Title: Atomic spin squeezing - concepts and experiments

Date: Apr 24, 2018 01:00 PM

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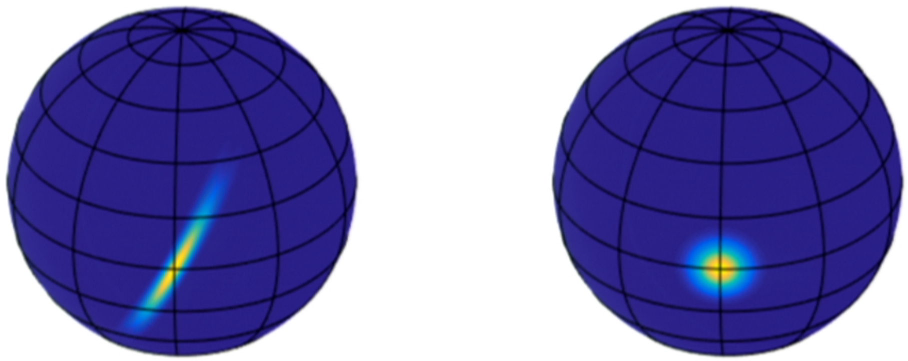
Abstract: <p>In the last decades, advances in the level of precision in controlling atomic and optical systems opened up the low-energy precision frontier to fundamental physics tests. Exploitation of quantum entanglement in such systems to further improve the sensitivity of certain existing approaches is currently an active field of research. Drawing from the experiments in our lab, in this talk I will focus on the properties, generation and usage of a particular set of entangled states called spin squeezed states.</p>

Atomic Spin Squeezing
concepts and experiments



Perimeter Institute 2018

Onur Hosten

STANFORD UNIVERSITY

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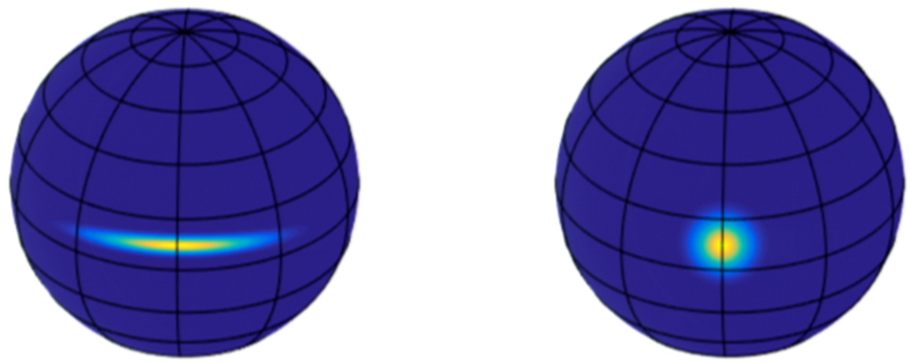

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Quantum sensing (broad sense)

Quantum sensor: Any physical object whose quantum mechanical properties are employed to make measurements of external perturbations

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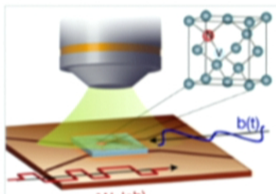
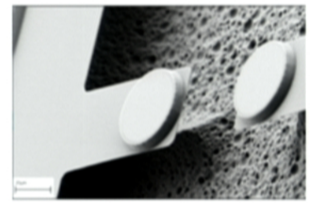
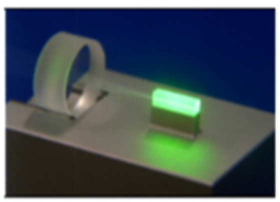


NV centers (spins) in diamond
(nano-scale magnetic field sensing)

Micro-mechanical oscillators
(force sensing)





Squeezed or other non-classical light
(Opt. interfermonetry, imaging)

Atomic vapors, trapped ions
(field & force sensing, time keeping)

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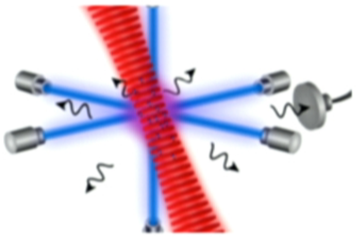
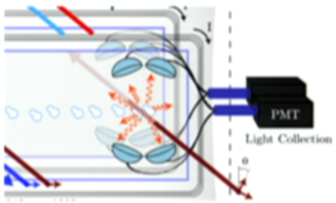
Precision sensing with atoms



Atomic clocks
(resolve gravitational time dilation)

Molecules for Electron EDM searches
energy level shifts in E field
(constraining supersymmetry)



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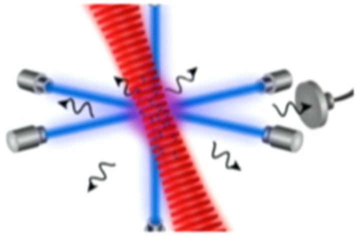

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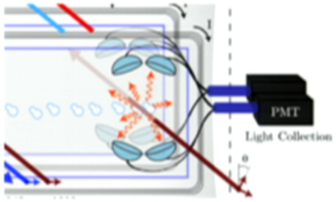
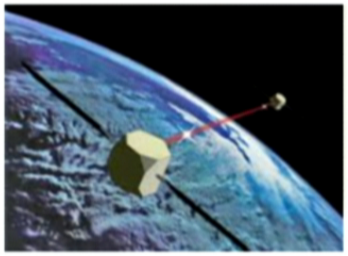
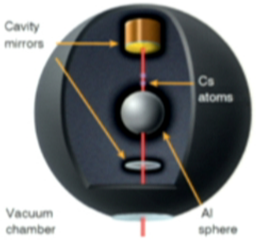




Atom interferometers
(Testing Einstein's equivalence principle)
(Gravitational wave detection)
(Searches of dark energy)
(Gravimetry, inertial navigation)



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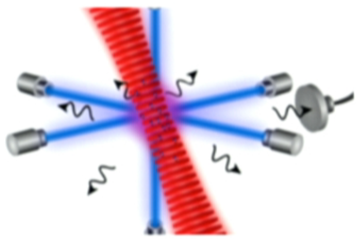

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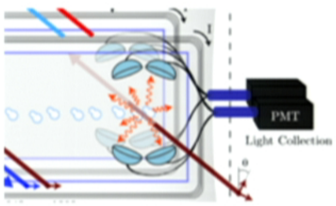

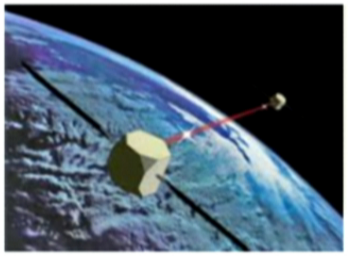

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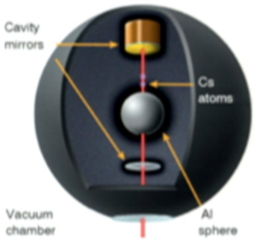

In common:

- Reduce to sensing w/ two-level quantum system
- Can be improved via entanglement (strict sense quantum metrology)

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The Question

How can we control and exploit quantum correlations in large collections of atoms and photons?

Study and engineer entanglement in large atomic ensembles

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The Question

How can we control and exploit quantum correlations in large collections of atoms and photons?

Study and engineer entanglement in large atomic ensembles

Specific goal:

Improve the best-performing atom interferometers/sensors

Engineered sensors run at the SQL and atom density limits

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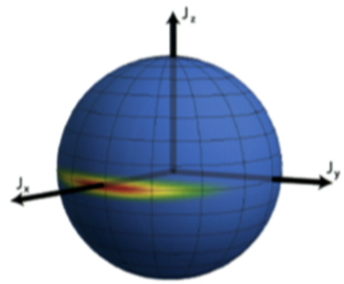
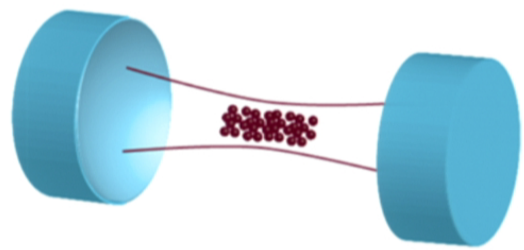
Outline

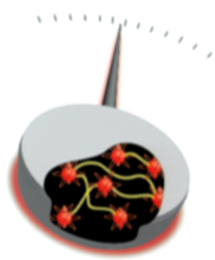
Quantum metrology /w atoms



Cavity QED with large atomic ensembles



Experimental highlights: past / present / future



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Sensing with two level atoms

Two level system: Spin ½ system – measure a small energy shift

$$|\downarrow\rangle \xrightarrow{R_{-y}} \frac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right) \xrightarrow{t} \frac{1}{\sqrt{2}}\left(e^{-i\phi}\,|\uparrow\rangle + e^{i\phi}\,|\downarrow\rangle\right)$$

$$\xrightarrow{R_x} \approx \frac{e^{-i\frac{\pi}{4}}}{\sqrt{2}}\left((1+\phi)\,|\uparrow\rangle + (1-\phi)\,|\downarrow\rangle\right) \Longleftarrow P_{\uparrow\downarrow} = \frac{1}{2} \pm \phi$$

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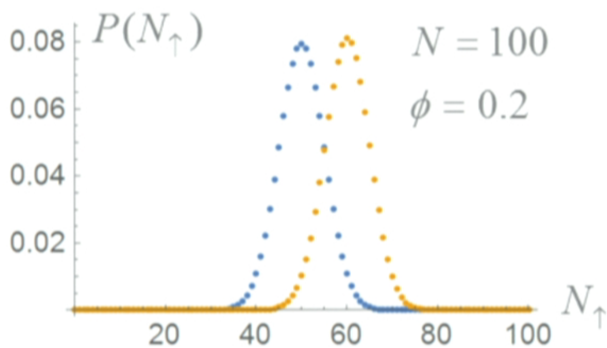
N identical copies to average down the noise (binomial dist.)

$$|\psi\rangle = \left(\tfrac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)\right)^{\otimes N} \xrightarrow{actions} \left(\tfrac{1}{\sqrt{2}}\left((1+\phi)\,|\uparrow\rangle + (1-\phi)\,|\downarrow\rangle\right)\right)^{\otimes N}$$



Shot/projection noise

$$\sigma = \frac{\sqrt{N}}{2} = 5$$

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Coherent states / Dicke states

N identical two level systems 2^N states. Symmetric subspace → N states

Coherent spin state (CSS):

$$|\theta,\phi\rangle = \left(\cos\tfrac{\theta}{2}|\downarrow\rangle + e^{i\phi}\sin\tfrac{\theta}{2}|\uparrow\rangle\right)^{\otimes N} = (\cos\tfrac{\theta}{2})^N\,|\downarrow ....\downarrow\rangle + ...$$

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$$= \sum_m c_m(\theta) e^{-i(J+m)\phi} |J,m\rangle$$

$$c_m(\theta) = \binom{2J}{J+m}^{1/2} (\cos\tfrac{\theta}{2})^{J-m} (\sin\tfrac{\theta}{2})^{J+m}$$

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Dicke states: A mapping onto angular momentum states $J_z |J,m\rangle = m|J,m\rangle$

$$J = N/2, \quad m = (N_\uparrow - N_\downarrow)/2$$

Example with 4 particles (entangled)

$$|2,2\rangle \equiv |\uparrow\uparrow\uparrow\uparrow\rangle$$

$$|2,1\rangle \equiv \tfrac{1}{2}\left(|\uparrow\uparrow\uparrow\downarrow\rangle + |\uparrow\uparrow\downarrow\uparrow\rangle + |\uparrow\downarrow\uparrow\uparrow\rangle + |\downarrow\uparrow\uparrow\uparrow\rangle\right)$$

$$|2,0\rangle \equiv \tfrac{1}{\sqrt{6}}\left(|\uparrow\uparrow\downarrow\downarrow\rangle + |\uparrow\downarrow\uparrow\downarrow\rangle + |\uparrow\downarrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\downarrow\rangle + |\downarrow\uparrow\downarrow\uparrow\rangle + |\downarrow\downarrow\uparrow\uparrow\rangle\right)$$

$$|2,-1\rangle \equiv \tfrac{1}{2}\left(|\uparrow\downarrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\downarrow\rangle + |\downarrow\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\downarrow\uparrow\rangle\right)$$

$$|2,-2\rangle \equiv |\downarrow\downarrow\downarrow\downarrow\rangle$$

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How we think of our atomic sensors

N 2-level atoms: Spin ½ systems (^{87}Rb hyperfine clock states)

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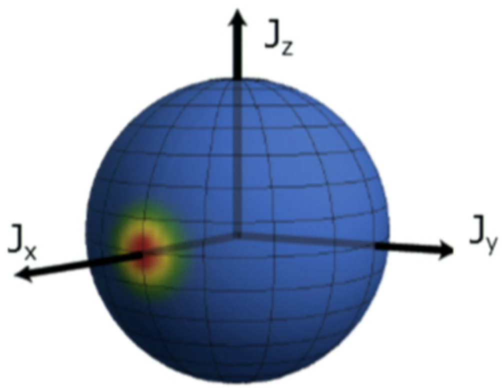
How we think of our atomic sensors

N 2-level atoms: Spin ½ systems (^{87}Rb hyperfine clock states)

Spin N/2 system: Collective angular momentum vector **J**



Coherent spin state (uncorrelated spins)
Representation on Bloch sphere (Wigner)

J_z : Population imbalance (-N/2 to N/2)
Arg[$J_x + i\, J_y$] : Phase difference between two levels

Uncertainty relation: $\Delta J_z \Delta J_y = N/4$
Shot noise: projection onto J_z axis $\sqrt{N}/2$

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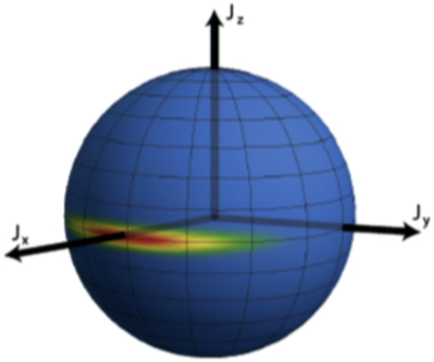
Spin Squeezed Atomic States

Spin squeezed states:



Reduced noise in ΔJ_z at the expense of ΔJ_y

$\Delta J_z < \sqrt{N}/2$

Necessarily implies entanglement

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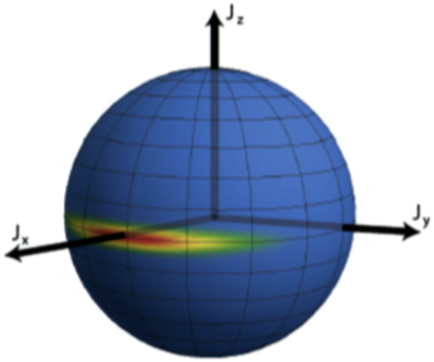

Reduced noise in ΔJ_z at the expense of ΔJ_y

$\Delta J_z < \sqrt{N}/2$

Necessarily implies entanglement

Population squeezed state:

Superposition Dicke states w/ distribution narrower than uncorrelated case

$$|\,squeezed\rangle = \sum_m c_m e^{-i(J+m)\phi}\,|\,J,m\rangle$$

$$std(J_z) = \left(\sum_m |\,c_m\,|^2 m^2\right)^{1/2} < \sqrt{N}\,/\,2$$

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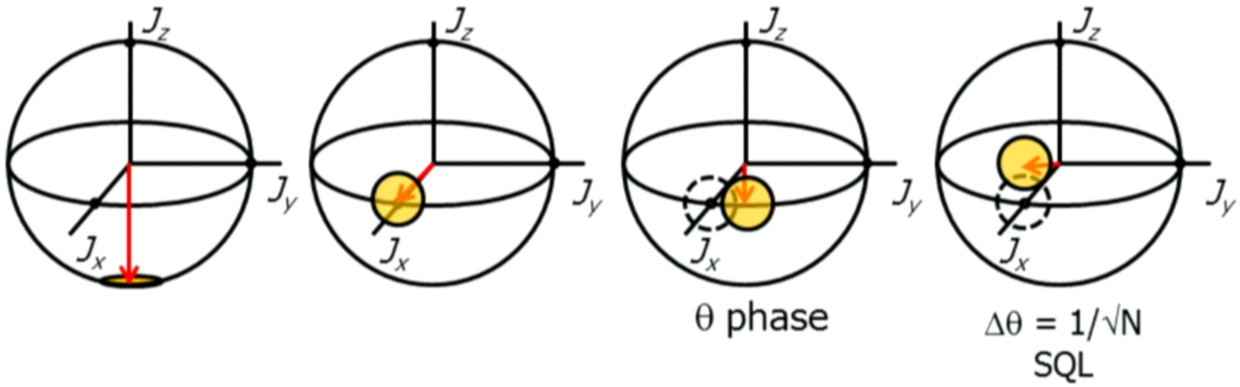
Generic atom sensor

Ramsey sequence: $\pi/2$ – precession - π /2 – read J_z



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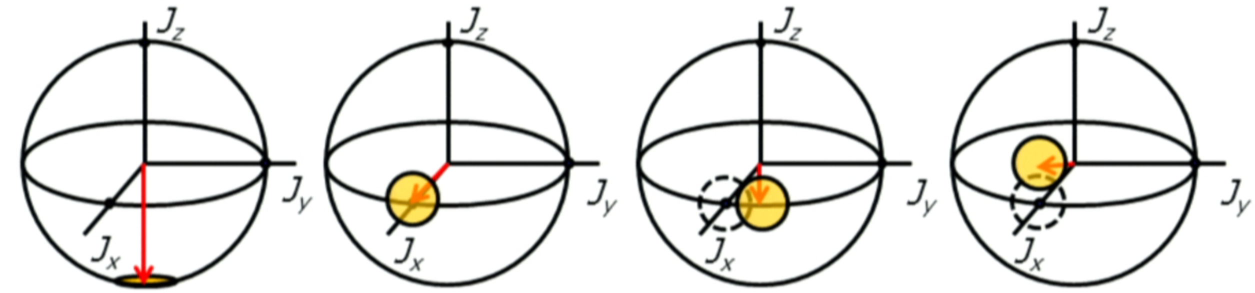
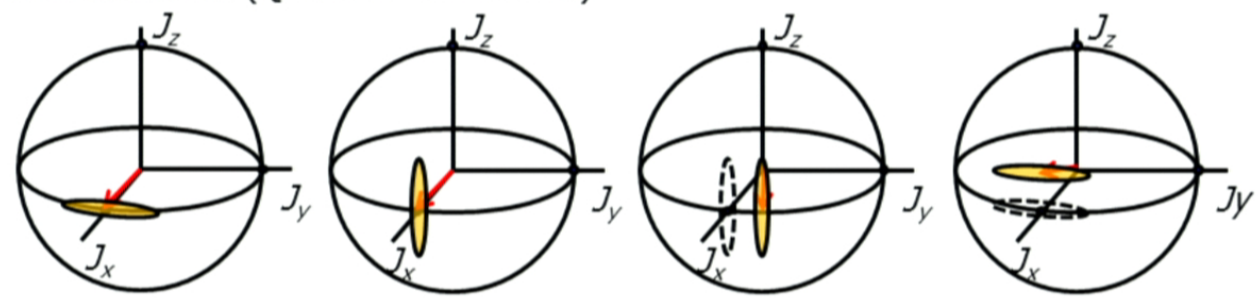


θ phase

Δθ = 1/√N
SQL

Squeezed states (Quantum correlations)



Number squeezed

Phase squeezed

Reduced noise
Δθ ~ 1/N in principle

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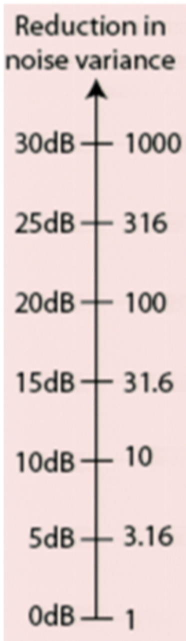
Squeezing Survey



Physical systems

Light: First large scale application

LIGO demonstrated operation with squeezed light(2.5dB impr.)

[The LIGO Scientific Collaboration, Nat. Photon. 7, 613–619 (2013)]

Microwaves:

Superconducting circuits/cavities (12dB sqz.)

[C. Eichler *et al.*, PRL 113, 110502 (2014)]

Mechanical oscillators:

Micron scale cryogenic oscillator (1dB)

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Previous strongest squeezing: photons

12.7dB directly measured squeezing

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Atoms…

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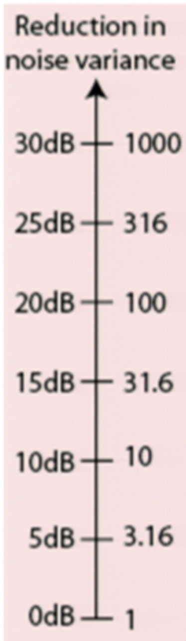

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Atoms…

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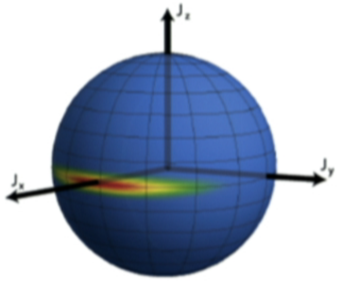
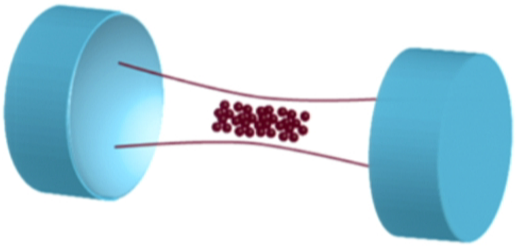
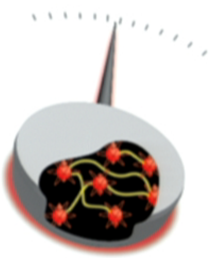


Cavity QED with
large atomic ensembles



Experimental highlights: past / present / future



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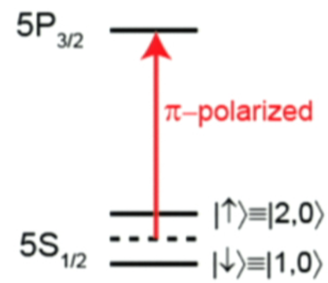
Cavity QED setup

Population difference measurement:
Phase shifts imparted on light is proportional to J_z
(projects the atomic state)



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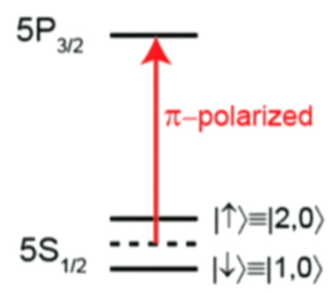
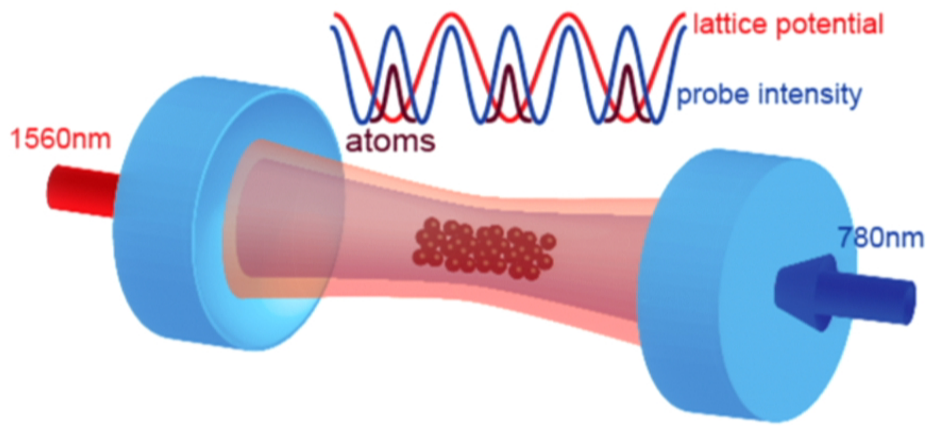


175k finesse optical cavity:



Cavity resonance shift: 5.5 Hz per spin-flip (8kHz linewidth)
Technical noise floor: 3 spin-flips (out of 1M)

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Atom – filed entanglement

Mathematical formalism: The population difference is coupled to the cavity field mode (harmonic oscillator)

$$H_I = -\hbar\, g\, J_z\, a^\dagger a$$

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Atom – filed entanglement

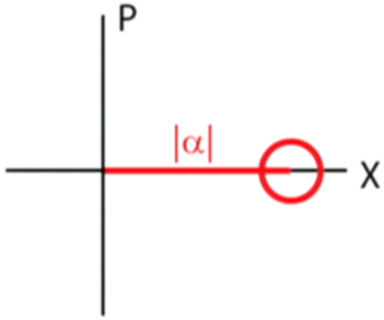
Mathematical formalism: The population difference is coupled to the cavity field mode (harmonic oscillator)

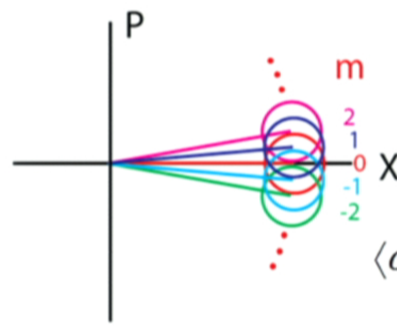
$$H_I = -\hbar g J_z a^\dagger a$$

This Hamiltonian generates phase shifts of the intra-cavity field.

$$|\psi\rangle = \left(\sum_m c_m |J,m\rangle\right) \otimes |\alpha\rangle$$

$$\rightarrow \sum_m c_m e^{-igtm a^\dagger a} |J,m\rangle |\alpha\rangle = \sum_m c_m |J,m\rangle |\alpha e^{-igtm}\rangle$$





$$\langle \alpha(m) | \alpha(m') \rangle \neq 0$$

Measurement of P quadrature projects atomic state to a narrower c_m distribution

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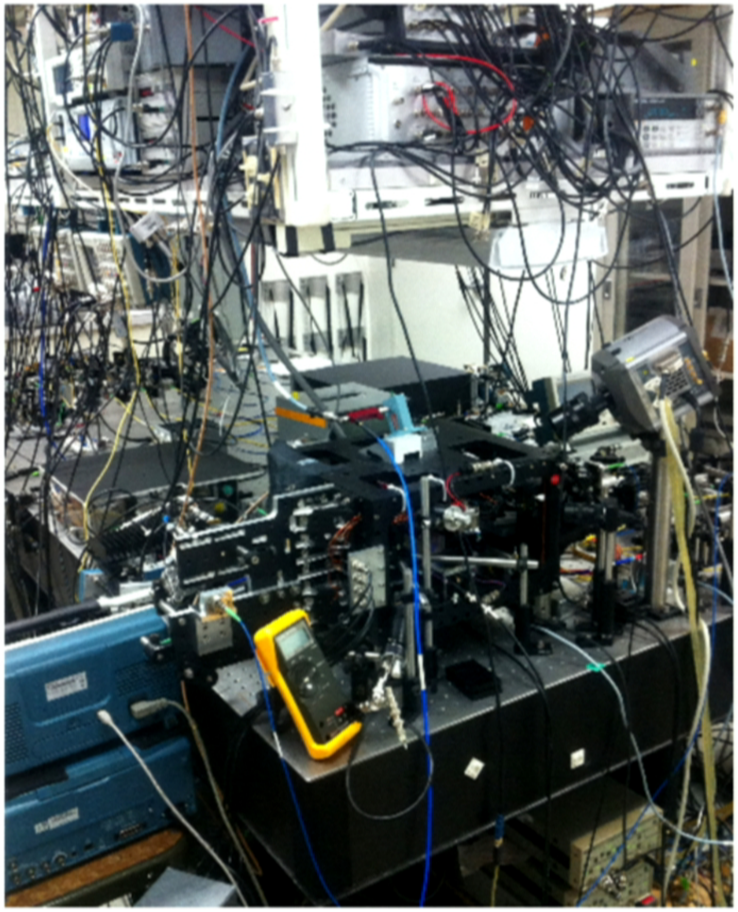
The Apparatus



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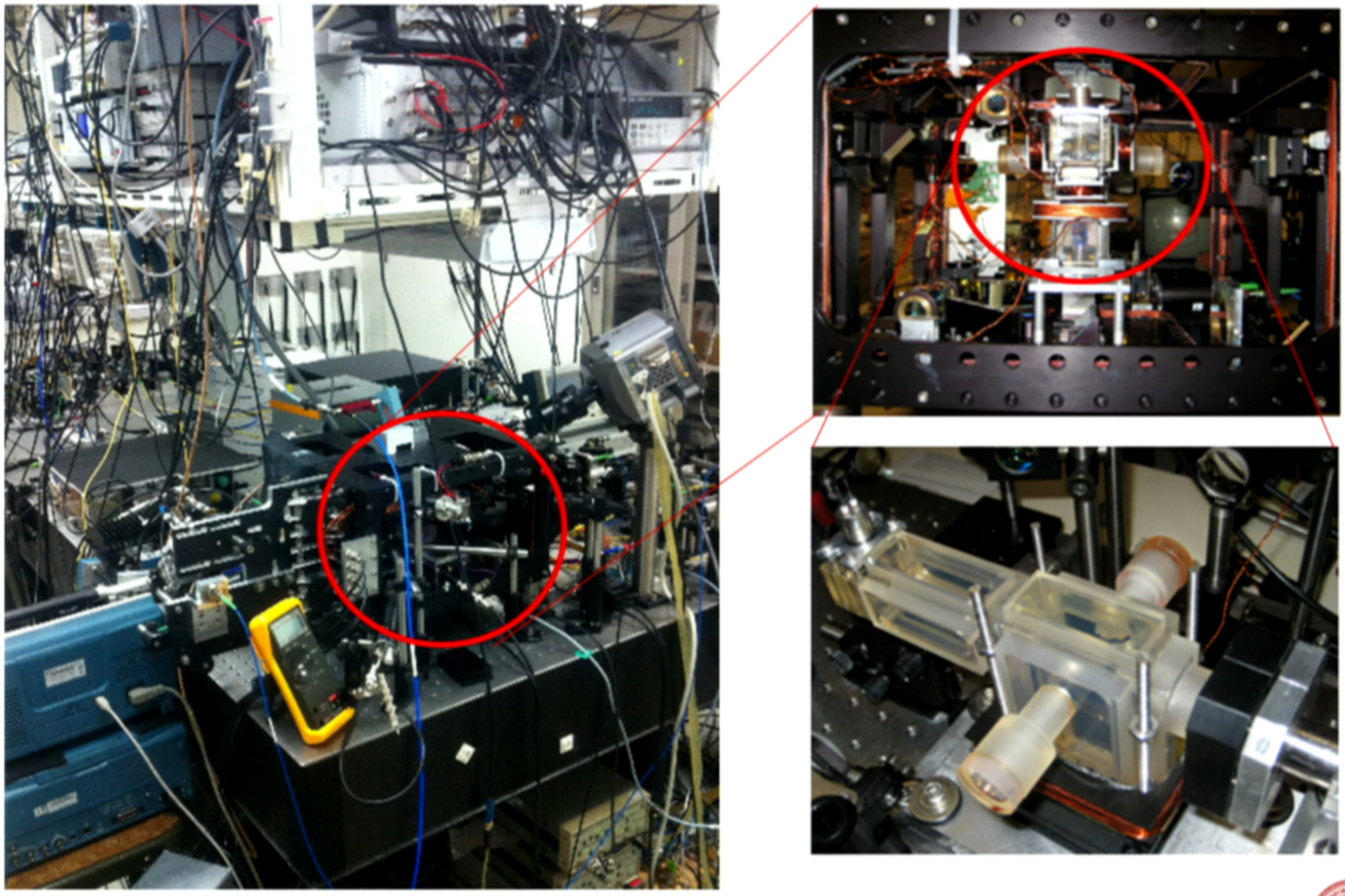

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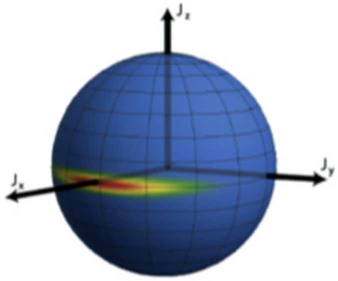

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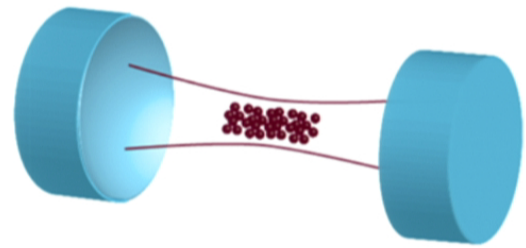

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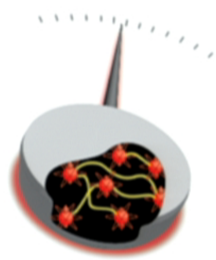
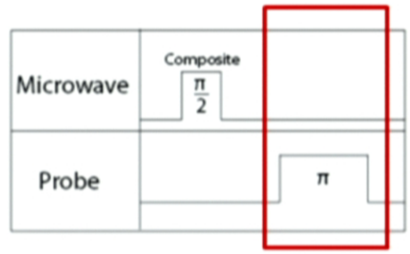
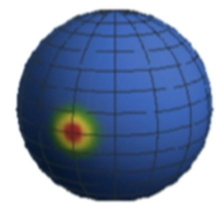


Pillar 1 : Atomic shot noise



200 μs
J_z measurements



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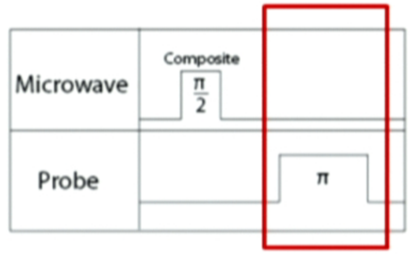
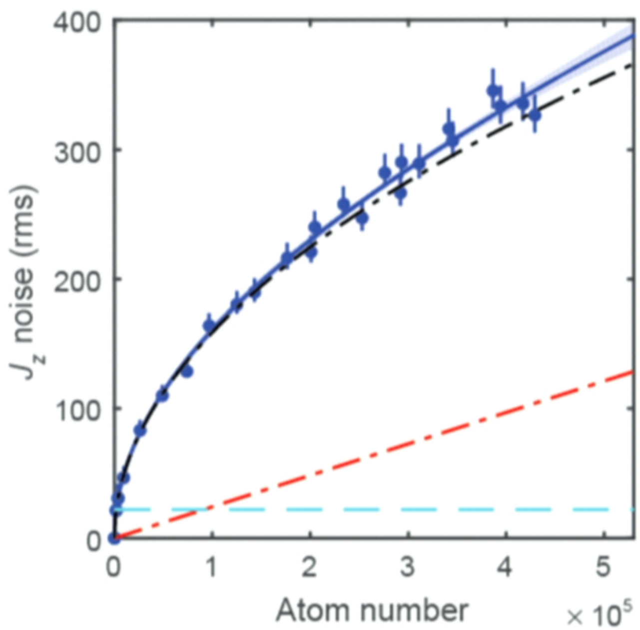
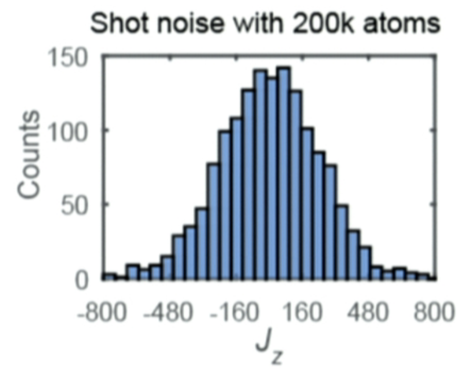
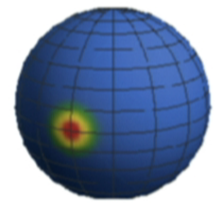


200 μs
J_z measurements







Black: expected shot noise
Cyan: empty cavity noise
Blue: fit
Red: Underlying rotation noise

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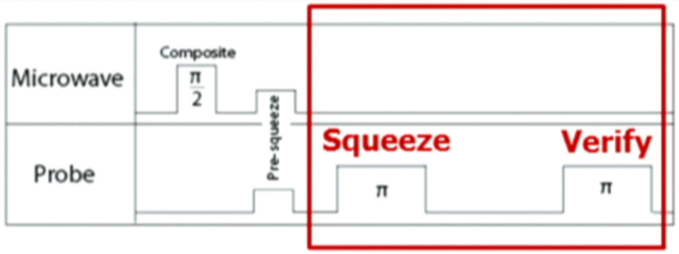
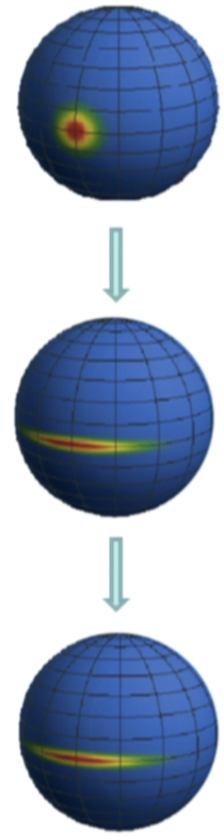
Pillar 2 : Spin noise reduction





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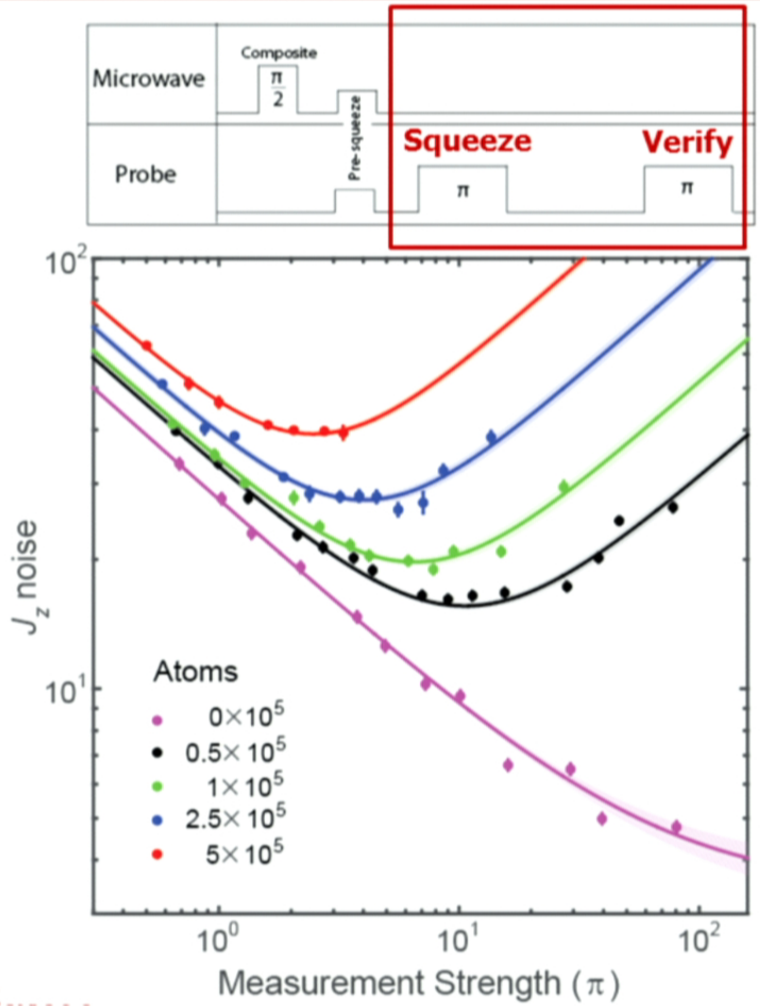

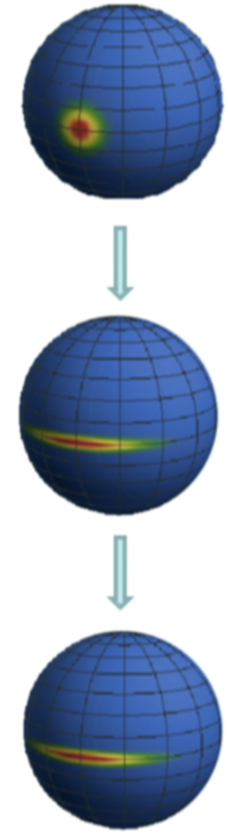

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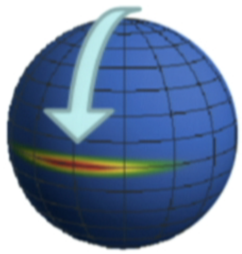
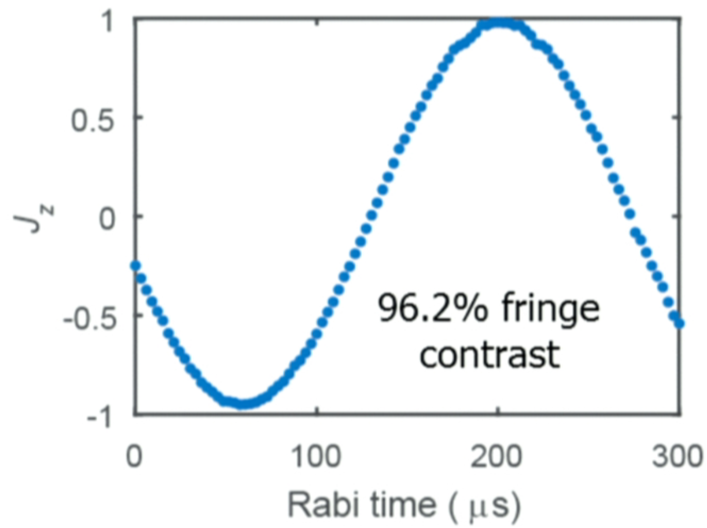
Pillar 3 : Coherence

Rabi oscillations after squeezing w/ 500k atoms & π-probe strength





Including loss in coherence

Metrological enhancement capacity:

20.7 dB – 0.6 dB = 20.1dB

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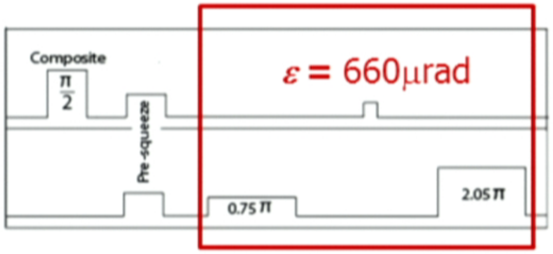
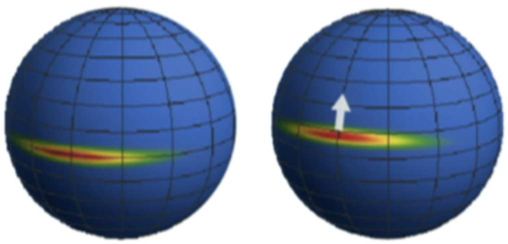
Metrology demonstration: Tipping





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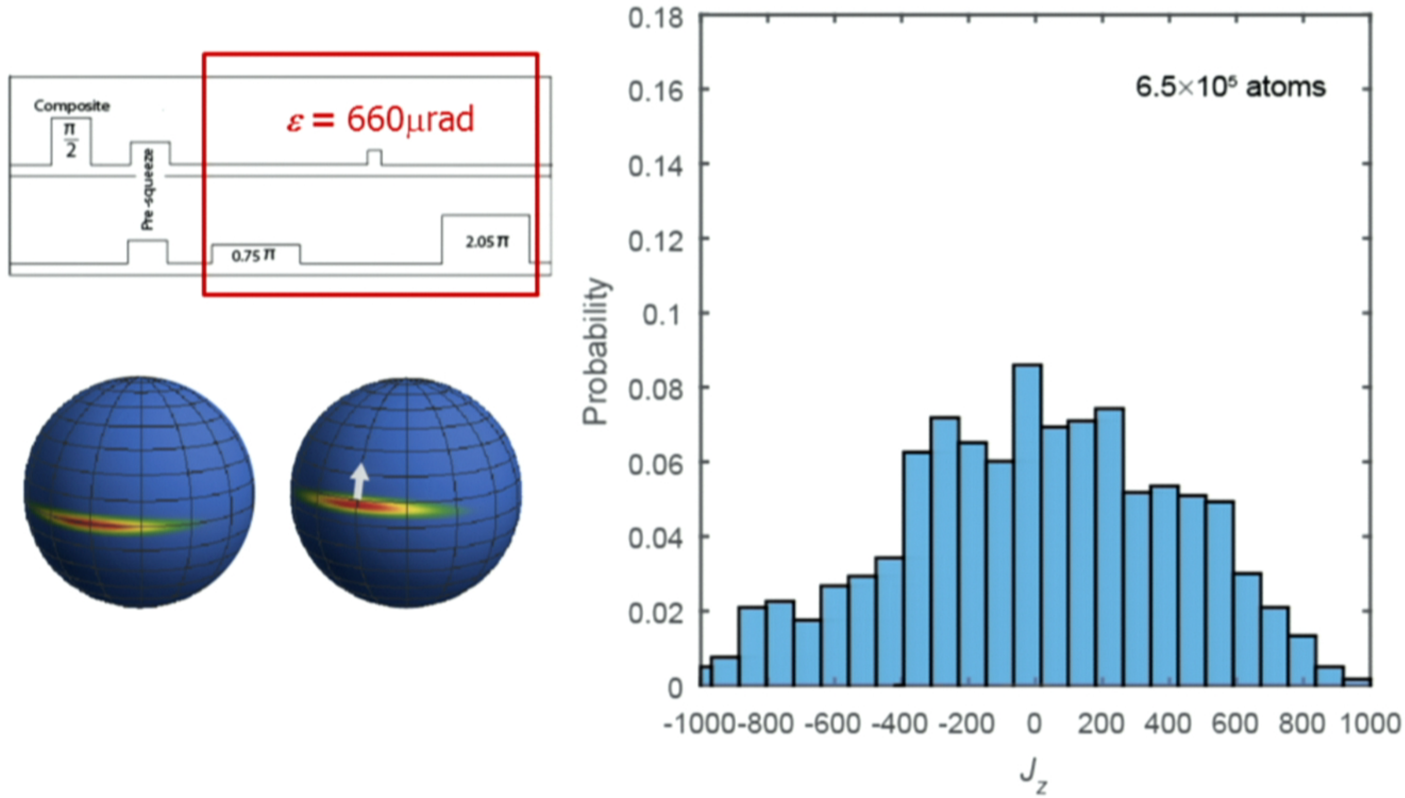

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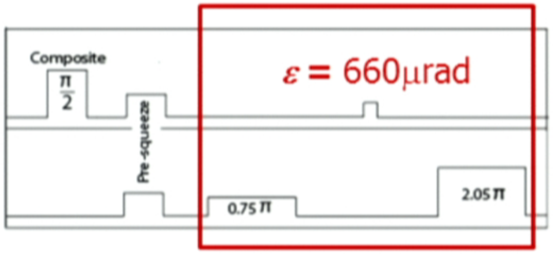
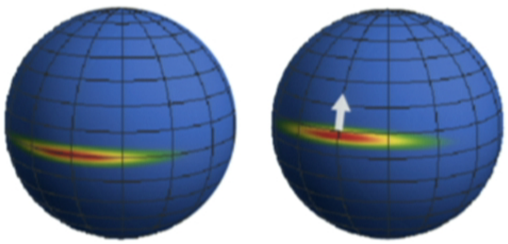
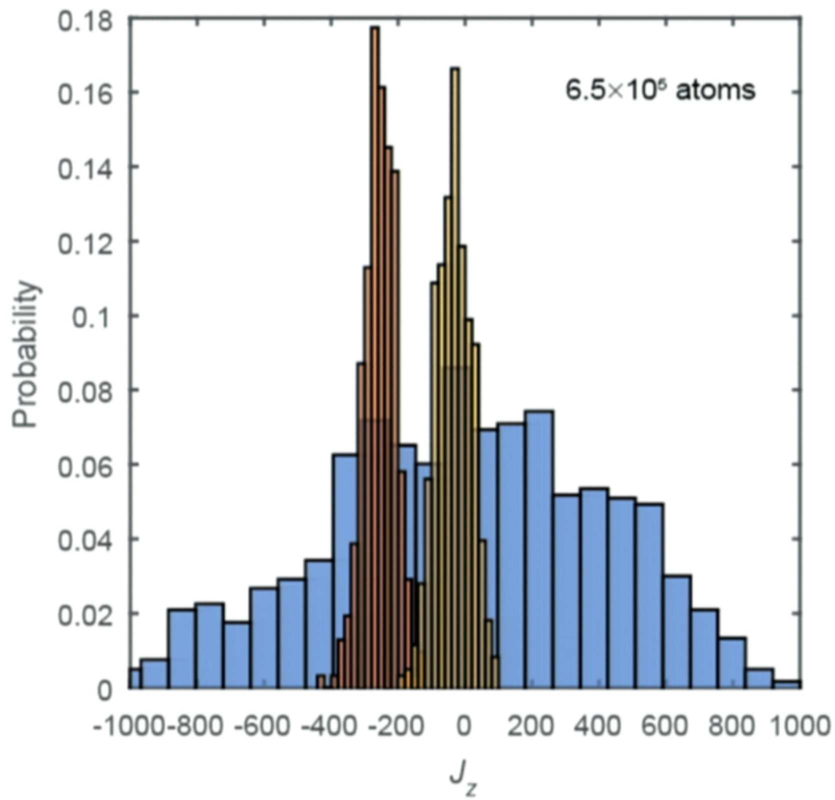




140 μrad rms resolution
≡ 70× unentangled atoms



18.8 – 0.3 = 18.5 dB metrology improvement

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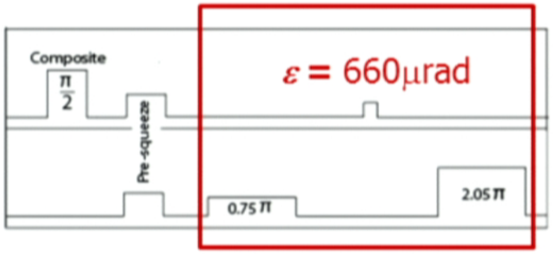

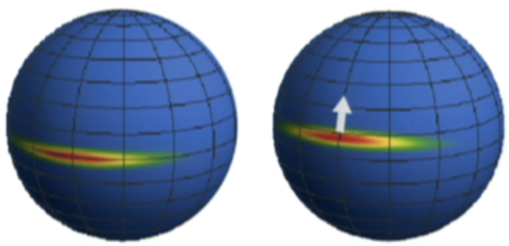

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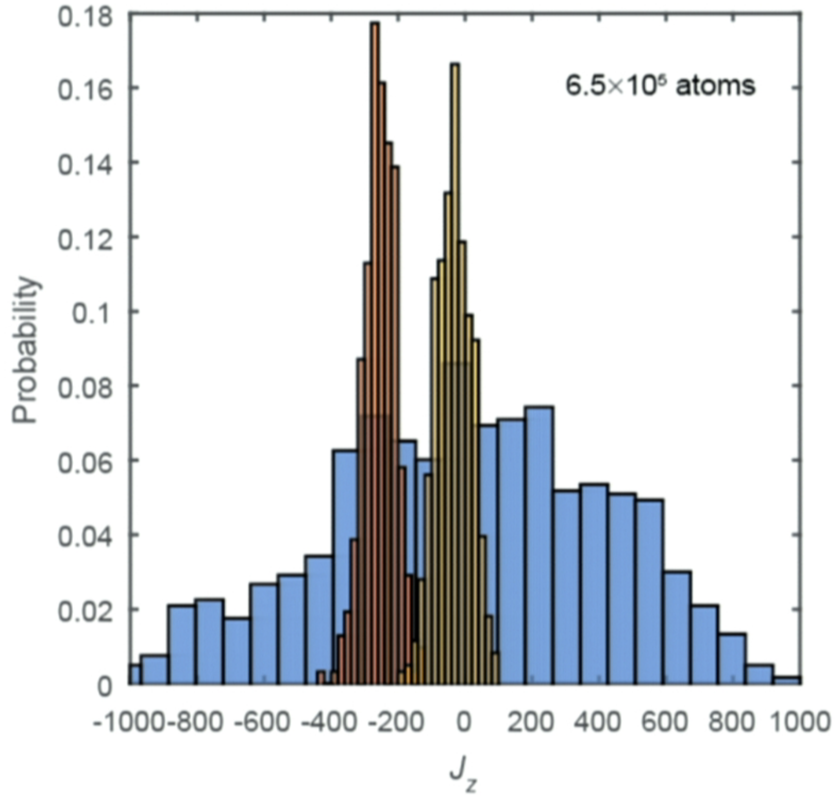

18.8 – 0.3 = 18.5 dB metrology improvement

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Clock measurement

1×10^5 atoms
(10.5dB sqz.)

220μs Ramsey time

1s rep rate

Performance limit: μ-wave LO

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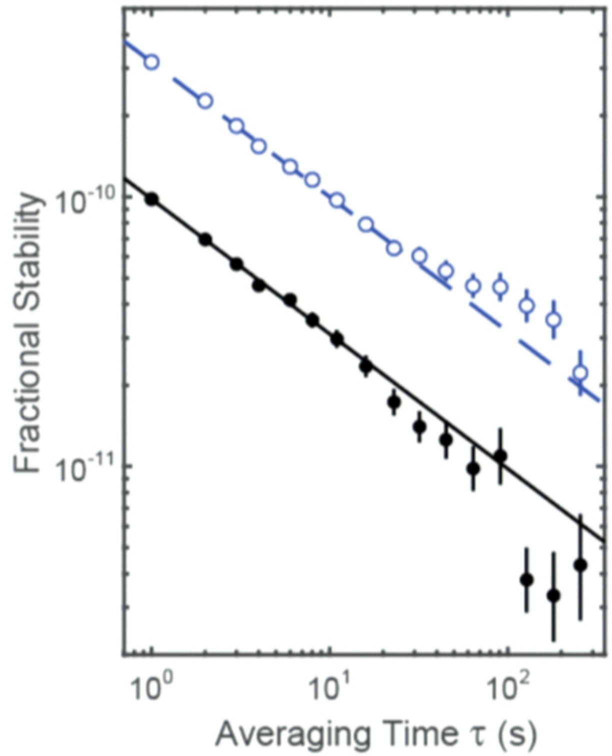

10.5dB boost: 11 times faster averaging.

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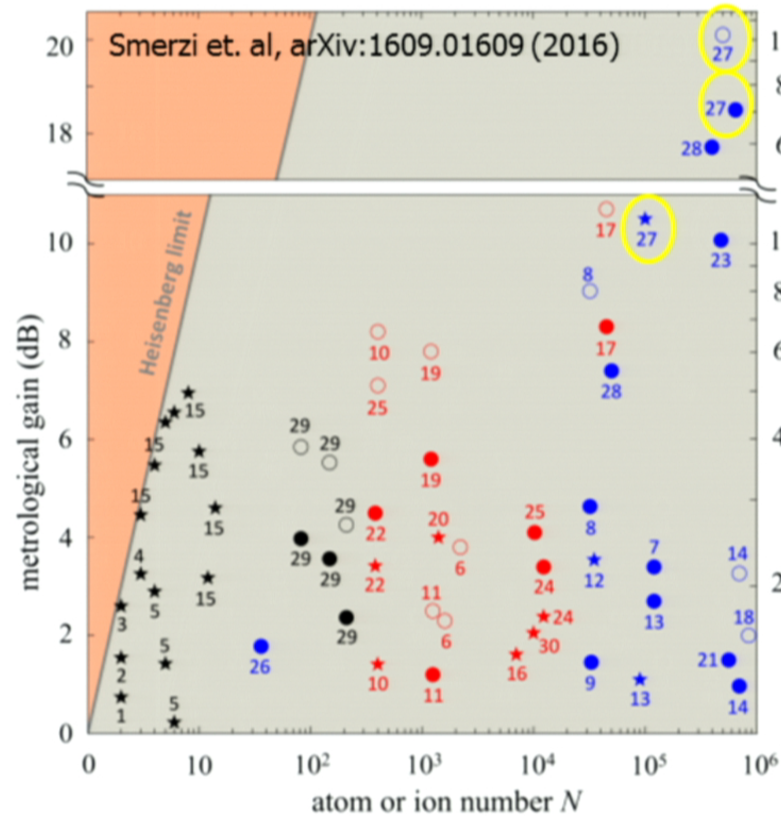
How well are we doing?



TRAPPED IONS
[1] Sackett et al., 2000
[2] Meyer et al., 2001
[3] Leibfried et al., 2003
[4] Leibfried et al., 2004
[5] Leibfried et al., 2005
[15] Monz et al., 2011
[29] Bohnet et al., 2015

BOSE-EINSTEIN CONDENSATES
[6] Estève et al., 2008
[10] Gross et al., 2010
[11] Riedel et al., 2010
[16] Lücke et al., 2011
[17] Hamley et al., 2012
[19] Berrada et al., 2013
[20] Ockeloen et al., 2013
[22] Strobel et al., 2014
[24] Muessel et al., 2014
[25] Muessel et al., 2015
[30] Kruse et al., 2016

COLD THERMAL ATOMS
[7] Appel et al., 2009
[8] Leroux et al., 2010a
[9] Schleier-Smith et al., 2010
[12] Leroux et al., 2010b
[13] Louchet-Chauvet et al., 2010
[14] Chen et al., 2011
[18] Sewell et al., 2012
[21] Sewell et al., 2014
[23] Bohnet et al., 2014
[26] Barontini et al., 2015
[27] Hosten et al., 2016a
[28] Cox et al., 2016

Open circles – Characterized states, Stars - full phase estimation protocol,
Closed circles – Directly measured w/o noise subtraction

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Quantum Phase Magnification

Problem: Bottleneck is the technical detection noise in resolving squeezing

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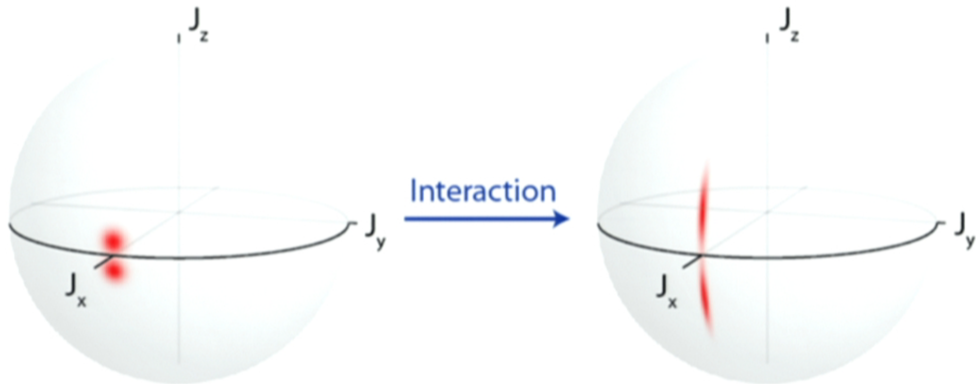
Quantum Phase Magnification

Problem: Bottleneck is the technical detection noise in resolving squeezing

QPM: Squeezed state metrology without the need for good detection sensitivity.
Generalization of a recent time-reversal proposal. E. Davis et al., PRL **116**, 053601 (2016)



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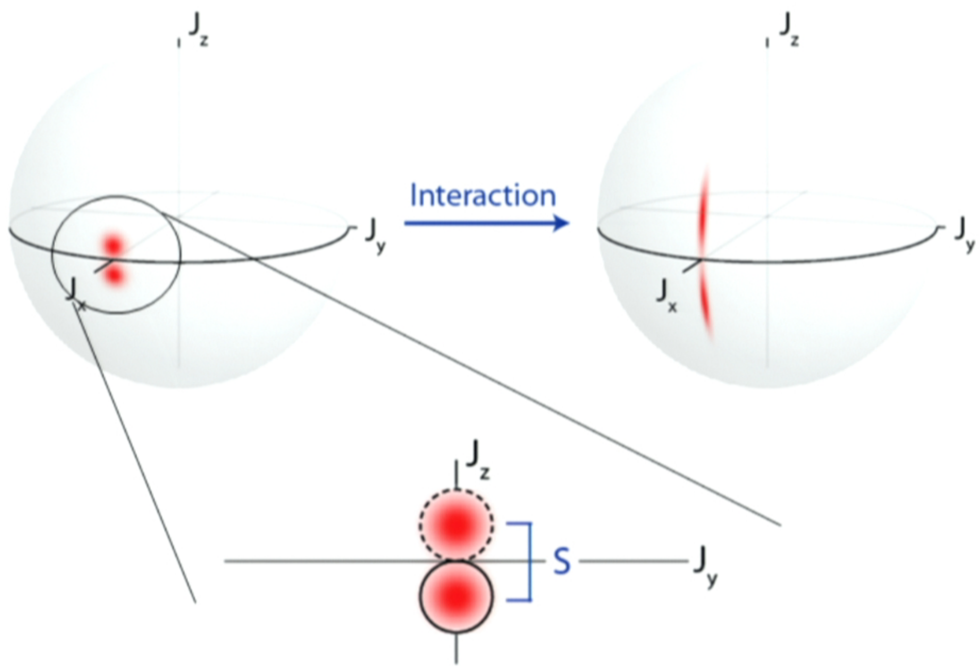

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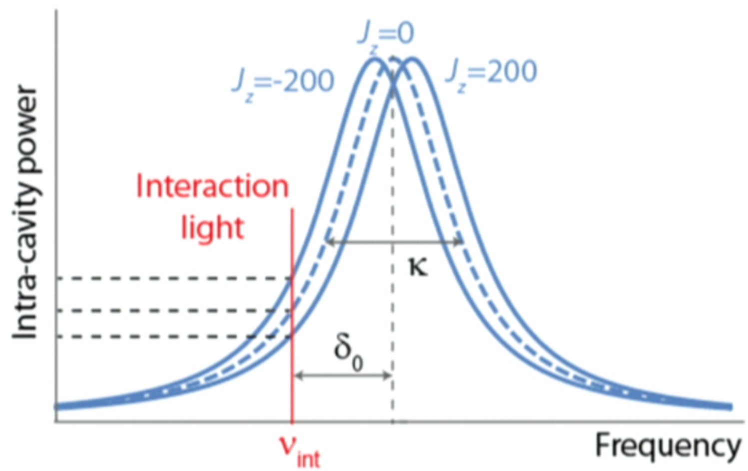
The interaction

Trick-1: Measuring J_z

Trick-2: Generating effective interactions between the atoms: $H = \chi J_z^2$



Atoms shift cavity resonance – intra-cavity power changes – ac-Stark shift on atoms change

Atomic phase shift proportional to J_z

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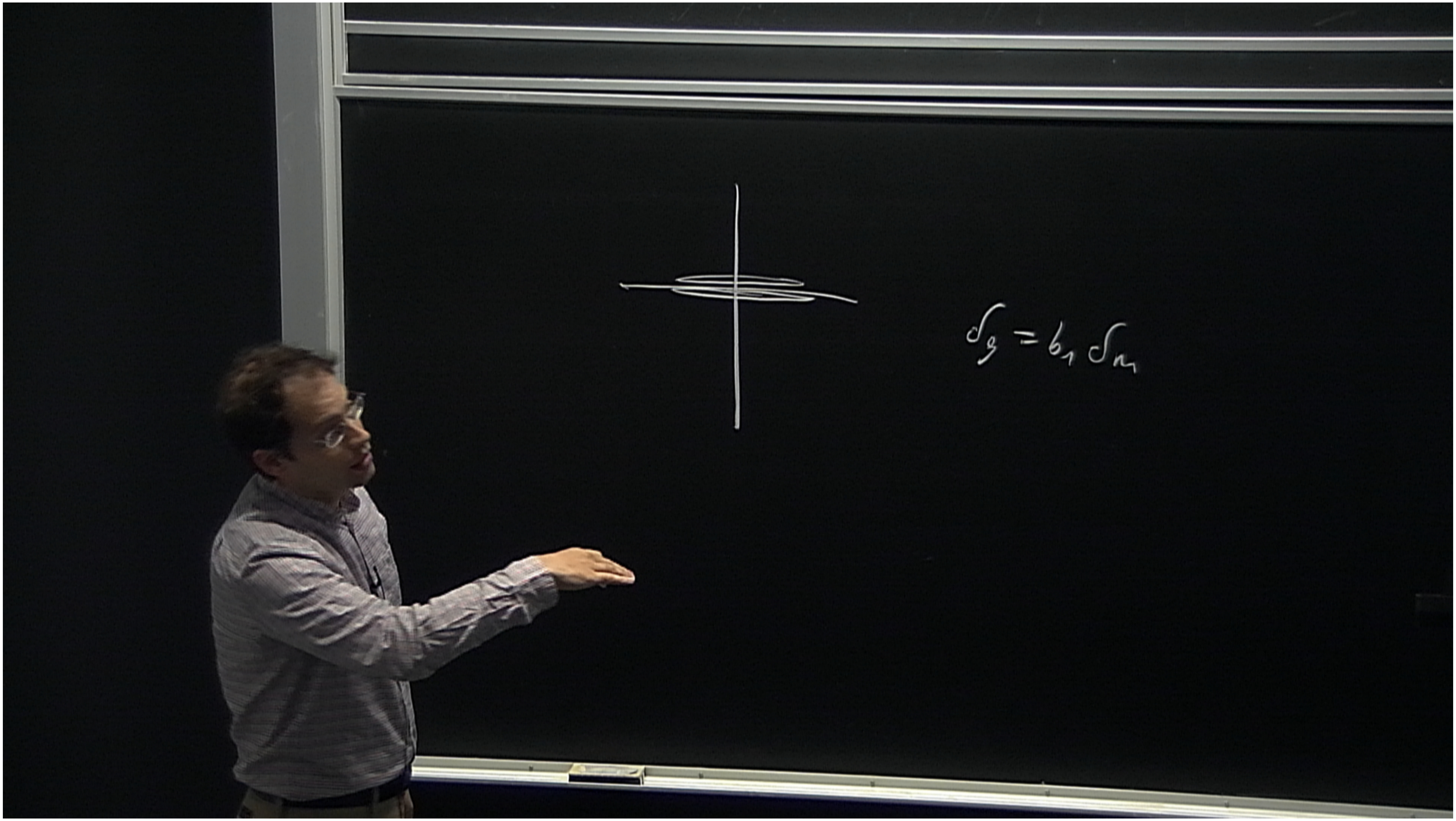
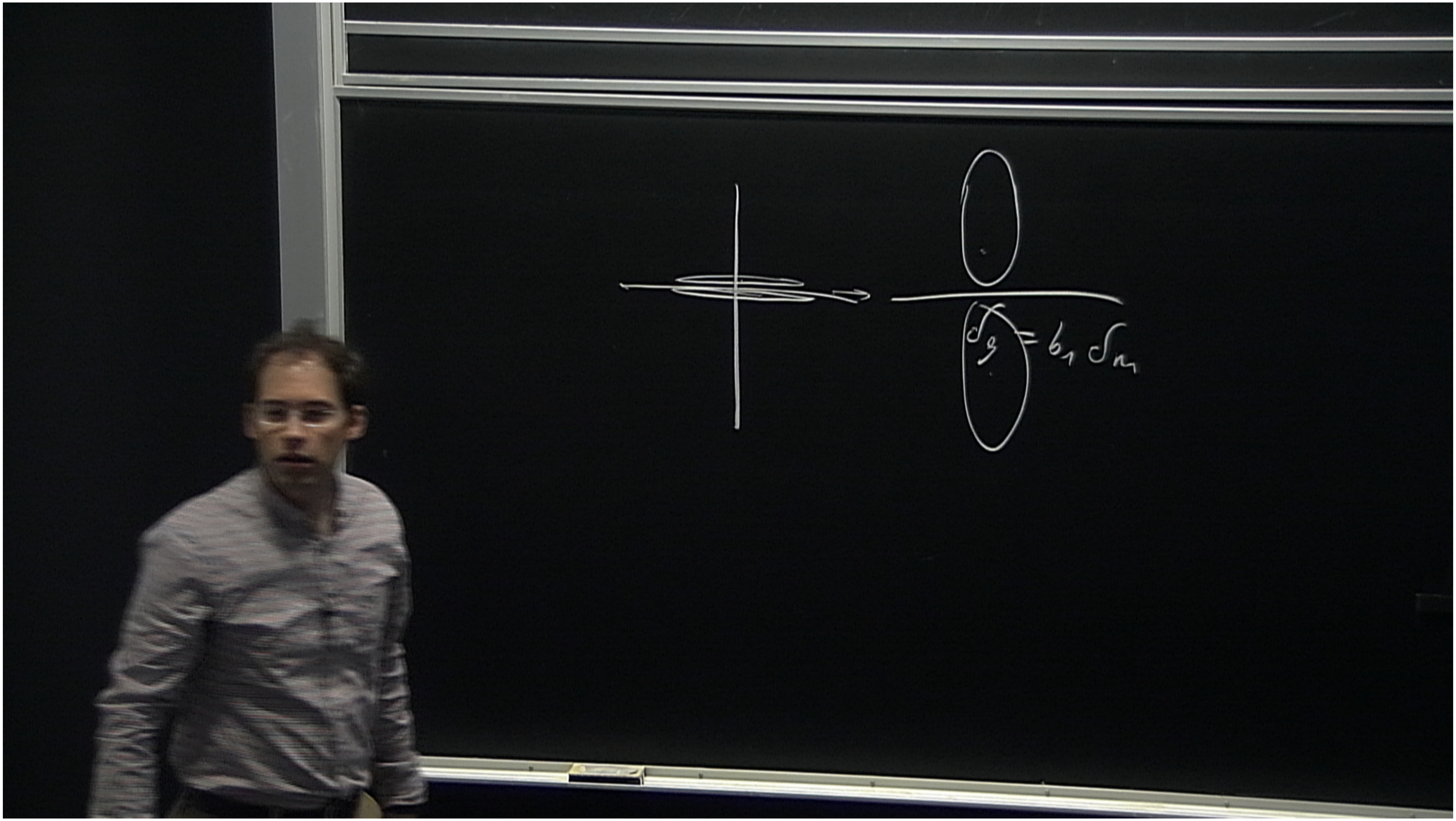

$\delta_g = b_1 \delta_m$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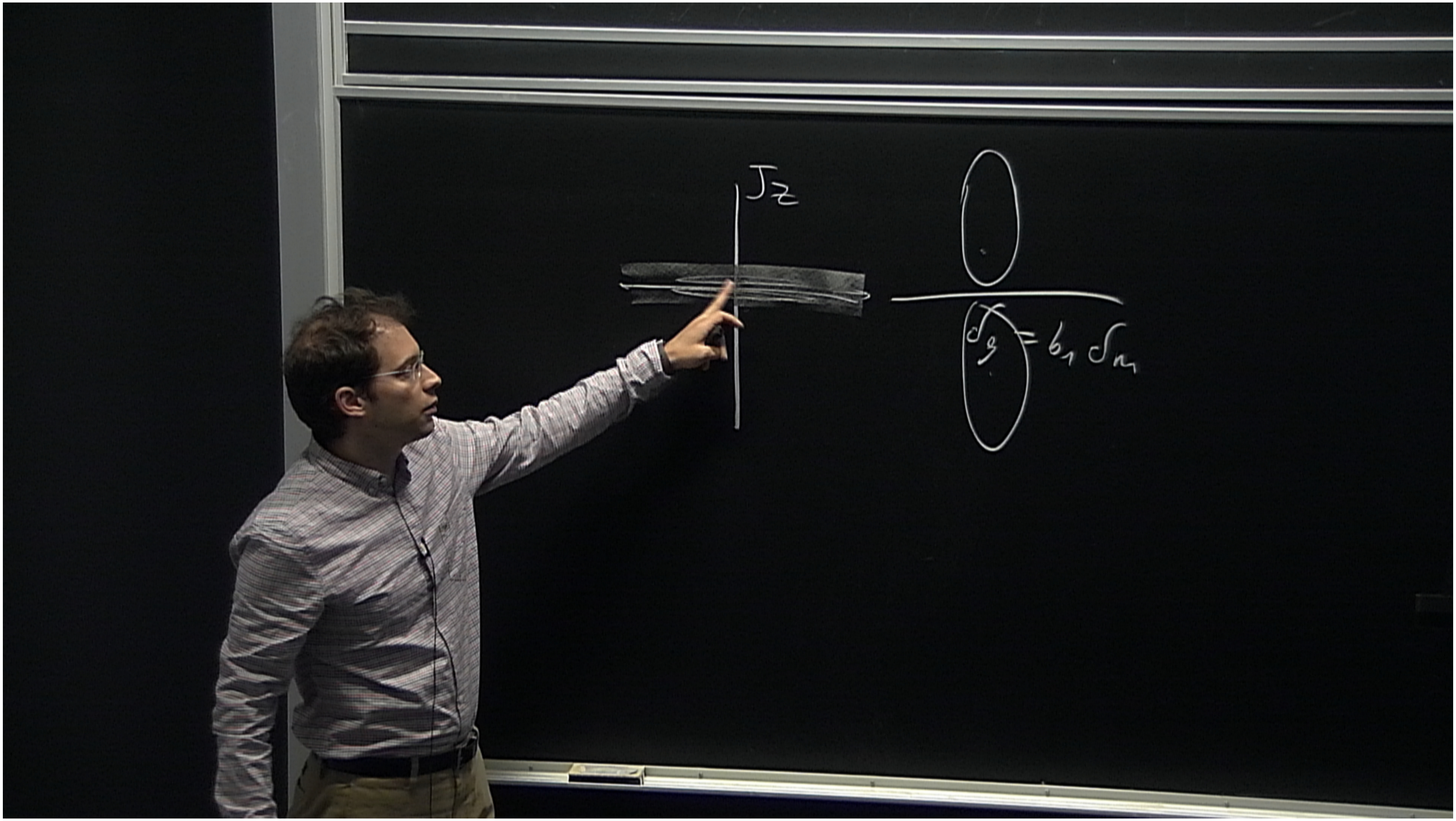
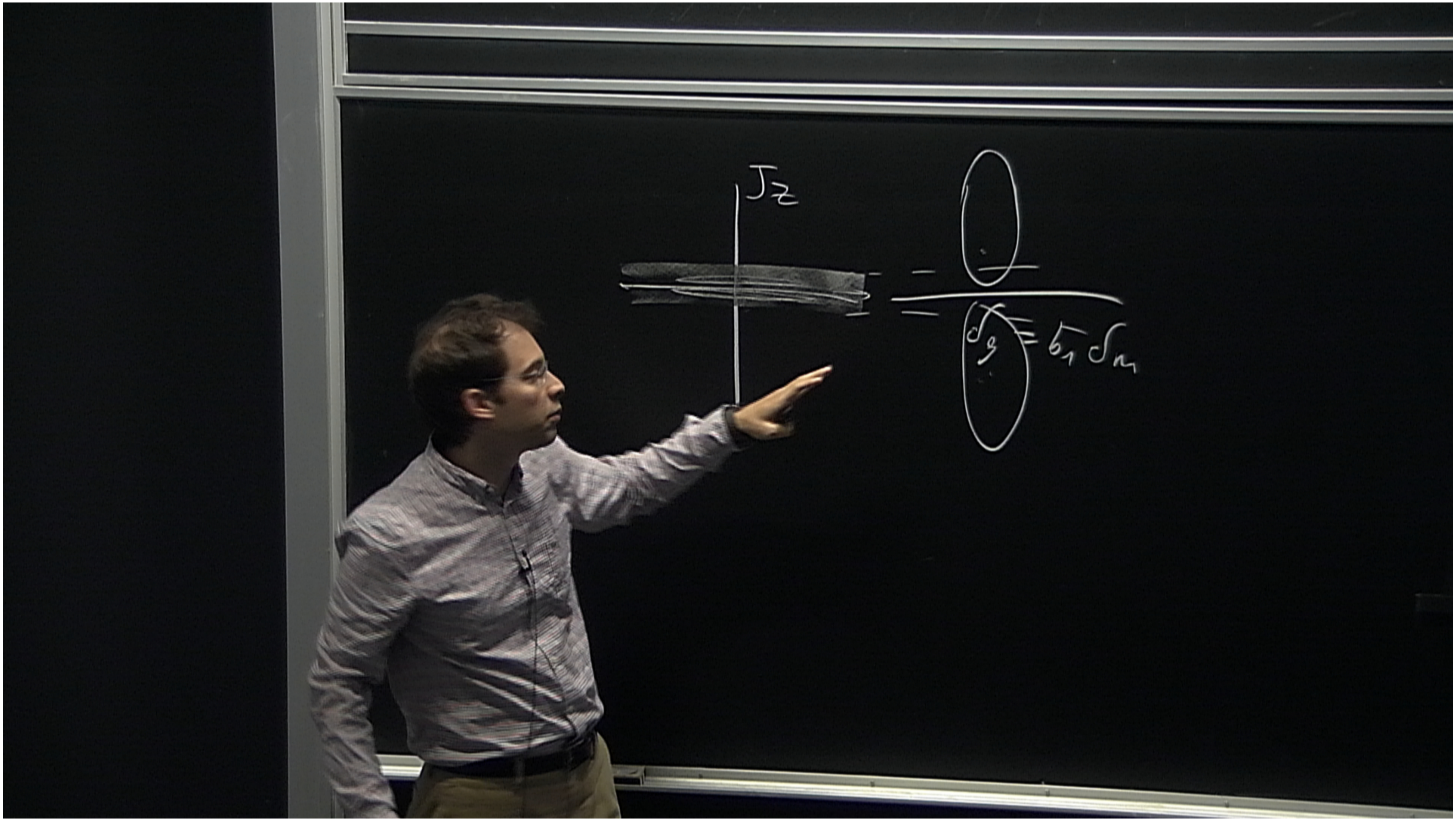
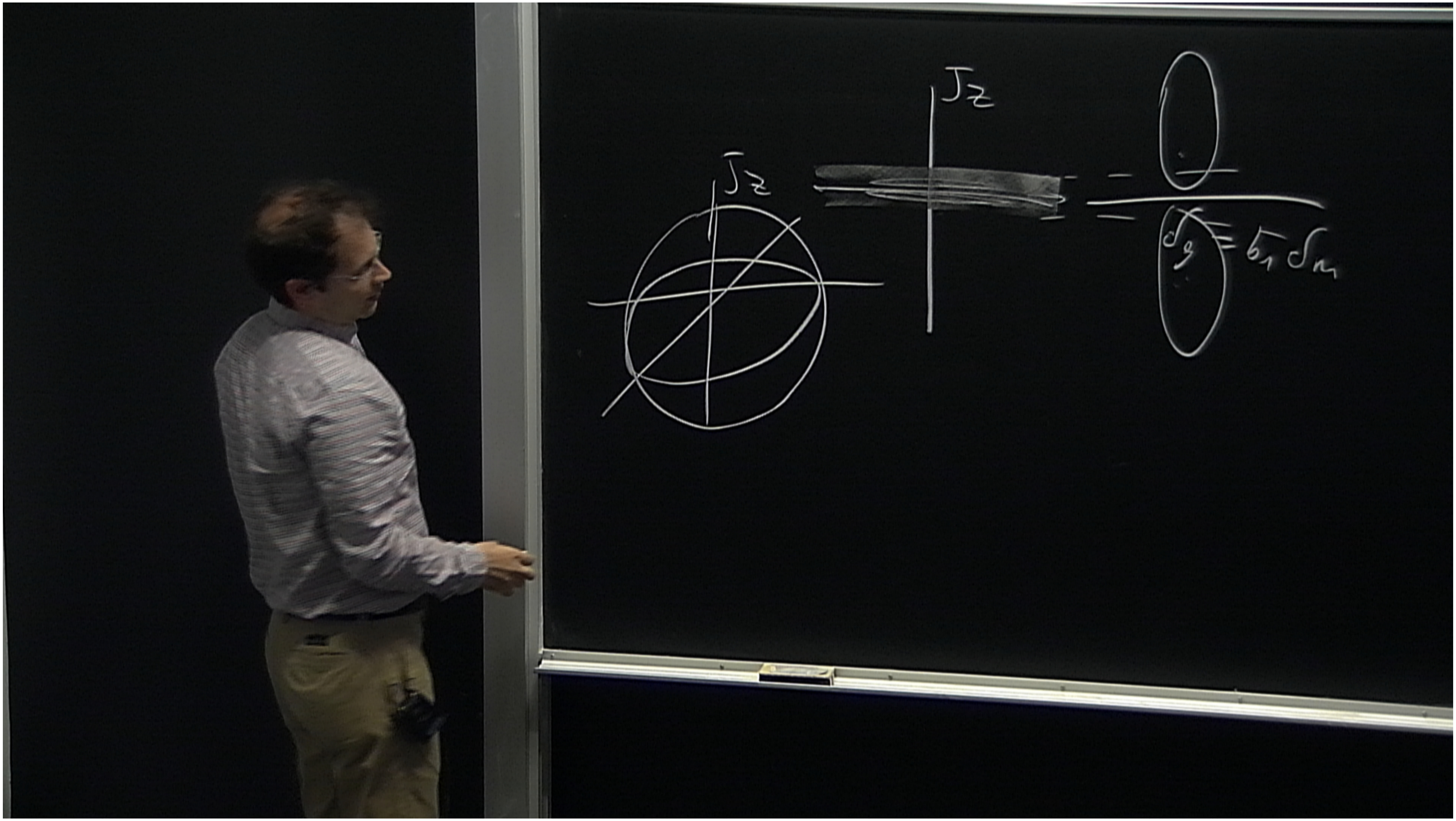
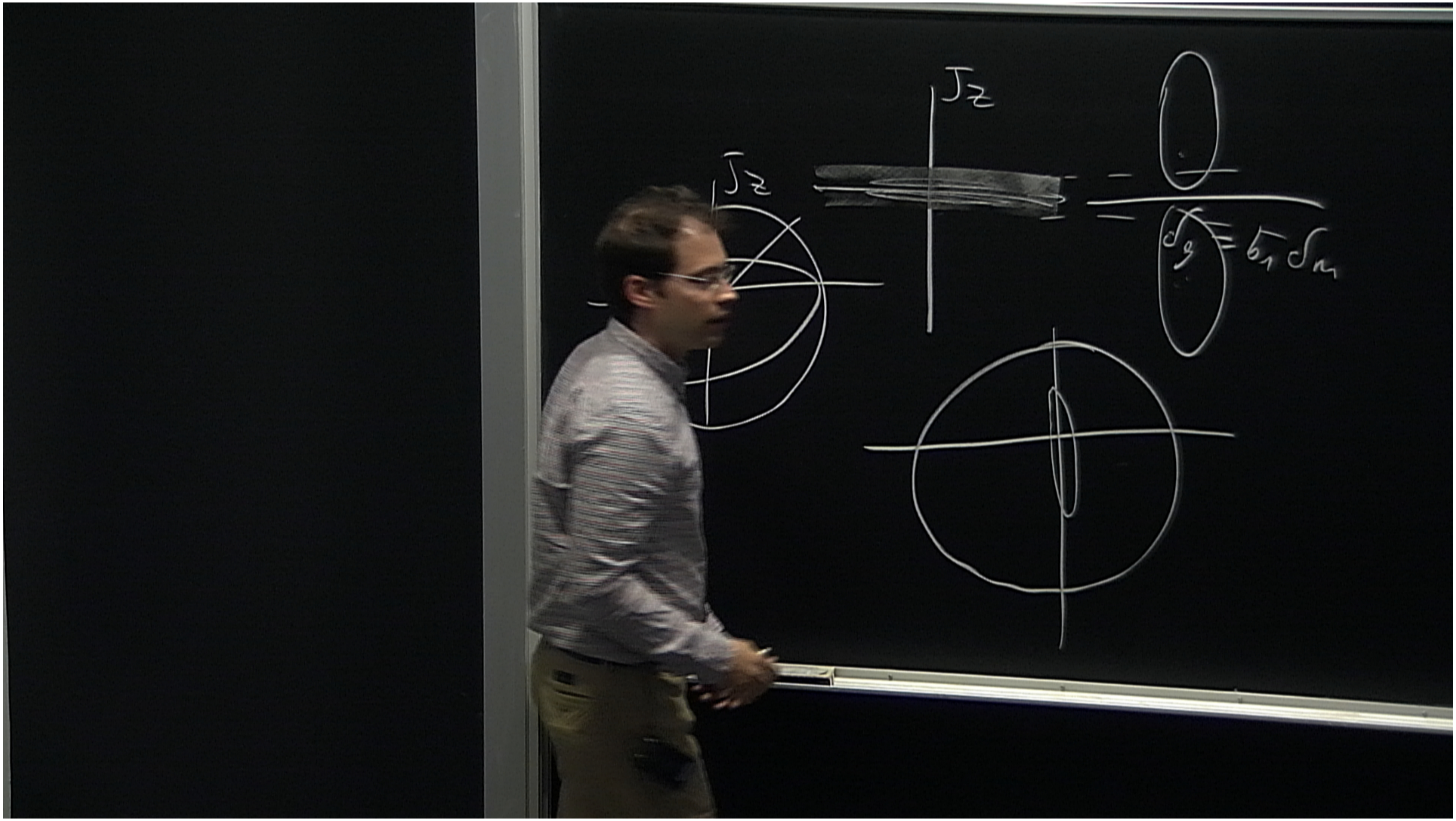

Jz
δg = b1 δm

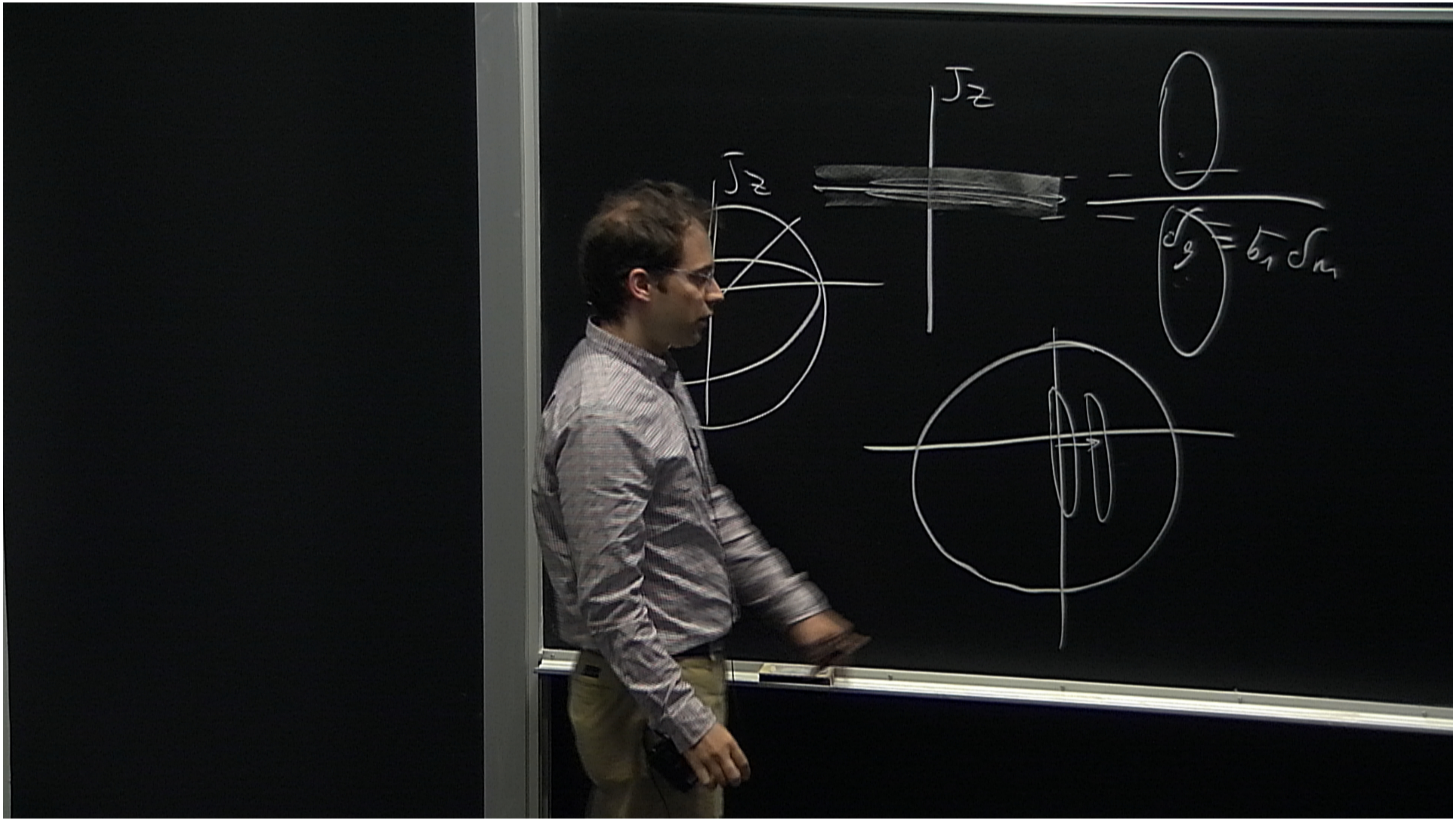


Jz

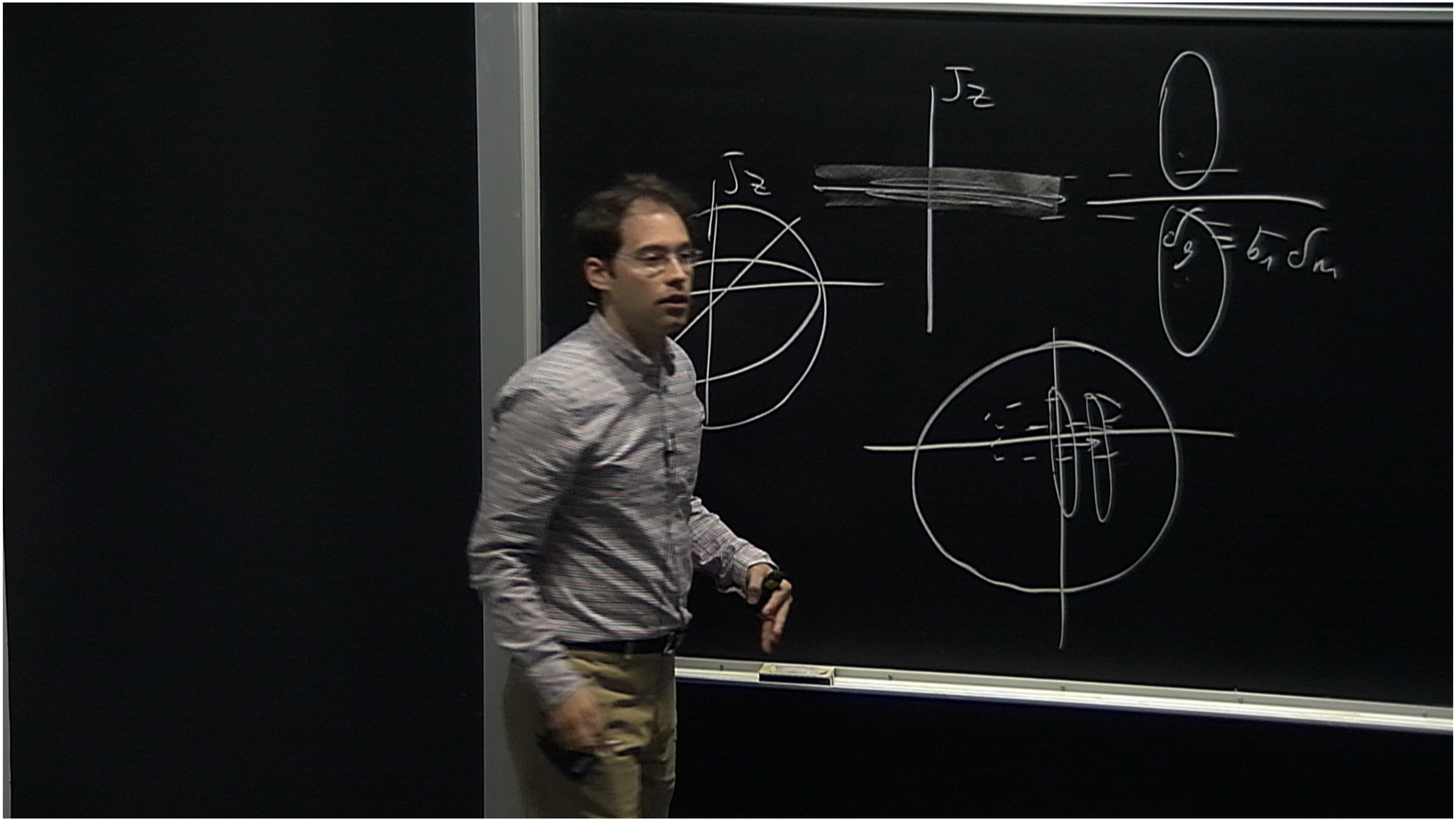


Jz
Jz

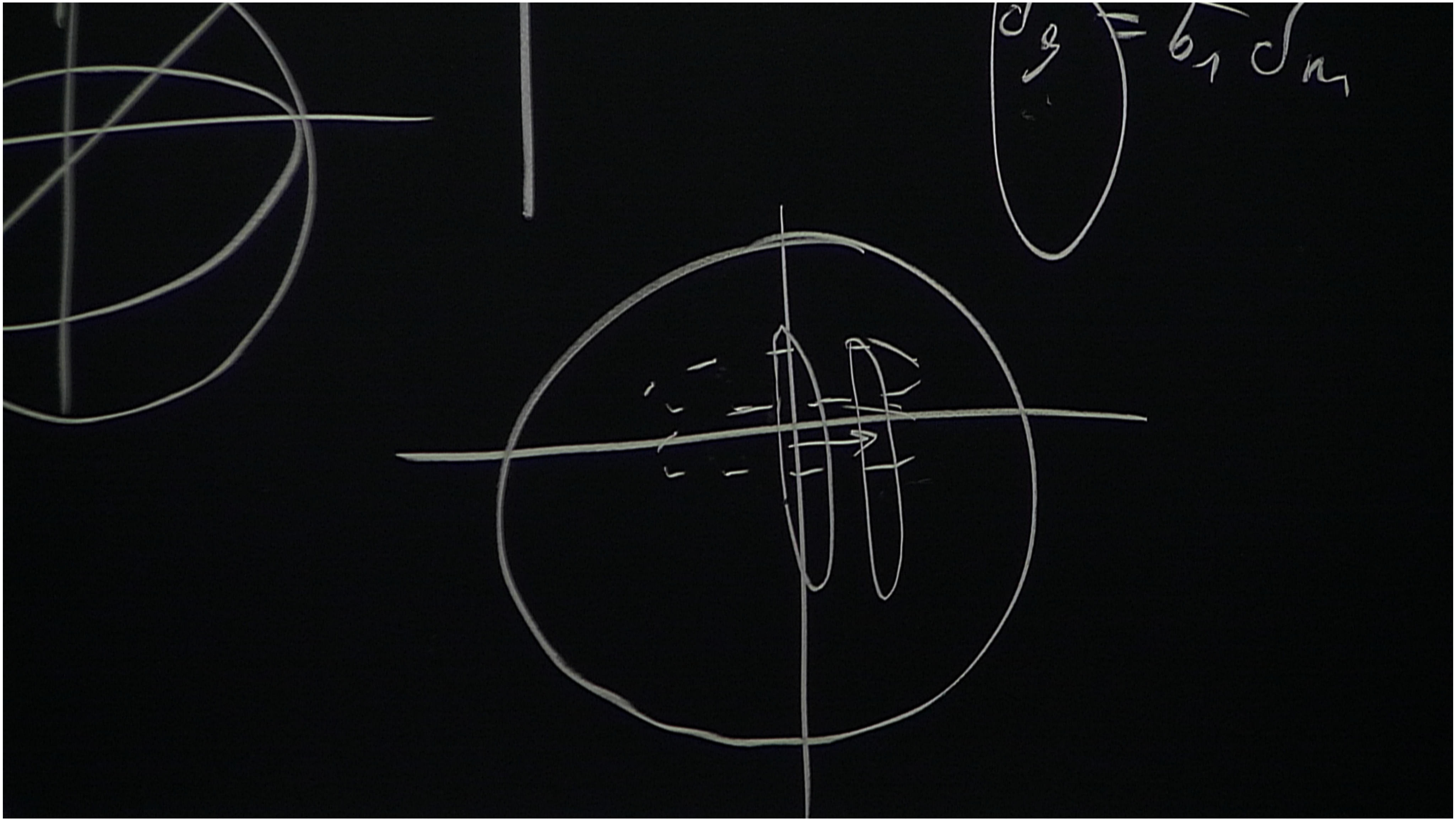

Jz
Jz

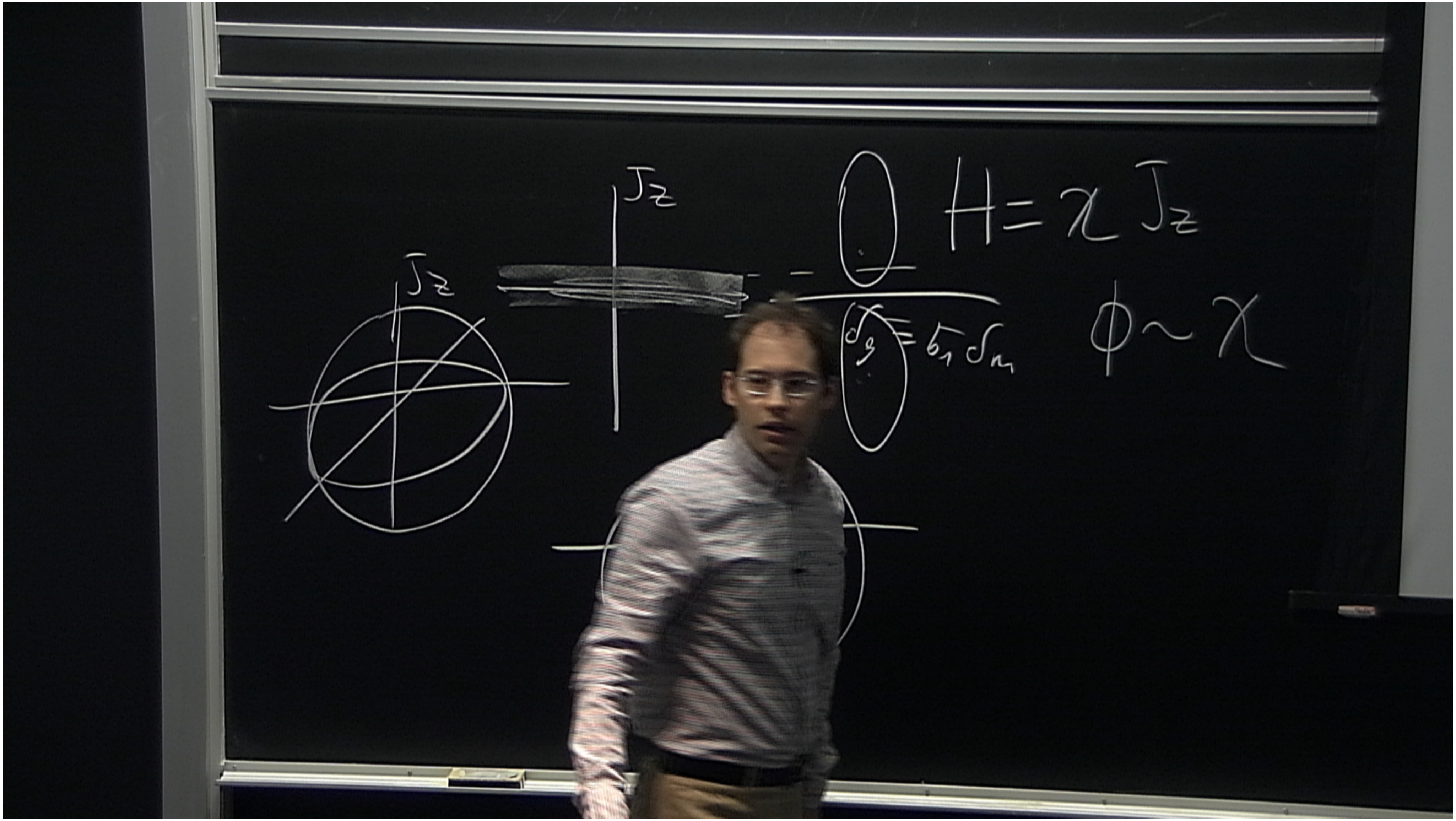


Jz
Jz

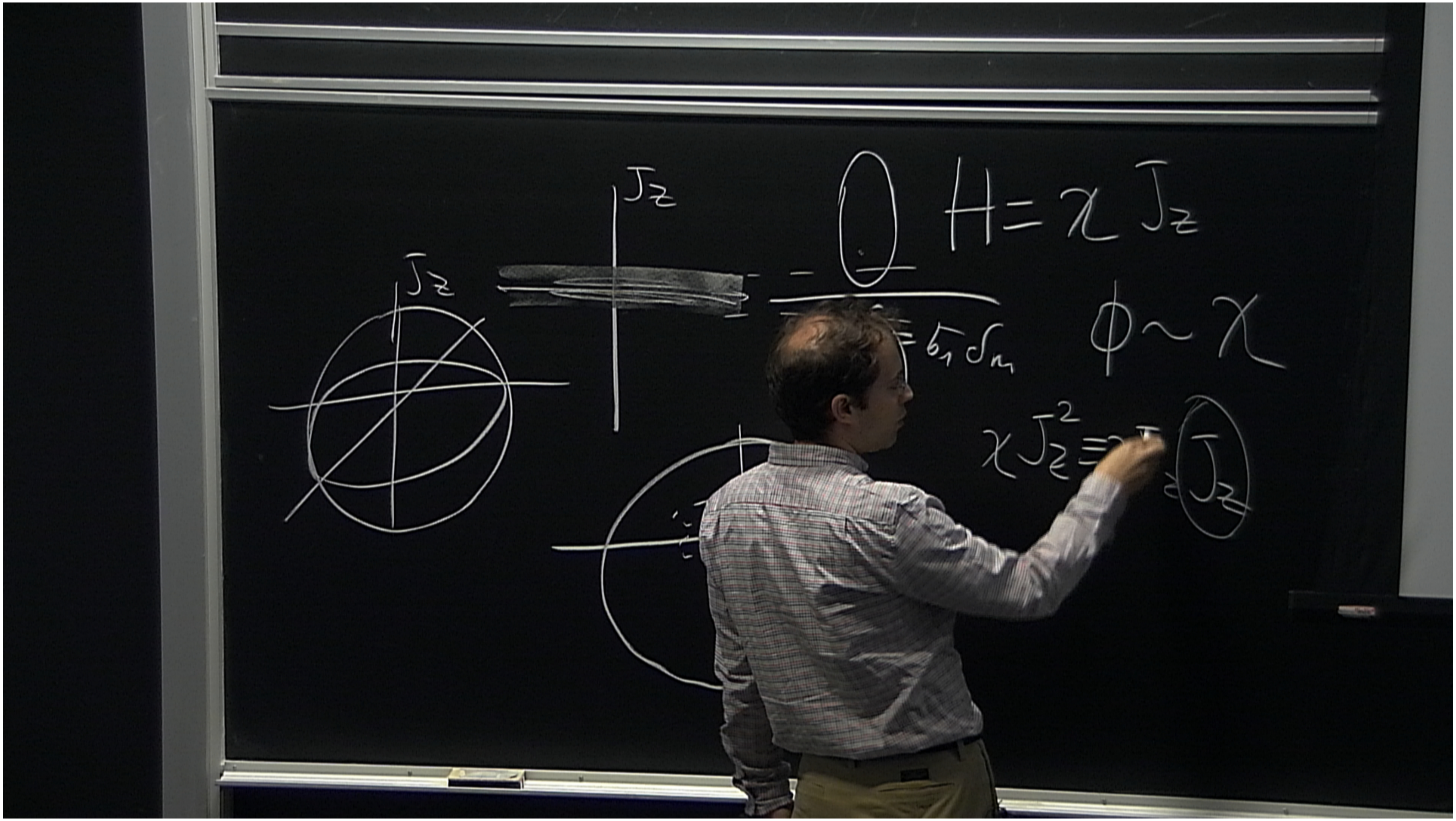


J_z
J_z

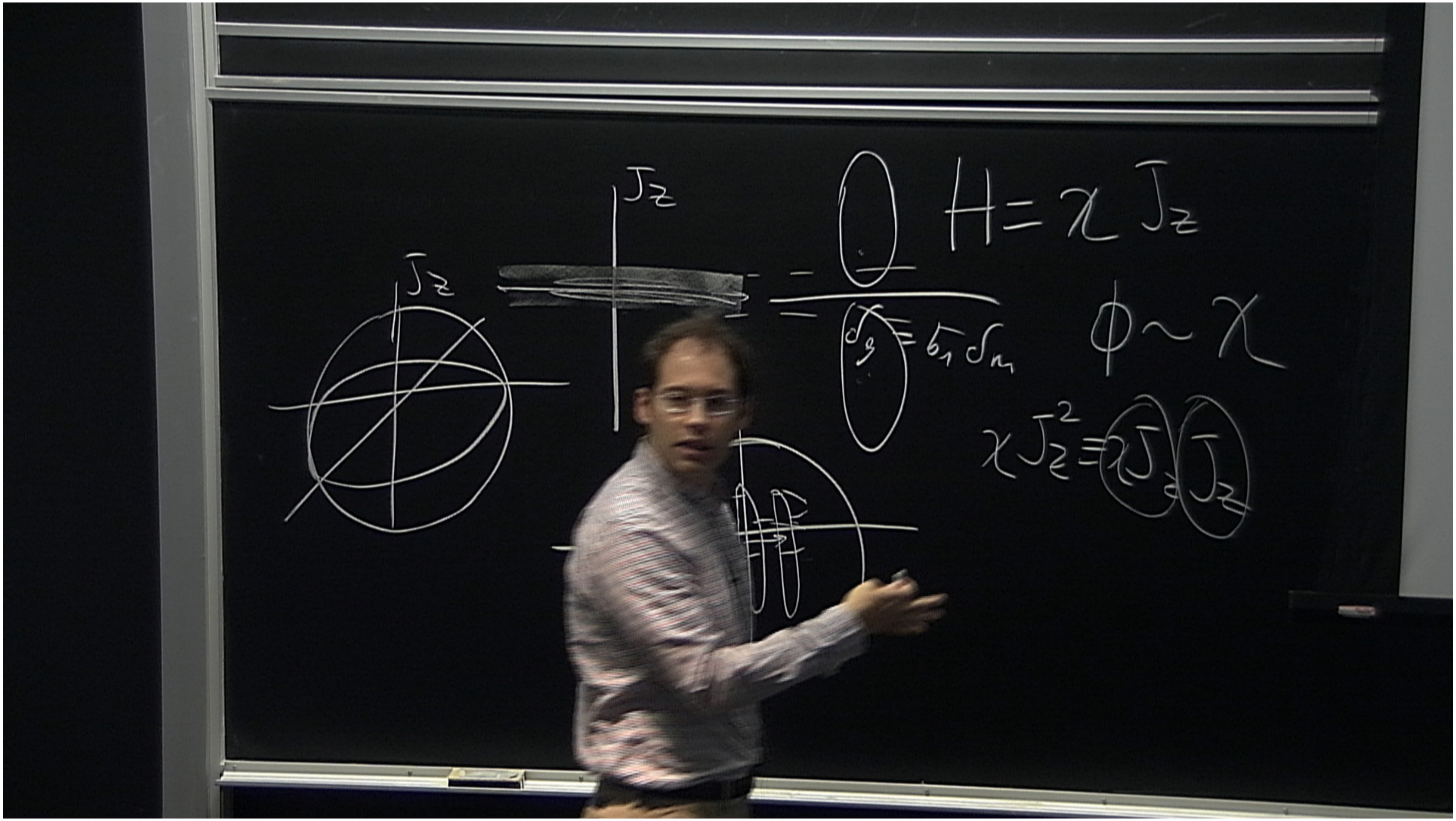

σg = b1 σm



J_z
J_z
$H = \chi J_z$
$\phi \sim \chi$



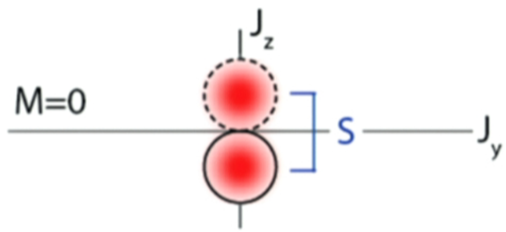
$H = \chi J_z$
$\phi \sim \chi$
χJ_z^2
J_z



J_z
$H = \chi J_z$
$\phi \sim \chi$
$\chi J_z^2 = \chi J_z J_z$

The Shearing Interaction

The interaction leading to state magnification: J_z dependent phase shift



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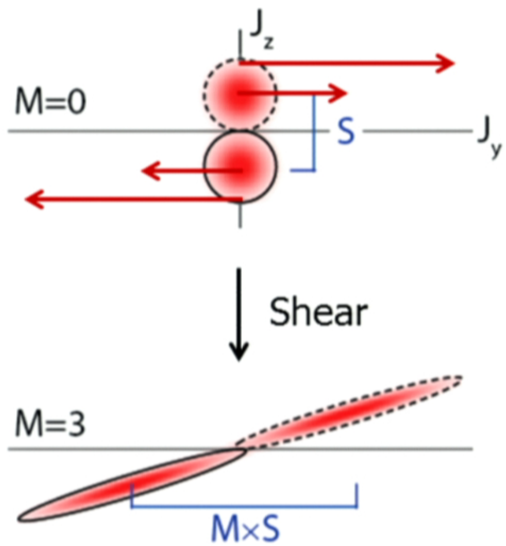

Analogous to free expansion of a gas

$$J_y \equiv X, \quad J_z \equiv P$$

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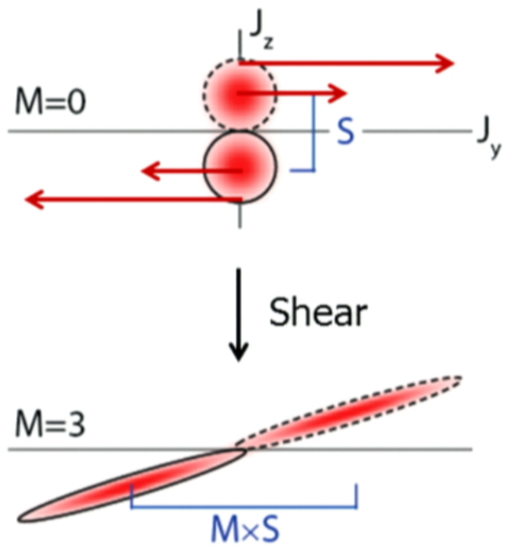

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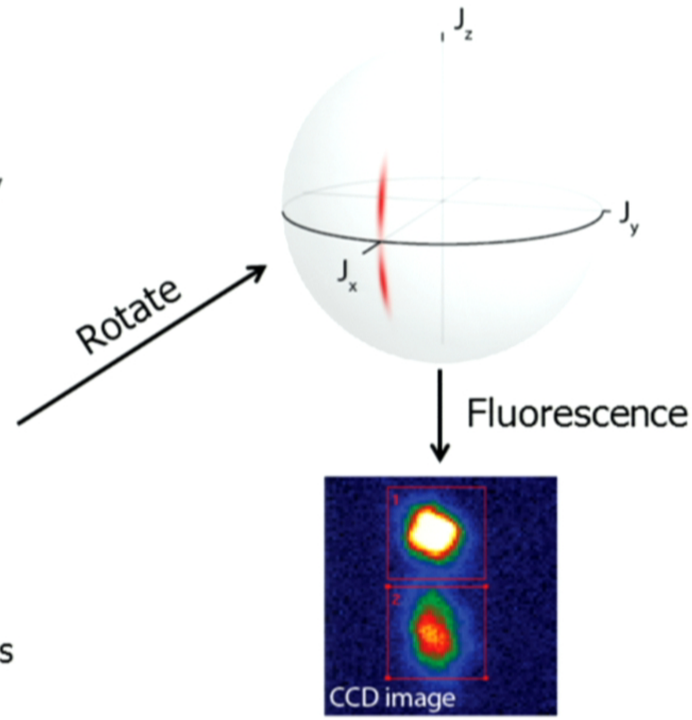

Noise floor +15dB

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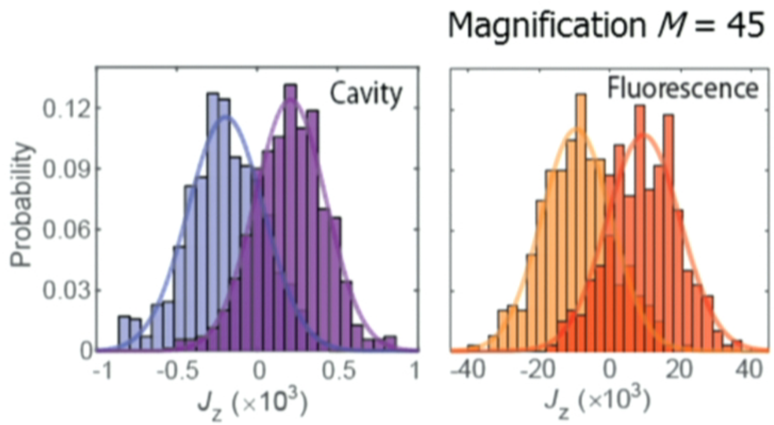
Magnification – Experiment w/ CSS

- Toggle between two separate initial CSSs (200k atoms)
- Compare cavity meas. with results of post-magnification meas.



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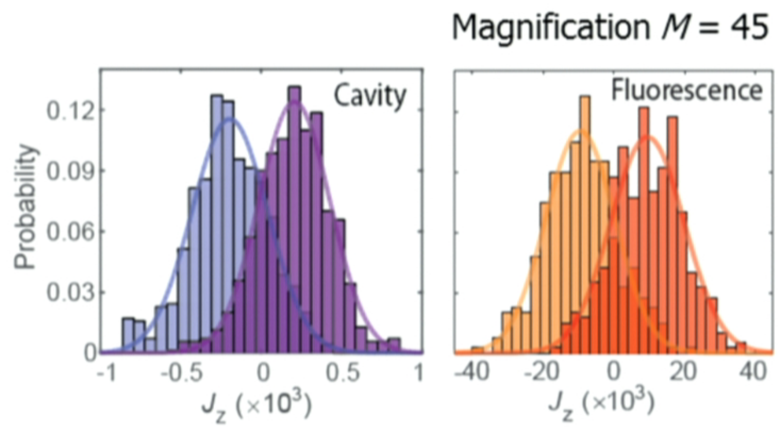

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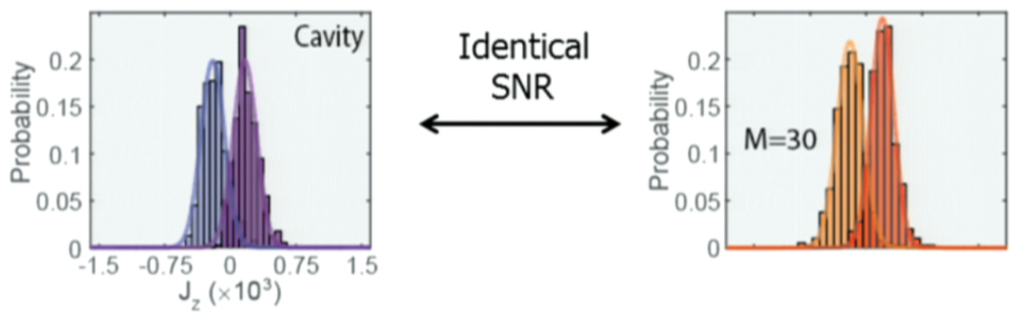
Squeezed states – Experiment

A variant of the magnification protocol with squeezed states

- Optimal mapping at a chosen magnification

8 dB-squeezed initial states

Magnified states



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Recent / near-term

Squeezed atoms in free fall

- Free the atoms from the optical lattice: fountain clocks/ interferometers
- Release/recapture → 12dB squeezing <1ms (manuscript in prep.)
- Fluorescence imaging → 5dB squeezing (preliminary)

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- States compatible with measured noise and coherence?
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- Atoms entangled in groups of > *n=1590*.

Bell Correlations

- Bell inequalities: QM inconsistent with local-realistic description of nature.
  J. Tura *et al.*, Science **344** 1256 (2014)
- 124-sigma violation of a Bell type correlation witness w/ 5×10^5 atoms.

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Near future: Atom interferometry

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