Light

15 November 4:15 PM-4:45 PM. Nature Conference. Disruptive Photonics Technologies, 15-17 November 2024, Guangzhou, China

Toroidal Electrodynamics News. Southampton edition by尼古拉 -哲鲁戴夫

Contents

Why the toroidal electrodynamics is important?

The Past:

- Dynamic toroidal moment
- Anapole
- Toroidal electromagnetic pulses

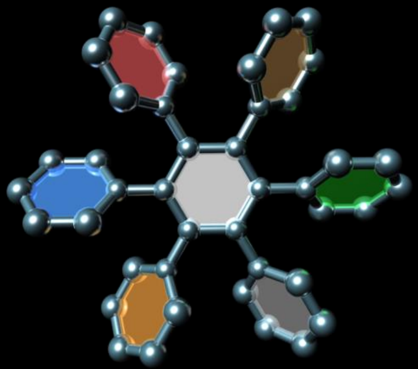
The Future:

- Toroidal transition in atoms
- Supertopoidal pulses
- Non-diffracting super-toroidal pulses
- Space-time superoscillations in super-toroidal pulses
- Super-toroidal anapoles
- Optical forces in super-toroidal matter
- Topology selective absorber of light and toroidal light pulses

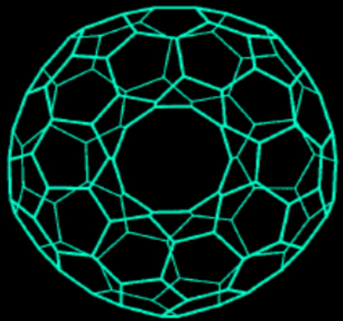
Other major contributors to the field: Tsai (CCUHK), Kuvshar (NAU), Miroshnichenko (UNSW), Singh (NTU), Van Aken (Stuttgart), Evlyukhin (Hannover), Basharin (UE Finland), Ellenbogen (TAU), Pin Chieh Wu (Taiwan), Bozhevolnyi (US Denmark), Wang (China) …. many others

Toroidal structures in nature

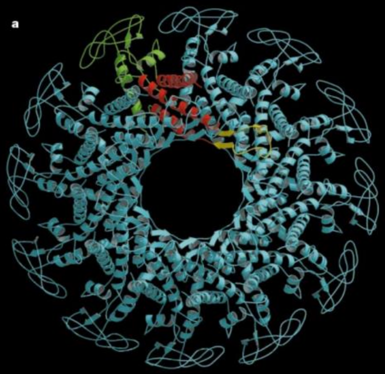
Hexa-aryl-benzenes



Fullerenes

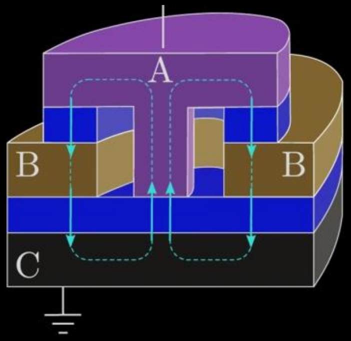


Bacteriophage



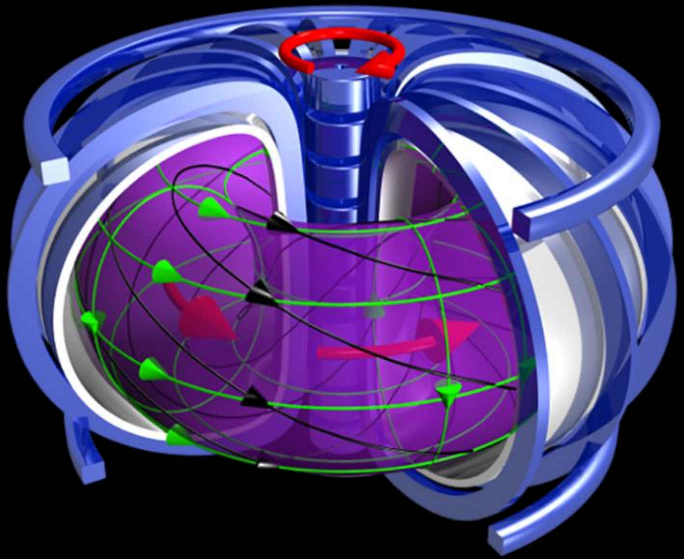
DNA exonuclease

Superconducting quantum qubit



Vortex in water

Ball lightening

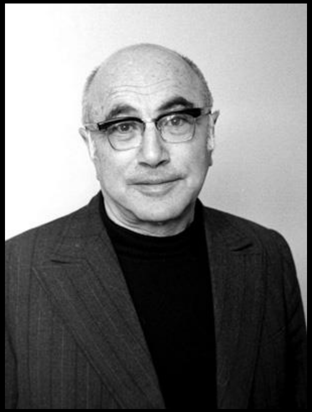


Magnetic Fusion Confinement: Tokamak

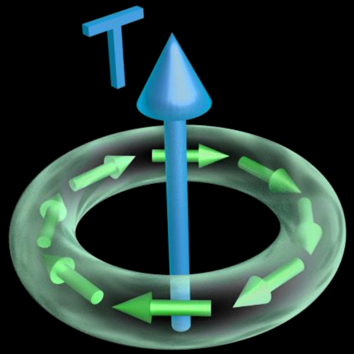
Static toroidal dipole

Y. Zeldovich. JETP Letters 33, 1531 (1957)

Yakov Zel'dovich
1914-1987

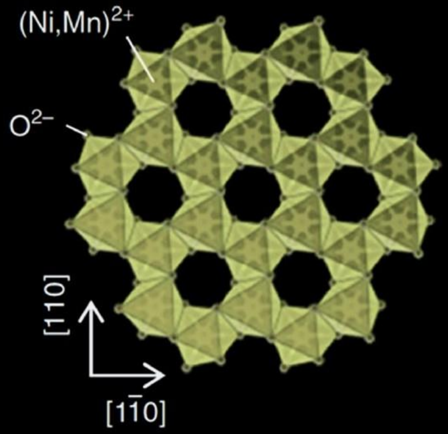


Obviously, it does not correspond to any magnetic multipole … can be represented as wire helix bent in a ring (toroid)”



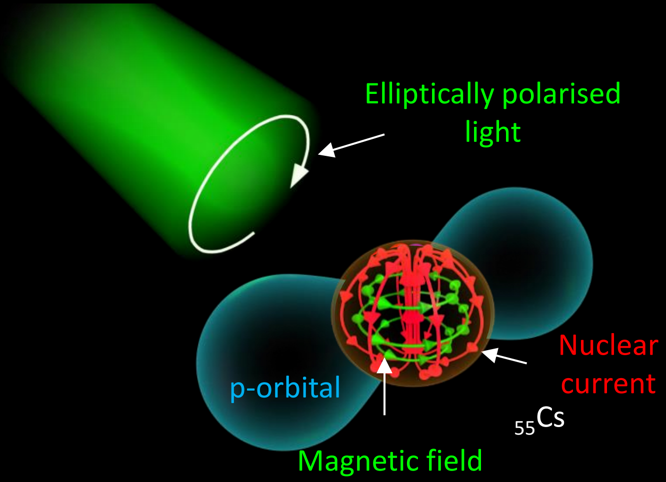
Static toroidal dipole

Static spin toroidal dipole in solid state



On the possibility of phase transitions with spontaneous toroidal moment formation in nickel. Sannikov & Zheludev. **Sov.Phys.Sol.St**. 27,826 (1985)

Static toroidal dipole & parity violation in atoms



Measurement of Parity Nonconservation and an Anapole Moment in Cesium. Wood, Bennett… Wieman . **Science,** 275, 1759(1997).

The Past

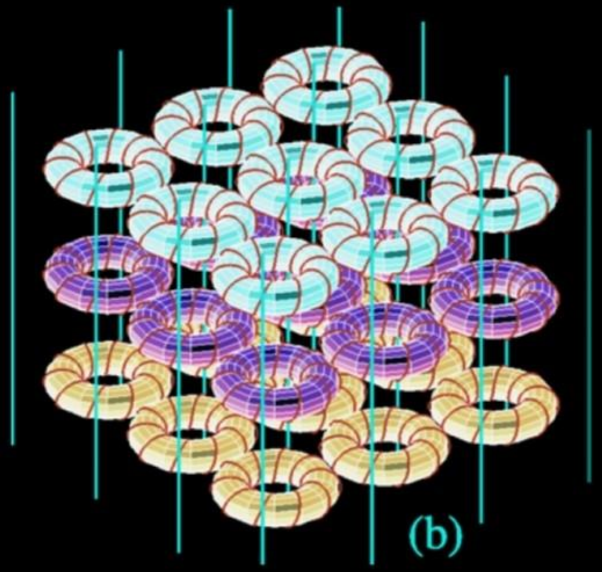
The Discovery of
Dynamic Toroidal Moment

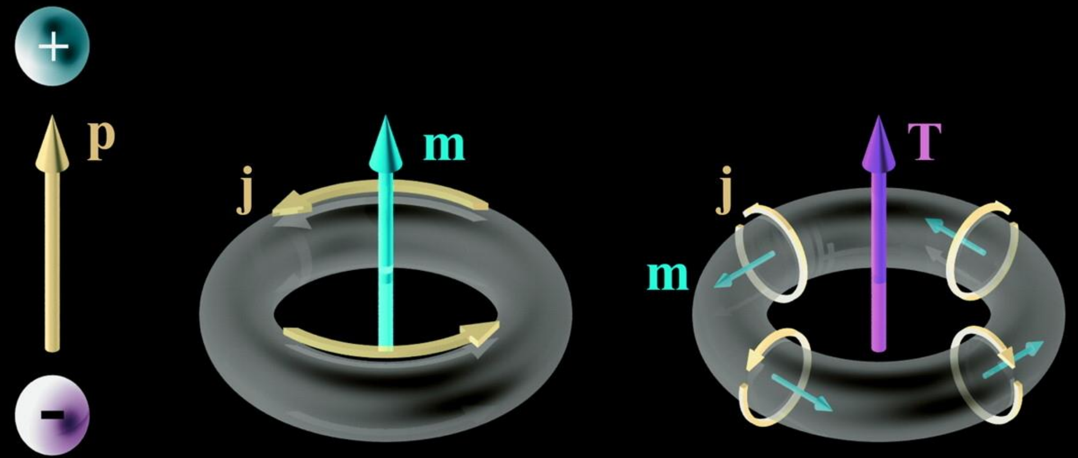
Why is it important?

Missing component of multipole expansion (Maxwell)
Electromagnetic properties of matter

Toroidal Metamaterial 2007

3D-array of toroidal solenoids





Displays a significant toroidal response that can be readily measured
Negative refraction
Backward waves

Toroidal metamaterial. Marinov, Boardman, Fedotov, and Zheludev. **New J. Phys.** 9, 324 (2007)

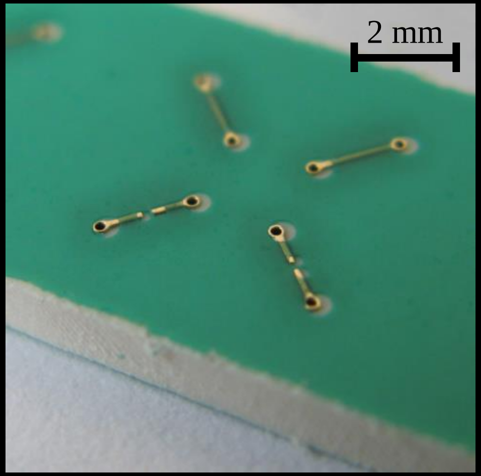
The Discovery of Toroidal Moment (2010)

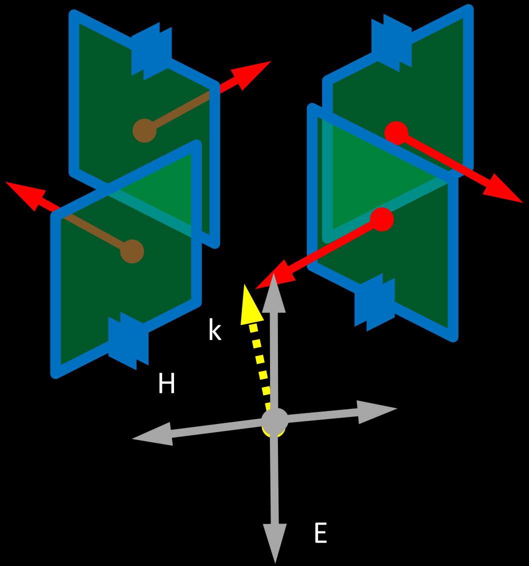
Multipole expansion

Dynamic multipoles

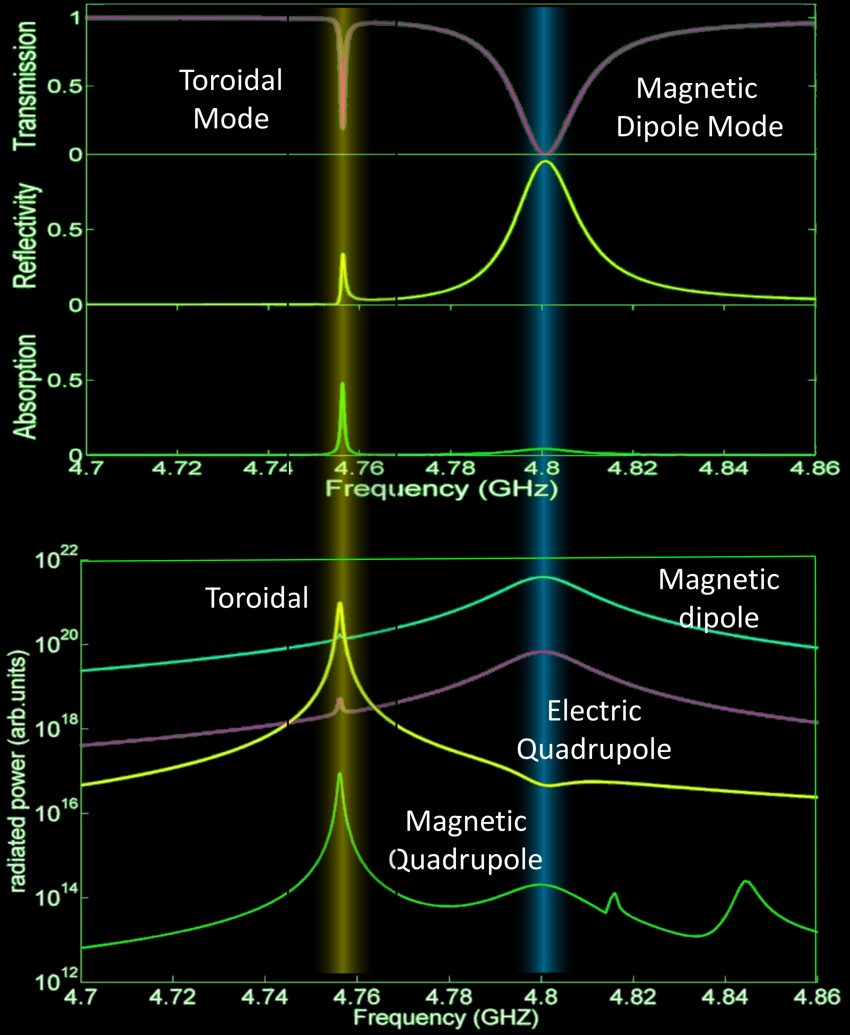
- Magnetic multipoles transverse currents
  - $\boldsymbol{m} = \frac{1}{2}\int (\boldsymbol{r} \times \boldsymbol{J})\, dr^3$
- Electric multipoles radial currents + charge
  - Electric Dipole
    - $\boldsymbol{p} = \frac{1}{i\omega}\int \boldsymbol{J}\, dr^3$
  - Toroidal Dipole
    - $\boldsymbol{T} = \frac{1}{10}\int [(\boldsymbol{r}.\boldsymbol{J})\boldsymbol{r} \; - 2\, r^2\, \boldsymbol{J}] dr^3$

Toroidal metamolecule





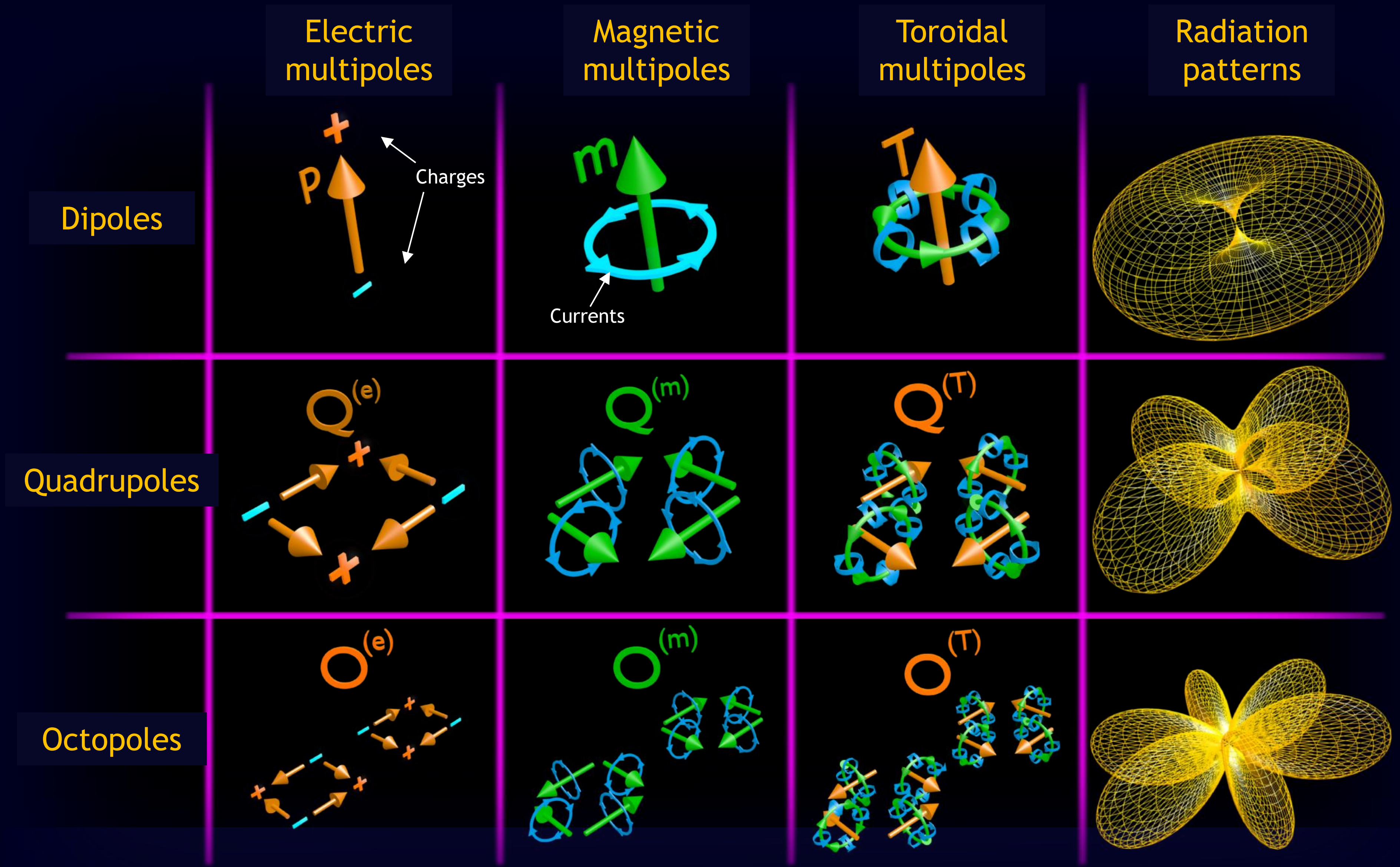
Spectra of Toroidal metamaterial



Toroid moments in electrodynamics and solid-state physics. Dubovik & Tugushev. **Phys. Rep.** 187, 145 (1990)

Toroidal Dipolar Response in a Metamaterial. Kaelberer, Fedotov, Papasimakis, Tsai, Zheludev. **Science.** 330, 1510 (2010)

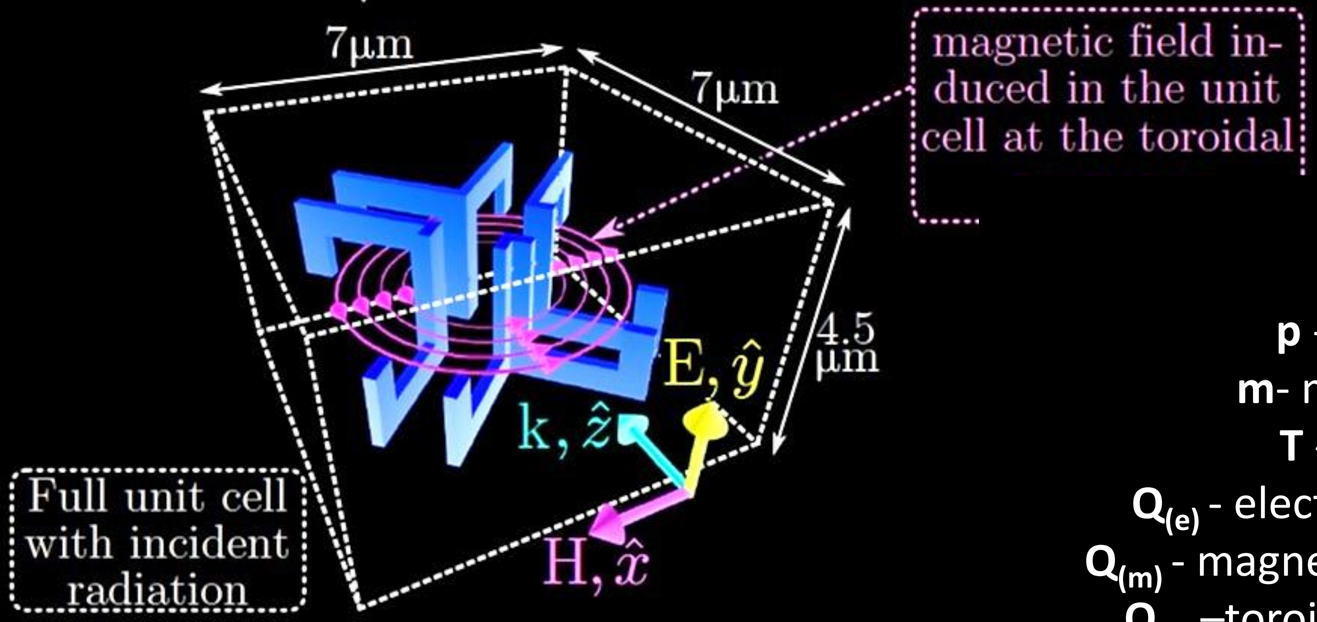
The multipole families



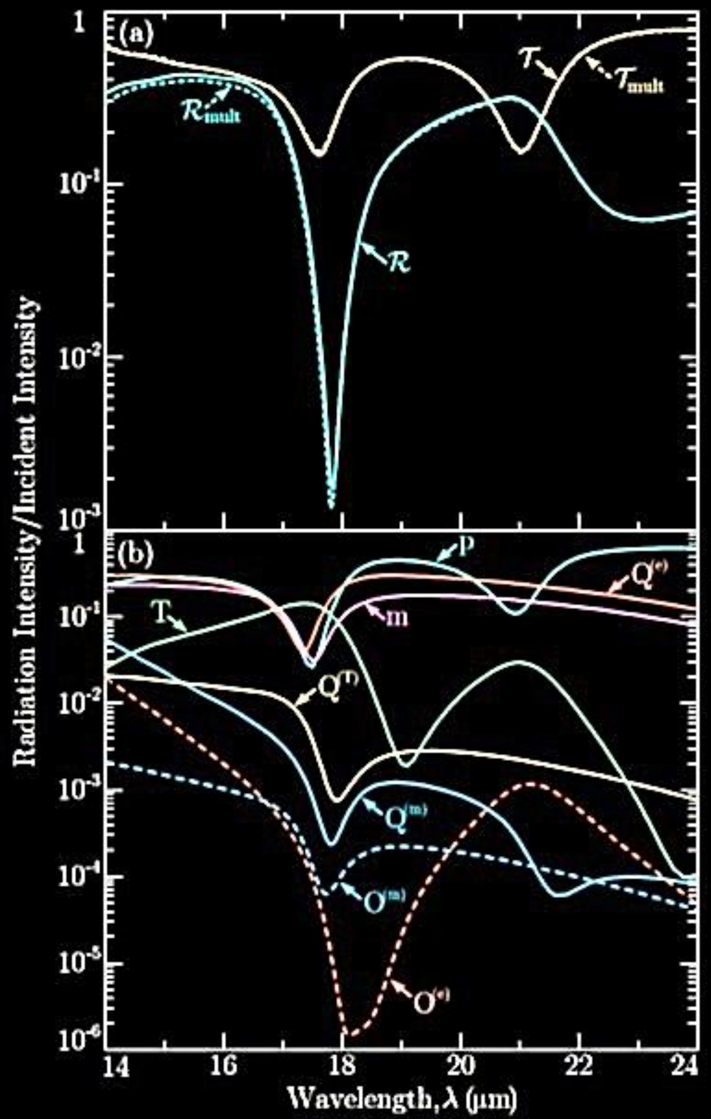
Electromagnetic toroidal excitations in matter and free space. N. Papasimakis, V. Fedotov, V. Savinov, T. A. Raybould, and N. I. Zheludev. **Nature Mater.** 15, 263 (2016)

Toroidal excitations and macroscopic properties of materials

An analytical approach to evaluate optical properties of matter exhibiting toroidal dipolar excitations.



p - electric dipole
m- magnetic dipole
T -toroidal dipole
$\mathbf{Q}_{(e)}$ - electric quadrupole
$\mathbf{Q}_{(m)}$ - magnetic quadrupole
$\mathbf{Q}_{(T)}$ –toroidal quadrupole
$\mathbf{O}_{(eo)}$ -electric octupole
$\mathbf{O}^{(m)}$ - magnetic octupole



Toroidal dipolar excitation and macroscopic electromagnetic properties of metamaterials
Savinov, Fedotov, Zheludev. **Phys. Rev. B,** 89, 205112 (2014)

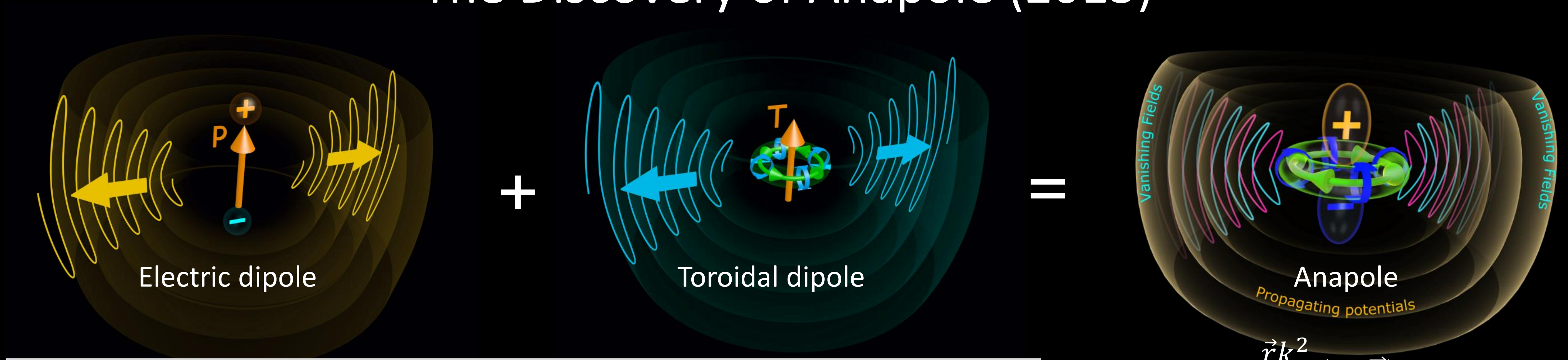
The Past

The Discovery of
Anapole

Why is it important?

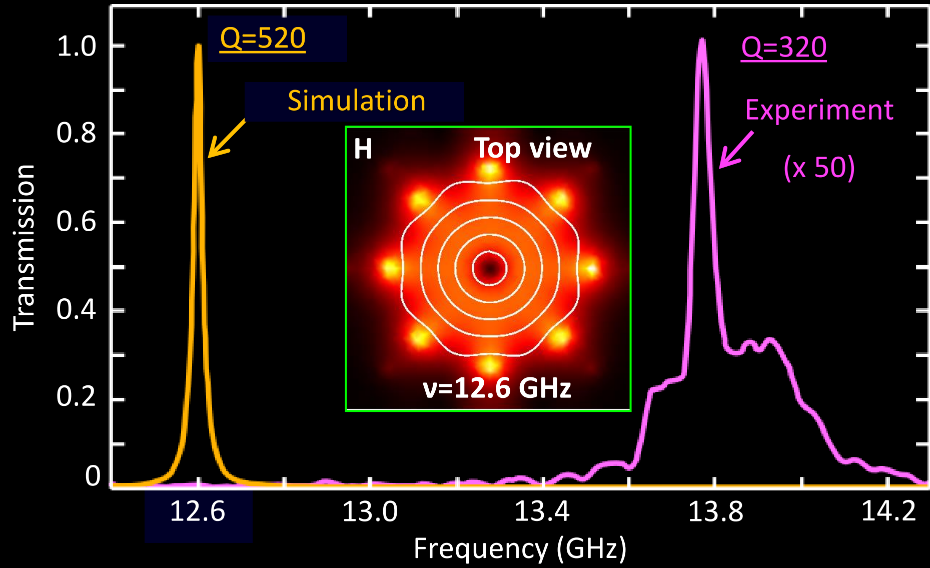
New electromagnetic “particle”
High-Q resonances
Quantum q-bits
Sensors

The Discovery of Anapole (2013)



The electromagnetic field of elementary time-dependent toroidal sources. Afanasiev and Stepanovsky. *J. Phys. A: Math. Gen.* **28** 4565 (1995)

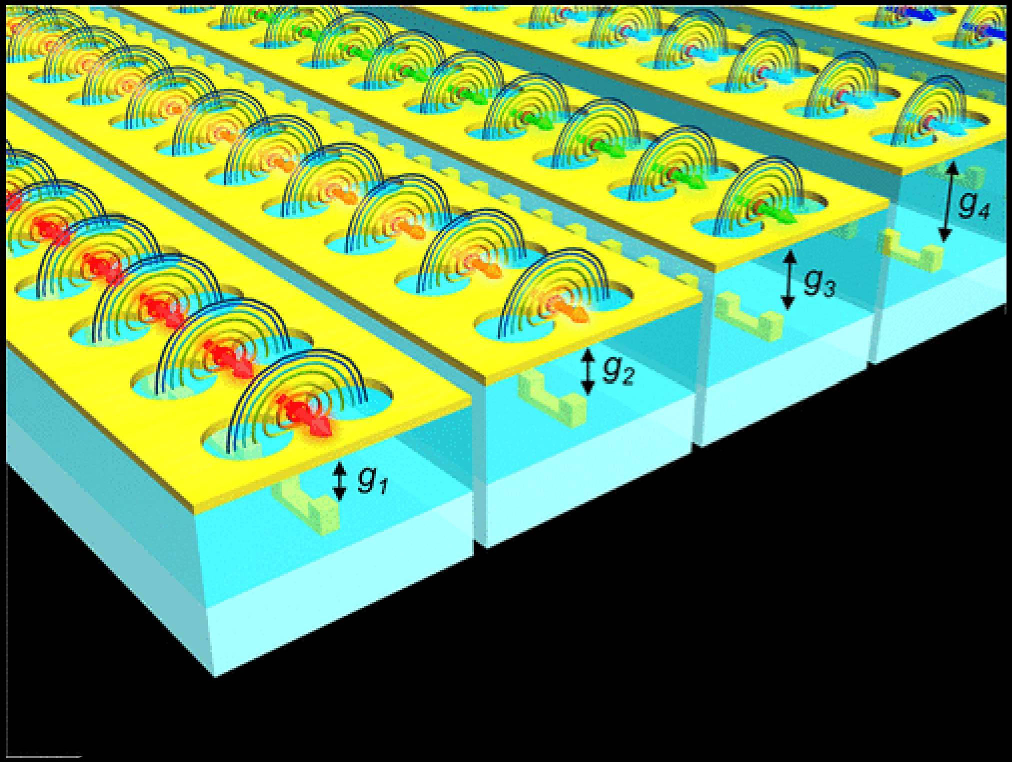
$$A = -\frac{\vec{r}k^2}{r^3}(\vec{r}\cdot\vec{T})e^{-ikr+i\omega t}$$



Resonant transparency and non-trivial non-radiating excitations in toroidal metamaterials. Fedotov, Rogacheva, Savinov, Tsai, Zheludev. **Scientific Reports.** 3, 2967 (2013)

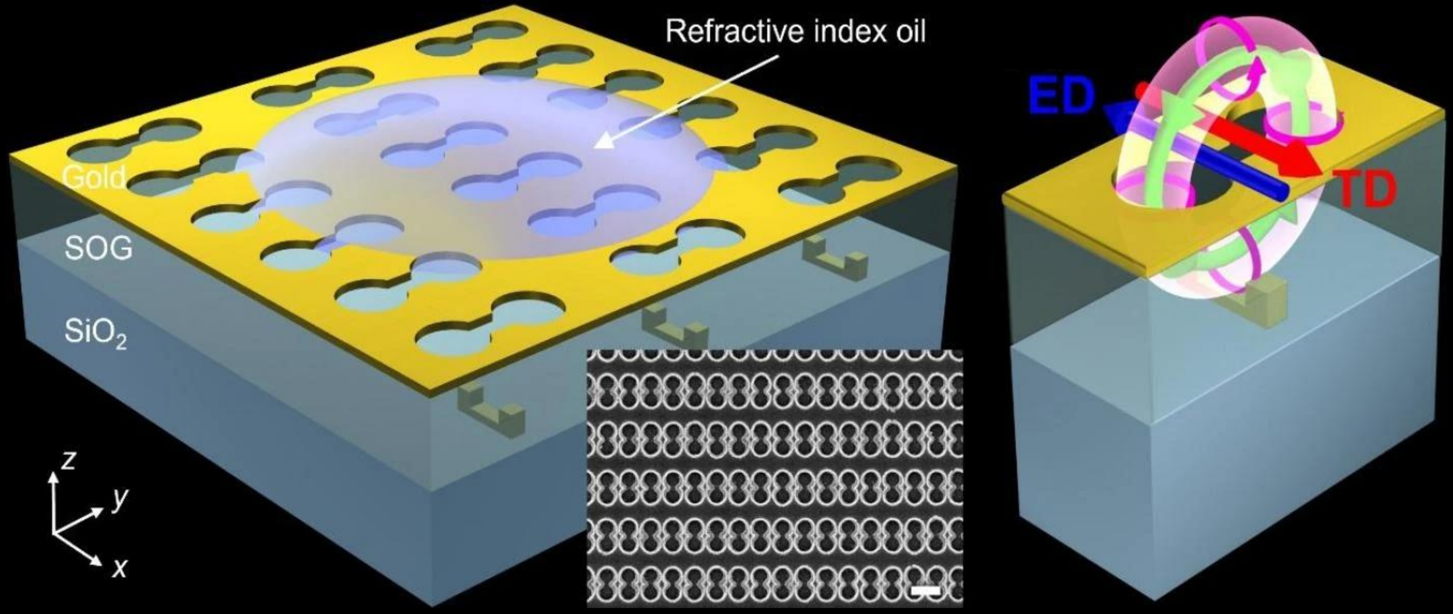
Optical anapole metamaterials

Anapole metamaterial



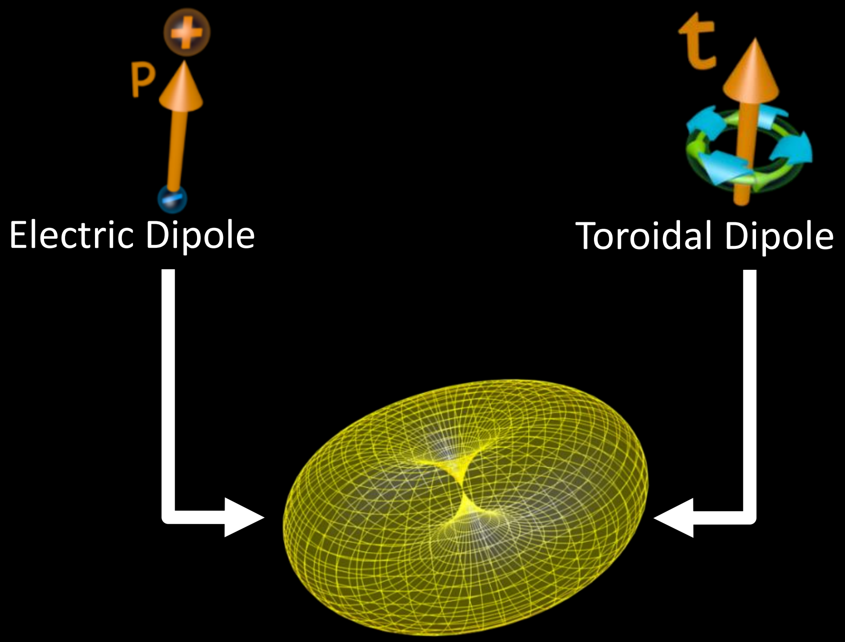
Optical anapole metamaterial.
Wu, Liao … Zheludev, Tsai. **ACS Nano** 12, 1920 (2018)

Plasmonic anapole metamaterial refractive index sensor



Plasmonic anapole metamaterial for refractive index sensing
Yao, Ou, V. Savinov … Zheludev, Tsai. **PhotoniX** 3, 23 (2022)

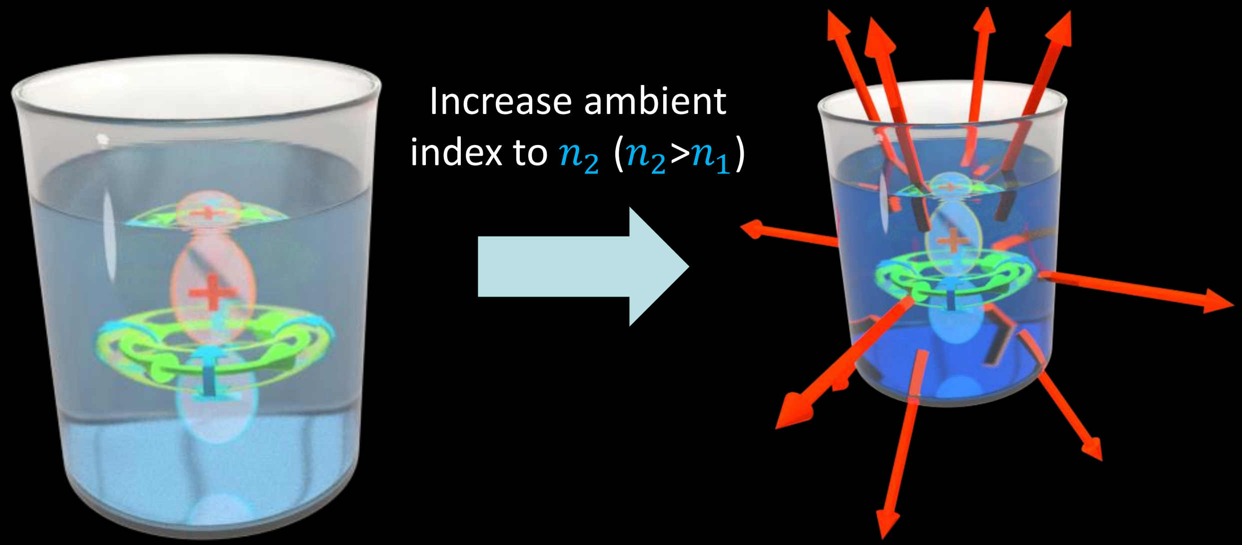
Solvatochromism: breaking of the anapole



Identical radiation pattern

But… Different dependence on ambient refractive index n

Solvatochromic breaking of anapole



Increase ambient index to n_2 (n_2>n_1)

Anapole condition valid for n_1

Toroidal dipole emission becomes stronger and anapole breaks (begins to emit light)

Emitted Power:

$$P_p = n \cdot \frac{\mu_0 \omega^4}{12\pi c} \cdot |p|^2$$

$$P_T = n^5 \cdot \frac{\mu_0 \omega^6}{12\pi c^3} \cdot |T|^2$$

Optical anapoles. Savinov, Papasimakis, Tsai & Zheludev. **NPG | Comms. phys. 2**, 69 (2019)

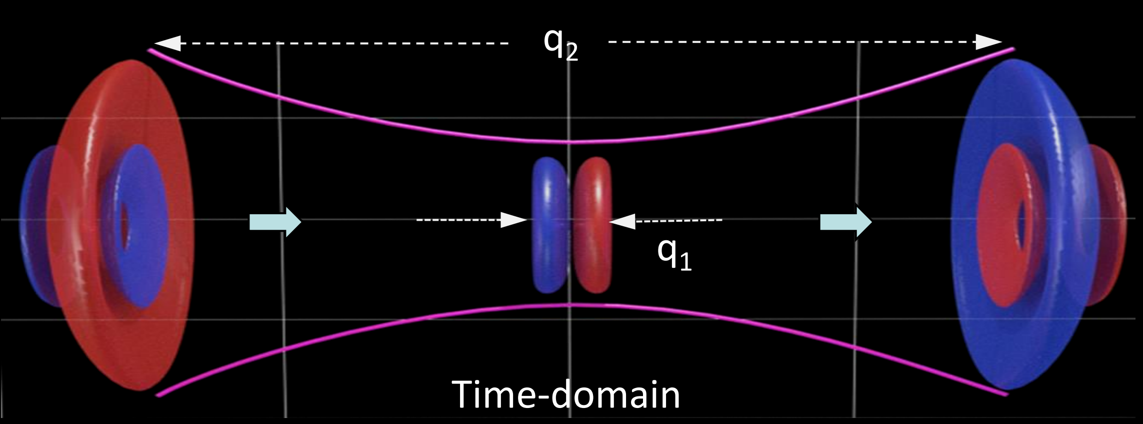
The Past

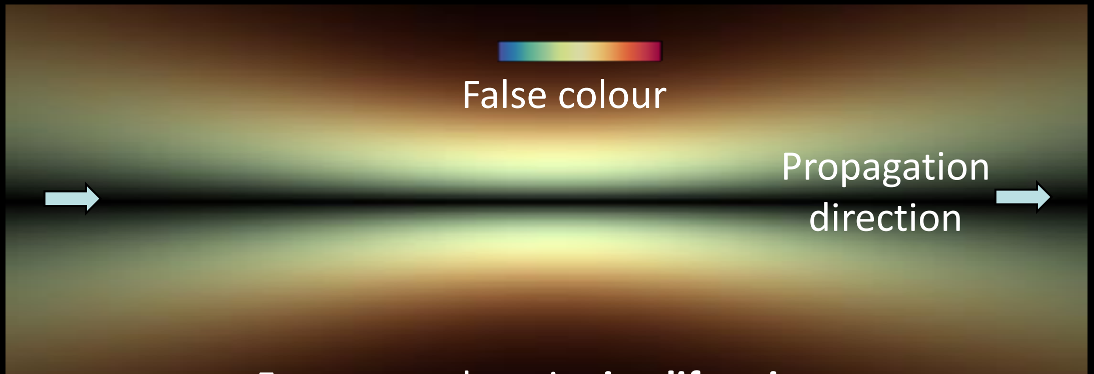
The Discovery of
Toroidal Electromagnetic Pulses

Why is it important?

Non-transverse electromagnetic wave
Rich topology
Spectroscopy

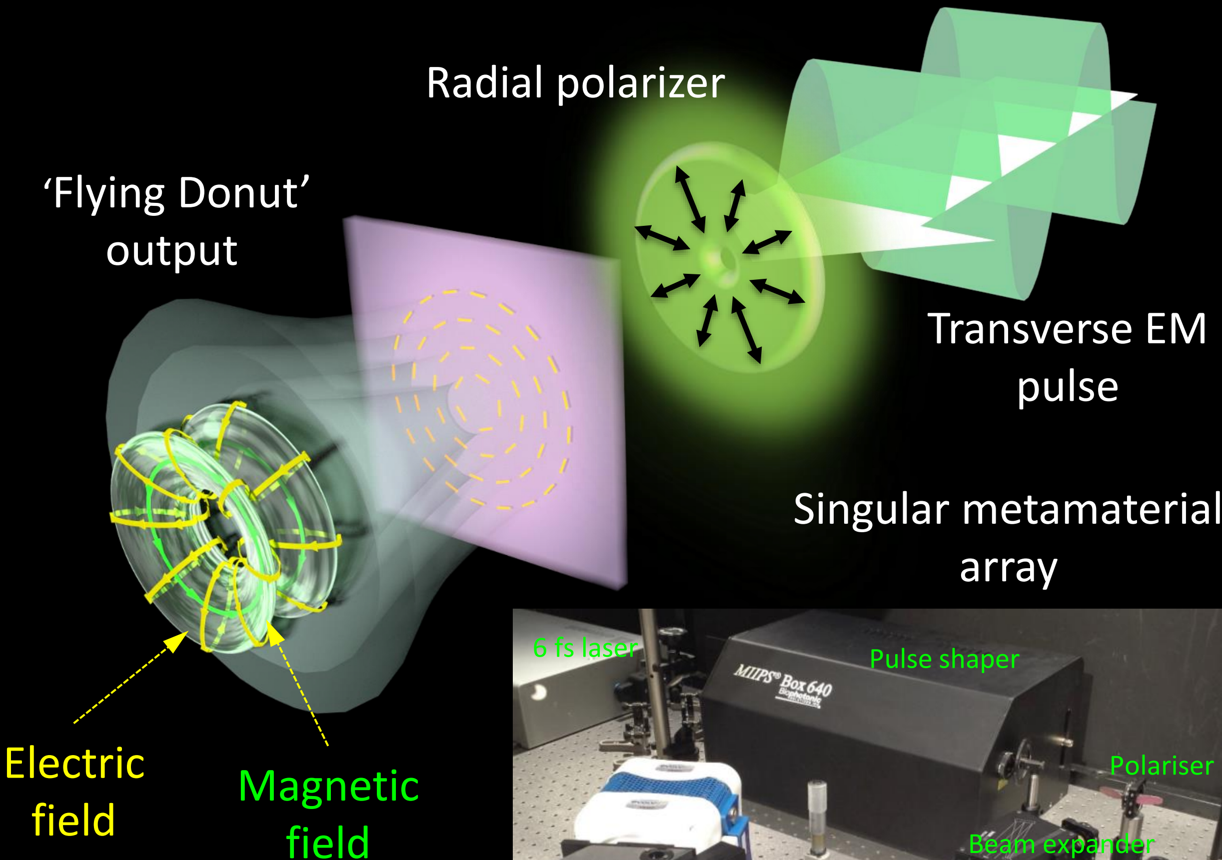
The Discovery of Toroidal Light Pulses (2018-2022)

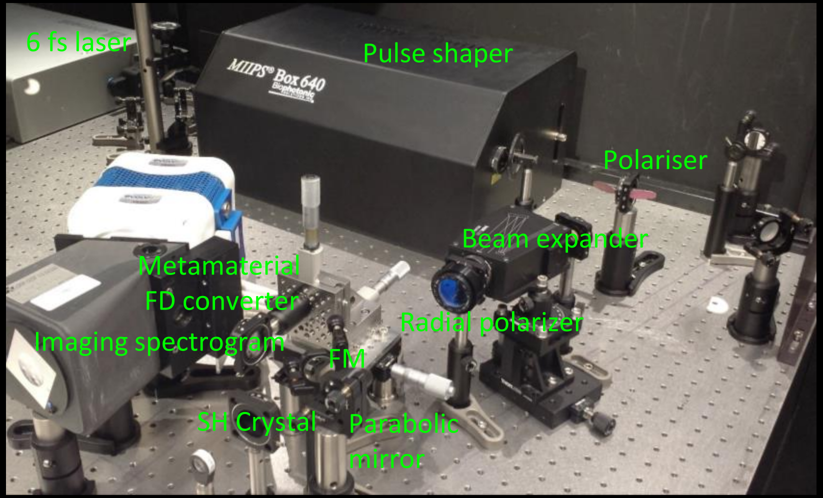




Frequency-domain: **isodifraction**:
Identical Rayleigh length for all frequencies

Focused one-cycle electromagnetic pulses. Hellwarth & Nouchi. Phys. Rev. E **54**, 889 (1996)



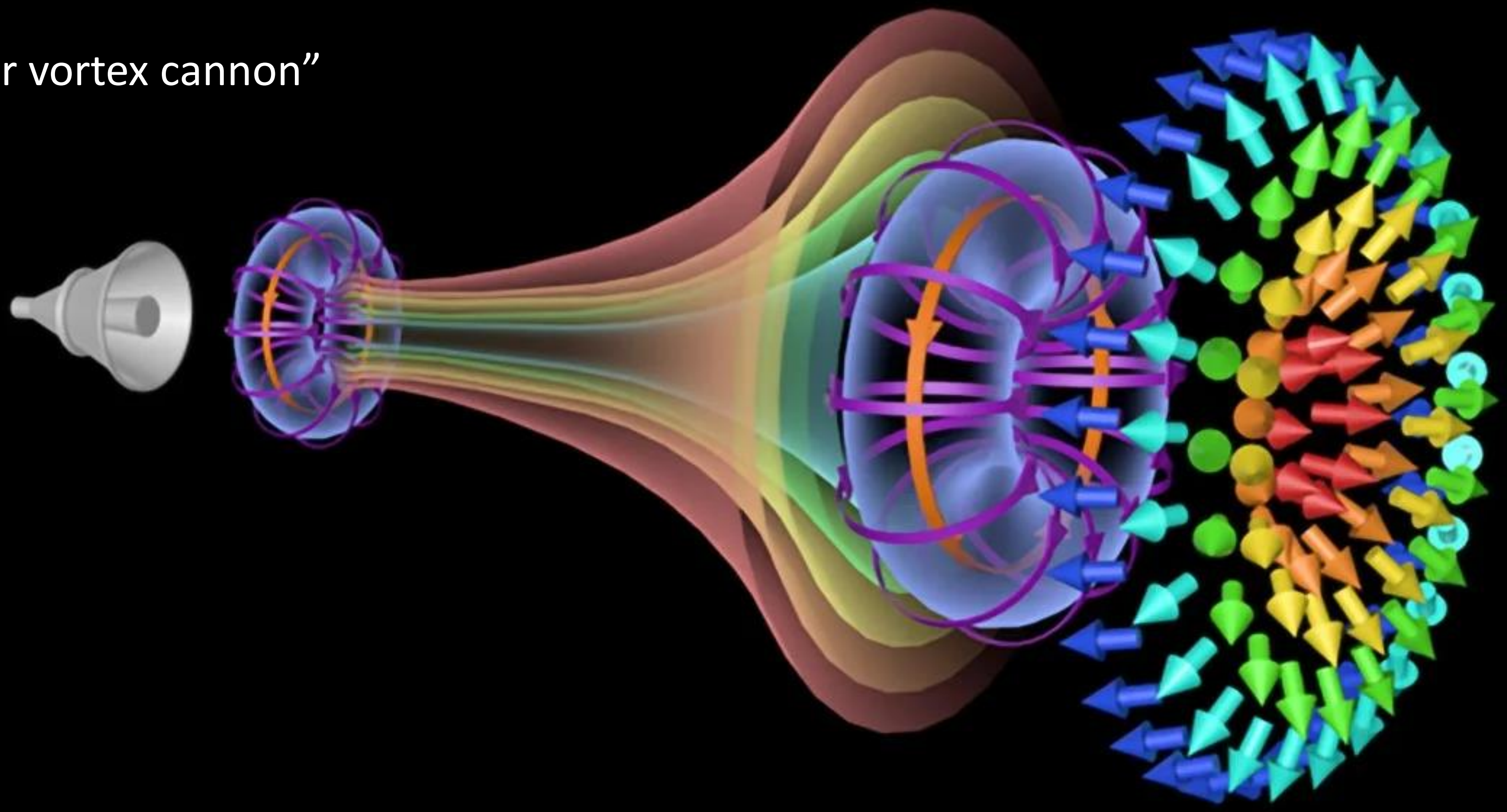


Observation of toroidal pulses of light. Zdagkas, Shen, McDonnell, Deng, Li, Ellenbogen, Papasimakis, and Zheludev. **Nature Photonics 16**, 523–528 (2022)

Pulse Generation Scheme for Flying Electromagnetic Doughnuts. Papasimakis, Raybould, Fedotov, Tsai, Youngs, Zheludev. **Phys. Rev. B.** 97, 201409(R) (2018)

The Discovery of Toroidal Light Pulses (2018-2023)

“Air vortex cannon”



During propagation, the pulses evolve towards closer proximity to the canonical Hellwarth–Nouchi toroidal pulses

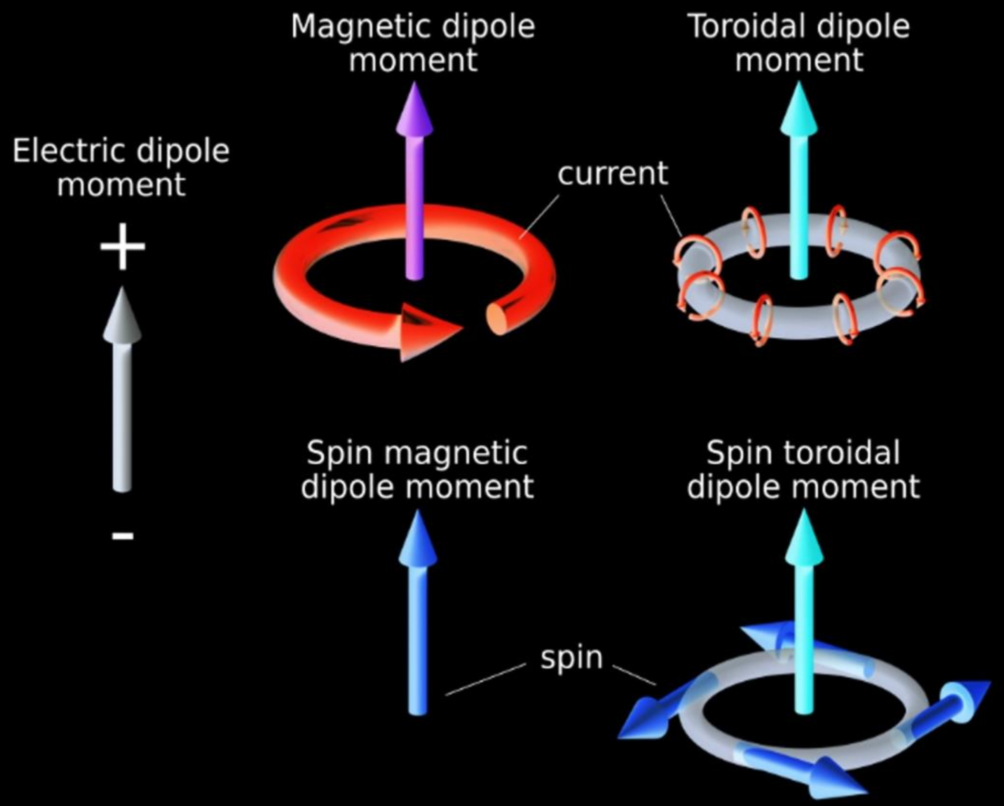
Observation of resilient propagation and free-space skyrmions in toroidal elm pulses. Ren Wang, Bao, Hu, Shi, Wang, Zheludev & Shen. **Appl. Phys. Rev.** 11, 031411 (2024)

The Discovery of
Toroidal Transitions in Atoms

Why is it important?

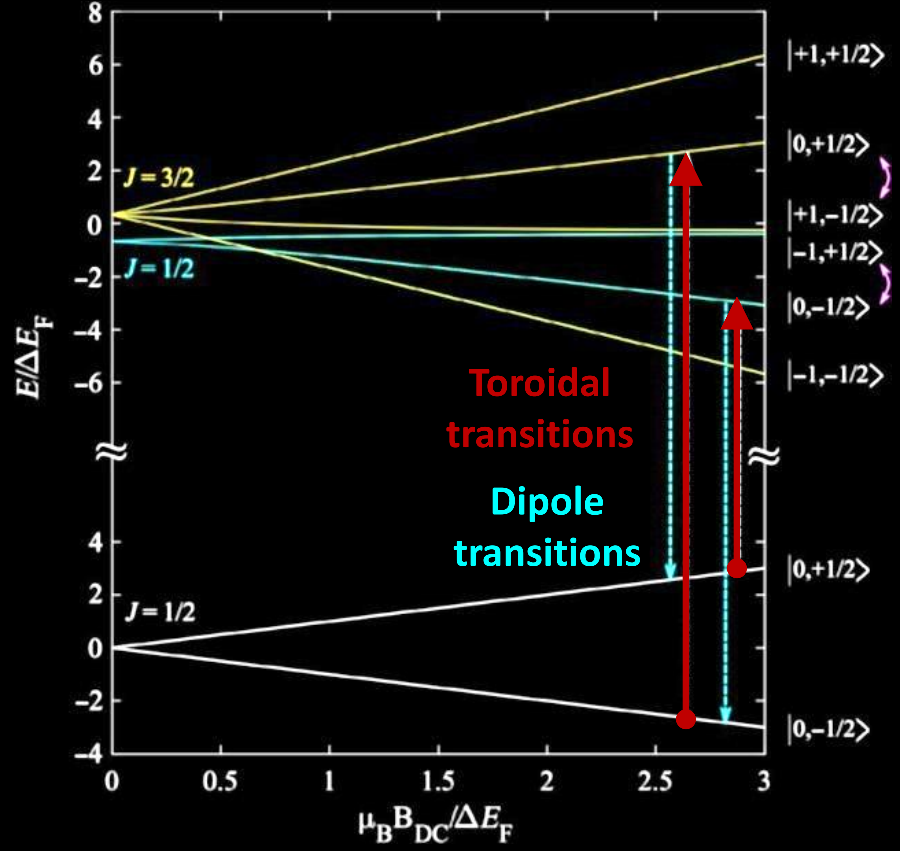
New atonic lines
New ways of exiting atoms

The Discovery of Spin Toroidal Moment (2022)



Transitions $\Delta m_s = \pm 1$ in combination with $\Delta L = \pm 1$ are only excited through the toroidal coupling and not through electric or magnetic dipole moments (m_s - the spin projection quantum number)

r × σ term
relativistic quantum mechanics



Transition $n\,^2S_{1/2} \rightarrow n'\,^2P_{3/2,1/2}$ as a function of the static magnetic field B_{DC}

Toroidal optical transitions in hydrogen-like atoms. Ilya Kuprov, David Wilkowski, Nikolay Zheludev. **Science Advances** 8, 45 (2022)
The rise of toroidal electrodynamics and spectroscopy. Zheludev and Wilkowski. **ACS Photonics** 10, 556 (2023)

Supertoroidal pulses

Why is it important?

A rich family of space-time non-separable pulses with unique properties
Flying skyrmion formation

The Discovery of Supertoroidal Pulses (2021)

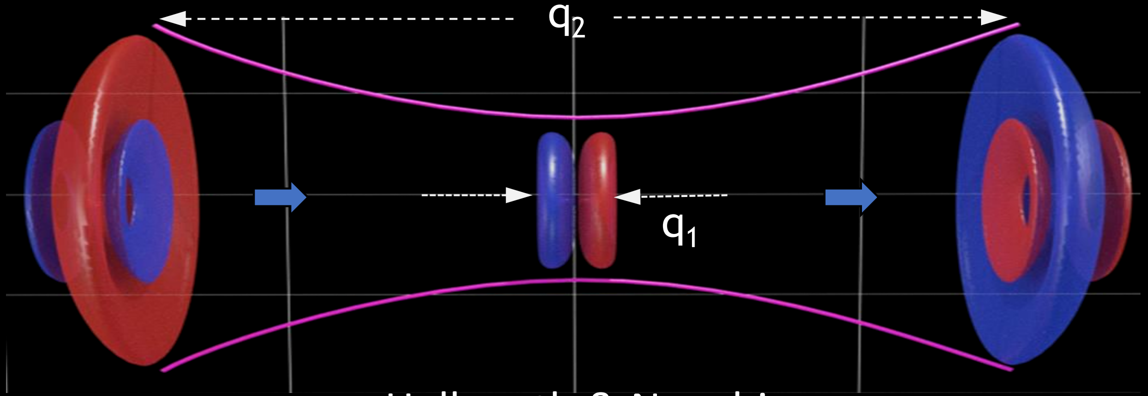
Scalar seed function

$$f = f_0 \frac{e^{-s/q_3}}{(q_1 + i\tau)(s + q_2)^{\alpha}}$$

Hellwarth & Nouchi
1996

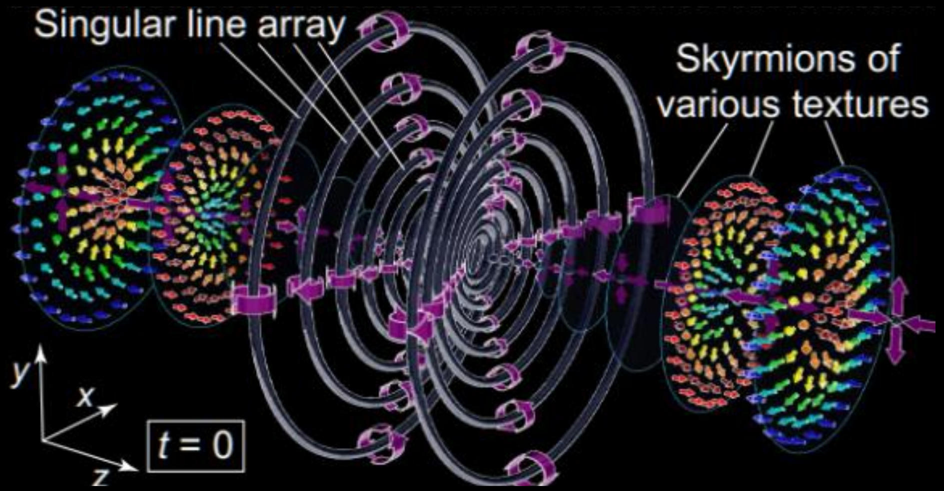
E,H are obtained by Hertz potentials

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) f(\mathbf{r}, t) = 0$$



Hellwarth & Nouchi
1996

$\alpha = 1, q_3 \to \infty$



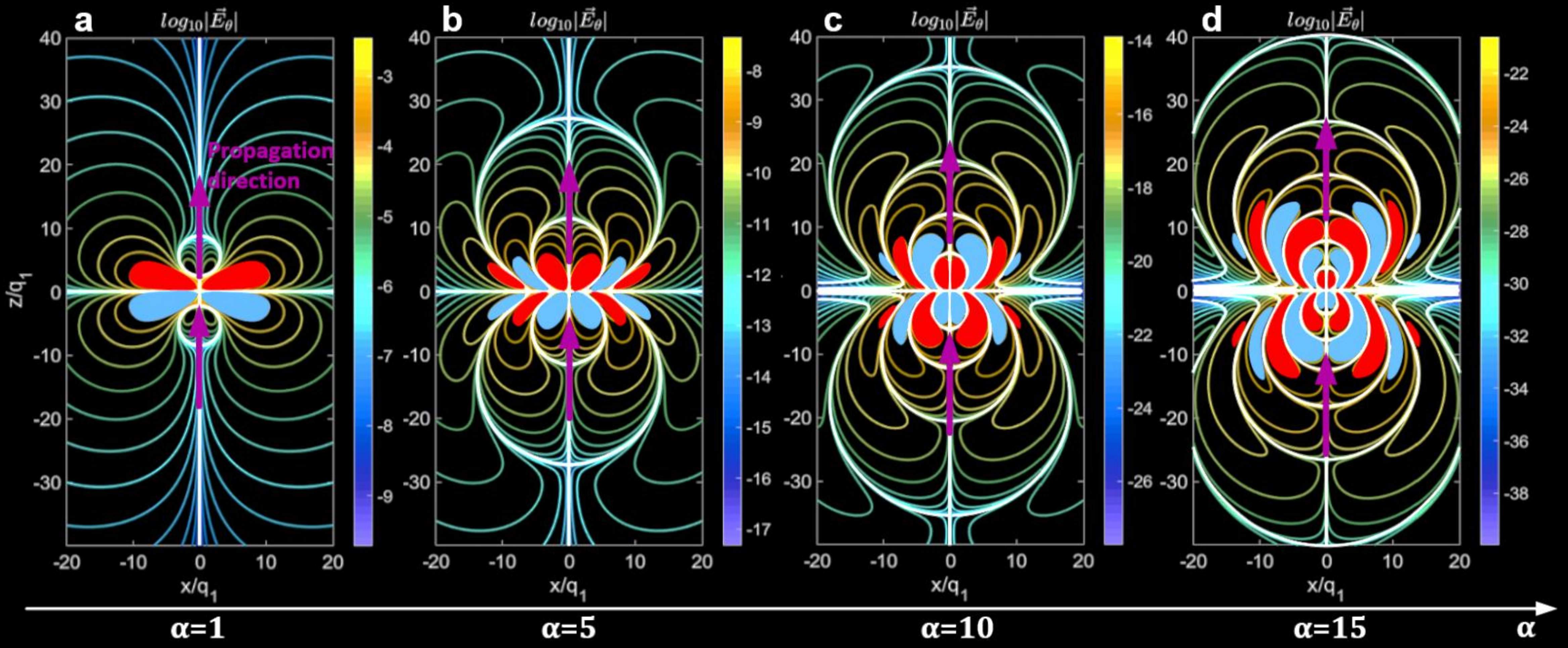
$\alpha > 1, q_3 \to \infty$

Focused one-cycle electromagnetic pulses.
Hellwarth & Nouchi. **Phys. Rev. E** 54, 889 (1996)

Supertoroidal light pulses: Propagating electromagnetic skyrmions in free space.
Shen,Hou, Papasimakis, Zheludev. **Nature Commun.** 12, 5891 (2021)

Self-Similarity in the Supertoroidal Pulse

Self-similar singular electric field “shells”

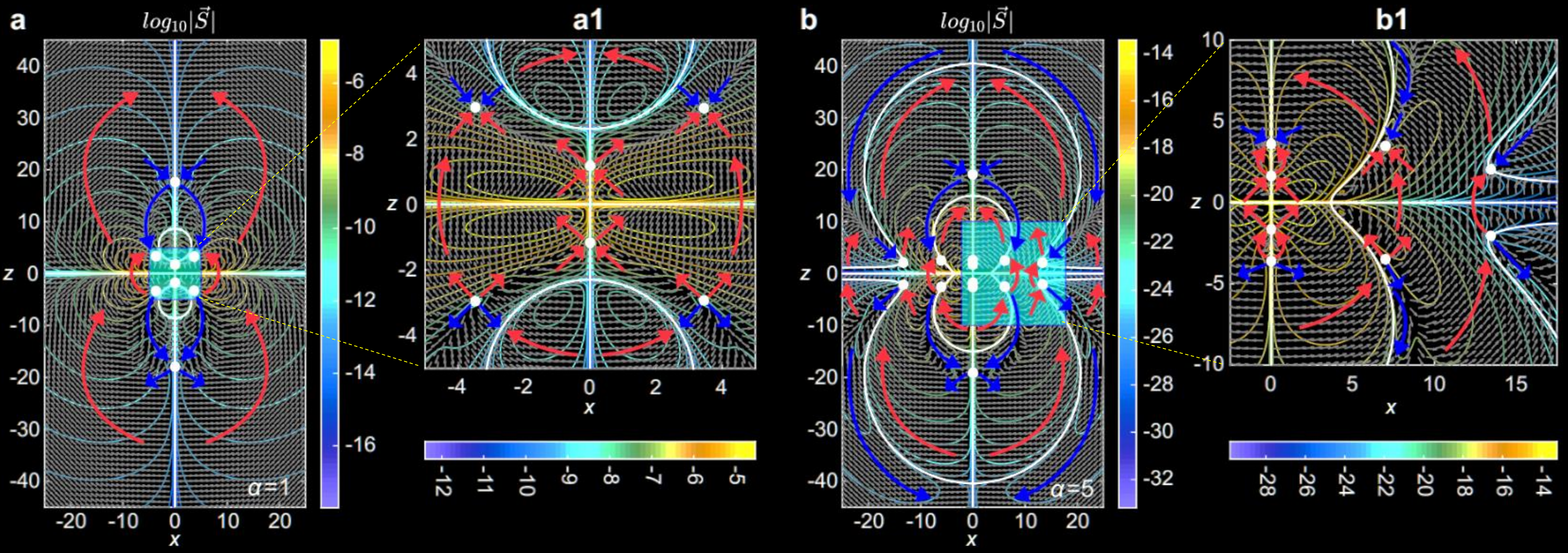


Supertoroidal light pulses: Propagating electromagnetic skyrmions in free space. Y Shen, Y Hou, N Papasimakis, NI Zheludev. **Nature Commun.** 12, 5891 (2021)

Energy flows/backflows of supertoroidal light pulses

Hellwarth and Nouchi Pulse

Supertoroidal pulse, α = 5



Complex Poynting vector distribution

Energy backflow → Multi-layer energy backflow

Supertoroidal light pulses: Propagating electromagnetic skyrmions in free space. Y Shen, Y Hou, N Papasimakis, NI Zheludev. *Nat. Commun.* 12, 5891 (2021)

Non-Diffracting Super-Toroidal Pulses

Why is it important?

Energy and information transfer

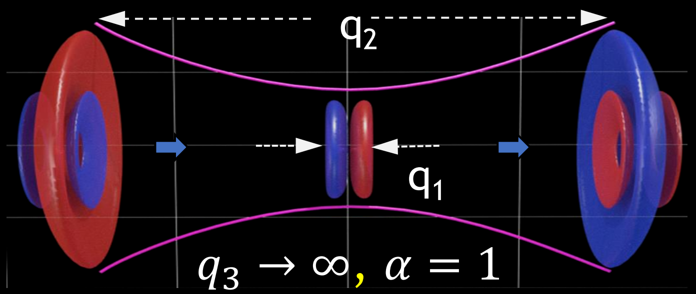
The Discovery of Non-Diffracting Toroidal Pulses (2024)

Hellwarth & Nouchi, !996

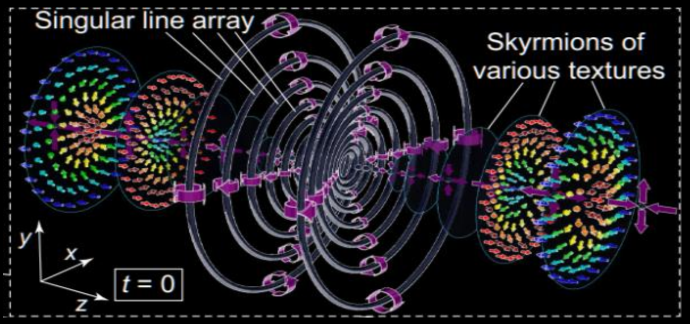
$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) f(\mathbf{r},t) = 0$$

$$f = f_0 \frac{e^{-s/q_3}}{(q_1 + i\tau)(s + q_2)^{\alpha}}$$

Toroidal pulse

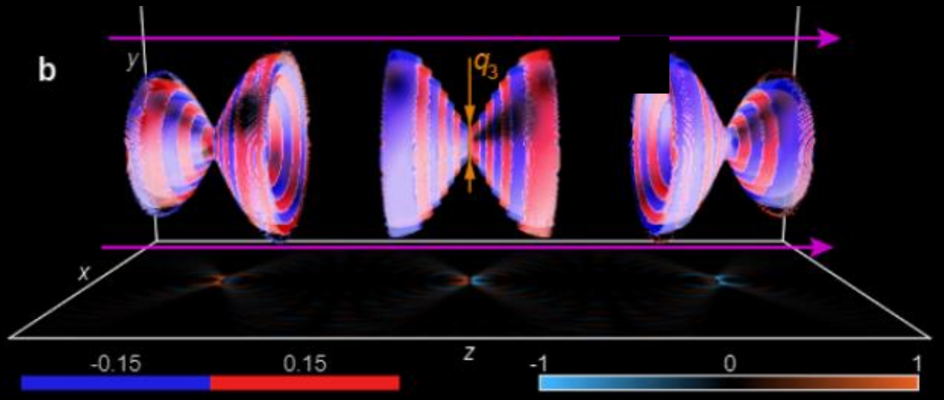


Supertoroidal pulse



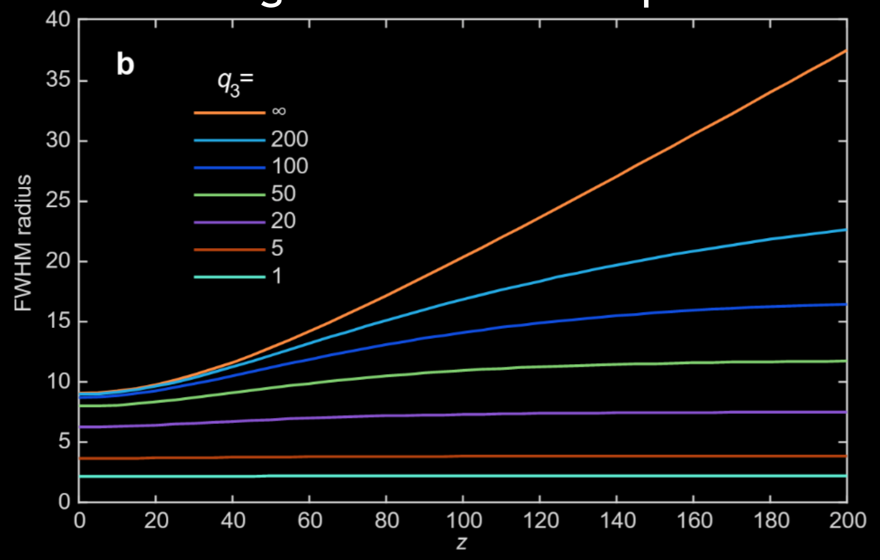
$q_3 \to \infty, \boldsymbol{\alpha} > \mathbf{1}$

Non-diffracting toroidal pulses



$q_3 = 1$ $\alpha = 1$

Divergence of toroidal pulses



Propagation-robust skyrmionic and vortex field configurations that persists over arbitrary propagation distances

Nondiffracting supertoroidal pulses and optical "Kármán vortex streets". Shen, Papasimakis and Zheludev. **Nature Comm. 15**, 4863 (2024)

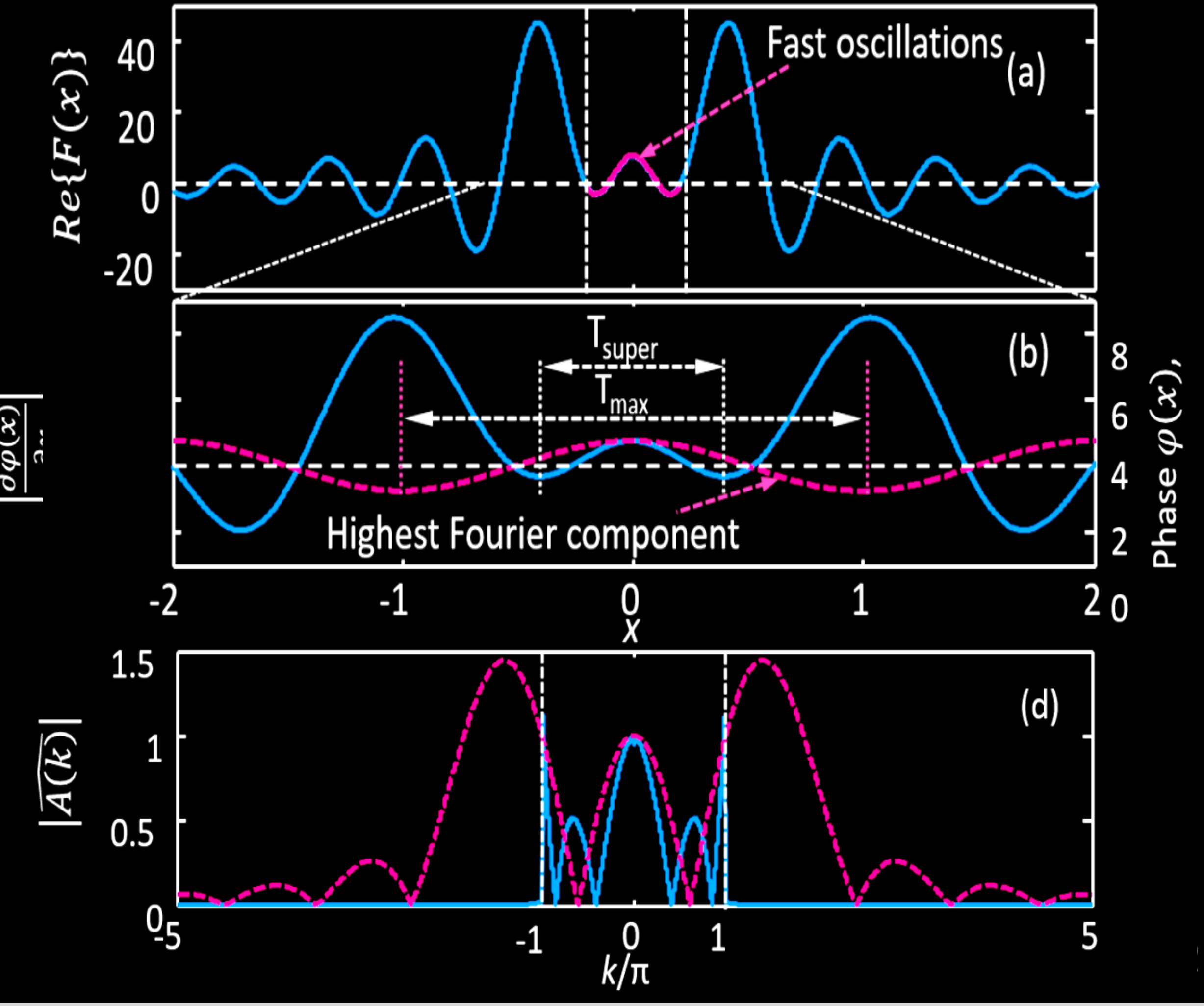
Space-time superoscillations in supertoroidal pulses

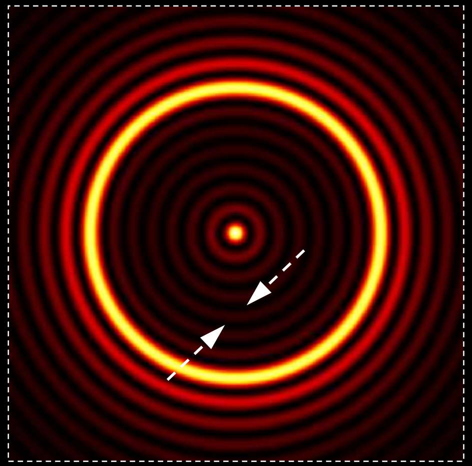
Why is it important?

A new class of superoscillation
Spectroscopy and metrology?

What are superoscillation?

Superoscillatory function (SO) in space or time is defined as a function with a band-limited spatial or temporal spectrum with a point in space or time where it changes faster than its fastest component of the spatial or temporal spectrum, correspondingly.





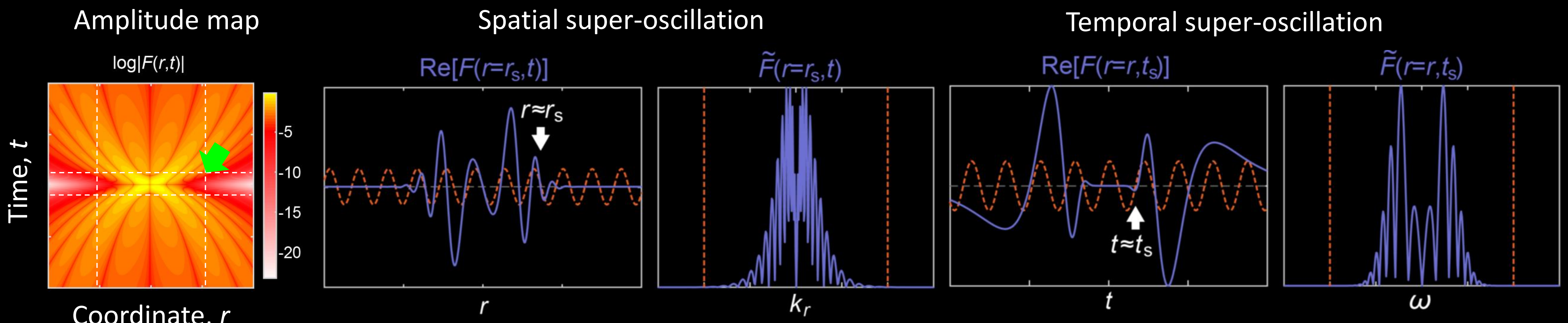
There is no limit to how small the super-oscillatory focus can be!

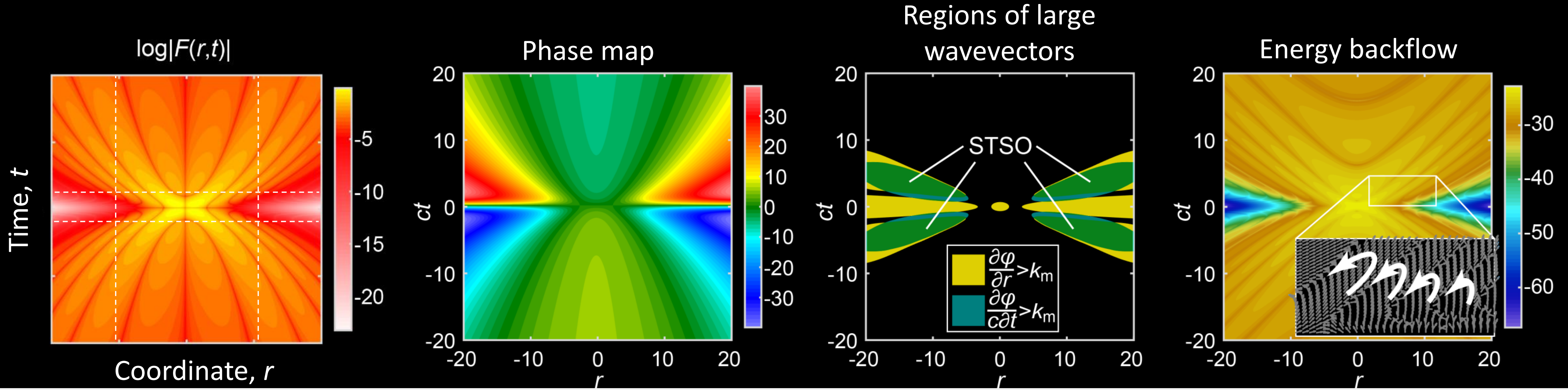
Space-time superoscillatory function (STSOs) as a function with simultaneously band-limited spatial and temporal spectra with a point in time and space where it changes in time faster than its fastest component of the temporal spectrum and simultaneously changes in space faster than the fastest component of its spatial spectrum.

Optical superoscillation technologies beyond the diffraction limit. Zheludev and Yuan. **Nature Reviews Physics** (2021) doi: 10.1038/s42254-021-00382-7

Superoscillations in super-toroidal pulses

(Supertoroidal pulse α=50, $q_2 = 100\ q_1$)





Space-time superoscillations in structured light pulses. Y. Shen, N. Papasimakis, M. R. Dennis, and N. I. Zheludev. **CLEO 2022**, San Jose, CA, USA, 15-20 May 2022

Supertoroidal anapoles

Why is it important?

A new class of high-Q excitations
Resonators, qubits

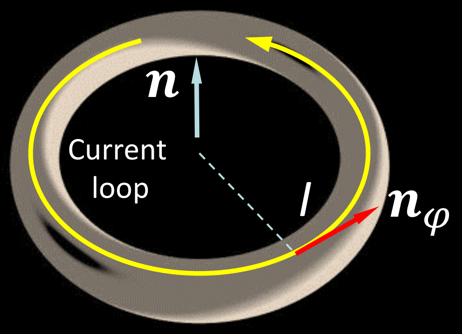
Super-toroidal currents

$$\overrightarrow{T^{(0)}} = \overrightarrow{M}$$

$$\mathbf{J} = f_0(t)\ curl(\mathbf{n}\delta^3(\mathbf{r}))$$

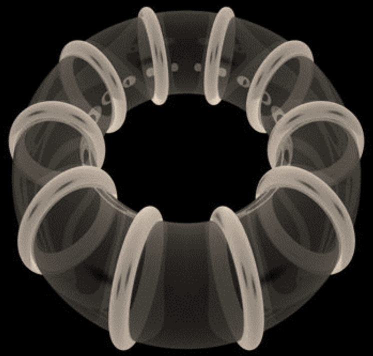
$$\overrightarrow{T^{(n)}} = \int \vec{r} \times \overrightarrow{T^{(n-1)}} dV$$

$$\mathbf{J} = f_m(t)\ curl^{m+1}(\mathbf{n}\delta^3(\mathbf{r}))$$



n=0

Magnetic dipole

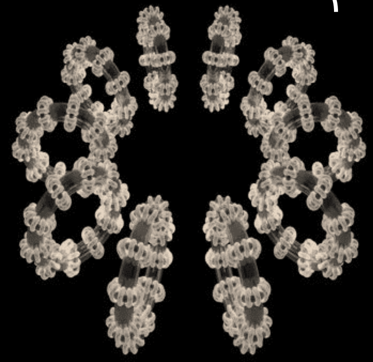


n=1

Toroidal dipole

n=2

Magnetic dipole
mean square radius



n=3

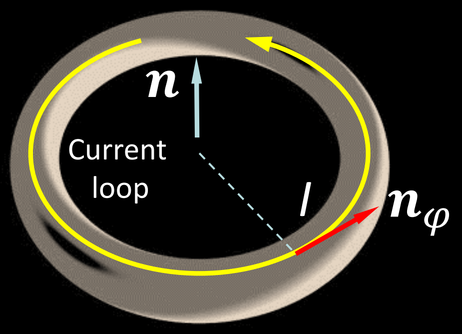
Toroidal dipole
mean square radius

Afanasiev & Stepanovsky, J. Phys. A Math. Gen. 28, 4565 (1995)

Toroidal and super-toroidal anapoles

$$\overrightarrow{T^{(0)}} = \overrightarrow{M}$$

$$\mathbf{J} = f_0(t)\ curl(\mathbf{n}\delta^3(\mathbf{r}))$$



Magnetic dipole, n=0

$$\overrightarrow{T^{(n)}} = \int \vec{r} \times \overrightarrow{T^{(n-1)}} dV$$

$$\mathbf{J} = f_m(t)\ curl^{m+1}(\mathbf{n}\delta^3(\mathbf{r}))$$

Toroidal dipole, n=1

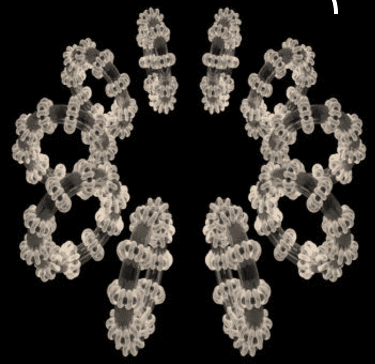
Electric dipole

Toroidal anapole

Magnetic dipole mean square radius (MSR), n=2

Electric dipole

Supertoroidal anapole

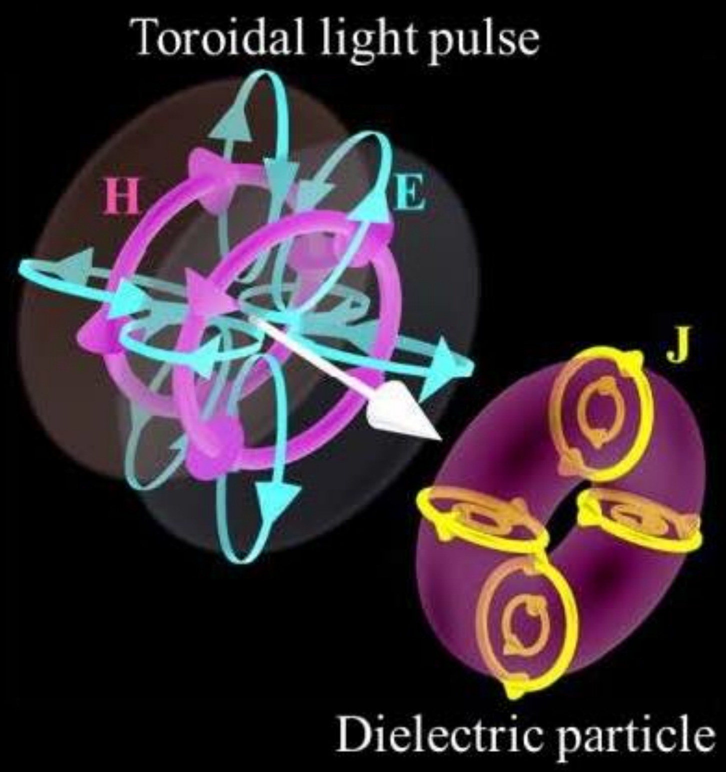


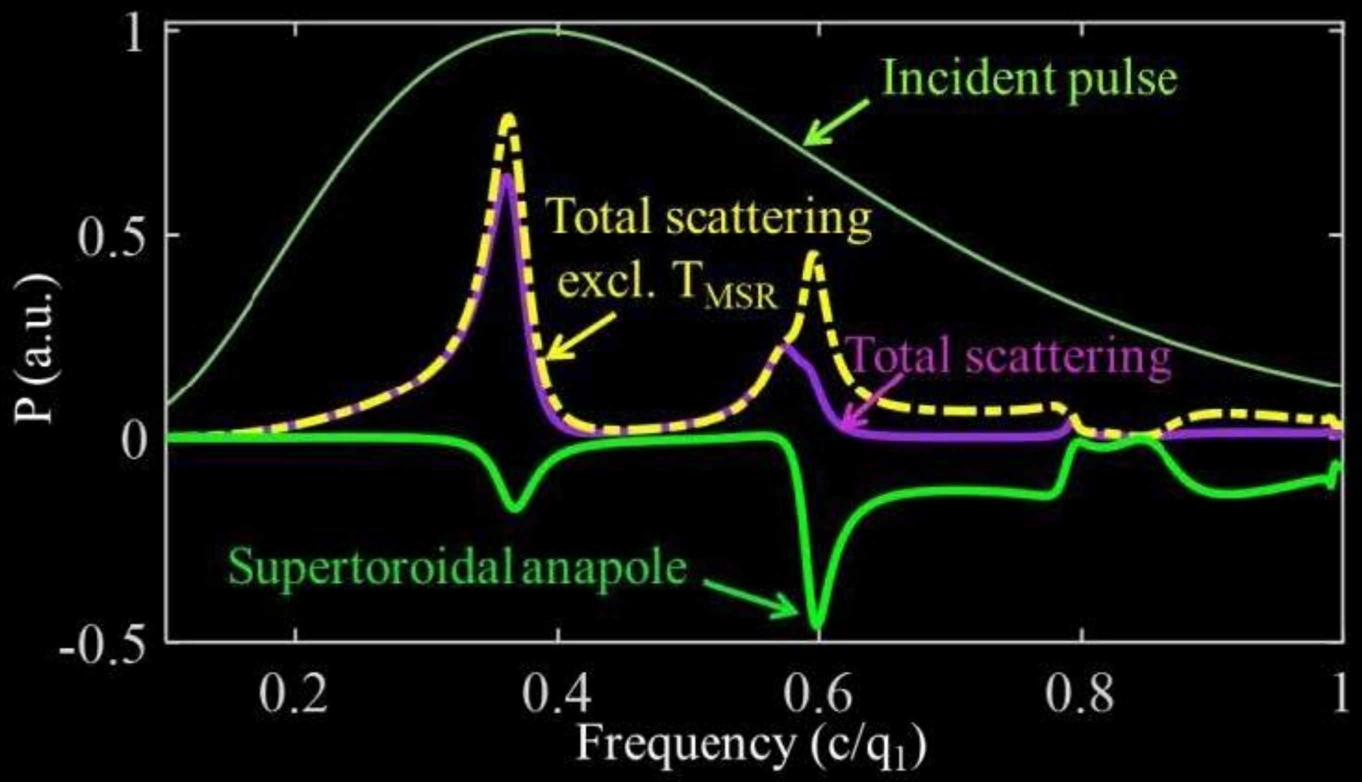
Toroidal dipole mean square radius MSR, n=3

Afanasiev & Stepanovsky, J. Phys. A Math. Gen. 28, 4565 (1995)

Nemkov, Basharin, Fedotov, Phys. Rev. A, 98, 023858 (2018)

How to observe a supertoroidal anapoles?





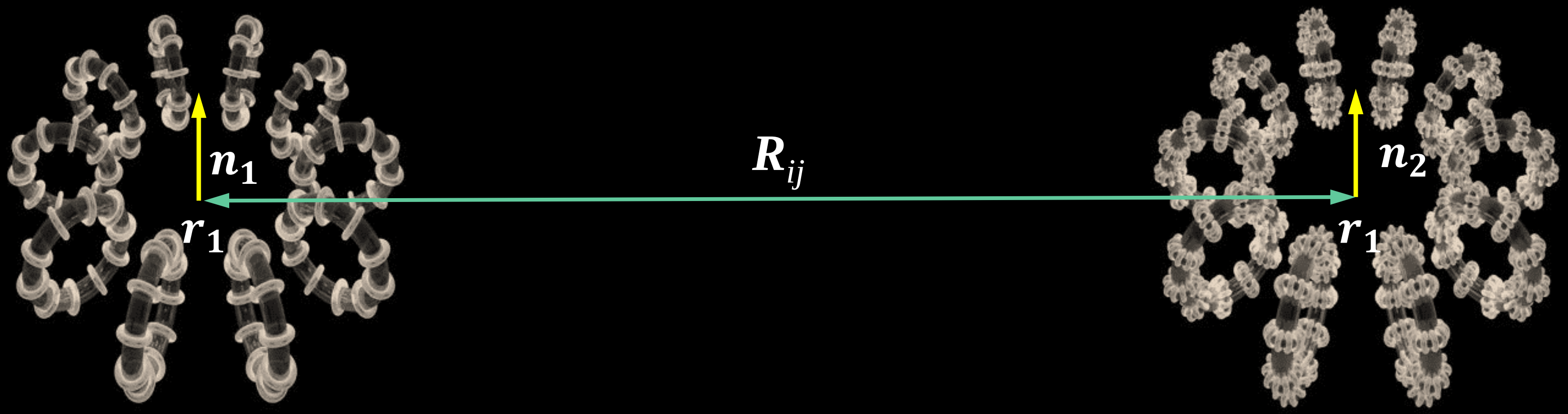
Anapole 2: Electric dipole + Magnetic dipole mean square radius

Optical forces in toroidal matter

Why is it important?

Molecular dynamics
Nonreciprocal phase transitions
Time crystals
Active Matter

Afanasiev (2001):
non-reciprocal **electromagnetic** interaction between toroidal currents



Even type current: $m_1 = 2q$

interaction energy

Odd type current: $m_2 = 2p + 1$

$$\boldsymbol{J_1} = f_1(t)\, curl^{(m_1+1)}(\boldsymbol{n_1}\delta^3(\boldsymbol{r} - \boldsymbol{r_1}))$$

$$\boldsymbol{J_2} = f_2(t)\, curl^{(m_2+1)}(\boldsymbol{n_2}\delta^3(\boldsymbol{r} - \boldsymbol{r_2}))$$

$$U_{12} \neq U_{12}$$

$$U_{12} = f_1(t)\frac{\boldsymbol{n_1}(\boldsymbol{R_{12}} \times \boldsymbol{n_2})}{R_{12}^2} \cdot \frac{\partial^{(m_1+m_2+1)} D(f_2(t))}{\partial t^{(m_1+m_2+1)}}$$

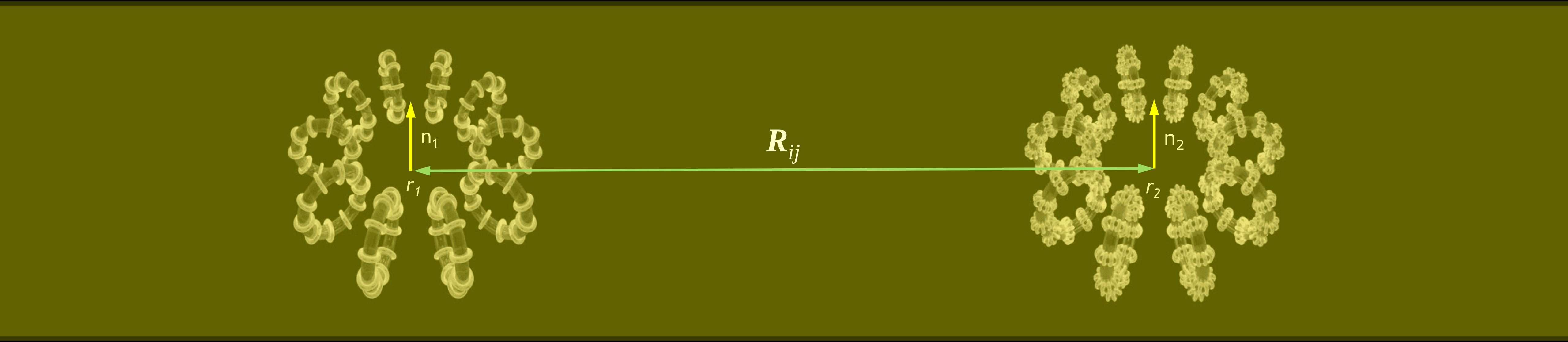
$$U_{21} = f_1(t)\frac{\boldsymbol{n_2}(\boldsymbol{R_{21}} \times \boldsymbol{n_1})}{R_{21}^2} \cdot \frac{\partial^{(m_1+m_2+1)} D(f_1(t))}{\partial t^{(m_1+m_2+1)}}$$

Reciprocity works if only:

- The time dependencies are the same for all space points of a particular source
  - The time dependencies in source 1 and source 2 are the same

Simplest sources of electromagnetic fields as a tool for testing the reciprocity-like theorems. Afanasiev, G. N. **Journal of Physics D-Applied Physics**, 34, 539 (2001)

Non-reciprocal light-induced mechanical interactions between toroidal currents

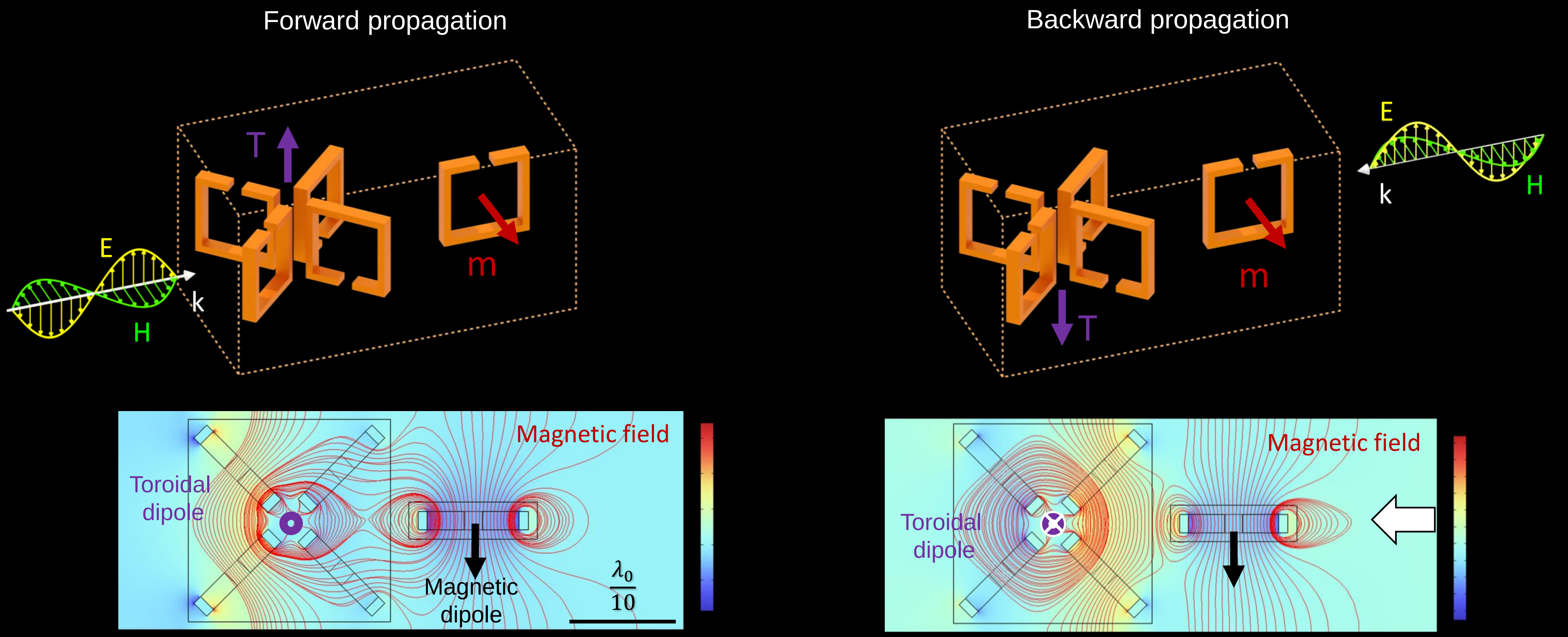


$$F_n \neq -F_m$$

$$\partial_z U_{12} \neq \partial_z U_{21}$$

Predator-Prey Nonreciprocal Interactions of Toroidal Charge-Current Configurations. Mididoddi , Papasimakis, Zheludev. **Metamaterials Congress 2004**, Crete.

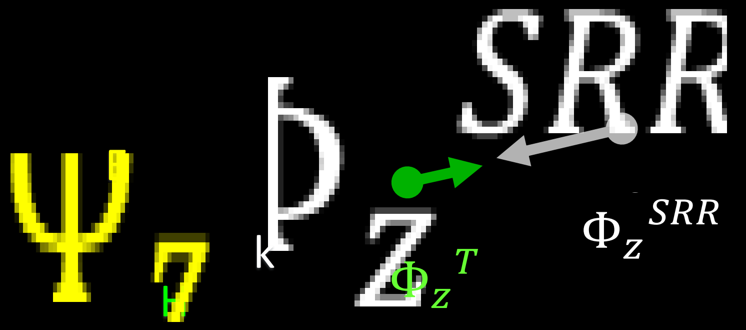
Propagation Dependent Optical Forces

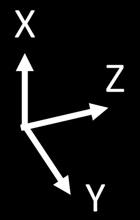


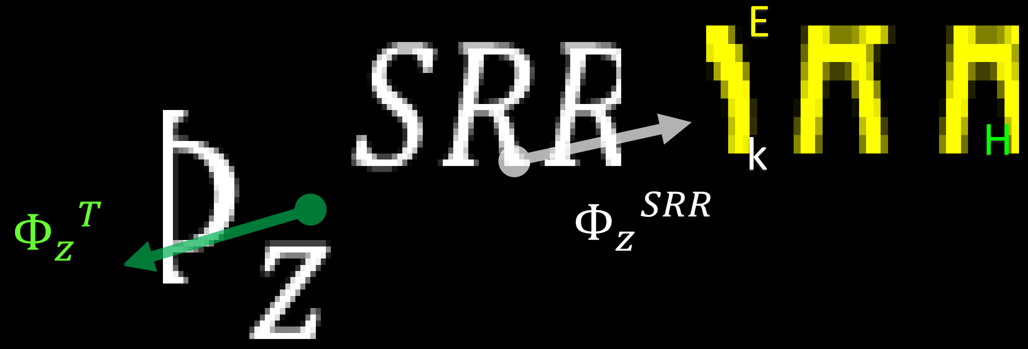
Lorentz reciprocity holds

Transmission is independent on propagation direction

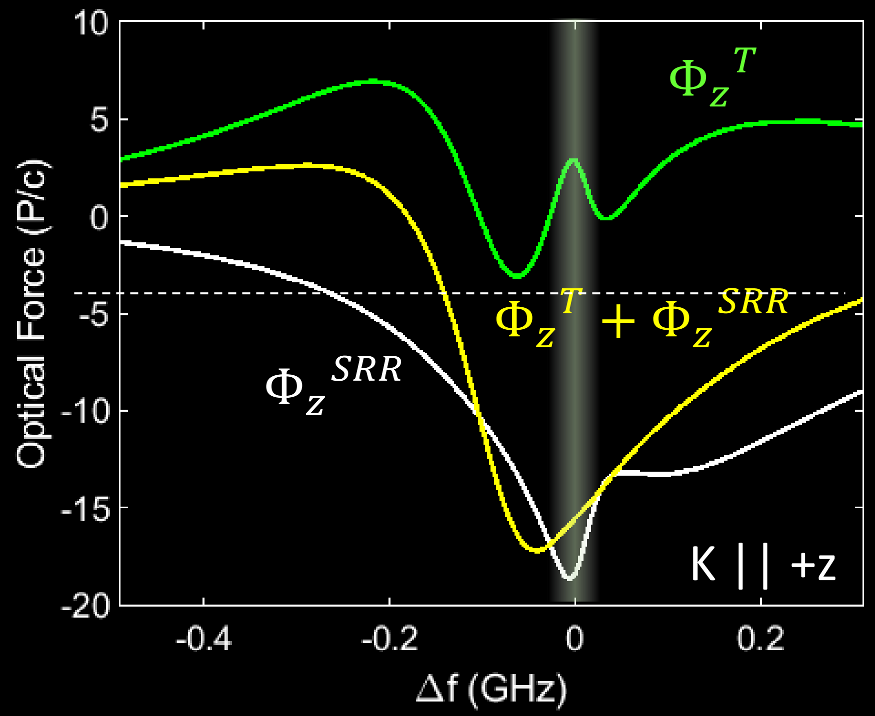
Optical Interaction forces between the metamolecules, *Φ*



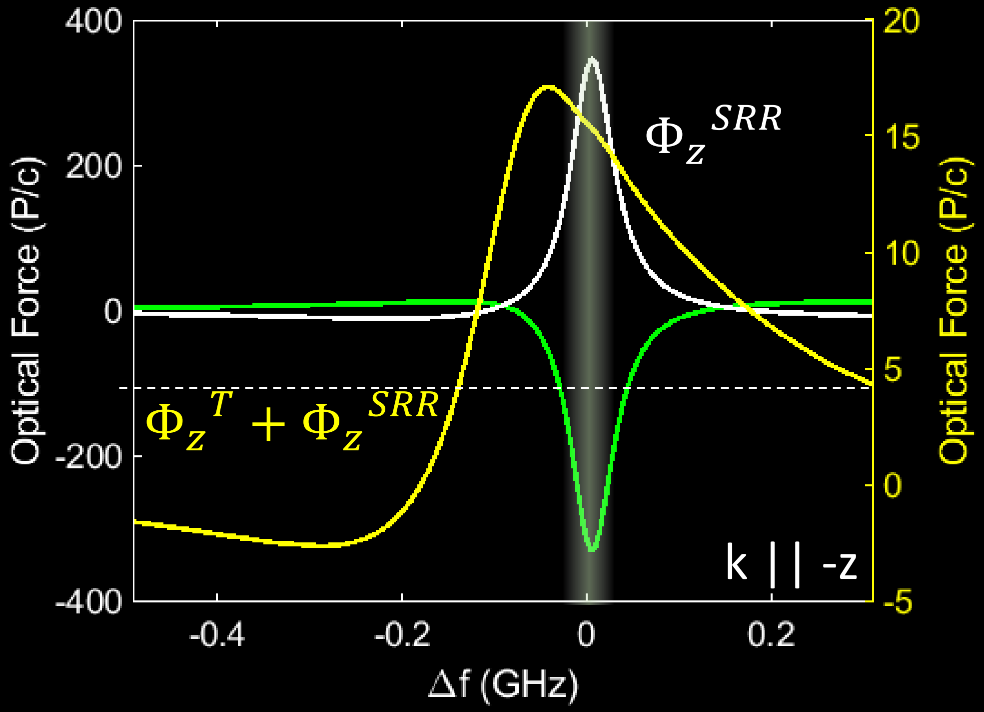




Weak attraction interaction forces, nonreciprocal at resonance



Strong repulsive interaction forces, weakly nonreciprocal



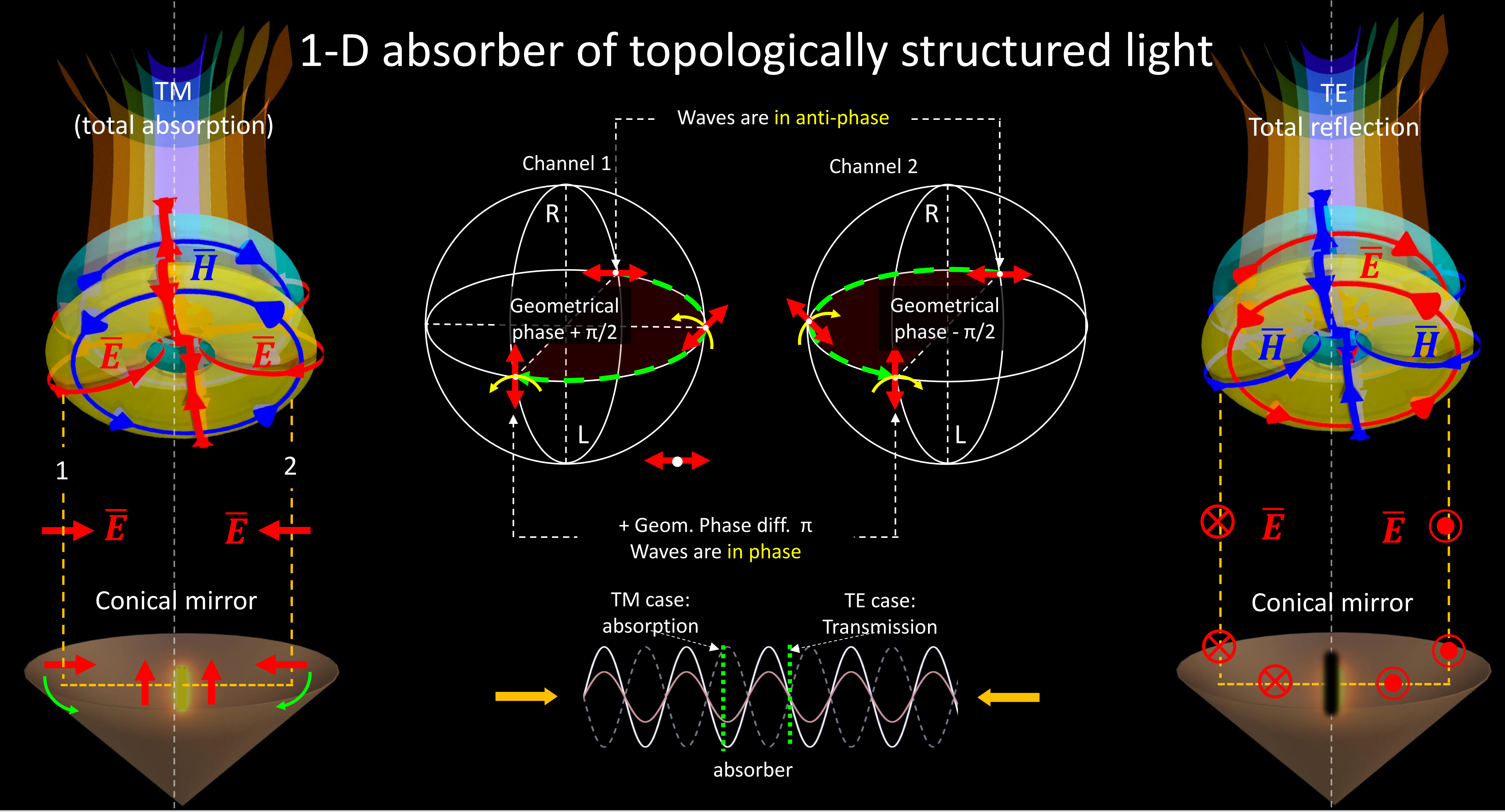
Predator-Prey Nonreciprocal Interactions of Toroidal Charge-Current Configurations. Mididoddi , Papasimakis, Zheludev. **Metamaterials Congress** 2004, Crete.

Absorber sensitive to topology of light

Why is it important?

Telecom
Spectroscopy

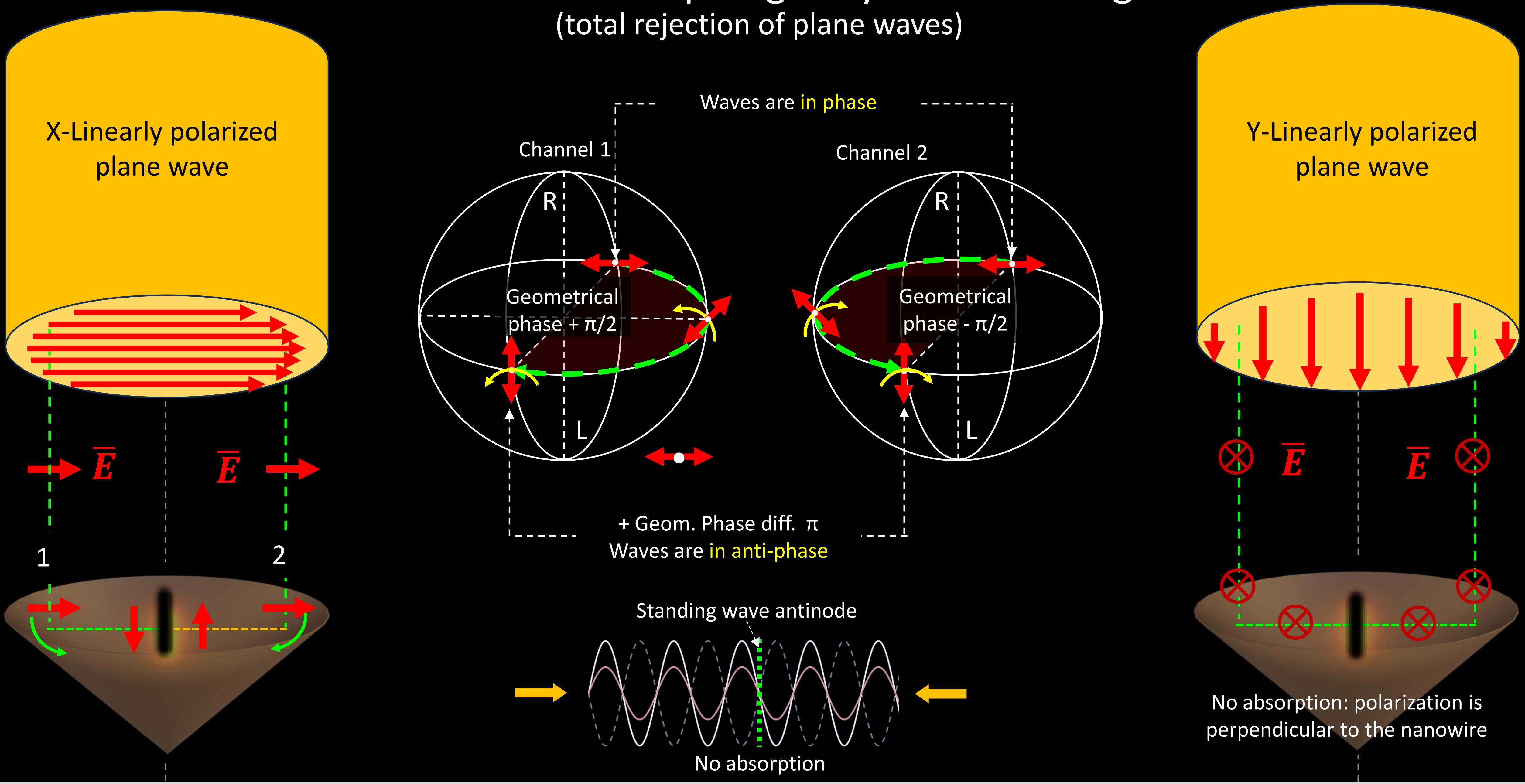
1-D absorber of topologically structured light



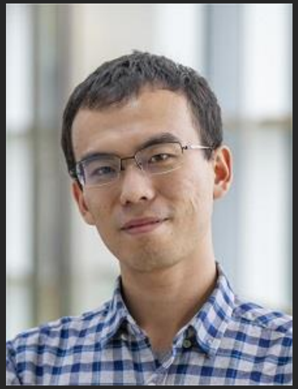
Coherent perfect absorption of light in a single nanowire. Vignjevic, Papasimakis, Plum, and Zheludev. **Metamaterials Congress 2024**, Crete, Greece, 9 – 14 Sept 2024

1-D absorber of topologically structured light

(total rejection of plane waves)



The Production Team



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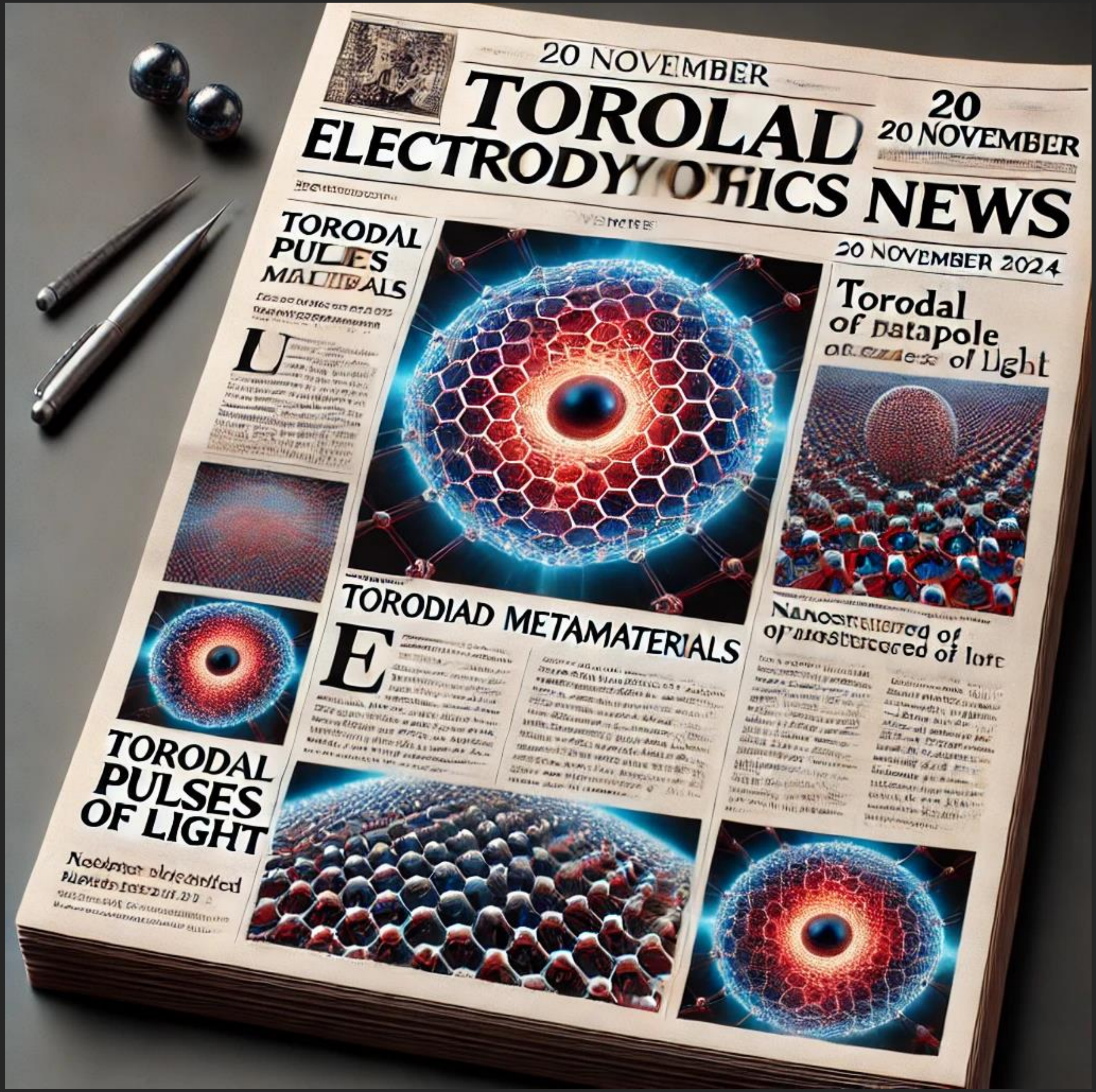

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