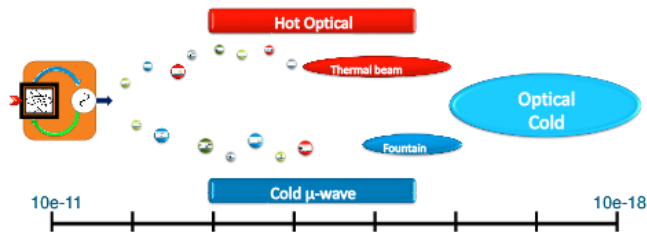
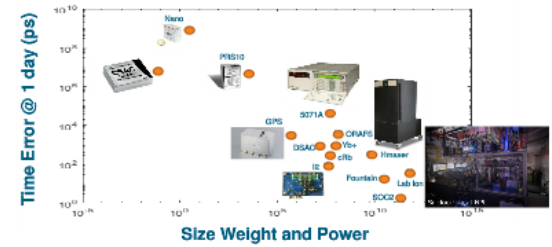


### Legacy to Future Performance



### Thank You



# Developing Atomic Clock Technologies and Applications

**Christopher Erickson**

Time and Frequency

Quantum Sensing Project

**[dstl]**

05 March 2019

© Crown copyright 2019 Dstl

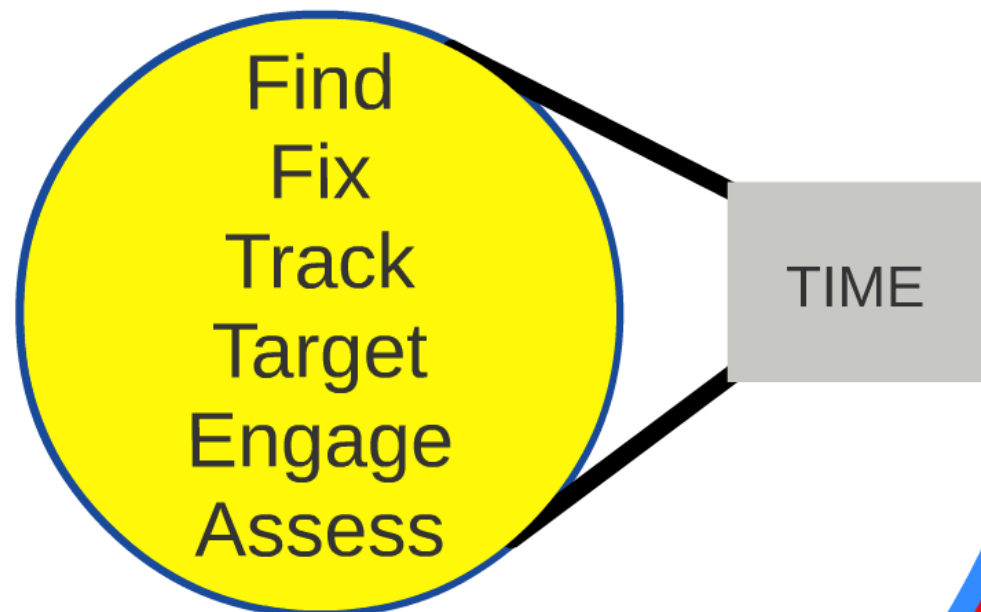
PUBLIC RELEASE

DSTL/CP114122



Ministry  
of Defence

# The Military Chain

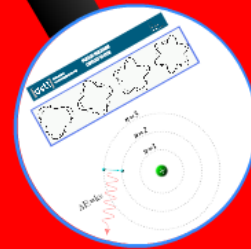


[dstl]

25 March 2019  
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Ministry  
of Defence



05 March 2019  
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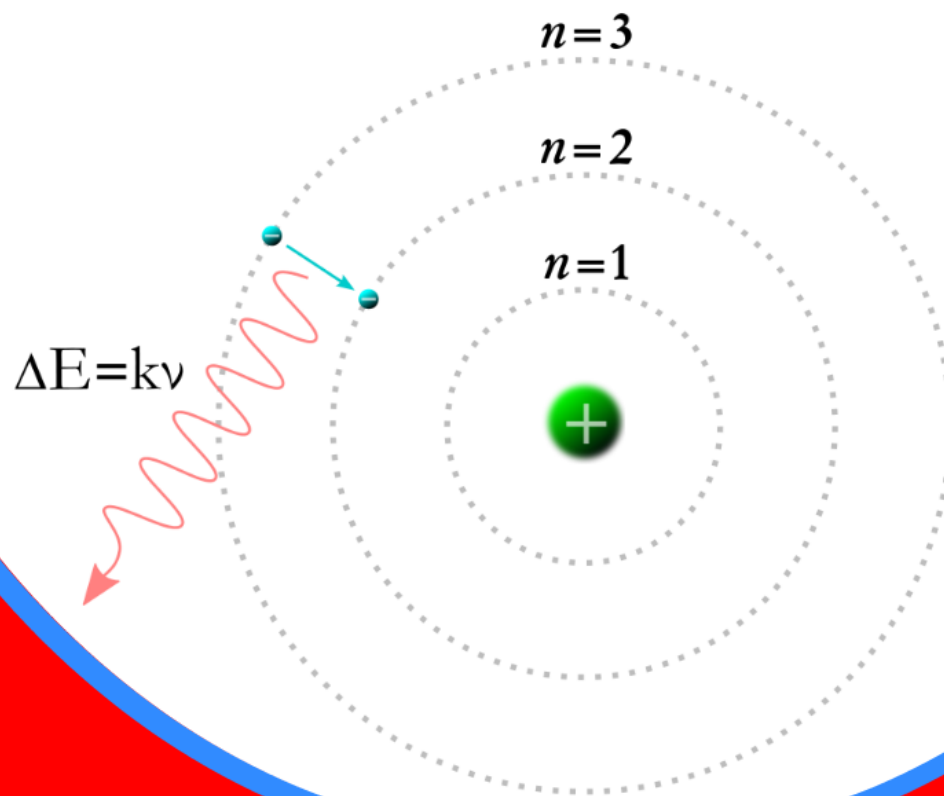
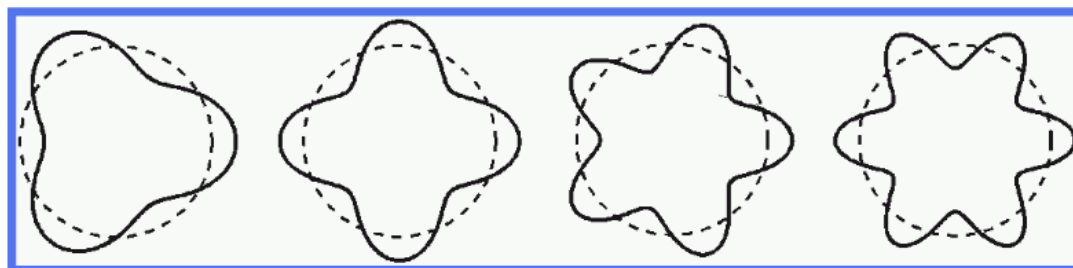
  
Ministry  
of Defence

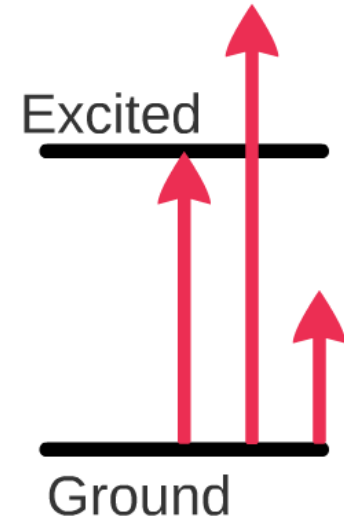
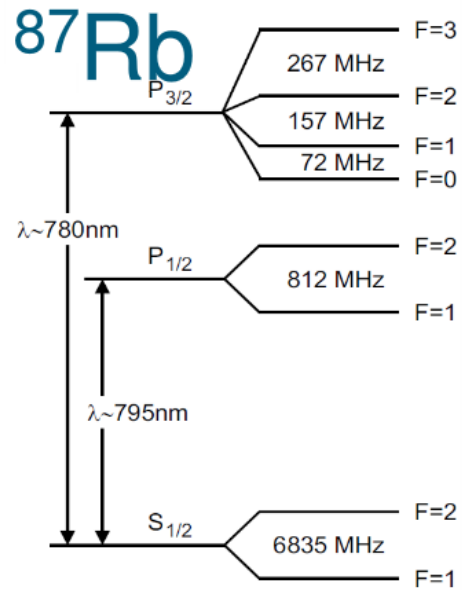
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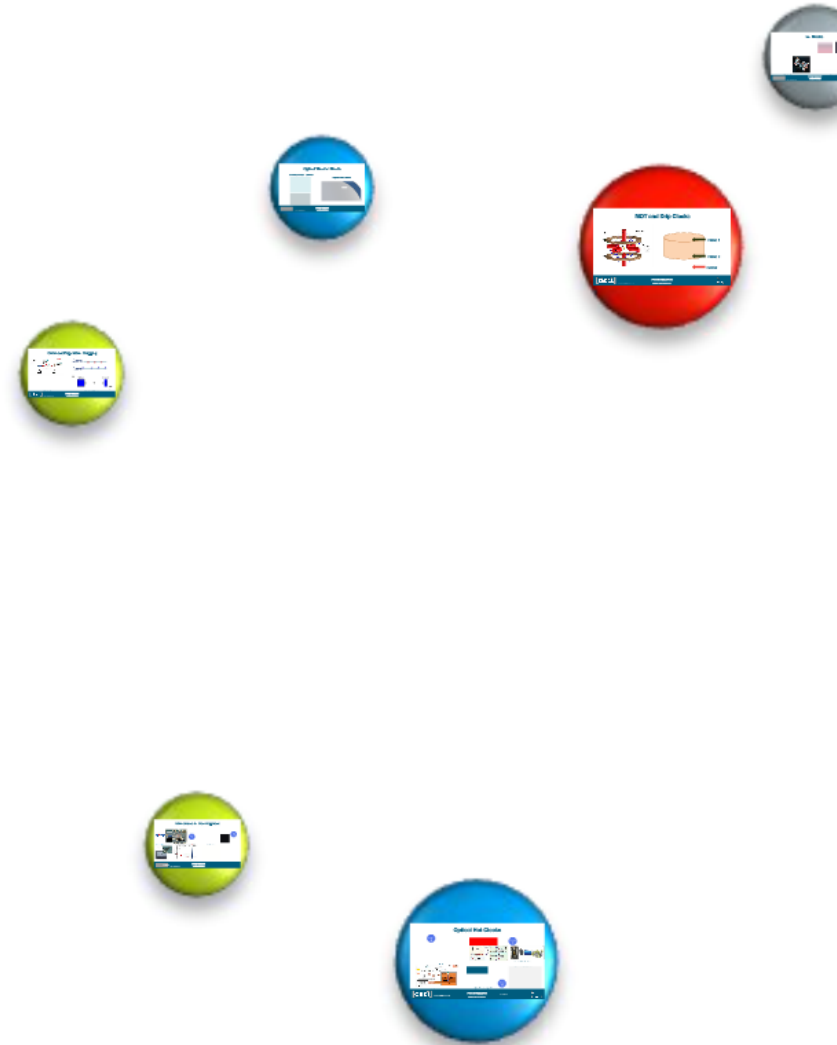
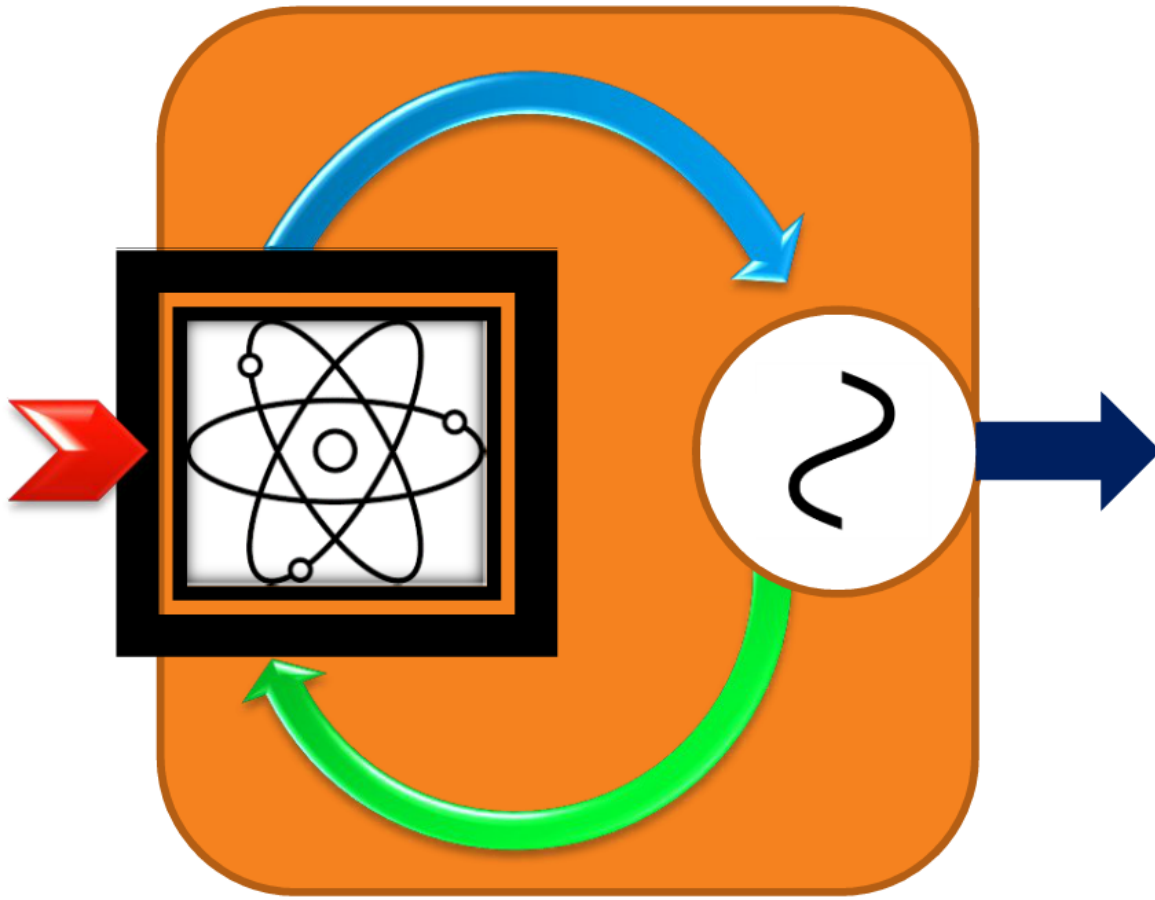
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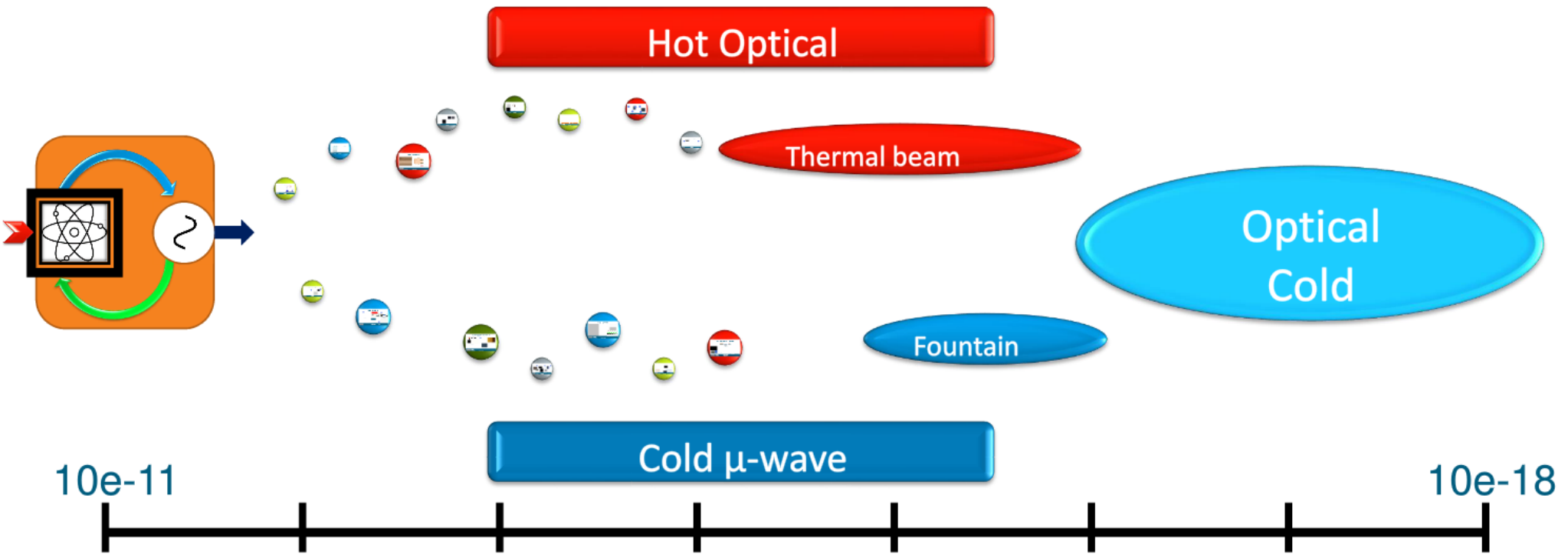
Ministry  
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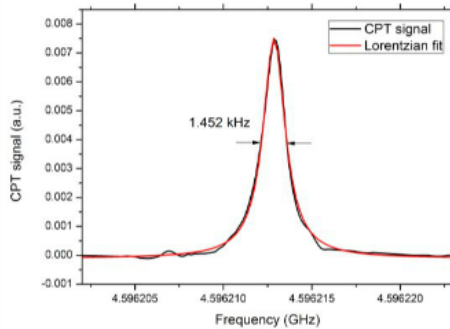
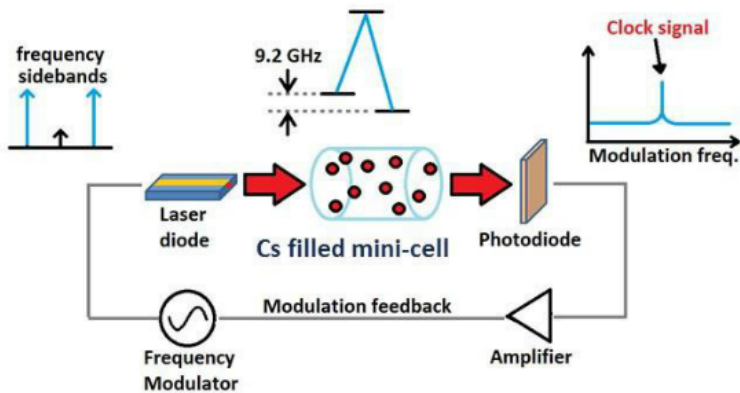


# Legacy to Future Performance

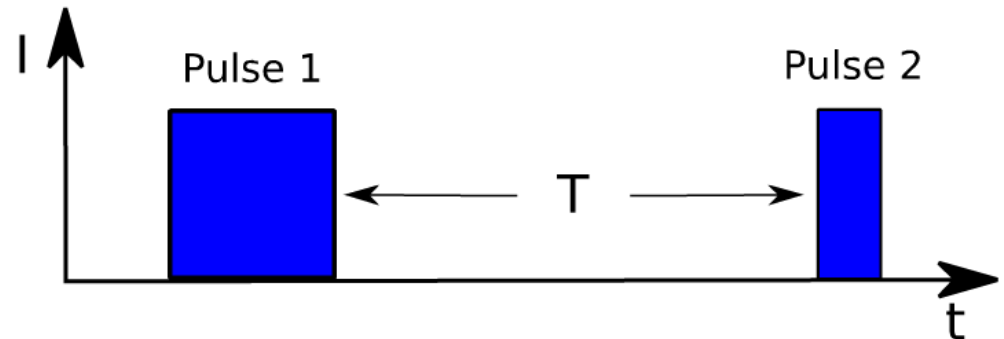
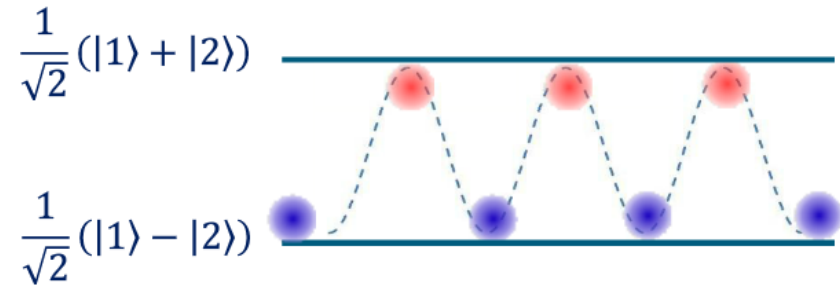




# Coherent Population Trapping



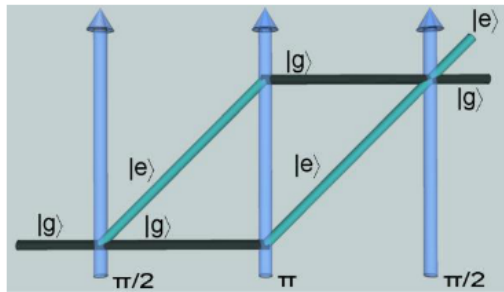
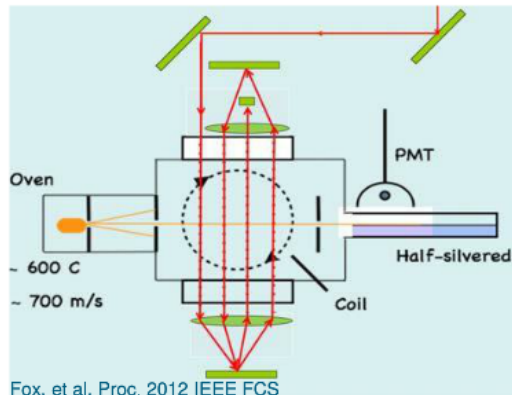
Courtesy of Patrick Gill, NPL



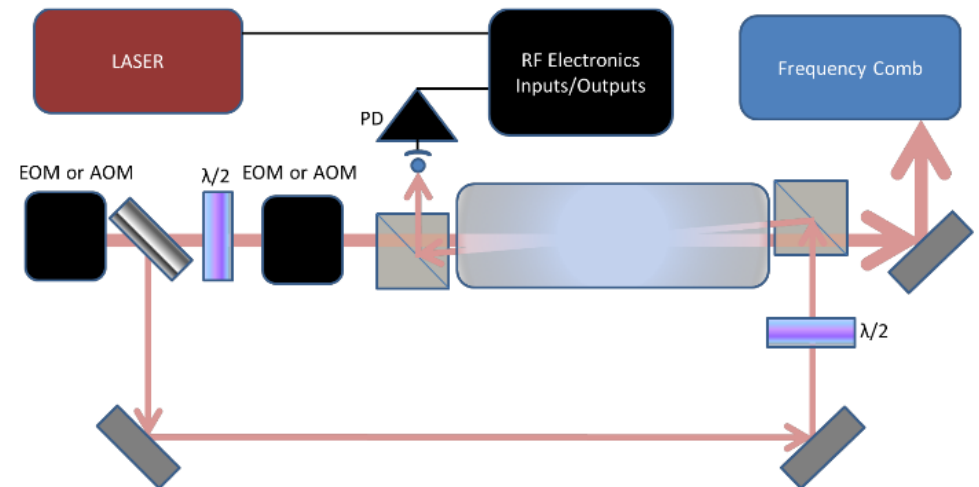
Courtesy of Erling Riis, Strathclyde University

# Optical Thermal Clocks

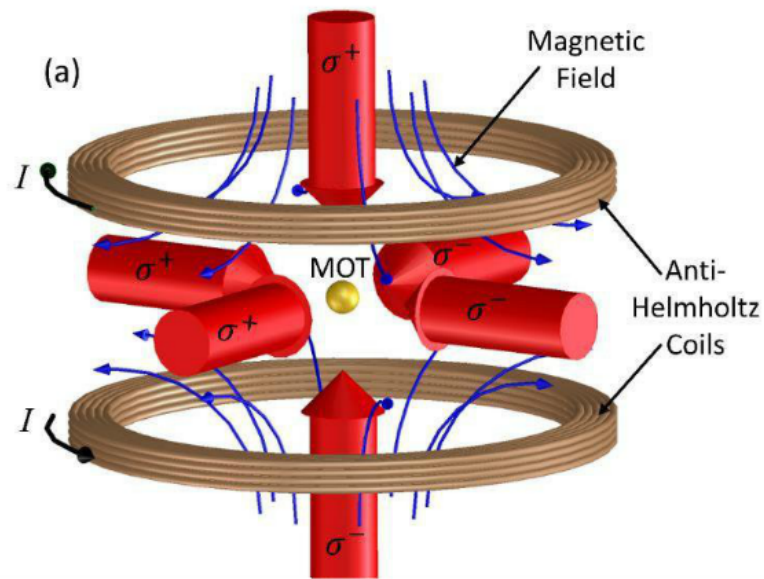
## Thermal Beam Clocks



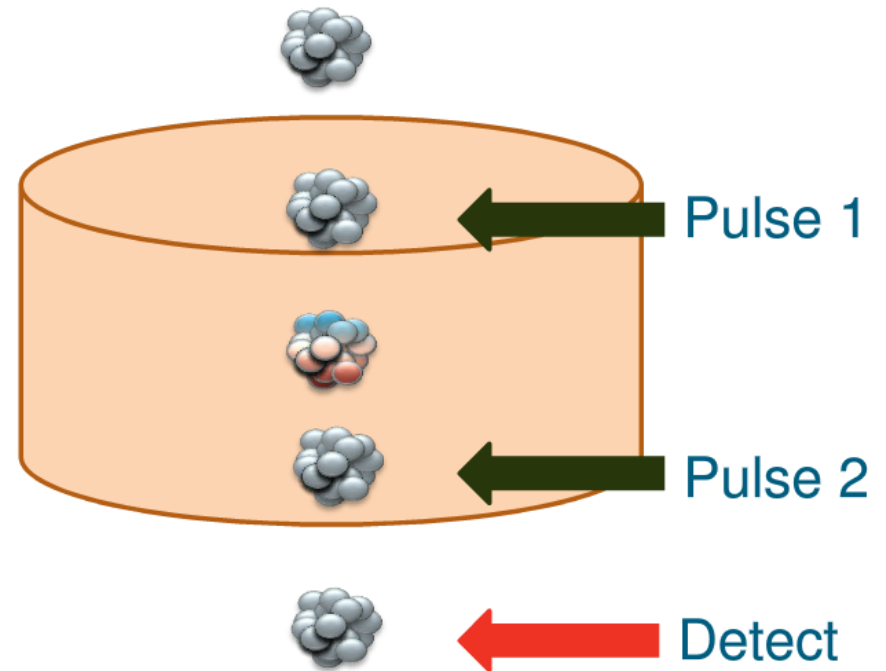
## Vapor Cell Clocks



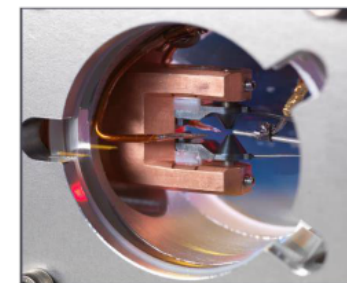
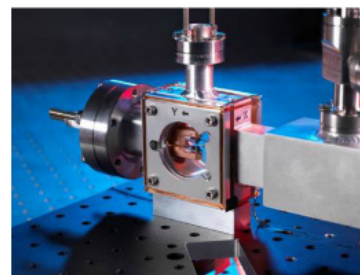
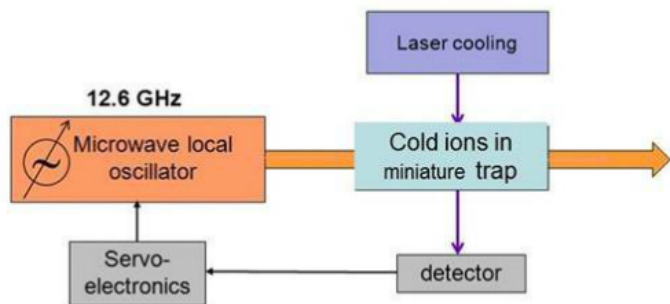
# MOT and Drip Clocks



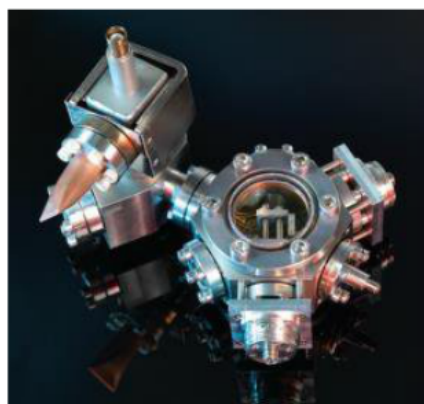
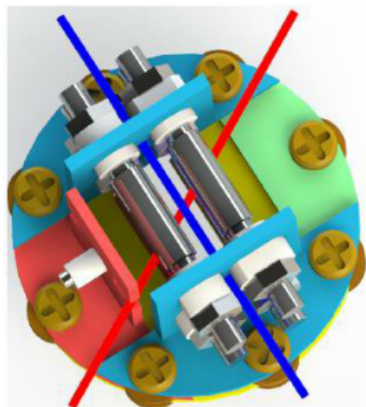
Moclelland et al. App. Phys. Rev. 2015



# Ion Clocks



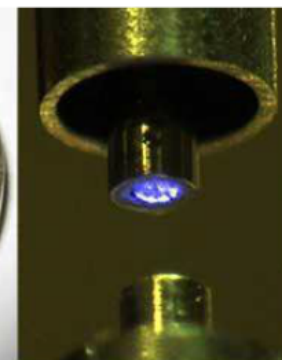
Courtesy of Patrick Gill, NPL



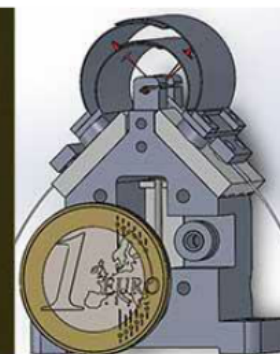
Courtesy of Patrick Gill, NPL



Trap electrode



Ion trap with integrated fibre



Fibre integrated ion trap

Courtesy of Matthias Kellier, University of Sussex

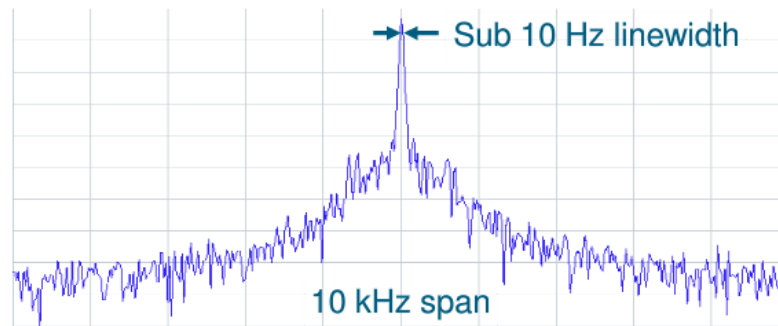
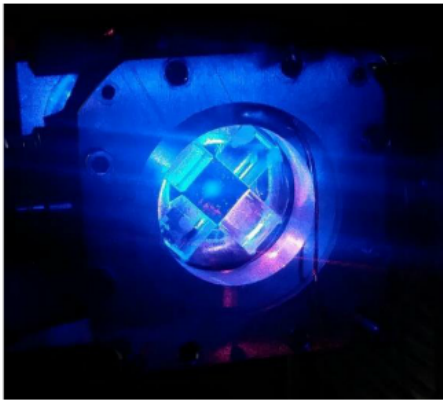
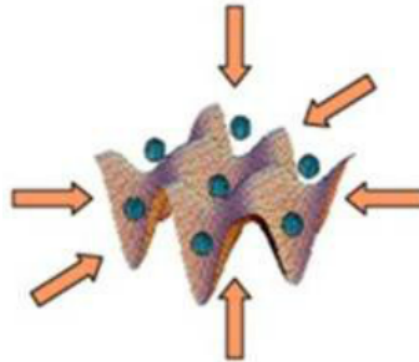
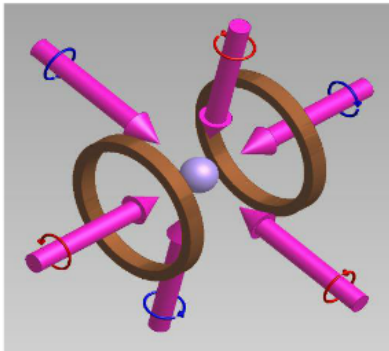
[dstl]

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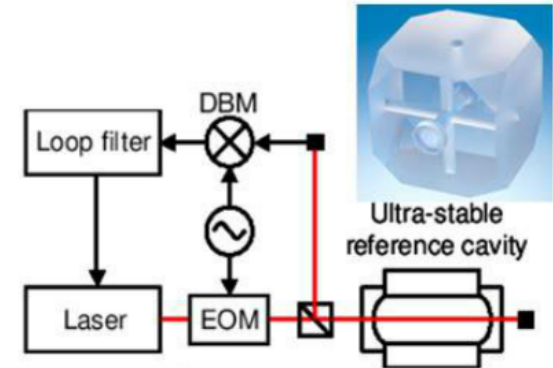
PUBLIC RELEASE  
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of Defence

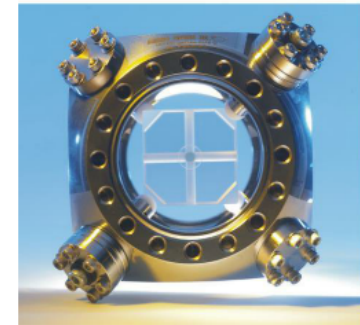
# Lattice Clocks



Courtesy of Yeshpal Sing, University of Birmingham



Courtesy of Patrick Gill, NPL



# Atomic Clock Difficulty



## Vacuum

V = 1  
HV = 2  
UHV = 3



## Sources

C = 1  
LL = 2  
Rest = 3



## Lasers

More = PAIN

$$E \text{ SCALE} = \text{Vacuum} * \text{Sources} * \# \text{Lasers}$$

# Microwave Available

E1  
~k\$



[www.thinksrs.com](http://www.thinksrs.com)

E10  
>100k\$



[www.muquans.com](http://www.muquans.com)

E6  
>100k\$



[www.microsemi.com](http://www.microsemi.com)

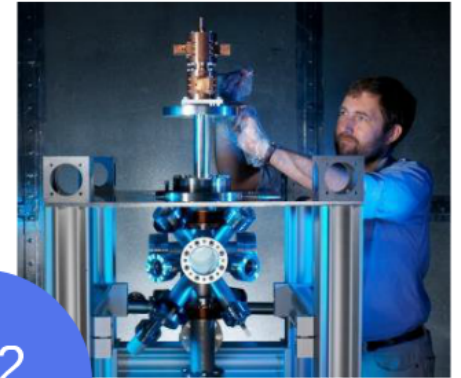
E3  
~100k\$



[www.microsemi.com](http://www.microsemi.com)

[www.oscilloquartz.com](http://www.oscilloquartz.com)

E12  
>M\$



[www.npl.co.uk](http://www.npl.co.uk)

[dstl]

27 March 2019  
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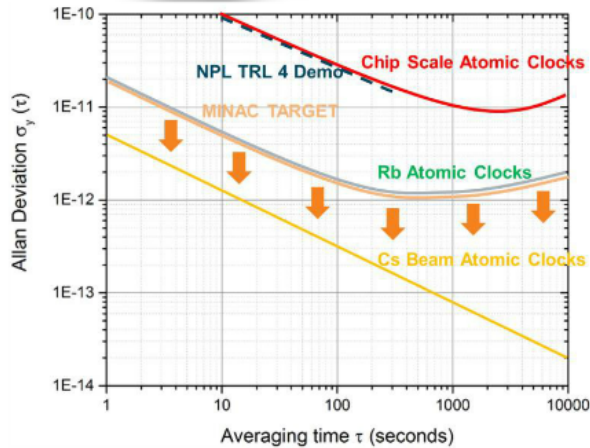
PUBLIC RELEASE  
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# Microwave Emerging



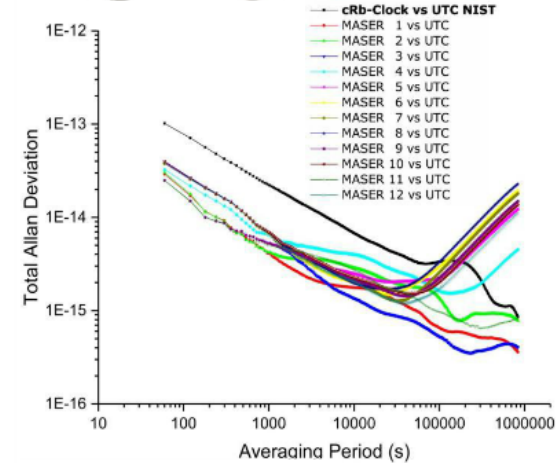
E1  
~1k\$



Courtesy of Teledyne e2v



E12  
~100k\$



Courtesy of Spectradynamics



26 March 2019  
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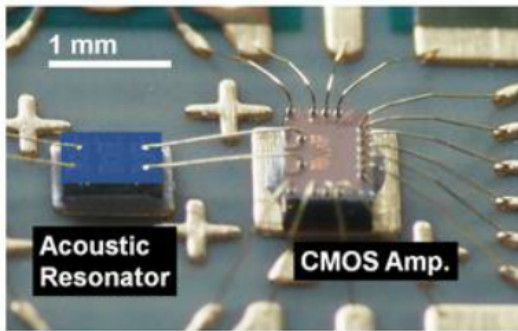
PUBLIC RELEASE  
DSTL/CP114122





# Microwave In Development

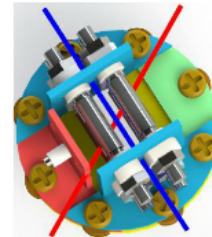
NICT



E2  
? \$

NPL  
National Physical Laboratory

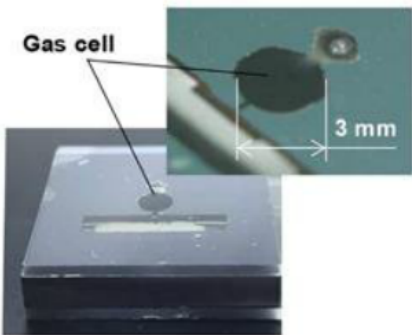
QMI  
Quantum Metrology Institute



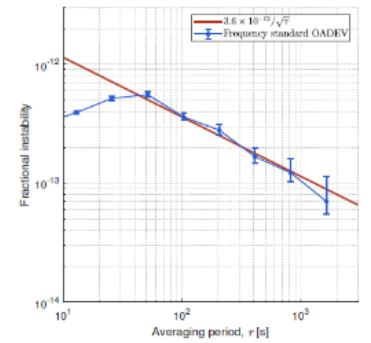
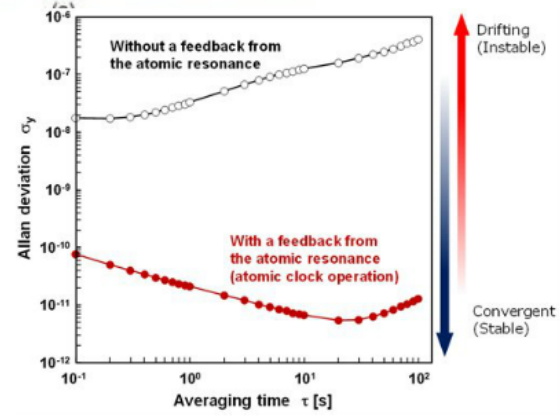
E36  
~100k\$

Courtesy of Patrick Gill

<https://www.nict.go.jp/en/press/2018/01/23-1.html>



(b)



[dstl] 21 March 2019

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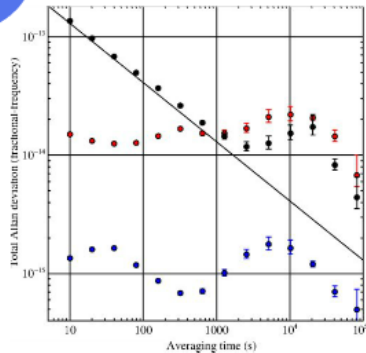
PUBLIC RELEASE  
DSTL/CP114122

Ministry of Defence

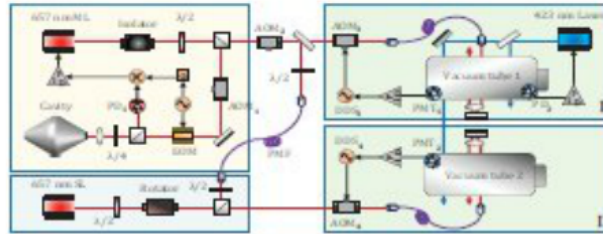
# Optical Hot Clocks



E3-4  
? \$



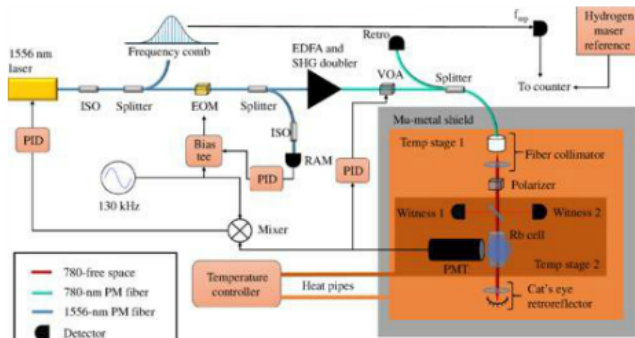
Martin et al. PRA (2017)



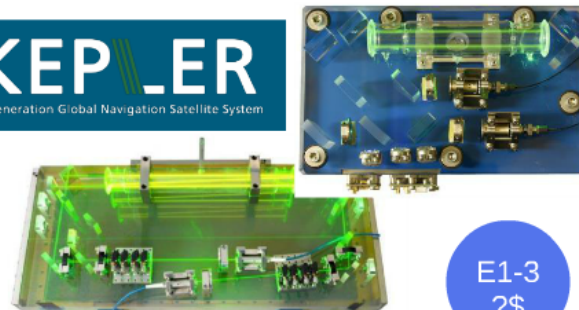
E12-15  
? \$



H Shang et al, Optics Express, 2017

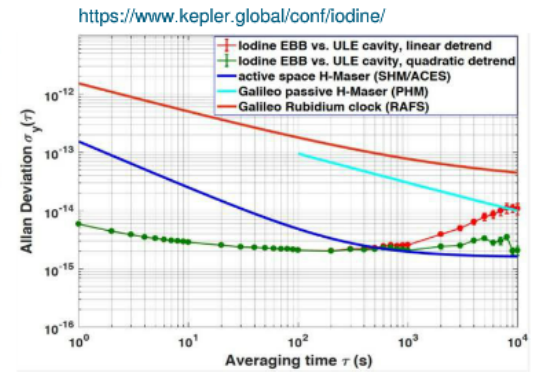


J. Burke, SPIE 2016



<https://www.dlr.de/irs/en/desktopdefault.aspx/tabid-11011/#gallery/26780>

E1-3  
? \$



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26 March 2019



# Portable(?) Optical Cold Clocks



UNIVERSITY OF BIRMINGHAM

E45  
>1M\$

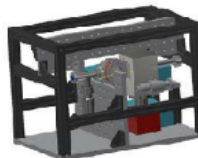


<https://www.ptb.de/cms/en/ptb/fachabteilungen/abt4/fb-43/ag-432/transportable-lattice-clocks.html>

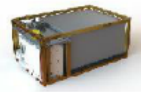
Courtesy of Yeshpal Singh



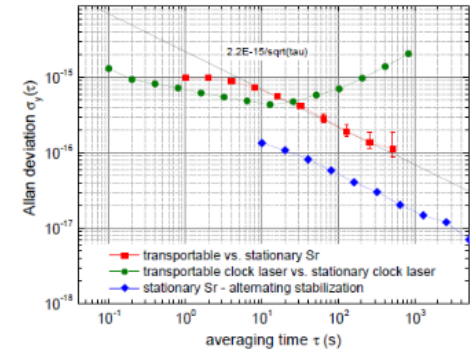
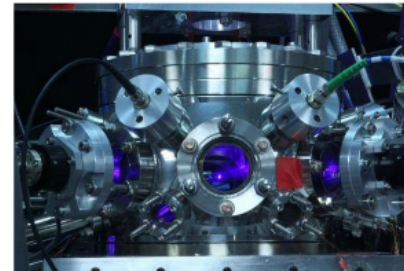
Control and Support Module (CSM)



Atoms Module (AM)



Clock Laser Module (CLM)



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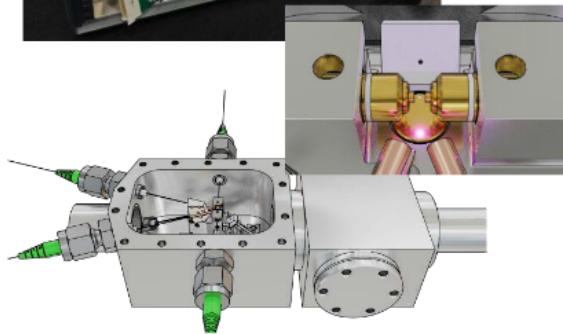


# Optical Ion Clocks



UNIVERSITY OF SUSSEX

E12-15  
~100k\$



Courtesy of Matthias Keller

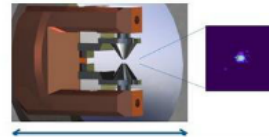
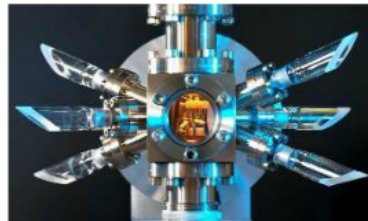


National Physical Laboratory



Quantum Metrology Institute

E12  
>1M\$

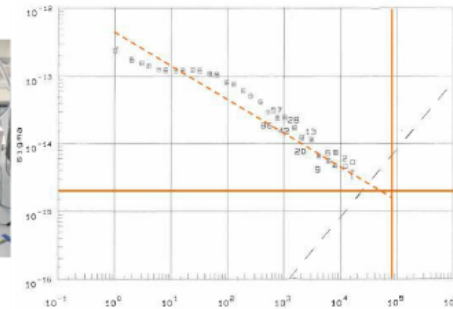
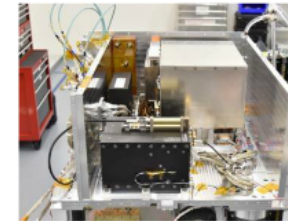
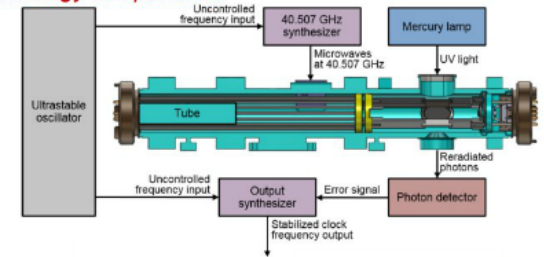


Courtesy of Patrick Gill



E4  
~100k\$

## Technology & Operation



TA Ely, et al, IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control · June 2018

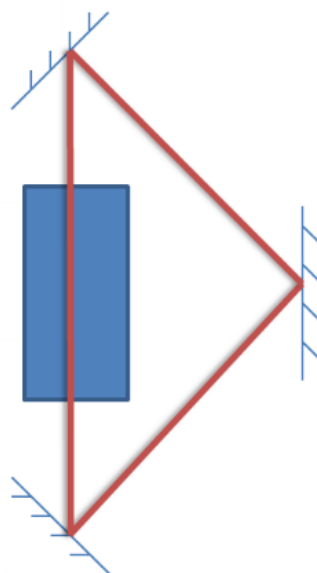
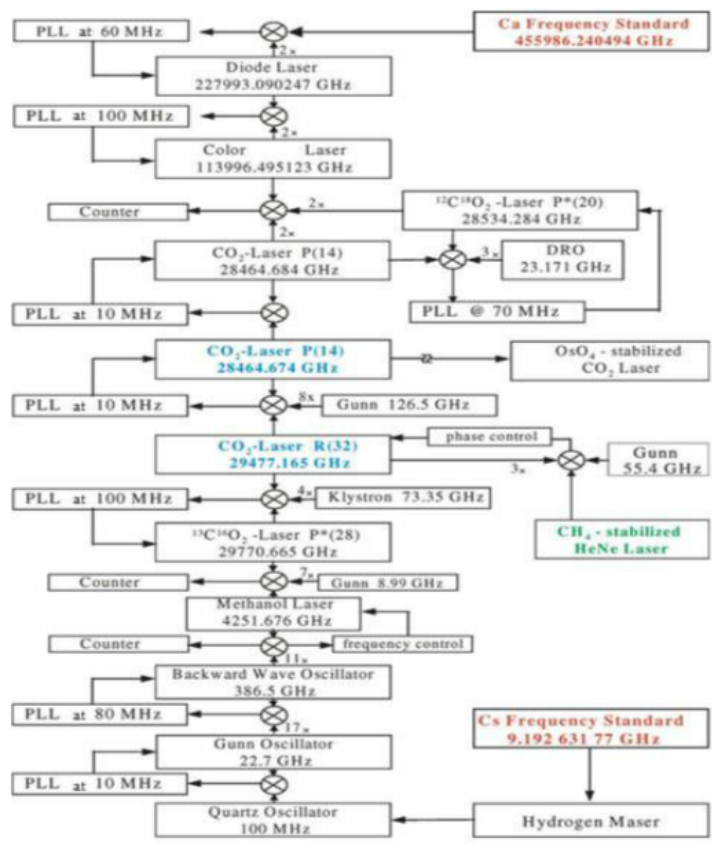


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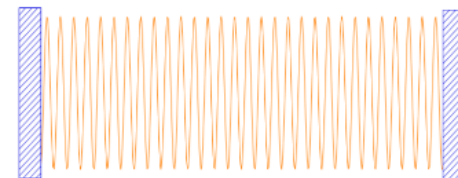
PUBLIC RELEASE  
DSTL/CP114122



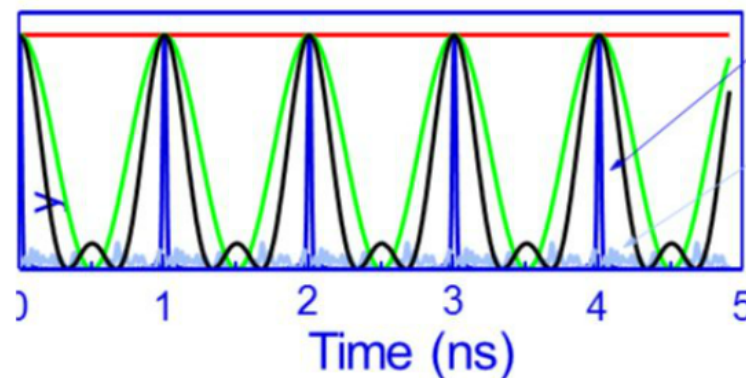
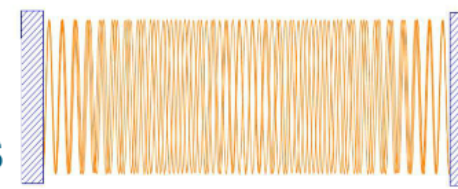
# Frequency Combs



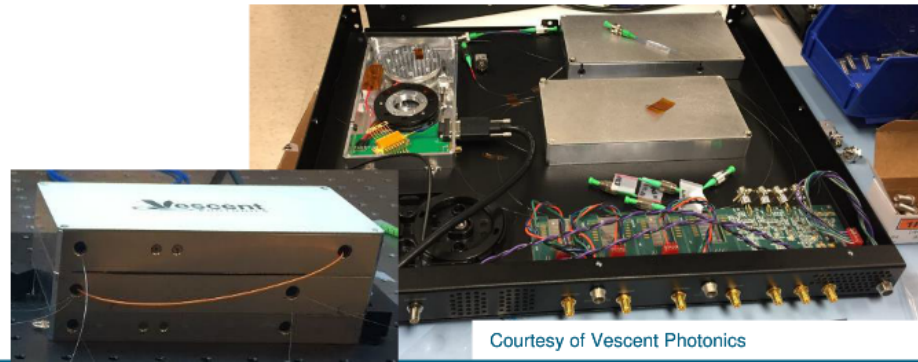
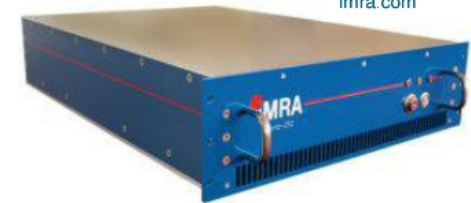
1 mode



30 modes



# Commercial Frequency Combs



[dstl]

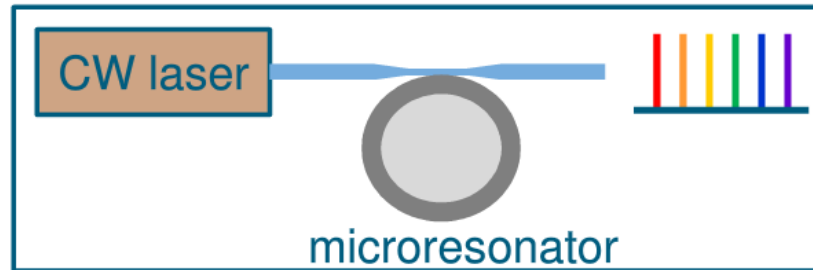
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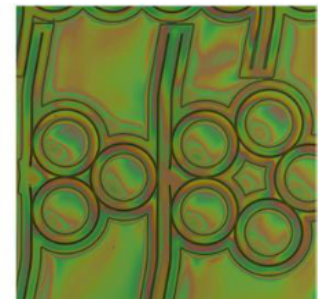
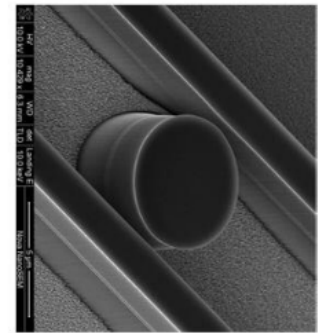
  
Ministry  
of Defence

# Developing Frequency Combs

**US**  
UNIVERSITY  
OF SUSSEX

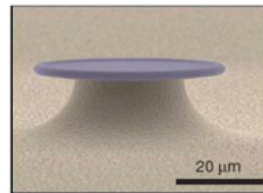


 University  
of Glasgow

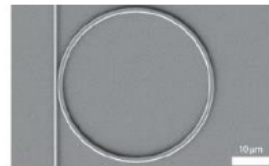


<https://www.gla.ac.uk/schools/engineering/research/divisions/ene/researchthemes/opto/srl/>

**NPL**  | **QMI**   
National Physical Laboratory | Quantum Metrology Institute



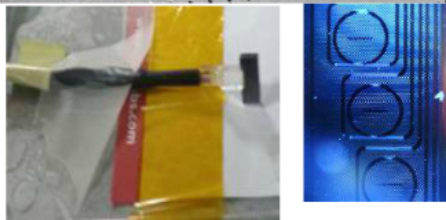
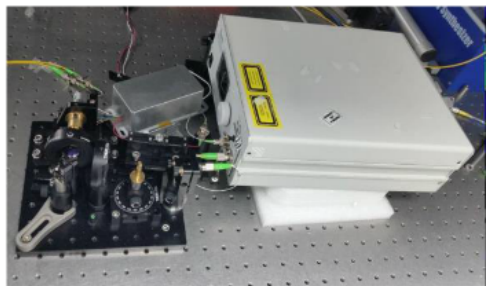
SiO<sub>2</sub> microtoroids,  
Del'Haye Nature (2007)



Si<sub>3</sub>N<sub>4</sub> ring resonators,  
Levy Nature Phot. (2007)



Fused quartz microrod,  
Del'Haye APL (2013)



Courtesy of Alessia Pasquazi, University of Sussex/

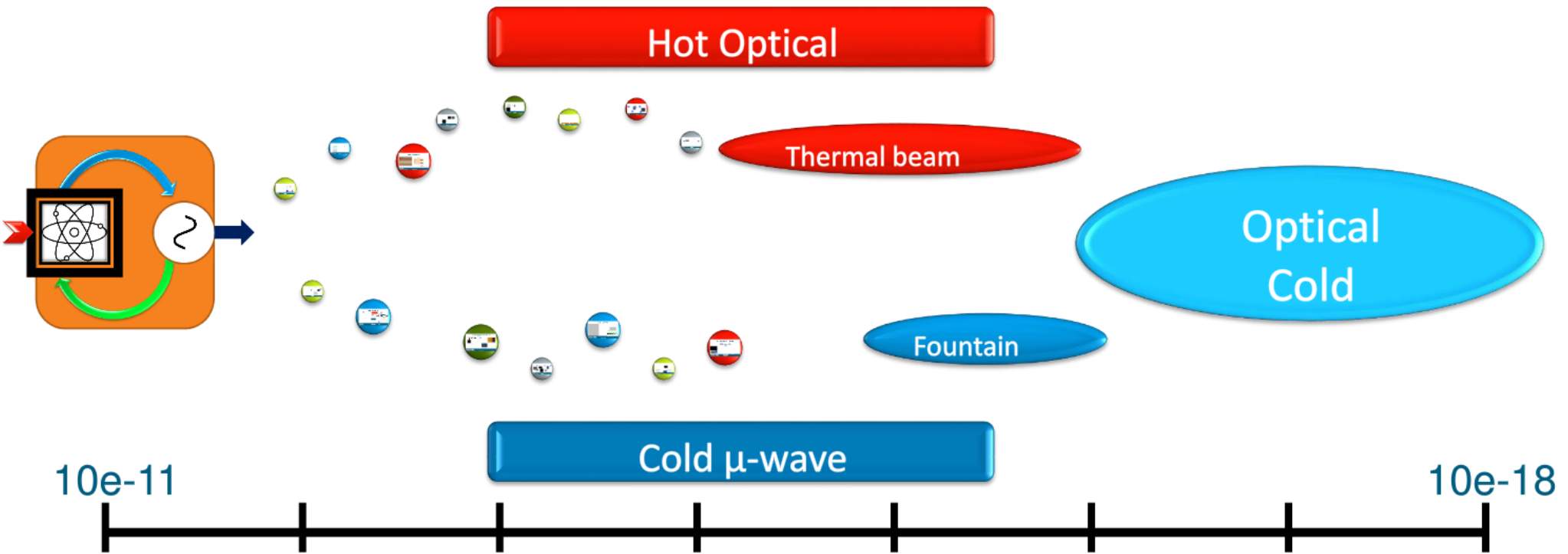
**[dstl]**

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# Legacy to Future Performance





# Thank You

