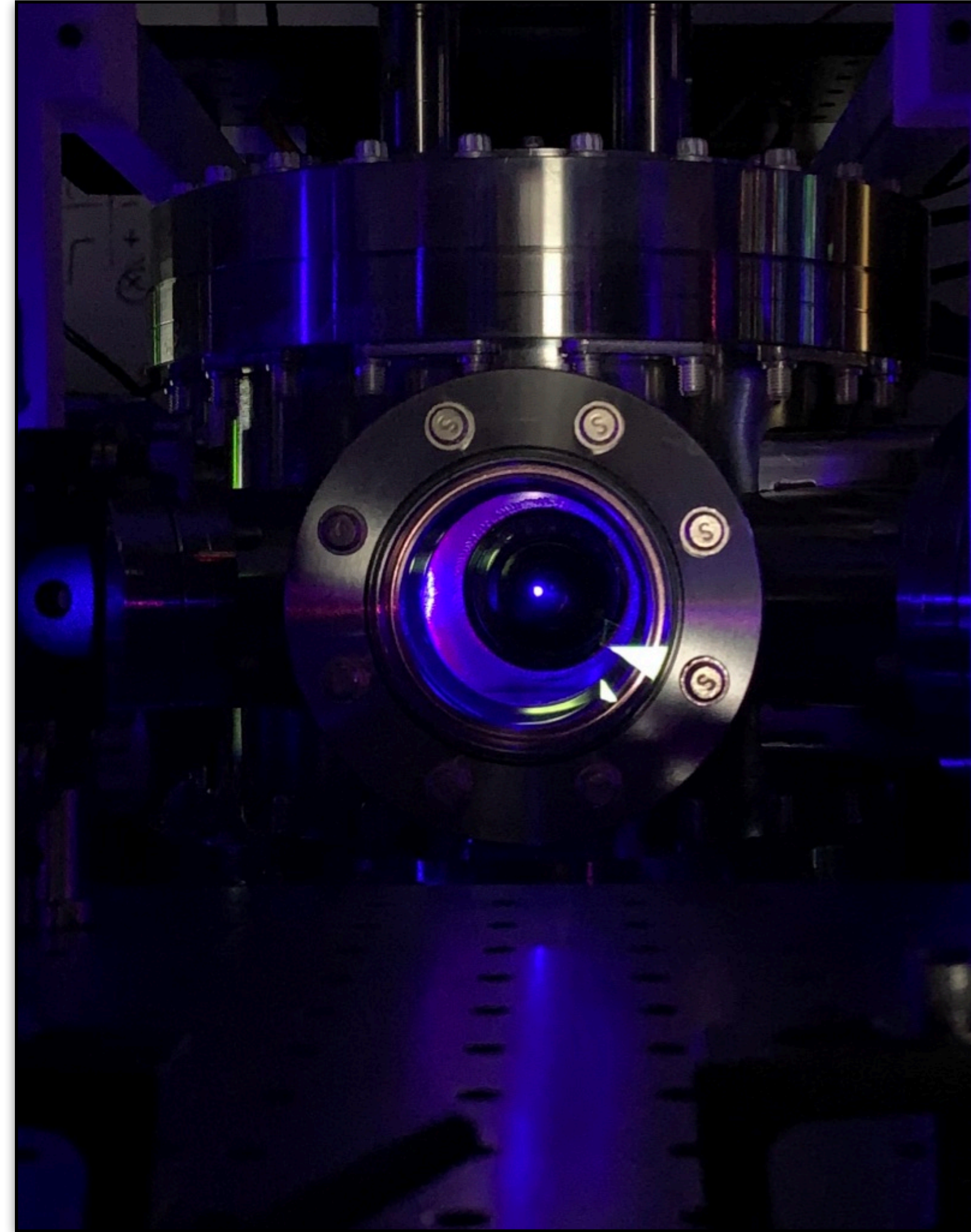
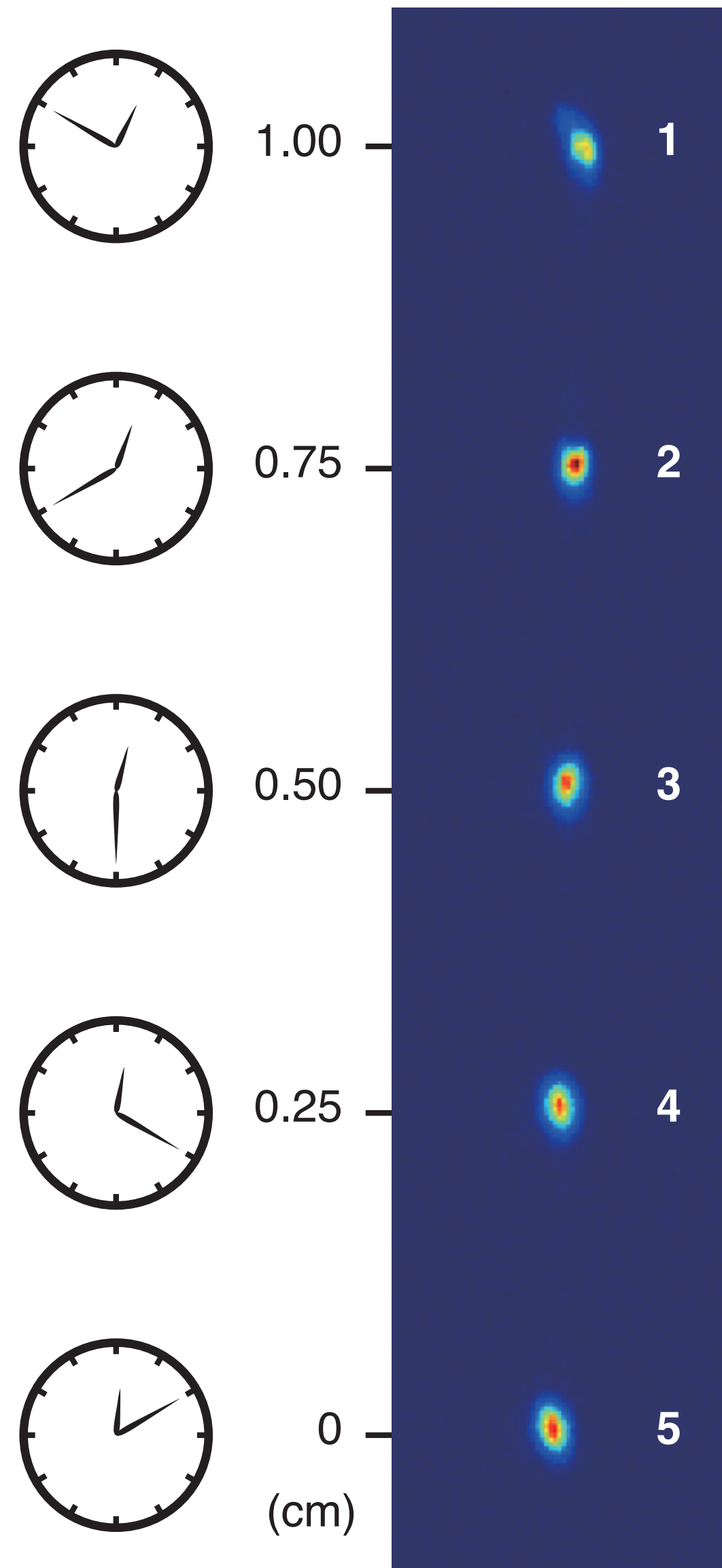
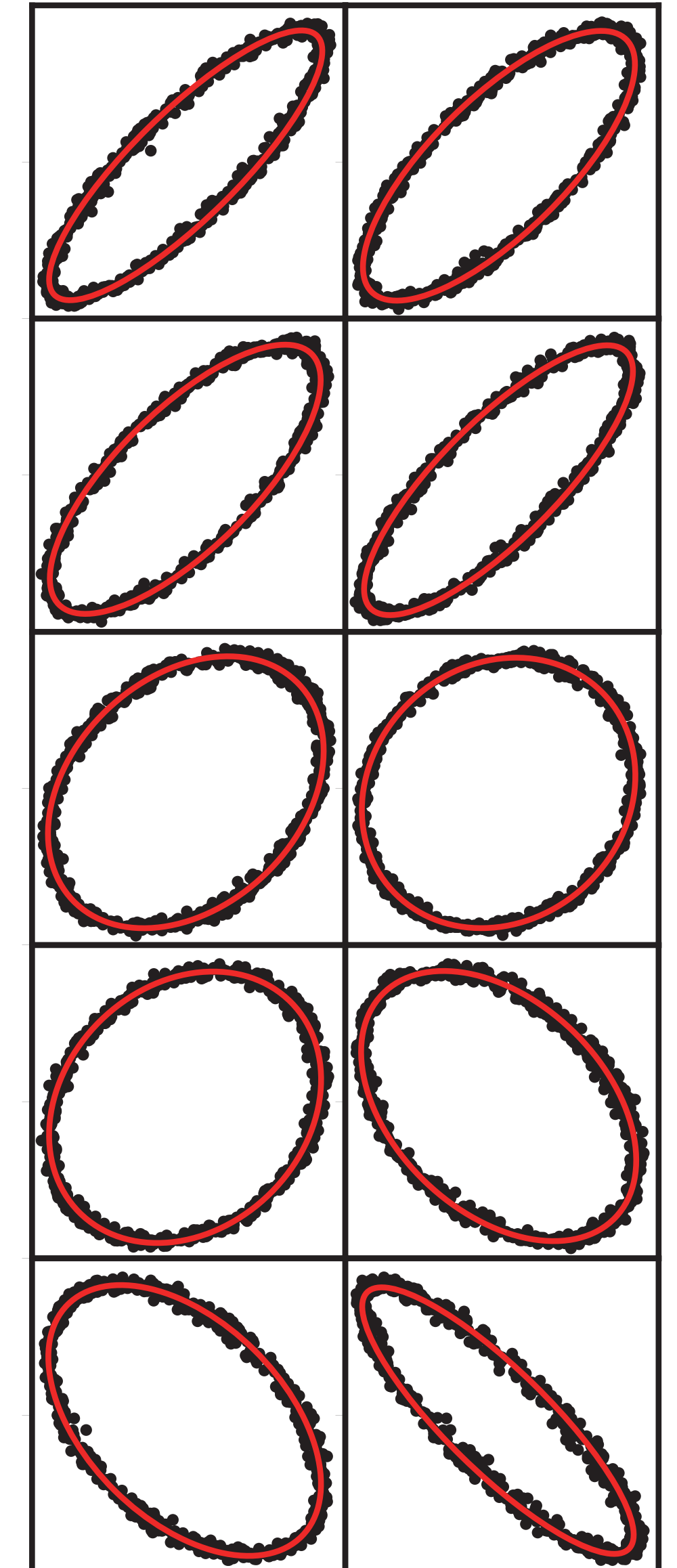


# Precision Clocks: Techniques, Advances in Technology, and Applications for Fundamental Physics Experiments



Shimon Kolkowitz  
UC Berkeley





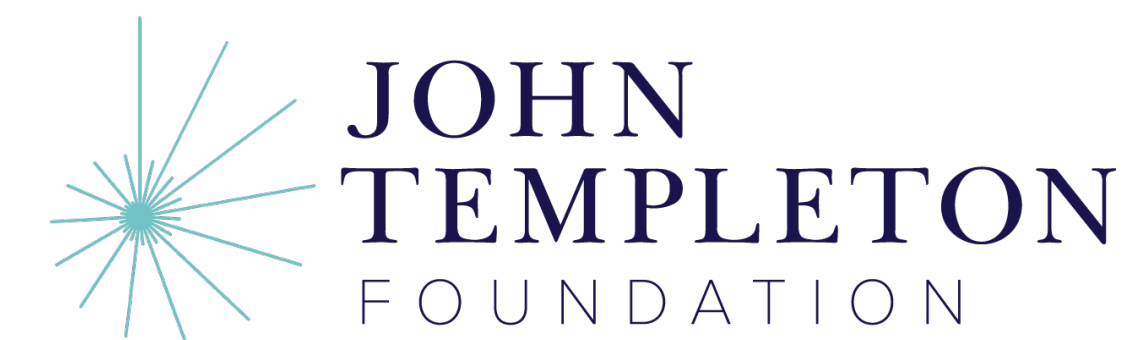
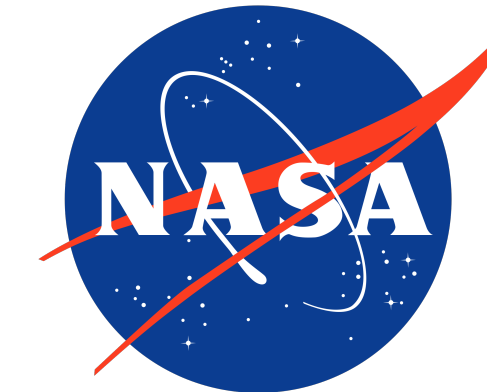
# Acknowledgements



[Xin Zheng], Bennett Christensen, Jack Dolde, Matt Cambria, Eric Gedimen, Sean Xu, Saroj Chand, SK, Dhruva Ganapathy, Shuo Ma, Anke Stoeltzel, Jenny Chen, Manasa Sriraj



This work was supported by the Gordon and Betty Moore Foundation, grant DOI 10.37807/gbmf12966.





# Science with optical clocks on the moon:

- Precision navigation and timing
- Very long baseline interferometry
- Tests of the gravitational redshift and relativity, geodesy of the moon(?)
- Doppler tracking of the moon, gravitational wave detection(?)
- Dark matter searches
- ????????



# Outline

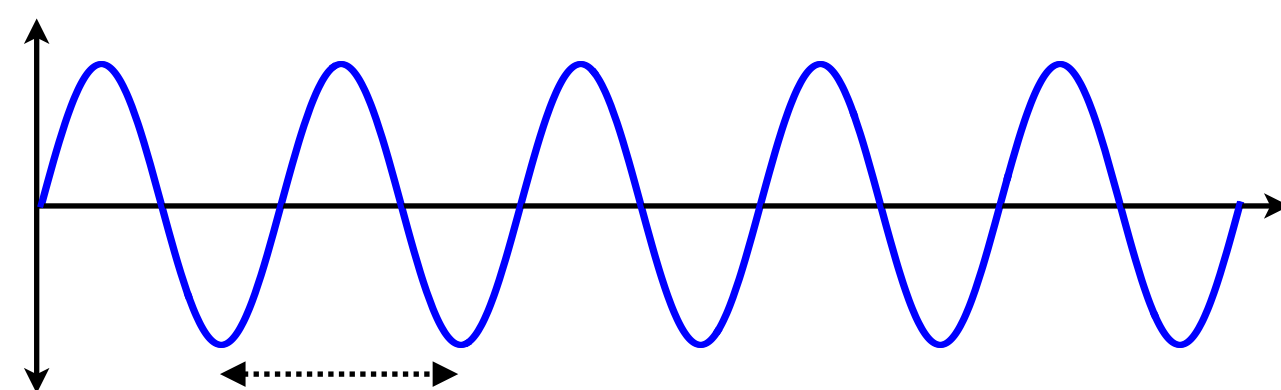
- Introduction to optical atomic clocks
- Optical clocks in space for fundamental physics
- Recent progress and advancements
- Testing relativity in the lab



# Principles of an atomic clock



Counter



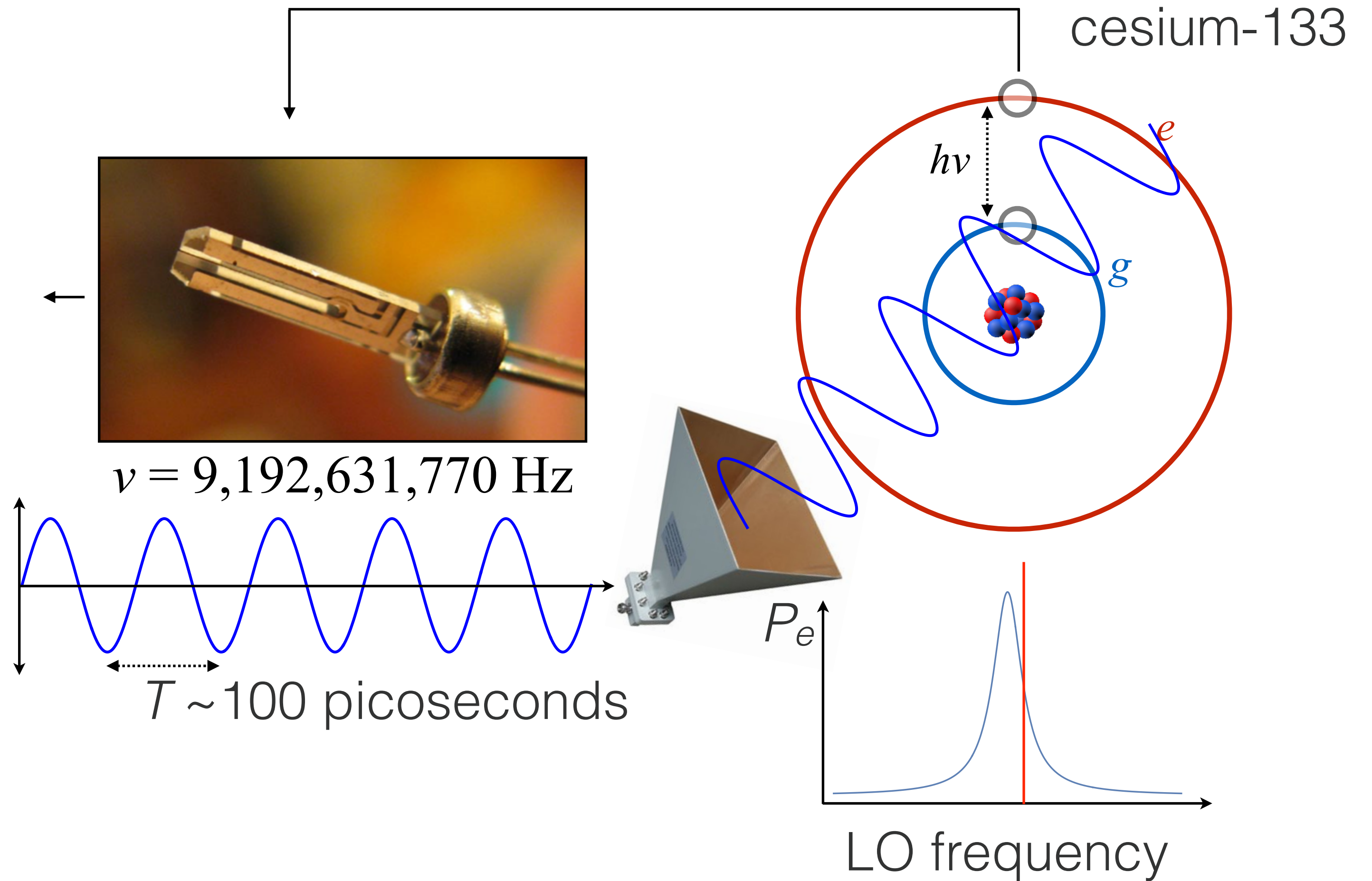
Local oscillator (LO)



# Principles of an atomic clock



Counter



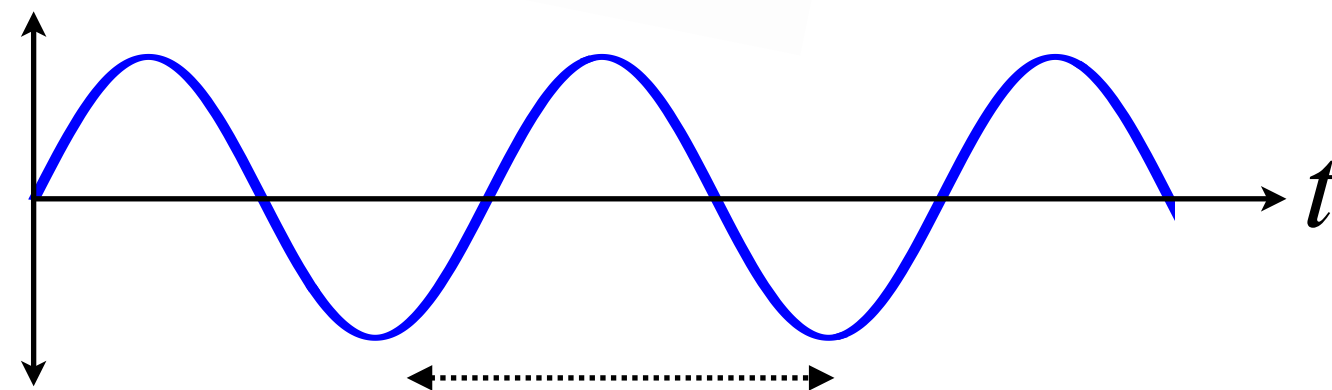
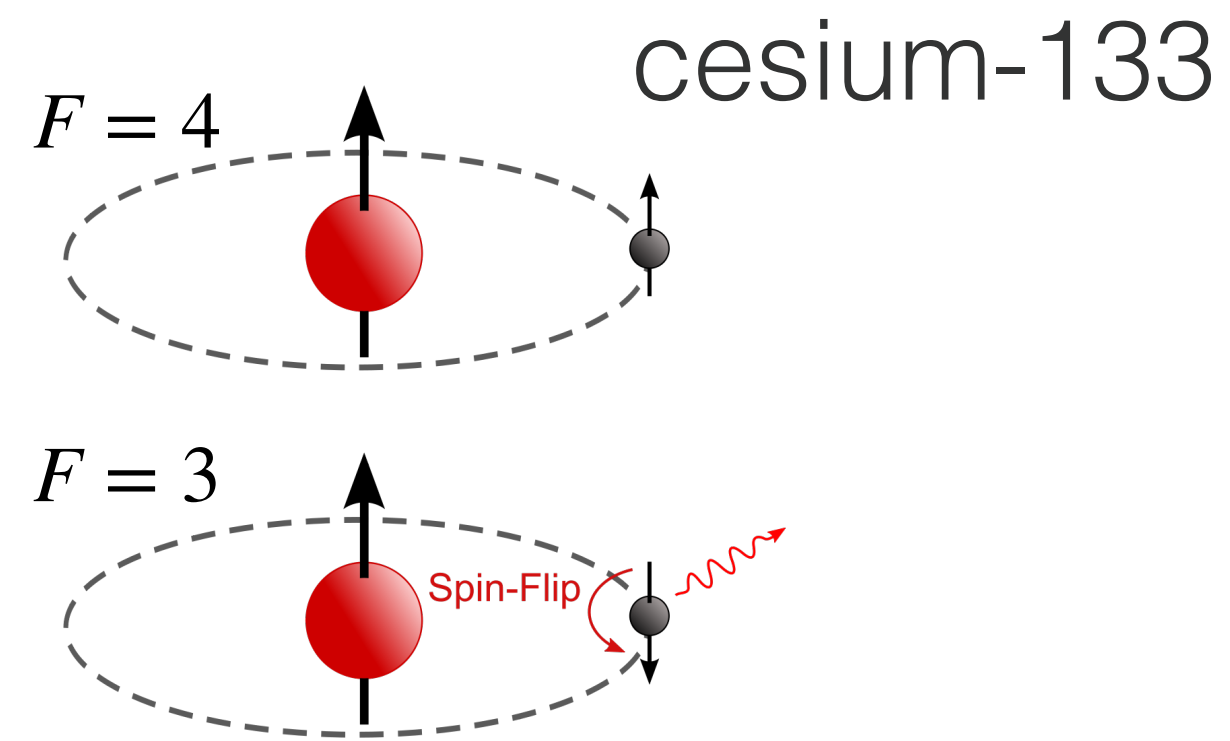
Local oscillator (LO)

Frequency reference



# Clock performance

## Microwave transitions



$T \sim 0.7$  nanoseconds

$\nu = 9,192,631,770$  Hz

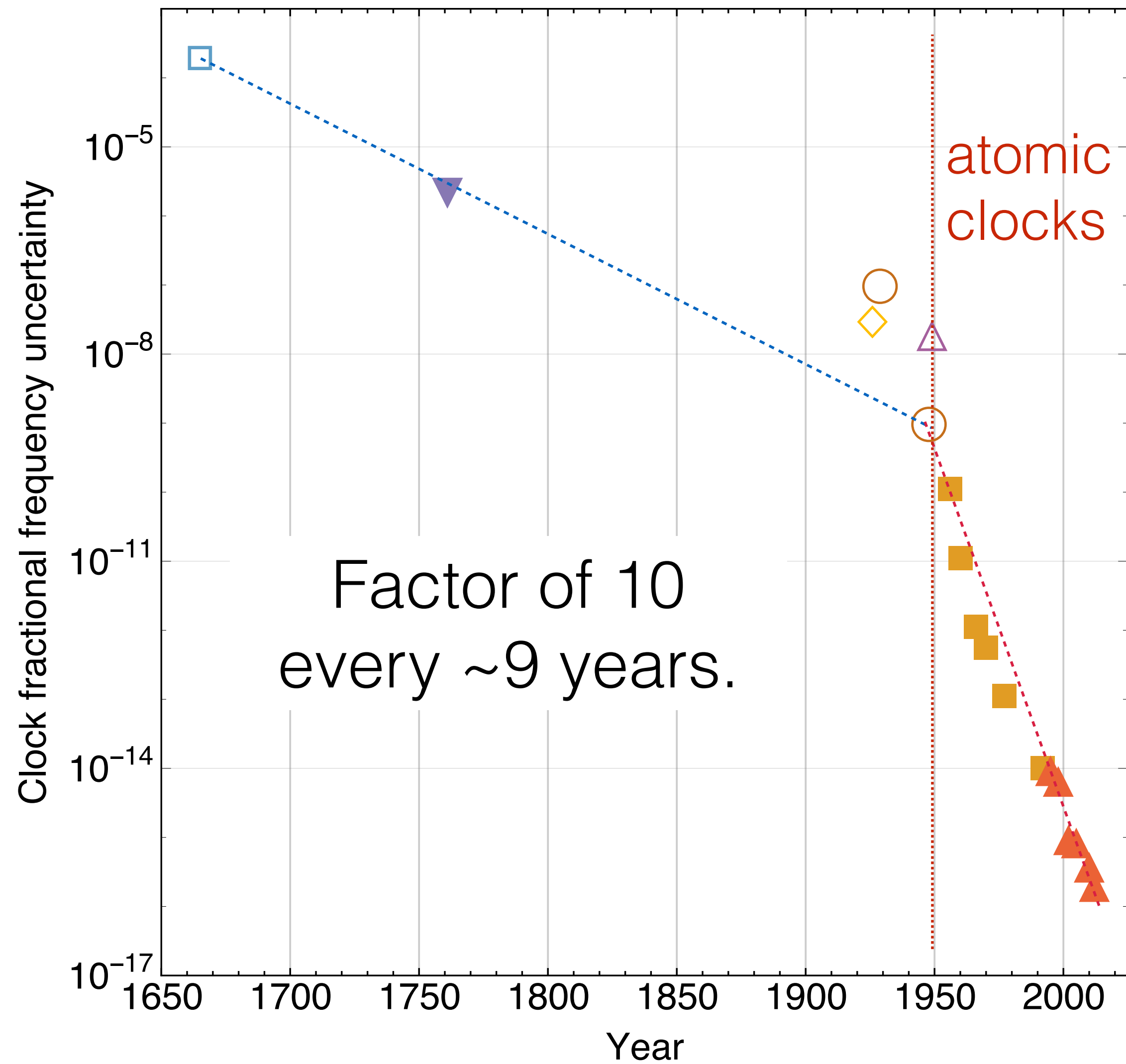
Fractional frequency instability  
from quantum projection noise:

$$\sigma \approx \frac{\delta\nu}{\nu_o} \times \frac{1}{SNR} = \frac{1}{2\pi\nu_o T} \sqrt{\frac{T + T_d}{N_d \tau}}$$



# Clock progress, 1656 - 2016

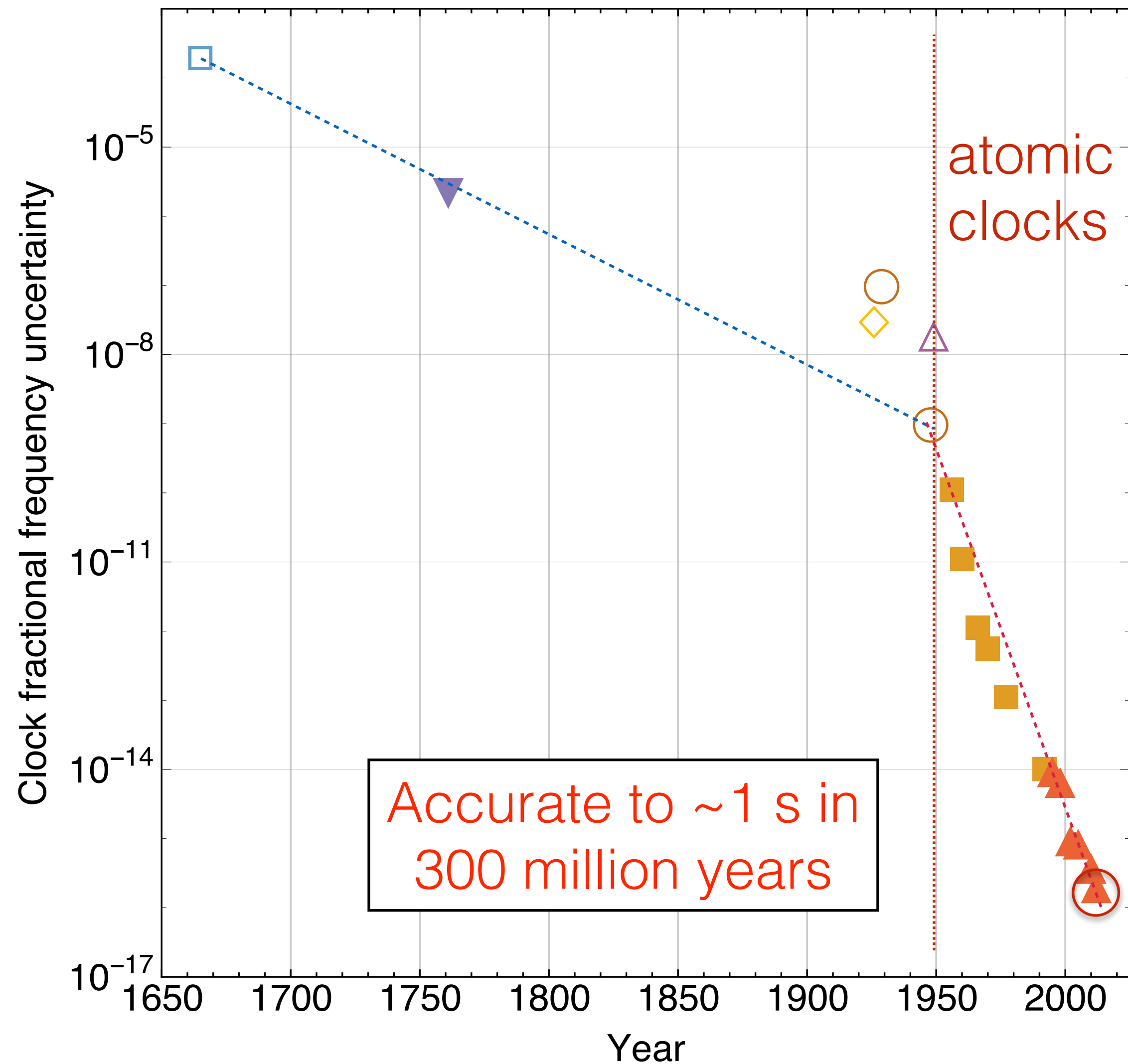
- Huygen pendulum
- ▼ Harrison H4
- ◇ Shortt pendulum
- NBS quartz
- △ Ammonia maser
- Cs beam
- ▲ Cs fountain





# Clock progress, 1656 - 2016

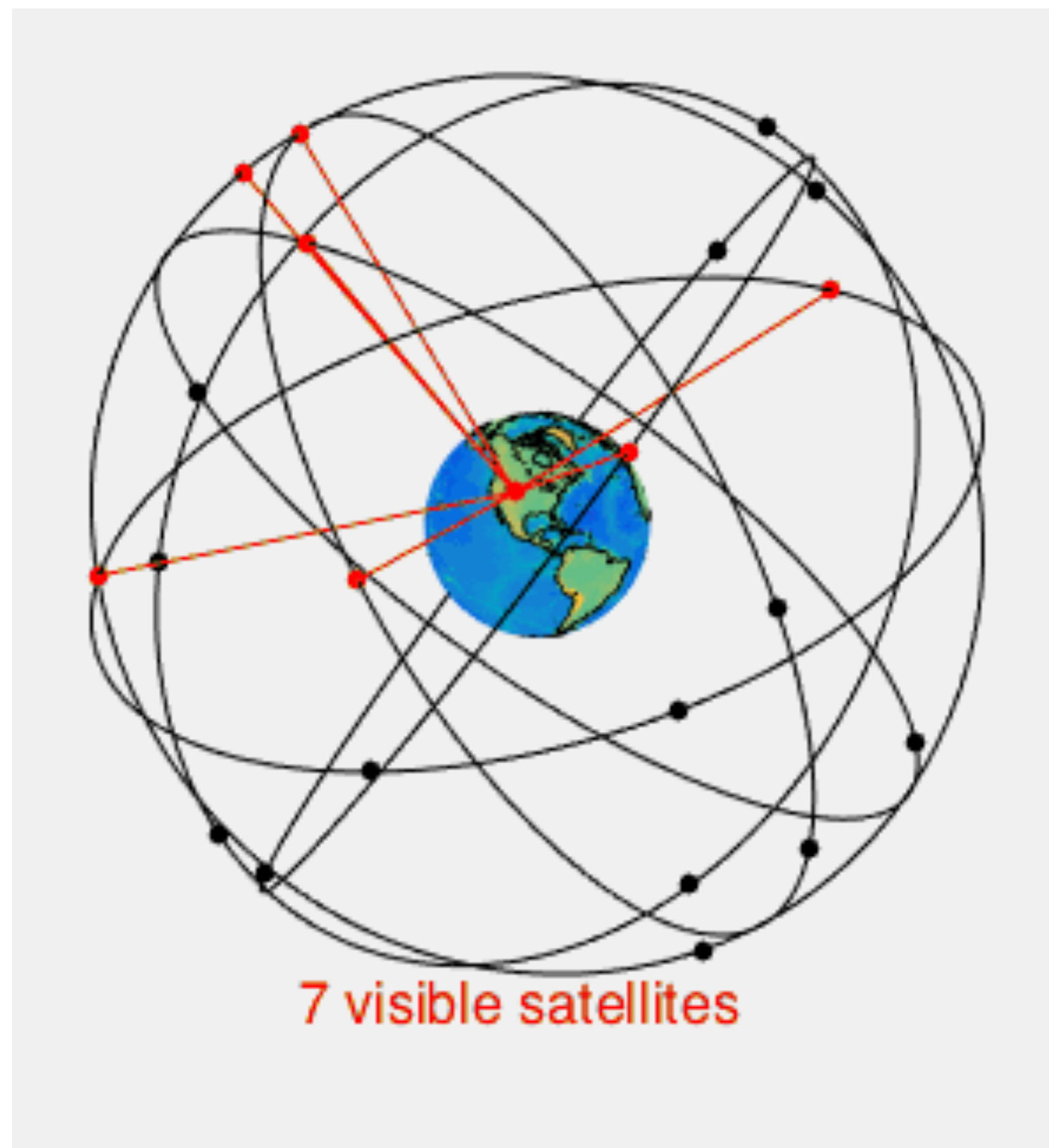
- Huygen pendulum
- ▼ Harrison H4
- ◇ Shortt pendulum
- NBS quartz
- △ Ammonia maser
- Cs beam
- ▲ Cs fountain



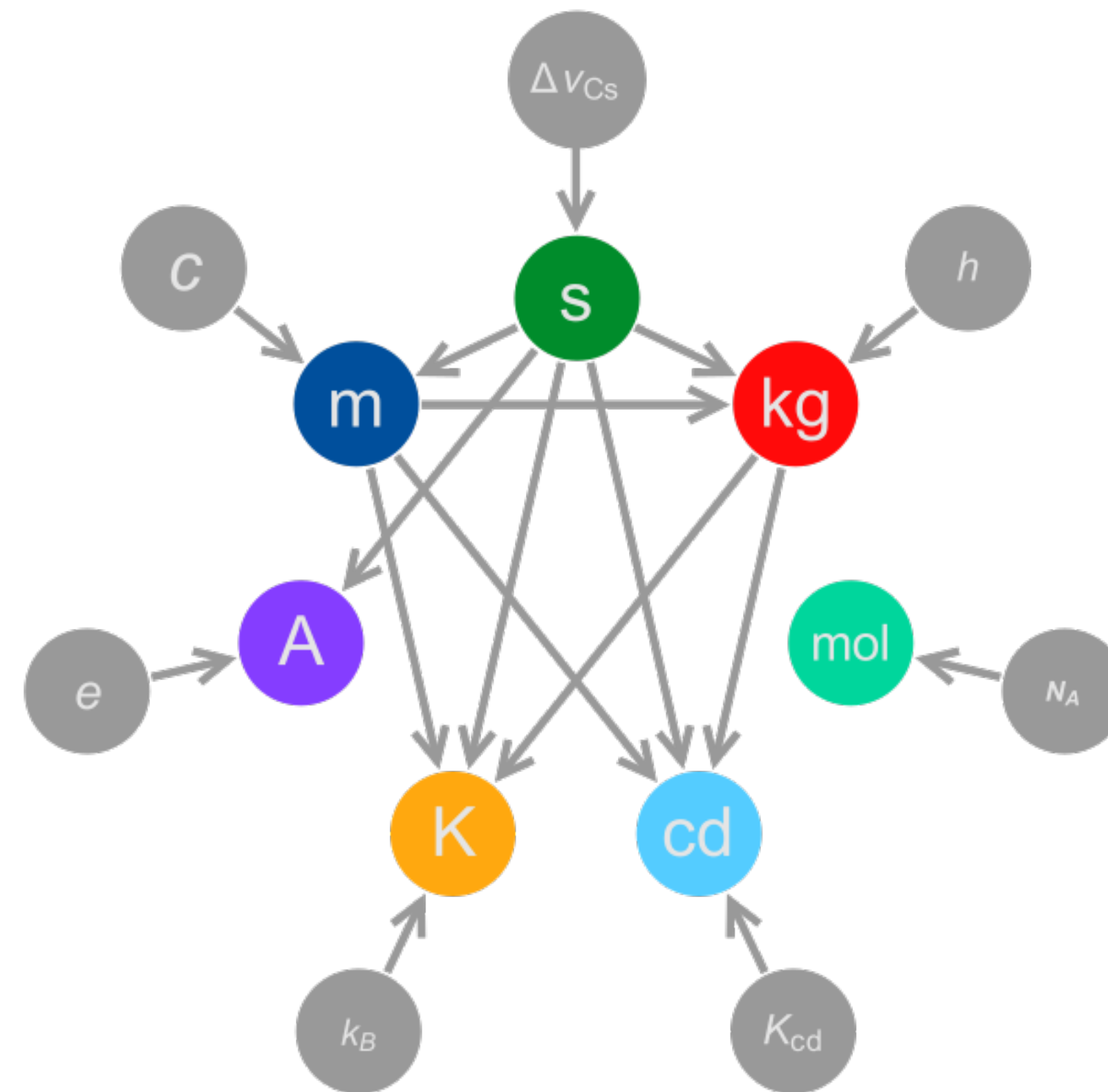


# Traditional atomic clock applications

Navigation:

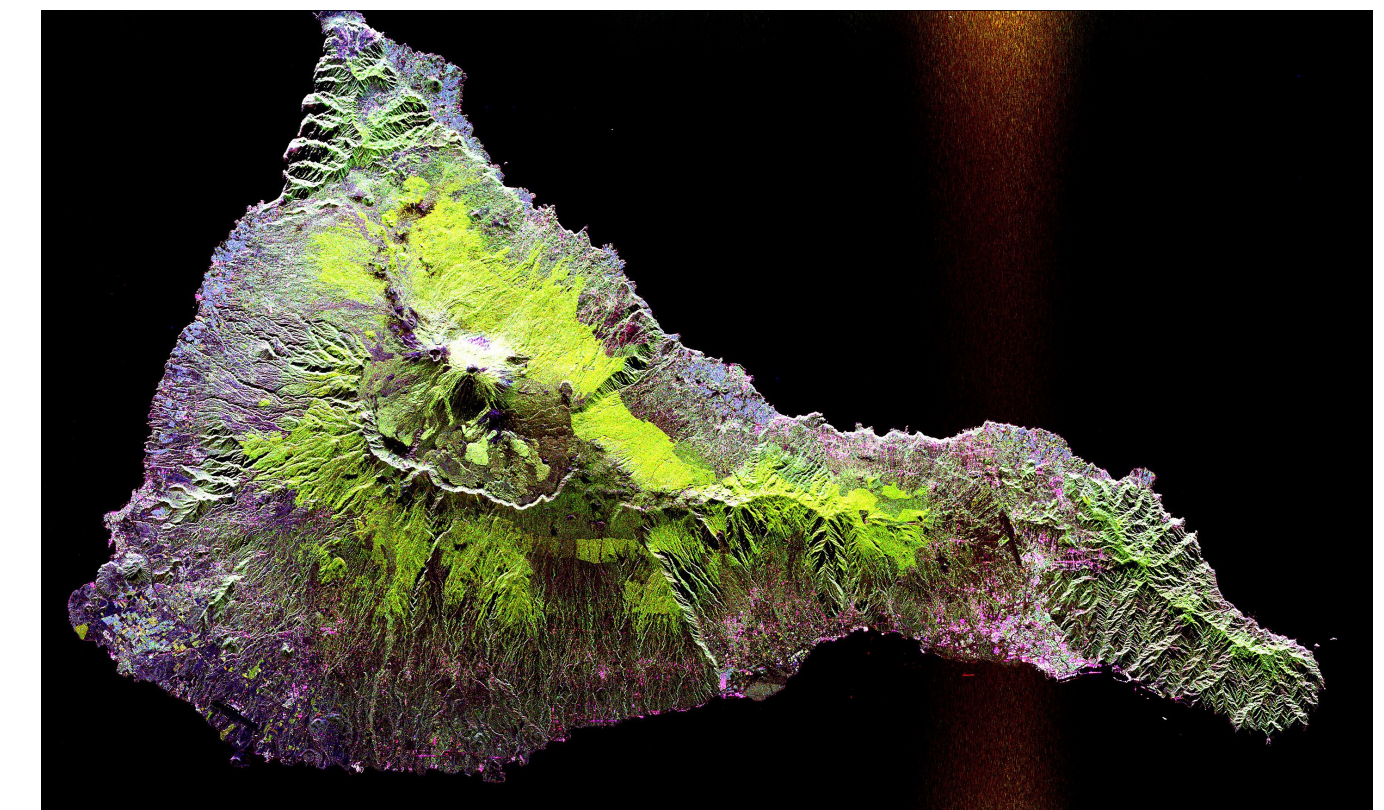
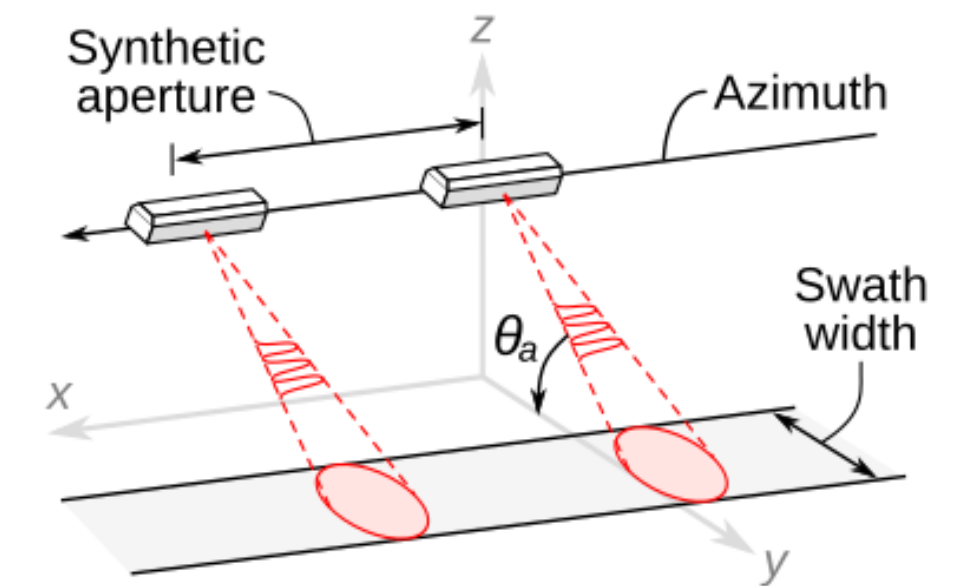


Unit definitions:



Sensing/  
communications:

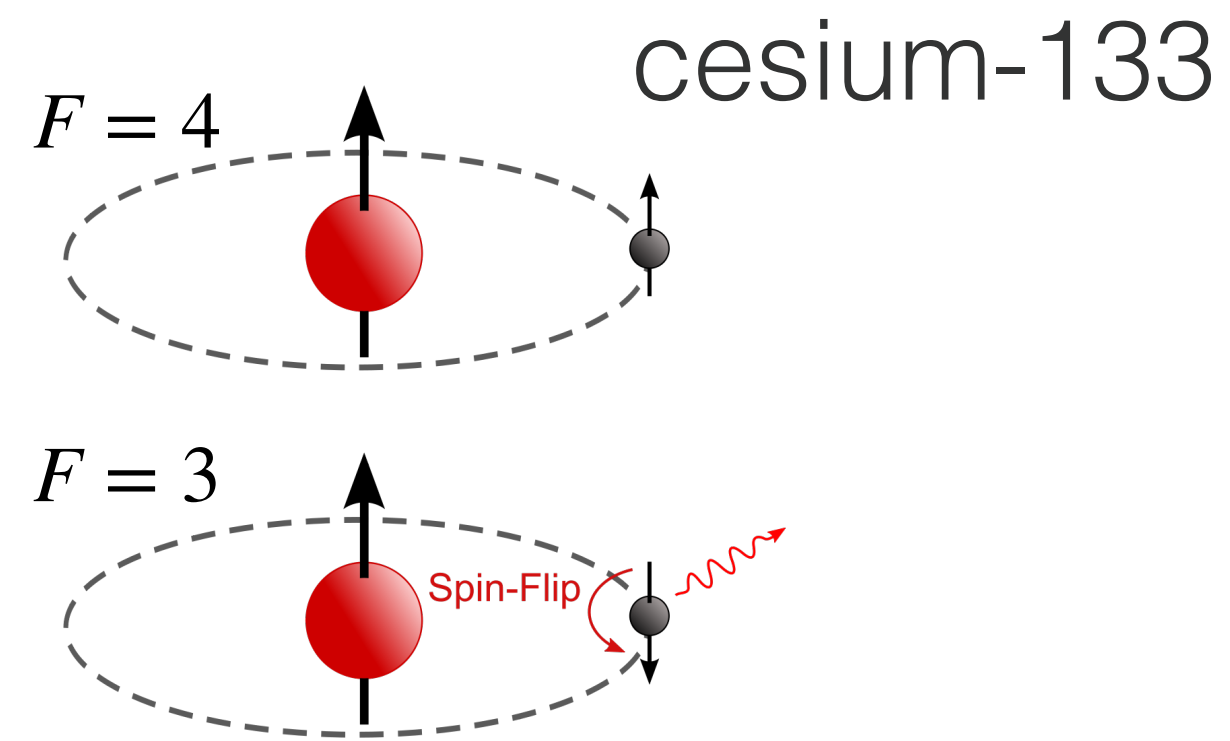
Synthetic aperture radar





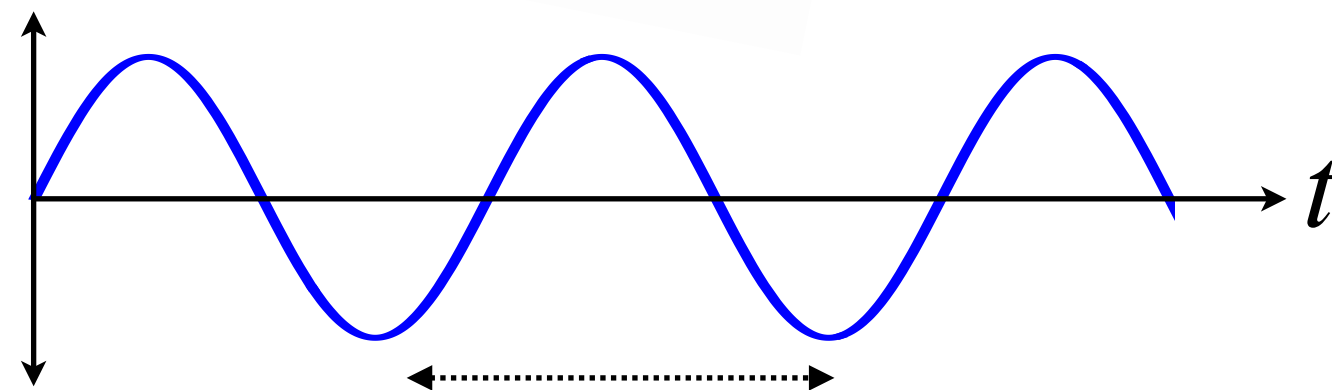
# How can we make an even better atomic clock?

## Microwave transitions



Fractional frequency instability  
from quantum projection noise:

$$\sigma \approx \frac{\delta\nu}{\nu_o} \times \frac{1}{SNR} = \frac{1}{2\pi\nu_o T} \sqrt{\frac{T + T_d}{N_d \tau}}$$



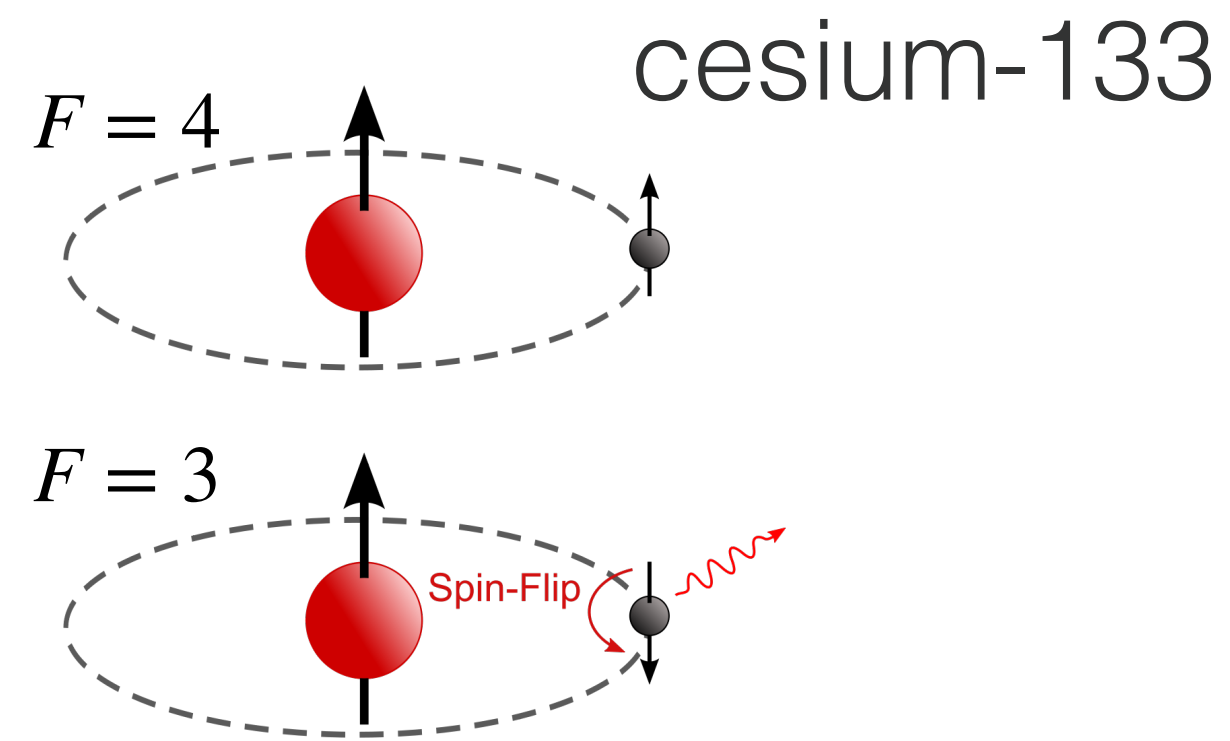
$T \sim 0.7$  nanoseconds

$\nu = 9,192,631,770$  Hz



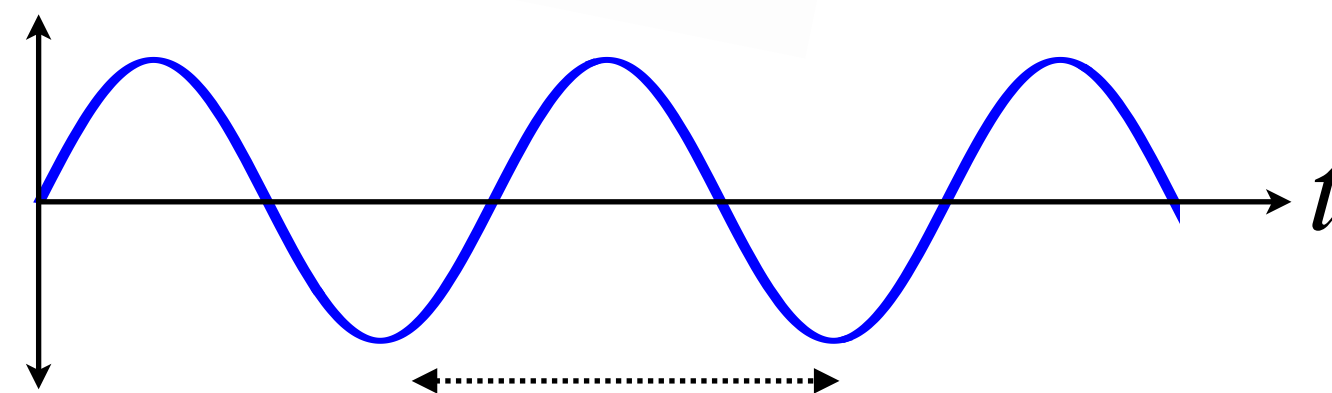
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## Microwave transitions



Fractional frequency instability  
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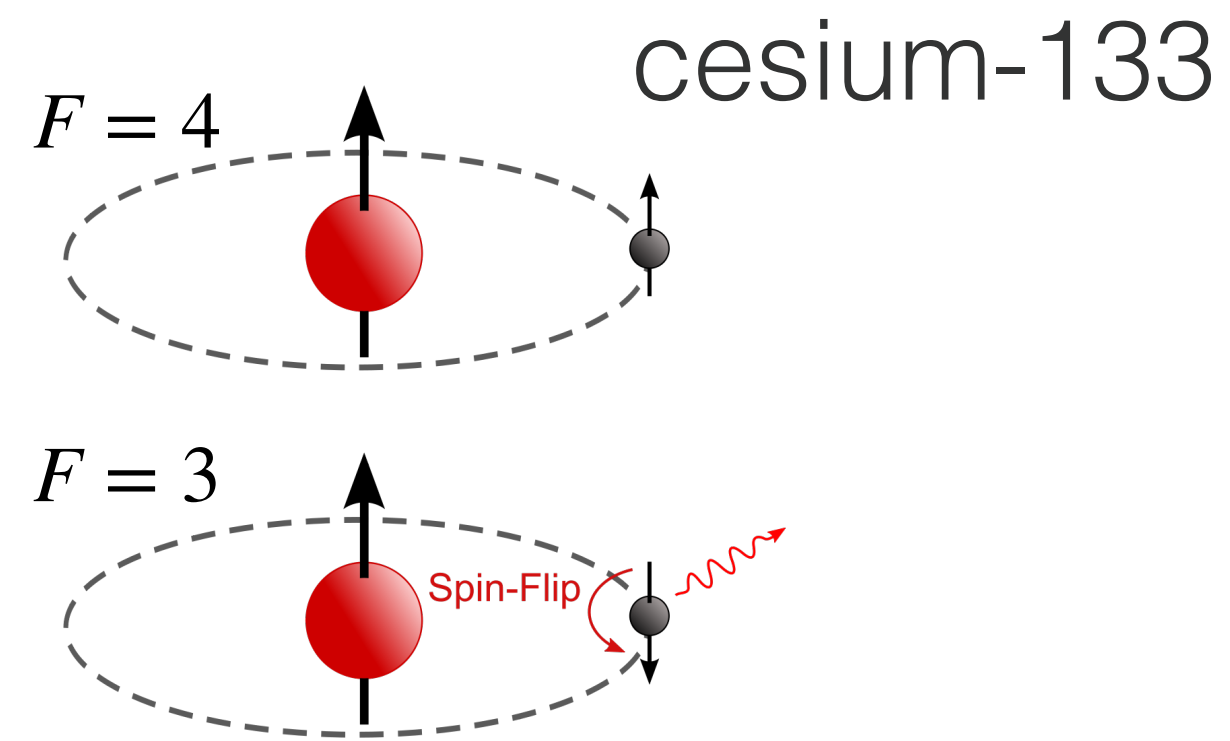
$T \sim 0.7$  nanoseconds

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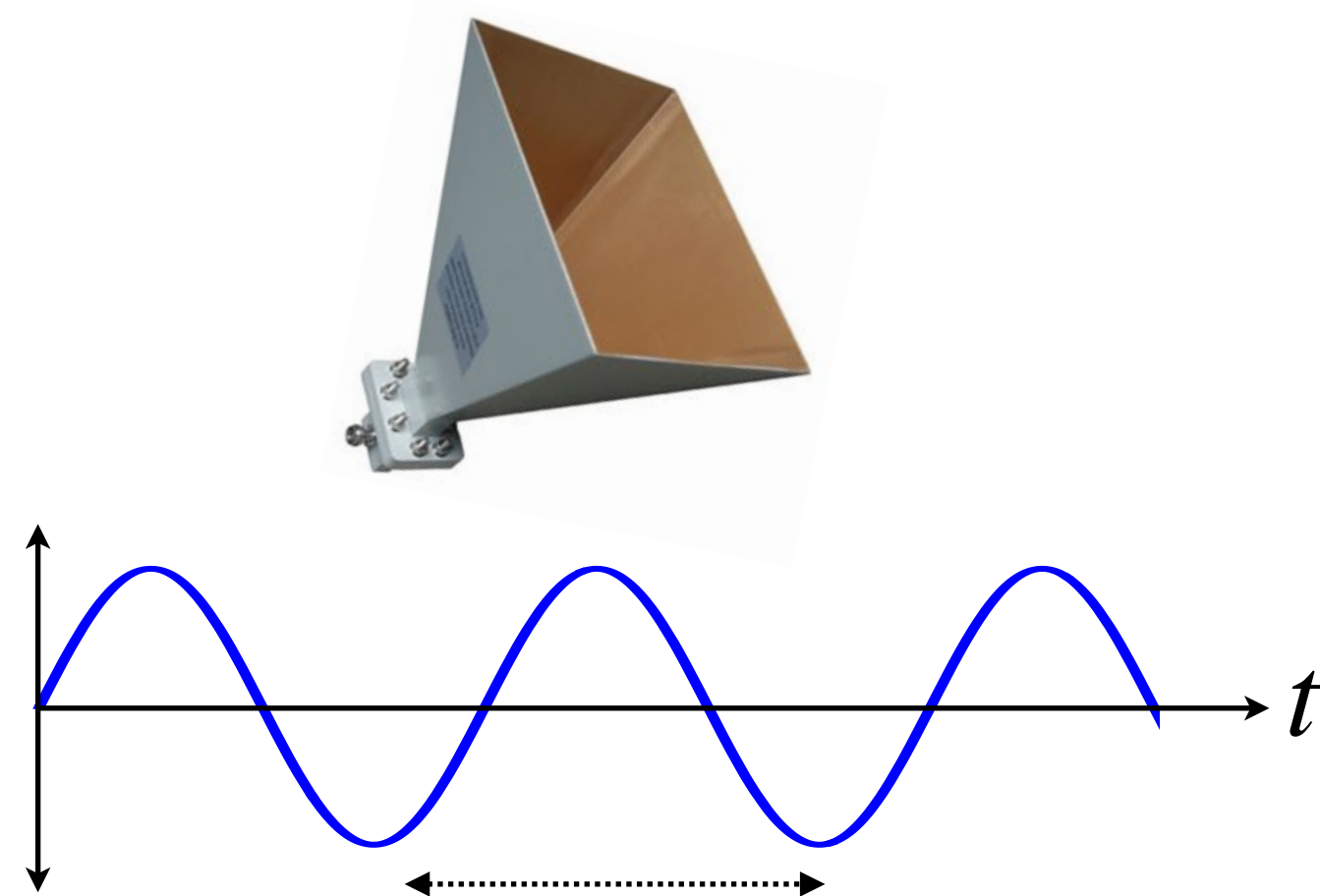
# How can we make an even better atomic clock?

## Microwave transitions



Fractional frequency instability  
from quantum projection noise:

$$\sigma \approx \frac{\delta\nu}{\nu_o} \times \frac{1}{SNR} = \frac{1}{2\pi\nu_o T} \sqrt{\frac{T + T_d}{N_d \tau}}$$



$T \sim 0.7$  nanoseconds

$\nu = 9,192,631,770$  Hz

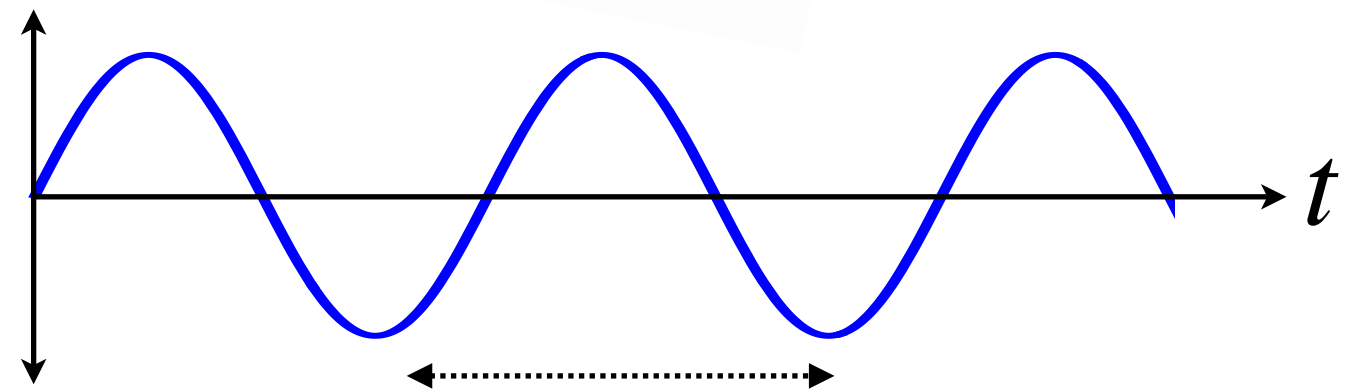
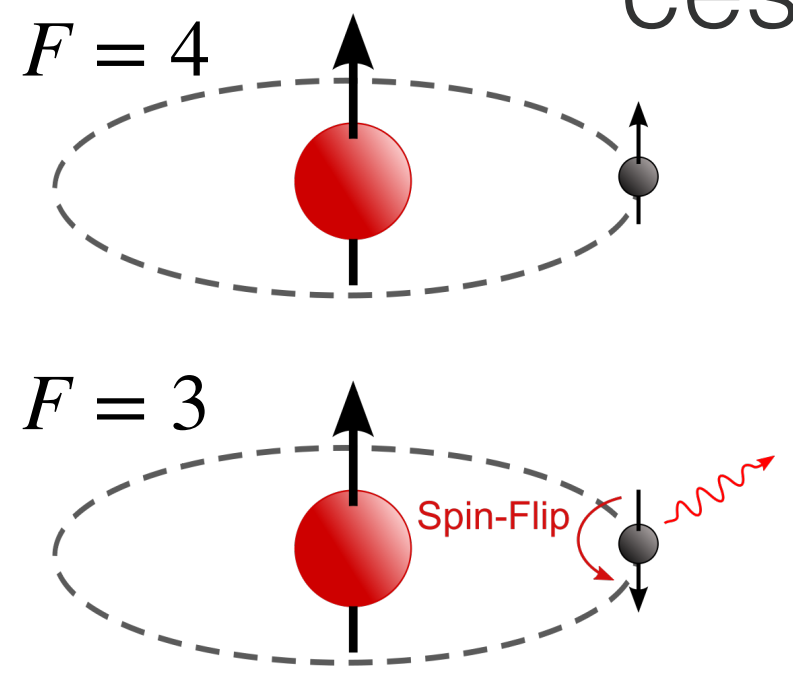
➡ Move from  $\nu_o = 10^{10}$  Hz to  $\nu_o = 10^{15}$  Hz



# Can we measure the gravitational redshift with clocks in the lab?

## Microwave transitions

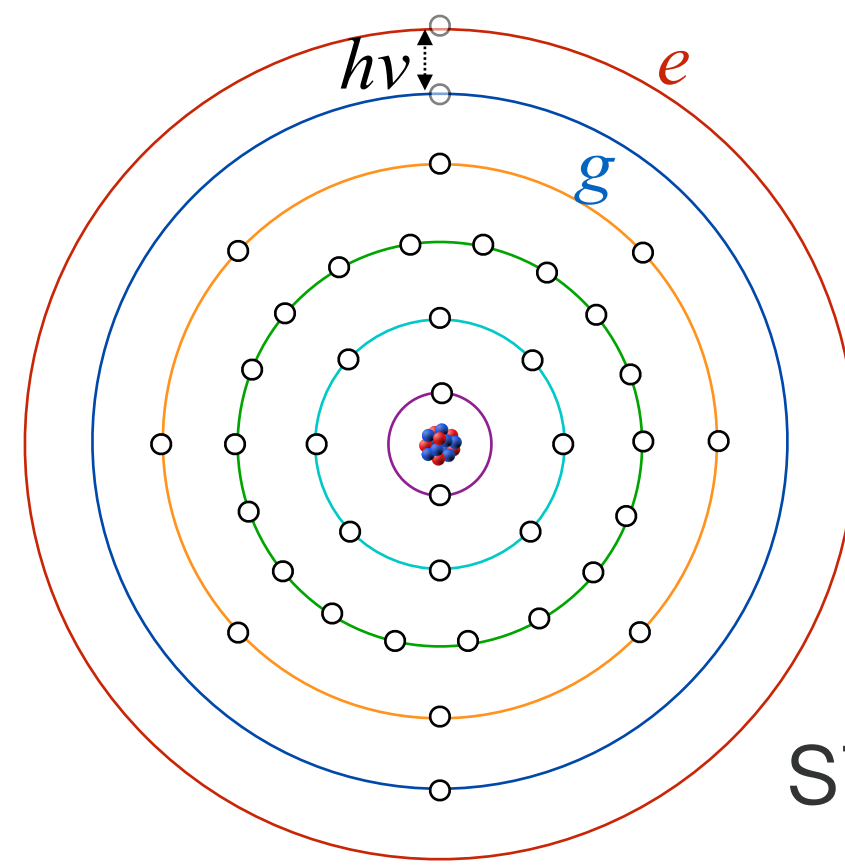
cesium-133



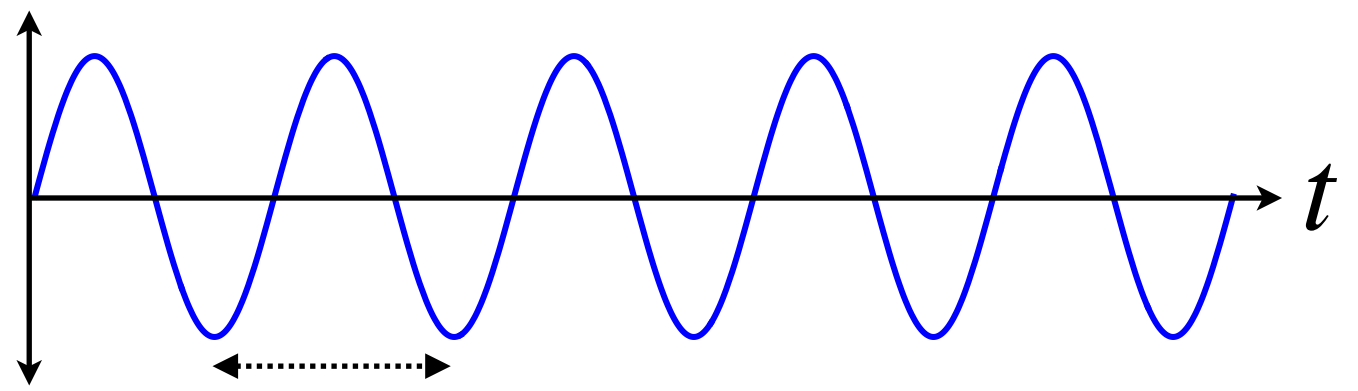
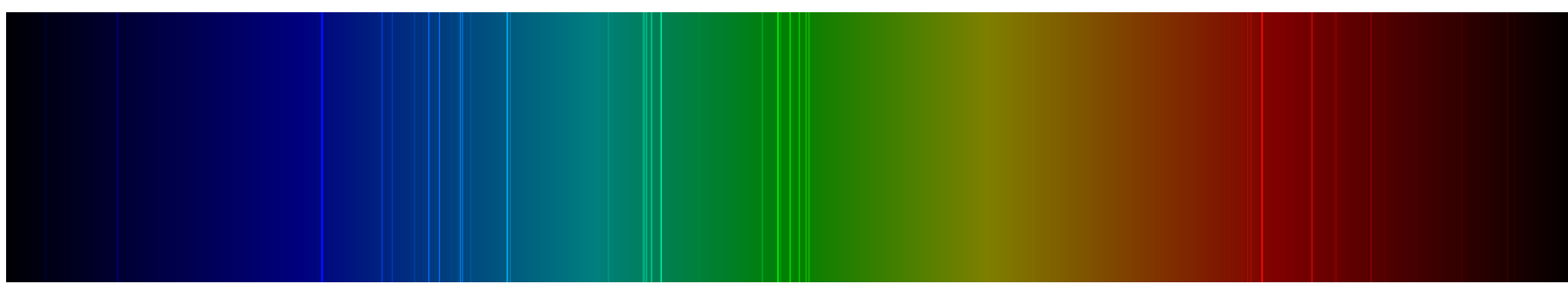
$T \sim 0.7$  nanoseconds

$\nu = 9,192,631,770$  Hz

## Optical transitions



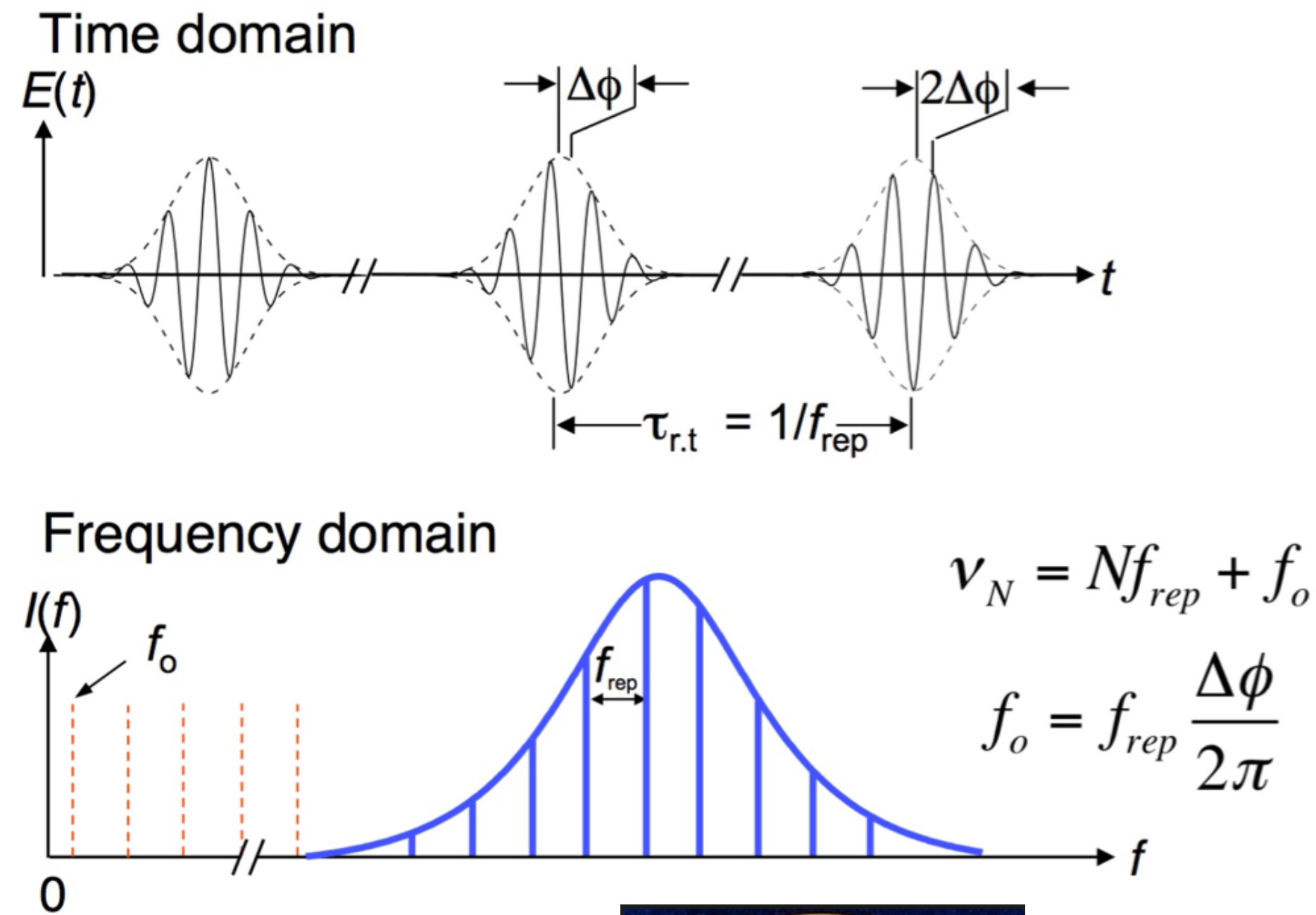
strontium



$T \sim 2.3$  femtoseconds

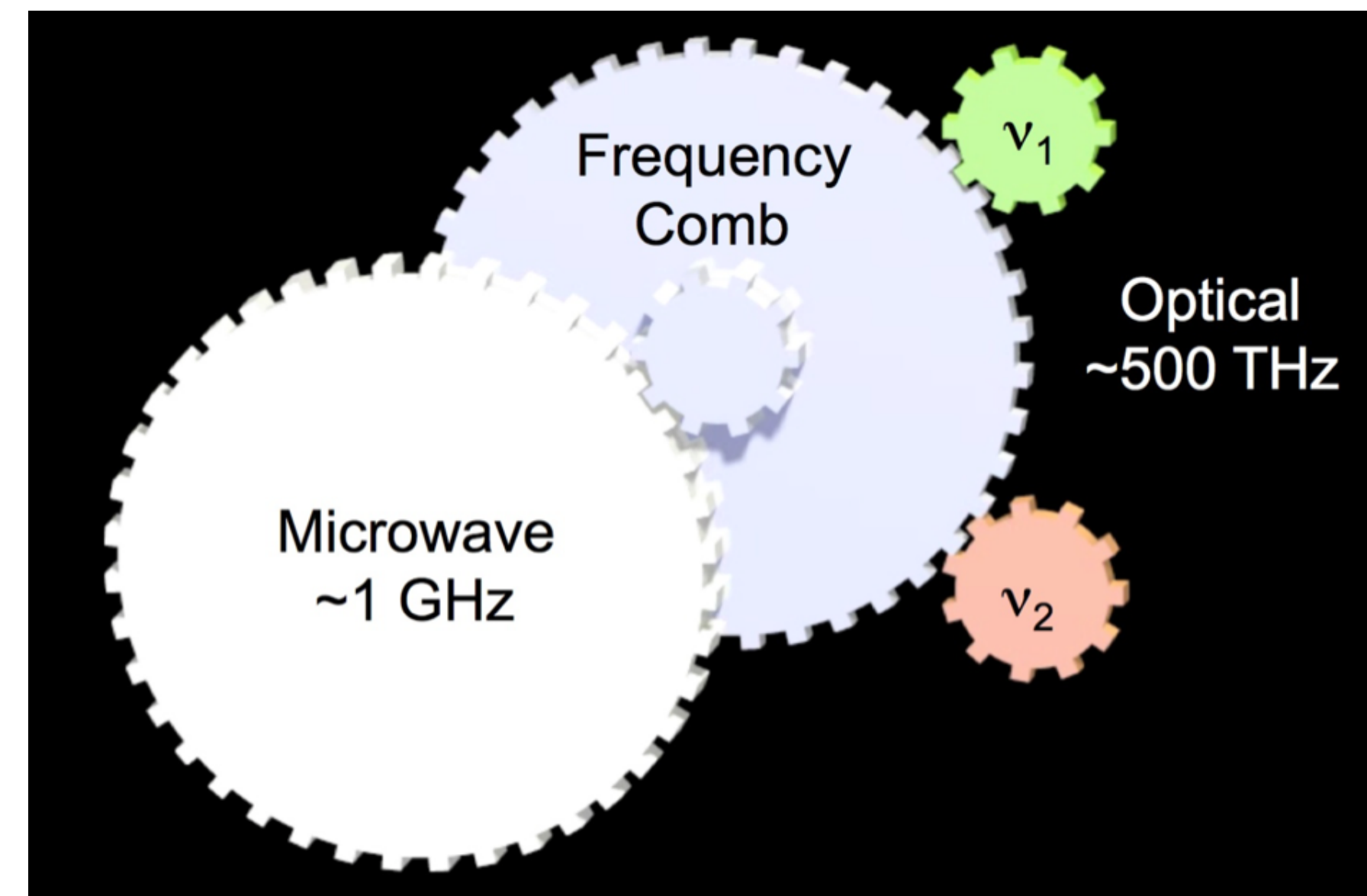
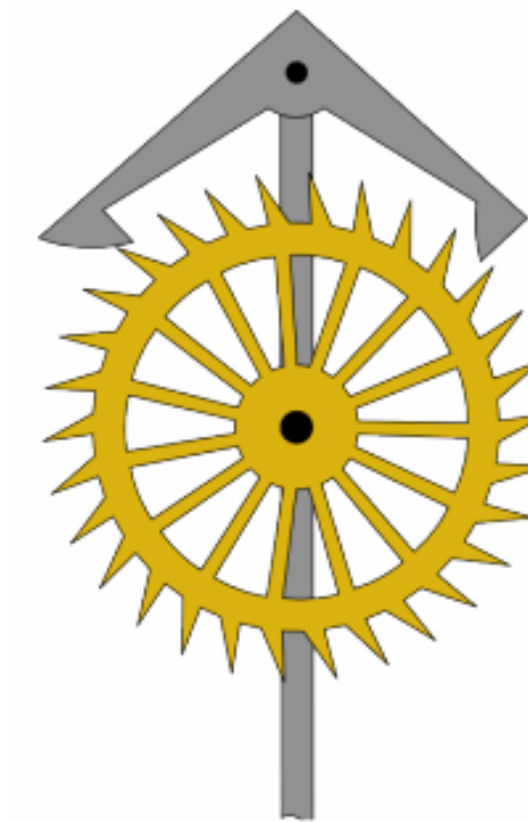
$\nu = 429,228,004,229,873.4$  Hz

# Laser frequency comb



2005 Nobel prize  
Hänsch and Hall

“optical escapement”





# Alkali microwave atomic clocks

| Group→  |  | 1        | 2        | 3              | 4         | 5         | 6         | 7         | 8         | 9         | 10        | 11        | 12        | 13        | 14        | 15        | 16        | 17        | 18        |
|---------|--|----------|----------|----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| ↓Period |  |          |          |                |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |
| 1       |  | 1<br>H   |          |                |           |           |           |           |           |           |           |           |           |           |           |           |           |           | 2<br>He   |
| 2       |  | 3<br>Li  | 4<br>Be  |                |           |           |           |           |           |           |           |           |           | 5<br>B    | 6<br>C    | 7<br>N    | 8<br>O    | 9<br>F    | 10<br>Ne  |
| 3       |  | 11<br>Na | 12<br>Mg |                |           |           |           |           |           |           |           |           |           | 13<br>Al  | 14<br>Si  | 15<br>P   | 16<br>S   | 17<br>Cl  | 18<br>Ar  |
| 4       |  | 19<br>K  | 20<br>Ca | 21<br>Sc       | 22<br>Ti  | 23<br>V   | 24<br>Cr  | 25<br>Mn  | 26<br>Fe  | 27<br>Co  | 28<br>Ni  | 29<br>Cu  | 30<br>Zn  | 31<br>Ga  | 32<br>Ge  | 33<br>As  | 34<br>Se  | 35<br>Br  | 36<br>Kr  |
| 5       |  | 37<br>Rb | 38<br>Sr | 39<br>Y        | 40<br>Zr  | 41<br>Nb  | 42<br>Mo  | 43<br>Tc  | 44<br>Ru  | 45<br>Rh  | 46<br>Pd  | 47<br>Ag  | 48<br>Cd  | 49<br>In  | 50<br>Sn  | 51<br>Sb  | 52<br>Te  | 53<br>I   | 54<br>Xe  |
| 6       |  | 55<br>Cs | 56<br>Ba | *<br>71<br>Lu  | 72<br>Hf  | 73<br>Ta  | 74<br>W   | 75<br>Re  | 76<br>Os  | 77<br>Ir  | 78<br>Pt  | 79<br>Au  | 80<br>Hg  | 81<br>Tl  | 82<br>Pb  | 83<br>Bi  | 84<br>Po  | 85<br>At  | 86<br>Rn  |
| 7       |  | 87<br>Fr | 88<br>Ra | *<br>103<br>Lr | 104<br>Rf | 105<br>Db | 106<br>Sg | 107<br>Bh | 108<br>Hs | 109<br>Mt | 110<br>Ds | 111<br>Rg | 112<br>Cn | 113<br>Nh | 114<br>Fl | 115<br>Mc | 116<br>Lv | 117<br>Ts | 118<br>Og |
|         |  |          |          | *<br>57<br>La  | 58<br>Ce  | 59<br>Pr  | 60<br>Nd  | 61<br>Pm  | 62<br>Sm  | 63<br>Eu  | 64<br>Gd  | 65<br>Tb  | 66<br>Dy  | 67<br>Ho  | 68<br>Er  | 69<br>Tm  | 70<br>Yb  |           |           |
|         |  |          |          | *<br>89<br>Ac  | 90<br>Th  | 91<br>Pa  | 92<br>U   | 93<br>Np  | 94<br>Pu  | 95<br>Am  | 96<br>Cm  | 97<br>Bk  | 98<br>Cf  | 99<br>Es  | 100<br>Fm | 101<br>Md | 102<br>No |           |           |

# Optical atomic clocks

| Group→  | 1        | 2        | 3              | 4         | 5         | 6         | 7         | 8         | 9         | 10        | 11        | 12        | 13        | 14        | 15        | 16        | 17        | 18        |
|---------|----------|----------|----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| ↓Period |          |          |                |           |           |           |           |           |           |           |           |           |           |           |           |           |           |           |
| 1       | 1<br>H   |          |                |           |           |           |           |           |           |           |           |           |           |           |           |           |           | 2<br>He   |
| 2       | 3<br>Li  | 4<br>Be  |                |           |           |           |           |           |           |           |           |           | 5<br>B    | 6<br>C    | 7<br>N    | 8<br>O    | 9<br>F    | 10<br>Ne  |
| 3       | 11<br>Na | 12<br>Mg |                |           |           |           |           |           |           |           |           |           | 13<br>Al  | 14<br>Si  | 15<br>P   | 16<br>S   | 17<br>Cl  | 18<br>Ar  |
| 4       | 19<br>K  | 20<br>Ca | 21<br>Sc       | 22<br>Ti  | 23<br>V   | 24<br>Cr  | 25<br>Mn  | 26<br>Fe  | 27<br>Co  | 28<br>Ni  | 29<br>Cu  | 30<br>Zn  | 31<br>Ga  | 32<br>Ge  | 33<br>As  | 34<br>Se  | 35<br>Br  | 36<br>Kr  |
| 5       | 37<br>Rb | 38<br>Sr | 39<br>Y        | 40<br>Zr  | 41<br>Nb  | 42<br>Mo  | 43<br>Tc  | 44<br>Ru  | 45<br>Rh  | 46<br>Pd  | 47<br>Ag  | 48<br>Cd  | 49<br>In  | 50<br>Sn  | 51<br>Sb  | 52<br>Te  | 53<br>I   | 54<br>Xe  |
| 6       | 55<br>Cs | 56<br>Ba | *<br>71<br>Lu  | 72<br>Hf  | 73<br>Ta  | 74<br>W   | 75<br>Re  | 76<br>Os  | 77<br>Ir  | 78<br>Pt  | 79<br>Au  | 80<br>Hg  | 81<br>Tl  | 82<br>Pb  | 83<br>Bi  | 84<br>Po  | 85<br>At  | 86<br>Rn  |
| 7       | 87<br>Fr | 88<br>Ra | *<br>103<br>Lr | 104<br>Rf | 105<br>Db | 106<br>Sg | 107<br>Bh | 108<br>Hs | 109<br>Mt | 110<br>Ds | 111<br>Rg | 112<br>Cn | 113<br>Nh | 114<br>Fl | 115<br>Mc | 116<br>Lv | 117<br>Ts | 118<br>Og |
|         |          |          | *<br>57<br>La  | 58<br>Ce  | 59<br>Pr  | 60<br>Nd  | 61<br>Pm  | 62<br>Sm  | 63<br>Eu  | 64<br>Gd  | 65<br>Tb  | 66<br>Dy  | 67<br>Ho  | 68<br>Er  | 69<br>Tm  | 70<br>Yb  |           |           |
|         |          |          | *<br>89<br>Ac  | 90<br>Th  | 91<br>Pa  | 92<br>U   | 93<br>Np  | 94<br>Pu  | 95<br>Am  | 96<br>Cm  | 97<br>Bk  | 98<br>Cf  | 99<br>Es  | 100<br>Fm | 101<br>Md | 102<br>No |           |           |



- Optical lattice clock atoms

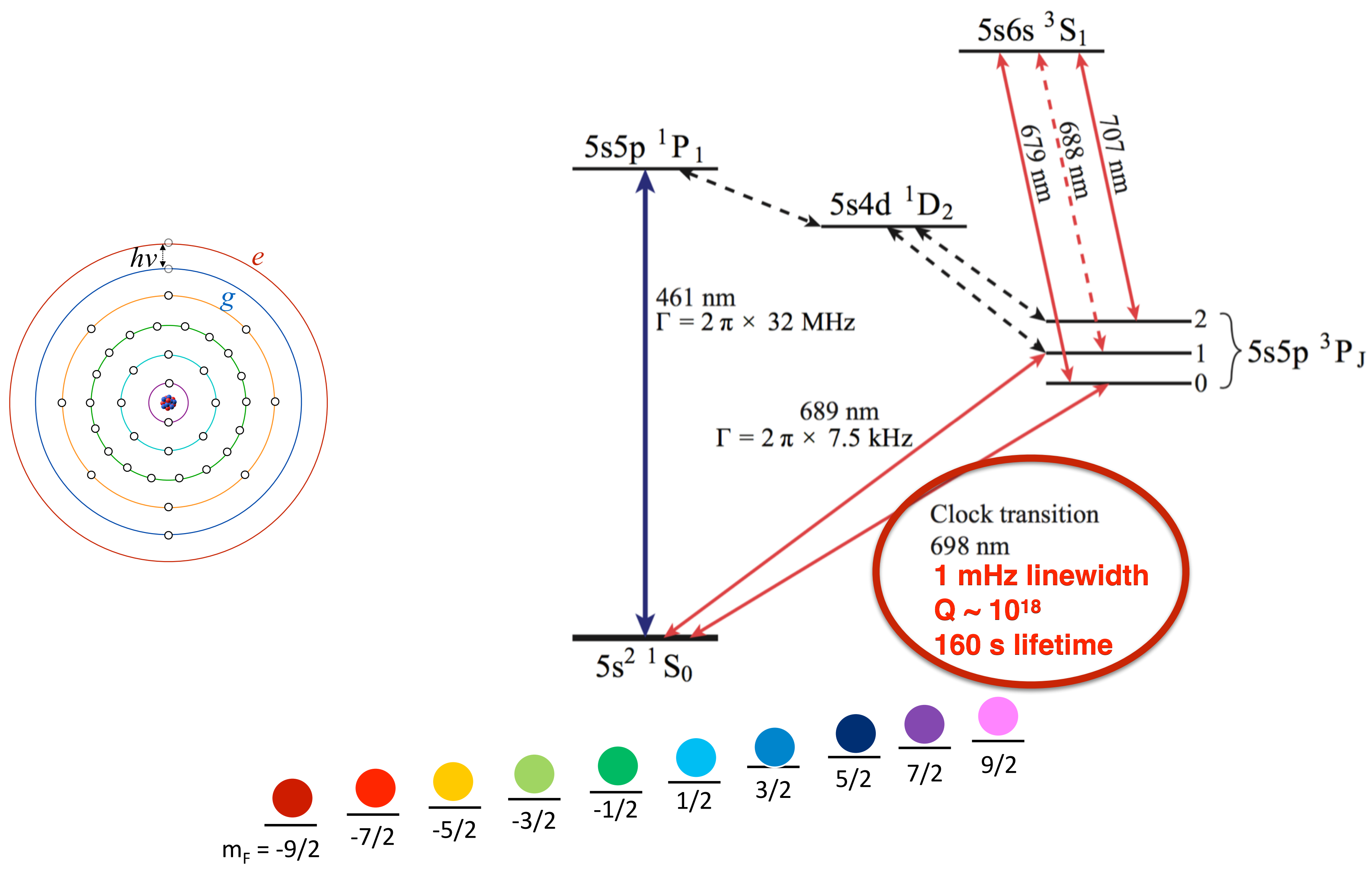


- Trapped ion clock atoms

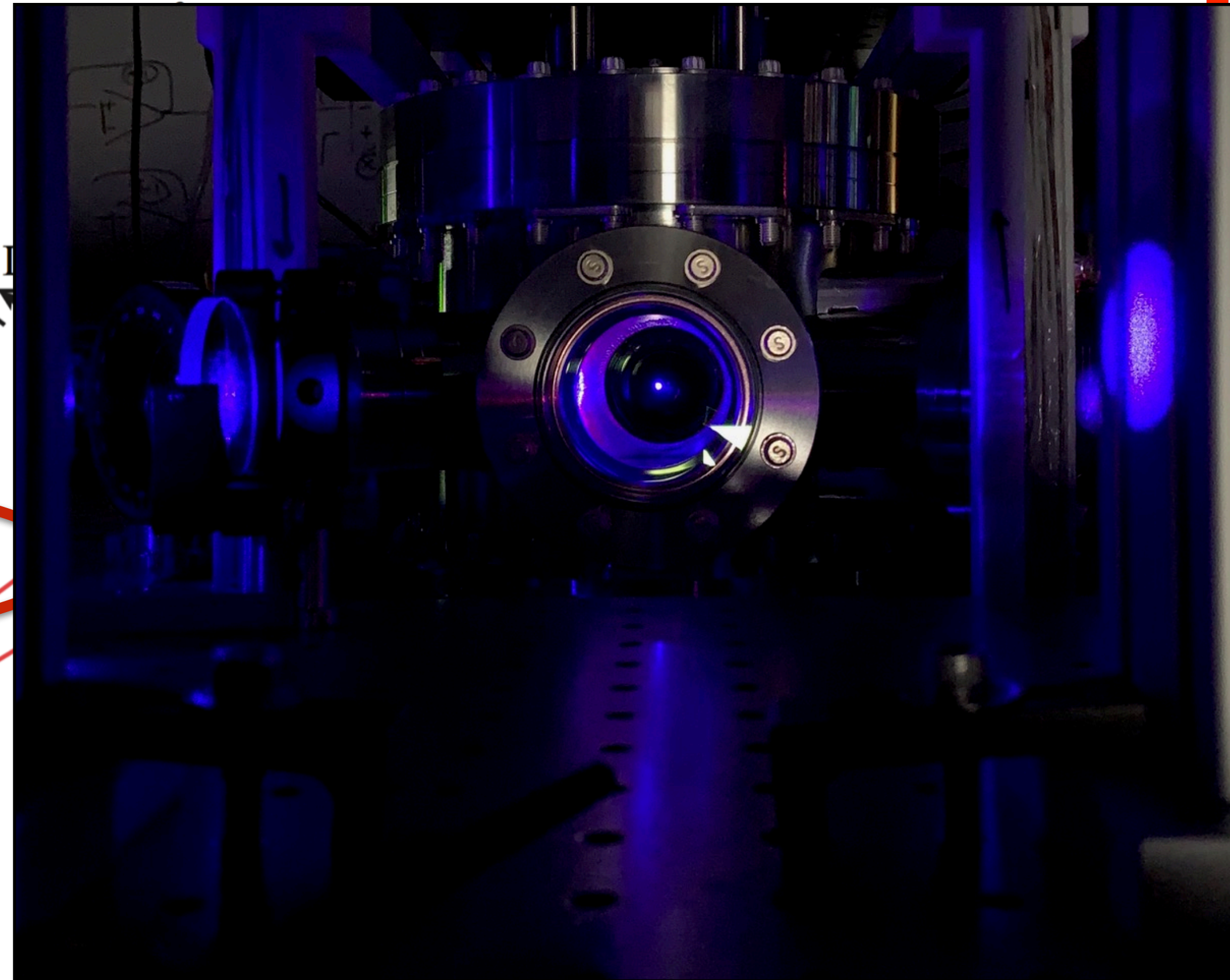
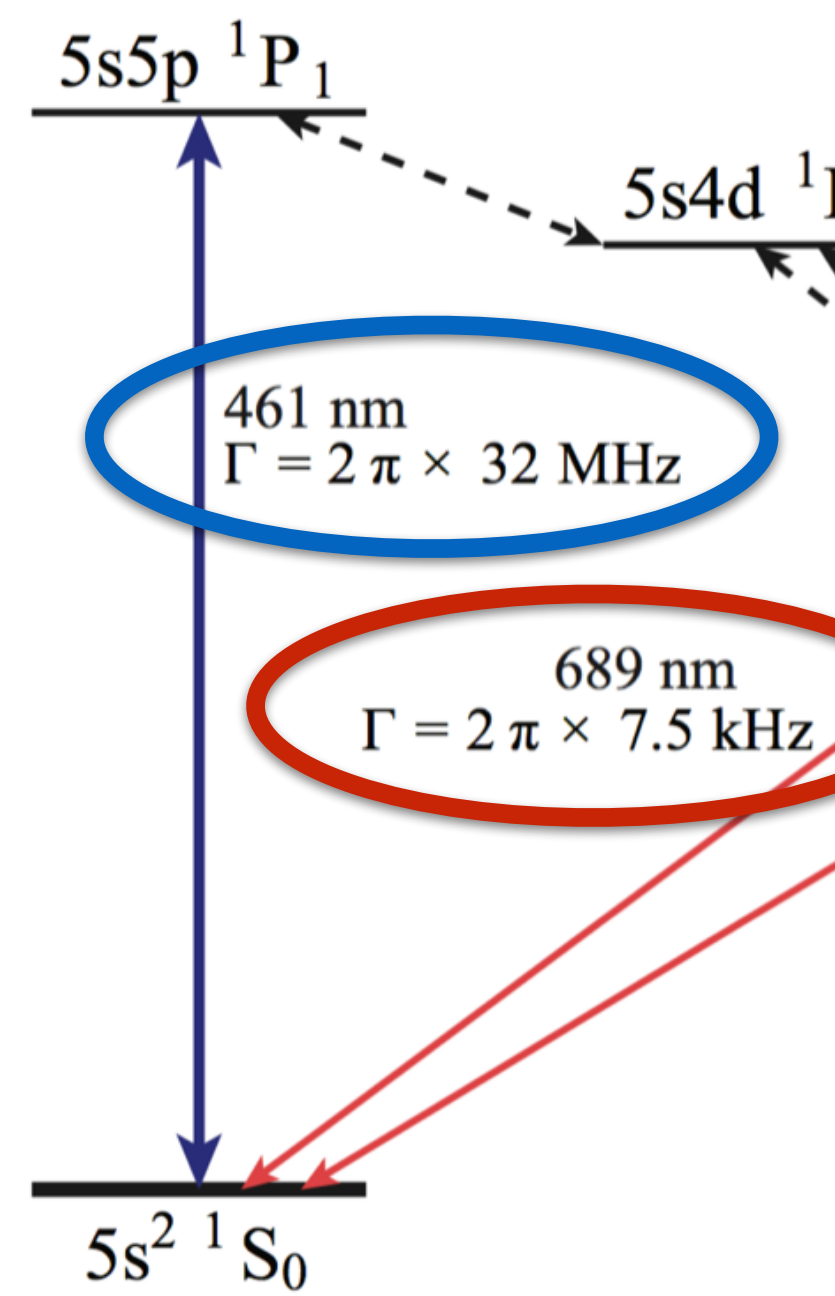
See Ludlow *et al.*, *Reviews of Modern Physics* (2015) for other species of optical clocks



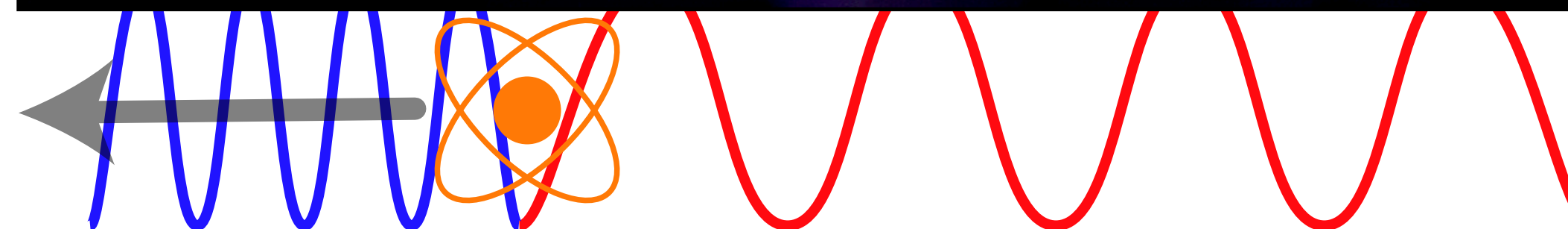
# <sup>87</sup>Strontium



# Laser cooling

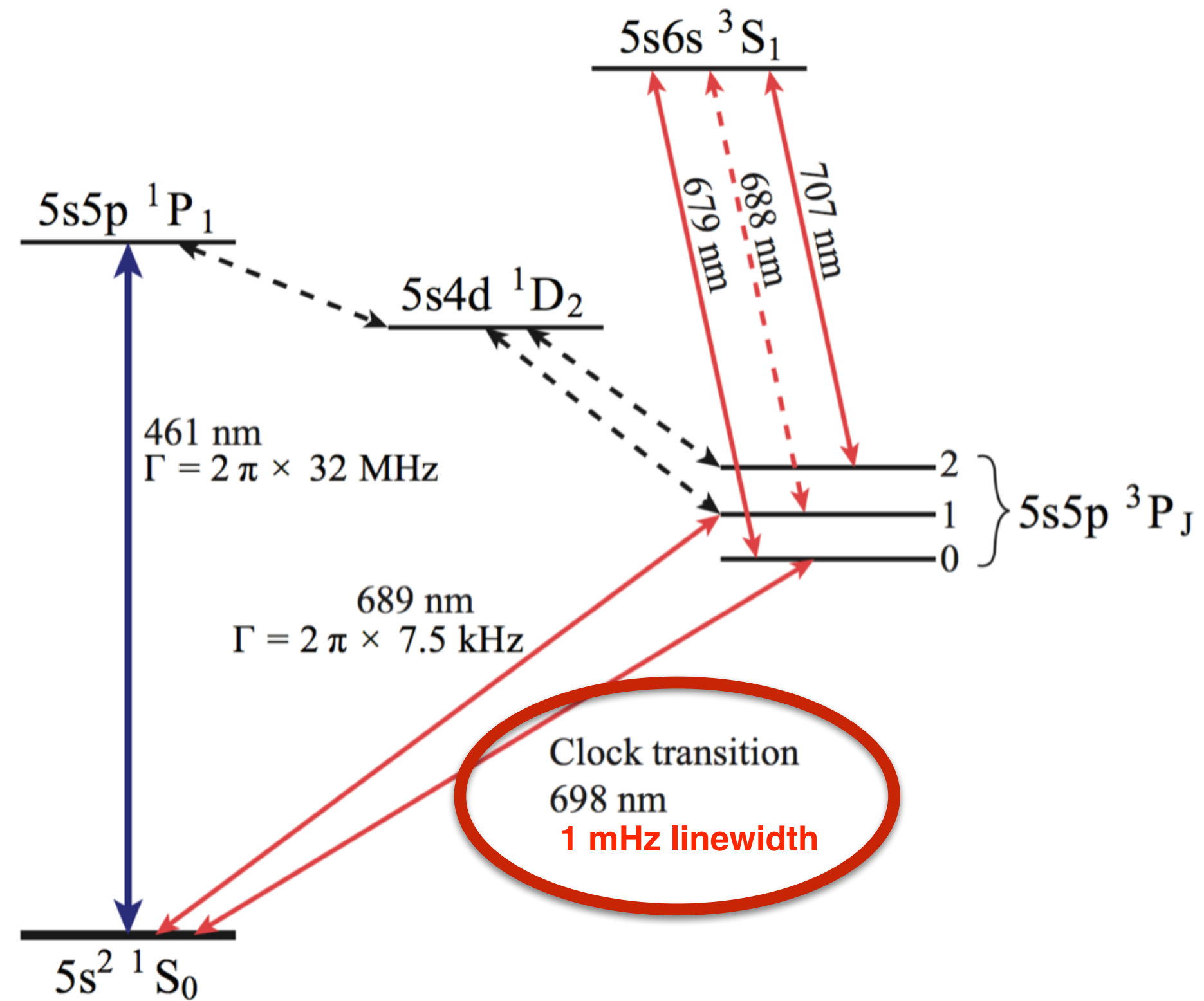


$T = 200 \text{ nK}$

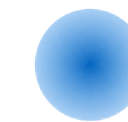




# Laser cooling

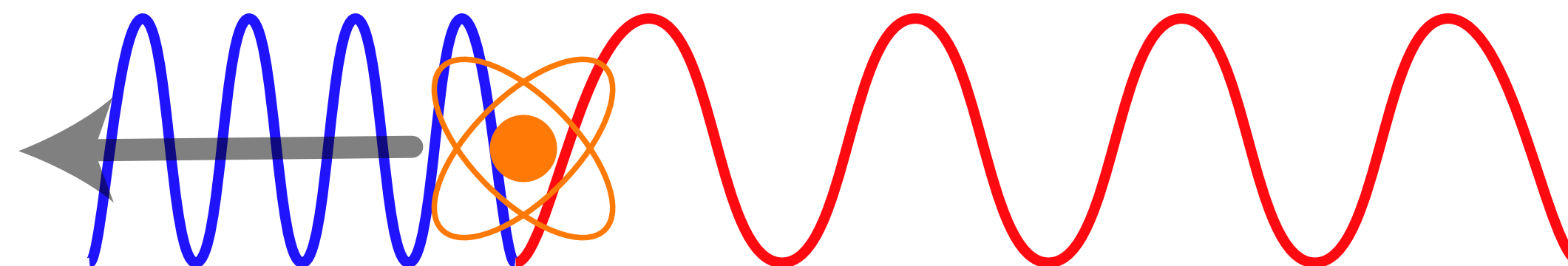


$$T = 2\ \mu\text{K}$$



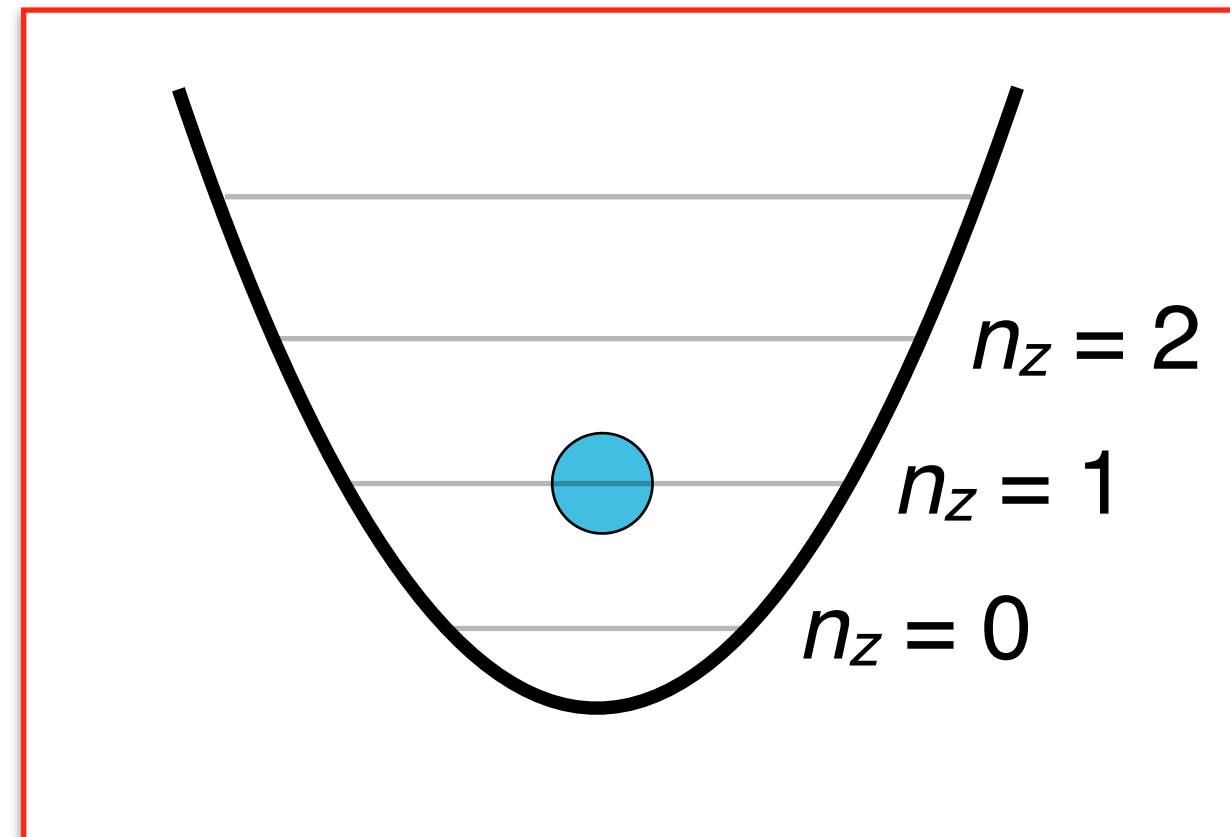
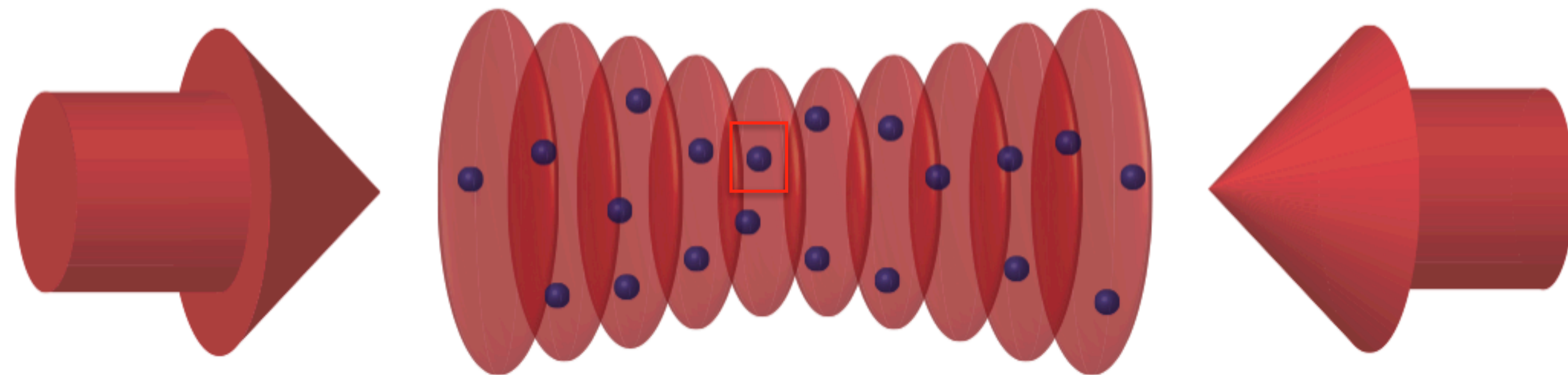
$$\Delta\nu = 40\text{ kHz}$$

Still too broad!



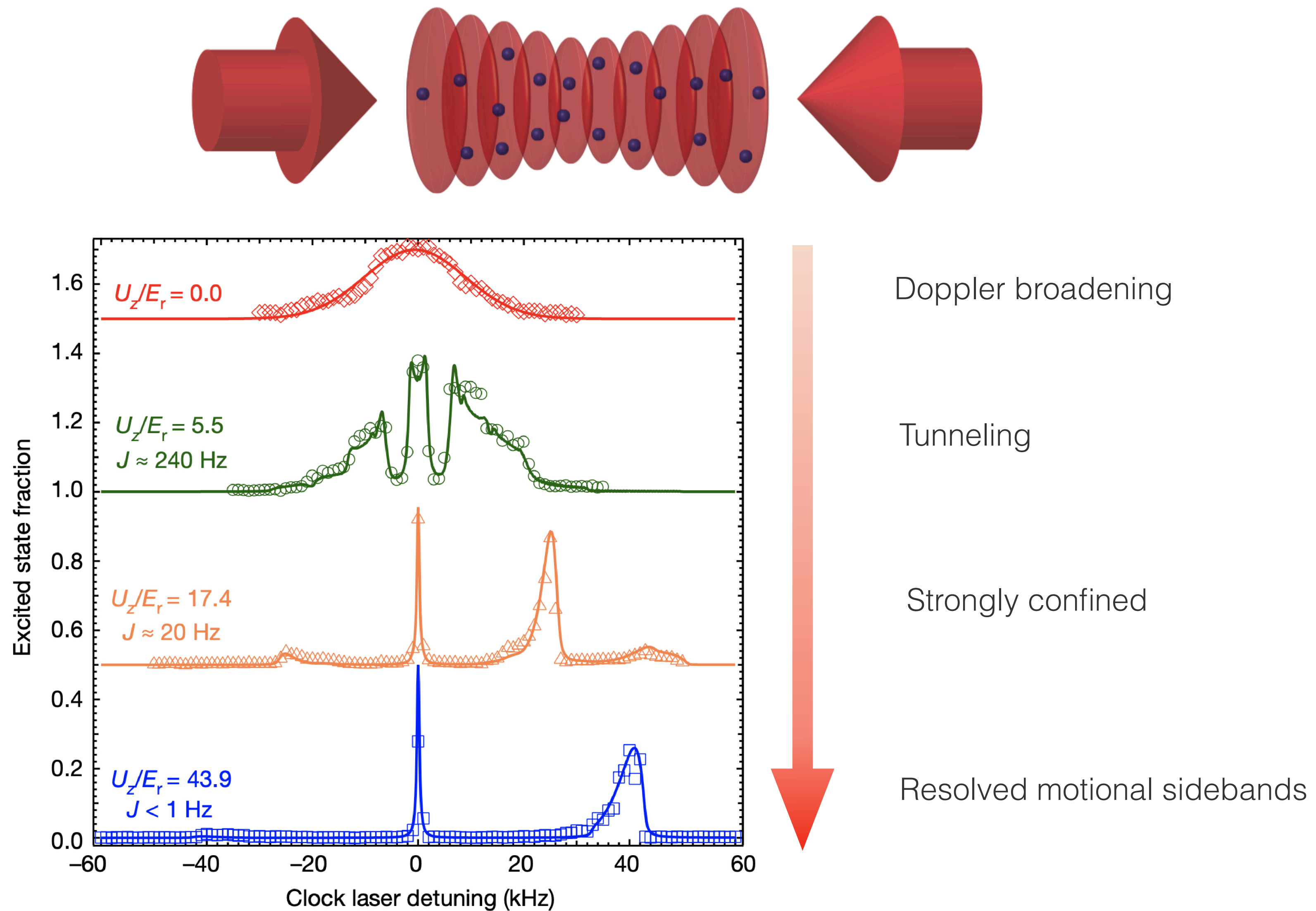
# Optical lattice trap

The solution?

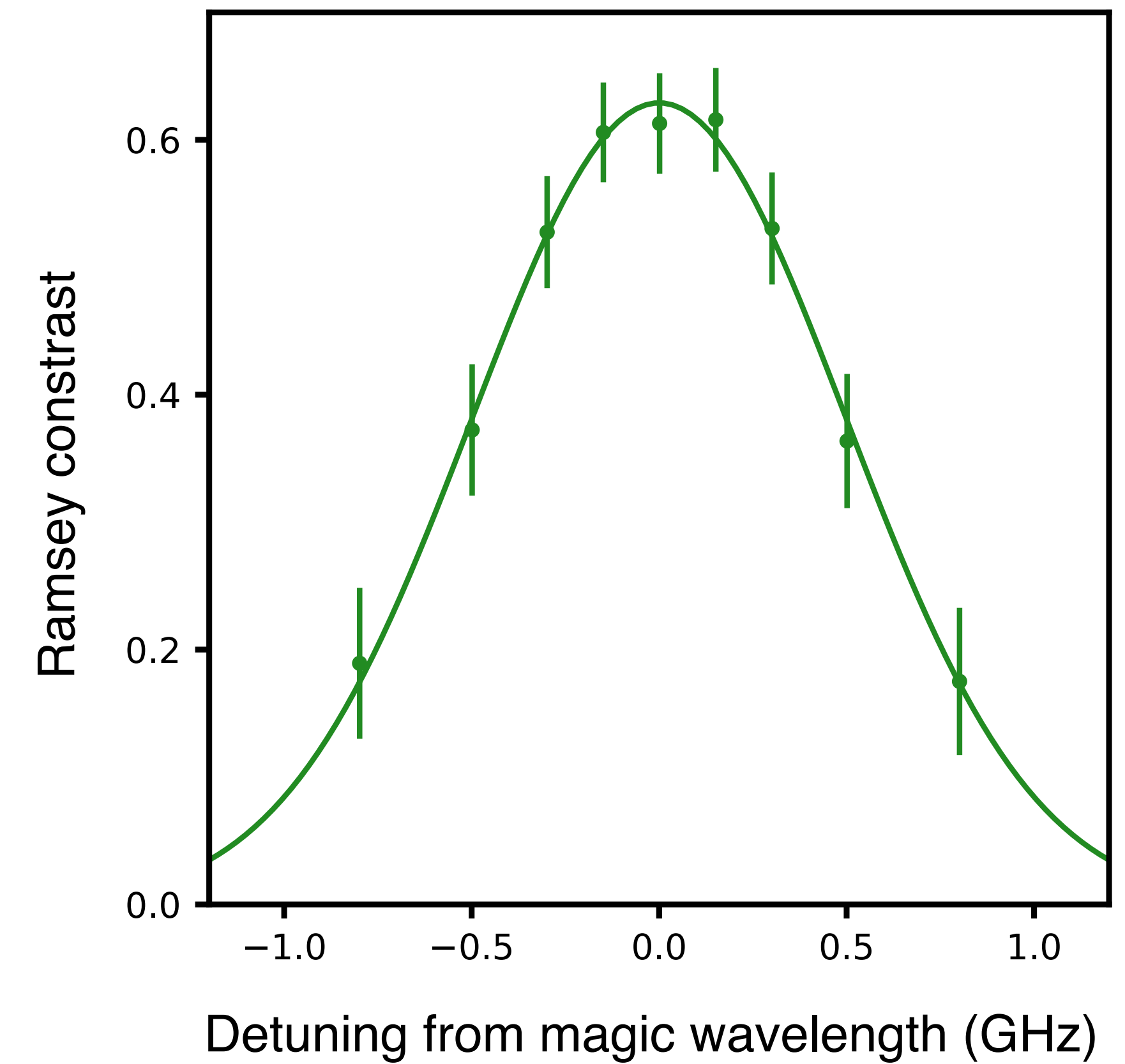
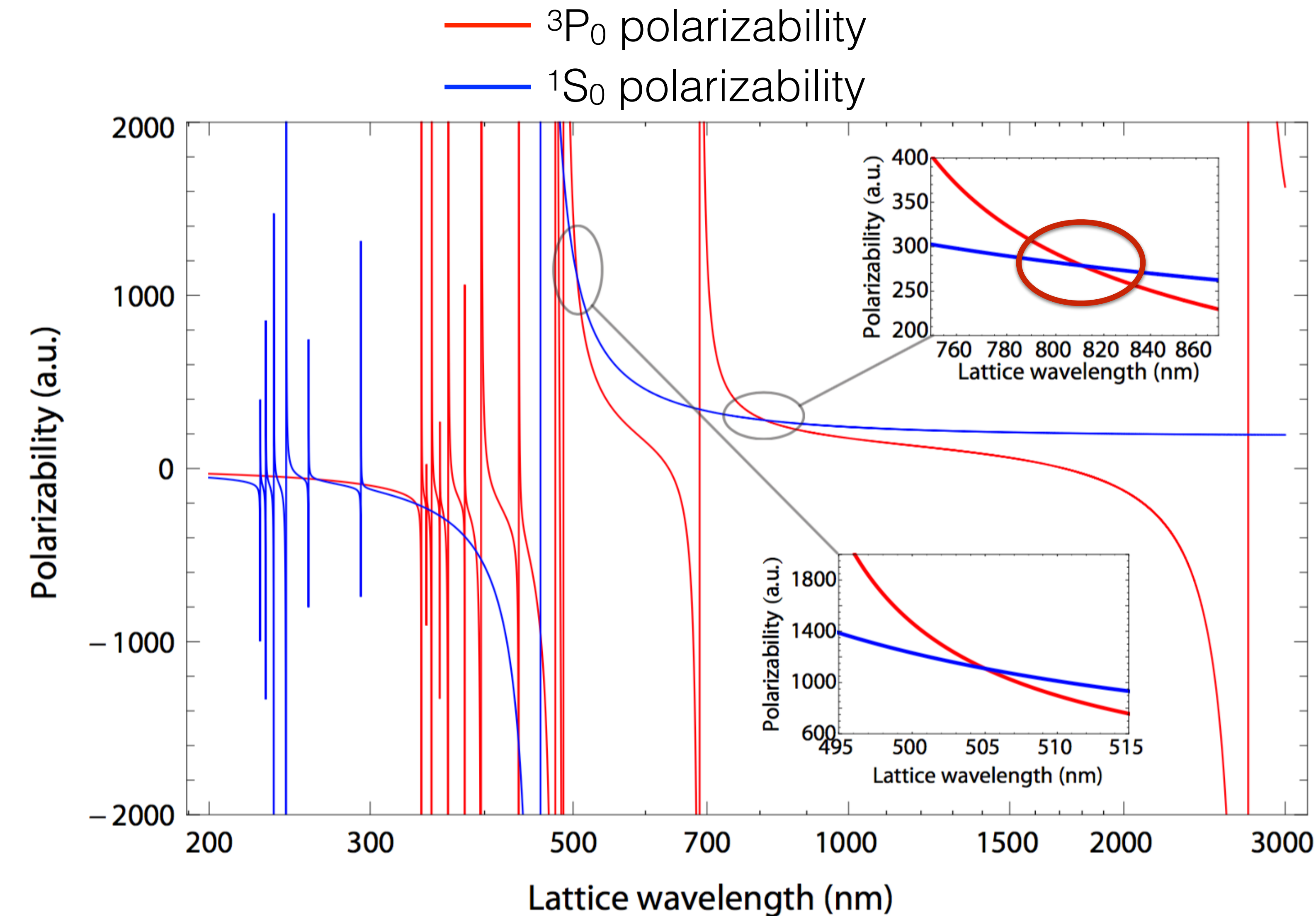




# Why do you need an optical lattice?

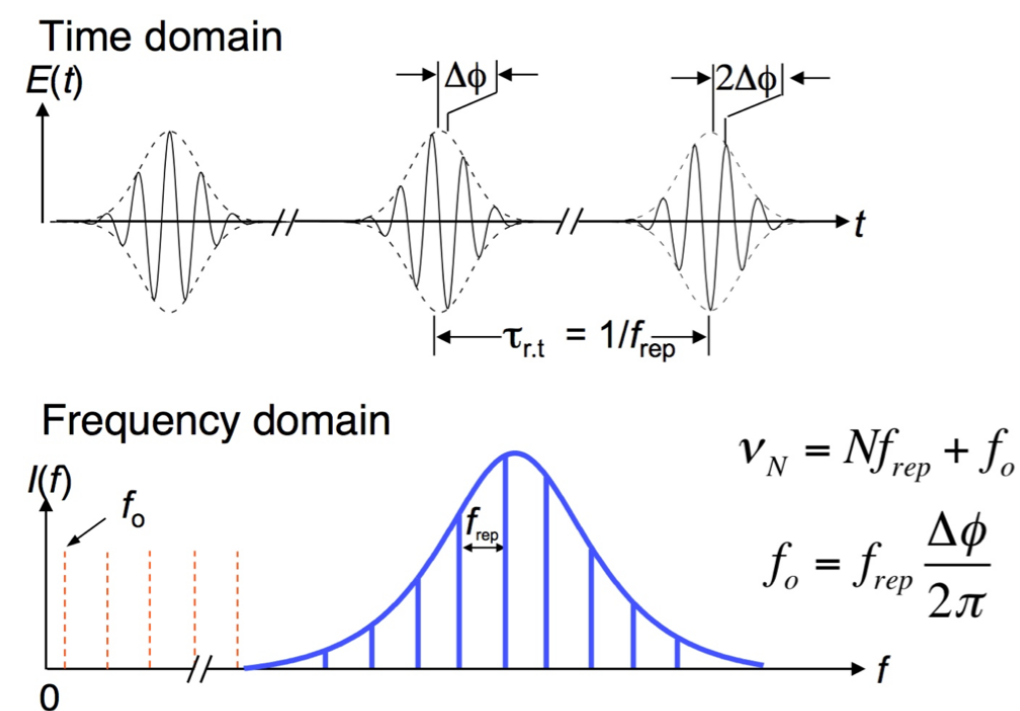


# A “magic wavelength” optical lattice

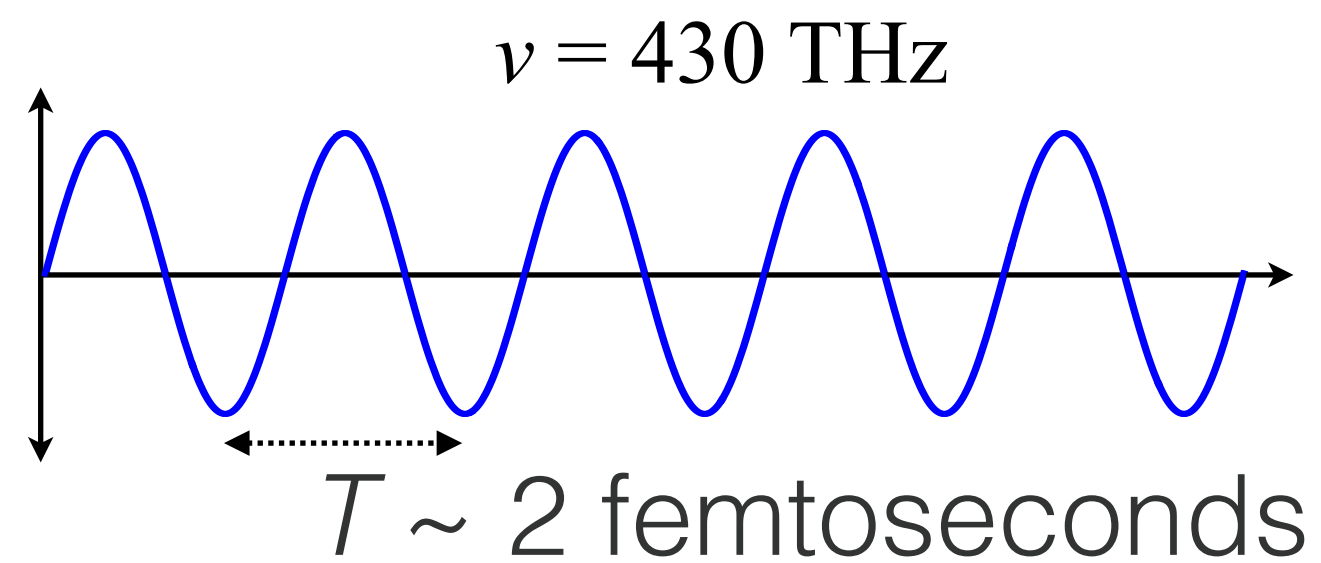




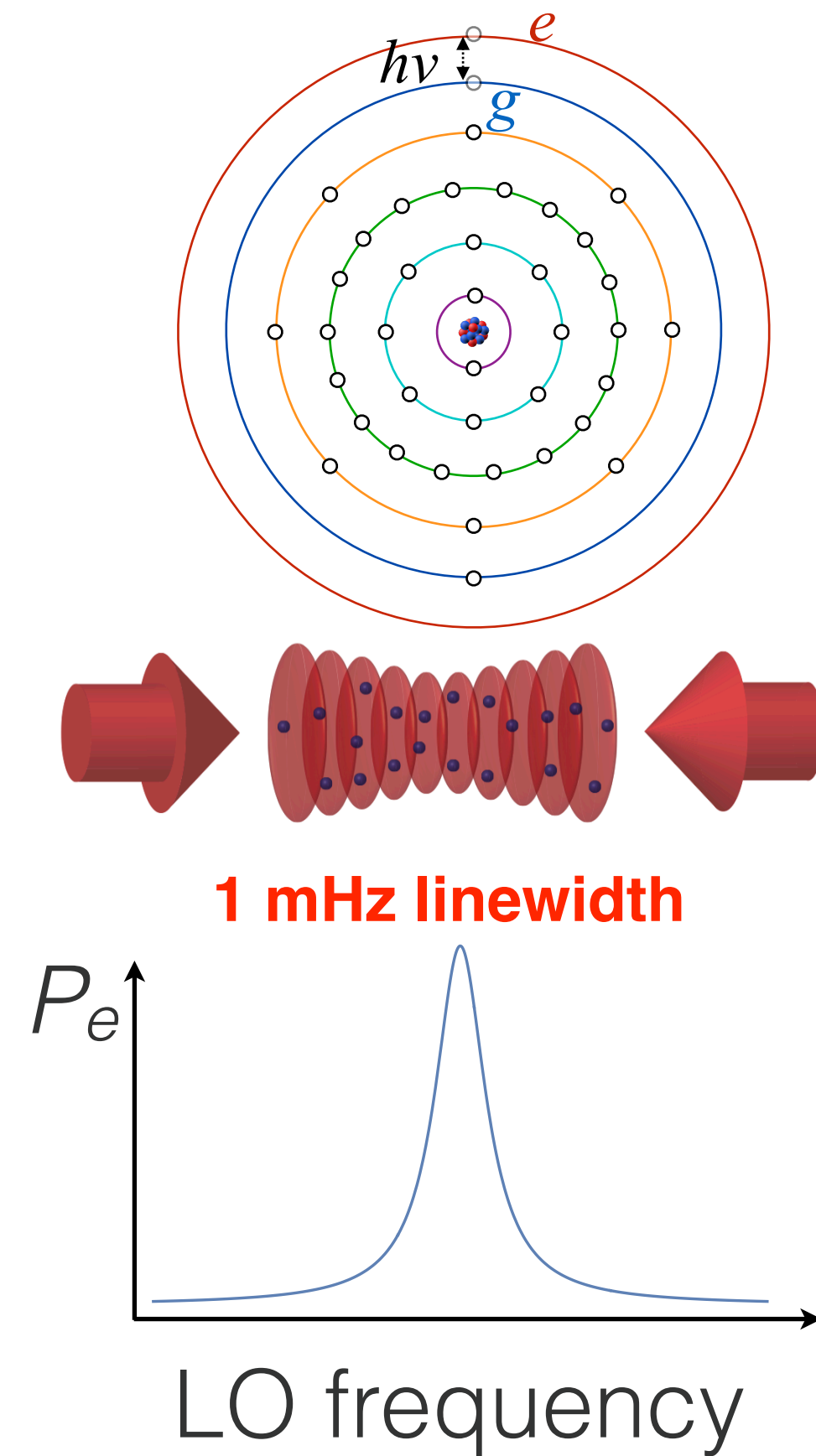
# Optical lattice clock



Counter

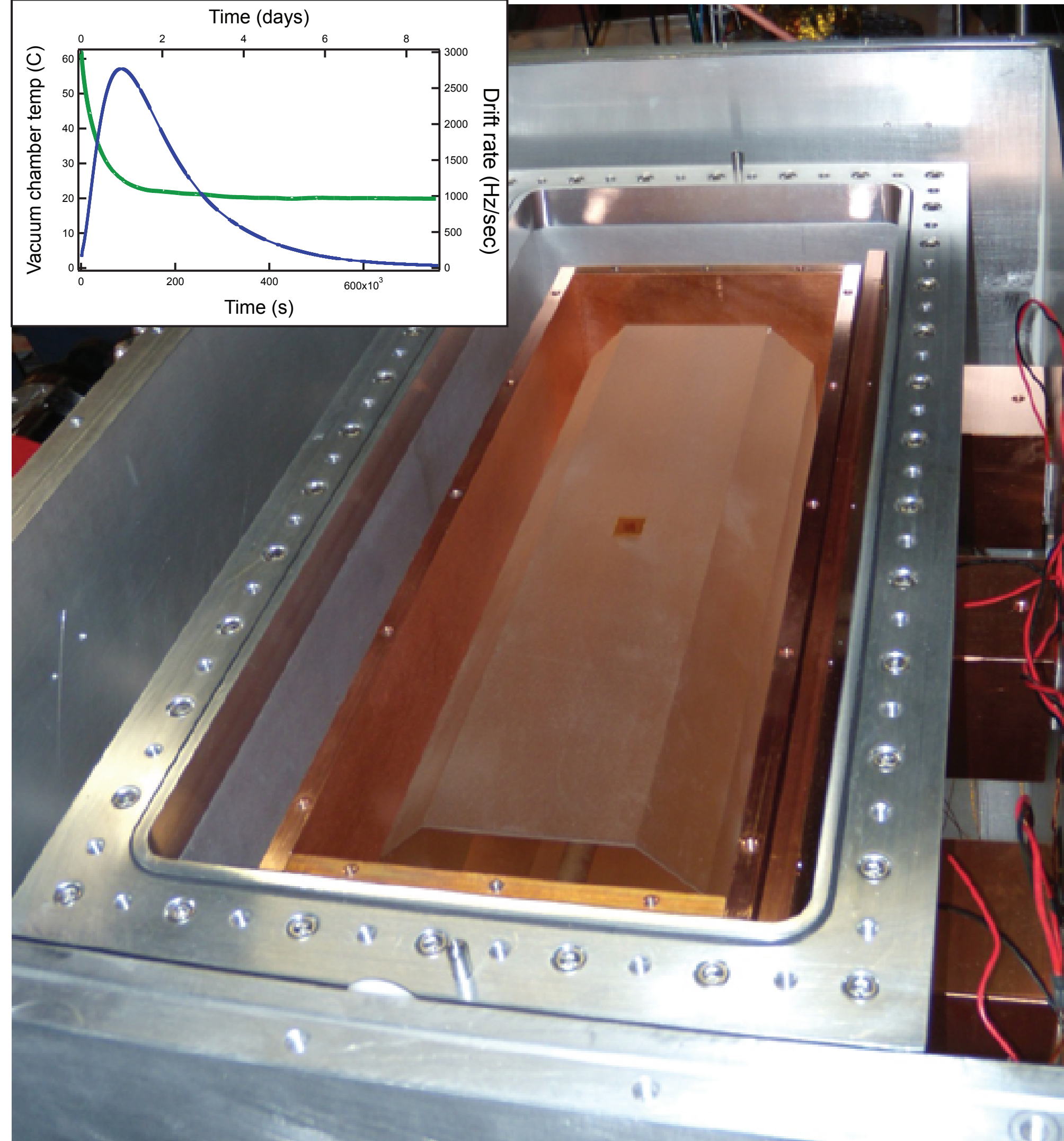
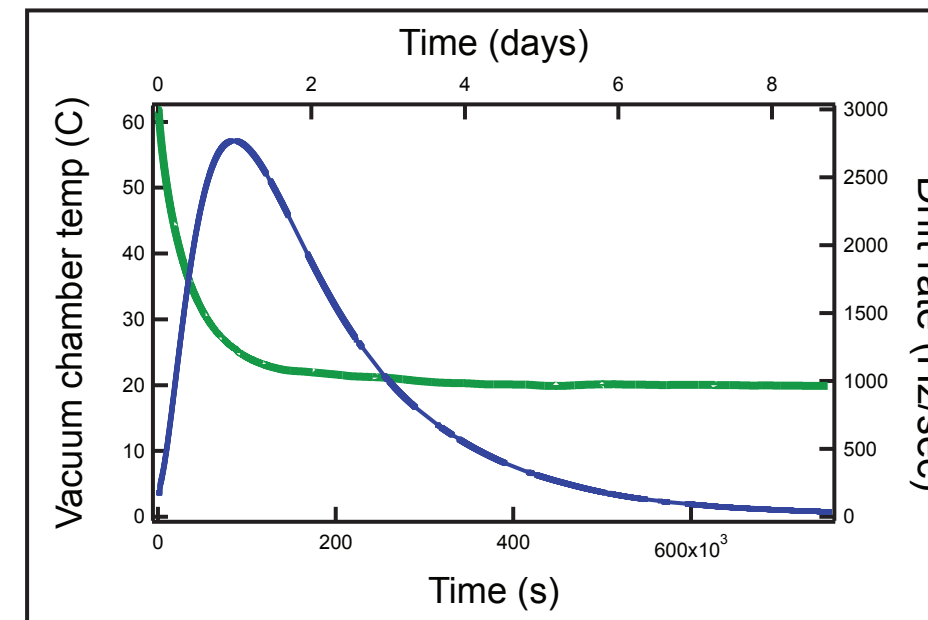
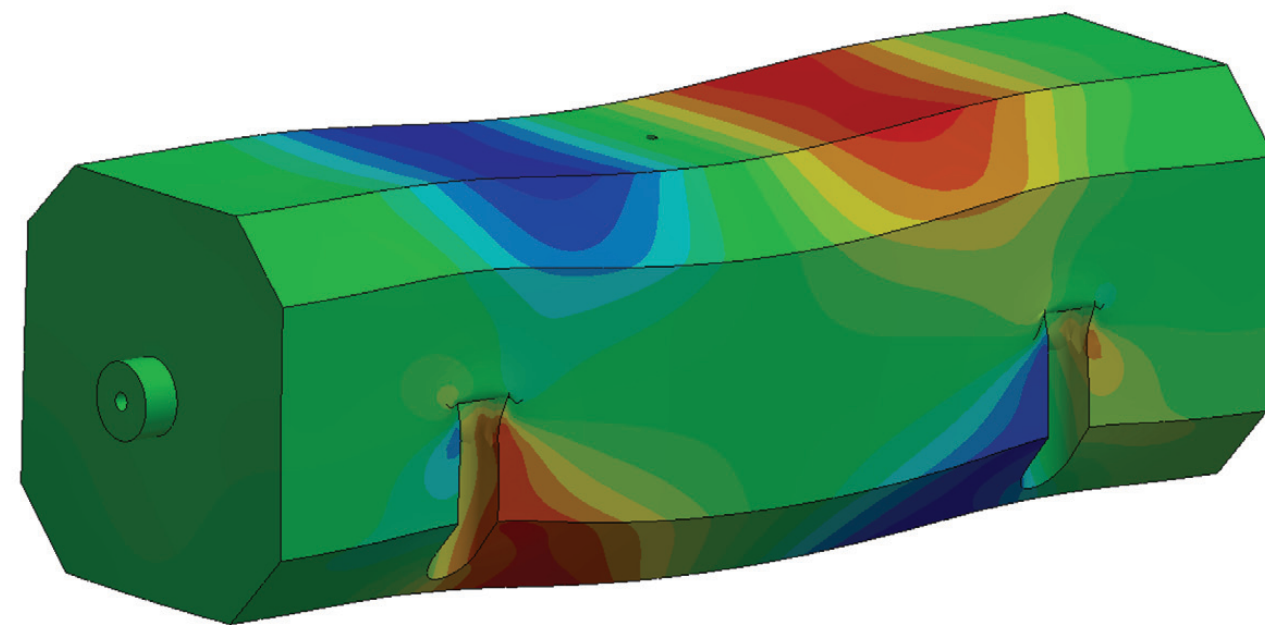
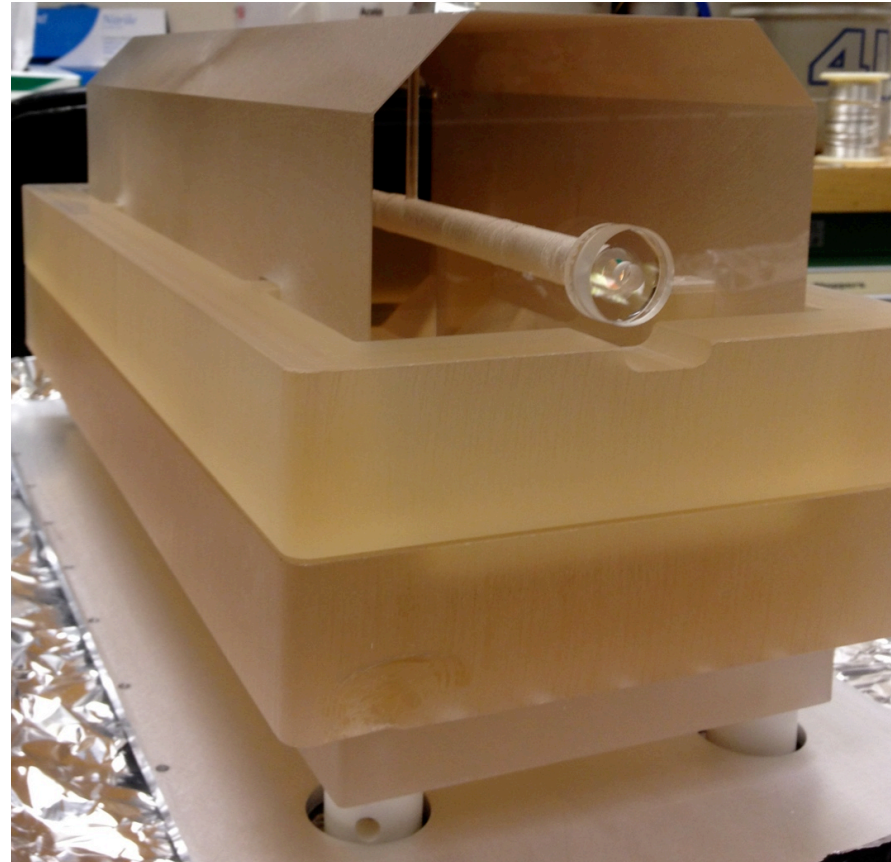


Local oscillator (LO)



Frequency reference

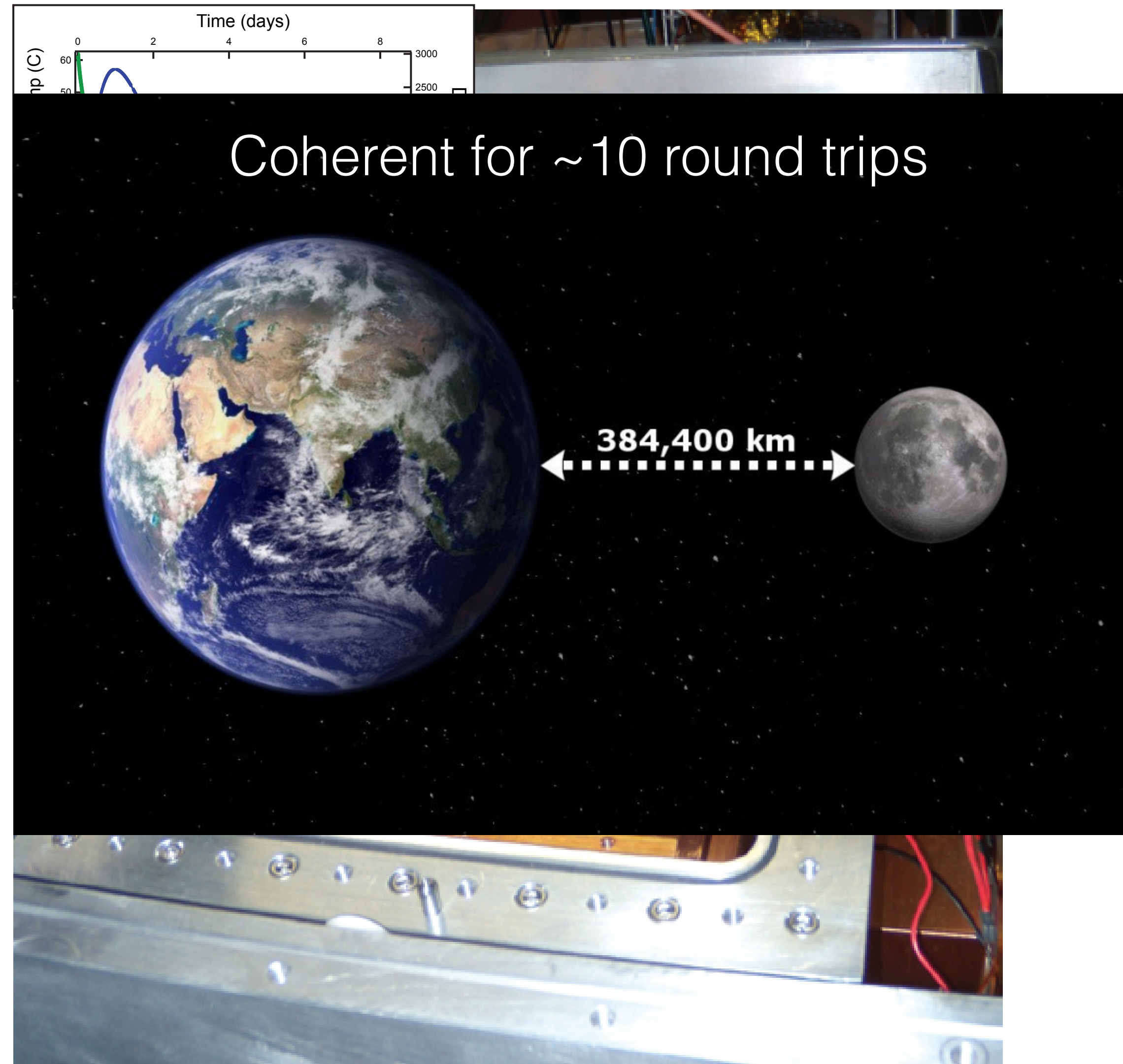
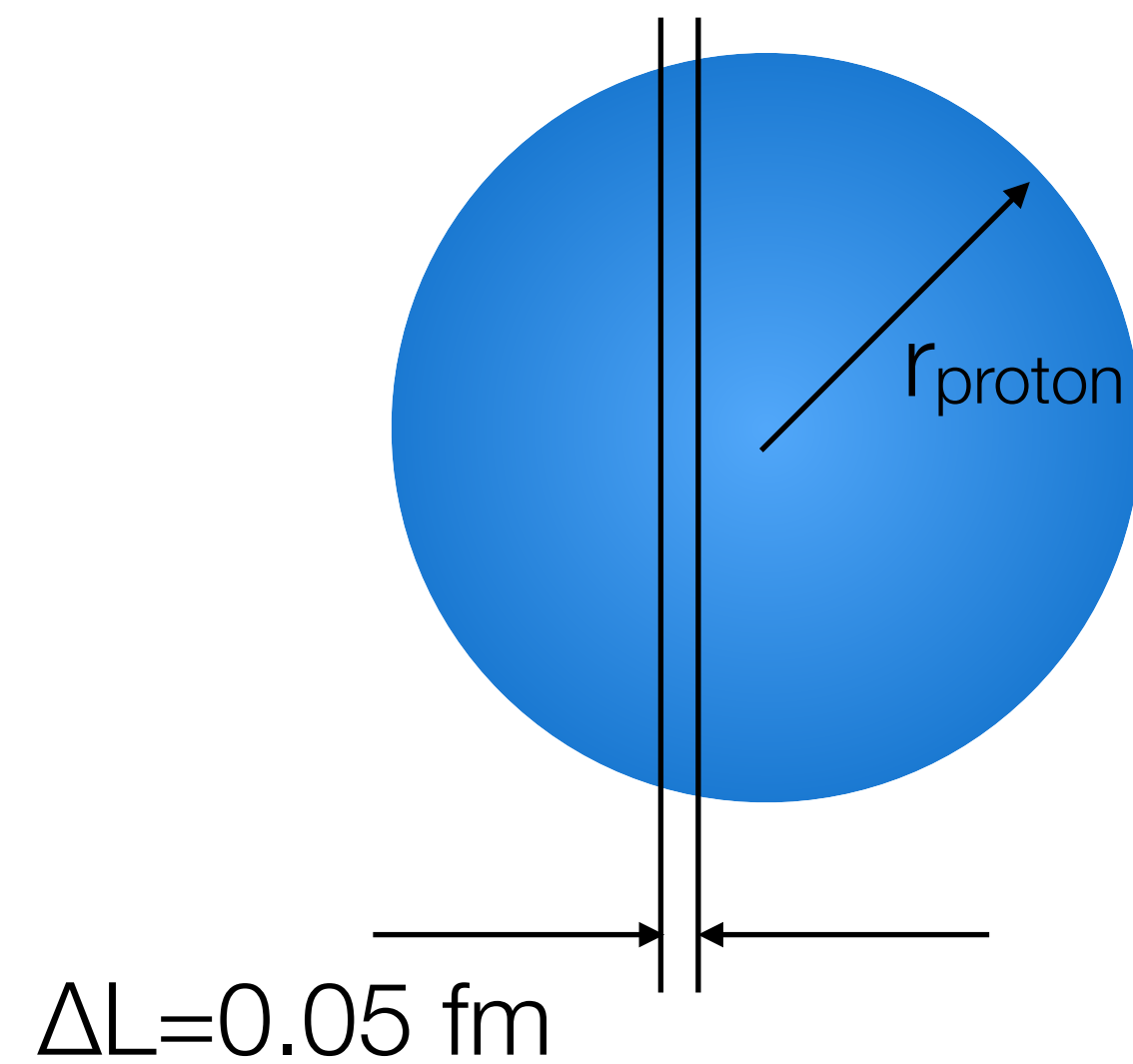
# 40 cm ultrastable ULE cavity



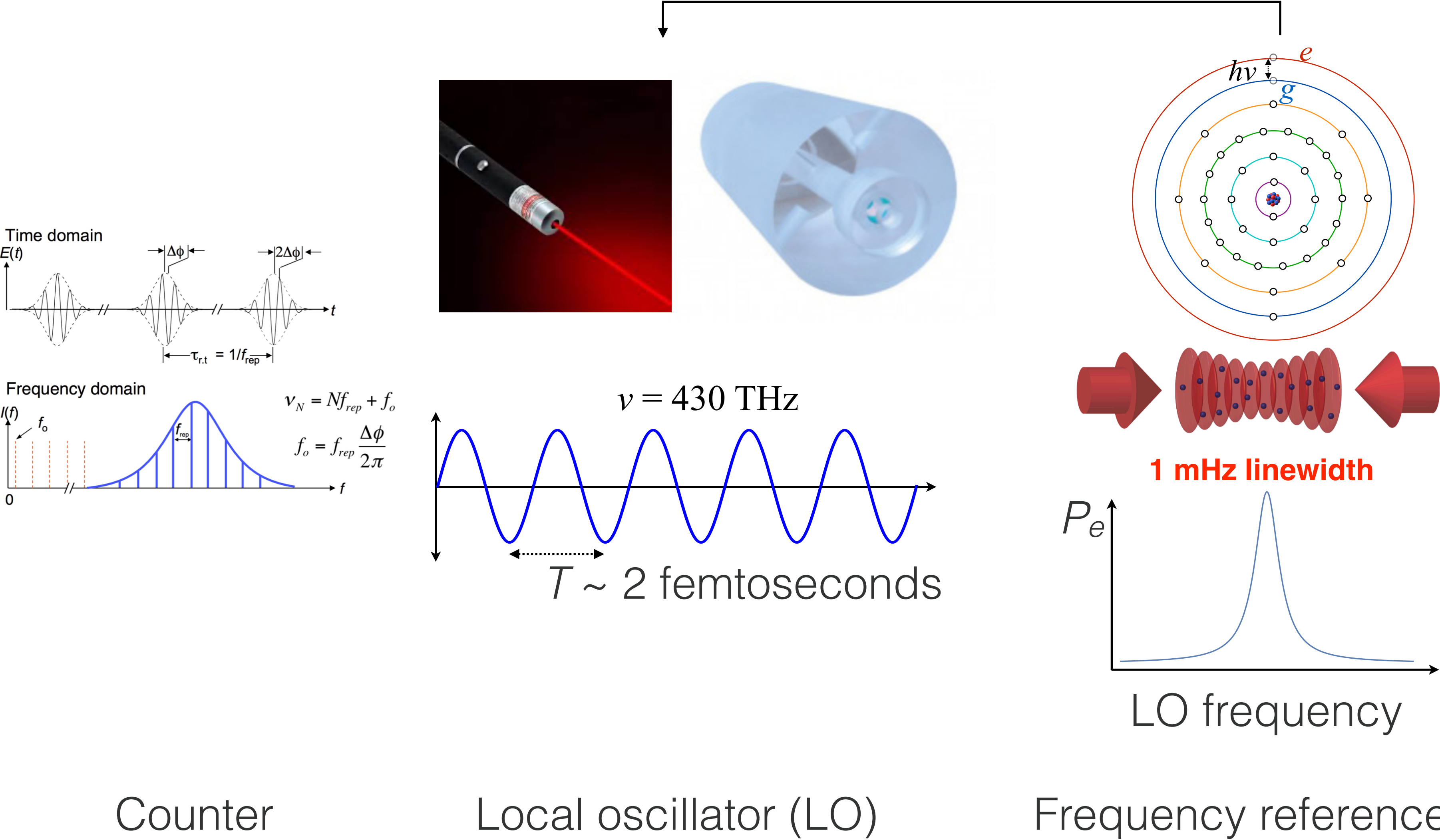


# 40 cm ultrastable ULE cavity

Linewidth: 26 mHz  
 $Q \sim 2 \times 10^{16}$   
 $\Delta L \sim 10^{-16} \text{ m}$  (1/10th  $r_{\text{proton}}$ )

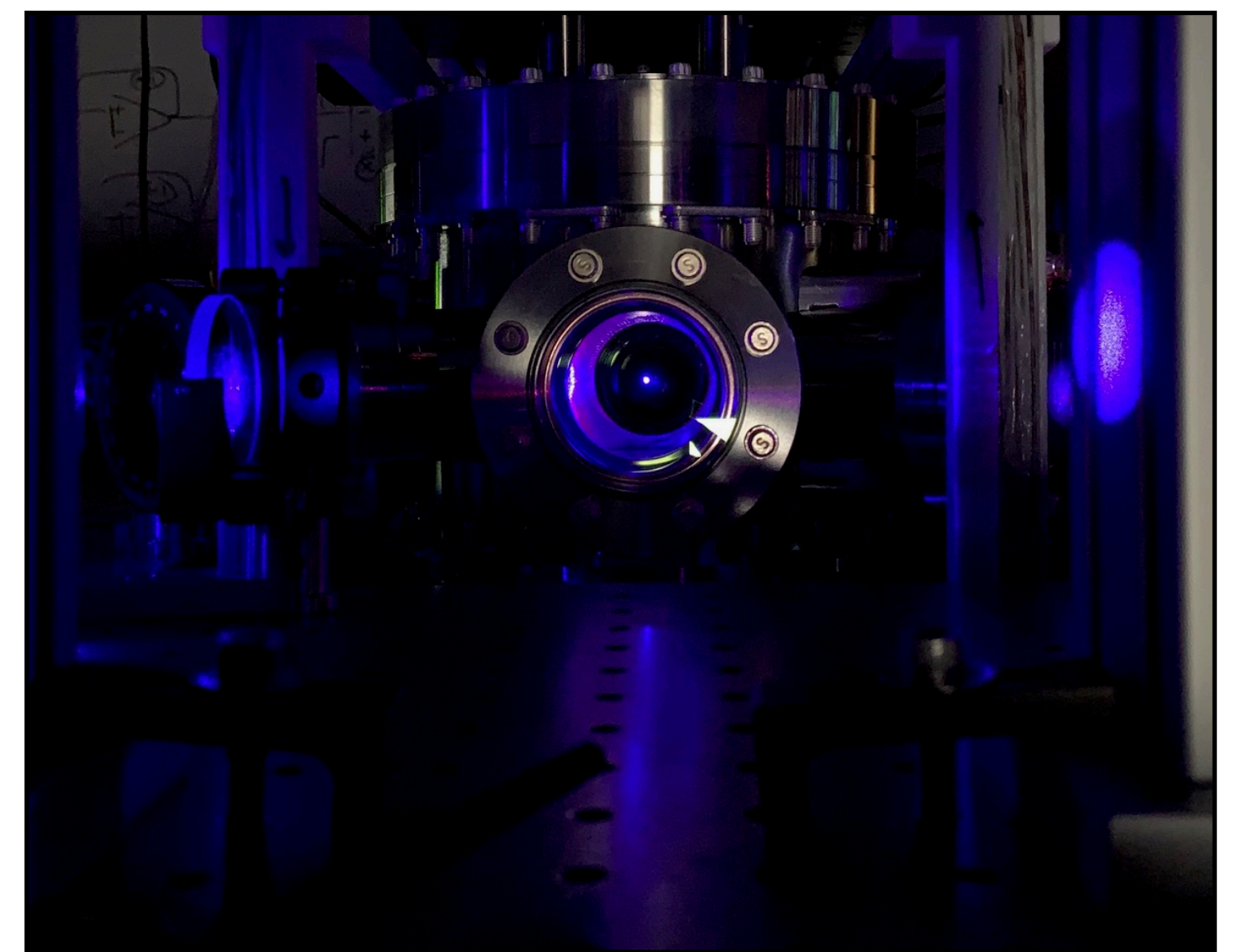
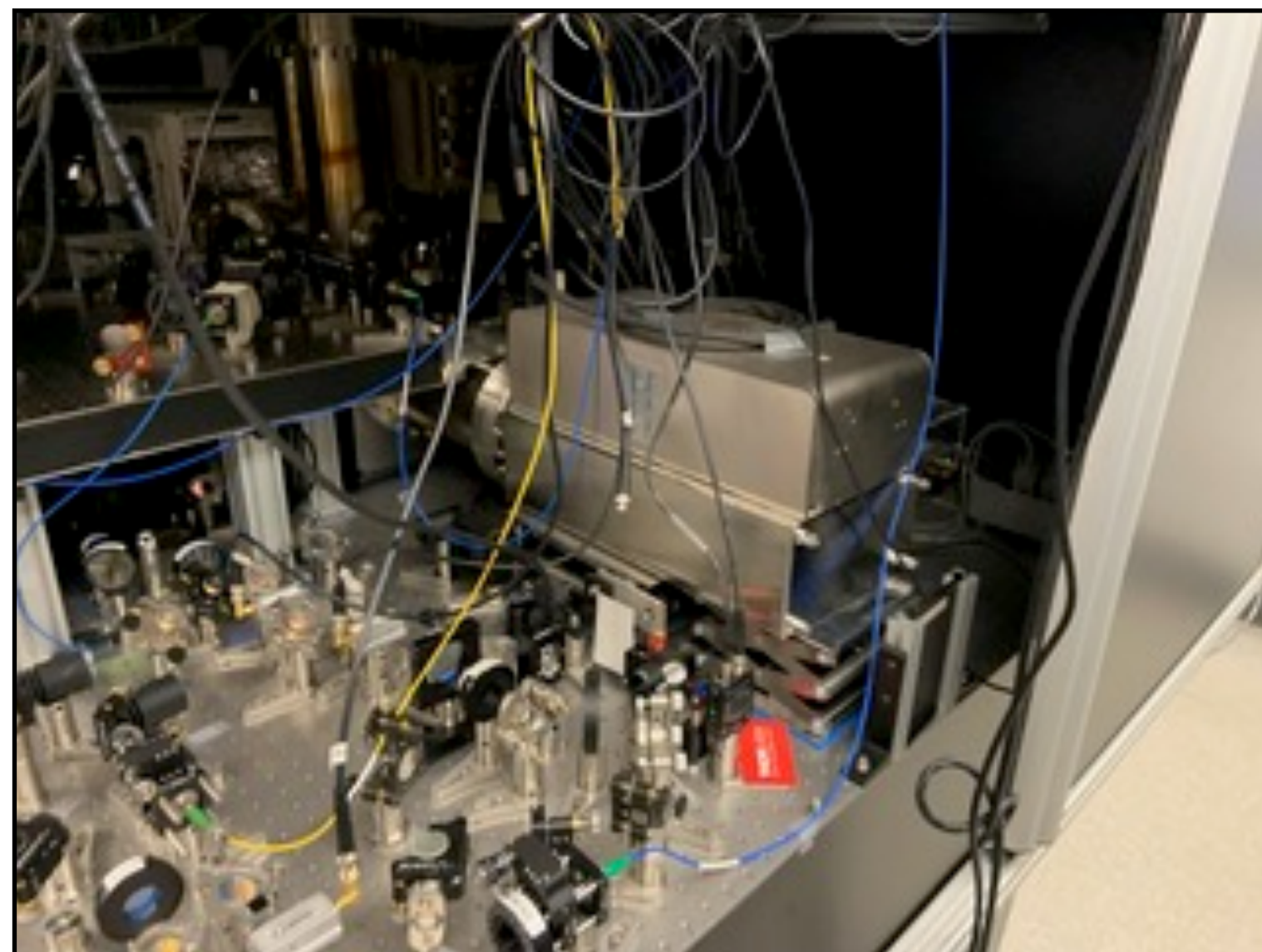
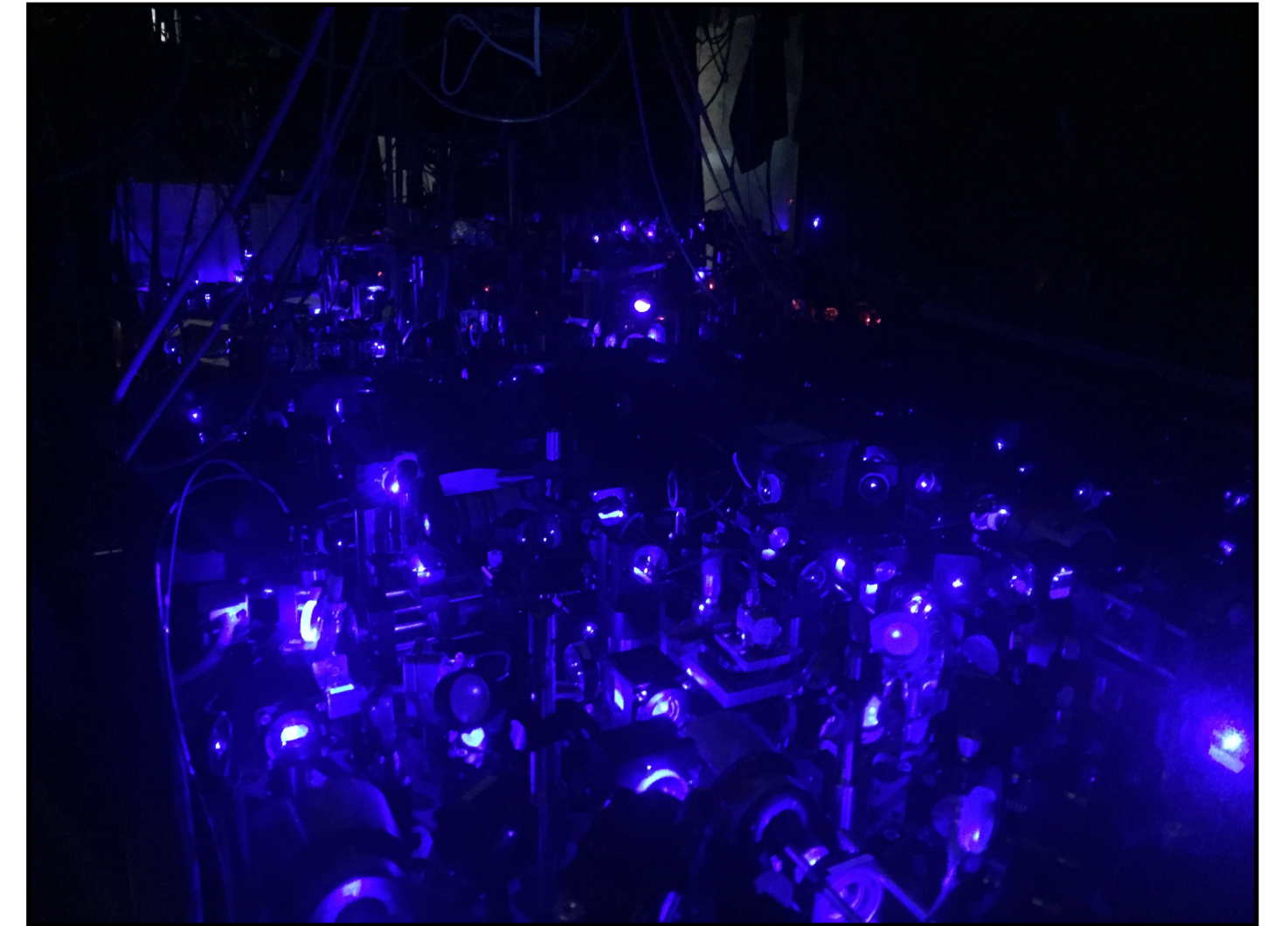
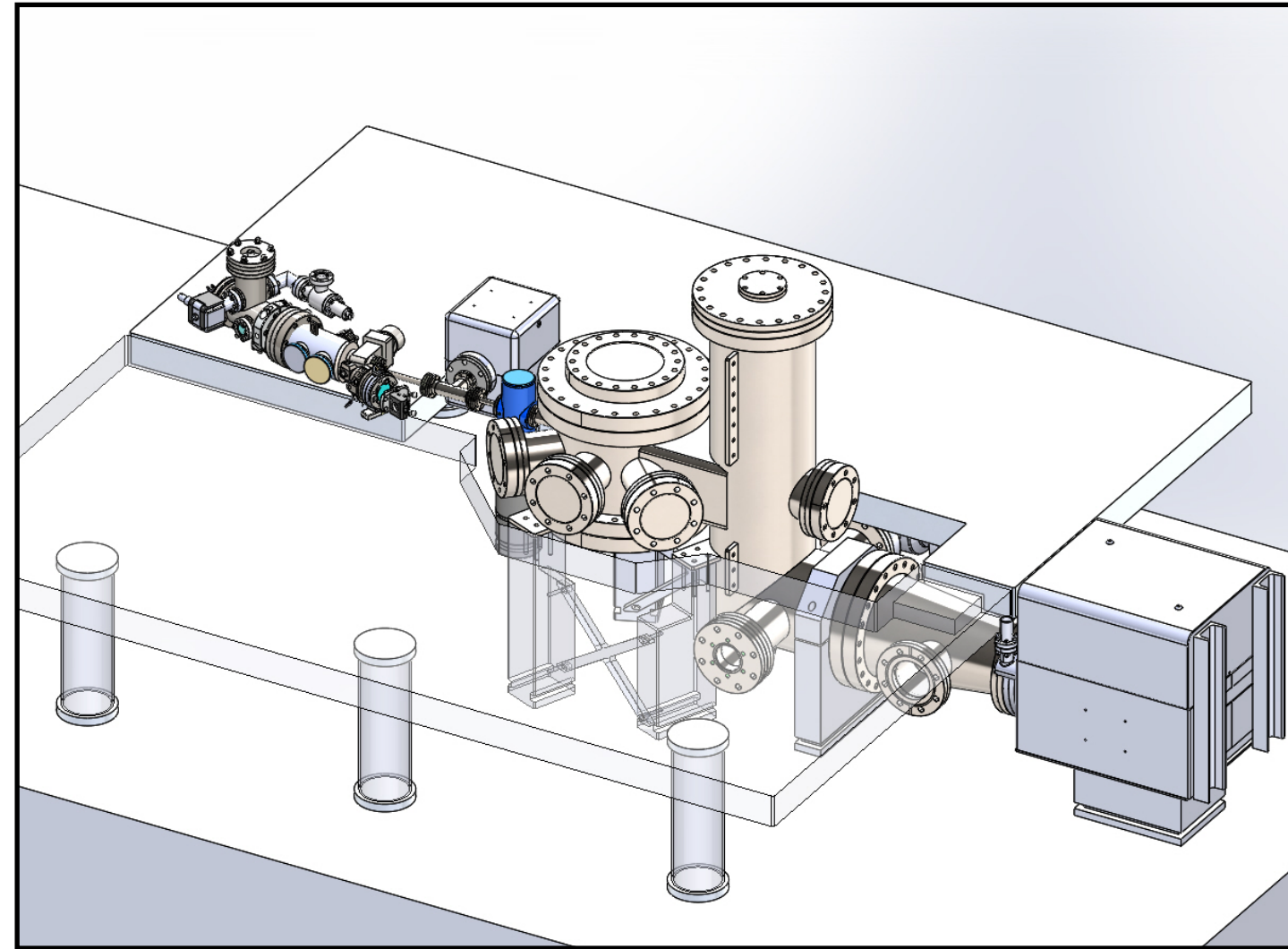


# Optical lattice clock





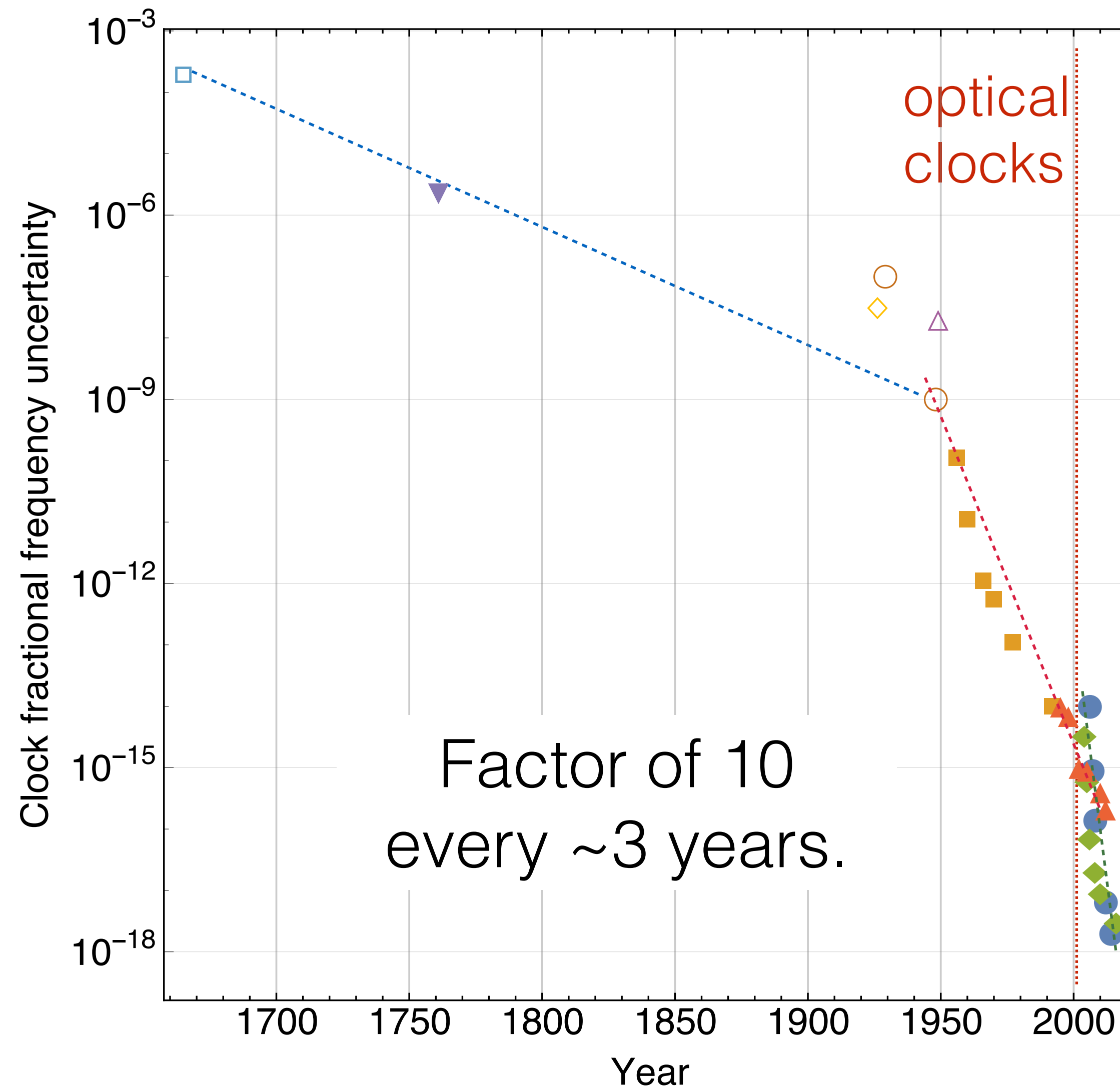
# UC Berkeley strontium optical lattice clock





# Clock progress, 1656 - 2018

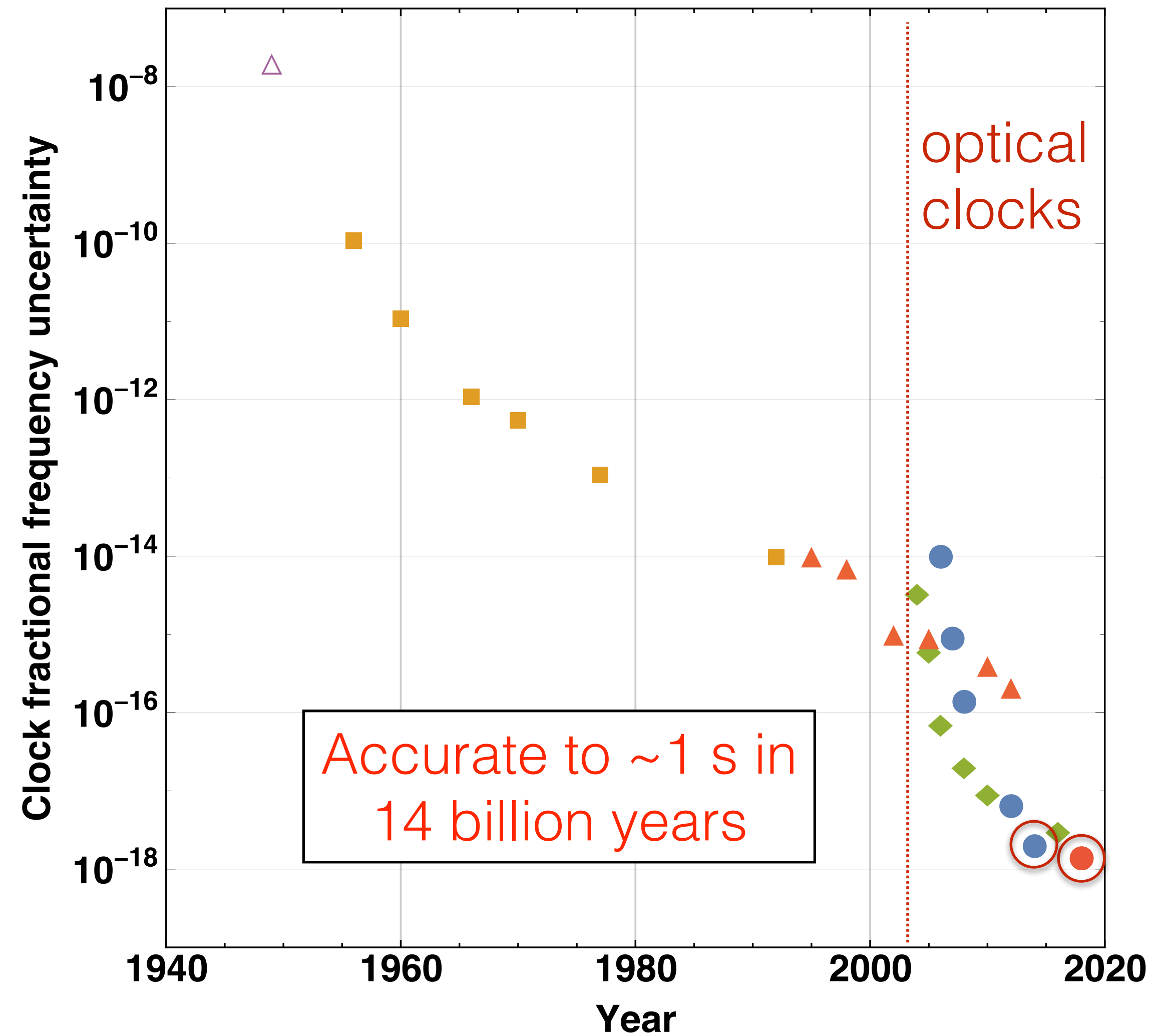
- Huygen pendulum
- ▼ Harrison H4
- ◇ Shortt pendulum
- NBS quartz
- △ Ammonia maser
- Cs beam
- ▲ Cs fountain
- ◆ Optical ion
- Optical lattice



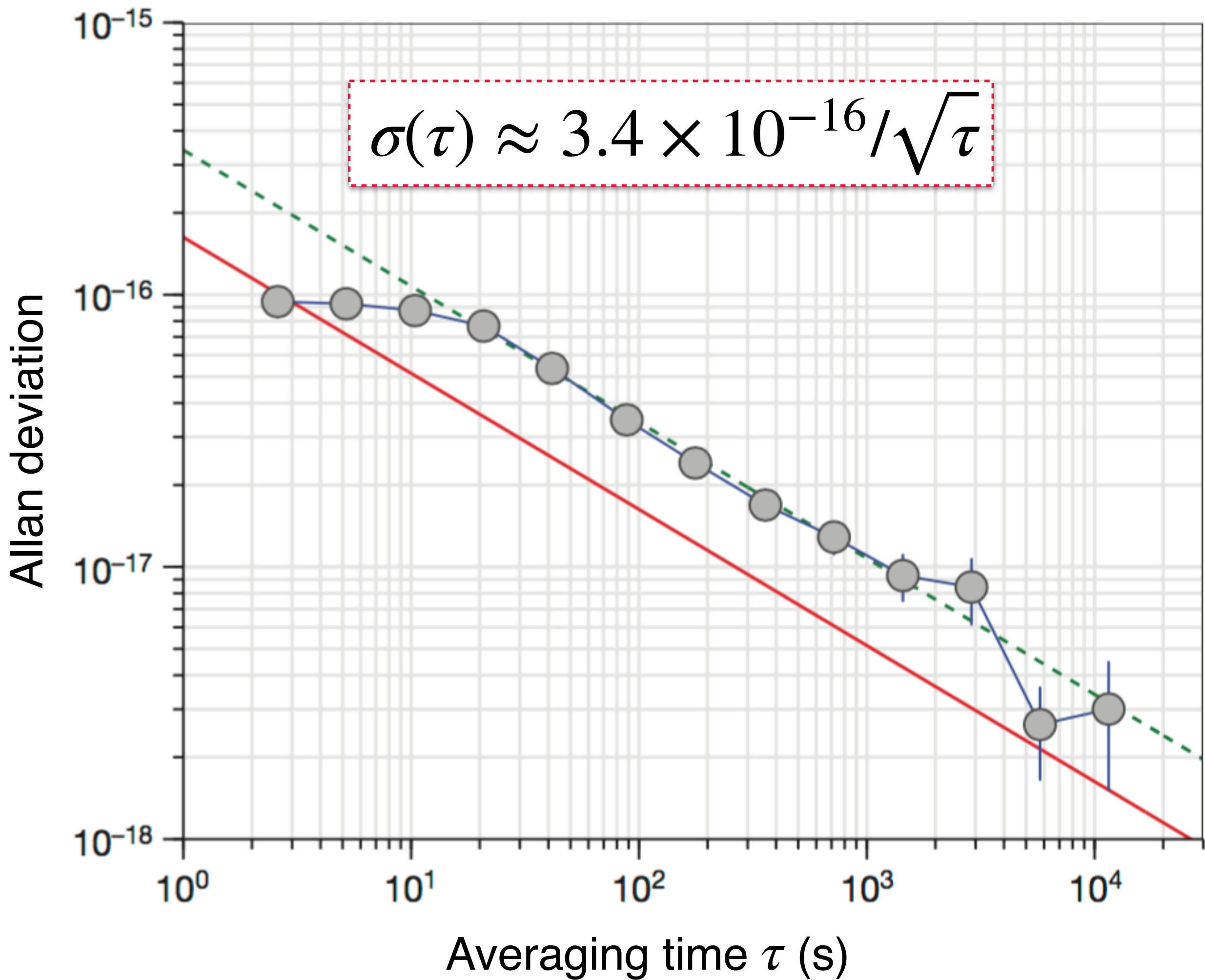


# Atomic clock progress, 1949 - 2019

- △ Ammonia maser
- Cs beam
- ▲ Cs fountain
- ◆ Ion optical clock
- Sr optical lattice clock
- Yb optical lattice clock



# Figures of merit for clock performance:

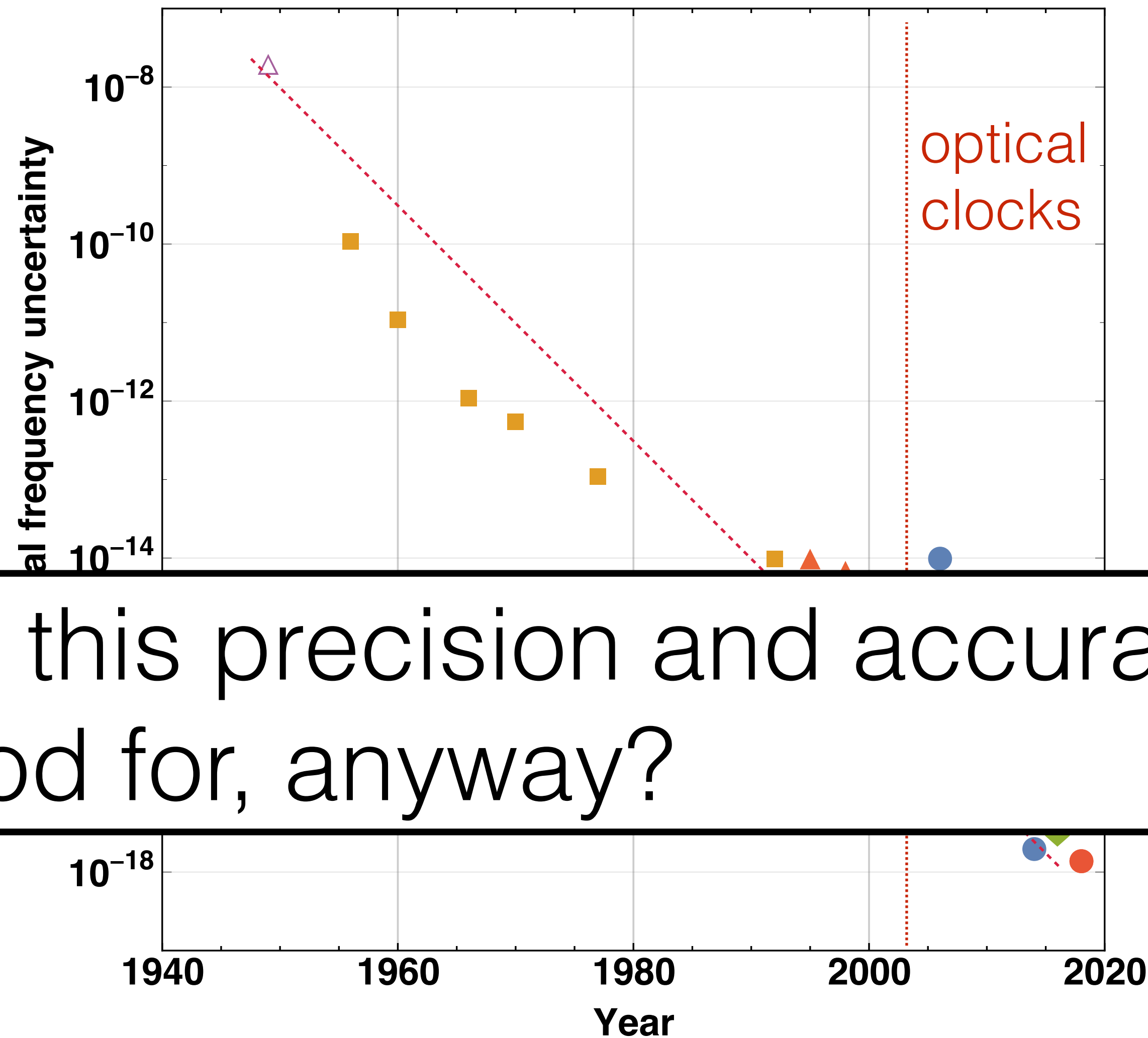


| Shifts and Uncertainties in Fractional Frequency Units $\times 10^{-18}$ |                  |             |                   |             |
|--------------------------------------------------------------------------|------------------|-------------|-------------------|-------------|
| Systematic Effect                                                        | First Evaluation |             | Second Evaluation |             |
|                                                                          | Shift            | Uncertainty | Shift             | Uncertainty |
| BBR Static                                                               | -4962.9          | 1.8         | -4562.1           | 0.3         |
| BBR Dynamic                                                              | -346             | 3.7         | -305.3            | 1.4         |
| Density Shift                                                            | -4.7             | 0.6         | -3.5              | 0.4         |
| Lattice Stark                                                            | -461.5           | 3.7         | -1.3              | 1.1         |
| Probe AC Stark                                                           | 0.8              | 1.3         | 0.0               | 0.0         |
| 1 <sup>st</sup> Order Zeeman                                             | -0.2             | 1.1         | -0.2              | 0.2         |
| 2 <sup>nd</sup> Order Zeeman                                             | -144.5           | 1.2         | -51.7             | 0.3         |
| Line pulling and tunneling                                               | 0.0              | <0.1        | 0.0               | <0.1        |
| DC Stark                                                                 | -3.5             | 2           | 0.0               | 0.1         |
| Background gas collisions                                                | 0.0              | 0.6         | 0.0               | <0.6        |
| AOM Phase Chirp                                                          | -1               | 1           | 0.6               | 0.4         |
| 2 <sup>nd</sup> -Order Doppler                                           | 0.0              | <0.1        | 0.0               | <0.1        |
| Servo Error                                                              | 0.4              | 0.6         | -0.5              | 0.4         |
| Total                                                                    | -5923.1          | 6.4         | -4924.0           | 2.1         |



# Atomic clock progress, 1949 - 2019

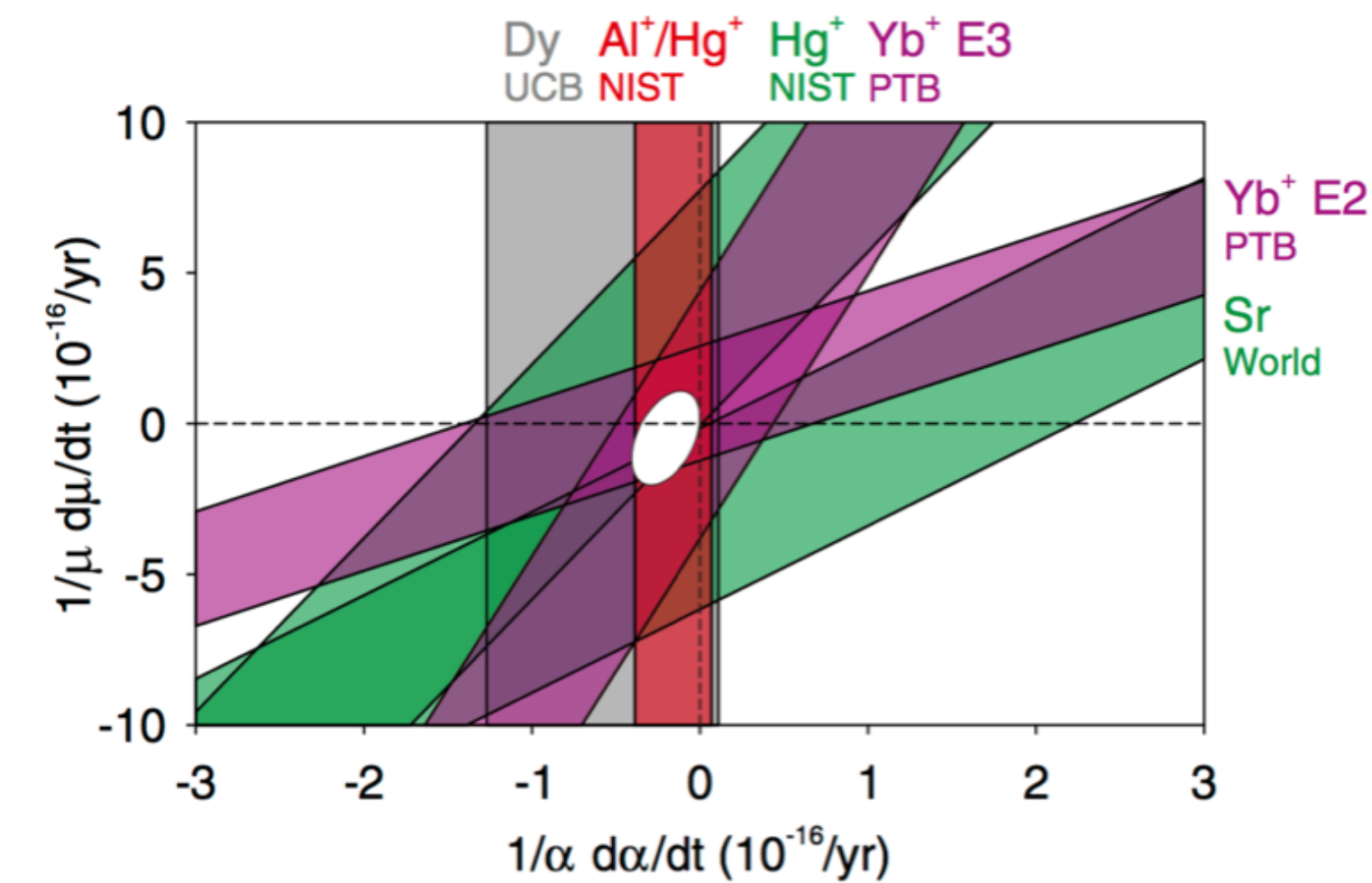
- △ Ammonia maser
- Cs beam
- ▲ Cs fountain
- ◆ Ion optical clock
- Sr optical lattice clock
- Yb optical lattice clock



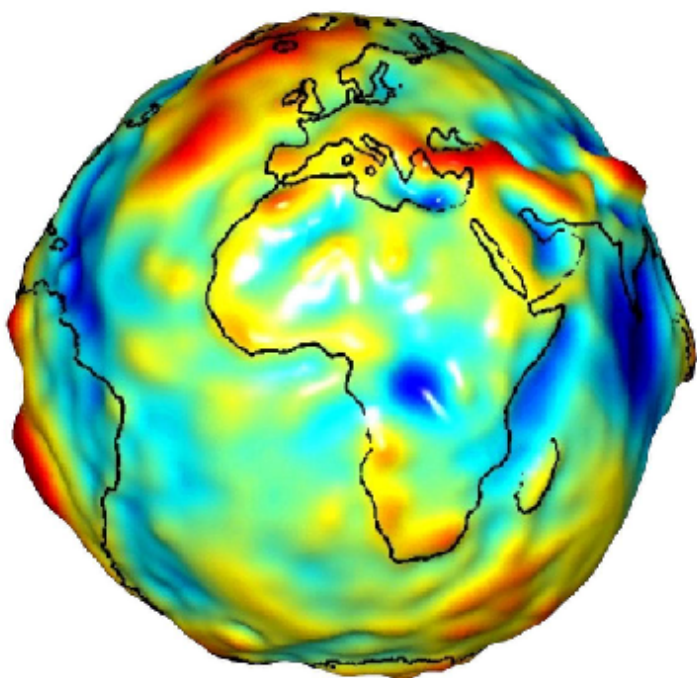
What (else) is all this precision and accuracy good for, anyway?

# Novel applications of optical clocks

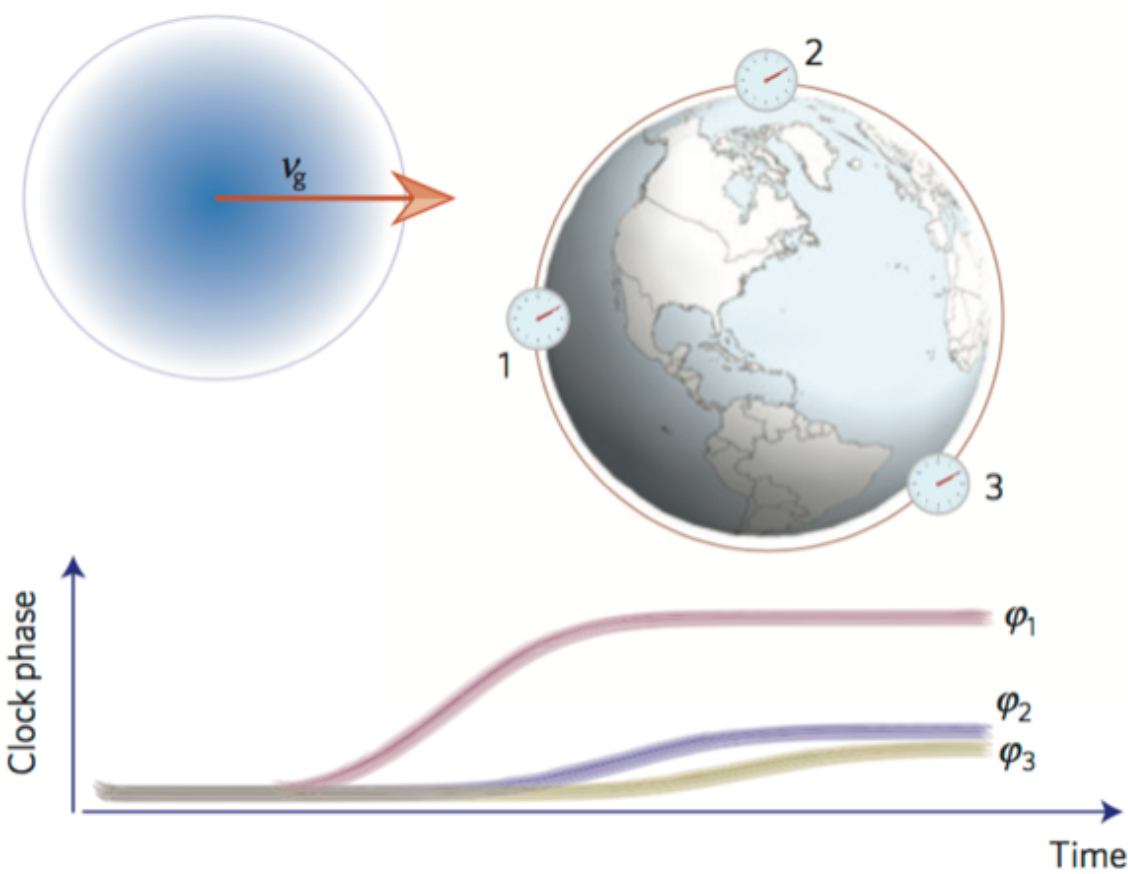
## Searches for new physics



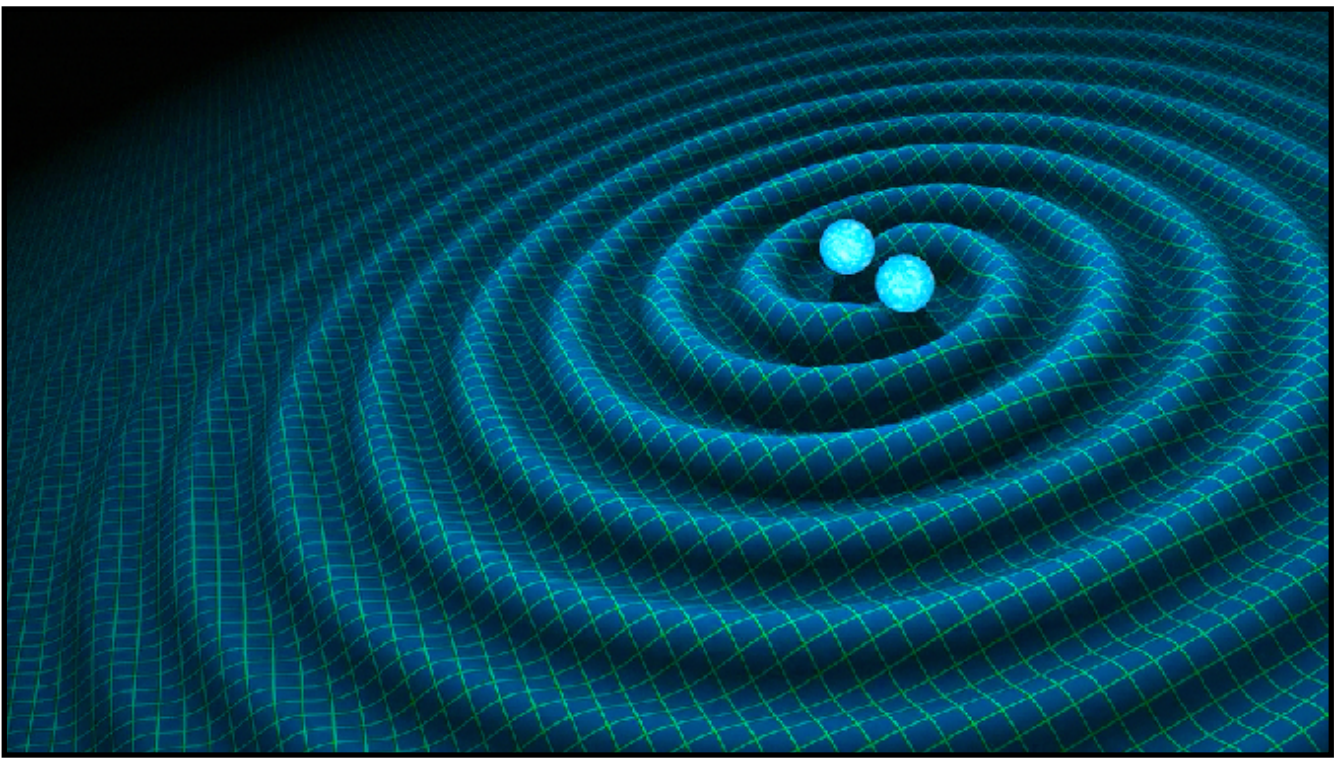
## Geodesy



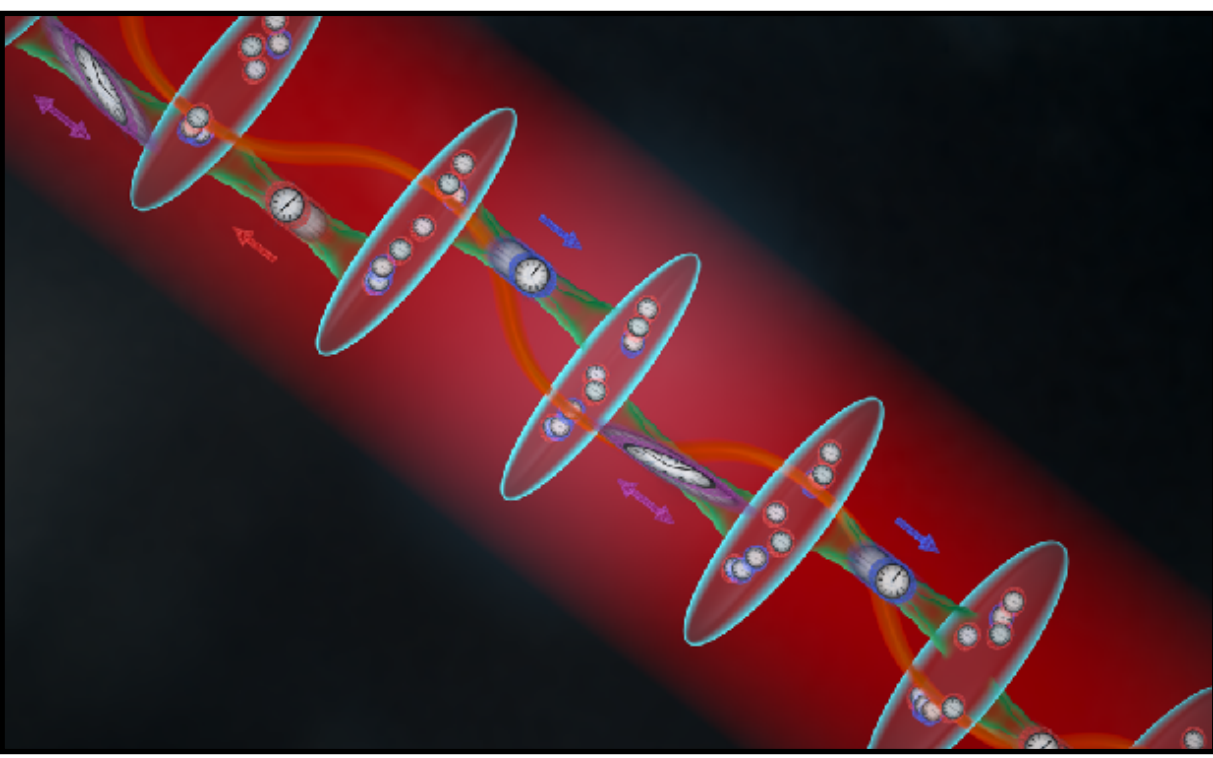
## Dark matter detection



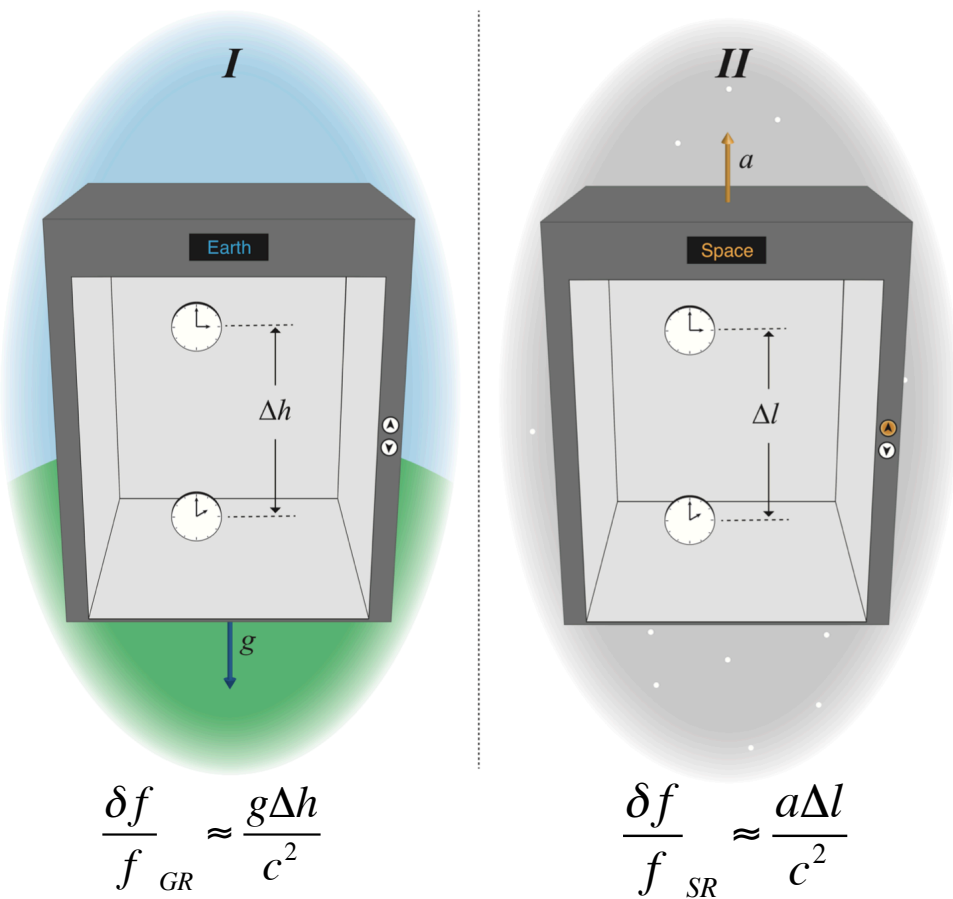
## GW detection



## Quantum simulation



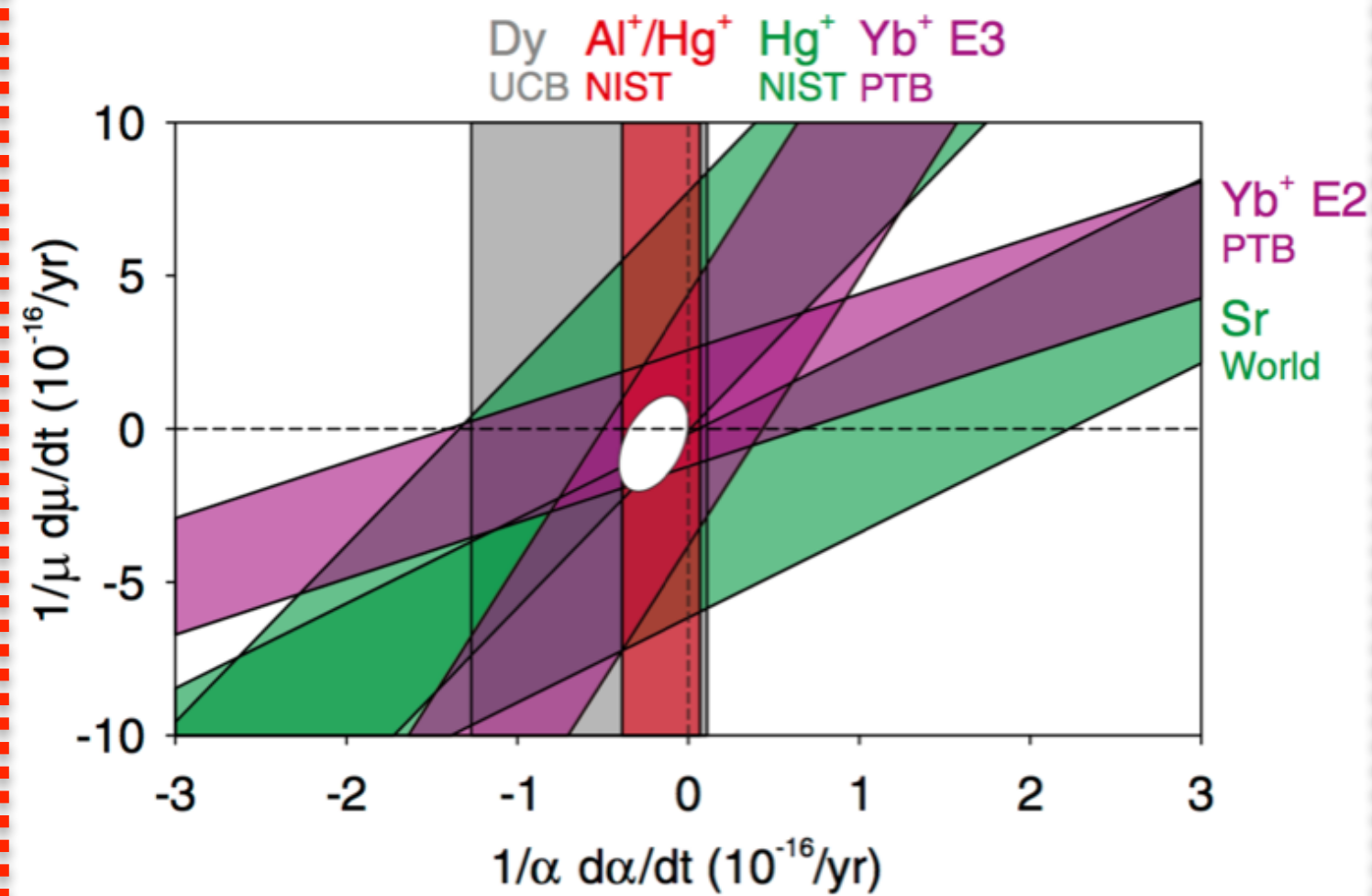
## Tests of relativity



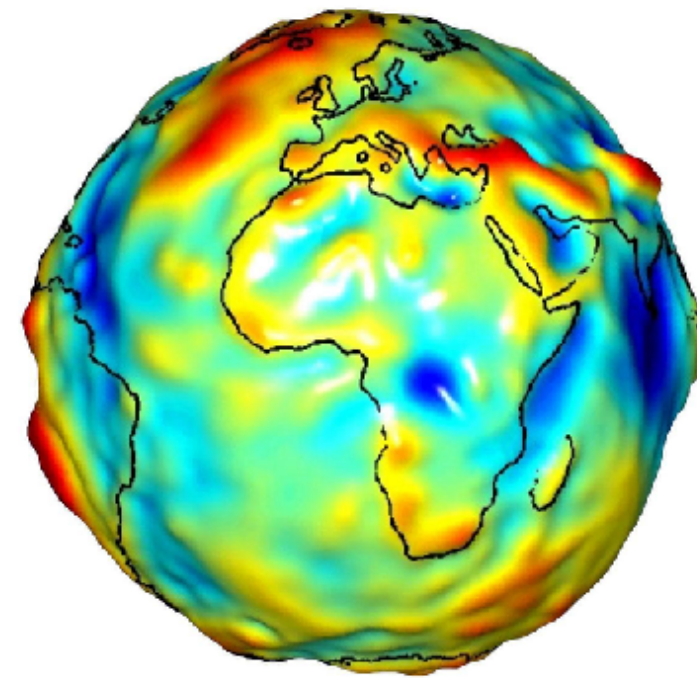


# Optical clocks in space for fundamental physics

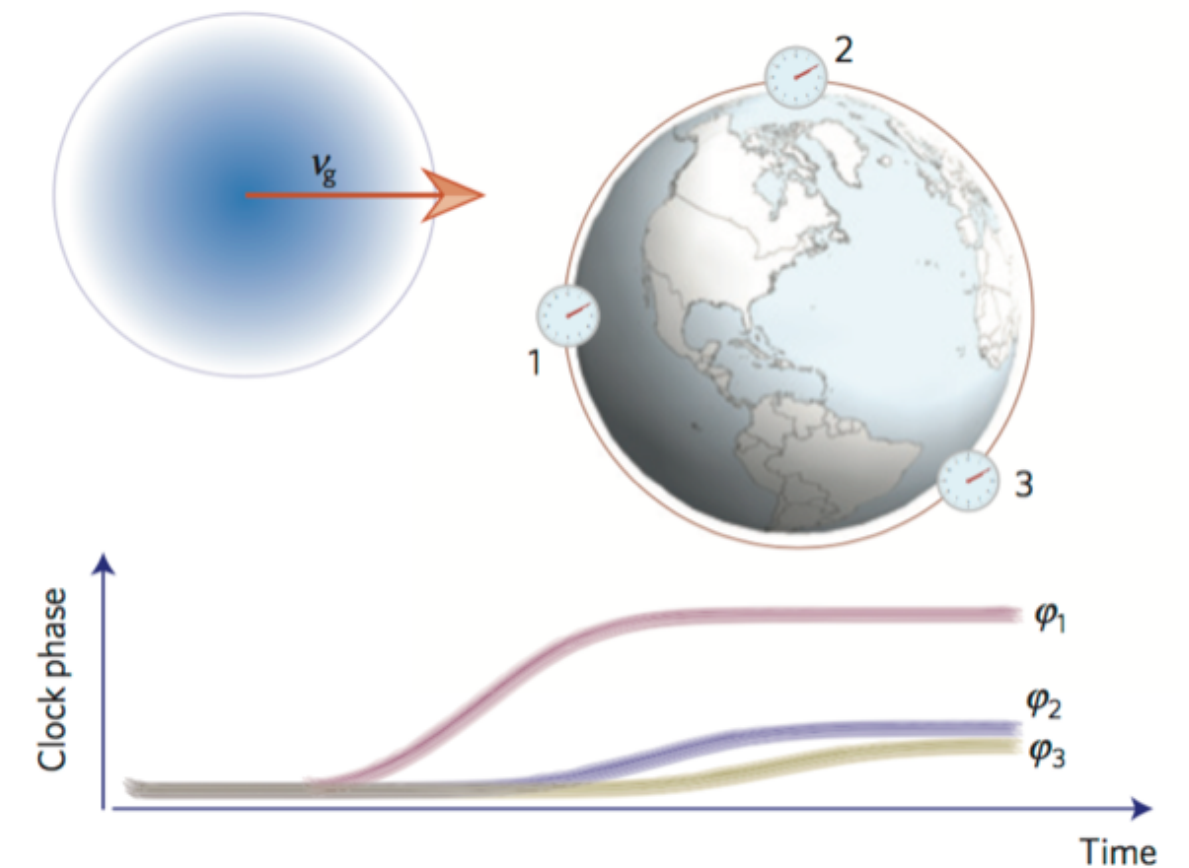
## Searches for new physics



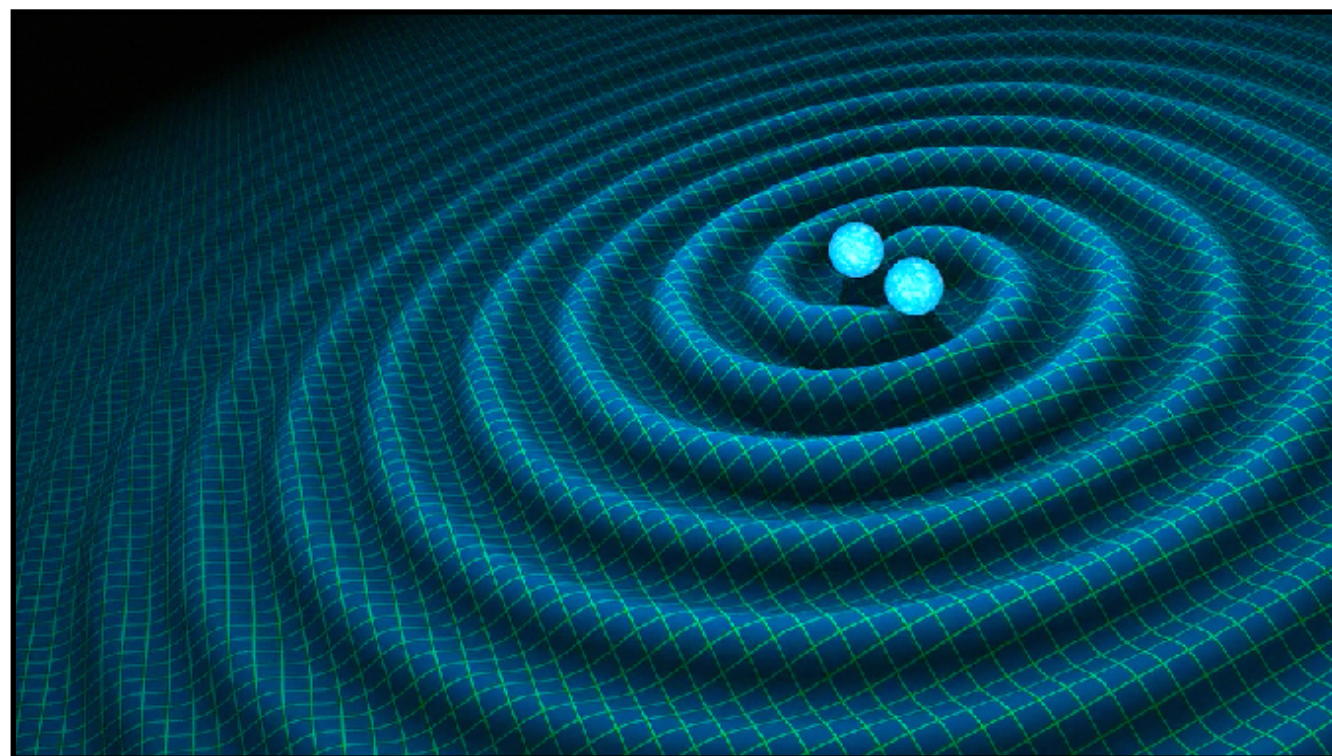
## Geodesy



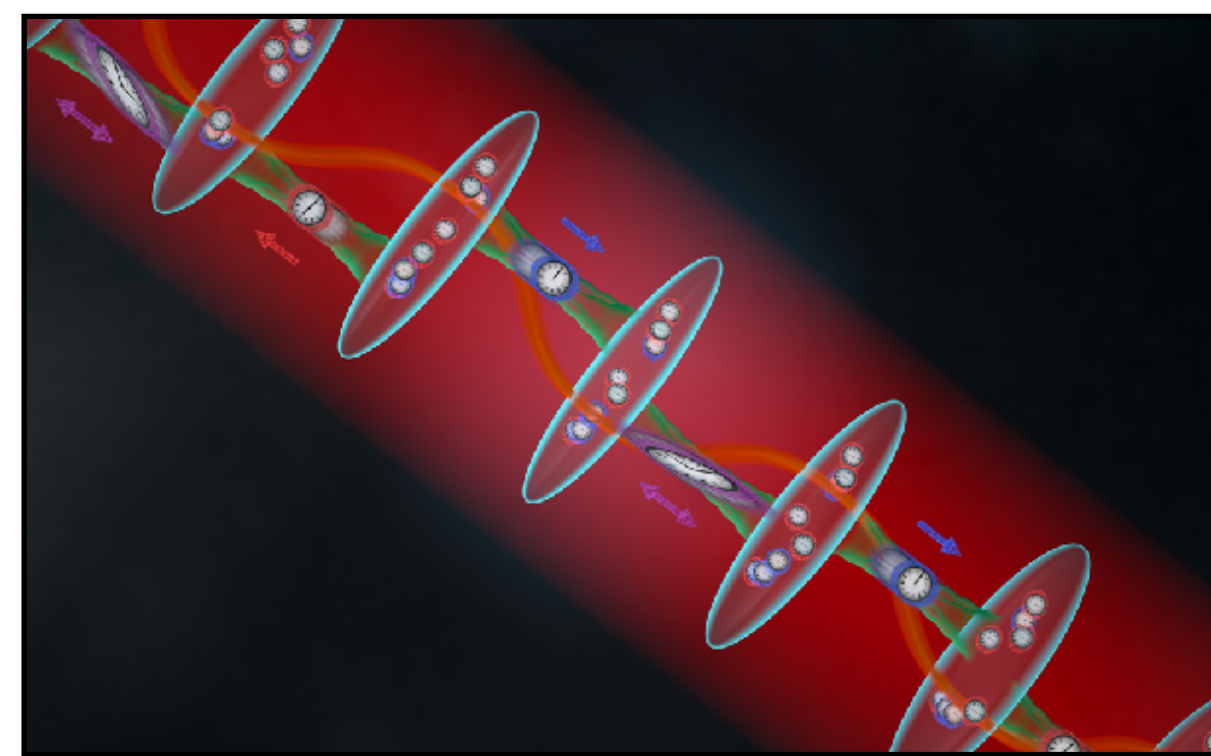
## Dark matter detection



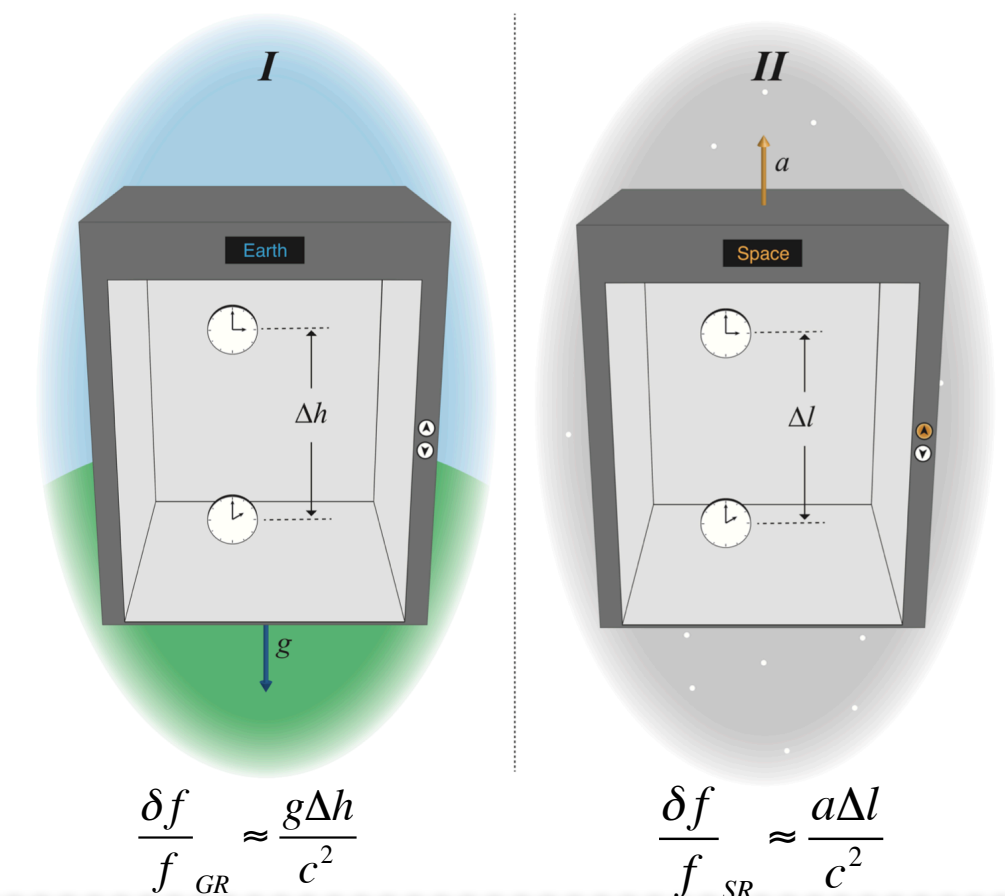
## GW detection



## Quantum simulation



## Tests of relativity



Huntemann *et al.* *PRL* (2014); Takano *et al.* *Nature Photonics* (2016); Dereviako, Pospelov, *Nature Physics* (2014)

SK *et al.* *PRD* (2016); SK *et al.*, *Nature* (2017); Arms, Serna, *arXiv* (2016)



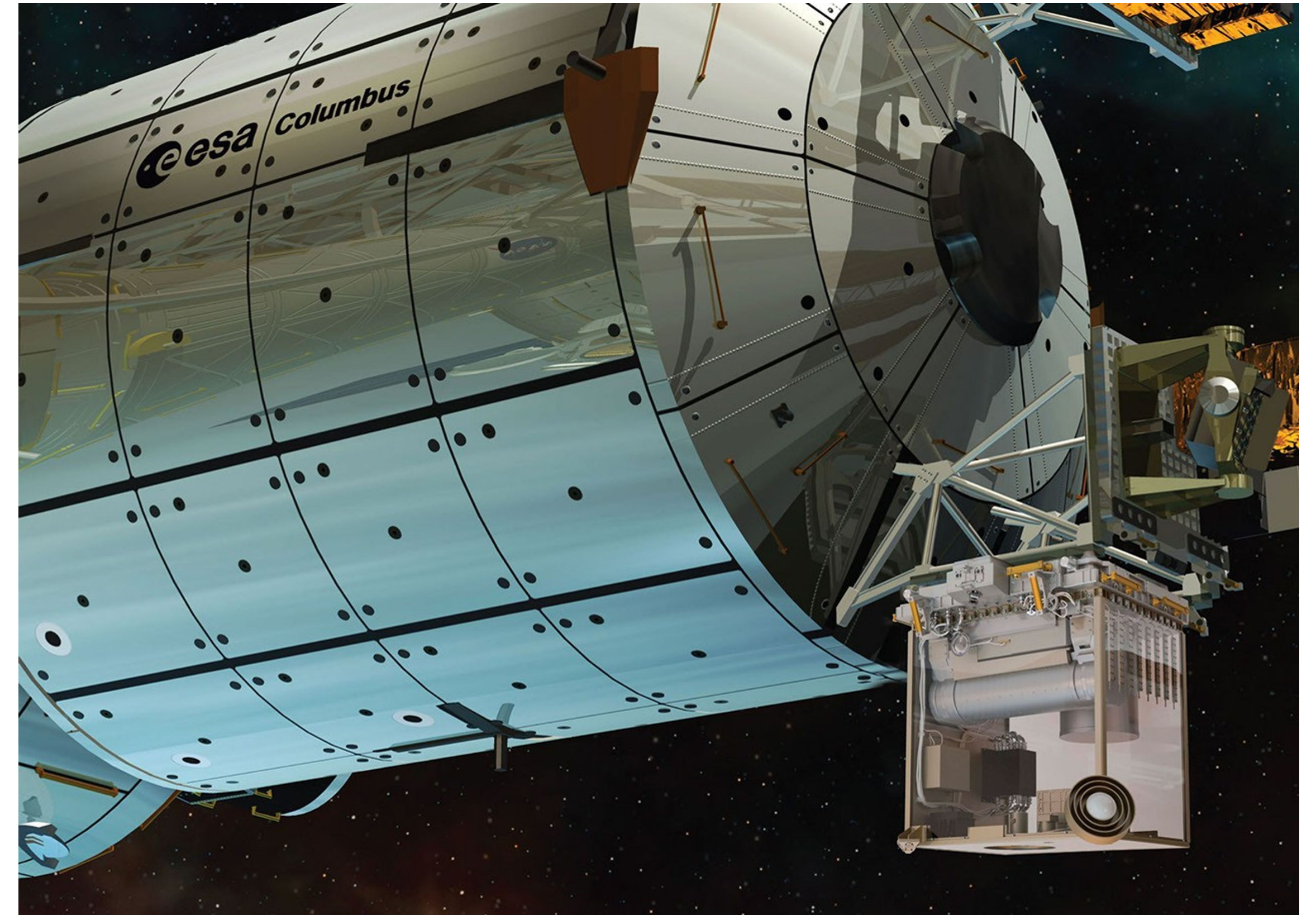
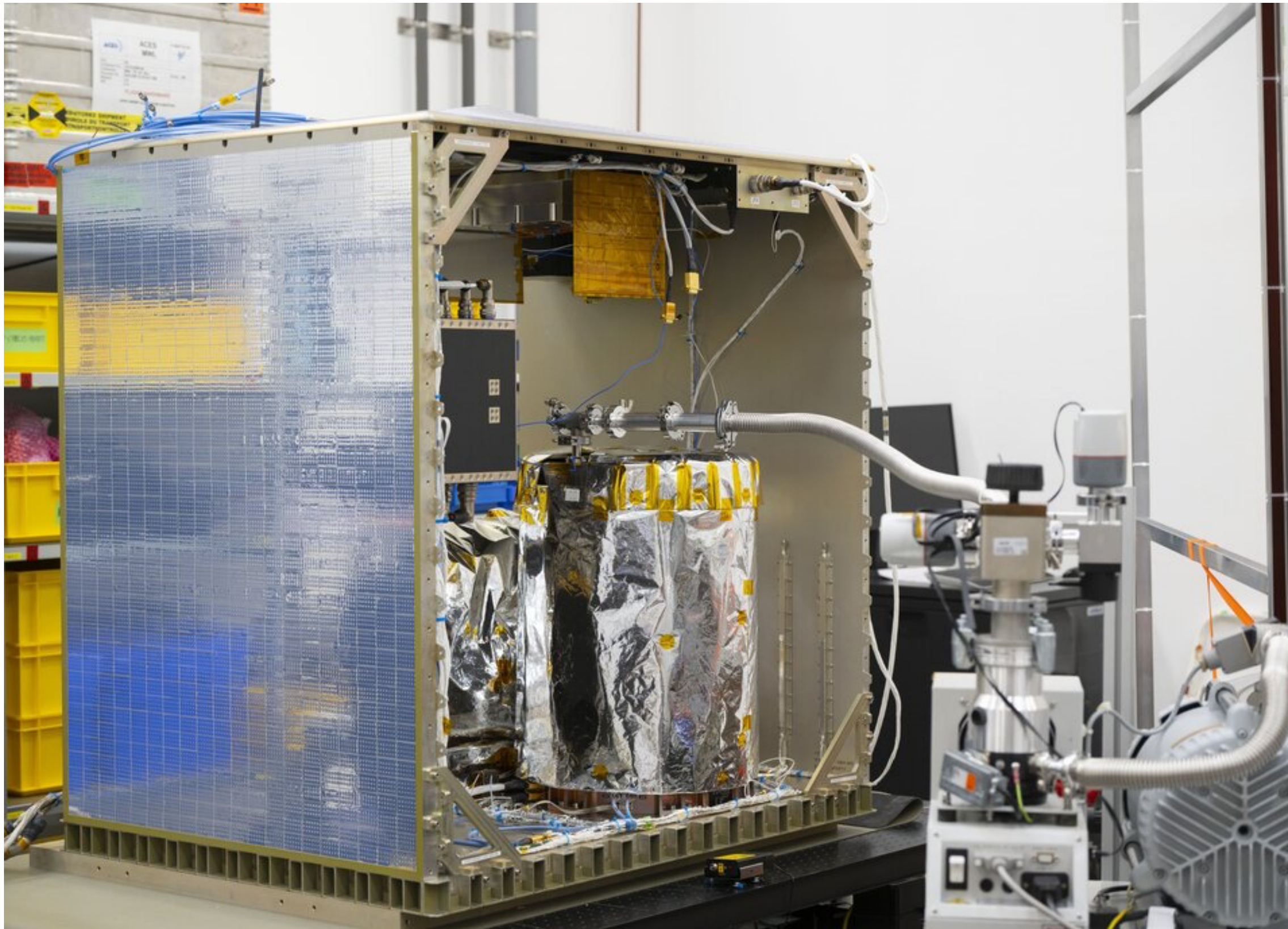
# Challenges

- Need low-SWaP and rad-hard lasers, opto-electronics, and cold-atom packages.
- Need to improve the robustness and autonomy of optical lattice clocks.
- Need ultra-stable clock lasers and frequency combs in low SWaP packages.



# State of the art space-based clocks

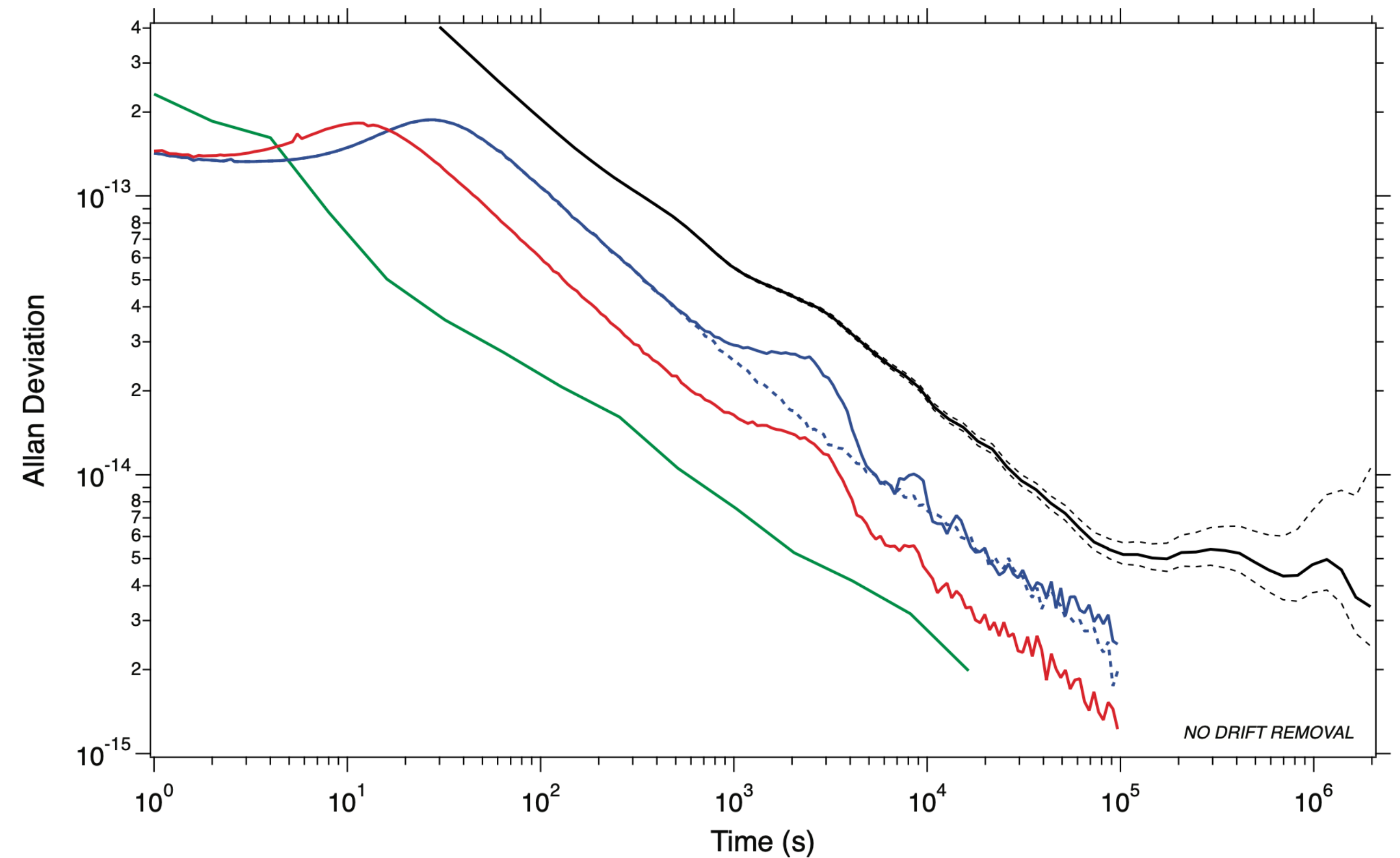
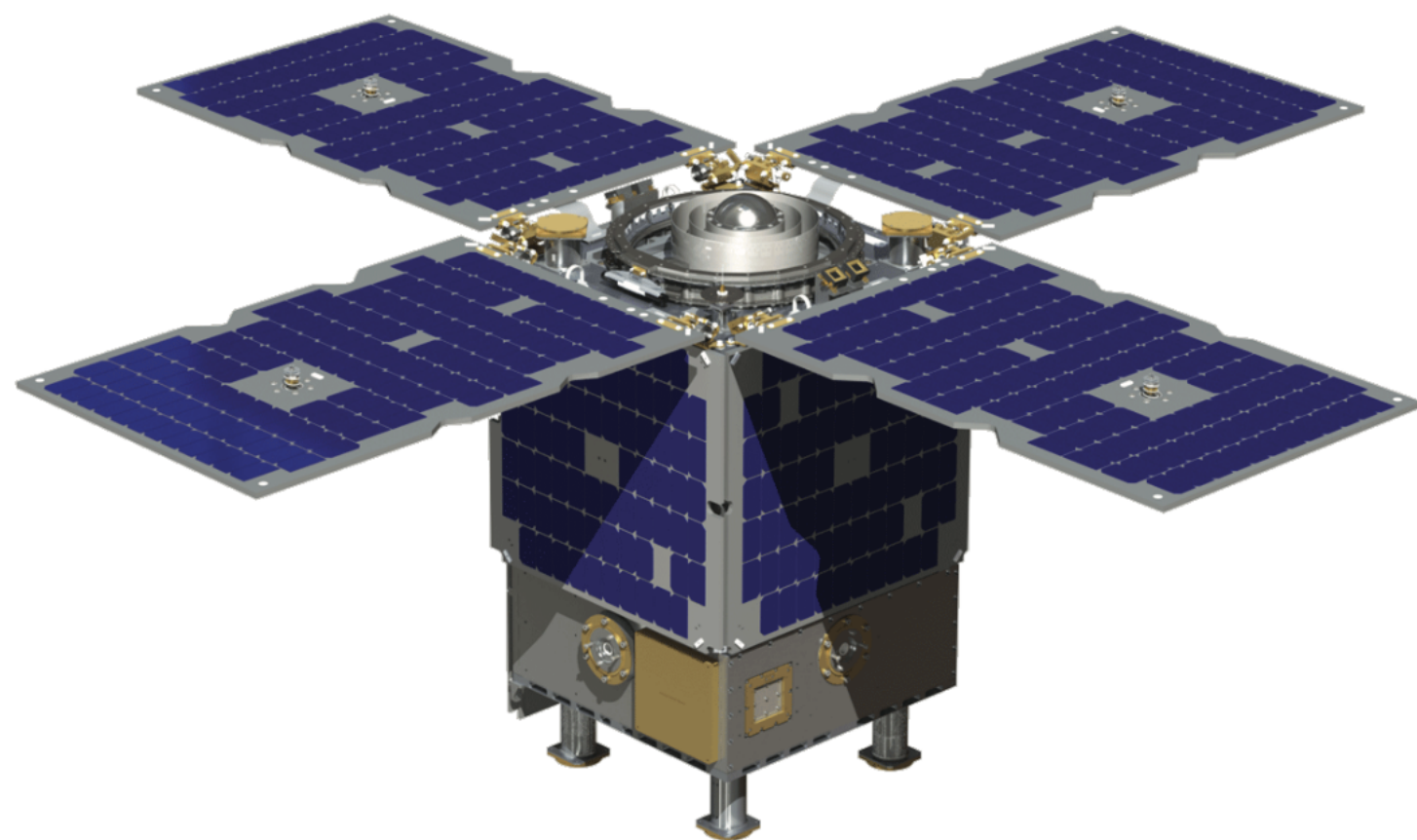
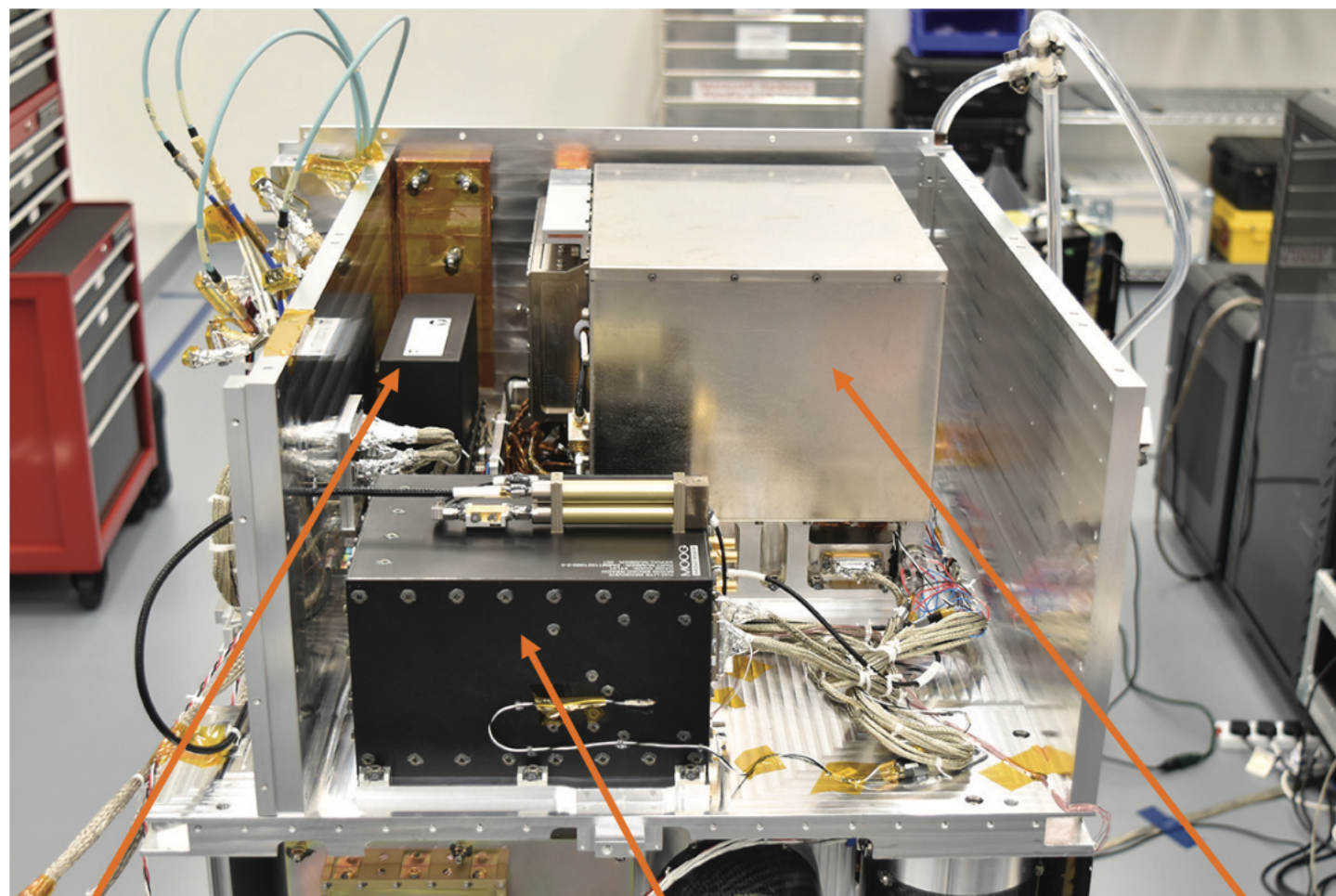
ACES: PHARAO (ultra-cold cesium clock) + SHM (space hydrogen maser)





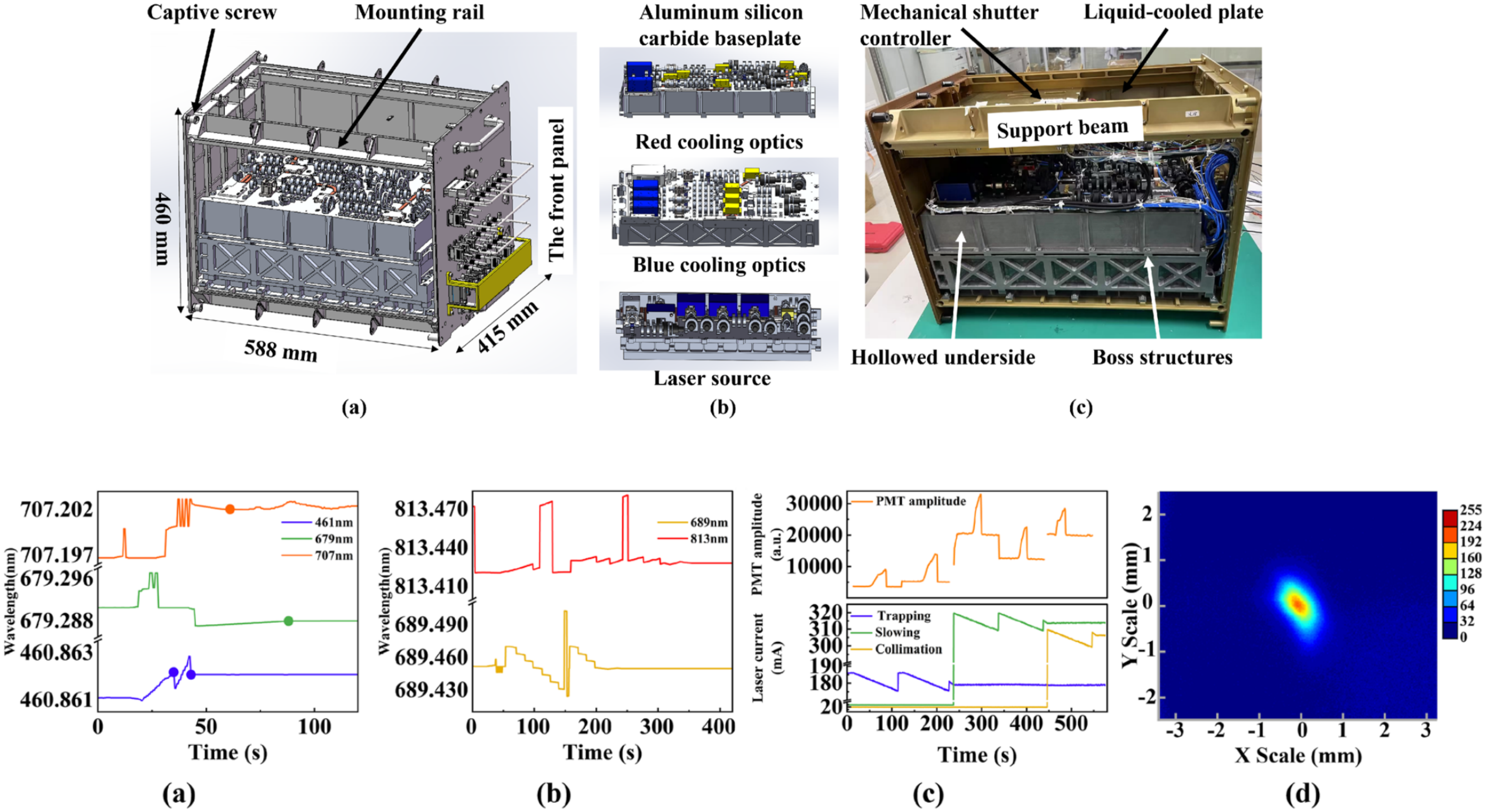
# State of the art space-based clocks

## Deep Space Atomic Clock (Hg<sup>+</sup> microwave clock)



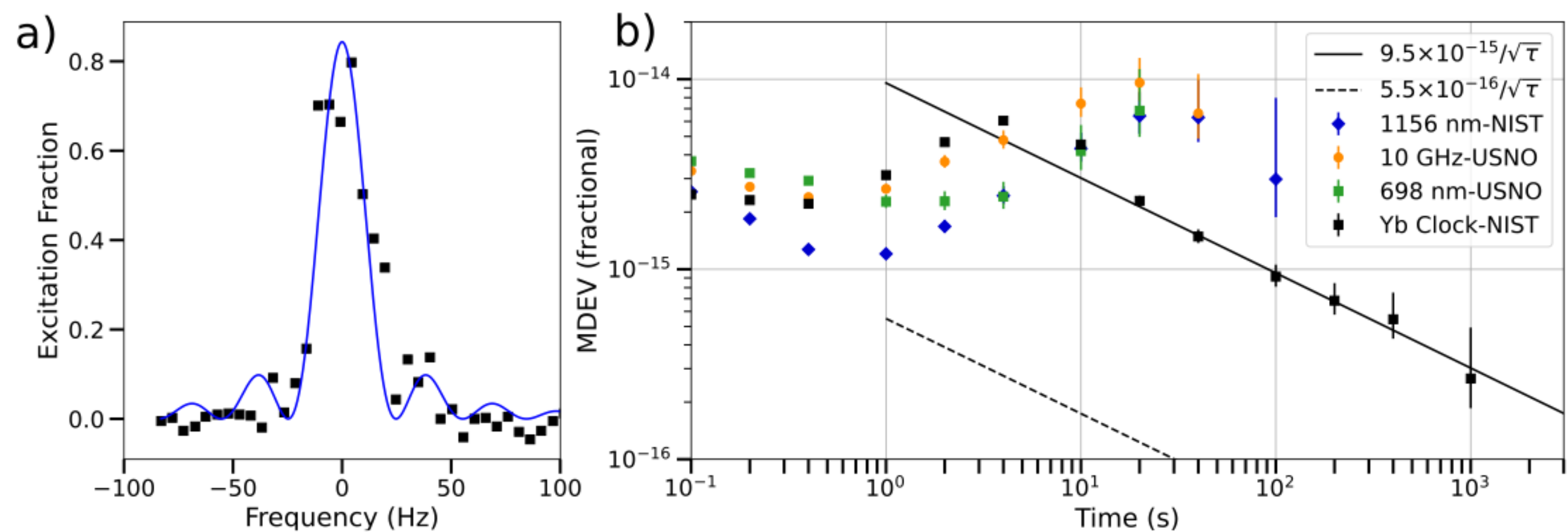
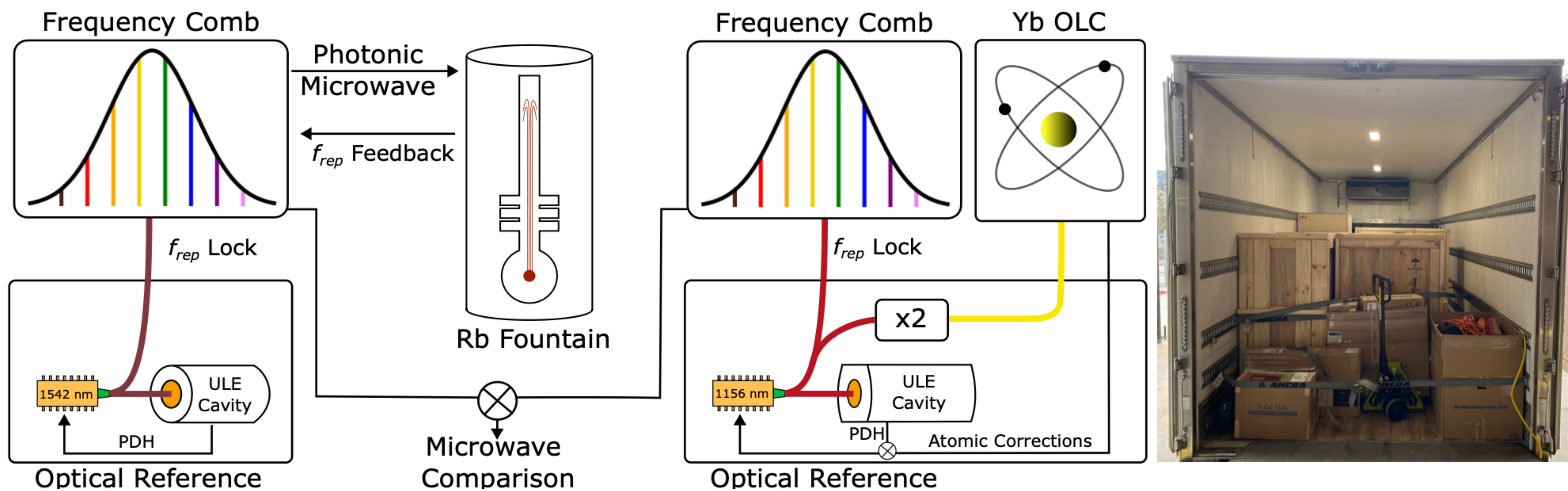


# State of the art space-based clocks





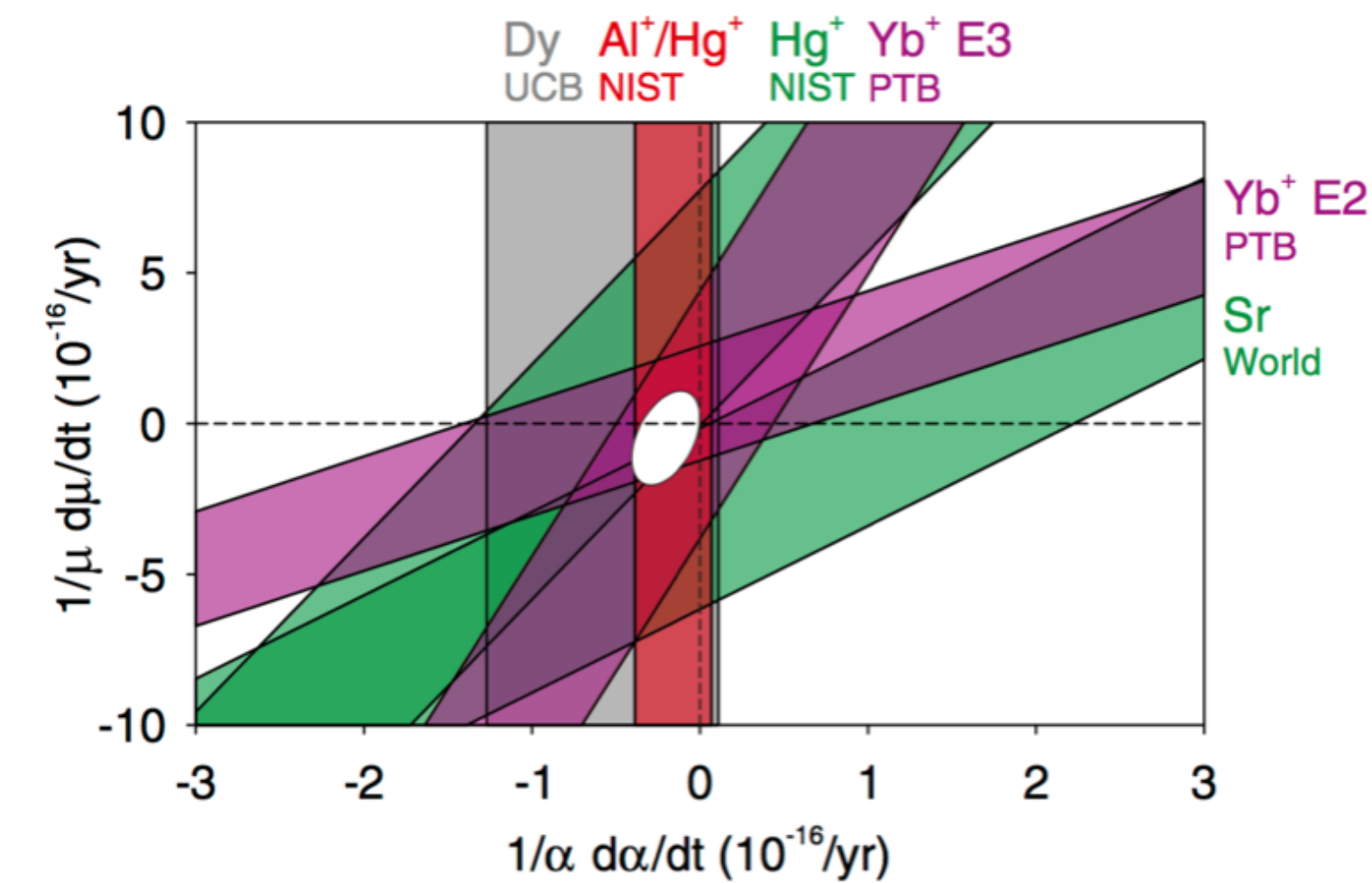
# State of the art portable optical clocks



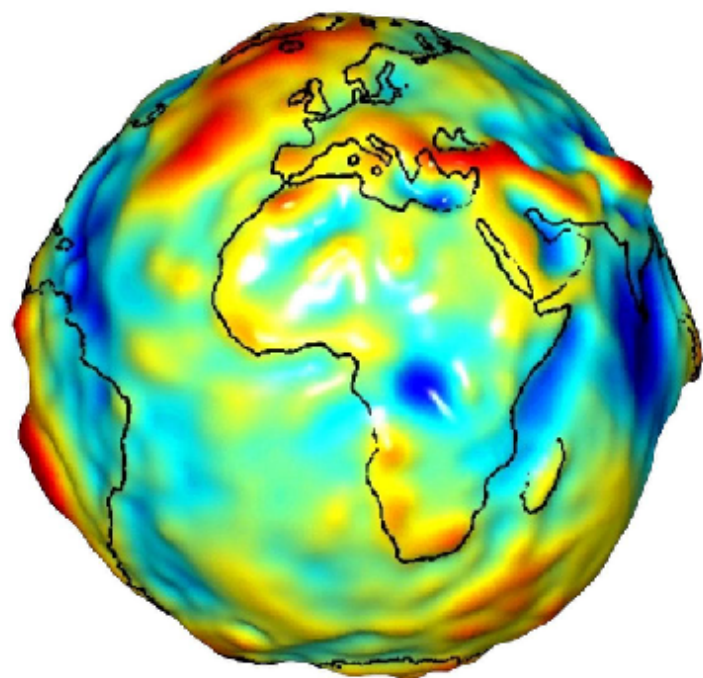


# Optical clocks in space for fundamental physics

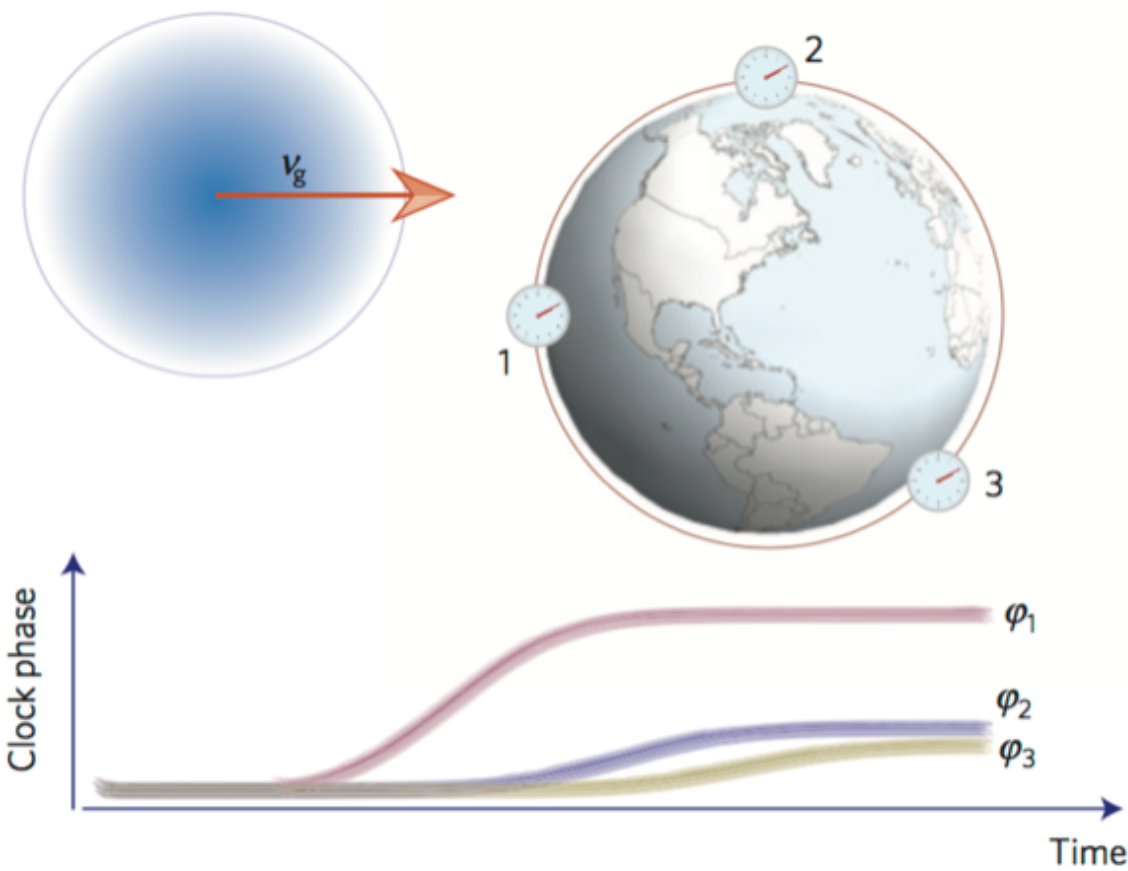
## Searches for new physics



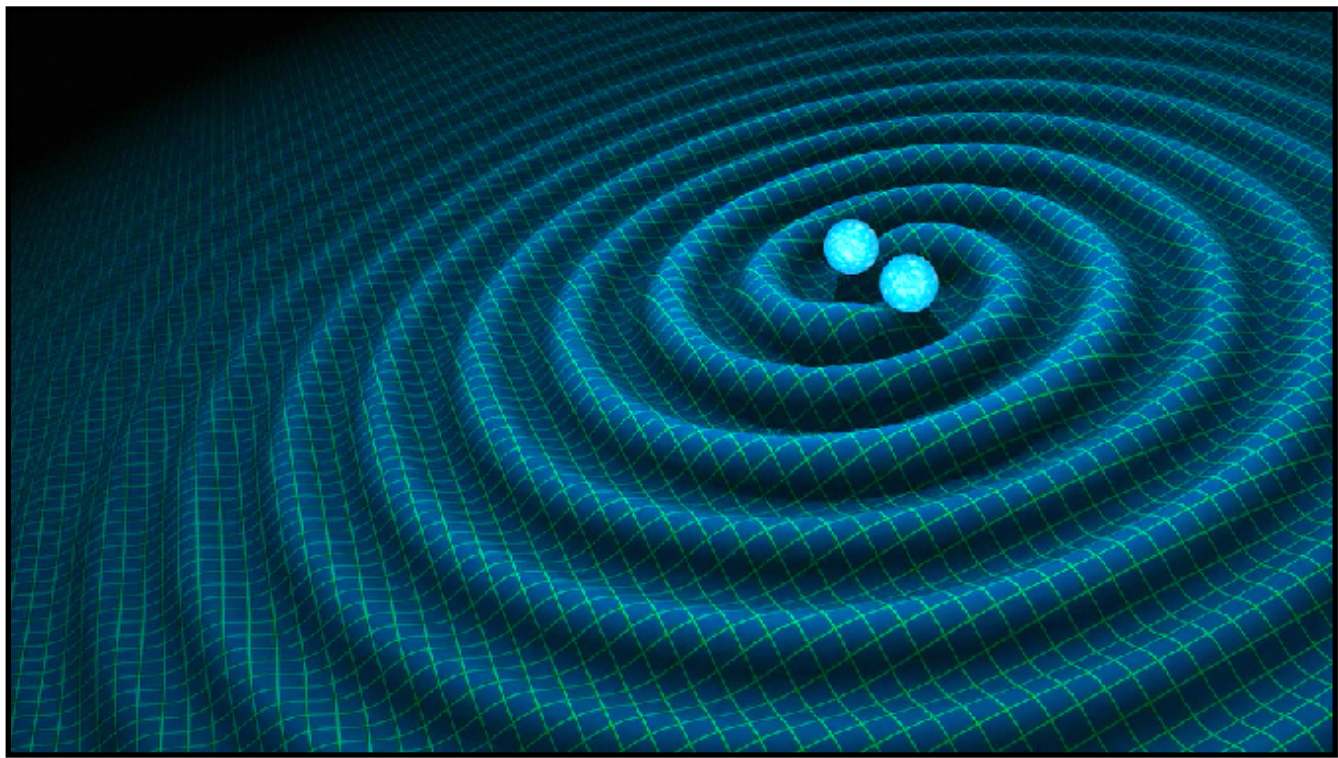
## Geodesy



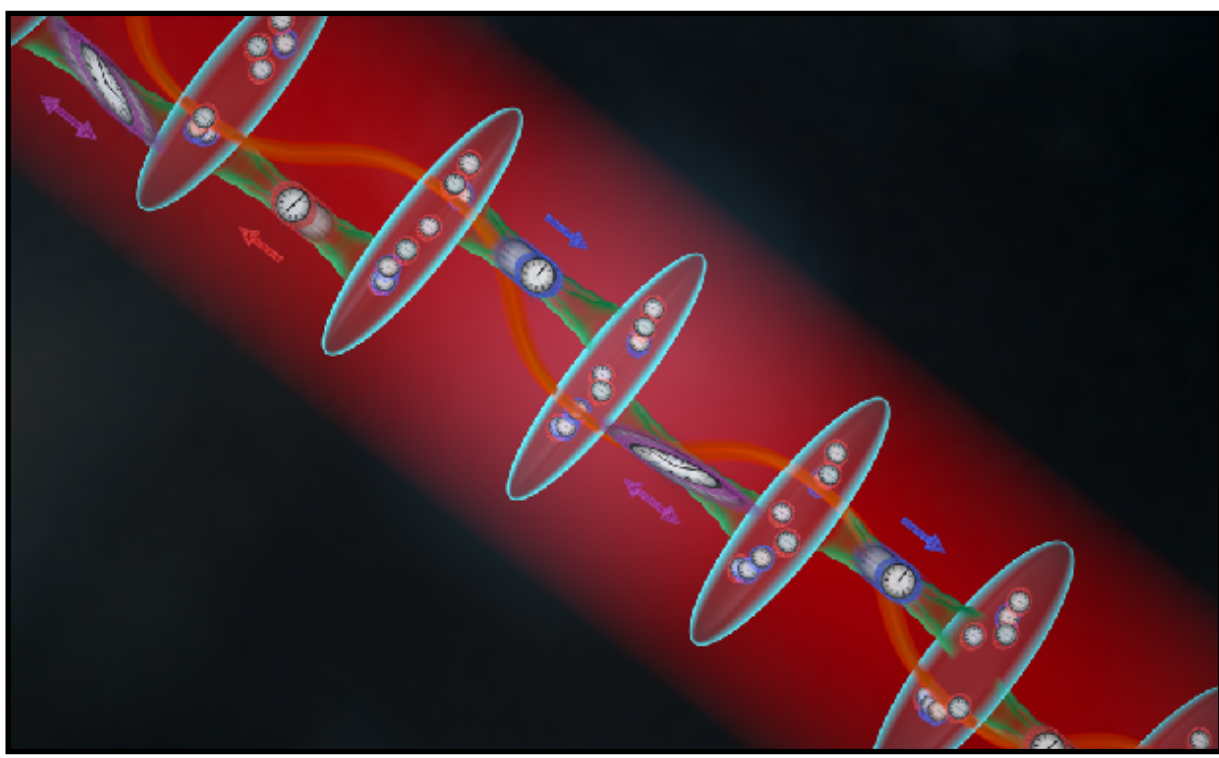
## Dark matter detection



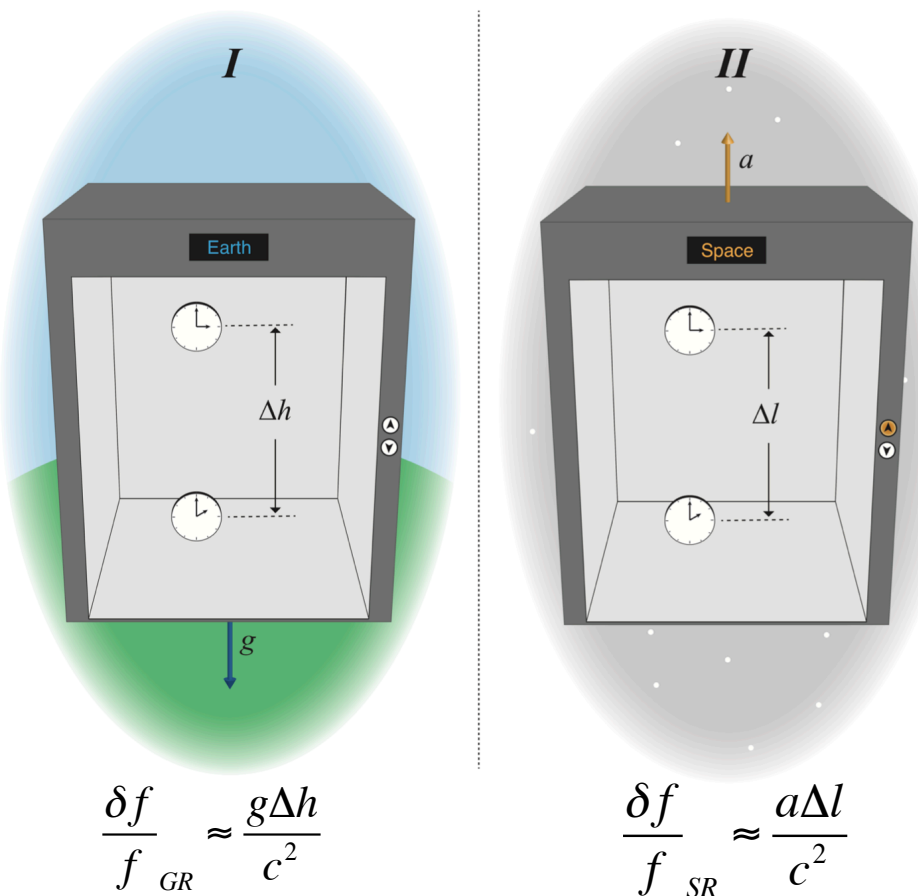
## GW detection



## Quantum simulation

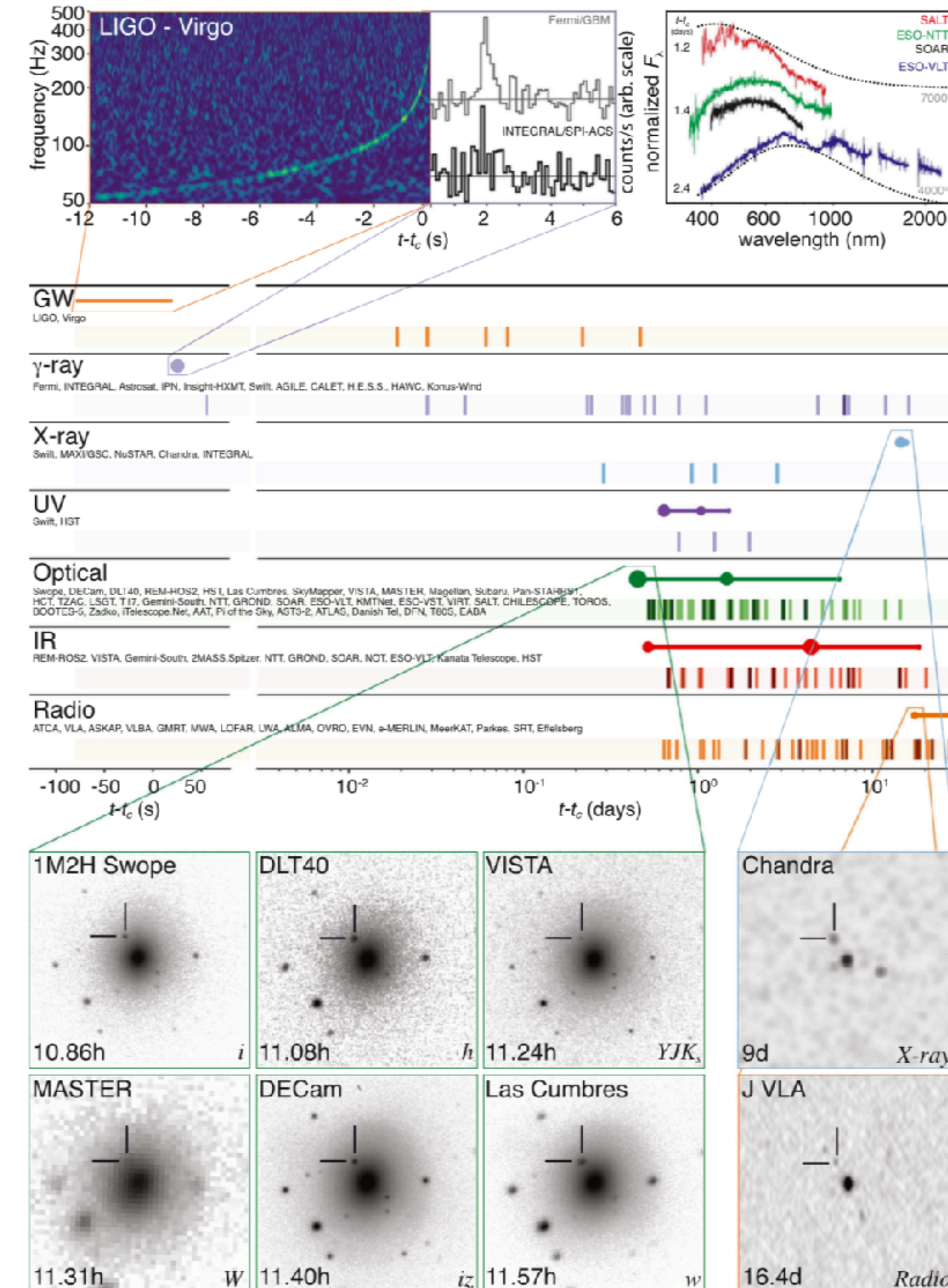
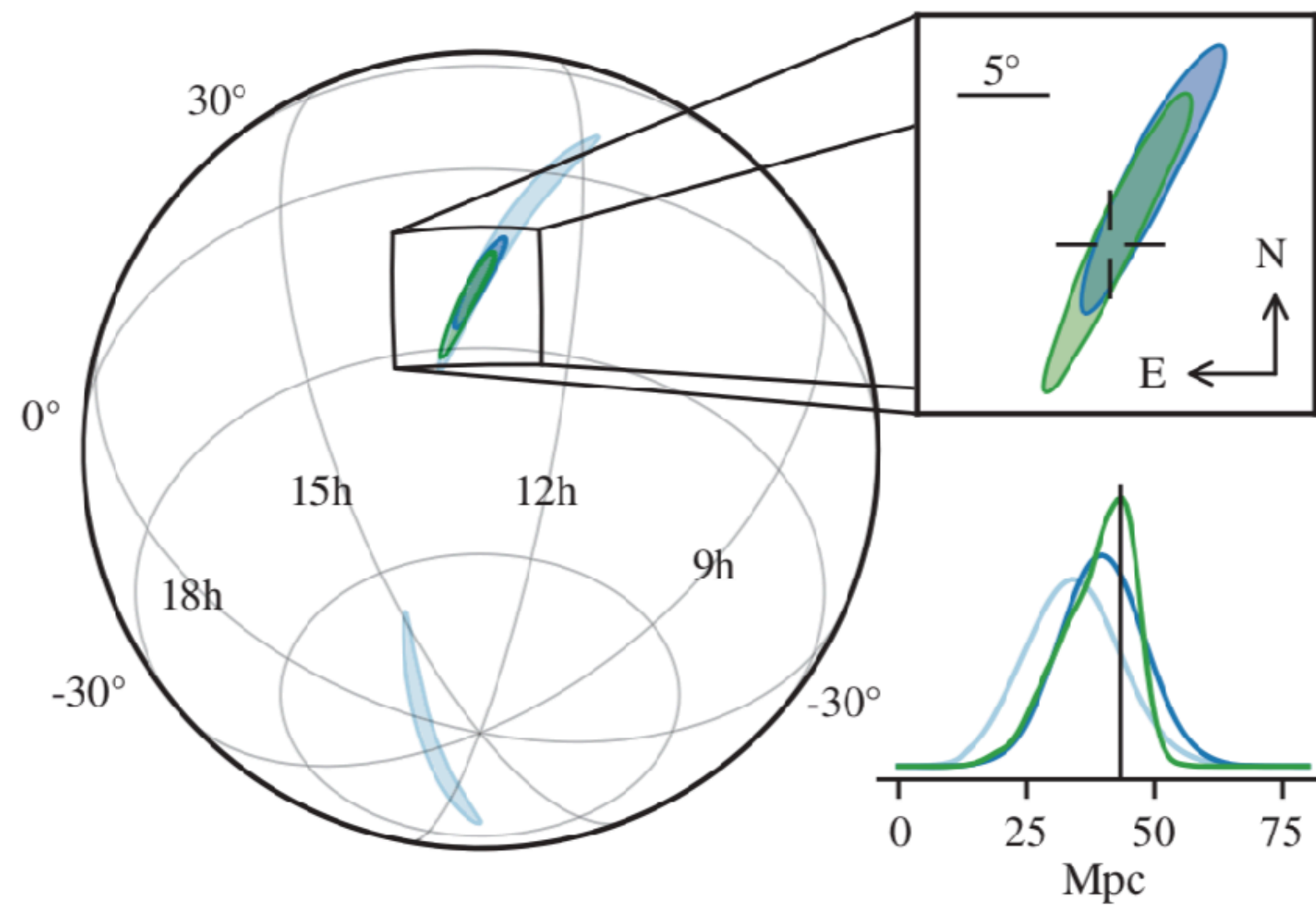
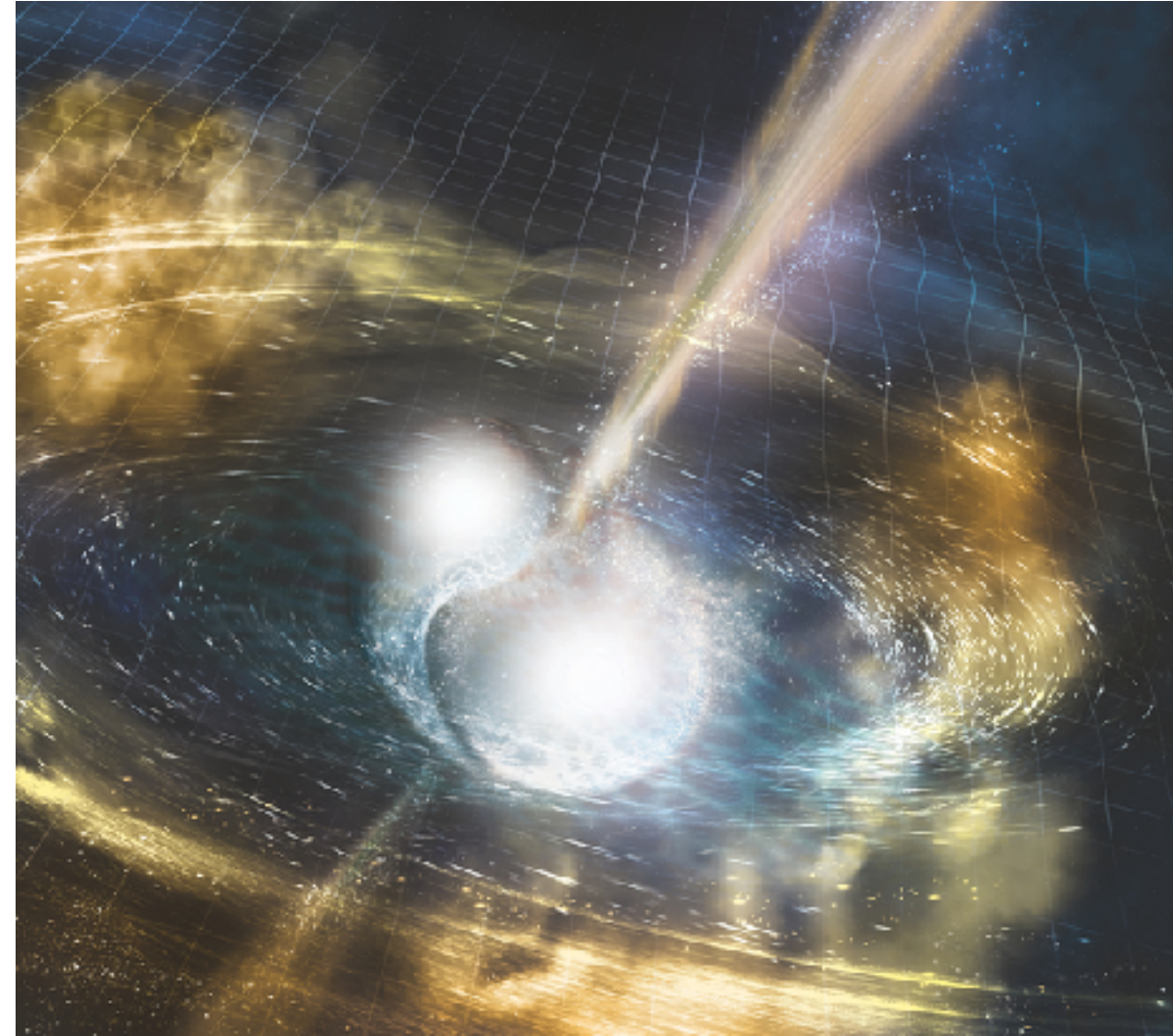


## Tests of relativity



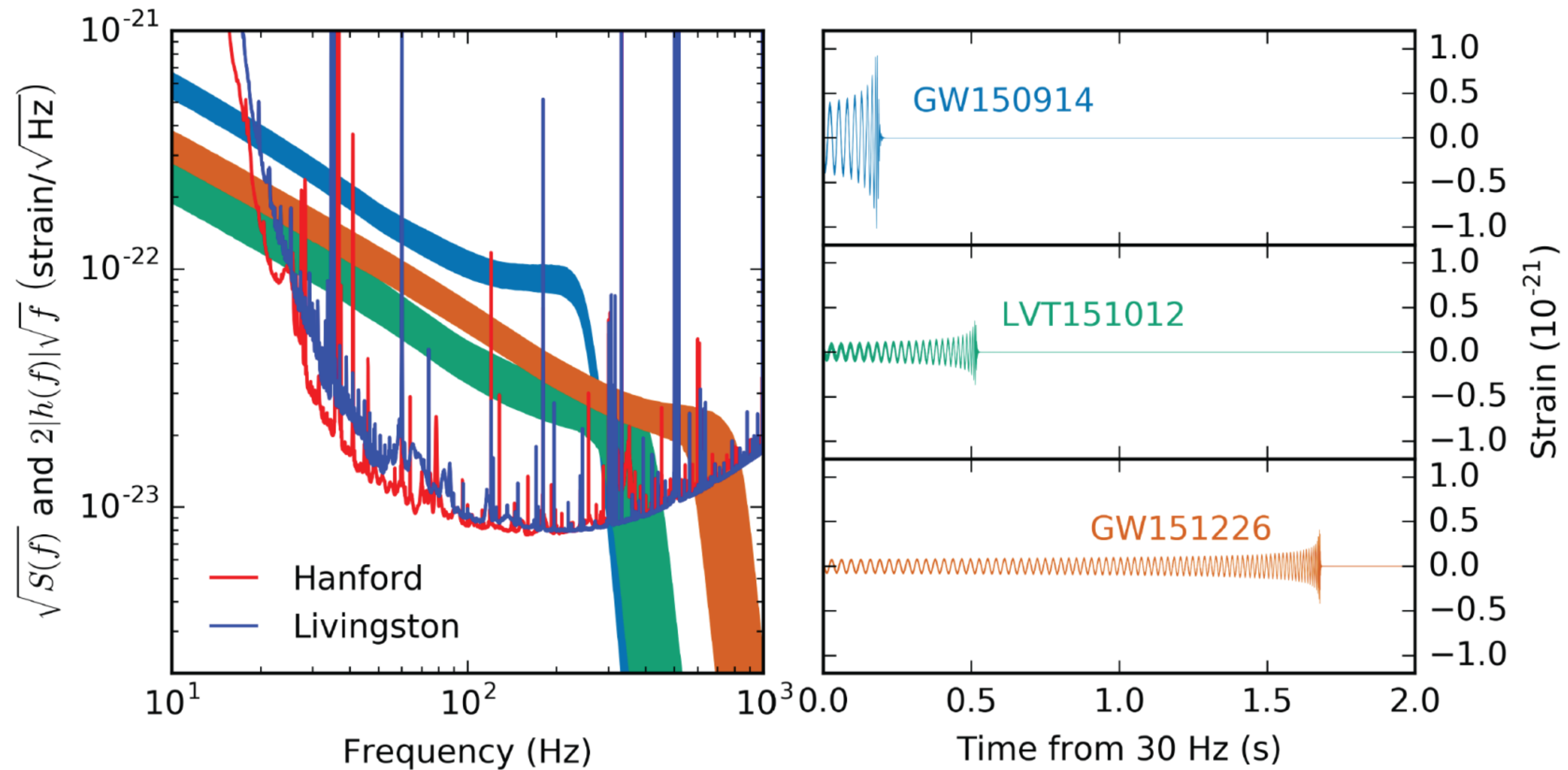


# Gravitational wave detection - GW170817



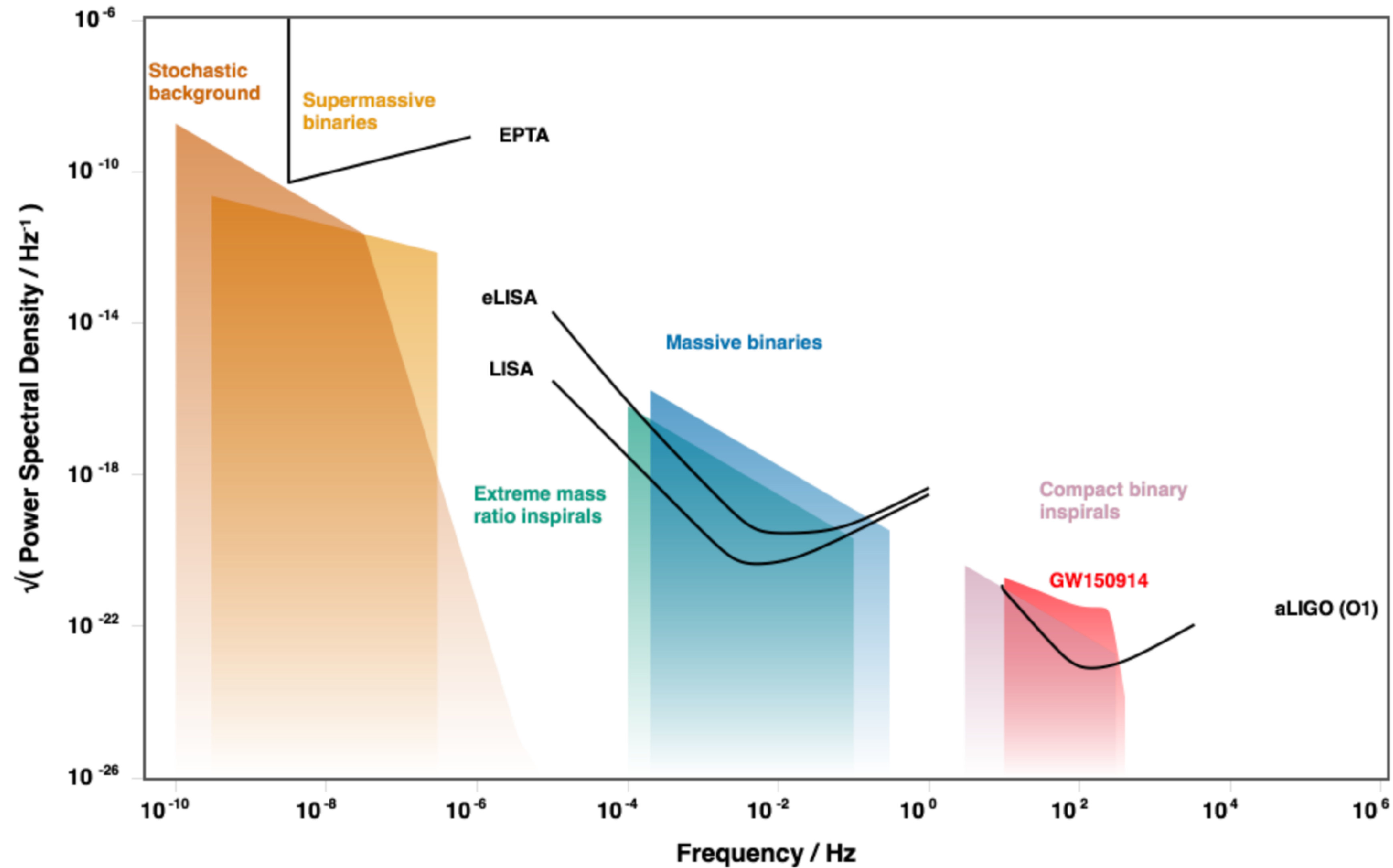


# Gravitational wave detection - LIGO



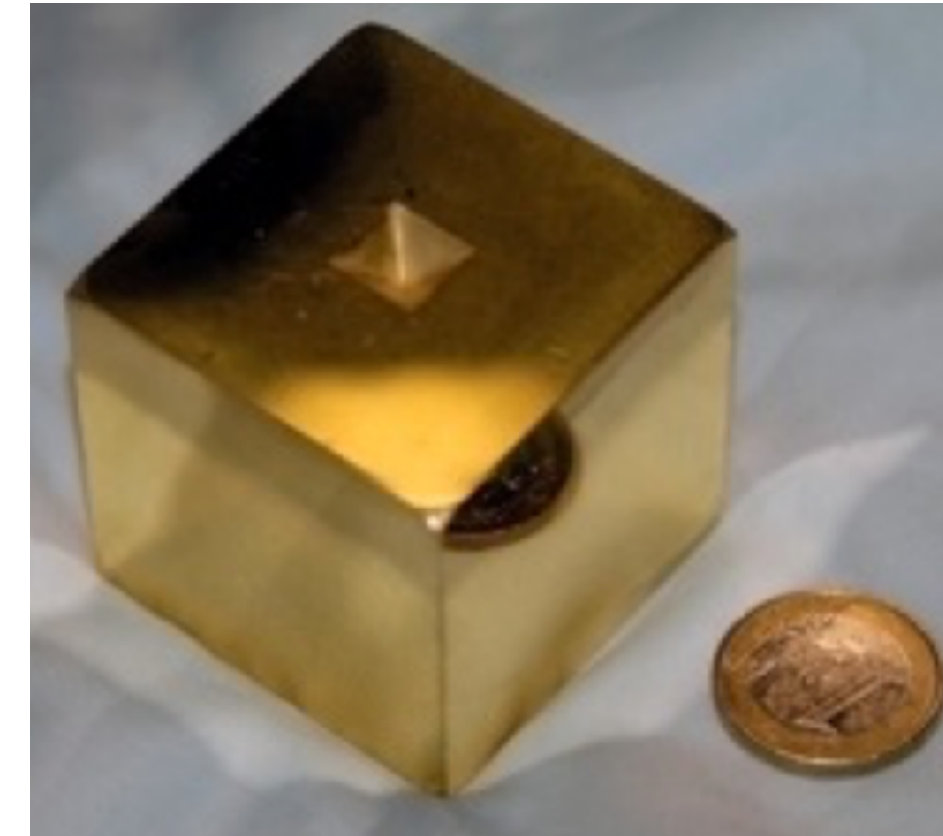
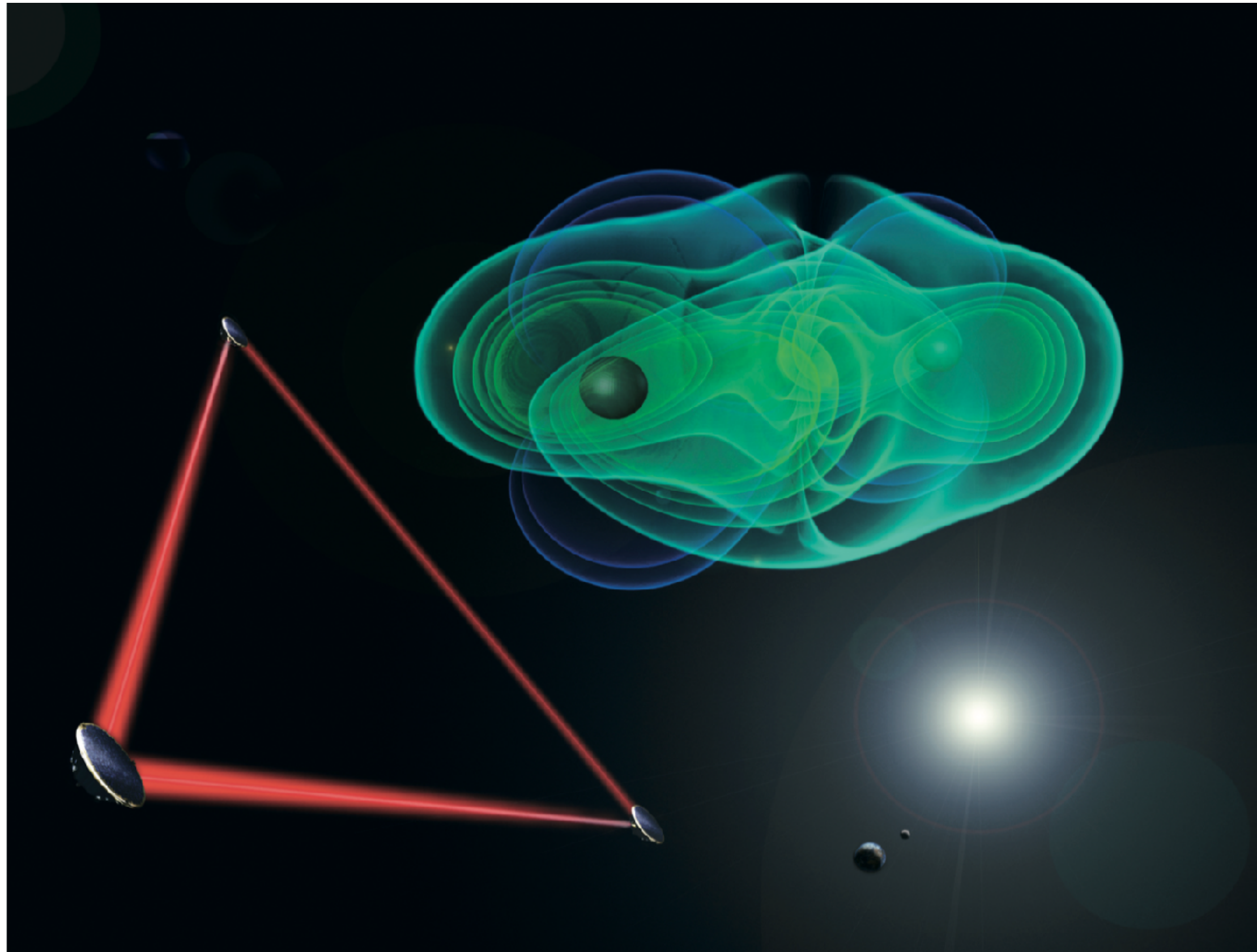


# Gravitational wave detection





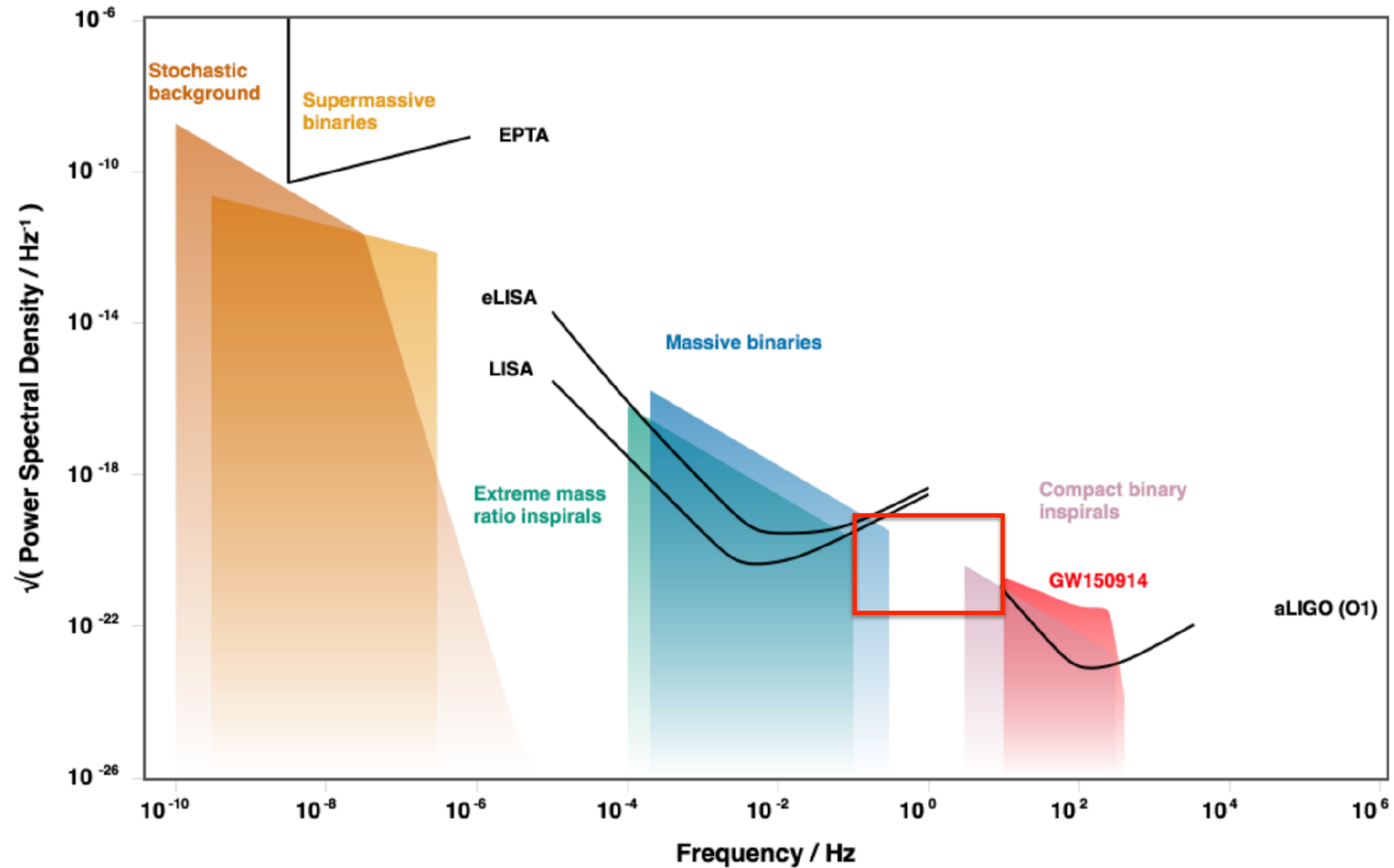
# LISA and eLISA



## LISA and eLISA:

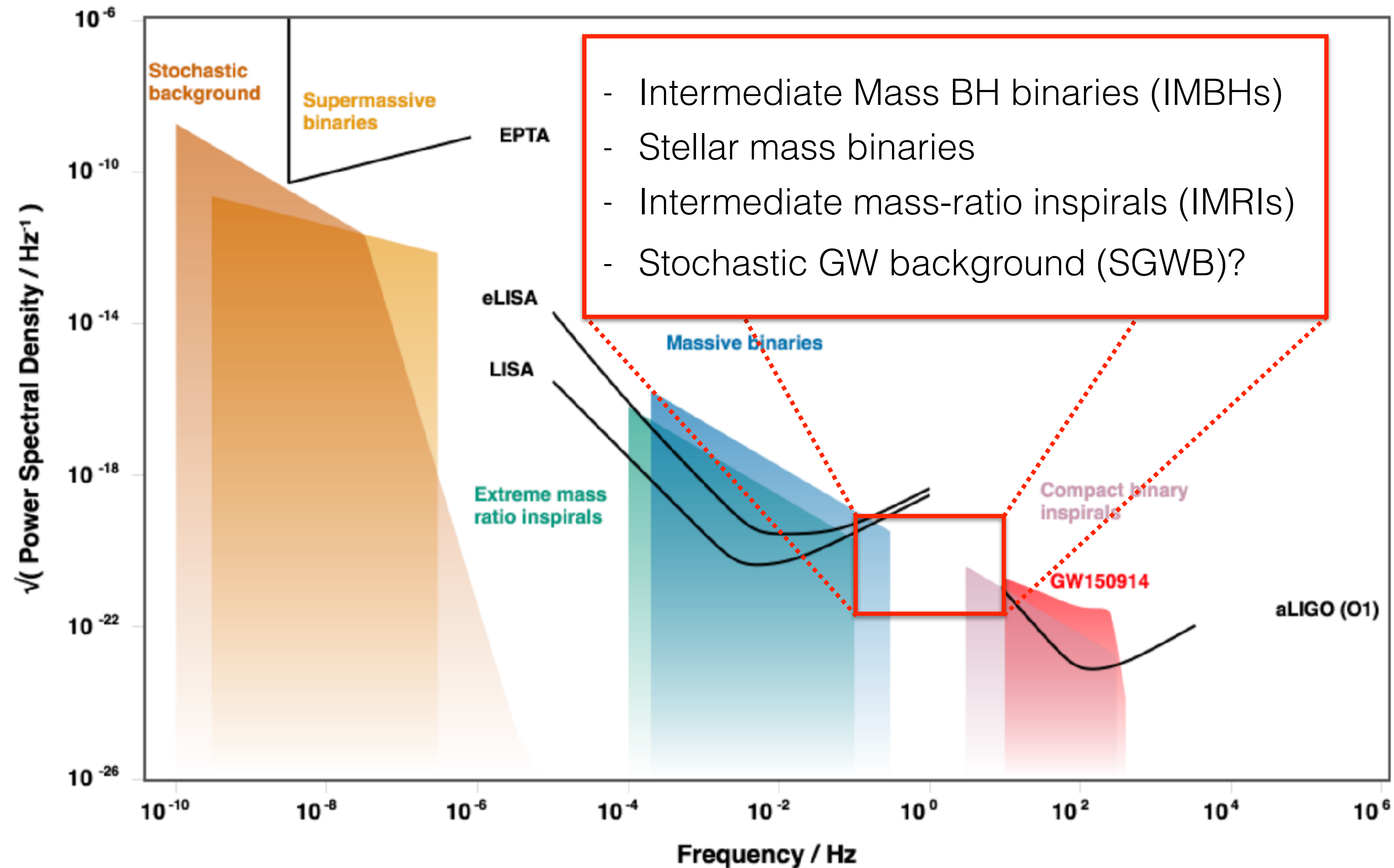
- Drag-free, space based version of LIGO
- $d = 5 \times 10^9$  m arm length

# Gravitational wave detection



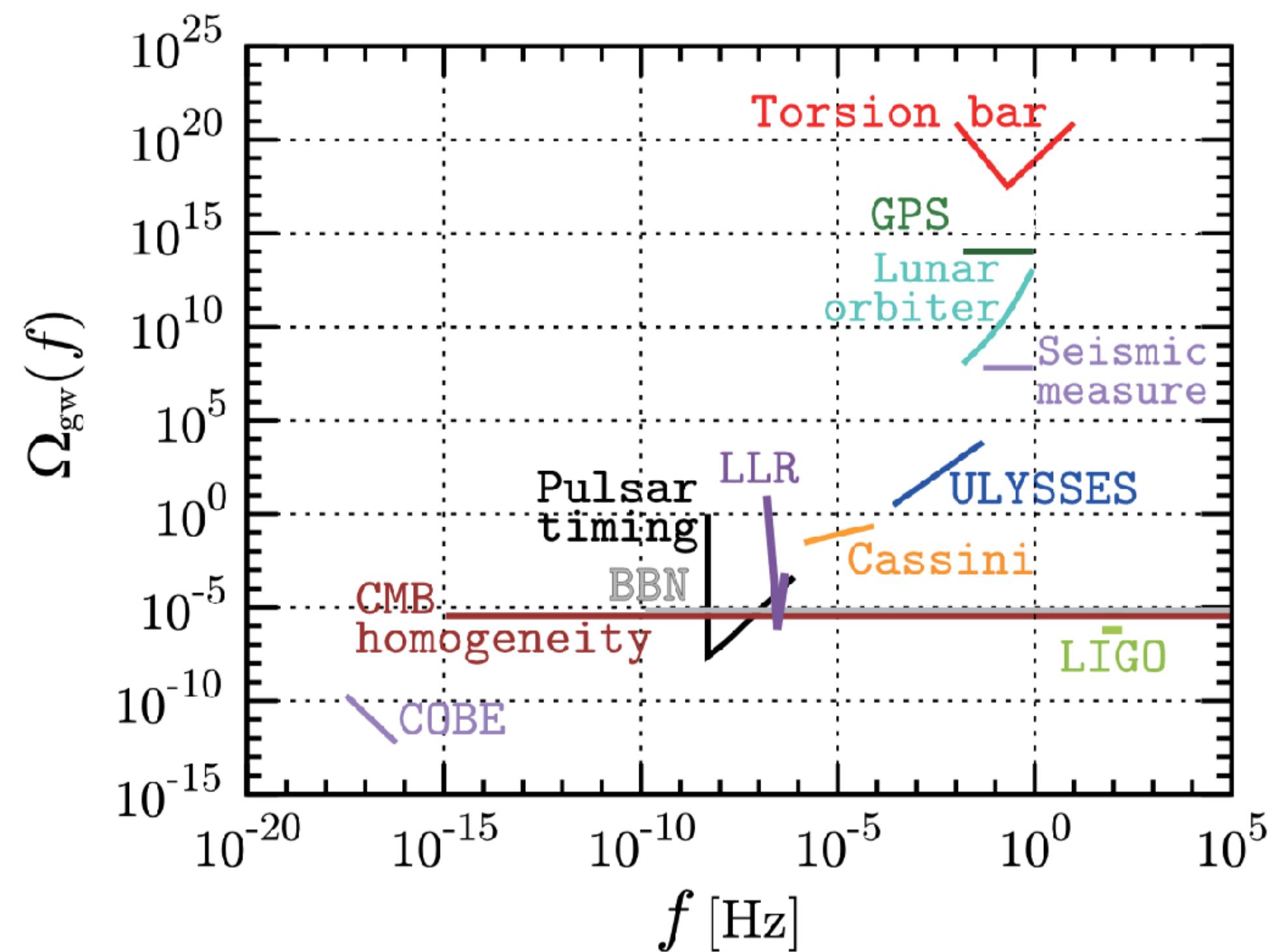


# Gravitational wave detection



# Doppler tracking searches

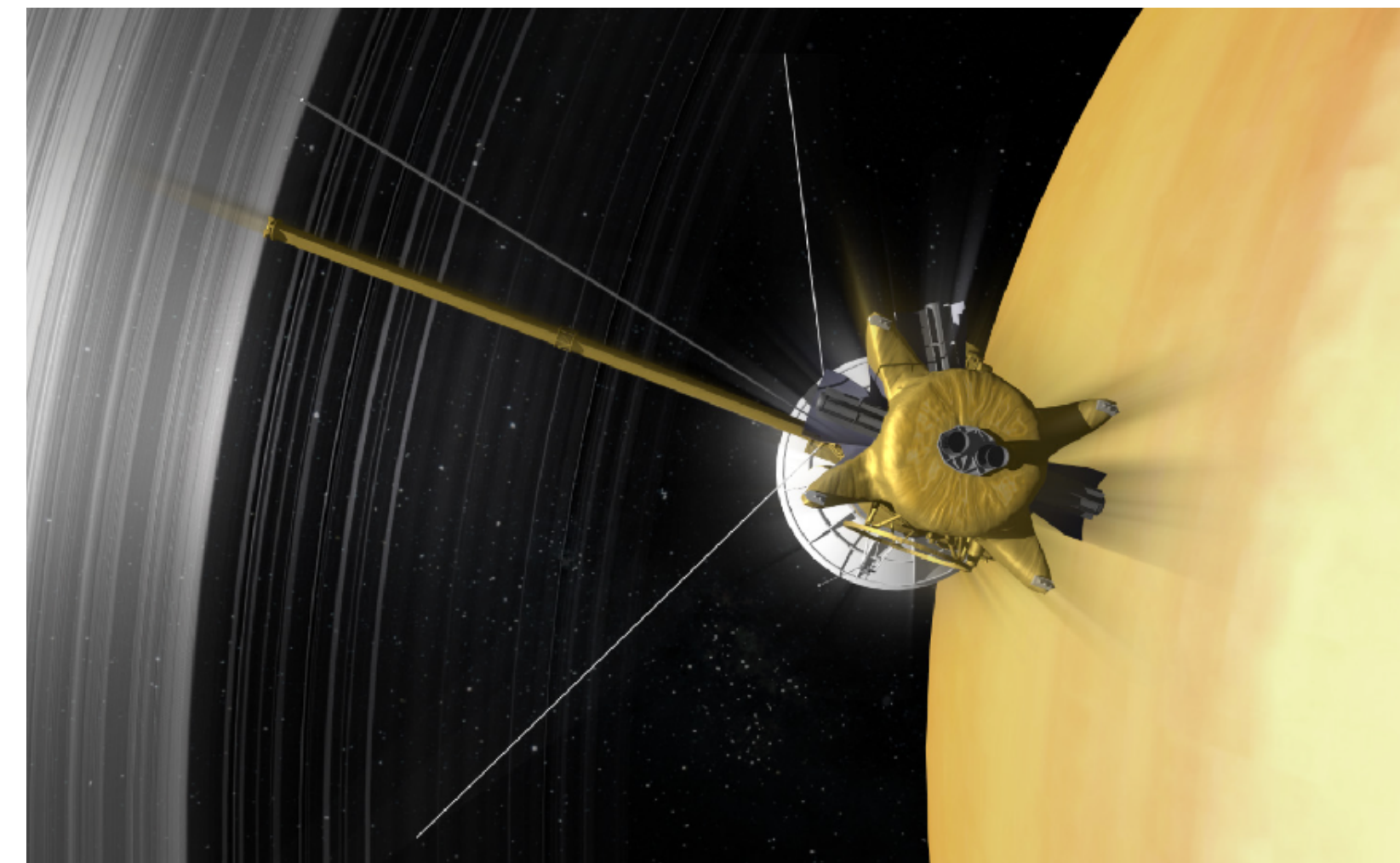
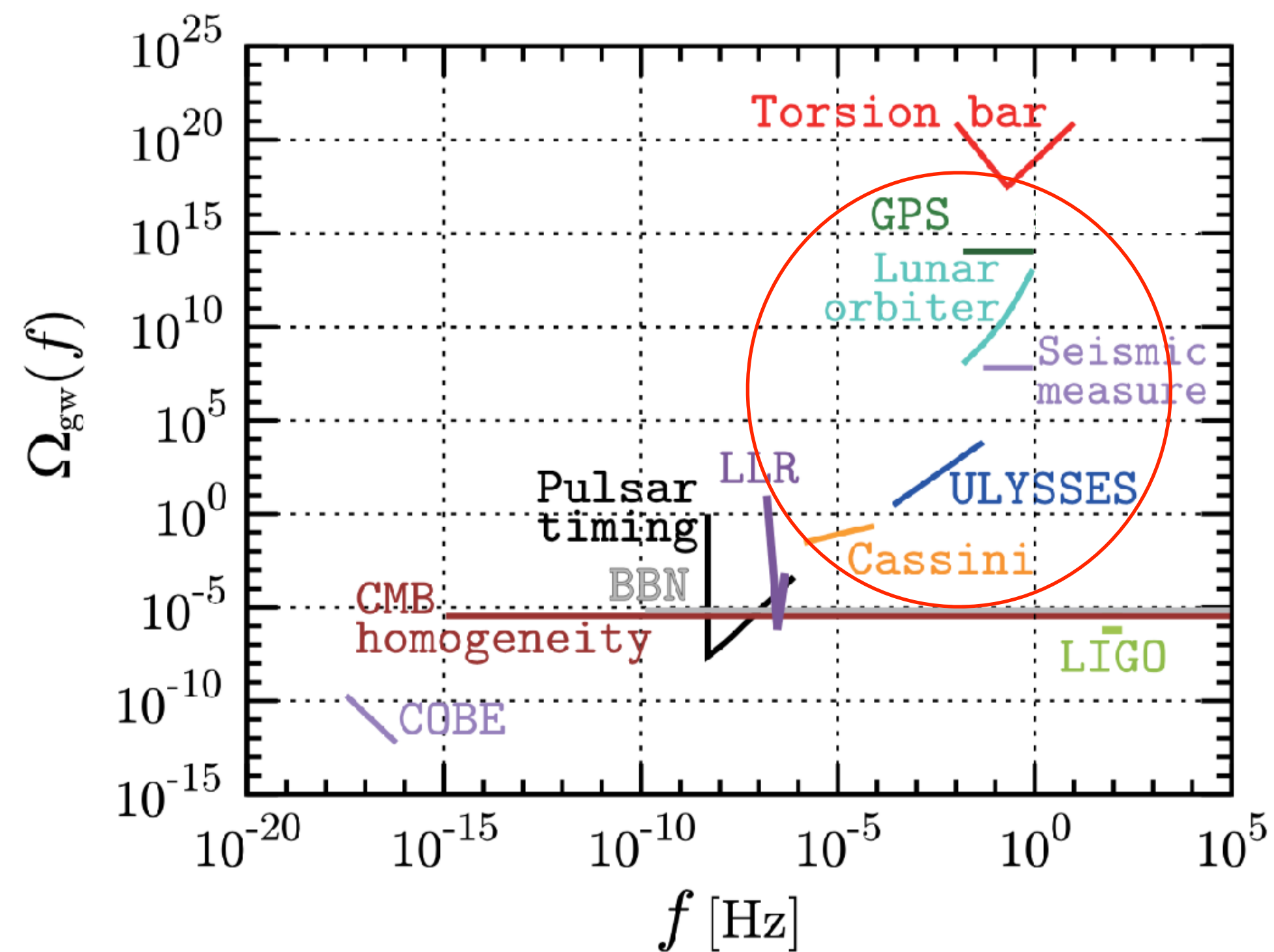
Previous limits on GW density:





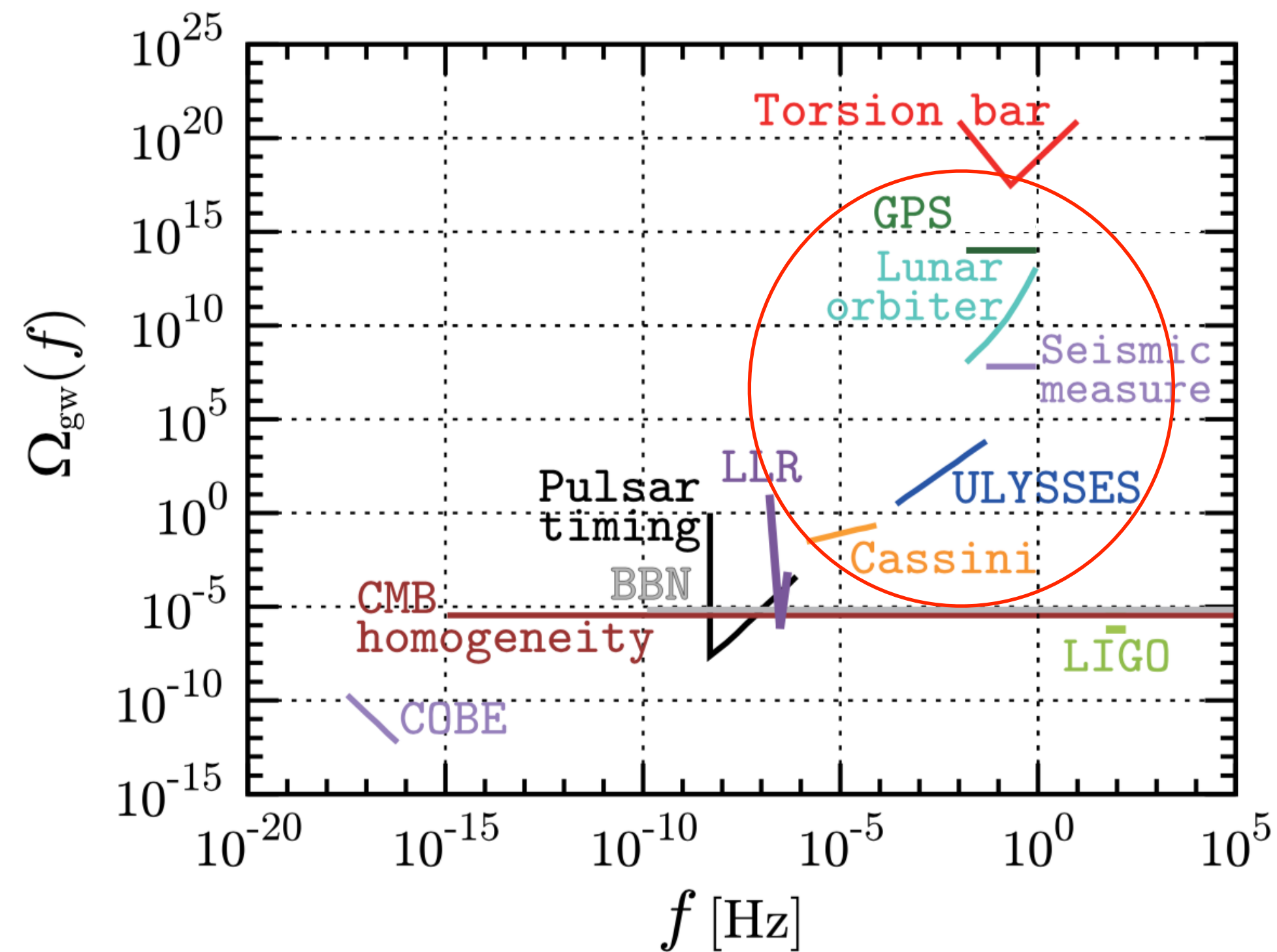
# Doppler tracking searches

Previous limits on GW density:

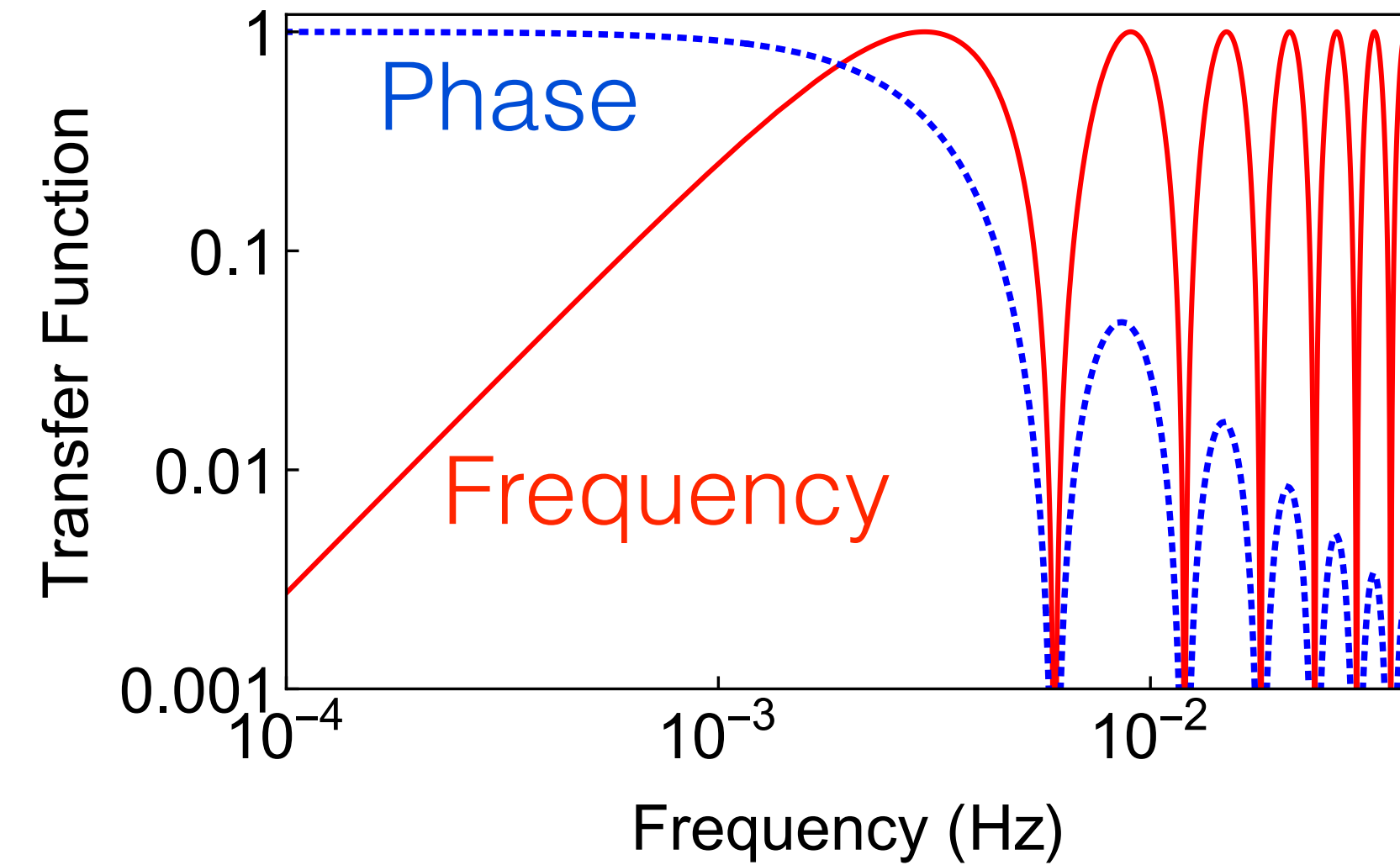


# Doppler tracking searches

Previous limits on GW density:

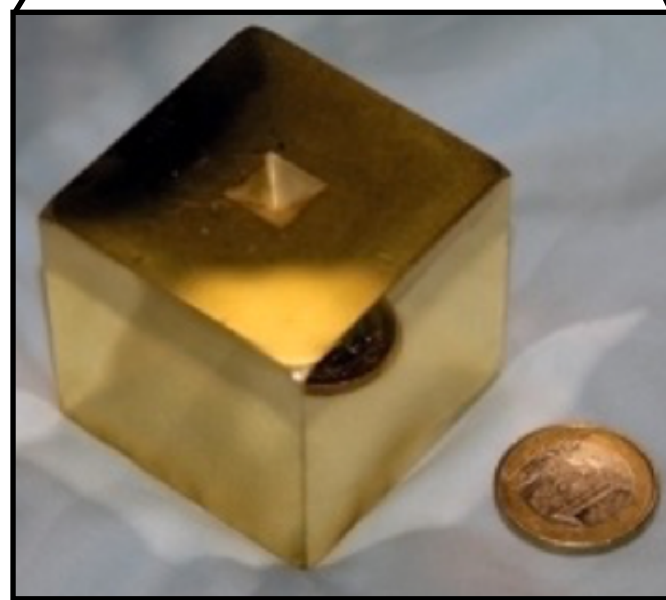
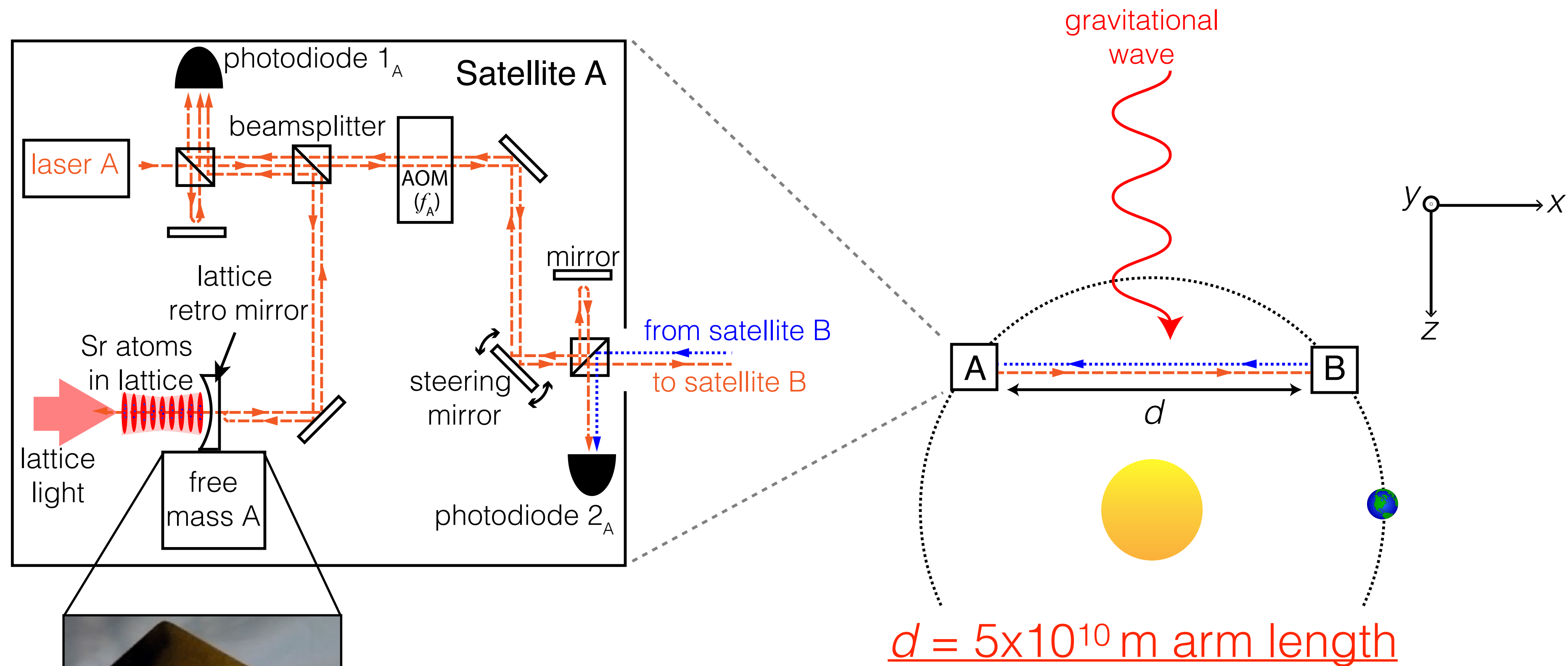


Detector transfer function:





# Gravitational wave detection with clocks



$$\sigma(\tau) = \left. \frac{\delta \nu}{\nu_o} \right|_{\tau} = \frac{\sqrt{\Delta_A}}{\nu_o \sqrt{2\pi\tau N}}$$

# Gravitational wave detection with clocks

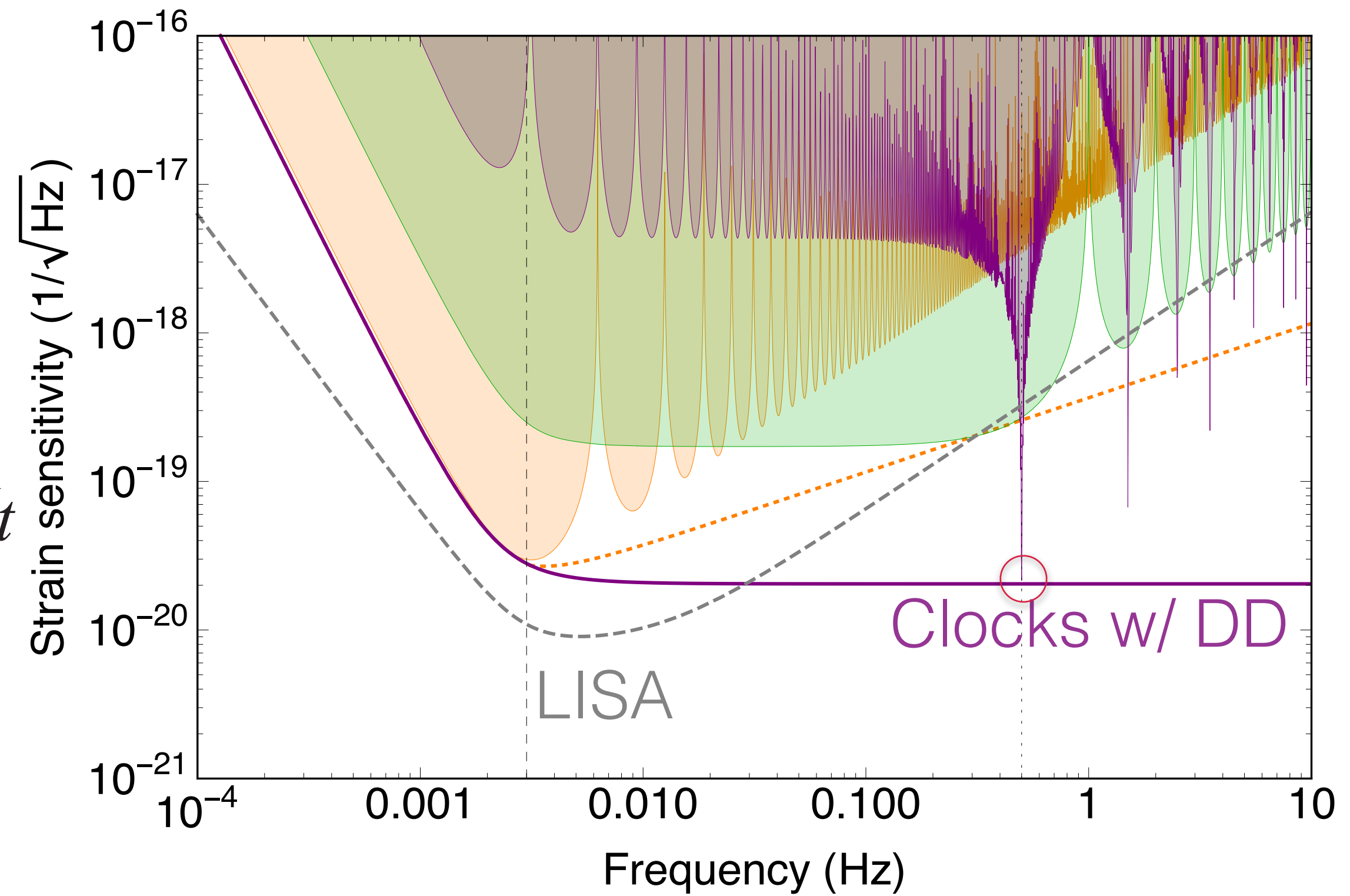
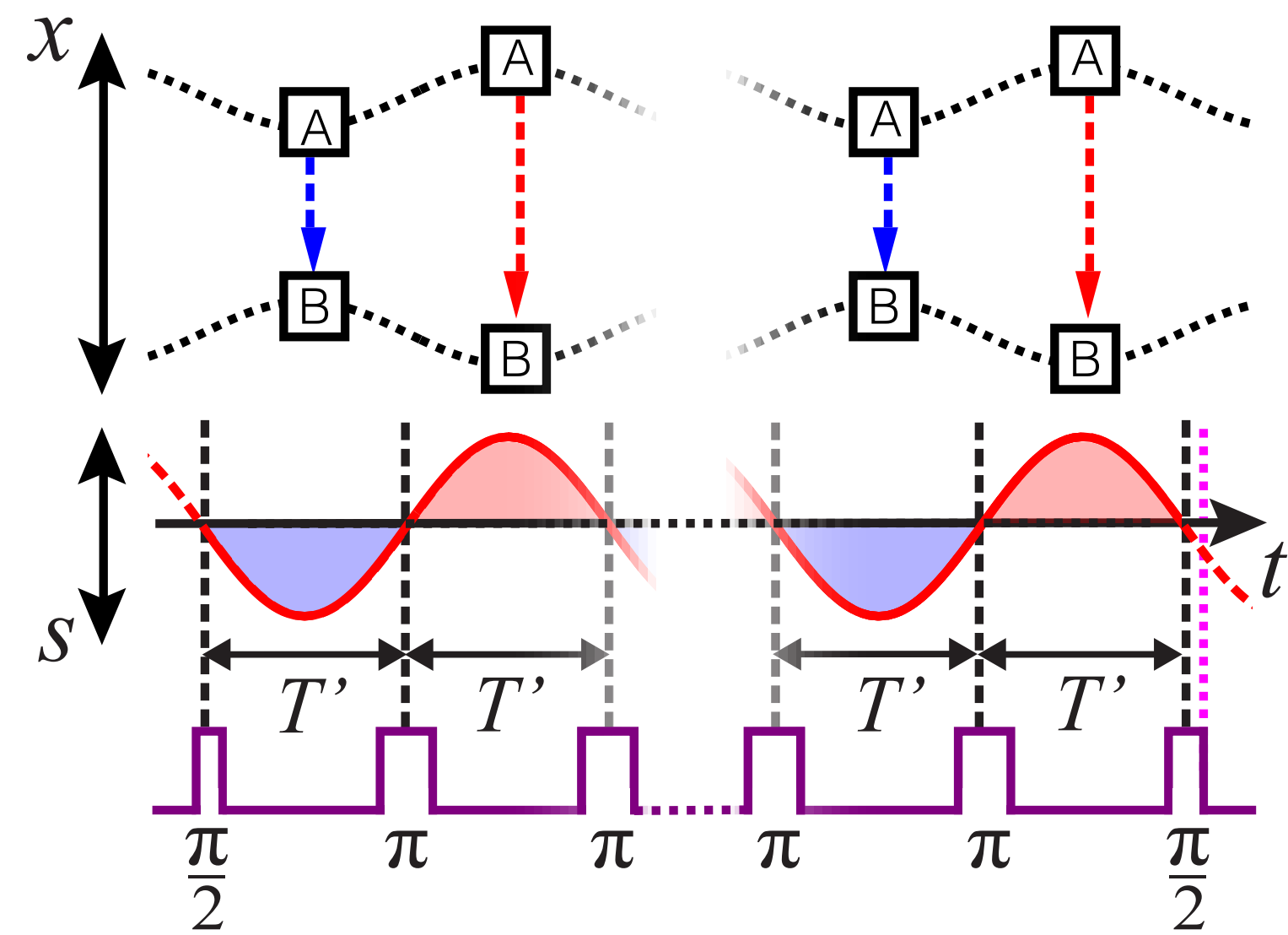
## Clock based detector

$d = 5 \times 10^{10}$  m arm length

$N = 7 \times 10^6$  Sr atoms per clock

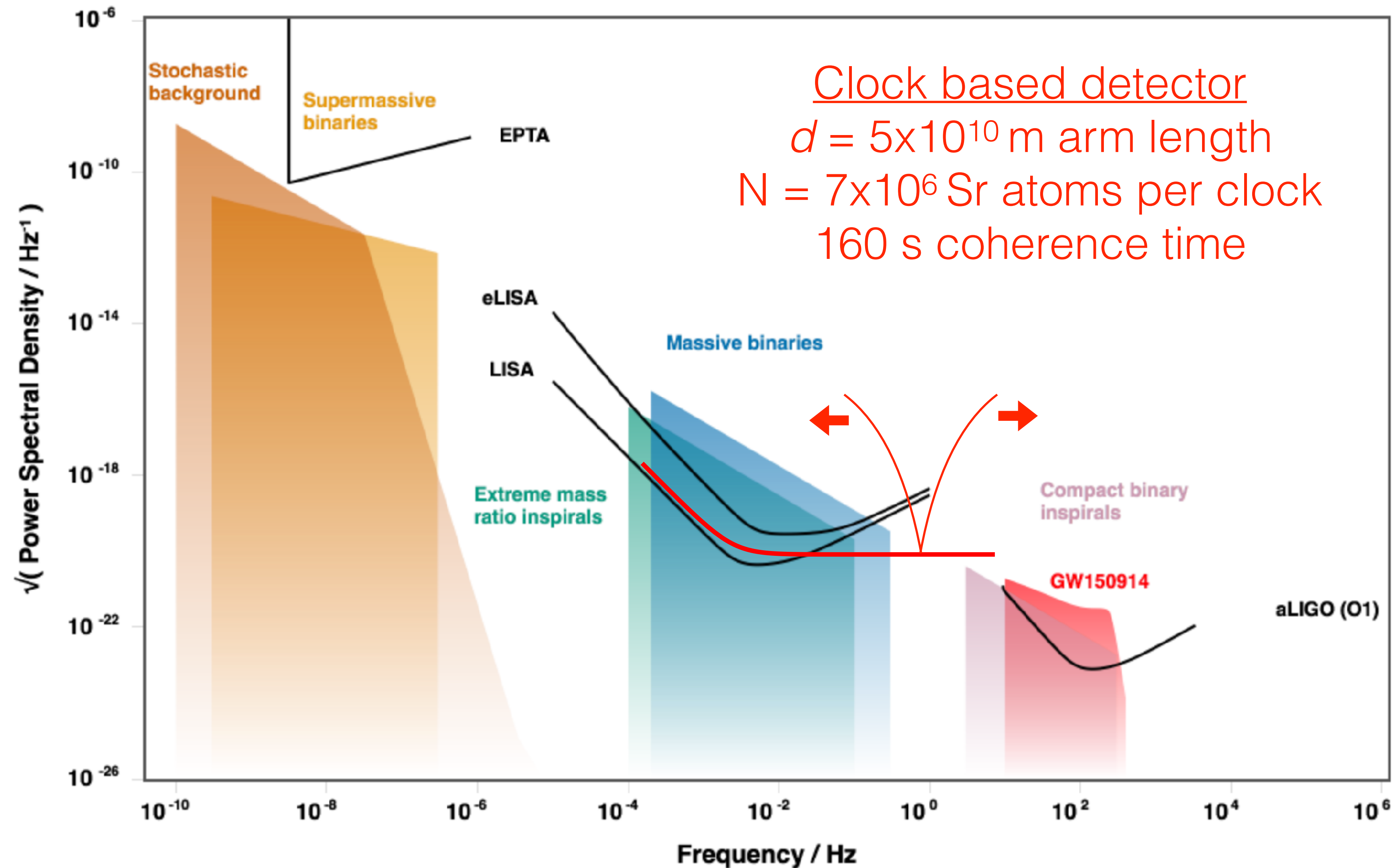
160 s coherence time

Dynamical decoupling  
sequence:





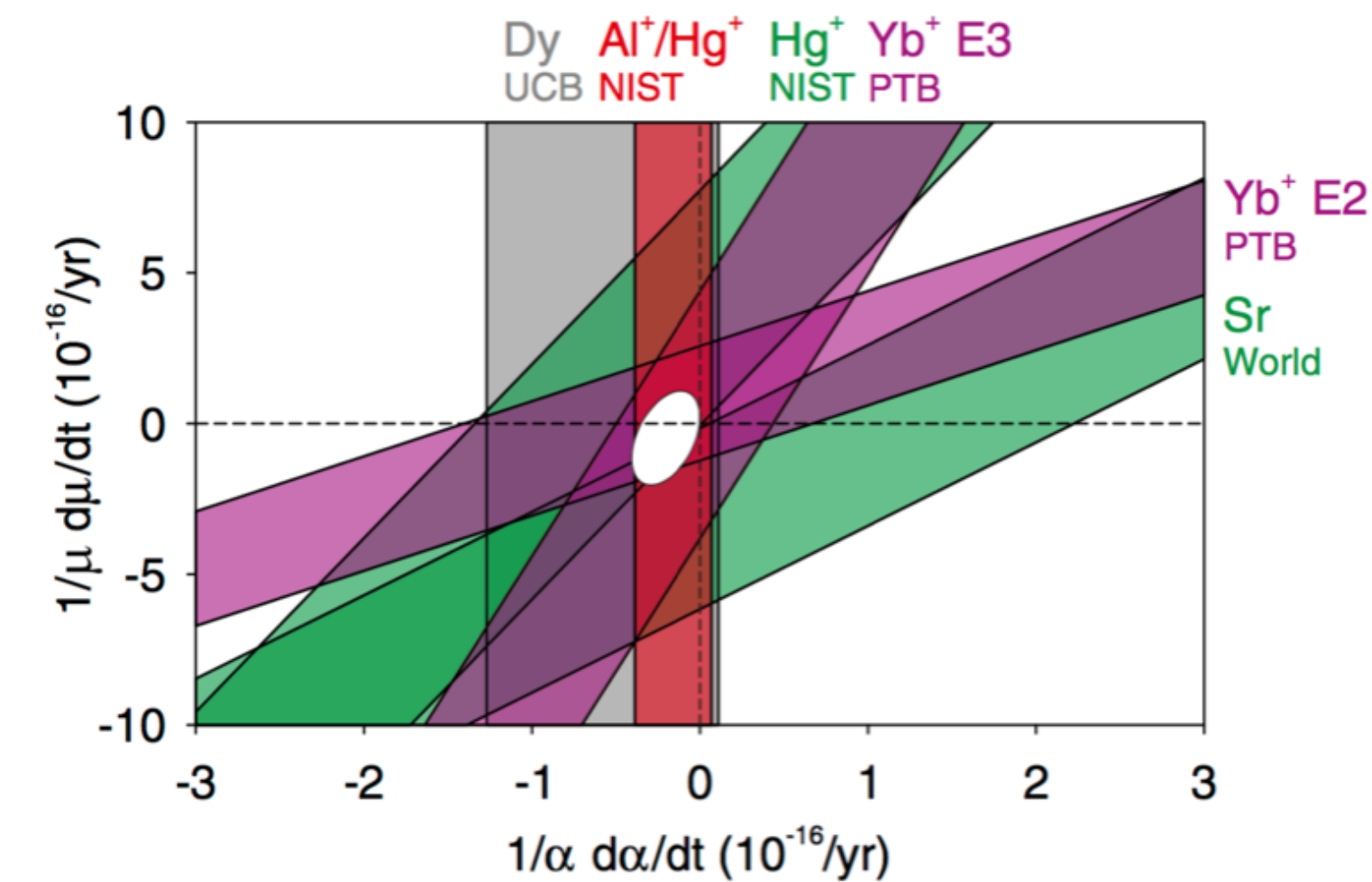
# Gravitational wave detection with clocks



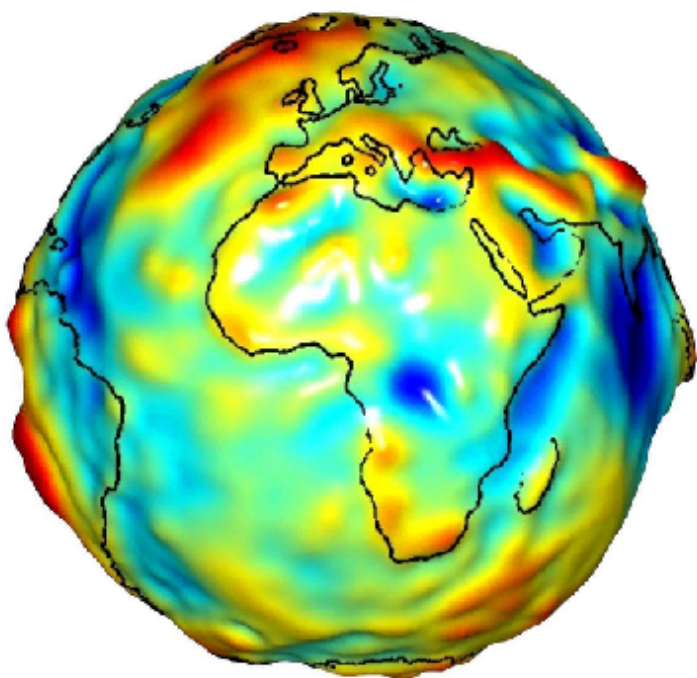


# Optical clocks in space for fundamental physics

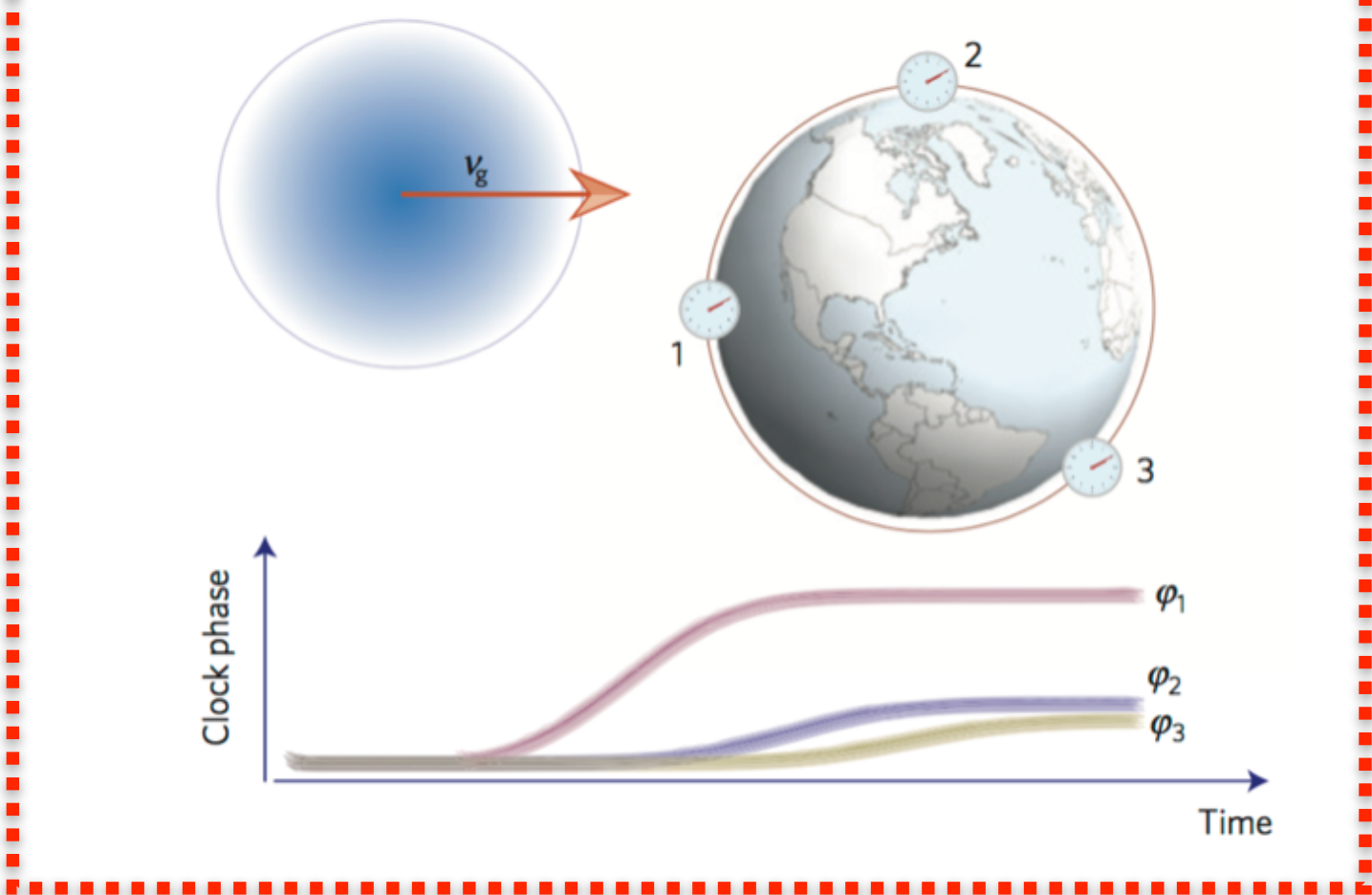
## Searches for new physics



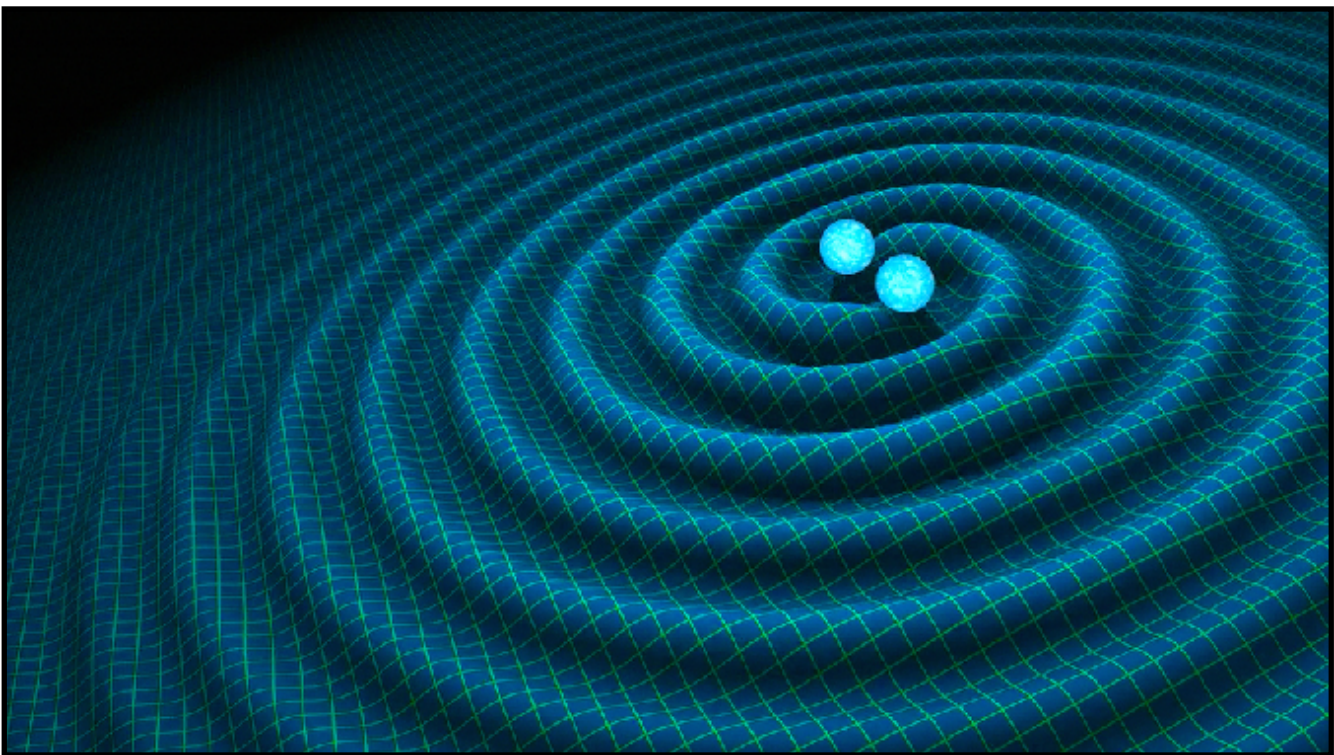
## Geodesy



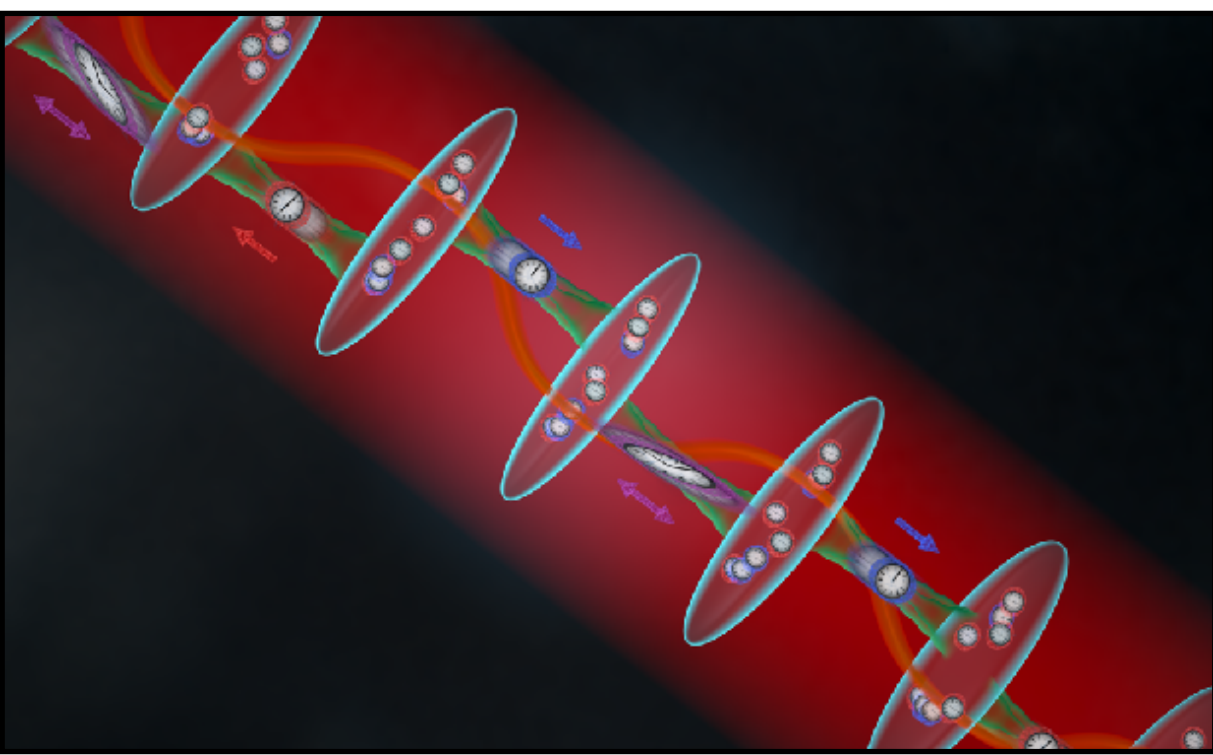
## Dark matter detection



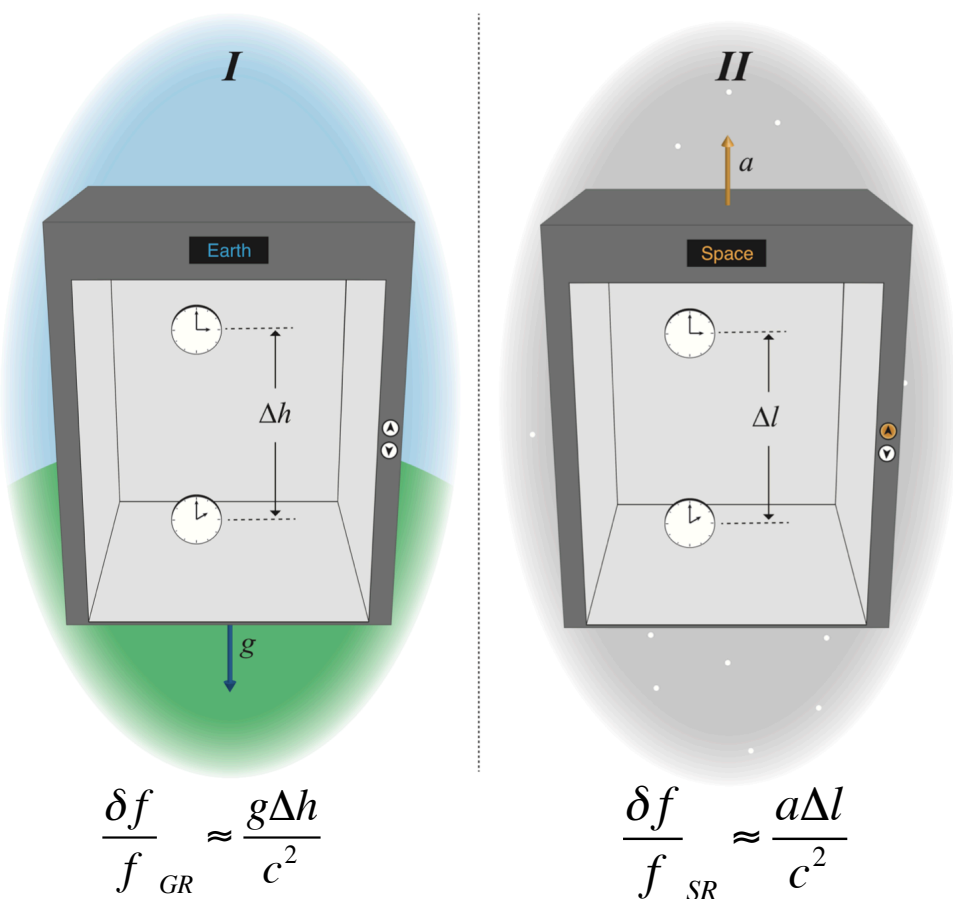
## GW detection



## Quantum simulation



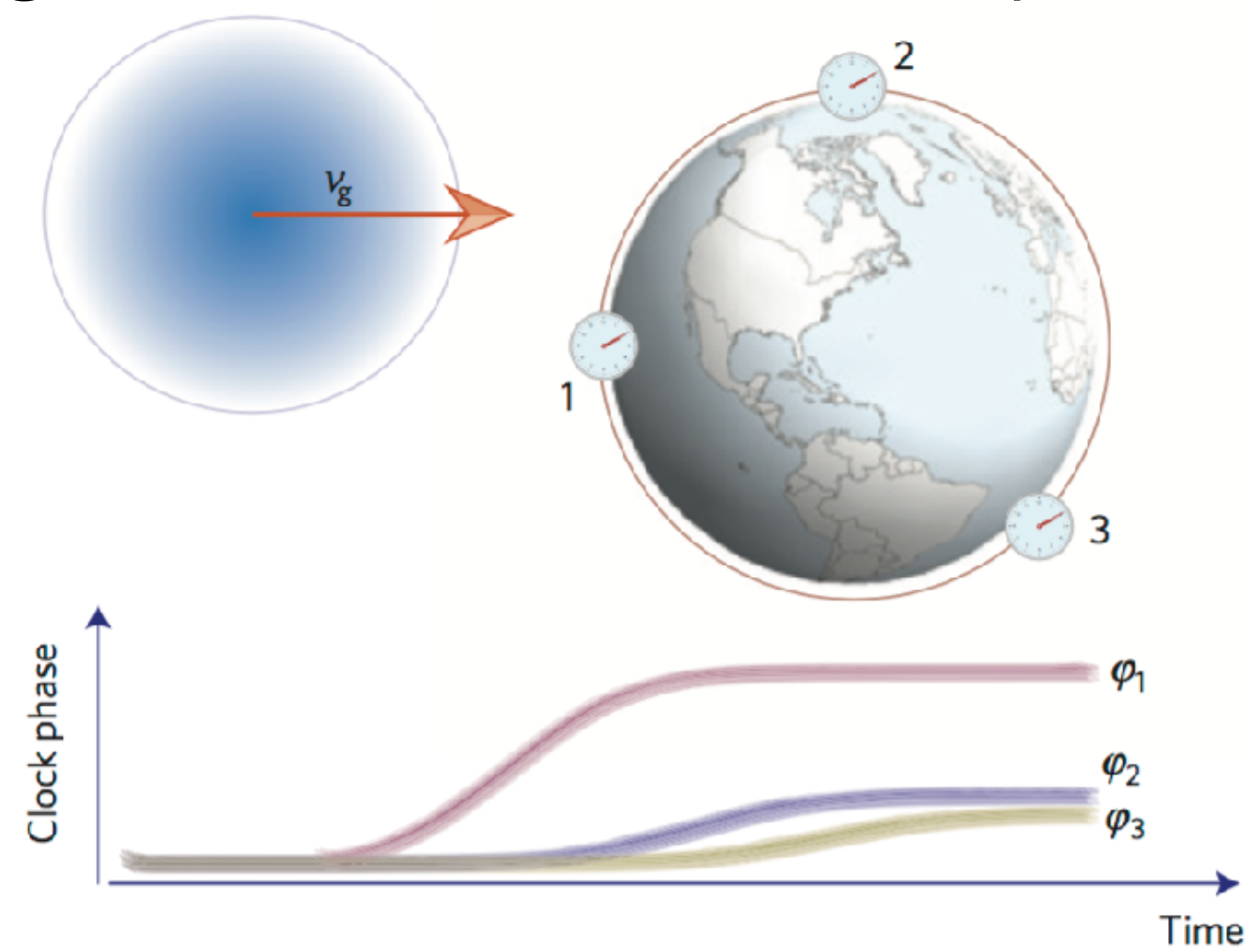
## Tests of relativity



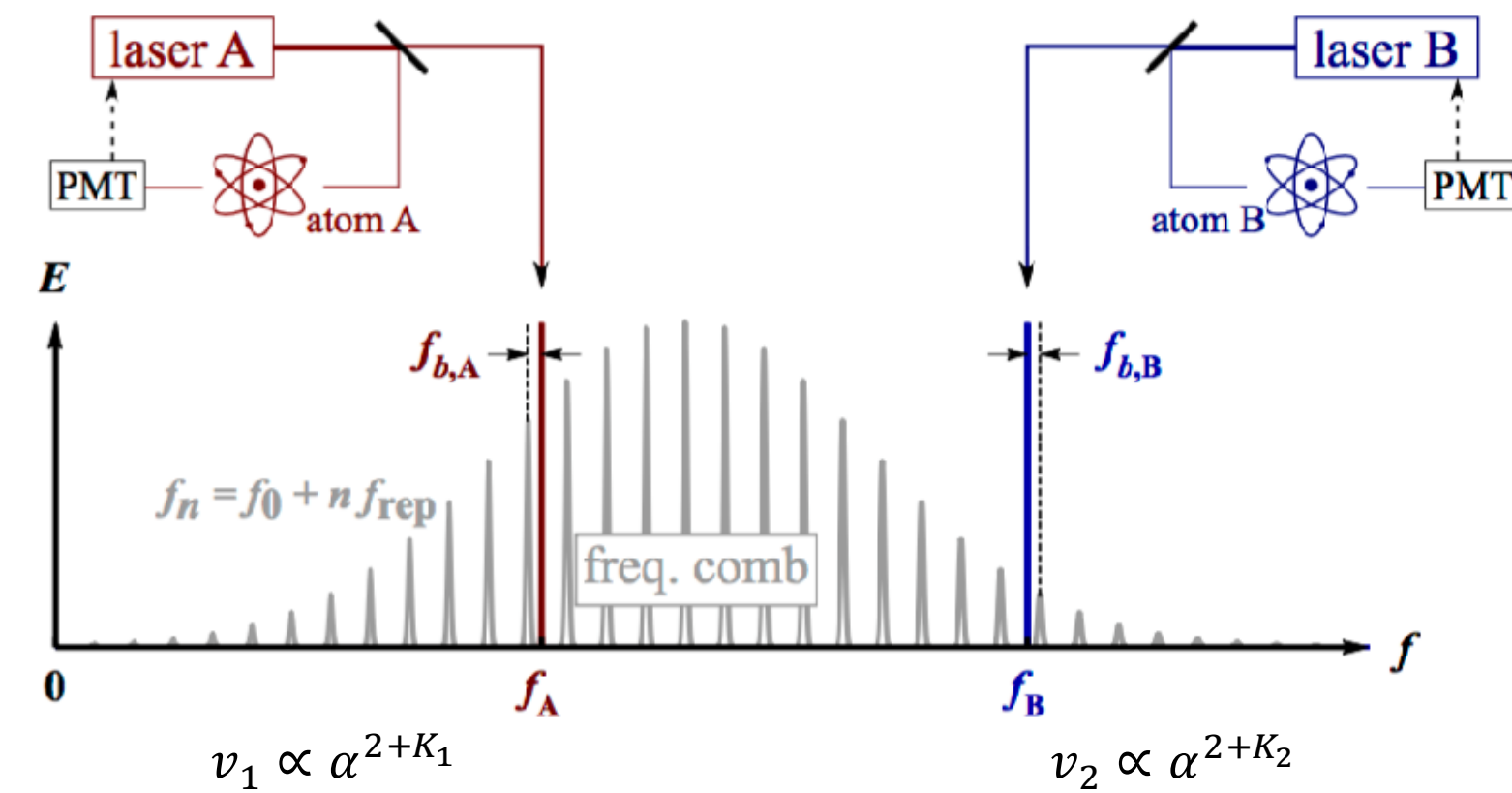


# Dark matter searches with atomic clocks

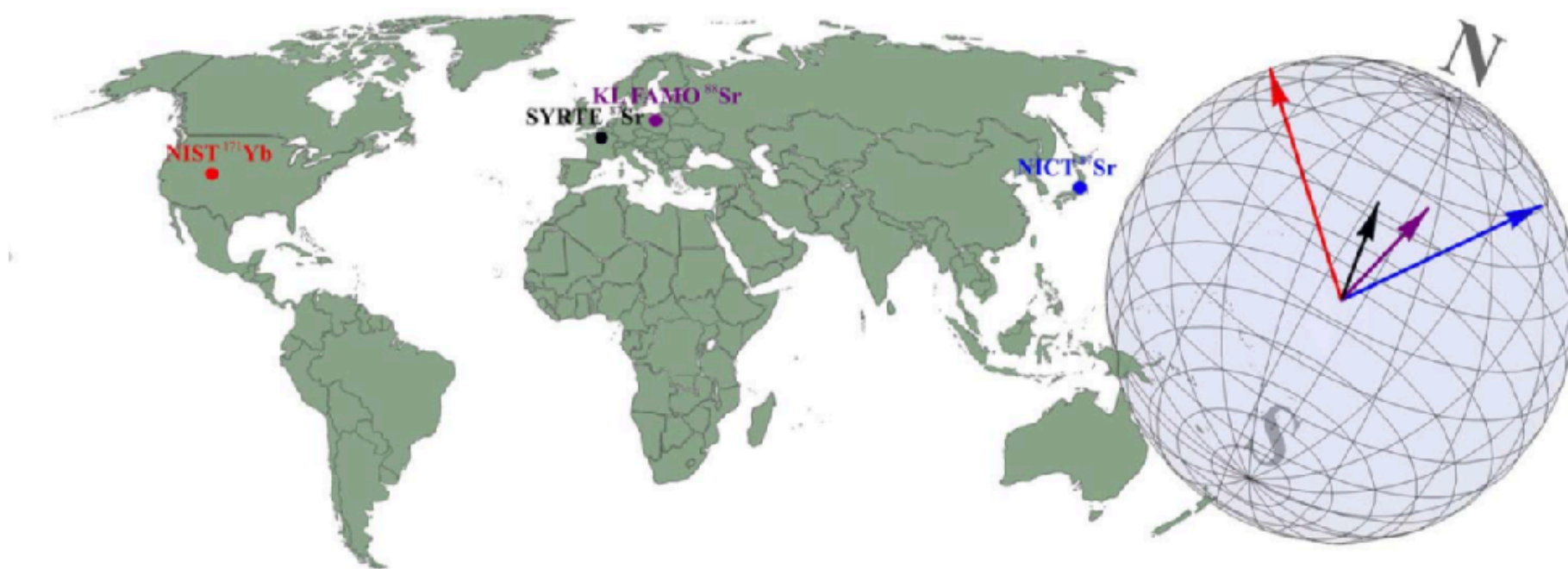
Long distance clock comparisons:



Multi-species comparisons:

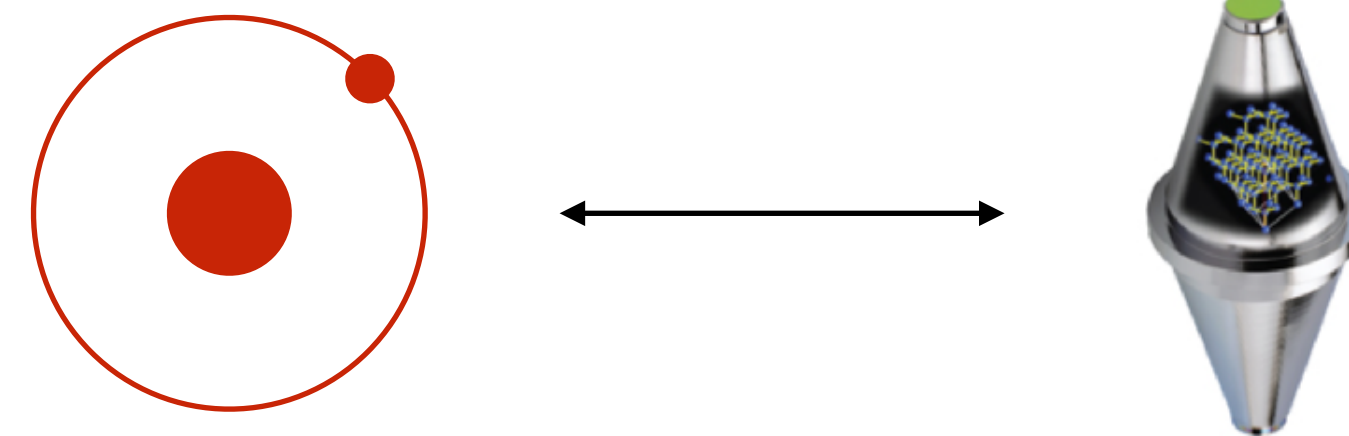


Atom-cavity comparisons:



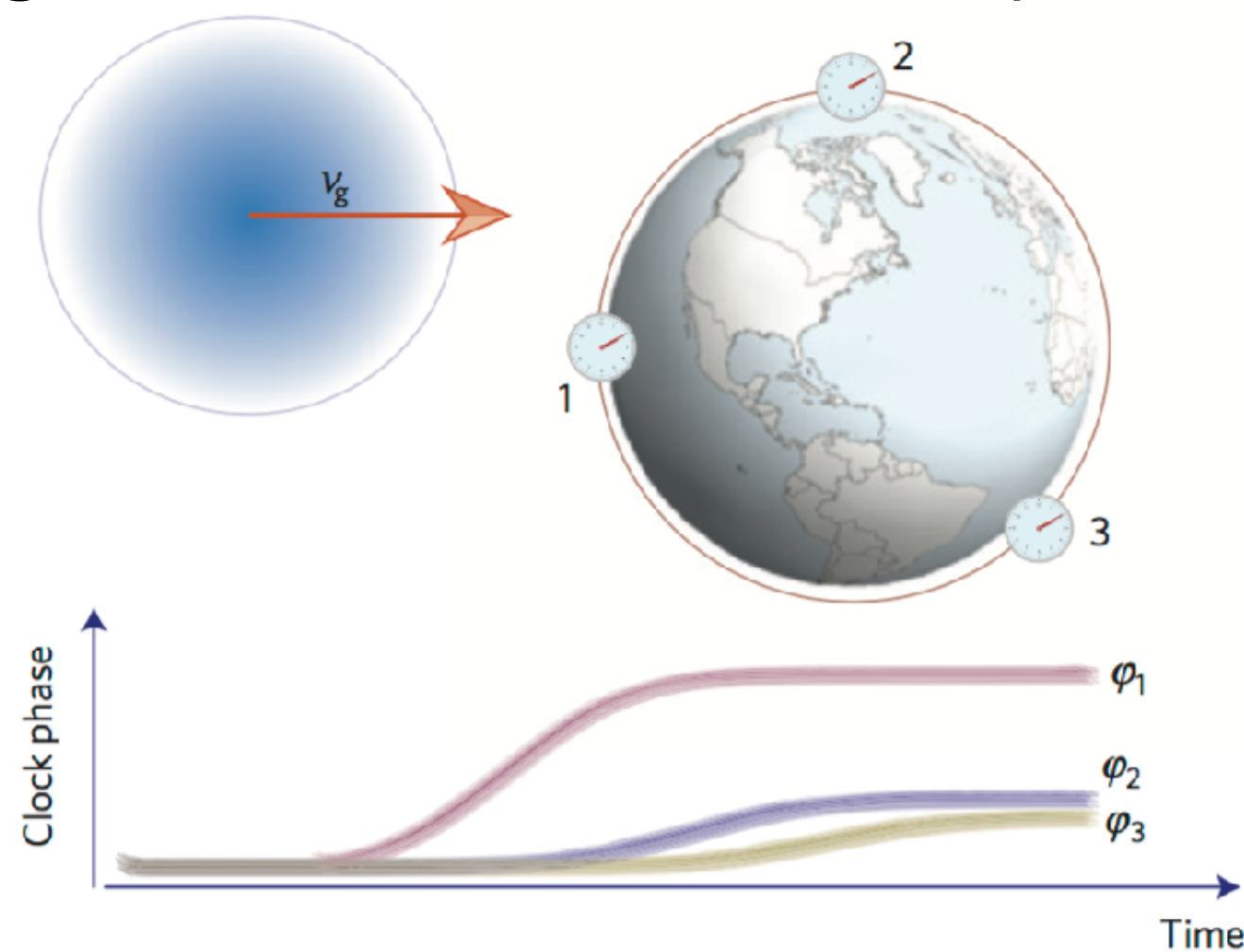
$$v_{Sr} \propto \alpha^2$$

$$v_{cav} \propto \frac{Nc}{2L} \propto \alpha$$

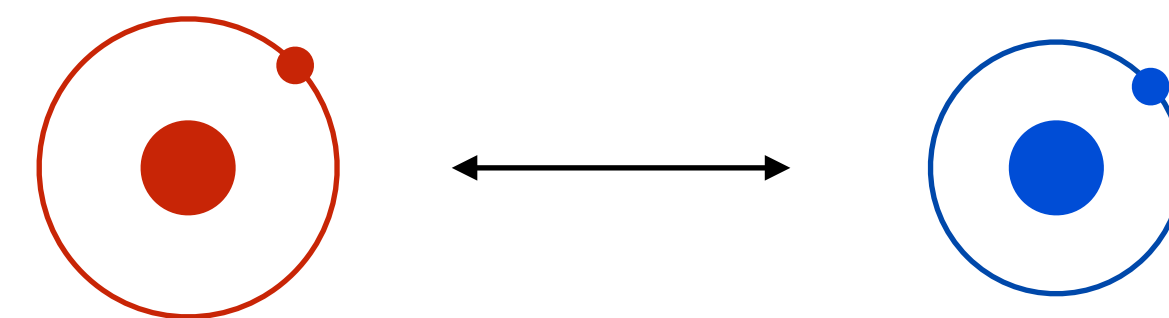
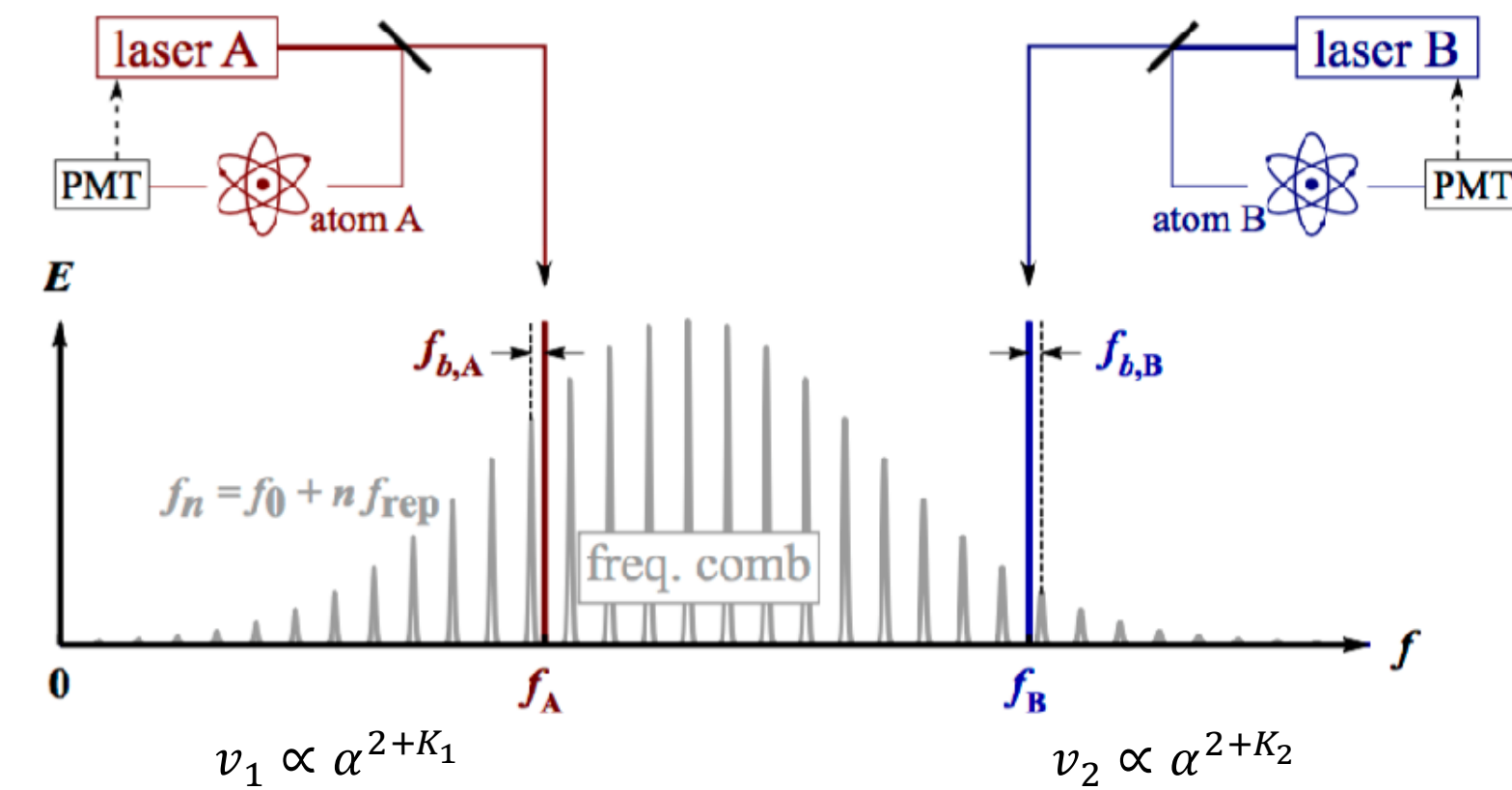


# Dark matter searches with atomic clocks

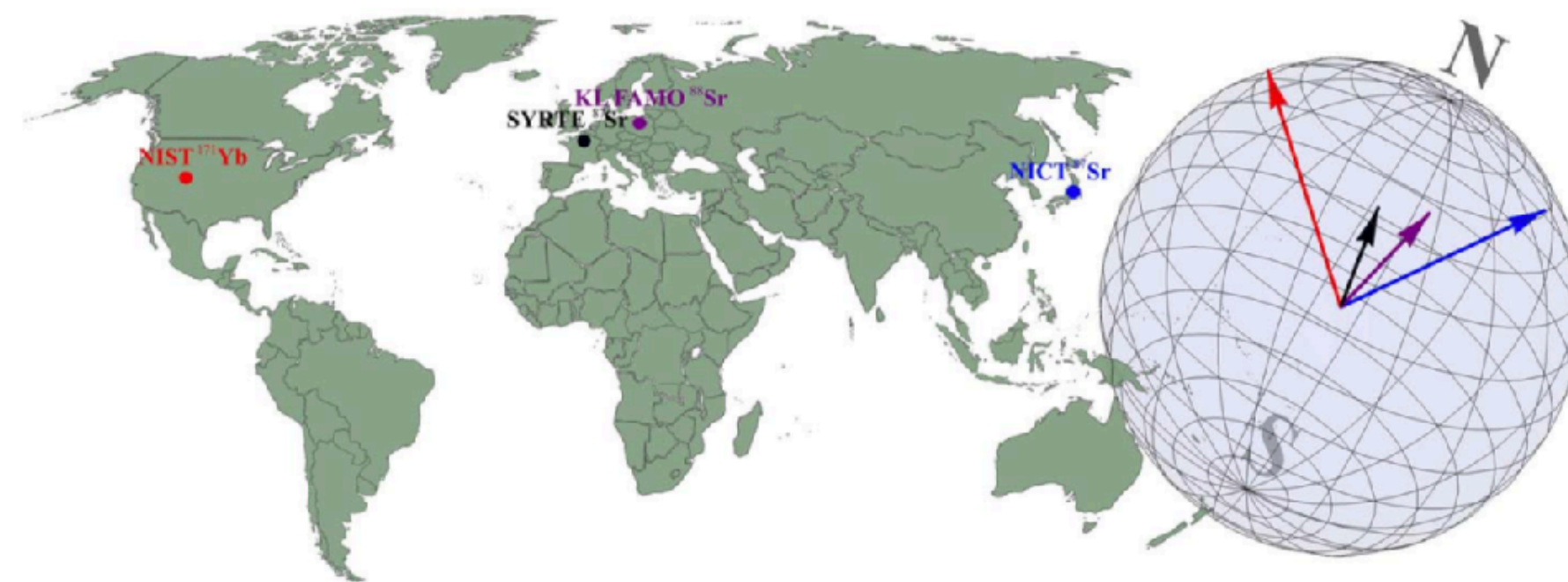
Long distance clock comparisons:



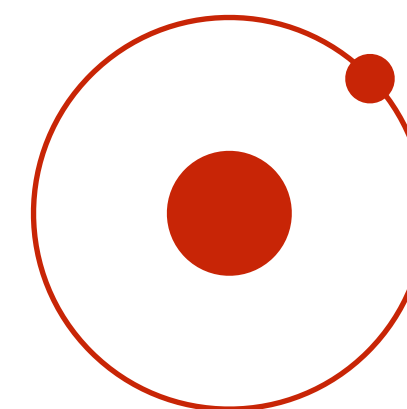
Multi-species comparisons:



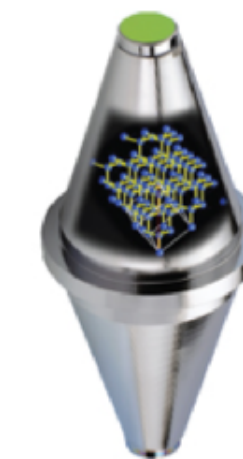
Atom-cavity comparisons:



$$v_{Sr} \propto \alpha^2$$

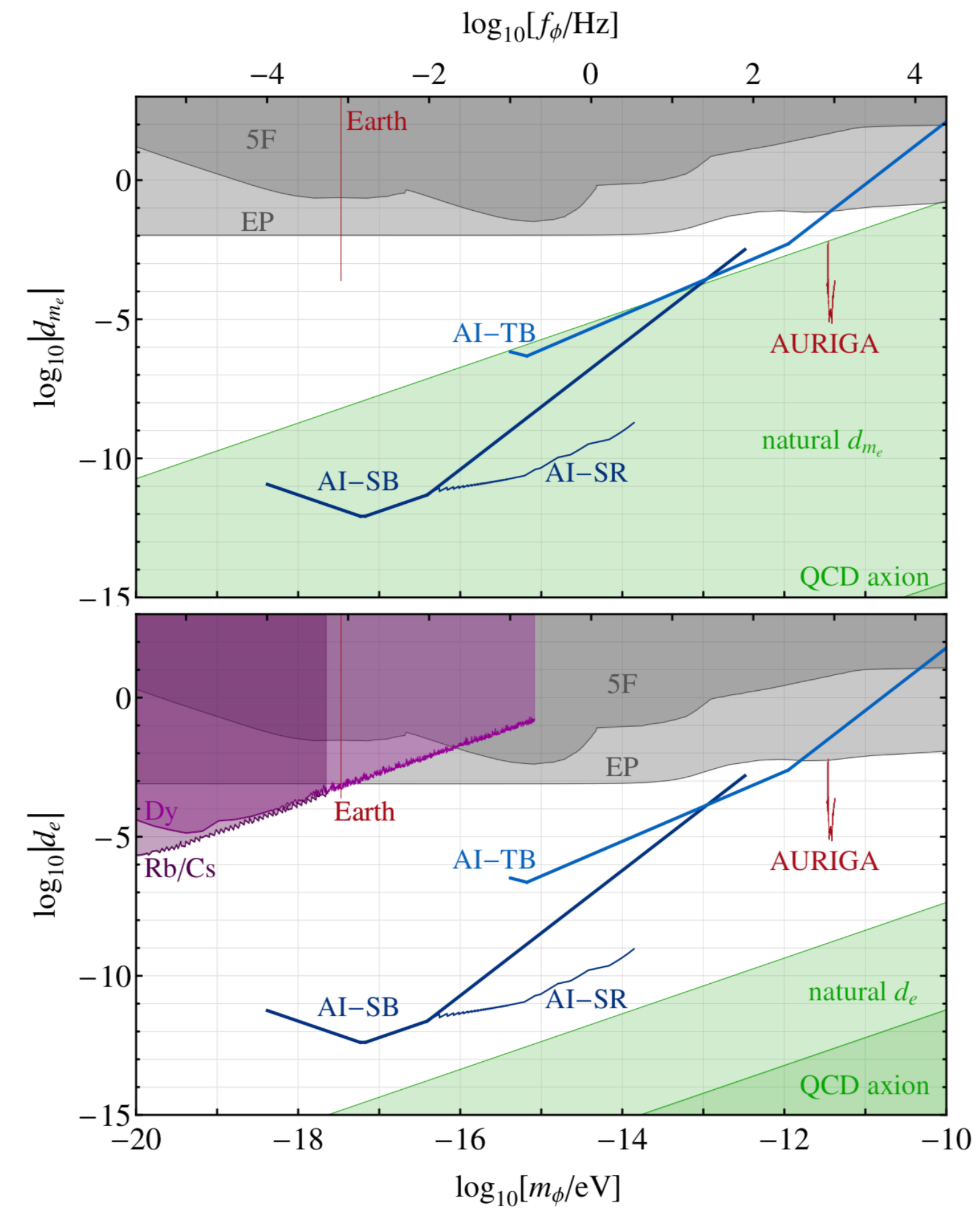
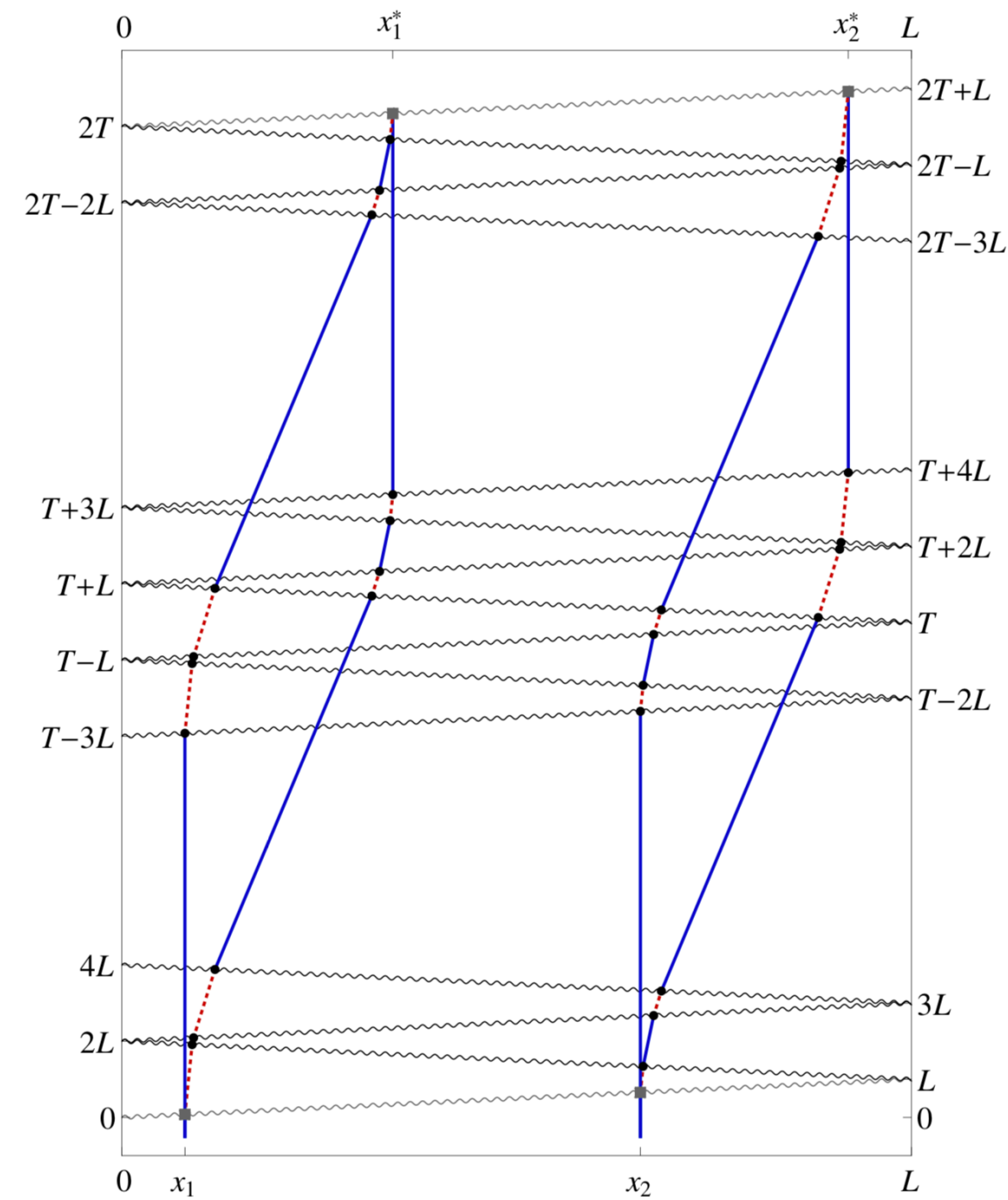
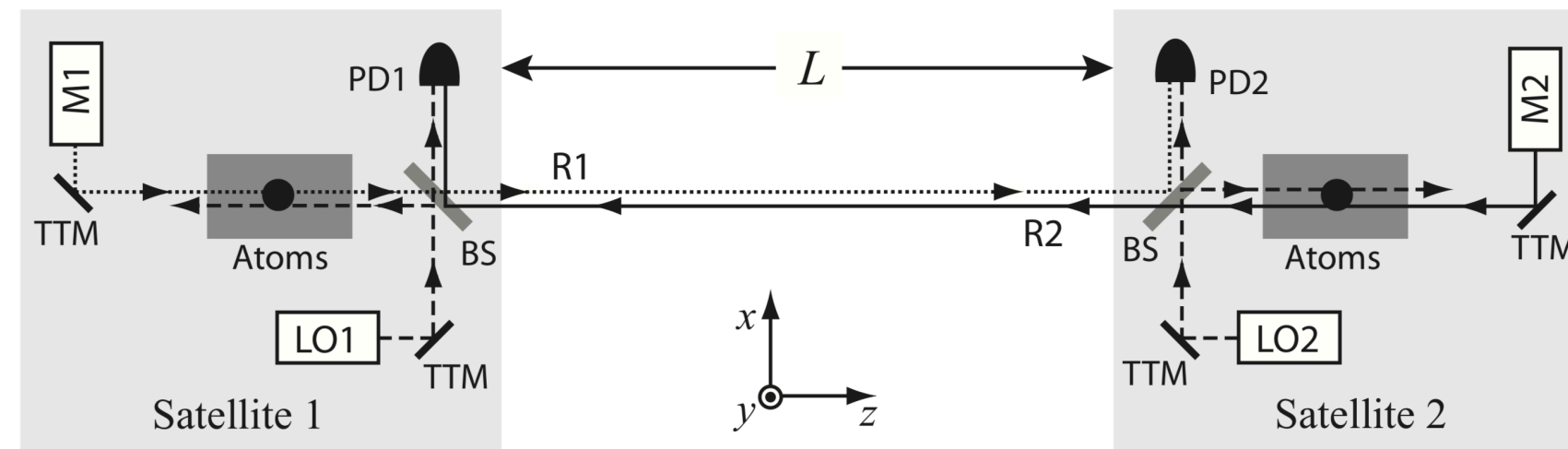


$$v_{cav} \propto \frac{Nc}{2L} \propto \alpha$$





# Scalar dark matter searches with atomic GW detectors



# Gravitational wave detection with clocks

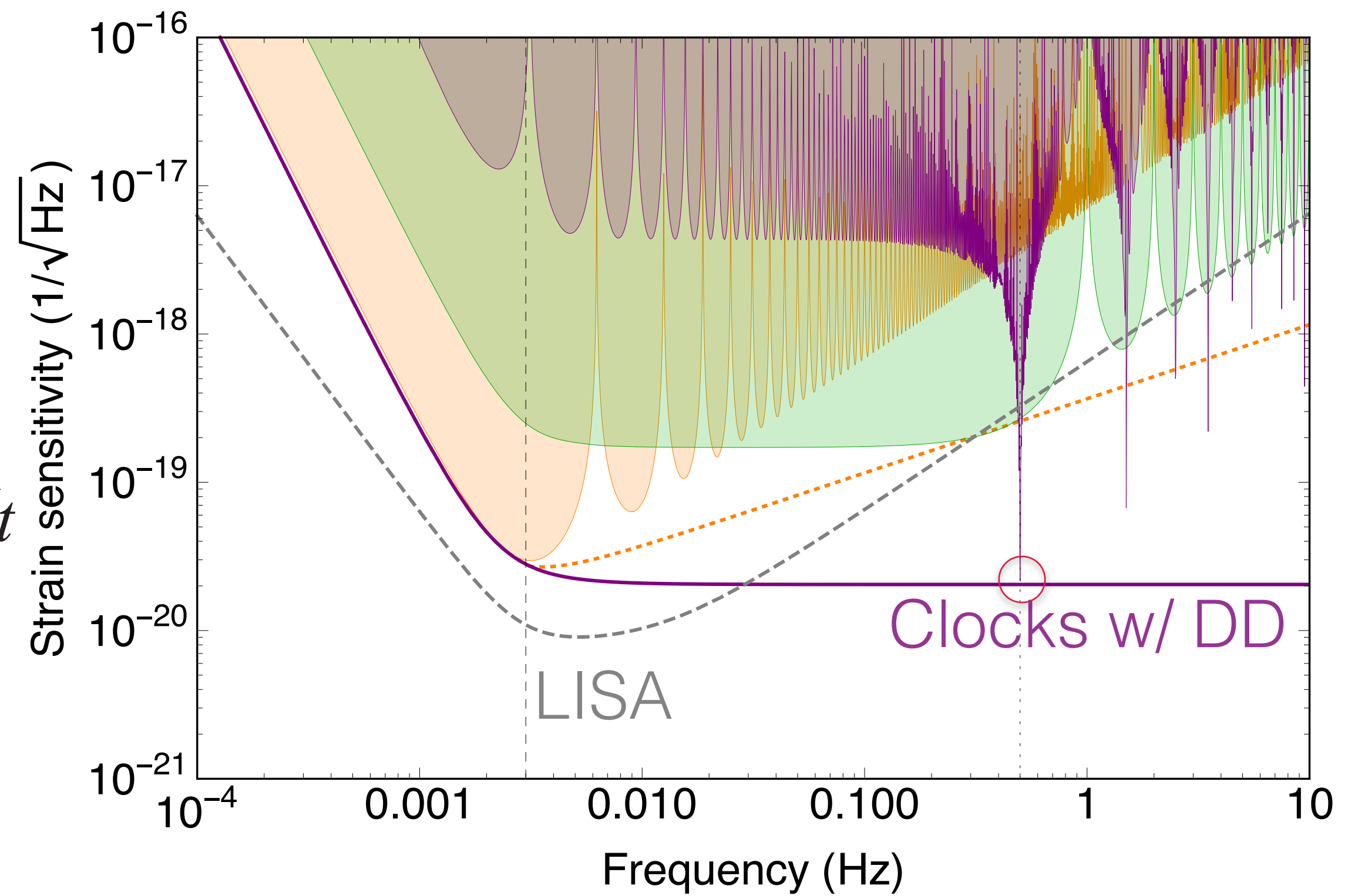
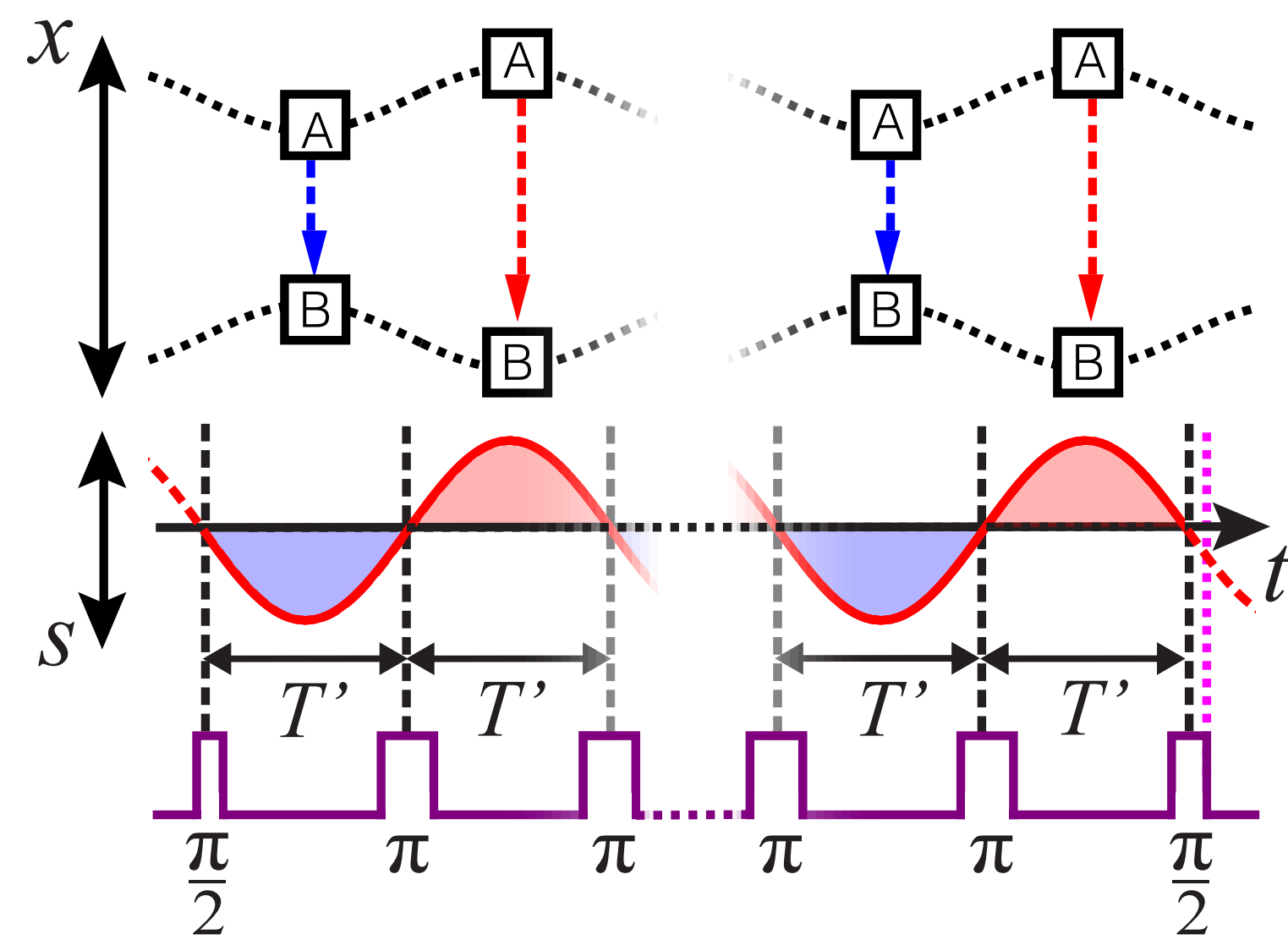
## Clock based detector

$d = 5 \times 10^{10}$  m arm length

$N = 7 \times 10^6$  Sr atoms per clock

160 s coherence time

Dynamical decoupling  
sequence:





# Gravitational wave detection with clocks

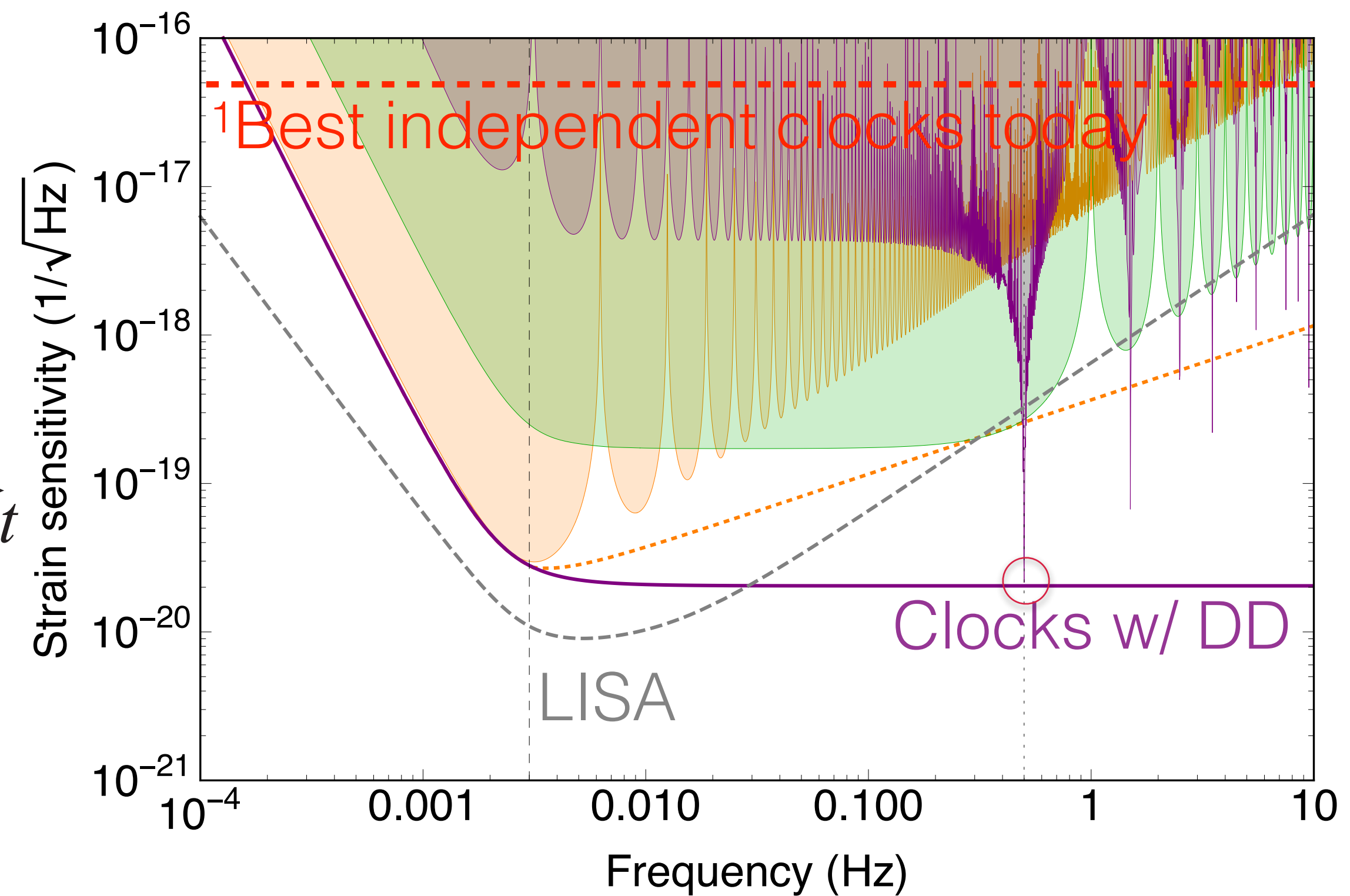
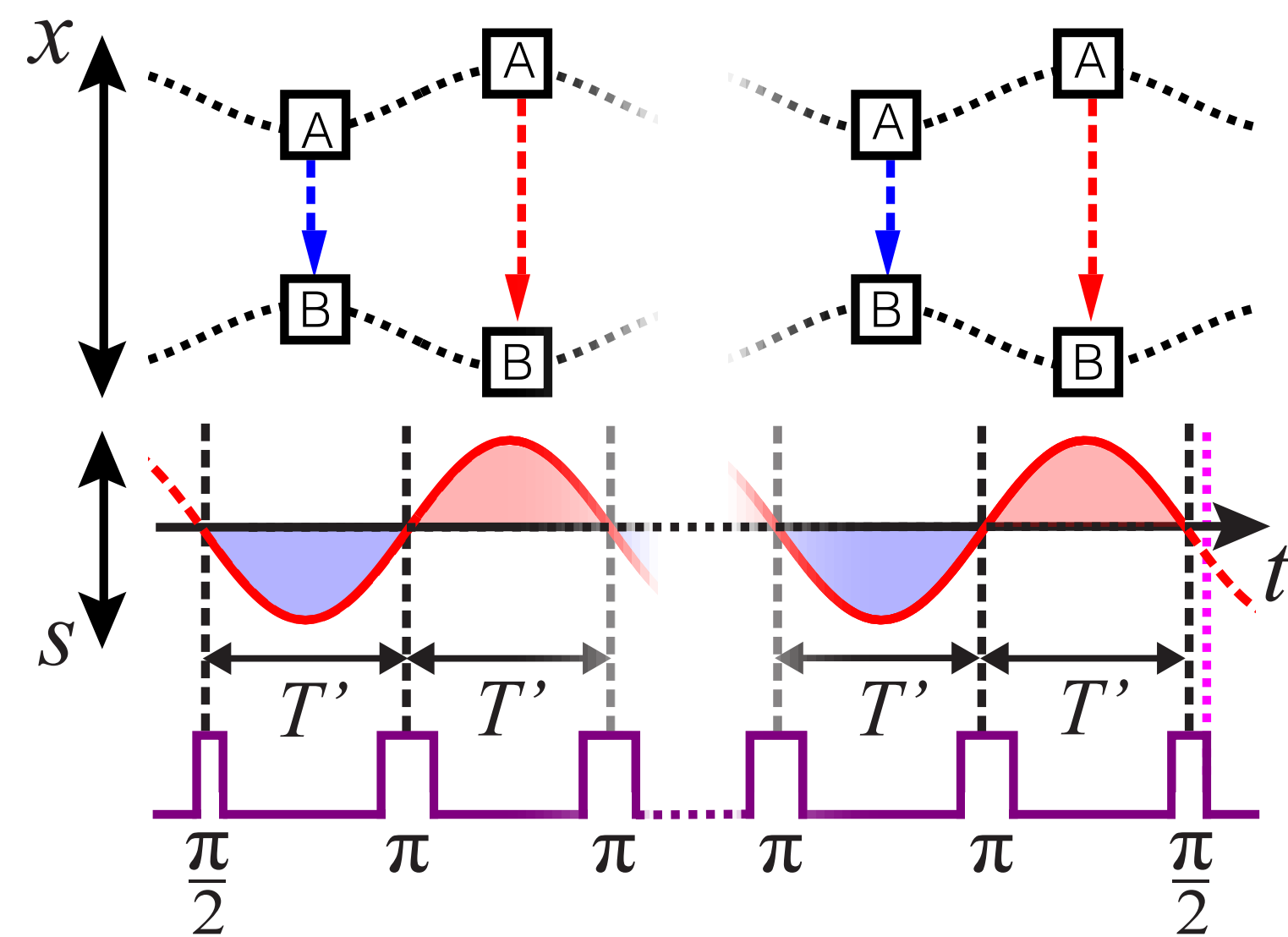
Clock based detector

$d = 5 \times 10^{10}$  m arm length

$N = 7 \times 10^6$  Sr atoms per clock

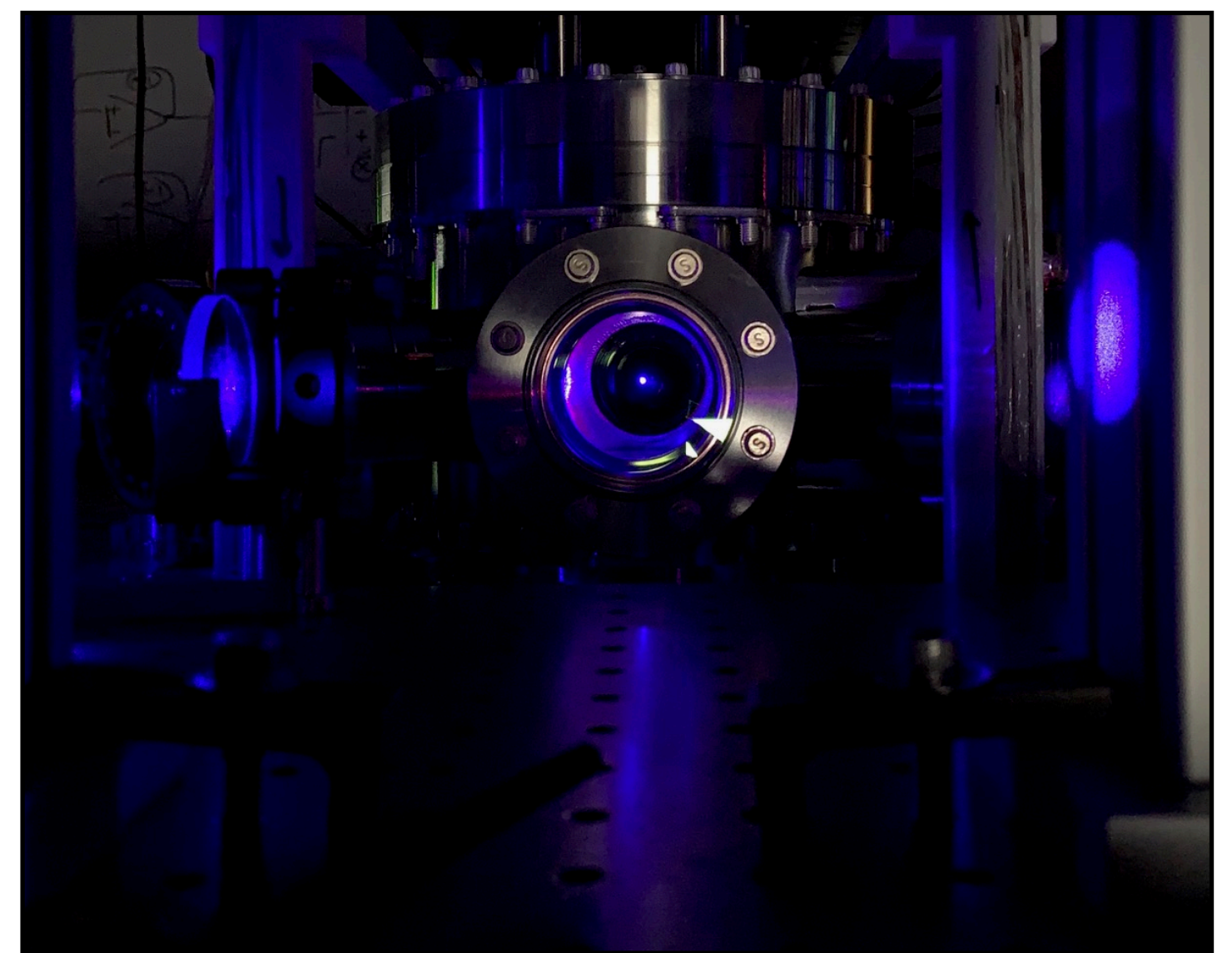
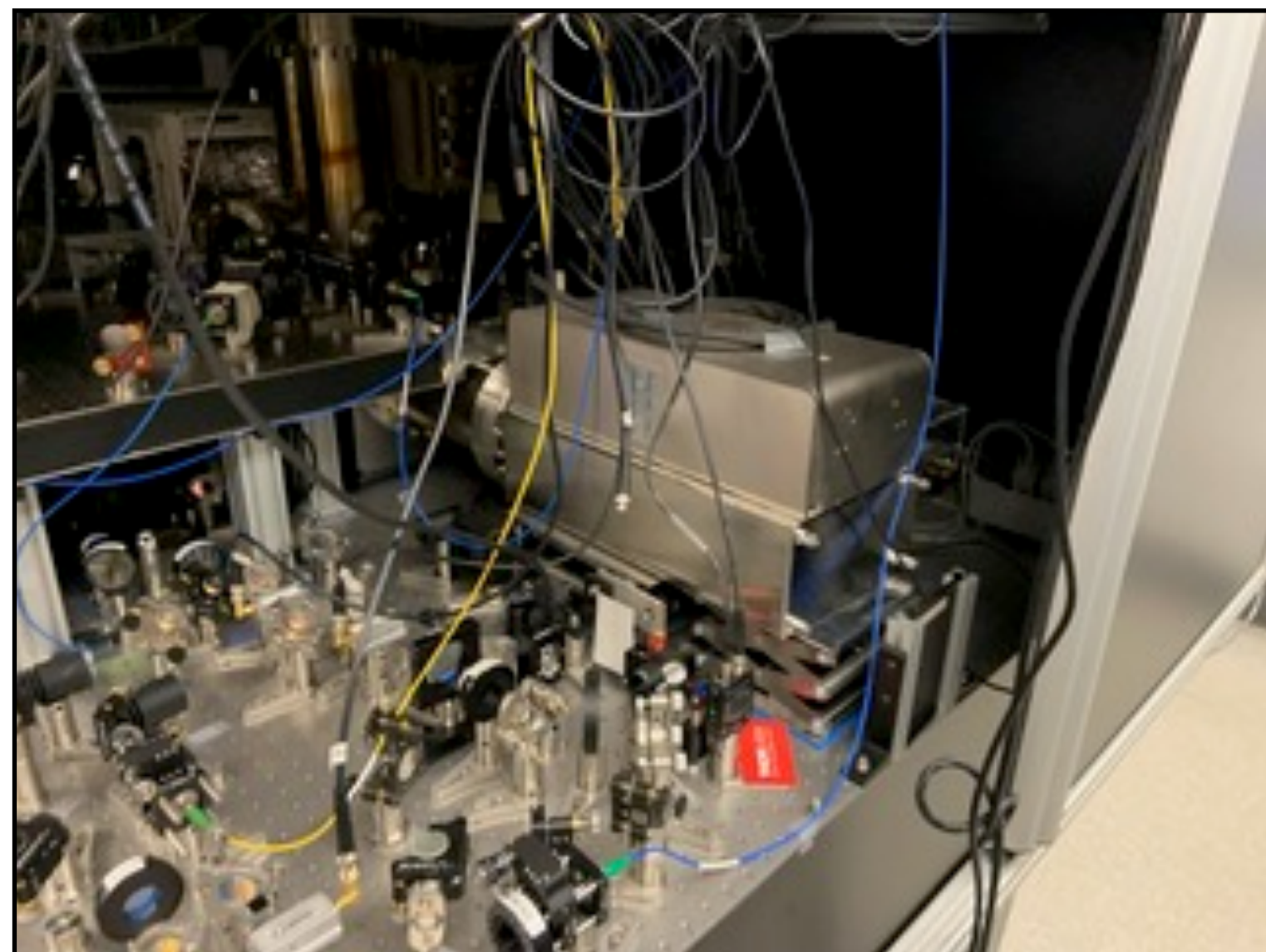
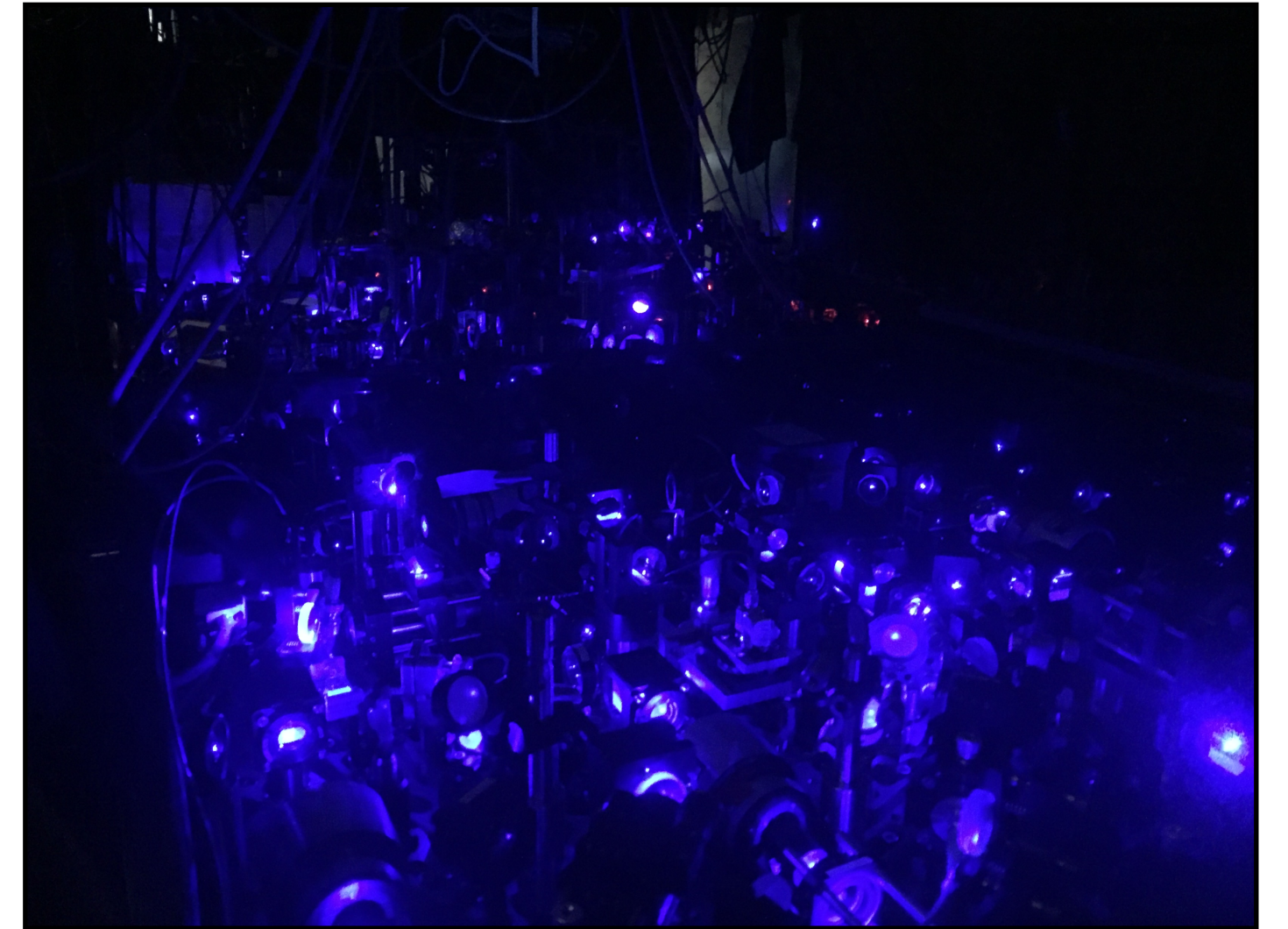
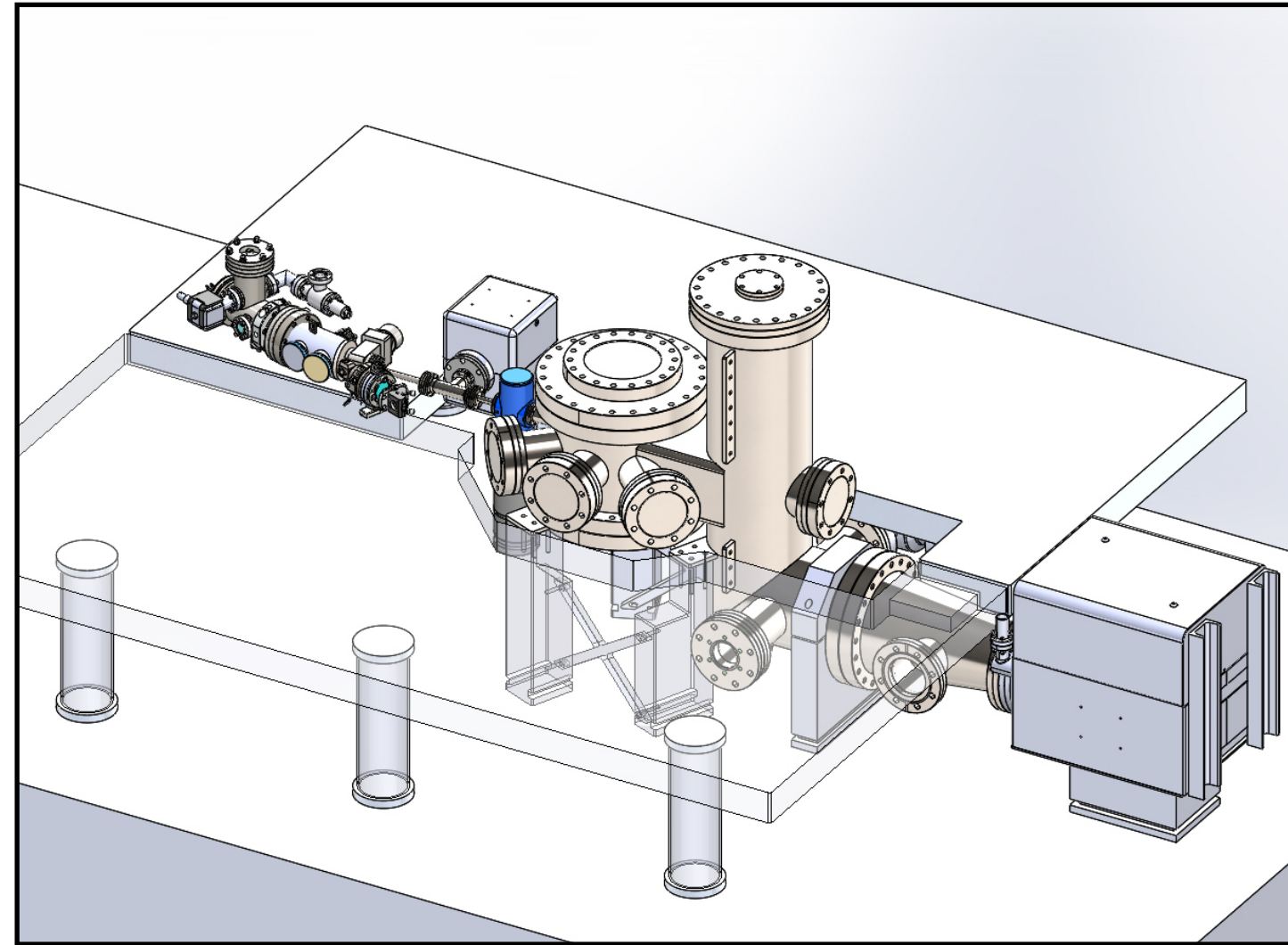
160 s coherence time

Dynamical decoupling  
sequence:





# A strontium optical lattice clock for tests of relativity



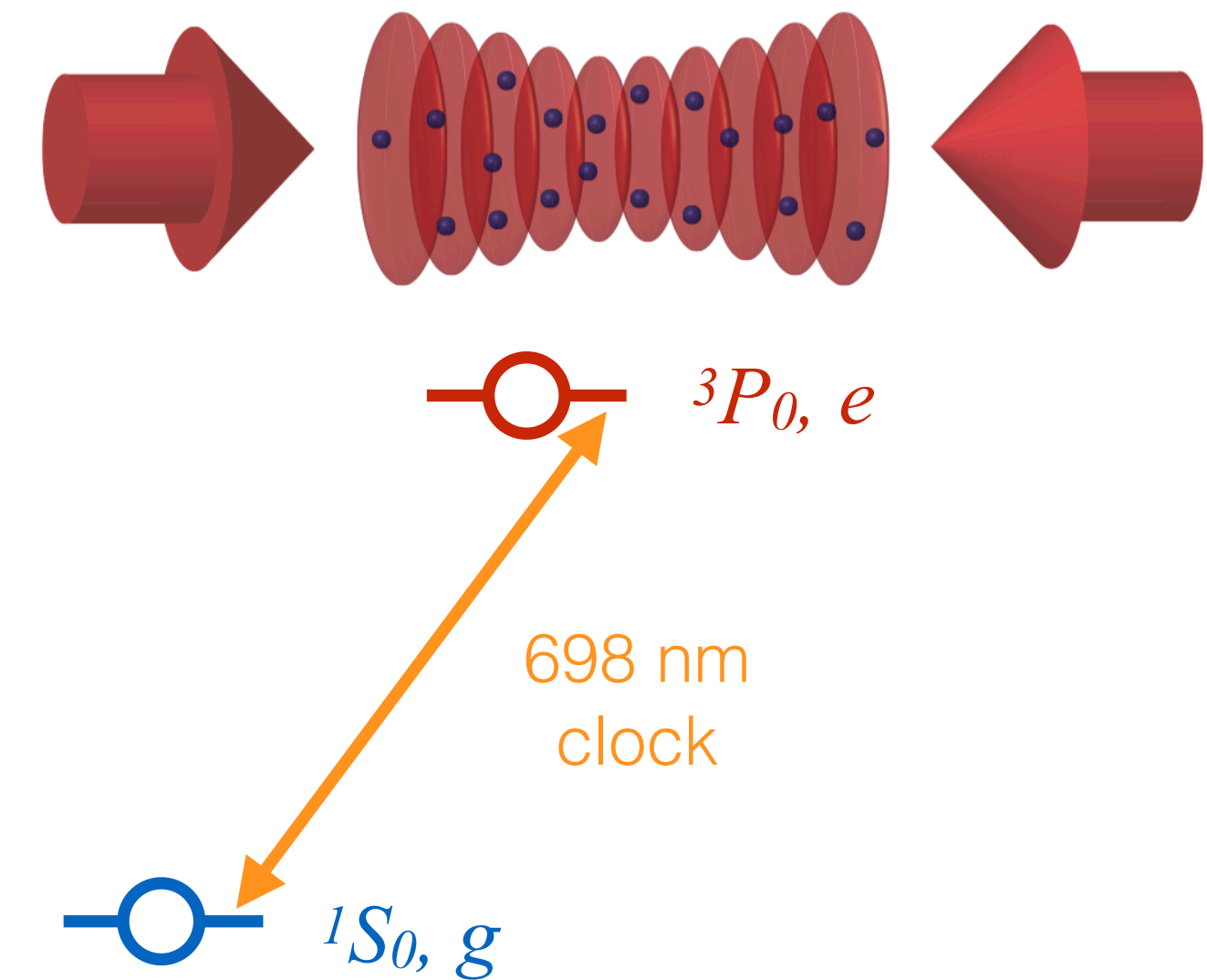
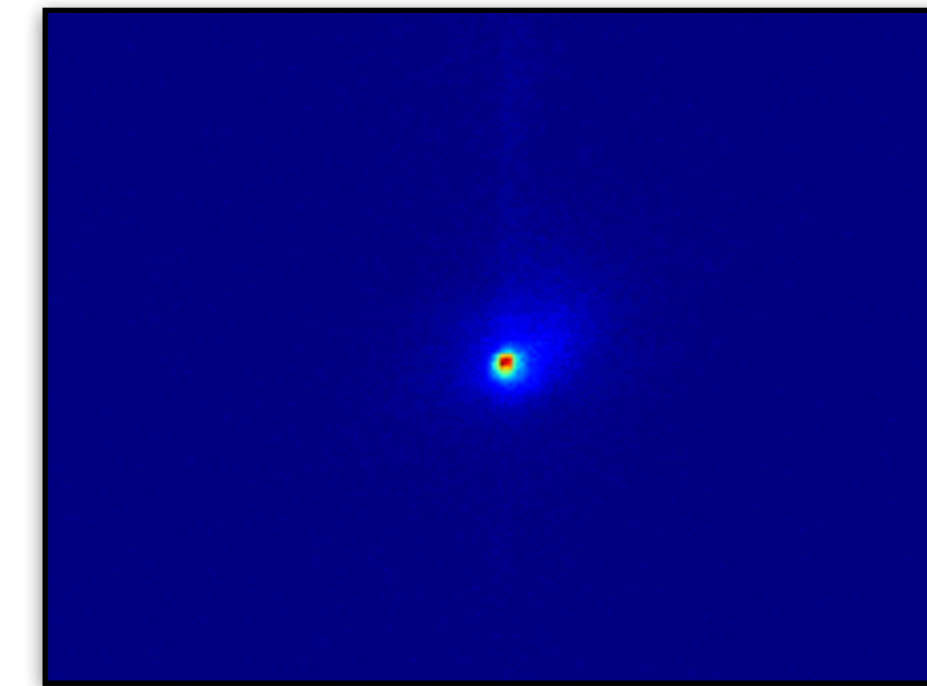


# A strontium optical lattice clock for fundamental physics

Racked mounted 12 cm ULE cavity:

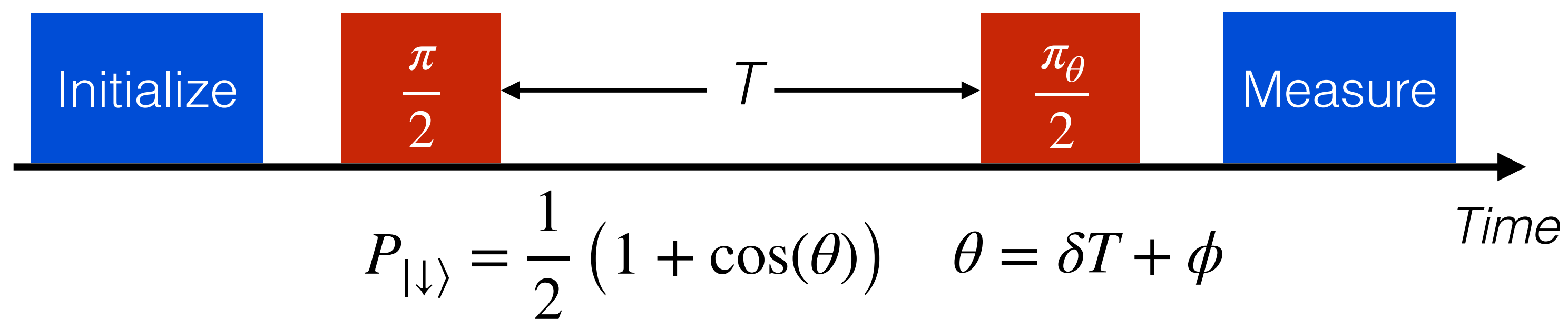
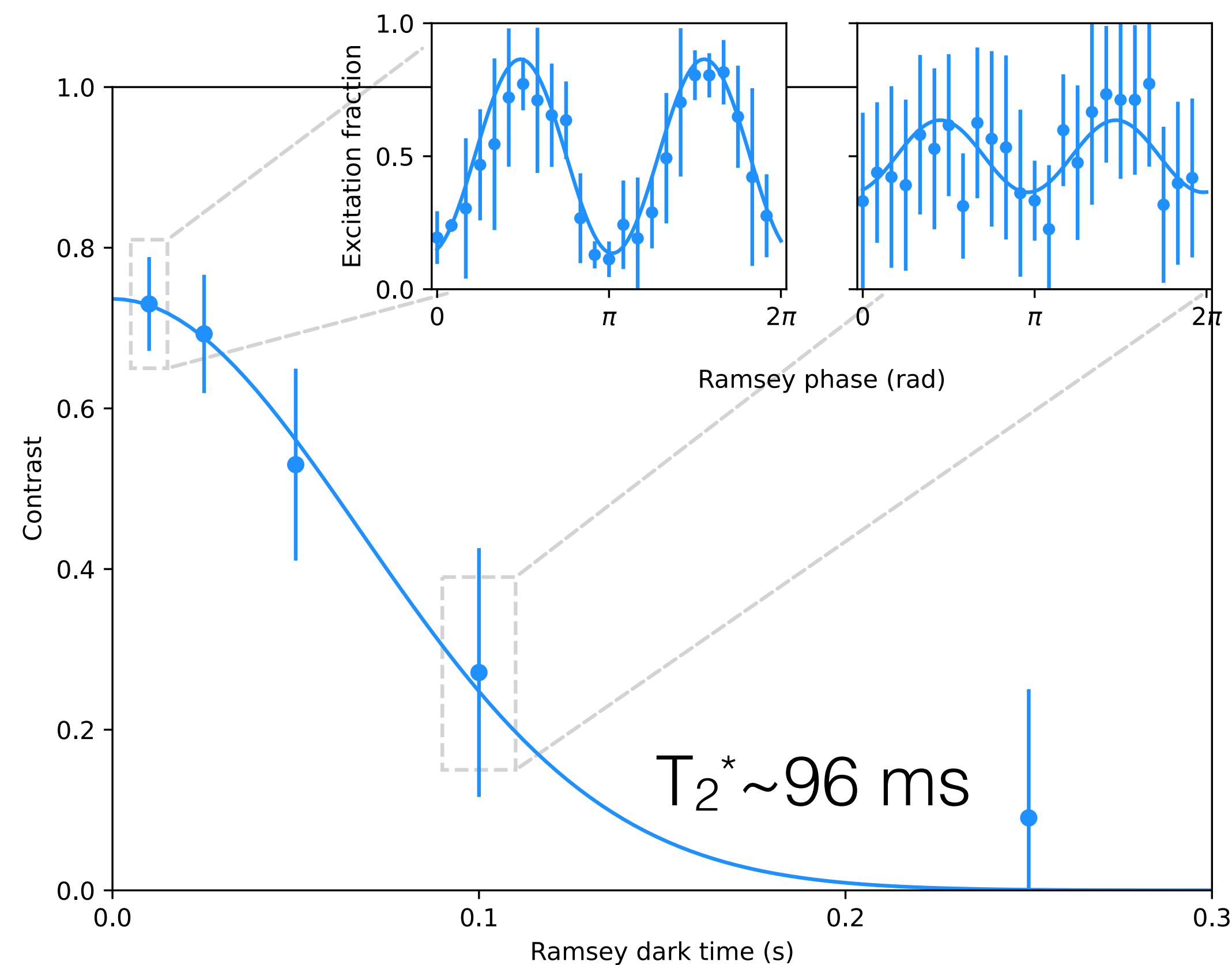


$^{87}\text{Sr}$  in a “magic wavelength”  
optical lattice:



1 mHz linewidth!

# Limitations from local oscillator noise

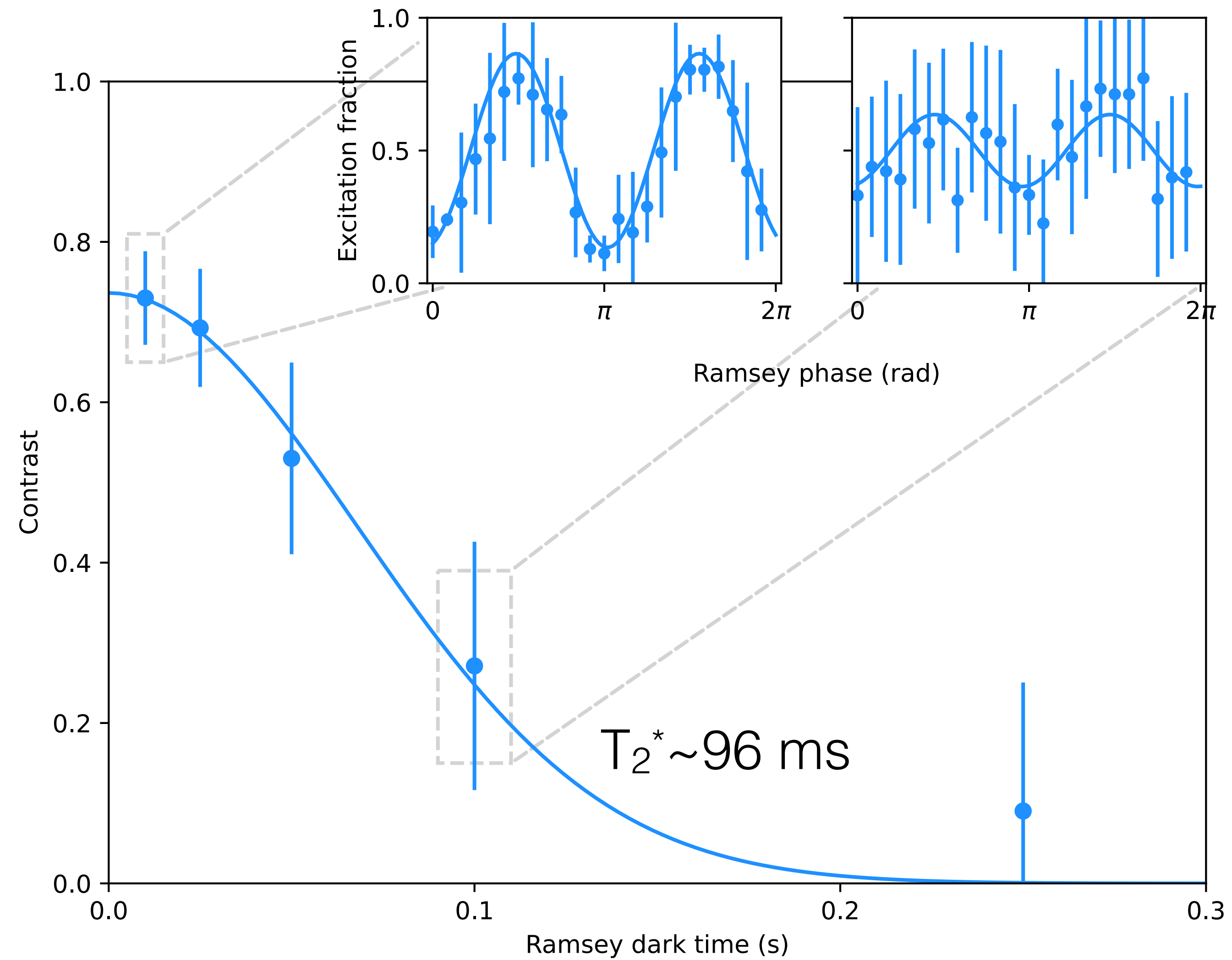




# Limitations from local oscillator noise

$$\sigma_{\text{QPN}}(\tau) = \frac{1}{2\pi\nu_o C(T)T} \sqrt{\frac{T + T_d}{N_d \tau}}$$

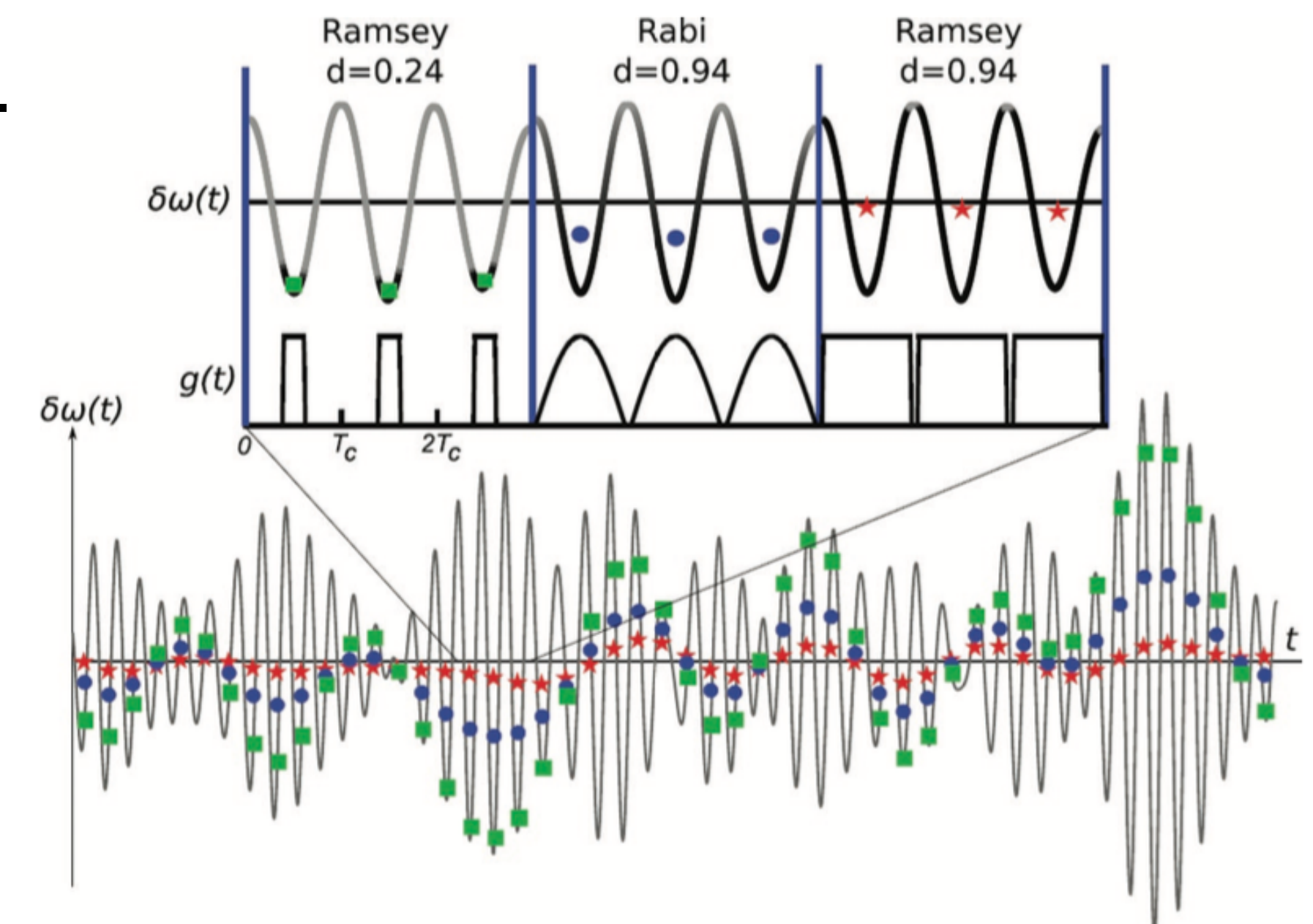
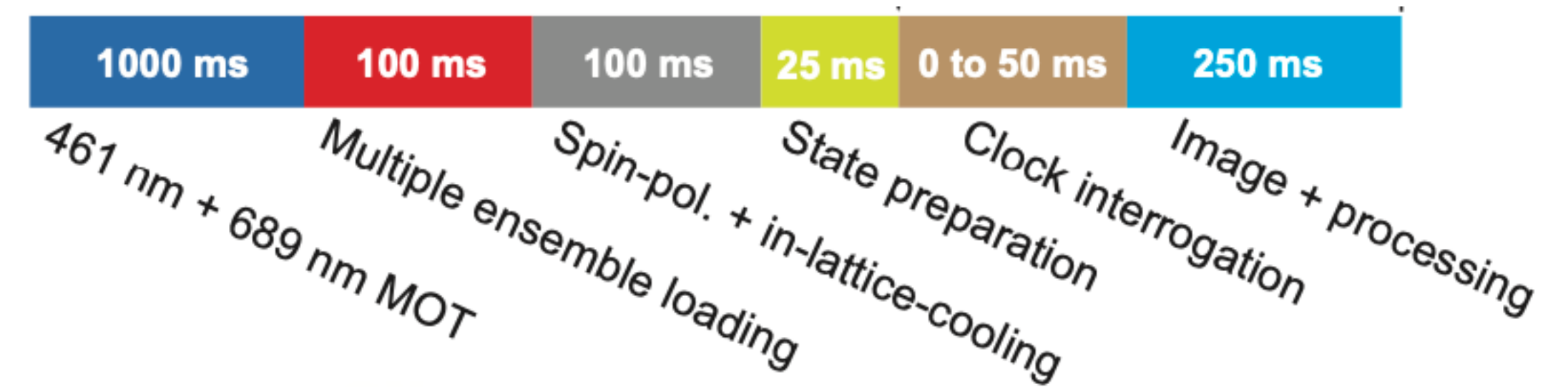
$$\sigma(\tau) \approx 4 \times 10^{-16} / \sqrt{\tau}$$



# Limitations from local oscillator noise

~~$$\sigma_{\text{QPN}}(\tau) = \frac{1}{2\pi\nu_o C(T)T} \sqrt{\frac{T + T_d}{N_d \tau}}$$~~

$$\sigma_{\text{Dick}}(\tau) = \frac{\sigma_{\text{LO}}}{\sqrt{2\ln 2}} \sum_{m=1}^{\infty} \left| \frac{\sin(\pi m T / (T + T_d))}{\pi m T / (T + T_d)} \right| \sqrt{\frac{T + T_d}{m \tau}}$$





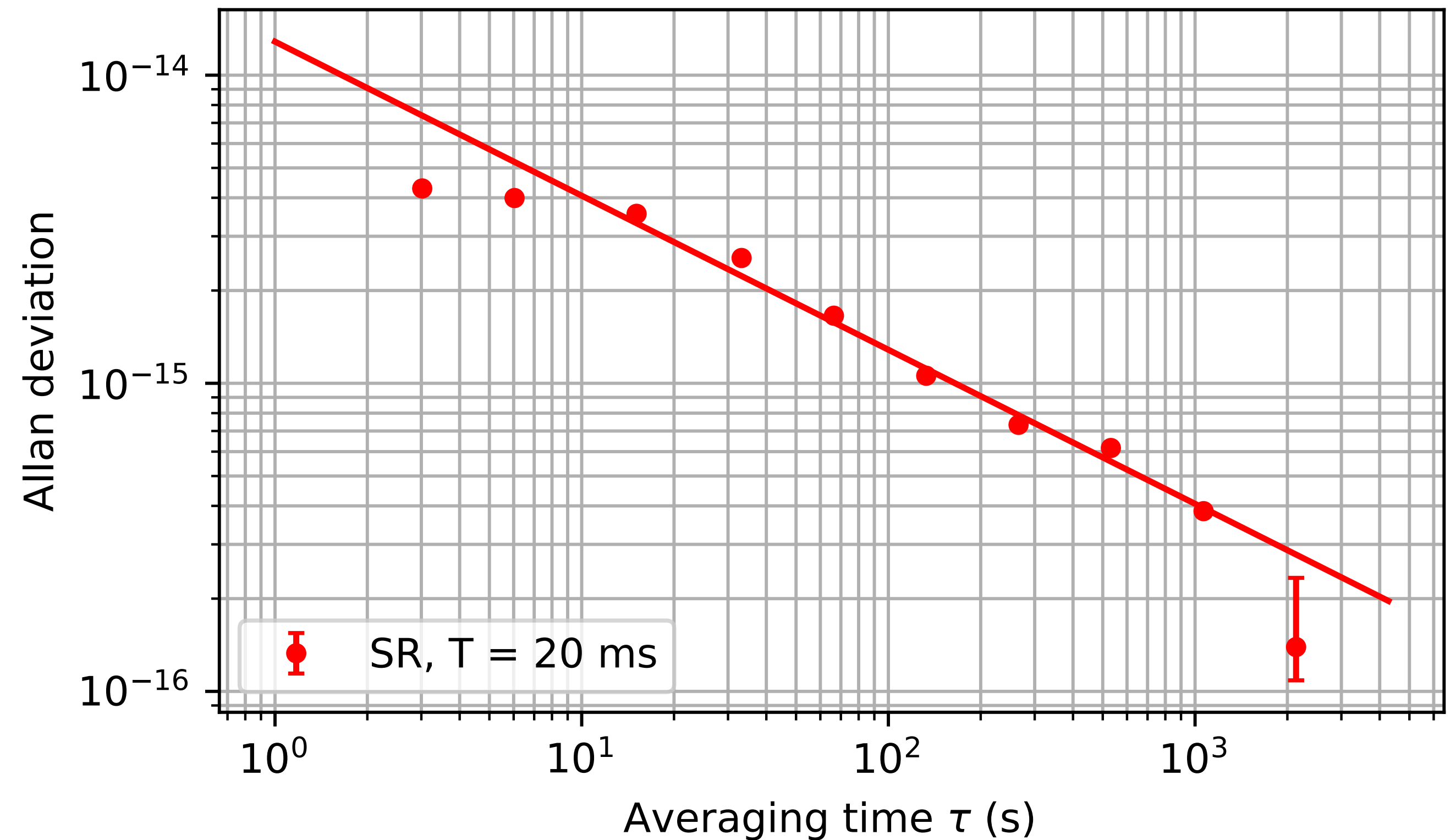
# Limitations from local oscillator noise

$$\sigma_{\text{QPN}}(\tau) = \frac{1}{2\pi\nu_o C(T)T} \sqrt{\frac{T + T_d}{N_a \tau}}$$

$$\sigma_{\text{Dick}}(\tau) \propto \frac{\sigma_{\text{LO}}}{T} \sqrt{\frac{T + T_d}{\tau}}$$

$$T \approx 20 \text{ ms}$$

$$T_d \approx 1.5 \text{ s}$$



$$\sigma(\tau) \approx 6 \times 10^{-15} / \sqrt{\tau}$$

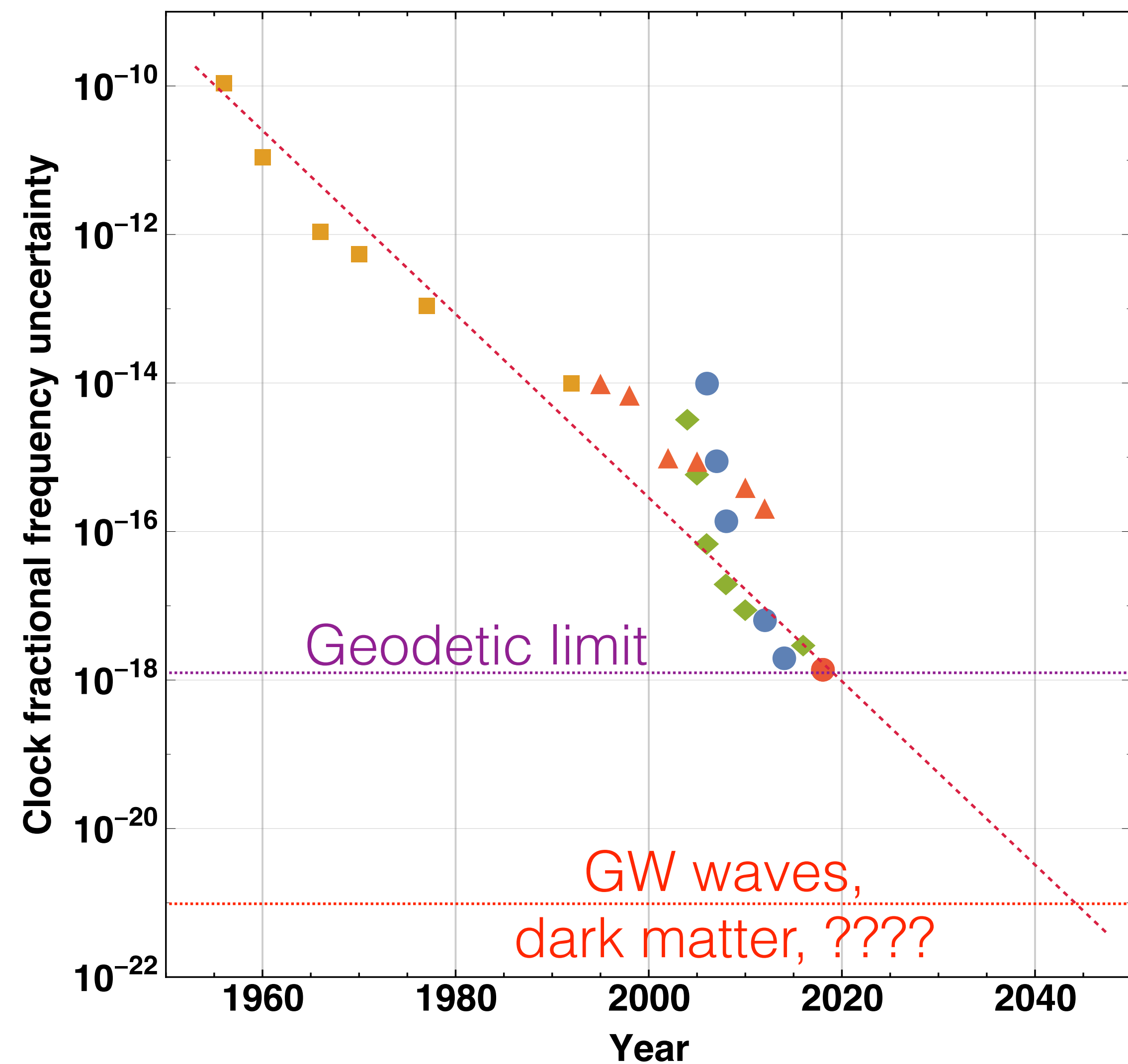
# Novel applications of optical lattice clocks

- Cs beam
- ▲ Cs fountain
- ◆ Ion optical clock
- Sr optical lattice clock
- Yb optical lattice clock

At a stability of

$$\sigma(\tau) \approx 6 \times 10^{-15} / \sqrt{\tau}$$

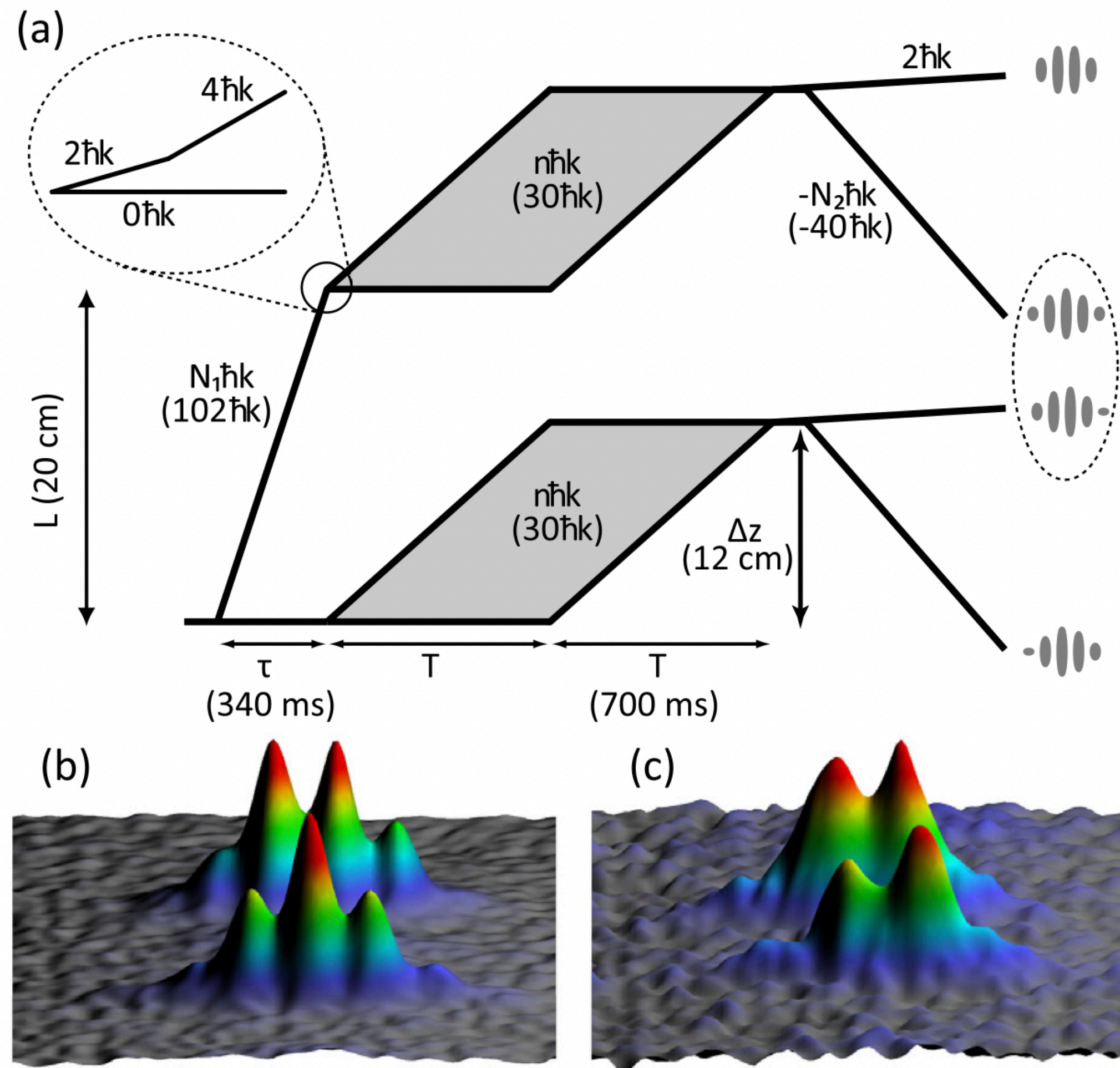
it would take ~11,000 years to average  
down to  $1 \times 10^{-20}$



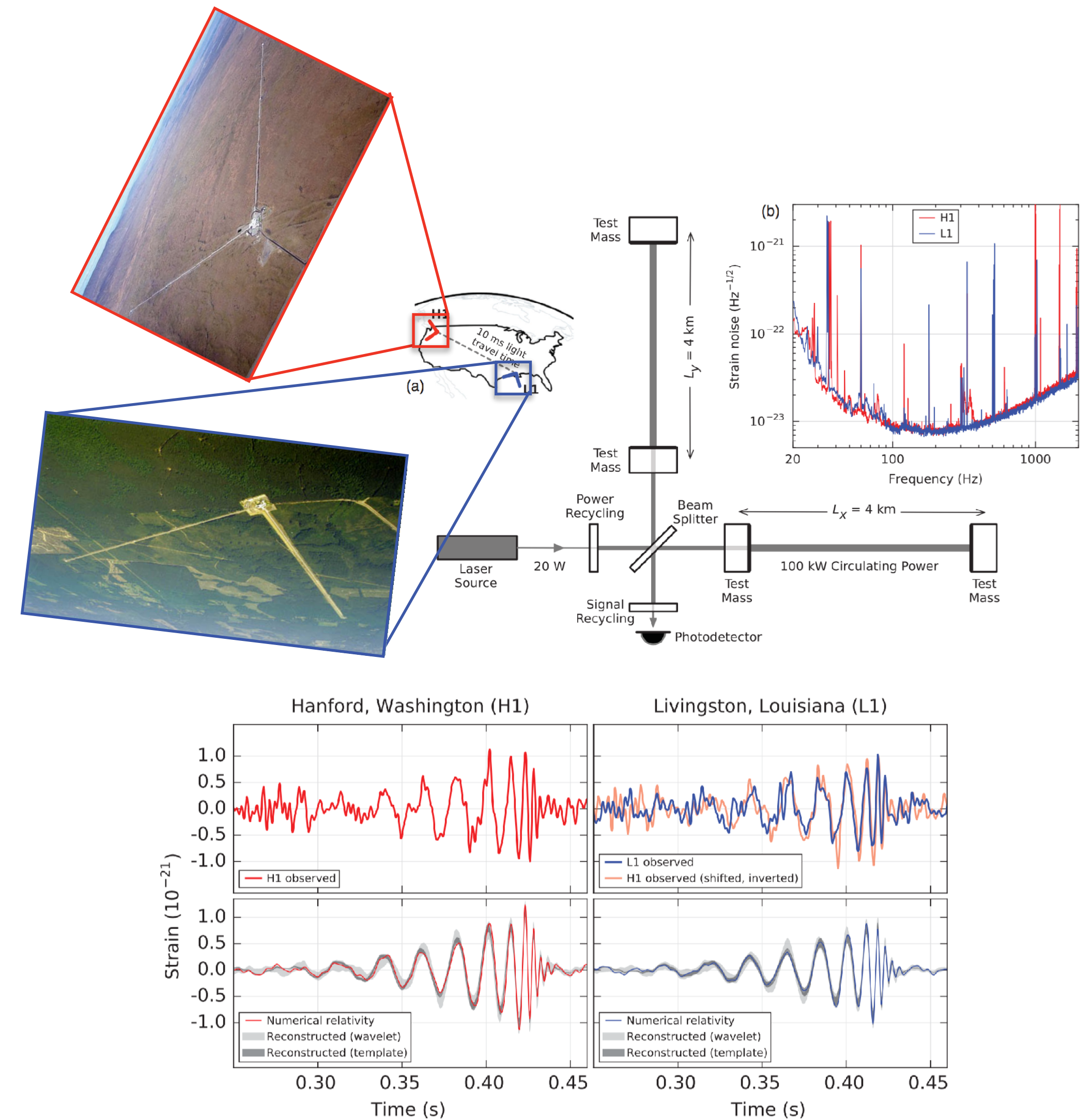


# Inspiration from other experiments

AI Gradiometers:

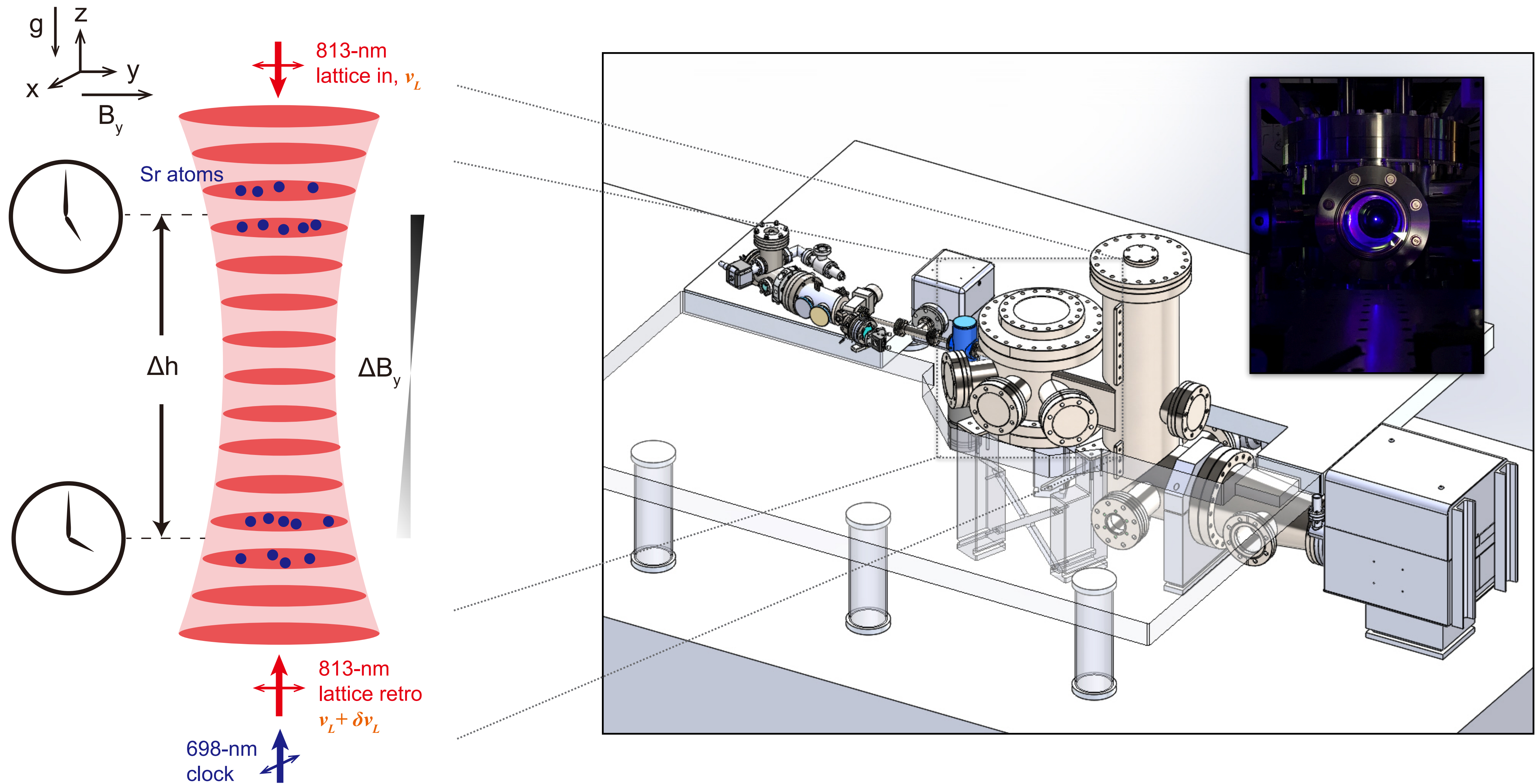


LIGO:





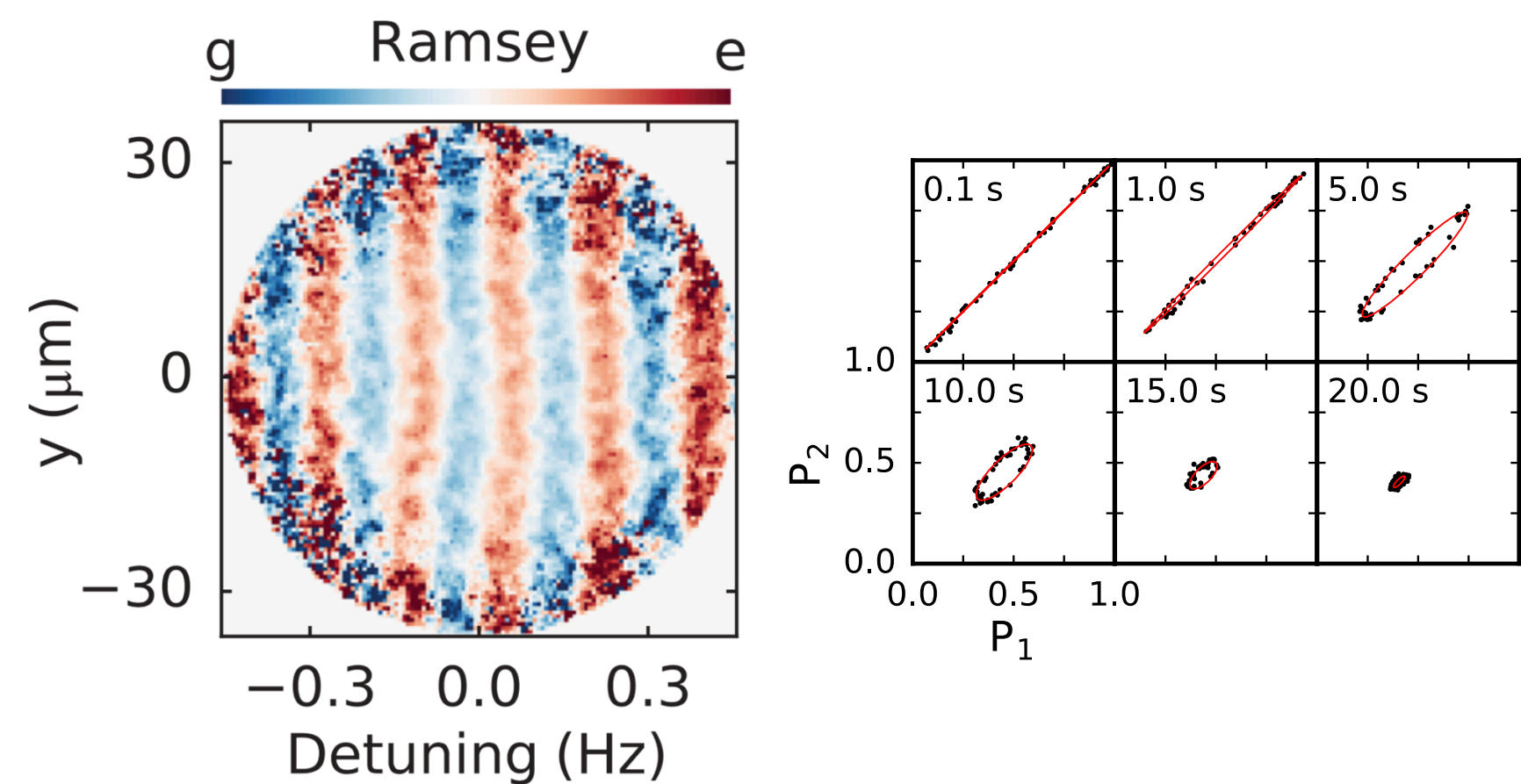
# A multiplexed strontium optical lattice clock



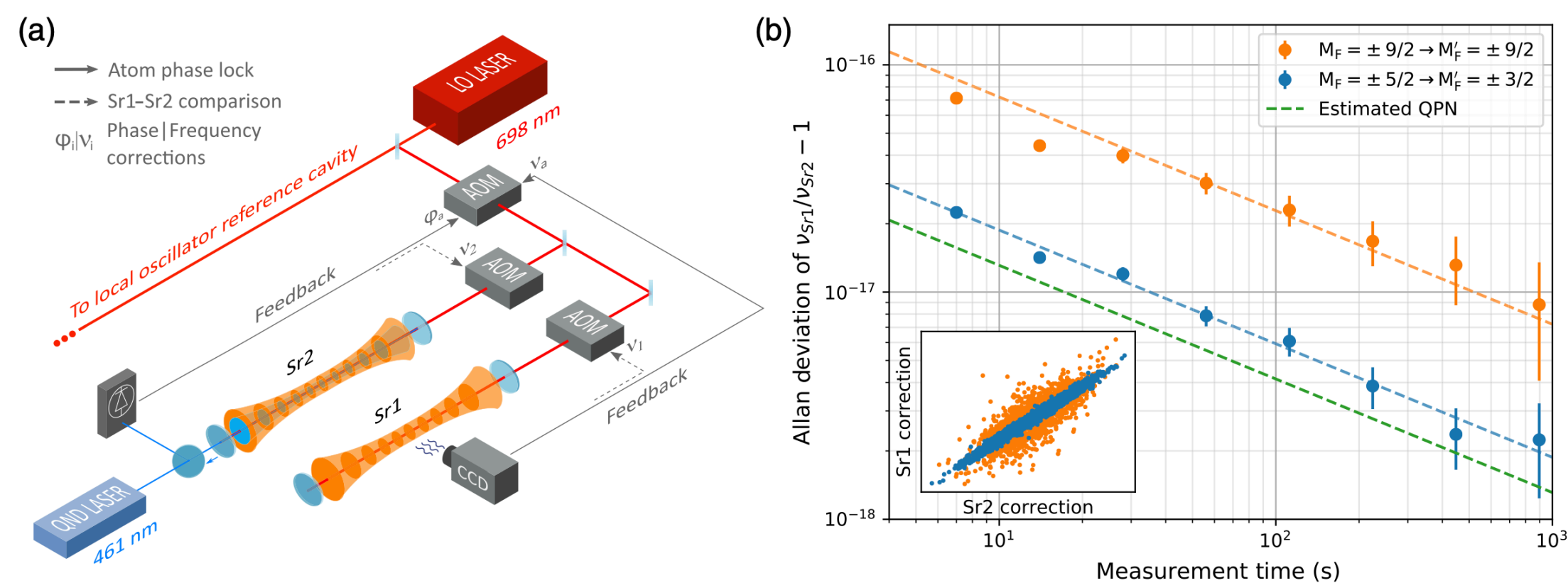


# Differential clock comparisons around the world

Ye group, JILA:



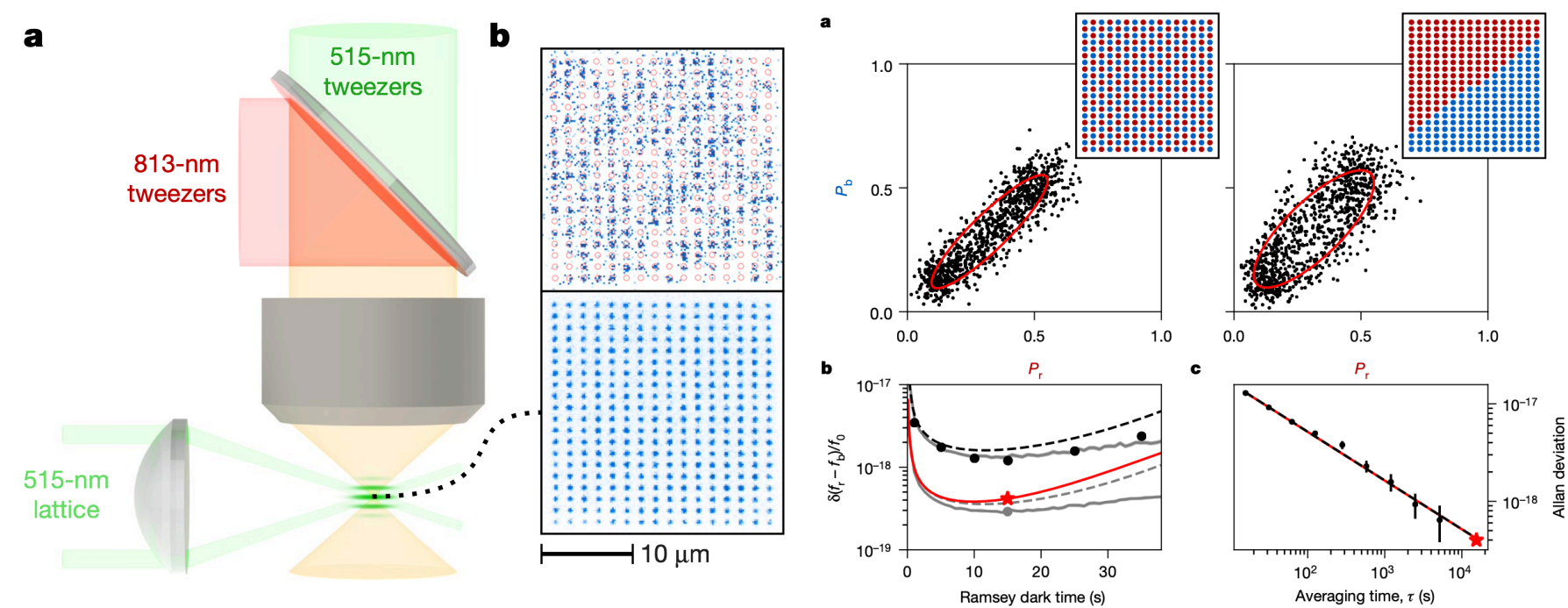
Hobson group, Imperial:



Bowden et al., *PRX* (2020)

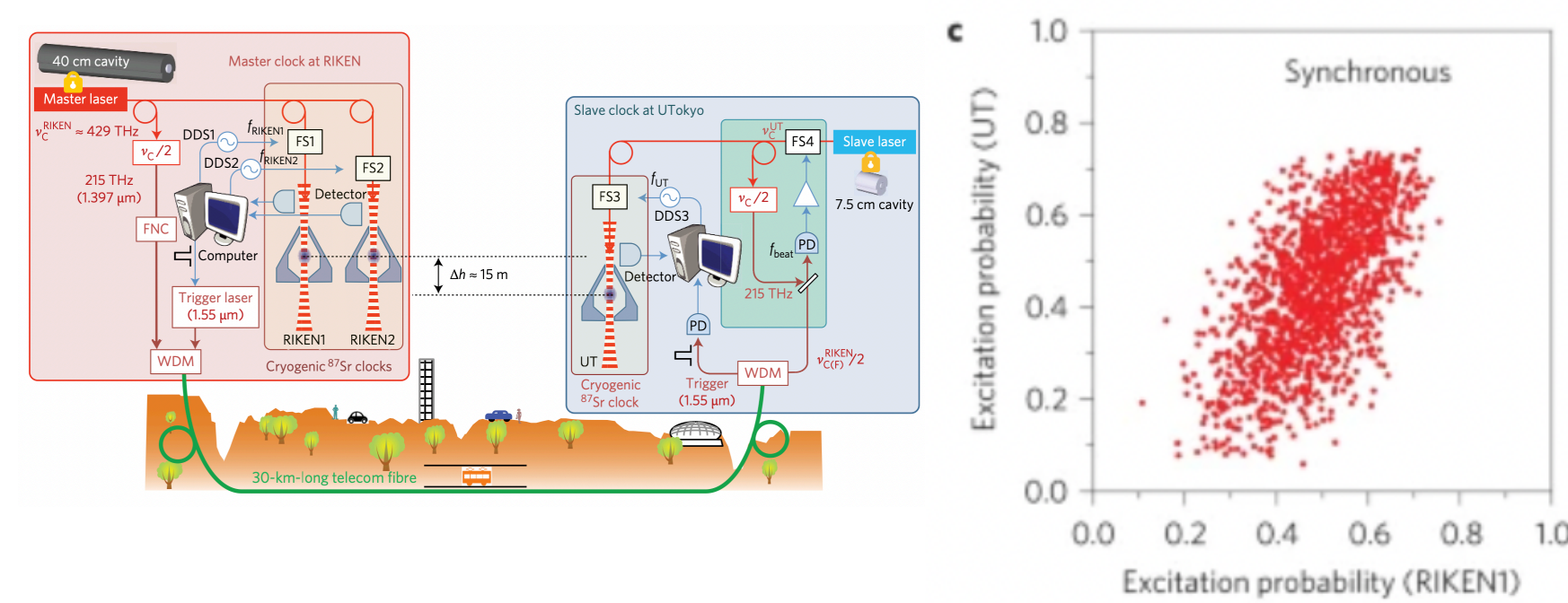
Marti et al., *PRL* (2018)

Kaufman group, JILA:



Young et al., *Nature* (2020)

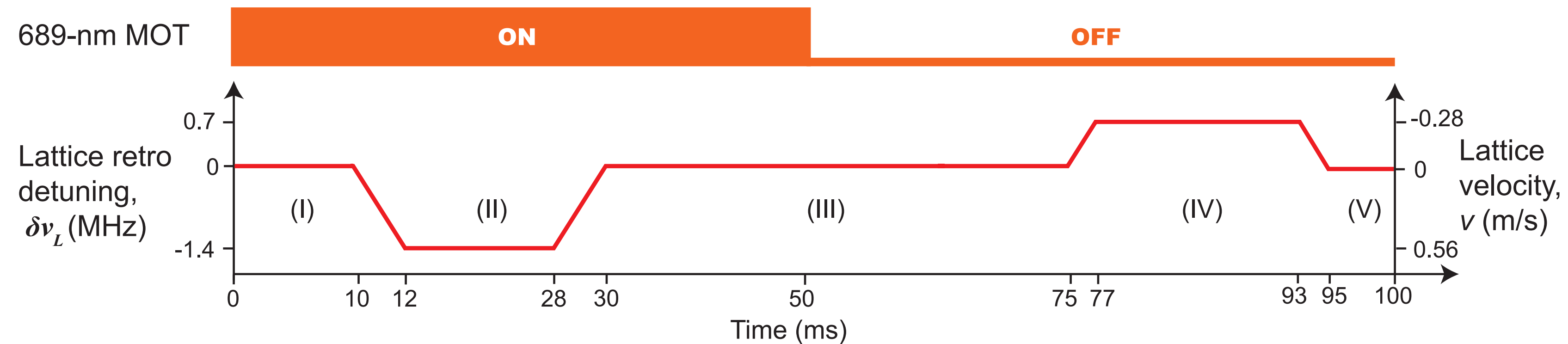
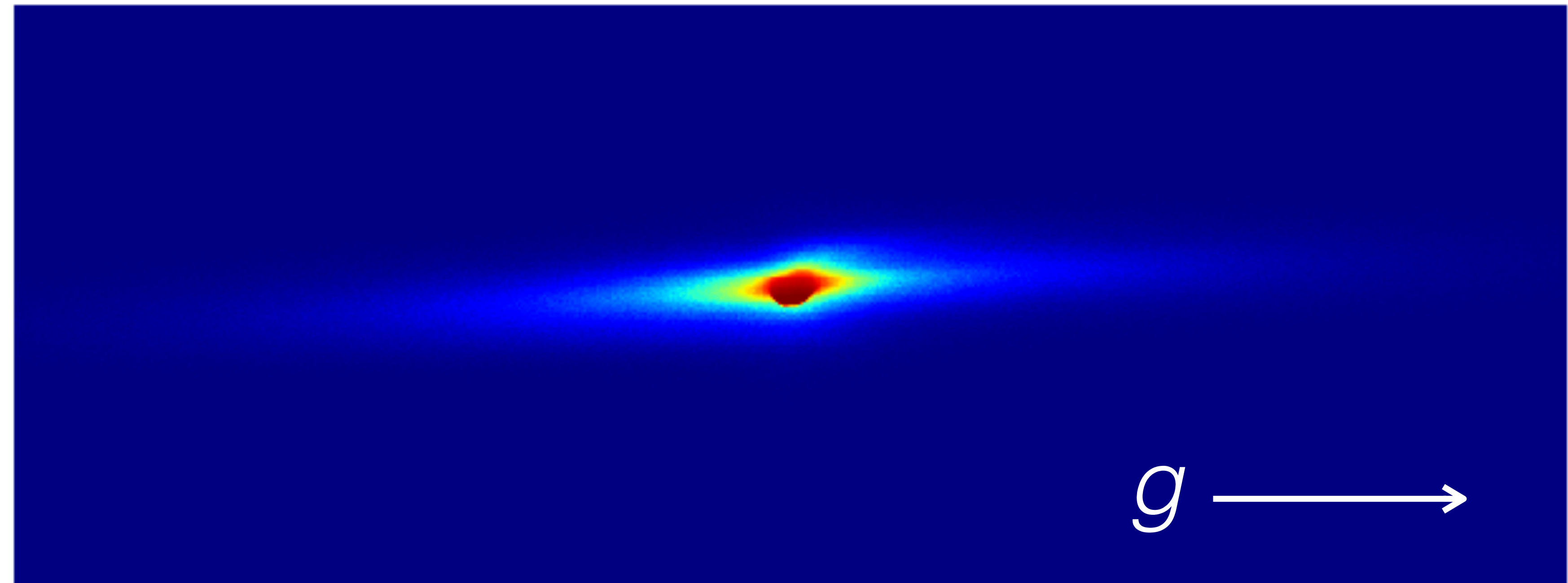
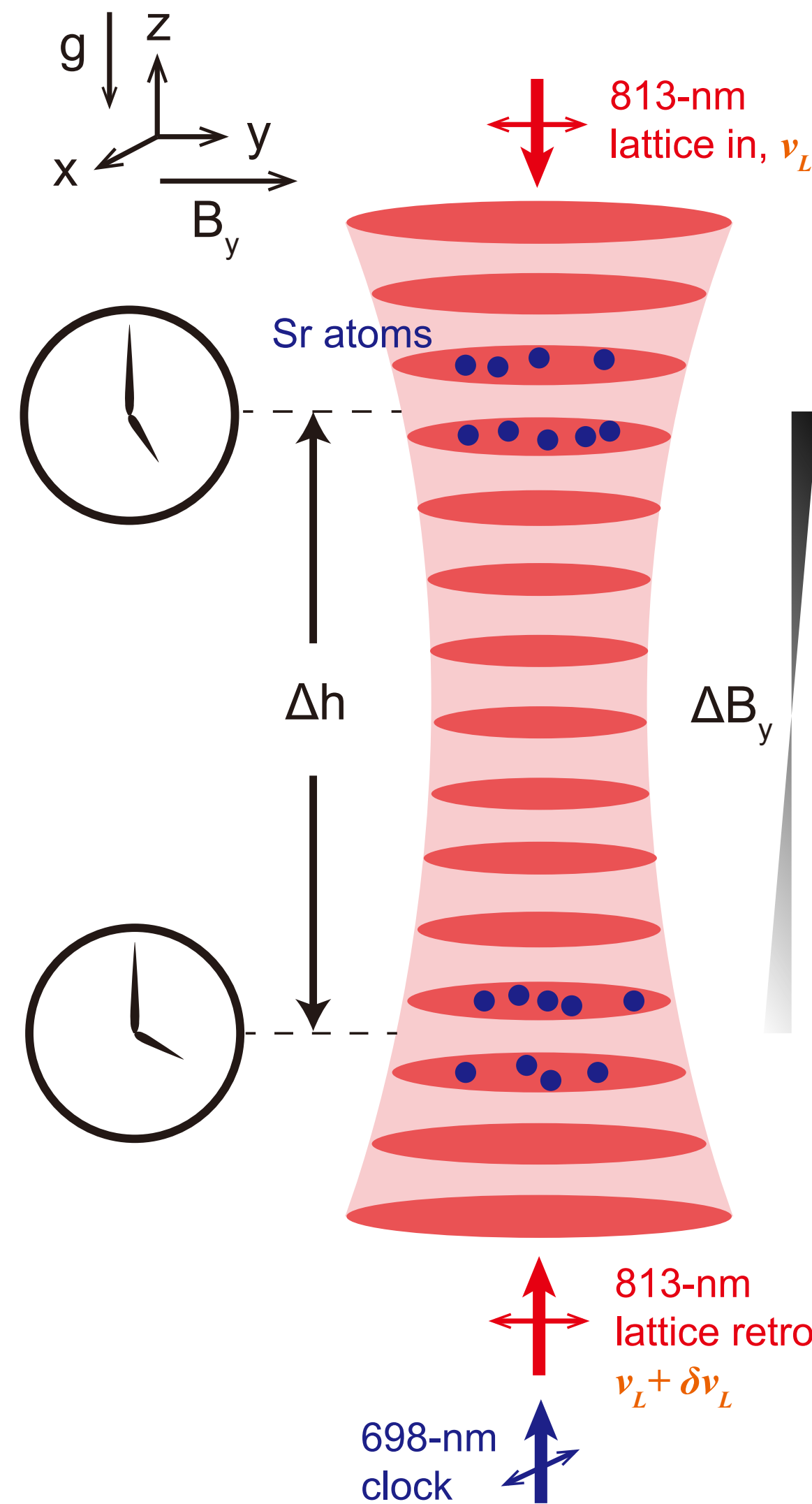
Katori group, RIKEN:



Takano et al., *Nature Photonics* (2016)

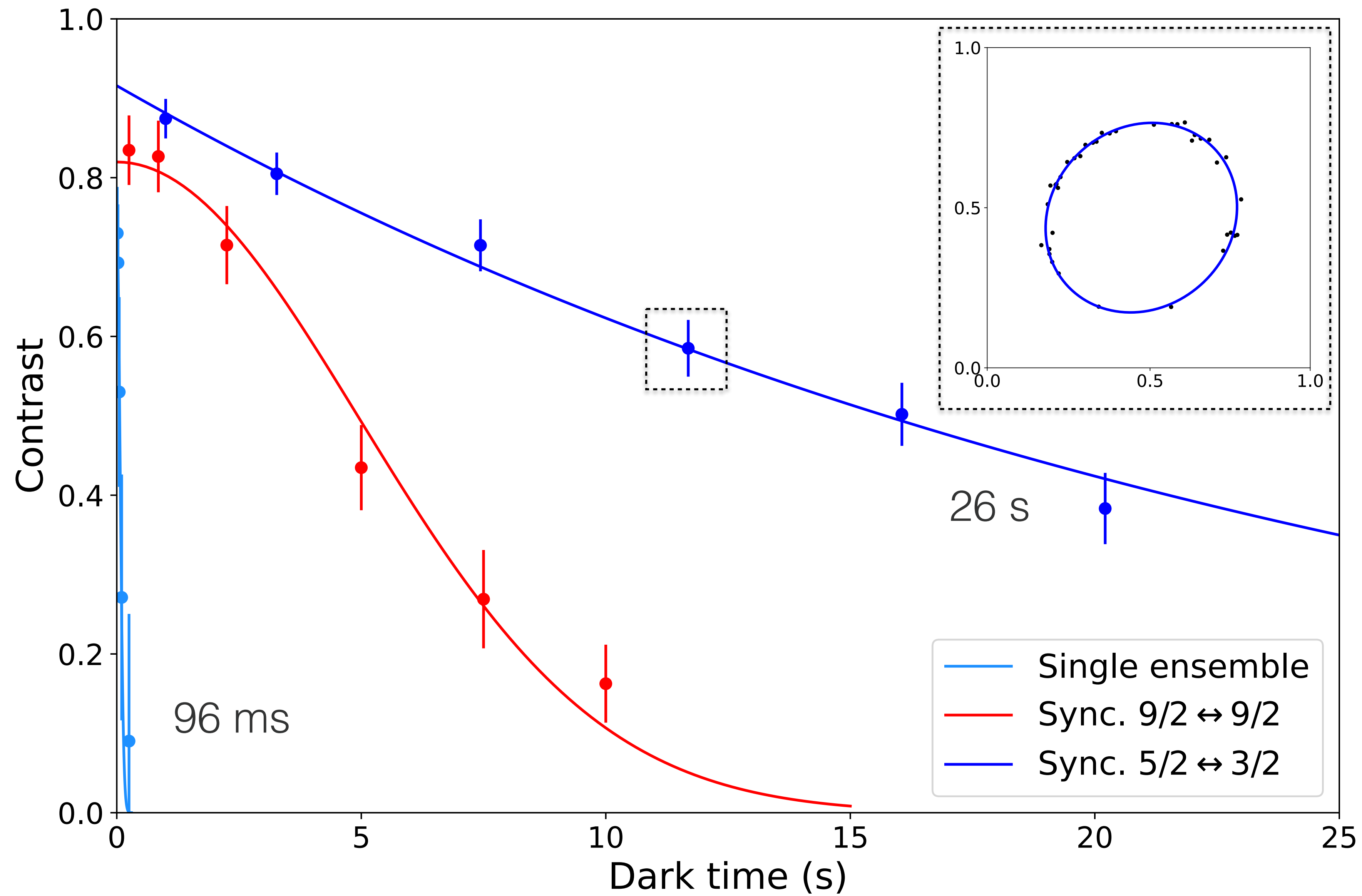
And others!

# A multiplexed strontium optical lattice clock

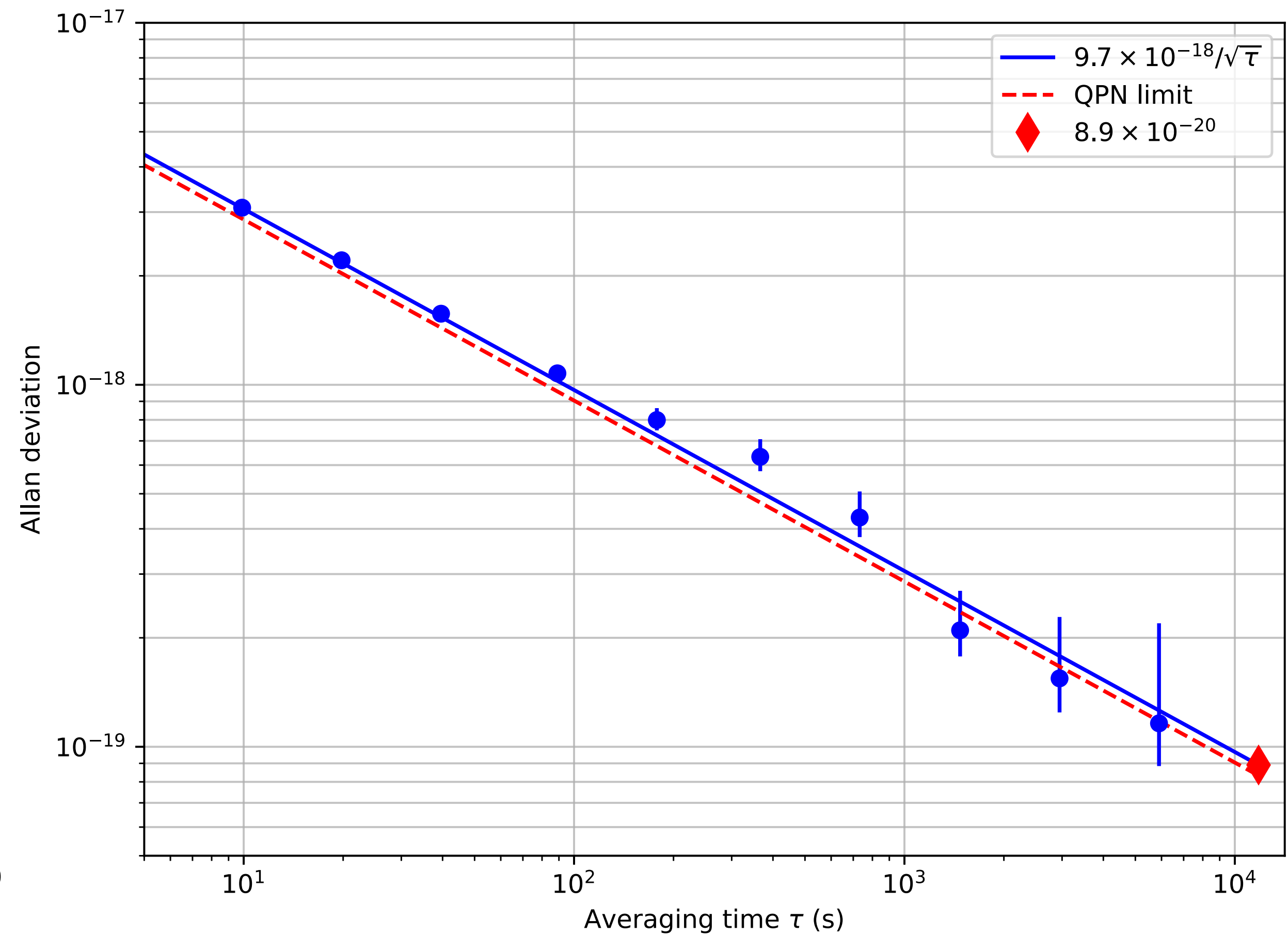
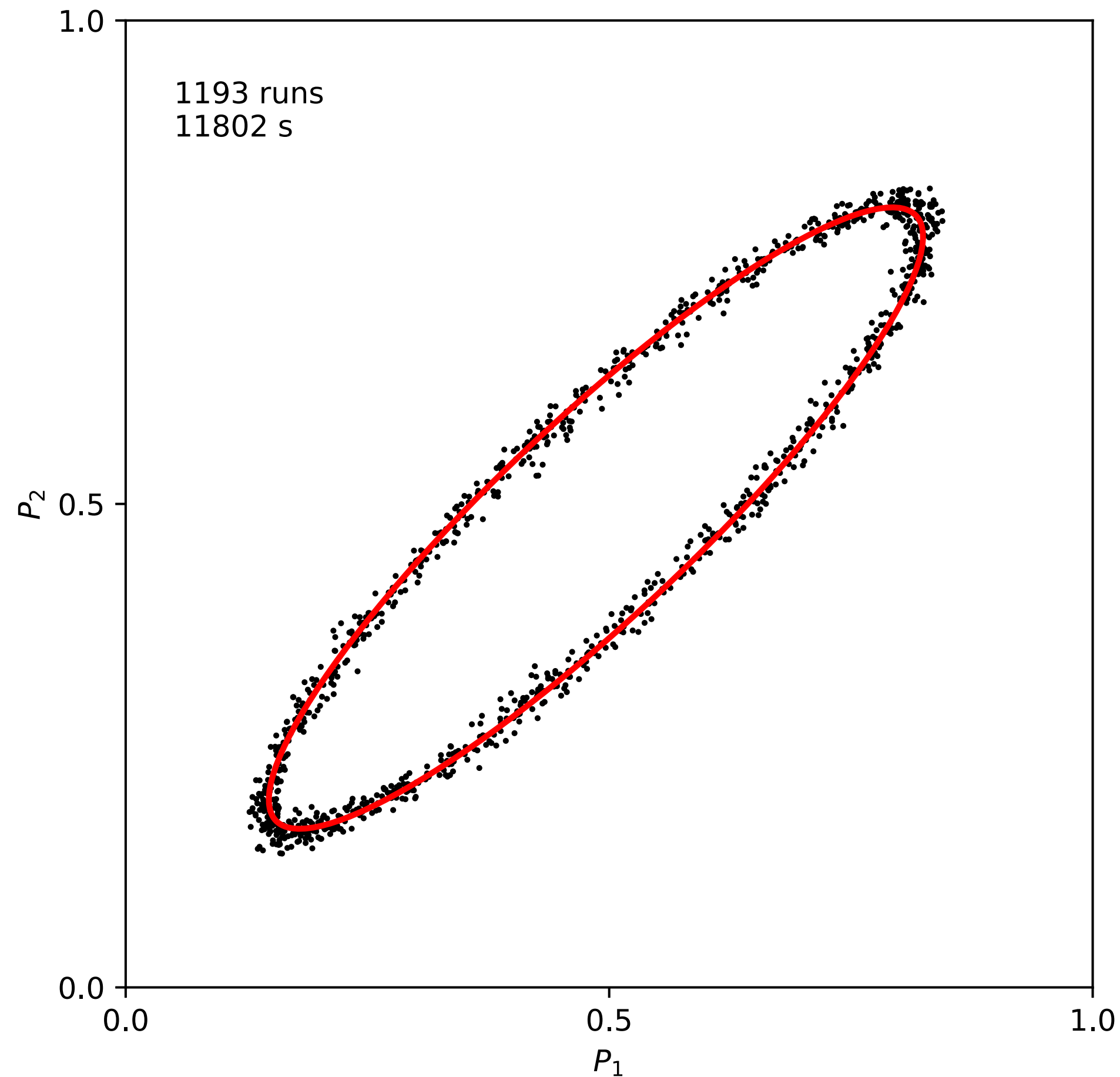
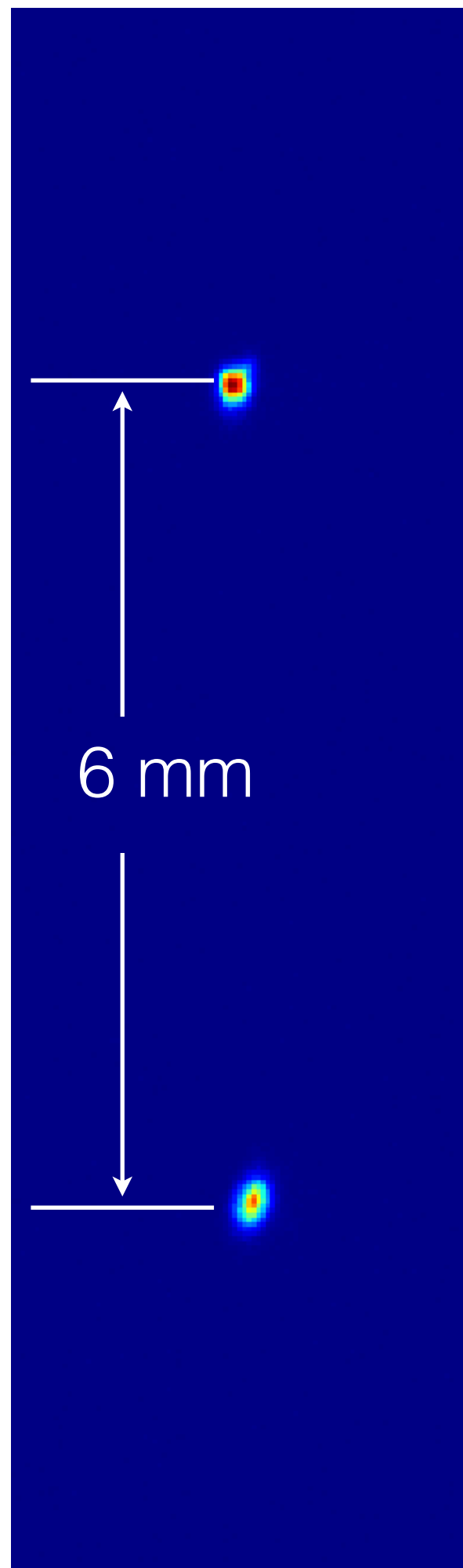




# Atom-atom coherence times



# High performance differential comparisons



Ramsey dark time:  $T_{\text{Ramsey}} = 8.205$  seconds

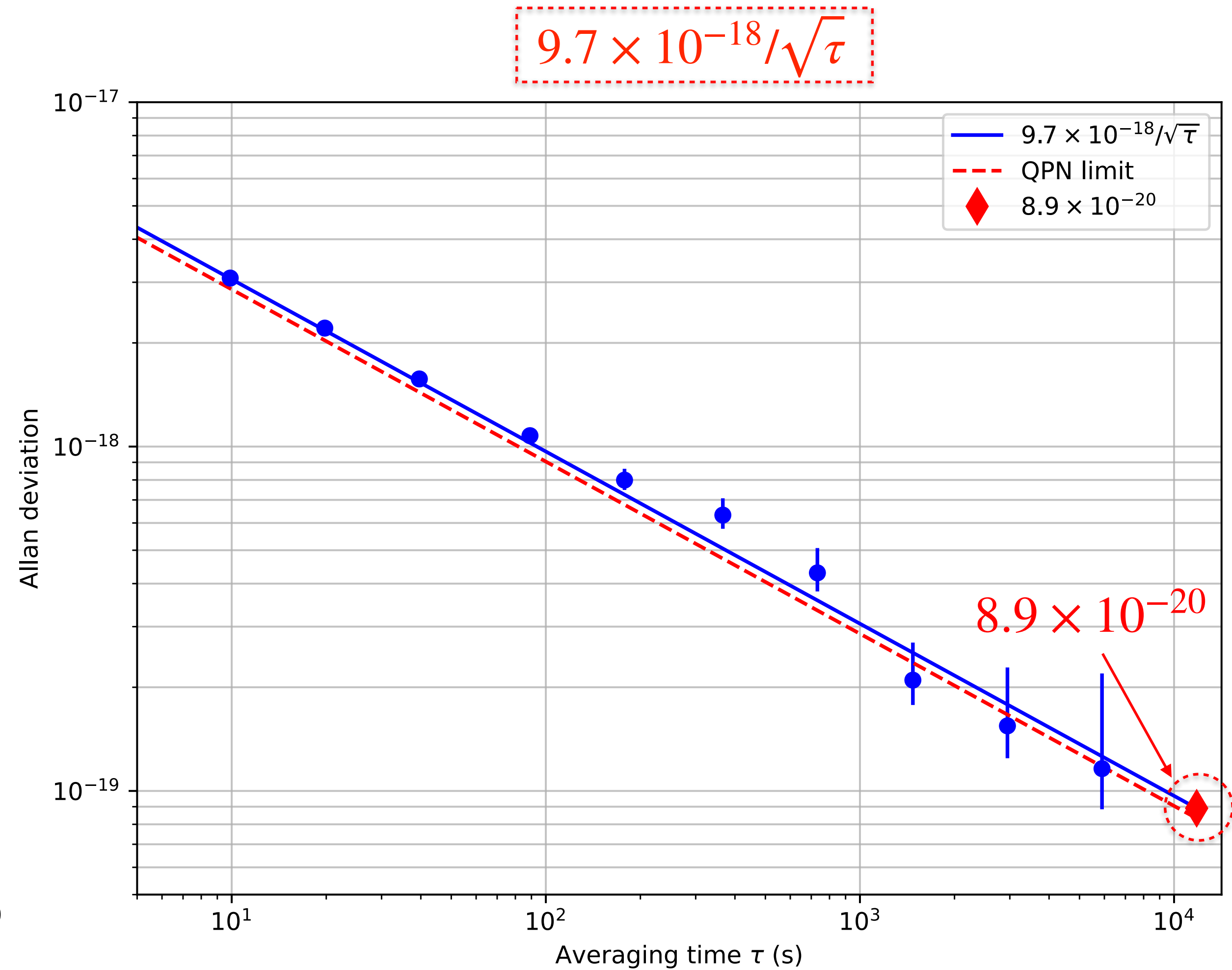
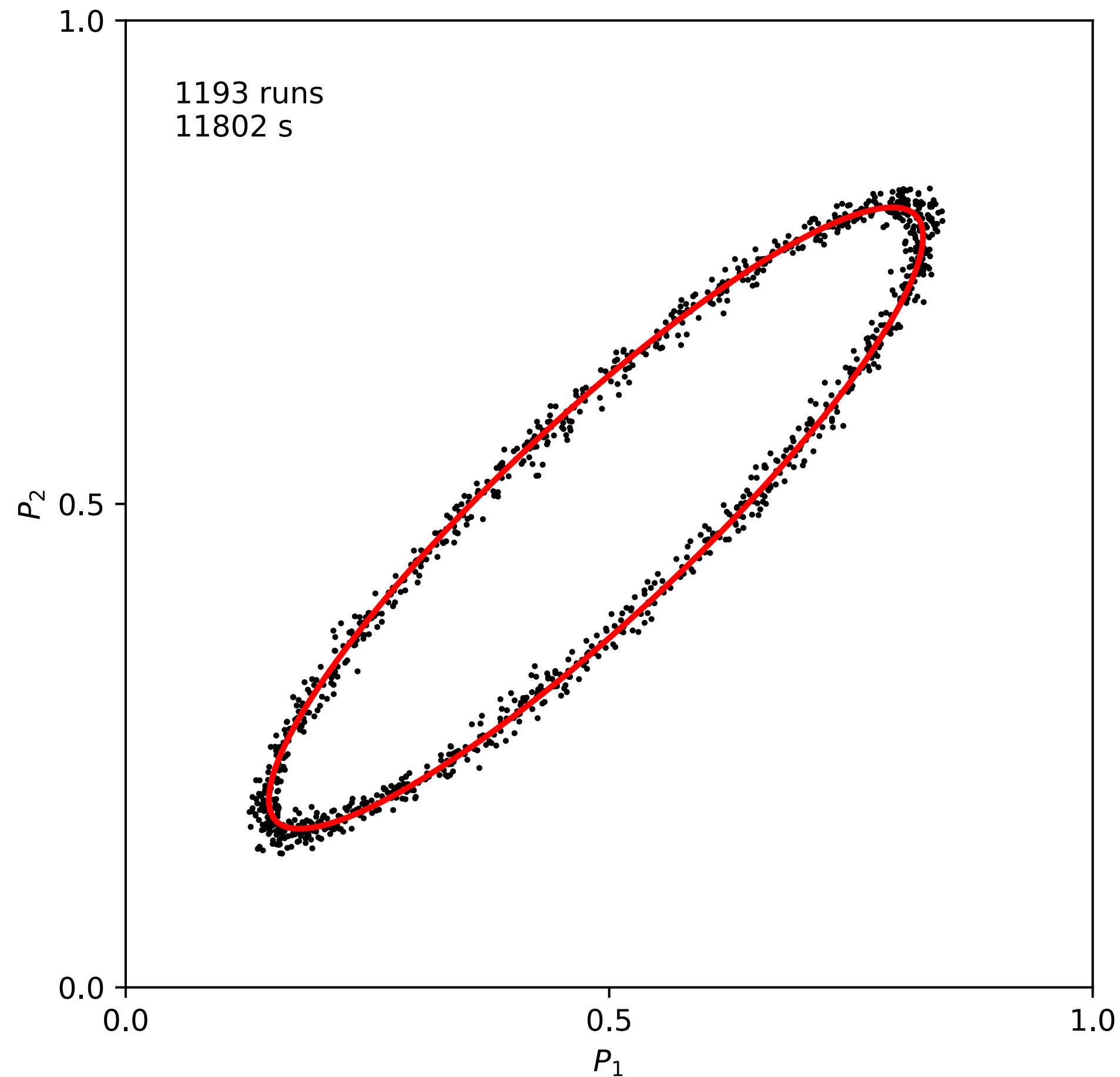
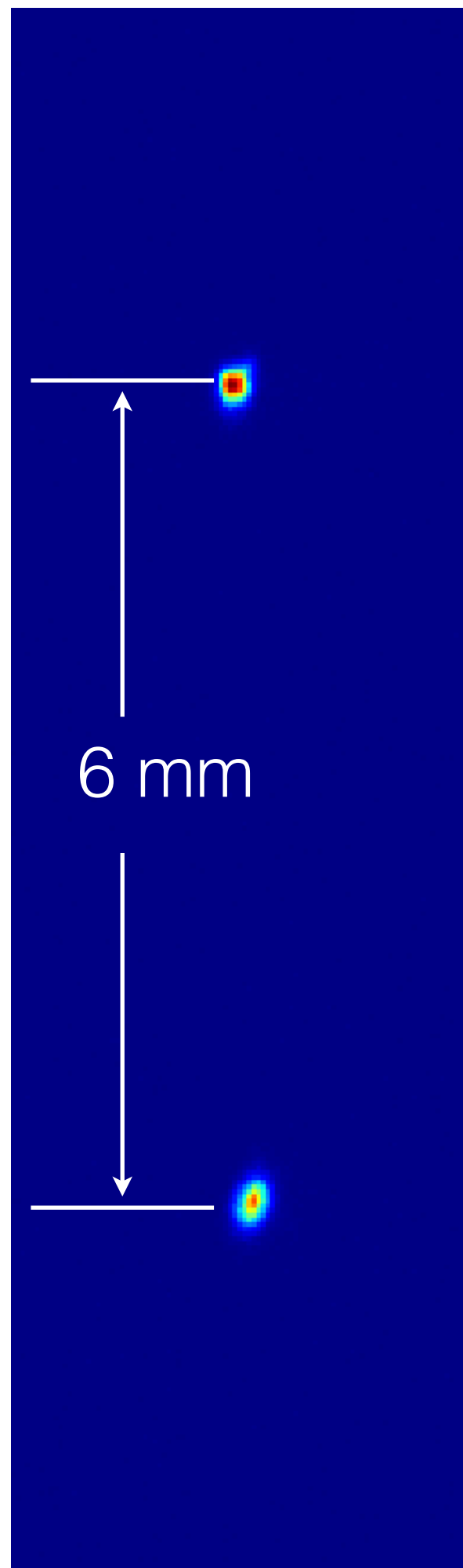
Atom number:  $n_{\text{atoms}} \approx 2400$  per region

Dead time:  $T_{\text{dead}} = 1.69$  seconds

Contrast:  $C(T_{\text{Ramsey}}) \approx 0.65$

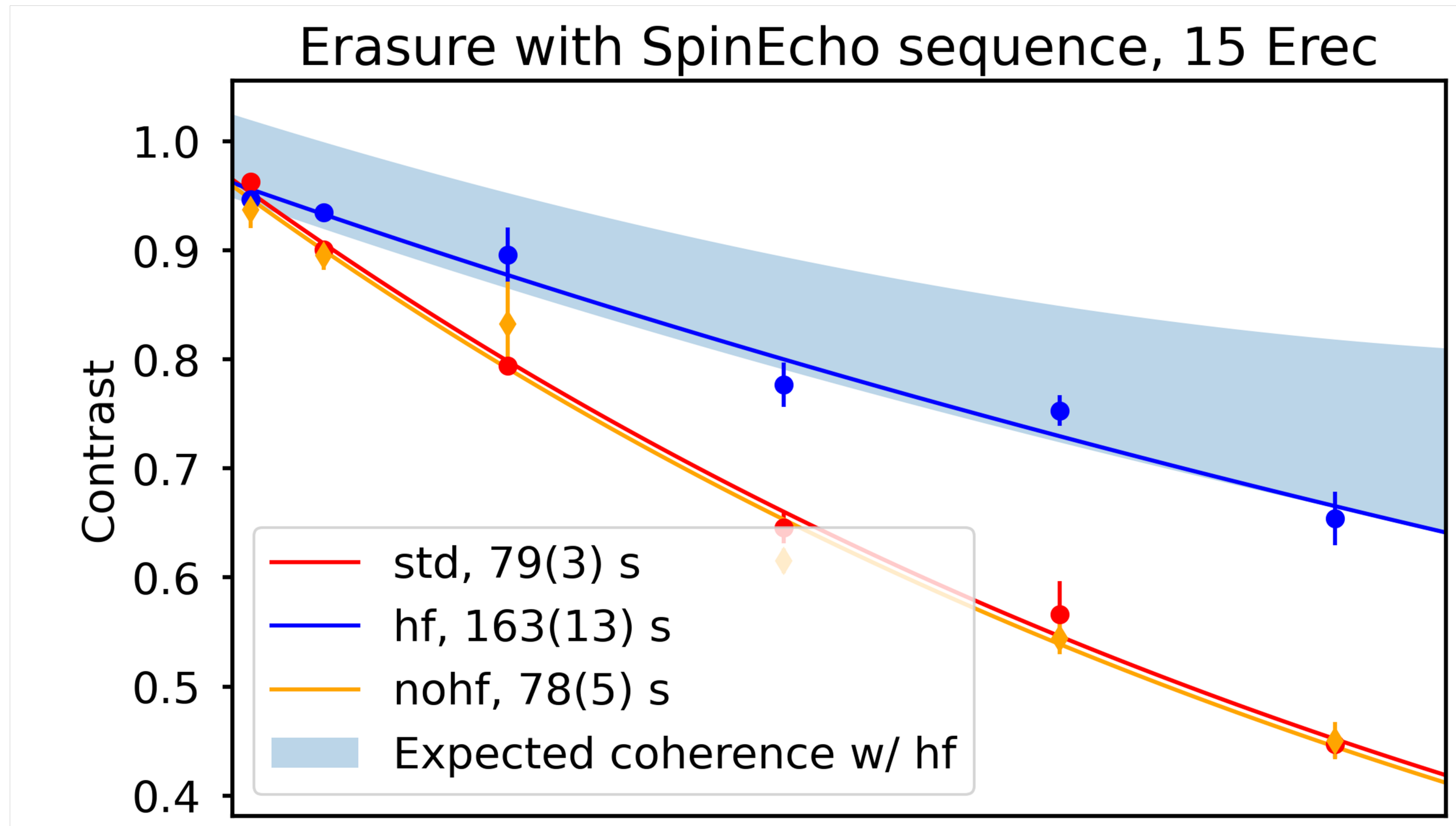


# High performance differential comparisons



Ramsey dark time:  $T_{\text{Ramsey}} = 8.205$  seconds    Atom number:  $n_{\text{atoms}} \approx 2400$  per region    Dead time:  $T_{\text{dead}} = 1.69$  seconds    Contrast:  $C(T_{\text{Ramsey}}) \approx 0.65$

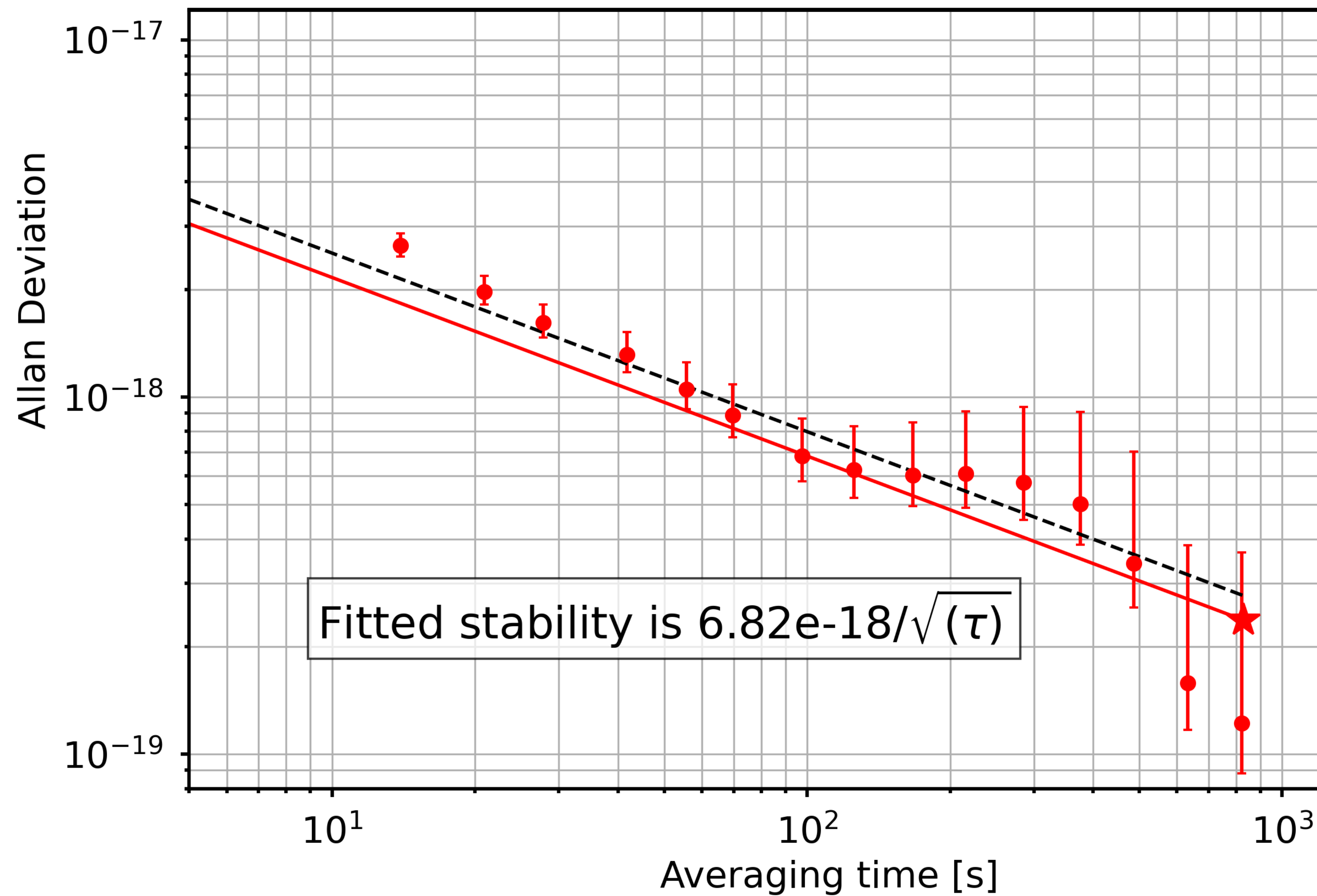
# Atom-atom coherence times



429,228,004,229,873 Hz transition!



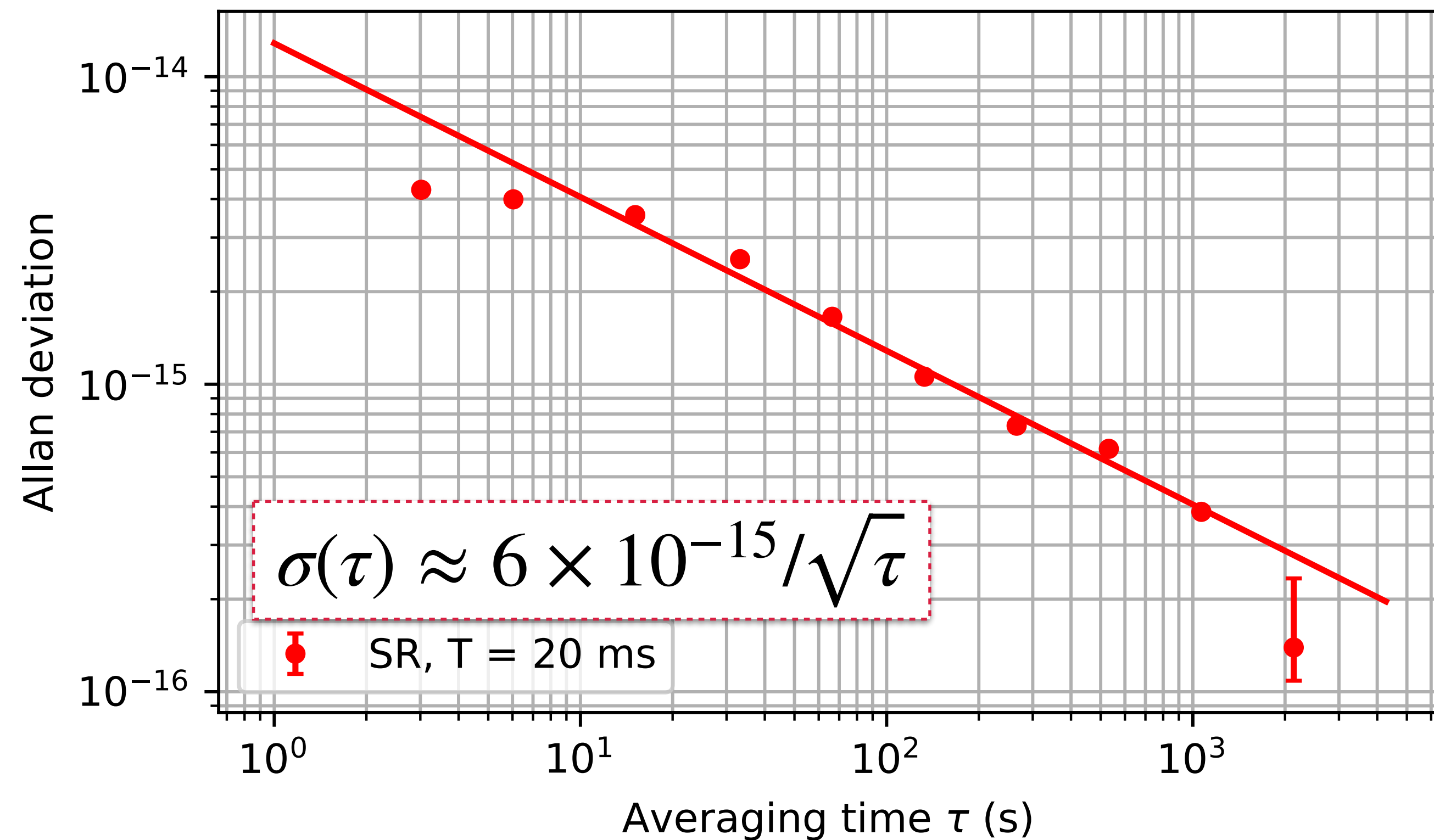
# High performance differential comparisons



# High performance differential comparisons

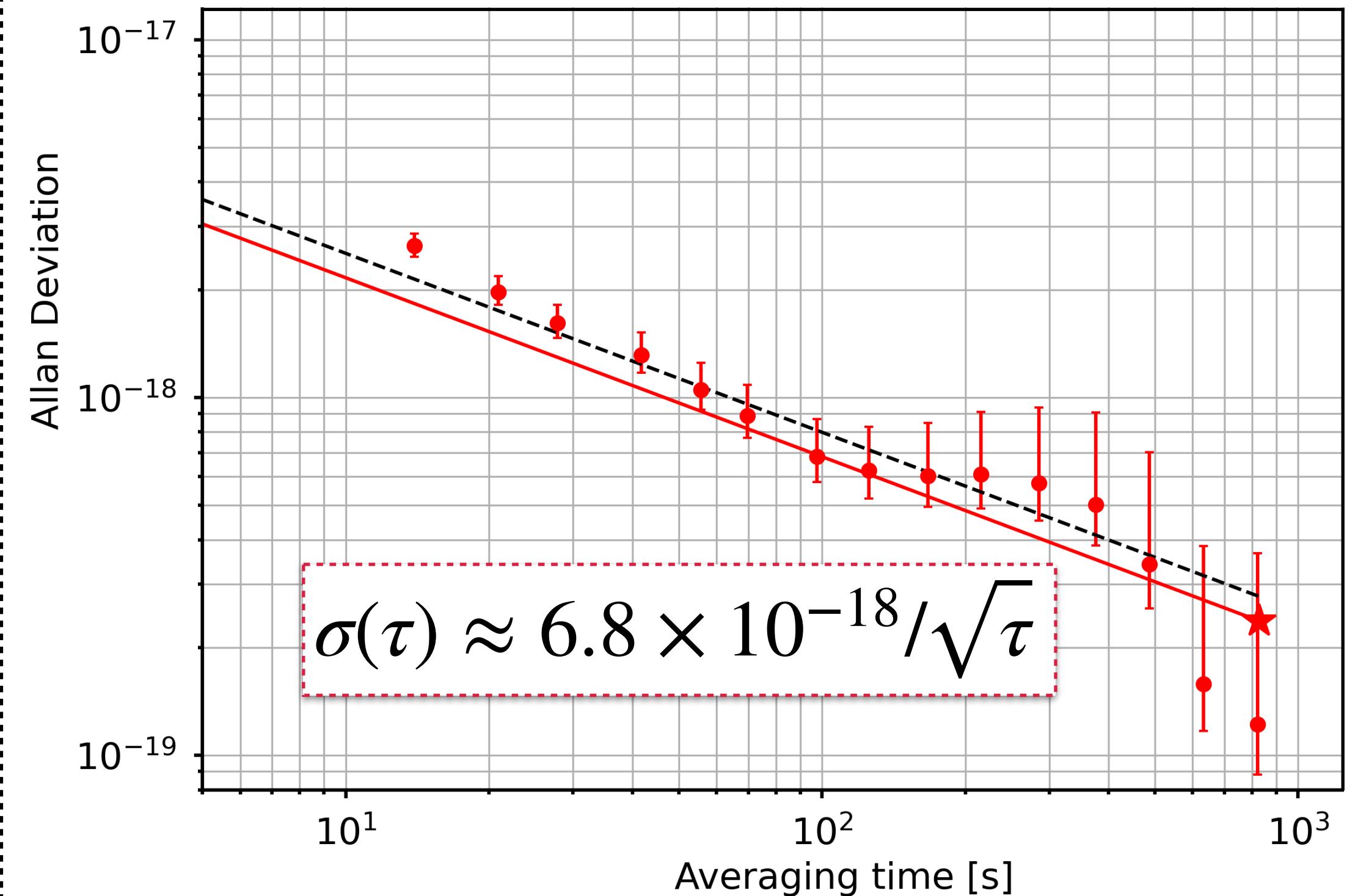
Standard clock:

$$\sigma_{\text{Dick}}(\tau) \propto \frac{\sigma_{\text{LO}}}{T} \sqrt{\frac{T + T_d}{\tau}} \quad T = 20 \text{ ms}$$



Synchronous differential comparison:

$$\sigma_{\text{QPN}}(\tau) = \frac{1}{2\pi\nu_o C(T)T} \sqrt{\frac{T + T_d}{N_d \tau}} \quad T \approx 10 \text{ s}$$

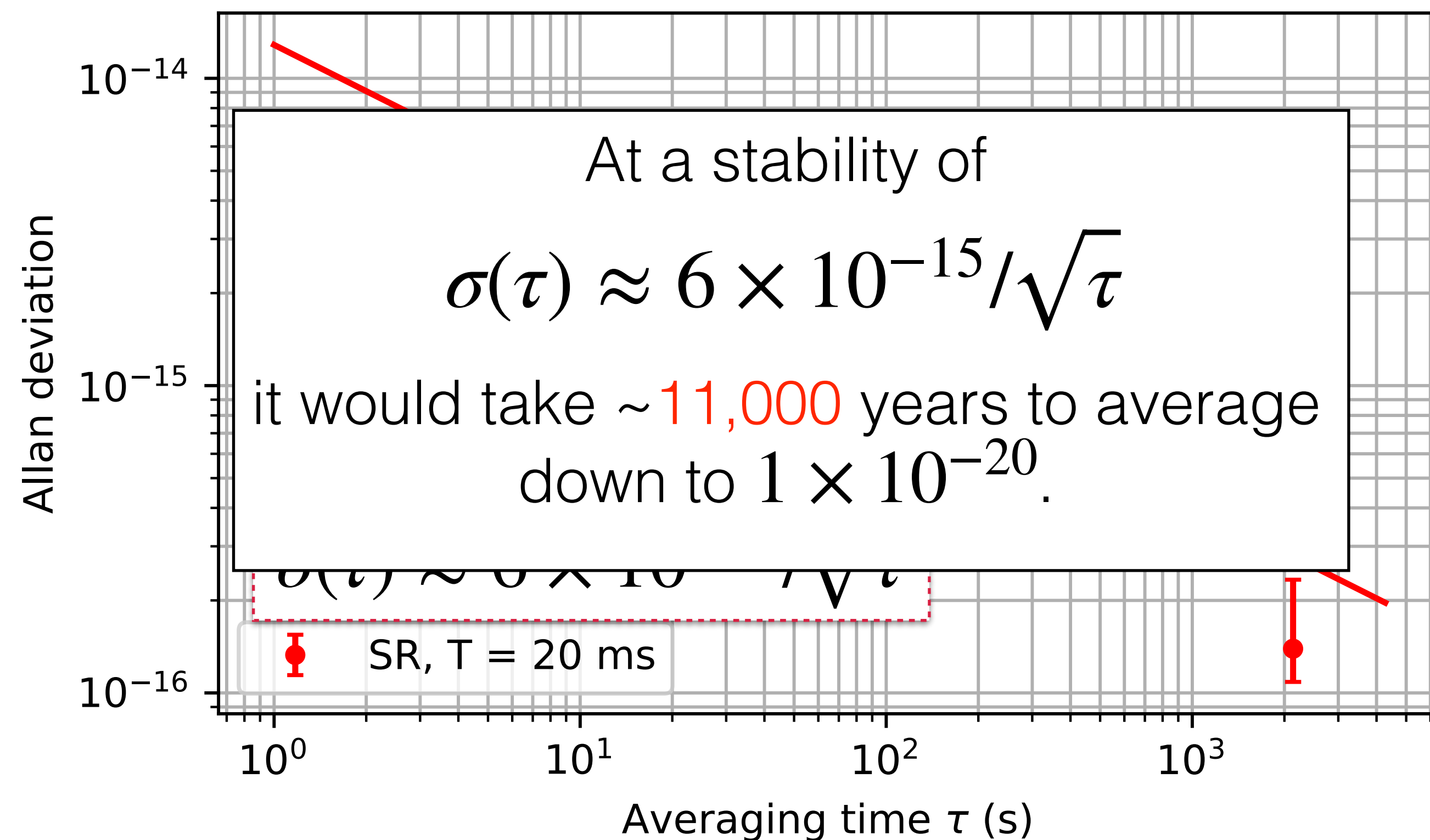




# High performance differential comparisons

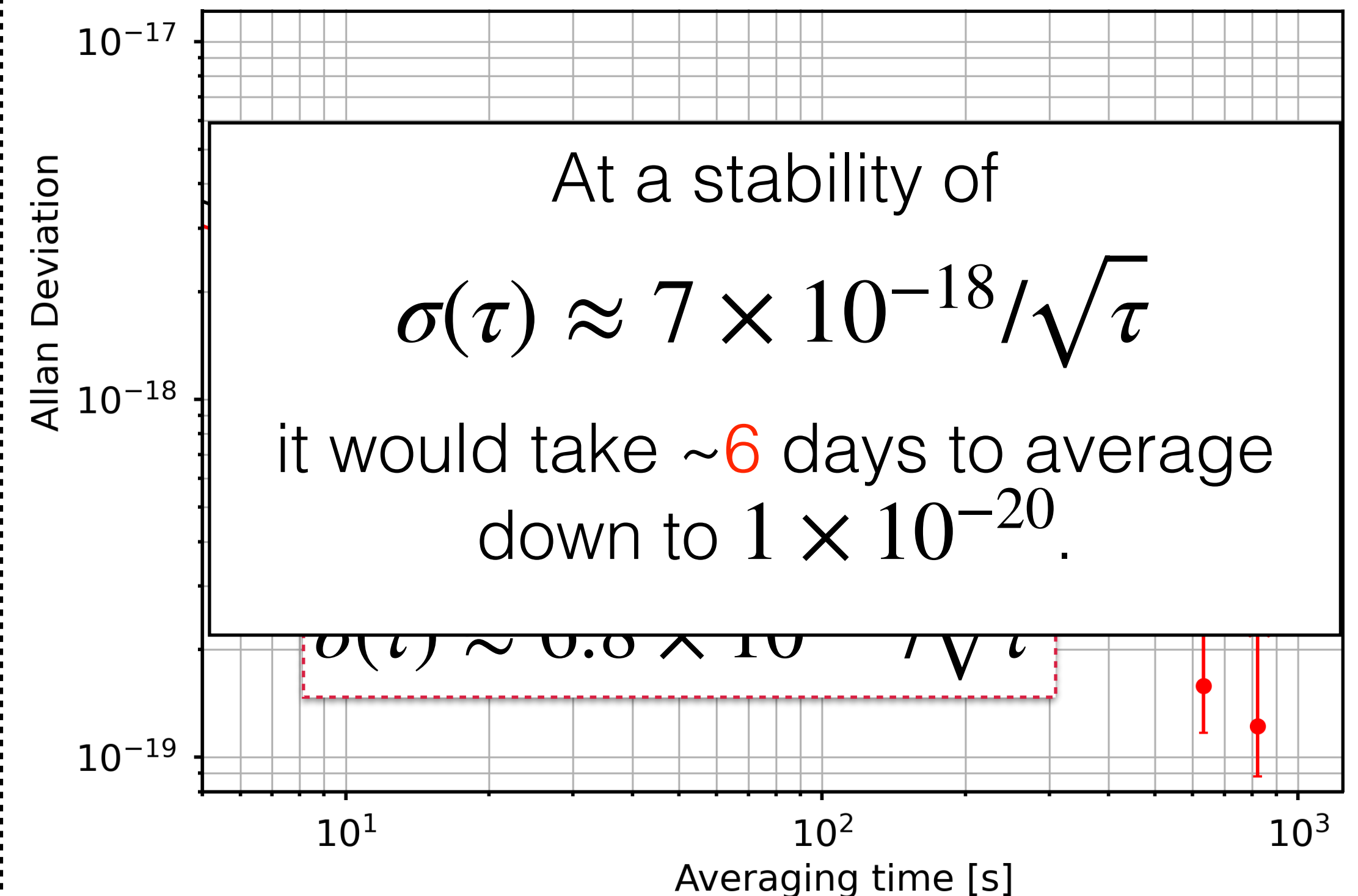
Standard clock:

$$\sigma_{\text{Dick}}(\tau) \propto \frac{\sigma_{\text{LO}}}{T} \sqrt{\frac{T + T_d}{\tau}} \quad T = 20 \text{ ms}$$

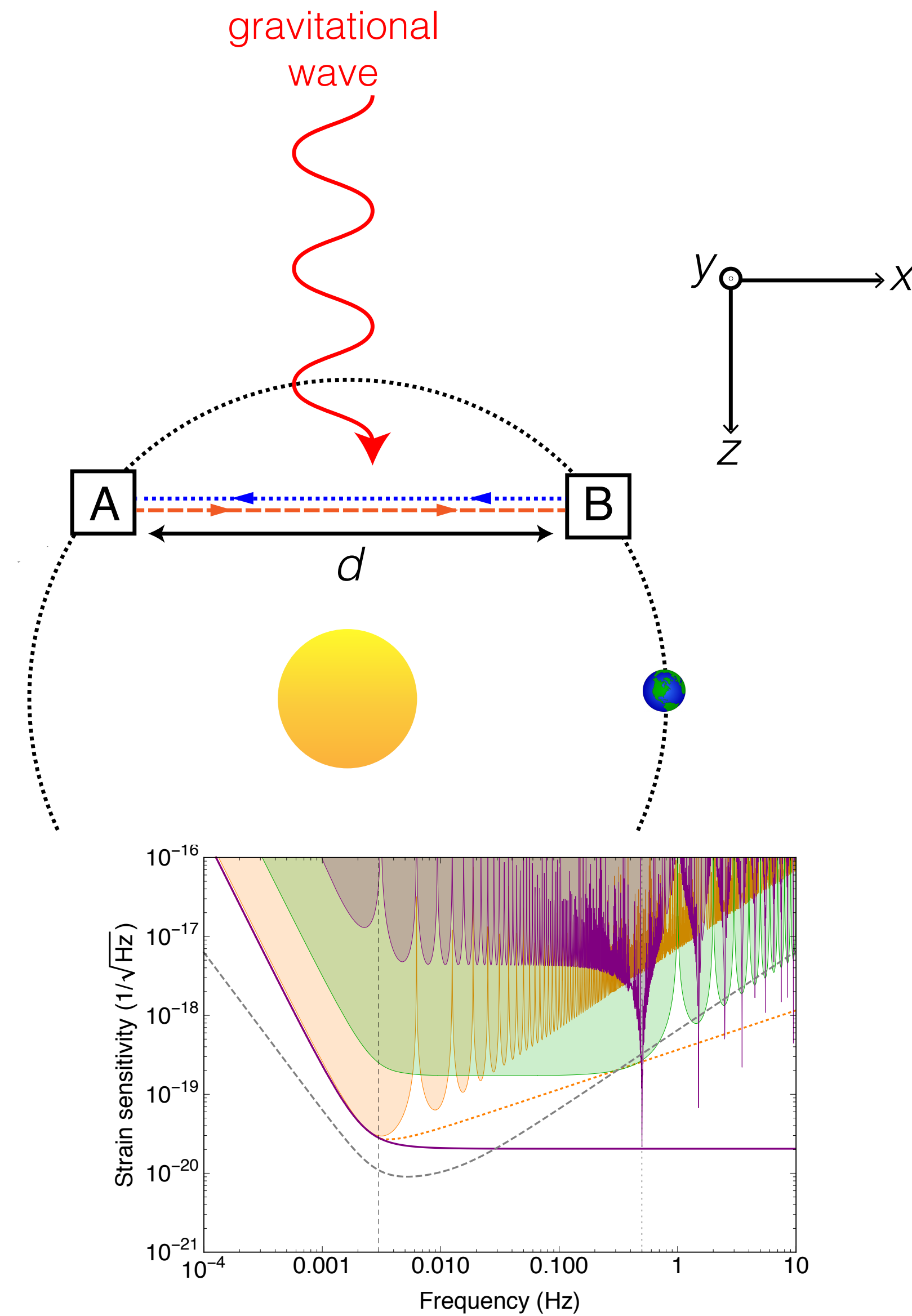


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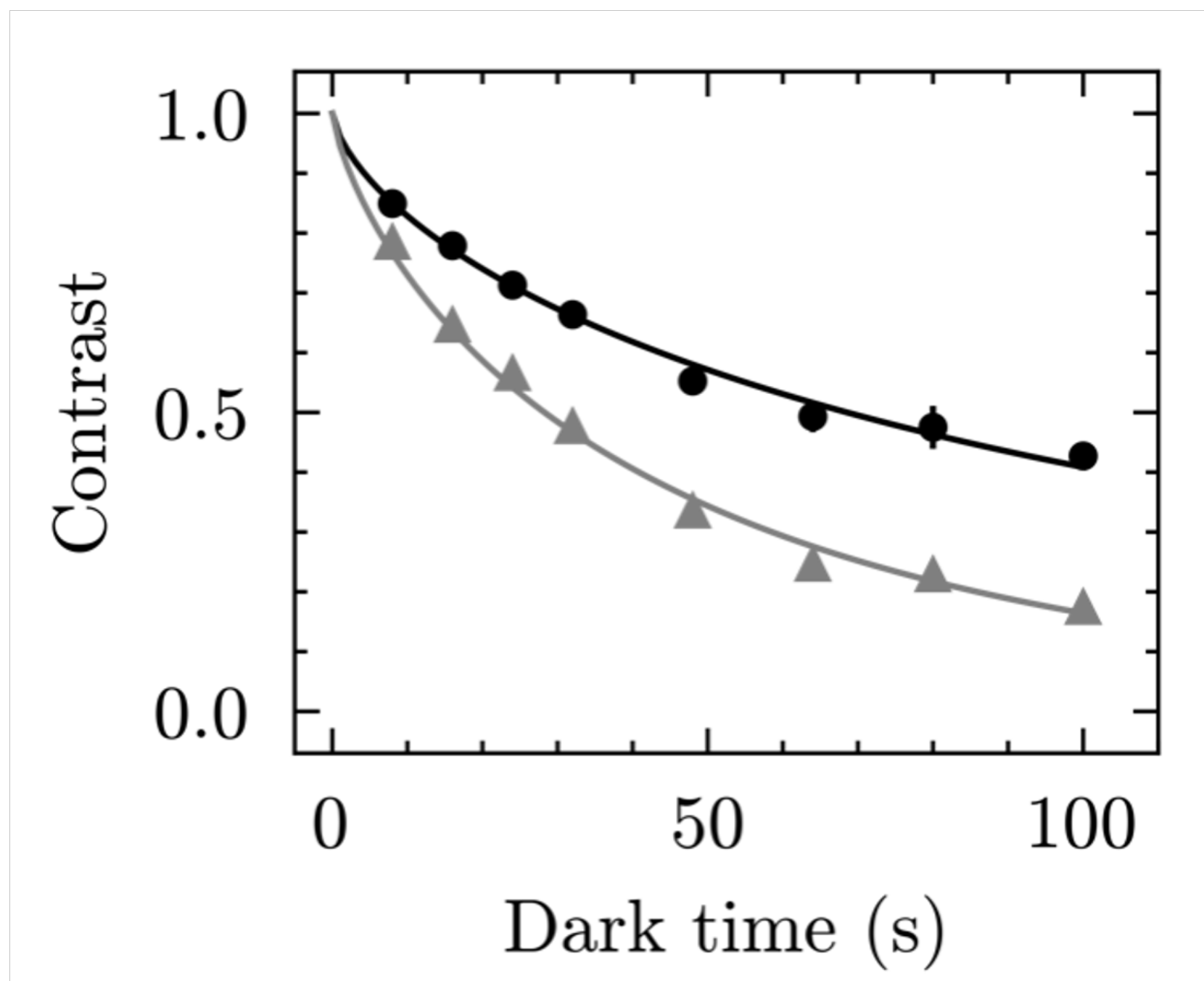


# Gravitational wave detection with clocks in space

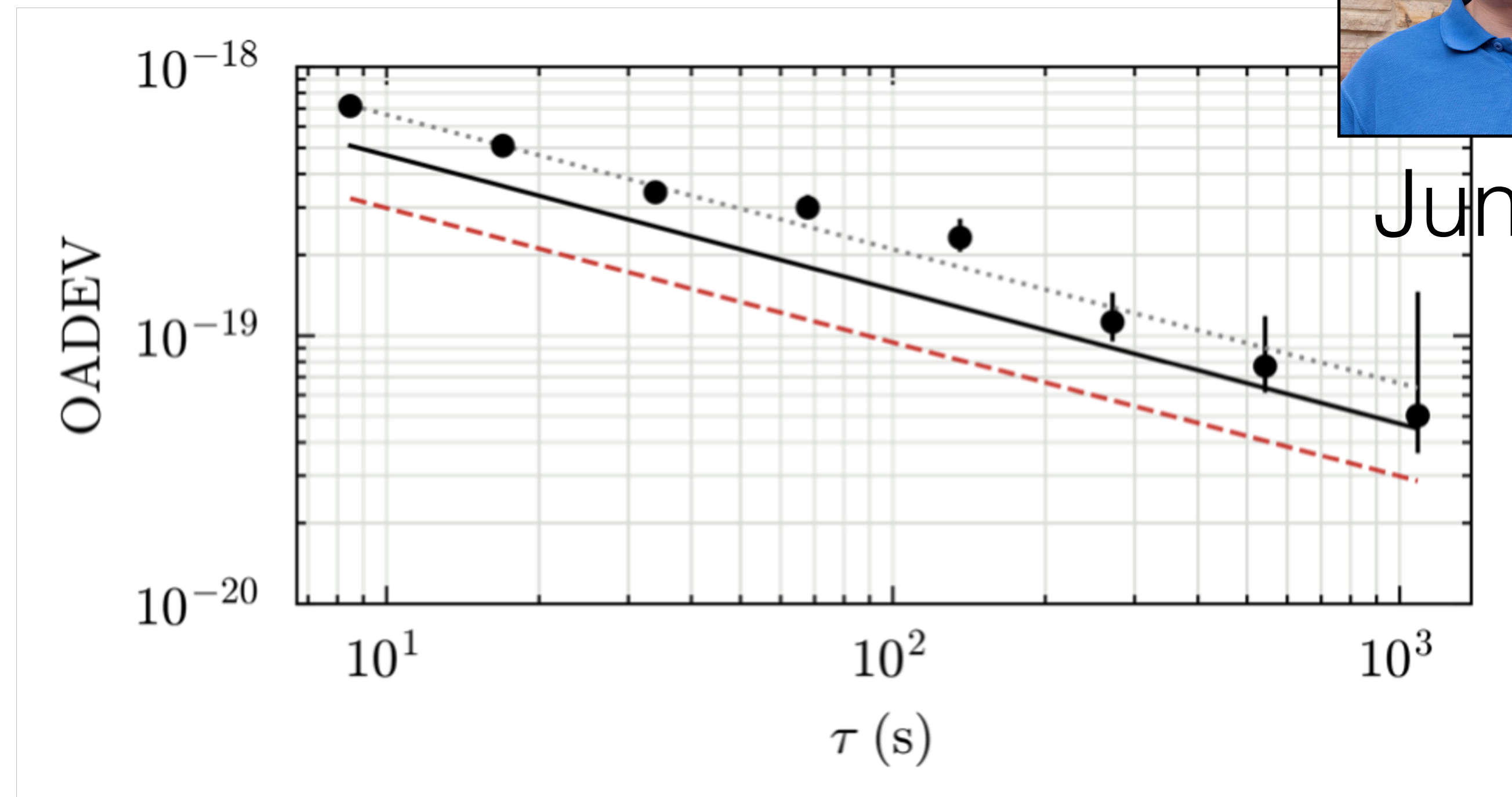




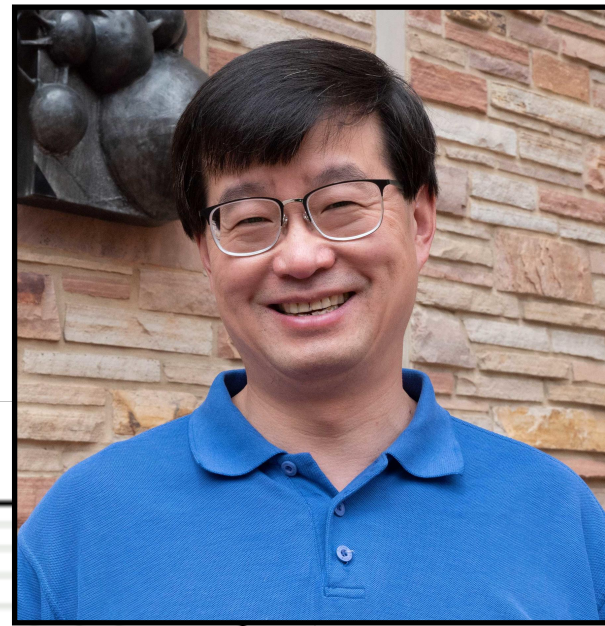
# Record differential stabilities



**Coherence time ~ 2 mins**



**Differential frequency measurement  
 $2.1 \times 10^{-18}$  @ 1 s (factor-2 improvement)**



Jun Ye

# Gravitational wave detection with clocks

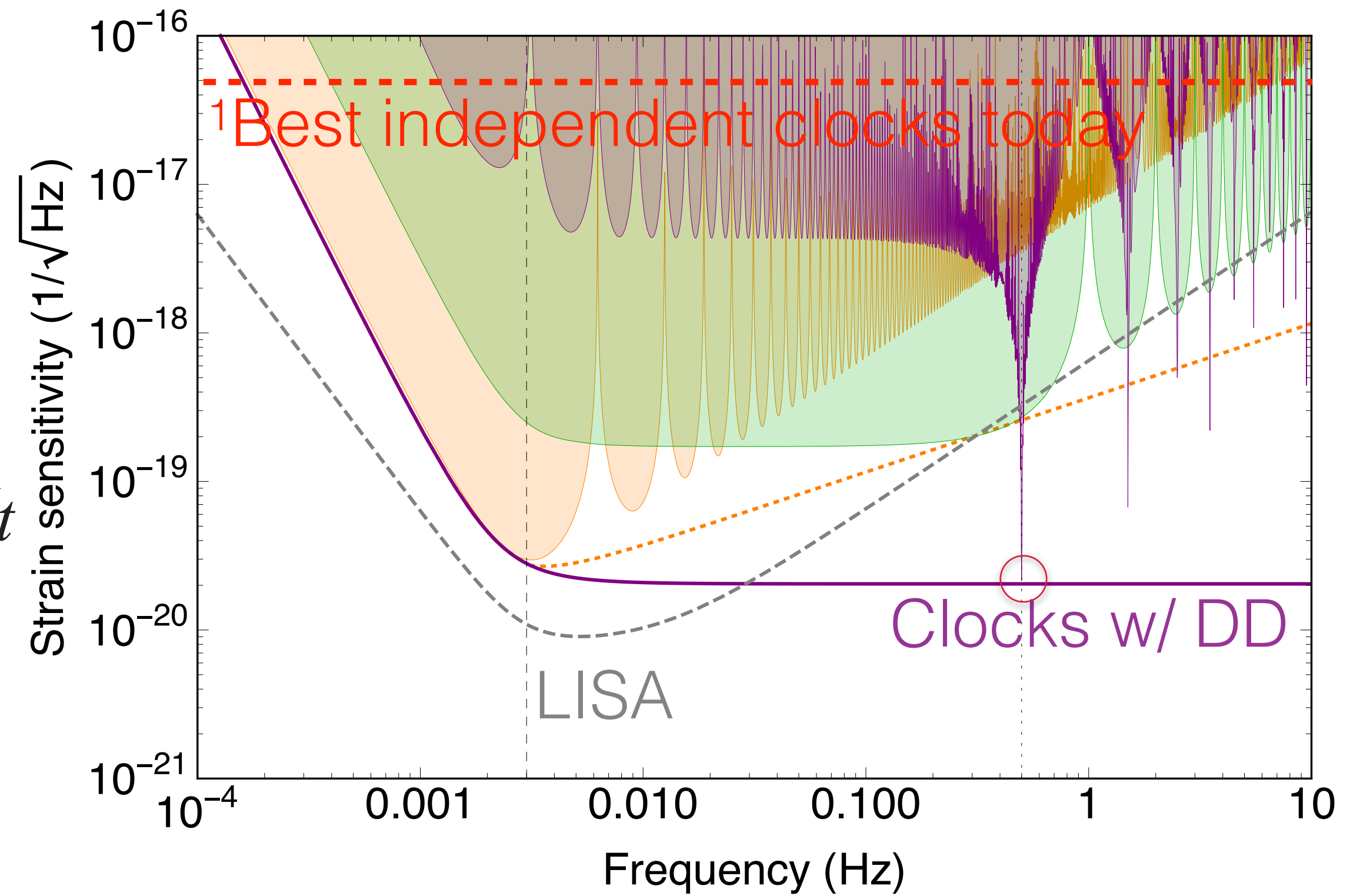
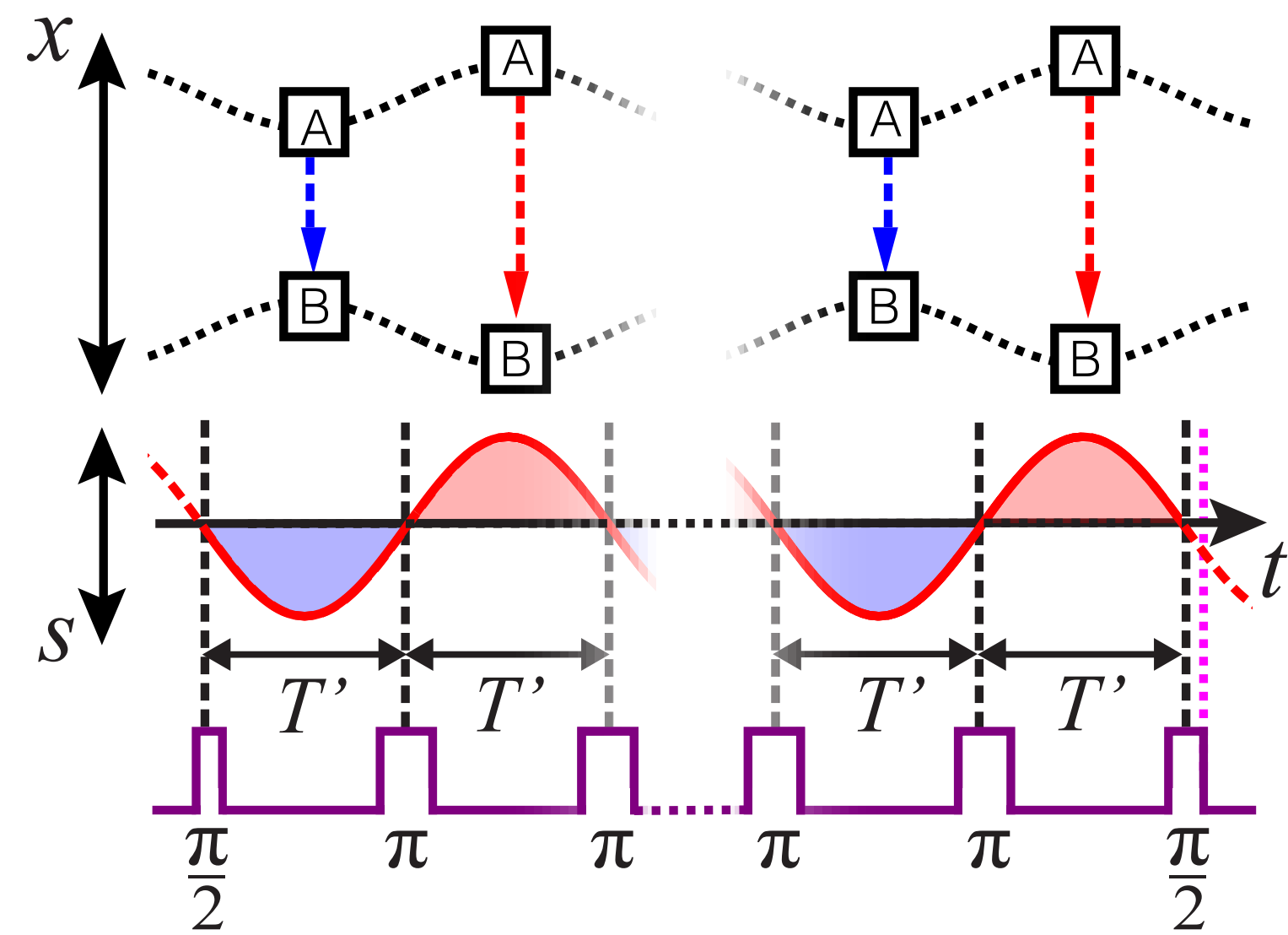
## Clock based detector

$d = 5 \times 10^{10}$  m arm length

$N = 7 \times 10^6$  Sr atoms per clock

160 s coherence time

Dynamical decoupling  
sequence:





# Gravitational wave detection with clocks

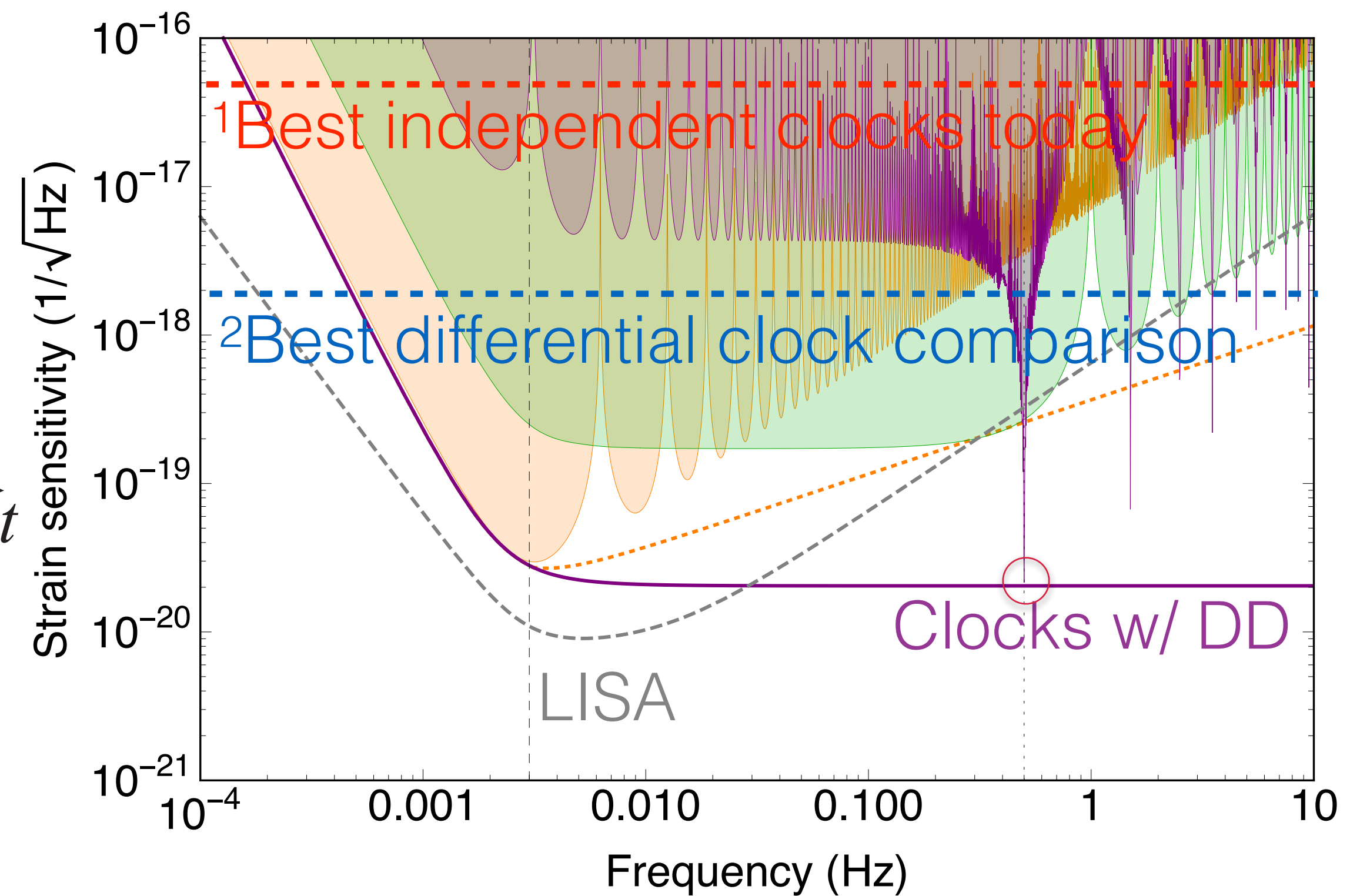
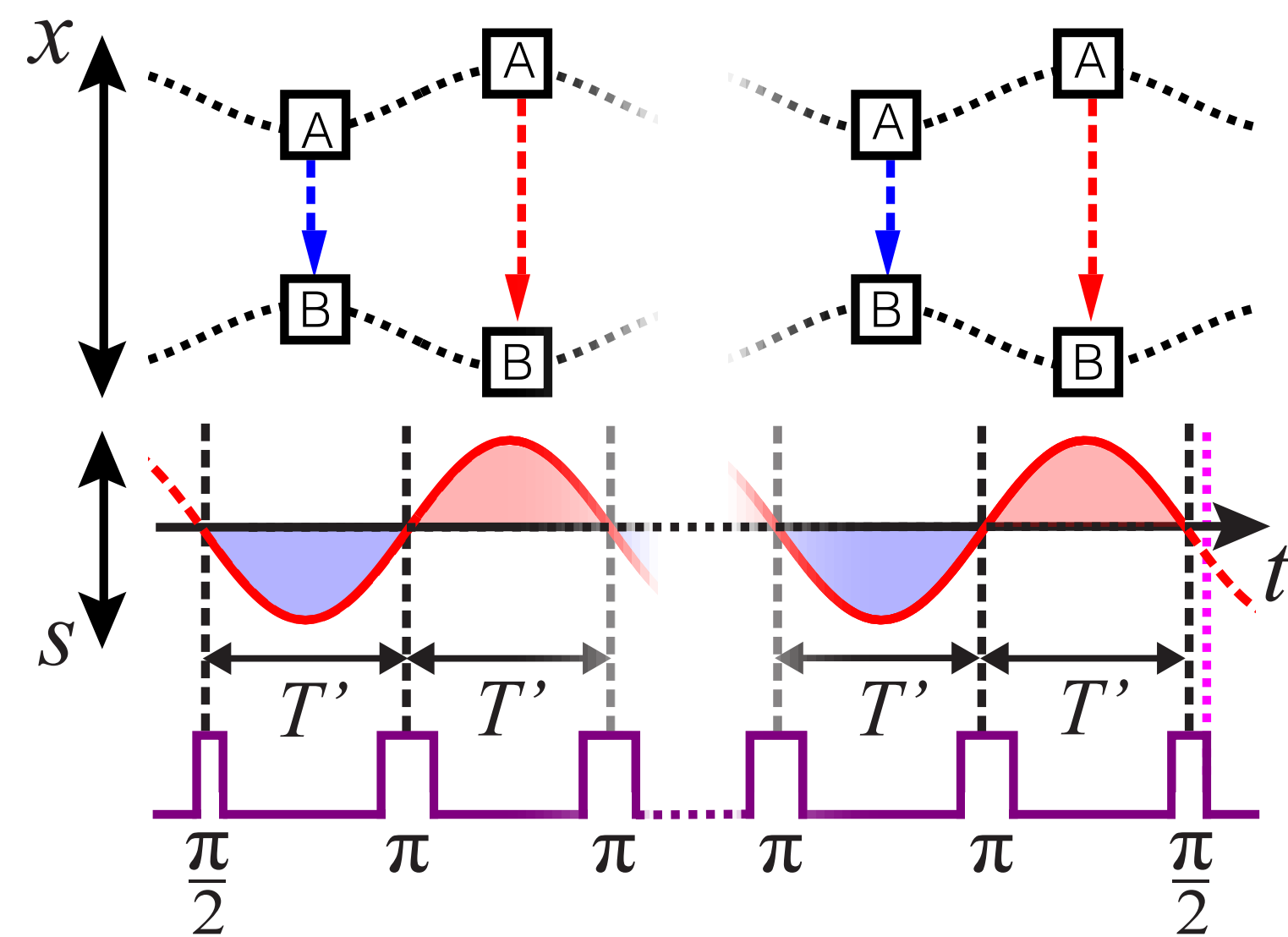
Clock based detector

$d = 5 \times 10^{10}$  m arm length

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160 s coherence time

Dynamical decoupling  
sequence:



# Challenges for optical clocks in space

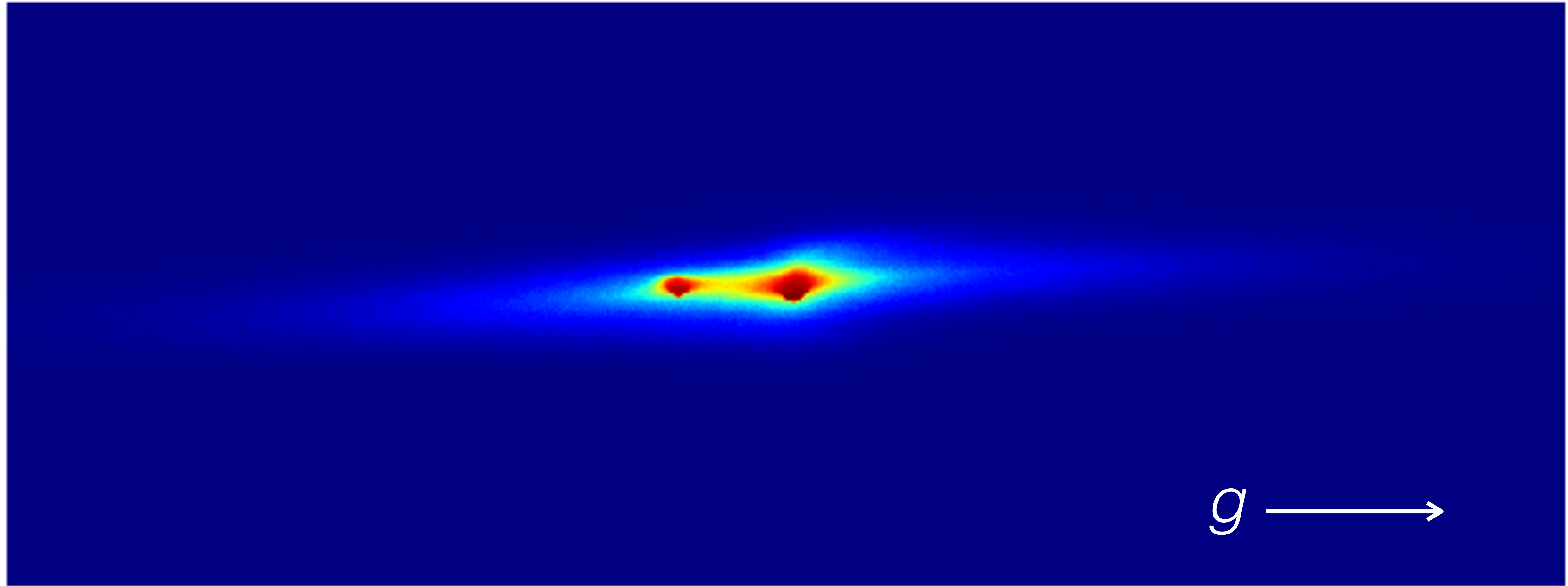
- Need low-SWaP and rad-hard lasers, opto-electronics, and cold-atom packages.
- Need to improve the robustness and autonomy of optical lattice clocks.
- Need ultra-stable clock lasers and frequency combs in low SWaP packages.



# Challenges for optical clocks in space

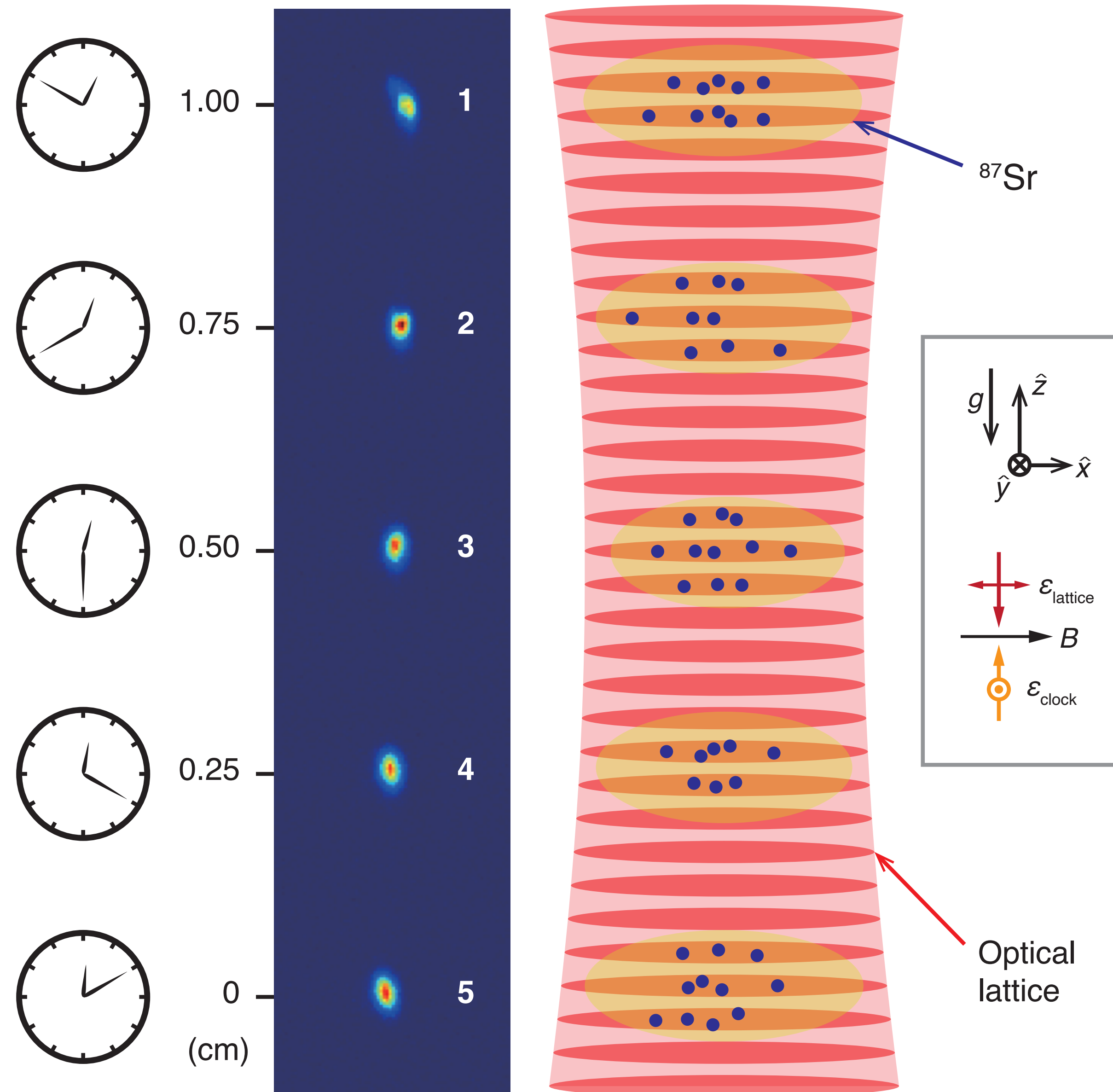
- Need low-SWaP and rad-hard lasers, opto-electronics, and cold-atom packages.
- Need to improve the robustness and autonomy of optical lattice clocks.
- ~~Need ultra-stable clock lasers and frequency combs in low SWaP packages.~~

# Loading more than two regions

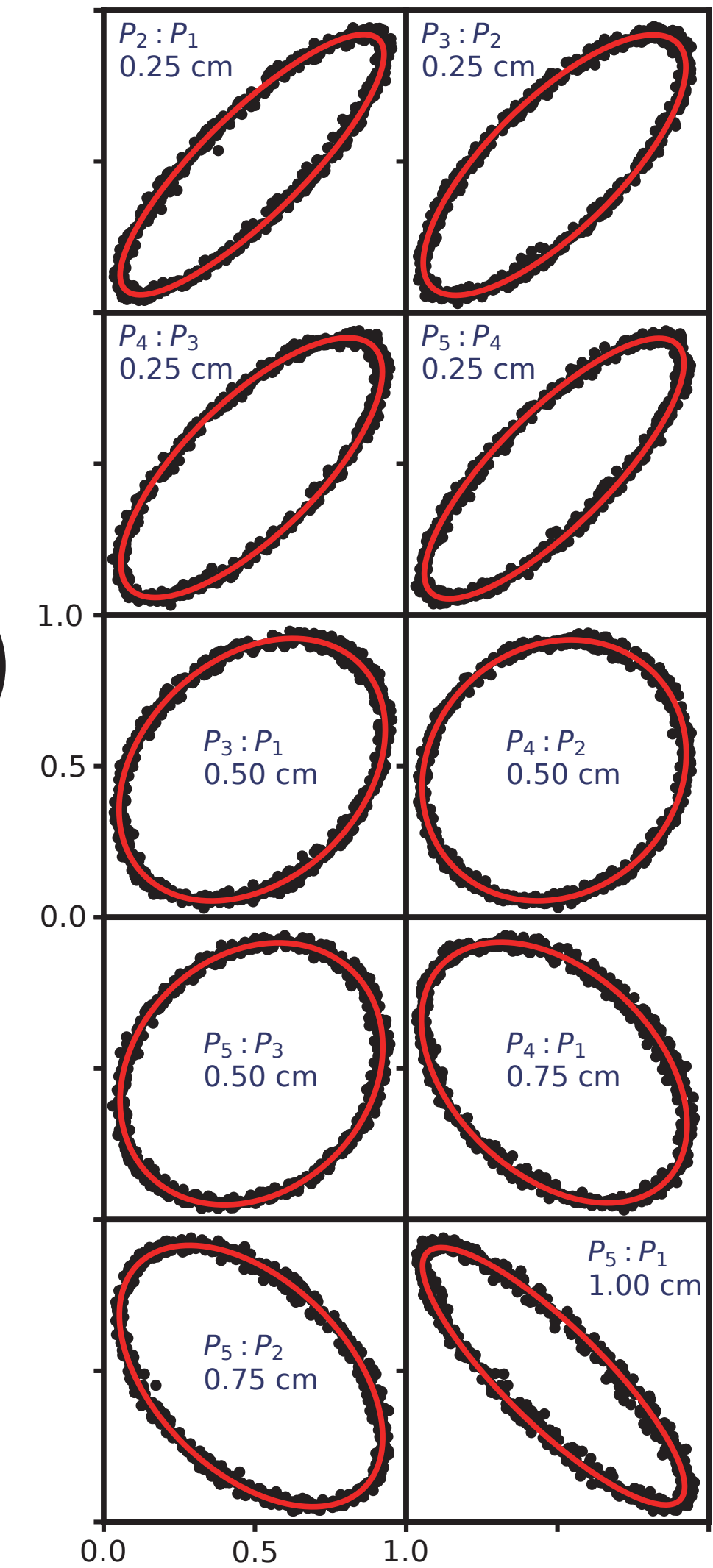
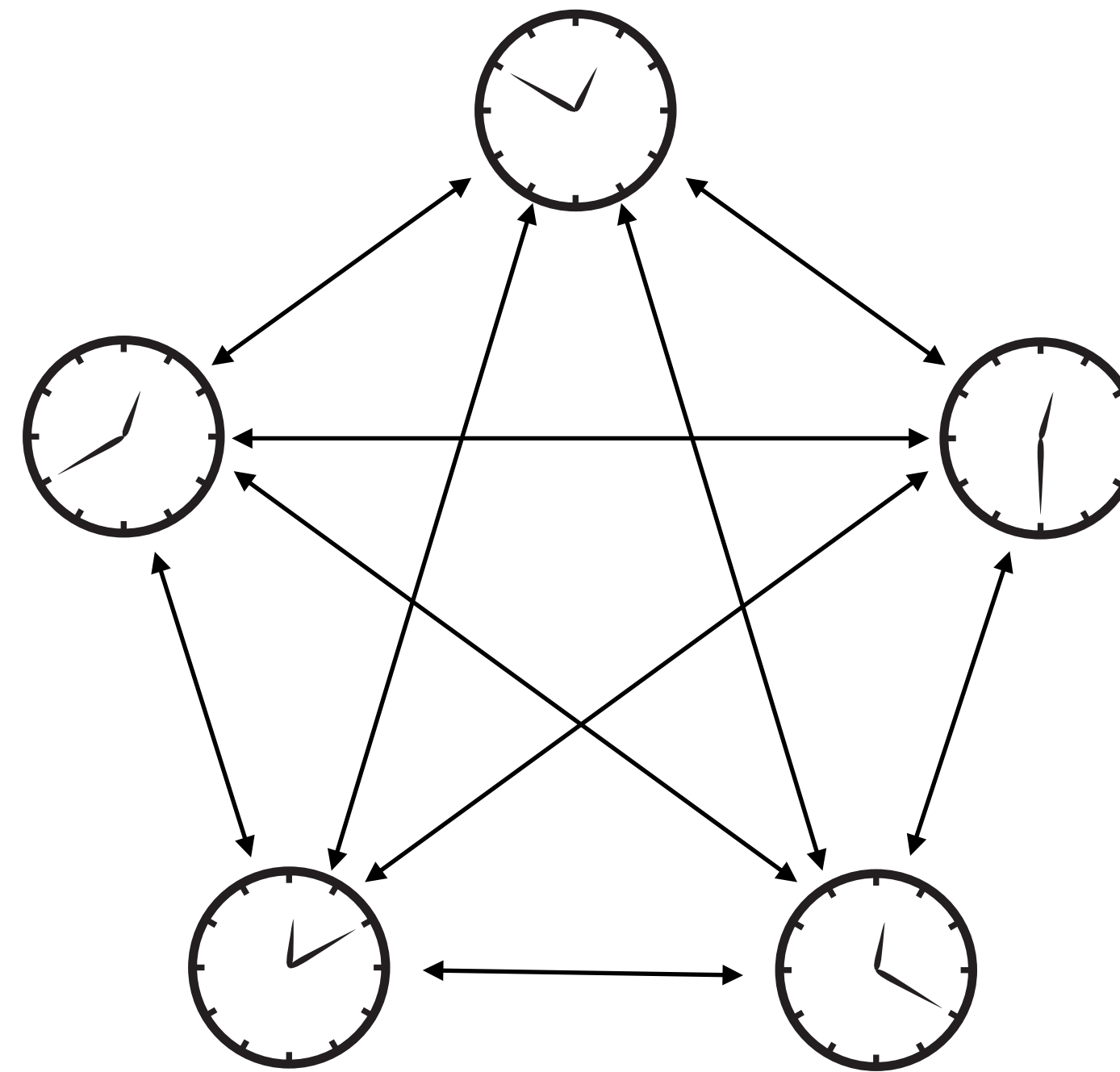
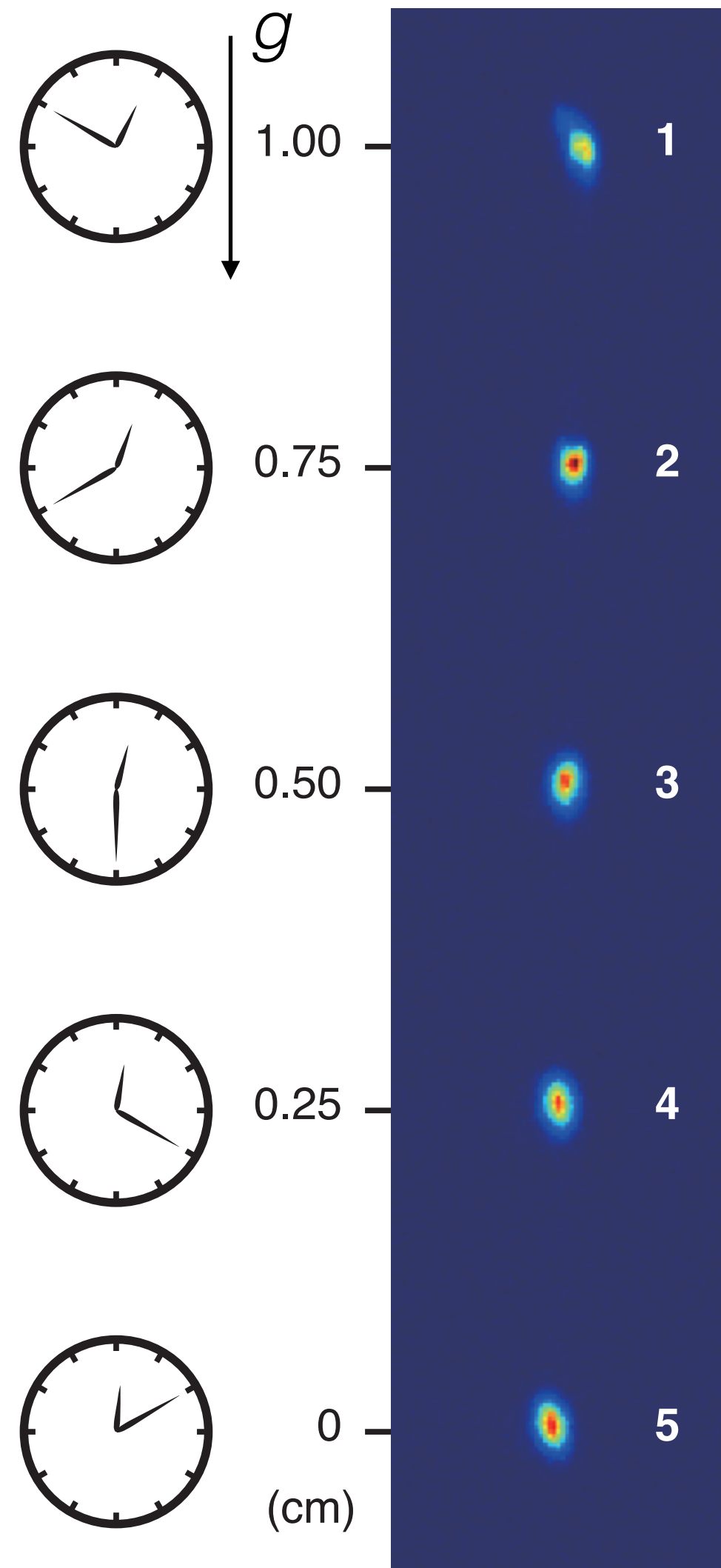




# Multiplexing - a miniature clock network



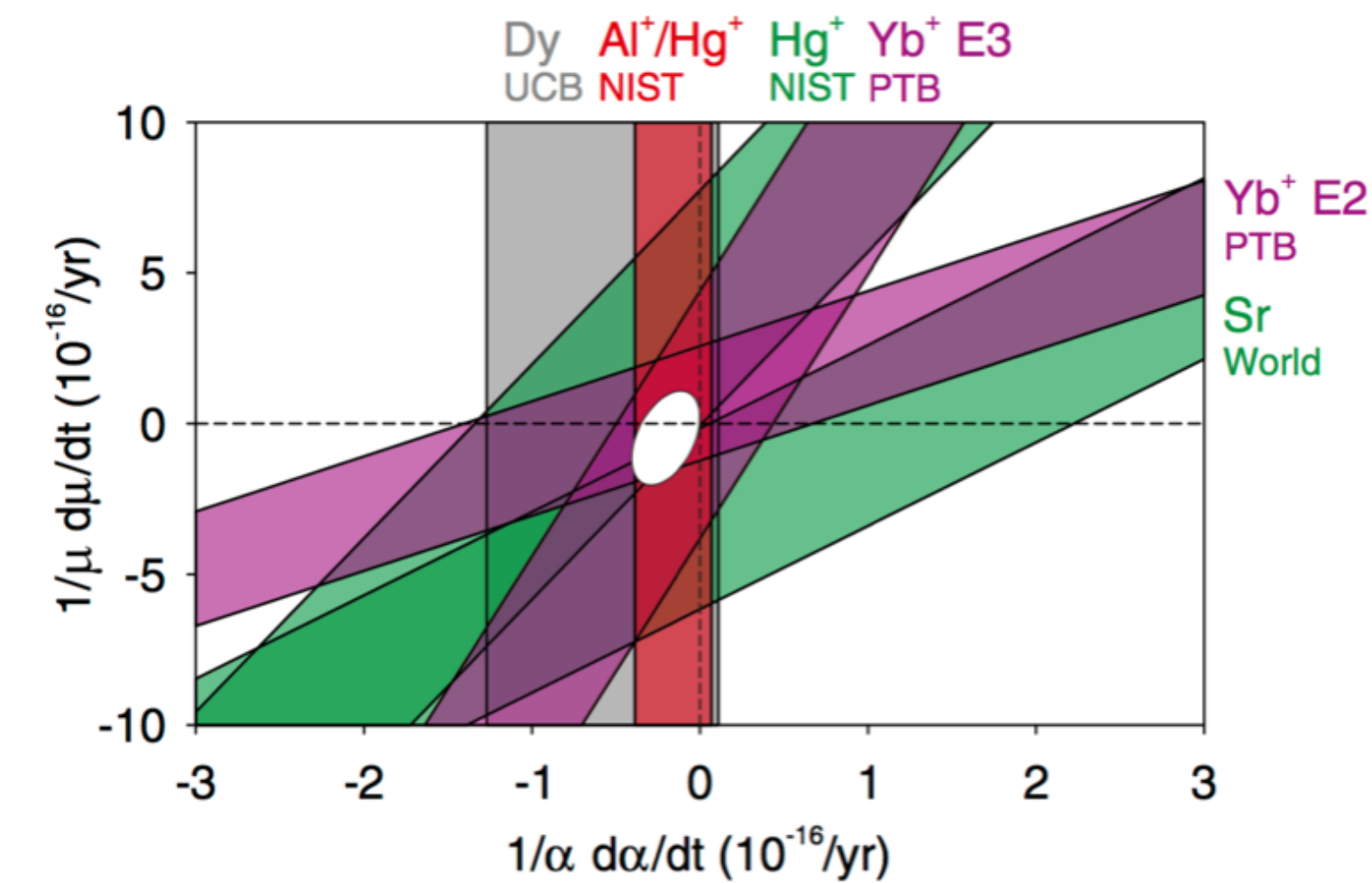
# Multiplexing - a miniature clock network



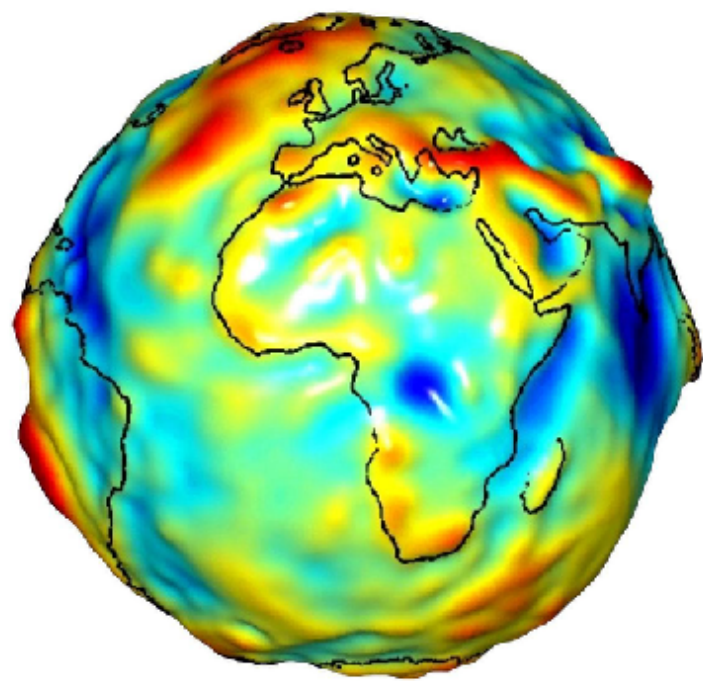


# Optical clocks in space for fundamental physics

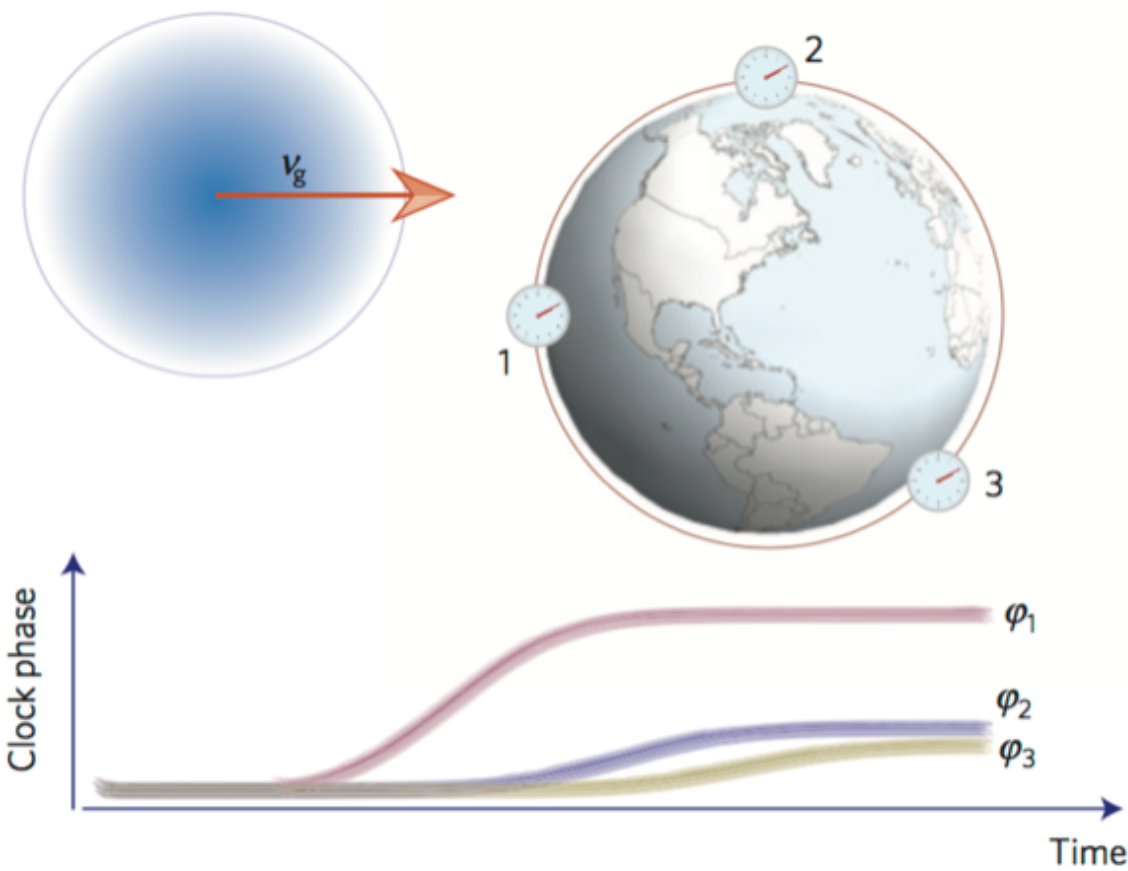
## Searches for new physics



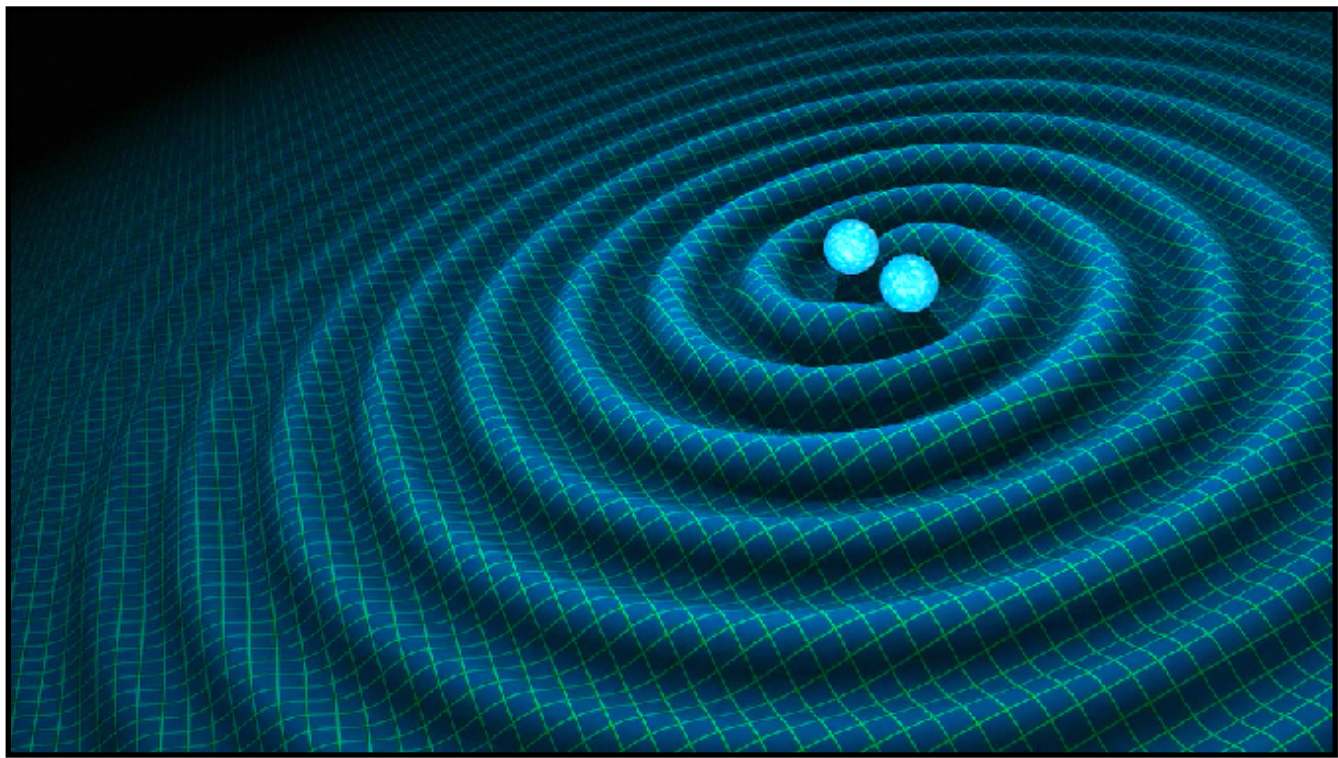
## Geodesy



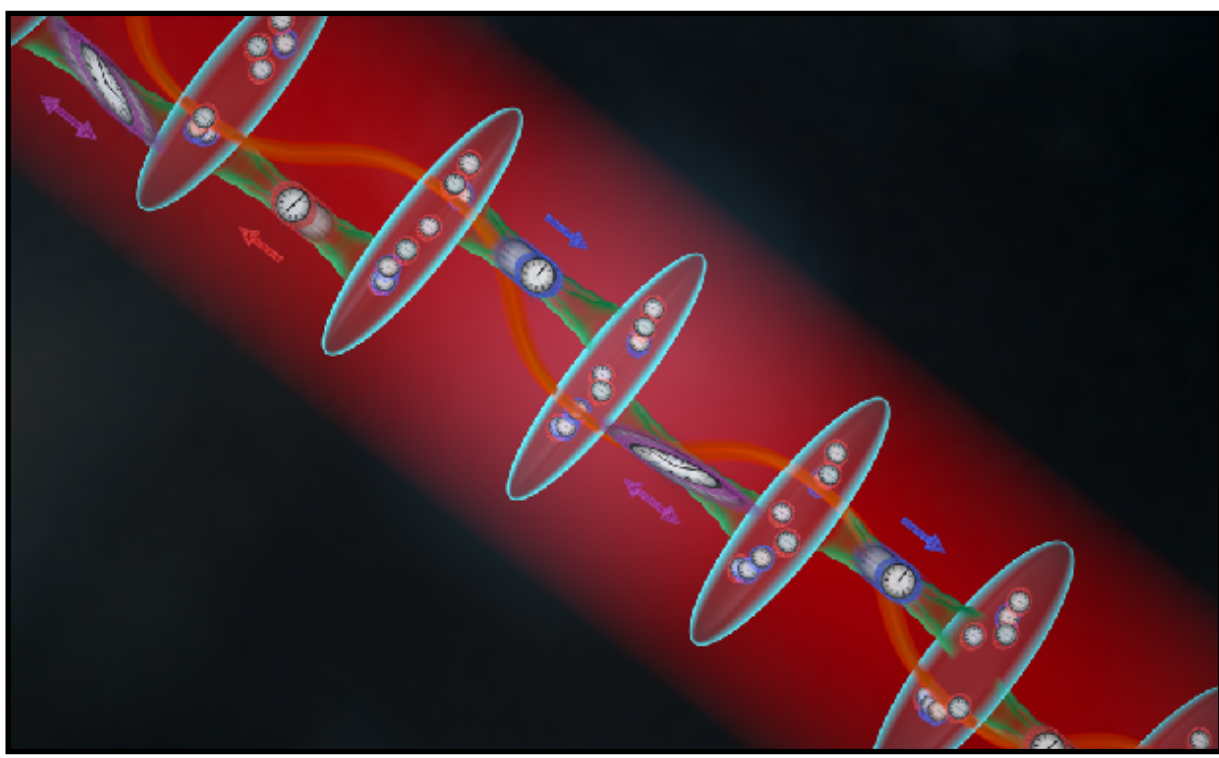
## Dark matter detection



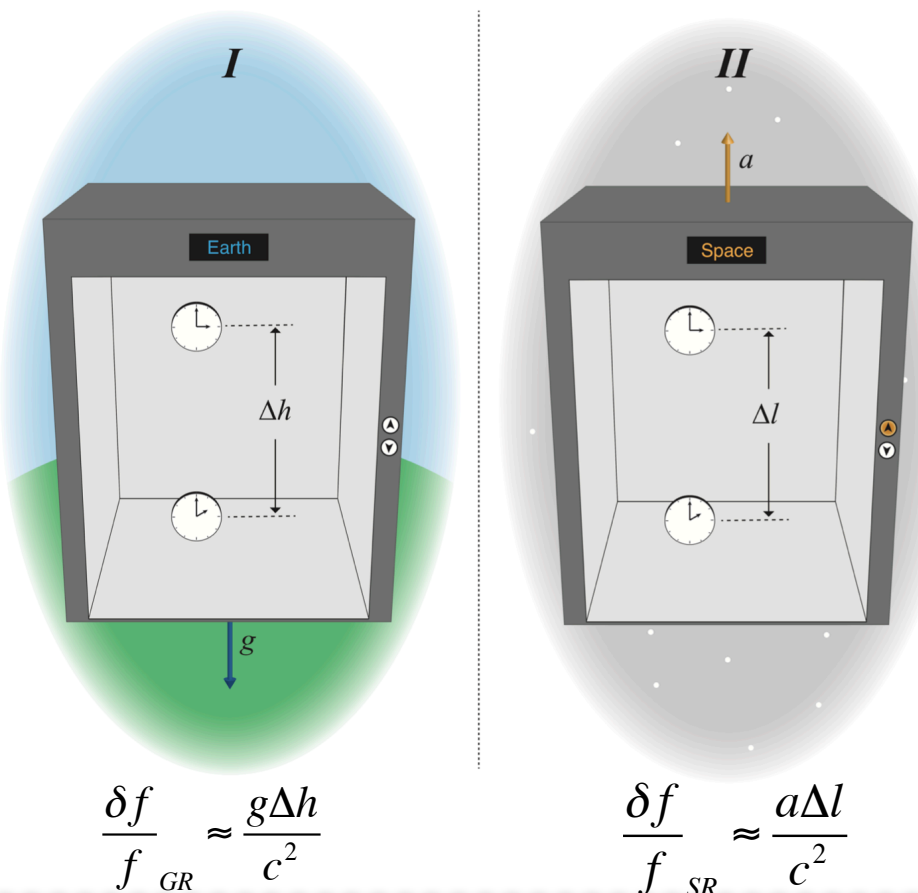
## GW detection



## Quantum simulation

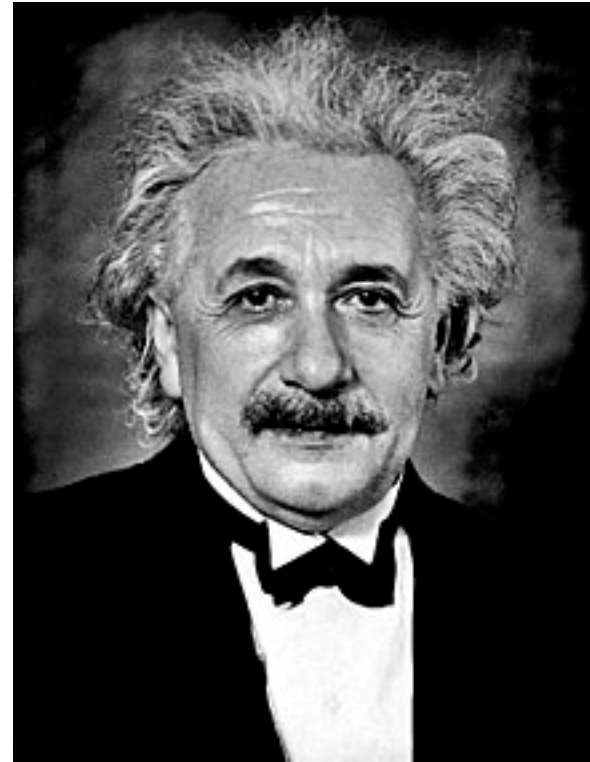


## Tests of relativity





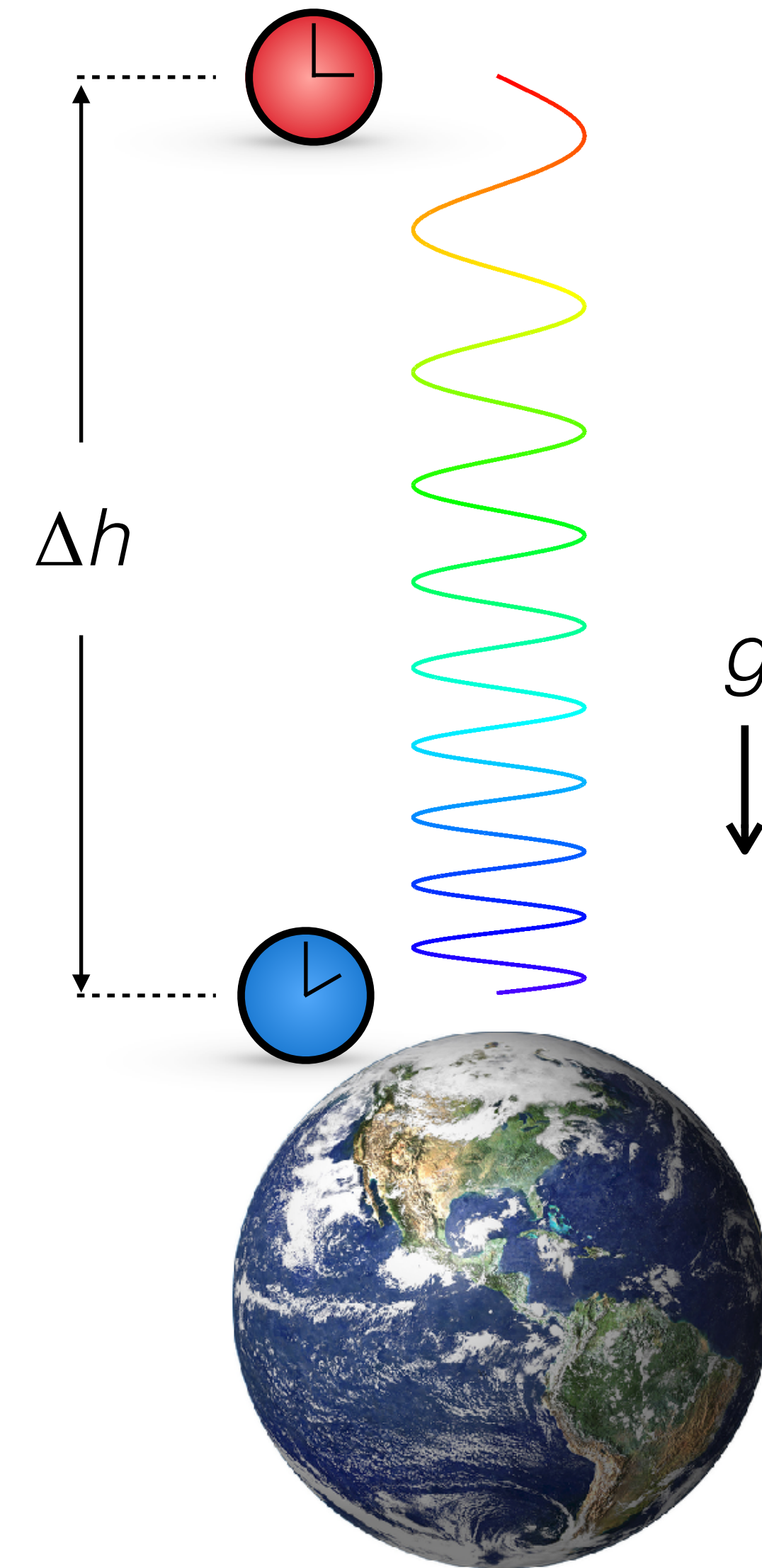
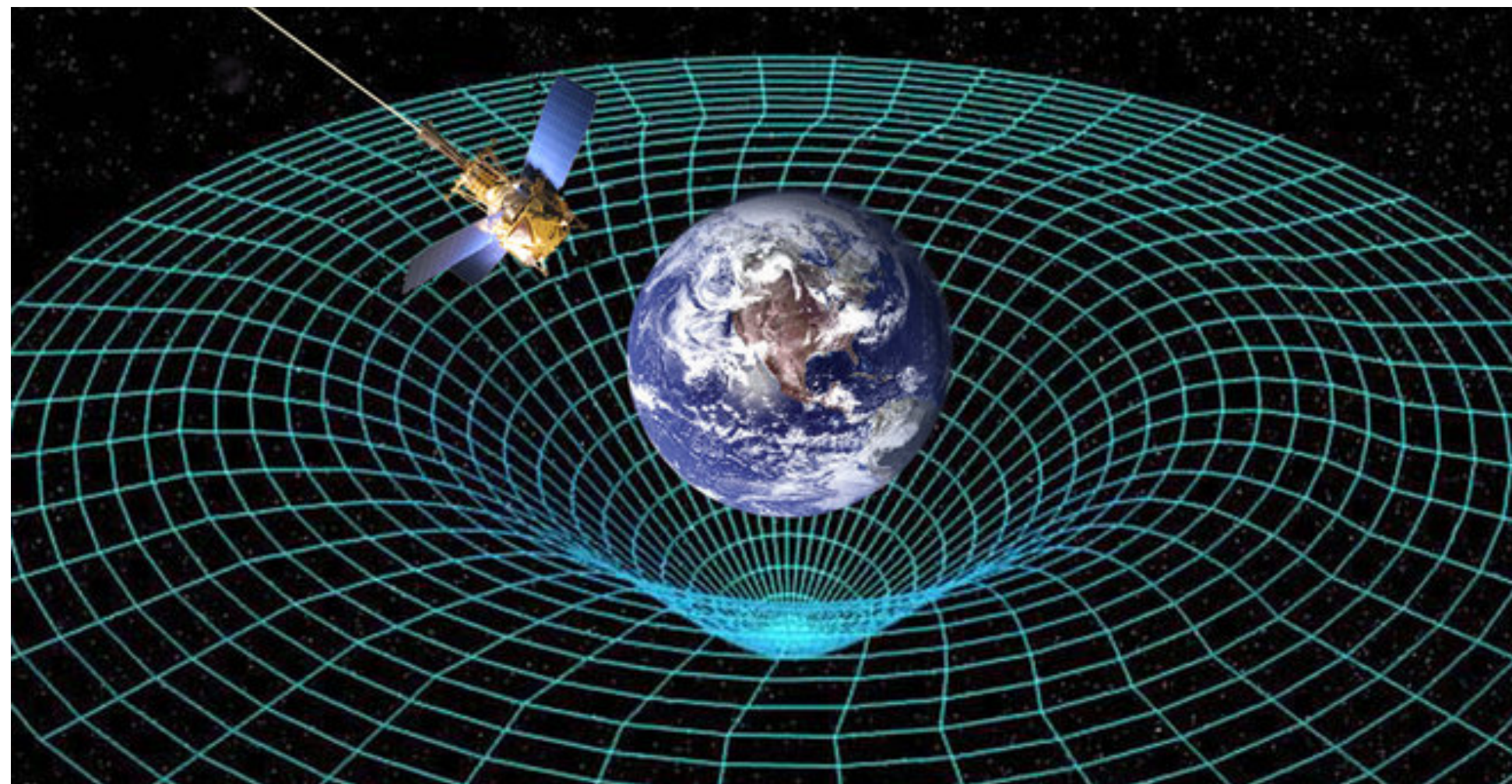
# Gravitational redshift



$$\frac{\delta f}{f}_{GR} \approx \frac{\delta \lambda}{\lambda}_{GR} \approx \frac{g \Delta h}{c^2}$$

For  $\Delta h = 1$  m:

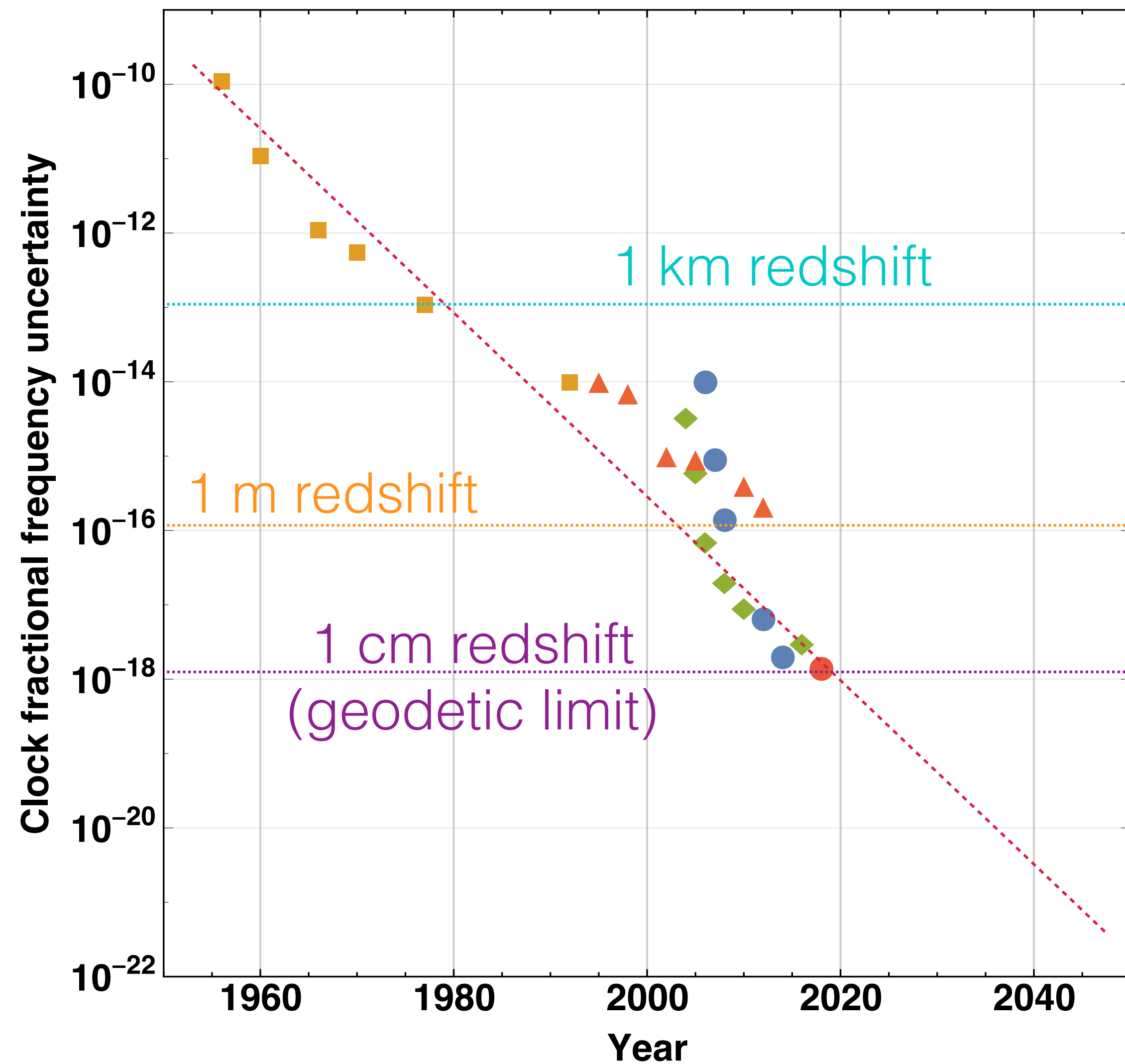
$$\frac{\delta f}{f}_{GR} \approx 1 \times 10^{-16}$$





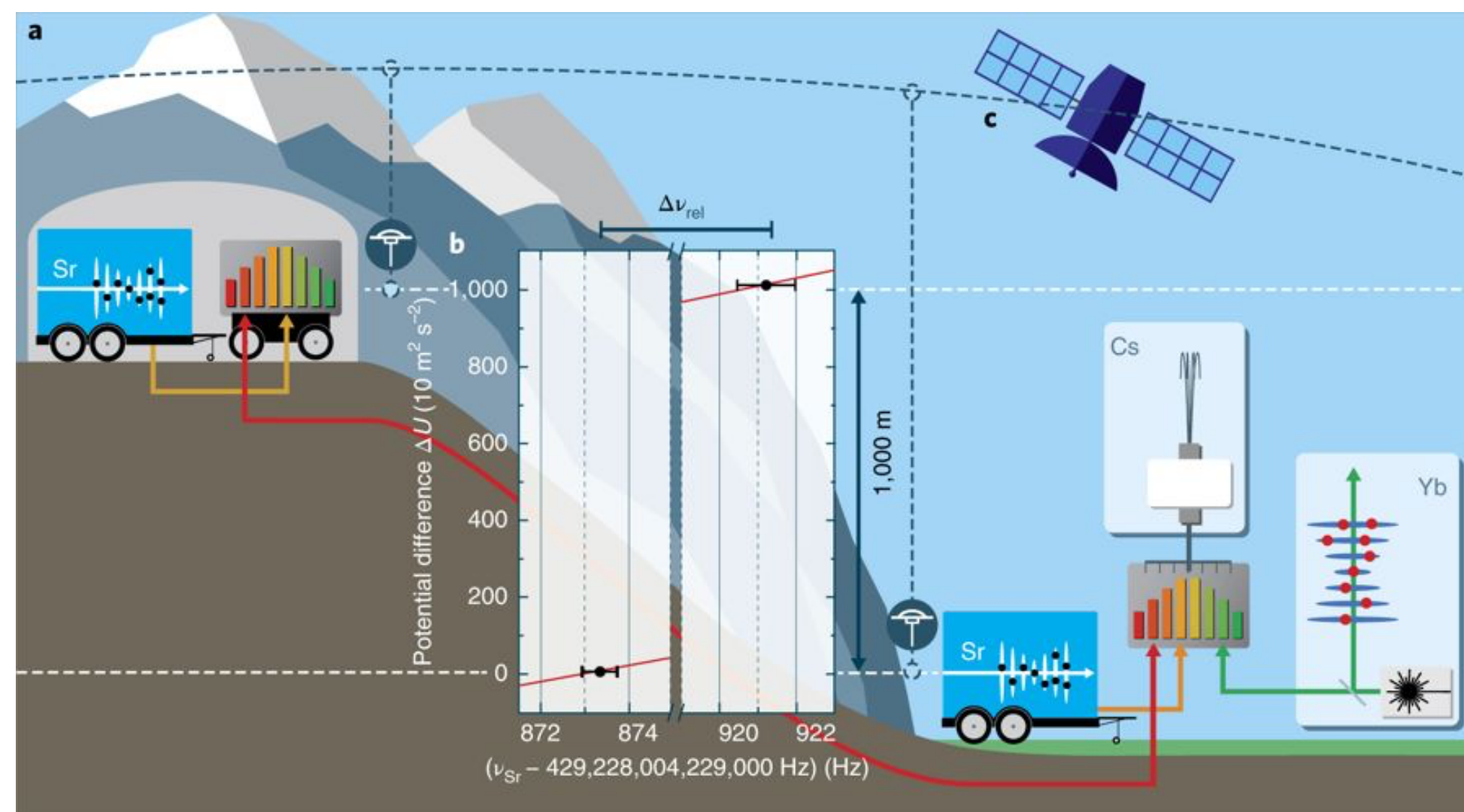
# Gravitational redshift and clocks

- Cs beam
- ▲ Cs fountain
- ◆ Ion optical clock
- Sr optical lattice clock
- Yb optical lattice clock

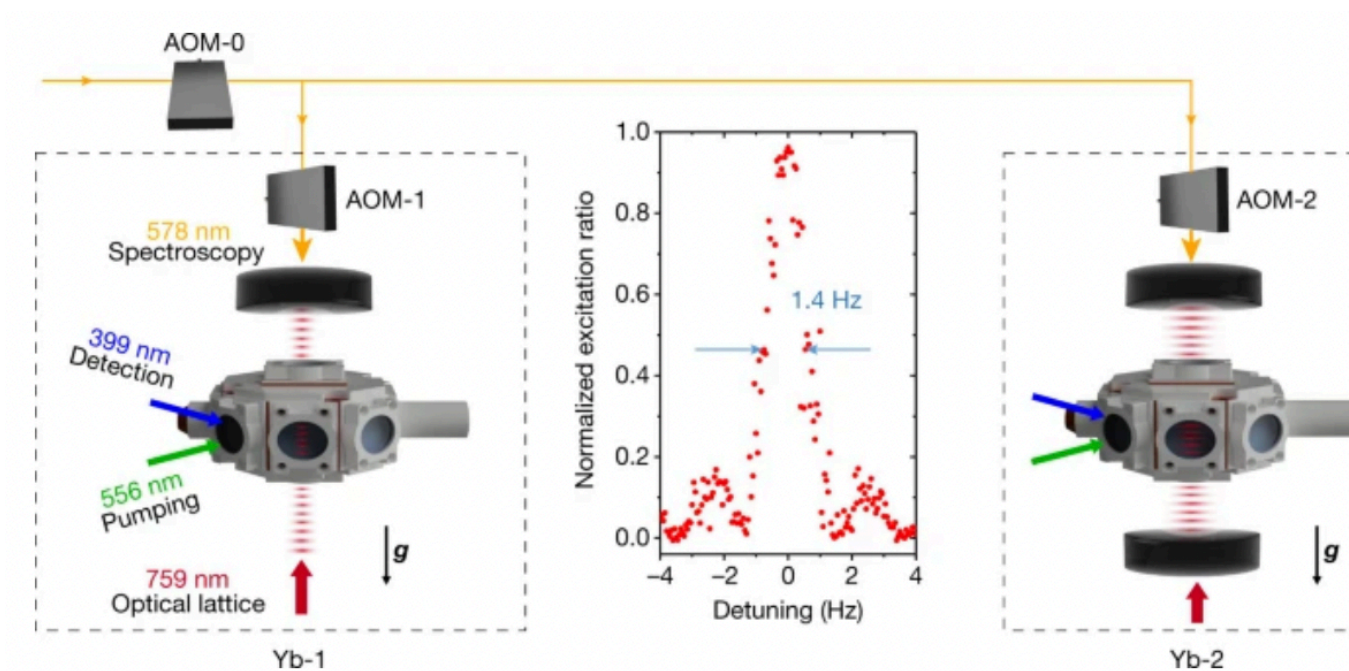
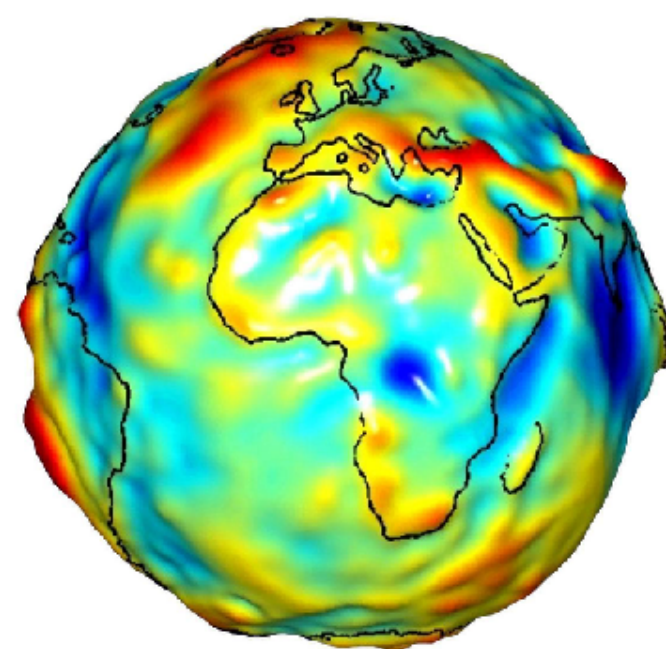




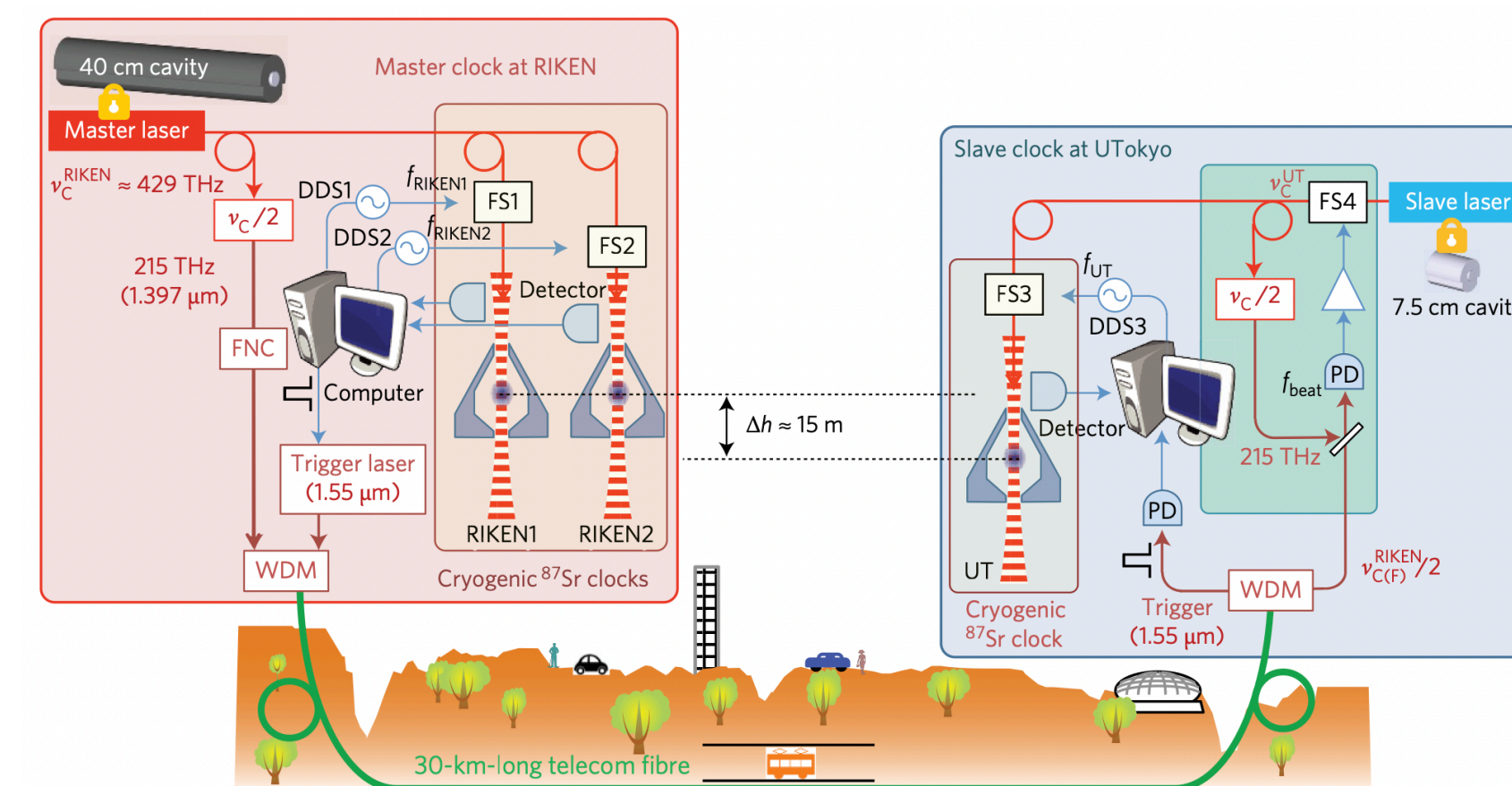
# Relativistic geodesy



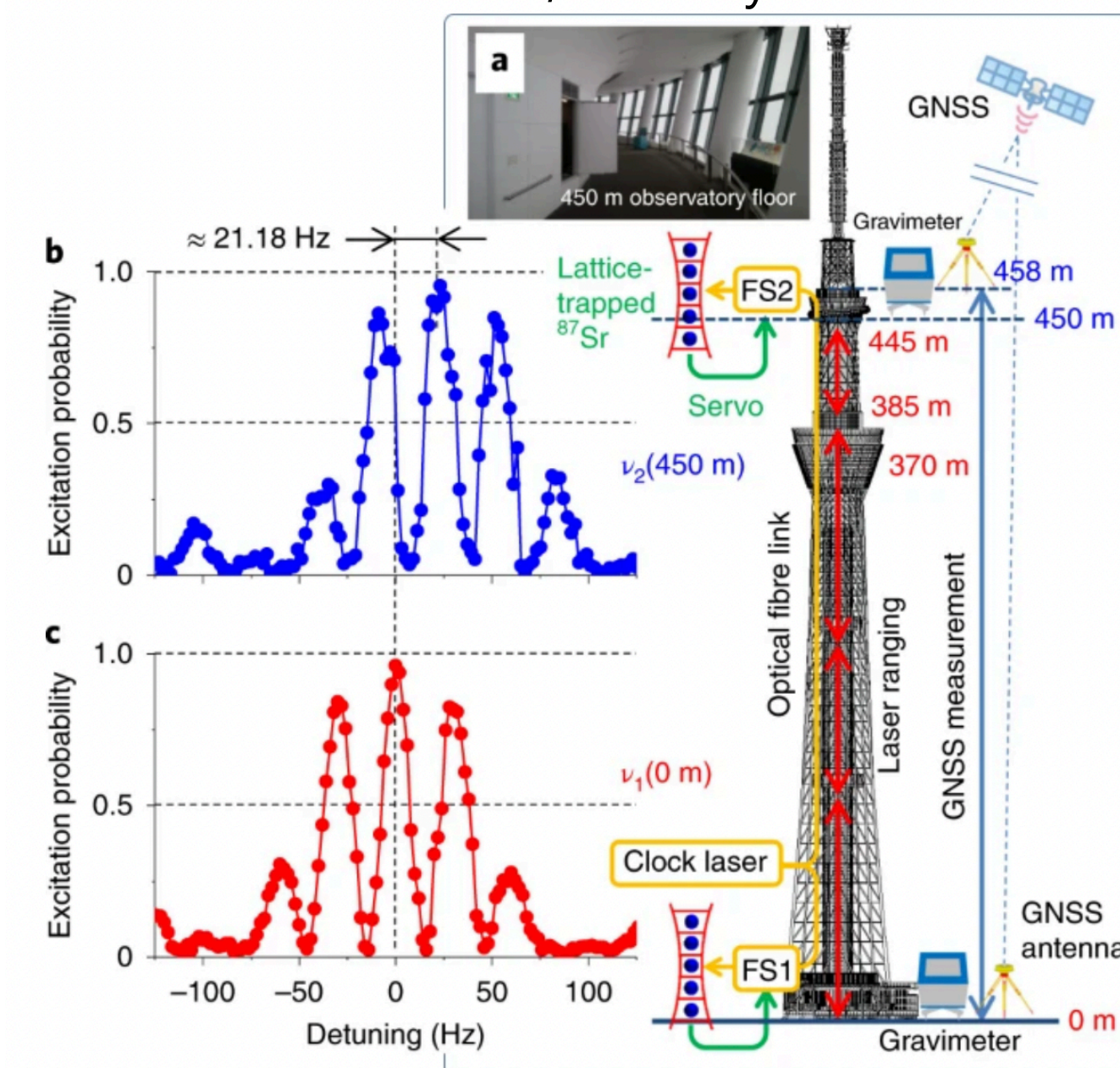
PTB-INRiM



NIST

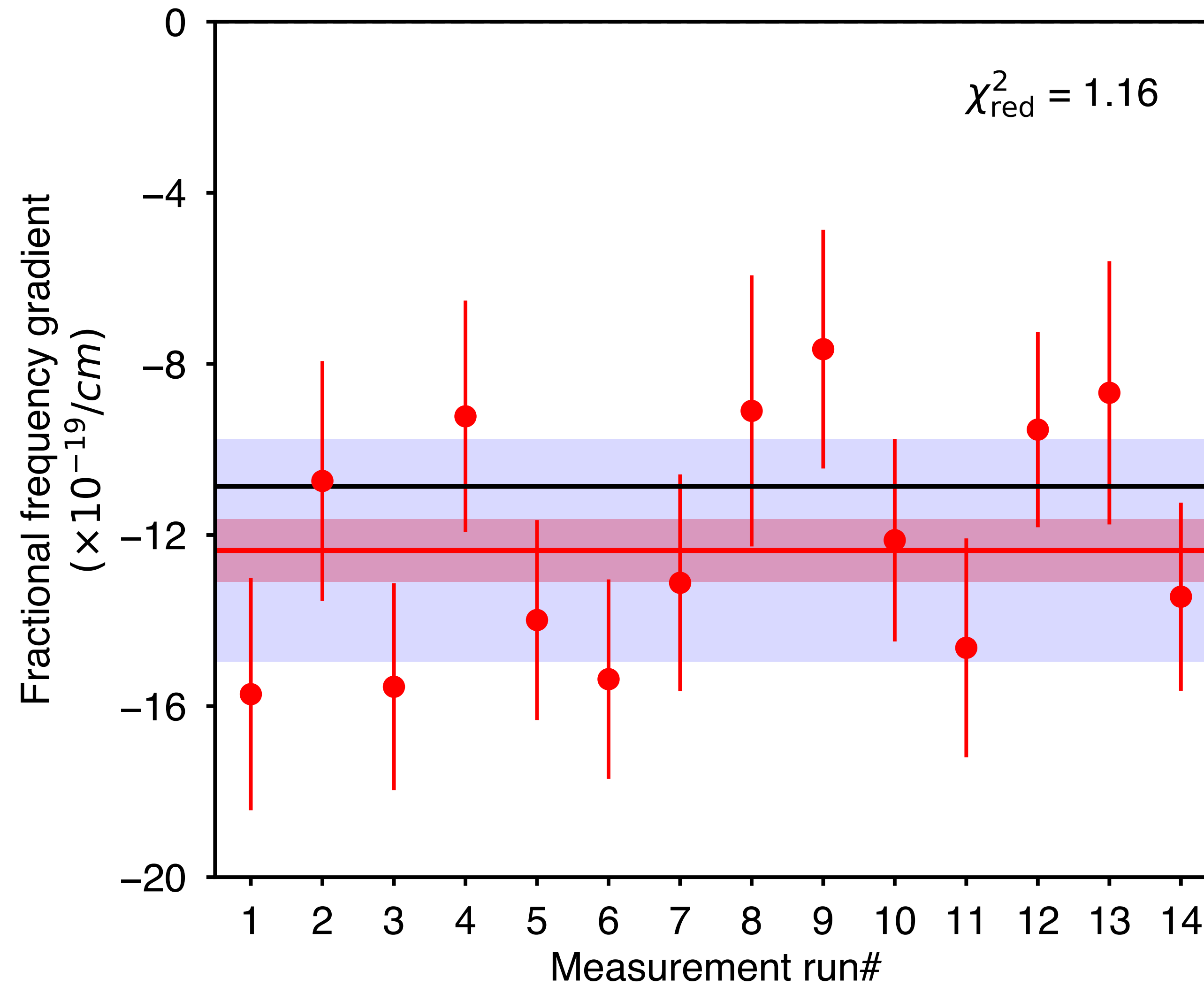
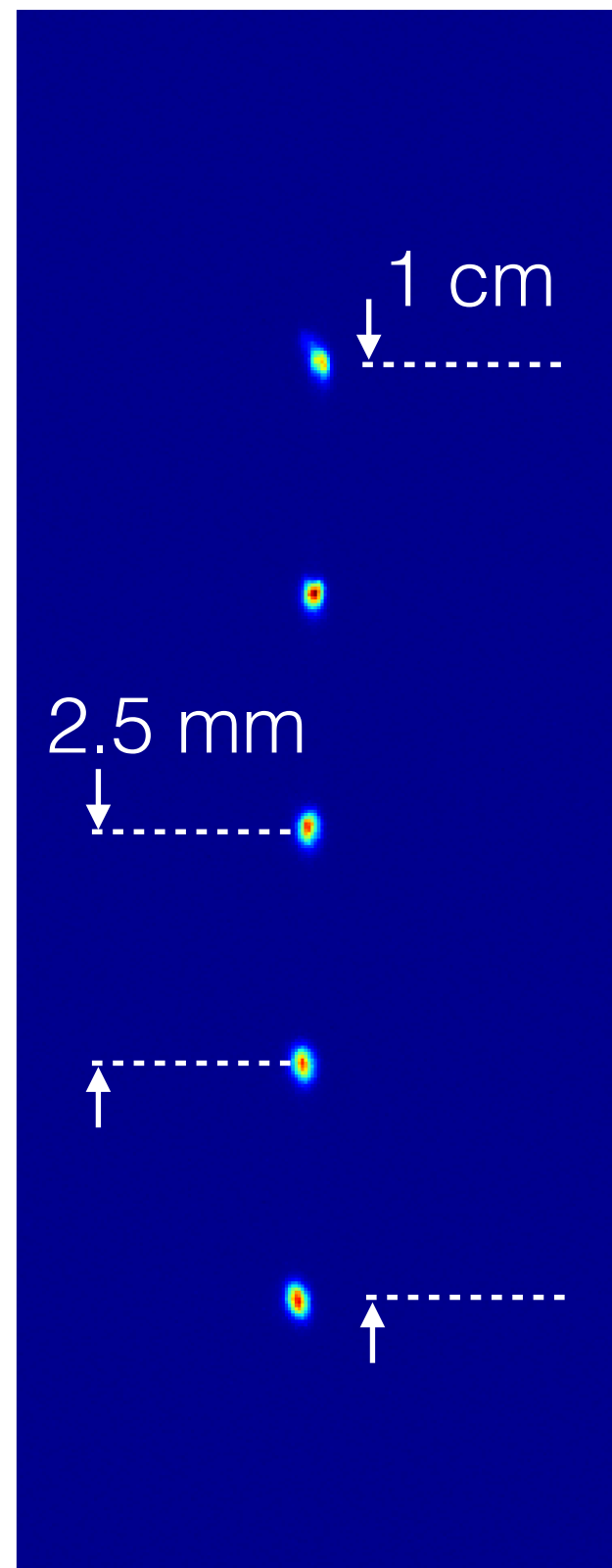


RIKEN/U. Tokyo

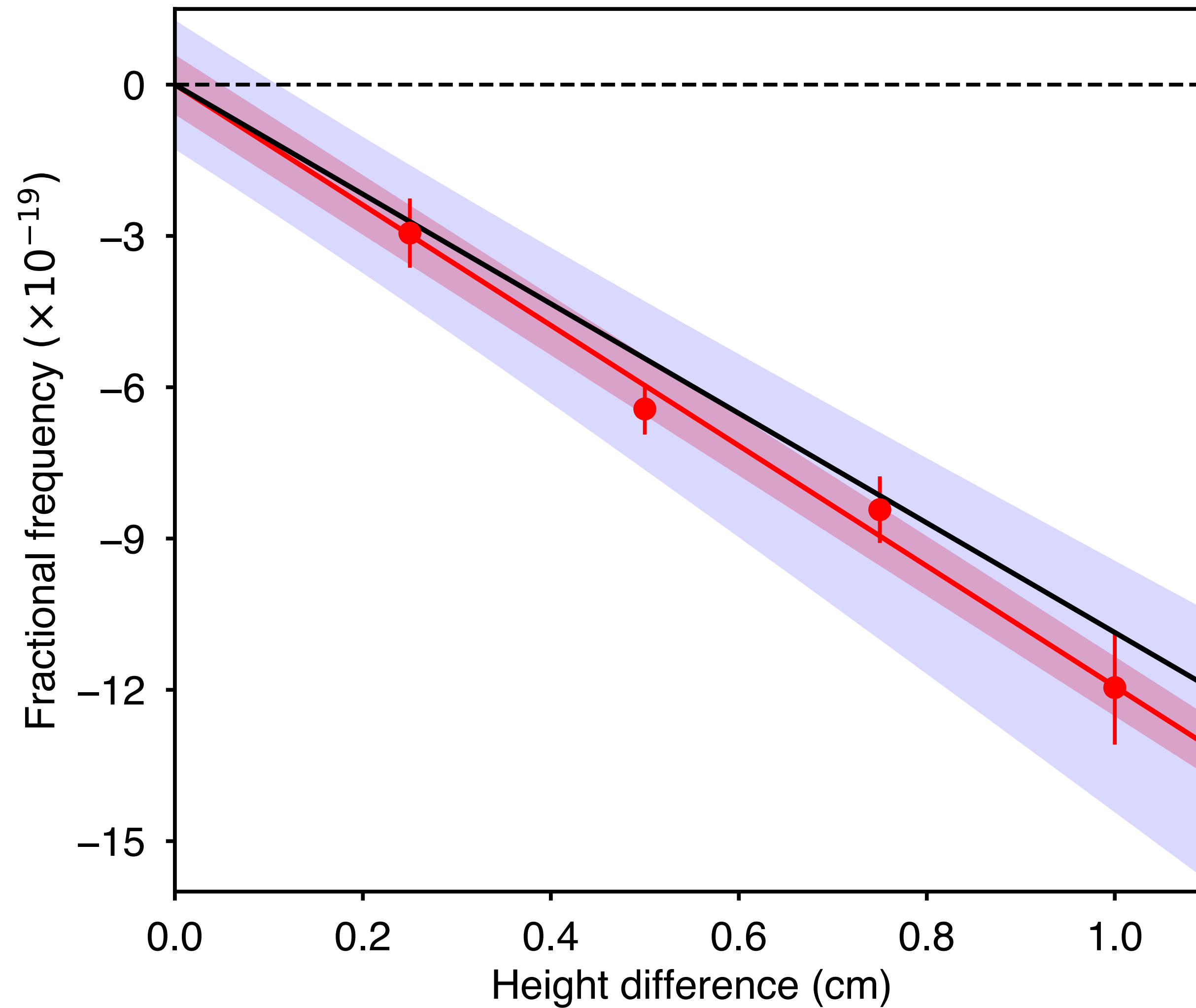
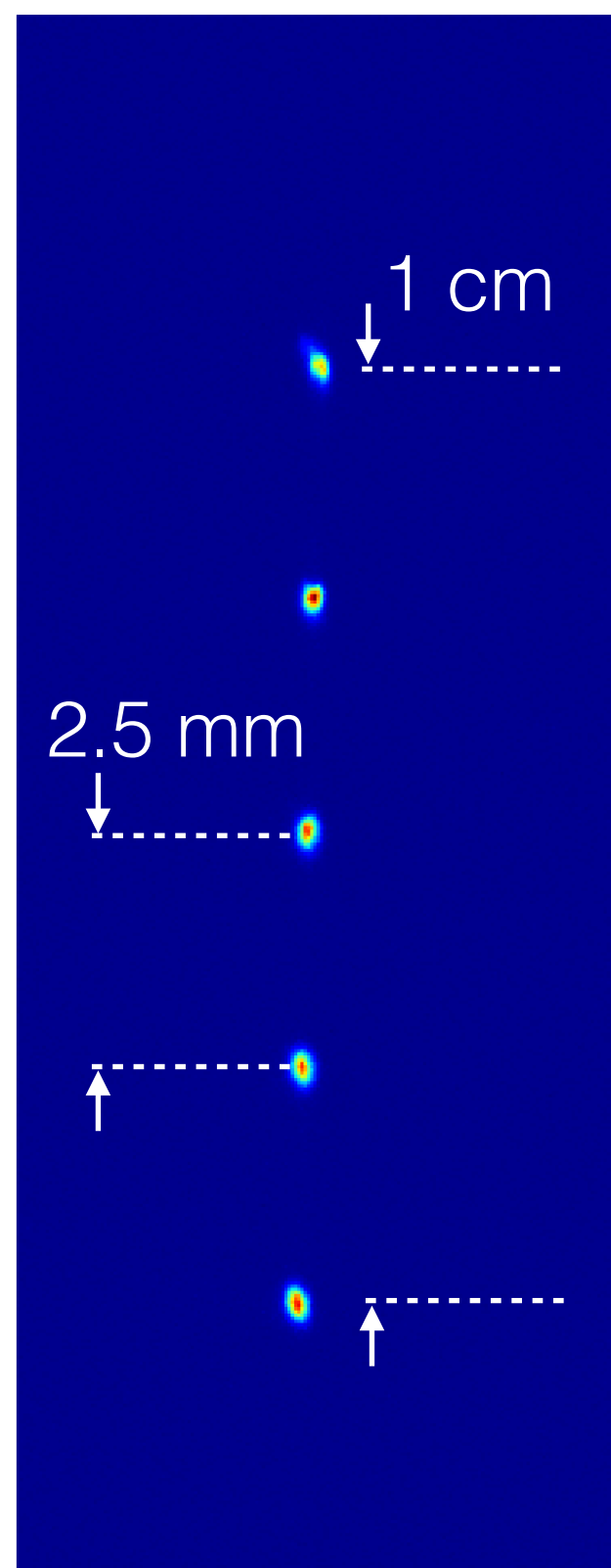




# Test of the gravitational redshift in the lab

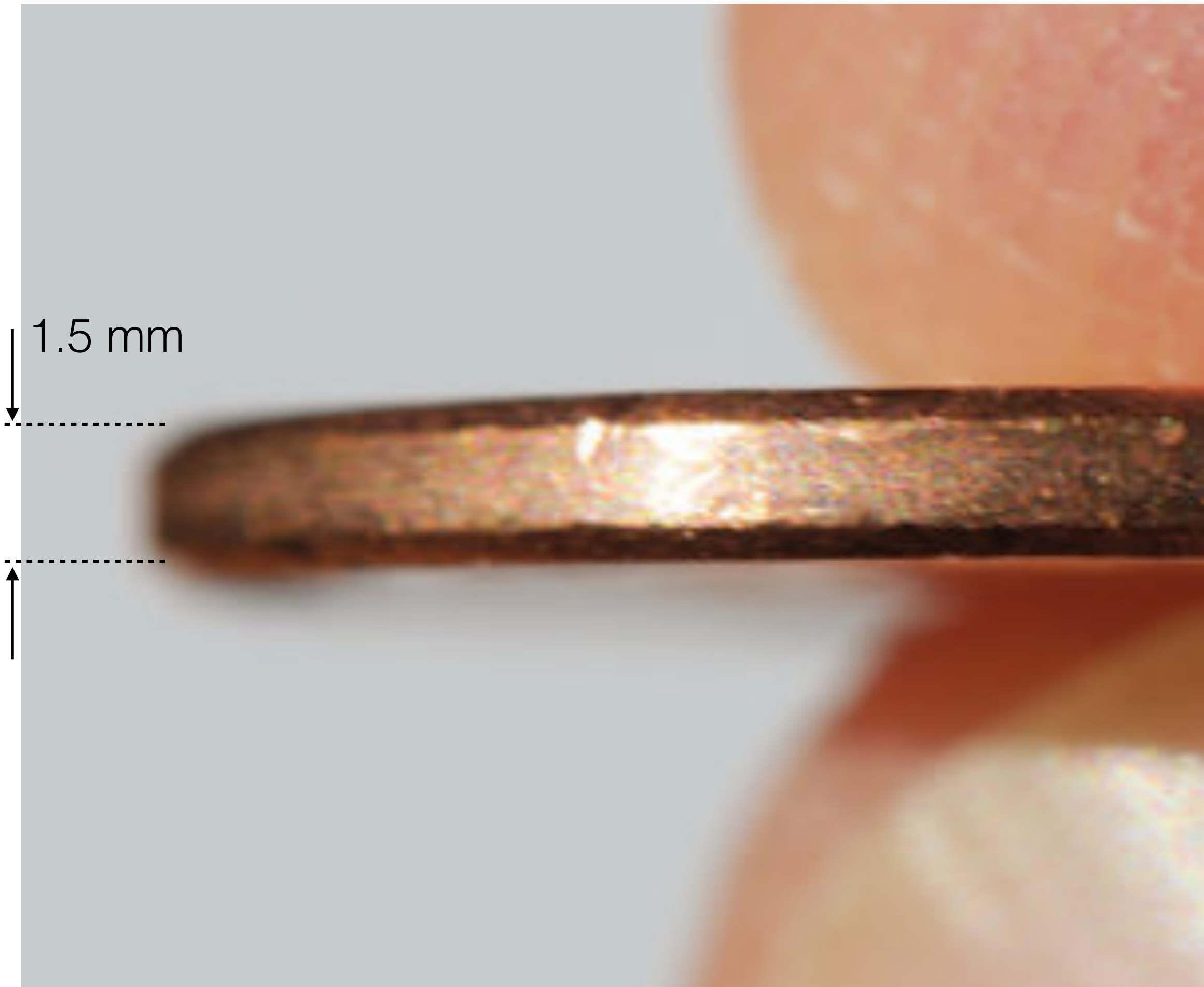
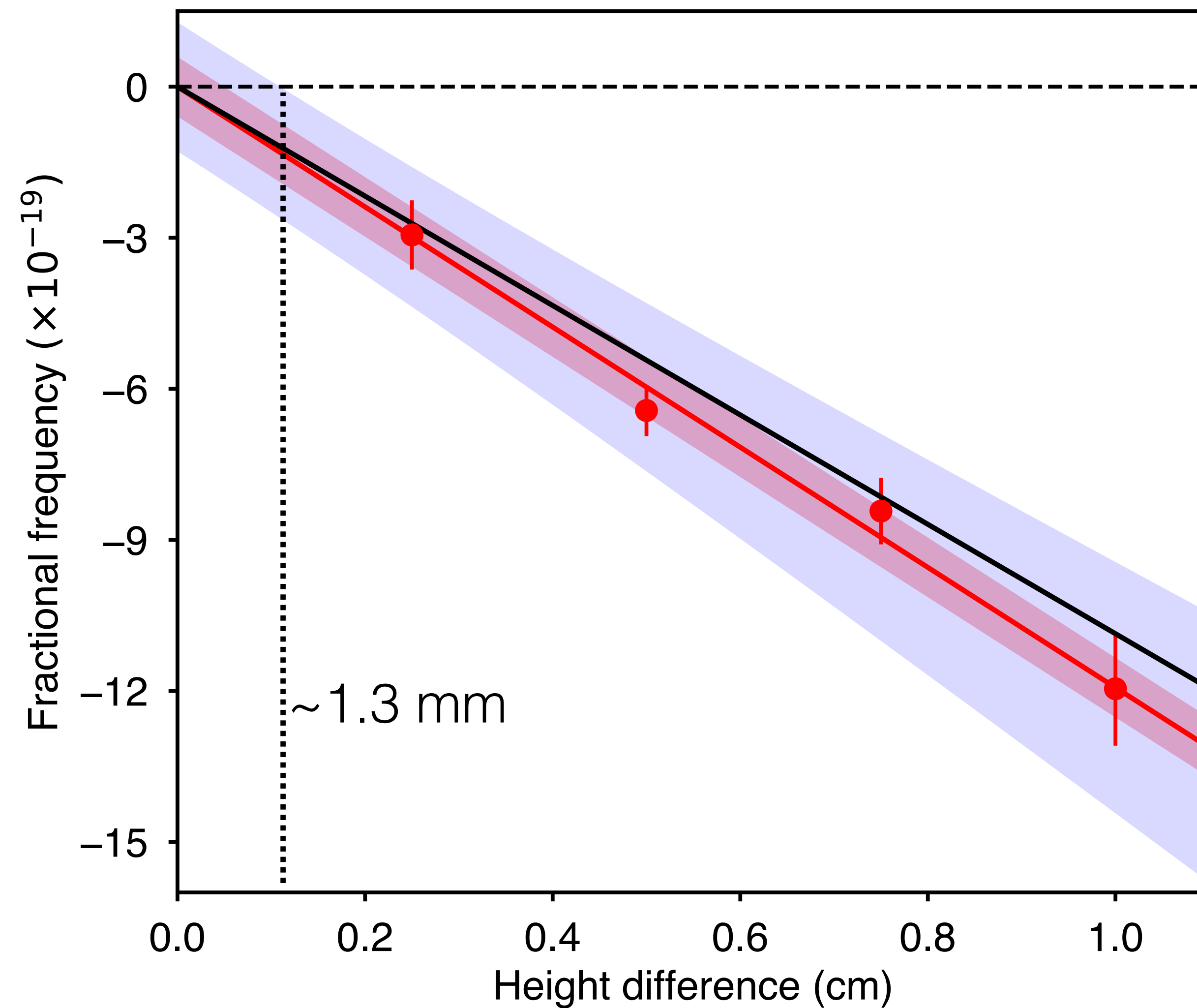


# Gravitational redshift height resolution

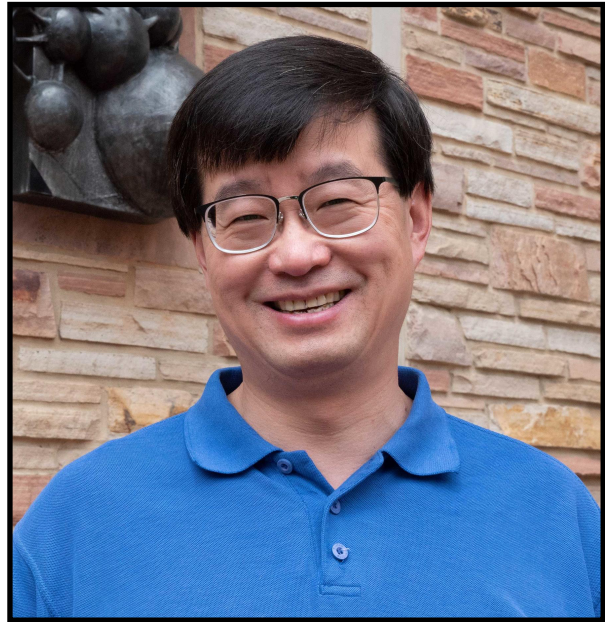




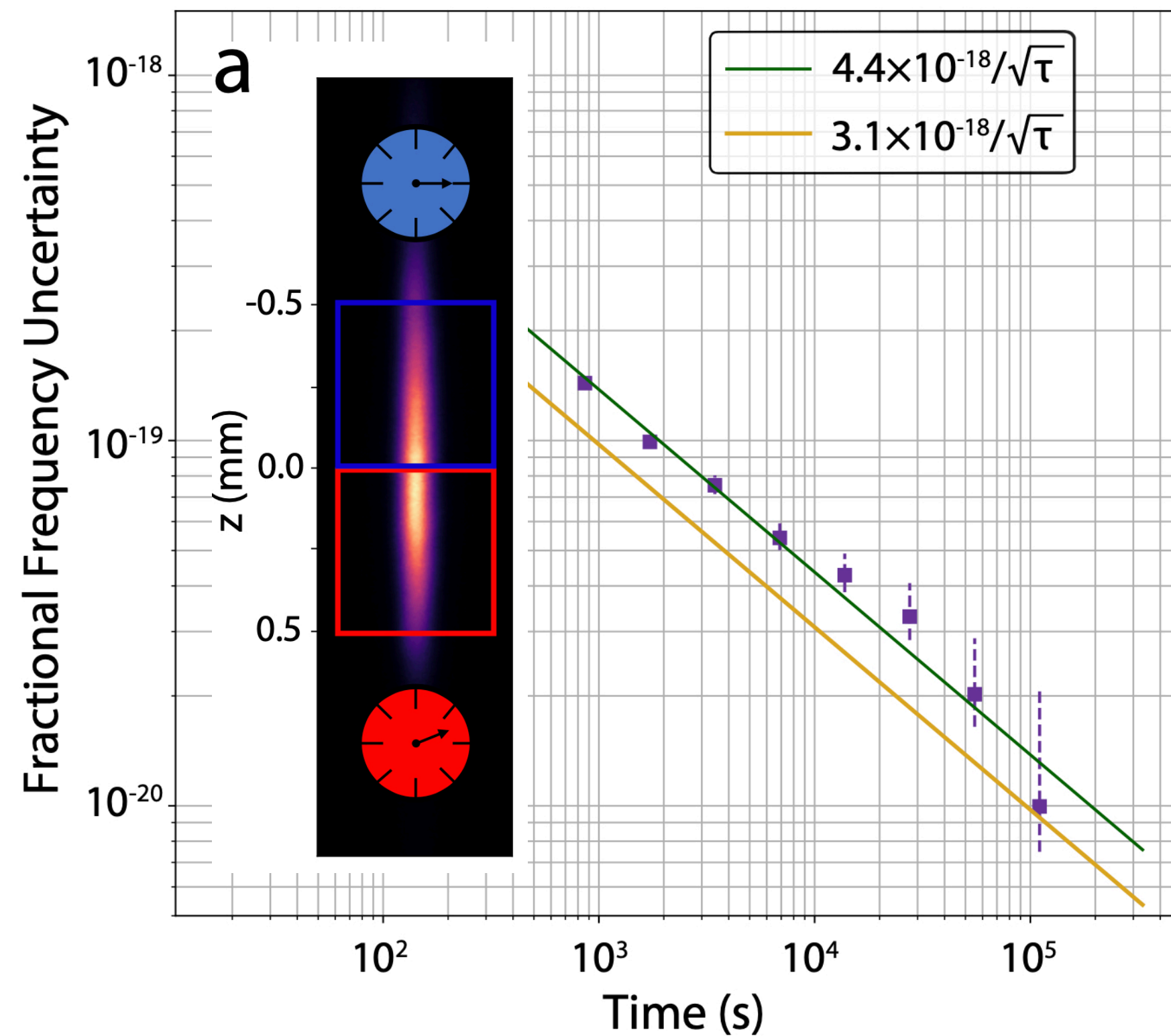
# Gravitational redshift height resolution



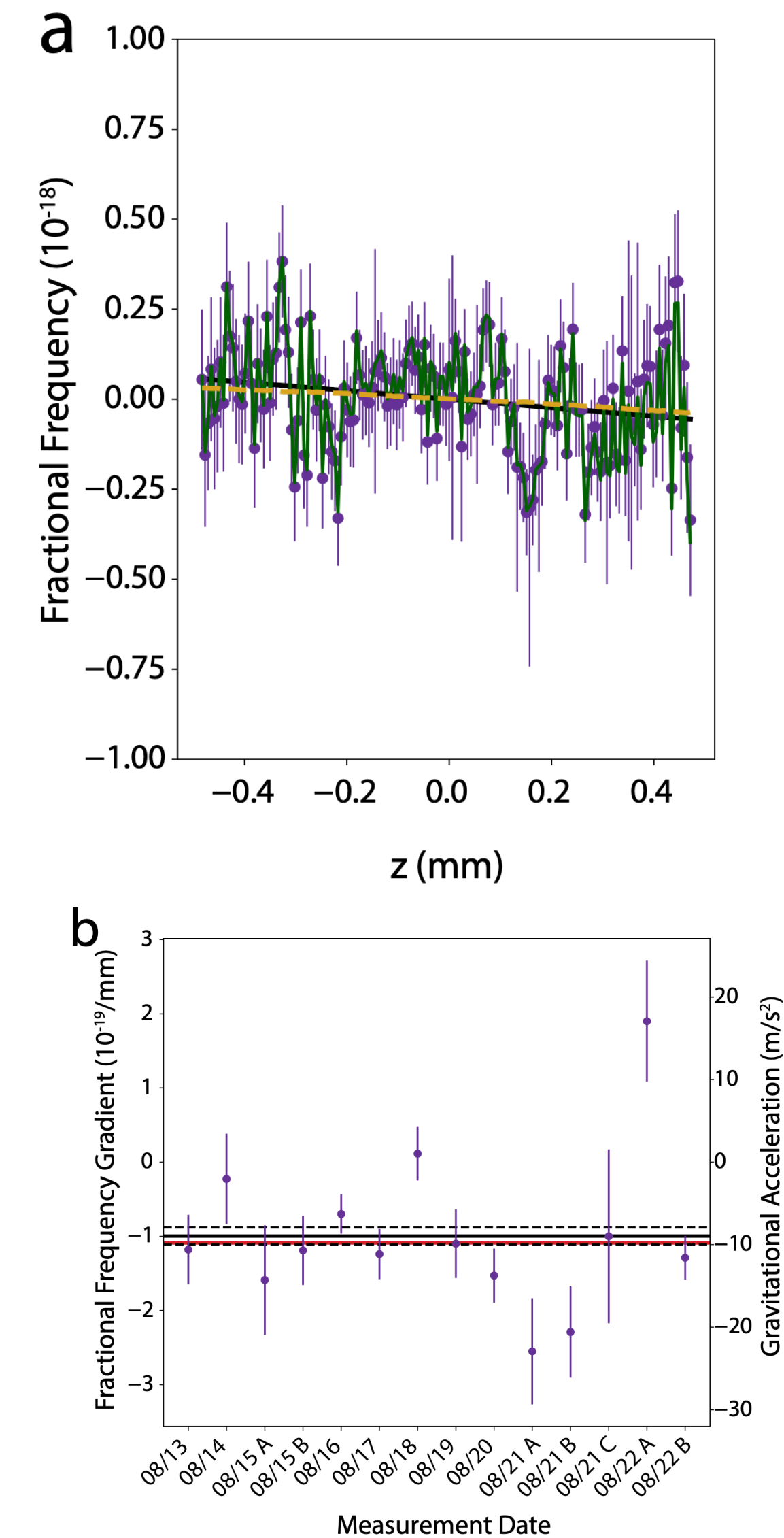
# Redshift across a single atomic ensemble



Jun Ye



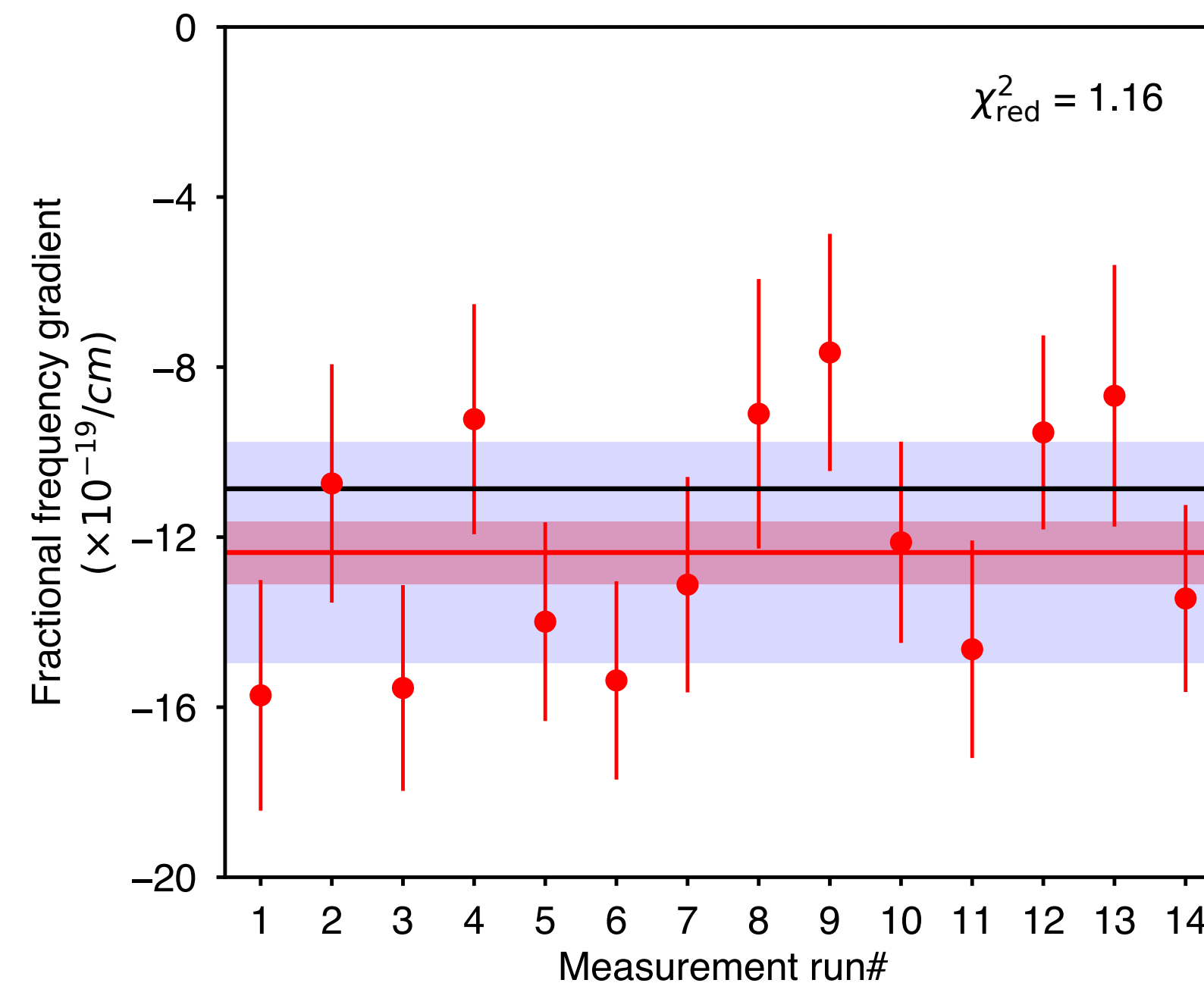
$$\frac{\delta f}{f_{GR}} \approx 1 \times 10^{-19}$$





# Test of the gravitational redshift in the lab

| Sources                                   | Gradient<br>( $\times 10^{-19}/\text{cm}$ ) | Uncertainty<br>( $\times 10^{-19}/\text{cm}$ ) |
|-------------------------------------------|---------------------------------------------|------------------------------------------------|
| BBR <sup>a</sup>                          | -15.7                                       | 1.5                                            |
| Lattice light                             | -11.8                                       | 1.2                                            |
| Density <sup>b</sup>                      | —                                           | 1.0                                            |
| 2 <sup>nd</sup> order Zeeman <sup>a</sup> | -95.3                                       | 1.0                                            |
| Probe Stark                               | 0                                           | 0.5                                            |
| DC Stark                                  | 0                                           | 0.1                                            |
| Ellipse fitting <sup>b</sup>              | —                                           | 0.5                                            |
| Total systematic correction               | +122.8                                      | 2.5                                            |
| Statistical gradient                      | -135.2                                      | 0.7                                            |
| <b>Corrected gradient</b>                 | <b>-12.4</b>                                | <b>2.6</b>                                     |
| <b>Expected redshift gradient</b>         | <b>-10.9</b>                                | <b>&lt;0.1</b>                                 |



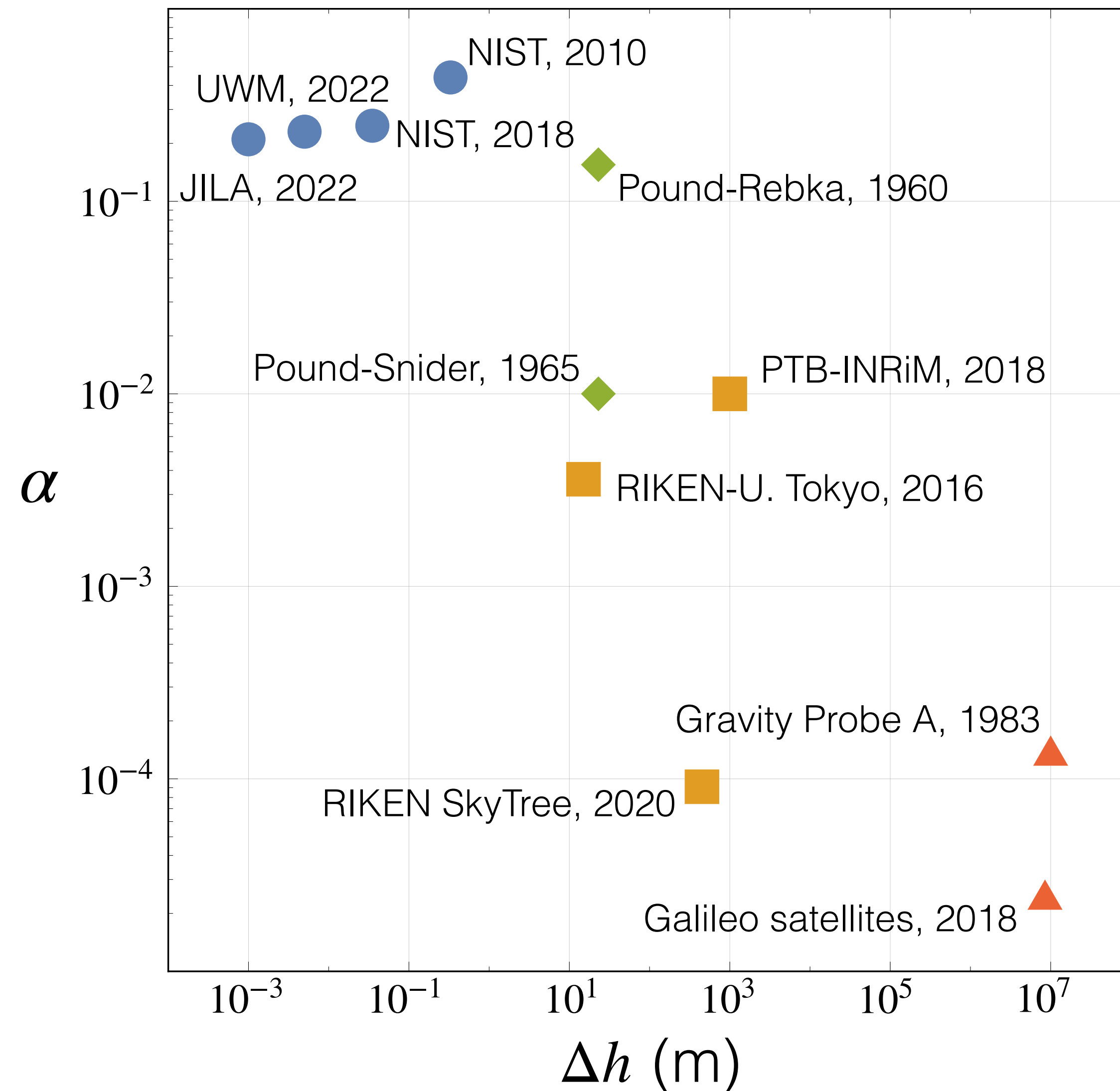
Expected redshift gradient:  $10.9 \times 10^{-19}/\text{cm}$

Measured redshift gradient:  $12.4 \pm 0.7_{(stat)} \pm 2.5_{(sys)} \times 10^{-19}/\text{cm}$

$$\frac{\delta f}{f}_{GR+} \approx (1 + \alpha) \frac{g\Delta h}{c^2} \quad 1 + \alpha = 1.13 \pm 0.23$$

# Tests of the gravitational redshift

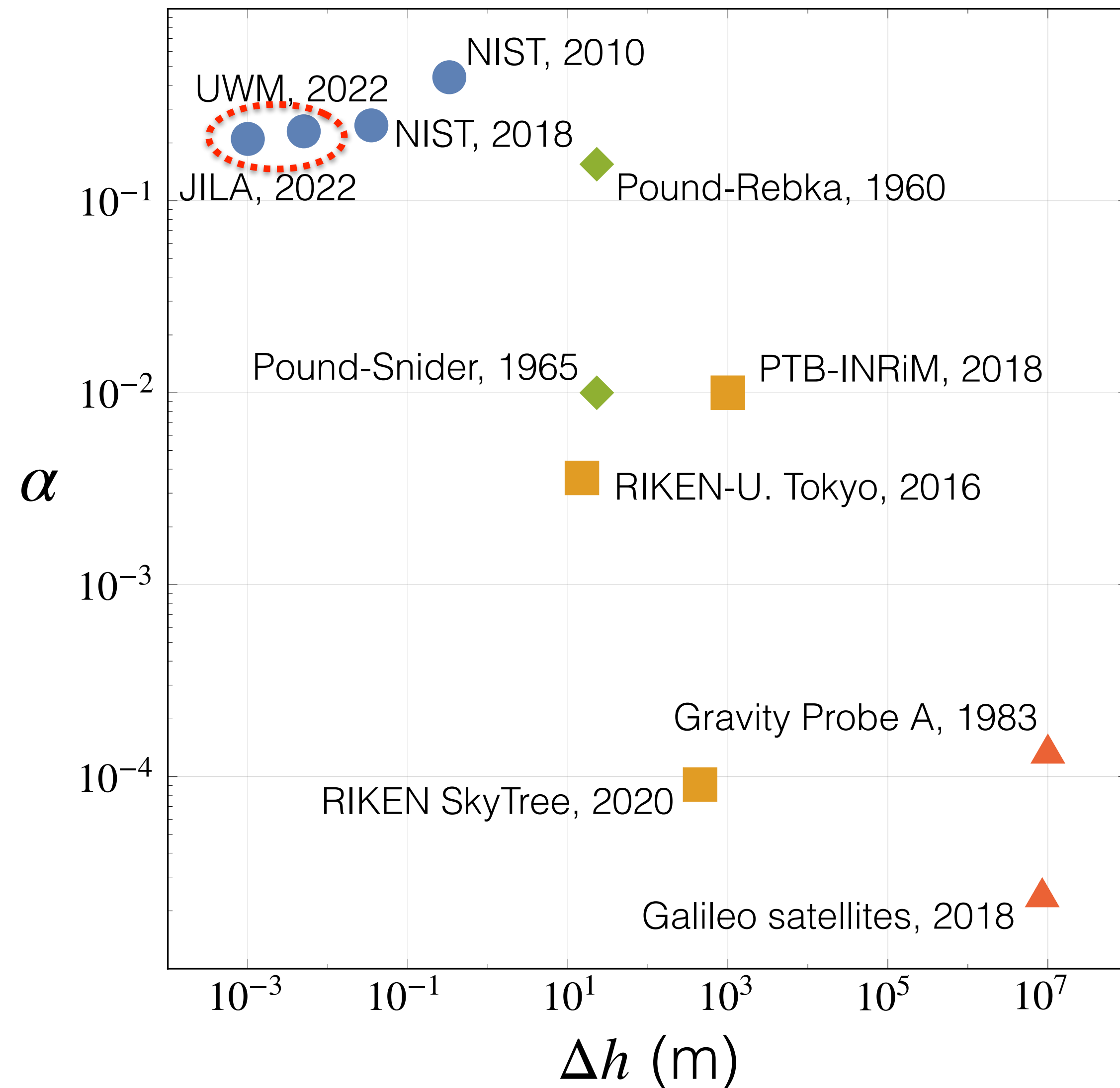
- Lab-based optical clocks
- Portable optical clocks
- ◆ Mössbauer
- ▲ Space-based MW clocks





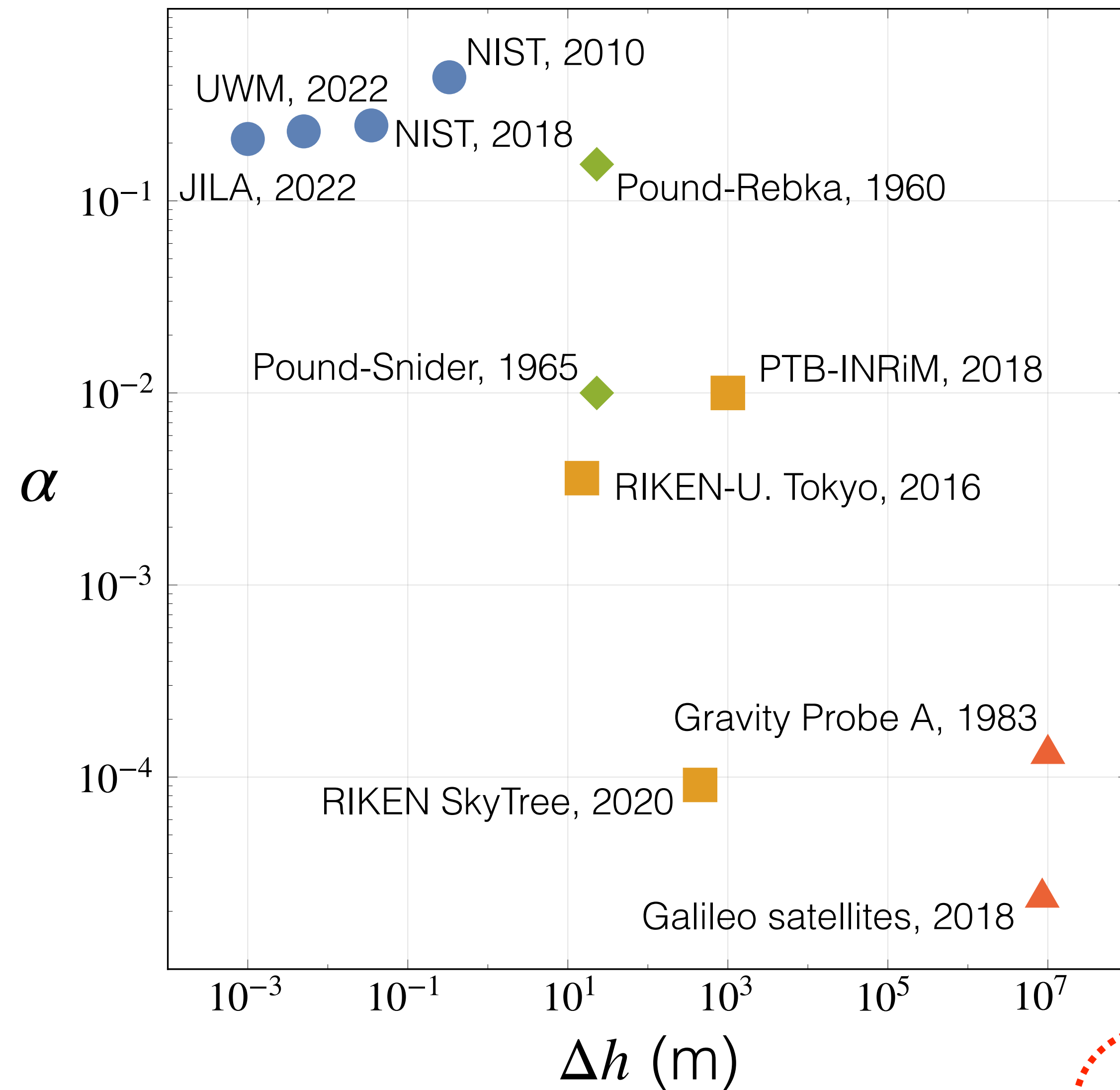
# Tests of the gravitational redshift

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# Tests of the gravitational redshift

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Optical clocks  
on the moon



# Science with optical clocks on the moon:

- Precision navigation and timing
- Very long baseline interferometry
- Tests of the gravitational redshift and relativity, geodesy of the moon(?)
- Doppler tracking of the moon, gravitational wave detection(?)
- Dark matter searches
- ????????



Thank you for your attention!



Questions?