基于微纳光力学系统的量子精密测量

朱卡的

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微纳光力学：研究光与机械振子相互作用的学科

机械振子的基态冷却

机械振子的量子控制、对光场调制

将量子光学、凝聚态物理、量子电动力学等结合起来

力学模式
光学模式
→
微纳光力学

纳米或亚波长尺度

调控自发辐射 | 复合体系量子干涉 | 可逆相互作用 | 量子信息研究

场量子化   量子体系结合

光子晶体 | 手性光子材料 | 超材料 | 拓扑光子结构
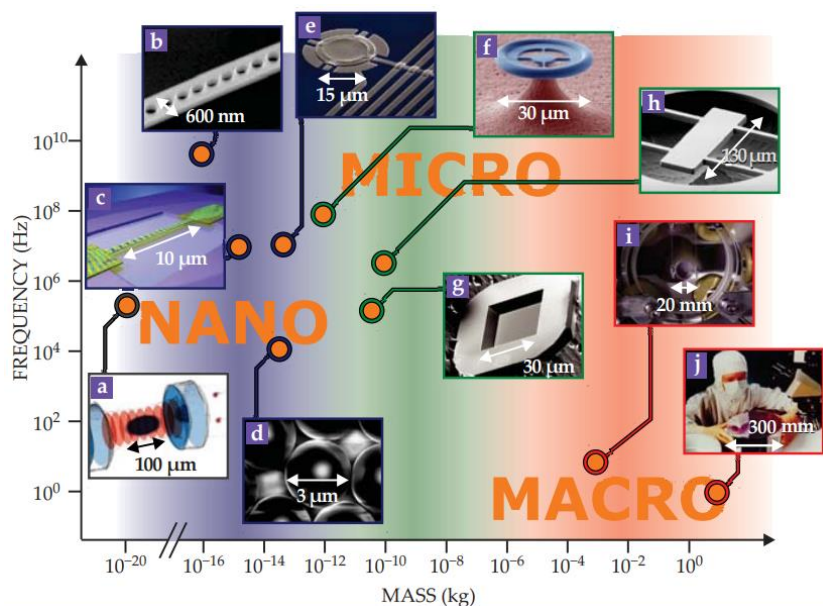
高灵敏度
体积小
重量轻
功耗低
可片上集成
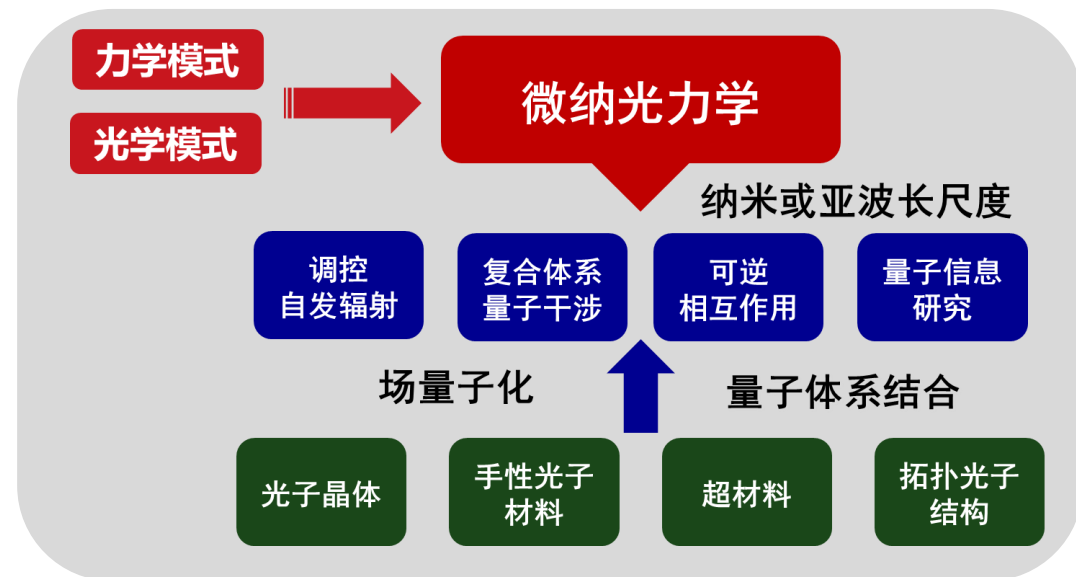
提出要求

发展高精度传感器件
通信和量子信息处理
基础量子科学检验

光具有动量，来源于光压（辐射压）
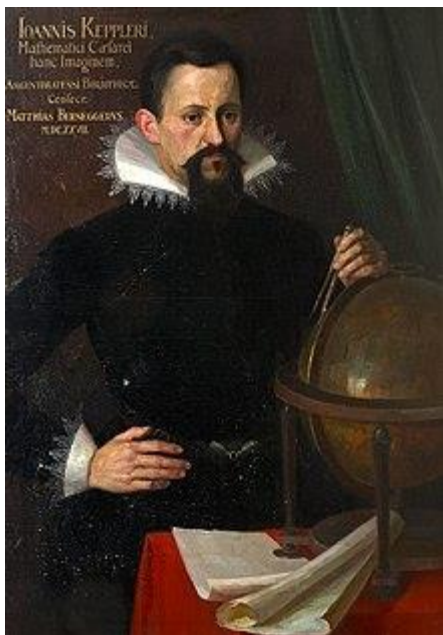
1619年，开普勒注意到了光压的存在

Kepler, J., 1619, De cometis libelli tres (Typis Andreae Apergiri).

$$F = 2\frac{P}{c}$$

垂直入射光功率为P

全反射镜

(a) 哈雷彗星
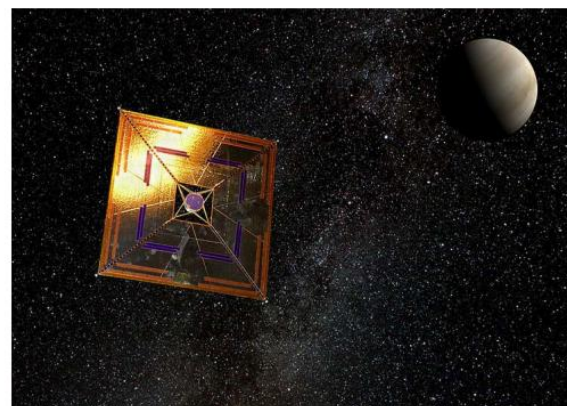
(b) 日本宇宙航空研究开发机构开发的 IKAROS 太空探测器

光的辐射压力使哈雷彗星出现彗尾及驱动 IKAROS 探测器用于探测宇宙深处
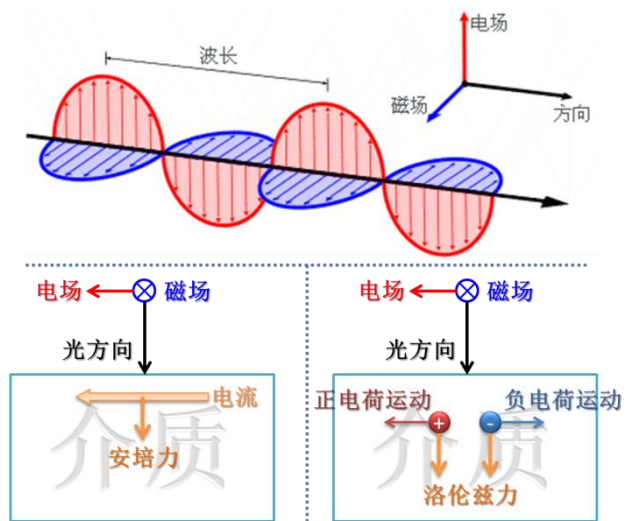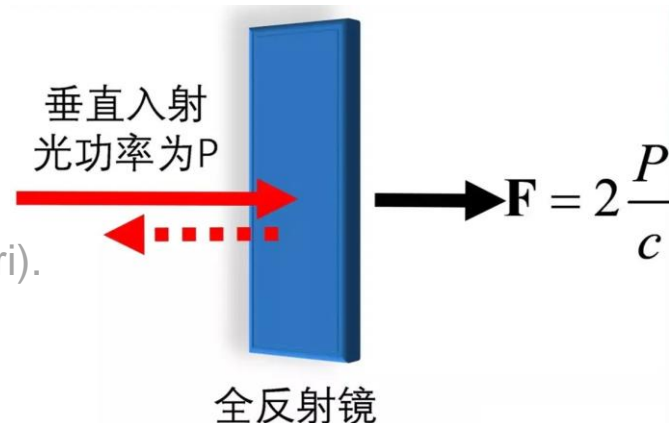
纳米技术思想启蒙、激光操控

1959年，费曼提出"纳米技术"设想；

There's Plenty of Room at the Bottom

Richard P. Feynman

Arthur Ashkin · Gérard Mourou · Donna Strickland

"for groundbreaking inventions in the field of laser physics"

THE ROYAL SWEDISH ACADEMY OF SCIENCES

1970年代，Ashkin，微米尺度的乳胶小球的加速运动和稳定悬浮；

1975年，辐射压的非保守力特征，用来冷却原子的可能性；

Hänsch, T. W., and A. L. Schawlow, 1975, Opt. Commun. 13, 68.
Wineland, D. J., and H. Dehmelt, 1975, Bull. Am. Phys. Soc. 20, 637.

1980年代，实验中首次实现激光冷却；

1986年，Ashkin 实现了对电介质微球的三维捕获——光镊。
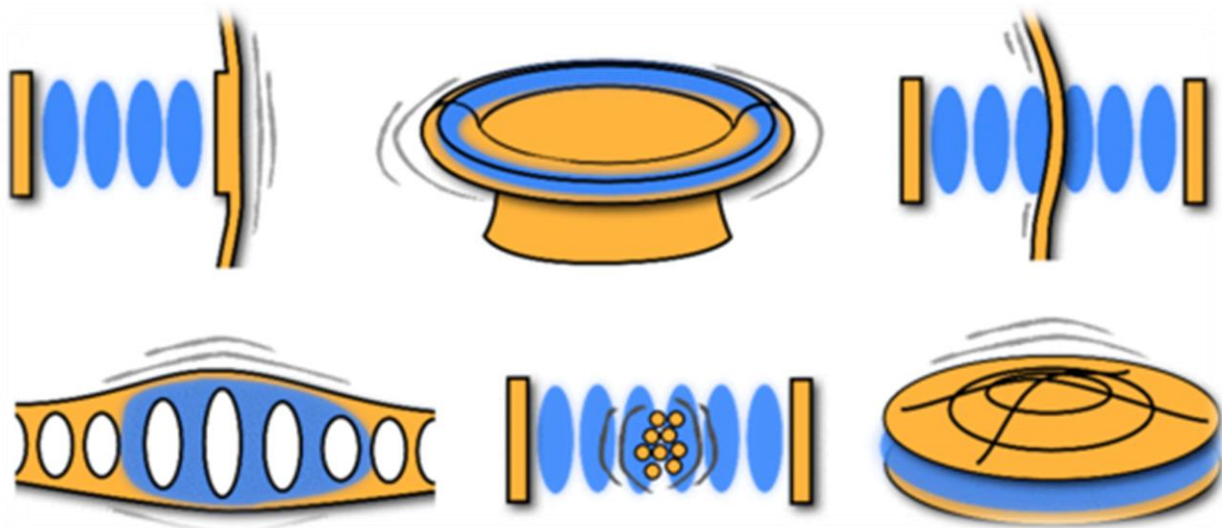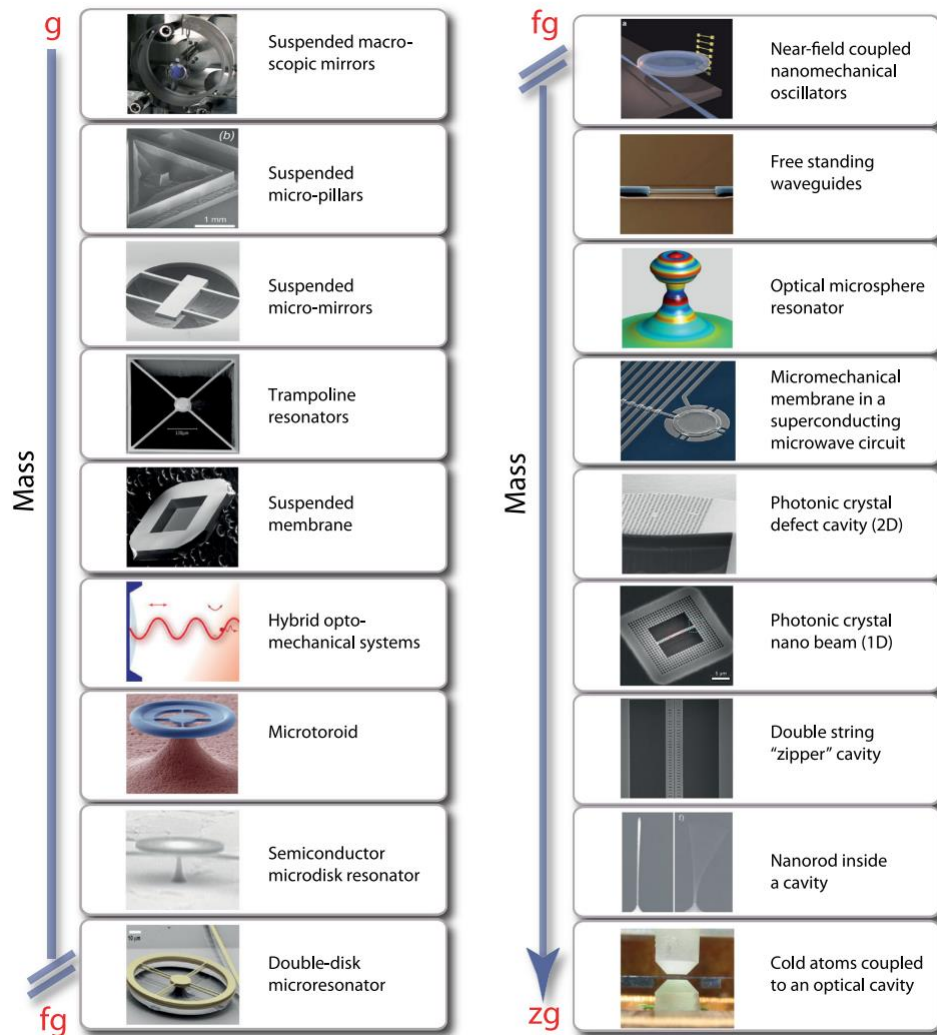
Stenholm, S., 1986, Rev. Mod. Phys. 58, 699.

"光""力"模式与腔光力学系统

辐射模式（模式形状）和振动自由度（灰色线条）

Aspelmeyer, M., Kippenberg, T. J., Marquardt, F., 2014, Rev. Mod. Phys. 86, 1391

g — Suspended macro-scopic mirrors

Suspended micro-pillars

Suspended micro-mirrors

Trampoline resonators

Suspended membrane

Hybrid opto-mechanical systems

Microtoroid

Semiconductor microdisk resonator

Double-disk microresonator — fg

Mass

fg — Near-field coupled nanomechanical oscillators

Free standing waveguides

Optical microsphere resonator

Micromechanical membrane in a superconducting microwave circuit

Photonic crystal defect cavity (2D)

Photonic crystal nano beam (1D)

Double string "zipper" cavity

Nanorod inside a cavity

Cold atoms coupled to an optical cavity — zg

Mass

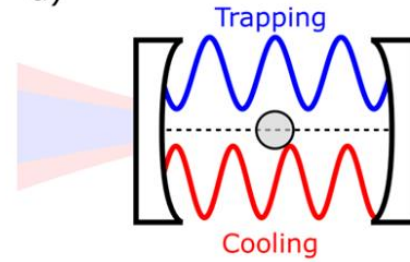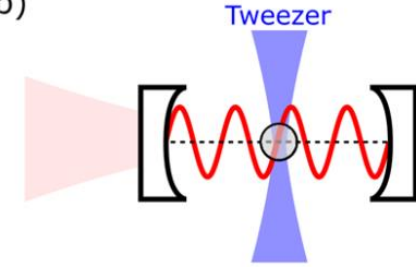**Optomechanics with levitated particles , J.Millen et al., Rep.Prog.Phys.83, 026401 (2020)**
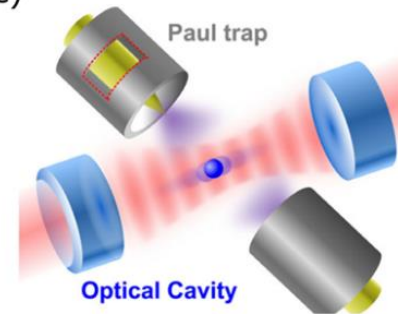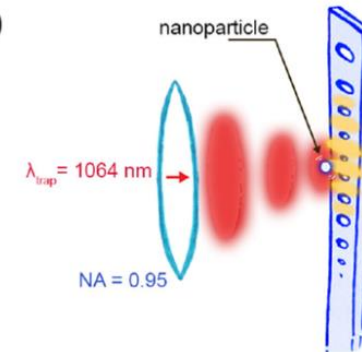
Leviated Cavity Optomechanics（悬浮腔光力学 ）

多场景应用

提高灵敏度
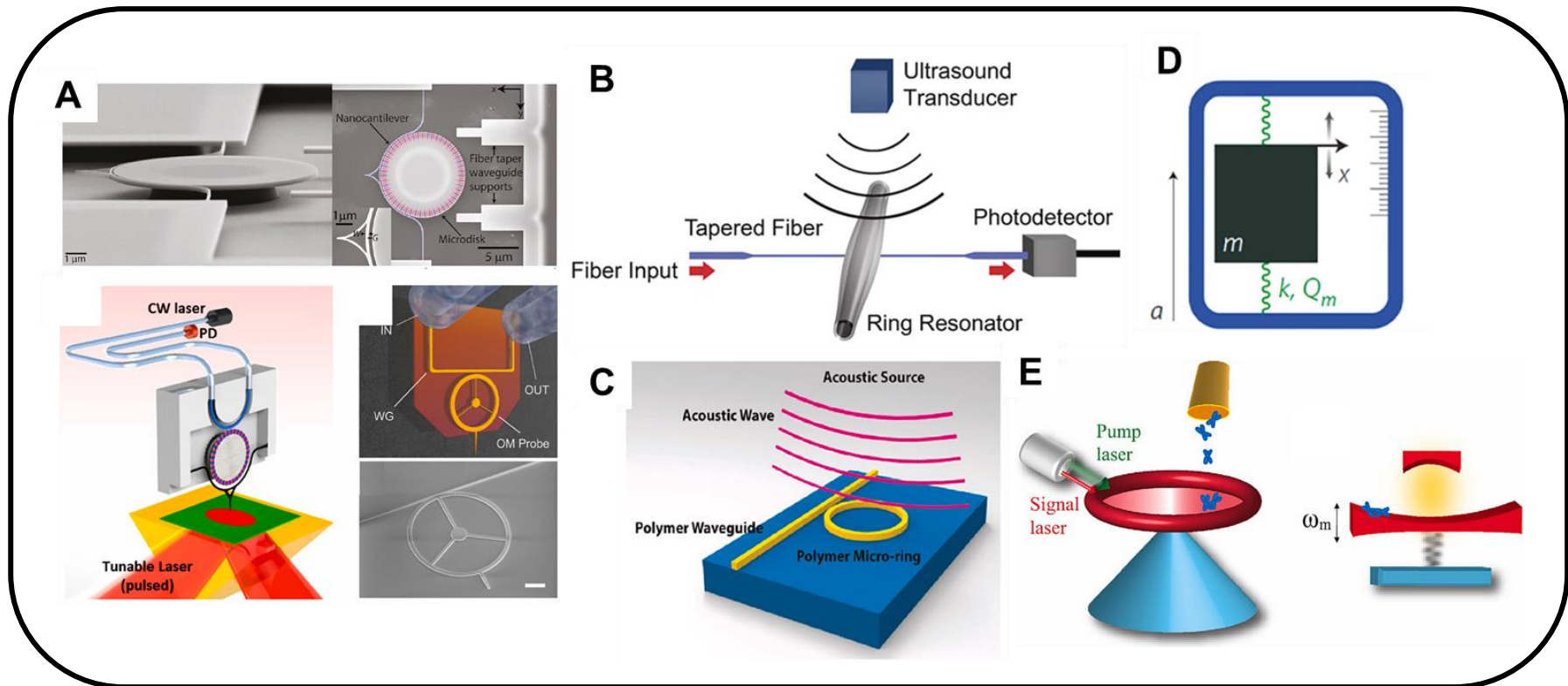
基础物理检验平台

Li, B., Ou, L., Lei, Y. & Liu, Y., Nanophotonics, 2021, 10(11), 2799-2832.
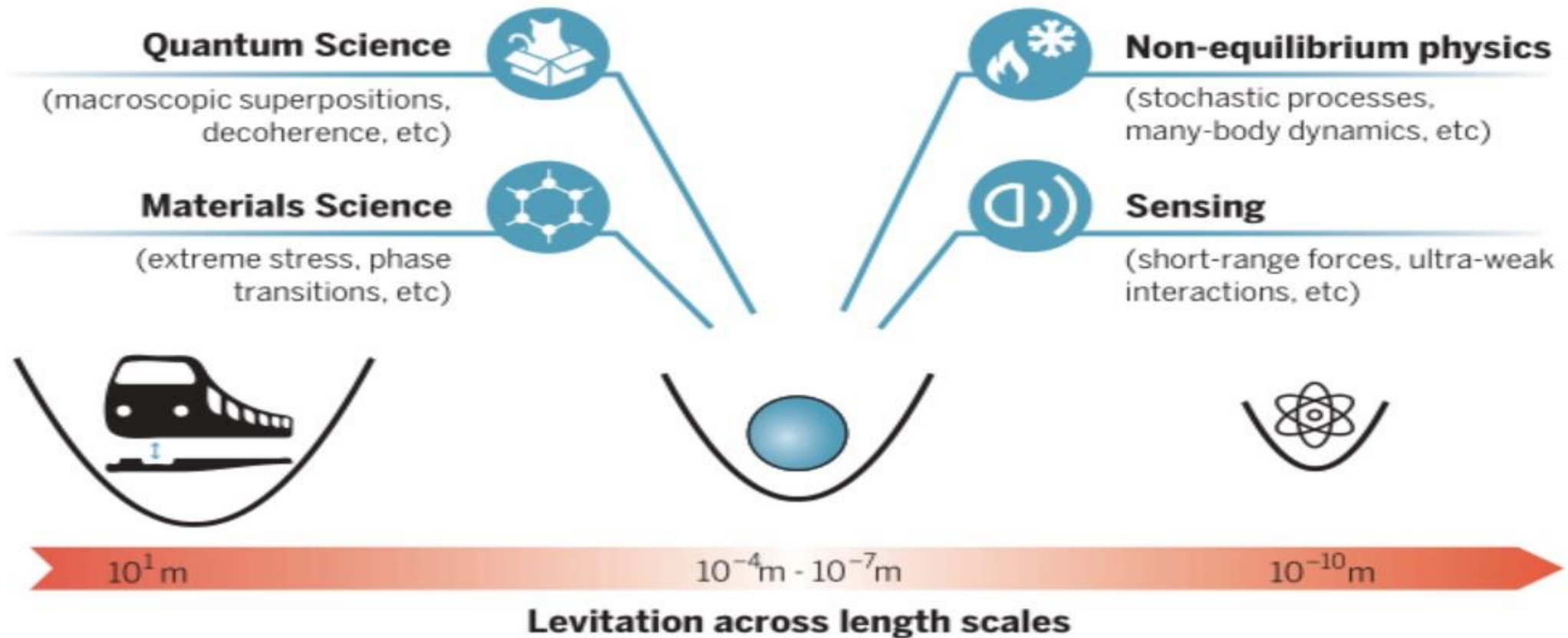
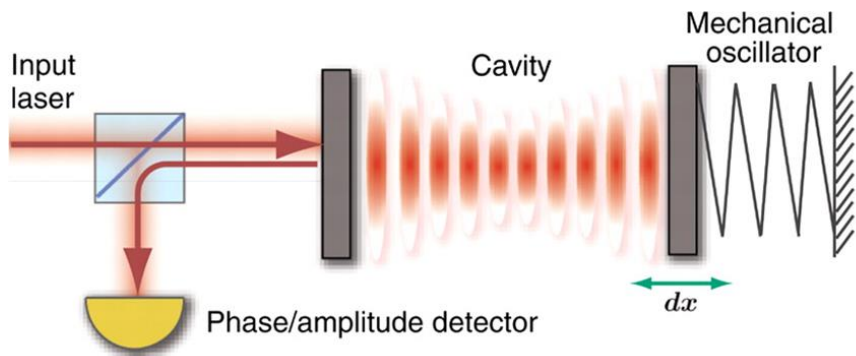**Levitodynamics: Levitation and control of microscopic objects in vacuum,** C.Gonzalez-Ballestero et al., Science 374, 168 (2021).
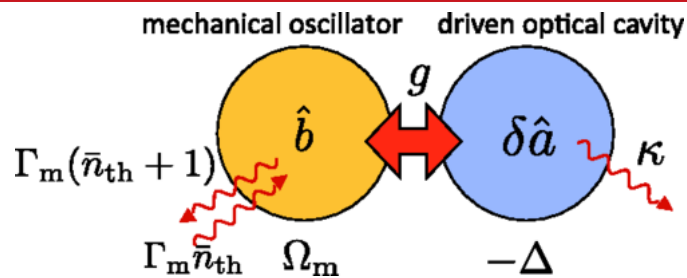
以典型的 Fabry-Pérot 腔构建微小**力传感**为例

T. J. Kippenberg, K. J. Vahala, Science 321,1172-1176(2008).

构建腔光力学反馈回路模型

理论解析模型

数值模拟与仿真
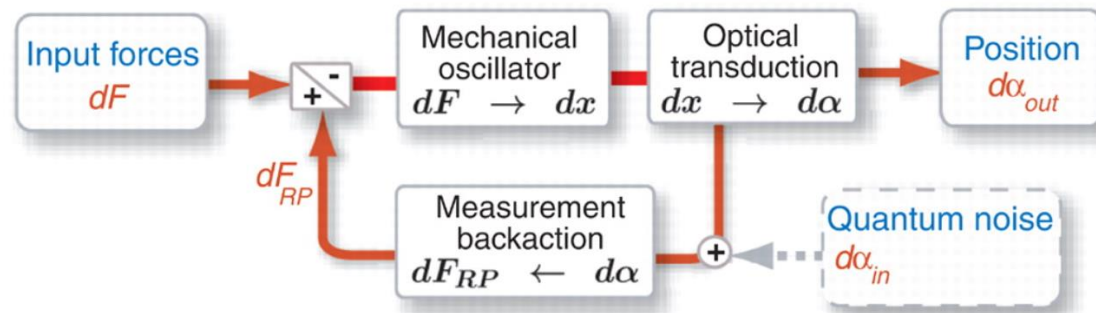
$$\hat{H} = -\hbar\Delta\hat{a}^{\dagger}\hat{a} + \hbar\Omega_m\hat{b}^{\dagger}\hat{b} - \hbar g_0\hat{a}^{\dagger}\hat{a}(\hat{b} + \hat{b}^{\dagger}) + \cdots,$$

海森堡方程

$$\frac{dP}{dt} = \frac{1}{i\hbar}\left[P_t, \widehat{H}_t\right]$$

量子朗之万方程

$$\dot{\hat{a}} = -\frac{\kappa}{2}\hat{a} + i(\Delta + G\hat{x})\hat{a} + \sqrt{\kappa_{\text{ex}}}\hat{a}_{\text{in}} + \sqrt{\kappa_0}\hat{f}_{\text{in}},$$

$$\dot{\hat{b}} = \left(-i\Omega_m - \frac{\Gamma_m}{2}\right)\hat{b} + ig_0\hat{a}^{\dagger}\hat{a} + \sqrt{\Gamma_m}\hat{b}_{\text{in}}.$$

原子力显微镜（AFM）工作原理
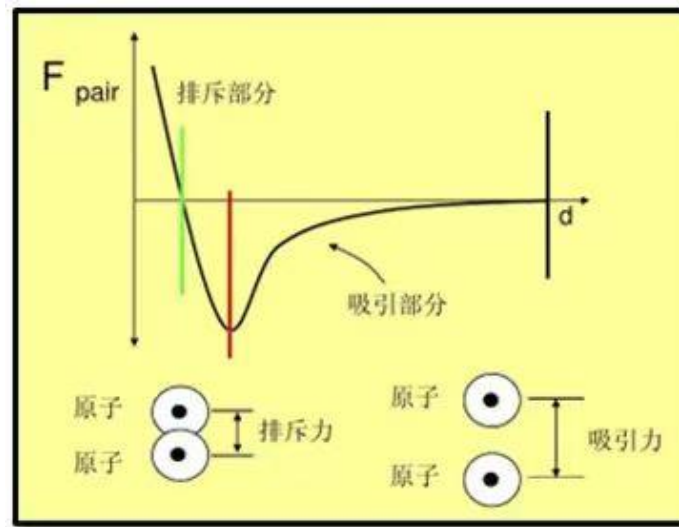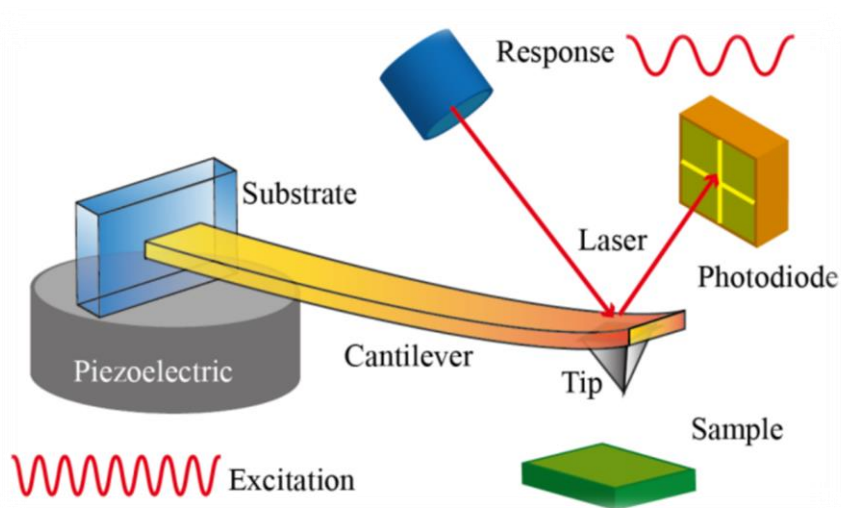
接触式：静态模式，排斥力致悬臂弯曲

非接触式：动态模式，针尖在样品上方摆动

轻敲模式：只针尖摆动到底部与样品接触

增强AFM灵敏度的方式：改进探针-样品间相互作用力的测量方式
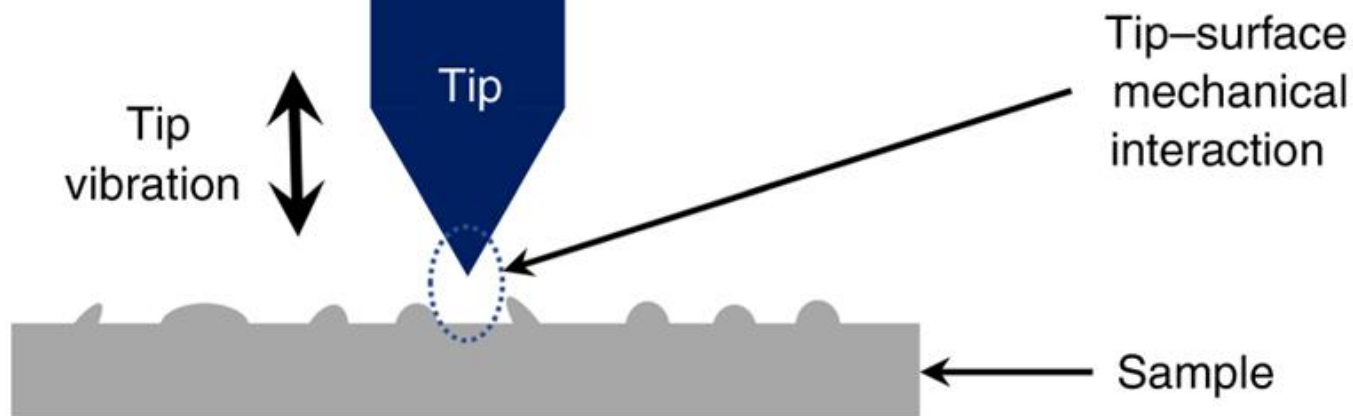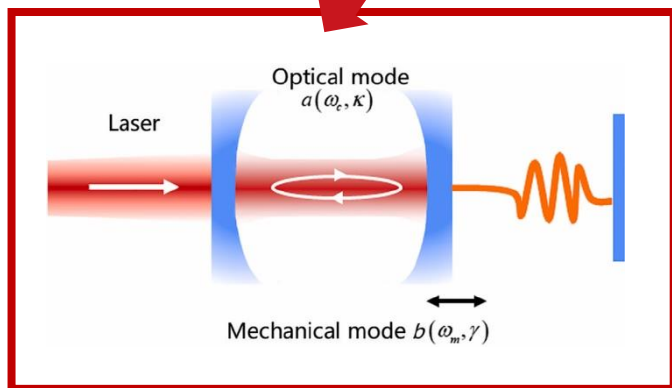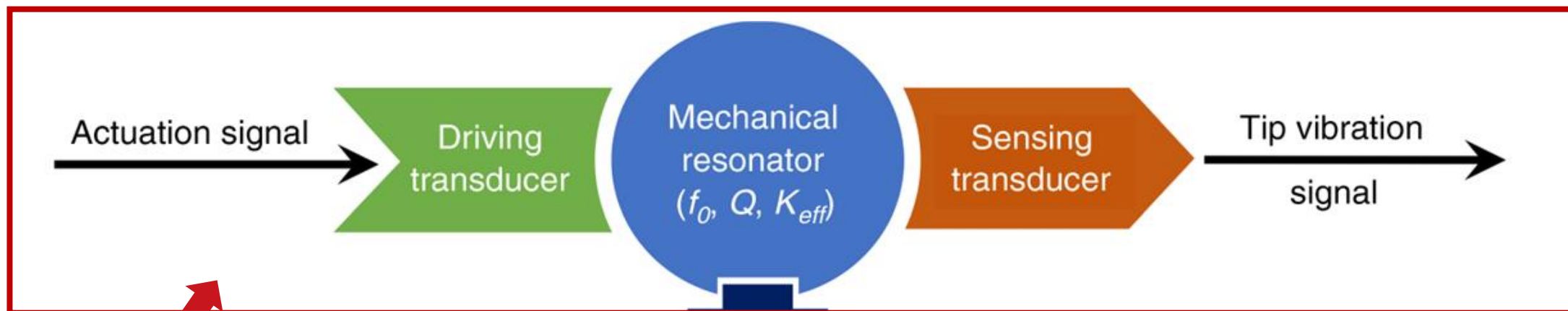
腔光力学增强AFM灵敏度：方案模型
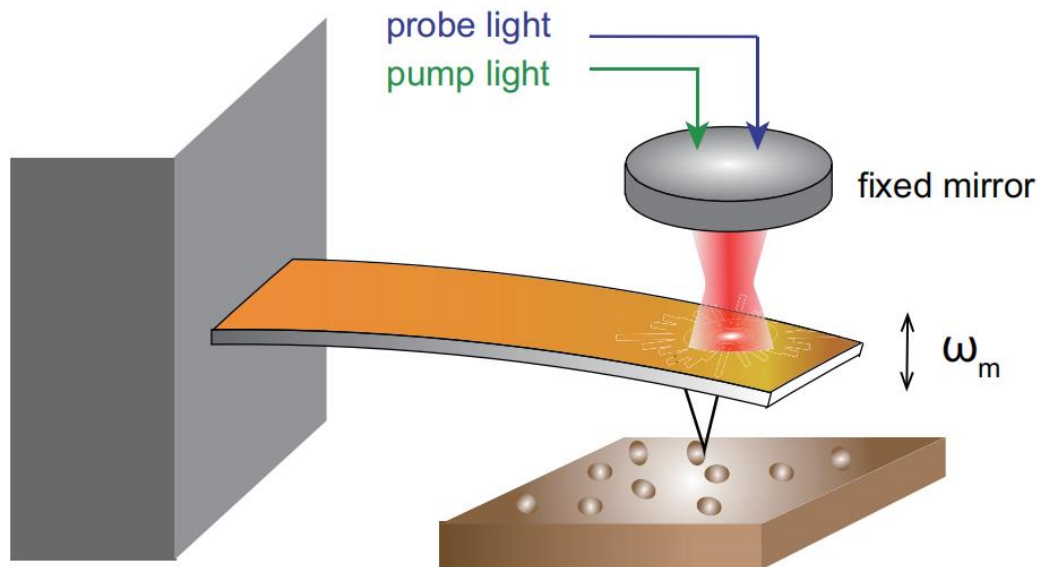
- 输入激光只驱动单一模 ω_c

  这个谐振腔模可以描述为：$H_c = \hbar\omega_c c^\dagger c$；

- 悬臂梁的机械模 ω_m 的哈密顿量为

$$H_m = \tfrac{1}{2}\hbar\omega_m(p^2 + q^2)\,;$$

- 光学谐振腔通过辐射压耦合到悬臂梁振子上

$$H_{int} = -\hbar G c^\dagger c q$$

  其中，$G = (\omega_c/L)\sqrt{\hbar/m\omega_m}$ 为耦合强度；

- 泵浦-探测光场

$$H_{op} = i\hbar E_{pu}(c^\dagger - c) + i\hbar E_{pr}(c^\dagger e^{-i\delta t} - c e^{i\delta t}),$$

$$\mathcal{H} = \hbar\Delta_{pu}c^\dagger c + \frac{1}{2}\hbar\omega_m(p^2 + q^2) - \hbar G c^\dagger c q$$
$$+ i\hbar E_{pu}(c^\dagger - c) + i\hbar E_{pr}(c^\dagger e^{-i\delta t} - c e^{i\delta t}),$$

S J T U

模型的解析

probe light
pump light

fixed mirror

ω_m
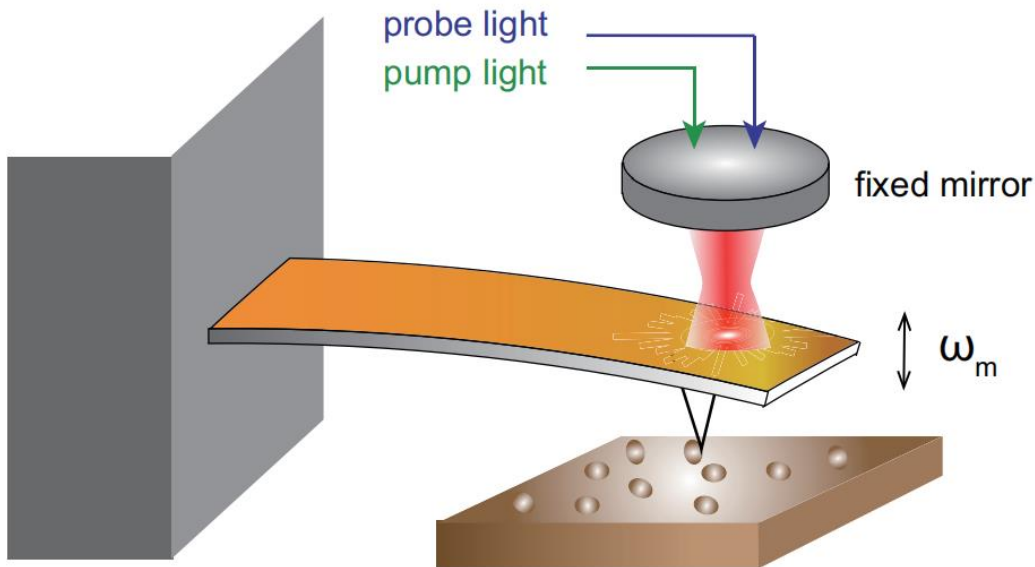
- 悬臂梁：热噪声
- 机械阻尼 γ_m
- 光学腔耗散 κ

$$\mathcal{H} = \hbar\Delta_{pu}c^\dagger c + \frac{1}{2}\hbar\omega_m(p^2 + q^2) - \hbar Gc^\dagger cq$$
$$+ i\hbar E_{pu}(c^\dagger - c) + i\hbar E_{pr}(c^\dagger e^{-i\delta t} - ce^{i\delta t}),$$

- 系统的演化的动力学 $i\hbar\frac{d\hat{O}}{dt} = [\hat{O}, \mathcal{H}]$

$$[c, c^\dagger] = 1 \qquad [q, p] = i$$

$$\frac{dc}{dt} = -(i\Delta_{pu} + \kappa)c + iGcq + E_{pu} + E_{pr}e^{-i\delta t}$$
$$+ \sqrt{\kappa_{ex}}\hat{a}_{in} + \sqrt{\kappa_0}\hat{f}_{in},$$
$$\frac{d^2q}{dt^2} + \gamma_m\frac{dq}{dt} + \omega_m^2 q = \omega_m Gc^\dagger c.$$

Langevin方程

- ansatz $c(t) = c_0 + a_+ e^{-i\delta t} + c_- e^{i\delta t}$

**线性光学极化率
相关的参数
实部：吸收谱**

$$c_+ = E_{pr}\left[\frac{-i\delta + (-i\Delta_{pu} + \kappa) + \Gamma}{(\kappa^2 - i\delta)^2 + (\Delta_{pu} + i\Gamma)^2 - \Xi}\right]$$

模型的求解与吸收谱

- 假设实验上我们选取波长为 532 nm 的激光,
- 反射镜的数值孔径(NA)为 0.8,
- 悬臂梁材料:氮化硅(并假设悬臂梁谐振频率 160 kHz)
- 有效质量: $M_{eff} = \dfrac{12}{\pi^2}\left(\dfrac{\pi}{4}\rho h_0 W^2\right)$

输入-输出关系

$$c_{in}(t) + c_{out}(t) = \sqrt{2\kappa}c(t)$$

$c_{in}(t)$ 期望为零

$$\langle c_{out}(t)\rangle = c_{out0} + c_{out+}e^{-i\delta t} + c_{out-}e^{i\delta t}$$

$$= \sqrt{2\kappa}(c_0 + c_+ e^{-i\delta t} + c_- e^{i\delta t})$$

线性光学极化率相关的参数实部:吸收谱

$$c_{out+} = \sqrt{2\kappa}c_+$$

±160 kHz吸收峰

(a) absorption Re(a_{out+}) vs δ (kHz); inset ∇F (N/m) vs $\Delta\omega$ (kHz); $\nabla F = 8\times10^{-12}$ (N/m), $\nabla F = 0$

(b) FWHM, $\Delta\omega$, δ (kHz)
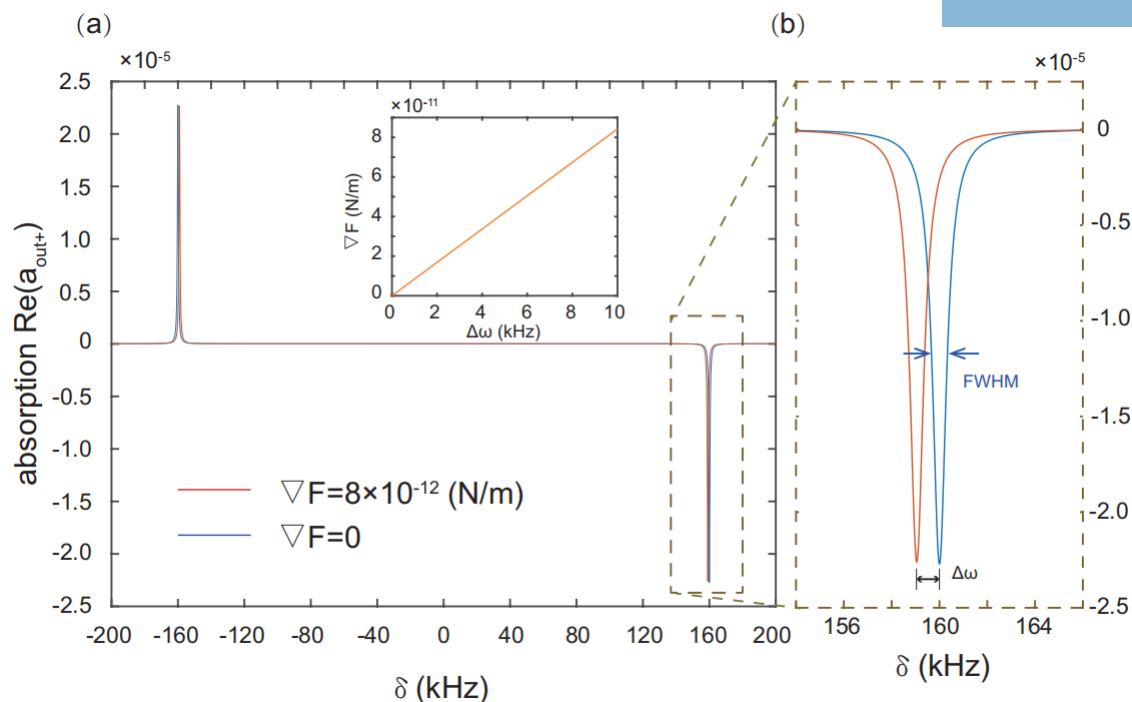
实验：引入待测样品

- 引入样品，悬臂平衡位置与样品之间~1 nm；

- 探针与样品作用力梯度 $\nabla F \sim 8 \times 10^{-12}$ N/m

  Y. Martin, C. C. Williams, H. K. Wickramasinghe,
  J. Appl. Phys.,1987, 61 (10), 4723–4729.

- 悬臂梁振动频移与力梯度的关系

$$\nabla F \approx \frac{2k\Delta\omega}{\omega_m},$$

- 计算可得，悬臂梁振动频移 $\Delta\omega \sim 0.95$ kHz

±159.05 kHz吸收峰
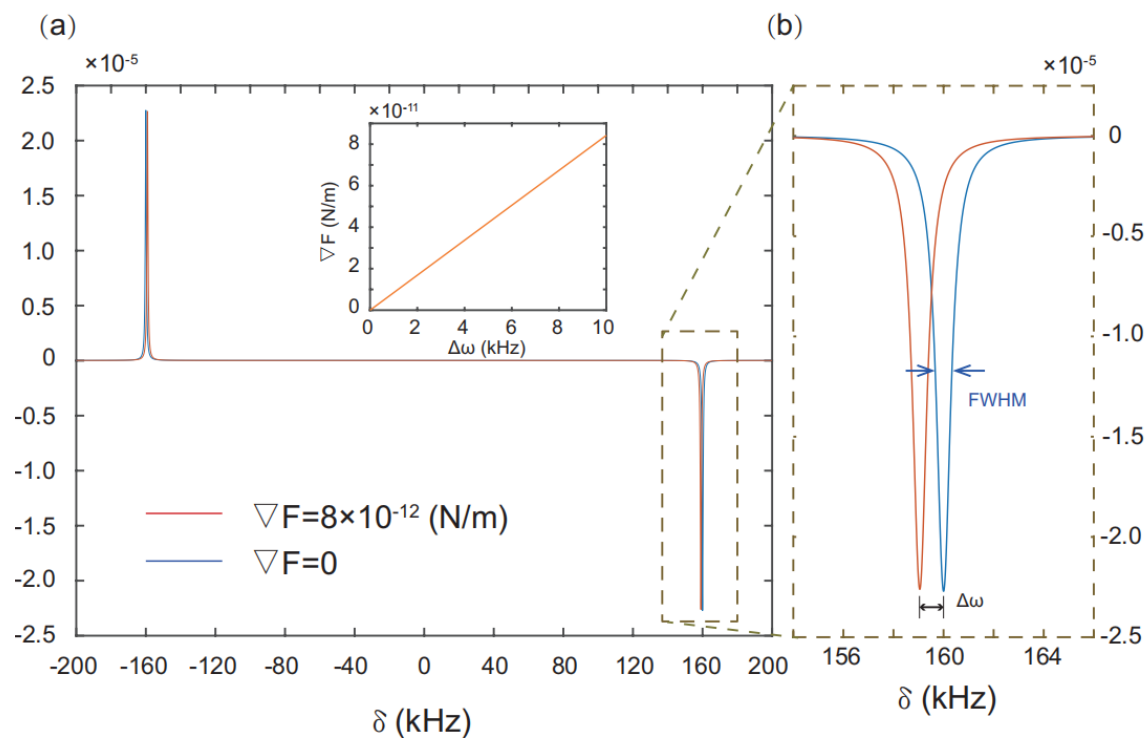
常温常压条件，探测极限

FWHM
（常温常压条件）

吸收谱的 FWHM ~ 0.72 kHz

$$\nabla F \approx \frac{2k\Delta\omega}{\omega_m},$$

常温常压：Q ~ 232

∇F ~ 6.06×10^{-9} N/m

考虑到典型的探针-样品距离 ~ 10 nm,

Sensitivity ~ 10^{-18} N
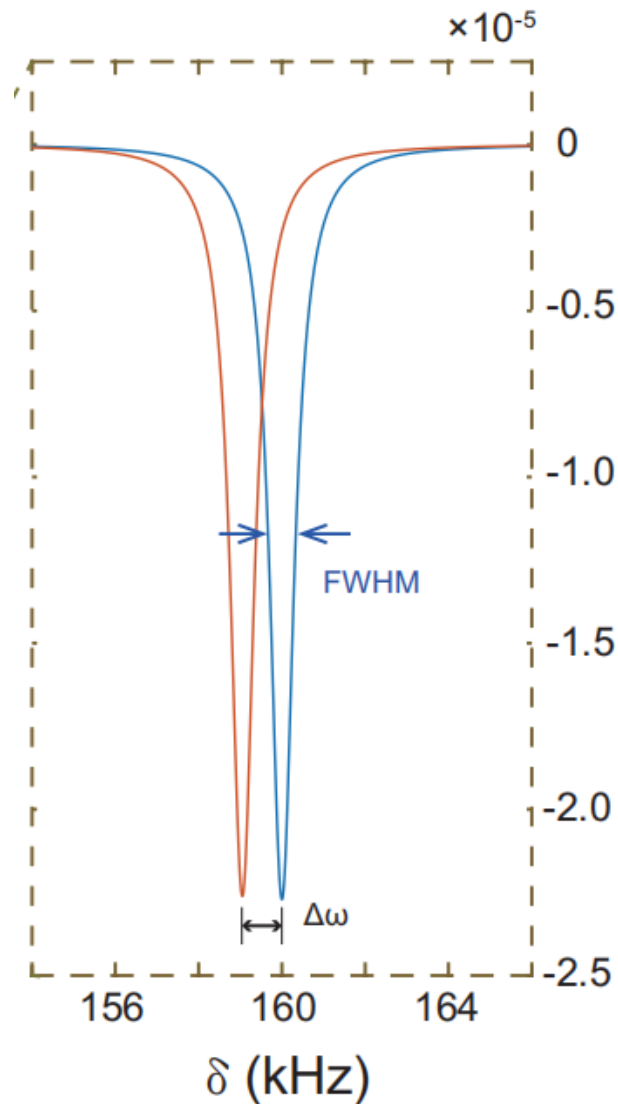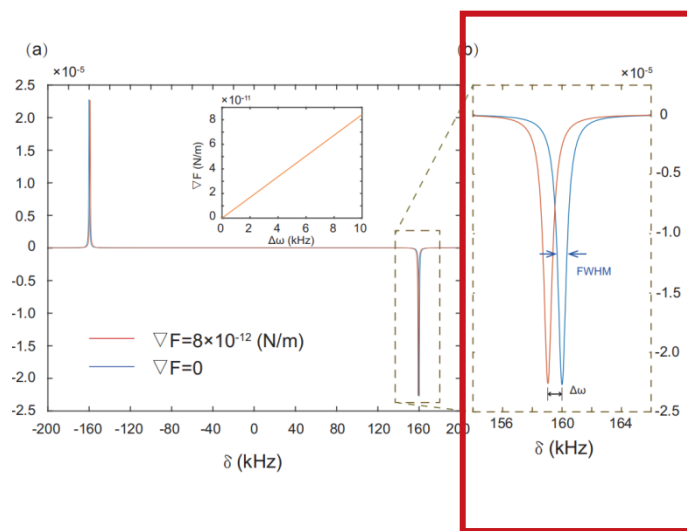
真空、冷却条件，探测极限

吸收谱的 FWHM ~ 0.16 Hz

$$\nabla F \approx \frac{2k\Delta\omega}{\omega_m},$$

真空冷却：Q ~ 10^6

∇F ~ 1.35×10^{-12} N/m

考虑到典型的探针-样品距离 ~ 10 nm，

Sensitivity ~ 10^{-21} N

**FWHM
(10^{-10} Torr & 1 mK)**

Liu J., Zhu K. D., Phys. Rev. D, 2017, 95, 044014.
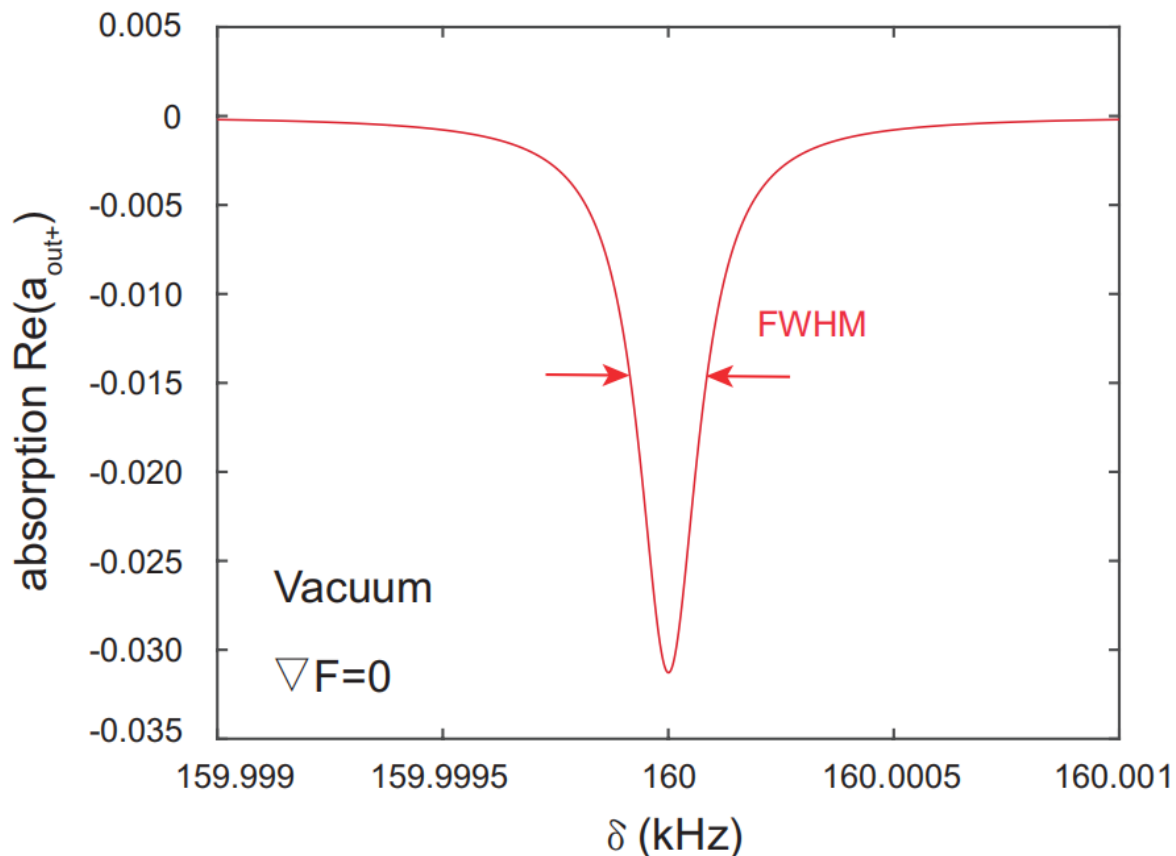
真空、冷却条件，探测极限

热噪声对力梯度探测的影响为

$$\delta F^{th} = \sqrt{\frac{4kk_BTB}{\omega_m Q \langle Z^2_{OSC}\rangle}}$$

T 是热力学温度，B 是测量带宽；

$\langle Z^2_{OSC}\rangle$ 是悬臂梁的均方振幅

Albrecht T. R., Grütter P., Horne D., et al., J. Appl. Phys, 1991, 69(2), 668-673.

F.He et al., Nanotechnology 32,085505(2021)

引力波的探测
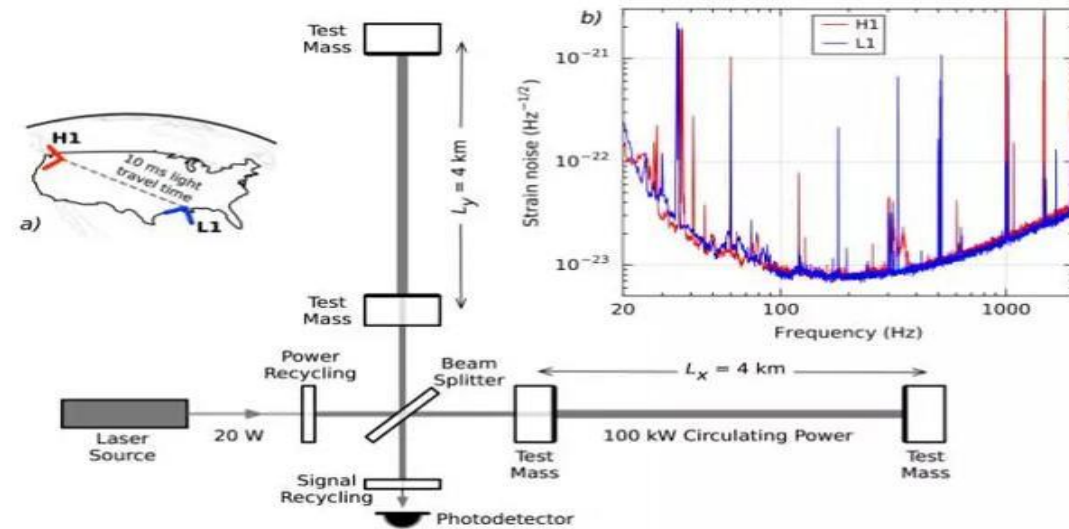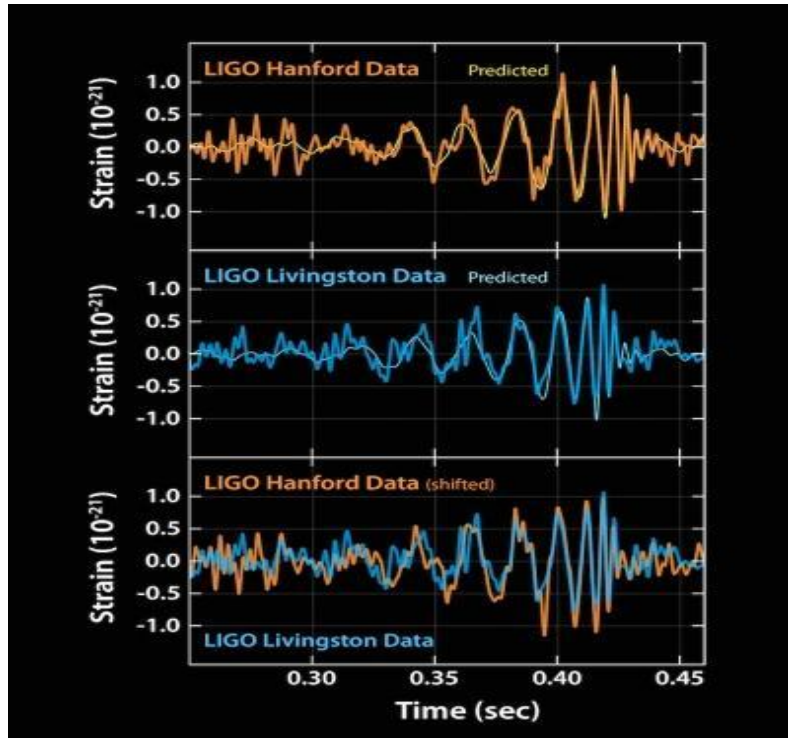
LIGO gravitational wave detector(Nobel Prize in Physics 2017)

广义相对论中引力波的两种极化方式

- 引力被时空弯是曲的一种效应，这种弯曲是因为质量的存在而导致

- 广义相对论预言，物体在空间中加速运动时，空间的曲率会不断发生变化，从而辐射出引力波

Einstein场方程

$$G_{\mu\nu} = 8\pi T_{\mu\nu},$$

Einstein 张量
（时空的几何属性）

能量-动量张量
（物质对时空的影响）

静态、各向同性
并线性化

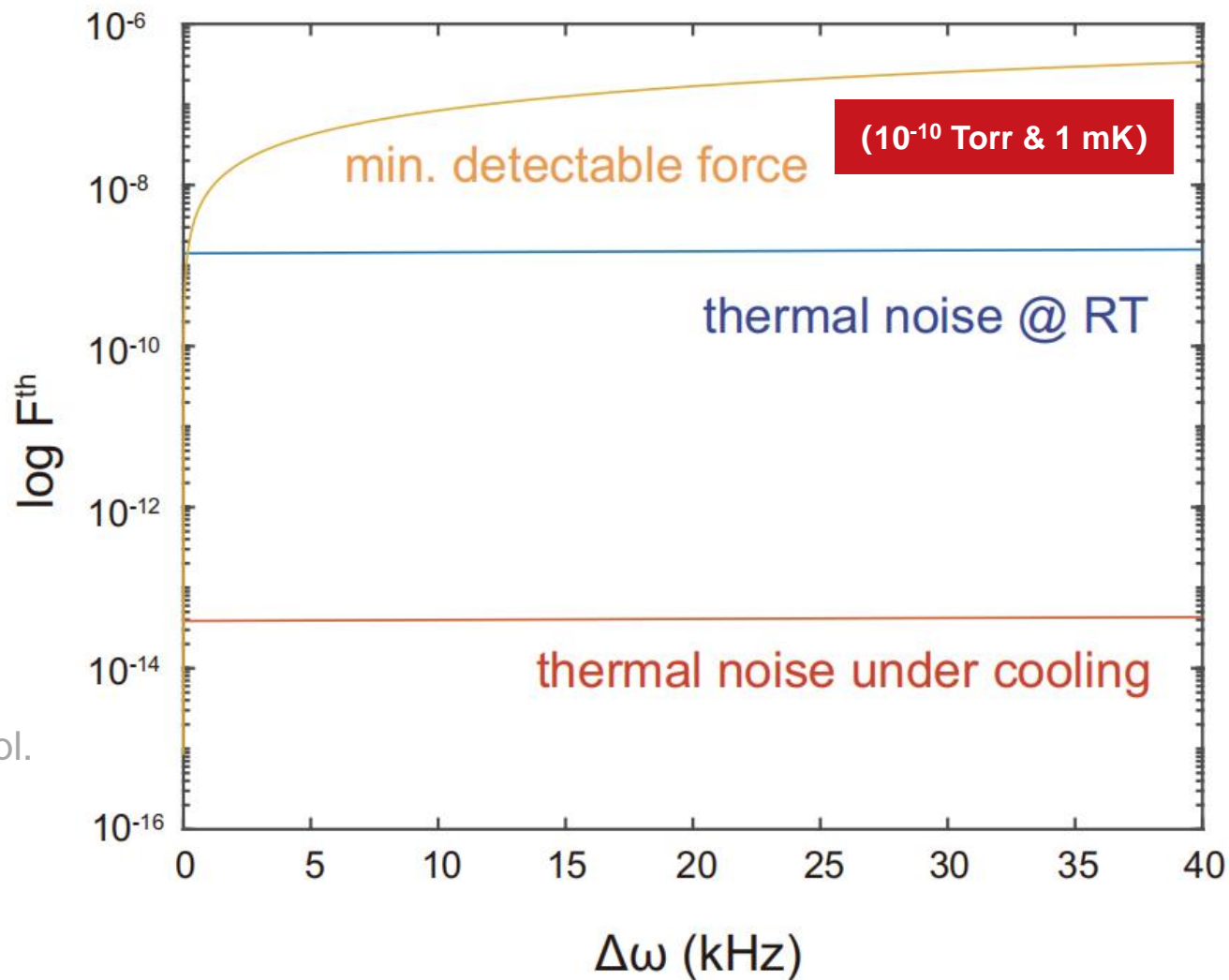$$\Box h_{\mu\nu} = 0,$$

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \epsilon_{11} & \epsilon_{12} & 0 \\ 0 & \epsilon_{12} & -\epsilon_{11} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cos\left[\Omega(t-z)\right],$$
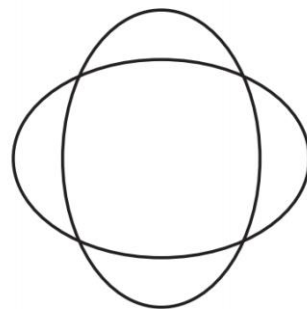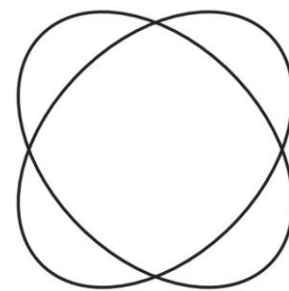
（a）加模式   （b）叉模式

引力波的探测

- 基于引力波的极化方式，可以设计激光干涉引力波探测器用来对引力波进行探测
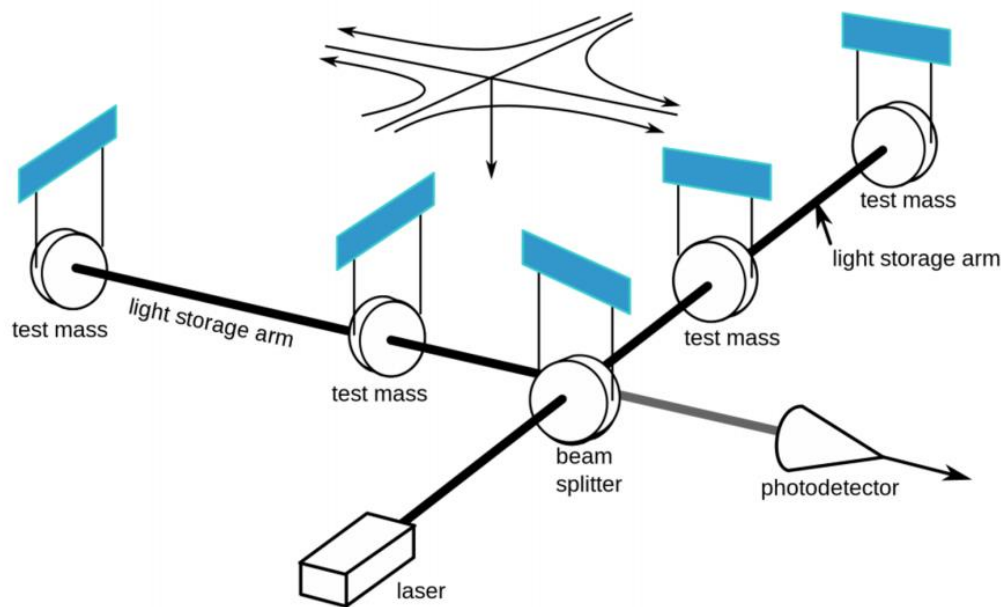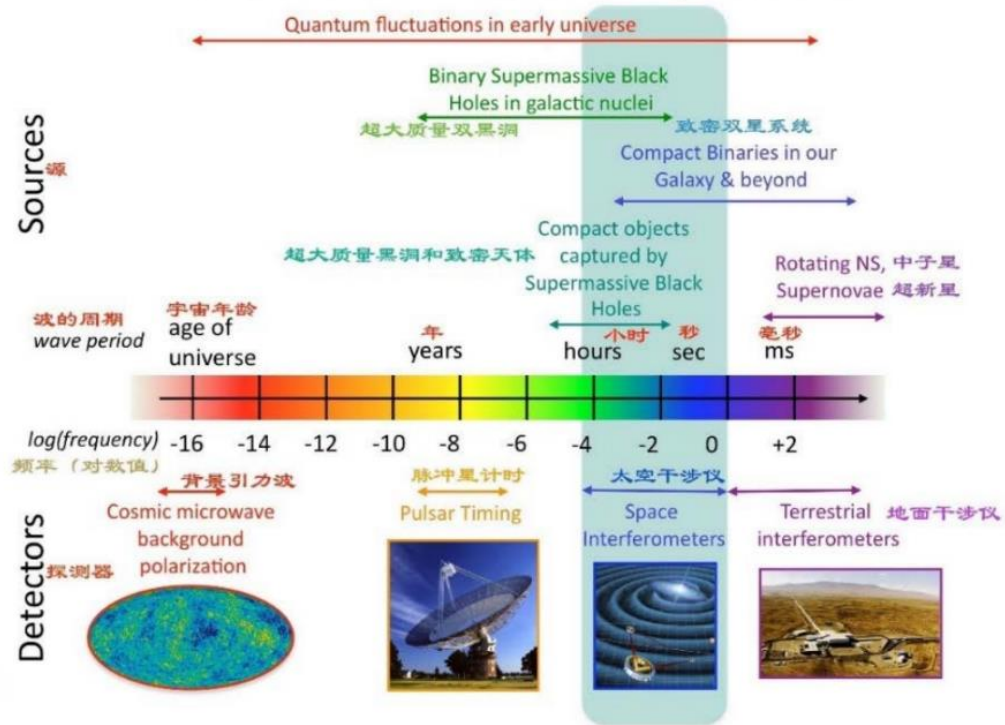
高频引力波的探测

- 黑洞的超辐射效应（BH Superradiance）导致QCD轴子湮灭为引力子产生 145 kHz 引力波
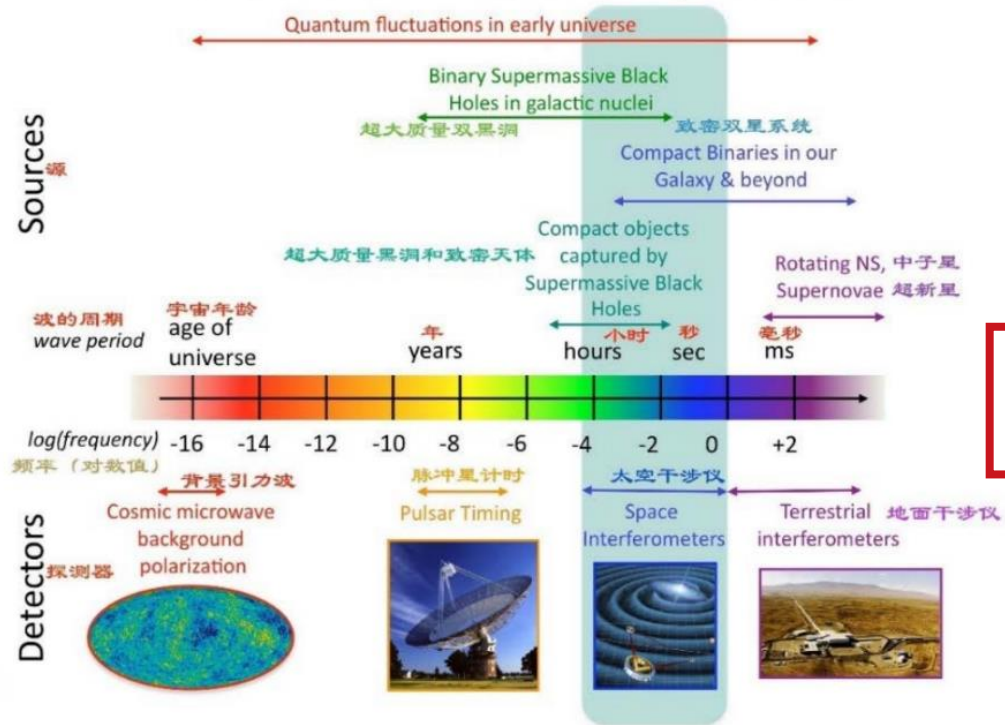
挑战

- 高频引力波探测：**难**

金刚石固态自旋与高频引力波的探测方案

金刚石氮空位色心（NV色心）：一种发光点缺陷，由一个氮原子取代碳原子并在临近形成一个空穴
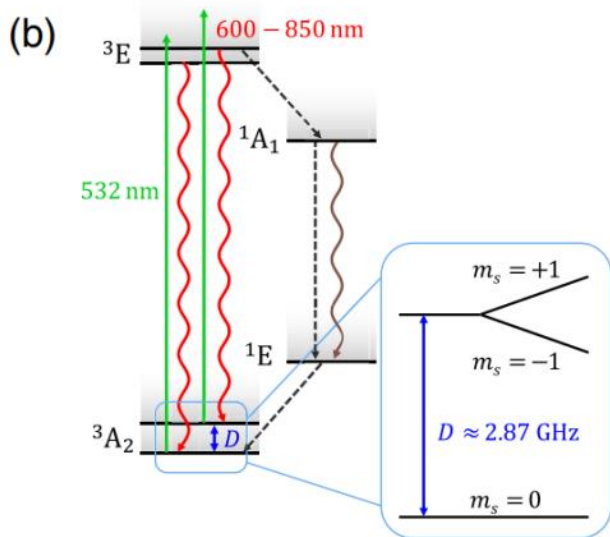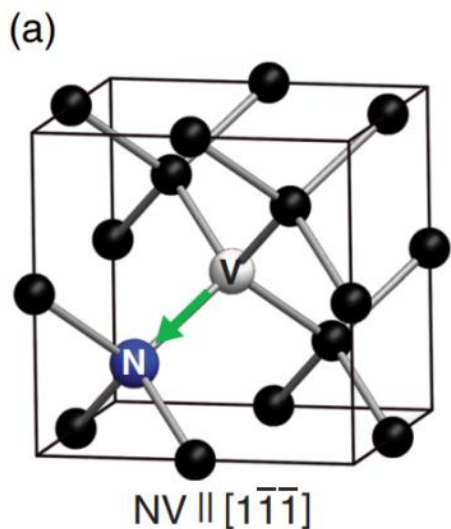
在轴向施加强磁场时，使 $|{+}1\rangle$ 与 $|{-}1\rangle$ 之间能隙减小
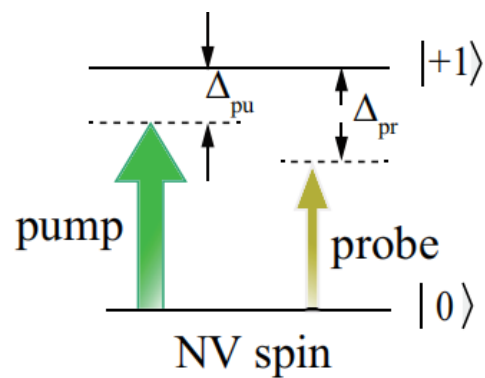
NV色心的哈密顿量

$$H_{NV} = \hbar\omega_{spin}s^z$$

23

悬浮纳米金刚石的运动分析
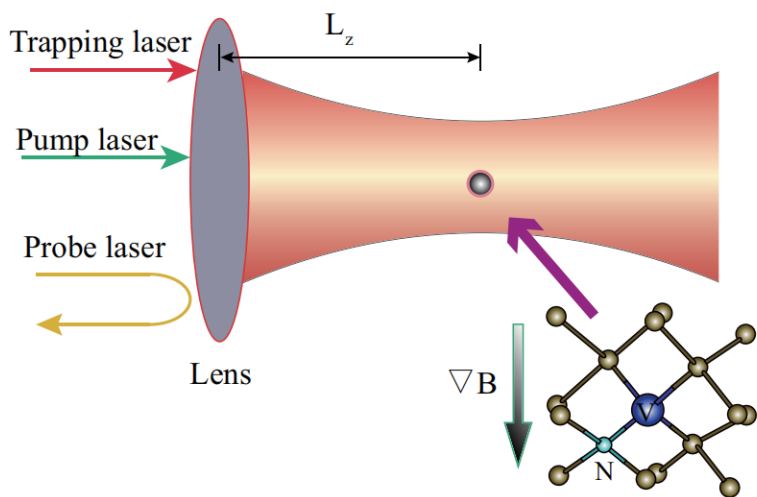
纳米金刚石振子

$$H_m = \hbar\omega_m a^\dagger a + \hbar\omega_{GW} b^\dagger b$$

◎ 纳米金刚石所受的梯度力：

$$\langle \vec{F}_g \rangle = -\alpha E_0^2(x, z; t) \begin{pmatrix} \dfrac{x z_0^2}{w_x^2(z^2+z_0^2)} \\ \dfrac{z}{2(z^2+z_0^2)} - \dfrac{z x^2 z_0^2}{w_x^2(z^2+z_0^2)^2} \end{pmatrix},$$

$$\omega_m = \left(\frac{2\alpha\pi^3 N A^6 P}{m\lambda^4 c\,\epsilon_0} \right)^{1/2}$$

◎ 引力波对纳米金刚石施加的简谐驱动力：

$$\langle F_{GW} \rangle = -\frac{m\omega_{GW}^2}{2} h_{GW} L_z \cos(\omega_{GW}t + \Phi).$$

◎ 运动方程为 $\ddot{Z} + 2\omega_m\zeta\dot{Z} + \omega_m Z = \dfrac{\langle F_{GW} \rangle}{m}$

◎ 进一步求解得到

$$Z = e^{-\omega_m\zeta t}(C_1\cos\omega_d t + C_2\sin\omega_d t) + H\sin(\omega_{GW}t + \phi),$$

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悬浮光力学模型构建

- 引入强泵浦激光（λ_{pu}=532 nm）激发 NV 色心，光场为

$$H_{opt} = -i\hbar\Omega_p(s - s^+) - i\hbar\Omega_r(se^{i\delta t} - s^+e^{-i\delta t})$$

- NV色心与振动模的耦合为

$$H_{NV-m} = \hbar\beta(a^\dagger + a)s^z + \hbar\lambda(b^\dagger + b)s^z$$

- 将系统做旋转波近似，

$$H = \hbar\Delta_p s^z + \hbar\omega_m a^\dagger a + \hbar\omega_{GW} b^\dagger b + \hbar\beta(a^\dagger + a)s^z + \hbar\lambda(b^\dagger + b)s^z$$

$$- \hbar(\Omega_p s^+ + \Omega_p^* s^-) - \hbar(\Omega_r s^+ e^{-i\delta t} + \Omega_r^* s^- e^{i\delta t}).$$

Trapping laser

Pump laser

Probe laser

Lens

L_z

∇B

N

S J T U
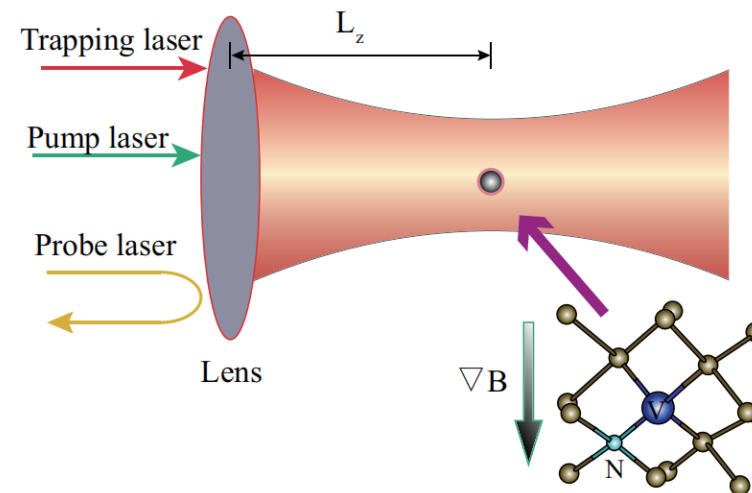
悬浮光力学模型解析

$$H = \hbar\Delta_p s^z + \hbar\omega_m a^\dagger a + \hbar\omega_{GW} b^\dagger b + \hbar\beta(a^\dagger + a)s^z + \hbar\lambda(b^\dagger + b)s^z$$

$$- \hbar(\Omega_p s^+ + \Omega_p^* s^-) - \hbar(\Omega_r s^+ e^{-i\delta t} + \Omega_r^* s^- e^{i\delta t}).$$

系统的演化的动力学 $i\hbar\frac{d\hat{O}}{dt} = [\hat{O}, \mathcal{H}]$

$$[c, c^\dagger] = 1 \qquad [q, p] = i$$

Langevin方程

**线性光学极化率
相关的参数
实部：吸收谱**

$$\chi^{dim} = \frac{\Gamma_2(\mathfrak{E}^*\mathfrak{M} - n_0\mathfrak{N})}{\mathfrak{P}\mathfrak{N} + \Omega_p\mathfrak{M}(\beta^2\eta_m + \lambda^2\eta_{GW})}.$$

$$\frac{ds^z}{dt} = -\Gamma_1\left(s^z + \frac{1}{2}\right) + i(\Omega_p s^+ - \Omega_p^* s^-) + i(\Omega_r s^+ e^{-i\delta t} - \Omega_r^* s^- e^{i\delta t});$$

$$\frac{ds^-}{dt} = -(i\Delta_p + \Gamma_2)s^- - i(\beta N_1 + \lambda N_2) - 2i\Omega_p s^z - 2i\Omega_r e^{-i\delta t}s^z + \hat{f}_{noise};$$

$$\frac{d^2 N_1}{dt^2} + \gamma_m \frac{dN_1}{dt} + \omega_m^2 N_1 = -2\omega_m\beta s^z + \xi_1(t);$$

$$\frac{d^2 N_2}{dt^2} + \gamma_{GW} \frac{dN_2}{dt} + \omega_{GW}^2 N_2 = -2\omega_{GW}\lambda s^z + \xi_2(t).$$

悬浮光力学模型解析

- 选取合理实验参数，计算吸收特性

- 热噪声对探测器的限制 $F_{min} = [4k_B T_{eff} m \Delta f \gamma_m]^{1/2}$

$$h_{min} = \frac{2}{L_z} \sqrt{\frac{4 m k_B T_{eff} \gamma_m \Delta f}{m^2 (\omega^2 - \omega_m^2)^2 + \gamma_m^2 \omega^2}}.$$

a

FWHM~ 5×10^{-10} KHz,
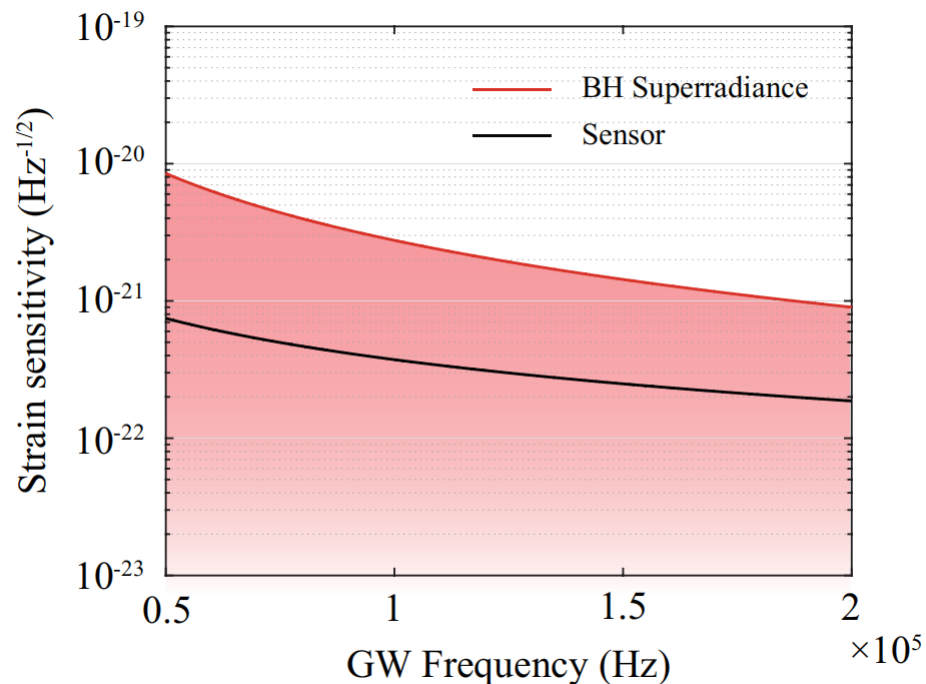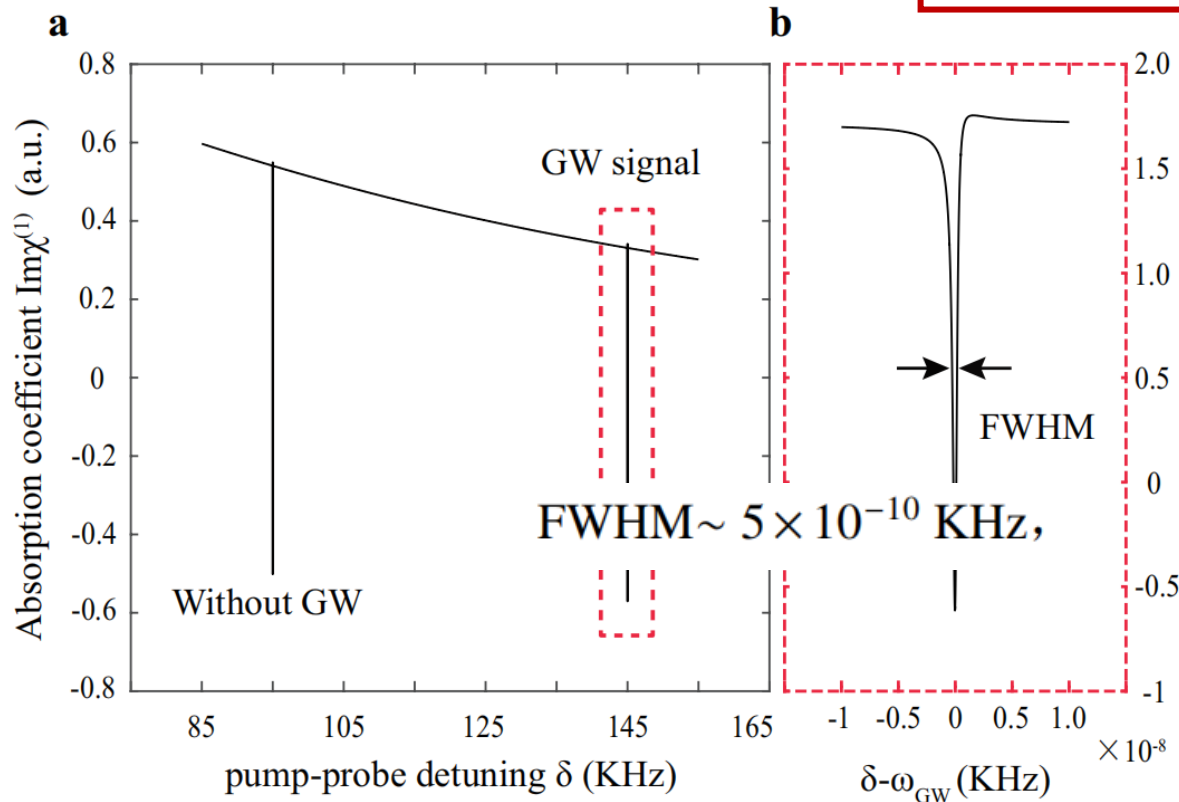
暗能量的探测
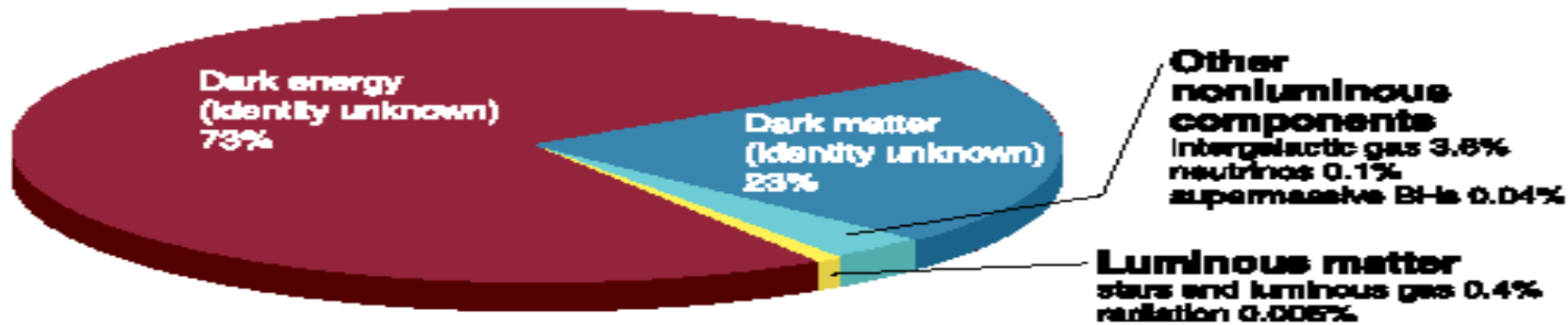
Ostriker & Steinhardt, Science 300, 1909(2003).

暗能量：73%
暗物质：23%
发光物质：0.4%（恒星和发光气体0.4%；辐射0.005%）
不可见的普通物质：3.7%（星系际气体3.6%；中微子0.1%；超重黑洞0.04%）

3.3、利用悬浮腔光力学系统测量暗能量的光学方案

$$H = \hbar\Delta_{pu}\hat{a}^{+}\hat{a} + \hbar\omega_1\hat{o}_A^{+}\hat{o}_A + \hbar\omega_2\hat{o}_B^{+}\hat{o}_B + \hbar g\hat{a}^{+}\hat{a}(\hat{o}_A^{+} + \hat{o}_A)$$
$$- i\hbar\Omega_p(\hat{a} - \hat{a}^{+}) - i\hbar\Omega_{pr}(\hat{a}e^{i\delta t} - \hat{a}^{+}e^{-i\delta t}) + H_{int},$$

Chameleon potential energy

$$V(r) = -\lambda_i^2 \frac{M_i^2}{4\pi M^2} \frac{e^{-r/R_{vac}}}{r},$$

with

$$\lambda_i = \begin{cases} 1 & screened \\ 3M\phi_{vac}/\rho_i R_i^2 & unscreened. \end{cases}$$

M_i : Mass of the microspheres
ρ_i : Density of the microspheres
r : Separation between the microspheres
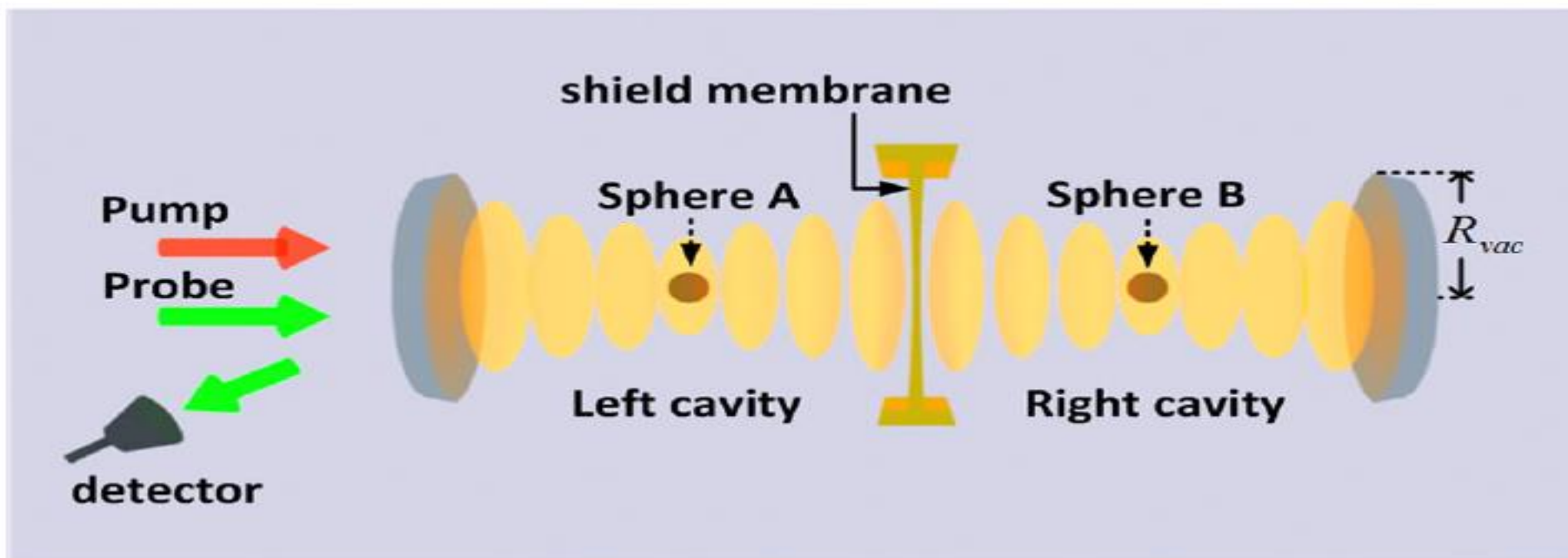R_{vac} : Radius of the cavity mirror
ϕ_{vac} : background value in the vacuum cavity
M : Interaction strength of chameleon particles with ordinary matter of density
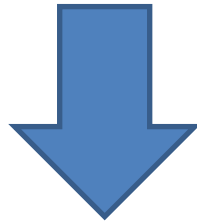
Chameleon induced coupling

$$H_{int} = -\lambda_i^2 \frac{M_i^2}{2\pi M^2 r_0^3} \vec{x_1}\vec{x_2} \approx \hbar\Psi(\hat{o}_A^+\hat{o}_B + \hat{o}_A\hat{o}_B^+),$$

and

$$\Psi = -\frac{\lambda_i^2}{2\pi} \frac{M_i^2}{M^2} \frac{1}{r_0^3 \sqrt{M_i^2}\sqrt{\omega_i^2}} = -\frac{\lambda_i^2}{2\pi\omega_i r_0^3} \frac{M_i}{M^2}.$$

Methods

Master equations:

$$\frac{d\langle \hat{a}\rangle}{dt} = -(i\Delta_{pu} + \kappa)\langle \hat{a}\rangle + ig\langle S_A\rangle\langle \hat{a}\rangle$$
$$+ \Omega_p + \Omega_{pr}e^{-i\delta t},$$

$$\frac{d^2\langle s_A\rangle}{dt^2} + \gamma_1\frac{d\langle s_A\rangle}{dt} + (\omega_1^2 + \Psi^2)\langle s_A\rangle - \Psi(\omega_1 + \omega_2)\langle s_B\rangle$$
$$= 2g\omega_1\langle \hat{a}^+\rangle\langle \hat{a}\rangle,$$

$$\frac{d^2\langle s_B\rangle}{dt^2} + \gamma_2\frac{d\langle s_B\rangle}{dt} + (\omega_2^2 + \Psi^2)\langle s_B\rangle - \Psi(\omega_1 + \omega_2)\langle s_B\rangle$$
$$= -2g\Psi\langle \hat{a}^+\rangle\langle \hat{a}\rangle.$$

Ansatz:

$$\langle \hat{a}(t)\rangle = a_0 + a_+e^{-i\delta t} + a_-e^{i\delta t},$$
$$\langle s_A(t)\rangle = s_{A0} + s_{A+}e^{-i\delta t} + s_{A-}e^{i\delta t},$$
$$\langle s_B(t)\rangle = s_{B0} + s_{B+}e^{-i\delta t} + s_{B-}e^{i\delta t}.$$

$$a_+ = \Omega_{pr} \frac{Z(\Gamma - \chi) + U\omega_0}{Z(\Gamma^2 - \chi^2) + 2\chi U\omega_0},$$

$$\Omega_{pu}^2 = [\kappa^2 + (\Delta_{pu} - gS_{A0})^2]\omega_0,$$

with $\Gamma = \kappa - i\delta$, $\chi = i\Delta_{pu} - igs_{A0}$, $Y_j = -\delta^2 - i\gamma_i\delta + \omega_i^2 + \Psi^2$ ($i = 1, 2$), $Z = Y_1 Y_2 - \Psi^2(\omega_1 + \omega_2)^2$, $U = 2ig^2\omega_1 Y_2 - 2ig^2\Psi^2(\omega_1 + \omega_2)$ and s_{A0}, s_{B0} can be resolved by

$$(\omega_1^2 + \Psi^2)s_{A0} - \Psi(\omega_1 + \omega_2)s_{B0} = 2g\omega_1\omega_0,$$

$$(\omega_2^2 + \Psi^2)s_{B0} - \Psi(\omega_1 + \omega_2)s_{A0} = -2g\Psi\omega_0.$$

The transmission of the probe beam:

$$t(\omega_{pr}) = \frac{\Omega_{pr}/\sqrt{2\kappa} - \sqrt{2\kappa}a_+}{\Omega_{pr}/\sqrt{2\kappa}} = 1 - 2\kappa a_+/\Omega_{pr}.$$
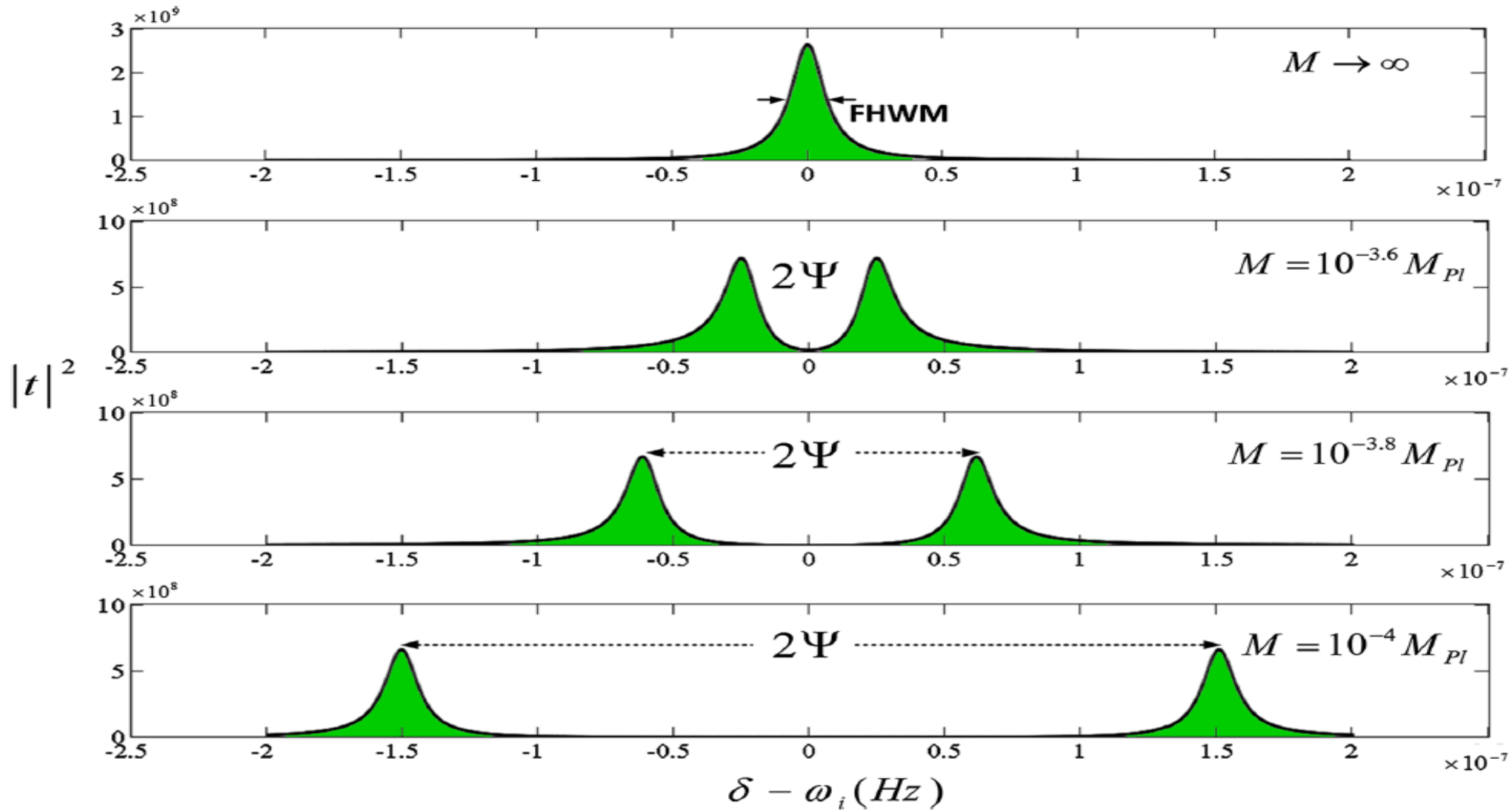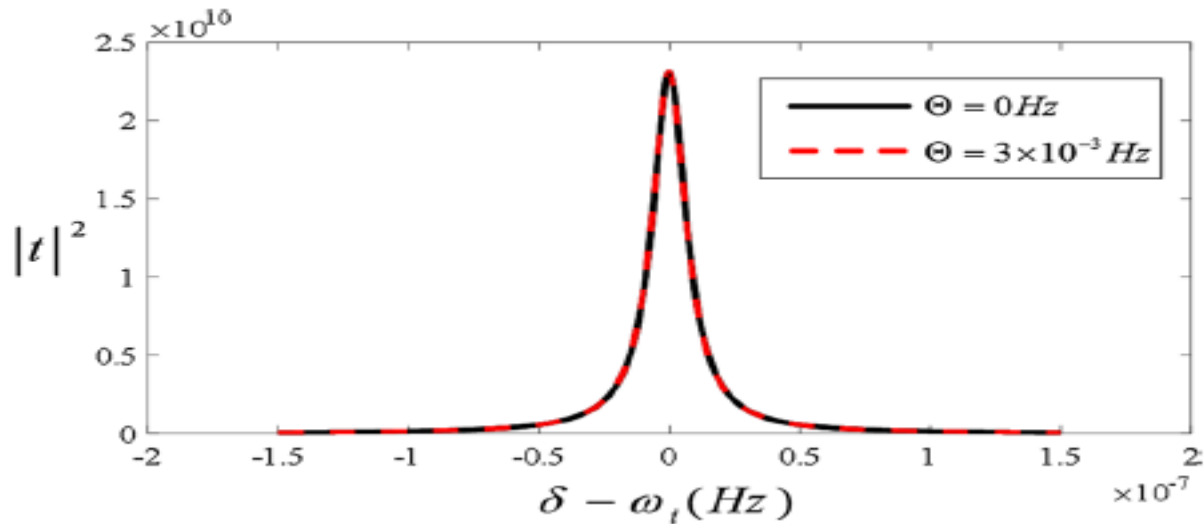
Chameleon induced splitting

Fig. 2 The plot of the probe transmission spectrum as a function of detuning $\delta - \omega_i$ with different chameleon -matter coupling strength M in the conditions of $r_i = 3\ \mu m$, $r_0 = 80\ \mu m$. The peak splitting caused by chameleon coupling between objects Ψ can be well recognized in the spectrum. The other parameters are $\omega_i = 100$ kHz, $g = 0.25$ Hz, $\kappa = 5 \times 10^8$ Hz, $\Omega_p = 1$ THz

Electrostatic force bacground noise and optomechanical screen

$$H_E = -\frac{\mu_i \mu_s}{\pi \varepsilon_0 d_0^5} \vec{x_1} \vec{x_s} \approx -\hbar \Theta(\hat{o}_A^+ \hat{o}_S + \hat{o}_A \hat{o}_S^+),$$

and

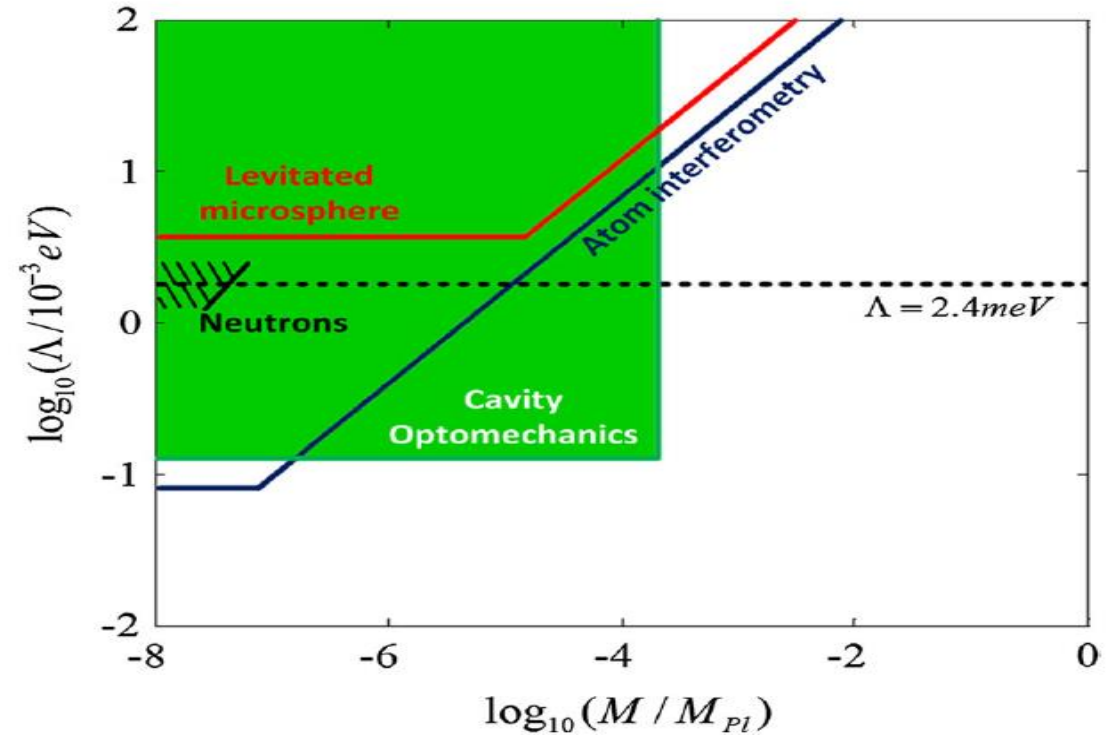$$\Theta = -\frac{\mu_i \mu_s}{\pi \varepsilon_0 d_0^5} \frac{1}{\sqrt{M_i M_s}\sqrt{\omega_i \omega_s}},$$

4.4 Constraints

The dipole-dipole coupling can't induce an optomechanical splitting on the spectrum in the condition of

$$\omega_s \neq \omega_i$$

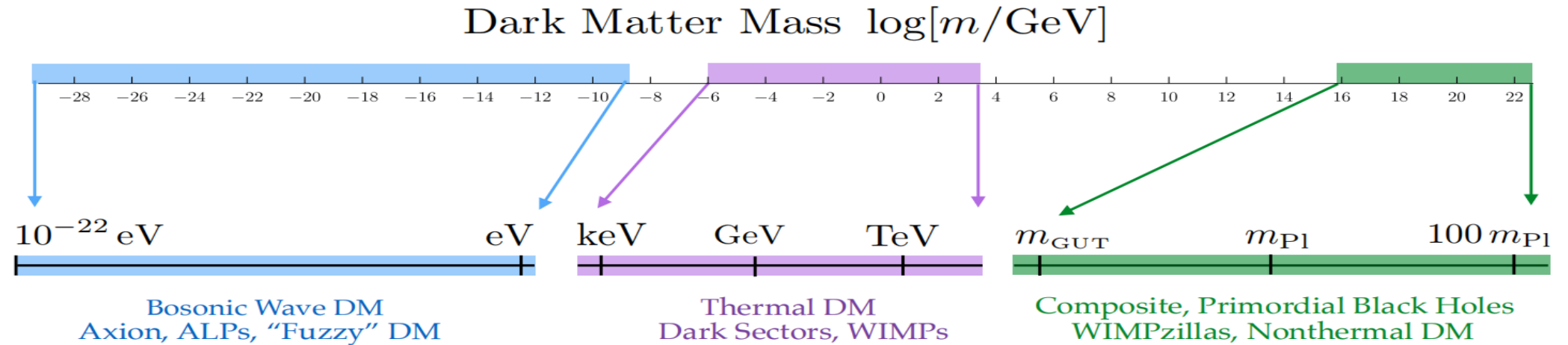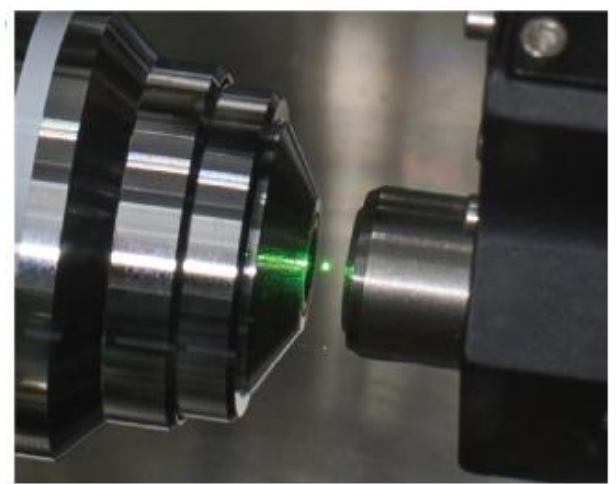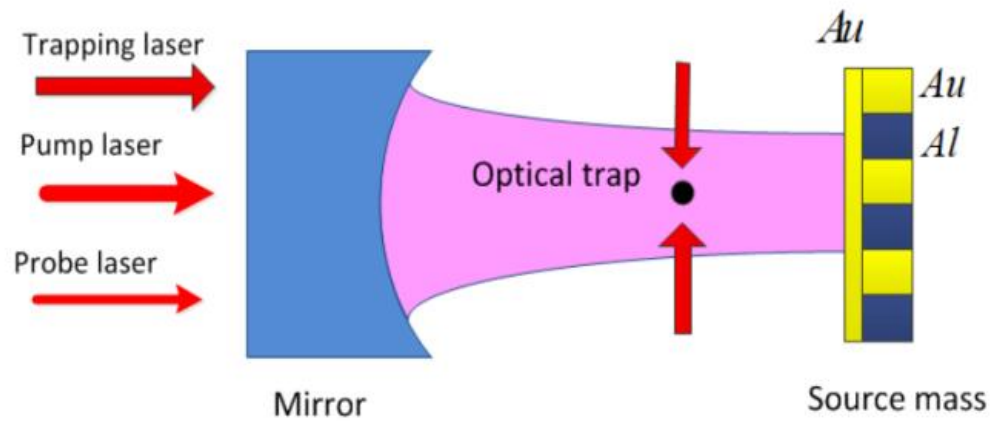**J.Liu and K.D.Zhu, Eur. Phys. J. C 78, 266 (2018)**

暗物质的探测

FIG. 1. *Range of available dark matter candidates.* Current observations allow for dark matter to consist of quanta with an enormous range of masses. Here we classify these candidates as particle-like when $m \gtrsim 1$ eV, and ultralight, wave-like dark matter when $m \lesssim 1$ eV. A few prototypical models are listed as examples.

Mechanical quantum sensing in the search for dark matter, D.Carney, et al., Quantum Sci.Technol.6, 024002 (2021).

图 8-1 装置的示意图。二氧化硅纳米球被俘获在由镜和源质量组成的腔中。涂有金层的金和铝交替构成的部分组成源质量。

提出了一种新的量子光力学的方法探测暗物质轴子-核子相互作用和非牛顿引力约束的光学方案。一个由二氧化硅纳米球和光腔组成的悬浮光力学系统，在该系统中，纳米球受到一个梯度力的作用，这个梯度力改变了纳米球的共振频率。

3.4、基于悬浮腔光力系统暗物质轴子和核子间相互作用和非牛顿引力的光学探测

$$V(r) = -\frac{g_{ak}^2 g_{al}^2}{32\pi^3 m^2}\frac{m_a}{r^2}K_1(2m_a r),$$

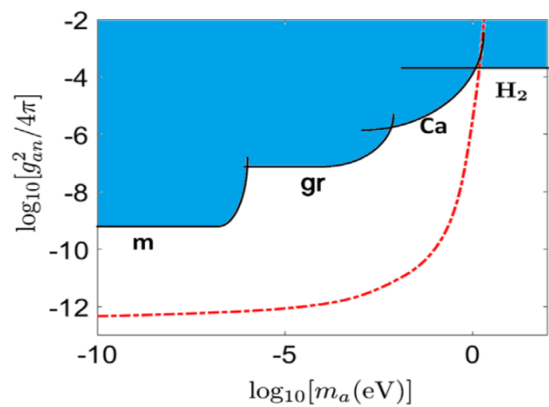$$V_{Yu}(r) = -G_N\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right).$$

FIG. 5. Constraints on the constant of axion-neutron interaction under the condition $g_{an}^2 = g_{ap}^2$ from the measurement of changes in the precession frequency [16] (line "m"), from the search for violations of the gravitational inverse-square law [17,18] (line "gr"), from a Casimir-less experiment [19,20] (line "Ca"), from measuring the forces between protons [34,35] (line "H$_2$"), and from our work (dashed red curve). The blue region is excluded.
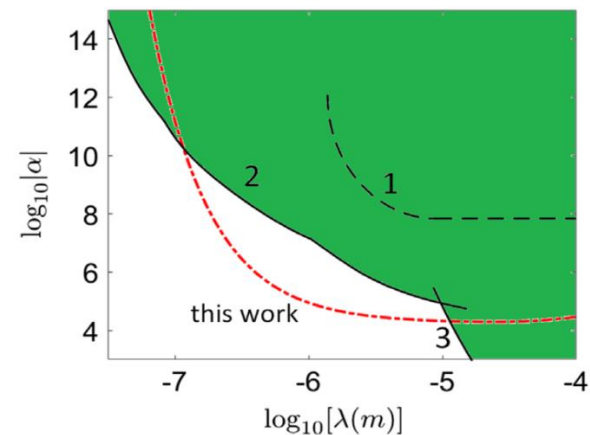
FIG. 6. Limit curve in the $\alpha - \lambda$ parameter space. Constraints were established via an optically levitated microsphere [68] (line 1), differential force measurements [20] (line 2), and torsion-balance experiments [18] (line 3). The dashed red curve represents our work. The green region is excluded.

基于该系统实现了暗物质轴子-核子相互作用和非牛顿引力的探测和新的约束，建立了轴子-核子耦合常数和Yukawa相互作用常数新的预期约束，这些新约束显著改善了现有的实验界限。(Constraining the axion-nucleon coupling and nonNewtonian gravity with a levitated optomechanical device, L.Chen et al.,Phys.Rev.D 106, 095007 (2022))

3.5、基于光力系统透射简并点的传感器

一般认为，用光谱对系统(图中以球形微腔为例)进行测量时，光谱的波峰/波谷位置对应着系统的特征值(即共振频率)实部，而谱线宽度对应着系统的特征值虚部。

在**Q.Geng&K.D.Zhu,Photonics Research 9, 1645(2021)**中，我们指出上述认知并不总是成立的。
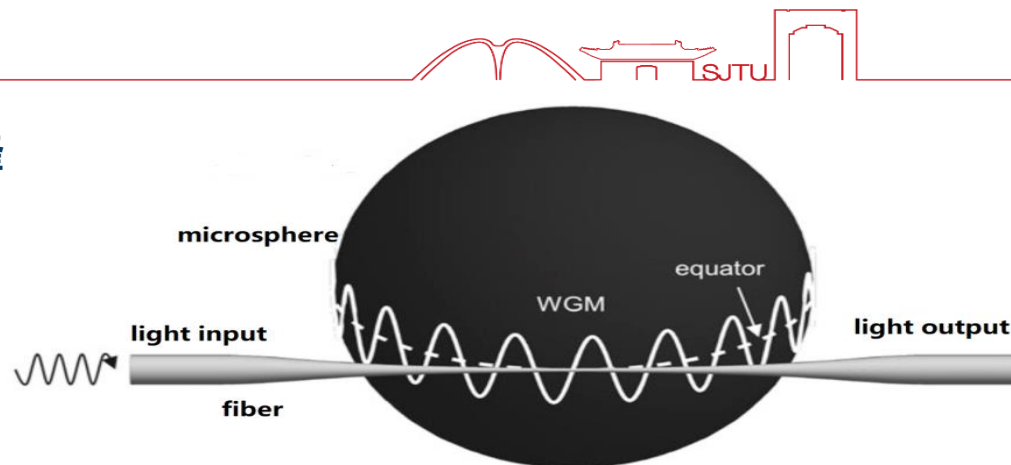
考虑一个双模模型（**Opt. Lett. 27, 1669 (2002)**），其哈密顿量为：

$$H = \begin{pmatrix} w_1 - i\kappa_1/2 & g \\ g & w_2 - i\kappa_2/2 \end{pmatrix}$$
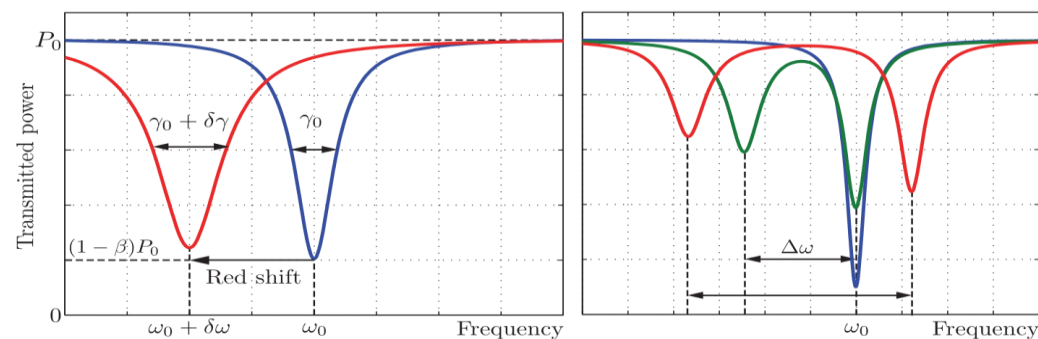
的系统，假设入射光场直接和第一个模式相作用，得到其对应的**振幅透射率**：

$$t = \frac{(w-\lambda_1)(w-\lambda_2) - i\kappa_{ex}(w-w_2+i\kappa_2)}{(w-\lambda_1)(w-\lambda_2)}$$

其中w是入射光频率，$\lambda_{1,2}$是H的**两个特征值**，κ_{ex}是光纤和球形微腔之间的耦合率。

我们指出：**透射谱波谷的位置对应于t分子部分的根，而不是特征值(分母部分的根)。**

**基于球形微腔的传感器：**当球形微腔受力或受热发生形变，或者在球形微腔表面放置微粒时，其共振频率会出现变化，并反映在谱线上。

外界条件的变化会使波谷频率和线宽发生变化（左图); 也可能使谱线发生劈裂（右图）。 通常被认为波谷的位置对应着系统的特征值实部，而线宽对应着特征值虚部。

3.5、基于光力系统透射简并点的传感器

Wiersig等人建立了基于EP的传感器的理论 （ Phys. Rev. Lett. 112, 203901 (2014)， Nature 548, 192(2017)等），其特征为谱线分裂大小与微扰的平方根成正比，所以在微扰较小值对应着较大的谱线分裂，使得可以测量比线宽极限更小的微扰。

类似于基于特征值简并点(即透射率分母有重根，**EP点**)附近的传感器，我们可以设想构建在**透射率分子部分重根附近的传感器**，我们基于这样**透射简并点**的测量光学方案具有类似的性质。

近年来对**EP传感器**是否具有更高信噪比进行了大量研究。最近，美国的Kottos研究组 （**Nature, 607, 697 (2022)**） 的加速度传感器实验工作引用了我们的工作，将我们提出的分子简并点称为**透射简并点**。该文作者们指出，**在透射简并点处拥有更高的信噪比**。
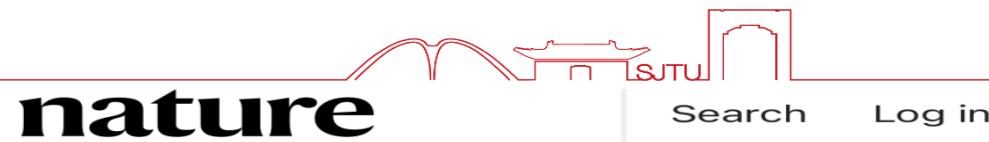
Exceptional-point-based accelerometers with enhanced signal-to-noise ratio

Rodion Kononchuk, Jizhe Cai, … Tsampikos Kottos ✉ + Show authors

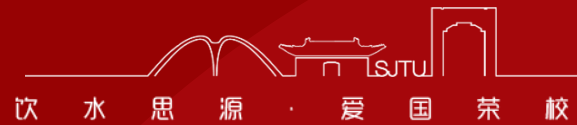which analysed the lasing modes detuning of a system in the proximity of an EP. Instead, our protocol relies on a distinction between EPs and the transmission peak degeneracies (TPDs) observed in the transmission spectrum of the $\mathcal{PT}$-symmetric sensor when it is interrogated via weakly coupled transmission lines (TLs). This fact has been already recognized in a previous theoretical work[29] for the analogous concept of transmission dips. We point out that in the absence of loss and gain, these transmission dips (or peaks in our case) and their associated degenerate point are related to the recently established concept of reflectionless scattering modes, which might exhibit an EP degeneracy[30,31]. Nevertheless, the transmission dips (peaks) and their associated TPDs in the case of $\mathcal{PT}$-symmetric systems are not directly related to the reflectionless-scattering-mode exceptional points.