基于里德堡原子的多体模拟和无线传感

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CONTENTS

研究背景

① 量子信息

② 量子通信/计算/测量

③ 量子模拟

① 量子信息

量子力学和信息科学产生了一个交叉学科

---世界研究焦点

② 量子通信/计算/测量

实现保密通信，解决复杂数学难题

实现超越经典的测量的方法

---巨大应用价值

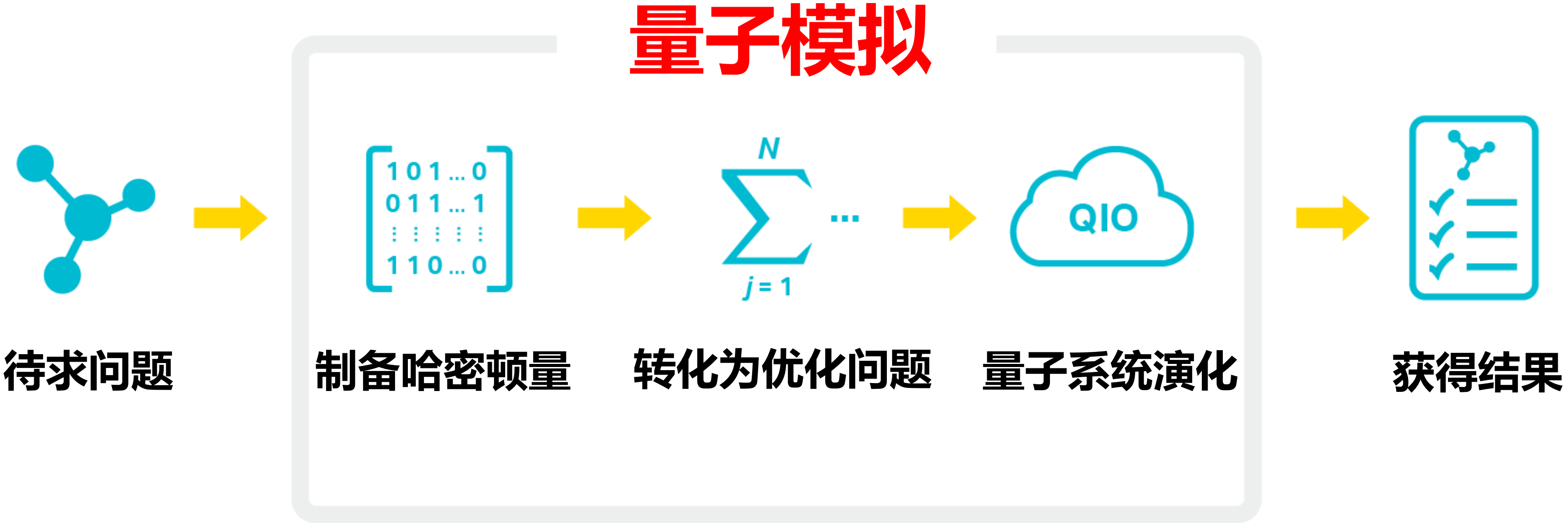
③ 量子模拟

量子计算机的雏形: 模拟自然界中的复杂问题，展现量子系统的优势。

---短期内量子计算的必经之路

研究背景

量子模拟的求解过程：

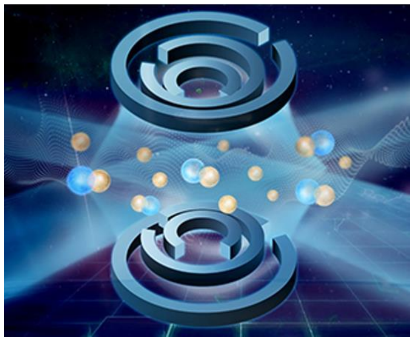
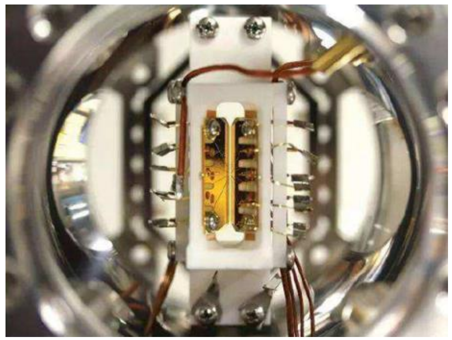


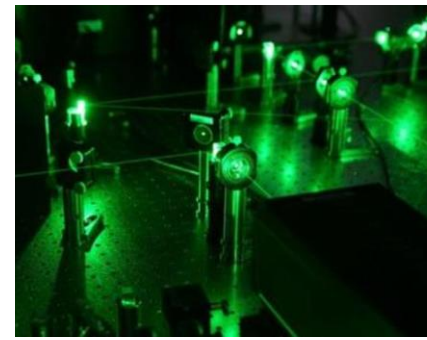
费曼猜想：创造一个人工的、符合量子规律的有效系统，使得这个有效系统所满足的量子力学方程同求解对象完全一致。通过控制这个量子系统，并在这个系统上做实验，读出实验结果即为我们所想求得的解。

研究背景

目前，潜在的量子模拟系统主要有：

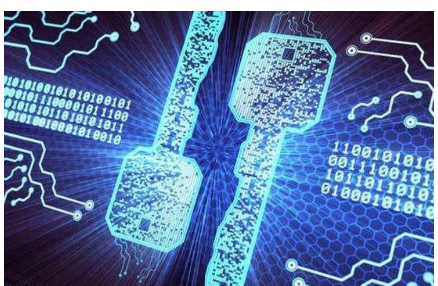
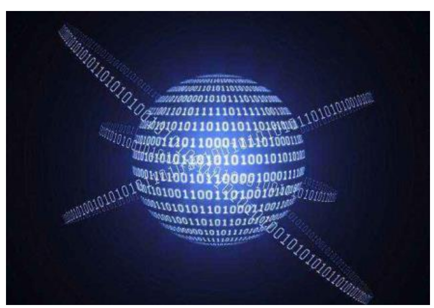
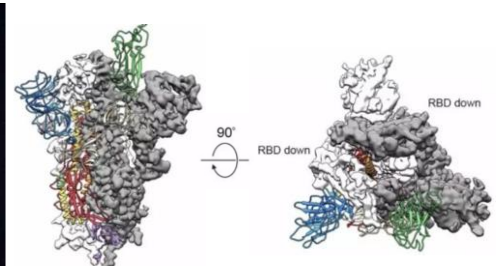
基态/Rydberg原子 离子阱 超导电路/硅基量子点 光子系统



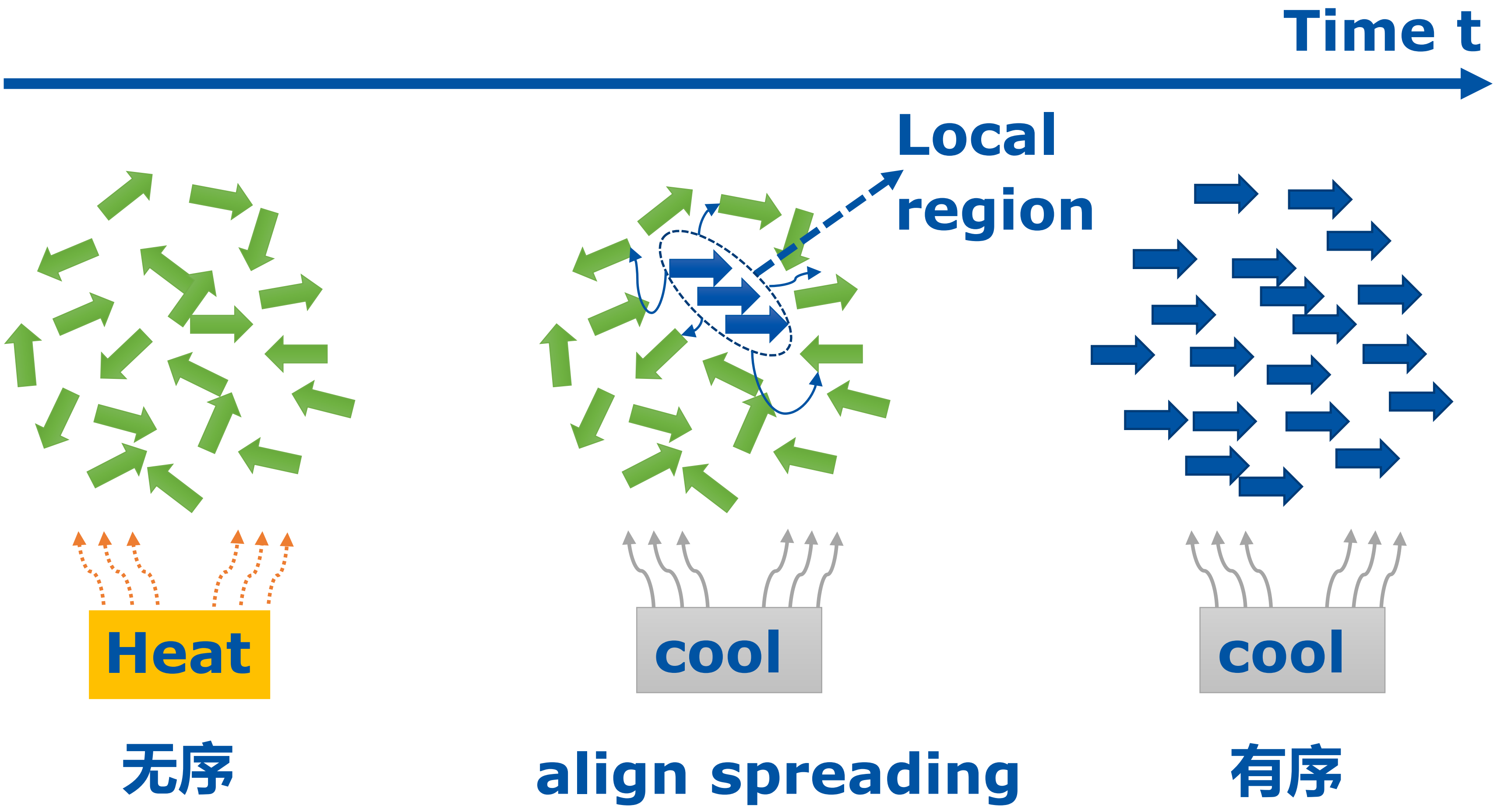
最终目标：提升运算速度，解决复杂问题

密码分析 大数据处理 药物设计 退火处理

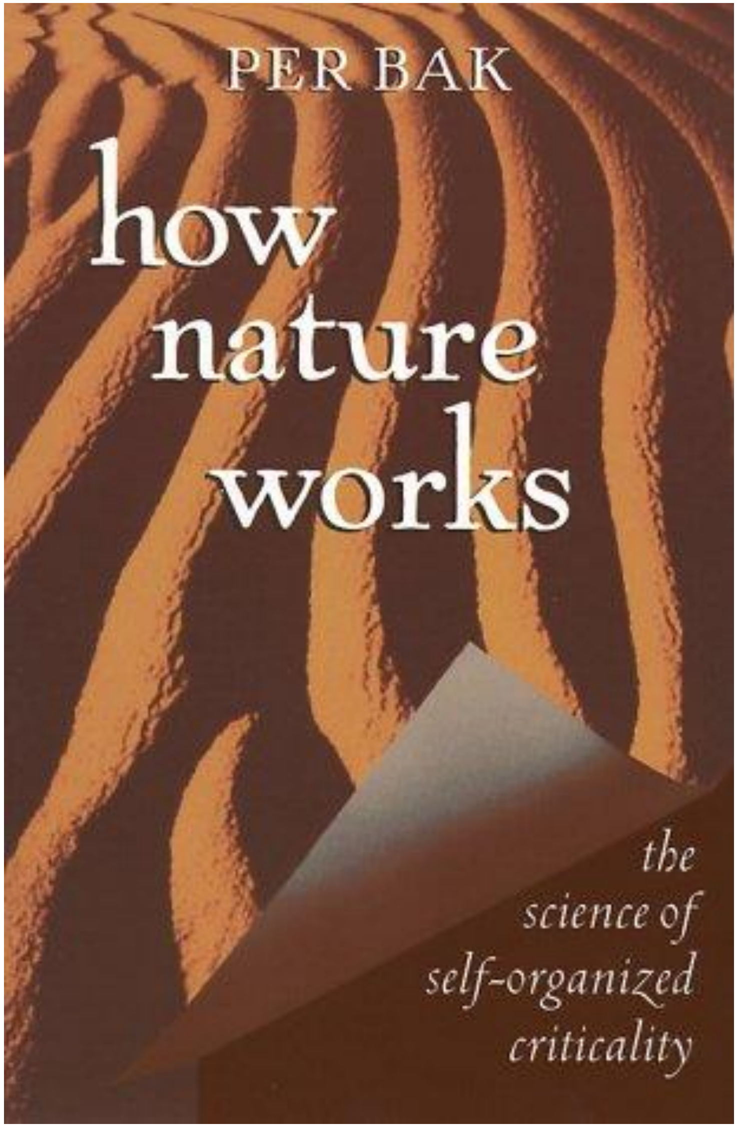




研究背景-自组织

磁化的物理过程



自组织



自组织（Self-organization）：
混沌系统在随机识别时形成耗散结构的过程

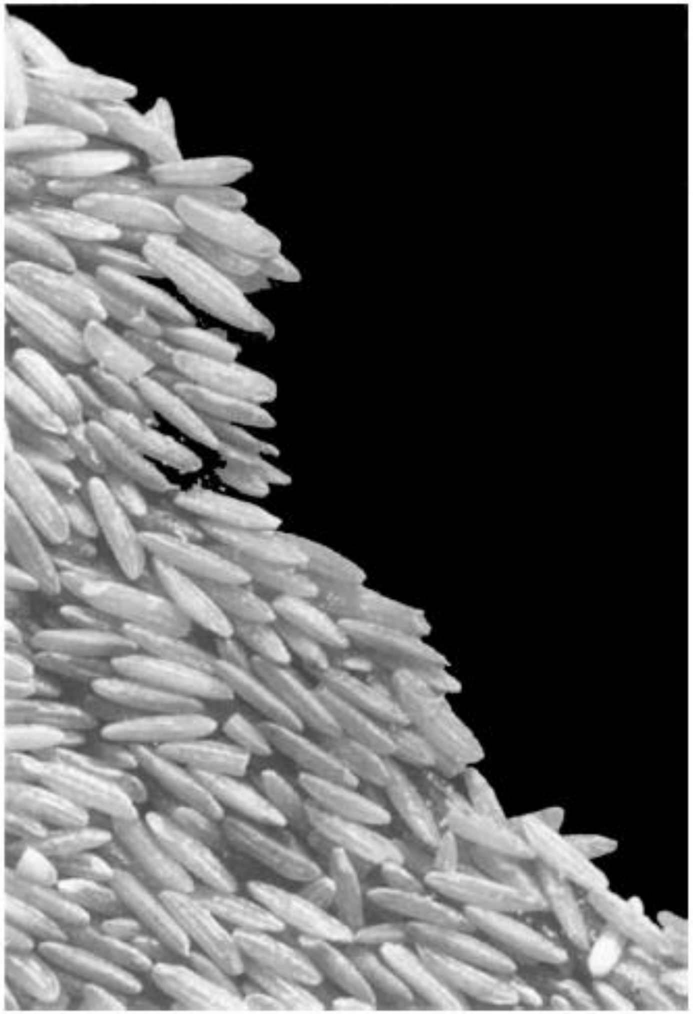
自组织临界性依赖于三个基本要素：

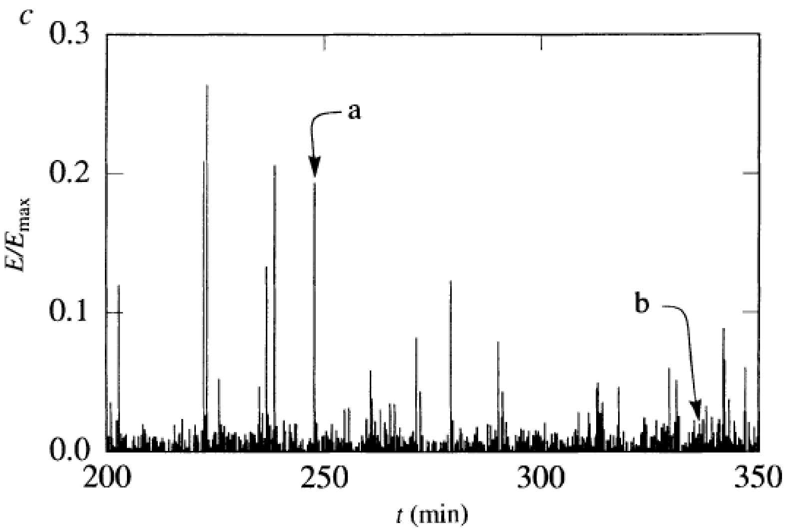
1.强非线性
2.驱动耗散平衡
3.多体相互作用

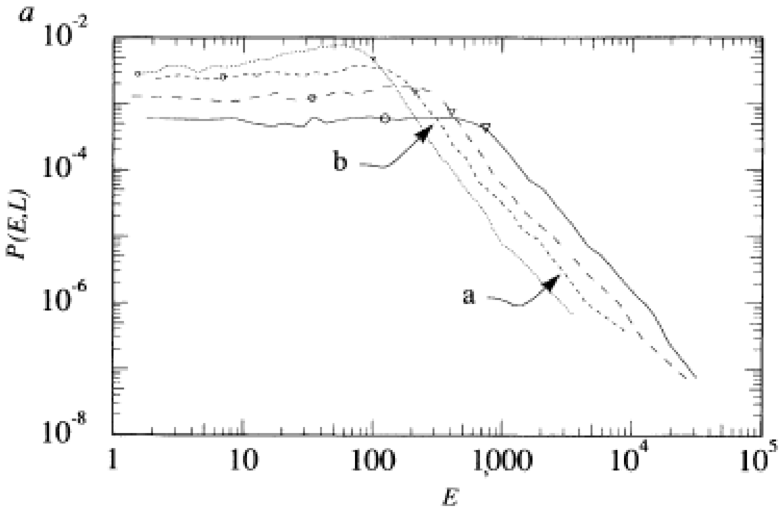
服从幂律分布的雪崩行为（特征1）
对噪声不敏感（特征2）
尺度不变性（特征3）

自组织现象

Avalanche dynamics in a pile of rice. Nature 379, 49 (1996)



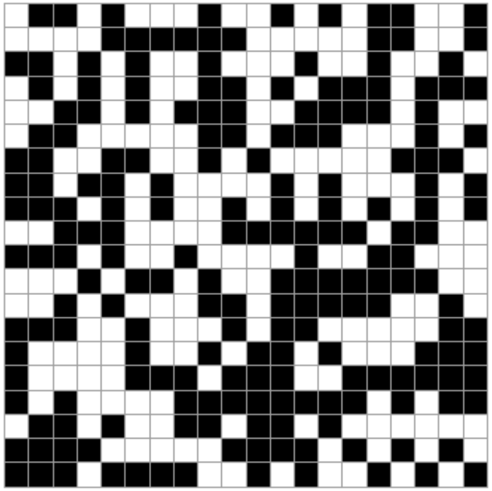


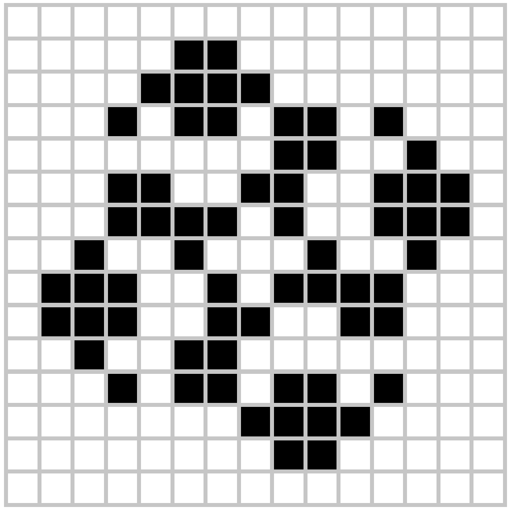


自组织现象

1. Sand pile model(沙堆模型)

2. Cellular Automata (元胞自动机)

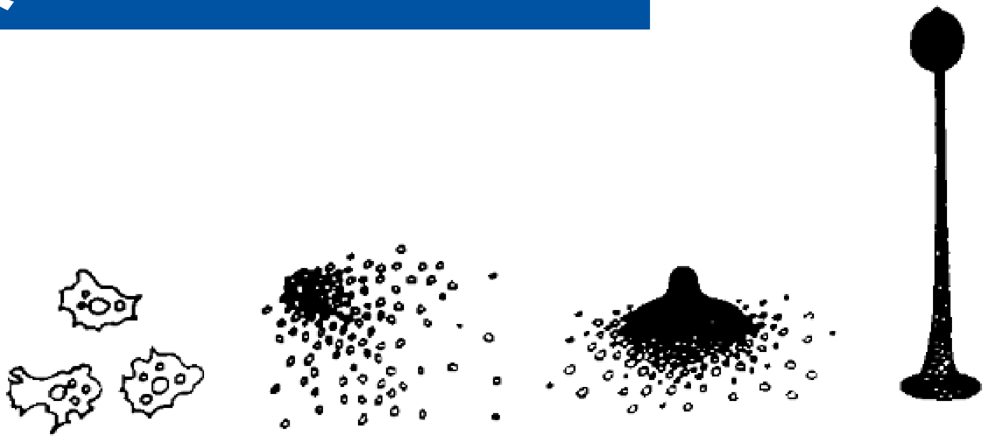




自组织现象

3. 鸟类的飞翔(集群行为)

4. 霉菌的生长



自组织模拟

- ✓ 强非线性
- ✓ 驱动耗散平衡
- ✓ 多体相互作用

- ✓ 展示计算潜力
- ✓ 能量上保持守恒
- ✓ 确保能连接所有格点

Part 1: 里德堡原子非平衡相变和相图

Dong-Sheng Ding *et al. PRX.* 10, 021023 (2020)

研究背景

Selected for a Viewpoint in *Physics*
PRL **108**, 023602 (2012) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2012

Collective Quantum Jumps of Rydberg Atoms

Tony E. Lee,[1] H. Häffner,[2] and M. C. Cross[1]
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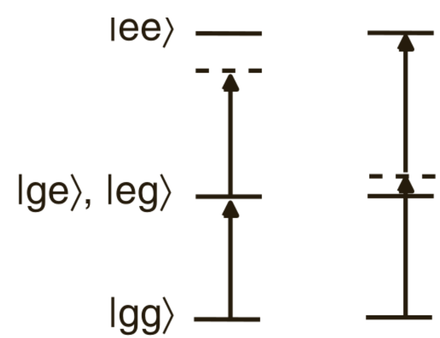
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
(Received 29 September 2011; published 9 January 2012)

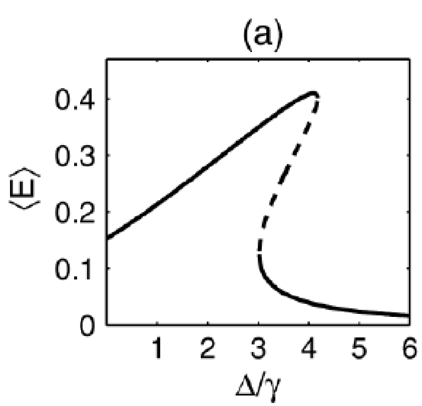
We study an open quantum system of atoms with a long-range Rydberg interaction, laser driving, and spontaneous emission. Over time, the system occasionally jumps between a state of low Rydberg population and a state of high Rydberg population. The jumps are inherently collective, and in fact, exist only for a large number of atoms. We explain how entanglement and quantum measurement enable the jumps, which are otherwise classically forbidden.

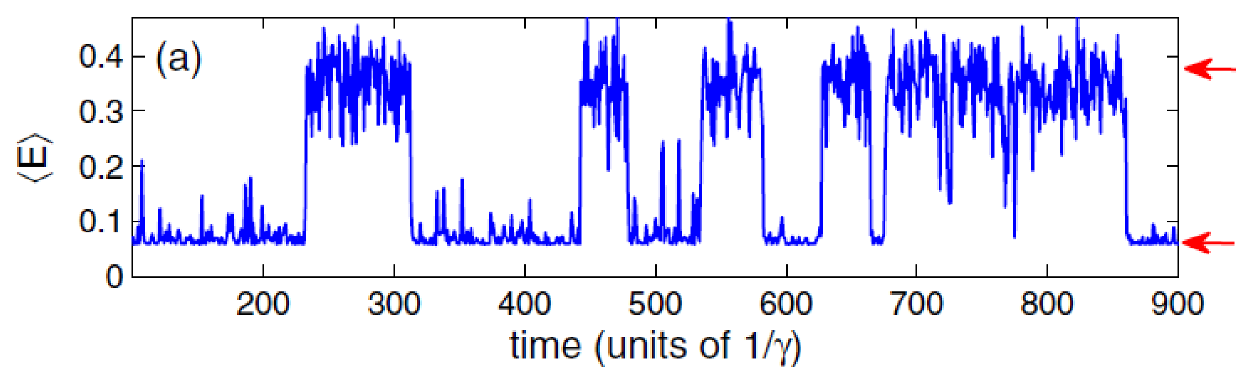
$$\dot{\bar{\rho}}_{ee} = -\Omega\,\mathrm{Im}\bar{\rho}_{eg} - \gamma\bar{\rho}_{ee},$$

$$\dot{\bar{\rho}}_{eg} = i(\Delta - V\bar{\rho}_{ee})\bar{\rho}_{eg} - \frac{\gamma}{2}\bar{\rho}_{eg} + i\Omega\left(\bar{\rho}_{ee} - \frac{1}{2}\right).$$

$$\Delta_{\mathrm{eff}} = \Delta - V\bar{\rho}_{ee}$$





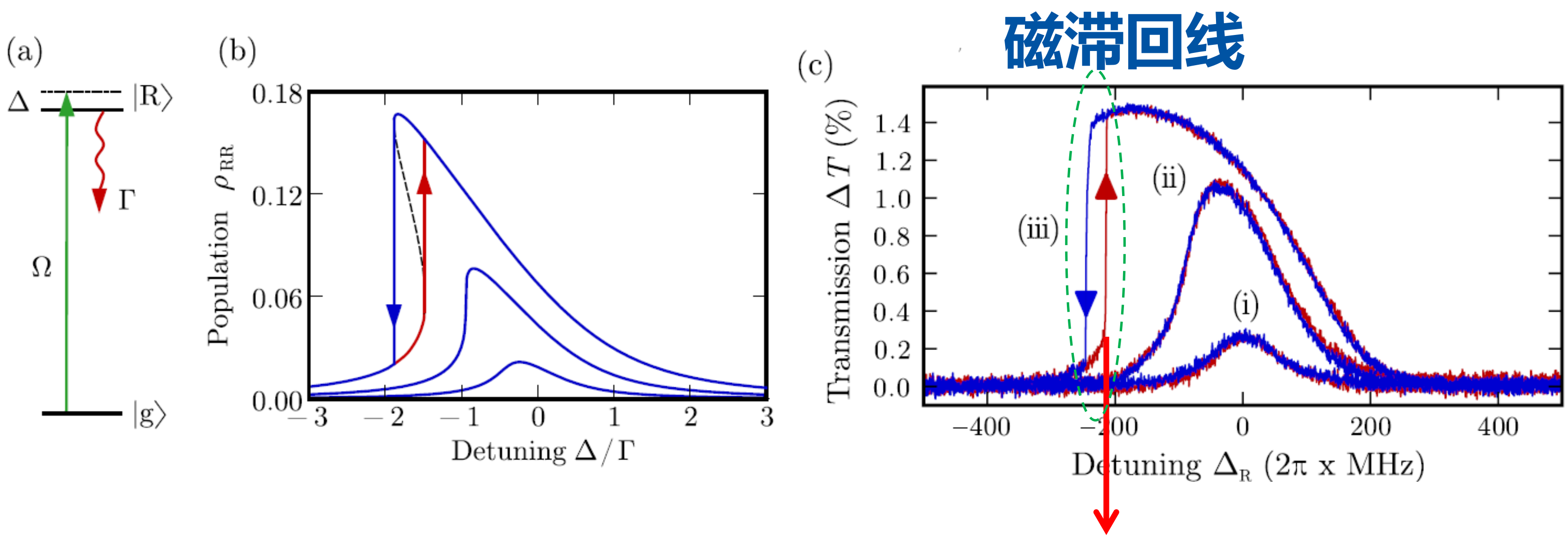


研究背景

PRL **111,** 113901 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Nonequilibrium Phase Transition in a Dilute Rydberg Ensemble

C. Carr, R. Ritter, C. G. Wade, C. S. Adams, and K. J. Weatherill
Department of Physics, Joint Quantum Centre (JQC) Durham-Newcastle, Durham University, South Road, Durham DH1 3LE, United Kingdom
(Received 28 March 2013; published 10 September 2013)



Jump

$$\dot{\rho}_{gR} = i\Omega\left(\rho_{RR} - \frac{1}{2}\right) + i(\Delta - V\rho_{RR})\rho_{gR} - \frac{\Gamma}{2}\rho_{gR},$$

$$\dot{\rho}_{RR} = -\Omega \mathrm{Im}(\rho_{gR}) - \Gamma\rho_{RR},$$

相变频率分辨率：~100 MHz

我们的工作

PHYSICAL REVIEW X **10**, 021023 (2020)

Featured in Physics

Phase Diagram and Self-Organizing Dynamics in a Thermal Ensemble of Strongly Interacting Rydberg Atoms

Dong-Sheng Ding,[1,2,*] Hannes Busche,[3,4] Bao-Sen Shi,[1,2,†] Guang-Can Guo,[1,2] and Charles S. Adams[3,‡]

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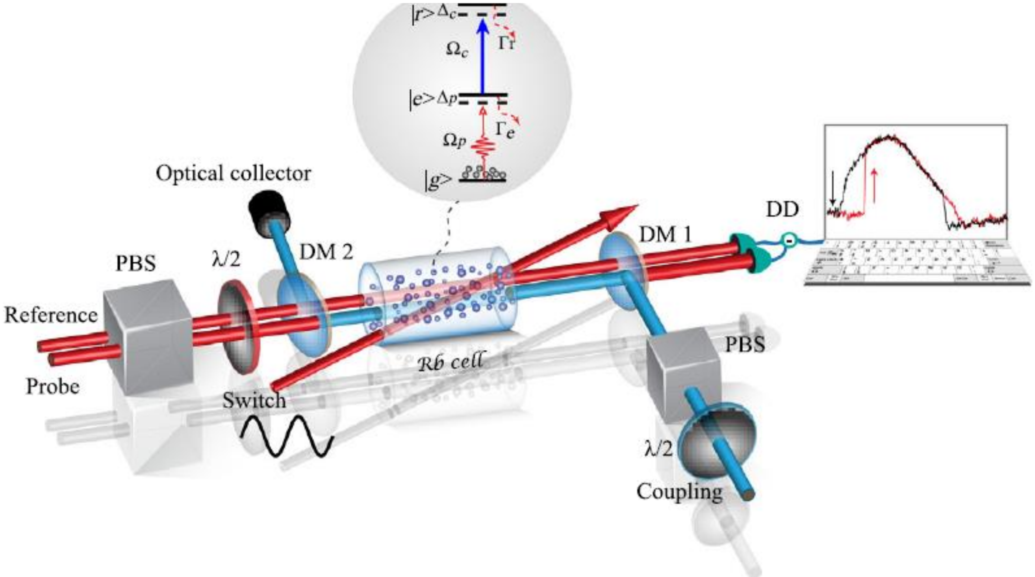
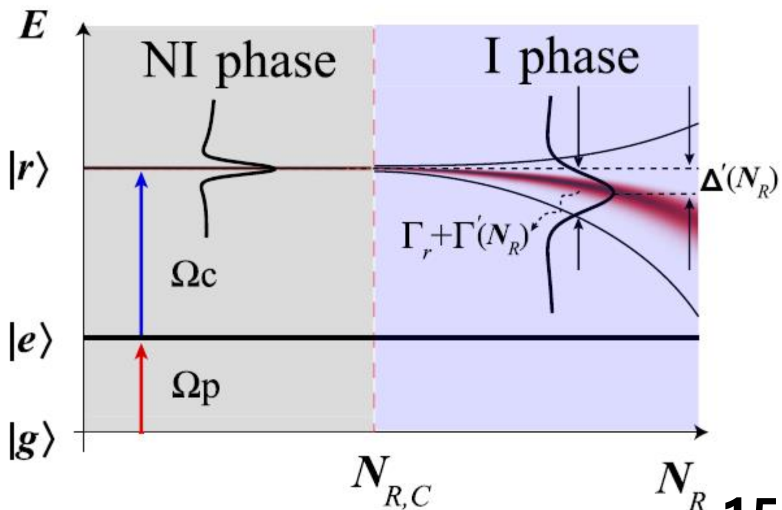
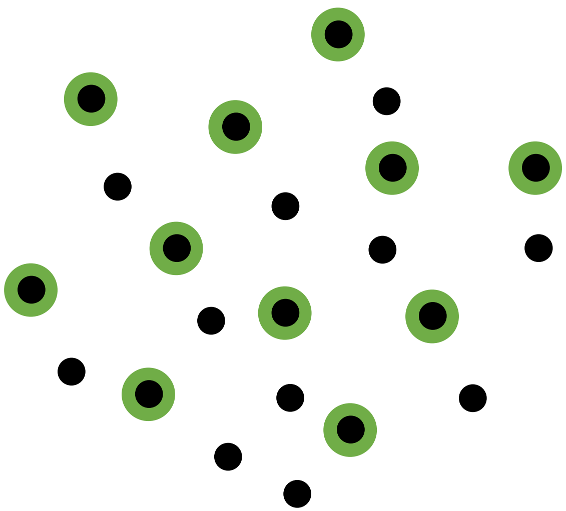


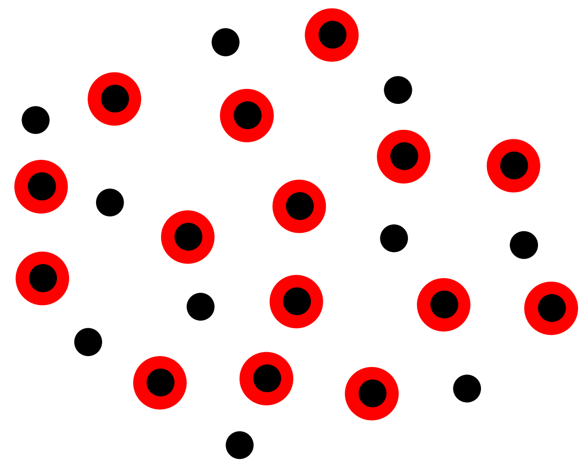


我们的工作

$D > d_{critical}$

$D < d_{critical}$





非相互作用相

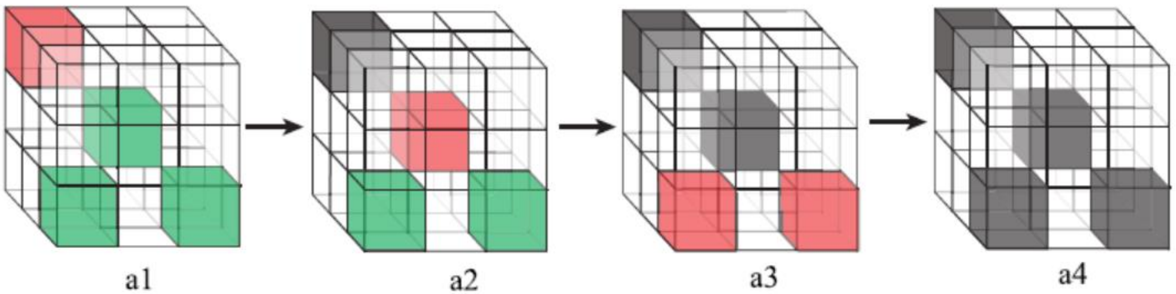
(NI-PHASE)

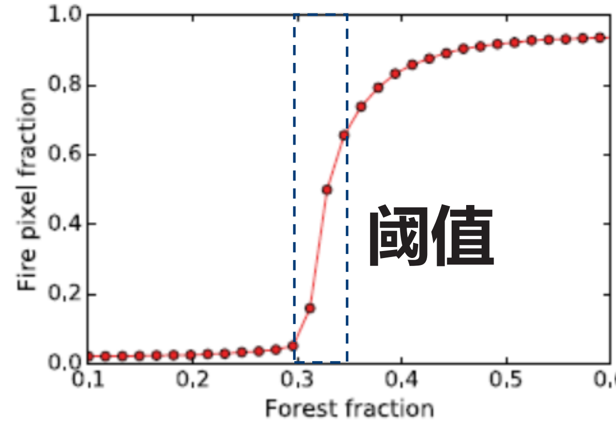
相互作用相

(I-PHASE)

森林火灾模型

A 3D array of 100 × 100 × 100 cells

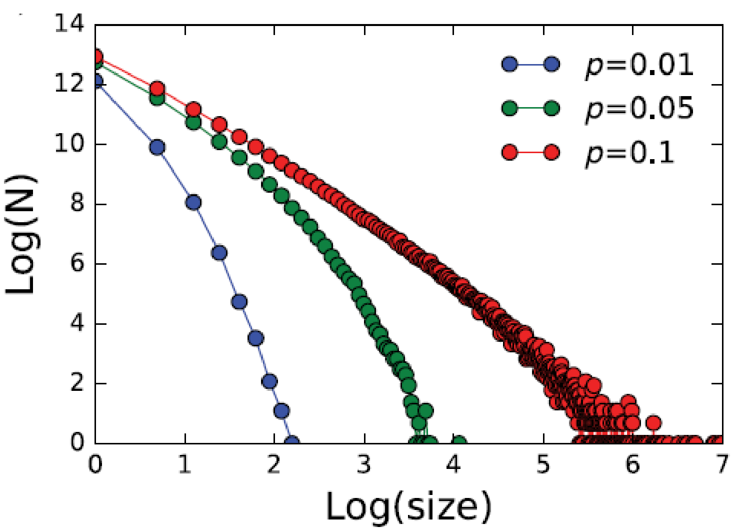




Green: NI phase if $N_R < N_{R;c}$.

Red: I phase for $N_R > N_{R;c}$.

Black: Depleted of Rydberg excitations.



所有迭代之后的集群大小具有幂律行为

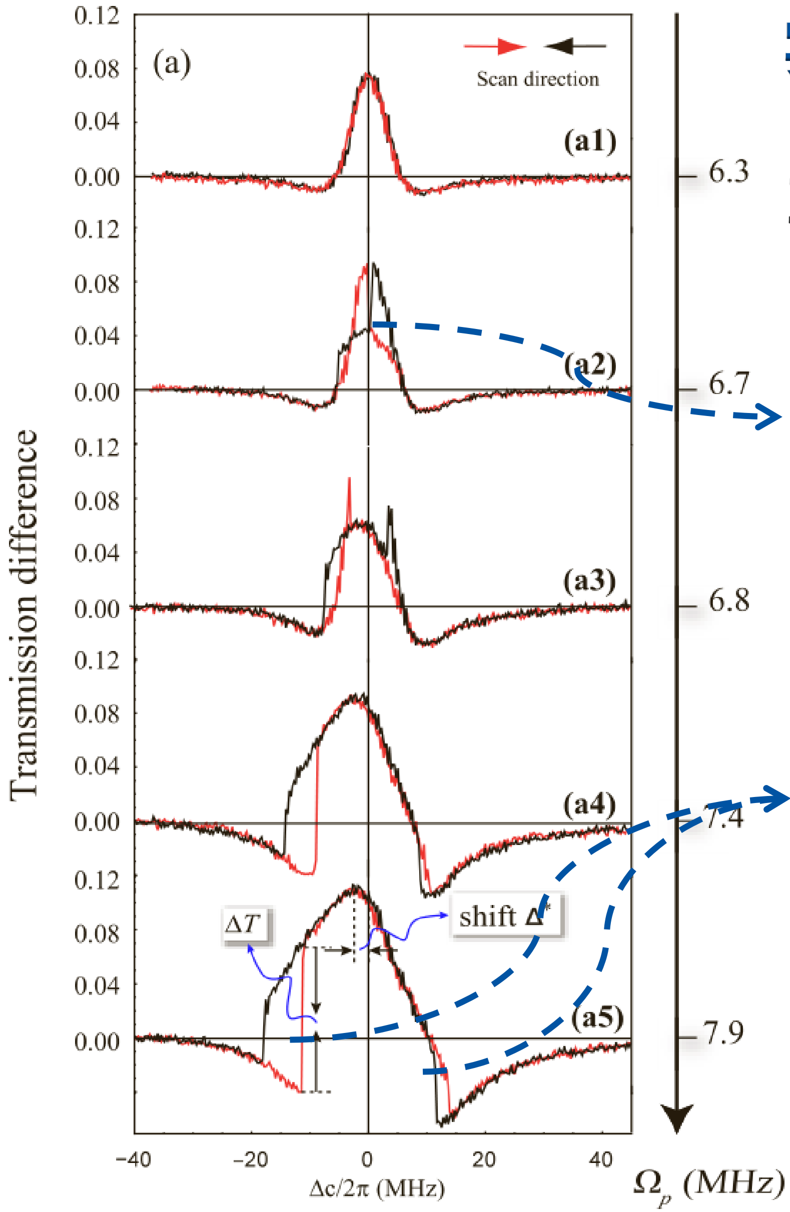
$$m(n_t) = n_t^{-b}$$

临界指数为b

$$m(Cn_t) = (Cn_t)^{-b} = C^{-b} m(n_t) \propto m(n_t)$$

它是尺度不变的，C表示尺度变换。

工作内容-非平衡相变



实验流程：

1、增加信号光的拉比频率：Ω_p

2、扫描控制光的detuning Δ_c

实验结果：

1、双稳窗口的频率带宽~0.5 MHz，比传统方法提升2个数量级

2、对称性双稳态（red- and blue-detuning）

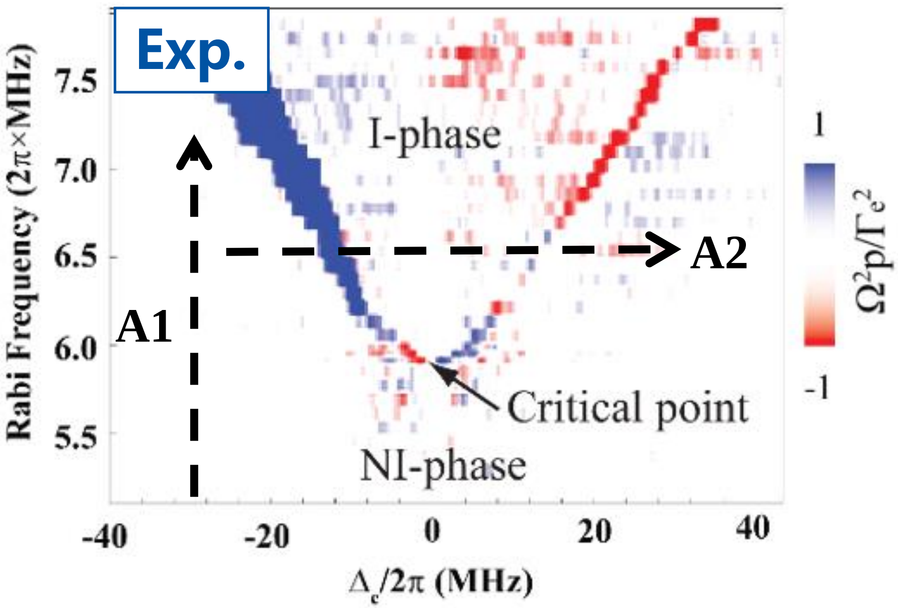
3、临界的原子密度

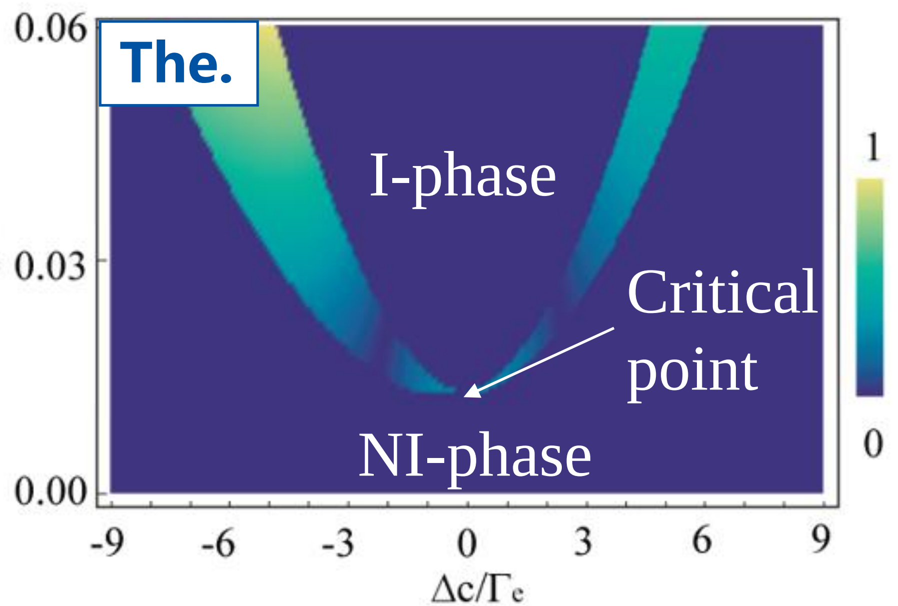
$$N_c = 2.9 \times 10^{10}\ cm^{-3}$$

相图

不同相之间存在可区分的Γr 和Δc.

$$\chi(v)\mathrm{d}v = \frac{|\mu_{ge}|^2}{\epsilon_0 \hbar}\rho_{eg}(v)\mathrm{d}v \quad \Gamma_r \to \Gamma_r + \Gamma'(N_R) \quad \Delta_c \to \Delta_c + \Delta'(N_R)$$





A1，A2（Δc，Ωp）:一阶相变 (discontinuous)

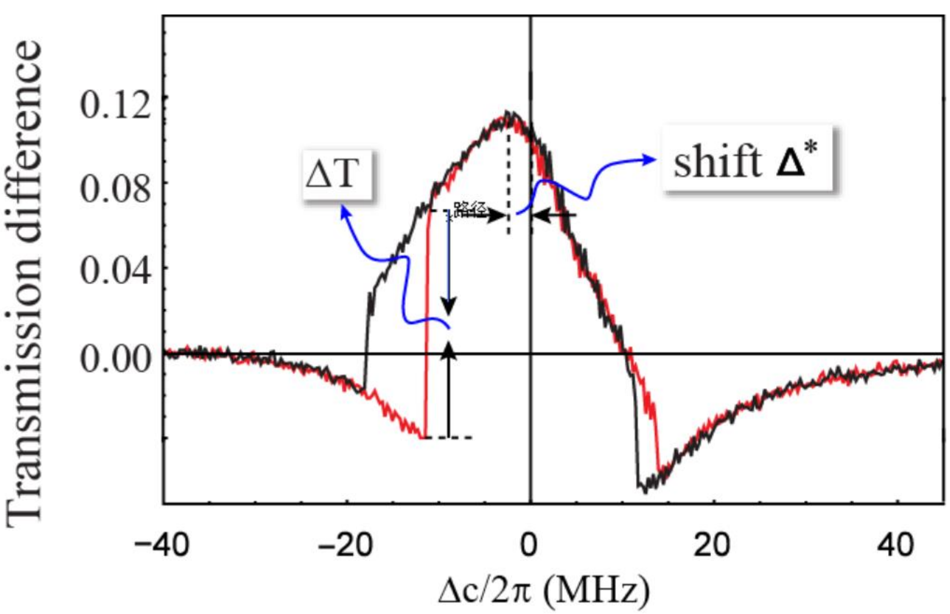
A1（Energy shift）：二阶相变 (continuous phase transition)

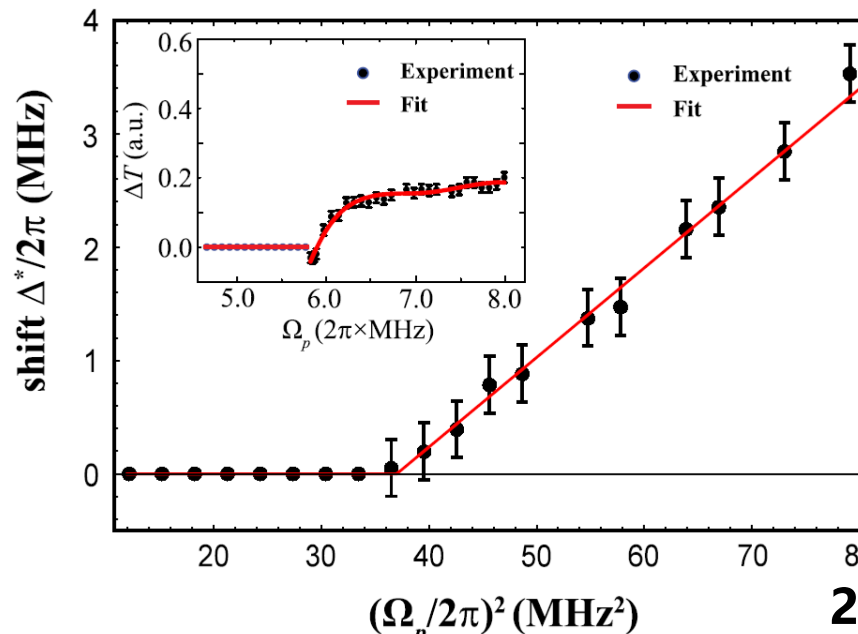
序参量

序参量定义为透射率峰值位置对应的失谐量

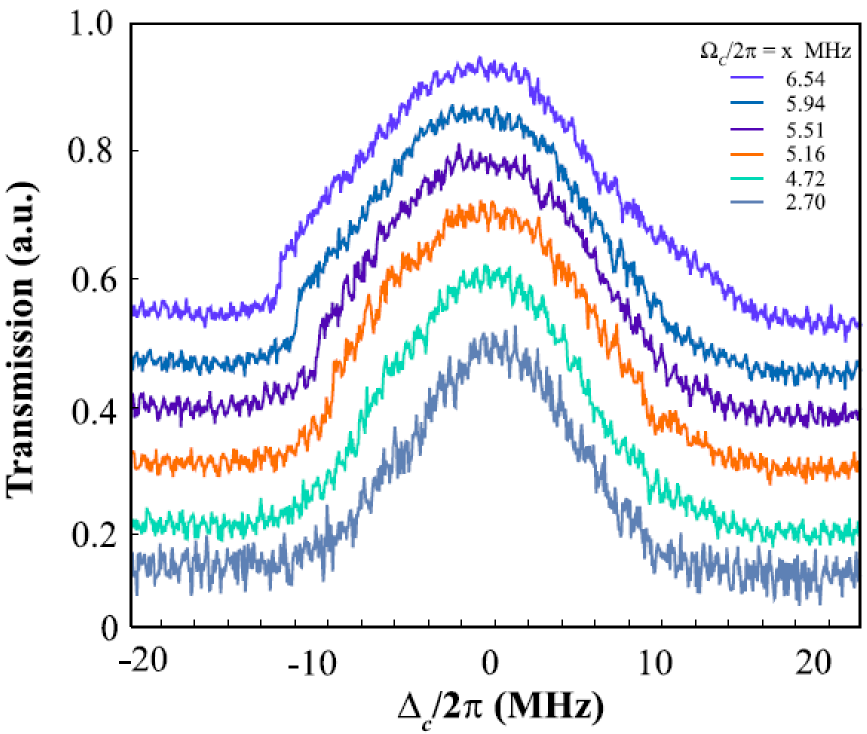
$$\Delta^* \propto \begin{cases} 0 \\ (\Omega_p^2 - \Omega_{p,(c)}^2)^\beta \end{cases}$$

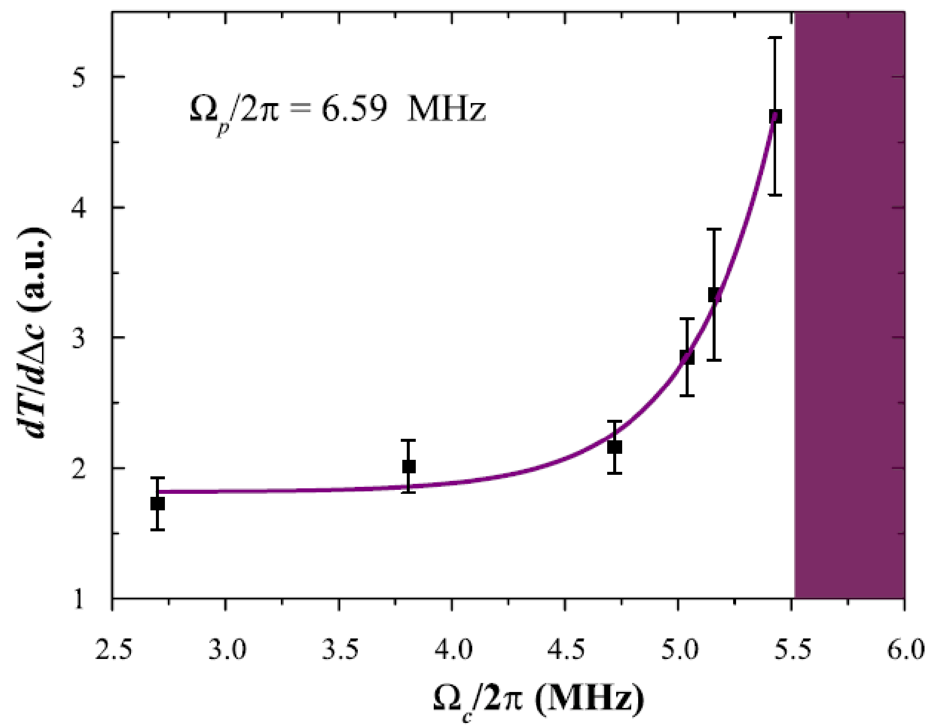
这里 $\Omega_{p,(c)}^2 = 37(2\pi \times \mathrm{MHz})^2$，指数 $\beta = 1$





极化



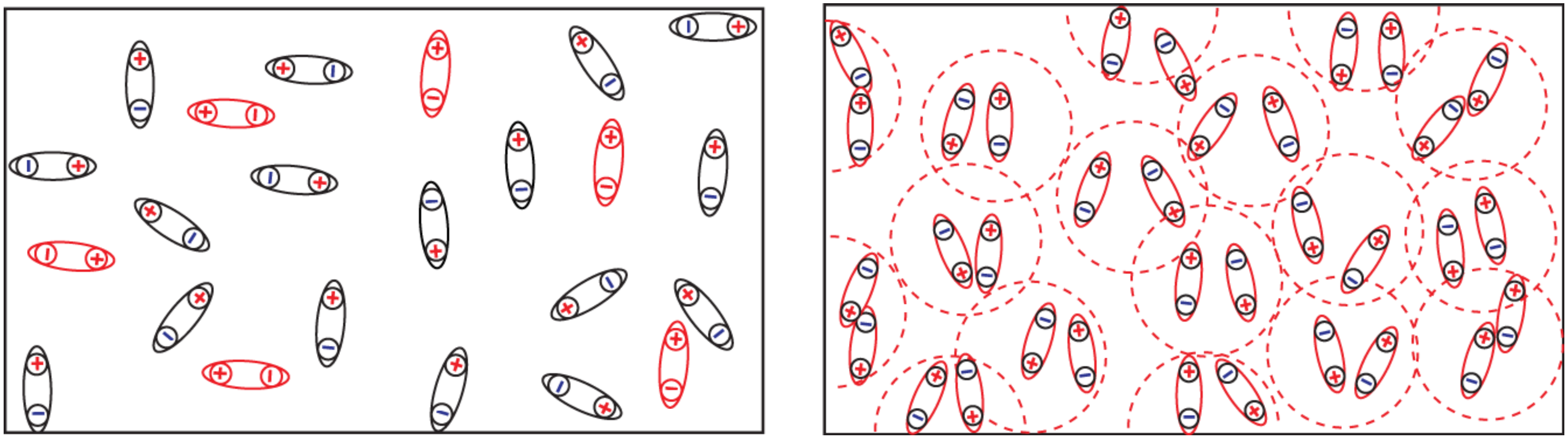


系统在临界点处随着控制拉比频率而发散，描述如下：

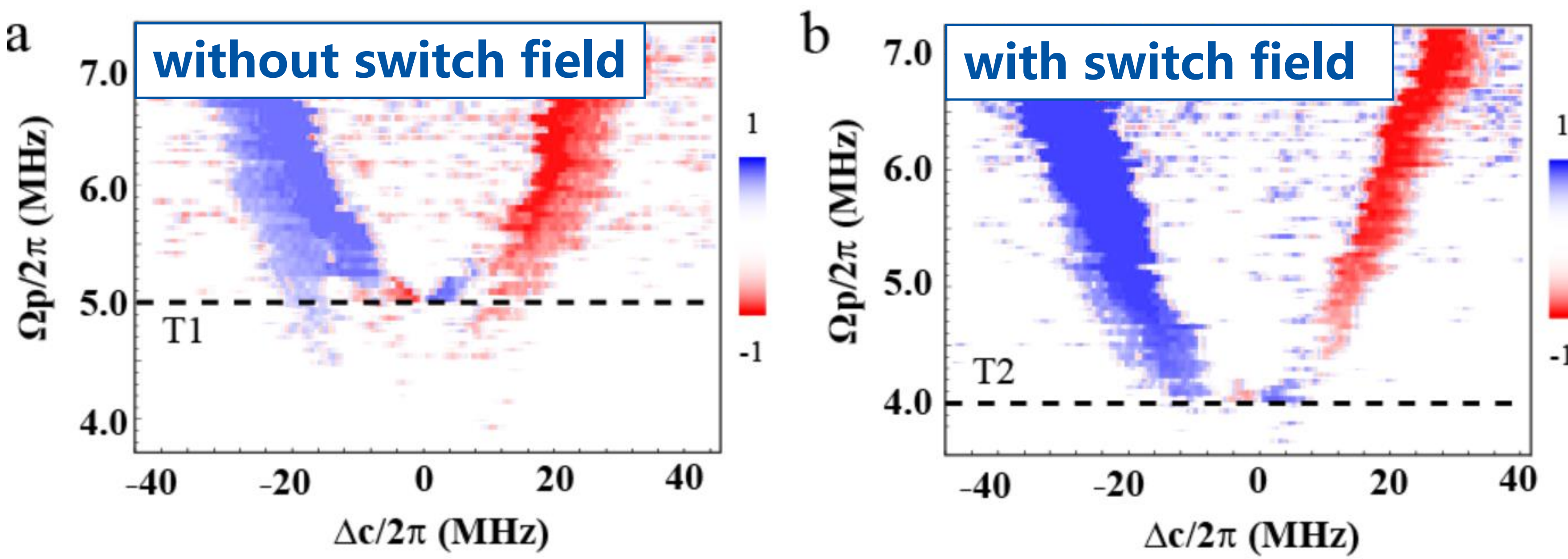
$$dT/d\Delta_c = 1.97 \times 10^6 e^{(\Omega_c/\xi)} + 1.82$$

这里 $\xi = 2\pi \times 0.38$ MHz 为临界指数

操控相图

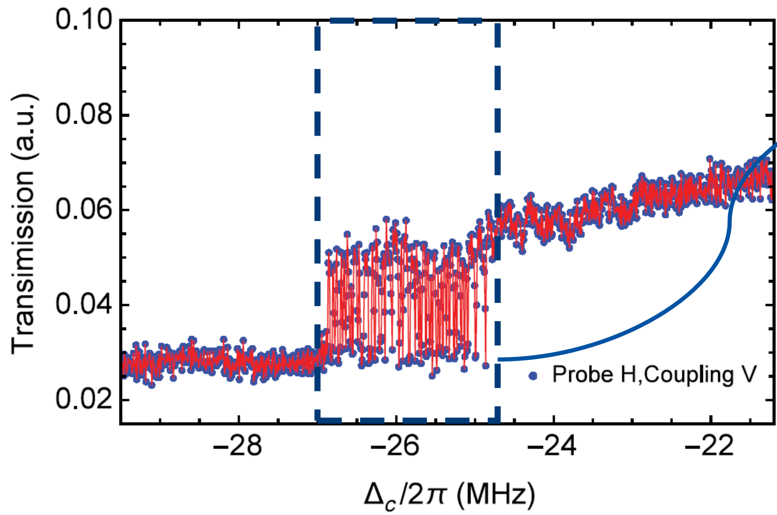


Switch Field：控制里德堡原子布局



慢扫描下的系统动力学

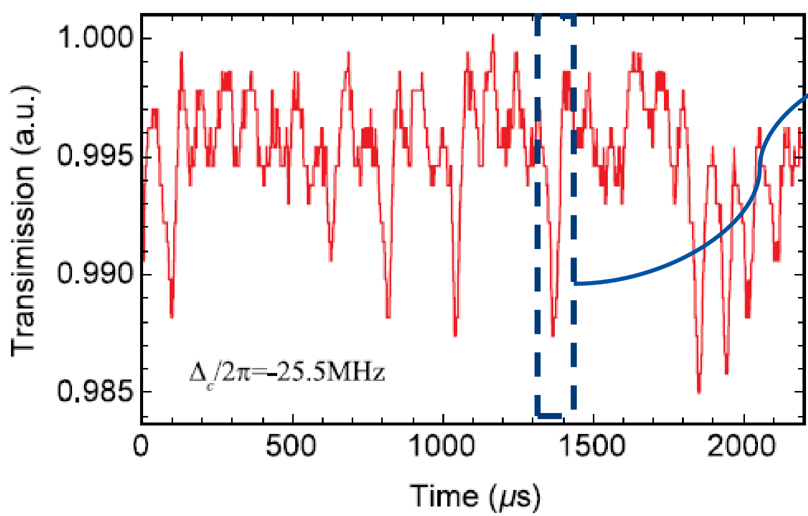
当慢速扫描Δc时，系统会在临界点附近震荡



Instability

系统会在NI-phase和I-phase之间震荡

The system oscillates when stopped scanning Δc

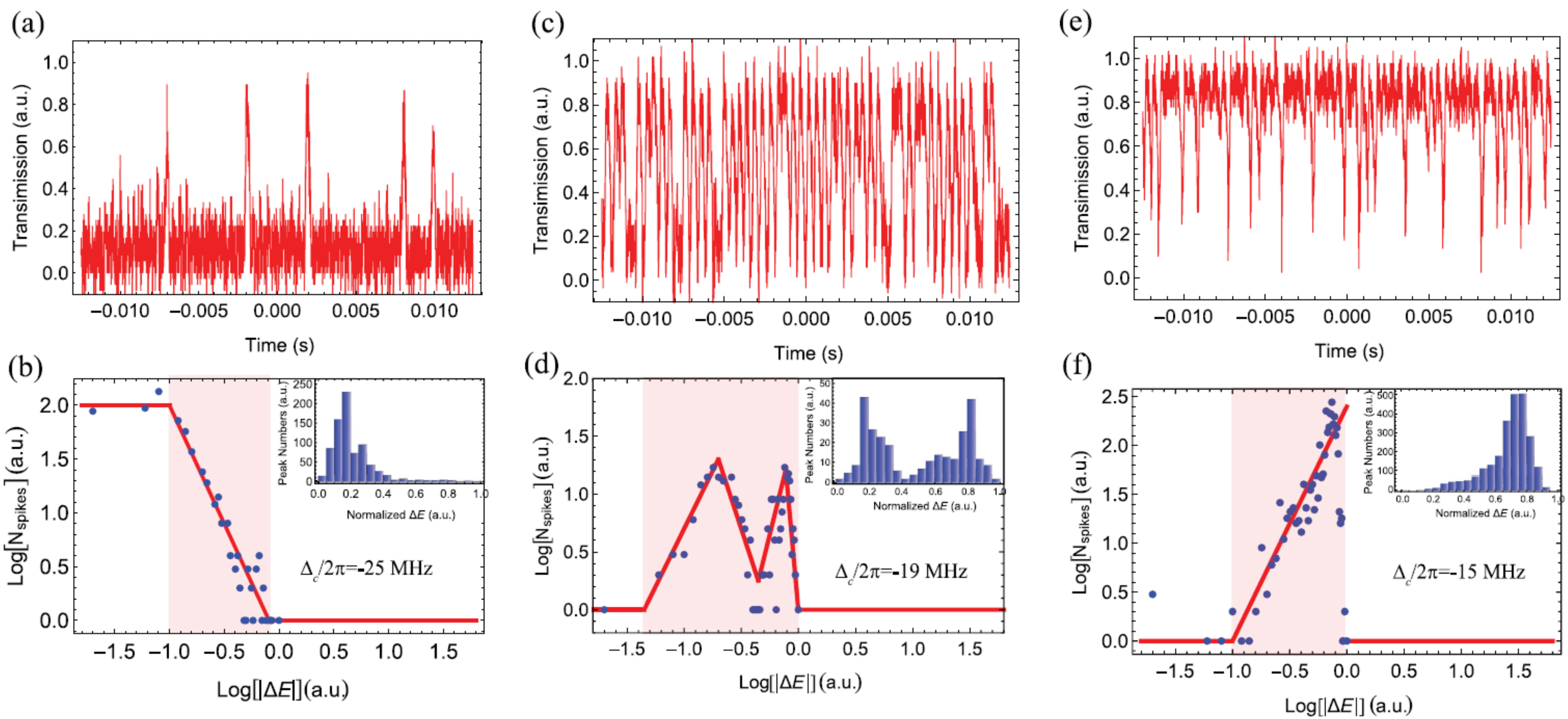


Collective jumps

一些里德堡原子被激发，然后又decay了

幂律标度

对雪崩进行统计



雪崩符合幂律标度分布，自组织的特征之一。

PRX viewpoint 报道

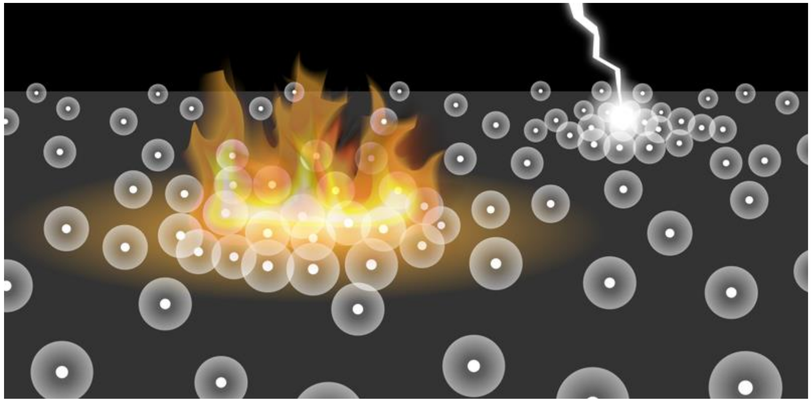
Physics

VIEWPOINT

Rydberg Atoms on Fire

A new experiment reveals unexpected connections between a nonequilibrium phase transition in Rydberg gases and the way fires spread through a burning forest.

loss and energy gain. A complete understanding of how this self-organization works is lacking, partly because the relevant systems are hard to control. A new experiment by Dong-Sheng Ding and colleagues of the University of Science and Technology of China in Hefei and their collaborators at the University of Durham, UK, shows that Rydberg atoms can provide a platform for studying the mechanisms behind self-organization and nonequilibrium phase transi-



中科大的丁冬生以及合作者展示了自组织相变的平台

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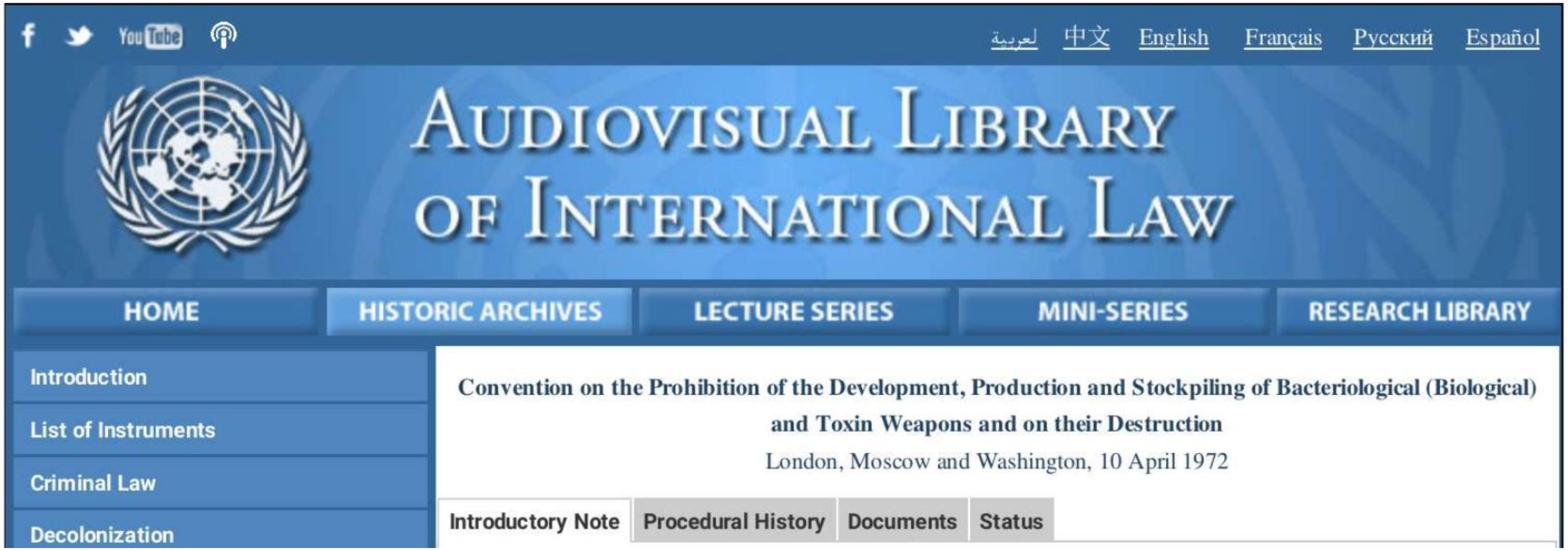
每年美国物理学会18000篇文章遴选100篇ViewPoint封面报道.

Part 2: 多级相变模拟病毒传播

Dong-Sheng Ding *et al.* arXiv:2106.12290 (2021).

出发点

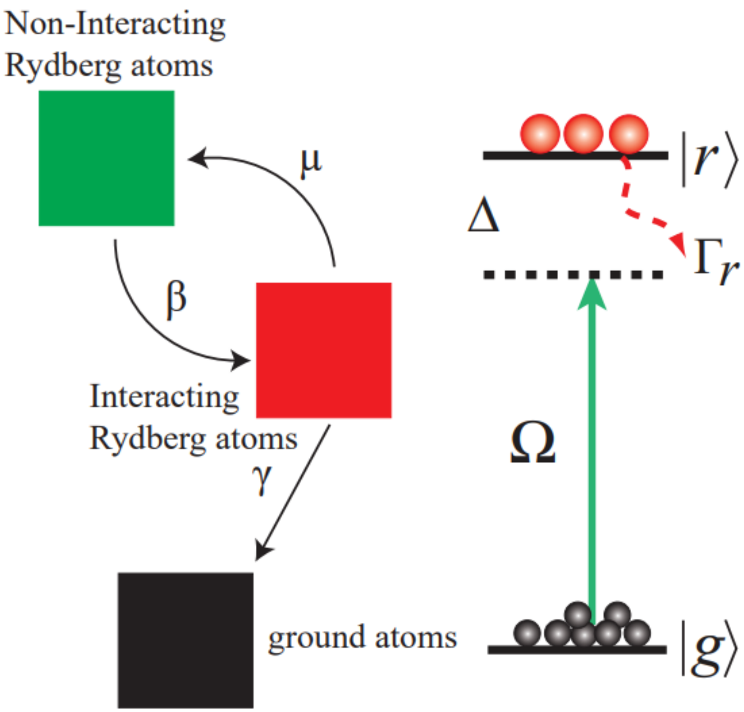
研究生命载体的病毒传播违反国际法《**禁止生物武器公约**》。

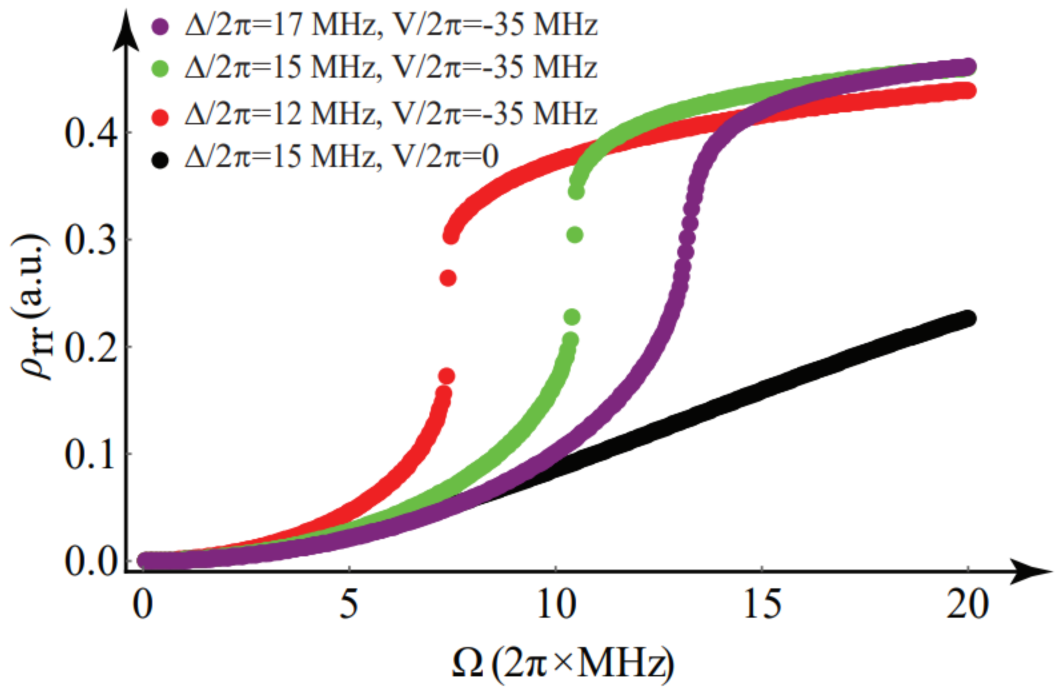


病毒传播属于自然灾害，无法给这样的实验提供大量的病毒载体。寻找一个具有病毒传播动力学且可控的无生命系统就成为研究该领域的关键问题。

我们的工作

Ref：Epidemic processes in complex networks **Rev. Mod. Phys.** 87, 925 (2015)





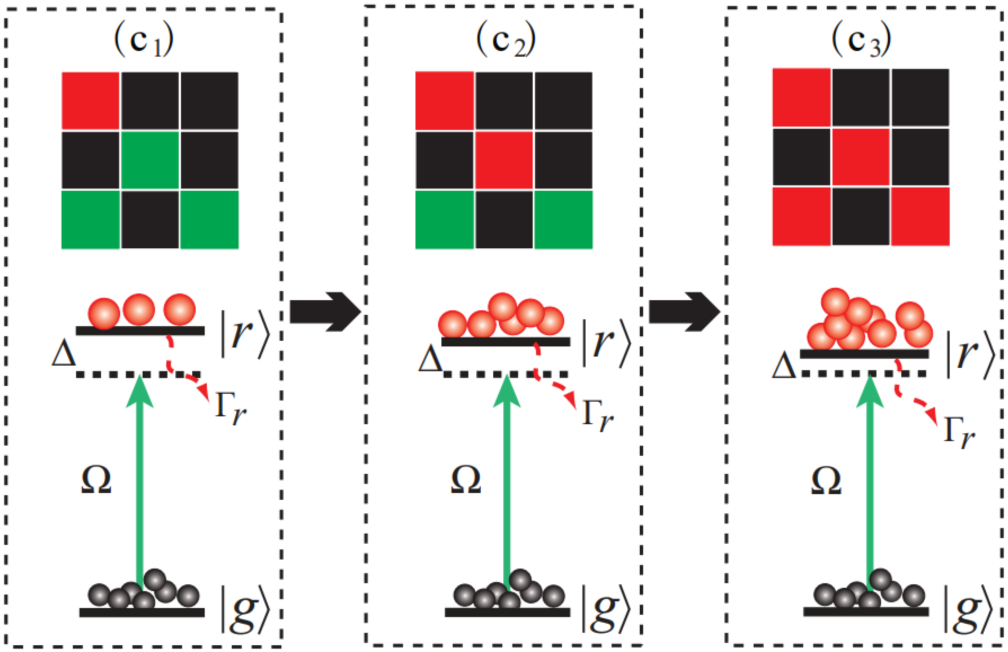
里德堡原子模型

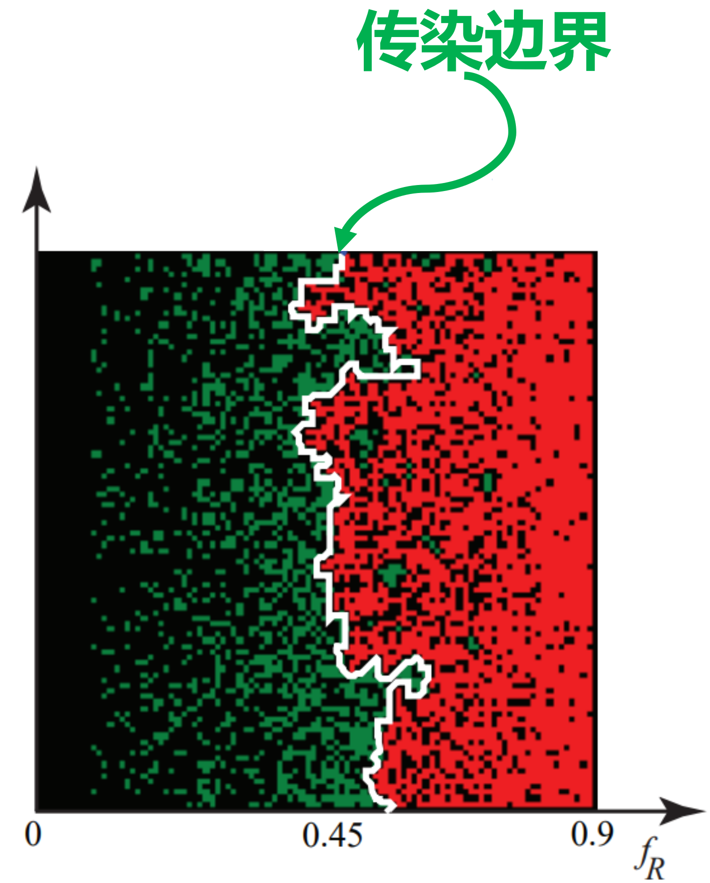
Ref. PRL.108, 023602(2012)

$$\dot{\rho}_{\mathrm{gr}} = i\frac{\Omega}{2}\left(\rho_{\mathrm{rr}} - \rho_{\mathrm{gg}}\right) + i\Delta_{\mathrm{eff}}\rho_{\mathrm{gr}} - \frac{\Gamma_r}{2}\rho_{\mathrm{gr}}$$
$$\dot{\rho}_{\mathrm{rr}} = -i\Omega\left(\rho_{\mathrm{gr}} - \rho_{\mathrm{rg}}\right) - \Gamma_r\rho_{\mathrm{rr}}$$

有效失谐量 $\Delta_{\mathrm{eff}} = \Delta - V\rho_{rr}$

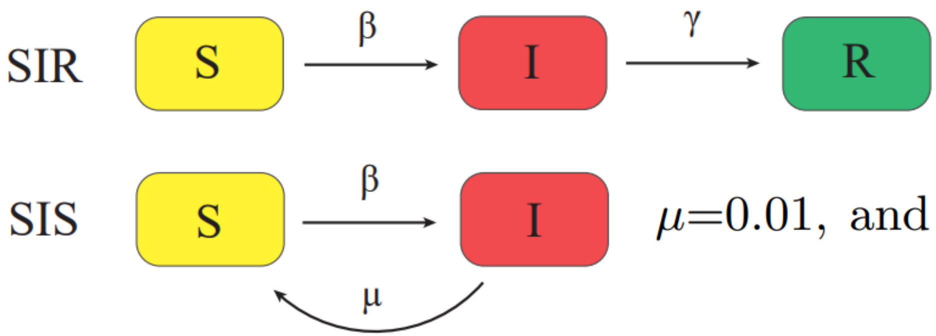
我们的工作





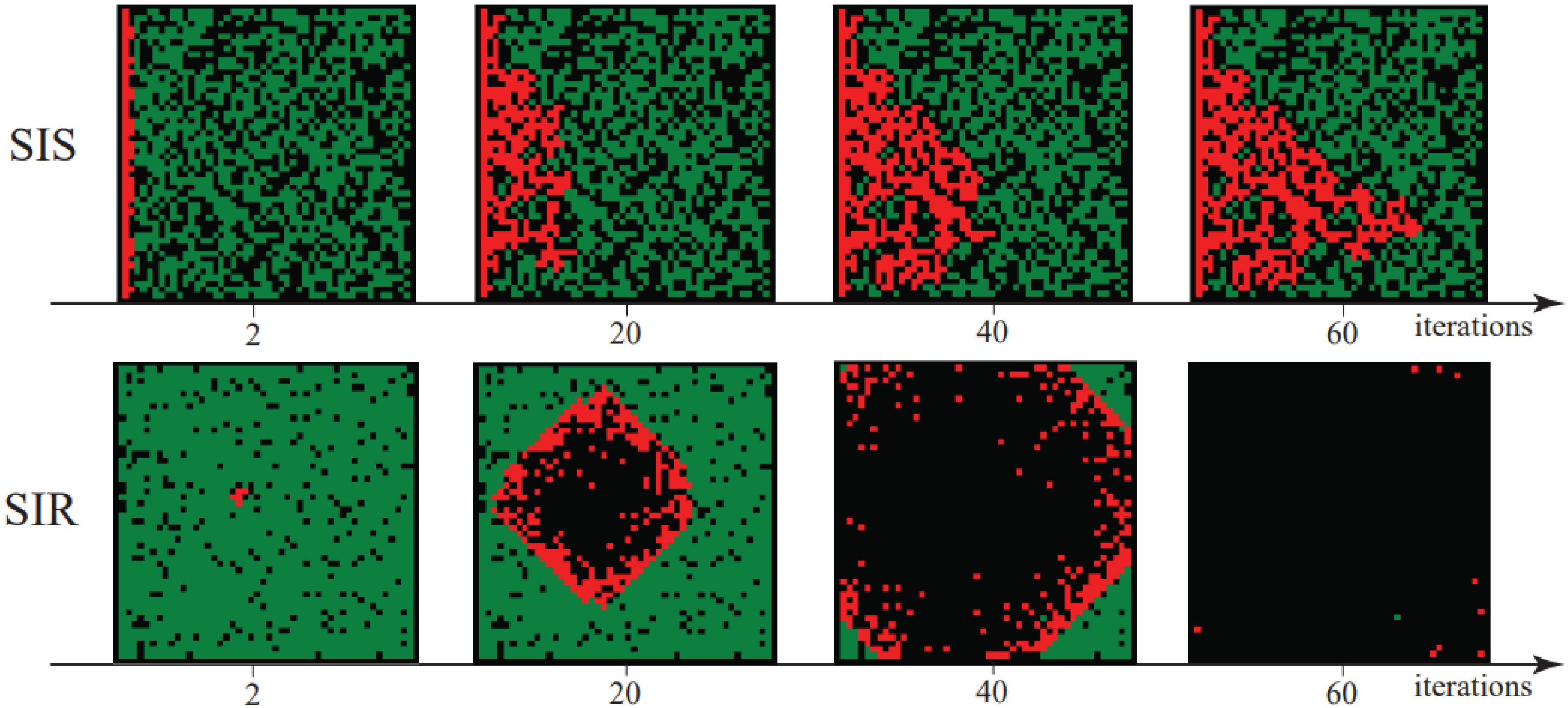
With the increase of Rydberg population（**susceptible**）above the threshold, the Rydberg population is increased （**Infected**）with a jump.

SIR and SIS models

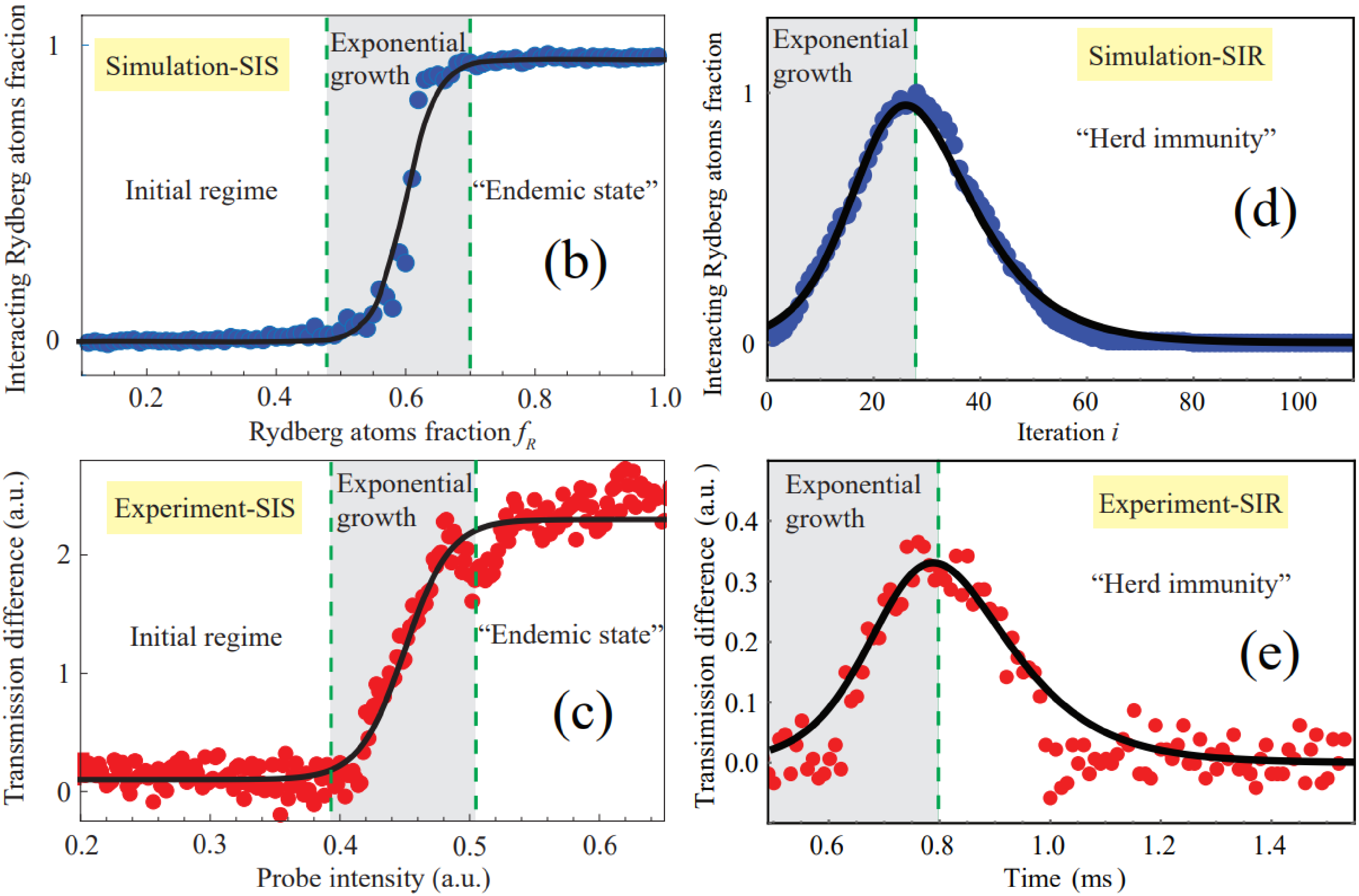


$\beta{=}0.95,\ \text{and}\ \gamma{=}0.2$

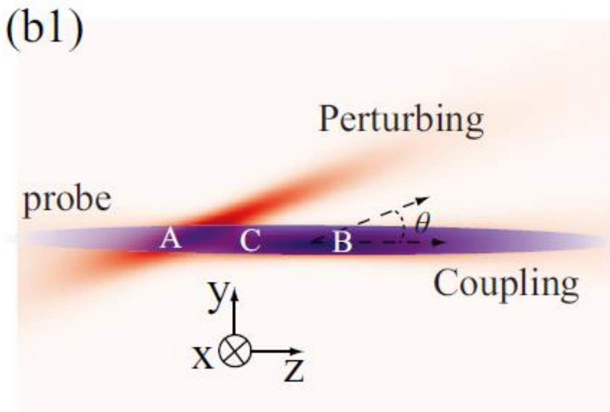
$\mu{=}0.01,\ \text{and}\ \beta{=}0.95,\ \gamma{=}0$

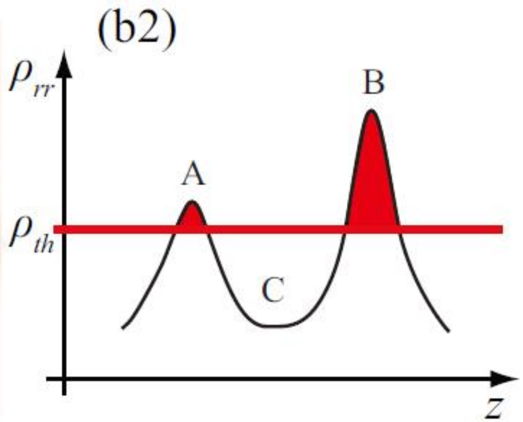


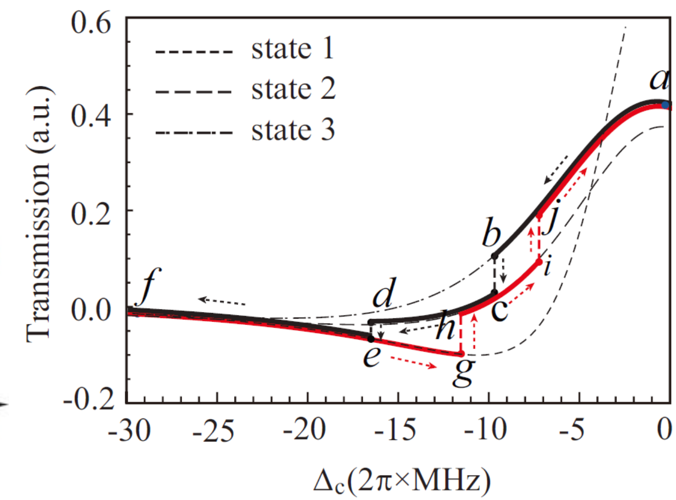
SIR and SIS models



多稳



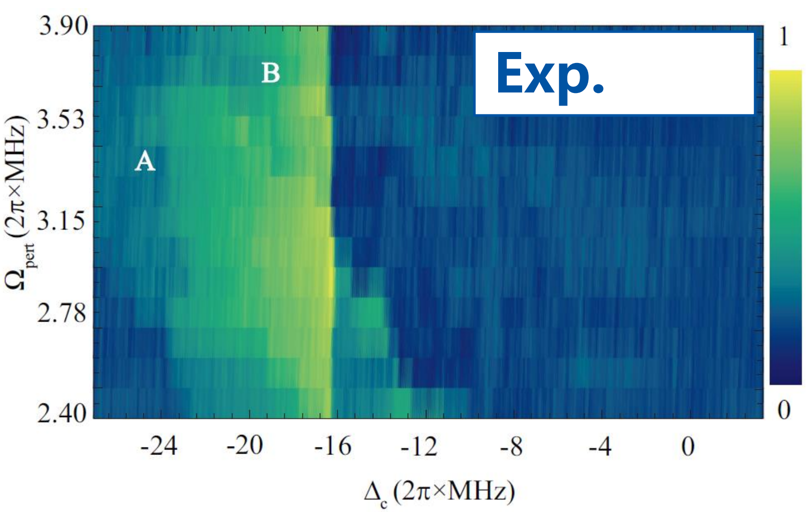


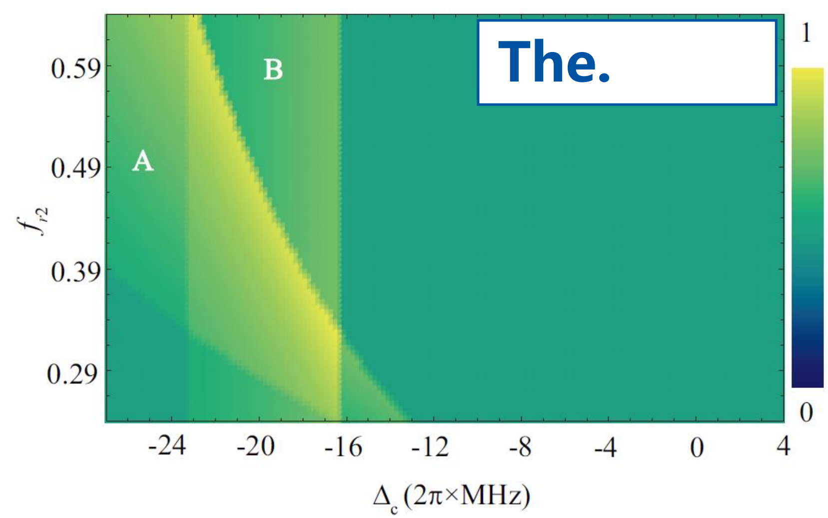


+Scan： f ->g -> h -> i -> j -> a

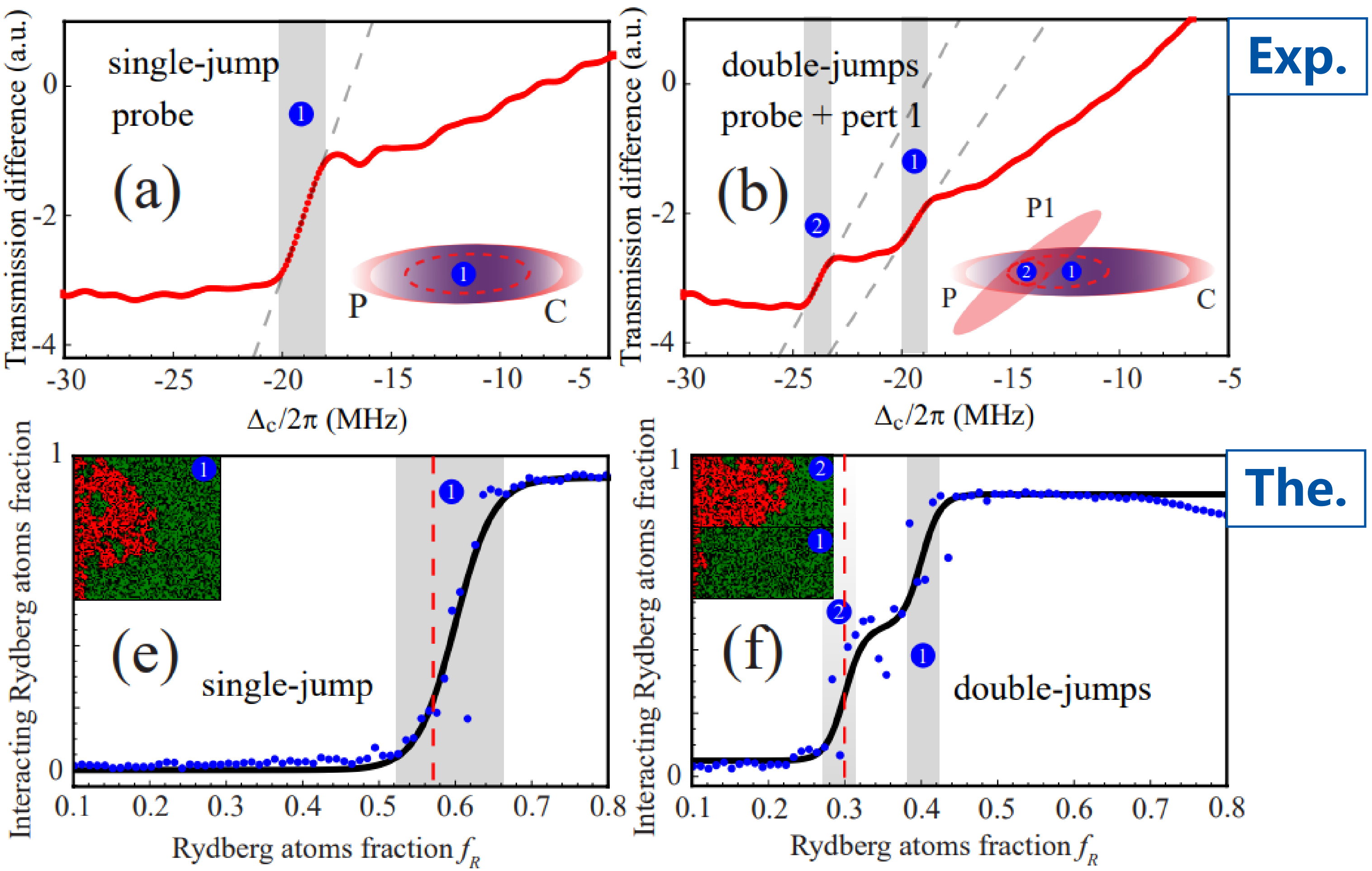
-Scan： a -> b -> c -> d -> e -> f

Multibistability





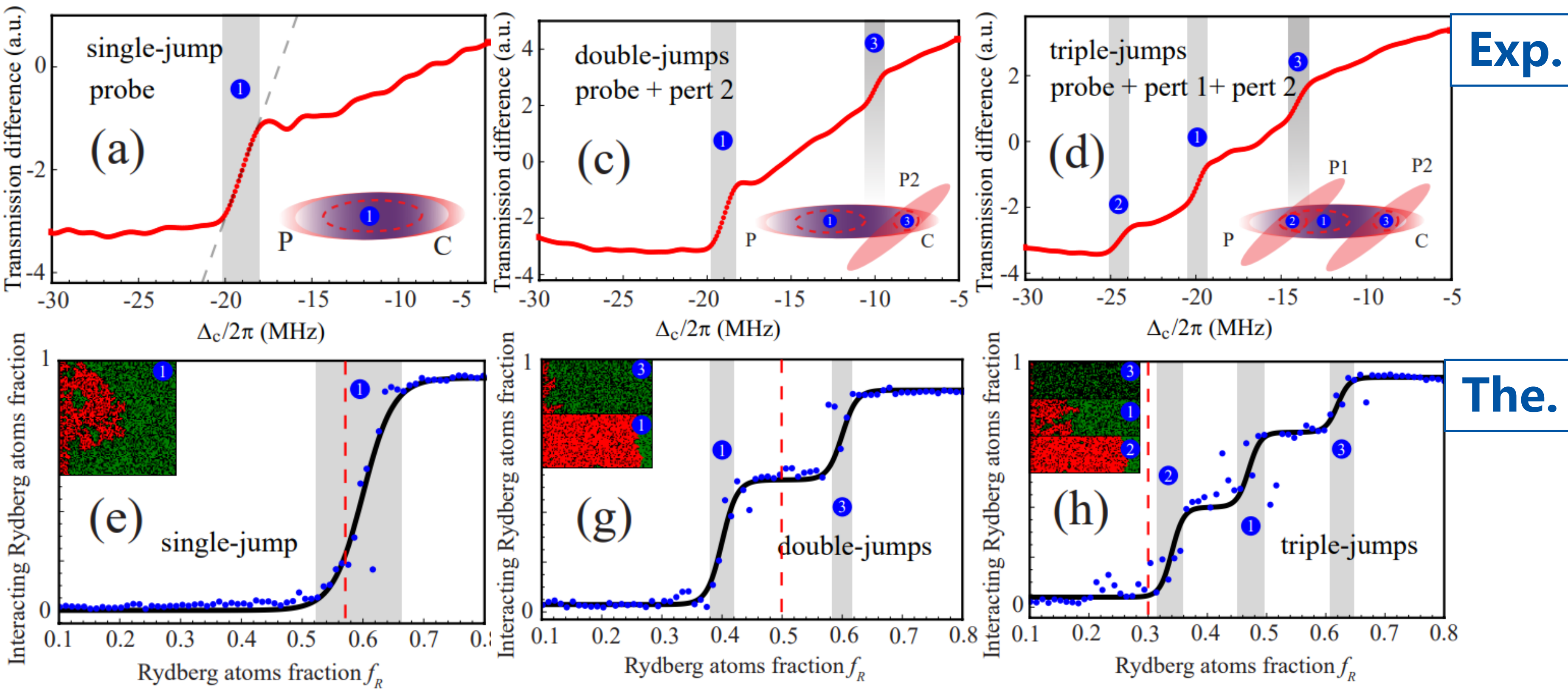
一个相劈裂成两个相



模拟: 疾病在同一个地方暴发了不同的强度。

产生多个Jump

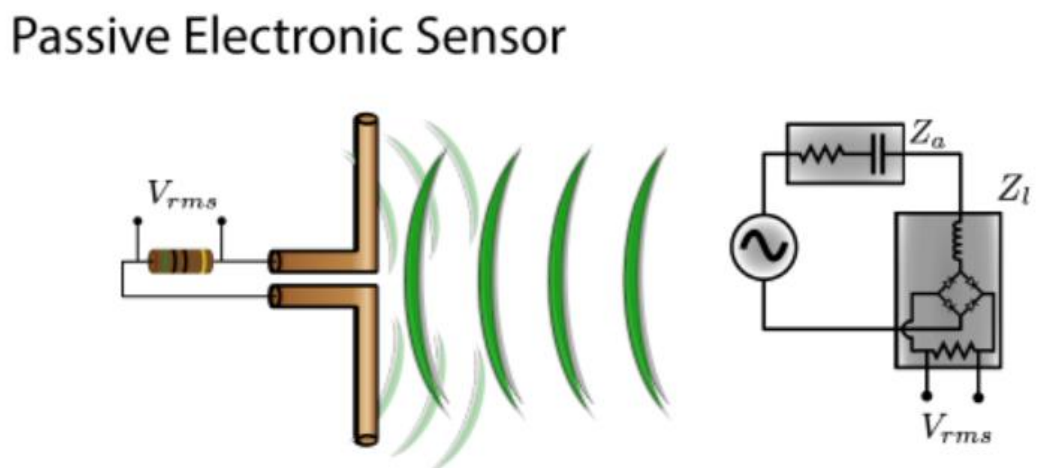
Single jump   Double jumps   Triple jumps



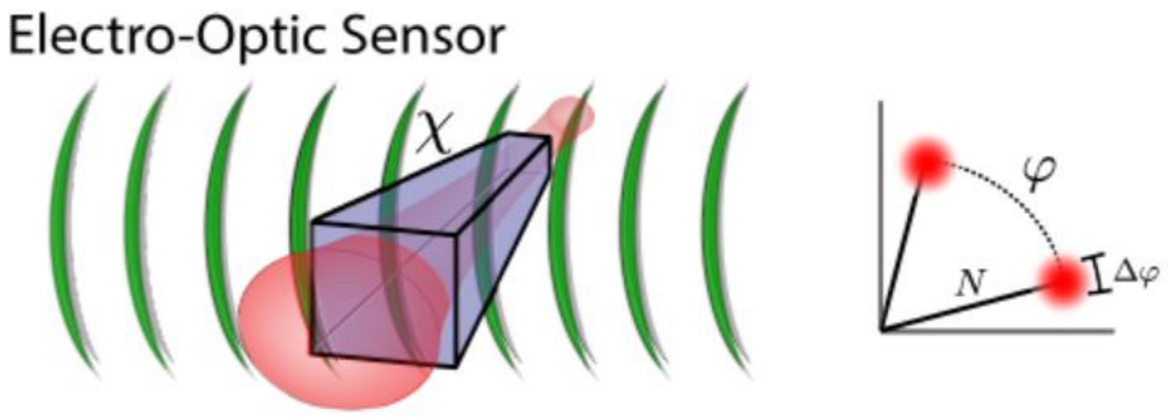
模拟: **疾病在多个地方暴发。**

二、基于里德堡原子的微波电场探测

传统微波电场测量的手段



传统基于偶极天线的方法，耦合强度和天线的大小、阻抗有关。



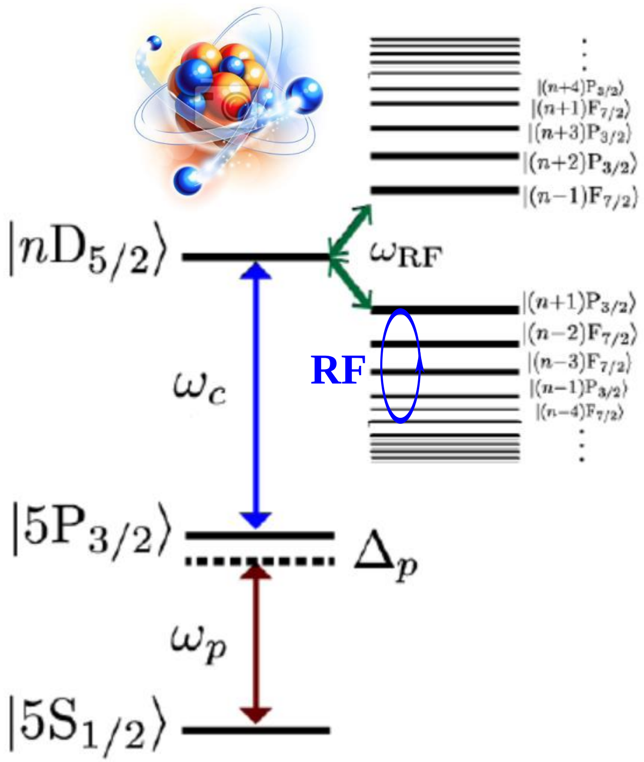
传统基于电光晶体的方法，需要应用信号光场提取位相信息。

里德堡原子的优点

里德堡原子：最外层电子被激发为高激发态的原子

优点

- □ 对外场极其敏感
  - ✓ 大电偶极矩 $d=e\times r\sim n^2$
  - ✓ 大的极化 $p=d^2/\Delta E\sim n^7$
- □ 易于操控
  - ✓ 能级覆盖带宽 100kHz~1THz



微波场测量过程

微波场测量 ➡ 光谱测量

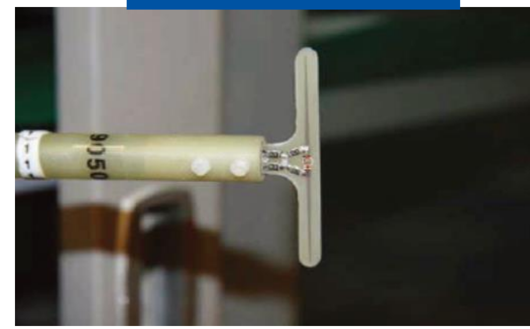
里德堡原子无线传感的优势

➢ 传统天线由金属构成，对**信号的探测精度受尺寸、形状、工作环境等限制（极限: 174 dBm/Hz）**；

➢ 传统装置需要**复杂的电路，噪声较大**；

➢ 传统天线通过**改变尺寸对某一频率微波**场探测。

传统金属天线



➢ **高灵敏：** 极限灵敏度远超过传统方法（**189 dBm/Hz**）；

➢ **低噪声、抗电磁干扰：** 玻璃泡中的原子不含电子元件，不受热噪声的干扰

➢ **大带宽：** 里德堡原子可以覆盖超宽的频段范围。

➢ **可溯源：** 响应函数可以溯源到一些基本物理常数

$$E_{\min} = \frac{h}{|\vec{\mu}_{\mathrm{RF}}| T_{\mathrm{meas}} \sqrt{N}}$$

（h为普朗克常数，μ_{RF}跃迁偶极矩）

➢ **便携化、集成化：** 尺寸可以做到厘米量级，便于携带、集成和小型化。

原子天线

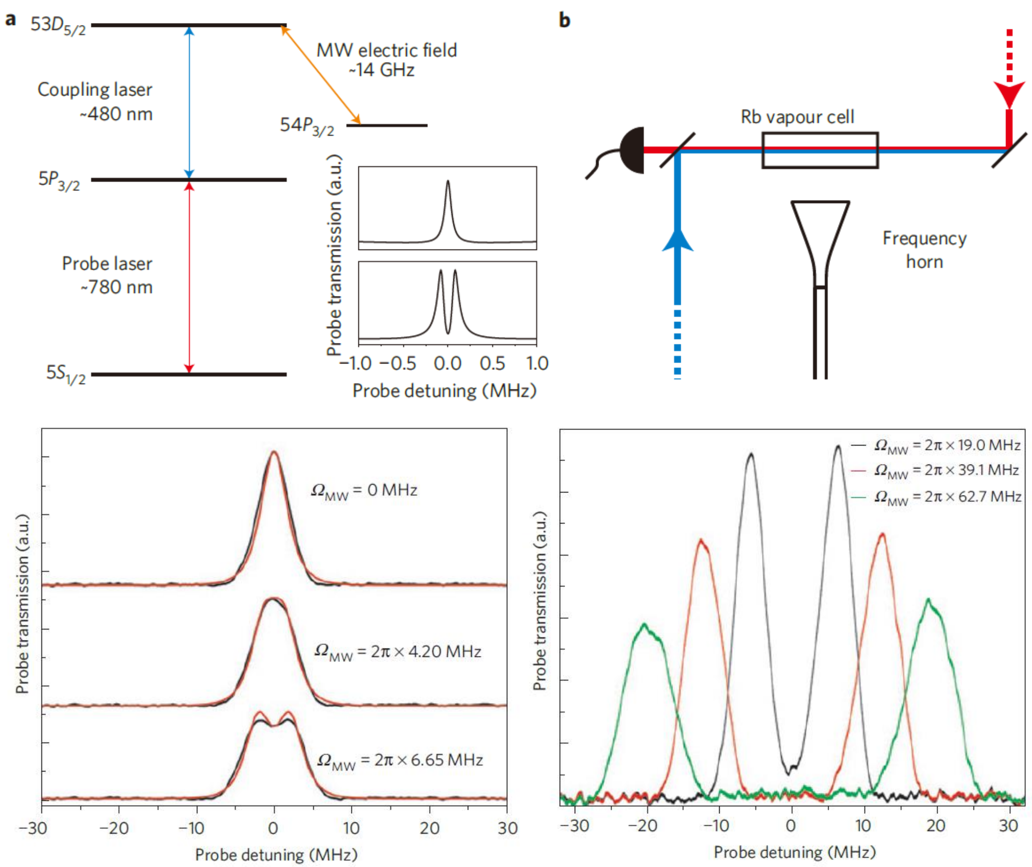
里德堡原子微波探测器

nature physics

ARTICLES

PUBLISHED ONLINE: 16 SEPTEMBER 2012 | DOI: 10.1038/NPHYS2423

Microwave electrometry with Rydberg atoms in a vapour cell using bright atomic resonances



技术方法：

基于Autler–Townes效应

技术指标：

探测灵敏度在μV/cm量级

里德堡原子微波探测器

nature physics

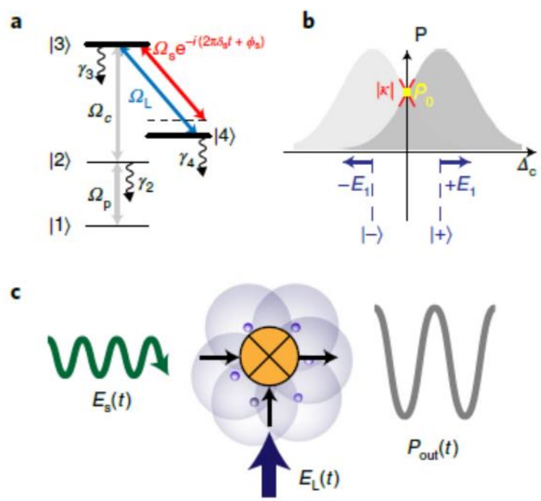
LETTERS

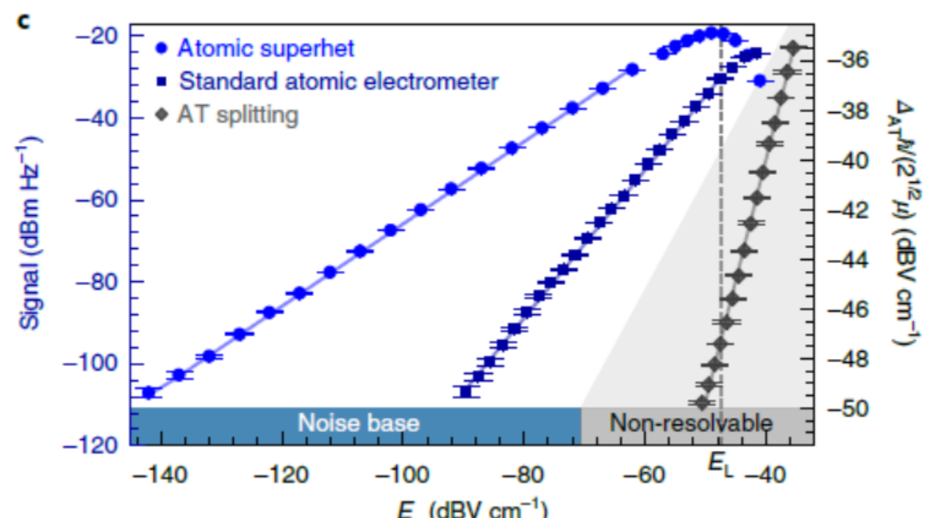
https://doi.org/10.1038/s41567-020-0918-5

Check for updates

Atomic superheterodyne receiver based on microwave-dressed Rydberg spectroscopy

Mingyong Jing[1,2,3], Ying Hu[1,2,3], Jie Ma[1,2], Hao Zhang[1,2], Linjie Zhang[1,2] ✉, Liantuan Xiao[1,2] ✉ and Suotang Jia[1,2]

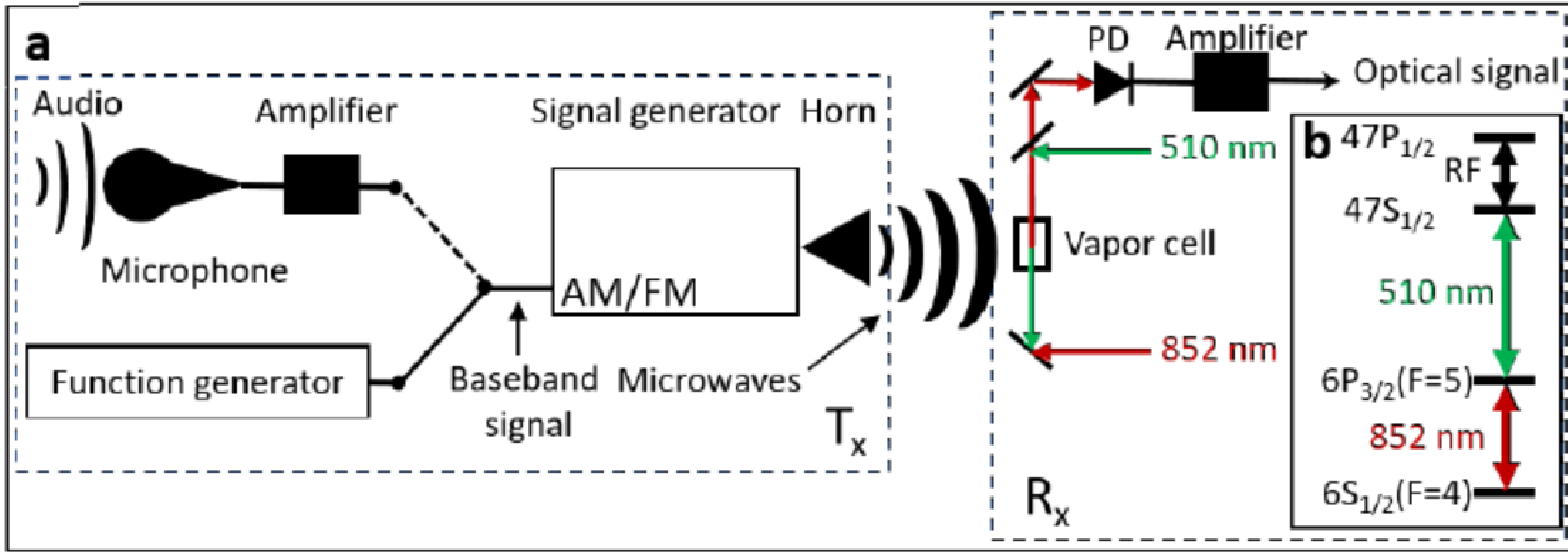


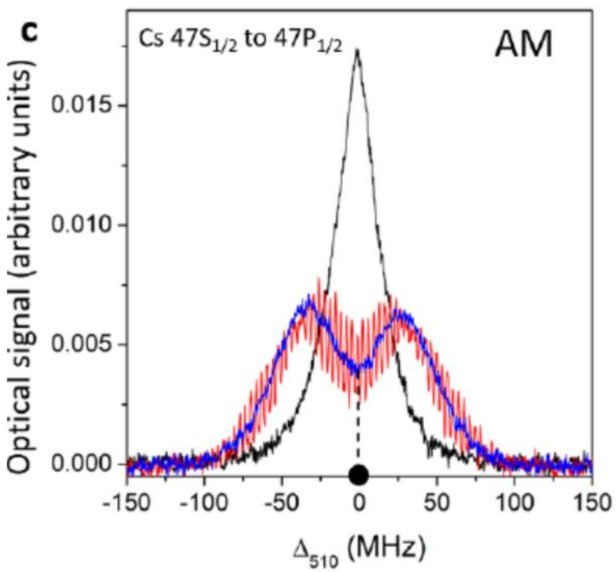


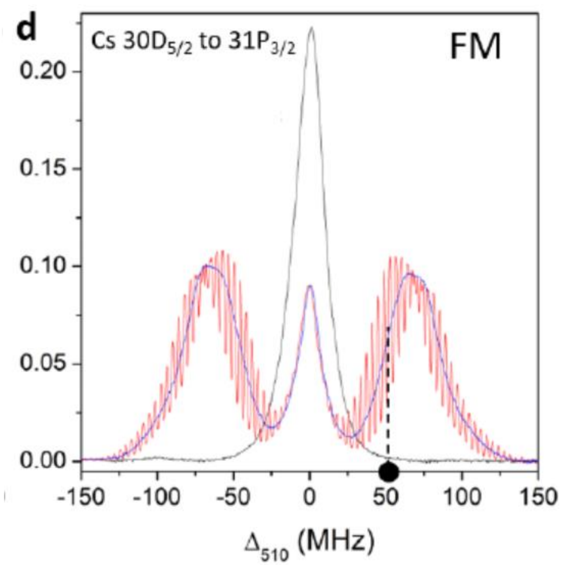
技术方法：原子超外差

技术指标：探测灵敏度在nV/cm量级

里德堡原子微波调幅(AM)和调频（FM)







技术方法：原子EIT

技术指标：

3-dB bandwidth

Baseband:100 kHz

DOI 10.1109/TAP.2020.2987112, IEEE

里德堡原子THz探测

技术方法：原子荧光探测

技术指标：频率~0.55THz

PHYSICAL REVIEW X **10**, 011027 (2020)

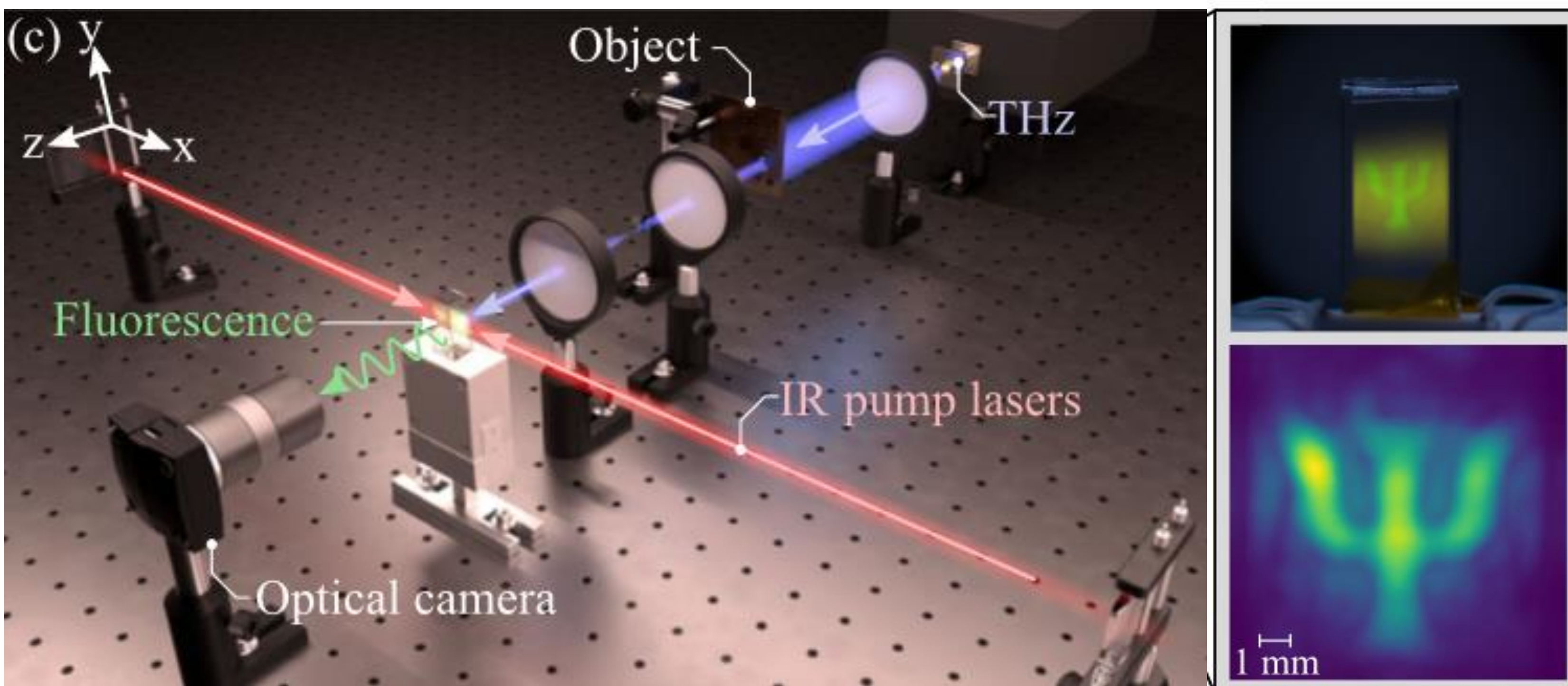
Featured in Physics

Full-Field Terahertz Imaging at Kilohertz Frame Rates Using Atomic Vapor

Lucy A. Downes,[1,*] Andrew R. MacKellar,[1] Daniel J. Whiting,[1] Cyril Bourgenot,[2]
Charles S. Adams,[1] and Kevin J. Weatherill[1]

[1] *Joint Quantum Centre (Durham-Newcastle), Department of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom*

[2] *Centre for Advanced Instrumentation, Department of Physics, Durham University, NETPark Research Institute, Joseph Swan Road, Sedgefield TS21 3FB, United Kingdom*



Part 1: 基于人工智能实现多频率的微波探测

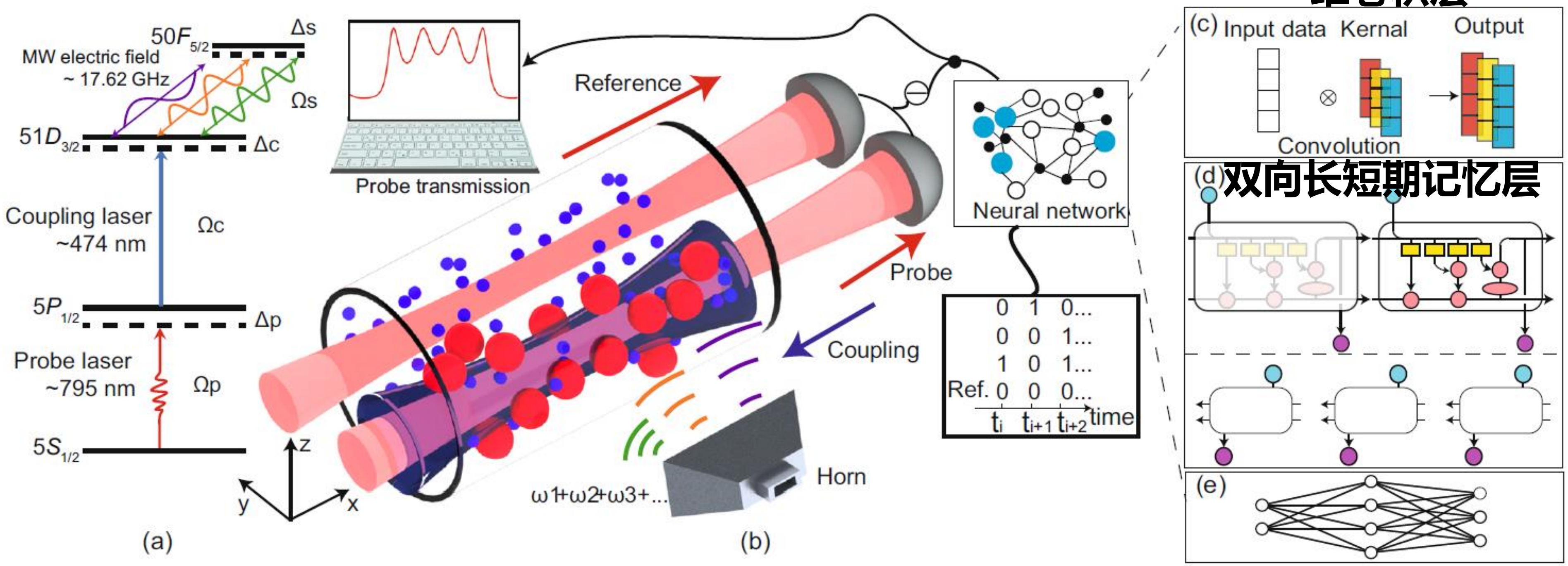
Zong-Kai Liu, et al. *Nat Commun.* 13, 1997 (2022)

工作内容

科学问题：多频率微波在原子中会引起复杂的干涉模式，严重干扰了信号接收与识别。

里德堡原子实验装置　　　　**深度学习神经网络**

一维卷积层



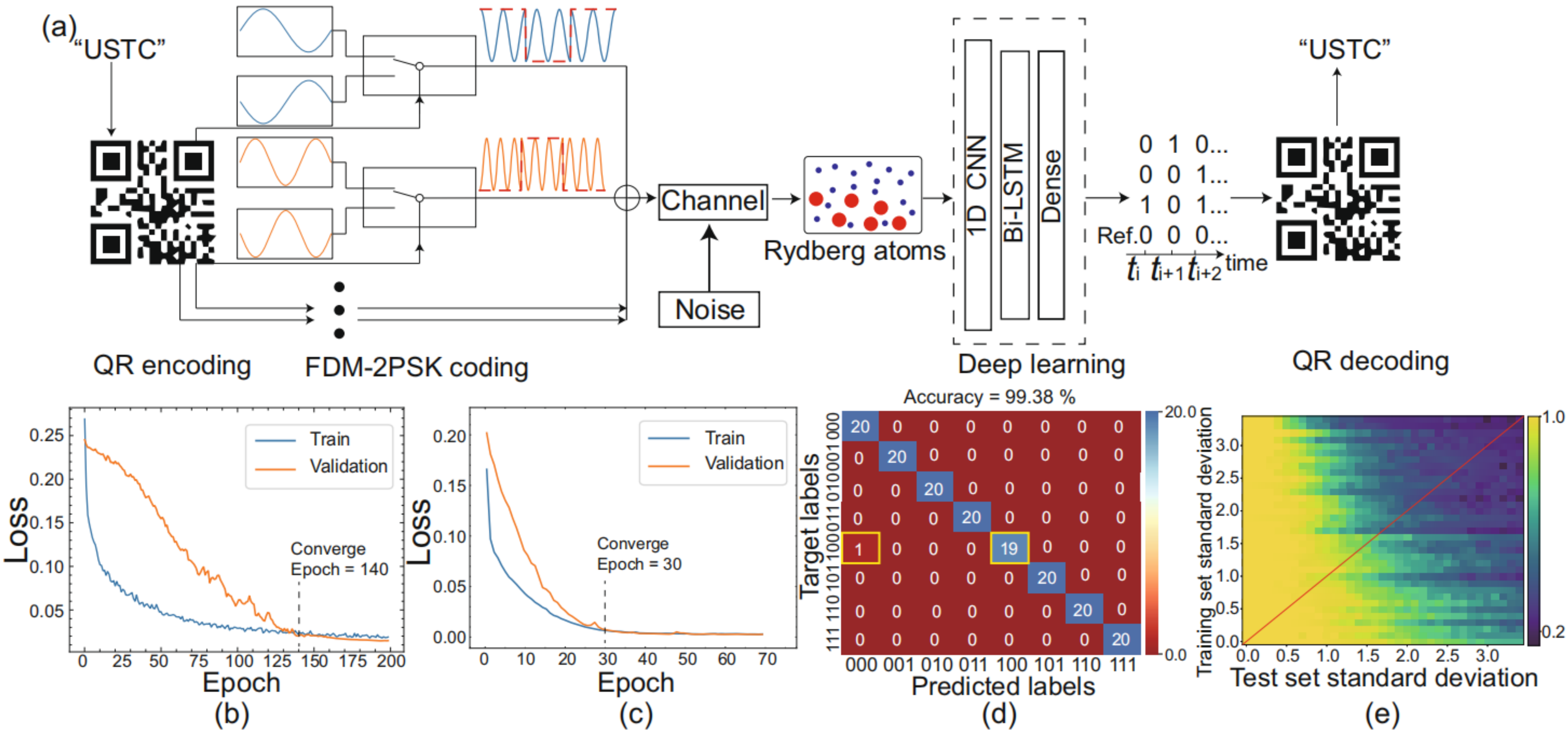
双向长短期记忆层

全连接层

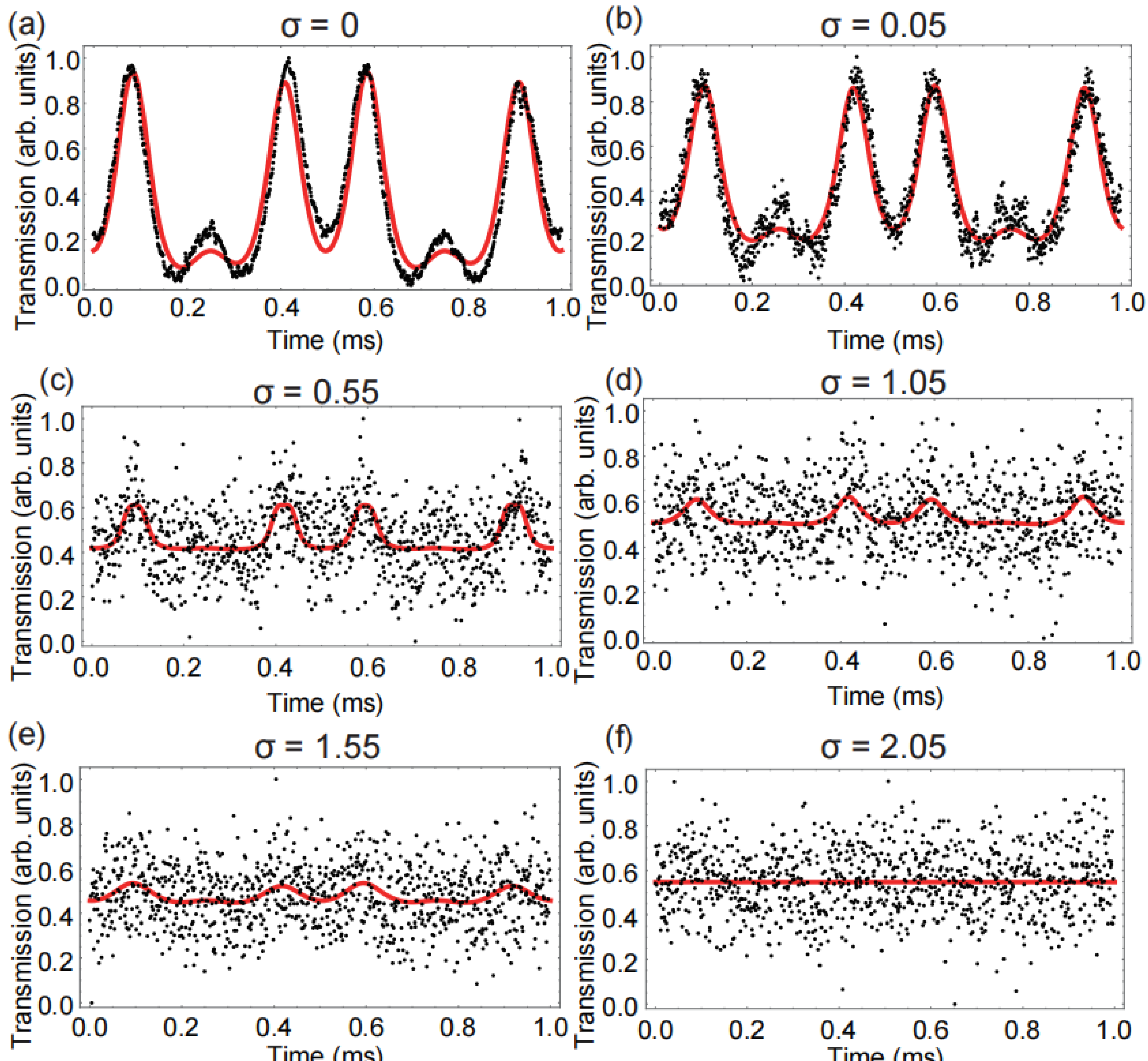
电磁诱导透明效应

工作内容

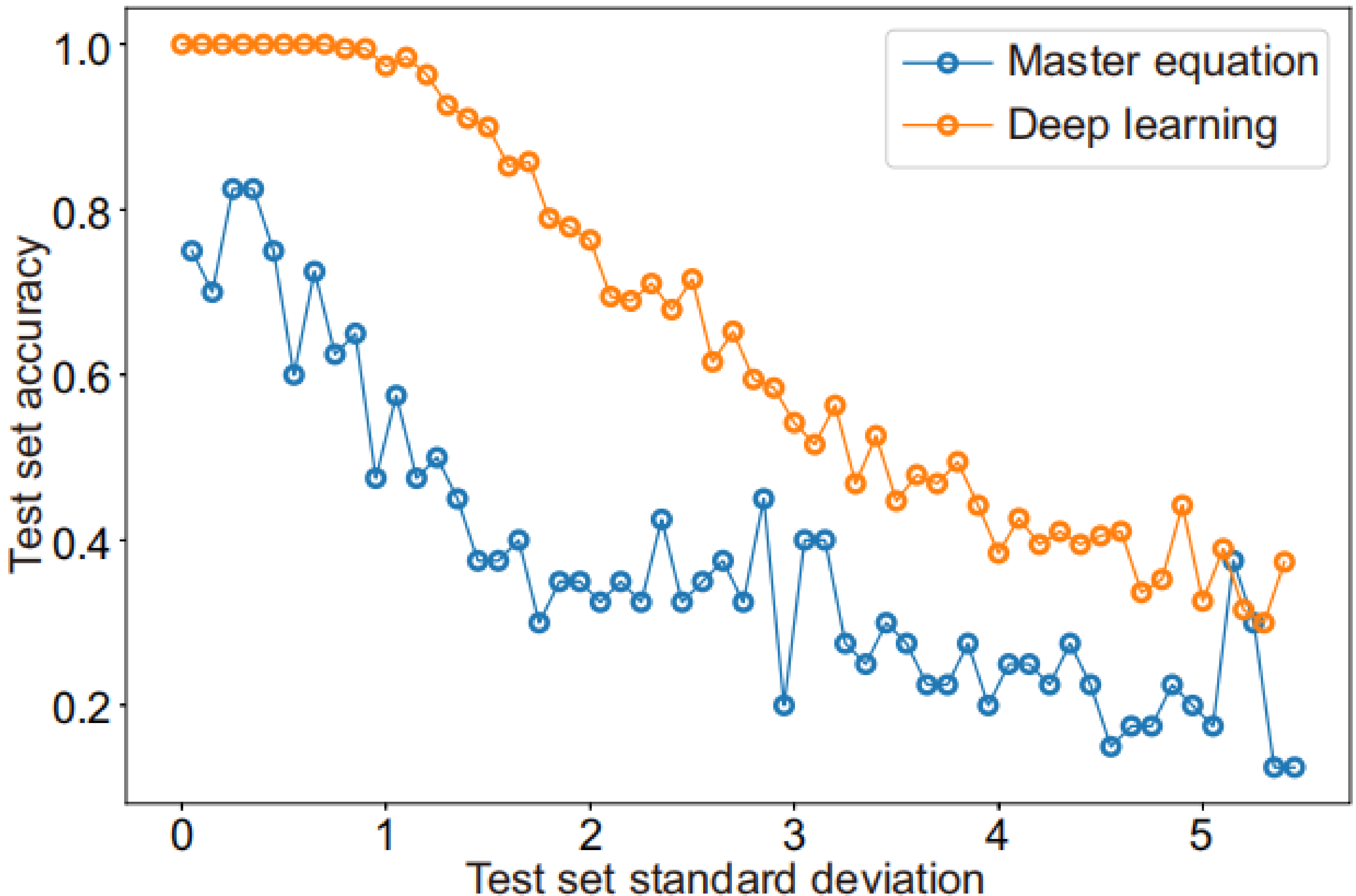
频分复用的二进制相移键控信号（一种在数字通信中广泛使用信号传输方式）



已取得的进展　　一阶主方程拟合结果

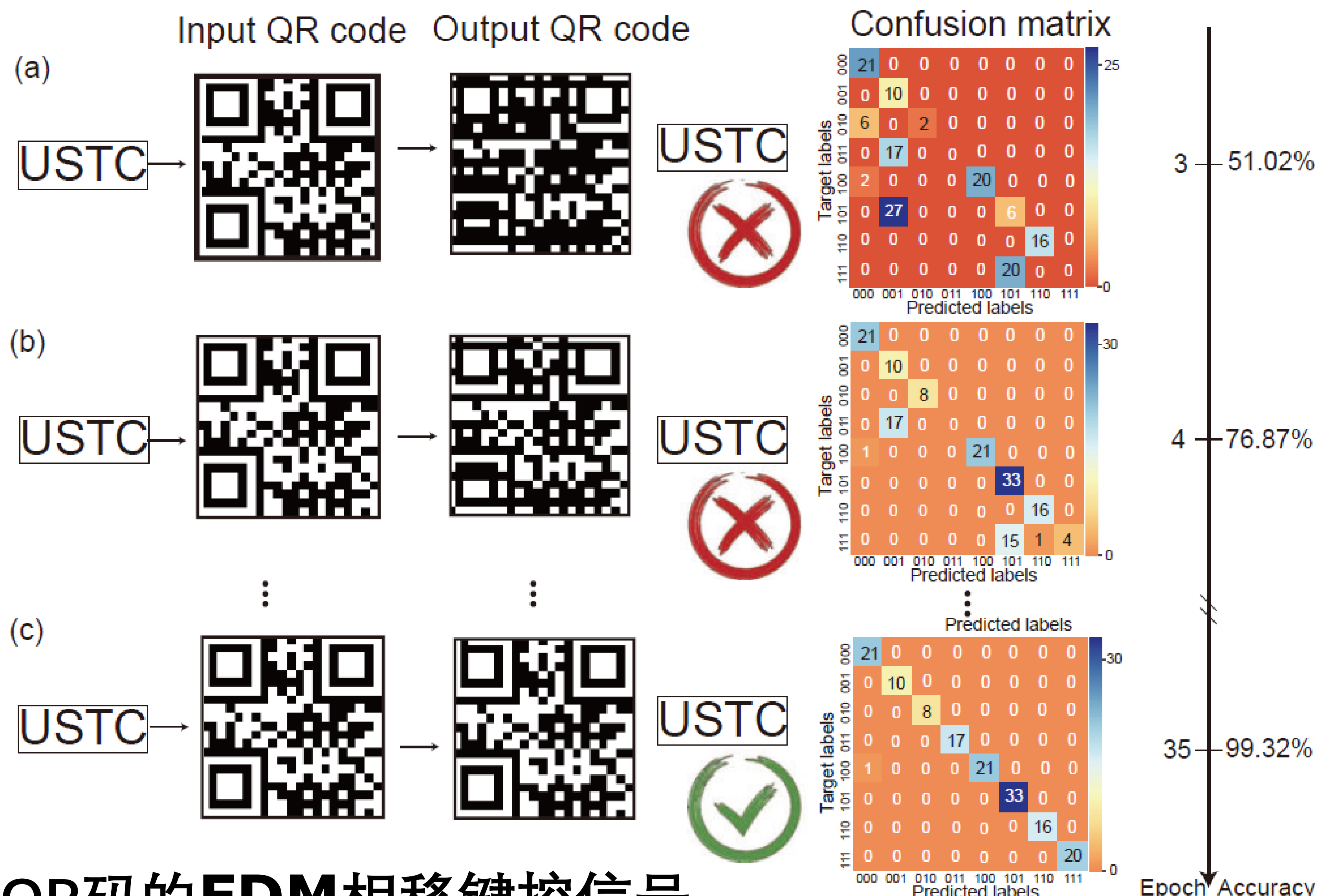


已取得的进展　主方程和机器学习的对比



已取得的进展

机器学习的结果

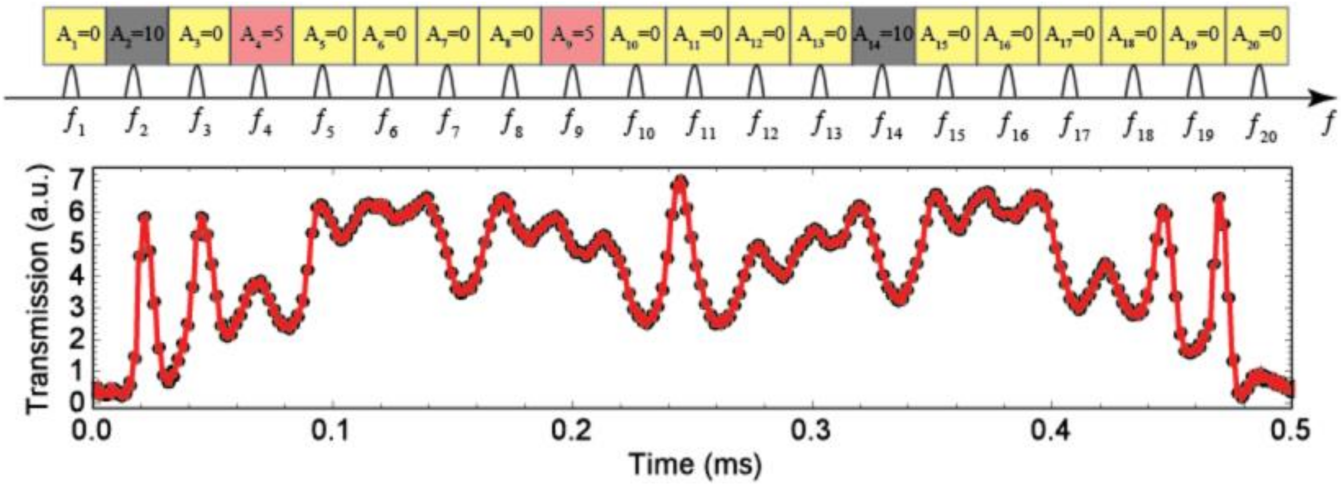


QR码的FDM相移键控信号

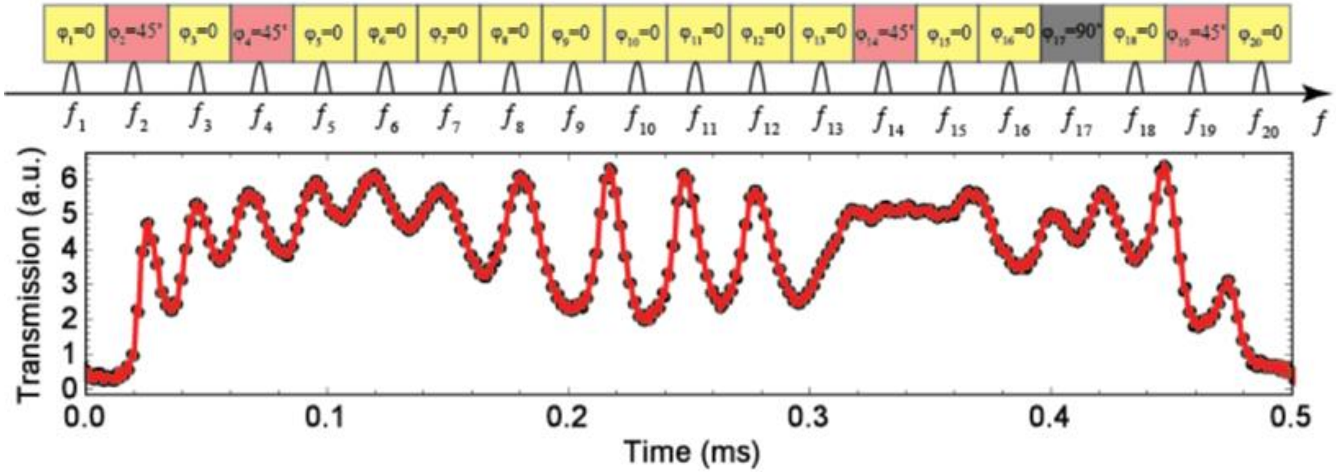
工作内容

调幅：20个频率振幅、相位编码和解码

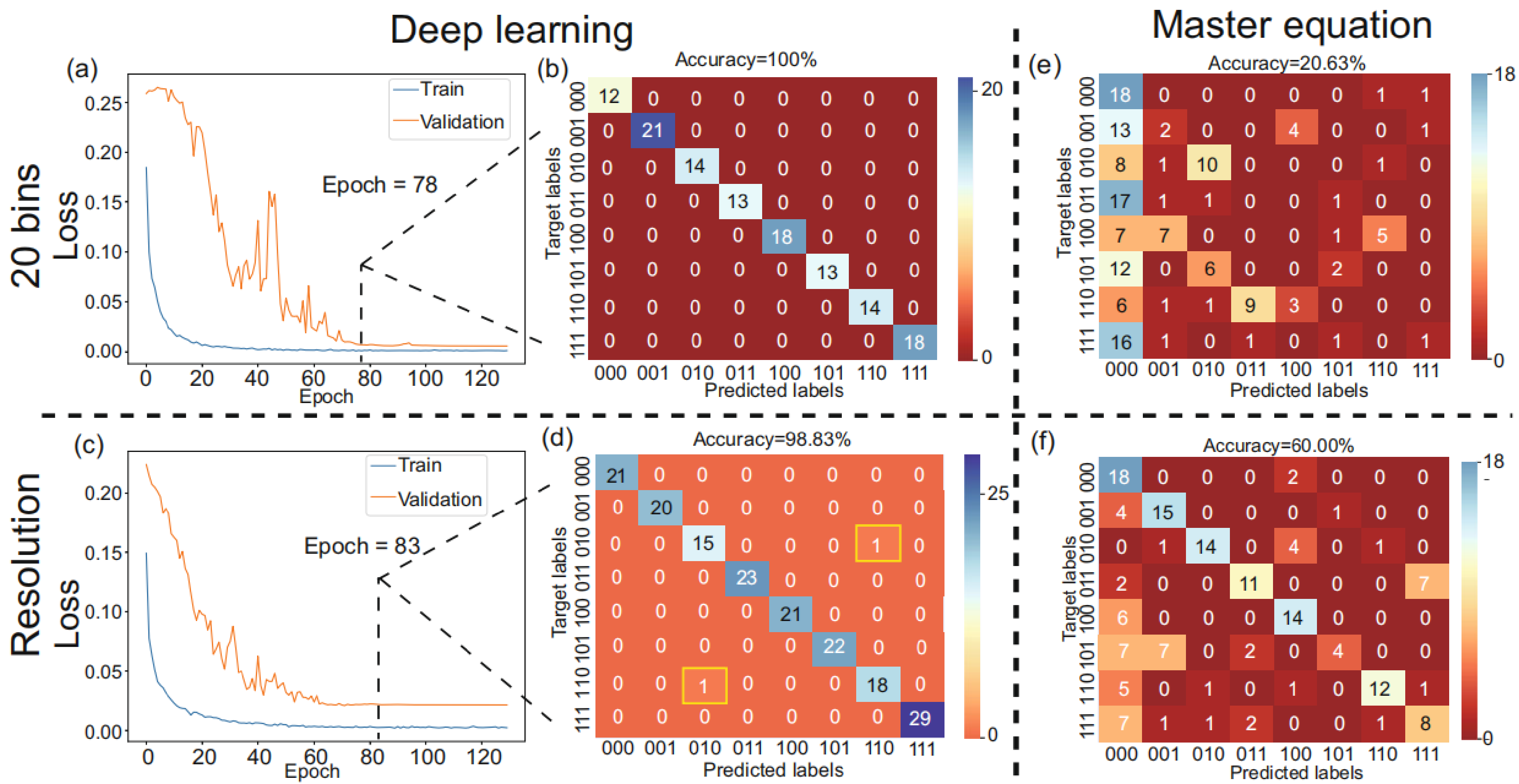
20位的幅度解码



20位的相位解码



已取得的进展 20个频率位的结果



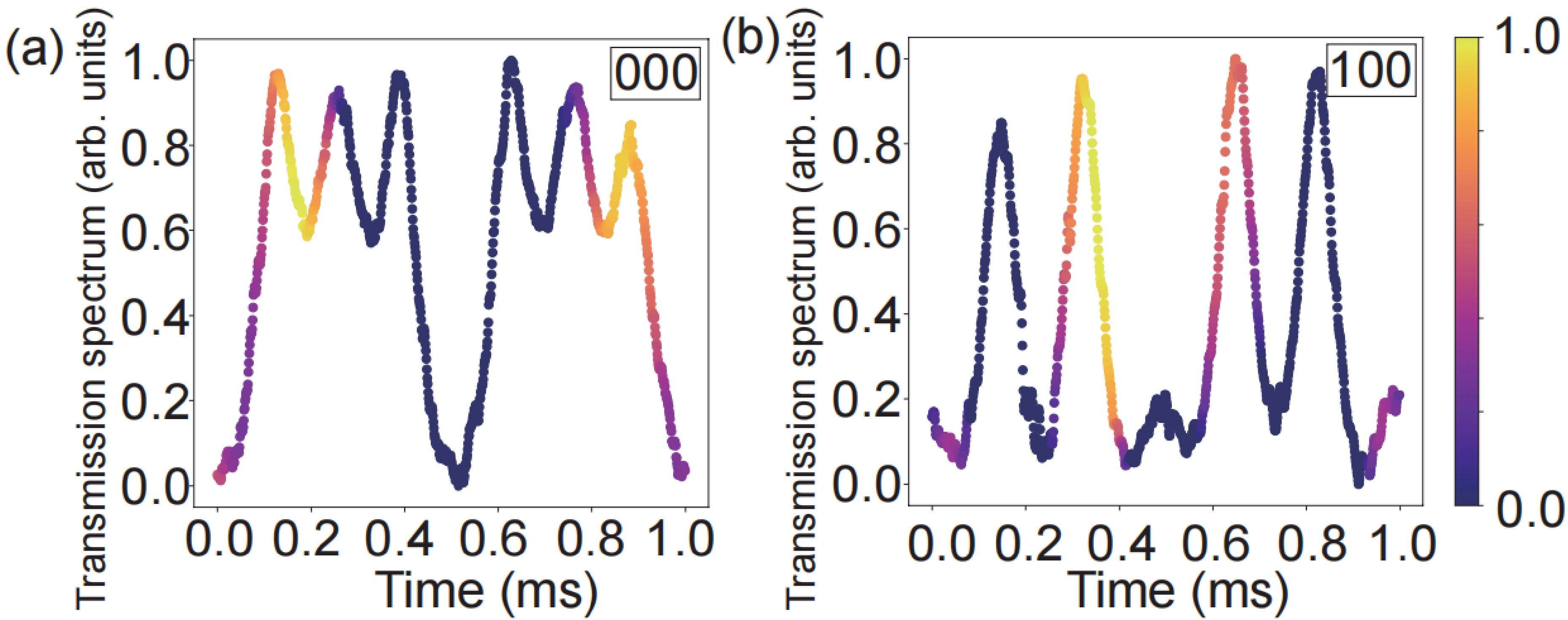
成功解码20路频分复用(FDM)信号

工作内容

中间结果可视化

Attention

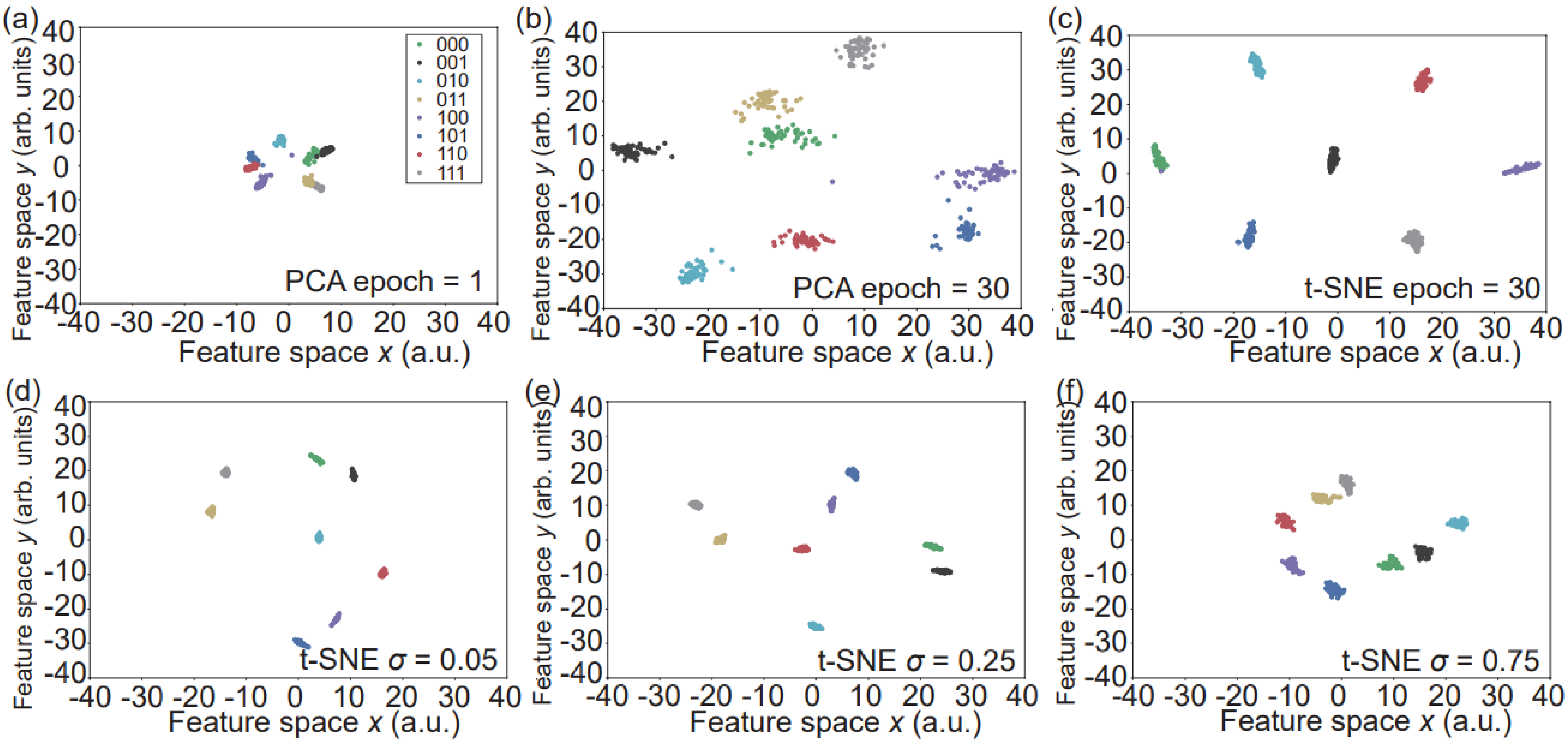
将模型对透射谱的不同部位的关注度可视化



已取得的进展

中间结果可视化（无监督）

将模型中间结果降维并可视化显示



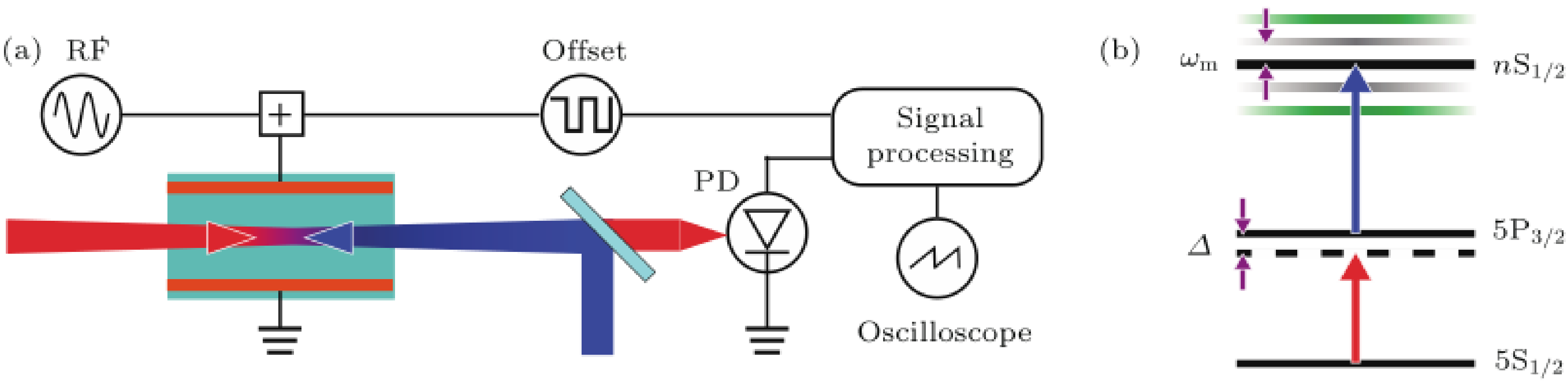
Part 2: 里德堡原子测量低频电场

Bang Liu, et al. Phys. Rev. Applied 18, 014045 (2022)

测量低频电场~30 MHz (波长为10米)

对于MHz调制的里德堡能级，弱场下里德堡能级在微波场的作用下产生一系列的边带信号以及AC-Stark能移。

$$\epsilon_N = E^{(0)} - \frac{\alpha}{2}\mathcal{E}_{\mathrm{dc}}^2 - \frac{\alpha^2}{4}\mathcal{E}_{\mathrm{ac}}^2 + N\hbar\omega_{\mathrm{m}}$$



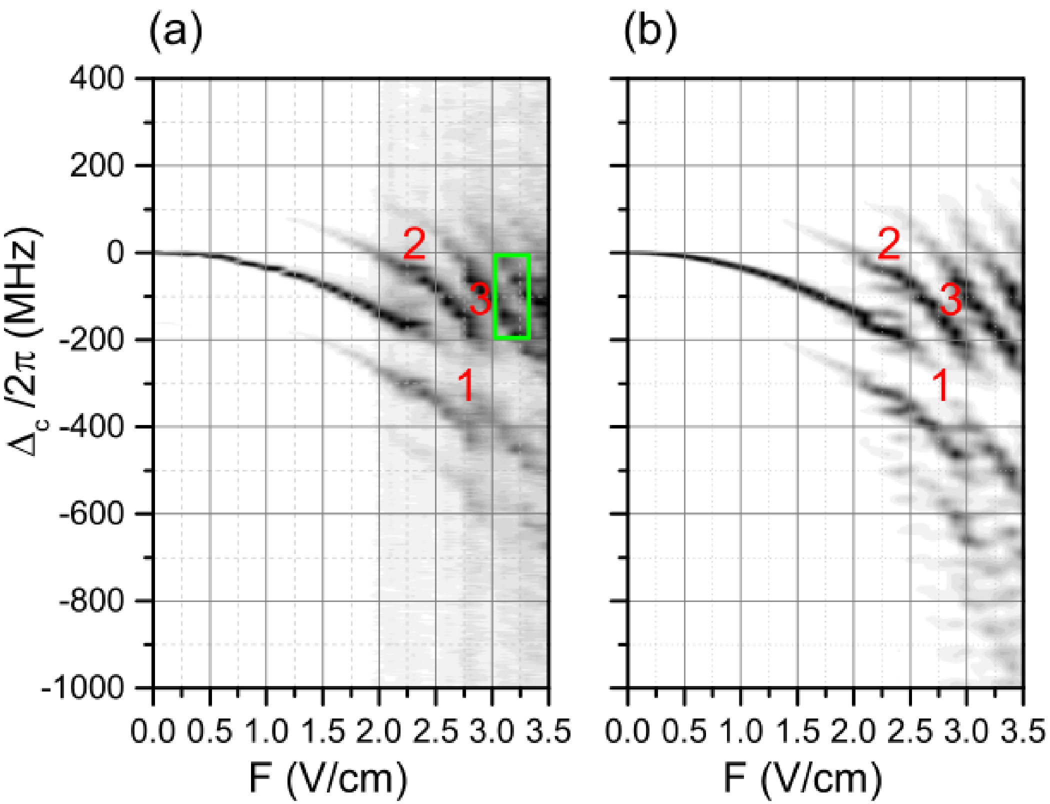
测量低频电场

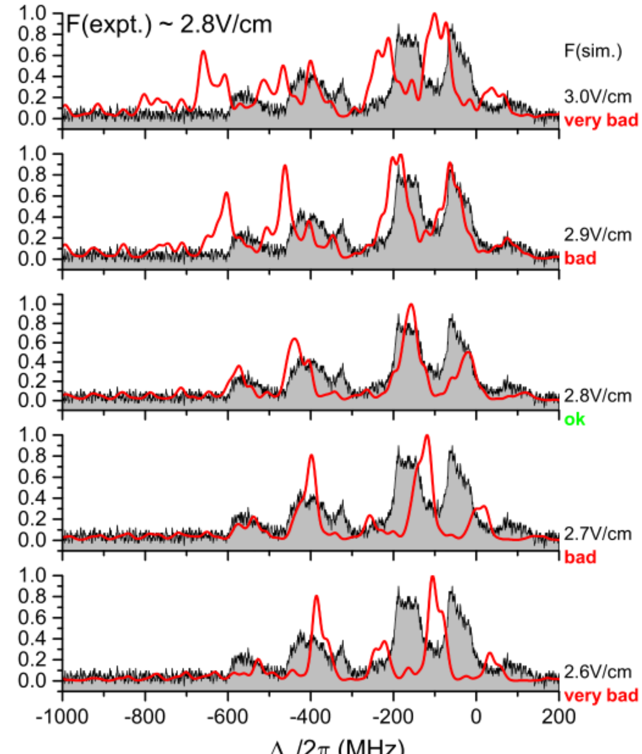
强场下的 Floquet 光谱分析

$$\hbar\omega_{\nu,N} = W_\nu + N\hbar\omega_m,$$

$$S_{\nu,N} = (eF_L/\hbar)^2 \left| \sum_k \tilde{C}_{\nu,k,N}\, \hat{\epsilon} \cdot \langle k|\hat{\mathbf{r}}|6P_{3/2}, m_j\rangle \right|^2$$

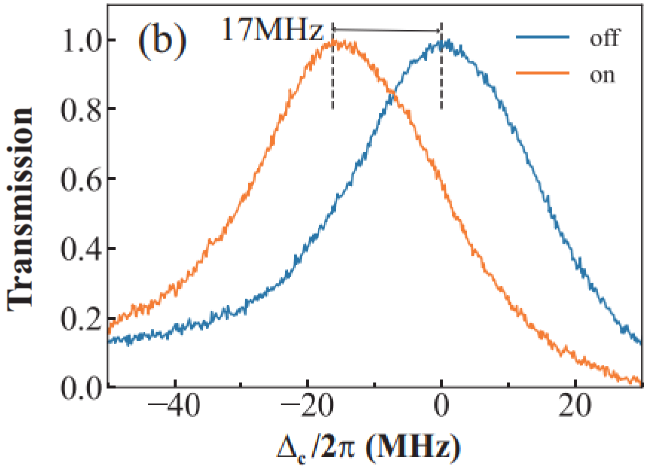
通过比较计算光谱与实验所得光谱，可以得到电场强度值，其不确定度为**~3%**，所能测量的最大场可达到**50V/cm** 的量级，无法实现高灵敏度的低频微弱电场测量**(V/cm)**





Physical Review A, 2016, 94(2): 023832.

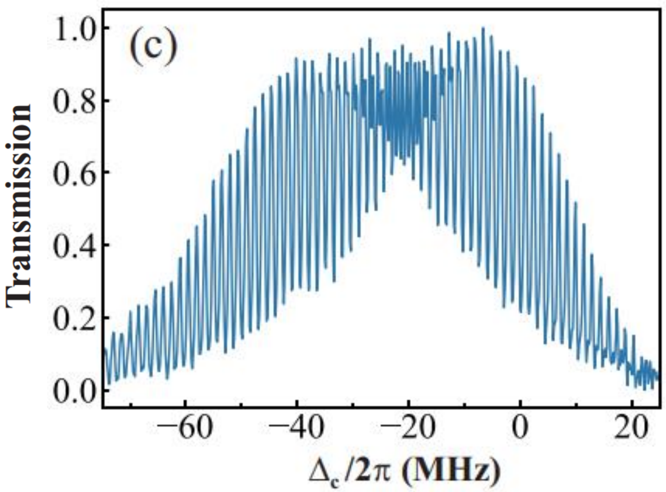
进展2：测量低频电场—指标



实验原理

The ac Stark shift $\delta = -\frac{1}{2}\alpha E^2$

α: 原子极化；E：电场幅度



$$\delta = -\frac{1}{2}\alpha\left(\mathbf{E}_{\mathrm{LO}} + \mathbf{E}_{\mathrm{sig}}\right)^2$$

$$\bar{\delta} = \bar{\delta}_0 - \frac{1}{2}\alpha\left[E_{\mathrm{LO}} E_{\mathrm{sig}} \cos(\Delta\omega * t)\right]$$

$$\bar{\delta}_0 = -\frac{1}{4}\alpha\left(E_{\mathrm{LO}}^2 + E_{\mathrm{sig}}^2\right)$$

进展2：测量低频电场—指标

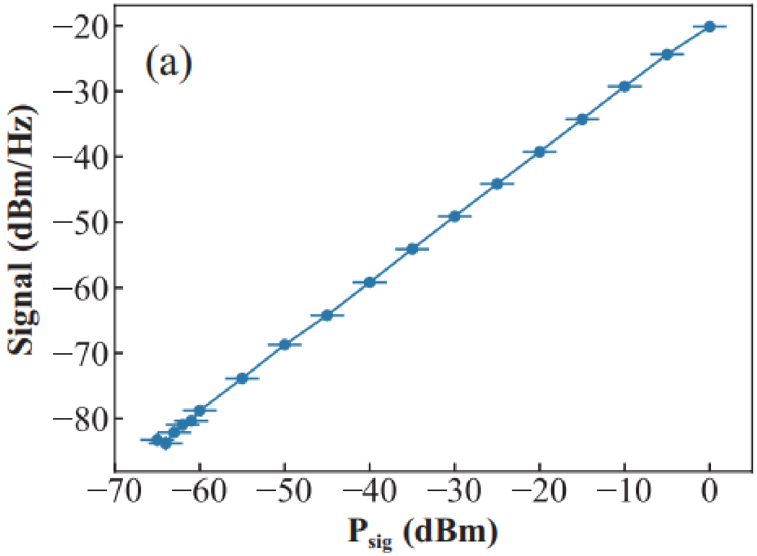
目前我们测得的灵敏度和动态范围如下:

灵敏度：~37.3 μV/cm/Hz$^{1/2}$

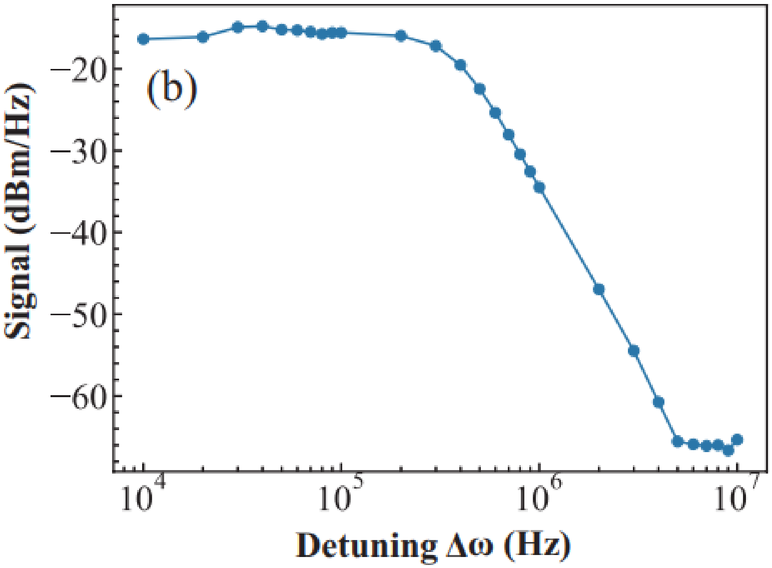
电场强度动态范围：~ 65dB

瞬时带宽: 1 MHz

动态范围



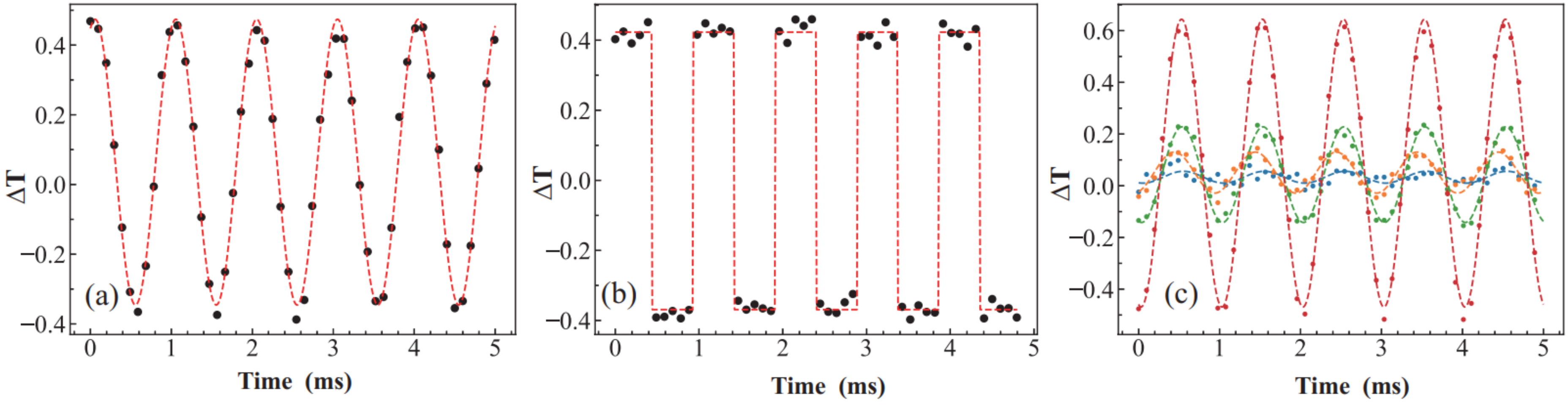
频率



进展2：信号调制

基于里德堡原子的AM调制信号解调过程

正旋调制　　方波调制　　改变调制幅度



解调保真度达到 98%

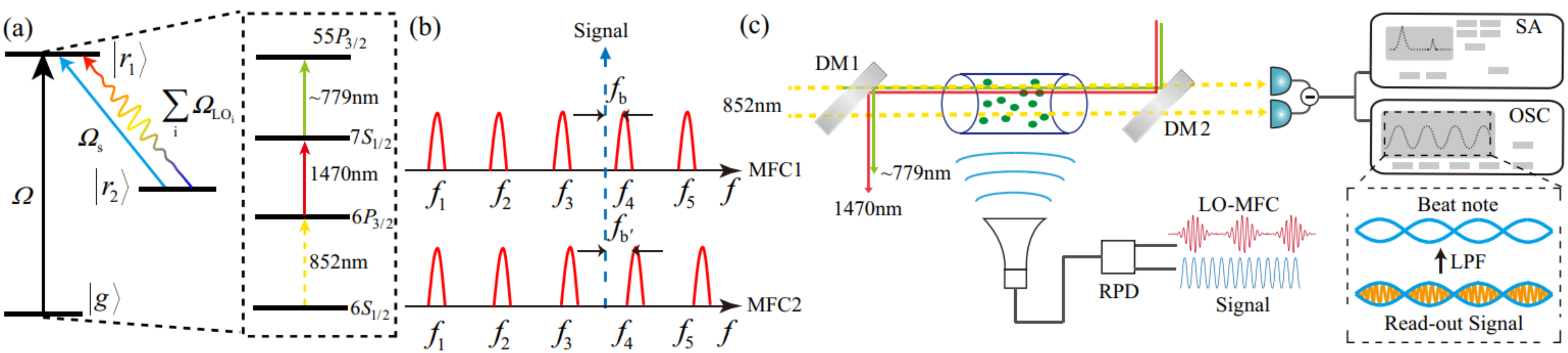
Part 3: 里德堡原子微波频率梳

Li Hua Zhang, et al. Phys. Rev. Applied. 18, 014033 (2022)

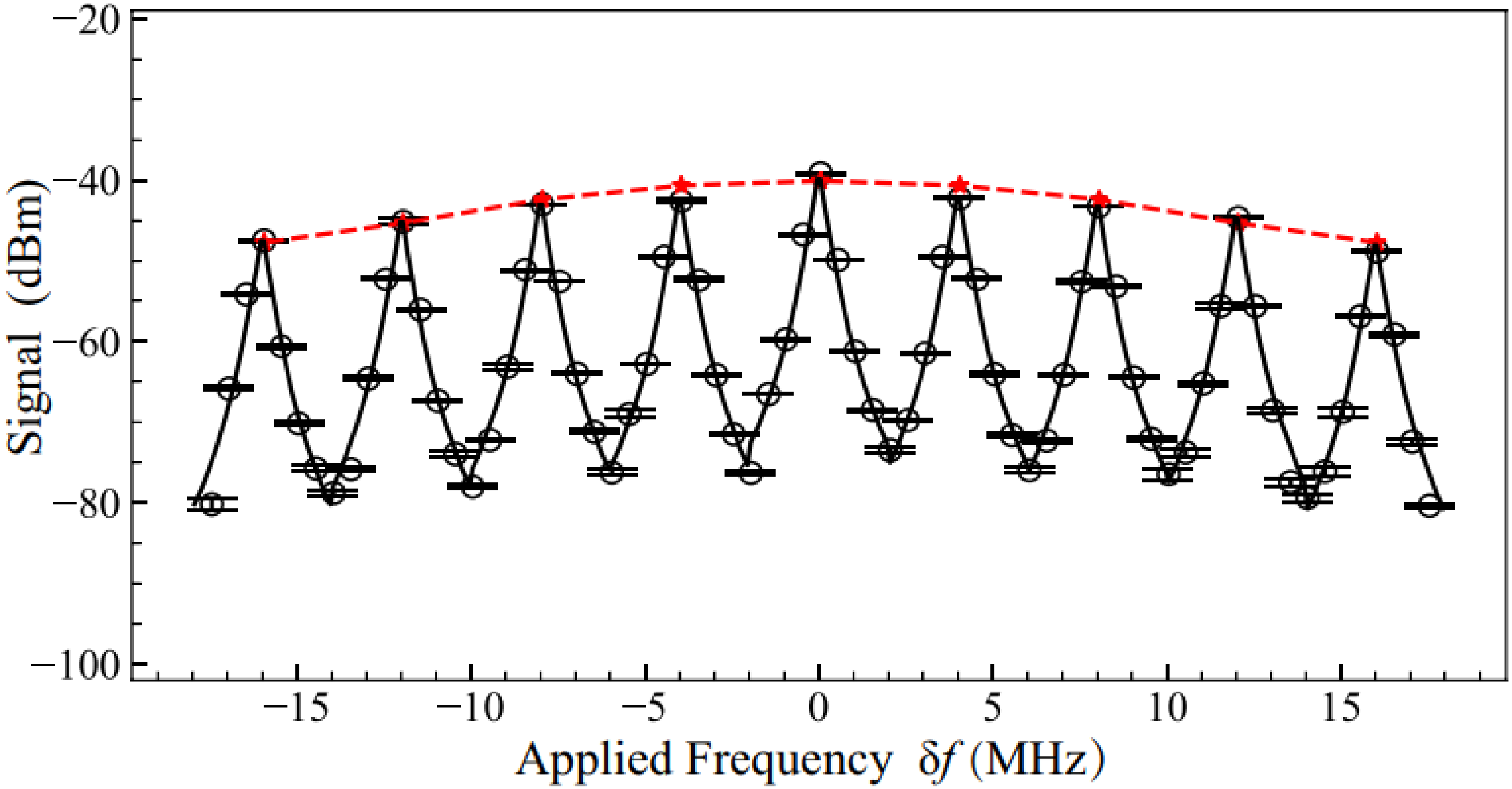
进展3：频率梳测量微波的频率

动机： 用超外差法实现的微波频率测量，无法鉴别和 f_{LO} 相差 $\pm\delta$ 频率的信号频率，用两列频率梳代替原来的单一频率的本振场，可以解决这个问题。

通过拍频反推级次和频率偏置 ⇨ 信号频率： $f_{sig} = mf_{\text{period}} + f_{offset}$

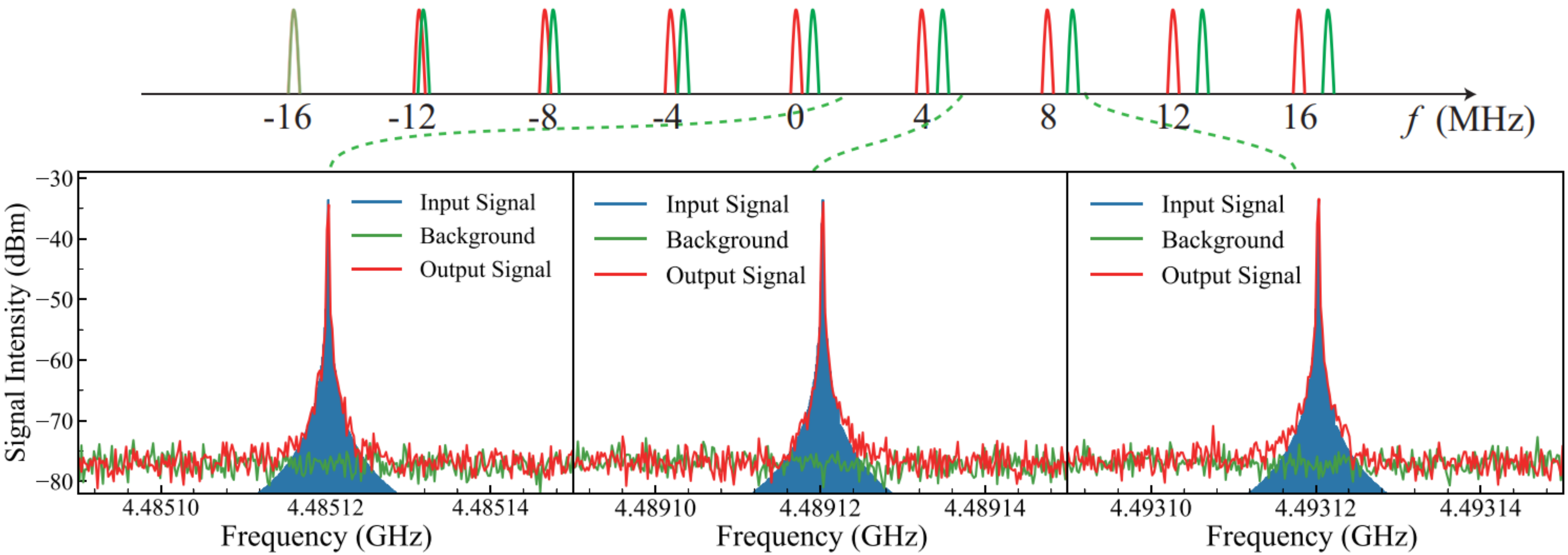


进展3：频率梳测量微波的频率



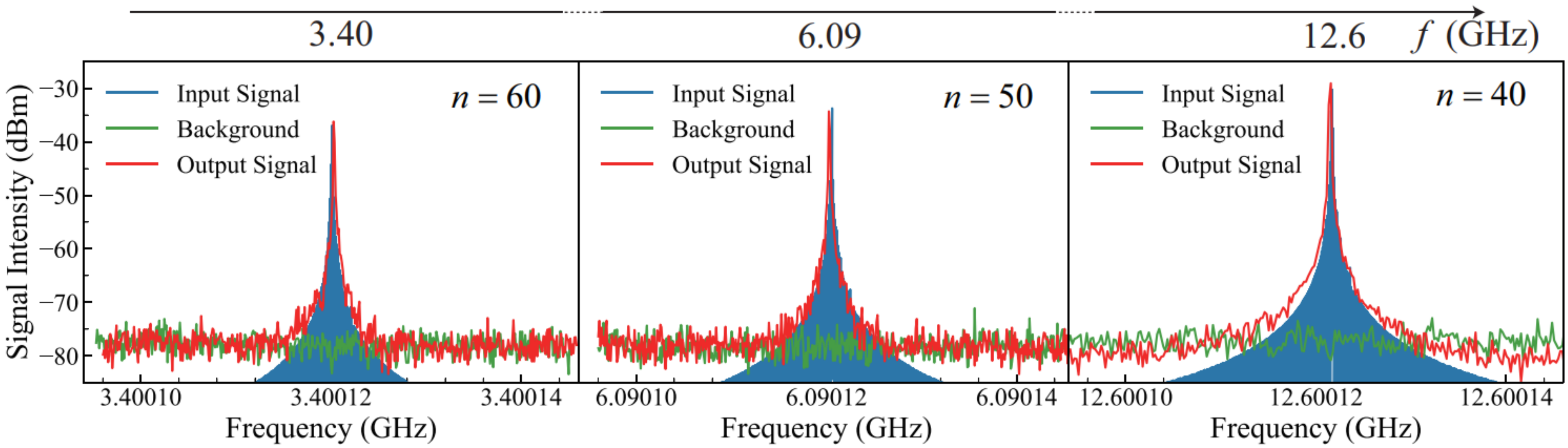
进展3：频率梳测量微波的频率

可以测量不同频率



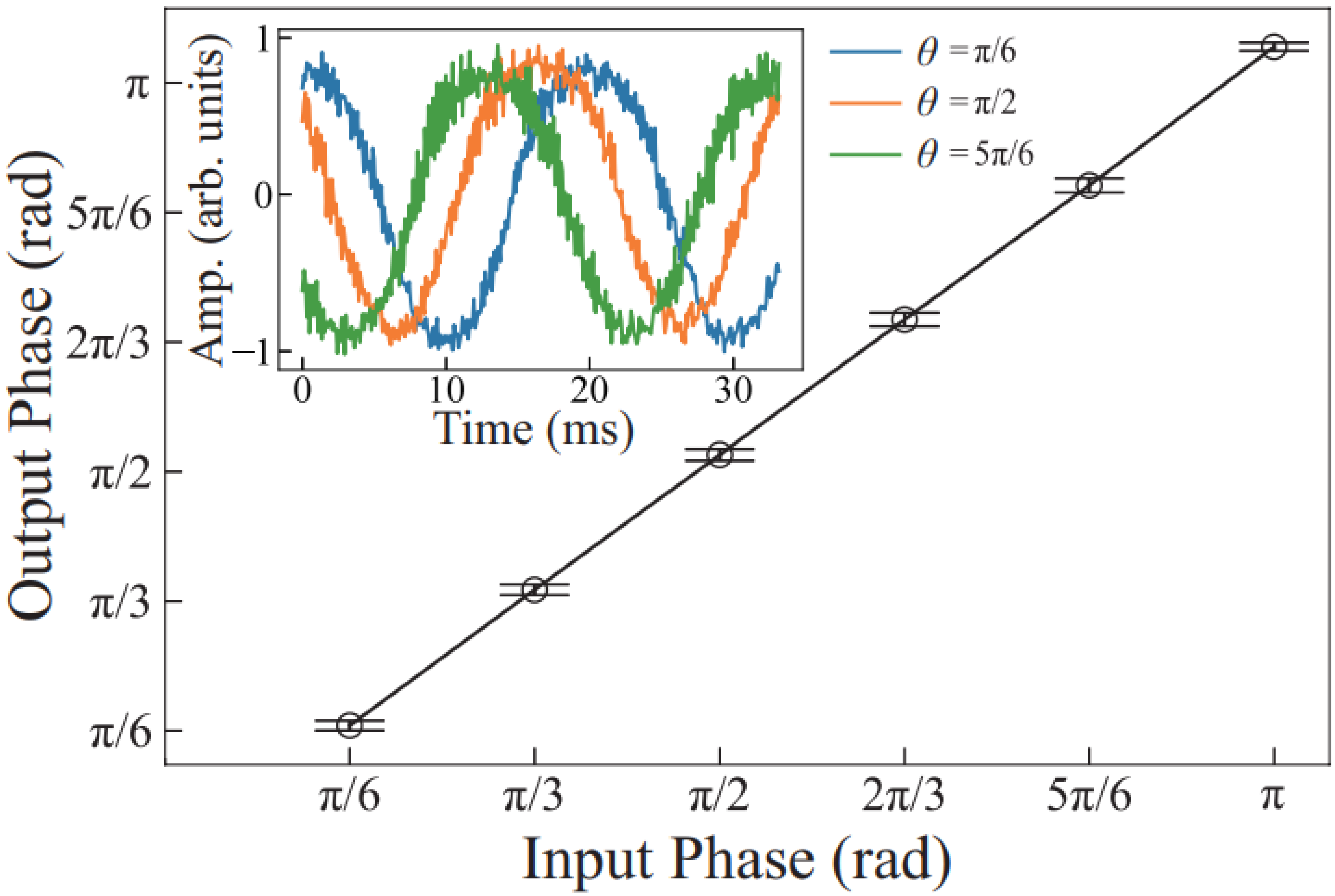
进展3：频率梳测量微波的频率

改变不同的主量子数



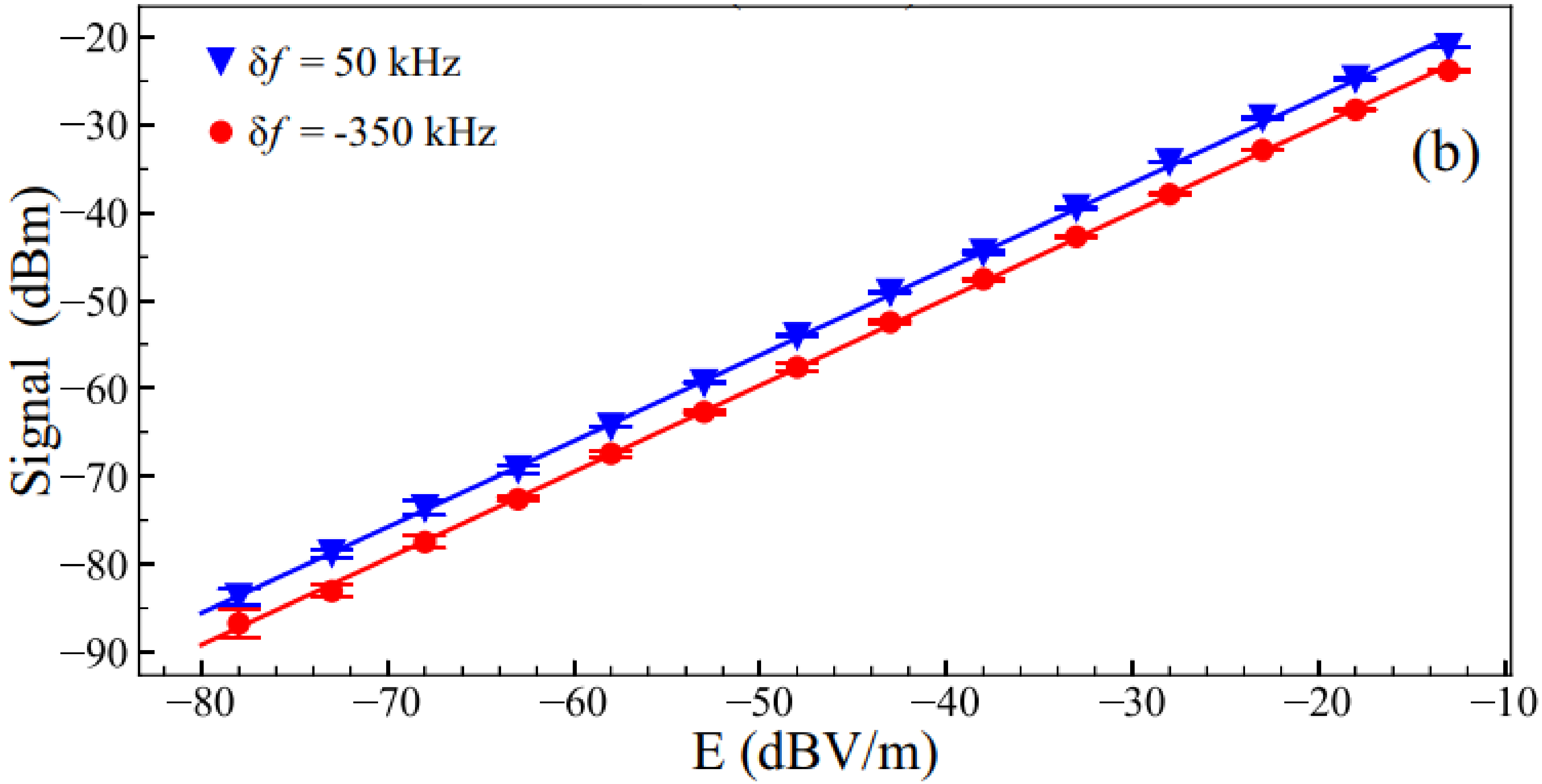
进展3：频率梳测量微波的频率

测量信号的相位



进展3：频率梳测量微波的频率

测量信号的幅度



三、基于多体临界的增强传感

Dong-Sheng Ding *et al. to appear in Nature Physics* (2022)

工作内容

PHYSICAL REVIEW A **78**, 042105 (2008)

Quantum criticality as a resource for quantum estimation

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Dynamical phase transitions as a resource for quantum enhanced metrology

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High-Density Quantum Sensing with Dissipative First Order Transitions

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工作内容

PHYSICAL REVIEW LETTERS **124,** 120504 (2020)

Critical Quantum Metrology with a Finite-Component Quantum Phase Transition

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Dynamic Framework for Criticality-Enhanced Quantum Sensing

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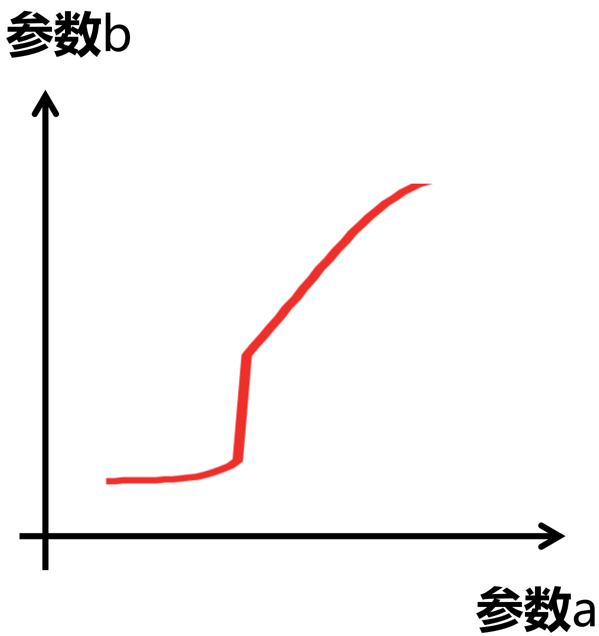
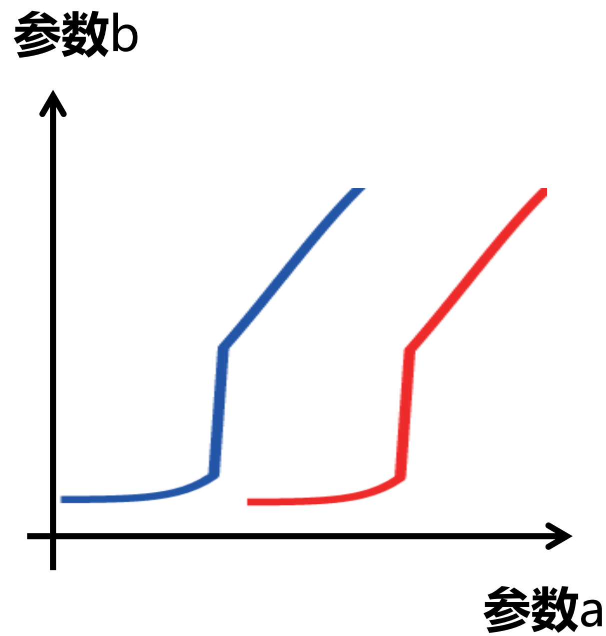
工作内容

虽然有大量理论报道利用强关联系统的临界状态去做量子传感，**从理论被提出来十几年后**，但在实验上一直未能成功实现。

工作内容

主要原因： 多体系统相变过程难制备、临界点的外场调控技术欠缺等。

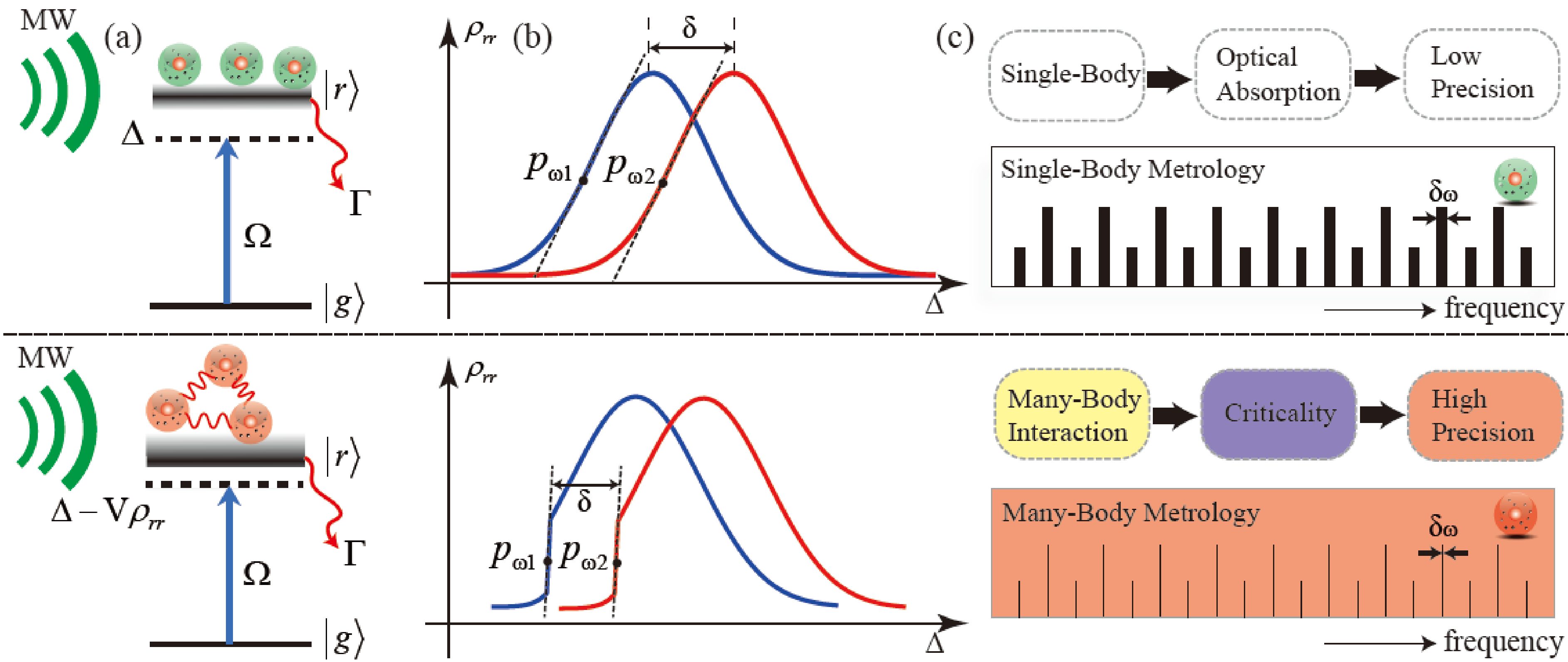




多体系统相变过程难制备　　**临界点的外场调控**

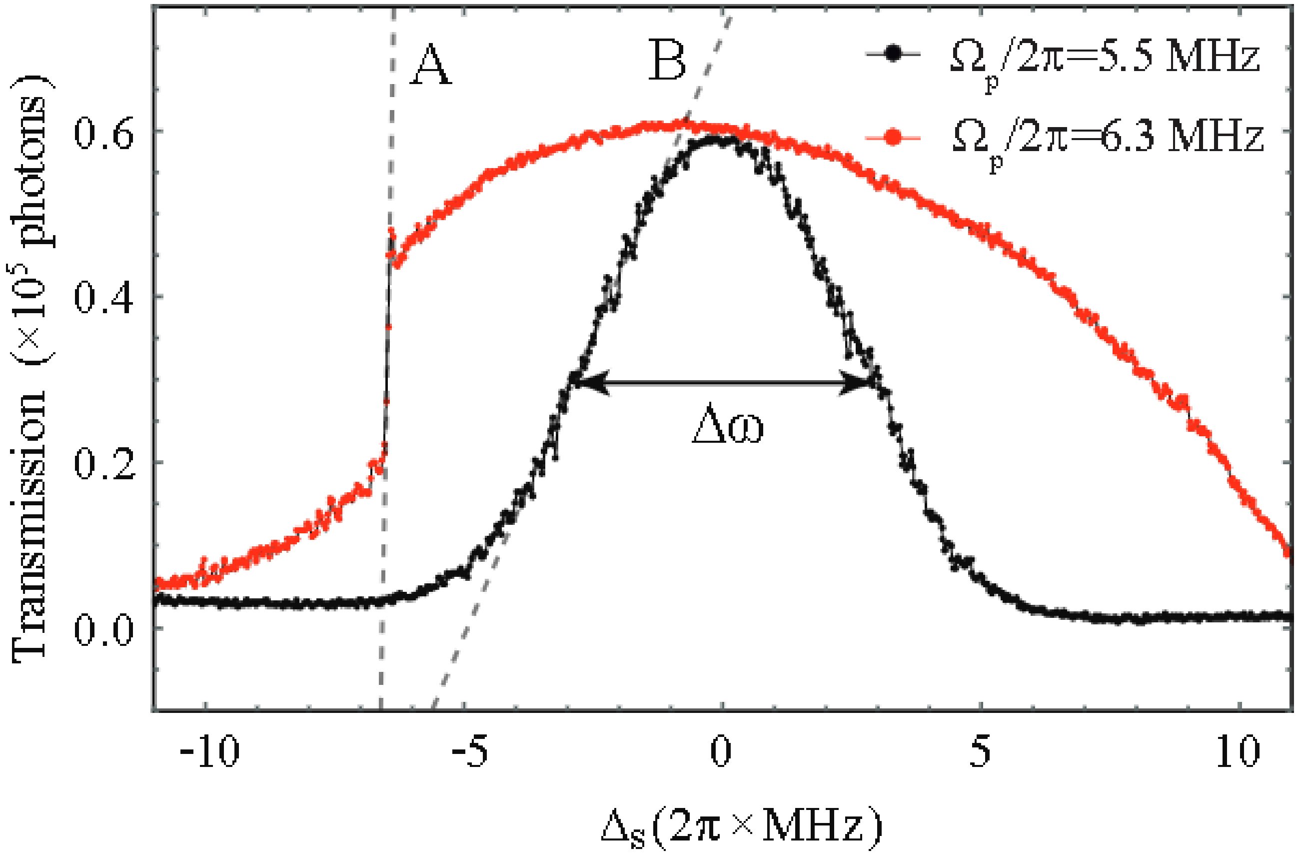
工作内容

单体模型



多体模型

工作内容

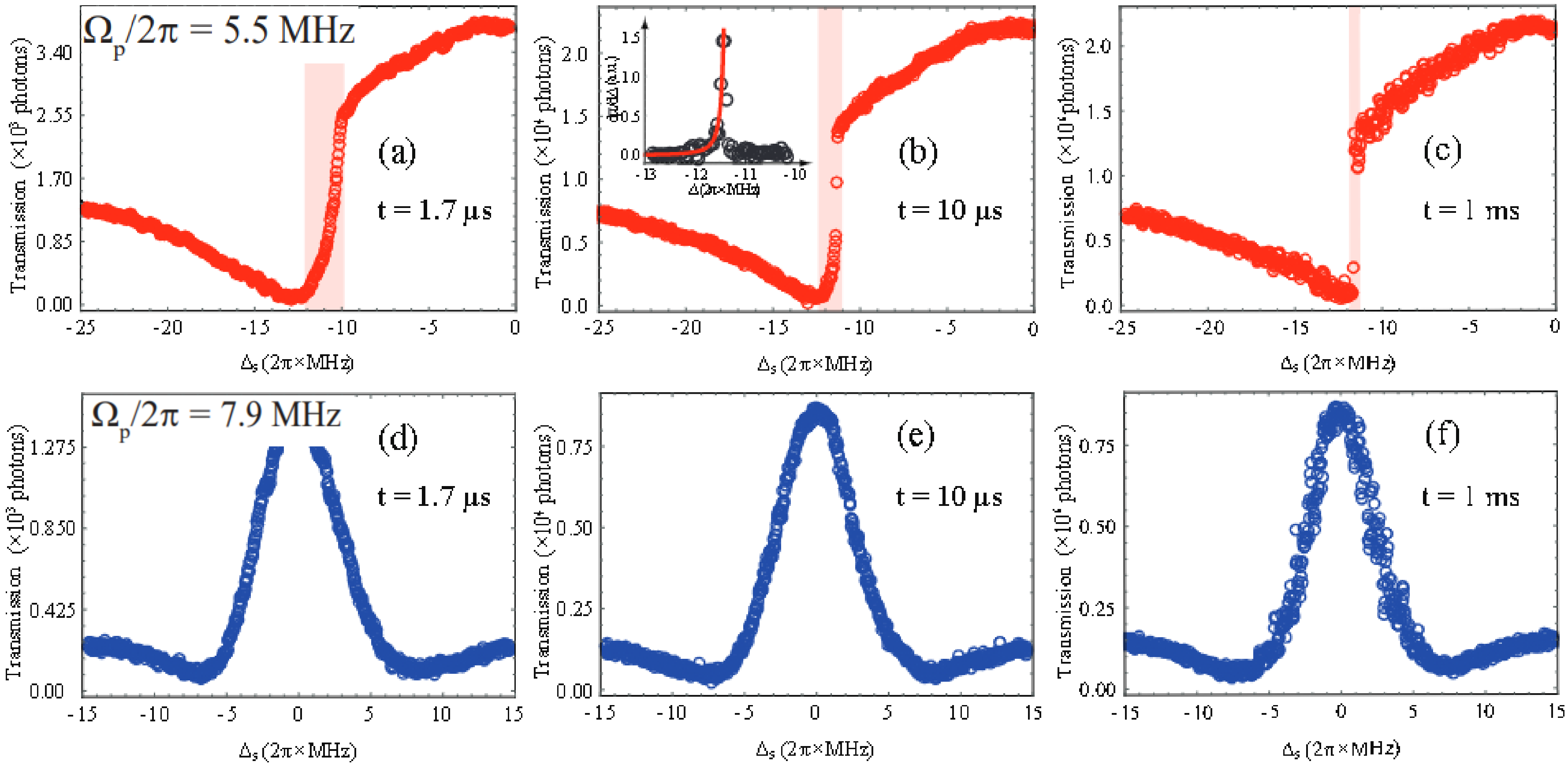


$$\left.\frac{\mathrm{d}\rho_{rr}}{\mathrm{d}\Delta}\right|_{\Delta=\Delta_c} = \frac{1}{V+\sqrt{(\Gamma^2+2\Omega^2)/3\rho_{rr}^2}}$$

$$\beta = \left.\frac{\mathrm{d}\rho_{rr}}{\mathrm{d}\Delta}\right|_{V\neq 0} \Big/ \left.\frac{\mathrm{d}\rho_{rr}}{\mathrm{d}\Delta}\right|_{V=0}$$

工作内容

扫描控制光的detuning



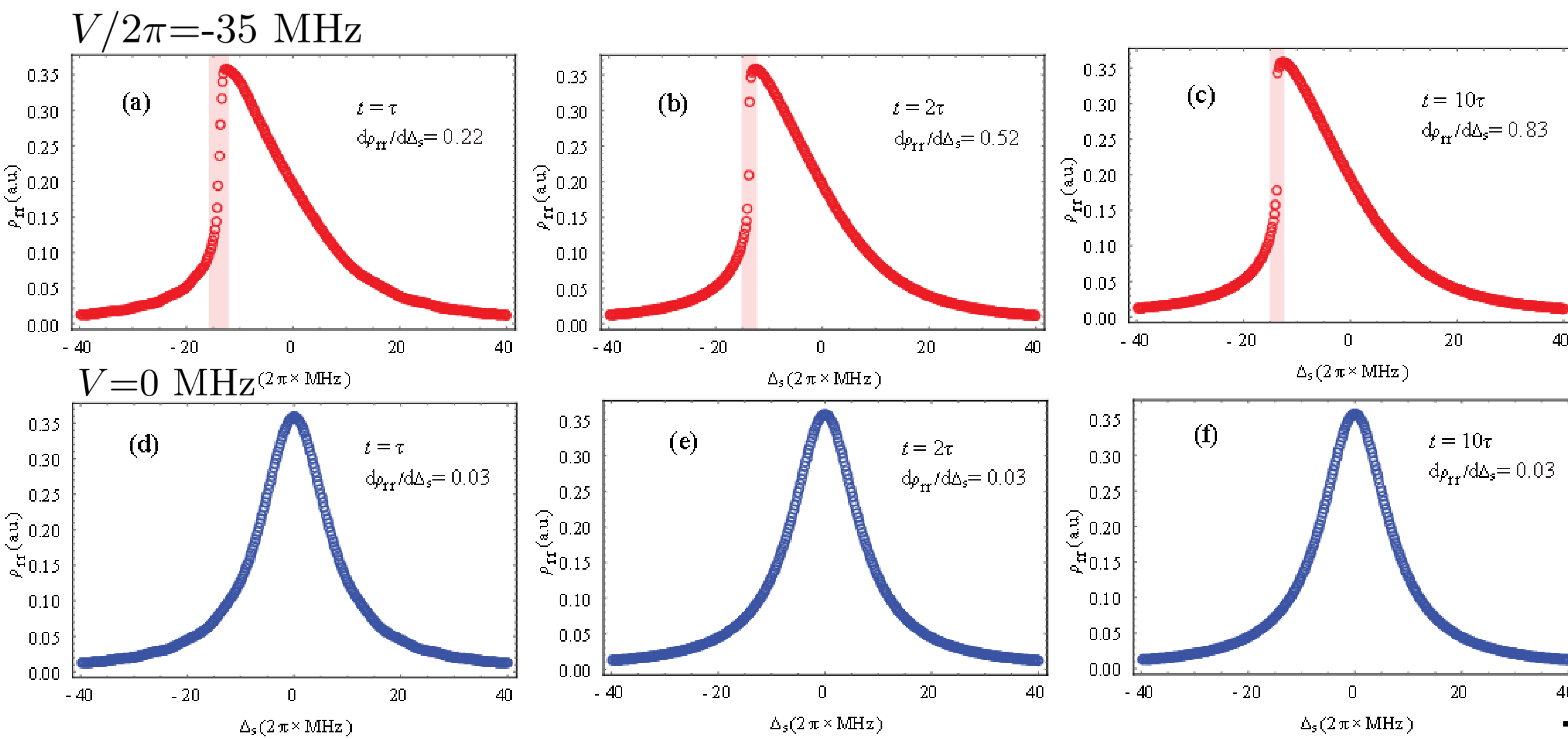
单体的波形不发生变化，多体光谱发生改变。

工作内容

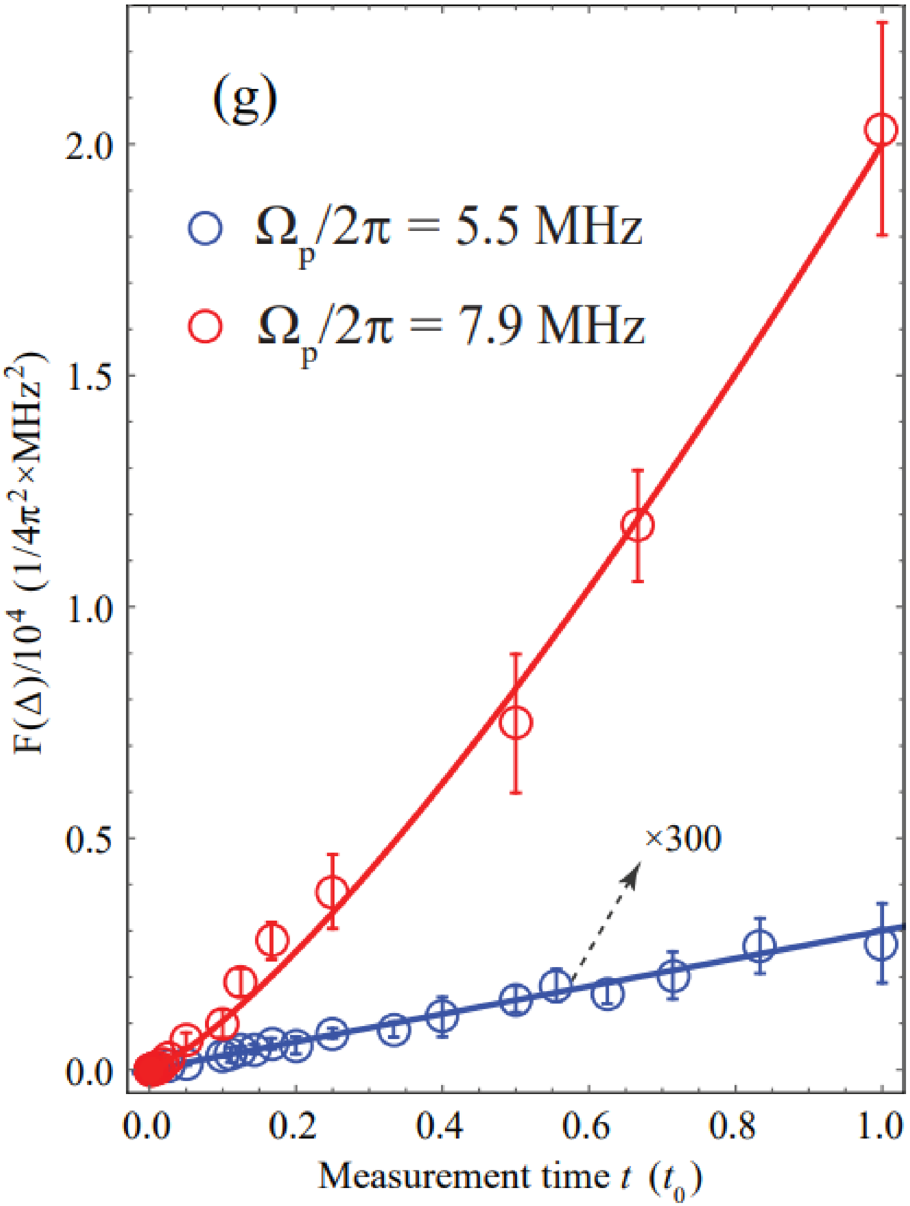
理论计算：平均场+相互作用的二能级原子

$$\dot{\rho}_{\mathrm{gr}} = i\frac{\Omega}{2}\left(\rho_{\mathrm{rr}} - \rho_{\mathrm{gg}}\right) + i\Delta_{\mathrm{eff}}\rho_{\mathrm{gr}} - \frac{\Gamma}{2}\rho_{\mathrm{gr}}$$

$$\dot{\rho}_{\mathrm{rr}} = -i\Omega\left(\rho_{\mathrm{gr}} - \rho_{\mathrm{rg}}\right) - \Gamma\rho_{\mathrm{rr}}$$



工作内容



Fisher Information

$$F(\Delta) = \frac{\overline{\mu}'(\Delta)^2}{Var(\mu)}$$

Cram´er-Rao bound

$$\delta\Delta \geq \frac{1}{\sqrt{F(\Delta)}}$$

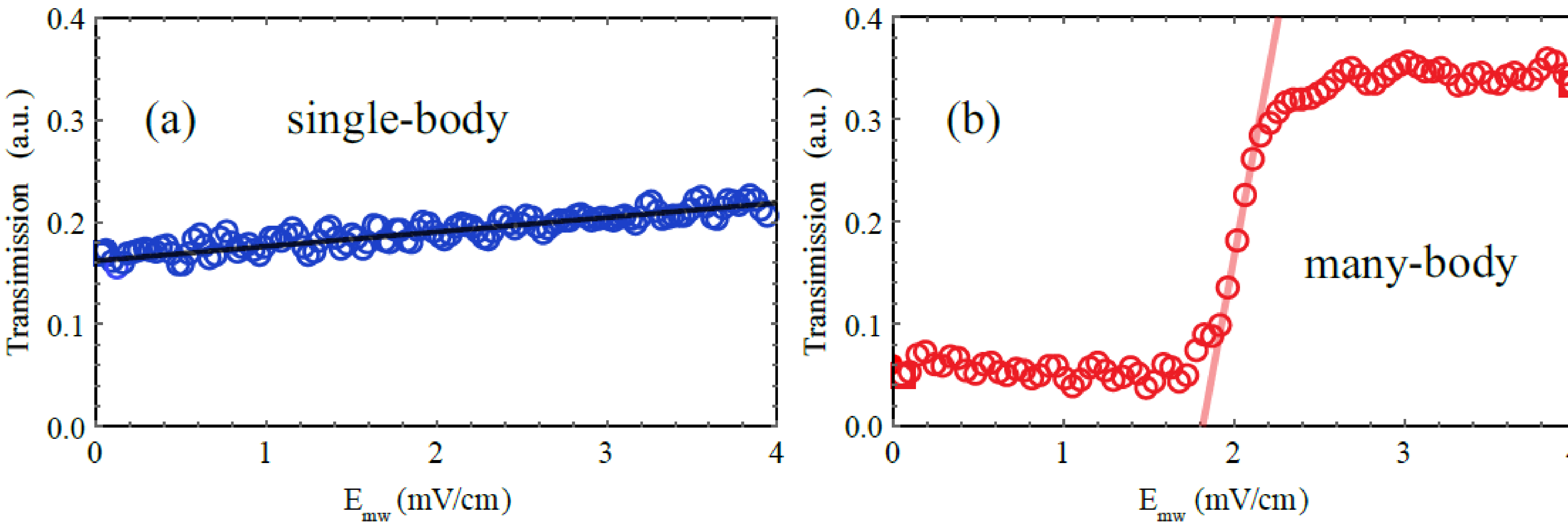
$$F = A(t/t_0)^\lambda$$

多体：$\lambda = 1.28$

单体：$\lambda = 1$

工作内容

每个数据点5微秒



最后的灵敏度49 nV/cm/Hz$^{1/2}$

已被Nature Physics正式接收

THANKS!