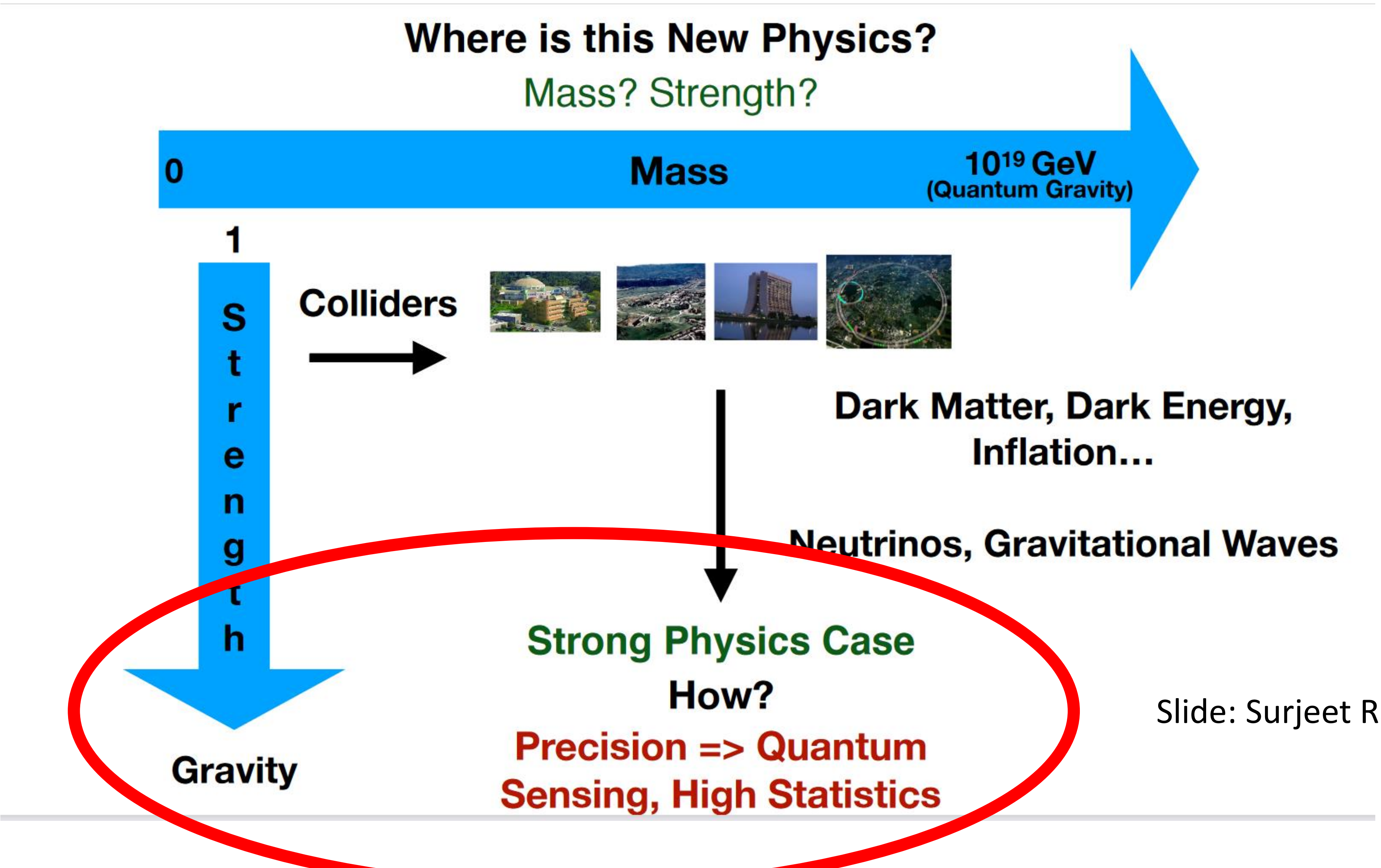
Developing New Directions in Fundamental Physics
(2020)

New Technologies and Techniques Session Summary

Conveners:

Alvaro Chavarria, Makoto Fujiwara, Oliver Stelzer-Chilton, **Gray Rybka**

Answering the Call of New Physics



Where is this New Physics?

Mass? Strength?

Colliders →

Dark Matter, Dark Energy, Inflation...

Neutrinos, Gravitational Waves

Strong Physics Case

How?

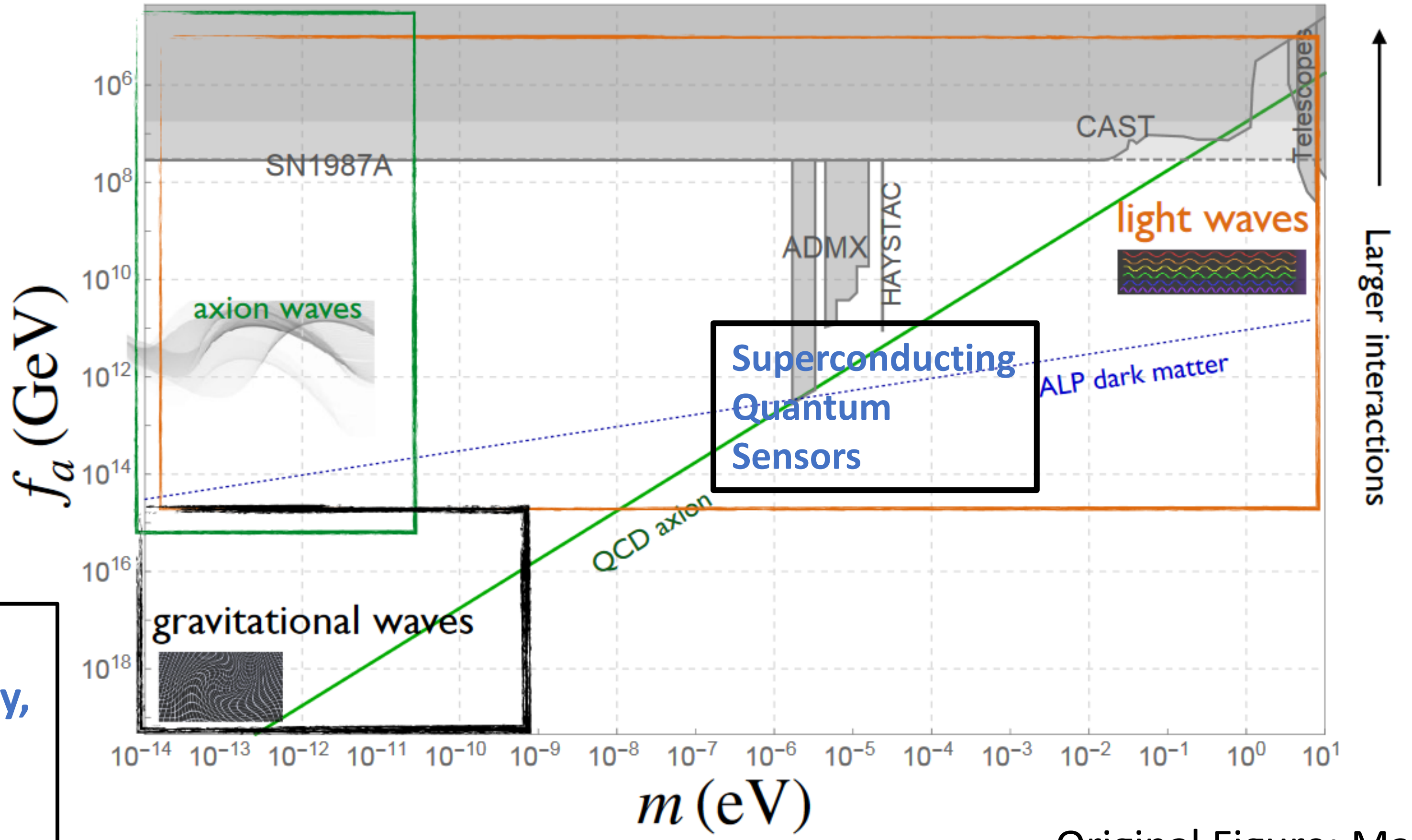
Precision => Quantum Sensing, High Statistics

Slide: Surjeet Rajendran

Common Themes is this Session

- Probing very low energy scales
    - Neutrino mass, Axion mass scale, anything below an eV
- Improving already sensitive technologies to the quantum level
    - Better clocks for longer coherence time, Qubits as sensors
- A certain obsession with gravity
    - Is it quantum? Is there a graviton?
- Dark Matter
    - Everybody wants to find it

The low-energy side of dark matter



Superconducting Quantum Sensors

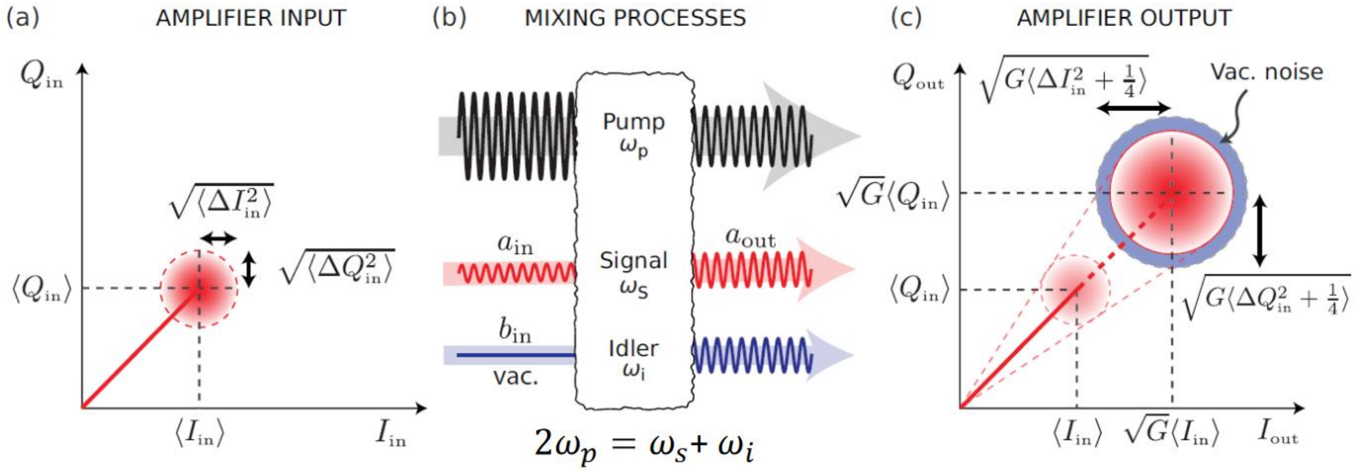
Torsion Pendula, Atom Interferometry, Cavity-atom clocks

Original Figure: Masha Baryakhtar

Weijian Chen – Superconducting Quantum Sensors and Tests of Quantum Mechanics

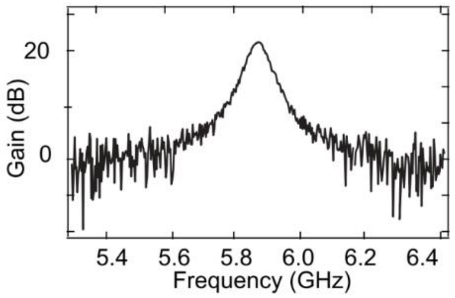
Parametric amplification

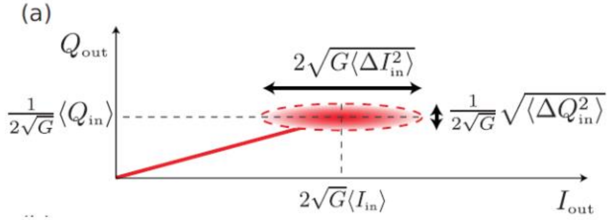
Washington University in St. Louis

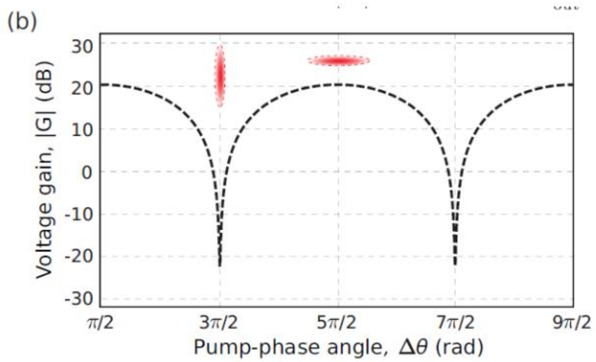


$$2\omega_p = \omega_s + \omega_i$$

Phase-preserving amplification







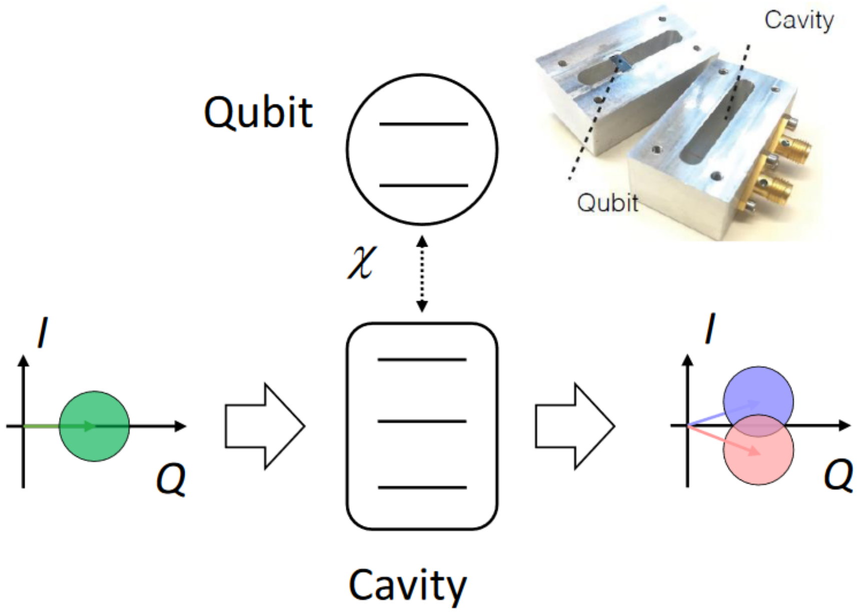
Phase-sensitive amplification

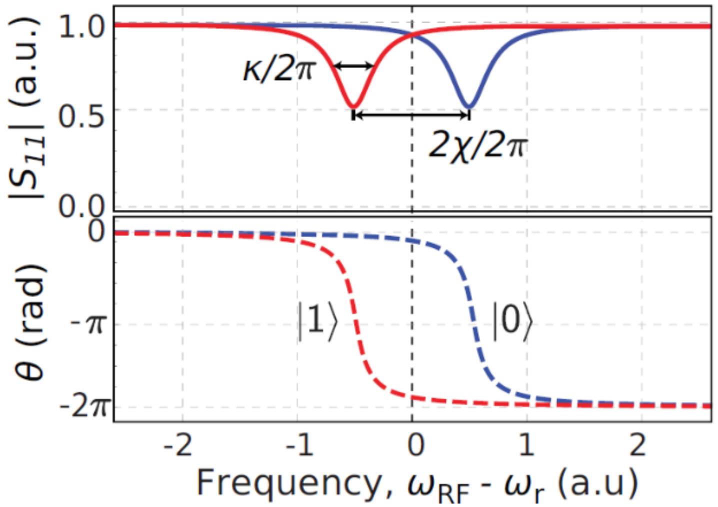
Krantz, *et al. Appl. Phys. Rev.* **6**, 021318 (2019).

Weijian Chen – Superconducting Quantum Sensors and Tests of Quantum Mechanics

Dispersive measurement

Washington University in St. Louis





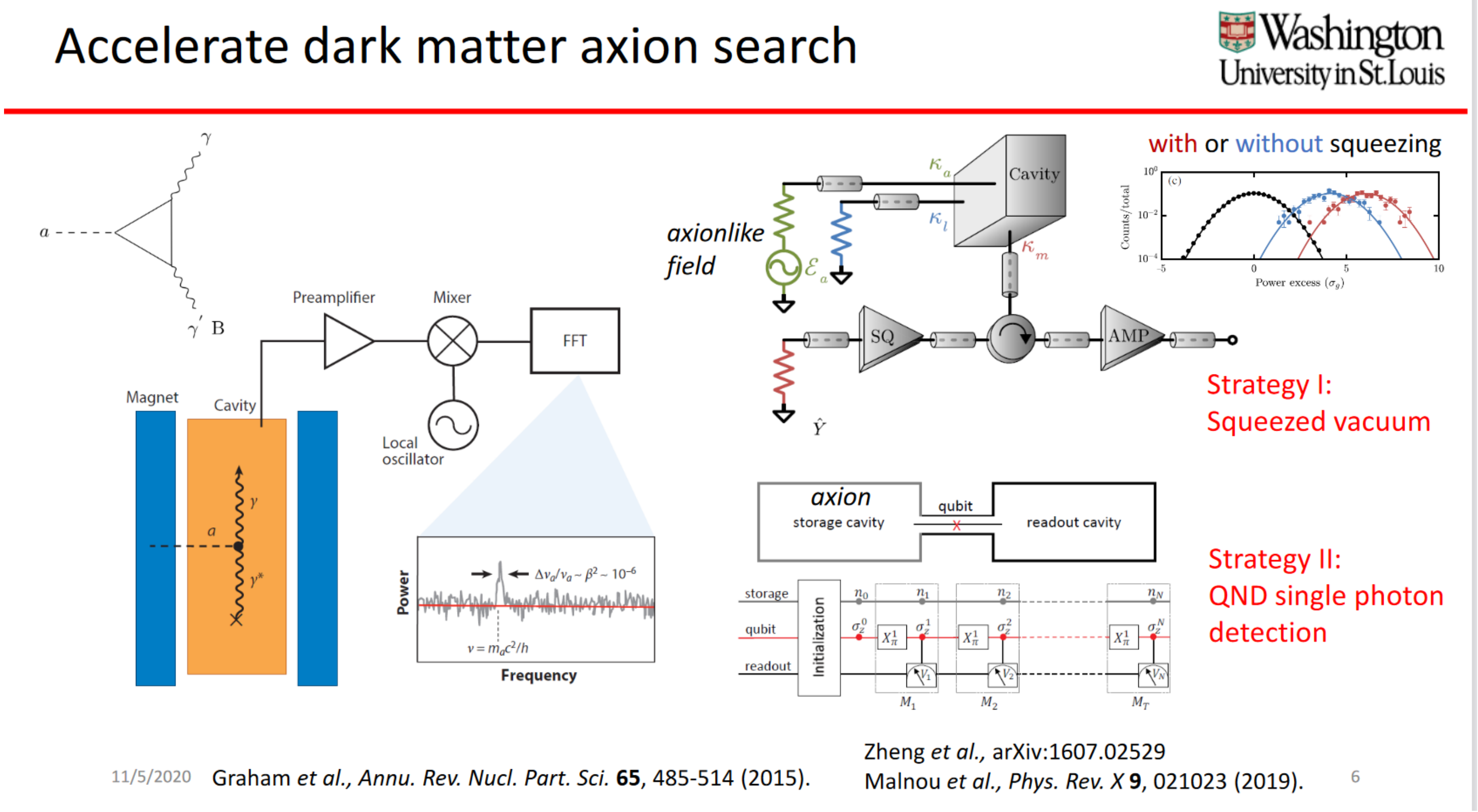
Dispersive approximation

$$H = \hbar\omega_c\left(a^\dagger a + \tfrac{1}{2}\right) + \frac{\hbar\omega_q}{2}\sigma_z + \hbar\chi\left(a^\dagger a + \tfrac{1}{2}\right)\sigma_z \quad = \hbar\boxed{\left(\omega_c + \chi\sigma_z\right)}\left(a^\dagger a + \tfrac{1}{2}\right) + \frac{\hbar\omega_q}{2}\sigma_z$$

Slide: Weijian Chen

Krantz, *et al.*, *Appl. Phys. Rev.* **6**, 021318 (2019).

Weijian Chen – Superconducting Quantum Sensors and Tests of Quantum Mechanics



Accelerate dark matter axion search

Washington University in St.Louis

with or without squeezing

Strategy I:
Squeezed vacuum

Strategy II:
QND single photon detection

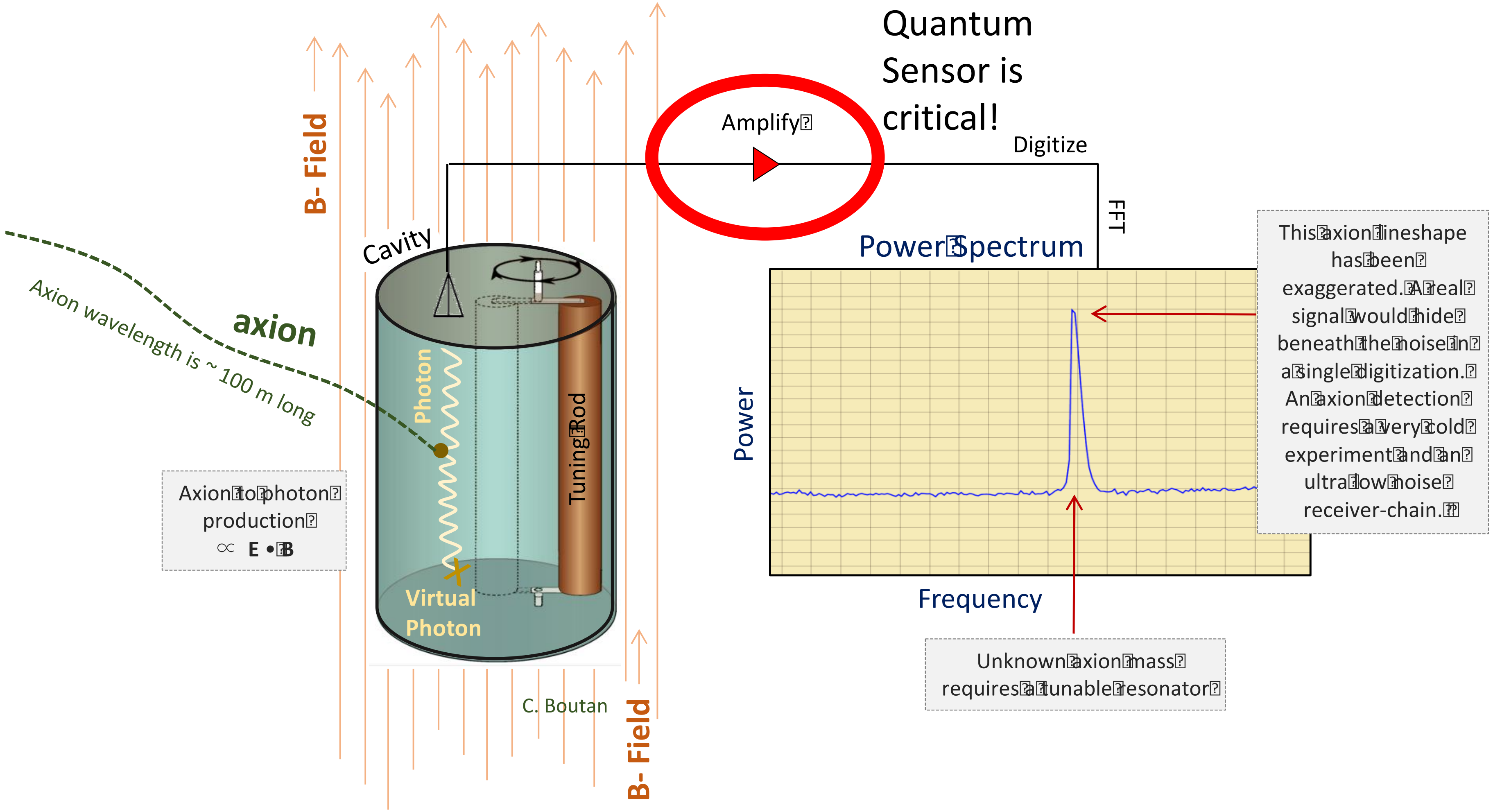
Graham *et al.*, *Annu. Rev. Nucl. Part. Sci.* **65**, 485-514 (2015).

Zheng *et al.*, arXiv:1607.02529
Malnou *et al.*, *Phys. Rev. X* **9**, 021023 (2019).

axion dark matter search in the ueV range

Interjection: ADMX and Quantum Sensors

The Axion Haloscope



Quantum Sensor is critical!

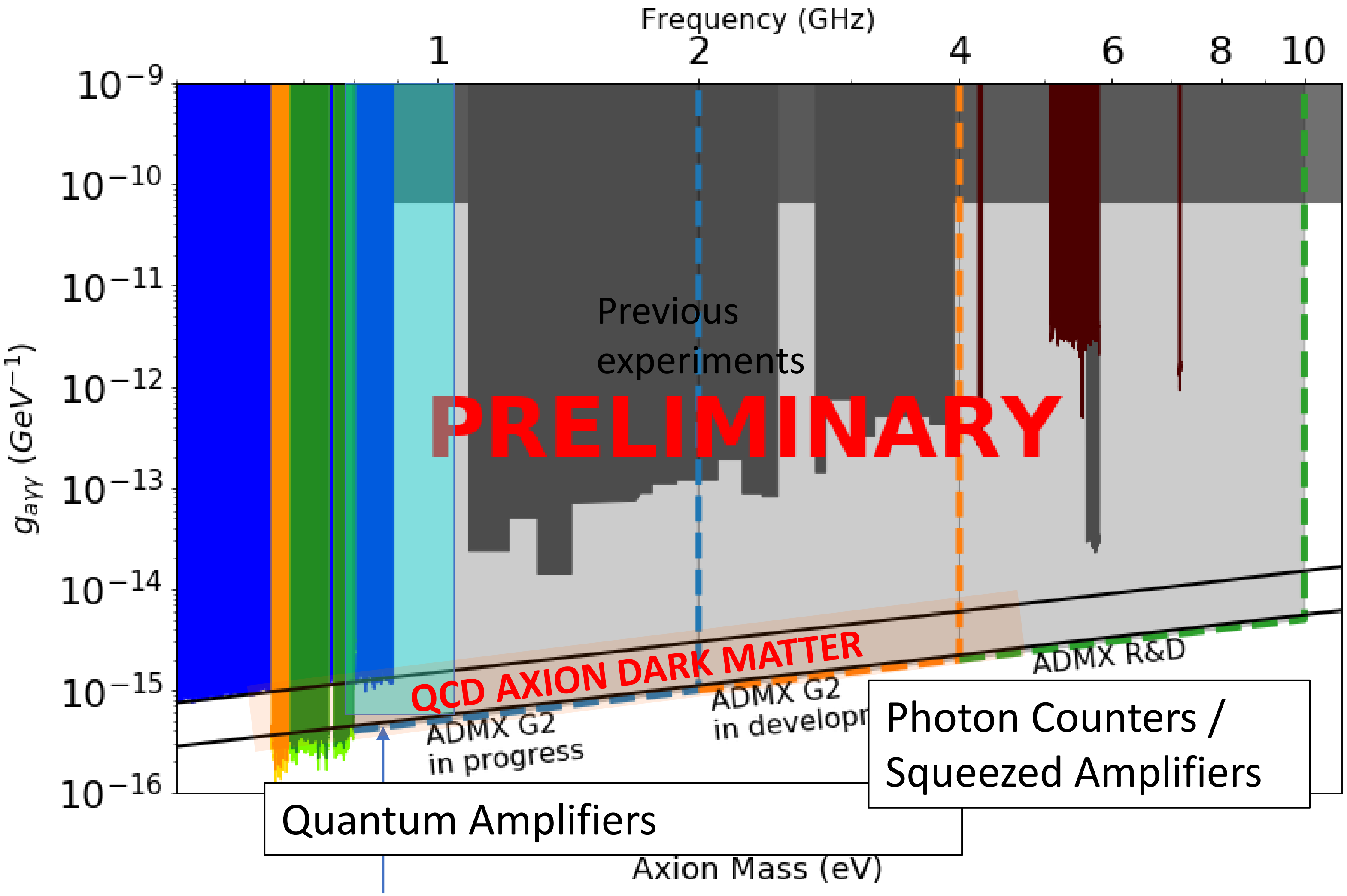
Axion to photon production
∝ **E • B**

This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator

ADMX at CENPA

Interjection: ADMX and Quantum Sensors



Quantum Amplifiers

Photon Counters / Squeezed Amplifiers

This is where we're scanning now (2020)

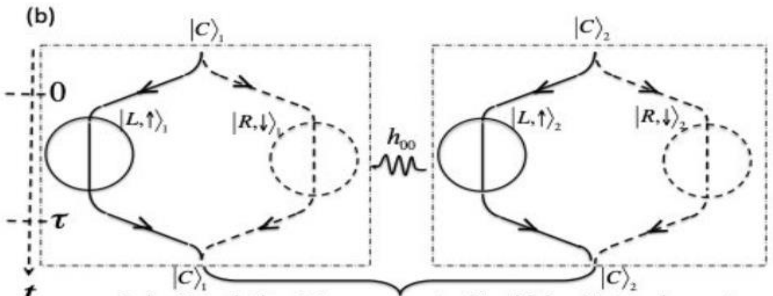
Daniel Carney – Tabletop experiments in quantum gravity

Example of alternative: “classical gravity”

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4}\langle T_{\mu\nu}\rangle \qquad\qquad i\partial_t\,|\psi\rangle = (H_{mat} + H_{grav})\,|\psi\rangle$$

First equation is in principle OK. Closing it with second is bad, but there are consistent versions now known, at least non-relativistically.

As far as I know, all share one property: no gravitational entanglement!



Spin Correlation Measurements Certifying Entanglement

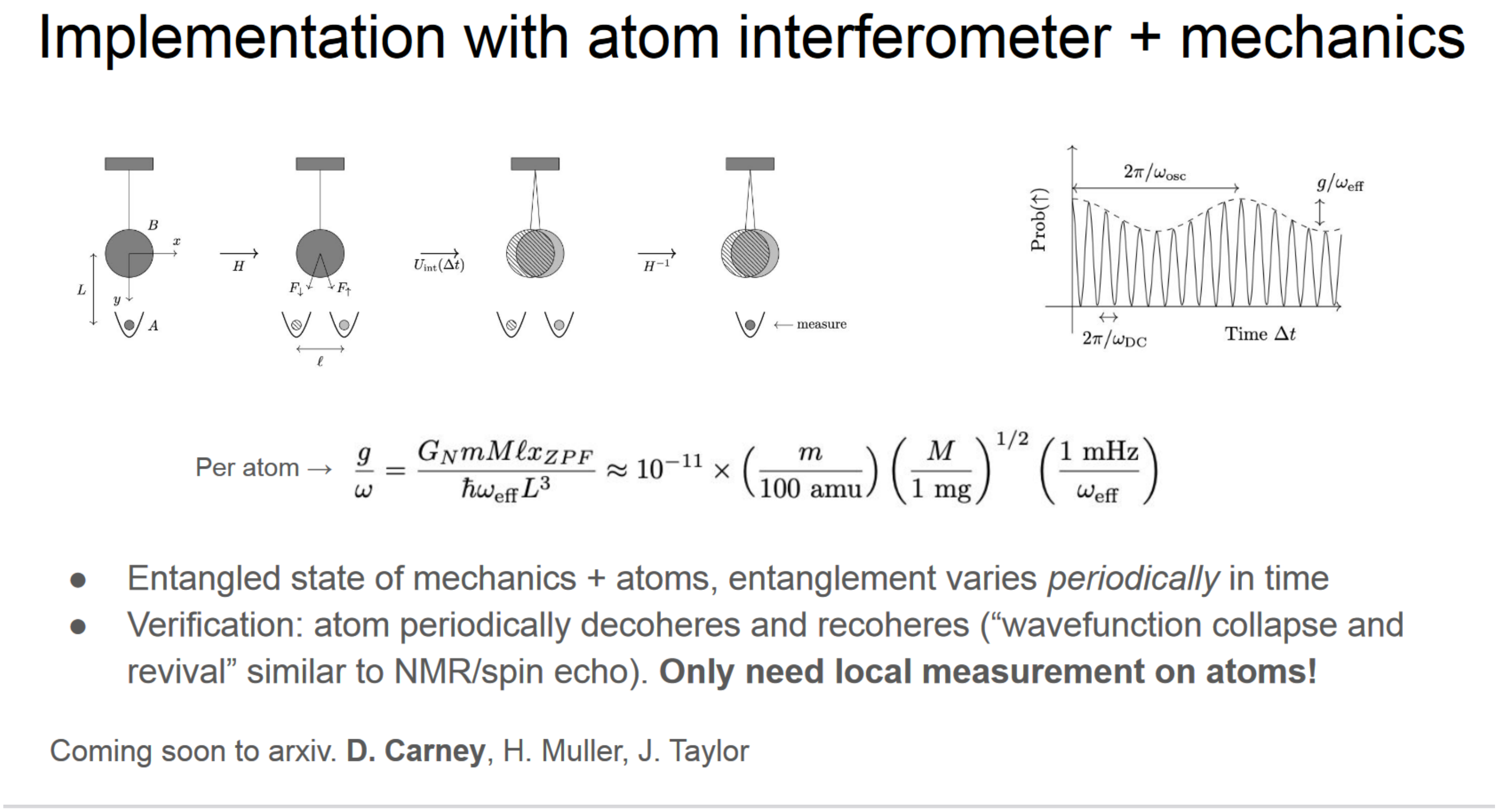
Quantized GR: $|LL\rangle \rightarrow |LL\rangle + |LR\rangle + \mathrm{e}^{\mathrm{i}\Delta\phi}|RL\rangle + |RR\rangle$

“Classical” GR: $|LL\rangle \rightarrow \left(|L\rangle + e^{i\Delta\phi}\,|R\rangle\right)_1 \otimes \left(|L\rangle + e^{-i\Delta\phi}\,|R\rangle\right)_2$

→ **no entanglement/Bell inequality violation**

Daniel Carney – Tabletop experiments in quantum gravity

measuring gravitational entanglement



Implementation with atom interferometer + mechanics

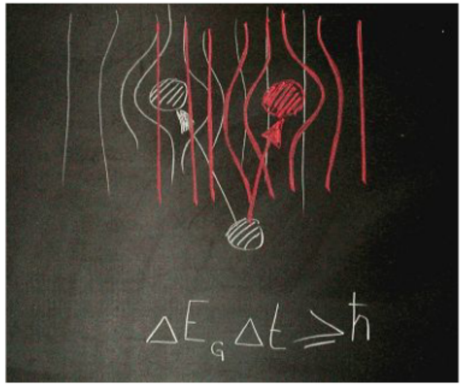
$$\text{Per atom} \rightarrow \quad \frac{g}{\omega} = \frac{G_N m M \ell x_{ZPF}}{\hbar \omega_{\text{eff}} L^3} \approx 10^{-11} \times \left(\frac{m}{100\ \text{amu}}\right) \left(\frac{M}{1\ \text{mg}}\right)^{1/2} \left(\frac{1\ \text{mHz}}{\omega_{\text{eff}}}\right)$$

- Entangled state of mechanics + atoms, entanglement varies *periodically* in time
- Verification: atom periodically decoheres and recoheres ("wavefunction collapse and revival" similar to NMR/spin echo). **Only need local measurement on atoms!**

Coming soon to arxiv. **D. Carney**, H. Muller, J. Taylor

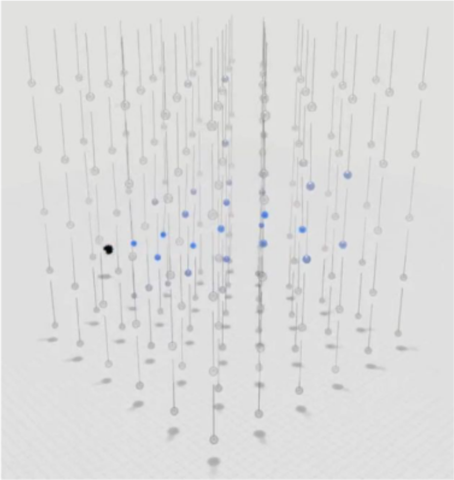
Daniel Carney – Tabletop experiments in quantum gravity

Related applications with same technology



- Testing other, crazier ideas about gravity + QM which are **NOT** predicted by perturbative quantum GR (e.g. Penrose decoherence)

  Review: **D. Carney**, P. Stamp, J. Taylor 1807.11494
  Snowmass: Theory frontier 1



- Dark matter detection of many flavors (notable: very heavy DM detection purely through gravity)

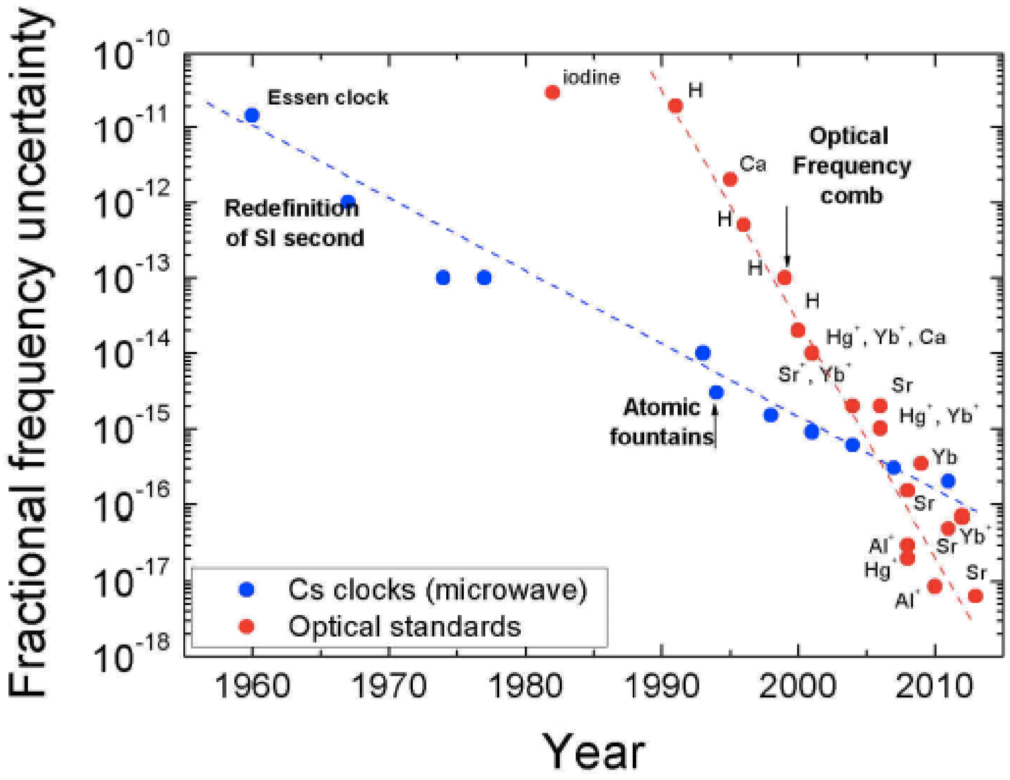
  Review: **D. Carney**, G. Krnjaic, C. Regal, D. Moore et al 2008.06074
  Snowmass: Instrumentation frontier 1

Jun Ye – Atomic Clocks and Fundamental Physics

Atomic clock: sensors of space-time

Quantum Technologies:

- Higher Q **optical** transitions:
  trapped ions & neutral atoms
- New laser stabilization methods:
  optical coherence ~ 30 s
- Many atoms in optical lattice:
  many-body, engineered states
- Optical frequency comb

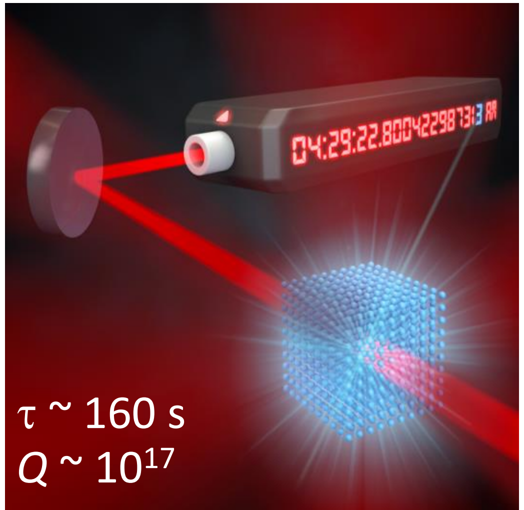


Sr, Yb, Al^+

10^{-20}

Poli *et al.*, *La rivista del Nuovo Cimento*, **36** 555 (2013); Ludlow *et al*, RMP **87**, 637 (2015).

- Current accuracy ~10^{-18} = grav. redshift @ 1 cm
- Precision ~3 x 10^{-19}
- (goal) Many-body protected quantum coherence

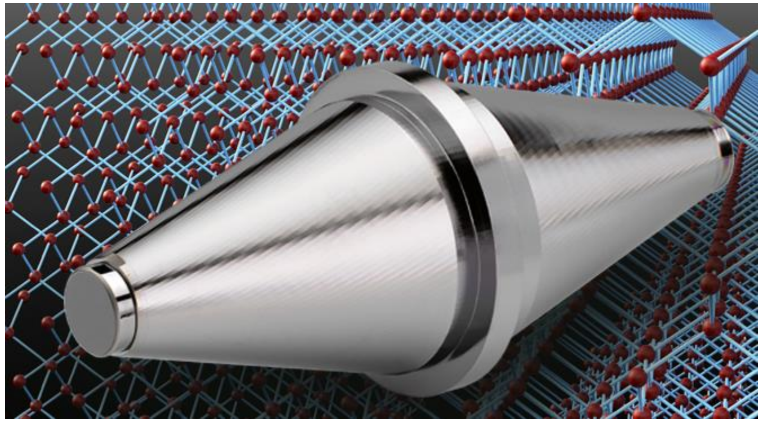


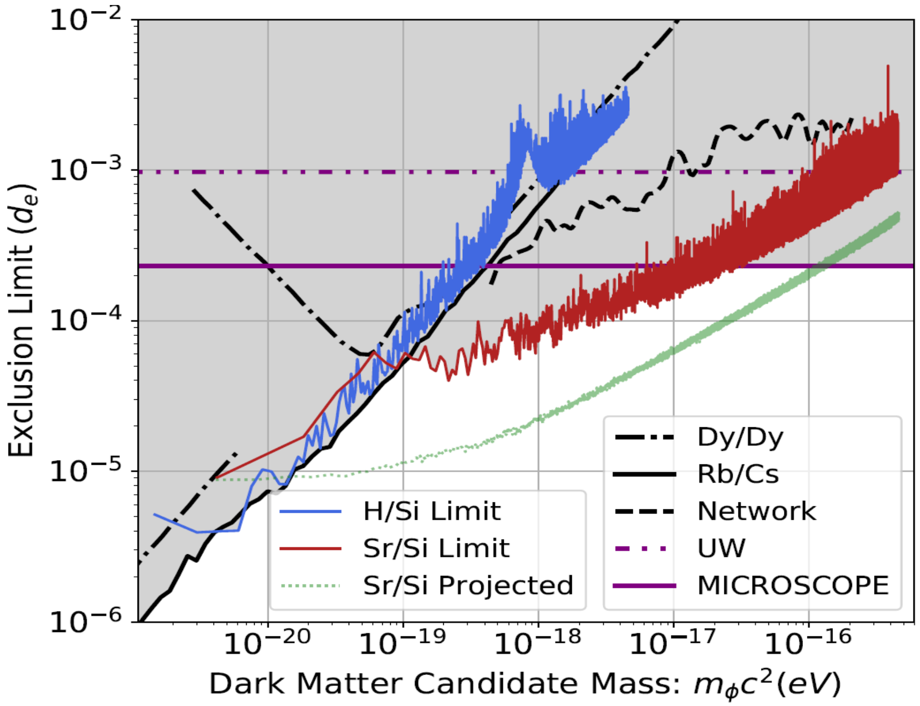
τ ~ 160 s
Q ~ 10^{17}

Jun Ye – Atomic Clocks and Fundamental Physics

- Quantized motion of crystals
- Entanglement under GR
- Wavelike dark matter searches
- Optical Nuclear Transitions

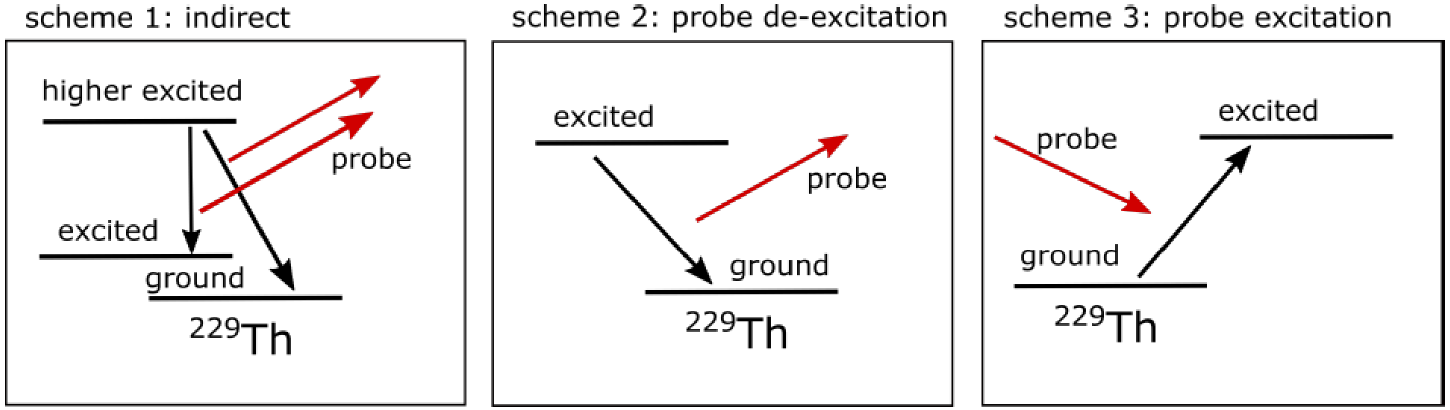
Example: Dilaton dark matter search





Jun Ye – Atomic Clocks and Fundamental Physics

Direct laser excitation of nuclear transition



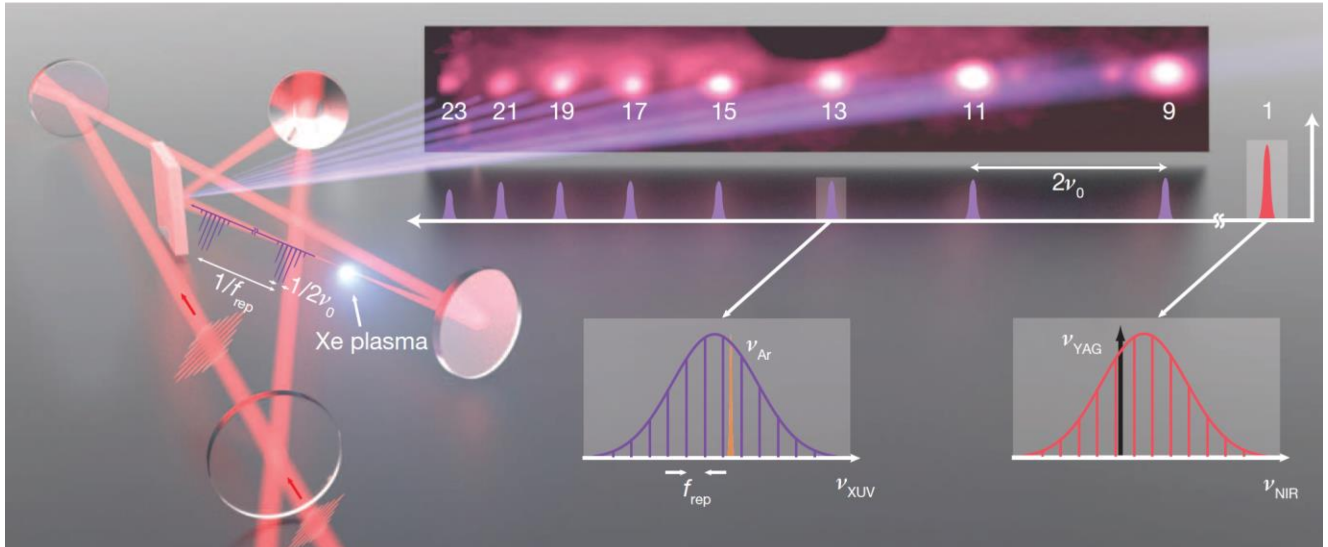
Historic approach	Working on	Future approach
old energy value:	best energy value:	expected energy value:
7.8 ± 0.5 eV[	10^{-16} (reference to Sr clock)	$< 40\ \mu$eV

Beck *et al.*, PRL **98**, 142501 (2007). Seiferle *et al.*, Nature **573**, 243 (2019).

VUV Comb:

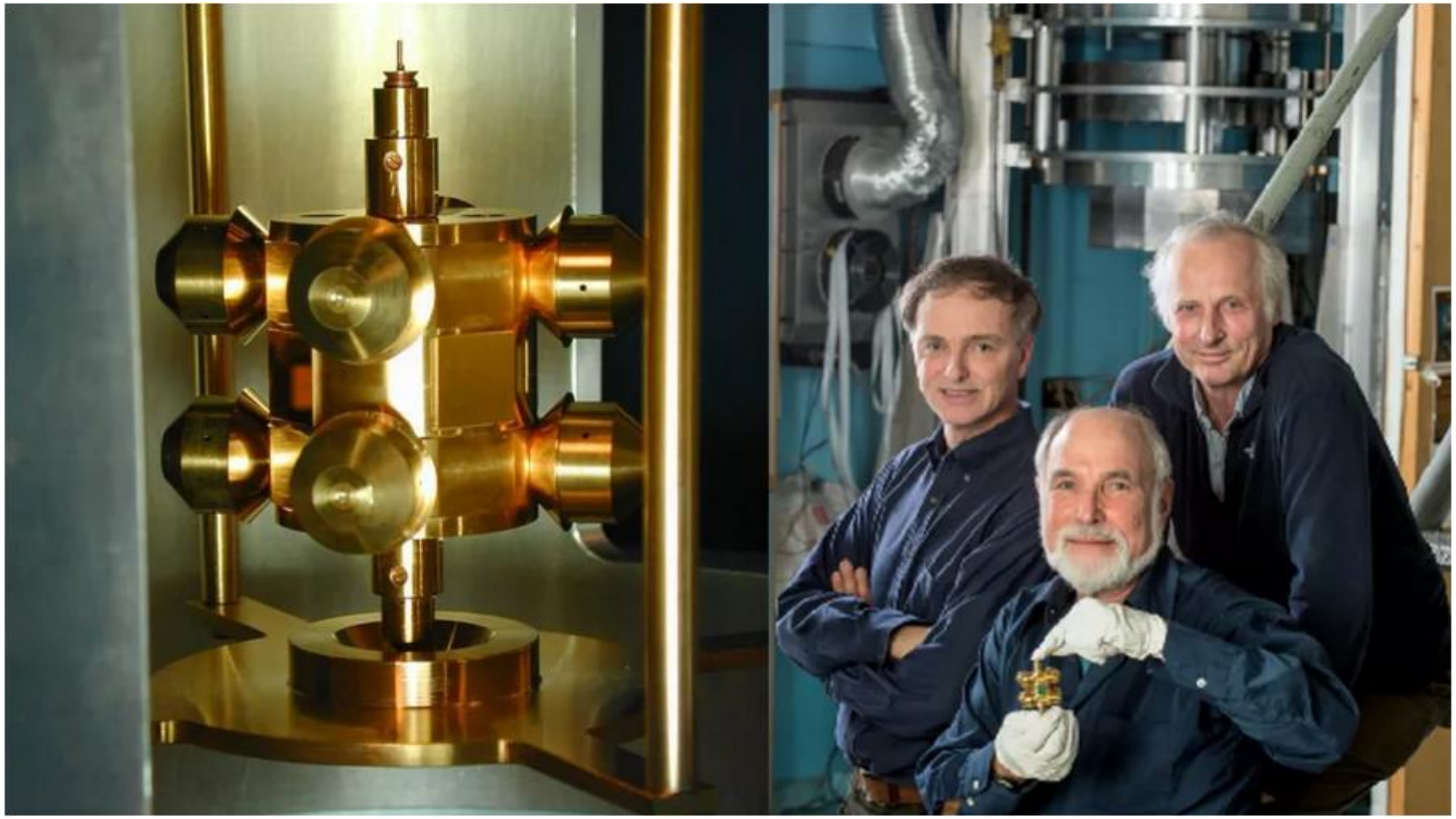
- **Linewidth < 1 kHz**
- **100 nW per comb**

L. von der Wense
C. Zhang



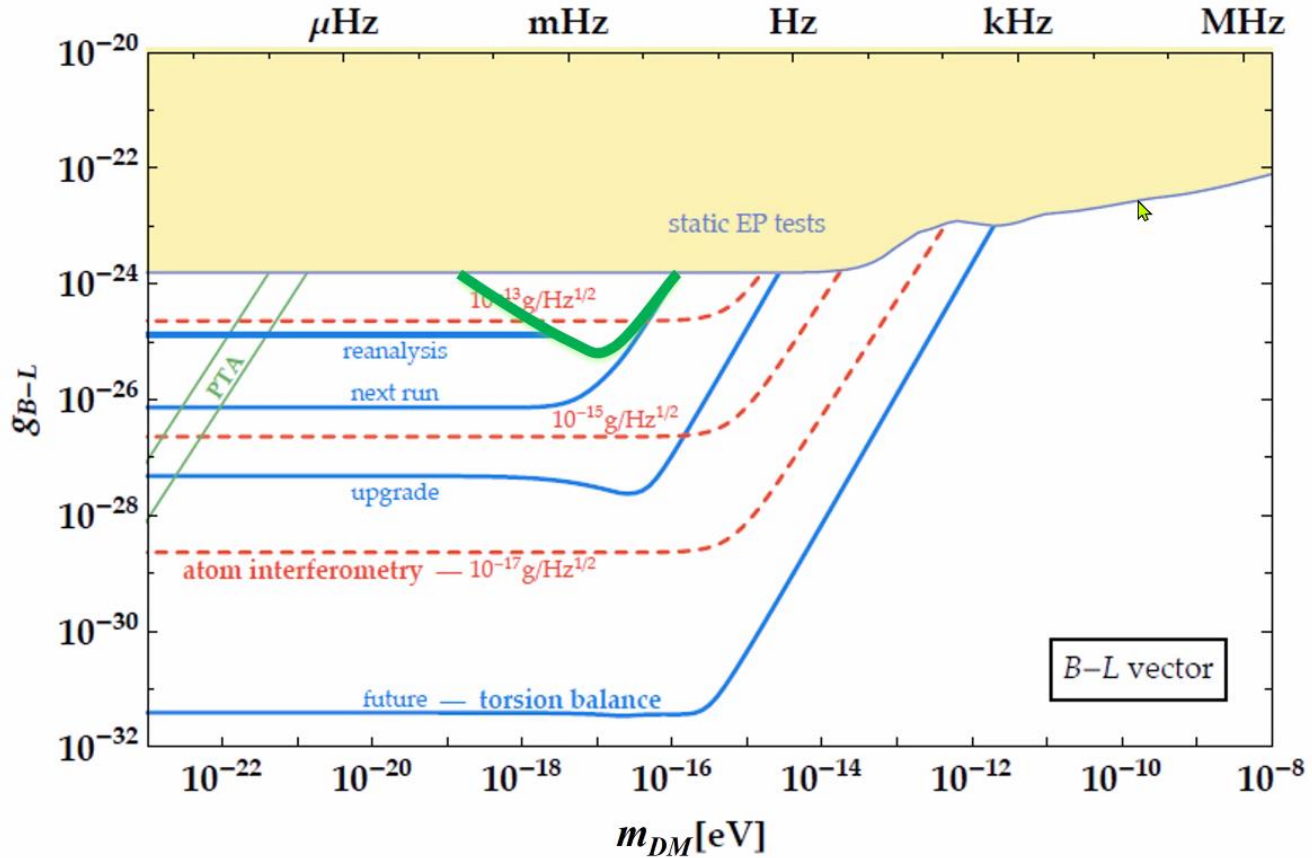
Jens Gundlach – Dark Matter Searches with Accelerometers

2021
Breakthrough
Prize for studies of
gravity done at
CENPA



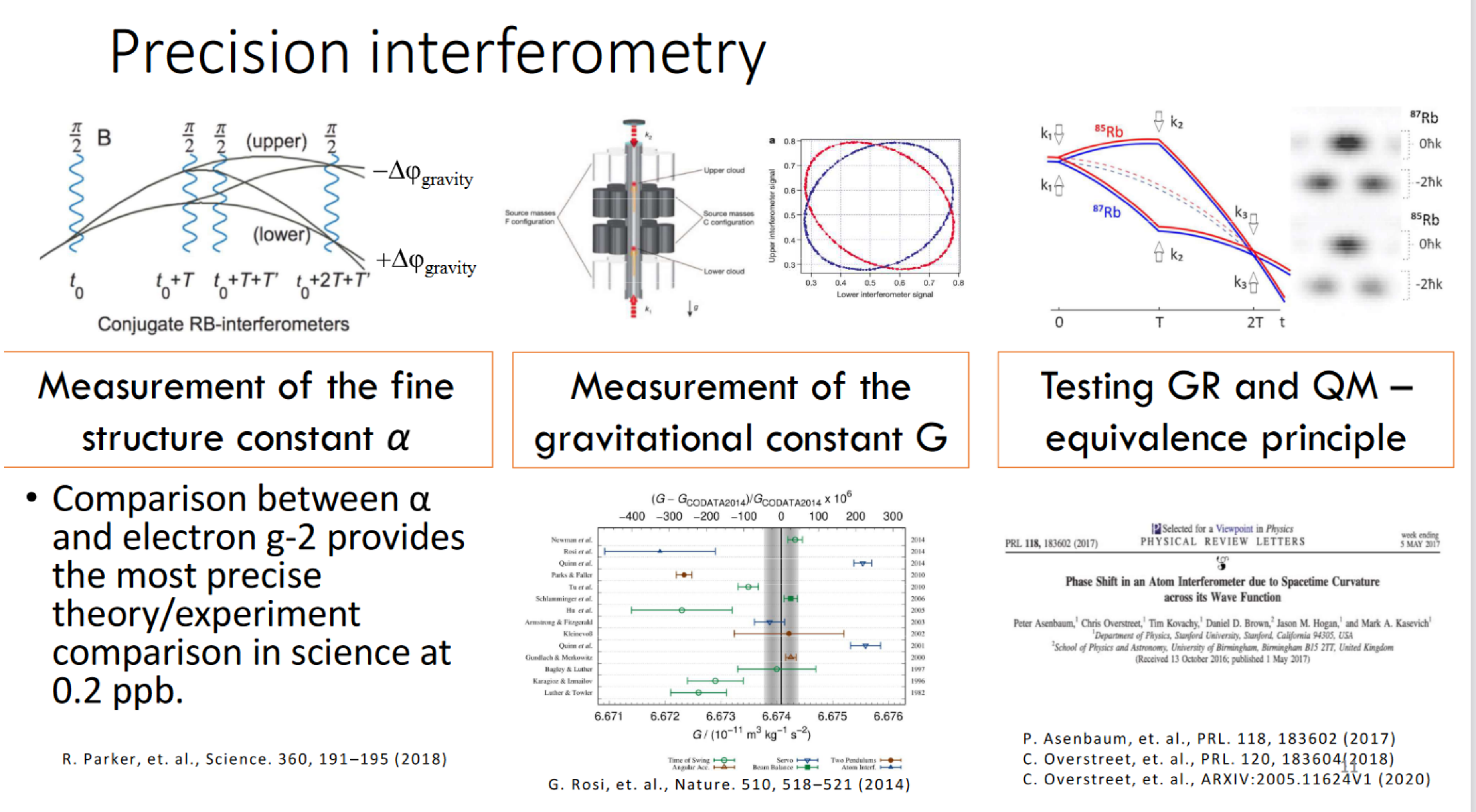
Jens Gundlach – Dark Matter Searches with Accelerometers

- Ultra-light new particles mediate ultra-weak forces may be detectable with torsion pendula
- Also sensitive to equivalence principle, some dark matter models (axion wind)



Graham et al (2016)

Cris Panda - Atomic Interferometry



Precision interferometry

Measurement of the fine structure constant α

- Comparison between α and electron g-2 provides the most precise theory/experiment comparison in science at 0.2 ppb.

R. Parker, et. al., Science. 360, 191–195 (2018)

Measurement of the gravitational constant G

G. Rosi, et. al., Nature. 510, 518–521 (2014)

Testing GR and QM – equivalence principle

PRL **118,** 183602 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

Phase Shift in an Atom Interferometer due to Spacetime Curvature across its Wave Function

Peter Asenbaum,[1] Chris Overstreet,[1] Tim Kovachy,[1] Daniel D. Brown,[2] Jason M. Hogan,[1] and Mark A. Kasevich[1]

[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*

[2]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*

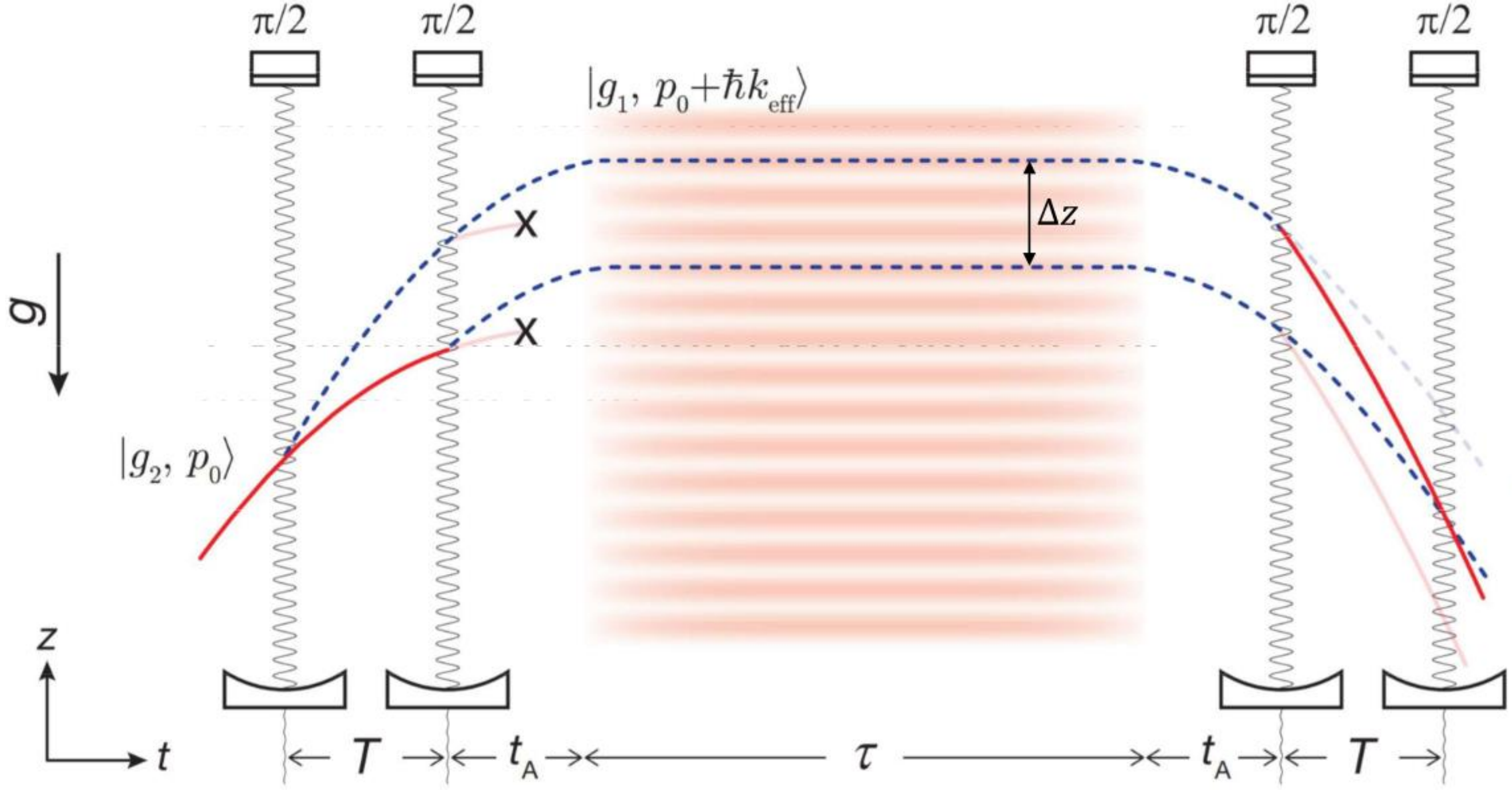
(Received 13 October 2016; published 1 May 2017)

P. Asenbaum, et. al., PRL. 118, 183602 (2017)
C. Overstreet, et. al., PRL. 120, 183604(2018)
C. Overstreet, et. al., ARXIV:2005.11624V1 (2020)

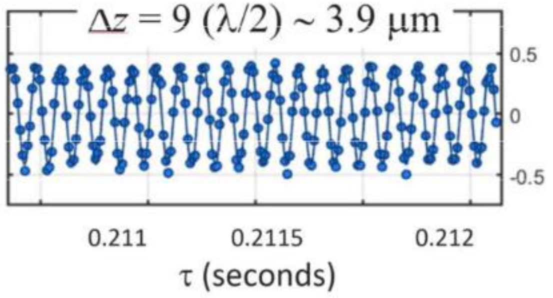
Cris Panda - Atomic Interferometry

Atom interferometer in an optical lattice

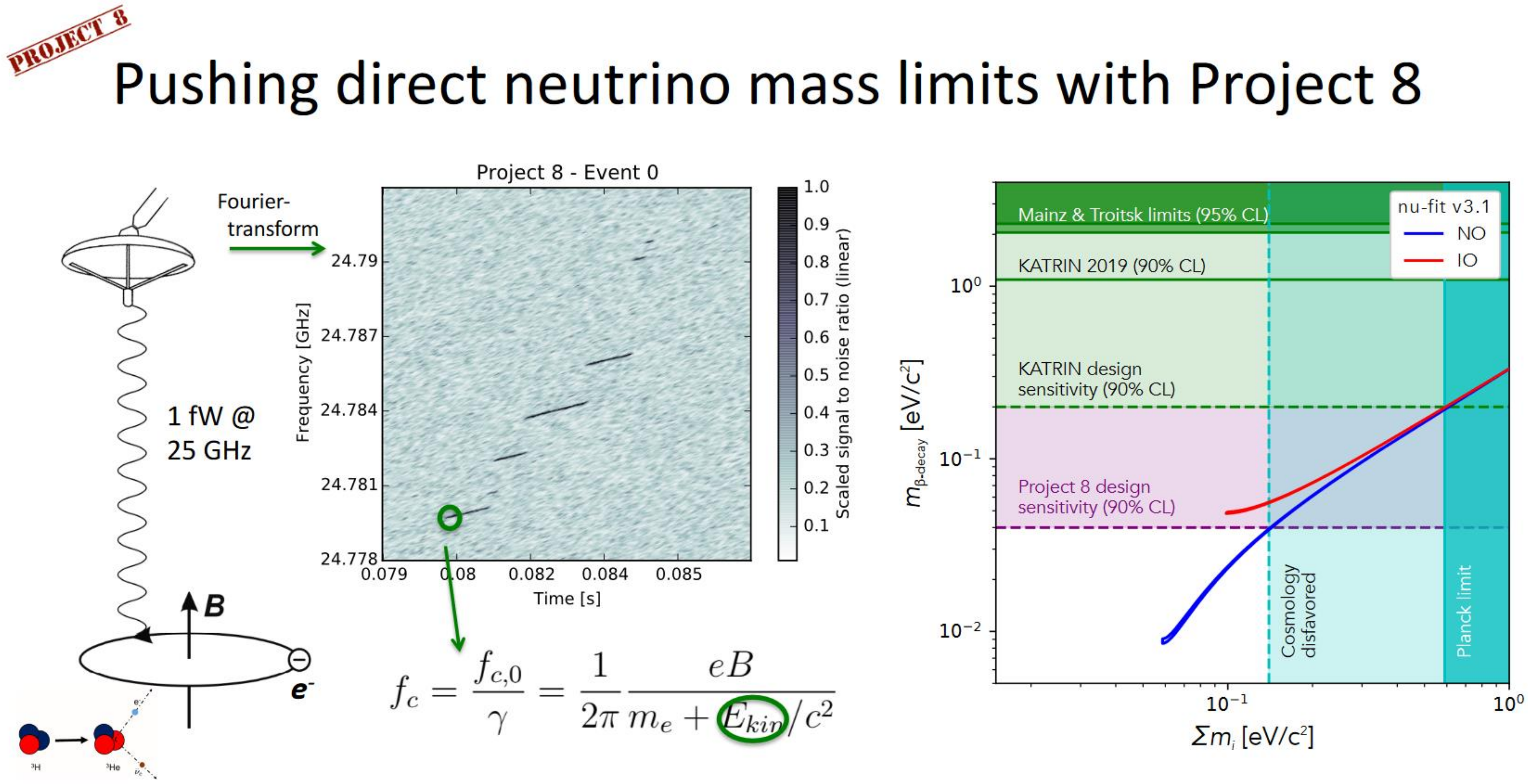
20 second coherence time



$$\Delta\phi_{\text{free}} = \frac{1}{\hbar}\int L\,dt$$
$$= \frac{mg\Delta z}{\hbar}\tau$$
$$\approx kgT\tau$$



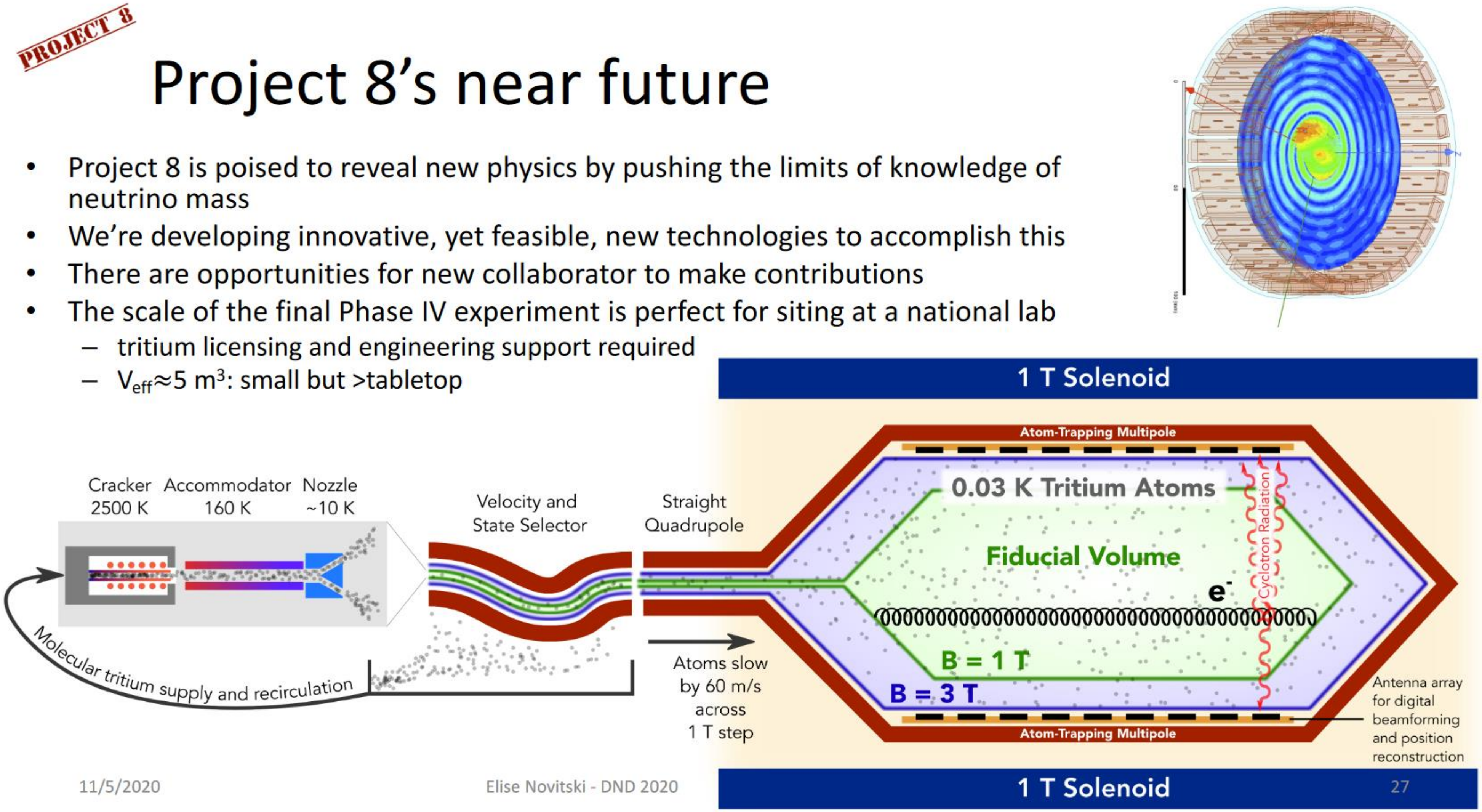
Elise Novitski – Laboratory Neutrino Mass Measurements



Pushing direct neutrino mass limits with Project 8

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{kin}/c^2}$$

Elise Novitski – Laboratory Neutrino Mass Measurements



Project 8's near future

- Project 8 is poised to reveal new physics by pushing the limits of knowledge of neutrino mass
- We're developing innovative, yet feasible, new technologies to accomplish this
- There are opportunities for new collaborator to make contributions
- The scale of the final Phase IV experiment is perfect for siting at a national lab
  - tritium licensing and engineering support required
  - $V_{eff} \approx 5\ m^3$: small but >tabletop

Makoto Fujiwara – New techniques for precision measurements on simple atoms/molecules

TRIUMF

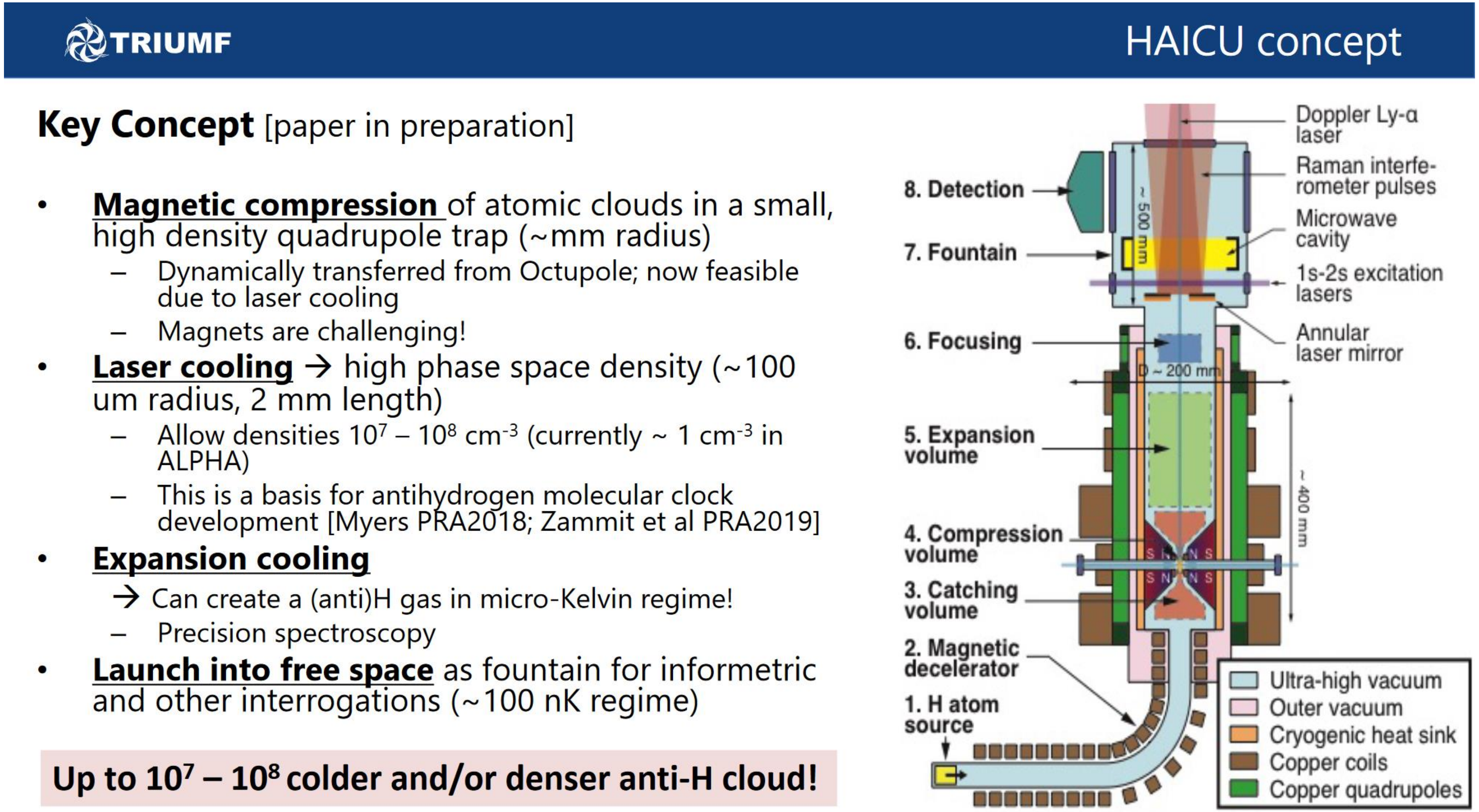
- Hydrogen
  - “Much of what we know about the Universe comes from looking at hydrogen”
  - 75% of *known* Universe
  - One of the most precisely measured physical systems

- Exotic hydrogen (TRIUMF/CENPA)
  - Muonium
  - Muonic Hydrogen
  - Hadronic Hydrogen
  - Antihydrogen
  - Positronium

Tests of QED, Quantum Field Theory, General Relativity
Fundamental Symmetries (CPT, Equiv. Principle etc)
“Are we asking the right question?” arXiv:1309.7468

If we can improve the precisions of simple systems, we should!

Makoto Fujiwara – New techniques for precision measurements on simple atoms/molecules



TRIUMF

HAICU concept

Key Concept [paper in preparation]

- **Magnetic compression** of atomic clouds in a small, high density quadrupole trap (~mm radius)
  - Dynamically transferred from Octupole; now feasible due to laser cooling
  - Magnets are challenging!
- **Laser cooling** → high phase space density (~100 um radius, 2 mm length)
  - Allow densities $10^7 – 10^8$ cm^{-3} (currently ~ 1 cm^{-3} in ALPHA)
  - This is a basis for antihydrogen molecular clock development [Myers PRA2018; Zammit et al PRA2019]
- **Expansion cooling**
  - → Can create a (anti)H gas in micro-Kelvin regime!
  - Precision spectroscopy
- **Launch into free space** as fountain for informetric and other interrogations (~100 nK regime)

Up to $10^7 – 10^8$ colder and/or denser anti-H cloud!

Outlook – Opportunity Highlights for TRIUMF Summary

- Develop better atomic clocks
- Develop superconducting sensors
- Search for Axion Dark Matter
- Develop Macroscopic/Quantum Mechanical pendula
- Develop Atom Interferometry
- Measure the Neutrino Mass Scale
- Improve Hydrogen/Antihydrogen Measurements

Outlook

“There’s plenty of room at the bottom”…. Of the energy scale!

Current thinking makes a strong physics case for studying low-energy, weakly-coupled phenomena.

Recent advances in quantum-scale high-precision techniques makes this possible.

It’s an ideal time to think about putting resources in this direction.