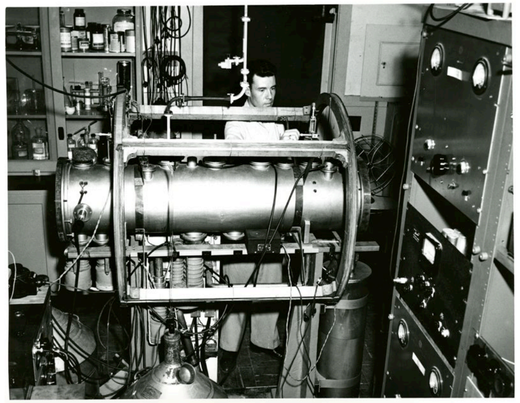
Theory advancing quantum many-body research and metrology

Ana Maria Rey

JILA NIST CU

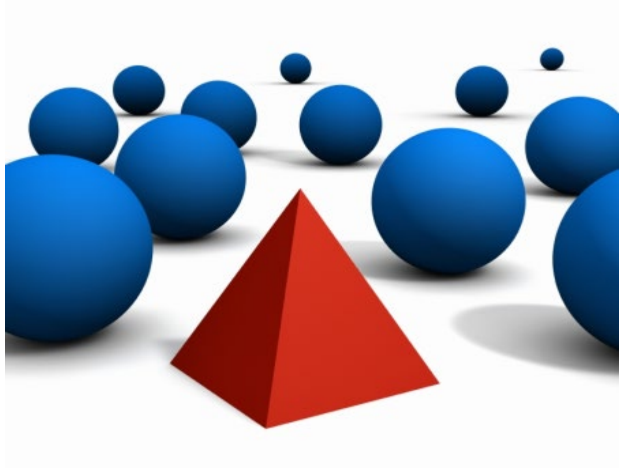
VCAT Meeting, June 11 (2024)

A Quantum Science HISTORY



NBS-1 atomic clock

atomic clocks



Different but very valuable

NIST

founded

1901

NIST Boulder labs

1954

JILA

CU+NIST
institute formed

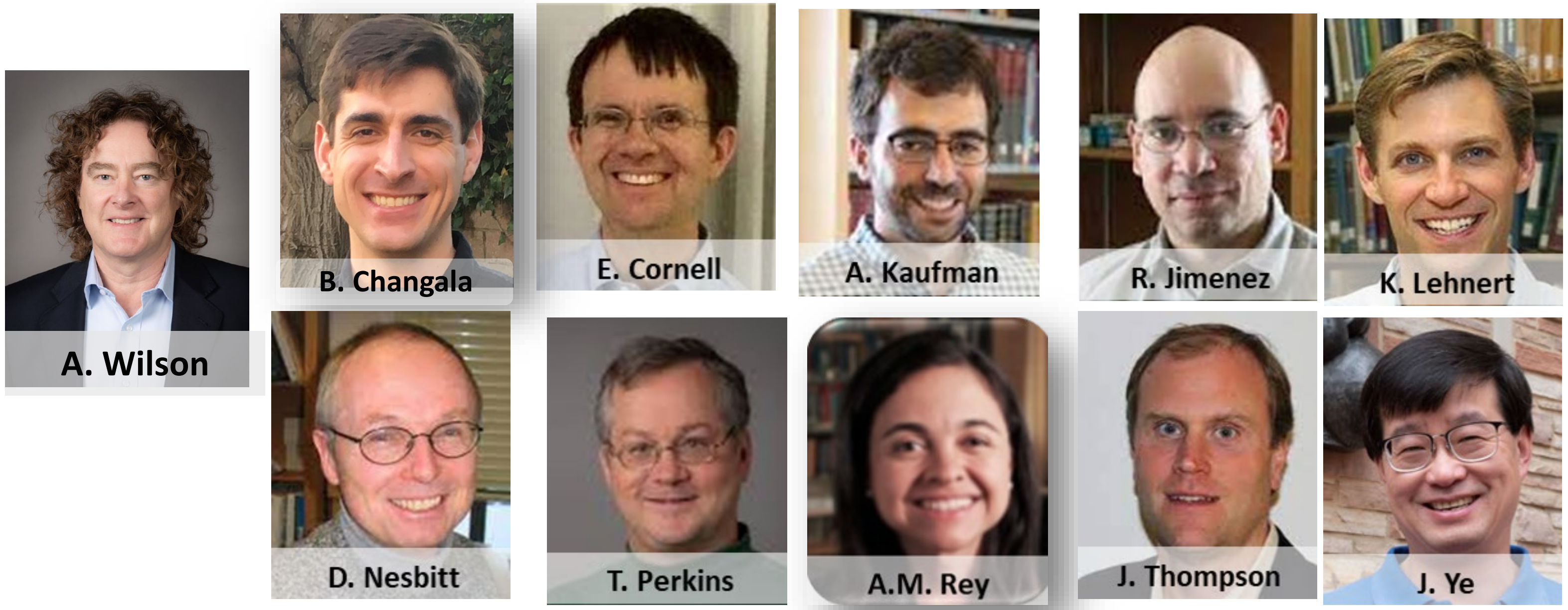
1962

JILA **Overview**

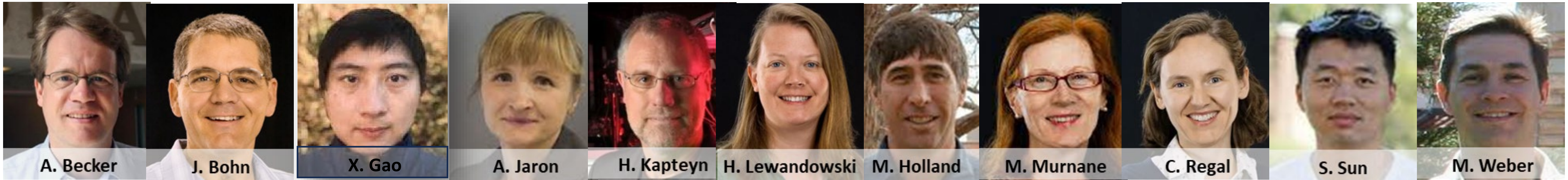
A joint CU/NIST interdisciplinary research institute located on the Univ. of Colorado Boulder campus

Complement and foster NIST mission to advance science, technology for the Nation

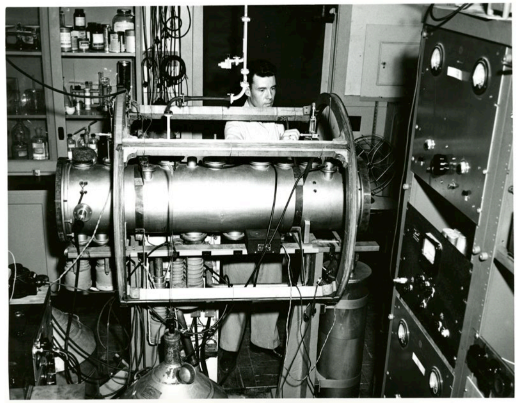
Current NIST Quantum Physics Division: PLAYERS



PART OF JILA TEAM



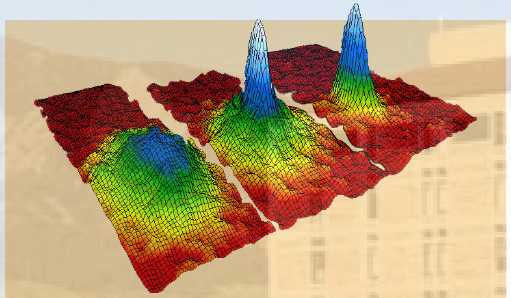
A Quantum Science HISTORY



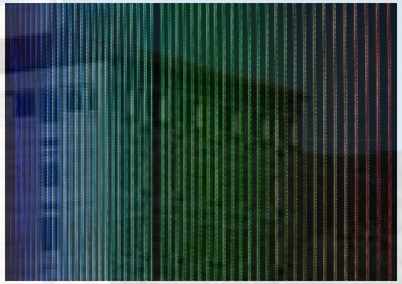
NBS-1 atomic clock

atomic clocks

Tremendous impact over years!!



Cornell & Wieman: BEC demonstrated



Hall: Frequency comb
Jin: Degenerate fermi gas

NIST
founded
1901

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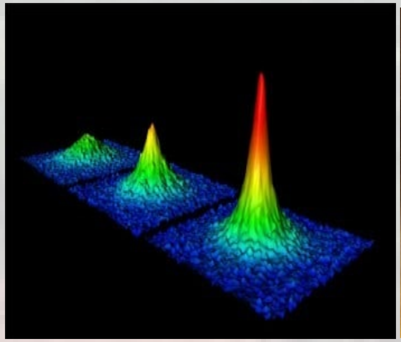
JILA
CU+NIST institute formed
1962

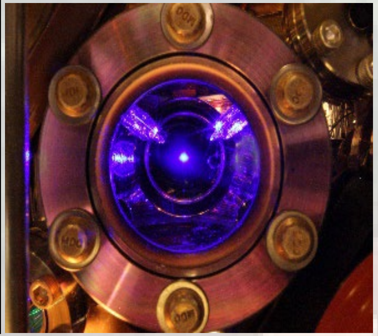
Laser cooling
1978

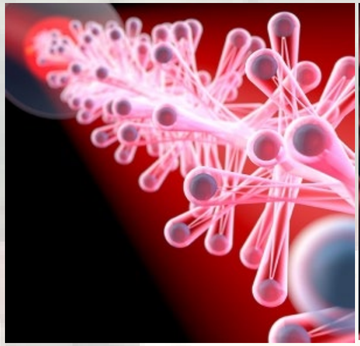
1995

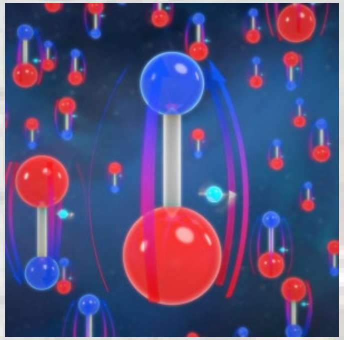
1999

JILA Pushes the Quantum Frontier









Jin: BEC-BSC crossover

2003

Jin-Ye: Ultracold polar molecules

2008

Ye: Sr lattice clock beats Cs Standard

2010

Thompson: 18 dB spin squeezing in a cavities

2016

Kaufman: Tweezer clock

2020

Thompson: Entangled interferometer

2022

Ye: Gravitational red shift within 1 mm

Cornell/Ye: eEDM of $|d_e| < 4.1 \times 10^{-30}$ *e* cm

2023

Ye: Thorium nuclear transition

2024

NIST Mission Expanded: External and internal collaborations

JILA Physics Frontier Center
A National Science Foundation Physics Frontier Center

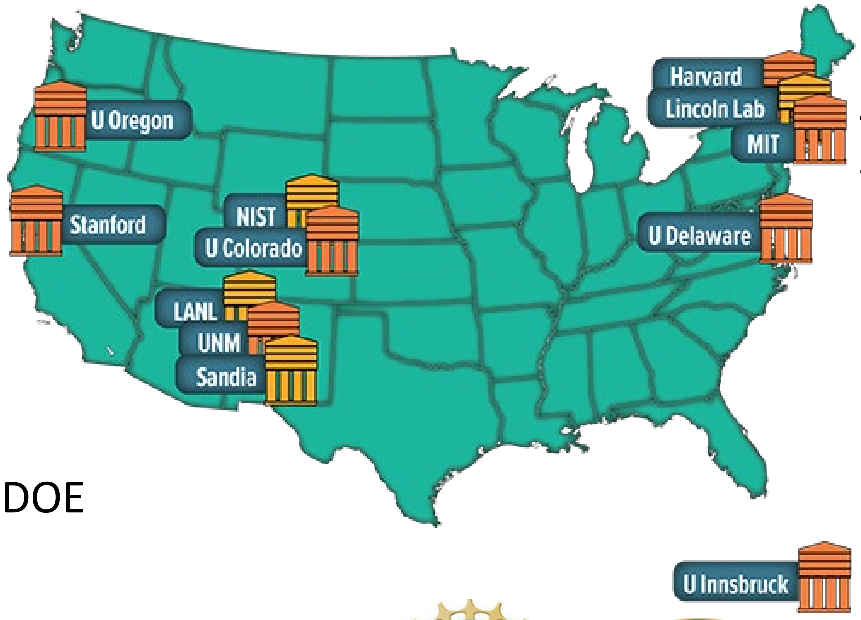
20 JILA Investigators: 6 The., 14 Exp.
25 M. 4.2 M/yr 2023-2029
Rey and Becker: Directors

Center for Theory of Quantum Matter
CTQM

12 JILA/CU/NIST Researchers:
All theorist

Q-SEnSE
An NSF Quantum Leap Challenge Institute

QLCI/Q-SEnSE: **Q**uantum **S**ystems through **En**tangled **S**cience and **E**ngineering
25 M 2020-2025, 5 M/yr



PIs and co-PIs:
J. Ye, JILA
S. Knappe, CU engineering
G. Rieker, CU engineering
M. Safranova, U Delaware
M. Kasevich, Stanford

QSA: **Q**uantum **S**ystems **A**ccelerator: DOE Quantum Information Science (QIS) Research Centers.

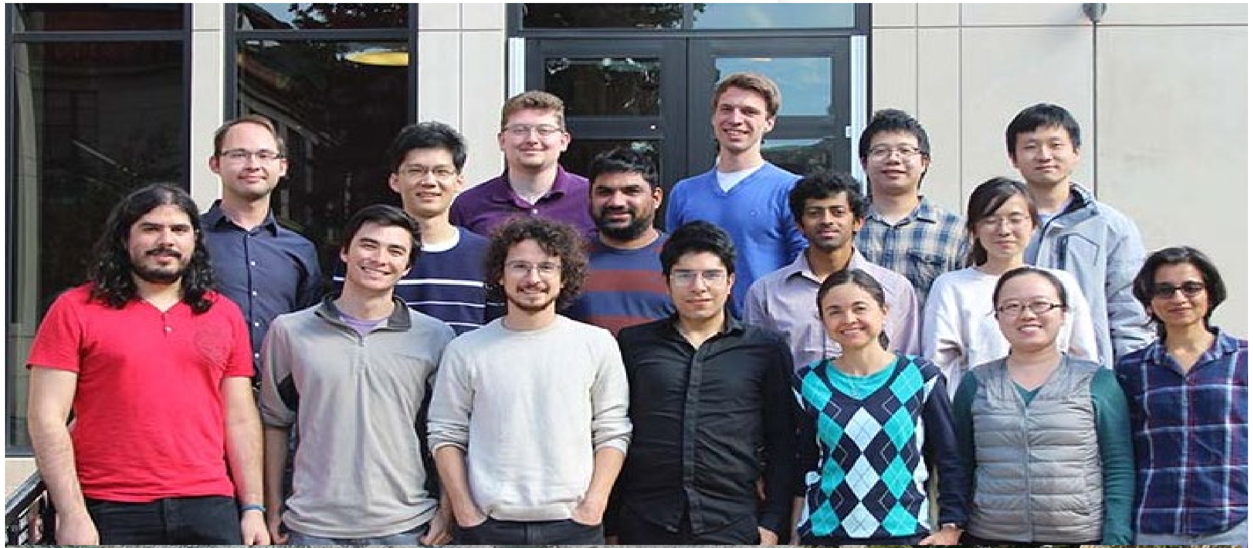
15 member institutions in North America, Lawrence Berkeley National Laboratory leads QSA with Sandia National Laboratories as lead partner.

NIST
Los Alamos National Lab
Sandia National Lab
Lincoln Lab

Lawrence Berkeley National Laboratory, Sandia National Laboratories, CU Boulder, MIT Lincoln Laboratory, Caltech, Duke, Harvard, MIT, Tufts, Berkeley, UMD, New Mexico, Southern California, UT Austin, and Canada's Université de Sherbrooke.

Academic Environment: Amazing undergrads, grads and postdocs

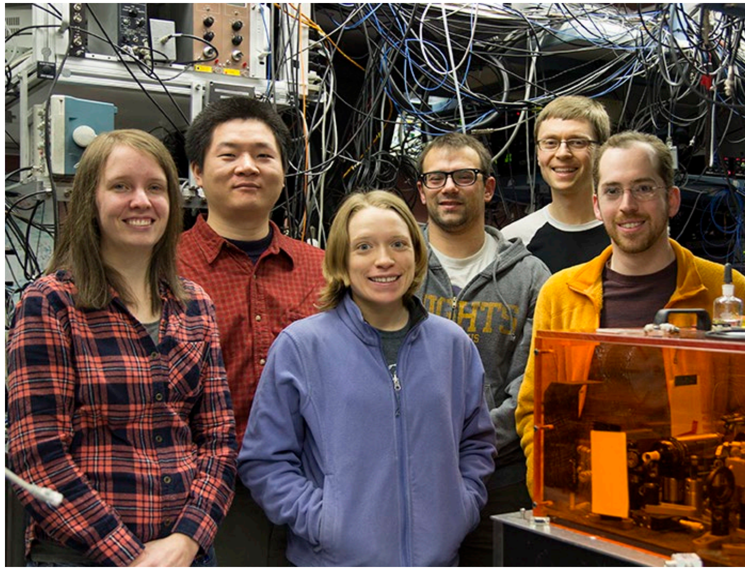
Rey Theory:



Thompson cavity

Ye KRb:

Ye Sr:

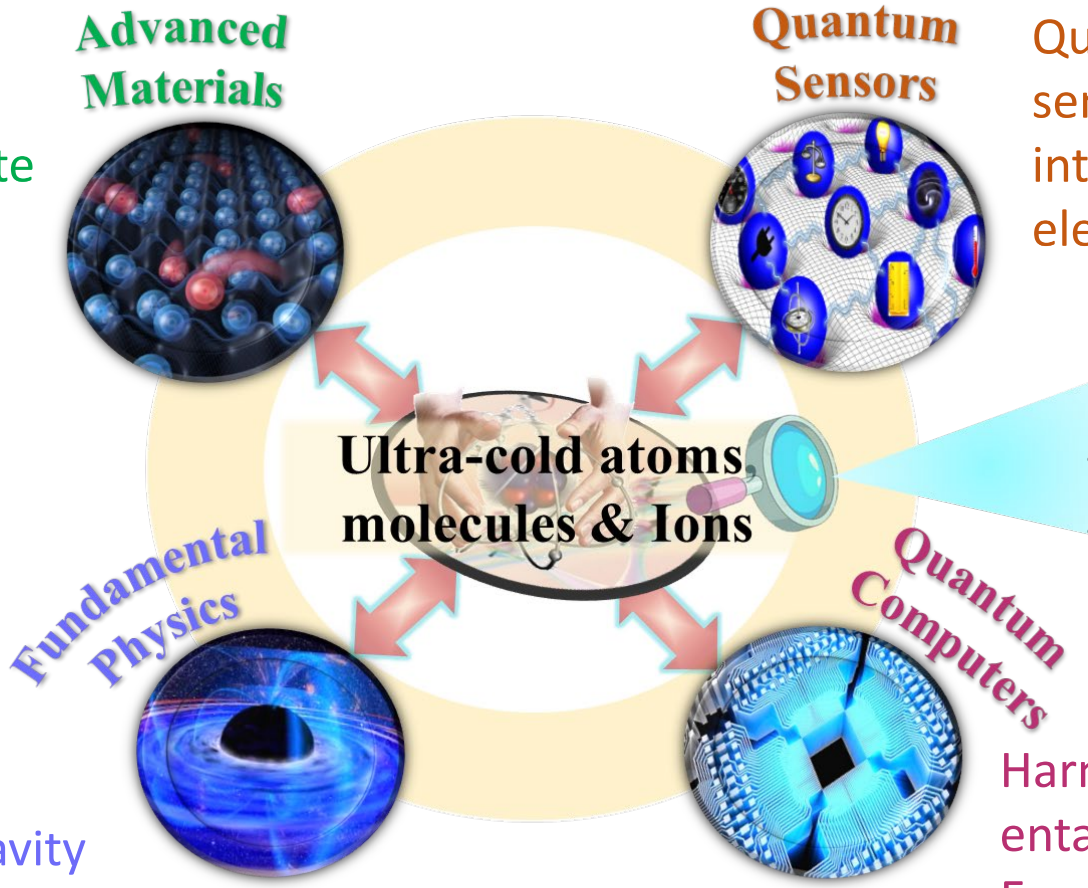


Scientific Vision: Harnessing quantum complexity

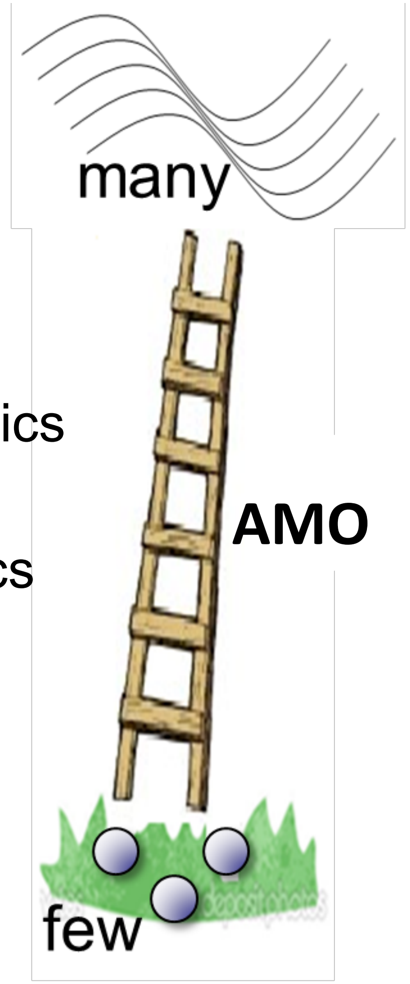
GOAL: Harnessing many-body quantum systems and using them for applications ranging from quantum simulation, information to metrology.

Quantum simulation: from solid state materials to high energy physics

Quantum enhanced sensing: clocks, interferometers, electric field sensors



- Well-understood microscopics
- Tunable interactions
- Access to quantum dynamics

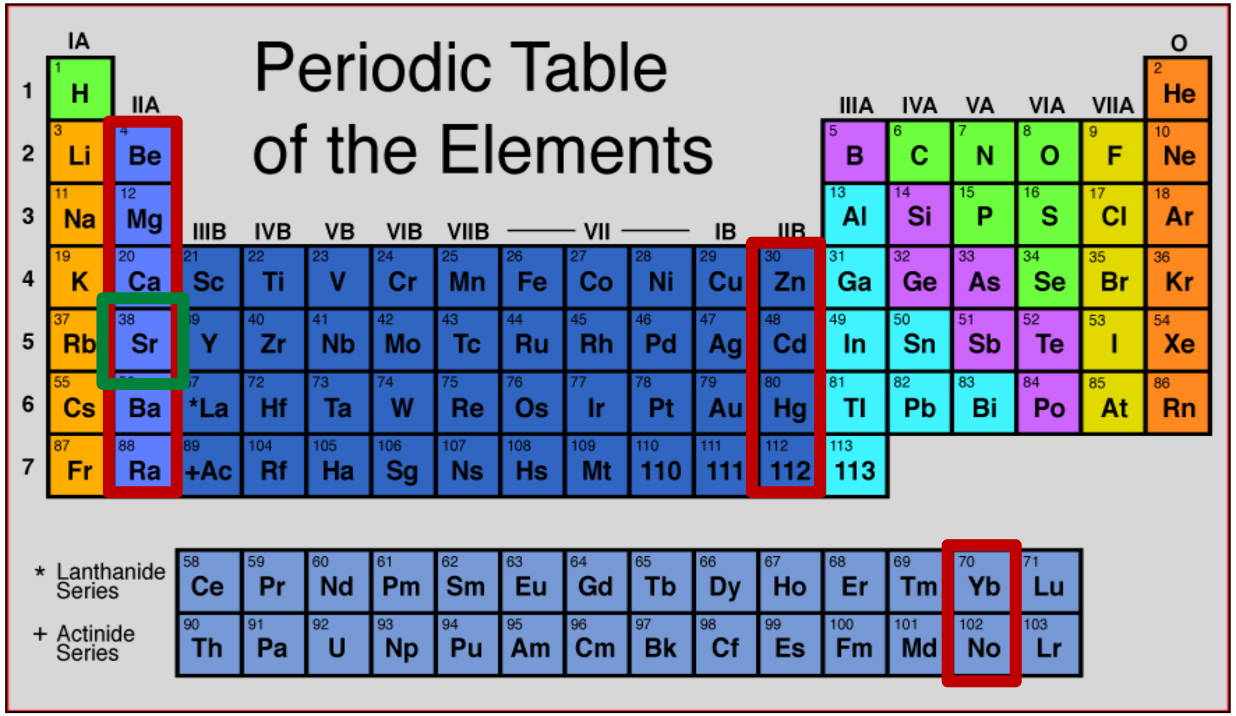


Dark matter, Beyond SM Interplay of gravity with quantum mechanics

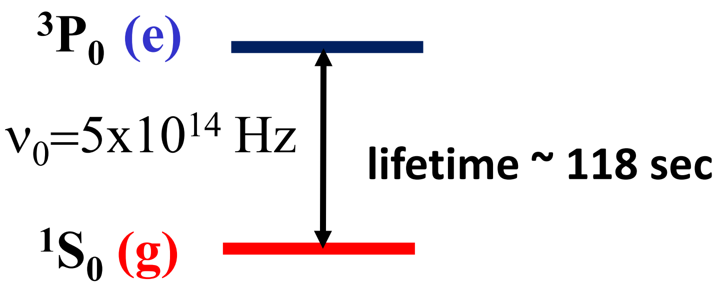
Harnessing entanglement, Error correction

Alkaline Earth (-like) Atoms: AEA

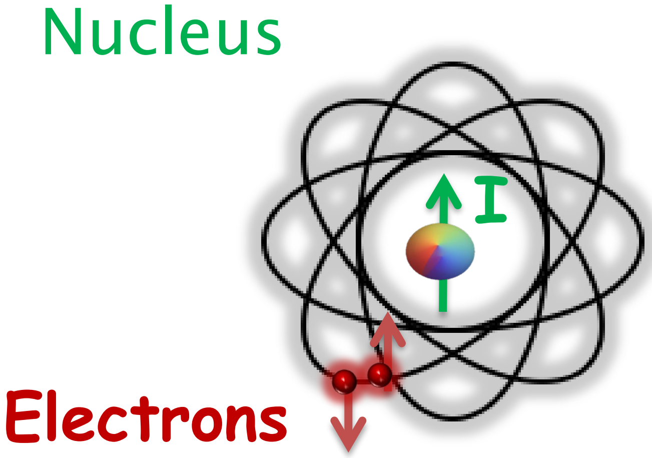
A TALE OF TWIN ELECTRONS



Metastable states: Dipole and spin forbidden



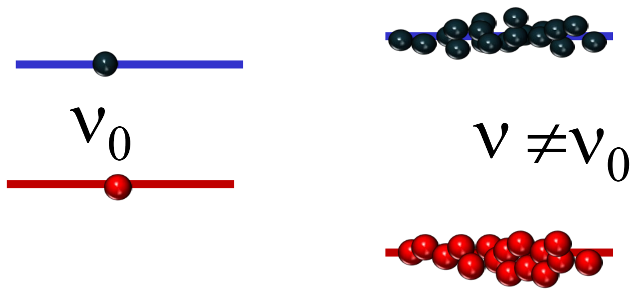
Linewidth $\Delta\nu_0 \sim$ mHz



Dilemma

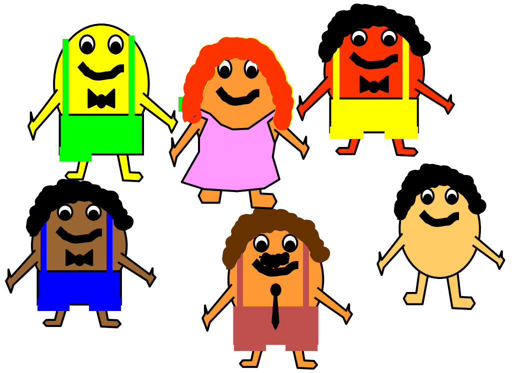
More atoms better signal to noise ~$\sqrt{N}$

Atoms collide and change the frequency. Packing more atoms makes the error worse



D. Jin

- IDEA: Use quantum statistics



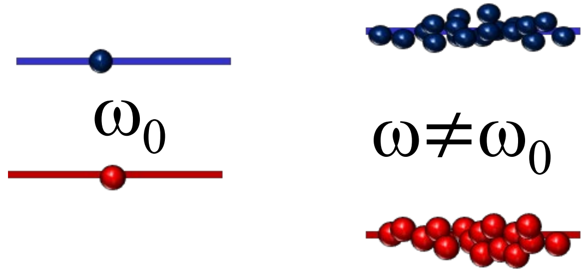
Fermions

DILEMMA

More atoms better signal to noise

Atomic collisions change the frequency. Packing more atoms makes the error worse

Interactions:



JILA:G. Campbell *et al* Science 324, 360 (09)

NIST: N. Lemke *et al* PRL 103,063001 (09)

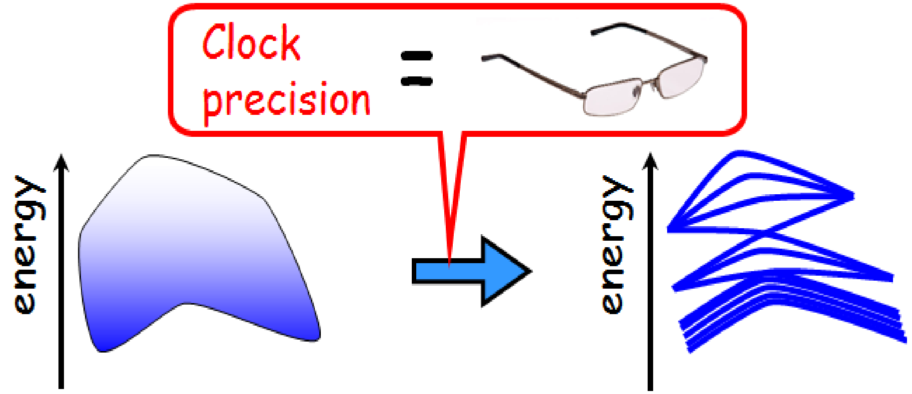
Need to understand interactions

- Degraded signal: Even in identical fermionic atoms. In 2008 gave rise to the second largest uncertainty to the 10^{-16} error budget

Many-body Physics with clocks

Atomic Clock

Many-body Physics



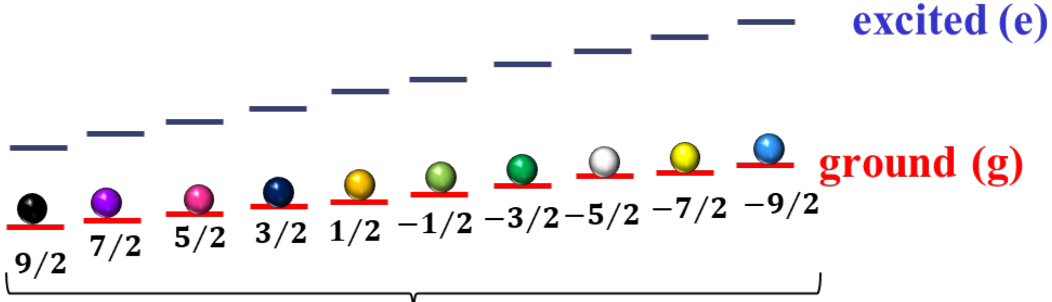
Exquisite Control

Ultra-precise

Long probing times

Quantum Magnetism, many-body physics

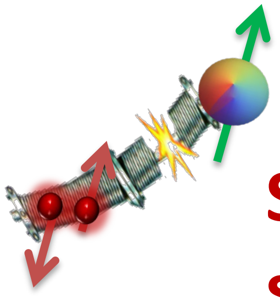
Strontium: ^{87}Sr



I=9/2 10 different states

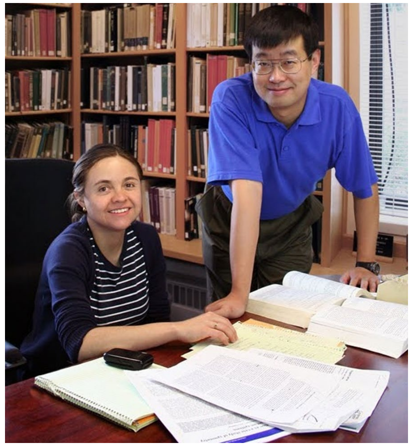
$I \cdot J = 0.$

Nuclear/electron spin decoupled



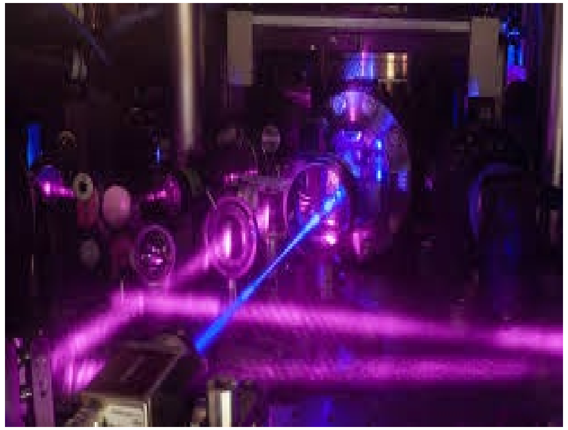
SU(N=2I+1=10) symmetry

Exploring many-body physics with clocks

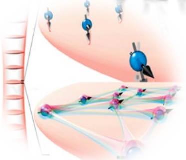


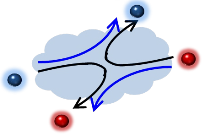
JILA clock has now 1000 better sensitivity compared to prior record (Ye: Nature 602, 420 (2022), Rey, Ye :Science Adv sciadv.adc924(2022))

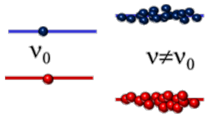
1000 times better than current cesium standard (2014)



(2014) @ 2.1 x10^{-18}







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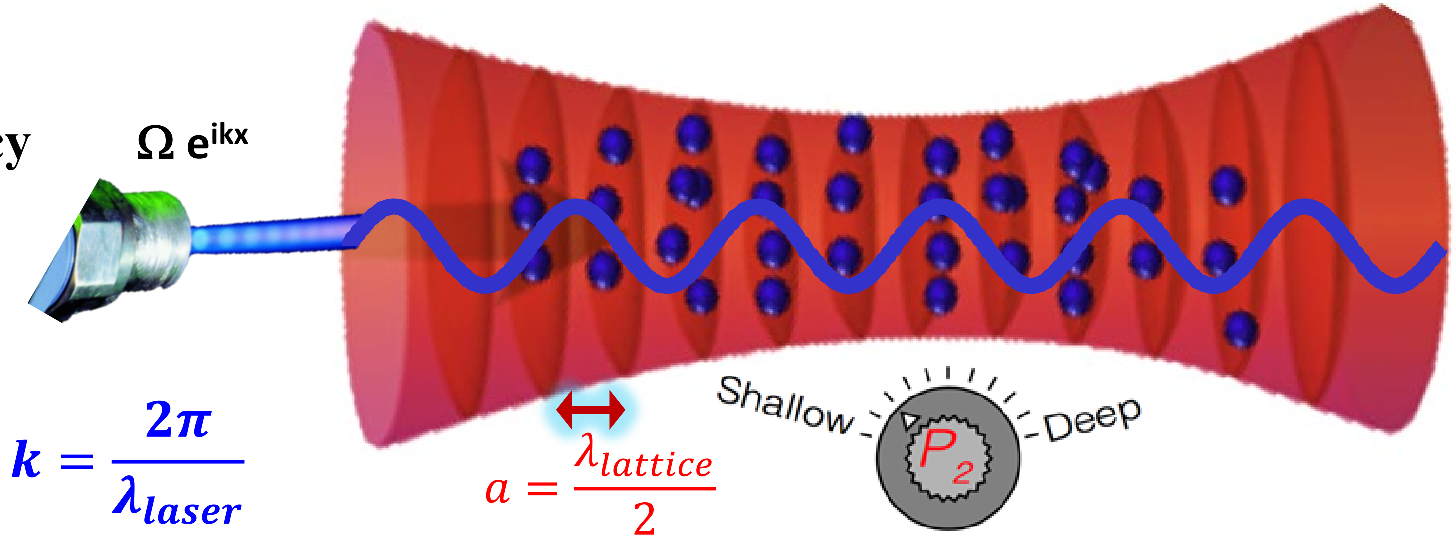
JILA y NIST clocks see atomic collisions: Science (2009).

Spin–Orbit Coupled Fermions in a Clock

Rabi frequency $\Omega\, e^{ikx}$

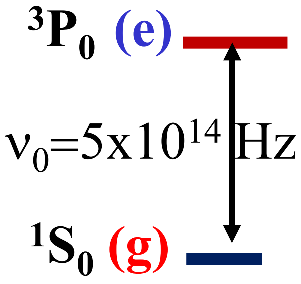


$k = \frac{2\pi}{\lambda_{laser}}$

$a = \frac{\lambda_{lattice}}{2}$

For Sr: $ka = \phi \sim 7\pi/6$

During interrogation the laser imprints a phase that it is different between lattice sites



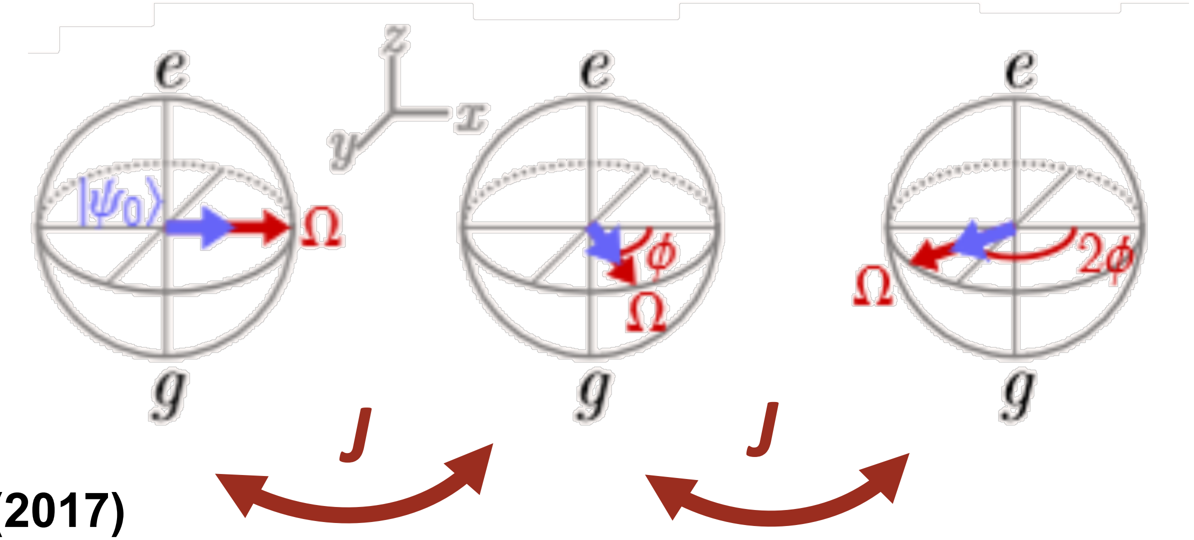
Atoms distinguishable:

With tunneling

S-wave collisions: Strong

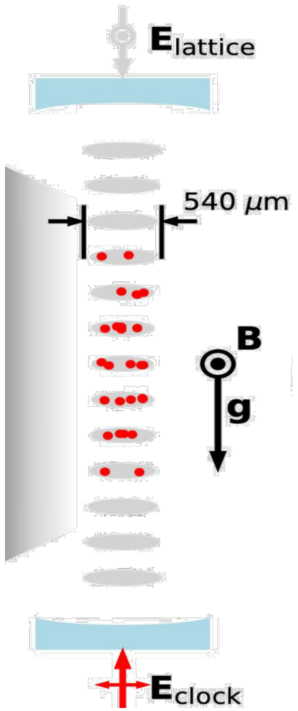
Bad for clocks

Tunneling allows atoms to feel the differential phase

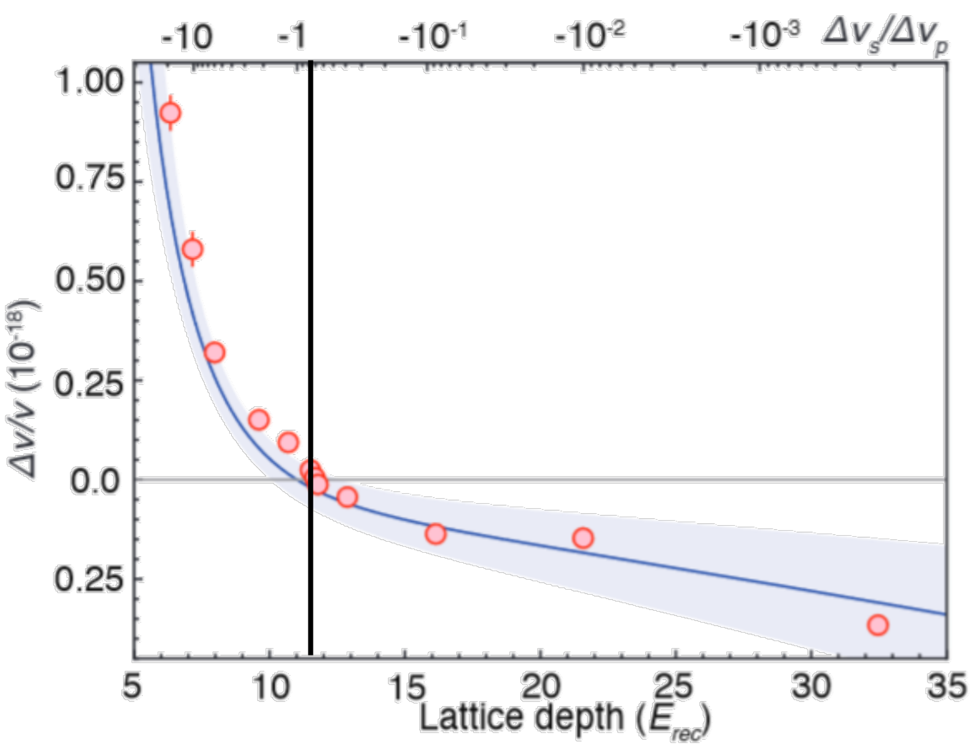


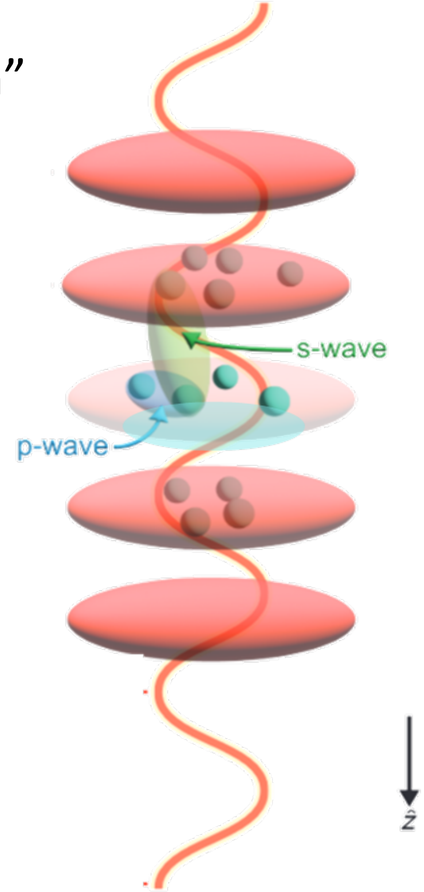
Wall,…Ye, Rey, PRL(2016)
Kolkowitz,..,Rey, Ye Nature (2017)

Win Win Wannier-Stark

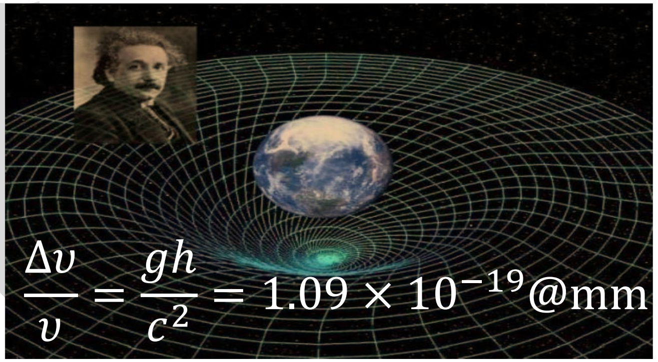


- **Ramsey Coherence times longer than half a minute:**
  - ✓ Wave functions localized enough to suppress undesirable motional decoherence.
  - ✓ Weaker confinement **suppresses detrimental p-wave inelastic losses and light scattering**
- **Hamiltonian Engineering: Suppression of undesirable frequency shifts**
  - ✓ Suppression of density shifts at "magic depth"





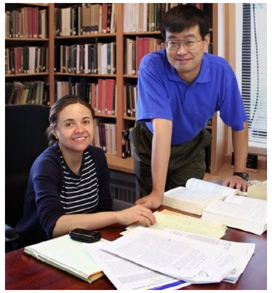
Exploring many-body physics with clocks

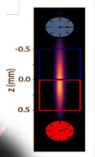


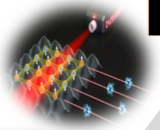
NIST Ion clock 30 cm (2010)

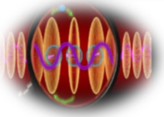
Sr clock 1 mm (2022)

(2022) Sensitivity @7.6 x10^-21









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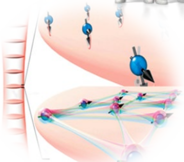

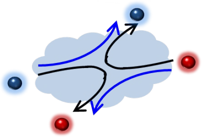

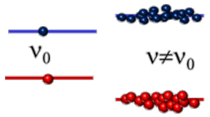

Resolving gravitational redshifts in a single mm sample (Nature 2022, Science Adv 2022)

Proposals on how to use clocks for quantum information: cluster(PRL 2019), cat (2020), spin squeezing (PRR2019,2020)

SU(N) thermalization (Nature Phys, 2020)

Observation of Multibody interactions (Nature 2018, NJP2018)

Clock simulates synthetic magnetic fields: Nature (2017), Nat Phys (2018)

JILA Best atomic clock: Nature (2014).

Clock measures SU(N) symmetry: Science (2014)

Clock as a simple quantum simulator: Science (2013)

Unraveled mysterious collisions in the clock:Science (2011).

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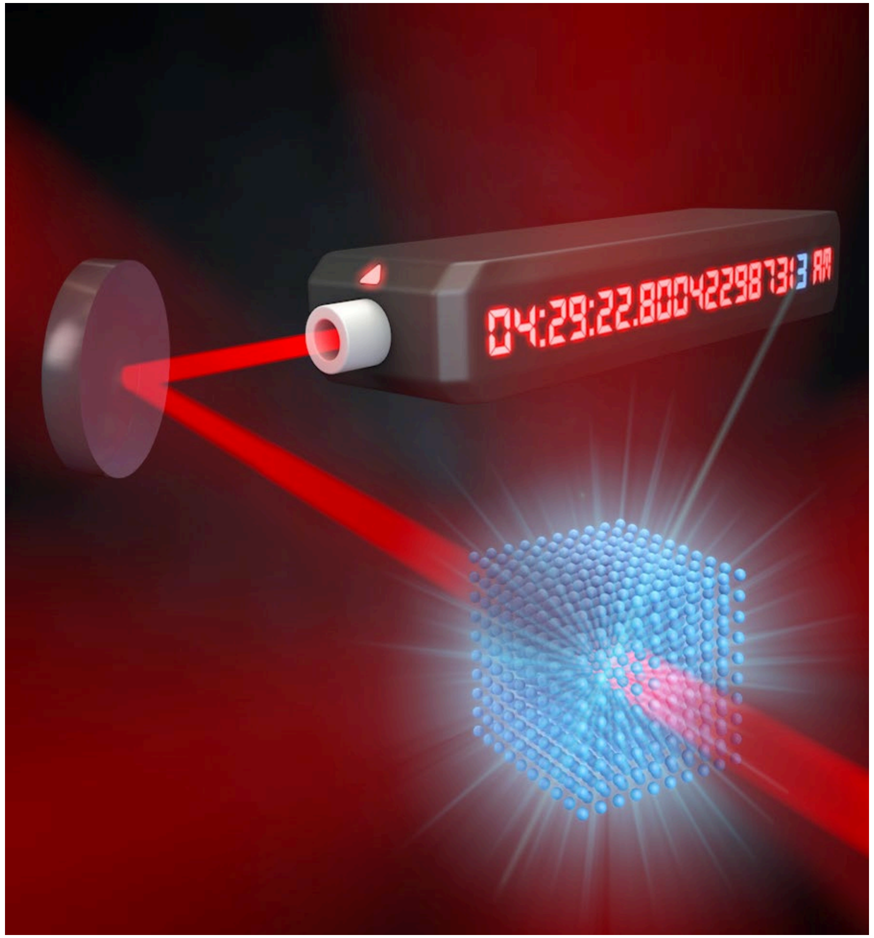
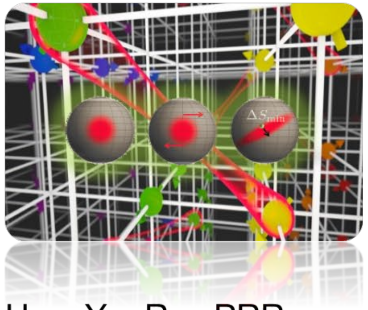
JILA y NIST clocks see atomic collisions: Science (2009).

New generation: 3D ultra-cold fermionic optical lattice clock

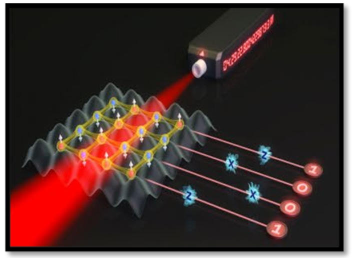


Spin Squeezed States



He,.. Ye, Rey PRR. 1,033075 (2019), Perlin,Chu, Rey PRL, 125, 223401 (2020)

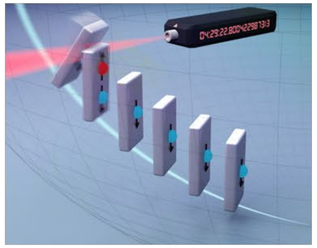
Cluster States



Mamaev,Blatt,Ye, Rey *PRL* 123, 130402 (2019)

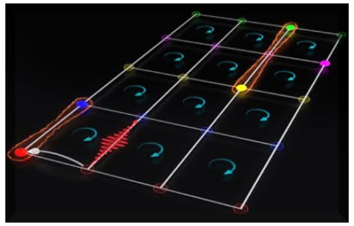
Mamaev,…,Rey PRR 3,013178 (2021)

Cat States



Mamaev& Rey PRL 124, 240401(2020)

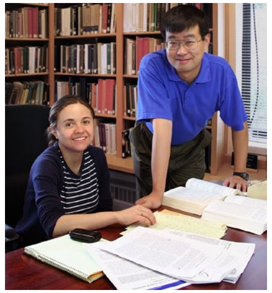
Chiral resonant transport



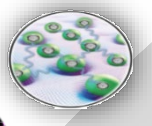
Mamaev,... Rey PRL 123, 130402 (2019)
Mamaev,.. Rey PRX Quantum 3, 030328(2022)

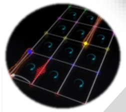
Exploring many-body physics with clocks

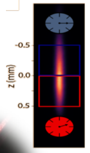
(2022) Sensitivity @7.6 x10^{-21}

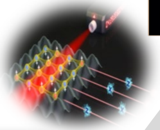


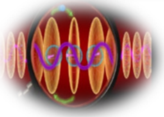
(2014) @ 2.1 x10^{-18}

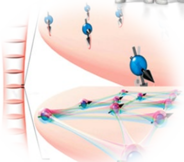


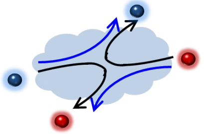


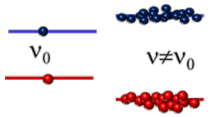












Interplay between mass-energy equivalence in GR and entanglement in OLC

Coherent superexchange interaction in OLC (arXiv:2402.13398, under review in science)

Spin squeezing in anisotropic models (PRA 109, 2024)

Resonant SU(N) interactions in a flux ladder(PRX Q 2022)

Resolving gravitational redshifts in a single mm sample (Nature 2022, Science Adv 2022)

Proposals on how to use clocks for quantum information: cluster(PRL 2019), cat (2020), spin squeezing (PRR2019,2020)

SU(N) thermalization (Nature Phys, 2020)

Observation of Multibody interactions (Nature 2018, NJP2018)

Clock simulates synthetic magnetic fields: Nature (2017), Nat Phys (2018)

JILA Best atomic clock: Nature (2014).

Clock measures SU(N) symmetry: Science (2014)

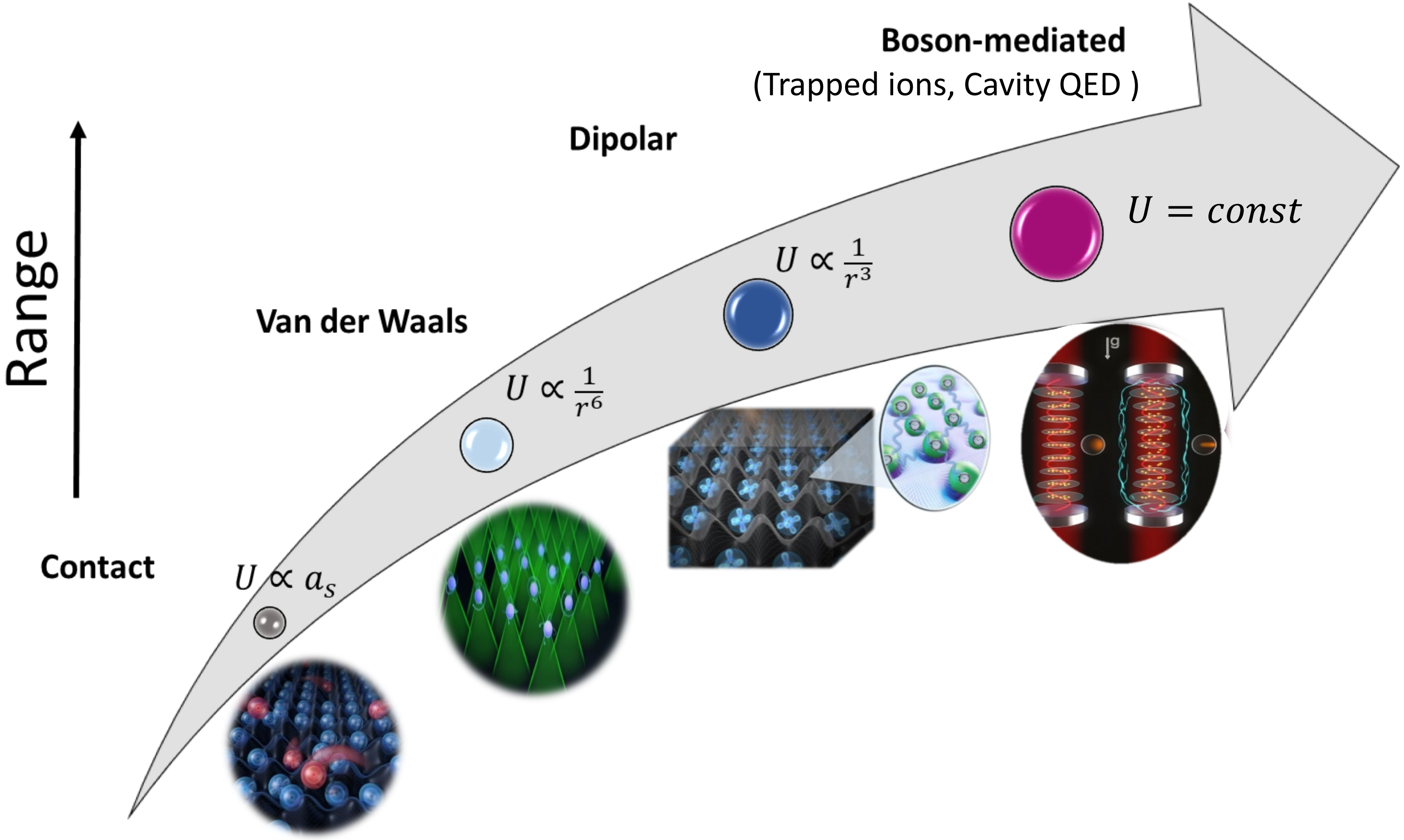
Clock as a simple quantum simulator: Science (2013)

Unraveled mysterious collisions in the clock:Science (2011).

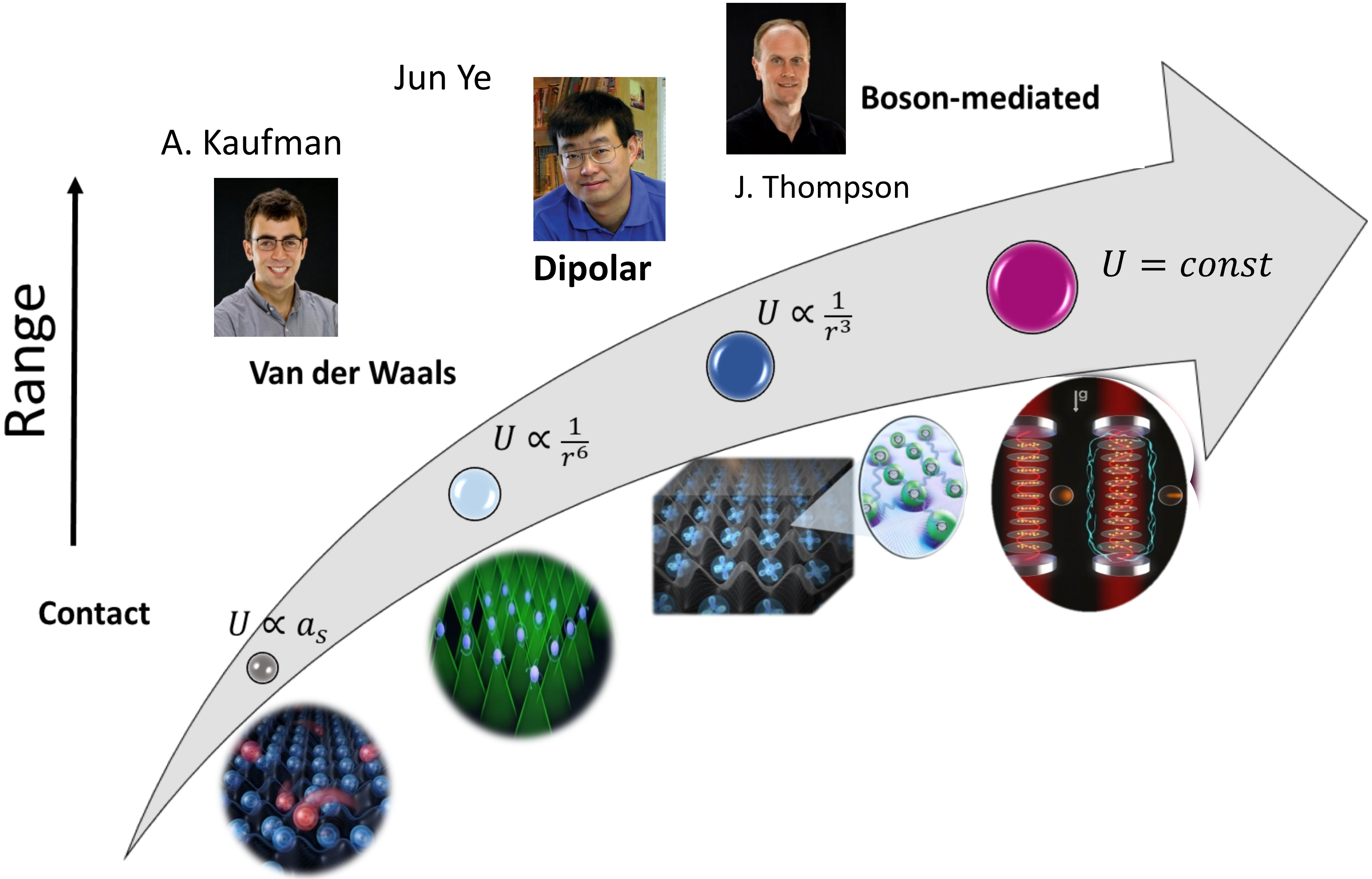
Theory proposal: Alkaline earth atoms exhibit exotic magnetism: Nature Physics (2010) , PRL (2009).

JILA y NIST clocks see atomic collisions: Science (2009).

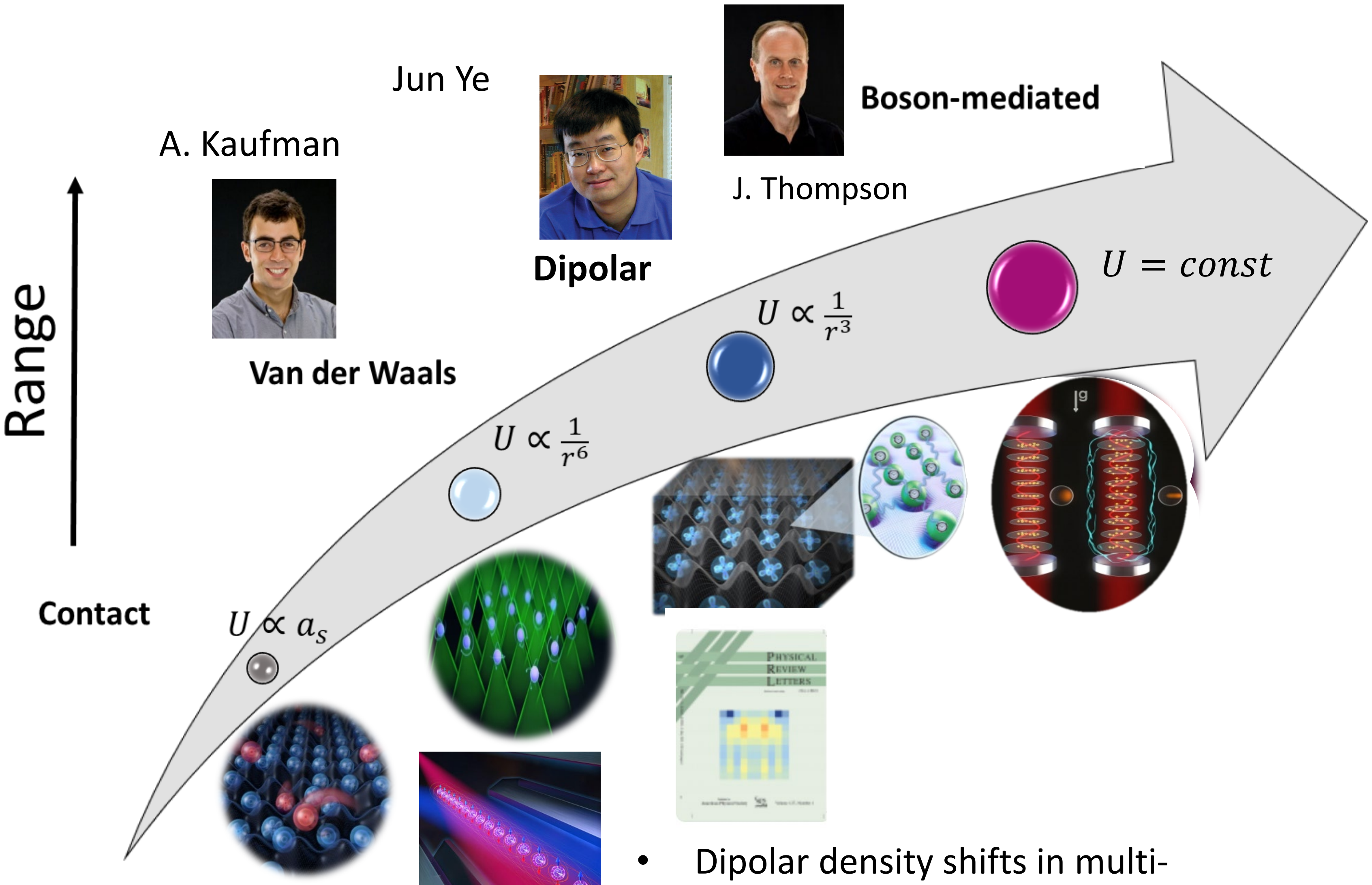
Even richer opportunities



Even richer opportunities

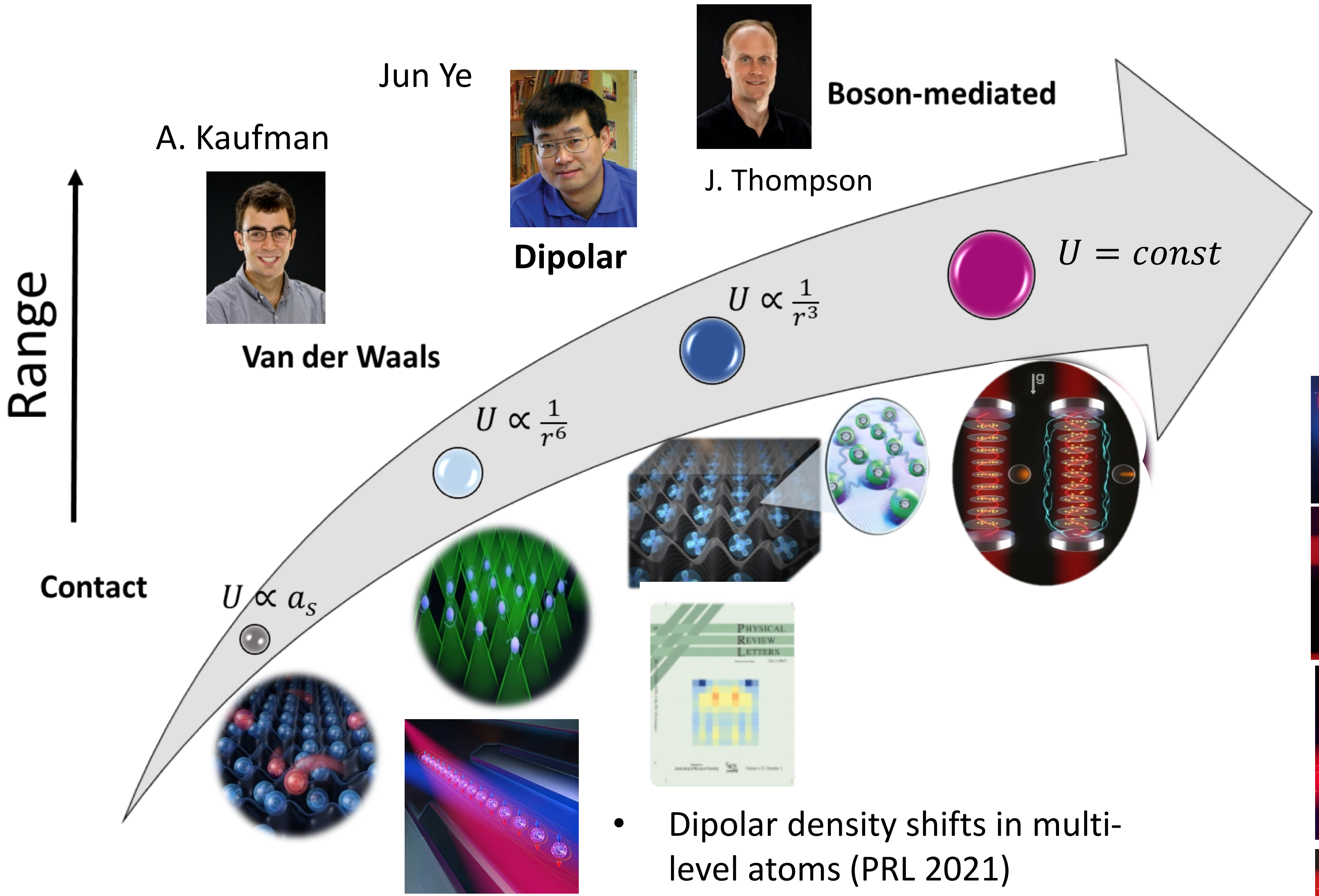


Even richer opportunities



- Dipolar density shifts in multi-level atoms (PRL 2021)
- Spin Squeezing with short-range interactions (PRL, 2020 Nature 2023)

Even richer opportunities



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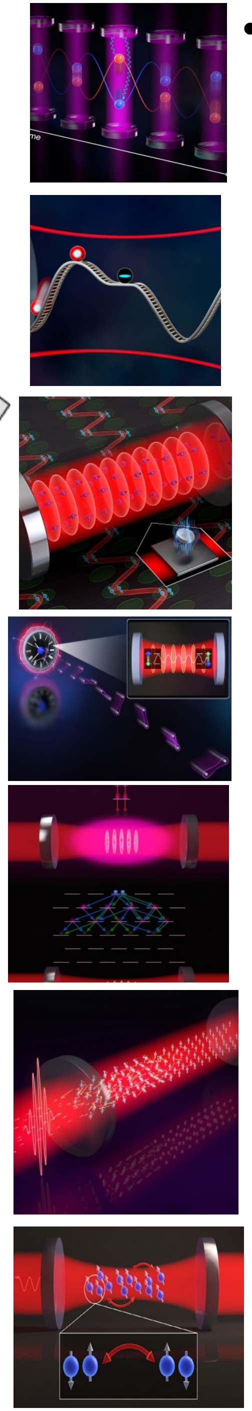

- Twisting and binding matter-waves, Science (2024).
- Multi-level squeezed States in a Cavity, PRL(2023).
- Simulating dynamical phases of superconductor in a Cavity, (PRL 2021, Nature 2024)
- Bosonic pair production in Cavities, (PRL, PRR 2023)
- Quantum enhanced cavity interferometer PRL (2021).
- Robust spin squeezing generation (PRL2018,PRL 2020, PRA2020)
- Multi-level Dark States in a Cavity, PRX (2022)
- Observation of dynamical Phase transition, LMG model(Nature 2020)
- Observation of exchange interactions in a cavity, (Science 2018)

Only the beginning: Bright vista ahead

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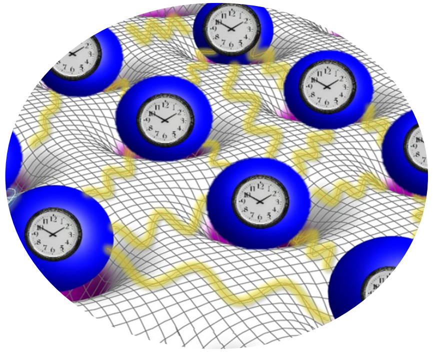
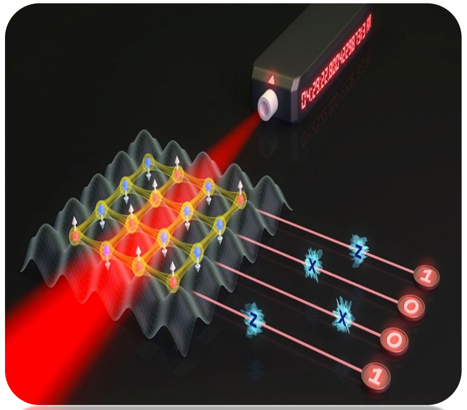
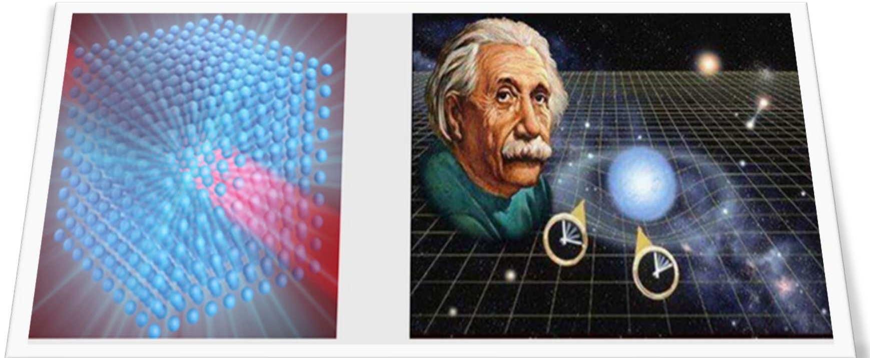
Entangled Clocks: EVEN BETTER



Quantum Computers



Exploring the Deep Secrets of the Universe



Ripples of space-time