Tunable negative refraction based on quantum interference

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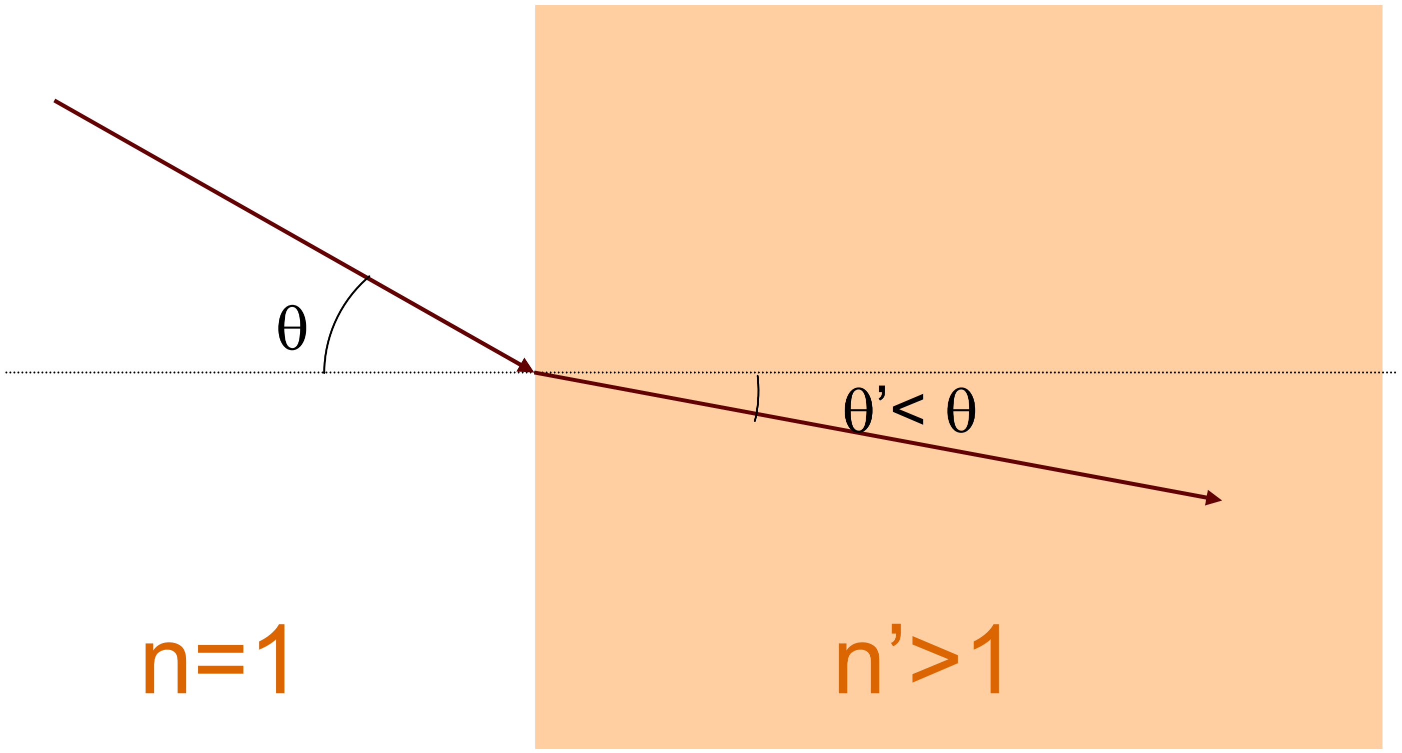
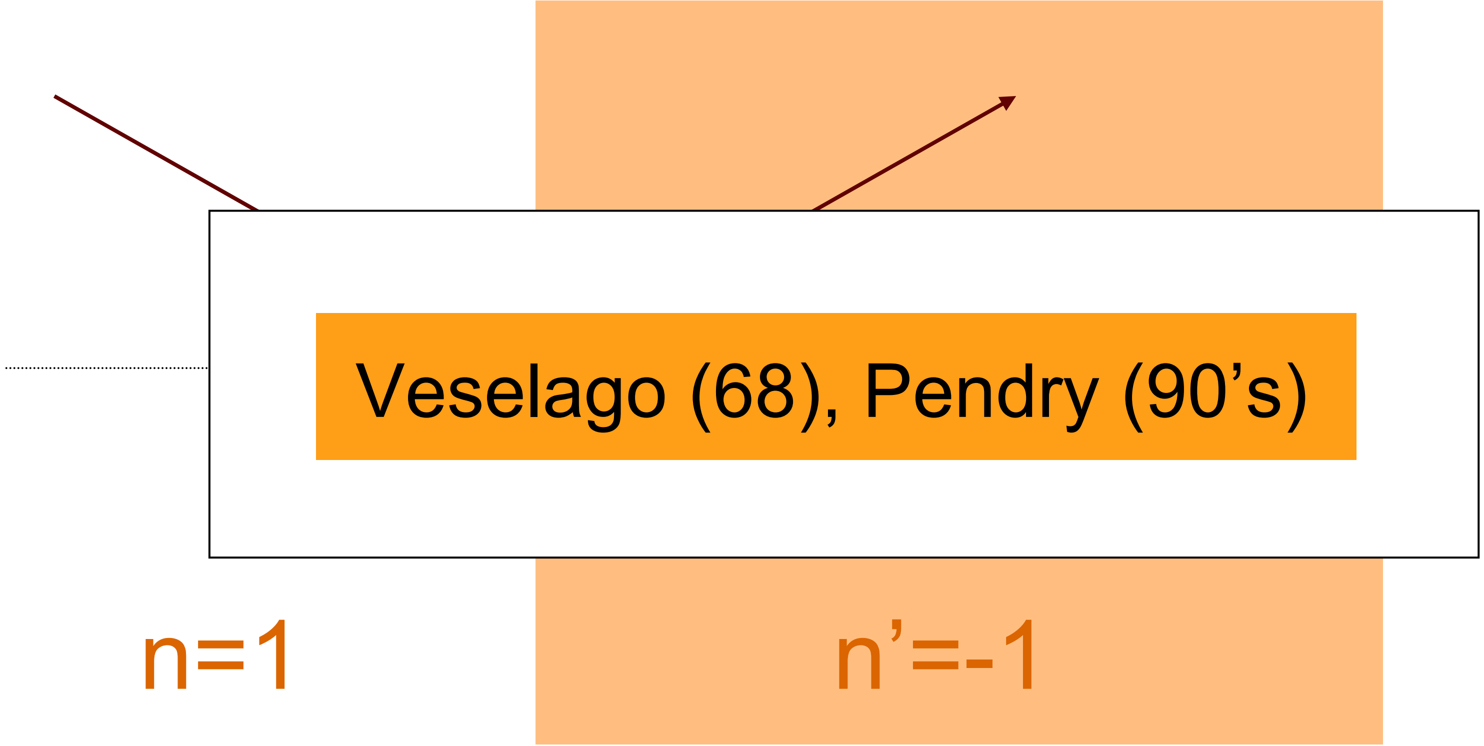
Breckenridge, August 25, 2006

Model



normal refraction
(Snell's law)

Model



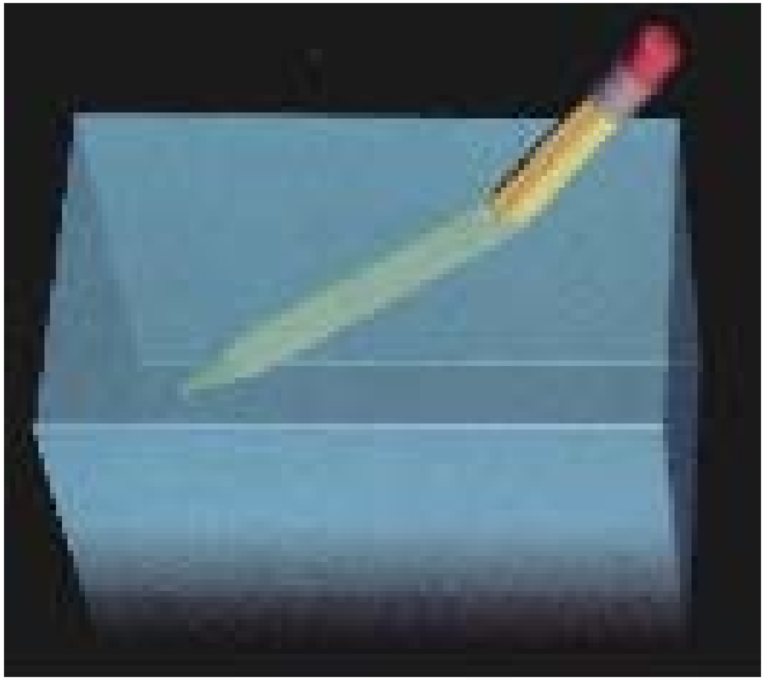
Veselago (68), Pendry (90’s)

n=1

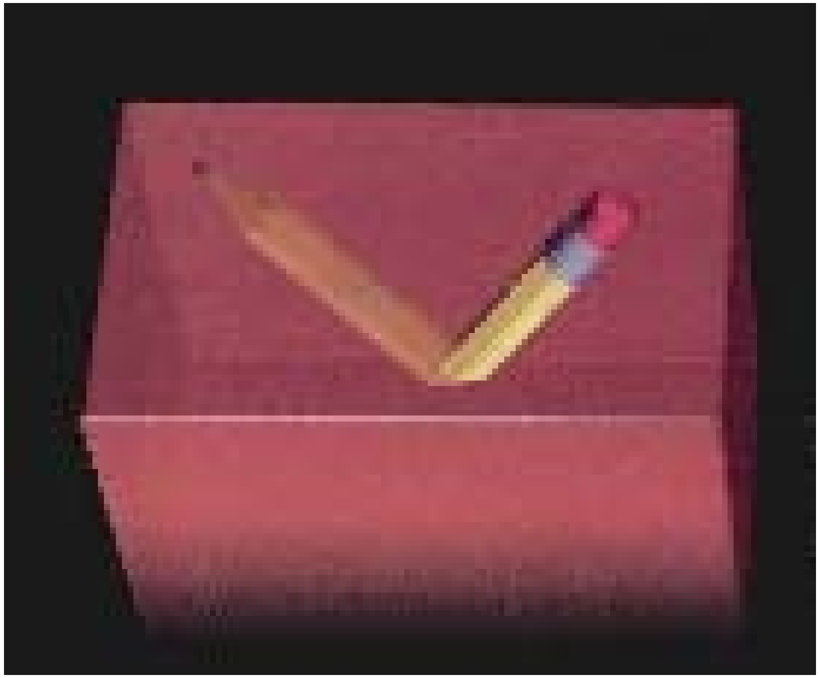
n’=-1

negative refraction
(Snell’s law) ⇨ “left-handed”:
E, **B**, and **k**

Scientific American, July 2006



normal refraction



negative refraction

Contents

- Definitions & examples
- Chiral media
- **EIT based negative refraction**
  - Local field effects
  - Tunability
- Conclusion

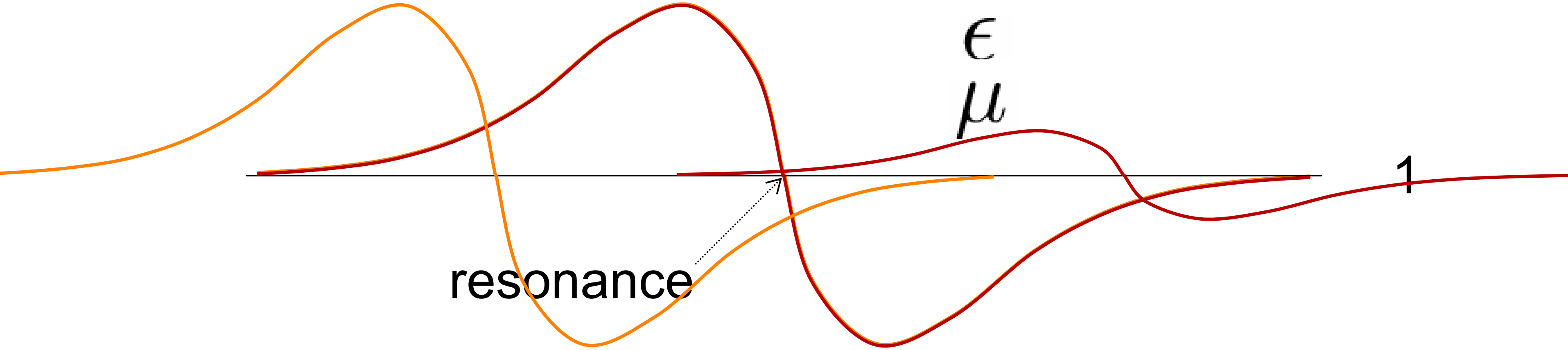
Origin of negative refraction

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

ϵ : electric permittivity

μ : magnetic permeability

With both, ϵ and μ negative ☑ n negative



Applications and Definitions

- Applications:
  - perfect lens

Superlens

normal lens:

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

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

Applications and Definitions

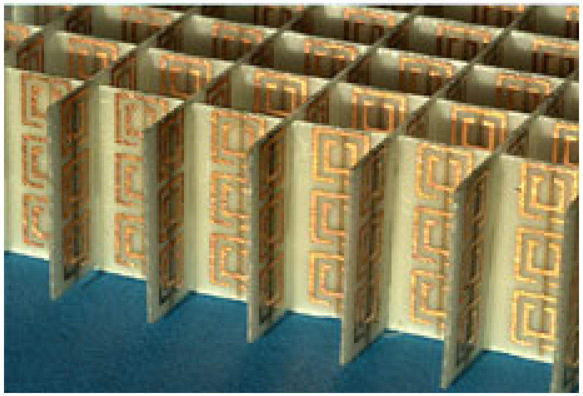
- Applications:
  - perfect lens

- Definitions:

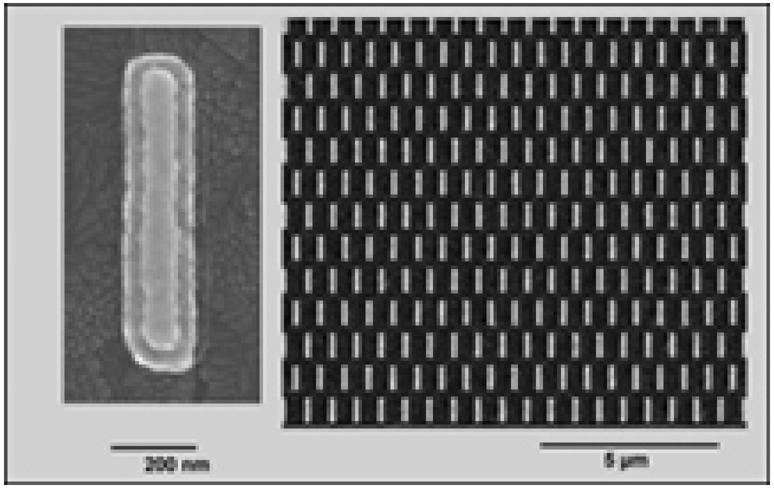
–negative refraction	Re(n) < 0
–left-handed materials	**E**, **B**, and **k** are lefthanded
–chiral materials	Turned polarization ⇔ **E-**, **B**-cross coupled
–meta-materials	man-made refraction

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!)

Absorption

So far: refraction/absorption ≈ 1…5

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

Occurrence of negative refraction

- Why does negative index not occur in Nature?

Large χ_m very difficult to achieve!

Optical frequencies

Magnitude of χ_m:

$$|\chi_\mathrm{m}| \approx \left(\frac{\mu_\mathrm{atom}}{\mathrm{d}_\mathrm{atom}}\right)^2 |\chi_\mathrm{e}| \approx \frac{1}{137^2} |\chi_\mathrm{e}|$$

Chiral media (Pendry)

- Remember: $n = \sqrt{\epsilon\mu}$

Chiral media (Pendry)

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

$$\begin{aligned} \mathbf{P} &= \chi_\mathsf{e}\mathbf{E} + \xi_\mathsf{eb}\mathbf{B} \\ \mathbf{M} &= \xi_\mathsf{be}\mathbf{E} + \chi_\mathsf{m}\mathbf{B} \end{aligned}$$

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

- Index of refraction

$$\boxed{\mathsf{n} = \sqrt{\varepsilon\mu} - \xi}$$

If we choose $\xi_\mathsf{EH} = -\xi_\mathsf{HE} = \mathsf{i}\xi$

EIT based negative refraction

V-type s

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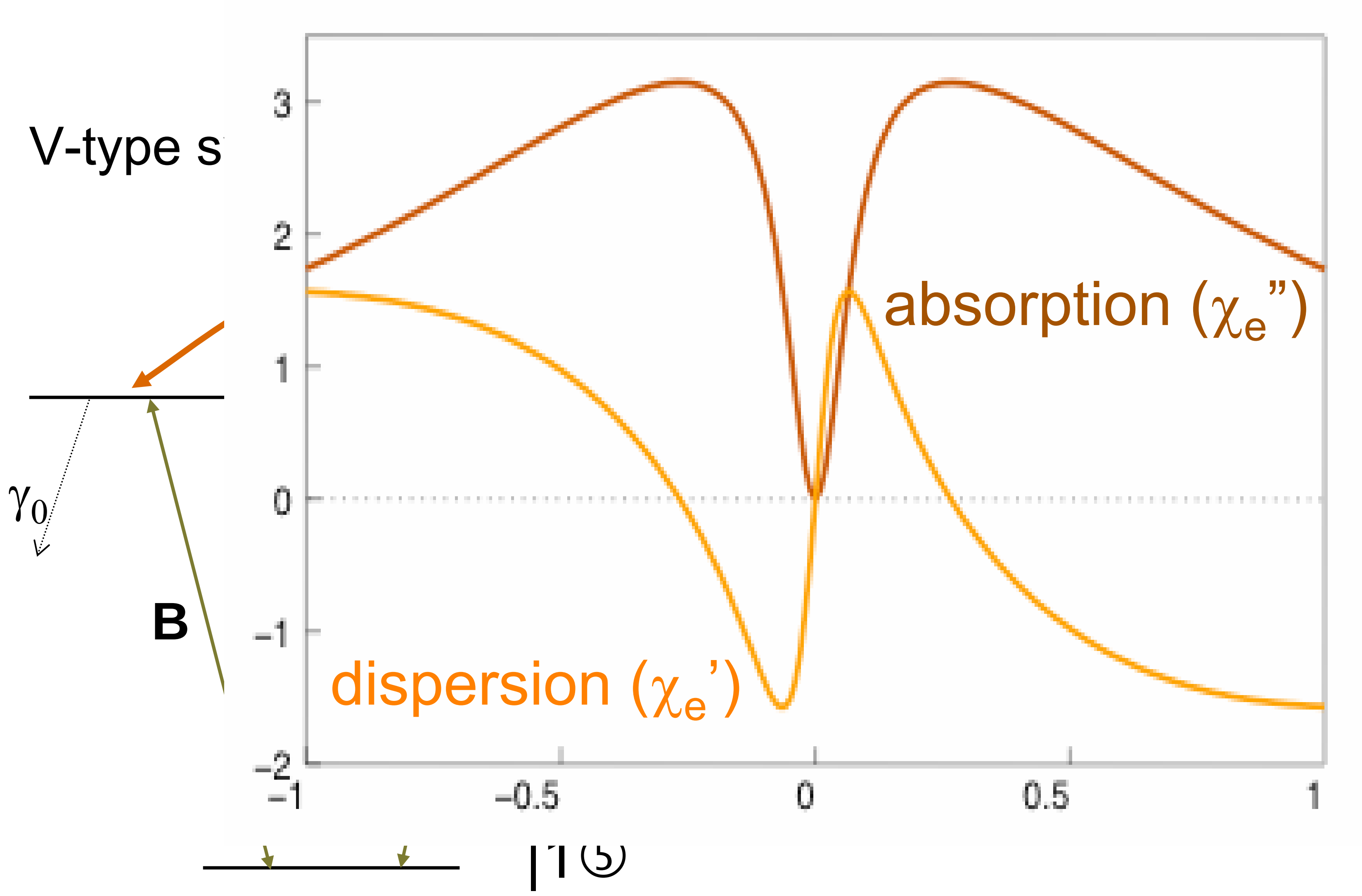
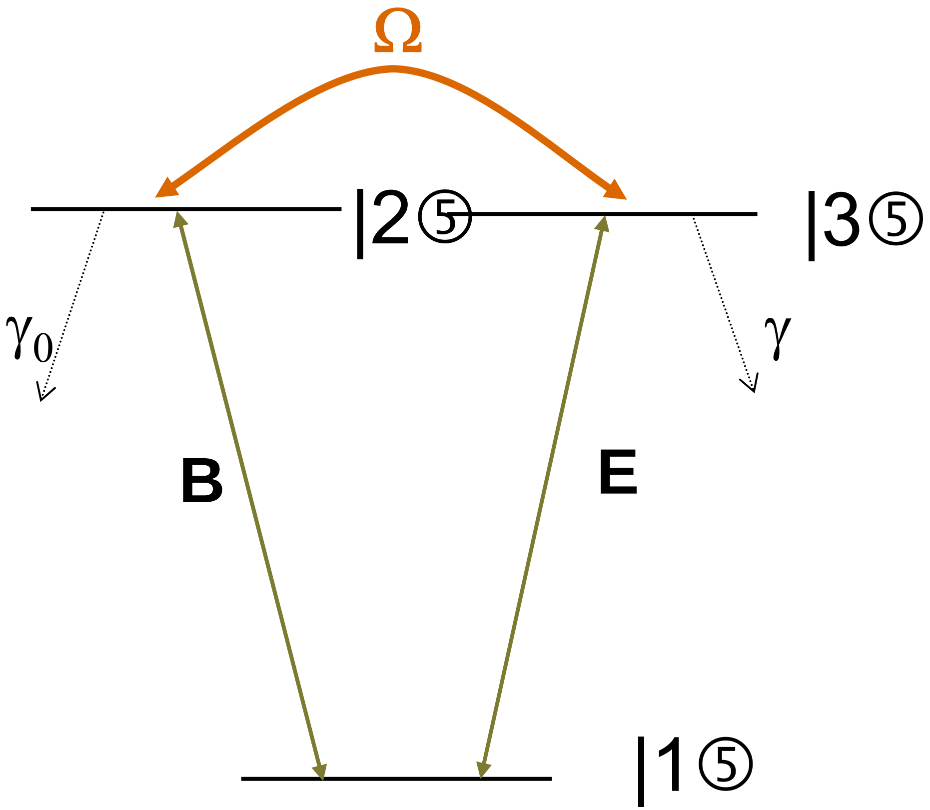


EIT based negative refraction

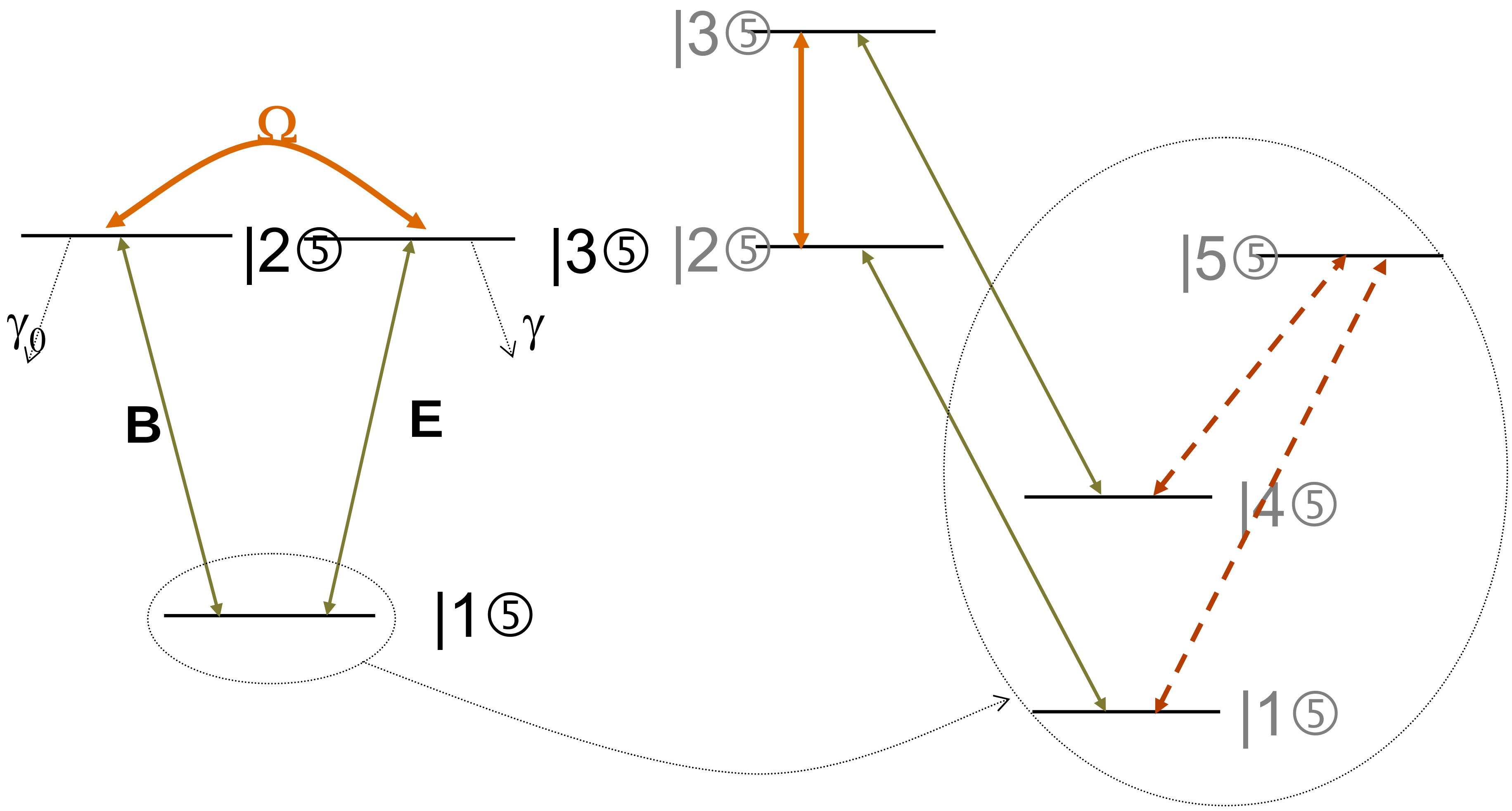
V-type system:



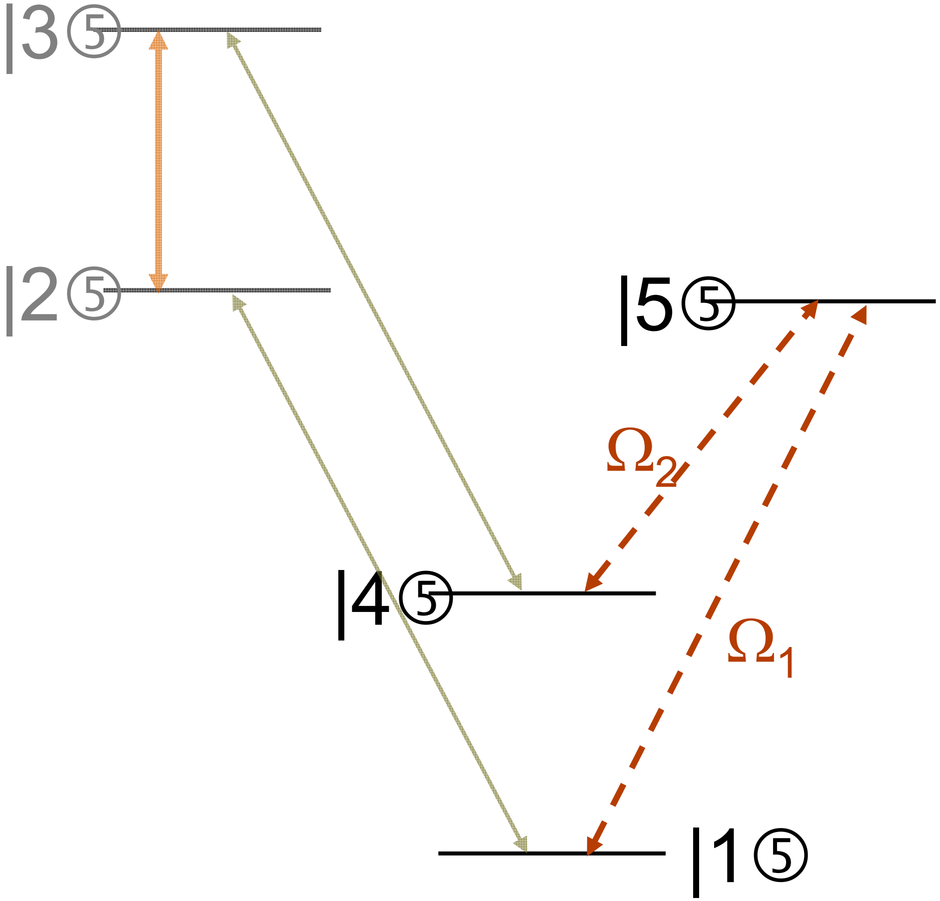
Problems:

- 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



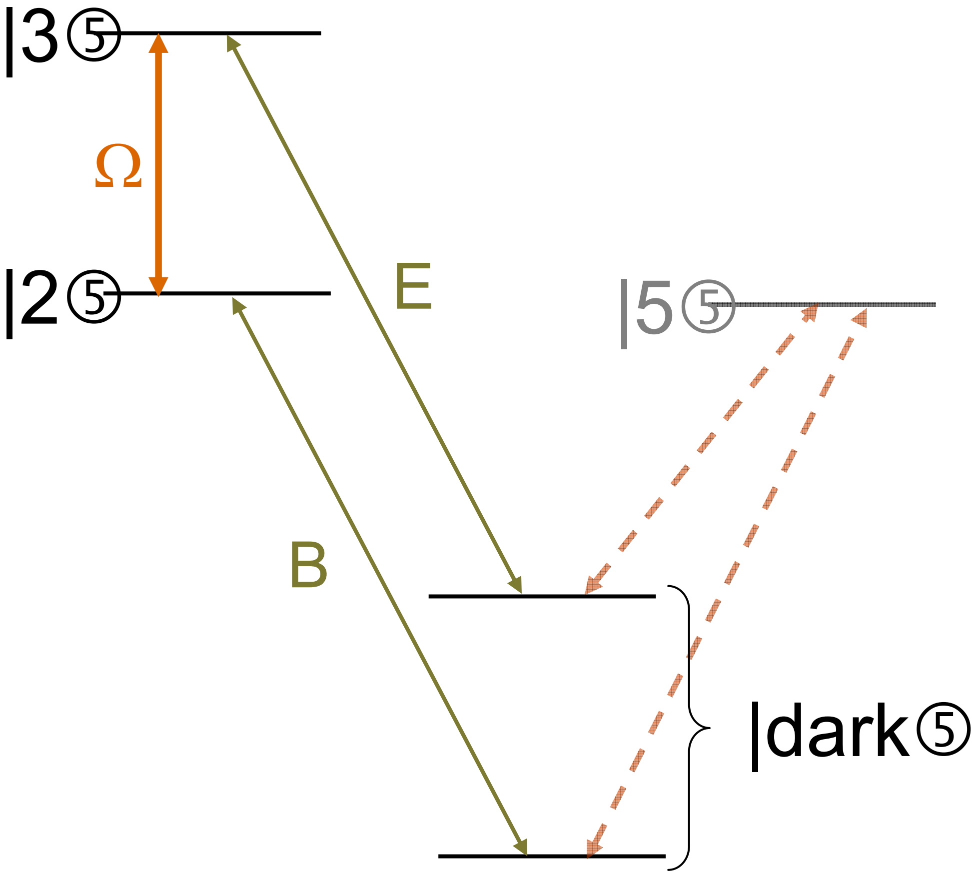
Realistic schemes



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

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

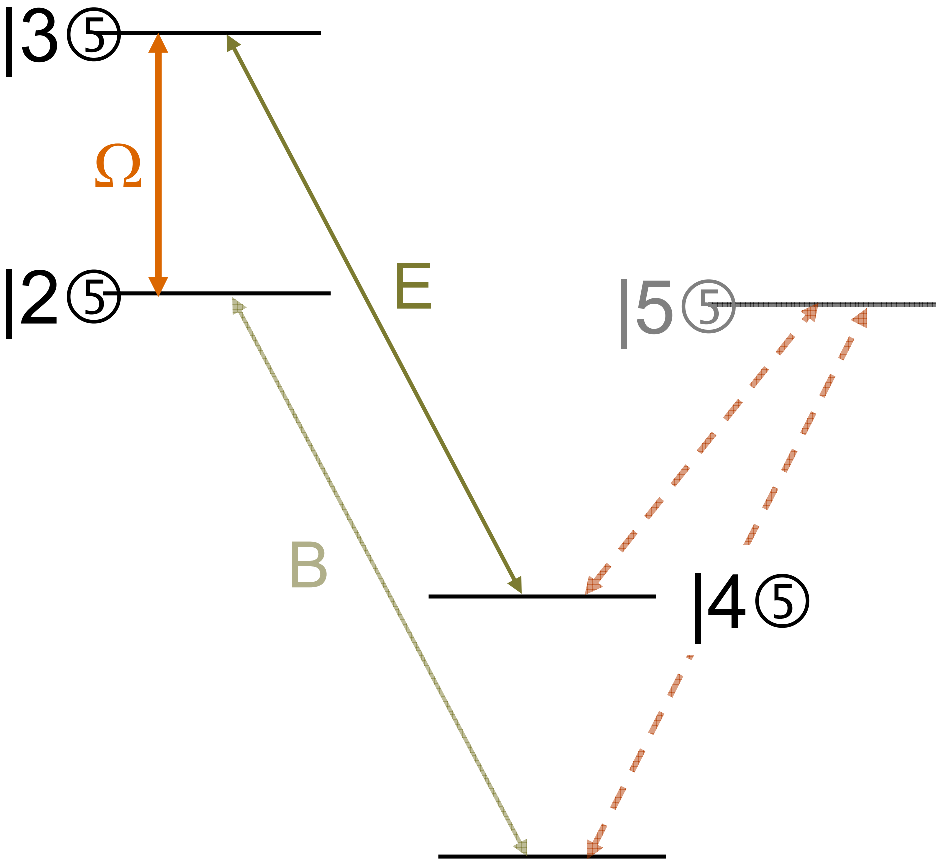
Realistic schemes



Advantages:

- Non-dc coupling field Ω
  - ☑ Choose phase

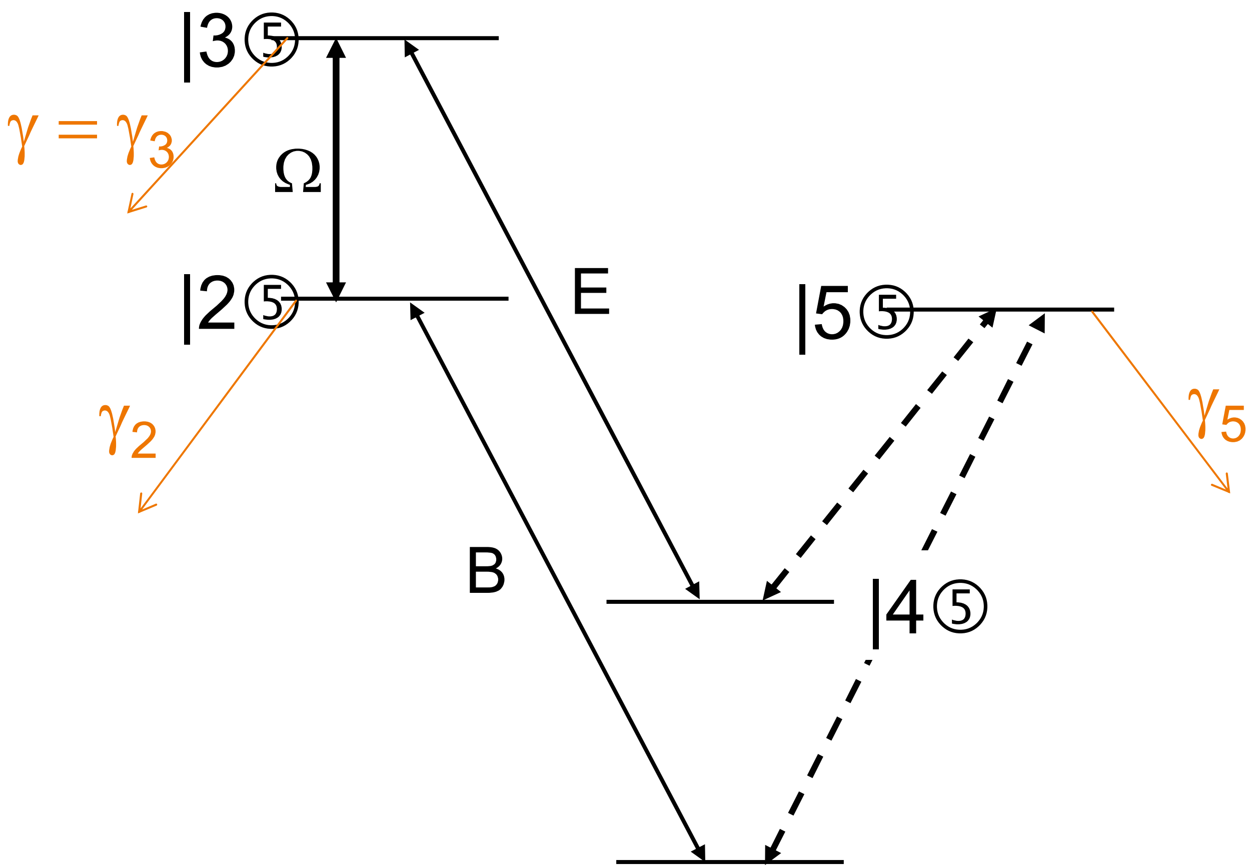
Realistic schemes



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

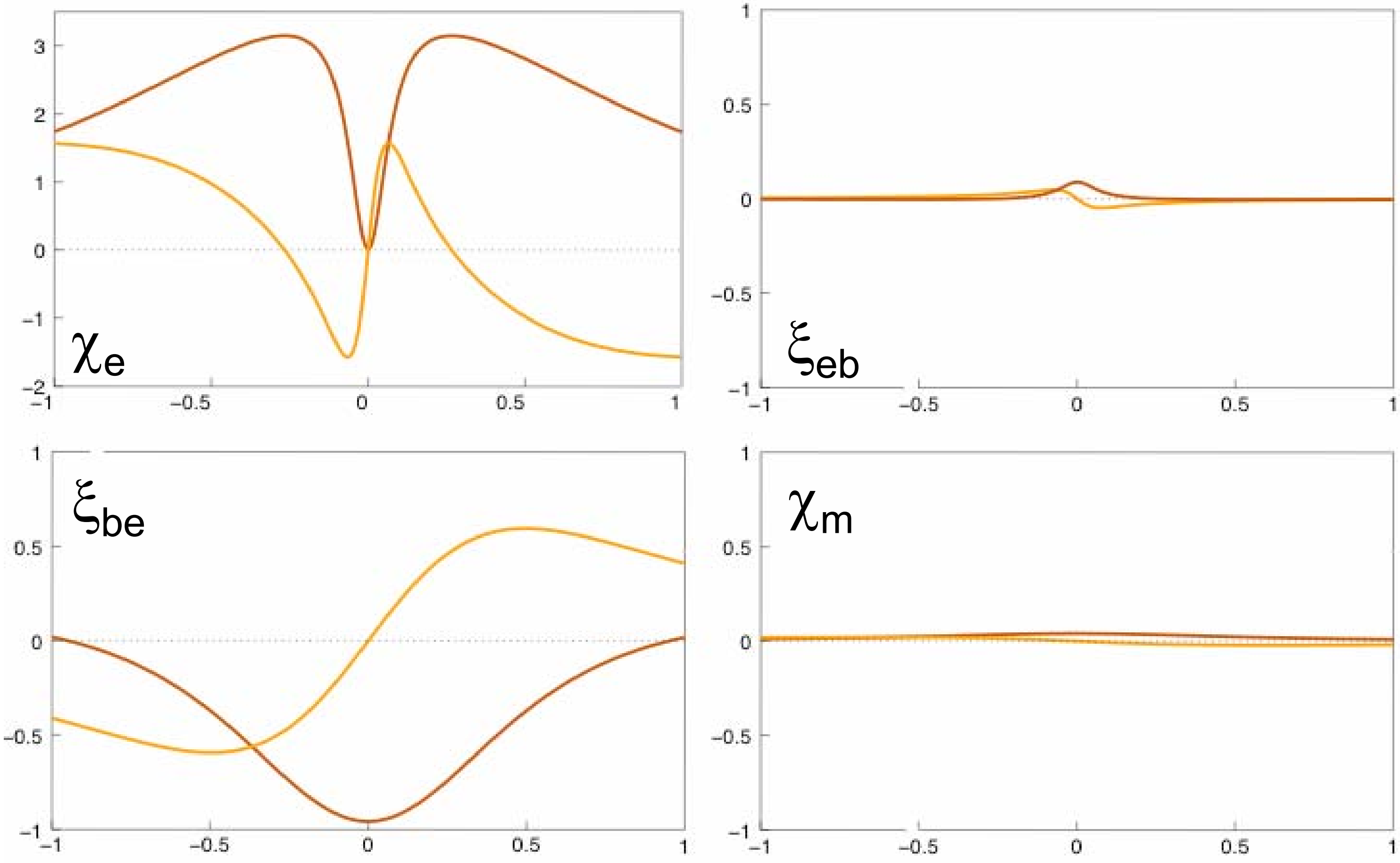
Realistic schemes



+ line broadening (inhomogeneous)

Cross couplings

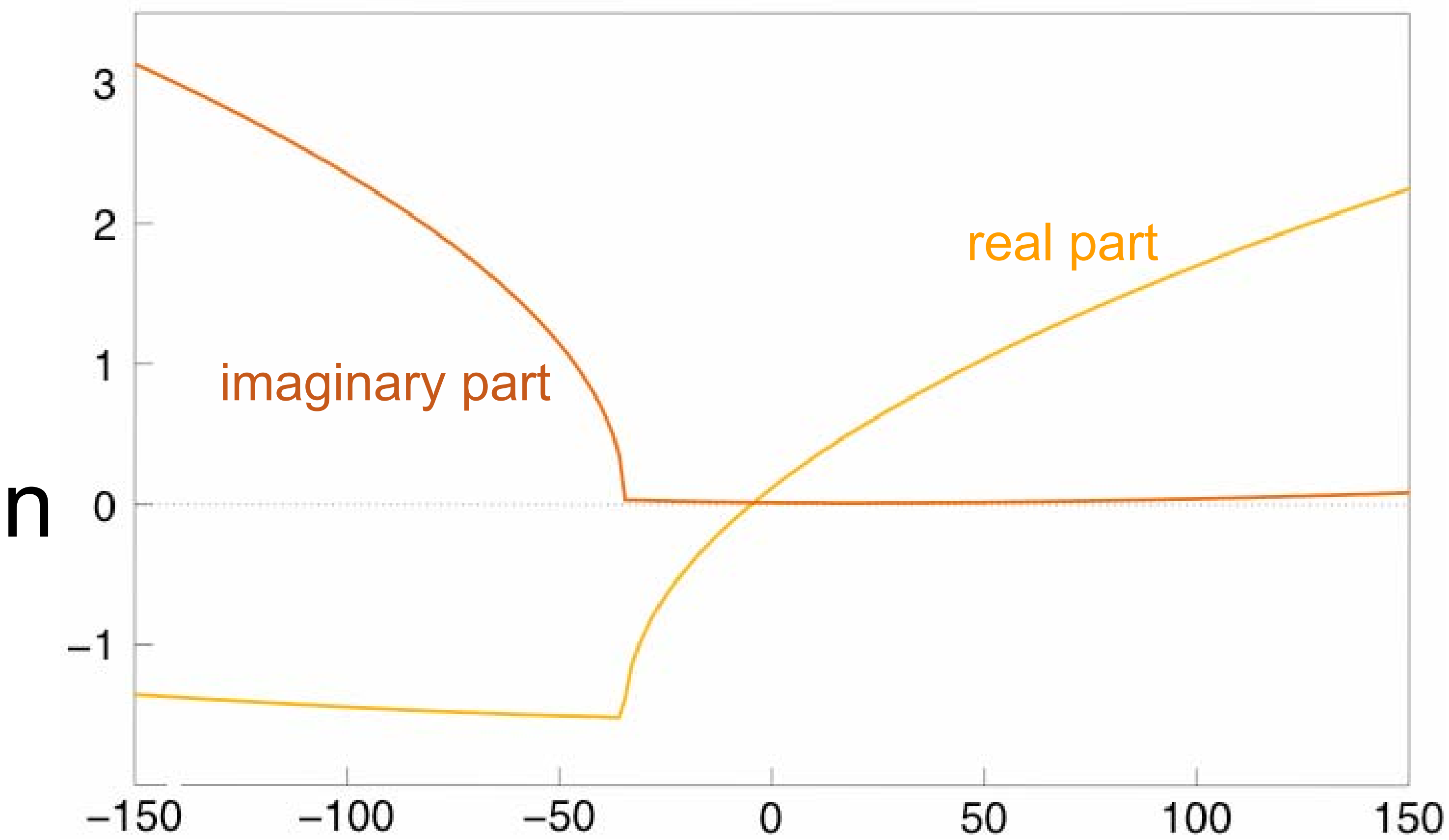
Inhomogeneous broadening ≈ decay rate γ



— real part — imaginary part

Index of refraction

density N = 5×10^{16} cm^{-3}



detuning from resonance Δ/γ

Local field corrections

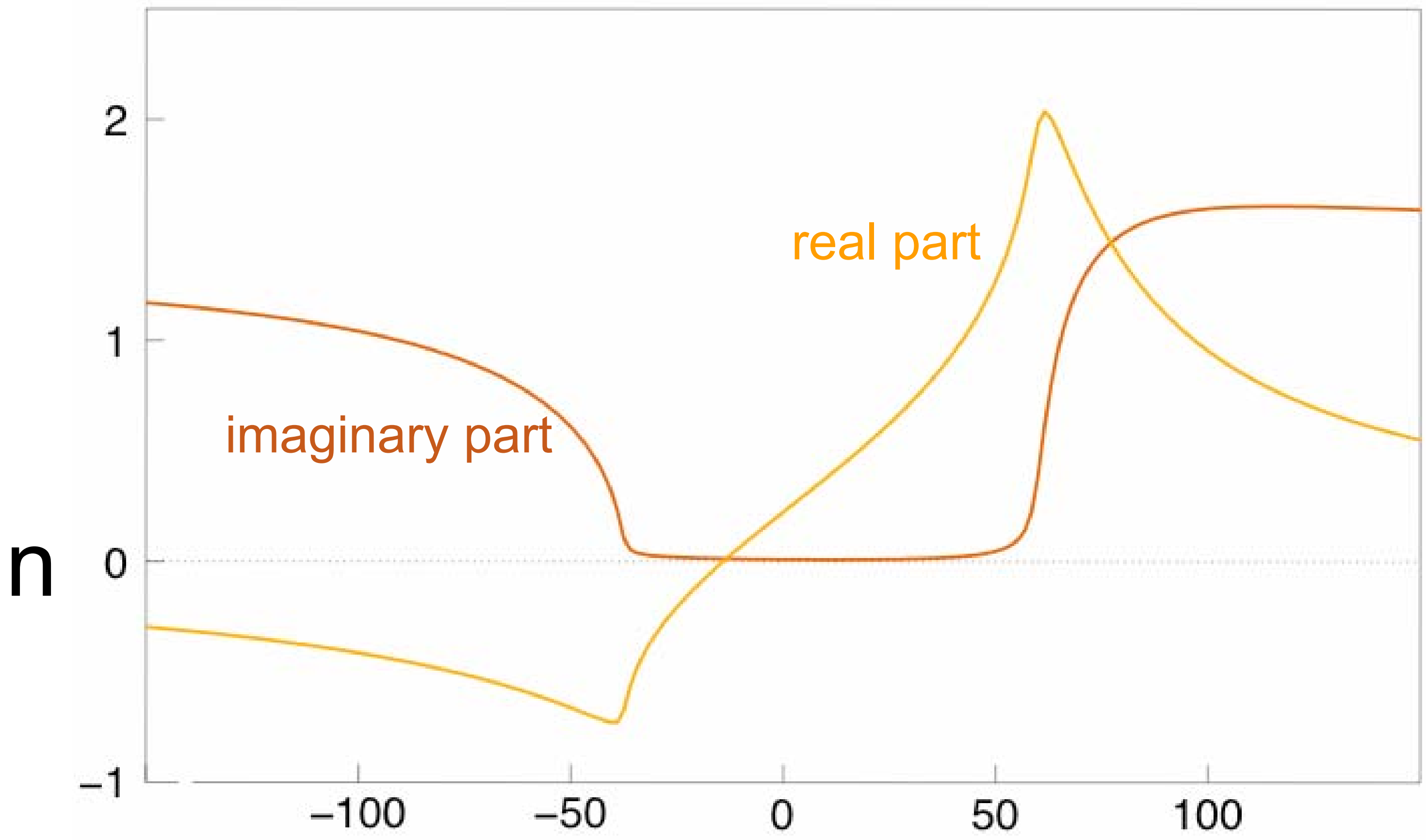
$$\mathsf{E} \quad \rightarrow \quad \mathsf{E}_{\mathsf{loc}} = \mathsf{E} + \frac{4\pi}{3}\mathsf{P}$$

$$\mathsf{B} \quad \rightarrow \quad \mathsf{B}_{\mathsf{loc}} = \mathsf{B} + \frac{4\pi}{3}\mathsf{M}$$

re-calculate χ’s and ξ’s . . .

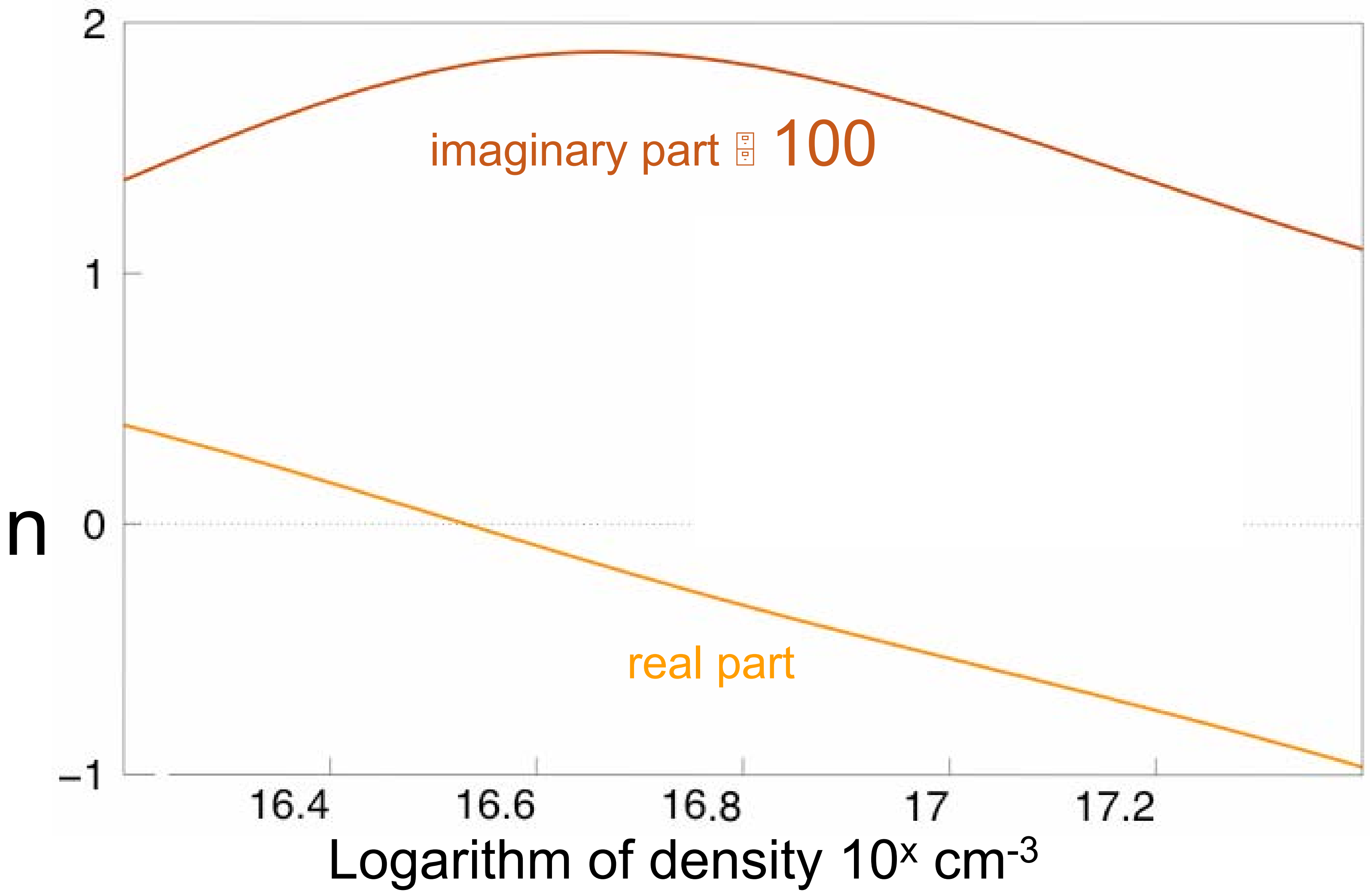
Local field corrections

density N = 5×10^{16} cm^{-3}



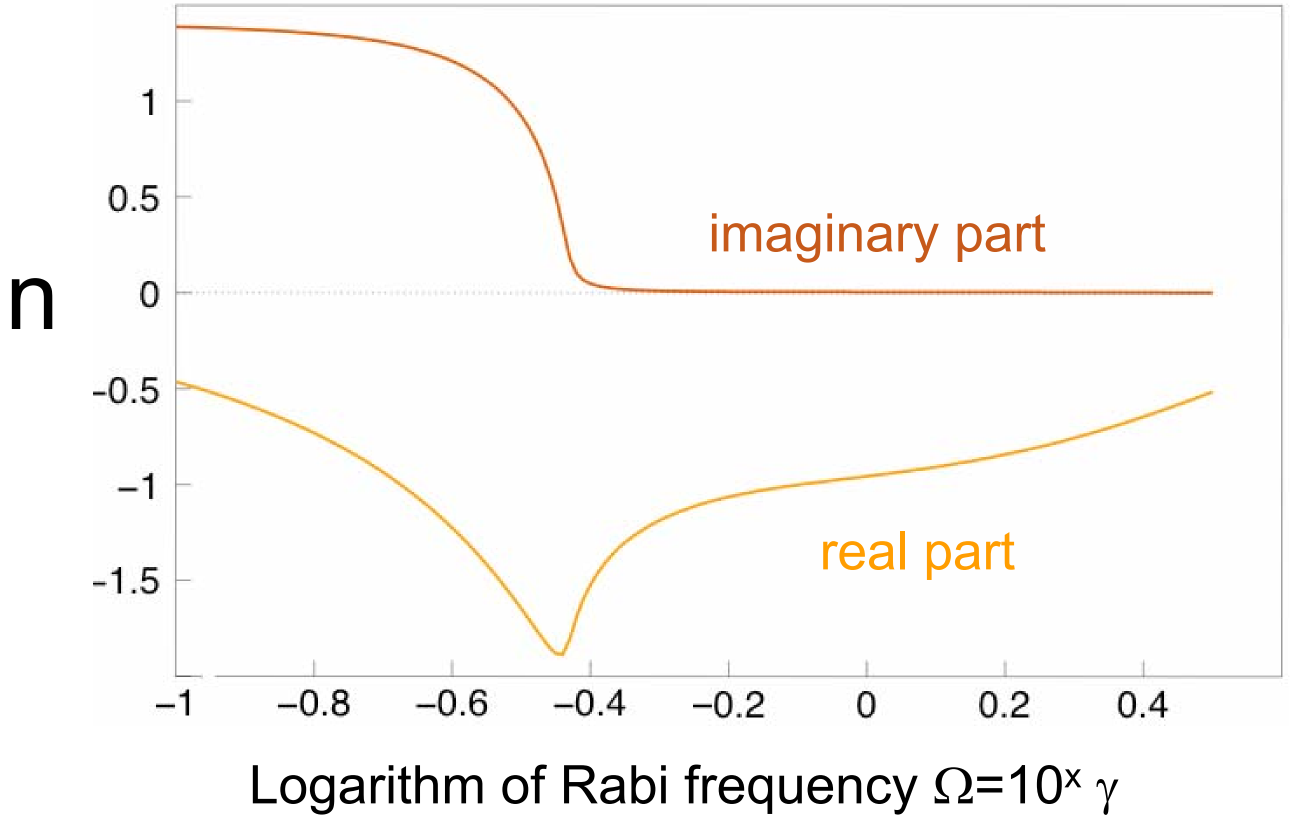
detuning from resonance Δ/γ

Density dependence



Fine tuning

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



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

Realization schemes

- Atoms: e.g. Neon
- 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.

Outlook

- Materials:
  - Problem of high-frequency M1 transitions in atoms and molecules
  - Parity in solid state systems
- Dimension: 3D?
- Comparison with “traditional” method + gain
- Systems:
  - Optimize level scheme
  - Utilize tensorial character of ε

Conclusions

- Use of negative refraction:
  - superlenses and others
- Metamaterials:
  - chiral media for presence of cross coupling
  - EIT for suppression of absorption
  - energy and Rabi freq. of coupling fields for tuning

Effects

normal refraction	negative refraction
phase velocity $v \approx c$	phase velocity $v \approx - c$
Group velocity $v_{gr} < v$	group velocity $v_{gr} \approx + c$

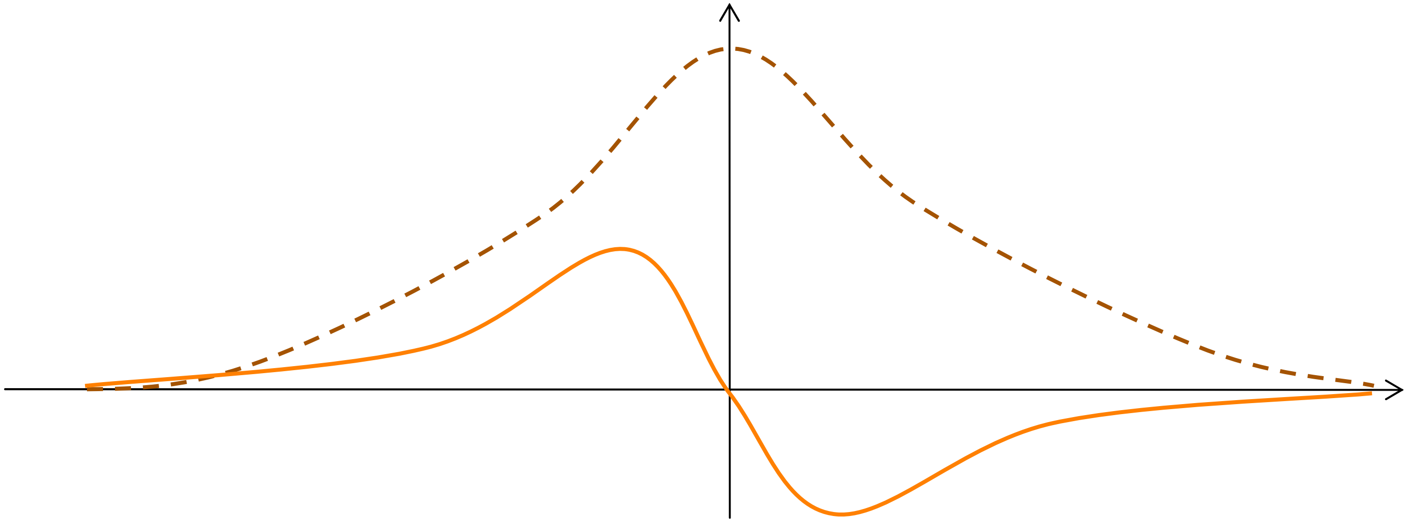
Pendry, Smith, Sci. Am., 7/06

Problem: absorption

Kramers - Kronig:

relationship between refraction/absorption

large χ_e' (refraction) ☑ large χ_e'' (absorption)



Cross couplings

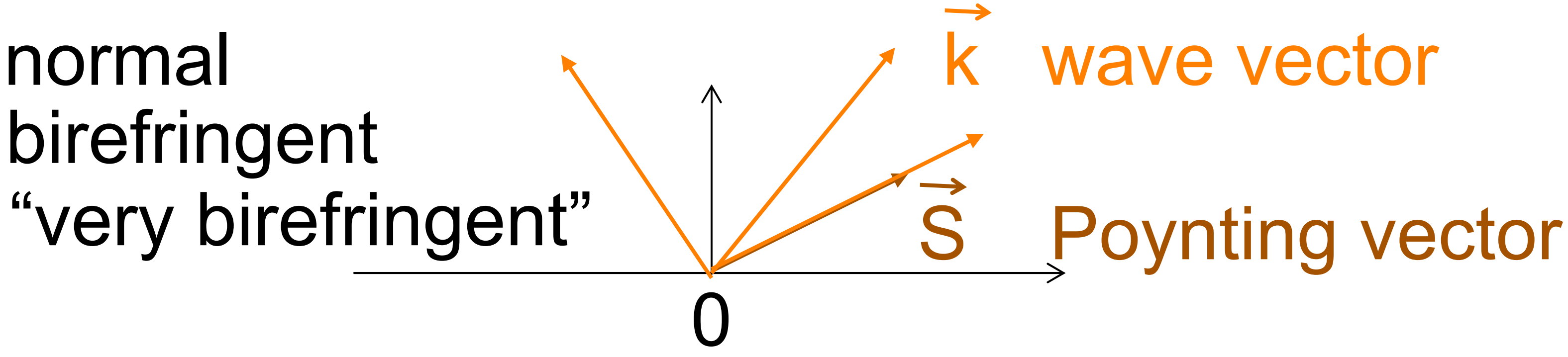
atomic picture:

$$\begin{aligned} \rho_{34} &= \alpha_{\mathsf{ee}}\mathsf{E} + \alpha_{\mathsf{eb}}\mathsf{B} \\ \rho_{21} &= \alpha_{\mathsf{be}}\mathsf{E} + \alpha_{\mathsf{bb}}\mathsf{B} \end{aligned}$$

Solve for α ☑ . . .

Different approach

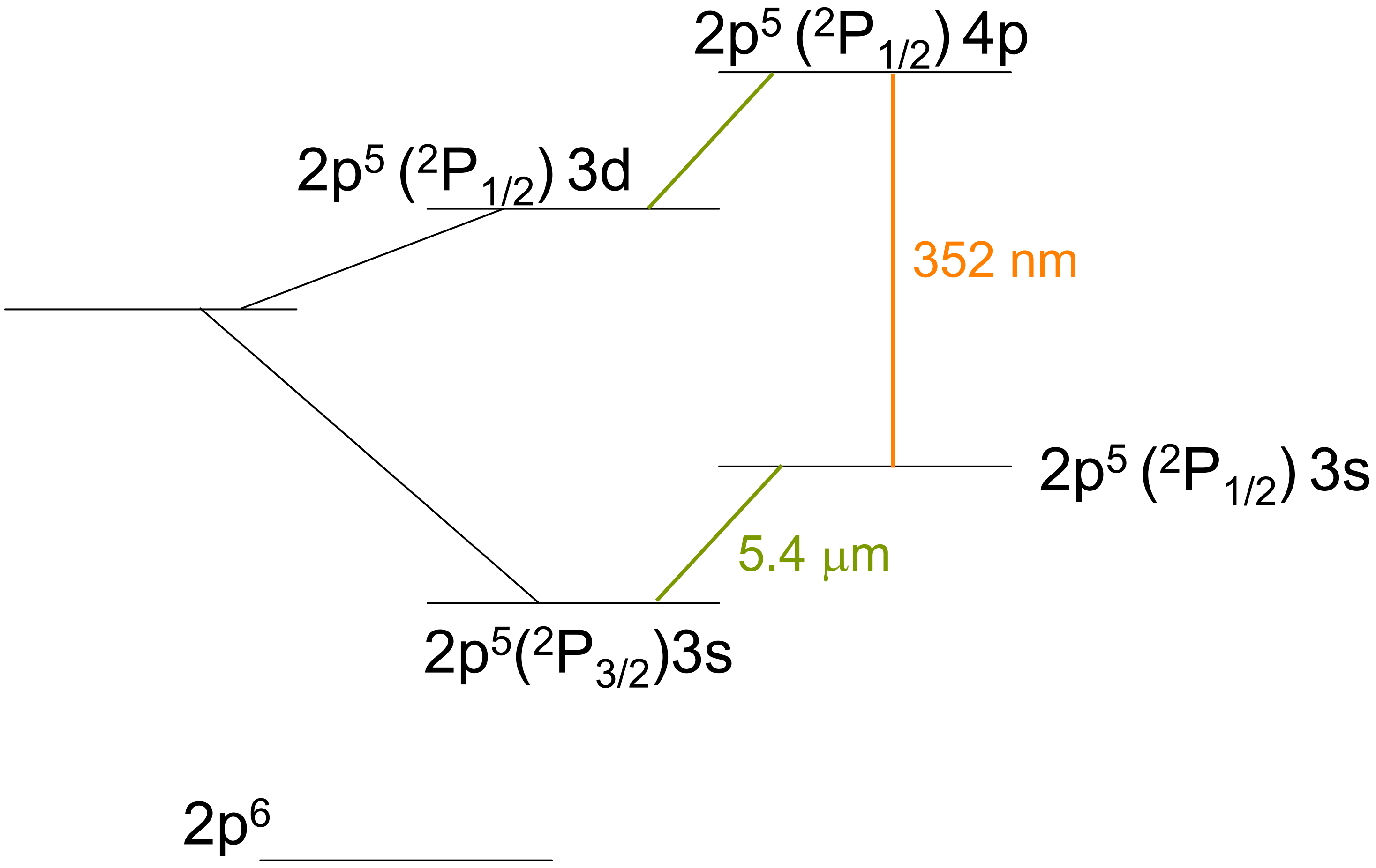
- usual problem: μ (χ_m)
- Instead: leave μ and make ε into tensor ("geometric approach")



Disadvantage: works only in waveguide (i.e. 1D)

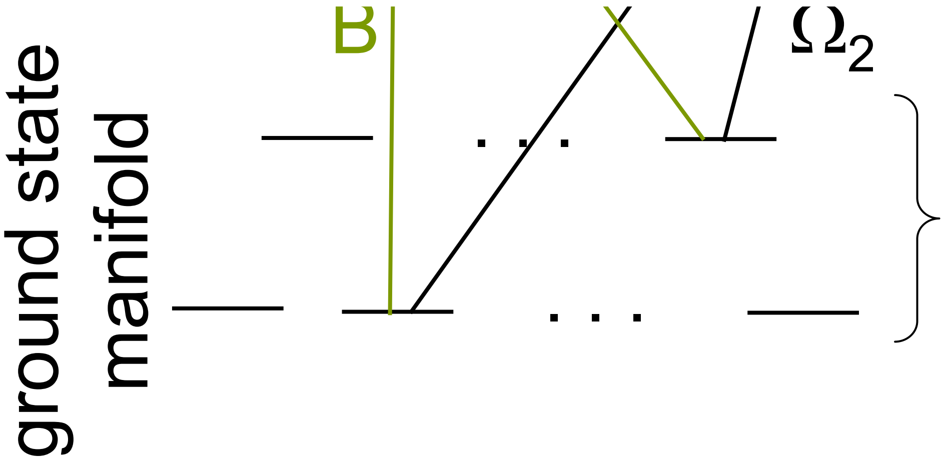
Podolskiy, Narimanov, PRB R201101, (2005)

Neon



Thommen, Mandel, PRL 96, 053601 (2006)

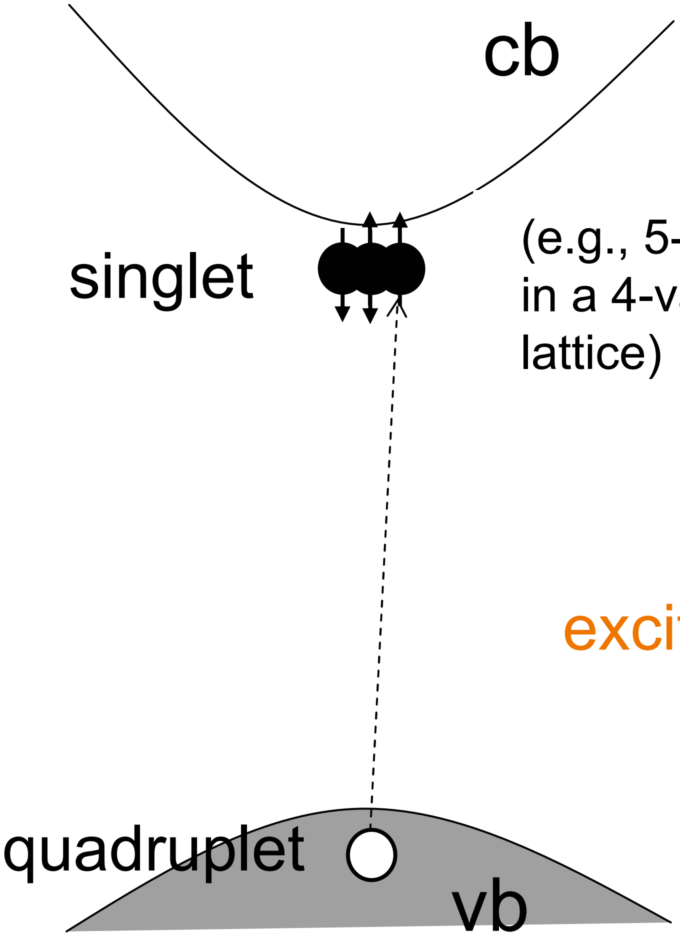
Molecular or solid state levels



one even, one odd parity (e.g., even and odd rotational level) for |1⑤ and |4⑤

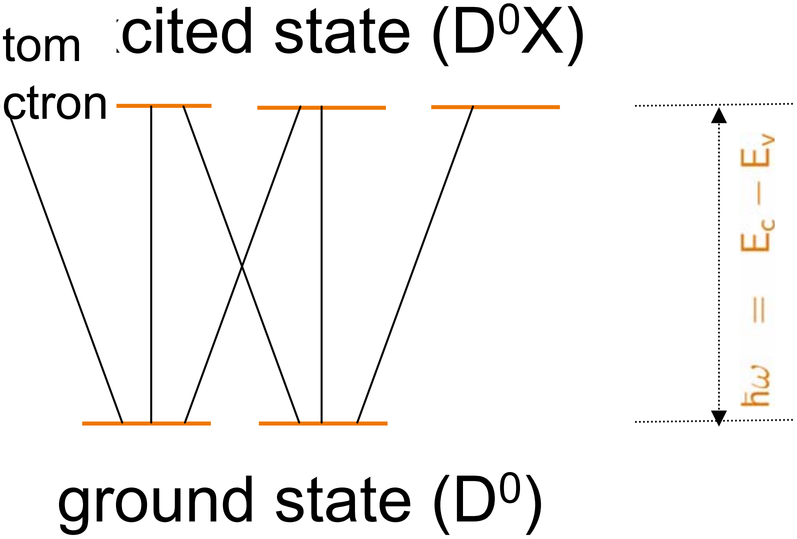
Bound exciton

momentum picture:



(e.g., 5-electron atom in a 4-valence electron lattice)

exciton



Bound exciton

momentum picture: