# Grating chips for quantum technologies

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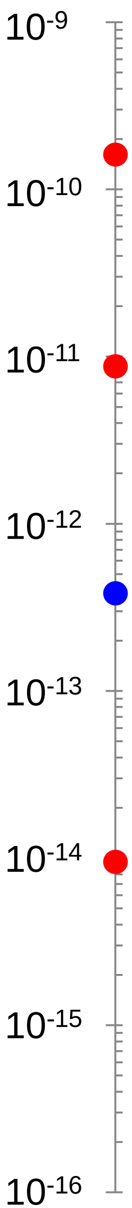
UK National Quantum Technology Hub Sensors and Metrology

esa European Space Agency

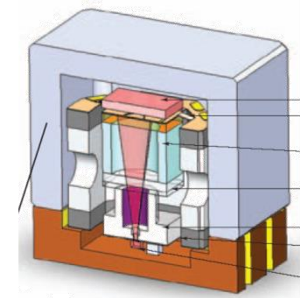
[dstl] EPSRC Innovate UK

# Why make things cold? *Accuracy*…

$$\sigma(\tau) = \frac{1}{\pi Q}\sqrt{\frac{T}{\tau}}\frac{1}{\sqrt{N}}$$

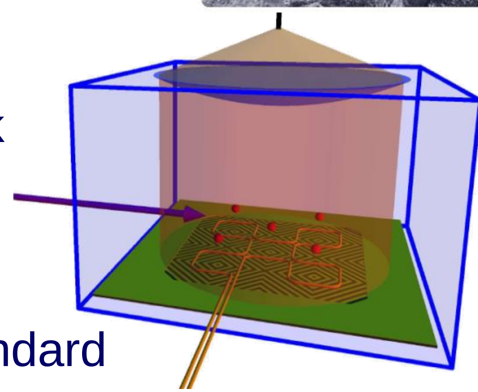



Consumer electronics

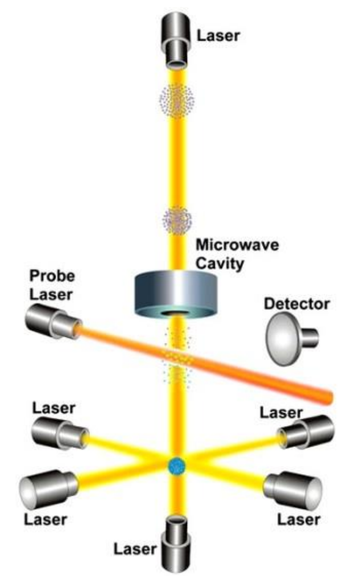



T&M tool

Miniaturised
cold atom clock

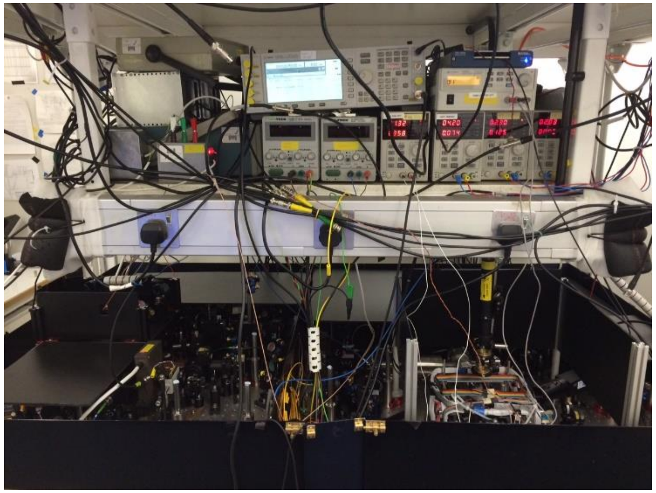


Primary standard

# Compact + rapid ultracold/BEC machines

Lab scale



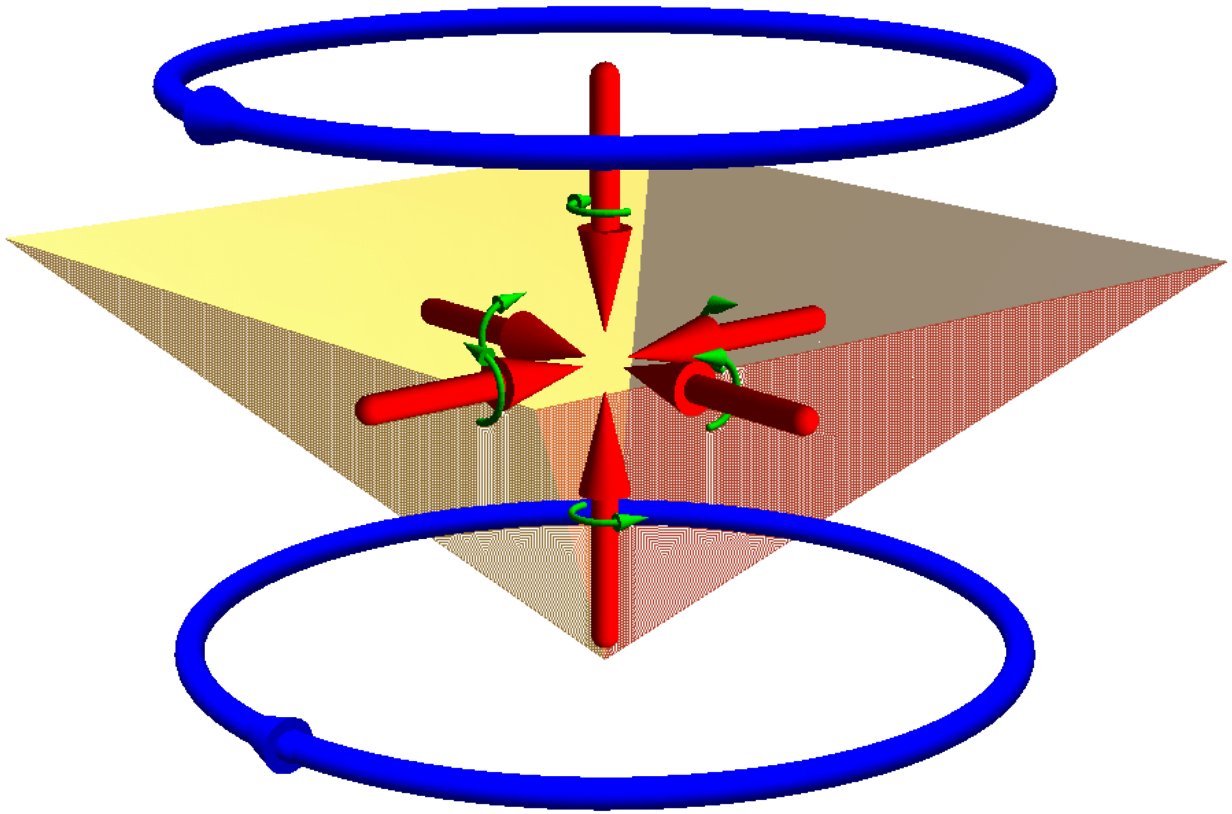
→

Portable

→

Hand-held/Space

# Laser cooling: ‘cubic’ geometries

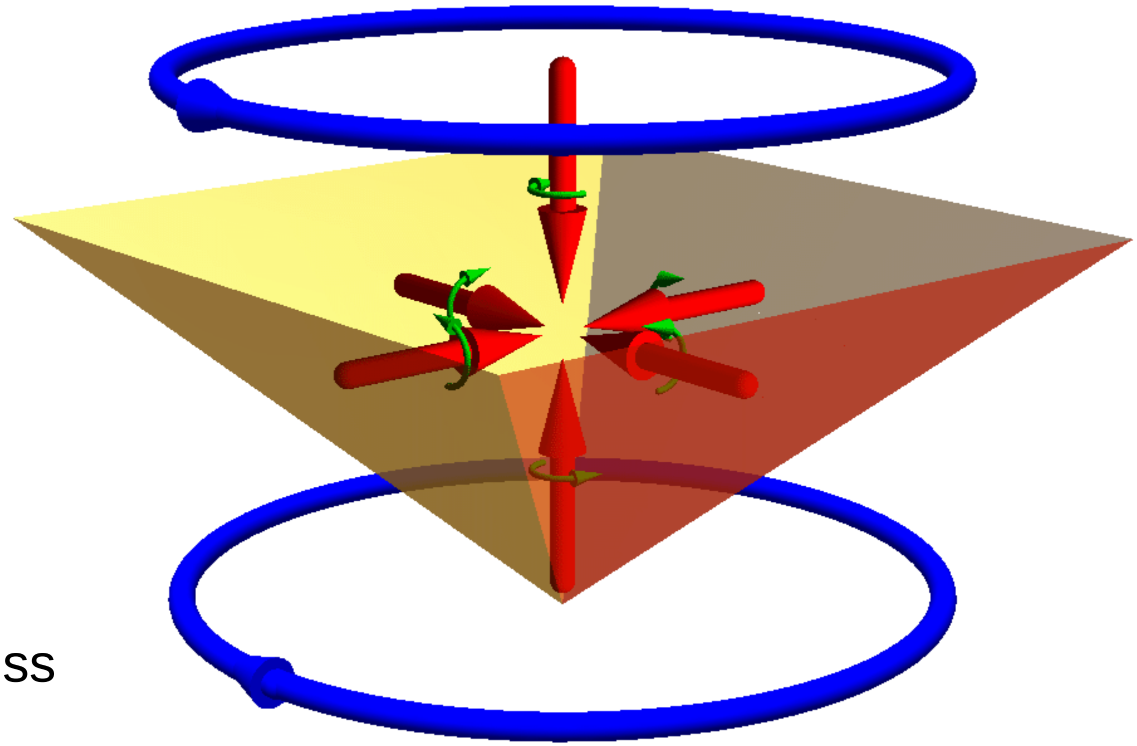


First MOT: Raab *et al*., PRL **59**, 2631 (1987), idea J. Dalibard.

First pyramid MOT: K. I. Lee *et al*., Opt. Lett. **21**, 1177 (1996).

Microfab pyramid: S. Pollock *et al*., Opt. Express **17**, 14109 (2009)

# Laser cooling: ‘cubic’ geometries



**Pyramid problems:**

Atoms hard to access

Must be in vacuum

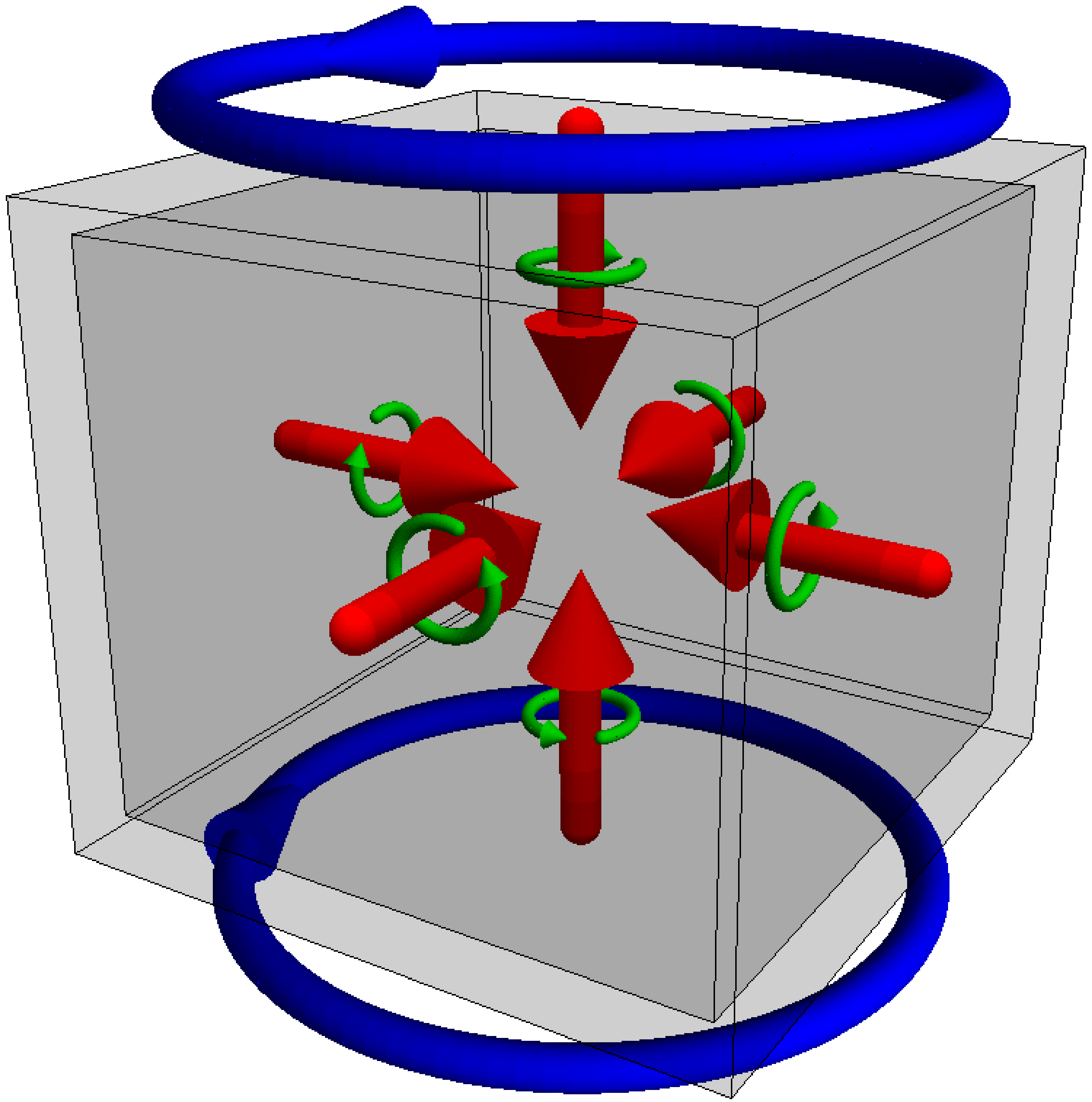
Pyramid apex angle critical

Shadow of atoms in the ‘reflected’ laser beam

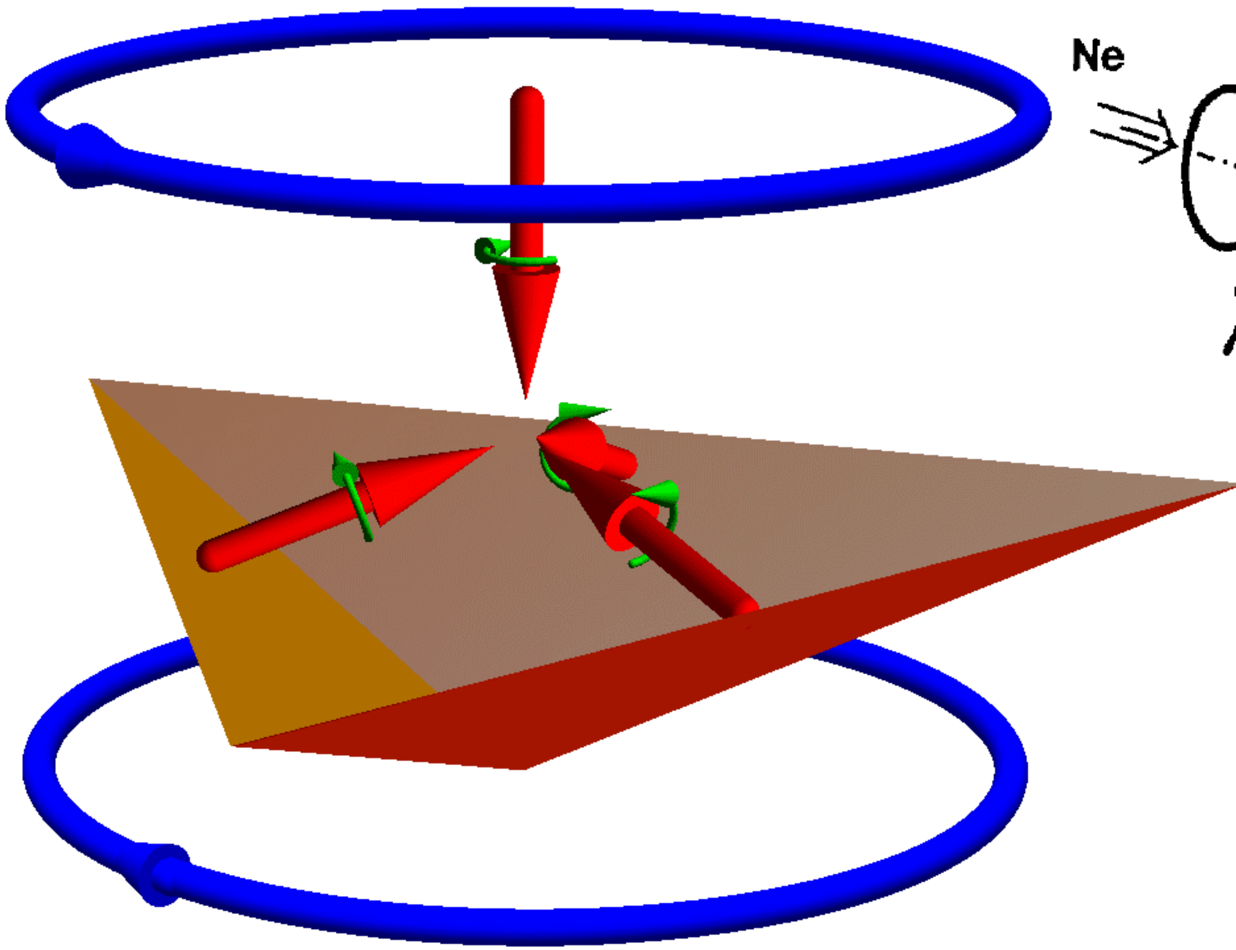
Hard to get low temperatures

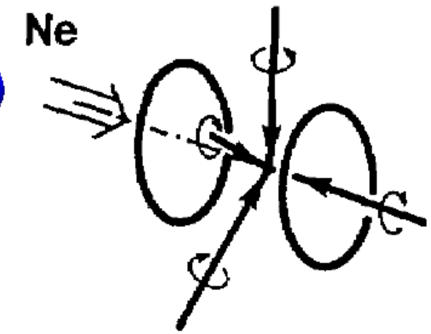
Hard to micro-fabricate/mass produce

# Minimum beams for an nD MOT? n+1



# Laser cooling: ‘tetra’ geometries






First 4-beam MOT: F. Shimizu *et al.*, Opt. Lett. **16**, 339 (1991).

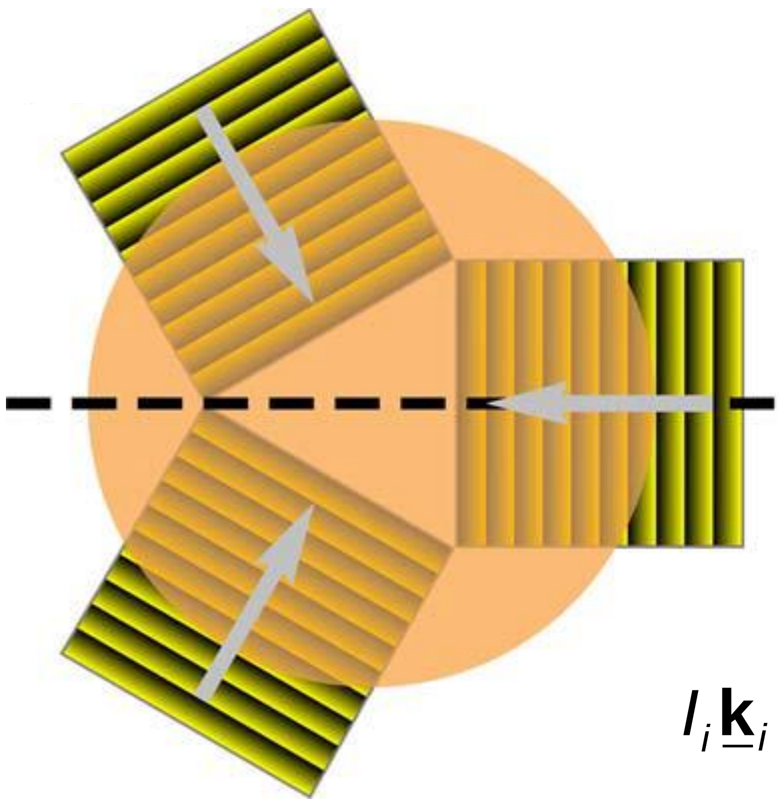
Tetrahedal pyramid MOT: M. Vangeleyn *et al*., Opt. Express **17**, 13601 (2009).

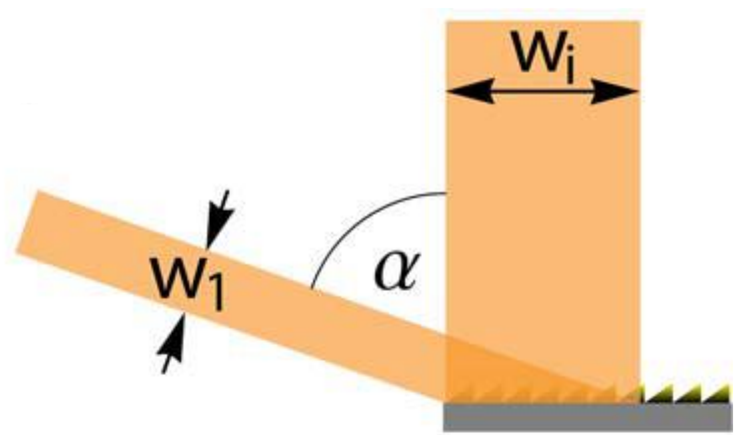
Pros: supra-plane imaging, no beam shadows in big MOTs, no apex/edge issues

# Grating MOT: totally planar geometry

Ideal for microfabrication – no ‘digging’ required

Intensity compression balances vertical **k** vector decrease... At all angles





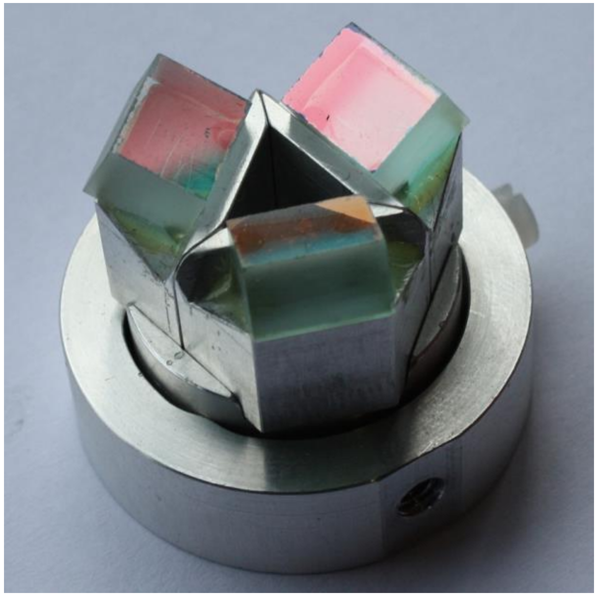

$$I_1 / I_i = R\, w_i / w_1 = R \sec\alpha$$

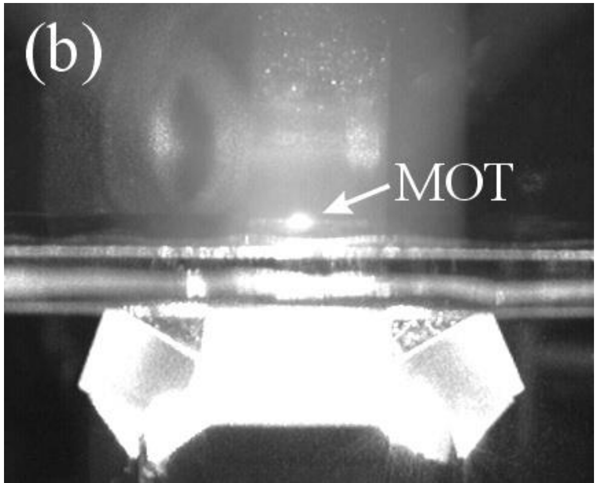
$$I_i \underline{\mathbf{k}}_i = N I_1 \underline{\mathbf{k}}_{\mathbf{1}} = N(R I_i \sec\alpha)(\underline{\mathbf{k}}_i \cos\alpha)$$

$$R = 1/N$$

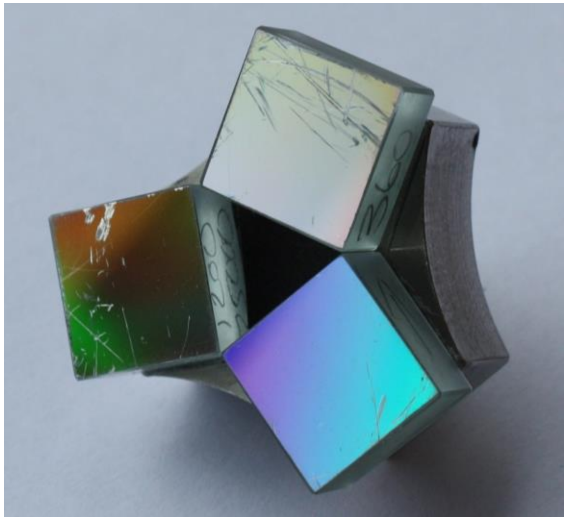
# Tetra/grating MOT - the experiment

Tetrahedral mirror MOT:
Opt. Express **17**, 13601 (2009).

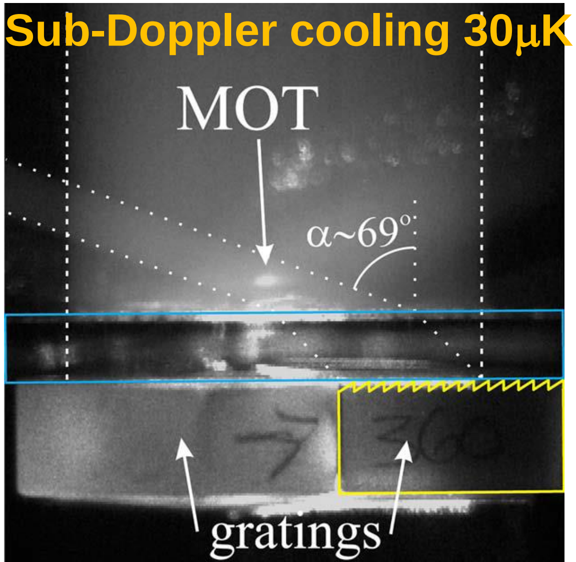




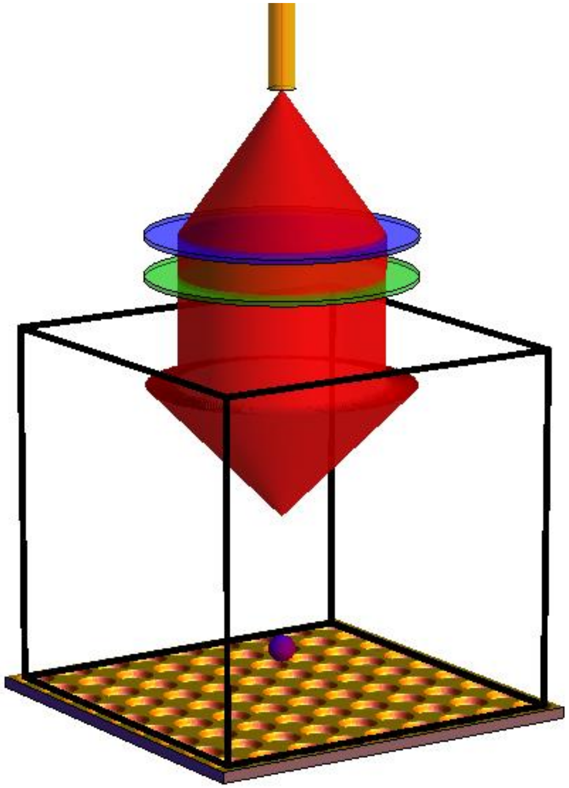

Tetrahedral grating MOT:
Opt. Lett. **35**, 3453 (2010).



Sub-Doppler cooling 30μK

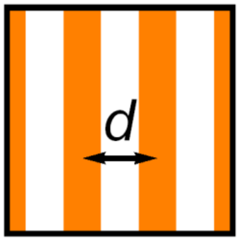


# MOT optical evolution



# Chip concept

Grating

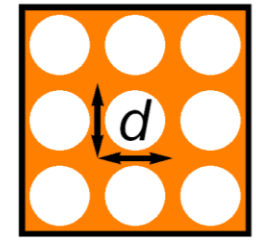


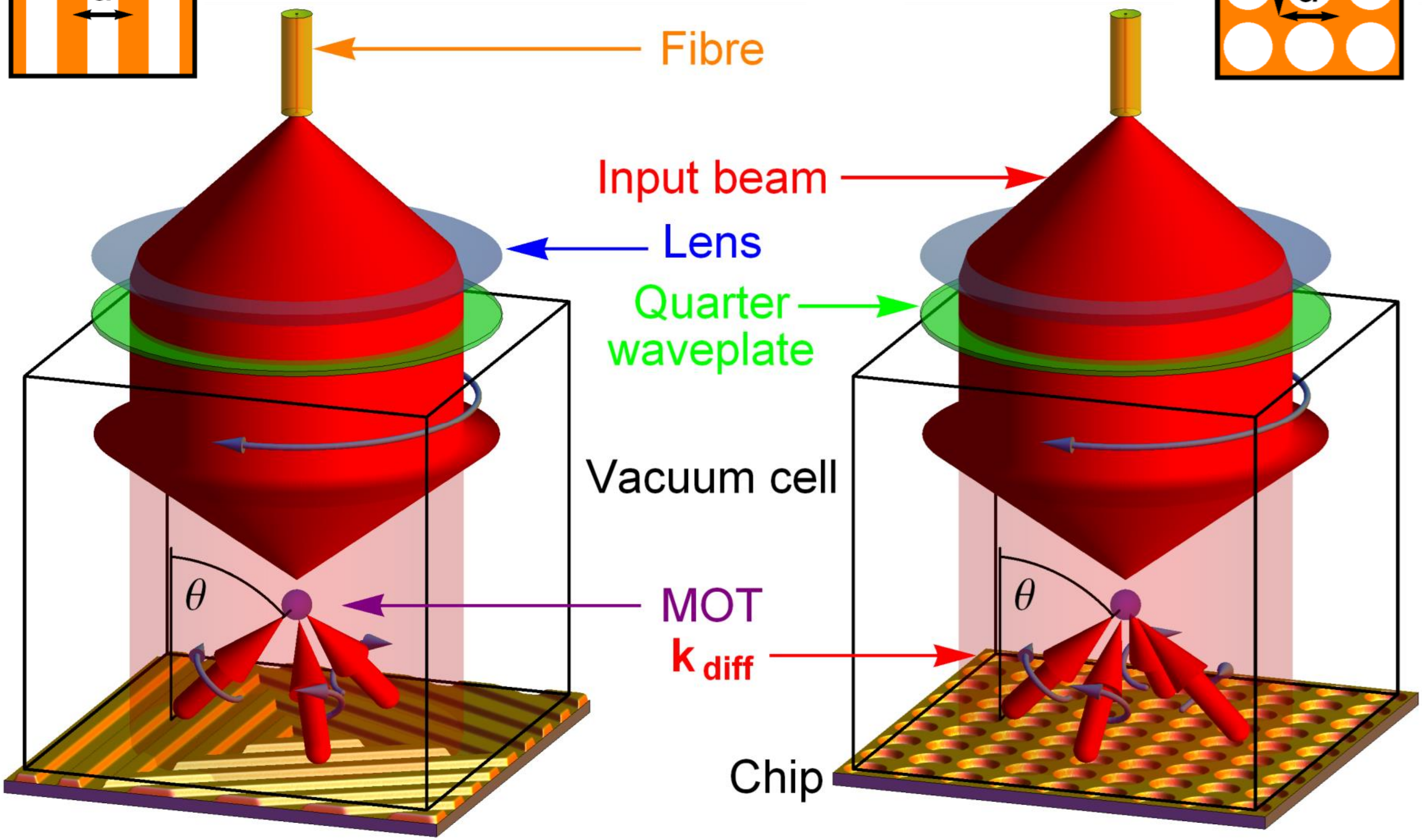

No 0[th] order: chip $\lambda/4$ deep

No high orders (> 1[st]):

$\lambda < d_{1D} < 2\lambda$ $\lambda < d_{2D} < 2^{1/2}\lambda$

Grating



# GMOT – chips?

Need ~500nm structures. Collaborations:

- **Alistair Sinclair + Patrick See (NPL)**

  e-beam lith GaAs

- **Charles Ironside (Glasgow) + KNT**

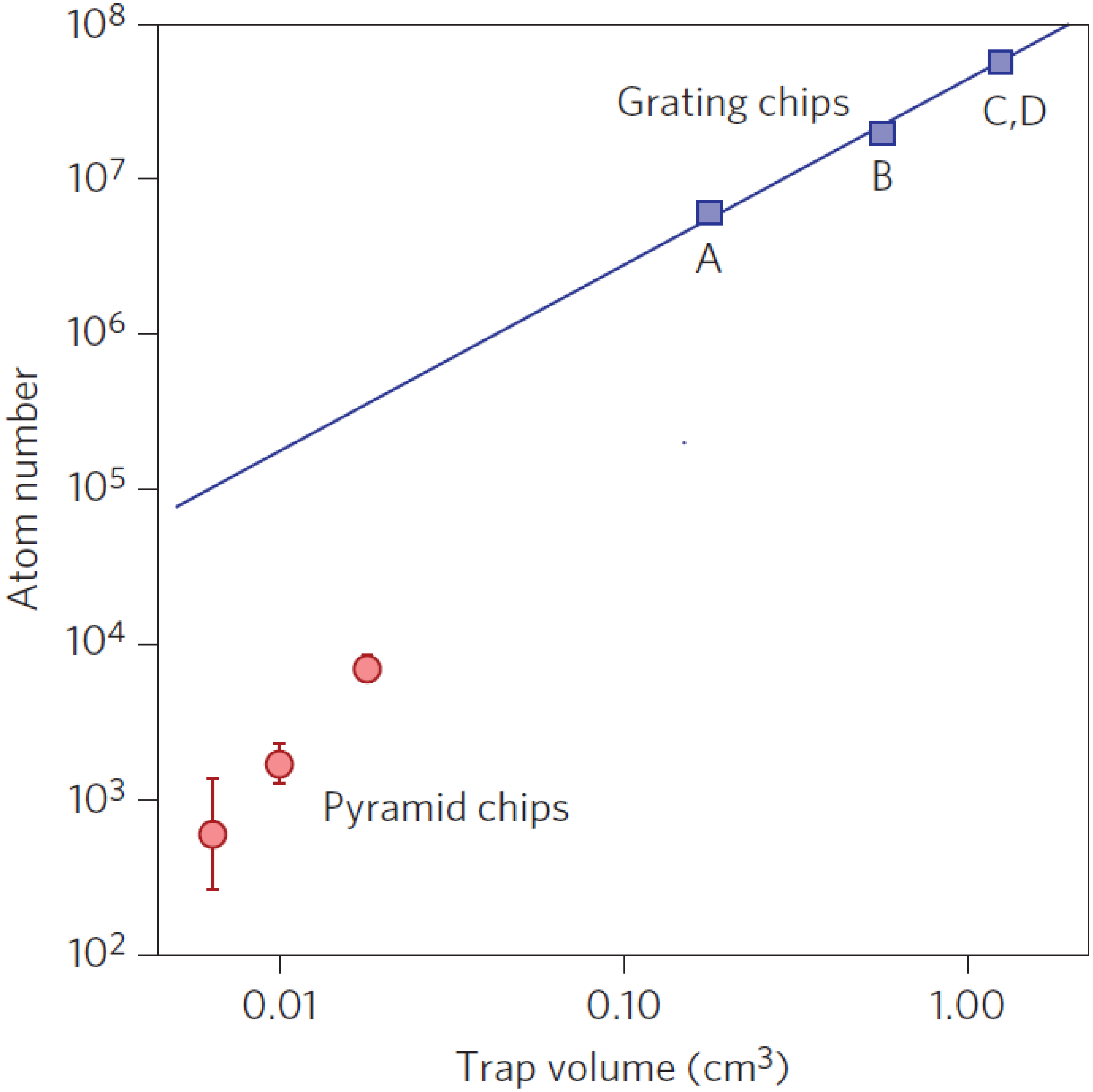
  e-beam lith Si *(ESA, Eamonn)*

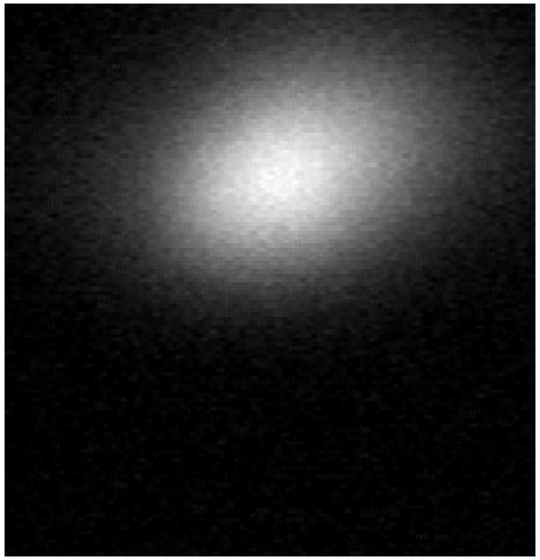
- **Joe Cotter and Ed Hinds (Imperial)**

  photo-lith Si


C.C. Nshii, M. Vangeleyn, J.P. Cotter, P.F. Griffin, E.A. Hinds, C.N. Ironside, P. See, A.G. Sinclair, E. Riis and A.S. Arnold, Nature Nanotech. **8**, 321 (2013).

# Comparison to other MOTs

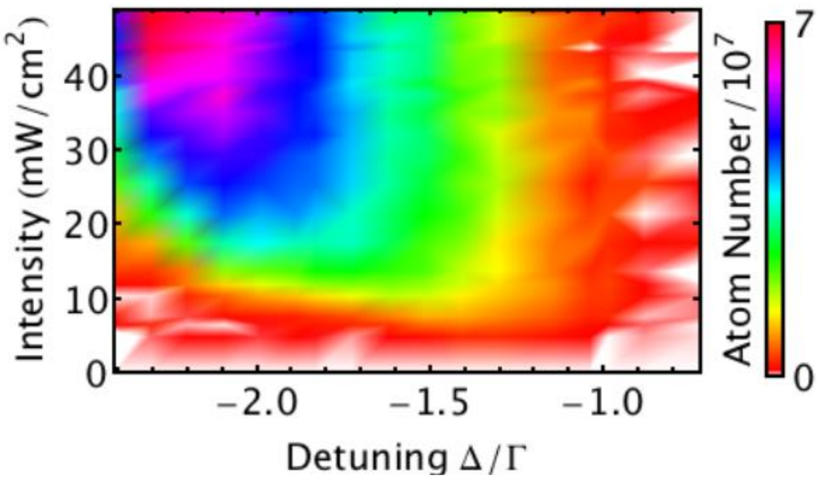


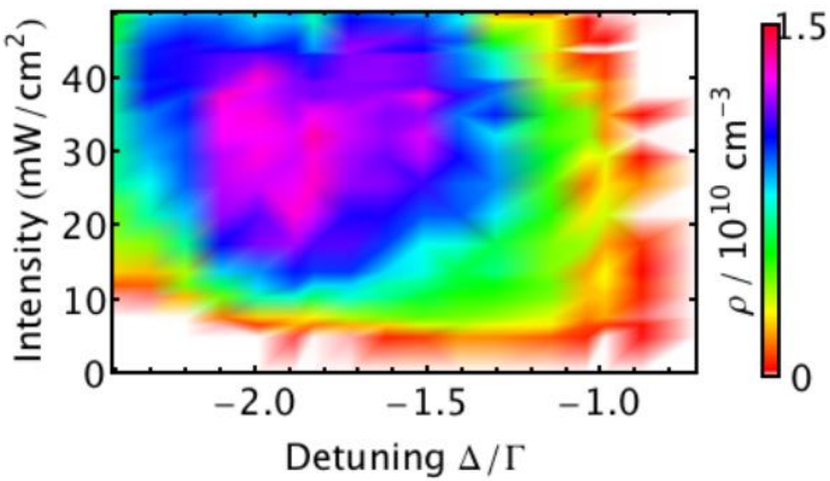



**Sub-Doppler temp.**
**$\{T_r, T_z\}$={50,60}μK**
**<140μK…but $N$~$10^6$**

***N* same as 6-beam MOT (1cm³ capture vol.).**

# GMOT new capabilities




Number and density of MOT measured by varying laser detuning and intensity

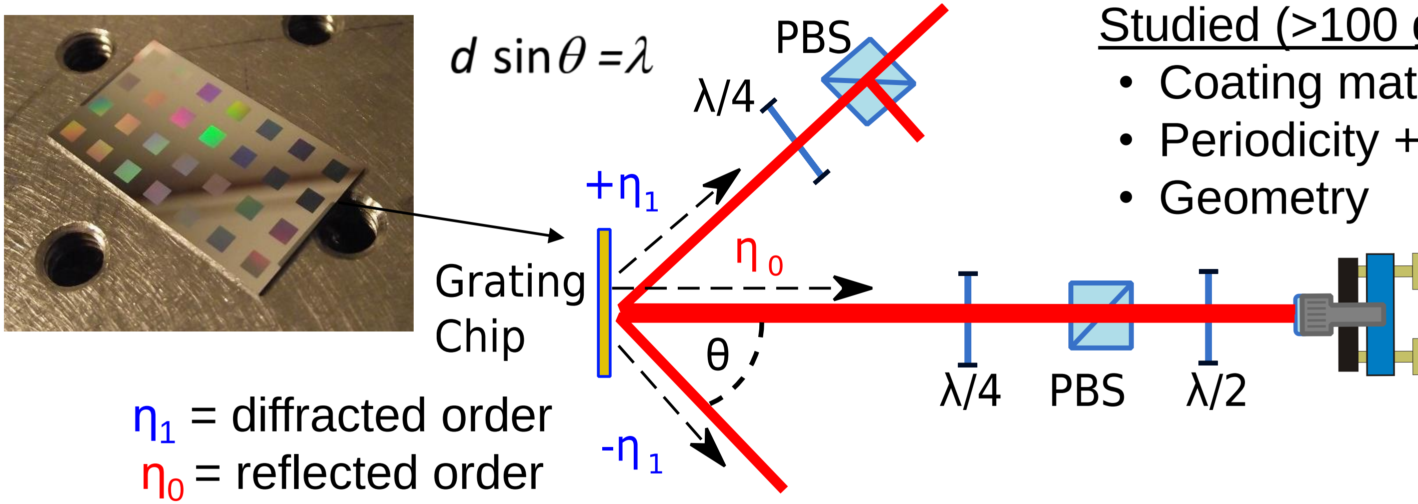
**MOT number:**
$N \approx \sim 3\text{x}10^7$

***AND***

**Molasses temperature:**
$T \approx$ 50 μK

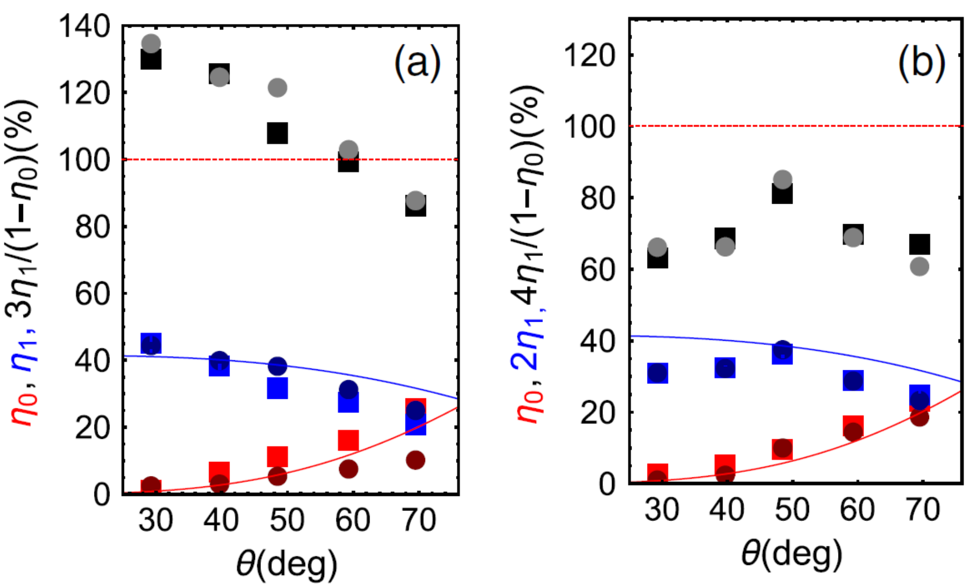
Phase space characterization paper, contrasting TRI12, TRI15 and CIR
J.P. McGilligan, P.F. Griffin, E. Riis and ASA, Opt. Express **23**, 8948 (2015).

# ESA project: optical grating characterisation

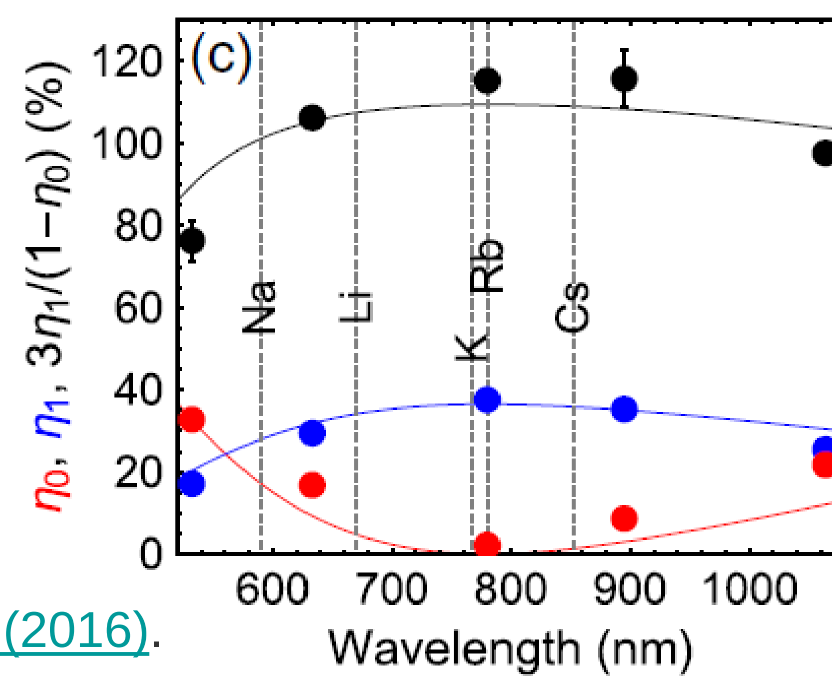



Studied (>100 gratings):

- Coating material+thickness
- Periodicity + duty cycle
- Geometry




**Surprising wavelength versatility**

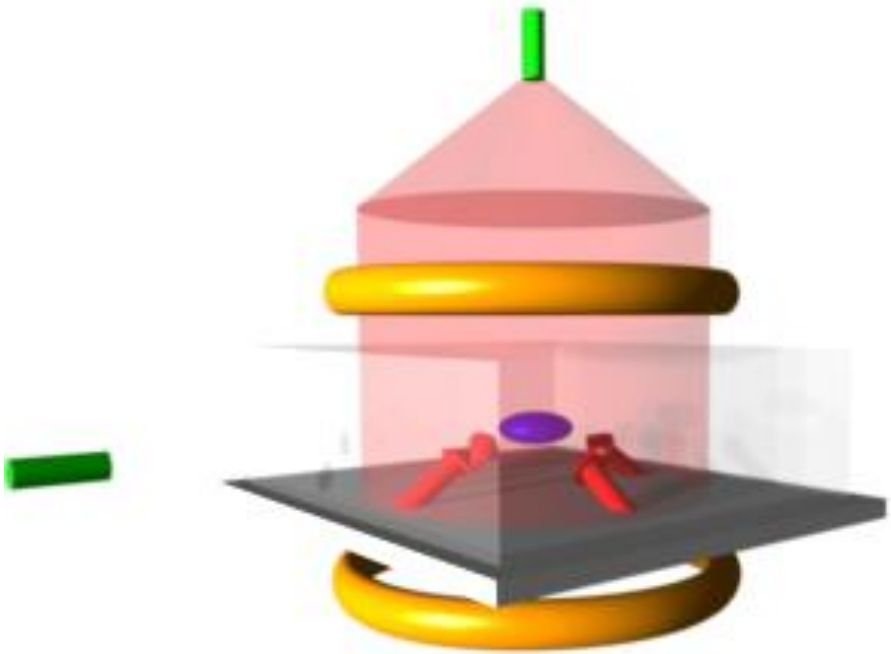



J.P. McGilligan *et al.*, JOSAB **33**, 1271-1277 (2016).

# Compact coherent measurement:

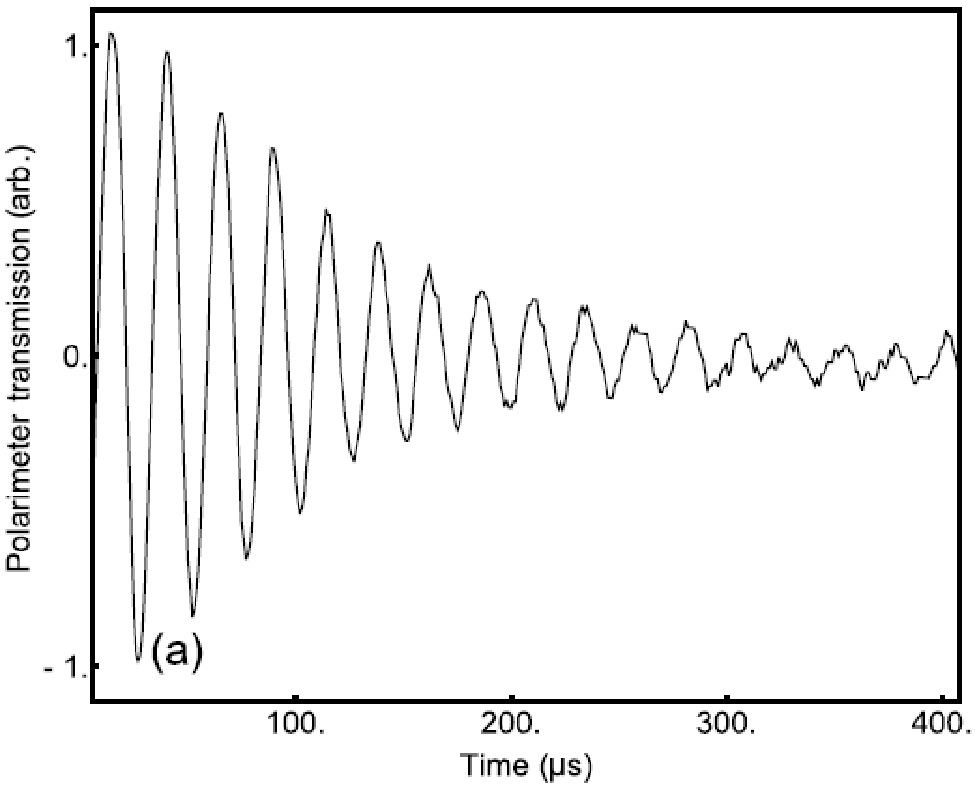
Why is this useful for a compact quantum device?

- Large optical access
- Simple single beam alignment
- Micro-fabricated
- Good Number
- Low Temperature
- Outside of vacuum

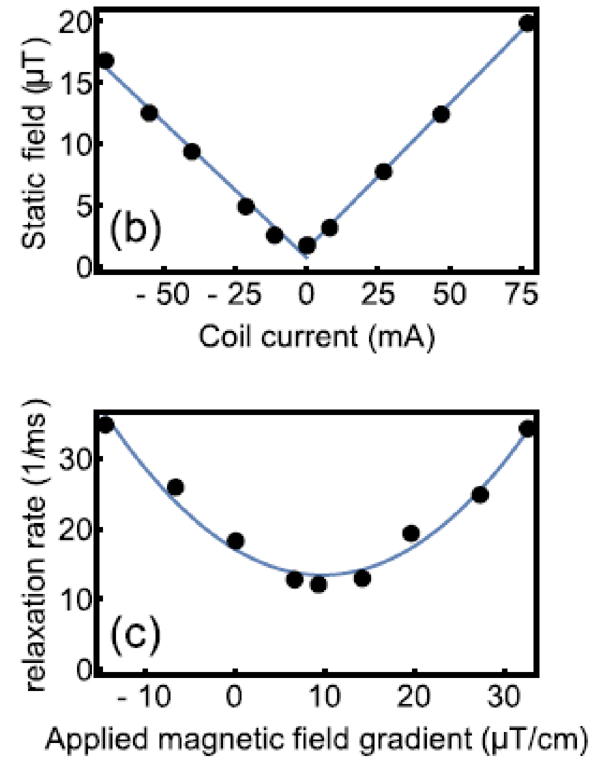


McGilligan *et al.* Scientific Reports **7**, 384 (2017).

# Compact coherent measurement




Spin precession measured from GMOT



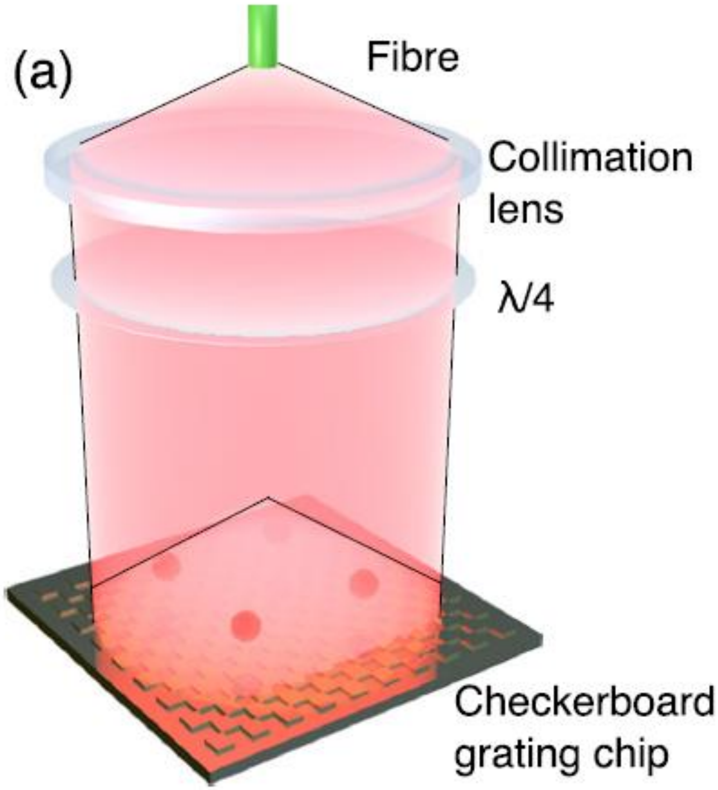

GMOT fields/relaxation rates vs coil current

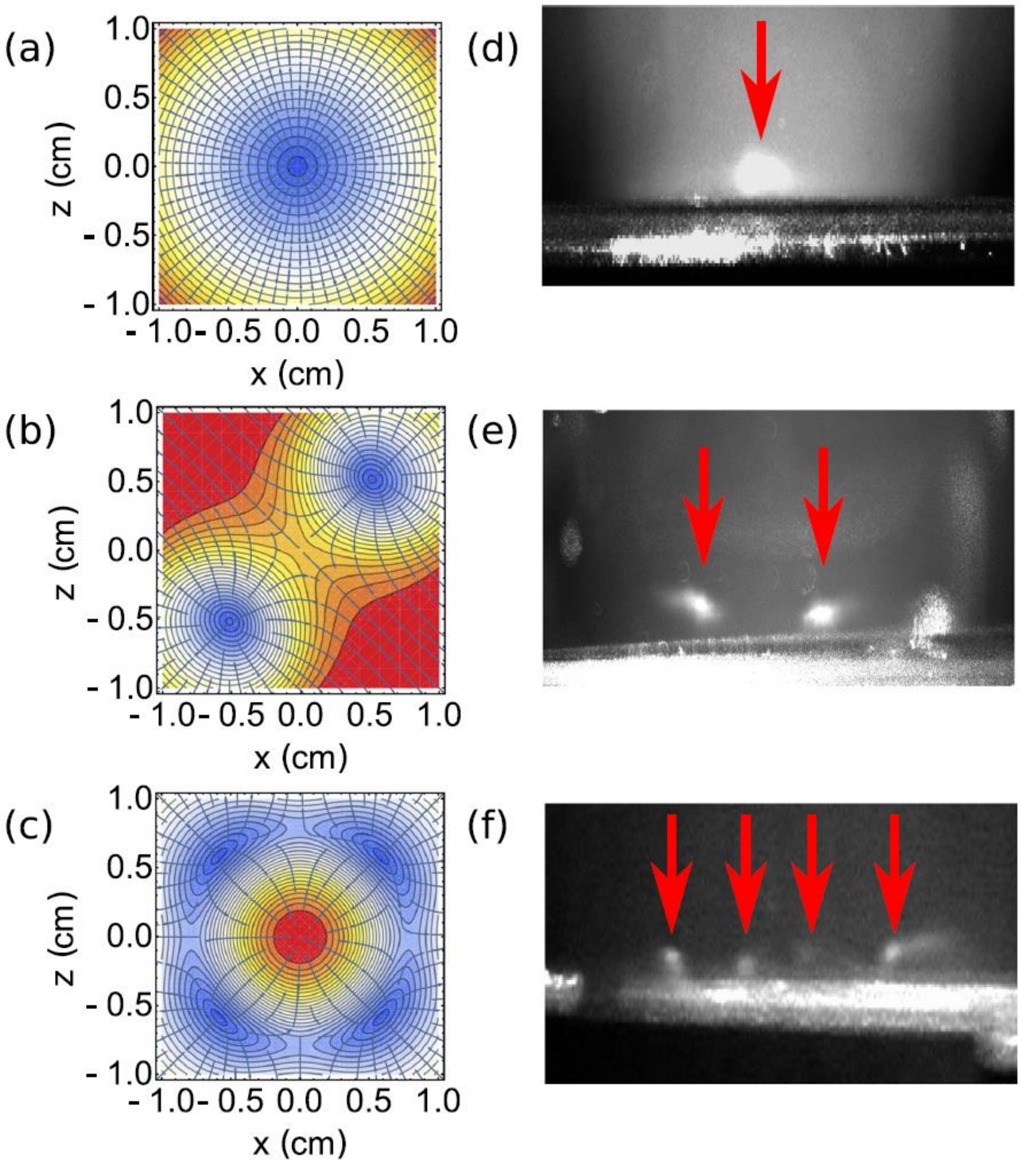
Interrogation beam optically pump atoms into coherent state where **B** field causes spin precession.

*'Side effect': N*=3×$10^6$ at *T*=3μK (|**B**| field <2μT)

McGilligan *et al.* Scientific Reports **7**, 384 (2017).

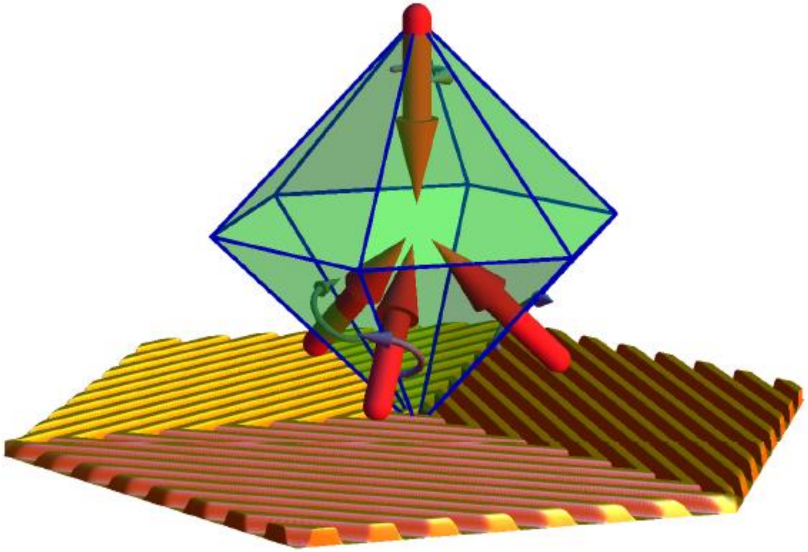
# Multiple MOTs for gradiometry

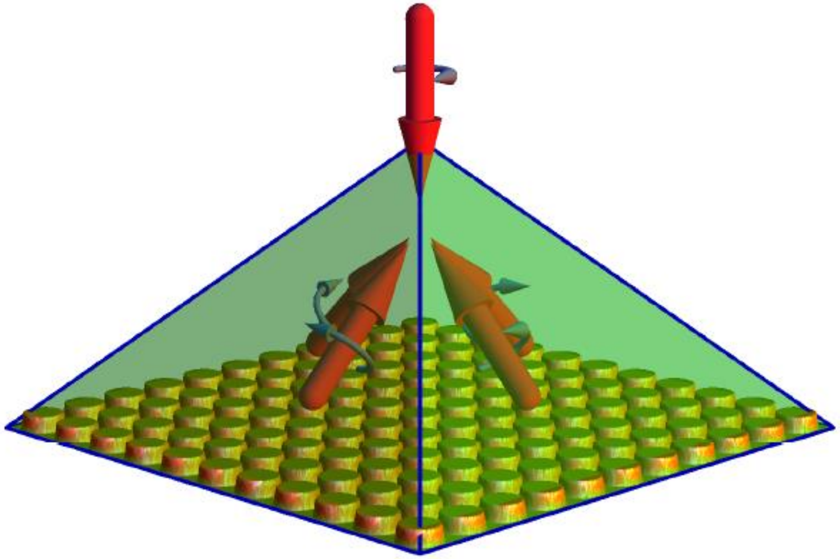


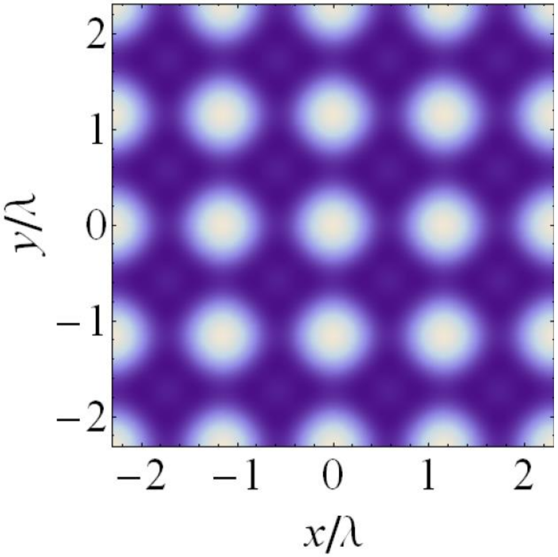

McGilligan *et al.* Scientific Reports **7**, 384 (2017).

# GMOT – novel, ultra-stable lattices

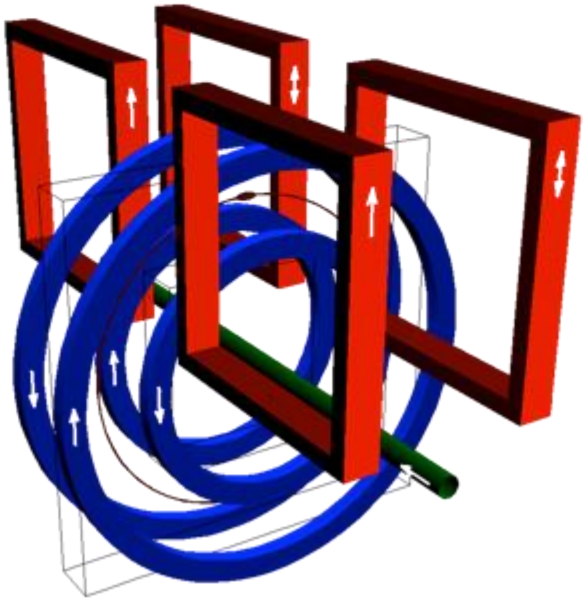


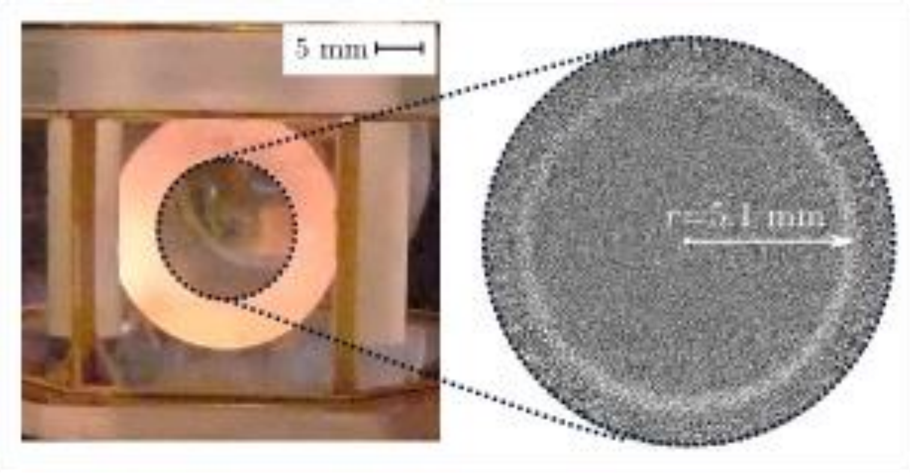


**bcc**



# Ring traps and BEC interferometers

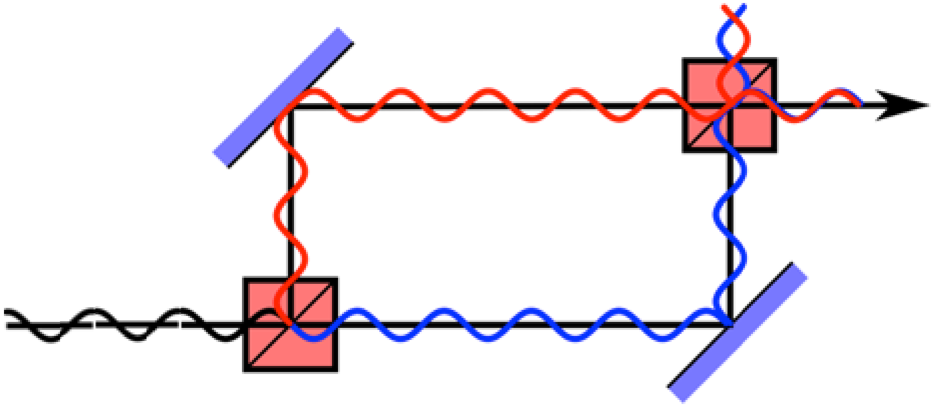




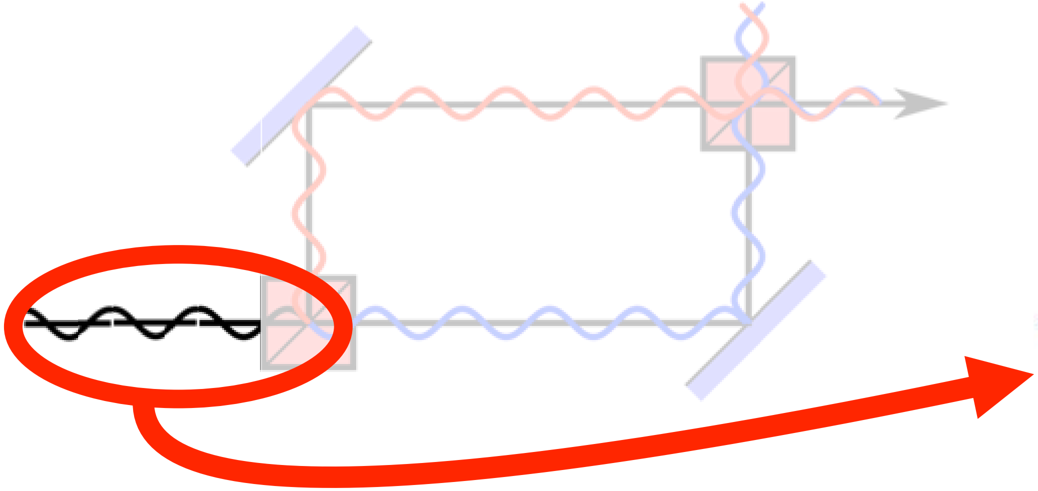

**Large DC ring trap**
J. Mod. Opt. **49**, 959 (2002)
Phys. Rev. A **73**, 041606(R) (2006)
Phys. Rev. A **81**, 043608 (2010)
+ *submitted…*

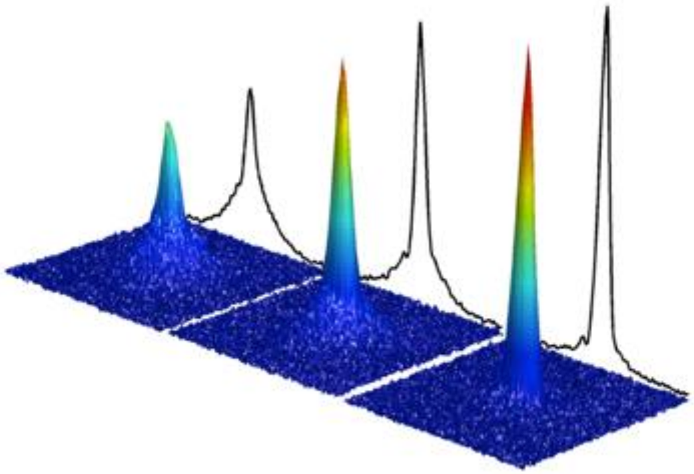
**AC/Inductive Ring Traps**
J. Phys. B **37**, L29 (2004)
Phys. Rev. A **77**, 051402(R) (2008)
New J. Phys. **14**, 103047 (2012)
J. Phys. B **47**, 071001 (2014) (with BG, HP)
Nature Comm. **5**, 5289 (2014) (with BG)
+ *submitted…*

# Matterwave interferometry



# Matterwave interferometry

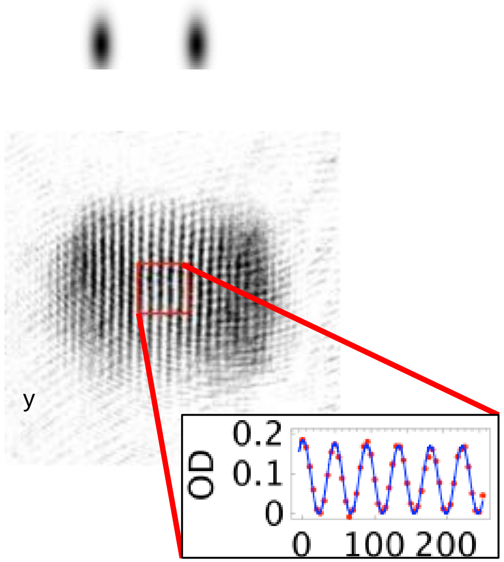




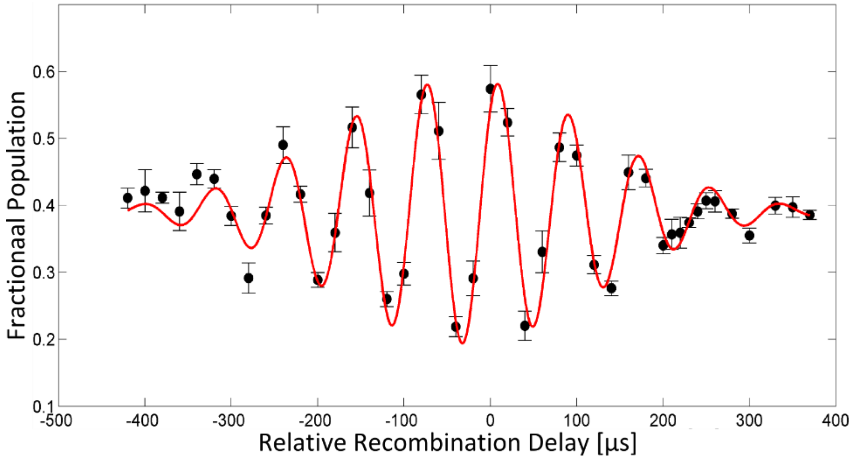
Input mode: $^{87}$Rb BEC, $N$=10$^5$

# Atom-interferometric sensing

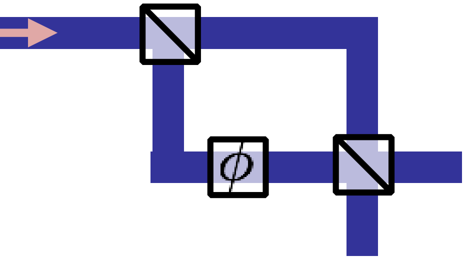
Young's slits



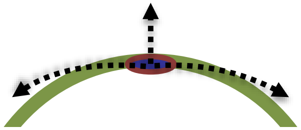

Mach-Zehnder



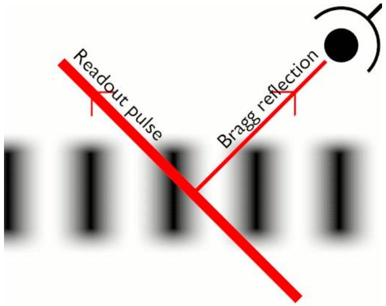
# Atom-interferometric sensing



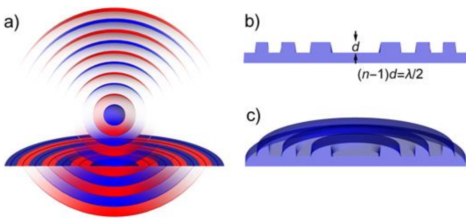

Atomic homodyne detection



Matterwave lenses

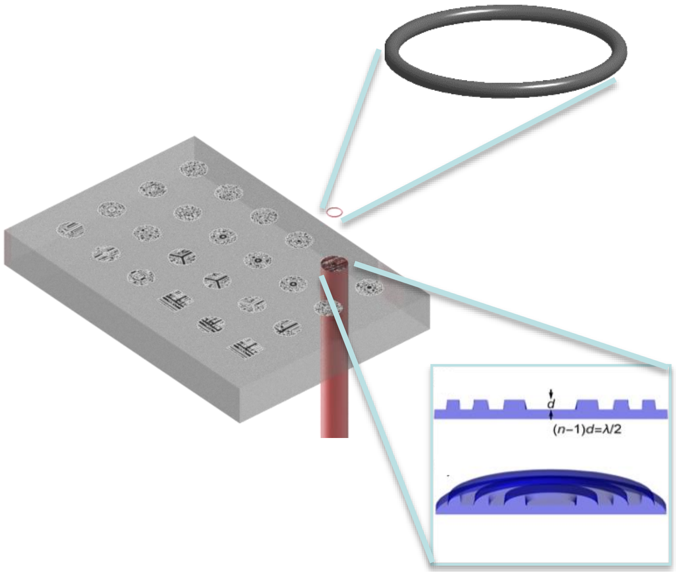



Bragg readout

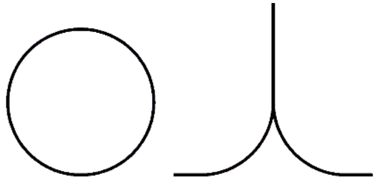



Holographic projection

# Fresnel holography




*V.A. Henderson, New J. Phys.* ***18,*** *025007 (2016).*



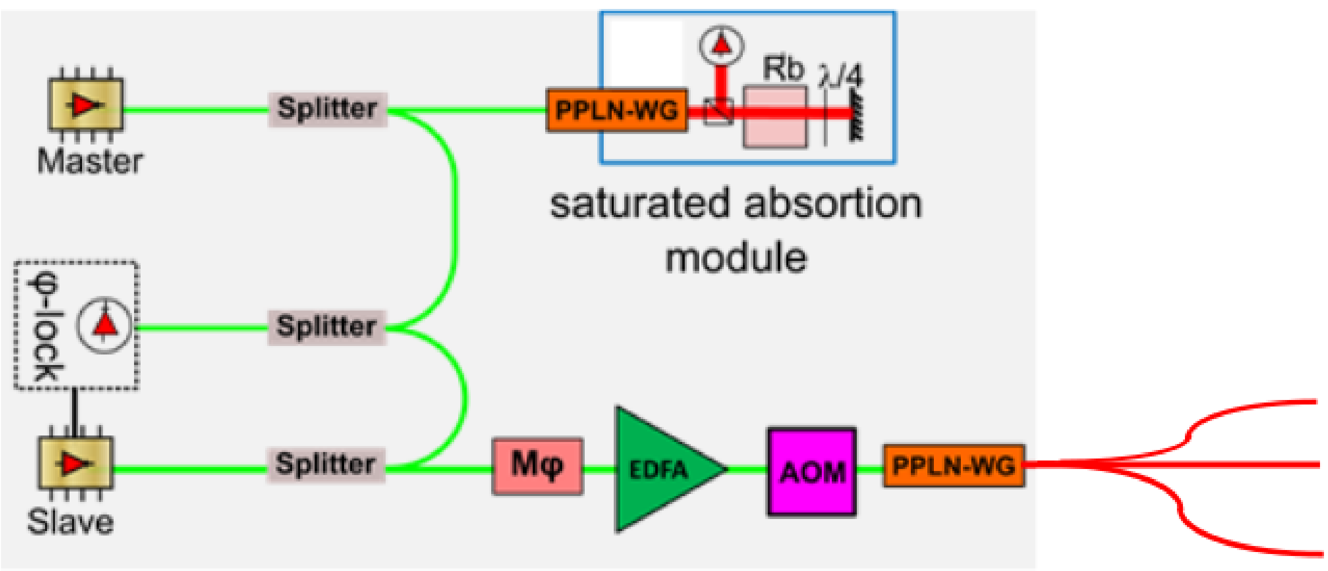
# New ESA TRP

All-Optical Diffractive Element Approach toward Compact, Simple, Rapid BEC Creation in Space

Lead: Dr Paul Griffin, University of Strathclyde

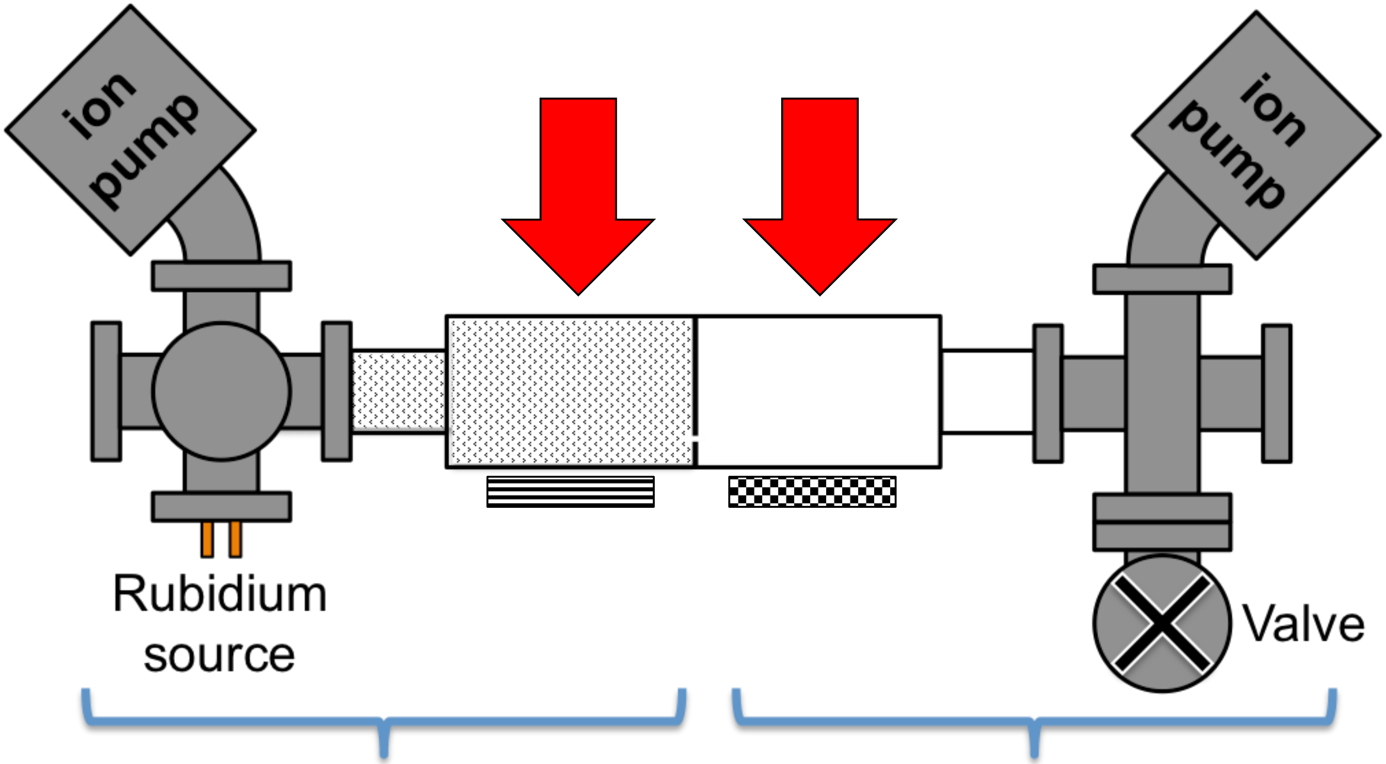
Prof. Ernst Rasel Leibniz Universität Hannover (Institut für Quantenoptik)

and Bruno Desruelle, Muquans as subcontractors



# New ESA TRP

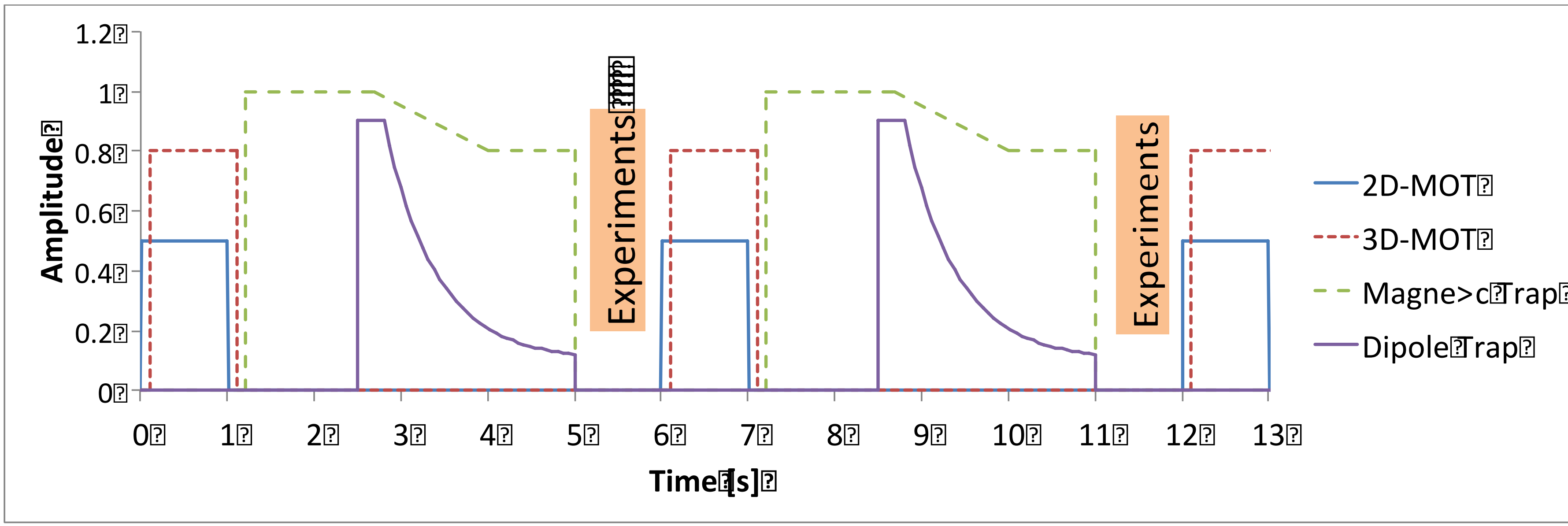
All-Optical Diffractive Element Approach toward Compact, Simple, Rapid BEC Creation in Space




*News:* Eric Imhof, arxiv:**1703.07926** 2D+3D grating MOT

# New ESA TRP

All-Optical Diffractive Element Approach toward Compact, Simple, Rapid BEC Creation in Space



# Experimental Quantum Technologists


Erling Riis


Paul Griffin


Carolyn O'Dwyer


Stuart Ingleby


Rachel Elvin


James McGilligan


Yogeshwar Kale

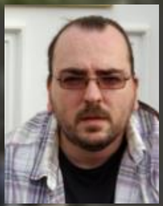

Oliver Burrow

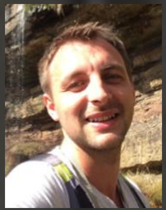

Jonathan Pritchard

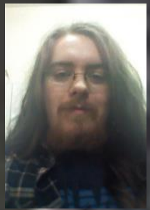

Vicki Henderson


Matthew Johnson


Billy Robertson


Andrew MacKellar


Jim Halket


Johnny Conway


Rachel Offer


Calum Macrae


Remy Legaie


Craig Picken

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UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME
Innovate UK Technology Strategy Board
dstl
esa
EPSRC