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

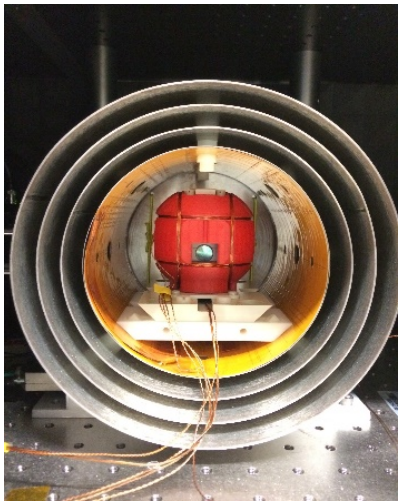
内容摘要

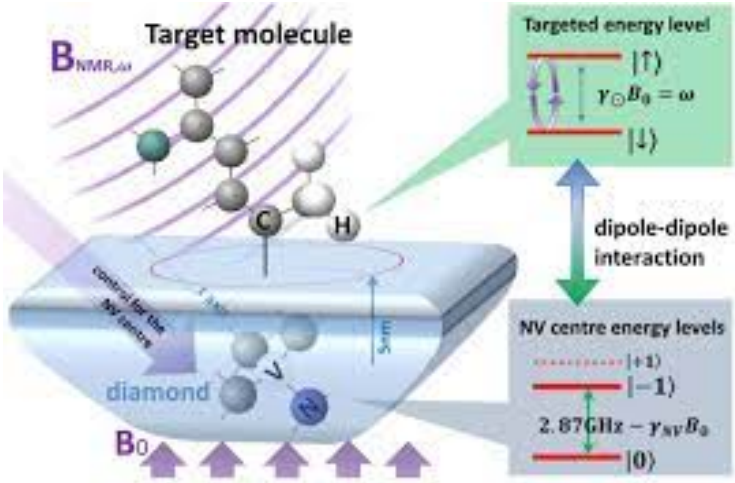
第一部分：　自旋和自旋磁共振

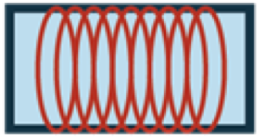
第二部分：　自旋量子精密测量

第一部分： 自旋和自旋磁共振

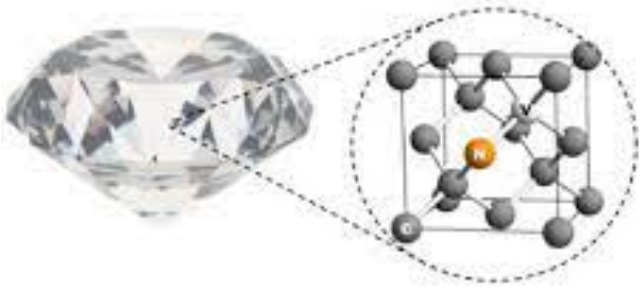












传统高场NMR

零场-超低场NMR

单分子NMR

内容摘要

第二部分：自旋量子精密测量

- 量子精密测量
- 原子磁力仪
- Rb-Xe磁力仪
- NV磁力仪

测量是科学发展的第一推动力



"测量是科学的眼睛和手段”
- 伽利略

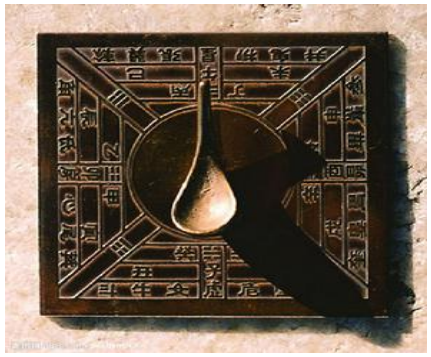


"科学是从测量开始的"
- 门捷列夫

精密测量是推动人类文明进步的重要引擎

- 对时间、质量、磁场、温度、压力等物理量精密测量是自然学科的重要基石
- 每次测量精度极限的突破，都革命性的改变人类的生活方式，推进人类文明进步

以磁场测量为例：



指南针：催动了航海时代的地理大发现



硬盘存储：信息时代必不可少的信息存储单元



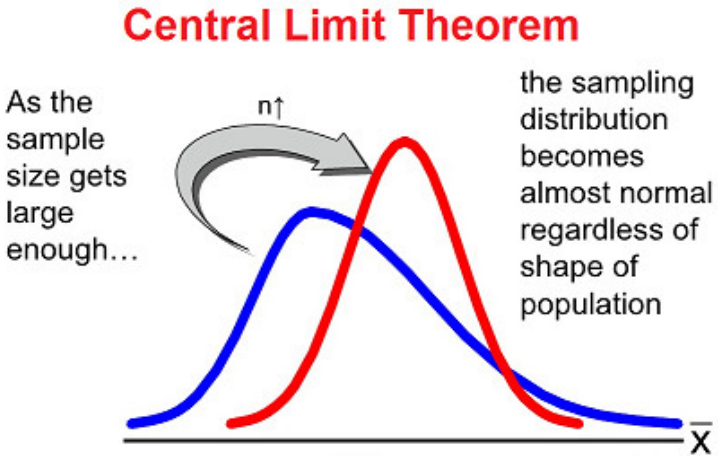
磁共振成像：已经成为医疗健康必不可少的检测设备，惠及万千民众

磁场强度

10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 单位：特斯拉

经典测量极限

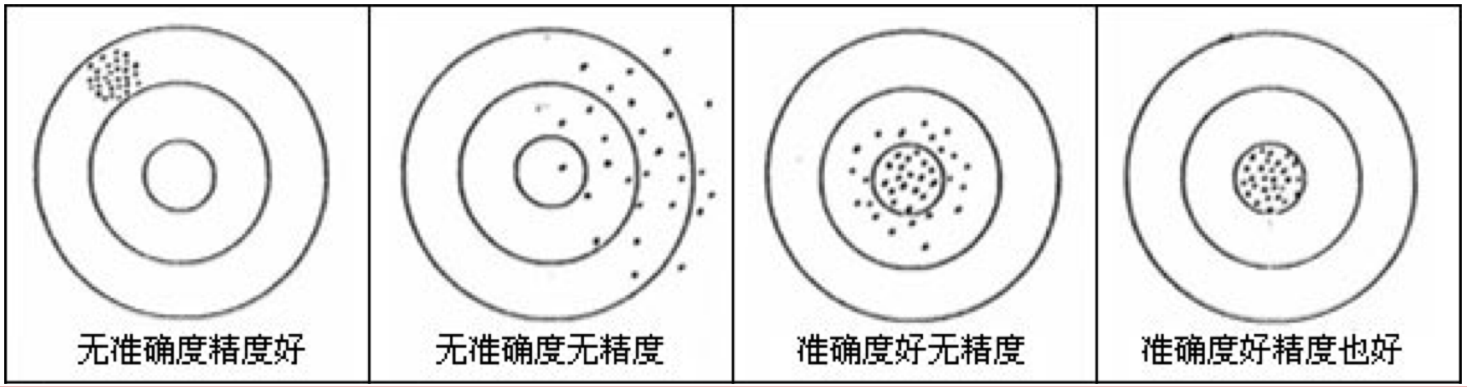
由于经典探测器构筑于宏观经典体系，因此测量灵敏度受到其本底噪声（包括热噪声、环境噪声等等）的制约。



$$\delta\hat{\theta} \equiv \sqrt{\langle(\hat{\theta}-\langle\hat{\theta}\rangle)^2\rangle} = \sqrt{\langle\hat{\theta}^2\rangle-\langle\hat{\theta}\rangle^2}$$

Cramer-Rao bound

$$\Delta\theta \geq \Delta\theta_{\mathrm{CR}} = \frac{1}{\sqrt{\nu F(\theta)}}$$



Quantum Enhanced Metrology

Higher Standards

This special issue of *Science* looks at the development of precision measurement, how its tools have been developed and adapted for better performance, and how the standards used today may be further improved. Historically, measurements were often based on somewhat arbitrary local units. In his Viewpoint, Ashworth (p. 1314) describes, from a British perspective, the development of a standardized metrology as applied to weights and measures and how the burgeoning commerce of the industrial revolution drove its development.

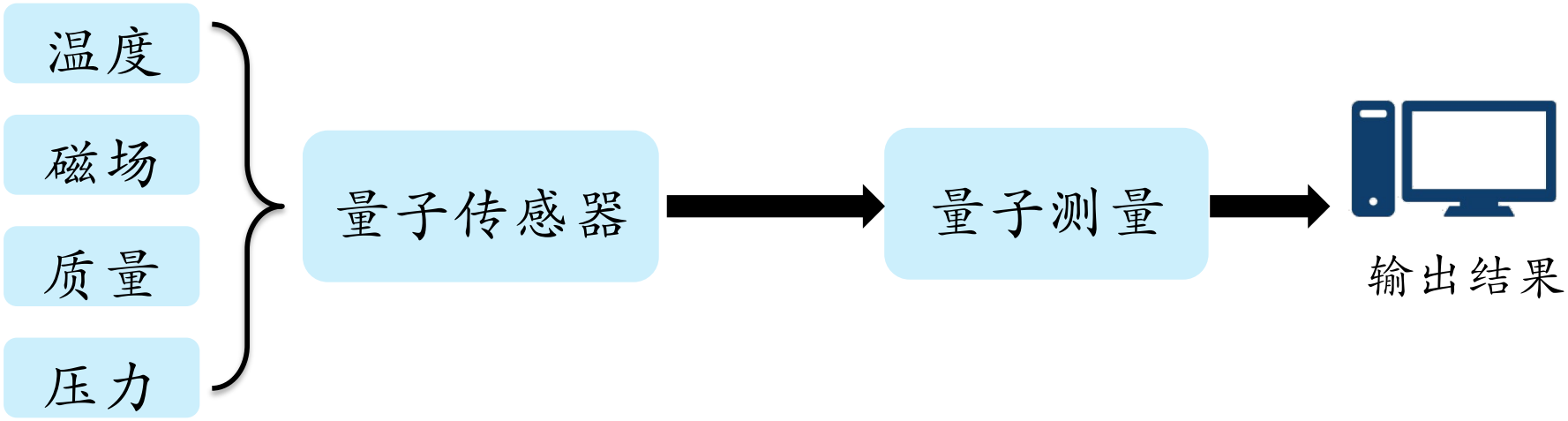
Quantum resources: Better Performance

Quantum mechanics, through the Heisenberg uncertainty principle, imposes limits on the precision of measurement. Conventional measurement techniques typically fail to reach these limits. Conventional bounds to the precision of measurements such as the shot noise limit or the standard quantum limit are not as fundamental as the Heisenberg limits and can be beaten using quantum strategies that employ ‘‘quantum tricks’’ such as squeezing and entanglement.

SCIENCE VOL 306 19 NOVEMBER 2004

量子测量突破经典测量极限

基于量子力学原理，利用量子力学特性(如原子能级、光子态或基本粒子的自旋)构筑新型量子传感器，突破经典测量极限的灵敏探测



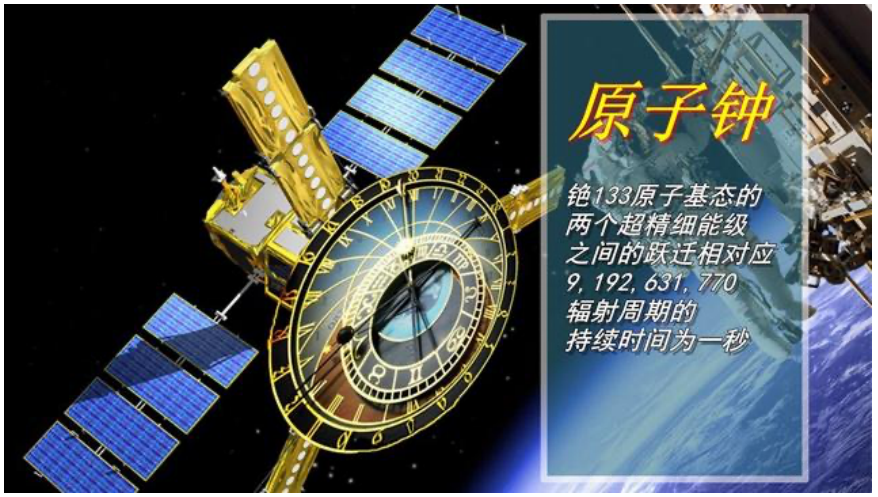
1. **Atomic clocks** for positioning, navigation, networking, and metrology.
2. **Atom interferometers**, e.g., gravimeters for remote sensing and accelerometers for navigation.
3. **Optical magnetometers** for bioscience, geoscience, and navigation.
4. **Devices utilizing quantum optical effects** for local and remote sensing, networks, and fundamental science.
5. **Atomic electric field sensors**, e.g., Rydberg atoms for GHz-THz radiation detection.

原子钟：时间测量从经典到量子

1945年， Rabi

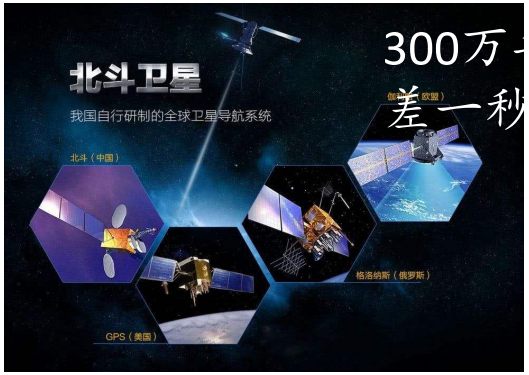
原子或分子振荡
的周期相当稳定

“国际秒”

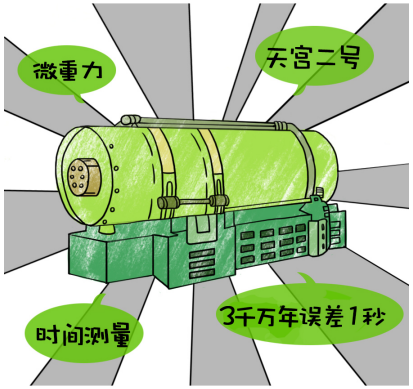


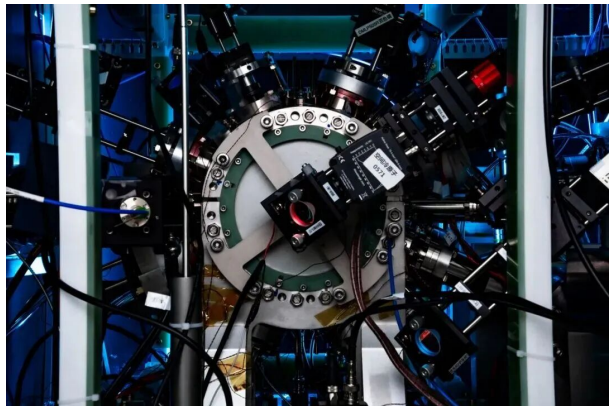
锶原子光钟：300亿年误差不超过一秒！

北斗系统　　铷原子钟



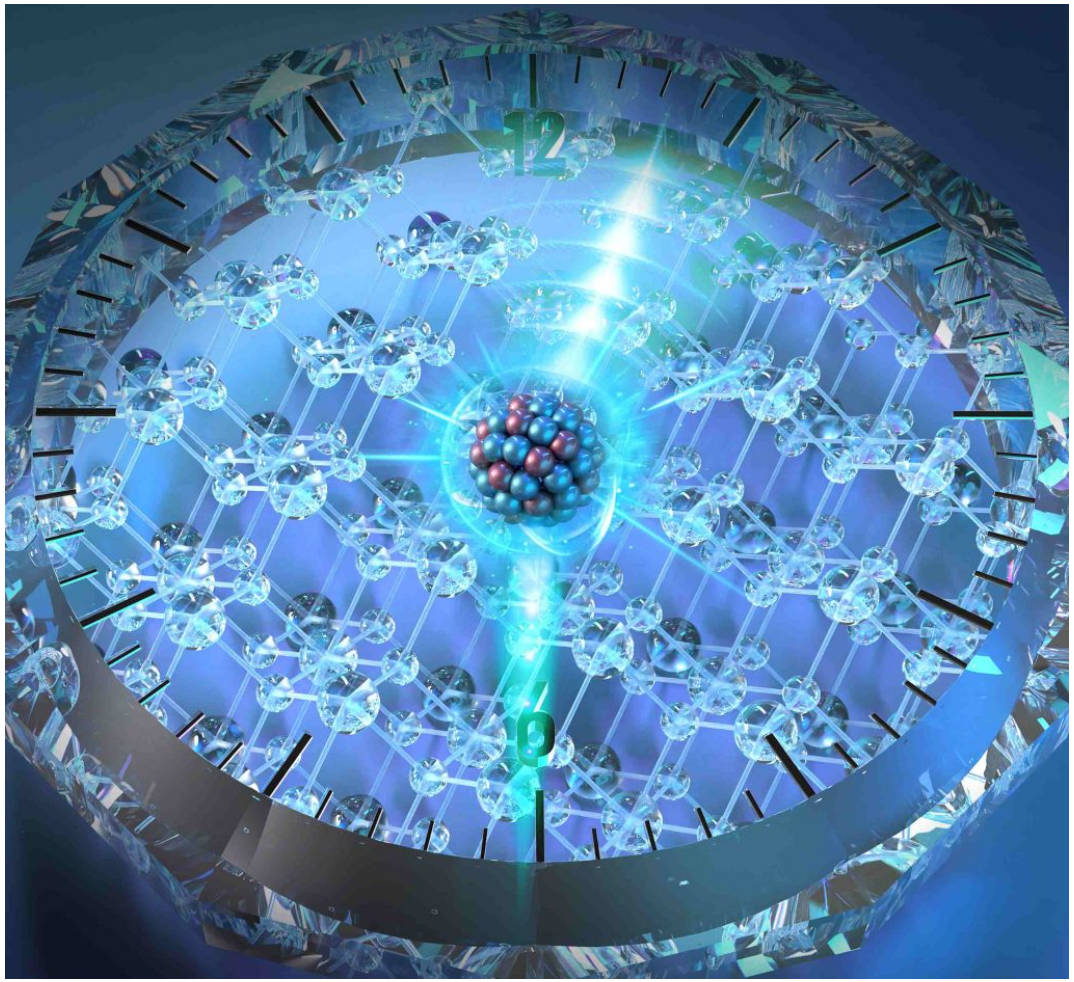
天宫二号空间冷原子钟





我国科学家研制成功核光钟

利用自主研制的148纳米连续波真空紫外激光以及掺钍-229氟化钙晶体，在国际上率先研制出核光钟并实现其稳定运行，将量子精密测量由电子跃迁拓展至原子核跃迁。



每400亿年才会出现1秒钟的误差

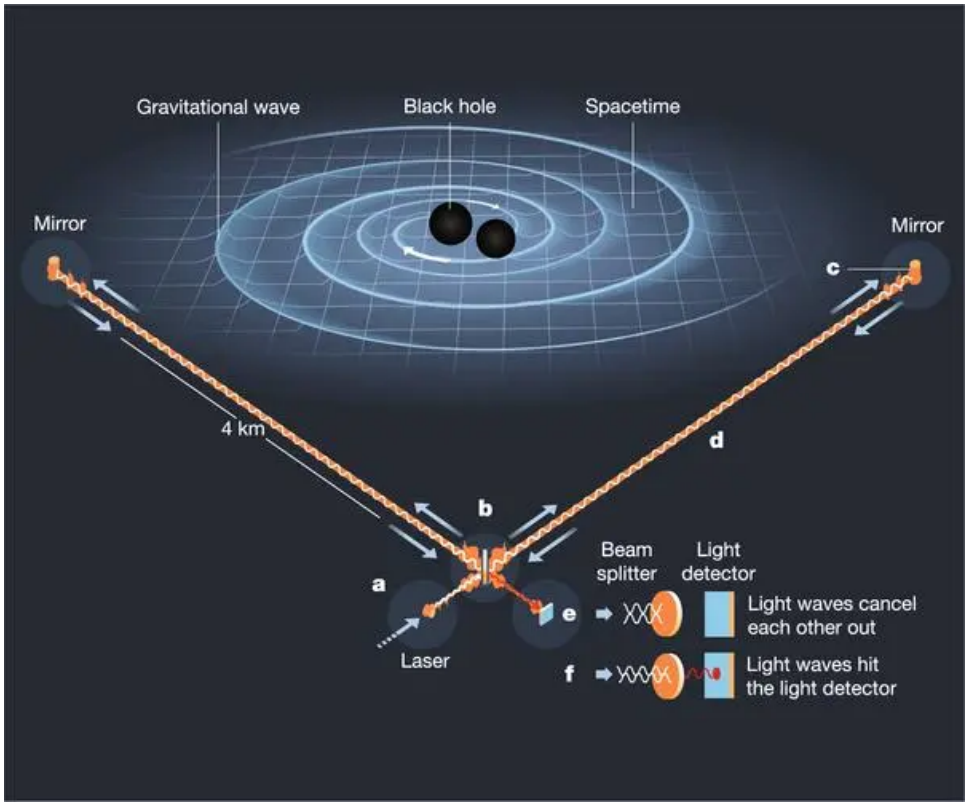
理论上可以做到3000亿年不差一秒

潜力精度有望逼近10^{-20}甚至更高量级

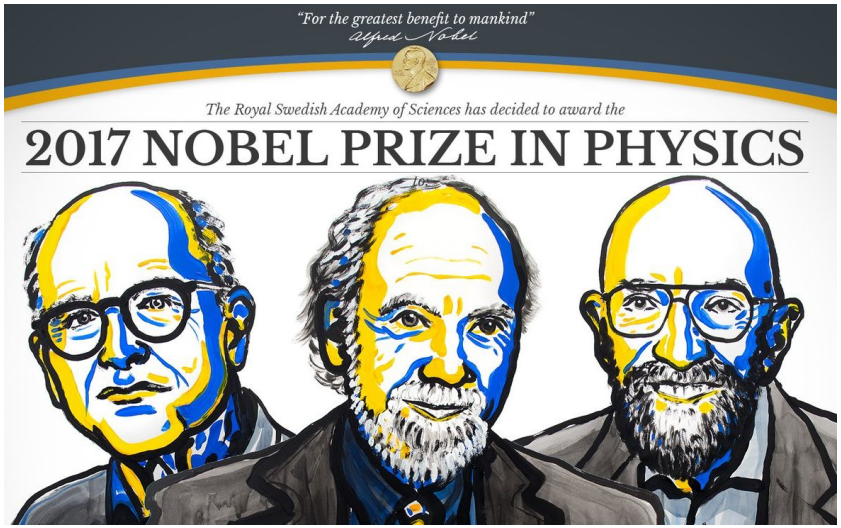
Nature **volume 658**, pages903–908 (2026)

LOGO：引力波探测

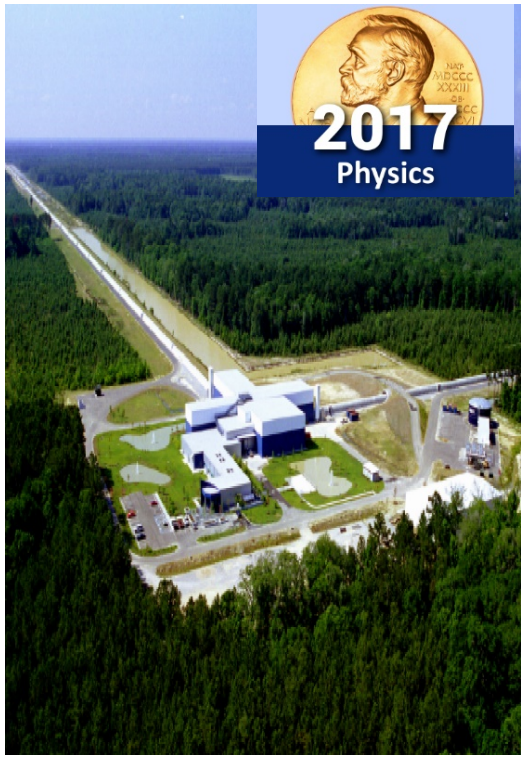
Laser Interferometer Gravitational-Wave Observatory (LIGO)



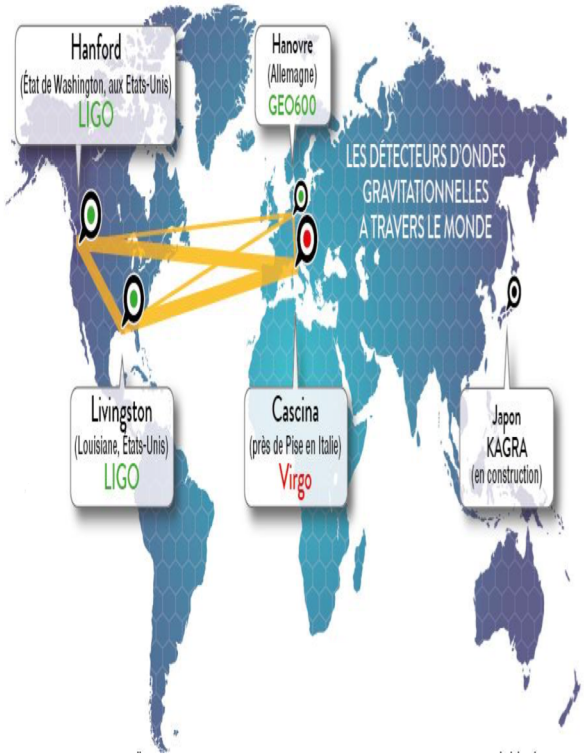
表彰他们在 LIGO项目和引力波观测中的决定性的贡献



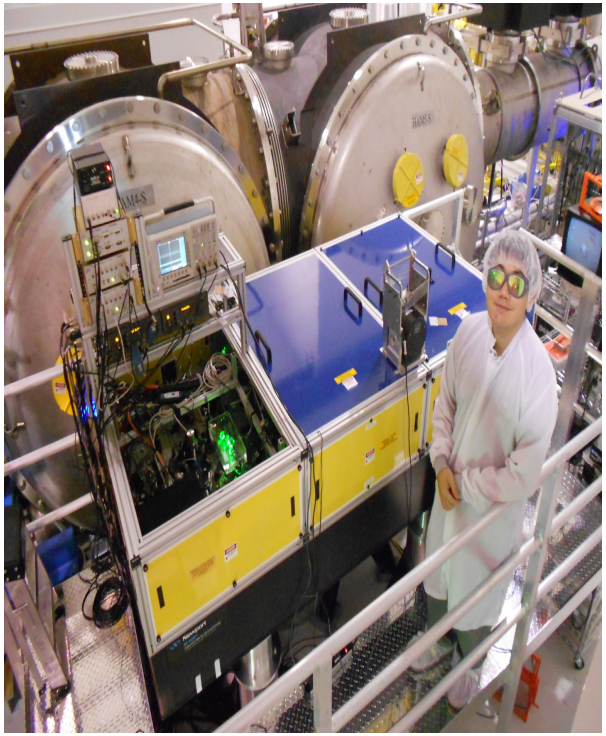
精密测量科学著名案例：引力波探测



2015年4月
LIGO首次直接探测到引力波



2017年8月
LIGO与VIRGO共同探测到引力波

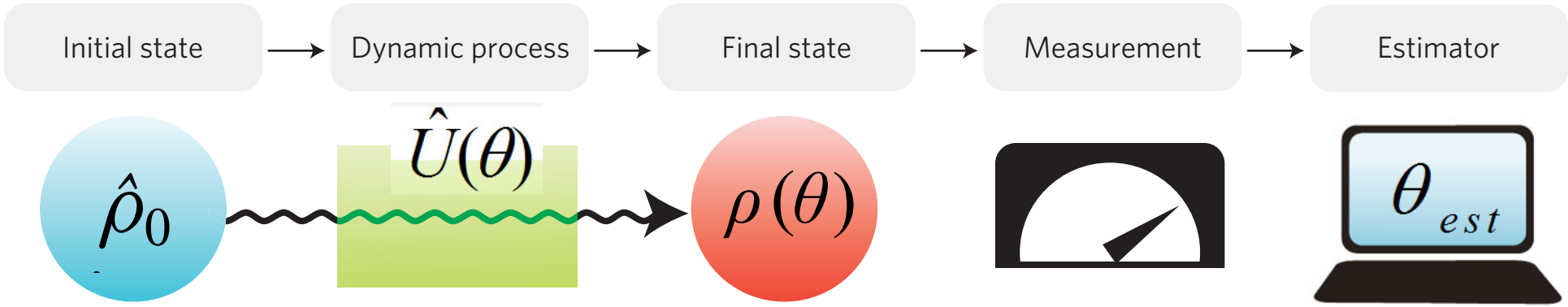


2019年4月
利用压缩光降低量子噪声，引力波探测数增加20%至50%

量子精密测量应用

General procedure

Quantum parameter estimation



POVM

the standard deviation of the parameter

$$\Delta\theta = \frac{\Delta\hat{O}}{|\partial\langle\hat{O}\rangle/\partial\theta|},$$

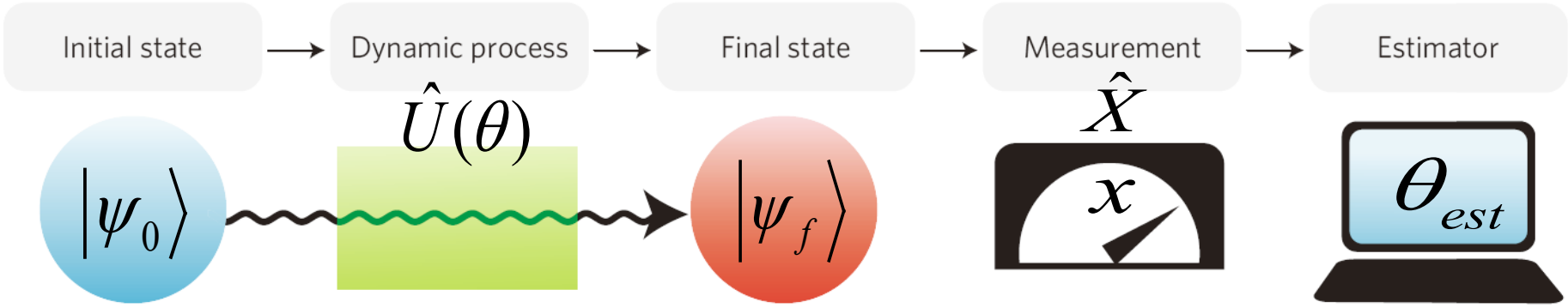
$$\Delta\hat{O} = \sqrt{\langle\hat{O}^2\rangle - \langle\hat{O}\rangle^2}$$

Quantum Cramér-Rao bound

$$\Delta\theta = \sqrt{\langle(\delta\theta)^2\rangle} \geqslant \frac{1}{\sqrt{\upsilon F_Q(\theta)}}$$

Nat Phys, 2011, *7*, 406

Closed quantum systems



$$|\psi_f(\theta)\rangle = \hat{U}(\theta)|\psi_0\rangle \qquad \hat{U}(\theta) = \exp(-i\hat{H}\theta)$$

$$F(\theta) = \sum_n \frac{1}{P(x_n|\theta)}\left[\frac{\partial P(x_n|\theta)}{\partial\theta}\right]^2 = 4\langle\psi(\theta)|[\hat{H} - G(\theta)]^2|\psi(\theta)\rangle.$$

$$G(\theta) = \langle\psi_0|\hat{H}|\psi_0\rangle$$

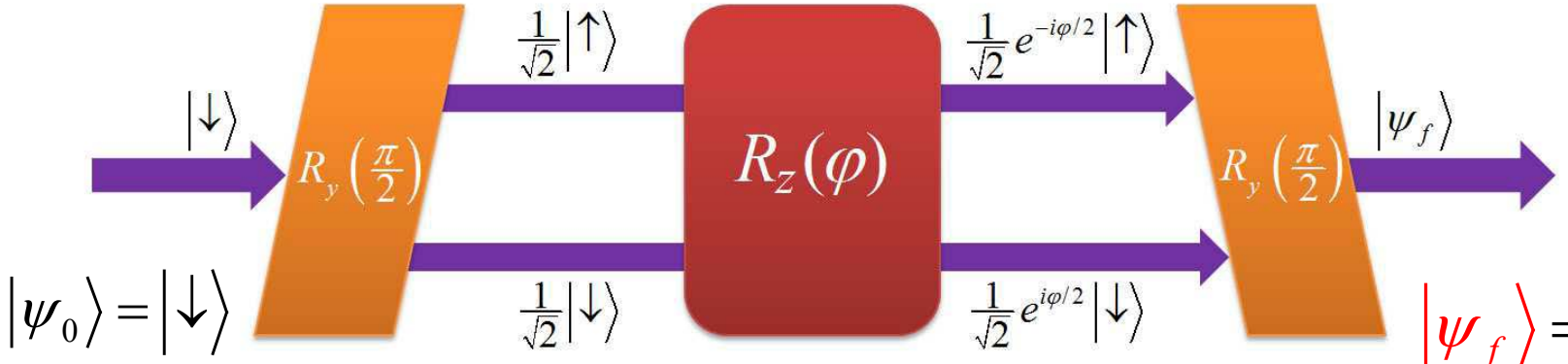
$$F(\theta) \leqslant 4\langle\psi_0|(\Delta\hat{H})^2|\psi_0\rangle \qquad \Delta\hat{H} = \hat{H} - \langle\hat{H}\rangle \qquad F_Q(\theta) = 4\langle\psi_0|(\Delta\hat{H})^2|\psi_0\rangle$$

$$\boxed{F_Q(\theta) = 4[\langle\psi'(\theta)|\psi'(\theta)\rangle - |\langle\psi'(\theta)|\psi(\theta)\rangle|^2]} \qquad |\psi'(\theta)\rangle = \frac{d}{d\theta}|\psi(\theta)\rangle$$

Measurement precision: Different encoding final state

Ramsey Interferometry

A single particle



$$|\psi_f\rangle=\hat{U}|\psi_0\rangle$$

$$\hat{U}=\exp\left(-i\frac{\pi}{2}\hat{S}_y\right)\exp\left(-i\varphi\hat{S}_z\right)\exp\left(-i\frac{\pi}{2}\hat{S}_y\right)$$

$$|\psi_f\rangle=\hat{U}|\psi_0\rangle=-\cos\frac{\varphi}{2}|\uparrow\rangle+i\sin\frac{\varphi}{2}|\downarrow\rangle$$

$$|\psi_f'\rangle=\frac{\mathrm{d}|\psi_f\rangle}{\mathrm{d}\varphi}=-\frac{1}{2}\sin\frac{\varphi}{2}|\uparrow\rangle+\frac{i}{2}\cos\frac{\varphi}{2}|\downarrow\rangle$$

QFI

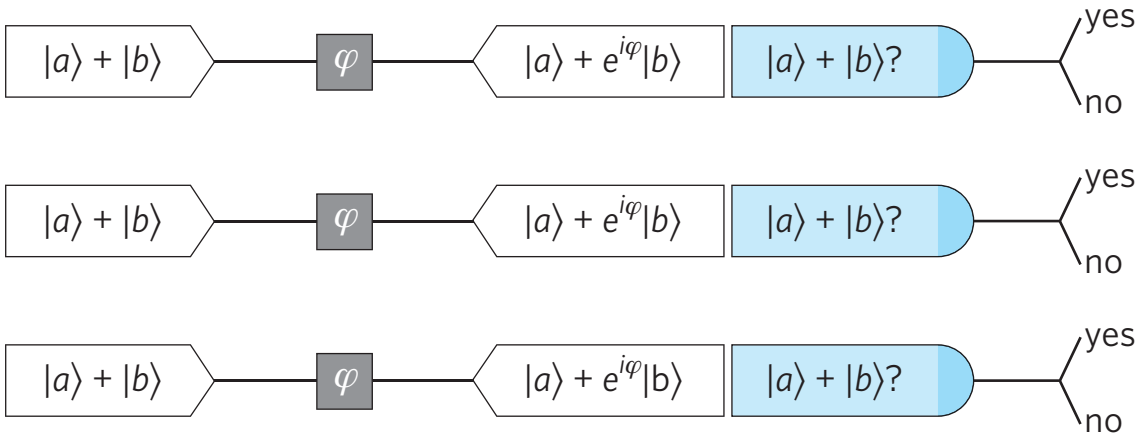
$$F(\varphi)=4\left[\langle\psi_f'|\psi_f'\rangle-|\langle\psi_f'|\psi_f\rangle|^2\right]$$

=1

QCRB: $\Delta\theta\geq\frac{1}{\sqrt{vF(\theta)}}=\frac{1}{\sqrt{v}}$

Ramsey Interferometry

A form of atom interferometry that uses the phenomenon of magnetic resonance to measure transition frequencies of atoms



N independent "atoms"

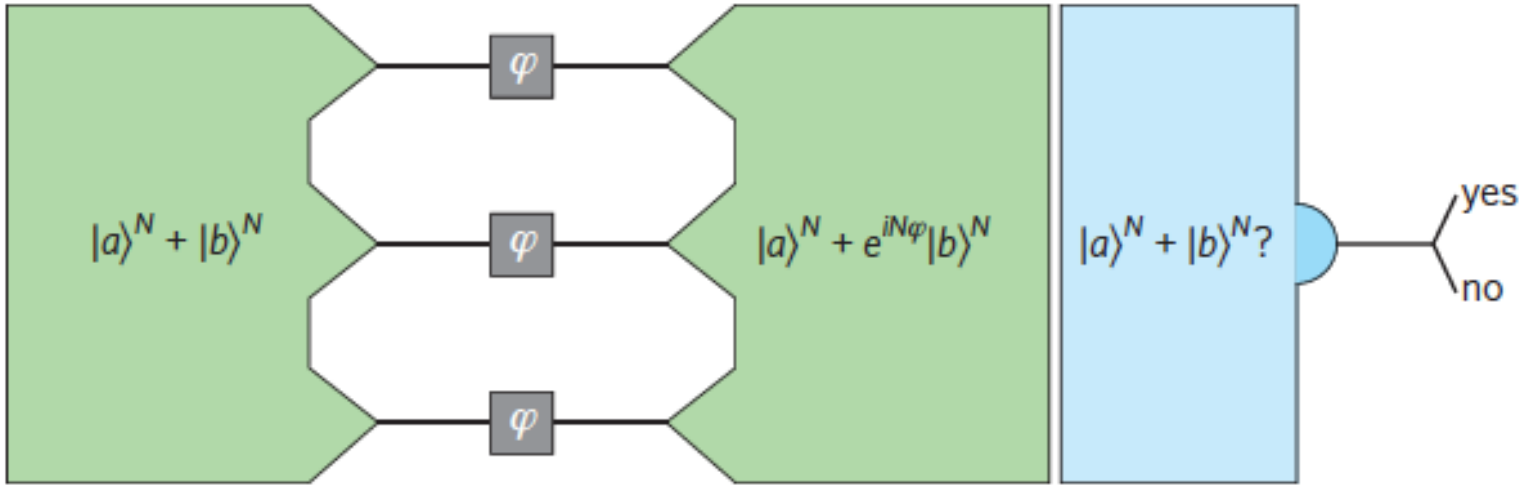
$$\text{(signal)} = \langle \sigma_z \rangle = -\cos \omega T$$

$$\text{(noise)} = \Delta\sigma_z = \sqrt{1-\cos^2 \omega T} = |\sin \omega T|$$

$$\Delta(\omega T) = \frac{1}{\sqrt{N}} \frac{\text{(noise)}}{|d(\text{signal})/d(\omega T)|} = \frac{1}{\sqrt{N}}$$

Frequency measurement
Time measurement
Clock synchronization

Cat-state Ramsey interferometry



$$p_{ent} = \frac{\#\text{yes (in } \nu \text{ repetitions)}}{\nu} \longrightarrow \frac{1 - \cos N\varphi}{2}$$

Fringe pattern with period $2\pi/N$

$$\text{(signal)} = \langle \sigma_z \rangle = -\cos N\omega T$$

$$\text{(noise)} = \Delta\sigma_z = \sqrt{1 - \cos^2 N\omega T} = |\sin N\omega T|$$

$$\Delta(\omega T) = \frac{1}{\sqrt{\nu}} \frac{\text{(noise)}}{|d(\text{signal})/d(\omega T)|} = \frac{1}{\sqrt{\nu}} \frac{1}{N}$$

ν = (number of trials)

***N* cat-state atoms**

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	$\delta\bar{\theta} = \frac{1}{\sqrt{N}}$ (Central limit)	$\delta\bar{\theta} = \frac{1}{\sqrt{N}}$ (Standard quantum limit)	$\delta\theta = \frac{1}{N}$ (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)

量子精密测量：国际战略布局



2019年7个国际基本计量单位“量子化”

- 秒，符号s，SI的时间单位。当铯的频率$\Delta\nu_{Cs}$，即铯-133原子基态的超精细能级跃迁频率以单位Hz，即s^{-1}，表示时，将其固定数值取为9 192 631 770来定义秒。

- 开尔文，符号K，SI的热力学温度单位。当玻尔兹曼常数k以单位J K^{-1}，即kg m^2 $s^{-2}K^{-1}$，表示时，将其固定数值取为1.380 649×10^{-23}来定义开尔文，其中千克、米和秒用h，c和$\Delta\nu_{Cs}$定义。

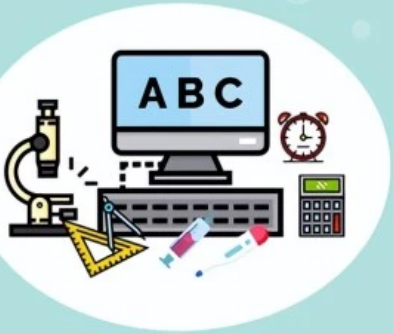
- 米，符号
以单位m
458来定

R，符号mol，SI的物质的量的单位。1摩尔精含6.022 140 76 ×10^{23}个基本粒子。该数即单位mol^{-1}表示的阿伏伽德罗常数N_A的固定数称为阿伏伽德罗数。

5月20日

世界计量日

数字时代的计量



- 千克，
单位J s，
为6.626
用c和$\Delta\nu_{Cs}$定义。

统的物质的量，符号n，是该系统包含的特定粒子数量的量度。基本粒子可以是原子、分离子、电子，其它任意粒子或粒子的特定组合。

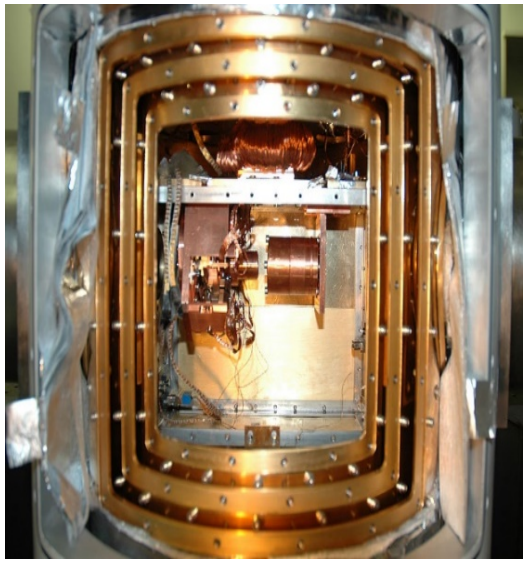
- 安培，符号A，SI的电流单位。当基本电荷e以单位C，即A s，表示时，将其固定数值取为1.602 176 634×10^{-19}来定义安培，其中秒用$\Delta\nu_{Cs}$定义。

- 坎德拉，符号cd，SI的给定方向上发光强度的单位。当频率为540×10^{12}Hz的单色辐射的发光效率以单位lm/W，即cd sr W^{-1}或cd sr $kg^{-1}m^{-2}$ s^3，表示时，将其固定数值取为683来定义坎德拉，其中千克、米、秒分别用h，c和$\Delta\nu_{Cs}$定义。

量子精密测量

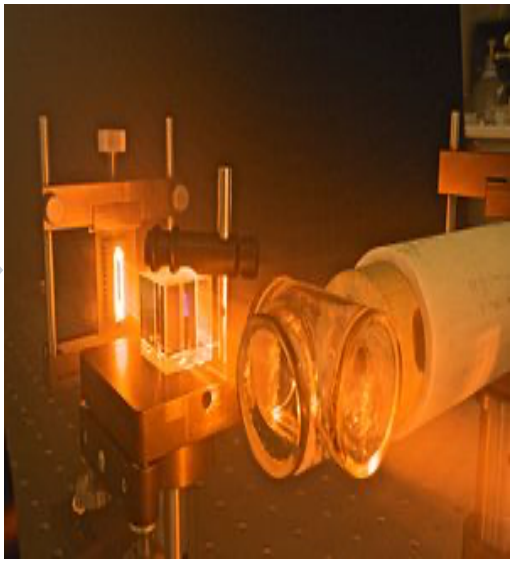
利用高精度量子操控和探测突破经典手段探测极限

量子体系分立能级



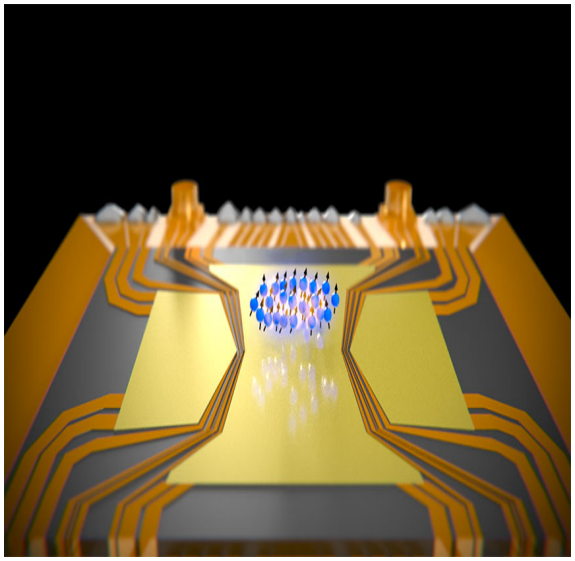
单电子晶体管
光力传感器等

量子相干叠加



原子磁力仪、
金刚石缺陷等

量子纠缠（关联）特性



压缩态、NOON态

测量精度受限于标准量子极限 $1/\sqrt{N}$

有望突破经典物理极限 $1/N$

电子的两大内禀属性

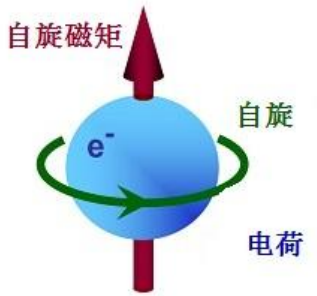
电荷
（电流起源）

古希腊时期：摩擦起电现象

1858年：发现阴极射线

1897年：汤姆逊实验

1909年：密立根油滴实验



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

这两大属性构成了现代科技特别是信息技术的物理基础

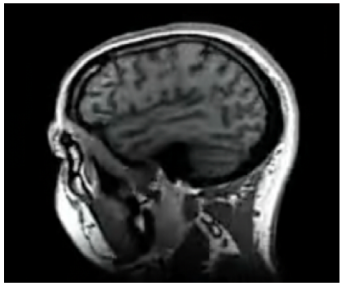
自旋是量子信息的重要物理载体

磁是普遍存在的自然属性

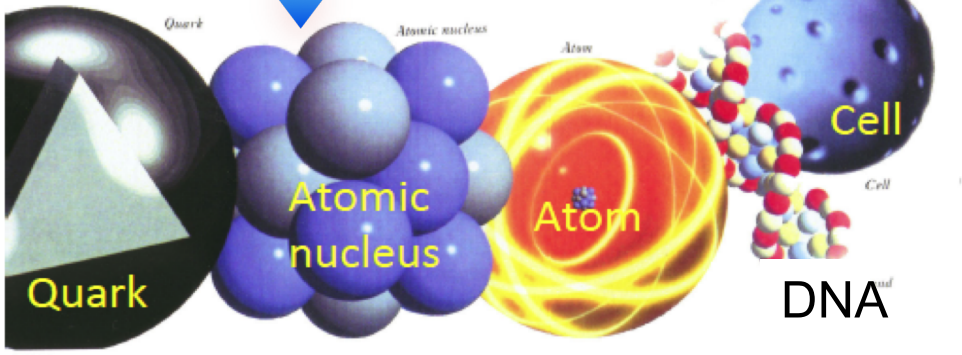
自旋 无处不在

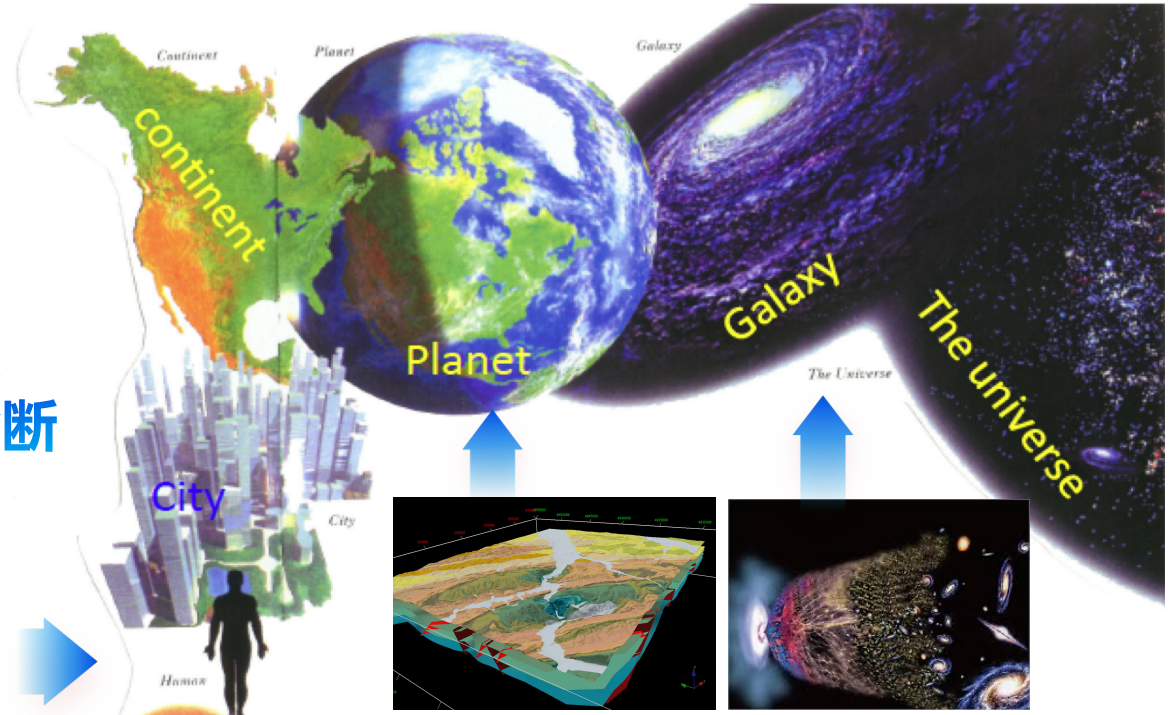
核磁共振
核磁共振成像

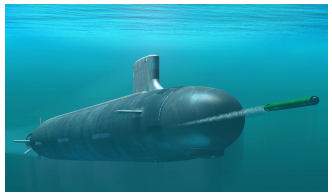
心脑磁图仪
生物医学诊断

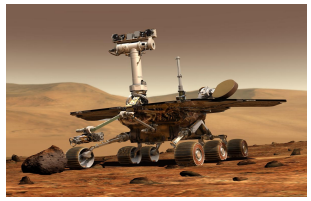












地质勘探
国防安全

火星磁场
暗物质探测

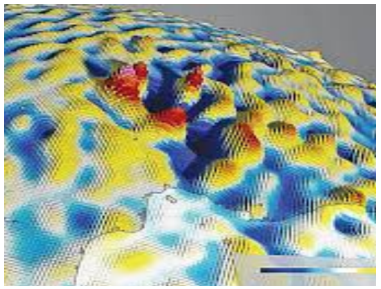
极弱磁场科学与技术

提升极弱磁场的测量精度，将推动相关科学发展

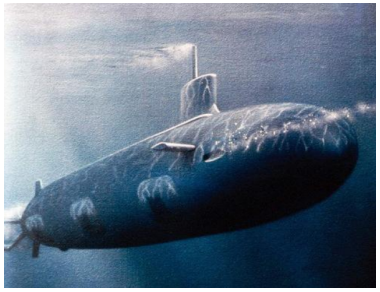
精密测量科学

面向国家重大战略需求

自主导航



磁异常探测

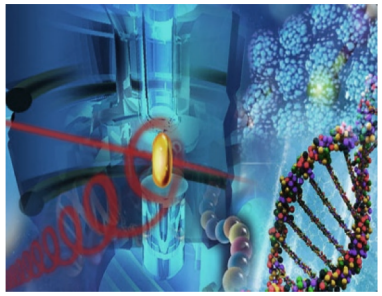


暗能量

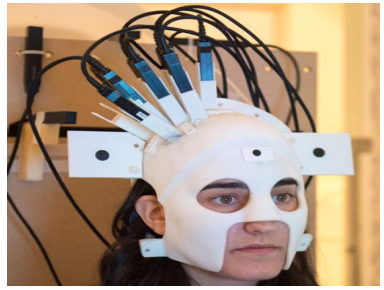


面向人民生命健康需求

医学成像

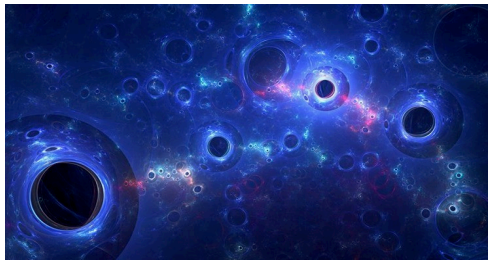


心脑疾病诊断

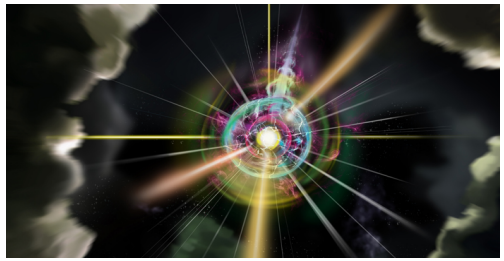


面向世界科技前沿

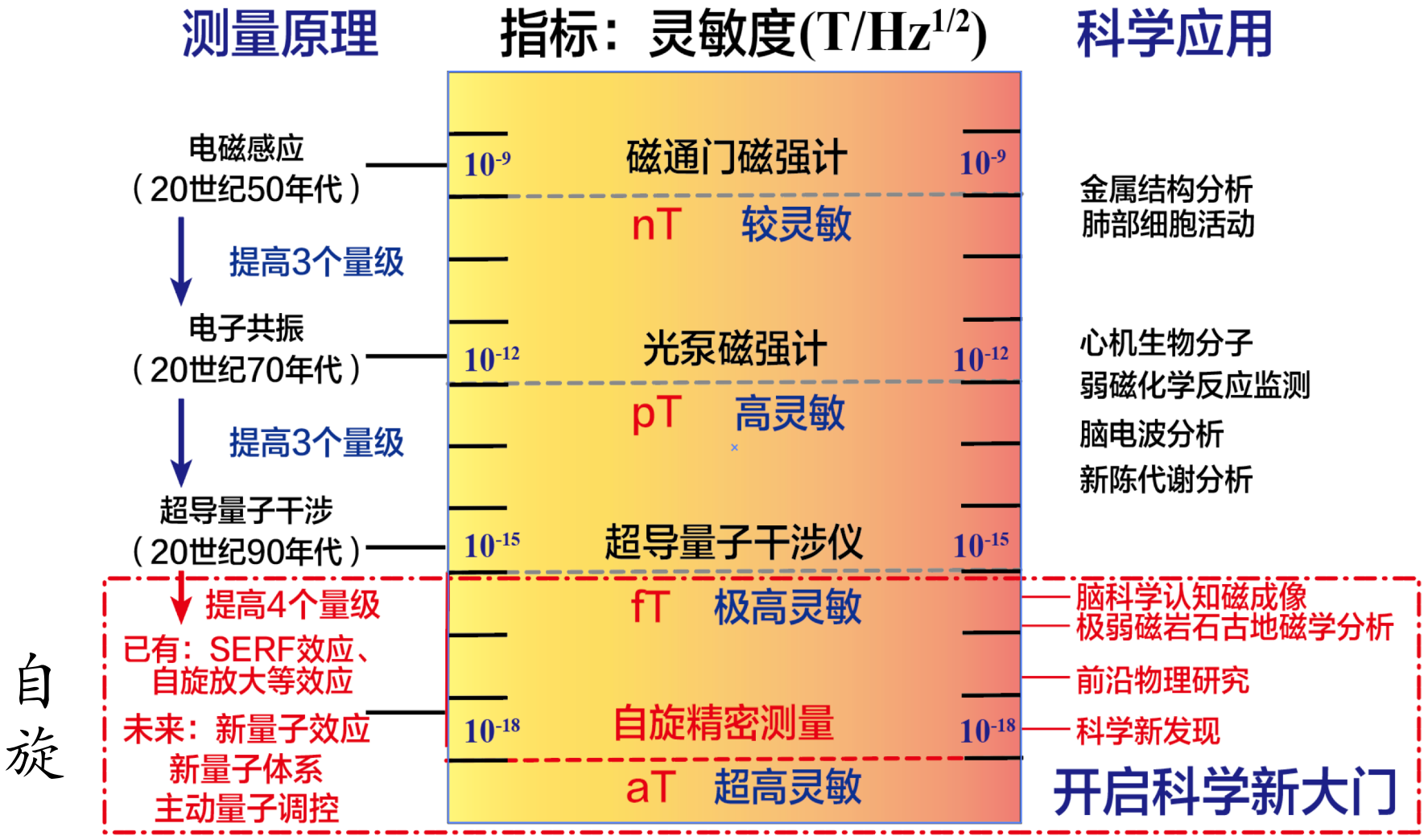
磁单极子



暗物质

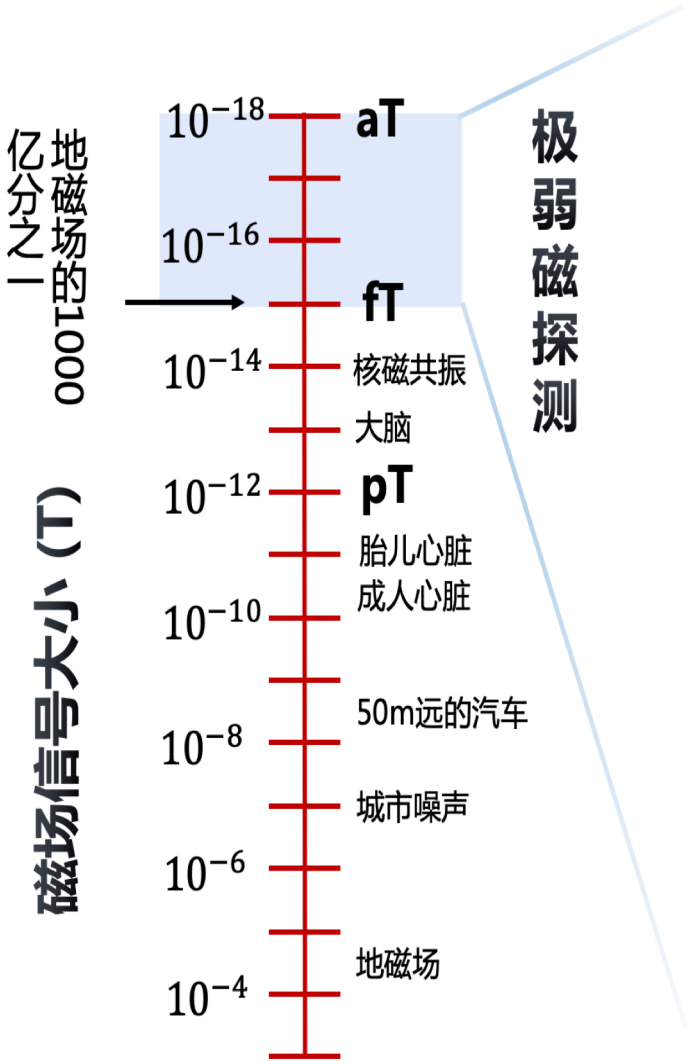


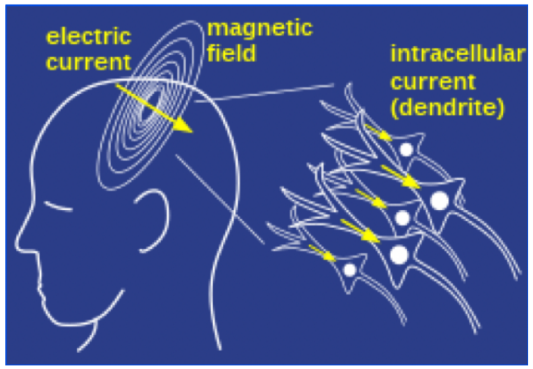
磁场精密测量：从经典到量子技术



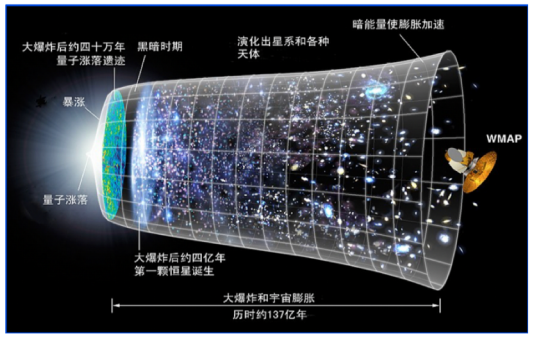
自旋

磁场探测具有重要科学意义









生物医学

心磁、脑磁、脑科学认知

地球和空间物理

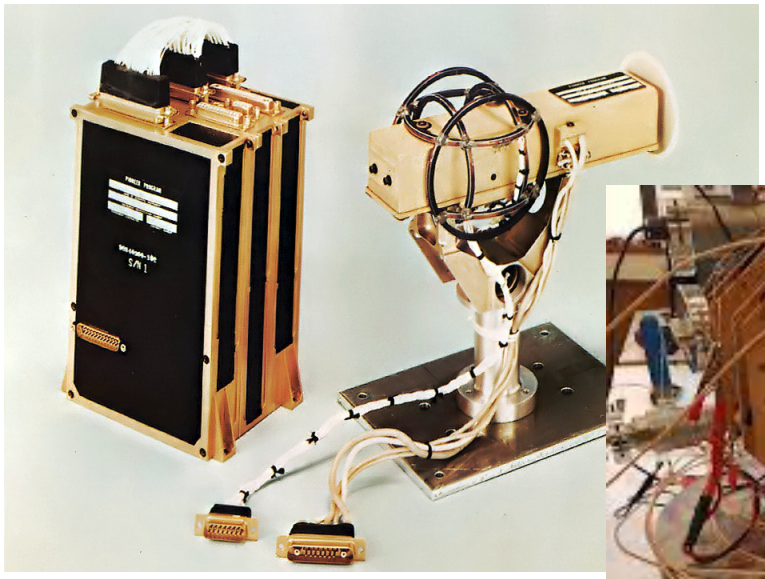
深空深地深海磁、古地磁

前沿基础物理

暗物质、EDM、磁单极子

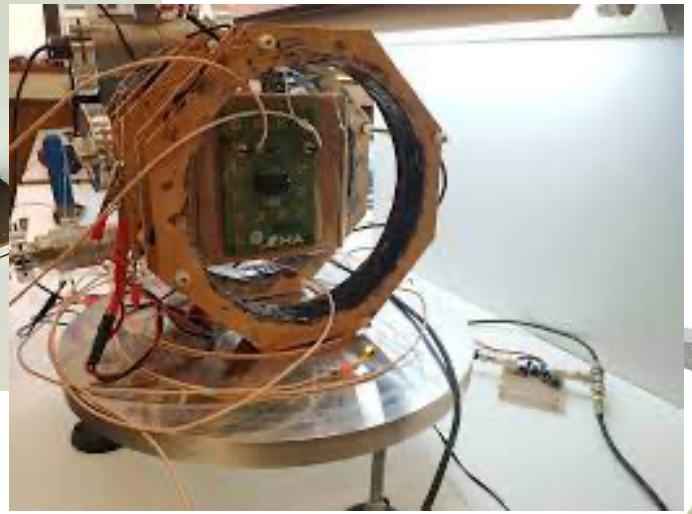
基于经典物理原理的磁力计

霍尔效应磁力计



精度：uT-mT

洛伦兹力磁力计



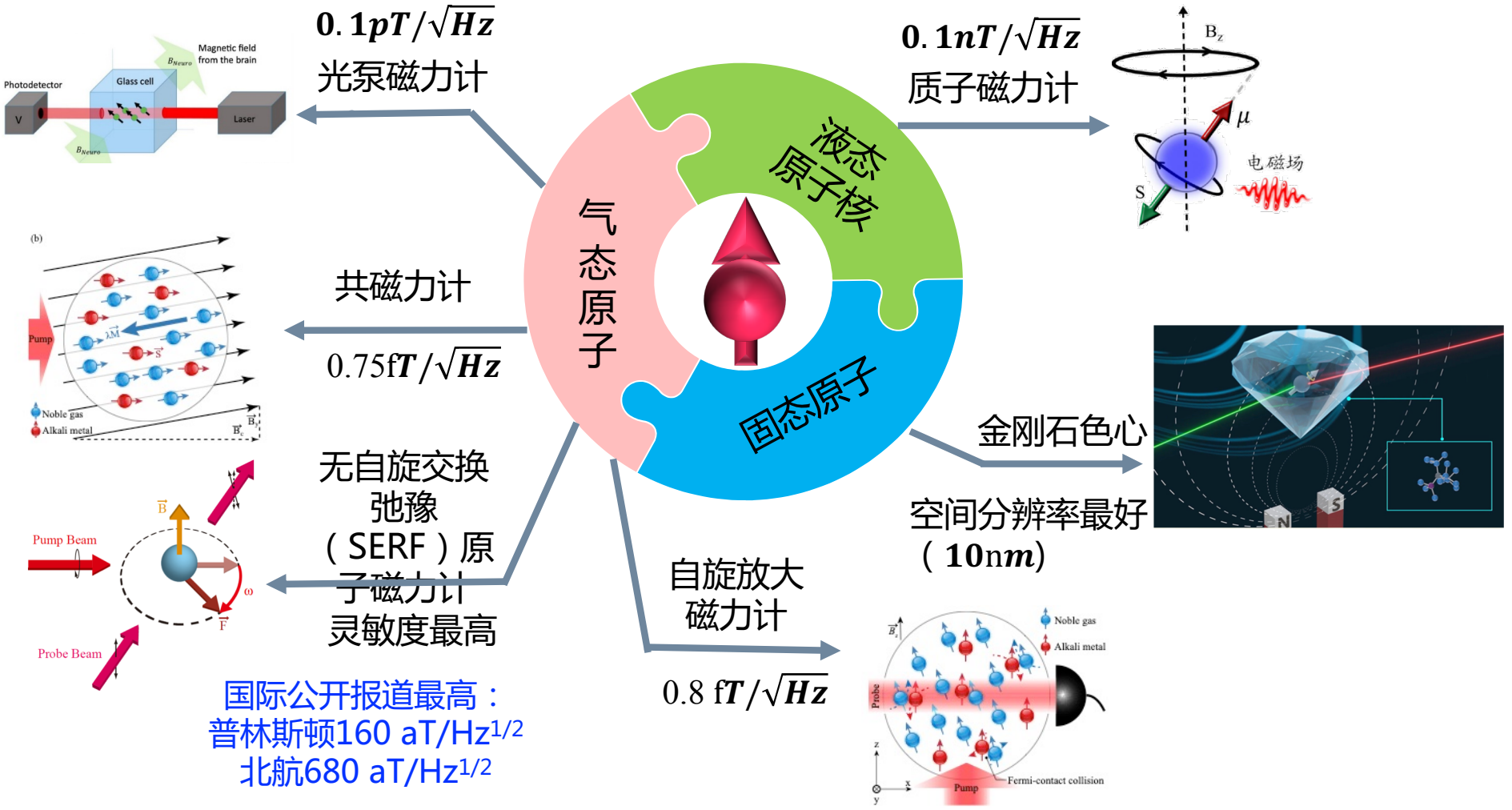
0.1-1uT

磁通门磁力计



1nT

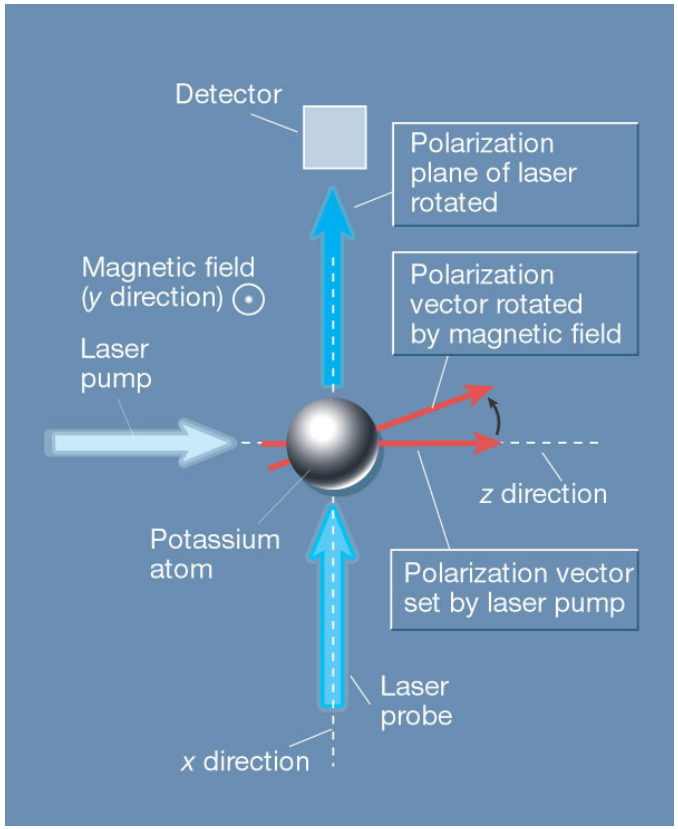
原子自旋磁力计


$0.1pT/\sqrt{Hz}$
光泵磁力计
Photodetector
Glass cell
Laser
Magnetic field from the brain
$0.1nT/\sqrt{Hz}$
质子磁力计
B_z
μ
S
电磁场
气态原子
液态原子核
固态原子
共磁力计
$0.75fT/\sqrt{Hz}$
Pump
Noble gas
Alkali metal
金刚石色心
空间分辨率最好
（$10nm$）
N
S
无自旋交换弛豫（SERF）原子磁力计
灵敏度最高
Pump Beam
Probe Beam
$\vec{B}$
$\vec{F}$
ω
自旋放大磁力计
$0.8\ fT/\sqrt{Hz}$
Noble gas
Alkali metal
Probe
Pump
Fermi-contact collision
国际公开报道最高：
普林斯顿160 aT/Hz$^{1/2}$
北航680 aT/Hz$^{1/2}$

Optical Magnetometer

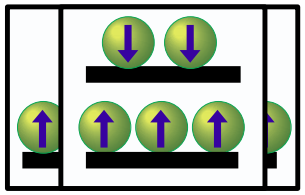
Alkali-metal Atomic Magnetometer

D.Budker. ***: A new spin on magnetometry*** *Nature (News&Views)* **422**, 574 (2003)

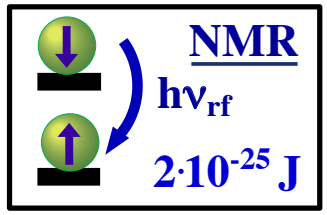


Optimal pumping/probe + NMR

Polarization

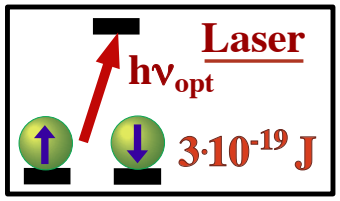


Signal Energy per Spin



NMR: $\frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \approx 10^{-5}$

Optically pumped: $\frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \Rightarrow 1$

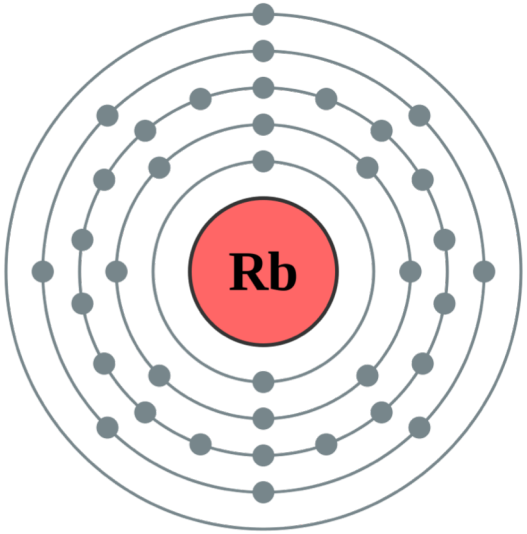


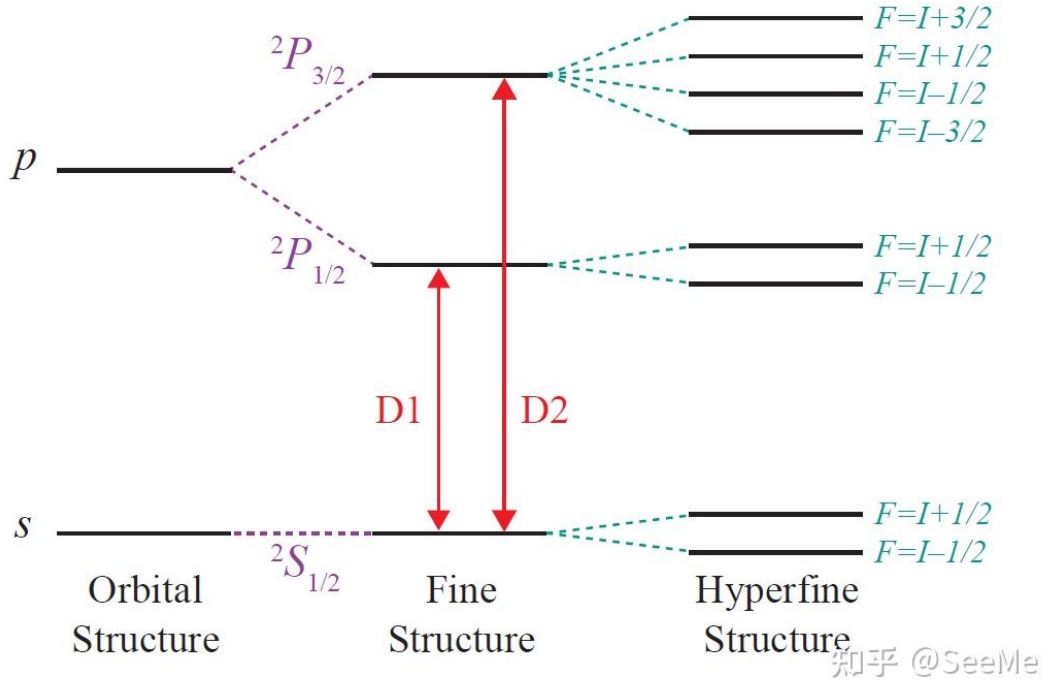
Sensitivity
increase by > 10 orders of magnitude

碱金属原子

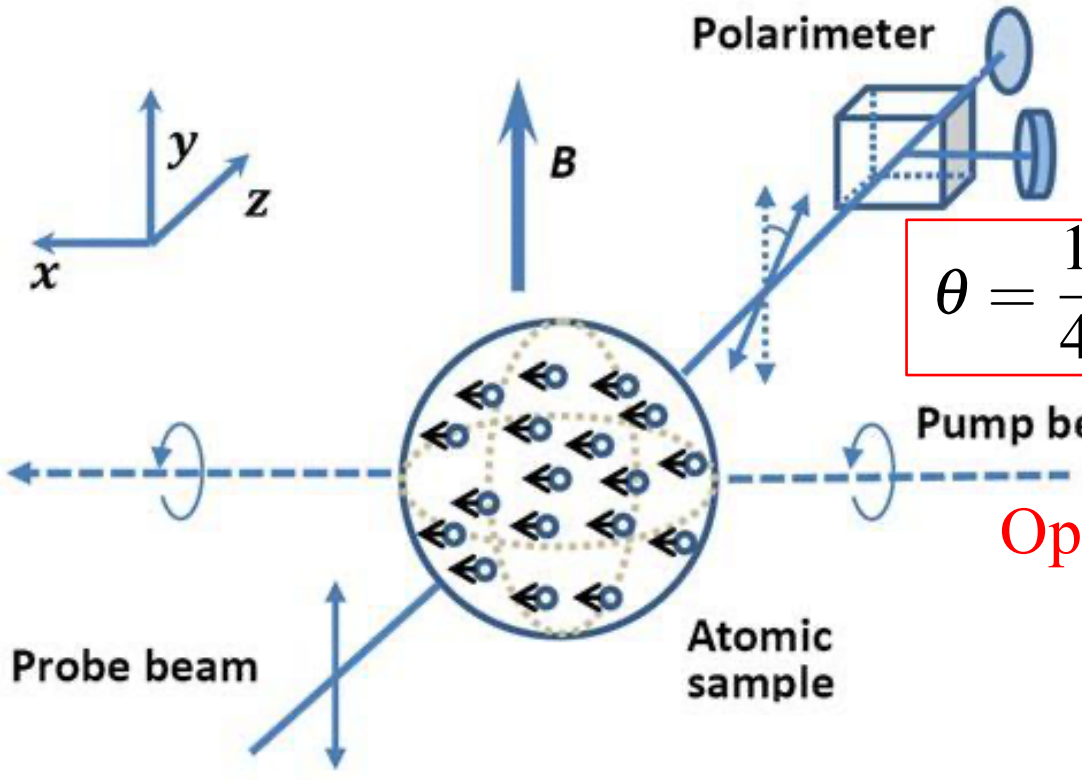
最外层只 有一个未配对的电子

37: Rubidium **2,8,18,8,1**





碱金属原子磁力计



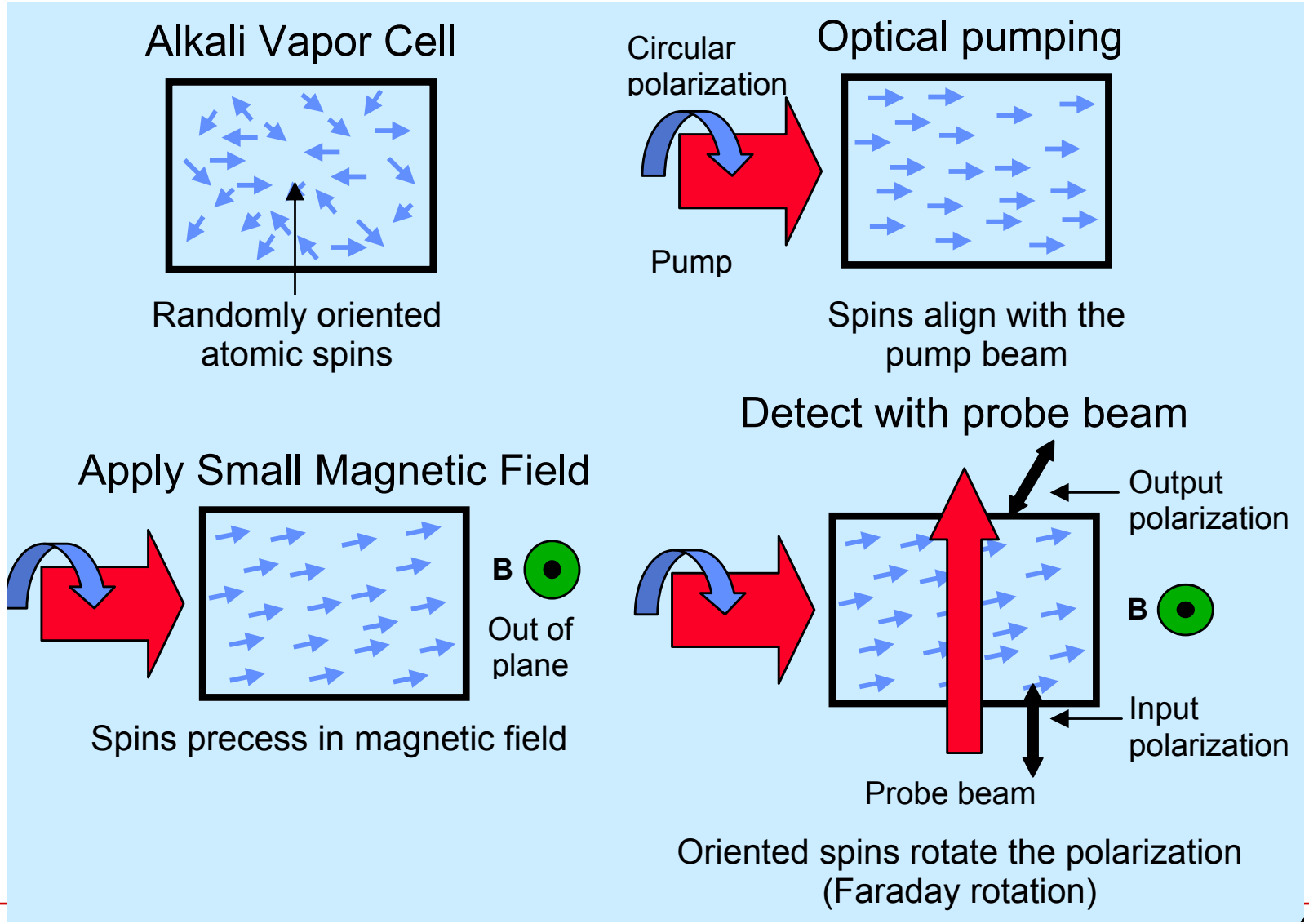
Polarization rotation due to the Faraday effect

$$\theta = \frac{1}{4} l r_e c f n P_x^e D(V)$$

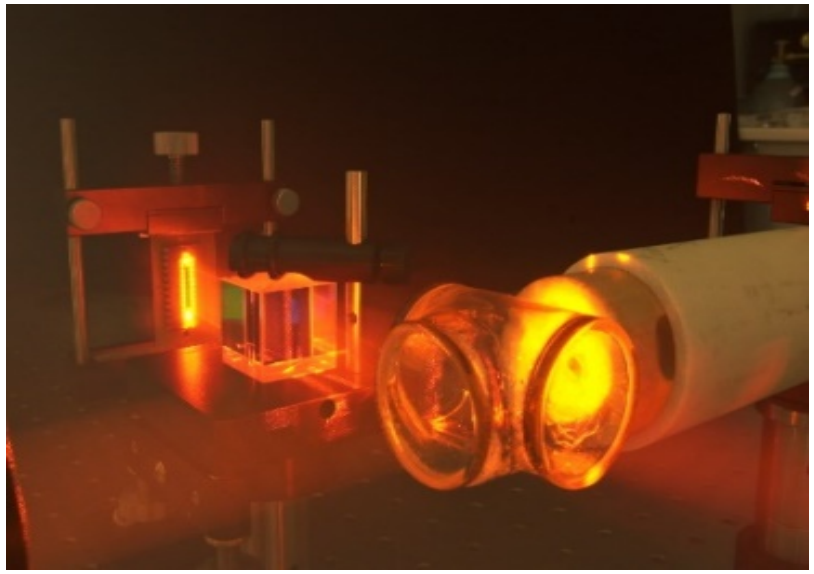
Optical pumping

利用原子自旋效应测量磁场

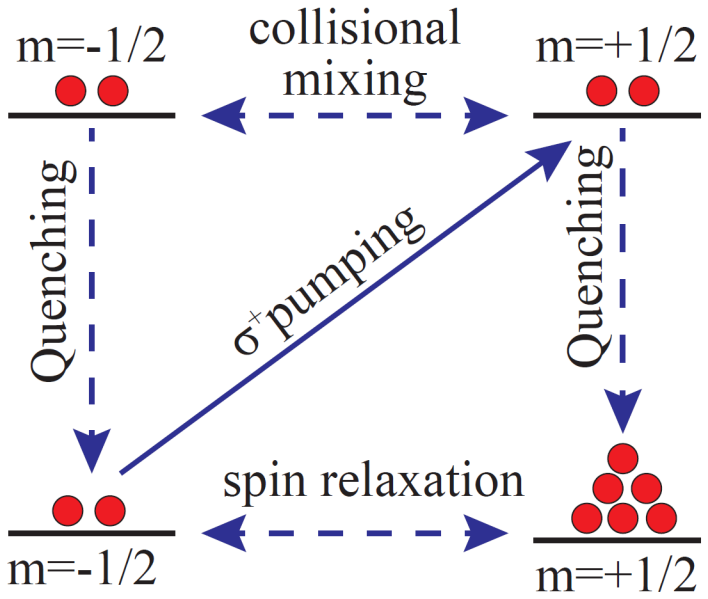
原子磁力计的基本原理


Alkali Vapor Cell
Randomly oriented
atomic spins
Circular
polarization
Pump
Optical pumping
Spins align with the
pump beam
Apply Small Magnetic Field
B
Out of
plane
Spins precess in magnetic field
Detect with probe beam
Output
polarization
B
Input
polarization
Probe beam
Oriented spins rotate the polarization
(Faraday rotation)

Preparation: Optical pumping



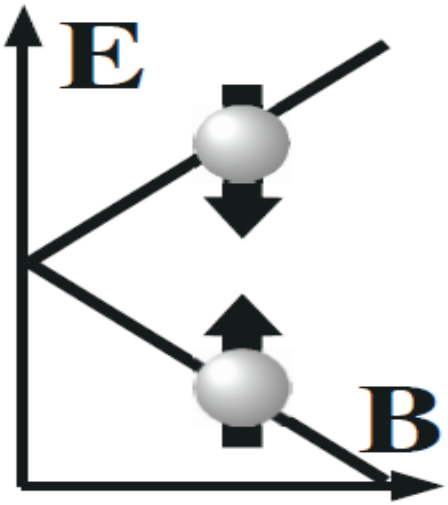
Alkali-metal: K or Rb



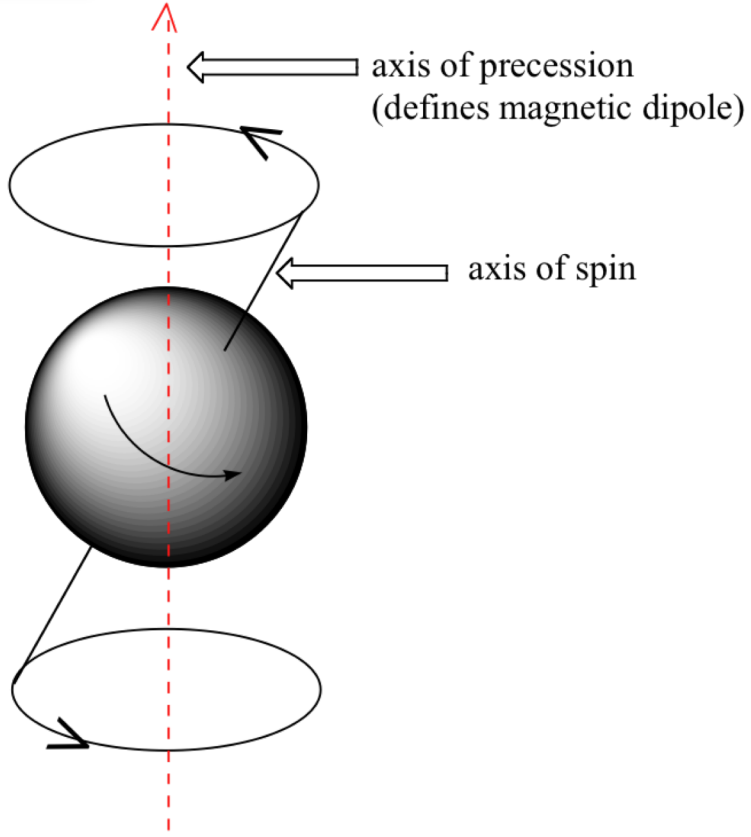
Close to 100% Alkali-metal atomic spin polarization!

Encoding: Lamer processing

$$\omega = \gamma B$$

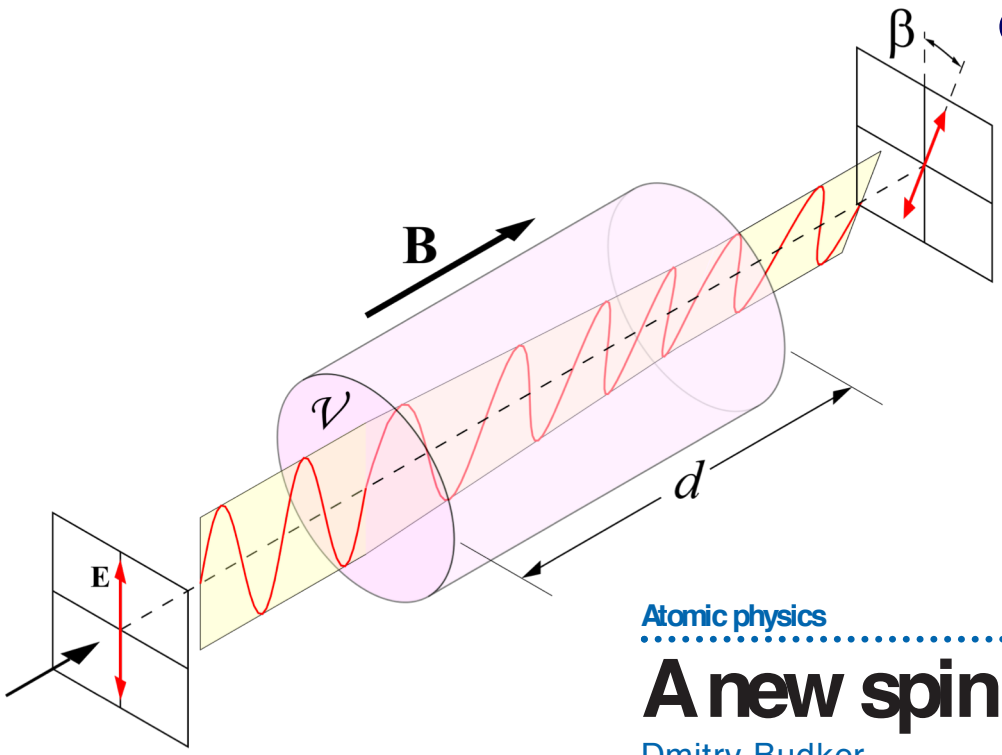






Readout: Faraday Effect

Polarization rotation due to the Faraday effect



linear polarized light

Optical rotation used for detection

the plane of polarization

Polarization angle rotation
$\propto \gamma B_y T_2$

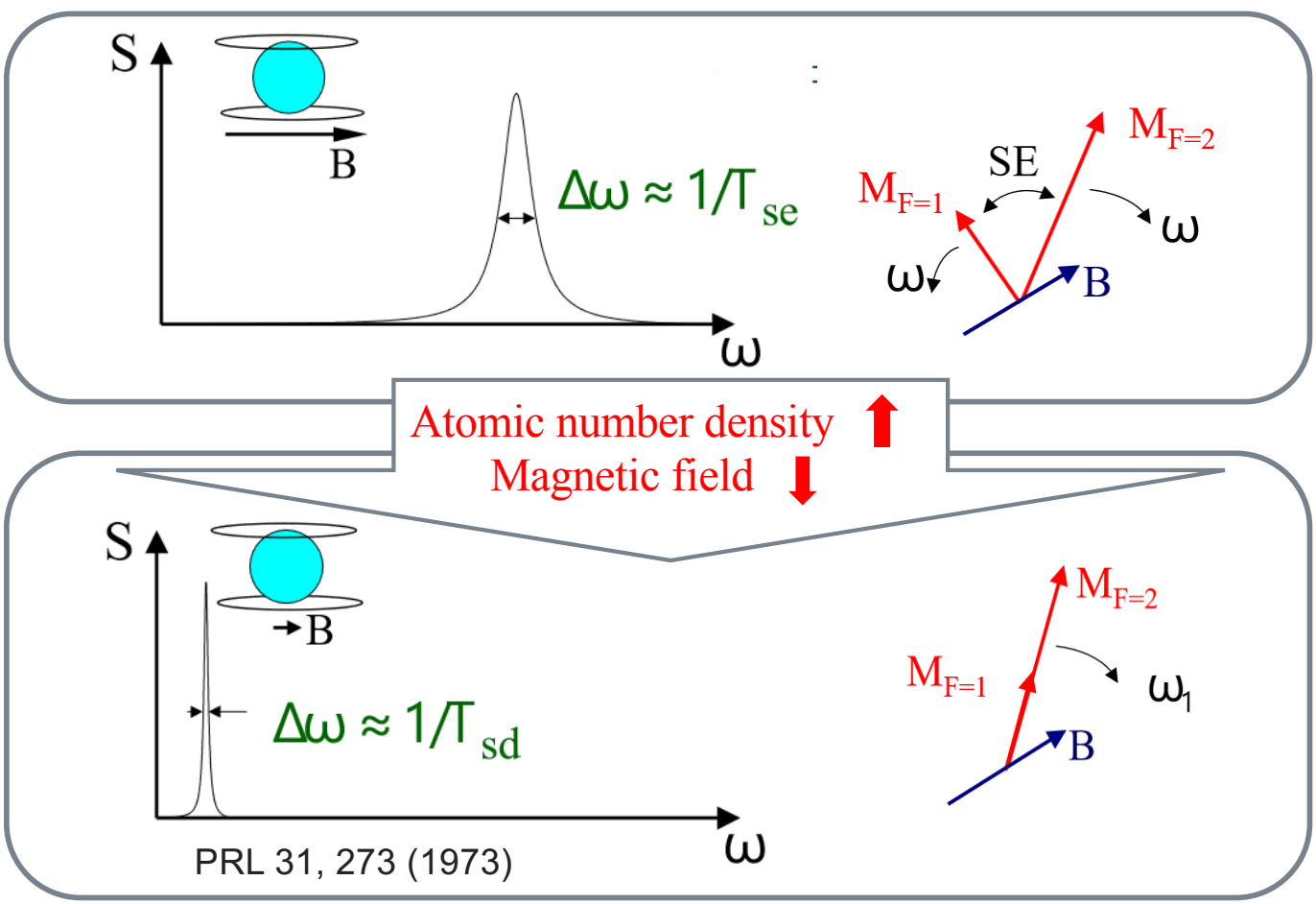
Atomic physics

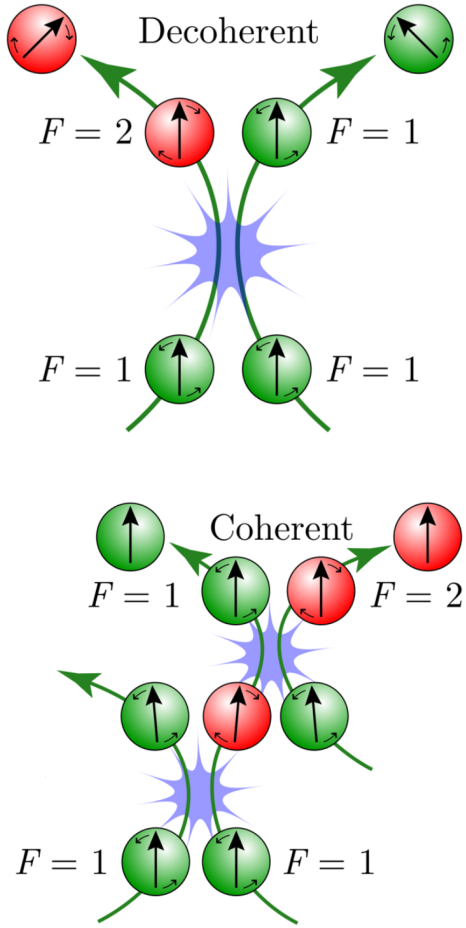
A new spin on magnetometry

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.

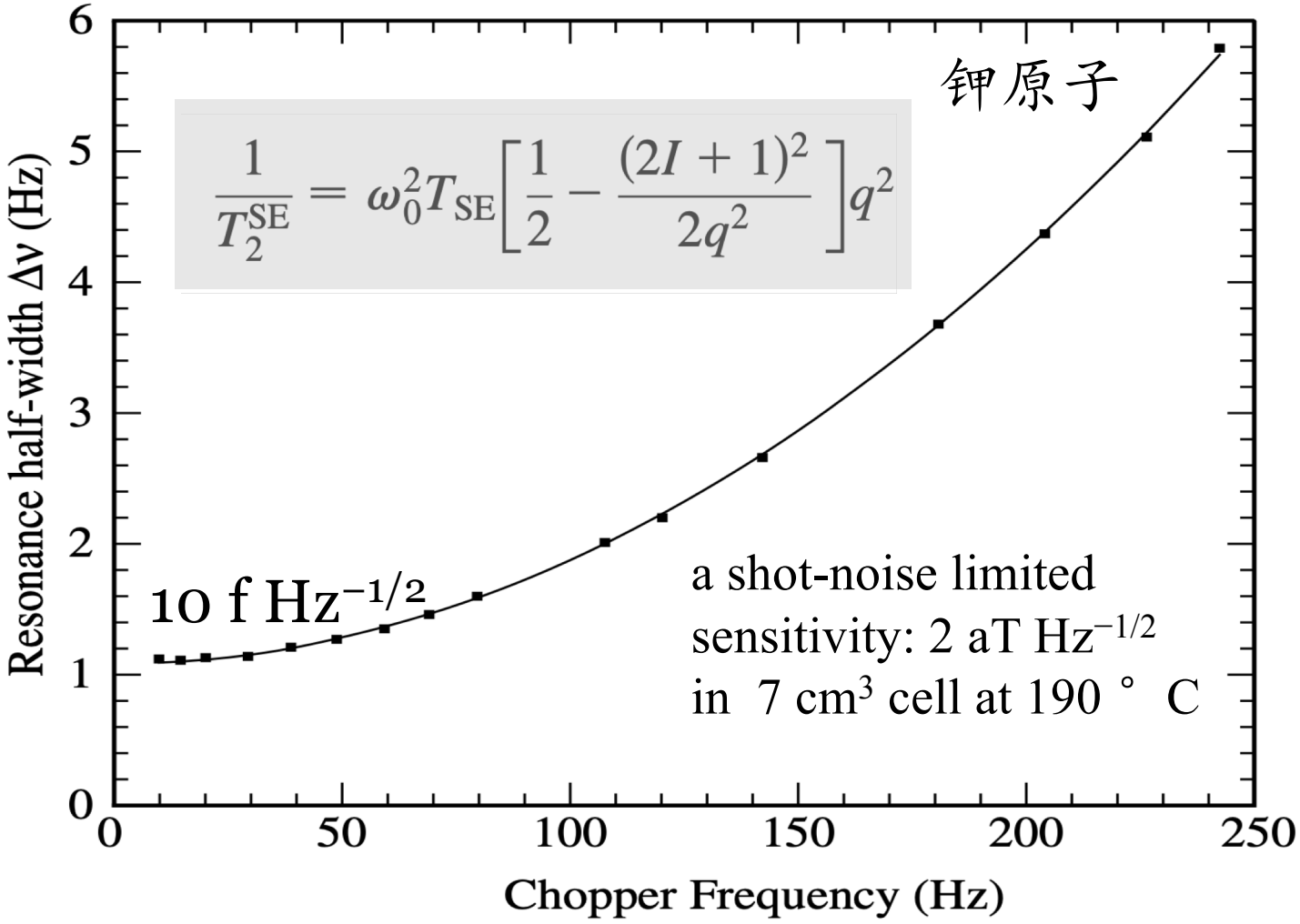
无自旋交换弛豫效应（SERF效应）





1973 年，Happer 等发现， 1977 年推导出这一现象的理论解释

无自旋交换弛豫效应（SERF效应）





M. Romalis

普林斯顿大学

首次实现SERF态

Phys. Rev. Lett., 89:130801, Sep 2002.

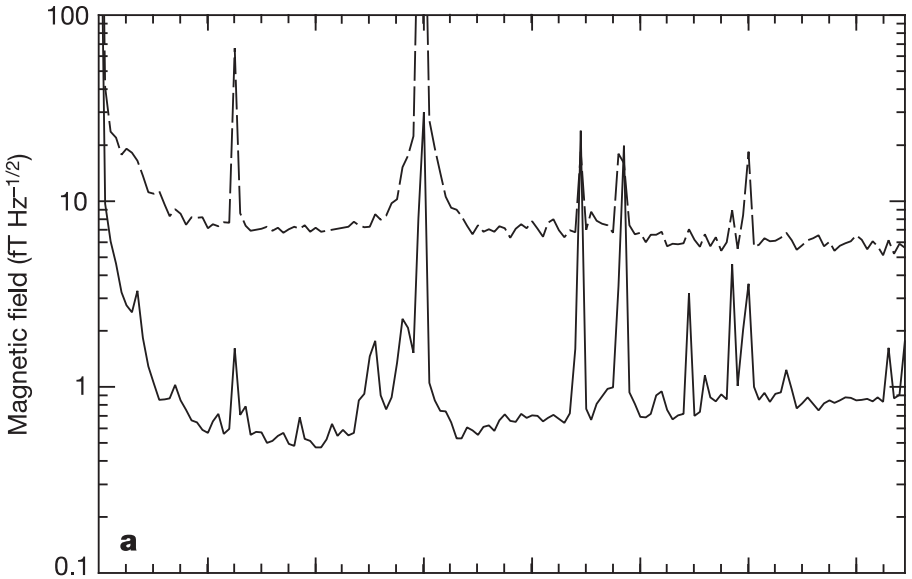
SERF原子磁强计

A subfemtotesla multichannel atomic magnetometer

I. K. Kominis*†, T. W. Kornack*, J. C. Allred‡ & M. V. Romalis*

* *Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
‡ *Department of Physics, University of Washington, Seattle, Washington 98195, USA*

The magnetic field is one of the most fundamental and ubiquitous physical observables, carrying information about all electromagnetic phenomena. For the past 30 years, superconducting quantum interference devices (SQUIDs) operating at 4 K have been unchallenged as ultrahigh-sensitivity magnetic field detectors[1], with a sensitivity reaching down to 1 fT $Hz^{-1/2}$ (1 fT = 10^{-15} T). They have enabled, for example, mapping of



钾原子

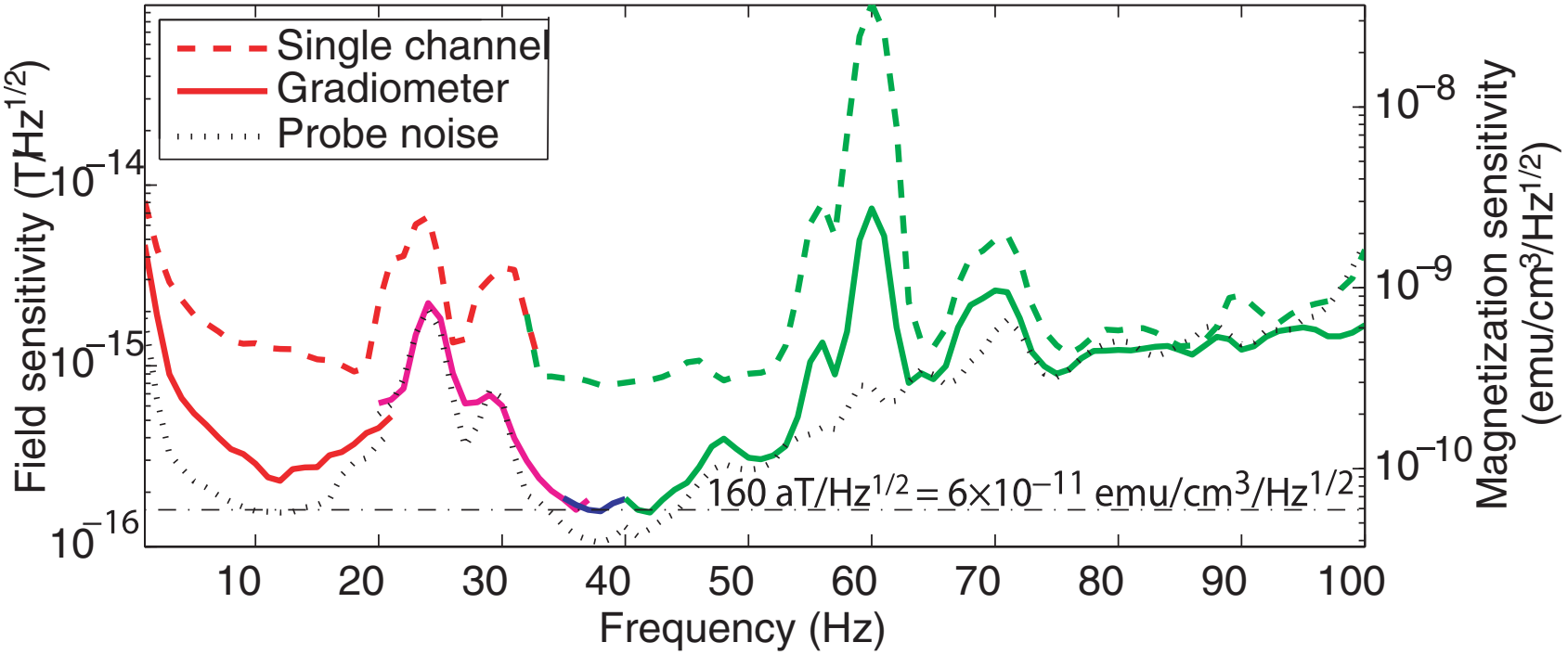
0.54 fT $Hz^{-1/2}$ in 0.3 cm^3

180 ° C

Nature, 422(6932):596–599, 04 2003

SERF原子磁强计：世界上最灵敏的磁力计

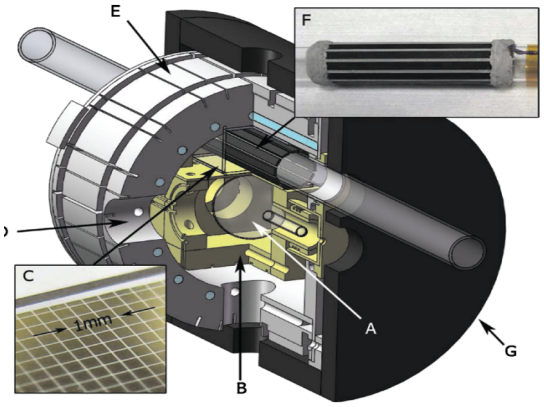
钾原子　　$0.16\ \mathrm{fT\ Hz^{-1/2}}$ in $0.45\ \mathrm{cm^3}$, 200° C



APPLIED PHYSICS LETTERS **97**, 151110 (2010)

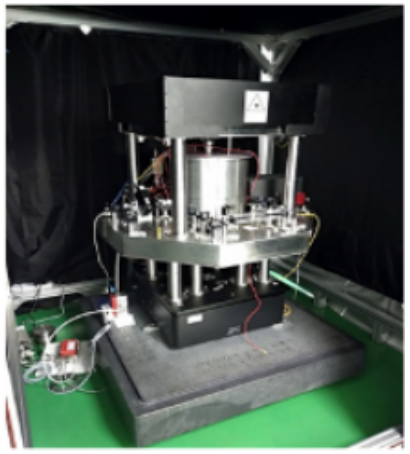
无自旋交换弛豫（SERF）原子磁力计

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
(0.16fT/Hz$^{1/2}$)

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

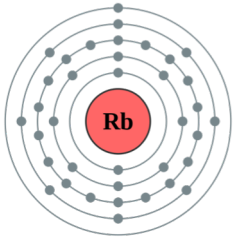


北航
(0.68fT/Hz$^{1/2}$)

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

2002年首次在实验层面验证SERF理论：

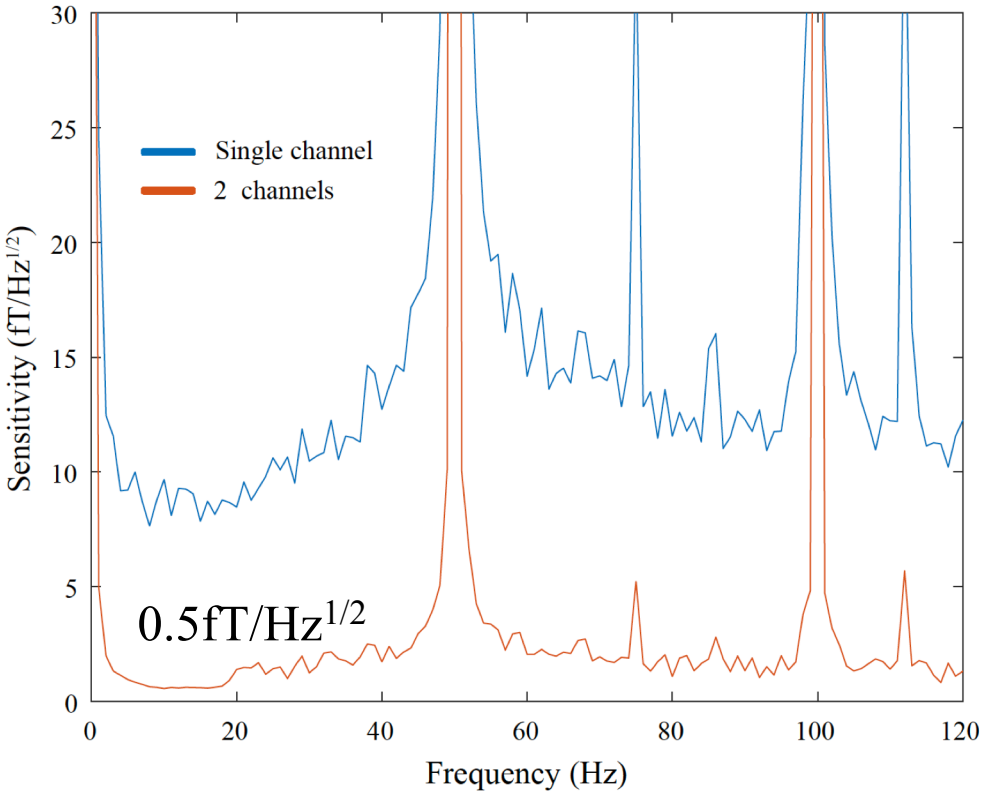
- 气室原子密度足够大
- 待测磁场足够小
- 预言SERF理论灵敏度最高可达1 aT/Hz$^{1/2}$

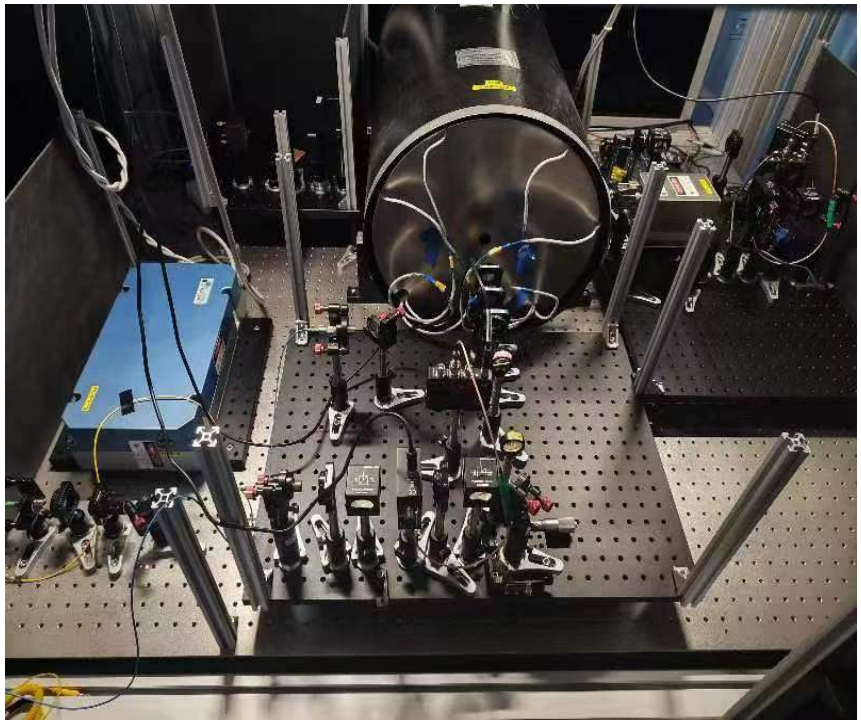


碱金属原子

我们组的研究进展： SERF磁力计

实现0.5fT/Hz$^{1/2}$磁场探测灵敏度（地磁场的1000亿分之一）





中国科大实验平台

Sensitivity: measuring the ability of the instrument

Key problem: How to improve the practical sensitivity?

Quantum noise
(Uncertainty principle)

Classical noise
(Technical noise)

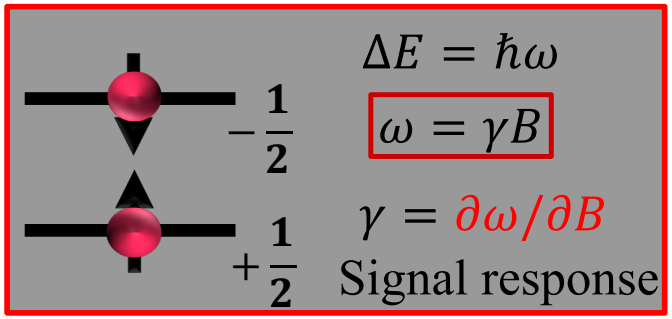
Fundamental limit SQL: $\propto 1/\sqrt{N}$
HL: $\propto 1/N$

Noise

Overcome

Fundamental Sensitivity

$$\delta B = \frac{\delta M}{|\partial M/\partial B|}$$



Enhance

Response

Physical systems

Encoding principle

Measurement strategy

关键科学问题

关键科学问题

如何利用量子效应增强响应？
如何克服量子和技术噪声？

基本灵敏度

$$\delta B = \frac{\delta\theta}{\left|\frac{\partial\langle M\rangle}{\partial B_z}\right|}$$

测量噪声 ↓ **Overcome**

信号响应 ↑ **Enhance**

光泵磁强计灵敏度极限

$$\delta B = \frac{1}{P\gamma\sqrt{N\mathrm{T}_2 t}}$$

极化度
旋磁比

测量时间
自旋驰豫时间
原子数

混合原子气室

核心思想 取长补短

碱金属

电子自旋磁矩大

自旋寿命短（ms级别）

数密度小（$10^{14}cm^{-3}$）

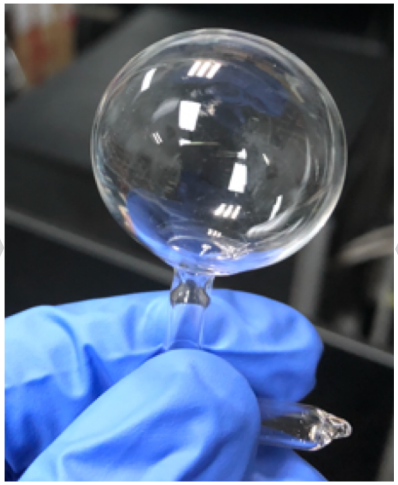
11 Na

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）

数密度大（$10^{19}cm^{-3}$）

基本灵敏度

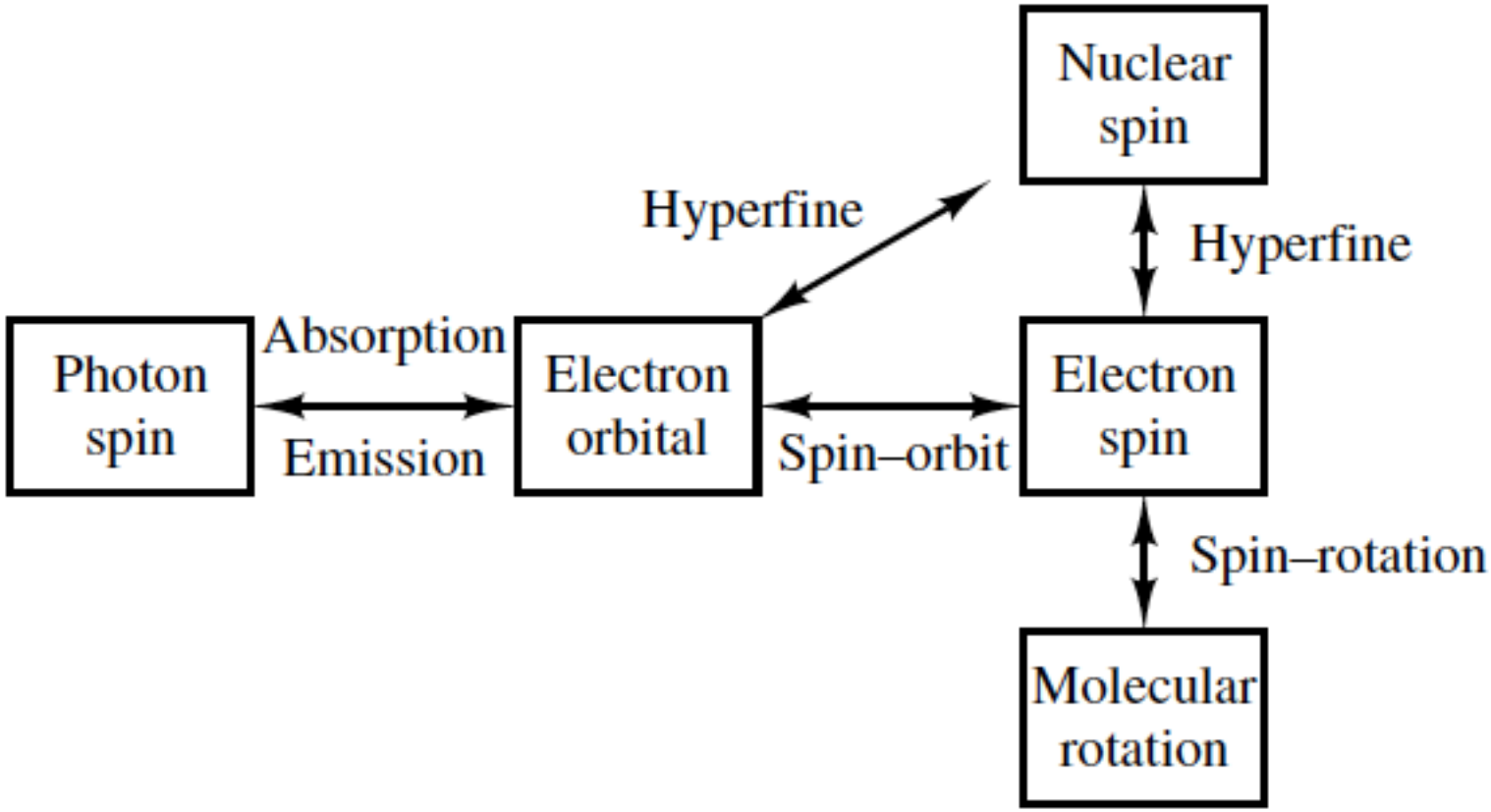
$$\delta B = \frac{1}{\gamma P \sqrt{nVT_2 t}}$$

相互补充？
新的效应？

提升灵敏度？

Angular Momentum Reservoirs

- No direct transfer to nuclear spins from photon. However, the coupling between electronic and nuclear angular momentum is usually strong enough to provide an efficient transfer mechanism.



两种自旋的耦合布洛赫方程

惰性气体-碱金属自旋演化的布洛赫方程

电子自旋

$$\frac{\partial \mathbf{P}^e}{\partial t} = \frac{\gamma_e}{Q}\left(B_z^0\hat{z} + \beta M_0^n \mathbf{P}^n\right) \times \mathbf{P}^e + \frac{P_0^e\hat{z} - \mathbf{P}^e}{T_e Q},$$

静磁场　等效磁场

核自旋

$$\frac{\partial \mathbf{P}^n}{\partial t} = \gamma_n\left(B_z^0\hat{z} + B_{\mathrm{ac}}\hat{y} + \beta M_0^e \mathbf{P}^e\right) \times \mathbf{P}^n + \frac{P_0^n\hat{z} - \mathbf{P}^n}{\{T_{2n}, T_{2n}, T_{1n}\}},$$

待测交流磁场

自旋的磁场放大效应

ARTICLES
https://doi.org/10.1038/s41567-021-01392-z
nature physics
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]

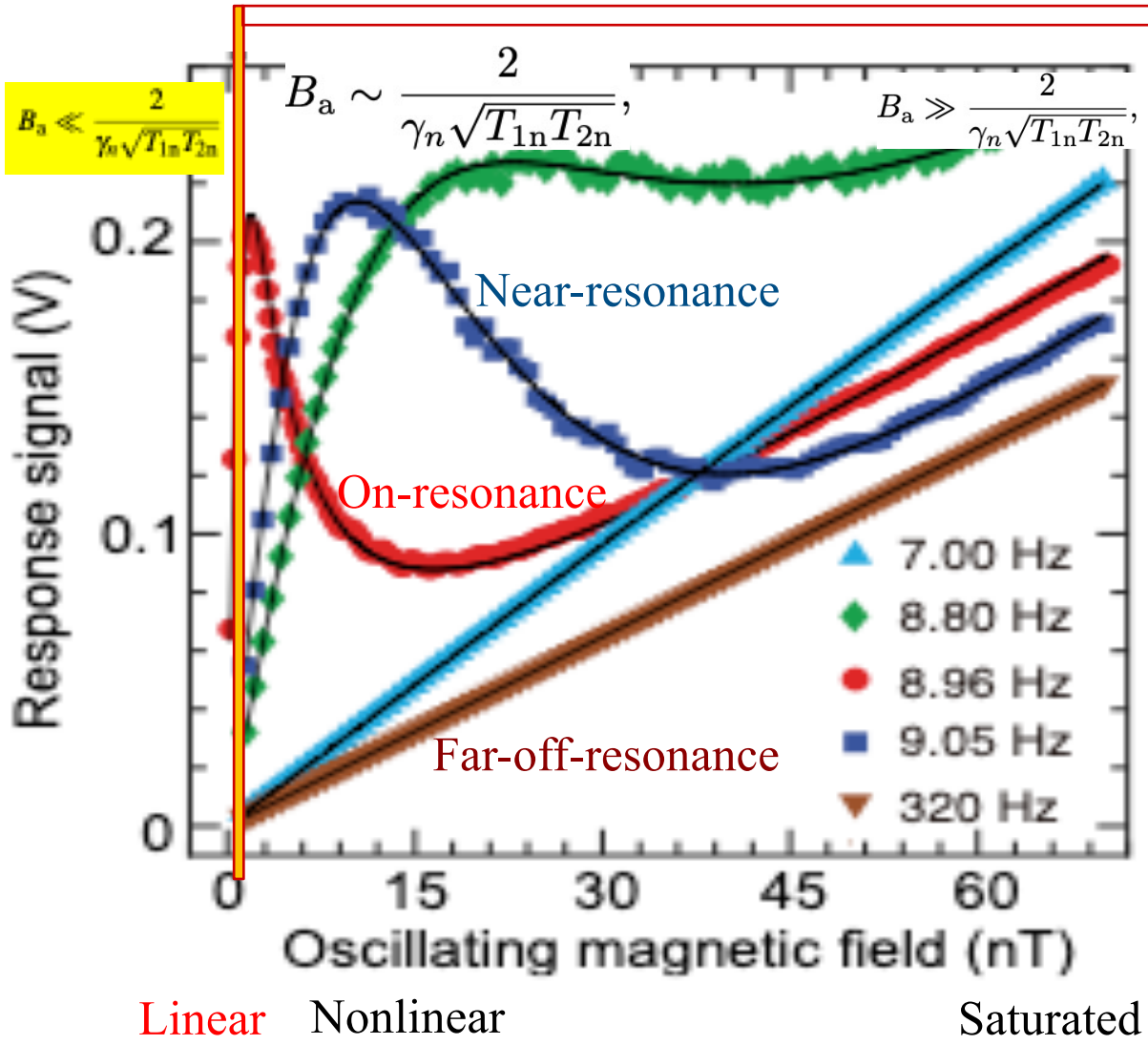
$$\mathbf{B}_{\mathrm{eff}} = \frac{1}{2}\lambda M^n P_0^n \gamma_n T_{2n} B_{\mathrm{ac}} \frac{\cos(2\pi\nu t) + 2\pi(\nu-\nu_0)T_{2n}\sin(2\pi\nu t)}{1+(\gamma_n B_{\mathrm{ac}}^y/2)^2 T_{1n}T_{2n} + [2\pi(\nu-\nu_0)]^2 T_{2n}^2}\boldsymbol{x}$$

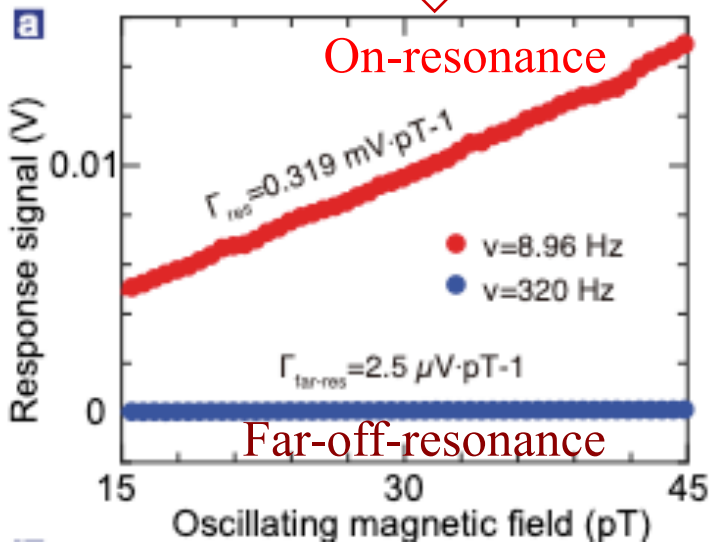
$$+ \frac{1}{2}\lambda M^n P_0^n \gamma_n T_{2n} B_{\mathrm{ac}} \frac{\sin(2\pi\nu t) - 2\pi(\nu-\nu_0)T_{2n}\cos(2\pi\nu t)}{1+(\gamma_n B_{\mathrm{ac}}^y/2)^2 T_{1n}T_{2n} + [2\pi(\nu-\nu_0)]^2 T_{2n}^2}\boldsymbol{y}$$

磁场放大因子　　功率饱和效应　　共振响应

磁场放大倍数：　$\eta = \frac{1}{2}\lambda M^n P_0^n \gamma_n T_{2n}$

Intrinsic time-independent spin systems

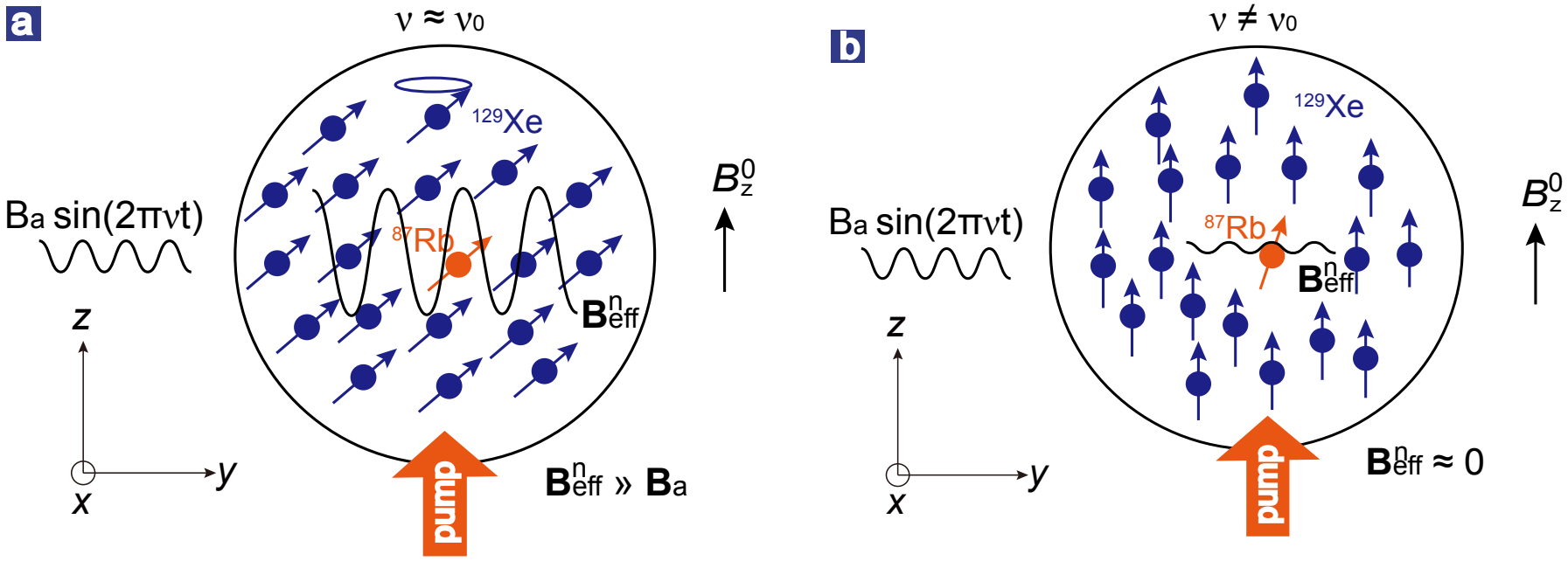




Slope: Response to the magnetic field

At least two orders of magnitude improvement

惰性气体的磁场量子放大效应



磁场放大增益:

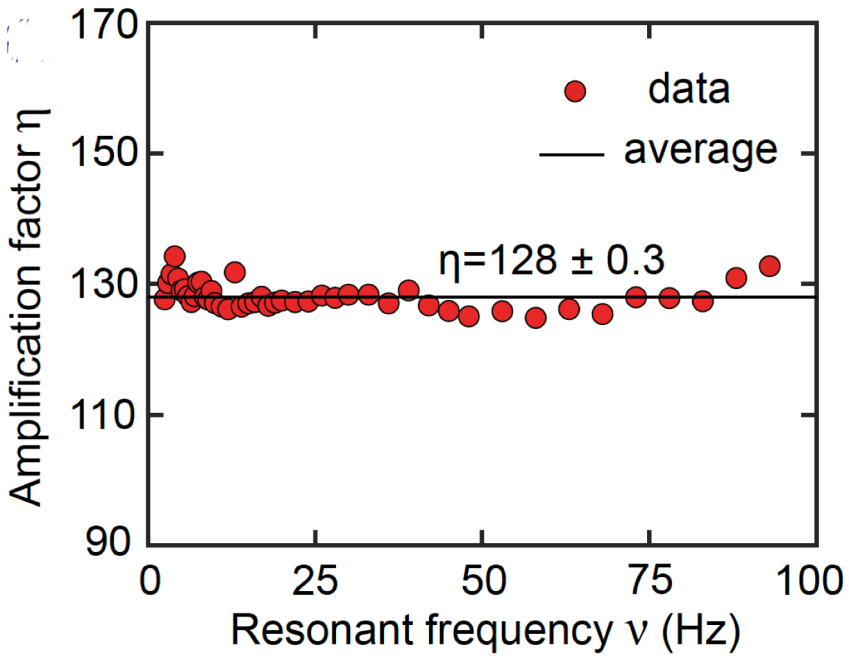
$$\eta = \frac{1}{2}\beta M_0^n P_0^n \gamma_n T_{2n} \gg 1$$

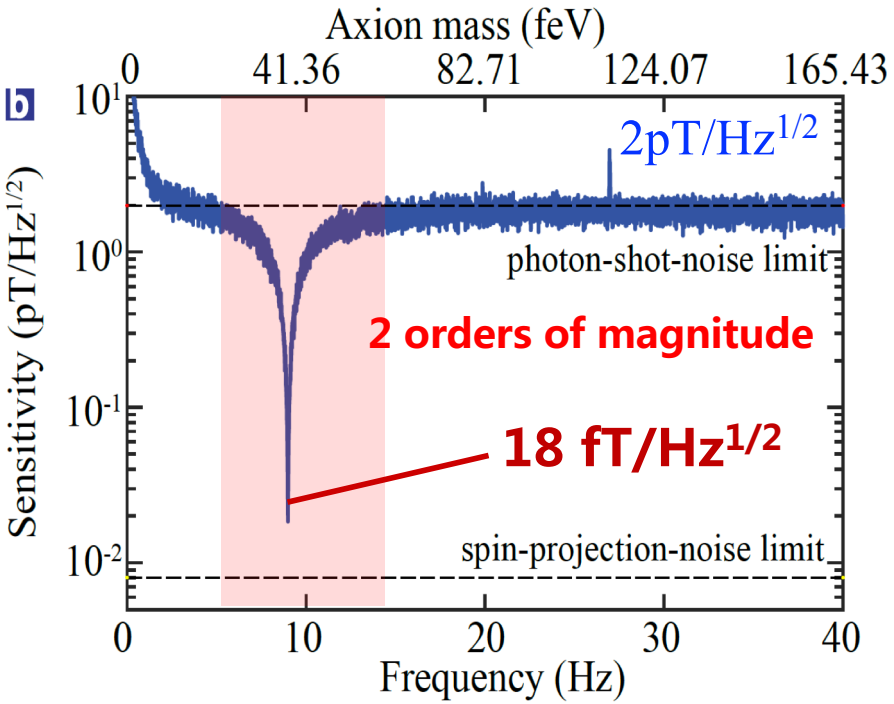
$$\eta \approx 0$$

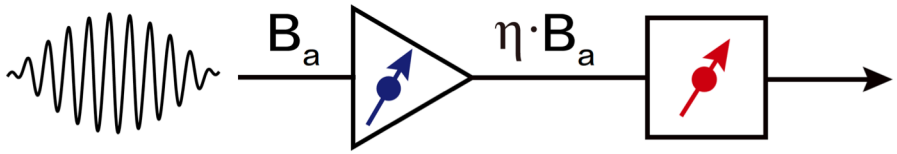
Jiang et al., Nature Physics **17**, pages 1402–1407 (2021)

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)

突破亚fT探测灵敏度

混合体系的优化

^{87}Rb-^{129}Xe

自旋破环碰撞截影响大

Xe原子相干时间短(~10s)

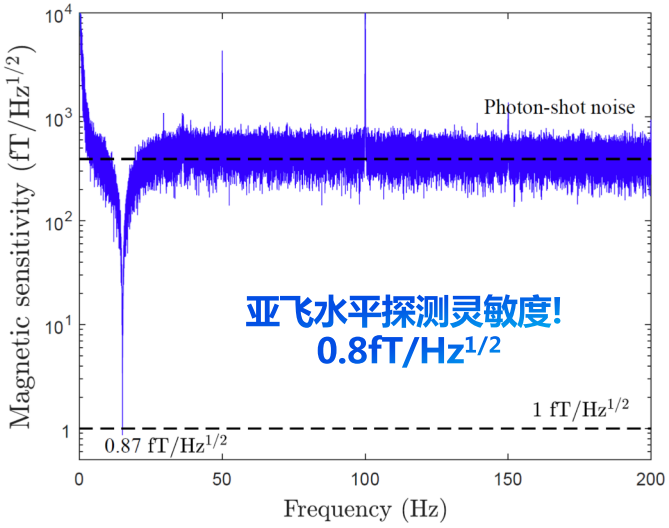
放大倍数(~100)

^{39}K-^{3}He

自旋破坏碰撞小5个量级

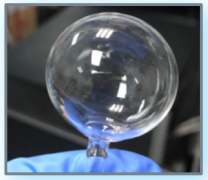
He原子相干时间长(1000s)

更大的放大倍数 (>1000)

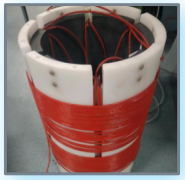


关键技术的突破

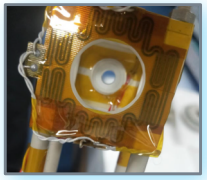
- 长相干时间低漏率的优质K-3He混合原子气室
- 坡莫合金与铁氧体的低磁噪声屏蔽系统
- 超低噪声的高稳定度无磁控温系统



低漏率
K-3He
气室



低噪声铁
氧体屏蔽

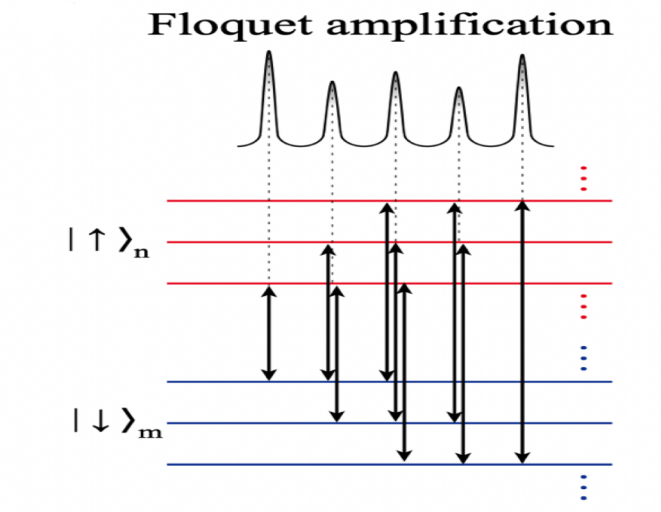


无磁超
稳控温

成为国际第三家自旋磁测量灵敏度突破fT的研究组

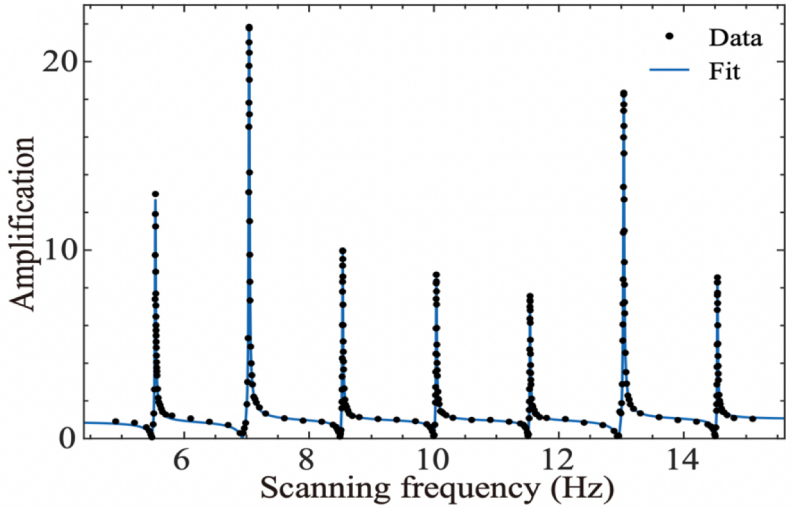
提出自旋放大频梳技术，实现多频段探测

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

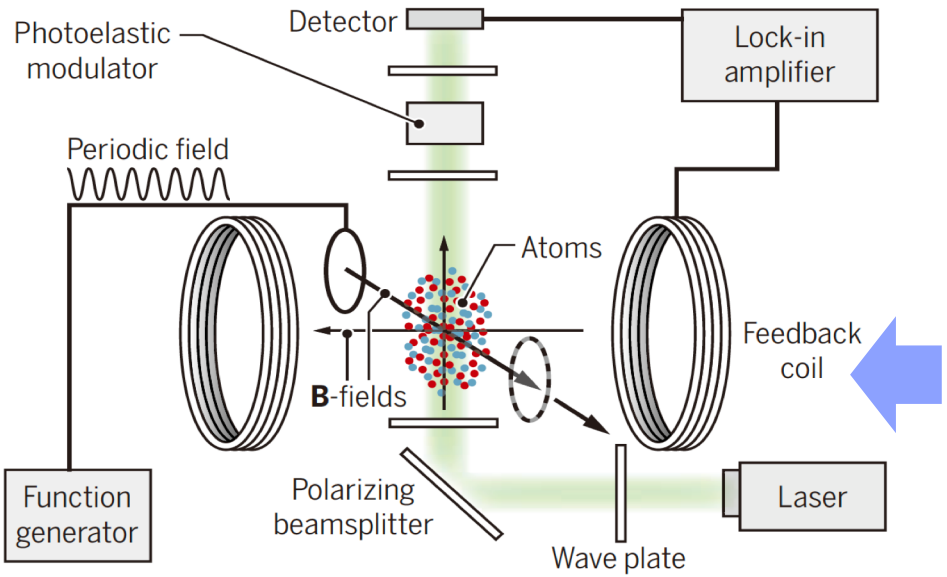
Nobel Prize: Maser and atomic clock


C. Townes


G.Basov


M. Prokhorov


N. F. Ramsey

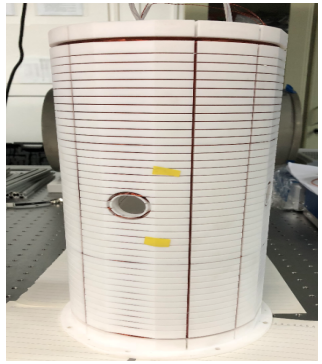




Optical frequency (Optical cavity)

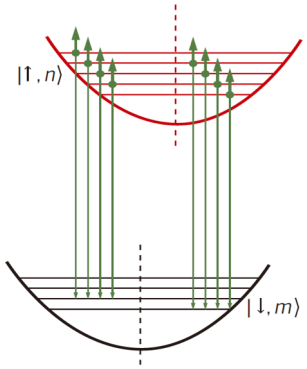


Microwave frequency (Cavity)

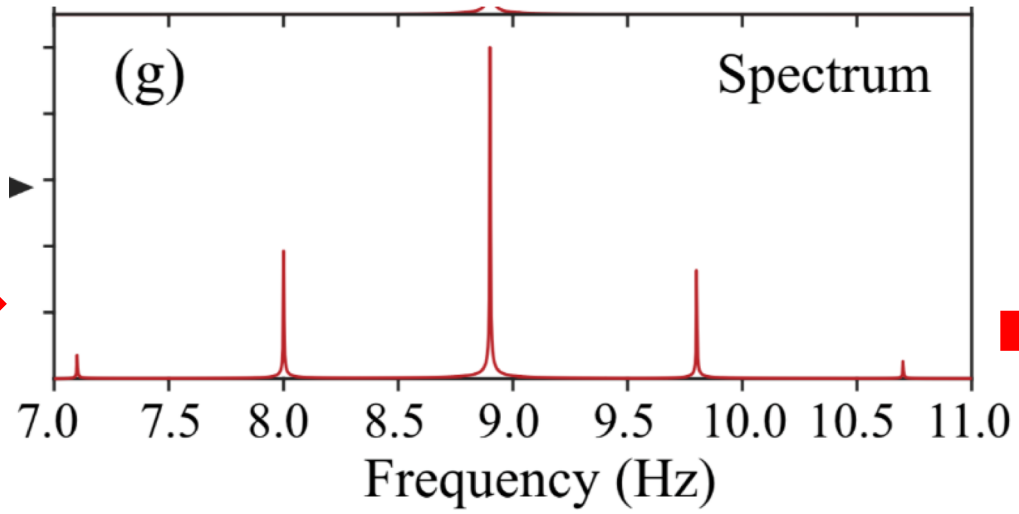


Radio frequency (feedback Coils)

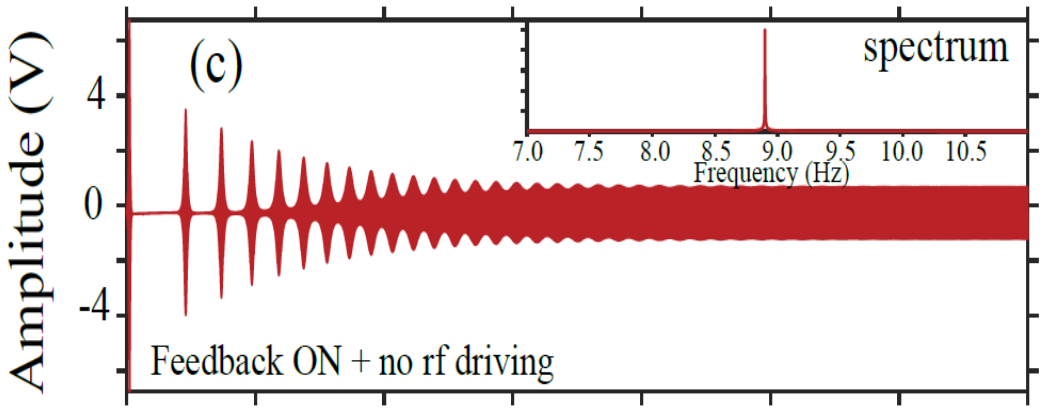
Floquet maser：首次使用Floquet介质作为增益介质

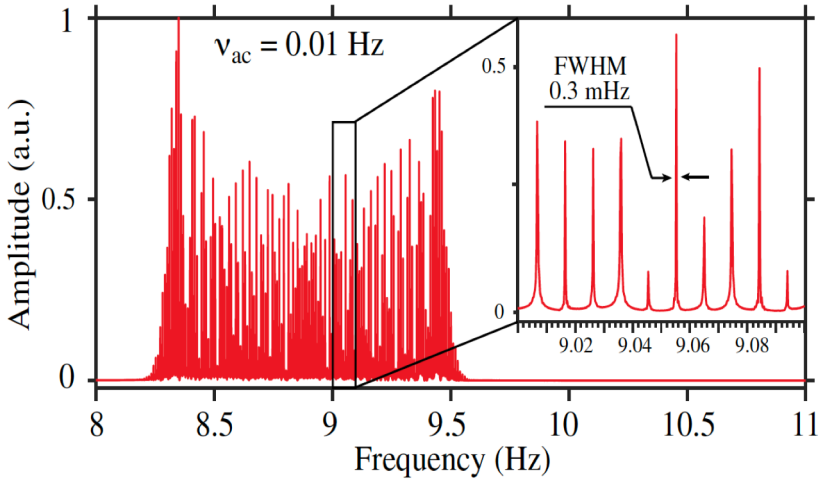


Weak Floquet driving



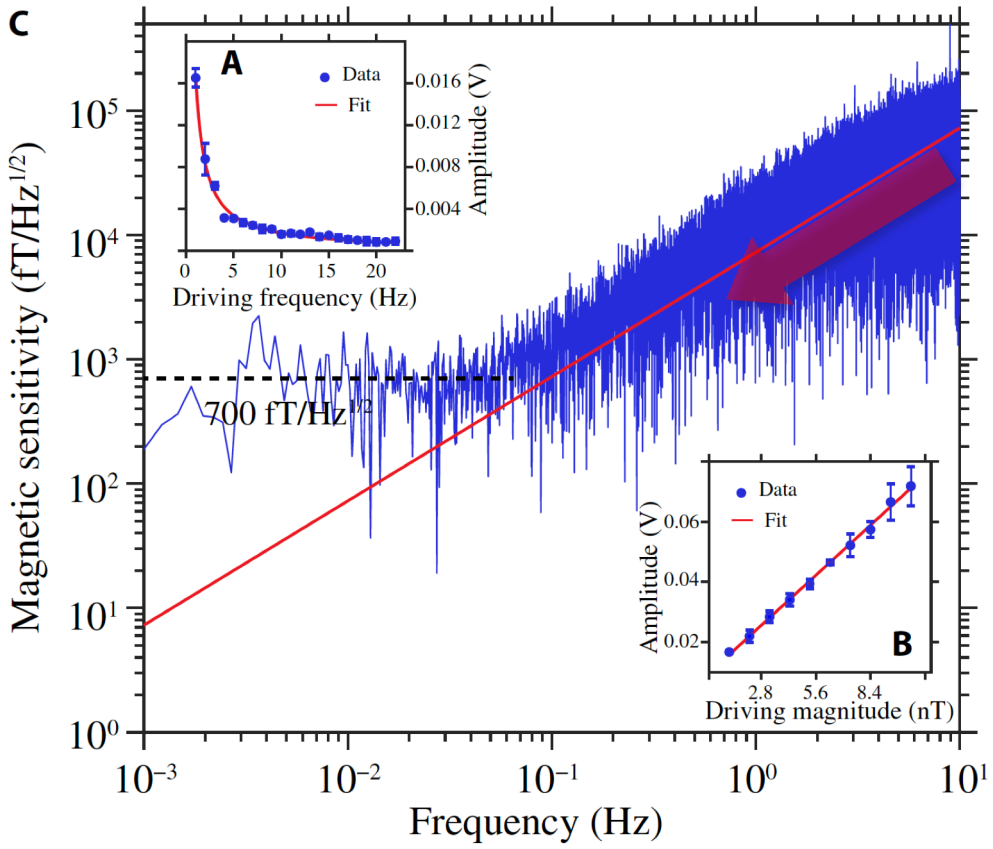
Strong Floquet driving





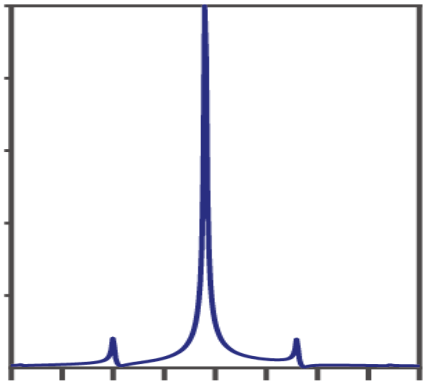
M. Jiang *et al.* **Science Advances** 7，eabe0719（2021）

磁场精密测量（via量子振荡器）：超低频率段



世界上最佳的超低频灵敏度！

$$S_1 \propto J_1\left(\frac{\gamma B_{ac}}{\upsilon_{ac}}\right) \approx \frac{\gamma}{2\upsilon_{ac}} B_{ac}$$



边带测磁灵敏度：

$\delta B \propto \upsilon_{ac}$

突破低频噪声极限和磁屏蔽约束！

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]

PHYSICS

Science

A masing ladder

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

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

PHYS.ORG

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

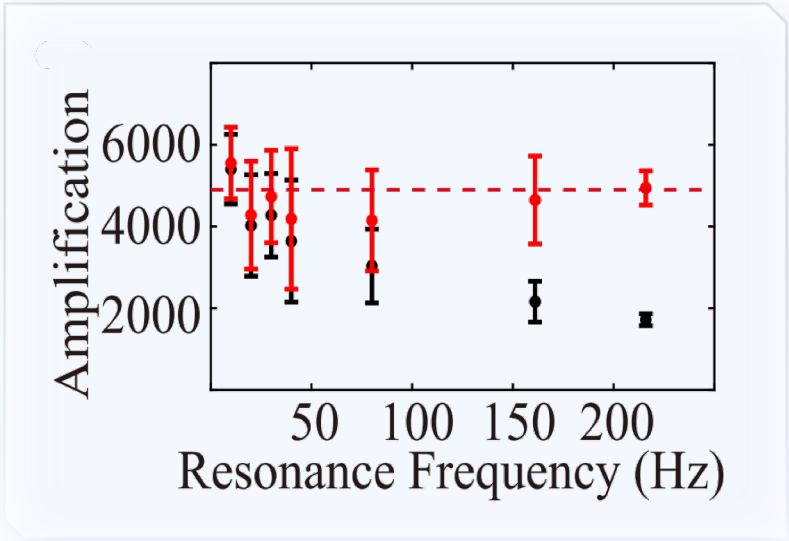
physicsworld RESEARCH UPDATE

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

《Science》Perspectives reports：

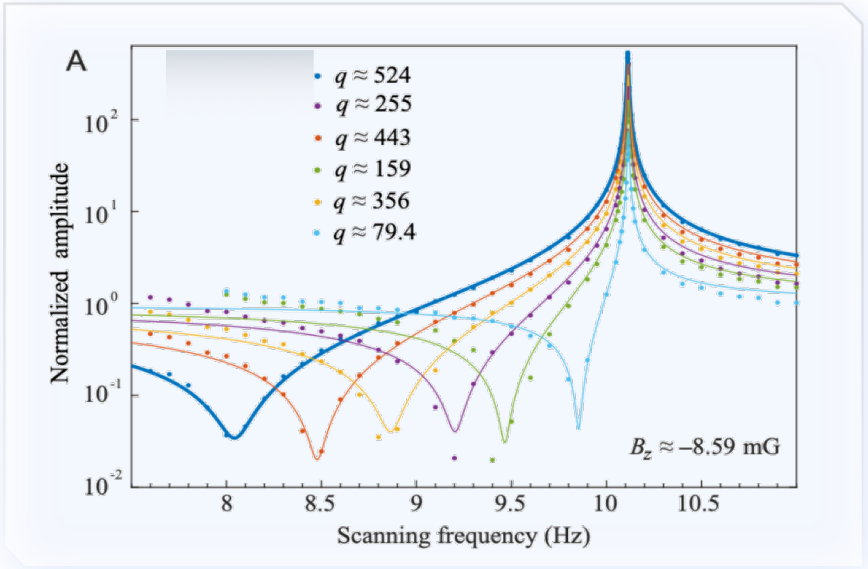
“… demonstrate a new type of maser… Conceivable applications of this work include precision clocks and detection of ultralight dark matter particles such as axions”

发现更多的混合自旋新效应（追求更高探测极限）



利用暗态自旋技术实现5400倍的磁场放大（相比之前指标提升至少1个量级）

PNAS， 121 (17) e231569612（2024）



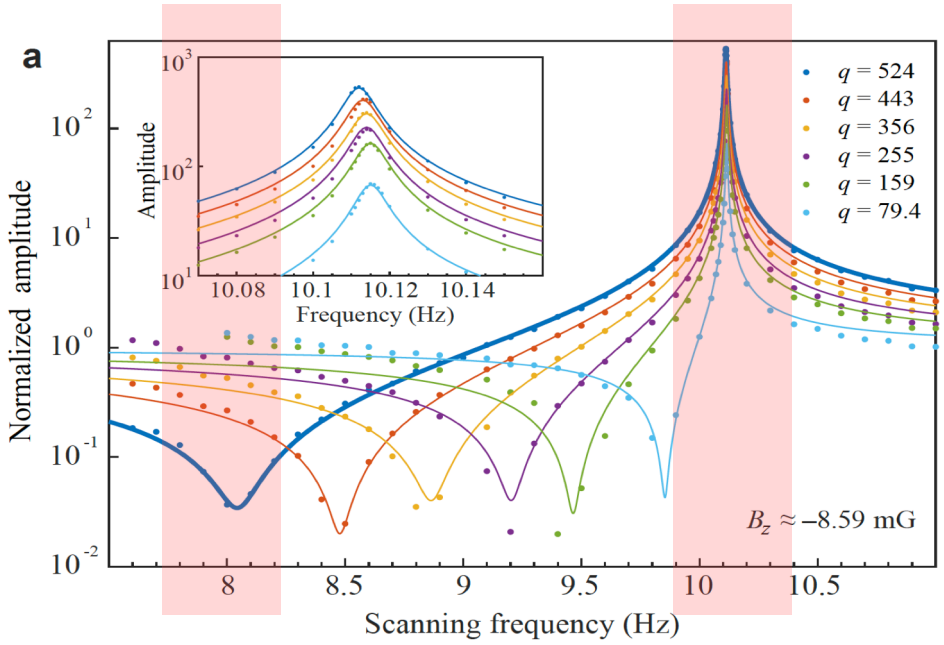
利用Fano效应实现优于10倍的磁噪声抑制

Phys. Rev. Lett. 133, 023202 (2024)

混合原子法诺干涉效应

Enhanced quantum sensing with amplification and deamplification

Min Jiang,[1,2,*] Yushu Qin,[1,2,*] Yuanhong Wang,[1,2] Ying Huang,[1,2] Xinhua Peng,[1,2,3,†] and Dmitry Budker[4,5,6]



碱金属-惰性气体自旋耦合模型：

$$\partial_t \begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix} = i \begin{pmatrix} \omega_a + i\Gamma_a & -J \\ -J & \omega_b + i\Gamma_b \end{pmatrix} \begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix} + \begin{pmatrix} h_a \\ h_b \end{pmatrix}$$

法诺干涉效应：

$$F(\varepsilon) = \mathscr{A}(\varepsilon)\frac{(q+\varepsilon)^2}{1+\varepsilon^2} + \mathscr{B}(\varepsilon)$$

法诺干涉效应：利用碱金属-惰性气体自旋的干涉效应抑制外界磁噪声

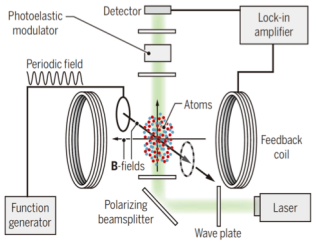
PNAS 2025 Vol. 122 No. 19 e2419683122

混合气室研究进展情况

开展研究

Sci. Adv. (2021)

利用量子反馈解决自旋退相干问题：新型微波激射器



2018

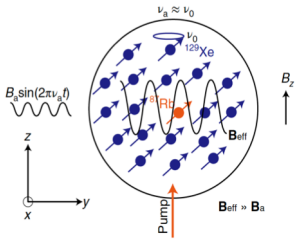
2020

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

（ 1-100mHz国际最高）

Nat. Phys. (2021)

首次发现惰性气体的磁场放大效应：增强自旋磁场响应



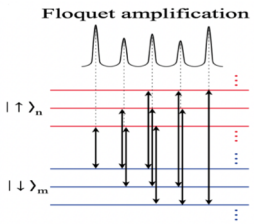
2021

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

（核自旋国际最高）

PRL (2022)

将量子放大扩展到周期自旋体系：解决带宽窄难题



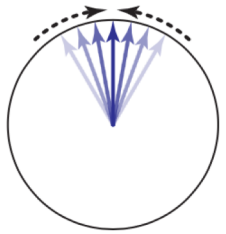
2022.6

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

(提升带宽1个量级)

PNAS (2024)

发现暗态量子放大效应

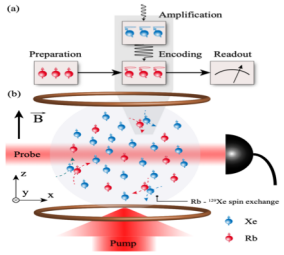


2022.8

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

PRA (2026)

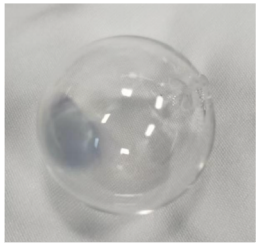
关键技术突破：采用^{3}He作为磁场放大物质



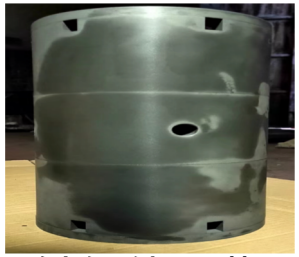
2023.1

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

技术突破



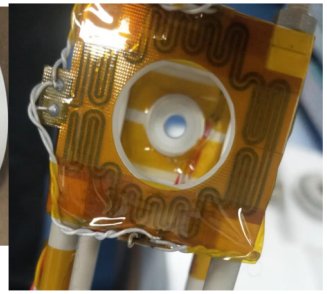
低漏率气室

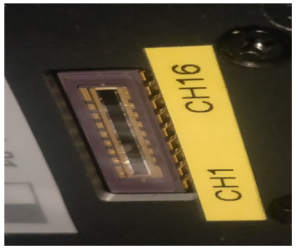


铁氧体屏蔽



真空无磁加热

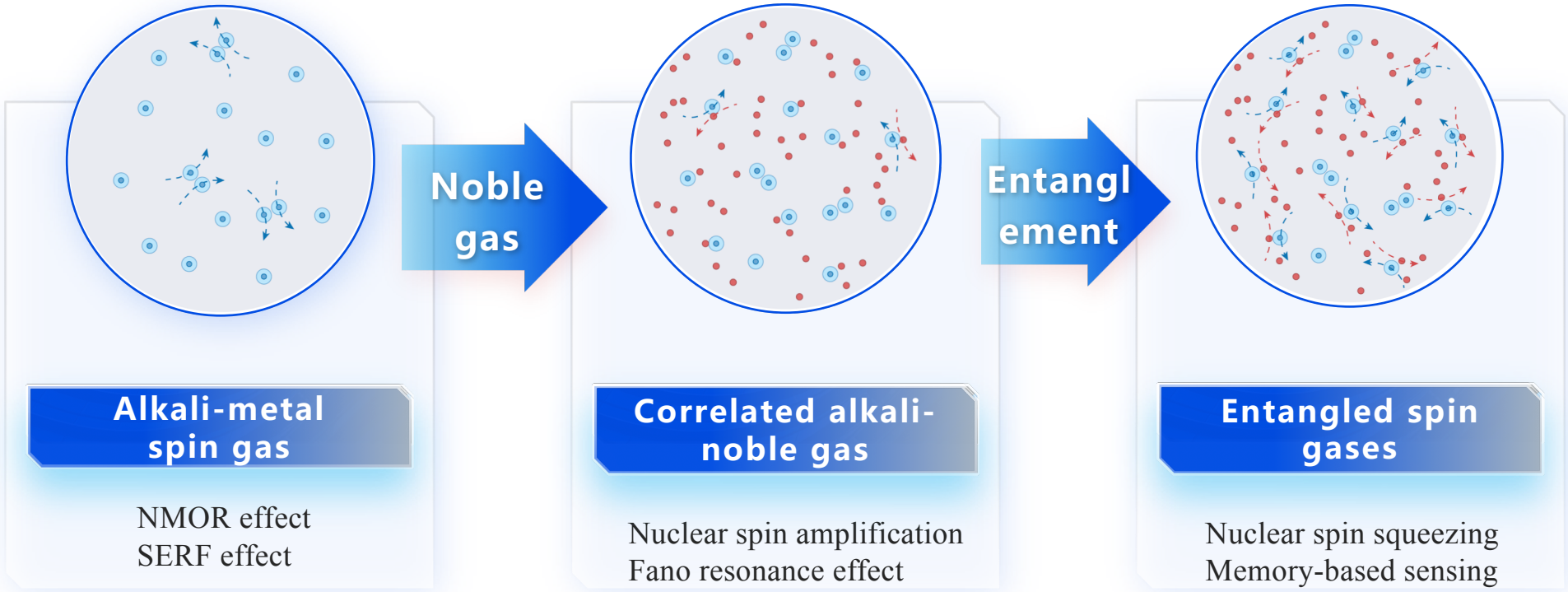




差分探测电子学

磁场测量灵敏度稳步提升，已经进入亚fT世界前沿水平

Opportunity: Interaction, Correlation, and Entanglement



SQL: $1/\sqrt{N}$

SQL: $1/\Sigma\sqrt{N}$

Heisenberg Limit: $1/N$

fT时代：有什么新的应用？

Quantum sensors will start a revolution — if we deploy them right

Kai Bongs, Simon Bennett & Anke Lohmann

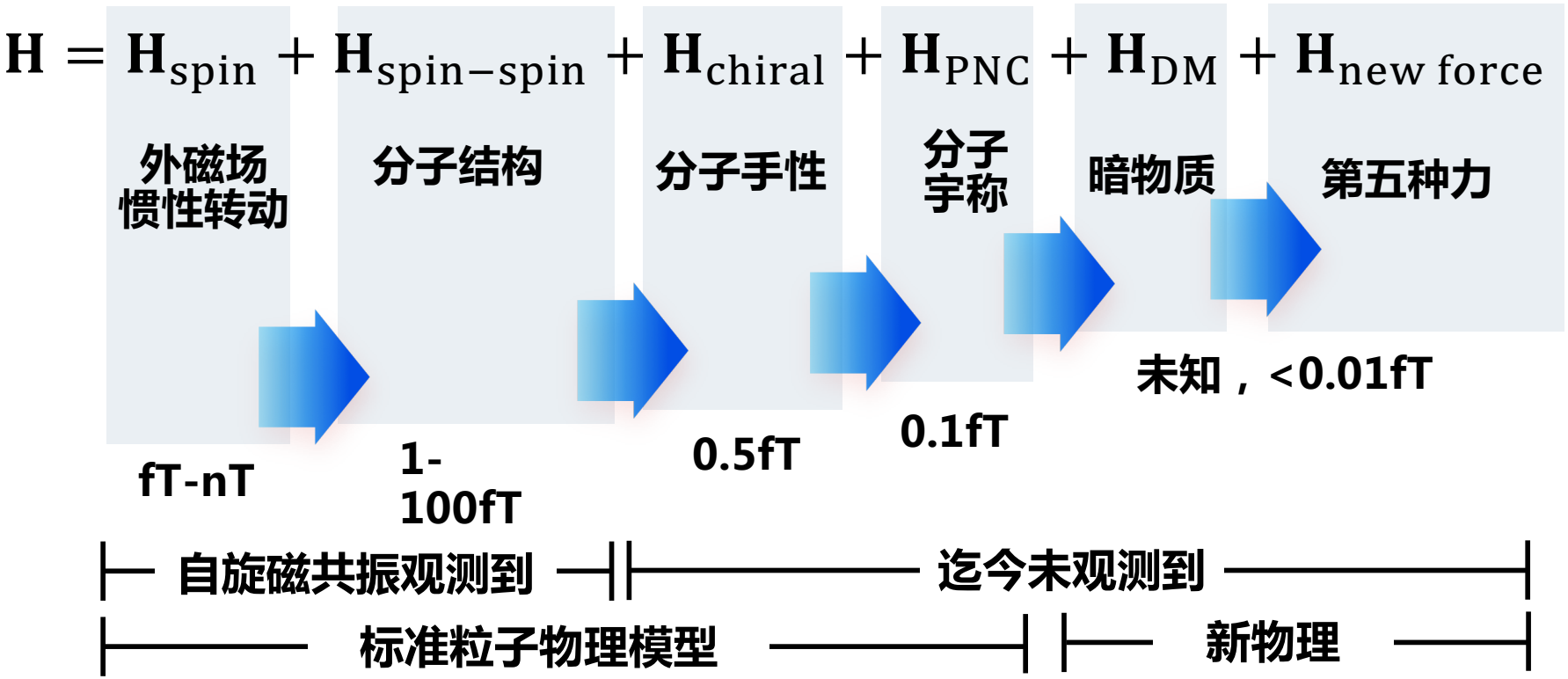
From underground exploration to brain science and air-traffic control, the sensing potential of quantum devices is enormous. But they must first get out of the laboratory.

Quantum sensors exploit the fundamental properties of atoms and light to make measurements of the world. The quantum states of particles are extremely sensitive to the environment, which is a virtue for sensing, if problematic for making a quantum computer. Quantum sensors that use particles as probes can quantify acceleration, magnetic fields, rotation, gravity and the passage of time more precisely than can classical devices that are engineered or based on chemical or electrical signals. They can be used to make atomic clocks that are smaller and more accurate, cameras that can see through fog and around corners, and devices for mapping structures underground, among many other potential applications. They stand to transform a multitude of sectors, from energy, land use and transport to health care, finance and security. But their commercial promise needs to be appreciated more.

As researchers developing quantum sensors in the laboratory, we are keen to make governments and industry more aware of the possible benefits — in particular, in improving the safety of national critical infrastructure that relies on sensors, such as air-traffic control systems and

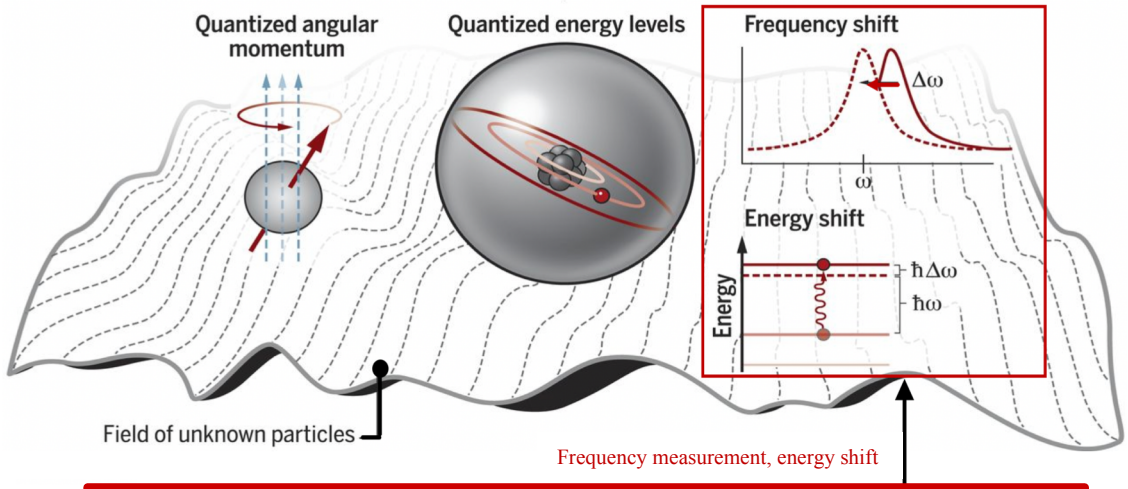
前沿应用 “相互作用”对应于一种“新应用”

不同强度大小的自旋作用伴随着精密测量新应用



Application: Fundamental physics & particle physics

Exotic interactions (e.g., axion-spin coupling) induce spin energy shift



"pseudo-magnetic" field:

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

Amplitude: Coupling strength

Oscillation frequency: Compton frequency

Axion (dark matter)

Hamiltonian =

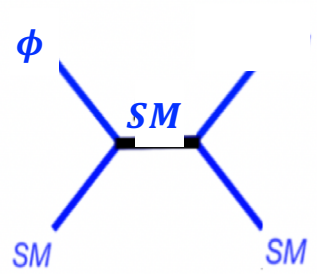
$$+\sqrt{\frac{\varepsilon_0}{\mu_0}}\, g_{a\gamma\gamma} \int a\mathbf{E}\cdot\mathbf{B}dV$$ **Axion-photon**

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

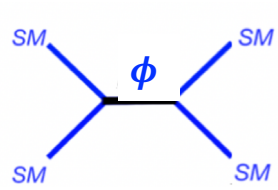
$$+\sqrt{\varepsilon_0 (\hbar c)^3}\, g_{\mathrm{EDM}}\, a\hat{\mathbf{S}}\cdot\mathbf{E}$$ **Axion-gluon**

SAPPHIRE project

Spin Amplifier for Particle PHysIcs Research







Wang, Y., Huang, Y., Guo, C., Jiang, M., ... & Budker, D.， Sci. Adv.9, eade0353 (2023)

Axion dark matter searches: Beyond astrophysical limit

nature physics

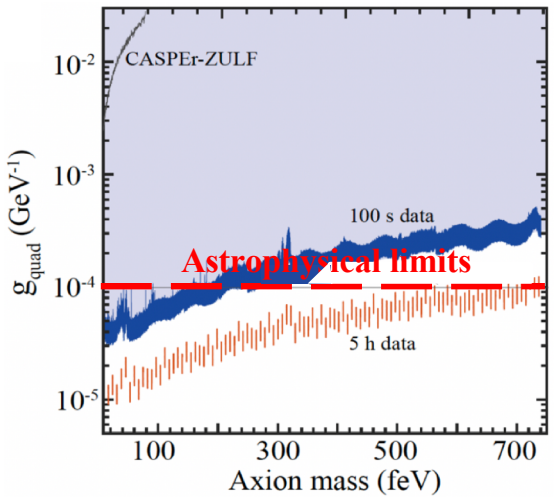
ARTICLES

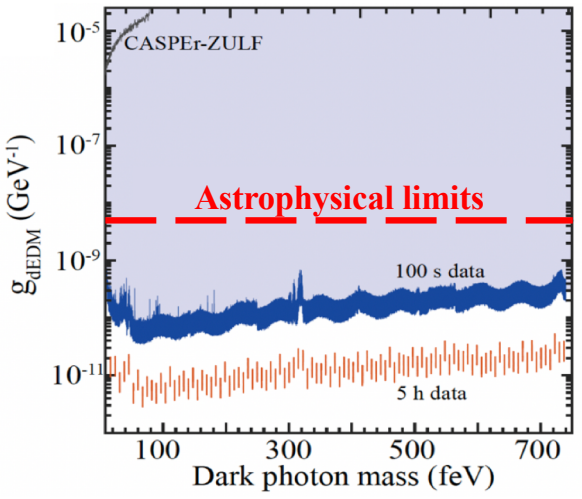
https://doi.org/10.1038/s41567-021-01392-z

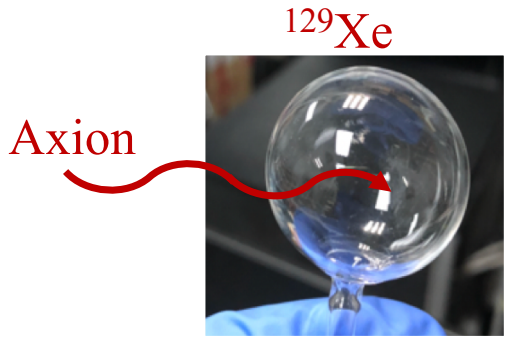
Check for updates

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]





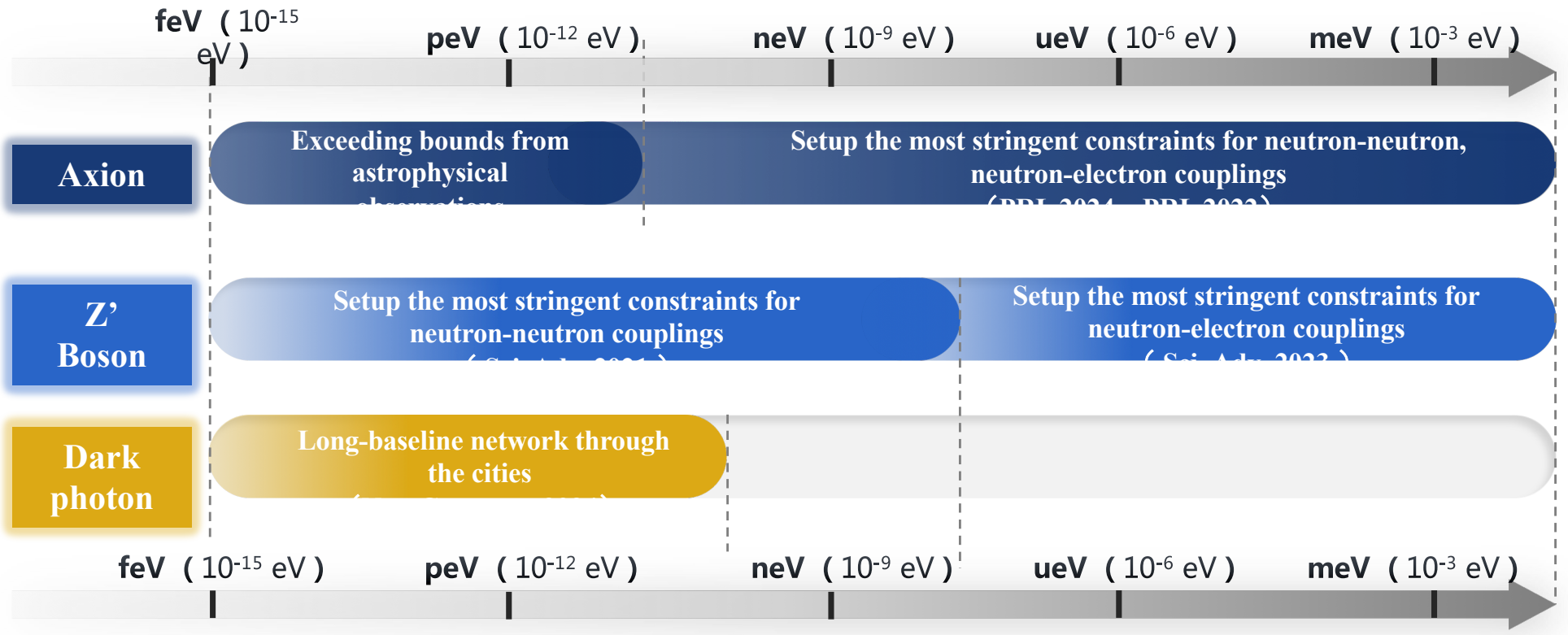


Spin-amplification: 128
Sensitivity: 18fT/Hz$^{1/2}$
5 hours average: 130aT
Axion-nucleon interaction:
$\leq 10^{-9}$GeV^{-1} (feV-peV)

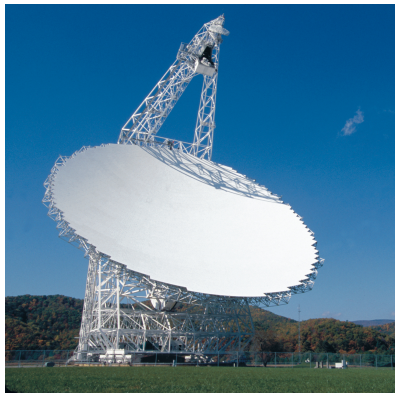
Establish the most stringent limits on axion-nucleon coupling **beyond astrophysical limits**

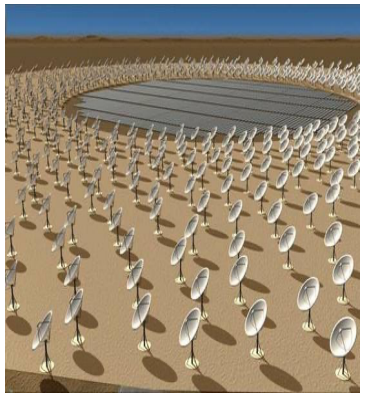
Searching ultralight dark matter

- Searching for different low energy regions for axions, Z'bosons and dark photons, providing the latest new constraints

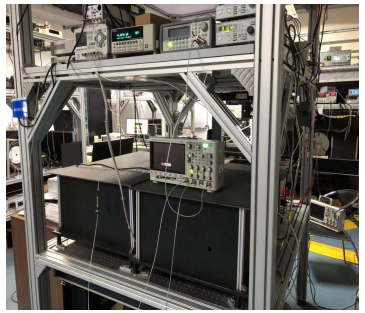
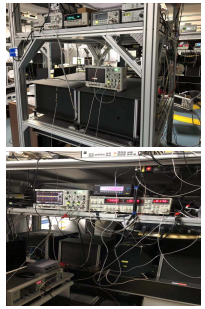
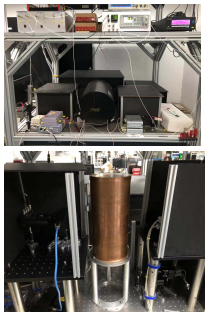


类比于望远镜的发展思路：“暗物质望远镜”






单一探测器　　大口径探测器　　阵列探测器　　空间探测器




已取得基础：从单一到多台，再到跨城市的量子传感网络

空间站、月球与深空

Correlation sensing via multiple-sensor network

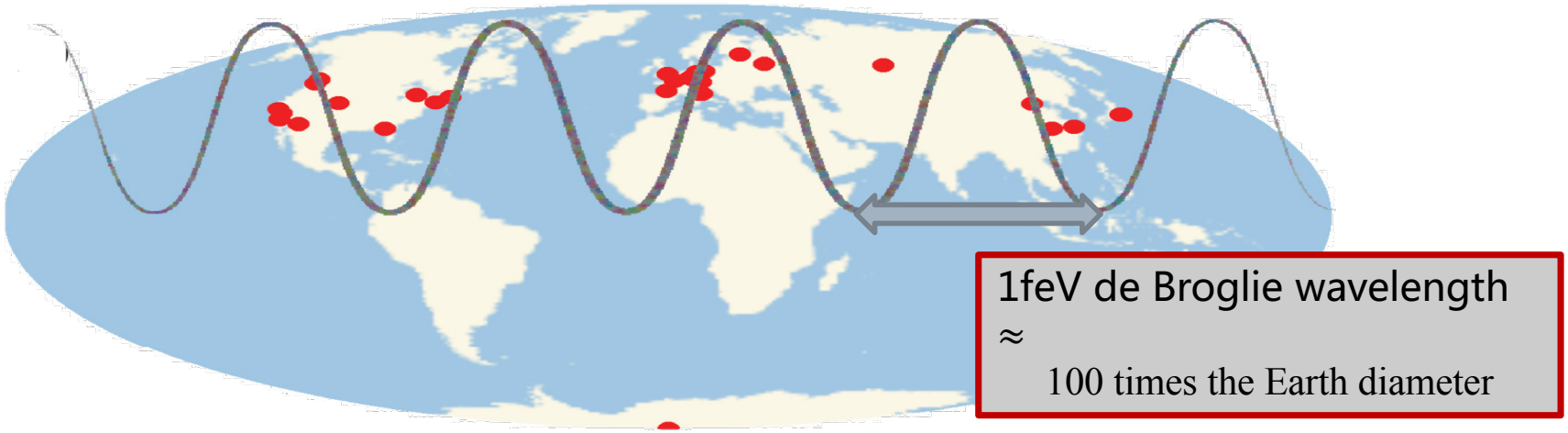
Single sensor

Localized noise is hard to suppress
Detection deadzone
Can't tell the orientation of DMs

N-sensor network

Suppress the false alarm rate $\propto p^N$
Enhance sensitivity $\propto 1/\sqrt{N}$
Omni-directional detection
Network contains DM orientation inf.

Ultralight dark matter with long de Broglie wavelength enables the network detection



Dark photon network searches （ AMAILS ）

nature communications

New limits on dark photon dark matter

Article

https://doi.org/10.1038/s41467-024-47566-0

Long-baseline quantum sensor network as dark matter haloscope

Received: 13 September 2023

Accepted: 4 April 2024

Min Jiang[1,2,3,12], Taizhou Hong[1,2,3,12], Dongdong Hu[3,4,12], Yifan Chen[5], Fengwei Yang[6], Tao Hu[7], Xiaodong Yang[7], Jing Shu[8,9,10] ✉, Yue Zhao[6] ✉, Xinhua Peng[1,2,3] ✉ & Jiangfeng Du[1,2,3,11]



Collaboration with Yue Zhao, Jing Shu, Yifan Chen

Correlation sensing via multiple-sensor network

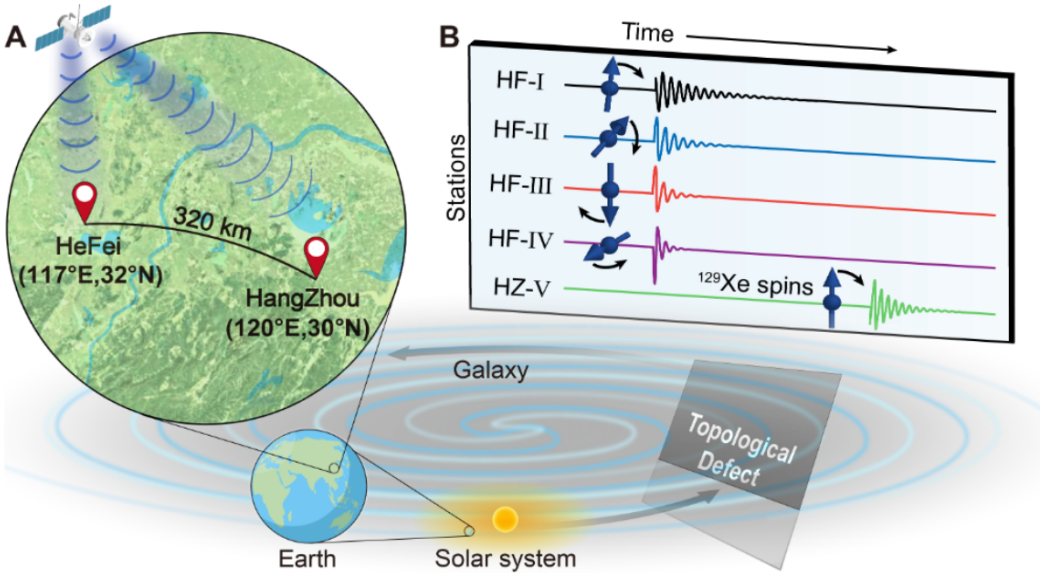
Article

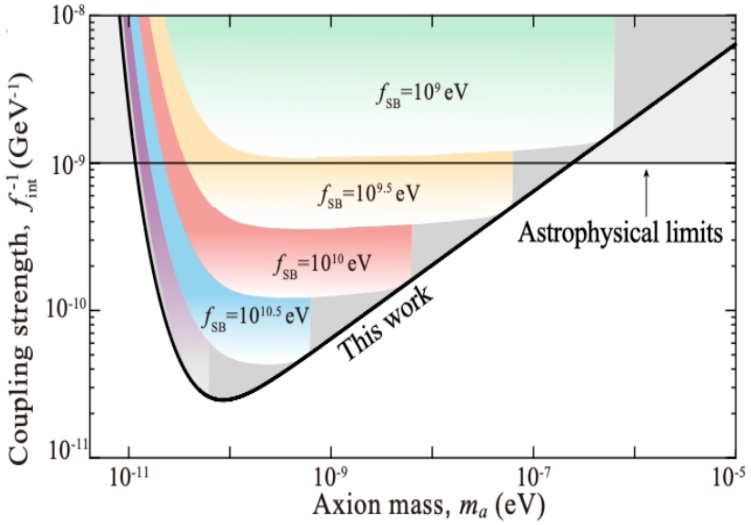
Constraints on axion dark matter by distributed intercity quantum sensors

Nature 650, 314 (2026)

https://doi.org/10.1038/s41586-025-10034-w
Received: 15 April 2025

Yuanhong Wang[1], Ying Huang[1], Xiang Kang[1], Dangui Chang[2], Jiaxuan Xu[1], Yifan Chen[3,4], Szymon Pustelny[5], Wenqiang Zheng[2], Min Jiang[1]✉, Xinhua Peng[1,6,7]✉ & Jiangfeng Du[6,8]



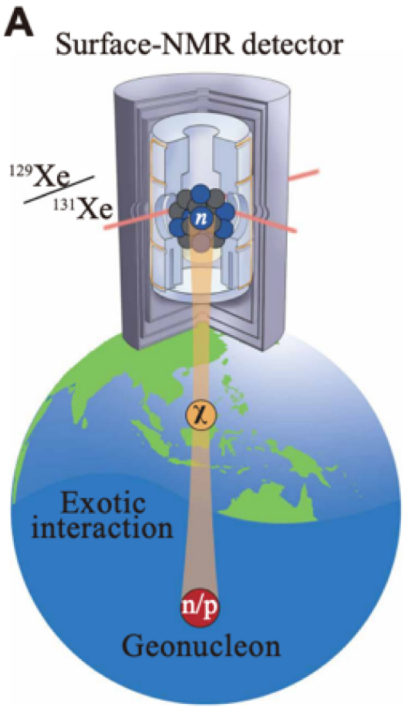


Collaboration with Szymon Pustelny

The first nuclear-spin quantum senor network

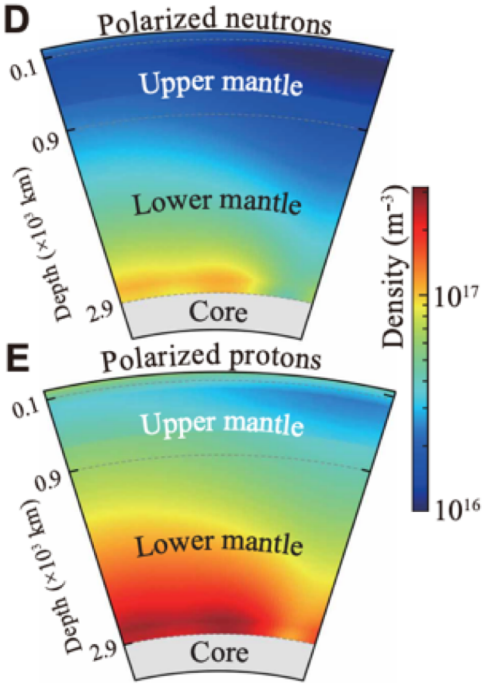


Earth as a source (nuclear spins)



Nuclear shell model
Schmidt model
FLP semiempirical model

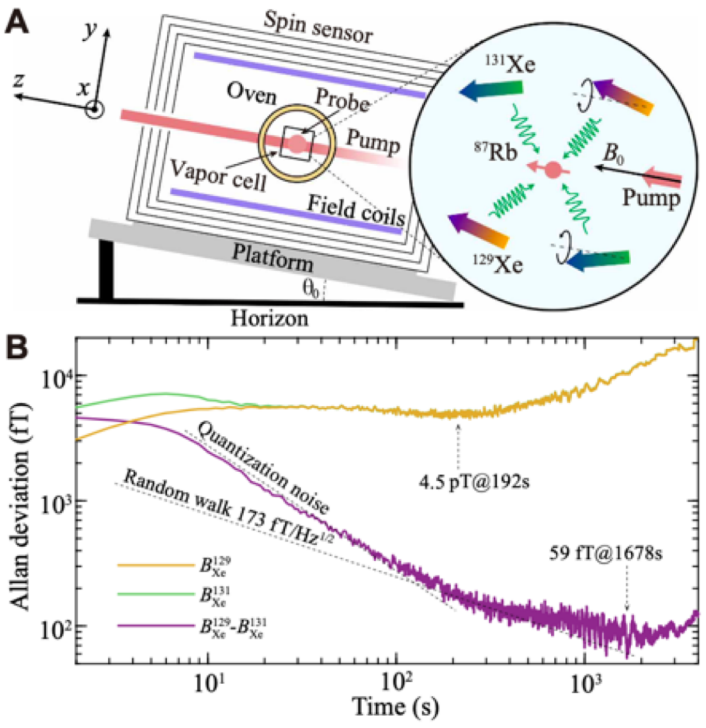
$\sim 2.2 \times 10^{37}$



$\sim 5.3 \times 10^{37}$

$> 10^{16}$ times than Lab

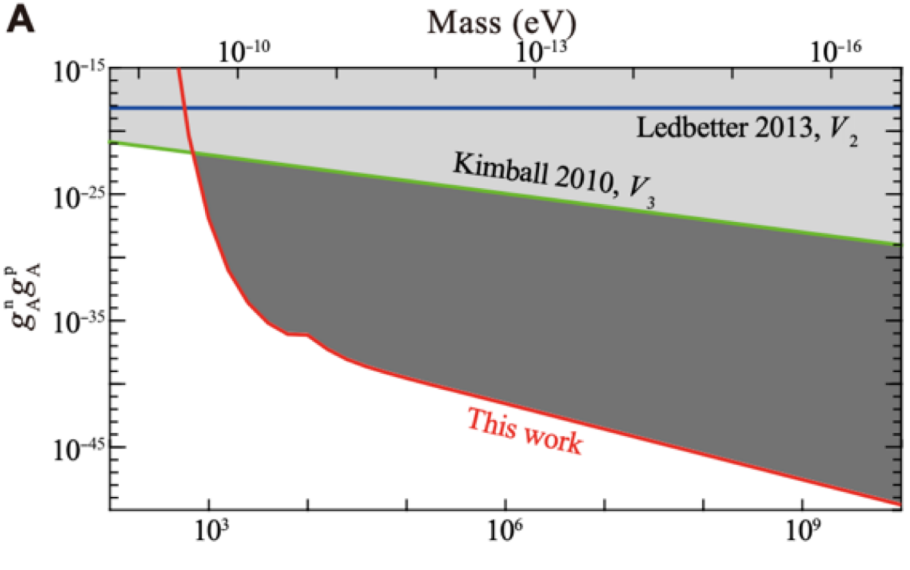
Surface- NMR detector



Constraints on spin- spin- interaction coupling constants

Z' boson–mediated proton- neutron coupling

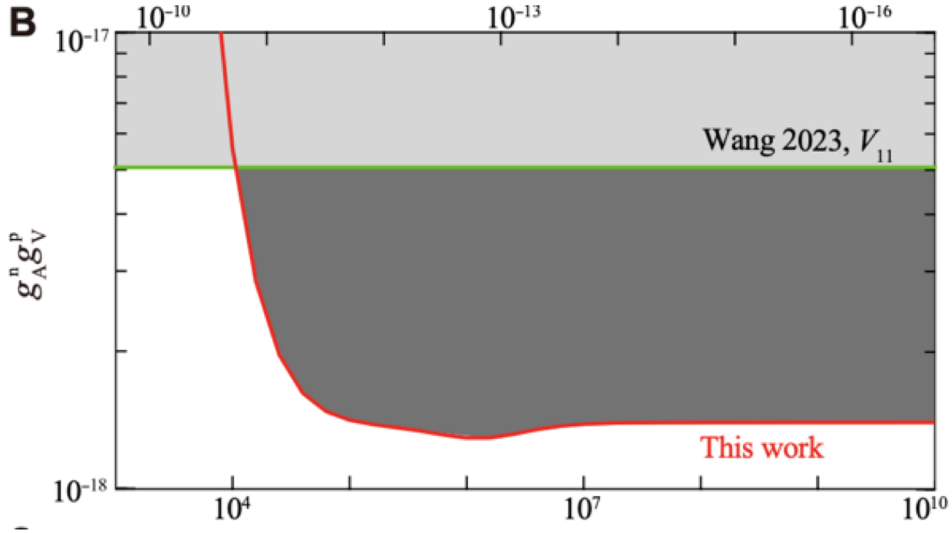
axial- vector/axial- vector coupling



Ledbetter 2013: Phys. Rev. Lett. 110, 040402 (2013)

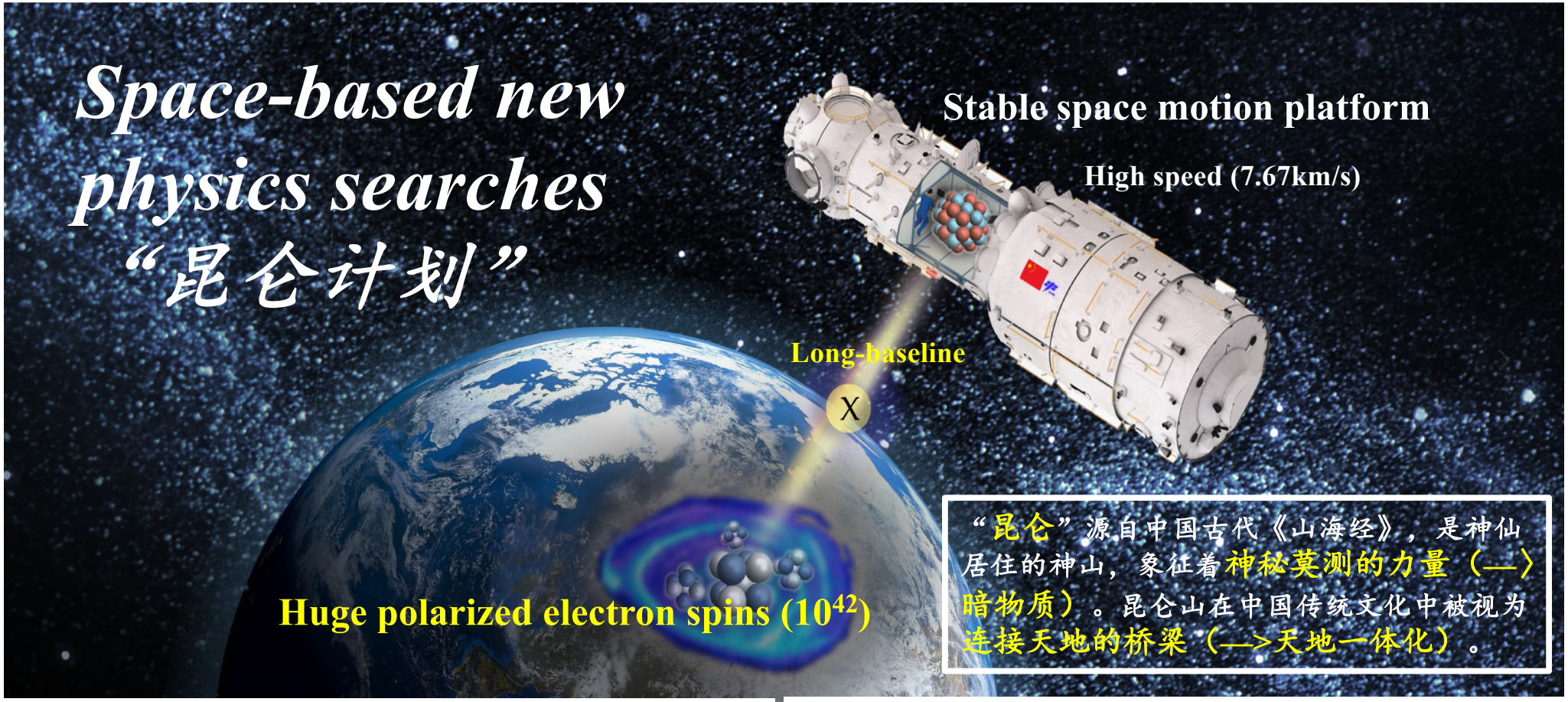
Kimball 2010: Phys. Rev. A 82, 062714 (2010).

axial- vector/vector coupling



Wang 2023: Sci. Adv. 9, eade0353 (2023).

This work: Wang et al., Sci. Adv. 12, eaeg0974 (2026)



PERSPECTIVE

National Science Review
12: nwaf389, 2025
https://doi.org/10.1093/nsr/nwaf389
Advance access publication 22 September 2025

PHYSICS

Quantum sensors in space: unveiling the invisible universe

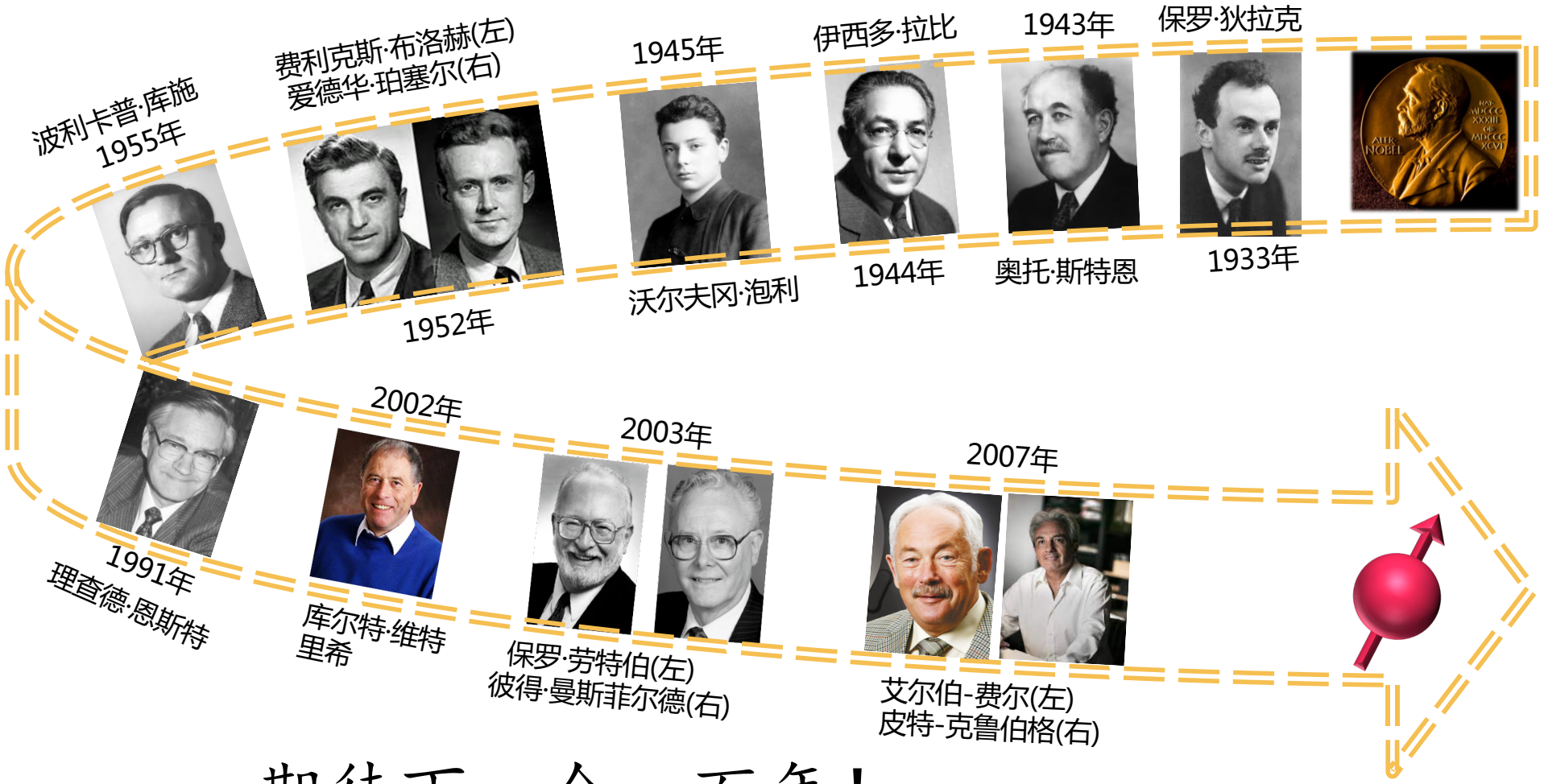
Yuanhong Wang[1,2,†], Xingming Huang[1,2,†], Min Jiang[1,2,*], Qing Lin[3,4], Wenqiang Zheng[4], Yuan Sun[5], Liang Liu[5], Xinhua Peng[1,2,*], Zhengguo Zhao[3,4] and Jiangfeng Du[2]

PHYSICAL REVIEW D **112,** 095015 (2025)

Hunting for exotic bosons with flying quantum sensors in space

Xingming Huang,[1,*] Yuanhong Wang,[1,*] Xiang Kang,[1] Jiaxi Li,[1,2] Haowen Su,[1] Zehao Wang,[1] Qing Lin,[3,4] Wenqiang Zheng,[5] Yuan Sun,[6] Liang Liu,[6] Min Jiang,[1,7,†] Xinhua Peng,[1,2,7,‡] Zhengguo Zhao,[3,4] and Jiangfeng Du[2,8]

自旋：昨天、今天、明天



期待下一个一百年！

Thanks to ……



Prof. Jiangfeng Du

Collaborators:
Prof. Dieter Suter
Prof. Dmitry Budker
Prof. Renbao Liu
Prof. Hui Zhai
Prof. Pengfei Zhang
Prof. Bei Zeng
Prof. Haidong Yuan
……

Funding:
USTC, CAS, NNSFC……





M. Jiang

Group members:
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Ze Wu (Postdoc.)
Haowen Su (Postdoc.)
Yuanhong Wang (Postdoc.)
Yuchen Li (Postdoc.)
Qing Li
Shiming Song
Minxiang Xu
Yushu Qing
Xingming Huang
……



中国科学院微观磁共振重点实验室
CAS Key Laboratory of Microscale Magnetic Resonance

中华人民共和国科学技术部
The Ministry of Science and Technology of the People's Republic of China

Email: xhpeng@ustc.edu.cn