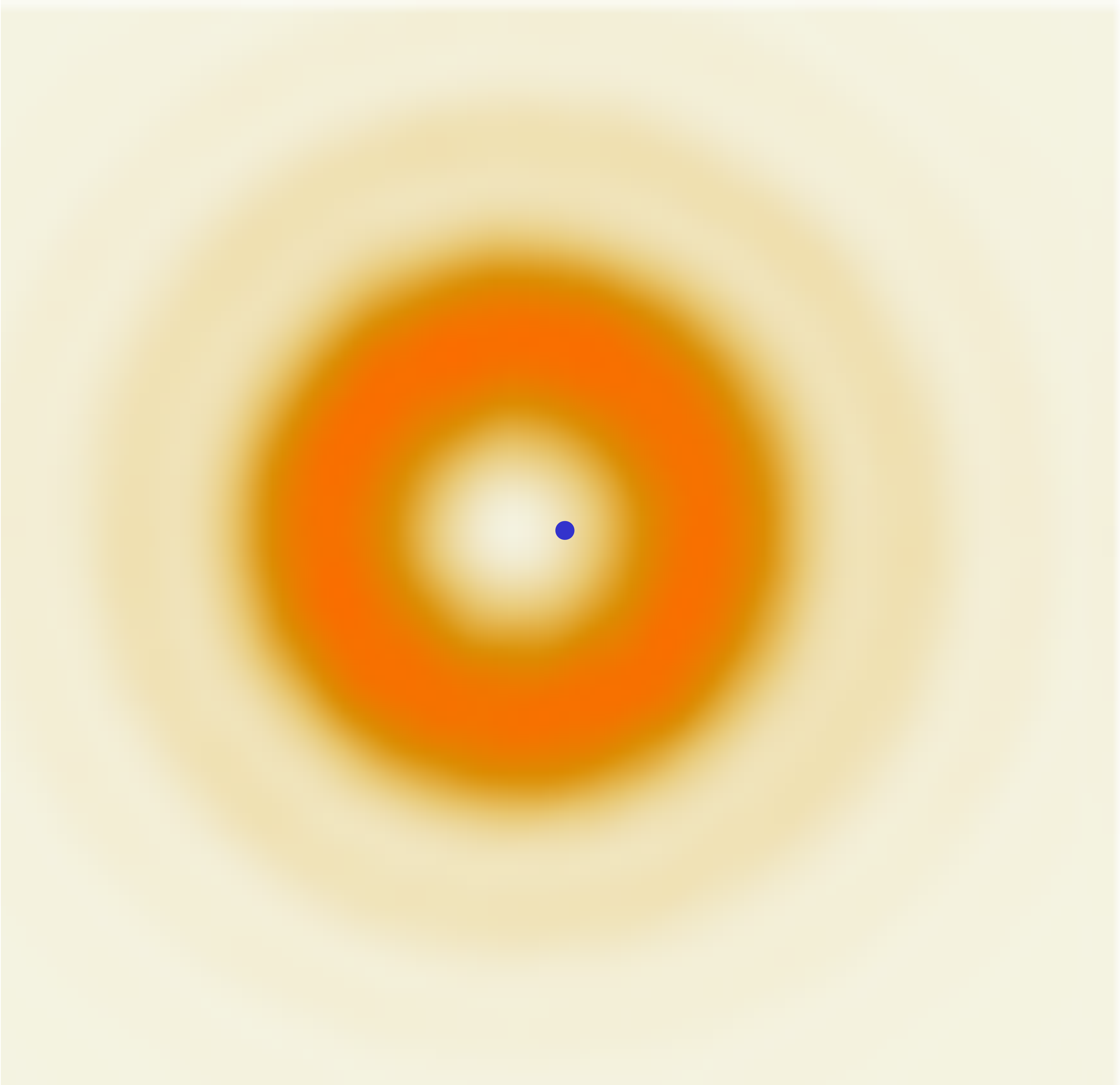
How to twist, turn, and kick ions using structured light



Slides ↓↓

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Paraty 2025 - RJ - Brasil

Structure of this course

1) Structured light basics

2) Structured light and atoms

3) Structured light and optical forces

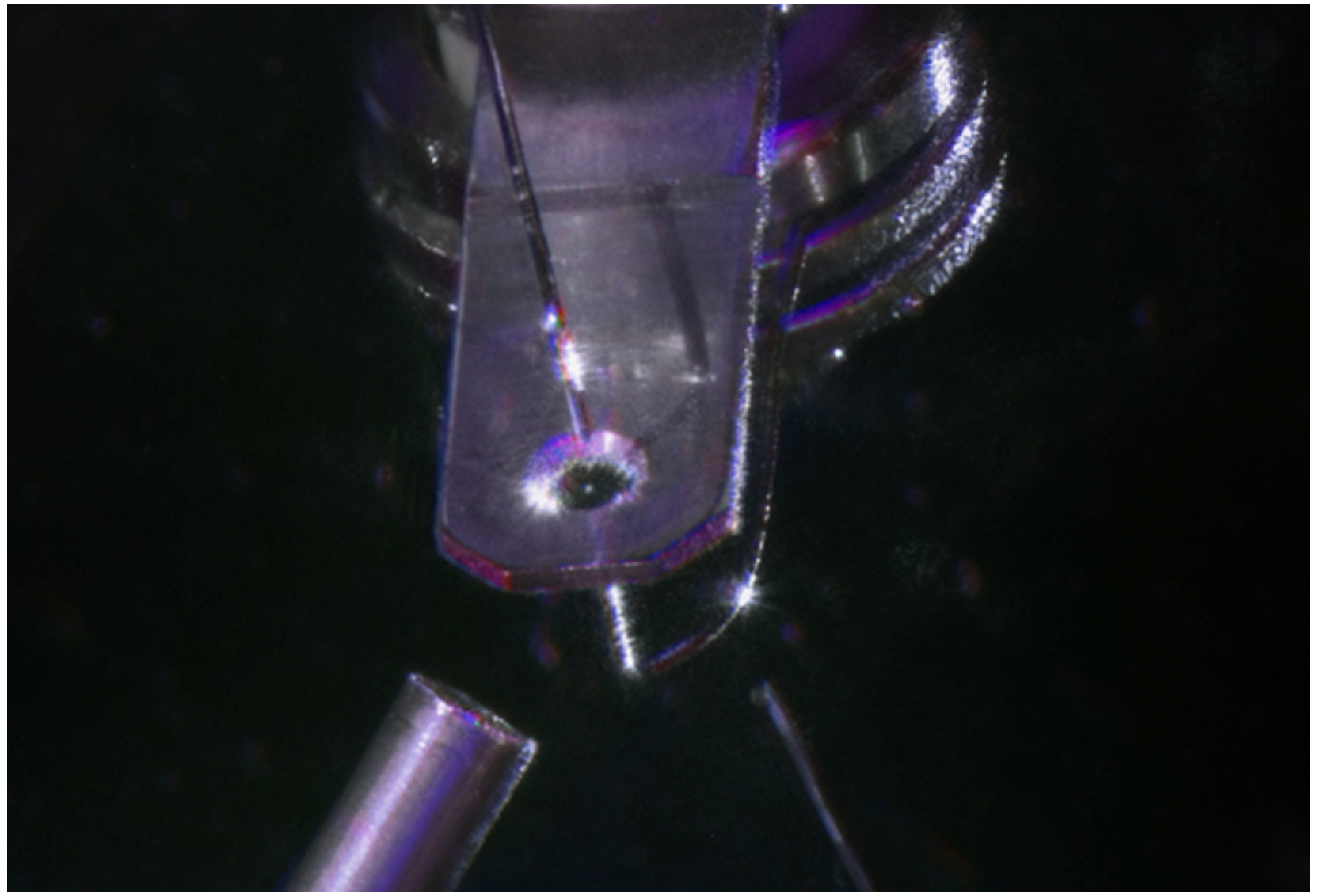
Day Three

Part 0

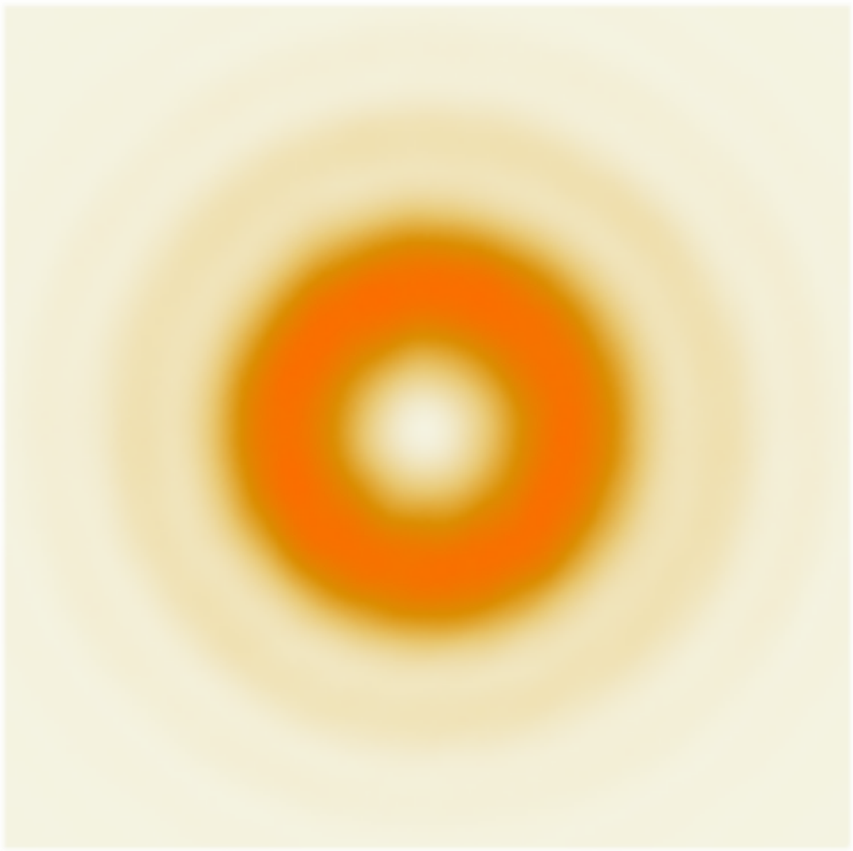
Review Day 1 & 2

Dancing in the dark - the Sao Paulo anecdote, ca. 2008

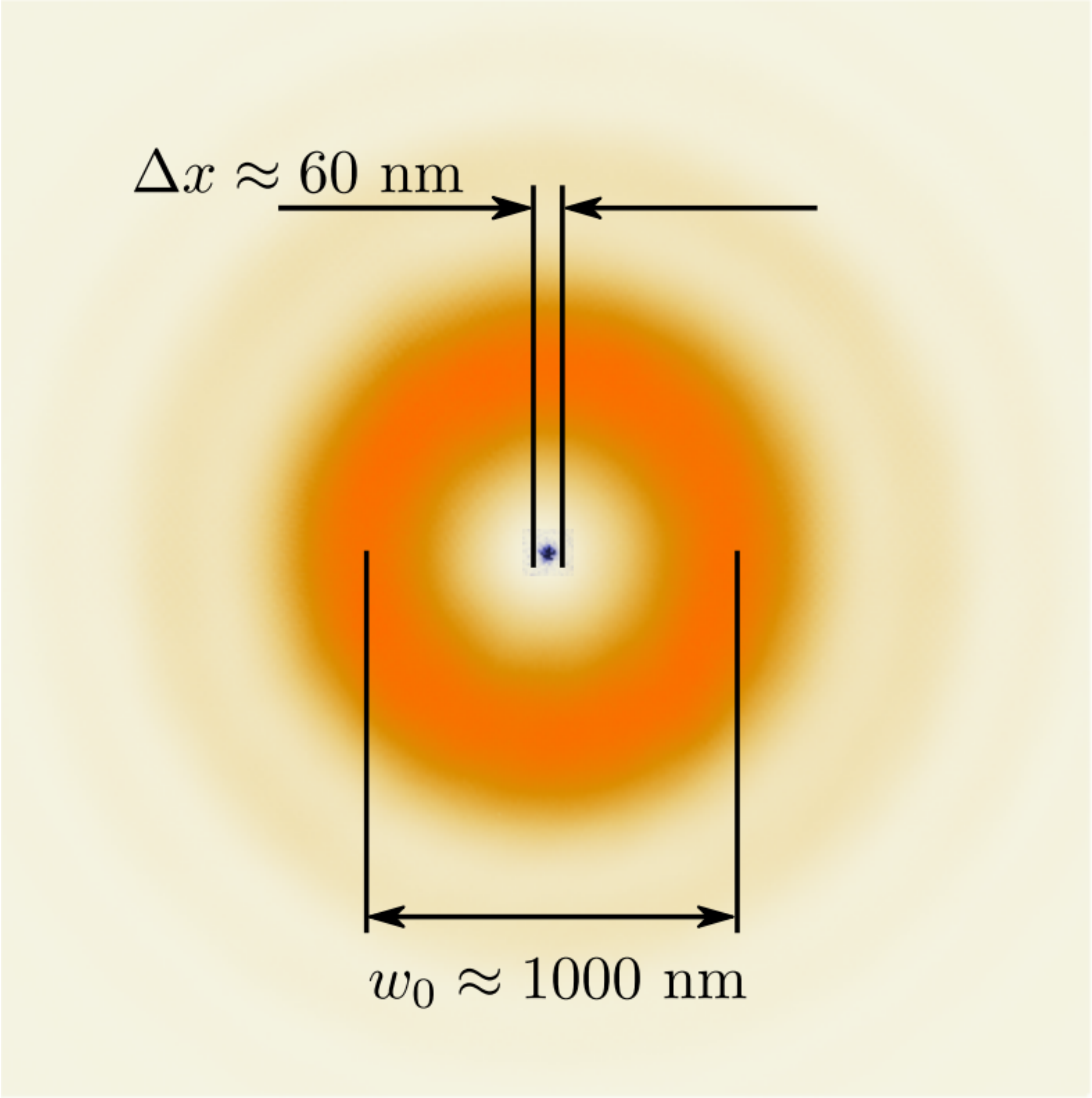
an ion trap



a hollow beam



ion in a beam



Twisted Light

$$A = A_{lp}(\rho, \phi, z)\vec{\epsilon} e^{ikz} e^{-i\omega t}$$

$$\mathbf{A}_{lp} = \mathbf{A_0}\ \frac{w_0}{w(z)} \exp\left(\frac{-\rho^2}{w(z)} + \frac{ik\rho^2}{2R(z)} + i\Phi_g(z)\right)$$

$$\sqrt{\frac{2p!}{\pi(|l|+p)!}} \left(\frac{\sqrt{2}\rho}{w(z)}\right)^{|l|} \mathcal{L}_p^{|l|}\left(\frac{2\rho^2}{w^2(z)}\right) \exp(il\phi)$$

$l = 0$ $l = 1$ $l = 2$

Dancing in the dark Structured light beams - Laguere- Gauss type.

Equation of the LG beams $A = A_{lp}(\rho, \phi, z)\vec{\epsilon} e^{ikz} e^{-i\omega t}$

$$\mathbf{A}_{lp} = \mathbf{A_0} \frac{w_0}{w(z)} \exp\left(\frac{-\rho^2}{w(z)} + \frac{ik\rho^2}{2R(z)} + i\Phi_g(z)\right)$$

$$\sqrt{\frac{2p!}{\pi(|l|+p)!}} \left(\frac{\sqrt{2}\rho}{w(z)}\right)^{|l|} \mathcal{L}_p^{|l|} \left(\frac{2\rho^2}{w^2(z)}\right) \exp(il\phi)$$

Light Angular Momentum

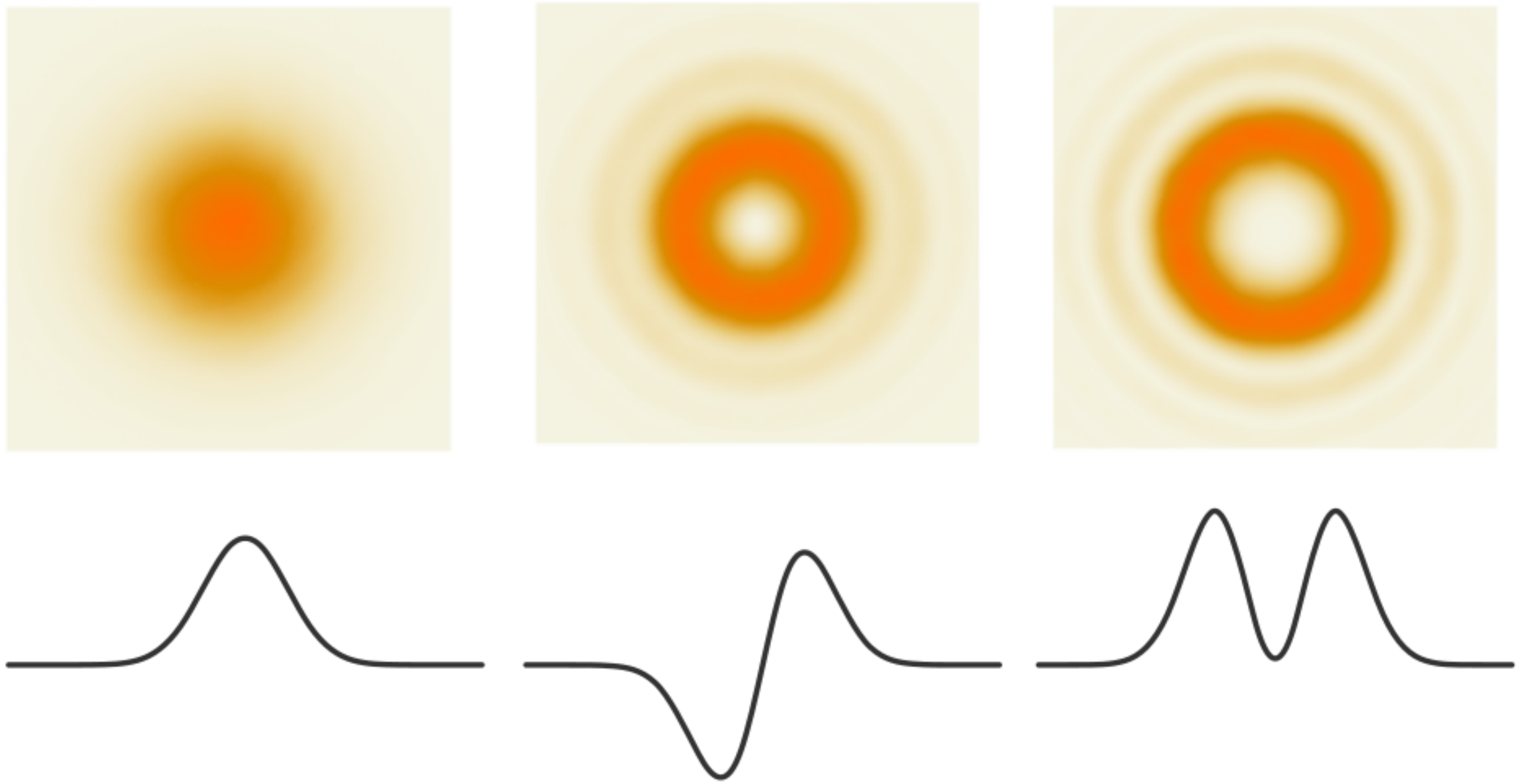
$$M_z = \frac{l}{\omega} |u|^2 + \frac{\sigma_z r}{2\omega} \frac{\partial |u|^2}{\partial r} .$$

$|A_{pl}(x,y)|^2$

Intensity

$A_{pl}(x)$

Field



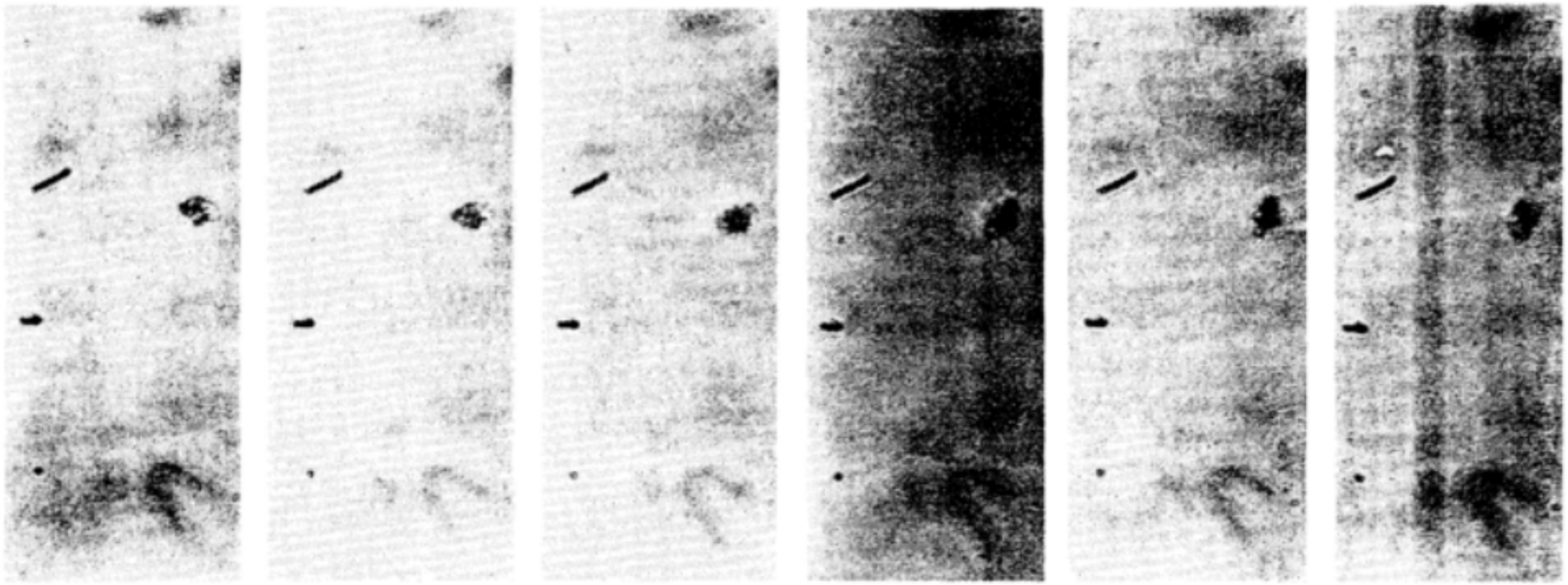
Orbital Angular Momentu - first experiment

VOLUME 75, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JULY 1995

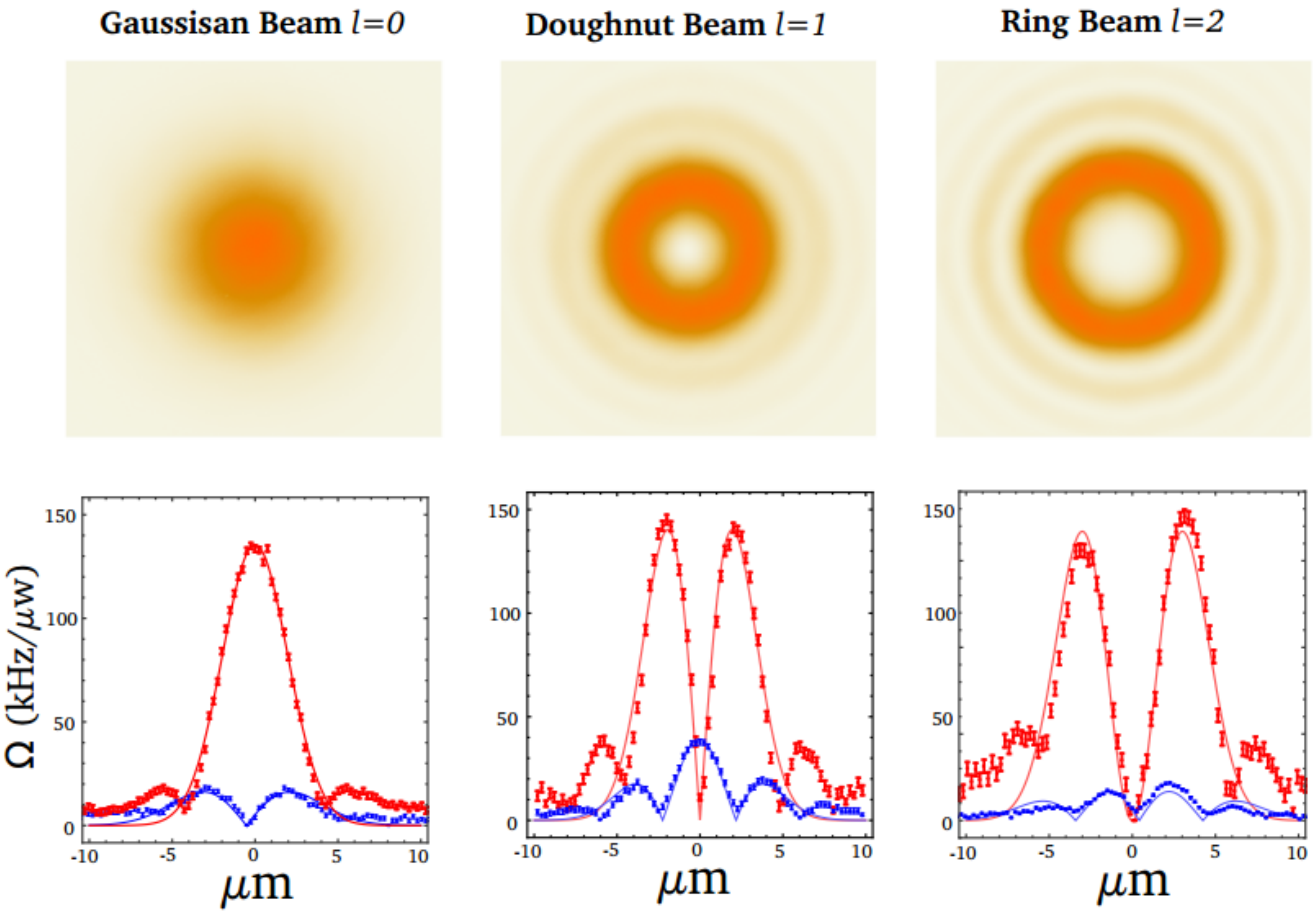
pg. 826

Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity

H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop
Department of Physics, The University of Queensland, Brisbane, Queensland, Australia Q4072



Beam Intensity Profiles
(measured with CCD
before focusing on the ion)



Quadrupole Excitation
as a function of the
position of the ion
in the beam

Longitudinal Gradient
proportional to sqrt(intensity)

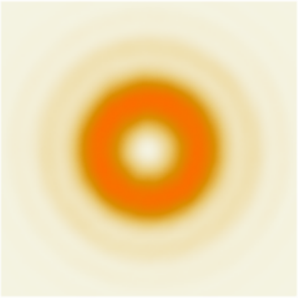
Transverse Gradient

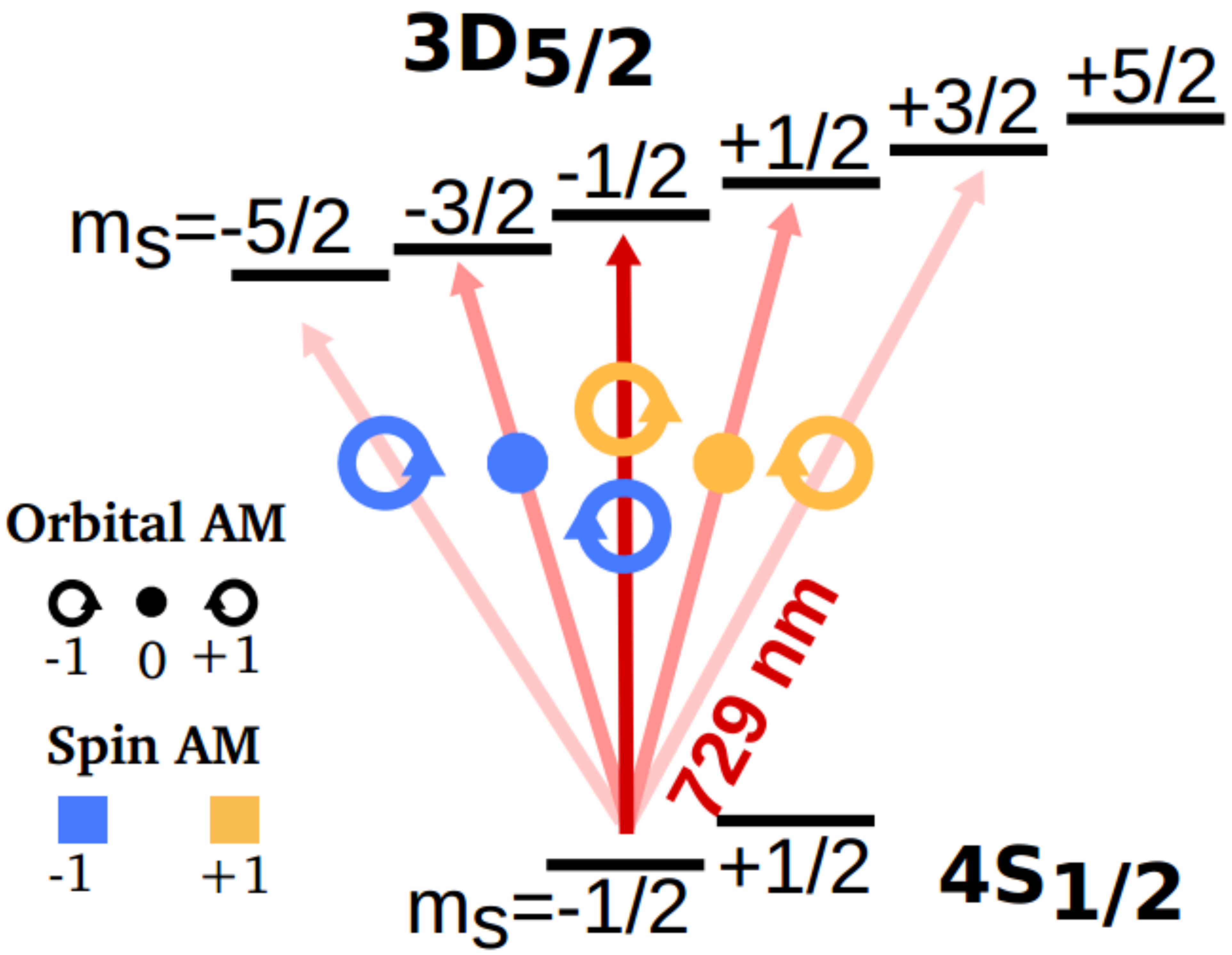
Nature communications 7, 12998 (2016)

Twisting in the dark selection rules, for a rotationally symmetric system B||k

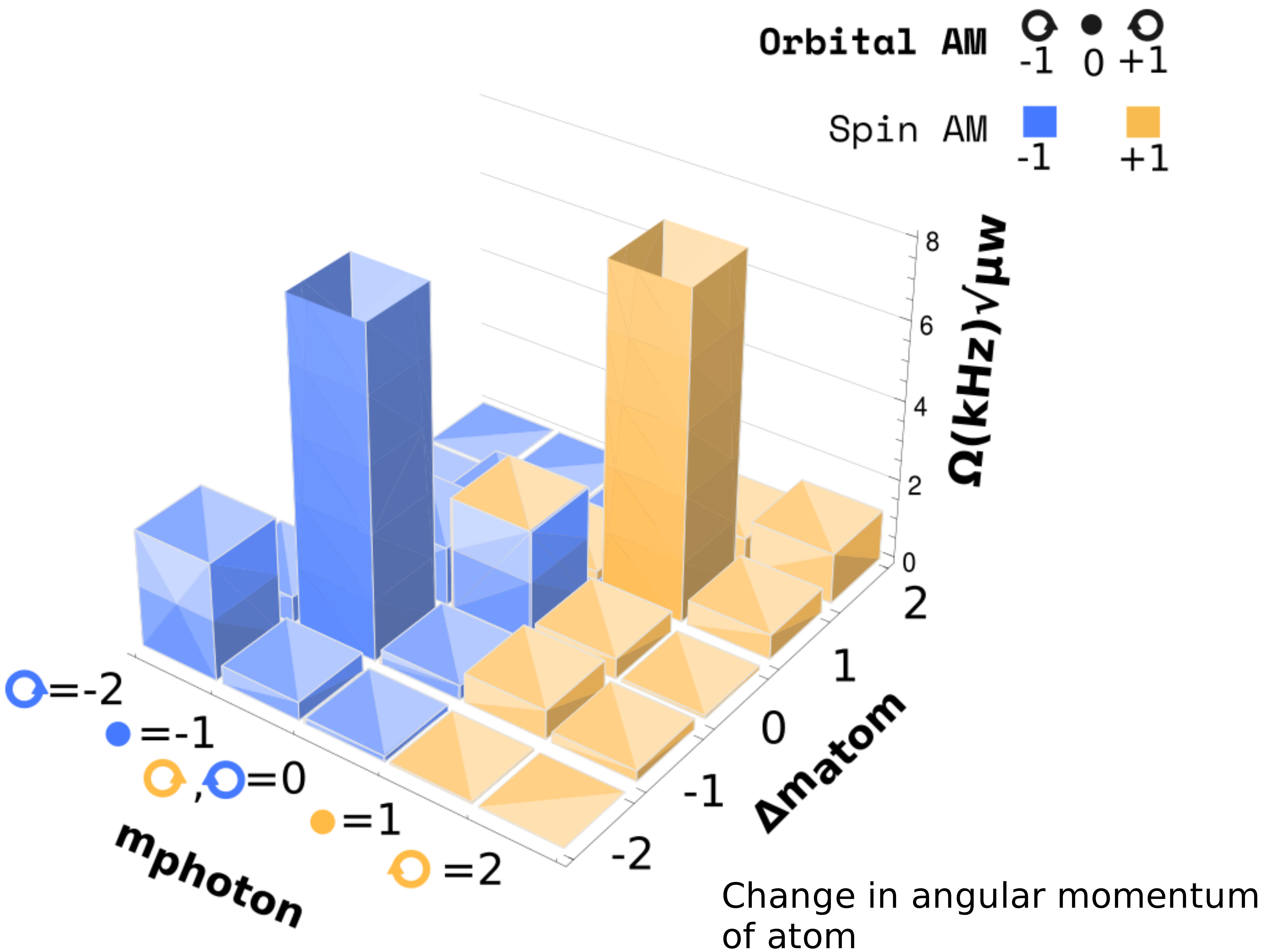
Nature communications 7, 12998 (2016)

Selection rules for polarization + structure





Rabi frequencies for each transition



Angular momentum of photon

Change in angular momentum of atom

Christian Schmiegelow - Universidad de Buenos Aires

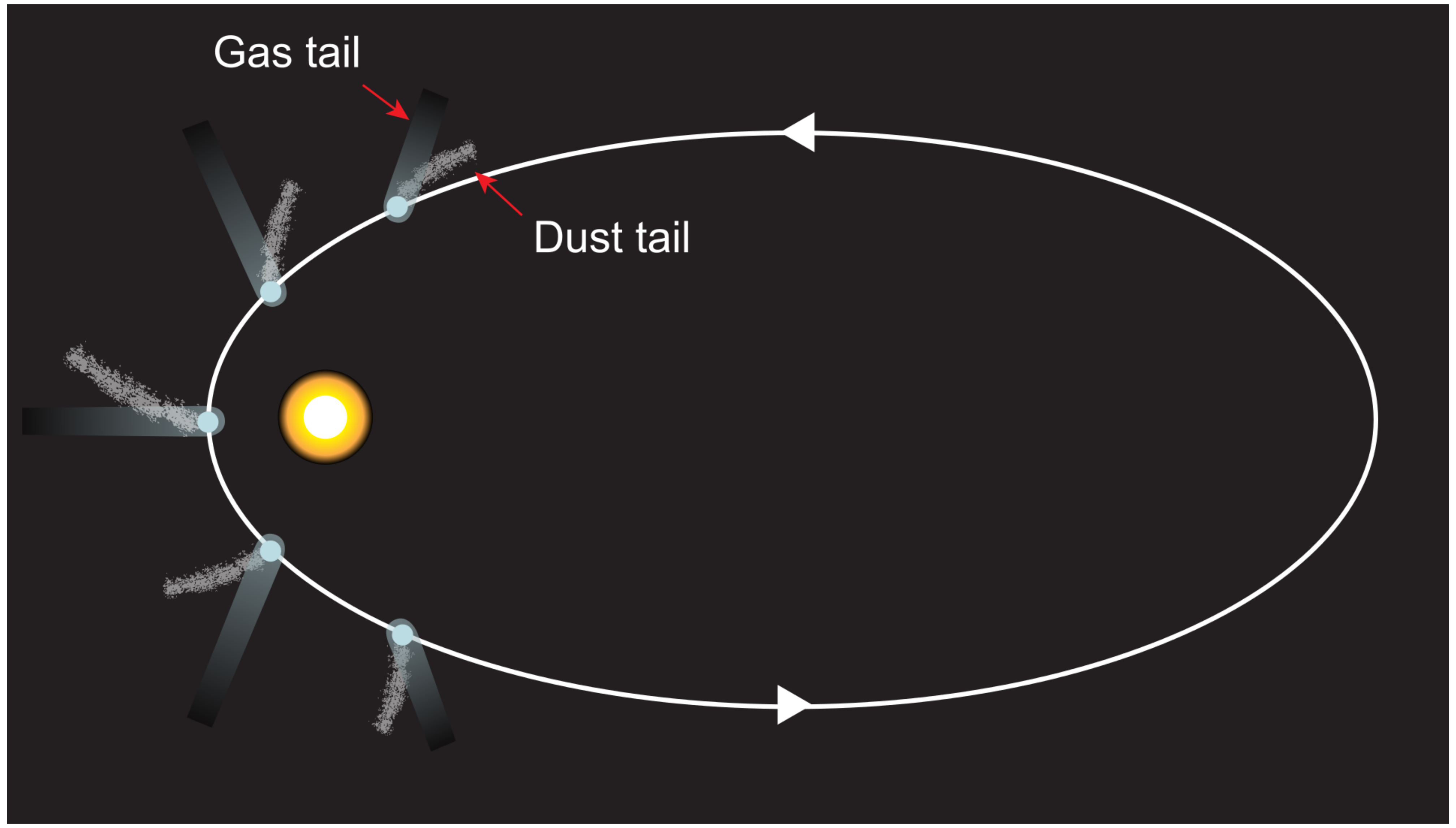
Day Three

Part 1

Center of mass motion with resonant interaction.

Moving in the dark the center of mass, trasnversal radiation pressure

Radiation pressure - comets and Kepler



Pressure is always in the propagation direction
- longitudinal -

wait!!

momentum transfer is the direction of the field gradient

... for plane waves

$$E = E_0 e^{ikz} \longrightarrow \Delta p = \hbar k \hat{z}$$

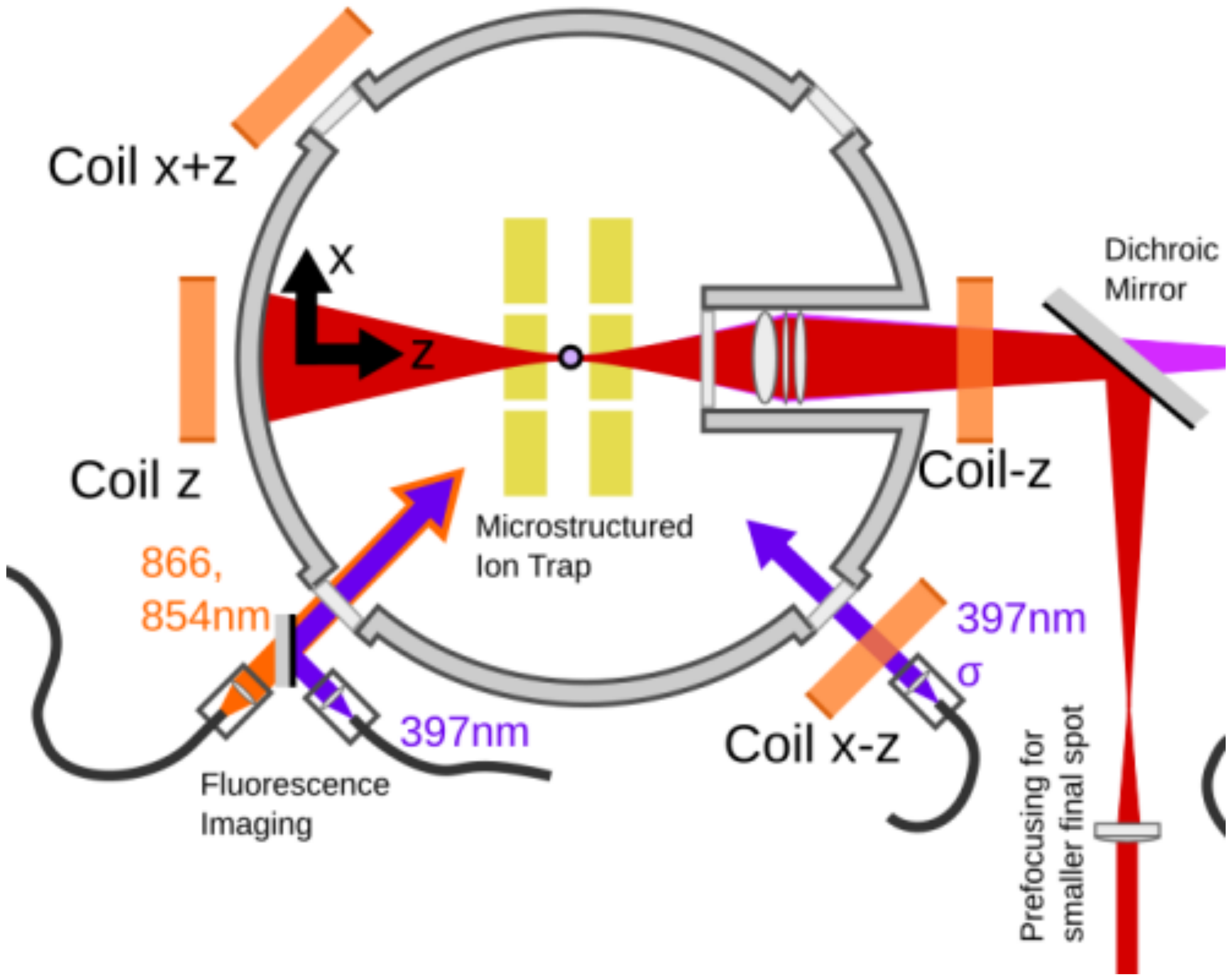
longitudinal momentum transfer

... but for structured beams

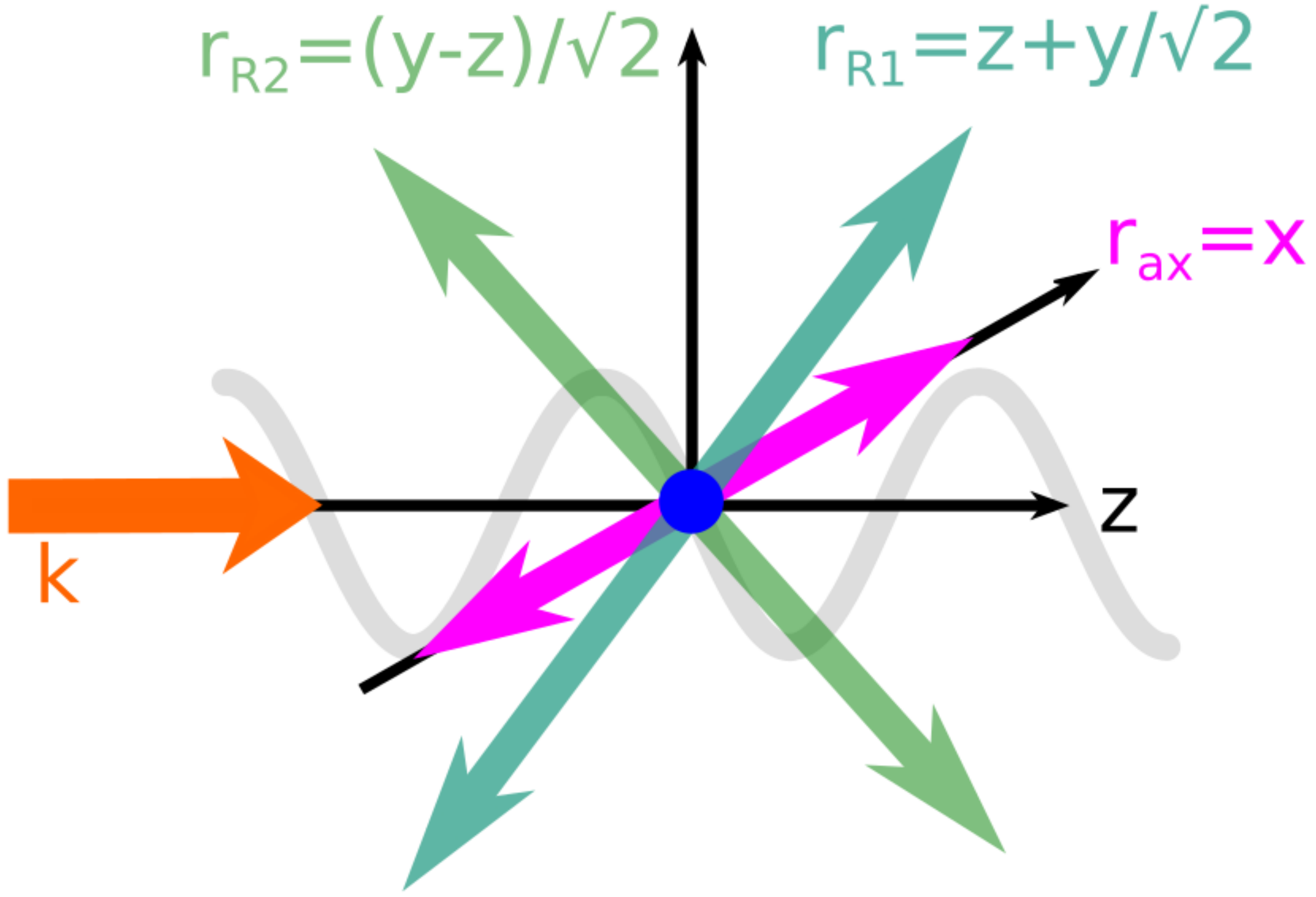
$$E = E_0 e^{ikz} \rho \longrightarrow \Delta p = \hbar \hat{\rho} / w_0$$

trasnverse momentum transfer

Moving in the dark the center of mass, trasnversal radiation pressure



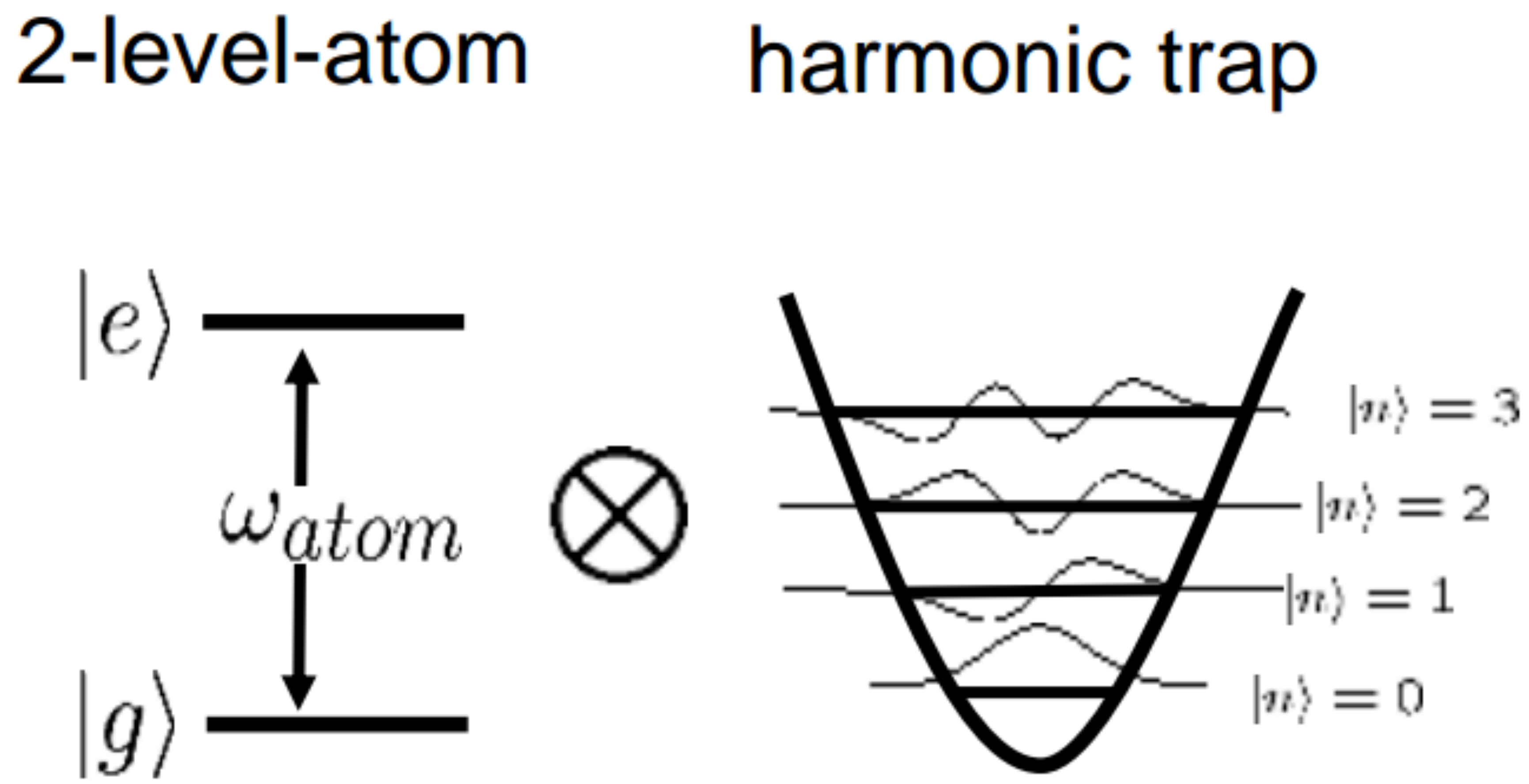
Trap and beam geometry



x-axial direction is trasnverse to the beam propagation direction

Moving in the dark trapped atom - light interaction physics

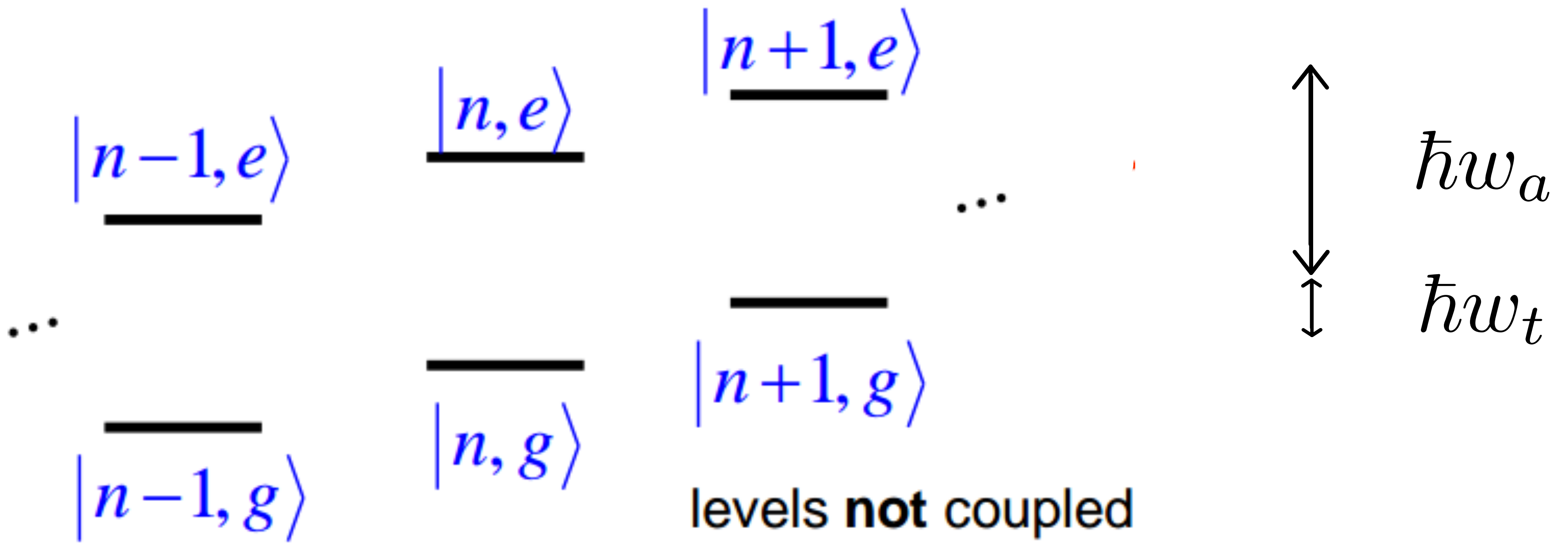
Jaynes-Cummings Hamiltonian



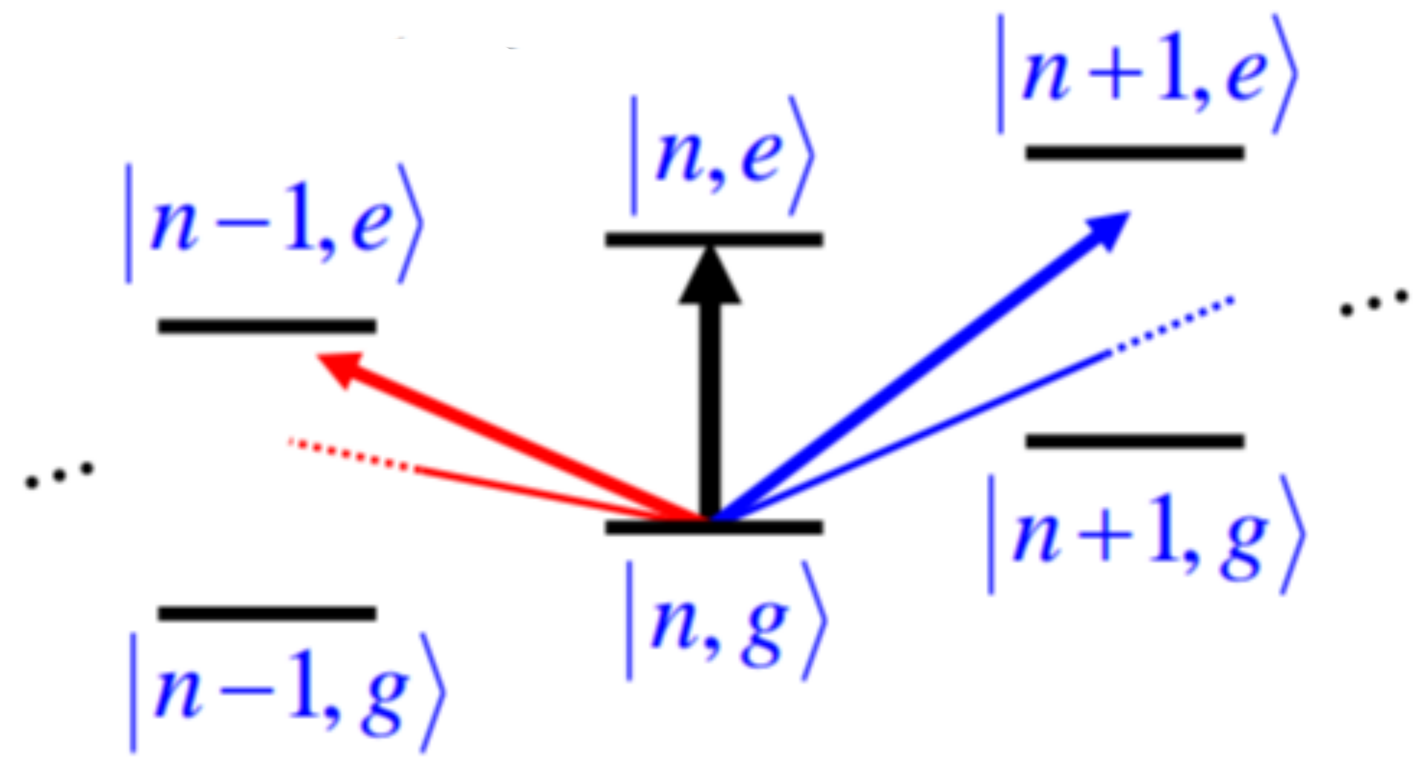
$$H_0 = \frac{1}{2} w_a \sigma_z + \frac{p^2}{2m} + \frac{1}{2} m w_t^2 x^2$$

electronic **center of mass**

Ladder reperesentation



Interaction Hamiltonians



for dipole transitions

$$H_{ge} = -\vec{d} \cdot \vec{E}$$

for quadrupole transitions

$$H_{ge} = -Q_{ij} \frac{\partial E_i}{\partial x_j}$$

in the dipole case...

$$H_{ge} = \frac{\hbar \Omega}{2} (\sigma^+ + \sigma^-) \sin (kx - w_l t + \phi)$$

after Rotating wave approximation in the interaction picture

$$H_I = \frac{\hbar \Omega}{2} \left(\sigma^+ e^{i\eta(a+a^\dagger)} e^{-i\Delta t} + \sigma^- e^{-i\eta(a+a^\dagger)} e^{i\Delta t} \right)$$

quantum harmonic oscillator

$$x = \sqrt{\frac{\hbar}{2mw}} (a + a^\dagger)$$

lamb-Dike parameter

$$\eta = k \sqrt{\frac{\hbar}{2m\omega}} = 2\pi \frac{x_0}{\lambda}$$

for trapped ions in quadrupole or Raman transitions

$$\eta \sim 0.05 - 0.2$$

Carrier transitions

order cero

$$H_{\text{carrier}} = \frac{\hbar \Omega}{2} (\sigma^+ + \sigma^-)$$

Red Sideband Transitions

order one

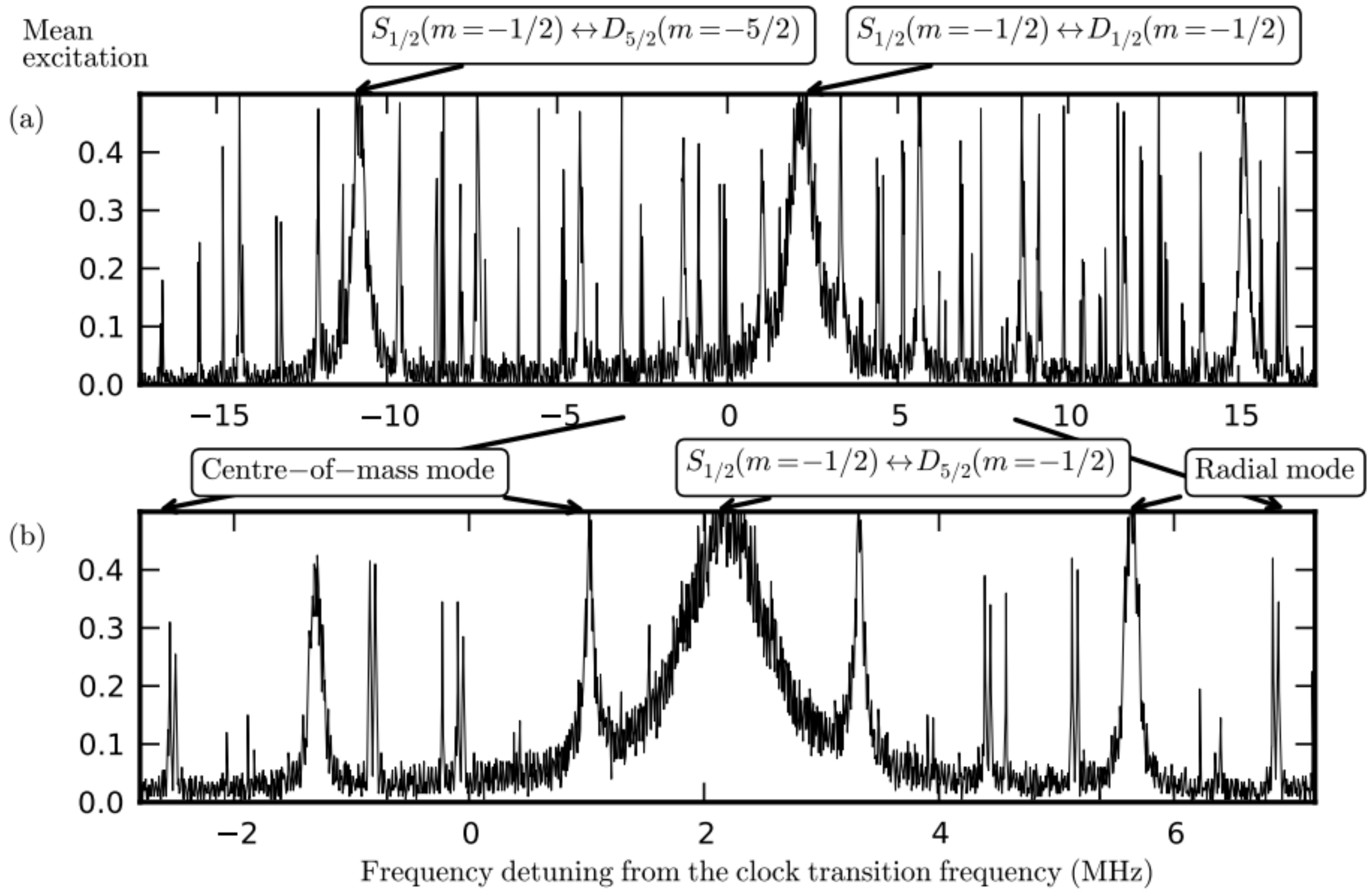
$$H_{\text{red}} = \frac{\hbar \Omega}{2} \eta (\sigma^+ a + \sigma^- a^\dagger)$$

Blue Sideband Transitions

order one

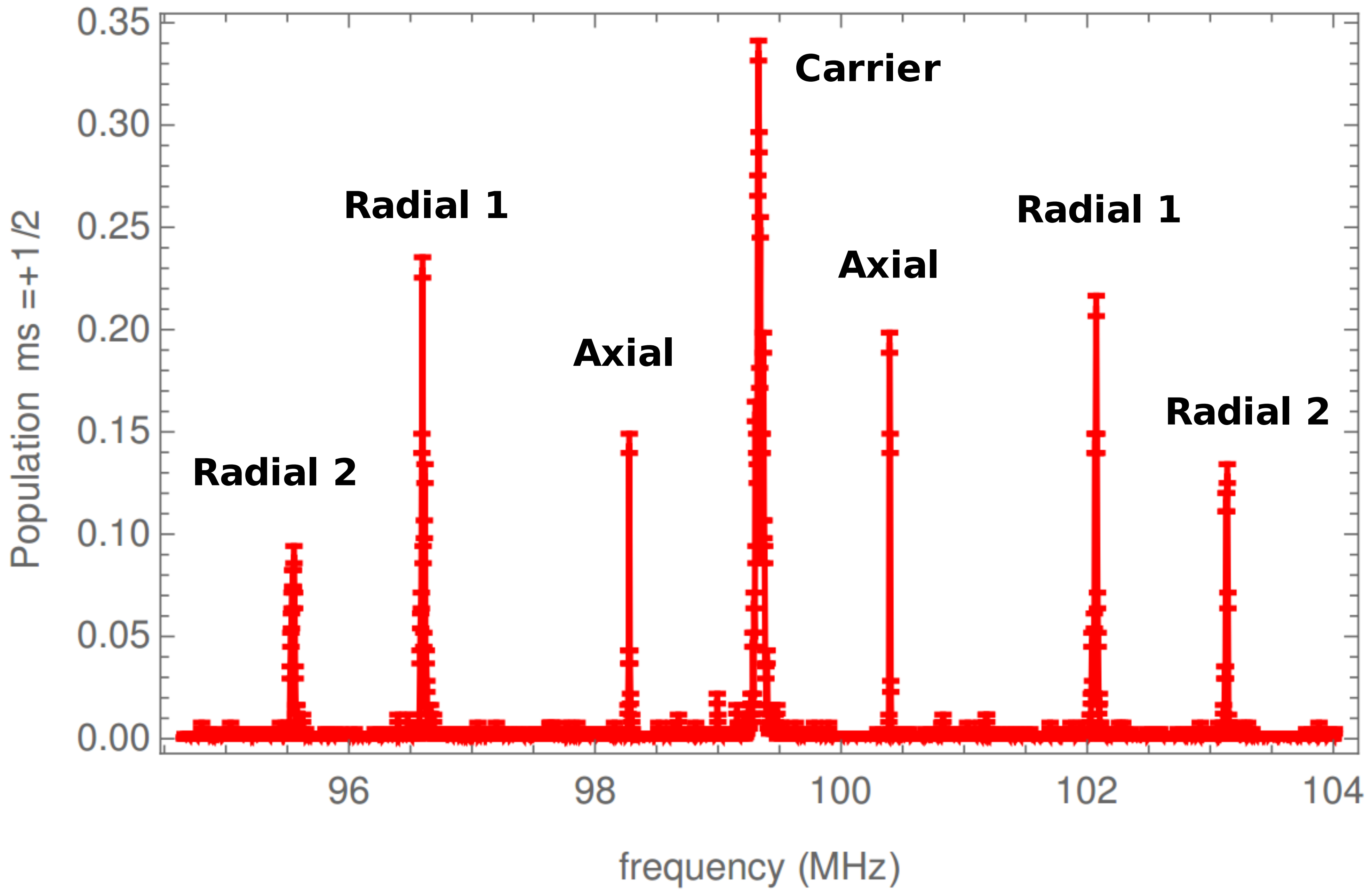
$$H_{\text{blue}} = \frac{\hbar \Omega}{2} \eta (\sigma^+ a^\dagger + \sigma^- a)$$

Moving in the dark Detecting motion via resolved sidebands

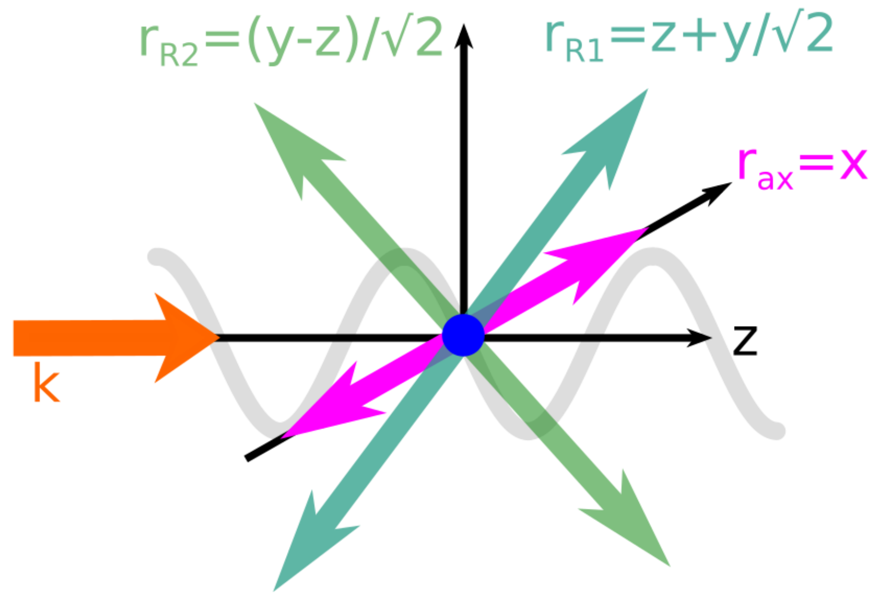


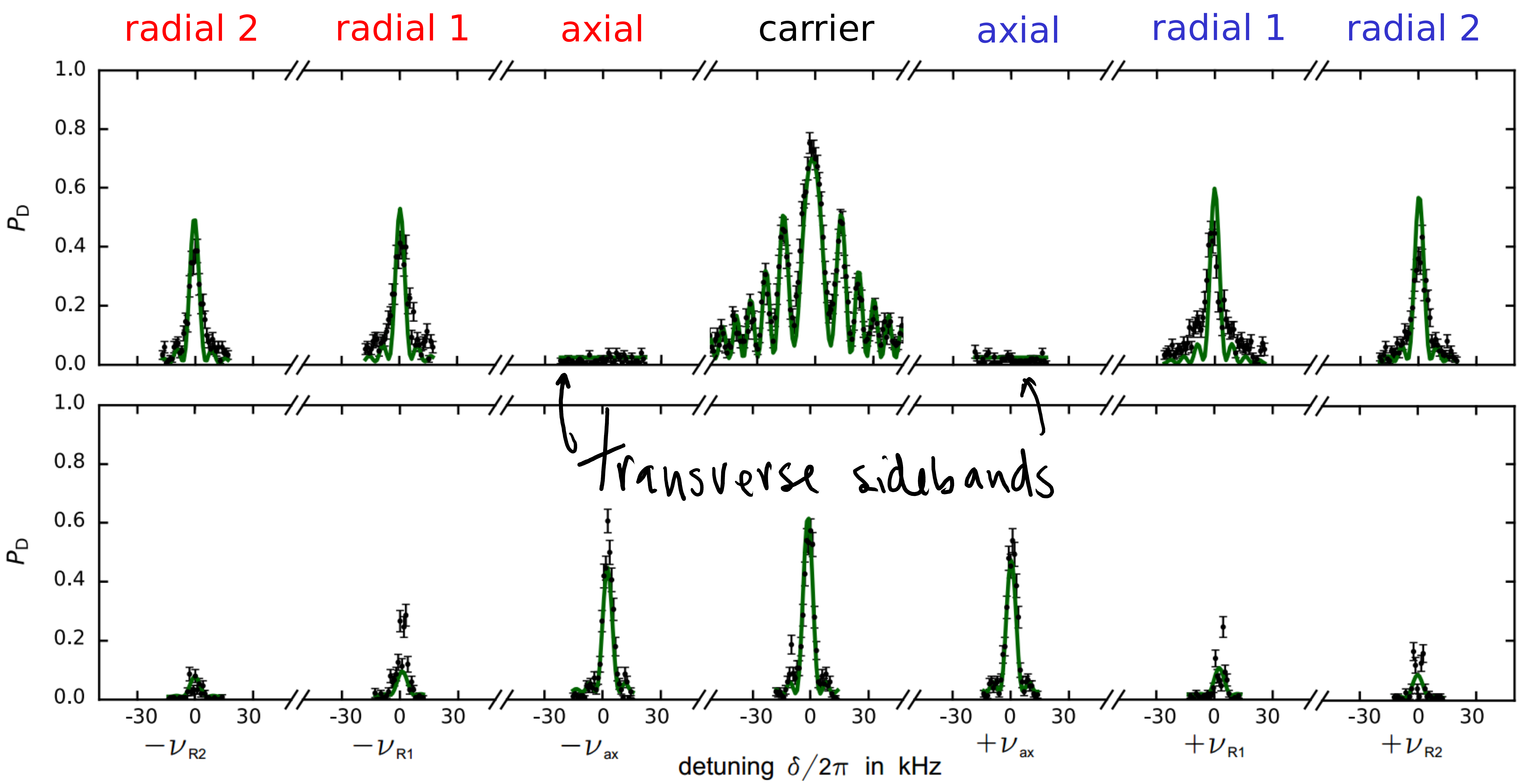
Black spectra borrowed from Monz, PhD Thesis

Very clear side-bands in the quadrupole spectrum

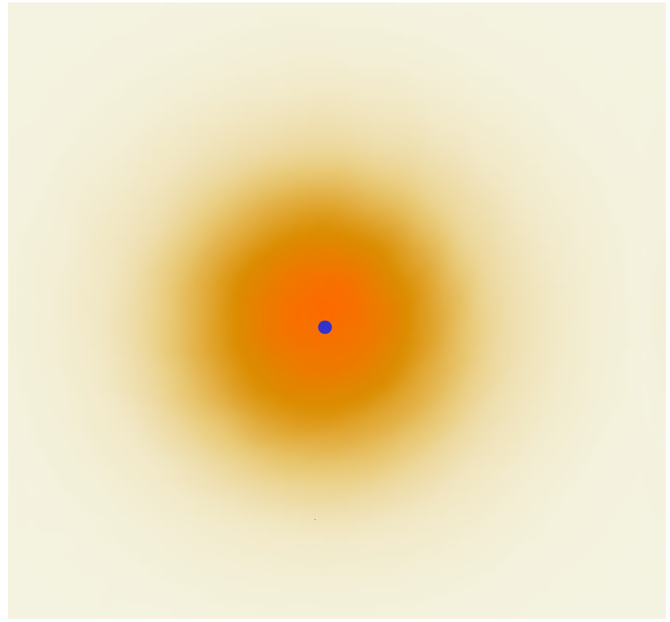


Moving in the dark Spectra: traveling wave vs transverse gradients

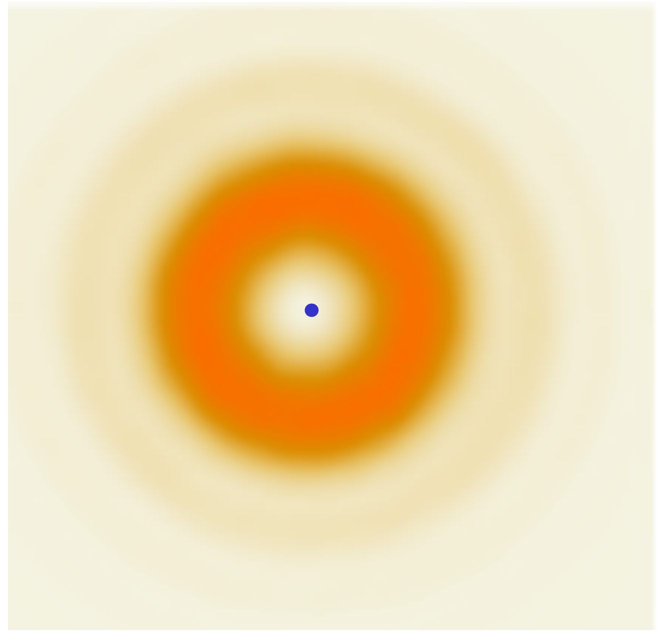




Gaussian



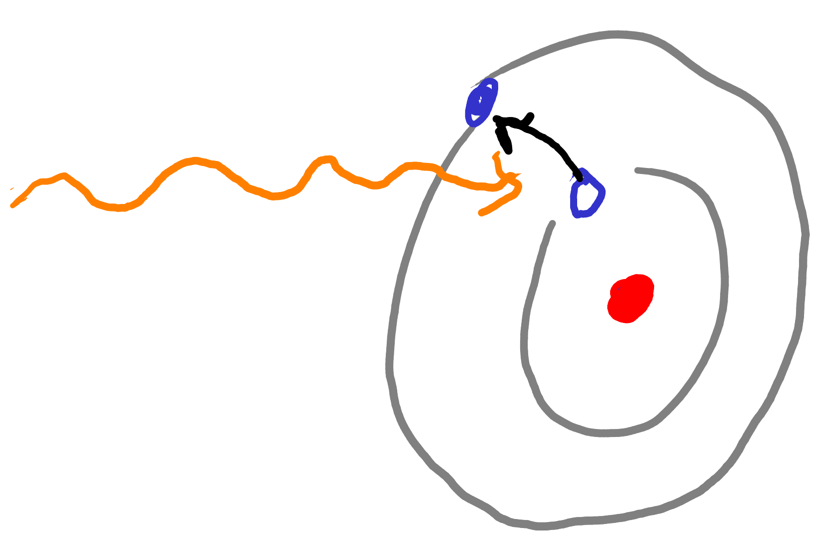
Vortex

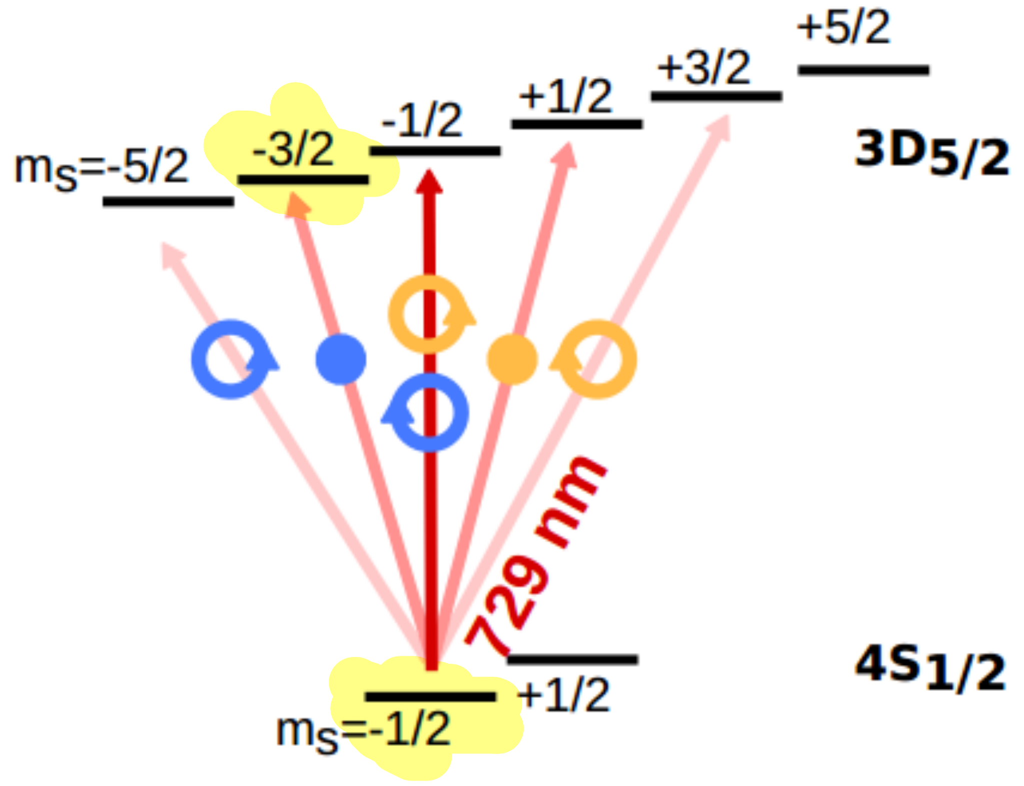


Physical Review Letters 129 (26), 263603 (2022)

Moving in the dark who does what?

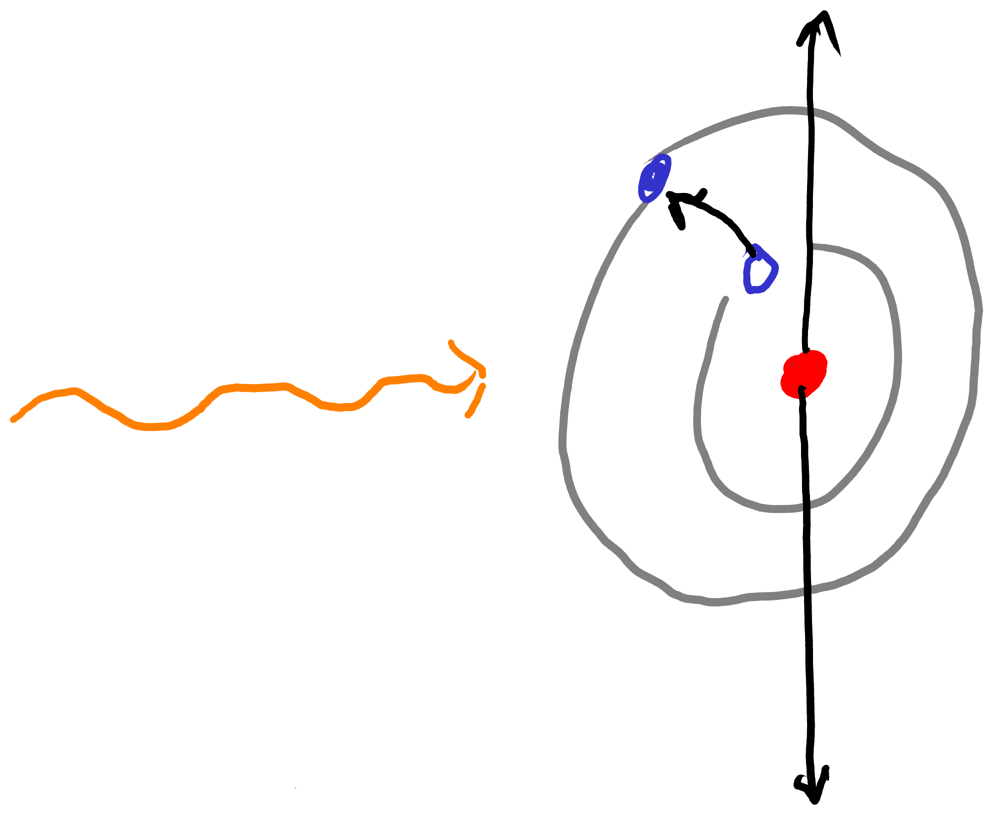
Polarization: change internal in motion

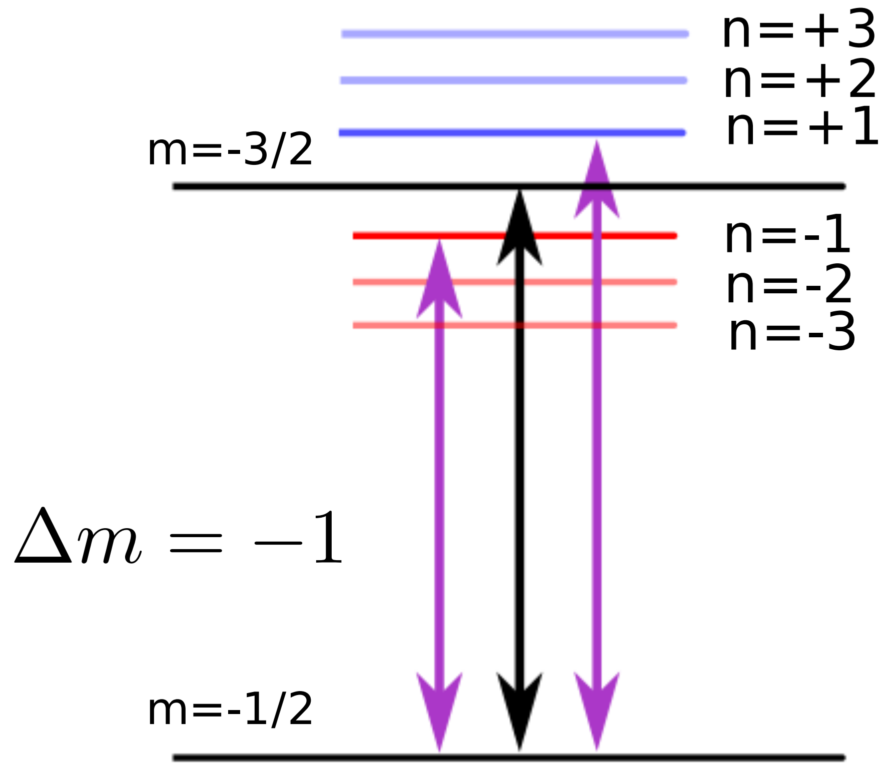




Structure: change in external motion

quantized
harmonic
oscillator





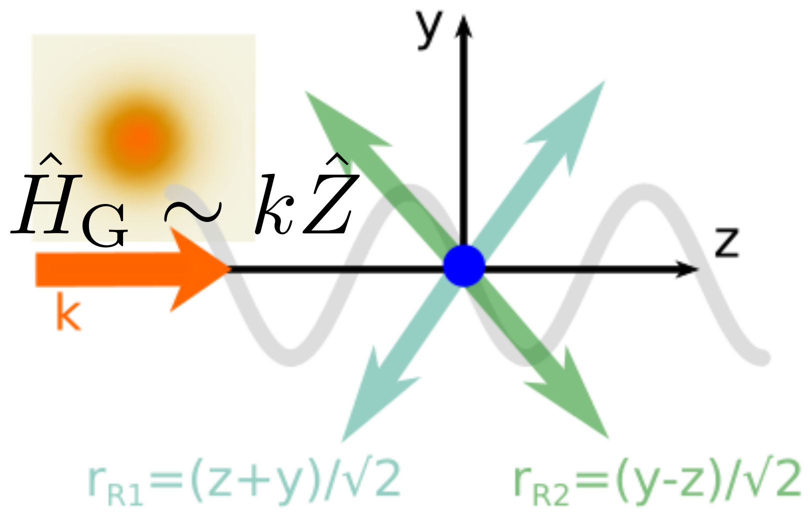
Moving in the dark EXTRA: theory of sidebands on quadrupole transitions

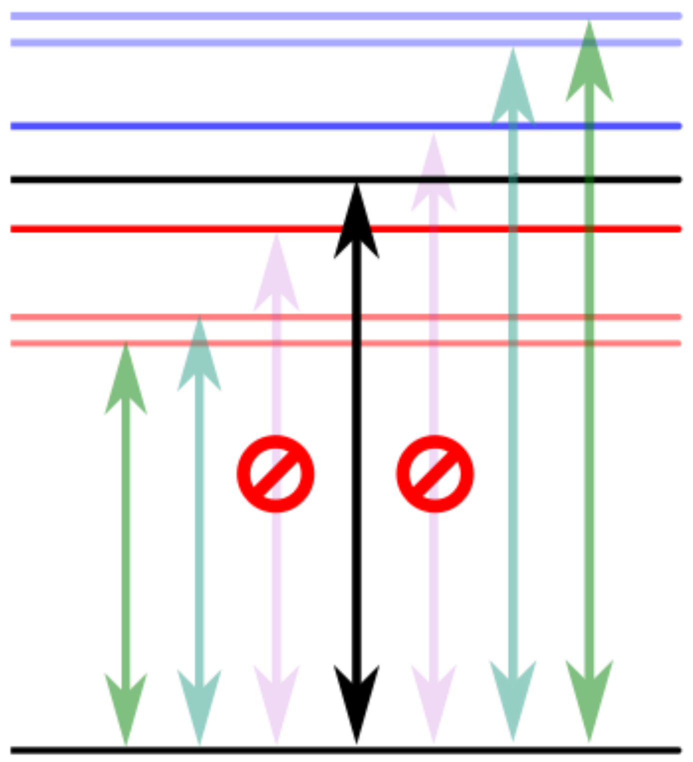
the general interaction term $$\hat{H}_\mathrm{Q} \sim \sum_{i,j} \hat{q}_i \hat{q}_j \left.\frac{\partial E_j^{(+)}}{\partial q_i}\right|_{\hat{Q}_i} \mathrm{e}^{-\mathrm{i}\omega t} + \mathrm{h.c.},$$

travelling wave term

$$\mathbf{E}_\mathrm{G}^{(+)} \sim E_0(\mathbf{e}_x + \sigma \mathrm{i}\mathbf{e}_y)\exp(\mathrm{i}kz)$$

$$\hat{H}_\mathrm{G} \sim k\exp\{\mathrm{i}k\hat{Z}\}$$





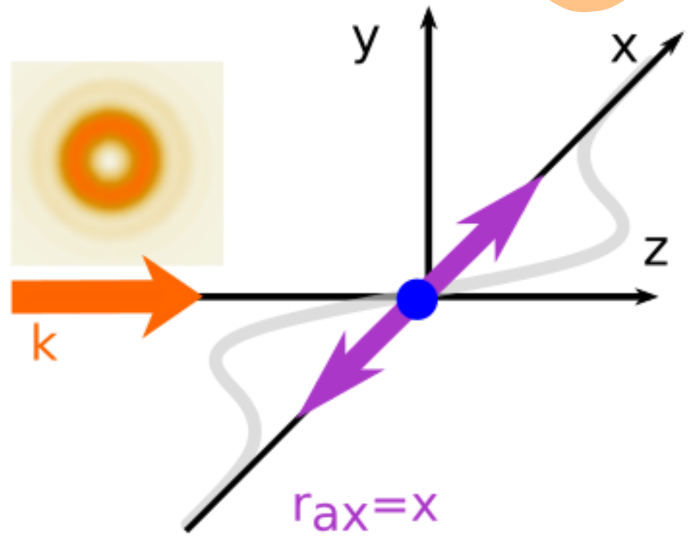
$$\eta_{\|} = kx_0$$

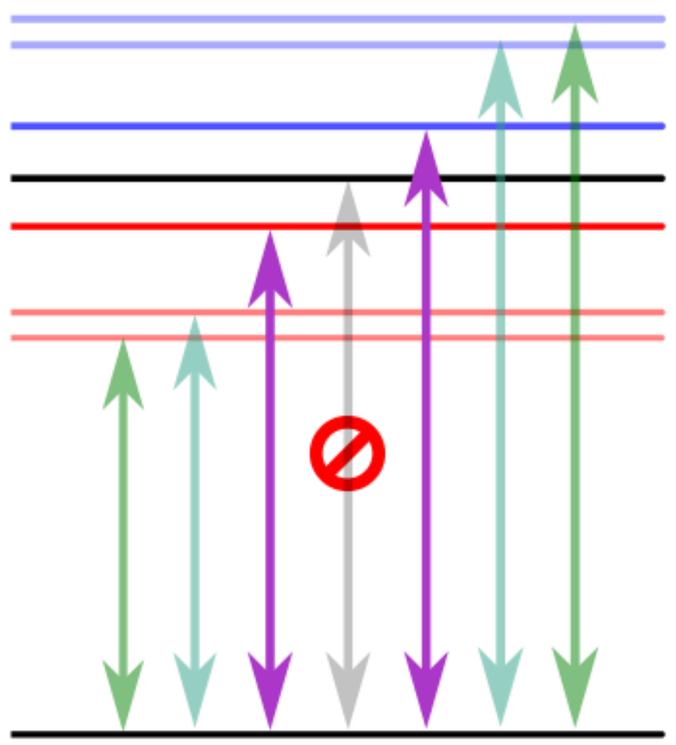
oam trasverse term

$$\mathbf{E}_\mathrm{LG}^{(+)} \sim E_0\sqrt{2}w_0^{-1}(\mathbf{e}_x + \mathrm{i}\sigma\mathbf{e}_y)\exp(\mathrm{i}kz)(x + \mathrm{i}ly)$$

$$\hat{H}_\mathrm{LG}^{\perp} \sim \exp\{\mathrm{i}k\hat{Z}\}\frac{\sqrt{2}}{w_0}\left(\hat{X} + \mathrm{i}\hat{Y}\right)$$

linear leading term



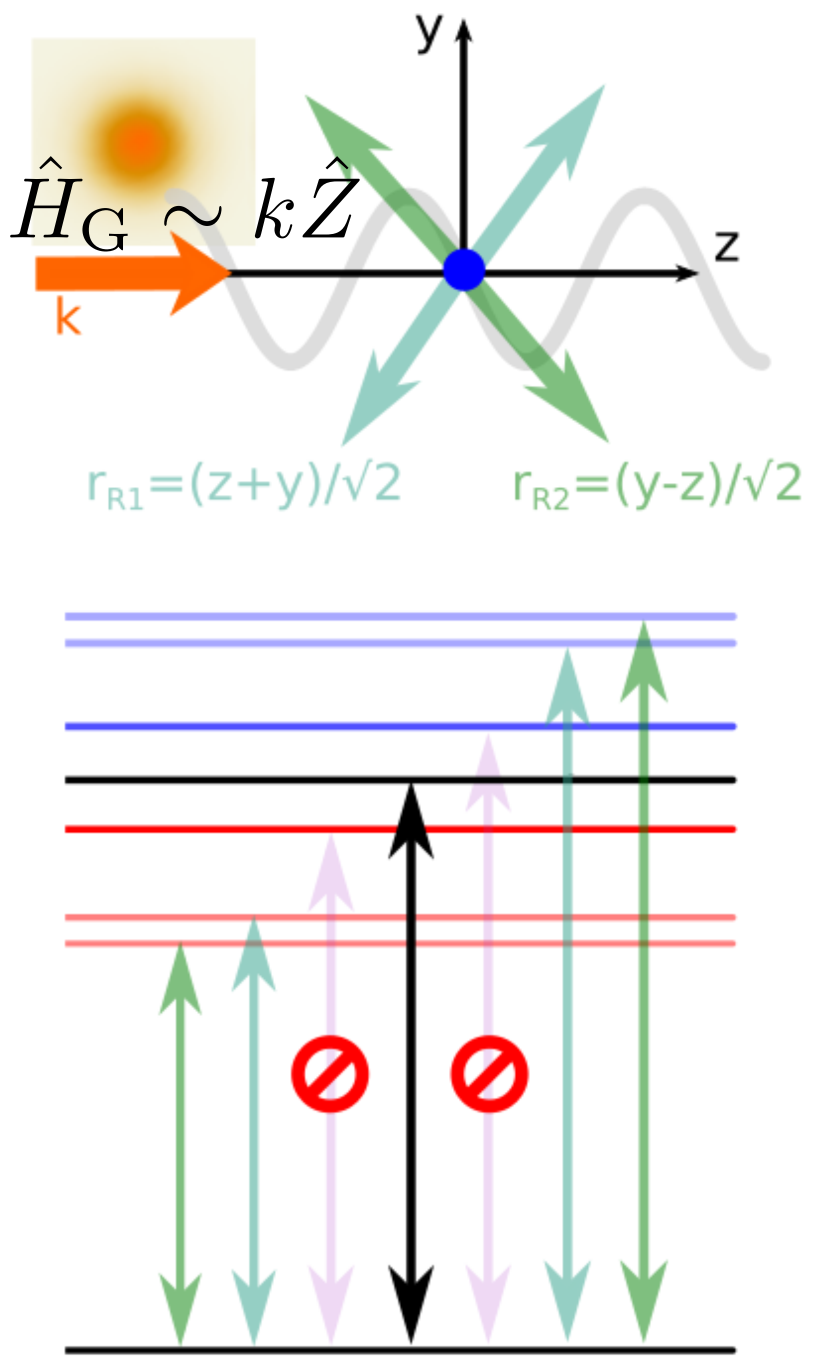


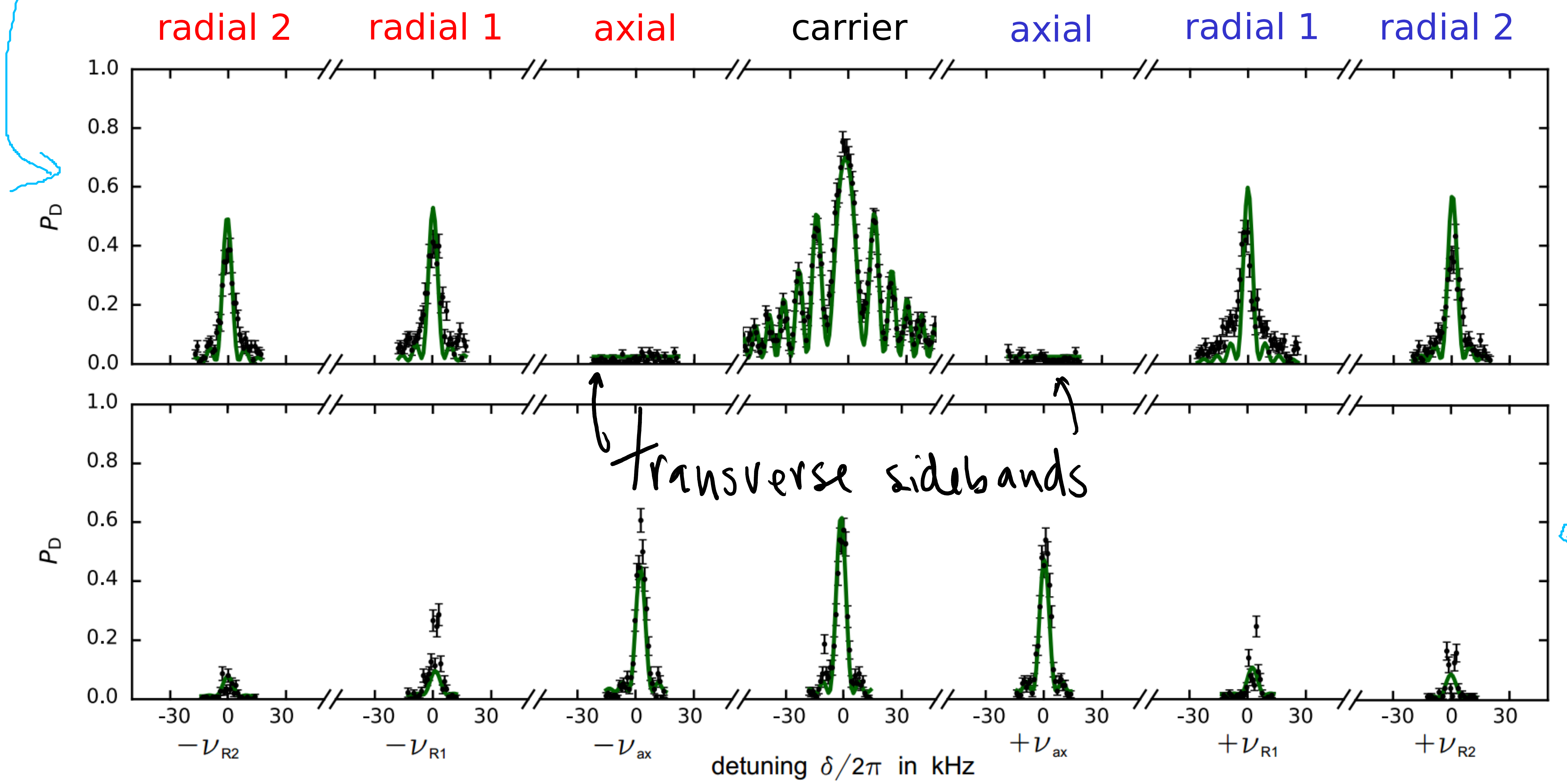
$$\eta_{\perp} = \sqrt{2}x_0/w_0$$

Lamb-Dicke parameters determine the sideband interaction strengths

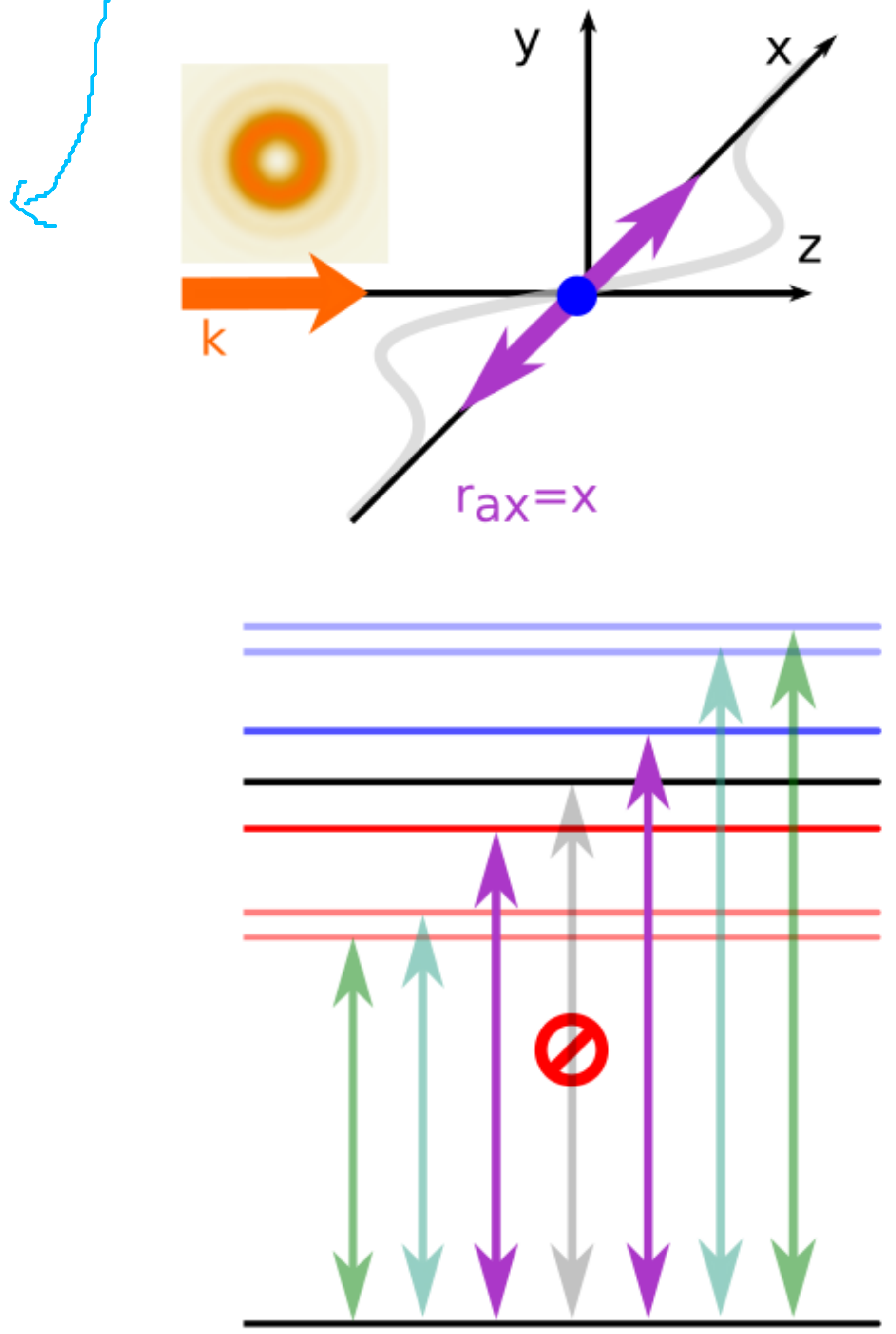
Moving in the dark EXTRA: theory of sidebands on quadrupole transitions

travelling wave term





oam trasverse term



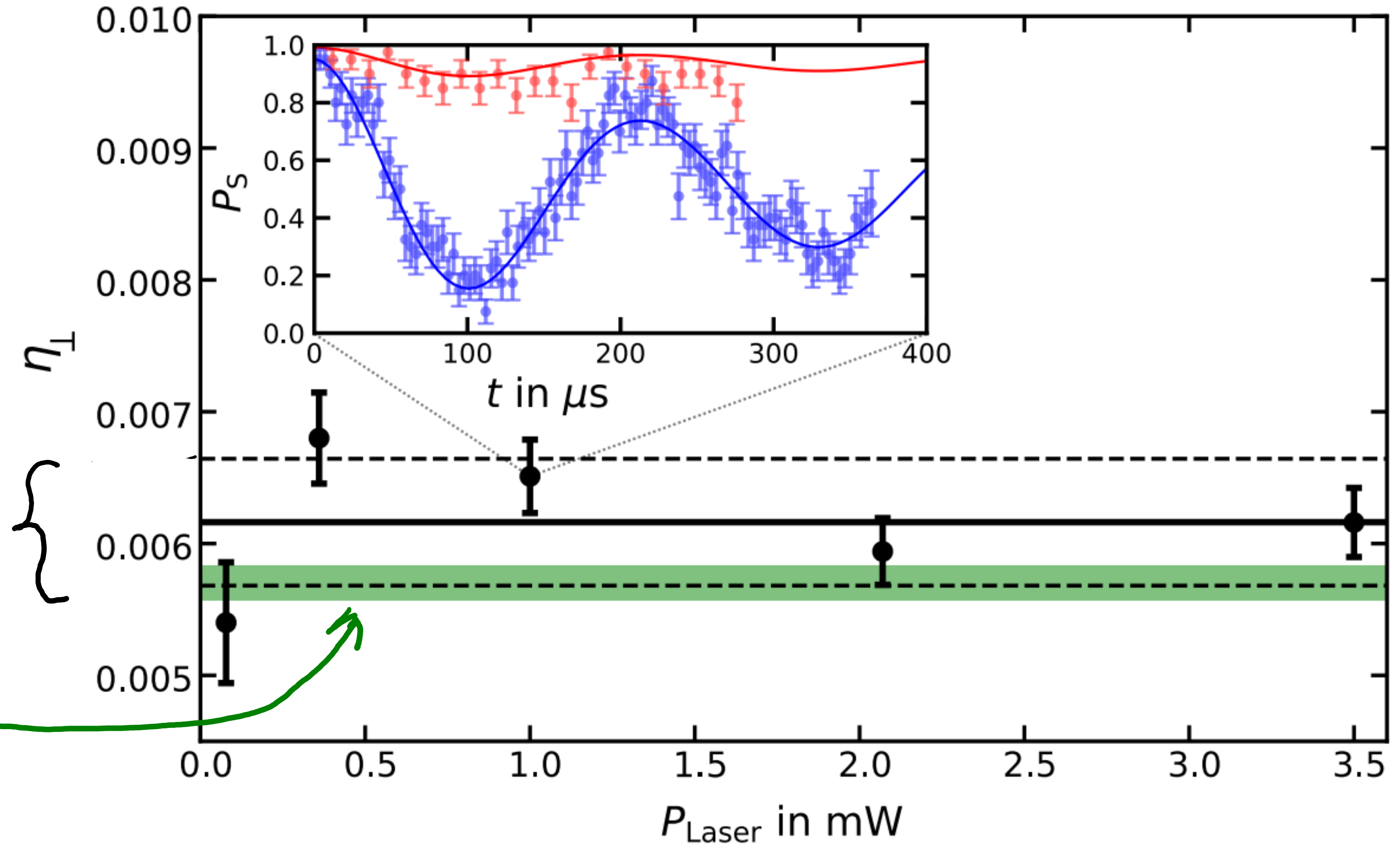
Determination of the transverse Lamb-Dicke parameter

exp: transverse sideband strength with respect to carrier strength

theo: $\eta_\perp^{\mathrm{theo}} = \sqrt{2} x_0 / w_0$

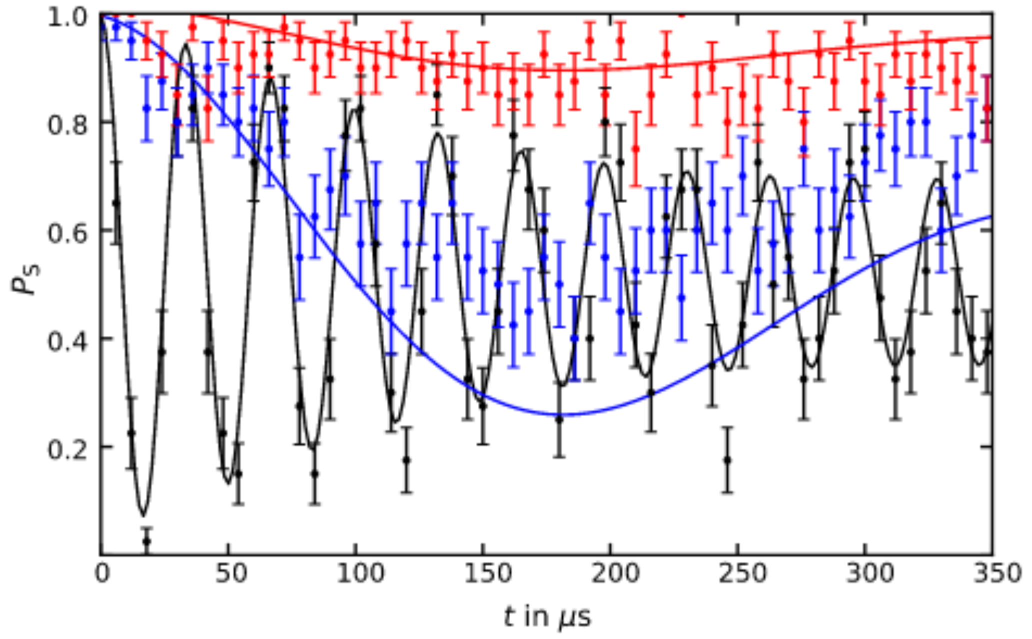
$\eta_\perp^{\mathrm{exp}} = 0.0062(5)$

$\eta_\perp^{\mathrm{theo}} = 0.0057(1)$



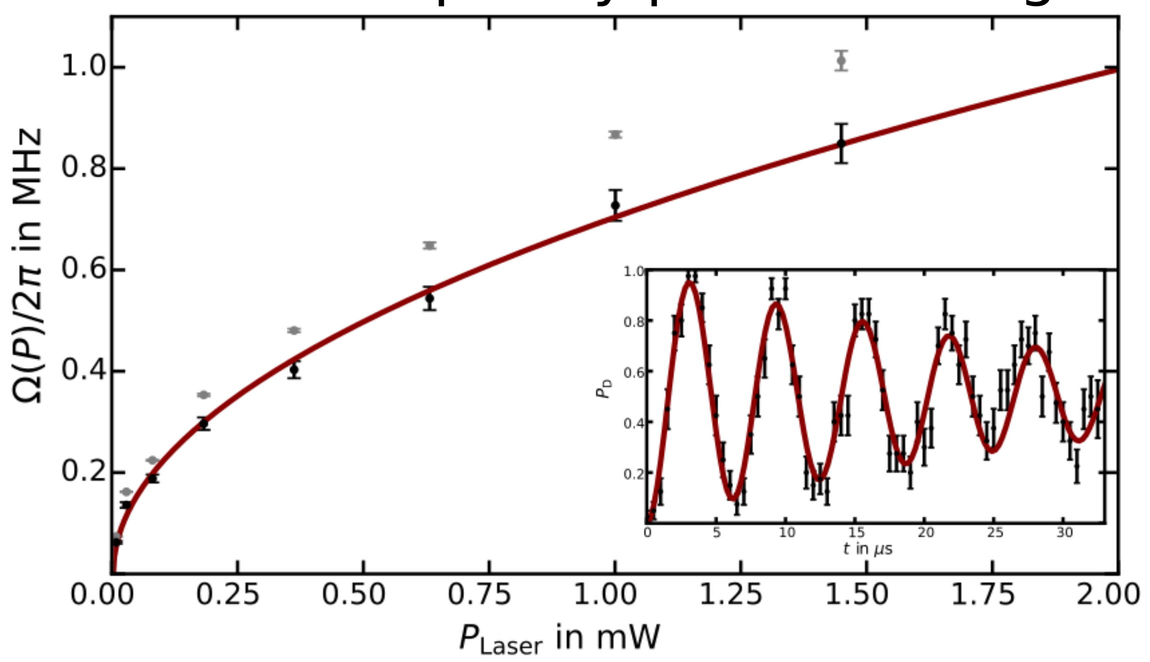
various calibration parameters

temperature

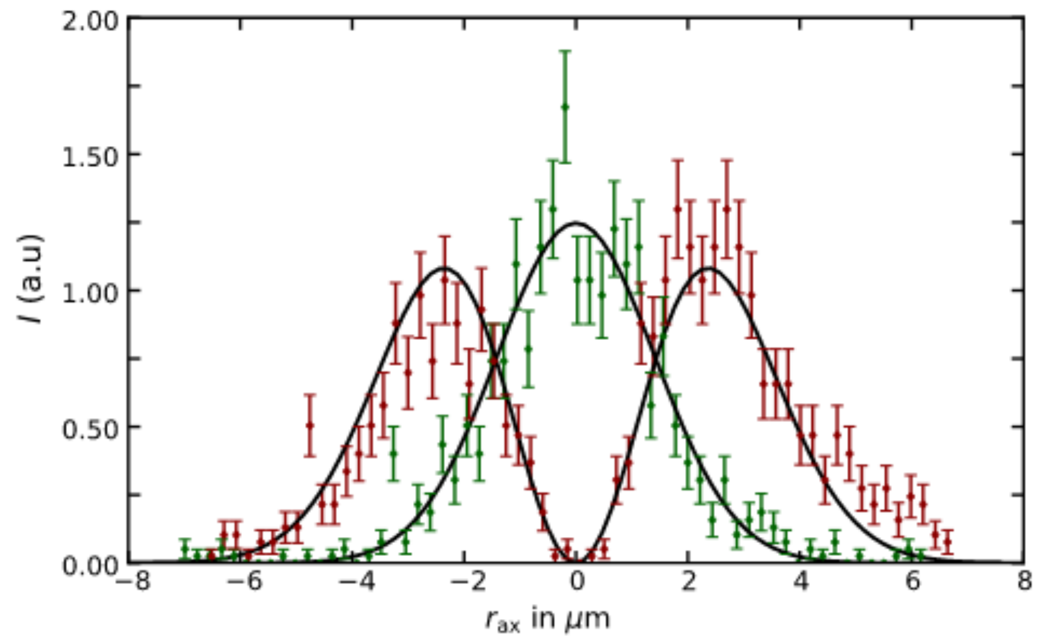


$\langle n_{\mathrm{ax}} \rangle = 0.19(10)$

Rabi frequency power scaling



beam waists



$w_{\mathrm{V}} = 3.34(7)\,\mu\mathrm{m}$

Physical Review Letters 129 (26), 263603 (2022)

Outlook

- Quadrupole-tuned vortices
  - Radially addressed axial gates
  - Thermometry on planar ion crystals
- Dipole-tuned vortices
  - Type of force
    - Detuned - conservative
    - Resonant - incoherent
  - Type of Crystal
    - two ion rotation
    - 2D shells

Day Three

Part 2 Stark Shift and Optical, spin-dependent, forces

Center of mass motion with resonant interaction.

AC Stark Shift, Autler-Townes effect hamiltonian and time evolution

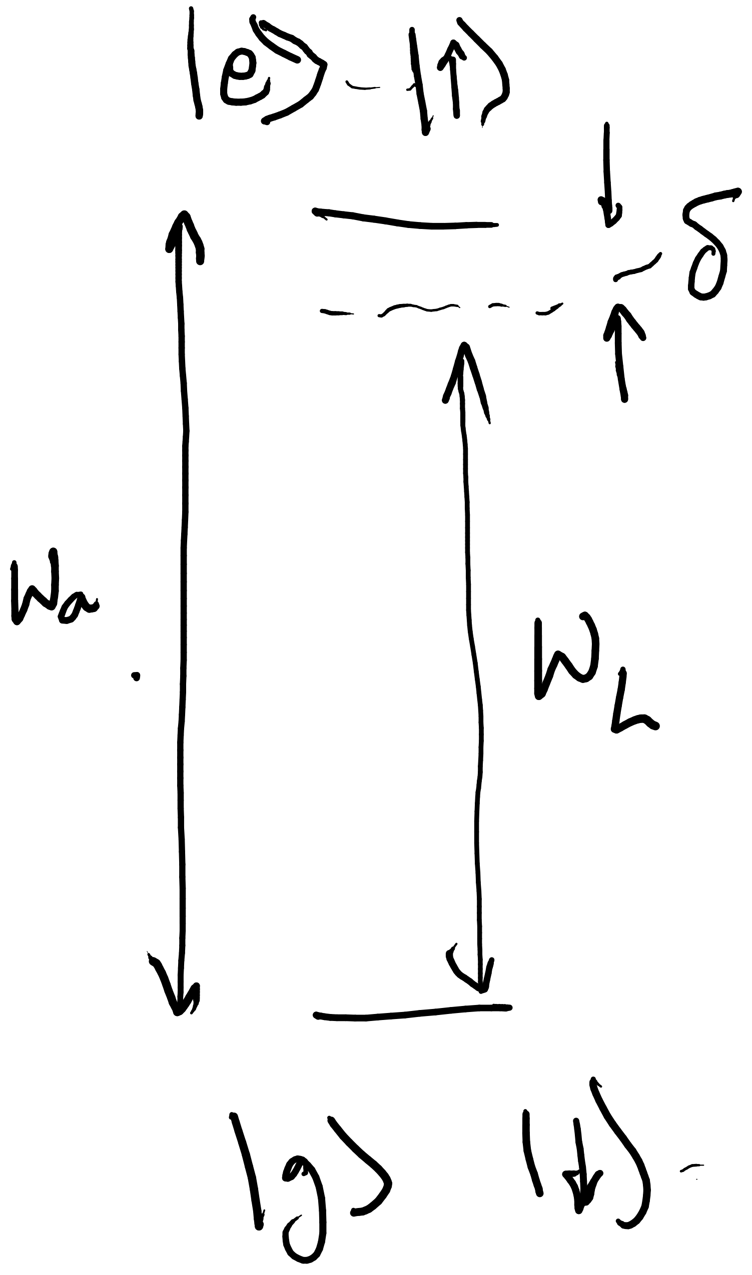
Hamiltonian

$$H = H_0 + H_{\text{int}}$$

$$H_0 = \sigma_z \frac{\hbar\omega_a}{2}$$

$$= \frac{\hbar\omega_a}{2}|e\rangle\langle e| - \frac{\hbar\omega_a}{2}|g\rangle\langle g|$$

$$H_{\text{int}} = \hbar\Omega\,\sigma_x \cos(\omega_l t)$$



Going to a frame rotating as...

$$U = \exp\{-i\sigma_z(\omega_l - \delta)t/2\}$$

The hamiltonian, tranforms, in the rotating wave approximation to:

$$H' \approx \frac{\hbar\delta}{2}\sigma_z + \hbar\Omega\,\sigma_x$$

$$H' \approx \hbar\Omega'\left(\frac{\delta}{2\Omega'}\sigma_z + \frac{\Omega}{\Omega'}\sigma_x\right)$$

where $\Omega' = \sqrt{\Omega^2 + \delta^2/4}$

when $\delta \gg \Omega$

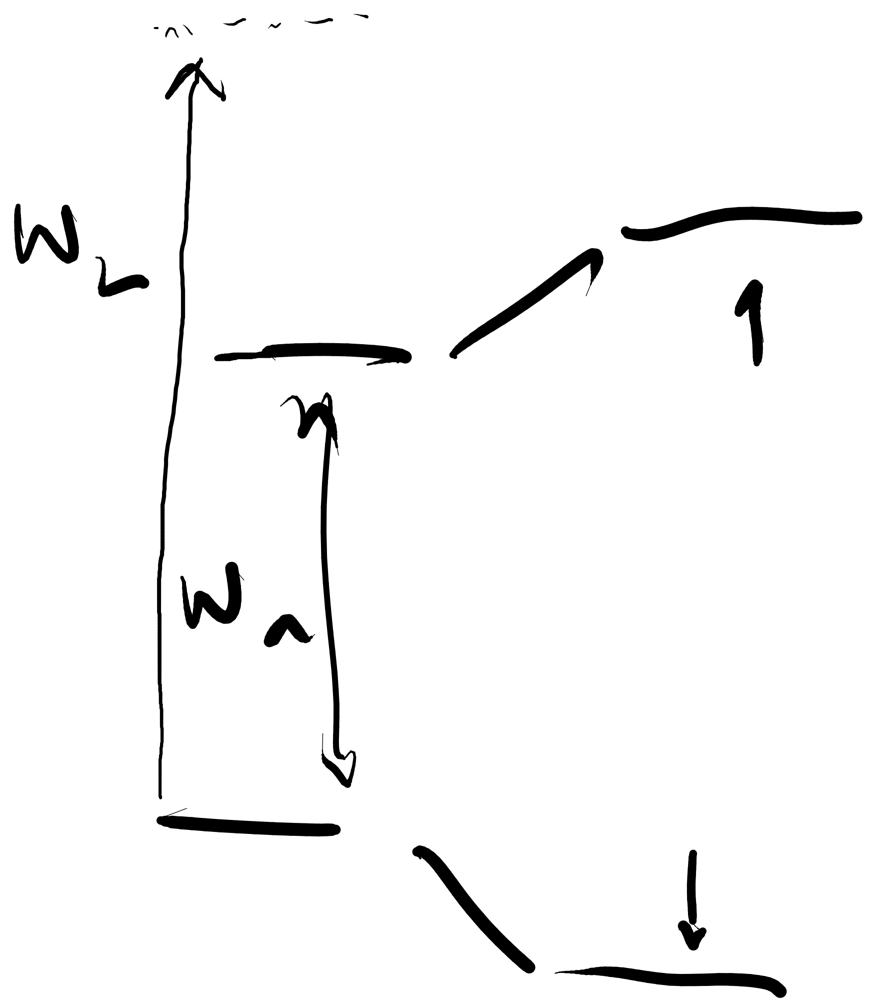
$$H' \approx \hbar\Omega'\left(\frac{\delta}{2\Omega'}\sigma_z + \frac{\Omega}{\Omega'}\sigma_x\right)$$

1 0

$$\Omega' \to \frac{\delta^2}{2} + \frac{\Omega^2}{\delta}$$

Trasnforming back

$$H = \sigma_z\left(\frac{\hbar\omega_a}{2} + \frac{\Omega^2}{\delta}\right)$$



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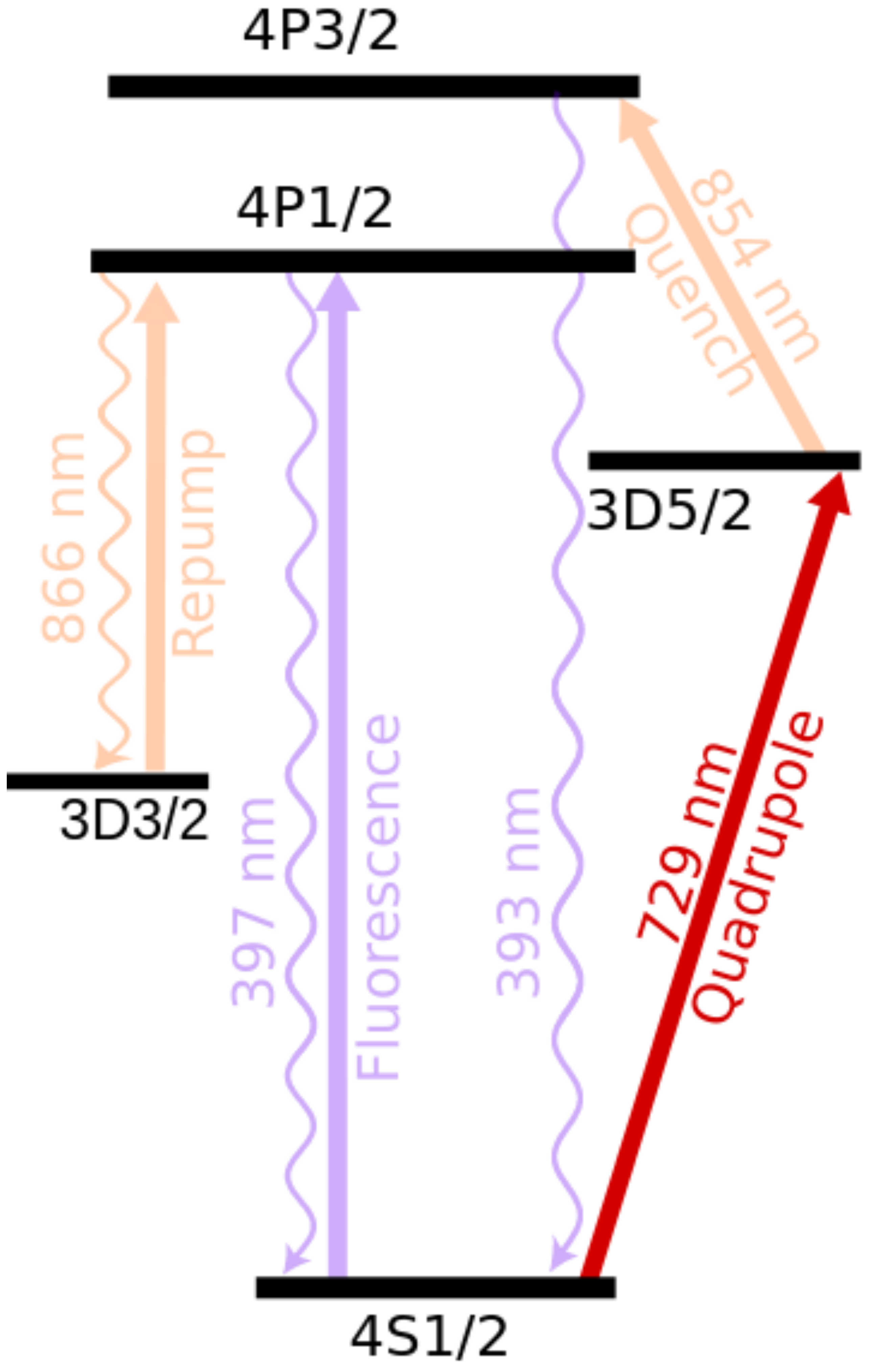
AC Stark Shift problems and applications

Problems for frequency standars



We demostrated a reduction in the AC stark shif of ~40x

AC Stark Shift   problems and applications

Problems for frequency standars

PHYSICAL REVIEW LETTERS **129,** 253901 (2022)

Excitation of an Electric Octupole Transition by Twisted Light

R. Lange,[1] N. Huntemann,[1,*] A. A. Peshkov,[1,2] A. Surzhykov,[1,2,3] and E. Peik[1]
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[2]*Institut für Mathematische Physik, Technische Universität Braunschweig, Mendelssohnstraße 3, 38106 Braunschweig, Germany*
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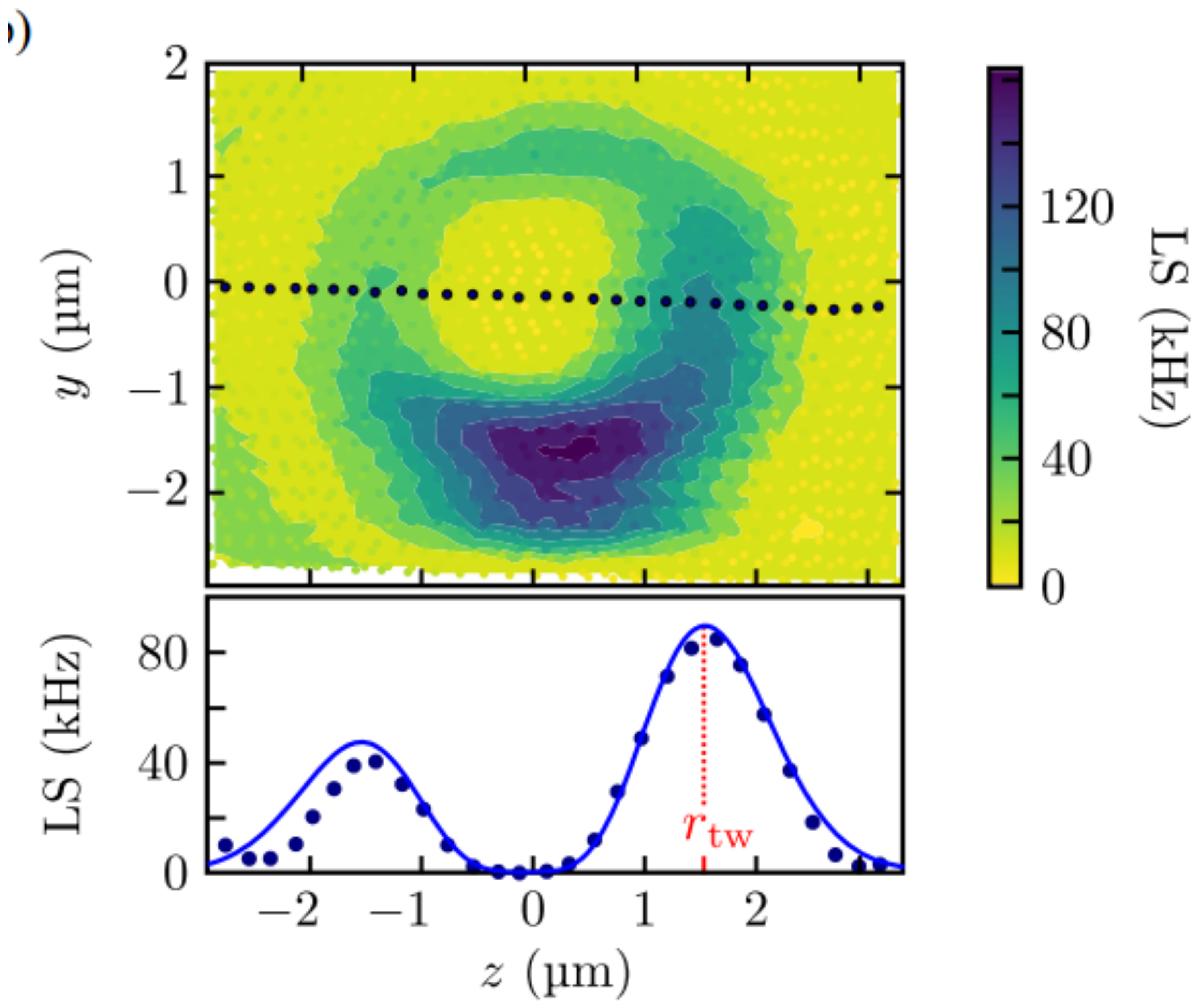
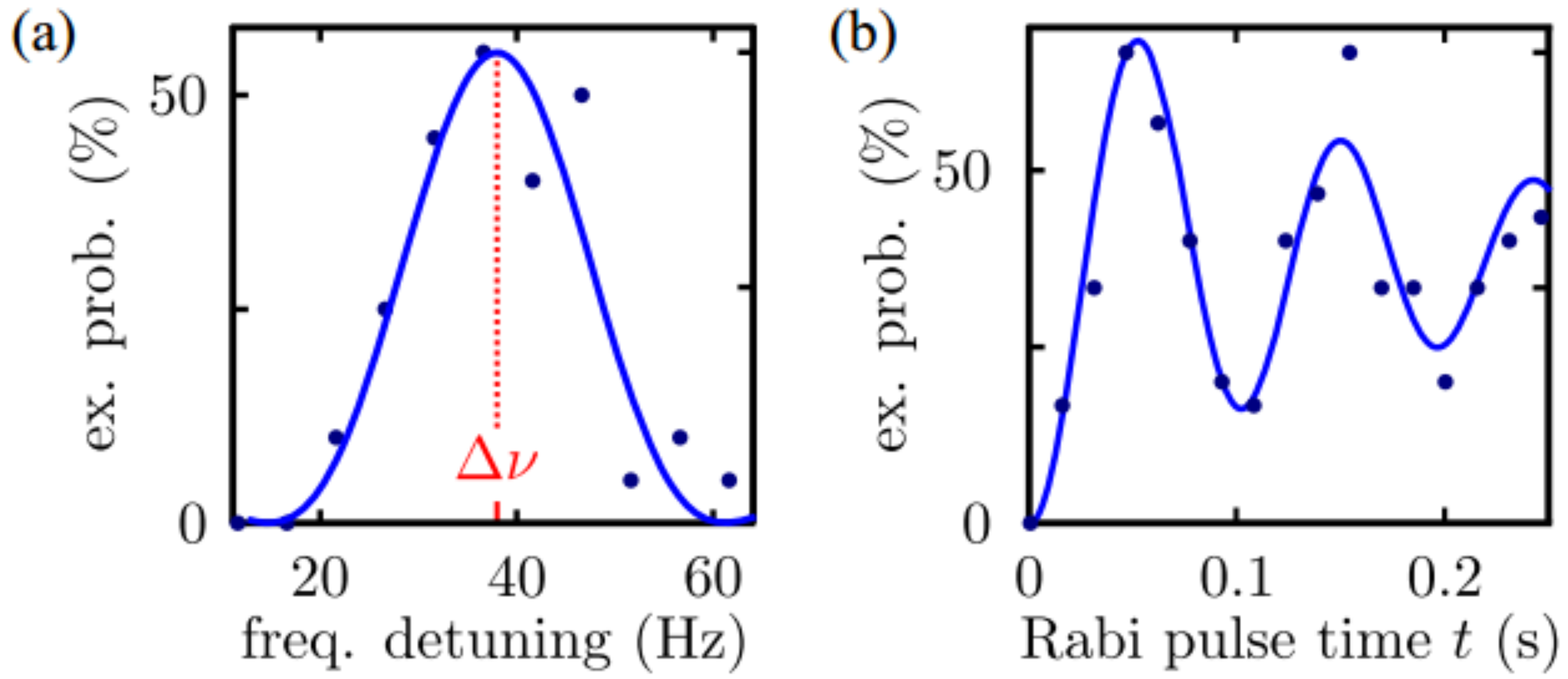
(Received 20 June 2022; accepted 14 November 2022; published 12 December 2022)





$$\xi = \Omega^2/\Delta\nu$$

$$\xi_{tw} = 135(5)\ \text{Hz}$$

$$\xi_{pl} = 30.3(9)\ \text{Hz}$$

$$\xi_{tw}/\xi_{pl} = 4.5(2).$$

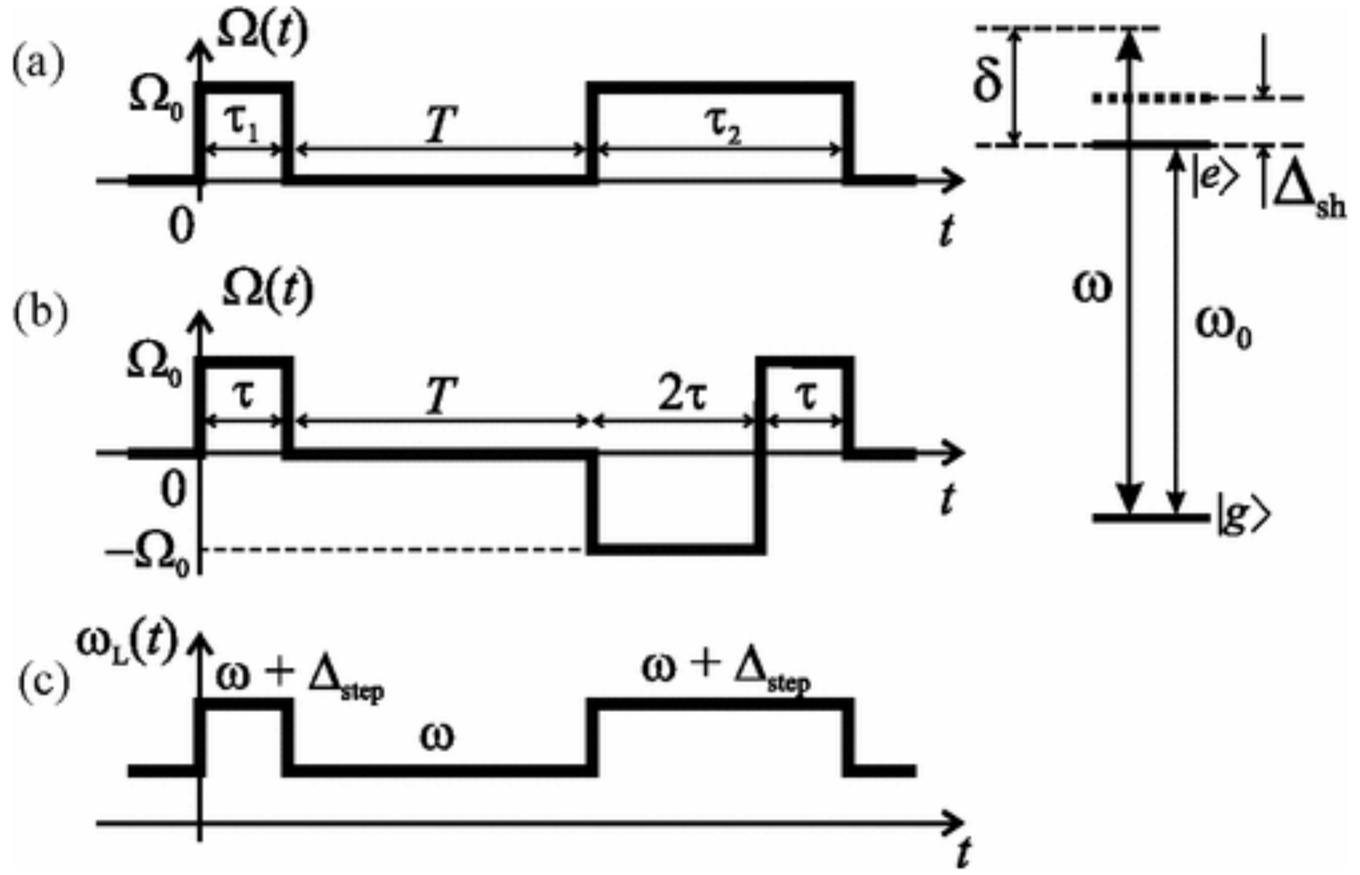
AC Stark Shift problems and applications

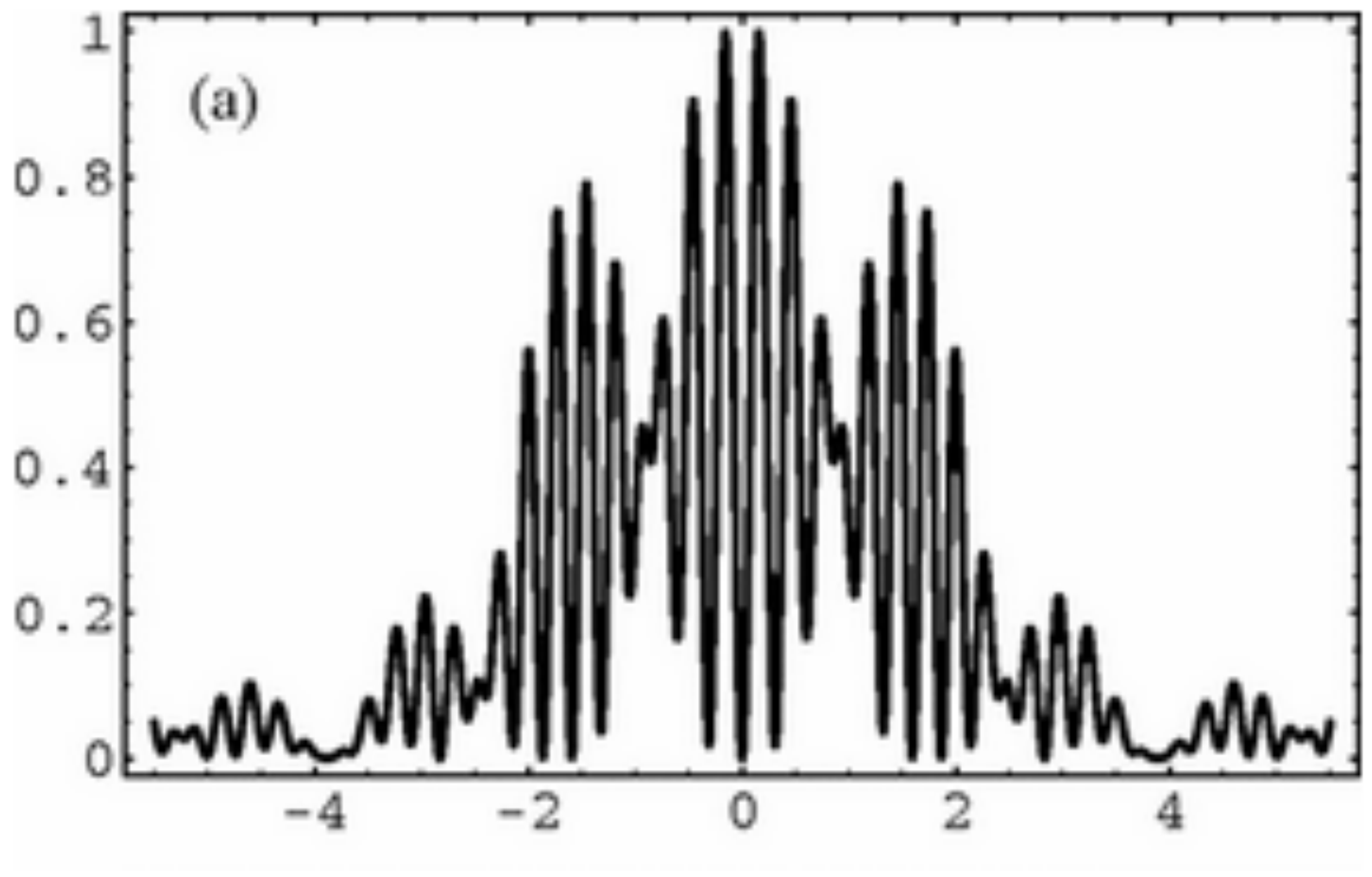
Problems for frequency standars

The devil's advocate: hyper-Ramsey and balanced-Ramsey spectrocopy

PHYSICAL REVIEW A **82**, 011804(R) (2010)

Hyper-Ramsey spectroscopy of optical clock transitions



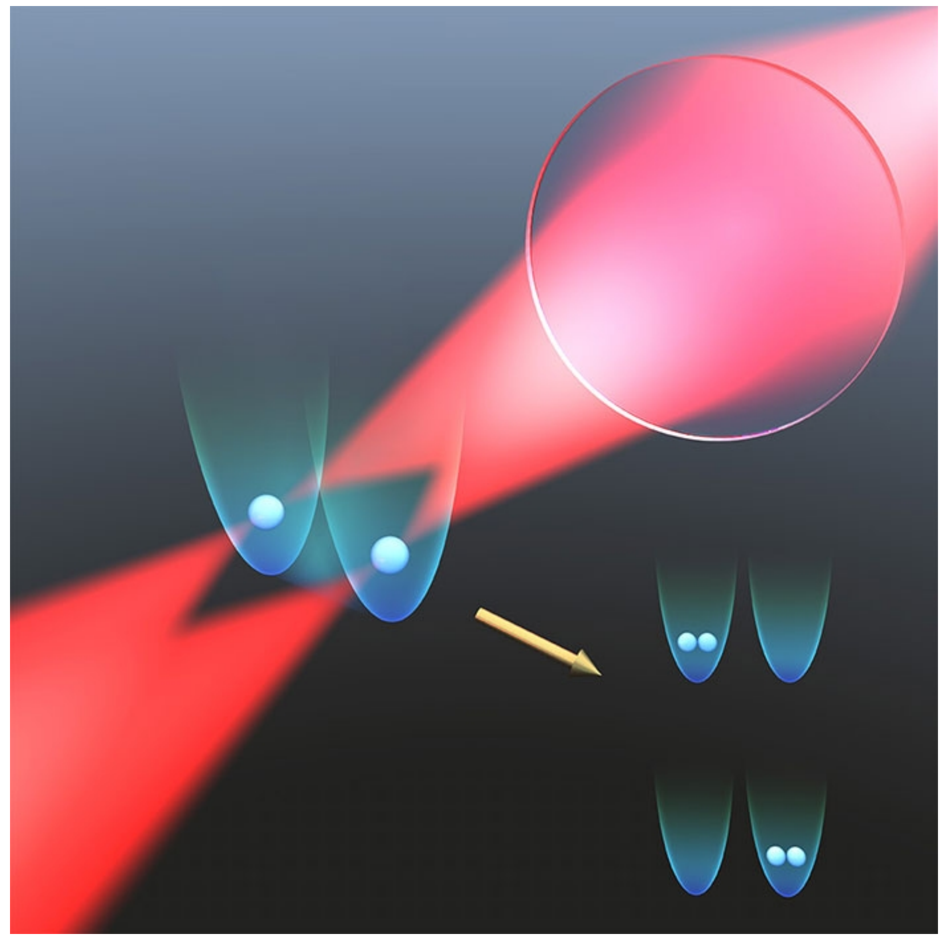


Suppression of AC stark Shift by 2-4 orders of magnitude

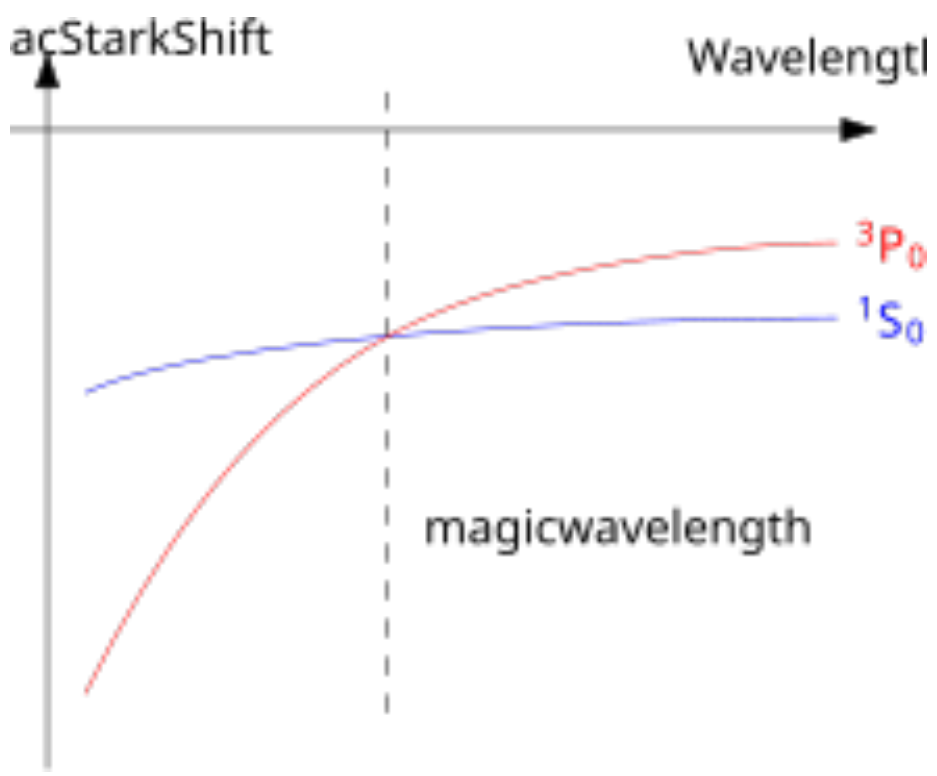
AC Stark Shift problems and applications

Optical Tweezers and Magic Wavelength

Low and high field seakers $\delta > 0$ or $\delta < 0$

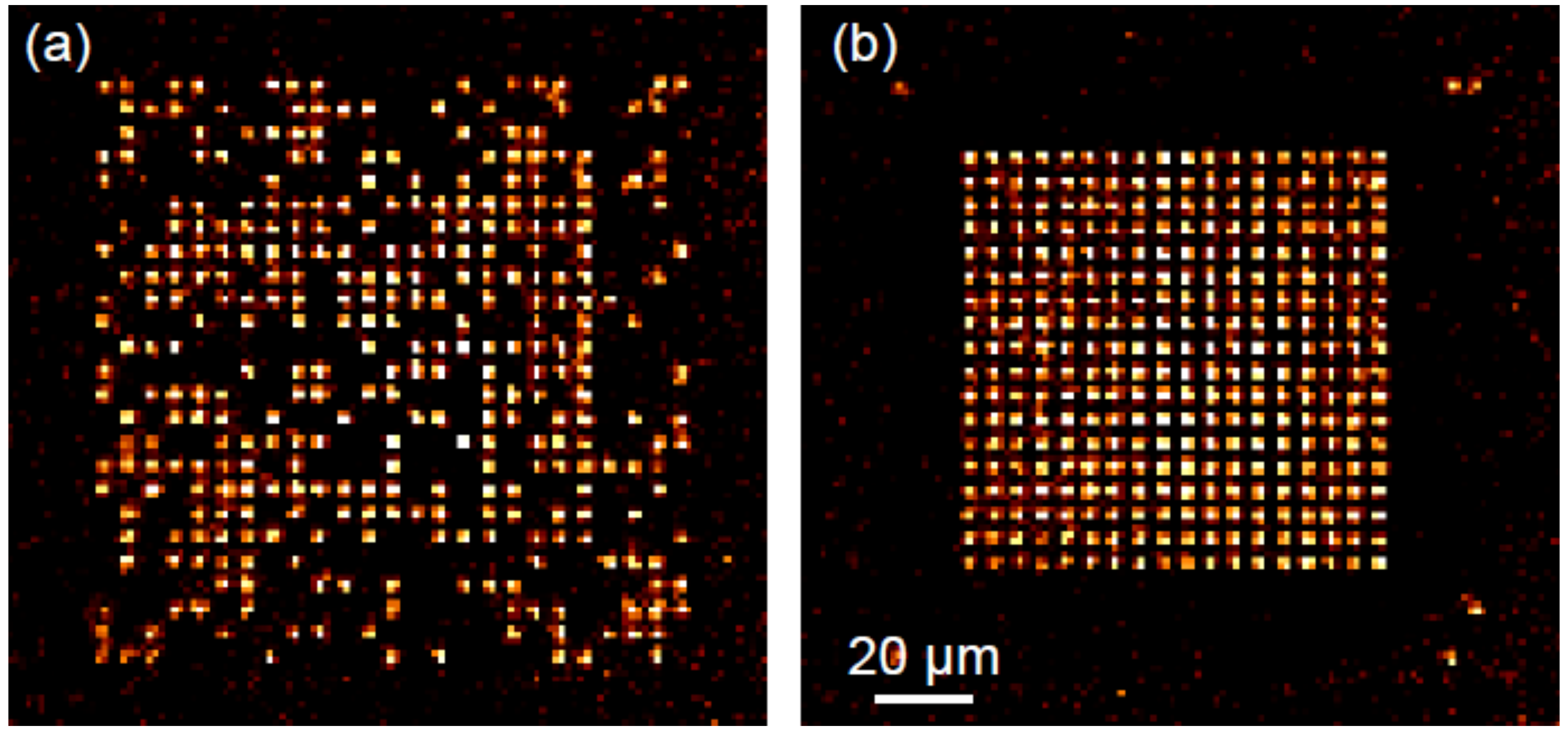


Magic Wavelength



Allows optical trapping,
leaving one (clock or qubit) transition undisturbed.

Atom arrays (record Quantum Volume by Lukin Group)

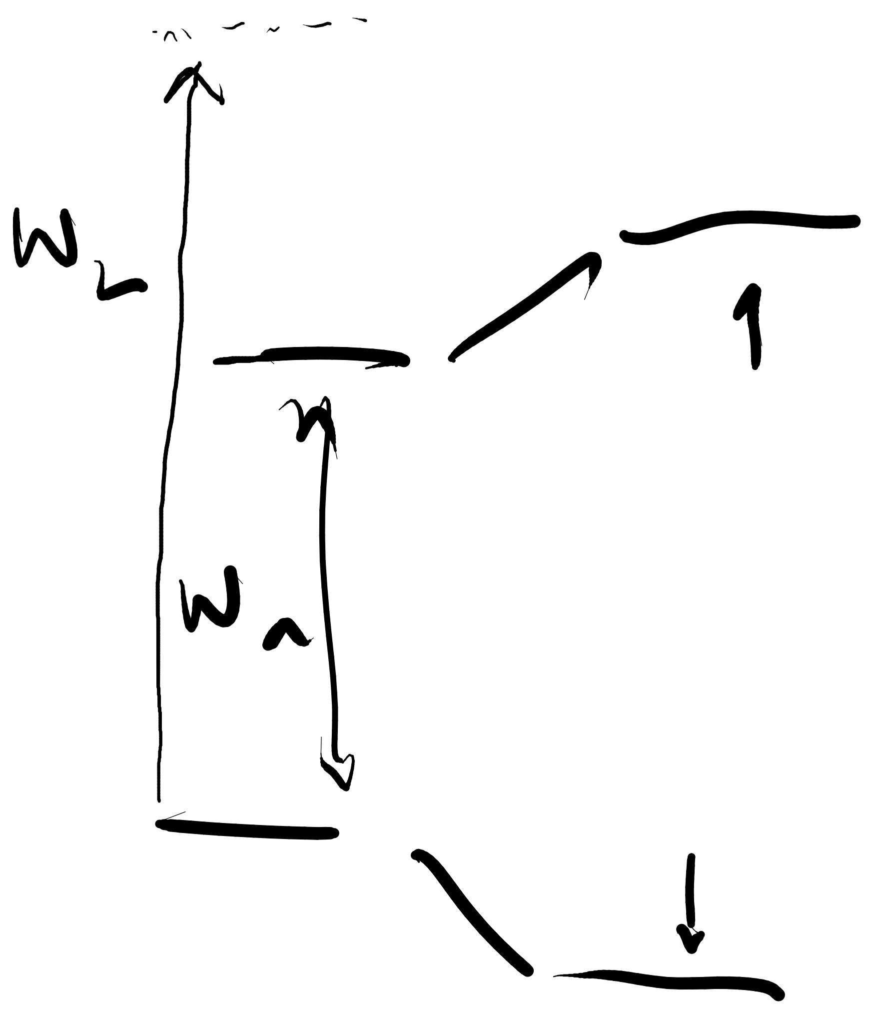


cred. Inst. d' Optique, Paris

AC Stark Shift problems and applications

Spin dependent forces.

Energy level shifts

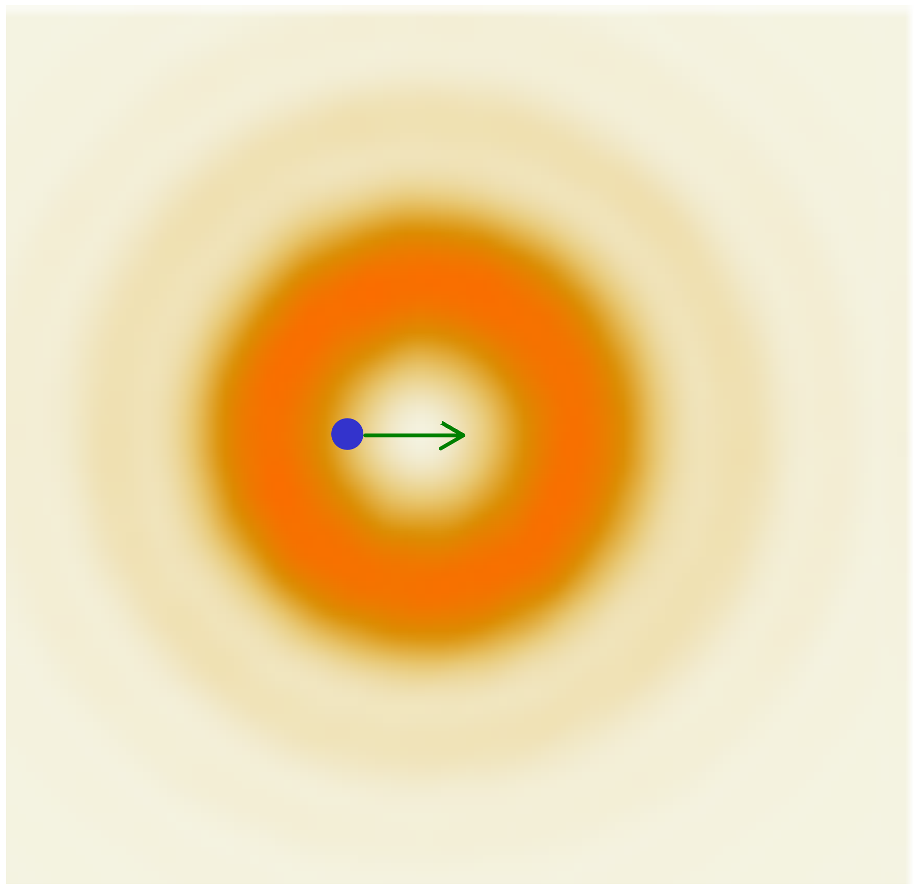


Standing Waves

Existing Applications

Gates betweeen ions.
Generation of cat states.
Generation of sweezed states.
Sping dpenedent motional control of ions and atoms.

Structured Beams

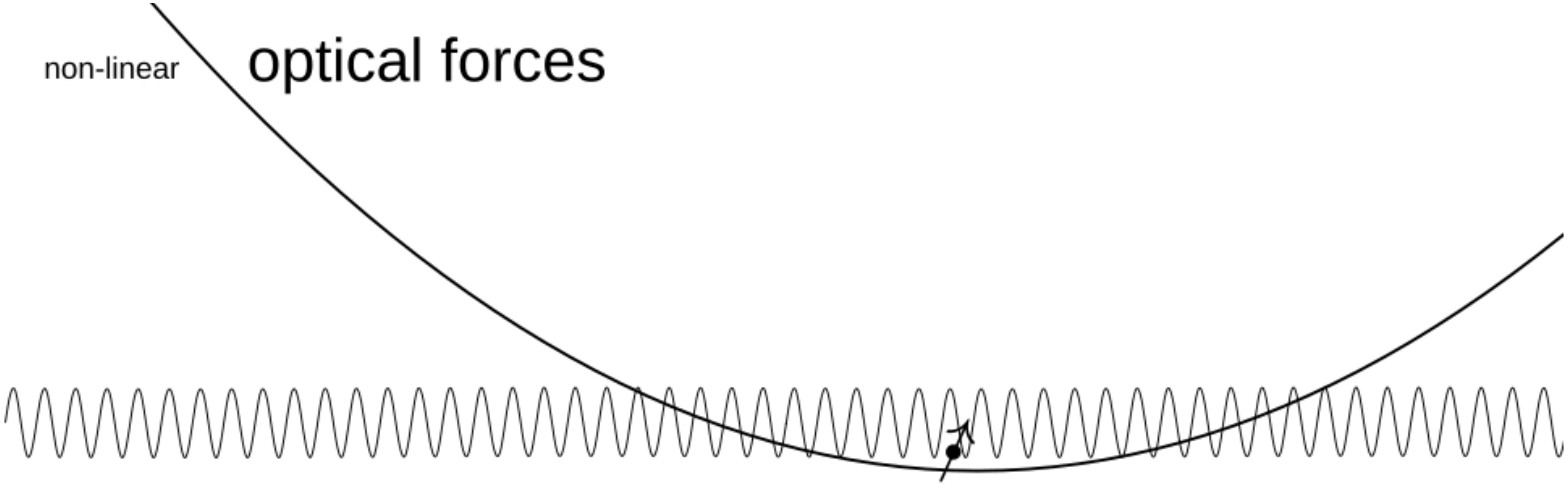


Proposed Applications

Same, but without problems of phase stability!

Forces on ions

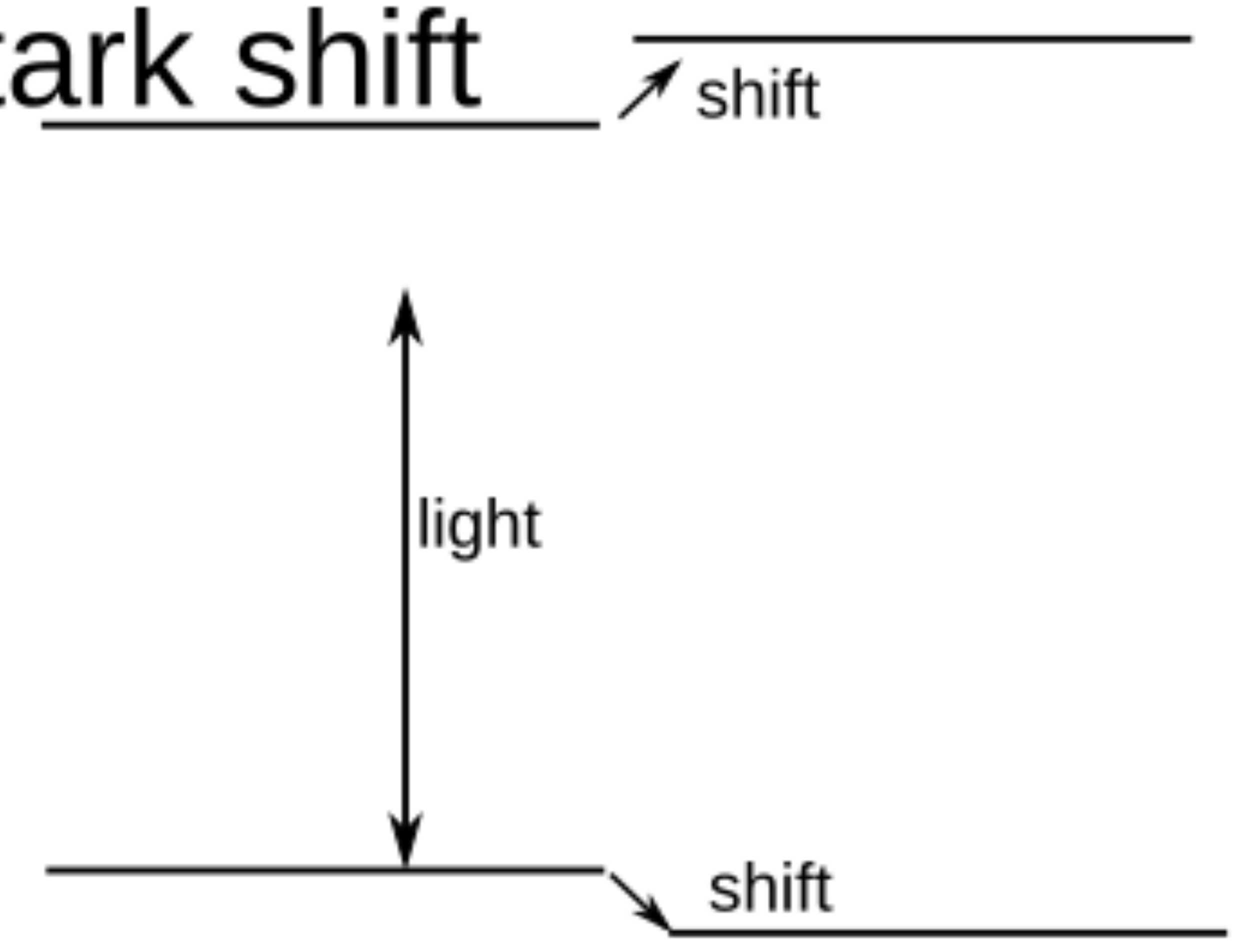
non-linear optical forces



characteristic scale $0.2\mu\mathrm{m}$

spin dependent

caused by an ac Stark shift



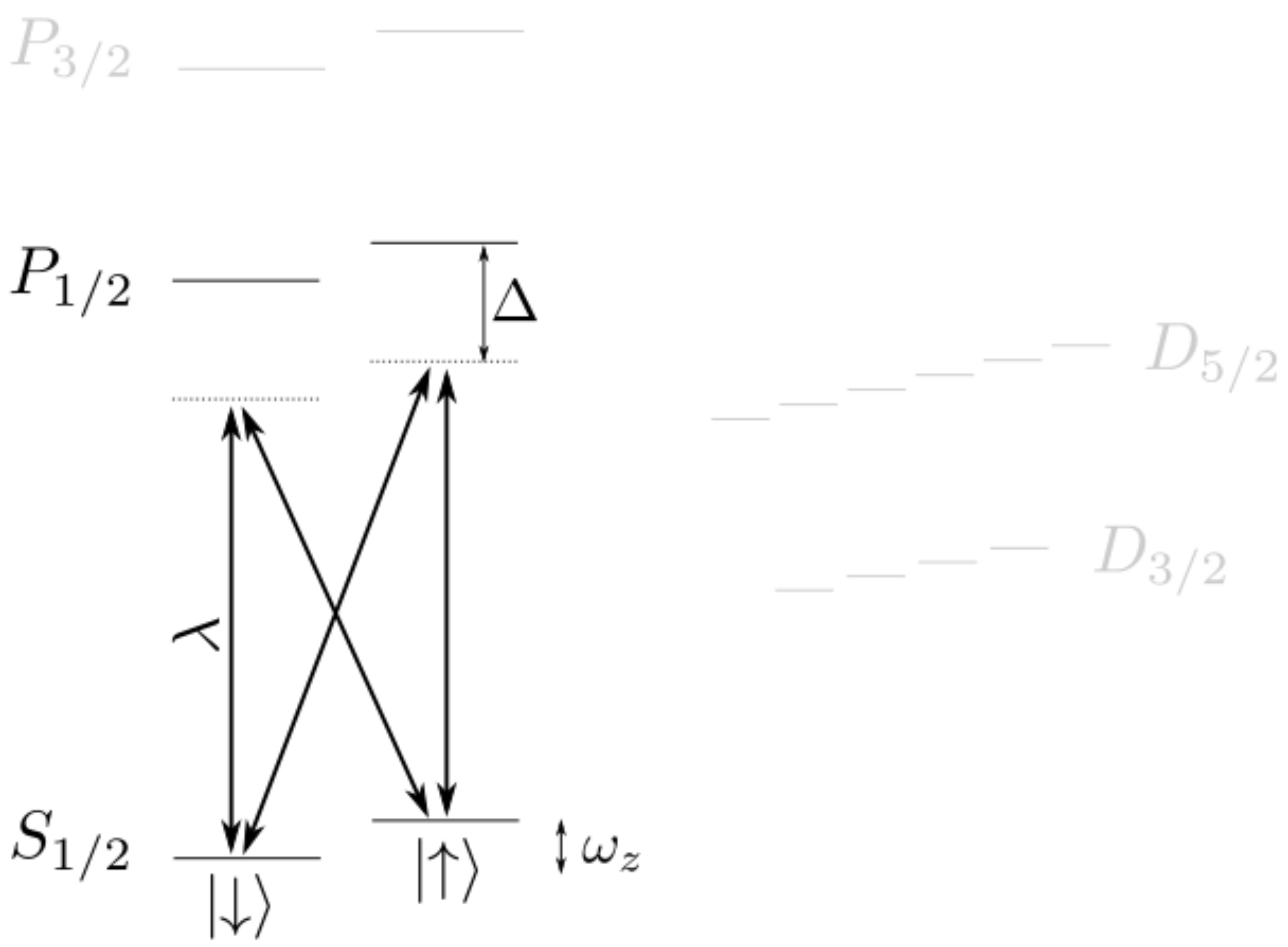
Forces on ions

our ion $^{40}\mathrm{Ca}$

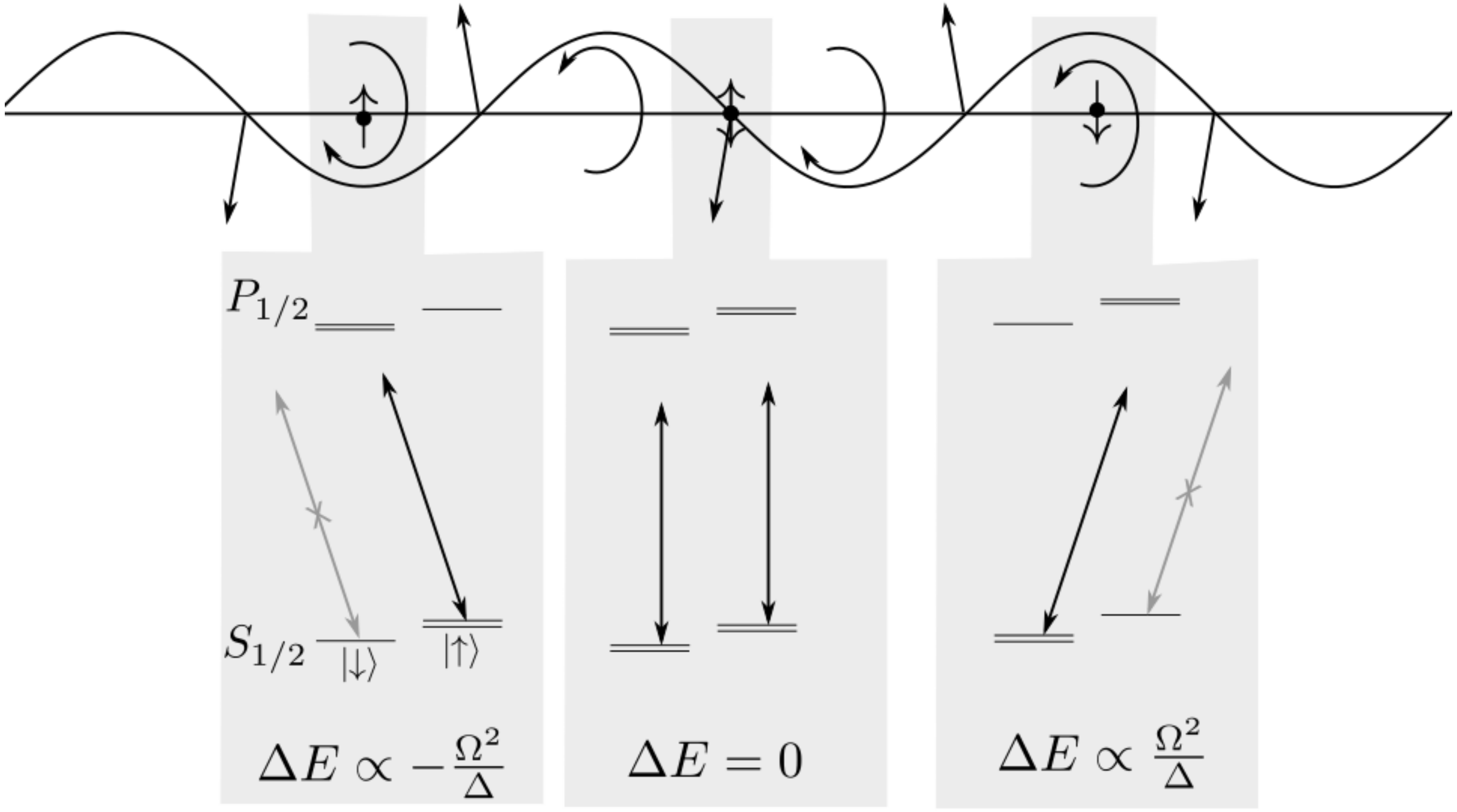
optical carrier $\lambda \approx 397\mathrm{nm}$

detuning from transition $\Delta/2\pi \approx 30\mathrm{GHz}$

Zeeman splitting $\omega_z/2\pi \approx 10\mathrm{MHz}$

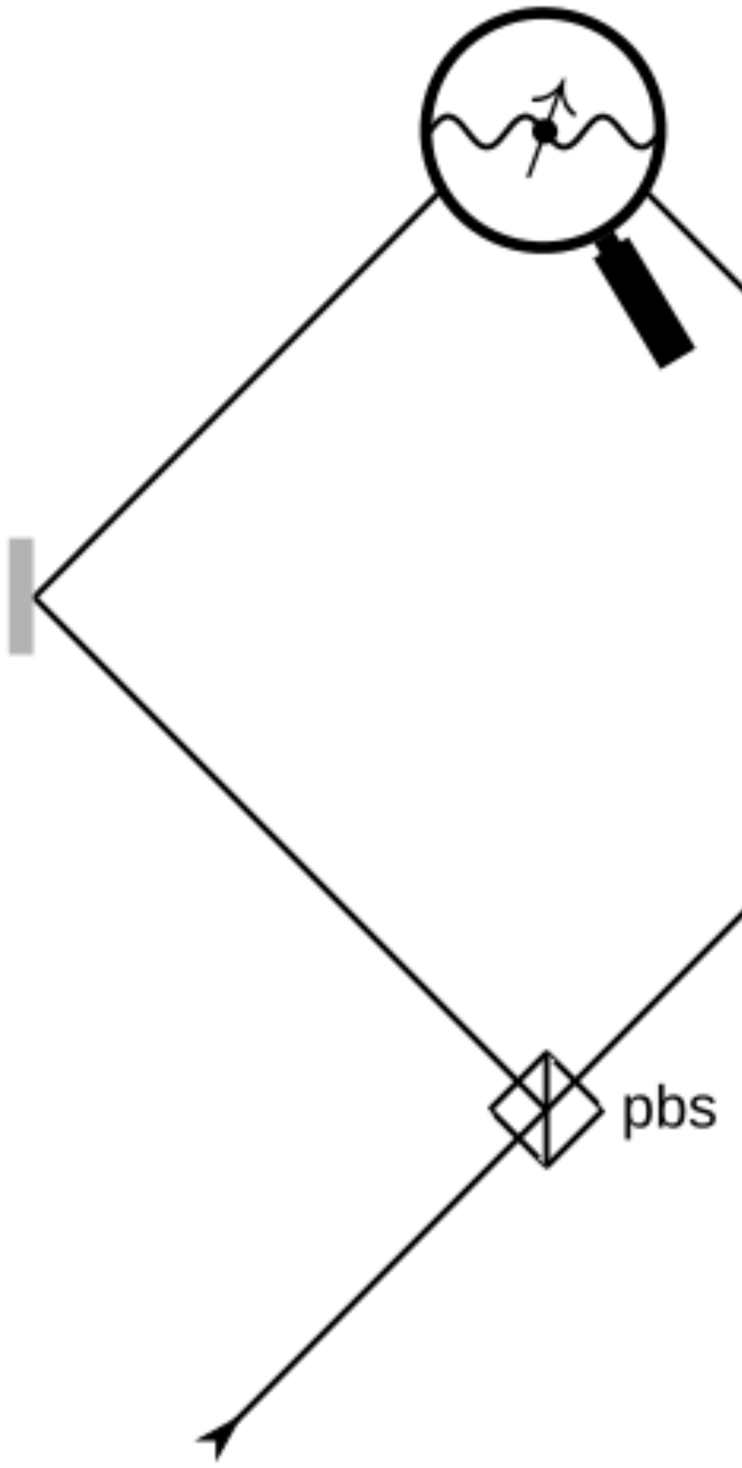


Forces on ions lin-perp-lin standing wave

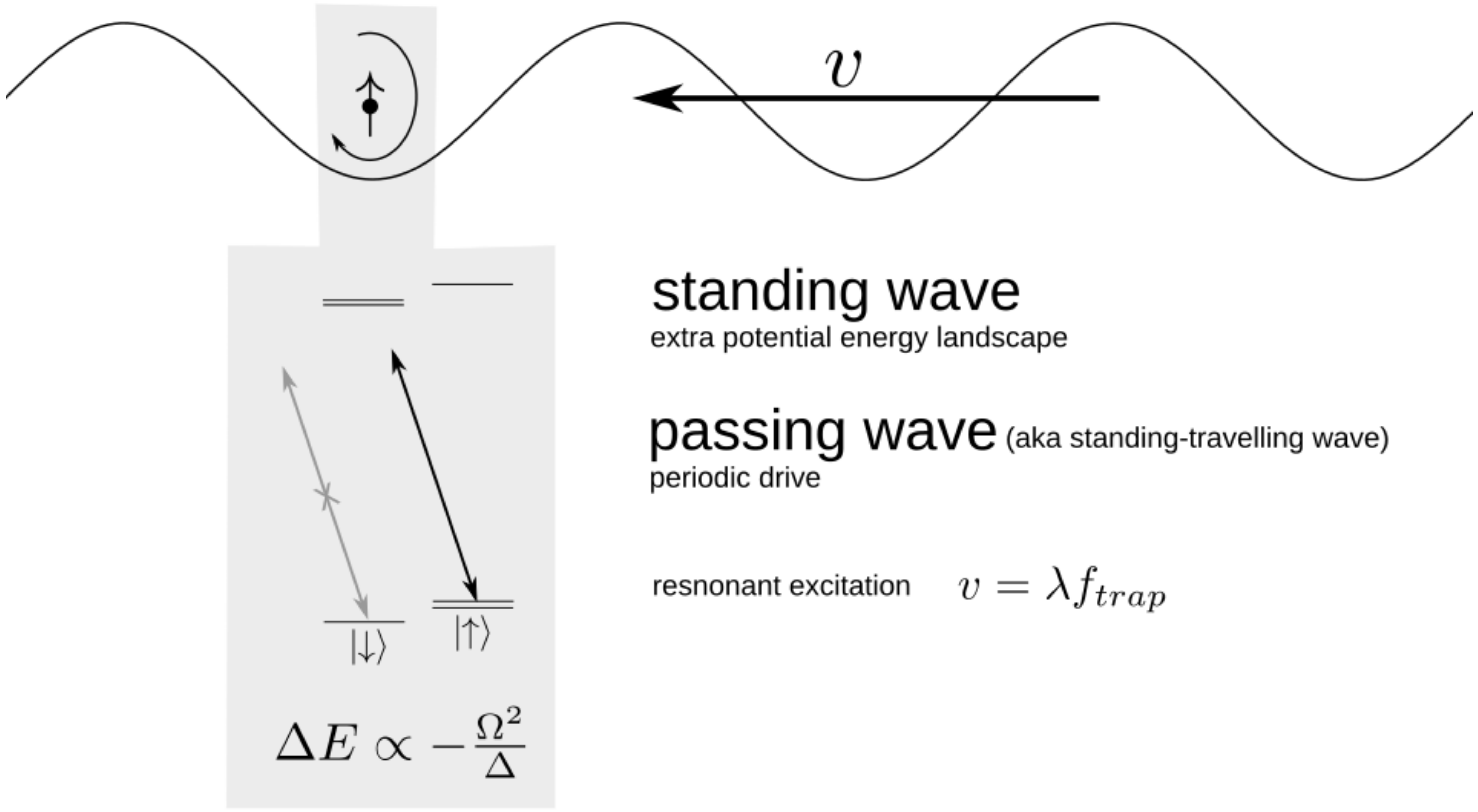


Forces on ions

lin-perp-lin standing wave



Forces on ions (off)-resonant motion excitation



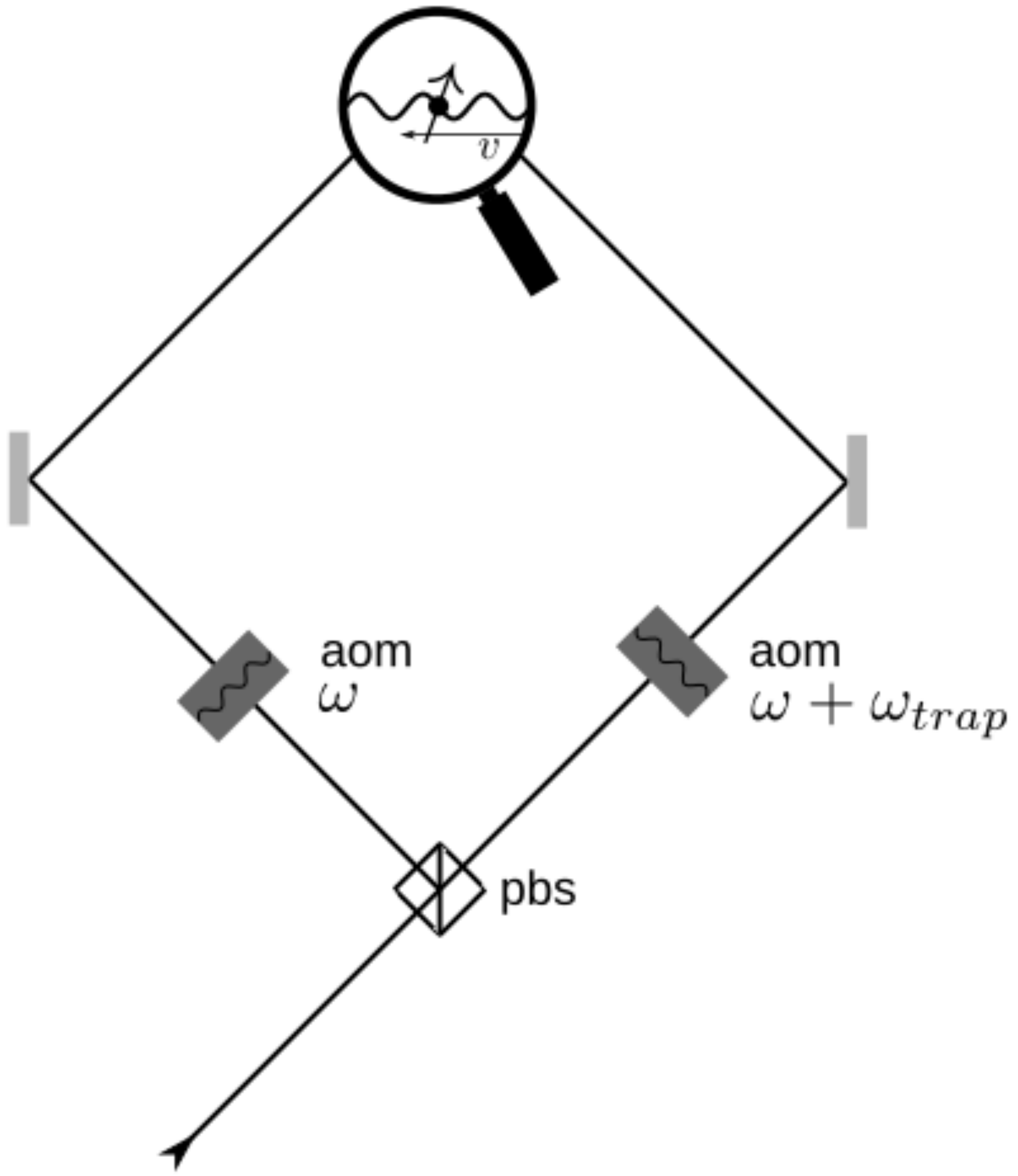
standing wave
extra potential energy landscape

passing wave (aka standing-travelling wave)
periodic drive

resnonant excitation $v = \lambda f_{trap}$

Forces on ions

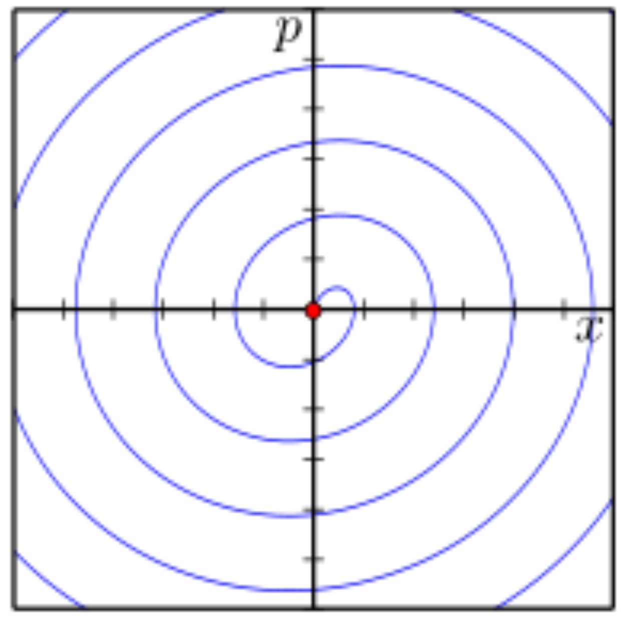
lin-perp-lin standing wave



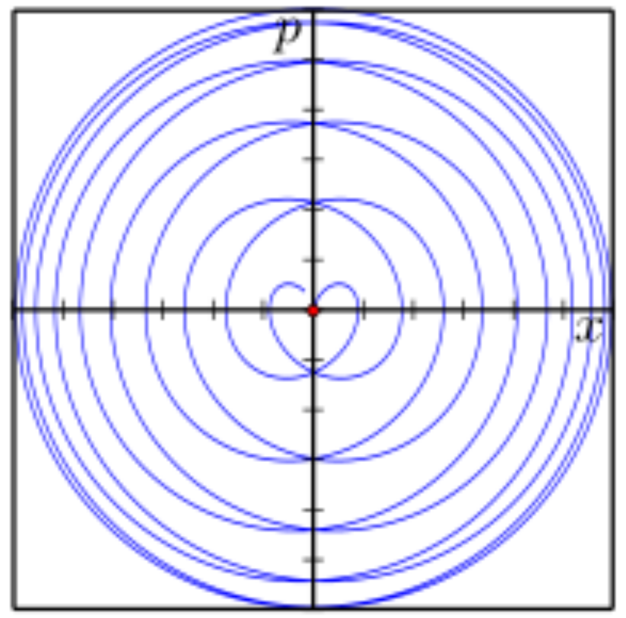
Forces on ions driven harmonic motion in phase space

phase space

resonant drive



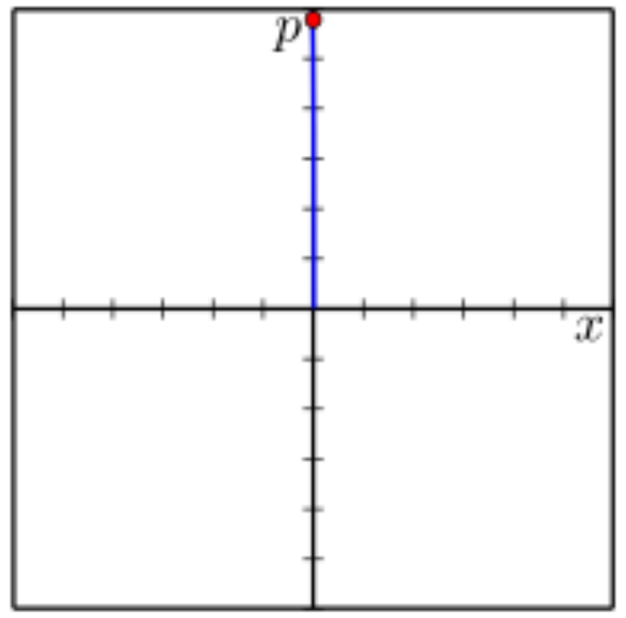
detuned drive



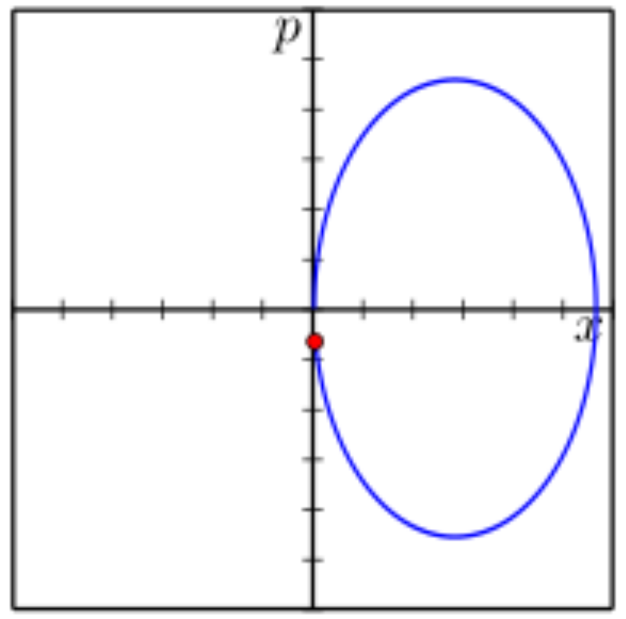
phase space

rotating frame

resonant drive



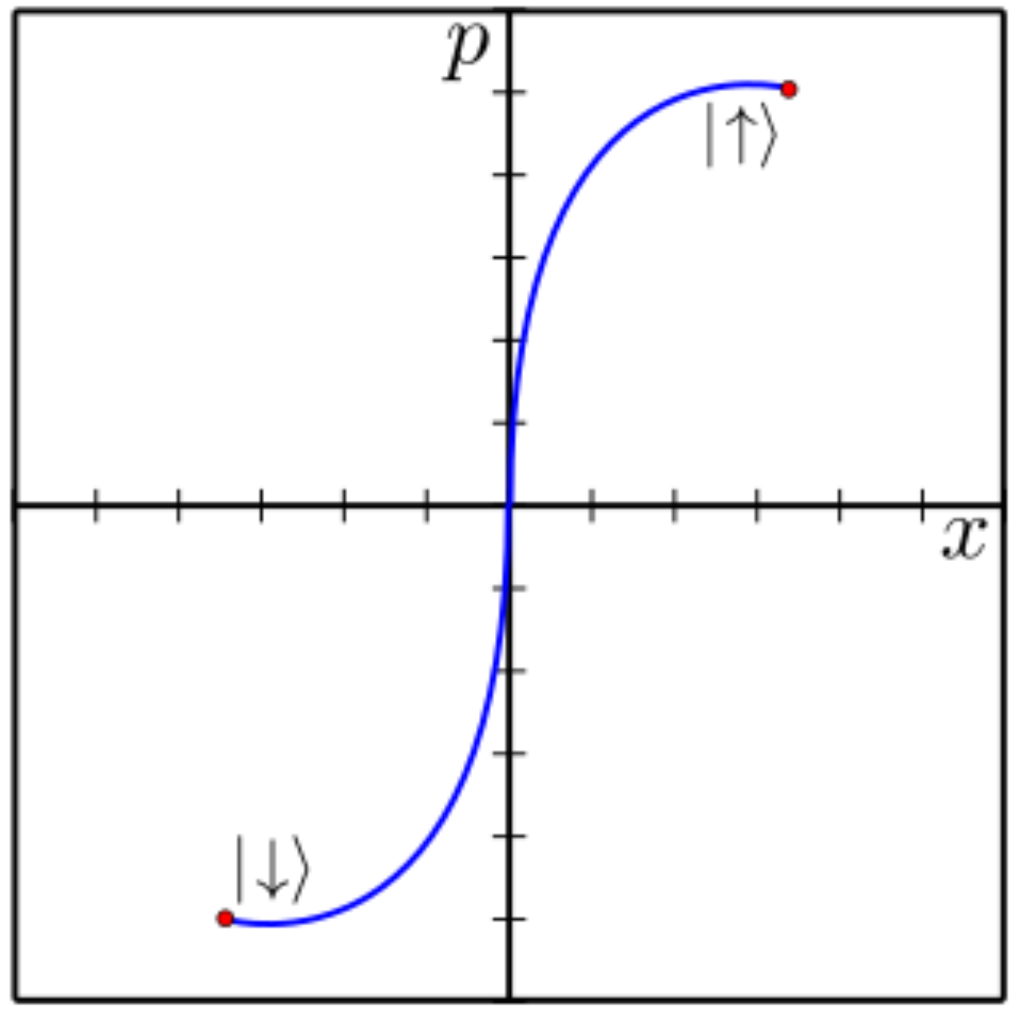
detuned drive



spin dependent force

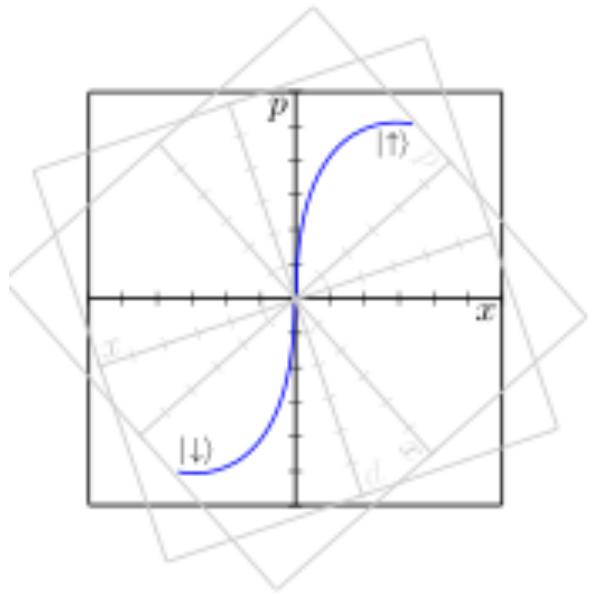
cat states

$(|\uparrow\rangle + |\downarrow\rangle)|0\rangle \rightarrow |\uparrow\rangle|\alpha\rangle + |\downarrow\rangle|-\alpha\rangle$



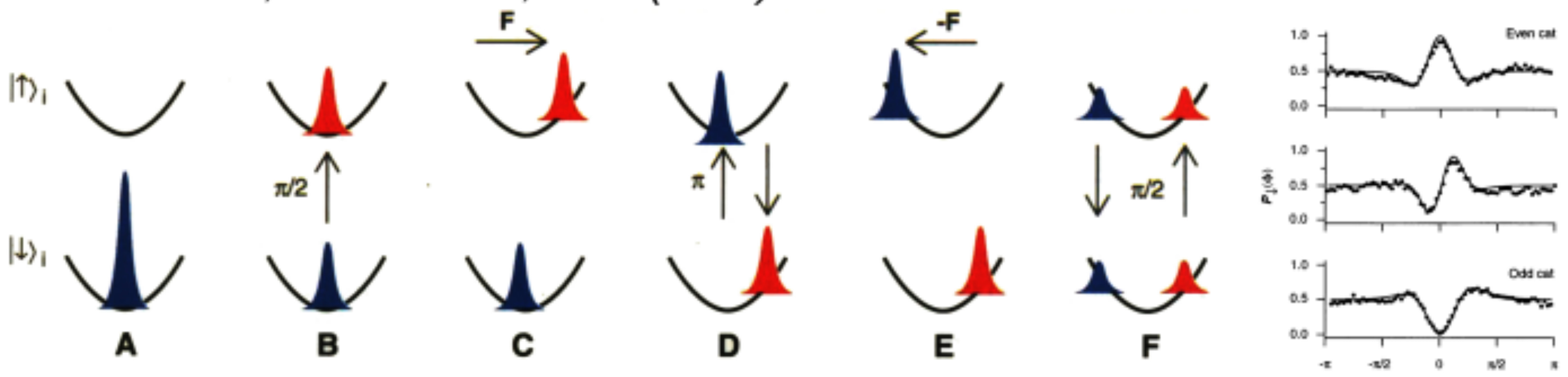
Forces on ions

no reference
to real axis

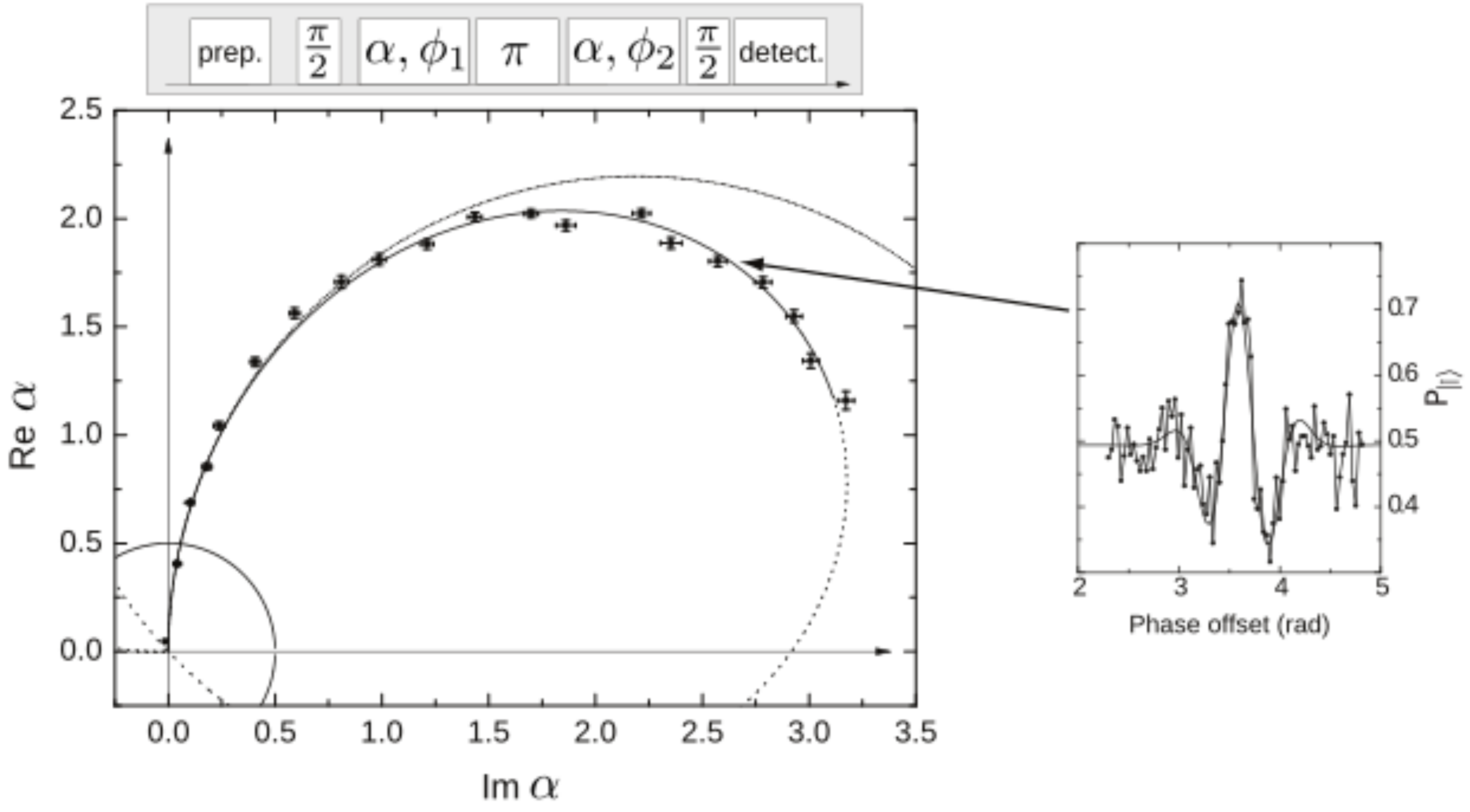


not a problem for interference singals

Schrödinger cat interference singals
Monroe et. al., Science 272, 1131 (1996)



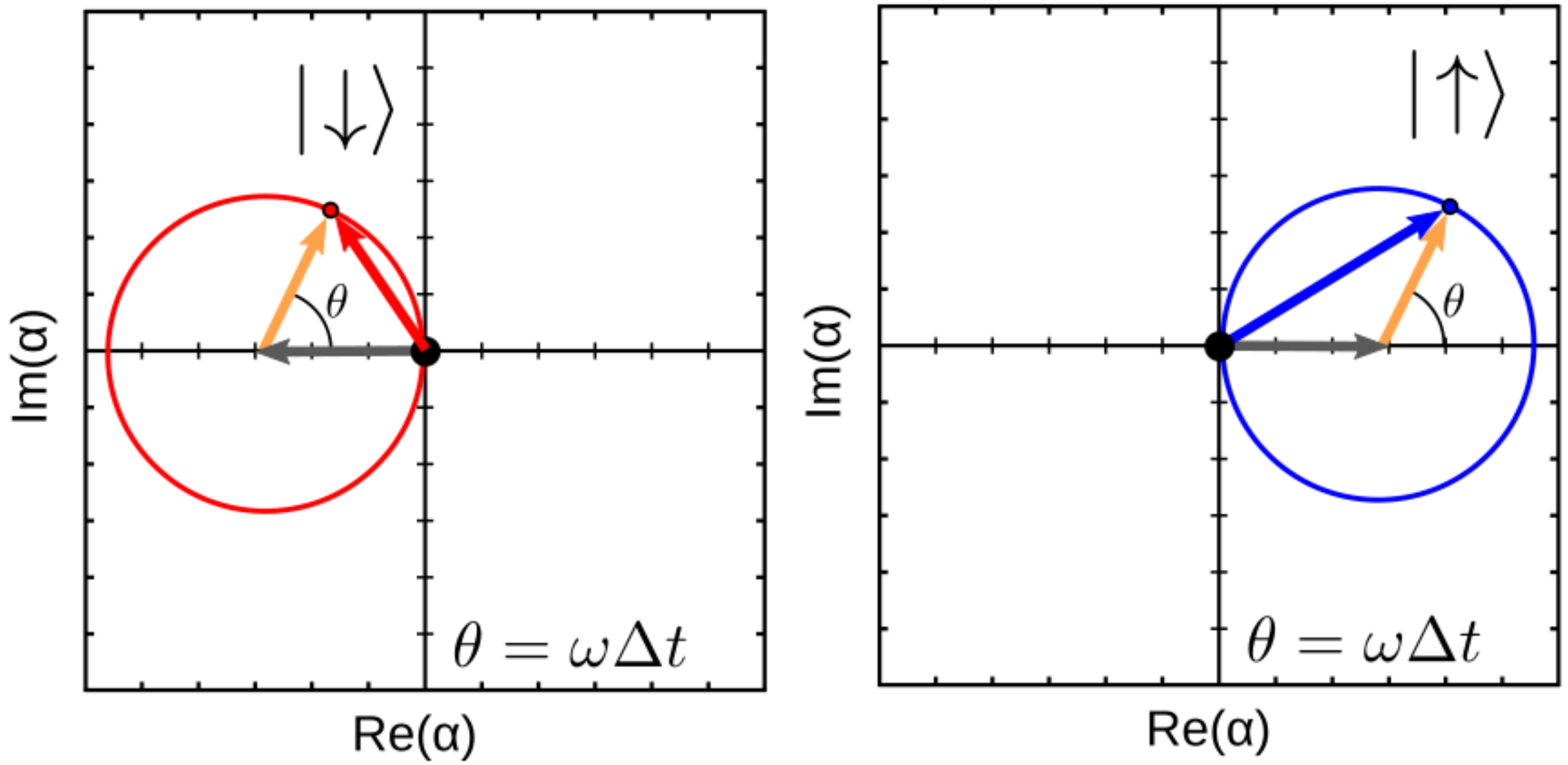
Schrödinger cat trajectory reconstruction
Poschinger et. al., PRL 105, 263602 (2010).

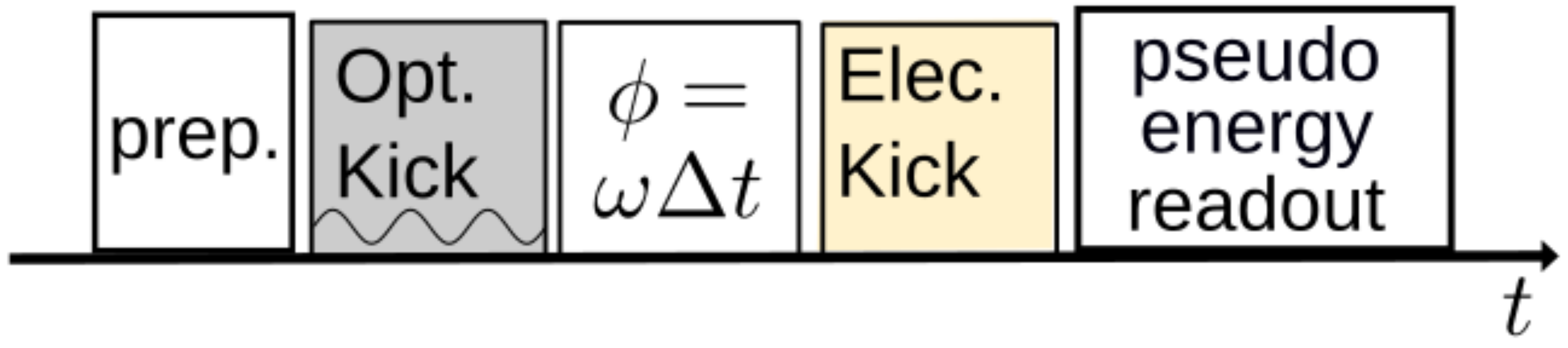


Forces on ions

phase stable optical forces

optical electrical kicks

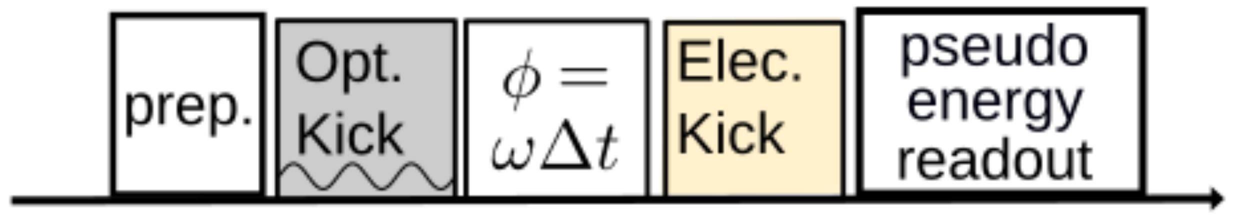


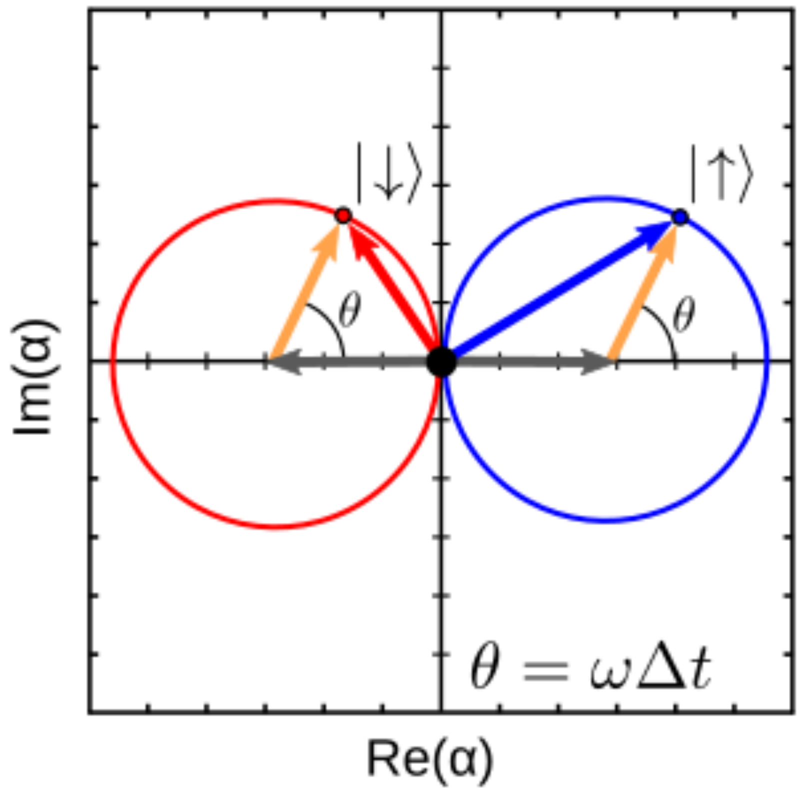


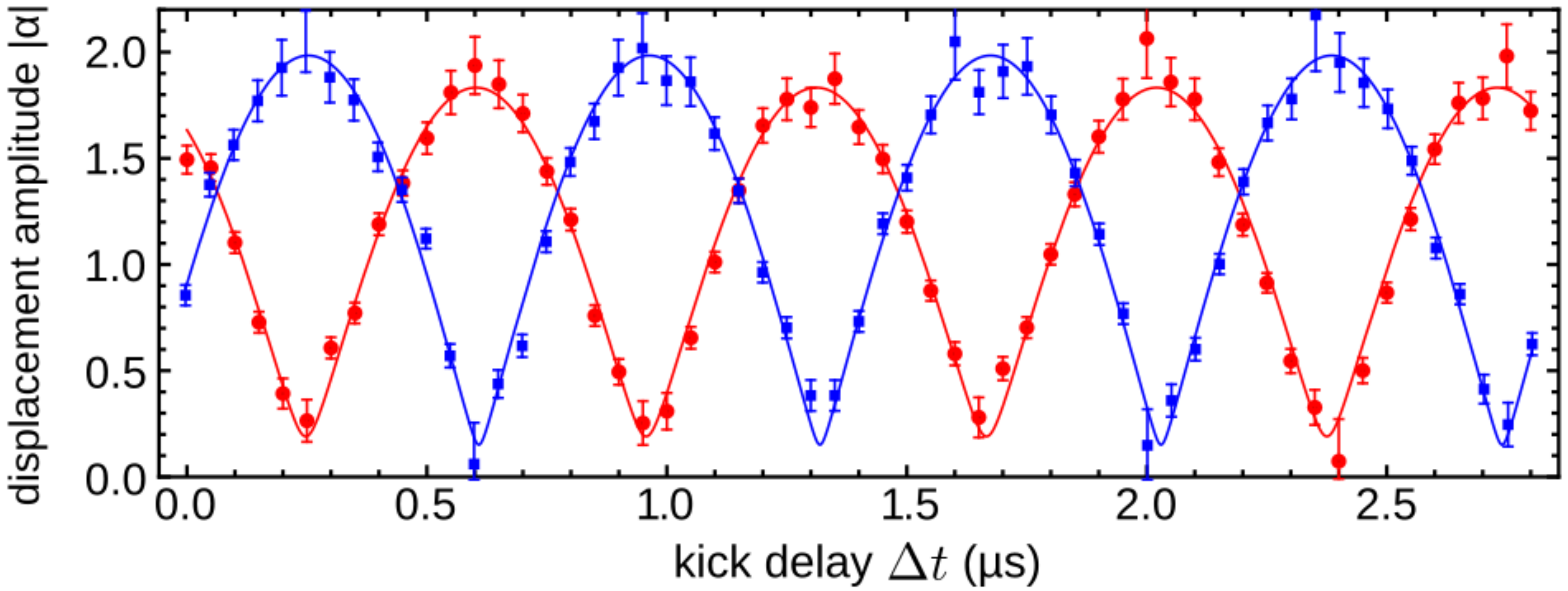
Forces on ions

phase stable optical forces

optical electrical kicks







Forces on ions

spin heat engine

coupled to a harmonic oscillator flywheel

PHYSICAL REVIEW LETTERS 123, 080602 (2019)

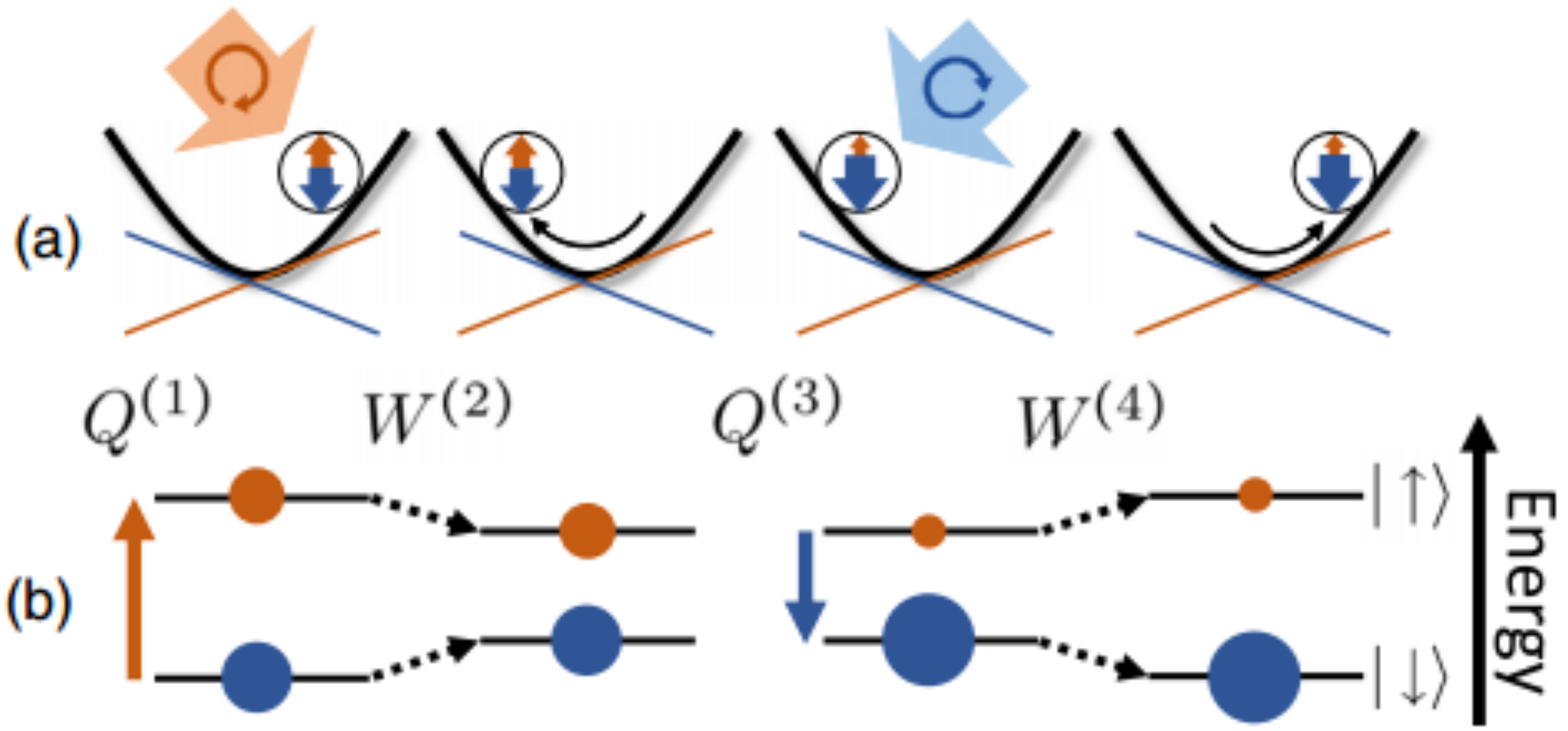
Editors' Suggestion | Featured in Physics

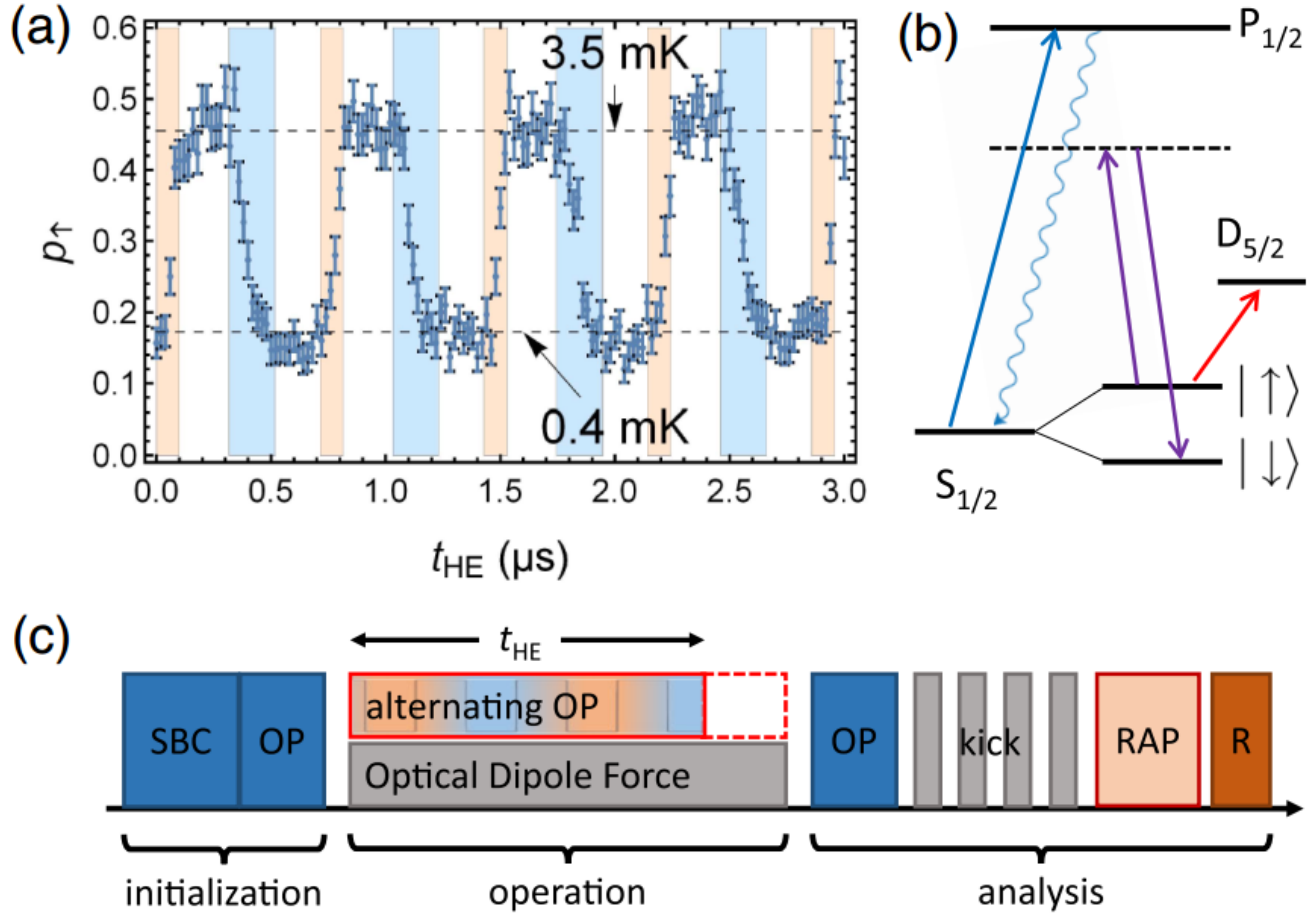
Spin Heat Engine Coupled to a Harmonic-Oscillator Flywheel

D. von Lindenfels,[1] O. Gräb,[1] C. T. Schmiegelow,[1,*] V. Kaushal,[1] J. Schulz,[1] Mark T. Mitchison,[2] John Goold,[2] F. Schmidt-Kaler,[1] and U. G. Poschinger[1,†]

[1]QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

[2]School of Physics, Trinity College Dublin, College Green, Dublin 2, Ireland





Forces on ions

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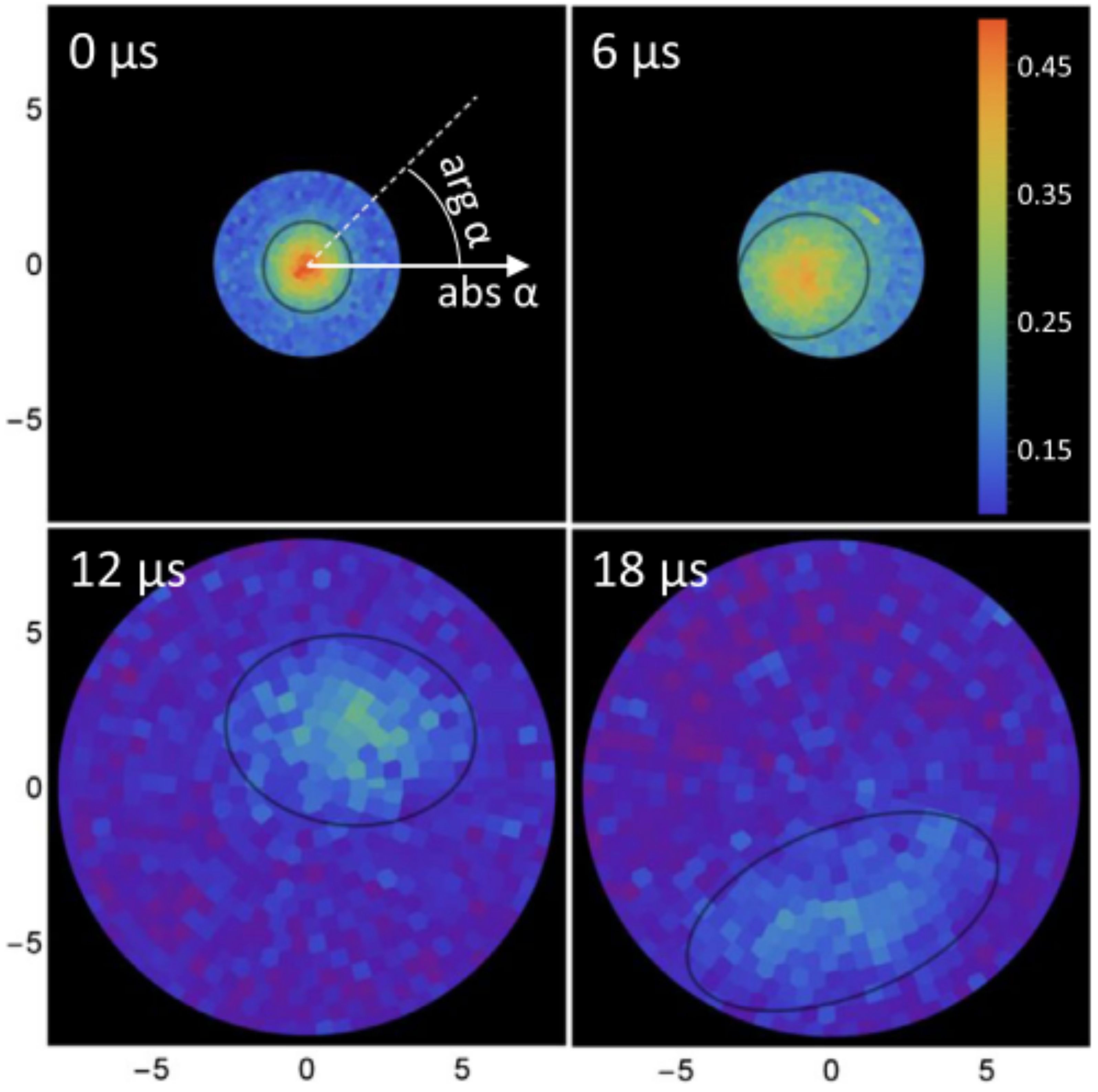
[2]*School of Physics, Trinity College Dublin, College Green, Dublin 2, Ireland*

Time evolution of the phase space distibutions.



Onset of the Spin Heat engine.

Forces on ions

Outlook and why go to structured beams.

Day Three

Part 3

More on interaction with gradients. Doppler shifts.

Rotating ambulances

the rotational doppler Effect

Nicolás Nuñez Barreto **PhD**

Muriel Bonetto **PhD Student**

Marcelo Luda **Associate researcher**

Cecilia Cormick **Researcher**

Observation of Space-Dependent Rotational Doppler Shifts with a Single Ion Probe

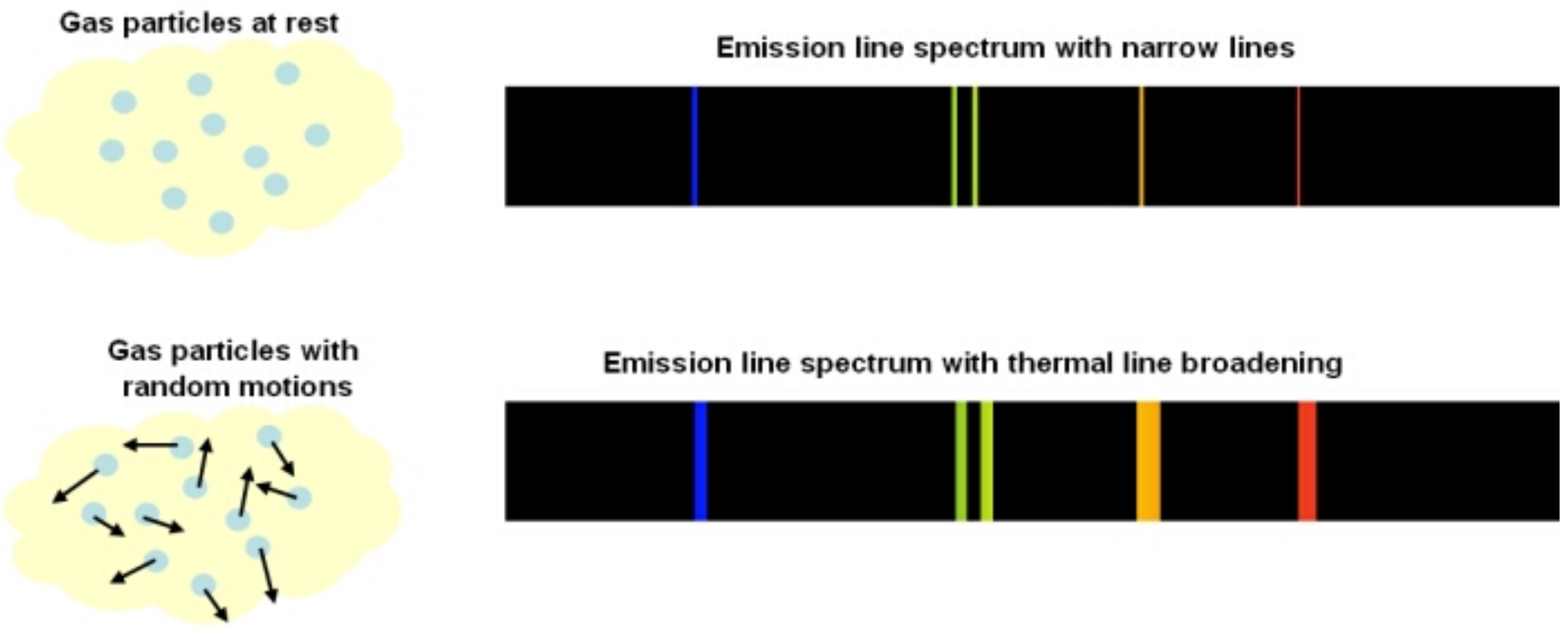
NA Nuñez Barreto, M Bonetto, MA Luda, C Cormick, CT Schmiegelow
Physical Review Letters 133 (18), 183601 (2024)

inspired by
Barreiro, S., Tabosa, J. W. R., Failache, H., & Lezama, A. (2006).
Spectroscopic observation of the rotational Doppler effect.
Physical Review Letters, 97(11), 113601.

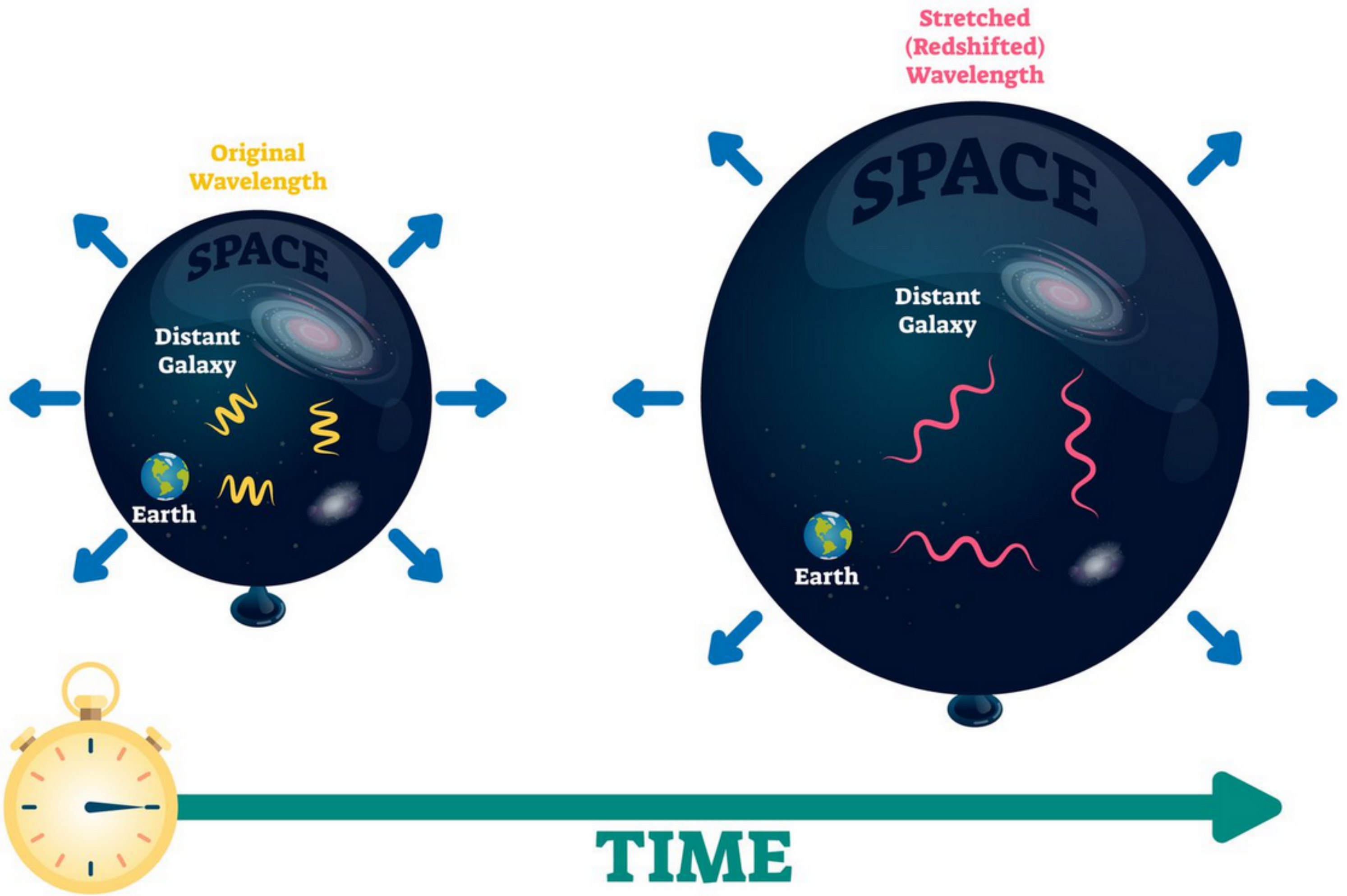
Doppler shifts atómicos - ubicuos en la física moderna

Astronomía
- velocidad de las fuentes

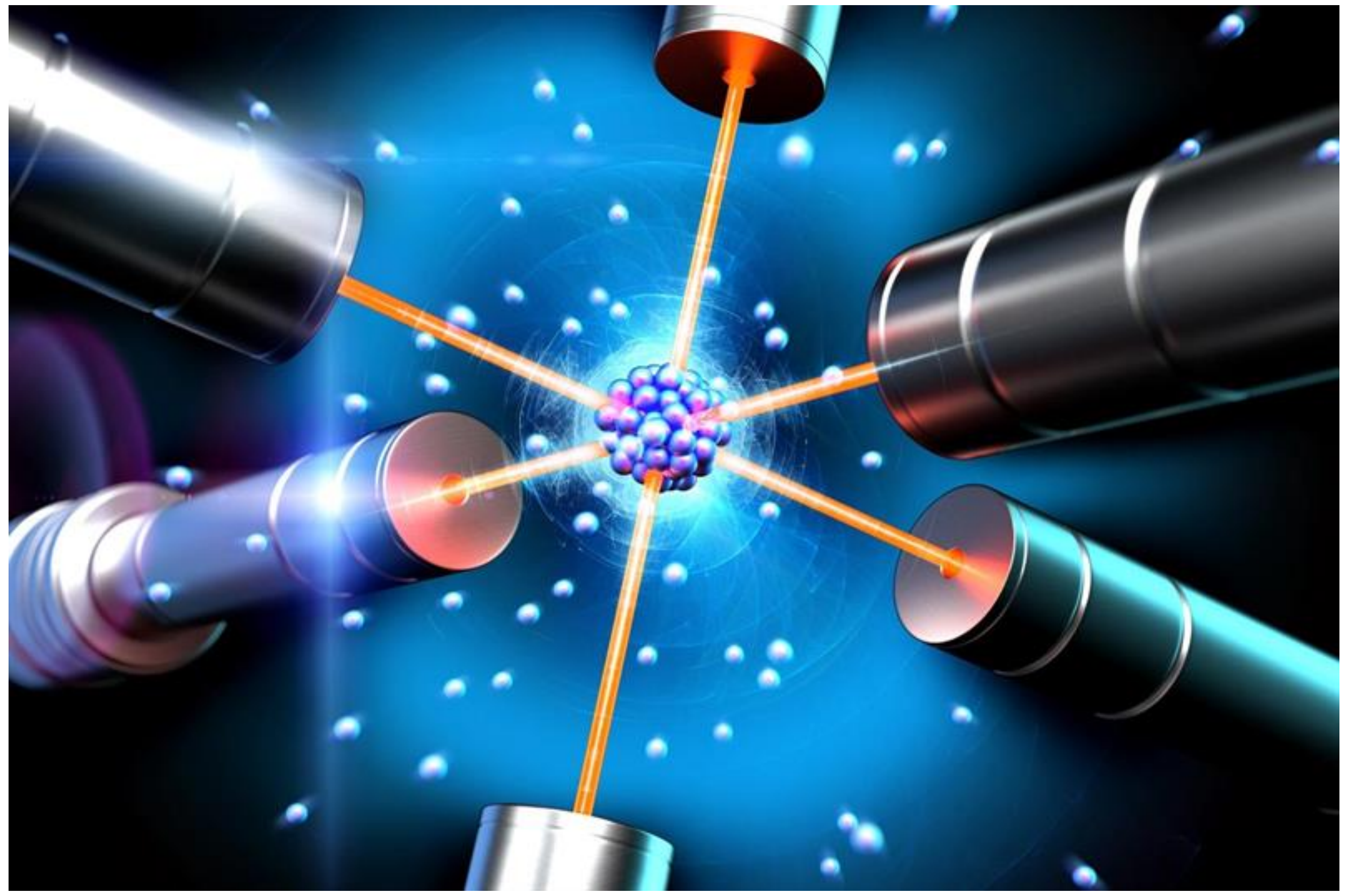
Espectroscopía
- temperatura de un gas



Cosmología
- edad de las fuentes

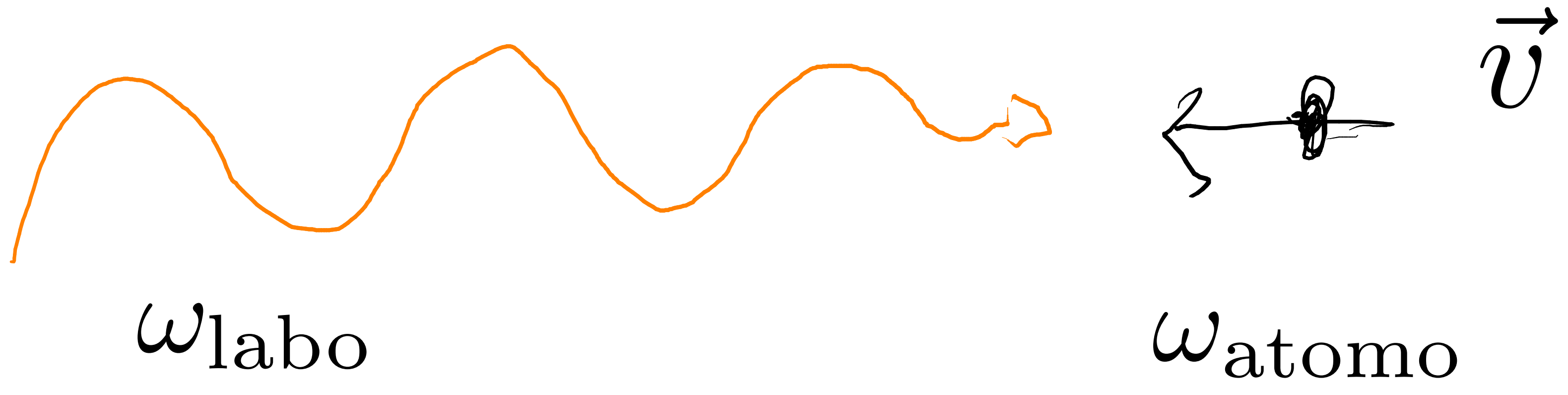


Óptica Cuántica
- enfriamiento y manipulación láser de átomos



Super-Doppler shifts - every actuator is a a sensor

Doppler effect for a plane wave



$$E = E_0 e^{ikz}$$

$$\omega_{\text{atomo}} = \omega_{\text{labo}} + \underbrace{\vec{k} \cdot \vec{v}}_{\delta}$$

Doppler effect for a generic wave

$$\delta = \frac{\vec{\nabla} E}{|E|} \cdot \vec{v}$$

Doppler effect for a Laguerre-Gauss Wave

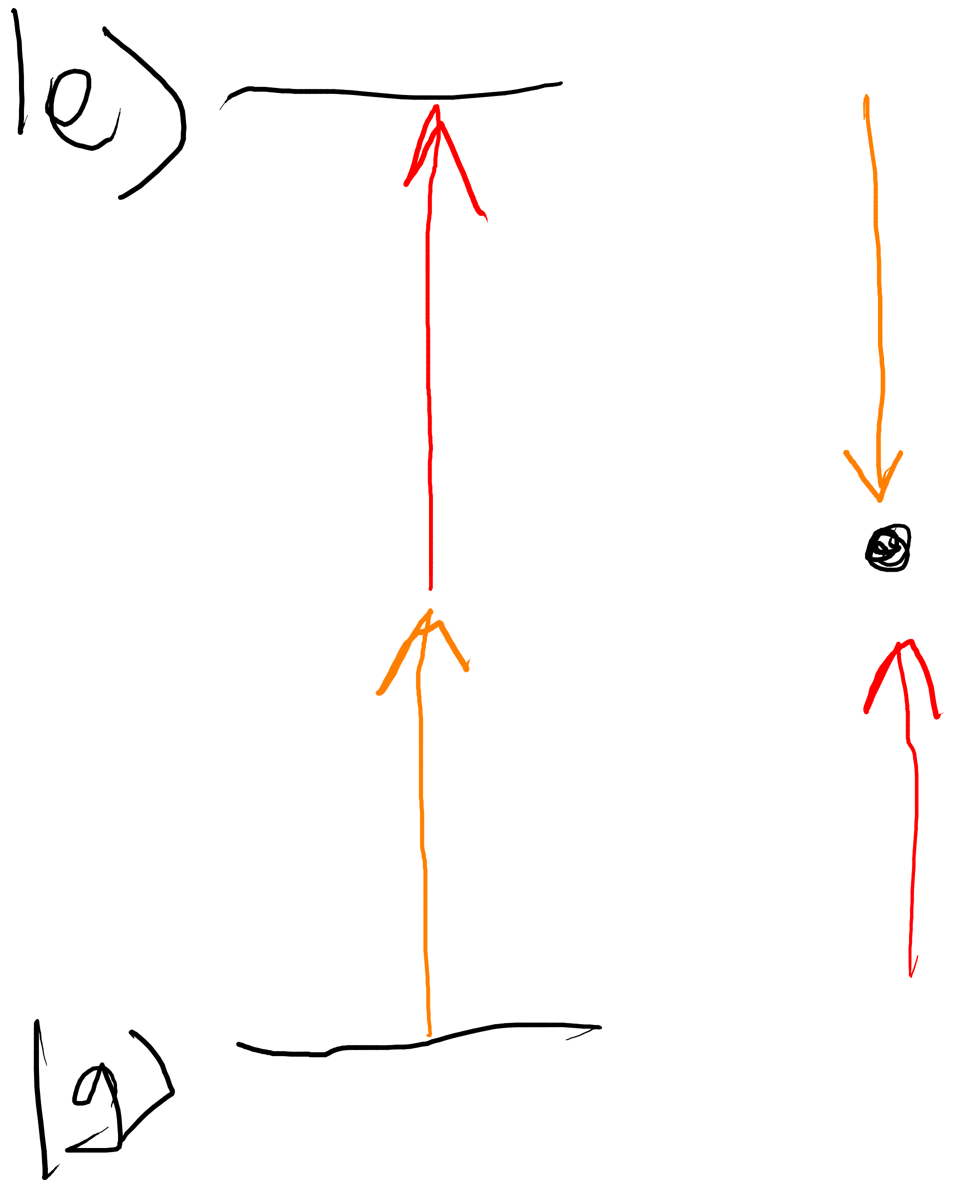
$$\delta_{LG} = -\left[k + \frac{kr^2}{2(z^2+z_R^2)}\left(\frac{2z^2}{z^2+z_R^2} - 1\right) - \frac{(2p+|l|+1)z_R}{z^2+z_R^2}\right] V_z - \left(\frac{krz}{z^2+z_R^2}\right) V_R - \left(\frac{l}{r}\right) V_\phi$$

Linear Curvature Gouy Curvature Azimuthal

Espectroscopía libre de Doppler - dos fotones

Physical Review Letters 133 (18), 183601 (2024)

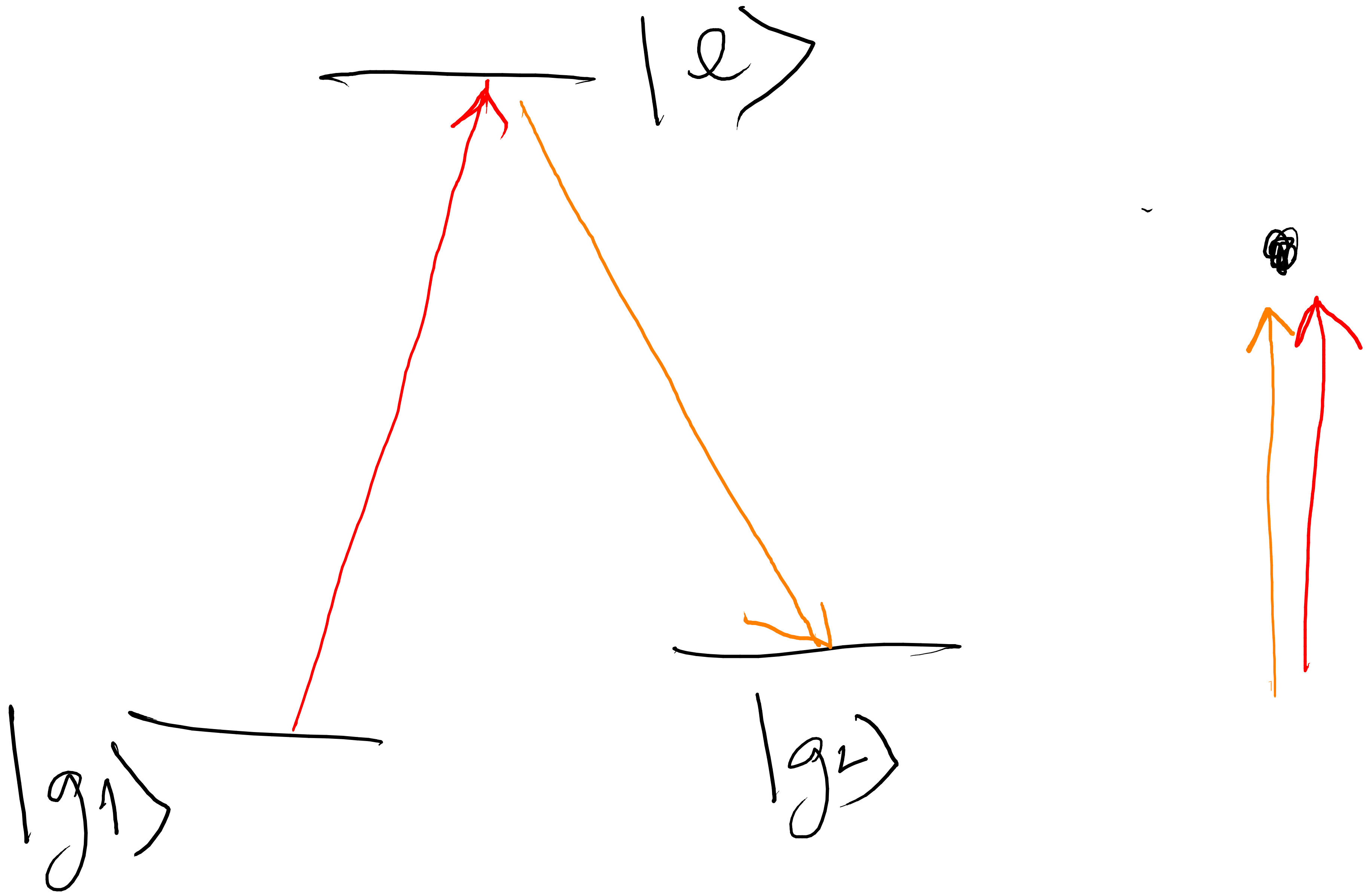
Transición de dos Fotones



$$\Delta\delta = \delta_{k1} - \delta_{k2} = k_1 v - k_2 v$$

$$k_1 = k_2 \longrightarrow \Delta\delta = 0$$

Transición Raman Estimulada



$$\Delta\delta = \delta_{k1} + \delta_{k2} = k_1 v + k_2 v$$

$$k_1 = -k_2 \longrightarrow \Delta\delta = 0$$

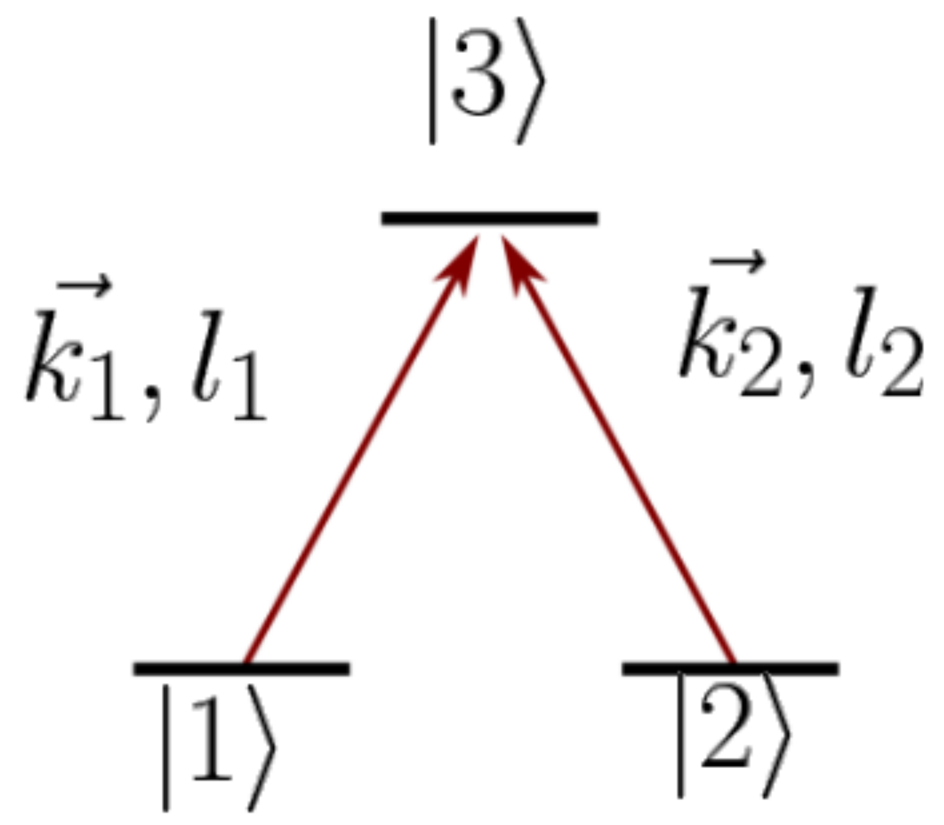
Christian Schmiegelow - Universidad de Buenos Aires

Super Doppler shifts - on two photon transitions

Doppler shift in a Laguerre-Gauss beam

$$\delta_{LG} = -\left[k + \frac{kr^2}{2(z^2+z_R^2)}\left(\frac{2z^2}{z^2+z_R^2} - 1\right) - \frac{(2p+|l|+1)z_R}{z^2+z_R^2}\right]V_z - \left(\frac{krz}{z^2+z_R^2}\right)V_R - \left(\frac{l}{r}\right)V_\phi$$

Two photon transitions



...they occur at equal detunings.

$$\Delta_1 = \Delta_2$$

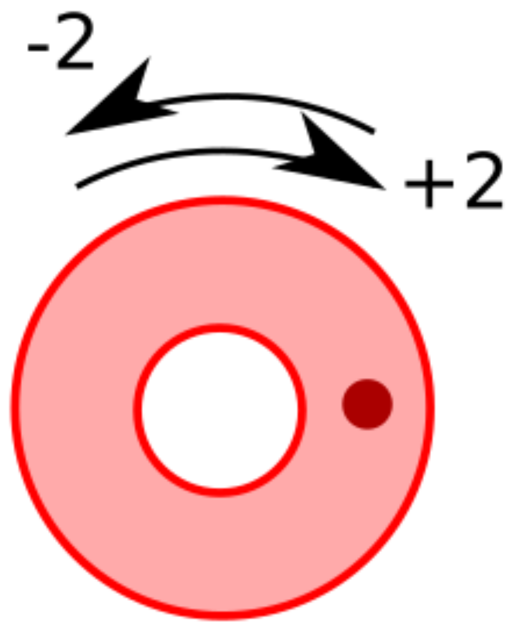
Plus, the Doppler shift for each beam!

$$\Delta_1 + \delta_{LG_1} = \Delta_2 + \delta_{LG_2}$$

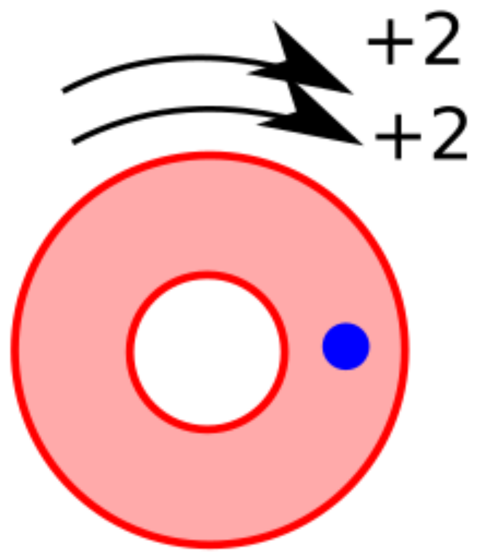
For two co-propagating beams

... all shift, except azimuthal are eliminated.

$$\Delta\delta \equiv \delta_{LG_1} - \delta_{LG_2} = \left(\frac{l_1 - l_2}{r}\right)V_\phi$$

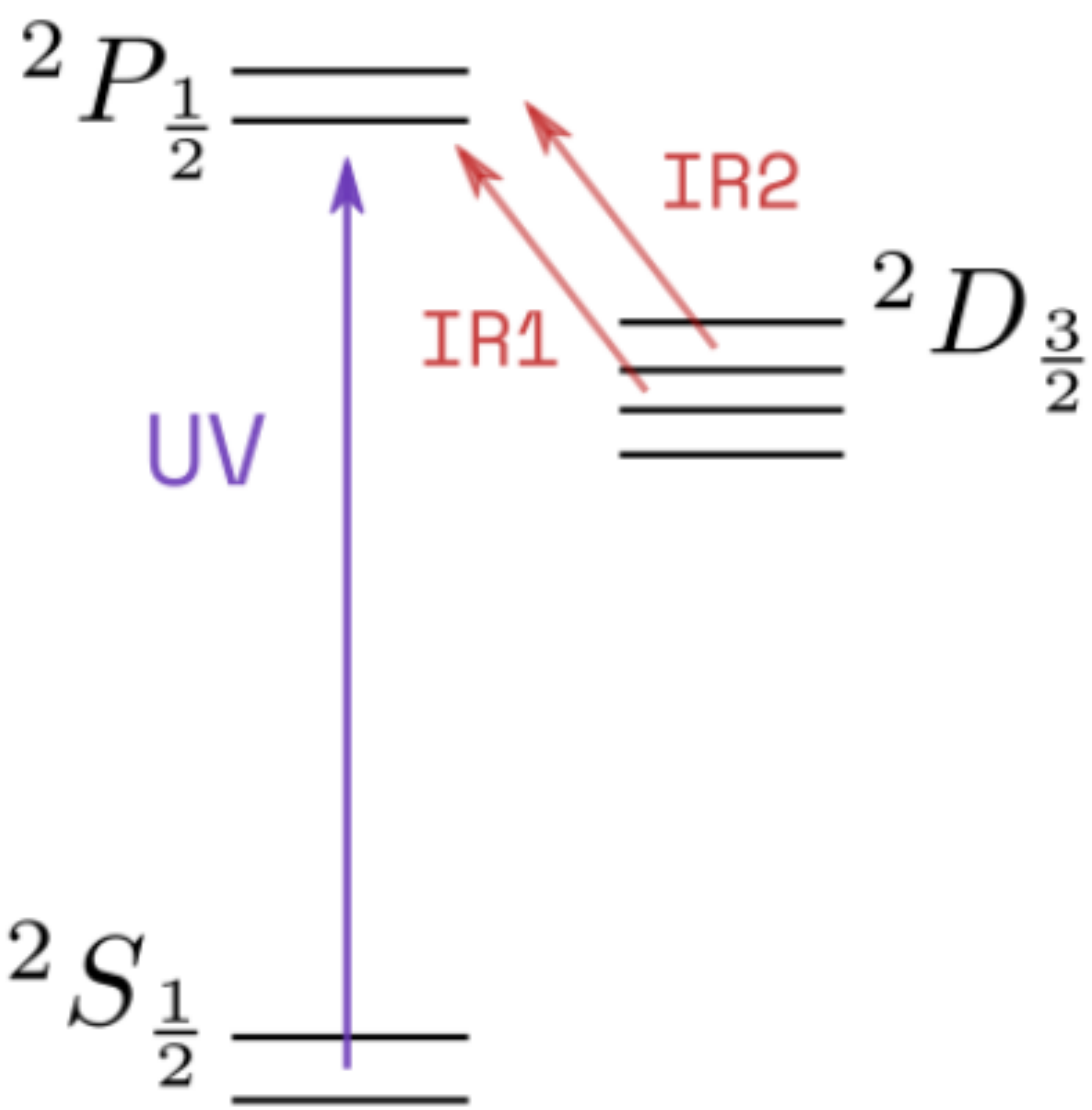


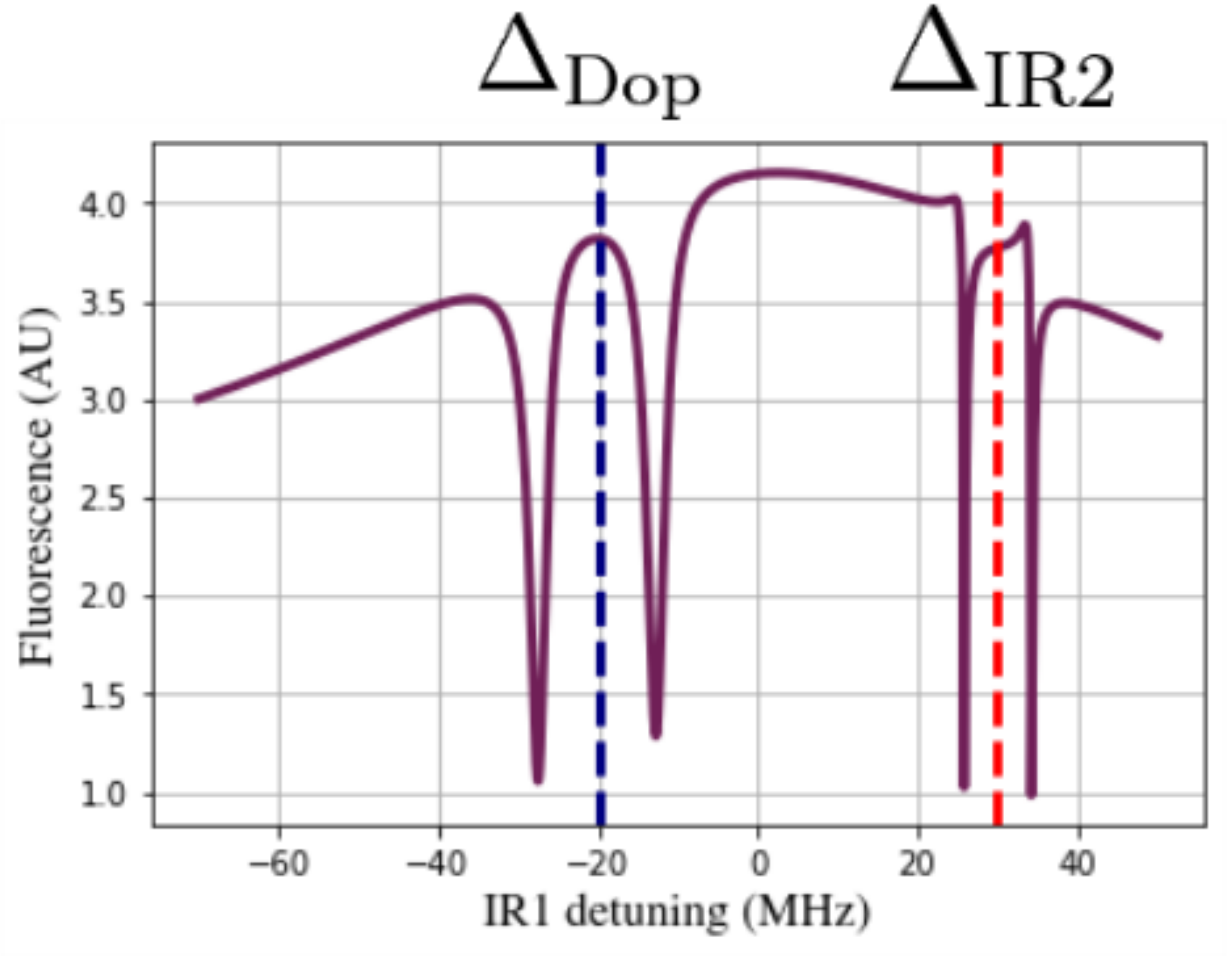
$$\Delta\delta = 0$$



$$\Delta\delta = \frac{4}{r}V_\phi$$

Experimental scheme with a trapped Ca^{+} ion and three lasers: **dark resonances**

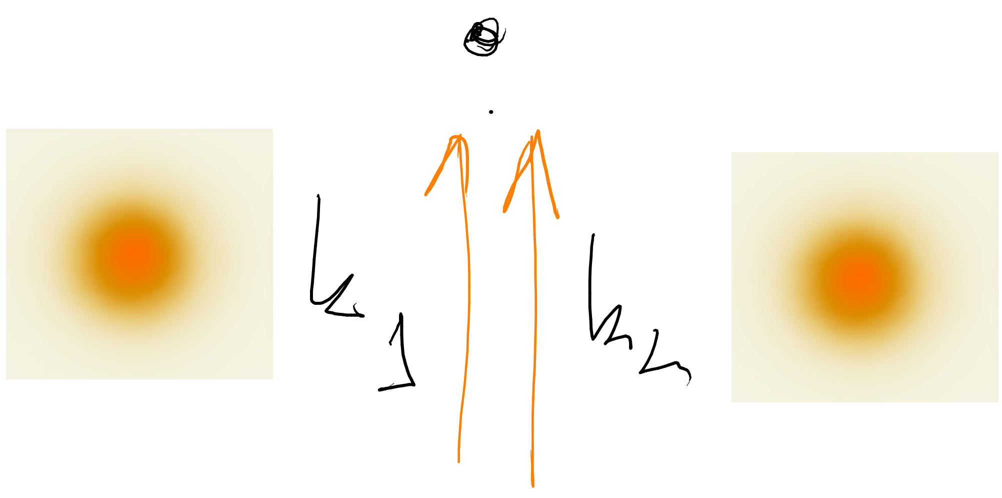




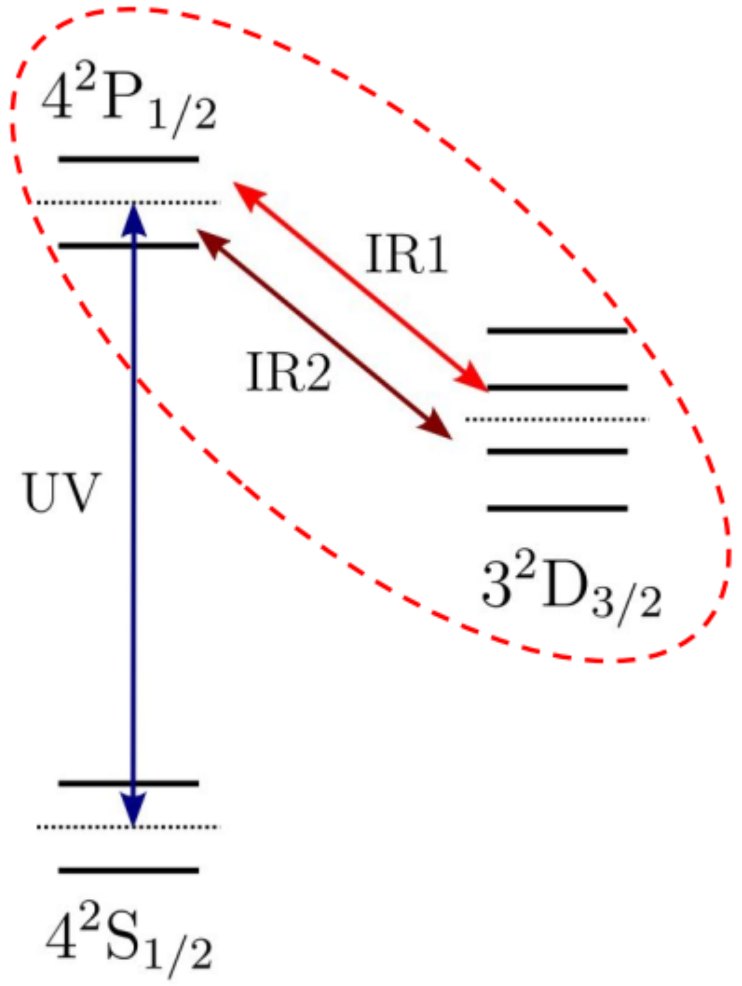
Movement insitivity - two identical beams

Stimulated Raman Transition

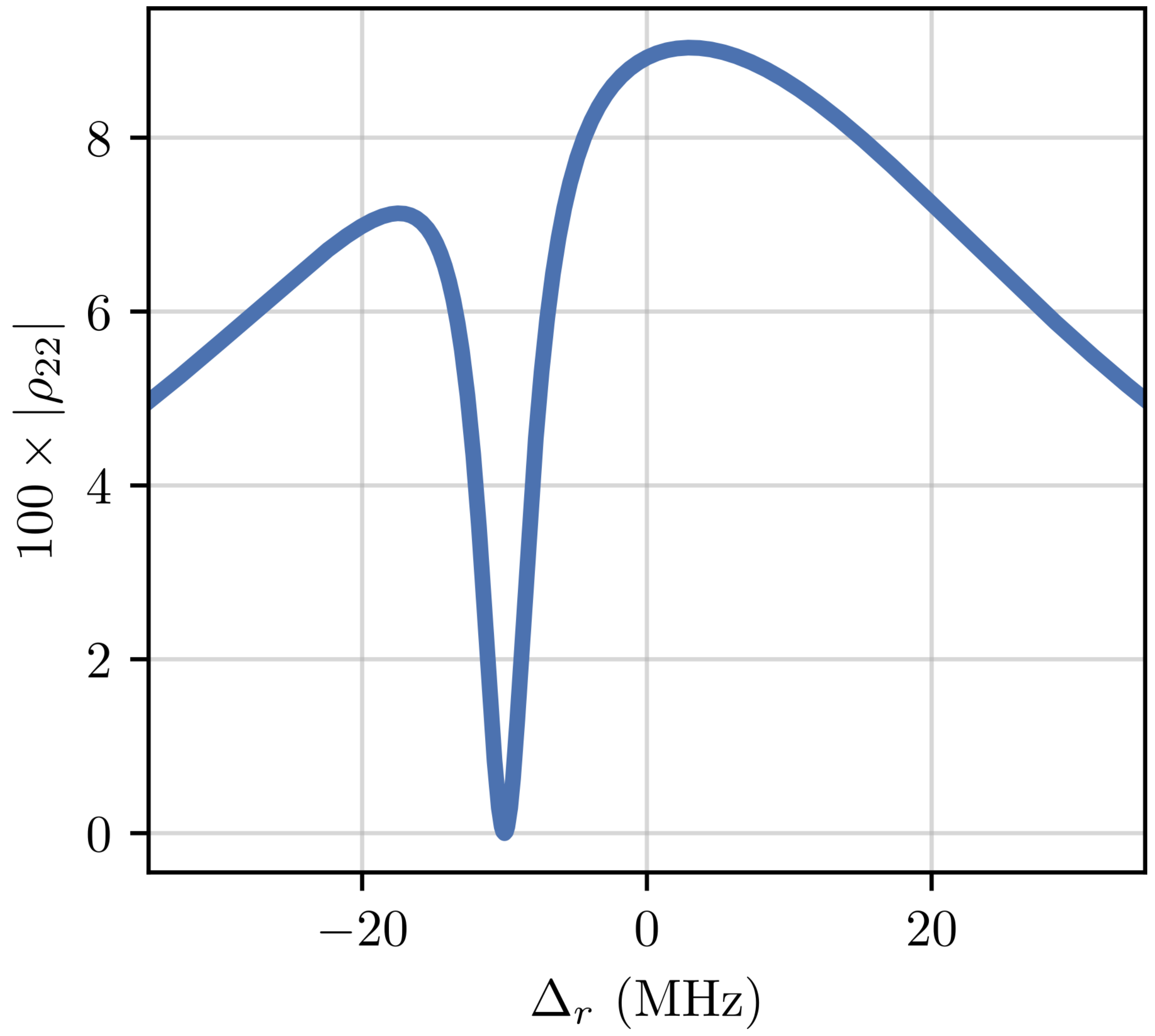
Expected shift



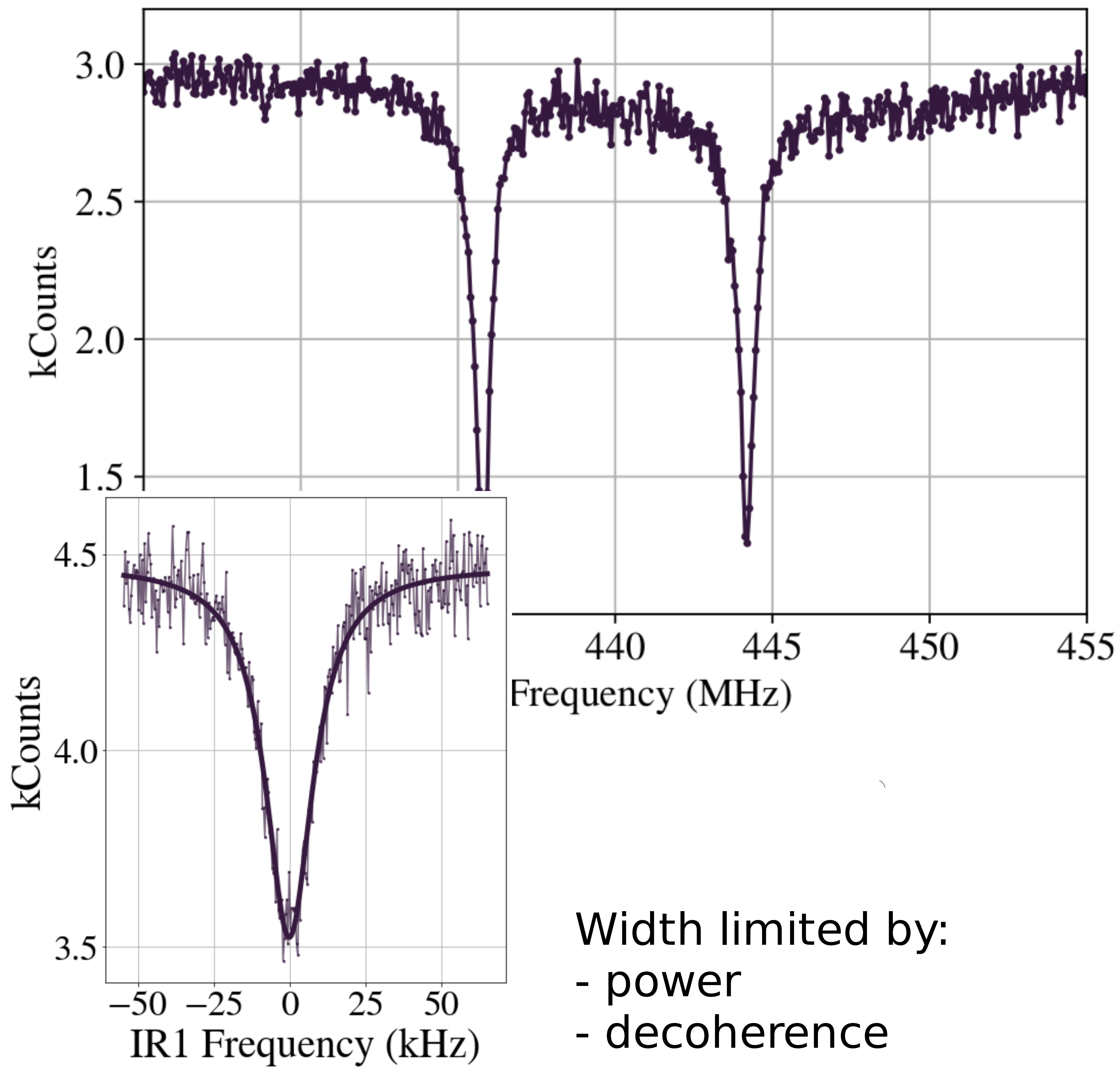
$$\Delta\delta = k_1 v - k_2 v = 0$$



Simulation



Results



Width limited by:
- power
- decoherence

- dipolar transition has ~10 MHz width
- dips have <10kHz width

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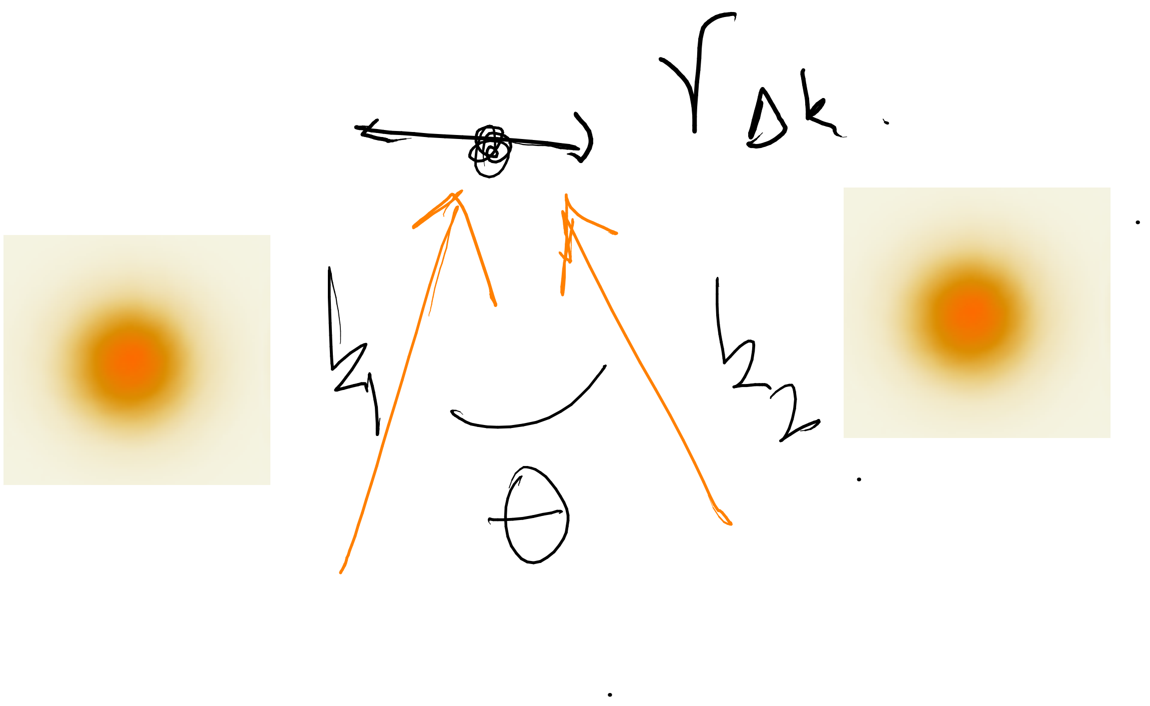
Doppler shifts - spectra with two beams at an angle

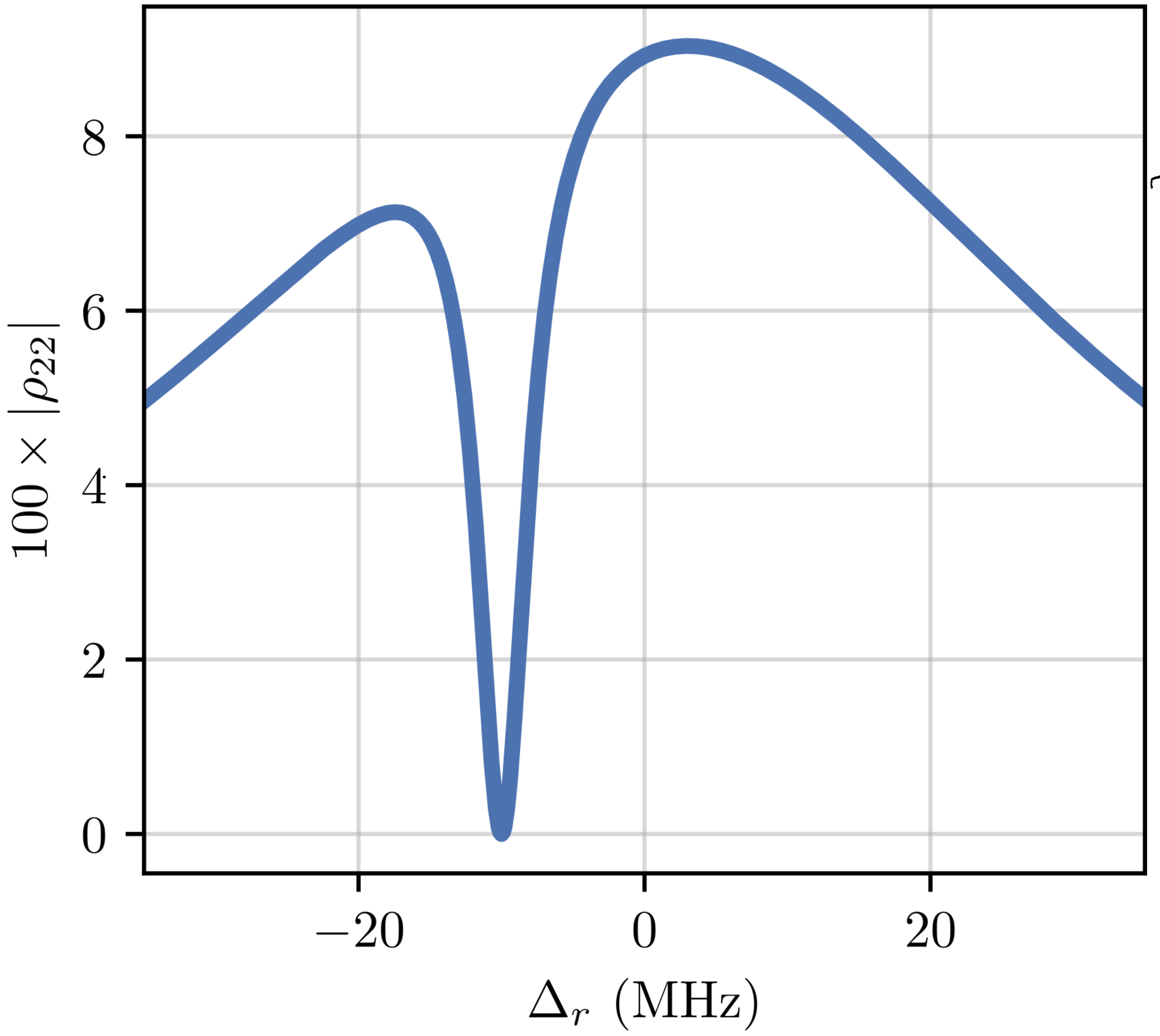
Expected shift



$$\Delta\delta = \Delta\vec{k}\cdot\vec{v}$$

$$\Delta\delta = \Delta k\, v_{\Delta k}\cos(\theta)$$

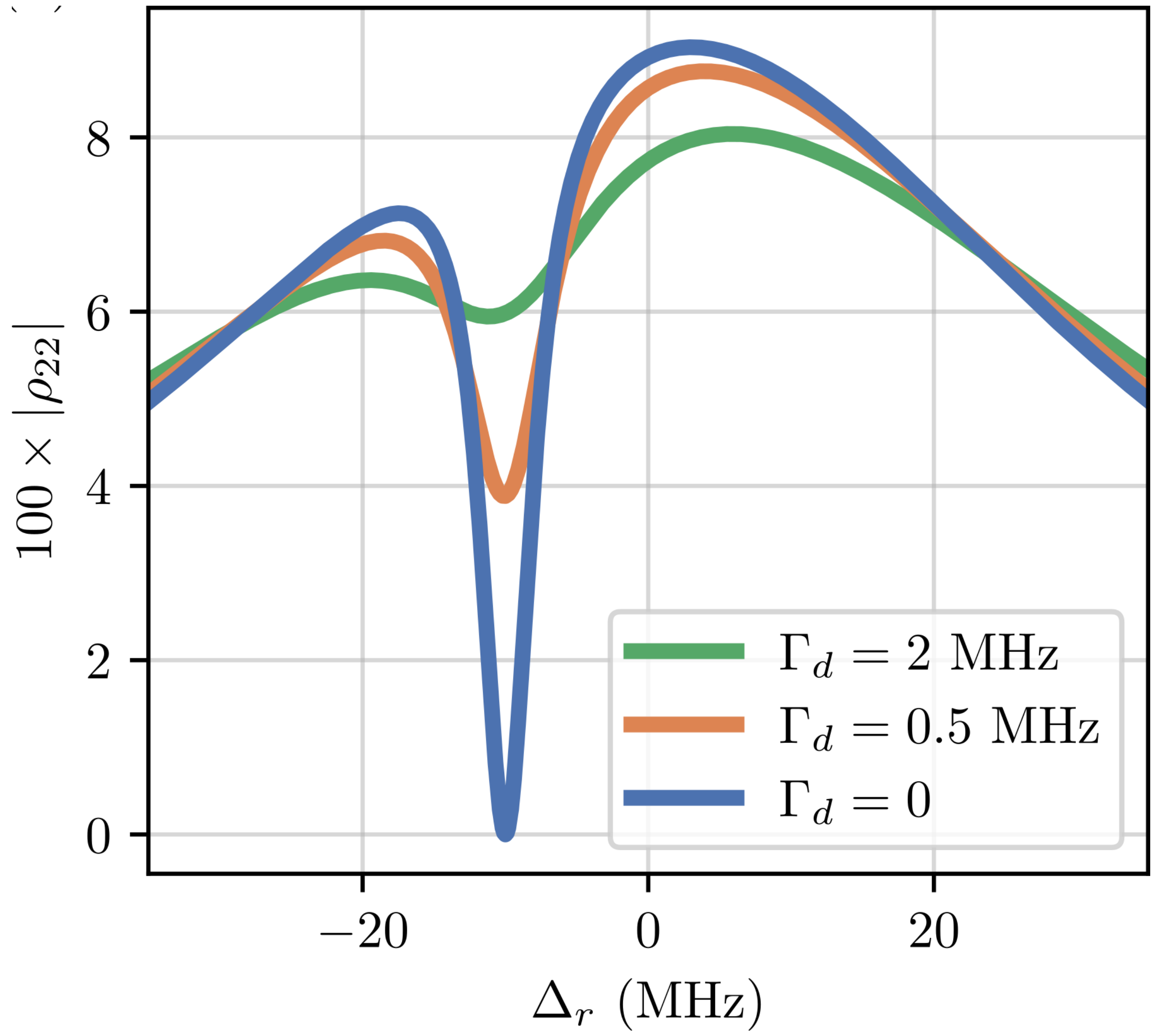
Simulation $v = 0$



Temperature

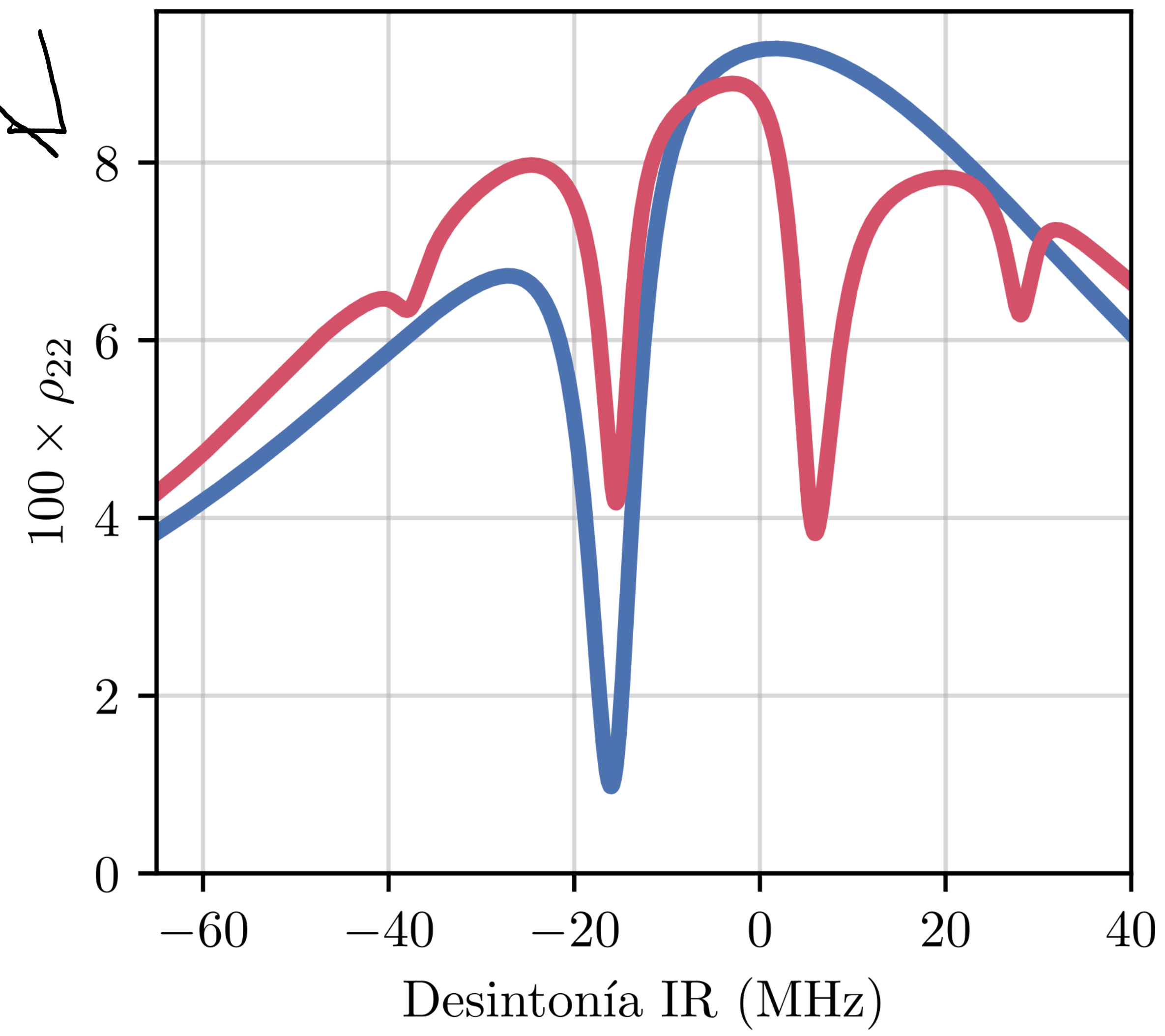
$p(v) \propto \exp\left(-mv^2/kT\right)$

Velocity distributions



Micromotion

$v = v_0 \sin\omega t$



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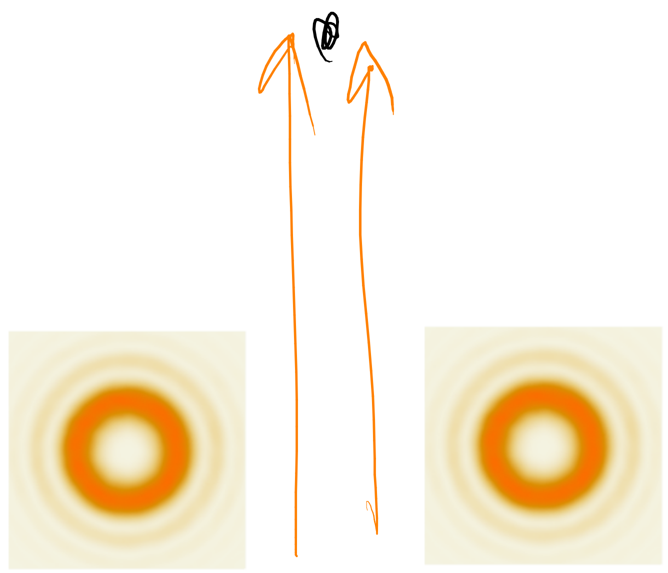
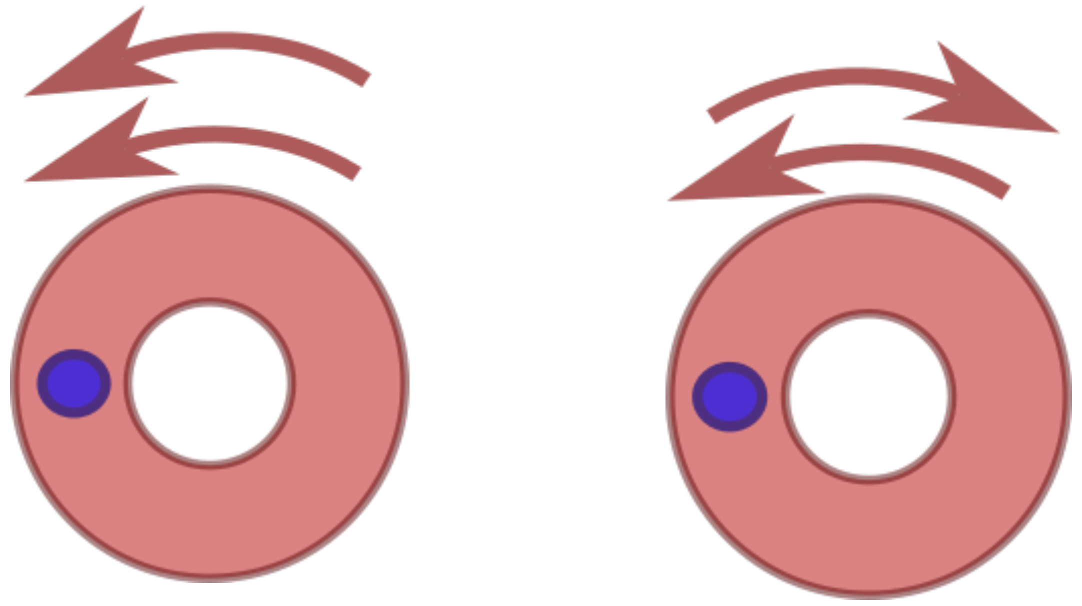
Rotational Doppler Effect - first evidence

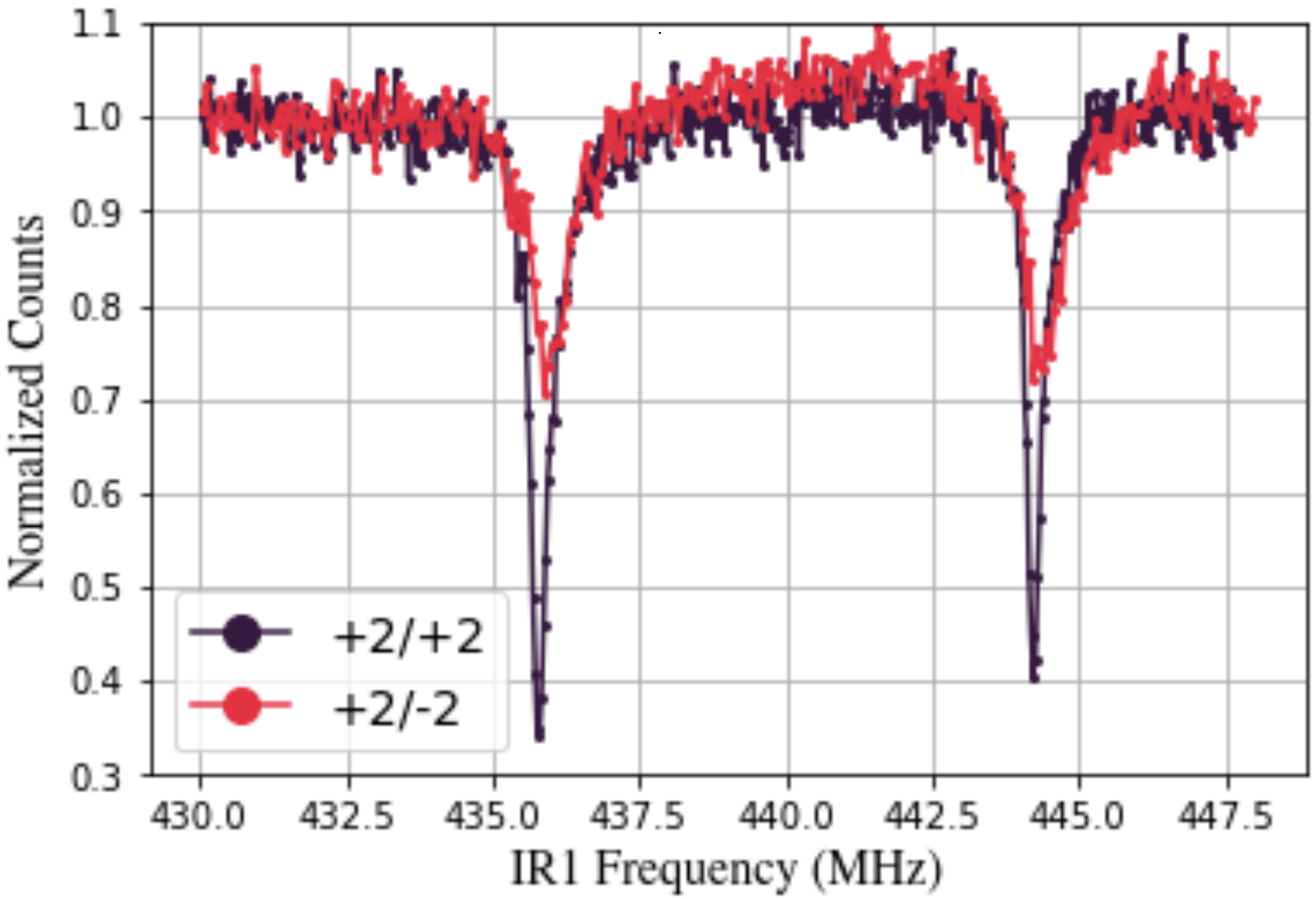
Expected shift for $l = 2$



$$\Delta\delta \equiv \delta_{LG_1} - \delta_{LG_2} = \left(\frac{l_1 - l_2}{r}\right) V_\phi$$



$$\Delta\delta = 0 \qquad \Delta\delta = \frac{4}{r} V_\phi$$



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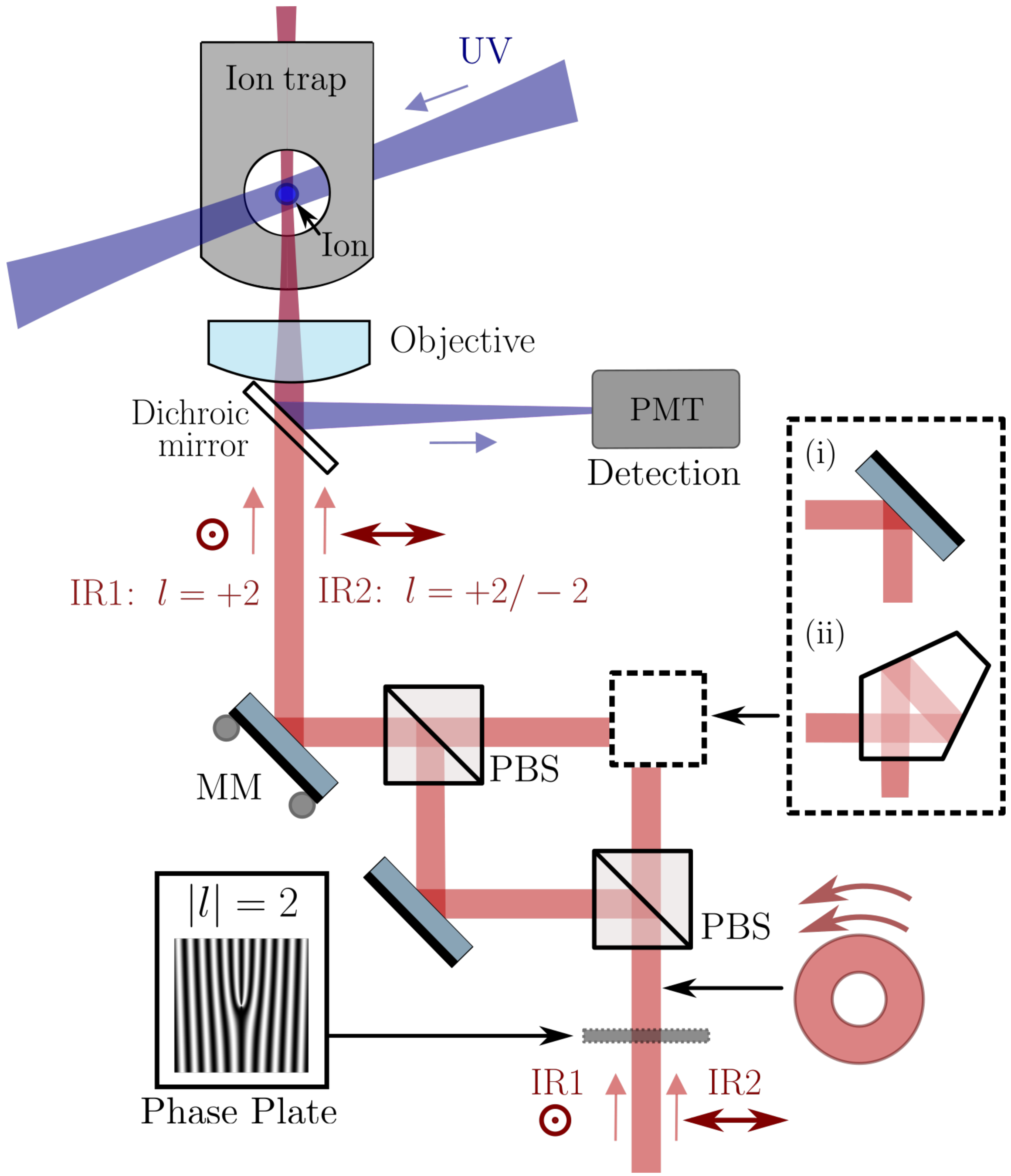
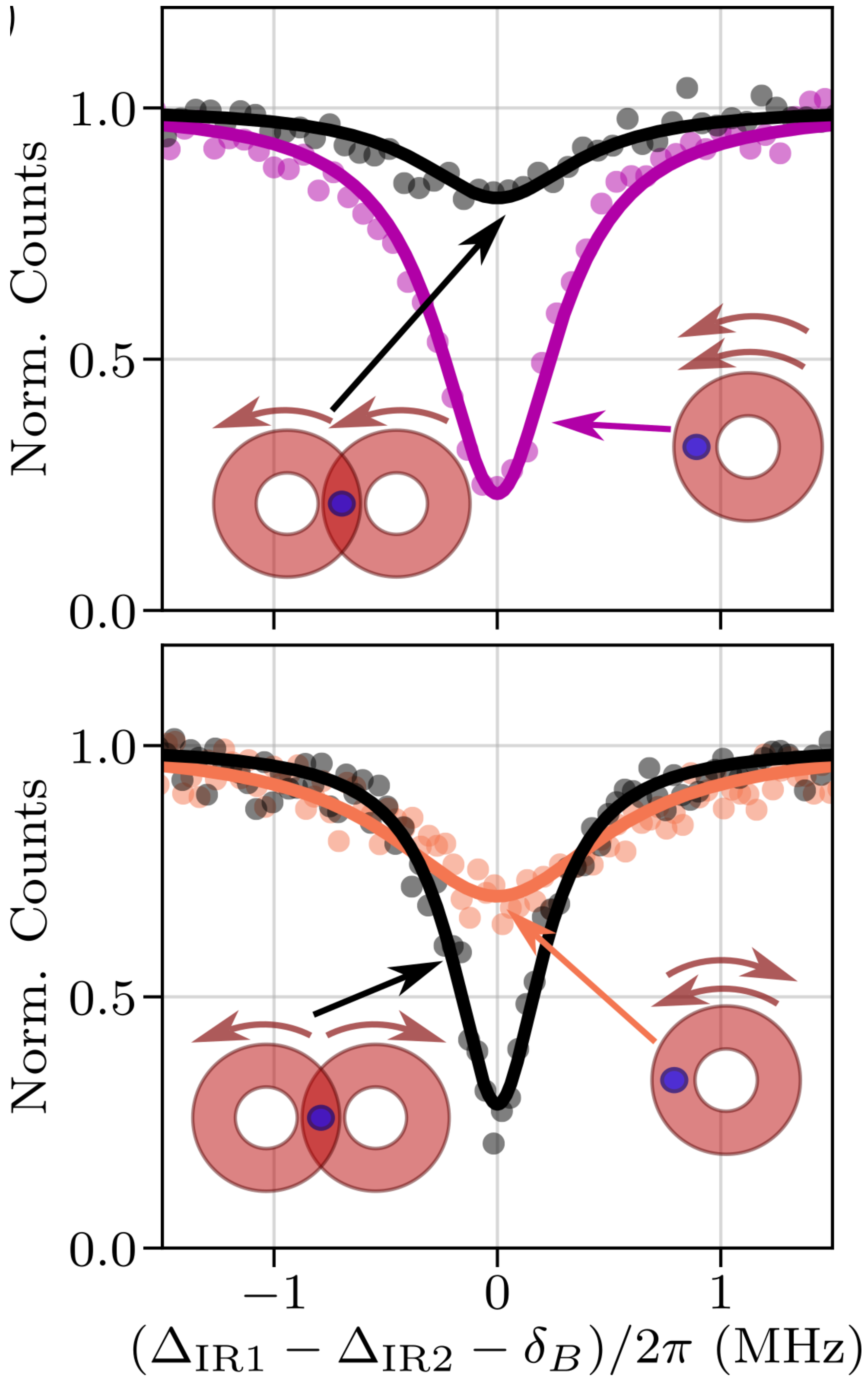
Rotational Doppler Effect - ruling out ghosts



different configurations

-> it is NOT a missalignment effect!



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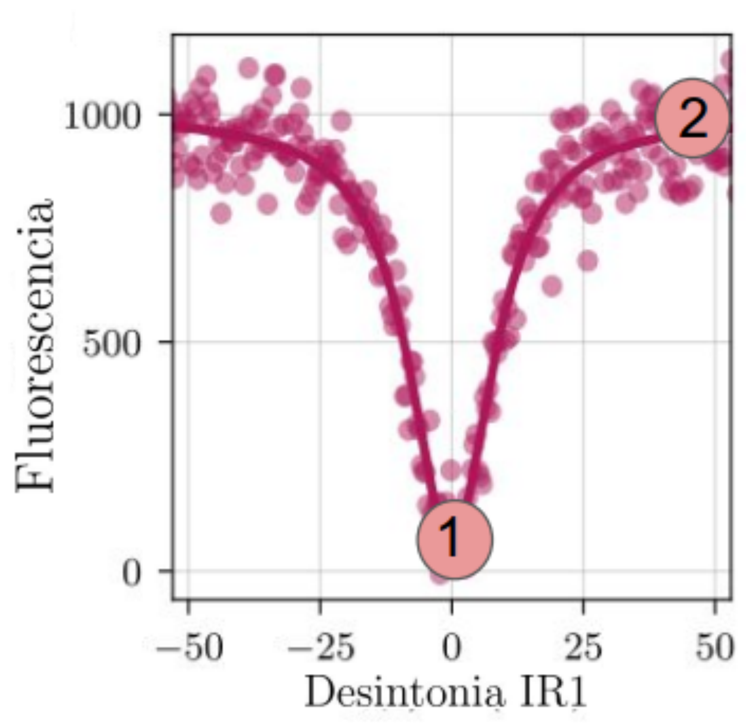
Rotational Doppler Effect - trasnversal scan

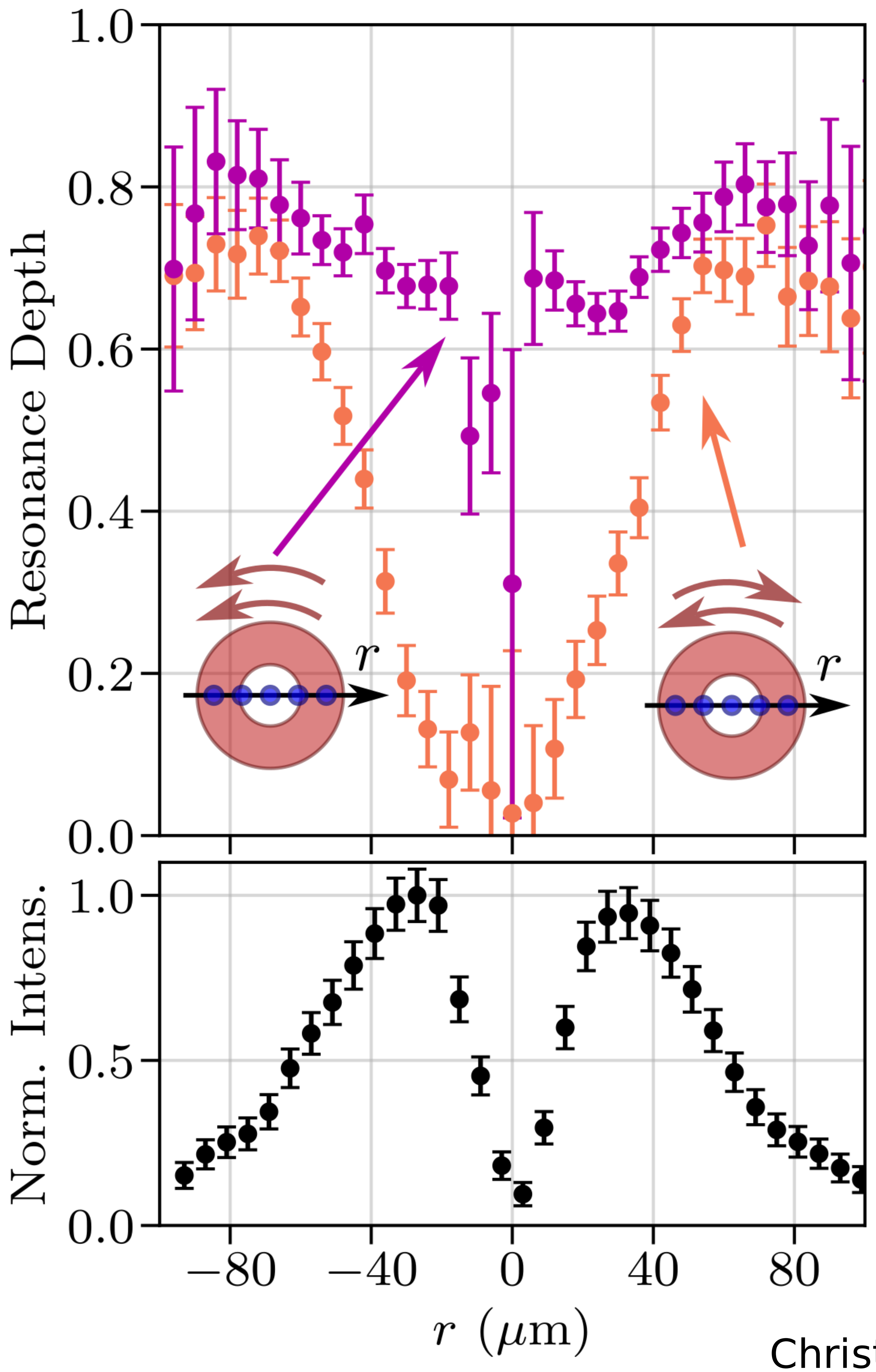
Measurement



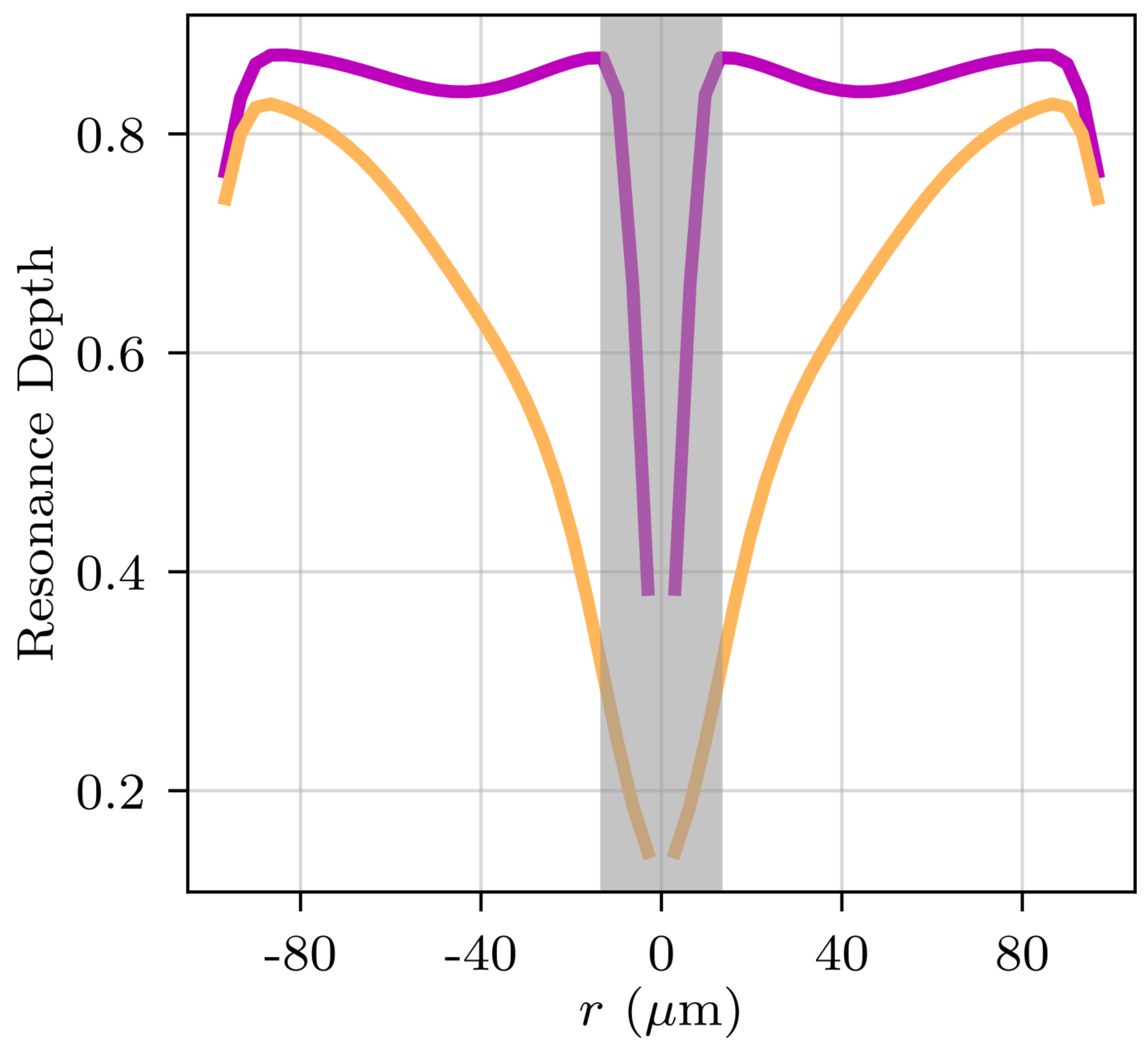
Resonance Depth

$$RD = 1 - \frac{F_1}{F_2}$$

Results



Simulation



Observations
- co-rotating: no big change
- ccounter-rotating: the dip vanished

+Vanishing dip indicates:
- diverging Doppler effect.

$$\Delta\delta = \frac{4}{r}V_\phi$$

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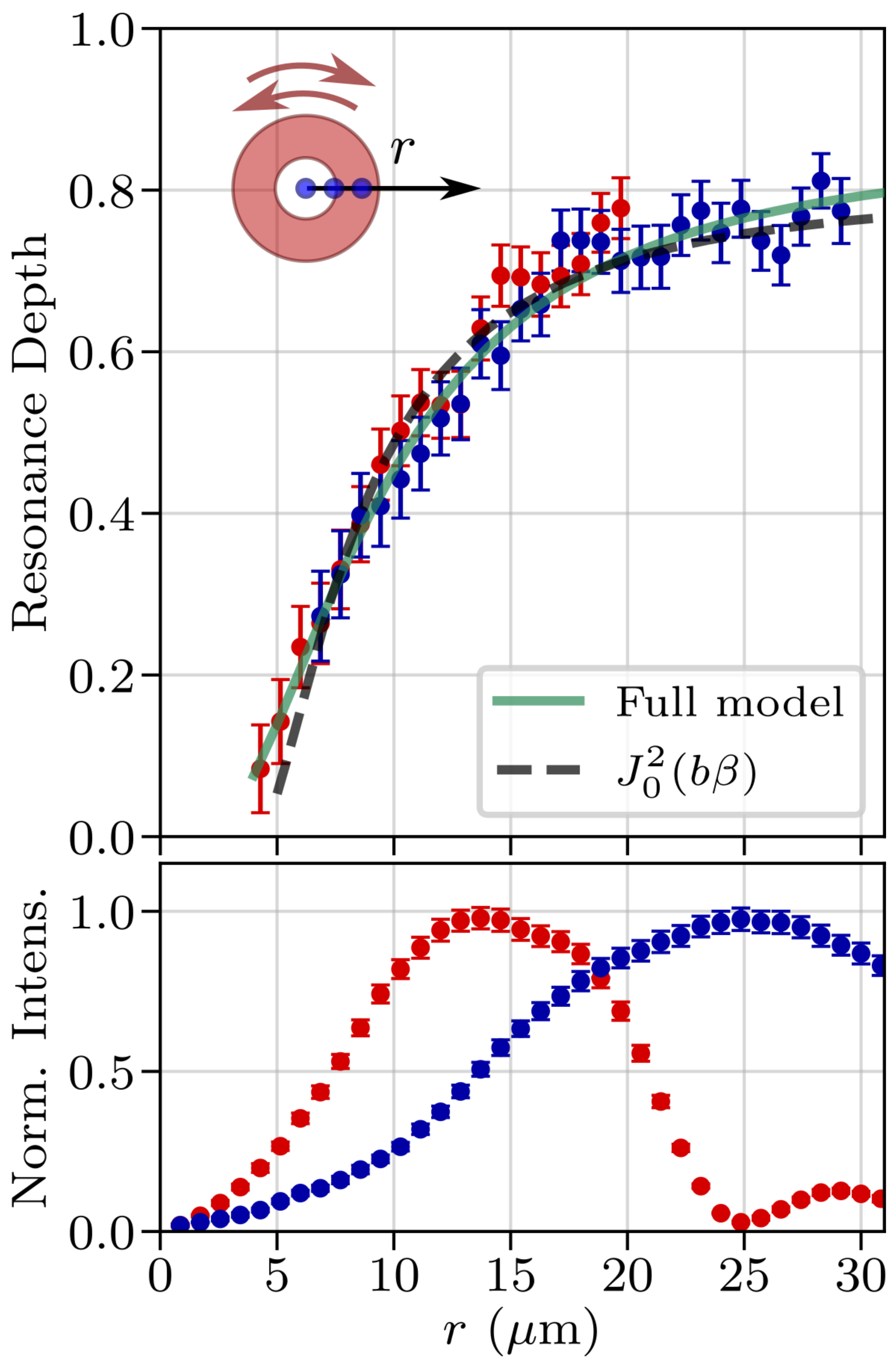
Scale invariance and modelling - trasnversal scan at constant intensity



Observations:
- it is invariant in the beam size

- full model and goss simplification fit the data!

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Conclusion

- there it is, we univocally see the doppler effect.
- it has all the structrual features we expected

Perspective

- can we reach the super Doppler shift limit?
- can we sense temperature with it?

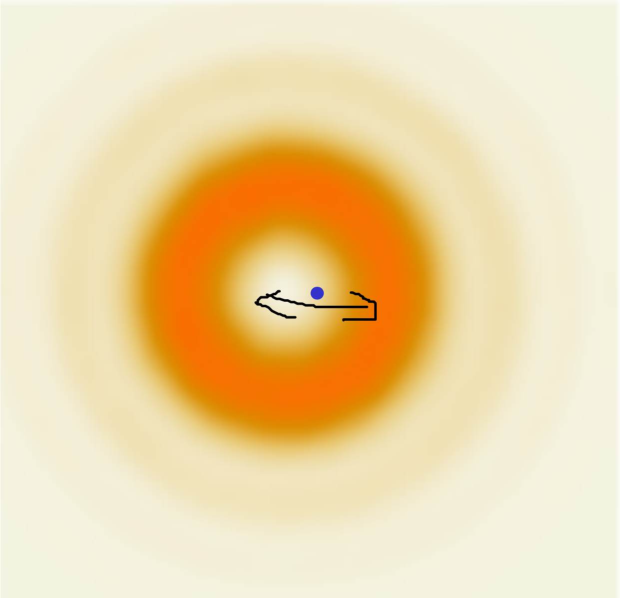
- could we observe Berry super-kicks?

Super-kicks - azimuthal kicks, the idea of Berry y Barnett

- every sensos is an actuator, and every actuator is a sensor -

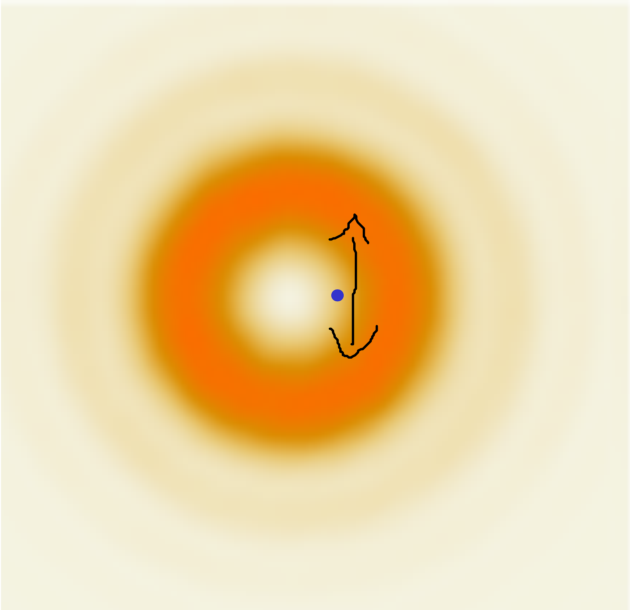
In a plan wave: longitudinal gradient

$$E = E_0 e^{ikz} \longrightarrow \Delta p = \hbar k \hat{z}$$



In previous experiment: radial gradient

$$E = E_0 e^{ikz} \rho \longrightarrow \Delta p = \hbar k \hat{z} + \hbar \frac{\hat{\rho}}{w_0}$$



and what about the azimuthal part?

$$E = E_0 e^{ikz} \rho \, e^{il\phi} \longrightarrow \Delta p = \hbar k \hat{z} + \hbar \frac{\hat{\rho}}{w_0} + \hbar \frac{l\hat{\phi}}{\rho}$$

trasnversal momentum trasnfer
- diverges at origin
- scale invariant!

Closing Remarks

Conclusions.

1) Atoms can be excited in the dark

2) Structured beams can transfer orbital angular momentum to bound electrons

3) Structured beams can trasfer linear trasnversal momentum to whole atoms

4) We have seen the footprint of a super-kick

Outlook

1) Turning ion crystals with structured beams

2) Specially structured vector beams for full atomic control

3) Quantum gates with strutured beams

Thank you for you attention.

Please leave you comments