Electromagnetic vorticity in astronomy
Part II

Workshop on Singular Optics and its Applications to Modern Physics

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The Key point again:
The importance of handling Quantum states conserved quantities of light for astronomy

- LIGHT is the **main** carrier of information for Astronomy. However, **light is more complex** than usually assumed.
- Additional states of light must be used to get and transfer much more information or to control better the field behavior.
- In particular, among the properties of light still poorly exploited, **the Orbital Angular Momentum (OAM) and the associated Vorticity**, which instead are well known in other disciplines.
- This means: WHAT ARE WE DOING?

OAM of light is not an *intrinsic* property of photons but an observable property of the field, also in the far field zone: IT WORKS FOR ASTRONOMY!!!

From Ettore Majorana's latest works

PHYSICAL REVIEW A 78, 1 (2008)

Photon wave function: A covariant formulation and equivalence with QED

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(Received 24 July 2008)

We discuss the limits of the photon wave function (PWF) formalism, which is experiencing a revival these days as a result of new practical applications in photonics and quantum optics. We build a Dirac-like equation for the PWF written in a manifestly covariant form and show that, in the presence of charged matter fields, it reproduces the standard formulation of (classical) electrodynamics. This shows that attempts to construct a full quantum theory of interacting photons (mutually or interacting with matter) based on the so-called photon wave function approach can lead only to results already described by standard quantum electrodynamics (QED). The PWF formalism can then be used only to provide an easier description of some particular situations—for example, the propagation of free photons or photons propagating in a medium as described in Bialynicki-Birula [in *Progress in Optics*, edited by E. Wolf (Elsevier, Amsterdam, 1996), pp. 245–294] especially when the photon number remains fixed in time but not to replace QED in toto.

Thoughts about OAM: Quantum states, yes, **but do not think in the first quantization way.** To carry the information of the field it is not mandatory that it must be an intrinsic property of the light quanta…

[27] By definition, the intrinsic properties of a particle are those that do not depend on the choice of a reference frame. Those quantities are simply rest mass, electric charge, and spin. If the OAM were an intrinsic property of the photon, being an orbital angular momentum, it should be related to the intrinsic component represented by the spin S, as that calculated with QED at the single-photon level. In that case the Dirac-like equation for the RS field would admit an infinite spectrum of intrinsic angular momentum states [5] for the PWF also at the single-photon level.

Nuovo Cimento 14, 171 (1937)

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

Symmetric formulation for electron's relativistic equation. Antiparticles.

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di «antiparticelle» corrispondenti ai «vuoti» di energia negativa.*

The Dirac equation can be formulated in terms of real-valued matrices.

Interpretation:

No negative states, *"holes"* in the energy vacuum state. Neutral particles such as neutrinos (Majorana neutrinos) and Photons do not have antiparticles correspondent to "holes"

(Majorana II).

Infinite spin component equation:

Relativistic formulation for particles with arbitrary mass and arbitrary intrinsic angular momentum.

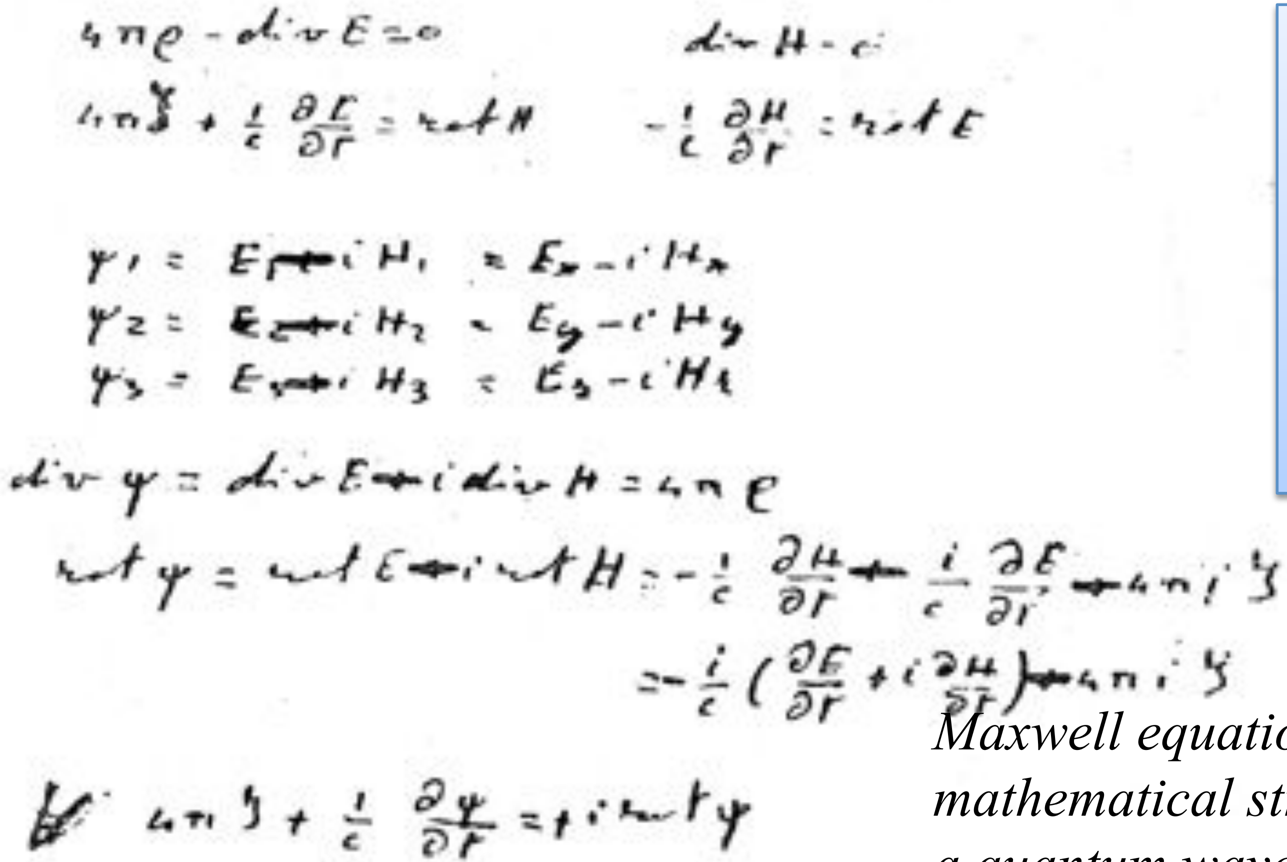
A Dirac Equation valid for spinors and bosons and then also for the quantization of the EM field in the *I-st* quantization language.

One-particle properties are not intrinsic properties of the particle. Two different languages, first and second quantization.

The intrinsic properties of a particle are only those valid in any reference frame:

- *Rest mass*, m
- *Charge*, q
- *Spin*, s

The Majorana-Wigner Quantization: quantizing a field in *I-st* quantization and its equivalence with QED



Majorana's handwritten notes:
The first attempt of quantizing the E-M field
(1930-1932)

Maxwell equations have an intrinsic mathematical structure similar to that of a quantum wave function in the relativistic quantum theory language.

Photon wavefunction and the Riemann-Silberstein Vector *F*

Elektromagnetische Grundgleichungen in bivectorieller Behandlung
(Annalen der Physik 22, 579 (1907))

$$F = \sqrt{\frac{\varepsilon_0}{2}}\left(E + icB\right)$$

$$\begin{aligned}
\nabla\cdot\mathbf{F} &= \nabla\cdot\frac{\mathbf{E}}{c} - i\nabla\cdot\mathbf{B} = \frac{\rho}{\varepsilon_o};\\
\nabla\times\mathbf{F} &= \nabla\times\frac{\mathbf{E}}{c} - i\nabla\times\mathbf{B}\\
&= -\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} - \frac{i}{c^2}\frac{\partial\mathbf{E}}{\partial t} - i\mu_o\mathbf{j}\\
&= -\frac{i}{c}\left(\frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} - i\frac{\partial\mathbf{B}}{\partial t}\right) - i\mu_o\mathbf{j}
\end{aligned}$$

The complex form of **Maxwell Equations** present a wavefunction-like structure for *F*

$$i\frac{\partial}{\partial t}F(\vec{x},t) = HF(\vec{x},t)$$

$$\mathbf{p} \leftrightarrow \hat{\mathbf{p}} \equiv -i\hbar\nabla$$

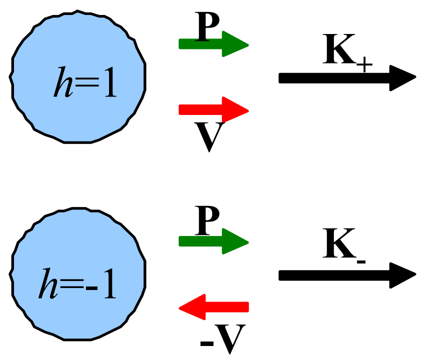
Complex form - Higher symmetry inside the equations they may correspond to the classical representation of a **su(2) X su(2)** form

Anyway… is it not a Wavefunction with the usual meaning. There are problems with the photon localization!

Photon helicity and photon wave functions

We define the helicity $h = \dfrac{\mathbf{P}\cdot\mathbf{V}}{|\mathbf{P}|^2}$

For right and left hand circularly polarized fields, $\mathbf{P}=\pm\mathbf{V}$. Then $h=\pm 1$



Photons of positive and negative helicity

$\mathbf{G}_\pm$ may be interpreted as wave functions for right and left handed photons

1. $\mathbf{G}_+$ and $\mathbf{G}_-$ obeys separate Maxwell equations
2. The right and left energies, $H_\pm$, and momenta, $\mathbf{K}_\pm$, obey separate conservation laws

$$\nabla\cdot\mathbf{G}_\pm = \rho/\varepsilon_0$$

$$\nabla\times\mathbf{G}_\pm = \pm i\left(\frac{1}{c}\frac{\partial\mathbf{G}_\pm}{\partial t} + Z_0\mathbf{j}\right)$$

$$\frac{1}{c}\frac{\partial H_\pm}{\partial t} + \nabla\cdot\mathbf{K}_\pm + \mathrm{Re}\left[\frac{\mathbf{j}\cdot\mathbf{G}_\pm^*}{c}\right] = 0$$

$$\frac{1}{c}\frac{\partial\mathbf{K}_\pm}{\partial t} + \nabla\cdot\tilde{\mathrm{T}}_\pm + \mathbf{F}_\pm^{\mathrm{RS}} = 0$$

Photon Orbital Angular Momentum

- We can now write down the POAM conservation law for right and left handed photons

$$\frac{1}{c}\frac{\partial}{\partial t}\mathbf{r}\times\mathbf{K}_{\pm}+\nabla\cdot\left(\mathbf{r}\times\tilde{\mathsf{T}}_{\pm}\right)+\mathbf{r}\times\mathbf{F}_{\pm}^{\mathrm{RS}}=0$$

- The standard OAM conservation law as is obtained as the sum of these two equations

$$\frac{1}{c}\frac{\partial}{\partial t}\mathbf{r}\times\mathbf{P}+\nabla\cdot\left(\mathbf{r}\times\mathsf{T}\right)+\mathbf{r}\times\mathbf{F}^{\mathrm{Lorentz}}=0 \qquad \mathbf{r}\times\mathbf{P}=\mathbf{r}\times\mathrm{Re}\left[\mathbf{E}\times\mathbf{B}^{*}\right]/Z_0$$

  - The standard OAM conservation law tells us about the <u>precession</u> of the linear momentum

- Taking the difference we obtain another OAM conservation law

$$\frac{1}{c}\frac{\partial}{\partial t}\mathbf{r}\times\mathbf{V}+\nabla\cdot\left(\mathbf{r}\times\mathsf{U}\right)+\mathbf{r}\times\mathbf{F}^{\mathrm{Spin}}=0 \qquad \mathbf{r}\times\mathbf{V}=-\varepsilon_0\mathbf{r}\times\mathrm{Im}\left[\mathbf{E}\times\mathbf{E}^{*}+c^{2}\mathbf{B}\times\mathbf{B}^{*}\right]/2$$

  - We interpret this OAM conservation law as the <u>nutation</u> of the linear momentum, yet not fully understood!

EM vorticity/OAM & atmospheric turbulence

PRL 94, 153901 (2005) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2005

Atmospheric Turbulence and Orbital Angular Momentum of Single Photons for Optical Communication

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The effects of propagation through random aberrations on coherence for single-photon communication systems based on orbital angular momentum states are quantified. A rotational coherence function is derived which leads to scattering equations for azimuthal modes of different orbital angular momentum states. The effect on a single-photon communication system is quantified using the channel capacity. The work shows that the decoherence effect of atmospheric turbulence on such systems is important even for weak turbulence.

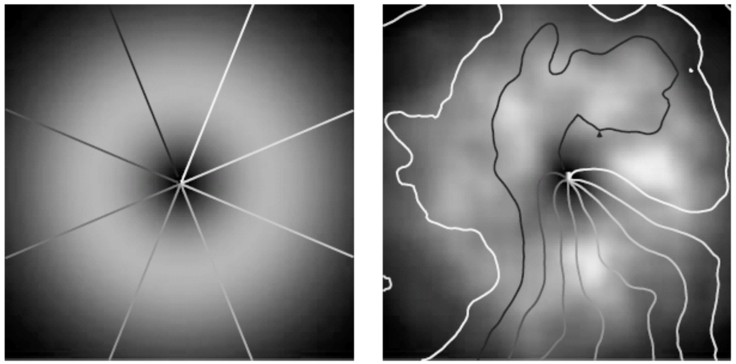

FIG. 1. Example intensity (gray scale) and phase map ($\pi/4$-spaced contours) of a pure LG_1^0 beam (left) and the same beam with aberrations caused by propagation through Kolmogorov turbulence (right).

Improving the resolving power of a diffraction-limited telescope of an order of magnitude!

PRL 97, 163903 (2006) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2006

Overcoming the Rayleigh Criterion Limit with Optical Vortices

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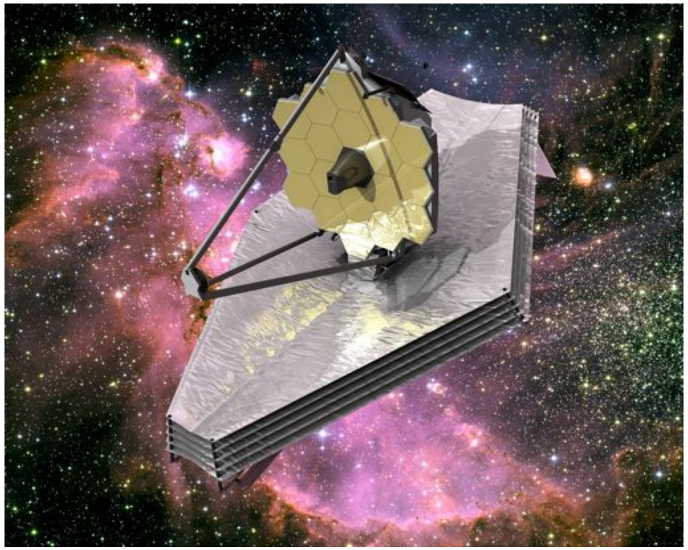
(Received 12 June 2006; published 16 October 2006)

We experimentally and numerically tested the separability of two independent equally luminous monochromatic and white light sources at the diffraction limit, using optical vortices (OV). The diffraction pattern of one of the two sources crosses a fork hologram on its center generating the Laguerre-Gaussian (LG) transform of an Airy disk. The second source, crossing the fork hologram in positions different from the optical center, generates nonsymmetric LG patterns. We formulated a criterion, based on the asymmetric intensity distribution of the superposed LG patterns so created, to resolve the two sources at angular distances much below the Rayleigh criterion. Analogous experiments in white light allow angular resolutions which are still one order of magnitude below the Rayleigh criterion. The use of OVs might offer new applications for stellar separation in future space experiments.

DOI: 10.1103/PhysRevLett.97.163903 PACS numbers: 42.25.−p, 42.40.Eq, 42.40.Jv, 42.87.Bg



The James Webb Space Telescope

Credit: ESA (C. Carreau)

Super Resolution with OVs in diffraction-limited telescopes and other optical instruments

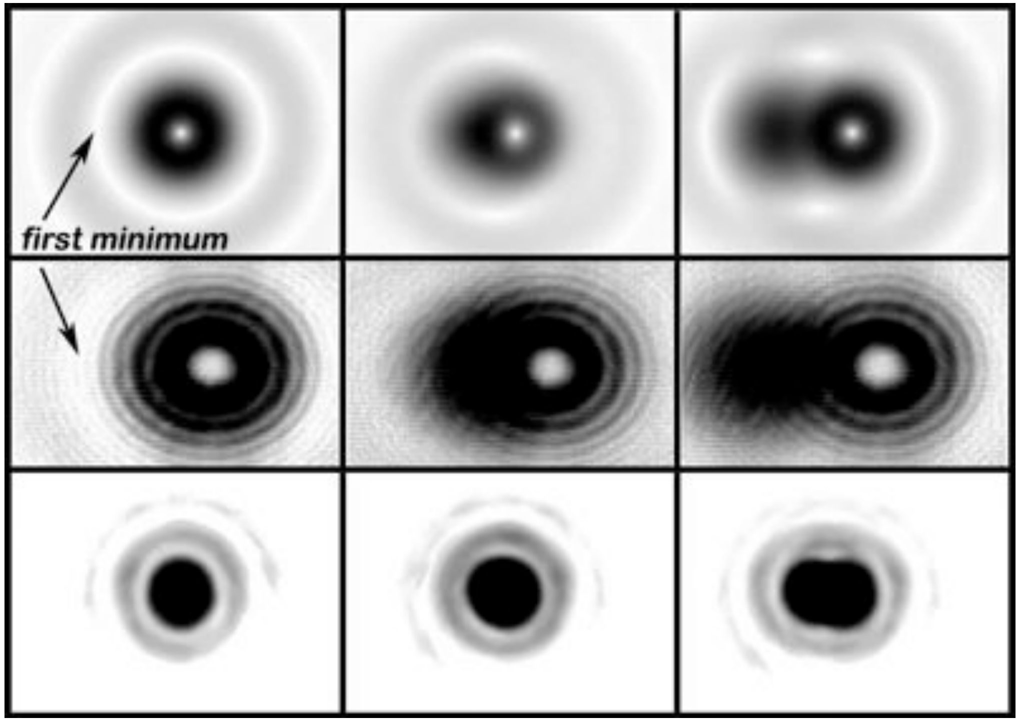


FIG. 2. Images of the separation of two nearby monochromatic sources having same intensity (inverted colors). Upper row: numerical simulations of LG modes generated by an $l = 1$ fork hologram at different separations. Central row: the corresponding experimental results. Bottom row: Airy patterns of the two sources on the hologram plane. Left column: the superposed sources. Mid column: the sources separated by 0.42 times the Rayleigh criterion. Right column: the sources separated by 0.84 times the Rayleigh criterion radius.

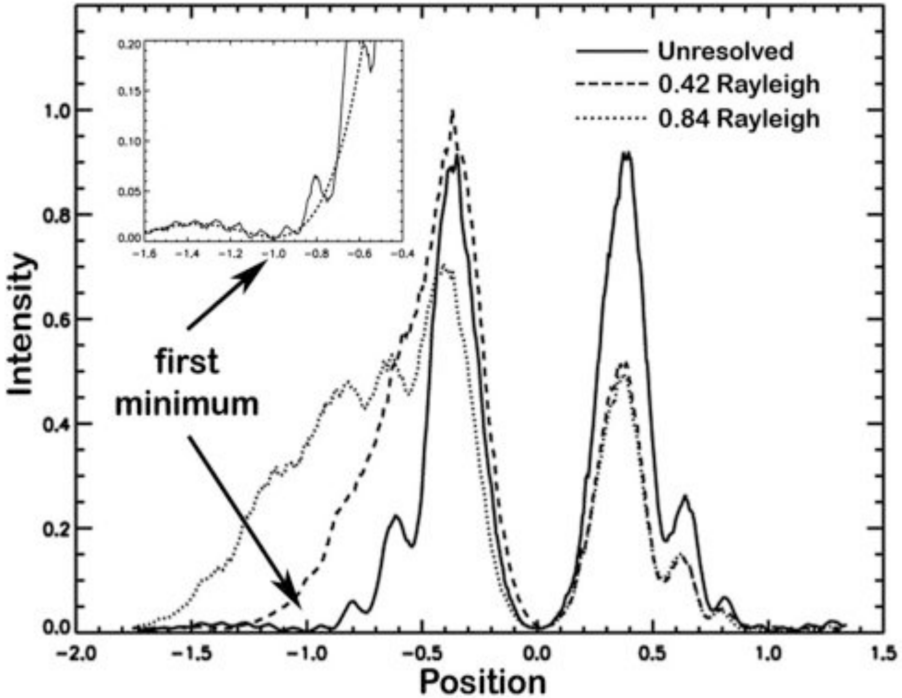


FIG. 3. Main figure: experimental intensity profiles of the superposed LG modes of the two monochromatic sources normalized with respect to the peaks relative to coincident sources. The three cases shown refer to the same separations as in Fig. 2. When one of the two sources is shifted to an off-axis position the combined profile becomes clearly asymmetric. Inset: zoom of the position of the *first minimum* of the LG transform of the Airy disk; the dotted curve represents the results of numerical simulations.

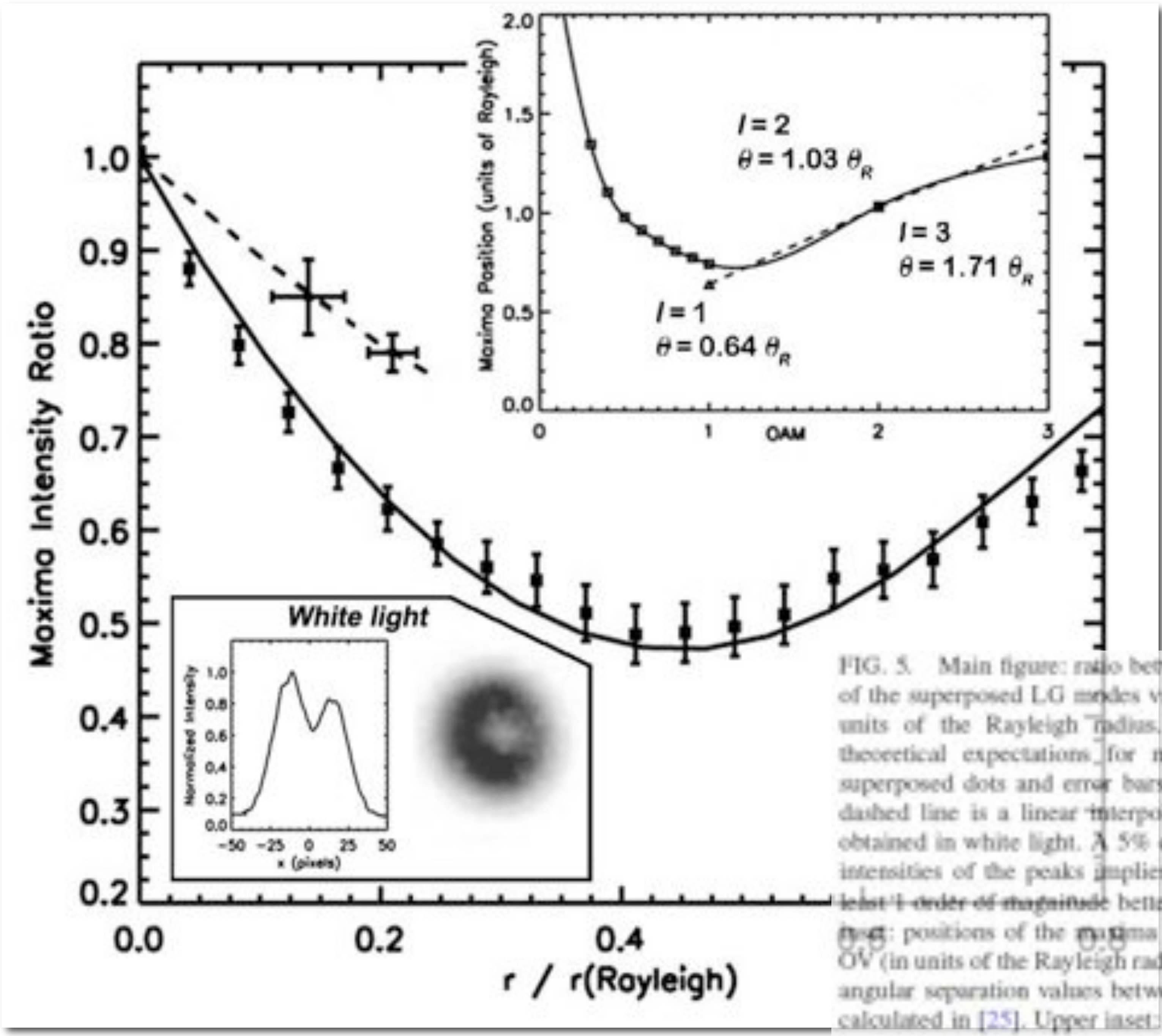


FIG. 5. Main figure: ratio between the intensities of the peaks of the superposed LG modes vs the off-axis shift of the spot in units of the Rayleigh radius. The solid line represents the theoretical expectations for monochromatic light, while the superposed dots and error bars are the experimental data. The dashed line is a linear interpolation of two experimental data obtained in white light. A 5% difference (see text) between the intensities of the peaks implies in both cases a separability at least 1 order of magnitude better than the Rayleigh limit. Lower inset: positions of the maxima of the LG modes relative to the OV (in units of the Rayleigh radius) vs OAM. Triangles show the angular separation values between two equally charged OVs as calculated in [25]. Upper inset: white light LG modes generated by two equally luminous simulated stars as seen with a diffraction limited telescope. The angular separation is ~10 times below the Rayleigh radius (empty diamond in the main figure).

OV manipulation for detection at the telescope Producing Optical Vortices with starlight and the problem of atmospheric seeing

A&A 488, 1159–1165 (2008)
DOI: 10.1051/0004-6361:200810469

Astronomy & Astrophysics

Optical vortices with starlight

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ABSTRACT

Aims. In this paper we present our first observations at the Asiago 122 cm telescope of $\ell = 1$ optical vortices generated with starlight beams.

Methods. We used a fork-hologram blazed at the first diffraction order as a phase modifying device. The multiple system Rasalgethi (α Herculis) in white light and the single star Arcturus (α Bootis) through a 300 Å bandpass were observed using a fast CCD camera. In the first case we could adopt the Lucky Imaging approach to partially correct for seeing effects.

Results. For both stars, the optical vortices could be clearly detected above the smearing caused by the mediocre seeing conditions. The profiles of the optical vortices produced by the beams of the two main components of the α Her system are consistent with numerically simulated on-axis and off-axis optical vortices. The optical vortices produced by α Boo can also be reproduced by numerical simulations. Our experiments confirm that the ratio between the intensity peaks of an optical vortex can be extremely sensitive to off-axis displacements of the beam.

Conclusions. Our results give insights for future astronomical applications of optical vortices both for space telescopes and ground-based telescopes with good seeing conditions and adaptive optics devices. The properties of optical vortices can be used to perform high precision astrometry and tip/tilt correction of the isoplanatic field. We are now designing a $\ell = 2$ optical vortex coronagraph around a continuous spiral phase plate. We also point out that optical vortices could find extremely interesting applications also in the infrared and radio wavelengths.

Key words. instrumentation: miscellaneous – techniques: high angular resolution – atmospheric effects

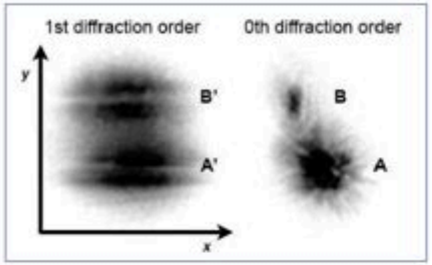
HIGHLIGHTS: this week in A&A

Volume 488-3 (September IV 2008)

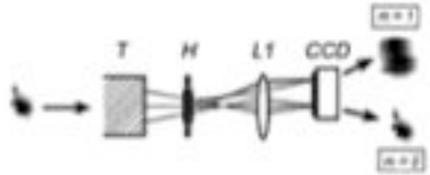
In section 13. Astronomical instrumentation

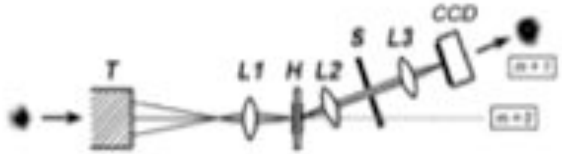
"Optical vortices with starlight", by G. Anzolin, F. Tamburini, A. Bianchini, G. Umbriaco, and C. Barbieri, A&A 488, p. 1159

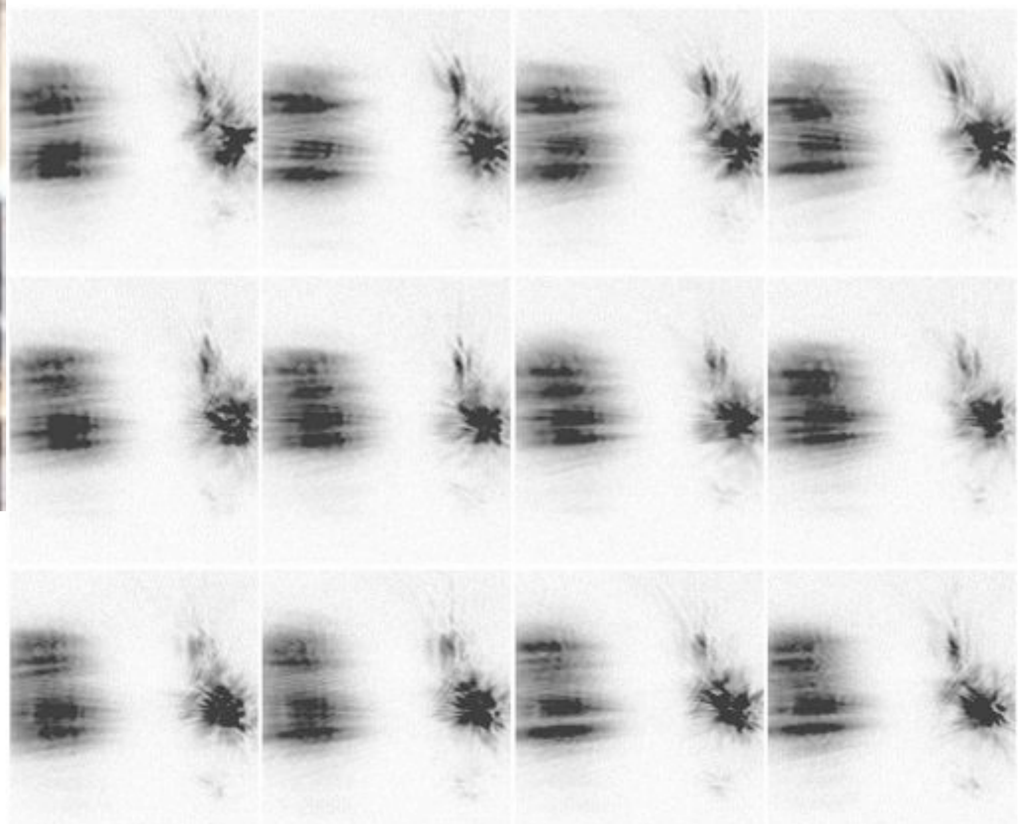
This paper describes two experiments with light beams carrying photon orbital angular momentum (POAM). The light beams were generated by an astronomical telescope using stars as light sources. The POAM was produced by means of a fork hologram and off-axis imaging, and measured by creating l = 1 focal plane images. These images were then compared with the predictions of theoretical optics. The experiments completed by the authors demonstrated the feasibility of POAM measurements with an astronomical telescope. They showed that instrumental effects can be predicted and seeing effects can be eliminated sufficiently to ensure that POAM measurements are possible even in poor atmospheric conditions. By presenting these results, this paper provides important information for potential, future observations of POAM in astronomical objects



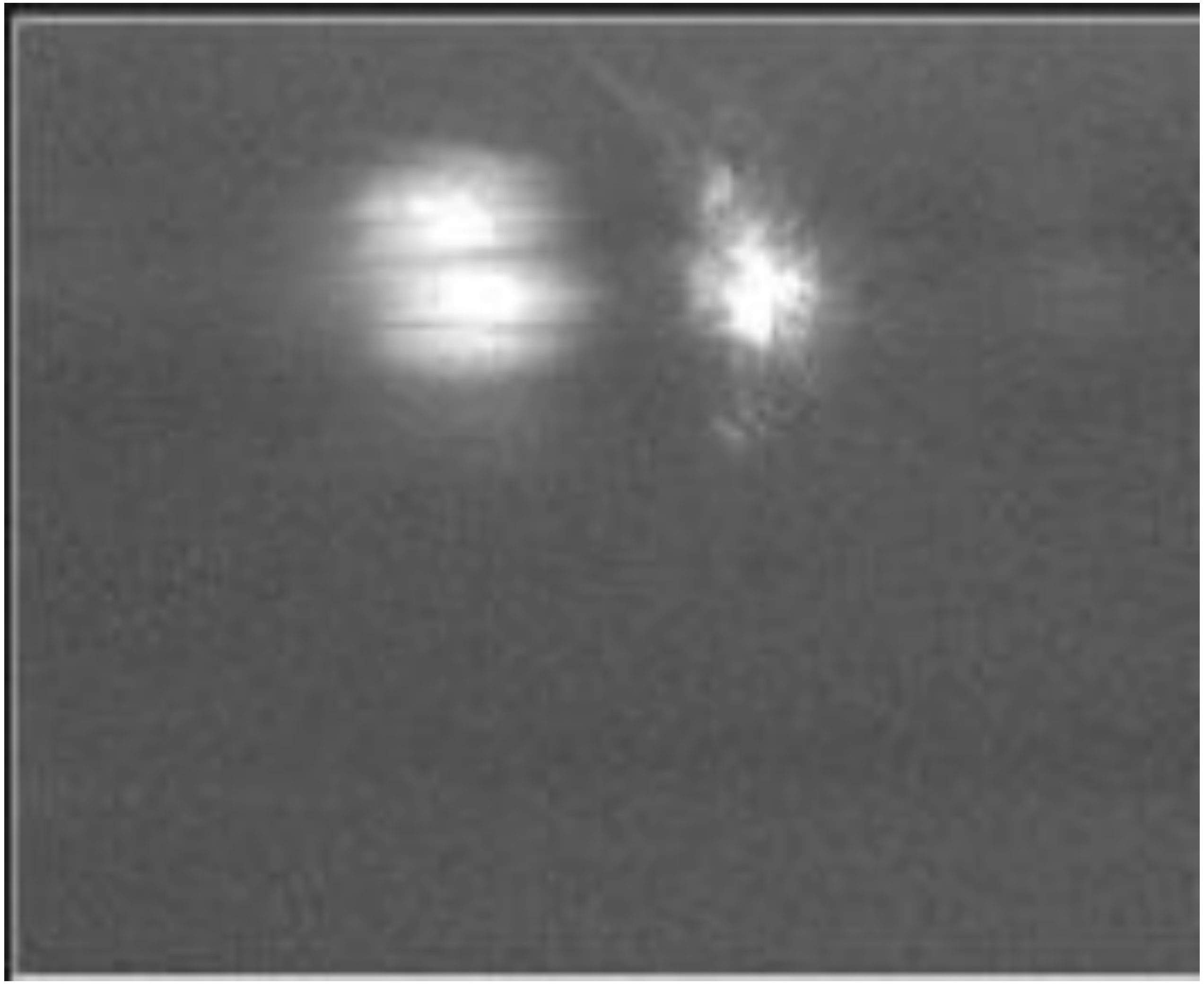
Test @ telescope: atmospheric seeing



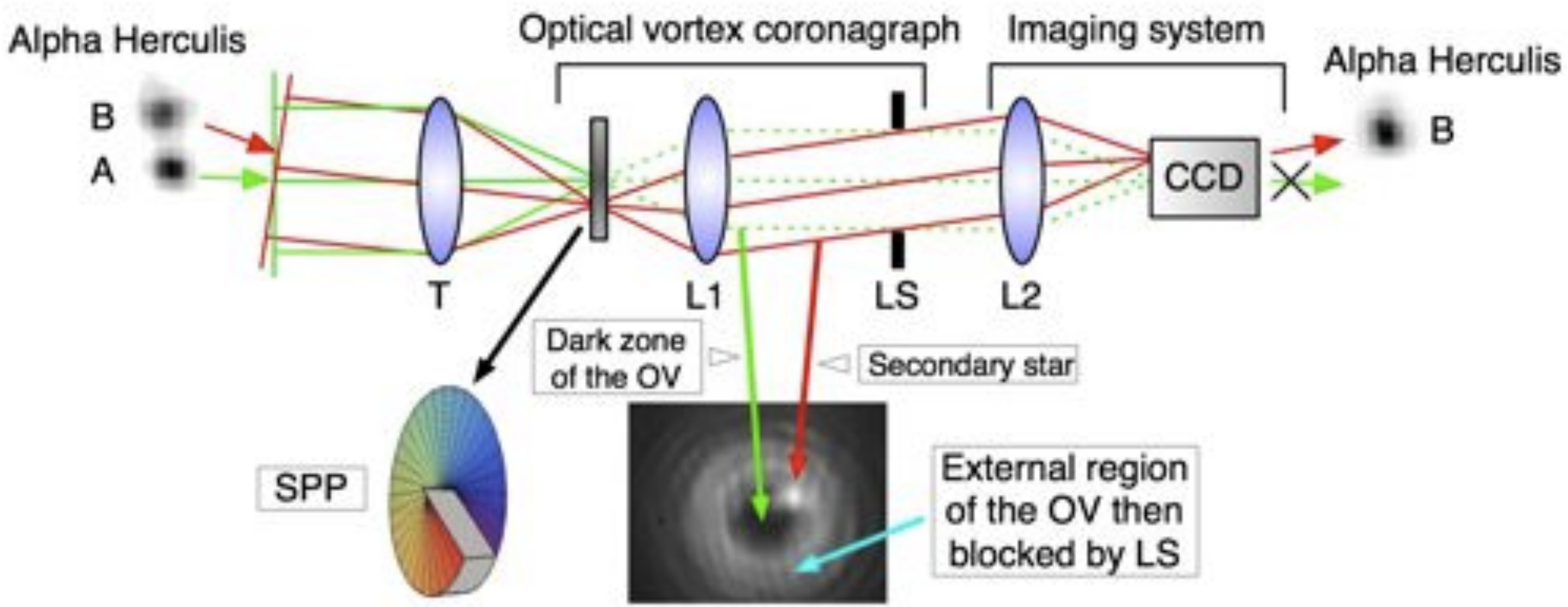




l=0 and l=1 vortices from starlight



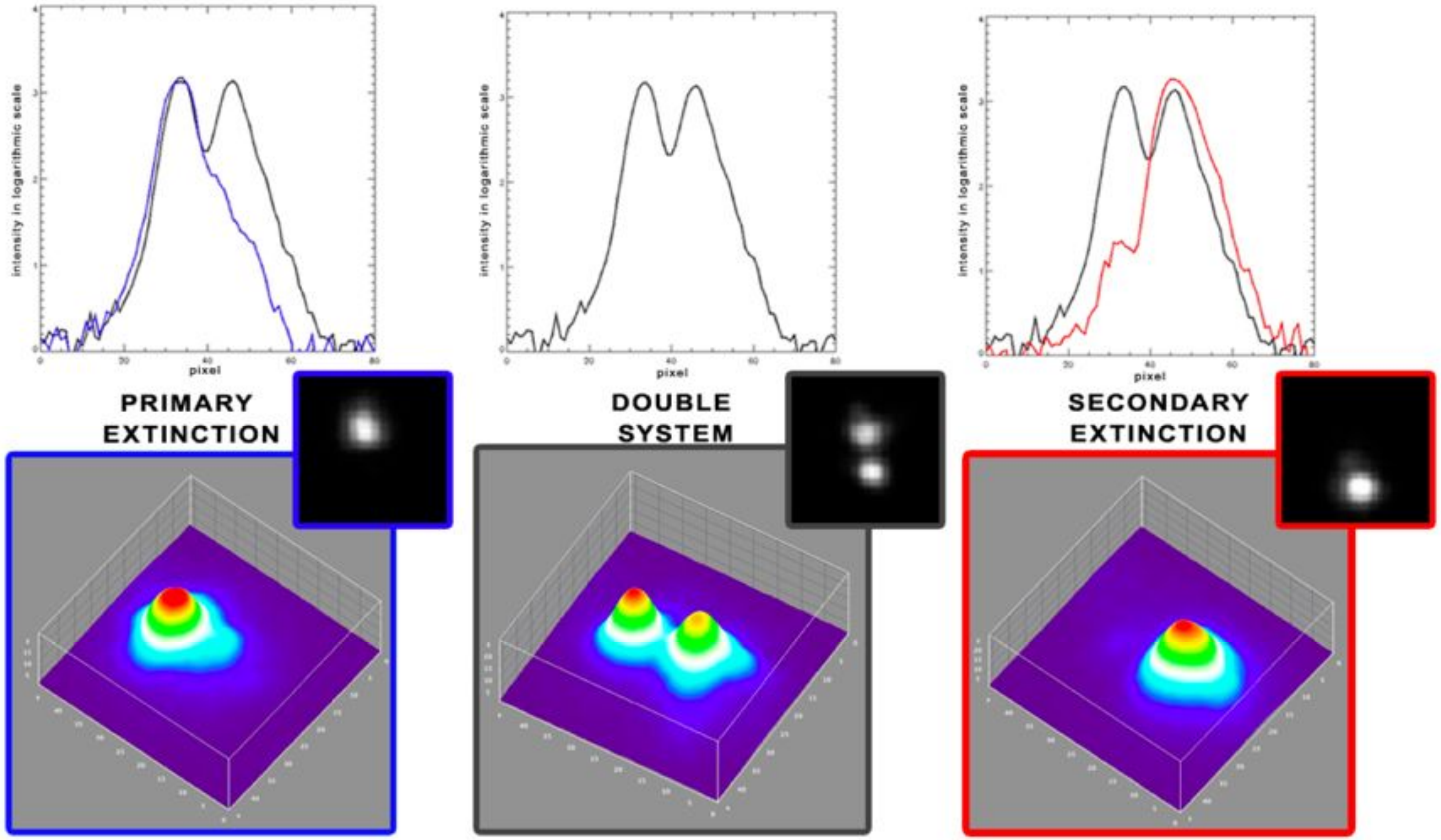
Optical Vortex Coronagraph



Schneider J. (LUTH), Boccaletti A. (LESIA), Aylward A. (UCL), Baudoz P.(LESIA), Beuzit J.-L. (LAOG), Brown R. (STScI), Cho J. (QMUL), Dohlen K. (LAM), Ferrari M. (LAM), Galicher R. (LESIA), Grasset O. (U. Nantes), Grenfell L. (Tech. U. Berlin), Guyon O. (Subaru)., Hough J. (U. HertfordS.), Kasper M. (ESO), Keller Ch. (U. Utrecht), Longmore A. (ROE), Martin E. (IAC), Mawet D. (JPL/ULg), Ménard F. (LAOG), Merin B. (ESTEC), Palle E. (IAC), Perrin G. (LESIA), Pinfield, D. (U. HertfordS.), Sein E. (Astrium), Shore P. (U. Cranfield), Sotin Ch. (JPL/U. Nantes), Stam D. (SRON), Surdej J. (ULg), Tamburini F. (U. Padova), Tinetti G. (UCL), Udry S. (Obs. Genève), Verinaud C. (LAOG), Walker D. (UCL/Zeeko Ltd)

Ask Elettra... See the poster

Coronagraphy @ T122 Asiago telescope



2-3 λ/D (a)

2.8×10^{-10} (b)

2-8 λ/D (a)

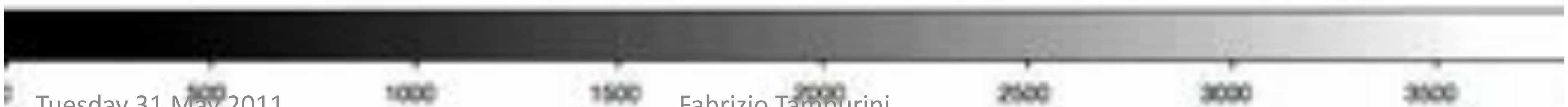
9.3×10^{-11} (b)

4-5 λ/D (a)

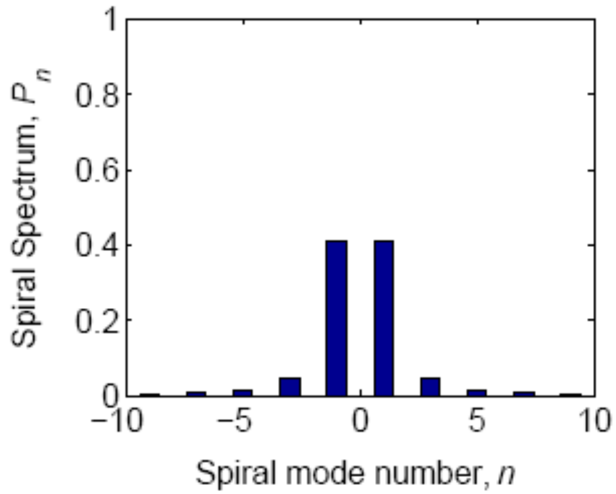
6.4×10^{-11} (b)

Theoretical contrast for a monochromatic source (a) *versus* the separation (b).
It is sufficient for the direct detection of extra-solar planets!

Lucky imaging & Coronagraphy



OAM spectrum, a new diagnostic in optics and astrophysics.



Input gaussian

Output OAM spectrum

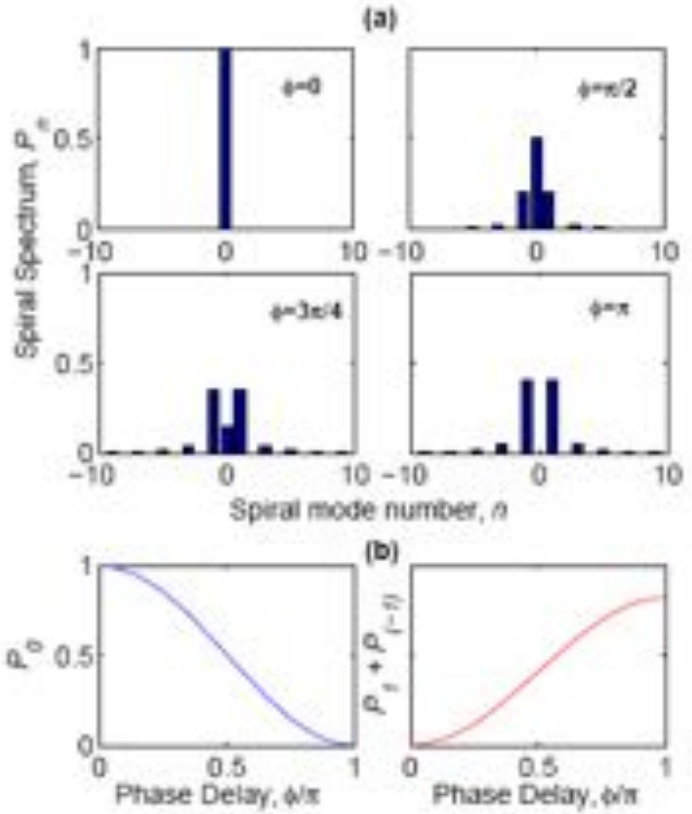


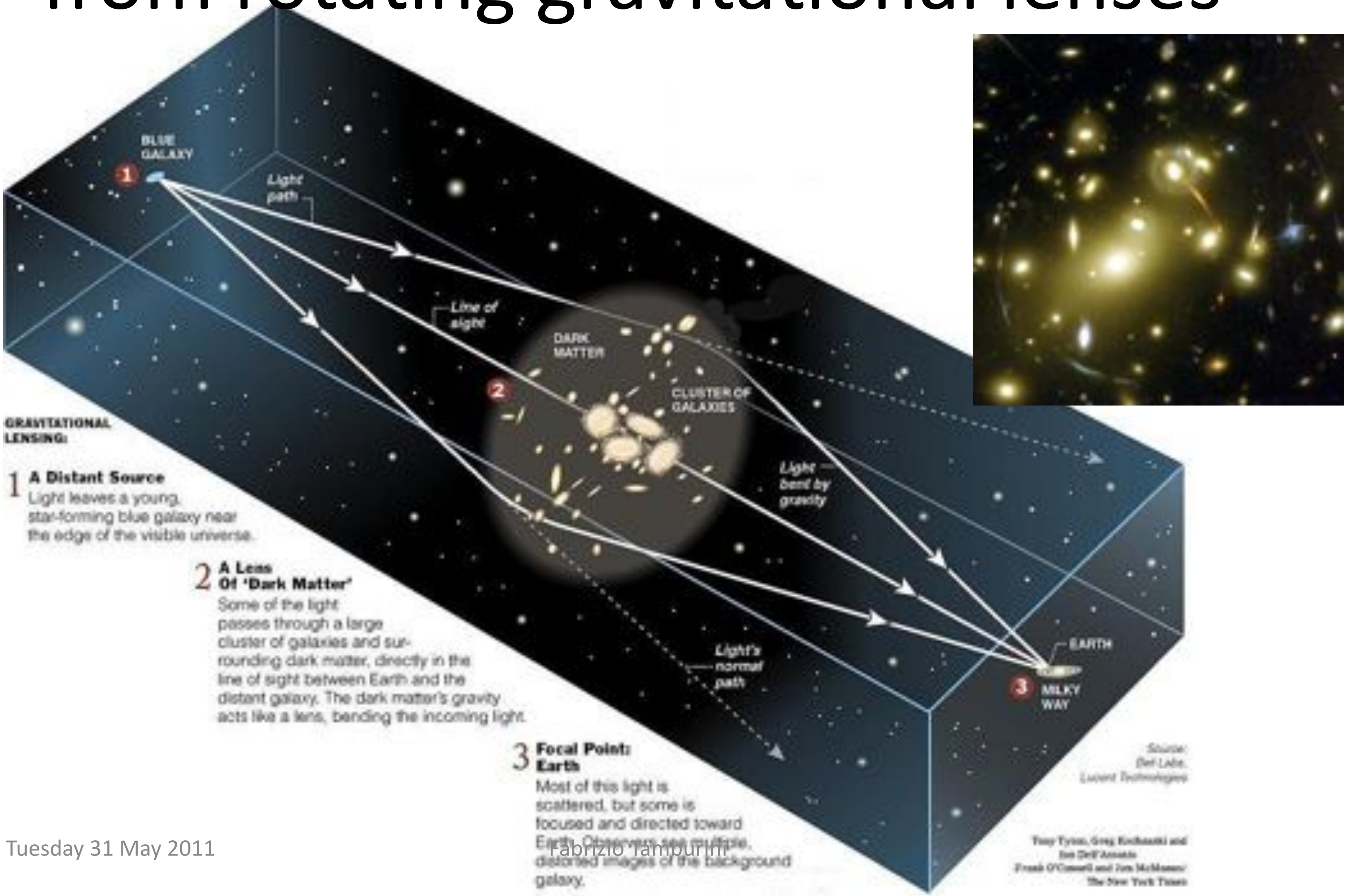
Fig. 2. Spiral spectra of the output field reflected/refracted from a target imprinting a π phase dislocation across in the center of the illuminating beam. The transfer function of such a target has the form: $R(x,y) = 1$ for $x < 0$, and $R(x,y) = -1$ otherwise. The input field is a Gaussian beam (pure LG_{00} mode).

Fig. 3. (a) Spiral spectra of the output field reflected/refracted from a target imprinting a ϕ phase dislocation across in the center of the illuminating beam for four selected values of the phase dislocation. (b) Weight of the central ($n = 0$), P_0 and the first adjacent ($n = \pm 1$) sidelobes, $P_1 + P_{(-1)}$ versus the normalized phase dislocation ϕ/π. The transfer function of the target has the form: $R(x,y) = 1$ for $x < 0$, and $R(x,y) = e^{i\phi}$ otherwise. The input field is a Gaussian beam.

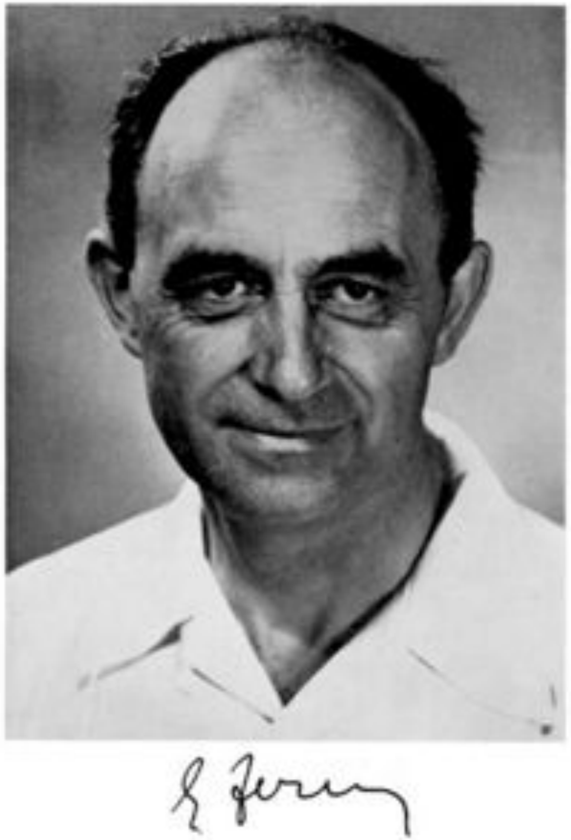
OAM from astrophysical sources 1 from plasma inhomogeneities

P.S.: Ask Anna Sponselli

OAM from astrophysical sources 2
from rotating gravitational lenses



What if the lens is rotating?



PROCEEDINGS OF THE ROYAL SOCIETY A

Proc. R. Soc. A (2007) **463**, 2185–2194
doi:10.1098/rspa.2007.1871
Published online 26 June 2007

On the dragging of light by a rotating medium

By Jörg B. Götte[1,*], Stephen M. Barnett[1] and Miles Padgett[2]

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When light is passing through a rotating medium the optical polarization is rotated. Recently, it has been reasoned that this rotation applies also to the transmitted image. We examine these two phenomena by extending an analysis of Player (Player 1976 *Proc. R. Soc. A* **349**, 441–445) to general electromagnetic fields. We find that in this more general case, the wave equation inside the rotating medium has to be amended by a term which is connected to the orbital angular momentum (OAM) of the light. We show that optical spin and OAM account for the rotation of the polarization and the rotation of the transmitted image, respectively.

Keywords: image rotation; polarization; rotating dielectric; specific rotary power

Sul trascinamento del piano di polarizzazione da parte di un mezzo rotante. (On the Rotation of the Plane of Polarization in a Rotating Medium.) Rend. Lincei, 32(5):115-118.

Rotating optical lens

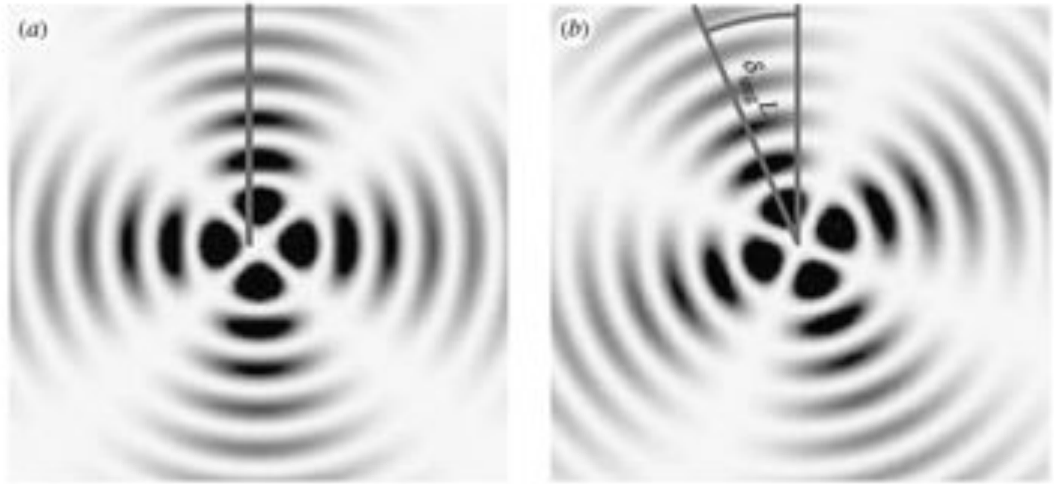

Figure 1. Image rotation. (a) Intensity pattern created by the superposition of Bessel beams in (4.1) for m=2. (b) On propagation, the relative phase between the constituent Bessel beams changes which leads to a rotation of the pattern. The angle of rotation at a propagation distance L is given by $\delta_{\rm long} L$.

Rotating Black Hole

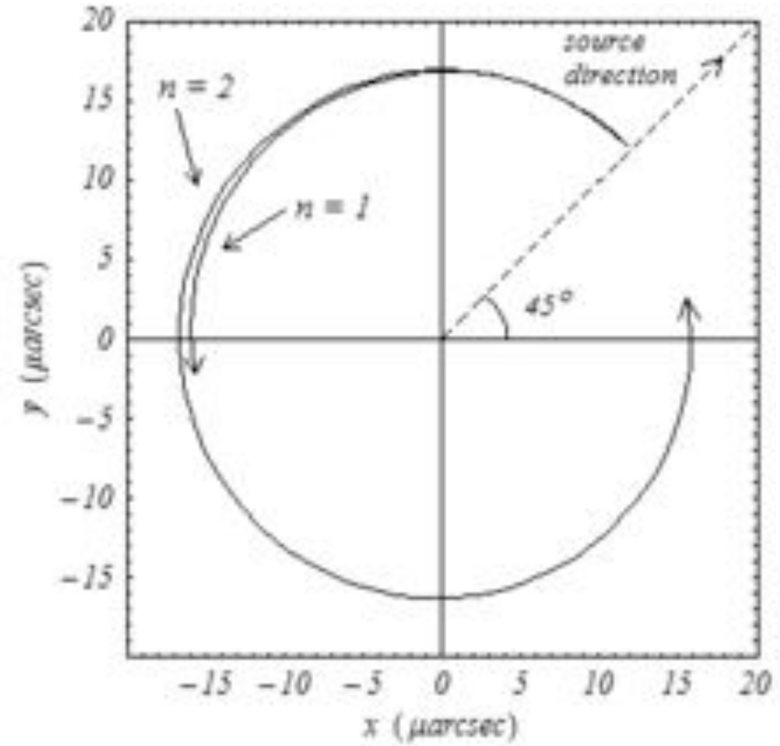

FIG. 6: Positions of the two lowest order primary RIs (n = 1, 2 and p = −1) as a function of the normalized angular momentum of the black hole a. The arrows in the curves represent the direction of the movement as we increase a from 0 to 1. The source is located at $\xi_s = 1$ μarcsec and $\varphi_s = \pi/4$.

Strong Field Gravitational Lensing by a Kerr Black Hole

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Nuovo Cim.B119:489-519,2004

tion $\Delta\varphi$ for a given a. The physical picture emerging is a very simple one: the angular momentum of the black hole just adds a "twist" in the direction of the rotation to the usual Schwarzschild trajectory. To give an intuition of the full movement of the images, including their separation ξ_i, in Fig. 6 we have plotted the position of the two lowest order images ($n = 1, 2$) as a function of the spin parameter a.

Faraday rotation - geometric optics

General Relativity and Gravitation, Vol. 2, No. 4 (1971), pp. 347–357.

On the Gravitational Field Acting as an Optical Medium†

FERNANDO de FELICE

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Mon. Not. R. Astron. Soc. **363,** 177–1

11/j.1365-296

Relativistic emission lines from accretion discs around black holes

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PLANE OF POLARIZATION ROTATION INDUCED BY A NON-MINKOWSKIAN SPACETIME

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Phase evolution of the photon in Kerr spacetime

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In this paper, we explore some aspects of the gravitational lens effects due to a Kerr black hole. Under the eikonal approximation of the Maxwell equations in curved space, the spin function of a photon in the degenerate metric is determined. Furthermore, we present an investigation of the phase factor that a photon acquires in Kerr spacetime. The resulting phase consists of two parts: a real and an imaginary one. The real part has been interpreted as contributing a rotational angle of the plane polarization for linearly polarized light, and the imaginary one results in the light intensity amplification along with the photon's trajectory in the gravitational field. Finally, we provide the so-called "Sagnac factor" related to the phase shift.

PACS number(s): 04.40.+c, 03.50.De, 03.65.Sq nature physics

LETTERS

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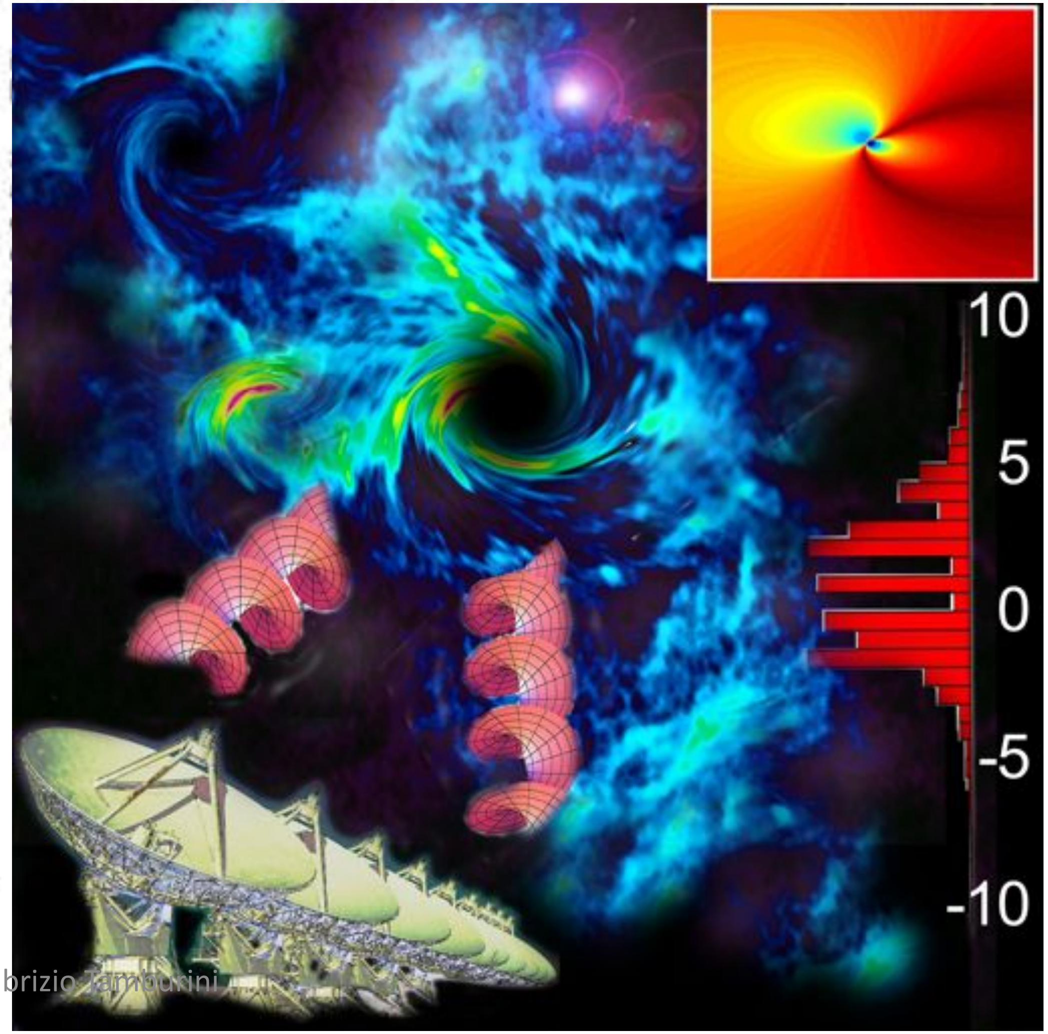
Twisting of light around rotating black holes

Fabrizio Tamburini[1], Bo Thidé[2]*, Gabriel Molina-Terriza[3] and Gabriele Anzolin[4]

Kerr black holes are among the most intriguing predictions of Einstein's general relativity theory[1,2]. These rotating massive astrophysical objects drag and intermix their surrounding space and time, deflecting and phase-modifying light emitted near them. We have found that this leads to a new relativistic effect that imprints orbital angular momentum on such light. Numerical experiments, based on the integration of the null geodesic equations of light from orbiting point-like sources in the Kerr black hole equatorial plane to an asymptotic observer[3], indeed identify the phase change and wavefront warping and predict the associated light-beam orbital angular momentum spectra[4]. Setting up the best existing telescopes properly, it should be possible to detect and measure this twisted light, thus allowing a direct observational demonstration of the existence of rotating black holes. As non-rotating objects are more an exception than a rule in the Universe, our findings are of fundamental importance.

In curved spacetime geometries, the direction of a vector is generally not preserved when parallel-transported from one event to another, and light beams are deflected because of gravitational



Author contributions

F.T., B.T. and G.M-T. developed the model. F.T. carried out the numerical simulations. G.A. calculated and plotted the OAM spectra. F.T. and B.T. wrote the manuscript. All authors discussed and commented on the manuscript.

Geometry

SUPPLEMENTARY INFORMATION DOI: 10.1038/NPHYS1907

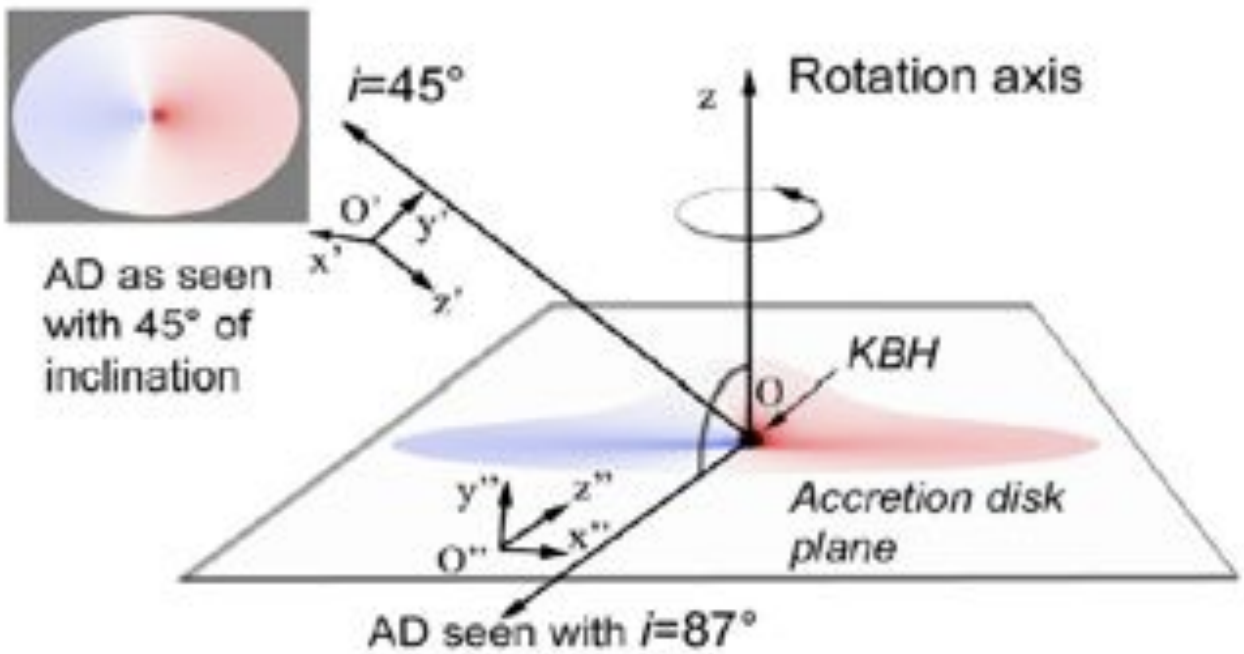
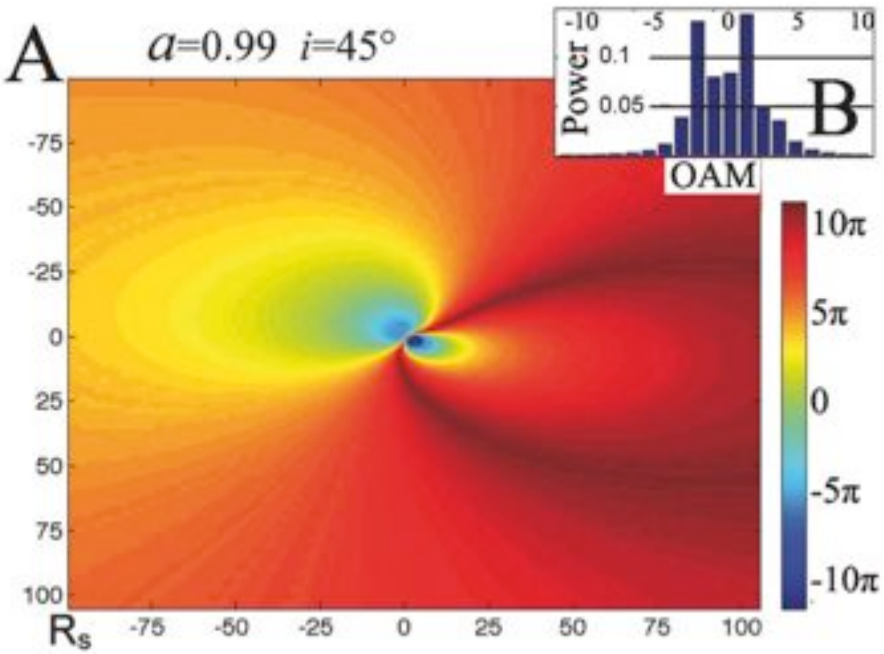


Figure 1: Thin accretion disk as seen by an observer at infinity at i=45° (x', y', z') and at i = 87° (x'', y'', z'').

OAM and rotating Black Holes



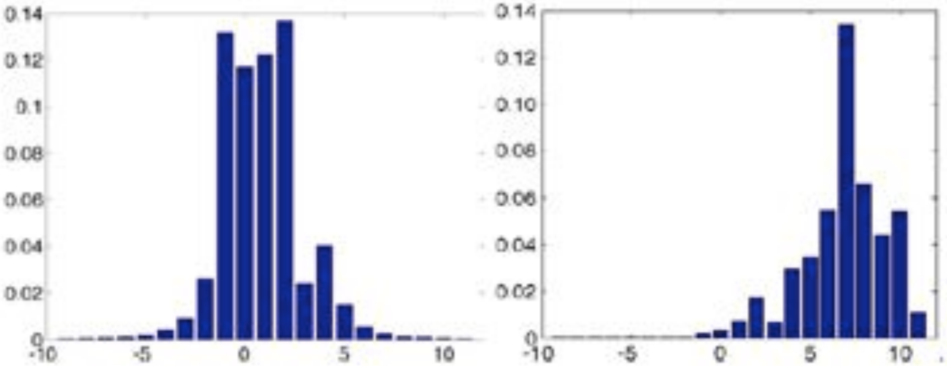
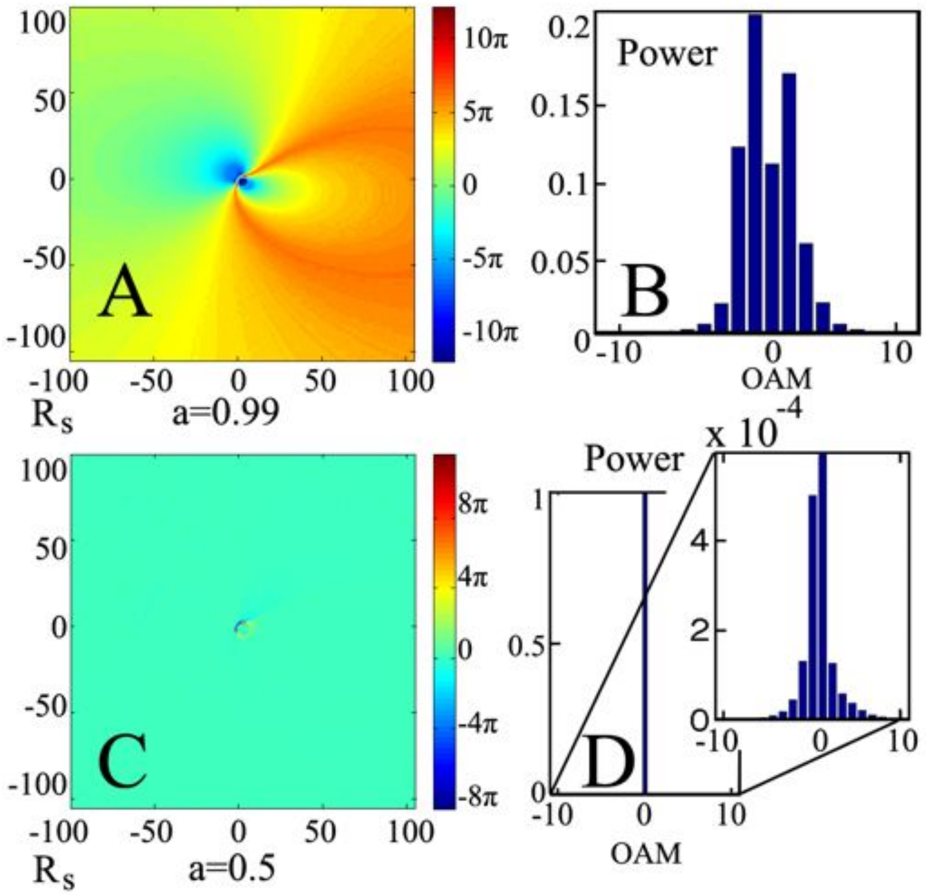


Figure 2: Spiral spectrum of an optically thin accretion disk and of an accretion disk with limb darkening emission.



Radio-astronomy and something new

Radio astronomical applications with Bo Thidé

Practical applications:

- Can OAM be used in the radio domain?
- Implications in Telecomm
- Many channels in a single frequency...

Radio OAM

PRL 99, 087701 (2007) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2007

Utilization of Photon Orbital Angular Momentum in the Low-Frequency Radio Domain

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We show numerically that vector antenna arrays can generate radio beams that exhibit spin and orbital angular momentum characteristics similar to those of helical Laguerre-Gauss laser beams in paraxial optics. For low frequencies ($\lesssim 1$ GHz), digital techniques can be used to coherently measure the instantaneous, local field vectors and to manipulate them in software. This enables new types of experiments that go beyond what is possible in optics. It allows information-rich radio astronomy and paves the way for novel wireless communication concepts.

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Exotic types of Poynting flux radiation patterns and corresponding instantaneous **E** field *vectors*

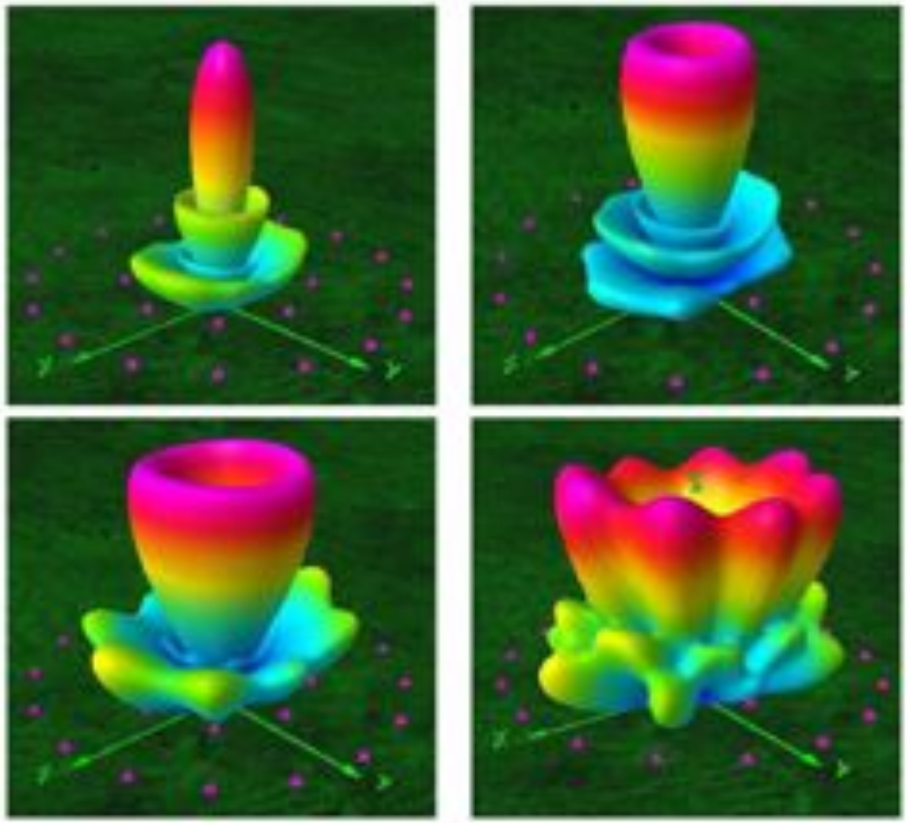

FIG. 1 (color online). Radiation patterns for radio beams generated by one circle of 8 antennas and radius λ plus a concentric circle with 16 antennas and radius 2λ; all antennas are 0.25λ over the ground. Notice the influence of l on the radiation pattern. Here $l = 0$ (upper left), $l = 1$ (upper right), $l = 2$ (lower left), and $l = 4$ (lower right).

FIG. 2. Samples of instantaneous electric field vectors **E** across the main lobes of the beams in Fig. 1 (same l values and plotting order). The size of an arrow is linearly proportional to the local $|\mathbf{E}|$. As expected for OAM carrying beams, the phase of the EM field changes by $l2\pi$ for a full turn around the beam axis.

Field *vector* sensing means *total* configurability

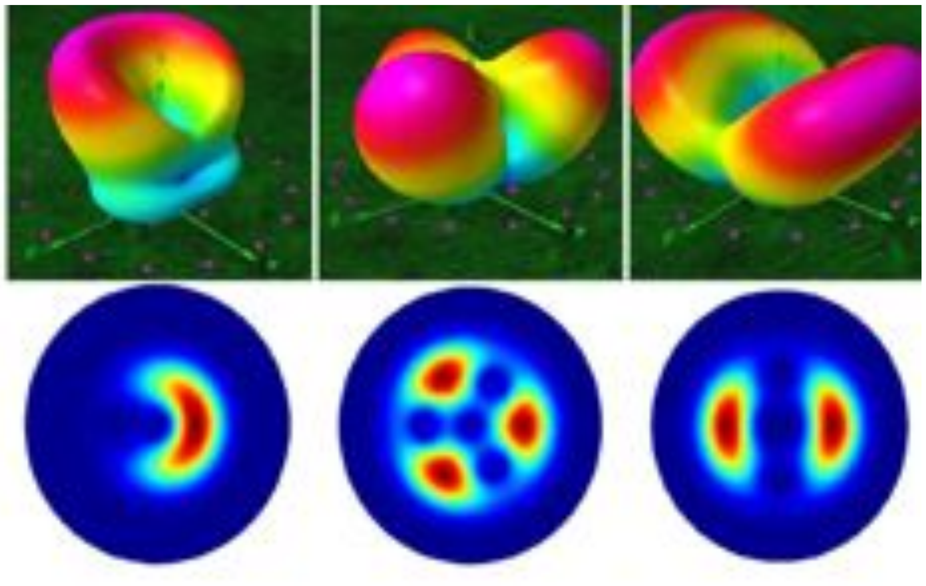

FIG. 3 (color online). Beams obtained by superimposing twc different OAM states. The upper three panels show the radiatior patterns for the antenna array, and the lower three panels show the corresponding intensity patterns, head on, calculated fo Laguerre-Gaussian beams. The leftmost are for $l_1 = 1$ and $l_2 =$ 2, the middle ones are for $l_1 = 1$ and $l_2 = 4$, and the rightmos are for $l_1 = 2$ and $l_2 = 4$. Notice the good agreement betweer the patterns obtained with the antenna array model and the paraxial LG beam model.

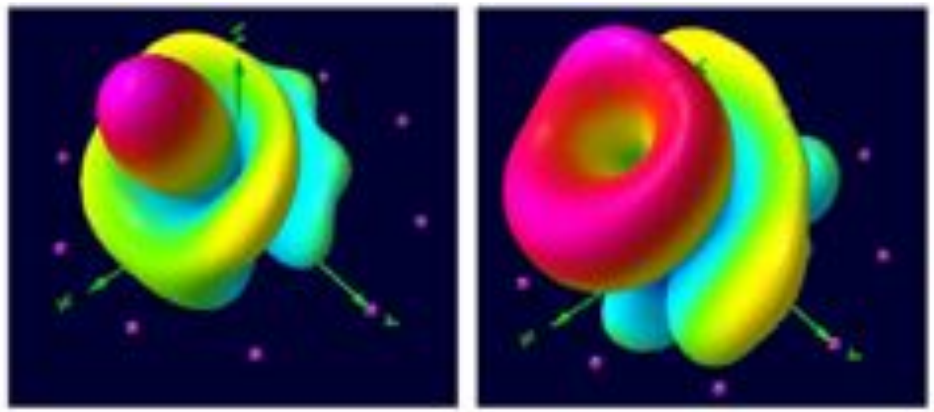

FIG. 4 (color online). Radiation patterns for a circularly polarized beam propagating obliquely ($\theta = 25°$) with $l = 0$ (left) and $l = 1$ (right), generated by phasing the individual elements of a ten-tripole array in free space. This illustrates that with a tripole array it is possible to control electronically both the beam direction and l. This is not possible with arrays of single or crossed dipoles. Note that for $l \neq 0$, there will be an on-beam-axis minimum which can be useful to block out a bright object when observing faint surrounding objects [31], e.g., in the solar corona [20].

The radio results are in agreement with EM OAM theory

•Theory predicts that a circular polarised radio beam in a pure OAM eigenstate with azimuthal phase dependence exp(i$l\varphi$), frequency ω, and energy H, should have a total angular momentum component $J_z^{EM} = lH/\omega$ along the z (beam) axis.

TABLE I. Scaling of $\omega J_z^{EM}/H$ as a function of l for a right-hand circular polarized beam ($s = -1$) formed by a ring array of 10 crossed dipoles. Array radius $D = \lambda$, antennas 0.1λ over perfect ground, polar angle $\theta = 0$.

l	s	$j = l + s$	$\omega J_z^{EM}/H$
0	−1	−1	−1.019
1	−1	0	−0.022
2	−1	1	0.971
3	−1	2	1.81

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News

Adding a twist to radio technology

Spiralling radio waves could revolutionize telecommunications.

Edwin Cartlidge

The bandwidth available to mobile phones, digital television and other communication technologies could be expanded enormously by exploiting the twistedness as well as wavelength of radio waves. That is the claim being made by a group of scientists in Italy and Sweden, who have shown how a radio beam can be twisted, and the resulting vortex detected with distant antennas.

Twisted radio waves could free up more bandwidth for mobile phones and computers.

Marcus Mok/Corbis

The simplest kind of electromagnetic beam has a plane wavefront, which means that the peaks or troughs of the beam can be connected by an imaginary plane at right angles to the beam's direction of travel. But if a beam is twisted, then the wavefront rotates around the beam's direction of propagation in a spiral, creating a vortex and leaving the beam with zero intensity at its centre.

Spiral waves

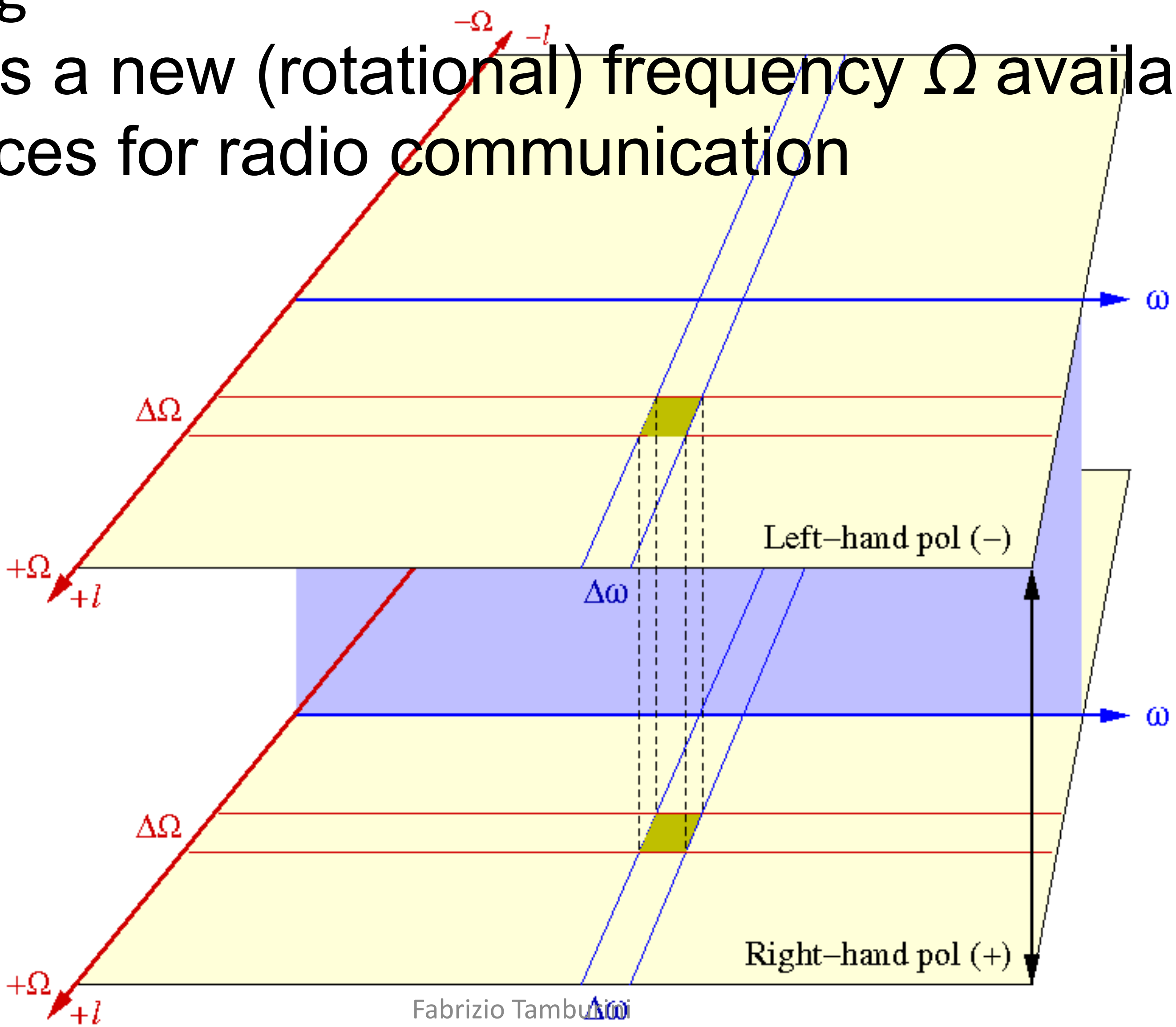
Now, a group led by Bo Thidé of the Swedish Institute of Space Physics in Uppsala and Fabrizio Tamburini of the University of Padua, Italy, has succeeded in twisting the waves emitted by the type of antenna used by standard wireless routers to transmit data over long distances[1]. The team did this by reflecting the waves off an eight-stepped, spiral-staircase-like structure

Radio waves and OAM

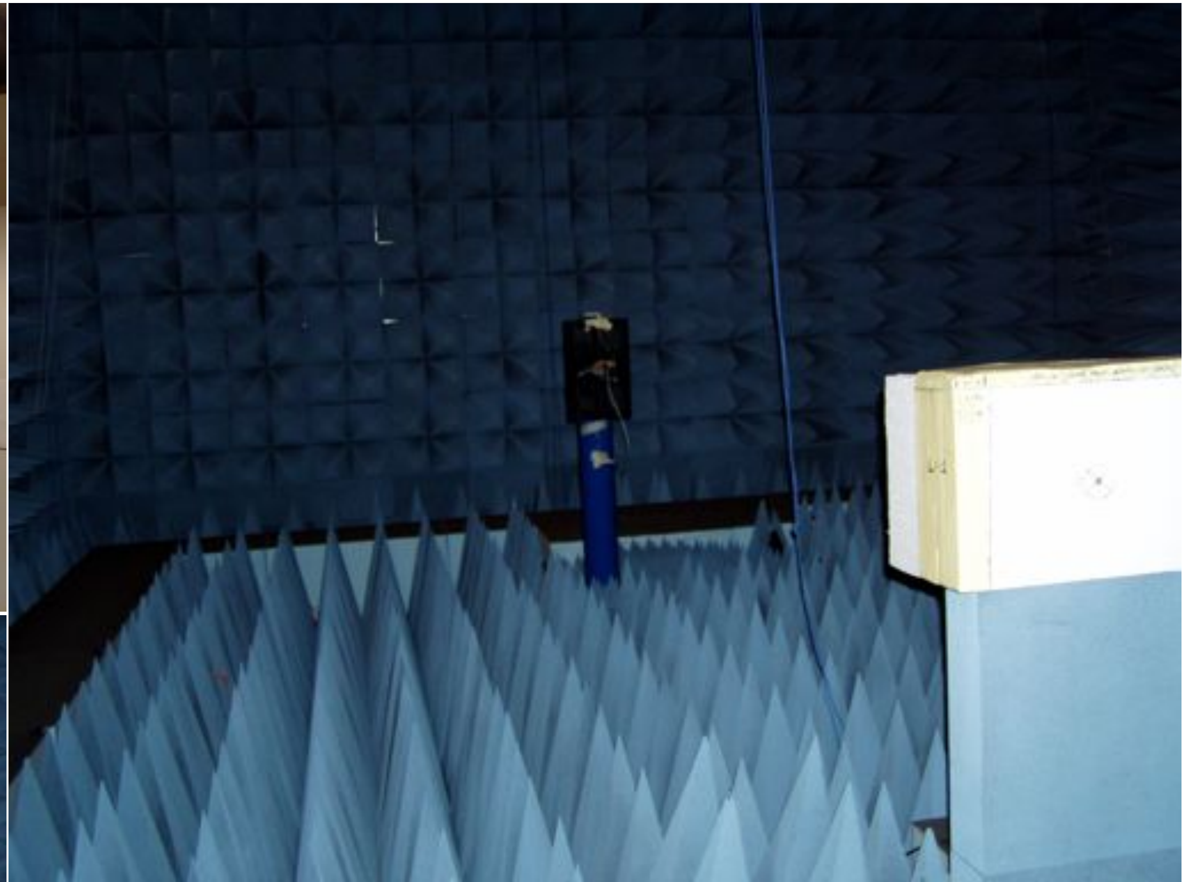
Hyper-Tuning

OAM makes a new (rotational) frequency Ω available

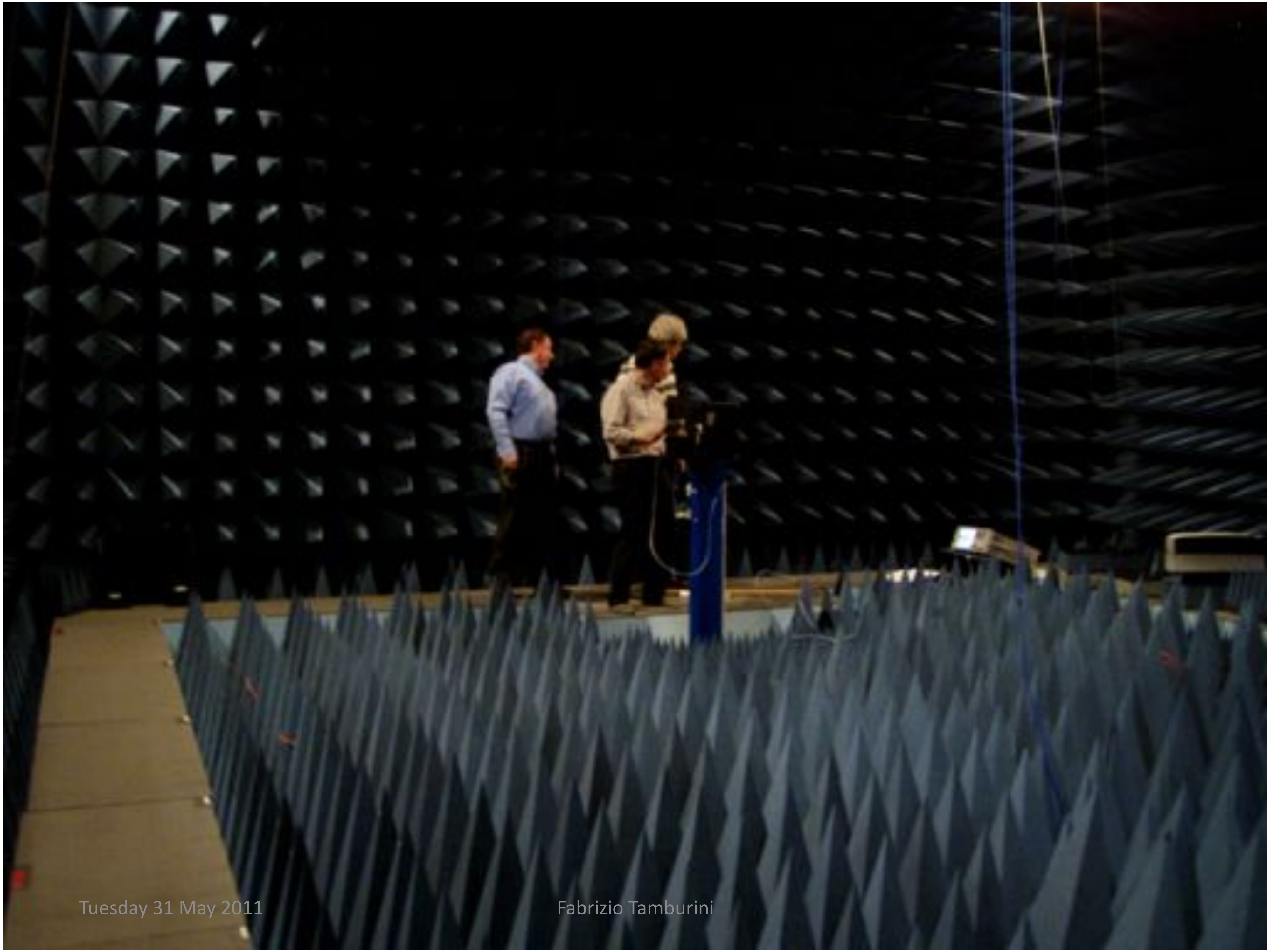
consequences for radio communication

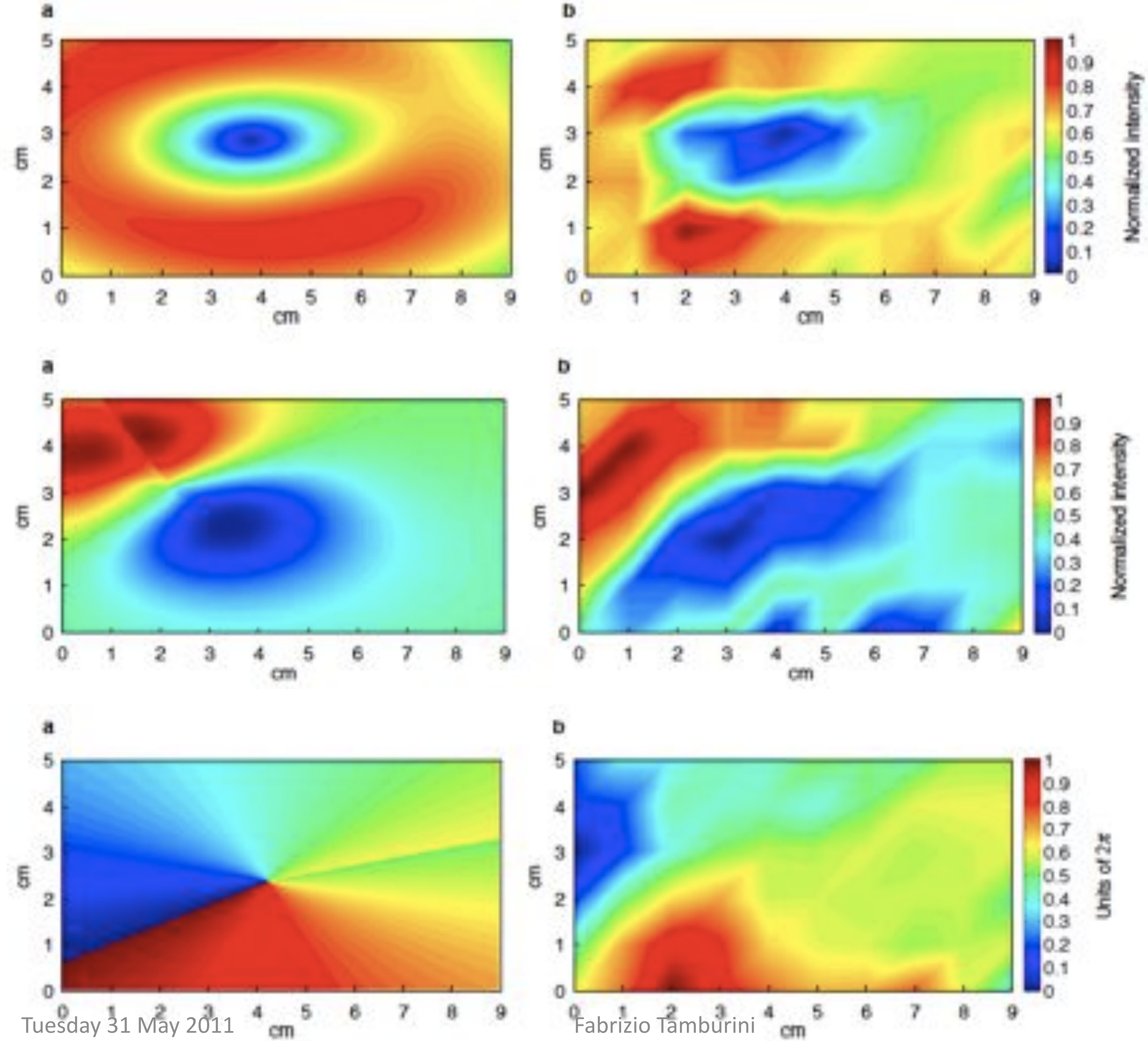


The first radio vortex @ 2.4GHz



Uppsala, Sweden December 2010




a
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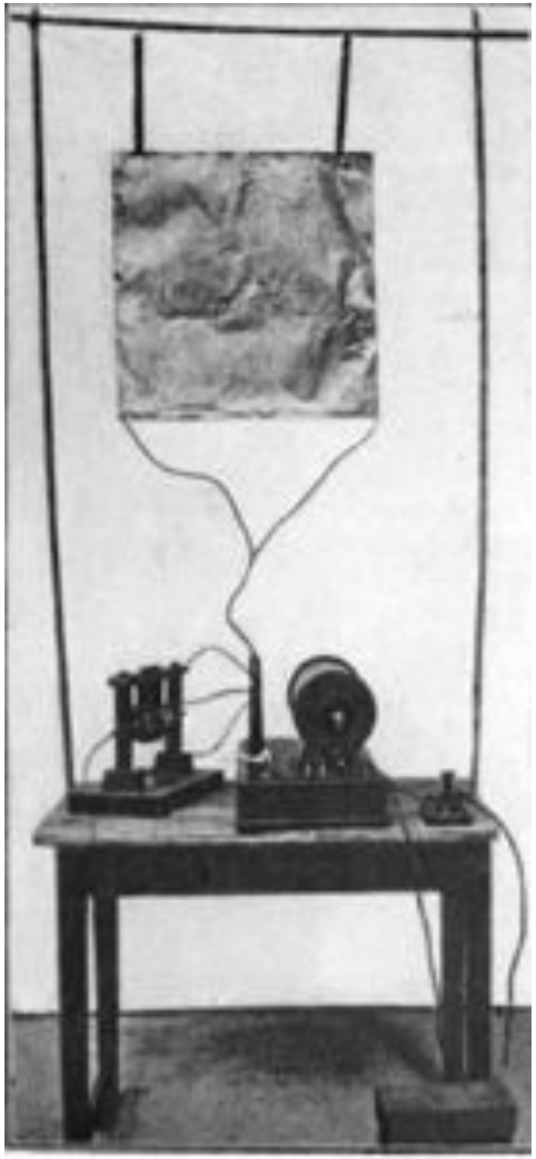
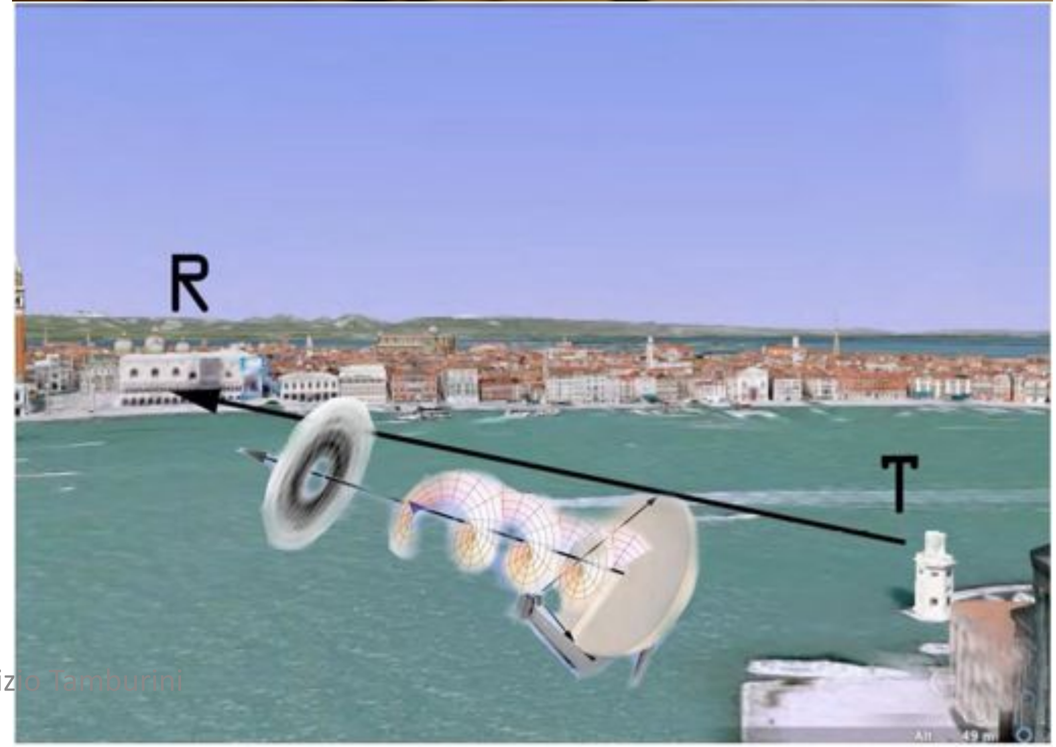
Units of 2π

Esperiment-Event San Marco
with Tullio Cardona, Antonio Bianchini
and the “vorticists”



[illegible] da Marconi con antenna formata da una lastra di latta ricavata da un bidone da petrolio per lume.



Conclusions

- There is a new land of conquest for astronomy, astrophysics and space science
- Revolution in telecommunications
- Test in San Marco, Venice, to measure, test and show the potentialities of these new degrees of freedom
- Future applications to radio-astronomy
- Far future the "Majorana Tower"