Negative refraction using atomic gases

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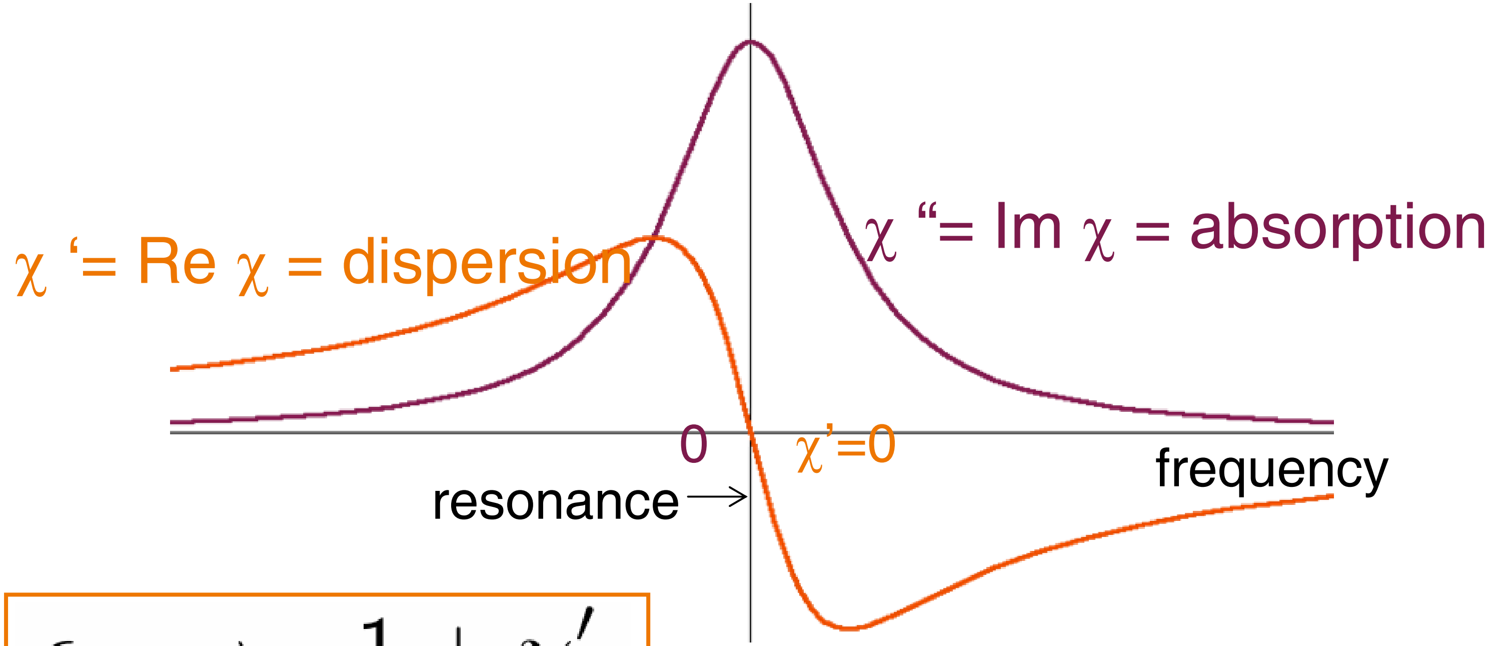
KITP, May 11, 2007

…but what about the basics?

susceptibility $\chi \propto \dfrac{\gamma}{\gamma + \mathrm{i}(\omega - \omega_0)}$

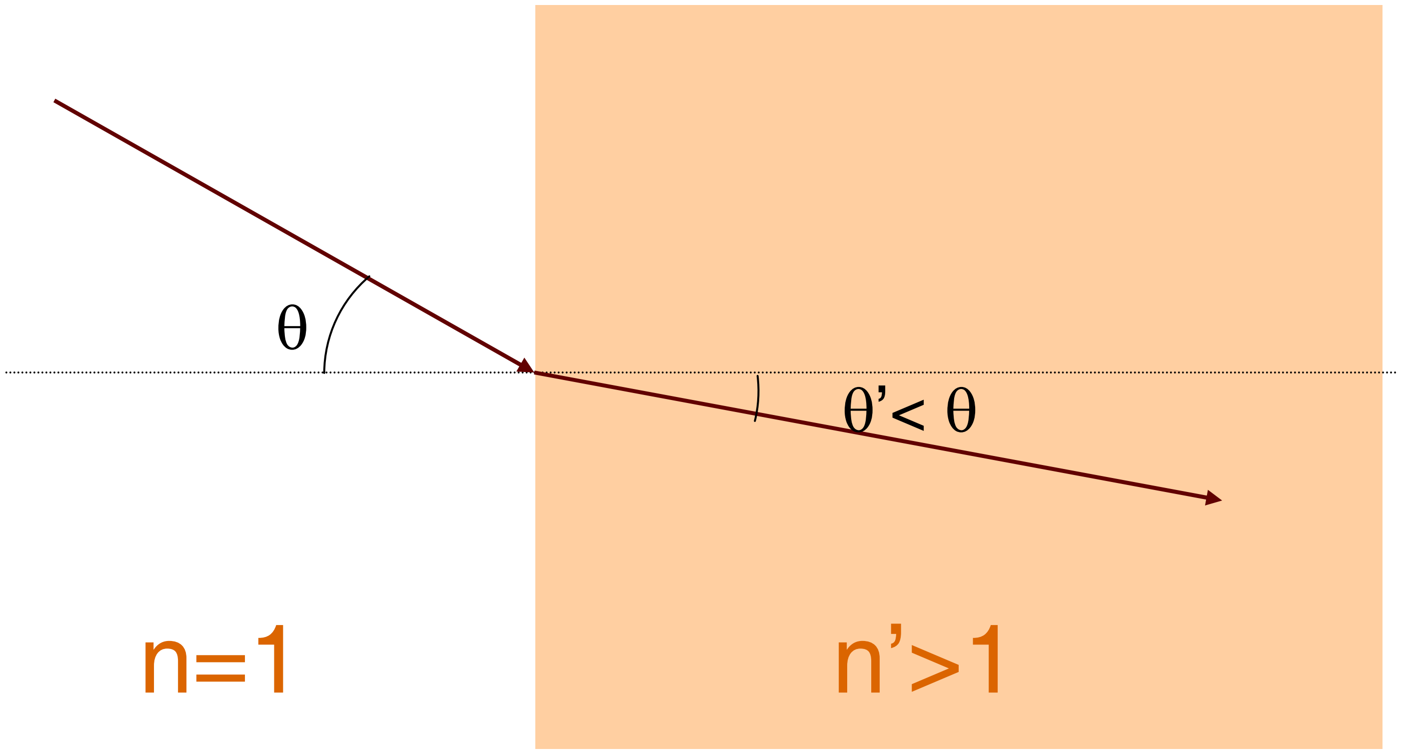


$$\begin{array}{ccc} \epsilon & \longrightarrow & 1 + \chi'_{\mathrm{e}} \\ \mu & \longrightarrow & 1 + \chi'_{\mathrm{m}} \end{array}$$

Contents:

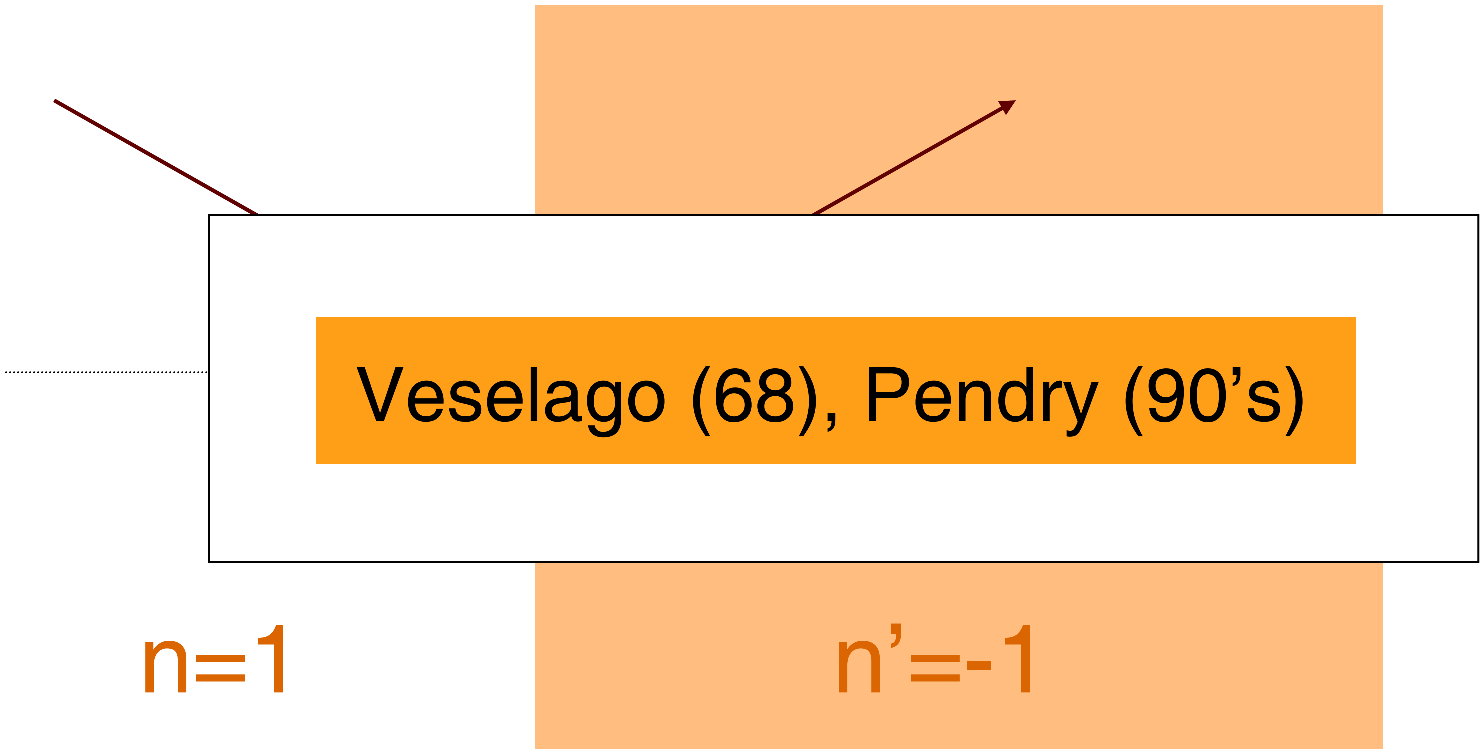
- Electromagnetically induced transparency (EIT)
- Negative refraction
  - EIC (elm. induced chirality)
  - Realiztion based on quantum optics
- Outlook

Model: normal refraction



normal refraction
(Snell's law)

Model: negative refraction



Veselago (68), Pendry (90’s)

n=1

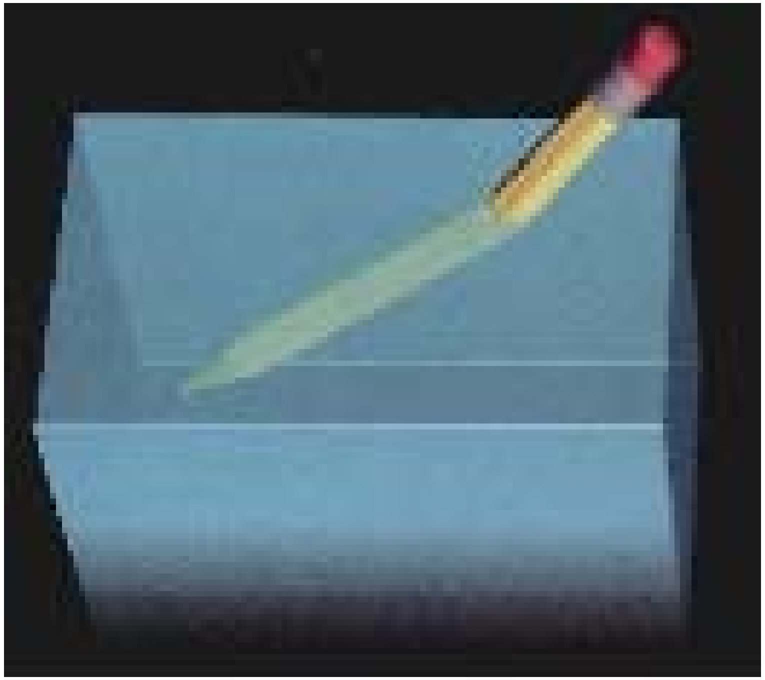
n’=-1

negative refraction
(Snell’s law)

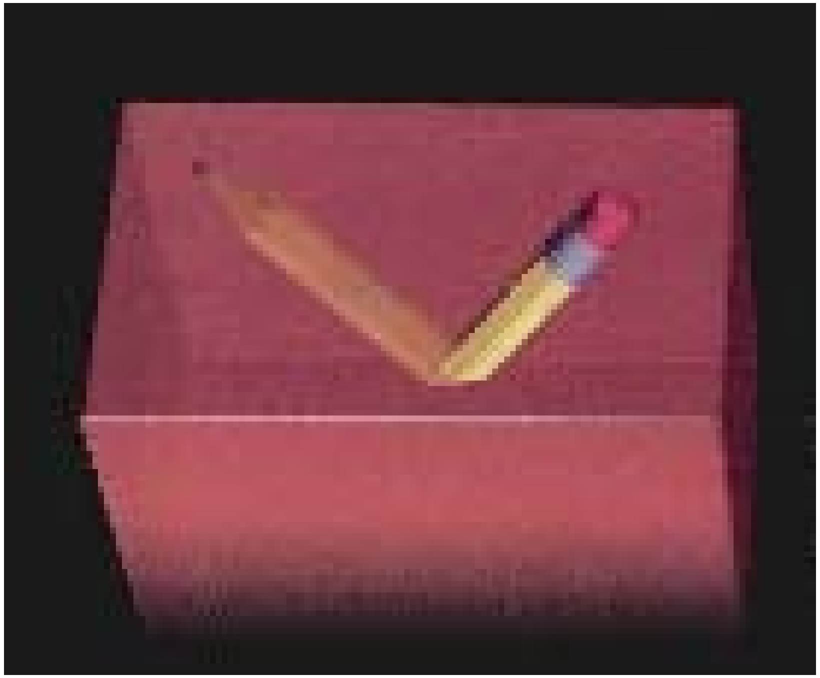
⇨

“left-handed”:
E, **B**, and **k**

Light bent backwards



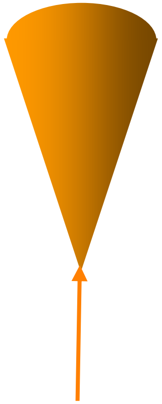
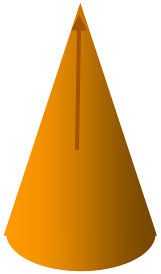
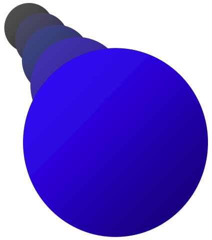
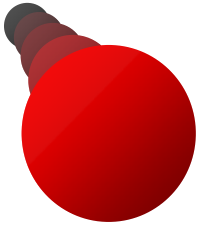
normal refraction



negative refraction

Scientific American, July 2006

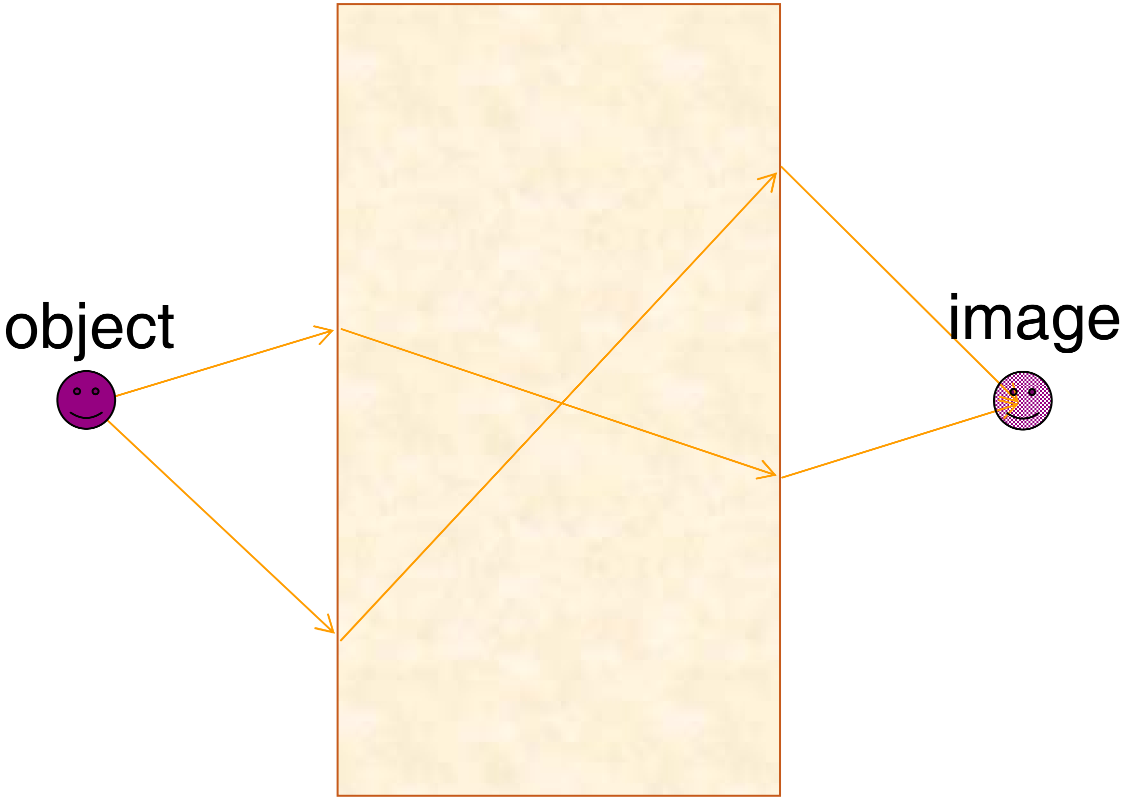
Effects

normal refraction	negative refraction
phase velocity $v \approx c$ Group velocity $v_{gr} < v$	phase velocity $v \approx -c$ group velocity $v_{gr} \approx +c$
Cerenkov radiation: forward cone 	backward cone 
Doppler effect: approaching object blue shifted 	red shifted 

Pendry, Smith, Sci. Am., 7/06

Applications

- Applications:
  - superlens (cf. Pendry, PRL 85, 3966 (2000))



Superlens

- normal lens:

$$k_x = \sqrt{\frac{\omega^2}{c^2} - k_z^2}$$

☑ Resolution: $2\pi k_x^{-1} \geq \lambda$ (diffraction limit)!

- superlens (negative refraction):

n<0 ☑ amplification of evanescent waves

k_z can be imaginary ☑ $k_x > \omega/c$ possible

Applications

- Applications:
  - perfect lens

  - far apart superradiance

  - and others …

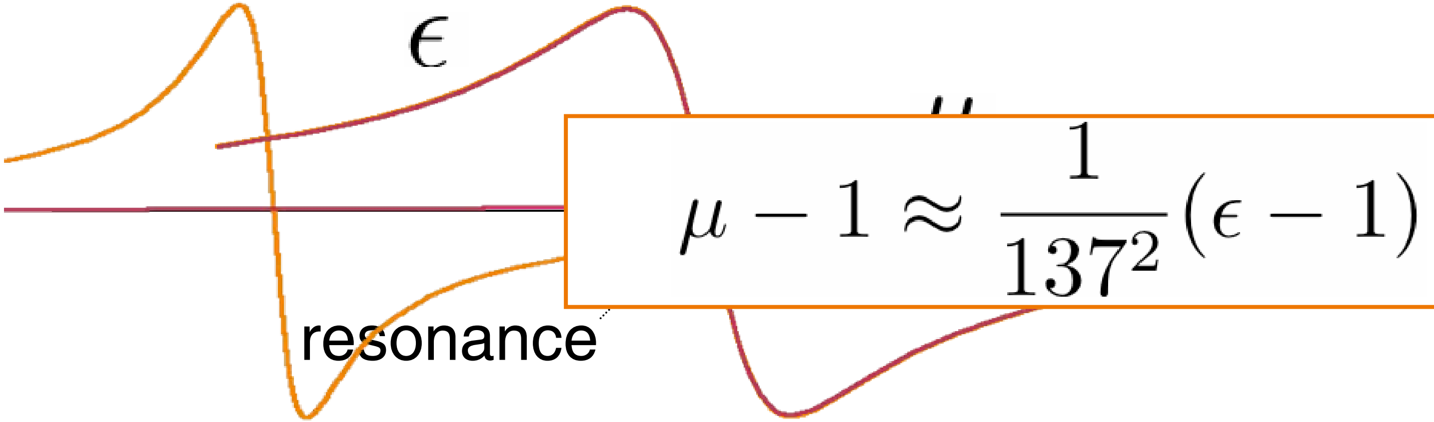
Origin of negative refraction

$$n = \sqrt{\epsilon\mu}$$

ϵ : electric permittivity

μ : magnetic permeability

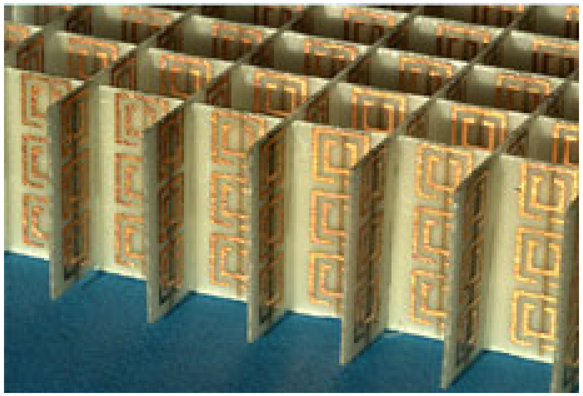
With both, ϵ and μ negative ☑ n negative



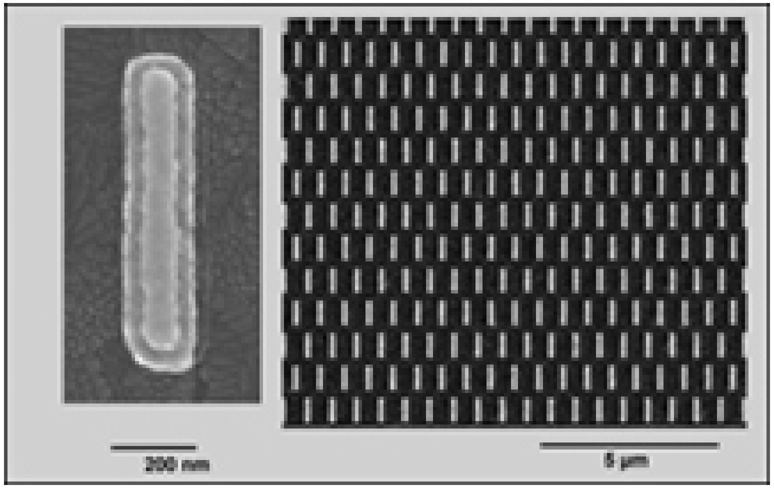
$$\mu - 1 \approx \frac{1}{137^2}(\epsilon - 1)$$

Material examples

- μ-wave structures:



Pendry



Shalaev

Photonic bandgap material

- Use band stucture of the photonic crystal to get a left-handed material ("flip over" k vector direction on Fermi surface)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

1 μm

Notomi

- For certain frequency: negative refraction
- But: not "metamaterial": No resolution beyond λ! (☑ no superlensing!)

Hyperlens

Cylindrical anisotropy …

$$\boxed{\frac{k_r^2}{\epsilon_\theta} - \frac{k_\theta^2}{\epsilon_r} = \frac{\omega^2}{c^2}}$$

… to create cylindrical lens with alternating dielectric/metal layers.

Jacob, Alekseyev, Narimanov, Opt. Exp. 14, 8247 (06)

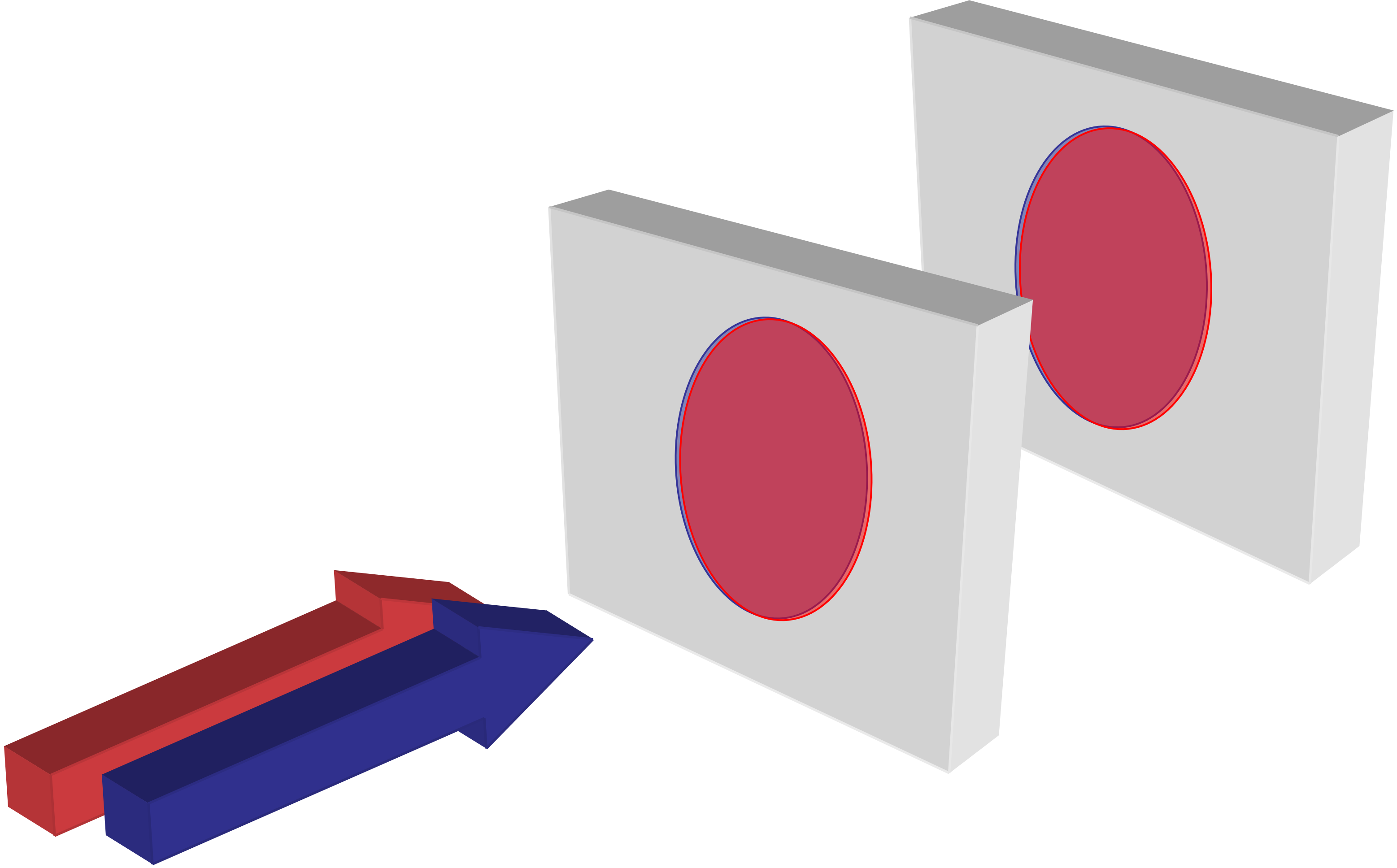
Absorption

So far: refraction/absorption $\approx$ 1…5

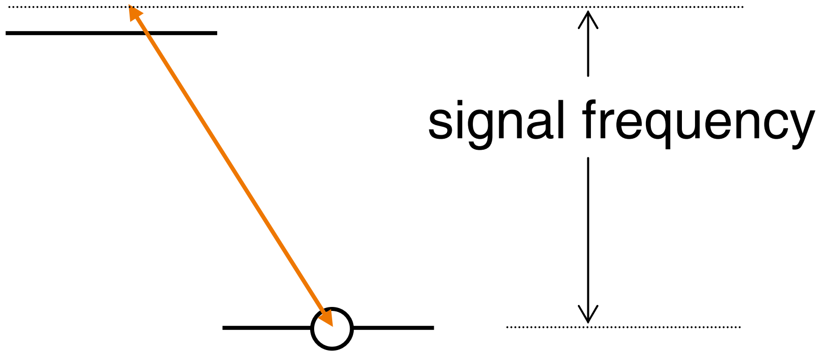
Our case: Re(n)/Im(n) = 100

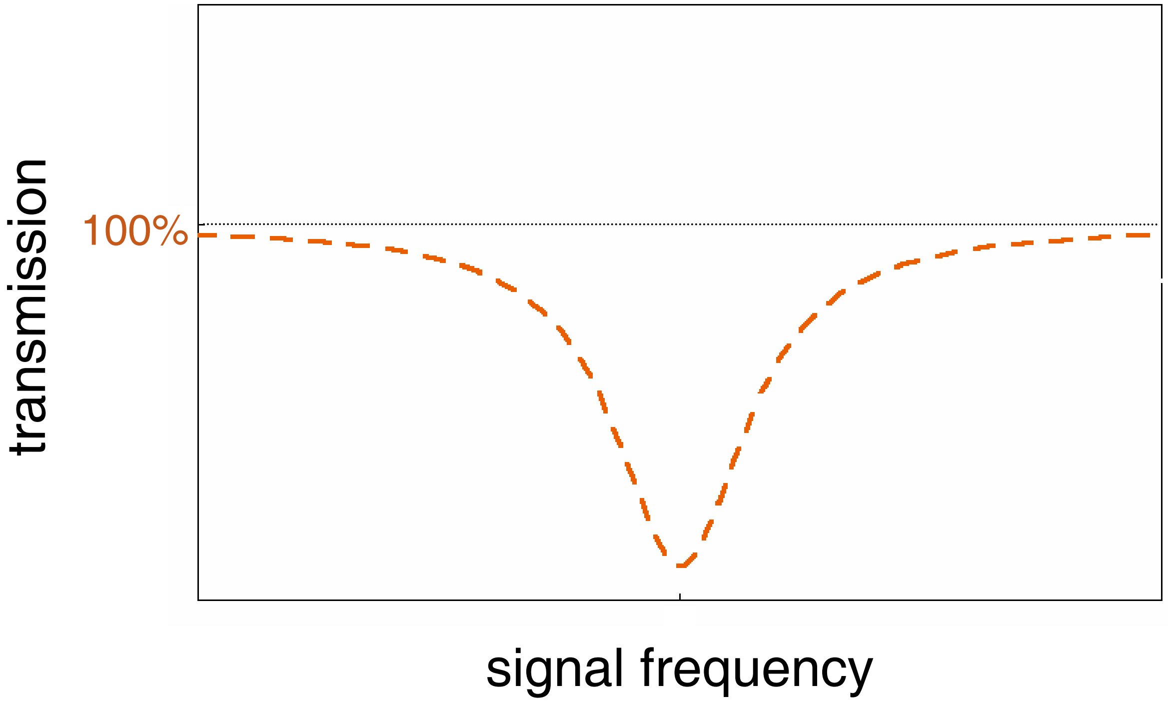
Matter absorbs resonant light:

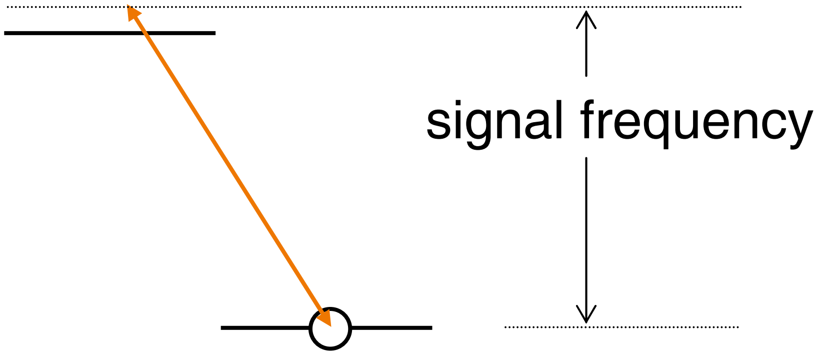
Manipulation with another beam leads to

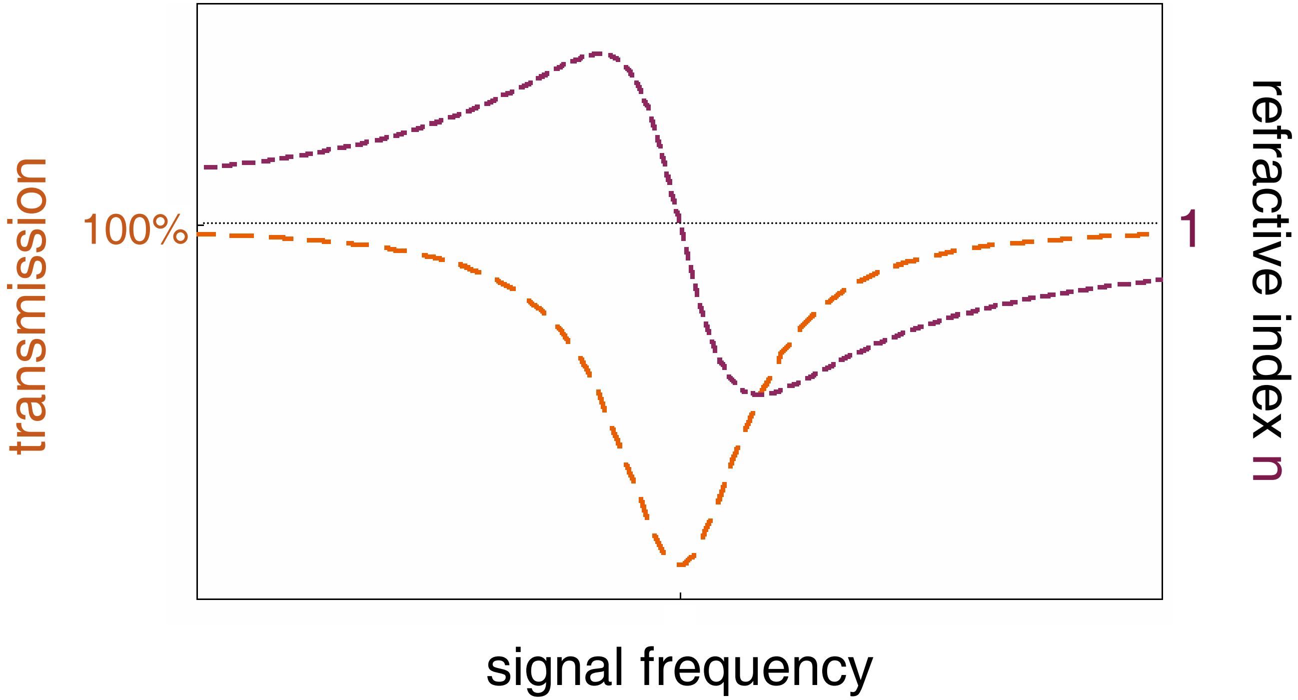


Electromagnetically induced transparency

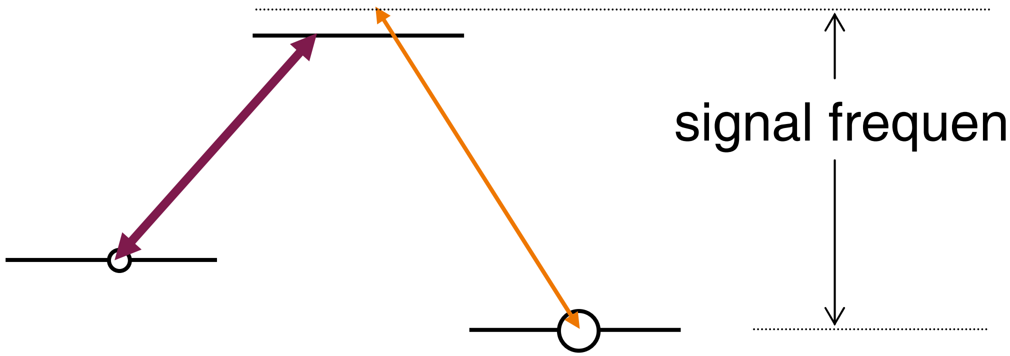

signal frequency

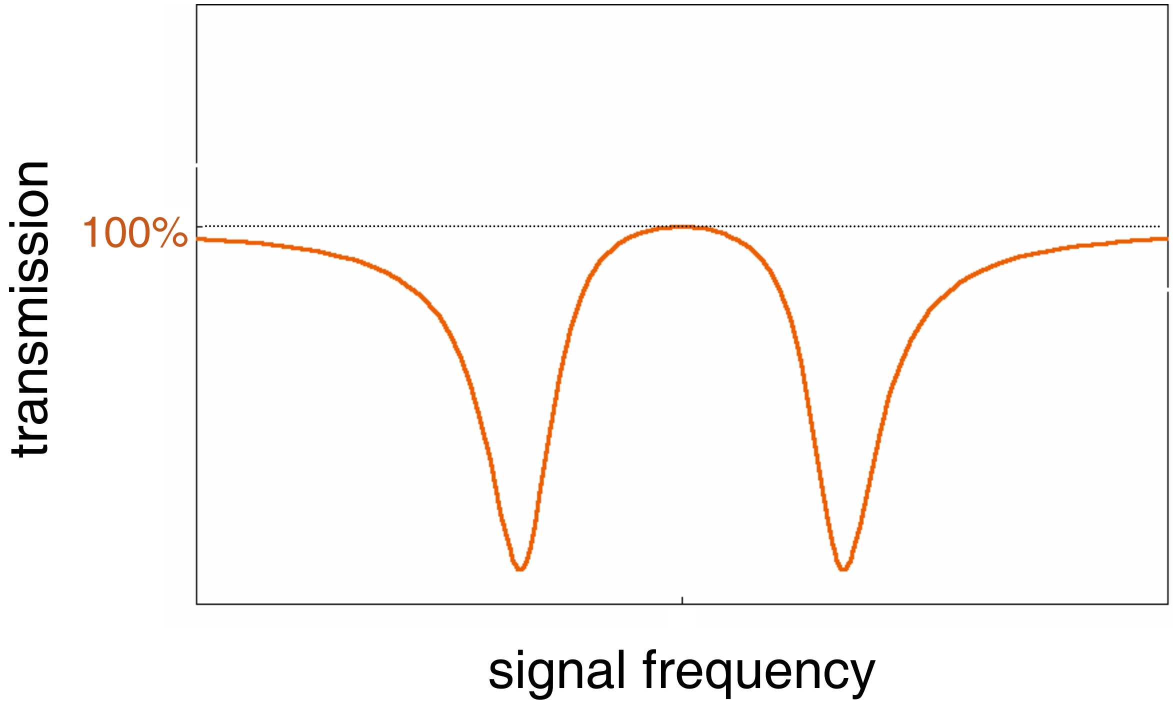

transmission
100%
signal frequency


signal frequency

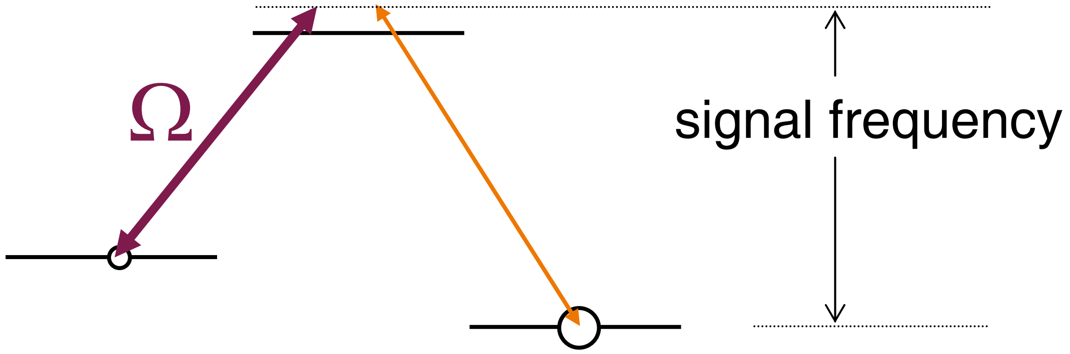

transmission
100%
1
refractive index n
signal frequency

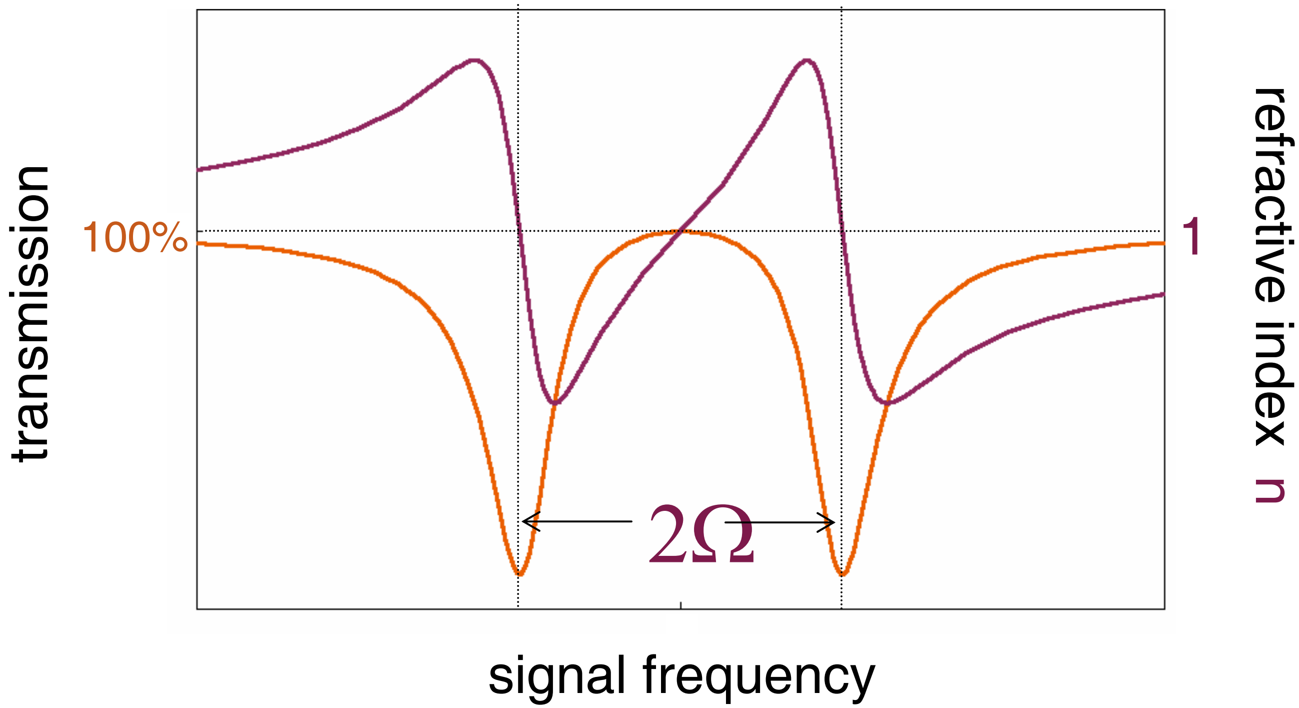
Electromagnetically induced transparency





Dispersion


Ω
signal frequency


transmission
100%
1
refractive index n
2Ω
signal frequency

Chiral media (Pendry)

- Remember: $n = \sqrt{\epsilon\mu}$
- Chiral media: cross coupling between electric and magnetic fields

$$\begin{aligned} \mathbf{P} &= \chi_e \mathbf{E} + \xi_{eb} \mathbf{B} \\ \mathbf{M} &= \xi_{be} \mathbf{E} + \chi_m \mathbf{B} \end{aligned}$$

with $|\xi| \propto \frac{1}{137} |\chi_e|$

- Index of refraction

$$\boxed{n = \sqrt{\epsilon\mu - \frac{(\xi_{eb} + \xi_{be})^2}{4}} + \frac{i}{2}(\xi_{eb} - \xi_{be})}$$

Electromagnetically induced chirality

- Remember: $\mathsf{n} = \sqrt{\epsilon\mu}$
- Chiral media: cross coupling between electric

$$\mathbf{P} = \chi_{\mathsf{e}}\mathbf{E} + \xi_{\mathsf{eb}}\mathbf{B}$$

$$\mathbf{M} = \xi_{\mathsf{be}}\mathbf{E} + \chi_{\mathsf{m}}\mathbf{B}$$

$\chi_e|$

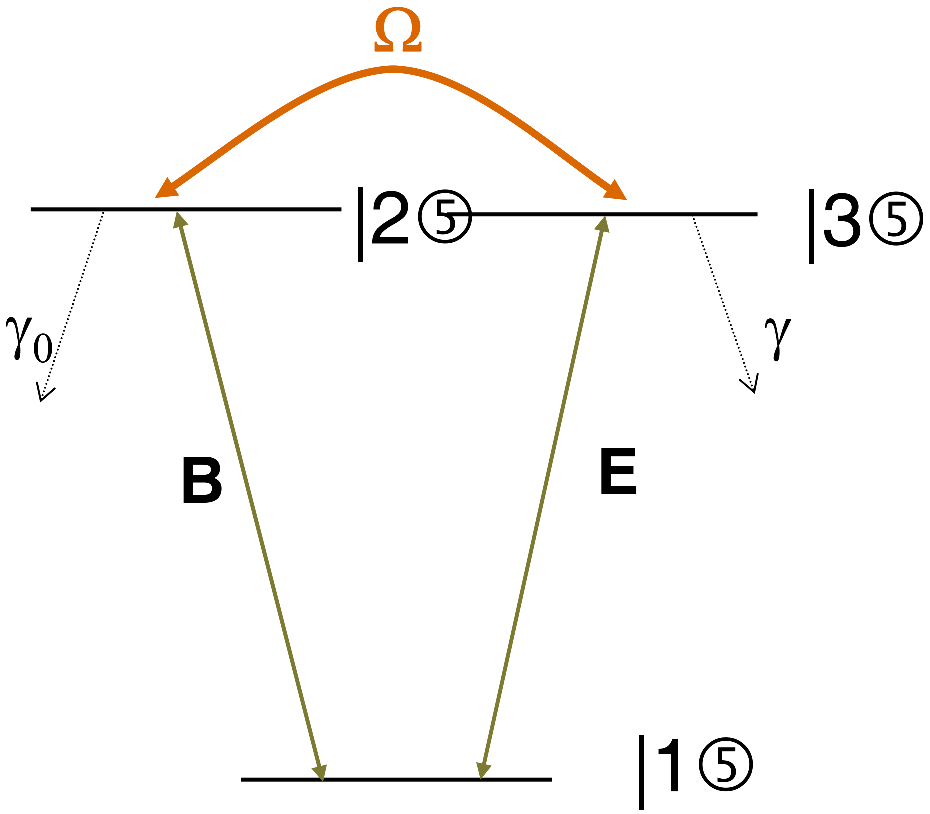
$$\mathsf{n} = \sqrt{\epsilon\mu} - \xi$$

optical

If we choose $= \mathsf{i}\xi$

EIT based negative refraction

V-type system:



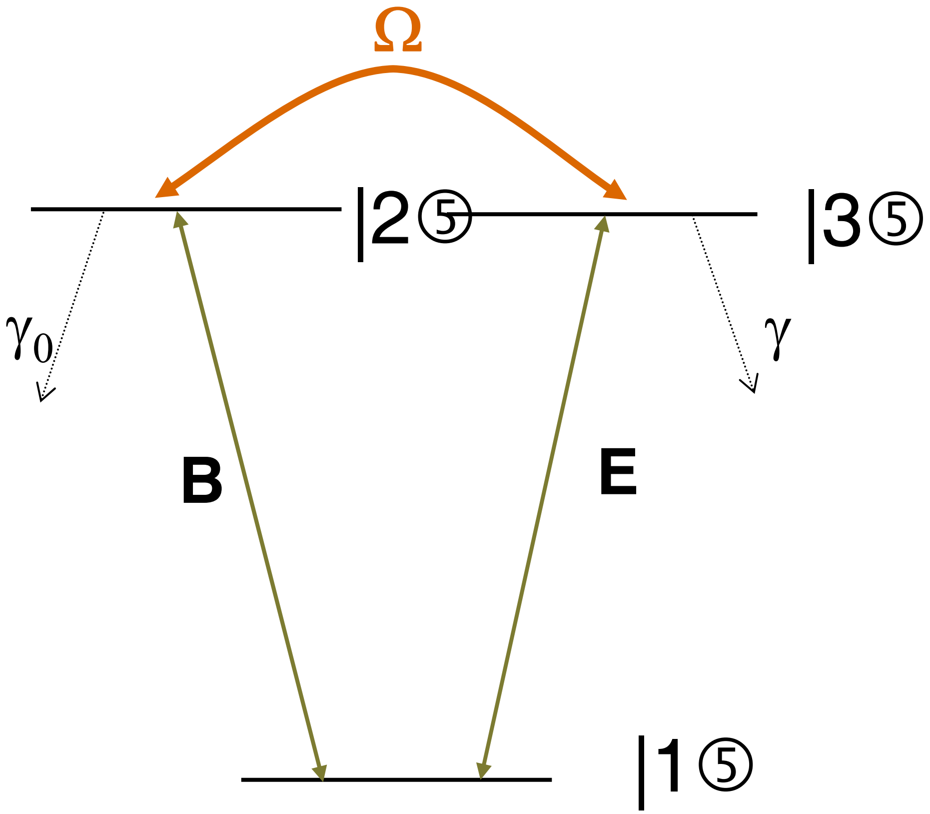
- **E, B** electric/ magnetic part of probe field
- Ω cross couples electric and magnetic transition

☑Chiral behavior

- γ_0 « γ ☑ EIT

EIT based negative refraction

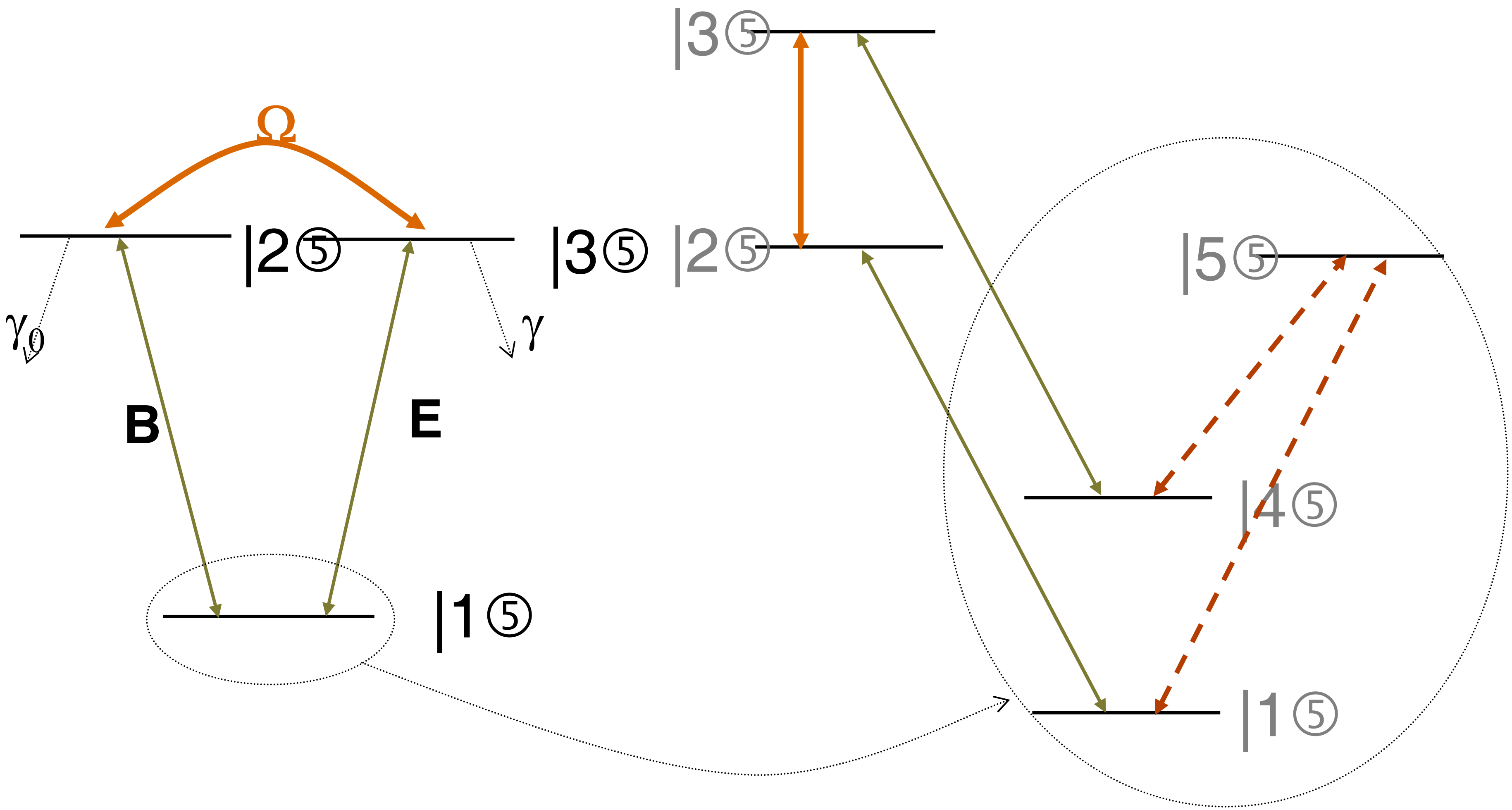
V-type system:



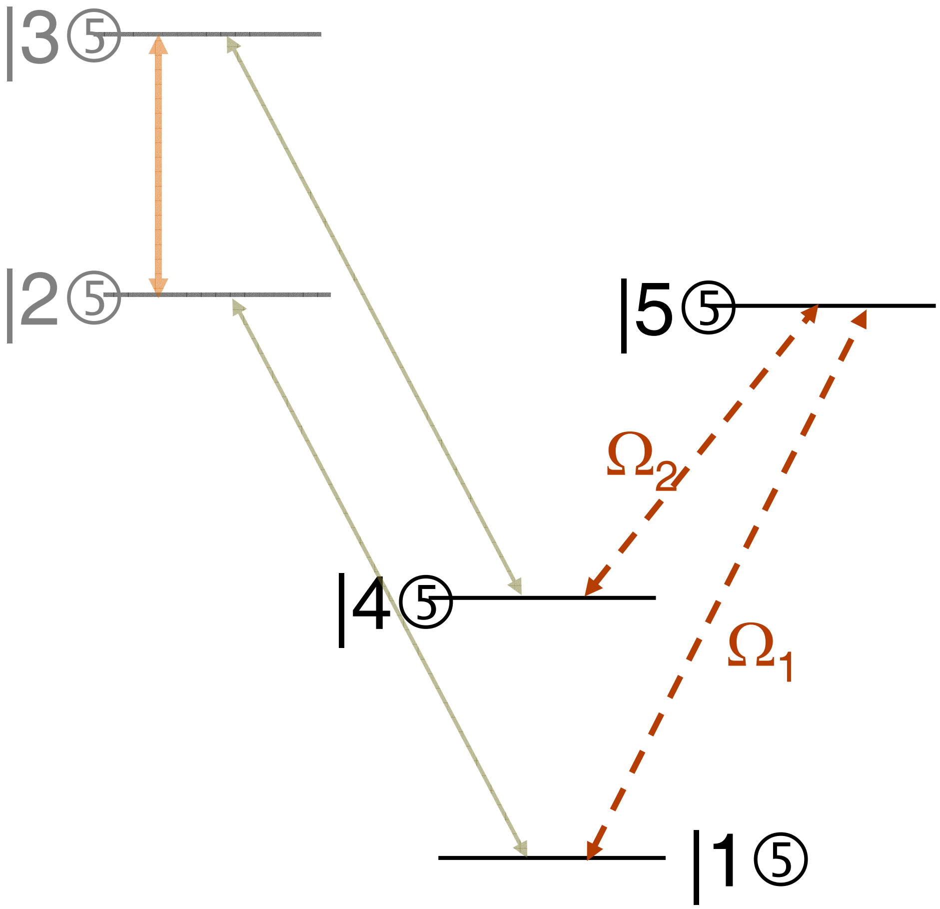
Problems:

- Ω: dc-coupling ☑ phase of ξ not free to choose
- Ω dc-coupling: very weak Rabi frequency
- no EIT for inhomogeneously broadened systems
- level scheme hard to find in real systems

Realistic schemes



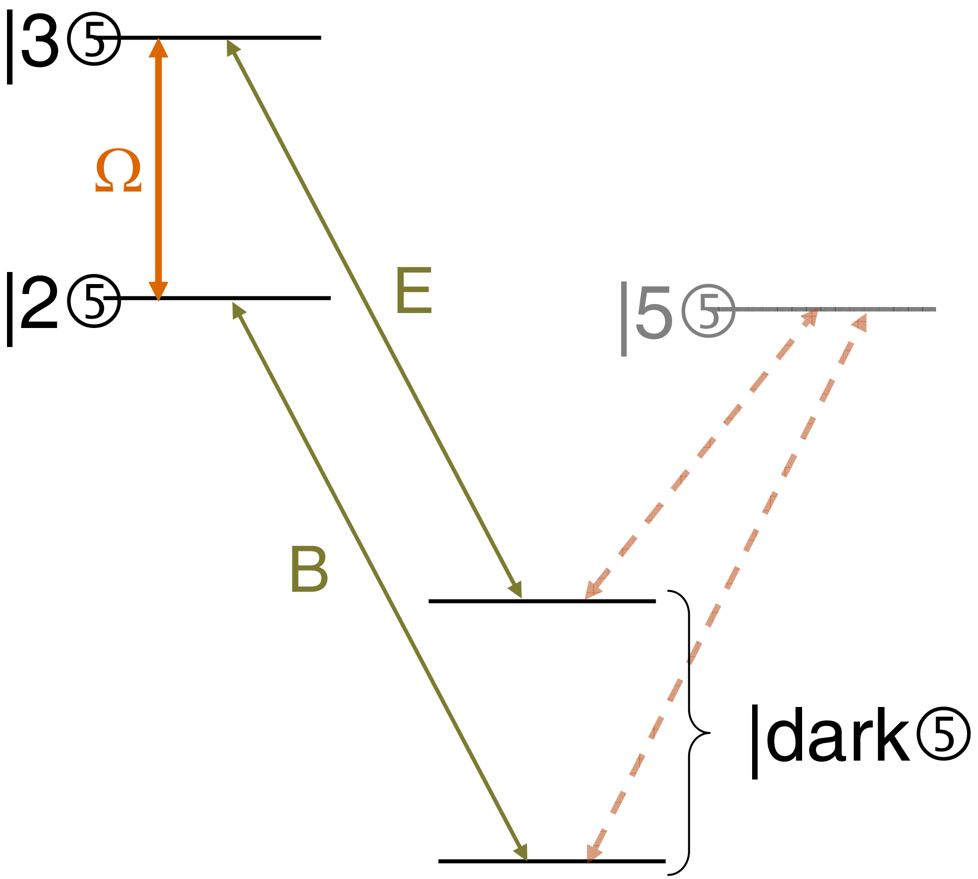
Realistic schemes



- Create dark state in superposition of |1⑤ and |4⑤
- Dark state acts like g.s. in 3-level system

$$\boxed{|\mathsf{dark}\rangle \propto \Omega_1 |1\rangle - \Omega_2 |4\rangle}$$

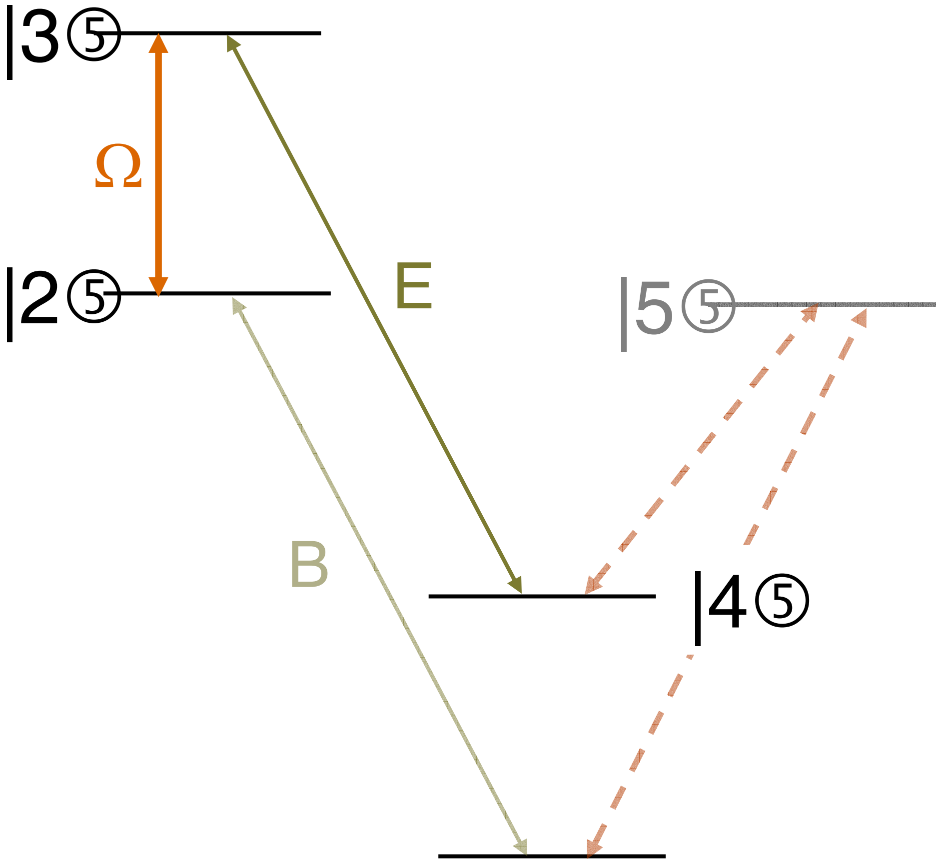
Realistic schemes



Advantages:

- Non-dc coupling field Ω
  - ☑ Choose phase

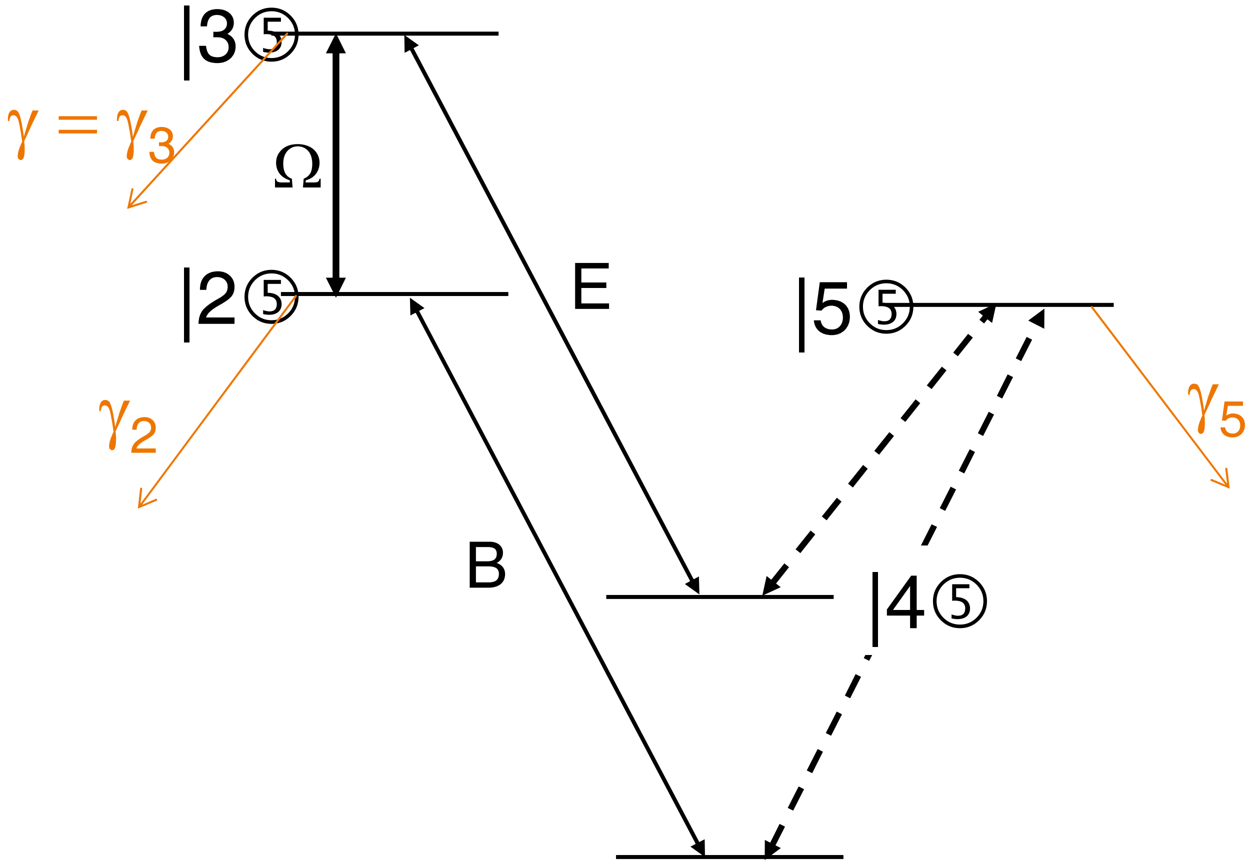
Realistic schemes



Advantages:

- Non-dc coupling field Ω
  - ☑ Choose phase
- States |2⑤ and |4⑤ can be chosen at similar energy
  - ☑ No Doppler broadening on sensitive Λ-type scheme (|4⑤, |2⑤, and |3⑤)
- Easier to realize

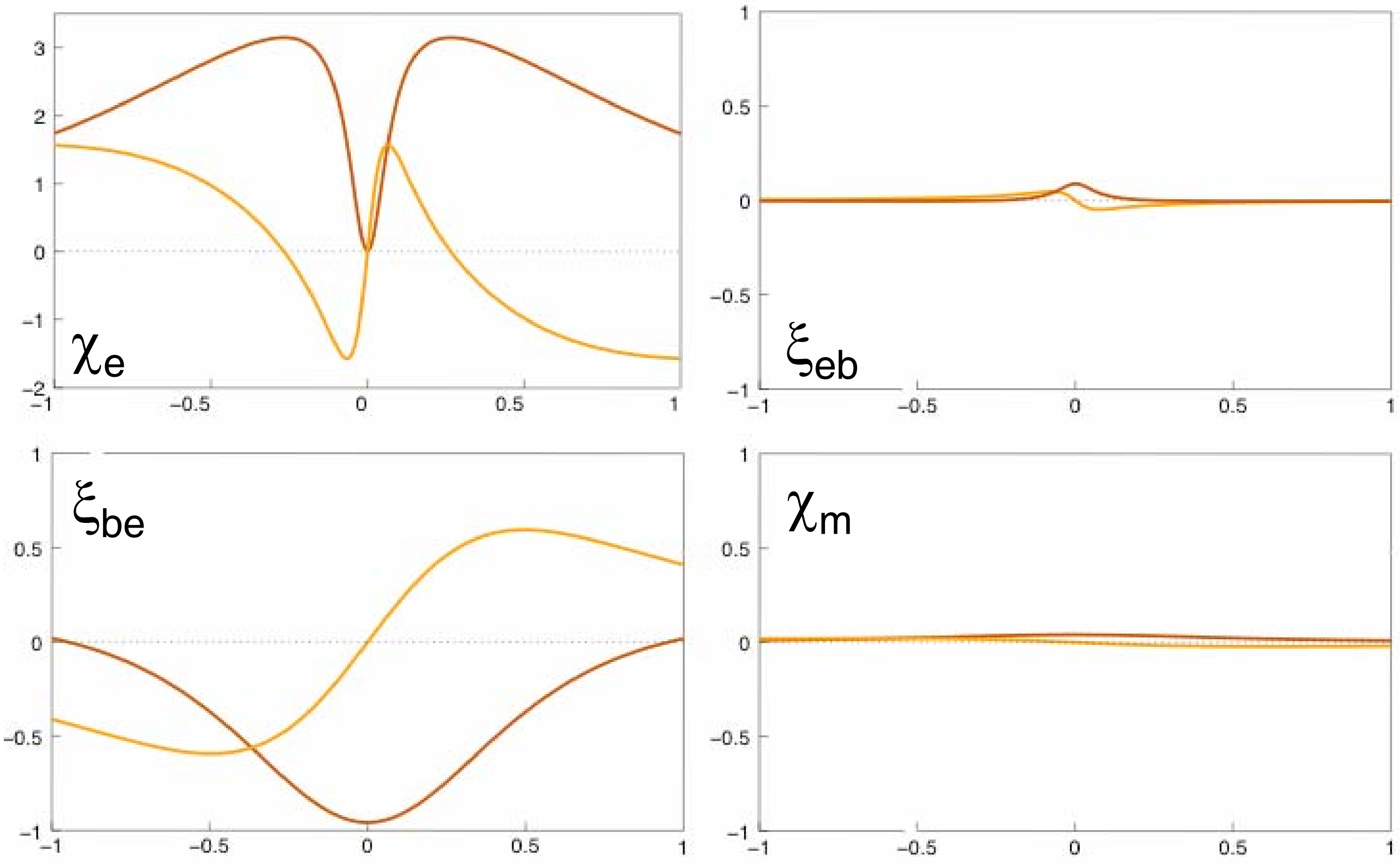
Realistic schemes



+ line broadening (inhomogeneous)

Cross couplings

Inhomogeneous broadening $\approx$ decay rate γ

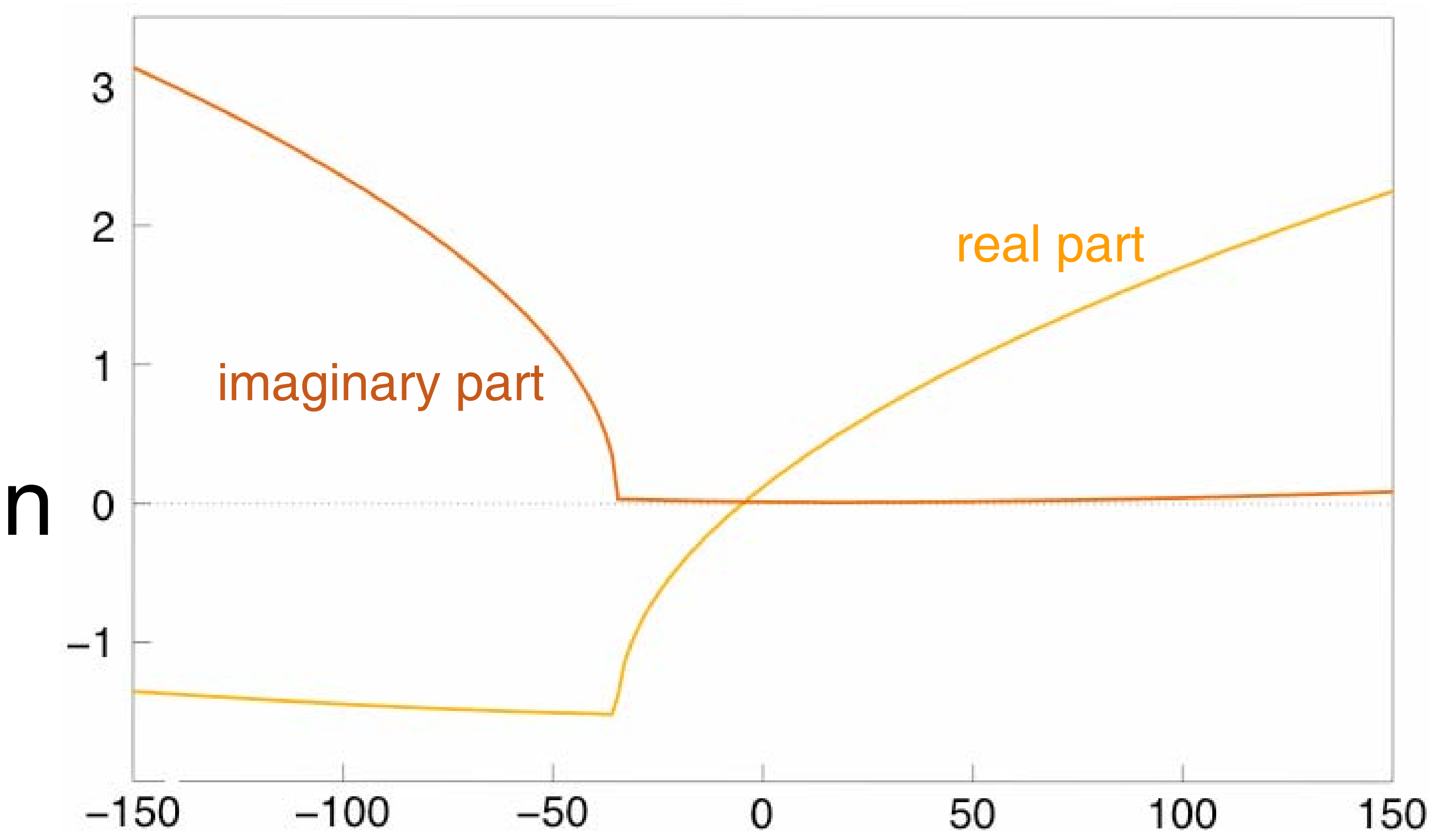


— real part

— imaginary part

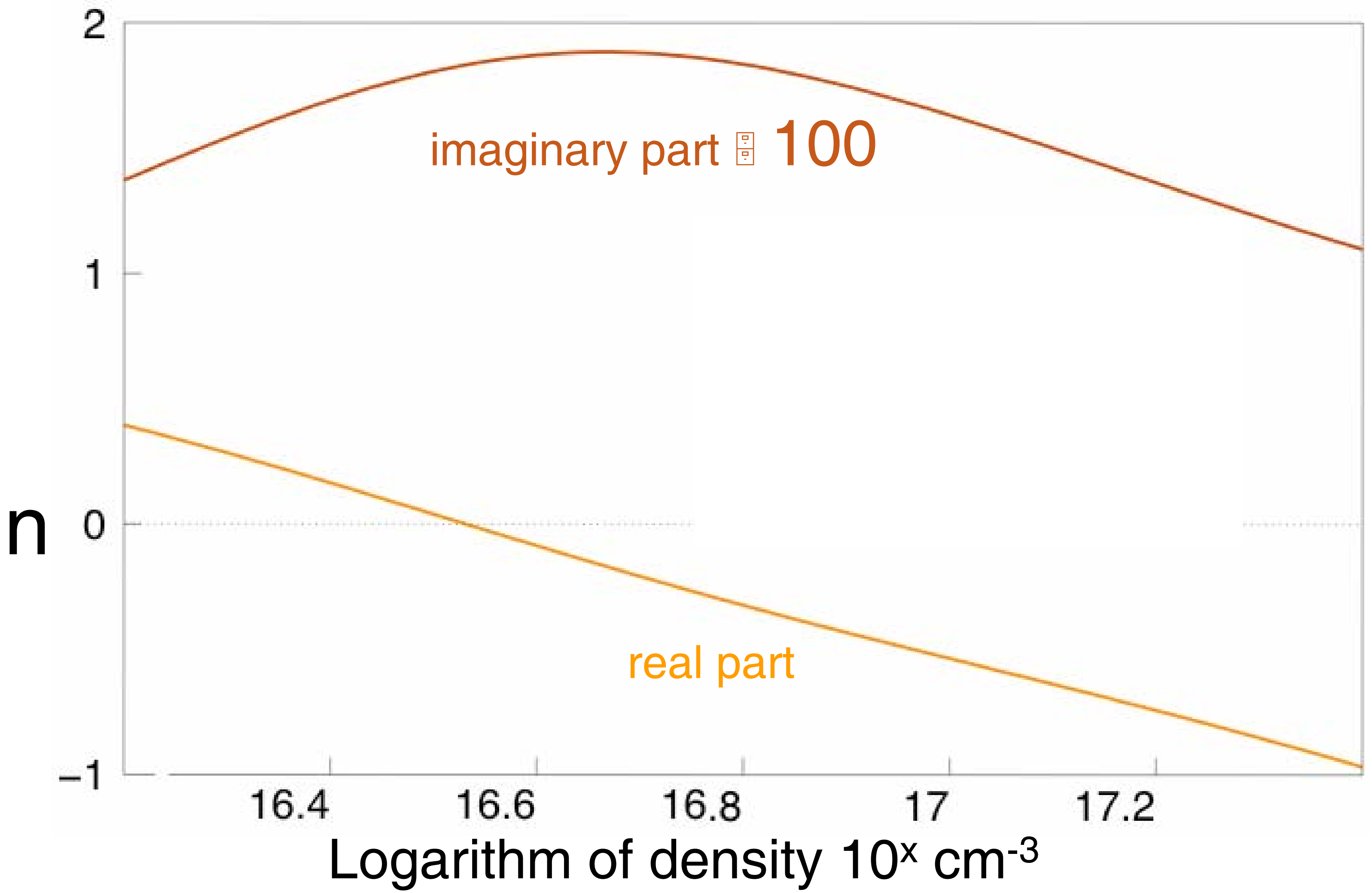
Index of refraction

density N = 5×10^{16} cm^{-3}



detuning from resonance Δ/γ

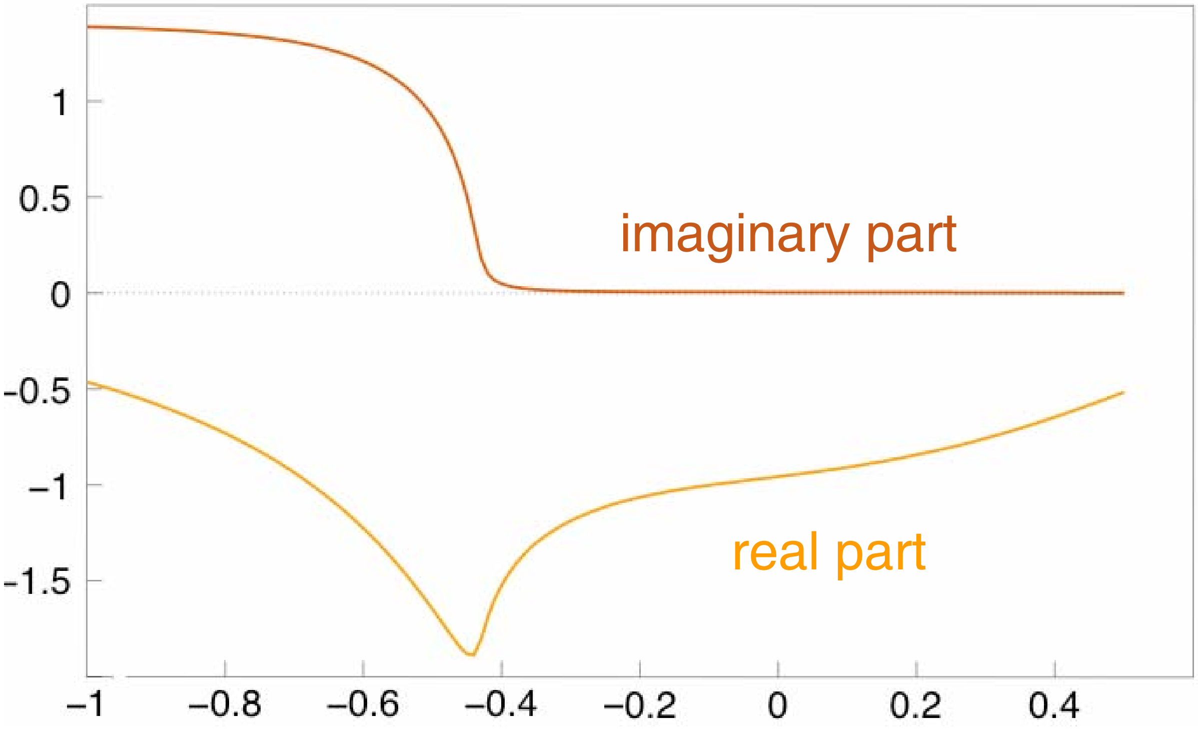
Density dependence



Fine tuning

n can be tuned by changing coupling field Rabi frequency Ω:

n



Logarithm of Rabi frequency $\Omega=10^x \gamma$

Application: e.g., for superlens, $n=-1$ is needed exactly!

Realization schemes

- Atoms: e.g. Neon, Dysprosium (i.e. heavy atoms for high frequencies)
- Molecules: Use different rotational levels for different parities
- Bound excitons: use D^0 states with different parities for lower, and D^0X states with different parities for upper states.

Collaborators

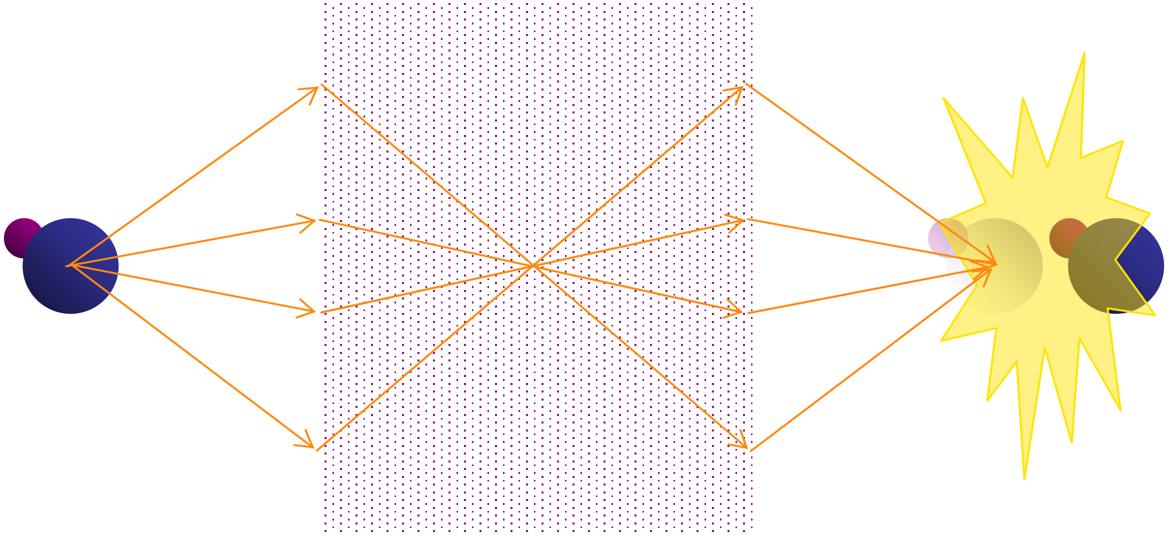
Collaborators:

Jürgen Kästel, Michael Fleischhauer, Ron Walsworth

Graduate students:

Tun Wang
Renuka Rajapakse
Lu Zhao
Timothy Bragdon
Sandipan Banerjee

Outlook: dipole-dipole interactions



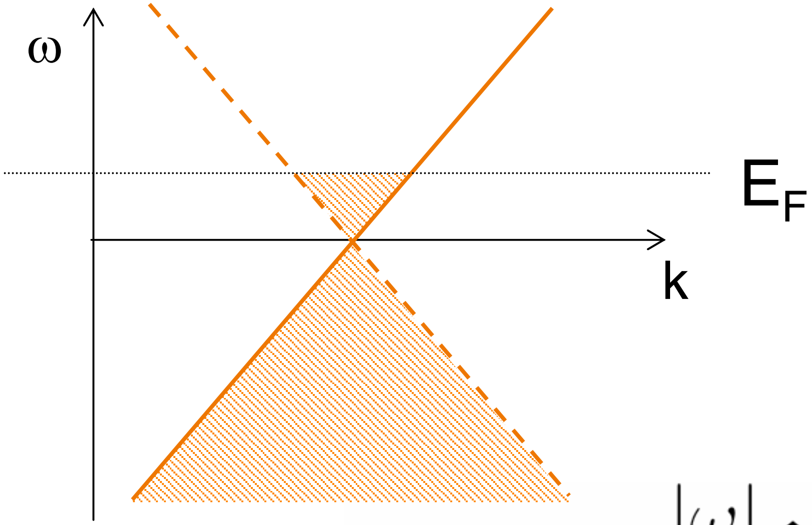
for exchange interaction:

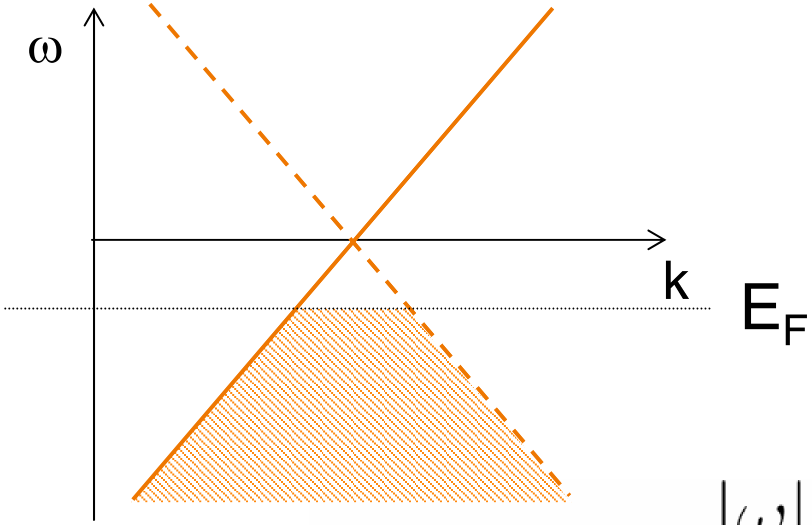
n = -1 for μ-waves

near-field: only ε = -1 necessary

Outlook: Optical-lattice based cold-atom lens

Cheianov, Fal'ko, Altshuler, Science 315, 1252 (07)





n-doped: $\mathbf{v}_{\text{group}} = \frac{|\omega|}{k}\hat{\mathbf{k}}$

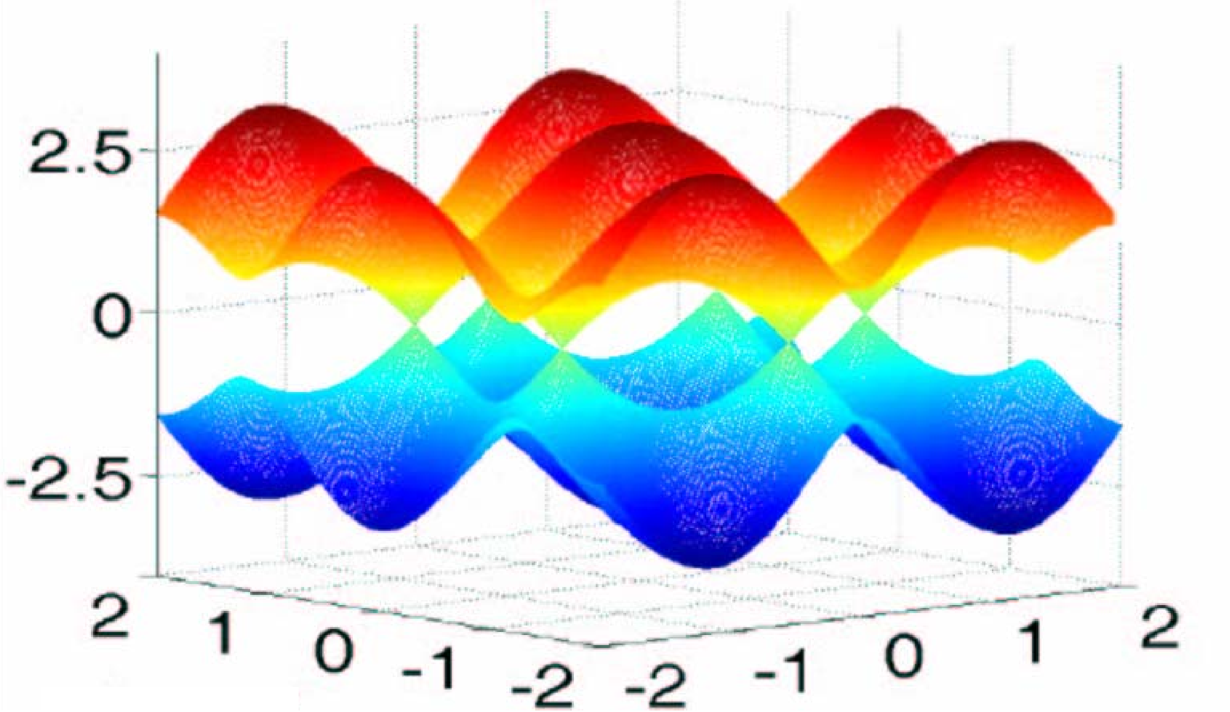
p-doped: $\mathbf{v}_{\text{group}} = -\frac{|\omega|}{k}\hat{\mathbf{k}}$

$n = 1$
for electrons

$n = -1$
for electrons

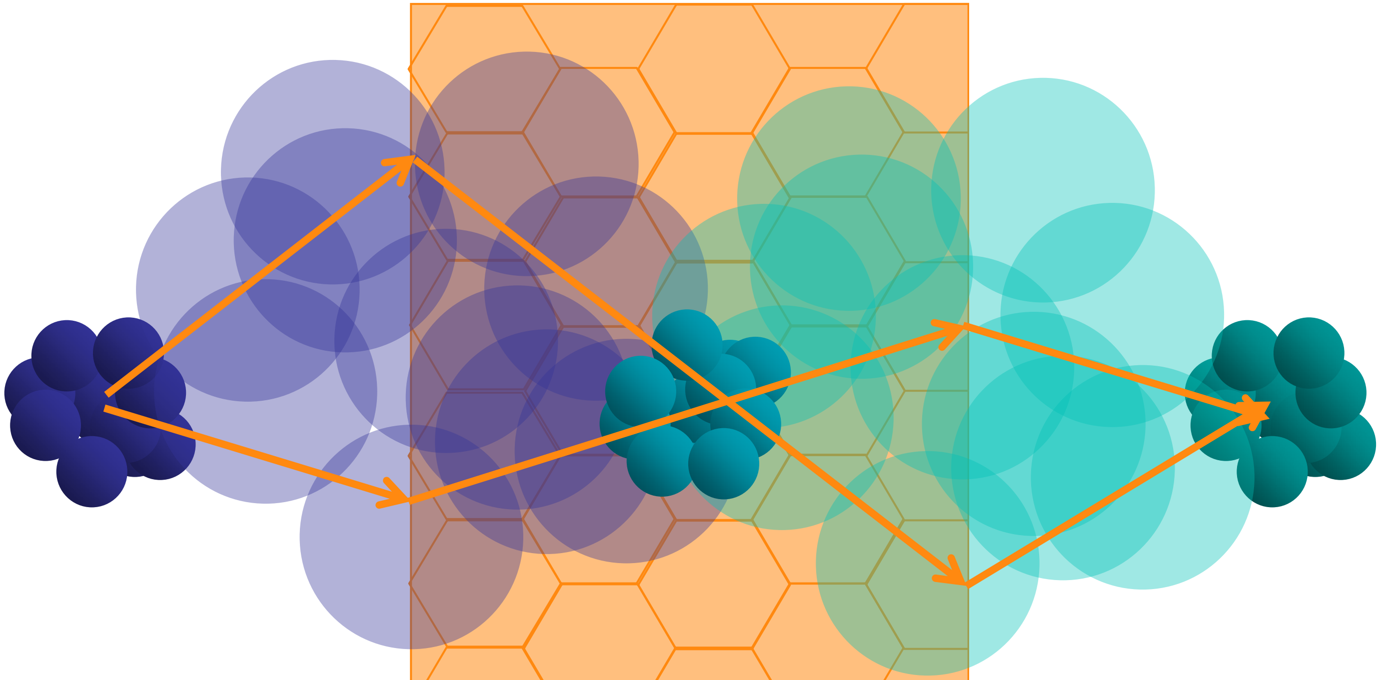
Outlook: Optical-lattice based cold-atom lens

Zhu, Wang, Duan, cond-mat/0703454



Same situation for cold atoms!

Outlook: Optical-lattice based cold-atom lens



“p-doped” - $\nu \leq 1/2$