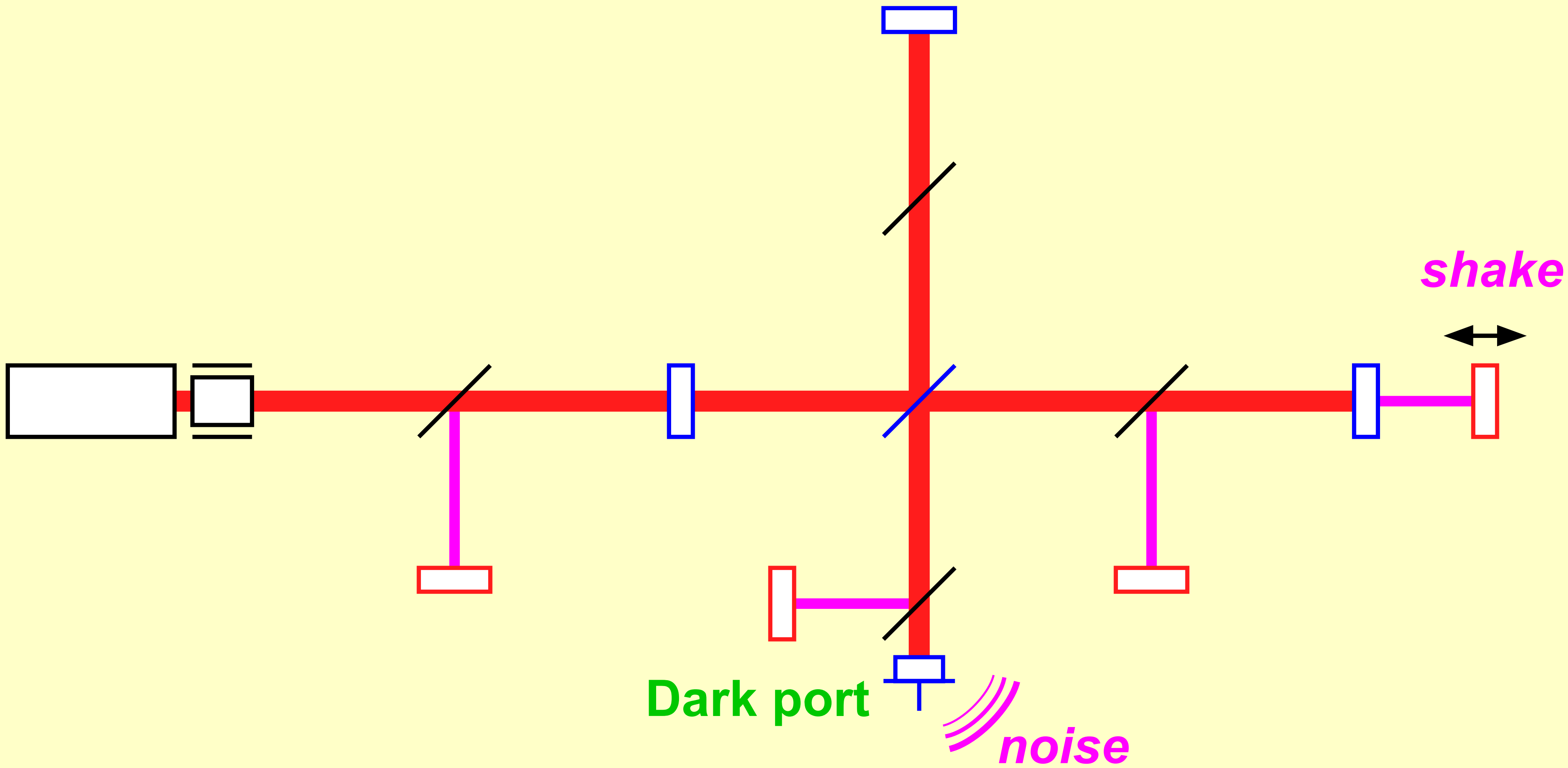
~ avoiding to disturb the internal condition



Simulation ~ MI/RMI model

Sweep the position of each scattering body

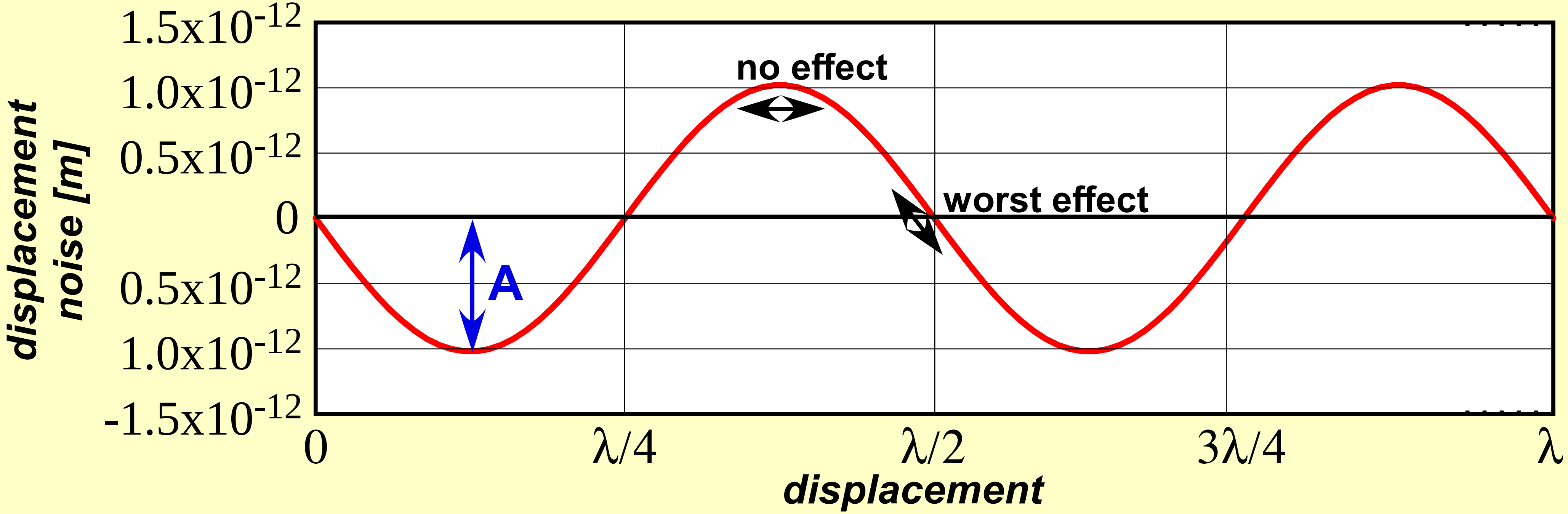
=> Look at the dark port signal



Simulation ~ how to evaluate the result

● Effect of the motion of the scattering source

Example: noise by the motion of the mirror behind the arm



> Small amplitude motion $\delta x_{max} = (4 \pi A / \lambda) \delta x_{scat}$

> Large amplitude motion $dx = A$ at $f = 2 v_{scat} / \lambda$ (fringe frequency)

> Note: Noise amplitude A is proportional to the "amplitude" of the scattered light

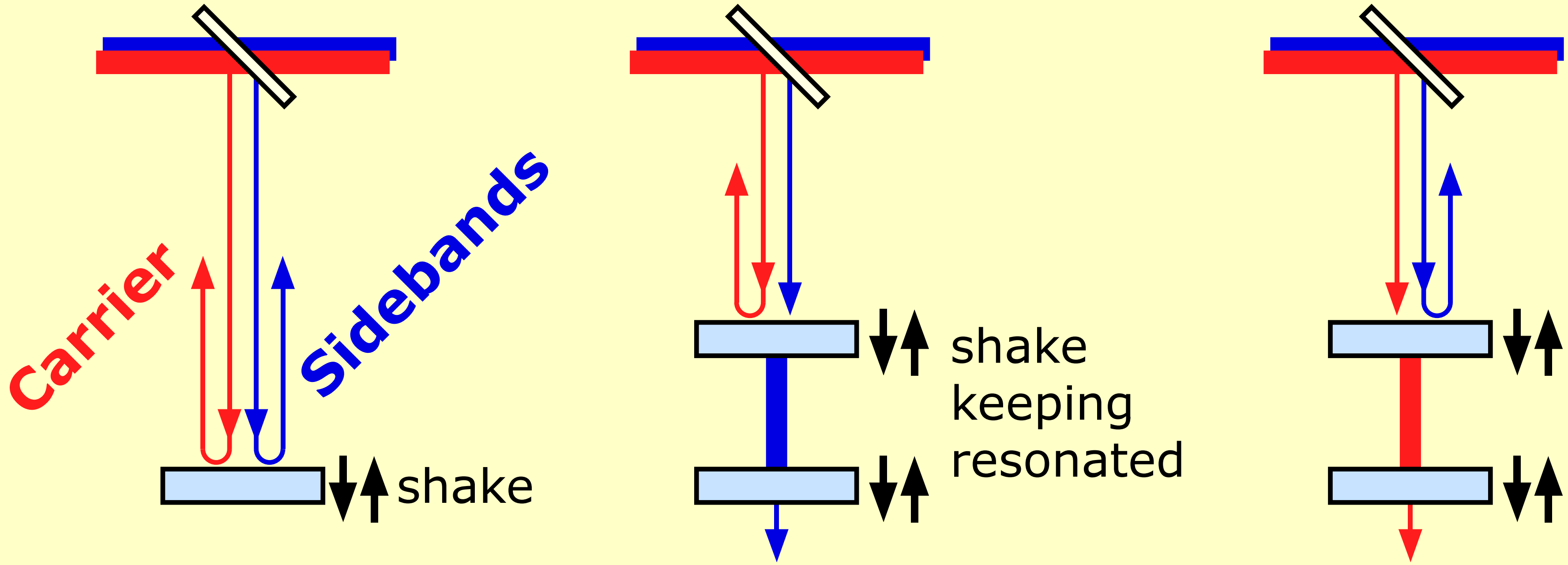
$R_{scat} = 1ppm \Rightarrow A$

$R_{scat} = 100ppm \Rightarrow A' = 10 A$

Simulation ~ Carrier/sideband decomposition

- Scattering source ~ **three kinds of "mirrors"**

  > Separating the contribution of
  the carrier and the modulation sidebands



Mirror:	SB resonant FP:	CA resonant FP:
CA reflected	CA reflected	CA absorbed
SB reflected	SB absorbed	SB reflected

(reflection 99.7%, absorption ~100%)

Simulation method summary

- Sweep the position of each scattering source

Scattering source at: Arm trans., BS AR coat, Dark, Bright

Detector output: Sin wave (amplitude A)

=> $A = (P_{out})^{\varepsilon} \alpha \, \eta_{scat}$ for $\eta_{scat} = 1$ ppm

- Decompose the contribution of CA/SB

Ordinary mirror: Carrier + Sidebands

SB resonant FP: only Carrier

CA resonant FP: only Sidebands

- Inject imperfections of the interferometer

Michelson offset: $dx = 10^{-12}$ m ~ 10^{-10} m

Reflectivity mismatch of the arm mirrors:

$dR = 100$ ppm ~ 10000 ppm

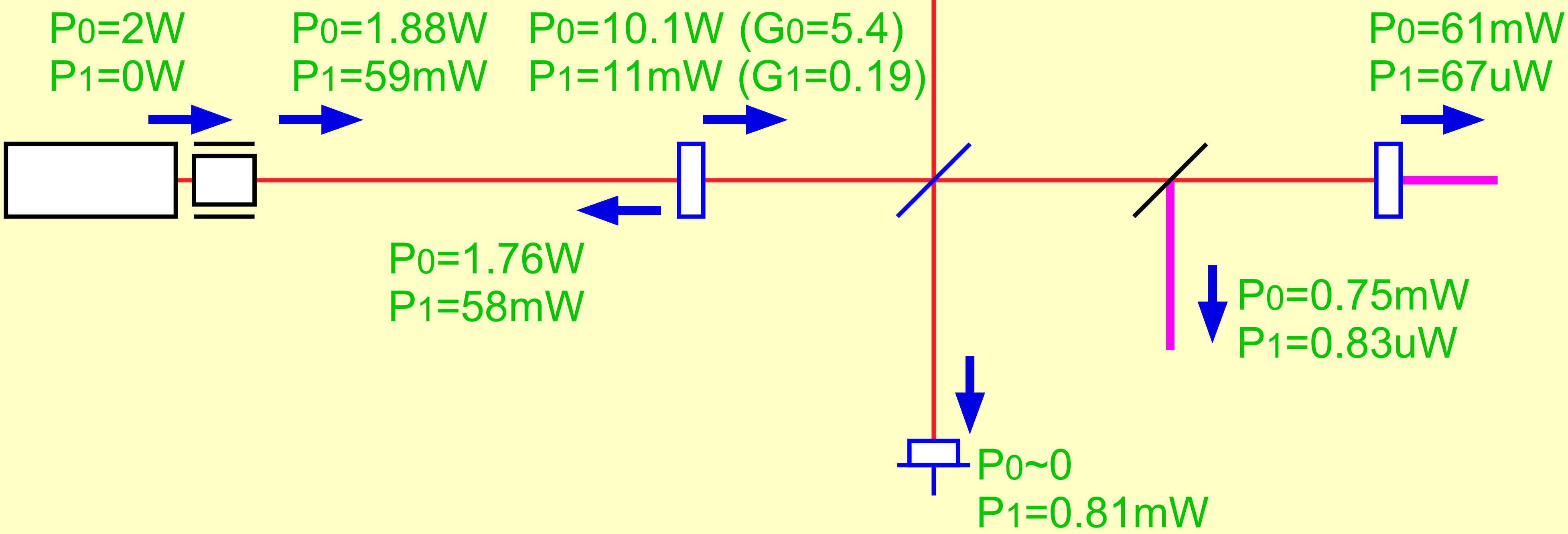
Note: Macro- and microscopic deviations of the recycling cavity hardly effect the results

MI/RMI model ~ DC power

RMI case:

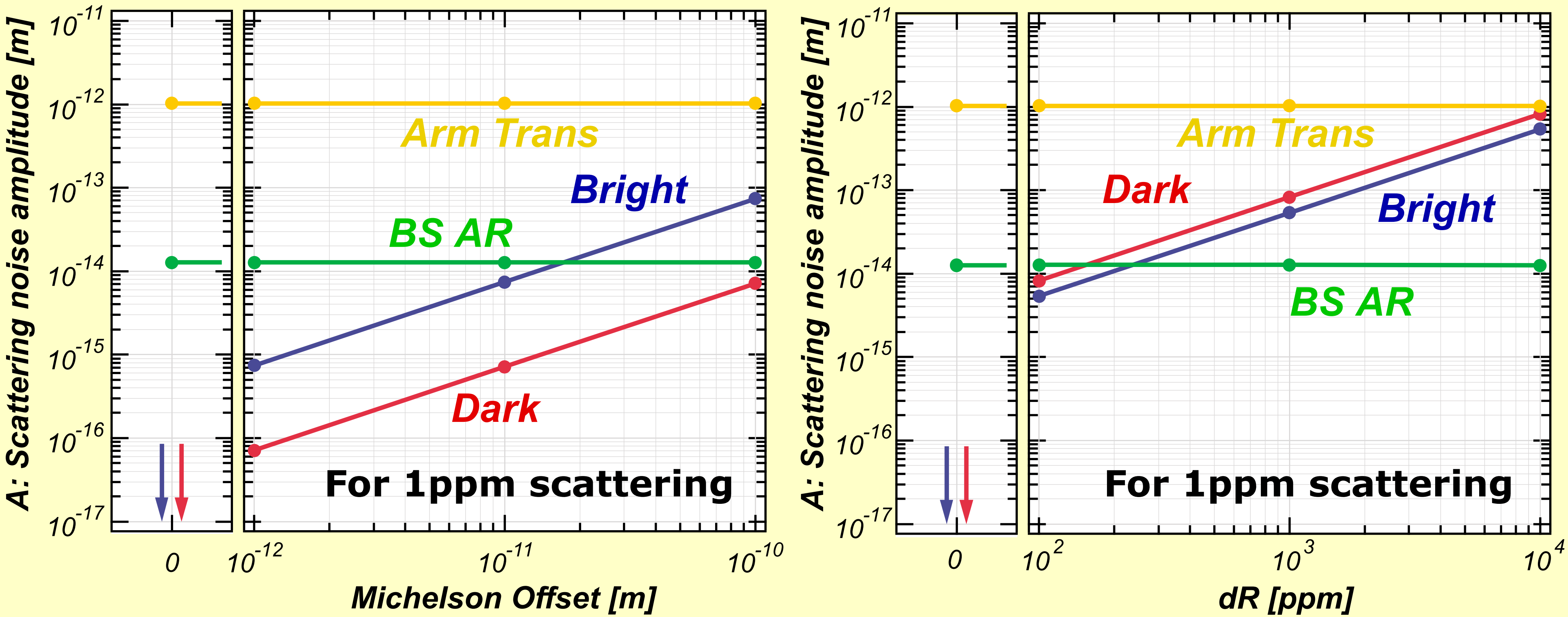
P0: carrier power
P1: sideband power

Power consumption:
94% is reflected to the bright port
60mWx2 (3%x2) transmitted from the arms



MI case: Change RM with R=0

MI model ~ Result



Arm trans. / BS AR noise level: not affected by the deviations

Carrier added to only one of the arm => becomes the signal directly

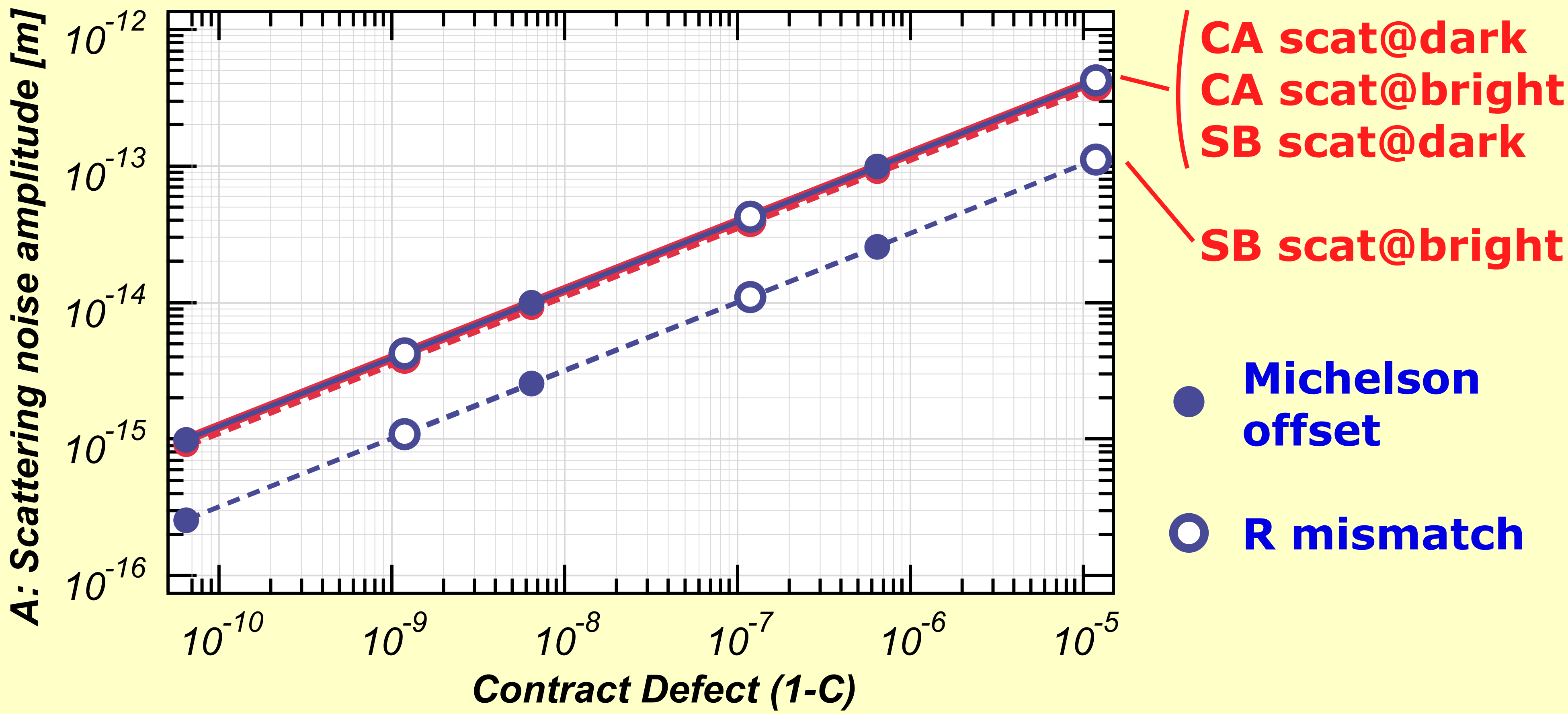
$A = 9.0 \times 10^{-11} P_{out}$ [*m*] (for 1ppm scattering)

Bright/Dark case: depends on how much the imperfection is

Ideal case: no noise <= No carrier at dark, perfect common mode rejection

MI model ~ Result

- Separate the contrib. of CA and SB



No matter what the origin of the leakage carrier is

~ Noise coupling is determined by sqrt of contrast defect

(= by the leakage carrier field at the dark)

MI model ~ Interpretation

- Noise coupling is determined
  by the leakage carrier at the dark

Leakage carrier field $\sqrt{P_{ca@dark}}$

Carrier scattering at the dark port:

All of the injected carrier from the dark port becomes the noise
=> Noise coupling is proportional to $\sqrt{P_{ca@dark}}$

Carrier scattering at the bright port:

How much the carrier does leak to the dark port
=> proportional to $\sqrt{P_{ca@dark}}$

Sideband scattering at the dark port/the bright port:

Some amount of the scattered sidebands appears at the dark port
=> Couples with the leakage carrier
=> Proportional to $\sqrt{P_{ca@dark}}$

MI/RMI model ~ DC power

RMI case:

P0: carrier power
P1: sideband power

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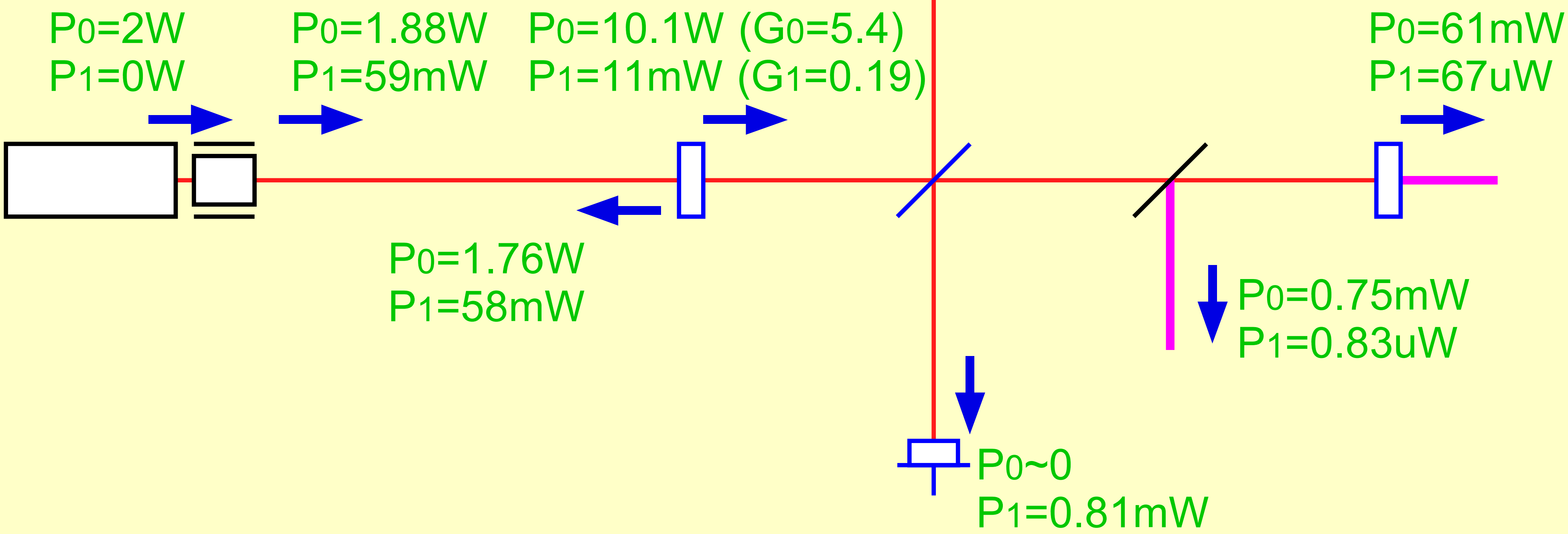


MI case: Change RM with R=0

MI/RMI model ~ RMI Result

- Power recycling does not change the situation

Power recycling increases the scattered light and the signal at the same rate

	MI (unit: m)	RMI (unit: m)
Arm Trans	1.02×10^{-12}	1.02×10^{-12}
BS AR	1.26×10^{-14}	1.26×10^{-14}
CA scat @ dark	$1.16 \times 10^{-10} \sqrt{(1-C)}$	$1.20 \times 10^{-10} \sqrt{(1-C)}$
SB scat @ dark	$1.07 \times 10^{-10} \sqrt{(1-C)}$	$1.14 \times 10^{-10} \sqrt{(1-C)}$
CA scat @ bright	$1.16 \times 10^{-10} \sqrt{(1-C)}$	$1.16 \times 10^{-10} \sqrt{(1-C)}$
SB scat @ bright	$2.98 \times 10^{-11} \sqrt{(1-C)}$	$3.39 \times 10^{-11} \sqrt{(1-C)}$

MI/RMI model ~ Result Summary

- Asymmetric scattered light

Constant noise coupling

~ Independent from the interferometer condition

$$A = 9.0 \times 10^{-11} P_{out} \quad [m] \qquad \text{(for 1ppm scattering)}$$

- Scattering at the dark port and the bright port

Dependent on the contrast defect

$$A \sim 1 \times 10^{-10} \sqrt{(1-C)} \quad [m] \qquad \text{(for 1ppm scattering)}$$

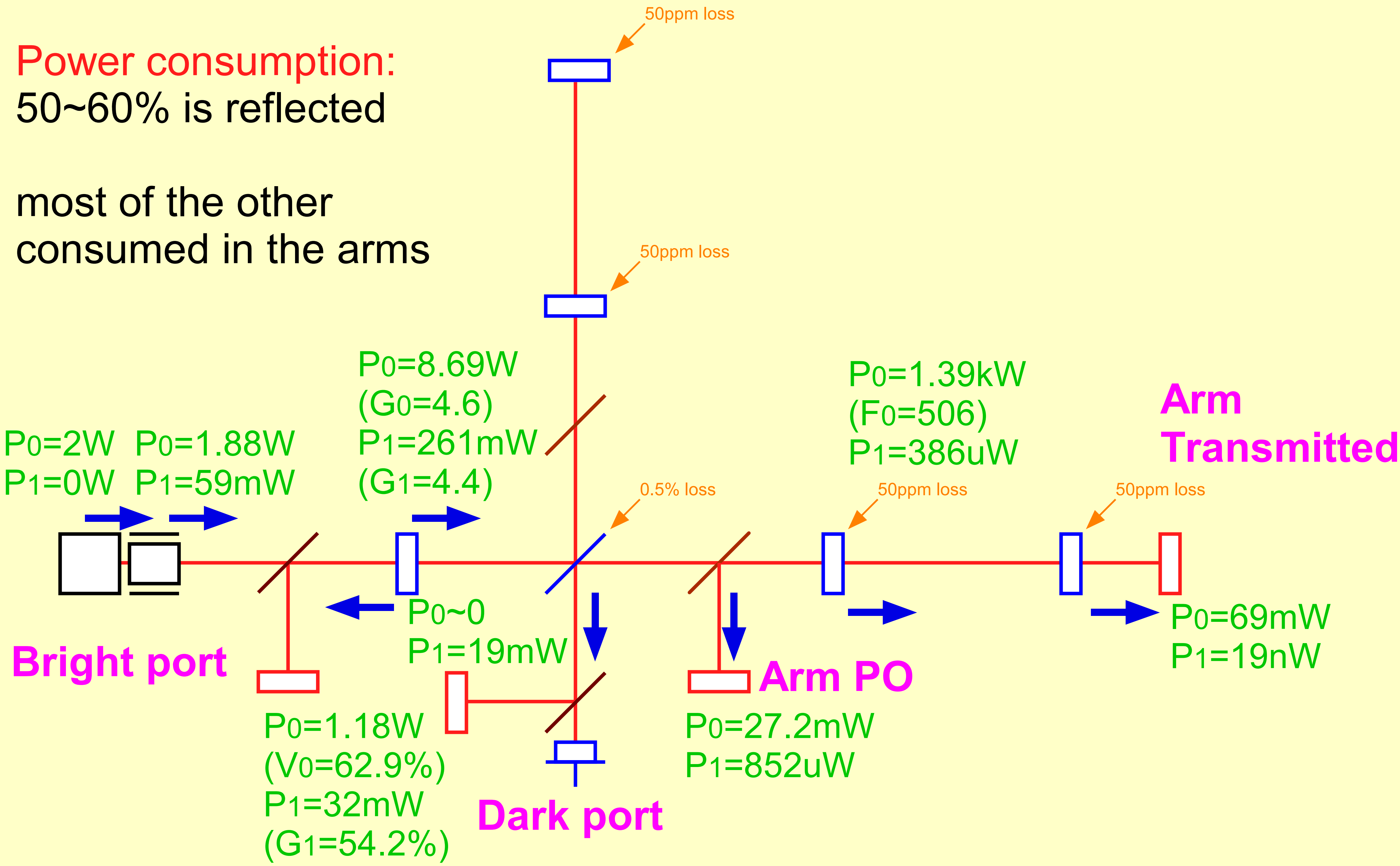
c.f. Bright port ~ Carrier of 2W
Dark port ~ Carrier of ~0W
=> Same order contribution

- Power recycling does not change the scattered light noise level

RFPMI model ~ DC light level

Power consumption:
50~60% is reflected

most of the other
consumed in the arms



RFPMI model ~ Result

- Even with the FP arms the noise coupling is understood as the Michelson case **by including the signal enhancement by the FP arm** (factor of N_{FP}=322)

	MI (unit: m)	RFPMI (unit: m)
FP Arm Trans		4.23×10^{-15}
BS AR (Arm PO)	$9.0 \times 10^{-11} P_{out}$	$9.0 \times 10^{-11} P_{out} / G_0 / N_{FP}$
CA scat @ dark	$1.16 \times 10^{-10} \sqrt{(1-C)}$	$1.11 \times 10^{-10} \sqrt{(1-C)}$
SB scat @ dark	$1.07 \times 10^{-10} \sqrt{(1-C)}$	$0.89 \times 10^{-10} \sqrt{(1-C)}$
CA scat @ bright	$1.16 \times 10^{-10} \sqrt{(1-C)}$	$0.91 \times 10^{-10} \sqrt{(1-C)}$
SB scat @ bright	$2.98 \times 10^{-11} \sqrt{(1-C)}$	$2.78 \times 10^{-11} \sqrt{(1-C)}$

This means:

Scattered light noise level with MI or RMI will appear in the RFPMI sensitivity by a factor of $1/N_{FP}$

Discussion

- Calculation shows:

Noise from the dark port vs Noise from the bright port

=> Comparable

Presence of higher order modes

=> Higher order modes increase the scattered light couples to the main beam

The noise from bright port is not affected by the higher order modes

=> It may be possible to estimate the imperfection level of the interferometer using the bright port

Conclusion

- Single mode simulation for scattered light noise

MI/RMI/RFPMI cases are essentially the same

=> Considering:

Recycling gain & Signal enhancement by the FP arm

Asymmetric scattered light has the constant contrib.

=> Independent from the interferometer condition

=> Dependent how much power appear at the optical port

Dark port and bright port

=> Dependent on the contrast defect

Presence of higher order modes

=> Increase the noise from the scattering at the dark port