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Electro-magnetically induced transparency of structured light

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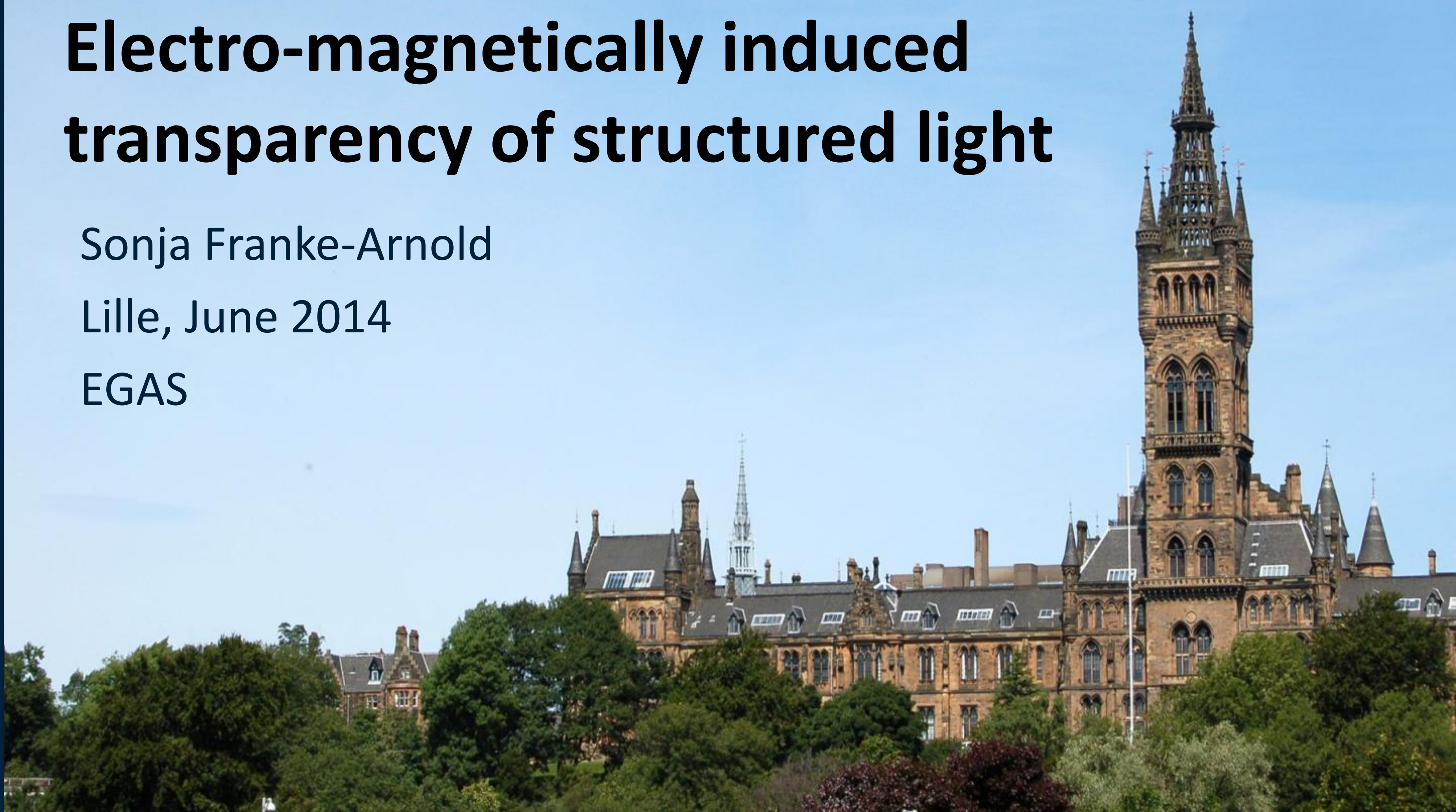
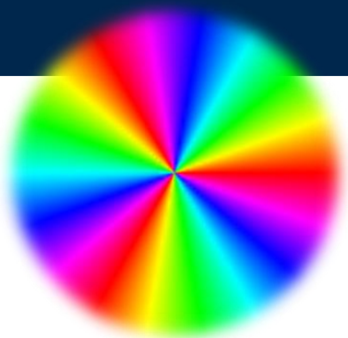
Lille, June 2014

EGAS



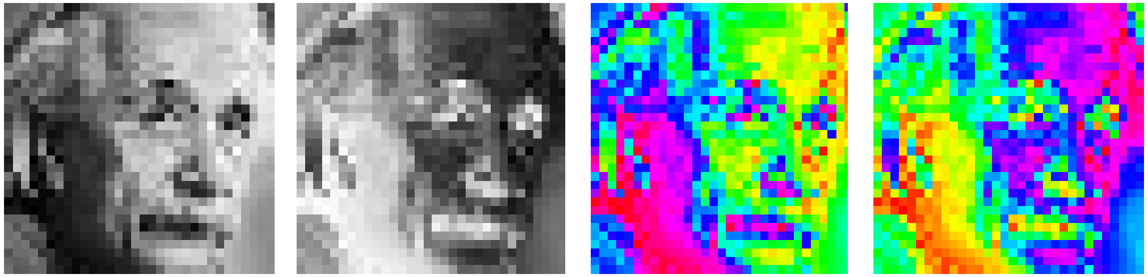
Outline



1. Structured light and atoms
   - 3D visualisation of structured light
   - Trapping in the dark
2. Structured EIT
   - Experiments: first data
   - Theory: closing the loop

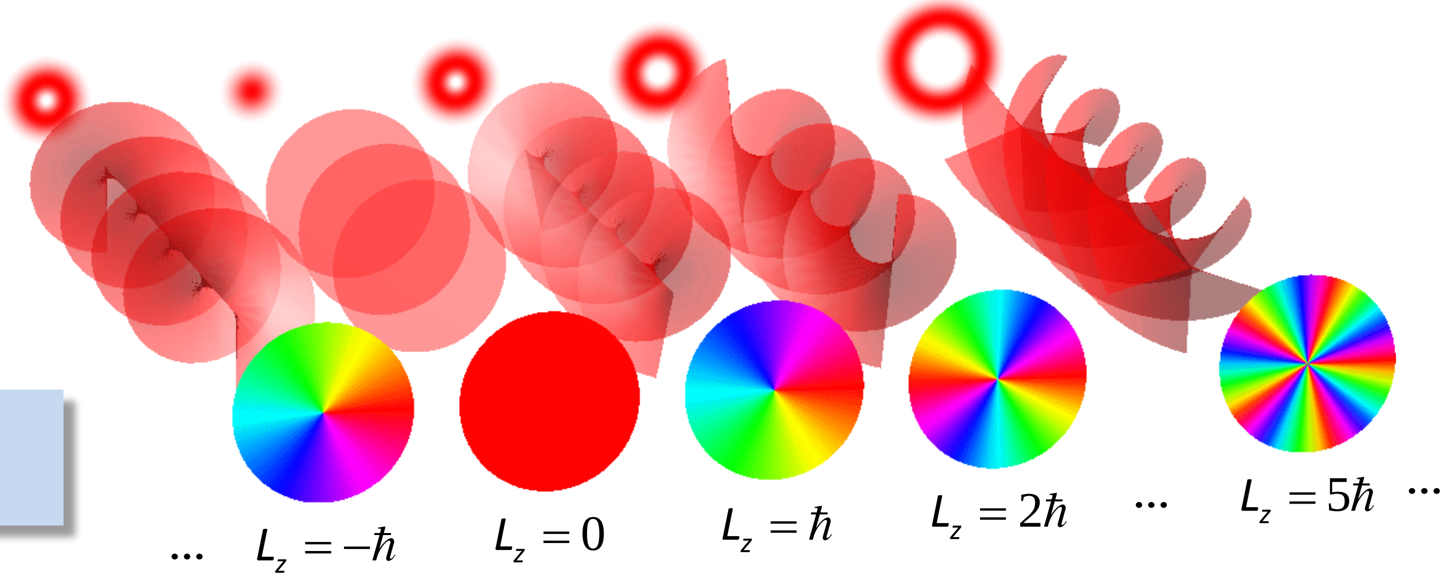
Why structured light?

- Efficient data encoding - much more than 2 degrees of freedom
  - Quantum images



Pixel basis system

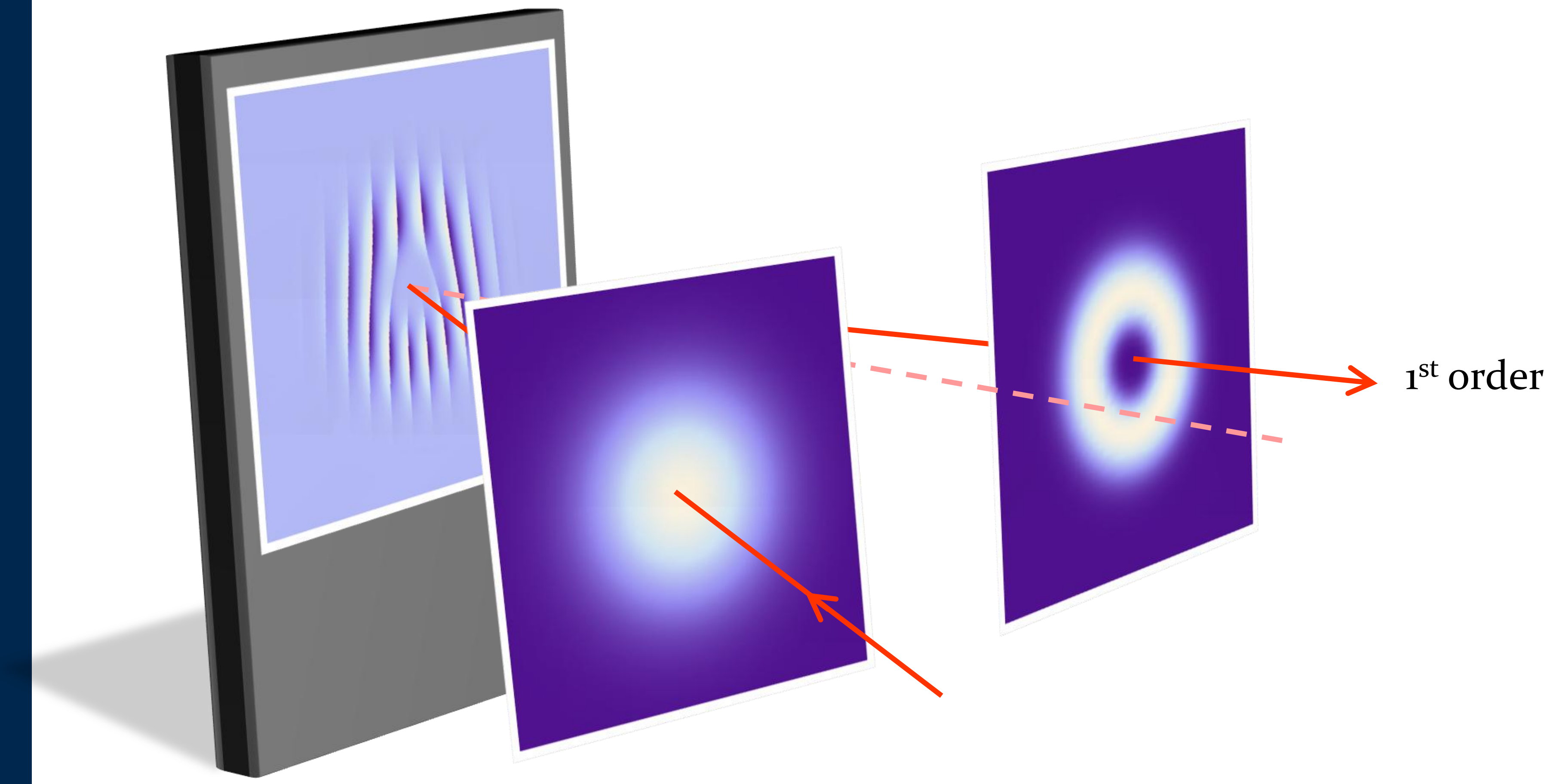
  - OAM modes – added convenience and interest



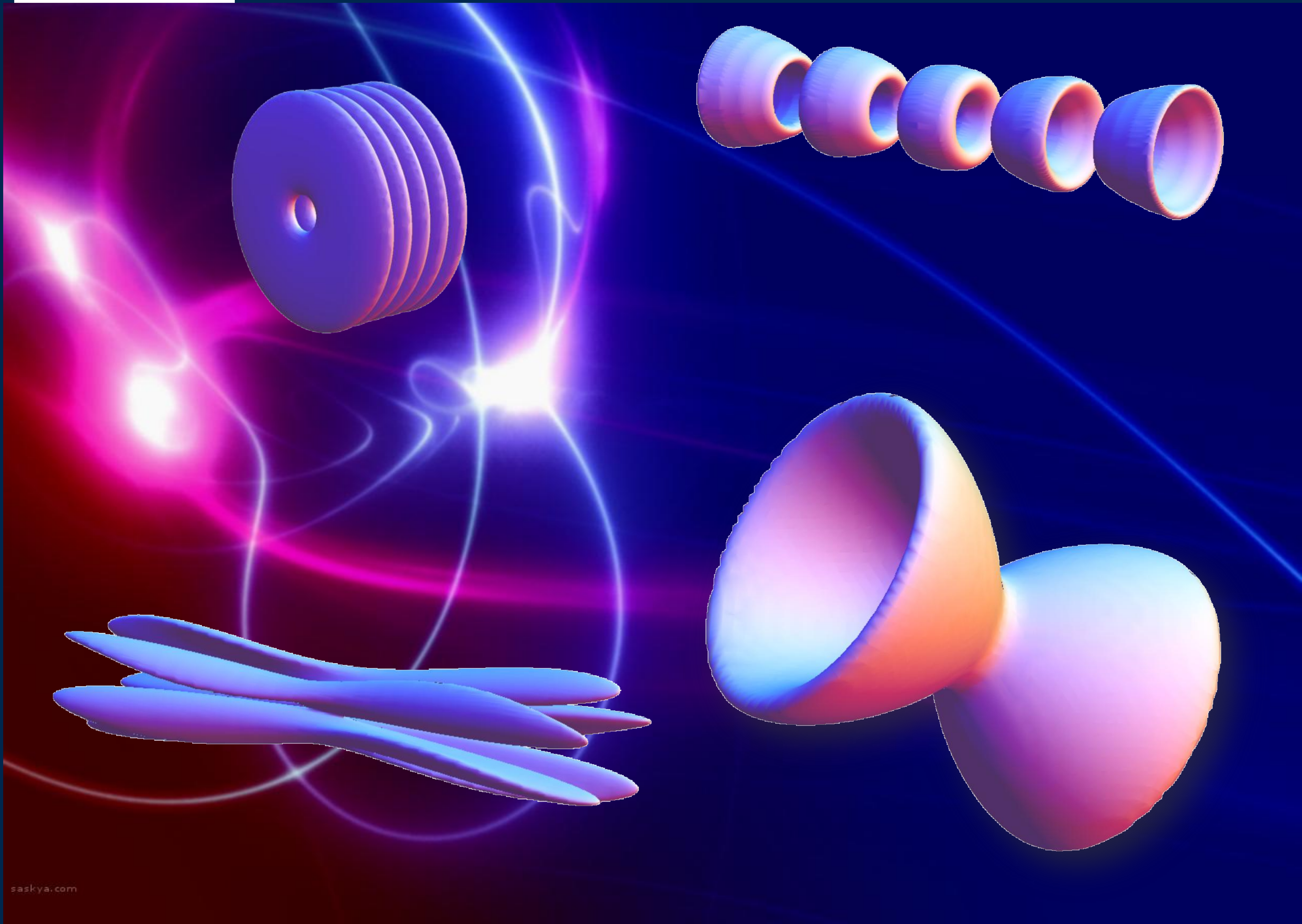
LG basis system

Orbital angular momentum

- Light with twisted phase fronts: $E(r,\varphi) \propto \exp(im\varphi)$
- Generation with spatial light modulators: liquid crystal devices that control the local phase delay pixel by pixel



3D visualisation of structured light



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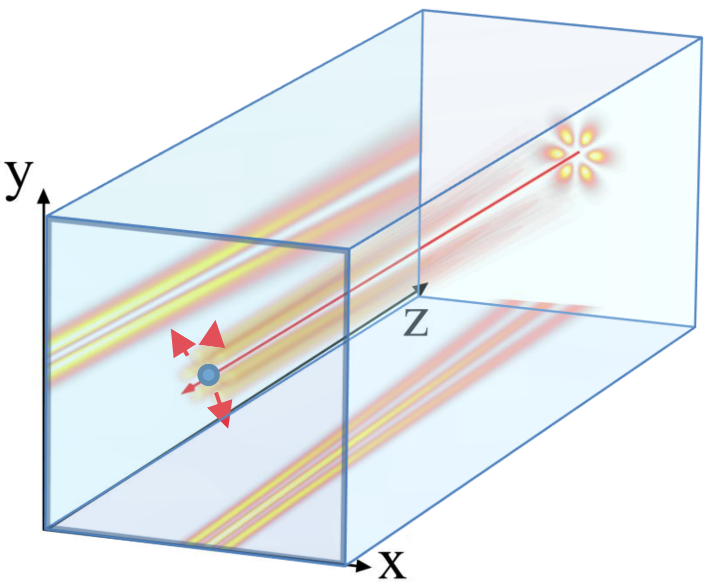
3D reconstruction from fluorescence

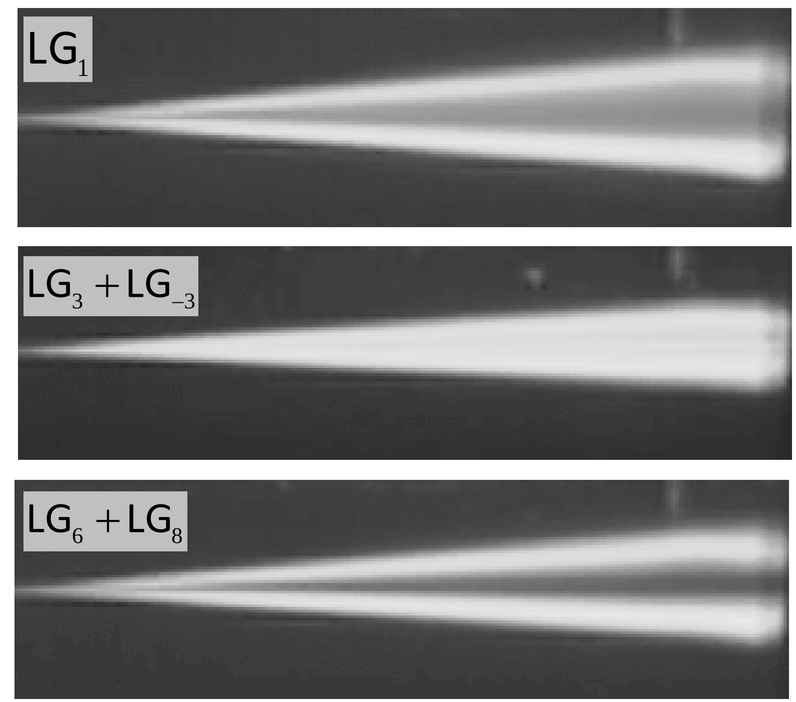
- Laser below saturation → fluorescence proportional to light intensity.

$$R_{scatt} \propto \frac{\Gamma}{2}\frac{I/I_{sat}}{1+I/I_{sat}+4(\delta/\Gamma)^2}$$

- Record pattern from the side, rotating the camera around the light structure. Or rotate beam.
- Full 3 D tomographic reconstruction.

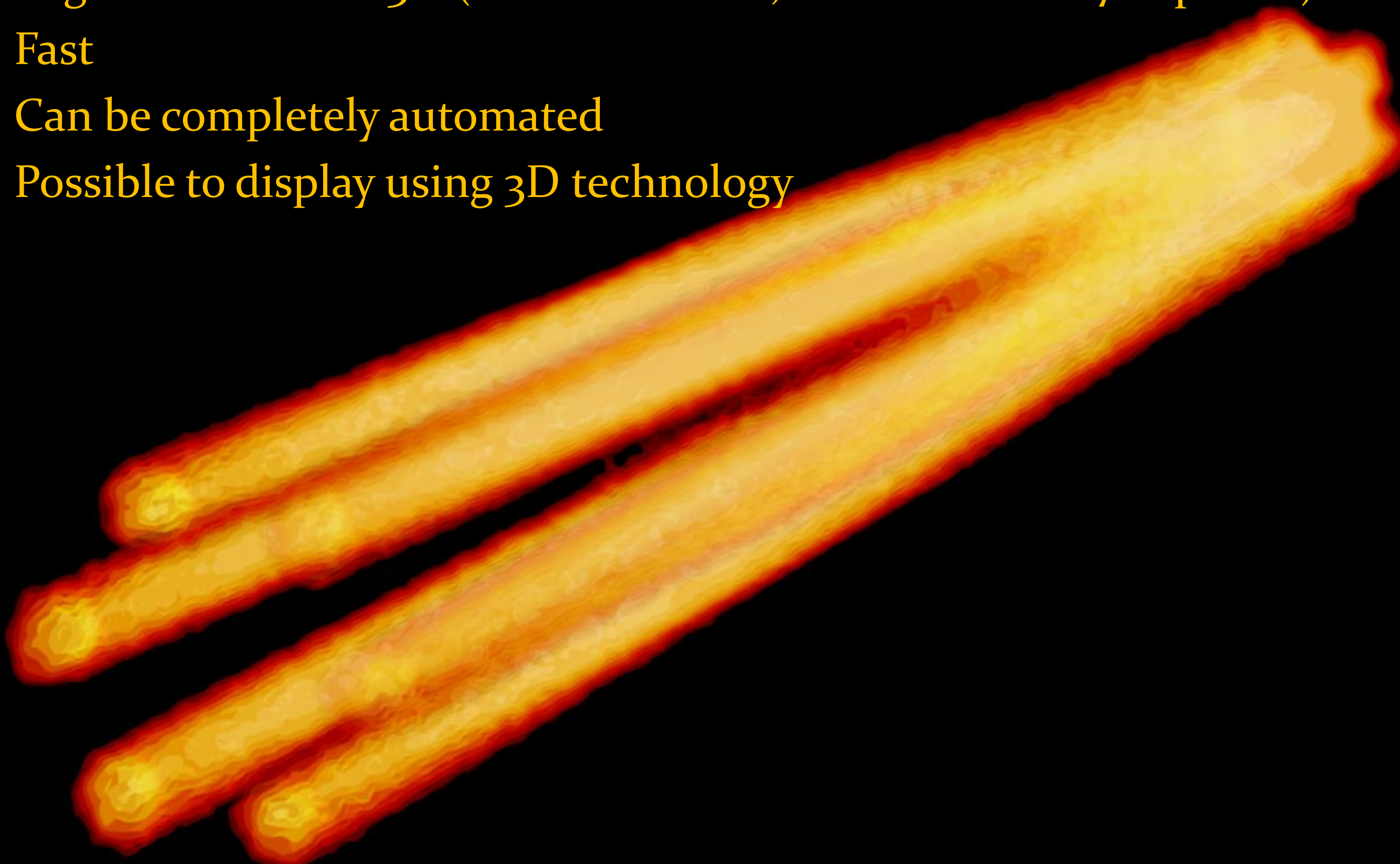


Recorded movies for rotating beams



3D reconstruction

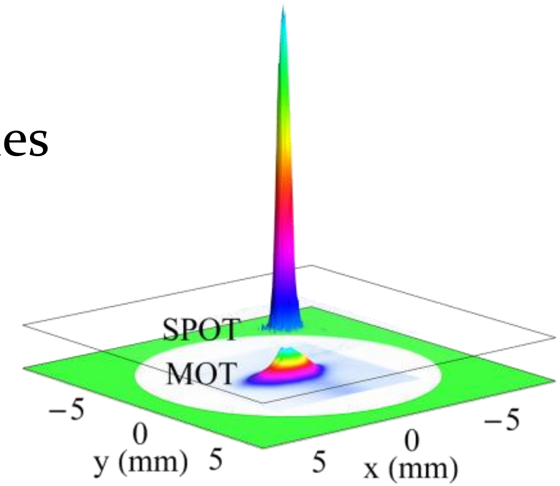
- Non-invasive
- High resolution in 3D (camera limited, i.e. 200 x 200 x 720 points)
- Fast
- Can be completely automated
- Possible to display using 3D technology



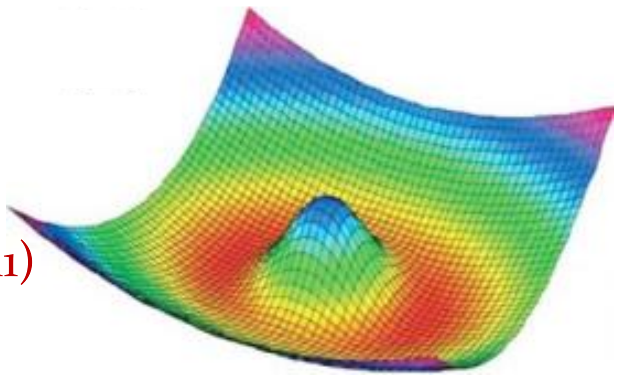
N.Radwell *et al*, Optics Express **21**, 22215 (2013)

Structured light in atom optics

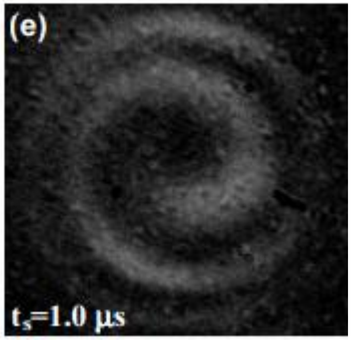
- Trapping and guiding in designed intensity profiles
  - Van Enk (1994), Franke-Arnold (2007), Andrews (2011), Ruseckas (2011), Volke-Sepúlveda (2011)
  - Pruvost (2014), **Franke-Arnold** (2013), …



- Quantised motion of BECs
  - Dalibard (2000), **Phillips** (2007, 2010) , …



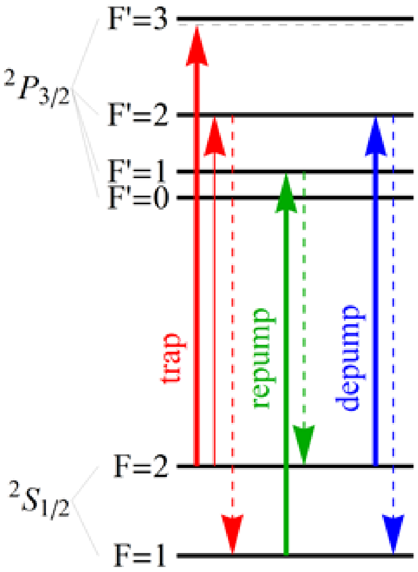
- Changing the selection rules
  - Tabosa (2003, 2009), **Kozuma** (2006, 2009, 2011)
  - Allen, Babiker (1996), Afanasev (2014), …
- Imprinting structured phase and amplitude onto atoms
  - Davidson (2007), Lett (2008), Giacobino (2014), …
  - Structured EIT

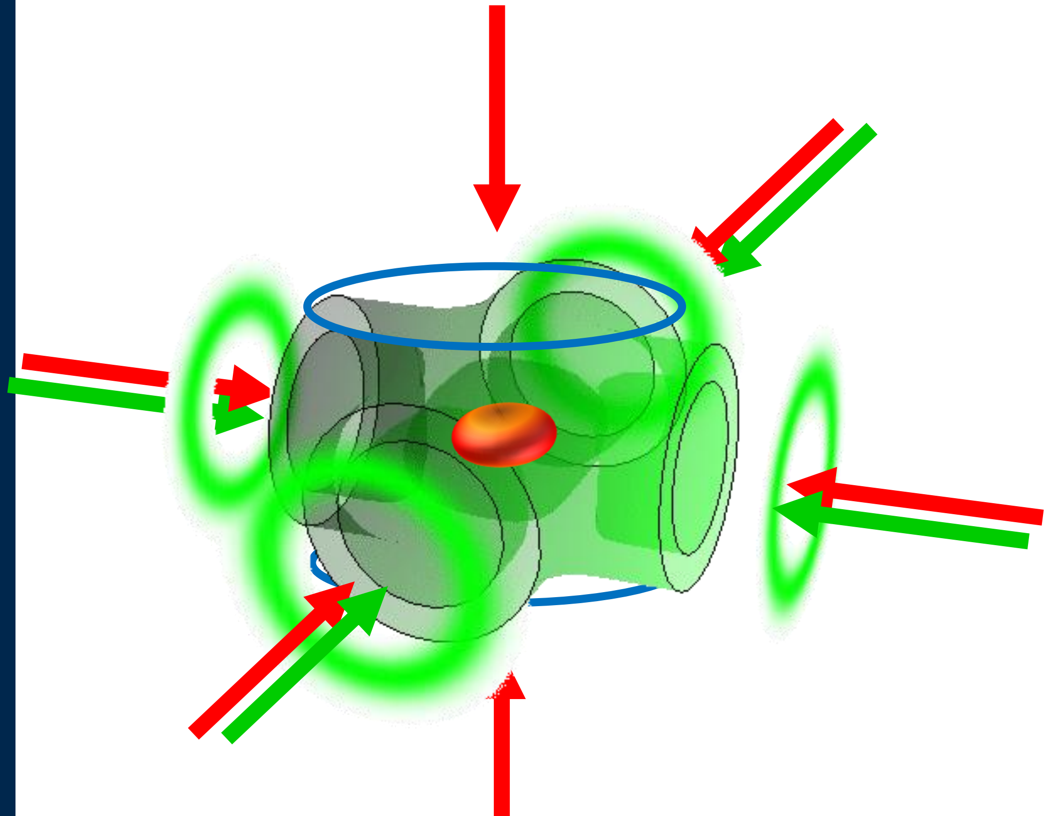


Trapping in the dark

Trapping in the dark

- We have developed a holographically shaped dark SPOT atom trap.
  - The dark SPOT geometry allows to shelter the atoms in the core of the trap from re-radiation forces, allowing atoms to accumulate at higher densities.





Trapping in the dark

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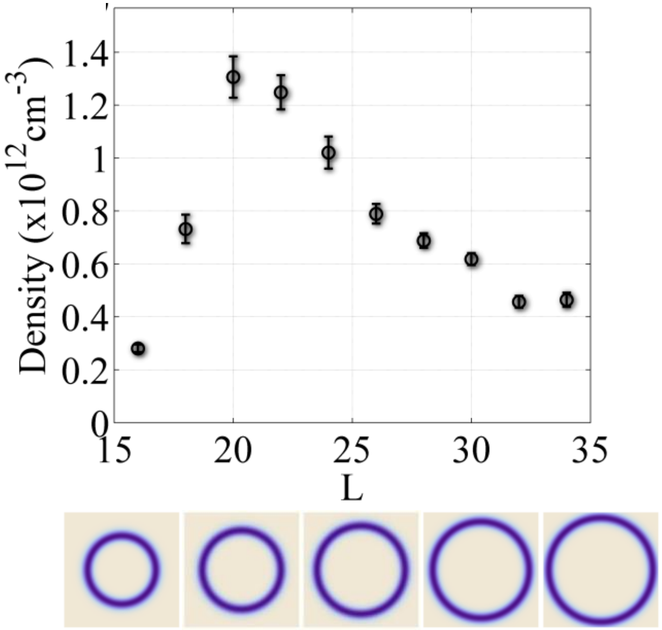
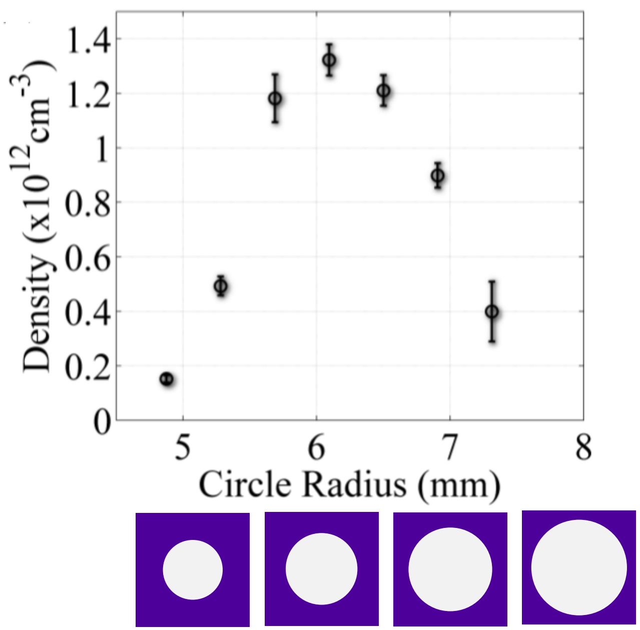
Atoms reloaded

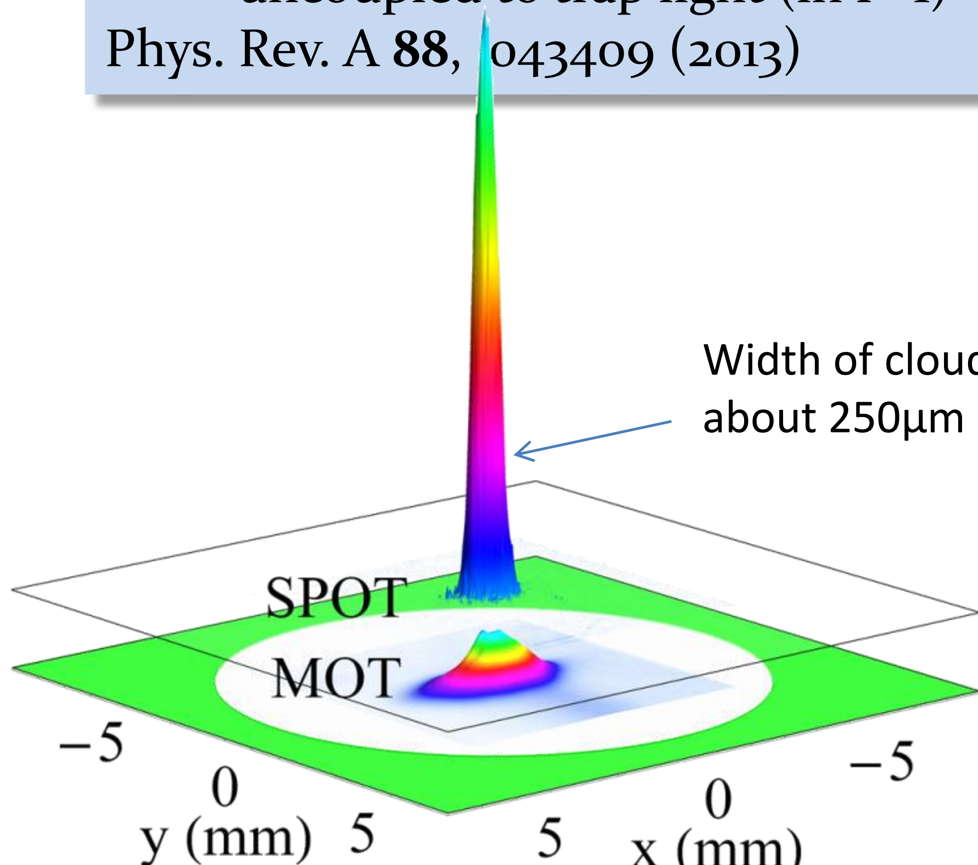
Capture atoms in standard MOT and reload into dark SPOT ($>10^8$ atoms).

- No heating (100μK)
- Density increase by 2 orders of magnitude ($1.3 \cdot 10^{12}$ /cm^3)
- uncoupled to trap light (in F=1)

Phys. Rev. A **88**, 043409 (2013)



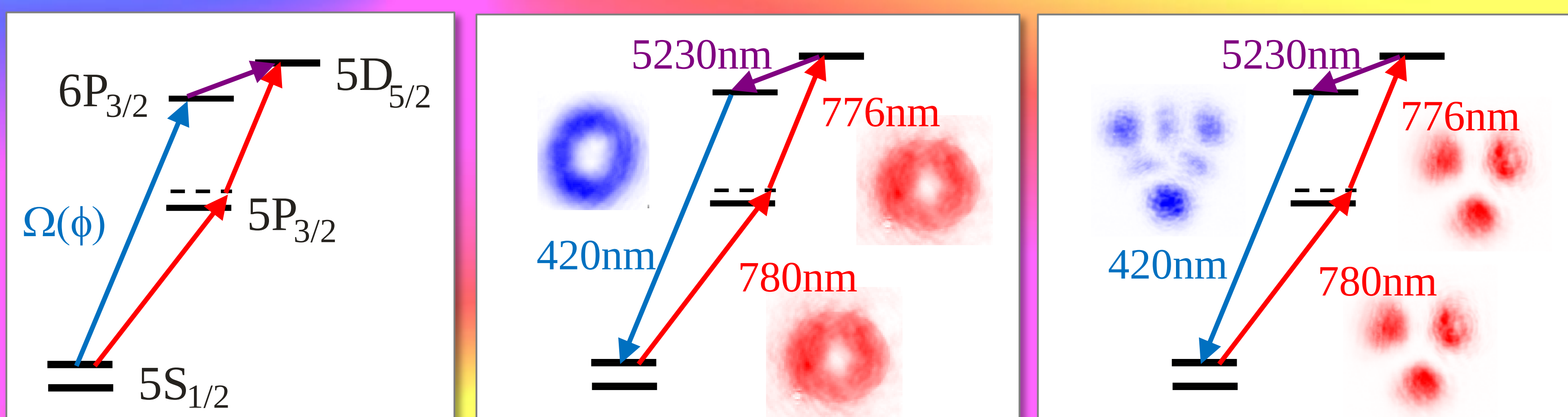




Trapping in the dark

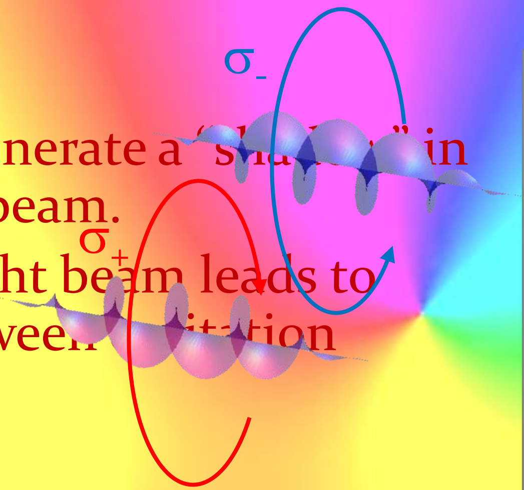
Making atoms see the (complex) light

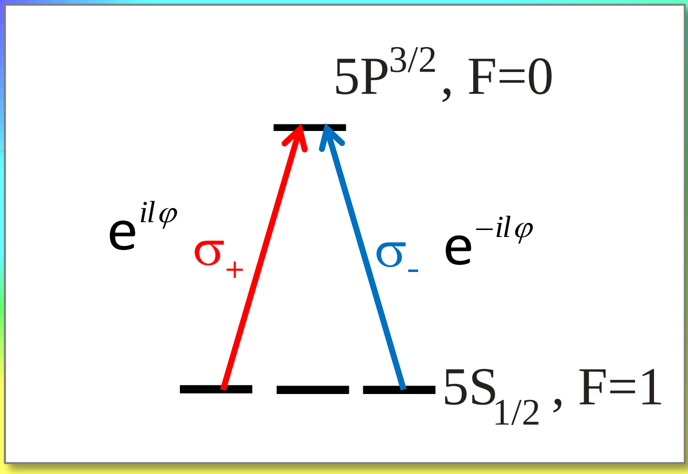
- **Interferometer within an atom:** Electronic transitions that connect atomic levels via multiple excitation paths become dependent on the optical phase.
  - "Phase-dependent interaction in a four-level atomic configuration" Morigi, Franke-Arnold and Oppo, Phys Rev A **66**, 053409 (2002)
- **Four wave mixing in a diamond system**
  - Phase-coherence → Conservation of OAM: $\ell_{780} + \ell_{776} = \ell_{5233} (+\ell_{420})$
  - "Trans-spectral OAM transfer…" Phys. Rev. Lett. **108**, 243601 (2012)



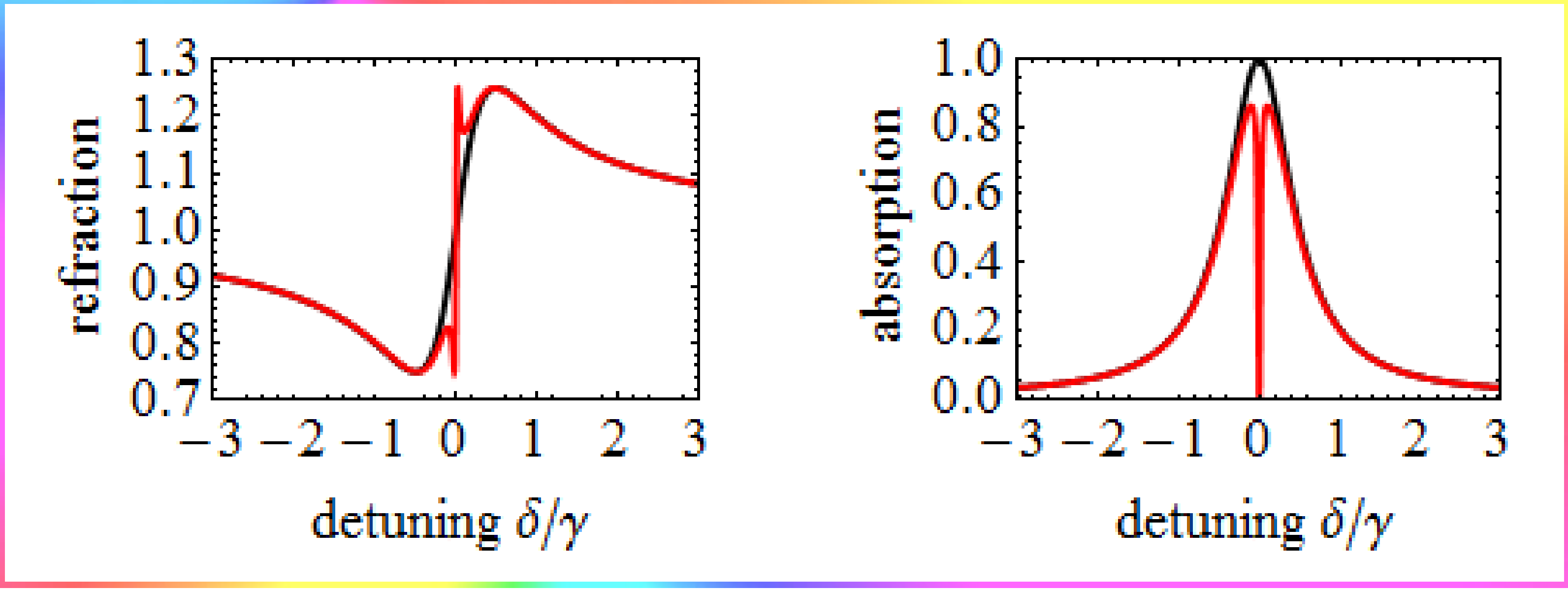
Making atoms see the (complex) light

- Reminder EIT
  - Atoms usually generate a "shadow" in a passing probe beam.
  - An additional light beam leads to interference between excitation amplitudes.





- **Can light with a phase pattern generate structured EIT?**

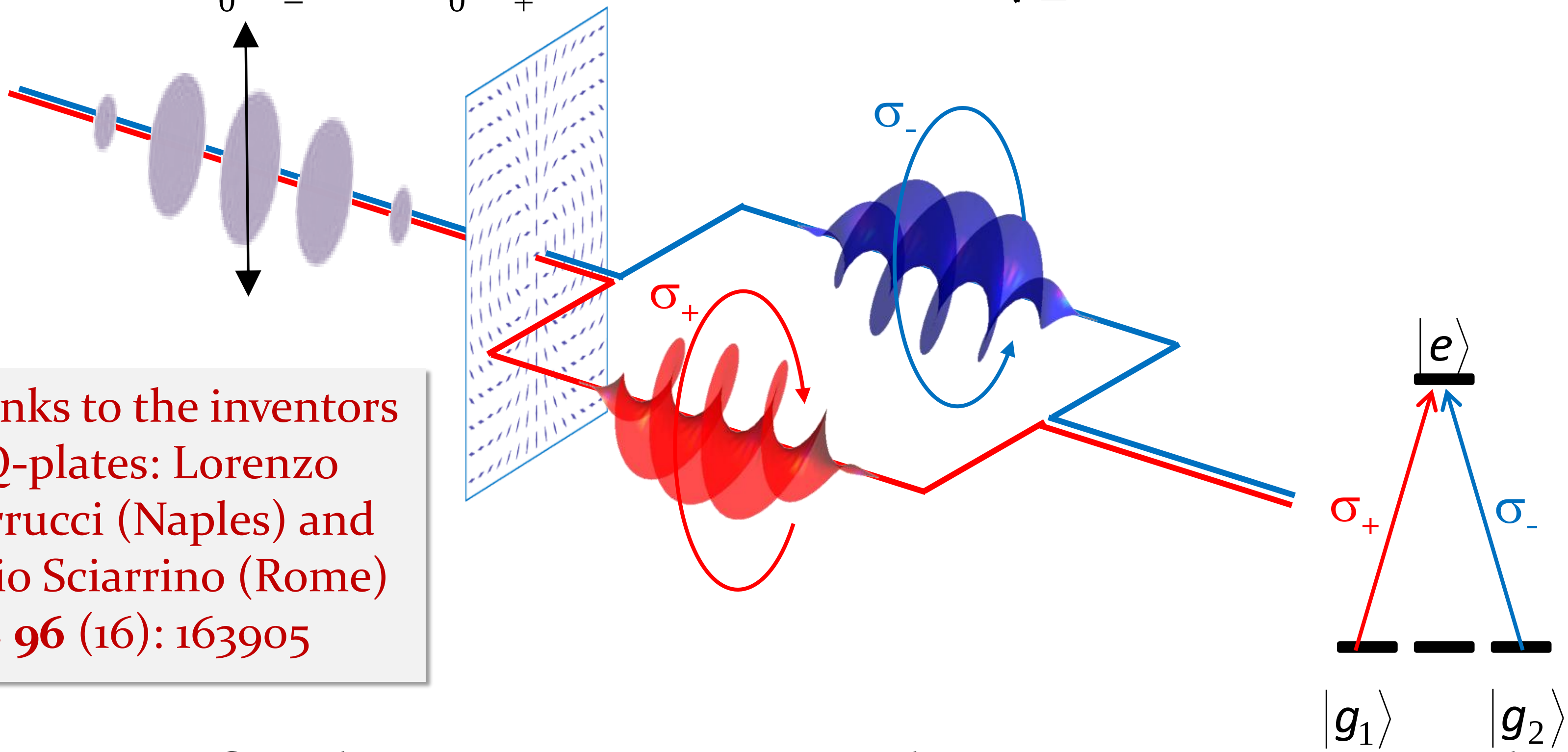


OAM controlled EIT

- Q-plates can convert spin to orbital angular momentum.
- Q-plates can "entangle" optical OAM and polarisation.

$$E_0\hat{\sigma}_+ \rightarrow E_0\hat{\sigma}_-\mathrm{e}^{il\varphi}$$
$$E_0\hat{\sigma}_- \rightarrow E_0\hat{\sigma}_+\mathrm{e}^{-il\varphi}$$

$$E_0\hat{x} \rightarrow \frac{E_0}{\sqrt{2}}\left(\hat{\sigma}_-\mathrm{e}^{il\varphi} + \hat{\sigma}_+\mathrm{e}^{-il\varphi}\right)$$

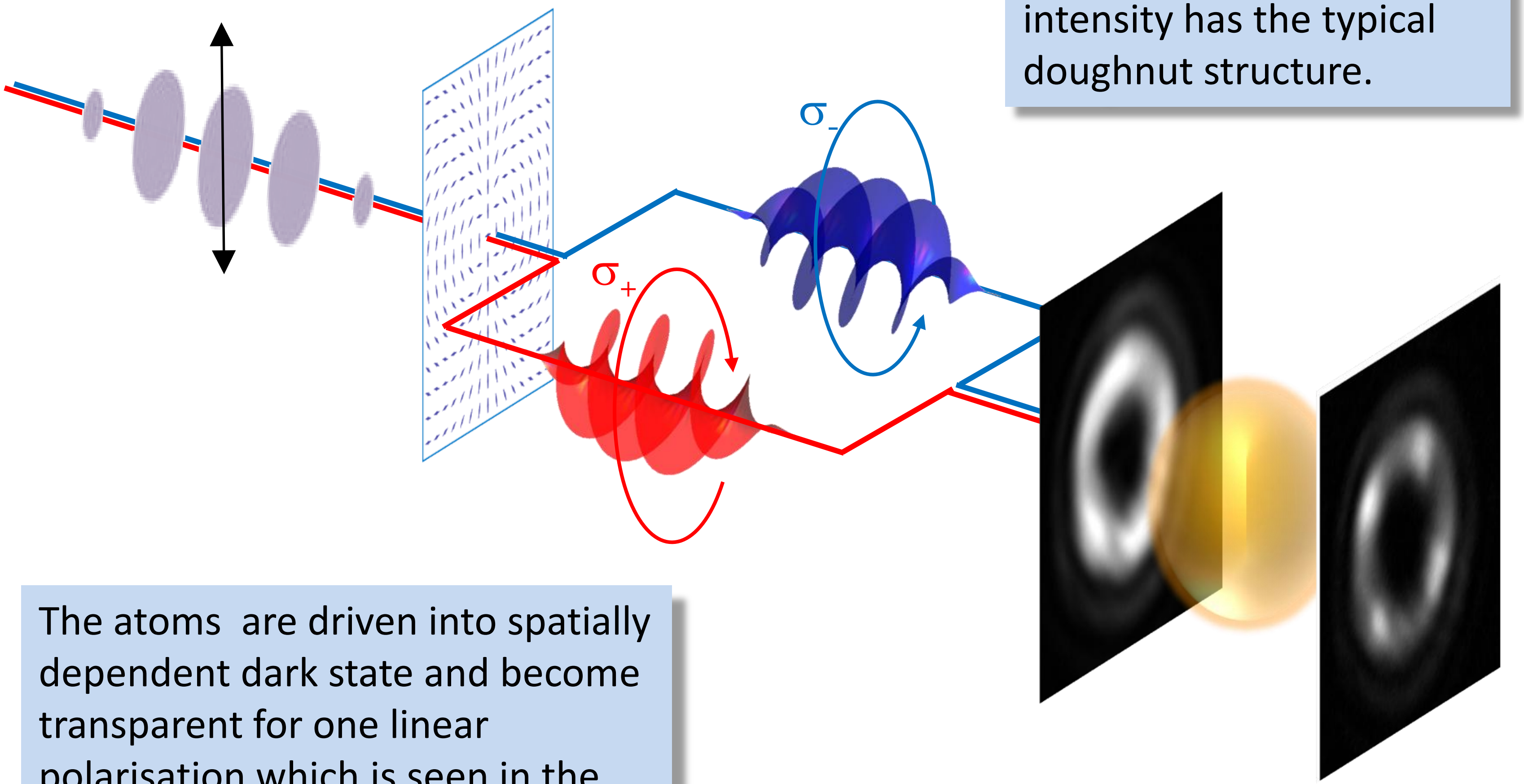


Thanks to the inventors of Q-plates: Lorenzo Marrucci (Naples) and Fabio Sciarrino (Rome) *PRL* **96** (16): 163905

- Transfer phase structure via polarisation to atomic coherence

Intensity profiles

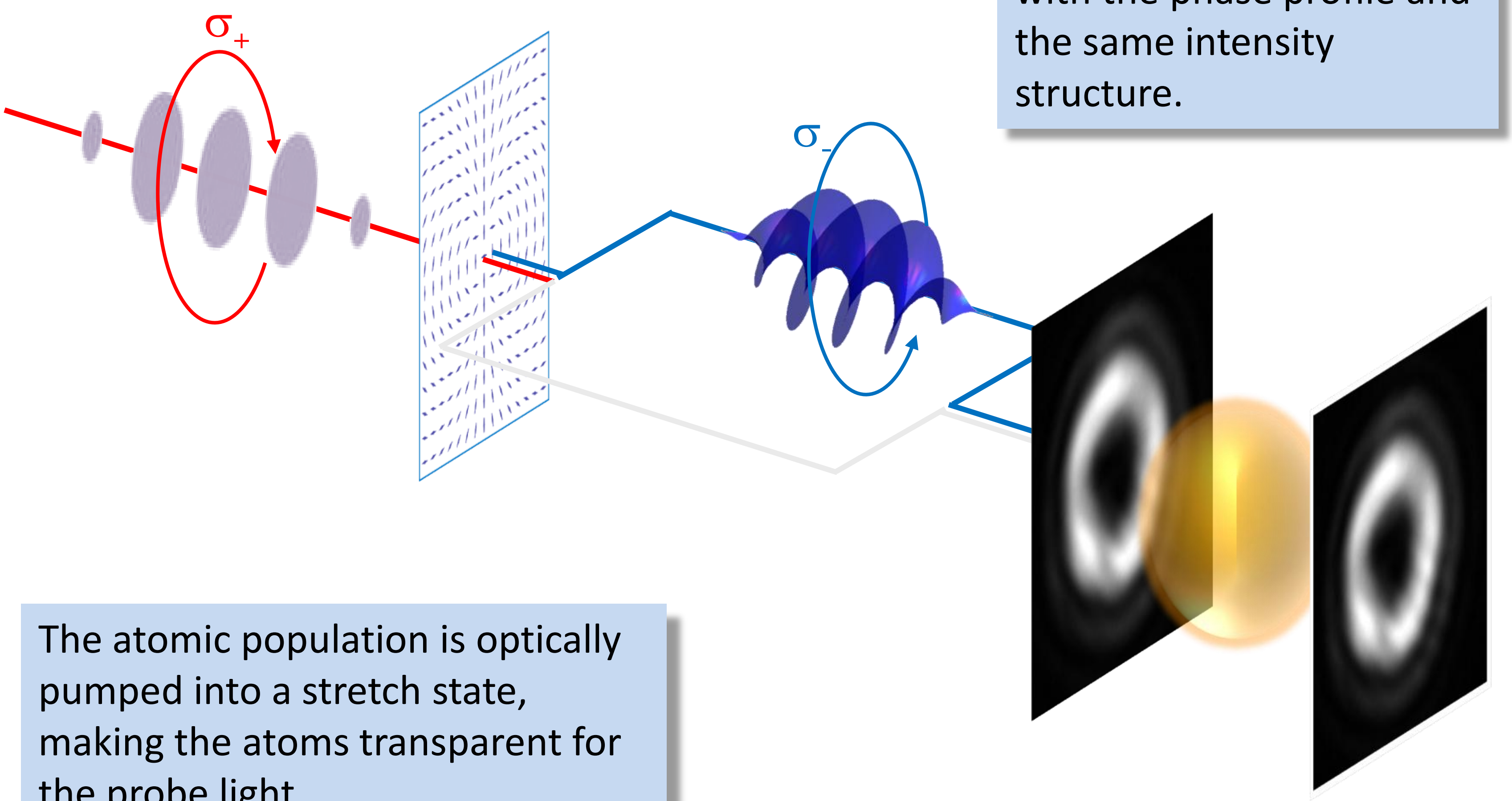
The σ+ and σ- light components don't interfere, and the light intensity has the typical doughnut structure.



The atoms are driven into spatially dependent dark state and become transparent for one linear polarisation which is seen in the transmitted intensity profile.

Intensity profiles

Instead, input σ+ light is converted into σ- light with the phase profile and the same intensity structure.



The atomic population is optically pumped into a stretch state, making the atoms transparent for the probe light.

OAM dependent dark states

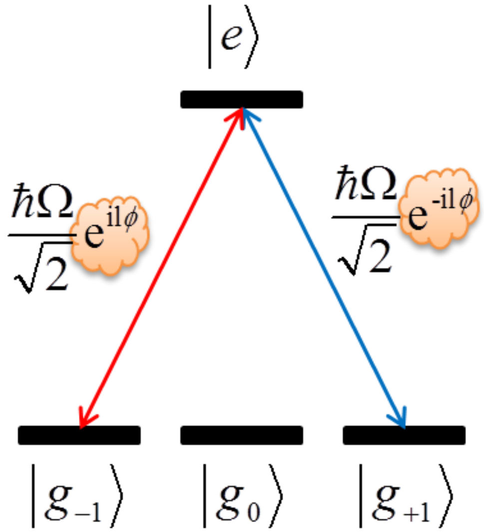
- “entangled” light field

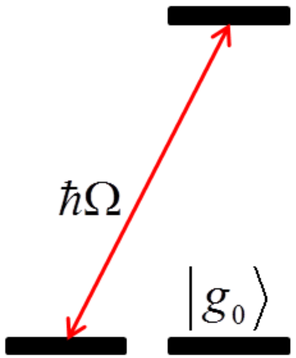
$$E_0\hat{x} \rightarrow \frac{E_0}{\sqrt{2}}\left(\hat{\sigma}_{-}\mathrm{e}^{il\varphi} + \hat{\sigma}_{+}\mathrm{e}^{-il\varphi}\right)$$

- Dipole interaction

$$H_D = \frac{\Omega}{\sqrt{2}}\left(\mathrm{e}^{il\varphi}|g_{+1}\rangle\langle e| + \mathrm{e}^{-il\varphi}|g_{+1}\rangle\langle e|\right) + \mathrm{h.c.}$$

$$H_D = \hbar\Omega|\psi_{+}\rangle\langle e| + h.c.$$

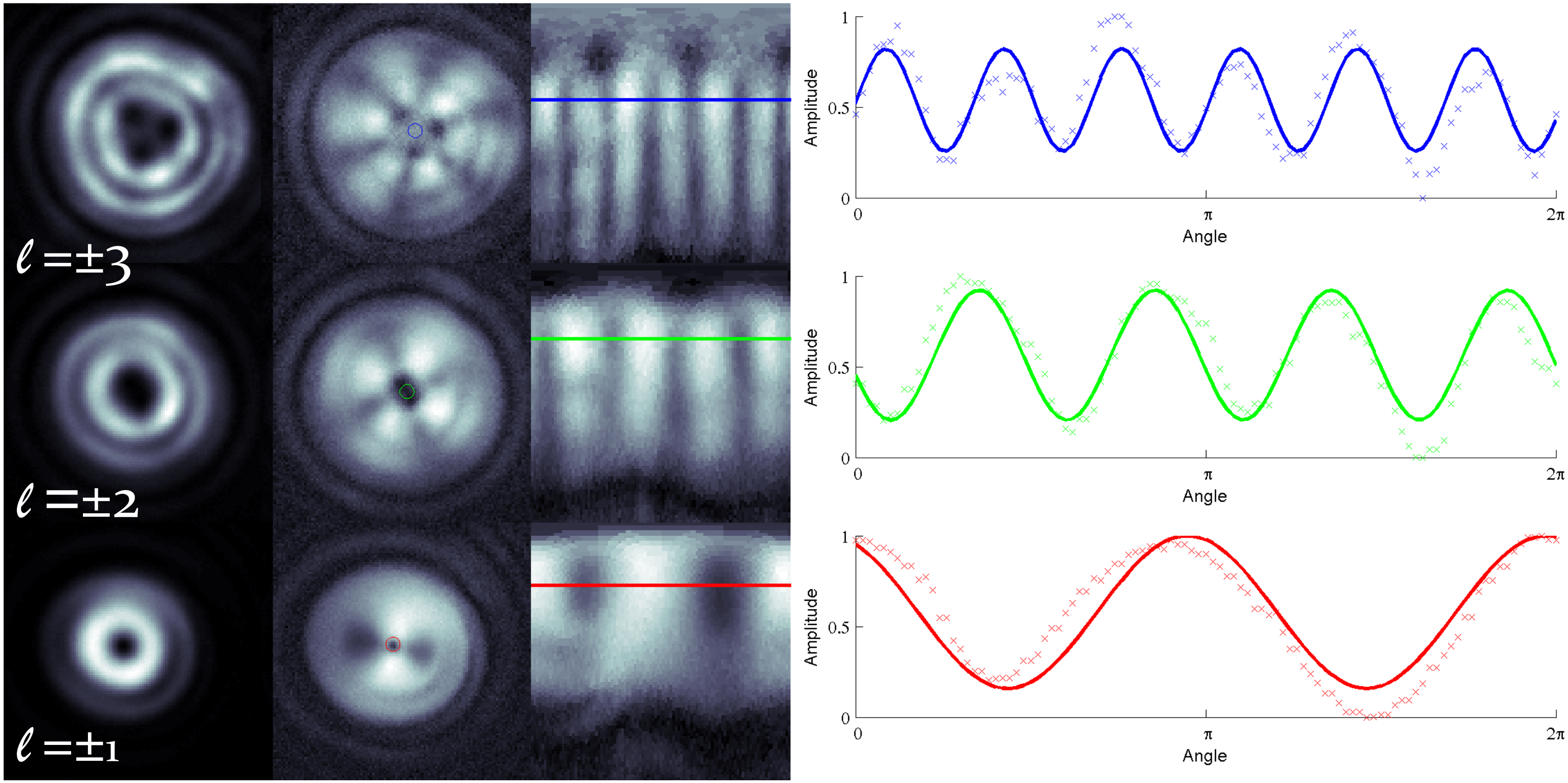




$$|\psi_{NC}\rangle = \frac{1}{\sqrt{2}}\left(e^{-il\phi}|g_{-1}\rangle - e^{il\phi}|g_{+1}\rangle\right)$$

$$|\psi_C\rangle = \frac{1}{\sqrt{2}}\left(e^{-il\phi}|g_{-1}\rangle + e^{il\phi}|g_{+1}\rangle\right)$$

Different geometries



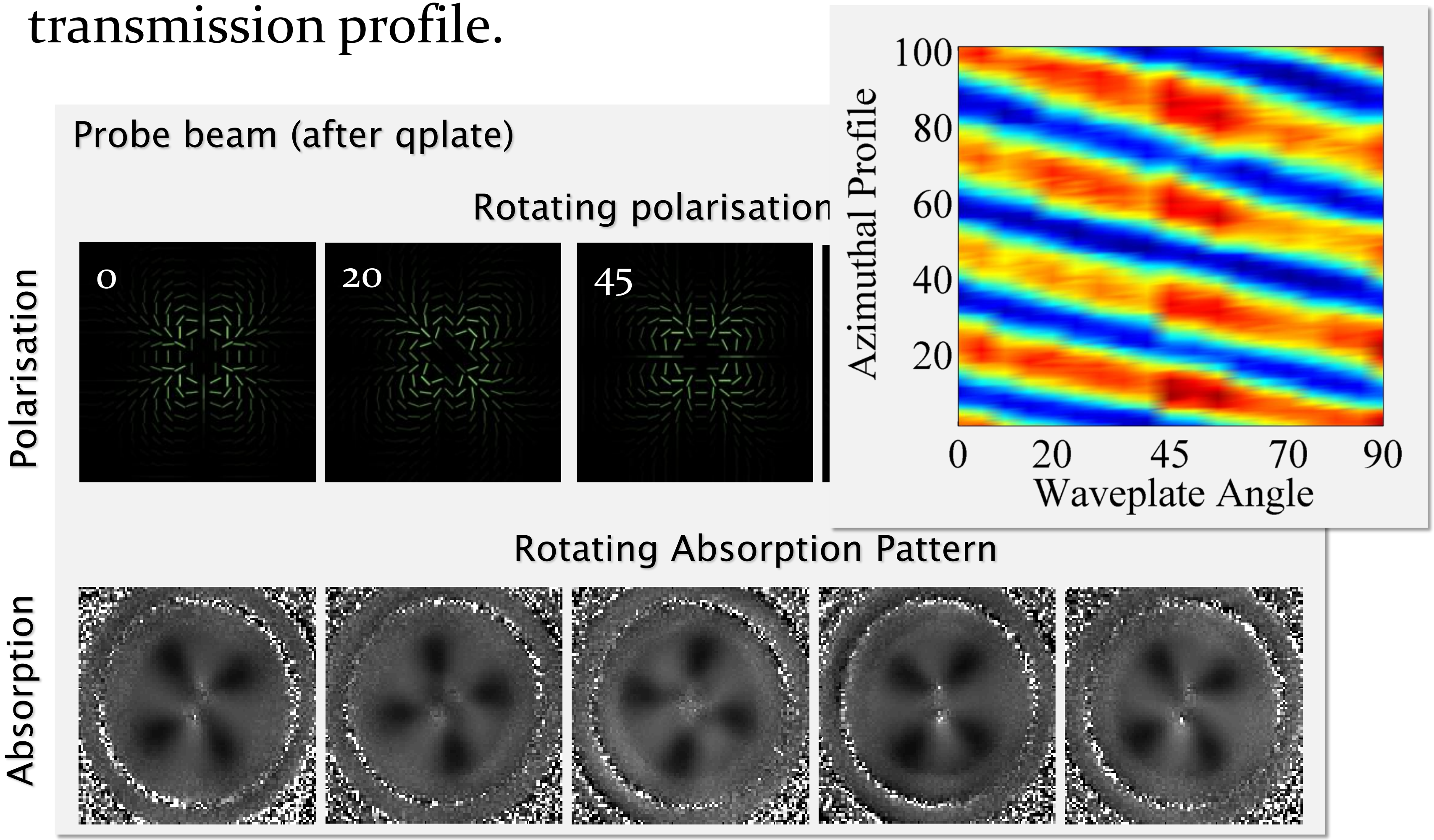
Input profile

Absorption profile

Polar plot

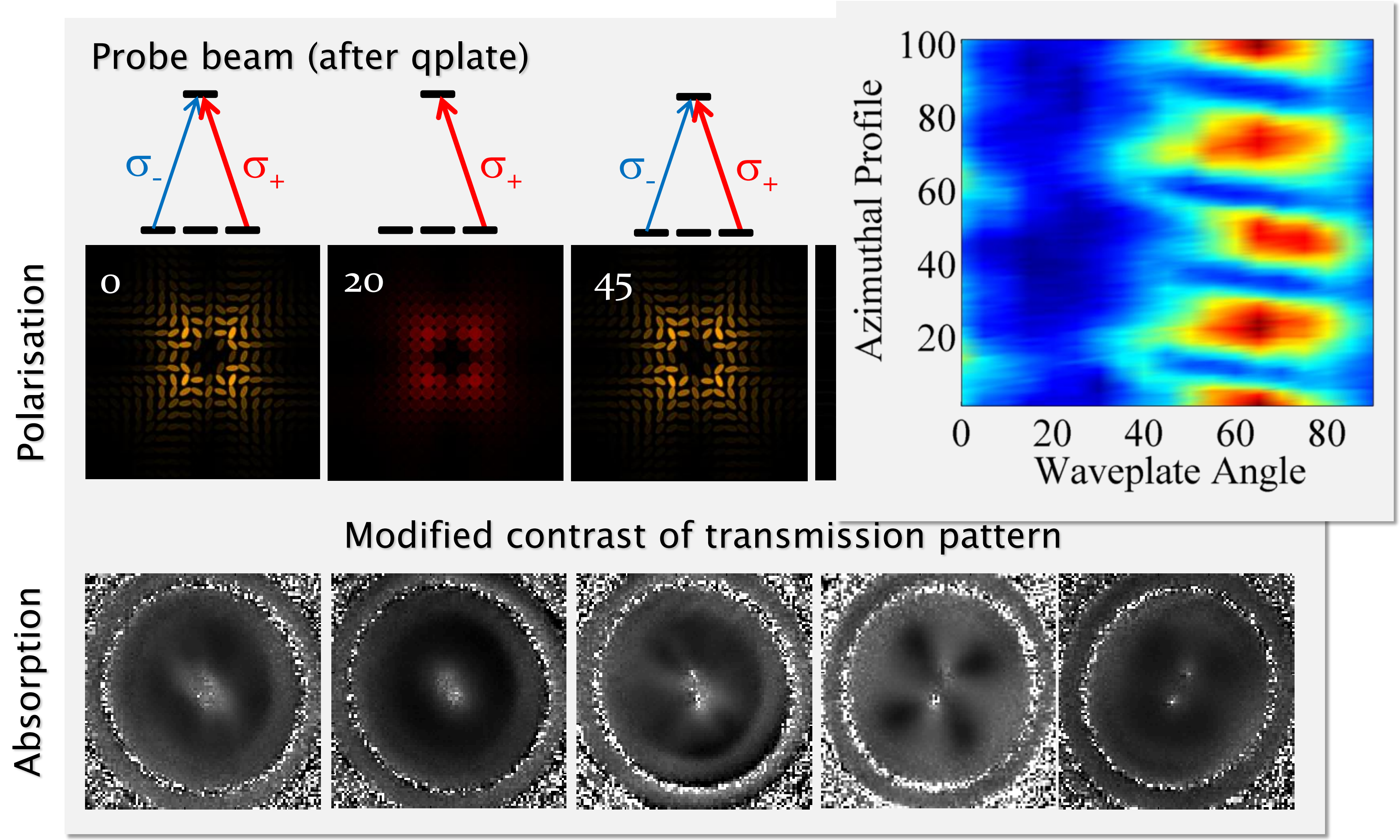
Changing orientation

- Rotating a λ/2 plate before the q-plate changes the orientation of the polarisation pattern and hence the transmission profile.



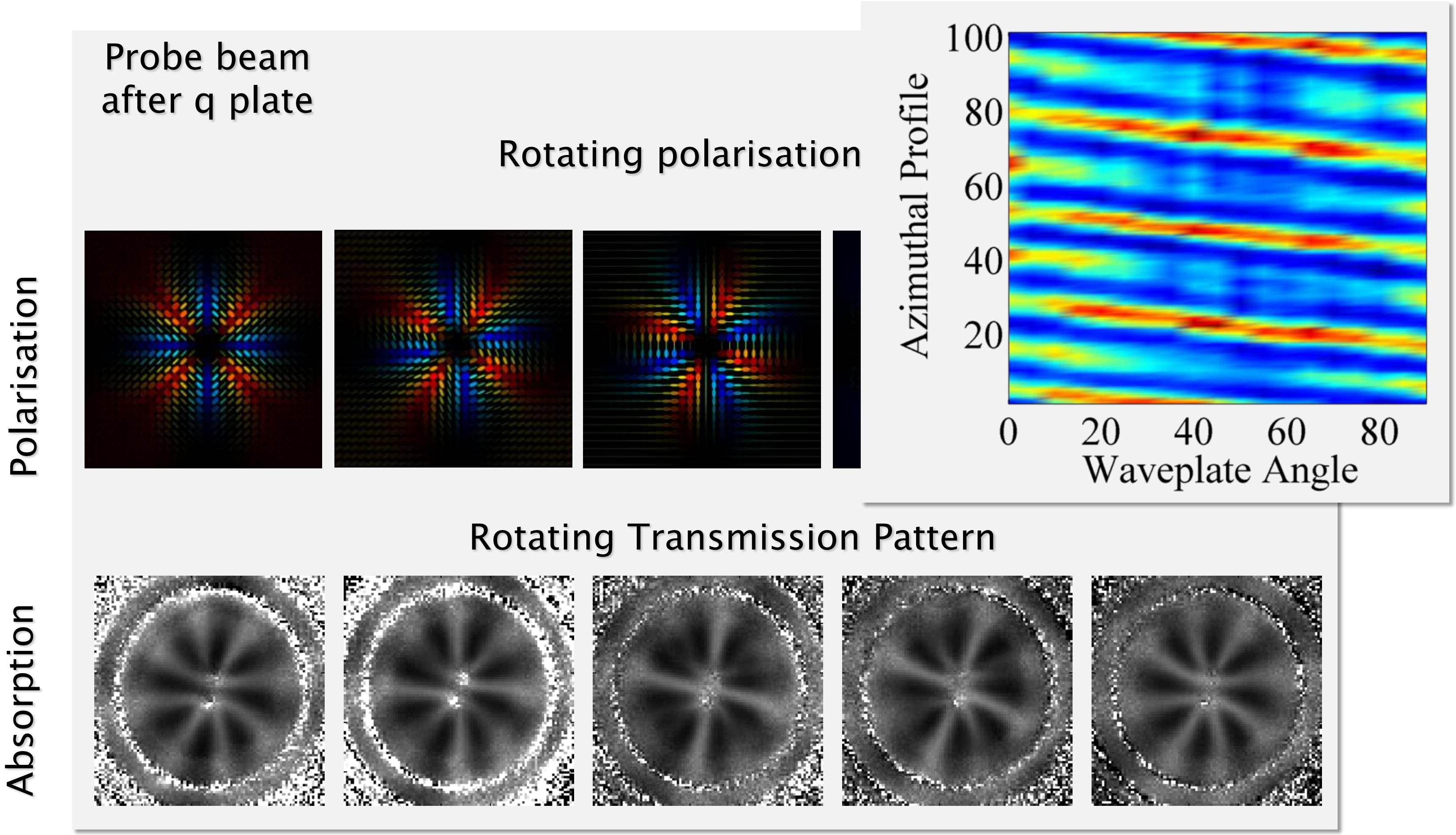
Changing balance of σ+ and σ-

- Rotating a λ/4 plate before the q-plate changes the mode decomposition and hence the contrast of the absorption.



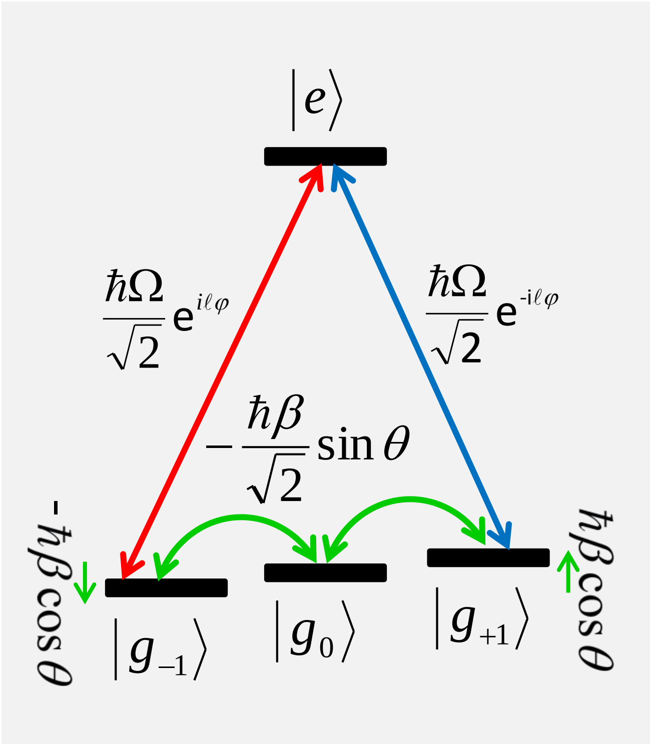
Adding spin angular momentum

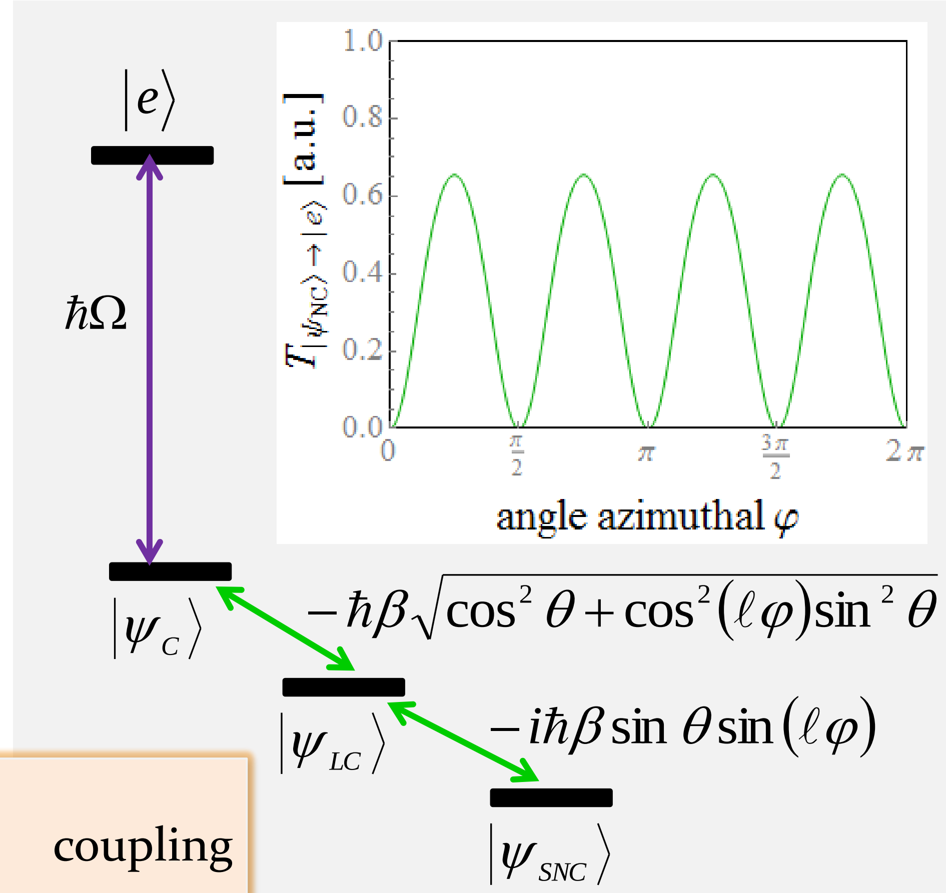
- A $\lambda/4$ plate **after** the q-plate adds spin angular momentum and changes the symmetry of the transmission pattern.



Closing the loop

- Add small B field:





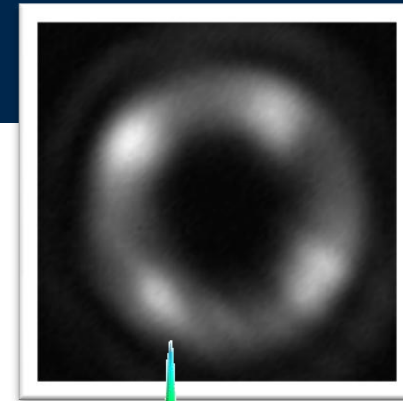
$$|\psi_C\rangle = \frac{1}{\sqrt{2}}\left(e^{-il\phi}|g_{-1}\rangle + e^{il\phi}|g_{+1}\rangle\right)$$ coupling

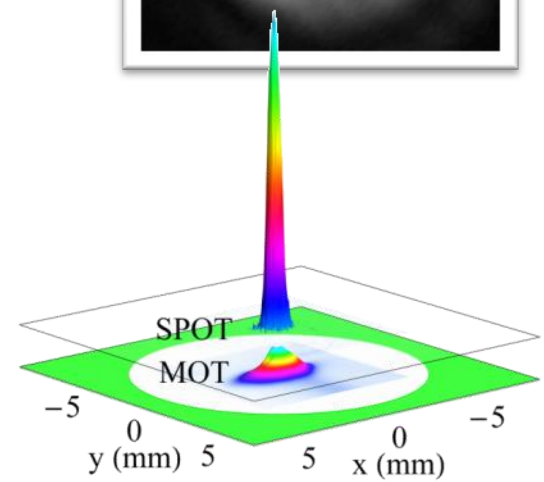
$$|\psi_{LC}\rangle = a|\psi_{NC}\rangle + b|g_0\rangle$$ a little coupling

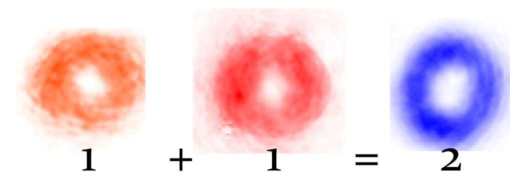
$$|\psi_{SNC}\rangle = b|\psi_{NC}\rangle - a|g_0\rangle$$ sometimes not coupling

Summary

- **First measurements of structured EIT**
- **Holographically shaped high-density trap**
  - N. Radwell et al, Phys. Rev. A **88**, 043409 (2013)
- **Frequency translation of optical OAM**
  - G. Walker et al., Phys. Rev. Lett. **108**, 243601 (2012)
- **3D beam reconstruction**
  - N. Radwell et al., Optics Express **21**, 22215 (2013)







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SEVENTH FRAMEWORK PROGRAMME

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