The World of Quantum Matter

ALBERT-LUDWIGS-
UNIVERSITÄT FREIBURG

Atomic and Molecular Quantum Dynamics

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Atomare und Molekulare
Quantendynamik

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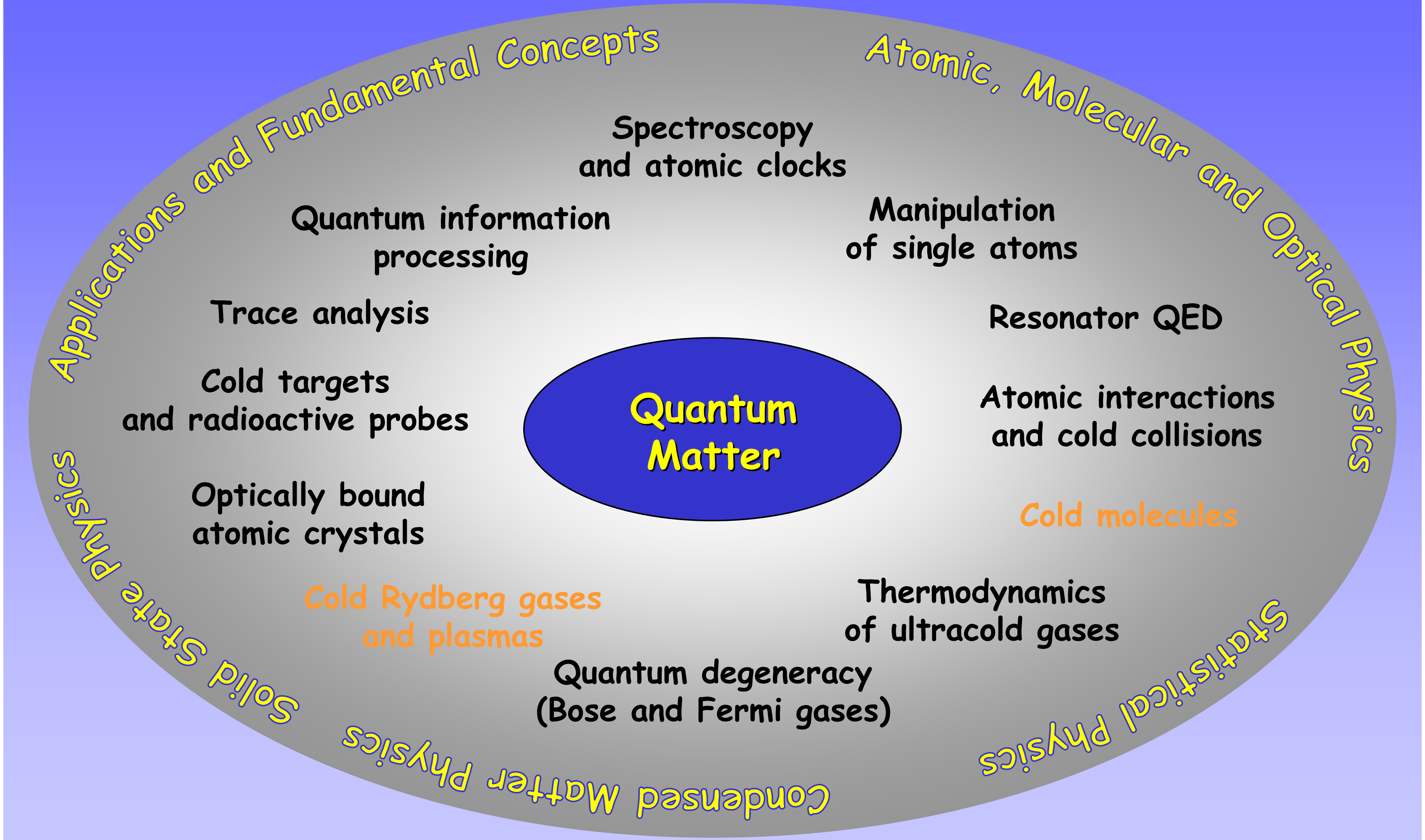
The World of Quantum Matter



Quantum Matter

Spectroscopy
and atomic clocks

Quantum information
processing

Manipulation
of single atoms

Trace analysis

Resonator QED

Cold targets
and radioactive probes

Atomic interactions
and cold collisions

Optically bound
atomic crystals

Cold molecules

Cold Rydberg gases
and plasmas

Thermodynamics
of ultracold gases

Quantum degeneracy
(Bose and Fermi gases)

Applications and Fundamental Concepts

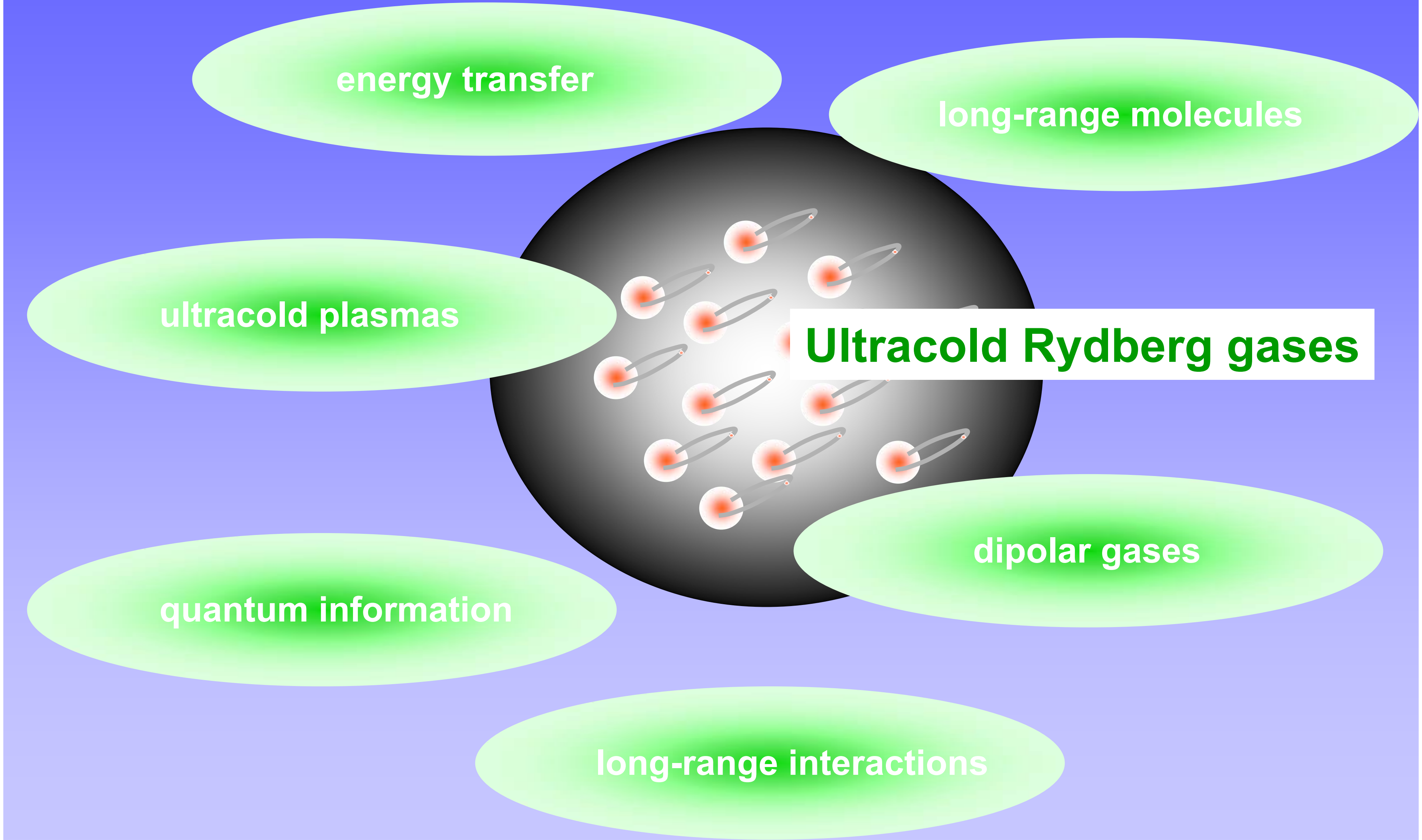
Atomic, Molecular and Optical Physics

Statistical Physics

Condensed Matter Physics

Solid State Physics

Ultracold Rydberg gases



energy transfer

long-range molecules

ultracold plasmas

Ultracold Rydberg gases

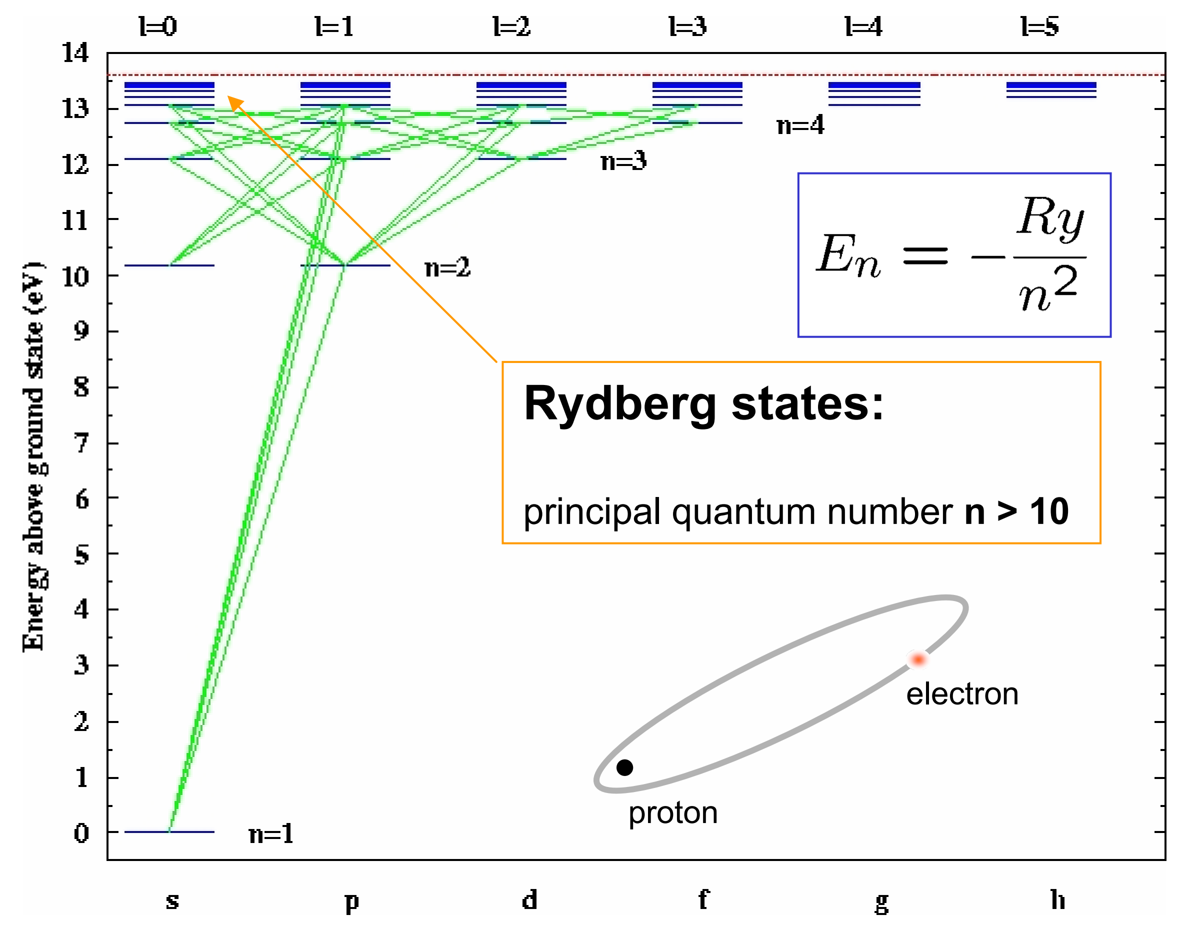
dipolar gases

quantum information

long-range interactions

Rydberg atoms

Hydrogen energy levels

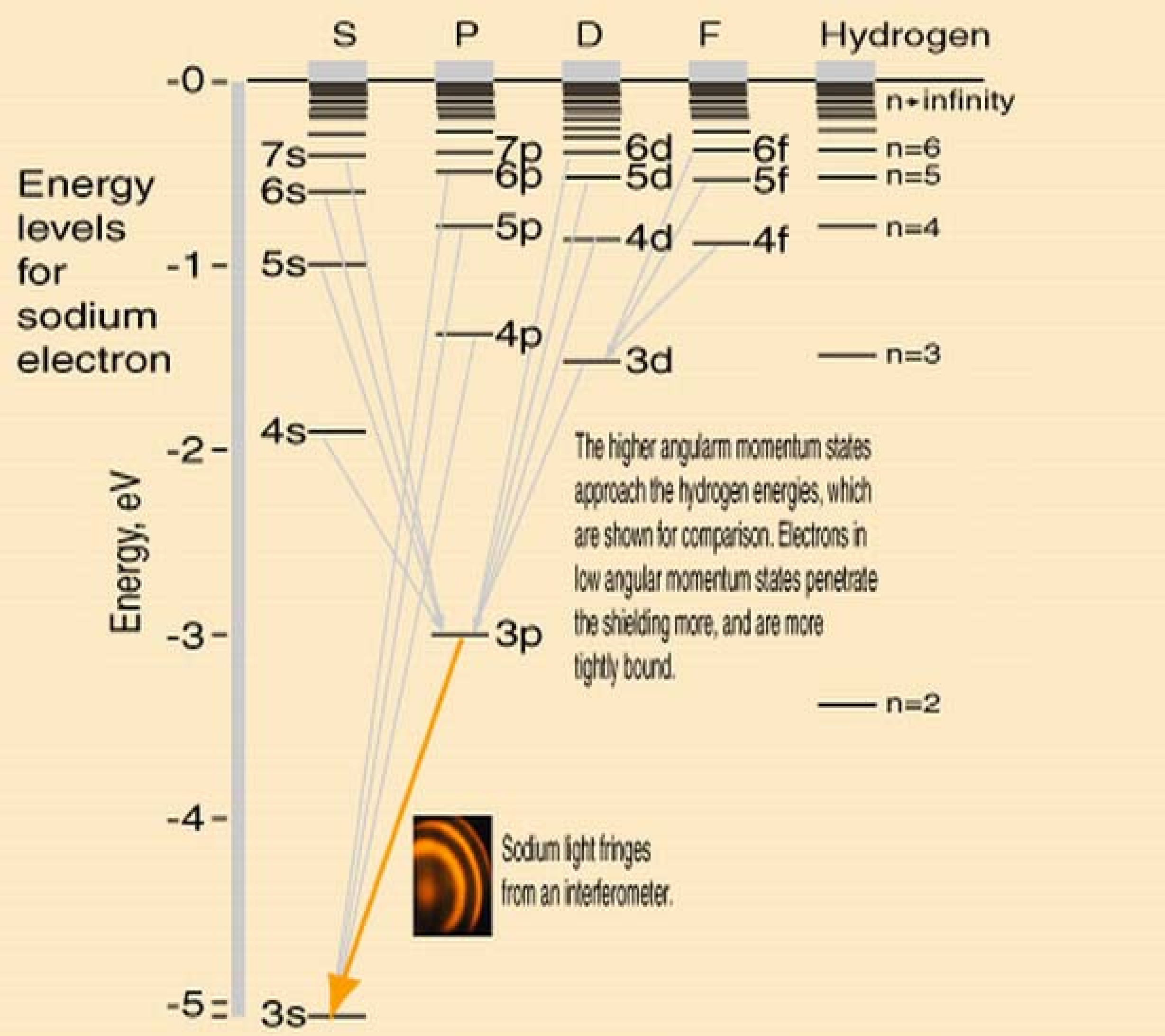


$$E_n = -\frac{Ry}{n^2}$$

Rydberg states:

principal quantum number **n > 10**

Alkali Ryberg atoms



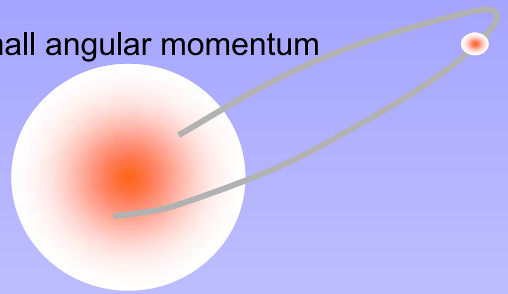
The higher angularm momentum states approach the hydrogen energies, which are shown for comparison. Electrons in low angular momentum states penetrate the shielding more, and are more tightly bound.

Sodium light fringes from an interferometer.

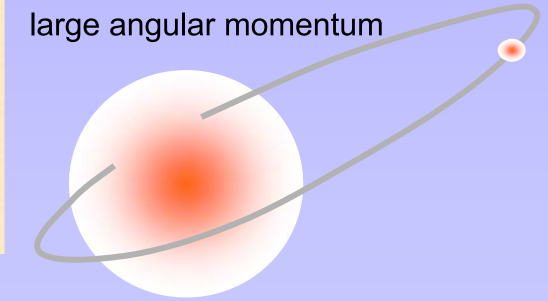
$$E_{n\ell} = -\frac{Ry}{(n-\delta_\ell)^2}$$

$\delta_0 = 1.348$
$\delta_1 = 0.855$
$\delta_2 = 0.015$
$\delta_3 = 0.011$

small angular momentum



large angular momentum



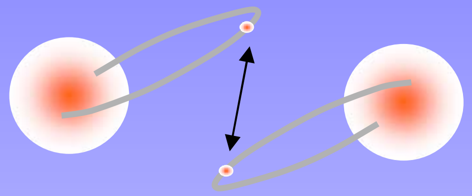
Interactions between Rydberg atoms

Highly excited electronic states :

- Small binding energy	$\propto n^{-2}$	(10 cm^{-1} @ n=100)
- Long radiative lifetimes	$\propto n^{3}$	(1 ms @ n=100)
- Orbital radius	$\propto n^{2}$	(0.5 μm @ n=100)

Strong dipole-dipole interactions:

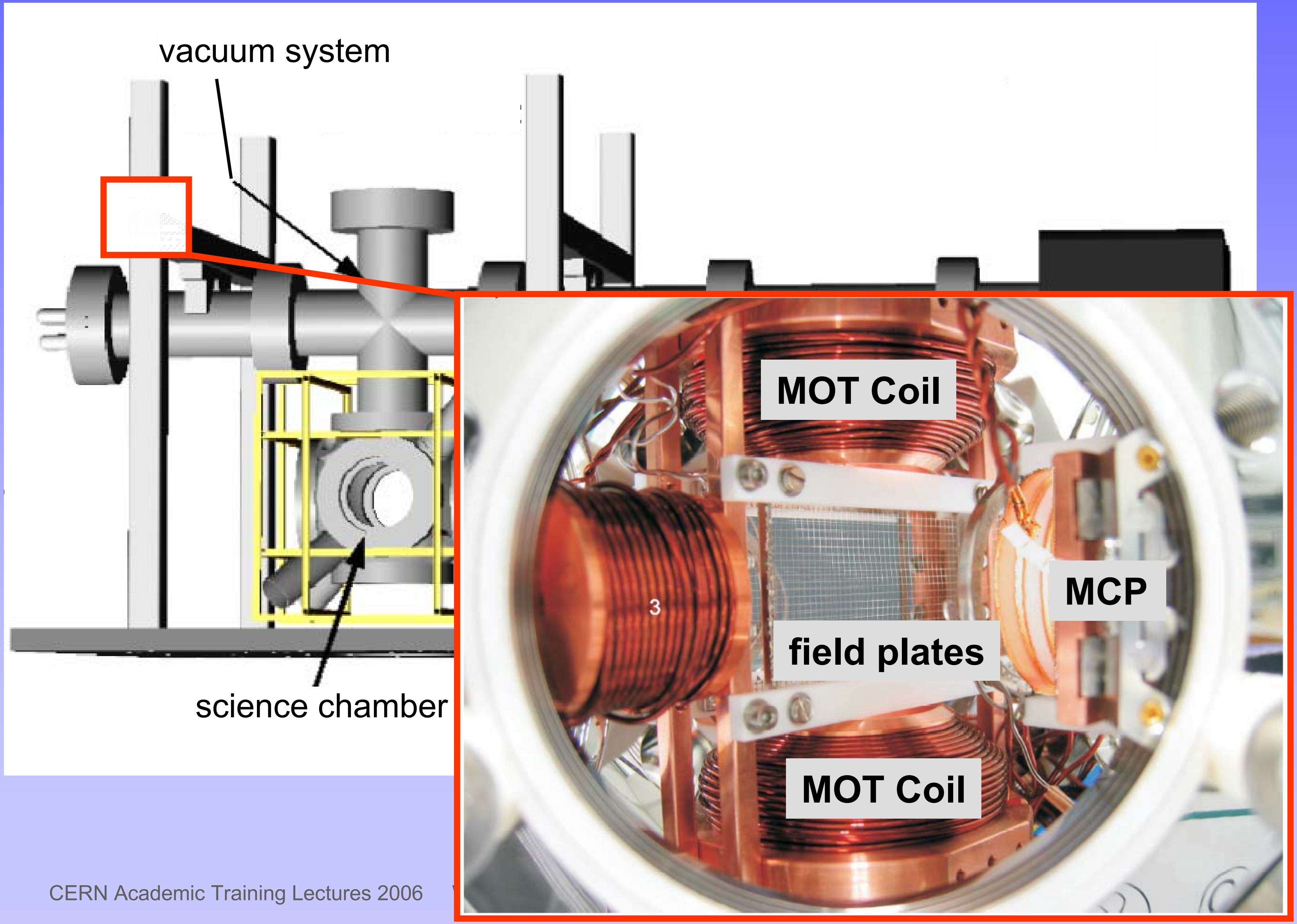
- **Large polarizability $\propto n^{7}$**
- **Strong van-der-Waals coefficient $\propto n^{11}$**



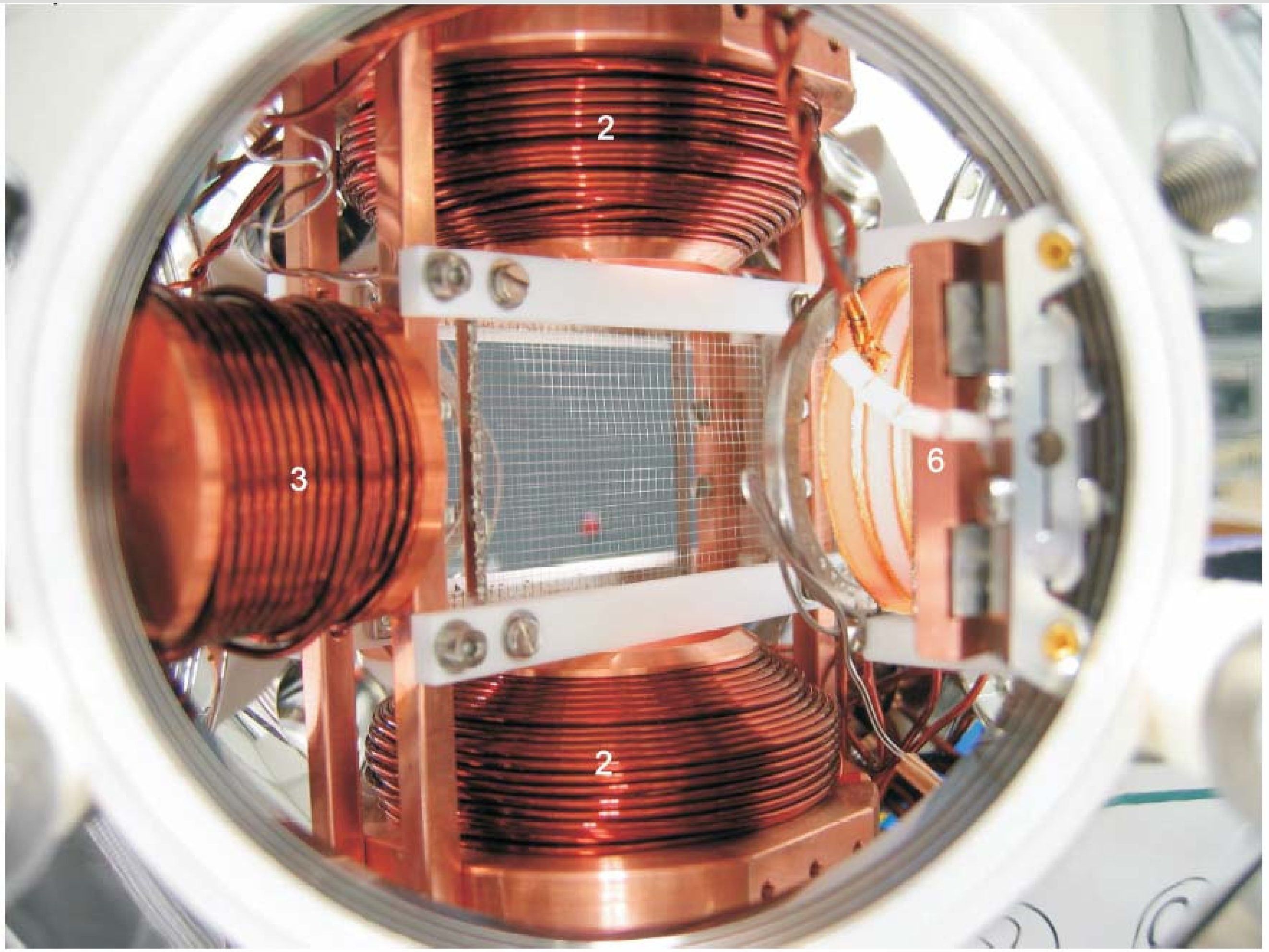
Laser-cooled atomic gases:

- Average distance ~ 5 µm (~ Rydberg extension)
- Thermal velocities ~ 0.1 µm / µs (“frozen” during excitation)
- Thermal energies << interaction energies

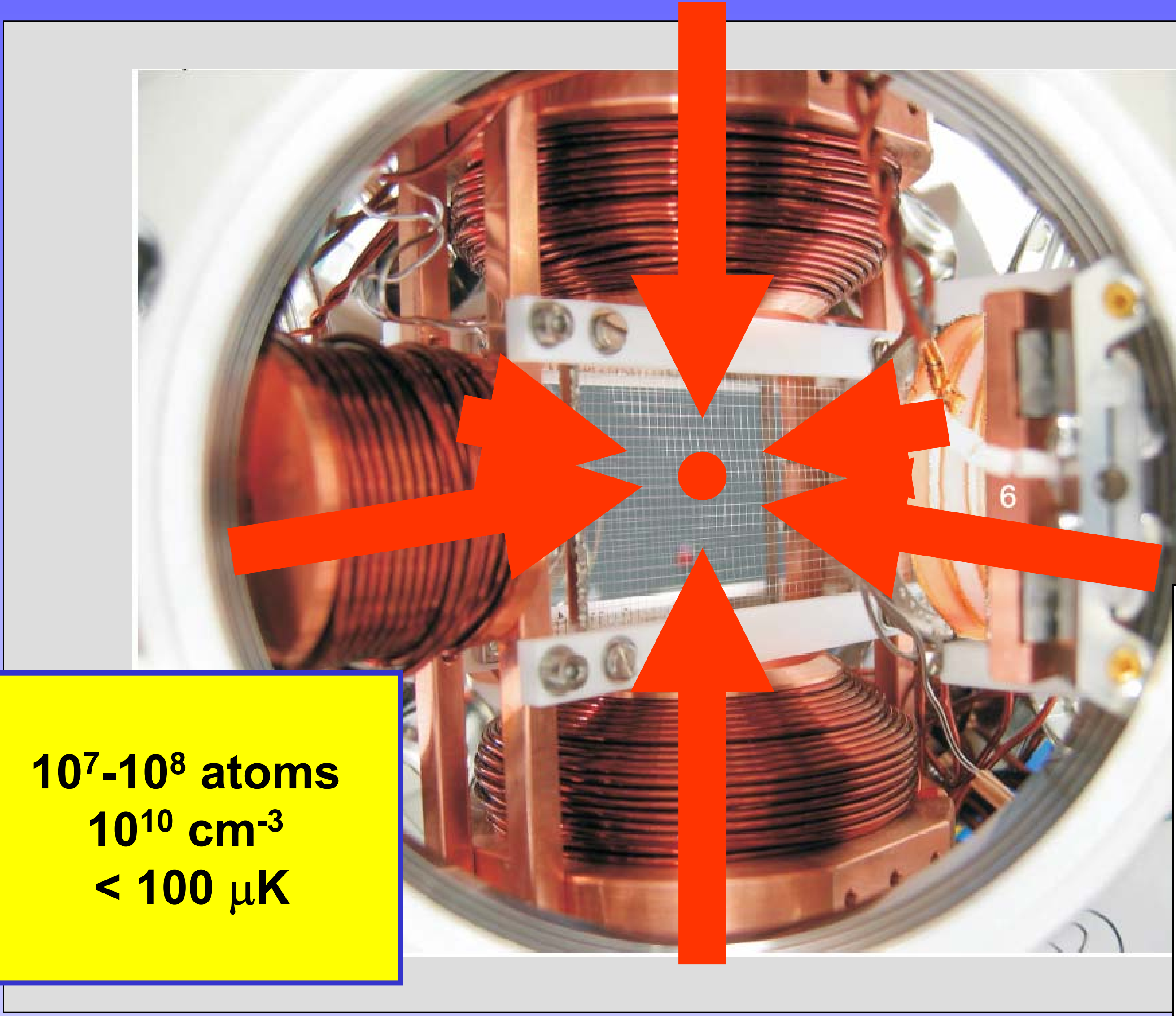
Freiburg Rydberg experiment



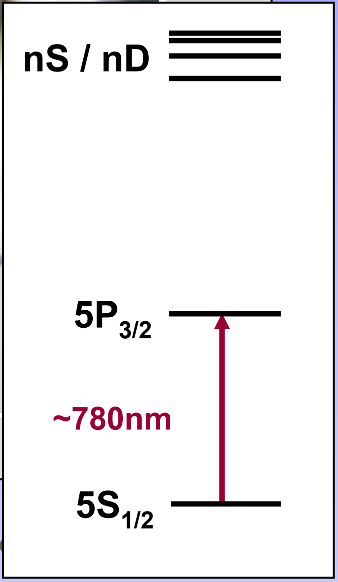
Science chamber



Creation of a cold gas

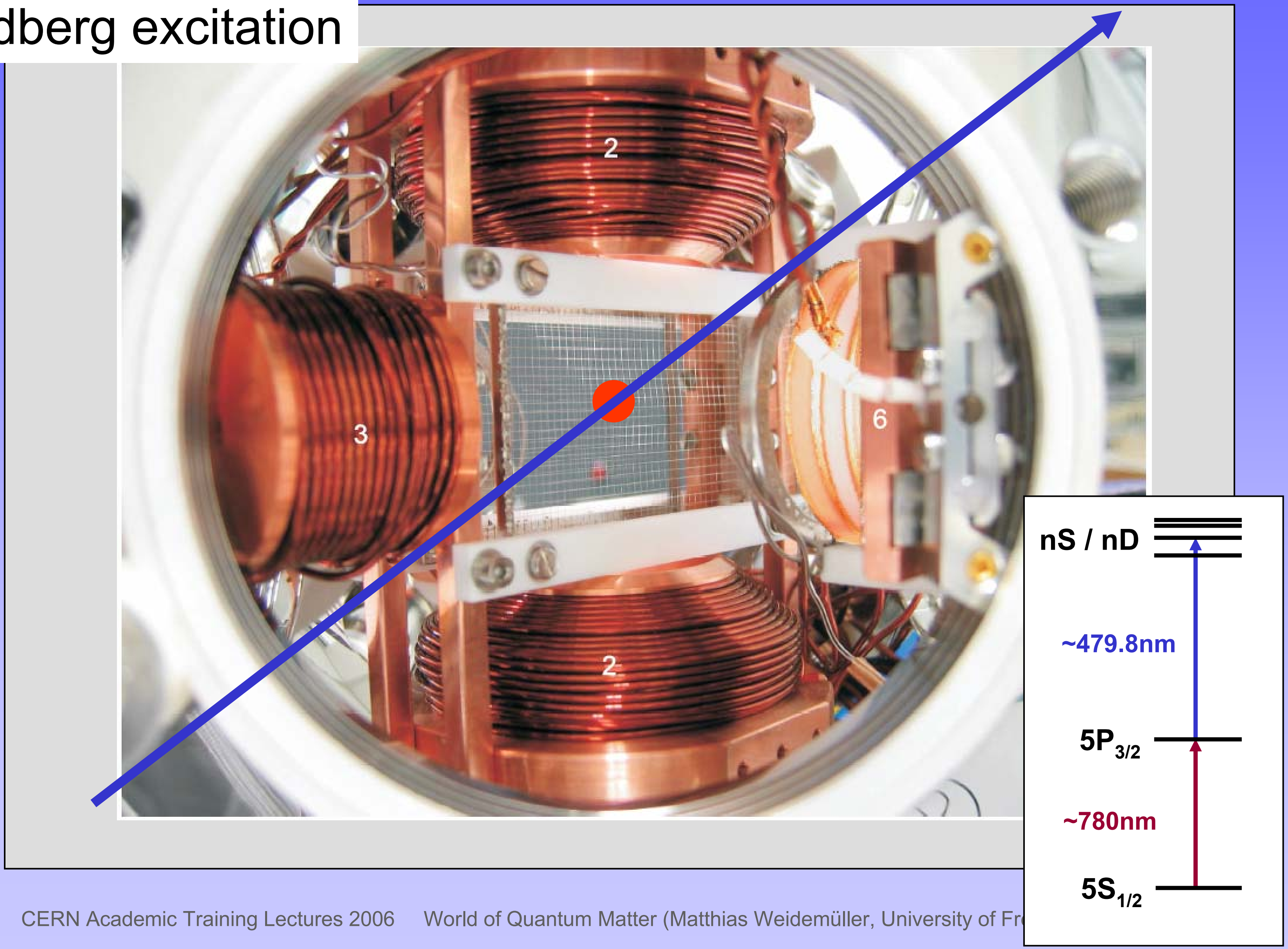


10^7-10^8 atoms
10^{10} cm^{-3}
$< 100\ \mu$K



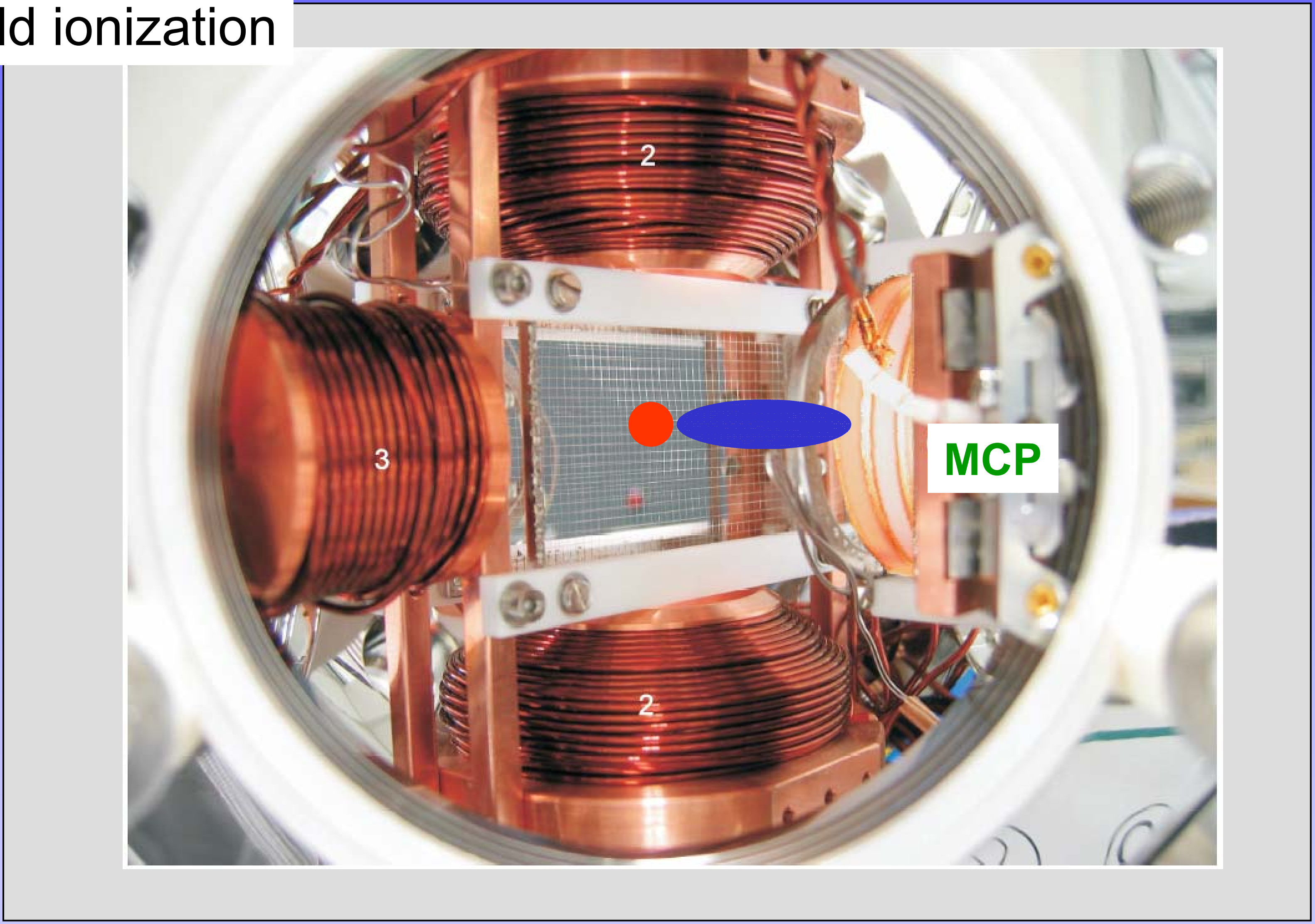
Excitation into a cold Rydberg gas

Rydberg excitation

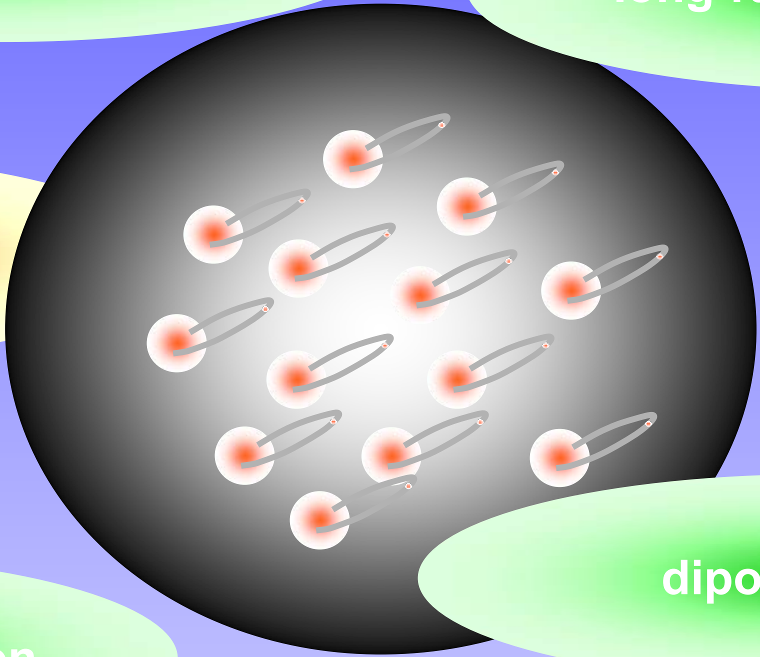


Detection of Rydberg atoms

Field ionization



Ultracold Rydberg gases



energy transfer

long-range molecules

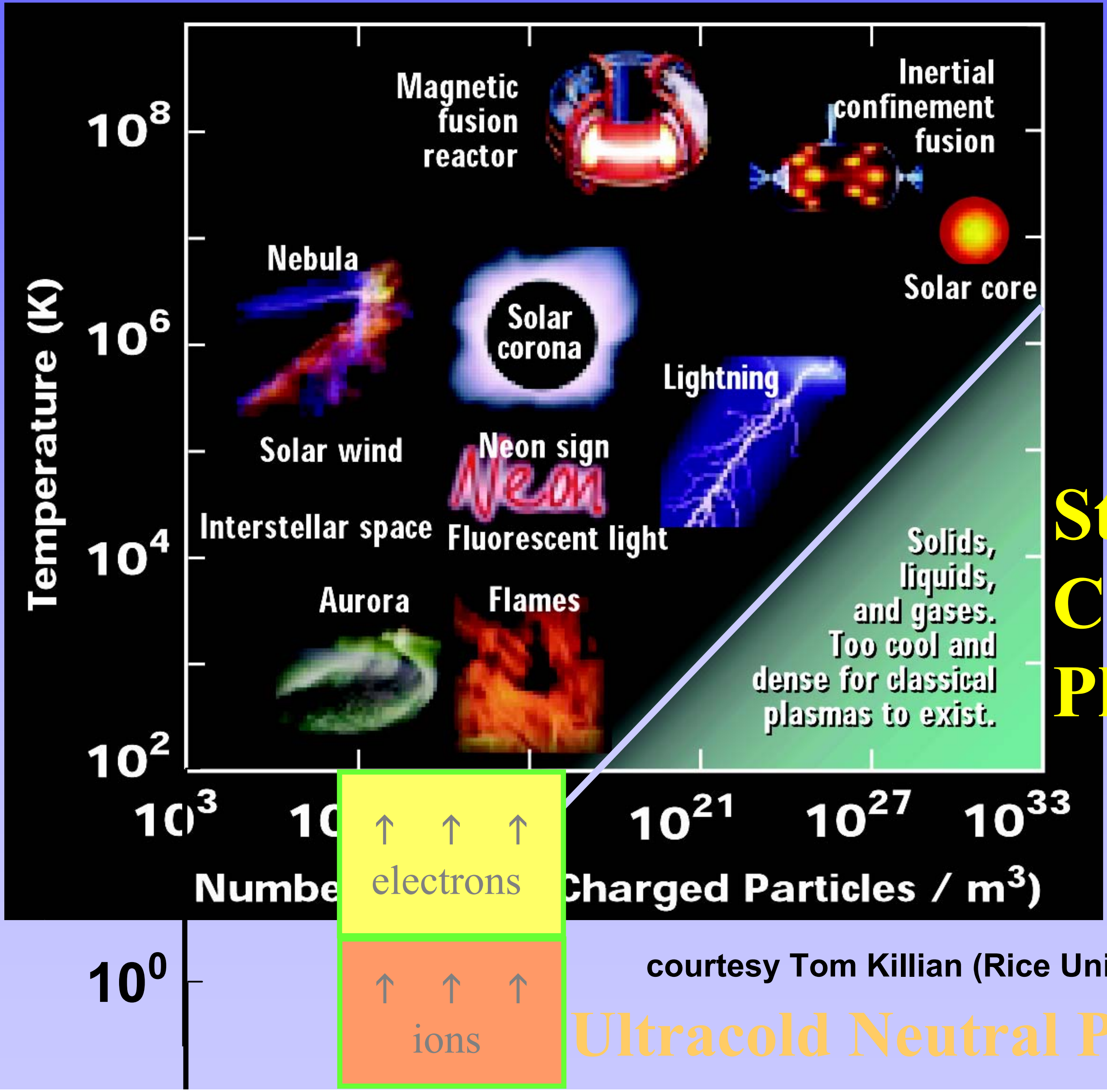
ultracold plasmas

dipolar gases

quantum information

long-range interactions

Plasmas

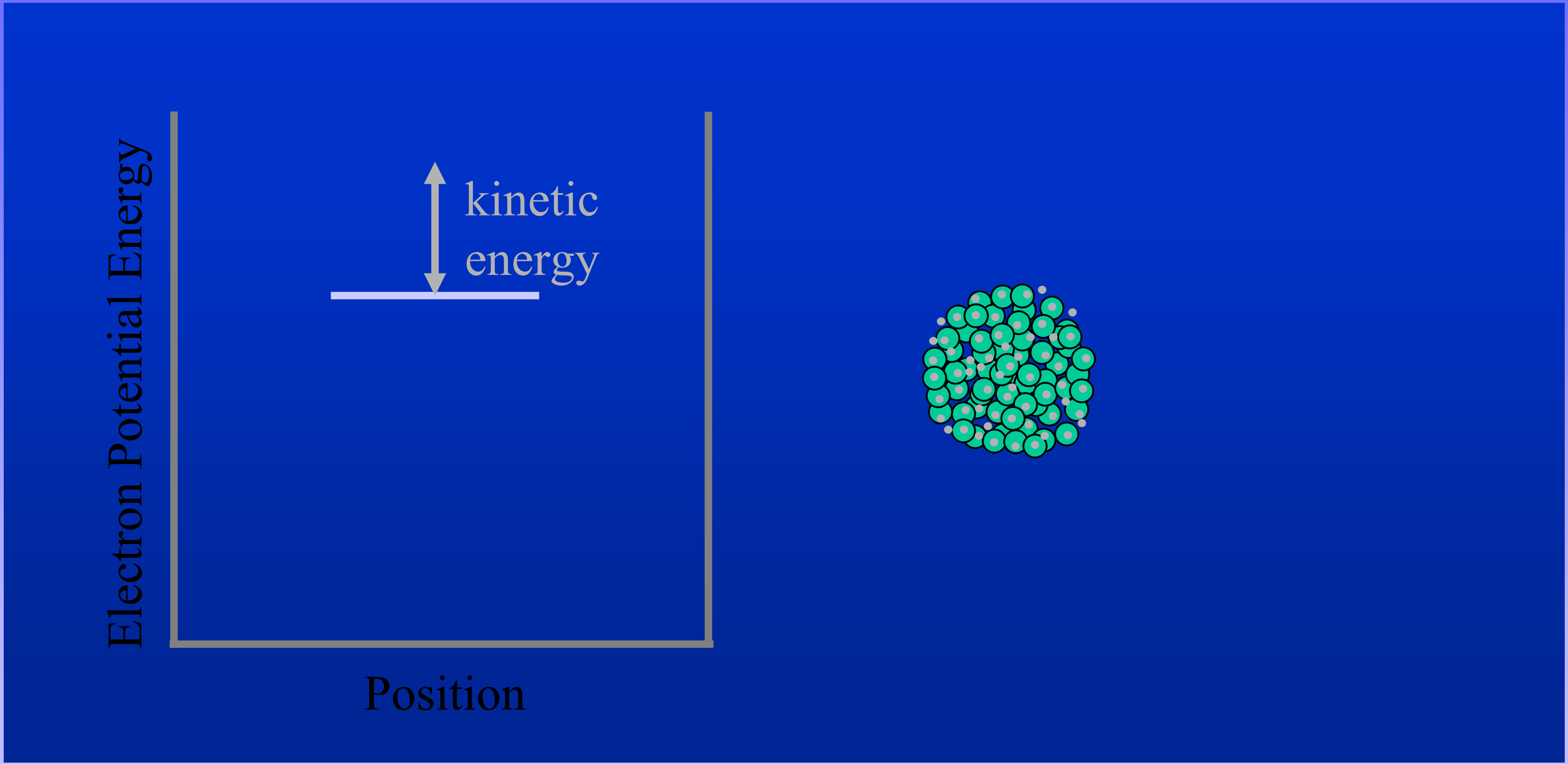


Strongly Coupled Plasmas

courtesy Tom Killian (Rice University, Houston)

Ultracold Neutral Plasmas

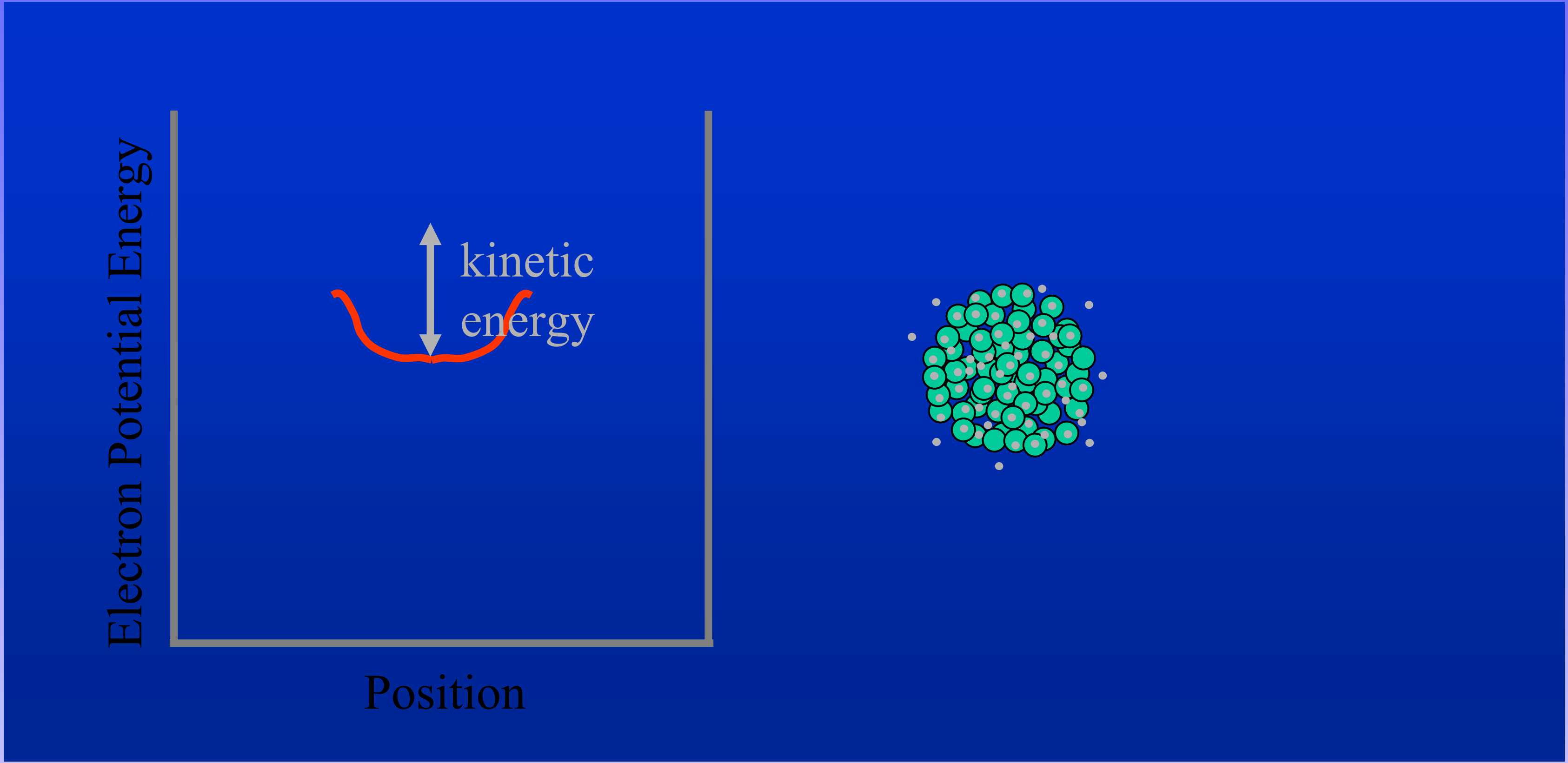
Model for Plasma Creation



At t=0: Just after ionization, the plasma is neutral everywhere and the potential is flat..

courtesy Tom Killian (Rice University, Houston

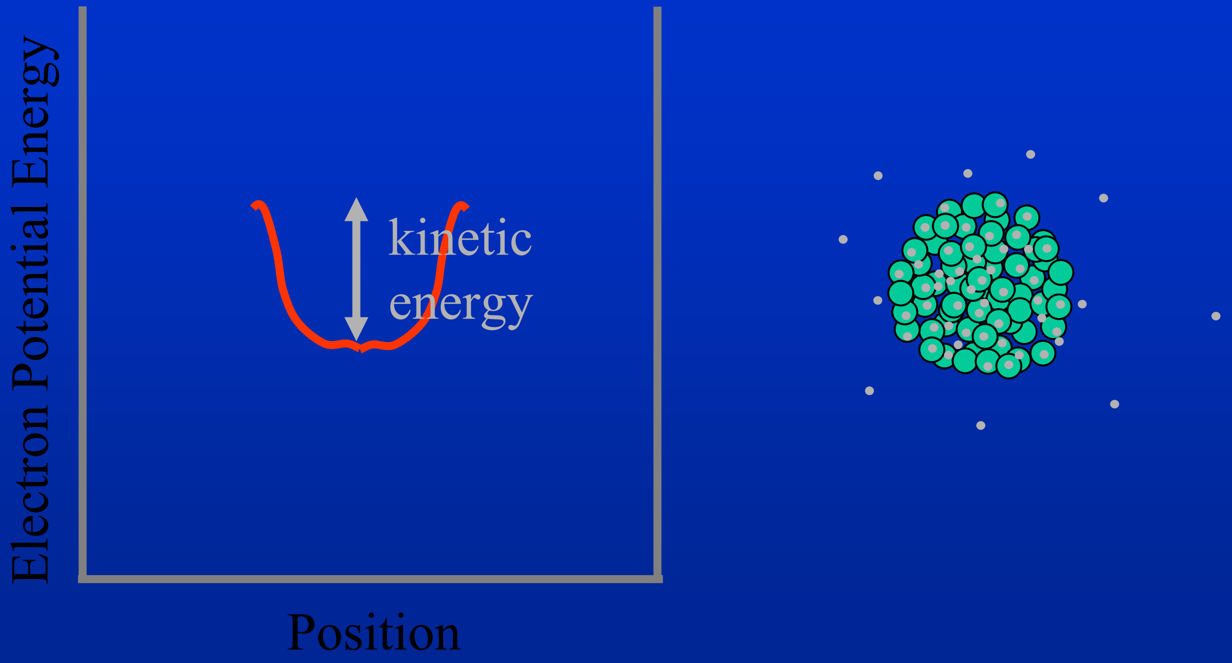
Model for Plasma Creation



At t_1~10ns: Electrons escape due to their kinetic energy and a charge imbalance builds up until electrons are trapped.

courtesy Tom Killian (Rice University, Houston

Model for Plasma Creation



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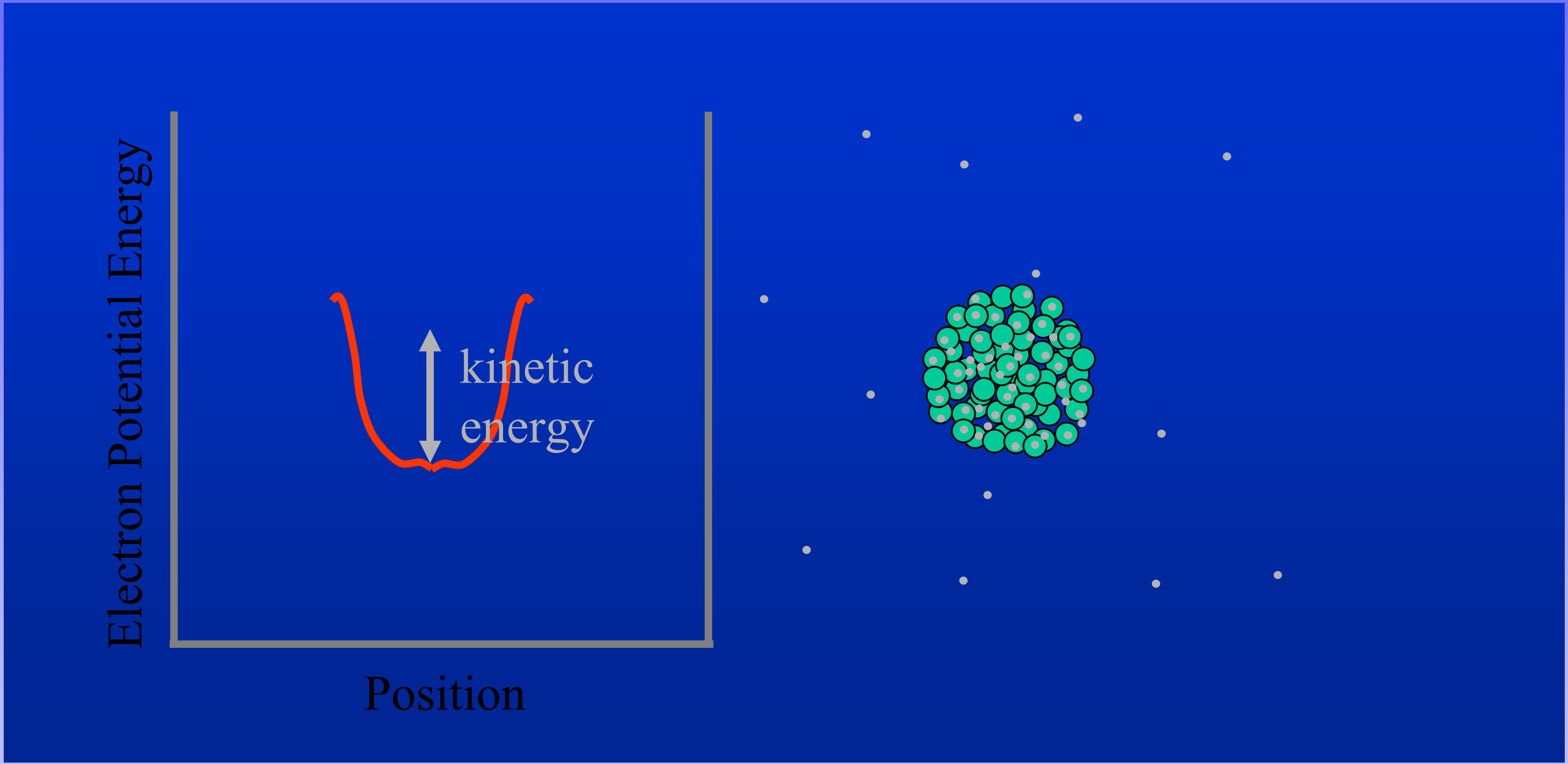
Model for Plasma Creation



At t_1~10ns: Electrons escape due to their kinetic energy and a charge imbalance builds up until electrons are trapped.

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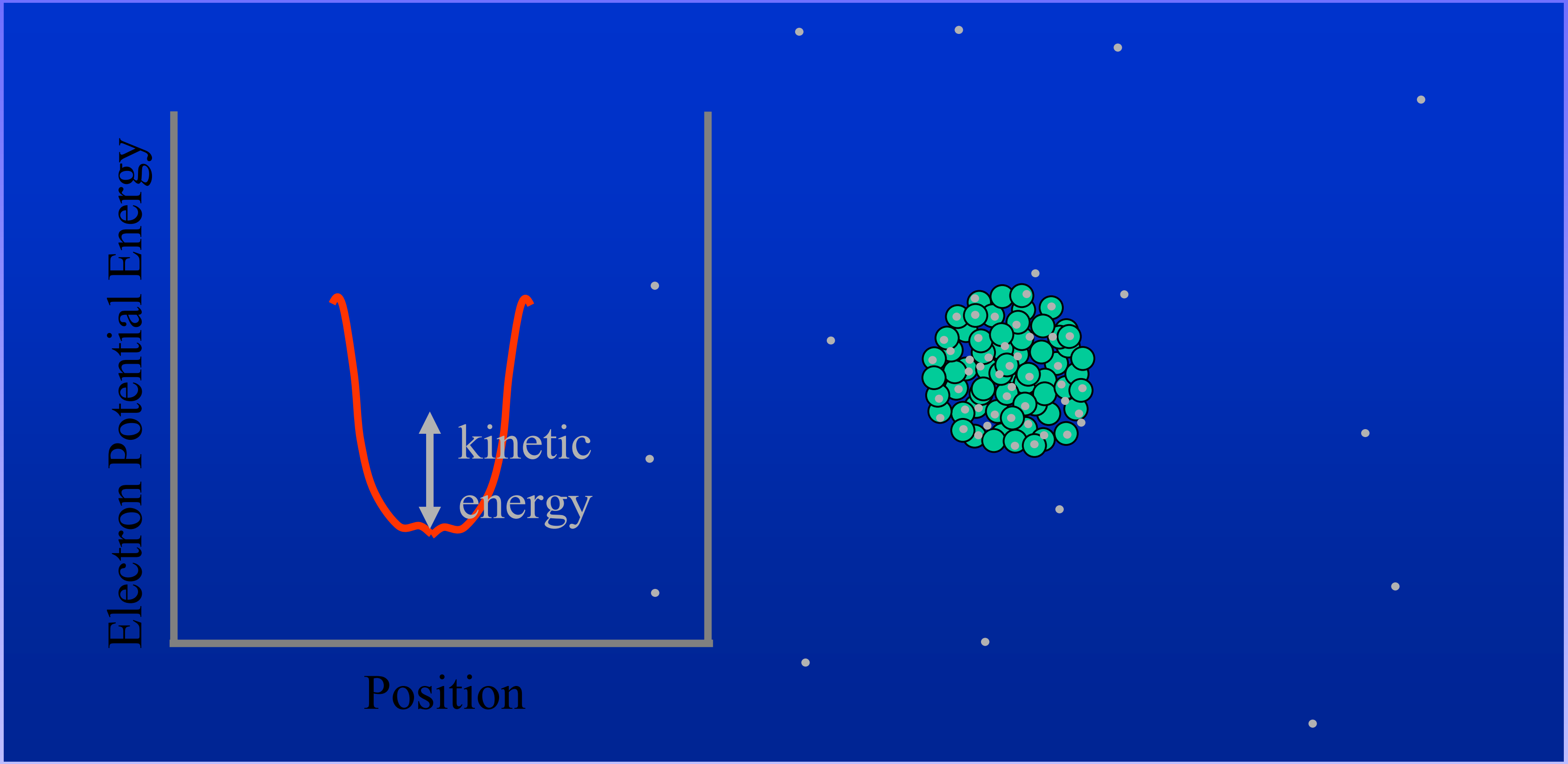
Model for Plasma Creation



At t_1~10ns: Electrons escape due to their kinetic energy and a charge imbalance builds up until electrons are trapped.

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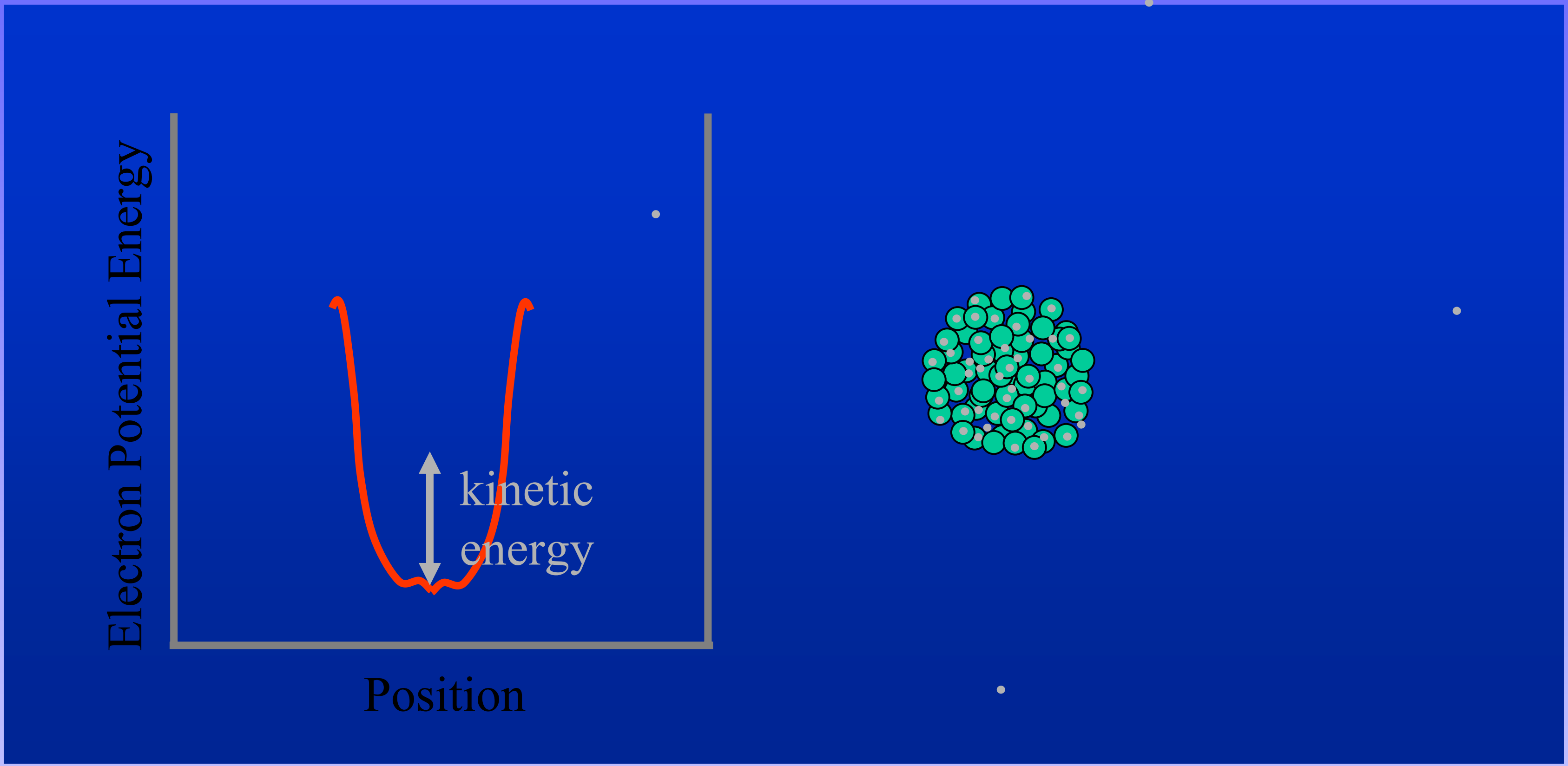
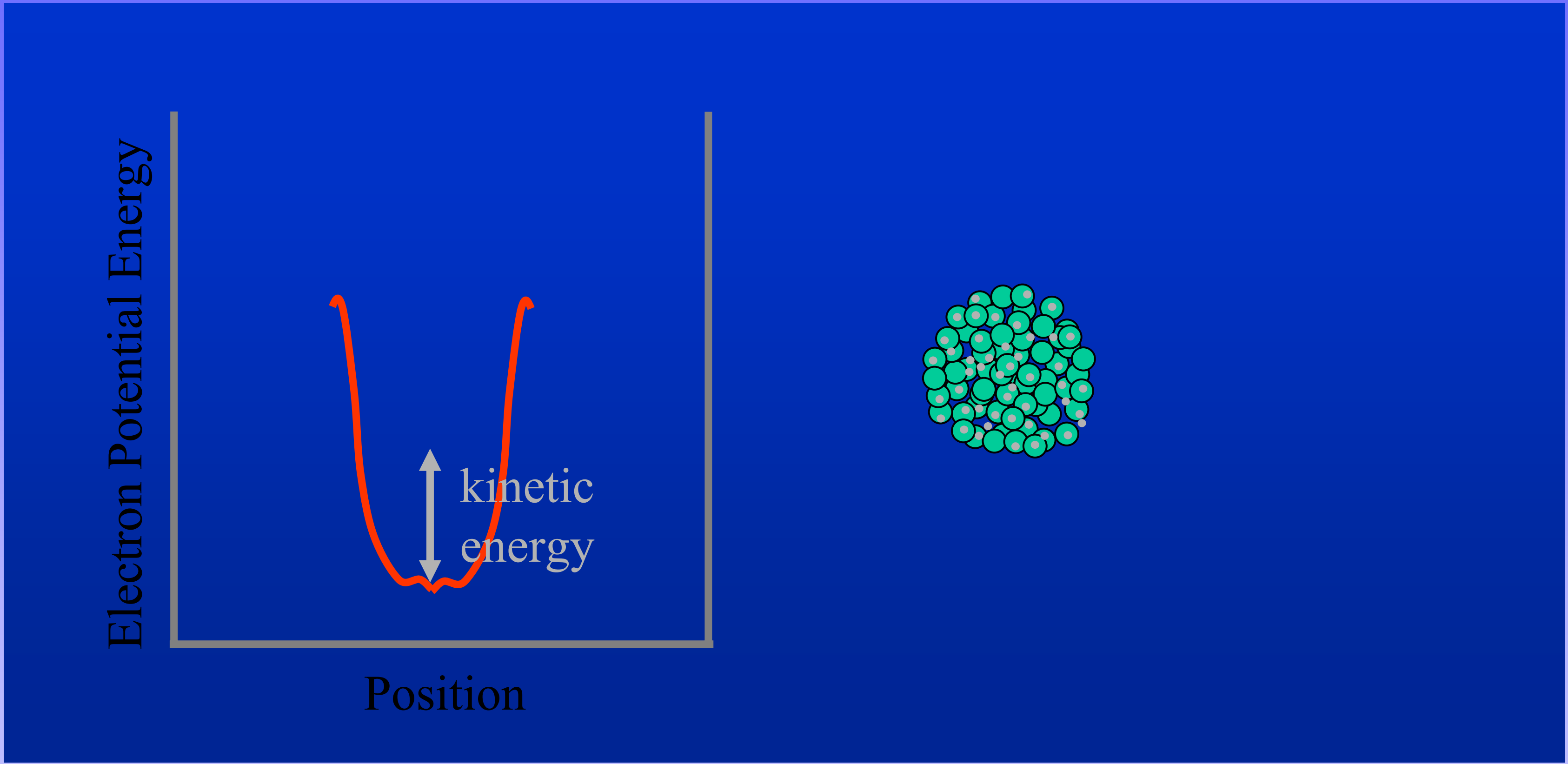
Model for Plasma Creation



At t_1~10ns: Electrons escape due to their kinetic energy and a charge imbalance builds up until electrons are trapped.

courtesy Tom Killian (Rice University, Houston)

Model for Plasma Creation

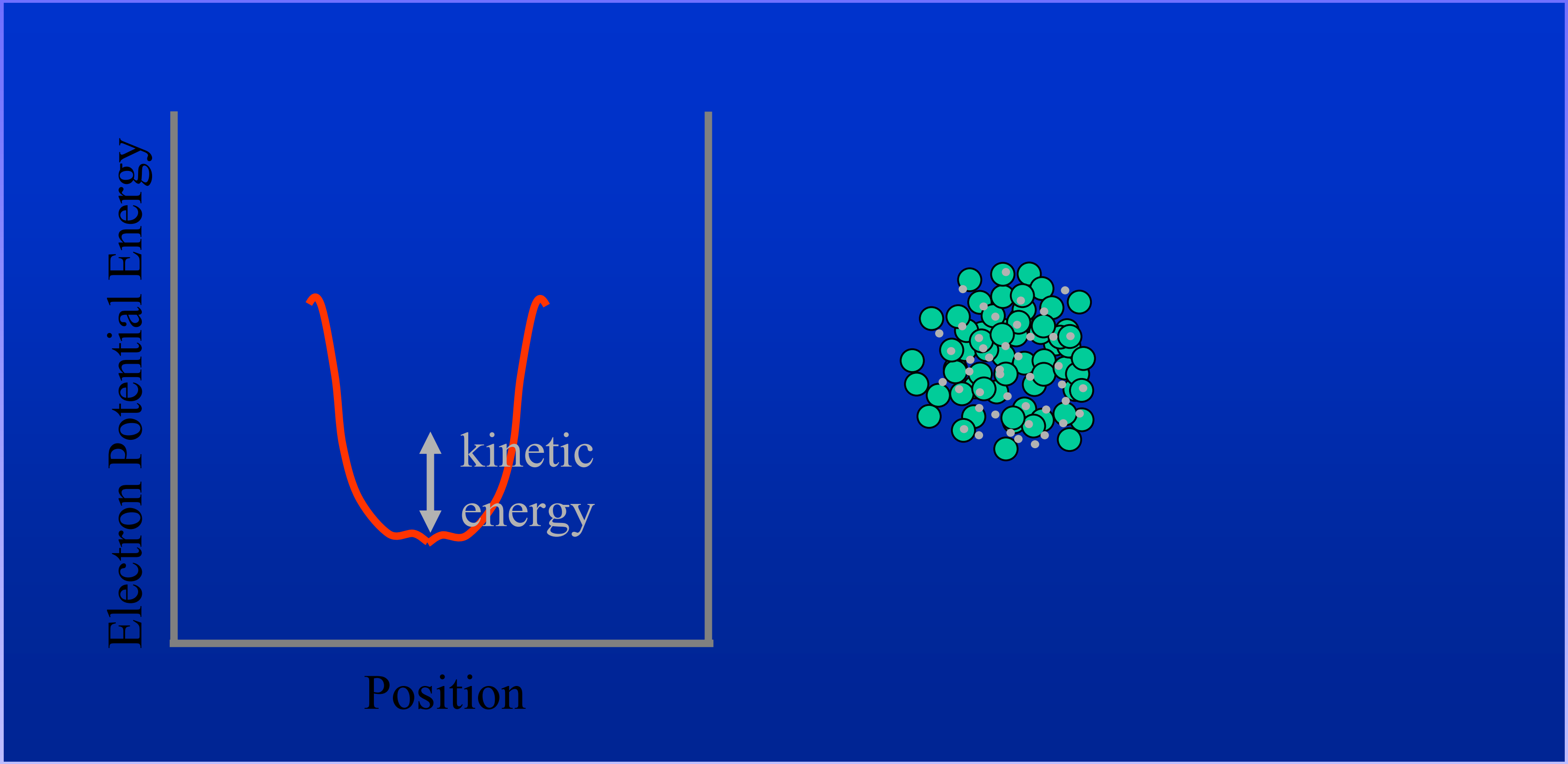


At t_2~.1–10μs: Ultracold plasma

Neutral in center

courtesy Tom Killian (Rice University, Houston

Model for Plasma Creation

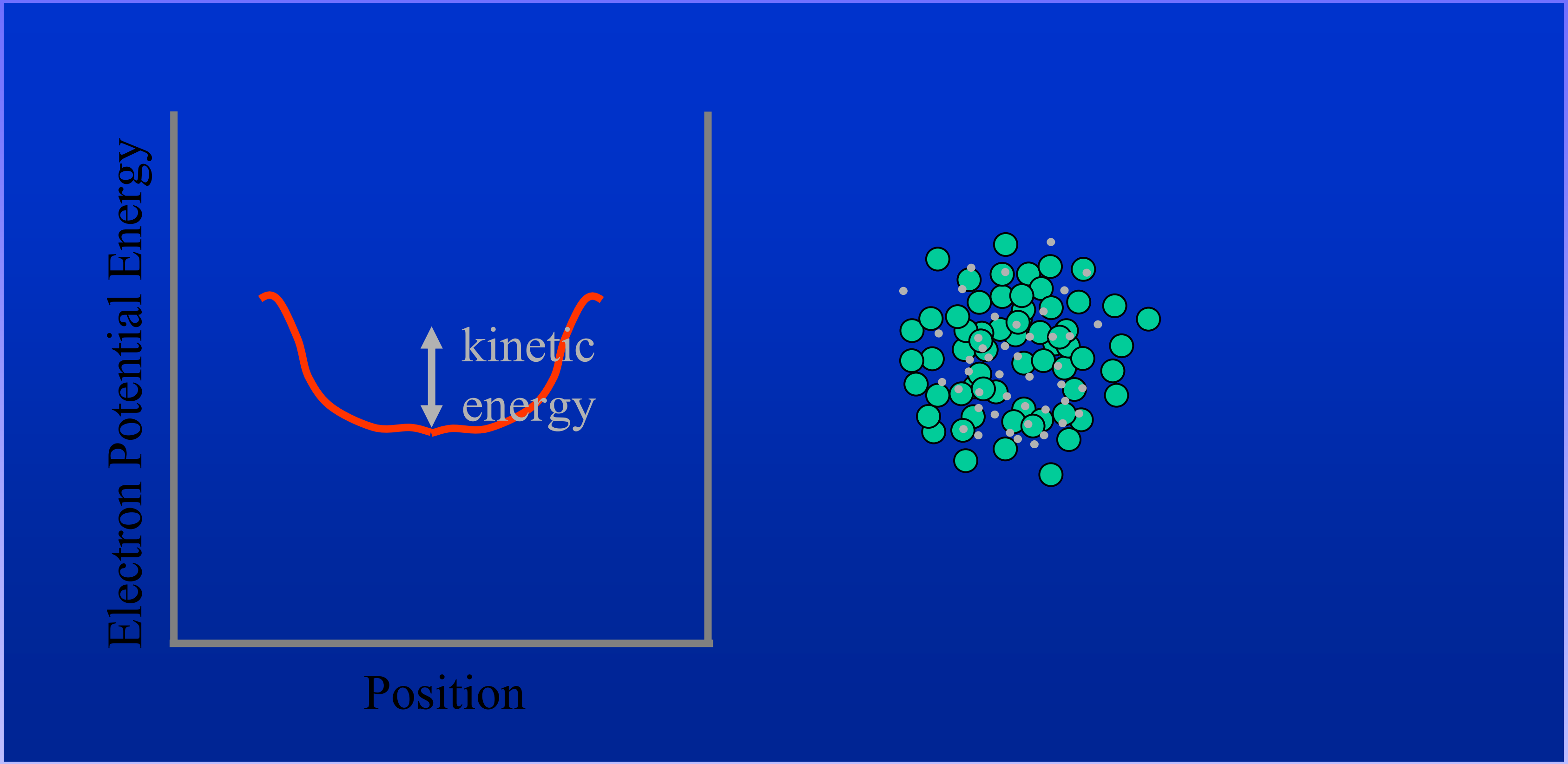


At t_2>10μs: Ions cloud expands.

Coulomb well depth increases.

courtesy Tom Killian (Rice University, Houston

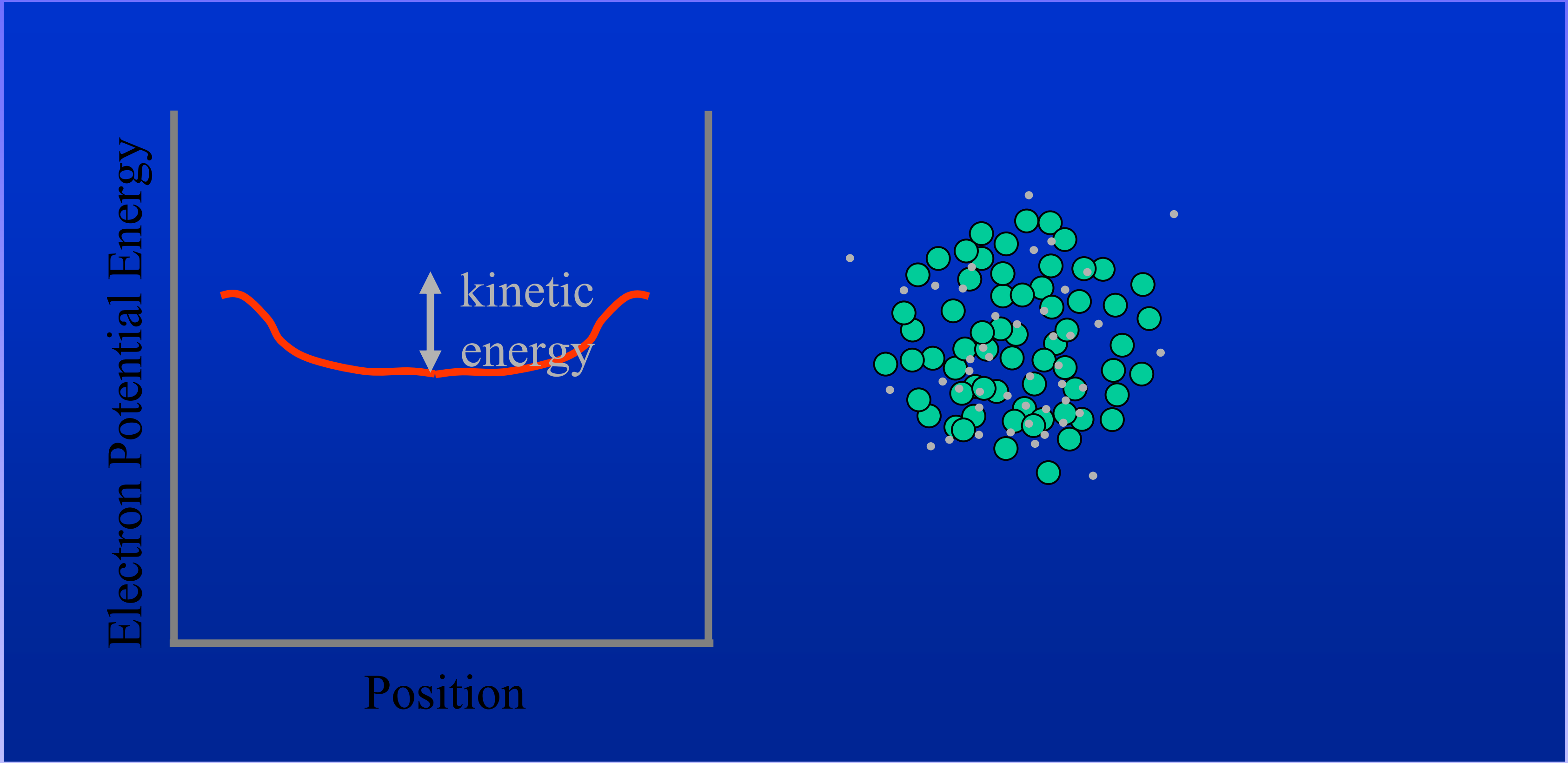
Model for Plasma Creation



At t_2>10μs: Ions cloud expands.
Coulomb well depth decreases.

courtesy Tom Killian (Rice University, Houston

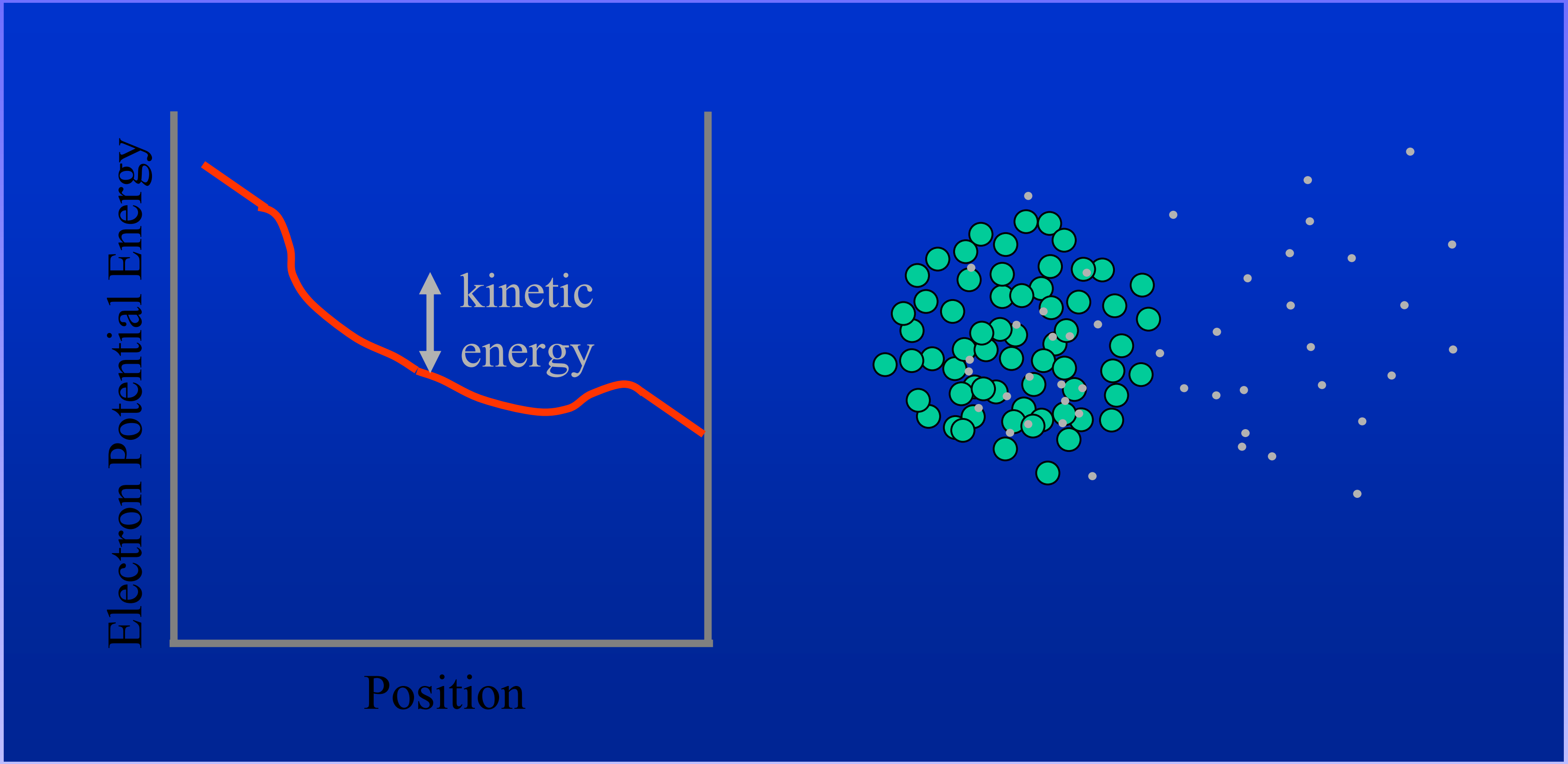
Model for Plasma Creation



At $t_2 > 10\mu s$: Electrons can escape

courtesy Tom Killian (Rice University, Houston

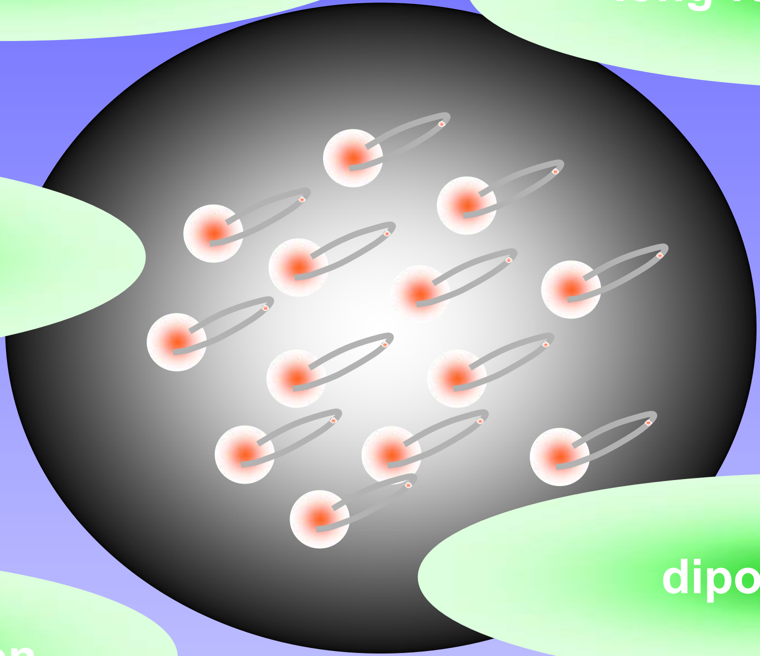
Model for Plasma Creation



At $t_2 > 10\mu s$: Electrons can escape, or be dragged out by residual electric fields.

courtesy Tom Killian (Rice University, Houston

Ultracold Rydberg gases



energy transfer

long-range molecules

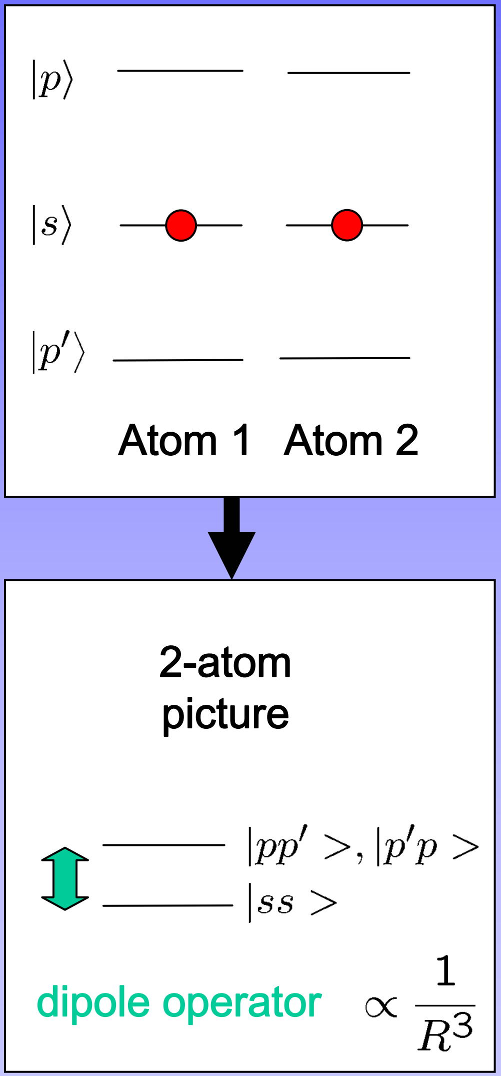
ultracold plasmas

quantum information

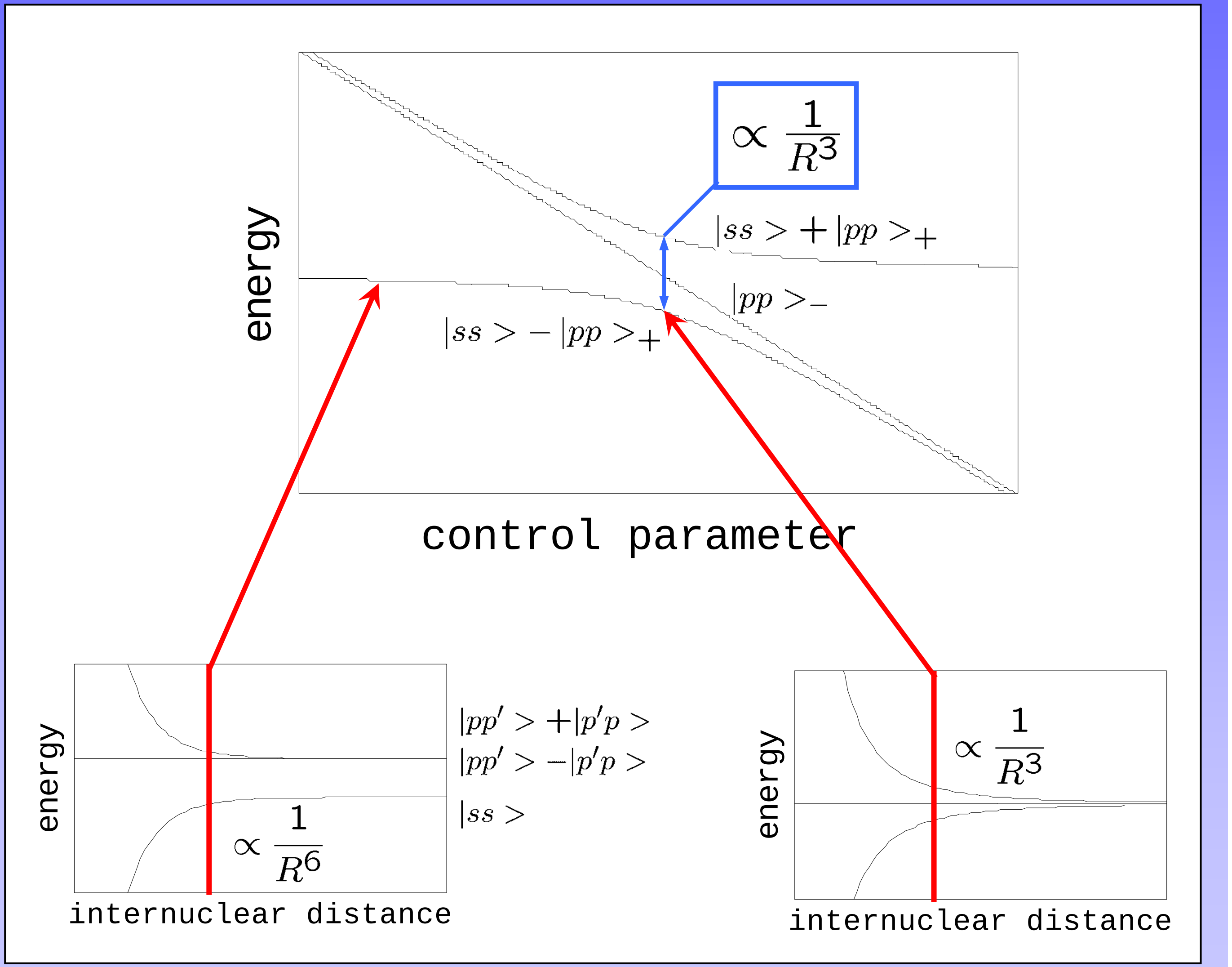
dipolar gases

long-range interactions

Dipole-dipole interaction of two atoms



dipole operator $\propto \frac{1}{R^3}$



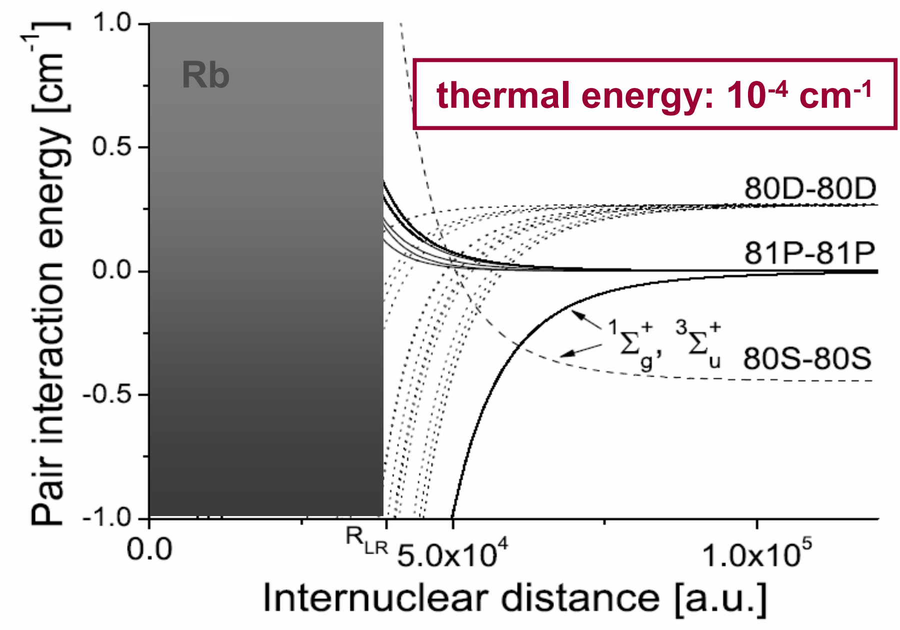
Van-der-Waals interaction

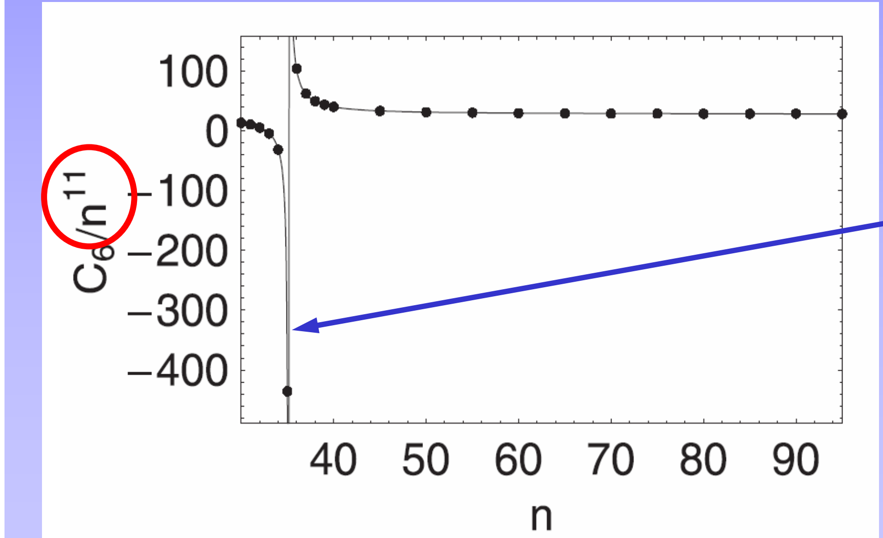
perturbative approach:

$$H = H_0 + V(\vec{r_1}, \vec{r_2})$$

$$V(\vec{r_1}, \vec{r_2}) = -\sum_{n=3}^{\infty} \frac{C_n}{R^n} = \sum_{\ell, L=1}^{\infty} \frac{V_{\ell L}(\vec{r_1}, \vec{r_2})}{R^{\ell+L+1}}$$

M. Marinescu, PRA **56** 4764 (1997)



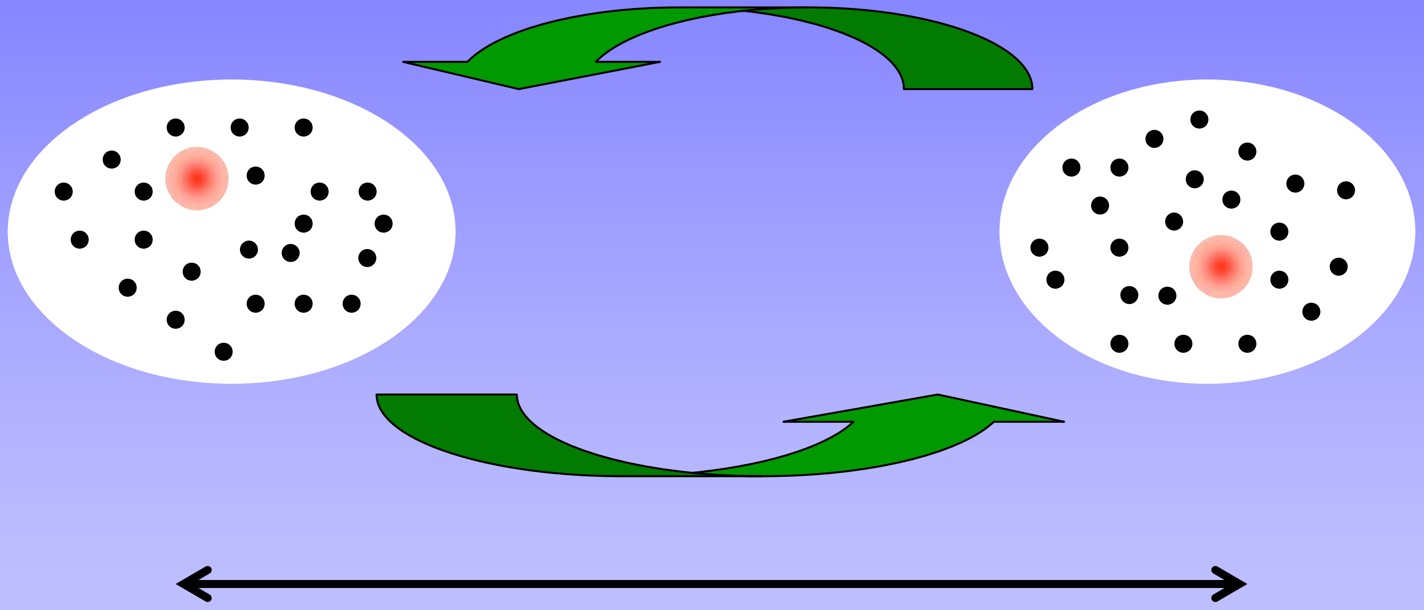


two particle degeneracy at n = 37

→ resonant dipole-dipole interaction $\propto 1/R^3$

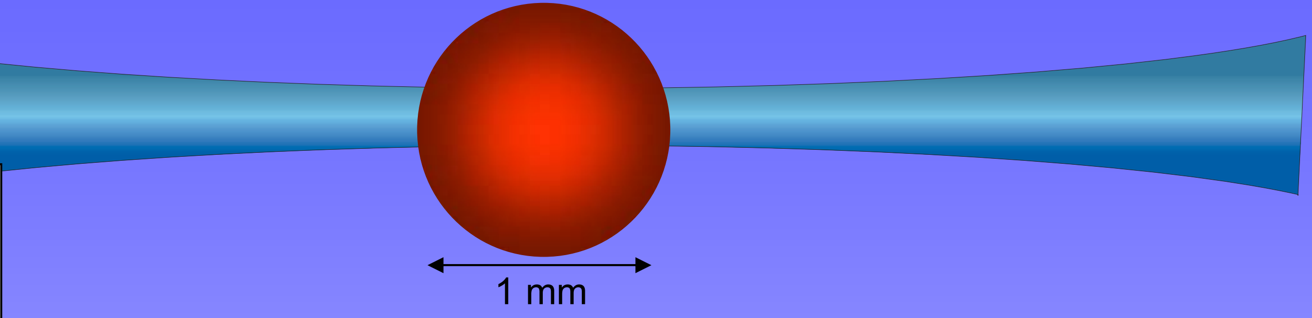
Singer, Stanojevic, Weidemüller and Côté, J.Phys. B **38** S295 (2005)

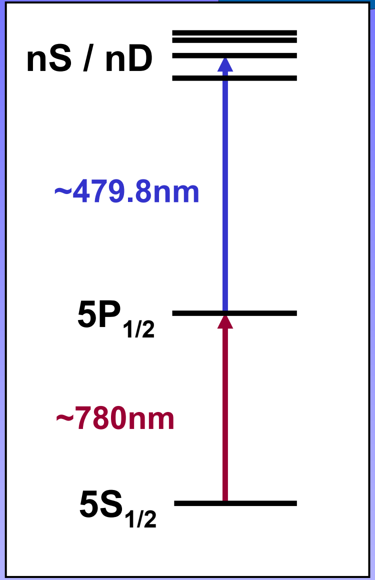
Controlled interaction between ensembles

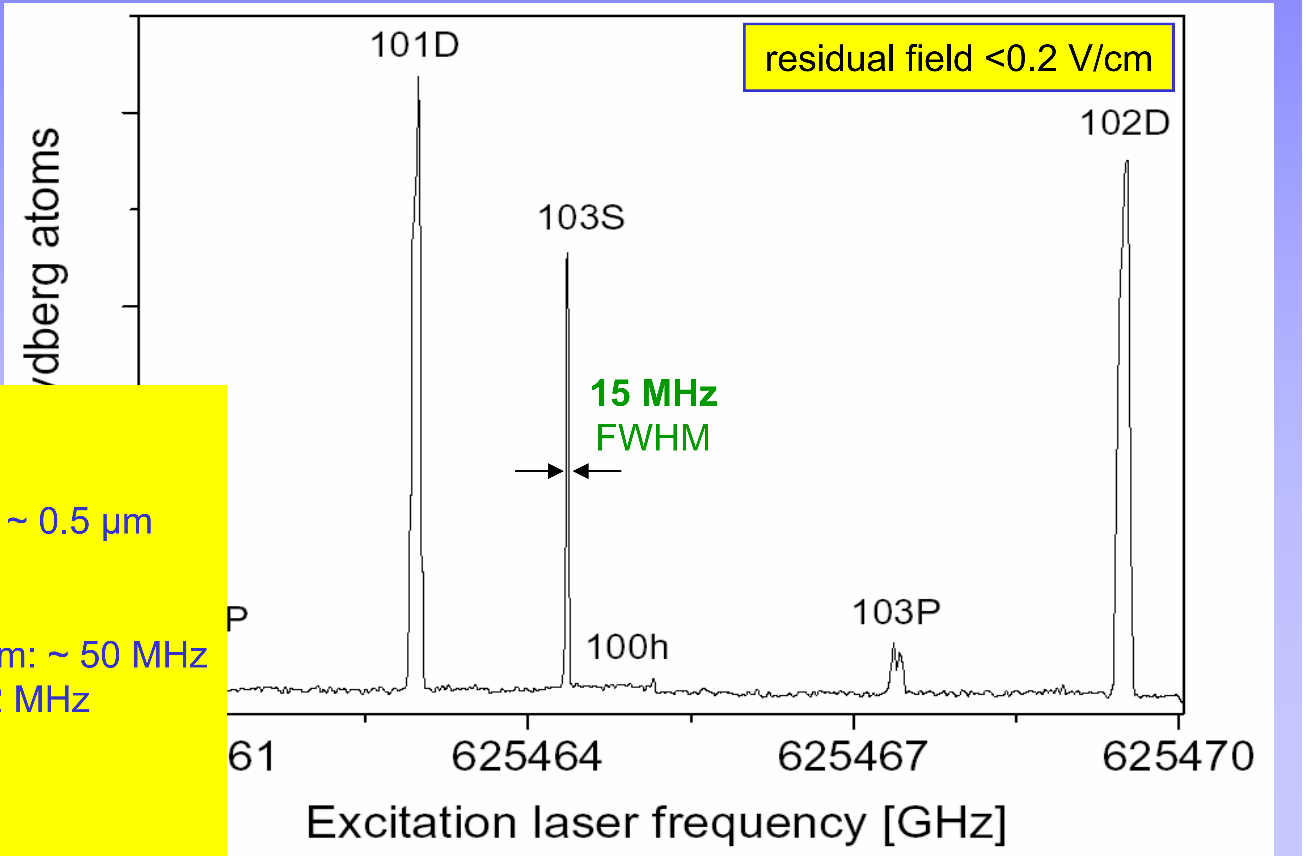


macroskopic distances (~10 µm)

Rydberg spectra @ n=100





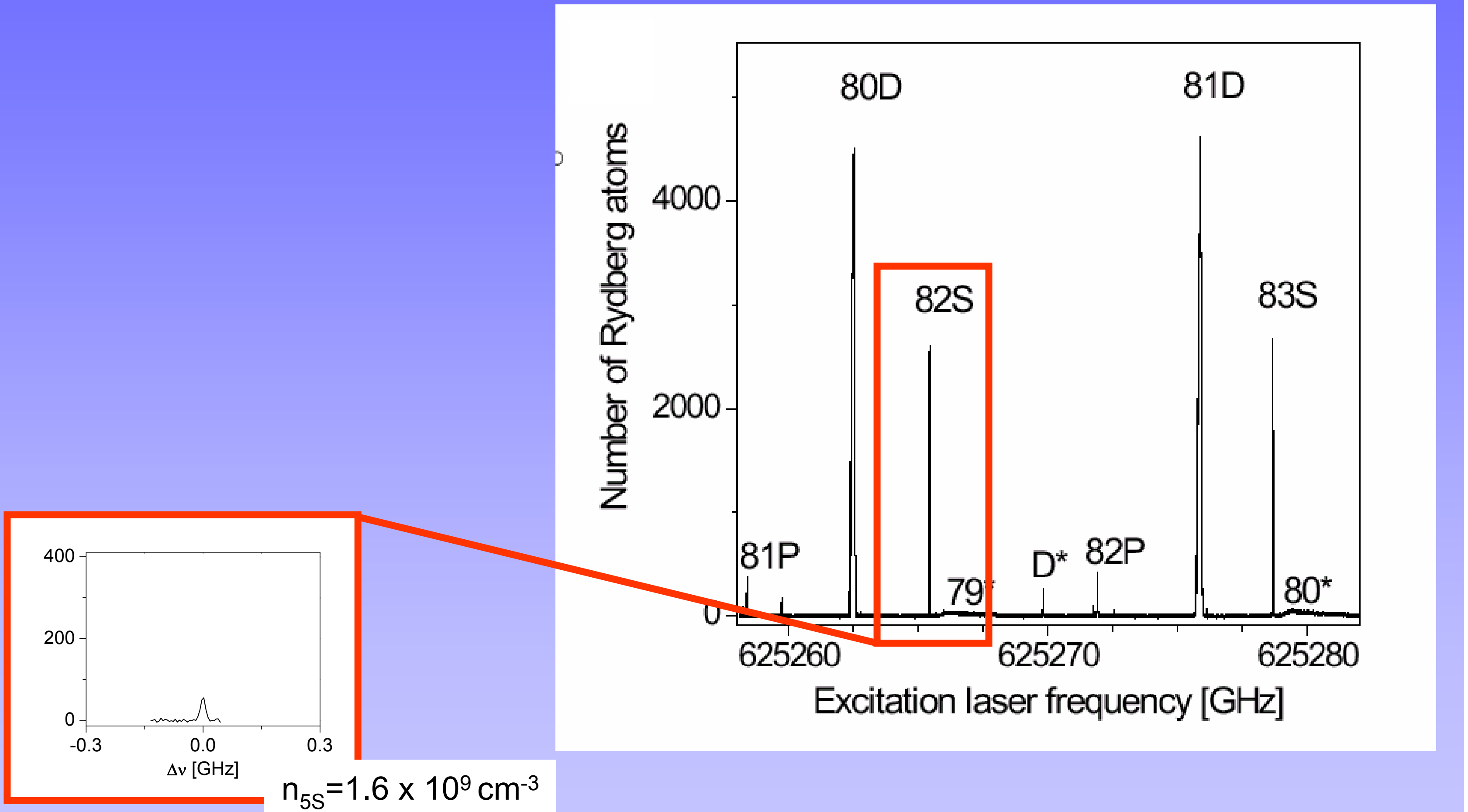


Laser cooled Rb @ n=100

- Extension of the wavefunction: ~ 0.5 µm
  Average distance: ~ 5 µm
- Van-der-Waals energy @ 10 µm: ~ 50 MHz
  Thermal energy @ 100 µK: ~ 2 MHz
  Laser linewidth: ~ 1 MHz
- Radiative lifetime: ~ 1 ms

Density variation of excitation

82 S *low* laser intensity (6 W/cm²)



n_{5S}=1.6 x 10^9 cm^{-3}

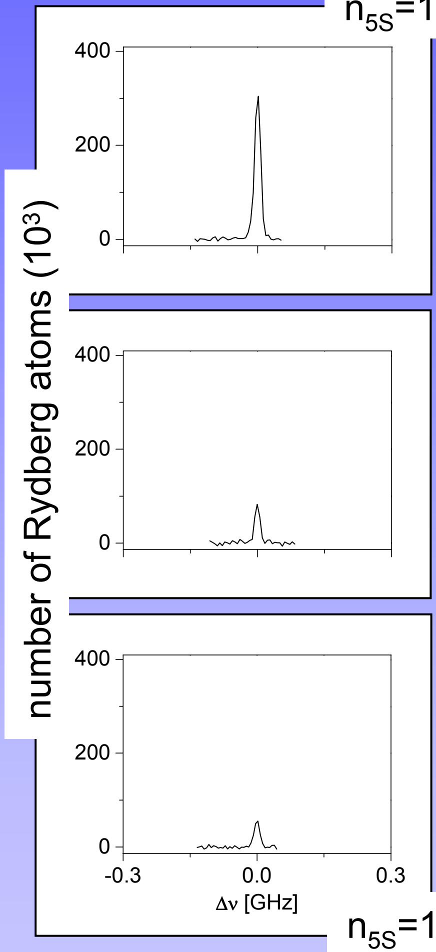
Density variation of excitation

82 S *low* laser intensity (6 W/cm²)

82 S *high* laser intensity (500 W/cm²)

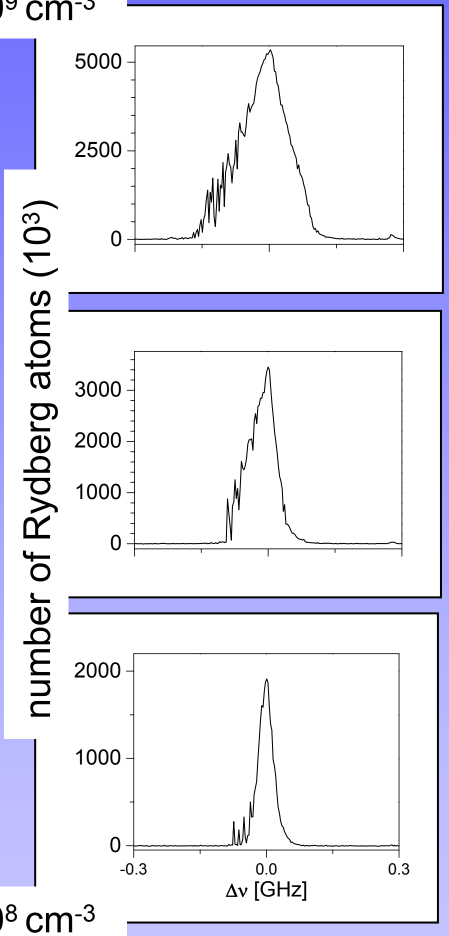
density of atoms in launch state

$n_{5S}=1.0 \times 10^{10}\ cm^{-3}$



$n_{5S}=1.6 \times 10^{9}\ cm^{-3}$

$n_{5P}=2 \times 10^{9}\ cm^{-3}$



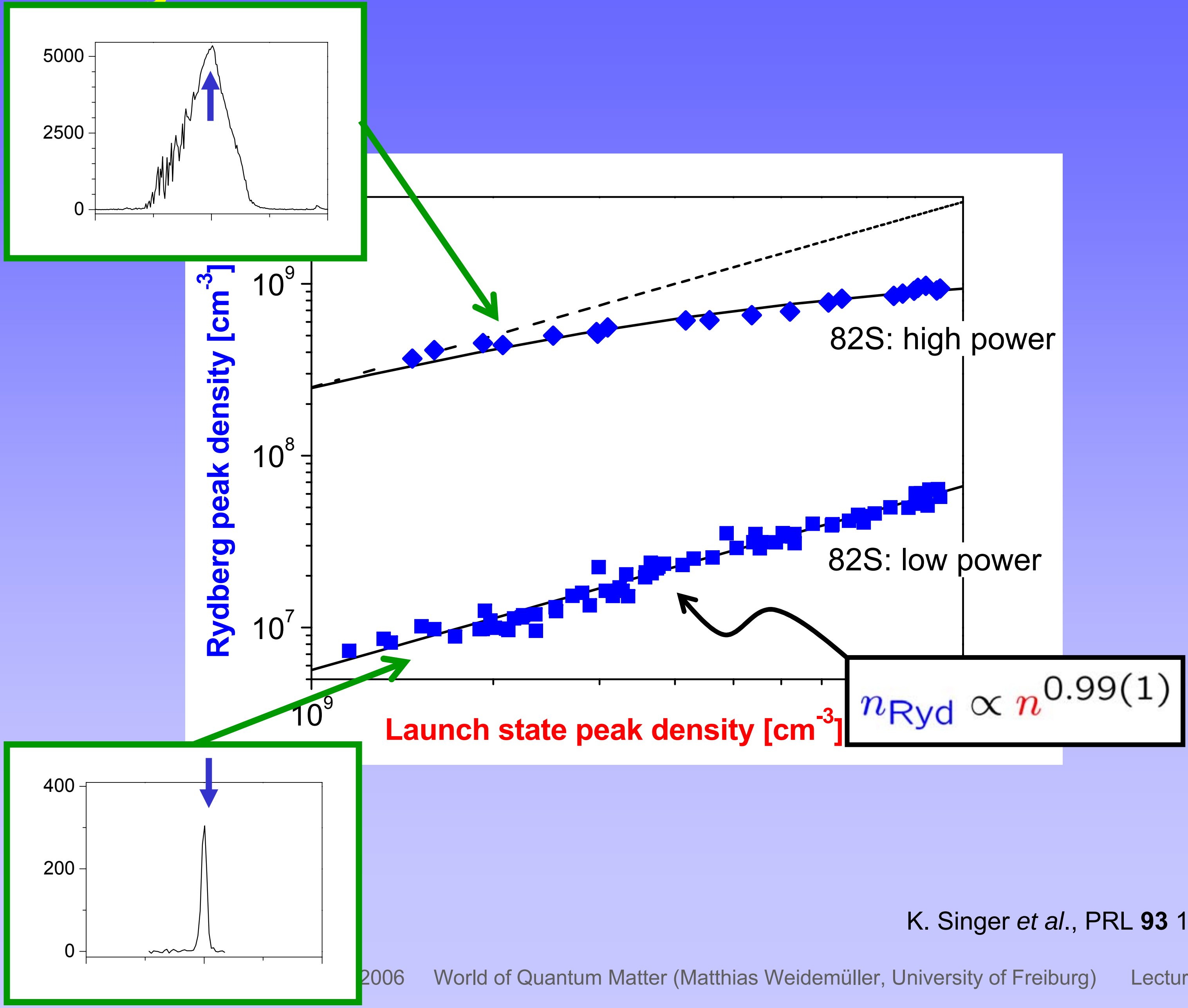
$n_{5P}=3 \times 10^{8}\ cm^{-3}$

density of atoms in launch state

- no broadening
- Rydberg density grows proportional to launch state density

- asymmetric broadening
- **Rydberg density saturates**

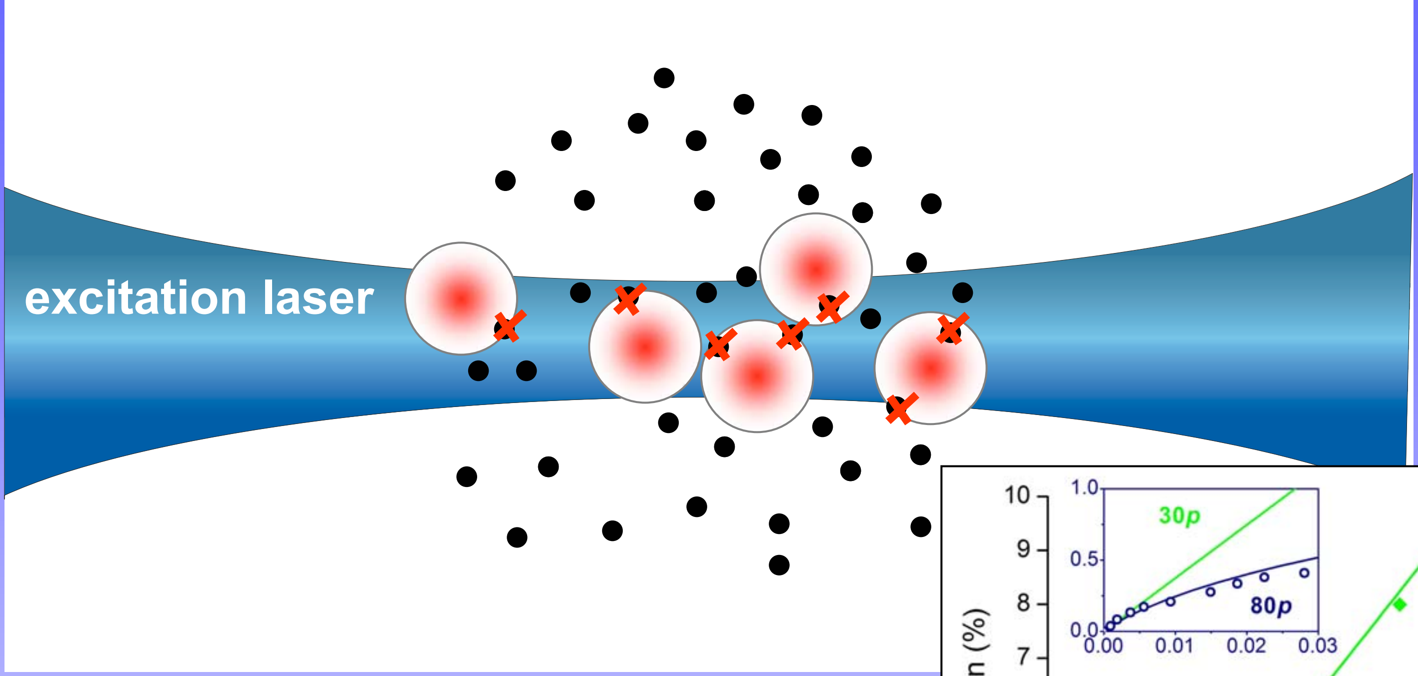
Density variation of excitation

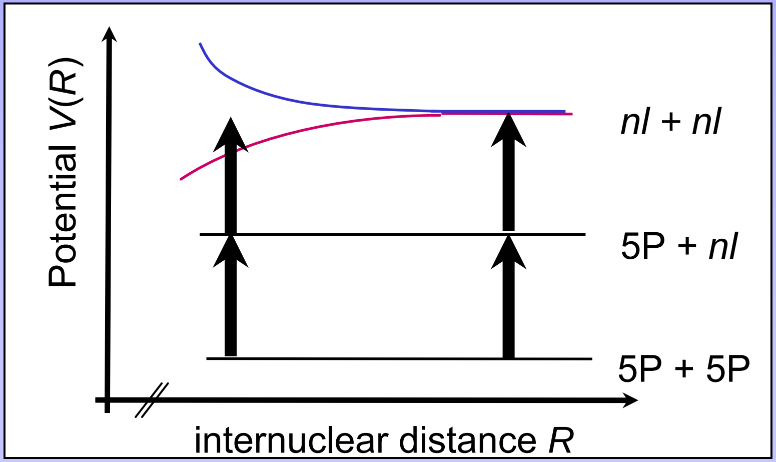


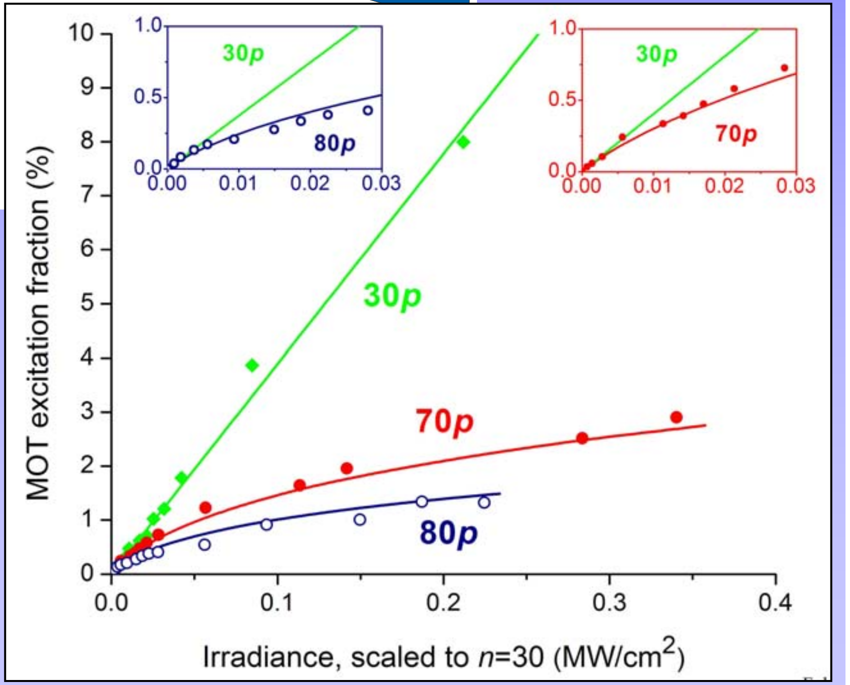
$n_{\text{Ryd}} \propto n^{0.99(1)}$

K. Singer *et al.*, PRL **93** 163001 (2004)

Local blockade of excitation

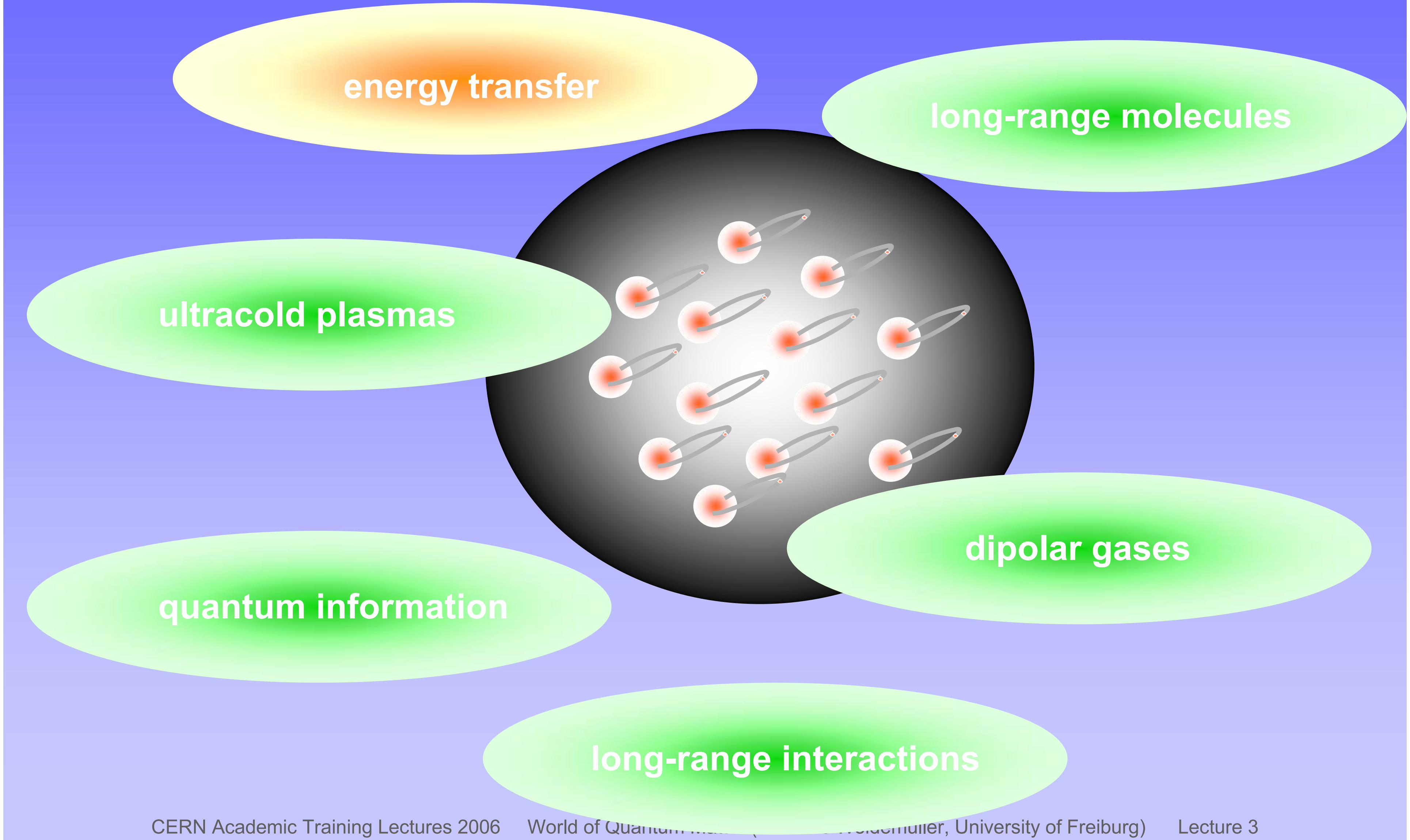






D. Tong *et al.*, PRL **93**, 063001 (2004)

Frozen Rydberg gases



energy transfer

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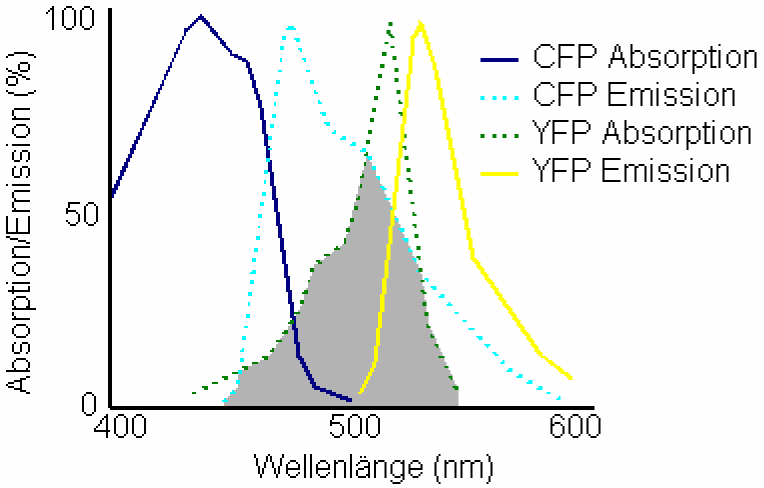
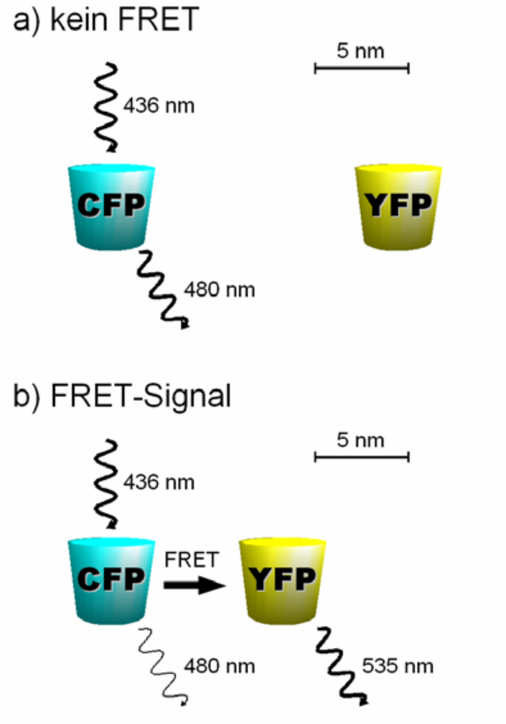
Fluorescence resonance energy transfer

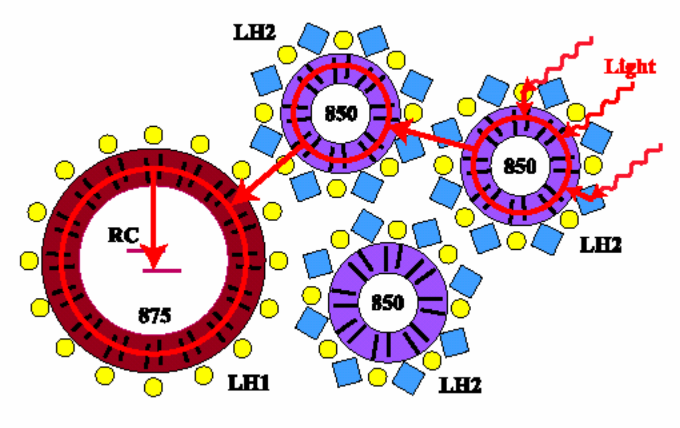
Förster resonance (1946):

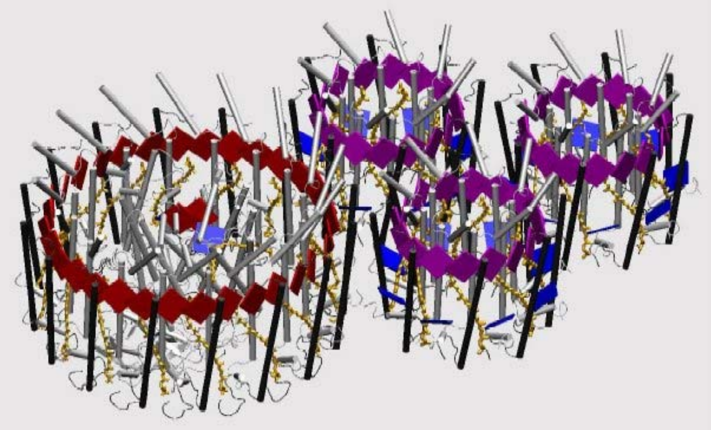
Ruler for nanometer scales



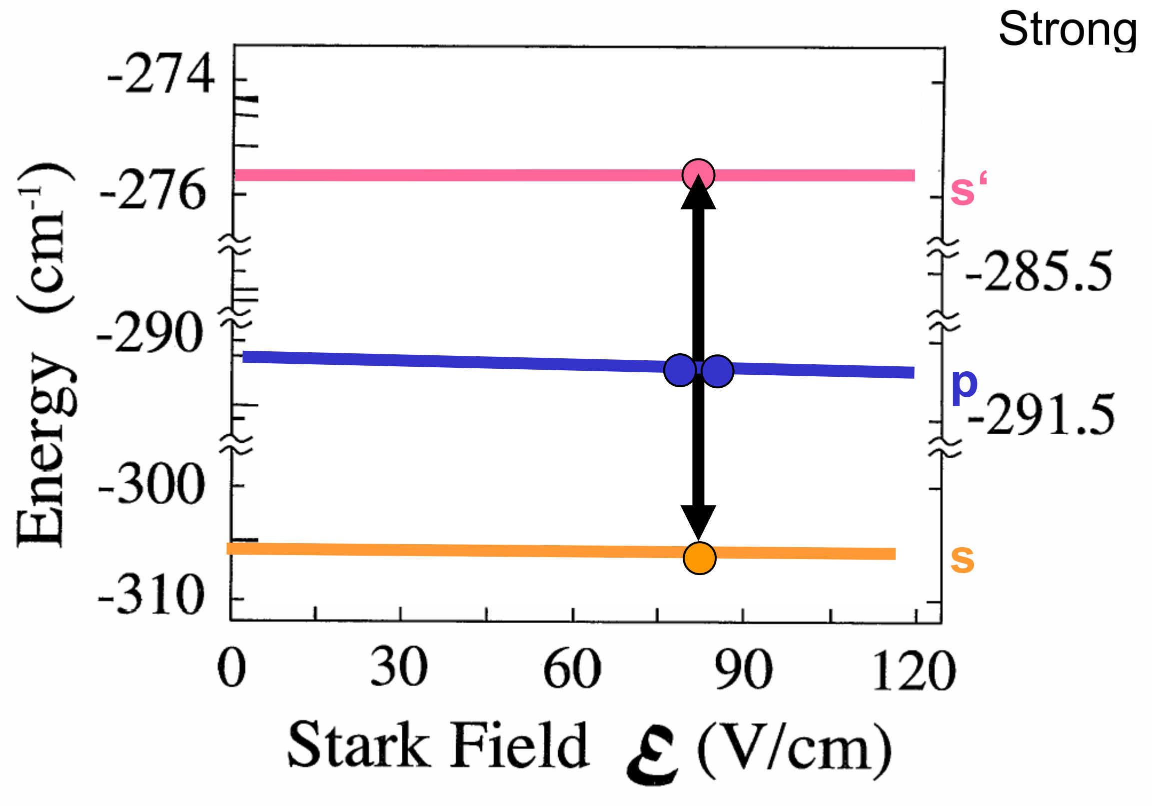


Photosynthesis





Förster resonance in Rydberg gases



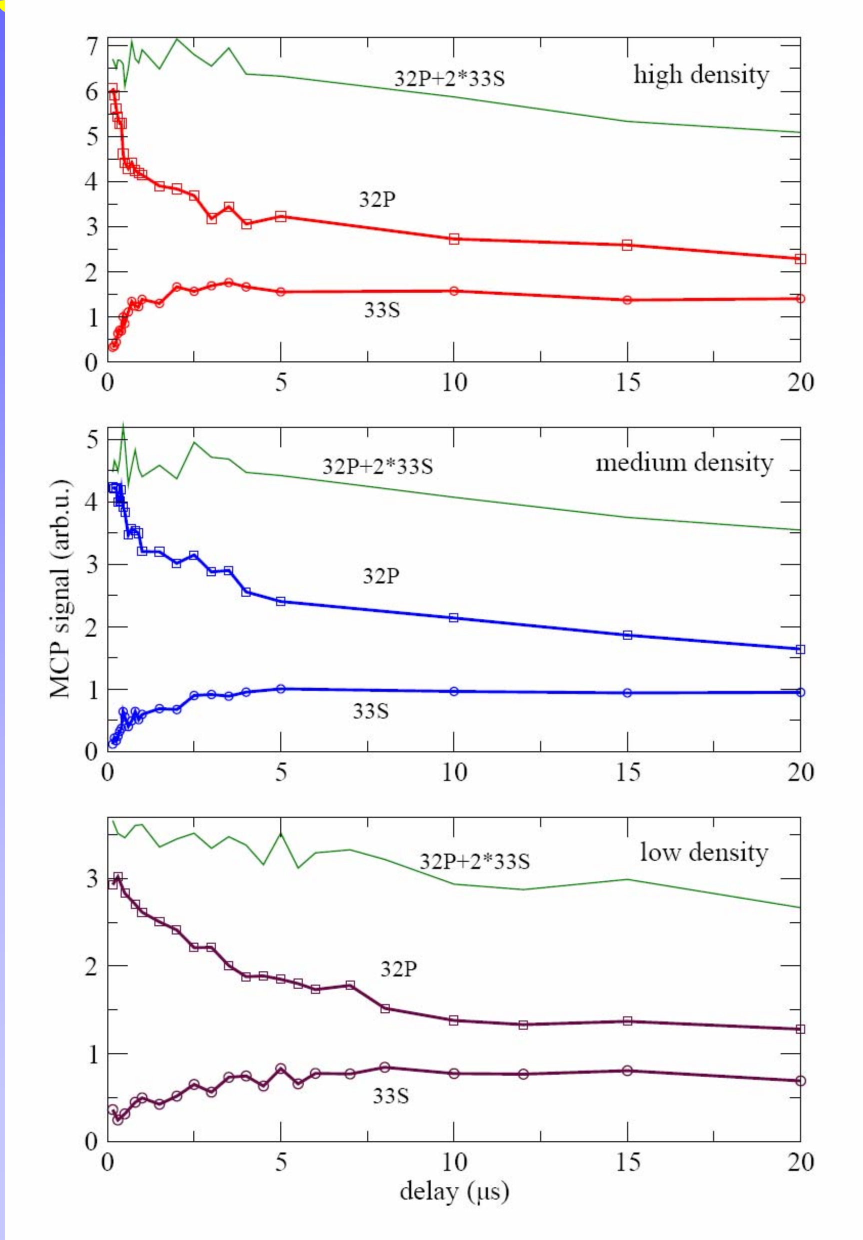
Strong resonant dipole-dipole

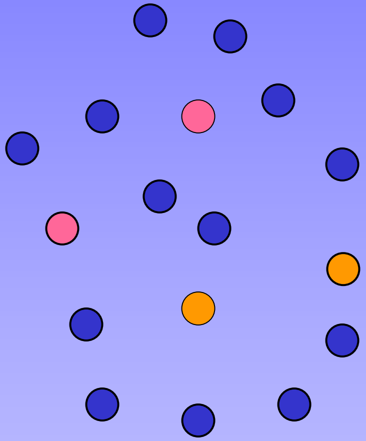
$$V = \frac{\mu_A \mu_B}{R_{AB}^3}$$

Resonant excitation exchange
(Förster Process)

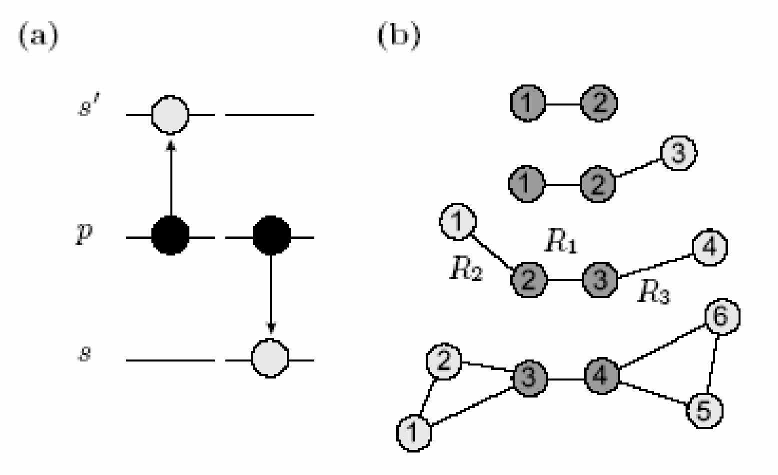
$$p + p \rightarrow s + s'$$

Temporal dynamics of the Förster resonance





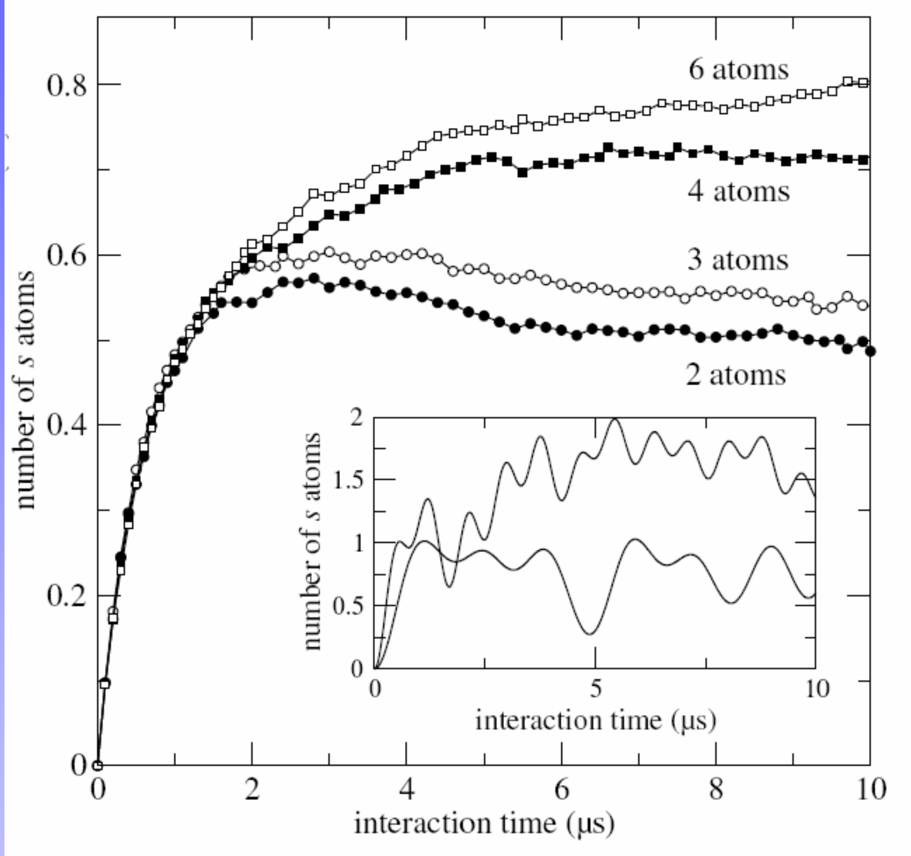
Model for many-body Förster transfer



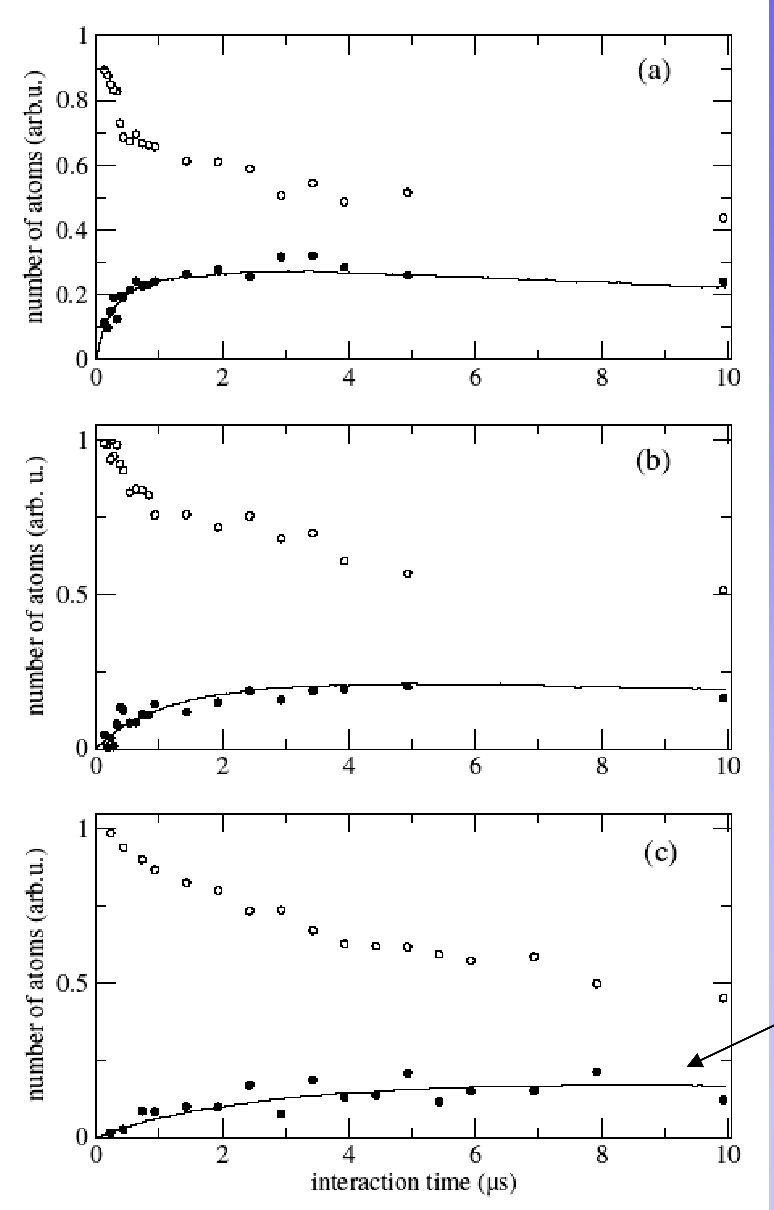
$$p + p \rightarrow s + s'. \qquad (1)$$

$$s + p \rightarrow p + s \qquad (2)$$

$$s' + p \rightarrow p + s' , \qquad (3)$$



Comparison with experiment



n = 2.5 × 10^8 atoms/cm^3

n = 0.5 × 10^8 atoms/cm^3

n = 0.15 × 10^8 atoms/cm^3

model with 6 atoms

S. Westermann *et al.*,
submitted to Eur.. Phys. J. D

Contents of the lectures

0. Primer on light-matter interactions
1. The way to absolute zero – cooling and trapping methods for atoms
2. Cold collisions
3. Bose-Einstein condensation
4. Degenerate Fermi gases
5. Cold Rydberg gases and plasmas
6. **Ultracold molecules**
7. Manipulation of single atoms
8. Cold atoms as targets for photon and particle beams

Lecture 1

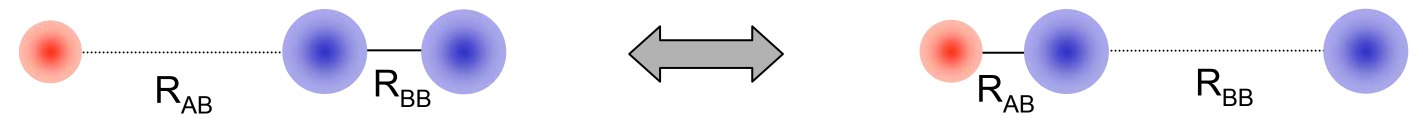
Lecture 2

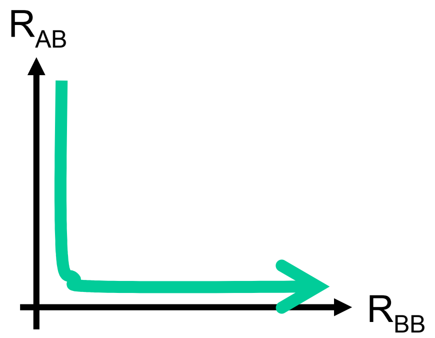
Lecture 3

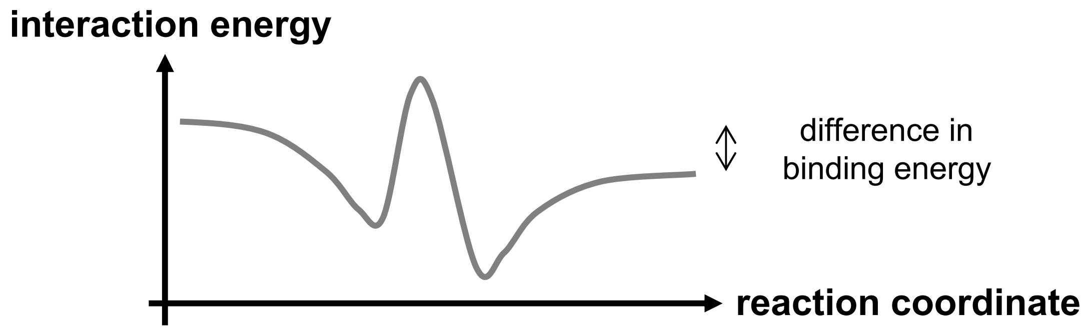
Lecture 4

Cold chemistry?

Exchange reaction $B + A_2 \rightarrow AB + A$





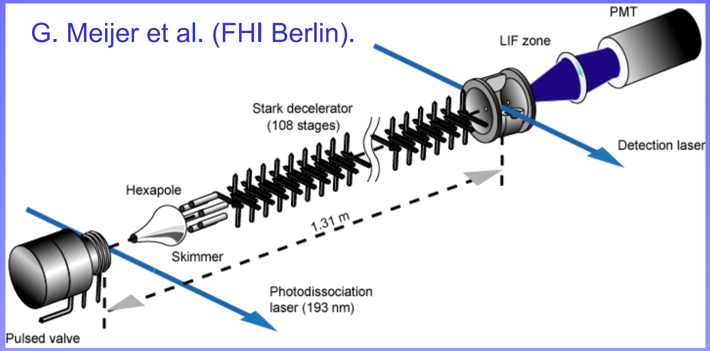


Temperature hierarchy:

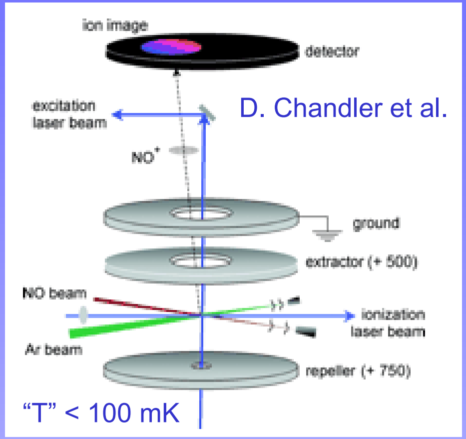
$T < 1$ K	**quantum state regime** vibrational and rotational degrees of freedom freeze out controlled quantum chemistry in well-defined internal states
$T < 1$ mK	**quantum scattering regime (mainly s-waves)** details of the interaction potential do not matter, interference of partial waves manipulation by external fields? resonances?
$T < 1$ μK	**quantum degeneracy regime** role of the mean field? appropriate picture of the reaction? wave-function driven chemistry?

Preparation of cold and ultracold molecular gases

Stark deceleration and trapping

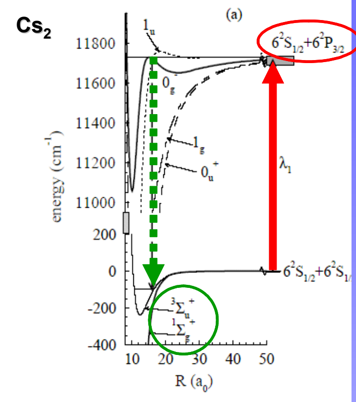

G. Meijer et al. (FHI Berlin).

Billard-like collisions

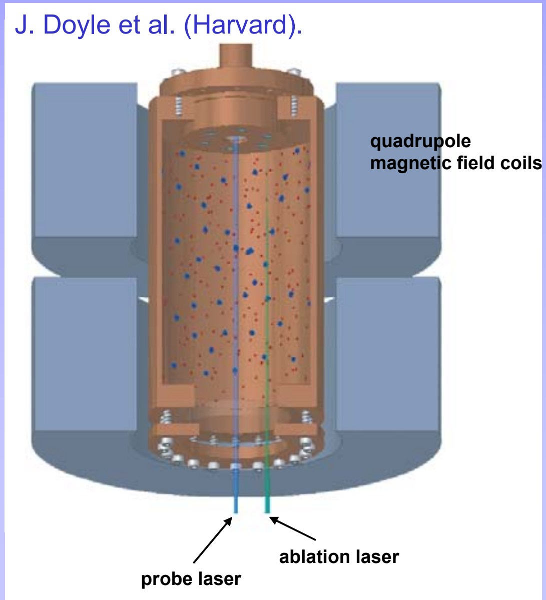

D. Chandler et al.

"T" < 100 mK

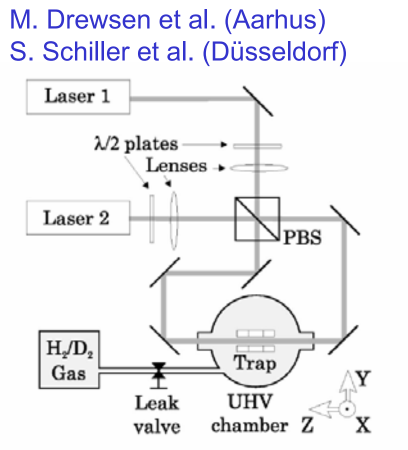
Photoassociation



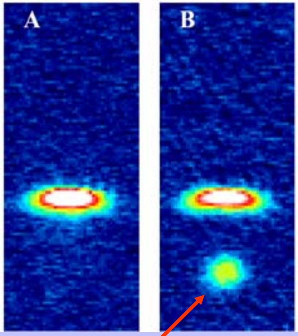
Buffer-gas cooling and magnetic trapping


J. Doyle et al. (Harvard).

Trapped ions and sympathetic cooling


M. Drewsen et al. (Aarhus)
S. Schiller et al. (Düsseldorf)

Molecular quantum gases



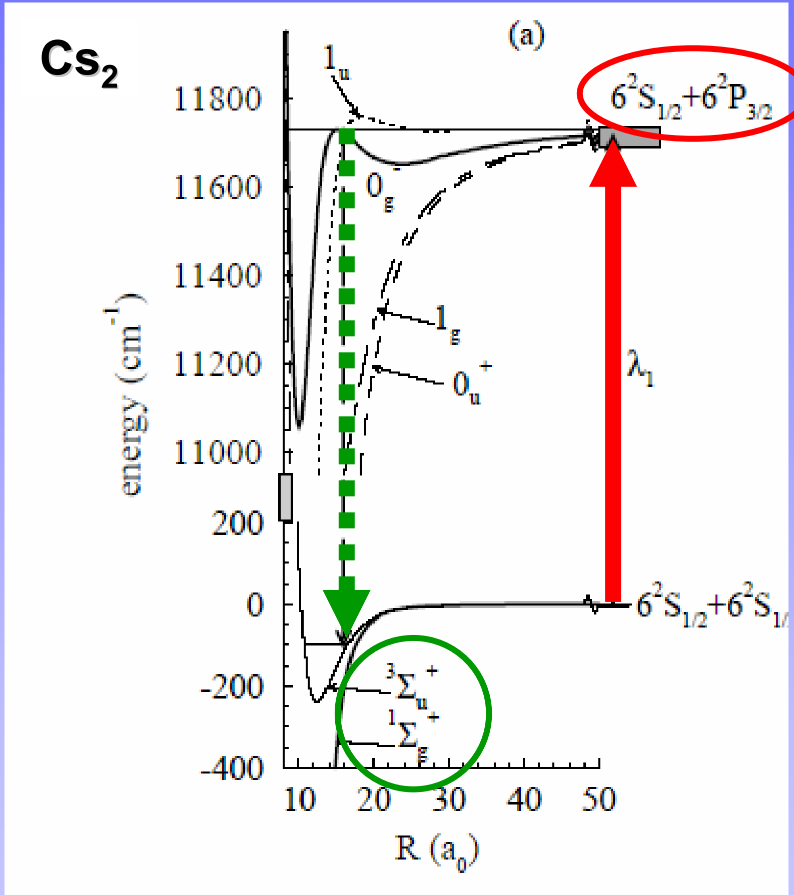
molecules reconverted into atoms

J. Herbig *et al.*, Science **301**, 1510 (2003)

Photoassociation of ultracold molecules

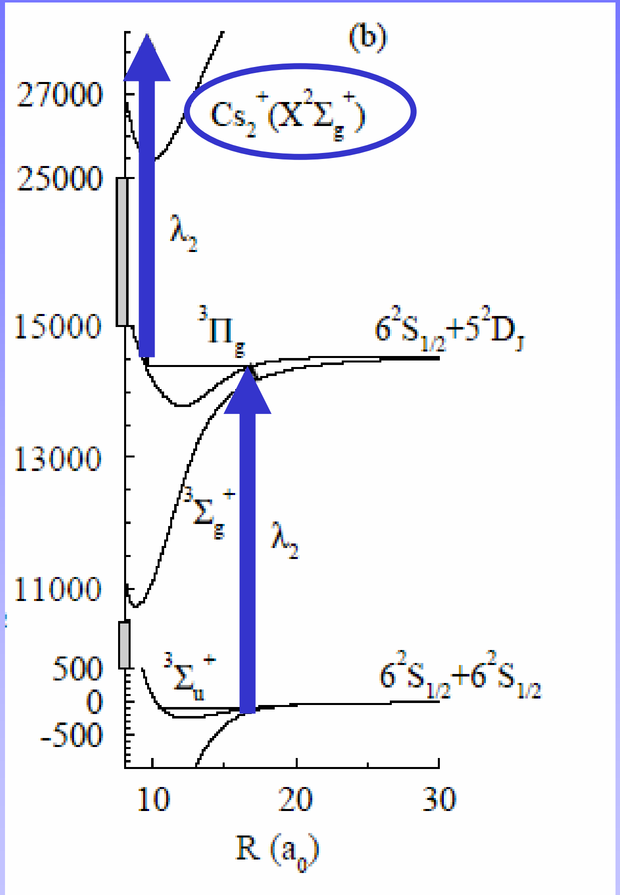
association

(spontaneous or induced)



detection

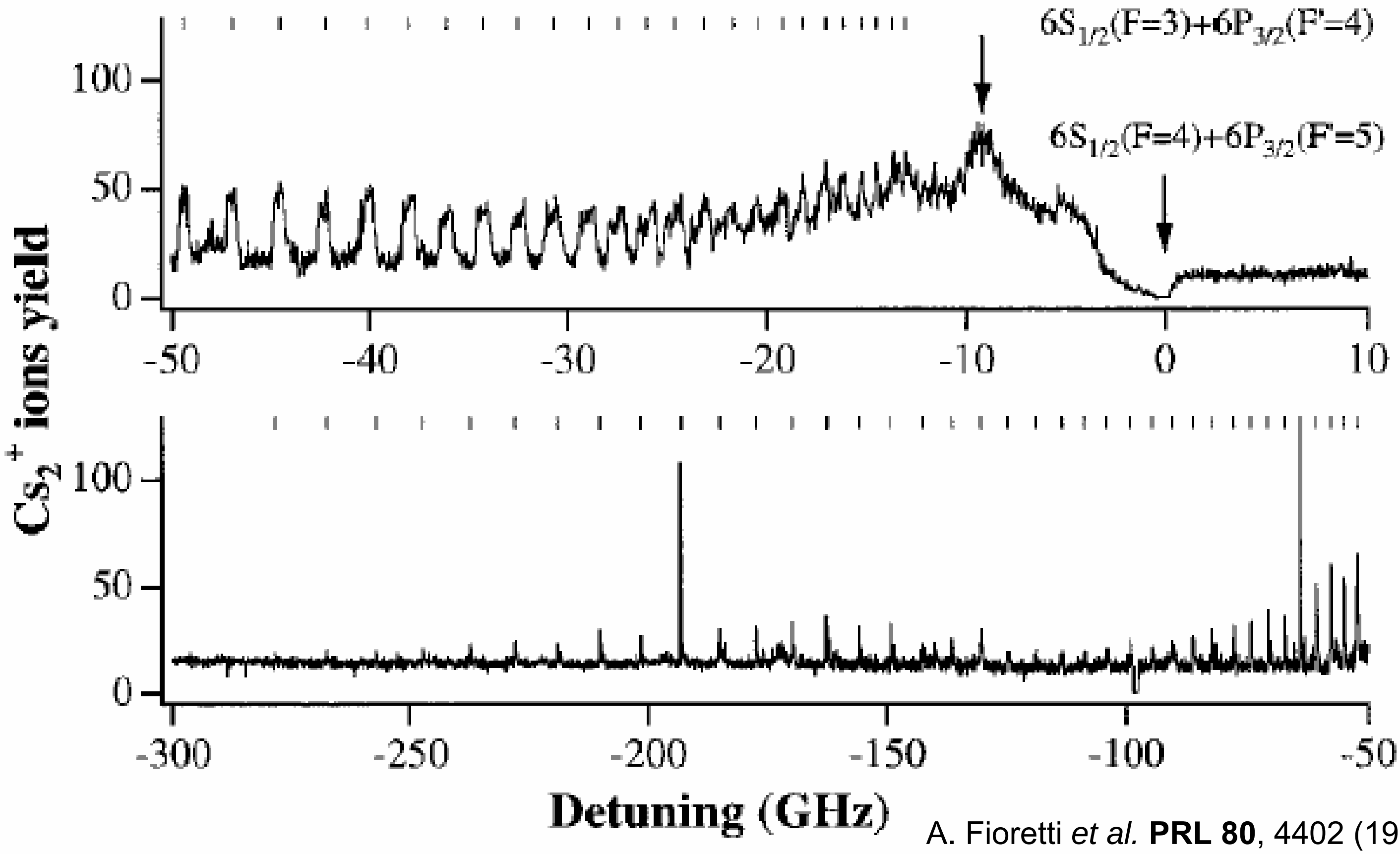
(REMPI)



A. Fioretti *et al.* **PRL 80**, 4402 (1998)

Photoassociation of ultracold molecules

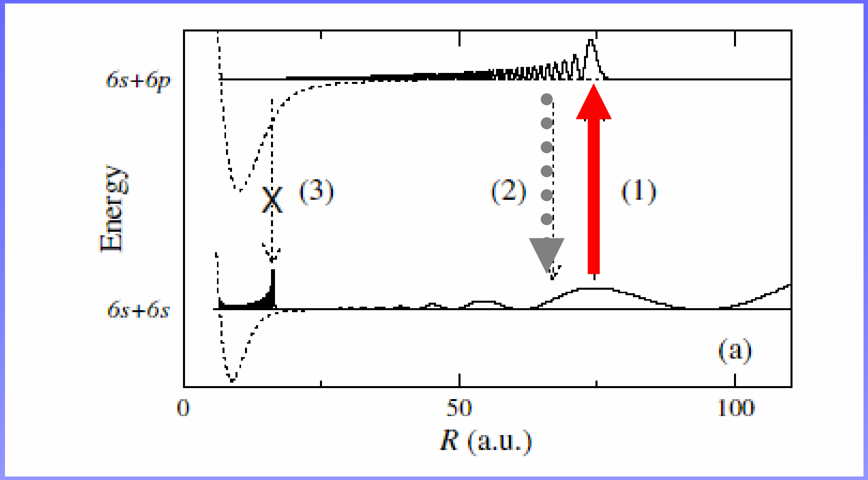
photoassociation spectrum



A. Fioretti *et al.* **PRL 80**, 4402 (1998)

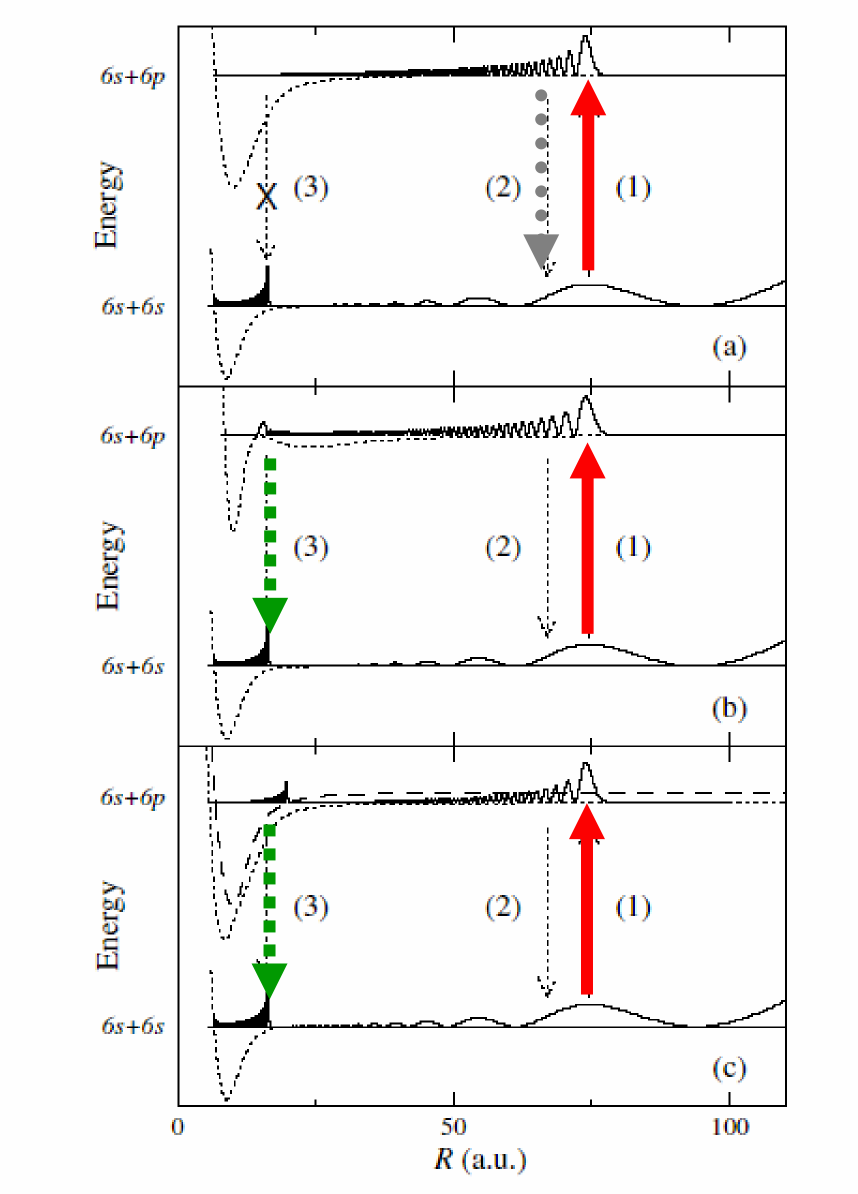
Cs_2 (Pillet, Weidemüller)
Rb_2 (Gabanini, Heinzen, Marcassa)
K_2 (Gould)
Li_2 (Hulet)

R-transfer



decay mainly into unbound (continuum) states

R-transfer



decay mainly into unbound (continuum) states

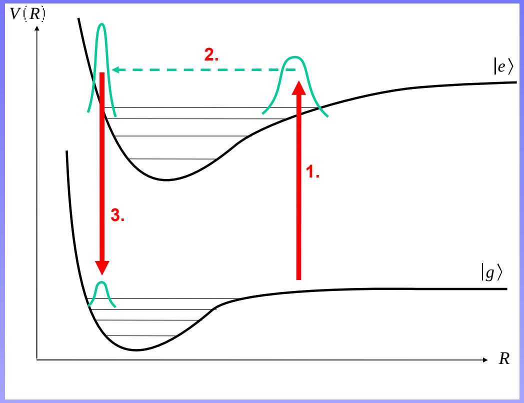
decay into bound states via double-well potential

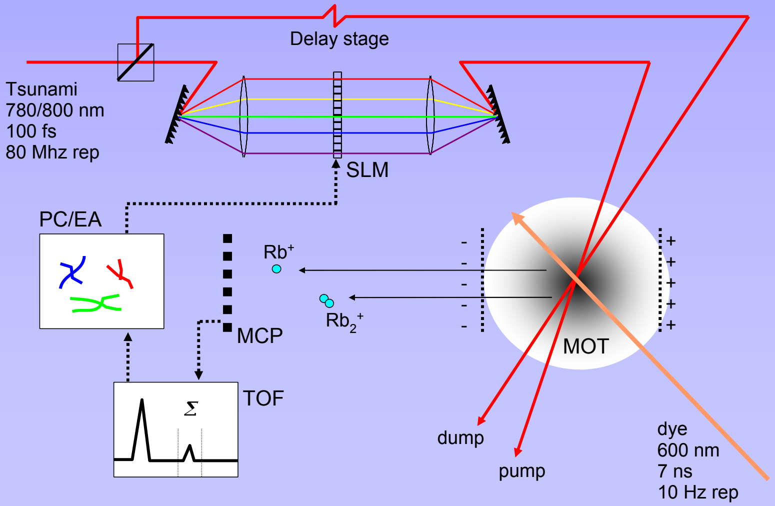
decay into bound states via coupled potential wells

R-transfer

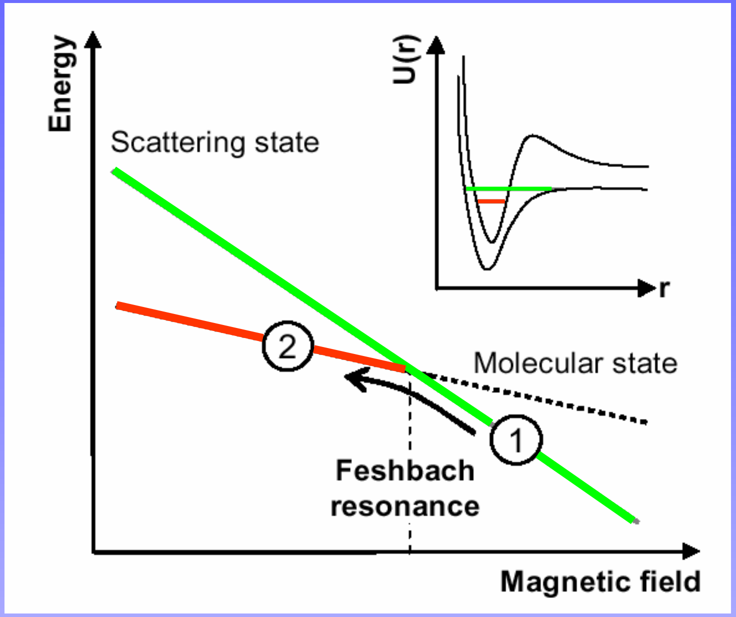
Shaped femtosecond laser pulses

(in collaboration with Wöste group @ FU Berlin)



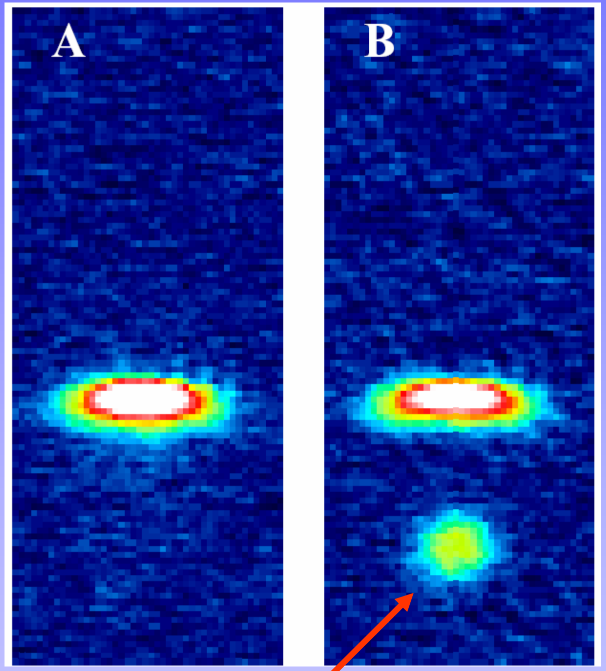


Ultracold molecules via Feshbach resonances



only highest vibrational state is populated → very "sloppy" molecules

Cs_2 molecules out of a Cs BEC (Grimm group)



molecules reconverted into atoms

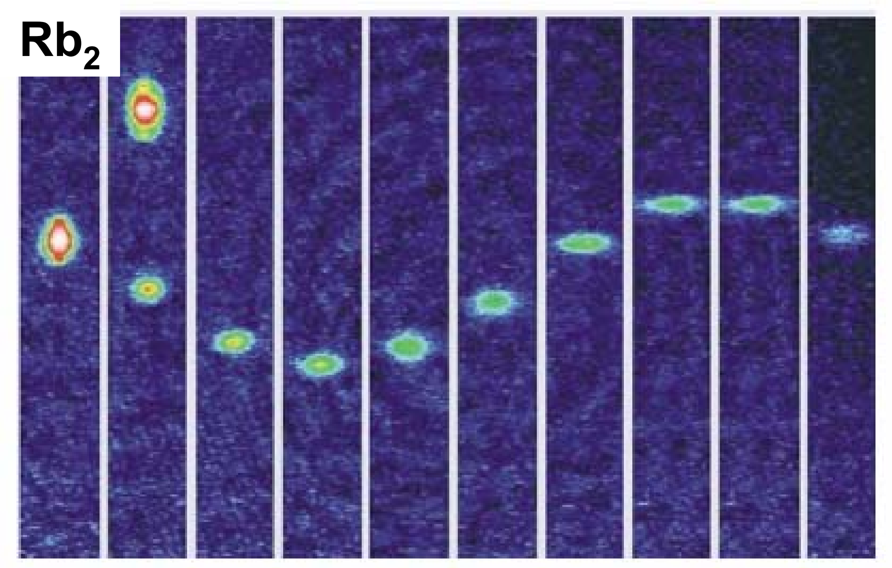
J. Herbig *et al.*, Science **301**, 1510 (2003)

Cs_2 (Grimm)
Rb_2 (Wieman, Rempe)
K_2 (Jin)
Na_2 (Ketterle)
Li_2 (Grimm, Salomon, Hulet *et al.*)

Tons of theory papers

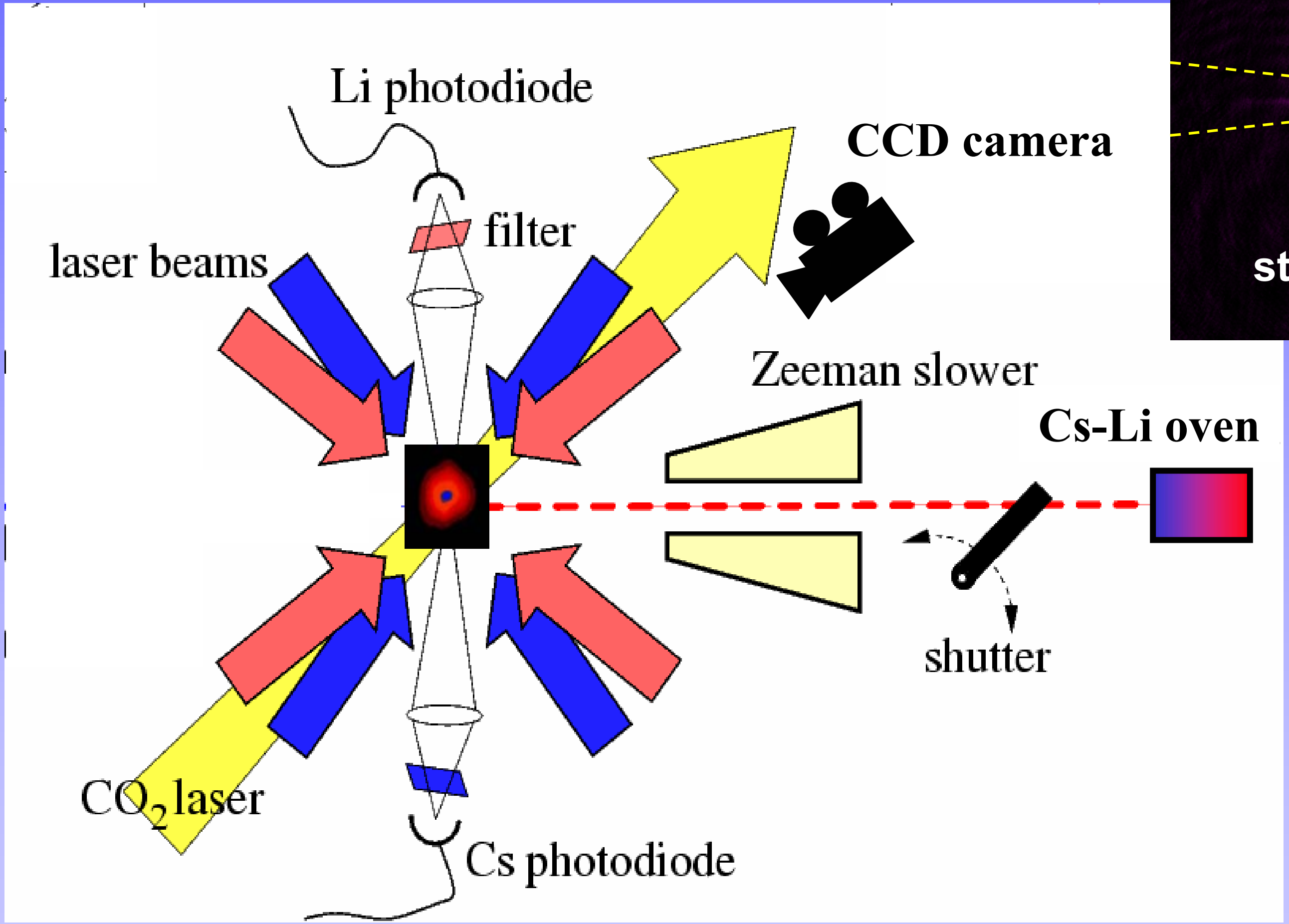
Magnetic trapping of cold molecules

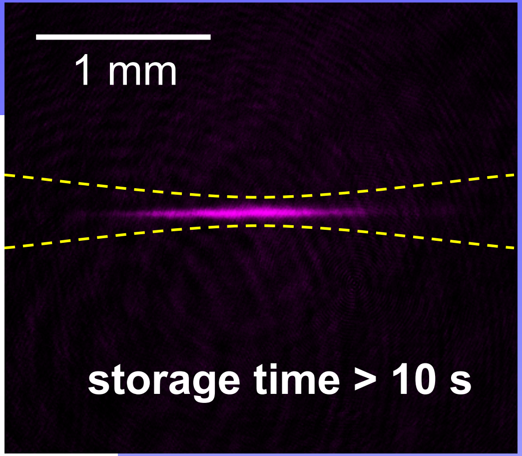
“Feshbach” molecules in a Joffe-Pritchard trap



Rempe group
S. Dürr *et al.*, Phys. Rev. Lett. **92**, 020406 (2004)

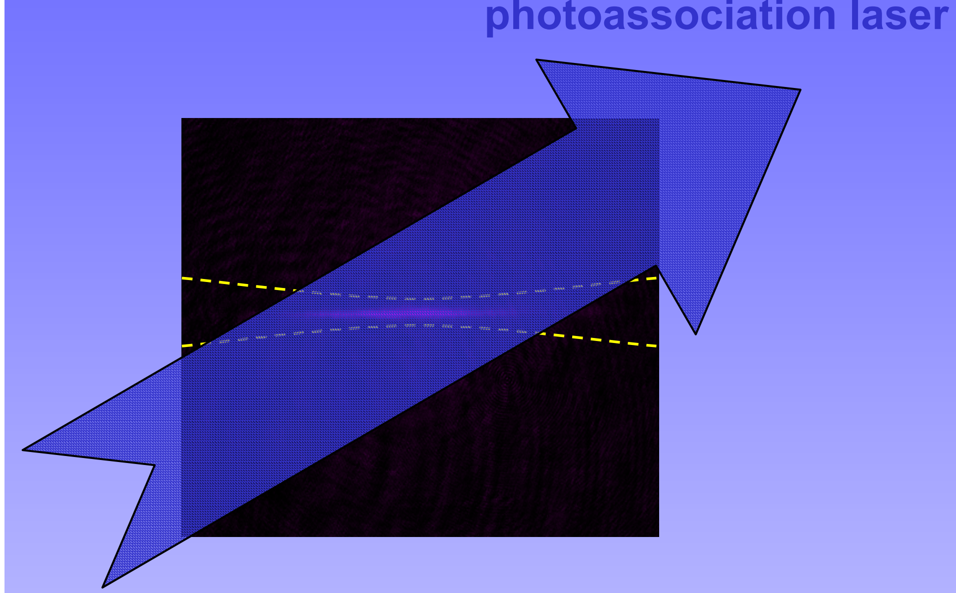
Optical trapping of cold molecules



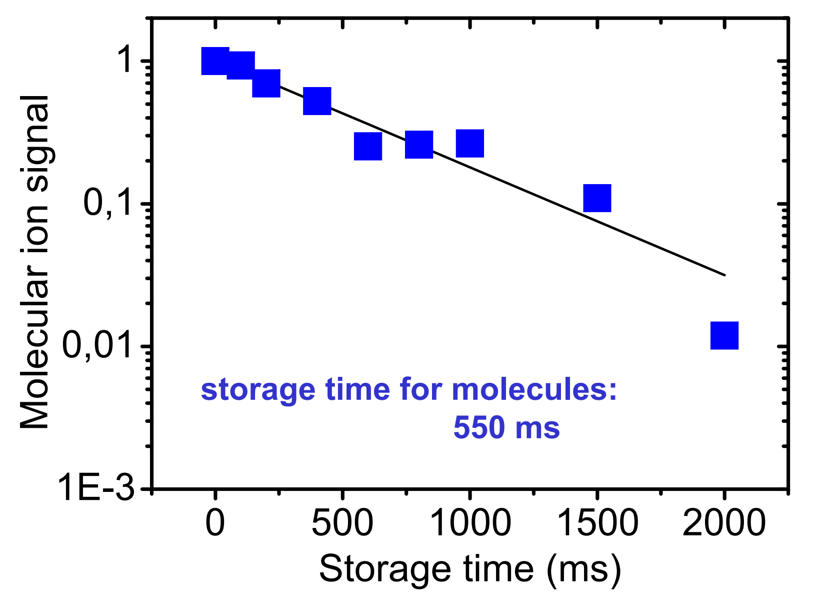


storage time > 10 s

Ground state molecules in optical dipole trap

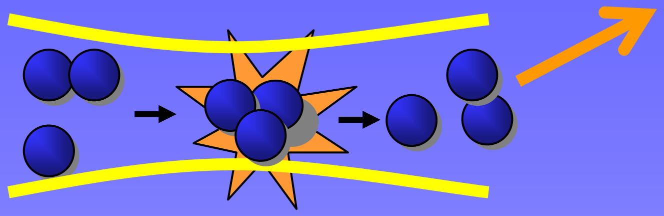


Storage of ultracold molecules



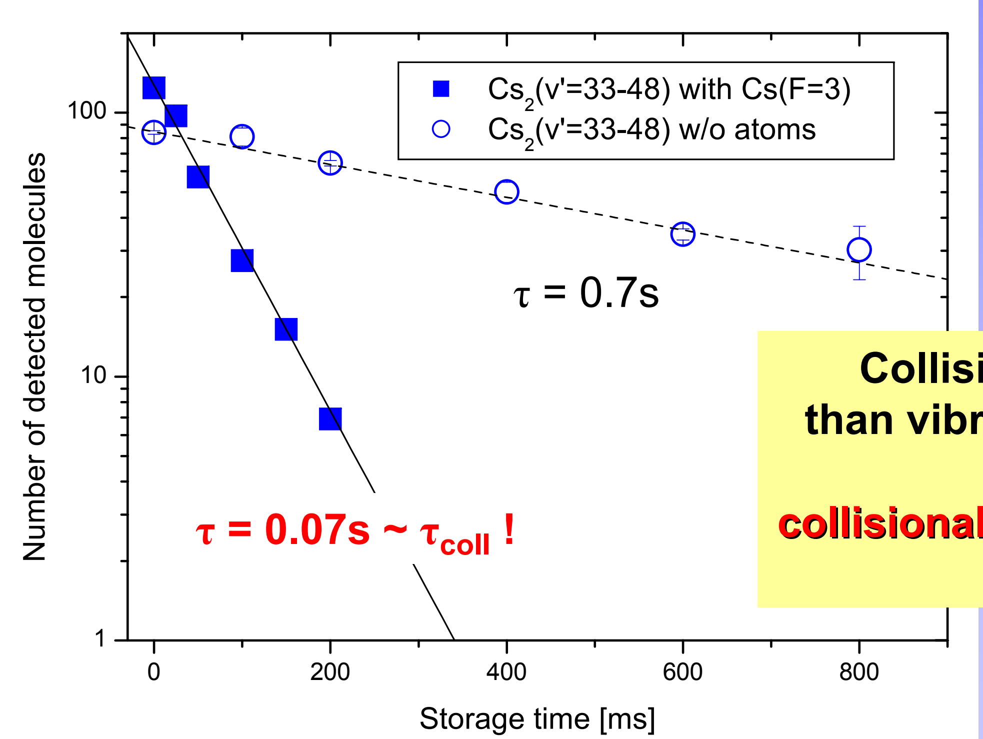
storage time for molecules: 550 ms

Evidence for ultracold atom-molecule collision



$Cs + Cs_2(v,J) \rightarrow Cs + Cs_2(v',J') + E_{kin}$

Storage times w/ and w/o atoms



$T_{Cs} \sim 60\ \mu K$

Collisional energy much smaller than vibrational and rotational energy

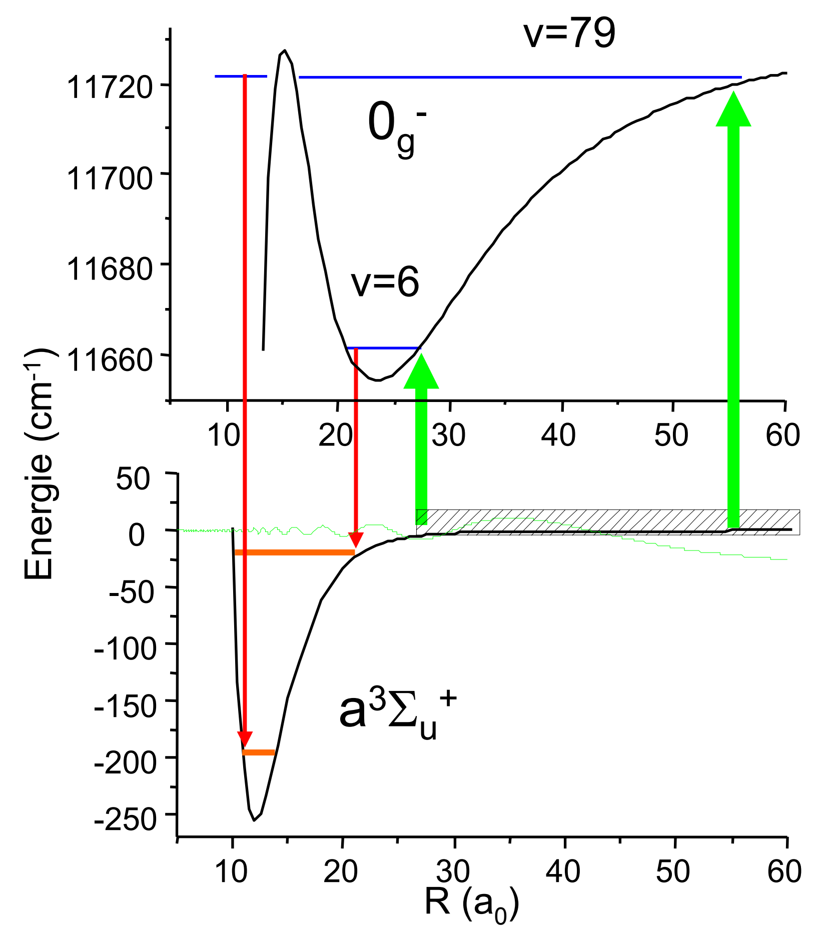
⇒

collisional deexitation only energetically allowed process

P. Staanum *et al.*, Phys. Rev. Lett., in press

Collisions of trapped Cs_2

Cs_2 decay in collisions with ultracold Cs

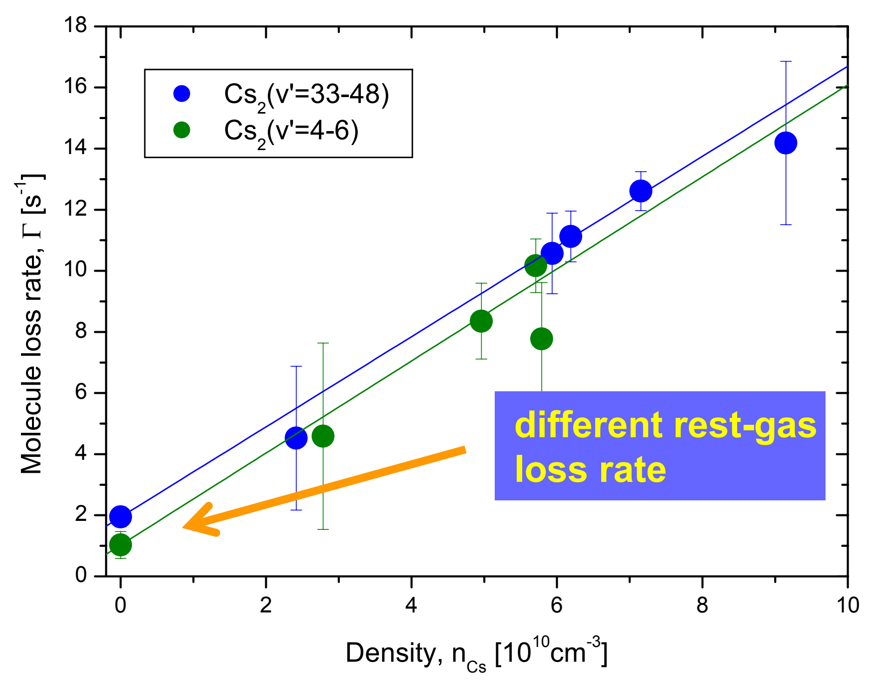


Cs, F=3
+
Cs_2, $a^3\Sigma_u^+$ (v=33...48, J=1,2,3)
(E_{vib}~ -2...-24 cm^{-1})

Cs, F=3
+
Cs_2, $a^3\Sigma_u^+$ (v=4...6, J=1,2,3)
(E_{vib}~ -175...195 cm^{-1})

Density dependence of the loss rate

Storage times vs. atom density for different target states



different rest-gas loss rate

$$\Gamma_{\mathrm{mol}} = \beta_{\mathrm{at-mol}}\, n_{\mathrm{at}}$$

β *(v=33-48)* = 1.51(4) × 10^{-10} cm^3/s

β *(v=4-6)* = 1.52(7) × 10^{-10} cm^3/s

P. Staanum *et al.*, Phys. Rev. Lett., in press

	J=0	J=1	J=2	J=3	J=4
β (10^{-10} cm^3/s)	1.8(6)	2.5(3)	2.1(4)	2.4(7)	2.2(4)

No dependence on rotational quantum number!

Scattering cross section

Threshold limit for inelastic s-wave collisions:

$$\beta_{s=0} = \langle \sigma_{s=0}\, v \rangle = \sqrt{2\pi\hbar^4/(m_{\mathrm{red}}^3 k_b T)}$$

For Cs-Cs_2 collision @ 50 μK: $\beta_{s=0} \sim 2 \times 10^{-11}$ cm^3/s (Exp: 10^{-10} cm^3/s)

Experimental value is larger: **p- and d-wave contributions contribute as well**

Measured rate coefficients are close to values predicted for **Na-Na_2** and **K-K_2** collisions

G. Quemener *et al.*, Eur. Phys. J. D **30**, 201 (2004); Phys. Rev. A **71**, 032722 (2005)

Next step:

More complex processes involving different species,
e.g., Cs_2 + Li ↔ Cs + LiCs

Summary of Lecture 4

- **Cold Rydberg gases**
  - extremely polarizable medium
  - ultracold, strongly-coupled plasmas
  - long-range interactions via electric dipole forces ⇒ dipole blockade
  - energy transfer and Förster resonances

- **Cold molecules**
  - formation of cold molecules (Photoassociation, Feshbach)
  - detection of cold molecules (REMPI, coherent dissociation)
  - trapping of cold molecules (magnetic and optical traps)
  - ultracold atom-molecule interactions