National Aeronautics and
Space Administration

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Space Administration

BPAC:

Fundamental Physics and Soft Matter

Mike Robinson 4/26/2024

Fundamental Physics Program Scientist

BPS

Biological & Physical Sciences

Fundamental Physics

"I didn't even know there was a problem about clocks initially. My wristwatch was pretty good."

Norman Ramsey, Father of the Atomic Clock

https://ethw.org/Oral-History:Norman_Ramsey_(1995)

→ GPS, MRI, NMR, …

BPS Fundamental Physics

- Transformational experiments that require the unique environment of space
  - Microgravity
  - Long baselines
  - Gravitational potentials

Interests

Quantum mechanics

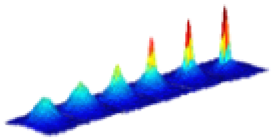
General relativity

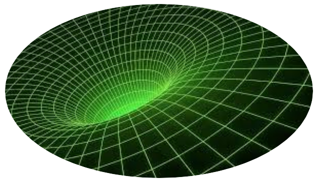
Equivalence principle

Dark matter

Dark energy

Exotic physics





Tools

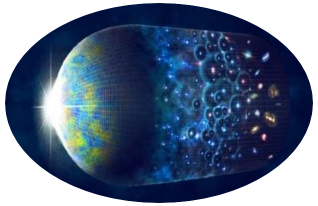
Cold atoms

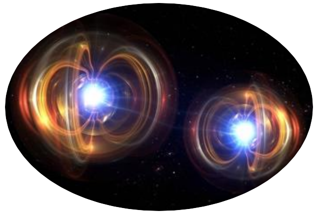
Atomic clocks

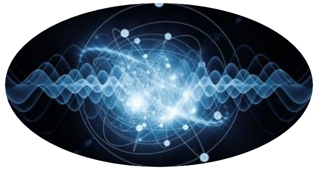
Atom interferometry

Quantum entanglement

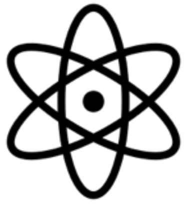
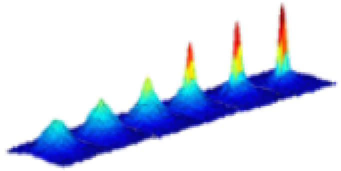
Collaboration



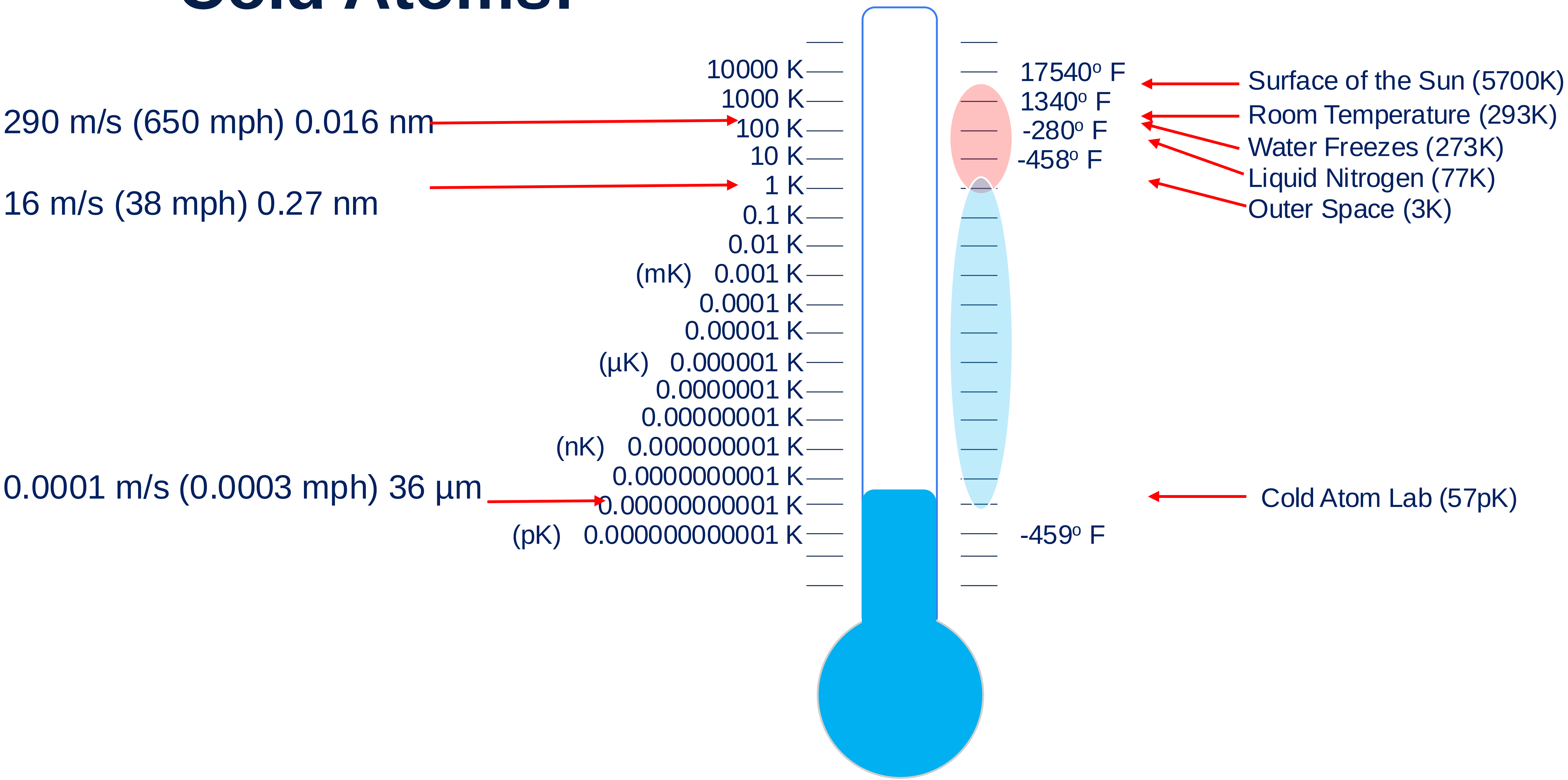




NASA Fundamental Physics Program

	Ground	*Space*	*Future*
Atomic Clocks 	Ground Lattice Clock (JPL, Berkeley)	ISS **ACES** (ESA) 2025	Deep Space Optical Clock; Clock Networks
Atom Interferometry 	Tractor Atom Interferometry (ARL); Drop Tower **D3E3** (DLR) 2025	ISS **CAL** 2018; ISS/CLD **BECCAL** (DLR) 2027	CLD Atom Interferometry; Free-flying Atom Interferometry Network
Quantum Entanglement 	Quantum Networks on Curved Space-Time Stevens; Ground 10km **DSQL, AST** 2025; Mountain Top **DSQL** 2025	ISS **SEAQUE** 2024; *Small Sat **QEYSSat** (CSA) 2027*	Ground-to-Space Interferometry; Earth-to-Moon Interferometry

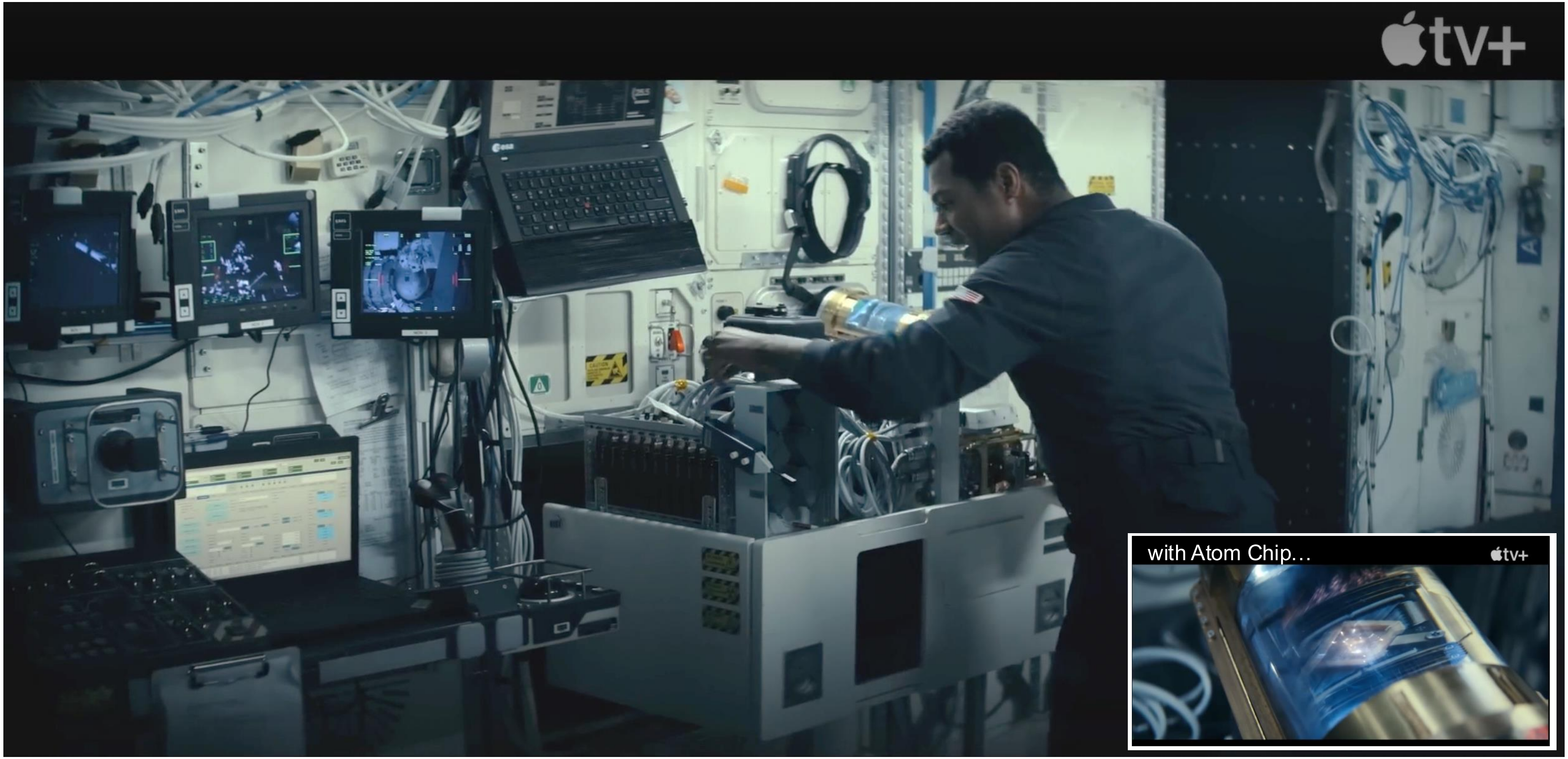
Cold Atoms:



Less than 4 orders of magnitude temperature difference between the surface of the sun and outer space.
~11 orders of magnitude difference between outer space and temperatures the Cold Atom Lab has reached.

Apple TV+ series "Constellation"

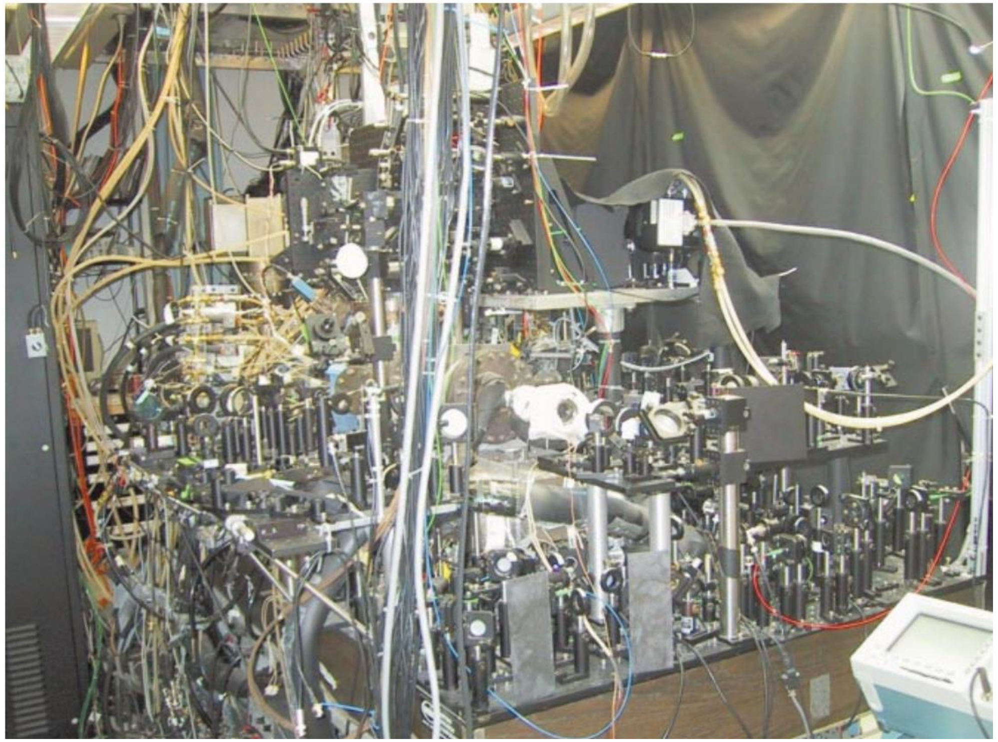
Features the Rocket Propulsion Laboratory (RPL) "Cold Atom Lab (CAL)" on ISS



CAL Update

- Dual species atom interferometry!
- Science Module 3b launched Aug 2 and installed Sep 25-29
  - Mesoscale trap -> more atoms
  - Replaces faulty electronics
  - Vacuum failed – replacing with original SM1
    - Installation pending/ion pump not connected
    - SM-3B returns for repair April 25
- Gaaloul, et al., “A space-based quantum gas laboratory at picokelvin energy scales.” Nature Communications, 22 December 2022. https://doi.org/10.1038/s41467-022-35274-6
- Elliott, E.R., Aveline, D.C., Bigelow, N.P. et al. Quantum gas mixtures and dual-species atom interferometry in space. Nature 623, 502–508 (2023). https://doi.org/10.1038/s41586-023-06645-w
  - First ever dual species atom interferometry in space. Space based AIs have applications in geodesy, gravitational wave detection, precision navigation, tests of the equivalence principle, dark matter/dark energy searches

Astronauts Jasmine Moghbeli and Loral O’Hara installing SM3b

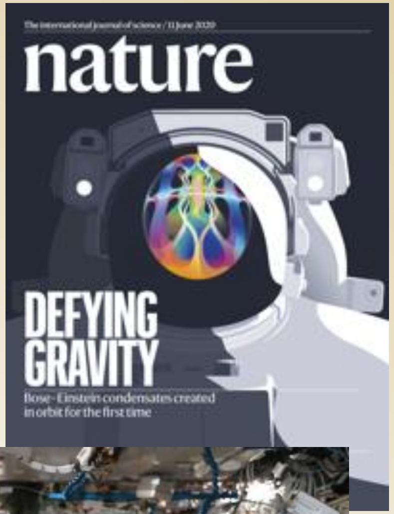


From W. Ketterle, *Nobel lecture: When atoms behave as waves: Bose-Einstein condensation and the atom laser,* REVIEWS OF MODERN PHYSICS, VOLUME 74, OCTOBER 2002

https://www.jpl.nasa.gov/missions/cold-atom-laboratory-cal

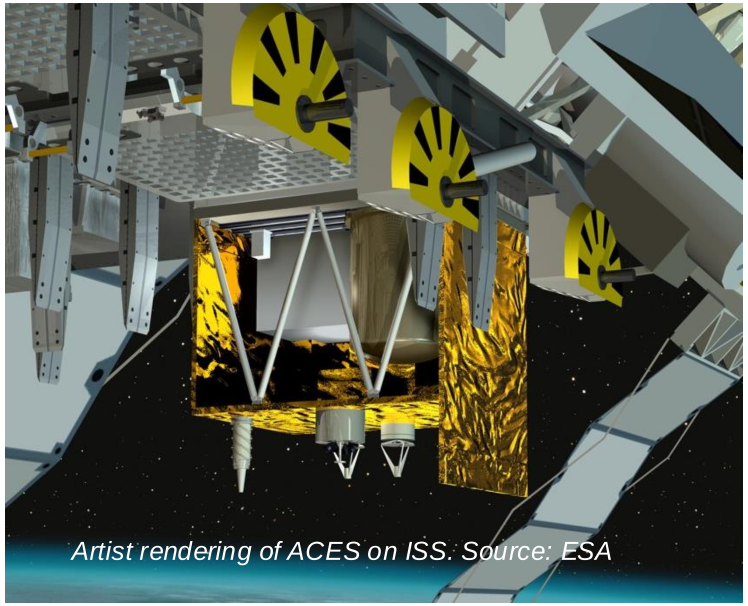
Current projects

- Cold Atom Lab (CAL)
  - Dual species Rb/K BEC and atom interferometry on ISS
  - User facility operated by JPL
- BECCAL
  - DLR collaboration follow on to CAL, 2027 FHA
  - Upgraded capabilities
  - Blue detuned box potentials and optical dipole trap
  - Equivalence principle tests
  - Dark energy search
  - Many-body physics
- Direct Detection of Dark Energy in the Einstein Elevator (D3E3)
  - DLR collaboration
  - Atom interferometry in the Einstein elevator
    - First drop March 2025
    - Periodic test mass for dark energy search



Current projects

- Atomic Clock Ensemble in Space (ACES)
  - ESA collaboration
  - Targeted SpaceX-32, Feb 2025
  - 10^{-16} Cs atomic clock on ISS
  - Gravitational redshifts
  - Physical constants
  - BPS-funded ground stations at NIST and JPL
- Space Entanglement and Annealing Quantum Experiment (SEAQUE)
  - Demonstrate source of entangled photons
  - Validate laser annealing to repair single-photon-detectors
  - Expected launch Sep 2024 SpaceX-31
  - Deep Space Quantum Link test bed
    - Long baseline Bell tests
    - Tests of quantum field theory in curved spacetime



Artist rendering of ACES on ISS. Source: ESA

Selections from ROSES 2022

- **CAL Flight Investigations**
  - Nicholas Bigelow, U. Rochester *Consortium of Ultracold Atoms in Space*
  - Nathan Lundblad, Bates *Quantum dynamics of ultracold bubbles*
  - Cass Sacket, *Bloch Oscillations in Microgravity*

- **Ground Investigations**
  - Shimon Kolkowitz, UC Berkeley *Developing new techniques for ultra-high-precision space-based optical lattice clock comparisons*
  - Vladimir Malinovsky, ARL *Tractor atom interferometer for fundamental physics, quantum sensing, and space science applications*
  - Alex Lohrmann, JPL *Teleportation of atomic states between Earth and space*
  - Igor Pikovski, Stevens Institute of Technology *Atomic quantum networks on curved space-time*

Awards Expected Soon

Decadal Survey – Fundamental Physics

Theme: Probing Phenomena Hidden by Gravity of Terrestrial Limitations

- Key Science Question 11. What new physics, including particle physics, general relativity, and quantum mechanics, can be discovered with experiments that can only be carried out in space?

Search for new physics with clocks.

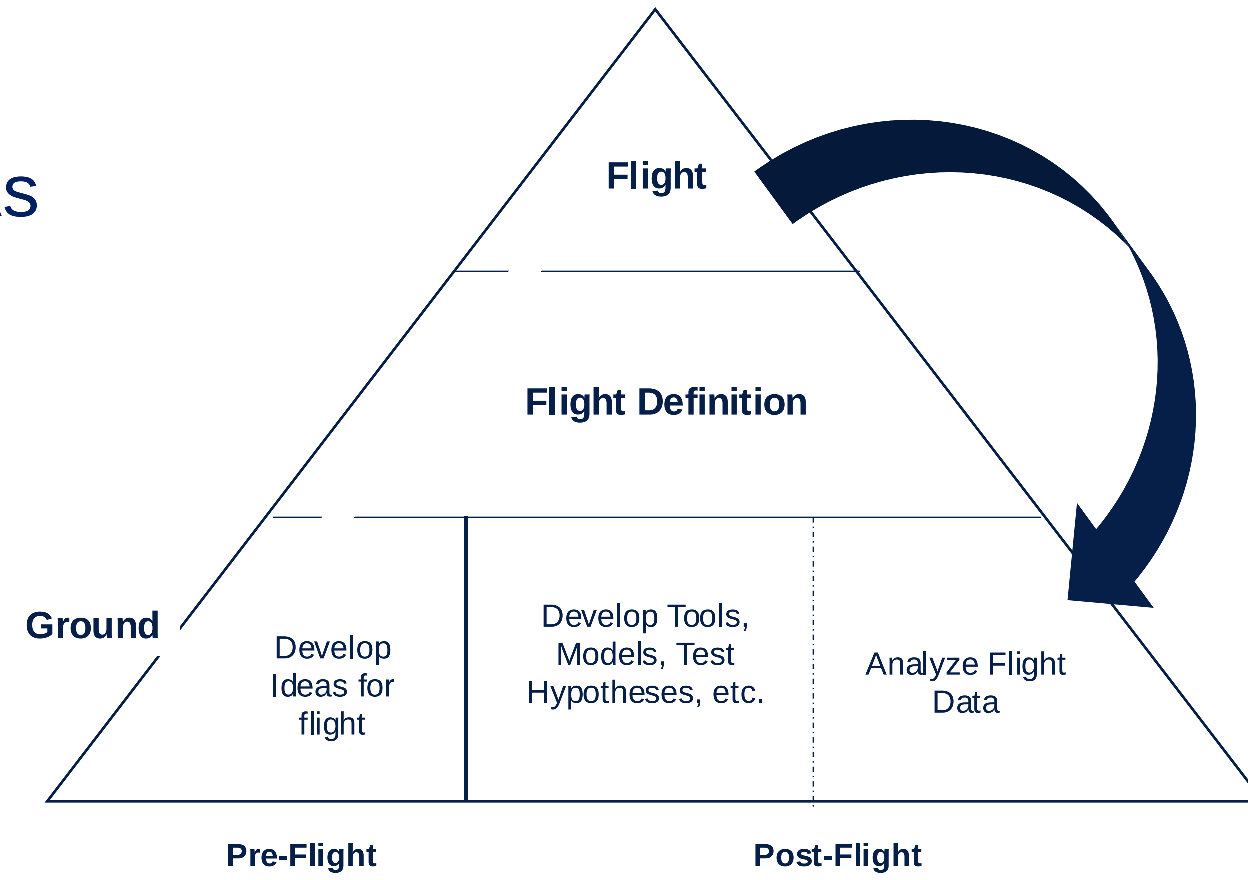
Gravitational effects on quantum optical systems and detectors.

Multi-Agency Opportunity: Probing the Fabric of Space-Time (PFaST)

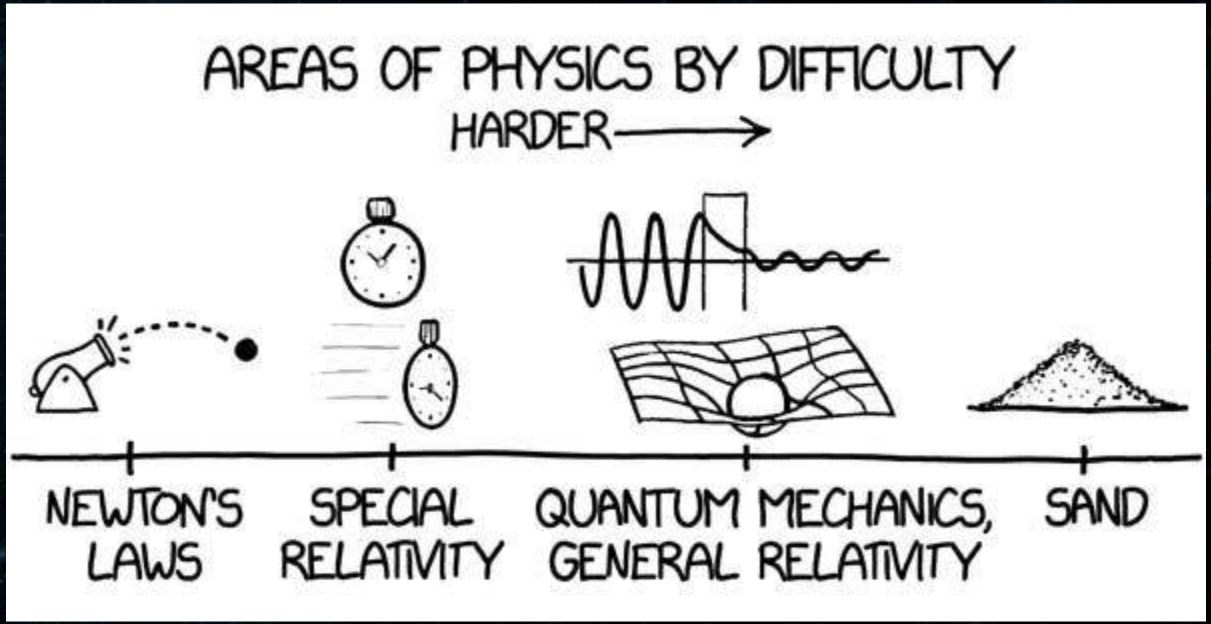
PFaST would use recent advances in atomic and optical clocks and spaceflight's ability to span large distances and large variations in gravitational fields to seek both validation of purely theoretical models as well as previously unobserved features of spacetime.

Future Portfolio

- Heavily influenced by Decadal Survey
  - Still digesting
- Expectation to restore annual cadence to fundamental physics NRAs



Soft Matter



https://www.nytimes.com/2020/11/09/science/what-makes-sand-soft.html

What is Soft Matter?

Pierre-Gilles de Gennes | Nobel Prize, Soft Matter, Polymer Science (1991)

- Soft matter as materials with two primary features – (a) complexity and (b) flexibility. In simple terms, soft matter aka complex fluids are materials that soft in nature and are neither pure elastic materials like steel nor Newtonian fluids like water.

- They are “soft” in nature and doesn’t follow linear Newtonian laws (e.g.- laws of elasticity, law of viscosity of Newtonian Fluids). Broadly, soft matter includes - polymers, foams, granular materials, colloids, gels, liquid crystals and other non-Newtonian fluids.

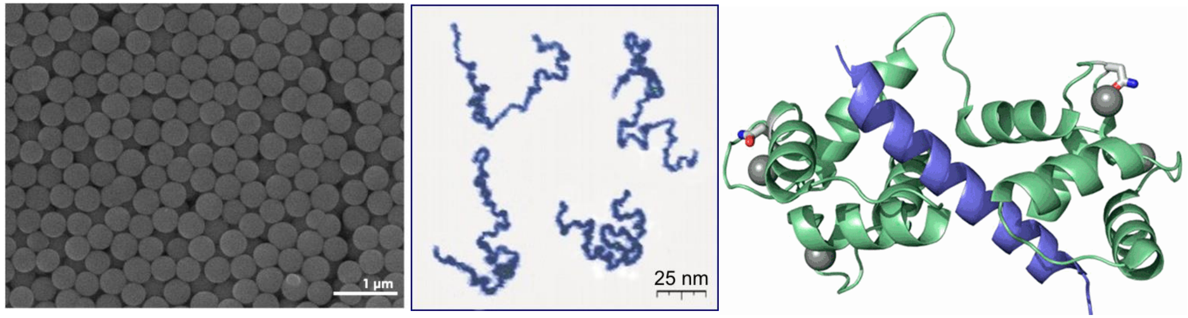
Our Perspective of Soft Matter

- **We broadly classify soft matter into two categories-**
  - ✓ Granular Media
  - ✓ Active Media

Granular Media

- ✓ Fundamental model describing rheology under different gravity conditions
- ✓ Understand impact of size, shape, electrostatic charge on flow behavior

Active Media



- ✓ Development of functional soft materials (e.g.- DNA functionalized colloidal particle)
- ✓ Understanding the interplay of competing microscopic forces in active matter

Why Study Active Matter in Microgravity?

Forces in Active Matter

Active matter's non-equilibrium status is an ensemble behavior of molecular level short-range forces

Present Knowledge Gap

Earth gravity overshadows short-range molecular forces making it difficult to study the non-equilibrium behavior.

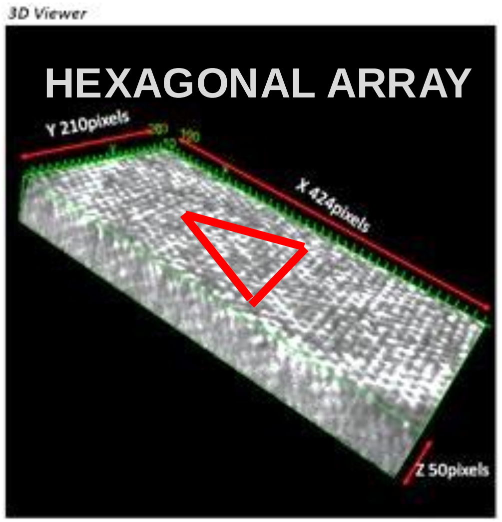
Uniqueness of Microgravity Environment

- ✓ Allows understanding of interplay of short-range molecular forces enriching fundamental understanding
- ✓ Allows studying without settling and buoyancy driven convection
- ✓ Allows us to produce unique technology platforms that aren't possible on earth

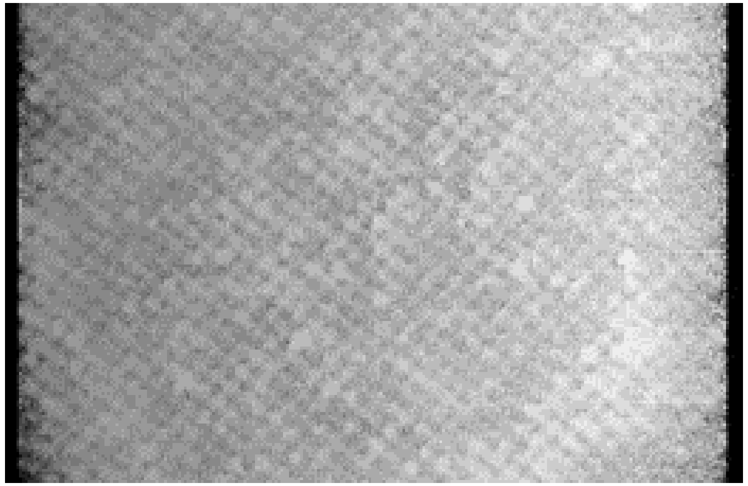
⇒Short-range molecular forces dominate behavior leading to 3D structures different from 2D assemblies seen in a terrestrial environment.

Some Active Matter Studies in Microgravity

ACE-T11



3D image stacks: ~ 40 x 20 x 5 microns.



Square phase cross section of FCC crystal near (100) plane; identified ~ 520 spheres of $1.3\mu m$ in diameter

Objective & Outcome of the Study

- ✓ Investigate self-assembly of micron-sized colloidal particles in microgravity
- ✓ Showed production of macroscopically large crystals (*perfect FCC Crystals*), which isn't possible on ground owing to settling

Importance of the Study

- ✓ Develop photonic crystals that control light, important for the communications industry and future optical computing

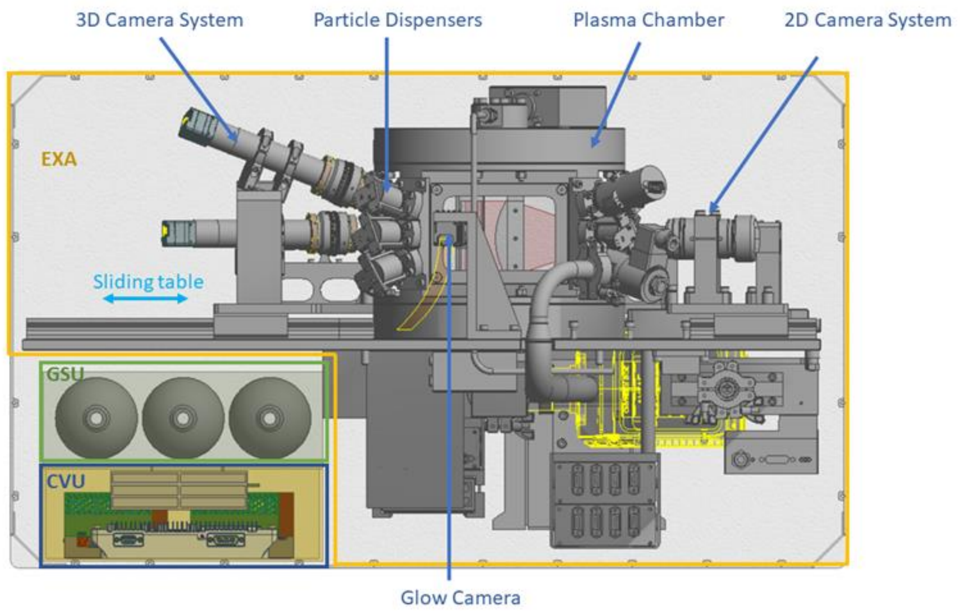
Publications

- ✓ Non-provisional Patent Application 01011879-1, Method And Apparatus For Fabrication Of Large Three-dimensional Single Colloidal Crystals For Bragg Diffraction Of Infrared Light
- ✓ Khusid, Chaikin, Hollingsworth, Meyer, et al., "Monster Hard Sphere Colloidal Crystals From Outer Space" (To Be Submitted To Nature)
- ✓ Khusid, Chaikin, Hollingsworth, Meyer, et al., "Large, defect-free FCC colloidal crystals under microgravity"

COMPACT

- Dusty plasma experiment
- DLR and NSF collaboration
  - DLR hardware build
  - NASA launch
  - Principal Investigators time: 50% DLR, 25% NASA, 25% NSF
- Planned launch 2028
  - Potential ISS or CLD

- **Statistical physics, phase transitions, and nonlinear dynamics**
- **Planetary physics**
- **Exploration dust management**



Decadal Survey – soft matter

- Key Science Question 1. How does the space environment influence biological mechanisms required for organisms to survive the transitions to and from space, and thrive while off Earth?
- Key Science Question 4. What are the important multi-generational effects of the space environment on growth, development, and reproduction?
- Key Science Question 5. What principles guide the integration of biological and abiotic systems to create sustainable and functional extraterrestrial habitats?
- Key Science Question 6. What principles enable identification, extraction, processing, and use of materials found in extraterrestrial environments to enable long-term, sustained human and robotic space exploration?
- Key Science Question 9. What are the fundamental principles that organize the structure and functionality of materials, including but not limited to soft and active matter?
- Key Science Question 10. What are the fundamental laws that govern the behavior of systems that are far from equilibrium?
- Campaign: Manufacturing Materials and Processes for Sustainability in Space (MATRICES)
- Campaign: Bioregenerative Life Support Systems (BLISS)

Publications in the last year – Fundamental Physics

- Elliott, E.R., Aveline, D.C., Bigelow, N.P. et al. Quantum gas mixtures and dual-species atom interferometry in space. Nature 623, 502–508 (2023). https://doi.org/10.1038/s41586-023-06645-w
- Alexander Lohrmann, Aileen Zhai, and Makan Mohageg "Classical clock synchronization for quantum communications using the quantum channel" Applied Optics (2023). https://doi.org/10.1364/AO.501323
- N. Ashby, B. Patla “A Relativistic Framework to Establish Coordinate Time on the Moon and Beyond“ arXiv preprint arXiv:2402.11150
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- Williams et al., “Interferometry of Atomic Matter Waves in the Cold Atom Lab onboard the International Space Station”, arXiv preprint: https://arxiv.org/abs/2402.14685

Publications in the last year – Soft Matter

- Chieco, Anthony T., and Douglas J. Durian. "A simply solvable model capturing the approach to statistical self-similarity for the diffusive coarsening of bubbles, droplets, and grains." arXiv preprint arXiv:2303.09612 (2023). https://arxiv.org/pdf/2303.09612
- Durian, Douglas J. "Effective exponents for the diffusive coarsening of wet foams and analogous materials." arXiv preprint arXiv:2304.00415 (2023). https://arxiv.org/pdf/2304.00415
- Sharma, Arjun, and Donald L. Koch. "Steady-state extensional rheology of a dilute suspension of spheres in a dilute polymer solution." Physical Review Fluids 8, no. 3 (2023): 033303. https://doi.org/10.1103/PhysRevFluids.8.033303
- "Missaoui, Amine, Adam L. Susser, Hillel Aharoni, and Charles Rosenblatt. ""Magnetic field-induced Freedericksz transition in a chiral liquid crystal."" Applied Physics Letters 122, no. 13 (2023): 134101. https://doi.org/10.1063/5.0146506
- Tan, Mingyang, Joshua A. Adeniran, and Travis W. Walker. "Dynamics and rheological properties of suspensions of paramagnetic spherical particles under constant magnetic fields." Physical Review Fluids 8, no. 4 (2023): 043701. https://doi.org/10.1103/PhysRevFluids.8.043701
- Pasquet, Marina, Nicolo Galvani, Olivier Pitois, Sylvie Cohen-Addad, Reinhard Höhler, Anthony T. Chieco, Sam Dillavou et al. "Aqueous foams in microgravity, measuring bubble sizes." Comptes Rendus. Mécanique 351, no. S2 (2023): 1-23. https://doi.org/10.5802/crmeca.153

- Chieco, Anthony T., and Douglas J. Durian. "A simply solvable model capturing the approach to statistical self-similarity for the diffusive coarsening of bubbles, droplets, and grains." arXiv preprint arXiv:2303.09612 (2023). https://arxiv.org/pdf/2303.09612
- Durian, Douglas J. "Effective exponents for the diffusive coarsening of wet foams and analogous materials." arXiv preprint arXiv:2304.00415 (2023). https://arxiv.org/pdf/2304.00415

- Chebotaeva, Victoria, and Paula A. Vasquez. "Erlang-Distributed SEIR Epidemic Models with Cross-Diffusion." Mathematics 11, no. 9 (2023): 2167. https://doi.org/10.3390/math11092167
- "Dillavou, Sam, Jesse M. Hanlan, Anthony T. Chieco, Hongyi Xiao, Sage Fulco, Kevin T. Turner, and Douglas J. Durian. ""Bellybutton: Accessible and Customizable Deep-Learning Image Segmentation."" arXiv preprint arXiv:2309.00058 (2023). https://doi.org/10.48550/arXiv.2309.00058
- Sharma, Arjun, and Donald L. Koch. "Finite Difference Method in Prolate Spheroidal Coordinates for Freely Suspended Spheroidal Particles in Linear Flows of Viscous and Viscoelastic Fluids." Available at SSRN 4441910 (2023). http://dx.doi.org/10.2139/ssrn

Publications in the last year – Soft Matter

- Missaoui, Amine, Adam L. Susser, Hillel Aharoni, and Charles Rosenblatt. "Energetics of topographically designed Smectic-A oily streaks." Soft Matter 19, no. 20 (2023): 3733-3738. https://doi.org/10.1039/D3SM00306J
- Krucker-Velasquez, Emily S., Zachary Sherman, and James William Swan. "Immersed Boundary Method for Dynamic Simulation of Polarizable Colloids of Arbitrary Shape in Explicit Ion Electrolytes." Available at SSRN 4491562. http://dx.doi.org/10.2139/ssrn.4491562
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- Barnes, Lauren. "Fluid Dynamics of Interacting Particles: Bouncing Droplets and Colloid-Polymer Mixtures." PhD diss., New Jersey Institute of Technology, 2023. https://search.proquest.com/openview/fa3c6ad21099e576481bcf8fe2d4c555/1?pq-origsite=gscholar&cbl=18750&diss=y
- Lynch, Matthew L., Thomas E. Kodger, Paolo Palacio-Mancheno, Mark W. Pestak, and William V. Meyer. "The Magnitude of the Soret Force on Colloidal Particles Measured in Microgravity." Gravitational and Space Research 12, no. 1: 1-17. https://doi.org/10.2478/gsr-2023-0002
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- Krucker-Velasquez, Emily, James W. Swan, and Zachary Sherman. "Immersed boundary method for dynamic simulation of polarizable colloids of arbitrary shape in explicit ion electrolytes." arXiv preprint arXiv:2401.04865 (2024). https://doi.org/10.48550/arXiv.2401.04865
- Lynch, Matthew L., Thomas E. Kodger, Paolo Palacio-Mancheno, Mark W. Pestak, and William V. Meyer. "The Magnitude of the Soret Force on Colloidal Particles Measured in Microgravity." Gravitational and Space Research 12, no. 1 (2024): 1-17 https://doi.org/10.2478/gsr-2023-0002

- Questions? -

Some Active Matter Studies in Microgravity

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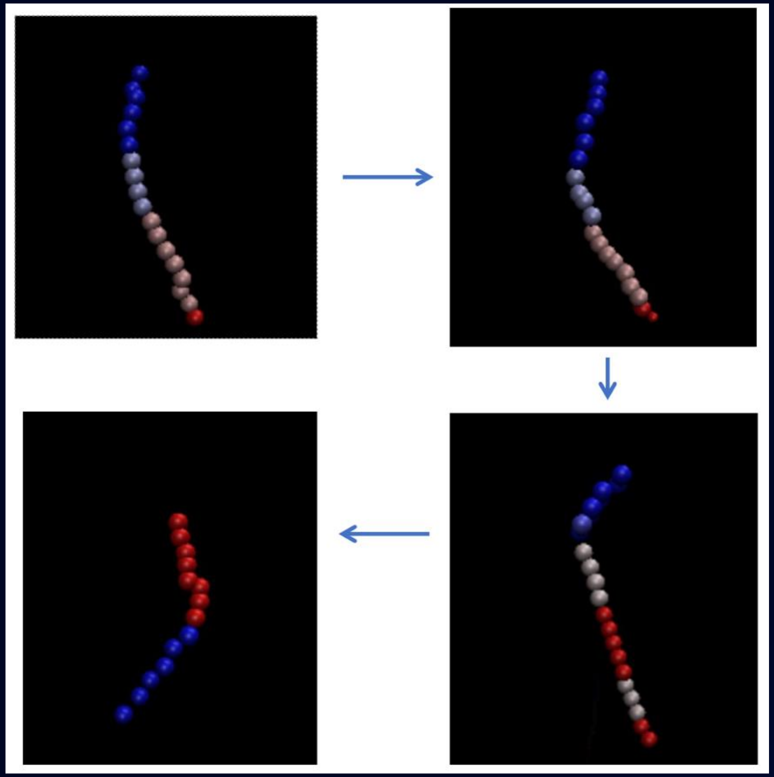


The temporal evolution of the 3D structure of a flexible chain mimicking protein folding

Objective & Outcome of the Study

- ✓ Investigated folding dynamics in protein chains using micron sized beads.
- ✓ Microgravity allows studying micron-sized particles without settling (not possible on ground)

Importance of the Study

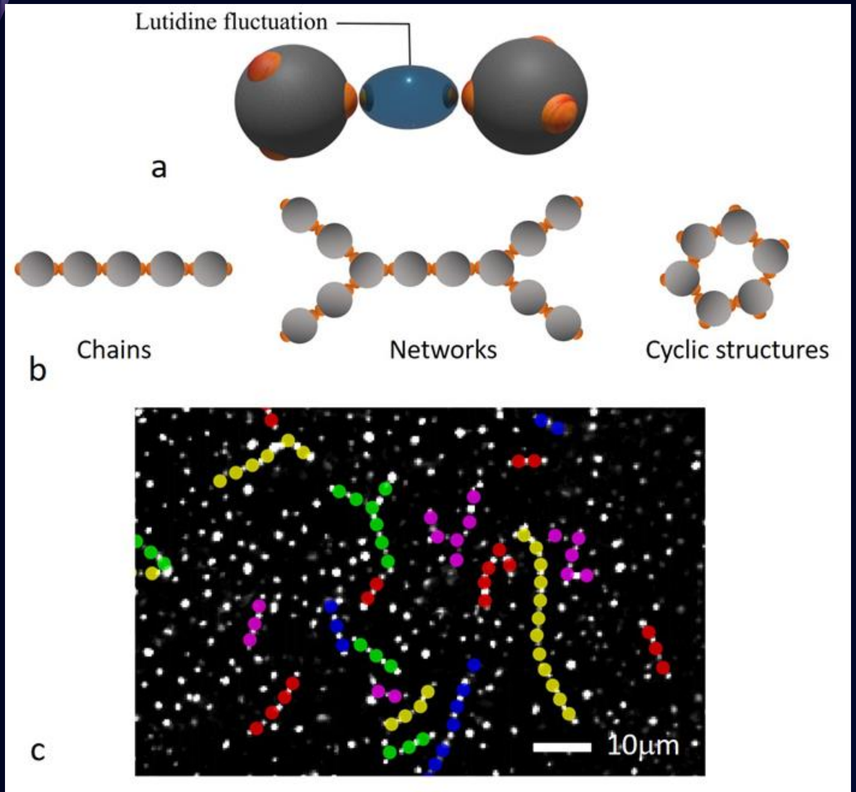
- ✓ Model dynamics of protein folding to develop knowledge base to develop active soft matter

Publications

- ✓ Ramona Mhanna, Yan Gao, Isaac Van Tol, Ela Springer, Ning Wu, David W. M. Marr, “Chain Assembly Kinetics from Magnetic Colloidal Spheres,” Langmuir, 2022, 38, 18, 5730–57370

Some Active Matter Studies in Microgravity

ACE-T2



(a) and (b) shows schematic of complex structure formation in patchy particles. (c) shows LMM images of clustered particles

Objective & Outcome of the Study

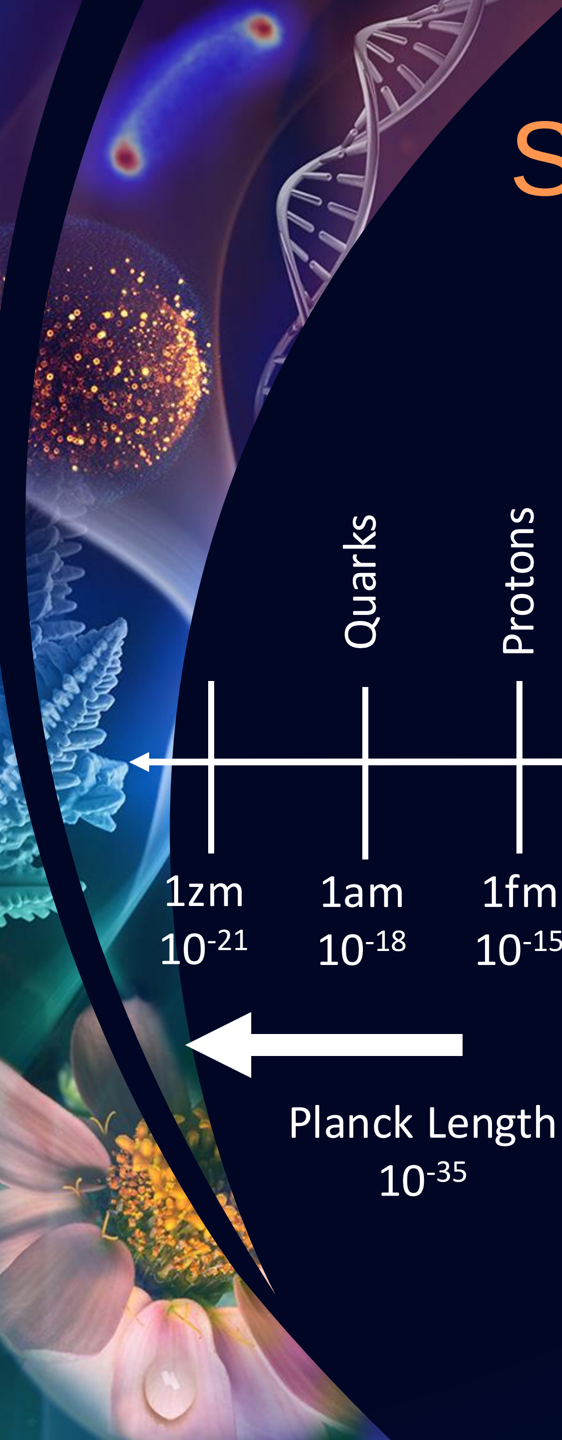
- ✓ Investigated the assembly of micron-sized “patchy” particles using critical Casimir forces.
- ✓ Microgravity allows studying 3D structure, which isn’t possible on ground

Importance of the Study

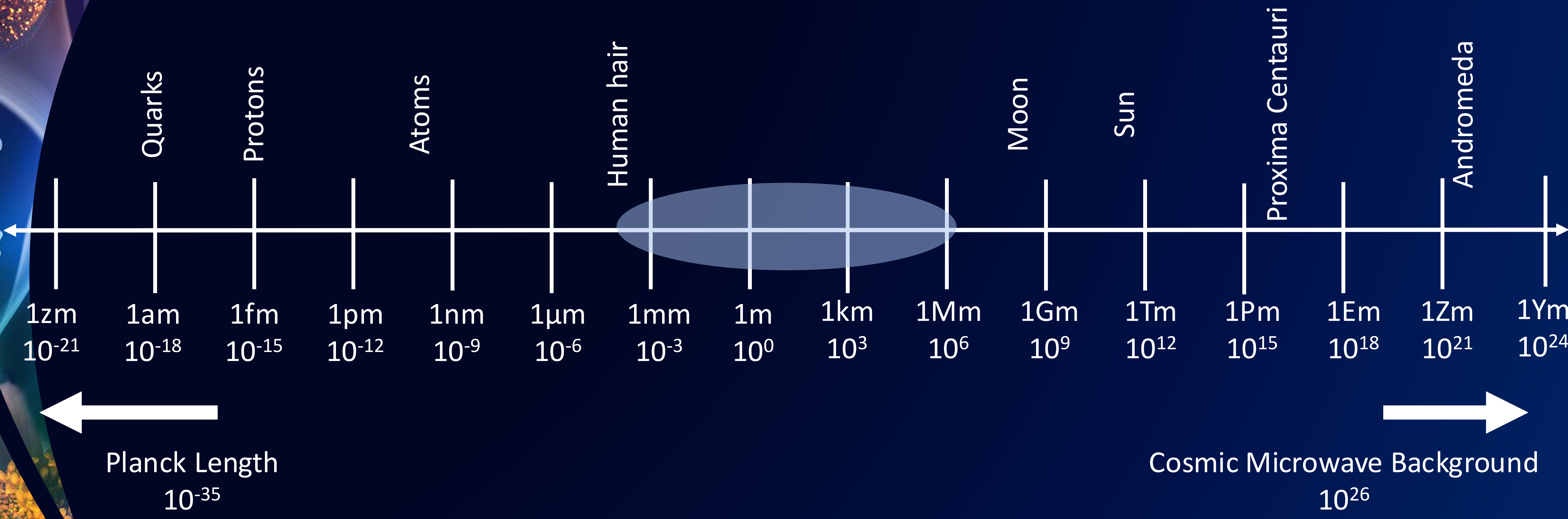
- ✓ Provided a better understanding of how complex interactions lead to complex structures, and to understand the dynamics of growth of these structures developing knowledge base for active soft matter

Publications

- ✓ P. J. M. Swinkels, R. Sinaasappel, Z. Gong, S. Sacanna, W. V. Meyer, Francesco Sciortino, P. Schall, “Networks of limited-valency patchy particles,” (submitted to PRL)



Scales



Quarks
Protons
Atoms
Human hair
Moon
Sun
Proxima Centauri
Andromeda
1zm 10^{-21}
1am 10^{-18}
1fm 10^{-15}
1pm 10^{-12}
1nm 10^{-9}
1µm 10^{-6}
1mm 10^{-3}
1m 10^{0}
1km 10^{3}
1Mm 10^{6}
1Gm 10^{9}
1Tm 10^{12}
1Pm 10^{15}
1Em 10^{18}
1Zm 10^{21}
1Ym 10^{24}
Planck Length
10^{-35}
Cosmic Microwave Background
10^{26}