自旋量子技术及其前沿交叉应用

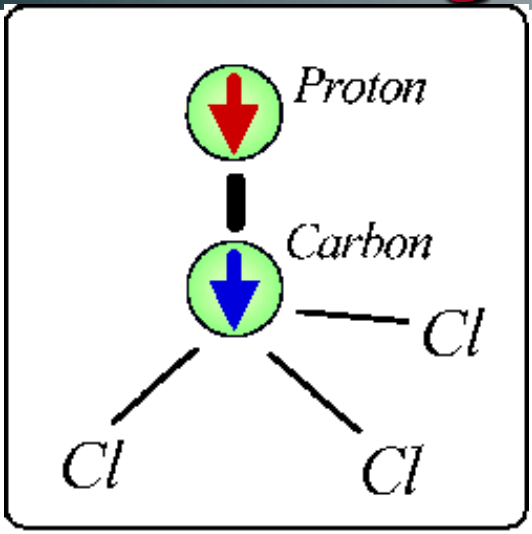
彭新华

中国科学技术大学近代物理系

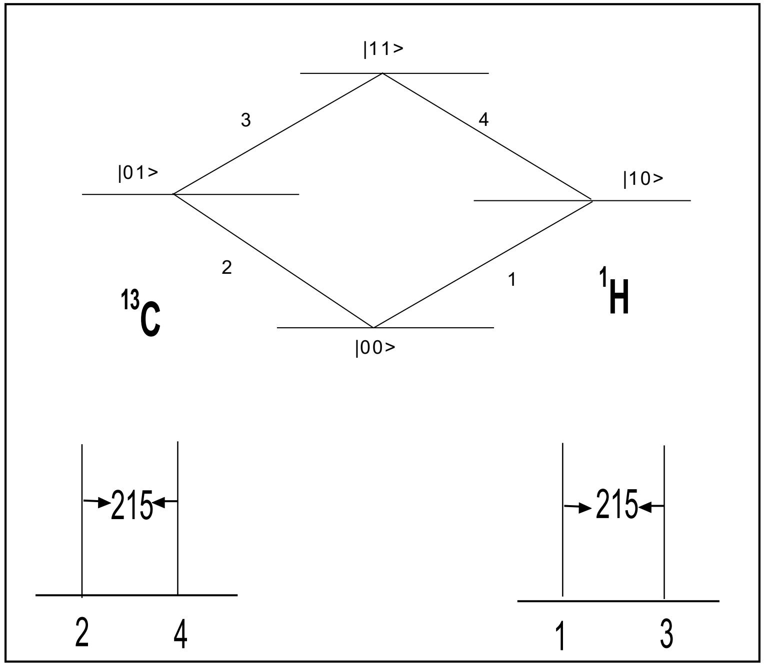
内容摘要

- 第一部分：　自旋和自旋磁共振
- 第二部分：　自旋量子计算与模拟
- 第三部分：　自旋量子精密测量

NMR QIP



$|0\rangle|0\rangle$



Bruker ARX-500

- **Qubit representation (Spin ½)**
- **Initial state preparation**

  ‘pseudo-pure state’ preparation techniques
- **Unitary operation**

  Hamiltonian $H \square -\omega_a I_z^a - \omega_b I_z^b \square 2\pi J_{ab} I_z^a I_z^b \square H^{rf}$
- **Readout**

  Quantum state tomography + NMR spectroscopy

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Nobel Prize in Physics 1964

Photo from the Nobel Foundation archive.

Charles Hard Townes

Prize share: 1/2

Photo from the Nobel Foundation archive.

Nicolay Gennadiyevich Basov

Prize share: 1/4

Photo from the Nobel Foundation archive.

Aleksandr Mikhailovich Prokhorov

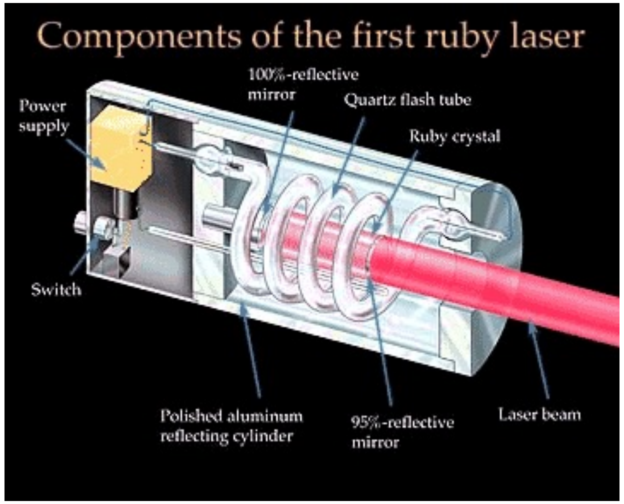
Prize share: 1/4

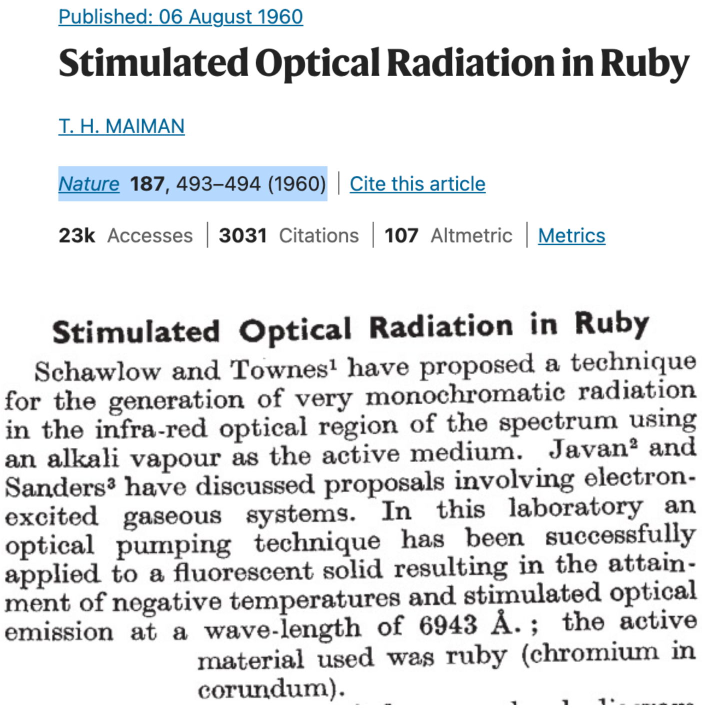
"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"

Maser （1953）

王天眷 先生
(创建武汉物数所
-波谱实验室)

Race to Make the first Laser





Published: 06 August 1960

Stimulated Optical Radiation in Ruby

T. H. MAIMAN

Nature **187**, 493–494 (1960) | Cite this article

23k Accesses | **3031** Citations | **107** Altmetric | Metrics

Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

Maiman, T.H. (1960)

- On May 16, 1960, at Hughes' Malibu, California, laboratories, Maiman's solid-state pink ruby laser emitted mankind's first coherent light.
- On June 22, submitted to PRL, and got rejected on 24th.
- One August 6, published on Nature.

1999年诺贝尔物理学奖

飞秒化学的先驱者——1999年诺贝尔化学奖

美国加州理工学院的物理化学和化学物理学家Ahmed H. Zewail教授,以表彰他在利用飞秒激光脉冲技术研究化学反应方面的开拓性工作

Photo from the Nobel Foundation archive.

Ahmed H. Zewail

Prize share: 1/1

"for his studies of the transition states of chemical reactions using femtosecond spectroscopy"

2018年、2023年诺贝尔物理学奖

三位科学家

分享2018年诺贝尔物理学奖

美国科学家
阿瑟·阿什金

法国科学家
热拉尔·穆鲁

加拿大科学家
唐娜·斯特里克兰

当地时间10月2日 瑞典皇家科学院宣布

将**2018年诺贝尔物理学奖**授予以上三位科学家
以表彰他们在**激光物理学领域**的突破性贡献

2018年的获奖研究为激光物理学带来革命性的变化

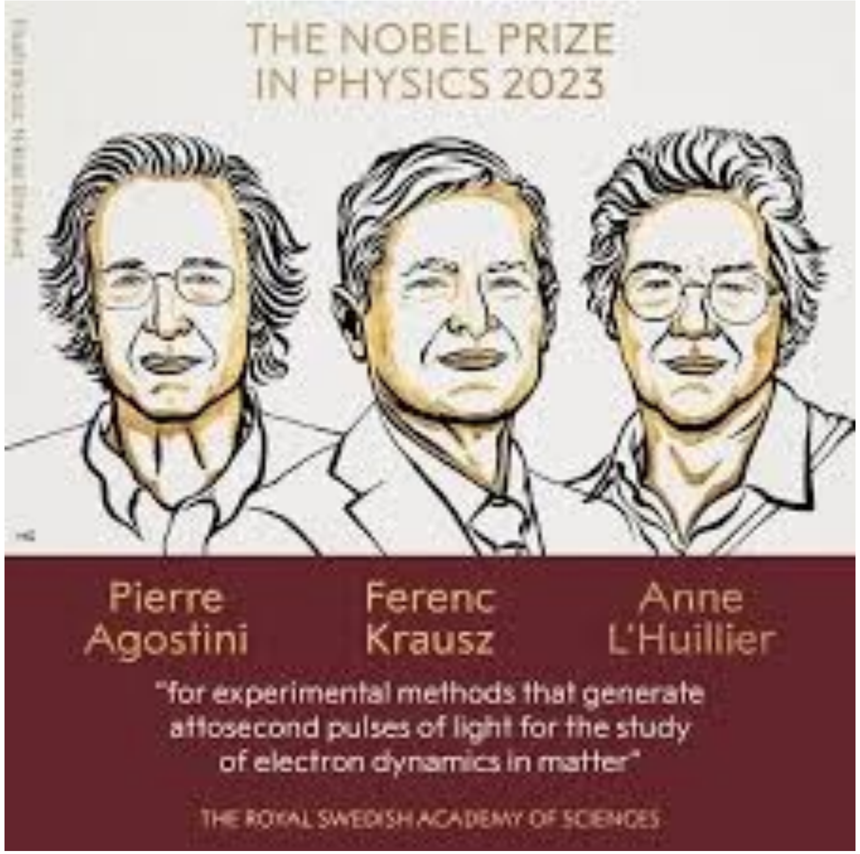
阿什金发明的光镊工具能够"夹"住微小如原子、病毒以及活细胞等物体

穆鲁和斯特里克兰的科研突破则为实现更短和更强的激光脉冲打下基础

新华社记者 施鲲珂 编制

阿秒激光

打开通往电子世界的大门



THE NOBEL PRIZE
IN PHYSICS 2023

Pierre
Agostini

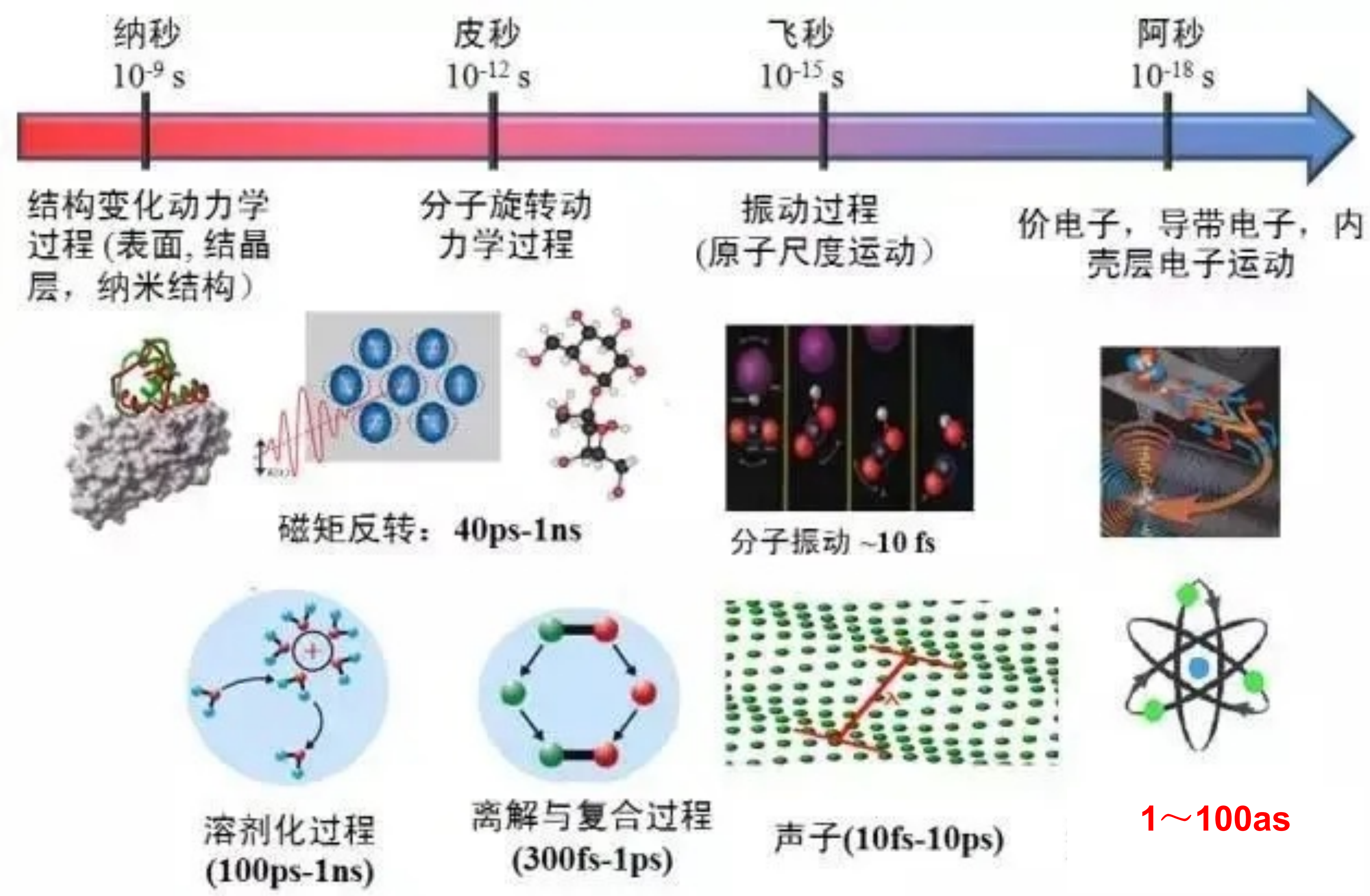
Ferenc
Krausz

Anne
L'Huillier

"for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter"

THE ROYAL SWEDISH ACADEMY OF SCIENCES

时间尺度与物理过程



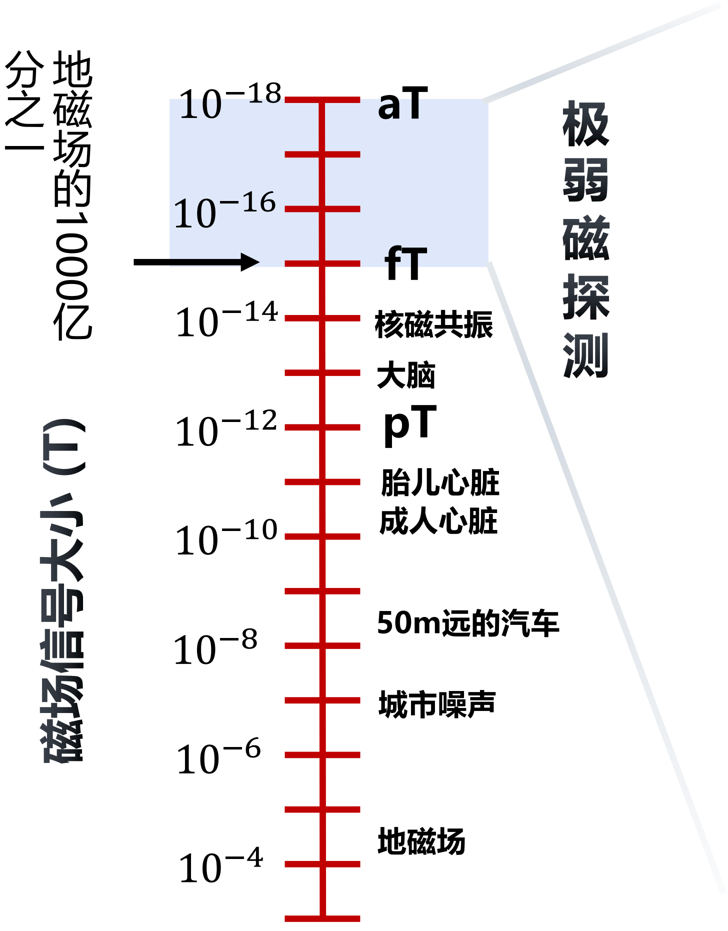
1～100as

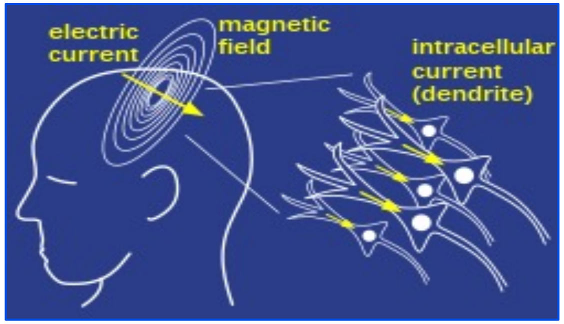
第三部分：自旋量子精密测量

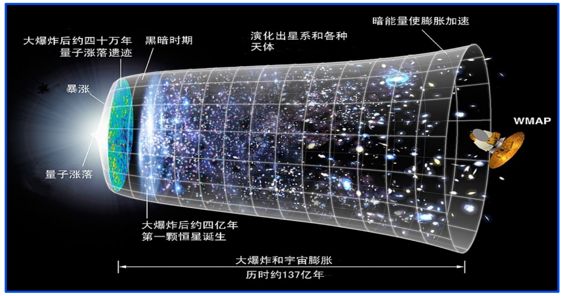
- □ 自旋与弱磁测量
- □ 自旋磁力仪
  - ➢ 原子磁力仪
  - ➢ Rb-Xe磁力仪
  - ➢ NV磁力仪
- □ 弱磁测量应用：暗物质探测

研究背景

极弱磁探测的科学意义







生物医学

心磁、脑磁、脑科学认知

地球和空间物理

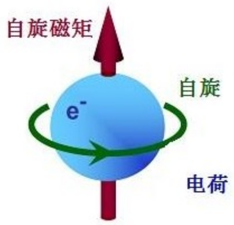
深空深地深海磁、古地磁

前沿基础物理

暗物质、EDM、磁单极子

自旋与磁

第一次量子革命



自旋
（磁性起源）

1922年：斯特恩-盖拉赫实验

1924年：泡利不相容原理

1925年：乌伦贝克-古兹密特理论

1928年：狄拉克电子相对论波动方程

自旋是量子信息的重要物理载体

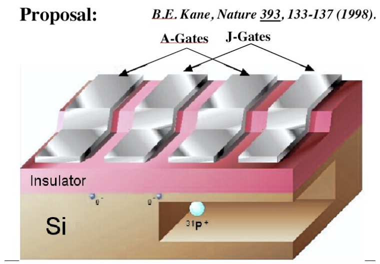
磁共振

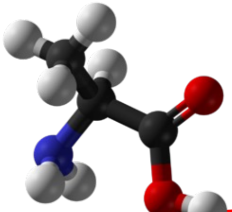
磁场中的自旋效应
获6次诺贝尔奖

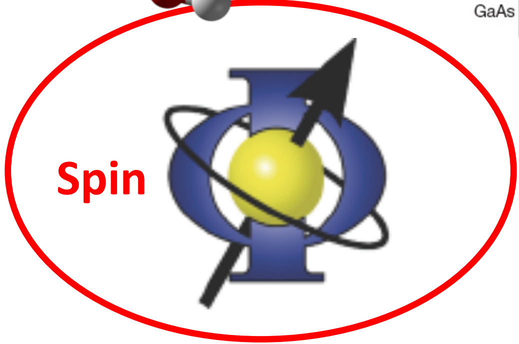
自旋与磁

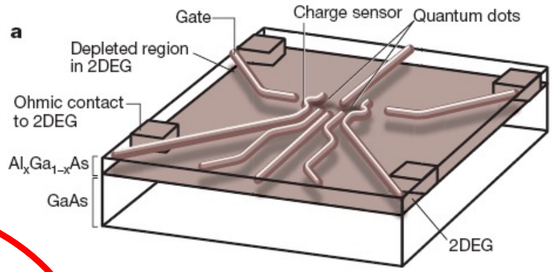
第二次量子革命

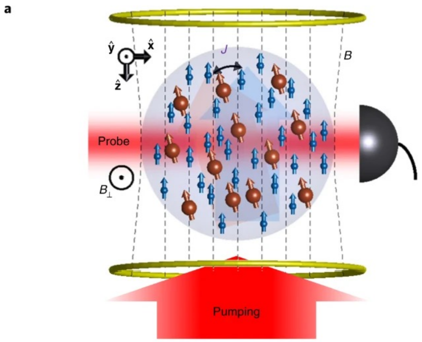
自旋量子信息处理

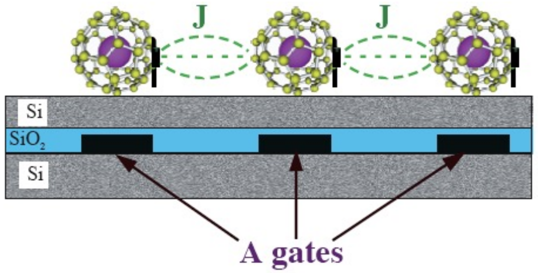


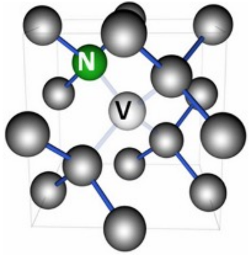








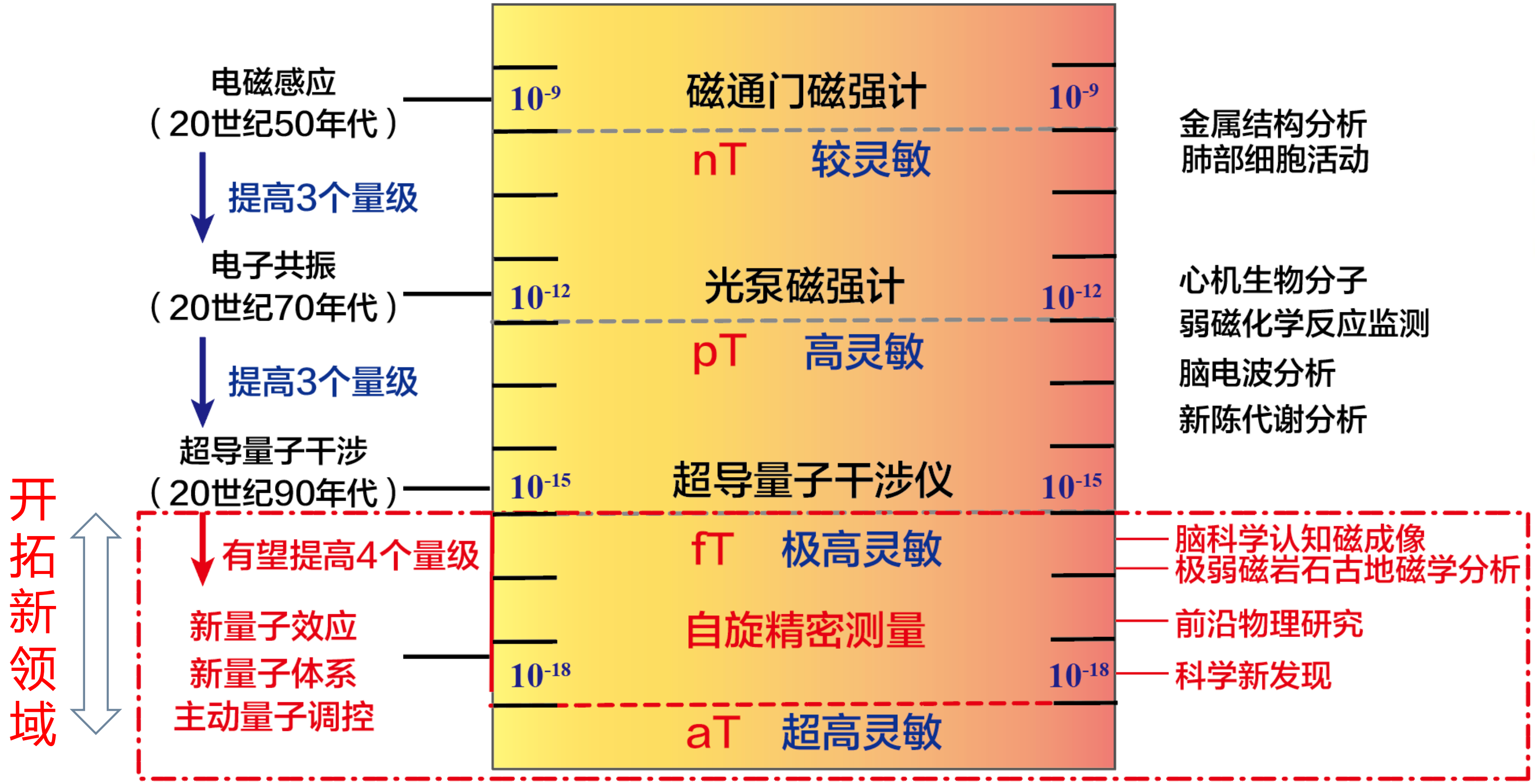




掌控量子效应、定制量子系统

磁场测量已迈入量子时代

测量原理　　指标：灵敏度$(T/Hz^{1/2})$　　科学应用



电磁感应
（20世纪50年代）

提高3个量级

电子共振
（20世纪70年代）

提高3个量级

超导量子干涉
（20世纪90年代）

有望提高4个量级

新量子效应
新量子体系
主动量子调控

开拓新领域

10^{-9}　磁通门磁强计　10^{-9}

nT　较灵敏

10^{-12}　光泵磁强计　10^{-12}

pT　高灵敏

10^{-15}　超导量子干涉仪　10^{-15}

fT　极高灵敏

自旋精密测量

10^{-18}　10^{-18}

aT　超高灵敏

金属结构分析
肺部细胞活动

心机生物分子
弱磁化学反应监测
脑电波分析
新陈代谢分析

脑科学认知磁成像
极弱磁岩石古地磁学分析
前沿物理研究
科学新发现

量子精密测量促进基本单位进入量子时代

发展量子精密测量技术极有望催生科学新发现

第三部分：自旋量子精密测量

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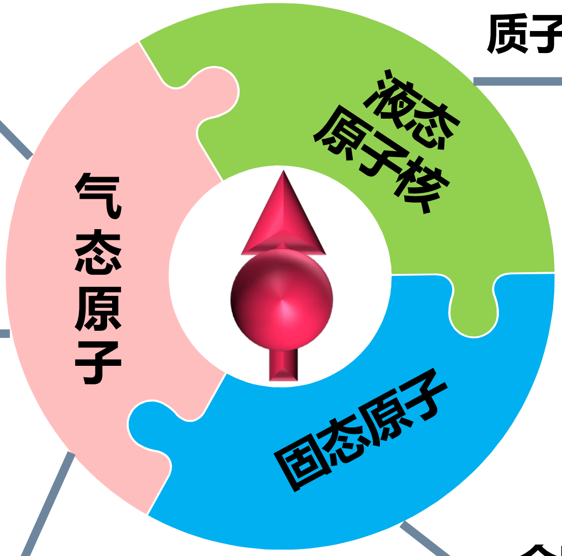
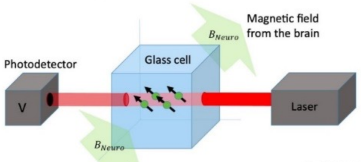
- □ 自旋磁力仪
  - ➢ 原子磁力仪
  - ➢ **Rb-Xe**磁力仪
  - ➢ **NV**磁力仪
- □ 弱磁测量应用：暗物质探测

自旋量子磁力计



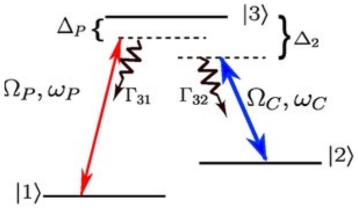
$0.1pT/\sqrt{Hz}$

光泵磁力计



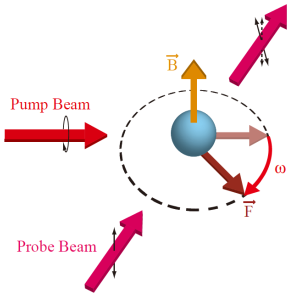
相干布居囚禁磁力计

$1pT/\sqrt{Hz}$



无自旋交换弛豫（SERF）原子磁力计

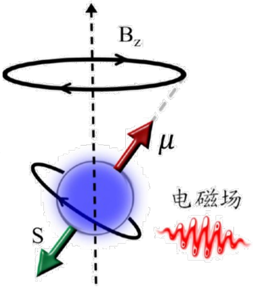
灵敏度最高



国际公开报道最高：
普林斯顿160 aT/Hz$^{1/2}$
北航680 aT/Hz$^{1/2}$

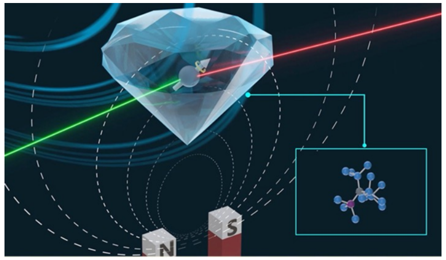
$0.1nT/\sqrt{Hz}$

质子磁力计



金刚石色心

空间分辨率最好（$10nm$）



第三部分：自旋量子精密测量

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- □ 自旋磁力仪
  - ➢ 原子磁力仪
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  - ➢ NV磁力仪
- □ 弱磁测量应用：暗物质探测

原子自旋磁力计 基本原理

Vapor cell: Alkali metal atoms

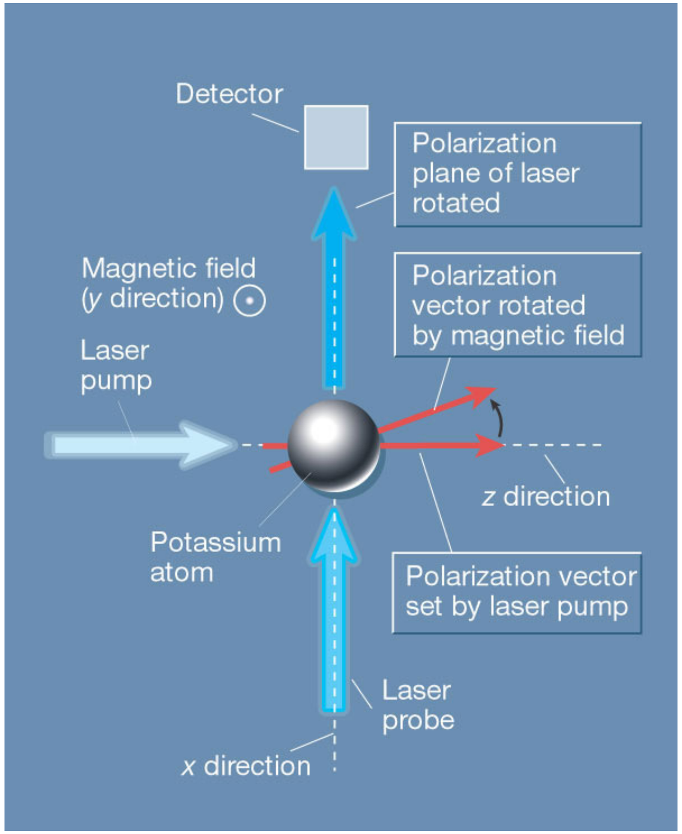
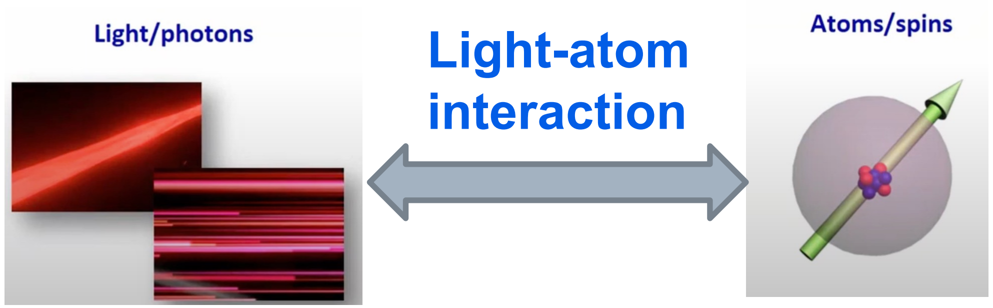


Figure from: D.Budker. : A new spin on magnetometry

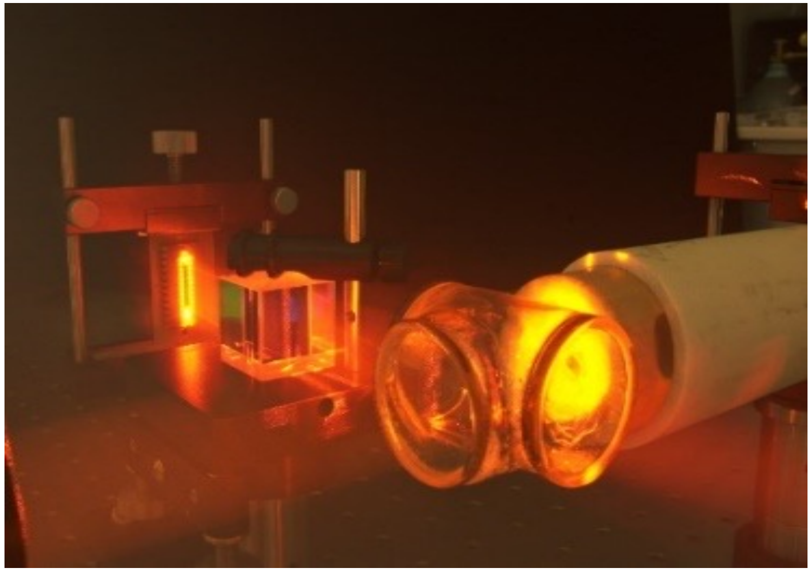
Nature (News&Views) **422, 574 - 575 (2003)**

- **Optical pumping**
- **Spin precession**
- **Probe (light intensity/light polarization)**

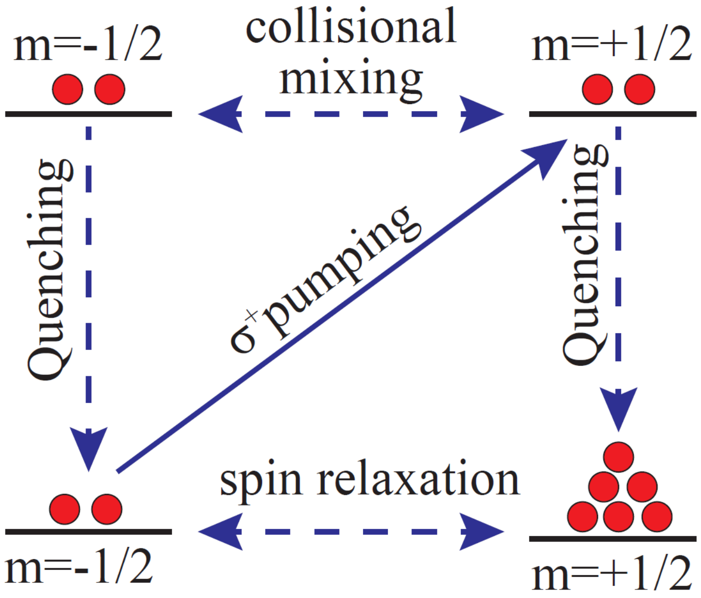


Light-atom interaction

Preparation: Optical pumping



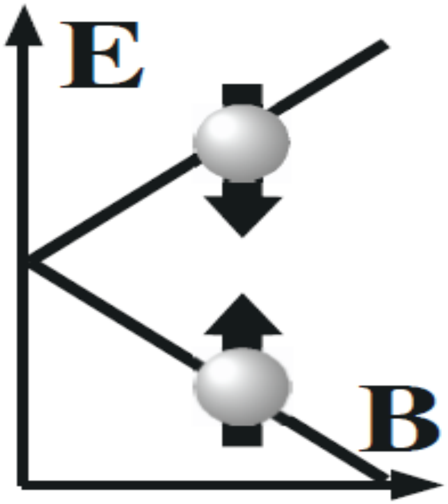
Alkali-metal: K or Rb

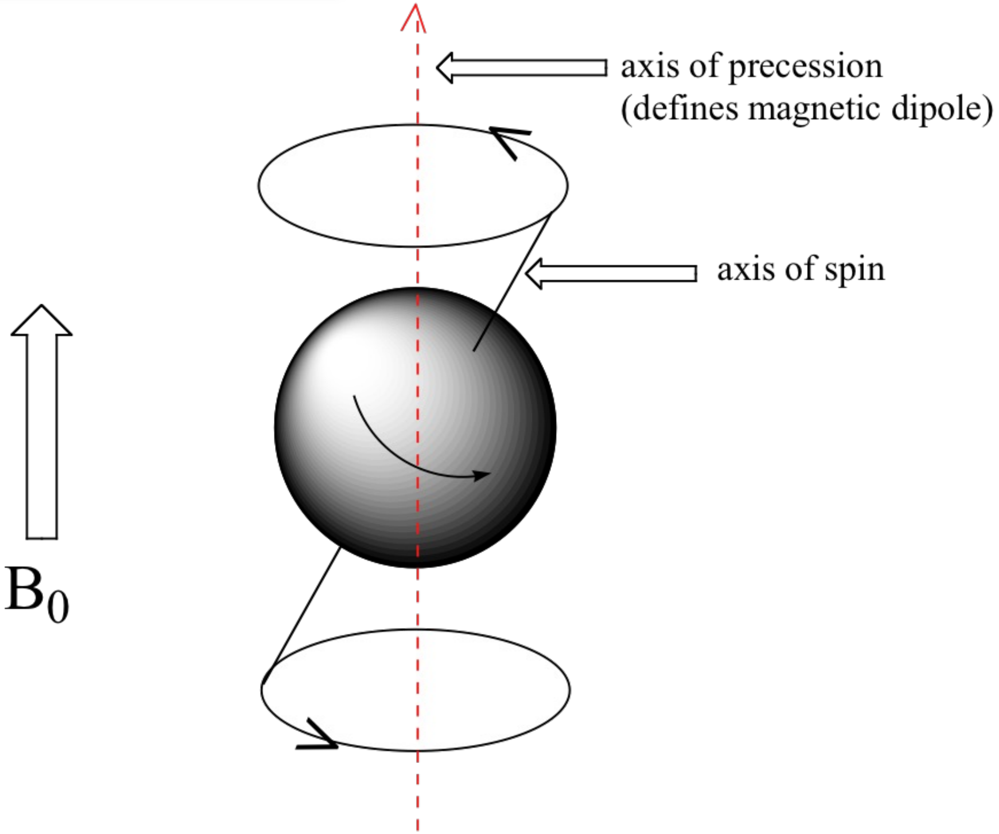


Close to 100% Alkali-metal atomic spin polarization!

Encoding: Lamer processing

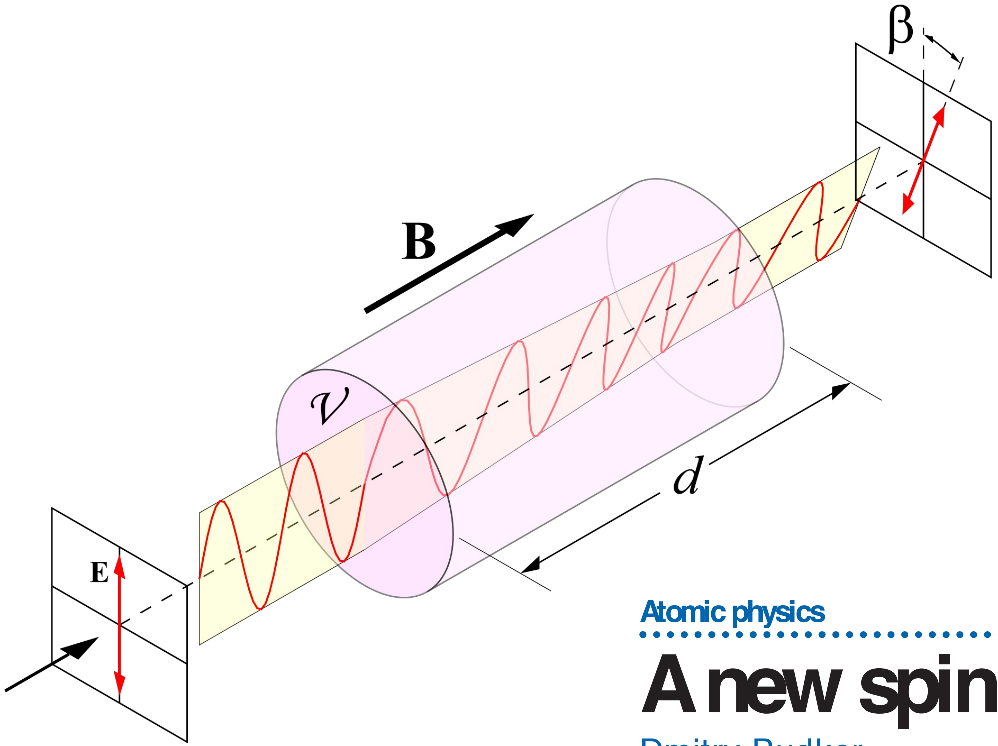
$$\omega = \gamma B$$





Readout: Faraday Effect

Polarization rotation due to the Faraday effect



Optical rotation used for detection

the plane of polarization

linear polarized light

Polarization angle rotation

$\propto \gamma B_y T_2$

Atomic physics

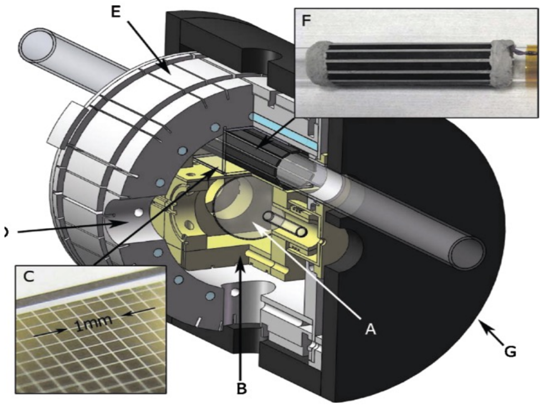
A new spin on magnetometry

Dmitry Budker

The capability to measure small, localized magnetic fields is valuable in biology as well as physics. A new device, based on spin-polarized alkali atoms, achieves better sensitivity and resolution than before.

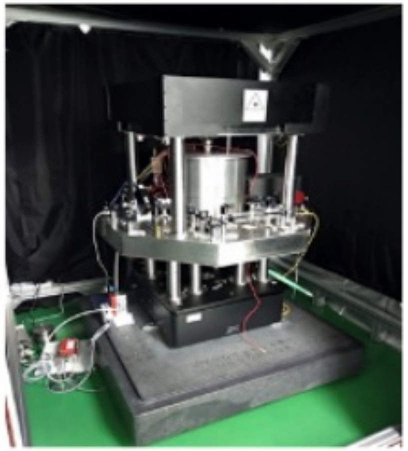
无自旋交换弛豫（SERF）原子磁力计

当前灵敏度最高的磁力计，无需低温、可小型化、结构简单，已成为SQUID的有力替代方案。



Princeton University
($0.16\mathrm{fT/Hz^{1/2}}$)

Materials today, 2011, 14(6): 258-262.

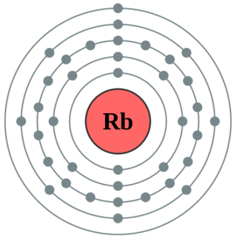


北航
($0.68\mathrm{fT/Hz^{1/2}}$)

Meas. Sci. and Tech., 2018, 30(1): 015005.

2002年首次在实验层面验证SERF理论：

- ■气室原子密度足够大
- ■待测磁场足够小
- ■预言SERF理论灵敏度最高可达1 $\mathrm{aT/Hz^{1/2}}$



碱金属原子

亚fT级别磁场测量新方法和技术

原理创新

取长补短

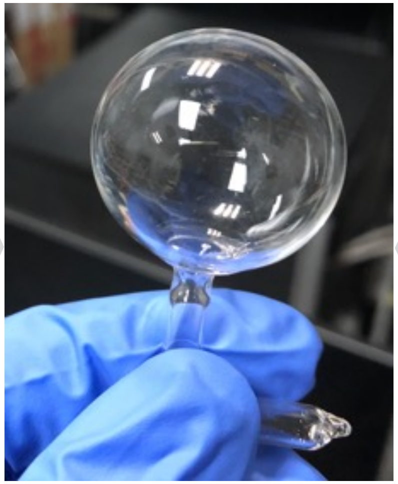
碱金属

电子自旋
磁矩大
自旋寿命短
(ms级别)
密度小
(10^{14}cm^{-3})

极化、读出

11 Na
19 K
37 Rb
55 Cs

混合原子气室



2 He
10 Ne
54 Xe

惰性气体

核自旋
磁矩小（小10^3倍）
自旋寿命长
(100s级别)
密度大
(10^{19}cm^{-3})

磁场量子放大
>10^2-10^6

1fT=10^{-15}T 相当于地磁场的1000亿分之一！

亚fT级别的磁场探测方法对比

超导量子干涉仪 (SQUID) 低温系统 体积庞大	原子磁力计 (SERF) 零磁场环境 要求磁屏蔽	**超灵敏核自旋** **量子放大** **接近室温** **非零磁场**

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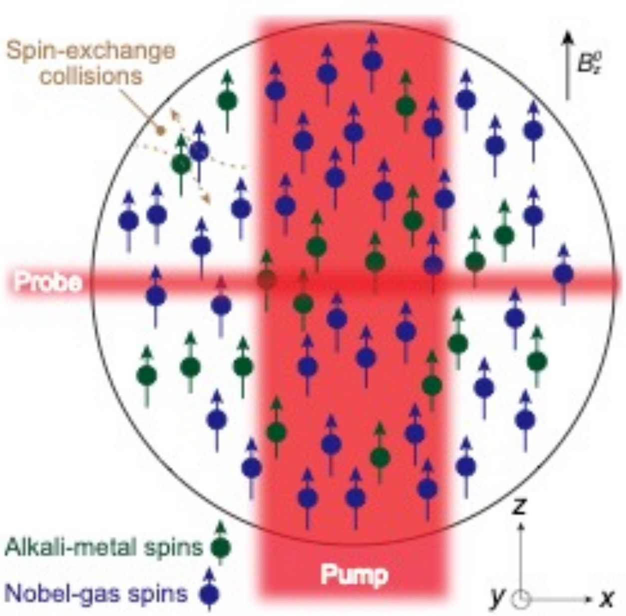
混合原子自旋量子精密测量

混合自旋动力学

耦合 Bloch 方程（碱金属电子自旋+惰性气体核自旋）



引入核自旋的演化方程和费米接触相互作用

$$\frac{\partial \mathbf{P}^e}{\partial t} = \frac{\gamma_e}{Q}(\mathbf{B}^0 + \beta M_0^K \mathbf{P}^K) \times \mathbf{P}^e + \frac{P_0^e \mathbf{z} - \mathbf{P}^e}{\{T_{2e}, T_{2e}, T_{1e}\}Q},$$

$$\frac{\partial \mathbf{P}^K}{\partial t} = \gamma_K(\mathbf{B}^0 + \beta M_0^e \mathbf{P}^e) \times \mathbf{P}^K + \frac{P_0^K \mathbf{z} - \mathbf{P}^K}{\{T_{2K}, T_{2K}, T_{1K}\}},$$

$$\beta M_0^e \mathbf{P}^e \ll \beta M_0^n \mathbf{P}^n$$

$$\frac{\partial \mathbf{P}^e}{\partial t} = \frac{\gamma_e}{Q}(\mathbf{B}^0 + \beta M_0^K \mathbf{P}^K) \times \mathbf{P}^e + \frac{P_0^e \mathbf{z} - \mathbf{P}^e}{T_e Q},$$

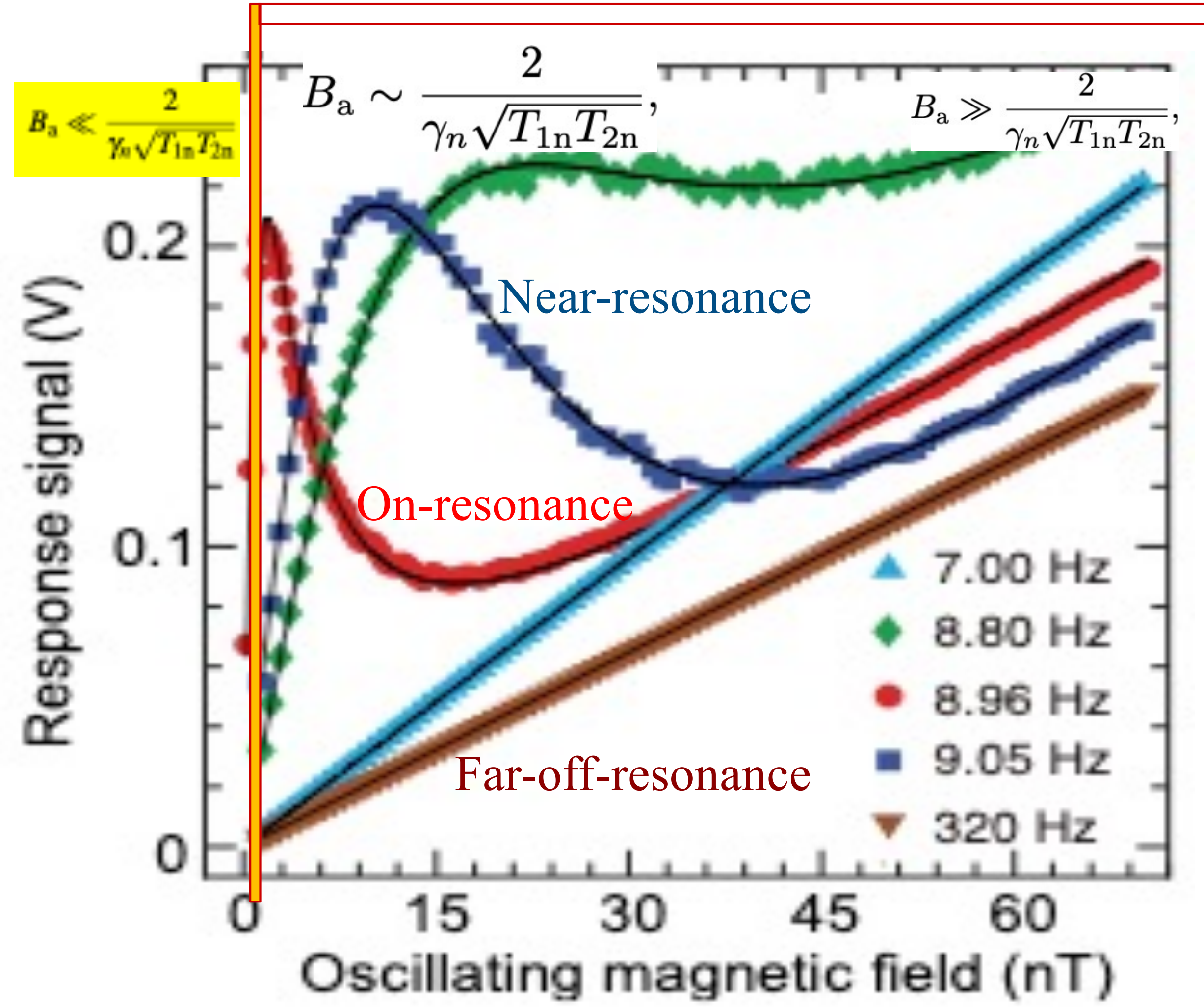
$$\frac{\partial \mathbf{P}^K}{\partial t} = \gamma_K \mathbf{B}^0 \times \mathbf{P}^K + \frac{P_0^K \mathbf{z} - \mathbf{P}^K}{\{T_{2K}, T_{2K}, T_{1K}\}}.$$

自旋动力学： 量子放大效应

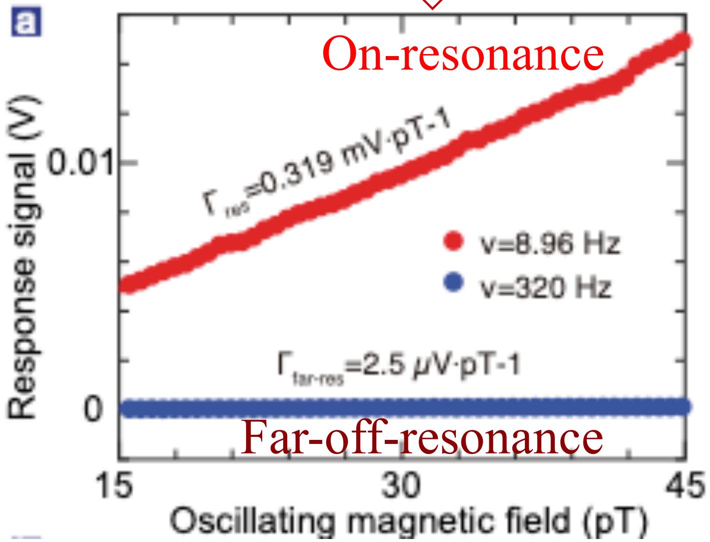
$B_a \ll \frac{2}{\gamma_n\sqrt{T_{1n}T_{2n}}}$

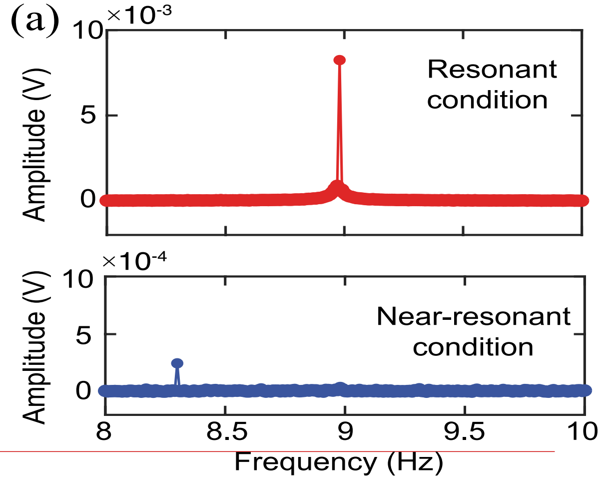
$B_a \sim \frac{2}{\gamma_n\sqrt{T_{1n}T_{2n}}},$

$B_a \gg \frac{2}{\gamma_n\sqrt{T_{1n}T_{2n}}},$

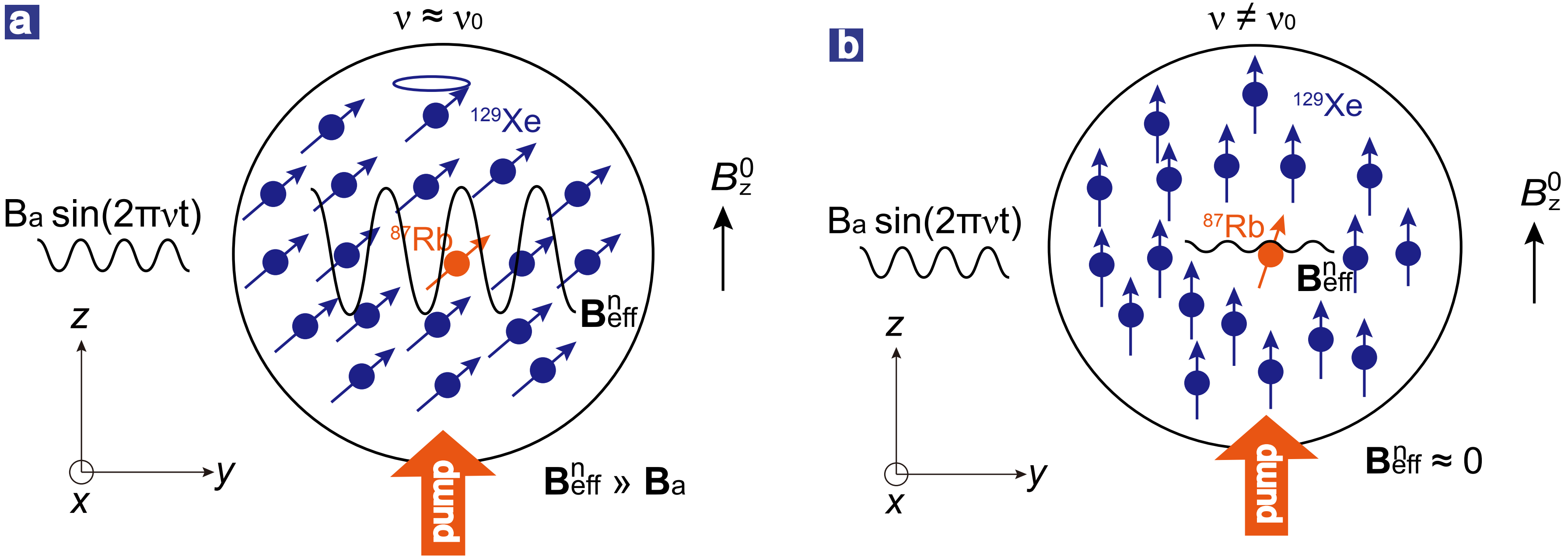


Linear Nonlinear Saturated





惰性气体的磁场量子放大效应



磁场放大增益:

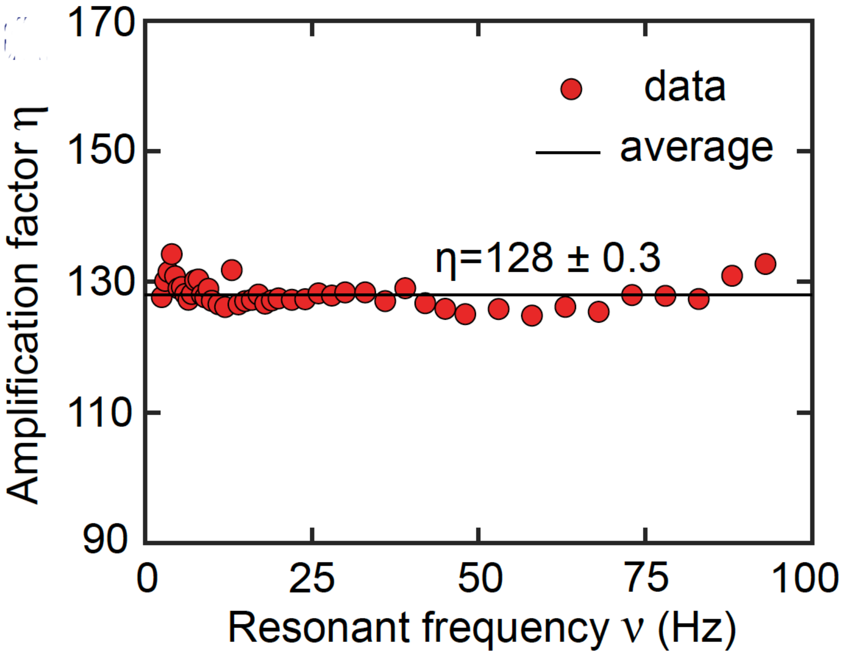
$$\eta = \frac{1}{2}\beta M_0^n P_0^n \gamma_n T_{2n} \gg 1$$

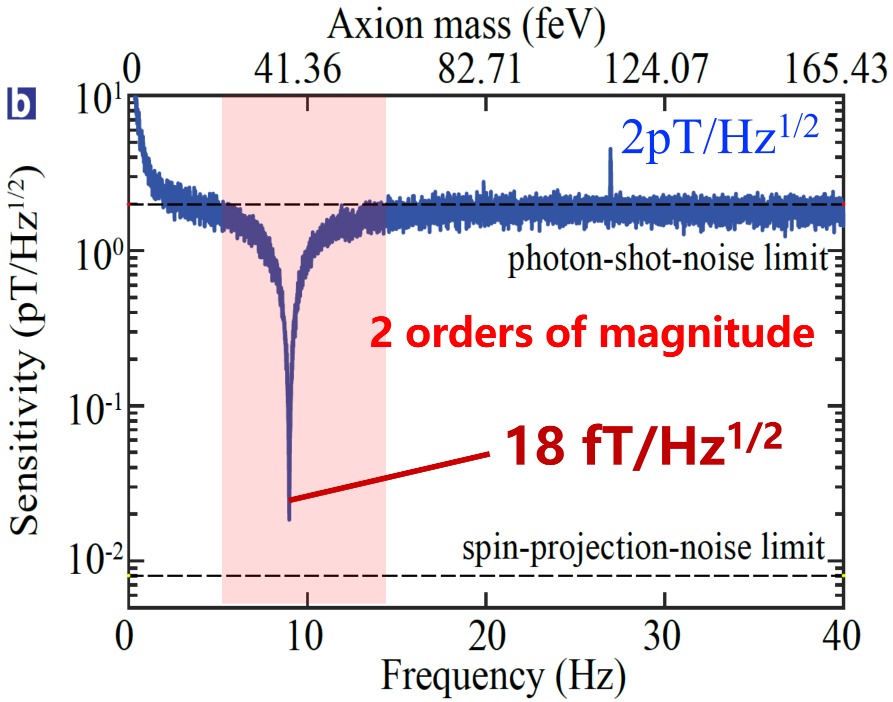
$$\eta \approx 0$$

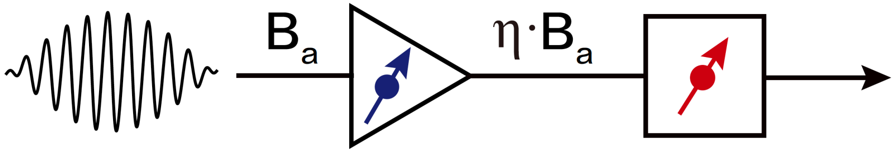
Jiang et al., Nature Physics **17**, pages 1402–1407 (2021)

惰性气体的磁场量子放大效应

利用自旋、原子、分子等物理体系实现磁场的超低噪声放大







最新进展：$0.8fT/Hz^{1/2}$

Jiang et al., Nature Physics **17**, pages 1402–1407 (2021)

Spin quantum amplification: sub-fT magnetic detection sensitivity

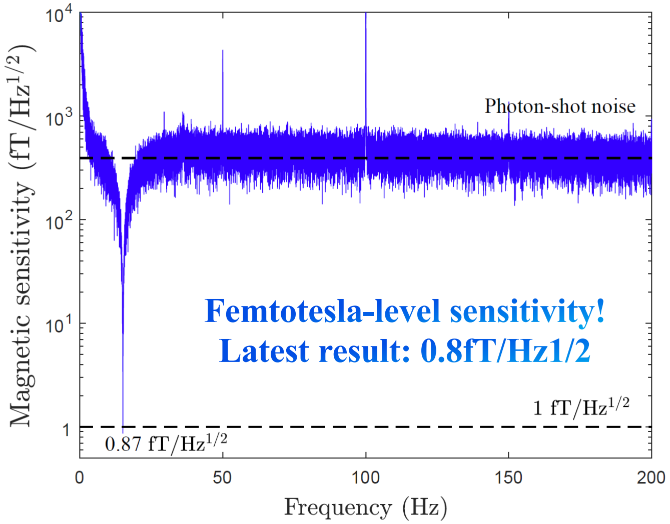
System improvement

^{87}Rb-^{129}Xe

- Large spin-destruction cross section
- Short noble gas coherence time(~10 s)
- Small noble gas gyromagnetic ratio (0.0118 T/Hz)

^{39}K-^{3}He

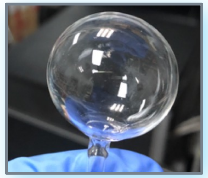
- Smaller spin-destruction cross section(five orders)
- Longer noble gas coherence time(~1000 s)
- Larger noble gas gyromagnetic ratio(0.0324 T/Hz)



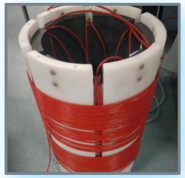
Femtotesla-level sensitivity!
Latest result: 0.8fT/Hz1/2

Key experimental technologies

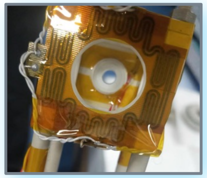
- High-quality hybrid atomic vapor cell with long coherence time
- Active and passive ultra-low magnetic noise shielding system
- Ultra-low noise high-power vacuum heating system



低漏率 K-3He 气室

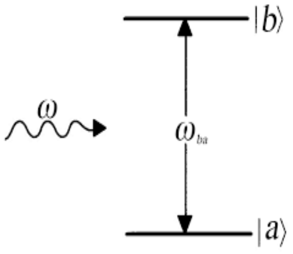


低噪声铁氧体屏蔽



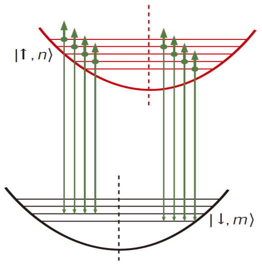
无磁超稳控温

Floquet(周期驱动)量子放大



挑战：
带宽窄
相干时间短

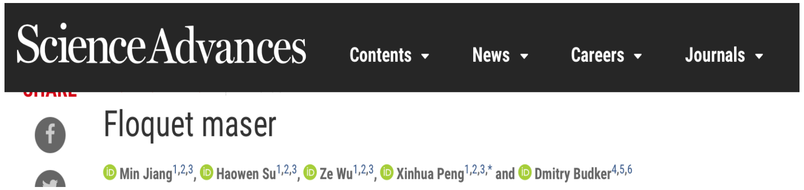
周期振荡磁场作为
“周期驱动力”



Floquet量子体系
具有丰富共振跃迁
自旋相干调控

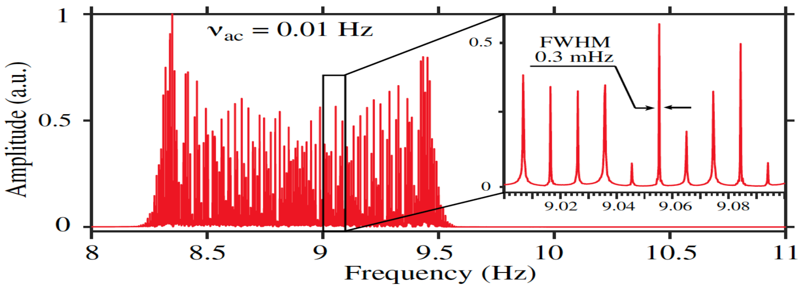
开展Floquet量子放大研究

实现新型微波激射器，创造1-100mHz频段世界最佳的灵敏度



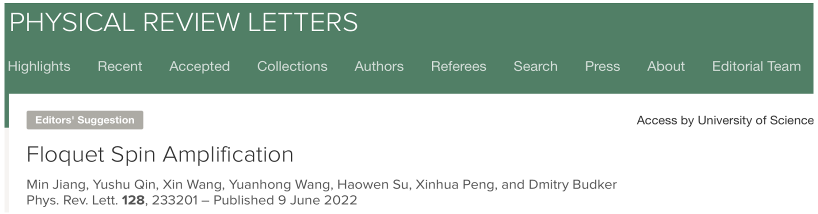
Floquet maser

Min Jiang[1,2,3], Haowen Su[1,2,3], Ze Wu[1,2,3], Xinhua Peng[1,2,3,*] and Dmitry Budker[4,5,6]



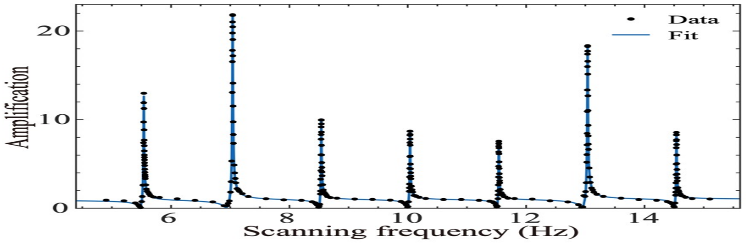
Jiang et al., Sci. Adv. 7，eabe0719（2021）

观测到Floquet体系的磁场放大效应，提升磁场测量带宽至少1个量级



Floquet Spin Amplification

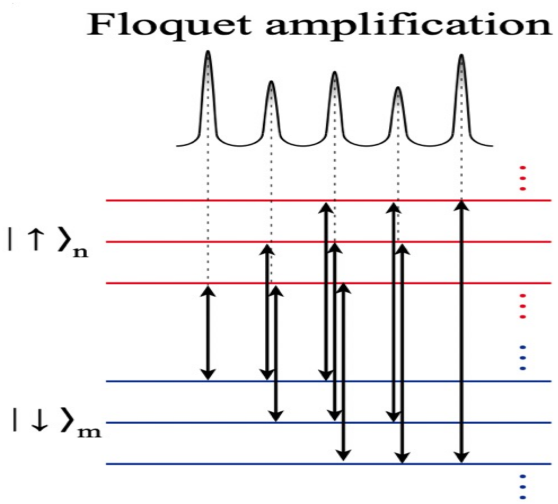
Min Jiang, Yushu Qin, Xin Wang, Yuanhong Wang, Haowen Su, Xinhua Peng, and Dmitry Budker
Phys. Rev. Lett. **128**, 233201 – Published 9 June 2022



Jiang et al., PRL 128, 233201 (2022)

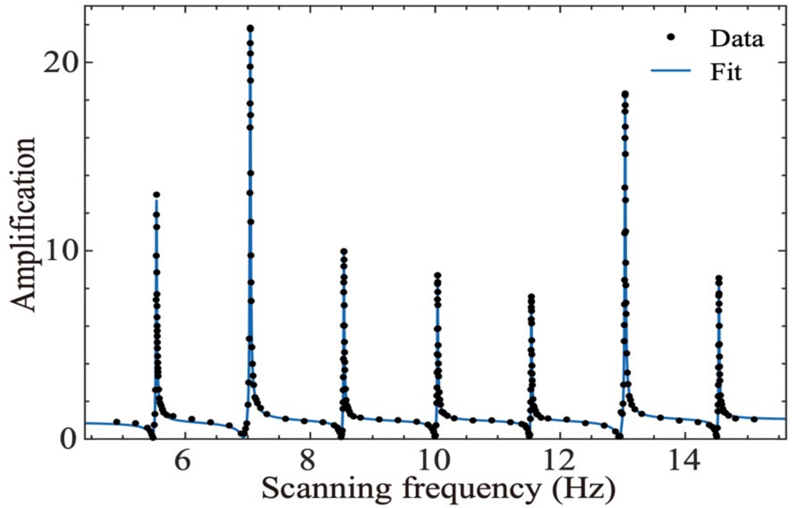
提出自旋放大频梳技术，实现多频段探测

挑战：放大频率带宽有限，仅在共振频率附近才能实现放大



提出Floquet spin amplification概念，给出理论放大增益

$$\eta_{k,0}(u) = \frac{4\pi}{3}\kappa_0 M^n P_0^n \gamma_n T_{2n} J_k^2(u)$$



提高放大带宽～10倍，均达到fT/Hz$^{1/2}$灵敏度

PRL: Editors’ suggestion

Jiang et al., PRL 128, 233201 (2022)

Measurement-feedback spin amplification

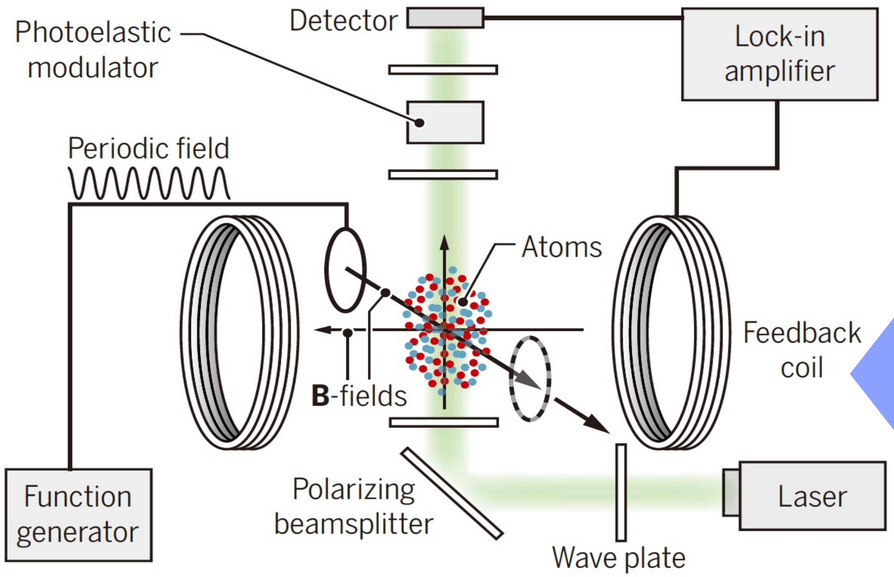
Nobel Prize: Maser and atomic clock

C. Townes

G.Basov

M. Prokhorov

N. F. Ramsey

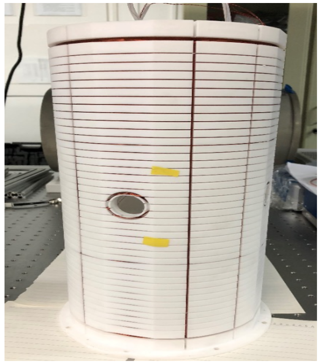


Optical frequency

(Optical cavity)

Microwave frequency

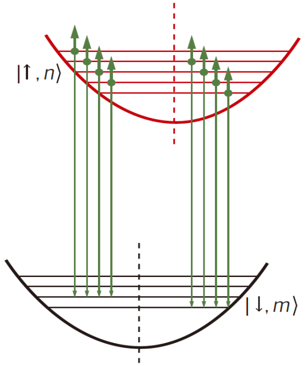
(Cavity)



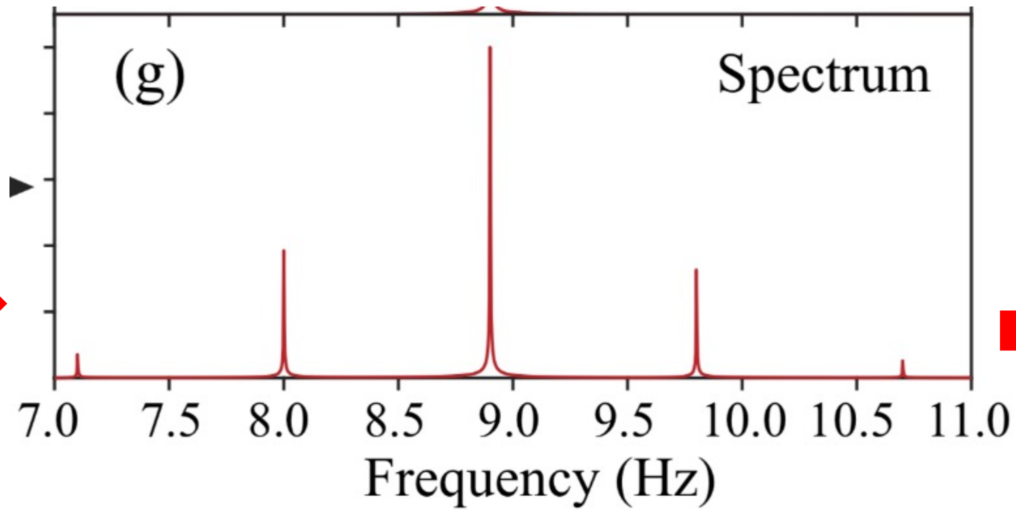
Radio frequency

(feedback Coils)

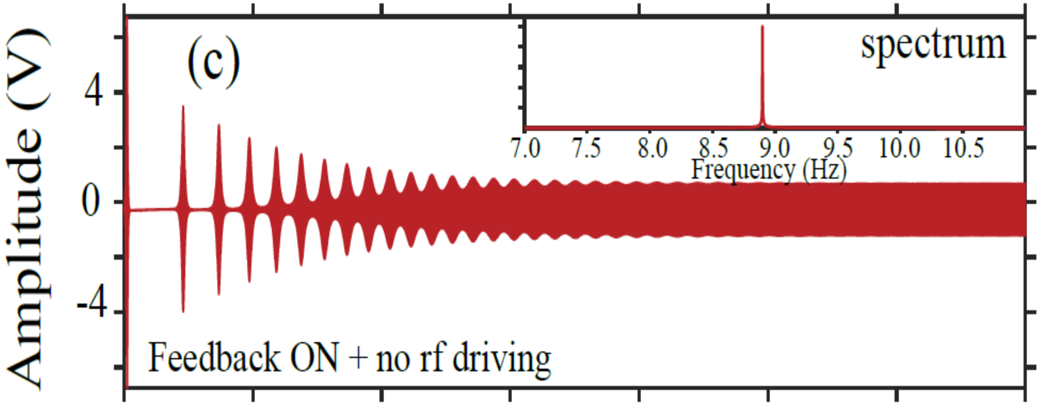
Floquet maser：首次使用Floquet介质作为增益介质

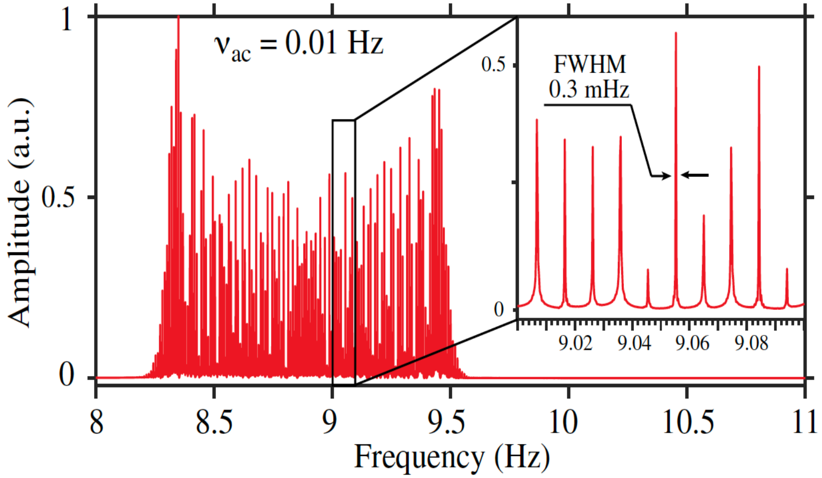


Weak
Floquet
driving

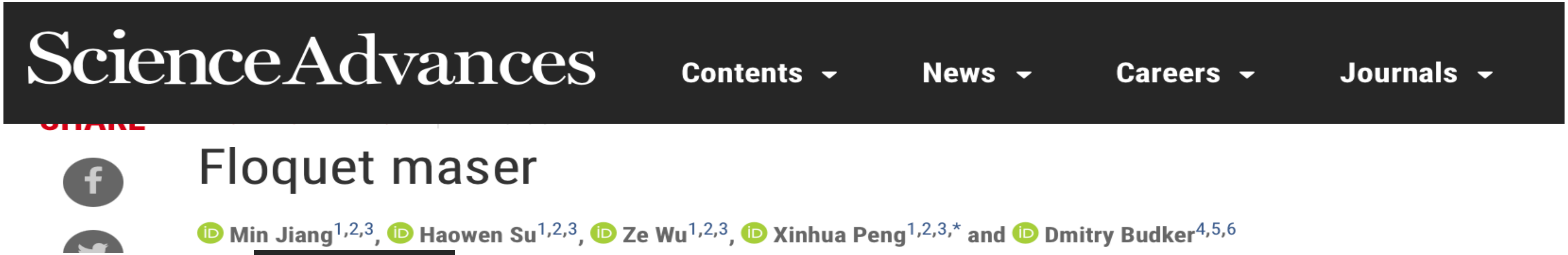


Strong
Floquet
driving



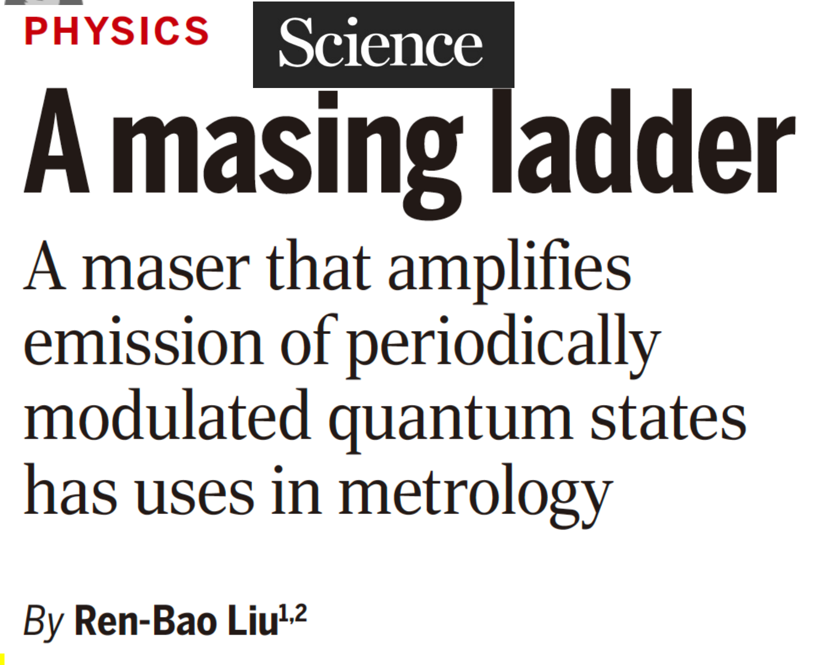


M. Jiang *et al.* **Science Advances** 7，eabe0719（2021）



Floquet maser

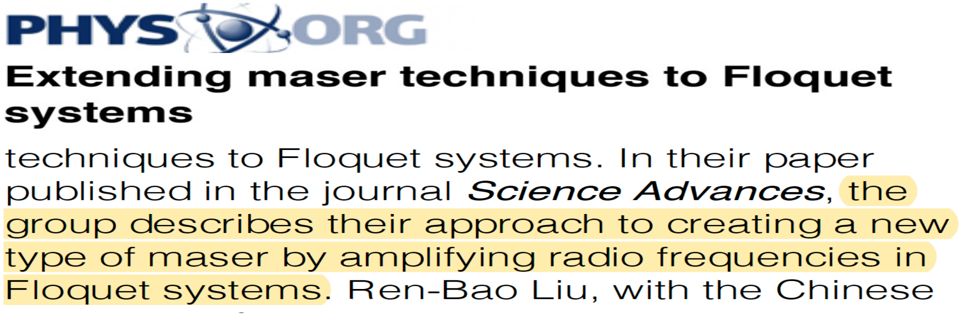
Min Jiang[1,2,3], Haowen Su[1,2,3], Ze Wu[1,2,3], Xinhua Peng[1,2,3,*] and Dmitry Budker[4,5,6]



A masing ladder

A maser that amplifies emission of periodically modulated quantum states has uses in metrology

By **Ren-Bao Liu**[1,2]



Extending maser techniques to Floquet systems

techniques to Floquet systems. In their paper published in the journal *Science Advances*, the group describes their approach to creating a new type of maser by amplifying radio frequencies in Floquet systems. Ren-Bao Liu, with the Chinese

New Floquet maser is very good at detecting low frequency magnetic fields

《Science》Perspectives reports：

“… demonstrate a new type of maser… Conceivable applications of this work include precision clocks and detection of ultralight dark matter particles such as axions”

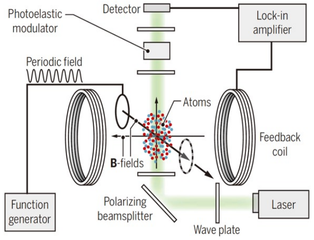
研究进展情况

开展研究

2018

Sci. Adv. 7 (2021)

利用量子反馈解决自旋退相干问题：新型微波激射器



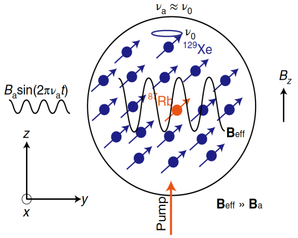
2020

700fT/Hz$^{1/2}$

（1-100mHz国际最高）

Nat. Phys. 17(2021)

首次发现惰性气体的磁场放大效应：增强自旋磁场响应



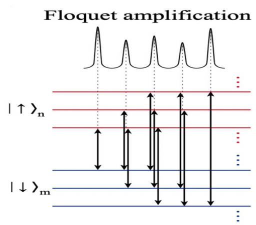
2021

18fT/Hz$^{1/2}$

（核自旋国际最高）

PRL 128 (2022)

将量子放大扩展到周期自旋体系：解决带宽窄难题



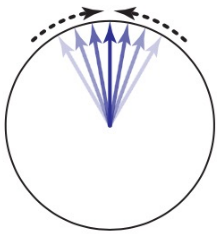
2022.6

10-30fT/Hz$^{1/2}$

（提升带宽1个量级）

文章审稿

发现暗态量子放大效应

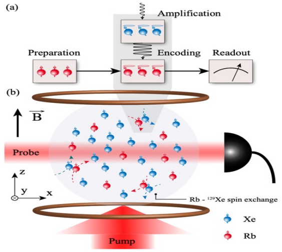


2022.8

3fT/Hz$^{1/2}$

文章准备中

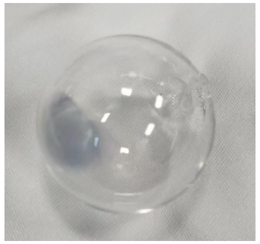
关键技术突破：采用^{3}He作为磁场放大物质



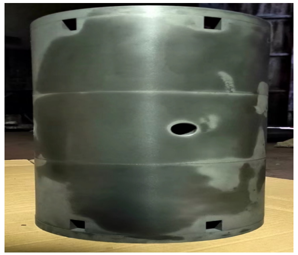
2023.1

0.8fT/Hz$^{1/2}$

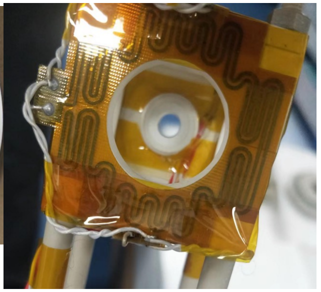
技术突破



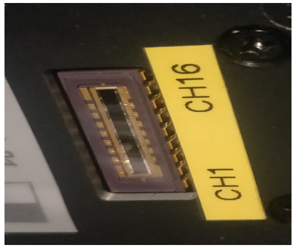
低漏率气室



铁氧体屏蔽

真空无磁加热



差分探测电子学

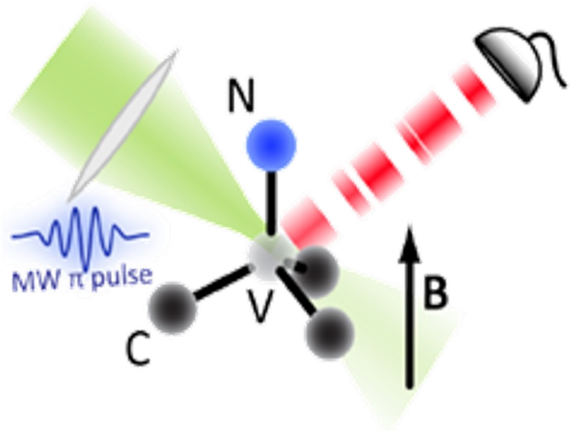
磁场测量灵敏度稳步提升，已经进入亚fT世界前沿水平

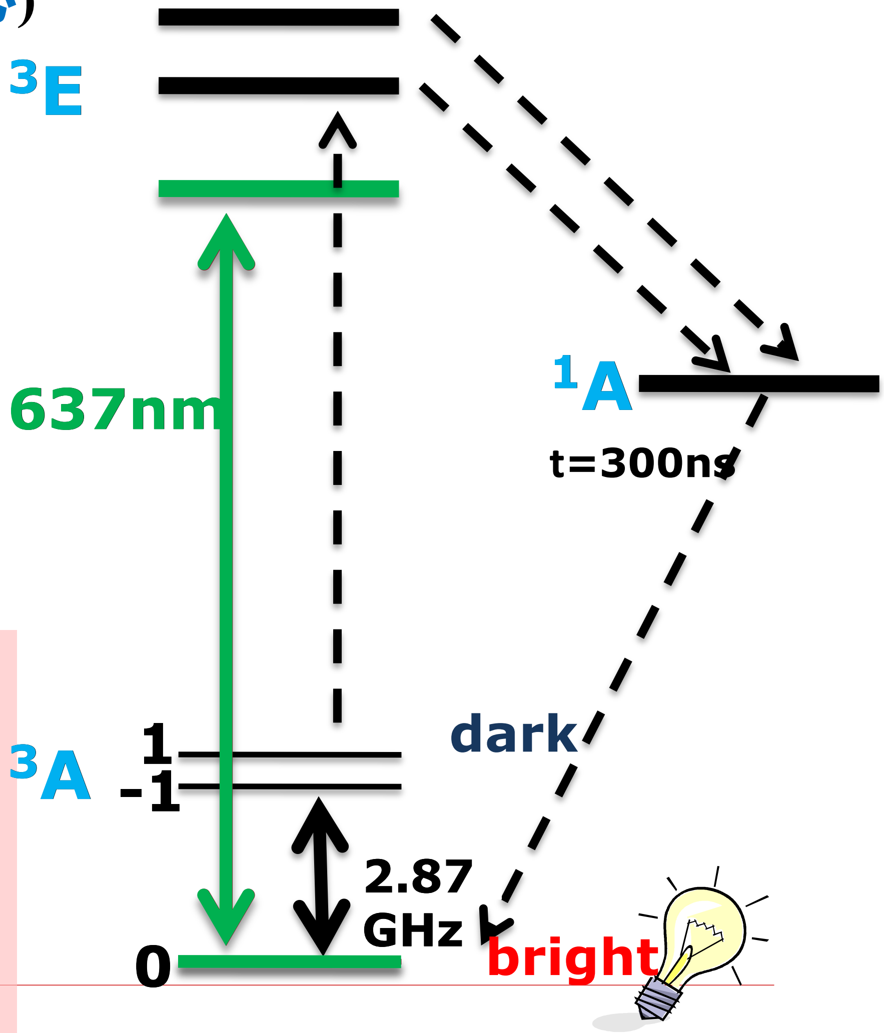
第三部分：自旋量子精密测量

- 自旋与弱磁测量
- 自旋磁力仪
  - 原子磁力仪
  - Rb-Xe磁力仪
  - NV磁力仪
- 弱磁测量应用：暗物质探测

氮-空位缺陷中心单自旋

由一个替位的氮(Nitrogen)和
一个邻位空位(Vacancy)组成(简称NV色心)

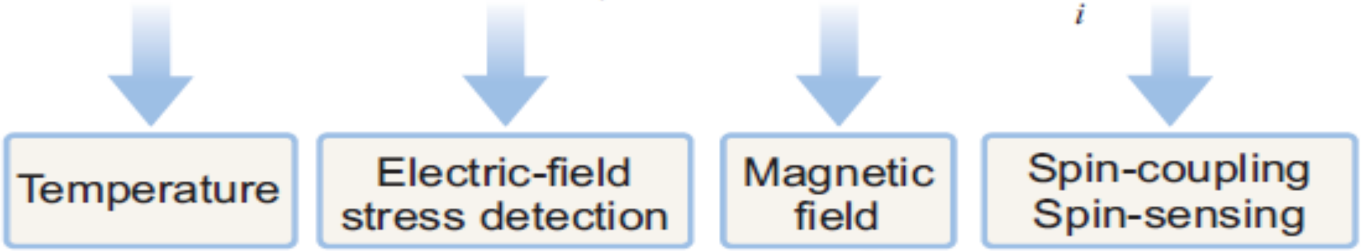




- 原子尺度：高空间分辨率
- 室温下的长量子相干时间结合动力学解耦技术：高灵敏度
- 被测磁信号可转化为自旋量子干涉仪的相位信息，光学手段读出

NV 单自旋量子传感器

$$H = D \cdot S_Z^2 + E \cdot (S_x^2 - S_y^2) - \gamma_e B \cdot S + S \cdot \sum_i A_i \cdot I_i$$



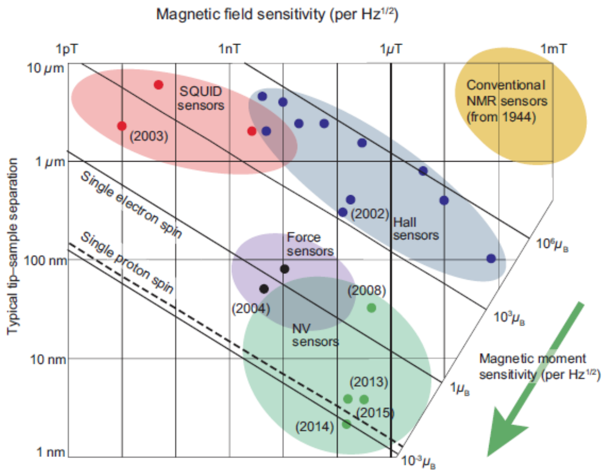
Temperature

Electric-field stress detection

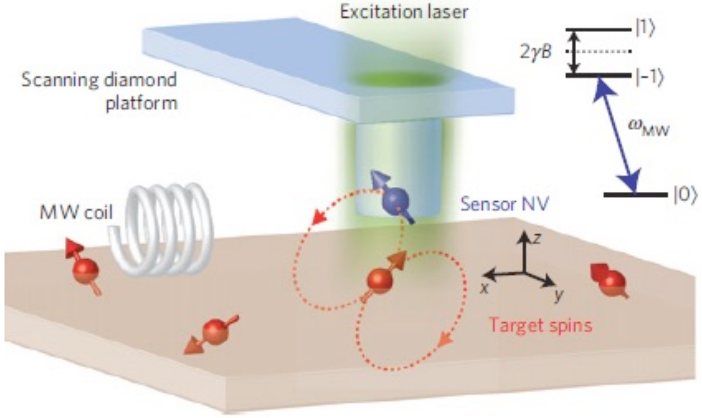
Magnetic field

Spin-coupling Spin-sensing

Diamond nanoscale magnetometry

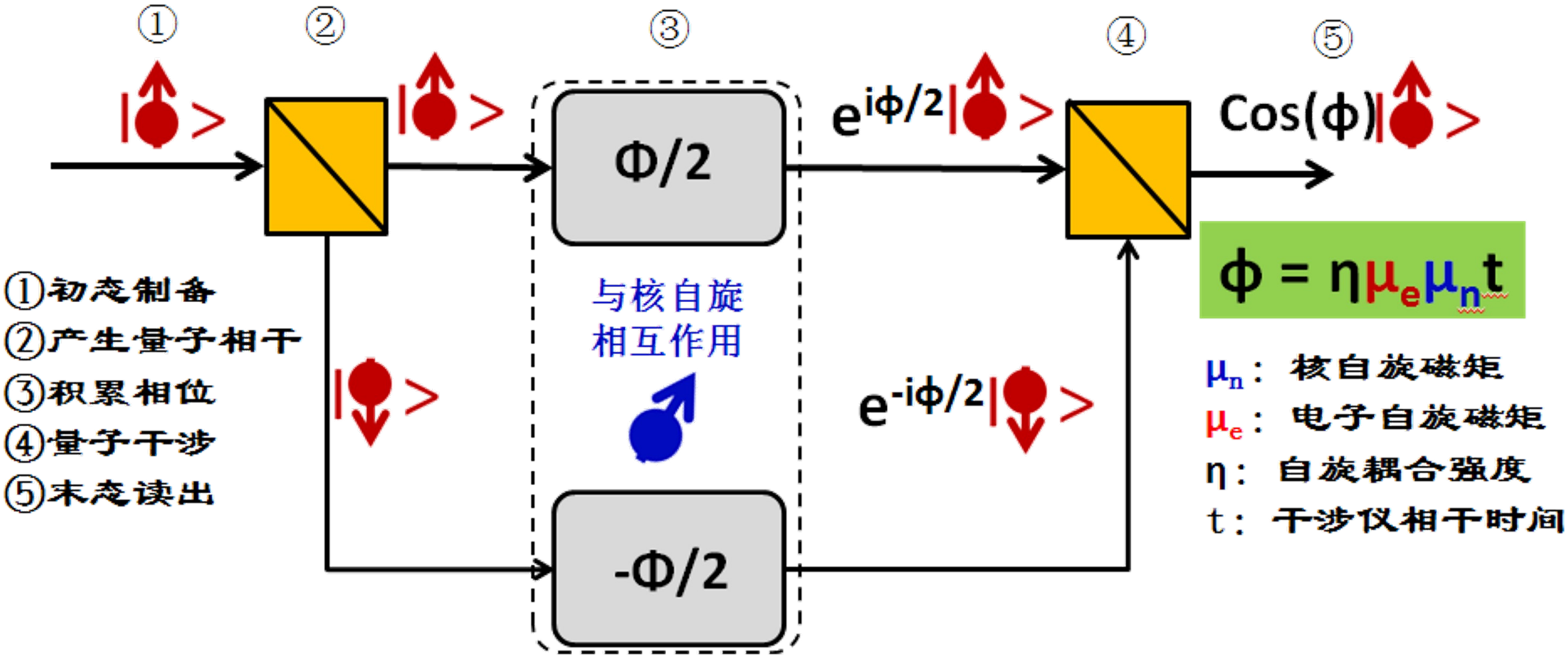


Nat. Nanotechnol. 3, 643(2008)



Nat. Phys. 9, 215 (2013)

NV 单自旋量子干涉仪



①初态制备
②产生量子相干
③积累相位
④量子干涉
⑤末态读出

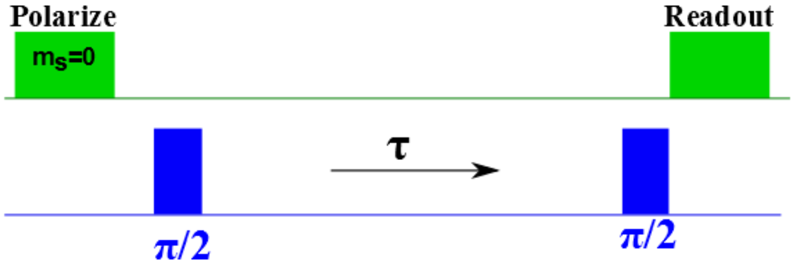
$$\phi = \eta\mu_e\mu_n t$$

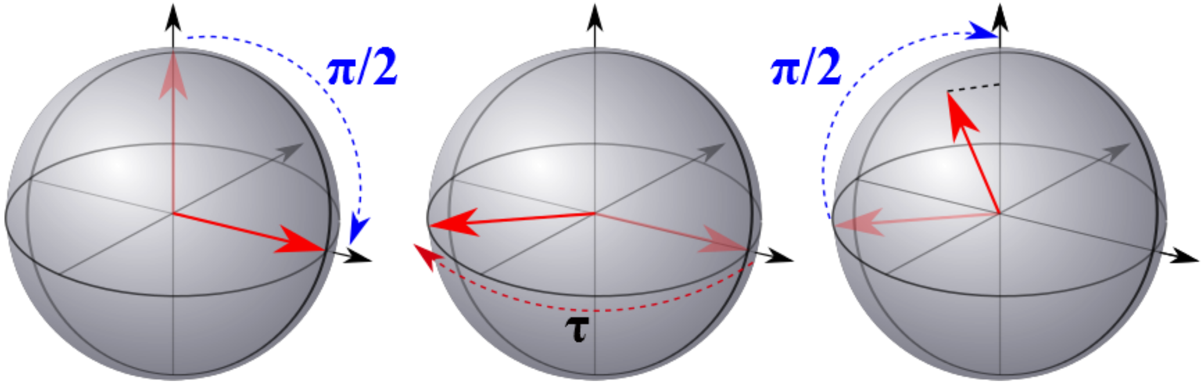
μ_n：核自旋磁矩
μ_e：电子自旋磁矩
η：自旋耦合强度
t：干涉仪相干时间

将微弱的核自旋信号μ_n转化为单电子量子干涉仪的相位信息，利用量子测量加以读出

DC Magnetometry

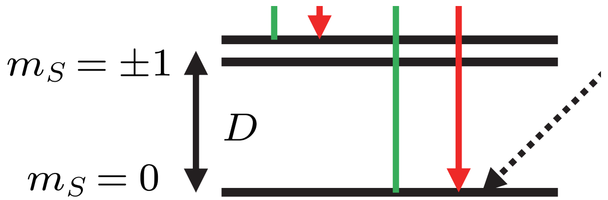
Ramsey pulse sequence





spin dynamics

$$\Phi = \gamma_e \int_0^{\tau} \Delta \mathrm{B}(t)dt$$



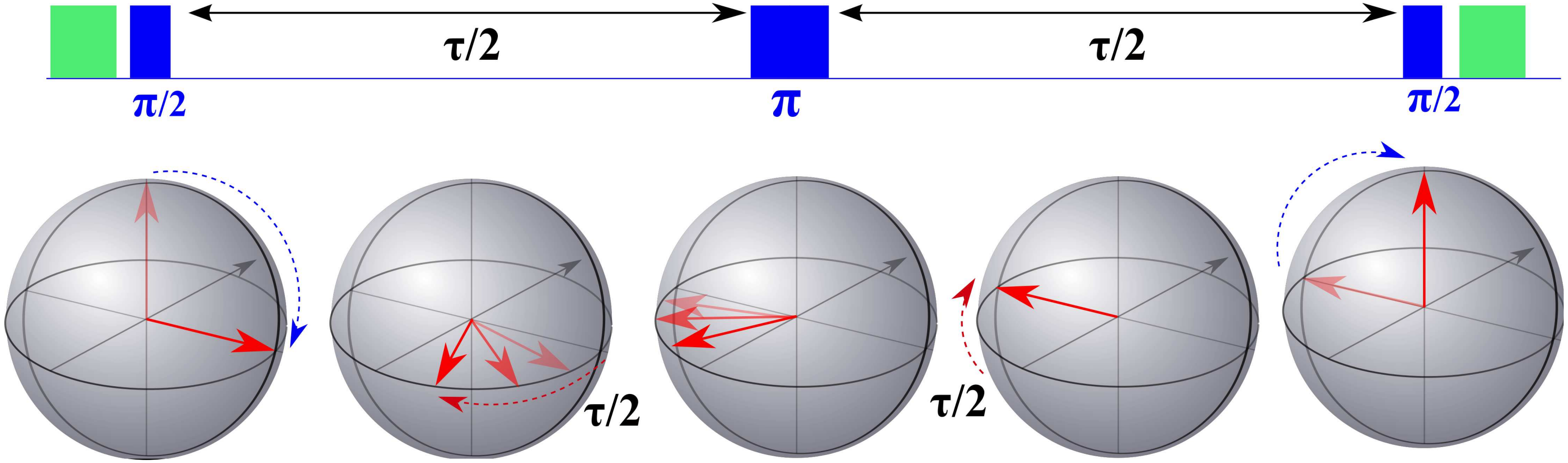
$$H = DS_z^2 \pm \underline{\gamma B_z S_z}$$

对于静磁场测量, 最简单和直接的方法 就是测量共振谱, 即光探测磁共振 (ODMR)谱

从共振谱得到的能级劈裂就可以计算出相应的磁场

AC Magnetometry

A variant of Ramsey sequence： Hahn- Echo or Spin-Echo (SE) sequence

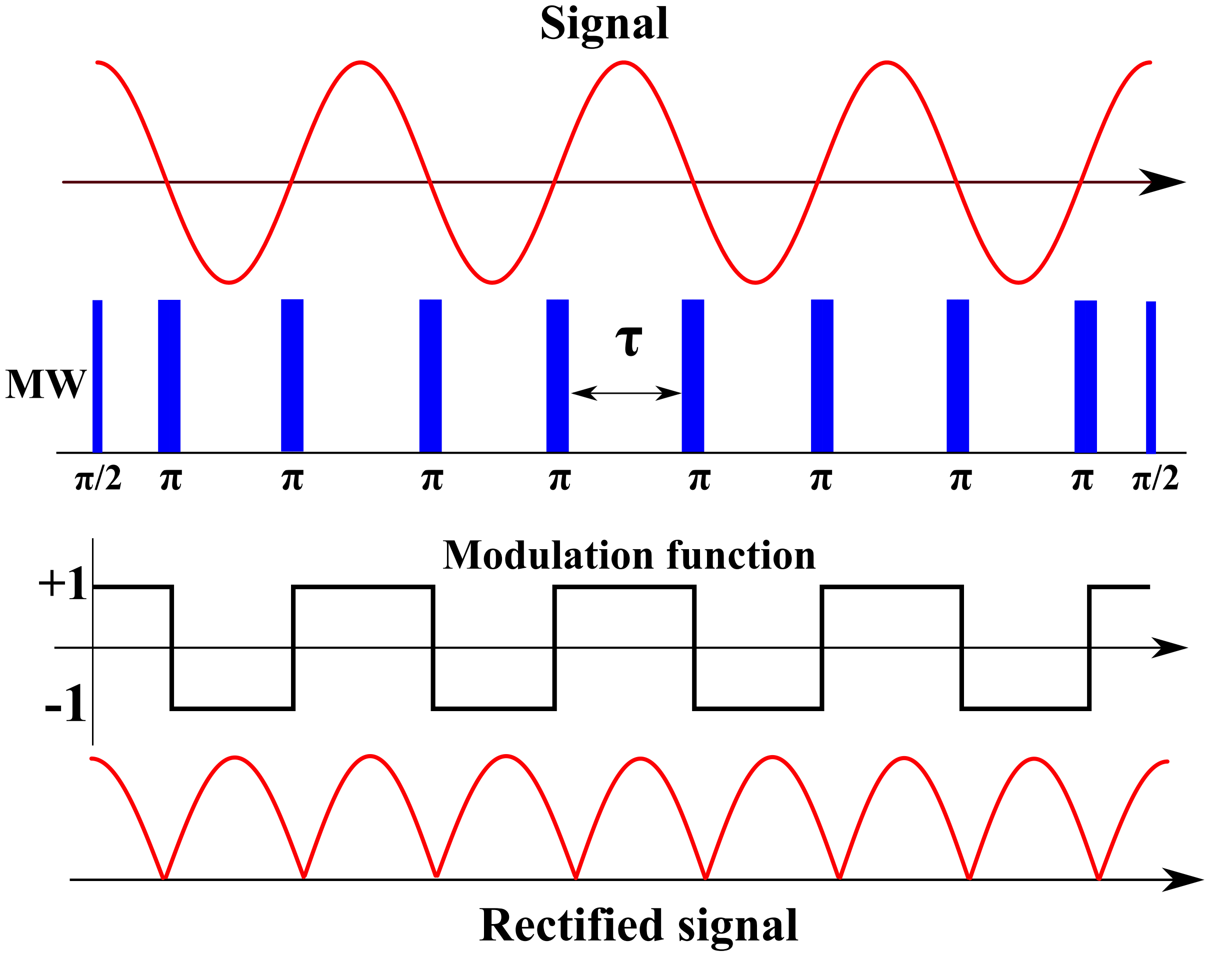


$$\Phi = \gamma_e \left(\int_0^{\tau/2} \Delta \mathrm{B}(t)dt - \int_{\tau/2}^{\tau} \Delta \mathrm{B}(t)dt \right)$$

$$B(t) \; = \; B_{AC} \cos(2\pi f t + \phi_0)$$

$$\Phi = \frac{2}{\pi} \gamma_e B_{\mathrm{AC}} \tau \cos(\phi_0)$$

AC Magnetometry



Dynamical decoupling

$$f_L = \frac{k}{2\tau}$$

k=1,3,5,...

modulation function g(t)

$$\Phi = \int_0^T \gamma_e B(t) g(t) dt$$

$$\Phi = \gamma_e T B_{AC} W(f_L, \phi_0)$$

the filter function

$$W(f_L, \phi_0) = 8 \sin^2\left(\frac{\omega T}{2}\right) \frac{\sin^4\left(\frac{\omega T}{4n}\right)}{\cos^2\left(\frac{\omega T}{2n}\right)}$$

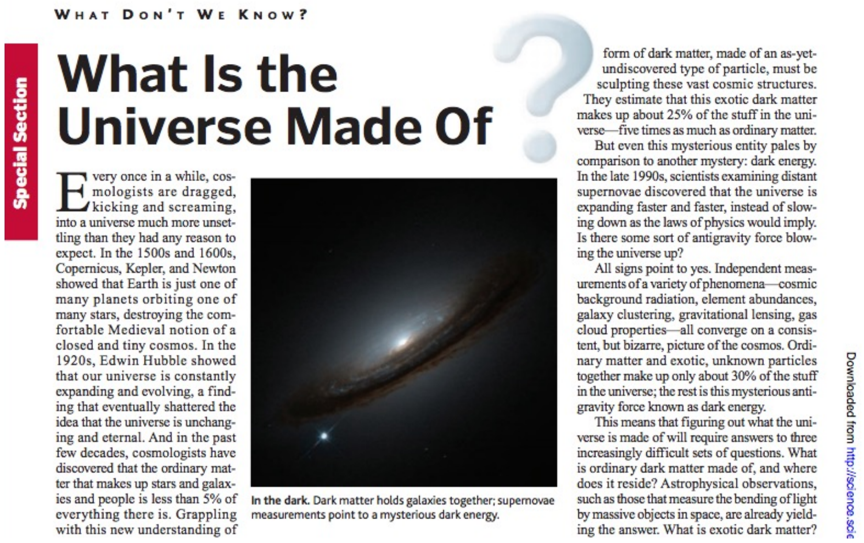
$$\omega = 2\pi f_L$$

第三部分：自旋量子精密测量

- 自旋与弱磁测量
- 自旋磁力仪
  - 原子磁力仪
  - **Rb-Xe**磁力仪
  - **NV**磁力仪
- 弱磁测量应用：暗物质探测

物质科学基本问题 宇宙由何构成?

被Science杂志列为125个最具挑战性科学问题的第一个



WHAT DON'T WE KNOW?

Special Section

What Is the Universe Made Of

Every once in a while, cosmologists are dragged, kicking and screaming, into a universe much more unsettling than they had any reason to expect. In the 1500s and 1600s, Copernicus, Kepler, and Newton showed that Earth is just one of many planets orbiting one of many stars, destroying the comfortable Medieval notion of a closed and tiny cosmos. In the 1920s, Edwin Hubble showed that our universe is constantly expanding and evolving, a finding that eventually shattered the idea that the universe is unchanging and eternal. And in the past few decades, cosmologists have discovered that the ordinary matter that makes up stars and galaxies and people is less than 5% of everything there is. Grappling with this new understanding of

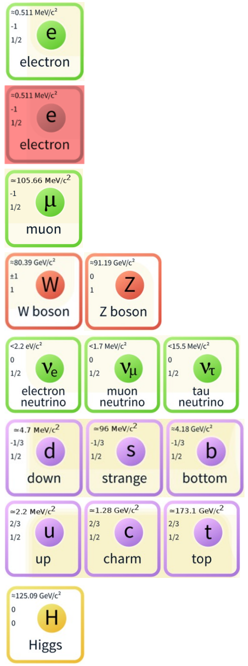
In the dark. Dark matter holds galaxies together; supernovae measurements point to a mysterious dark energy.

form of dark matter, made of an as-yet-undiscovered type of particle, must be sculpting these vast cosmic structures. They estimate that this exotic dark matter makes up about 25% of the stuff in the universe—five times as much as ordinary matter.

But even this mysterious entity pales by comparison to another mystery: dark energy. In the late 1990s, scientists examining distant supernovae discovered that the universe is expanding faster and faster, instead of slowing down as the laws of physics would imply. Is there some sort of antigravity force blowing the universe up?

All signs point to yes. Independent measurements of a variety of phenomena—cosmic background radiation, element abundances, galaxy clustering, gravitational lensing, gas cloud properties—all converge on a consistent, but bizarre, picture of the cosmos. Ordinary matter and exotic, unknown particles together make up only about 30% of the stuff in the universe; the rest is this mysterious antigravity force known as dark energy.

This means that figuring out what the universe is made of will require answers to three increasingly difficult sets of questions. What is ordinary dark matter made of, and where does it reside? Astrophysical observations, such as those that measure the bending of light by massive objects in space, are already yielding the answer. What is exotic dark matter?



16次

电子 1906 汤姆孙

正电子 1932 安德逊

介子 1949 汤川秀树

W/Z 玻色子 1984 卡罗鲁比亚等

中微子 1988, 1995, 2002, 2015

夸克 2004 格罗斯等人

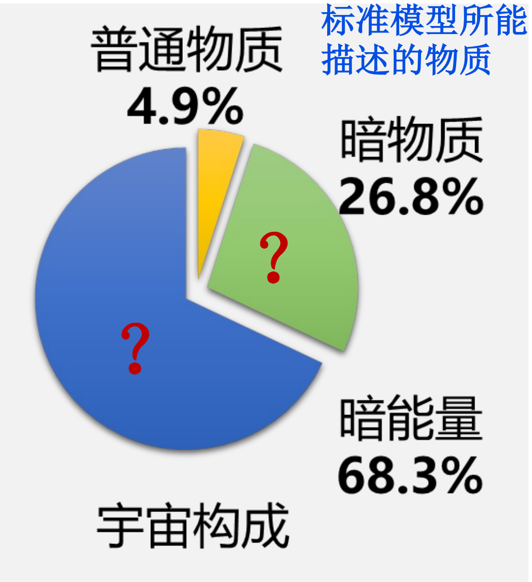
希格斯玻色子 2013 希格斯等人

粒子物理标准模型成功描述了基本粒子及其相互作用，
被认为是二十世纪物理学最成功的理论之一

暗物质

标准模型正面临重大挑战

二十一世纪物理学的两朵“乌云”

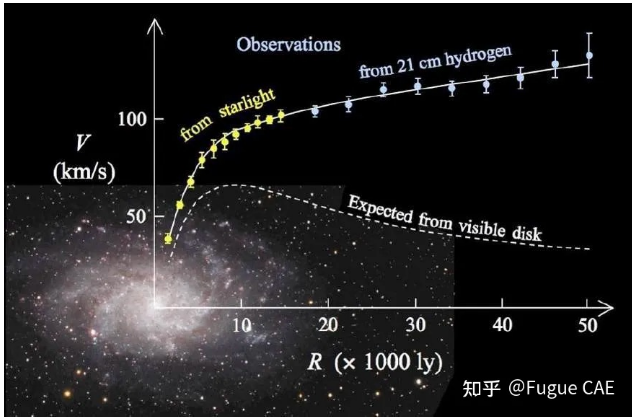


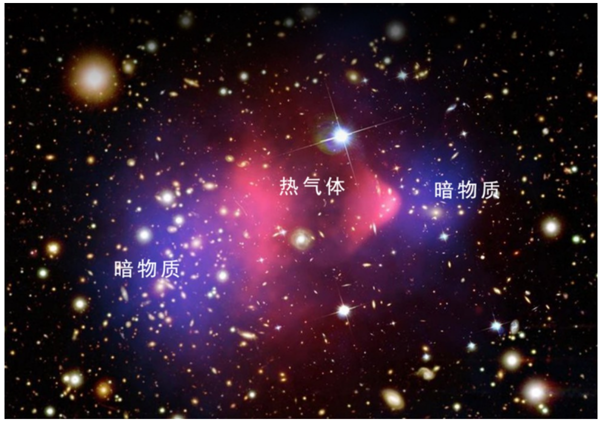
宇宙构成

暗物质存在的证据（天文观测）

星系旋转曲线

子弹星系团





1.参与引力相互作用，具有质量属性

2.与光子、电子和质子之间的相互作用极其微弱(甚至没有)

星系中的幽灵“雾霾”

在最大尺度上，暗物质主宰着宇宙

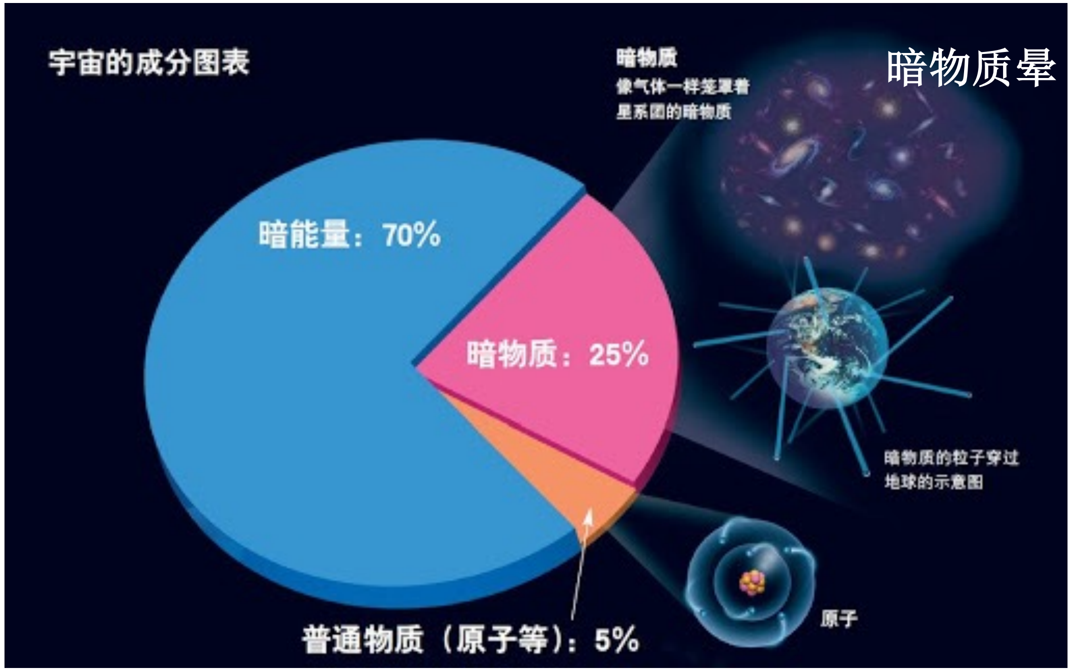
我们所处地区

暗物质的局部密度～10^{-21} kg/m^3
人体的密度～1000 kg/m^3

每秒有多少暗物质穿过人的身体?

每秒，每个人会经历2.5 ×10^{-16}kg的暗物质穿过身体

- 每秒约有10^8个暗物质（100GeV）穿过身体
- 每个人身体上有10^{29}个原子



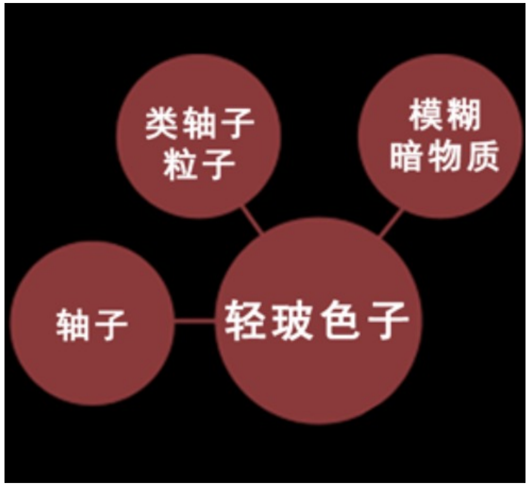
可是每年暗物质和每个人的碰撞次数 <1
（实验结果）

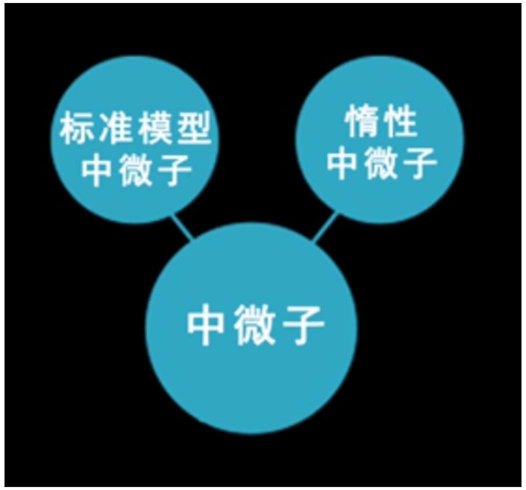
而我们的身体每天和环境中的宇宙射线和伽马射线碰撞10^8次

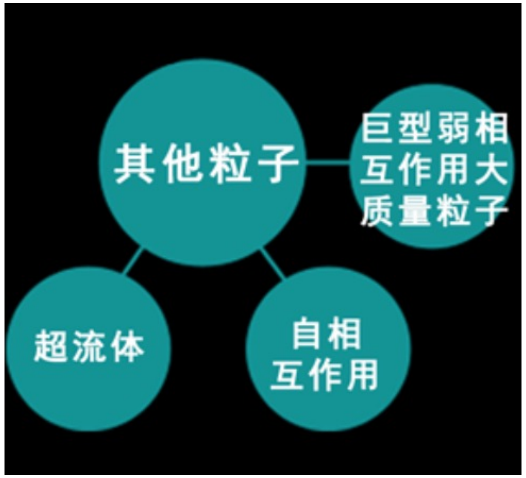
暗物质的本质

超越标准模型的新物理

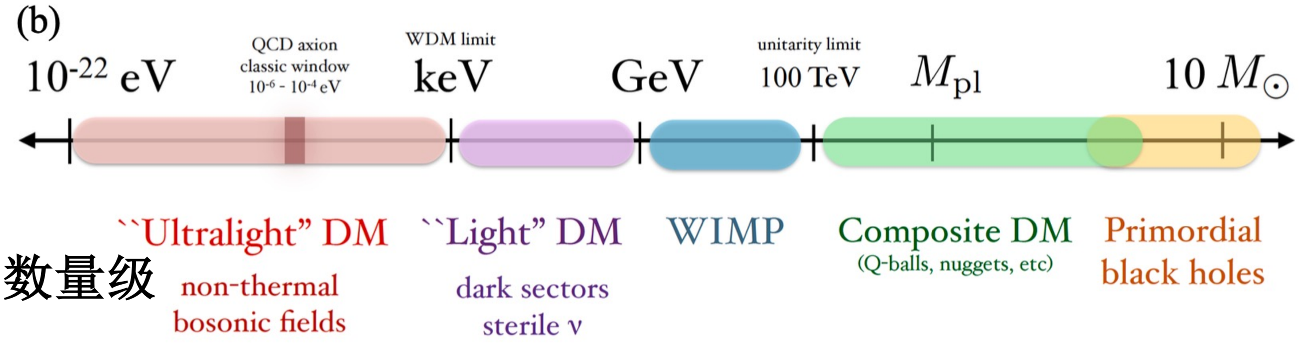
理论学家提出了暗物质可能是由一种或者多种超越标准模型的新粒子组成。







热门的暗
物质候选
粒子



90 个数量级

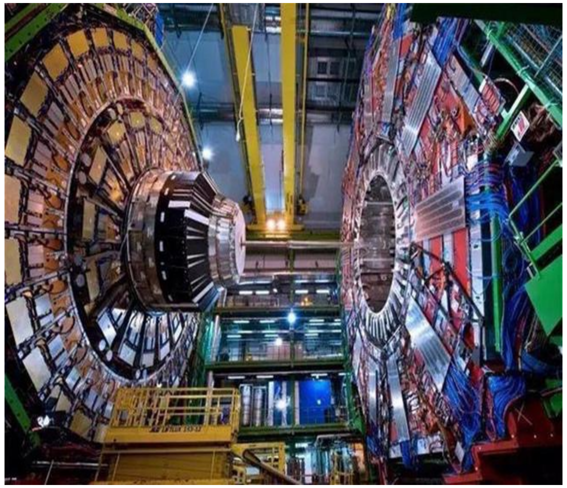
寻找暗物质

实验探测途径

10^{-22} eV　10^{-18} eV　10^{-14} eV　10^{-3} eV　10^{5} eV

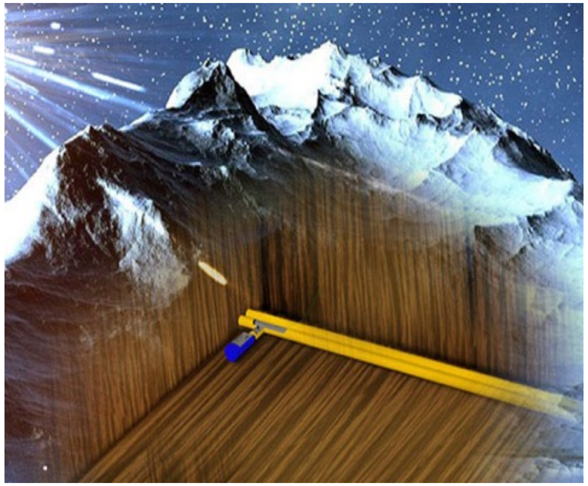
低能区暗物质： 波动性
德布罗意波长通常大于观测仪的尺寸

高能区暗物质： 粒子性
粒子探测器



对撞机实验
(LHC、BESIII等)

空间实验
(DAMPE、AMS等)

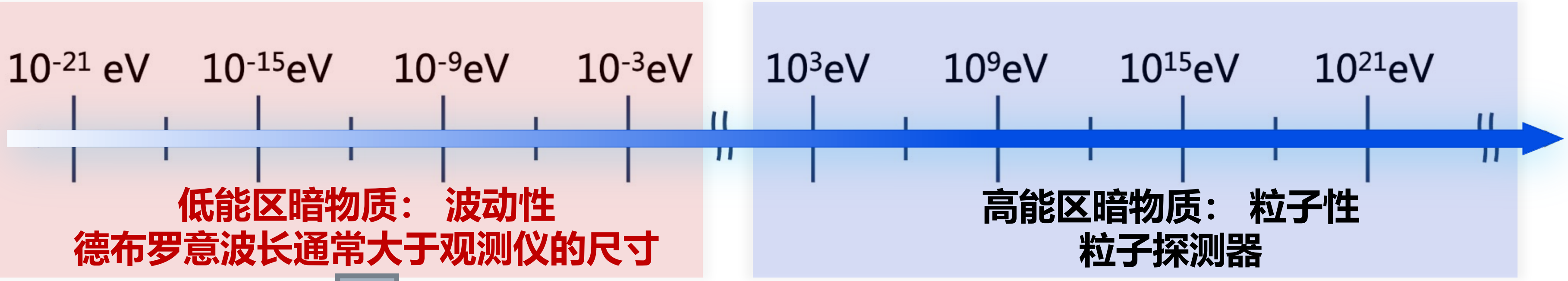


地下实验
(PandaX、CDEX等)

目前仍未找到证据

寻找暗物质

“桌面式”实验搜索

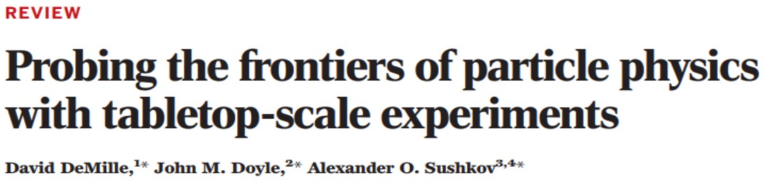


低能区暗物质： 波动性
德布罗意波长通常大于观测仪的尺寸

高能区暗物质： 粒子性
粒子探测器

✓ 能区范围广 ✓ 信号极其微弱

新途径：量子精密测量技术


REVIEW

Probing the frontiers of particle physics with tabletop-scale experiments

David DeMille,[1]* John M. Doyle,[2]* Alexander O. Sushkov[3,4]*

DeMille et al., Science 357, 990 (2017)


Search for new physics with atoms and molecules

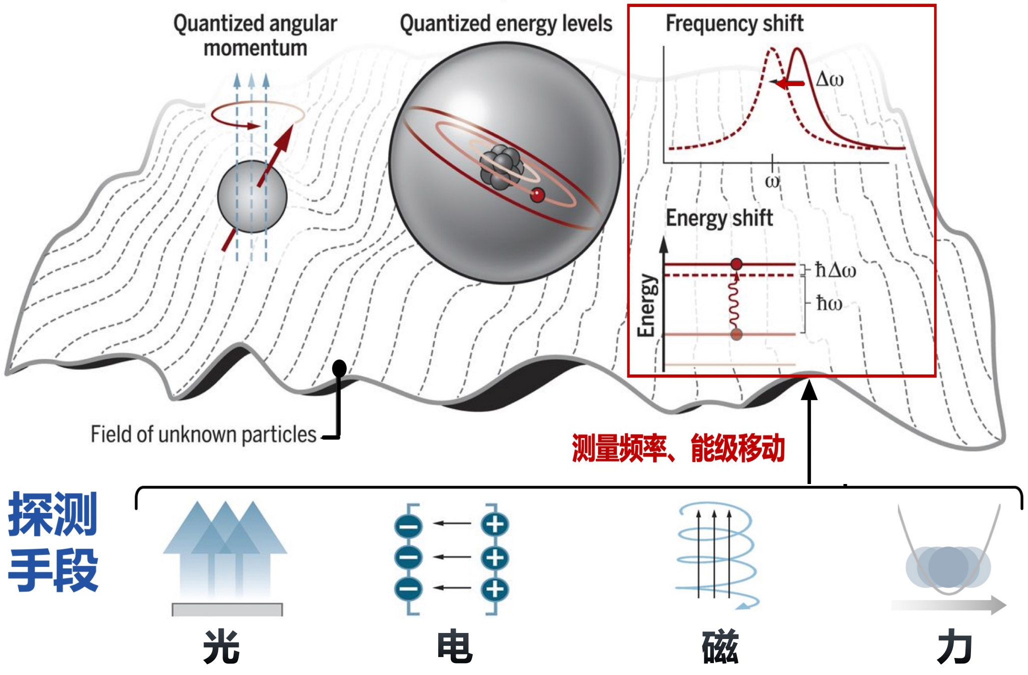
Safronova et al., Rev. Mod. Phys. 90, (2018)

- ■ **高灵敏**：受限于量子噪声
- ■ **小型化**：不受实验场地限制
- ■ **阵列式**：更高精度和置信度

为超轻质量暗物质搜寻提供全新的研究手段，带来新的机遇！

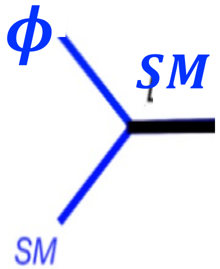
寻找暗物质　“桌面式”量子精密测量

测量原理：未知新物理场导致自旋频率、能级移动



探测手段

轴子（Axion）：



未知场：$a(t) = a_0\cos(\omega' t)$

Hamiltonian = **Coupling**

$+\sqrt{\frac{\varepsilon_0}{\mu_0}}\, g_{a\gamma\gamma}\int a\mathbf{E}\cdot\mathbf{B}\,dV$ **Axion-photon**

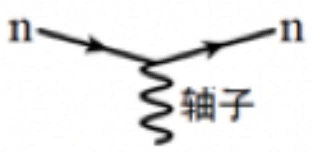
$+\, g_{aff}\,\hbar c\,\nabla a\cdot\hat{\mathbf{S}}$ **Axion-spin**

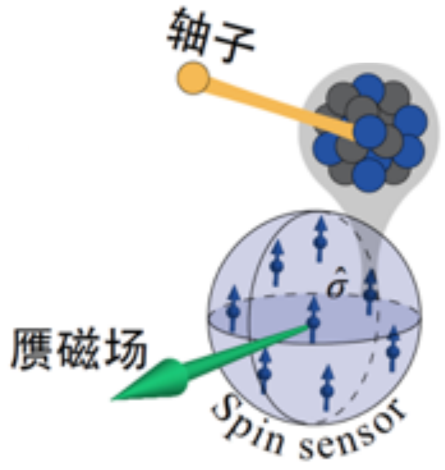
$+\sqrt{\varepsilon_0(\hbar c)^3}\, g_{EDM}\, a\hat{\mathbf{S}}\cdot\mathbf{E}$ **Axion-gluon**

基于核自旋量子精密测量的轴子探测

直接探测

（轴子直接与自旋作用）

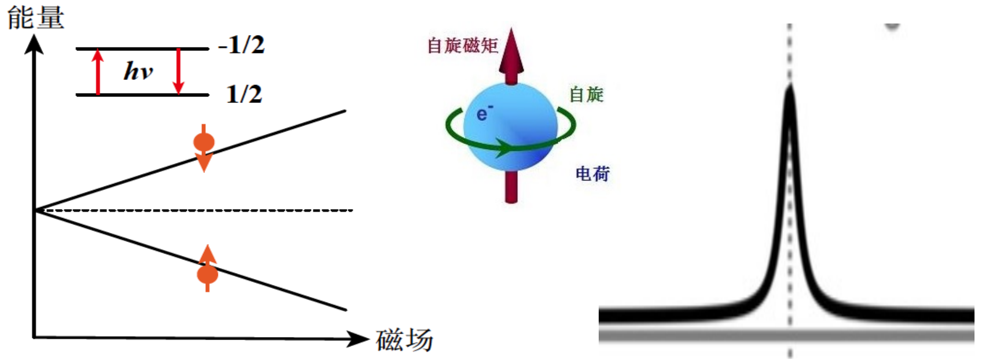




暗物质候选粒子

轴子和核自旋相互作用引起能量移动，
等效于在核自旋上产生一个赝磁场

$$\delta E = g_{\mathrm{aff}} \hbar c \nabla a \cdot \hat{\mathrm{S}} = \hbar \gamma \vec{B}_{ALP}$$



"pseudo-magnetic" field:

$$\vec{B}_{\mathrm{ALP}} \propto \underline{g_{\mathrm{aNN}}} \cos(\underline{m_{\mathrm{ALP}}} t)\vec{v}$$

低能区 m_{ALP} ➡ 低频磁传感器

更小相互作用g_{aNN} ➡ 高灵敏磁传感器

Sapphire project （“蓝宝石”计划）

Spin Amplifier for Particle PHysIcs Research

实验结果

暗物质与普通物质的“作用”上限

nature physics

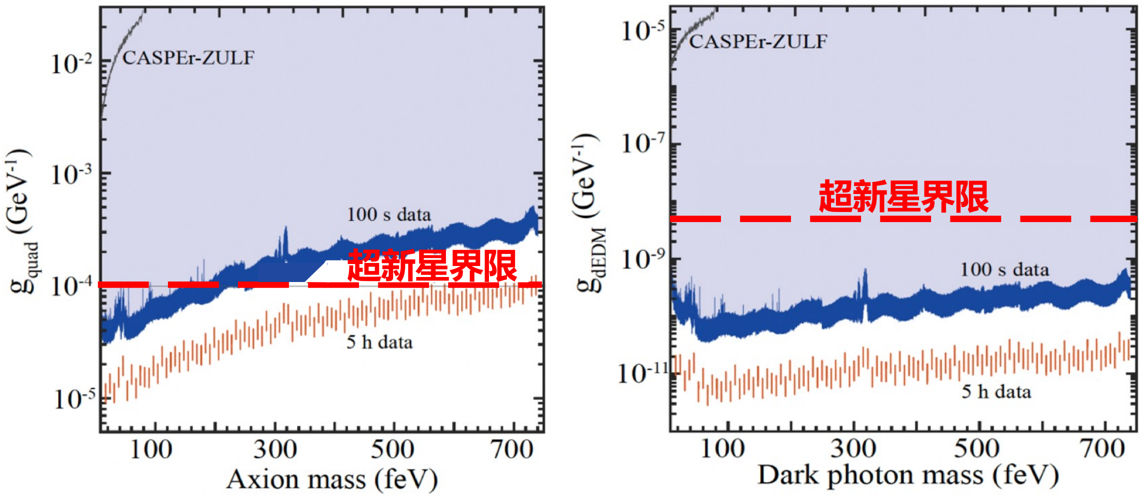
ARTICLES

https://doi.org/10.1038/s41567-021-01392-z

Check for updates

Search for axion-like dark matter with spin-based amplifiers

Min Jiang[1,2,3,7], Haowen Su[1,2,3,7], Antoine Garcon[4,5], Xinhua Peng[1,2,3] ✉ and Dmitry Budker[4,5,6]



暗物质观测突破超新星观测界限

人民日报

中科大发布新成果

为搜寻暗物质提供超灵敏量子精密测量技术

本报合肥11月28日电 （记者**田先进**）记者近日从中国

旋量……技术，实现了新型核自旋磁……利用

激光先……化铷原子蒸气，再利用铷与气态氙原子的……

碰撞，从而将氙原子的核自旋极化。基于该物理机制，研究人

员设计出磁场量子放大器，并将这台自旋放大器与团队已发

展的原子磁力计相结合，将原子磁力计的磁探测灵敏度提高了100倍。

理论预测，暗物质与原子核会发生极微弱的相互作用，这种相互作用相当于在原子核自旋上施加一个微小磁场——“赝磁场”。利用超灵敏磁场探测装置可以检验这一微小的“赝磁场”，以此来寻找暗物质粒子存在的迹象。彭新华研究组利用自旋放大器来放大暗物质产生的“赝磁场”，大大提高了暗物质的搜寻灵敏度。相比传统大型暗物质科学装置，该设备只需要桌面尺寸的空间布局。

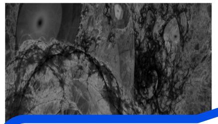
这一成果充分展示了量子精密测量技术与暗物质探测的交叉融合，有望推动宇宙天文学、粒子物理学和原子分子物理学等多个基础学科的发展。

这一成果充分展示了量子精密测量技术与暗物质探测的交叉融合

PHYS.ORG

DECEMBER 13, 2021

New spin amplifier accelerates search for dark matter



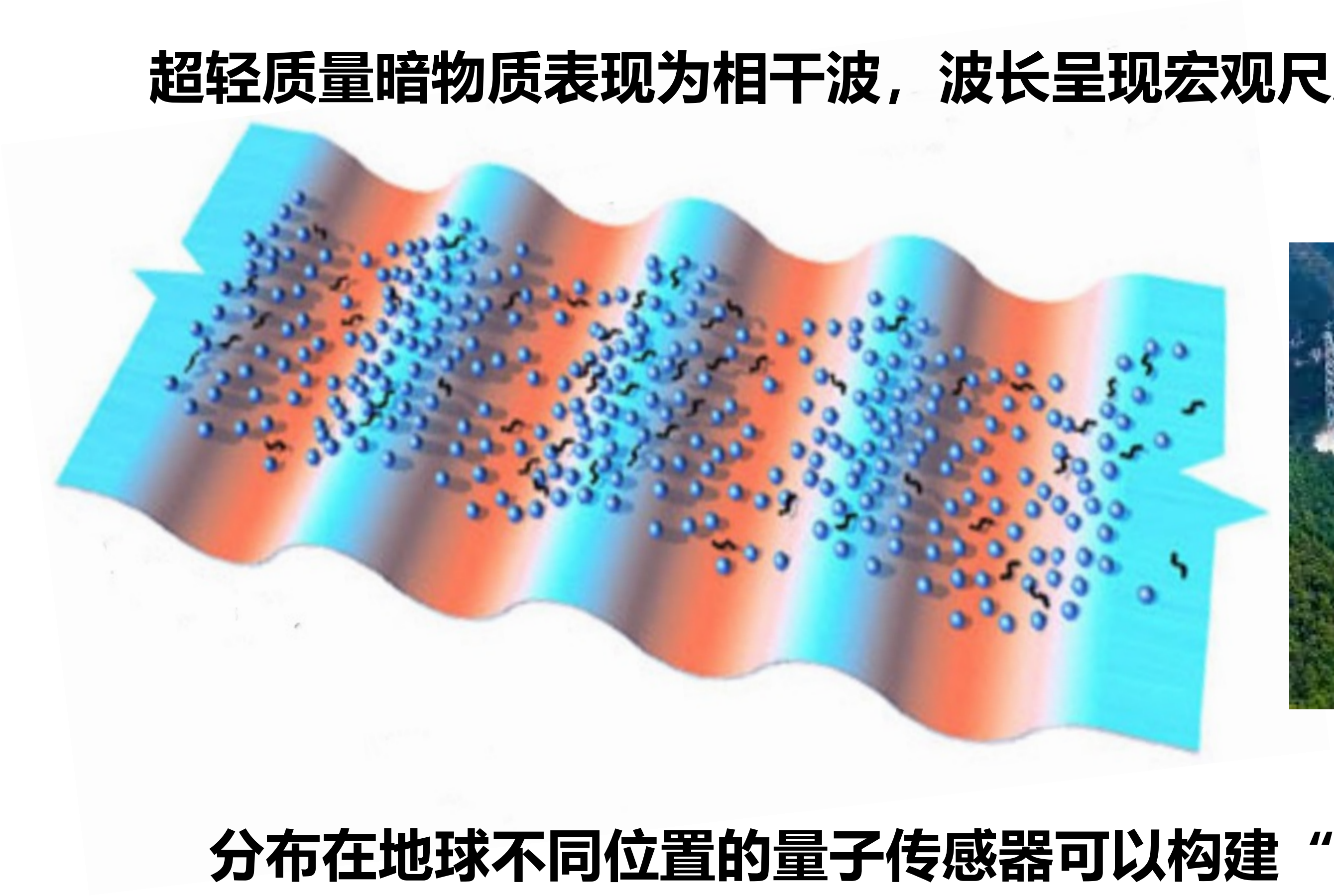
They found that the nuclear spins of xenon can act as a pre-amplifier for the exotic magnetic field generated by dark matter, and rubidium magnetometer further reads out the amplified signal. They showcased the capability of the spinbased amplifier to surpass the photon-shot-noise limit of the rubidium magnetometer itself, approaching the spin-projection-noise limit of the latter. This technique has a significantly better performance than that of other etometers demonstrated with nuclear spins, which are sitivity of a few picotesla.

he ultra-sensitive spin-based amplifier, the onducted experimental searches for axion-like dark photons. They found no evidence of the ark matter in the search area, and probed the coupling down to values below the established onstraints.

提出的自旋放大技术提供了一种独特的类轴子和暗光子的超高精度测量方法

分布式搜寻暗物质

超轻质量暗物质表现为相干波，波长呈现宏观尺度　**1feV**≈ 100**倍地球直径**

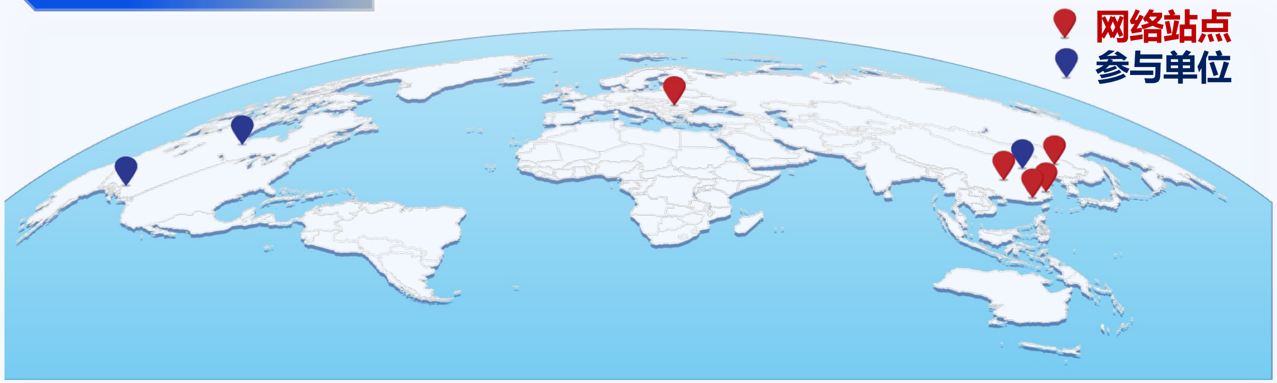


分布在地球不同位置的量子传感器可以构建“大口径观测望远镜”

提高灵敏度 $\propto 1/\sqrt{N}$　**显著降低报警率**$\propto p^N$　**结构信息**

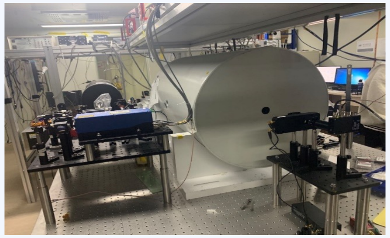
蓝宝石计划（Spin Amplifier for Particle PHysIcs Research)

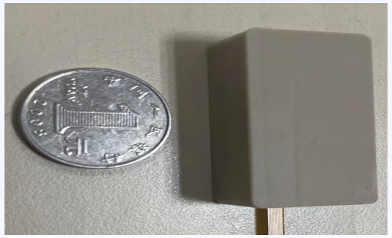
蓝宝石计划



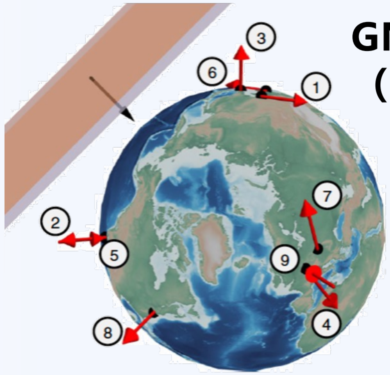
国内外参与单位：

中国科学技术大学 (平台型，4台)，中国
浙江工业大学（平台型，1台），中国
德国亥姆霍兹研究所（平台型，1台），德国
哈尔滨工业大学（微型化，2台），中国
中科院苏州医工所（微型化，13台），中国
北京大学，中国
犹他州大学，美国
伯克利分校，美国

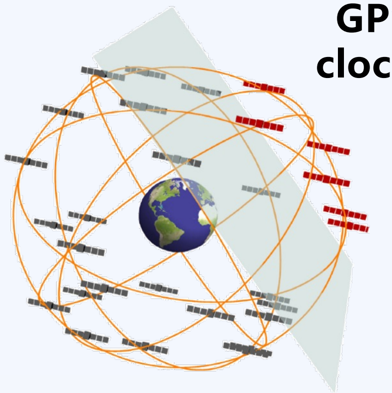




国际暗物质探测网络



GNOME
（参与）

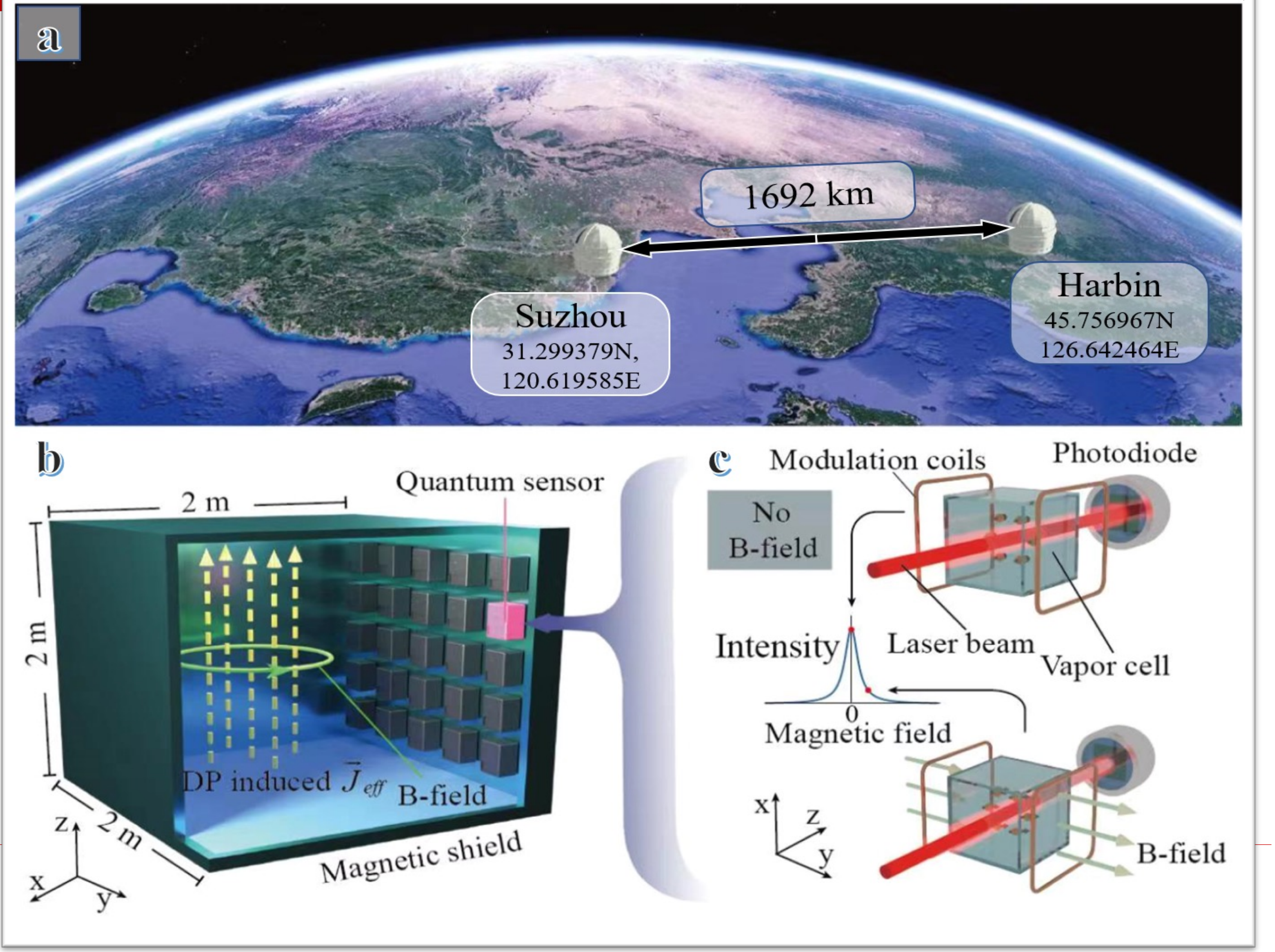


GPS
clocks

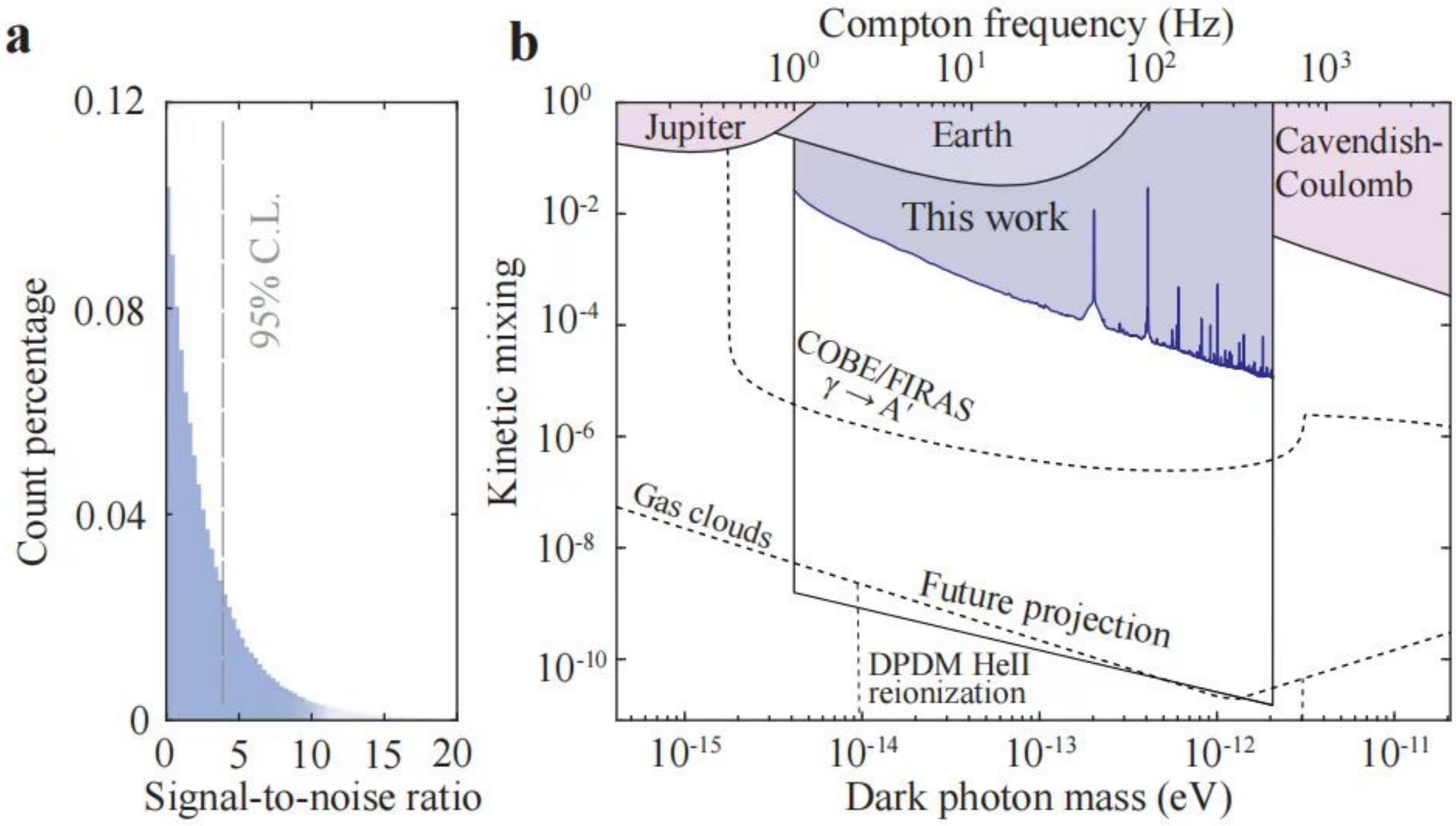
Search for dark photons with synchronized quantum sensor network

Min Jiang,[1, 2, 3, a)] Taizhou Hong,[1, 2, 3, a)] Dongdong Hu,[4, a)] Yifan Chen,[5] Fengwei Yang,[6] Tao Hu,[7] Xiaodong Yang,[7] Jing Shu,[8, 9, b)] Yue Zhao,[6, c)] and Xinhua Peng[1, 2, 3, d)]

arXiv:2305.00890v1 (2023)

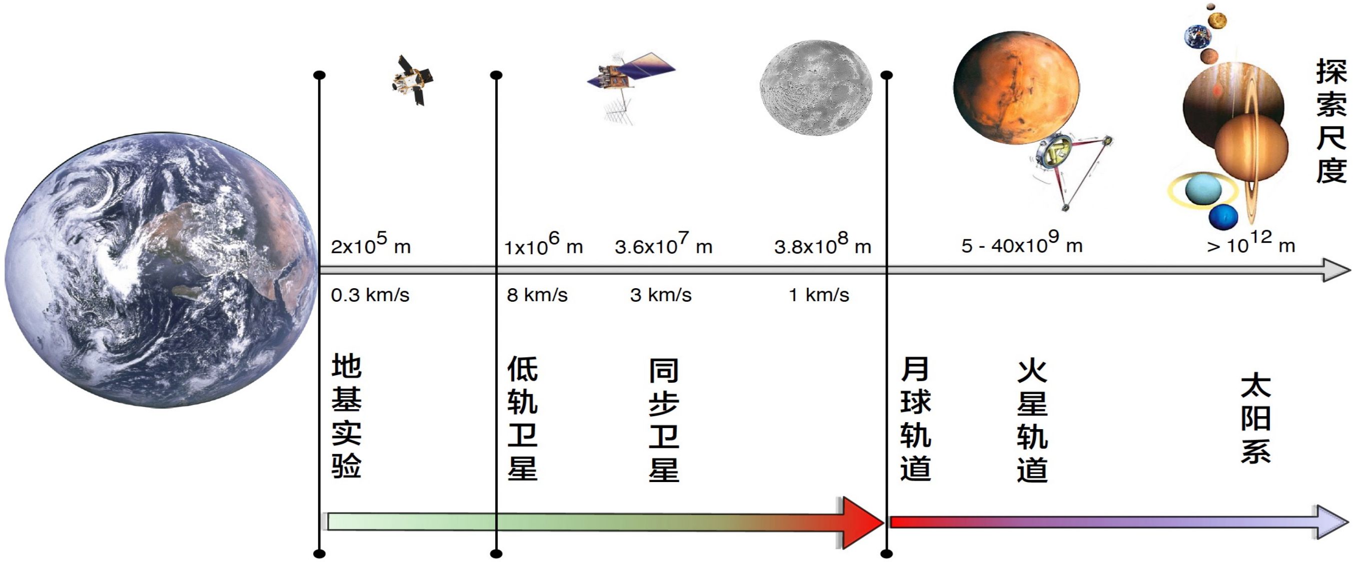


最新的dark photon暗物质结果



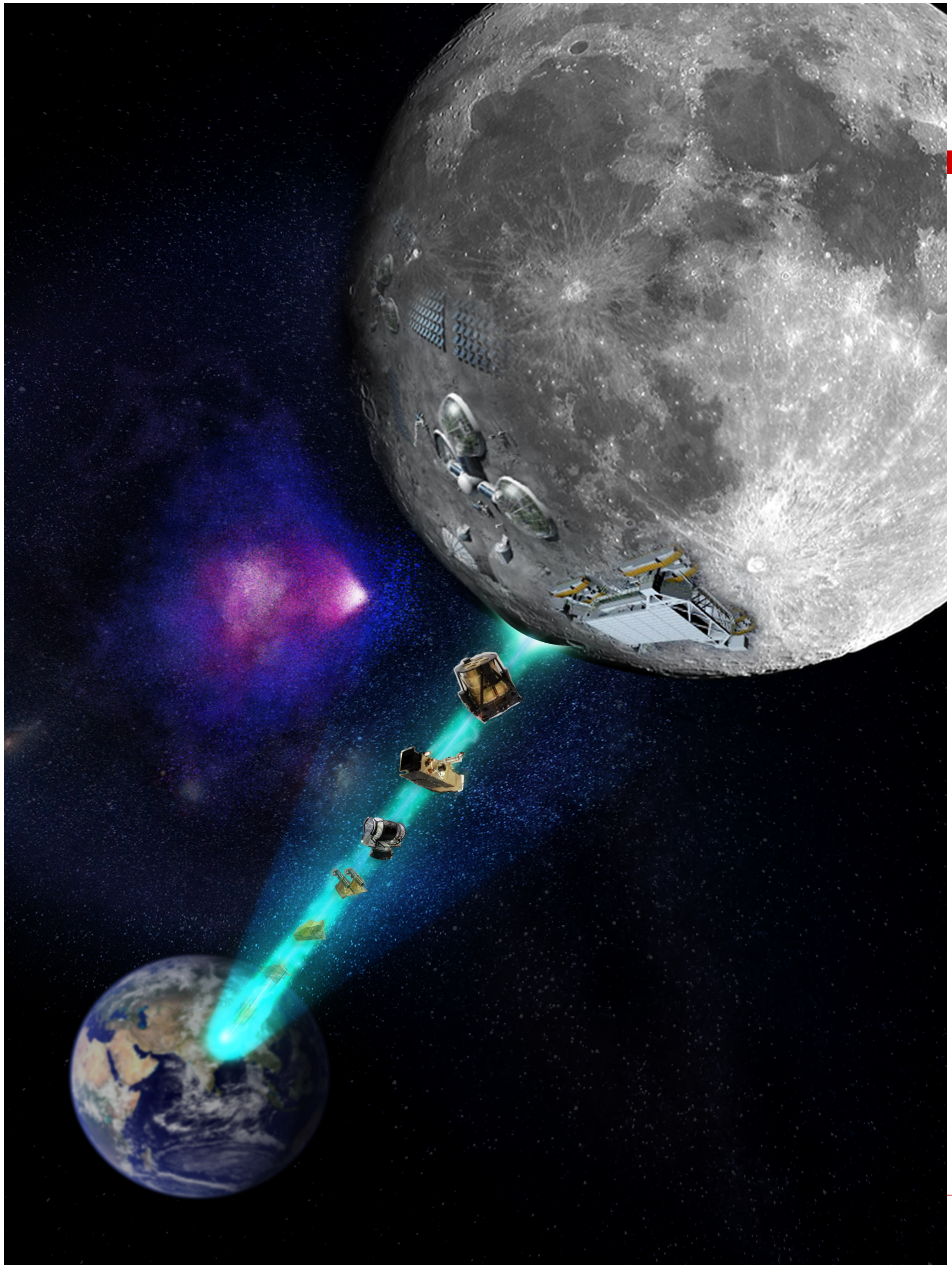
空间量子精密测量网络：“天地一体化”

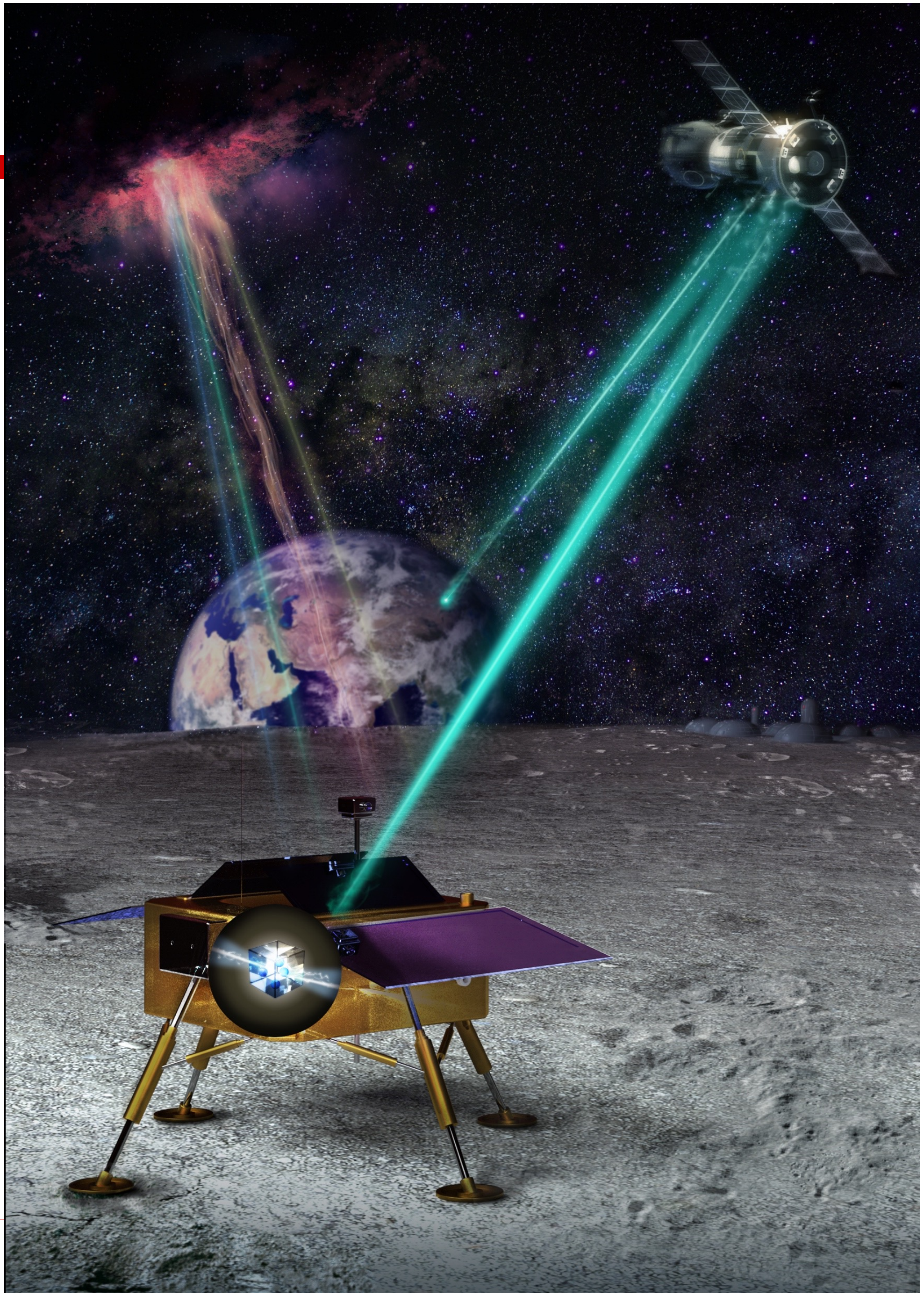
发展空间弱磁量子精密测量技术，探索重大基本科学问题，服务深空探测



中国空间站

- ✓ 不同实验尺度可以检验不同力程（质量）的轴子相互作用
- ✓ 天然的高速运动实验室：（部分）轴子诱发的自旋-自旋作用被增强
- ✓ 提供天然的大尺度且高达10^{42}极化电子数的极化粒子源
- ✓ 人类文明影响小（各种人造电磁波影响）



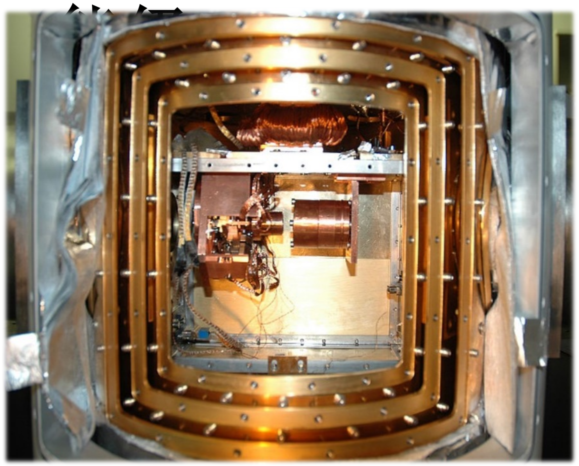


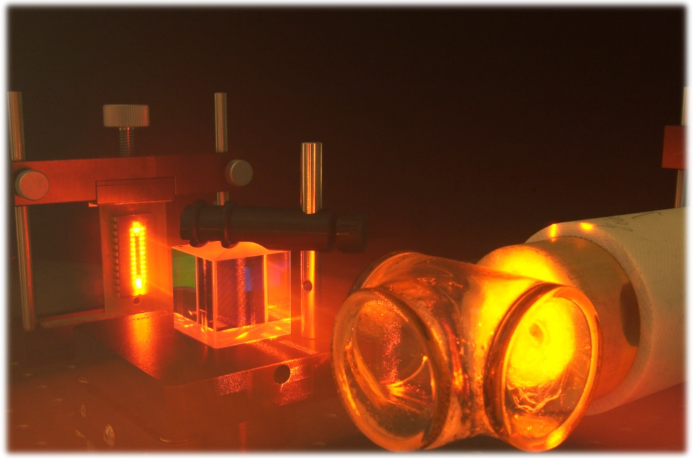
量子传感的三种类型

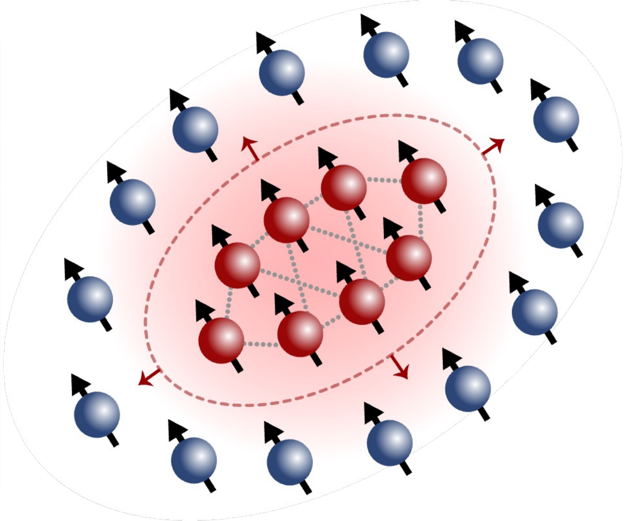
利用量子
体系分立

利用量子
相干叠加

利用量子纠缠
（关联）特性







**单电子晶体管
光力传感器**

**SQUID、质子磁力
仪、原子磁力仪**

……

测量精度受限于标准量子极

突破经典
物理的限
但技术成
熟度较低

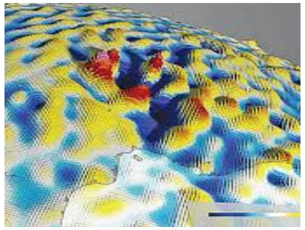
Rev. Mod. Phys., 89:035002, Jul 2017.

Classical sensing vs. quantum sensing

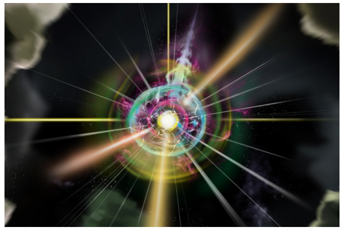
	Classical sensing	**Quantum sensing**	**Quantum sensing**
Probe	Classical	Quantum	Quantum
Parameter	Classical[*]	Classical[*]	Classical[*]
Available resources	Repeated measurement: N	Repeated measurement: N	N-probe entanglement
Spatial resolution	Macroscale	**Nanoscale**	**Nanoscale**
Error	$\delta\bar{\theta} \,\square\, \frac{1}{\sqrt{N}}$ (Central limit)	$\delta\bar{\theta} \,\square\, \frac{1}{\sqrt{N}}$ (Standard quantum limit)	$\delta\theta \,\square\, \frac{1}{N}$ (Heisenberg quantum limit)

[*]: Classical signal (e.g., magnetic field) or classical parameter of a quantum object (e.g., Zeeman frequency of a spin-1/2, parameters in a wave function)

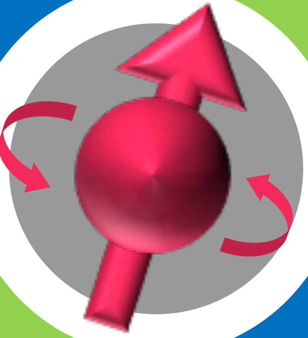
弱磁探测战略意义


自主导航


磁异常探测


暗物质搜寻


引力波探测

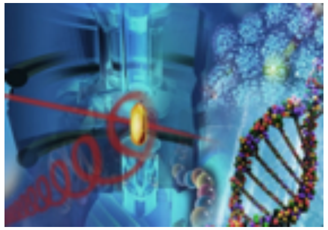


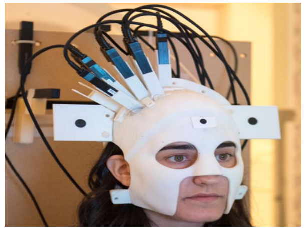
面向国家重大需求

面向世界科技前沿

面向人民生命健康

面向经济主战场

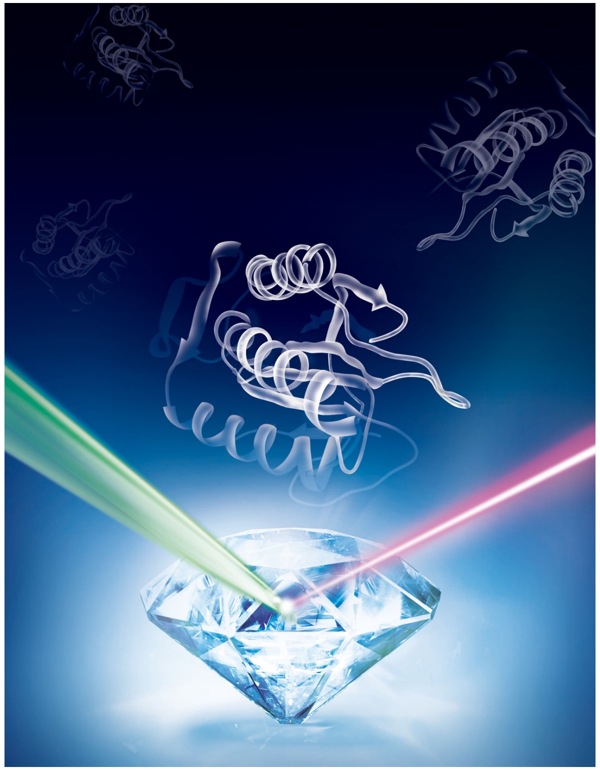

医学成像


心脑疾病诊断

小型化零场磁力计


钻石原子力显微镜

总结： 自旋与弱磁探测



fT磁探测灵敏度
量子放大

里德堡原子微波电
场探测： μV/cm
1—500 GHz超宽频段

nm空间分辨率

Thanks for your attention!

CAS Key Laboratory of Microscale Magnetic Resonance
(Directed by Prof. Jiangfeng Du)

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