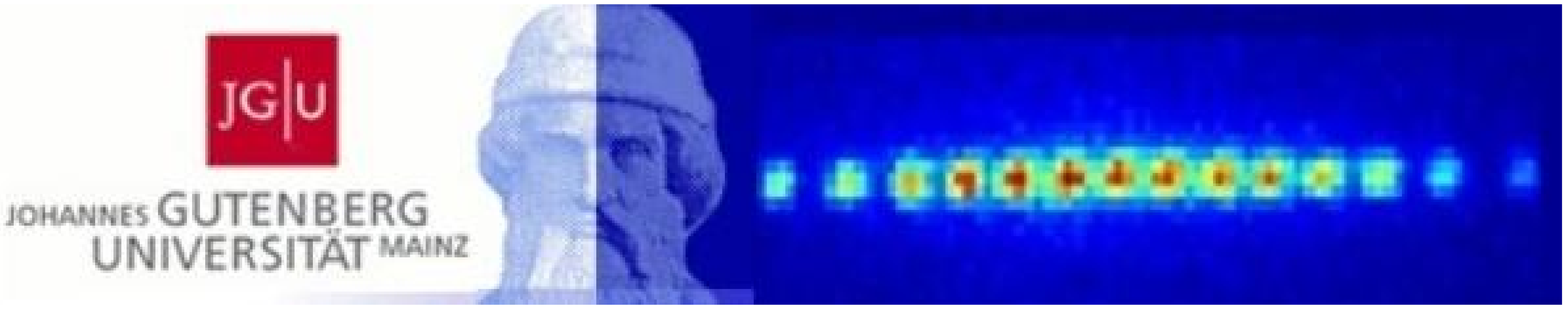
Quantum simulation with cold ions and atoms

Brighton December 2013

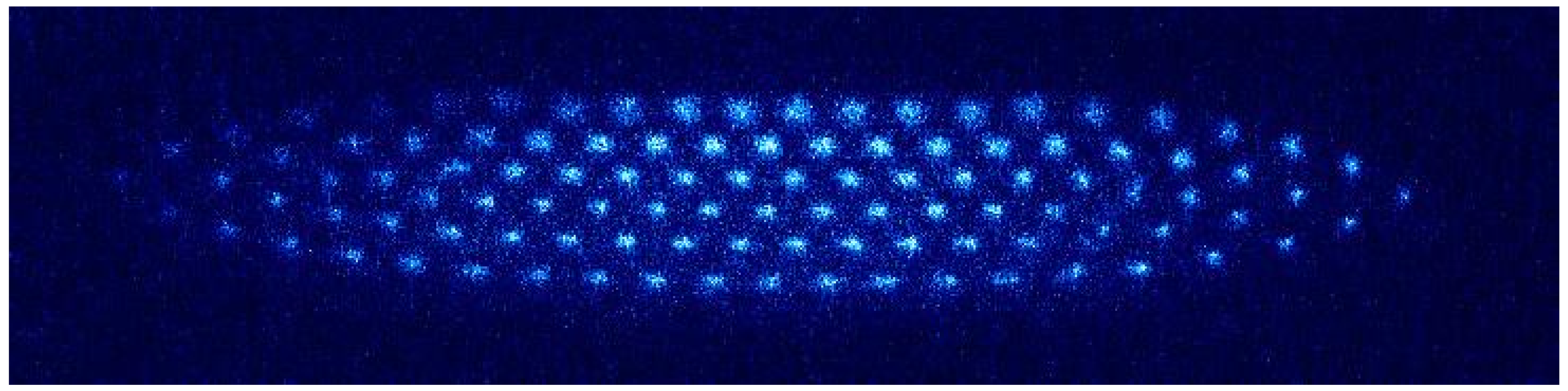
Rene Gerritsma

University Mainz
Ion trapping group

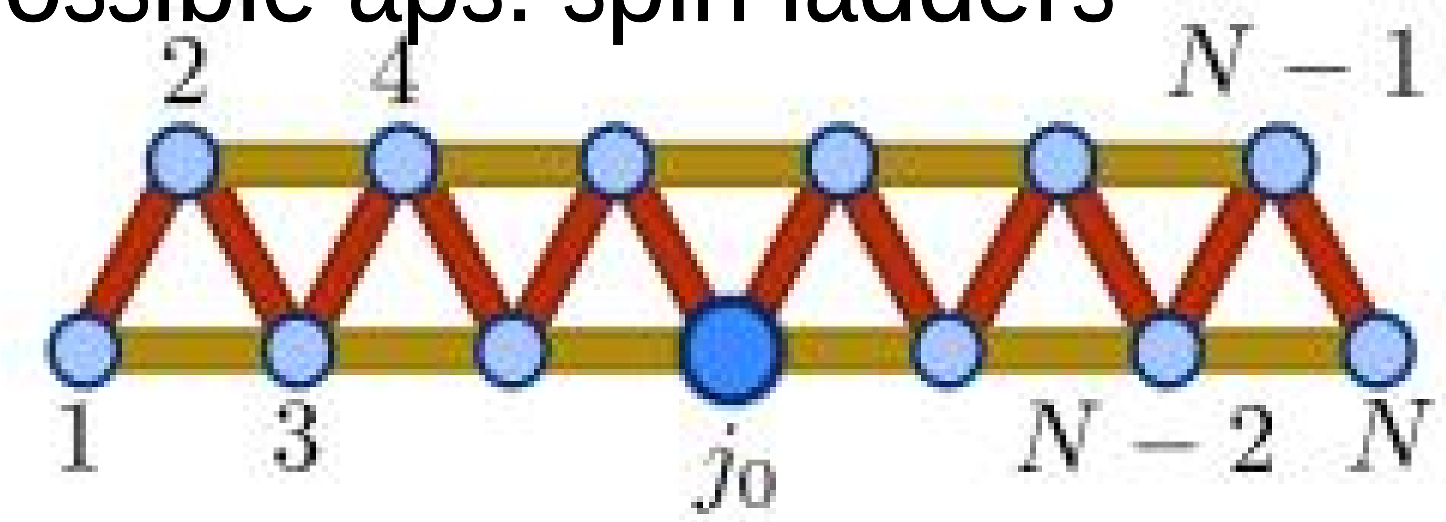


Quantum simulation with trapped ions in Mainz

2D crystals for studying frustration

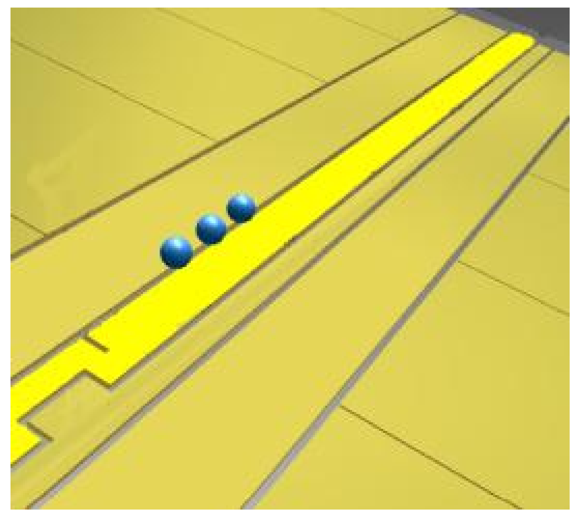


Possible aps: spin ladders



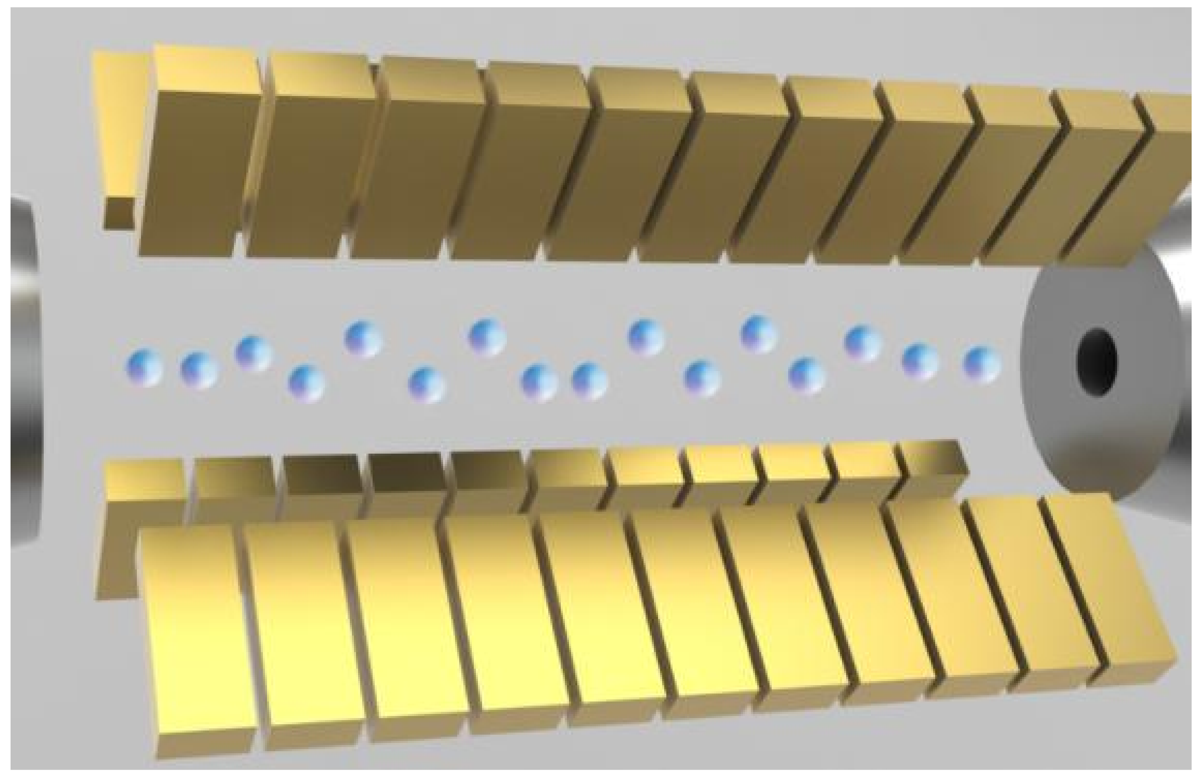
H. Kaufmann *et al.*, PRL 109, 263003 (2012)
A. Bermudez *et al.*, PRL 107, 207209 (2011)

Magnetic field based qSim



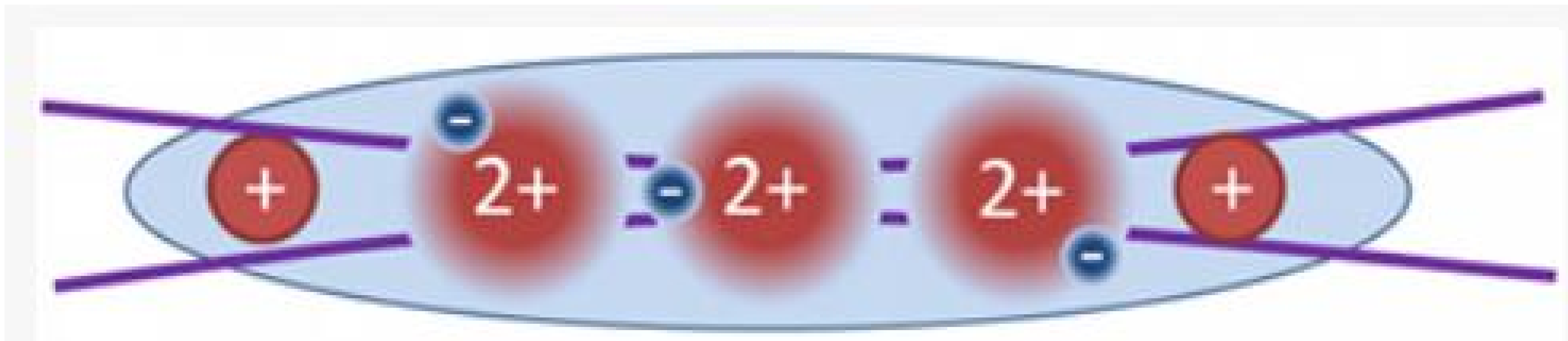
J. Welzel *et al.*, EPJD 65, 285 (2011).
Also: Siegen, NIST, Sussex, …

Defects in ion crystal phase transitions



S. Ulm *et al.*, *Nature Communications* 4, 2290 (2013).
Poster Kilian Singer, Mehlstauebler, Schätz

Rydberg ions

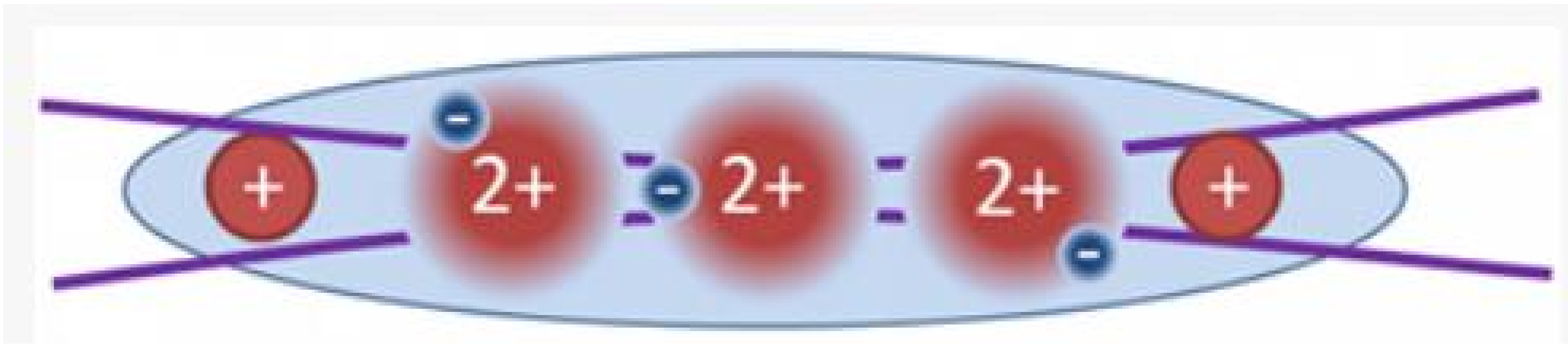


T. Feldker *et al.*, *arXiv:1306.1109* (2013).
Zoller, Lesanovsky, also: Hennrich

Contents

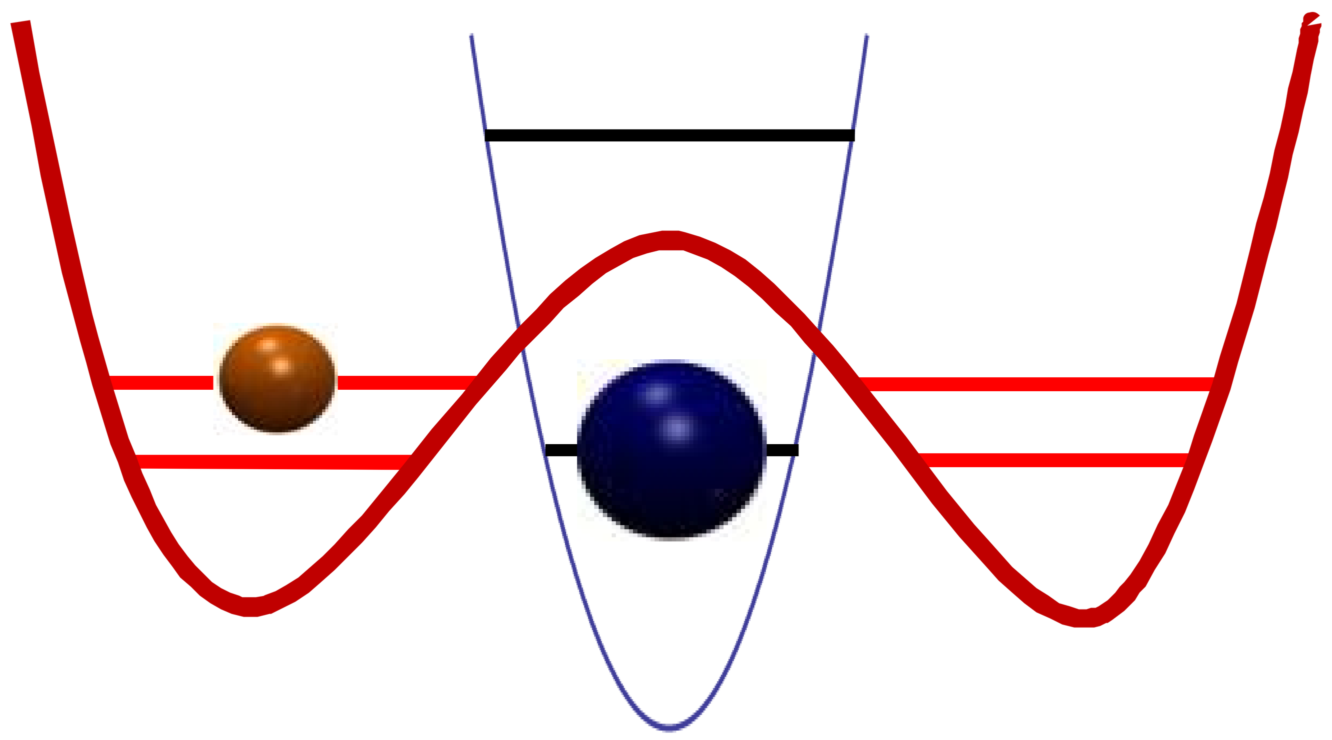
Part one

New quantum simulations using ion Rydberg excitation

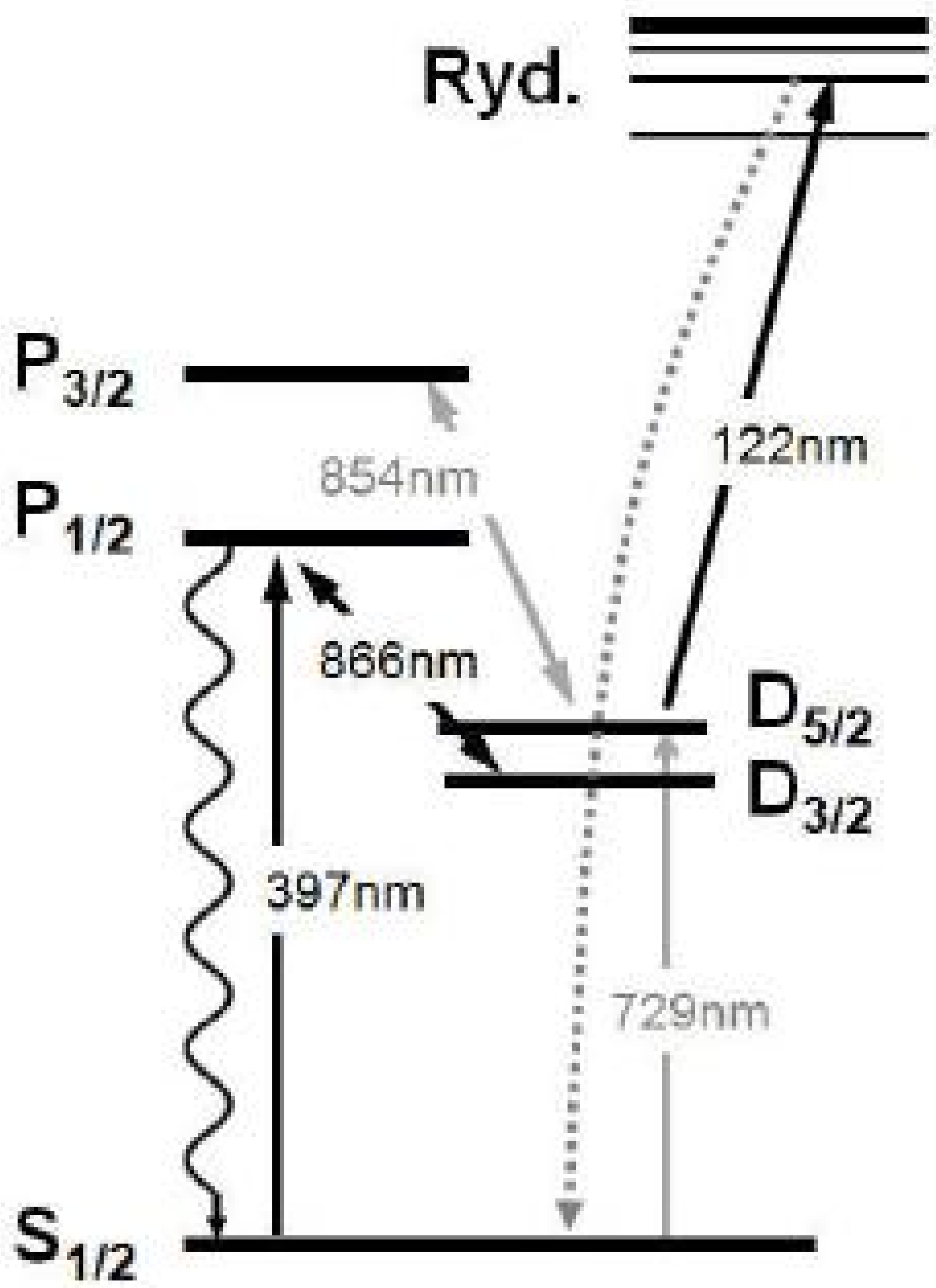


Part two

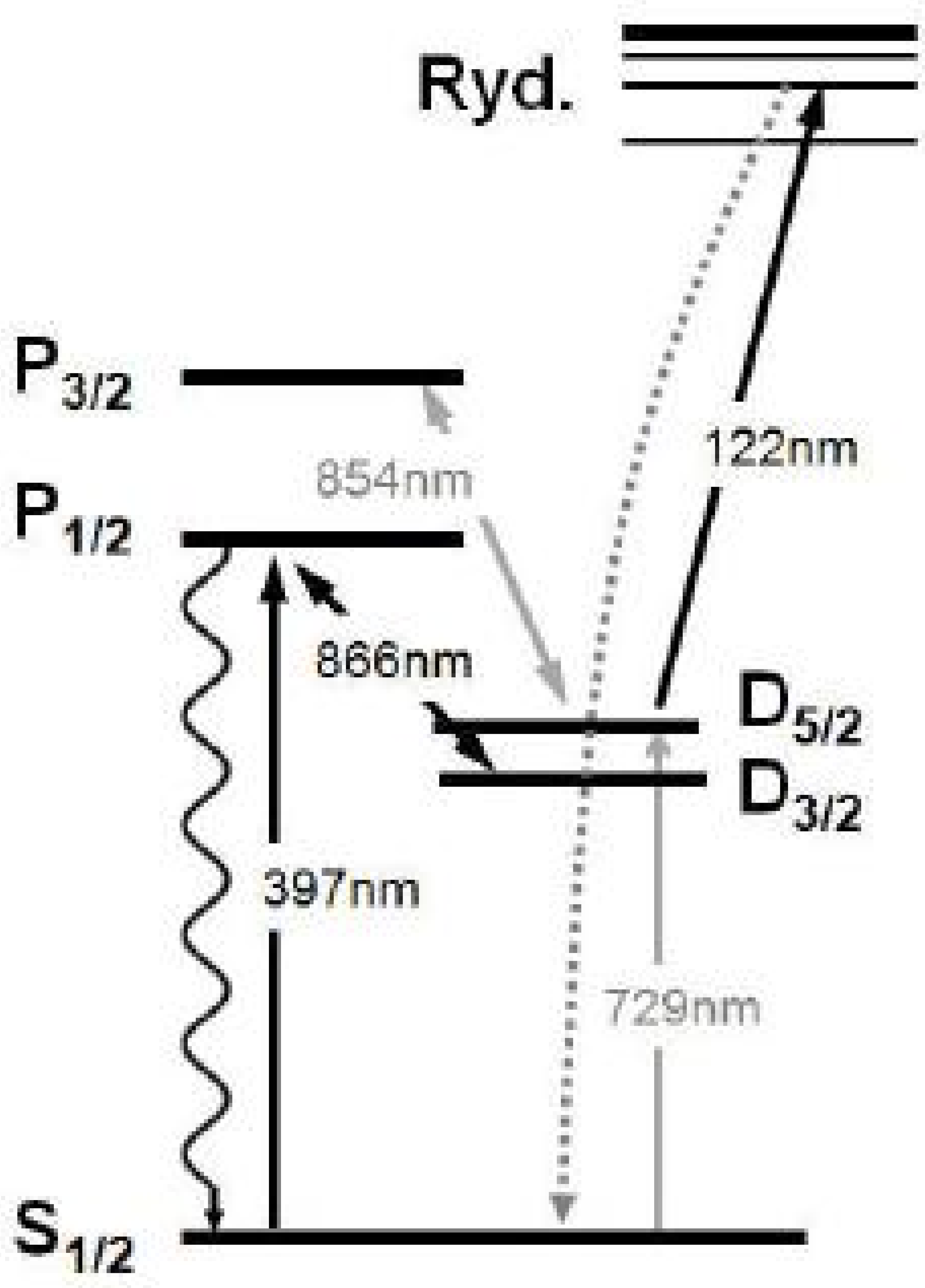
Prospects for using atom-ion mixtures in quantum simulation

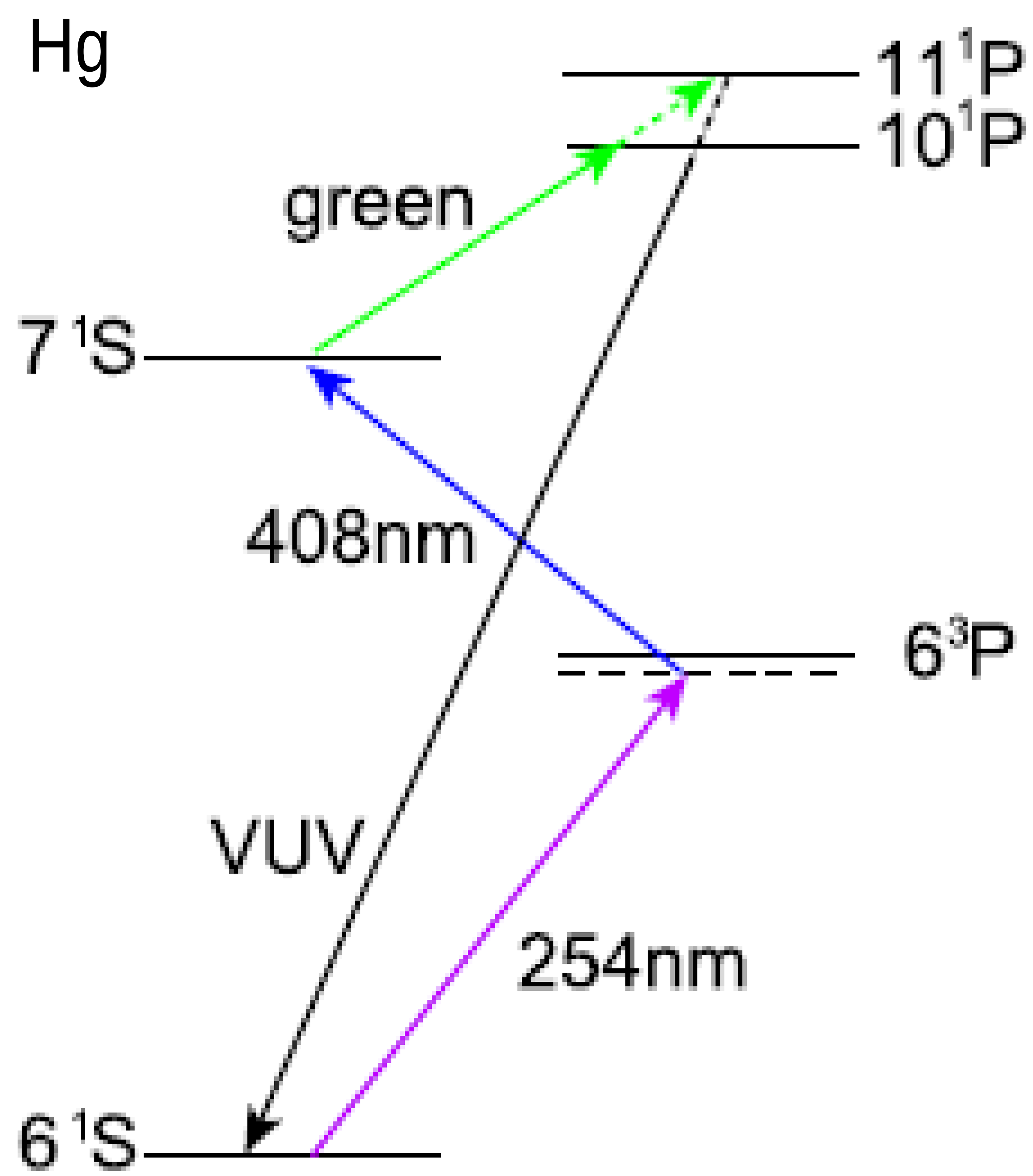


Quantum simulation with Rydberg ions



Quantum simulation with Rydberg ions





Generation of VUV light

Laser system: Jochen Walz

Schmidt-Kaler, Feldker, Kolbe, Walz, Müller, Zoller, Li, Lesanovsky,
NJP 13, 075014 (2011).

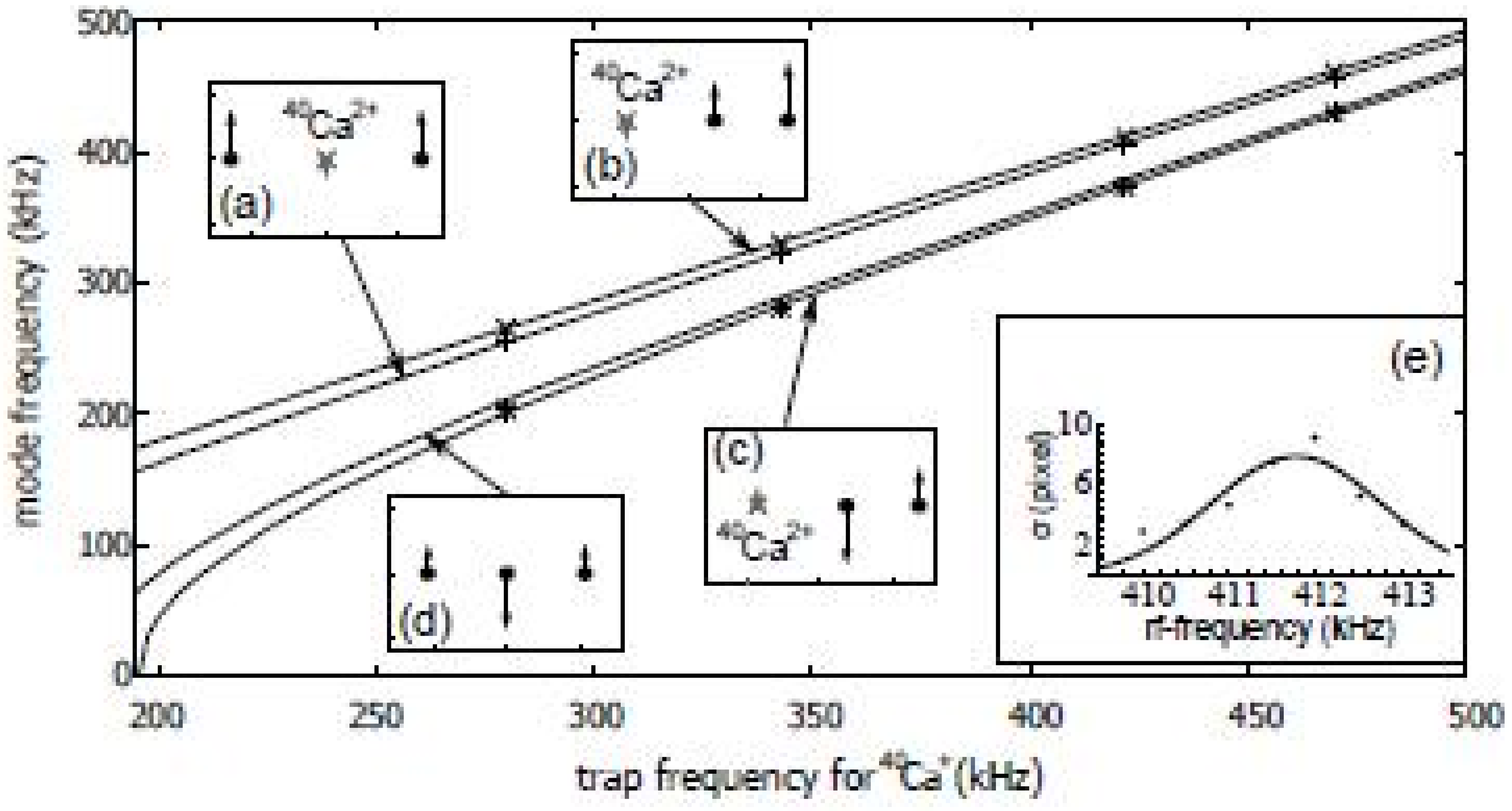
Using Rydberg ions for mode shaping

Since the Rydberg ions have a dipole moment the trap frequency changes significantly

$\omega_{ryd} = \beta\, \omega_i$

With $0.5 < \beta < 2$

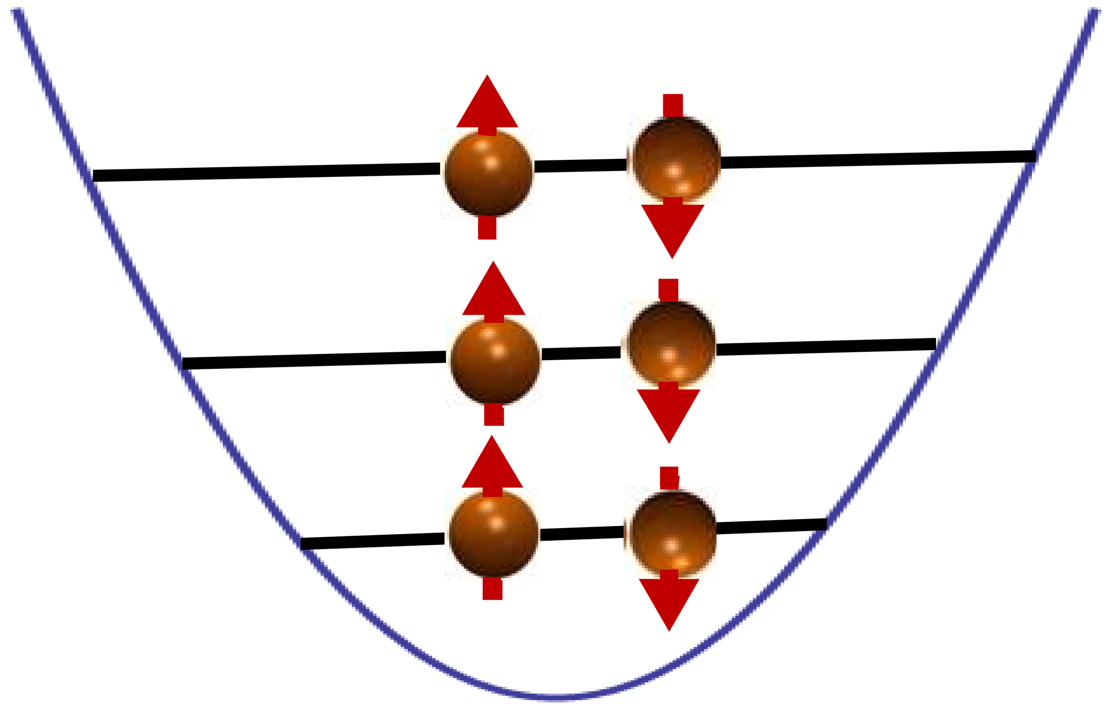
Extreme case: doubly ionised Ca2+

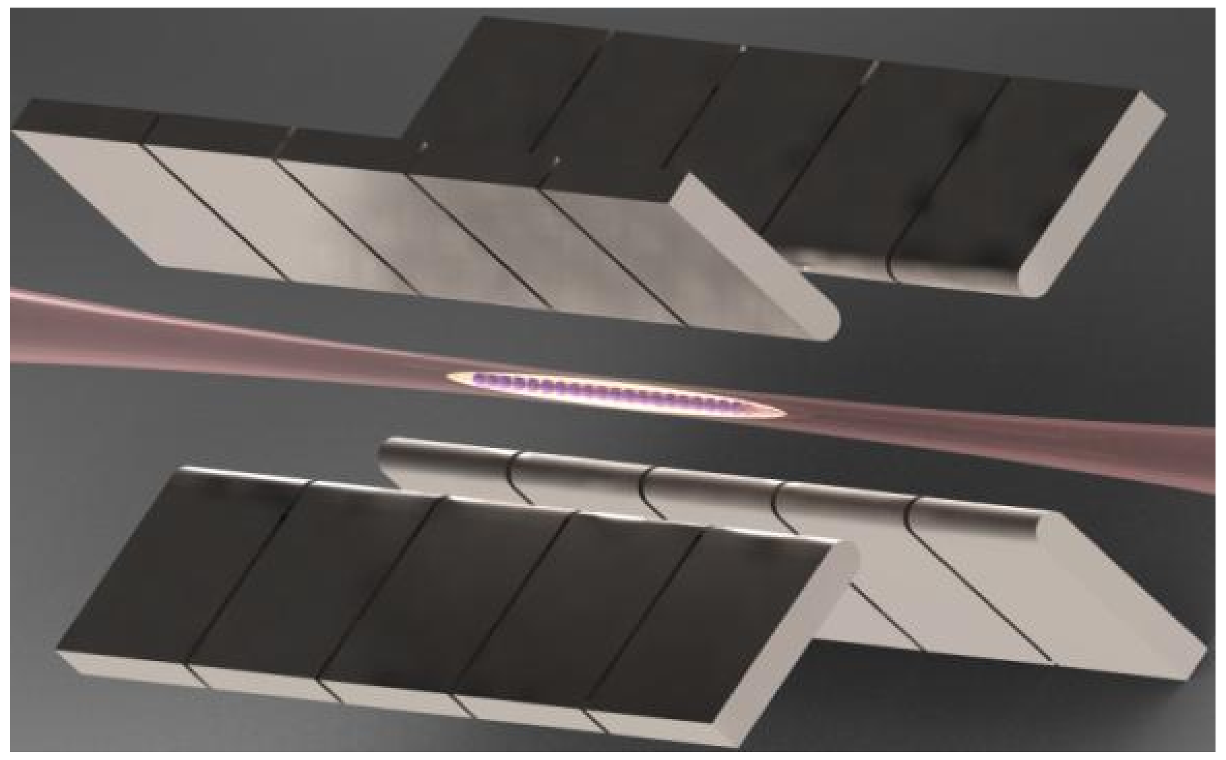


Feldker *et al.*, arXiv:1306.1109 (2013).

Li, Glaetzle, Nath and Lesanovsky, PRA 87,052304 (2013).
Schmidt-Kaler, Feldker, Kolbe, Walz, Müller, Zoller, Li, Lesanovsky, NJP 13, 075014 (2011).

Quantum simulation with cold ions AND atoms





Benasque October 2013

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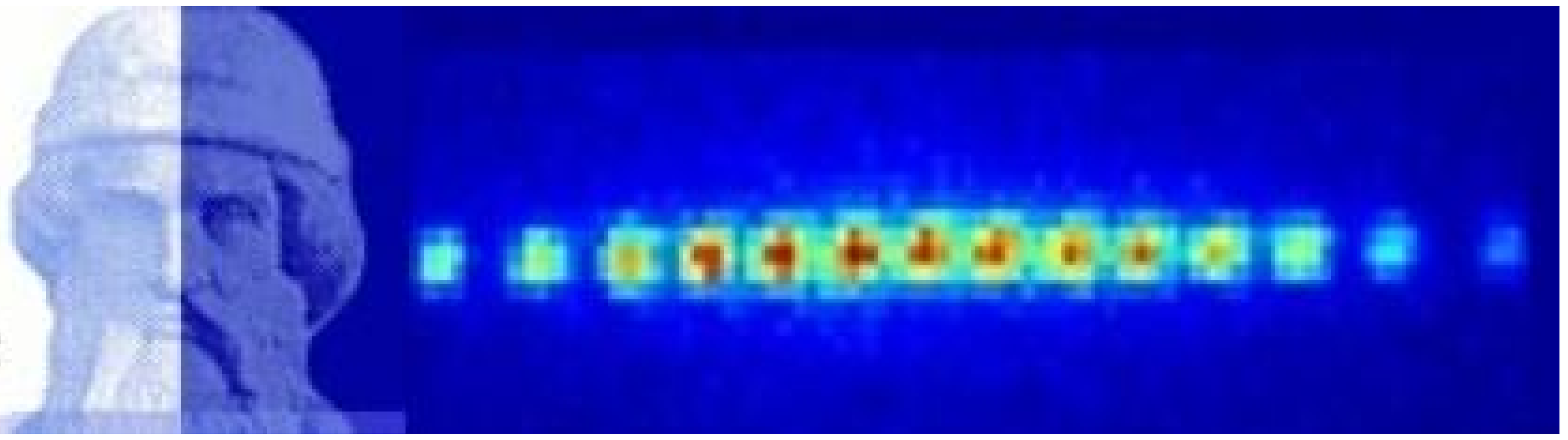
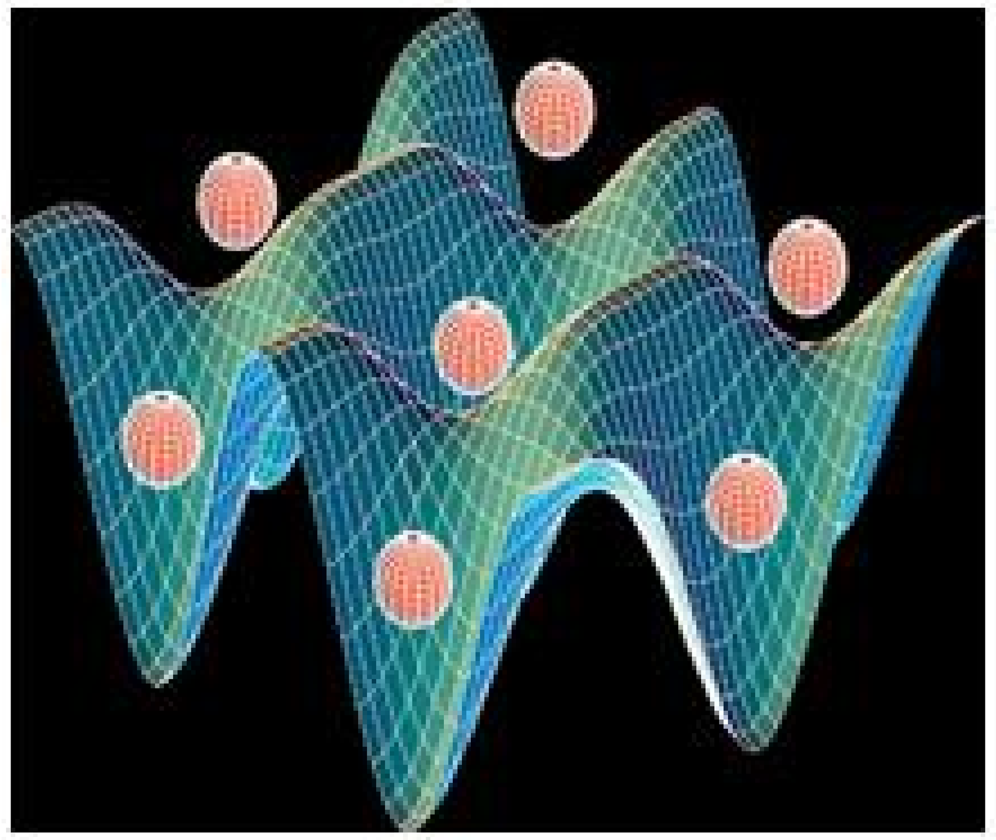


Atoms or ions

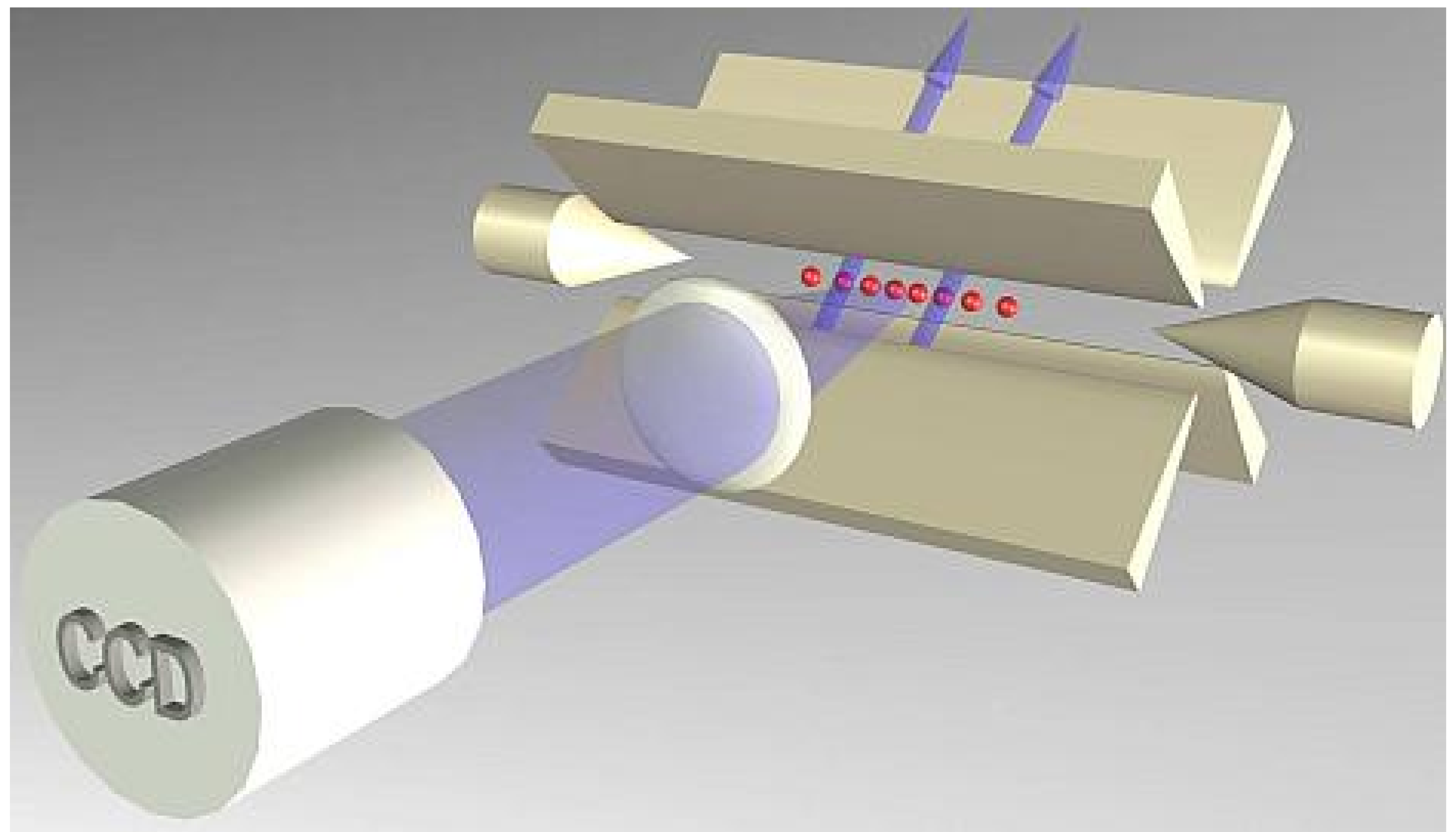
Cold atoms or ion are great for studying quantum many-body physics

Atoms in an optical lattice:
'Artificial solids'



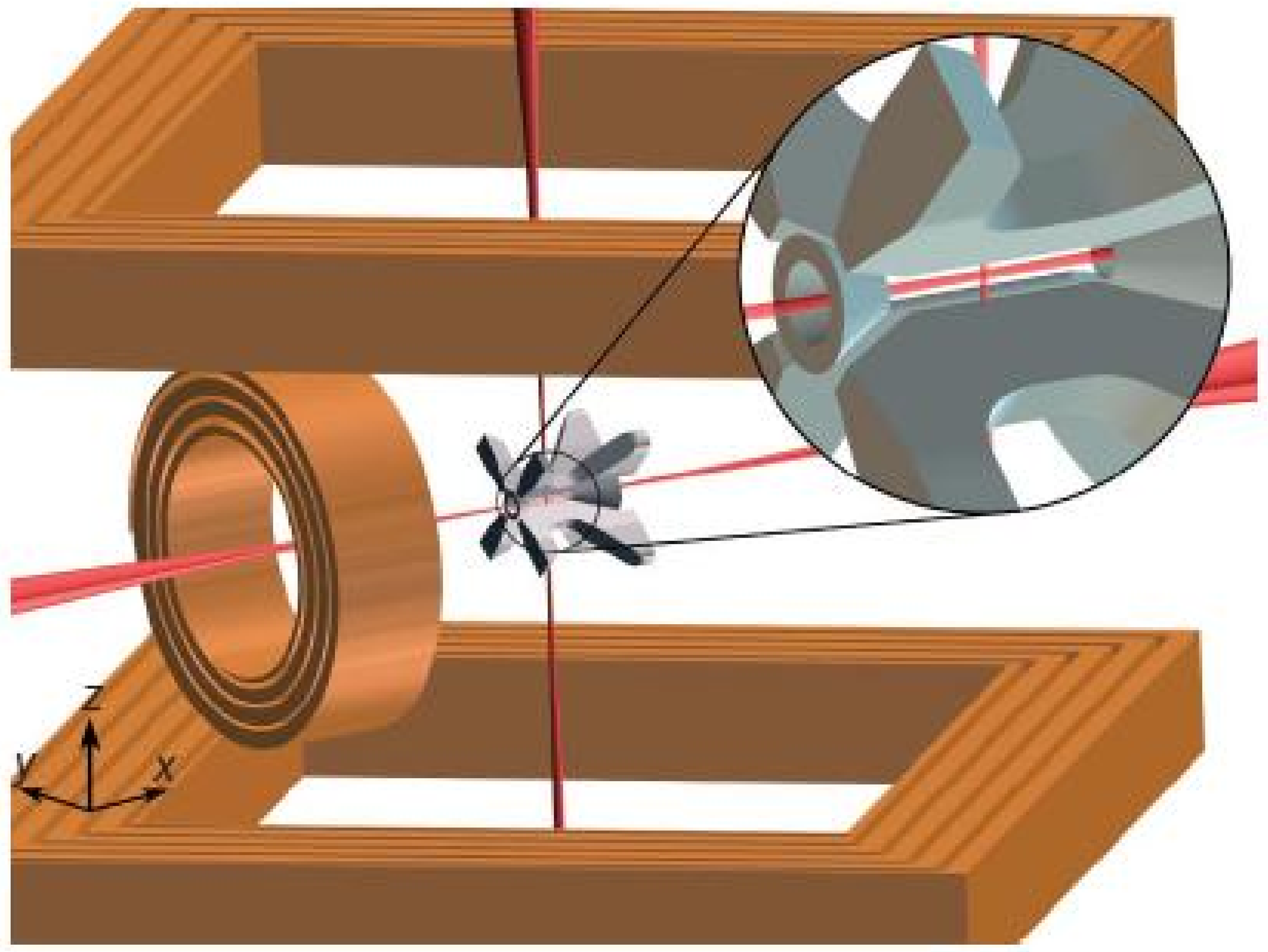
Easily scalable
Fermionic statistics
Harder to get long-range interaction
Harder to control/measure

Trapped ions:
'Arrays of interacting spins'

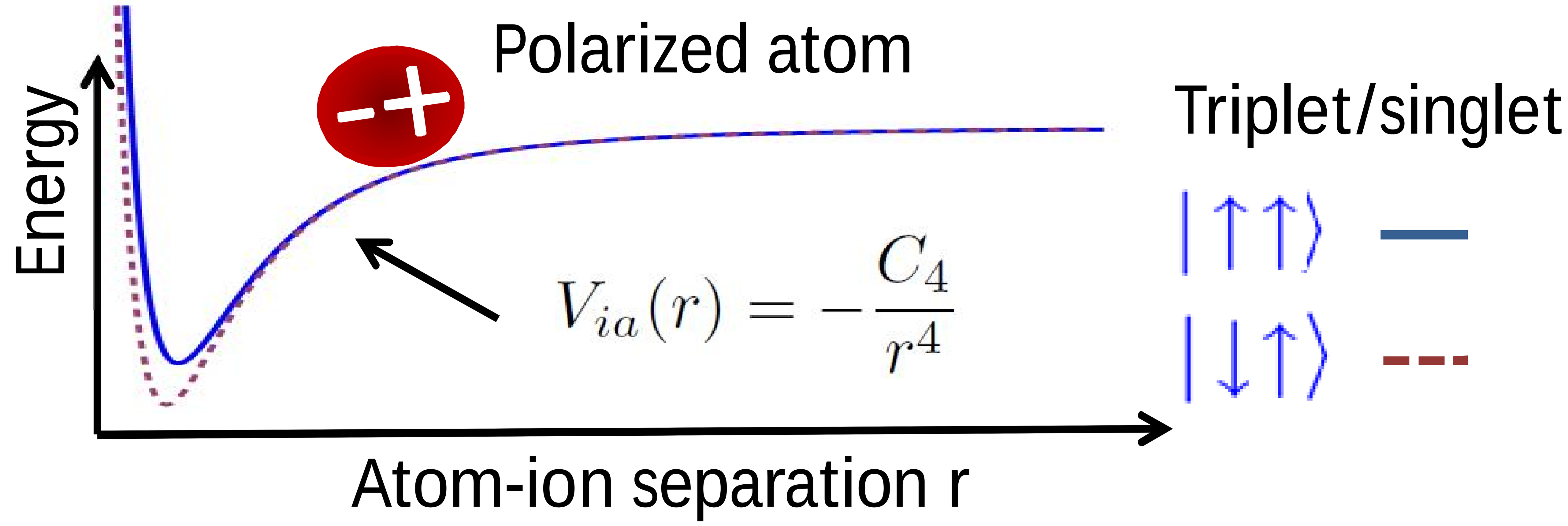


Superb control and readout
Long range interactions
Not easy to scale
No Fermionic statistics

Hybrid atom-ion systems



Picture: Michael Köhl



→ Sympathetic cooling
→ Ultracold collisions
→ Cold chemistry

Group	Species	S-wave limit (μK)	Interaction range (nm)
MIT	^{172}Yb / $^{174}Yb^+$	0.044	252
Ulm/Freiburg	^{87}Rb / $^{138}Ba^+$	0.052	295
Cambridge	^{87}Rb / $^{174}Yb^+$	0.044	307
	^{40}K / $^{174}Yb^+$	0.15	219
Mainz	^{6}Li / $^{174}Yb^+$	8.7	70

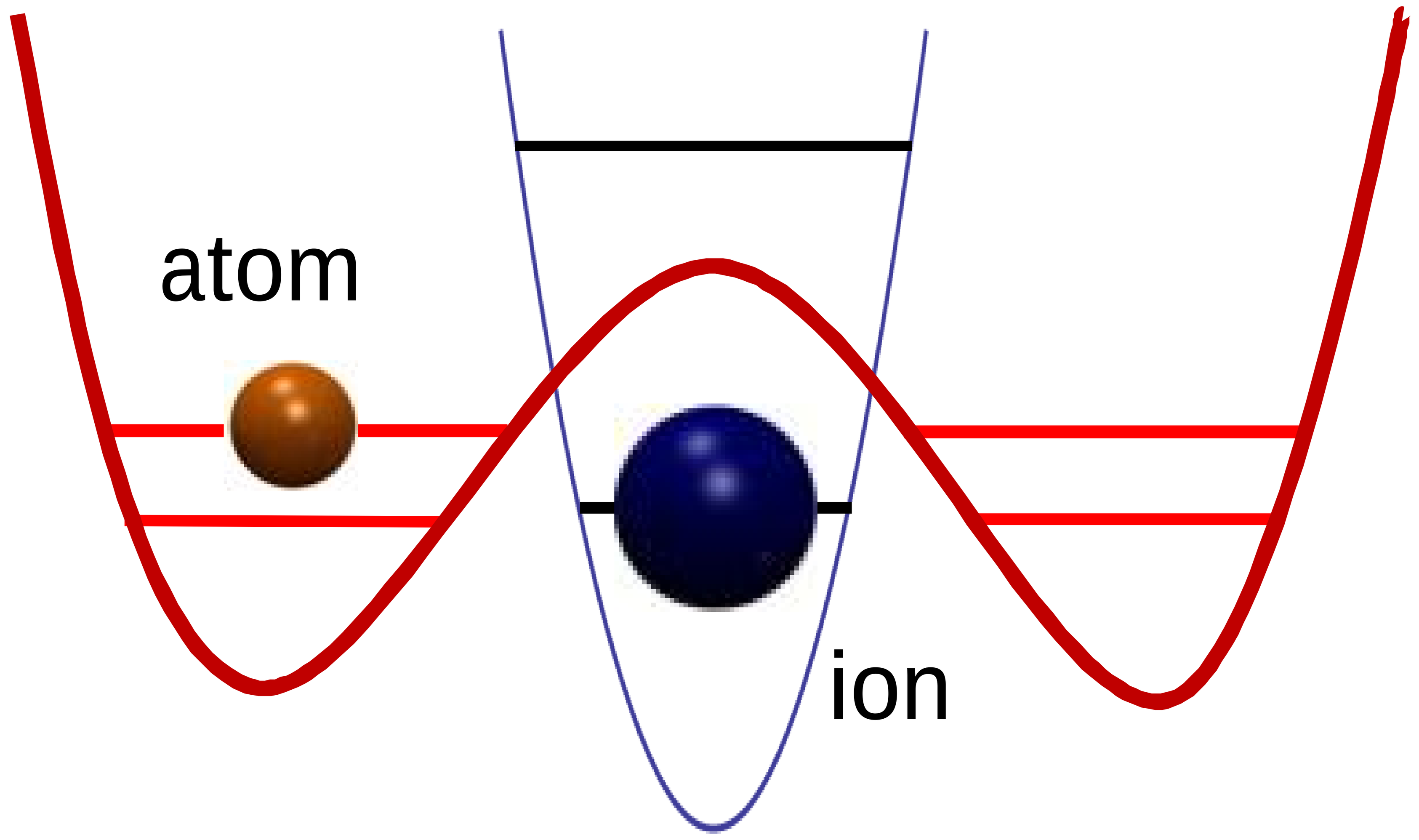
Bosons

Fermions

A. T. Grier *et al.*, PRL 102, 223201 (2009).
C. Zipkes *et al.*, Nature 464, 388 (2010).
S. Schmid *et al.*, PRL 105, 133202 (2010).
S. Schmid *et al.*, PRL 105, 133202 (2010).
A.Härter and J. Hecker Denschlag, arXiv:1309.5799

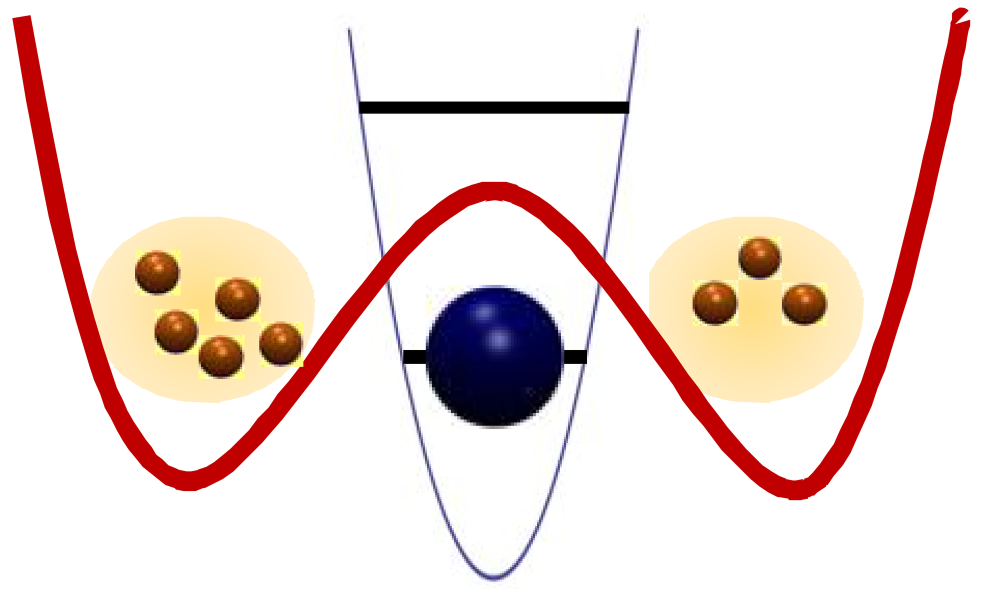
Atom-ion quantum simulator 'unit cell'

A single atom in a double-well potential with a single trapped ion in its center.

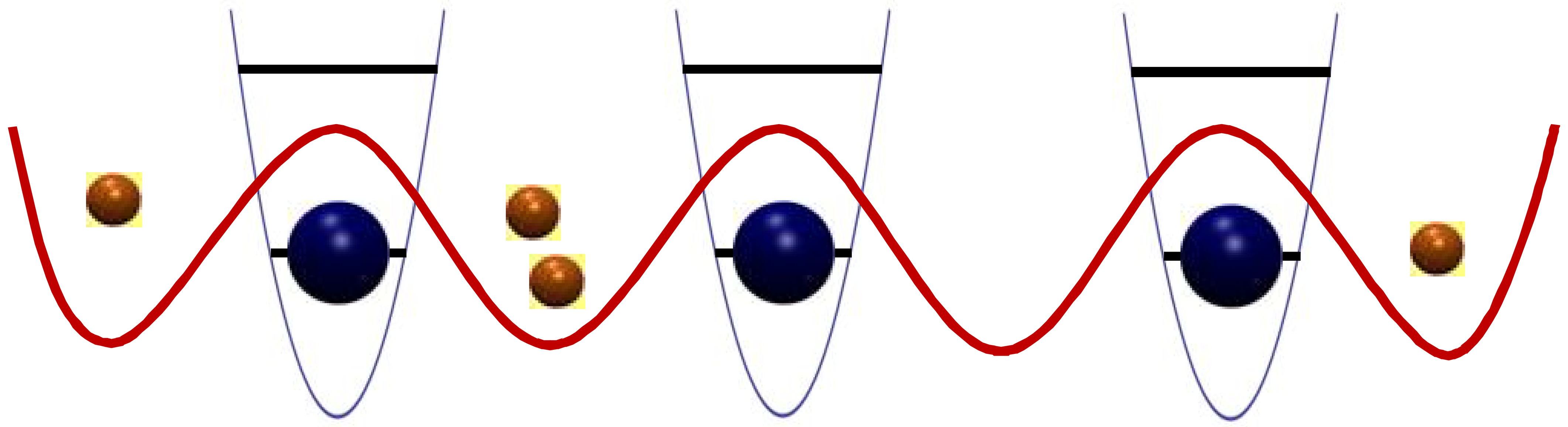


Why this system?

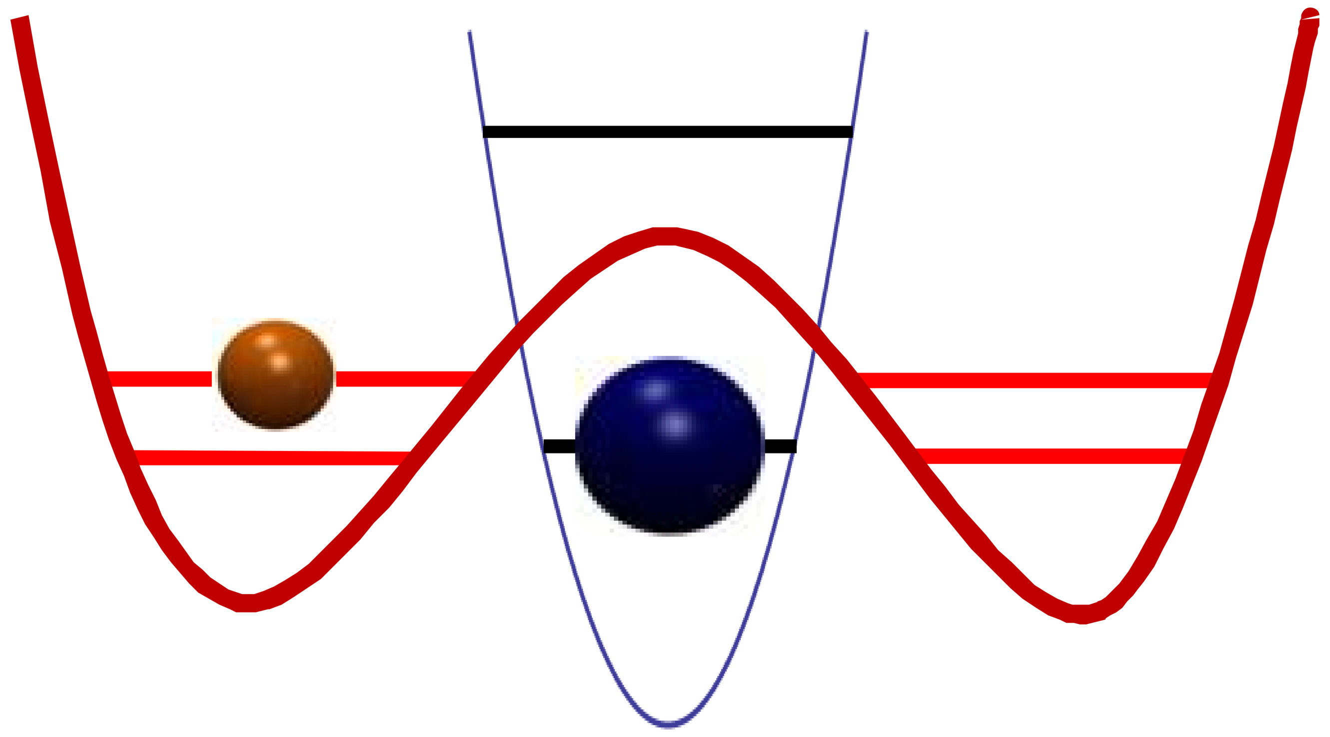
- Because it is not too easy, not too hard
- Many atoms: Atomic Josephson Junction
- Add spin degree of freedom
- Easy to build up larger systems from unit cell



RG, Negretti *et al.*, *PRL* 109, 080402 (2012).
J. Joger et al., *in prep*



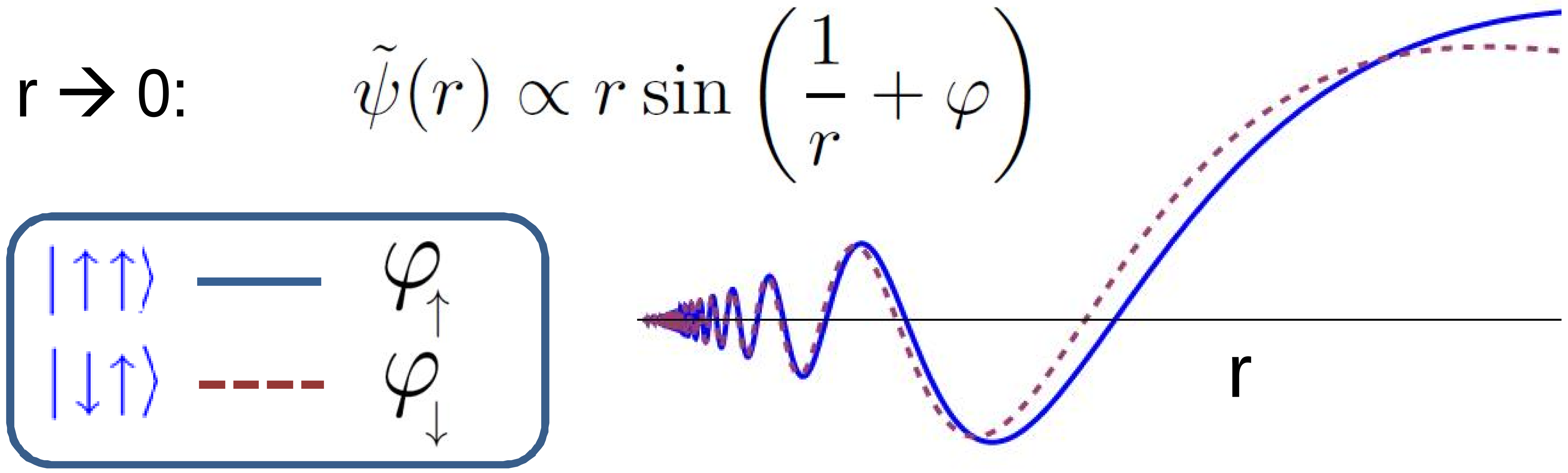
Dealing with the ion: Quantum defect theory



→ Atom-ion interaction at long range

$$V_{ia}(r) = -\frac{C_4}{r^4}$$

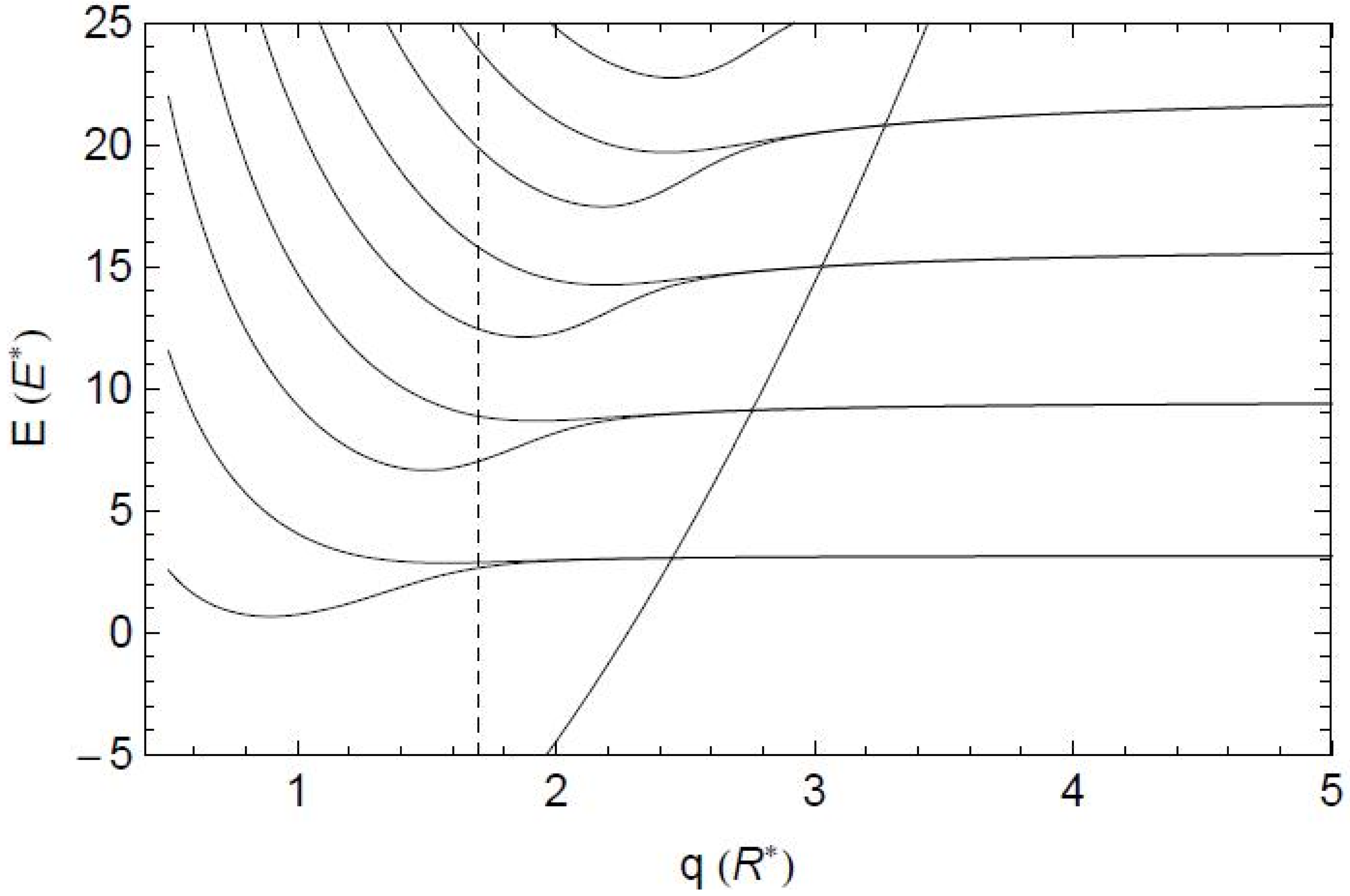
→ Wave function for r → 0: $\tilde{\psi}(r) \propto r \sin\left(\frac{1}{r} + \varphi\right)$

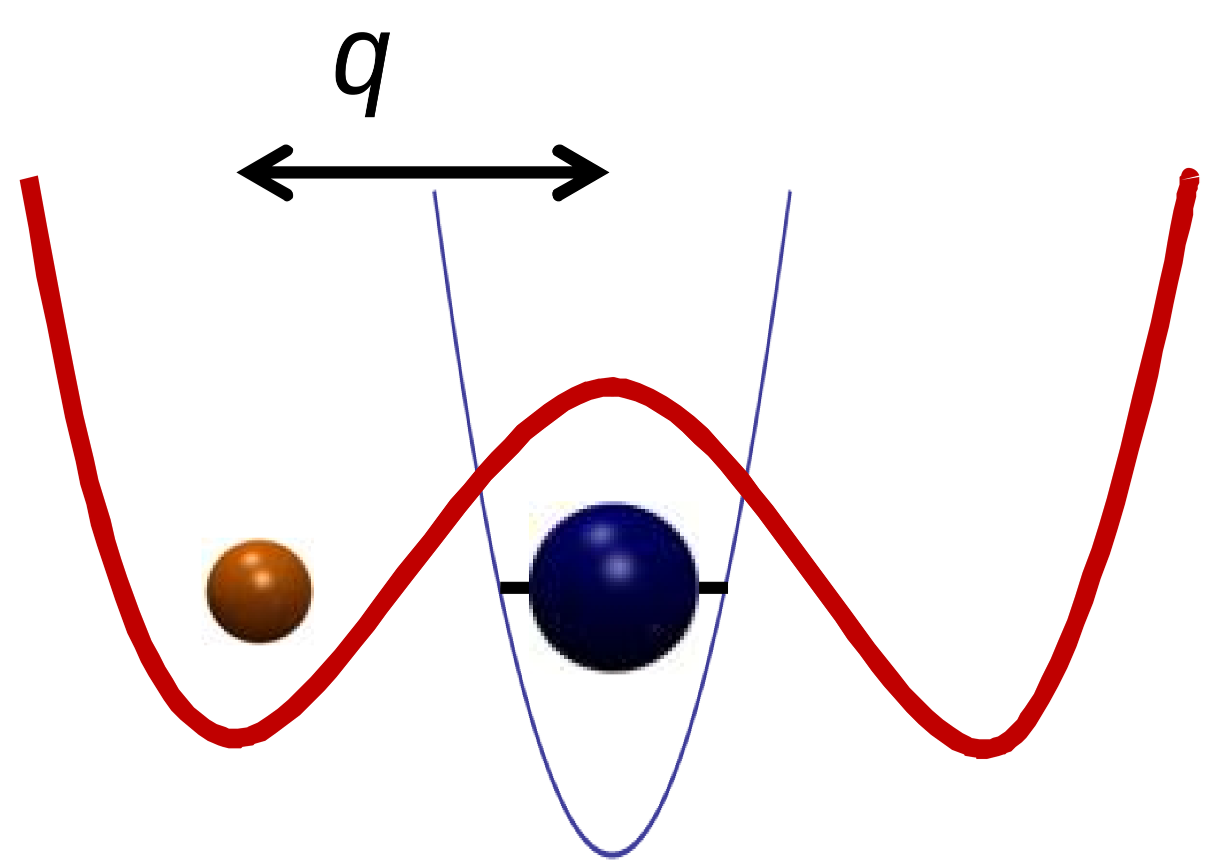


→ φ is related to the s-wave scattering length: $a = -R^* \cot \varphi$

Z. Idziazsek, T. Calarco and P. Zoller, PRA 76, 033409 (2007).

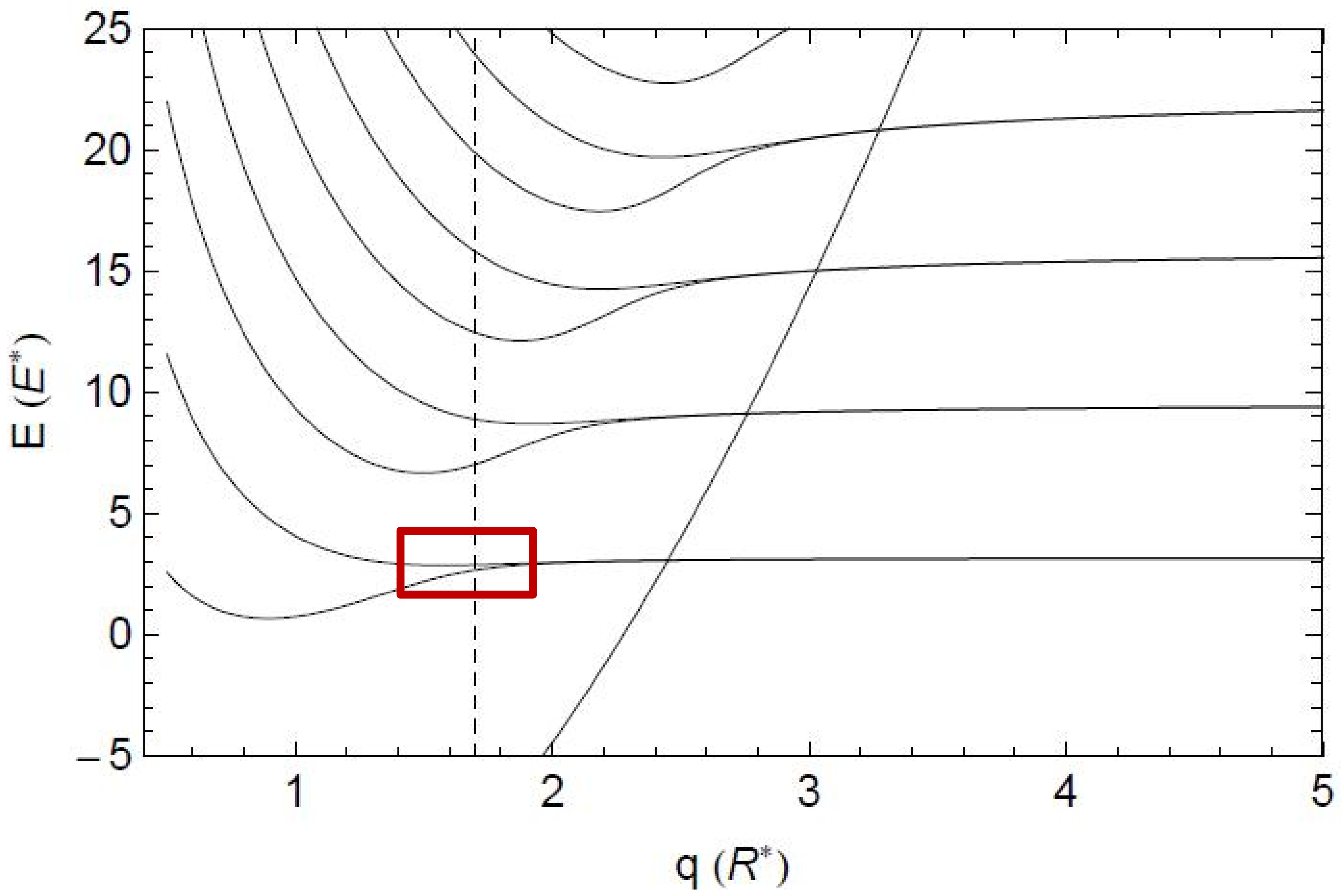
The simplest model: A static ion

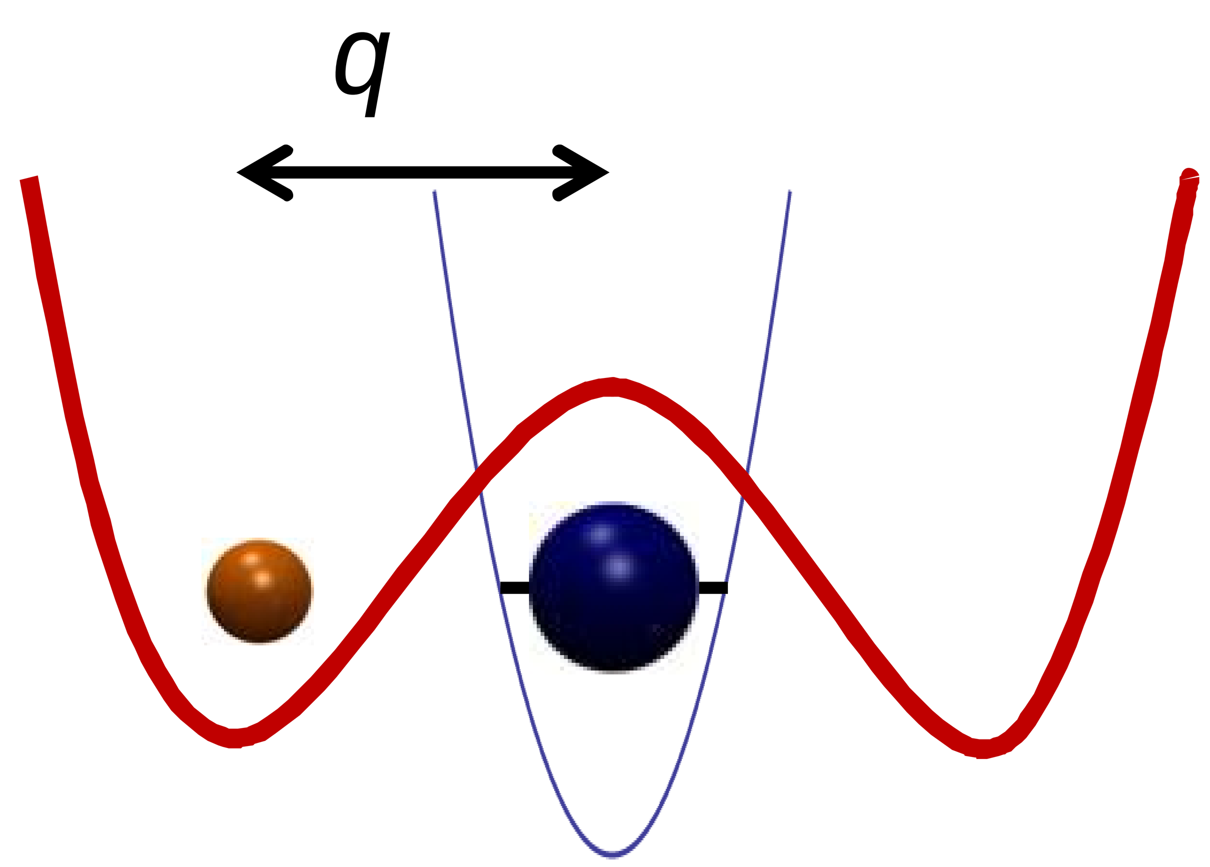




$$H_a = \frac{p_a^2}{2m_a} + V_{dw}(r_a) - \frac{C_4}{r_a^4}$$

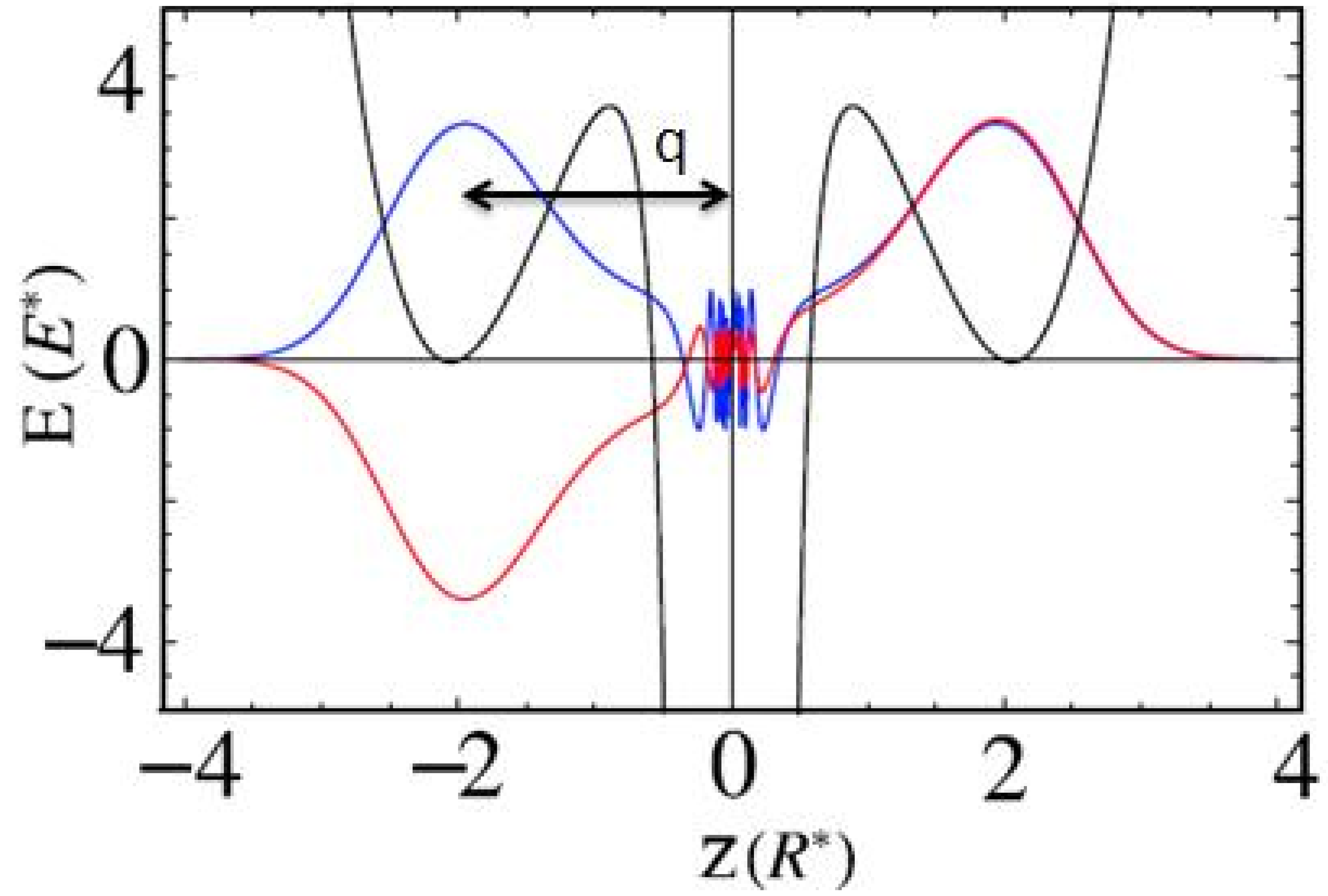
The simplest model: A static ion





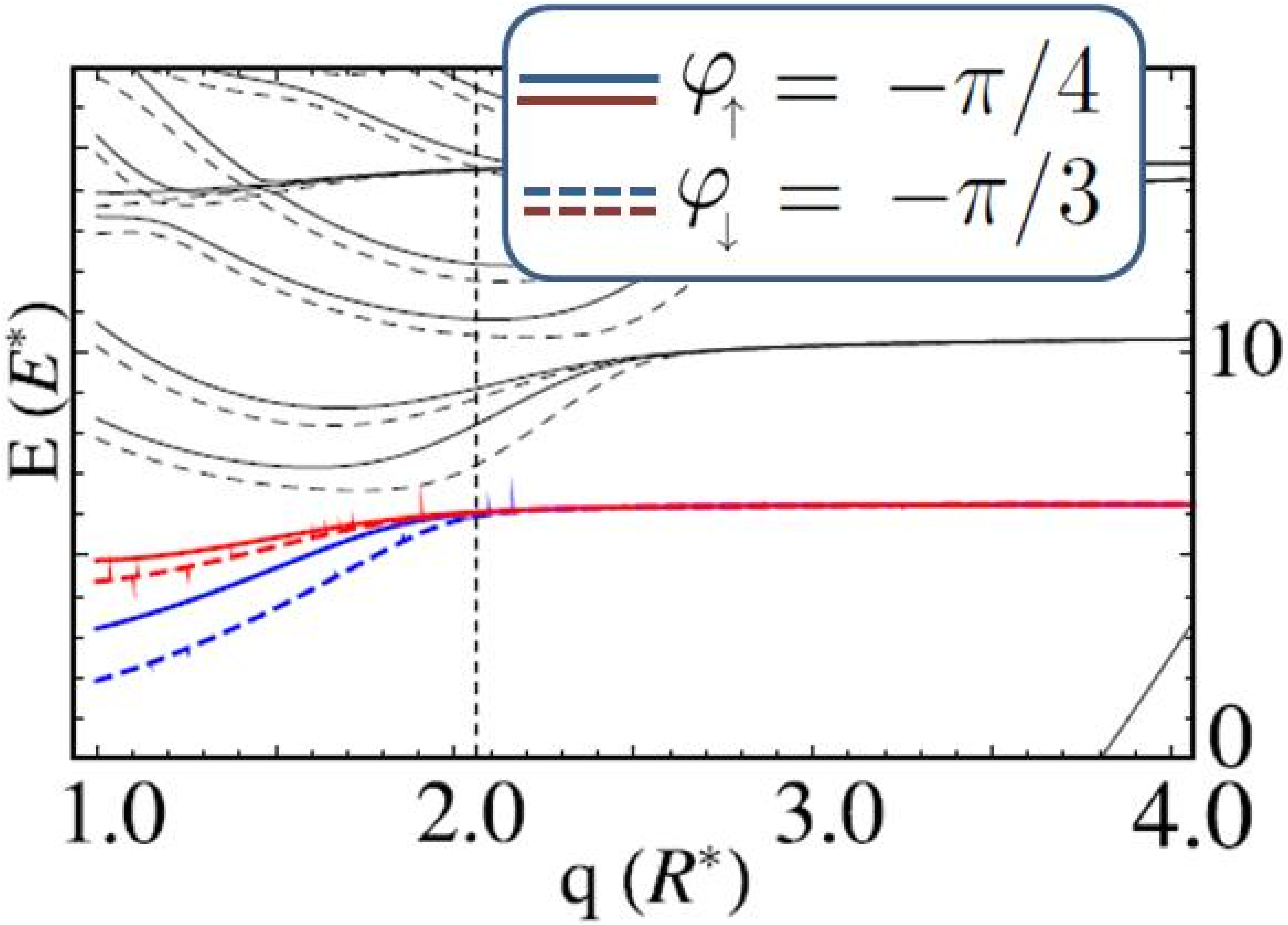
$$H_a = \frac{p_a^2}{2m_a} + V_{dw}(r_a) - \frac{C_4}{r_a^4}$$

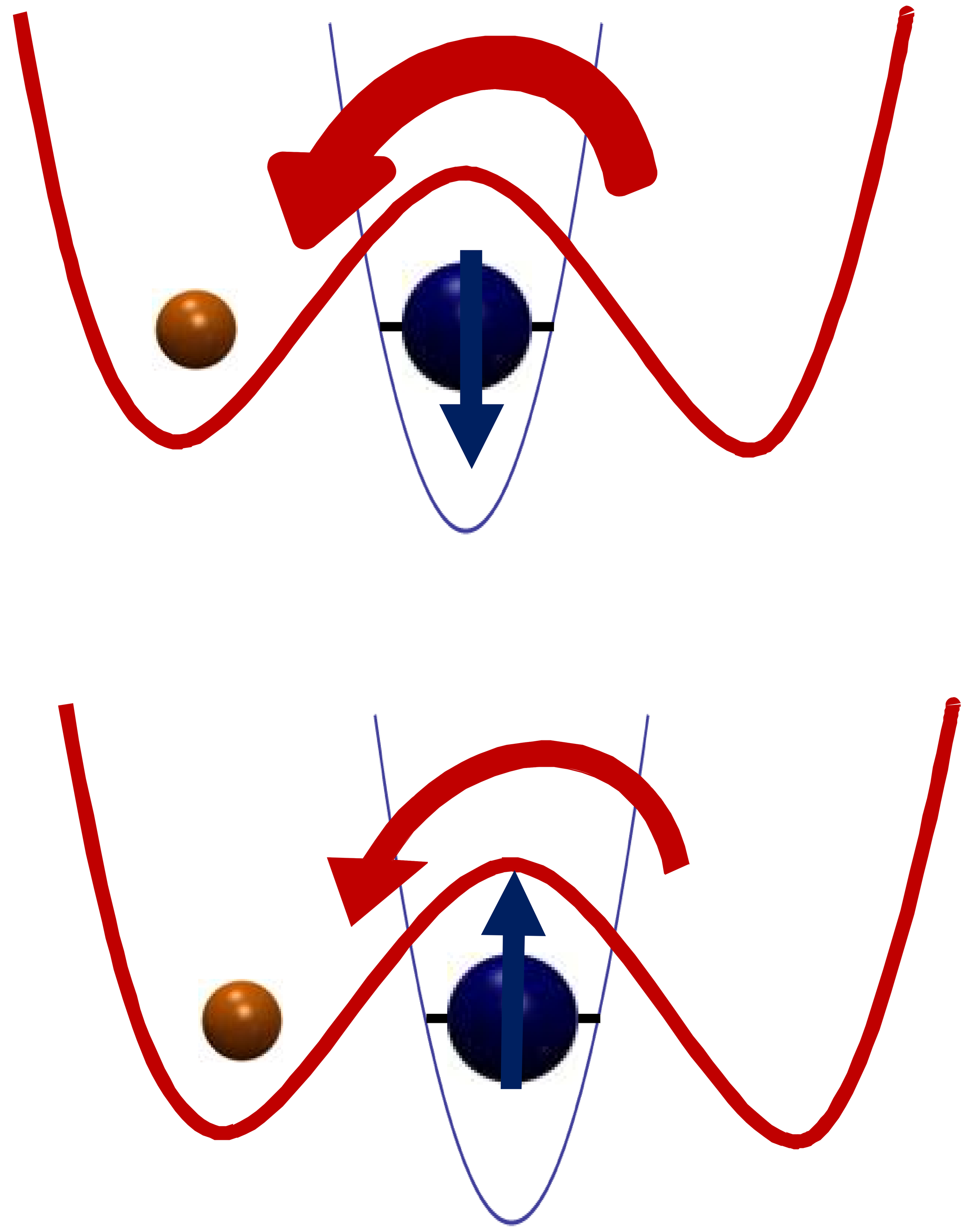
‘Ground state’ orbitals



- → Large inter well distance: independent wells, No coupling to ion.
- → Closer distances: splitting into even and odd states.
- → 2-mode approximation!
- → Small coupling to molecular states.

Spin dependence (3D)





Ground states are superpositions of localised modes

$$\Phi_{g,e}(\mathbf{r}) = (\Phi_L(\mathbf{r}) \pm \Phi_R(\mathbf{r}))/\sqrt{2}$$

Interwell coupling:

$$\Omega = \Delta E/\hbar$$
$$\Delta E = E_e - E_g$$

Many atoms (bosons)

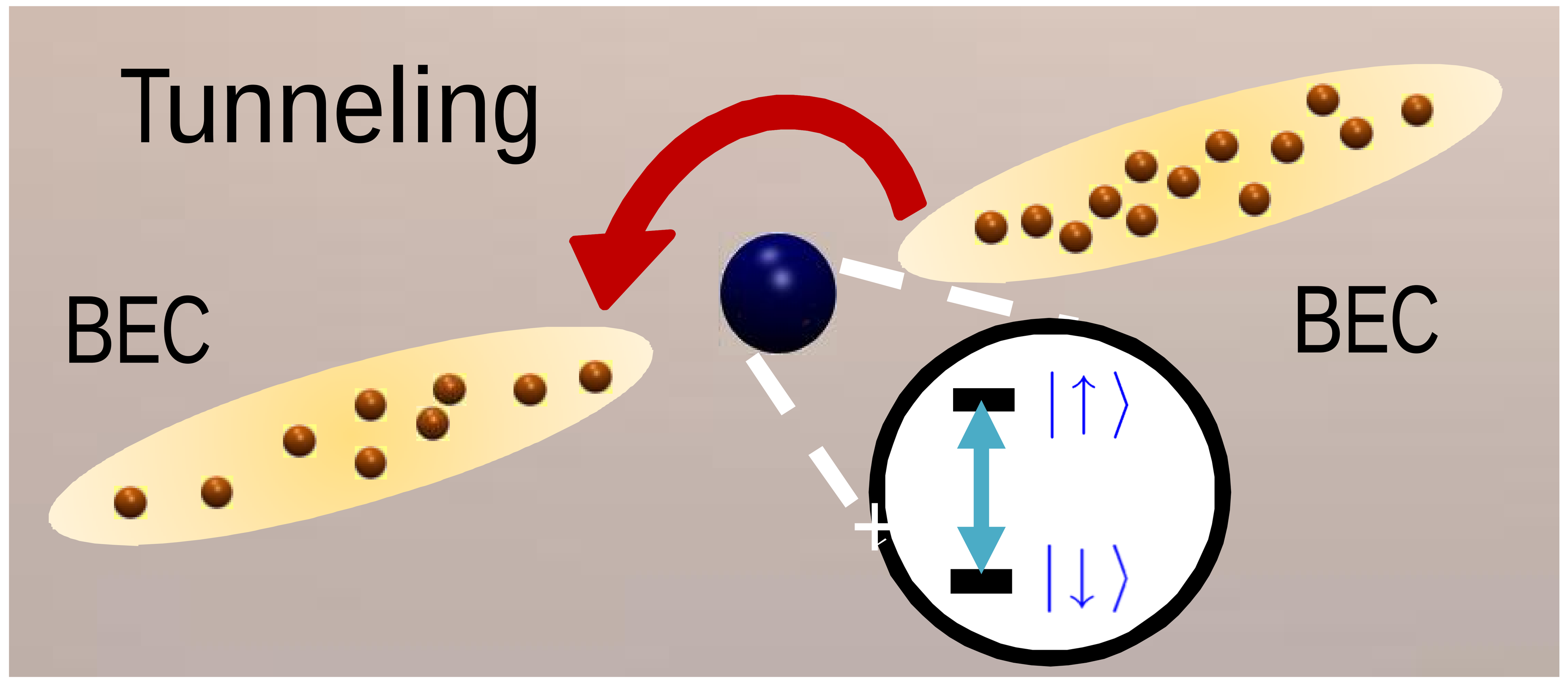
Bose-Hubbard Hamiltonian:

$$\hat{H} = \hbar\hat{J}\left(\hat{c}_L^\dagger\hat{c}_R + \hat{c}_R^\dagger\hat{c}_L\right) + \frac{\hbar}{4}\hat{U}\left(\hat{c}_R^\dagger\hat{c}_R - \hat{c}_L^\dagger\hat{c}_L\right)^2$$

State dependent!

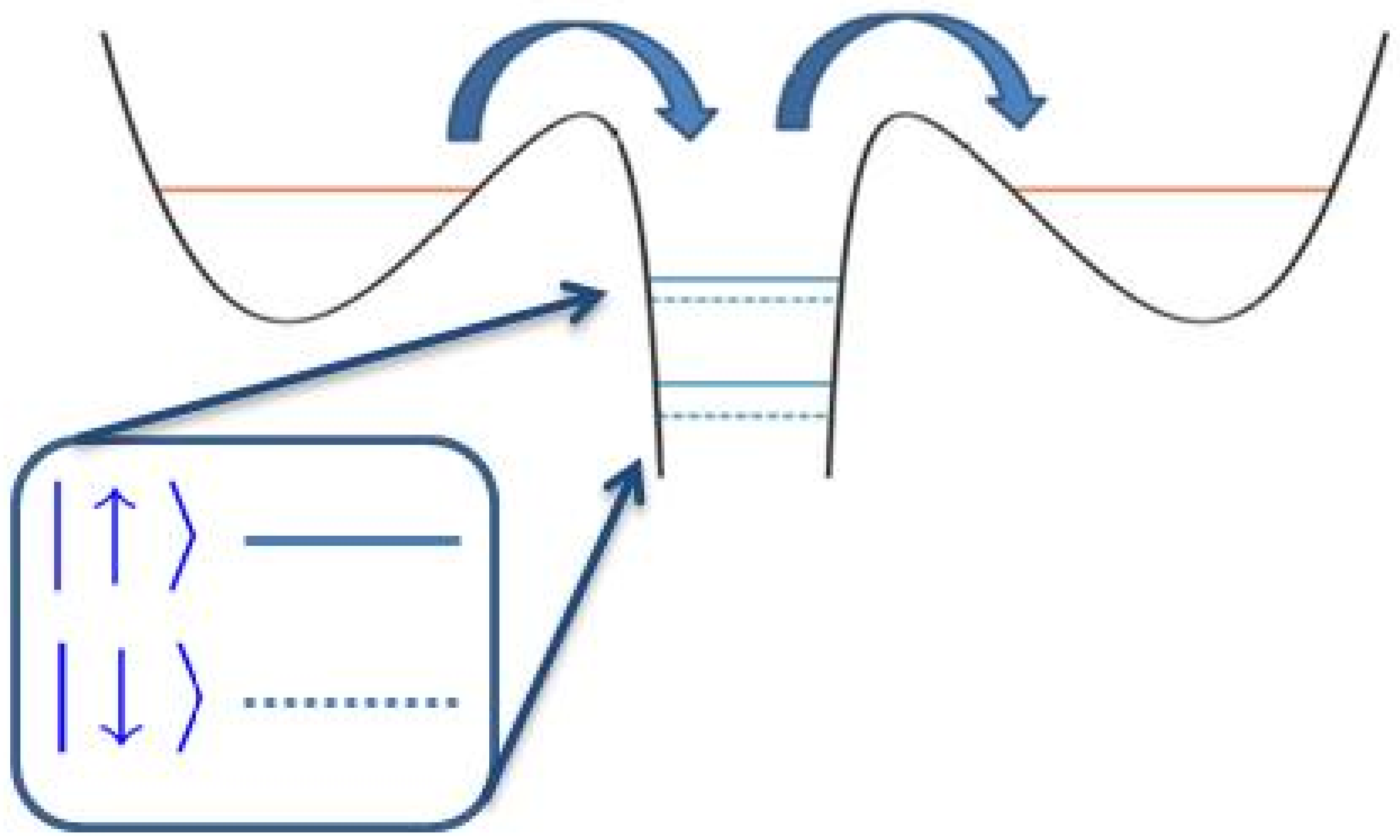
$$\Delta E = E_e - E_g \qquad J = \Delta E/(2\hbar)$$

$$U = \frac{U_0}{\hbar}\int d\mathbf{r}|\Phi_L(\mathbf{r})|^4 \qquad U_0 = \frac{4\pi a_a \hbar^2}{m_a}$$



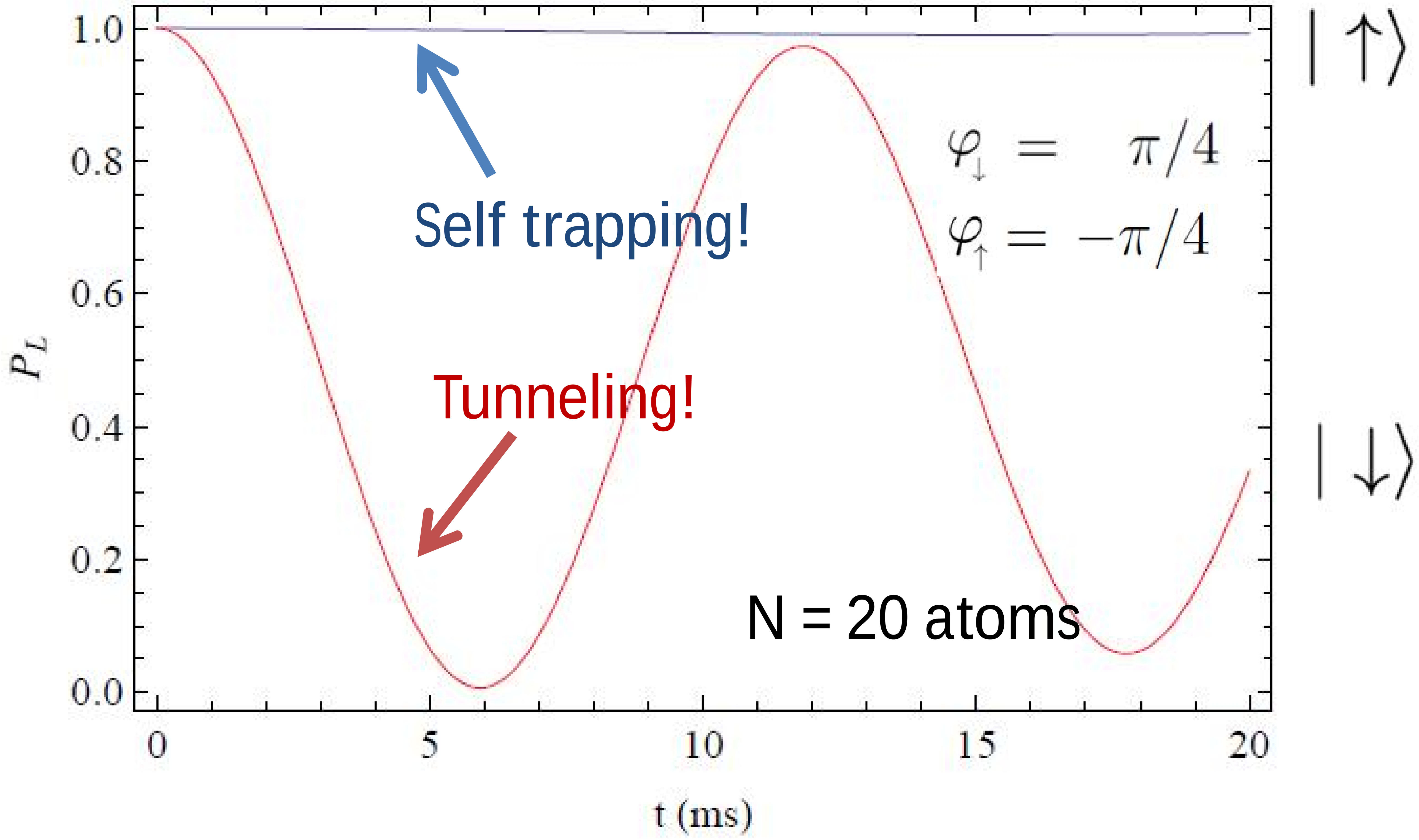
$\cong$

Picture: 3-well



Related work:
U. R. Fischer *et al.*, PRA 77, 031602R (2008).

Superpositions of many-body dynamics



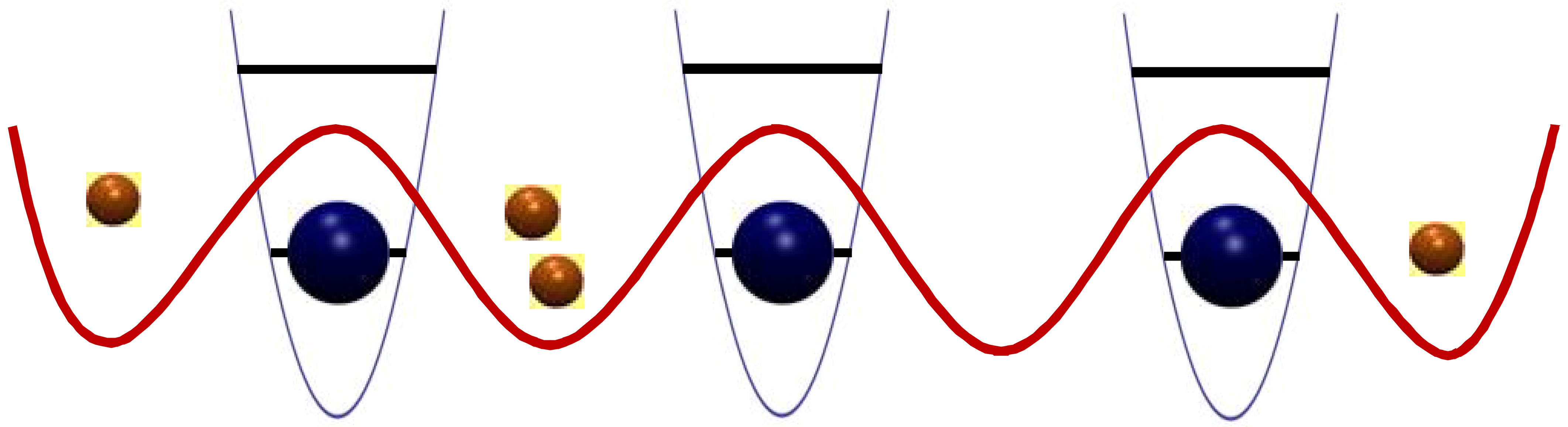
spin

Rb and Yb^+, local trapfreqs of 2π 200 Hz

→ Requires sufficiently large difference between spin short range phases.

→ Need to go beyond BH model for long time scales
K. Sakmann *et al.*, Phys. Rev. Lett. 103, 220601 (2009).

Large systems

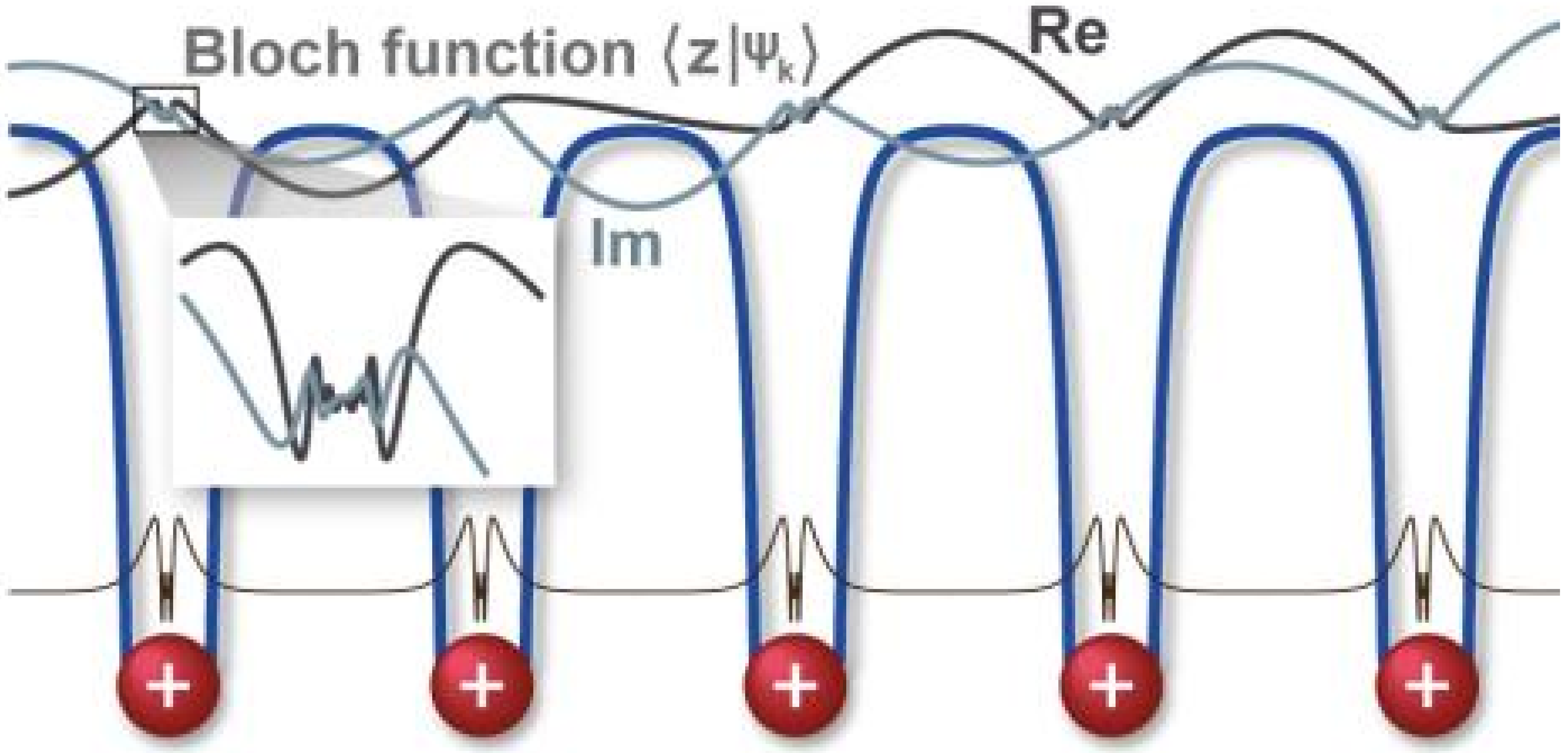


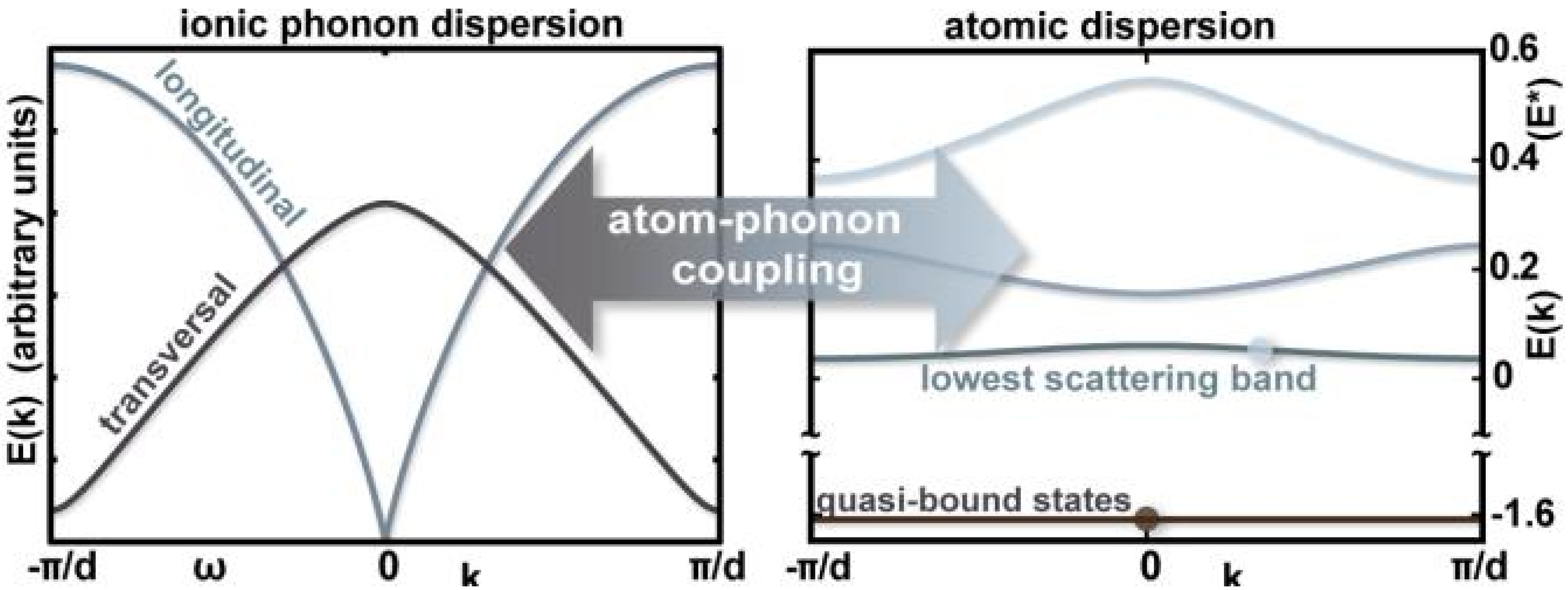
→ A string of ions overlapped with a cloud of ultracold fermions: an artificial solid??

	Solid state	^{6}Li-^{174}Yb$^+$	^{40}K-^{40}Ca$^+$
Lattice spacing d (nm)	0.3–0.6	10^3–10^4	10^3–10^4
Length scale R^* (nm)	0.026	71	245
Energy scale E^* (kHz)	10^{13}	166	2.1
d/R^*	10–20	14–140	4–40
m_i/m_f	10^4–10^5	29	1.0
Fermi energy (MHz)	10^8	0.02	0.02
Phonon energy (MHz)	10^6	0.01–10	0.01–10

Bandstructure

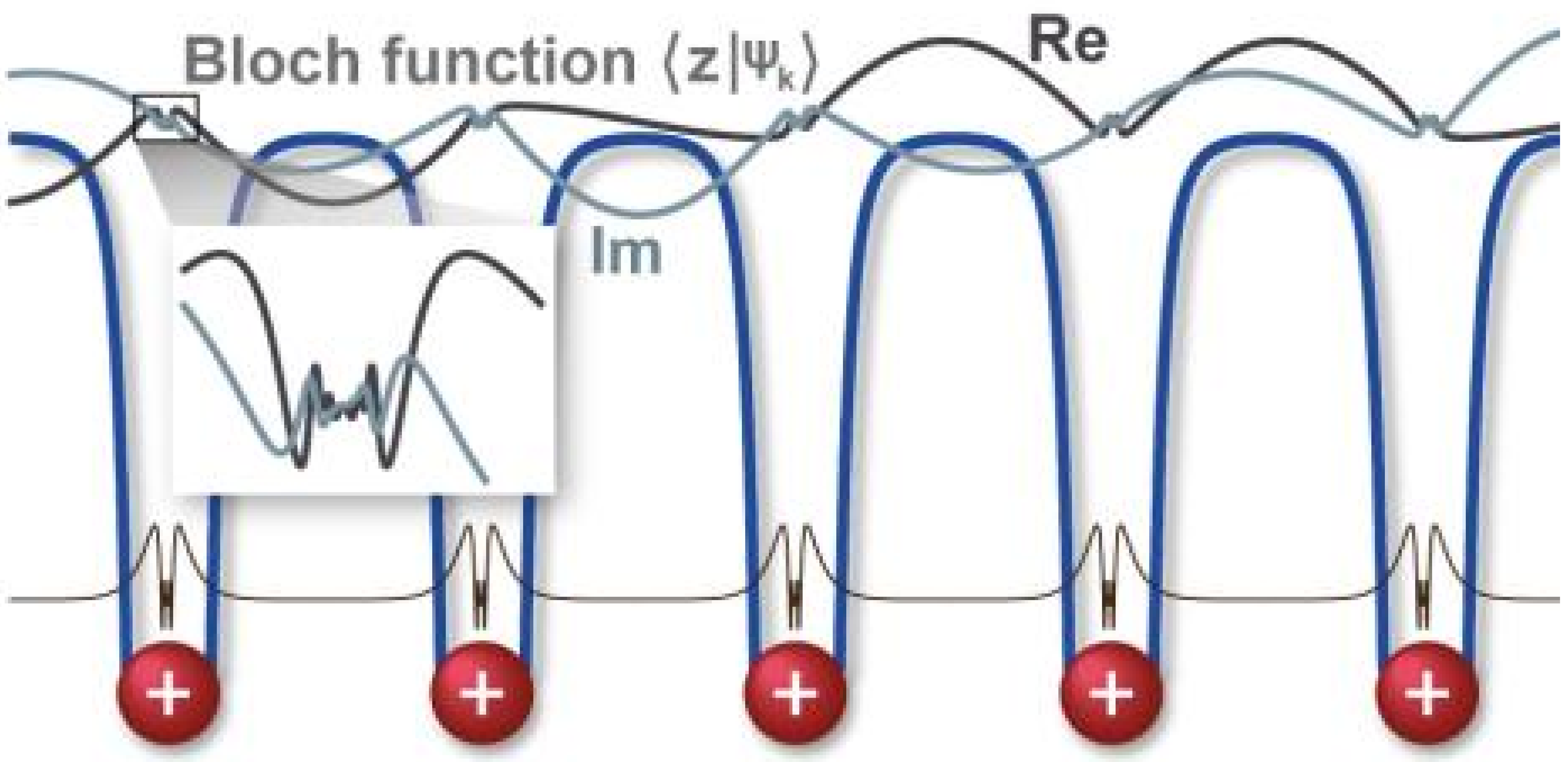
→ Combine quantum defect theory with the Bloch theorem
→ Find phonons of ion string
→ Compute first order coupling





U. Bissbort, D. Cocks, A. Negretti, Z. Idziaszek, T. Calarco, W. Hofstetter, F. Schmidt-Kaler and RG, Phys. Rev. Lett. 111, 080501 (2013).

Fermion-phonon coupling



Ion crystal + atoms: Fröhlich model

- Atomic bandstructure
- Fermion-phonon coupling
- phonon mediated interactions
- Polarons
- Peierls instabilities

Fröhlich type Hamiltonian

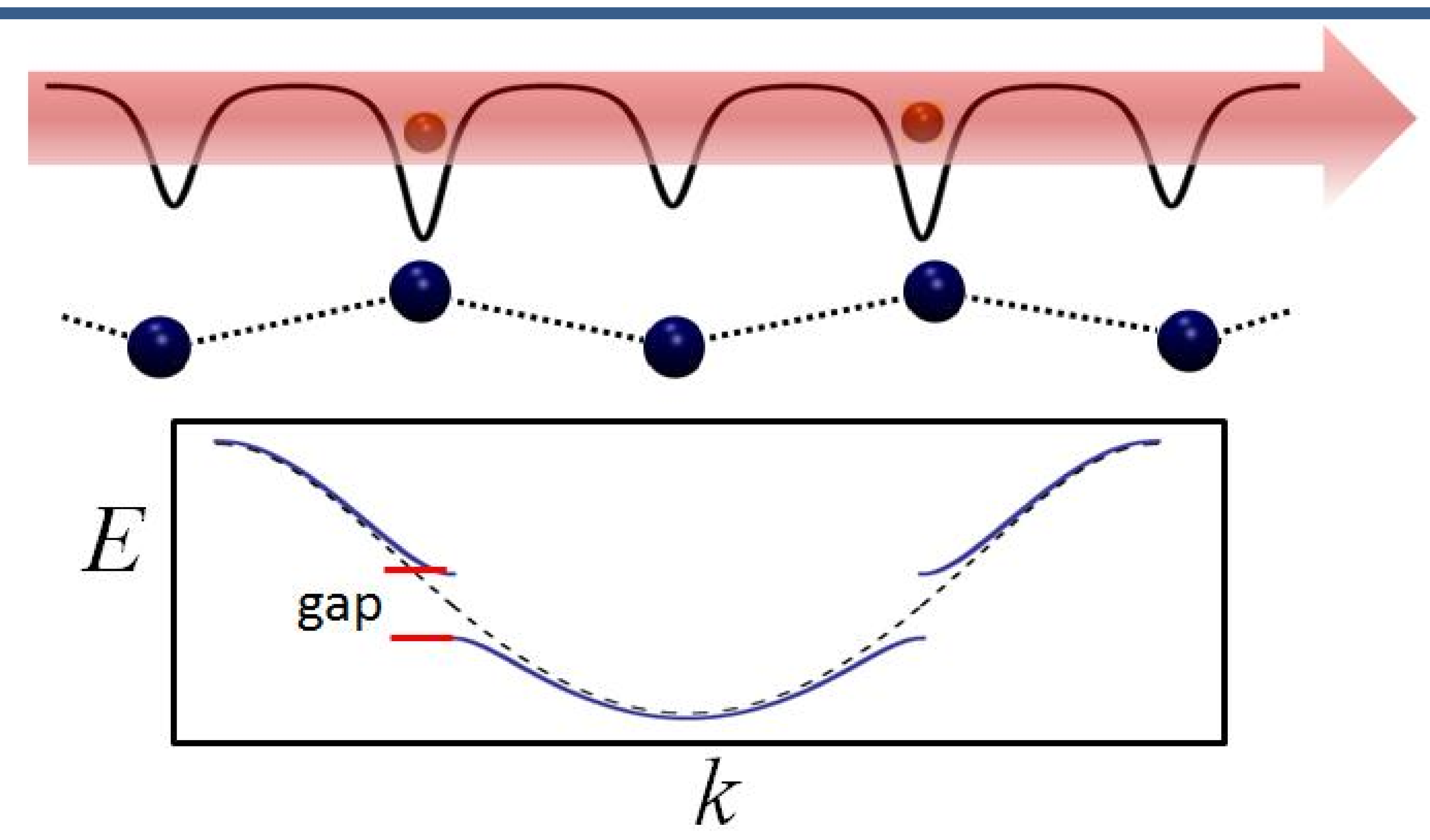
$$\mathcal{H} = \underbrace{\sum_n \hbar\omega_n a_n^\dagger a_n}_{\text{Phonons}} + \underbrace{\sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c_{\mathbf{k}}^\dagger c_{\mathbf{k}}}_{\text{Fermions}} + \underbrace{\sum_{\mathbf{k}\mathbf{k}'s} \lambda_{\mathbf{k}\mathbf{k}'s}(a_s^\dagger + a_s) c_{\mathbf{k}}^\dagger c_{\mathbf{k}'}}_{\text{Fermion-phonon coupling}}$$

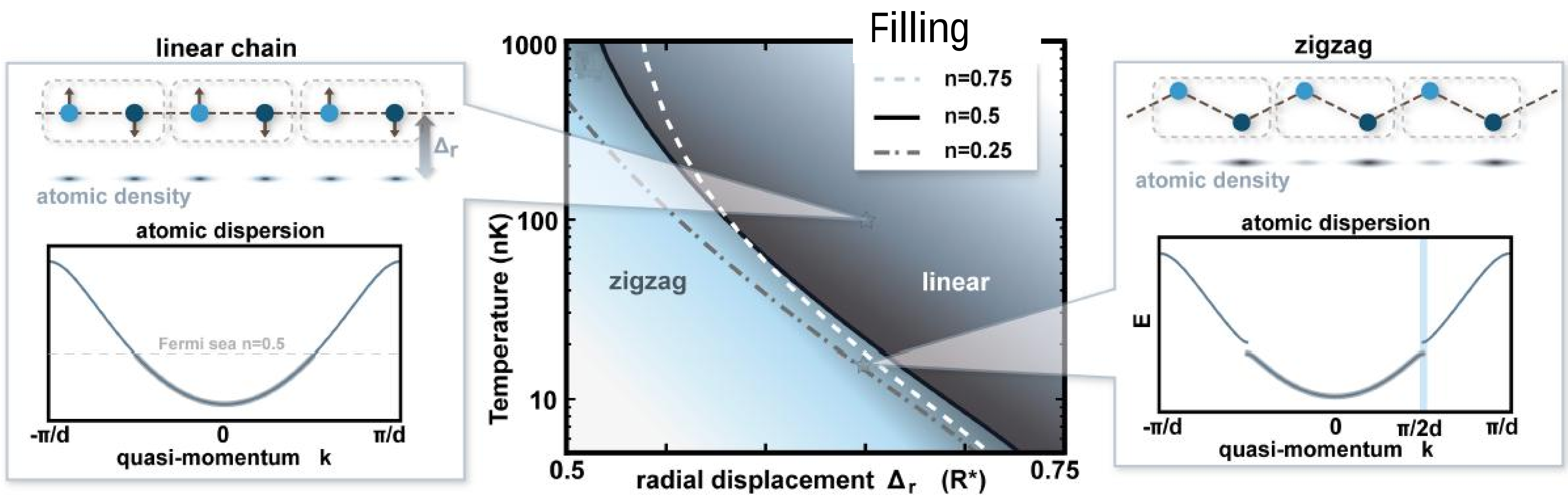
Polarons, Phonon-mediated interactions, Peierls instability,....

Peierls type instability

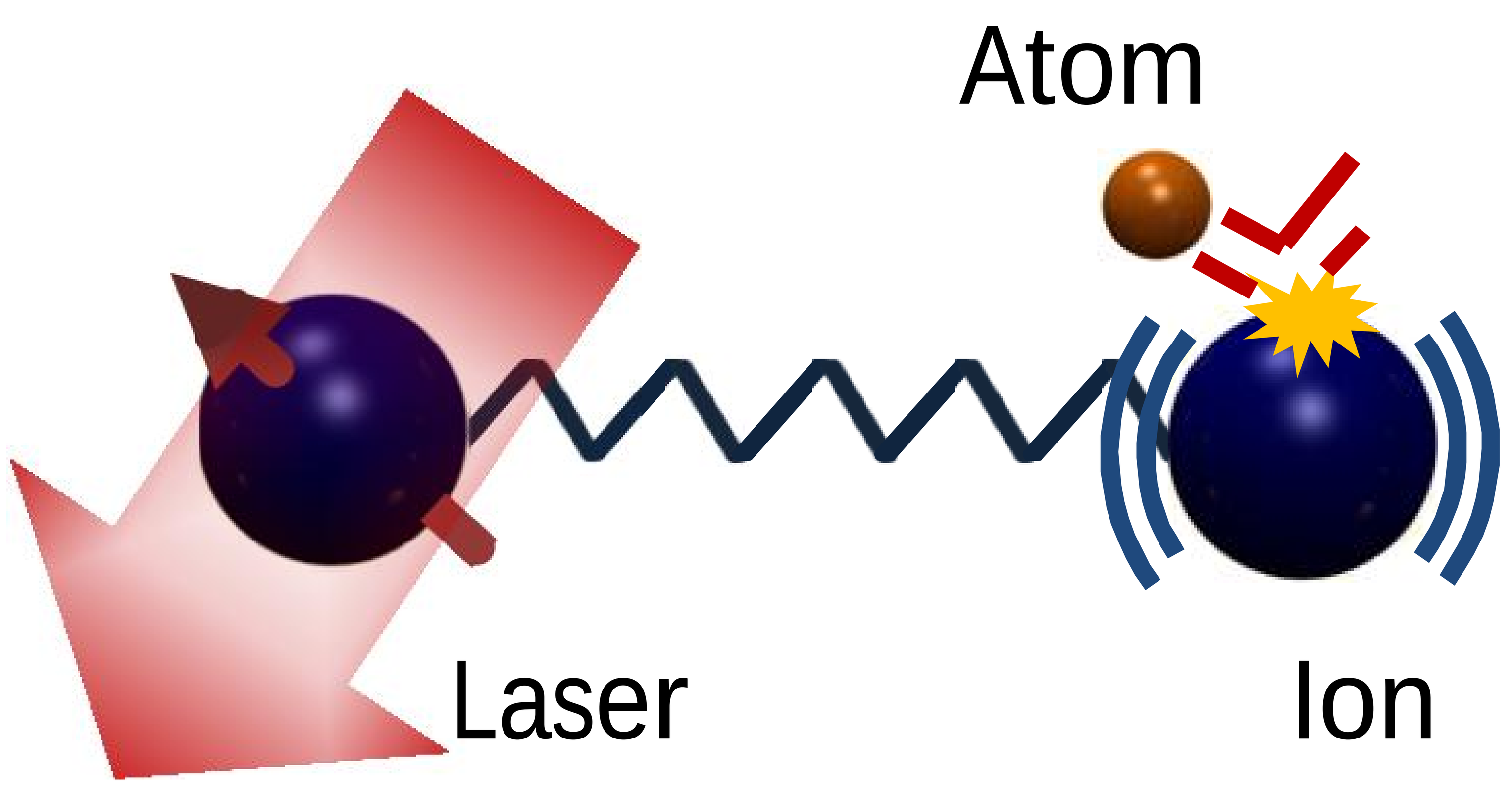
Peierls transition

- Conduction to insulator transitions in 1D
- Caused here by *transverse* phonons
- No ion-atom overlap
- Fermionic effect!
- Here: $^{40}Ca^{+}$ and ^{40}K



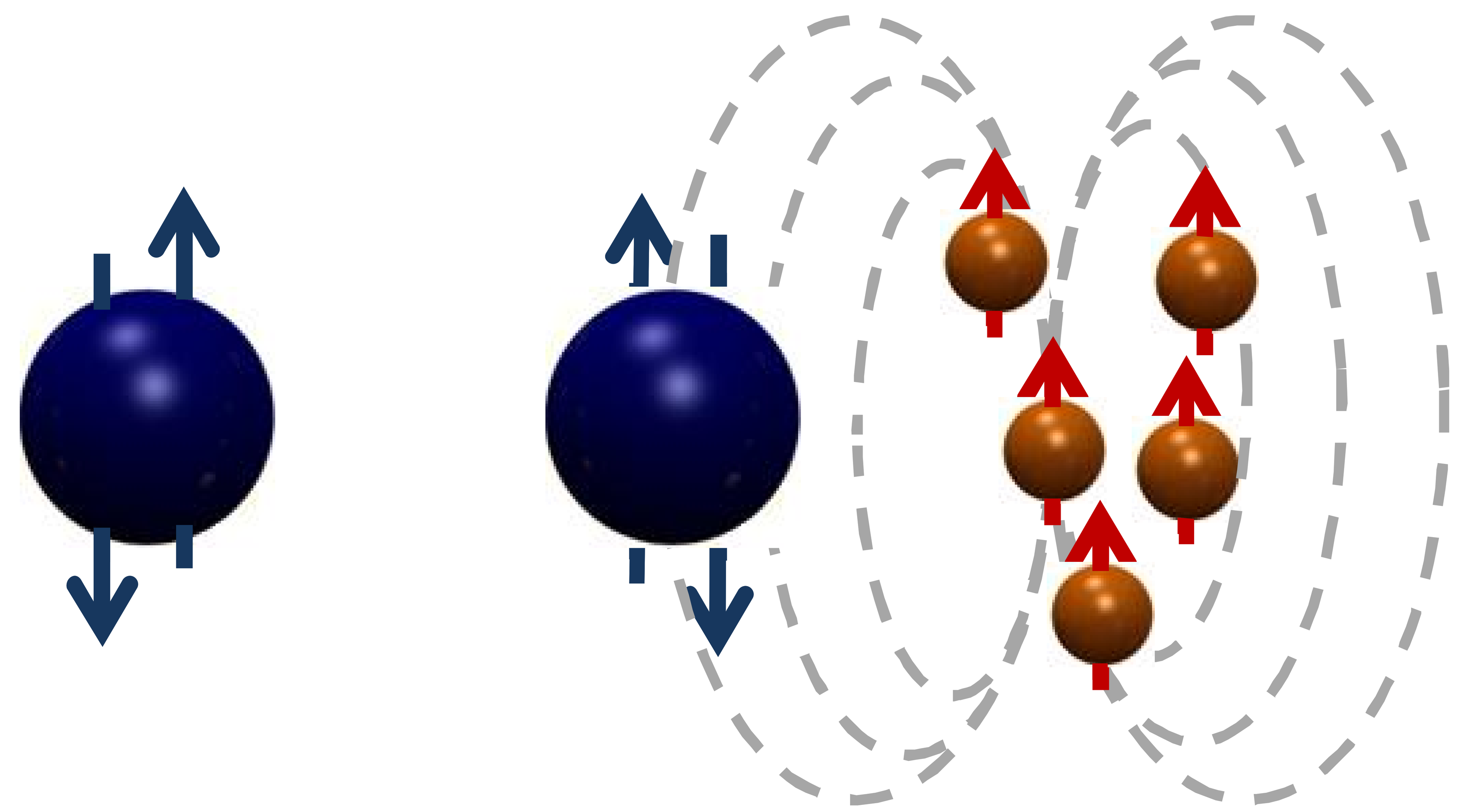


Probing atom-ion systems



→ Spin-motion entanglement in a two-ion string
→ Ion-atom collisions show up as decoherence

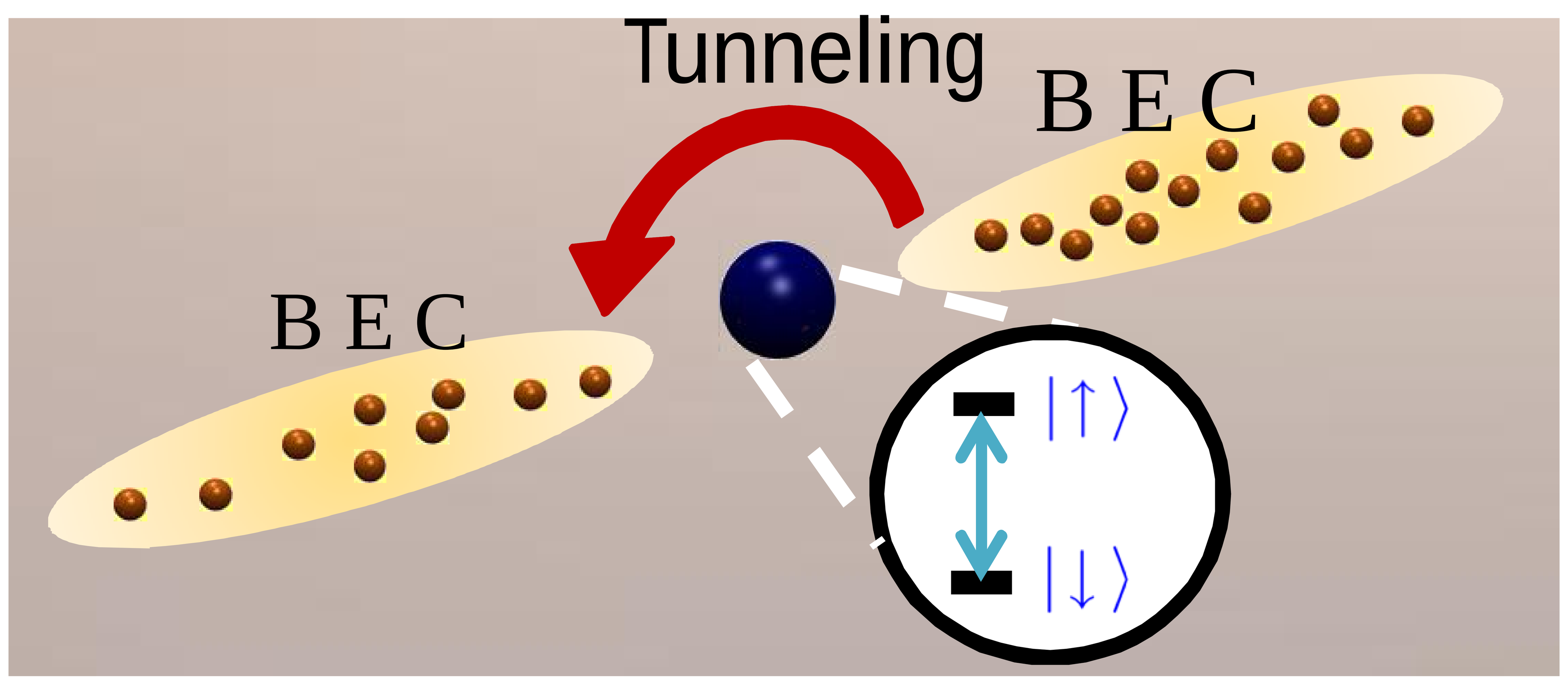
→ Using Bell states to detect the spin of single atoms.
→ Magnetic coupling
→ See talk by Ozeri

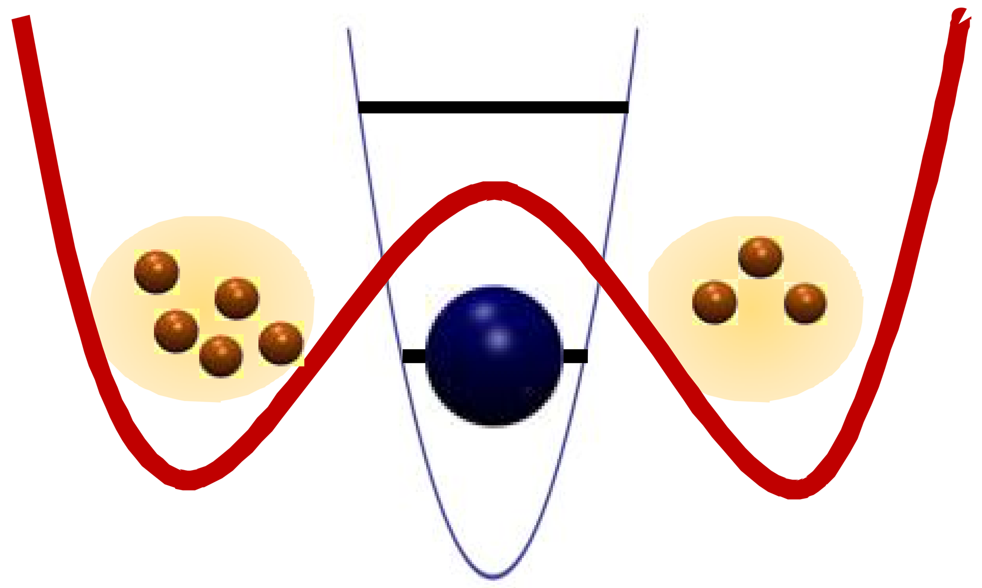


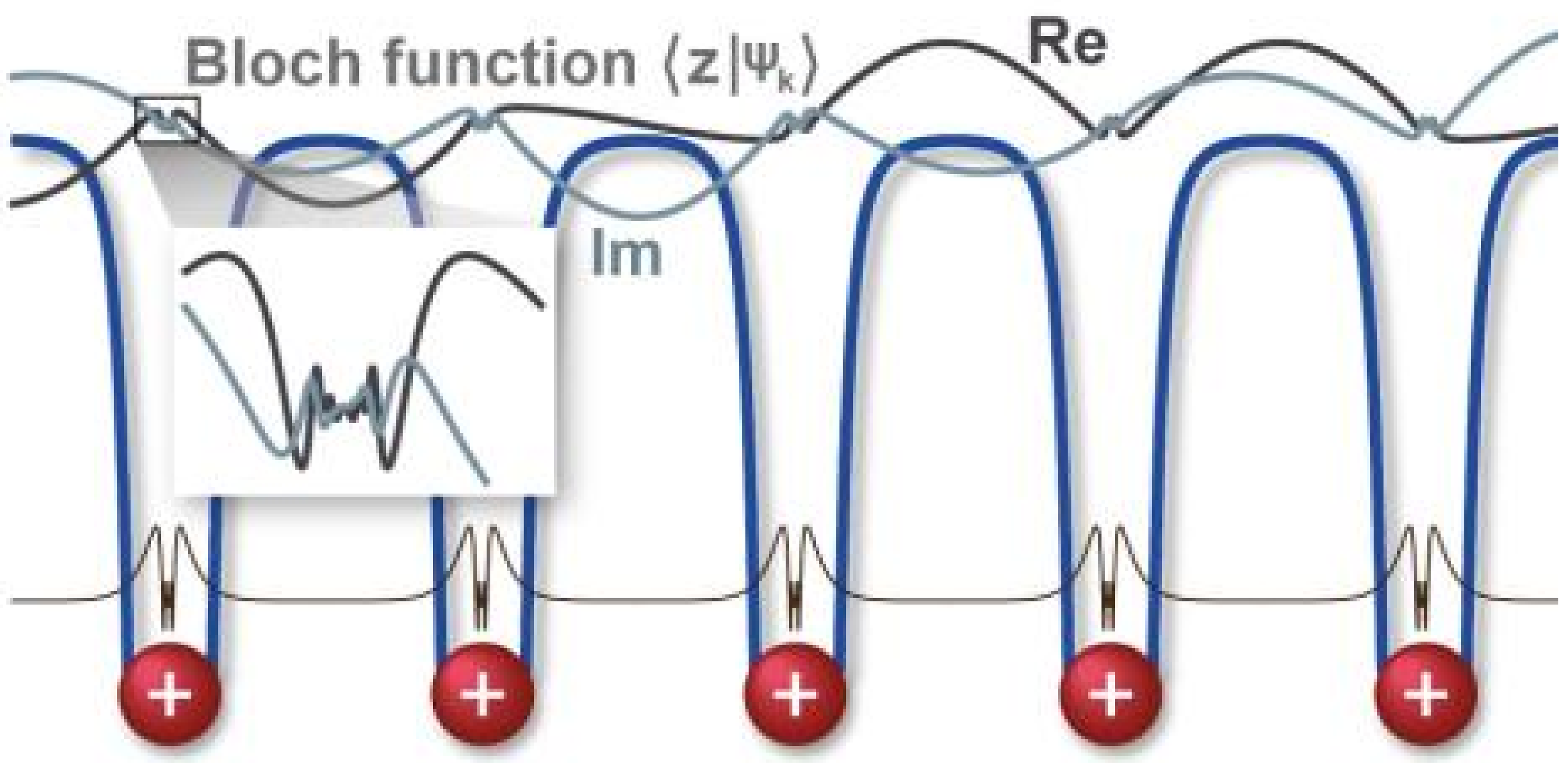
C. Hempel, B. P. Lanyon, P. Jurcevic, RG, R. Blatt and C. F. Roos, Nature Photonics 7, 630-633 (2013).
F. Schmidt-Kaler & RG, *EPL* 99, 53001 (2012).

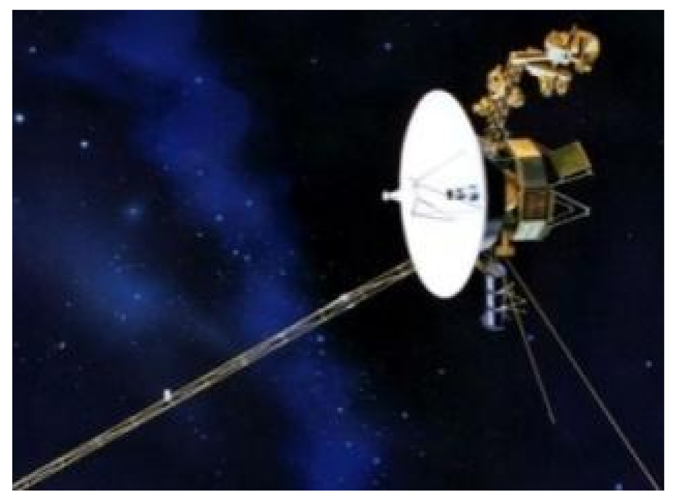
The end

Also see: poster by Jannis Joger



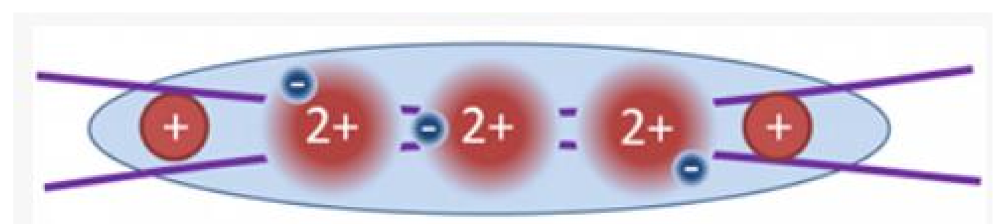






Collaborators:
Jannis Joger, Antonio Negretti, Ulf Bissbort, Daniel Cocks, Walter Hofstetter,
Tommaso Calarco, Zbigniew Idziaszek, Ferdinand Schmidt-Kaler

Rejish Nath, Alexander Glaetzle, Marcello Dalmonte, Peter Zoller



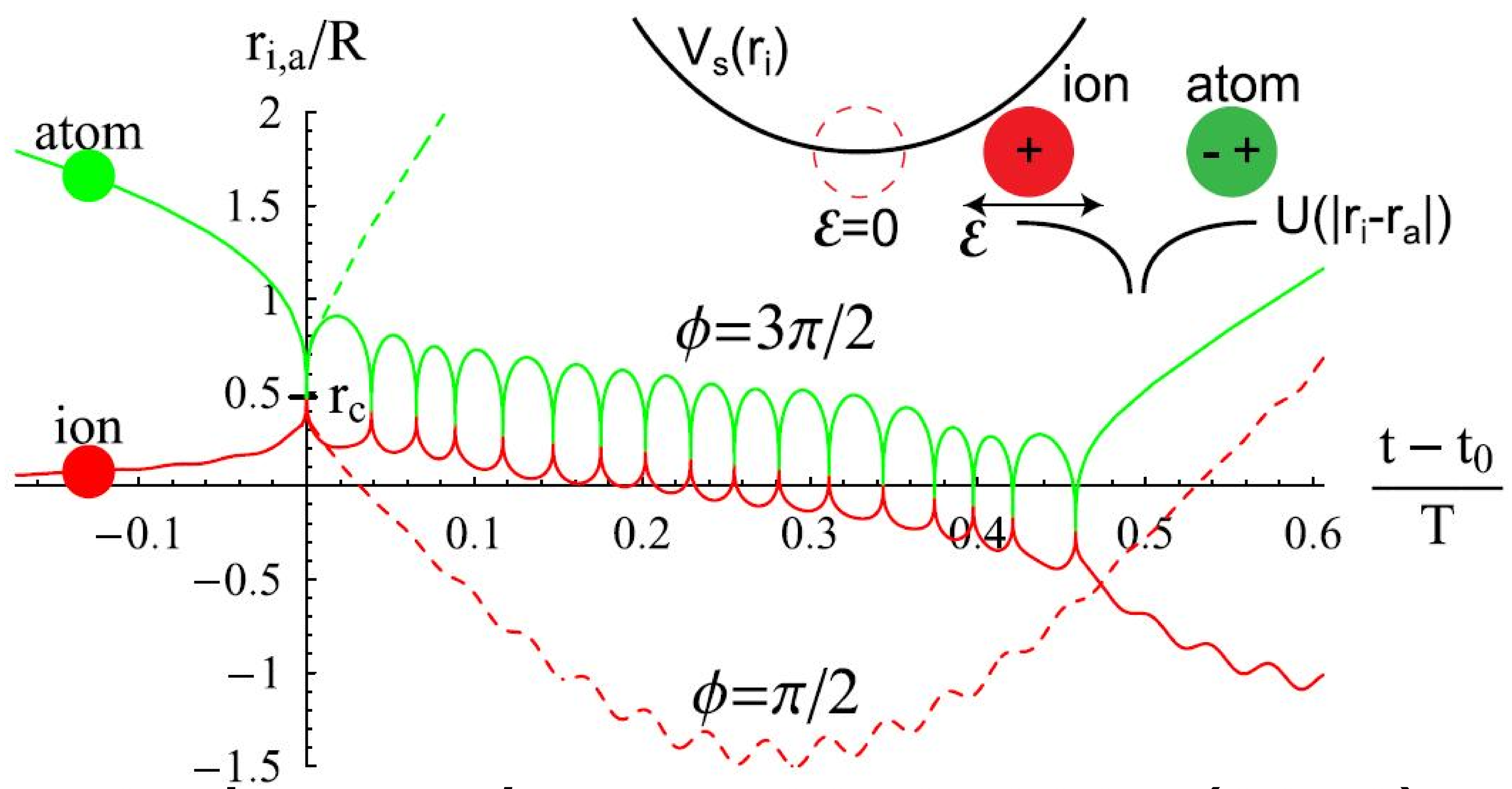
Another word on micromotion

Group	Species	Quantum limit (μK)	Mass ratio
MIT	^{172}Yb / $^{174}Yb^{+}$	0.044	1.01
Ulm	^{87}Rb / $^{138}Ba^{+}$	0.052	1.58
Cambridge	^{87}Rb / $^{174}Yb^{+}$	0.044	2
	^{40}K / $^{174}Yb^{+}$	0.15	4.35
Mainz	^{6}Li / $^{174}Yb^{+}$	8.7	29

Bosons

Fermions

Need high mass ratio!



M. Cetina *et al.*, PRL 109, 253201 (2012).