Improving the sensitivity of gravitational wave detectors at the kiloHertz Band

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Mainly collaborate with Yanbei Chen, Chuming Wang, Haixing Miao, Enping Zhou

Dialogue at the Dream Field, May-13, 2024, Guizhou, China

Outline

- **Detect gravitational waves at kiloHertz band**
- **What limits the sensitivity at kiloHertz band**
- **Method for improving the kiloHertz sensitivity**
- **A possible design of the configuration**

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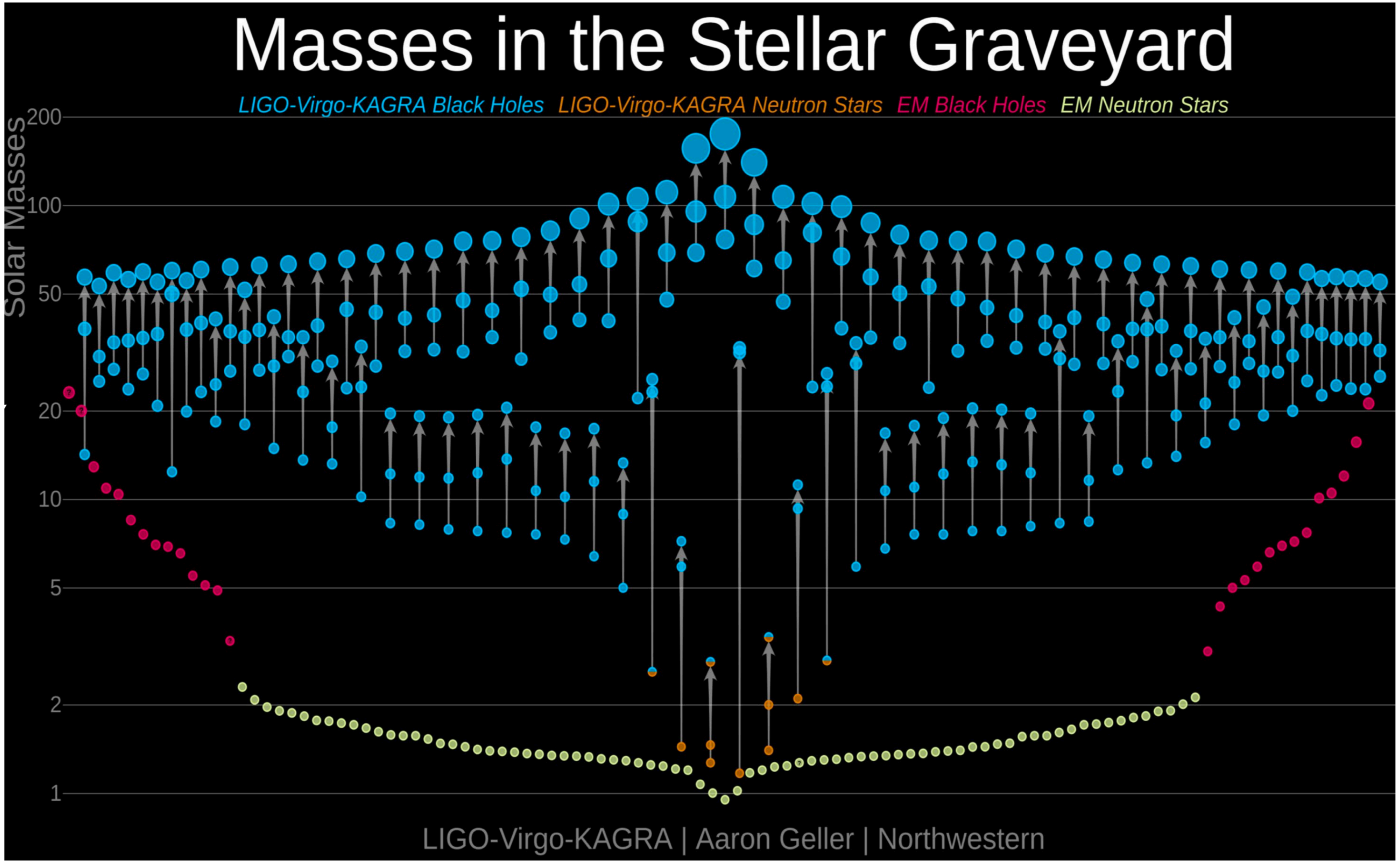
Gravitational Wave Detection

LVK collaboration, GWTC-3, Phys. Rev. X, 13, 041039 (2023)



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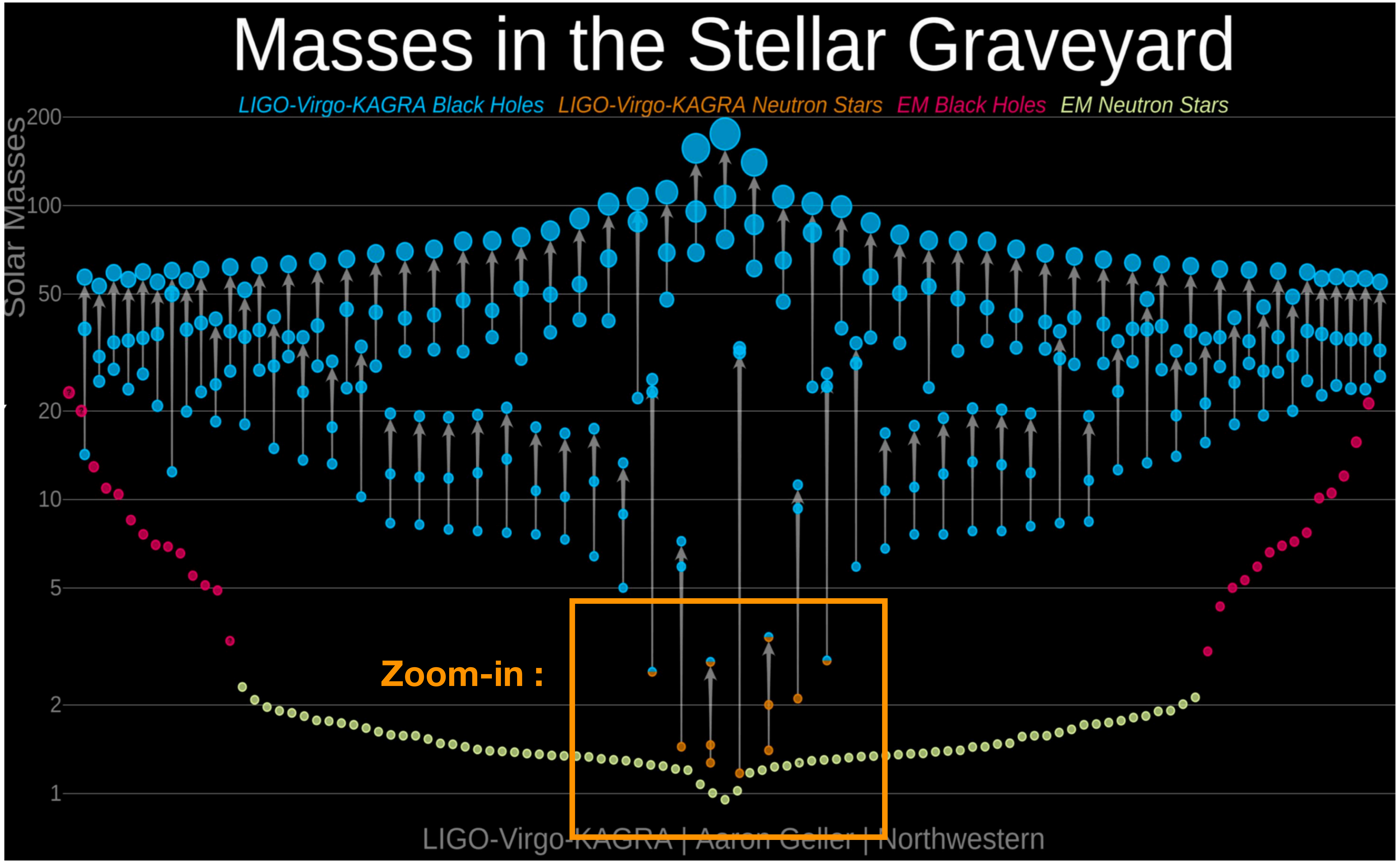

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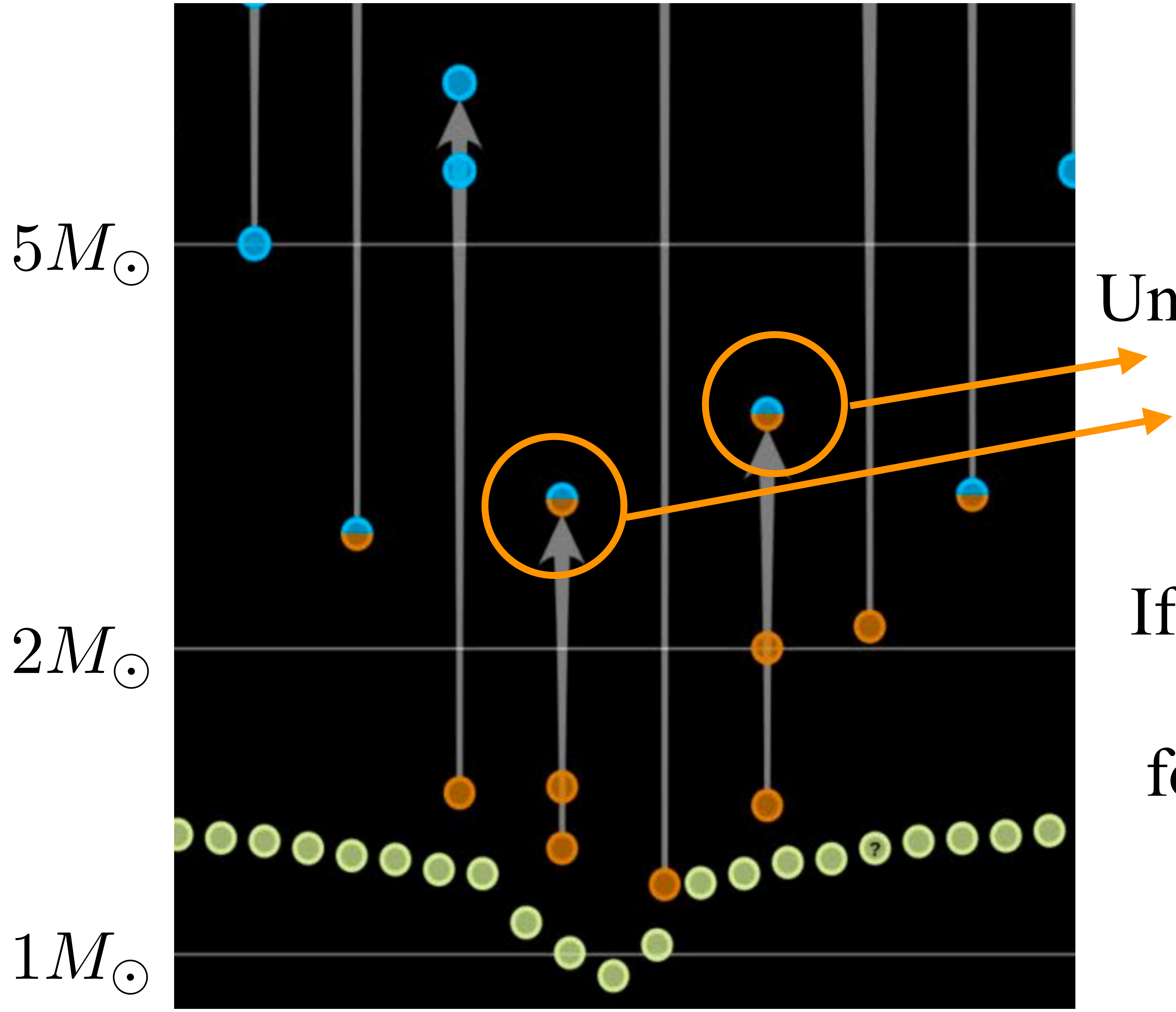
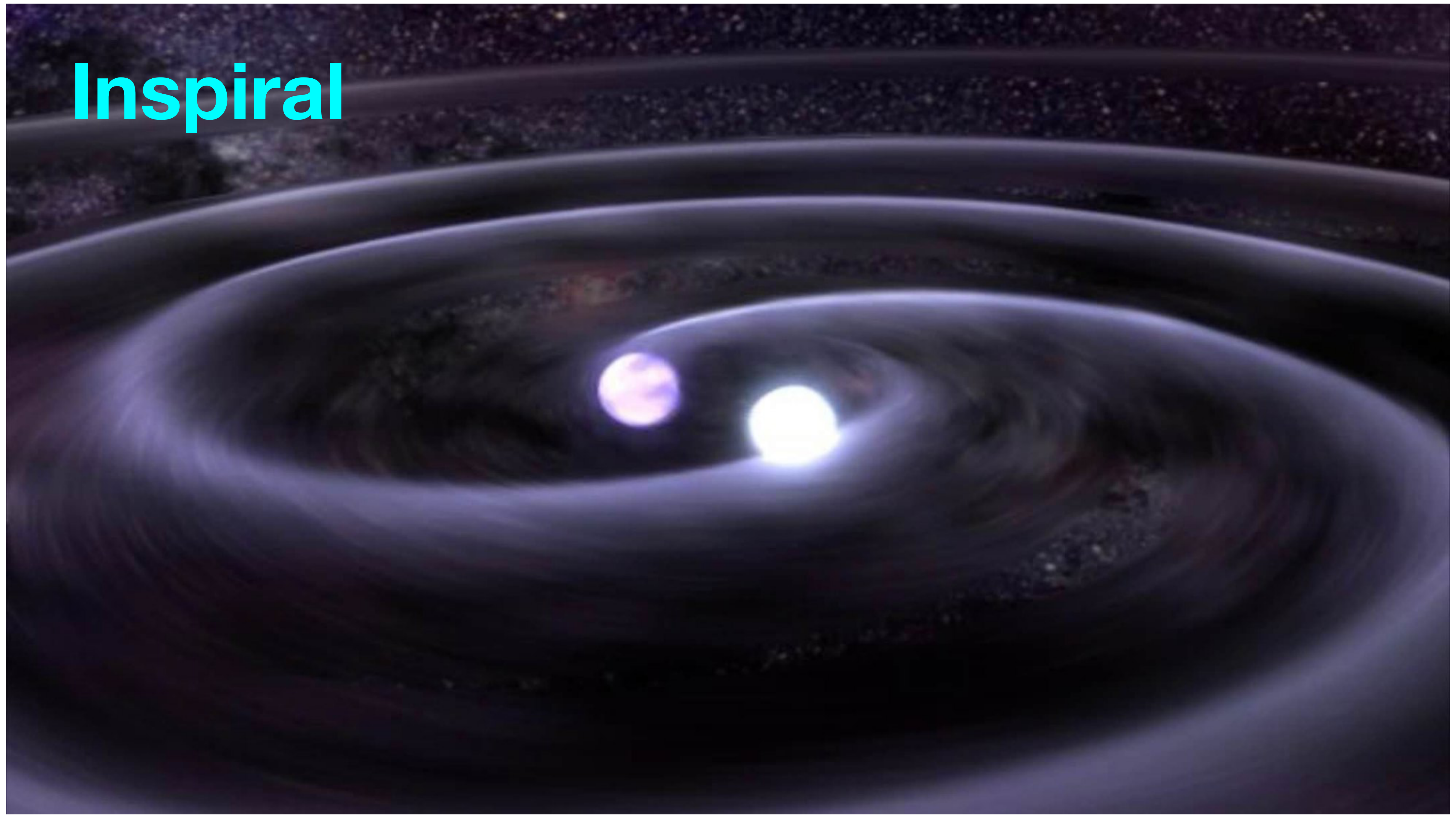


Unknown remnant state:
BH? NS?

If it is a NS, what will be the EoS for the dense matter?

Binary Neutron Star Coalescences



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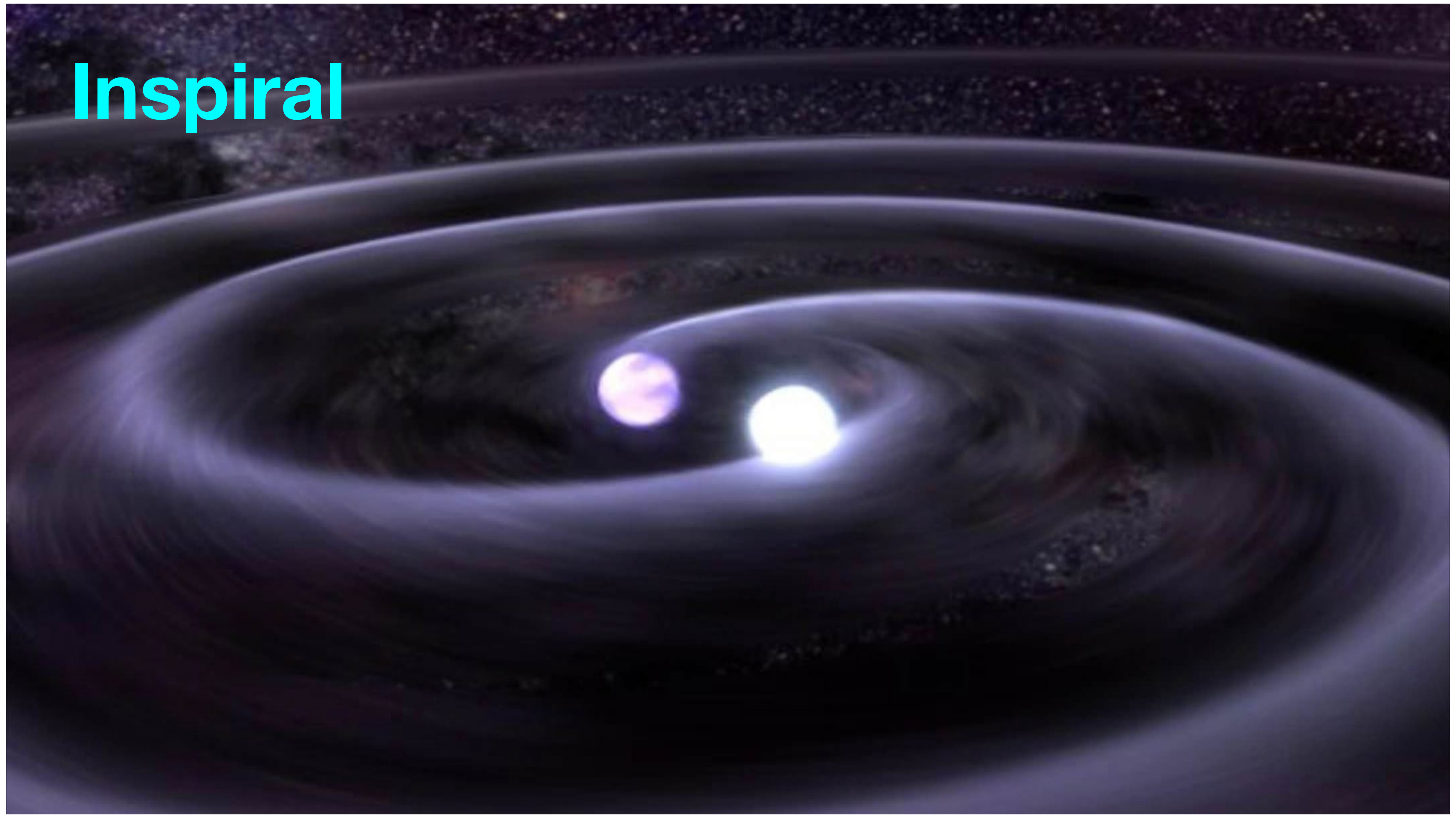
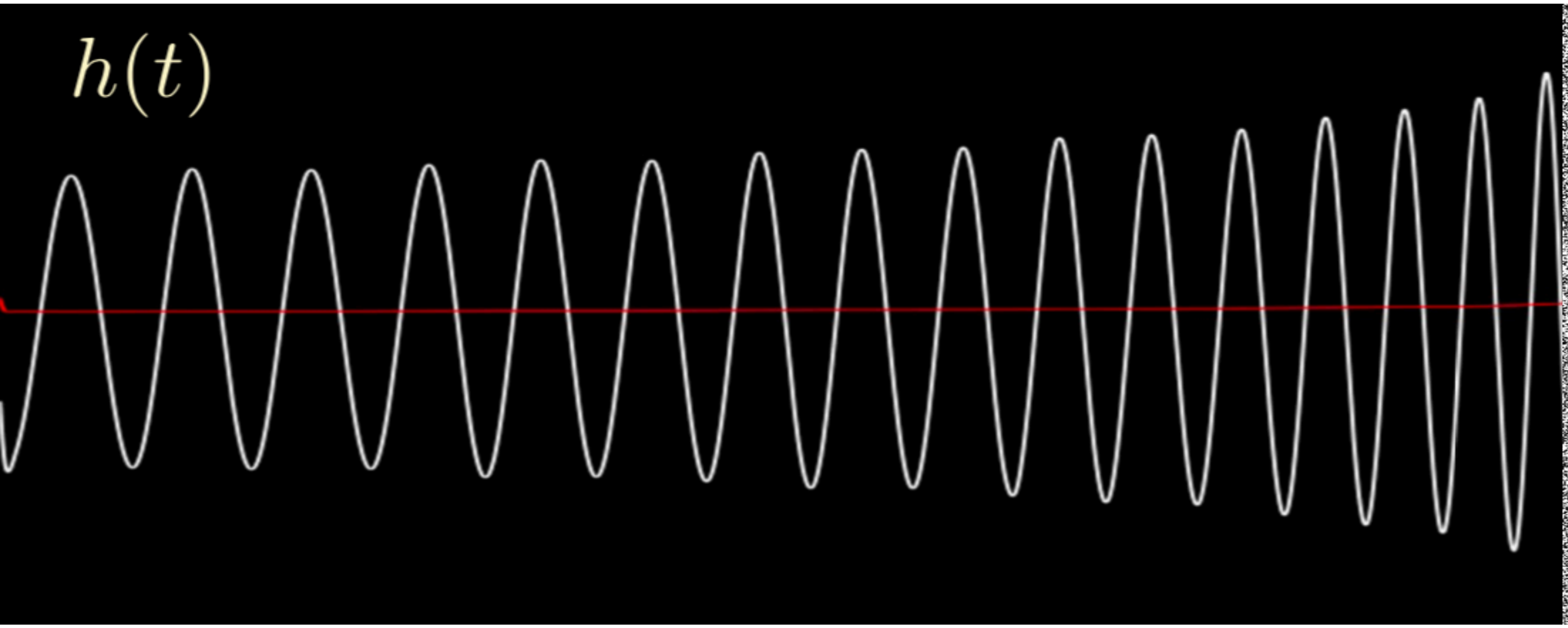
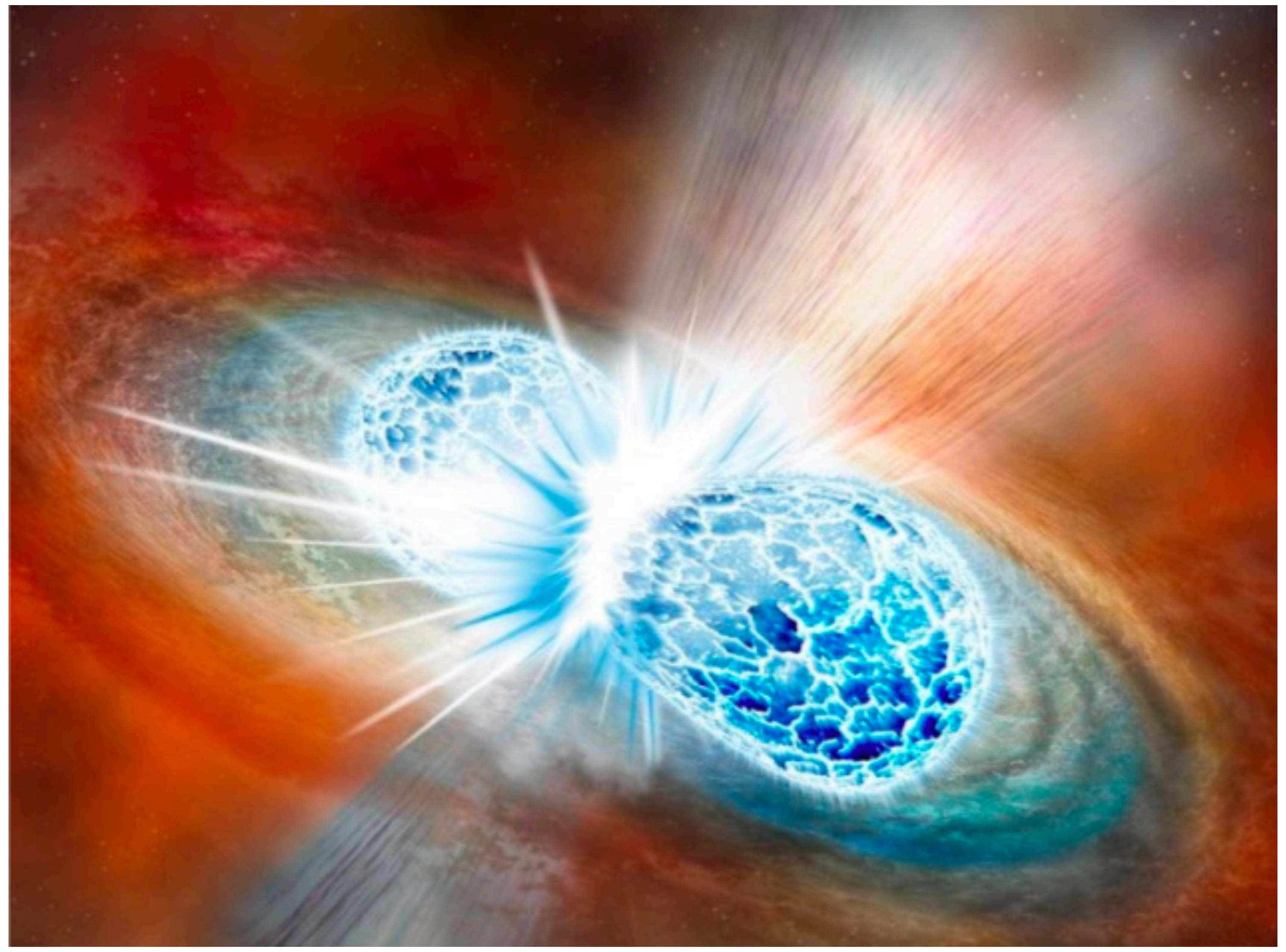


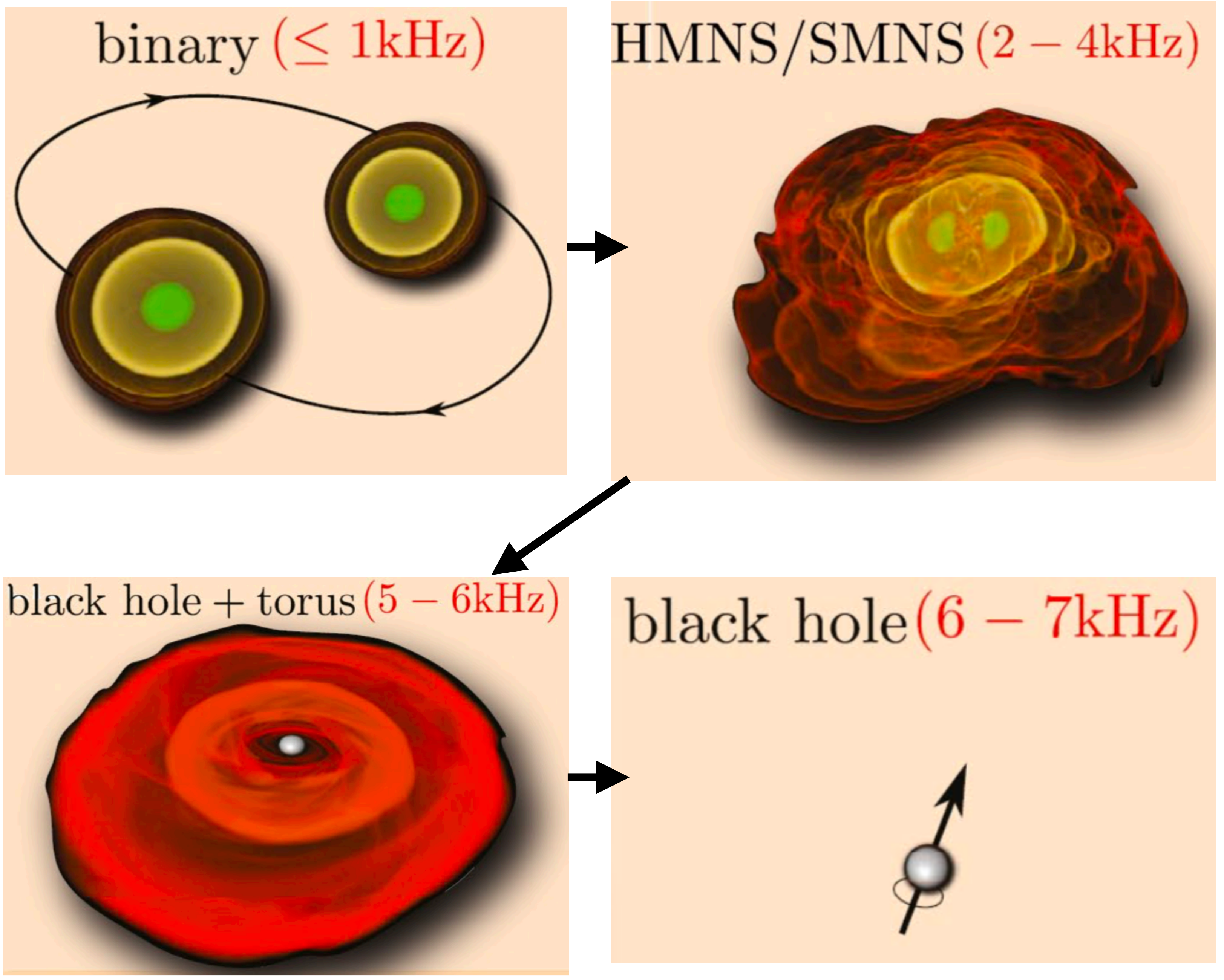


BNS merger remnants: rich physics



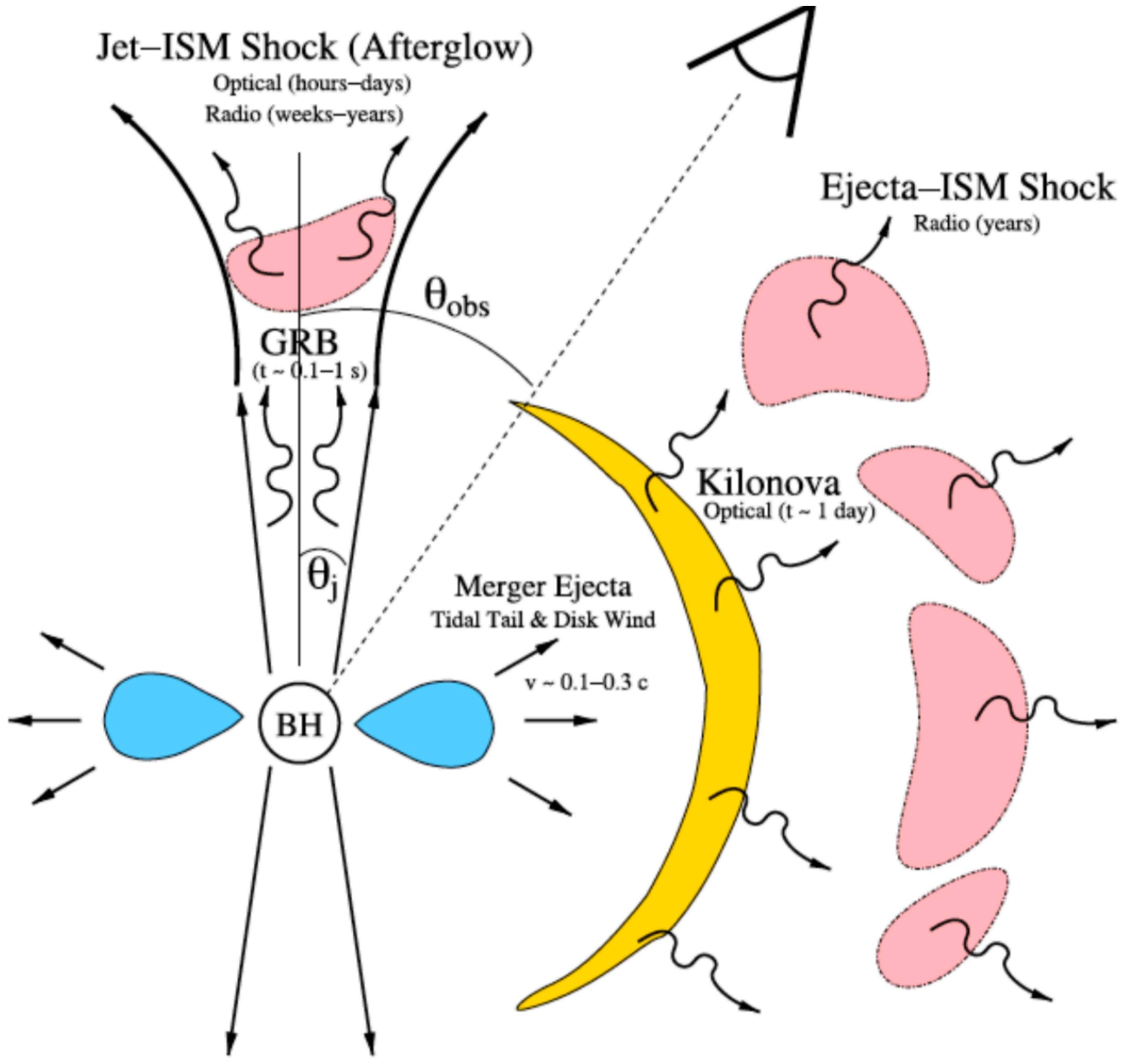
"Cosmic Collider"
Exploring extremal matter
State

A. Bauswein et al,
PRL **122**, 061102 (2016)



Formation of BH

N. Andersson *et al*,
GRG **43**, 409 (2011)



Engine of Short GRB
Kilonova
Multimessenger astronomy

Metzger and Berger
ApJ **746**, 48 (2012)

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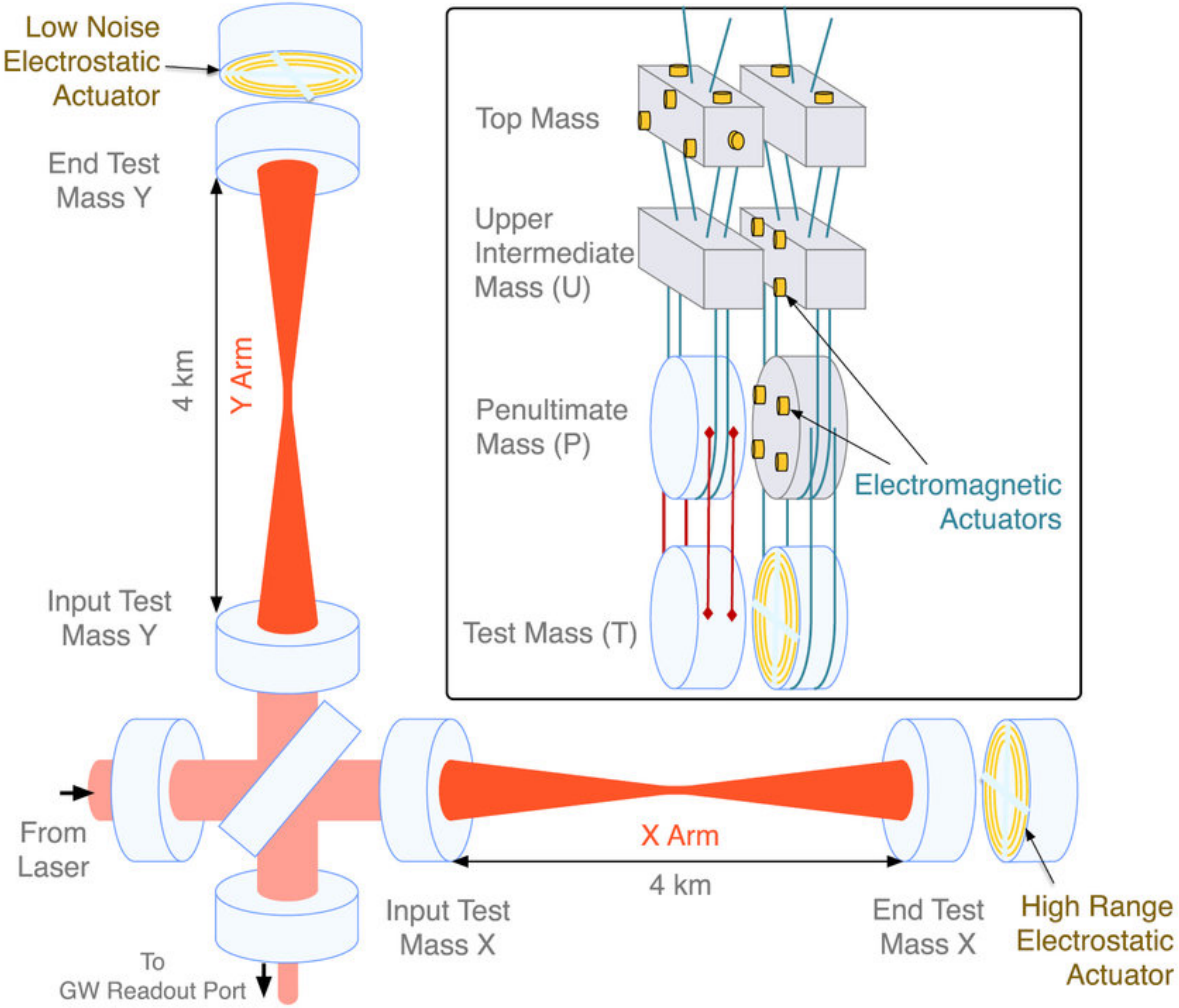
Laser Interferometer GW detector



Dual recycling configuration

Low-loss coating

Interferometer/cavity locking system

High power instability control

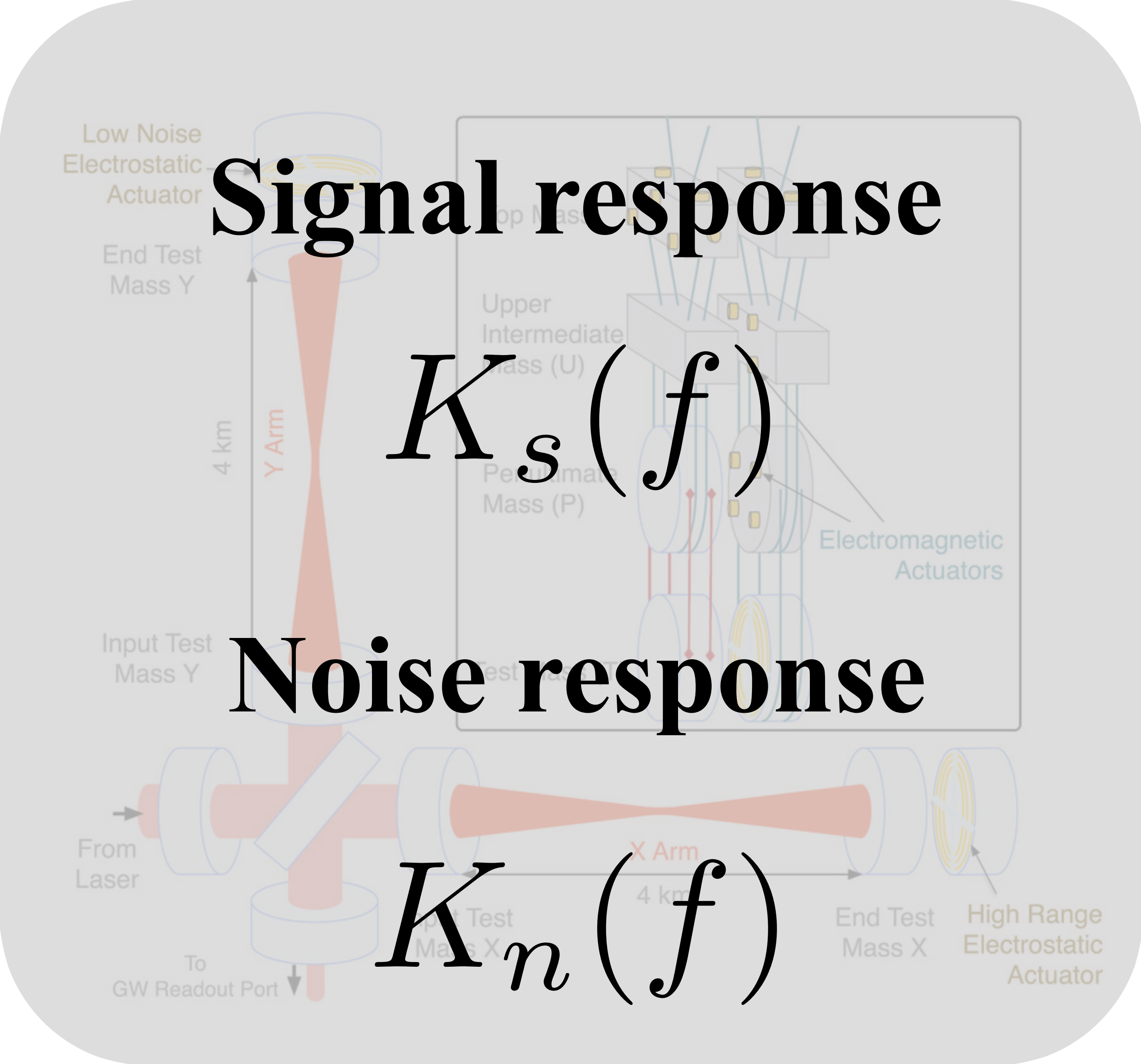
Multi-stage suspension system

passive+active isolation

...

Complicated machine!

Detector as a transducer



$h(f)$ →

$n(f)$ →

Signal response

$K_s(f)$

Noise response

$K_n(f)$

→

Output data

$$y(f) = K_s(f)h(f) + K_n(f)n(f)$$

↓

"Estimation" of the signal

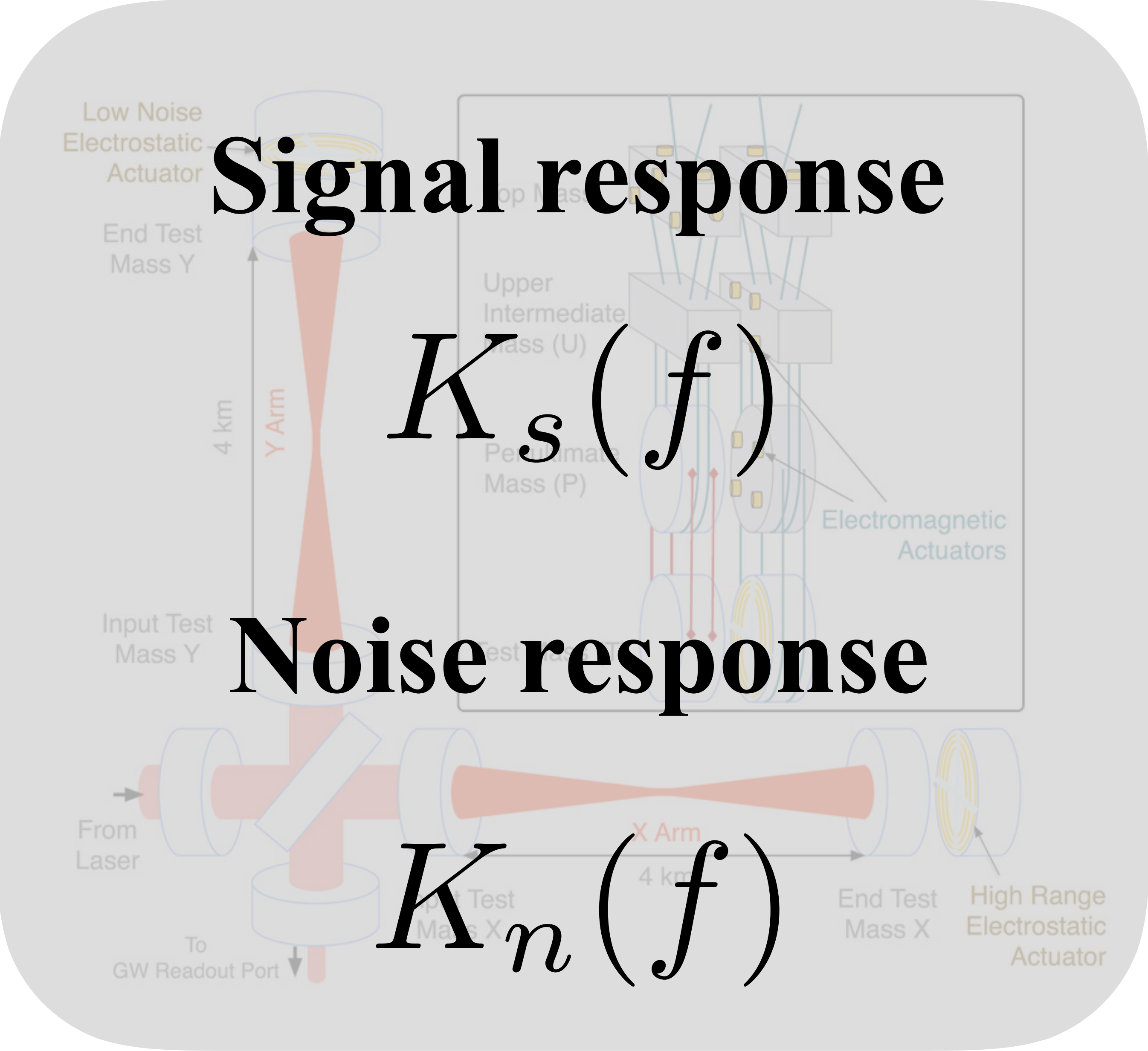
$$\tilde{y}(f) = h(f) + \frac{K_n(f)}{K_s(f)} n(f)$$

Signal **Noise**

Detector as a transducer

$h(f)$ →

$n(f)$ →



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Signal **Noise**

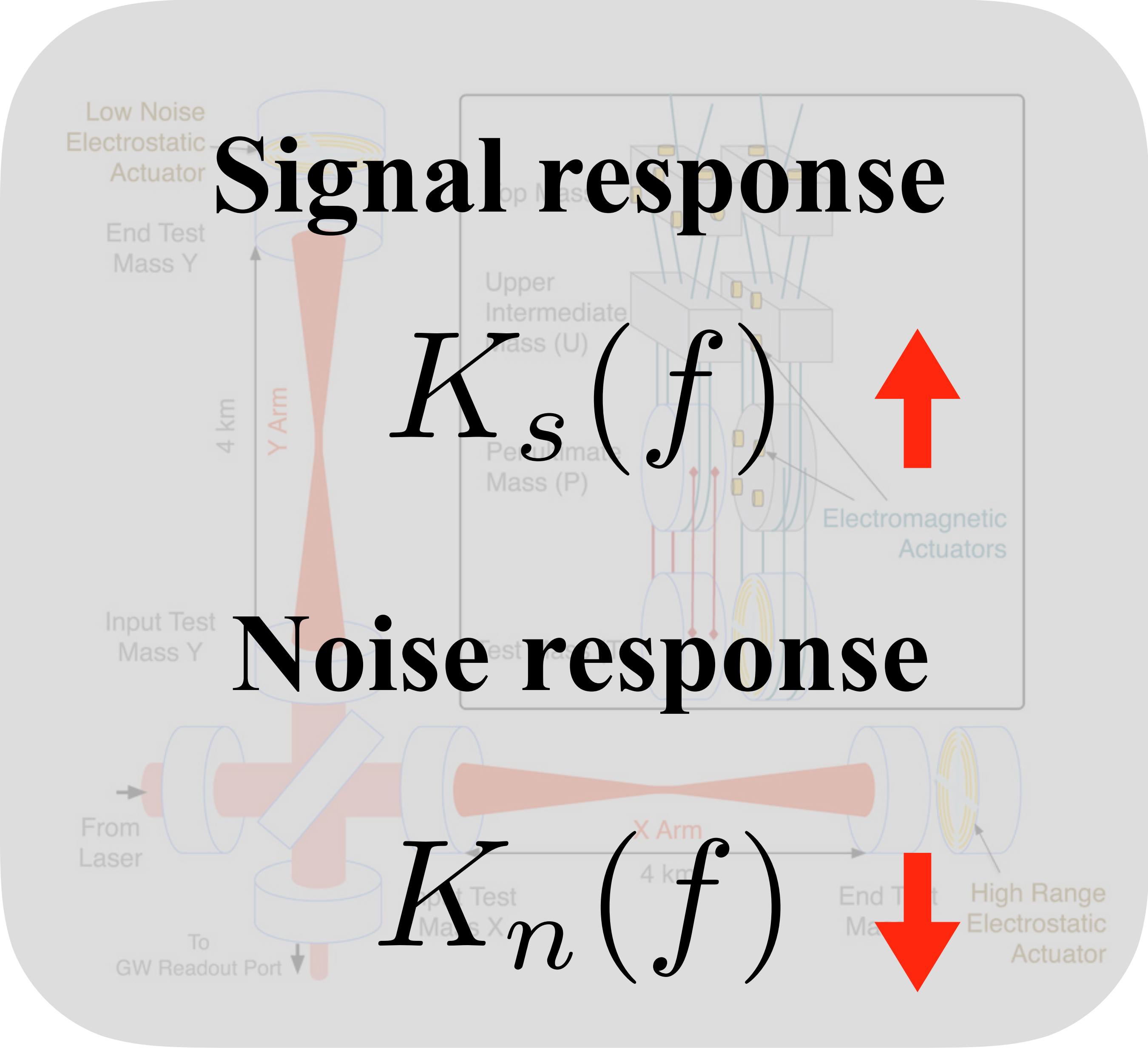
A stochastic quantity with a spectrum:
"strain noise"

$$S_{hh}(f) = \left|\frac{K_n(f)}{K_s(f)}\right|^2 S_{nn}(f)$$

Detector as a transducer

$h(f)$ →

$n(f)$ ↓ →



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$K_s(f)$ ↑

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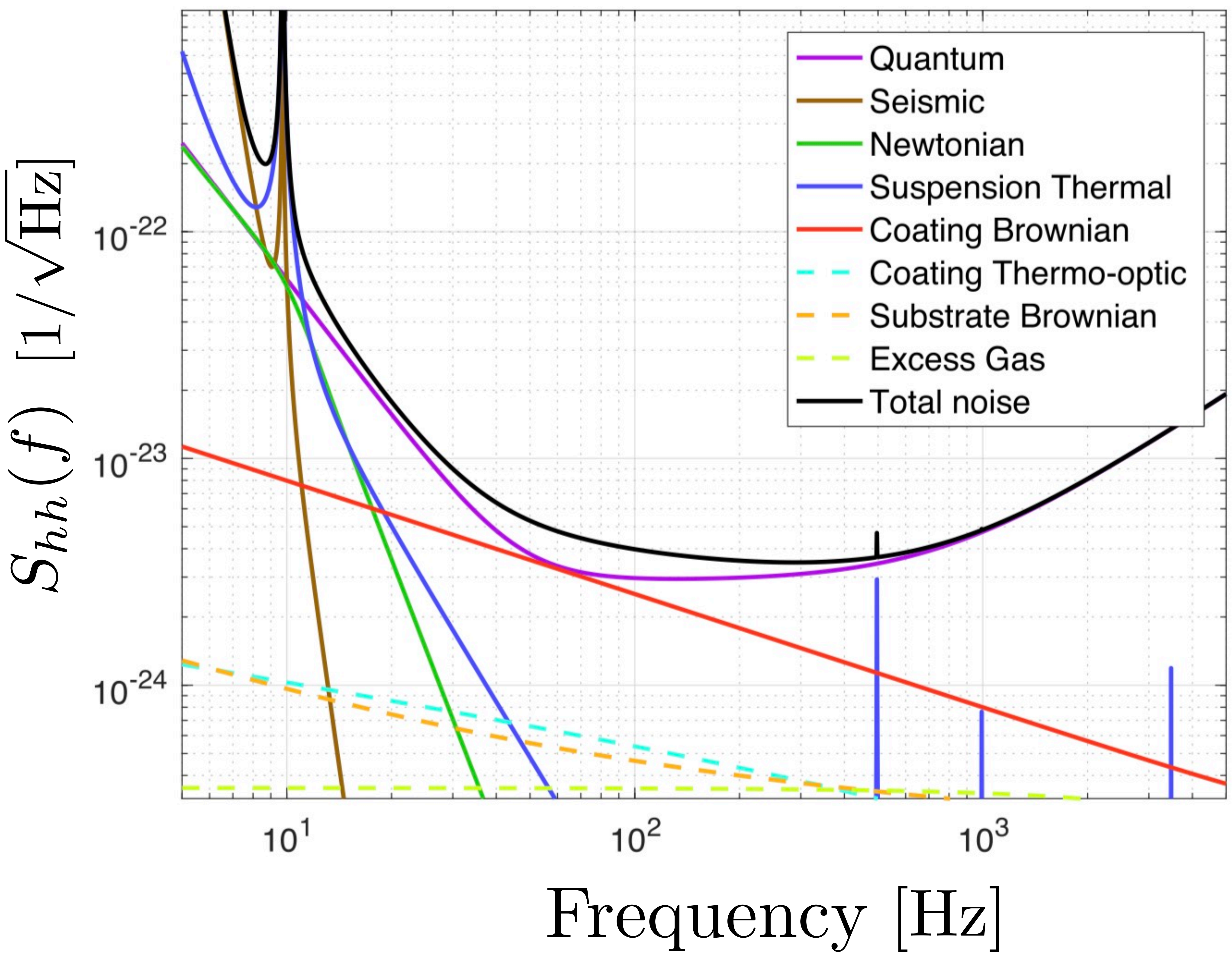
Signal **Noise**

A **stochastic quantity** with a **spectrum**:
“strain noise”

$$S_{hh}(f) = \left|\frac{K_n(f)}{K_s(f)}\right|^2 S_{nn}(f)$$

The lower, the better.

Strain sensitivity



Design sensitivity (LoveLace *et al*, CQG **35** (2018))

$$S_{hh}(f) = \left|\frac{K_n(f)}{K_s(f)}\right|^2 S_{nn}(f)$$

Feature: $|K_n(f)|^2 S_{nn}(f)$

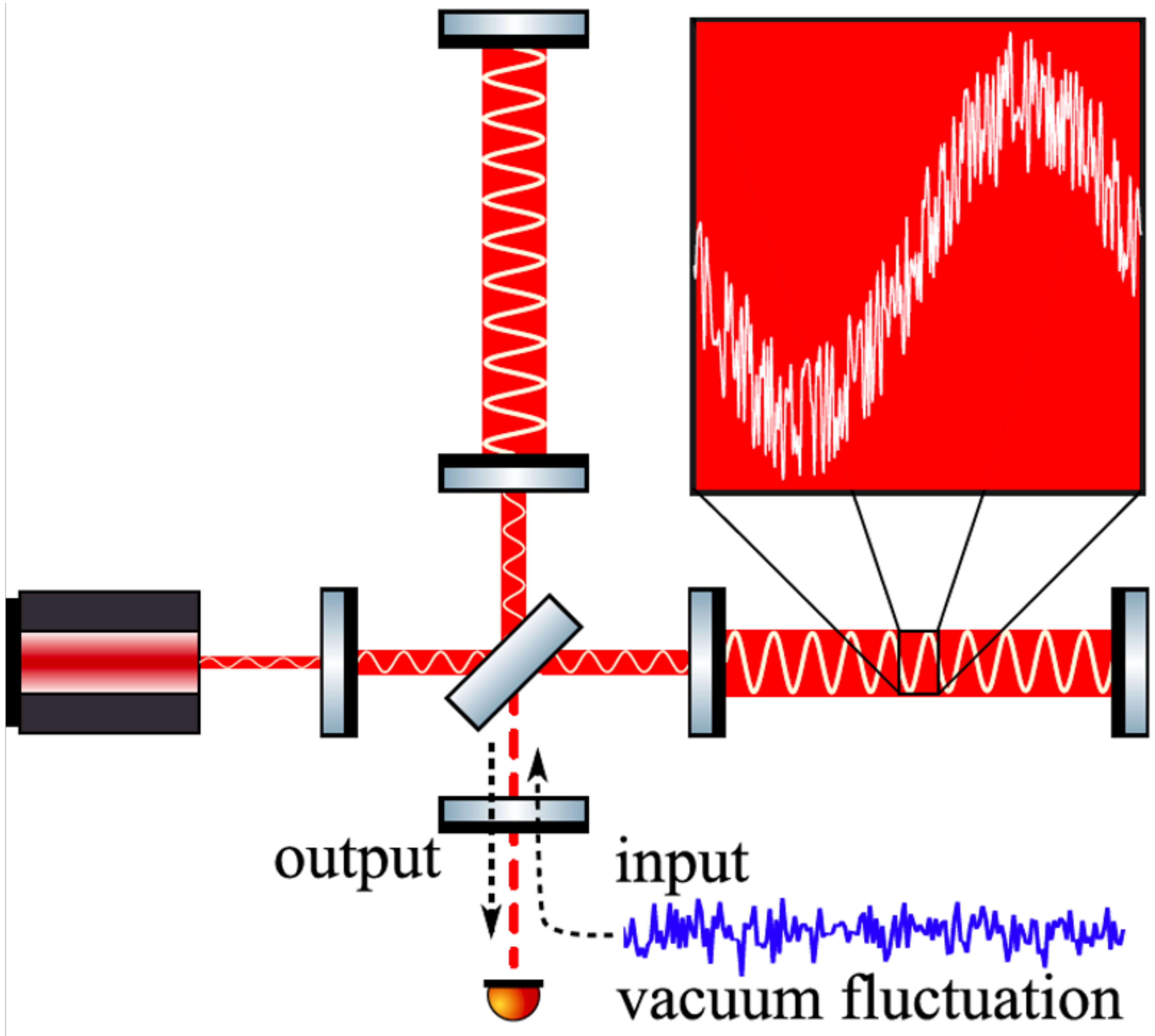
Low f: Force noise

$$S_{xx}(\Omega) = \left|\frac{1}{m\Omega^2}\right|^2 S_{FF}(\Omega) \quad (\Omega = 2\pi f)$$

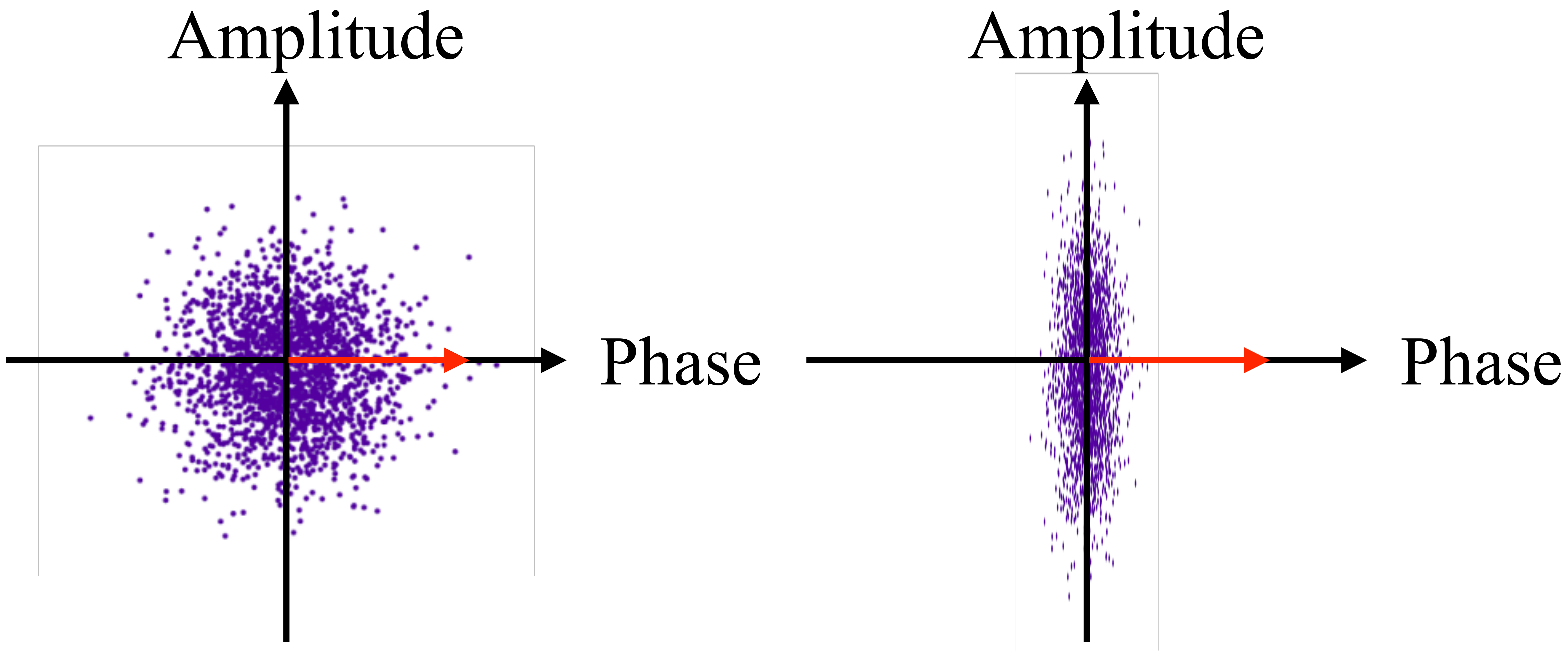
High f: Sensing noise (shot noise)

$$|K_n(f)|^2 S_{nn}(f) = \text{const}$$

Strain sensitivity: Noise that limits the kiloHertz sensitivity



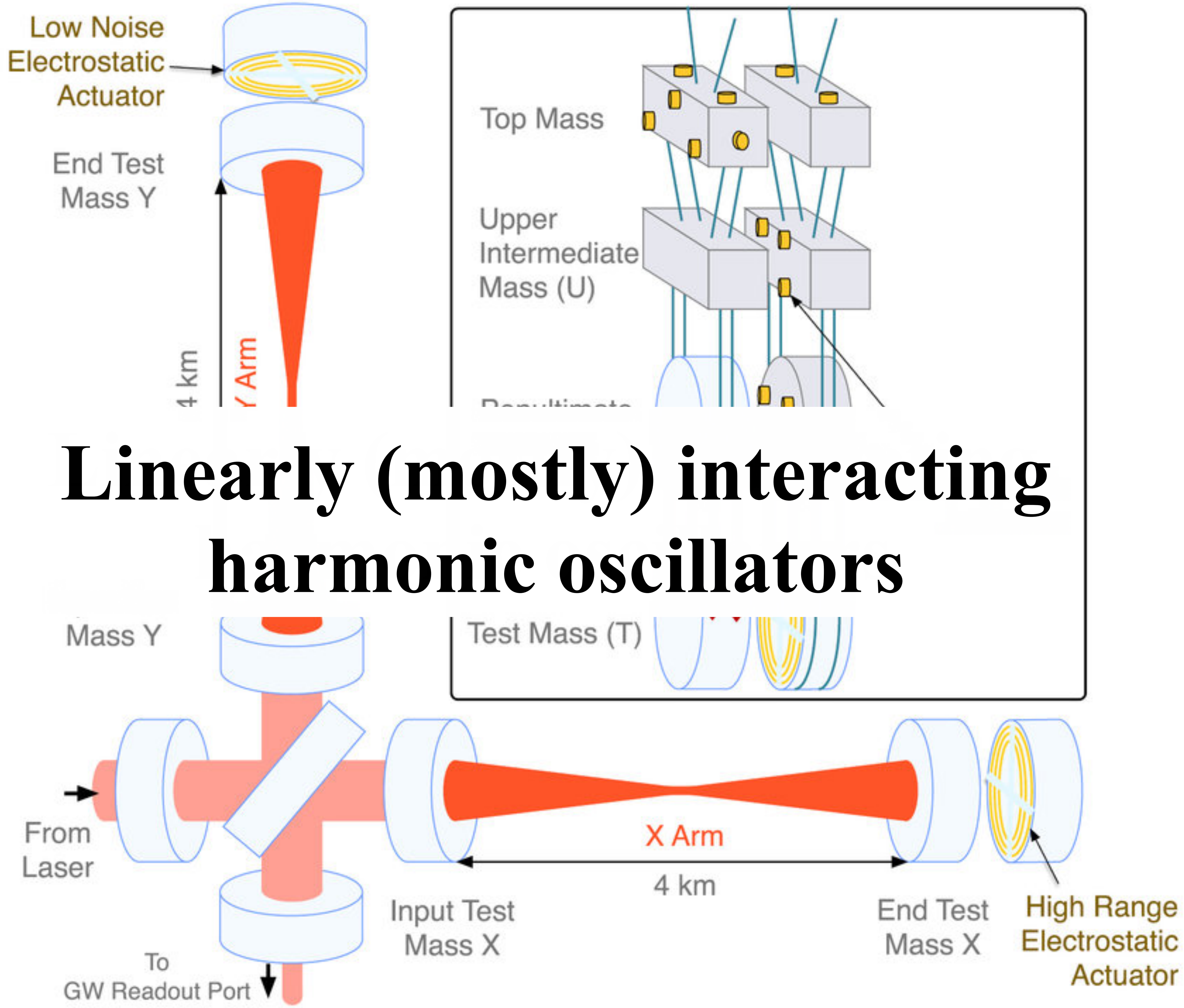
C. Caves, Phys. Rev. D **23**, 1693 (1981).



Suppression:
Increase the power or use "squeezed light"

What about the signal response?

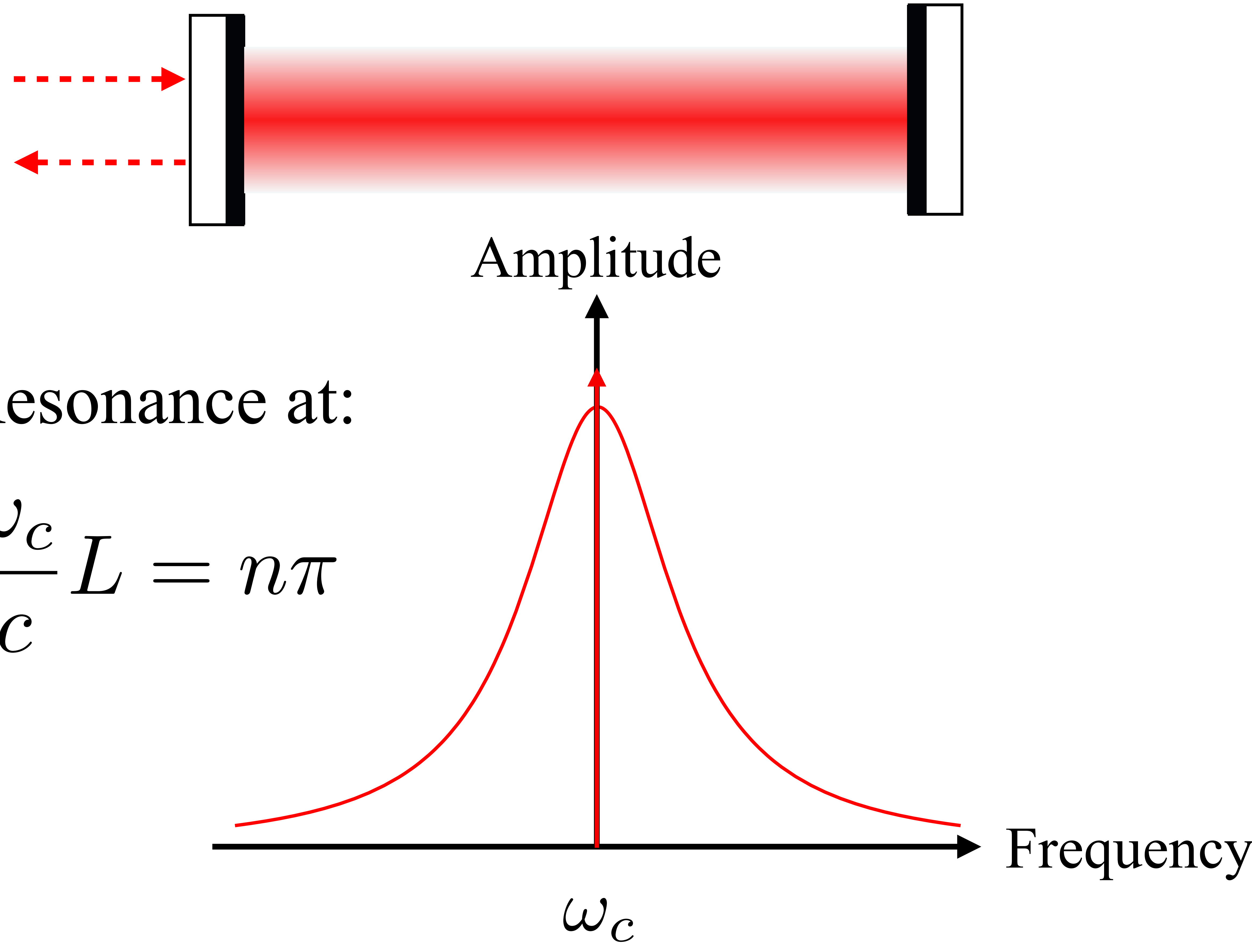
Signal response



Linearly (mostly) interacting harmonic oscillators

Detector in a nutshell:

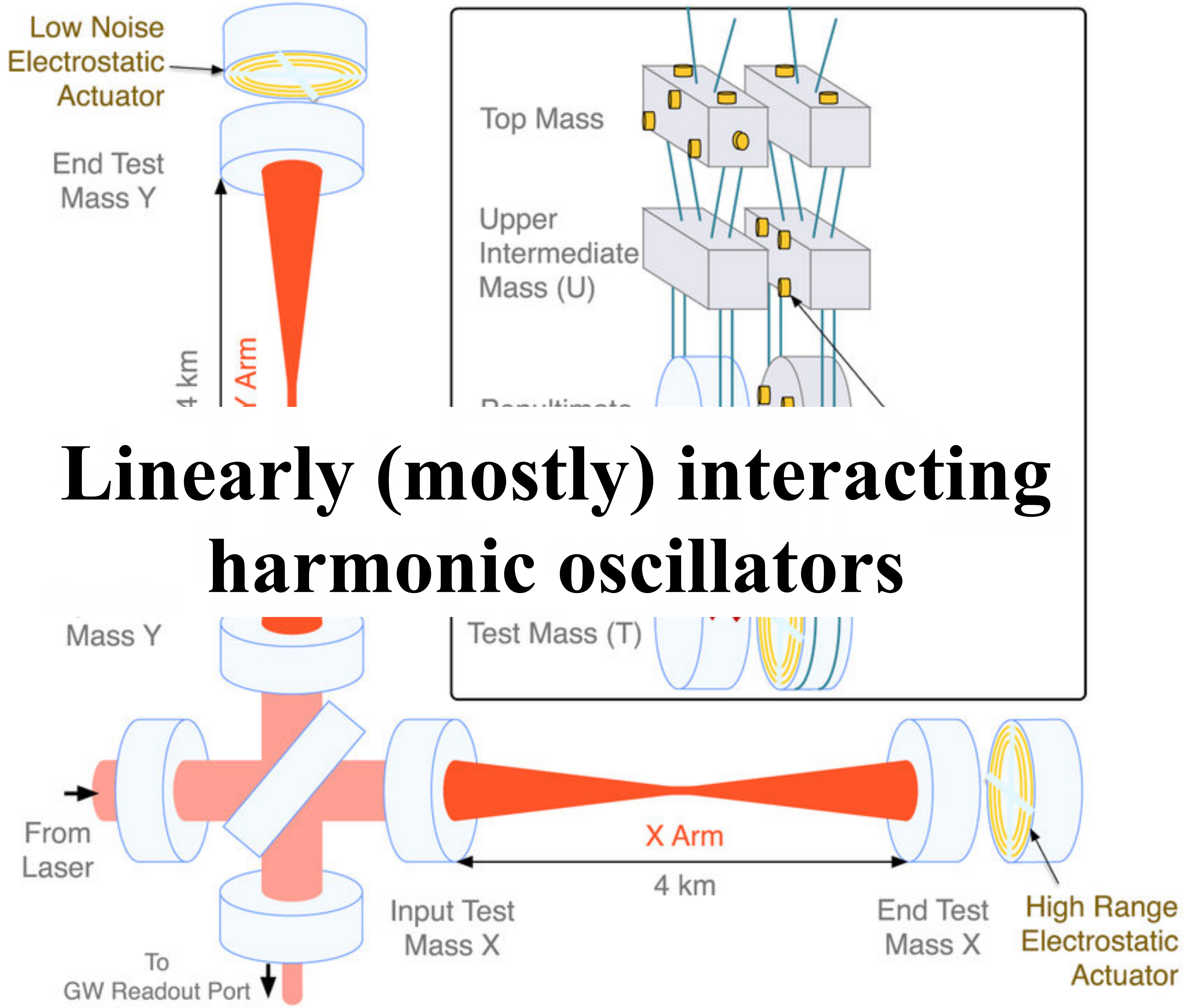
The key harmonic oscillator: optical cavity



Resonance at:

$$\frac{\omega_c}{c} L = n\pi$$

Signal response



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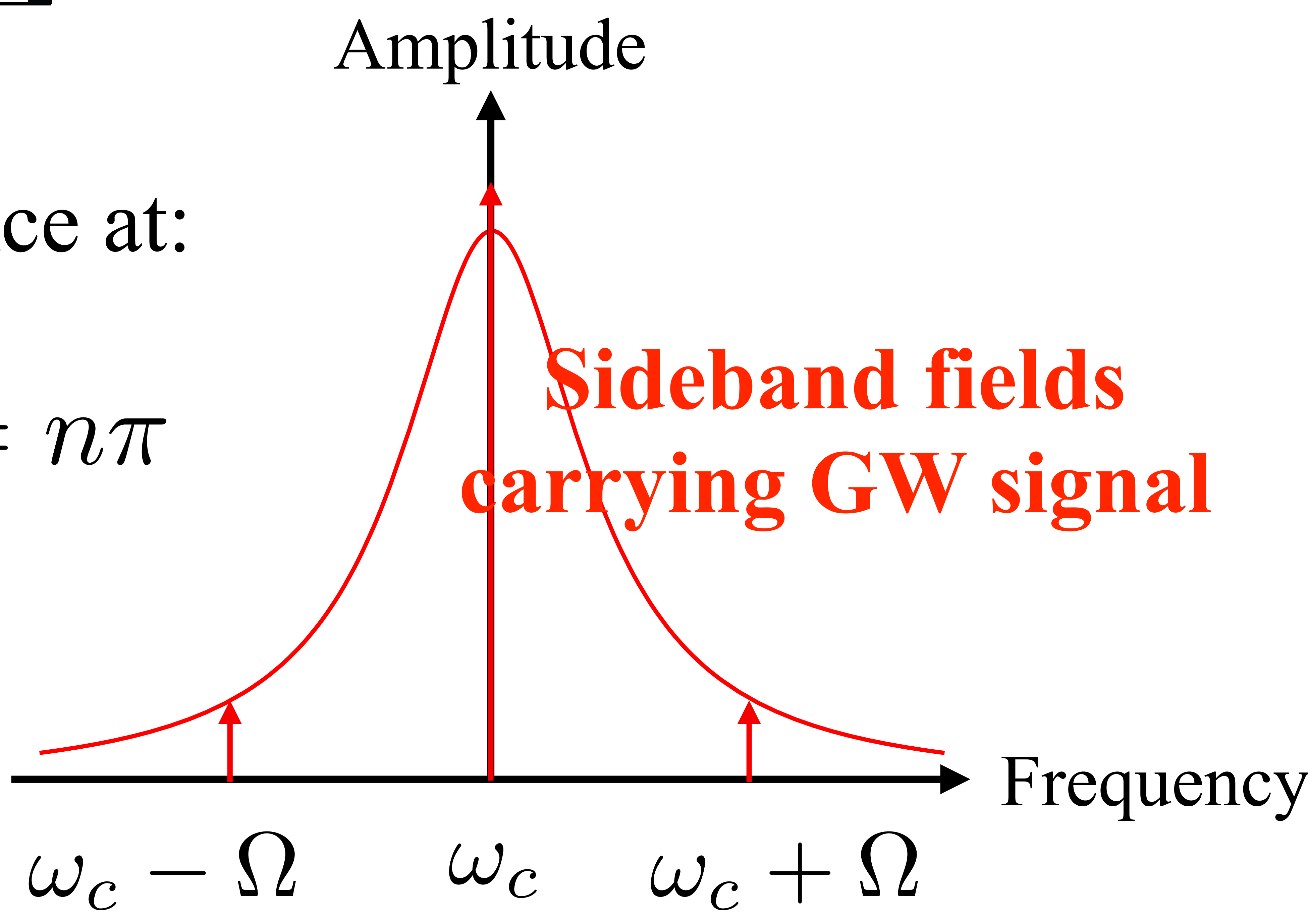
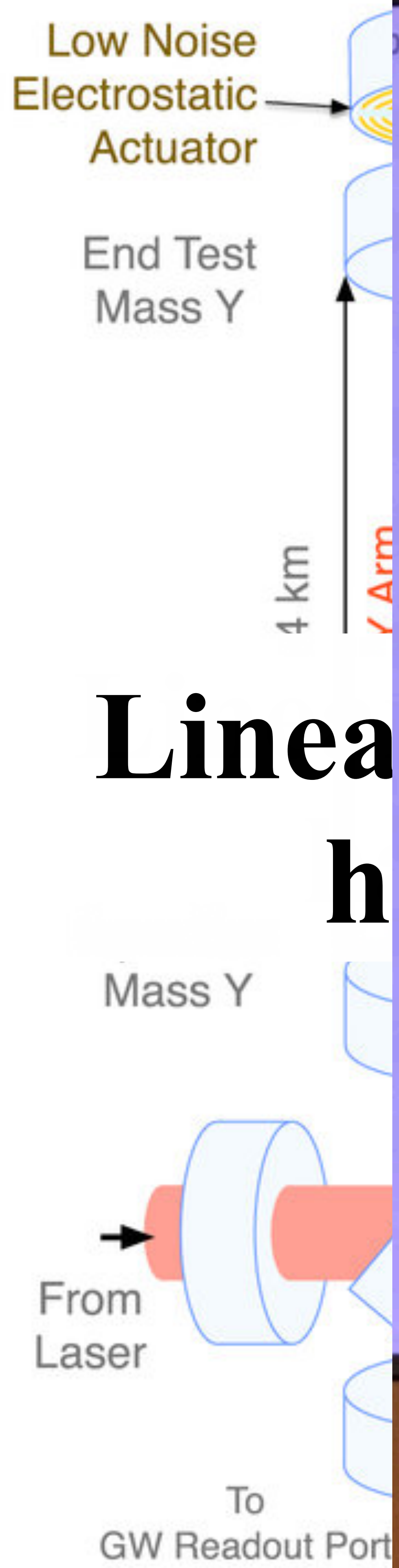


Sign

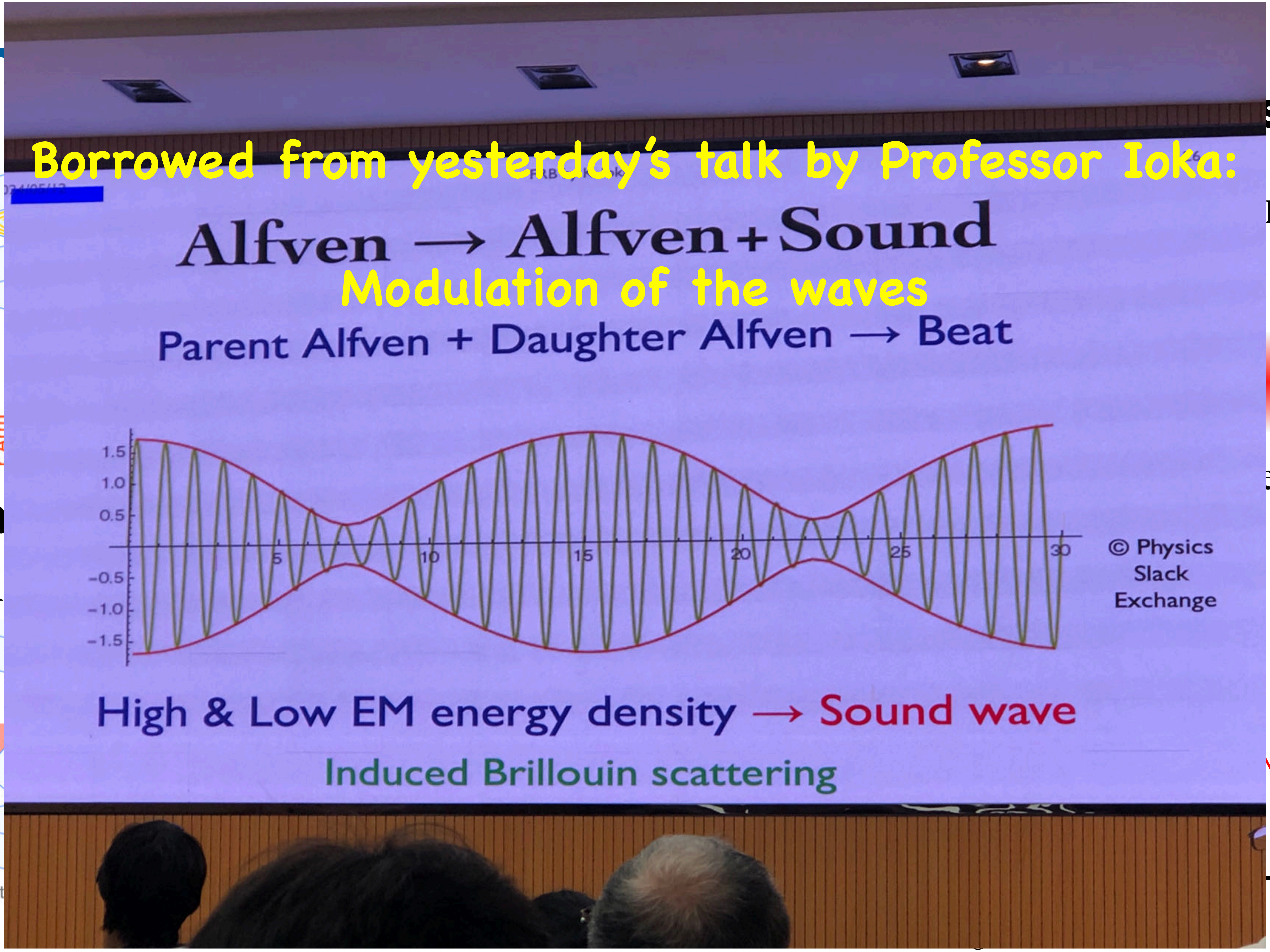


Linea

h

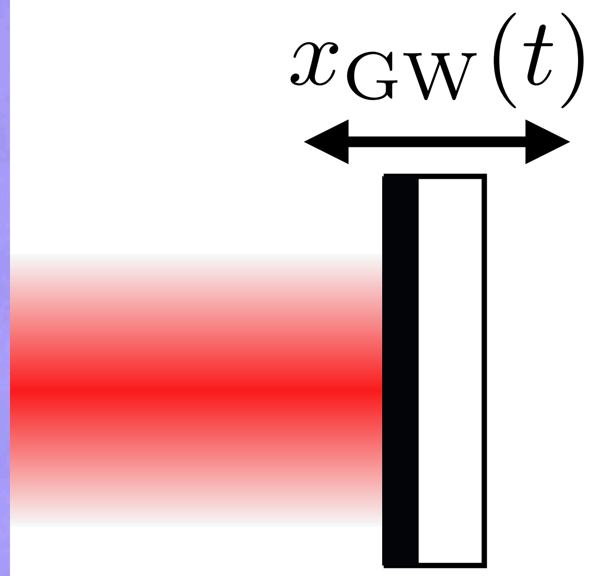
Borrowed from yesterday's talk by Professor Ioka:

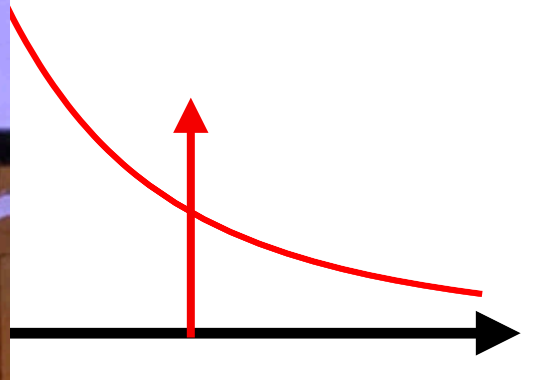
Modulation of the waves



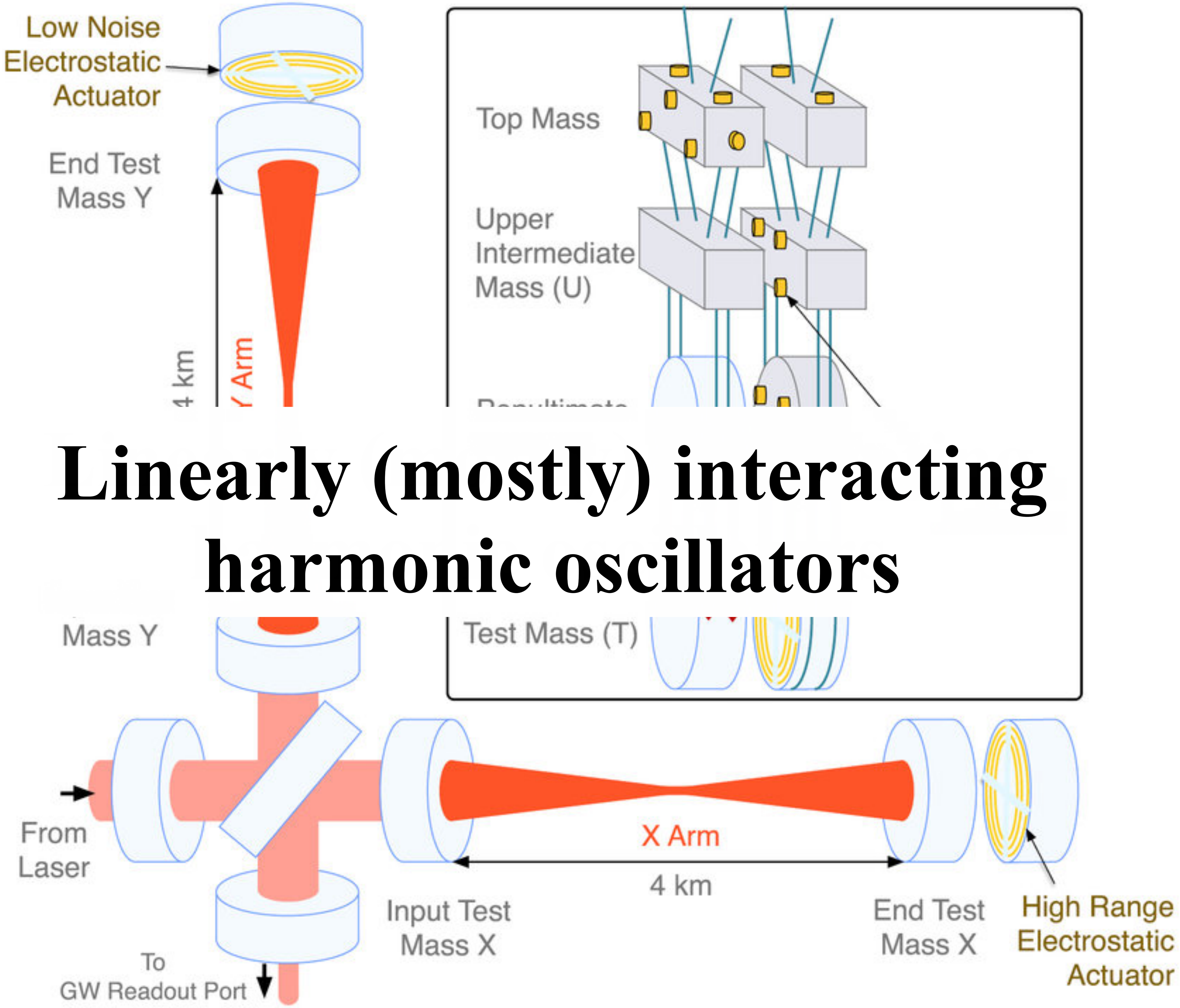
shell:

r: optical cavity





Signal response



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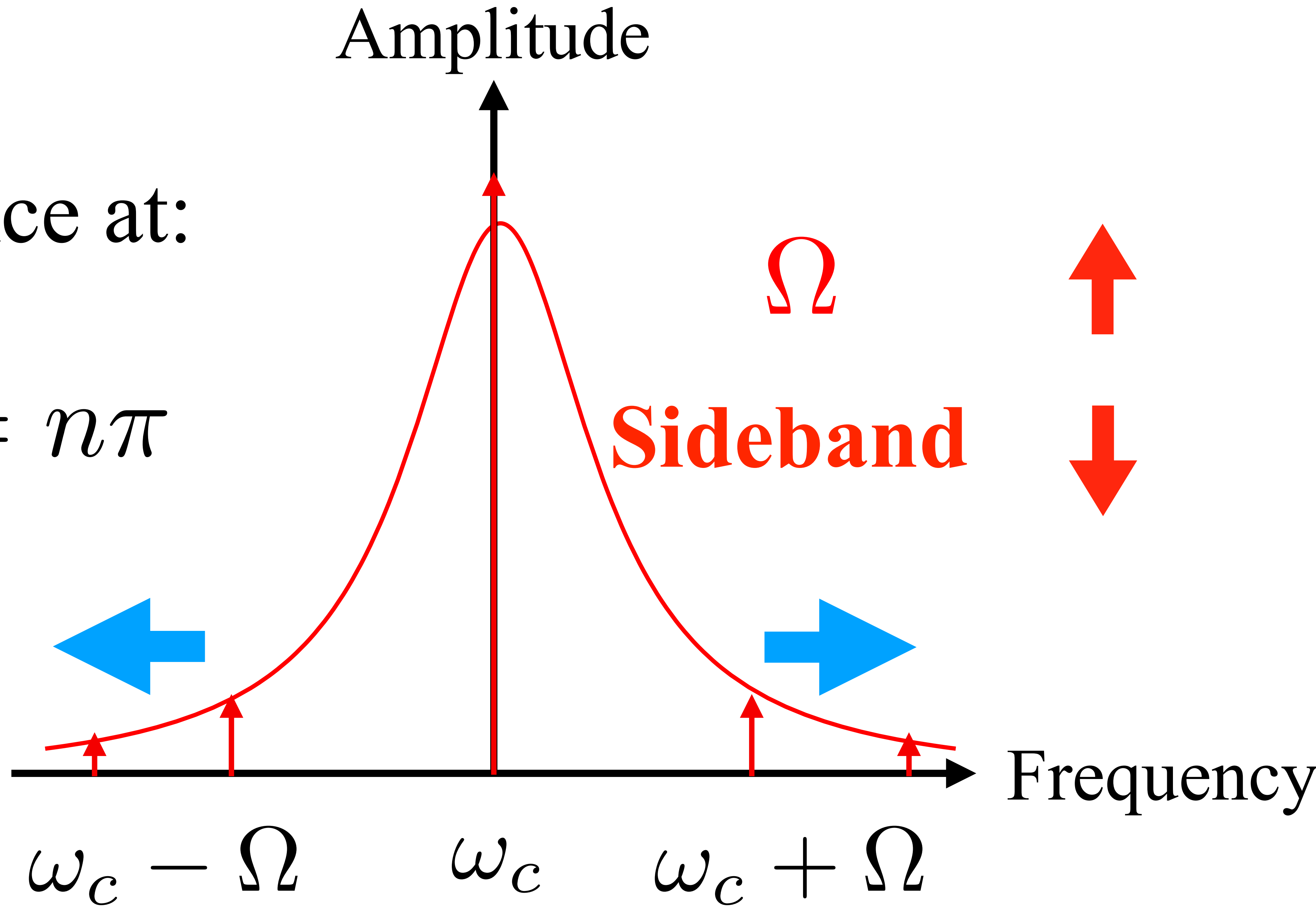
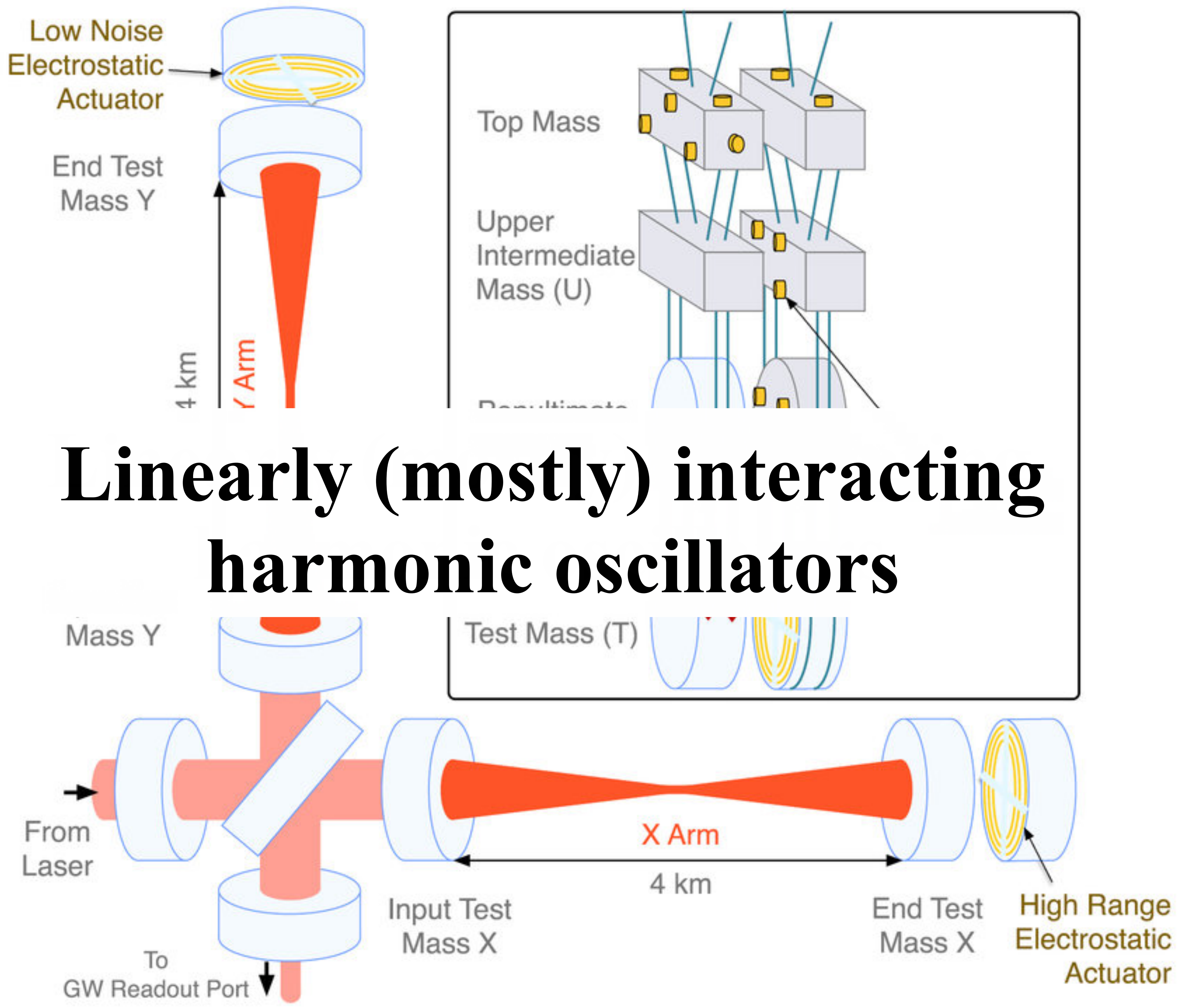


Signal response



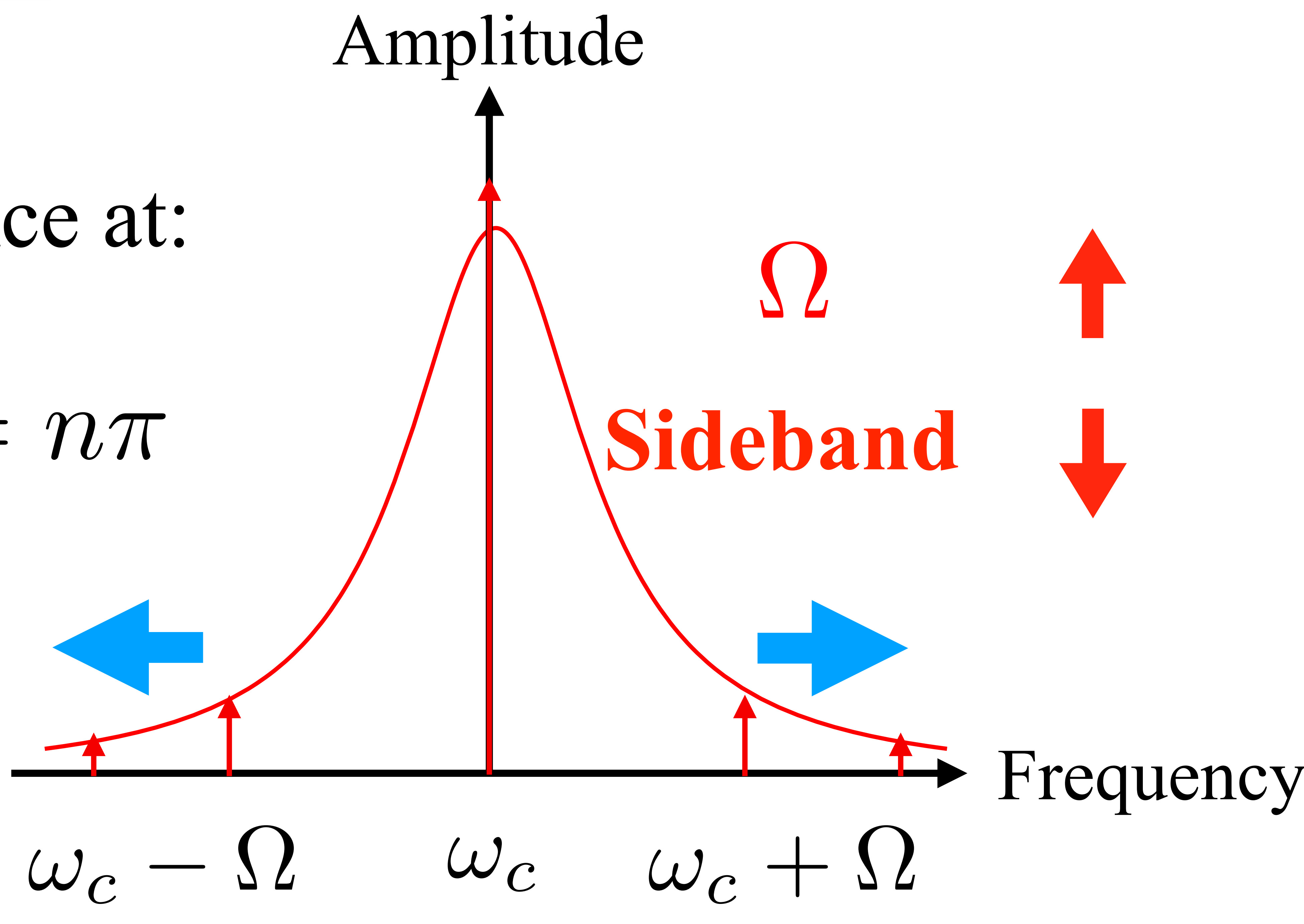
Linearly (mostly) interacting harmonic oscillators

Signal response at kiloHertz is weak!

This is why we have low sensitivity at KiloHertz!

Resonance at:

$$\frac{\omega_c}{c} L = n\pi$$



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- Method for improving the kiloHertz sensitivity
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Methods for improving kHz sensitivity

- **Upgrade to 3rd generation detector**

  Event rate is still low, see ⟶

- **Australian's NEMO: High Power+squeezing**

  K. Ackley *et al.*, PASA **37**, e047 (2020).

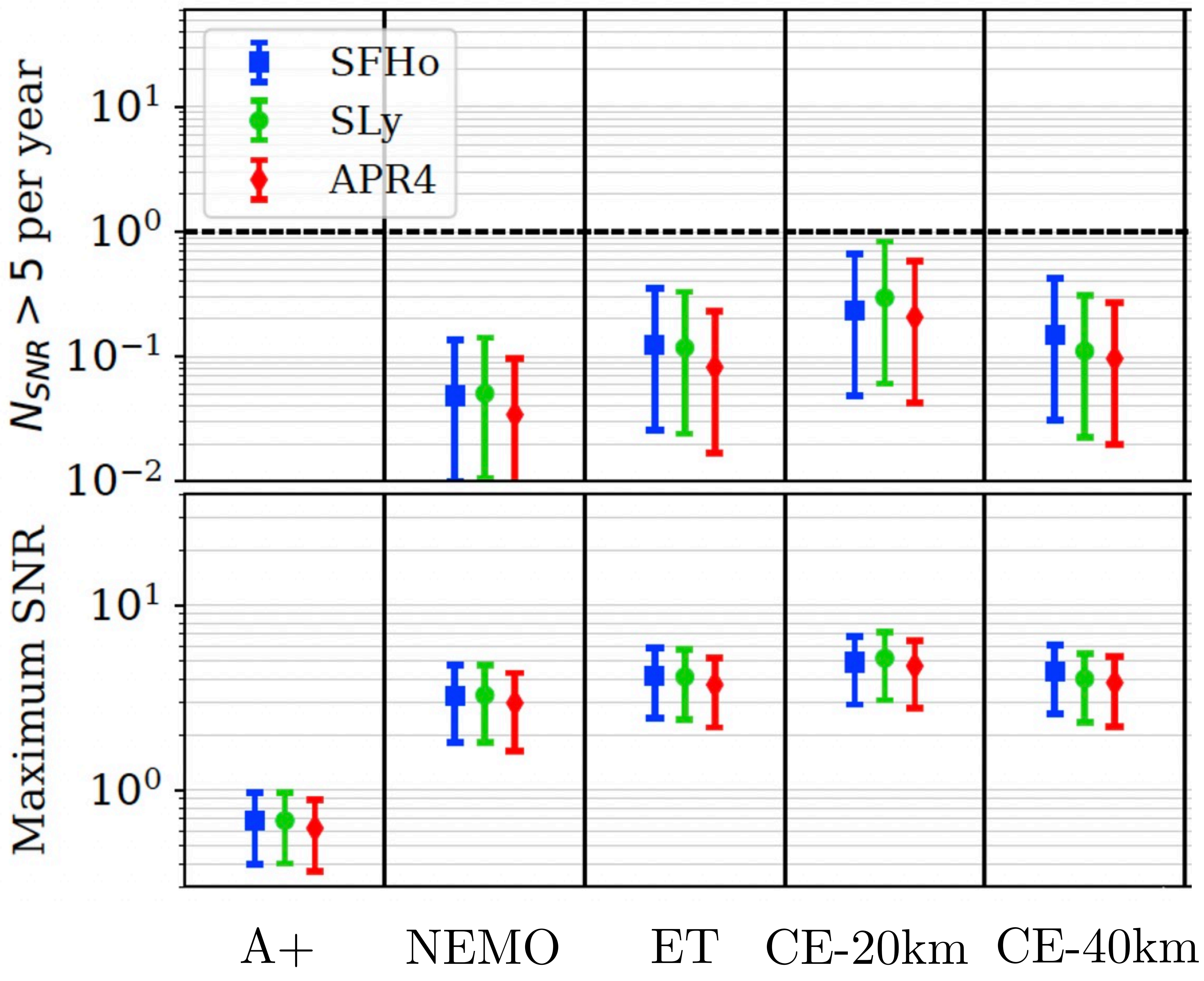
- **Long signal recycling cavity**

  Martynov *et al*, PRD 99, 102004 (2019)

- **Configuration beyond Michelson Interferometer**

  Zhang *et al*, PRX **13**, 021019 (2023)

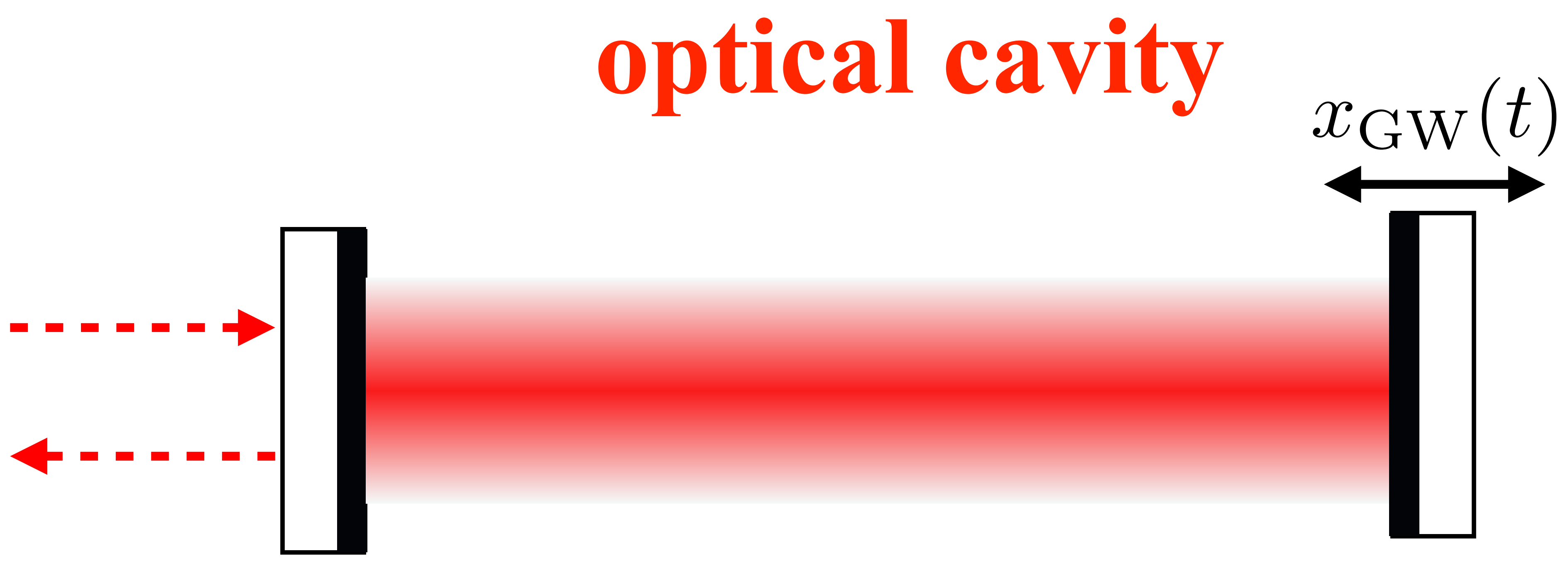
BNS Merger rate 1540 Gpc^-3yr^−1 is used



Martynov *et al*, PRD 99, 102004 (2019)

A possible new configuration

Step 1: Shift the resonance by tuning the Signal recycling mirror



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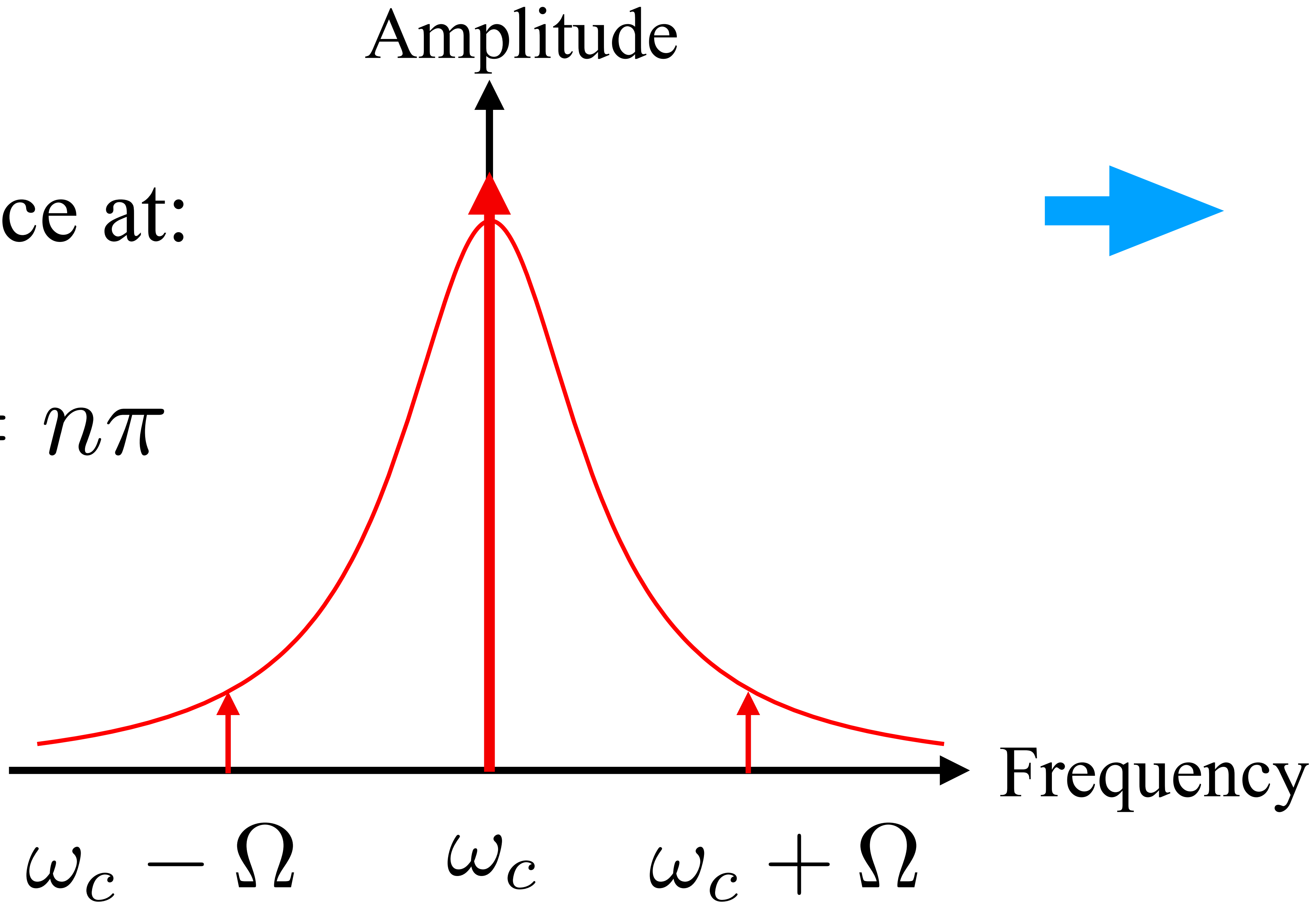
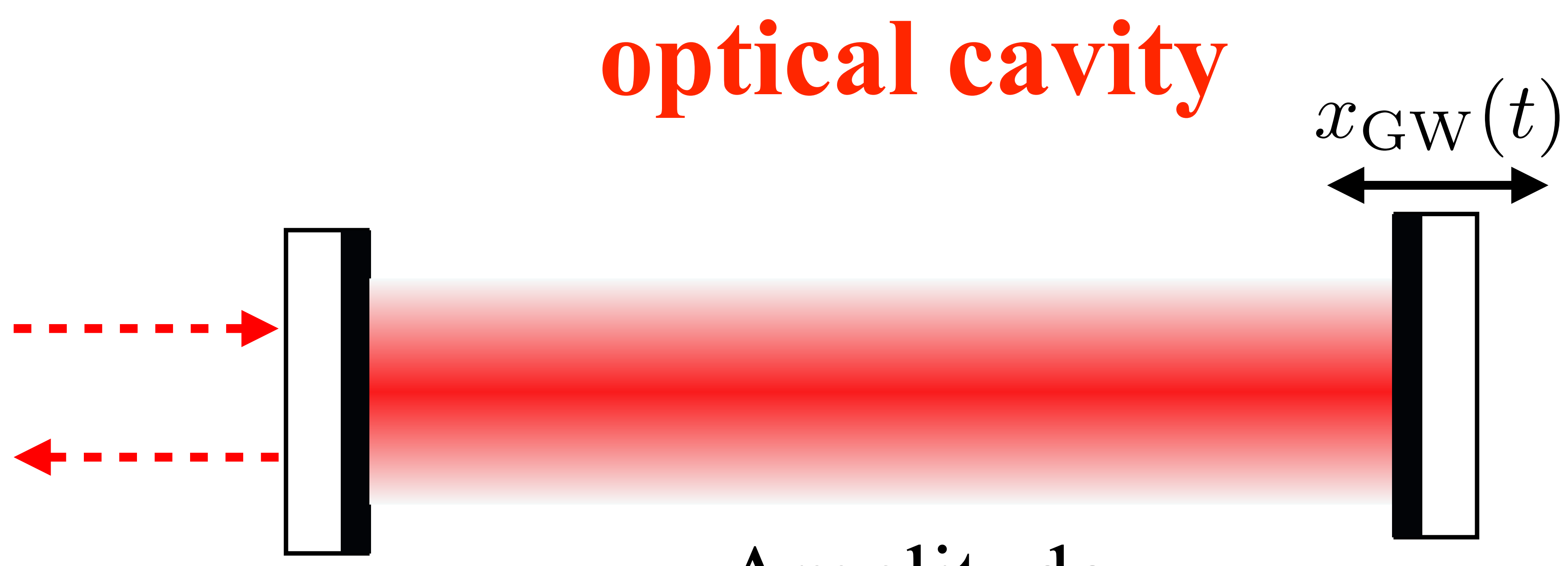
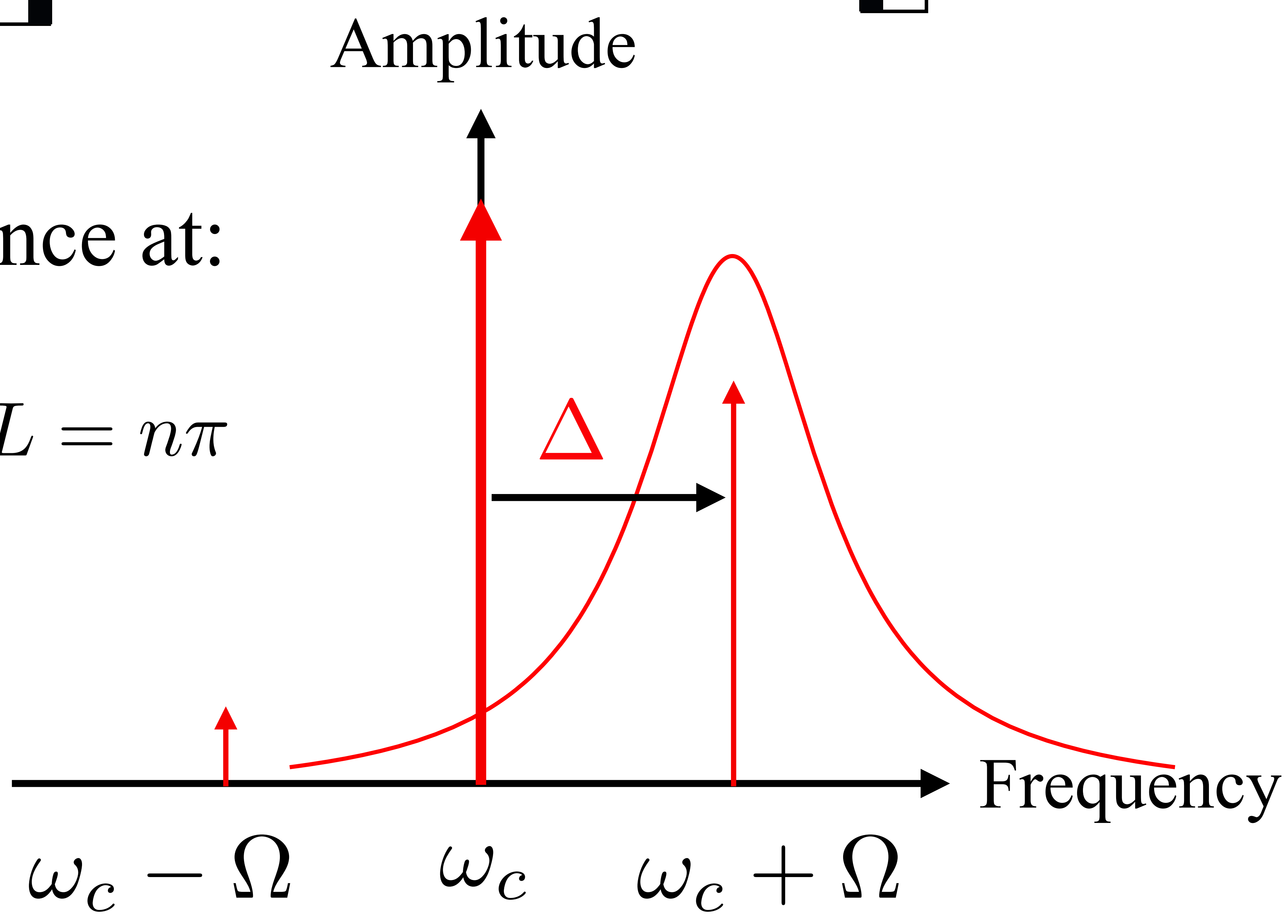




Resonance at:

$$\frac{\omega_c + \Delta}{c}L = n\pi$$



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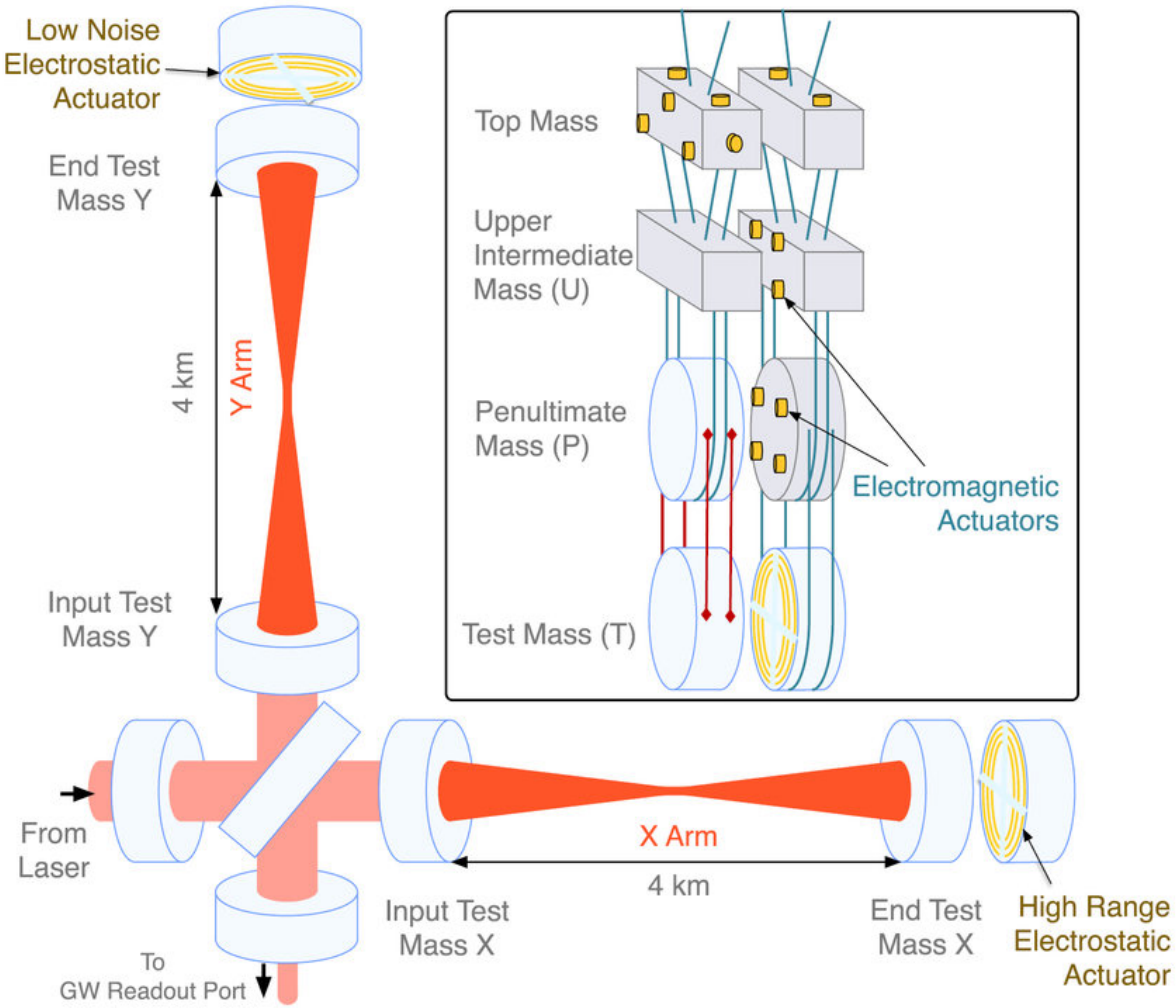

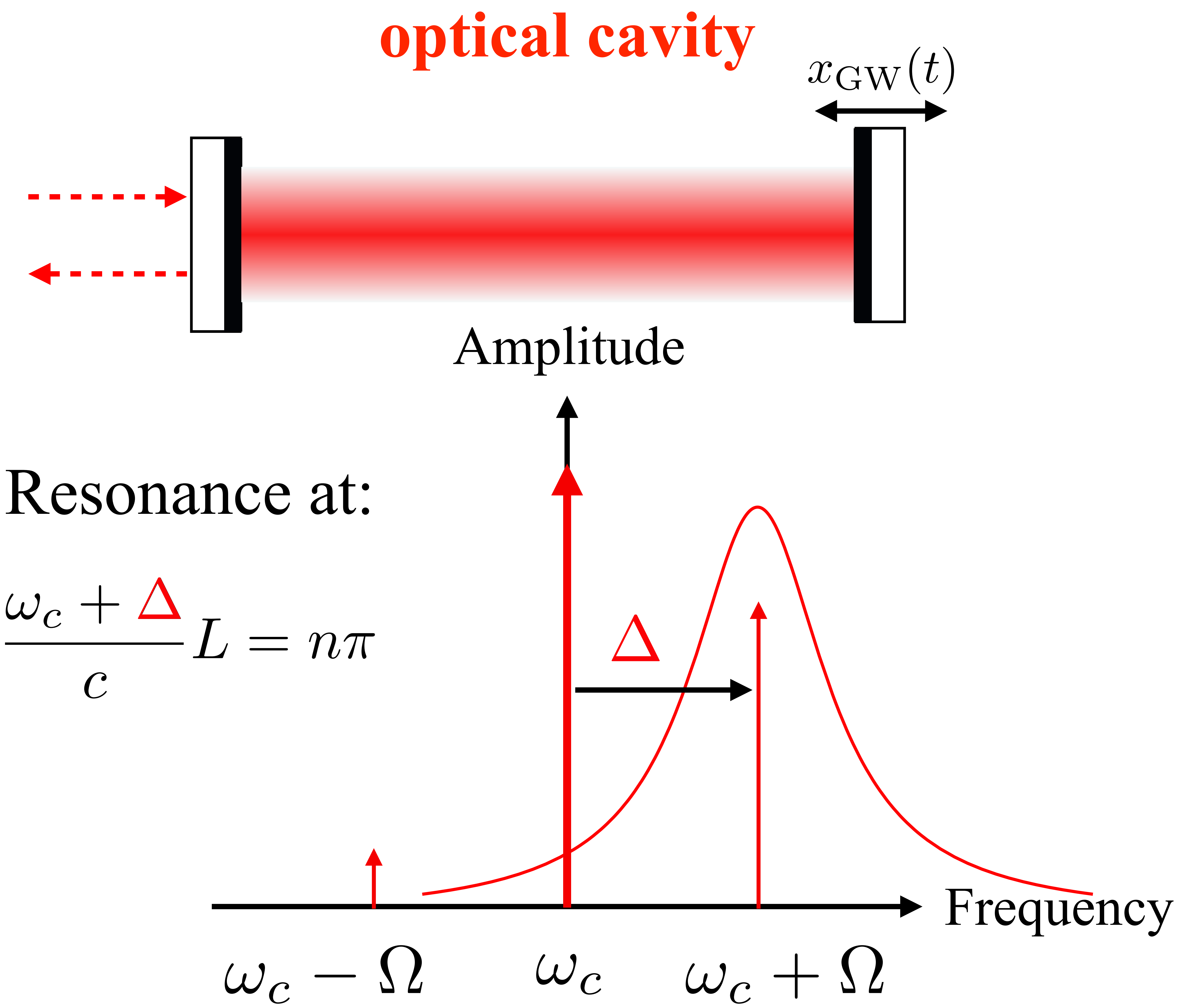

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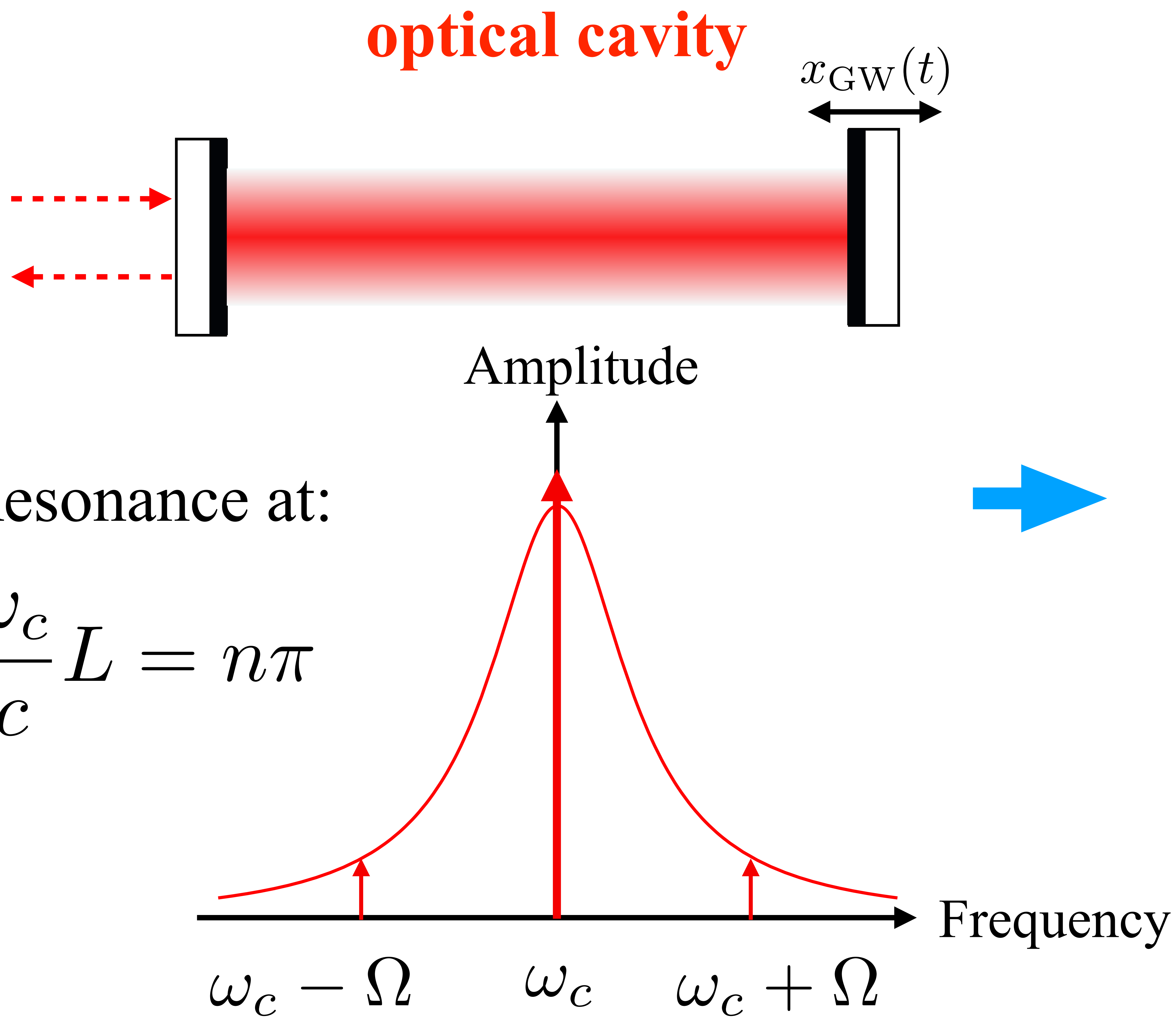

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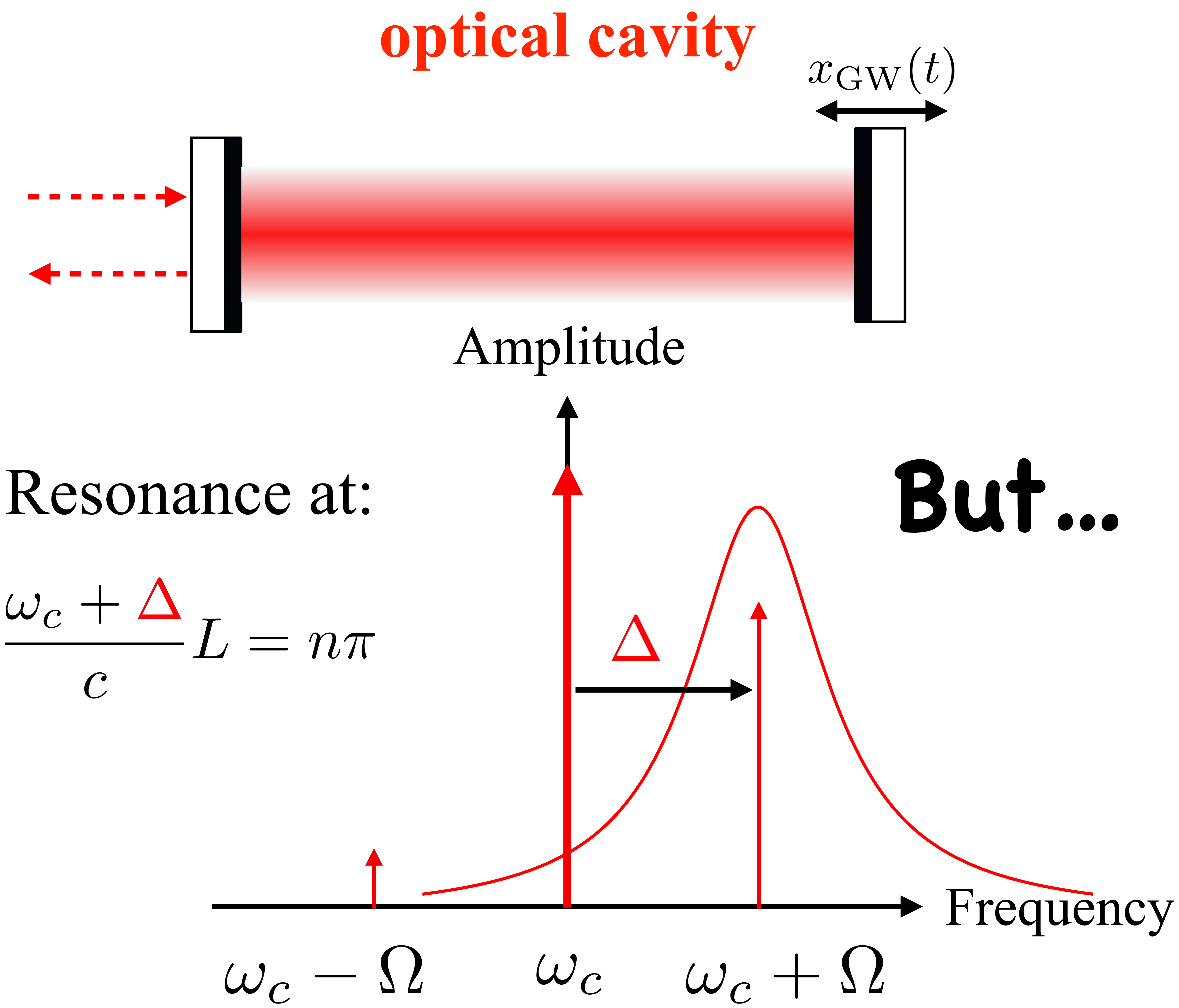


Resonance at:

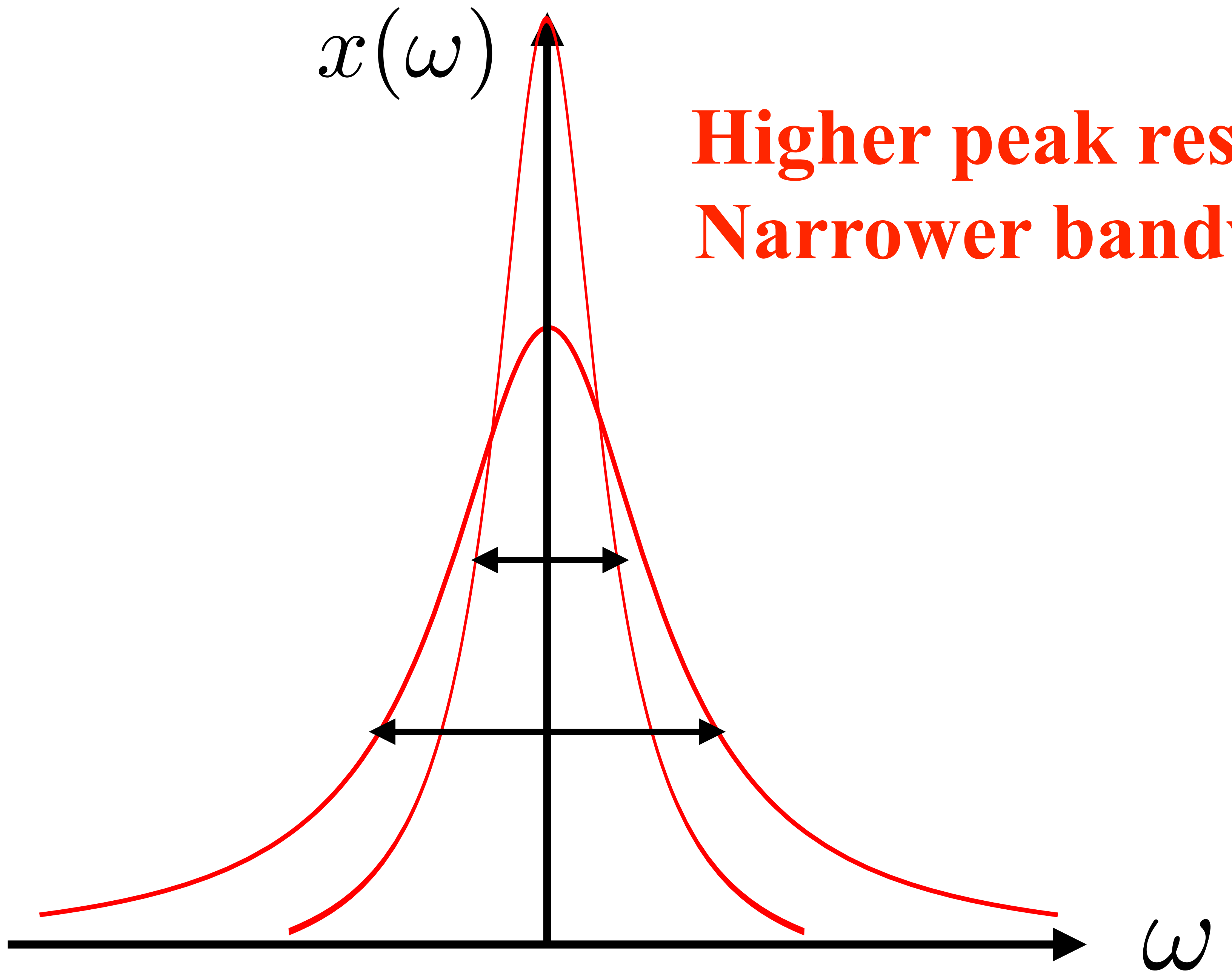
$$\frac{\omega_c + \Delta}{c} L = n\pi$$

But...

Gain-bandwidth trade-off

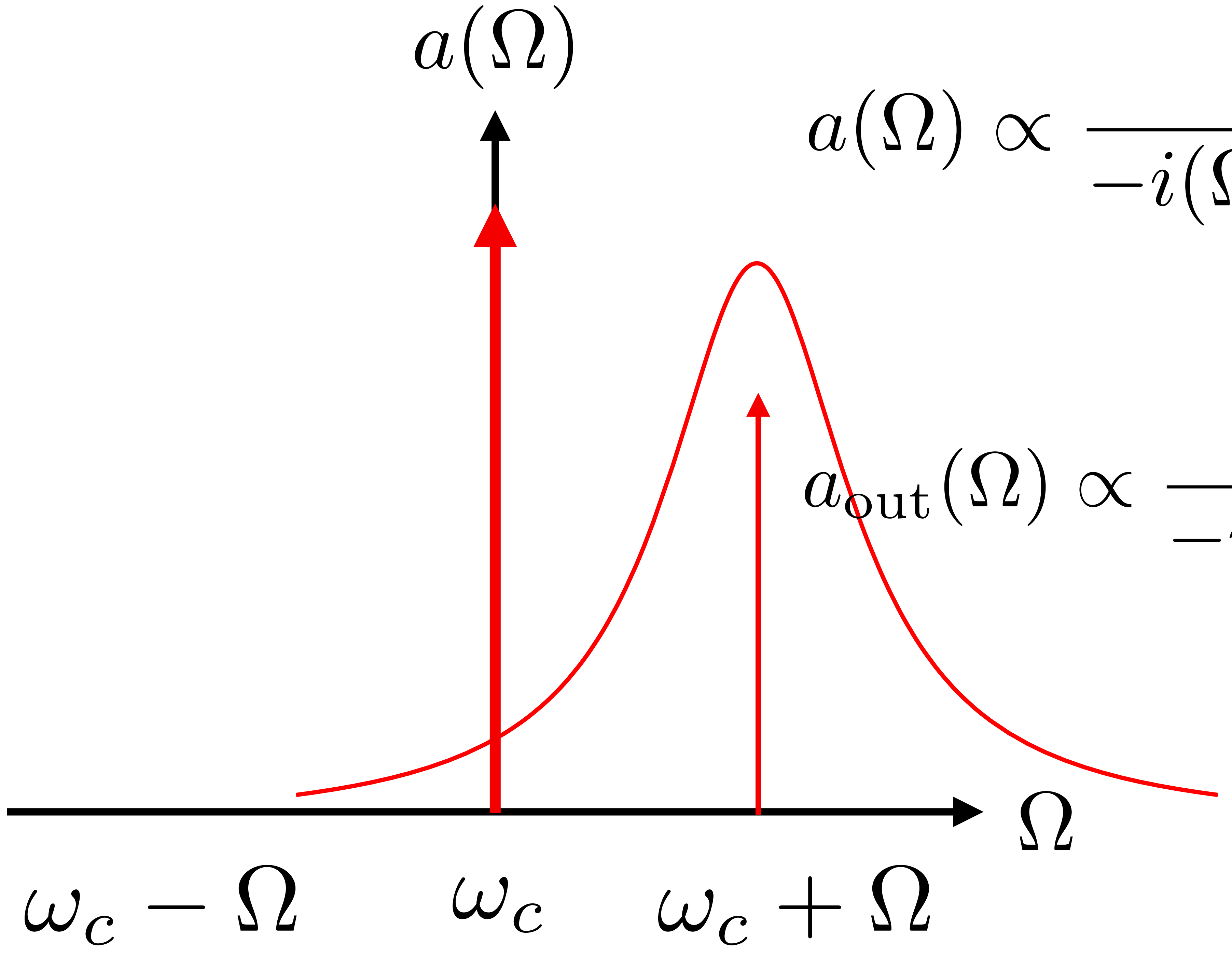
a simple driven Harmonic oscillator
Near resonace response:

$$x(\omega) \propto \frac{1}{-i(\omega-\omega_m)+\gamma_m/2} f(\omega)$$



Higher peak response,
Narrower bandwidth!

Similar for optical cavity



$$a(\Omega) \propto \frac{1}{-i(\Omega-\Delta)+\gamma} h(\Omega)$$

$$a_{\mathrm{out}}(\Omega) \propto \frac{\sqrt{2\gamma}}{-i(\Omega-\Delta)+\gamma} h(\Omega)$$

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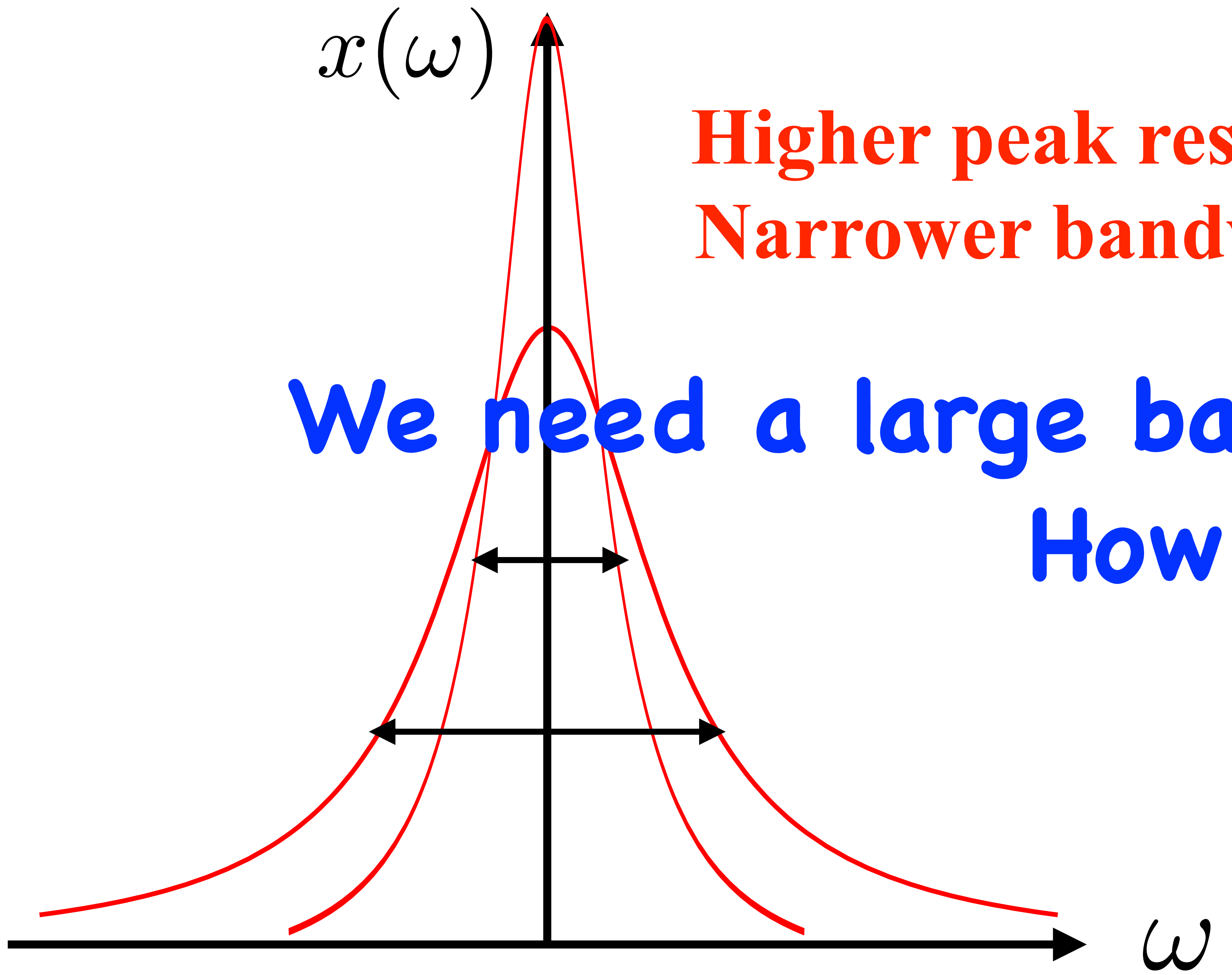

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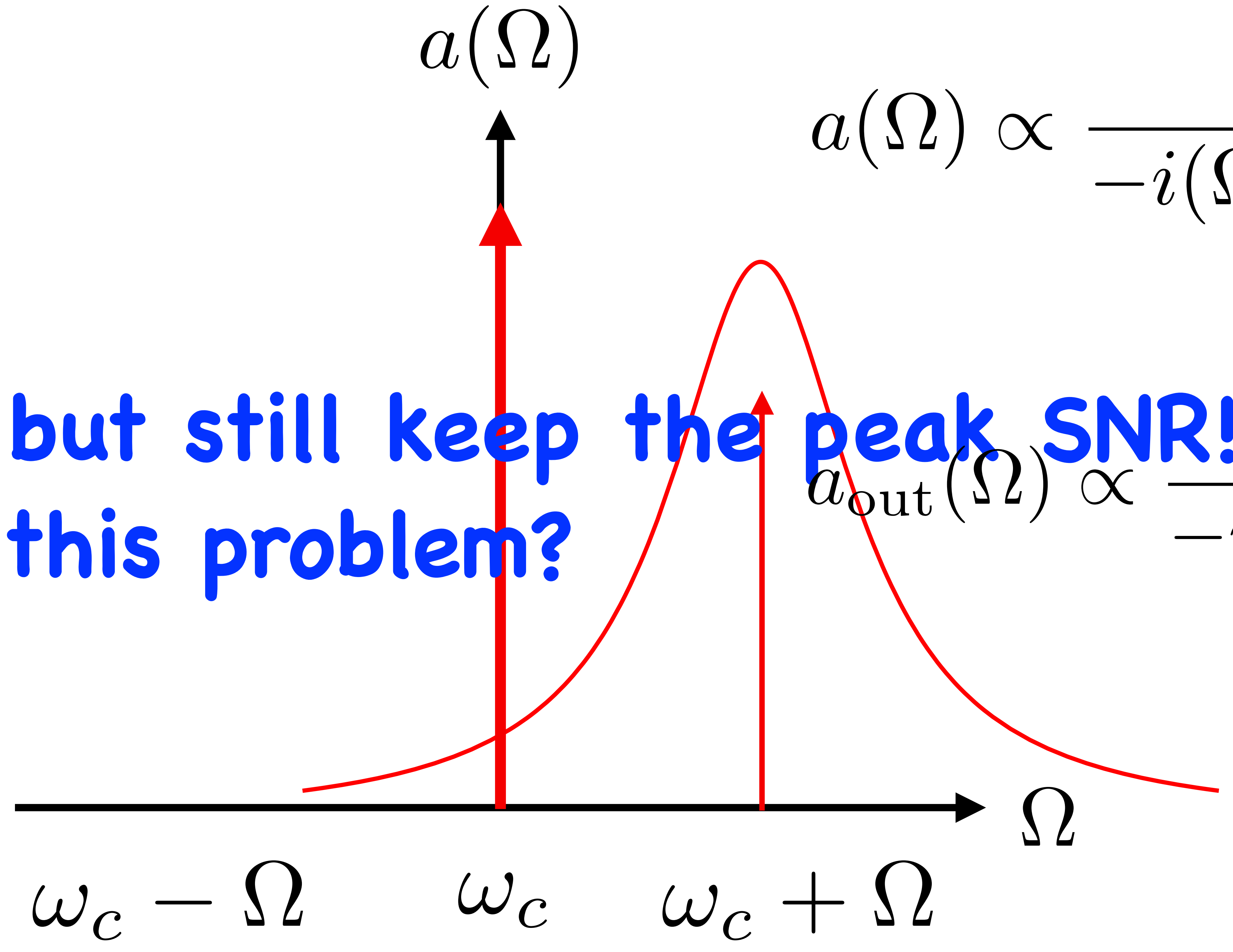
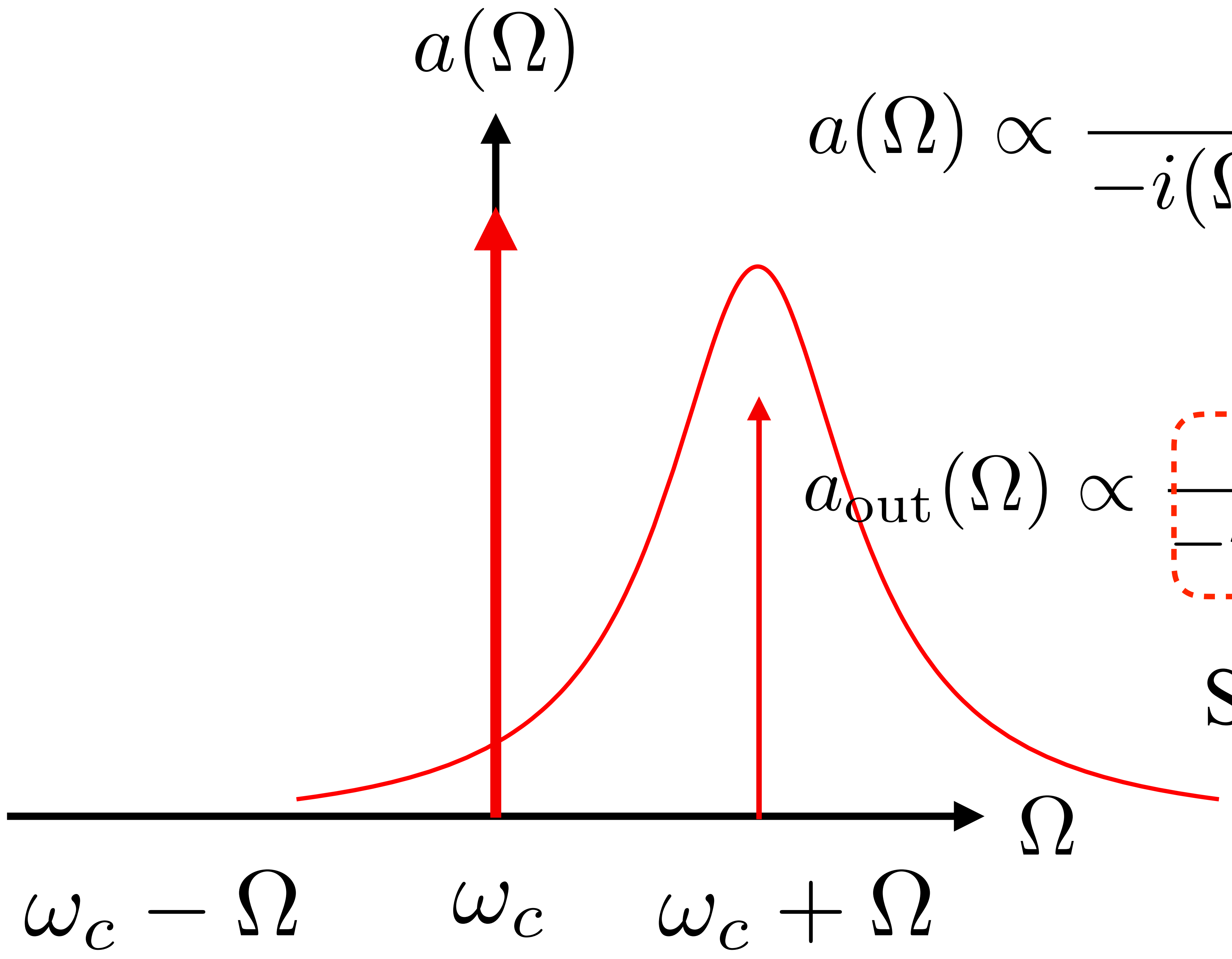


$$a(\Omega) \propto \frac{1}{-i(\Omega - \Delta) + \gamma} h(\Omega)$$

$$a_{\rm out}(\Omega) \propto \frac{\sqrt{2\gamma}}{-i(\Omega - \Delta) + \gamma} h(\Omega)$$

We need a large bandwidth but still keep the peak SNR!
How to solve this problem?

Surpass gain-bandwidth trade-off



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$$a_{\mathrm{out}}(\Omega) \propto \frac{\sqrt{2\gamma}}{-i(\Omega - \Delta) + \gamma} h(\Omega)$$

Signal response $K_s(\Omega)$

$$\mathrm{SNR} \propto \int \frac{d\Omega}{2\pi} \frac{1}{S_{hh}(\Omega)}$$

With $\dfrac{1}{S_{hh}(\Omega)} \propto |K_s(\Omega)|^2$

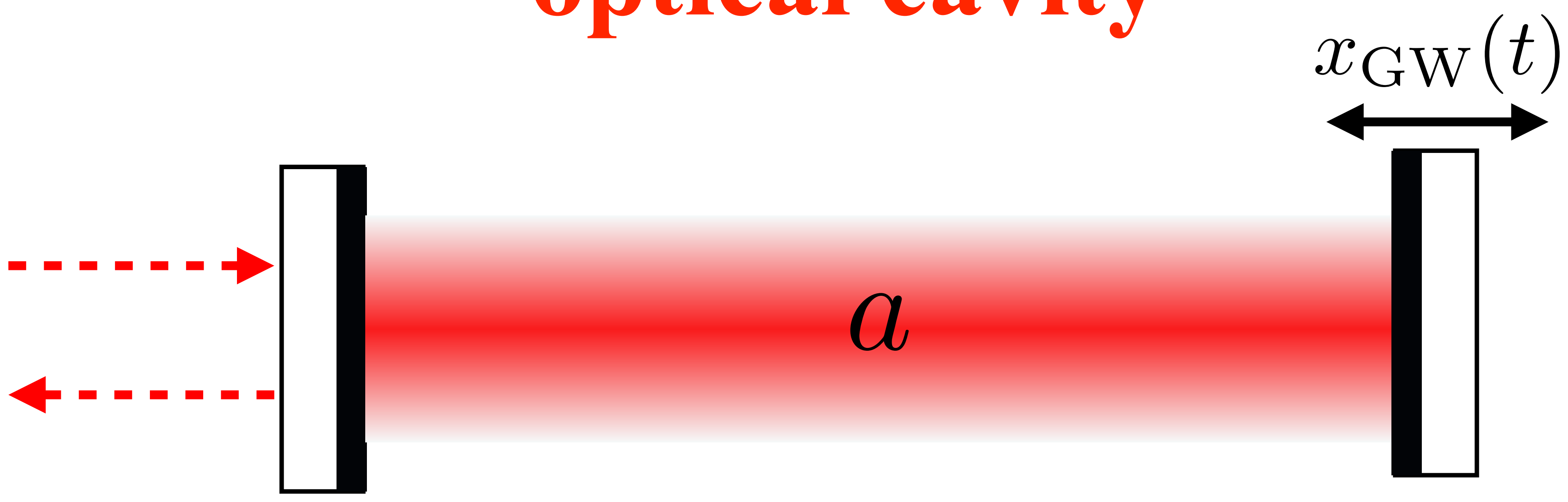
If: $\hat{a}_{\mathrm{out}}(\Omega) \propto \dfrac{\sqrt{2\gamma}}{-i(\Omega - \Delta)} h(\Omega)$

New Signal response

SNR can have a significant boost

Time domain:

optical cavity



$$a(\Omega) \propto \frac{1}{-i(\Omega-\Delta)+\gamma} h(\Omega)$$

$$\left(\frac{d}{dt} + i\Delta + \gamma\right) \hat{a}(t) = \alpha h(t)$$

Couples to other modes

$$\left(\frac{d}{dt} + i\Delta\right) \hat{A} = \alpha h(t)$$

Step 2: Couple the cavity mode to a new mode

$$\left(\frac{d}{dt} + i\Delta + \gamma'\right) \hat{a} = -\gamma' \hat{c}^\dagger + \alpha h(t)$$

$\sim e^{-i\Delta t - \gamma' t}$

``time reversal''

$$\left(\frac{d}{dt} - i\Delta - \gamma'\right) \hat{c} = \gamma' \hat{a}^\dagger$$

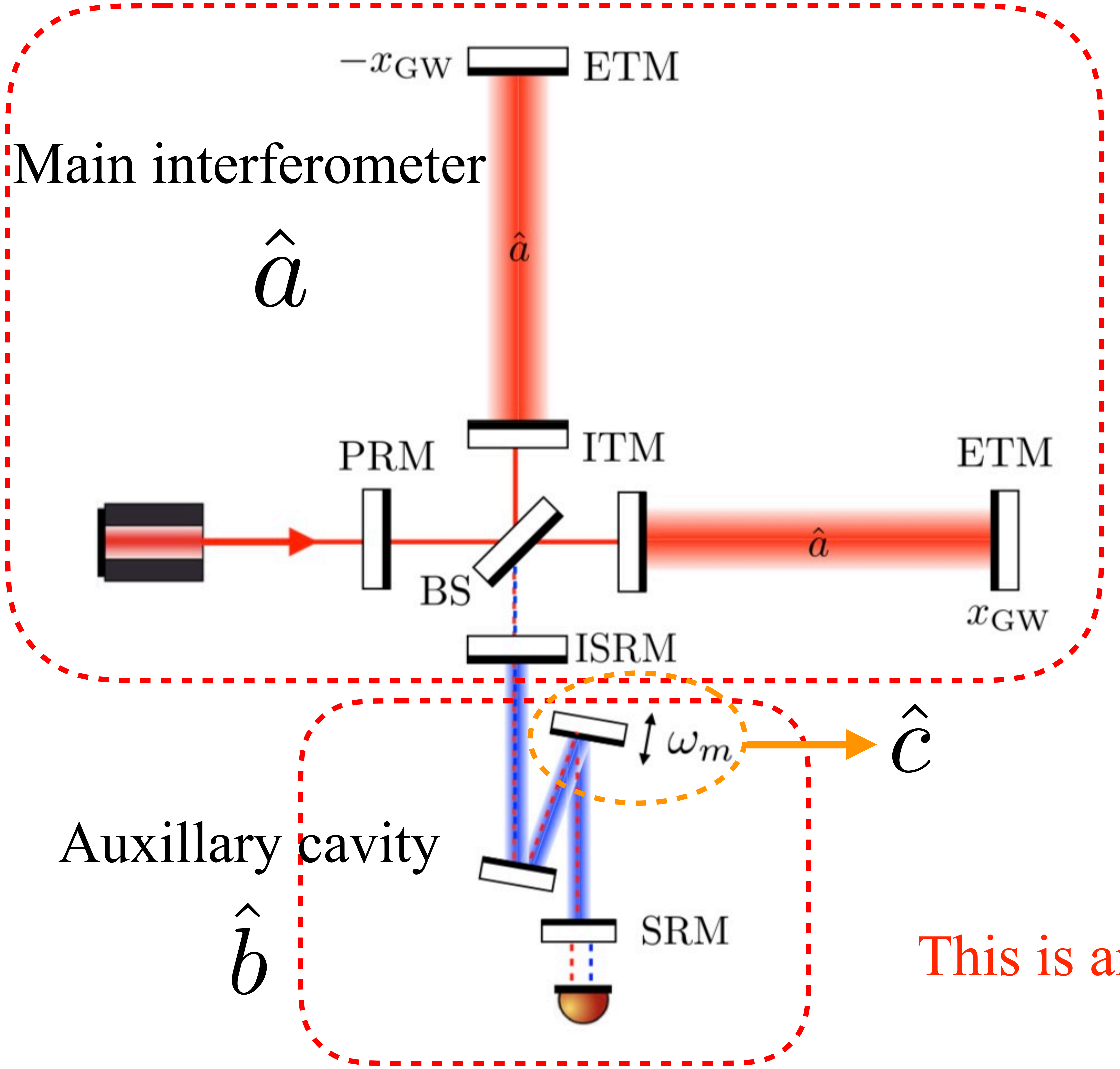
$\sim e^{i\Delta t + \gamma' t}$

Combine $\hat{A} = \hat{a} + \hat{c}^\dagger$

$$\left(\frac{d}{dt} + i\Delta\right) \hat{A} = \alpha h(t)$$

Not just a math game!

Configuration



1: Main interferometer recieves GWs

$$h(t) \rightarrow \hat{a}$$

2: Signal slosh into the auxillary cavity

$$\omega_s(\hat{a}^\dagger \hat{b} e^{-i\Delta t} + \hat{a}\hat{b}^\dagger e^{i\Delta t})$$

3: Pair creation happen inside the cavity

$$g(\hat{b}^\dagger \hat{c}^\dagger e^{i\delta t} + \hat{b}\hat{c} e^{-i\delta t})$$

4: Extract the signal from the output of auxillary cavity

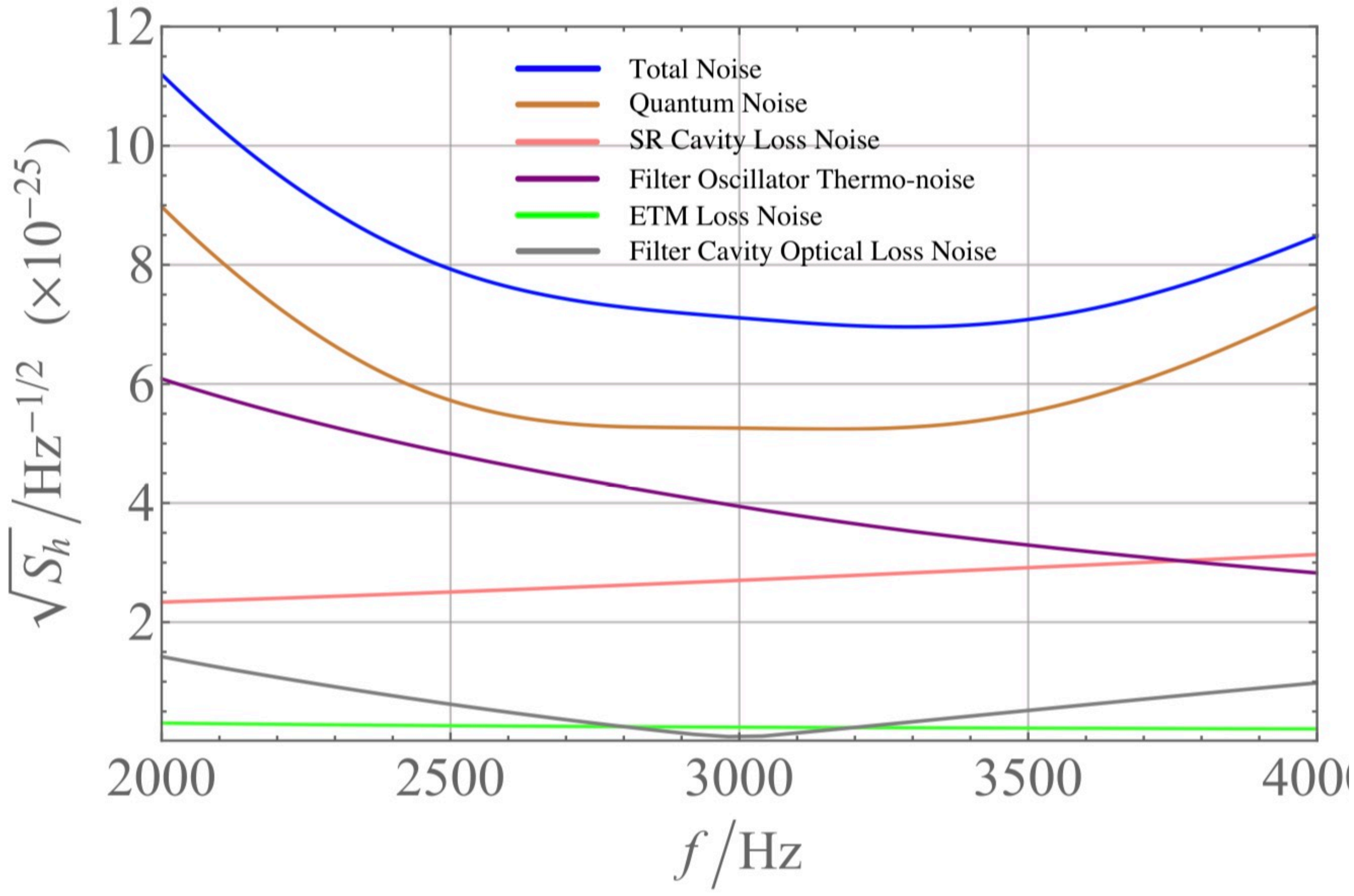
Condition: $\omega_s = g \quad \Delta = -\delta$

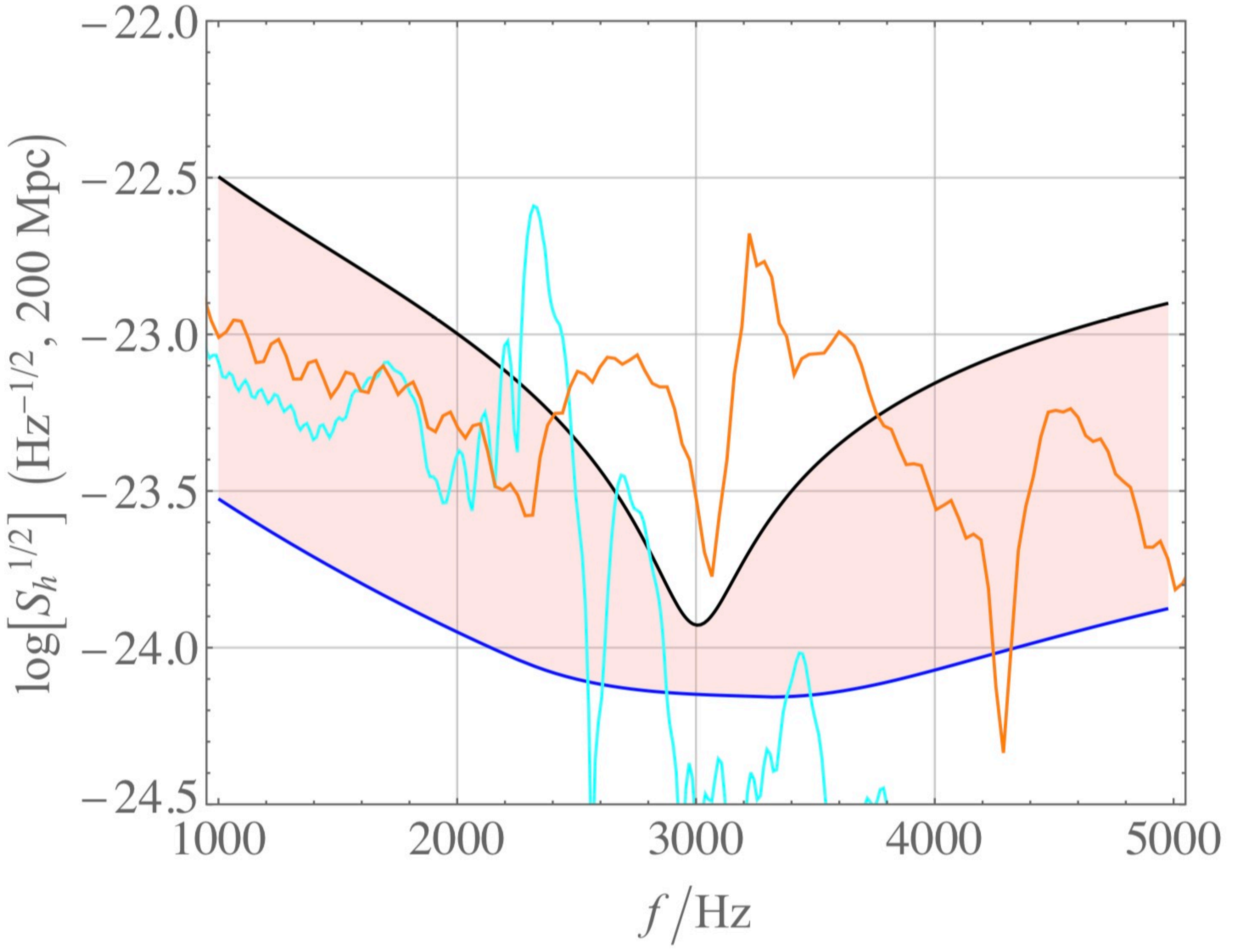
This is an ideal concept, while many imperfections (losses, instability…) needs to be considered.

Wang *et al*, Phys. Rev. D 106, 082002 (2022); Li *et al*, Phys. Rev. D **103**, 122001 (2021)

Key noise budget & improvement

Wang *et al*, Phys. Rev. D 106, 082002 (2022); Li *et al*, Phys. Rev. D **103**, 122001 (2021)





Summary

- **Detect gravitational waves at kiloHertz band:**
  is very important
- **What limits the sensitivity at kiloHertz band:**
  signal response+shot noise
- **Method for improving the kiloHertz sensitivity:**
  improving signal response/reduced shot noise
- **A possible design of the configuration:**
  Surpassing the gain-bandwidth trade-off at kiloHetz

Thank you for your attention!