# Quantum sensors and devices for Navigation, Timekeeping and healthcare


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- I-Hub Quantum Technology Foundation

**IISER Pune**


**FIRST INTERNATIONAL QUANTUM COMMUNICATION CONCLAVE**
**27 – 28 March 2023**



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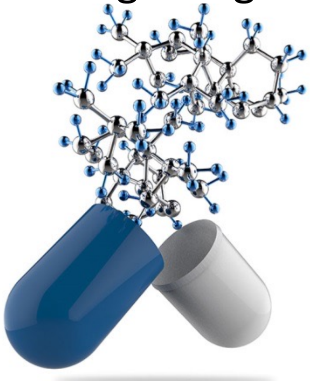
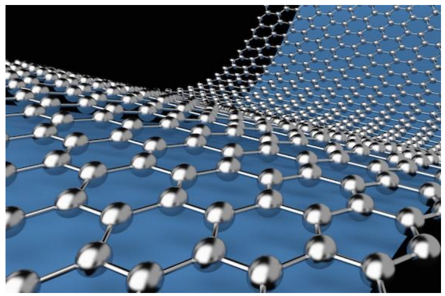
# Quantum Technology: Some applications

## Drug Design



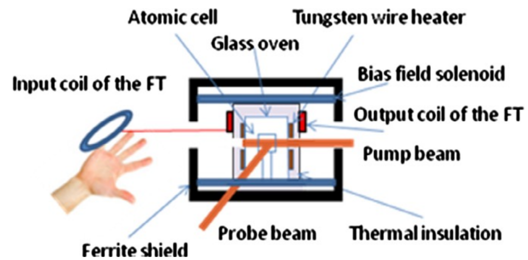
http://wp.umaryland.edu

## Materials Engineering



https://www.aiche.org

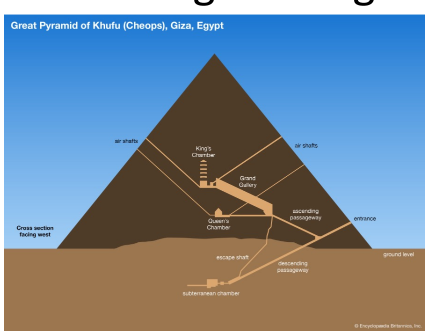
## Healthcare



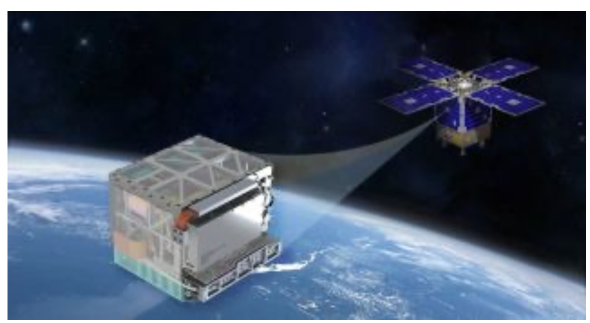

https://www.sciencedirect.com/science/article/pii/S1090780713000773

- Fintech
- CyberSecurity

## Civil Engineering

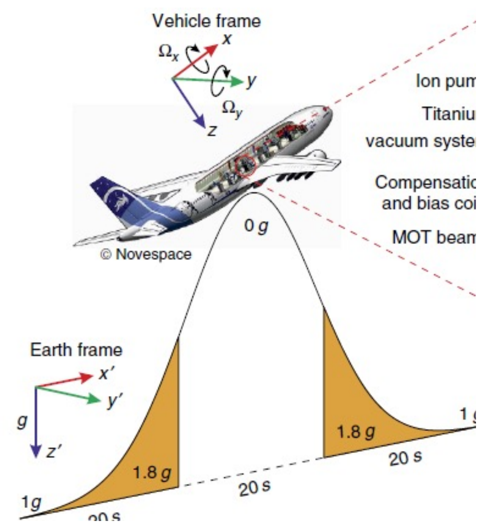



## Atomic Clocks: Deep Space Navigation

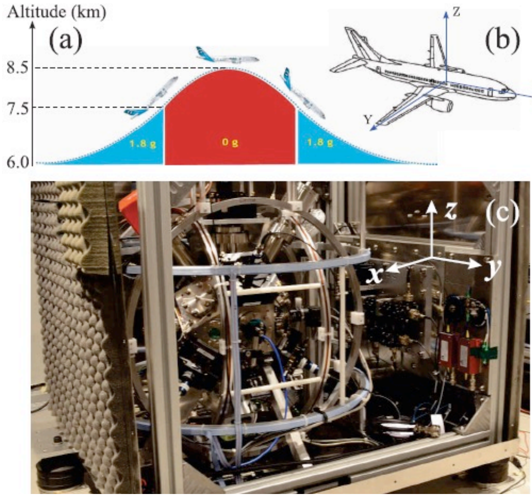


NASA: https://www.space.com

## Atomic Inertial sensors

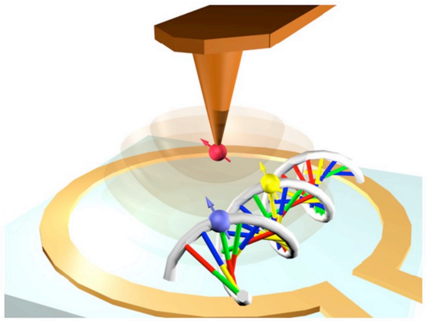


# Quantum sensors



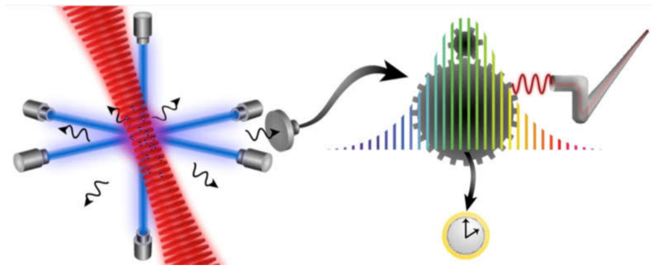

Atomic sensors (inertial navigation)

*arXiv:1603.03246v1*



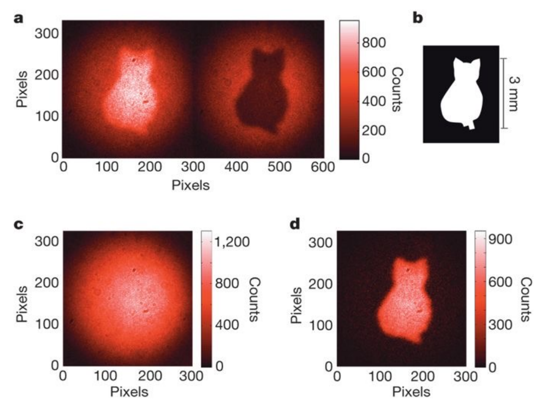
Spin qubit sensors

*New J. Phys. 20 (2018) 080201*



Quantum Clocks

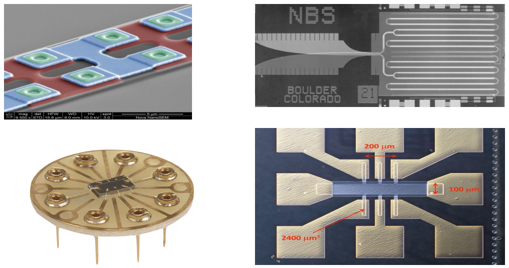
*jila.colorado.edu*



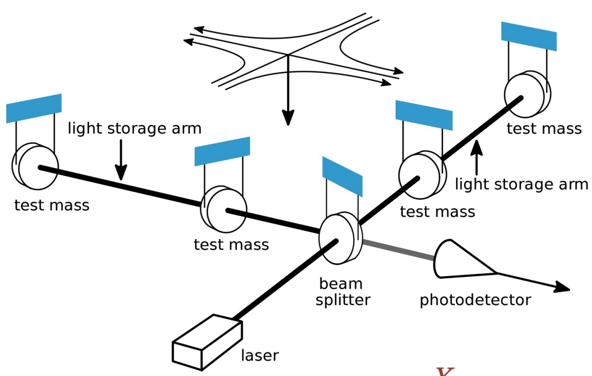

Quantum Imaging

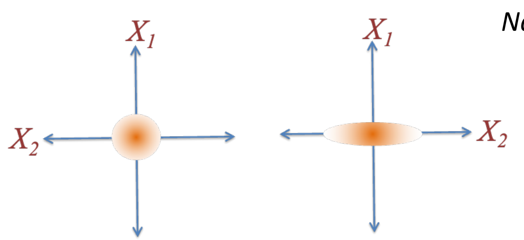
*Nature* **volume 512**,409(2014)

Josephson Voltage Standard




Quantum Hall Standard

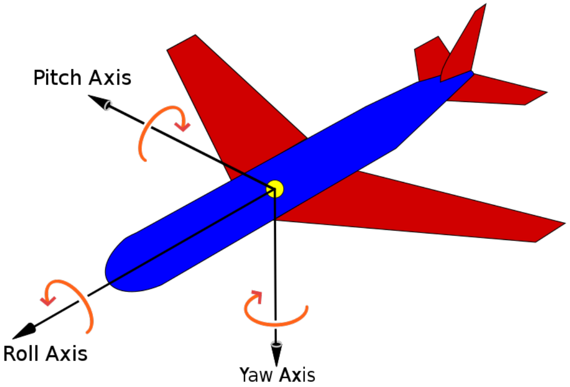


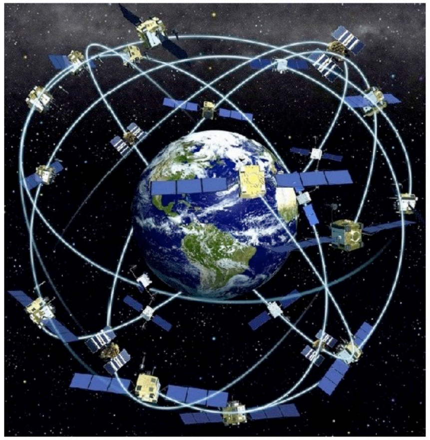

Squeezed light

*www.ligo-india.in*

# Quantum Sensors

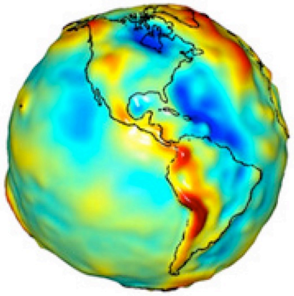



- Rotations, accelerations, Gravity etc.
- Magnetic fields
- Electric fields (AC,DC)
- Time measurement



GPS

MEG



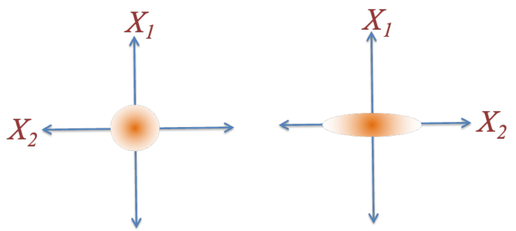
Geodesy

wikipedia

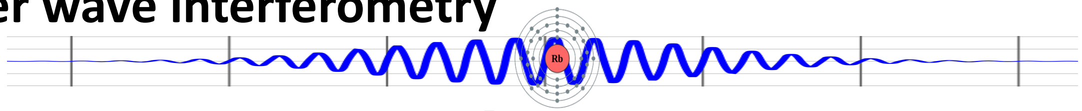
# Quantum Sensors

## Quantum features

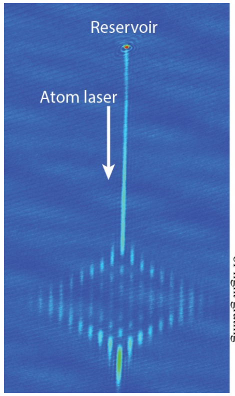
- **Standard Quantum Limit (SQL) → Sensitivity $\propto \sqrt{N}$**



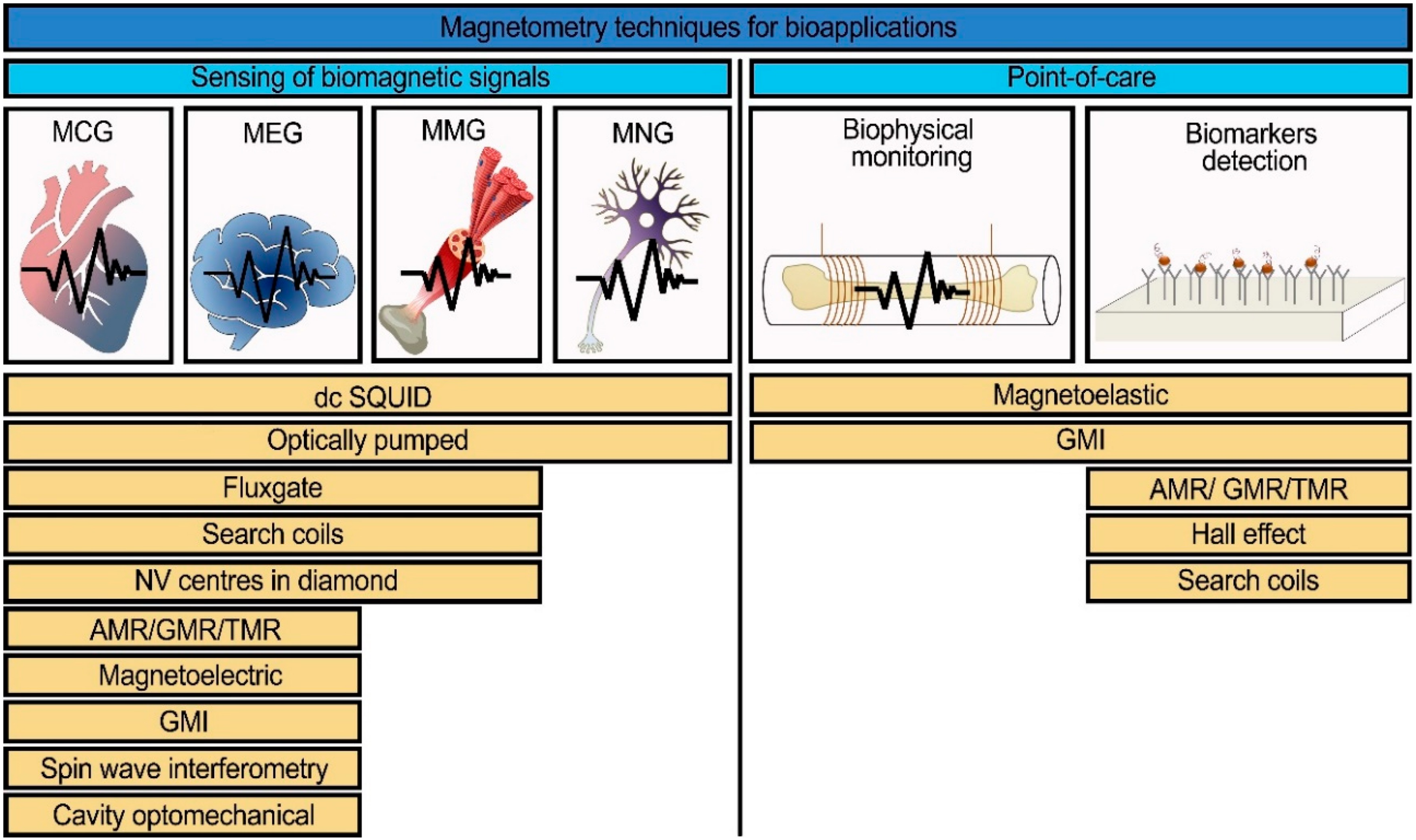

- **Squeezing → beyond shot noise**
- **Wave-particle duality → matter wave interferometry**




- **Precision Spectroscopy with single quantum object → Atomic clocks, NV centers**
- **Use of entangled quantum states → Imaging, sensitivity enhancement**
- **Quantum Tunneling → SQUIDs**

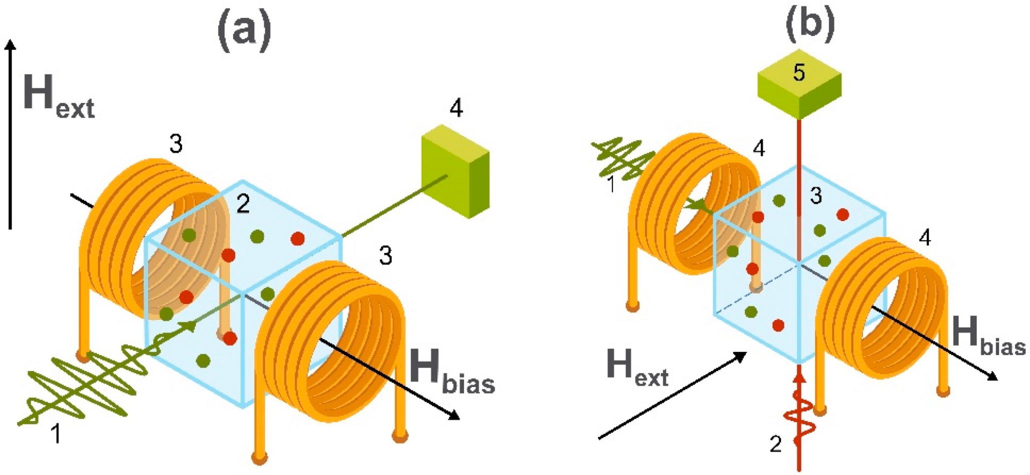


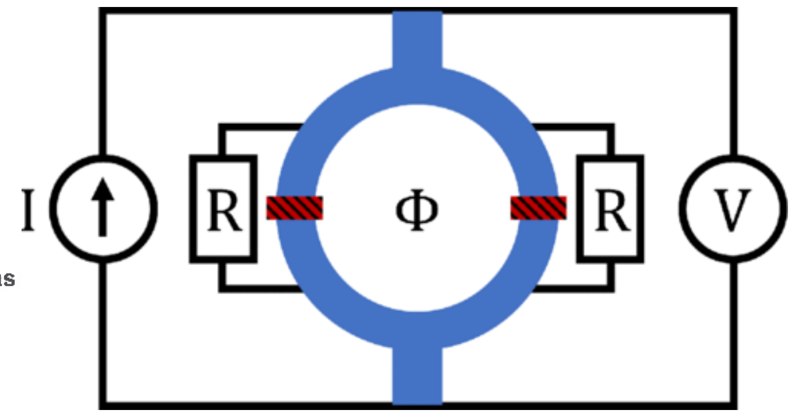
# Magnetic sensors for healthcare




*Sensors* **2020**, *20*(6), 1569; https://doi.org/10.3390/s20061569

# Magnetic field sensing




Atomic Magnetometers

$$\propto 10 \text{ f T}/\sqrt{(Hz)}$$

*Room temperature*

*Sensors* **2020**, *20*(6), 1569

Squid Sensor

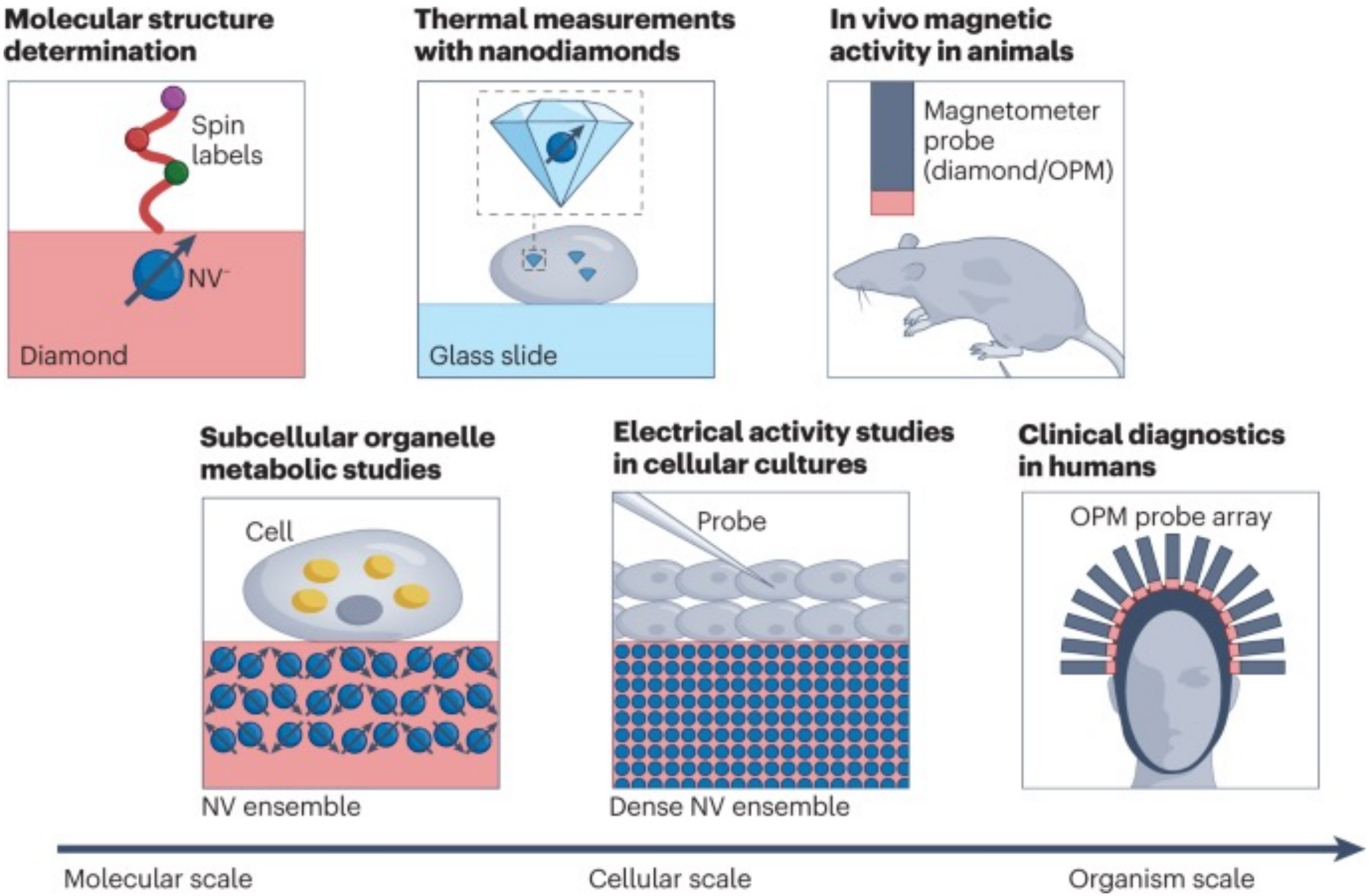
$$\propto 1 \text{ f T}/\sqrt{(Hz)}$$

*Cryogenic*

*Rev. Mod. Phys.* ***92****, 021001*

# Magnetic field sensing

NV centers




*Nature Reviews Physics* **5**, 157 (2023)

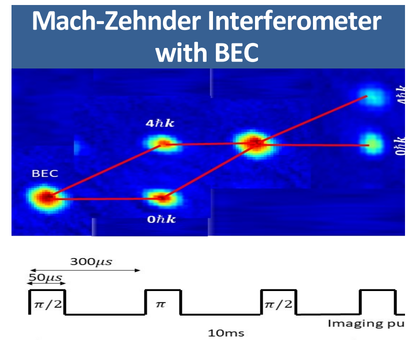
# Quantum sensors: Atomic sensors

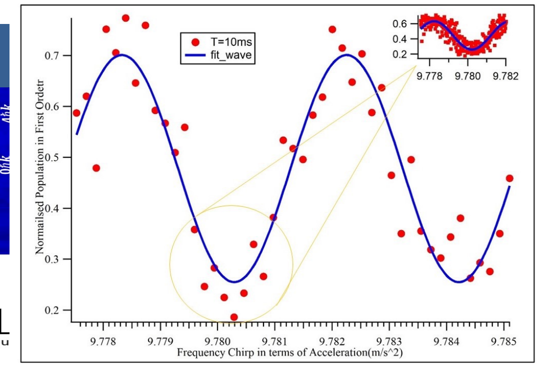
- Matter wave interferometry → gravity, rotation, magnetic field, time

  - Infrastructure
  - Climate research
  - Geophysics
  - Underground Aquifiers investigations
  - Oil and Gas
  - Prewarning of earthquakes/volcanoes

- Atomic magnetometers

  (cold atoms, thermal vapor)




Interferogram time
T = 10 ms

| T(ms) | $\left(\frac{\Delta g}{g}\right)_{limit}$ | $\frac{\Delta g}{g}$ |
|---|---|---|
| 10 | $9.4 * 10^{-7}$ | $2 * 10^{-6}$ |

Current Sensi
~200 micro-g

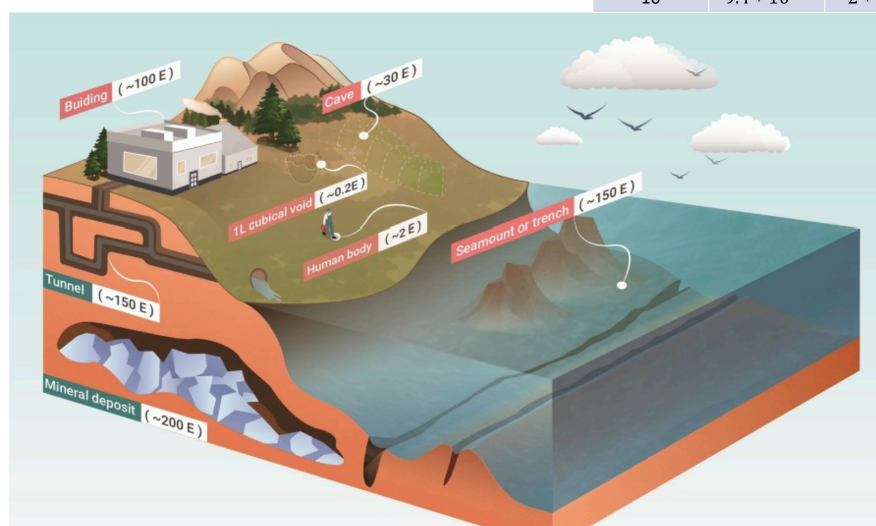
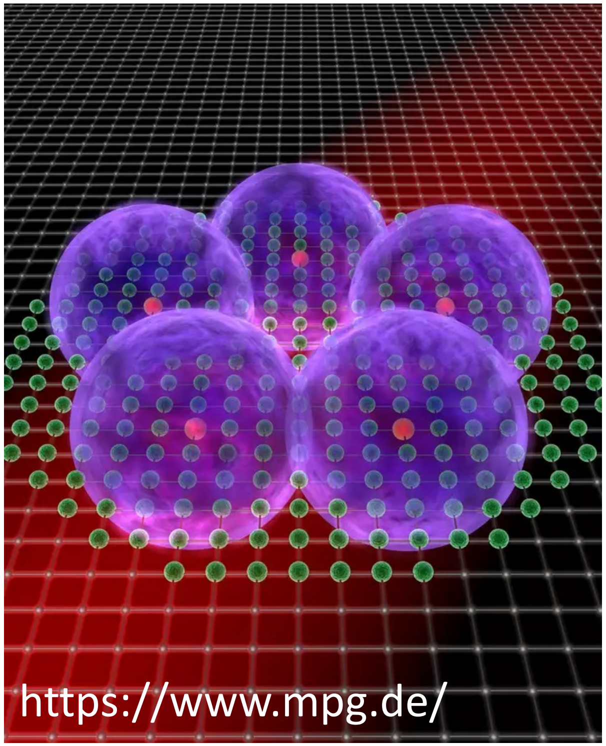



Illustration: Richard Lane -- Geo- science Australia

# Quantum sensors: Atomic sensors

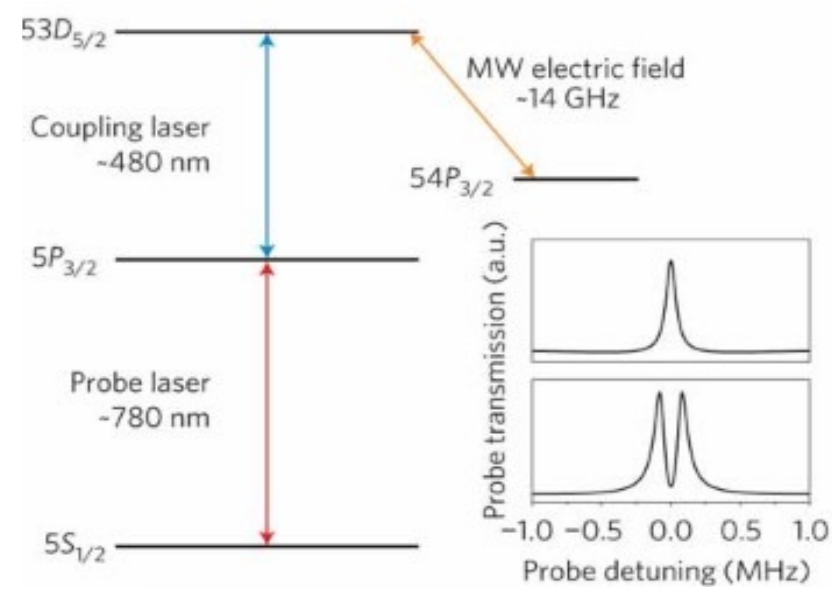


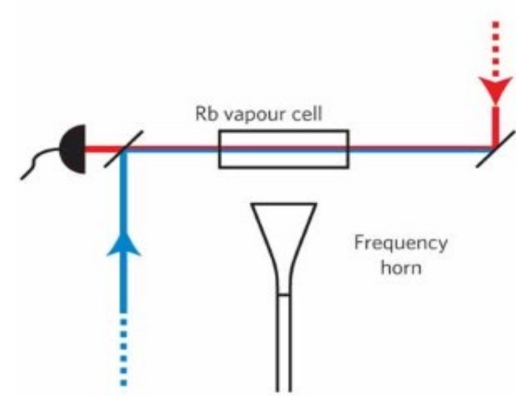

Use of 'Super Atoms'

Atoms excited to highly excited states

*Space and time resolved measurement of electric field*

## Rydberg Electrometry

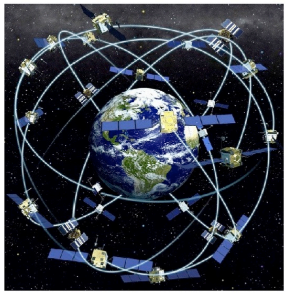


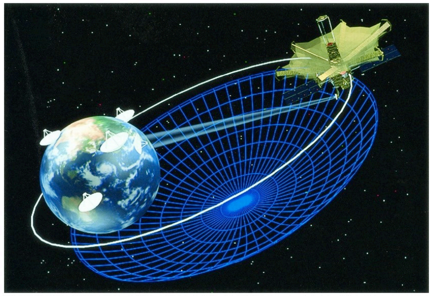

*Nature Physics* **volume 8**, pages 819–824 (2012)

# Quantum sensors: Atomic clocks

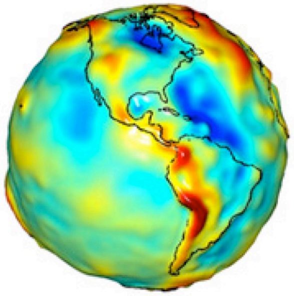
## Applications of precise clocks



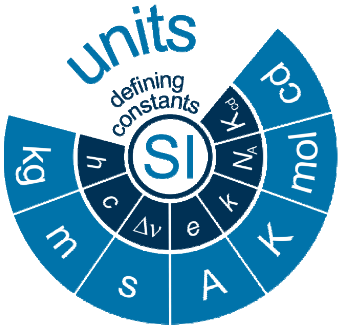
GPS



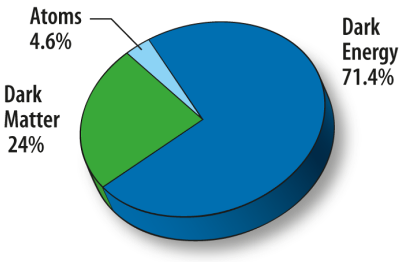
Very long baseline interferometry



Relativistic geodesy



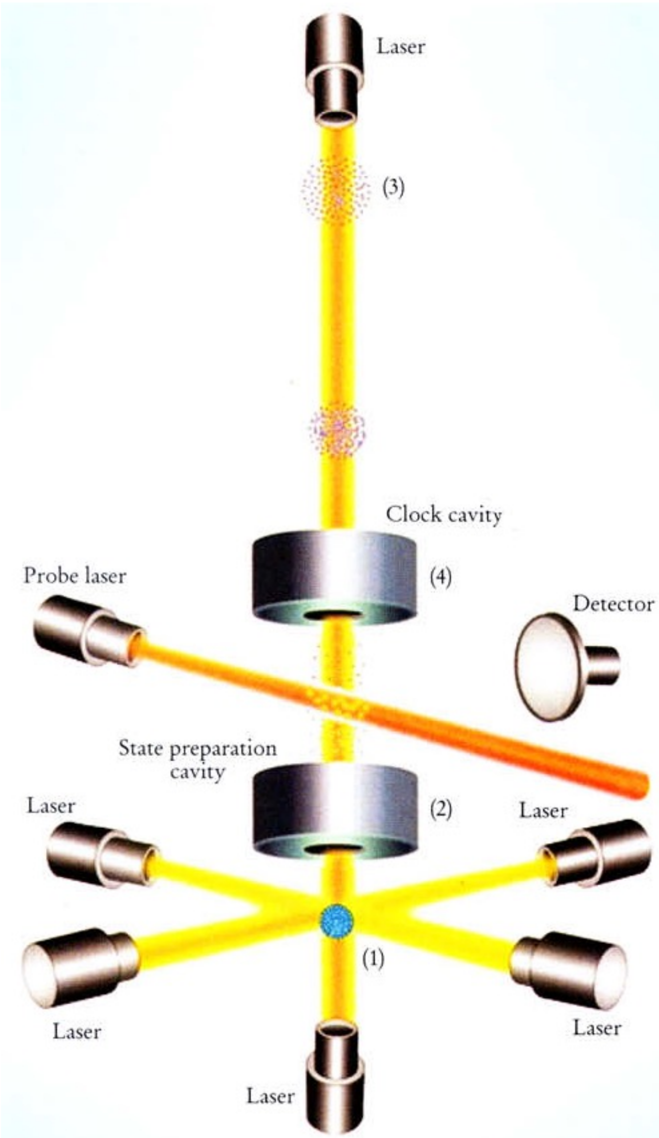

Definition of the second




Search for physics beyond the standard model

Picture credit: Marianna Safronova, University of Delaware

# Current Time standard: Cs Fountain clock




1 s = 9.192 631 770 GHz

≅ Ground state hyperfine splitting of $^{133}Cs$

$F = 3, m_F = 0 \leftrightarrow F = 4, m_F = 0$

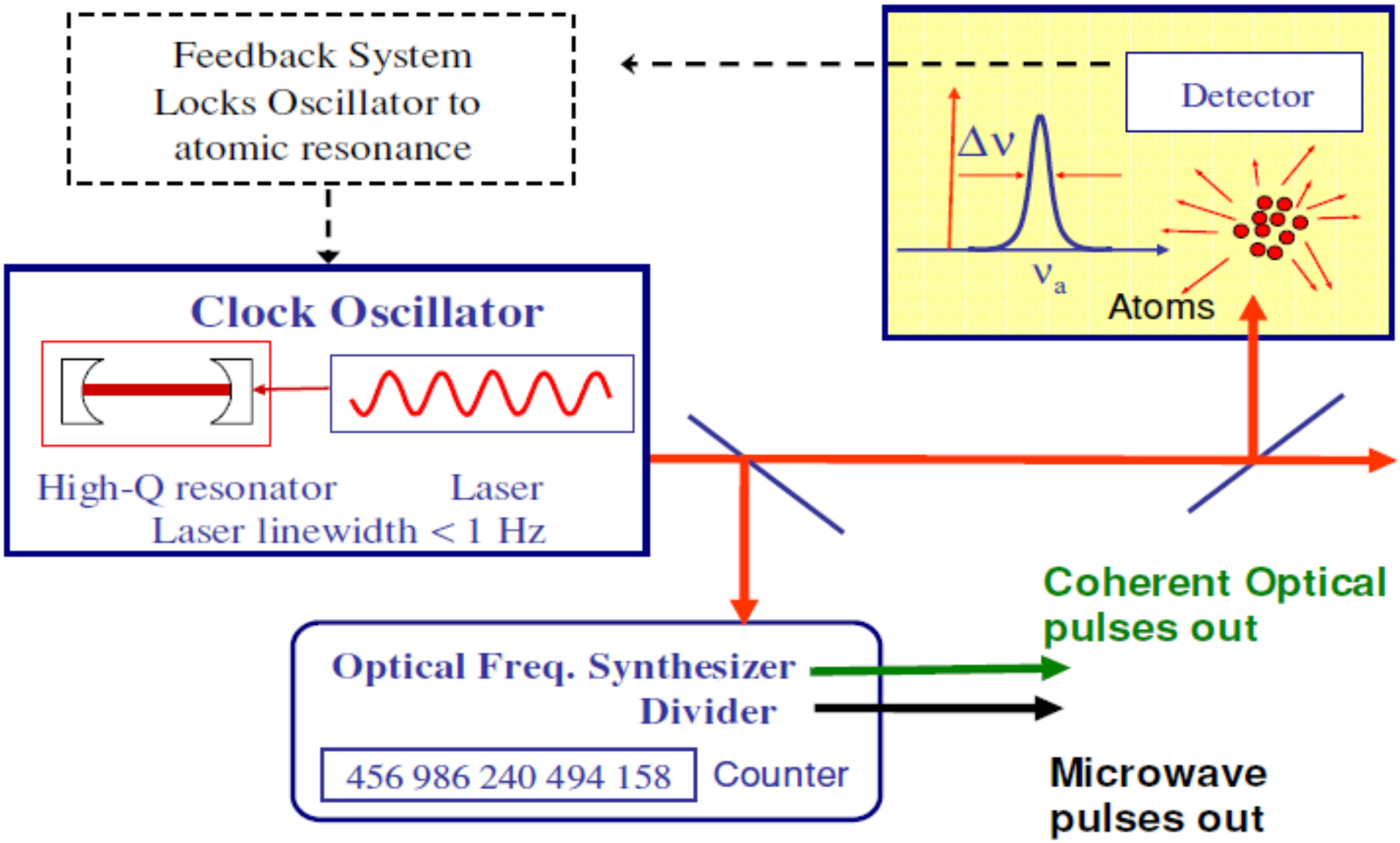
Best Cs fountain clock → NIST-F1

Fractional instability ~ **4 e-16**

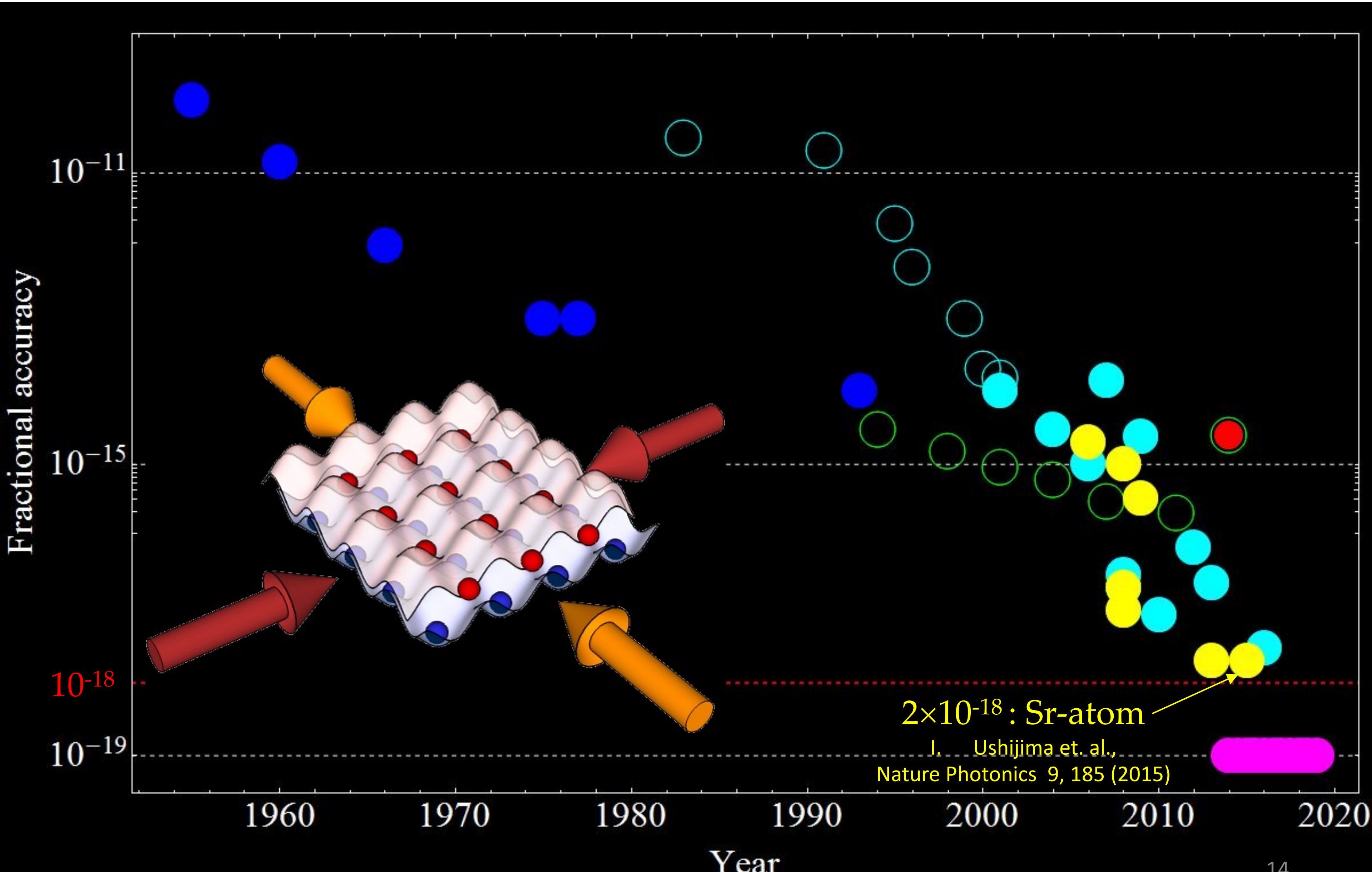
Projected fractional instability ~5 X $10^{-17}$

$$\frac{\Delta\nu}{\nu}\ \frac{1}{S/N}$$

# Modern Optical Frequency standard



# International status of the optical atomic clocks



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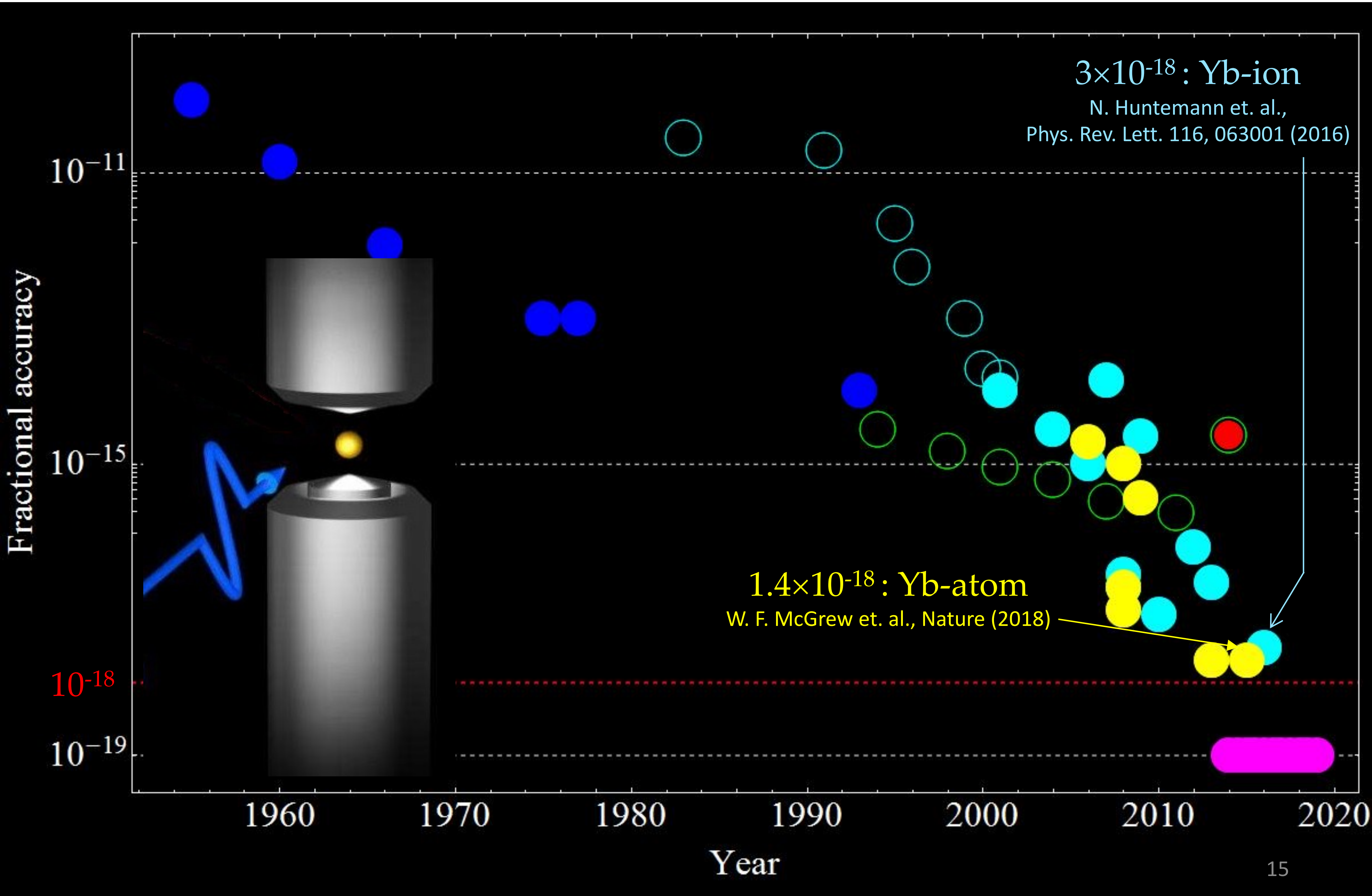

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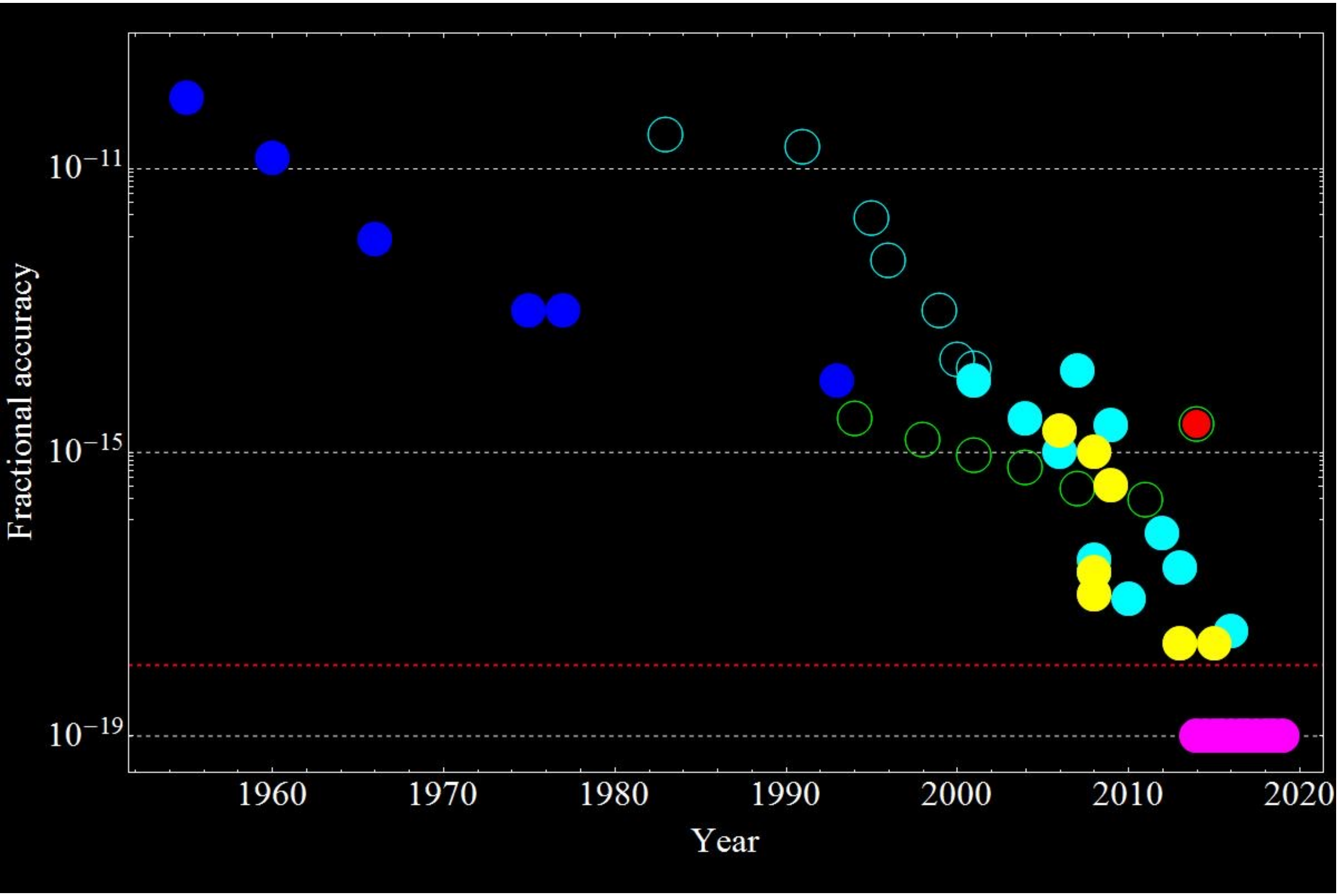


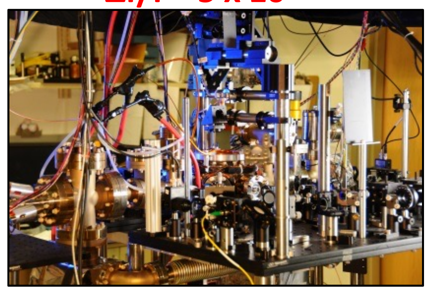

$7.6 \times 10^{-21} \rightarrow 2022$

*Nature* **volume 602**, pages 420–424 (2022)

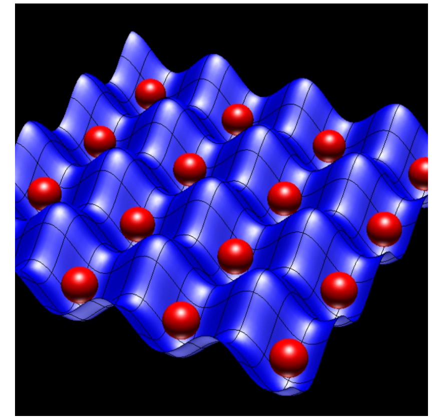
# Candidate species

| | | | |
|---|---|---|---|
| $Al^+$ | 1124 THz | } | Ions |
| $Hg^+$ | 1064 THz | | |
| Yb | 520 THz | } | Neutrals |
| Ca | 456 THz | | |
| Sr | 429 THz | | |
| Cs | 0.0092 THz | | |

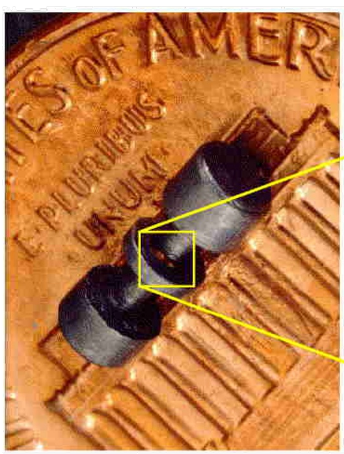
**$\Delta f/f \sim 5 \times 10^{-19}$**



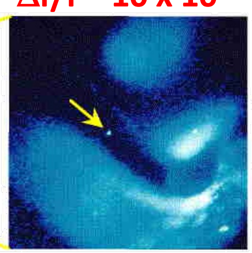
**Sr or YB optical lattice clocks**



**Single Hg ion trap**

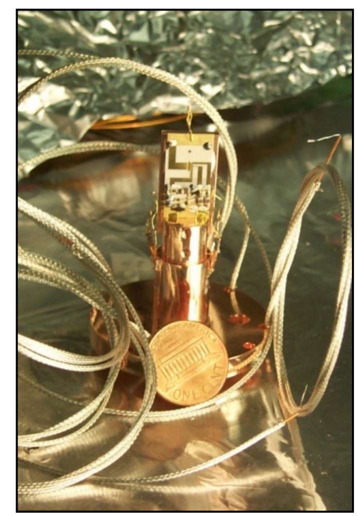


**$\Delta f/f \sim 10 \times 10^{-18}$**



**$\Delta f/f \sim 9 \times 10^{-19}$**

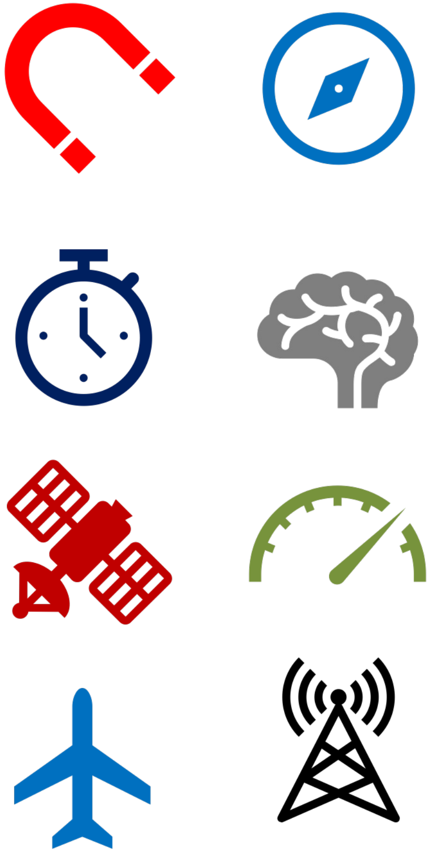
**Al ion logic clock**



W. H. Oskay et al.,Phys. Rev. Lett. 97, 020801 (2006)
J.-S. Chen et al, Phys. Rev. Lett. 118, 053002 (2017)
S. L. Campbell, Science 358, 90–94 (2017).

# Summary

- Quantum resources → to surpass classical systems' noise
- Controllable systems with immunity to environmental noise
- Wide ranging applications → healthcare, geophysics, navigation, communications etc.



Thank you