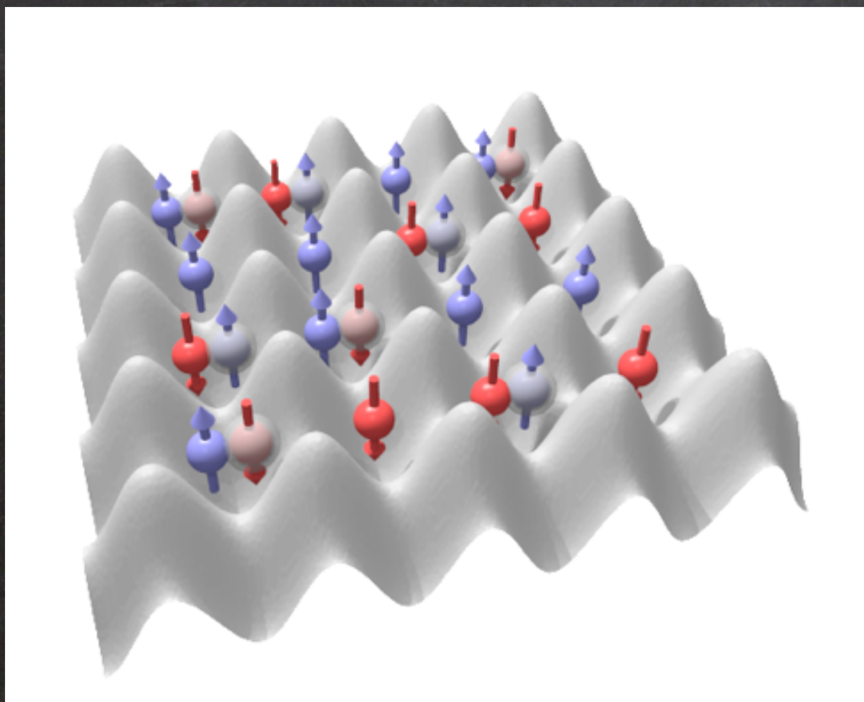
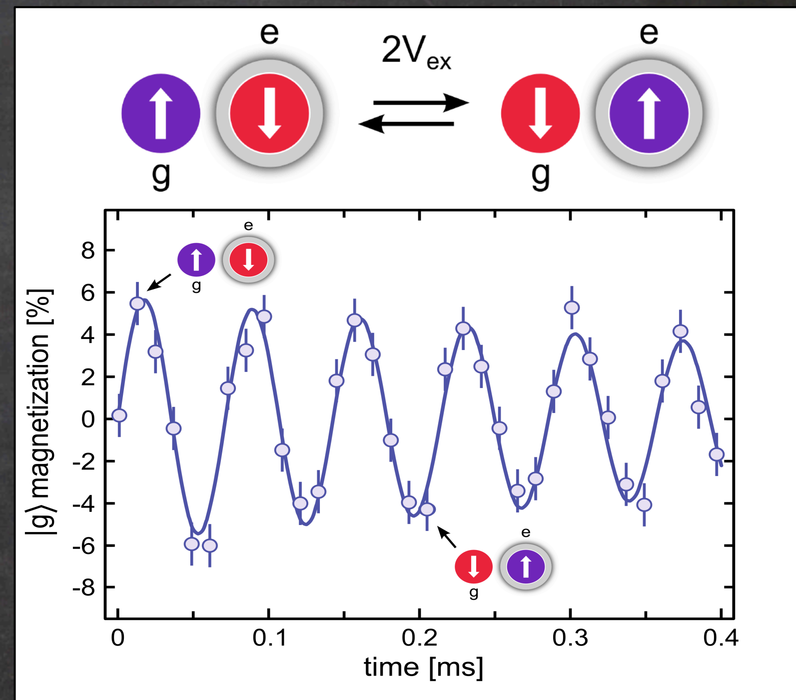
Orbital magnetism with SU(N) fermions

ESX 2014, Trieste, 29th October 2014





SCUOLA NORMALE SUPERIORE

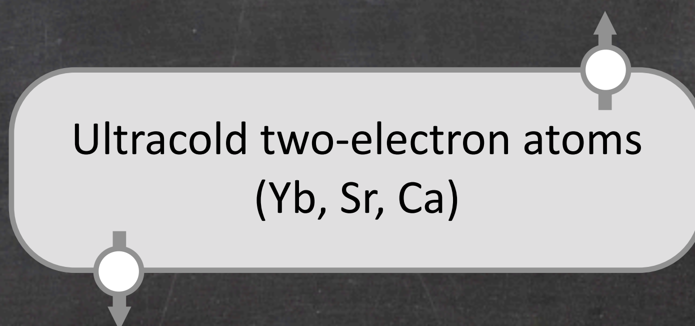
lens European Laboratory for Non-Linear Spectroscopy

Guido Pagano

Scuola Normale Superiore & LENS

Two-electron atoms

A valuable atomic platform for quantum science and technology



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Metrology, optical clocks

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Ultracold two-electron atoms
(Yb, Sr, Ca)

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New quantum simulation: SU(N) physics, gauge fields, …

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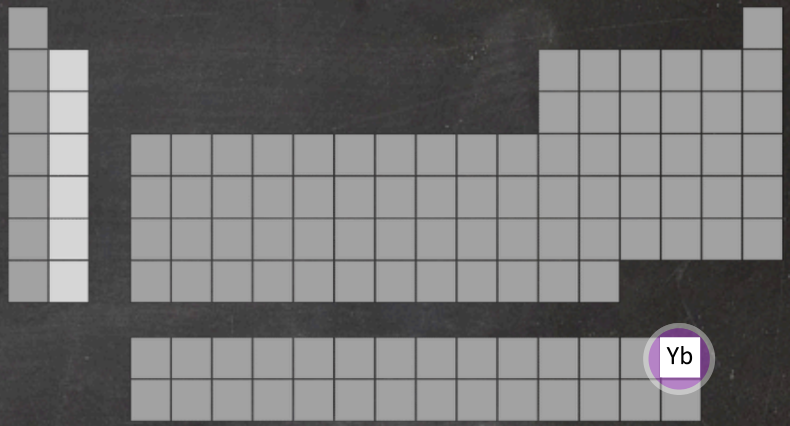
Ytterbium

Alkaline-earth-like structure

Electronic configuration [...]$6s^2$



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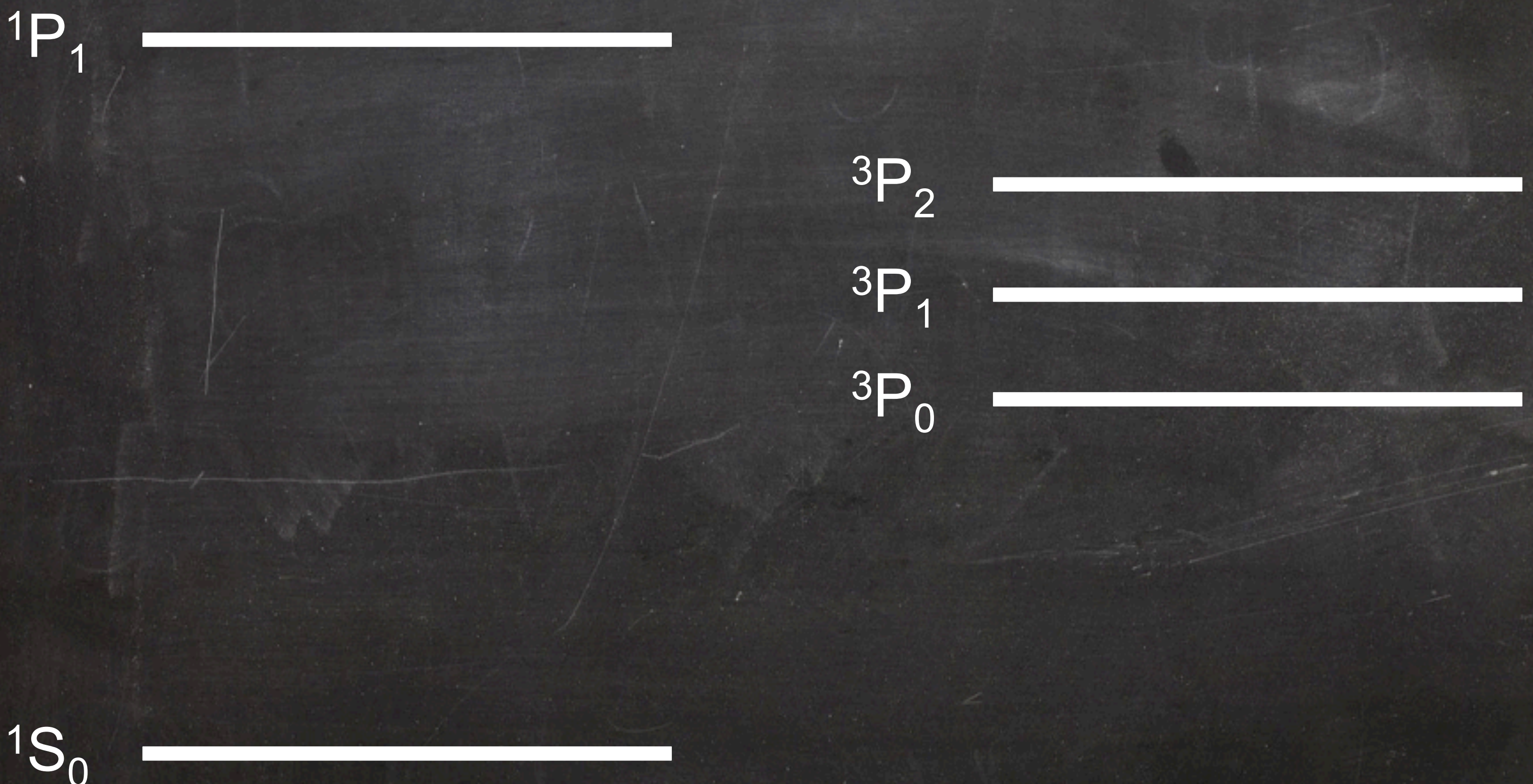

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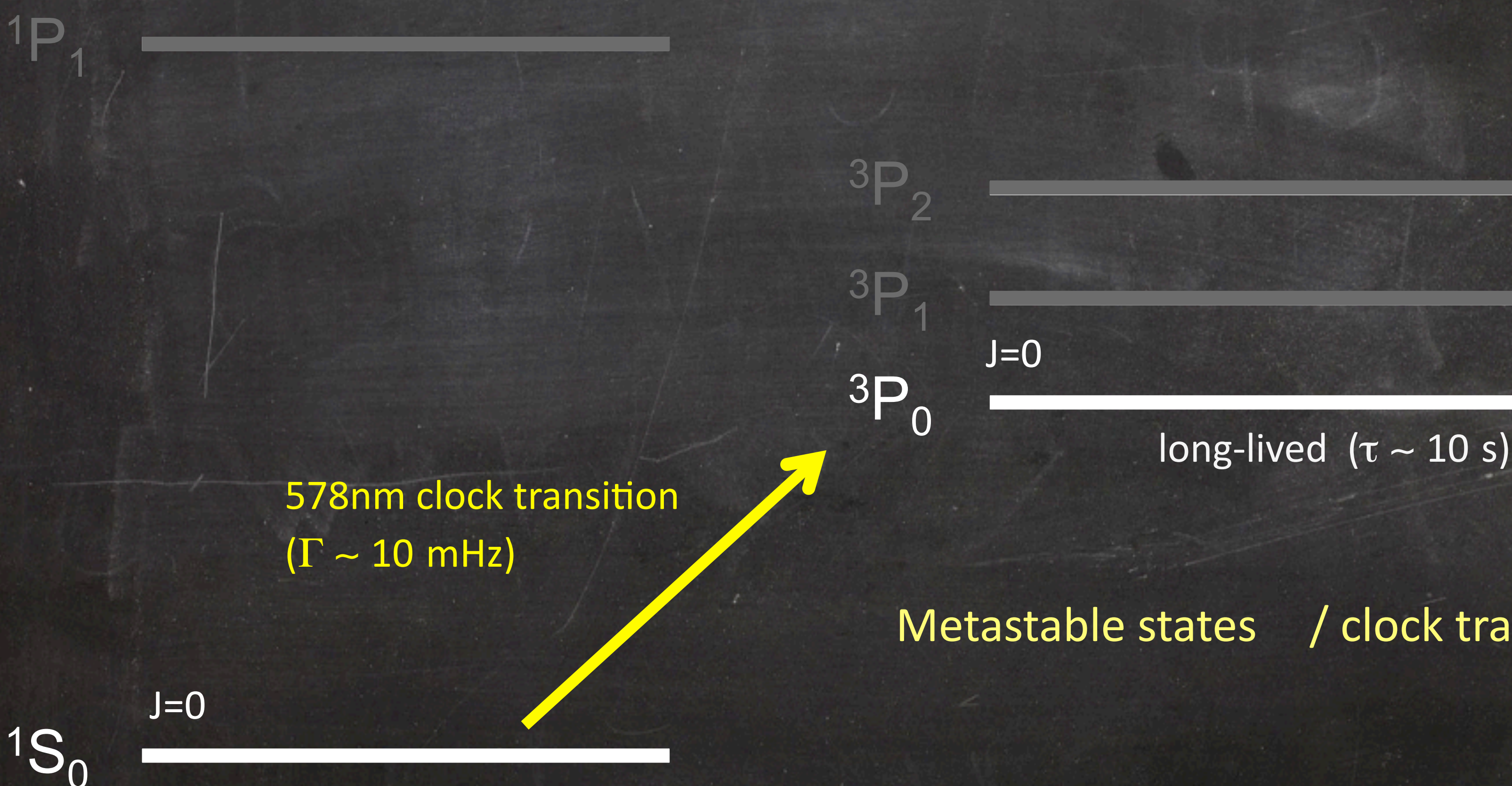

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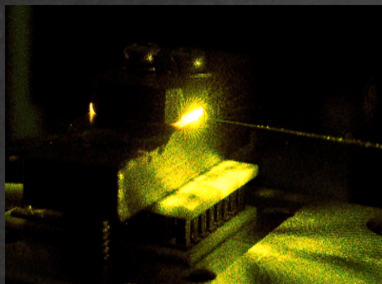
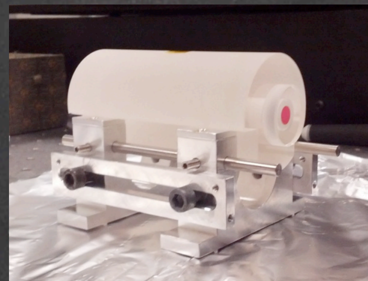
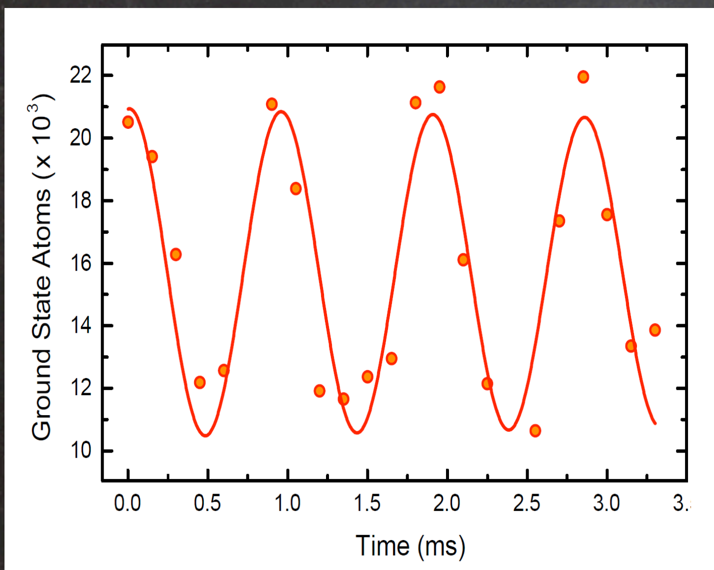
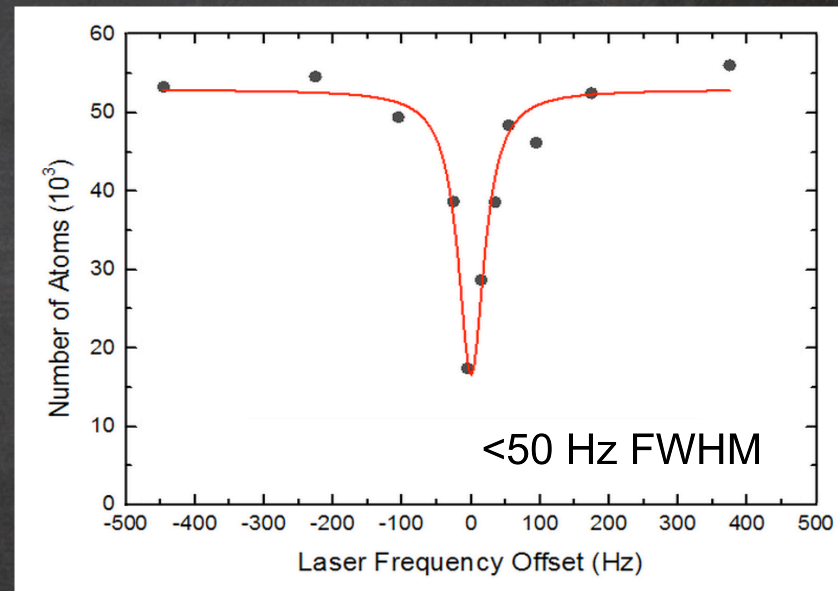




Rabi oscillations:



Clock transition spectrum @ 578nm in a magic-wavelength 3D lattice:



J=0

$^3P_0$

long-lived ($\tau \sim 10$ s)

578nm clock transition

($\Gamma \sim 10$ mHz)

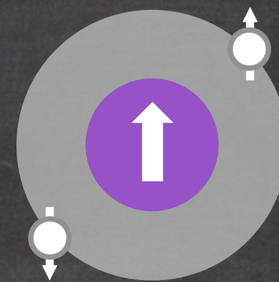
Metastable states / clock transition

J=0

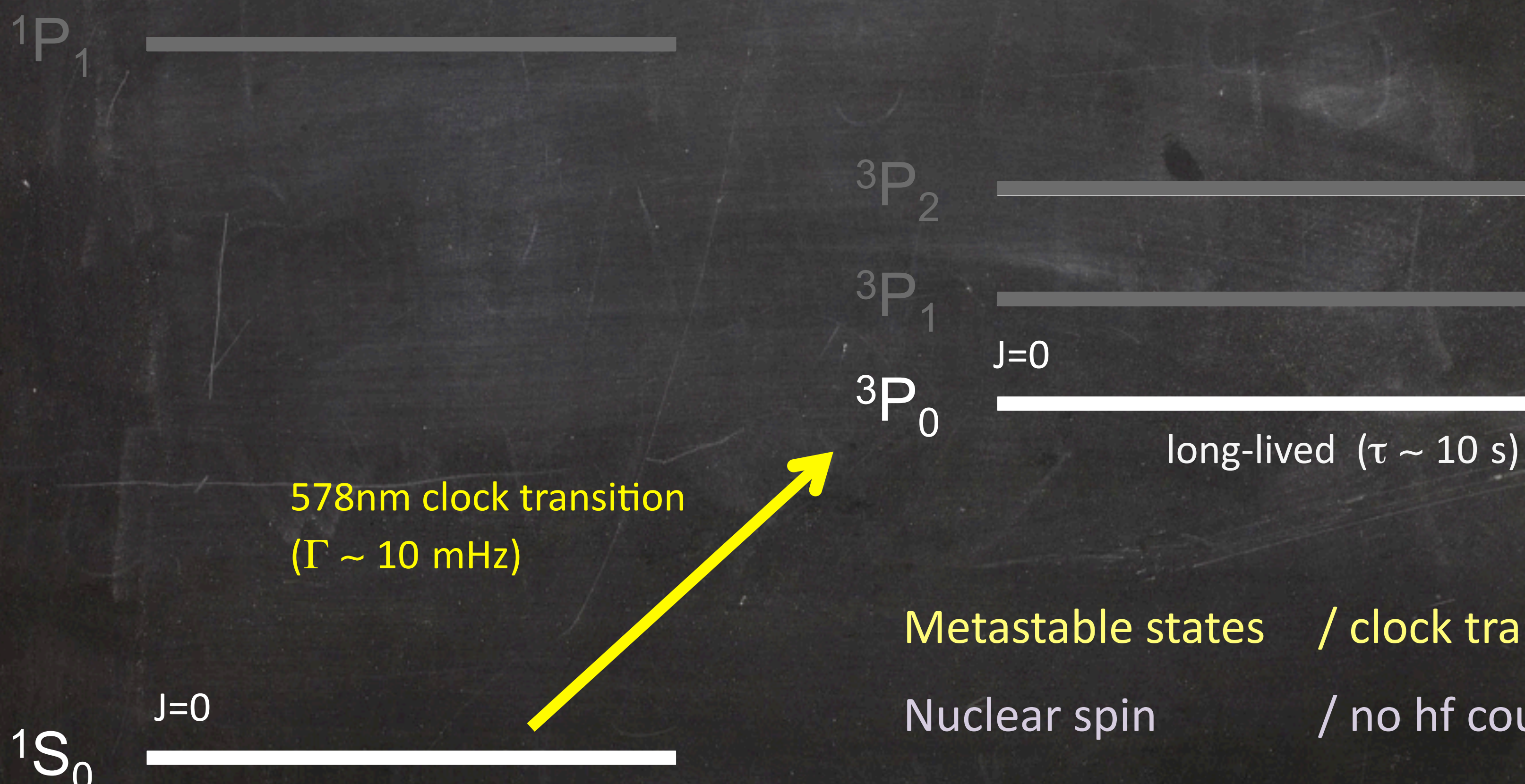
$^1S_0$

Ytterbium

Alkaline-earth-like structure
Electronic configuration [...]$6s^2$



nuclear spin I



Metastable states / clock transition

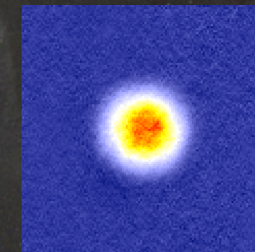
Nuclear spin / no hf coupling

^{173}Yb Fermi gas

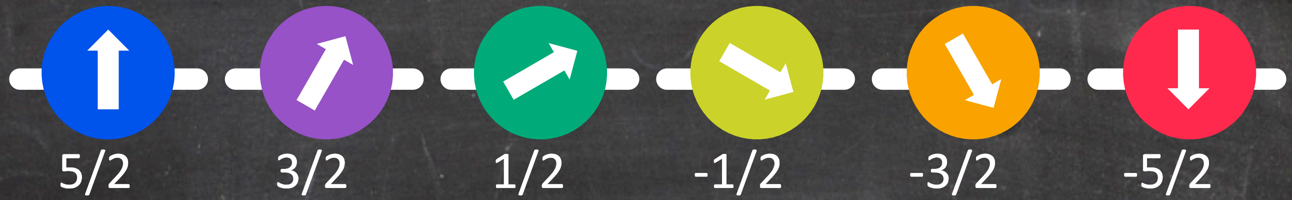
Ultracold ^{173}Yb Fermi gas

$T \sim 10$ nK $\sim 0.1\ T_F$

$N = 10^4$ atoms/spin



Purely nuclear spin I=5/2



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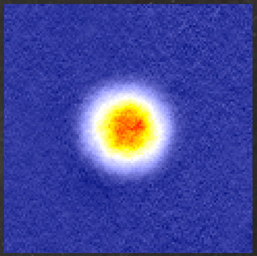

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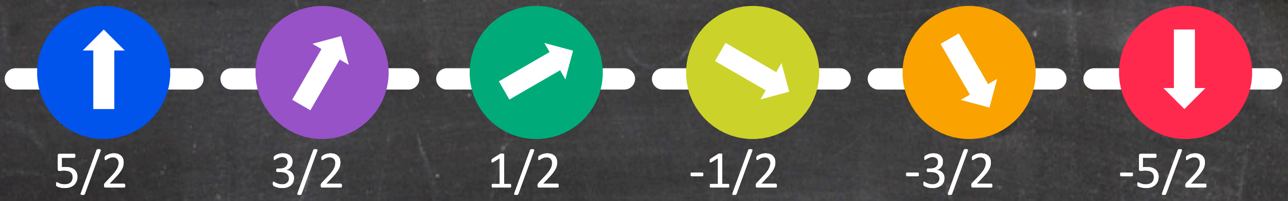

Same interaction between different spins ⟶ SU(6) symmetry

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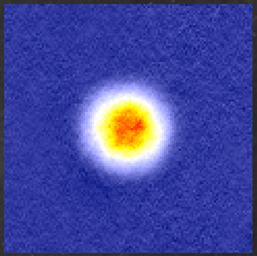

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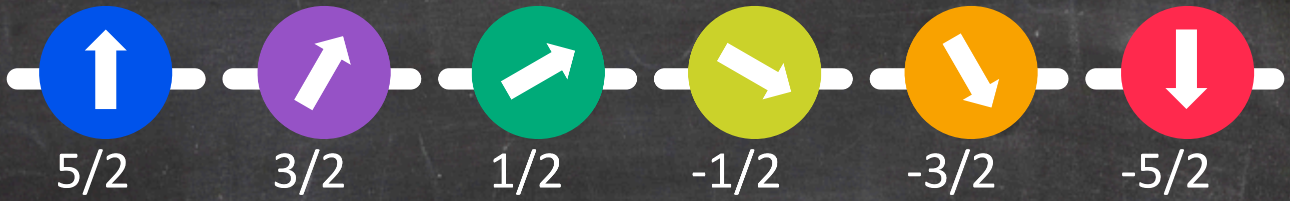


Same interaction between different spins → SU(6) symmetry

M. Cazalilla et al., NJP 11, 103033 (2009)

A. Gorshkov et al., Nat. Phys. 6, 289 (2010)

No spin-changing collisions → all mixtures are stable

g-g spin-preserving collisions

g +5/2

g –5/2

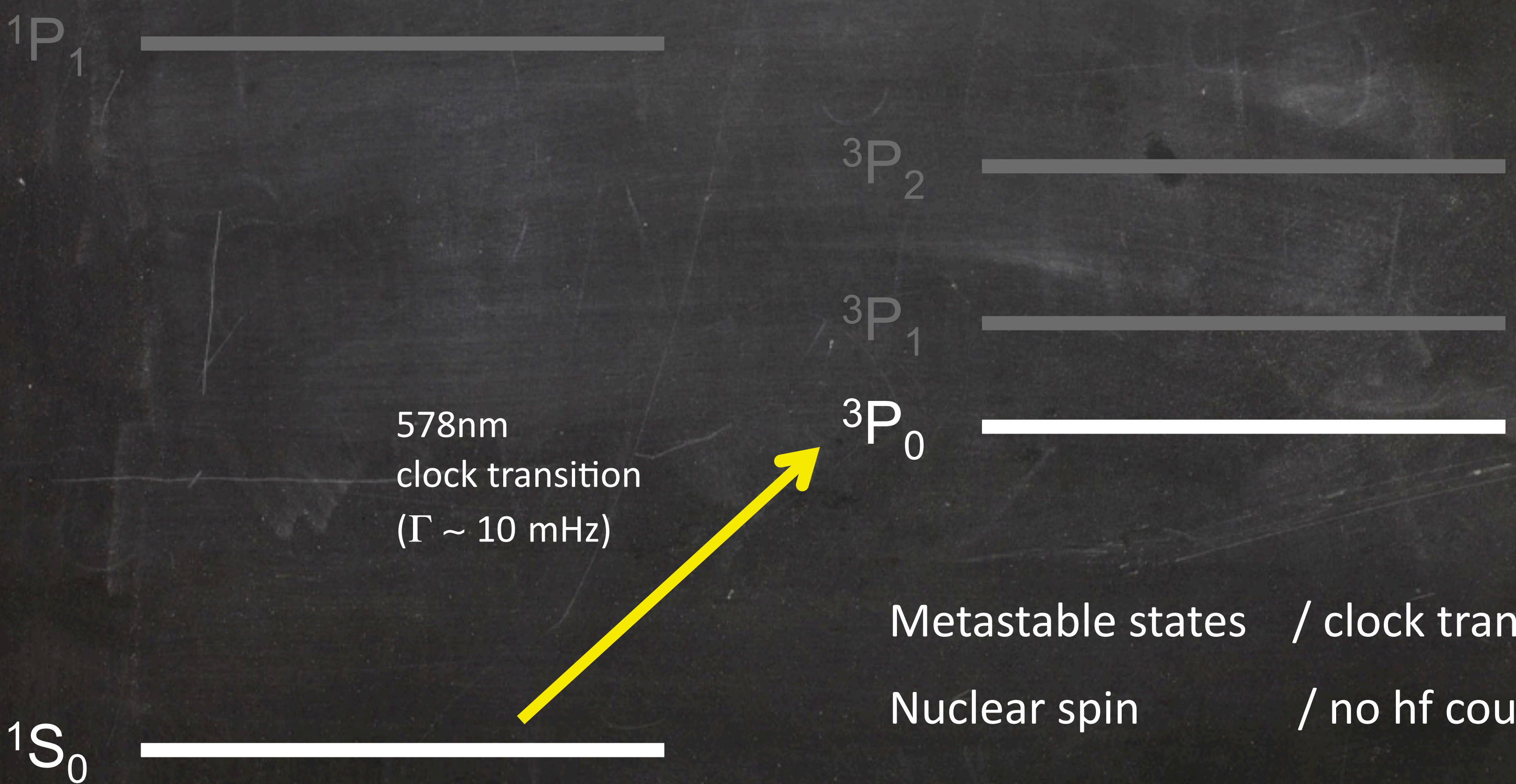
g-g spin-preserving collisions

g-g spin-preserving collisions

Ytterbium $^3P_0$ Metastable state

Ytterbium

Nuclear + electronic degrees of freedom



Metastable states / clock transition

Nuclear spin / no hf coupling

Ytterbium $^3P_0$ Metastable state

Ytterbium

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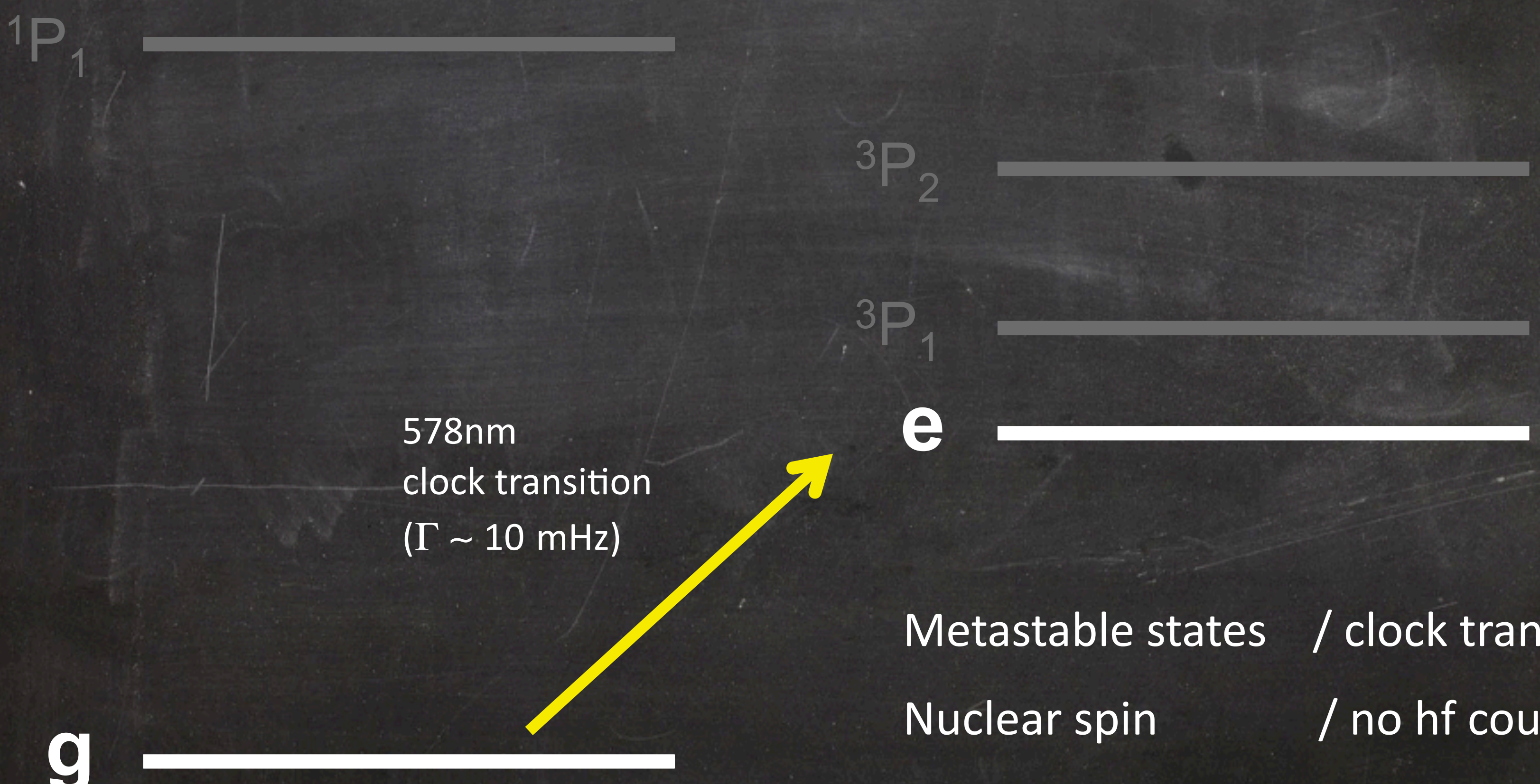

Metastable states / clock transition

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Ytterbium

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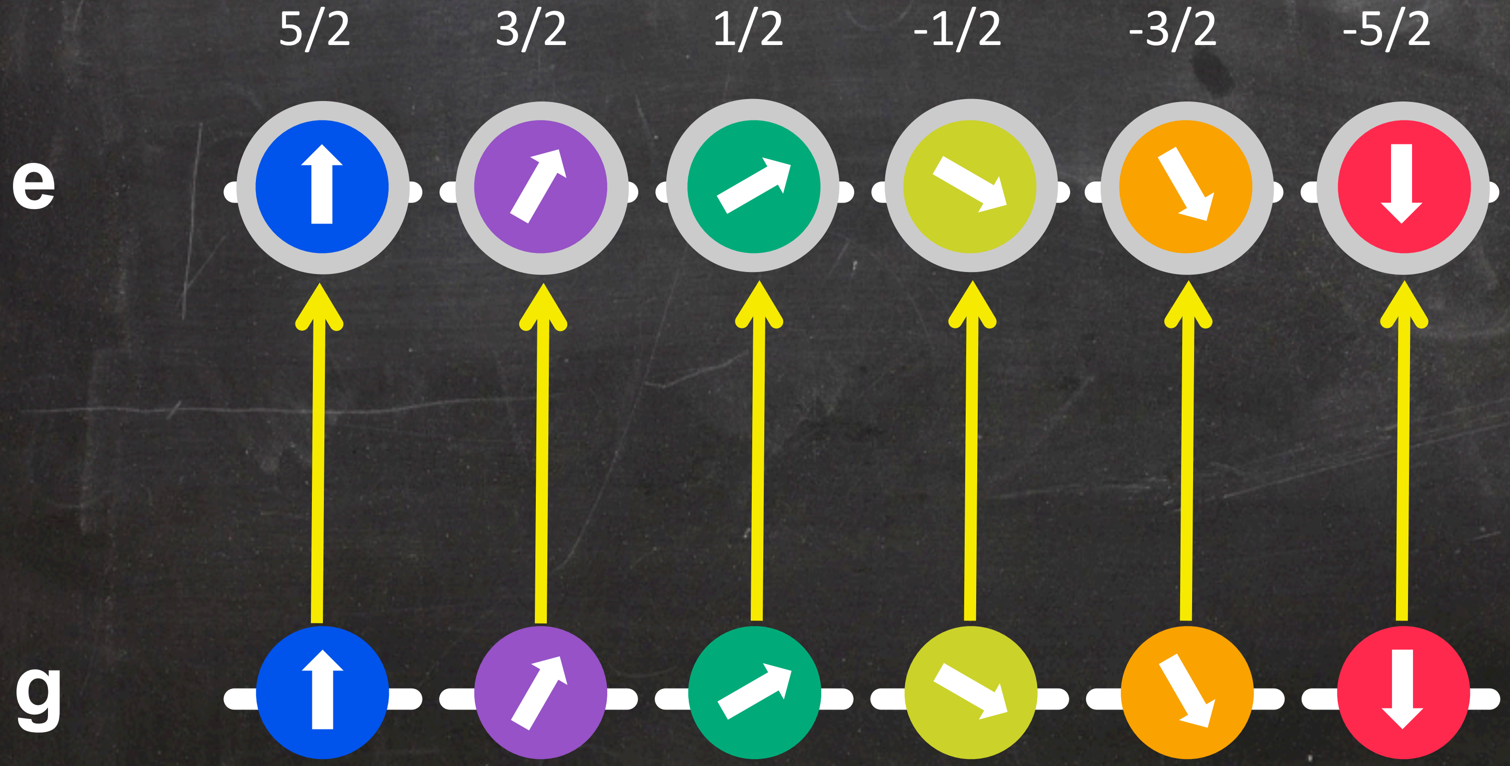


g-e spin-exchange collisions

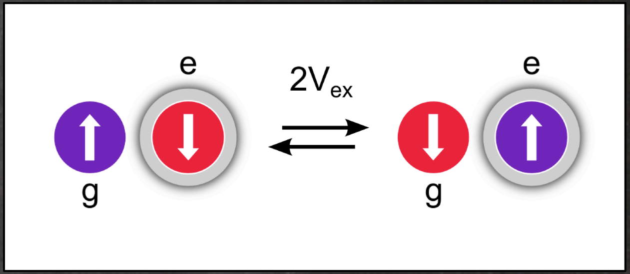
g-e spin-exchange collisions

g-e spin-exchange interaction

Two entangled internal degrees of freedom:

Coherent control of nuclear and electronic state

Quantum information processing



related spin-exchange dynamics in
M. Anderlini et al., Nature 448, 452 (2007)

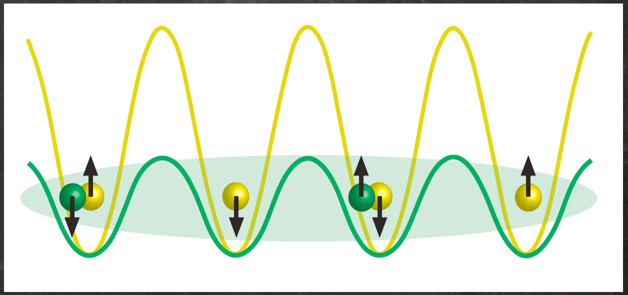
New quantum simulation of strongly-correlated systems:

Strong spin-orbital interaction:

Orbital magnetism, Kondo model

$$\hat{H} = -J_g \sum_{<i,j>,\sigma} \hat{c}^\dagger_{ig\sigma}\hat{c}_{jg\sigma} + V_{ex}\sum_{i\sigma'\sigma}\hat{c}^\dagger_{ig\sigma}\hat{c}^\dagger_{ie\sigma'}\hat{c}_{ig\sigma'}\hat{c}_{ie\sigma}$$

SU(N) magnetism



A. Gorshkov et al., Nat. Phys. 6, 289 (2010)
M. Foss-Feig et al., PRA. 81, 3-6 (2010)

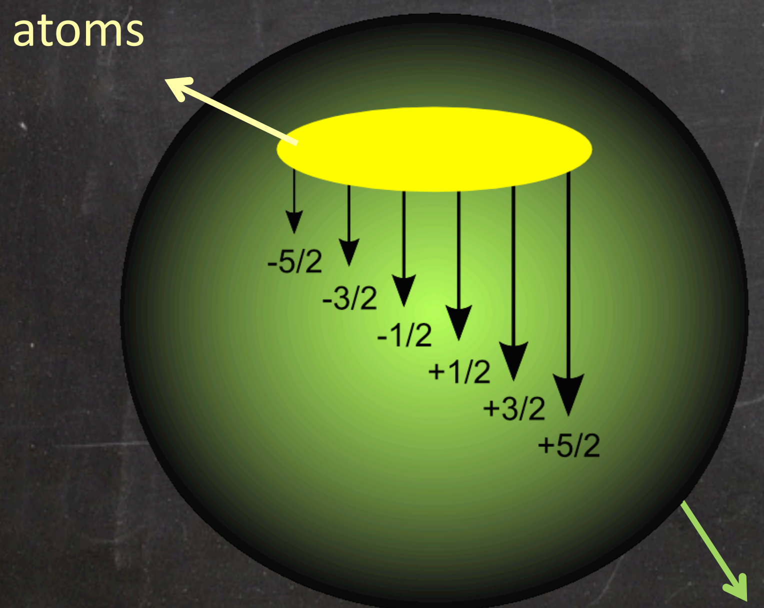
F. Zhang et al., Science 345, 1467-1473, F. Scazza et al., Nature Phys. 10, 779–784 (2014)

Spin detection and manipulation

Optical Stern-Gerlach detection

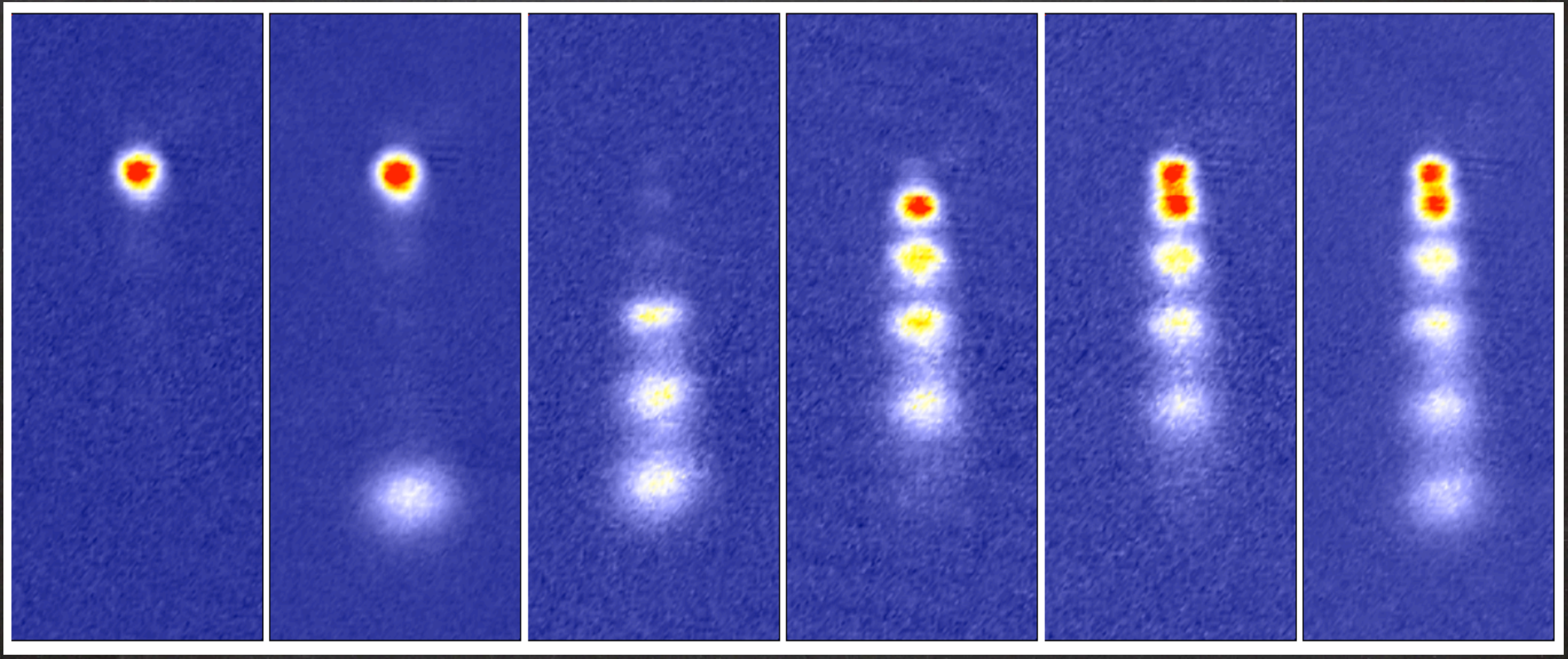
S. Taie et al., PRL (2010)

State-dependent optical dipole force



Spin detection and manipulation

^{173}Yb Fermi gases in an arbitrary number of equally-populated components:

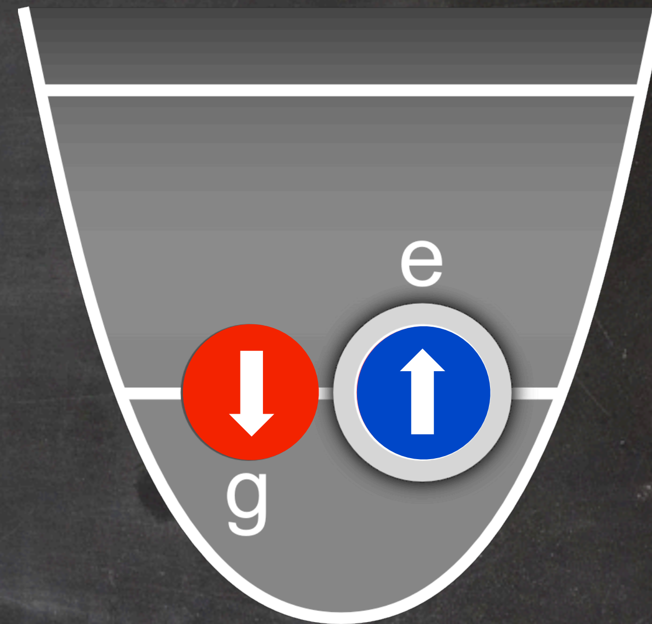


1 spin | 2 spins SU(2) | 3 spins SU(3) | 4 spins SU(4) | 5 spins SU(5) | 6 spins SU(6)

g-e spin-exchange collisions

Two fermions (g+e) in a trap

A. Gorshkov et al., Nat. Phys. 6, 289 (2010)



Antisymmetrization of the two-particle state:

$$|eg^-\rangle \propto \left[g_1 e_2 - e_1 g_2\right]\left[\uparrow_1 \downarrow_2 + \downarrow_1 \uparrow_2\right]$$

orbital-antisymmetric spin-triplet

$$|eg^+\rangle \propto \left[g_1 e_2 + e_1 g_2\right]\left[\uparrow_1 \downarrow_2 - \downarrow_1 \uparrow_2\right]$$

orbital-symmetric spin-singlet

g-e spin-exchange collisions

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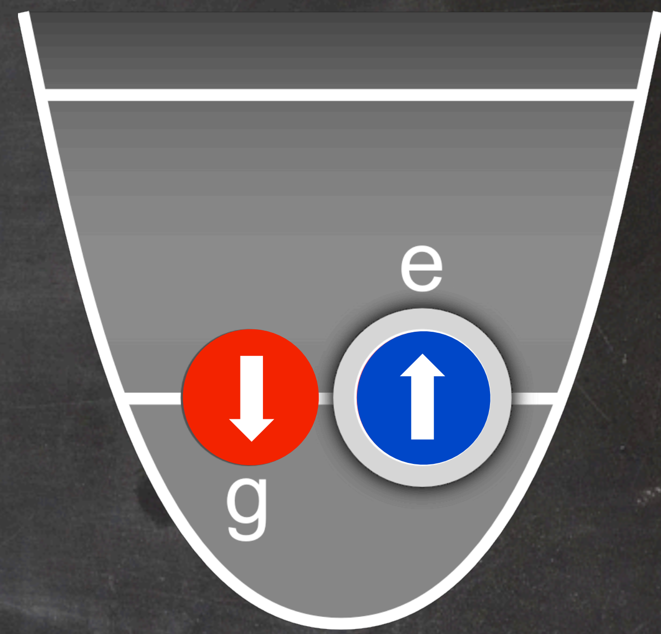
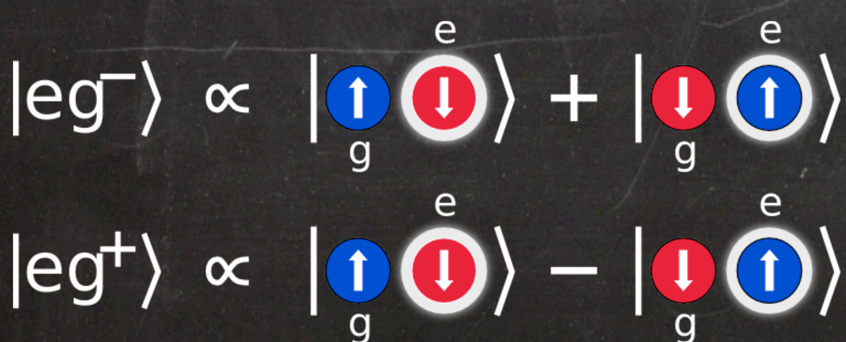
A. Gorshkov et al., Nat. Phys. 6, 289 (2010)

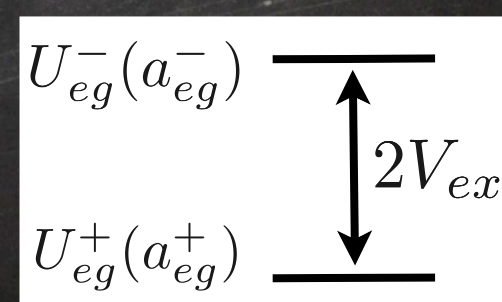


A local spin-exchange interaction between different "orbitals" arises:

$$\hat{H} = \begin{pmatrix} U_{eg}^{+} & 0 \\ 0 & U_{eg}^{-} \end{pmatrix}$$

Different scattering lengths for the two states:





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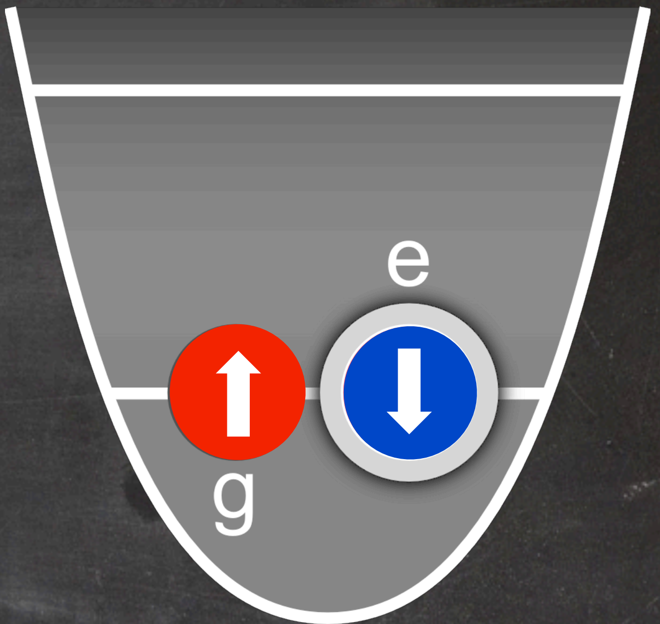

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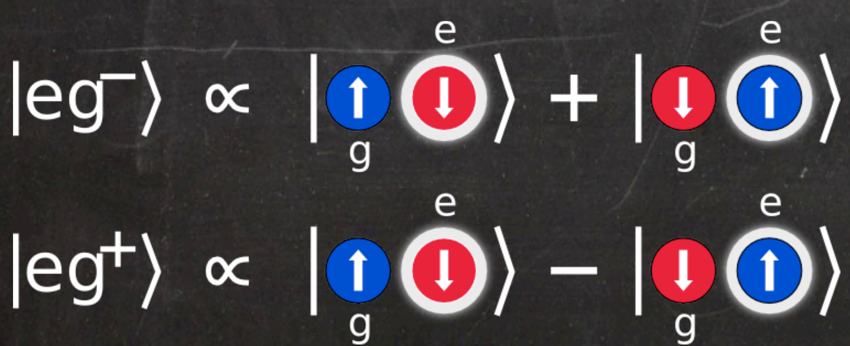
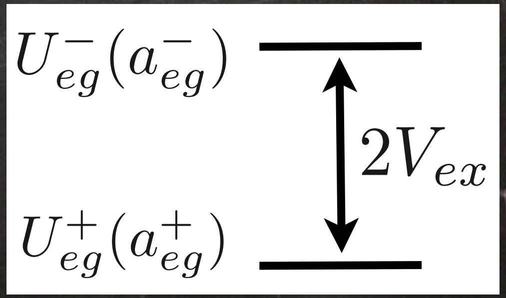
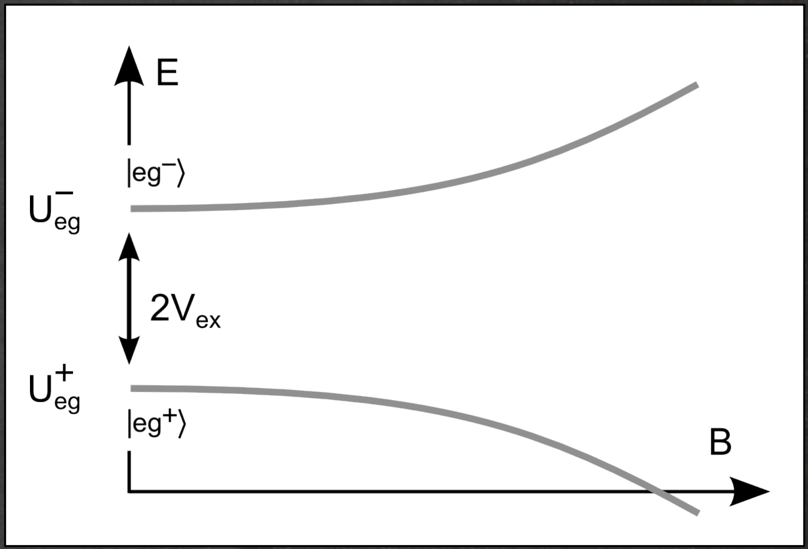




g-e spin-exchange oscillations

A magnetic field B induces a mixing between the two channels:

$$|\psi\rangle = \alpha|eg^+\rangle + \beta|eg^-\rangle$$



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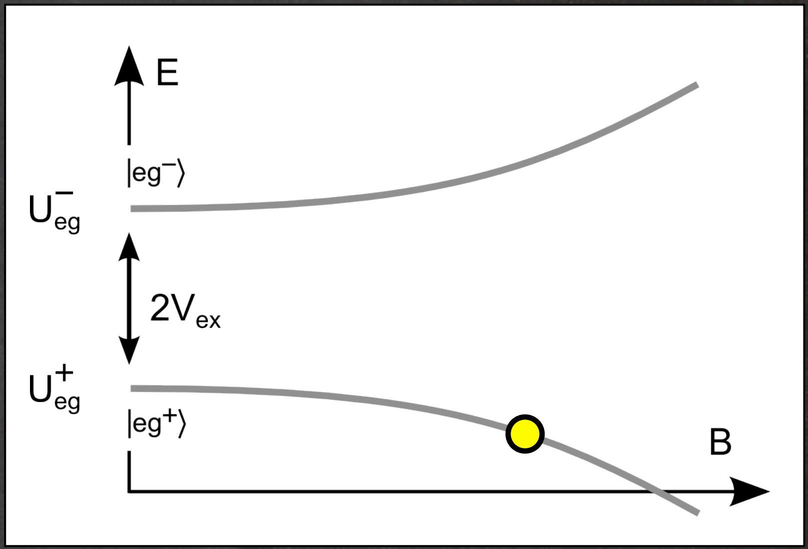

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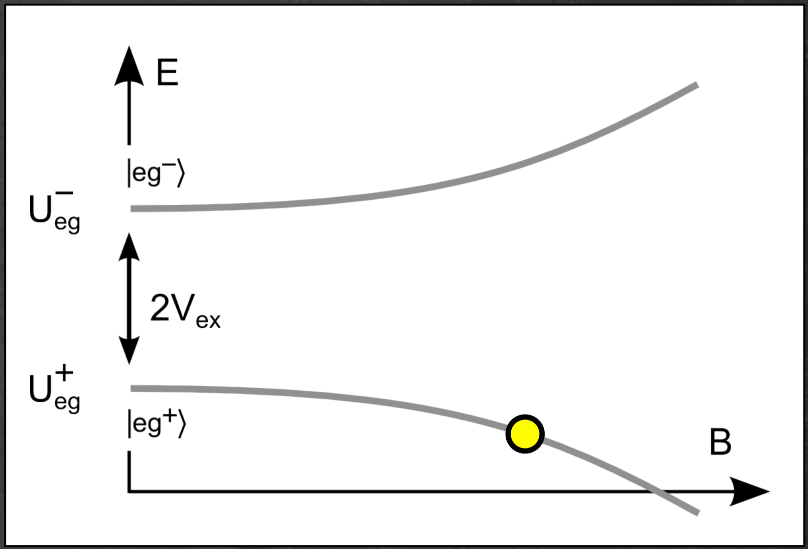

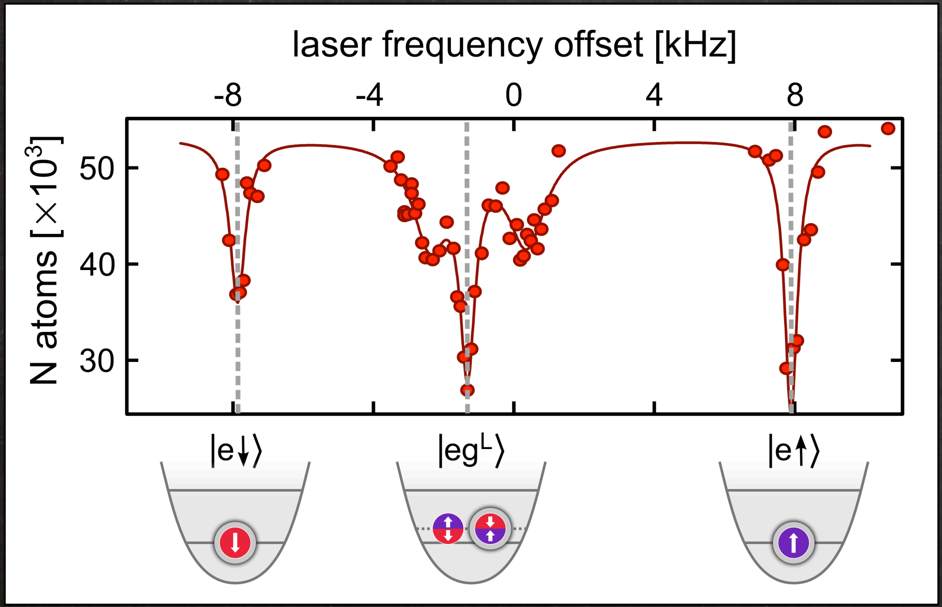

Spectrum of the 578nm clock transition in a 3D optical lattice

see related work by Fölling/Bloch group:

F. Scazza et al., Nat. Phys. 10, 779–784 (2014)

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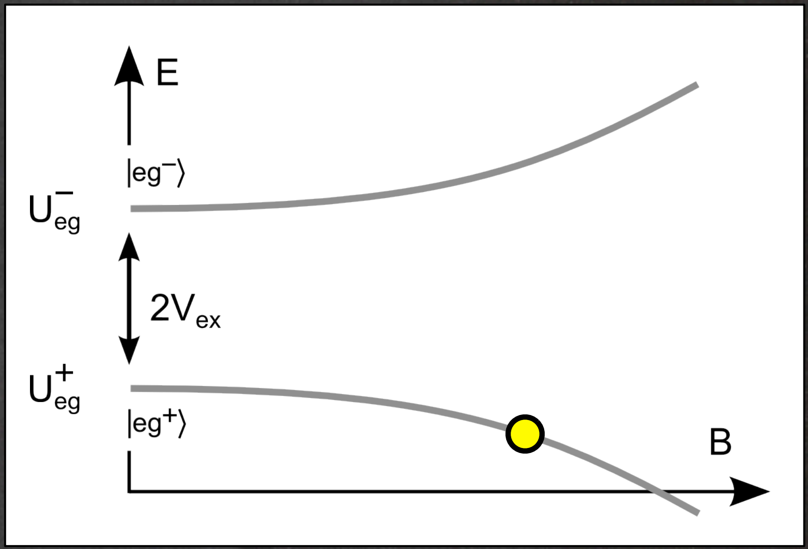

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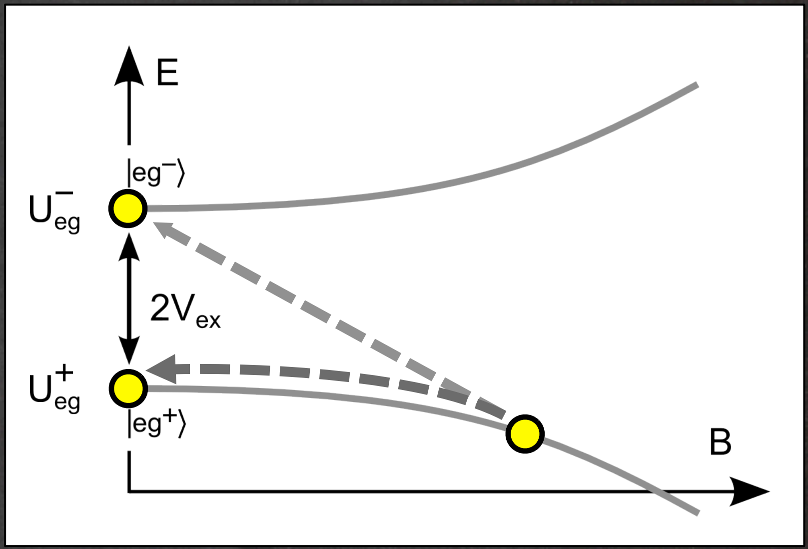
B field quench



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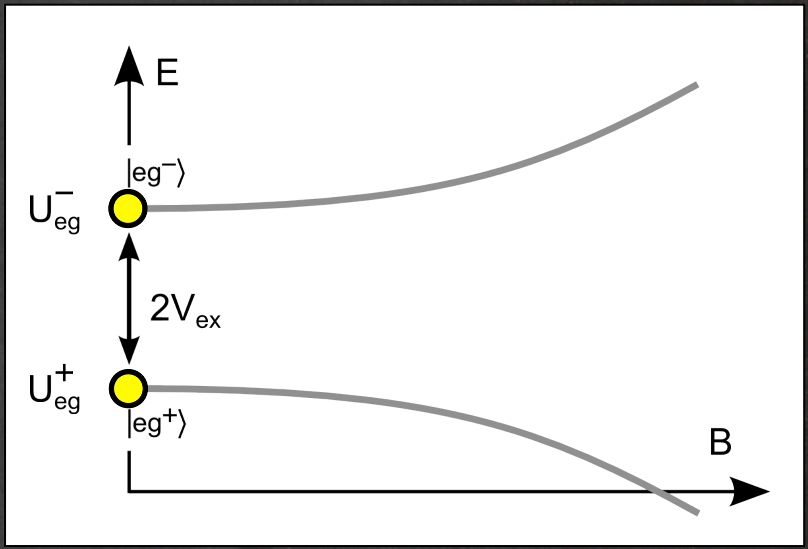
B field quench + free evolution

$$|\psi(t)\rangle = \alpha|eg^+\rangle + \beta e^{-i2V_{ex}t/\hbar}|eg^-\rangle$$



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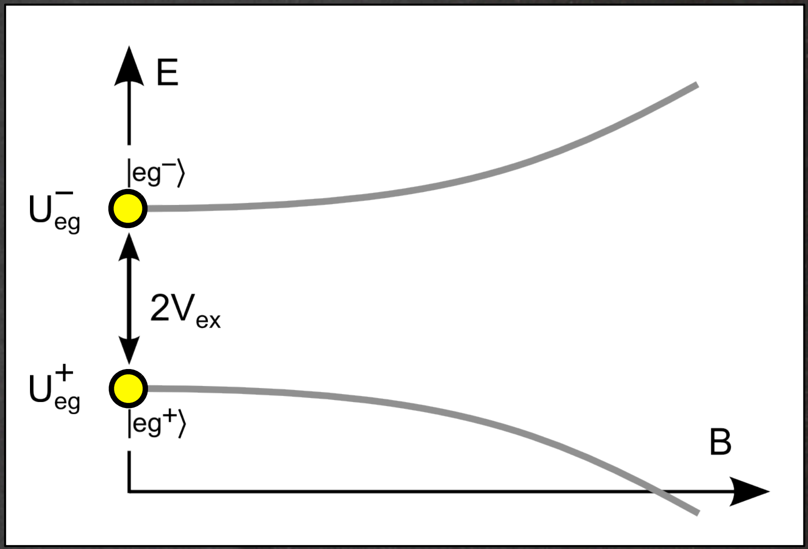

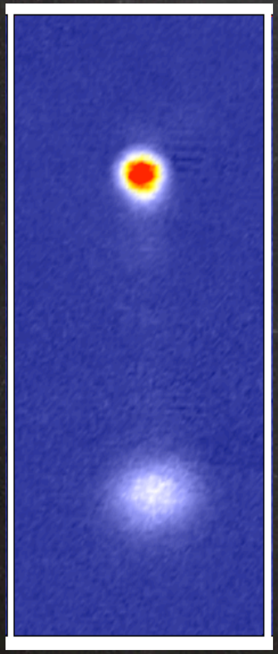

Ground-state magnetization:

$$|\langle g\uparrow|\psi(t)\rangle|^2 = \frac{1}{2} + \alpha\beta\cos\left(\frac{2V_{ex}t}{\hbar}\right)$$

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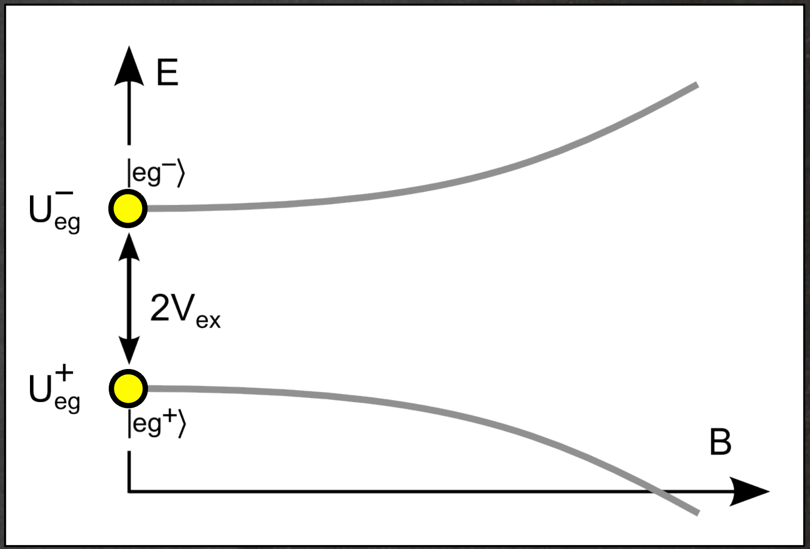

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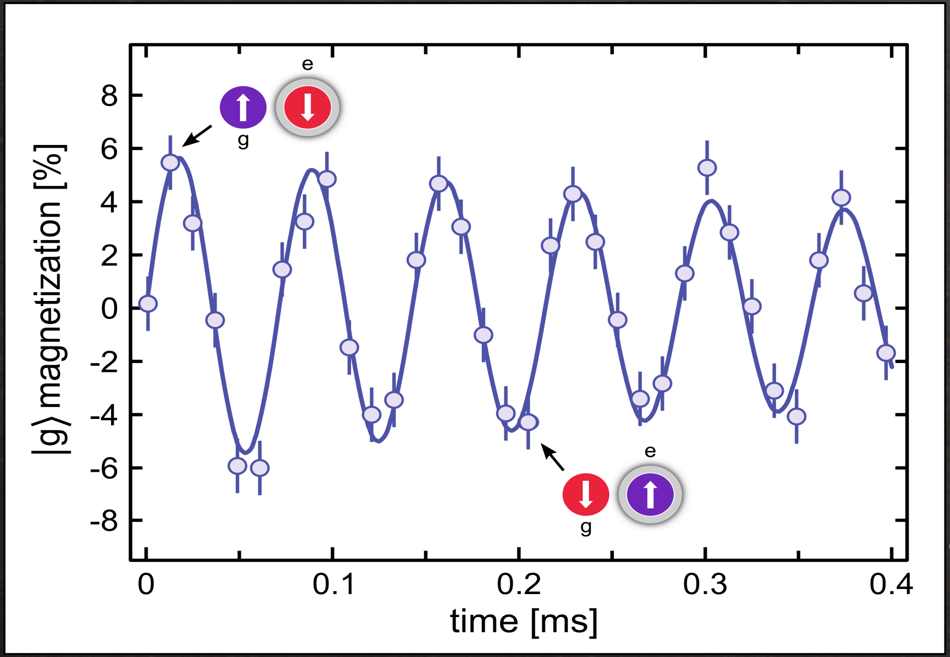

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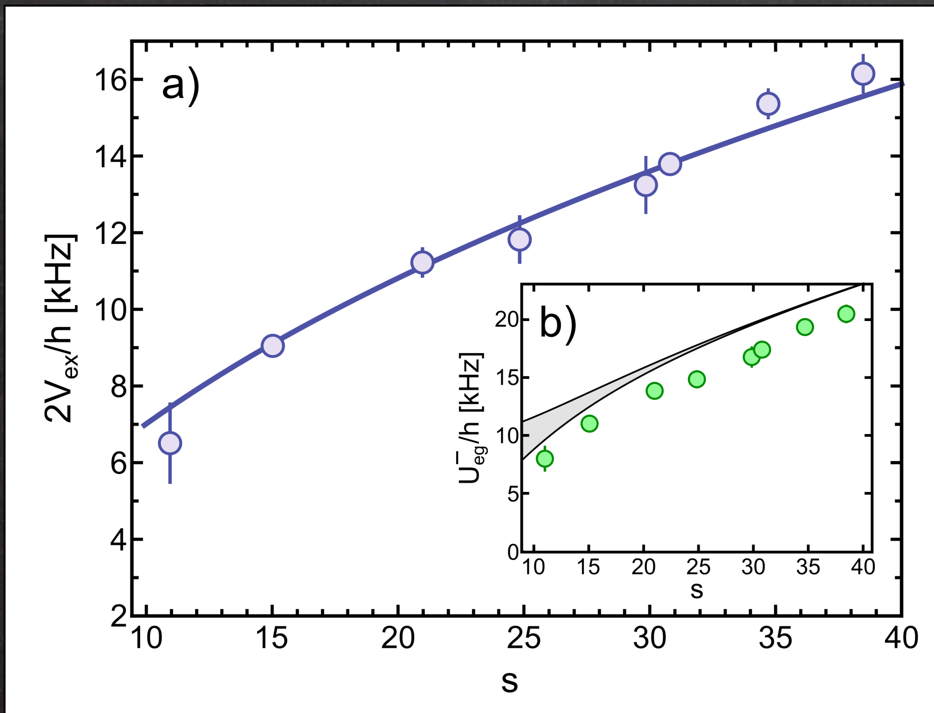
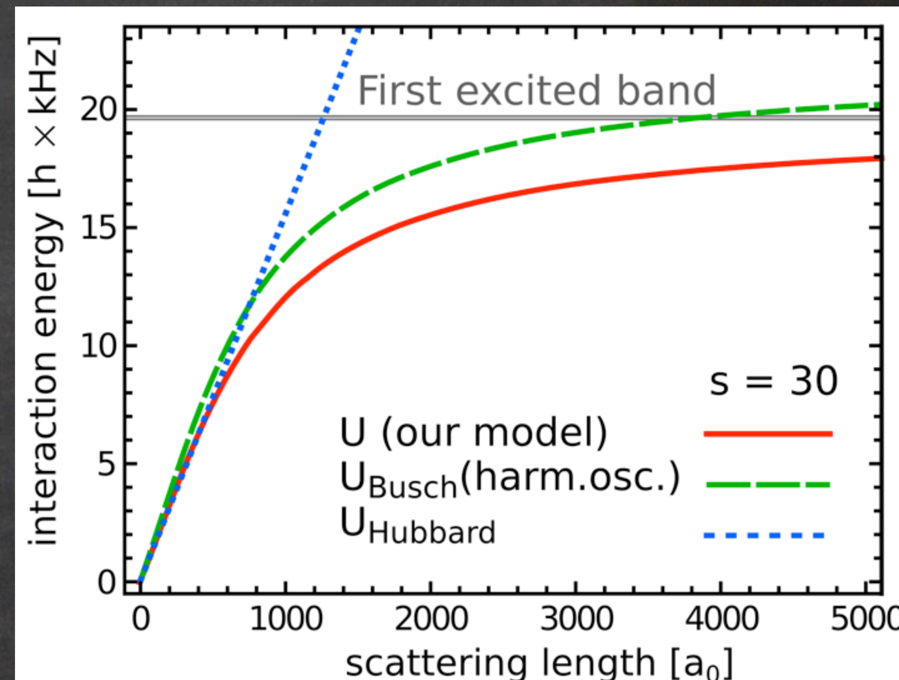
Direct observation of long-lived spin-exchange oscillations

G. Cappellini et al., PRL 113, 120402 (2014) Physics

g-e spin-exchange interaction

Very large spin-exchange energy!!! $V_{ex} \gg k_B T$





Strong repulsion in the $|eg^-\rangle$ state, close to the lattice band separation

Beyond standard Hubbard treatment of interactions ("fermionization" of spatial wavefunction)

$$a^+_{eg} = 220\,a_0$$
$$a^-_{eg} = 3300\,a_0$$

T. Busch et al., Found. Phys. 28, 549 (1998)
Zurn et al., PRL 108, 075303 (2012)

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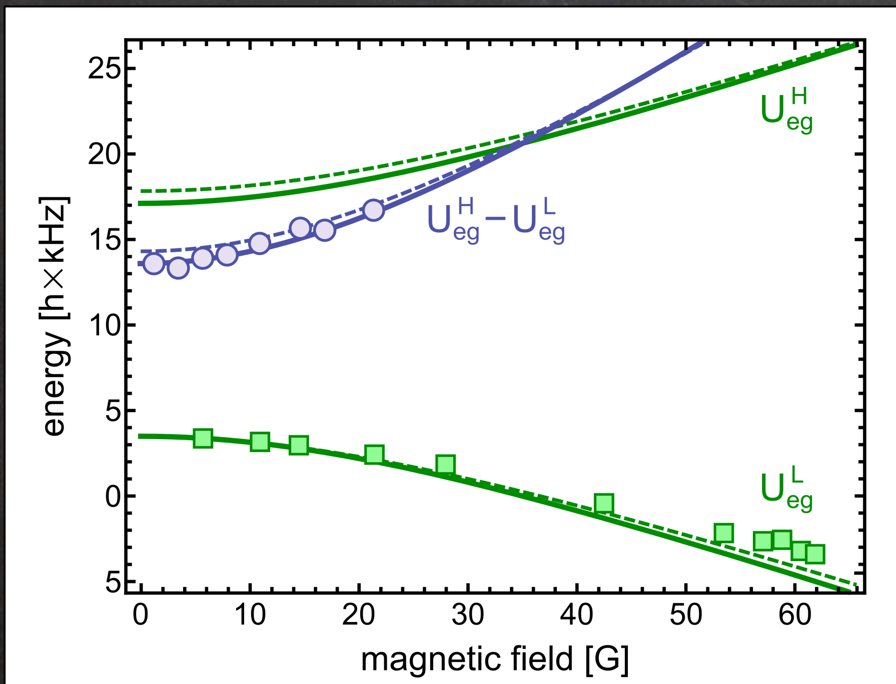
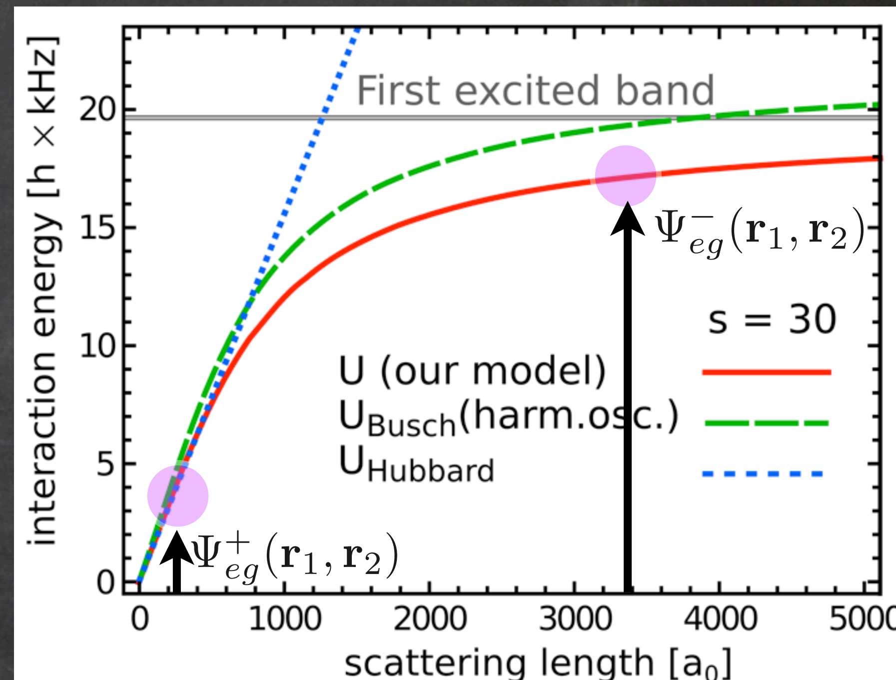
$V_{ex} \gg k_B T$





Frank-Condon Factor necessary to take into account spatial wavefunction fermionization

$$\hat{H} = \begin{pmatrix} U^{+}_{eg} & F\Delta B \\ F\Delta B & U^{-}_{eg} \end{pmatrix}$$

$$F = \iint d\mathbf{r}_1 d\mathbf{r}_2 \Psi^{+}_{eg}(\mathbf{r}_1, \mathbf{r}_2)\Psi^{-}_{eg}(\mathbf{r}_1, \mathbf{r}_2) < 1$$

$$a^{+}_{eg} = 220\, a_0$$
$$a^{-}_{eg} = 3300\, a_0$$

Outlook

For more details...

G. Pagano, M. Mancini, G. Cappellini et al., Nature Phys. 10, 198 (2014)

G. Cappellini, M. Mancini, G. Pagano et al., PRL 113, 120402 (2014) Physics

F. Zhang et al., Science 345, 1467-1473, F. Scazza et al., Nat. Phys. 10, 779–784 (2014)

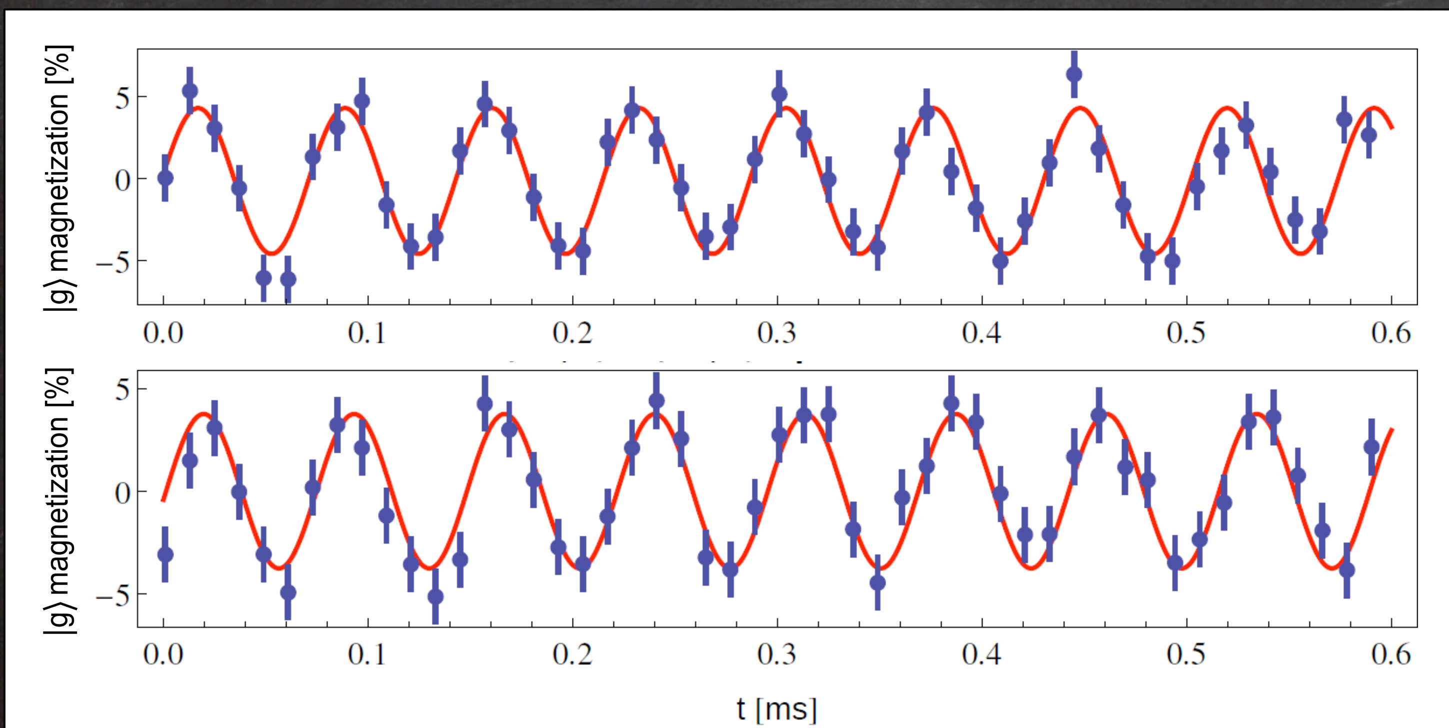
Outlook

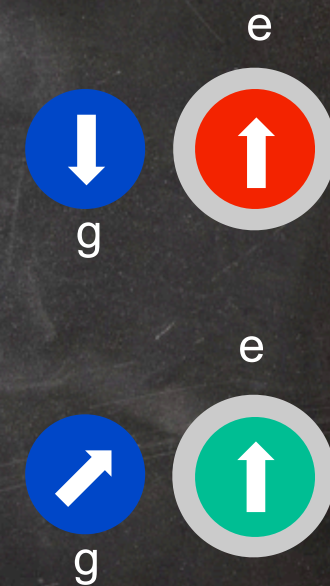
For more details...

G. Pagano, M. Mancini, G. Cappellini et al., Nature Phys. 10, 198 (2014)

G. Cappellini, M. Mancini, G. Pagano et al., PRL 113, 120402 (2014)

Measurement of spin-exchange frequency to probe the SU(N) symmetry

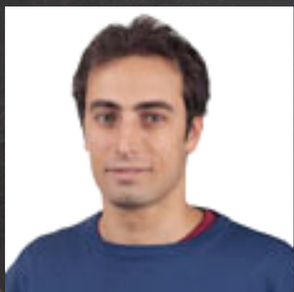




F. Zhang et al., Science 345, 1467-1473, F. Scazza et al., Nat. Phys. 10, 779–784 (2014)

Credits

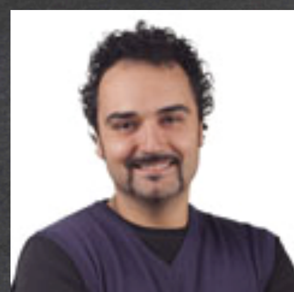
Guido Pagano



Marco Mancini

Giacomo Cappellini

Former members:
F. Schaefer
P. Lombardi



Jacopo Catani

Carlo Sias

Massimo Inguscio

Leonardo Fallani

Collaboration with Yb clock experiment @ INRIM (Torino): M. Pizzocaro, D. Calonico, F. Levi

Funding from EU, ERC, MIUR, IIT

Credits

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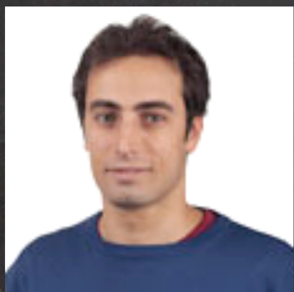
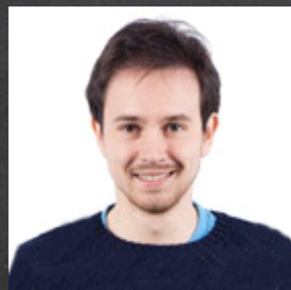


Marco Mancini



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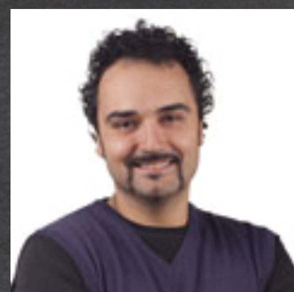

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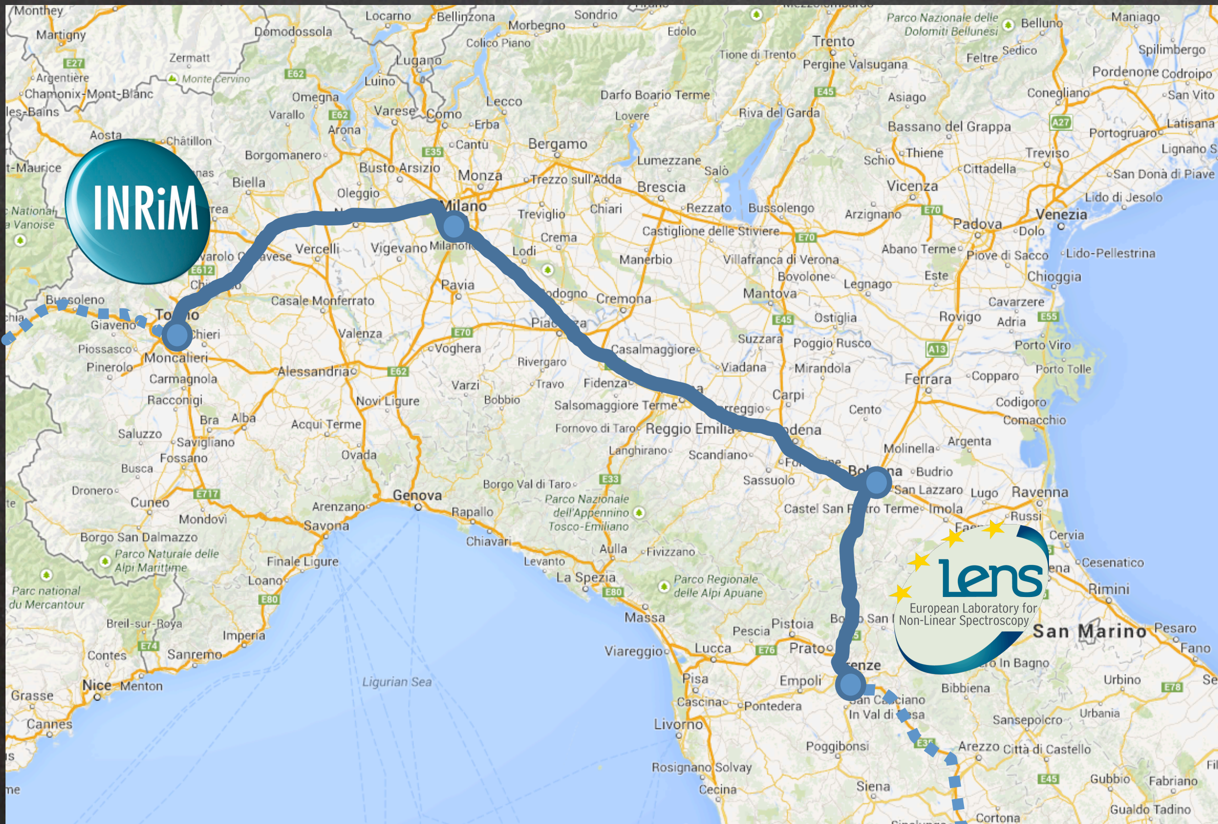
Thanks for your attention!

Funding from EU, ERC, MIUR, IIT

Credits



620km-long dedicated optical frequency link

remote comparison between Yb experiments

Collaboration with Yb clock experiment @ INRIM (Torino): M. Pizzocaro, D. Calonico, F. Levi

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