Fundamental Symmetries with Atoms, Molecules, and Optics (AMO)

Nick Hutzler

Caltech

State of the field

- Molecules have been used to search for the electron electric dipole moment with high precision
  - Already probing the ~50 TeV (~2 TeV) scale for CPV physics at 1 (2) loops
  - ~100x EDM sensitivity improvement since last Snowmass
  - Leverages combination of intrinsic amplification of CPV moments, coherent quantum control, and robustness against systematics

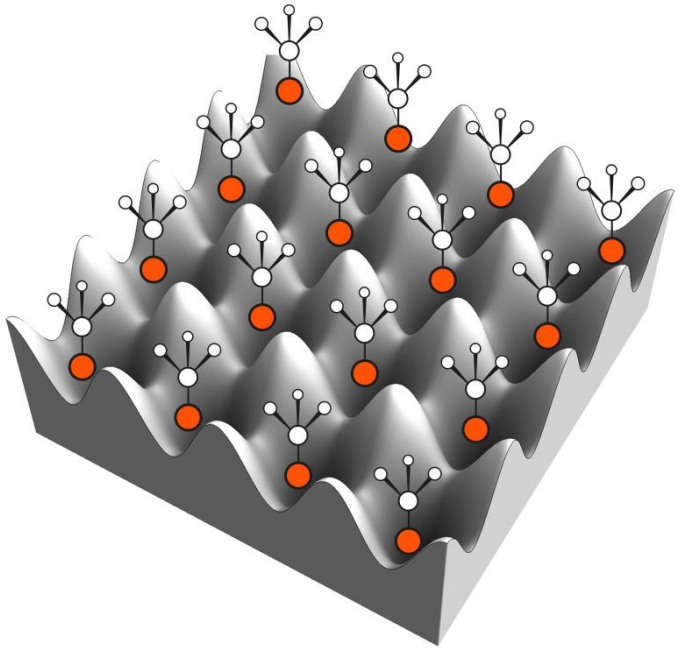
State of the field

- Molecules have been used to search for the electron electric dipole moment with high precision
  - Already probing the ~50 TeV (~2 TeV) scale for CPV physics at 1 (2) loops
  - ~100x EDM sensitivity improvement since last Snowmass
  - Leverages combination of intrinsic amplification of CPV moments, coherent quantum control, and robustness against systematics
- Next-generation searches are starting
  - Upgrades to existing experiments
  - New methods with enhanced sensitivity
  - Access to new parameter spaces (leptonic and hadronic)

State of the field

- Molecules have been used to search for the electron electric dipole moment with high precision
  - Already probing the ~50 TeV (~2 TeV) scale for CPV physics at 1 (2) loops
  - ~100x EDM sensitivity improvement since last Snowmass
  - Leverages combination of intrinsic amplification of CPV moments, coherent quantum control, and robustness against systematics
- Next-generation searches are starting
  - Upgrades to existing experiments
  - New methods with enhanced sensitivity
  - Access to new parameter spaces (leptonic and hadronic)
- Major advances will take place in the next decade
  - Implementation of advanced quantum control
  - New measurement approaches
  - Access to exotic nuclei
  - These are getting started!

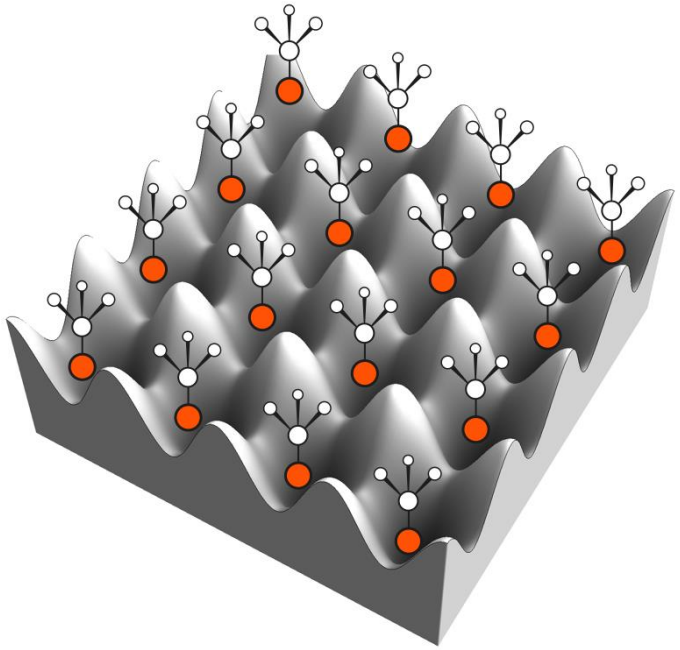
10^6 molecules
100 s coherence time
Heavy, deformed nucleus
Quantum control
Robust error rejection
Two weeks integration



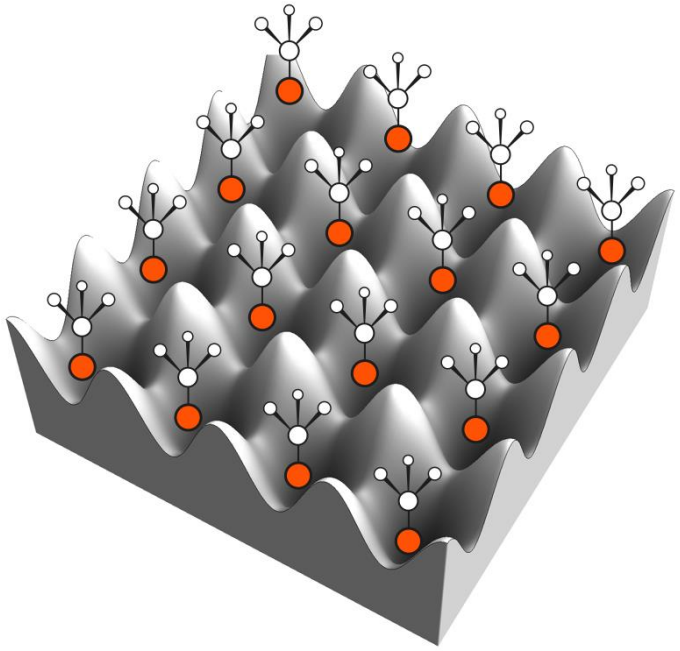
10^6 molecules
100 s coherence time
Heavy, deformed nucleus
Quantum control
Robust error rejection
Two weeks integration

→

~PeV-scale CP-violating physics @ 1 loop
~100 TeV-scale CP-violating physics @ 2 loops
Both leptonic and hadronic sectors
Extreme precision, $\theta_{QCD} \lesssim 10^{-14}$
~10 year time scales



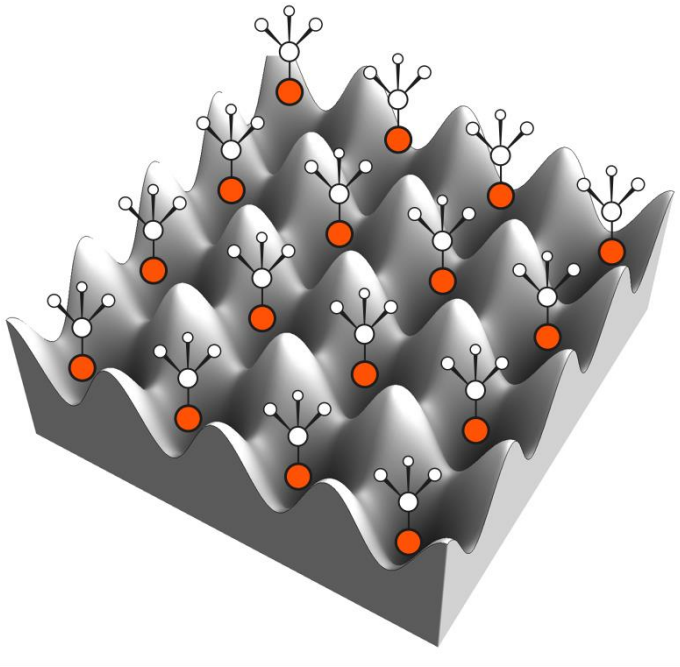
10^6 molecules
100 s coherence time
Heavy, deformed nucleus
Quantum control
Robust error rejection
Two weeks integration



~PeV-scale CP-violating physics @ 1 loop
~100 TeV-scale CP-violating physics @ 2 loops
Both leptonic and hadronic sectors
Extreme precision, $\theta_{QCD} \lesssim 10^{-14}$
~10 year time scales

Future orders-of-magnitude improvements from quantum-enhanced metrology, highly exotic nuclei, …
+ ~5-10 year time scale?

10^6 molecules
100 s coherence time
Heavy, deformed nucleus
Quantum control
Robust error rejection
Two weeks integration

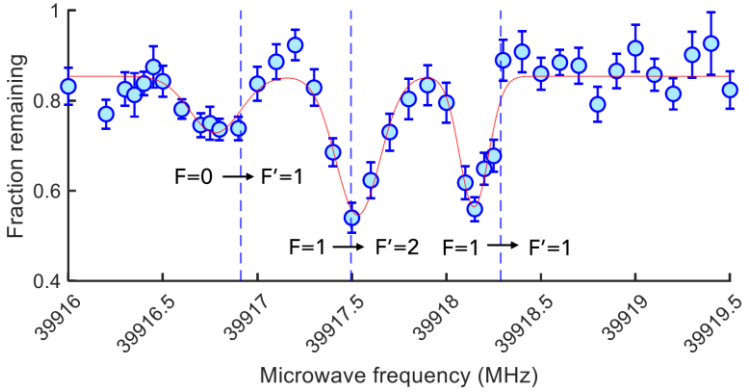


~PeV-scale CP-violating physics @ 1 loop
~100 TeV-scale CP-violating physics @ 2 loops
Both leptonic and hadronic sectors
Extreme precision, $\theta_{QCD} \lesssim 10^{-14}$
~10 year time scales

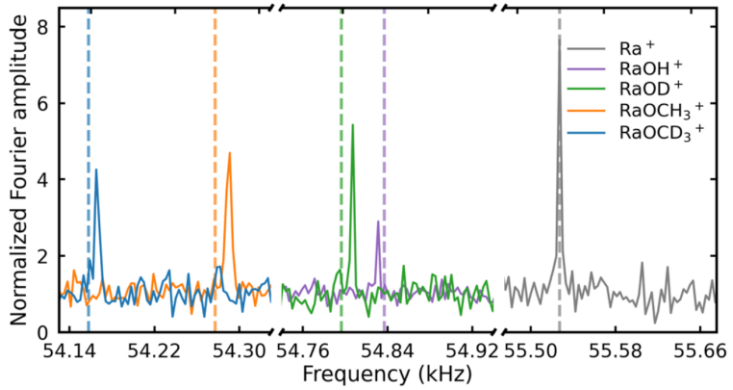
Future orders-of-magnitude improvements from quantum-enhanced metrology, highly exotic nuclei, …
+ ~5-10 year time scale?

- This is just *one* specific approach as a motivating example
- There are many complementary approaches which can leverage these advances
- How can we realize *this* experiment?

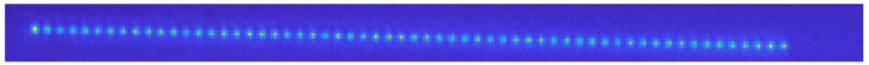
Progress in the last ~year



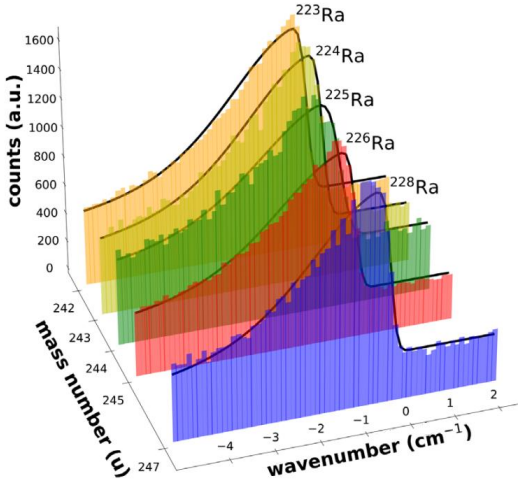
Precision spectroscopy in trapped, ultracold, engineered molecules



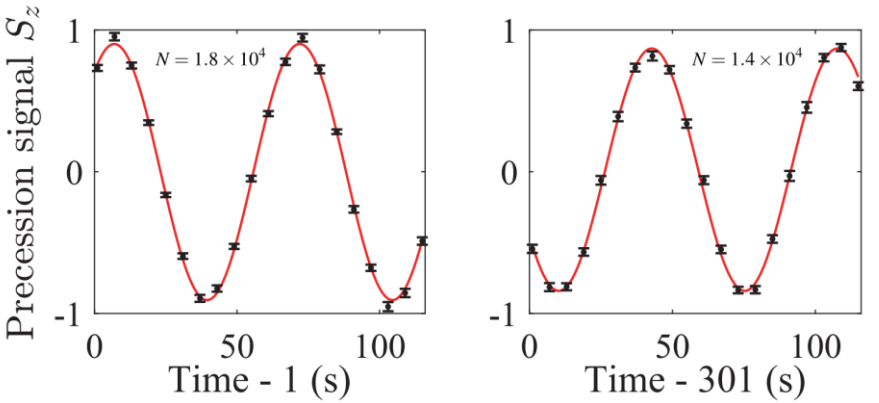
Creation, trapping, cooling, control of radioactive molecular ions



Quantum-controlled ultracold molecules



Precision spectroscopy of radioactive molecules

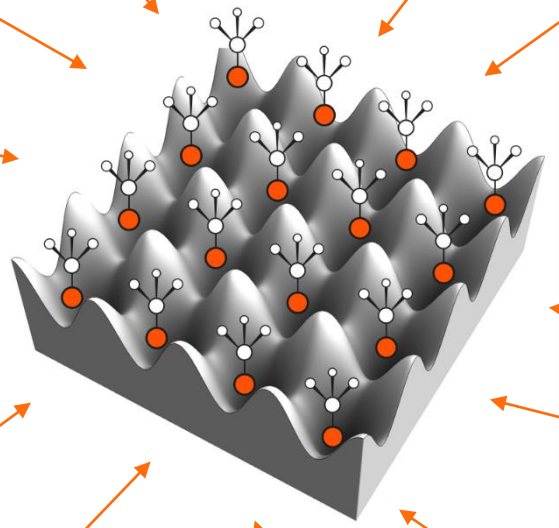


Long spin coherence times in optical traps

PolyEDM Collaboration
Fan *et al.*, PRL 126, 023002 (2021)
Doyle Group @ Harvard

Udrescu *et al.*, PRL 127, 033001 (2021)
Zheng *et al.*, arXiv:2207.08140 (2022)

What will it take to access CPV?



BSM Phenomenology

Molecular spectroscopy

Sensitive Detection

Radiochemistry

Beam facilities

Molecular production

Laser cooling/trapping

And more…

Particle Theory

Quantum control

Nuclear structure

QIS

QCD

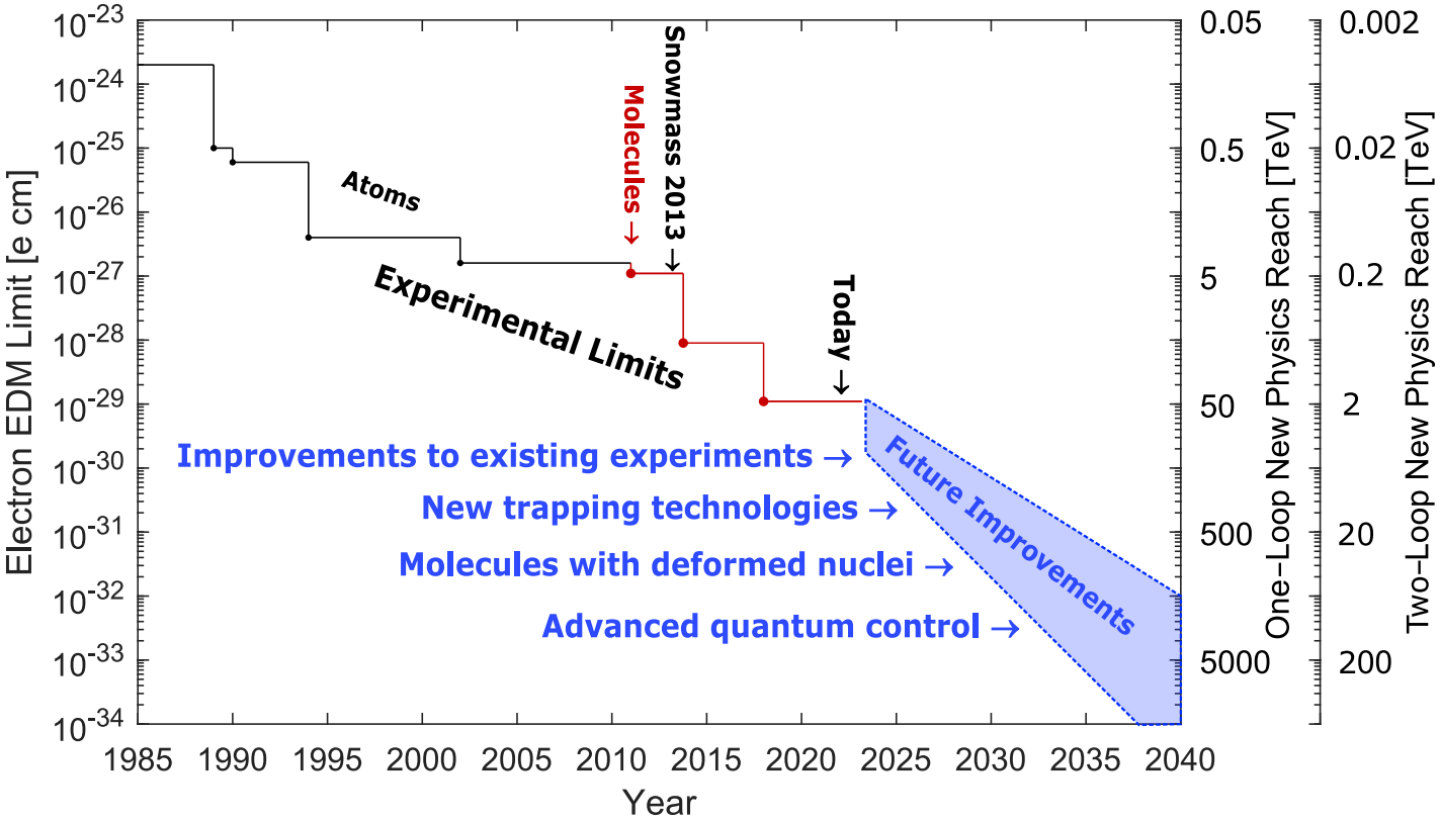
Physical chemistry

Atomic/molecular structure

Relativistic quantum chemistry

Again, this is just a *particular* example, but many of the challenges are shared

Looking Ahead

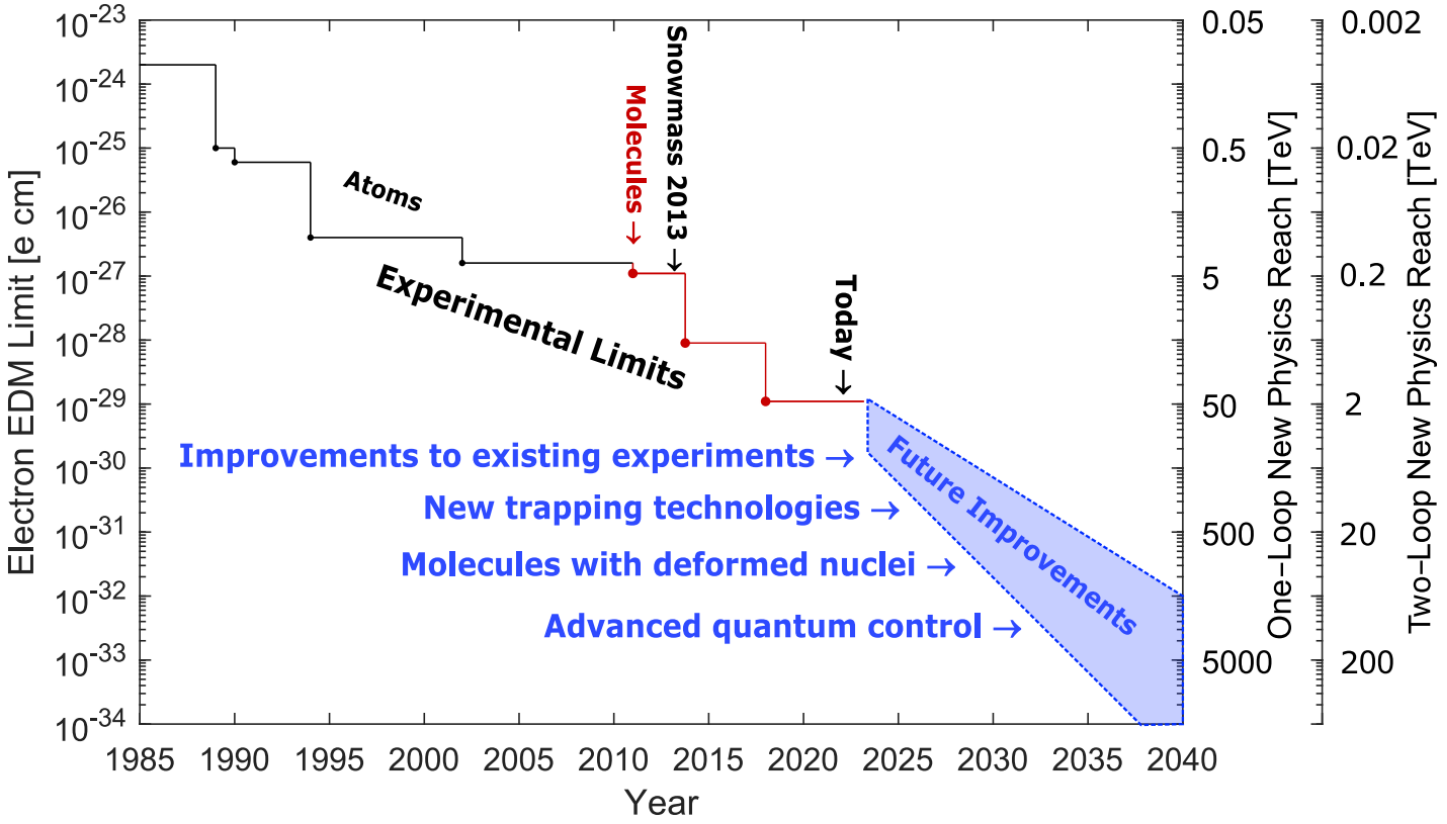


Orders-of-magnitude gains in energy reach are possible in next 10 years, and beyond

Long-term roadmap includes quantum-enhanced metrology, extremely exotic nuclei, and more

Looking Ahead

- All of the pieces are there
  - *Not* the case at last Snowmass

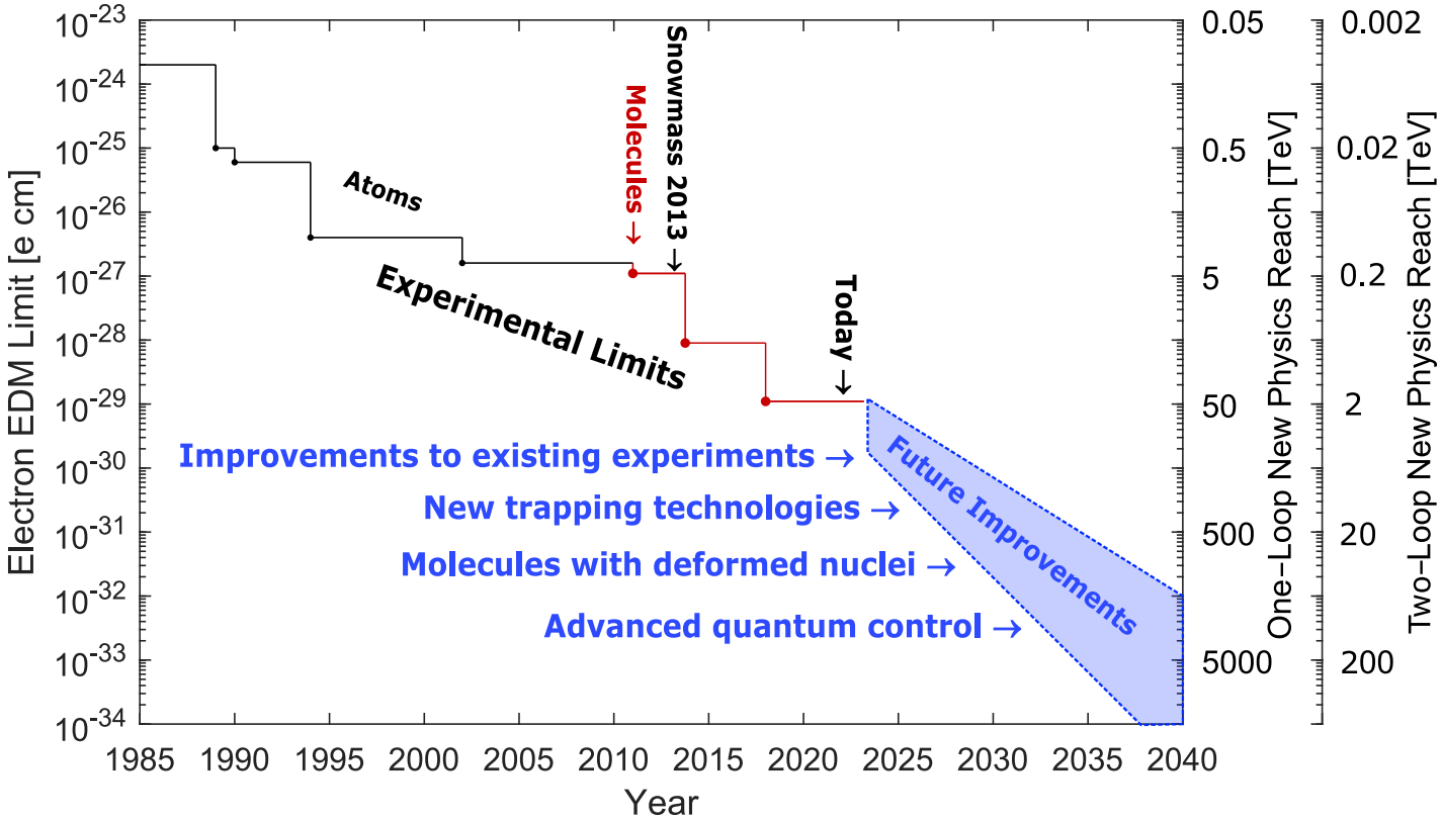


Orders-of-magnitude gains in energy reach are possible in next 10 years, and beyond

Long-term roadmap includes quantum-enhanced metrology, extremely exotic nuclei, and more

Looking Ahead

- All of the pieces are there
  - *Not* the case at last Snowmass
- Need sustained support and coordination
  - Theory and experiment
  - AMO, HEP, NP, QIS, chemistry, beam facilities, …

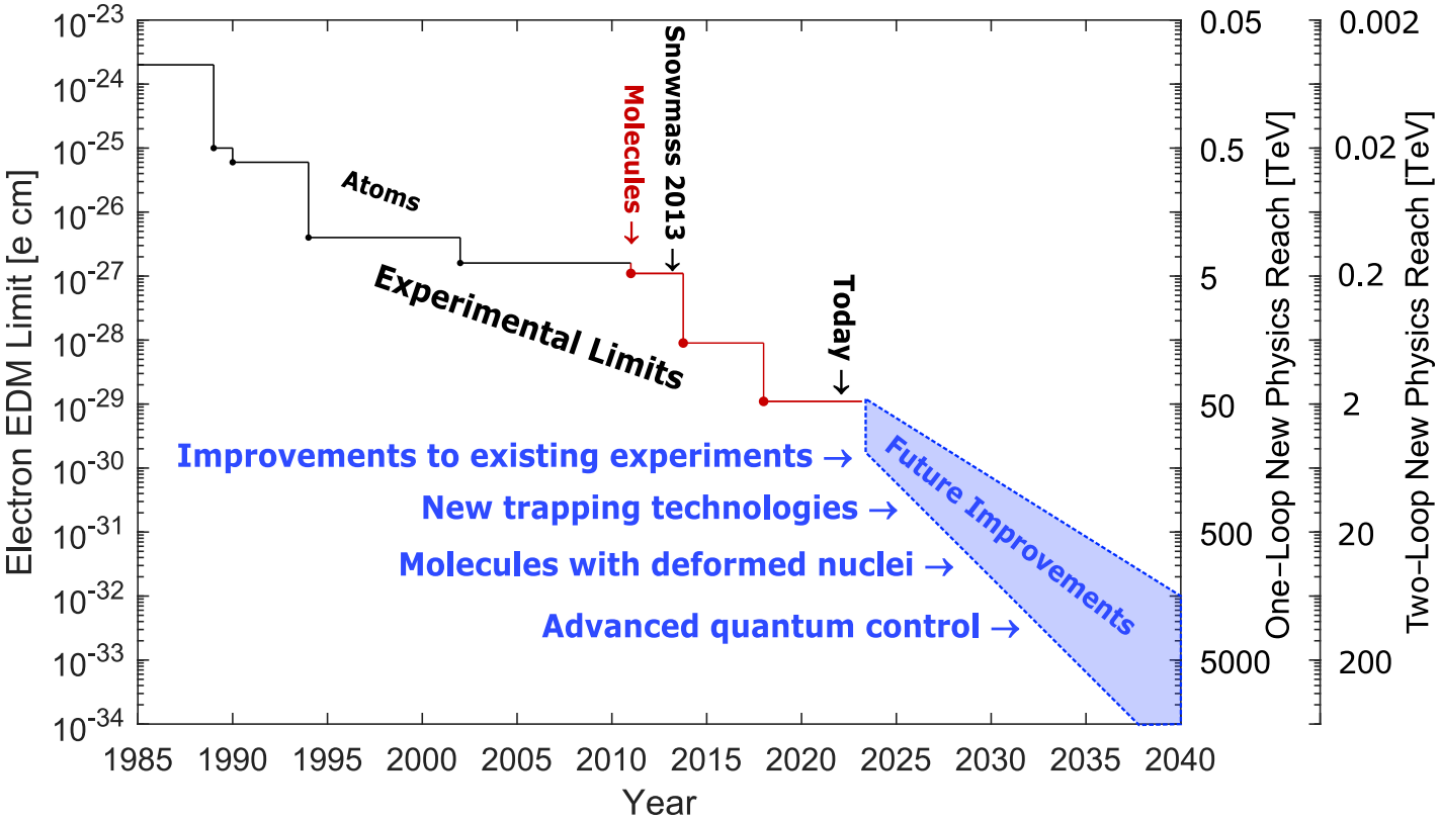


Orders-of-magnitude gains in energy reach are possible in next 10 years, and beyond

Long-term roadmap includes quantum-enhanced metrology, extremely exotic nuclei, and more

Looking Ahead

- All of the pieces are there
  - *Not* the case at last Snowmass
- Need sustained support and coordination
  - Theory and experiment
  - AMO, HEP, NP, QIS, chemistry, beam facilities, …
- Complementary approaches are required
  - Broad parameter space!
  - Multiple AMO systems
  - srEDM for nucleons/nuclei

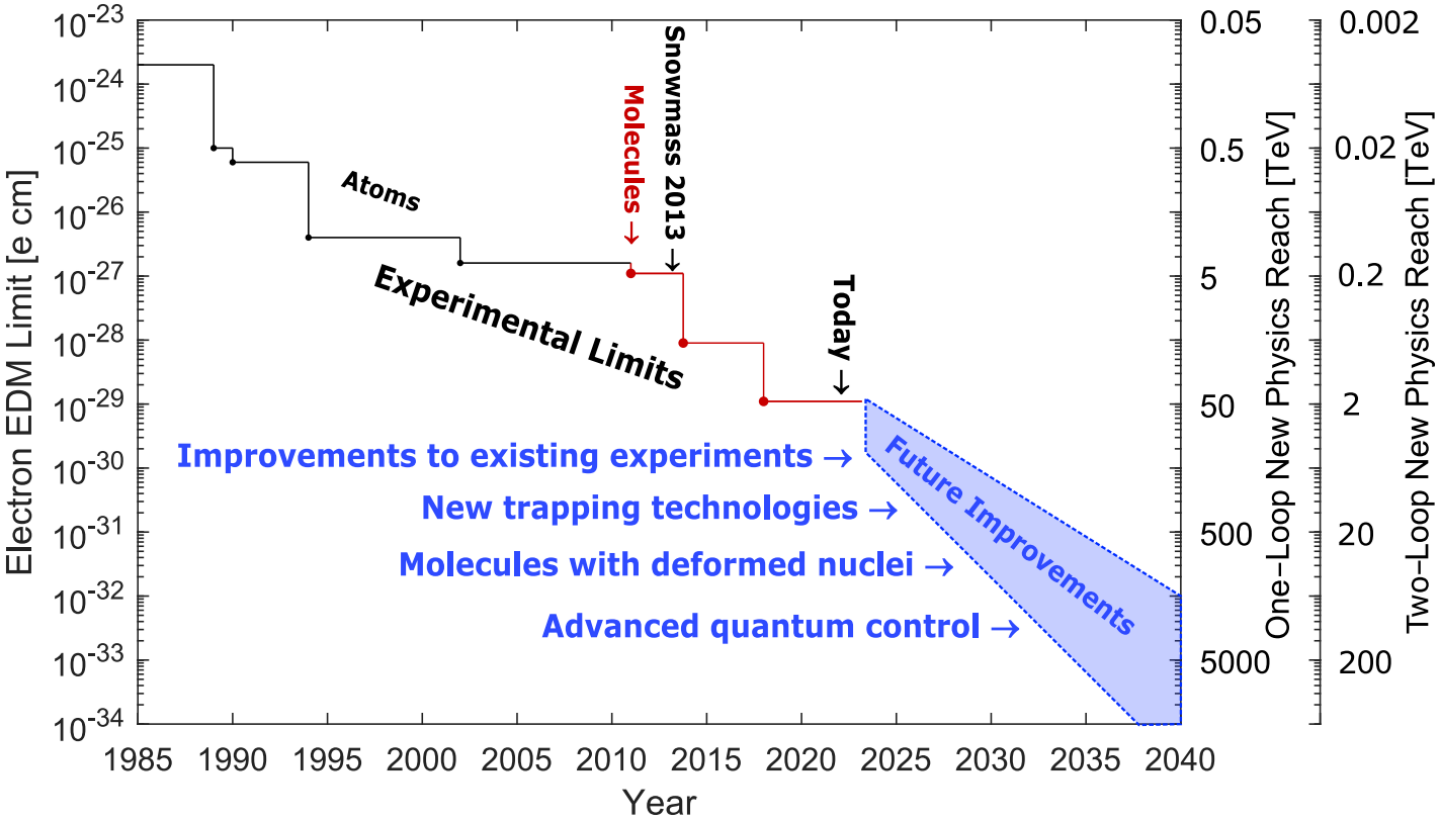


Orders-of-magnitude gains in energy reach are possible in next 10 years, and beyond

Long-term roadmap includes quantum-enhanced metrology, extremely exotic nuclei, and more

Looking Ahead

- All of the pieces are there
  - *Not* the case at last Snowmass
- Need sustained support and coordination
  - Theory and experiment
  - AMO, HEP, NP, QIS, chemistry, beam facilities, …
- Complementary approaches are required
  - Broad parameter space!
  - Multiple AMO systems
  - srEDM for nucleons/nuclei
- Most new AMO CPV experiments are multi-PI, multi-institution, multi-year
  - Necessitated by both scale and complexity
  - This is *not* the "traditional" AMO operating condition
  - Challenges most existing AMO support and coordination models



Orders-of-magnitude gains in energy reach are possible in next 10 years, and beyond

Long-term roadmap includes quantum-enhanced metrology, extremely exotic nuclei, and more