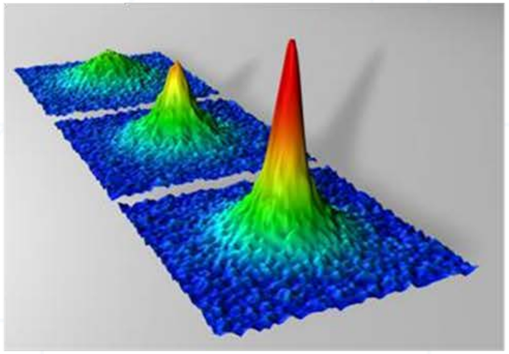
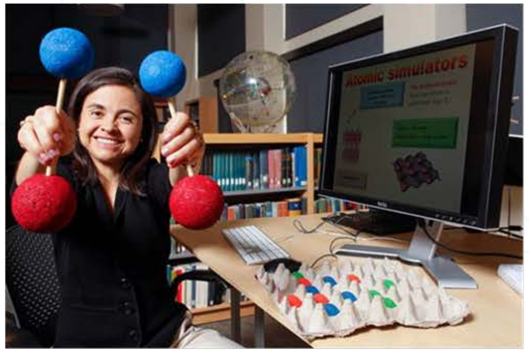
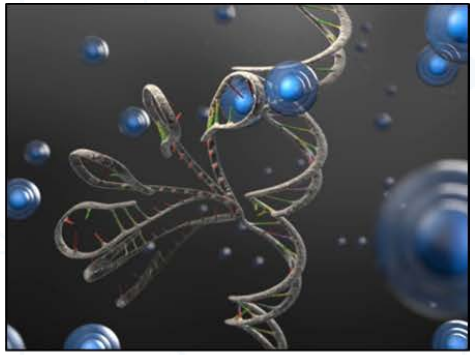
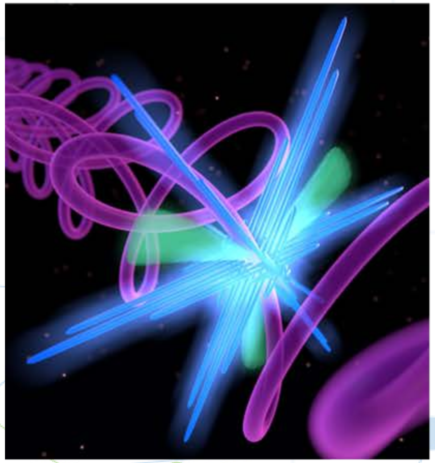
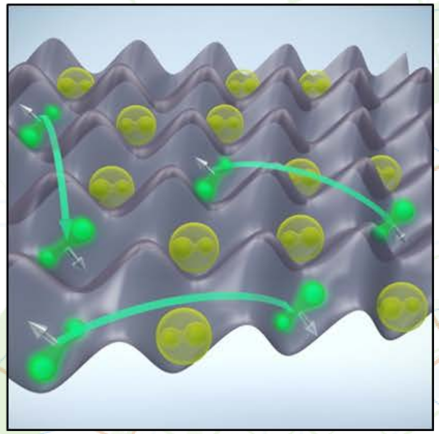




jila.colorado.edu

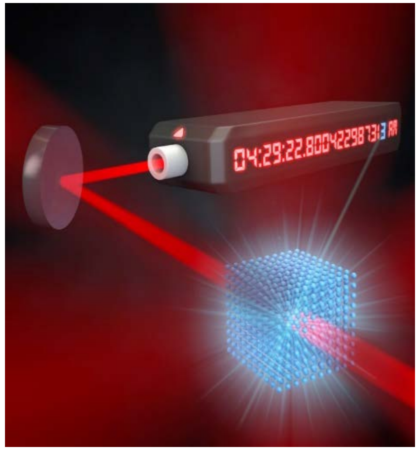
JILA: NIST/CU Partnership for Technology, Training and Transformation

JILA NIST CU





NIST Quantum Physics Division (QPD) / JILA
JILA/QPD Roles in QIS



- ***Technologies:*** Pioneer new quantum technologies broadly used across NIST and across the world for QIS including quantum R&D, quantum engineering, quantum metrology, quantum SI (NIST program areas).
    - Fermi degenerate gas optical lattice clock.
    - Quantum degenerate molecular gases.
    - Precision frequency spectroscopy of large-scale quantum matter.
    - New methods for large-scale entanglement/state squeezing. Etc.

- ***Training:*** Building the quantum workforce of today and tomorrow.
    - Over the past 10 years, ~150 JILA PhDs and postdocs have taken jobs in QIS US industry and Federal labs.
        - Large companies: Microsoft QC, HRL QC, Honeywell quantum tech, Google QC, Lockheed Martin QC and quantum tech, etc.
        - Growing companies: Rigetti QC, AOSense quantum tech, etc.
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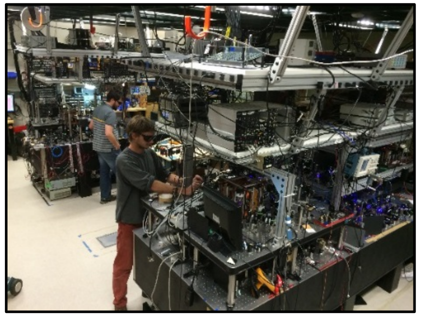


- ***Transformation:*** Continually expand into new areas.
    - Creating, controlling, measuring quantum many-body systems to enable quantum measurements, quantum computing, quantum simulation.
    - Quantum-based tabletop “big physics.”
    - Quantum biometrology.

JILA in Brief

NIST

- Joint research and training institute of NIST and University of Colorado (CU).

- Founded 1962 as "Joint Institute for Laboratory Astrophysics."
    - First full government/university R&D partnership.
    - Continual evolution of scientific areas.

- Physically located on CU campus.

- 28 JILA Fellows (CU and NIST).
    - Quantum Physics Division is the NIST part of JILA.
    - NIST employee JILA Fellows (QPD) hold unique ***Adjoint*** CU faculty appointments: CU employees.
    - Roughly analogous to NIST Group Leaders, but CU employee students/postdocs/scientists comprise the Group members.

- ~300 personnel, including Fellows, Research Associates, postdocs, graduate and undergraduate students, technical and administrative staff.
- ~1/2 supported by NIST (JILA Cooperative Agreement, Grants to NIST JILA Fellows, etc.).

Recognition for JILA

- Three Nobel Prizes in Physics
- Three MacArthur “Genius” Fellows
- Eight Members of the National Academy of Sciences
- Five Members of the Academy of Arts and Sciences
- ***Impact*** **of award-winning measurement science**

JILA Scientist receiving Nobel Prizes from King Carl XVI Gustaf of Sweden

National Academy of Sciences Evaluation of JILA

- “Undeniable world leader in many areas of quantum optics.”
- “Students in JILA receive an outstanding education in fundamental measurement science.”
- “Provides a stream of young talent for future needs.”

U.S. News

BEST GRAD SCHOOLS U.S.News & WORLD REPORT RANKINGS

- Ranked #1 or #2 AMO Physics graduate program for decades.
- Ranked #6 Quantum Physics graduate program.

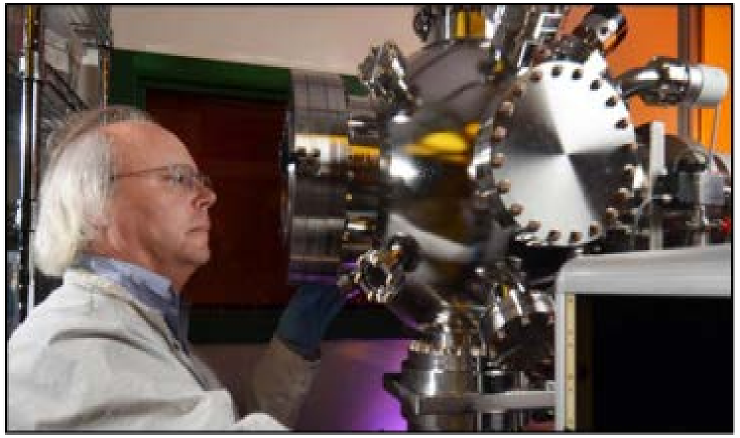
Unique JILA Technical & Support Infrastructure

- Administrative support. ~20 FTE
  - Grant application and administration.
  - HR (constant student/postdoc turnover).
  - Procurement.
  - Admin assistants to Fellow groups.
  - Etc.

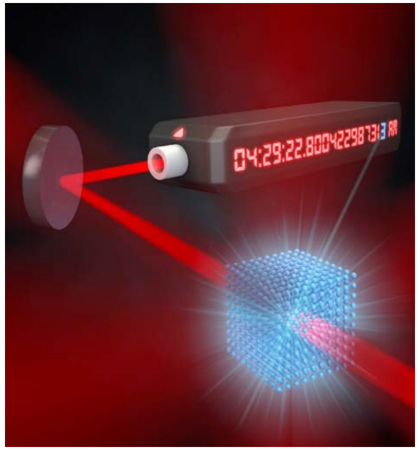
- Technical support. ~20 FTE.
  - Instrument shop.
  - Electronics shop.
  - IT shop.
  - Micro/nanofab.
  - Precision measurement lab.
  - Scientific Communications Office.
  - Facilities engineers.

- Goal 1: JILA Fellows and trainees spend the ***minimum possible time on anything other than research and training***.

- Goal 2: Trainees leave JILA with the confidence that they ***can design and build anything, including things never before built (mechanical, electronic, optical, micro/nanofab, etc.)***



JILA/QPD Roles in QIS



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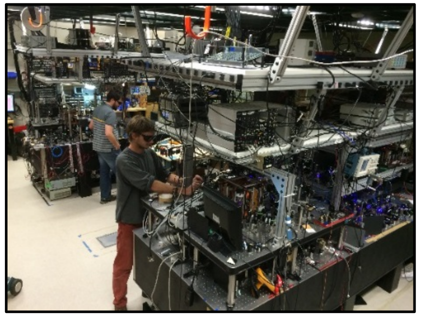

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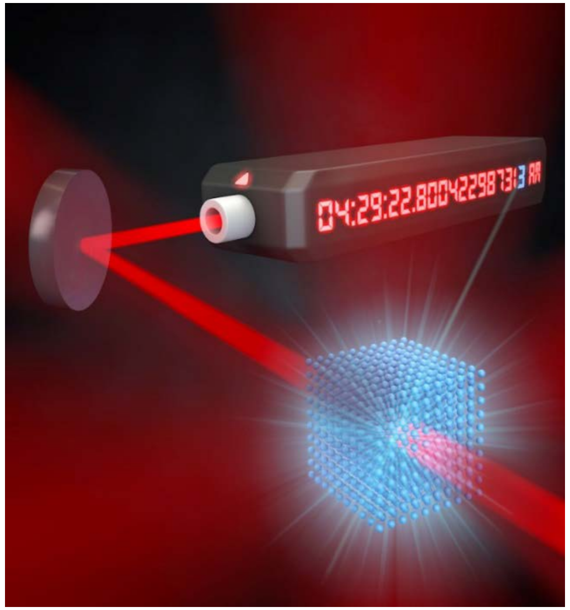
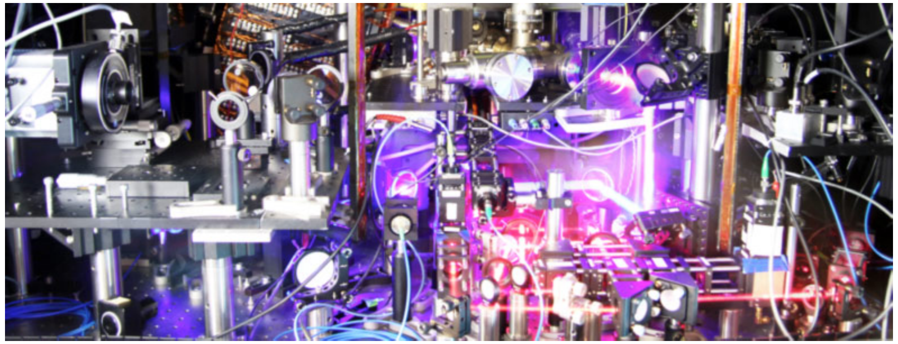
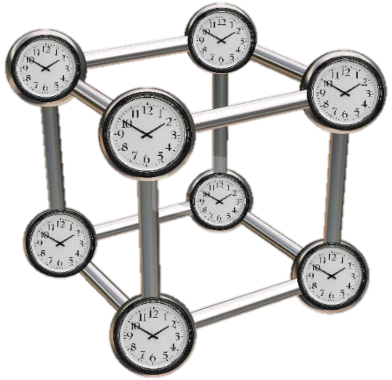
JILA/QPD Roles in QIS: *Technologies*

3D Fermi gas strontium (Sr) optical lattice clock

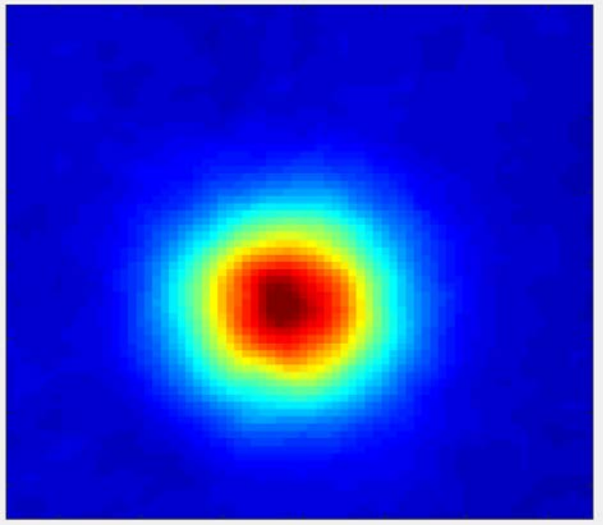






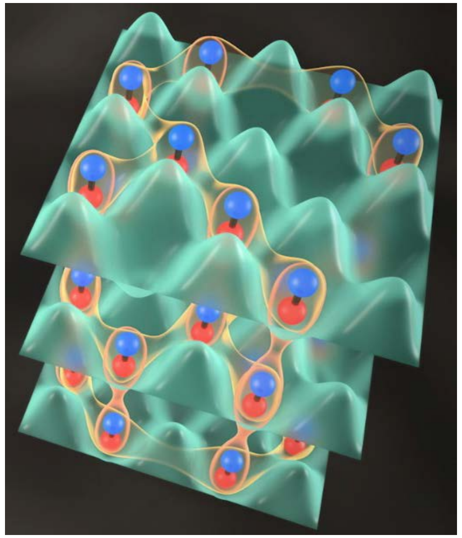
- First application of a quantum degenerate gas to improve a “practical” measurement.
- ~1 million atoms.
  100 x 100 x 100 3D lattice.
- Pauli exclusion: Only one atom per lattice site.
- Precision 3 x 10^{-20} in one second, on path to 10^{-22} in a few years.
- Coherence time 160 seconds and improving.
- “Traditional” precision timing applications.
- Laboratory for quantum physics, including quantum gravity.

JILA/QPD Roles in QIS: *Technologies*

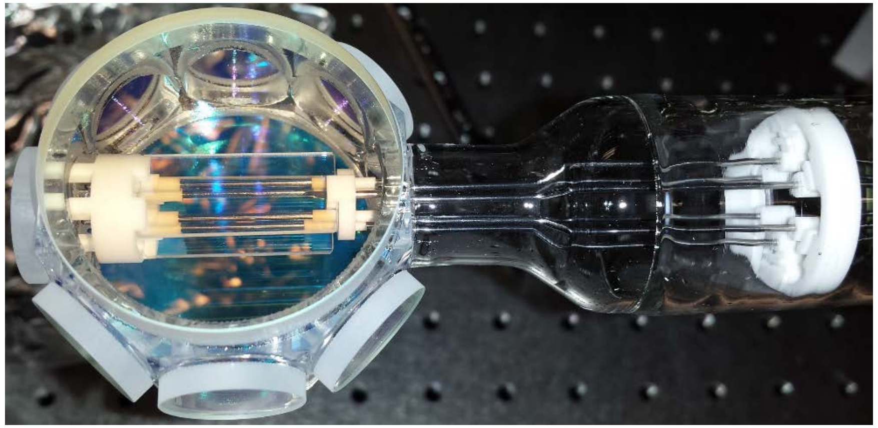


First ***molecular*** Fermi degenerate gas.

- Number = 40,000
- Temp = 80 nK
- T/T_F = 0.6

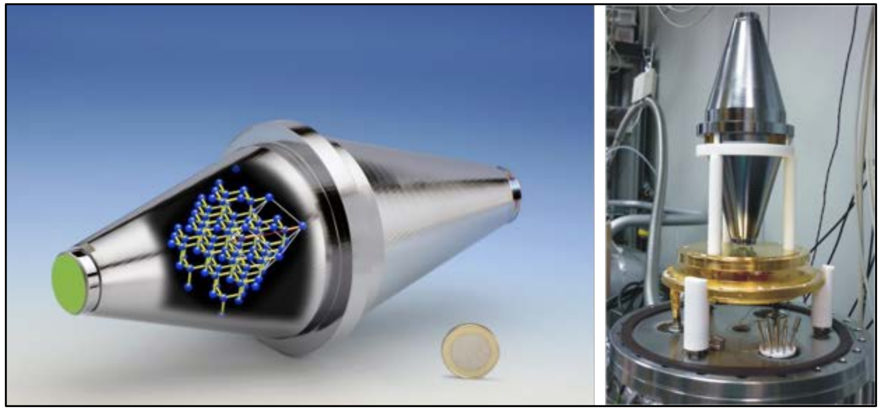


- Large scale, long-range quantum correlations.
- Laboratory for quantum many-body physics, topological matter, quantum simulation, etc.



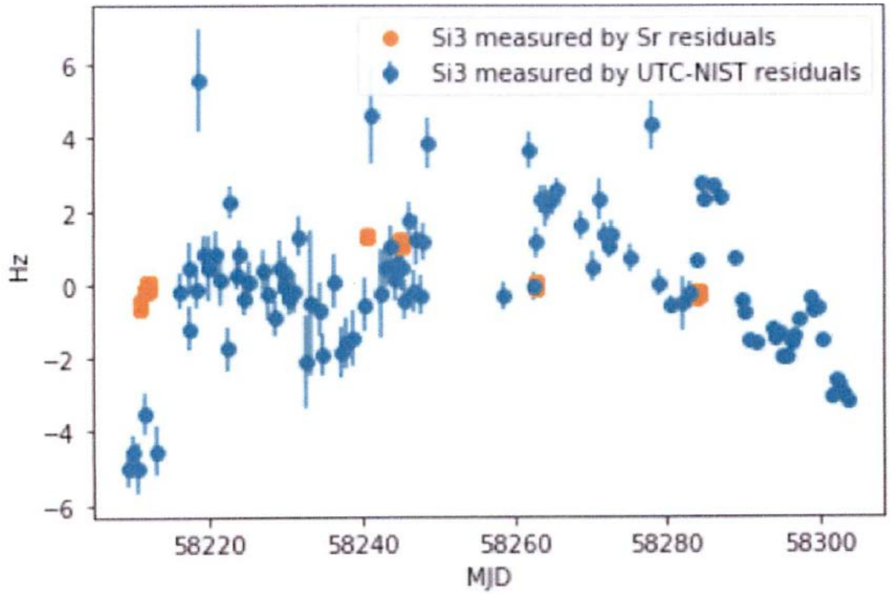
- Bosonic and Fermionic quantum degenerate gases serve as laboratories for quantum many-body physics, topological matter, human-controlled quantum chemistry, quantum simulation, etc.

JILA/QPD Roles in QIS: ***Technologies***



World's most stable laser.
~10^{-17}

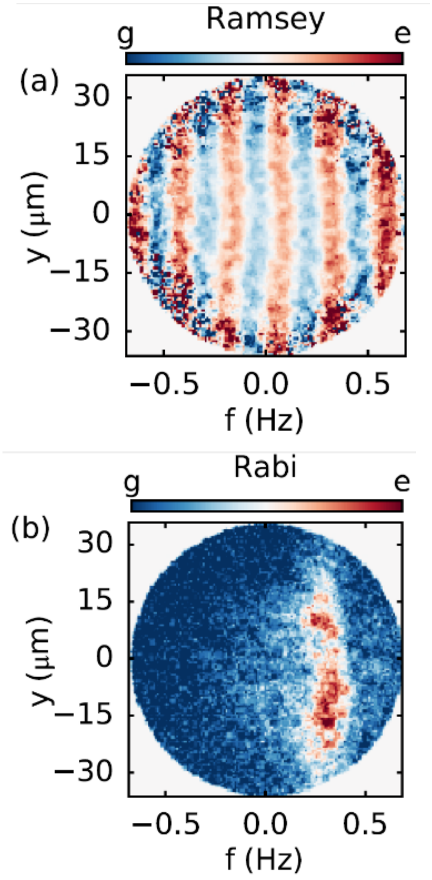
- Monolithic silicon cavity.
- Unique multi-layer end mirrors. Collaboration with Crystalline Mirror Solutions.

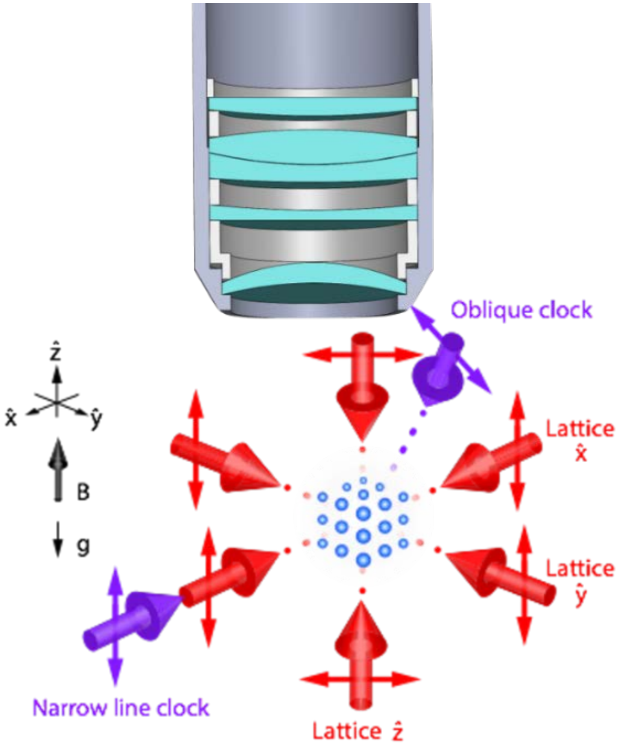


- ***Free-running*** Si cavity compared to UTC(NIST) over ~3 months.

JILA/QPD Roles in QIS: *Technologies*

Precision Imaging
Frequency Spectroscopy

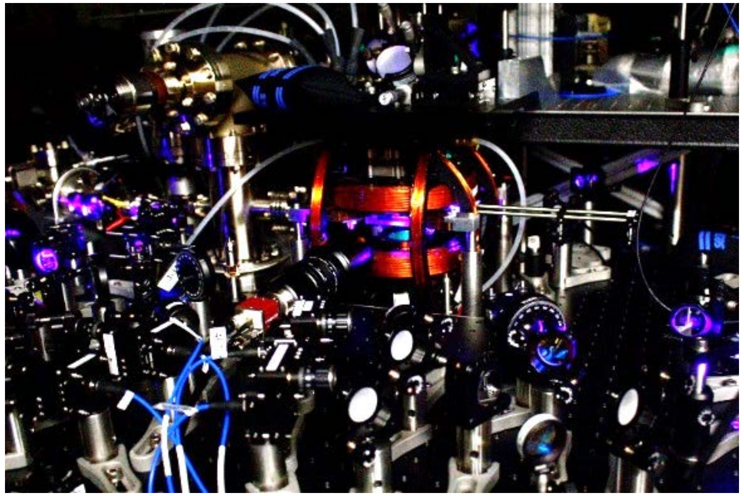


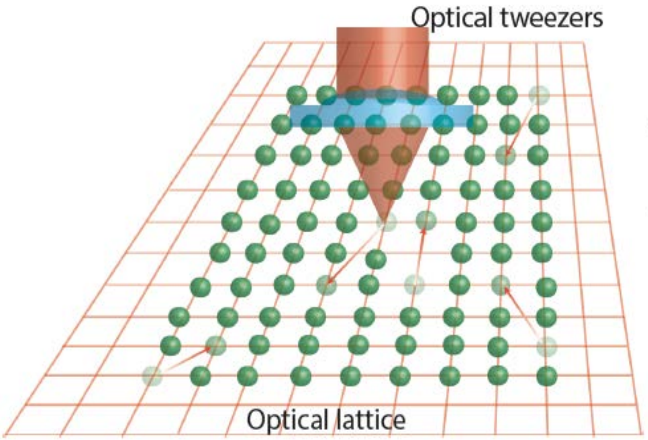


- Image 3D lattice to measure optical frequencies with 10^{-4} Hz precision at 1 μ spatial resolution.
- On path to simultaneously imaging frequency of each individual atom in 3D lattice of ~1 million atoms.
- Quantum sensor to precisely measure gradients of gravity, electromagnetic fields, etc. Broadly applicable, invention disclosure filed.
- Directly observe the transition from single body physics to many-body physics (strongly-correlated quantum states). Fundamental information for vast range of new quantum technologies.
- Future: Probe the fundamental interactions of gravity and quantum mechanics – Einstein's last big unsolved challenge.

JILA/QPD Roles in QIS: *Technologies*

Large-scale quantum correlated systems for QIS, Metrology, Research





- **Combined quantum gas microscope/optical tweezers using cold Sr atoms/ions.**

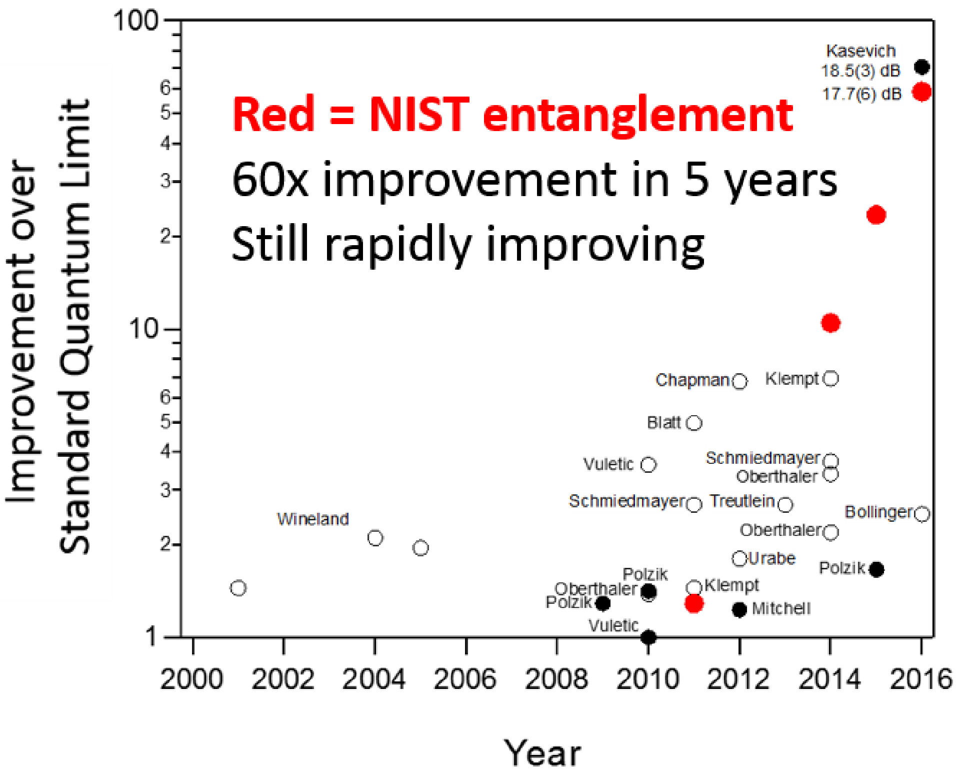
- Precise, fast, individual control and measurement of large arrays of quantum interacting atoms and ions:
    - Quantum computing and simulation.
    - Precision quantum measurements.
    - Quantum materials.

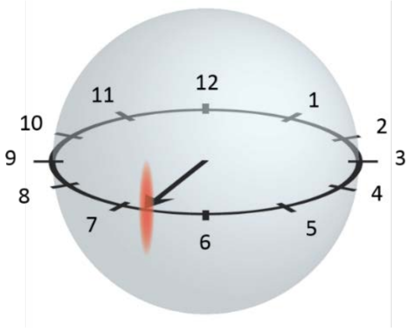
- From empty lab to lattice of 200+ strontium atoms in ~8 months.

- Scalable to arrays of 10^5 or more atoms/ions, each individually addressable for large scale quantum computing, quantum measurements, etc.

JILA/QPD Roles in QIS: ***Technologies***

Large-scale quantum correlated systems for QIS, Metrology, Research

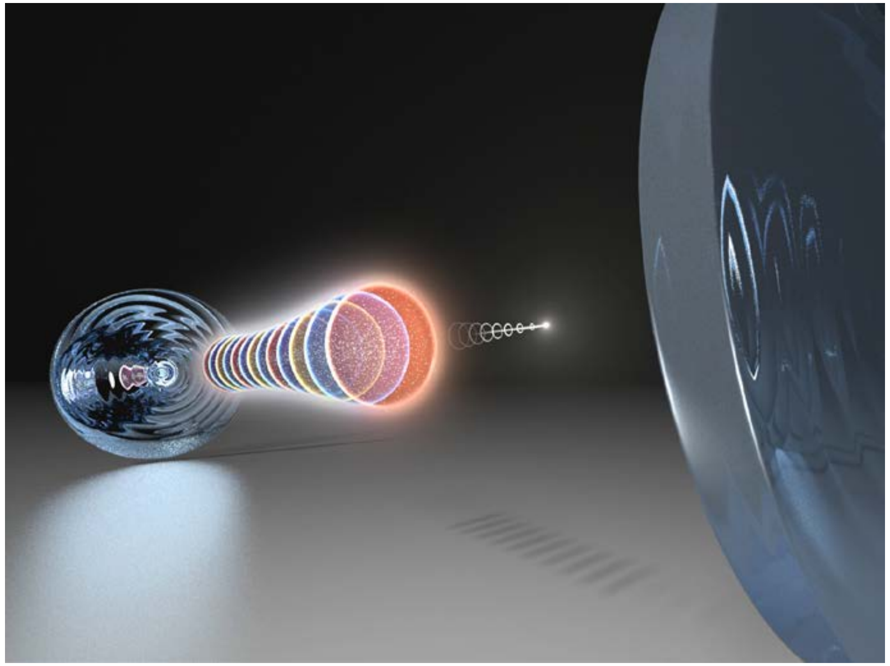




- **Entangling (state squeezing) large numbers of cold Rb atoms.**
- Tied for world-record improvement over Standard Quantum Limit in measurements. Still rapidly improving.
- Near-term application: High performance matter wave interferometers for precision measurement of gravity.
    - Resource location, undersea navigation, improved flood prediction, etc.

JILA/QPD Roles in QIS: *Technologies*

Large-scale quantum correlated systems for QIS, Metrology, Research



- **Super-radiant laser (ultracold Sr).**
- Laser phase information stored in Sr ***atoms*** rather than ***cavity length***.
- Long lifetime Sr transition provides potential for 10^{-20} laser stability.
- ~10,000 times less sensitive to cavity noise than “traditional” cavity-based laser.
  - Precision laser applications out of the metrology lab.
  - Frequency, length, gravity, etc. metrology in the field.

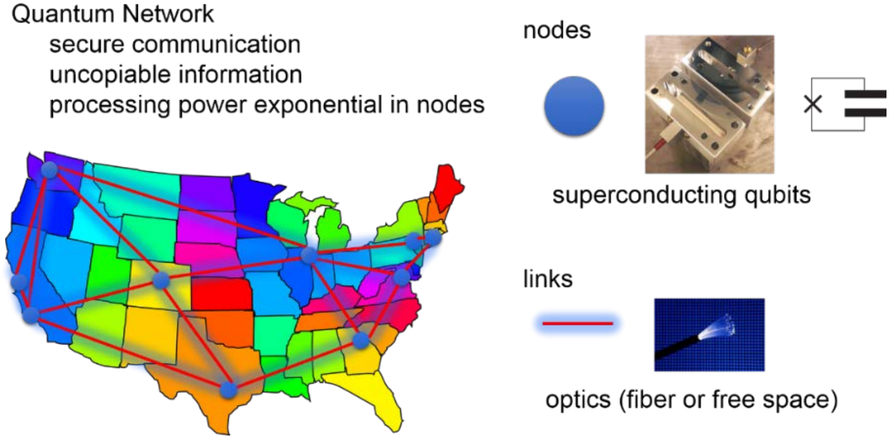
JILA/QPD Roles in QIS: *Technologies*

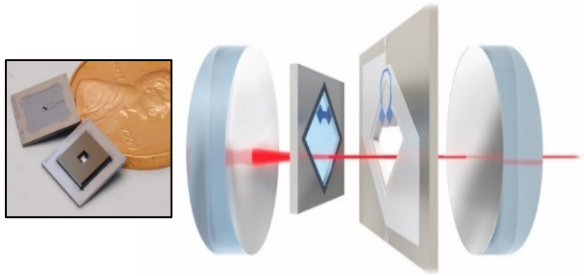
Quantum Transducers for Entangled Quantum Network

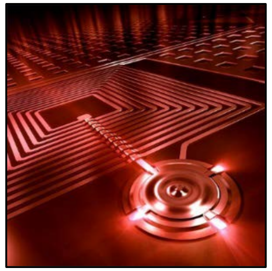
- Entangle processing nodes (superconducting qubits, ion qubits, etc.) through optical connections preserving quantum states.

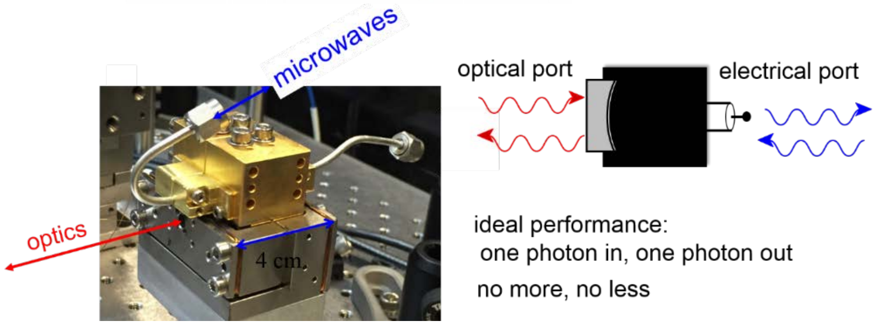
- Entanglement increases processing power exponentially.

- Secure, uncopiable networking.









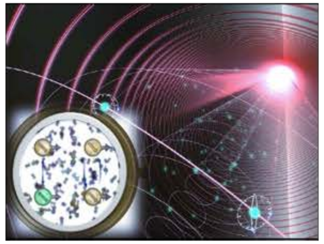
Published Results	Efficiency	Noise Photons
2014	8.5%	1500
2017	47%	13

- On path to demonstration of full quantum network.

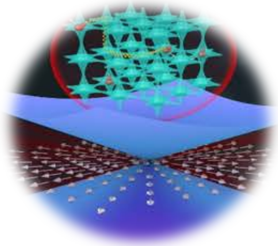
JILA/QPD Roles in QIS: *Technologies*

Close theory/experiment collaboration directly enabling new quantum technologies

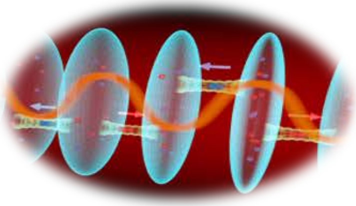
SU(N) symmetry | **Stable orbitals** | **Synthetic gauge fields**



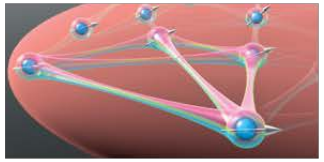
SU(N) spectroscopy
Science (2014)



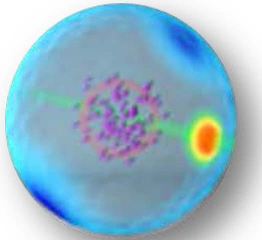
Weyl quasiparticles
Nature Com. (2016)



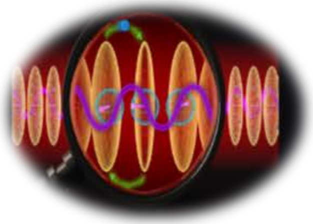
SOC & Interactions
Nature Phys. (2018), Nature (2017)



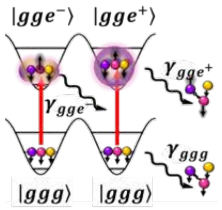
Beyond mean-field spin correlations Science (2013)



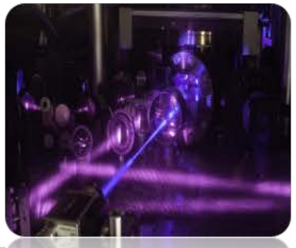
Radiating dipoles
Nature Com. (2016)



Proposal: SOC in optical clock, PRL (2016)

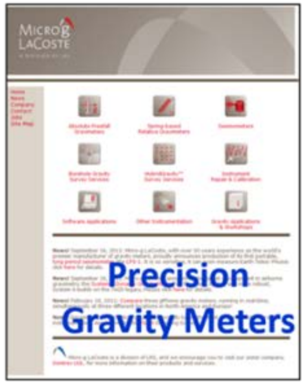


Multi-body SU(N) interactions
Nature 2018 (in press)



Ultra-precise Atomic Clock

JILA/QPD Roles in QIS: *Technologies*



JILA trainees and faculty start high-tech companies

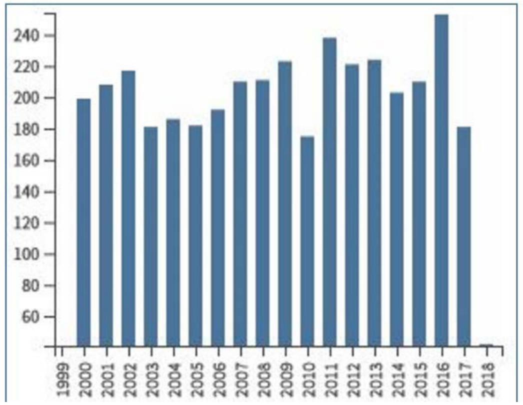
JILA innovations commercialized by other companies (PDH laser stabilization)

Neutral atom QC

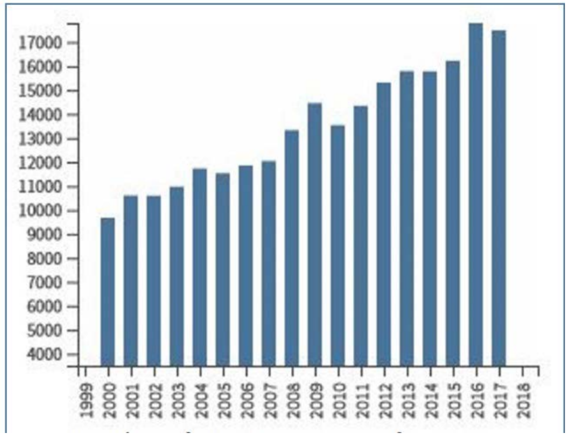
Vector Atomic Quantum sensors

JILA/QPD Roles in QIS: *Technologies*

Snapshot of JILA Publications



Number of **JILA publications** per year. March 2018.



Number of **citations of JILA publications** per year. March 2018.

Data from March 2018

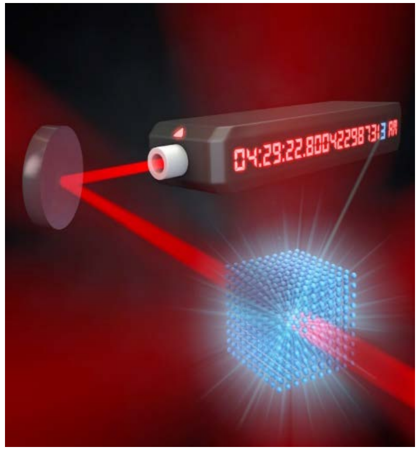
h-index: 225
Total publications: 8,021
Total citations: 356,418
Average citations per item: 44.44

Average ~200 publications/year in recent years

In **2016-2017**, JILA published 337 scientific items.
About 50% of those publications were in the highest impact international journals reflecting QPD/JILA's primary research areas, including:

- 22 *Physical Review Letters*
- 18 *Nature* group publications
- 17 *Science* articles
- 12 articles in *Optics Express* or *Optics Letters*
- 11 *Biophysical Journal* articles
- 4 *Journal of Physical Chemistry Letters*
- 7 *Nano Letters*

JILA/QPD Roles in QIS



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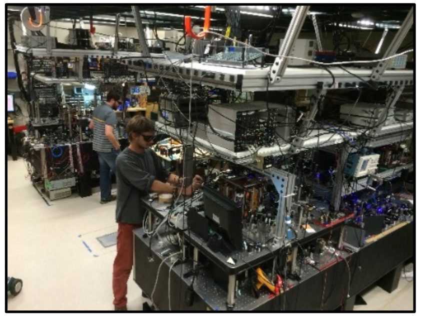

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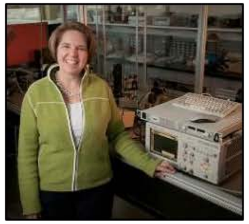
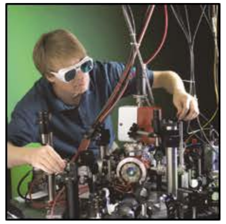
JILA/QPD Roles in QIS: ***Training***

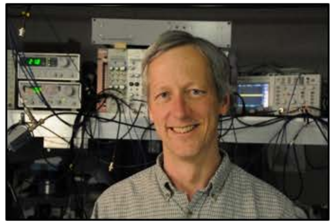


Marla Dowell
Director, Communications Technology Lab

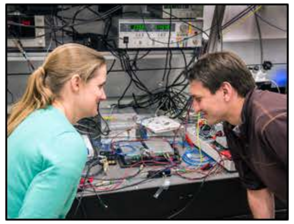
Gretchen Campbell
Co-Director, Joint Quantum Institute



Chris Oates
Chief, Time & Frequency Division

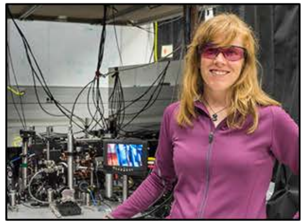


Nate Newbury, **NIST Fellow**
Chief, Applied Physics Division



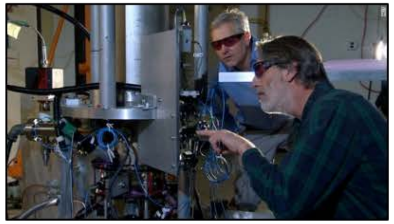
Laura Sinclair, Ian Coddington
Frequency combs for environmental sensing

John Kitching, **NIST Fellow**
Chip-scale atomic devices



Liz Donley
Miniature cold atom devices

Scott Diddams, **NIST Fellow**
Chip-scale frequency combs



Steve Jefferts, Tom Heavner
US national time standards

- >200 JILA alumni and trainees working at NIST (employees and associates).
- JILA alumni establish high-tech companies, lead industrial research, lead research at national labs, lead research at universities, etc.

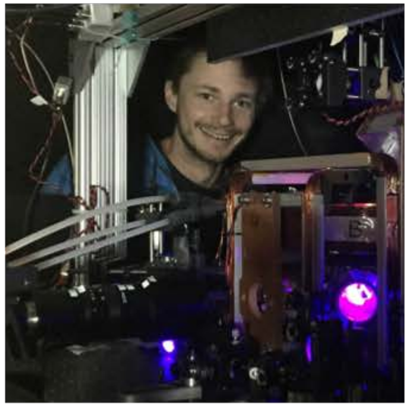
JILA/QPD Roles in QIS: *Training*

Impact of Current or Recent JILA Trainees

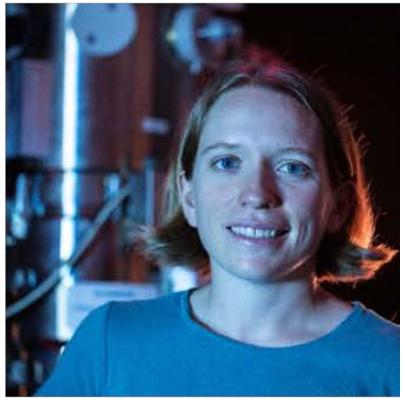
Marissa Weichman
2017 APS Thesis Prize
Chemical Physics
Frequency comb spectroscopy of large organic molecules

David Jacobson
2017 APS Thesis Prize
Biophysics
AFM studies of membrane proteins

Leah Dodson
2017 Miller Thesis Prize
Molecular Spectroscopy
Ultrafast chemical kinetics and dynamics



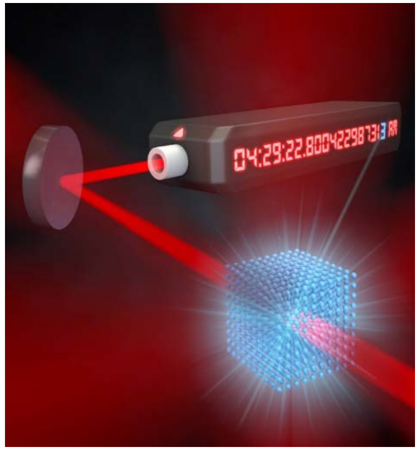
Matt Norcia
2018 Finalist for APS Thesis Prize
AMO Physics
Quantum gas microscopy



Sara Campbell
2018 APS Thesis Prize
Laser Science
Fermi degenerate gas atomic clock

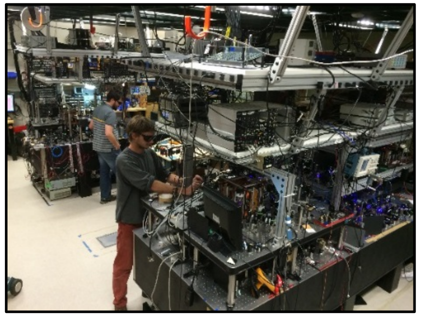
2018 Howard Hughes Medical Institute
Early Career Fellowship ($1.4 M)

JILA/QPD Roles in QIS



- ***Technologies:*** Pioneer new quantum technologies broadly used across NIST and across the world for QIS including quantum R&D, quantum engineering, quantum metrology, quantum SI (NIST program areas).
    - Fermi degenerate gas optical lattice clock.
    - Quantum degenerate molecular gases.
    - Precision frequency spectroscopy of large-scale quantum matter.
    - New methods for large-scale entanglement/state squeezing. Etc.

- ***Training:*** Building the quantum workforce of today and tomorrow.
    - Over the past 10 years, ~150 JILA PhDs and postdocs have taken jobs in QIS US industry and Federal labs.
        - Large companies: Microsoft QC, HRL QC, Honeywell quantum tech, Google QC, Lockheed Martin QC and quantum tech, etc.
        - Growing companies: Rigetti QC, AOSense quantum tech, etc.
        - Start-ups founded by JILA grads: Atom Computing QC, Vector Atomic quantum sensors, etc.



- ***Transformation:*** Continually expand into new areas.
    - Creating, controlling, measuring quantum many-body systems to enable quantum measurements, quantum computing, quantum simulation.
    - Quantum-based tabletop "big physics."
    - Quantum biometrology.

JILA/QPD Roles in QIS: *Transformation*

- **JILA continually evolves and reinvents its scientific portfolio in response to changing needs and opportunities.**

  - 1995: First quantum degenerate gas of atoms (BEC).
  - 2008: Quantum degenerate molecular gases and human controlled quantum chemistry.
  - 2017: Fermi quantum degenerate gas clock – first "practical" application of quantum degenerate gas to improve metrology.
  - Today: Studying and applying large-scale quantum collective phenomena to quantum technologies.

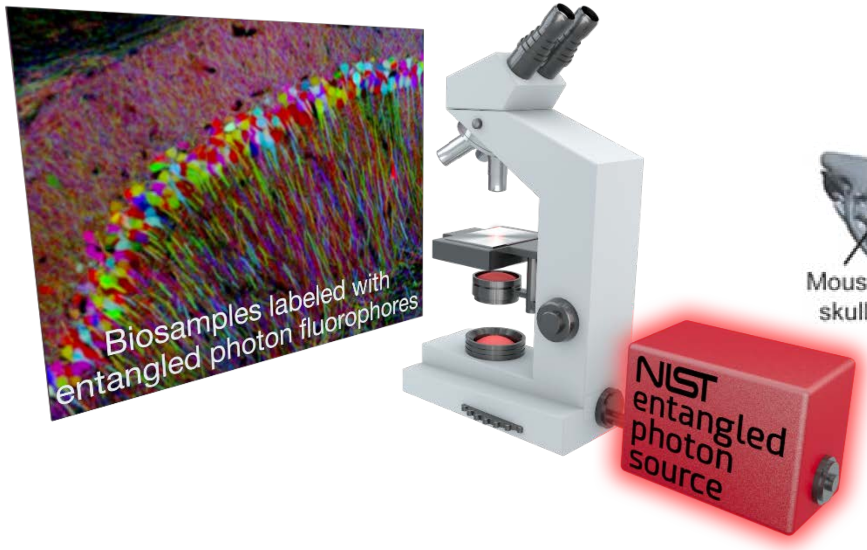
  - 1970: Precision gas-phase chemical spectroscopy.
  - 2005: Ultrafast spectroscopy of simple chemical reaction dynamics.
  - Today: Fully-resolved precision spectroscopy of large organic molecules using frequency combs (rotation, vibration, electronic, folding, etc.).

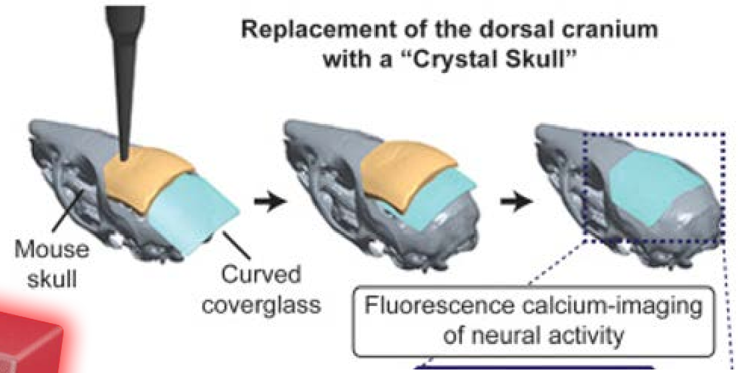
  - 1962: JILA founded to study laboratory astrophysics.
  - 1990: No laboratory astrophysics.
  - Today: "Tabletop big physics" experiments for key astrophysical/cosmological questions: Standard Model tests, dark matter/energy, gravity waves, etc. Complement or exceed capabilities of multibillion dollar big physics facilities while pioneering new ultraprecision metrology capabilities.

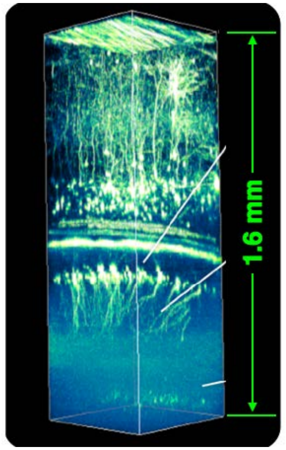
  - Many other examples of QPD/JILA transformation: Biophysics, quantum physics of macroscopic systems (quantum transduction), etc.

JILA/QPD Roles in QIS: ***Transformation***

Quantum biometrology: 3D real-time fluorescence imaging of living tissues with entangled photons







Current: 10% penetration of mouse brain, hours of collection time.

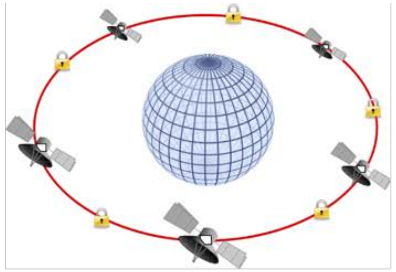
- Use entangled photons and new bioengineered fluorophores (bio markers) to enable minimally invasive fluorescence microscopy of living tissues.
- $>10^6$ quantum enhancement in imaging efficiency to enable 10x greater depth penetration and resolution without laser damage/perturbation to normal biochemistry and physiology.
- Initial goal: Enable real-time fluorescence imaging of entire living mouse brain.

JILA/QPD Roles in QIS: *Transformation*

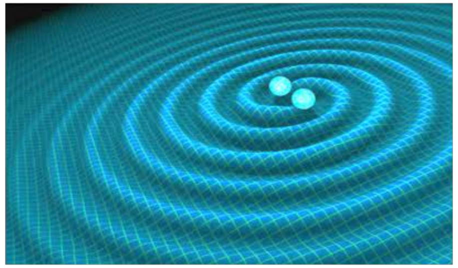
NIST

Tabletop fundamental physics complementing or exceeding multibillion dollar "big physics" experiments:

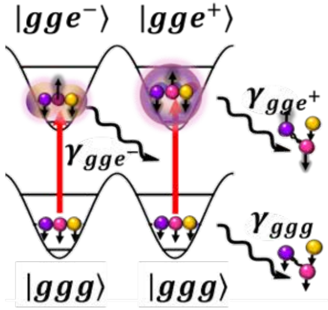
Dark matter detection/measurement



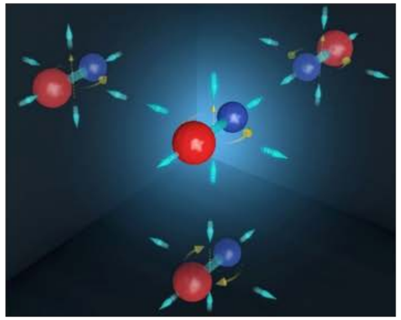
Global network of precision clocks (10^{-21}) for secure quantum communications networks, long-baseline astronomical observation, etc.



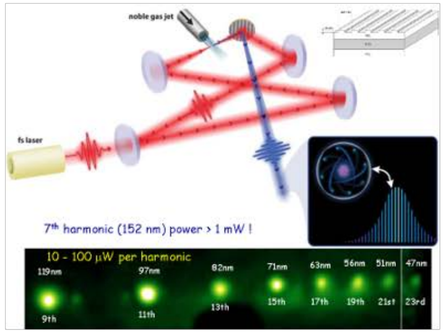
Gravity wave measurement at frequencies inaccessible to LIGO/VIRGO



Study of multi-body SU(N) interactions in atomic systems: Probe details of Standard Model on tabletop. (June 2018)



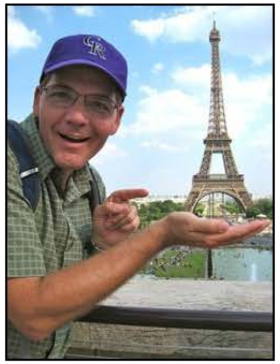
Measurement of electric dipole moment of electron (eEDM) at 10^{-30} precision. Probes Standard Model, big-bang cosmology.

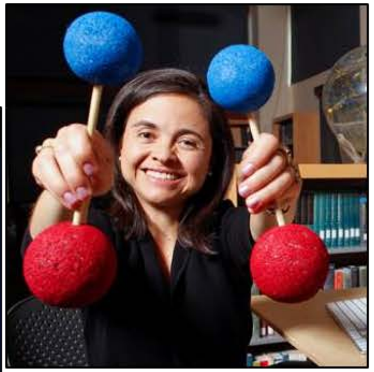


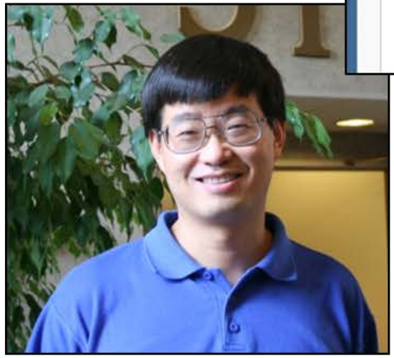
XUV laser frequency comb, down to ~20 nm with continuing higher energies, brighter than synchrotron.

JILA: More Information

jila.colorado.edu







JILA: More Information

Additional Slides

NIST Scientist JILA Fellows (QPD)

NIST

John Bohn
Theory
Ultracold atoms & molecules
Quantum many-body
QIS

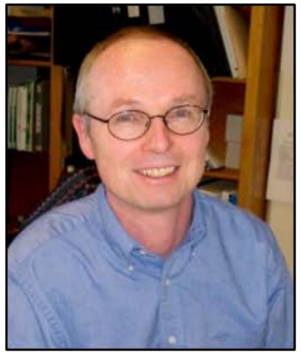
Eric Cornell
Experiment
Ultracold atoms & molecules
Precision measurements
QIS

Ralph Jimenez
Experiment
Biophysics
Ultrafast phenomena
QIS

Ana Maria Rey
Theory
Ultracold atoms & molecules
Quantum many-body
QIS

James Thompson
Experiment
Quantum many-body
Precision measurements
QIS

Konrad Lehnert
Experiment
Quantum transduction
Precision measurements
QIS



David Nesbitt
Experiment
Chemical physics
Biophysics
QIS

Tom Perkins
Experiment
Biophysics
Precision measurements

Jun Ye
Experiment
Ultracold atoms & molecules
Quantum many-body
Ultrafast phenomena
Precision measurements
QIS

Adam Kaufman
Newest JILA Fellow (Fall 2017)
Experiment
Quantum many-body
Precision measurements
QIS

CU Faculty JILA Fellows (Non-NIST)

Close and continual collaborations between NIST and nearly all CU JILA Fellows

- Dana Anderson, CU Physics, quantum sensors, precision measurements, **QIS**
- Phil Armitage, CU Astrophysics, black holes, galaxy/planet formation
- Andreas Becker, CU Physics, ultrafast phenomena, **QIS**
- Mitch Begelman, CU Astrophysics, astrophysical gas & magnetohydrodynamics
- Andrew Hamilton, CU Astrophysics, black holes, cosmology
- Murray Holland, CU Physics, ultracold atoms & molecules, quantum optics, **QIS**
- Agnieszka Jaron-Becker, CU Physics, ultrafast phenomena, **QIS**
- Henry Kapteyn / Margaret Murnane, CU Physics, ultrafast phenomena, quantum optics, **QIS**
- Heather Lewandowski, CU Physics, ultracold molecules, chemical physics, **QIS**
- Carl Lineberger, CU Chemistry, chemical and molecular physics
- Anne-Marie Madigan, CU Astrophysics, planetary dynamics
- Cindy Regal, CU Physics, quantum nanomechanics, **QIS**
- Graeme Smith, CU Physics, quantum information theory, **QIS**
- Juri Toomre, CU Astrophysics, solar/stellar structure and evolution
- Mathias Weber, CU Chemistry, chemical and molecular physics