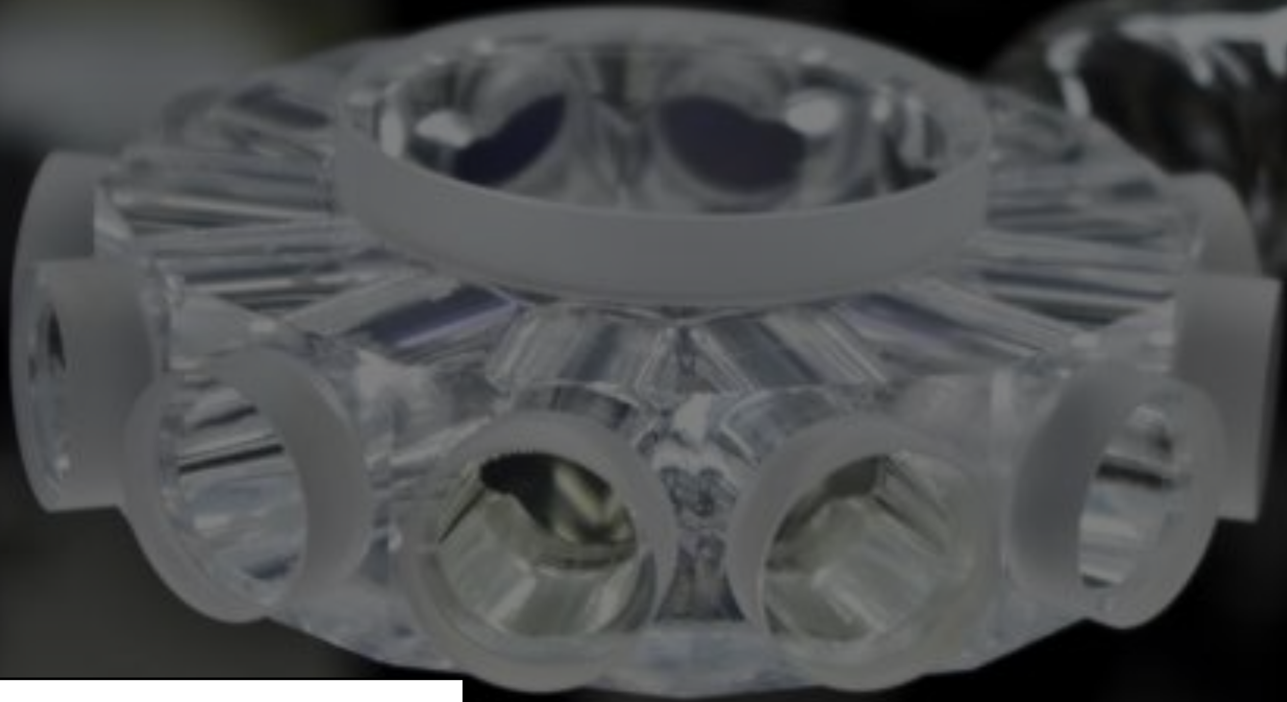
Quantum Physics & Quantum Information

Experiments with Ultra-cold Atoms



Yu-Ao Chen
陈宇翔

CAS Center for Excellence in
Quantum Information and Quantum Physics,
University of Science and Technology of China

Axions in Stockholm – Reloaded
Nordita 29 Nov. 2018

中国科学技术大学
University of Science and Technology of China

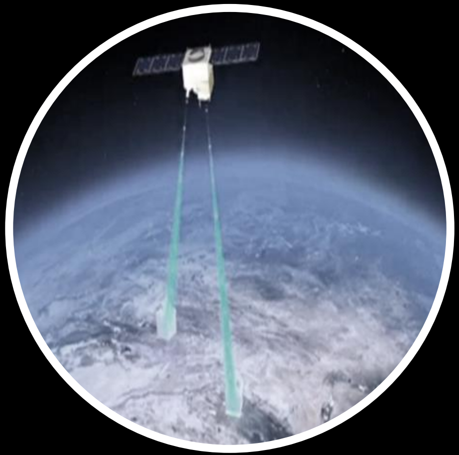
Quantum Information Science

Born from the tests of "spooky action at a distance"

→ Coherent manipulation of quantum systems

Harness the strange properties of quantum mechanics such as superposition and entanglement for enhanced ways of information processing

Unconditional security

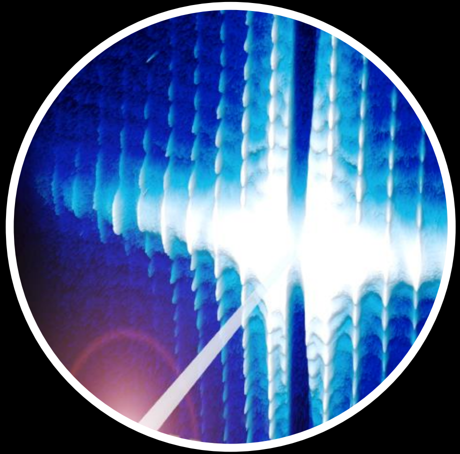


Quantum communication

Computational capacities

Quantum computation and simulation

Super-resolution



Quantum Metrology

Introduction to our group

Excellence Center for Quantum Information and Quantum Physics

- Jointly supported by CAS and the Ministry of Education

Hosted by **USTC**

includes top institutes and universities on quantum physics

Shanghai Institute of Technical Physics

Institute of Semiconductor

Institute of Optics and Electronics

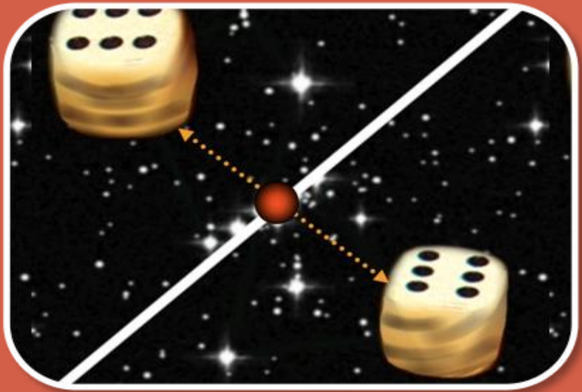
Nanjing University

and excellence groups among China’s universities:

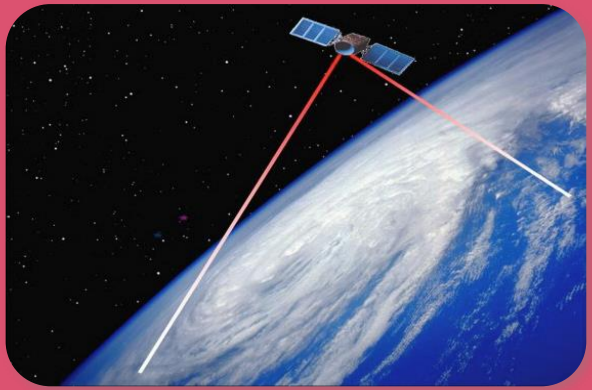
Tsinghua University, Peking University, Fudan University, etc.

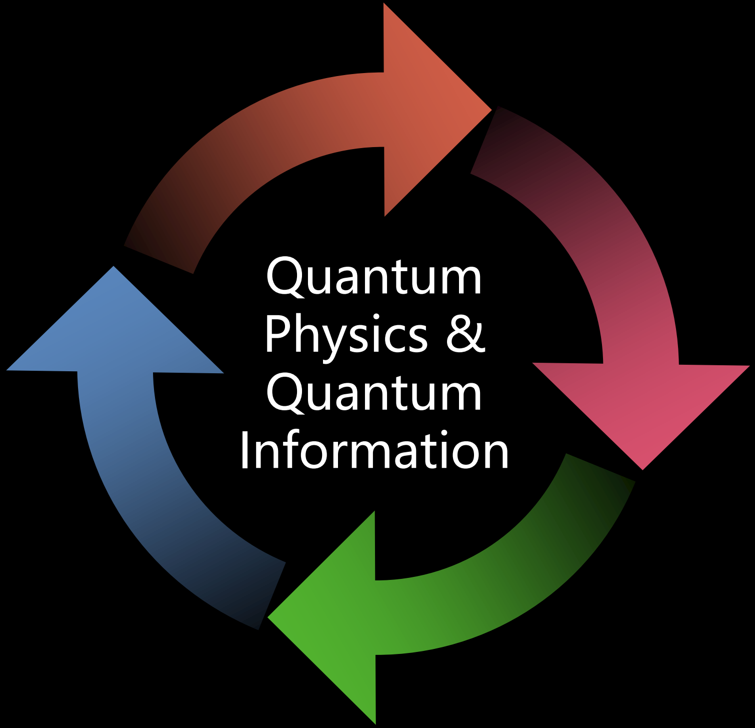
Introduction to our group

Quantum Foundations



Quantum Communication





Quantum Physics & Quantum Information

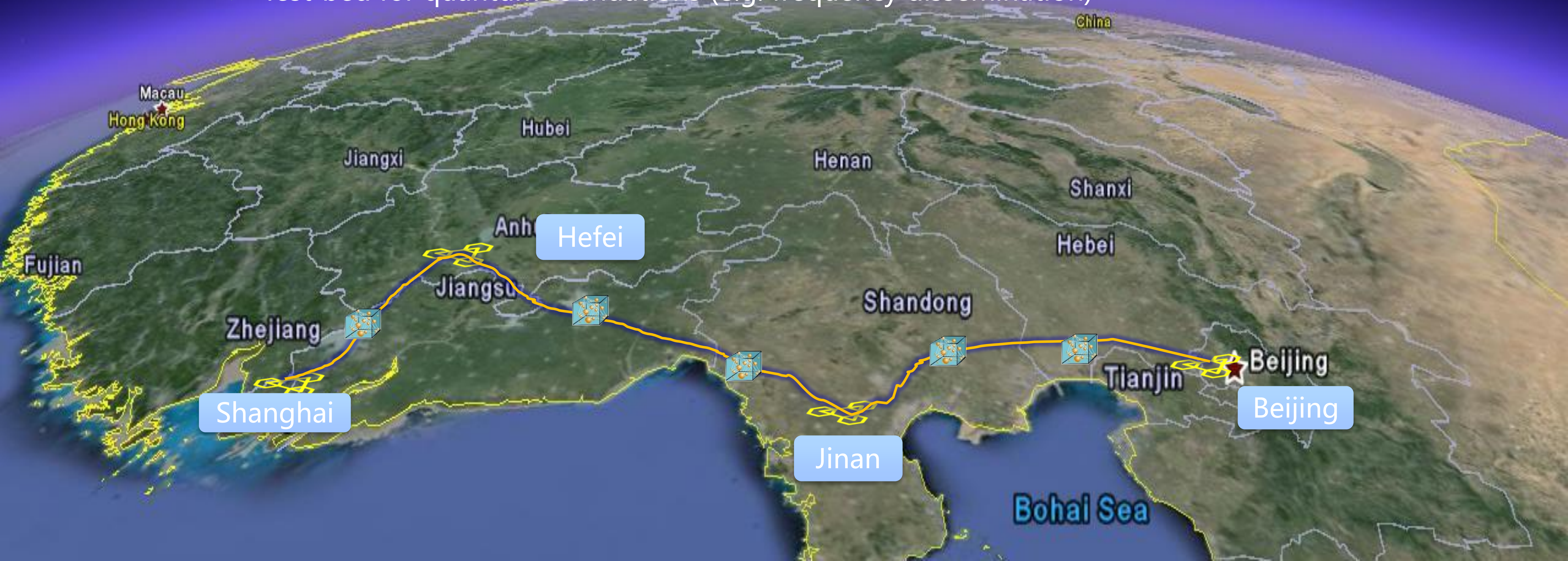
Quantum Metrology

Quantum Computation & Simulation

Introduction to our group

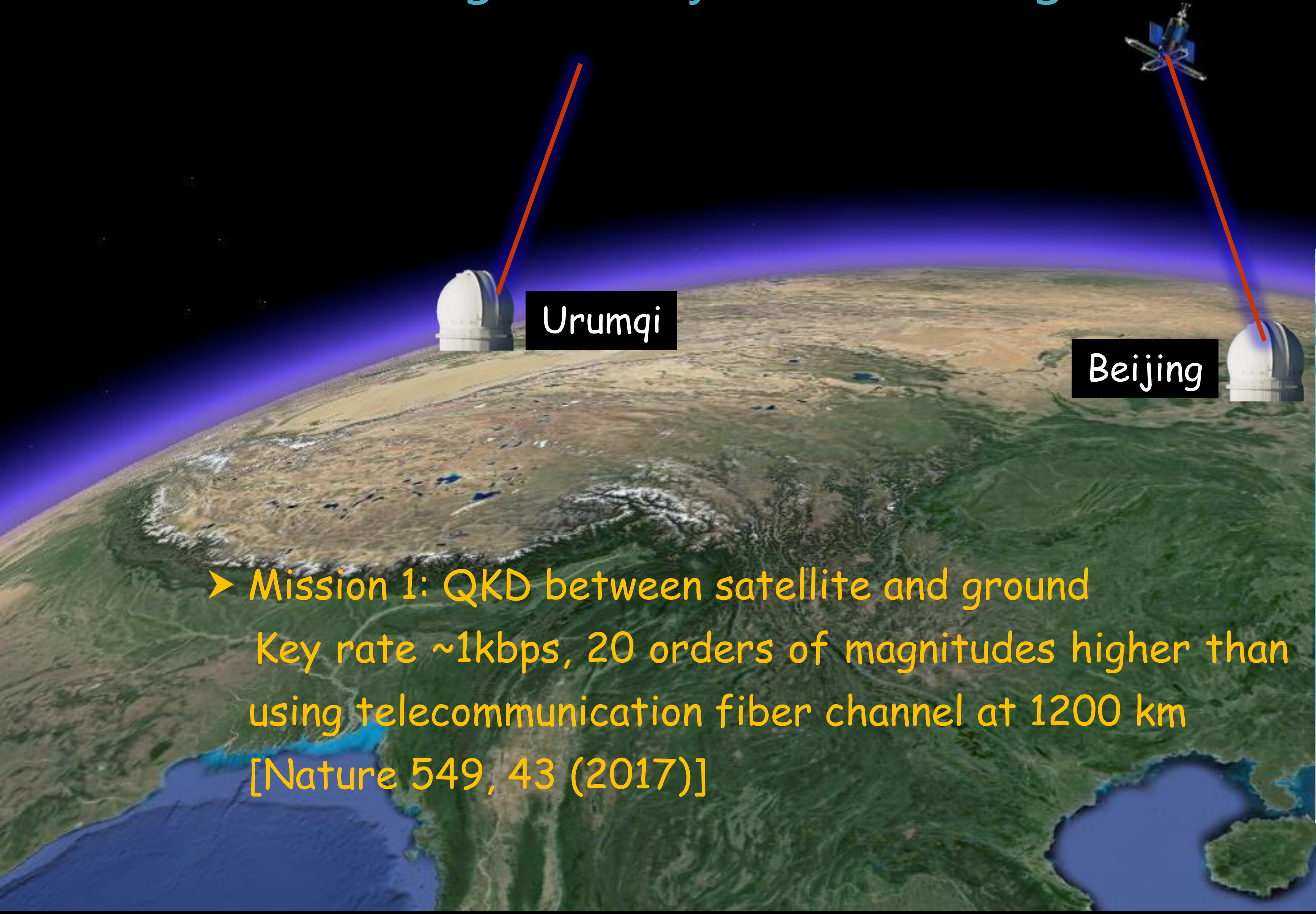
National Quantum Communication Backbone Project

- Inter-city quantum communication backbone with 32 trusted relays (~2000km)
- Inter-connection of four intra-city metropolitan networks
- For financial applications, public affairs, etc.
- Test-bed for quantum foundations (e.g. frequency dissemination)



Introduction to our group

CAS Strategic Priority Research Program: Quantum Satellite



- Mission 1: QKD between satellite and ground
  Key rate ~1kbps, 20 orders of magnitudes higher than using telecommunication fiber channel at 1200 km
  [Nature 549, 43 (2017)]


nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Evolutionary history of reef fish reveals how marine life diversifies near islands and seamounts
PAGE 92

SEA CHANGES

SPECIAL REPORT
SCIENCE IN GERMANY
The strategies driving Europe's rising research star
PAGES 10, 26 & 119

PUBLISHING
WASTED LIVES AND MONEY
The true cost to biomedicine of predatory journals
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APPLIED PHYSICS
LONG-DISTANCE INFORMATION
Satellite signals set standard for quantum communication
PAGES 41, 43 & 70

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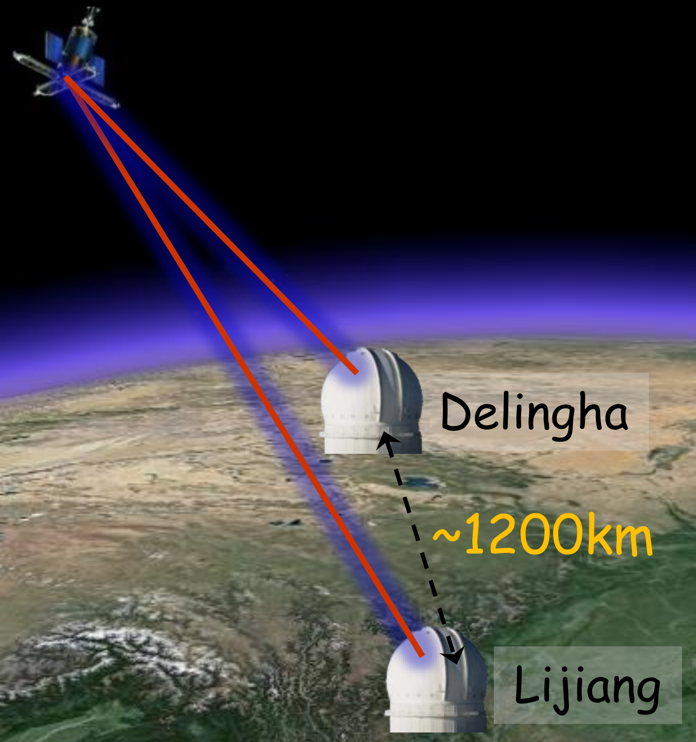
7 September 2017 £10
Vol. 549 No. 7670

Introduction to our group

CAS Strategic Priority Research Program: Quantum Satellite



- Mission 2: Quantum entanglement distribution over 1200 km, and test of "spooky action at a distance" under strict Einstein's locality condition [Science 356, 1140 (2017)]


Retired research chimps stuck in limbo p. 1114
Job losses undermine educational advancement p. 1127
Marine predators shape prey defenses p. 1178

Science

$15
16 JUNE 2017
sciencemag.org

AAAS

QUANTUM REACH

Entangled photon pairs sent from space to Earth
pp. 1110 & 1140

Introduction to our group

CAS Strategic Priority Research Program: Quantum Satellite

- Mission 3: Quantum teleportation between ground and satellite [Nature 549, 70 (2017)]

nature

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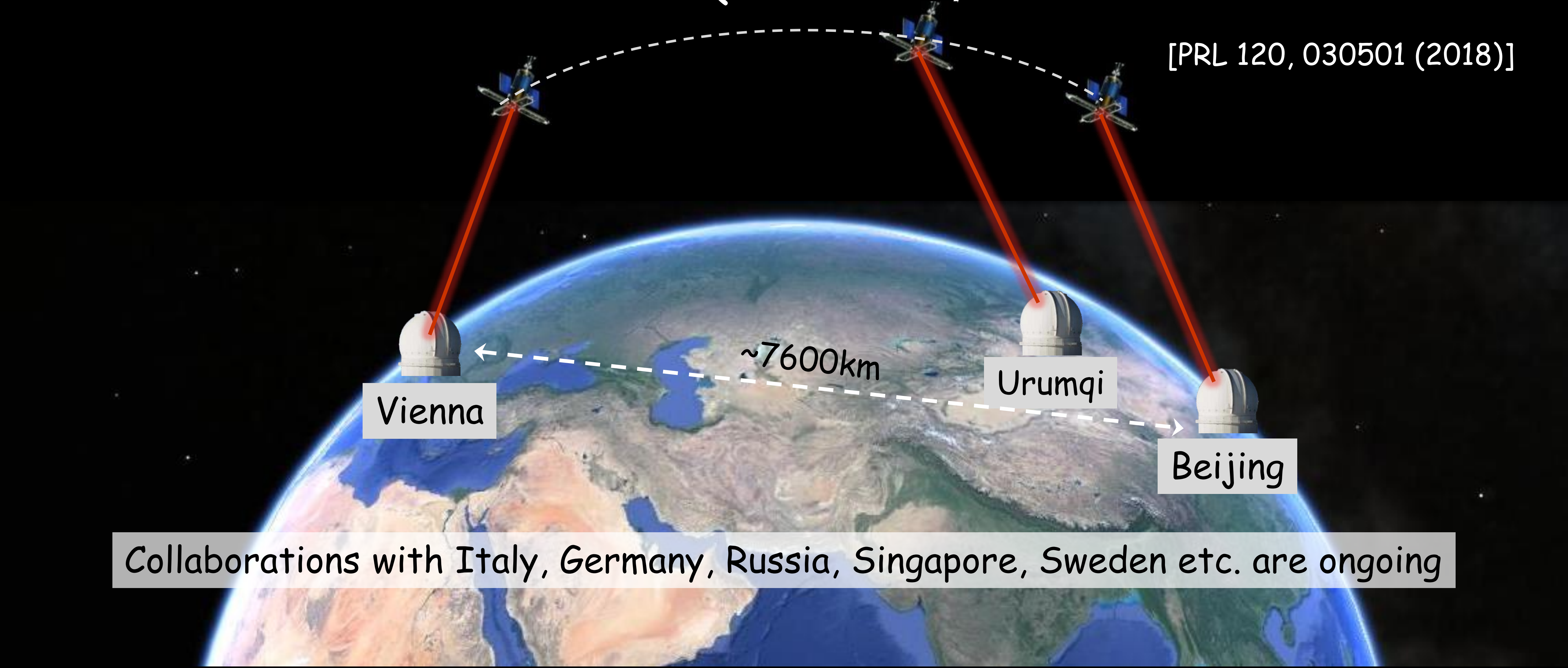
QKD and teleportation papers

Introduction to our group

CAS Strategic Priority Research Program: Quantum Satellite

Intercontinental Quantum Key Distribution

[PRL 120, 030501 (2018)]

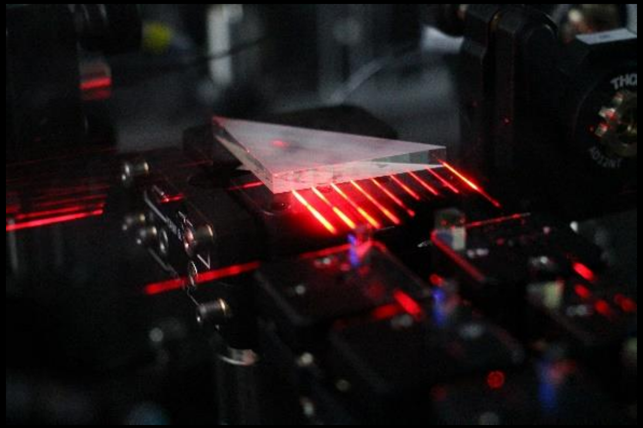


Collaborations with Italy, Germany, Russia, Singapore, Sweden etc. are ongoing

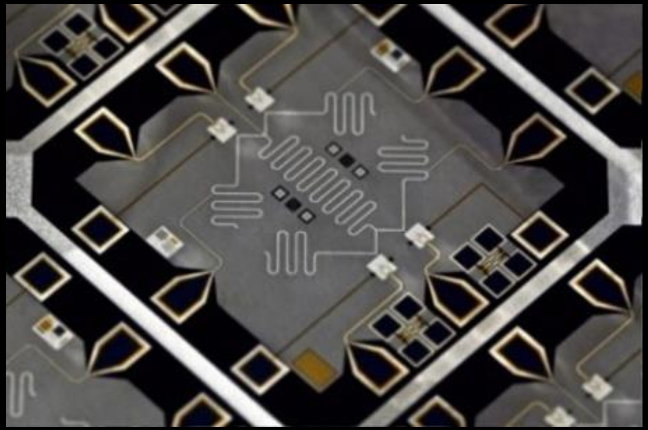
Introduction to our group

Research field: quantum information processing with photons and atoms

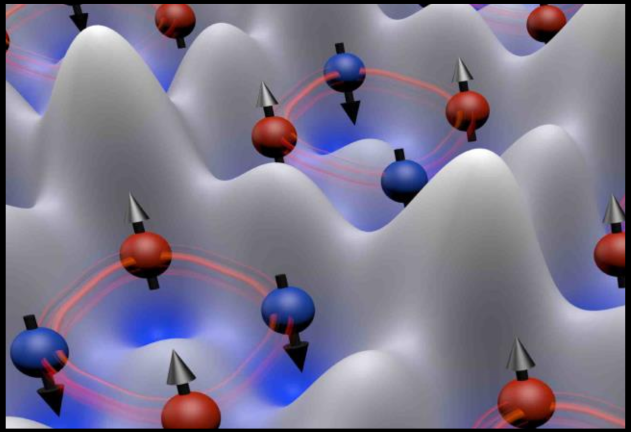
- Quantum computation and simulation with



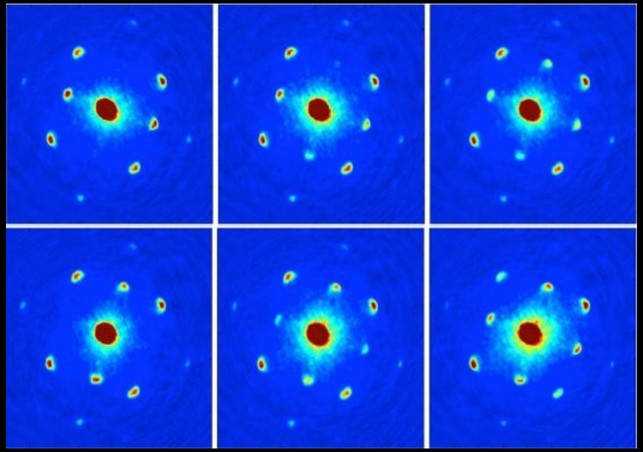
Multi-photon entanglement



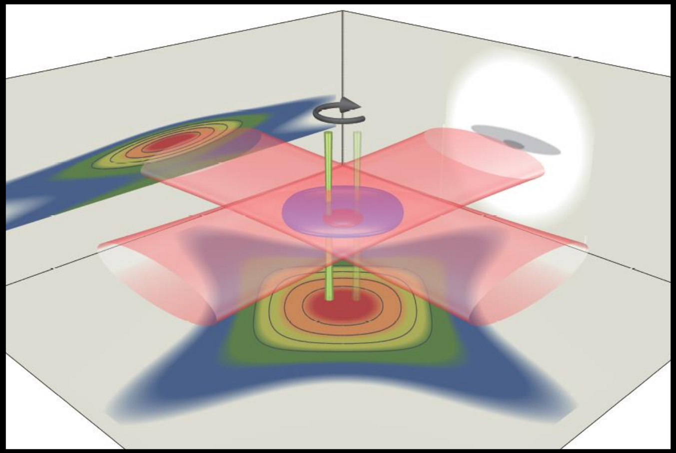
Superconducting qubit



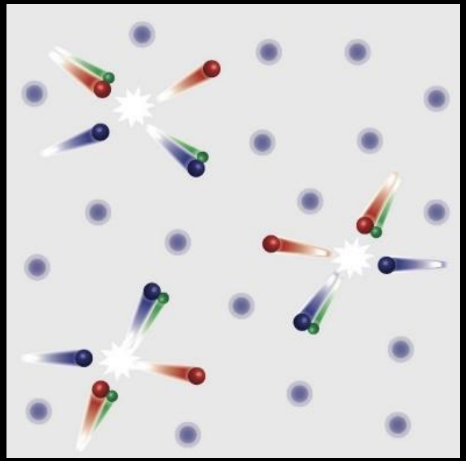
Atom-atom entanglement



Ultra-cold Bose gases



Ultra-cold Fermion mixture



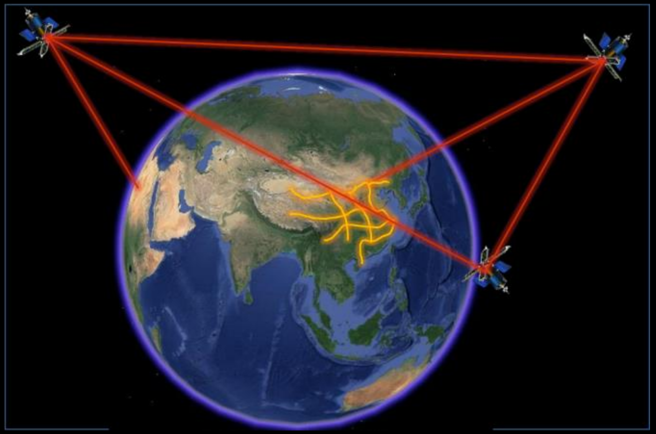
Ultra-cold molecule


回想自己一生，经历过许多
坎坷，唯一希望的就是祖国繁荣
昌盛，科学发达，我们已经尽了
己的力量，但国家尚未摆脱贫
落后，尚需当今与后世无
请勿吸烟
NO SMOKING
请勿喧哗
KEEP SILENT

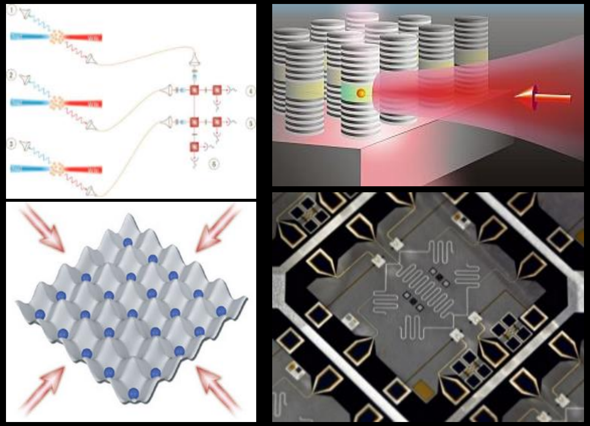
China’s Future National Projects

The Center is now playing a leading role in organizing

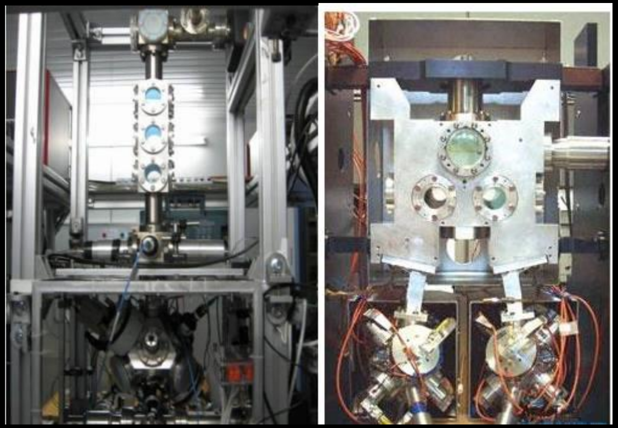
- National Science and Technology Project on Quantum Information in the next 15 years, similar to European Quantum Technologies Flagship
- National Laboratory for Quantum Information Sciences (NLQIS)



Global Quantum Communication Networks



Scalable Quantum Computation and Quantum Simulation



Super-resolution Quantum Metrology

…nature isn‘t classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

–Richard P. Feynman, May 1981

Published: Int. J. Theo. Phys. (1982)

Quantum computation and Simulation

FEYNMAN'S ANSWER

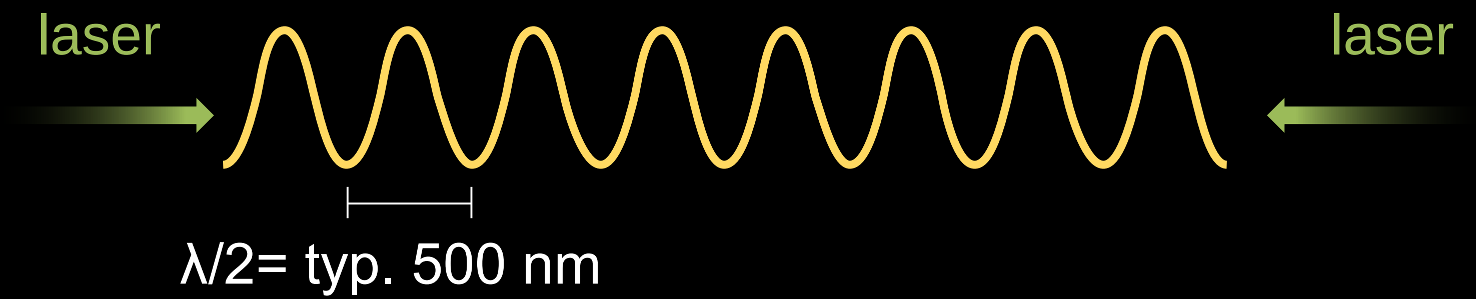
make the simulator (the computer) itself quantum mechanical effective memory scales up due to superposition

Idea: quantum simulator

- can efficiently do a specific class of simulation problem
- structure of implementation similar to the problem: “model”

Why ultra-cold atoms

Optical standing wave: **perfect** lattice



Why ultra-cold atoms

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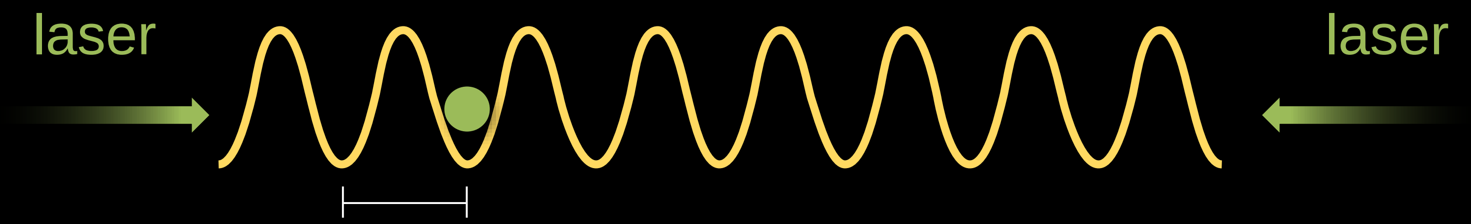


λ/2= typ. 500 nm

Ultracold atoms: move in optical lattice just like the electrons

For low enough energies: described by Hubbard model Hamiltonian:

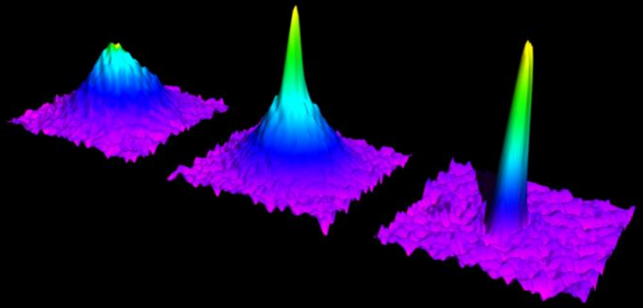
$$H = -J \sum_{\langle i,j \rangle,\sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + U \sum_i \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

Why ultra-cold atoms

low enough means: nano-Kelvin required!

a billion times colder than real material

Bose-Einstein-Condensate territory



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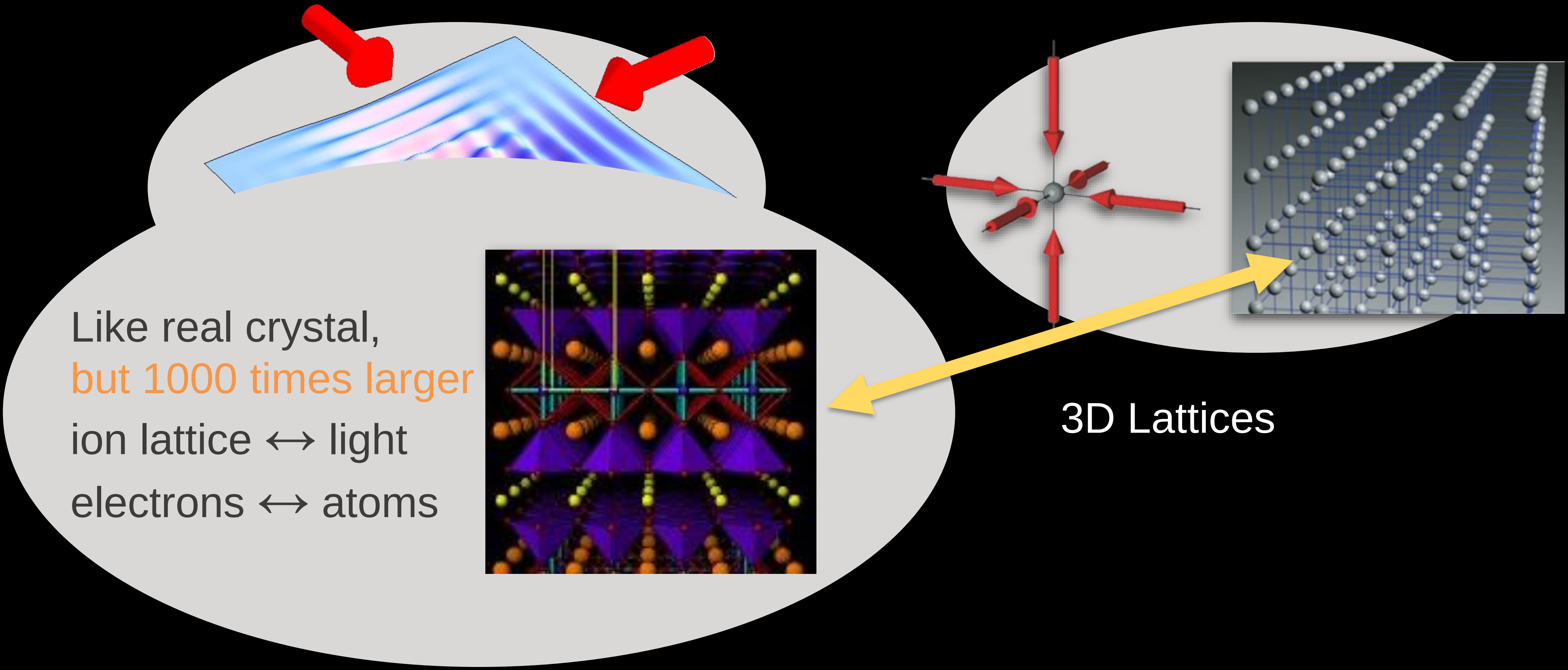
Why ultra-cold atoms



Like real crystal,
but 1000 times larger
ion lattice ↔ light
electrons ↔ atoms

3D Lattices

Physical System

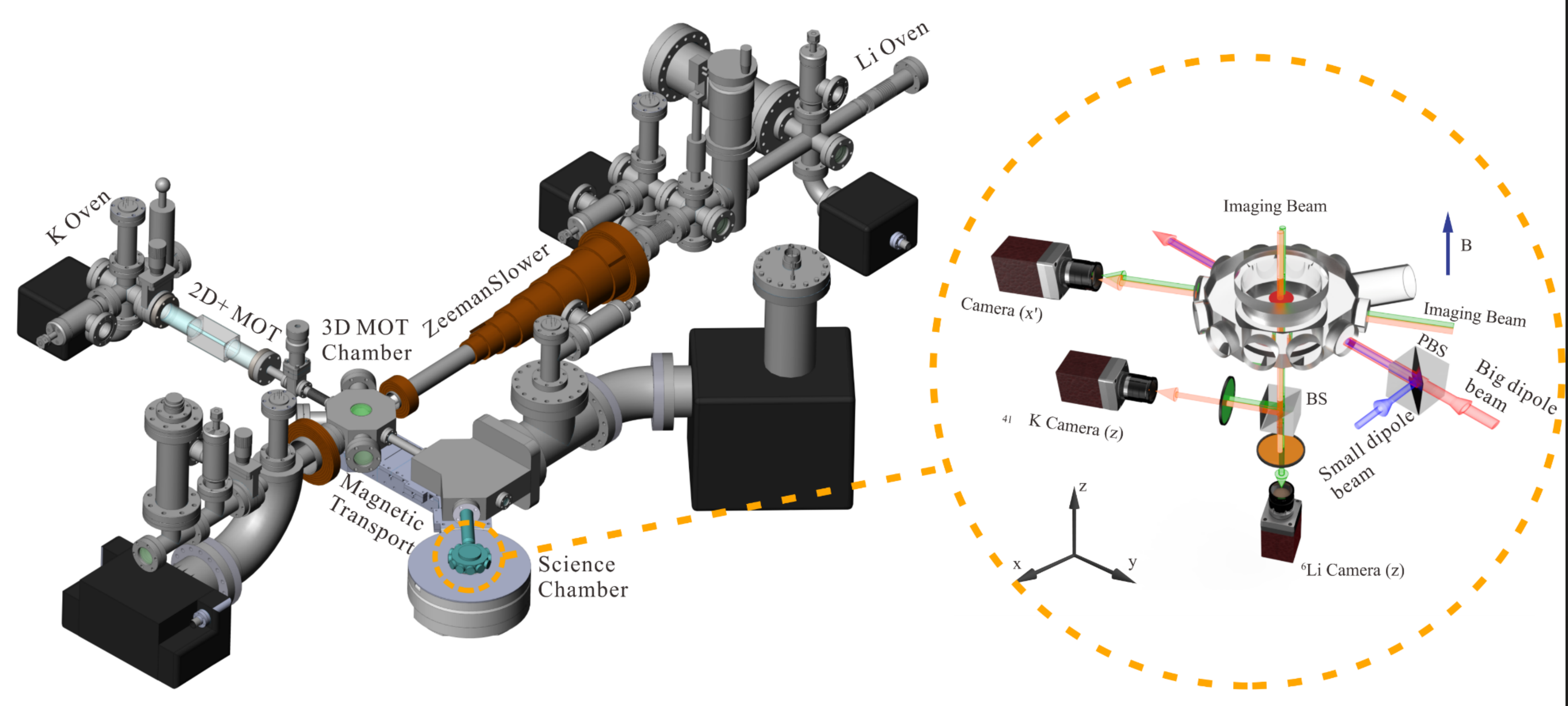
Two-species mixture of Li and K atoms
Larger atom number, lower temperature, high resolution

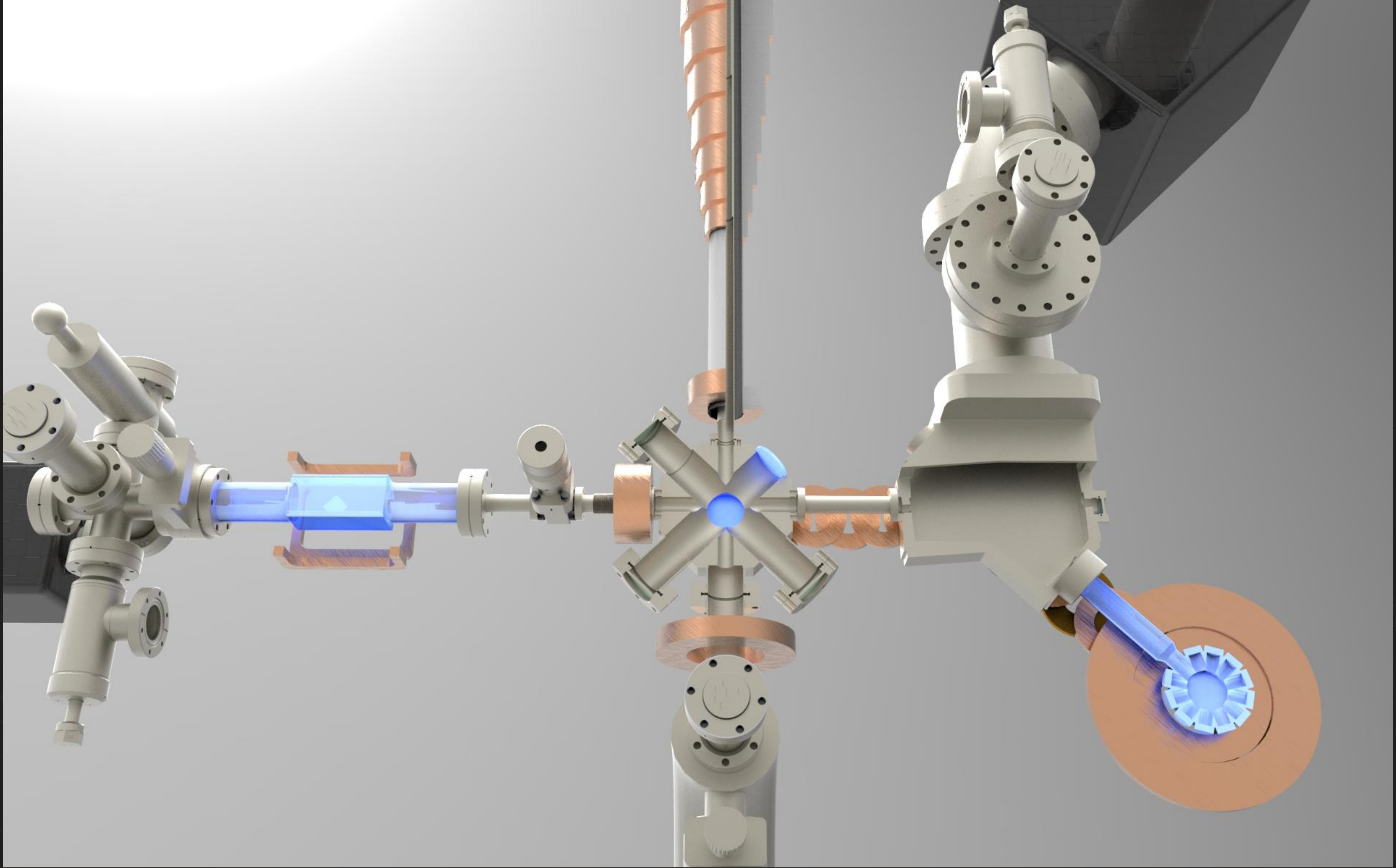
- Mass imbalance: ratio about 7

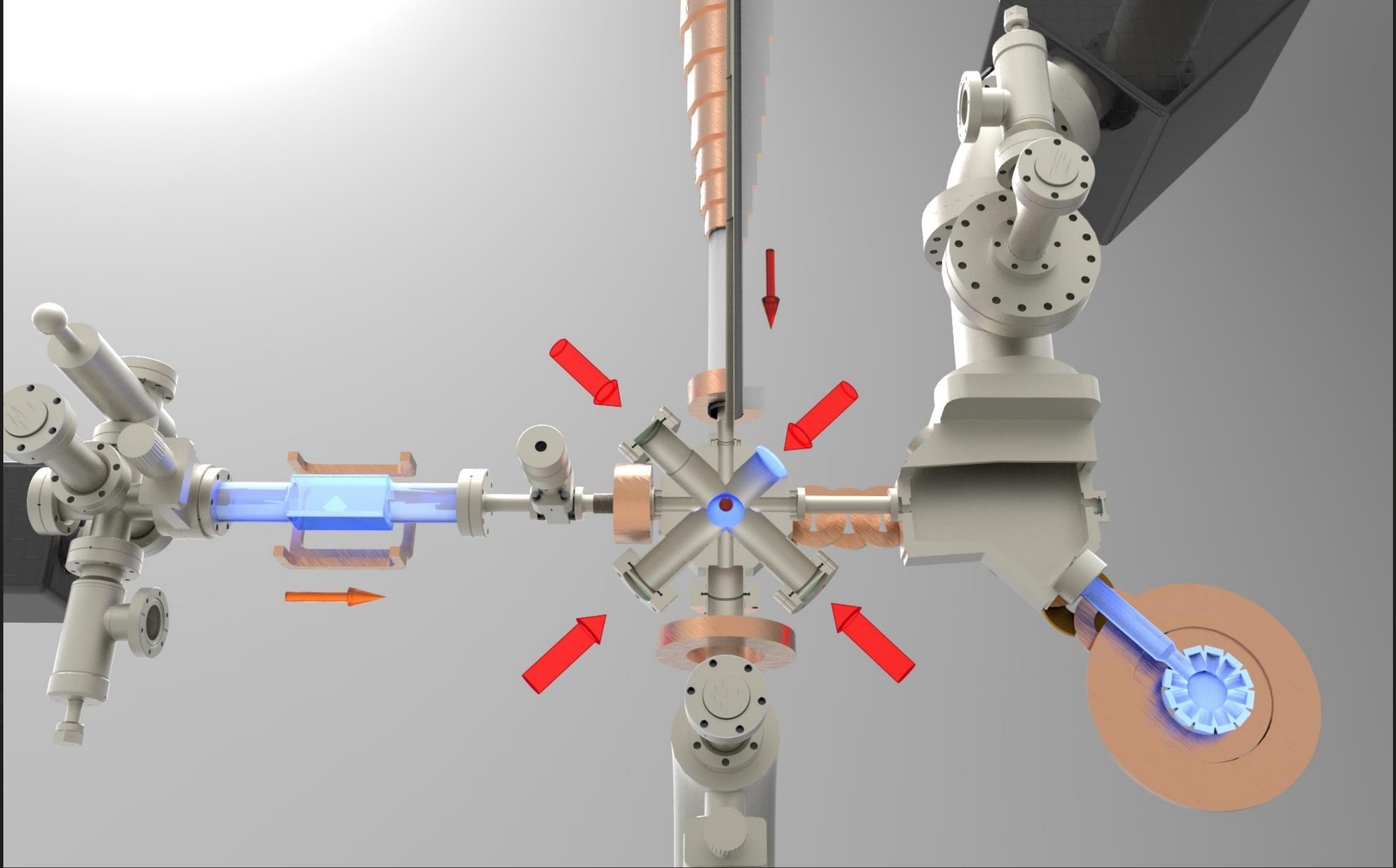
- Bose-Fermi mixture
  - Bose and Fermi superfluid mixture
  - Bose polaron

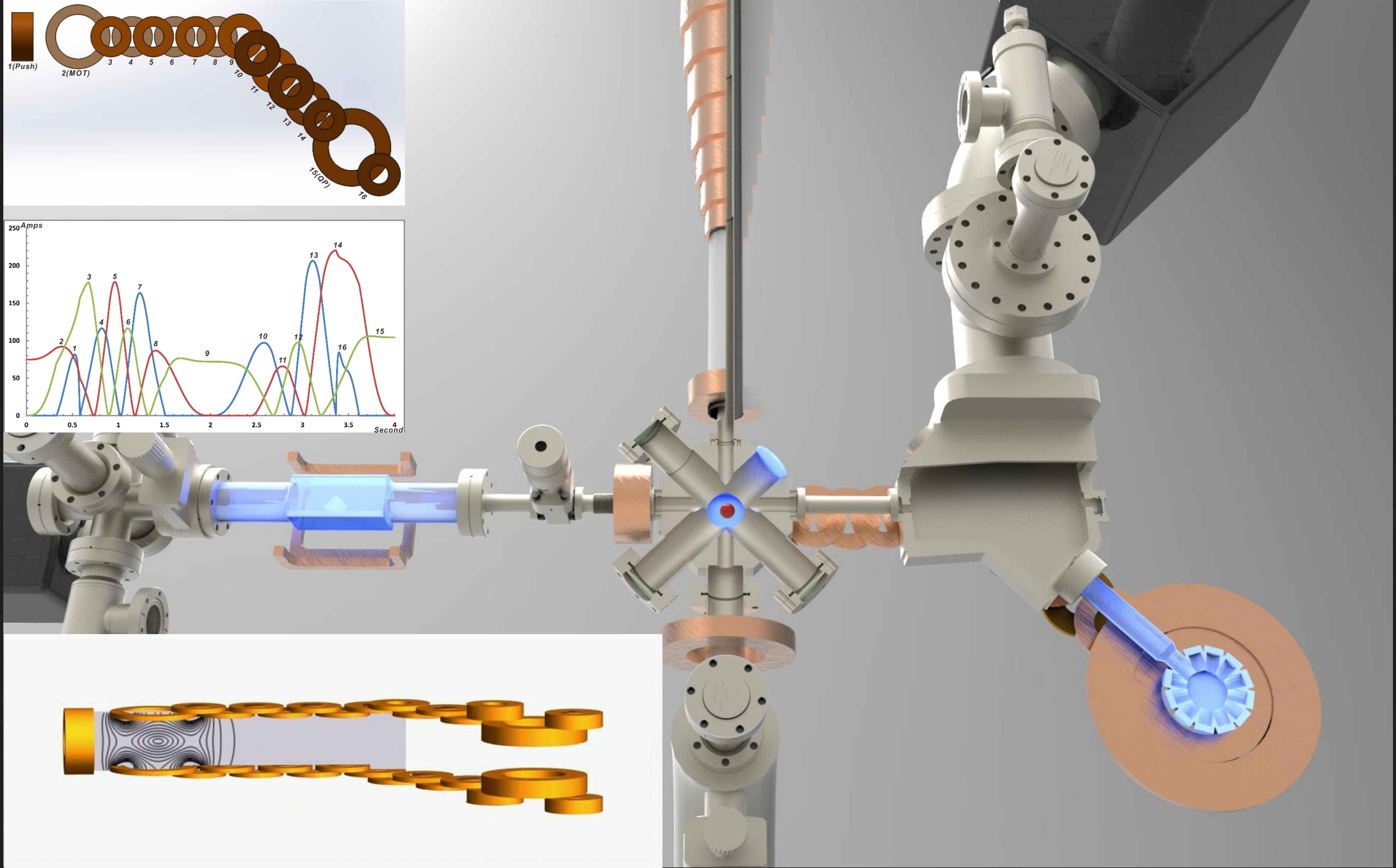
- Fermi-Fermi mixture
  - Fermi Hubbard model with impurity
  - Non-equilibrium physics with vortices

Experimental Setup








1(Push)
2(MOT)
3
4
5
6
7
8
9
10
11
12
13
14
15(QP)
16
250
Amps
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
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Second
1
2
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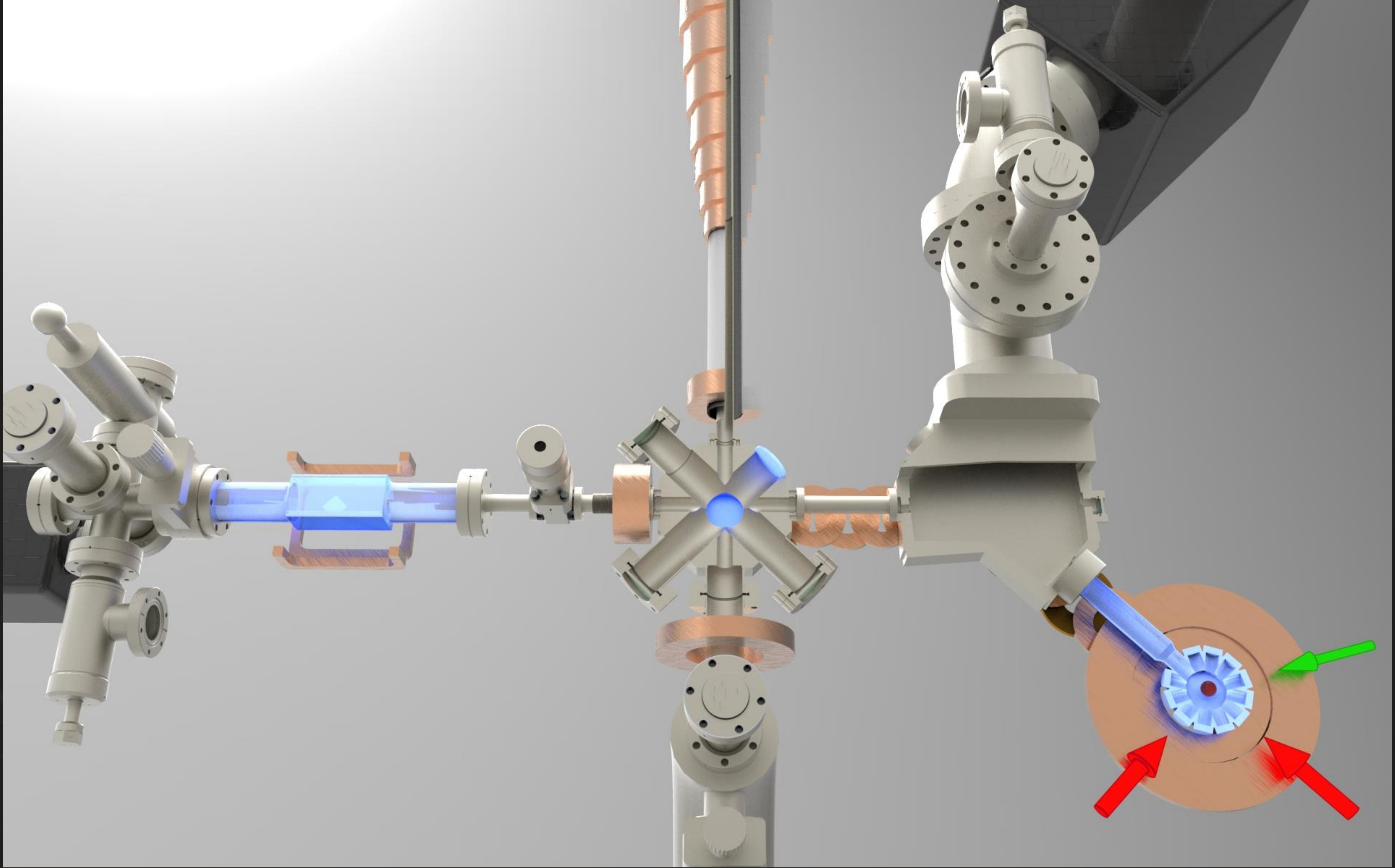
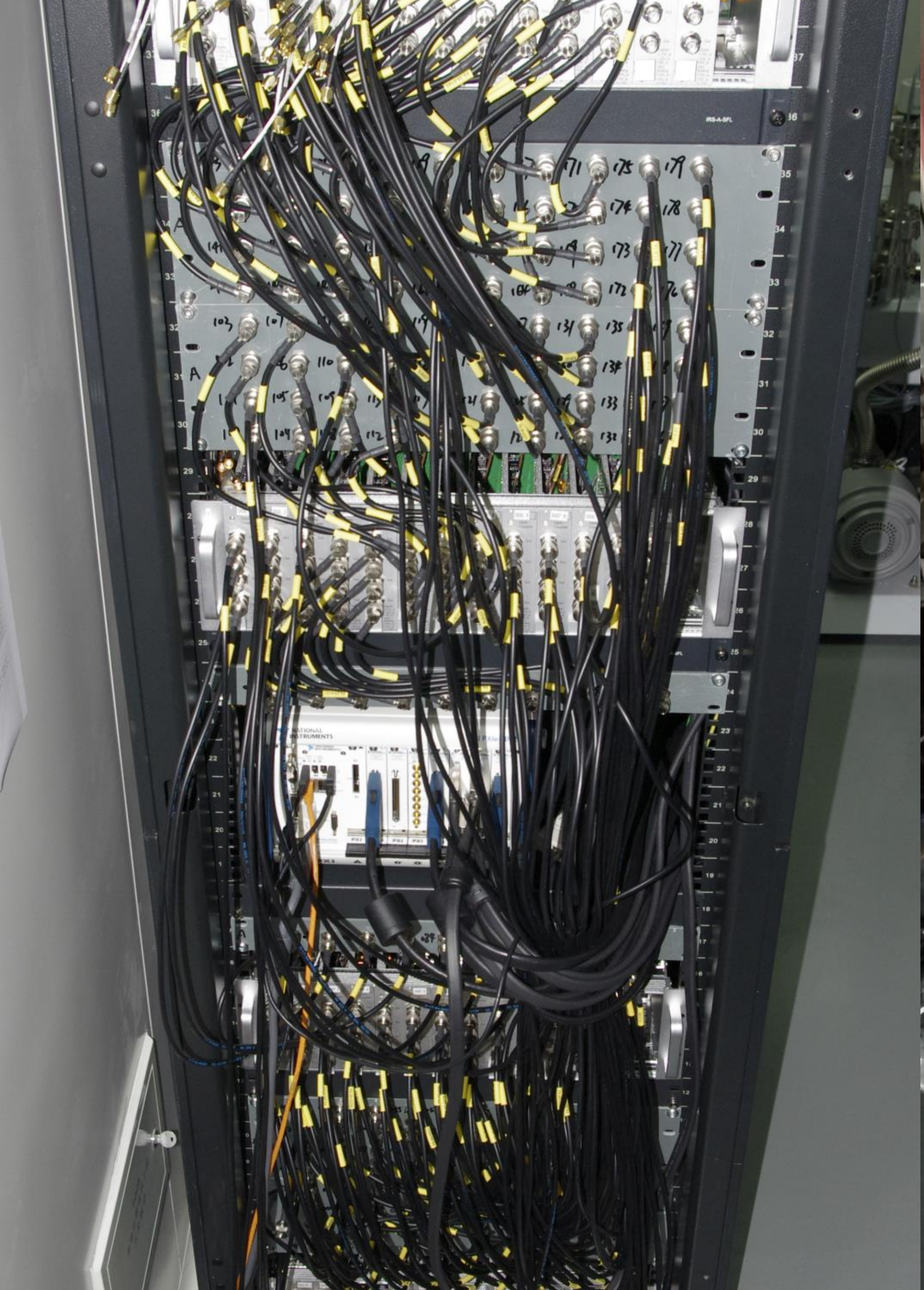
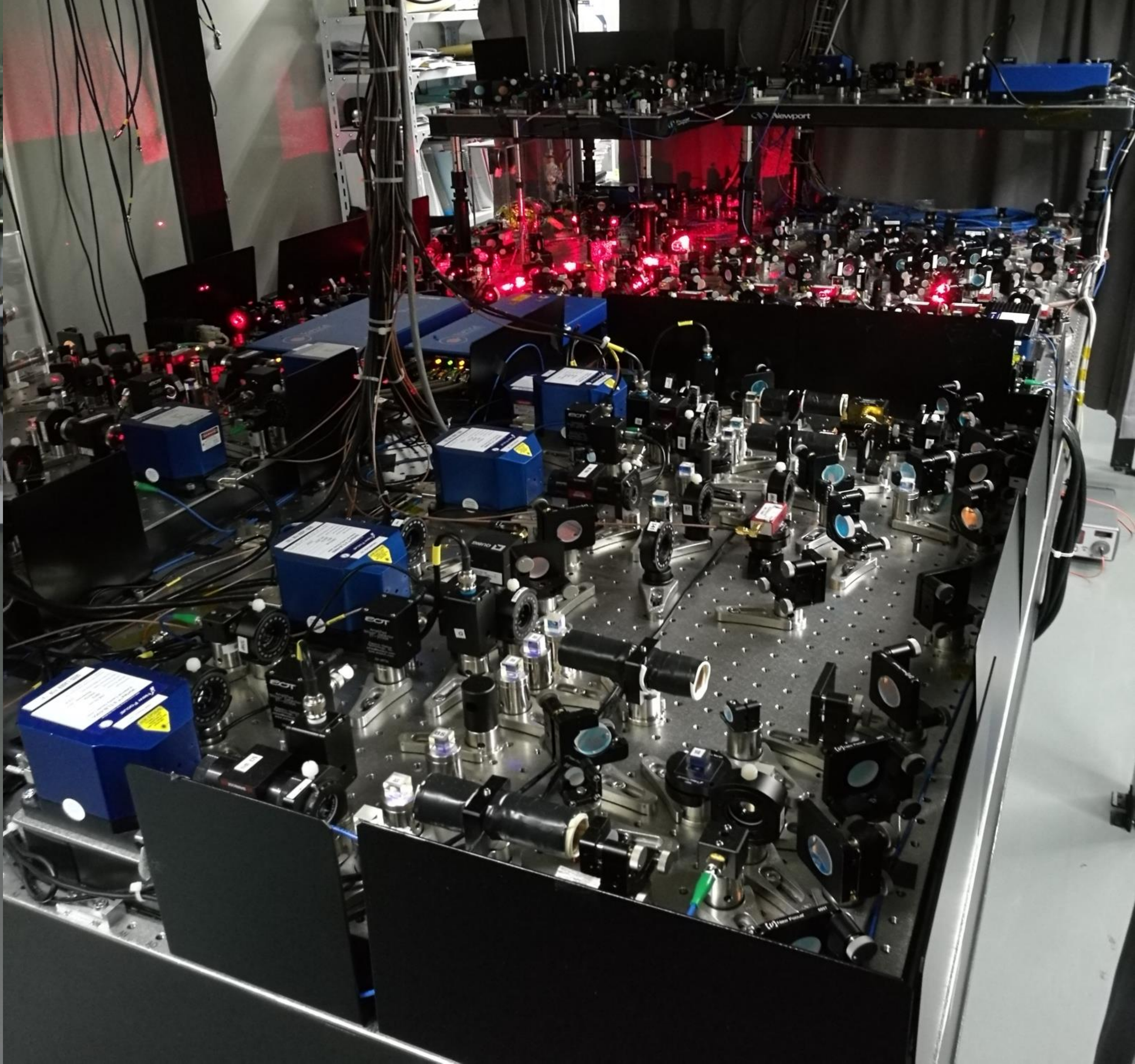
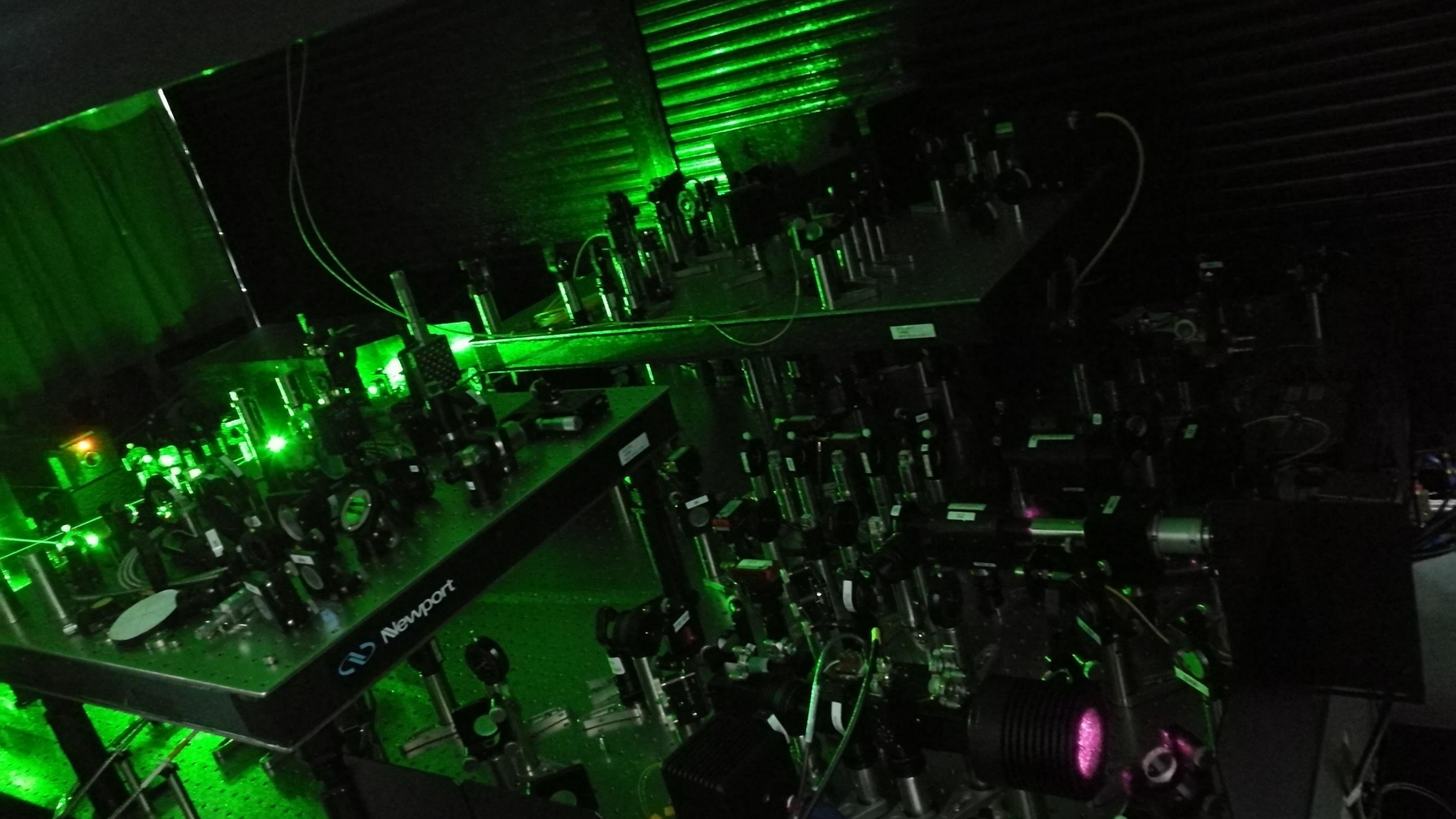
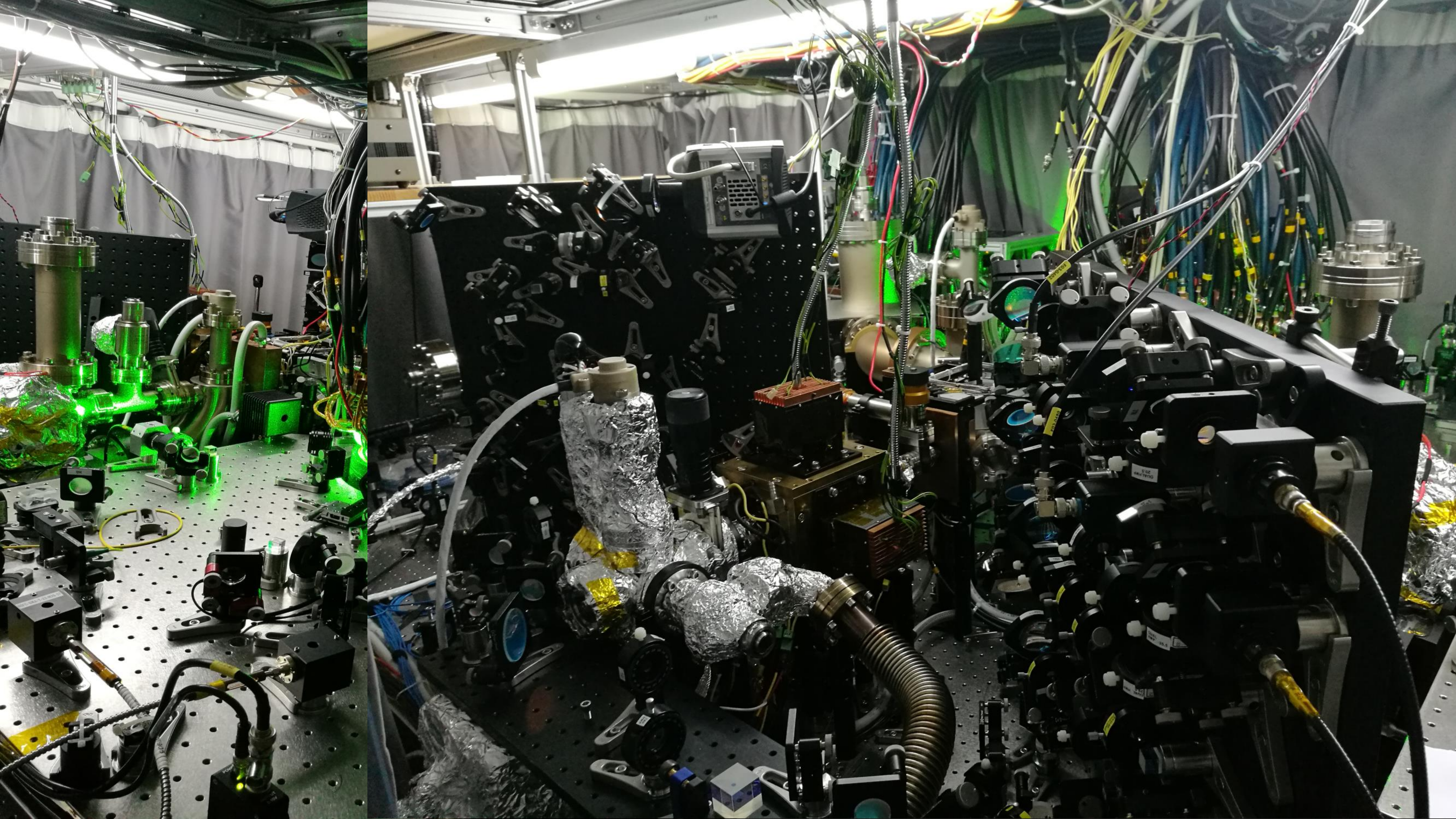


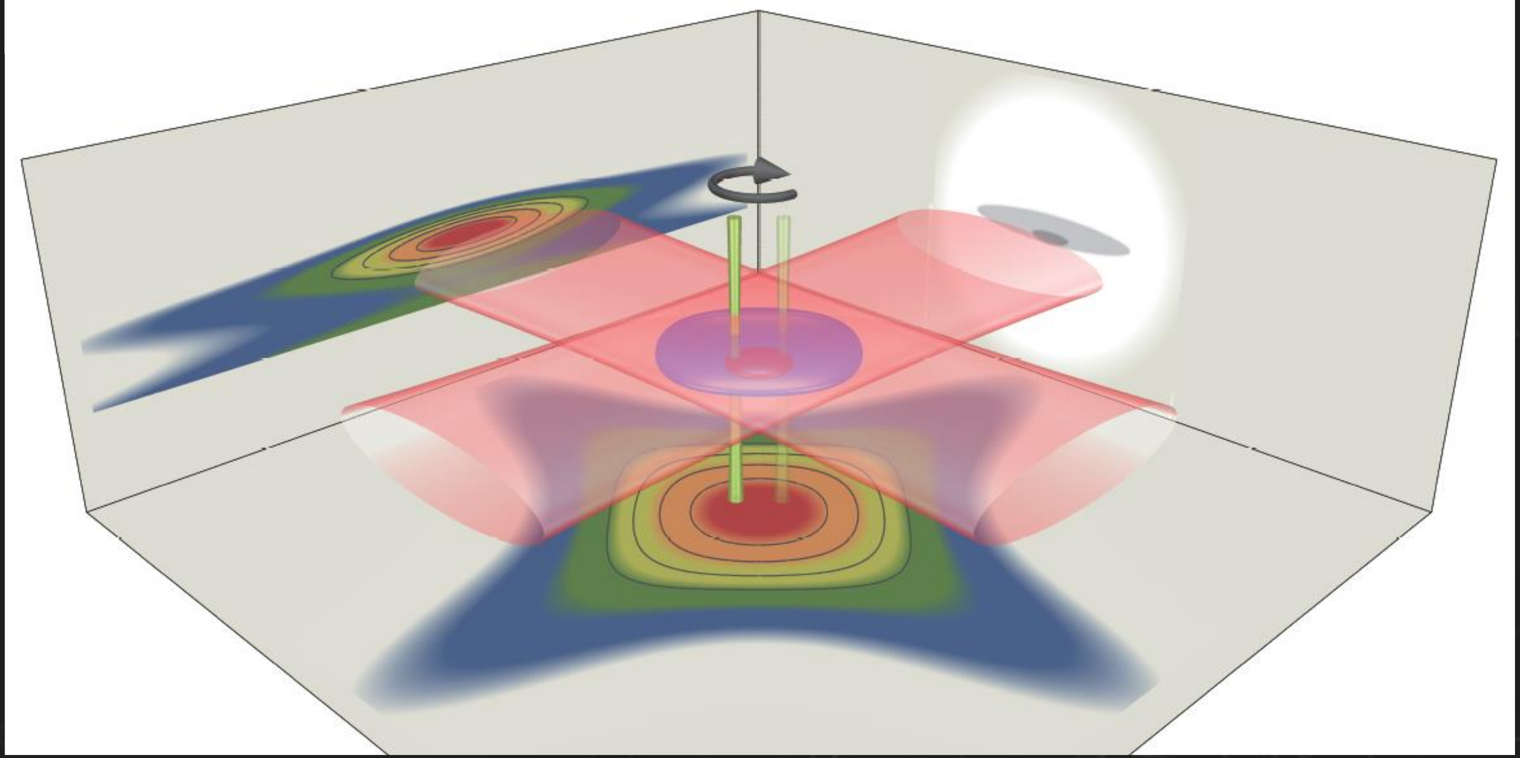

NATIONAL INSTRUMENTS


Newport
EOT


Newport



A disk-like trap



90^0 cross beam with aspect ratio of 4: r_z = 48 μm , $r_x = r_y$ = 200 μm

Two species superfluid in a Disk-like trap

（1）K41： trap frequency $2\pi\times(20，85)$Hz, trap depth 46.7 nK,

BEC 1.5×10^5 (**10^6 w/o Li6**)

$\mu = 18.5$nK, Tomas-Fermi radius (22.3 μm， 5.5 μm)，

Peak Density $n_{peak} = 3.9\times10^{13}cm^{-3}$

（2）Li6： trap frequency $2\pi\times(40，237)$Hz, trap depth 517nK，

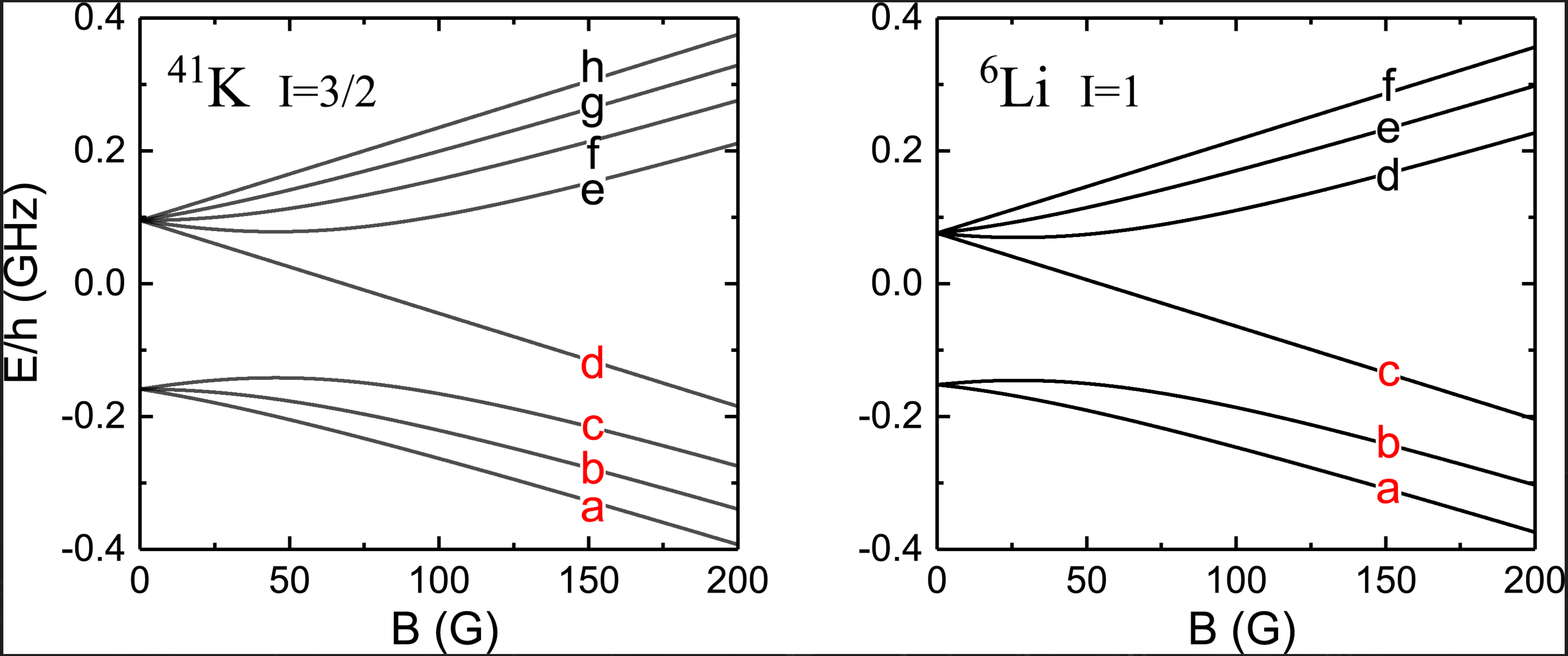
$N_\uparrow=N_\downarrow=7.5\times10^5$ (**2×10^6 each w/o K41**)

$\mu = \xi E_F = 198$nK, Fermi radius (121 μm， 21 μm) ，

Peak Density $n_{peak} = 1.86\times10^{11}cm^{-3}, \frac{\mathrm{T}}{\mathrm{TF}} = 0.07,$

$$\frac{1}{K_F} = 271\ nm$$

Collision Properties

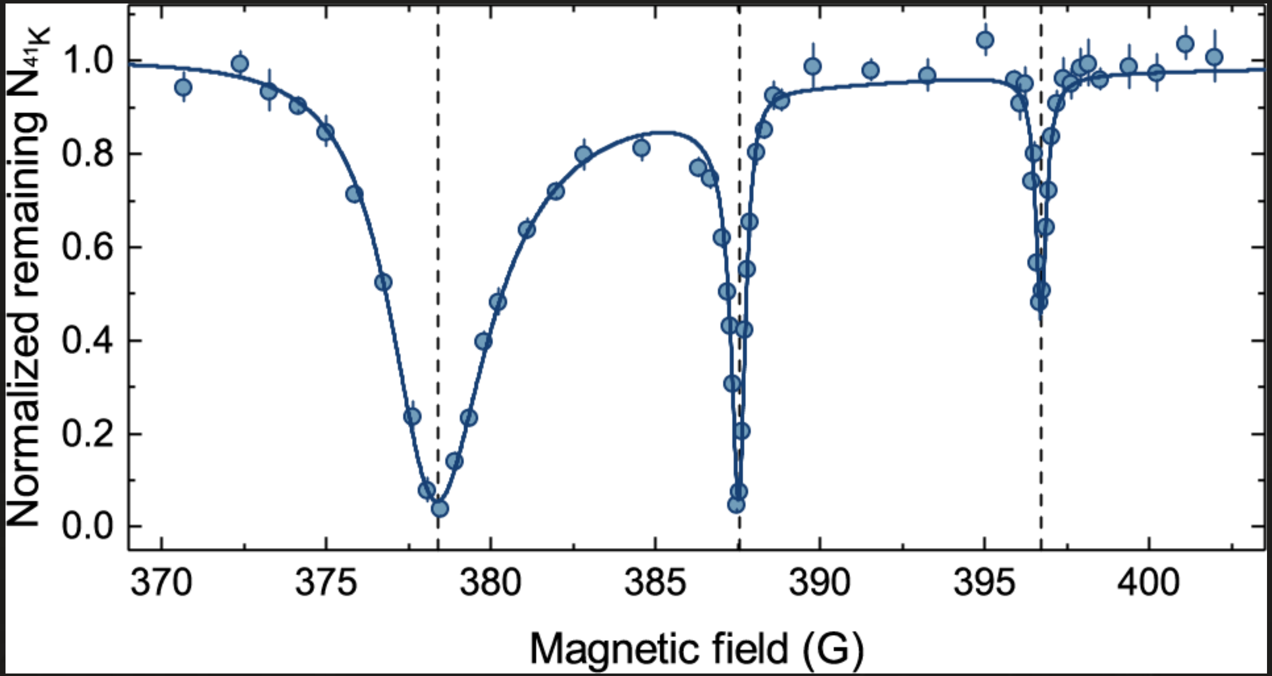


s-Wave Resonances of ^{41}K-^{6}Li Mixture

Elastic channels:
|aa>, |ba>, |ca>, |cb>

Inelastic channels:
|ab>, |ac>, |bb>, |bc>, |cc>, |da>

- ➢ 56 resonances
- ➢ All are narrow



Examples of loss spectroscopy of |ca> channel

Asymmetric Lorentz function

$$N \propto 1/(4(B-B_0)^2+\omega^2)$$

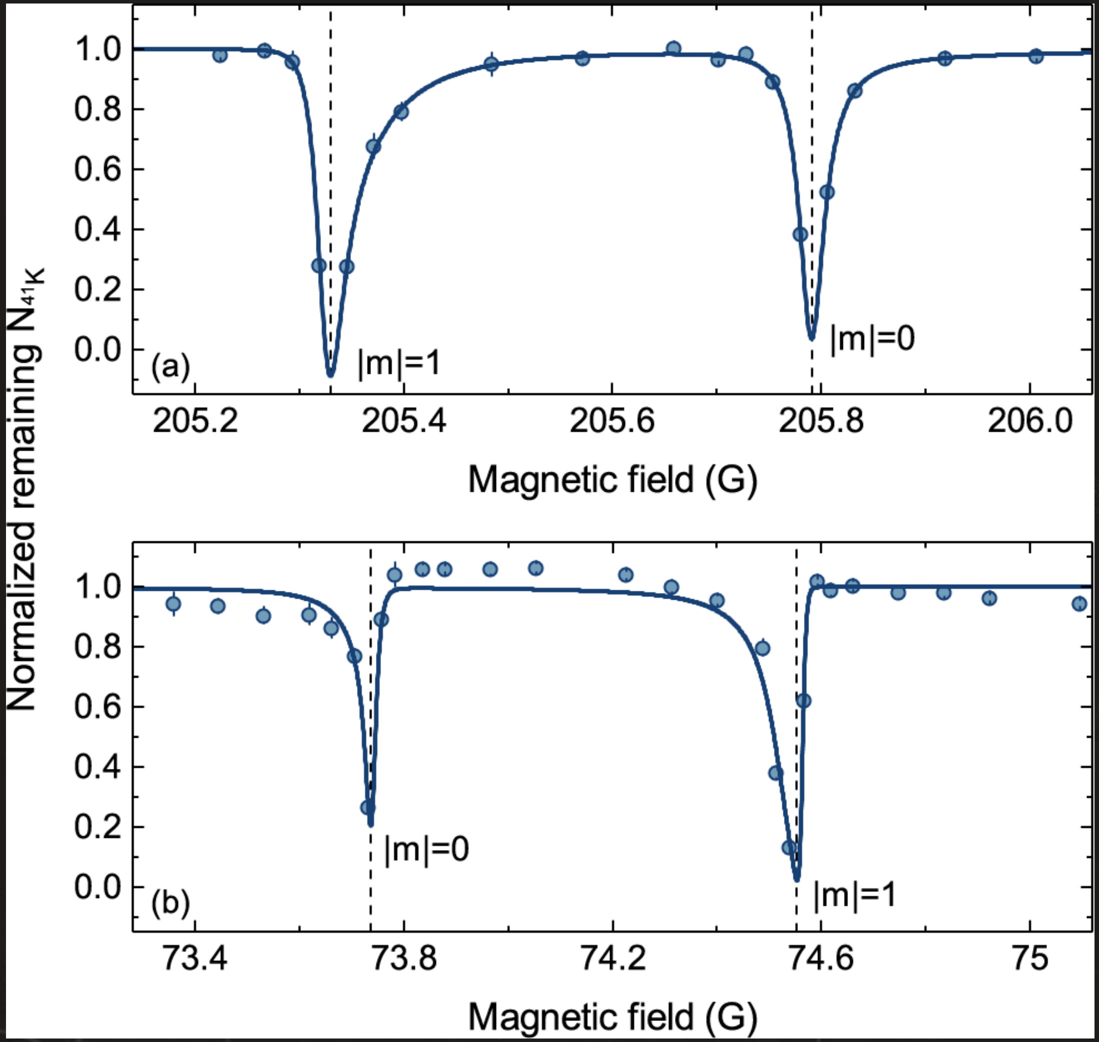
where

$$\omega = 2\omega_0/(1+\exp(F\cdot(B-B_0)))$$

p-Wave Resonances of ^{41}K-^{6}Li Mixture

Elastic channels:
|aa>, |ba>, |ca>, |cb>

- 13 resonances
- Doublet split structure
- Inversed doublet distribution and asymmetric lineshape

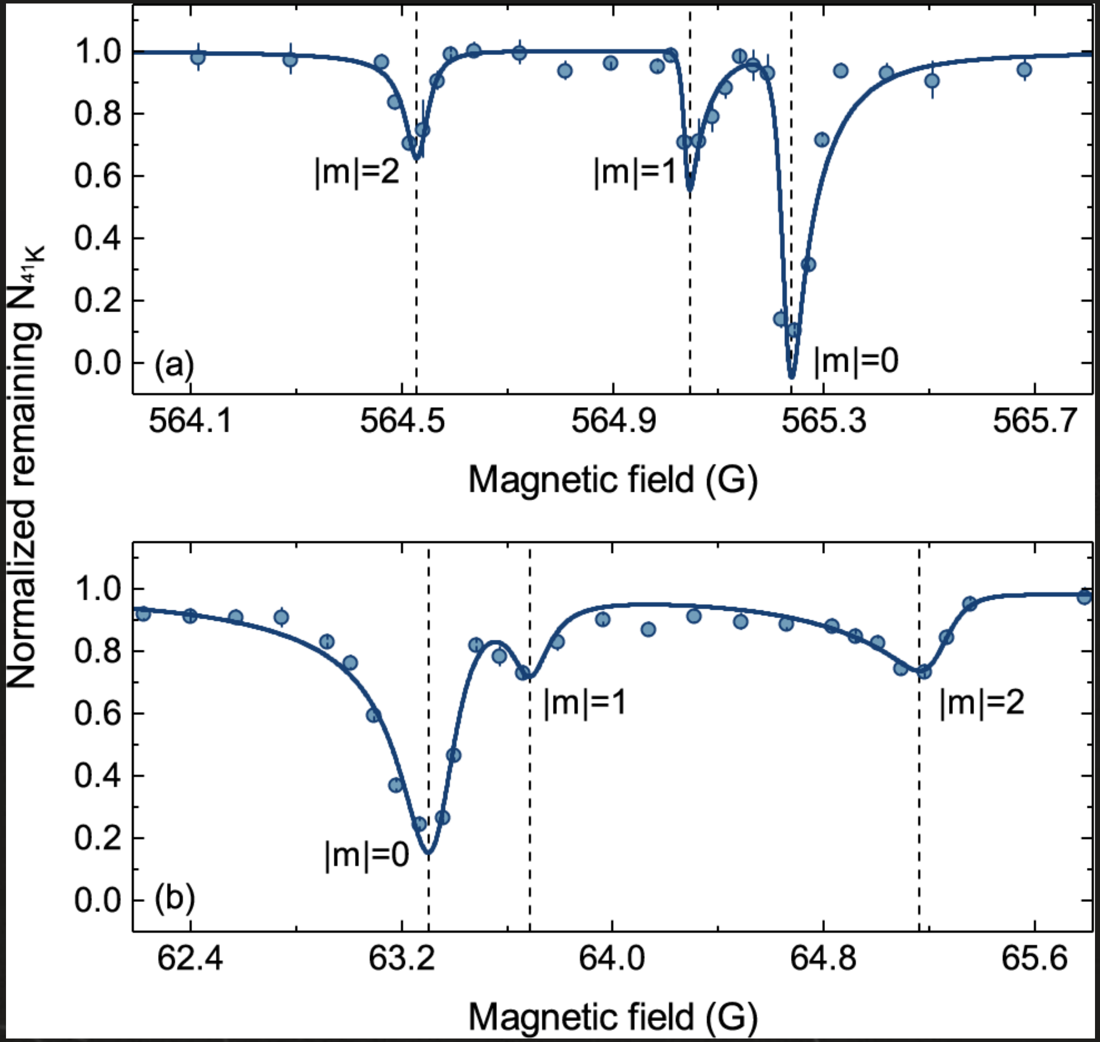


Examples of loss spectroscopy of |cb> channel

d-Wave Resonances of single ^{41}K

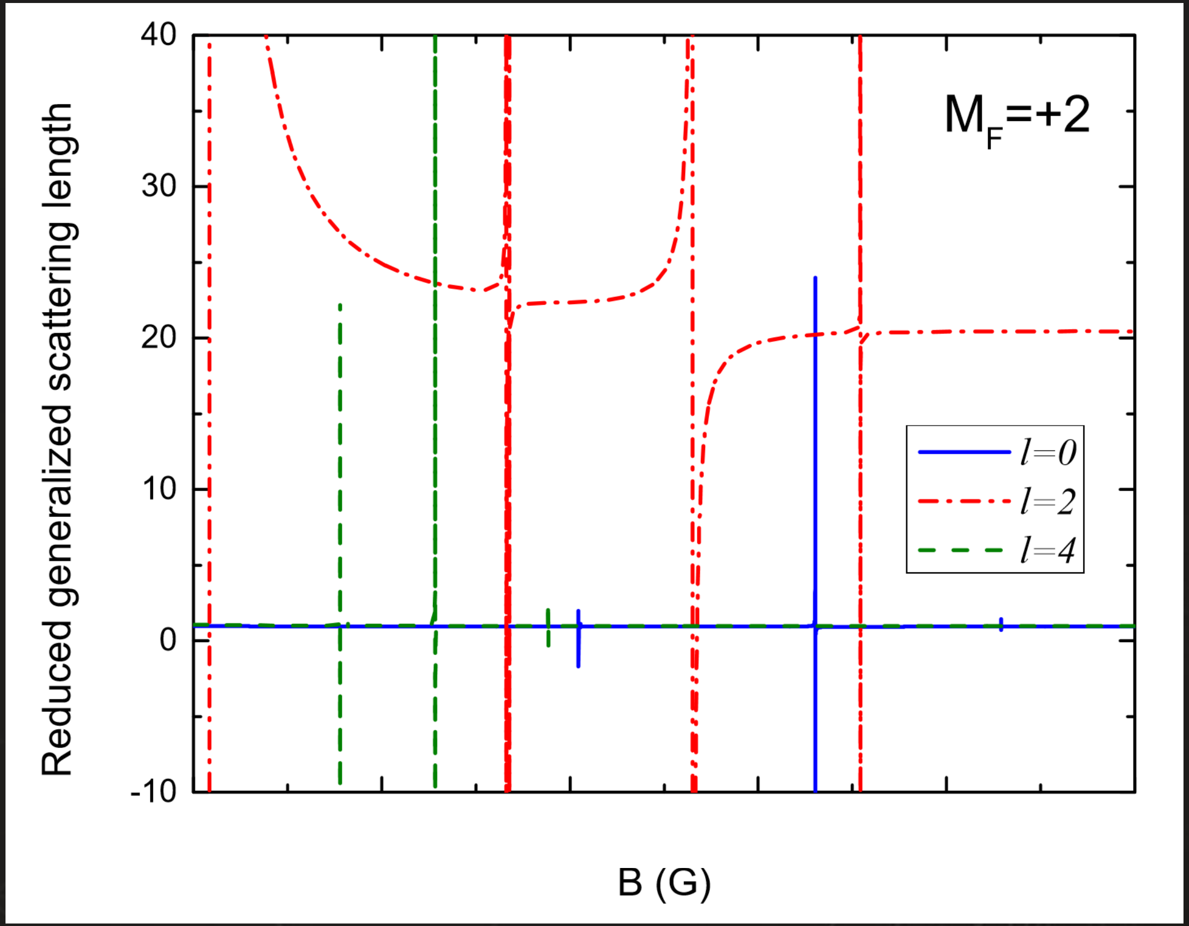
Channels: |aa>, |ab>, |bb>, |cc>

- ➢ 7 broad resonances
- ➢ Triplet split structure
- ➢ Inversed triplet distribution and asymmetric lineshape



Examples of loss spectroscopy of |bb> channel

d-Wave Resonances in ^{41}K

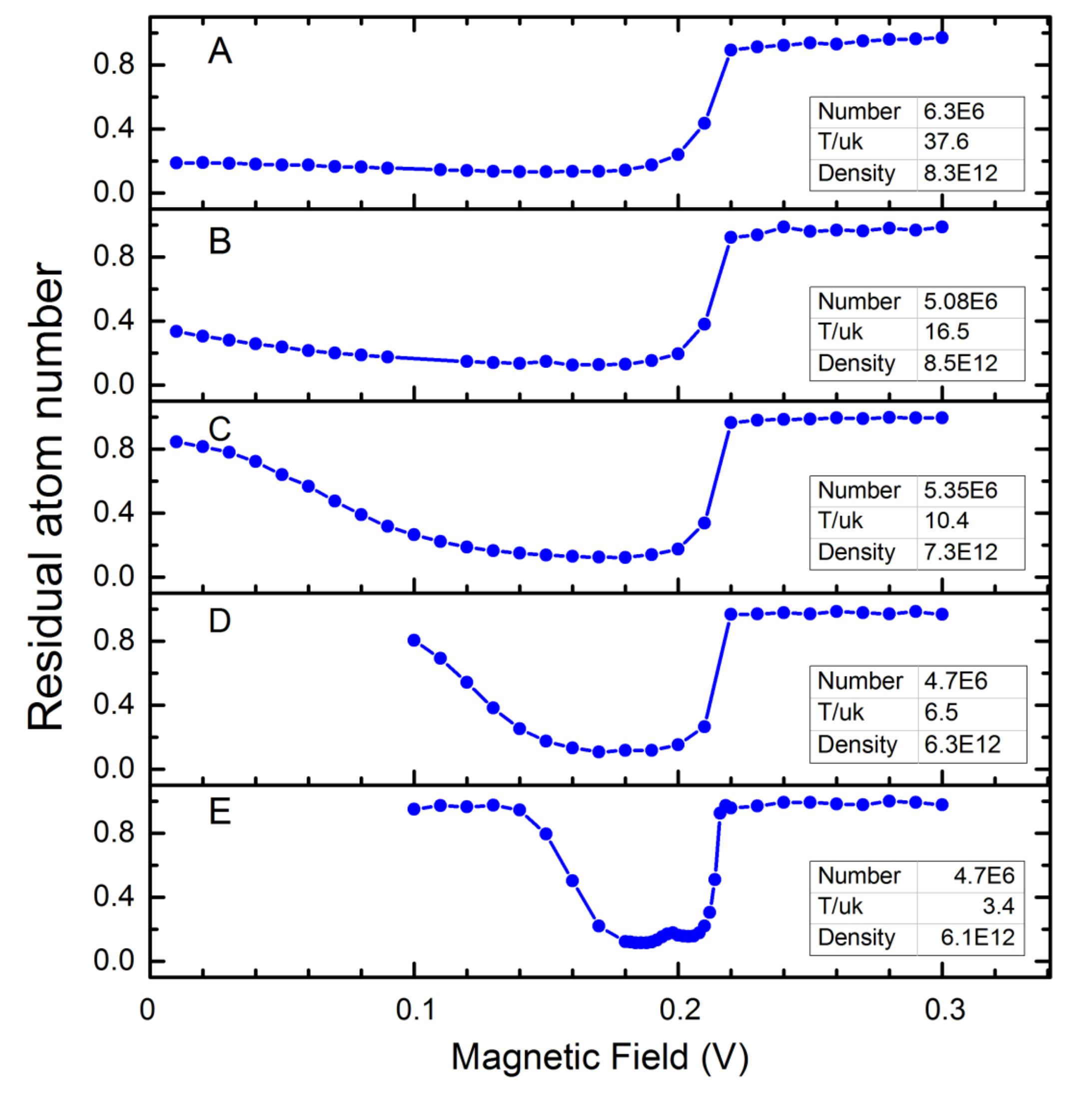


MQDT calculation

- Rich d-wave resonances
  - Extremely wide shape resonance
  - Wide Feshbach resonance
  - Narrow Feshbach resonance
- Ideal high partial wave system for study three-body physics
- d-wave molecular BEC?

Yao et al., arXiv:1711.06622

Loss curve measurement



A

Number	6.3E6
T/uk	37.6
Density	8.3E12

B

Number	5.08E6
T/uk	16.5
Density	8.5E12

C

Number	5.35E6
T/uk	10.4
Density	7.3E12

D

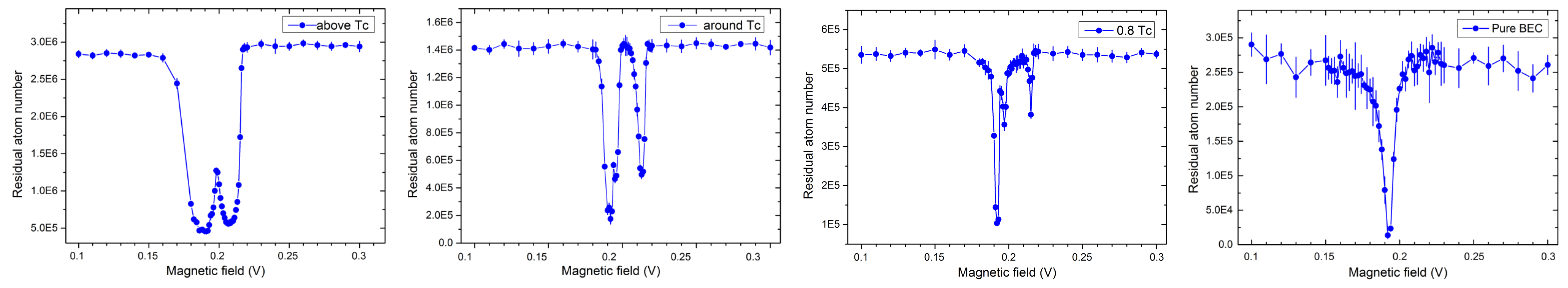
Number	4.7E6
T/uk	6.5
Density	6.3E12

E

Number	4.7E6
T/uk	3.4
Density	6.1E12

Loss curve measurement

Prepare BEC at 300 G → **Quench B field to $B < B_0$** → **Holding at target B field** → **Imaging at 300 G**



How to understand?

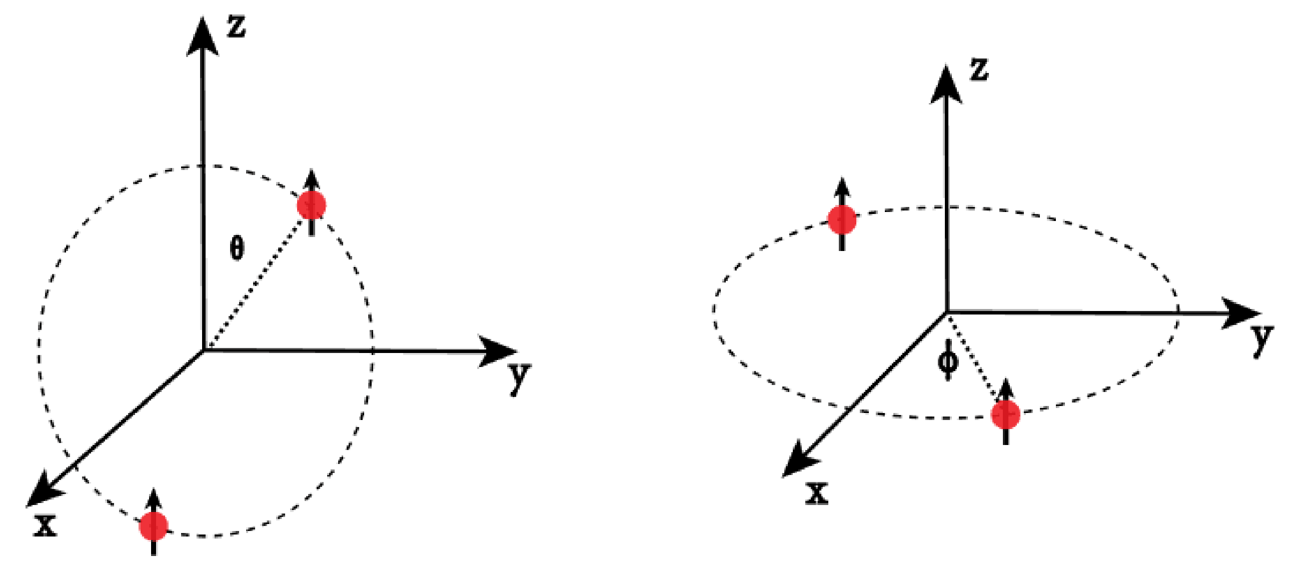
- The d-wave bound states with different magnetic quantum number ($|m|_l=0,1,2$) will be split due to anisotropic dipole-dipole interaction.
- The binding energy can be estimated with first order perturbation theory:

$$E_m = E^{(0)} + \langle \psi_m | V_d(\vec{r}) | \psi_m \rangle$$

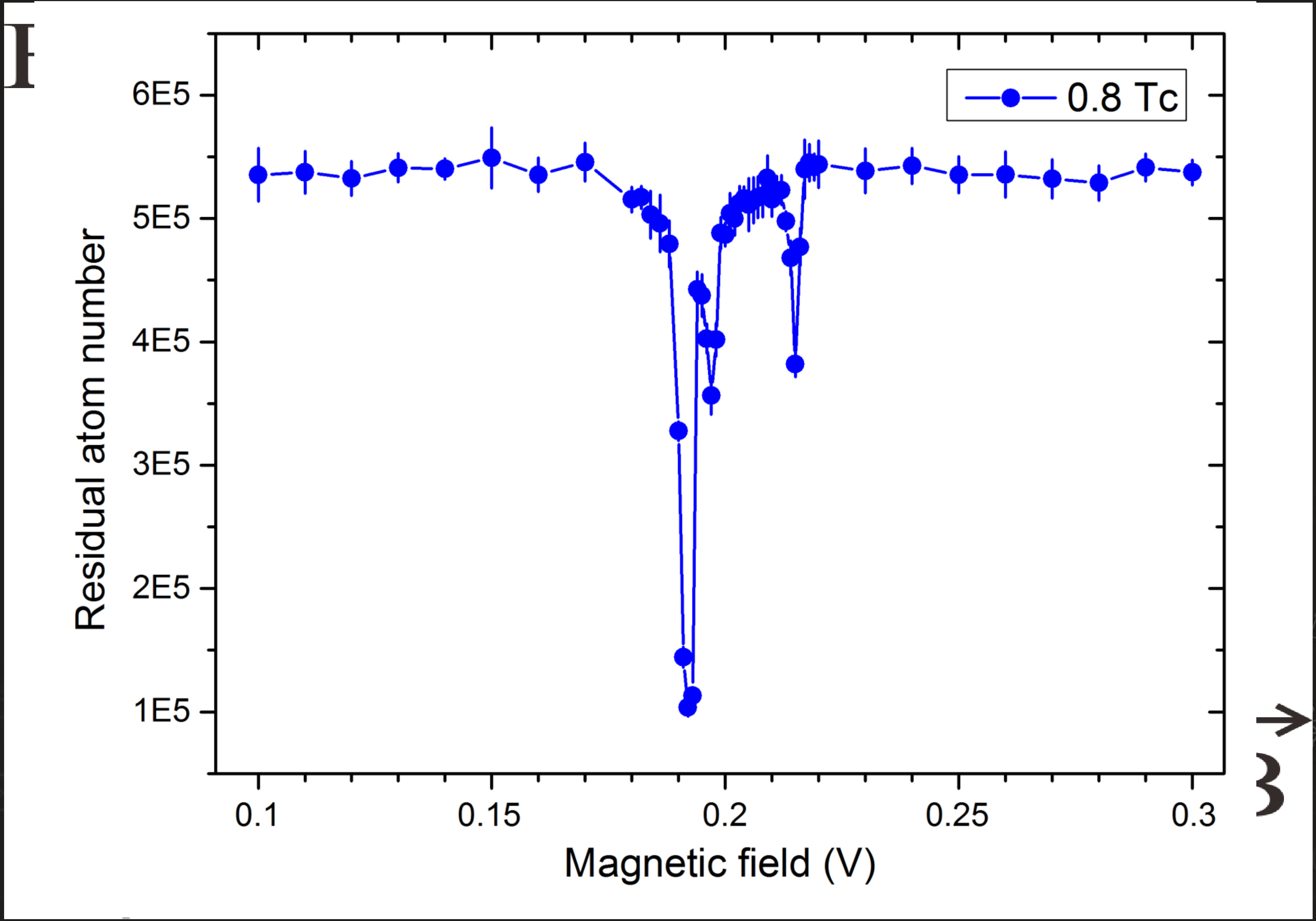
$$V_d(\vec{r}) = \frac{d^2}{m} \frac{1-\cos\theta_{\vec{r}}}{r^3}$$

Zero energy bound state wave function of pure Van de Waals interaction :

$$\psi_m(\vec{r}) = Y_{2m}(\theta,\phi) R_{\ell=2}(r)$$

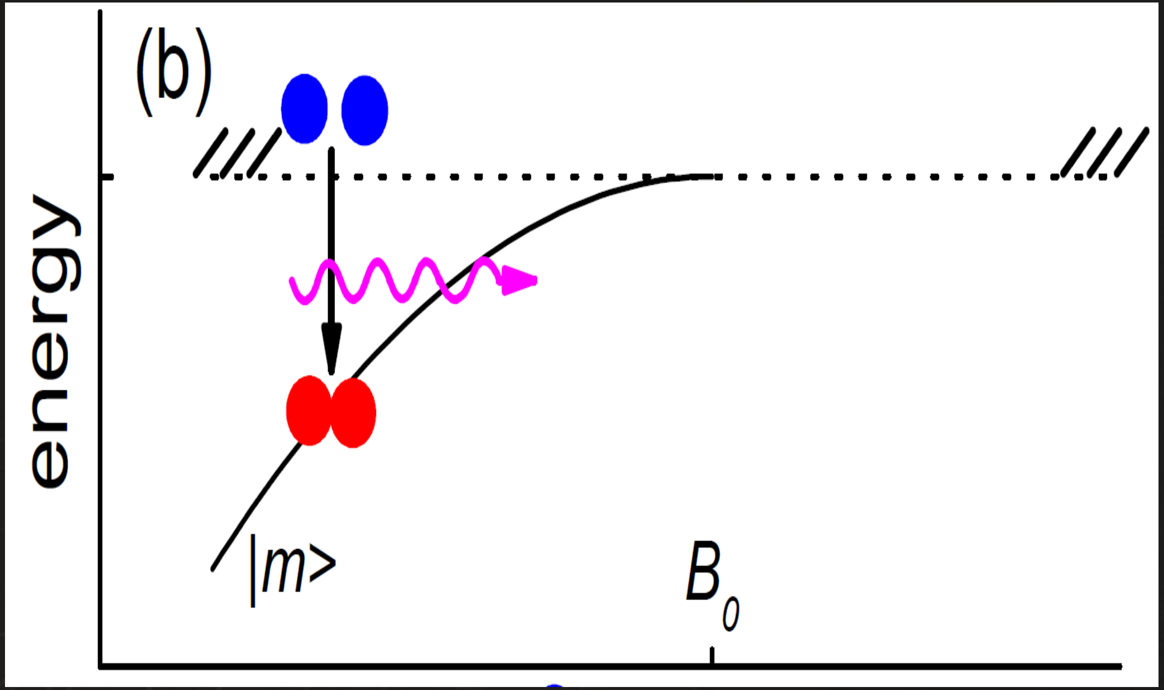


How to understand?

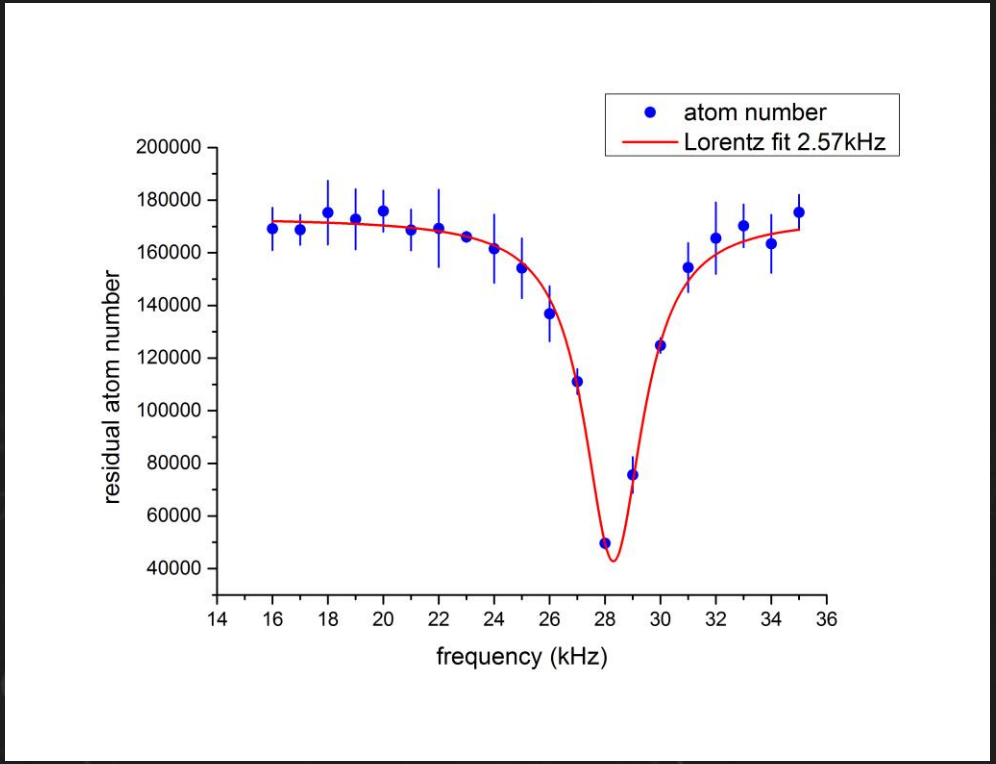


Binding energy measurement

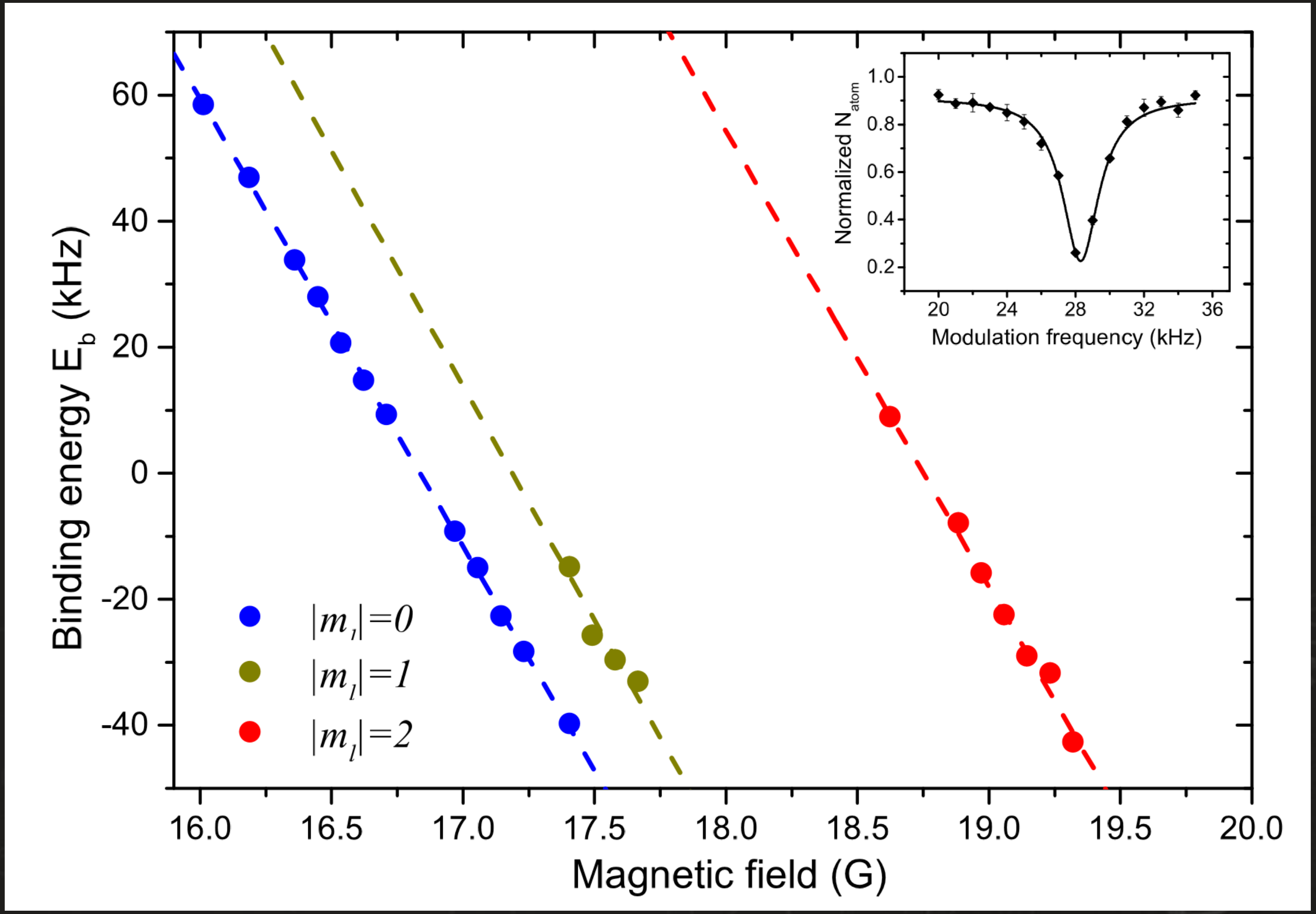
Prepare BEC at 300 G → **Quench B field to $B < B_0$** → **Holding at target B field** → **Modulation for 200 ms** → **Imaging at 300 G**



oscillatory magnetic field drives the transition from the scattering state to the molecular state



Binding energy measurement

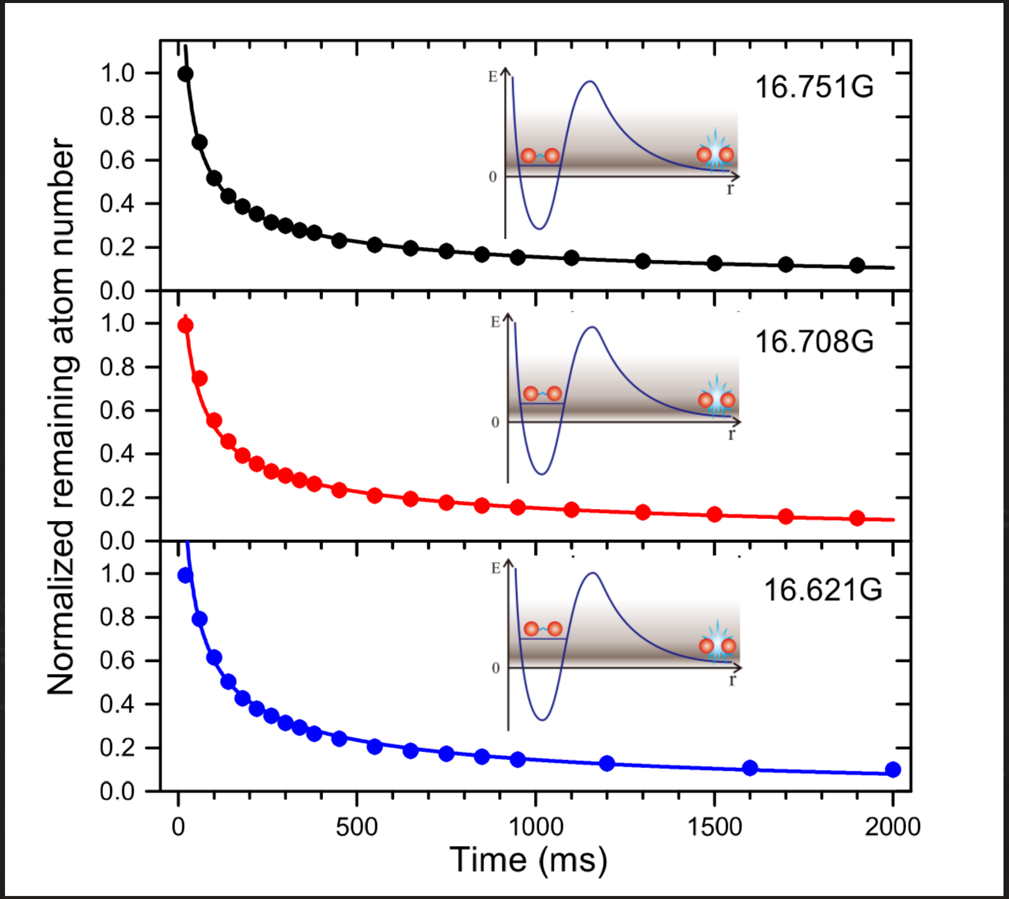


Resonance	Position (G)	Slope (kHz/G)
$\|m_l\|=0$	16.833(3)	70.36(58)
$\|m_l\|=0$	17.19(6)	74(12)
$\|m_l\|=0$	18.75(1)	72(2)

Splitting	1.56 (6) G 0.357 (60) G
Branching Ratio	4.37 (75) : 1

Lifetime measurement

Prepare gas slightly below T_c at 300 G → Quench B field to $B < B_0$ → Ramp B field to B’ → Holding trap → Imaging at 300 G



- ➢ Gas temperature~about 300 nK or 6.2 kHz
- ➢ Binding energy~k_bT_c, 1.5 k_bT_c, 2.5 k_bT_c
- ➢ Simple double exponential fits~100 ms 1/e decay constant

Loss mechanism

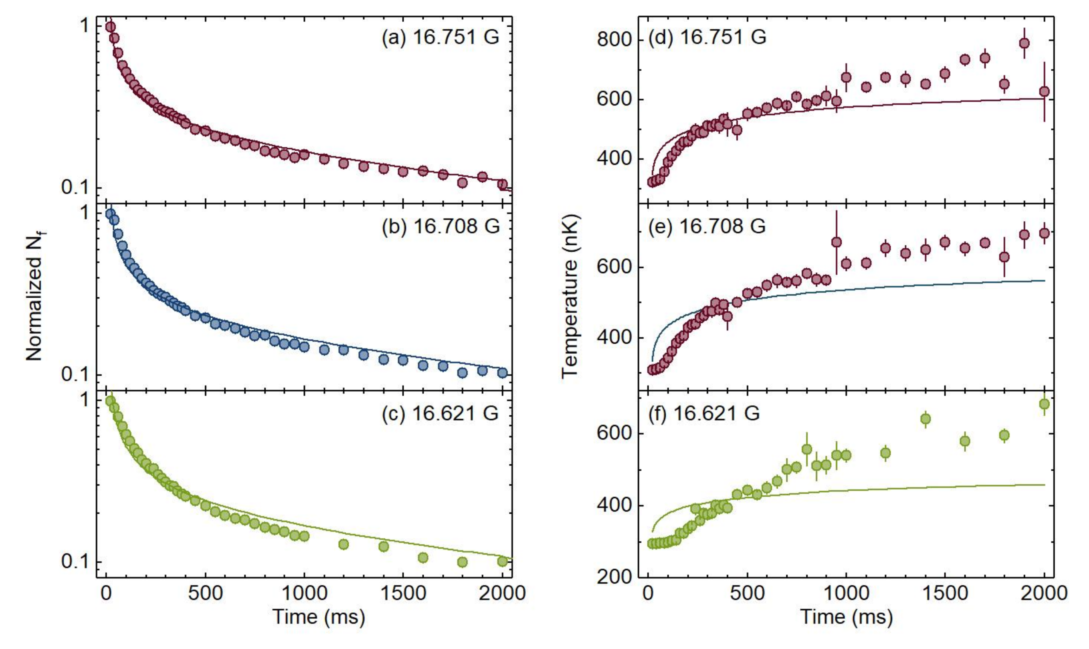
In the vicinity of a scattering resonance, the temperature of the cloud increases due to the three-body loss, for s-wave resonance, we have:

$$\frac{dT}{dt} = K_3 \left(\frac{m\bar{\omega}^2}{2\sqrt{3}\pi k_B} \right)^3 \frac{N^2}{T^3} \frac{T + T_h}{3}$$

Phys. Rev. Lett. 91, 123201 (2003)

$$\frac{dN}{dt} = -\frac{N}{\tau_1} - K_3 \left(\frac{m\bar{\omega}^2}{2\sqrt{3}\pi k_B} \right)^3 \frac{N^3}{T^3}.$$

$$K_3 = \frac{1}{\tau_3} \left(\frac{m\bar{\omega}^2}{2\sqrt{3}\pi k_B T_0} \right)^{-3}.$$

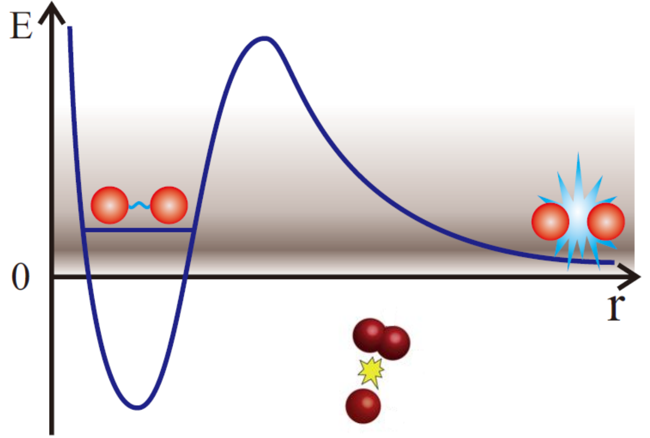


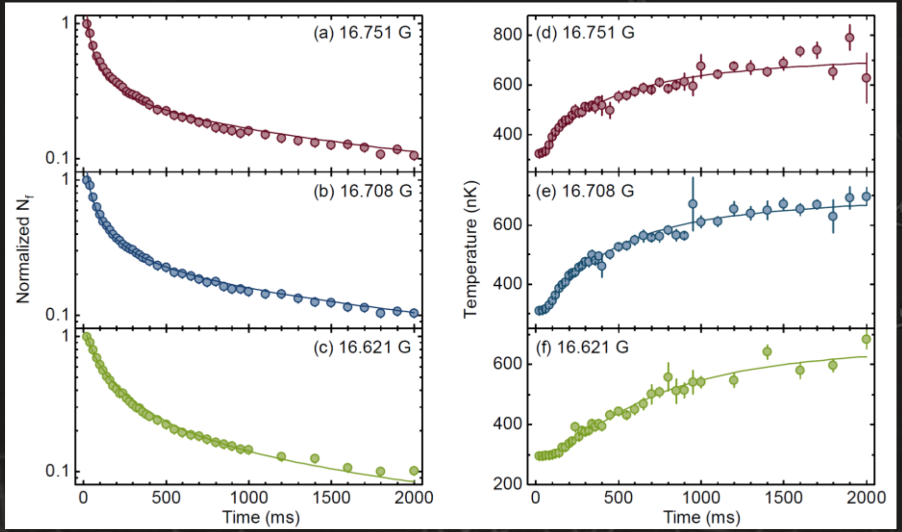
Bad fitting quality, why?

Loss mechanism

- We use a simple analytic form to directly fit the experimental data of temperature $T(t) = \mathrm{T}_0\left[1 + \frac{\alpha}{1+\left(\frac{\tau_h}{t}\right)^{\beta}}\right]$

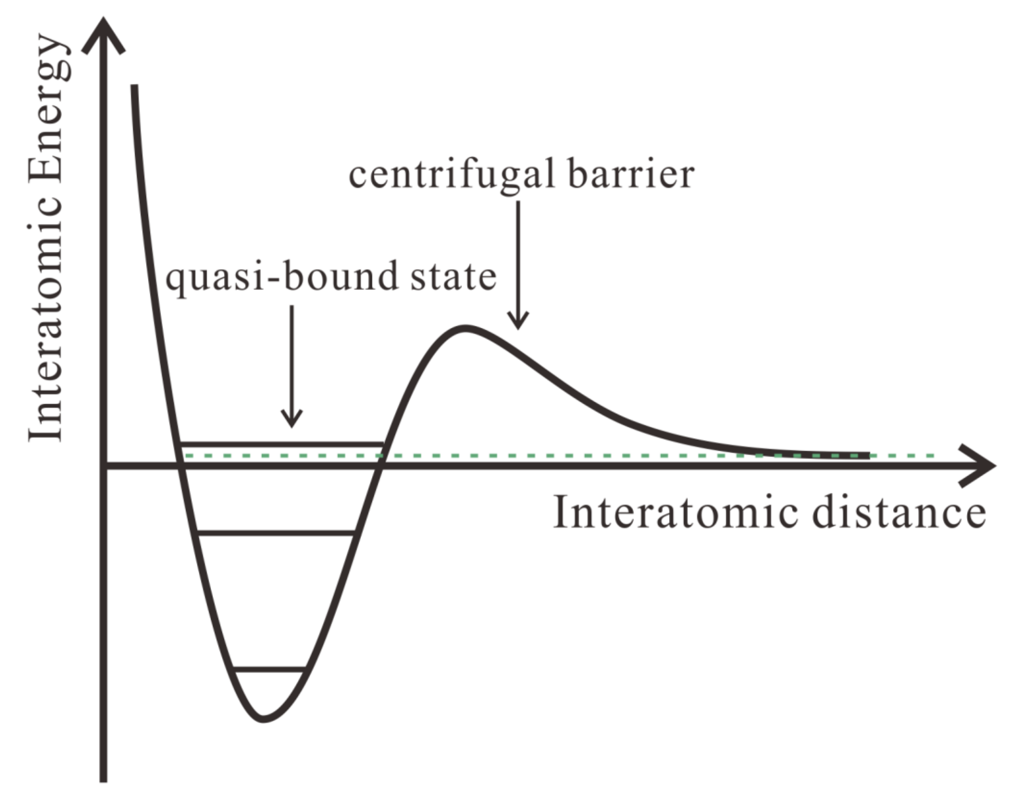
- We assume that $K_3(T) \propto \exp\left(-\frac{\gamma E_b}{k_B T}\right)$,where $\exp\left(-\frac{\gamma E_b}{k_B T}\right)$ is proportional to the two-body scattering amplitude of high partial wave resonance.





Clearly shows the temperature dependence of K_3

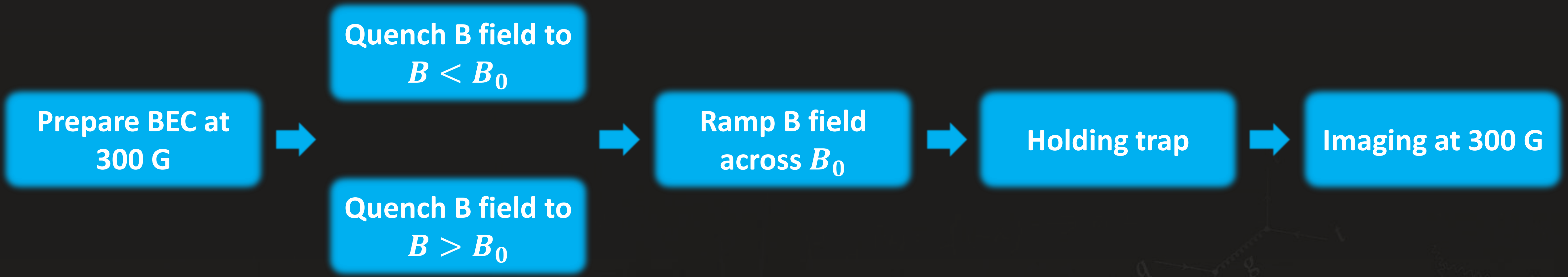
Searching for d-wave molecular



Two mechanism of molecular formation:

- ➢ Thermal atoms, d-wave to d-wave, tunneling
- ➢ Pure BEC, d-wave coupled with s-wave

Striking collective oscillation



Prepare BEC at 300 G

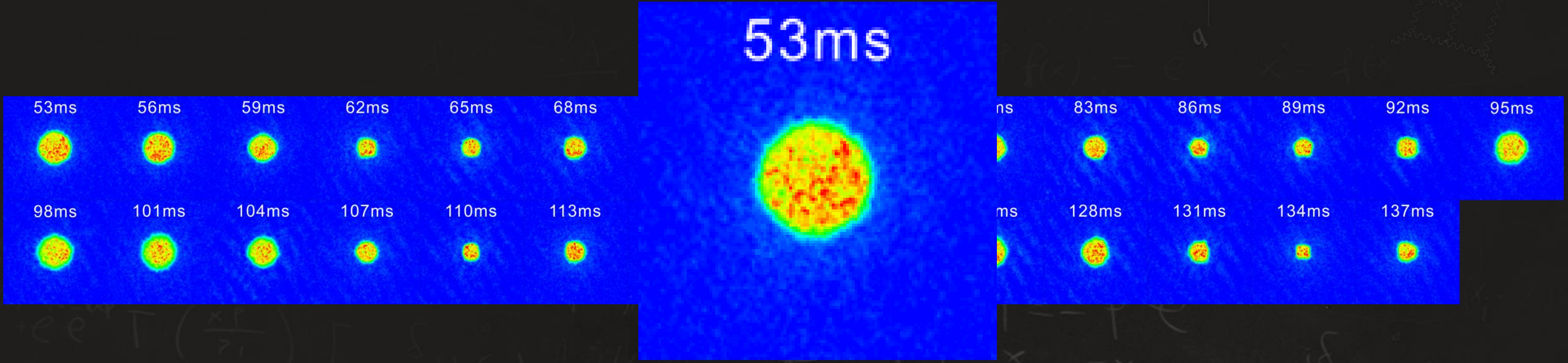
Quench B field to $B < B_0$

Quench B field to $B > B_0$

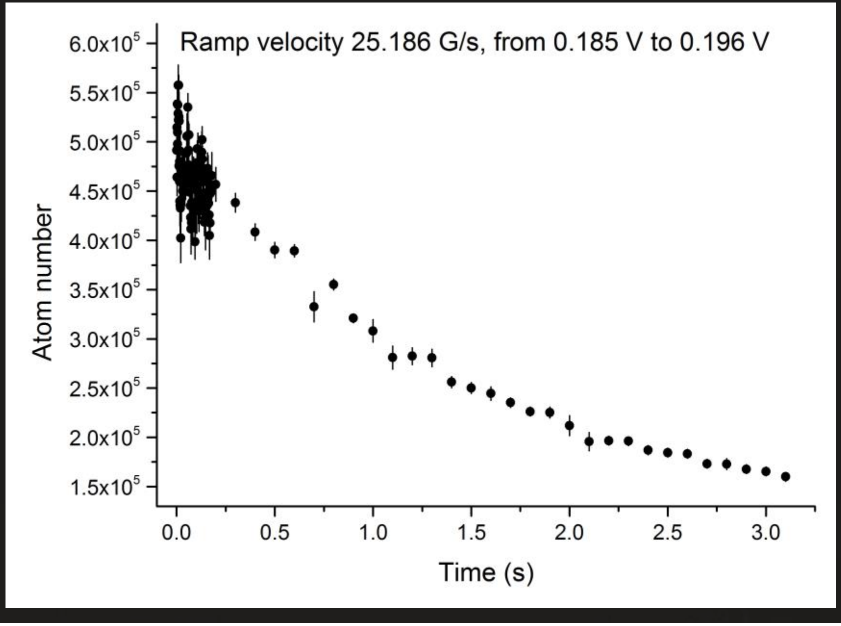
Ramp B field across B_0

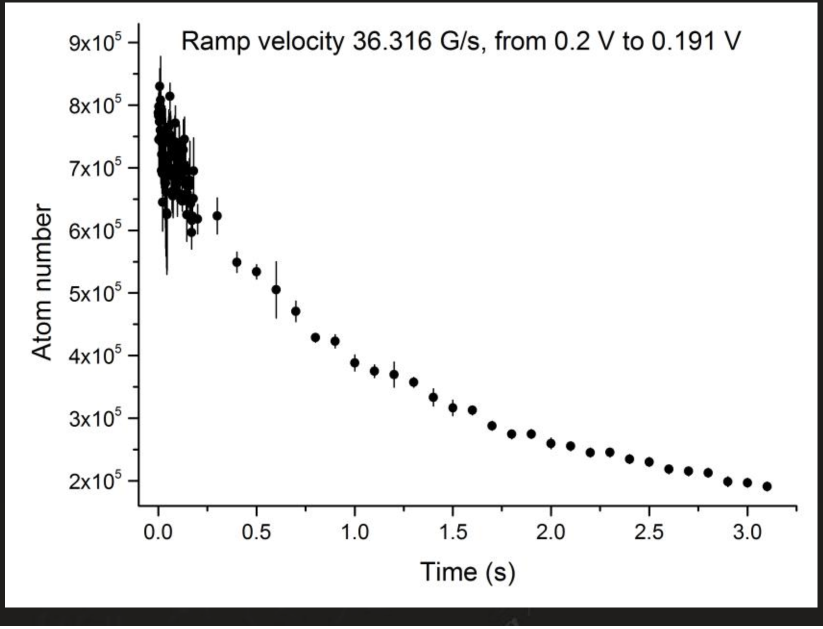
Holding trap

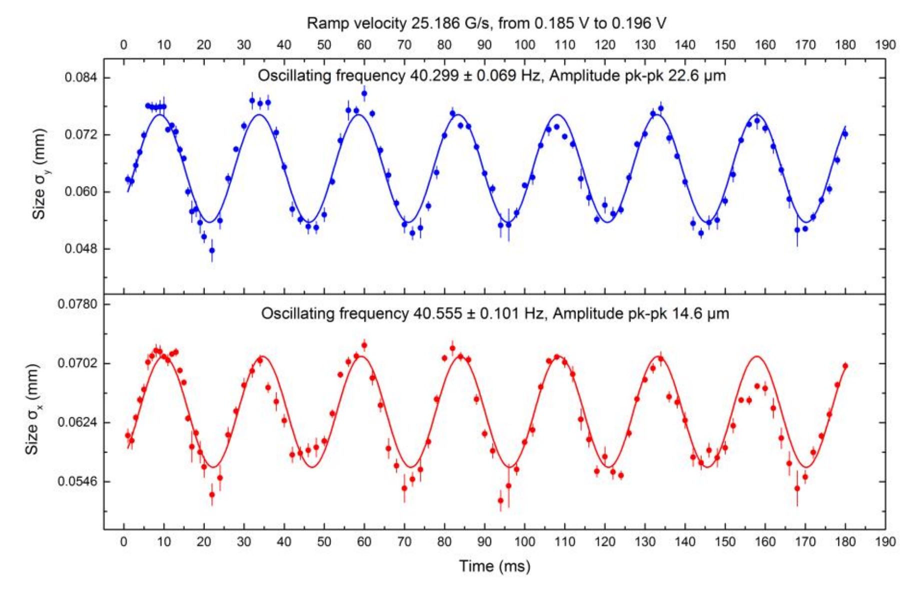
Imaging at 300 G

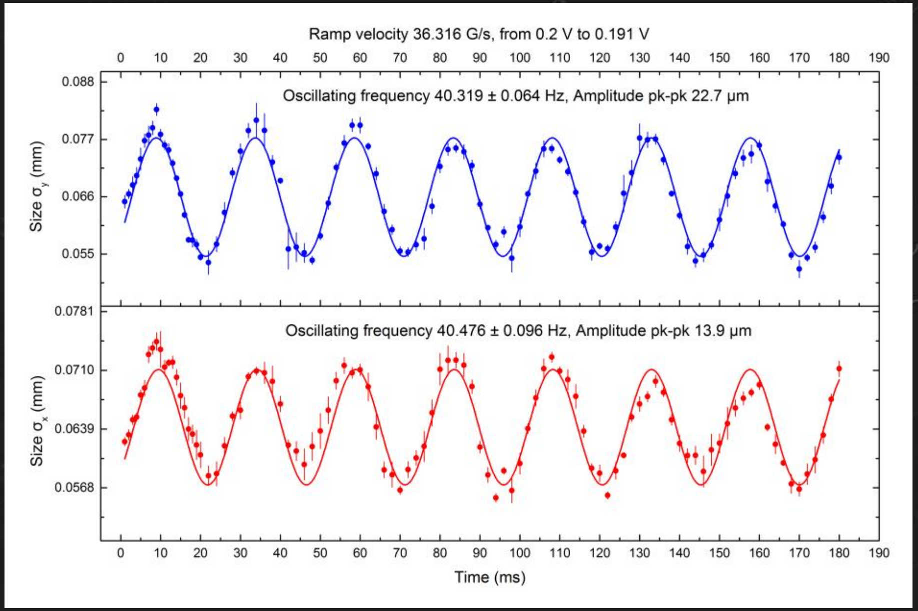


Striking collective oscillation

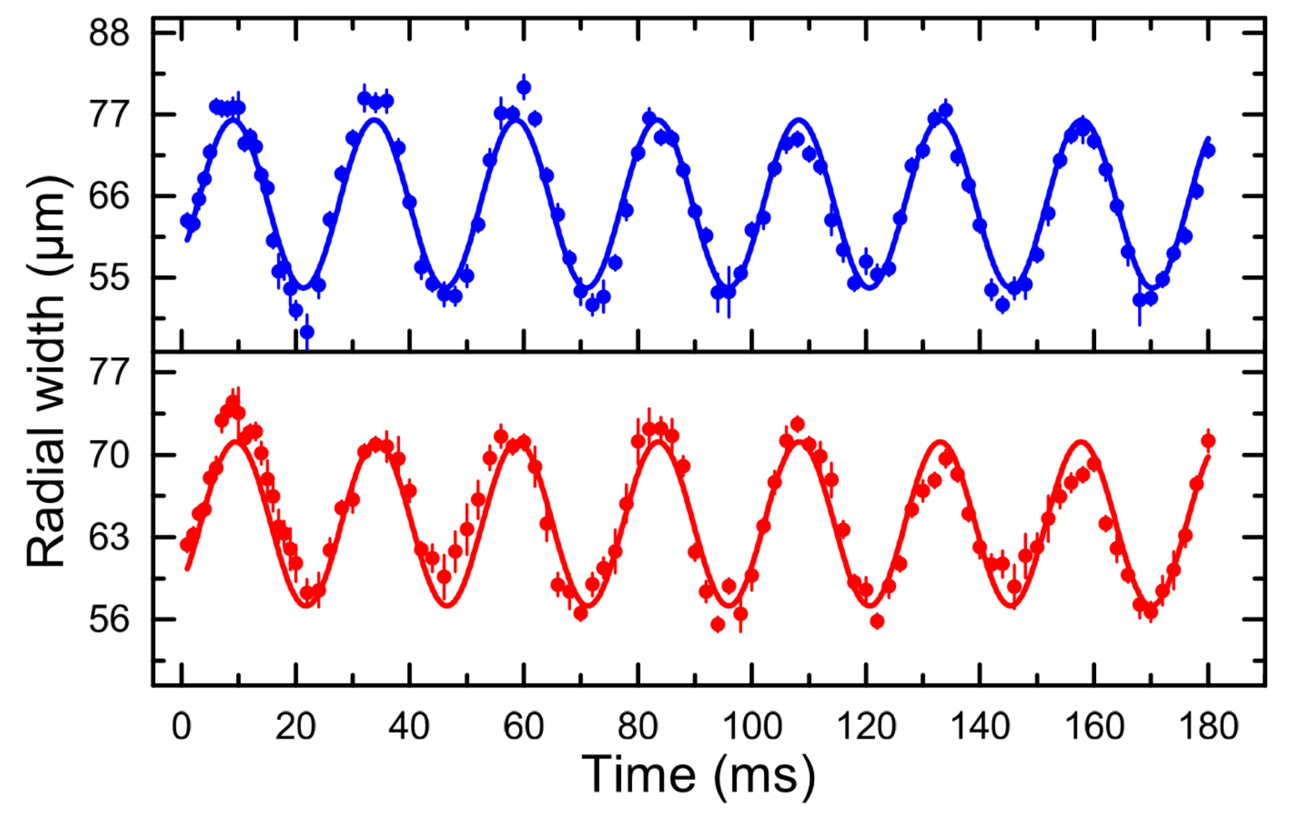






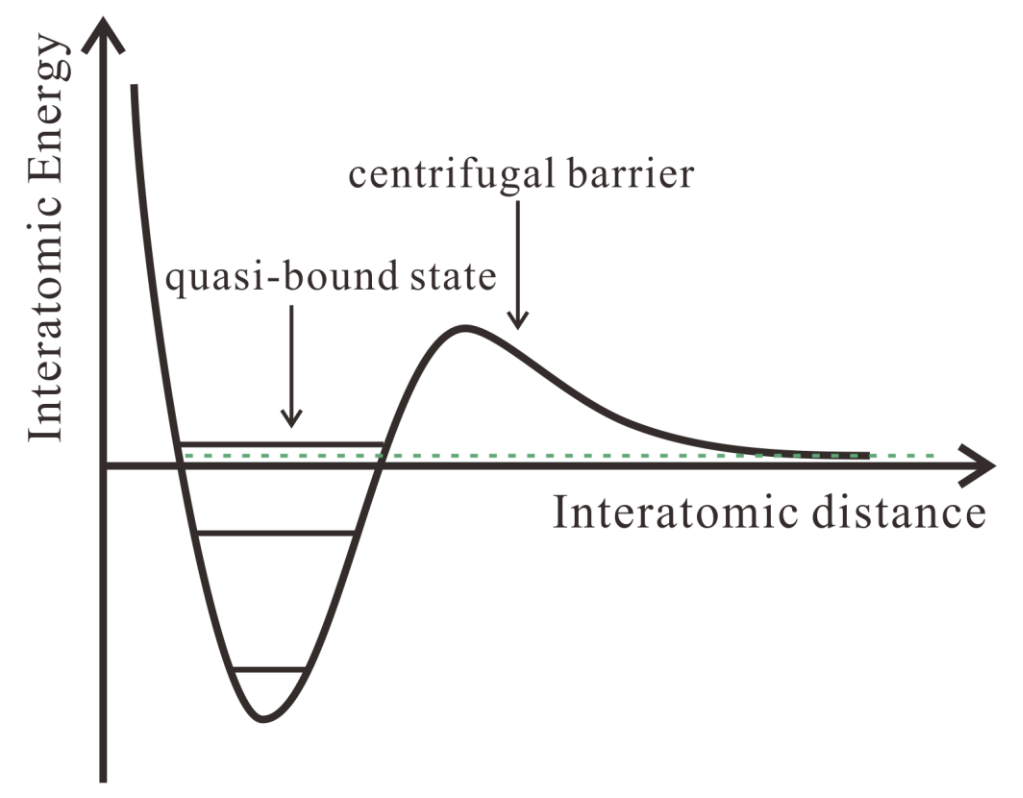


Striking collective oscillation



Ramp direction	upward	downward
Ramp velocity (G/s)	36.3	35.2
Oscillation frequency (Hz)	40.56	40.48
Oscillation frequency/Trap frequency	~1.95	

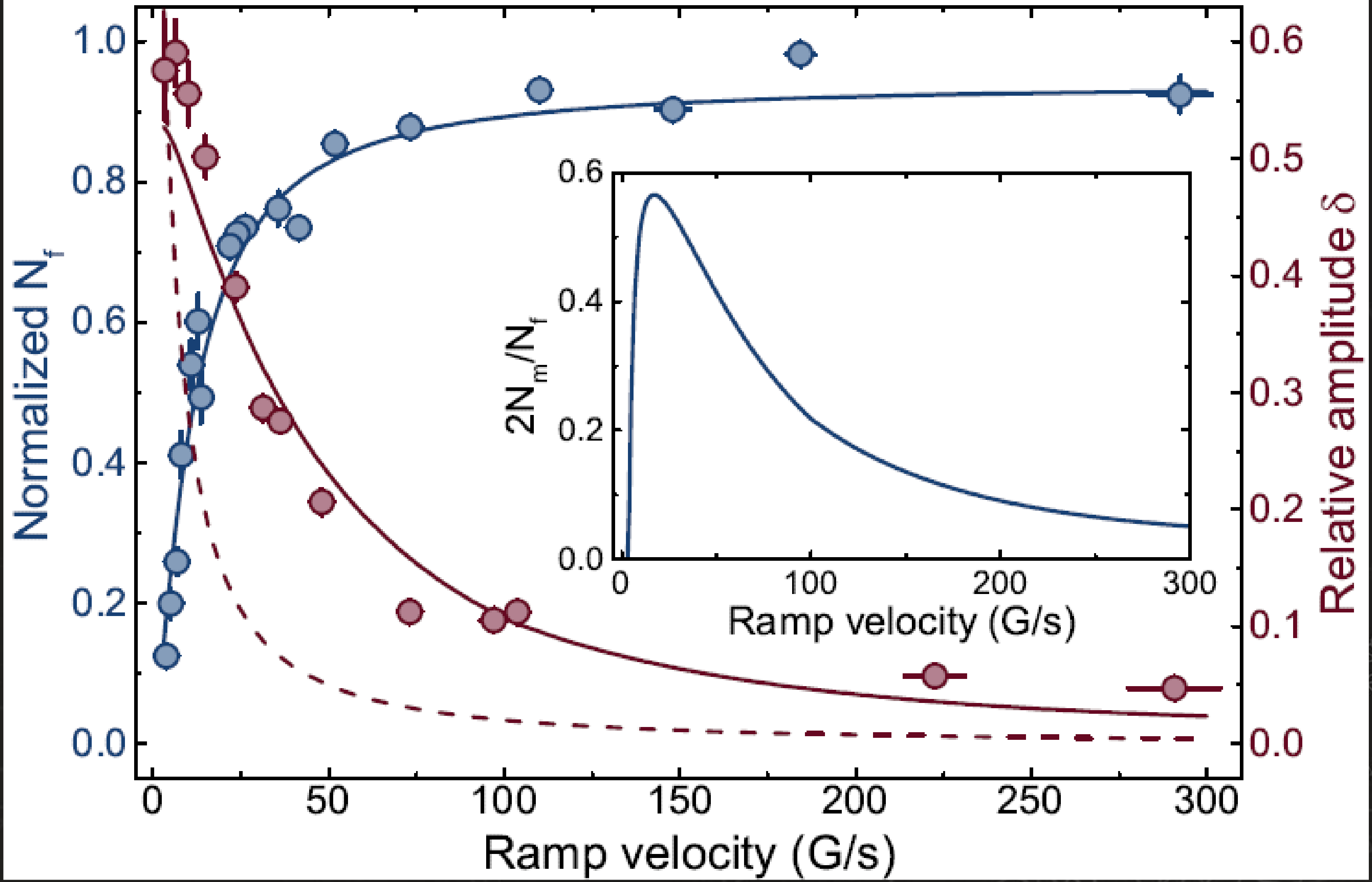
How to detecting d-wave molecular?



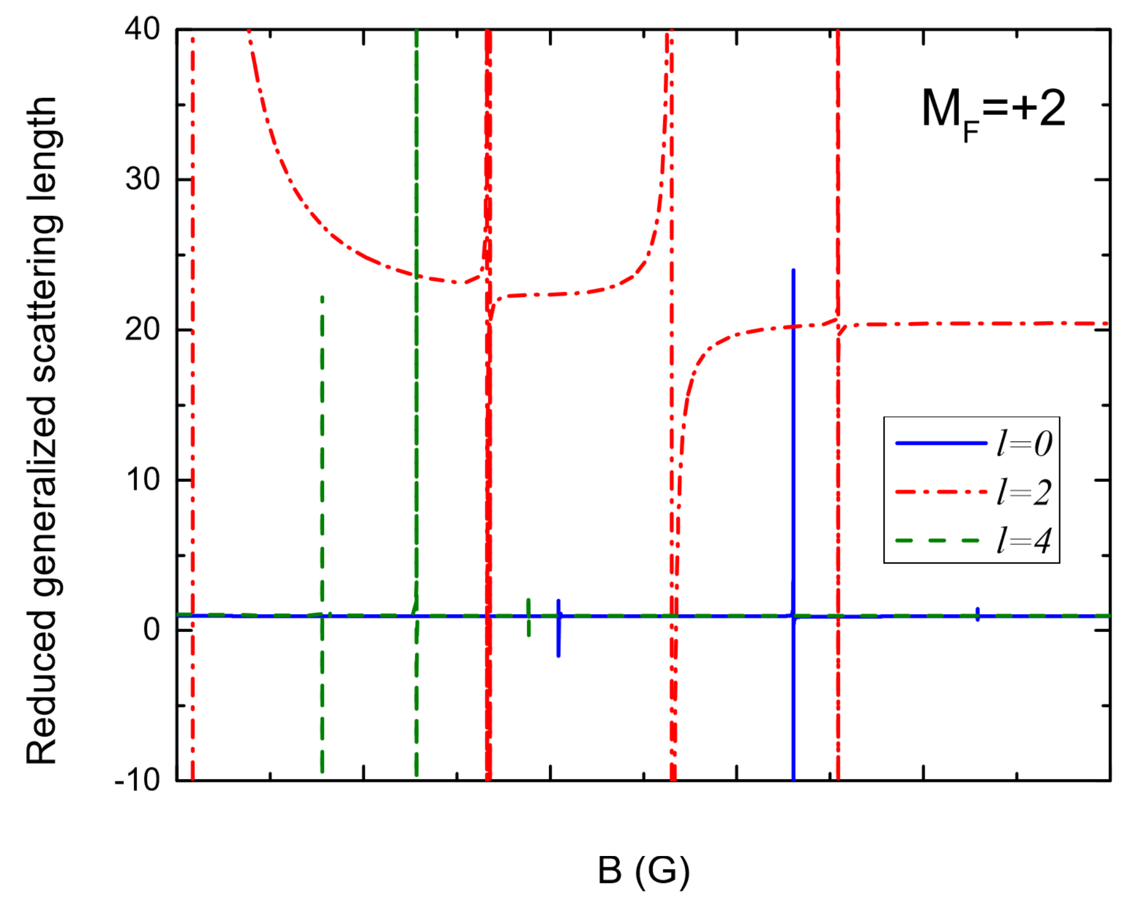
Difficulty:

- Very long lifetime quai-bound state, disassociation is impossible
- rf spectroscopy is impossible
- Gravity lag versus trap depth?

Ramp velocity versus amplitude and BEC number



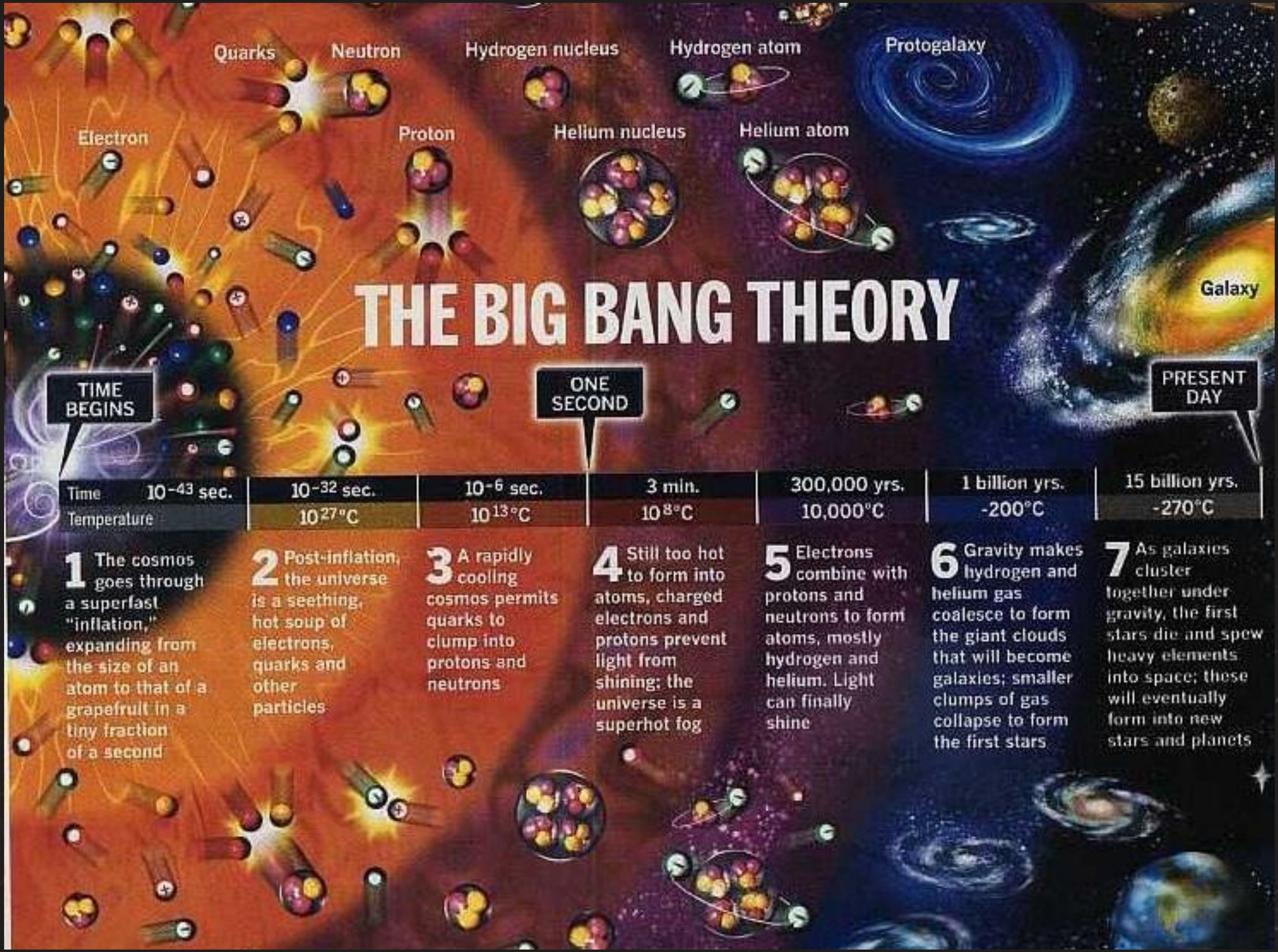
d-wave Resonance



MQDT calculation based on experiment data by Bo Gao

- Rich d-wave resonances
  - Extremely wide shape resonance
  - Wide Feshbach resonance
  - Narrow Feshbach resonance
- Ideal high partial wave system for study three-body physics
- d-wave molecular BEC?

Outlook——Three-body physics of high partial wave collision



Time	10^{-43} sec.	10^{-32} sec.	10^{-6} sec.	3 min.	300,000 yrs.	1 billion yrs.	15 billion yrs.
Temperature		10^{27}°C	10^{13}°C	10^{8}°C	10,000°C	-200°C	-270°C

1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second

2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles

3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons

4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog

5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine

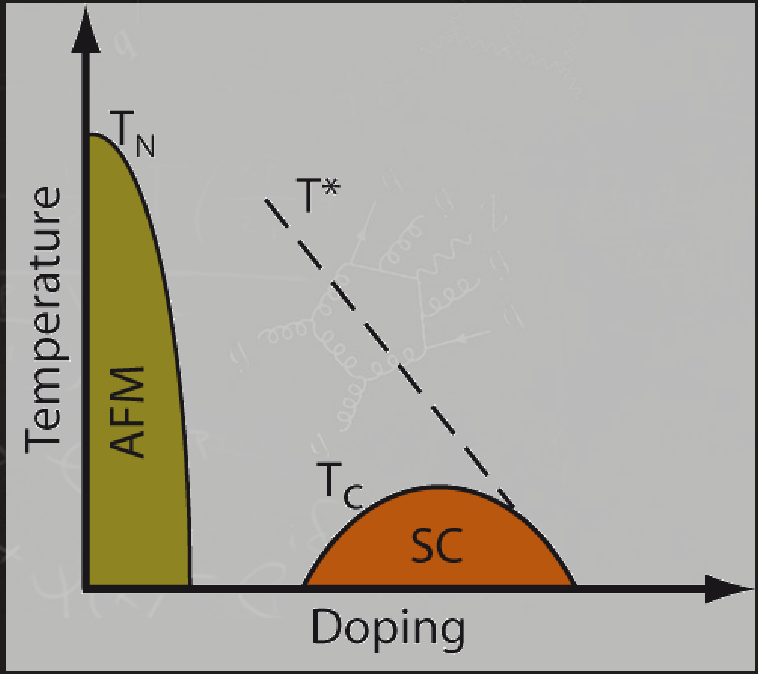
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars

7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

Outlook——Li-K mixture in optical lattices

Simulating motion of electrons, understand complex problem in condense matter physics

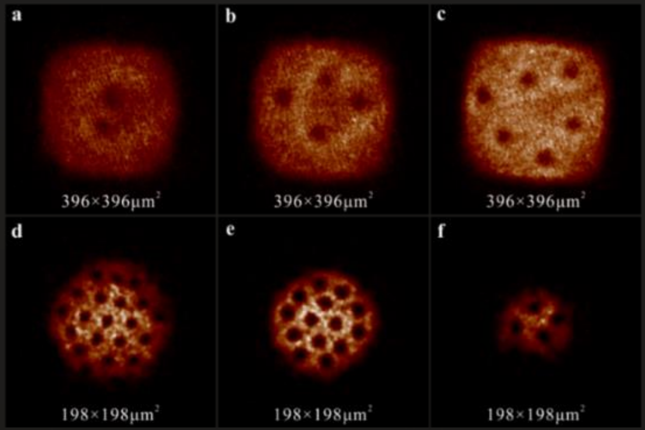
- Dopped Fermi Hubbard model
- Non-equlibrium dynamics
- FFLO
- Breached pair superfluidity
- Crystalline
- …

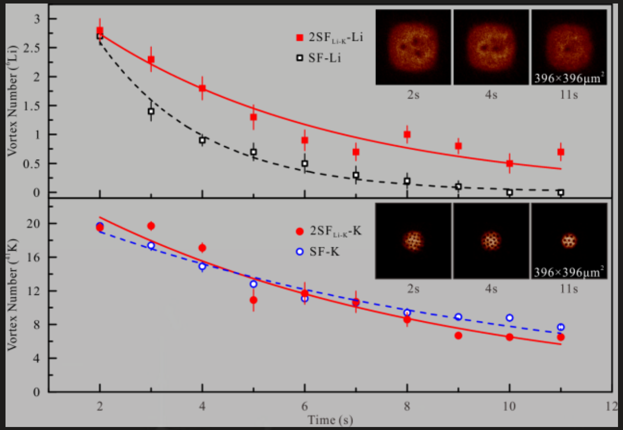


Bose and Fermi superfluid mixture

- ✓ ^{6}Li/ ^{41}K vortex lattices

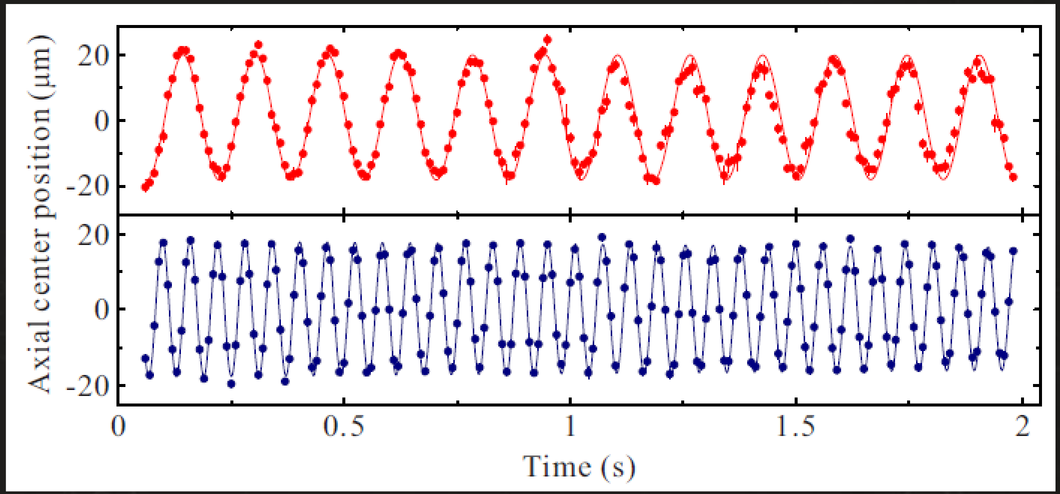
  Yao et al., PRL 117, 145301 (2016)

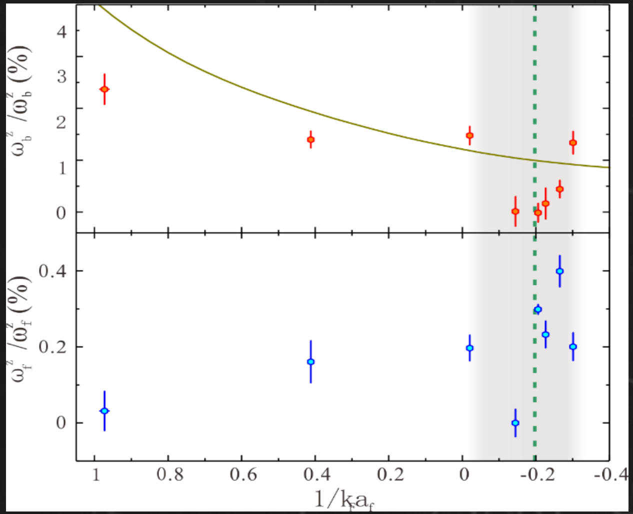


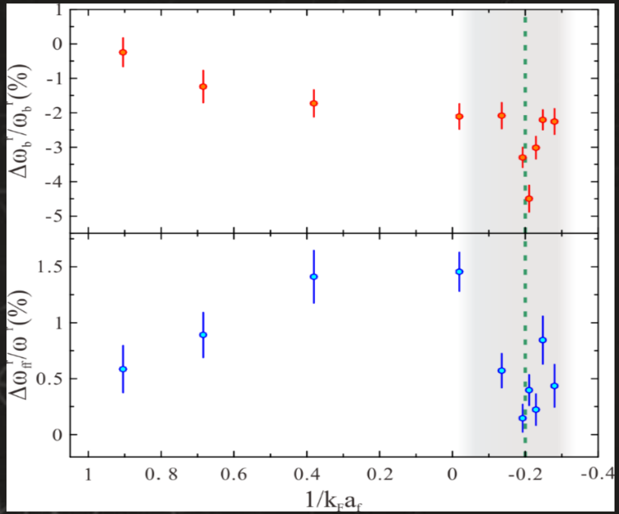


- ✓ ^{6}Li- ^{41}K collective oscillation

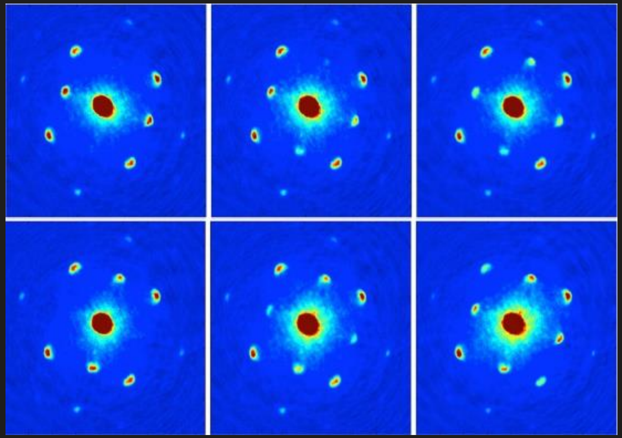
  Wu et al., **arXiv:1705.04496,** PRB 97, 020506(R) (2018)





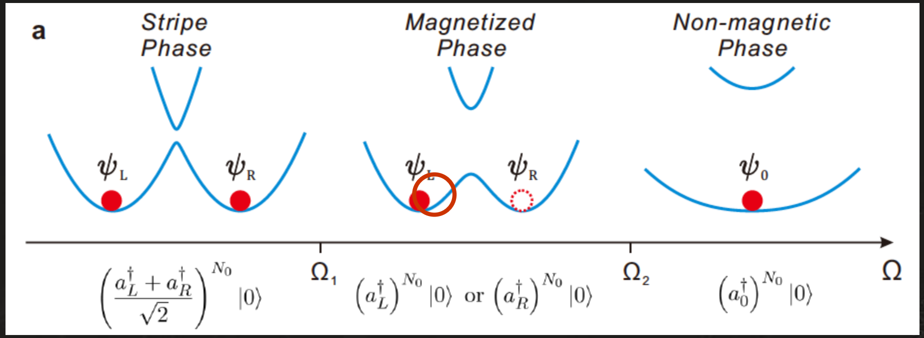


BEC with spin-orbit coupling



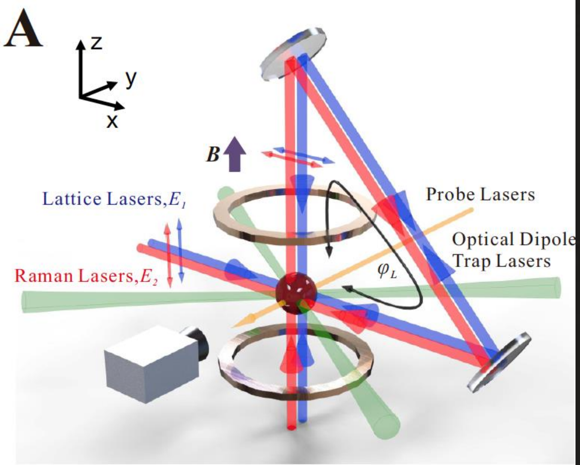
Artificial Gauge potential with neutral atoms (^{87}Rb)

- Characterizing the phase diagram of 1d spin-orbit coupling at zero temperature [PRL 109, 115301 (2012)]



- Determination of 1d SOC phase diagram at the finite temperature phase diagram [Nature Physics 10, 314 (2014)]

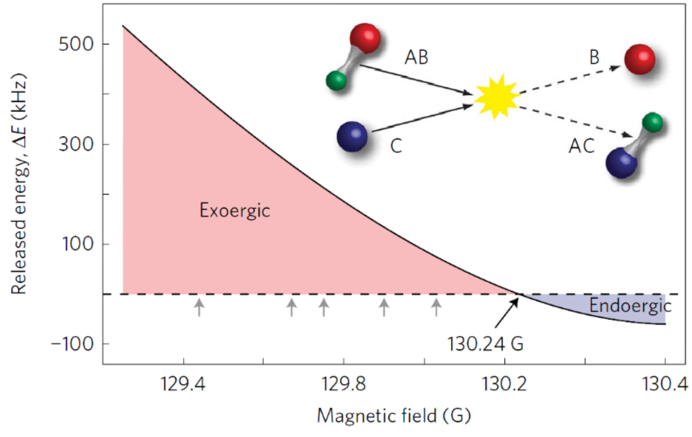
- Realization of 2d SOC for BEC [Science 354, 83 (2016)]
  Topological quantum matter must be driven by 2D or higher SOC

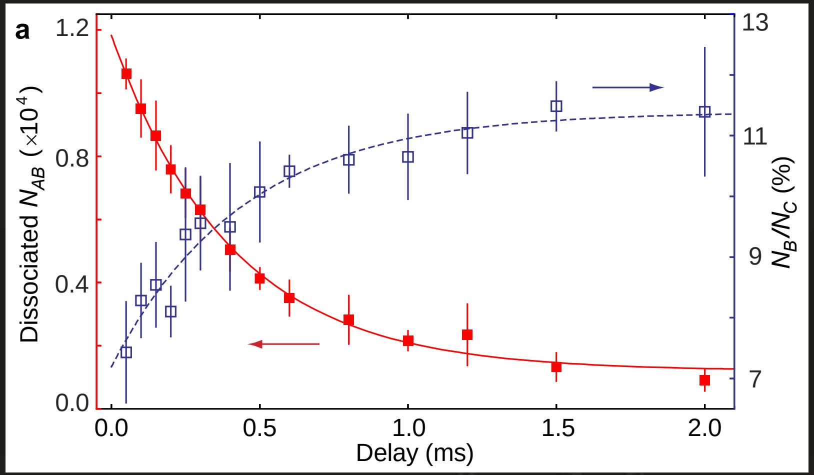


Ultra-cold state-to-state atom-exchange reaction

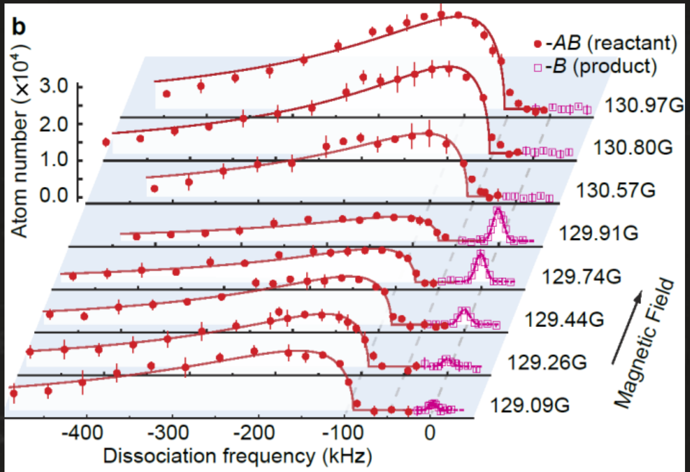
In Na-K system

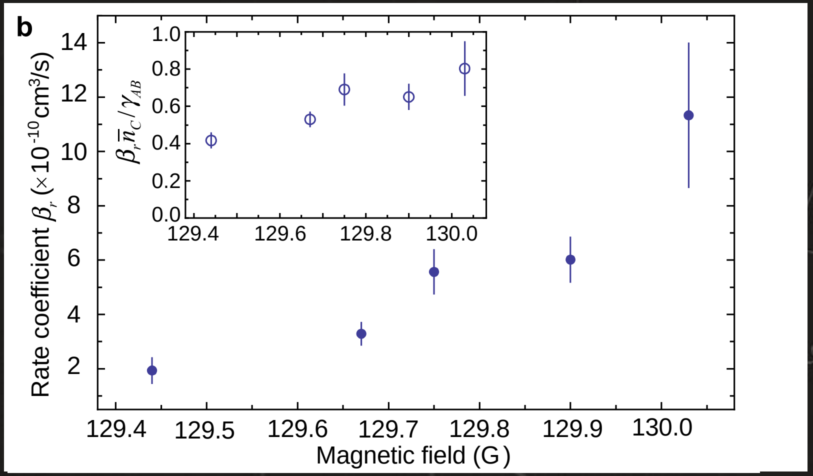
$$AB + C \rightarrow AC + B$$





☑ Study state-to-state reaction dynamics





☑ Observation of the reaction product

Both in exothermic and endothermic regimes

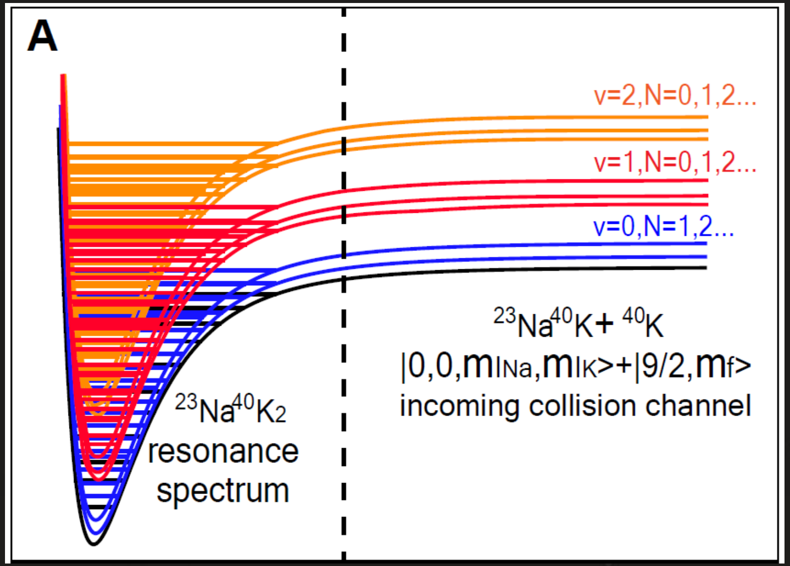
☑ Control the reaction rate by the magnetic field

Rui *et al.*, Nature Physics 13, 699 (2017)

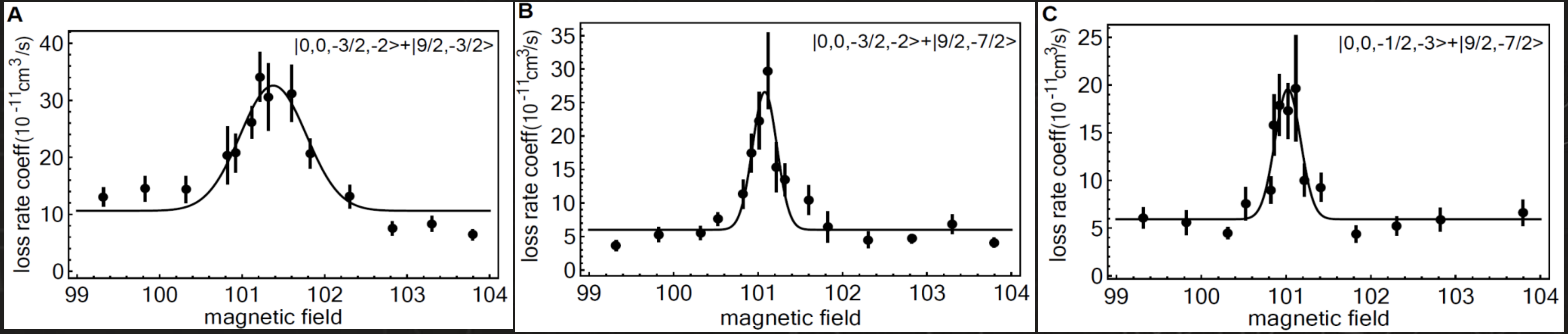
Feshbach resonances in NaK+K collision

Resonances in ultracold collisions involving heavy molecules

- Remarkable quantum phenomenon
- Unique probe of the potential energy surface
- Extremely difficult to calculate
- Challenging to observe



Feshbach resonances probe the short range high density of resonant states

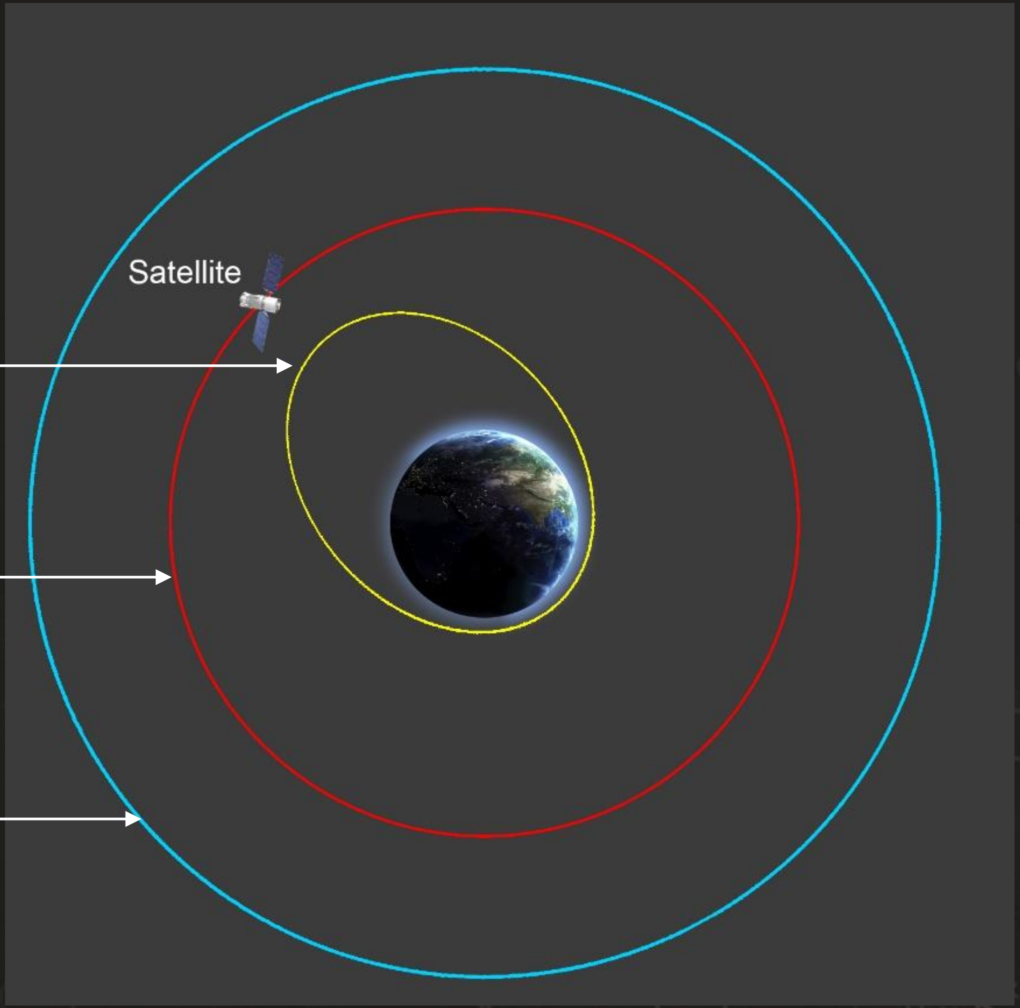


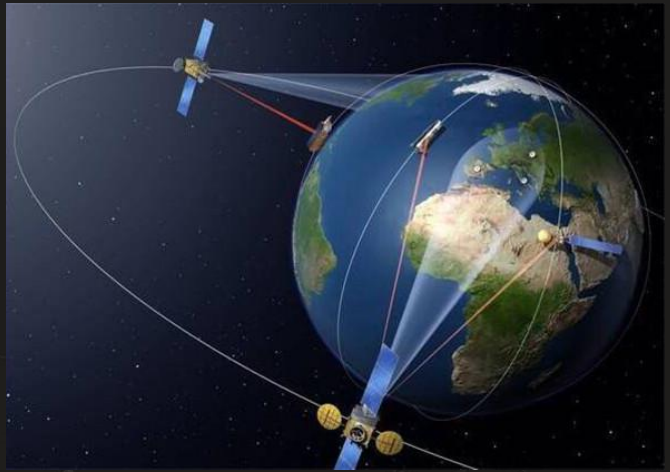
Future Prospect: MEO to GEO Quantum Satellite

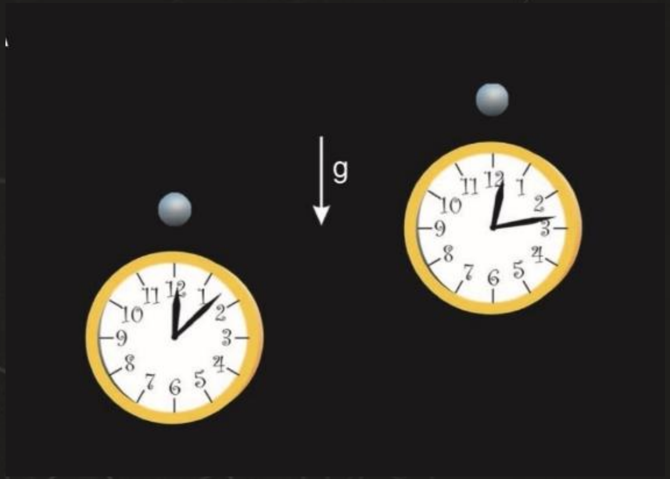
Phase 1: Elliptical orbit
Perigee 1000 km
Apogee 10000 km

Phase 2: Medium Earth orbit
20000 km

Phase 3: Geostationary orbit
35786 km





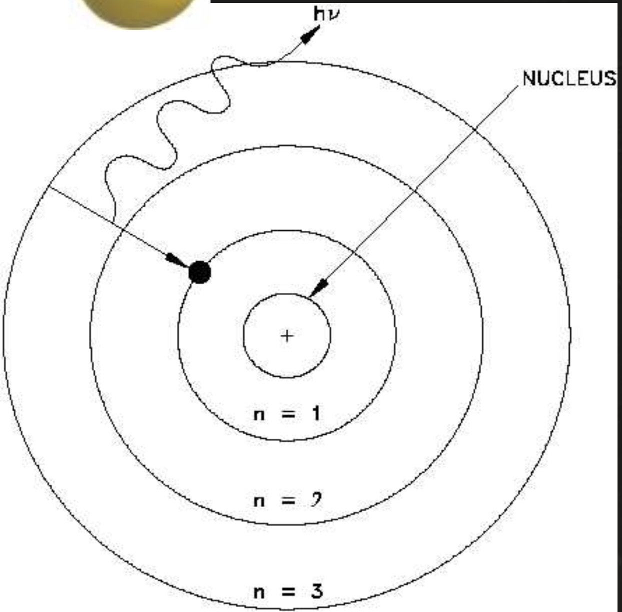


Time Scales

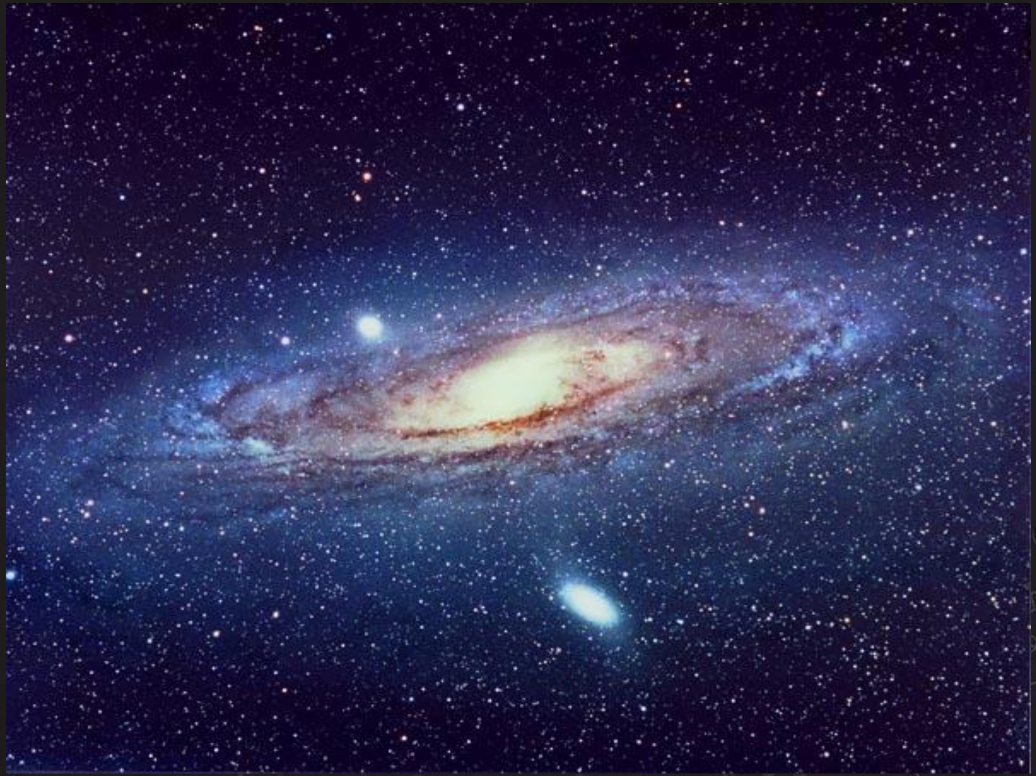
Quantum pendulum period: 10^{-15} s
0.000,000,000,000,001 seconds

Sr atoms:

- **$^1S_0 \leftrightarrow {}^3P_0$ (160 s)**
- **$Q \sim 10^{17}$**



The geometric mean
~30 s



Life of the Universe: 15 billion years (10^{18} s)
1000,000,000,000,000,000 seconds

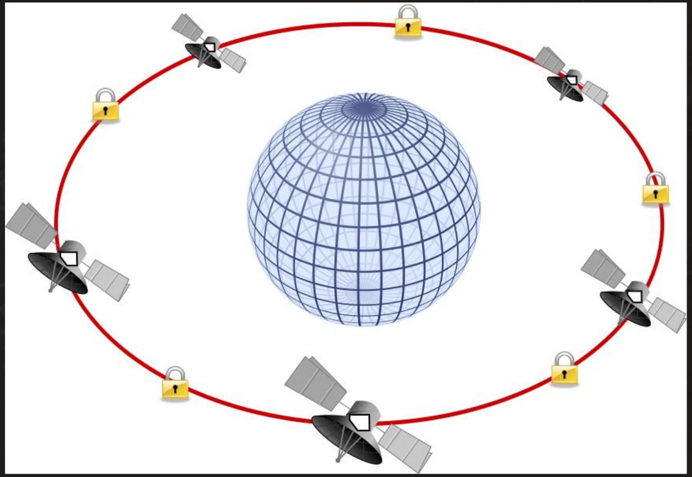
Probes for fundamental Physics

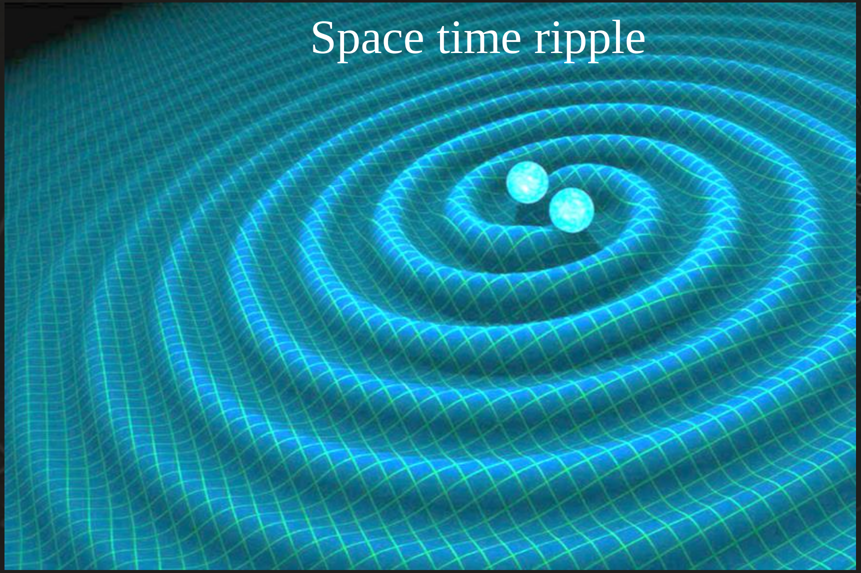
Kómár *et al*., Nat. Phys. **10**, 582 (2014);   Kolkowitz *et al*., Phys. Rev. D **94**, 124043 (2016).


Unruly spiral galaxies

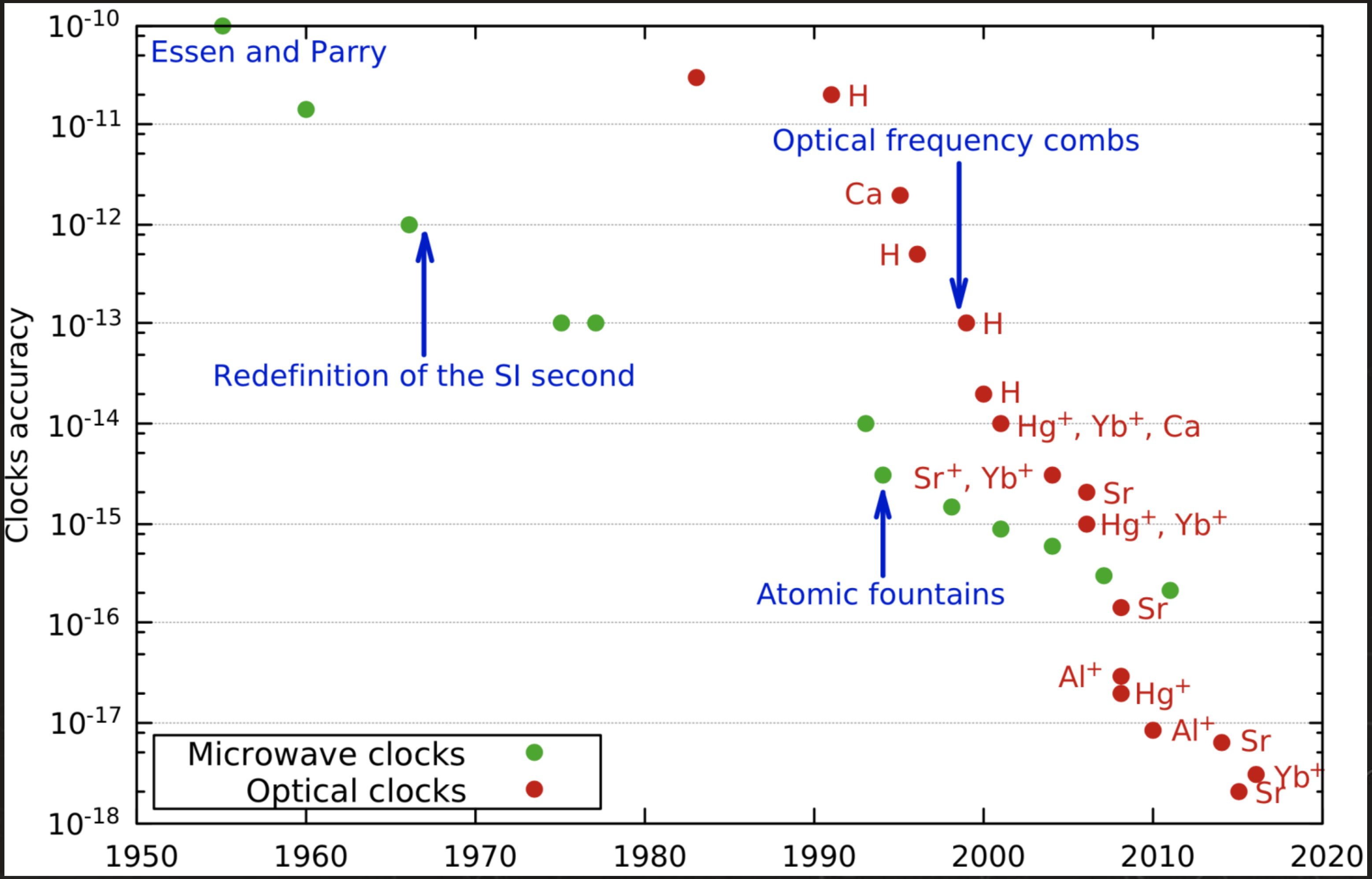

Dark matter halo

Network of clocks (**10^{-21}**):
long baseline interferometry



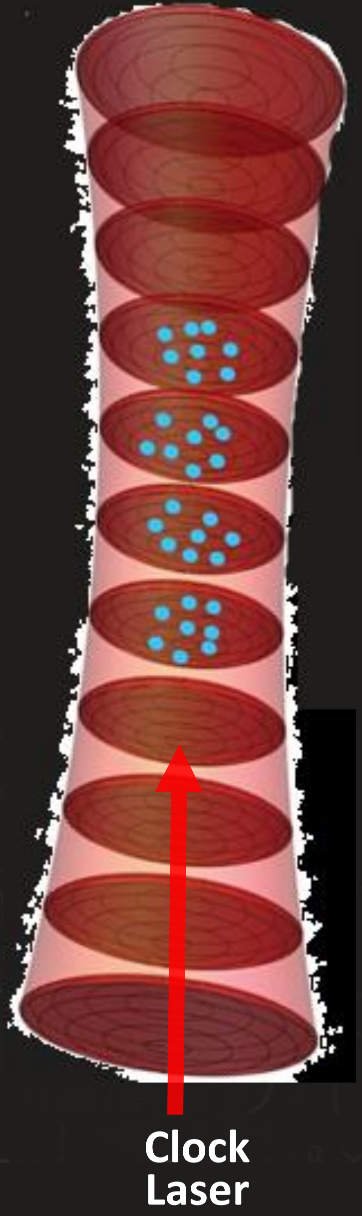

Space time ripple

Continuous progress in atomic clocks



- Microwave clocks: $\omega_0\ /2\pi \cong 10^{10}$ Hz, $Q \cong 10^{10}$
- Optical clocks: $\omega_0\ /2\pi \cong 1015$ Hz, $Q \cong 10^{15}$

Optical Lattice Clock



- ☐ Probe on a narrow optical resonance with an ultra-stable “clock” laser (high Q)
- ☐ Trap atoms in an optical lattice potential
  - ➢ Lamb-Dicke regime: insensitive to motional effects
  - ➢ Trap light at magic wavelength: minimal light-shift effects
  - ➢ Large number of interrogated atoms
- ☐ Record stability: a few $10^{-16}/\sqrt{\tau}$
- ☐ Record accuracy: a few 10^{-18}

JILA, NIST, SYRTE, PTB, NPL, Florence, Tokyo, RIKEN, NICT, NMIJ, KRISS, NIM, NTSC, ECNU, Wuhan, …

Space missions of optical

First cold atoms in space:

☐ ***Laser-cooled Rb clock experiment on Tiang-Gong 2, 9/2016***

Atomic clocks in space orbital are coming soon!

Announced missions:

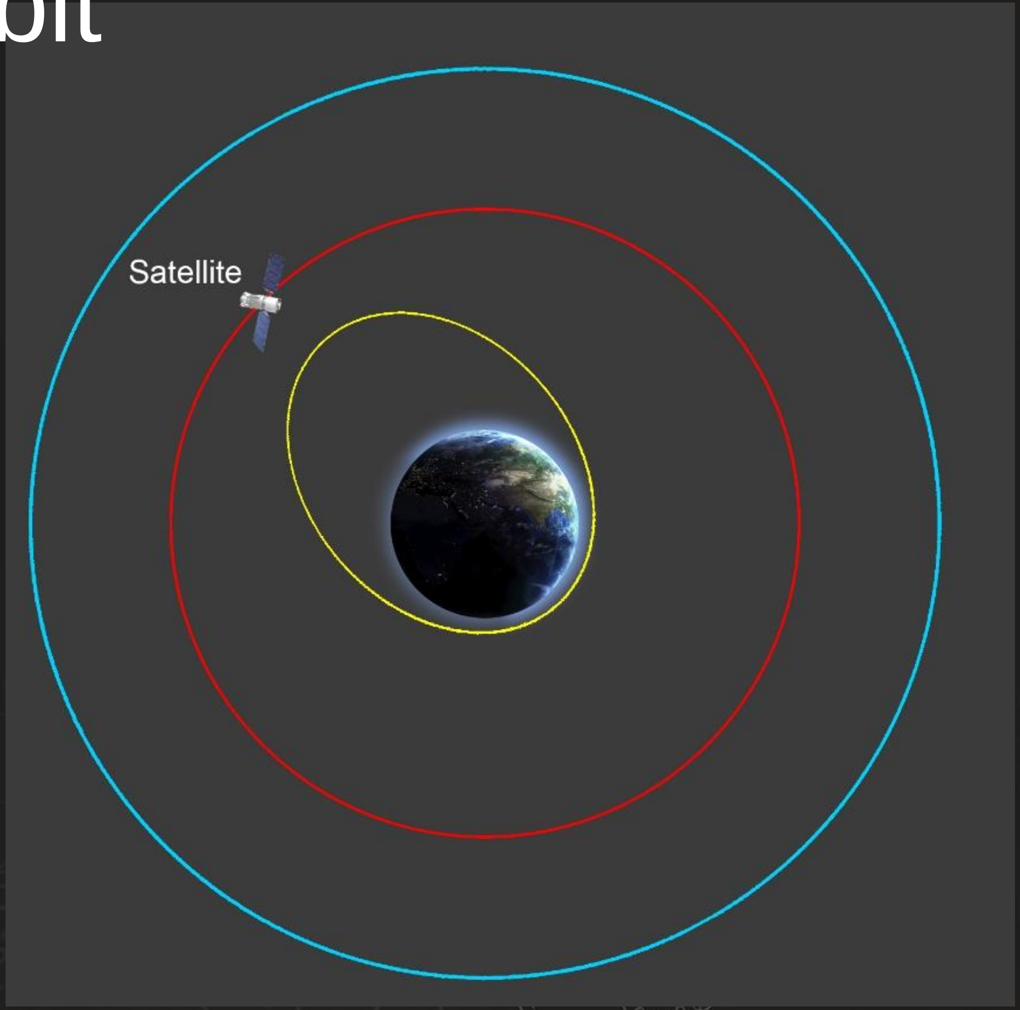
☐ *Mission ISOC (Space Optical Clock) by ESA in 2022+*

☐ *Future Tian-Gong station in 2022+*

H-maser, Cs cold atom clock, Sr optical clock will be launched

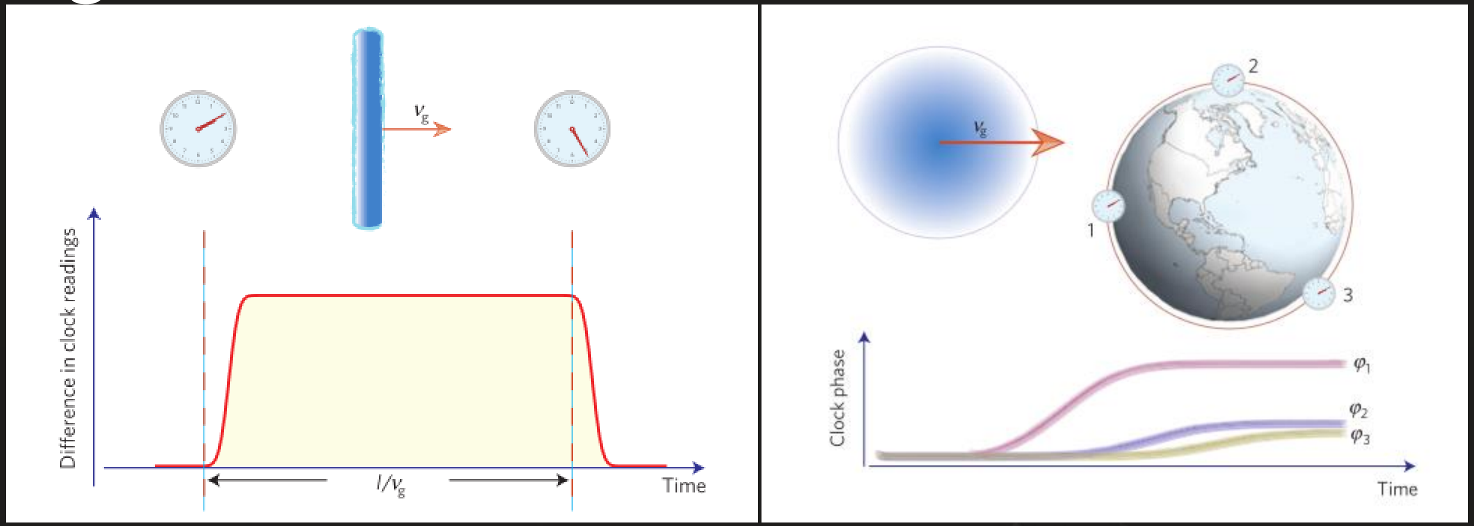
Optical Clock in High Earth Orbit

- ☐ Next generation quantum satellite
  - ➢ MW and optical links to ground
  - ➢ quantum channels
- ☐ High earth orbit
  - ➢ 10000~36000 km
  - ➢ 24-hour classical or quantum communication
- ☐ Future applications
  - ➢ probes for quantum gravity / general relativity
  - ➢ world-wide atomic time-frequency distribution
  - ➢ world-wide clock comparisons



- 1st stage: 1000~10000 km
- 2nd stage: 20000 km
- 3rd stage: 35786 km

Topological Dark Matter



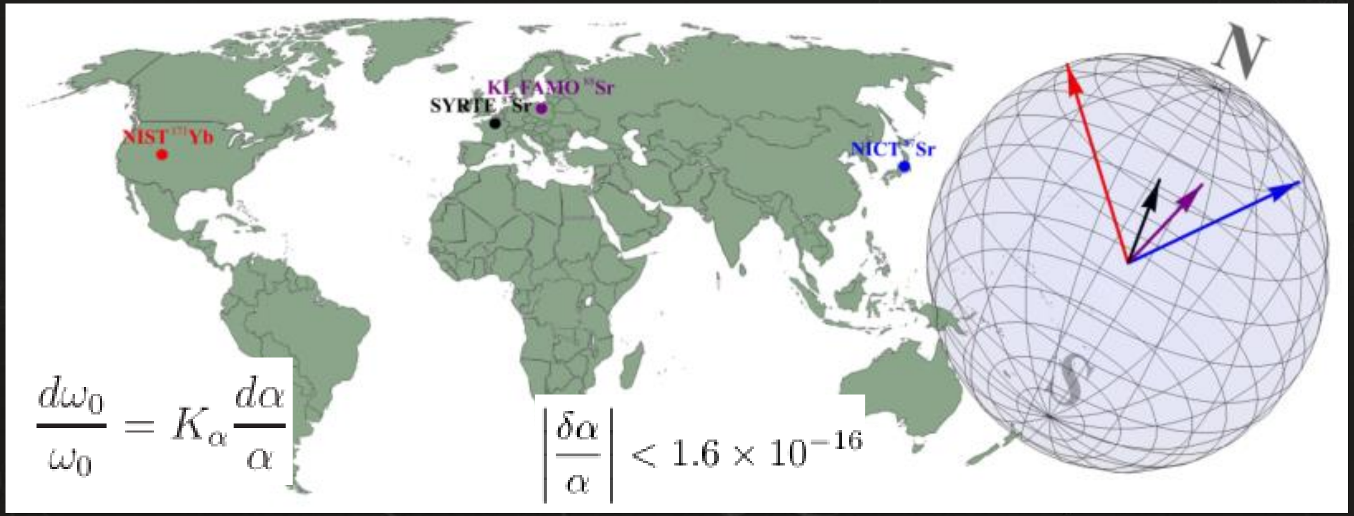
A.Derevianko and M.Pospelov, Nat. Phys. 10, 933–936 (2014)

If dark matter is light non-Standard Model field (including axion) ,its topological defects may cause time discrepancies between distant optical clocks

$$-\mathcal{L}_{\rm int}=\phi^2\left(\frac{m_e\bar{\psi}_e\psi_e}{\Lambda_e^2}+\frac{m_p\bar{\psi}_p\psi_p}{\Lambda_p^2}-\frac{1}{4\Lambda_\gamma^2}F_{\mu\nu}^2+\cdots\right)$$

$$\to m_{e,p}^{\rm eff}=m_{e,p}\left(1+\frac{\phi^2}{\Lambda_{e,p}^2}\right);\quad \alpha^{\rm eff}=\frac{\alpha}{1-\phi^2/\Lambda_\gamma^2}$$

$$\Delta\varphi(t)=g\int_{-\infty}^{t}(f(t'-l/v_g)-f(t'))\mathrm{d}t'\equiv\omega_0\Delta t(t)$$



$$\frac{d\omega_0}{\omega_0}=K_\alpha\frac{d\alpha}{\alpha}$$

$$\left|\frac{\delta\alpha}{\alpha}\right|<1.6\times10^{-16}$$

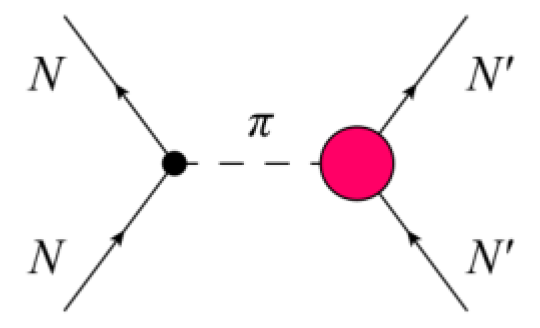
P. Wcisło et al., Nat. Astr. 1, 0009 (2016).

P. Wcisło, et al., arXiv:1806.04762

Axion Dark Matter interacting with Atoms

Oscillating Electric Dipole Moments

P,T-conserving πNN coupling



Axion-induced P,T-violating πNN coupling

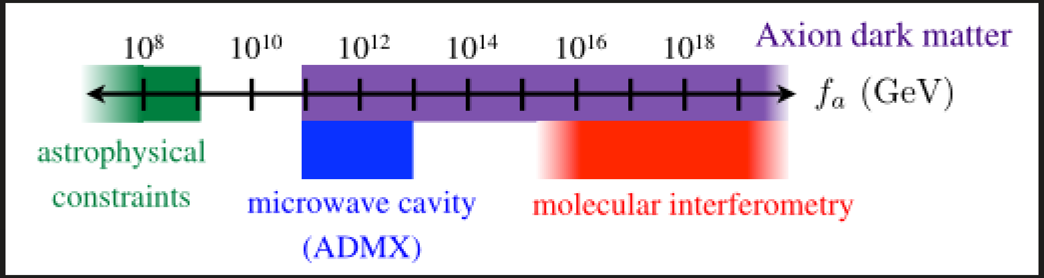
neutron

$$d_n(t) \approx 1.2 \times 10^{-16} \, \frac{a_0}{f_a} \cos(m_a t) \; e \cdot \mathrm{cm}$$

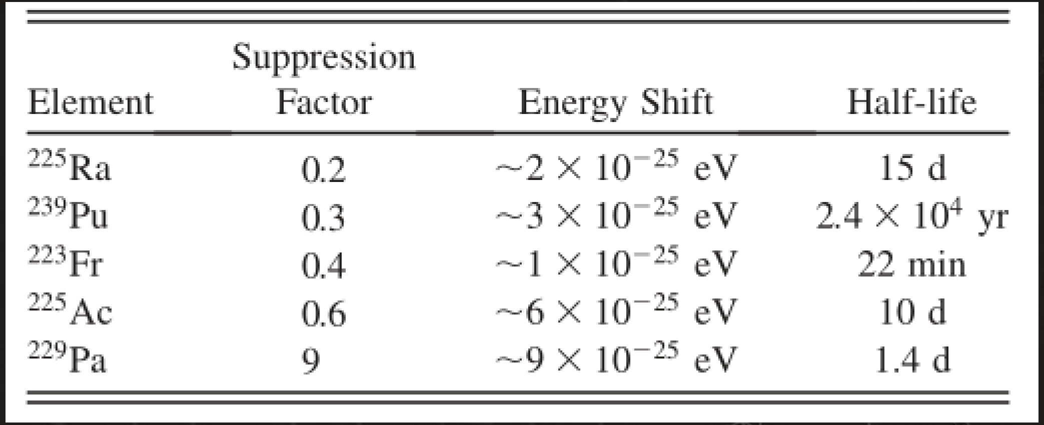
atoms

$$d(^{199}\mathrm{Hg}) \approx -1.8 \times 10^{-19} \, \frac{a_0}{f_a} \cos(m_a t) \; e \cdot \mathrm{cm}$$

$$d(^{225}\mathrm{Ra}) \approx 9.3 \times 10^{-17} \, \frac{a_0}{f_a} \cos(m_a t) \; e \cdot \mathrm{cm}$$



Atoms with large Schiff moments to form spontaneous parity violation states like molecules.



Element	Suppression Factor	Energy Shift	Half-life
^{225}Ra	0.2	$\sim 2 \times 10^{-25}$ eV	15 d
^{239}Pu	0.3	$\sim 3 \times 10^{-25}$ eV	2.4×10^4 yr
^{223}Fr	0.4	$\sim 1 \times 10^{-25}$ eV	22 min
^{225}Ac	0.6	$\sim 6 \times 10^{-25}$ eV	10 d
^{229}Pa	9	$\sim 9 \times 10^{-25}$ eV	1.4 d

$$m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz} \left(\frac{10^{16}\ \mathrm{GeV}}{f_a} \right)$$

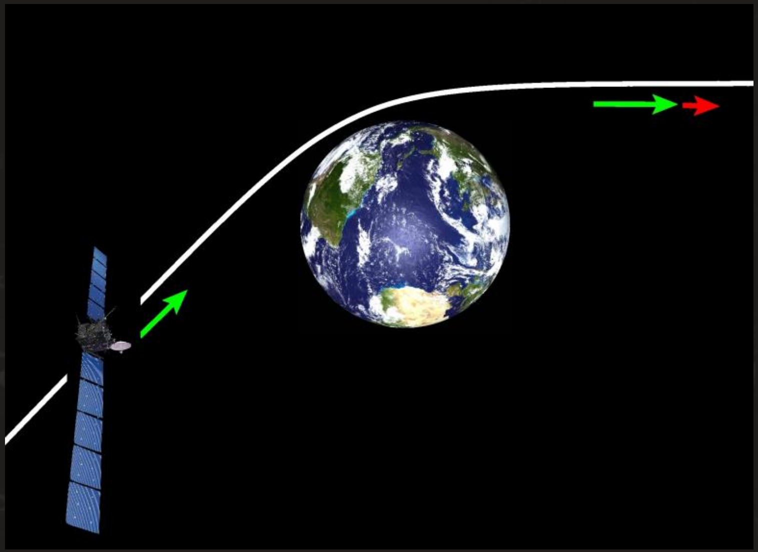
P. W. Graham & S. Rajendran, Phys. Rev. D 84, 055013 (2011)

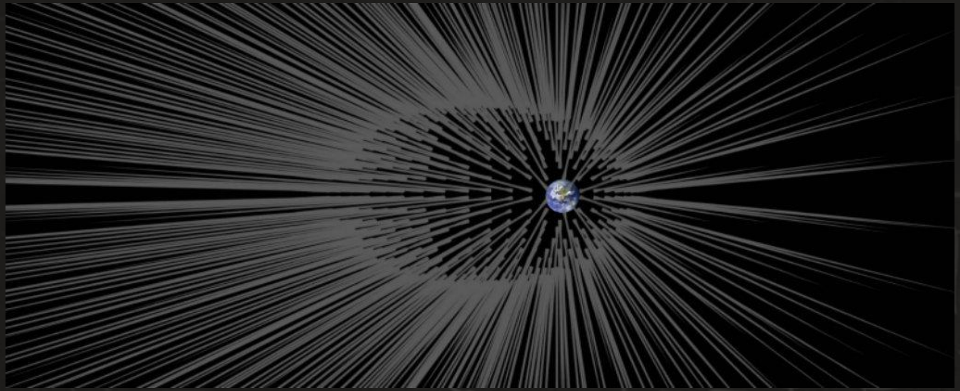
Flyby anomaly

- Spacecraft gains greater speed than predicted
- No convincing explanation now.

$$\frac{dV}{V} = \frac{2\omega_{\mathrm{E}} R_{\mathrm{E}}(\cos\varphi_{\mathrm{i}} - \cos\varphi_{\mathrm{o}})}{c}$$

Quantity	Galileo I	Galileo II	NEAR	Cassini	Rosetta-I	MESSENGER	Rosetta-II	Rosetta-III	Juno	Hayabusa 2	OSIRIS-REx
Date	1990-12-08	1992-12-12	1998-01-23	1999-08-18	2005-03-04	2005-08-02	2007-11-13	2009-11-13	2013-10-09	2015-12-03	2017-09-22
Speed at infinity, km/s	8.949	8.877	6.851	16.01	3.863	4.056				4.7	
Speed at perigee, km/s	13.738	—	12.739	19.03	10.517	10.389	12.49	13.34		10.3	8.5
Impact parameter, km	11261		12850	8973	22680.49	22319					
Minimal altitude, km	956	303	532	1172	1954	2336	5322	2483	561	3090	17237
Spacecraft mass, kg	2497.1		730.40	4612.1	2895.2	1085.6	2895	2895	~2720	590	
Trajectory inclination to equator, degrees	142.9	138.9	108.8	25.4	144.9	133.1					
Deflection angle, degrees	47.46	51.1	66.92	19.66	99.396	94.7				80	
Speed increment at infinity, mm/s	3.92±0.08	−4.60±1.00	13.46±0.13	−2±1	1.82±0.05	0.02±0.01	~0	~0	0±0.8	?	?
Speed increment at perigee, mm/s	2.56±0.05		7.21±0.07	−1.7±0.9	0.67±0.02	0.008±0.004	~0	−0.004±0.044		?	?
Gained energy, J/kg	35.1±0.7		92.2±0.9		7.03±0.19					?	?



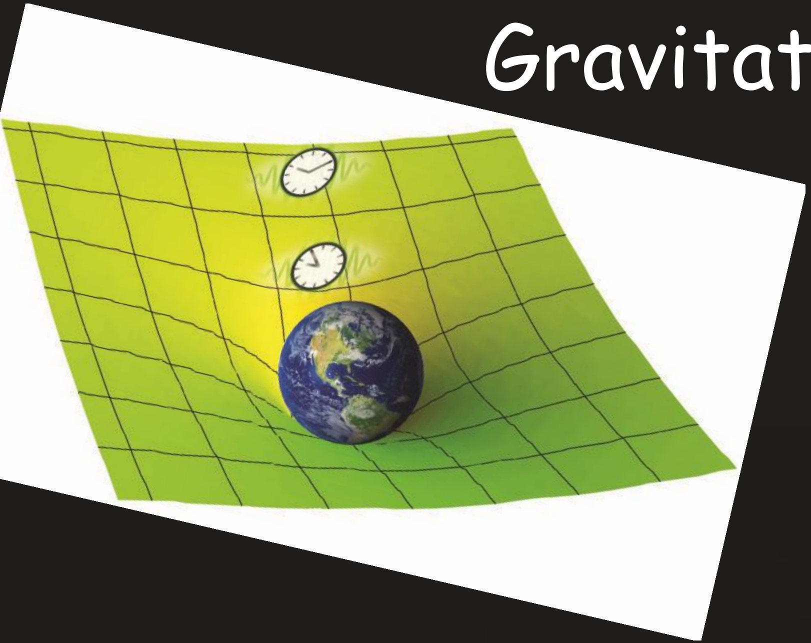


Caused by dark matter halo around earth?
S. L. Adler, Phys. Rev. D, 79, 023505 (2008)

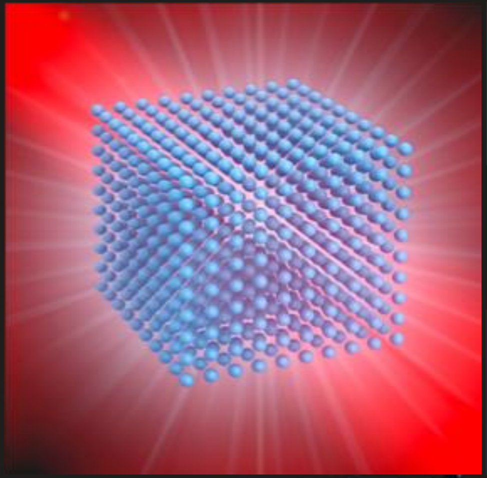
If so, distribution of dark matter halo could be measured by an optical clock in a flyby satellite

- ✓ Doppler effect
- ✓ Gravitational redshift
- ✓ …

Gravitational potential & gravity at once ?

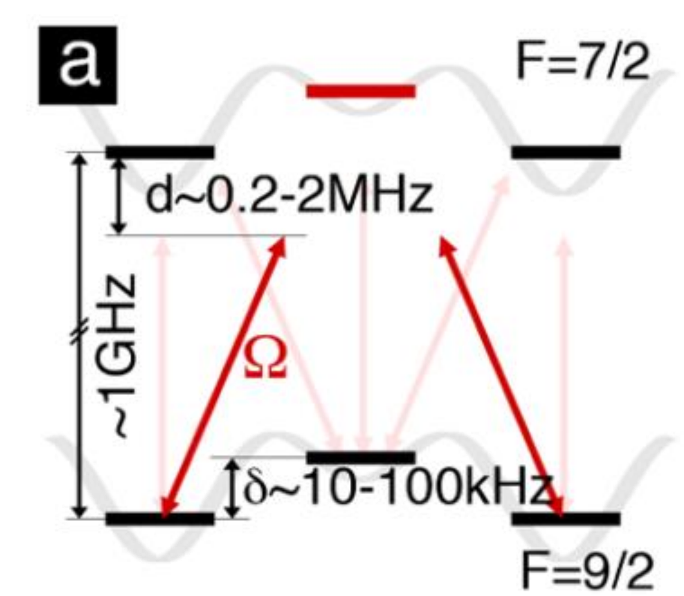


Extreme spatial resolution & precision



10 µm height: 10^{-21} effect

Simulating Axion Electrodynamics in Optical Lattices



Wilson fermions with an inverted mass give rise to a certain Axion background

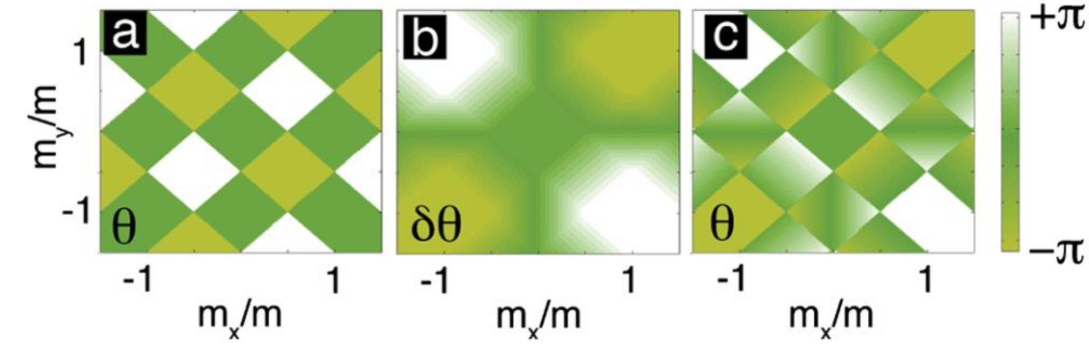


FIG. 3 (color online). (a) Axion index as a function of the masses m_y/m, m_x/m, and setting $m_z = m/2$. In the $\mathcal{U}_a$ invariant regime, only fixed values of the axion $\theta = \{0, \pi\}$ are allowed. (b) Perturbations to the axion term $\delta\theta$ in the $\mathcal{U}_a$-breaking regime. (d) Total axion term θ in the $\mathcal{U}_a$-breaking regime.

Bermudez et al., Phys Rev Lett.105.190404 (2010)

Quantum Physics & Quantum Information

Thanks!

Ultracold atoms can be used to emulate complex, condensed-matter systems that are hard to study experimentally, like supersolids, superconductors or even black holes.