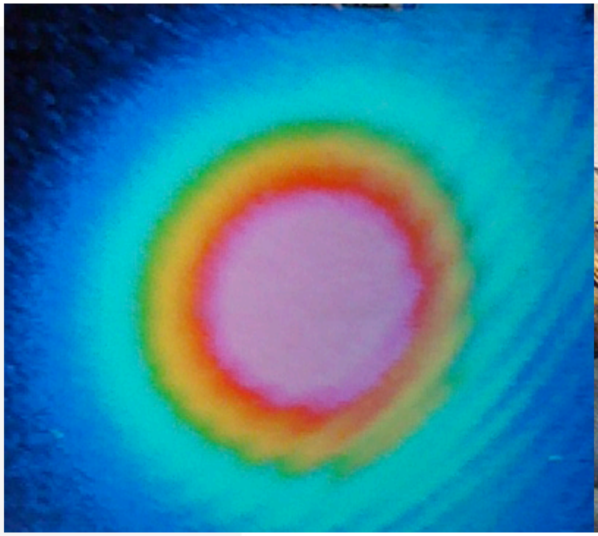
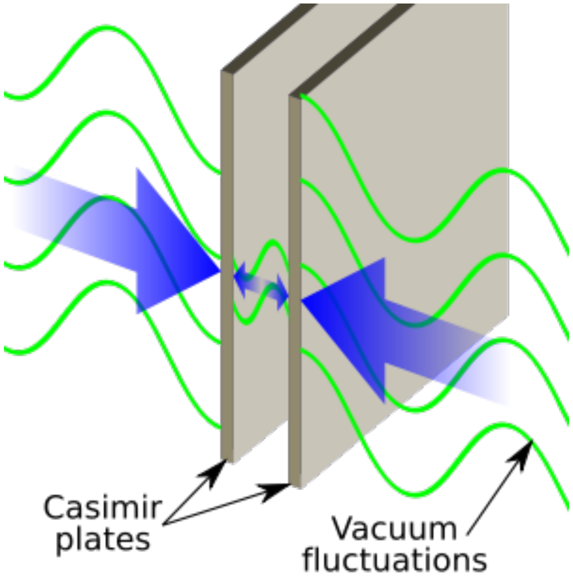


Axions

Holographic information bound



# Probes of fundamental physics using intense photon beams

Aaron S. Chou
Wilson Fellow, FNAL

TIPP 2011 Conference
June 9, 2011

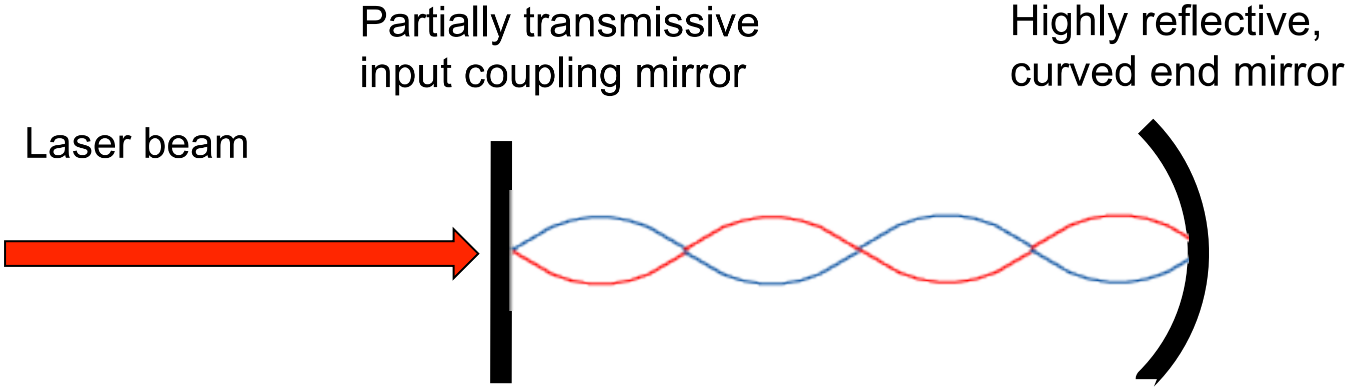
Fermilab

# Use large, coherent photon fluxes for

Increasing craziness

1) Searches for exotic, rare scattering processes
2) Precision position measurements
3) Measure properties of the vacuum?

# Power Recycling using optical cavities

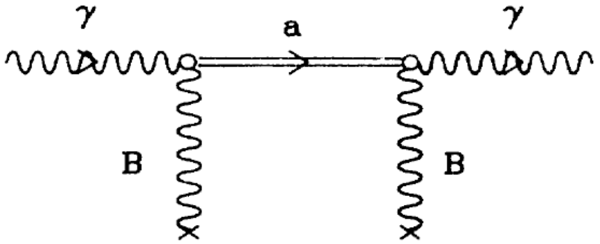


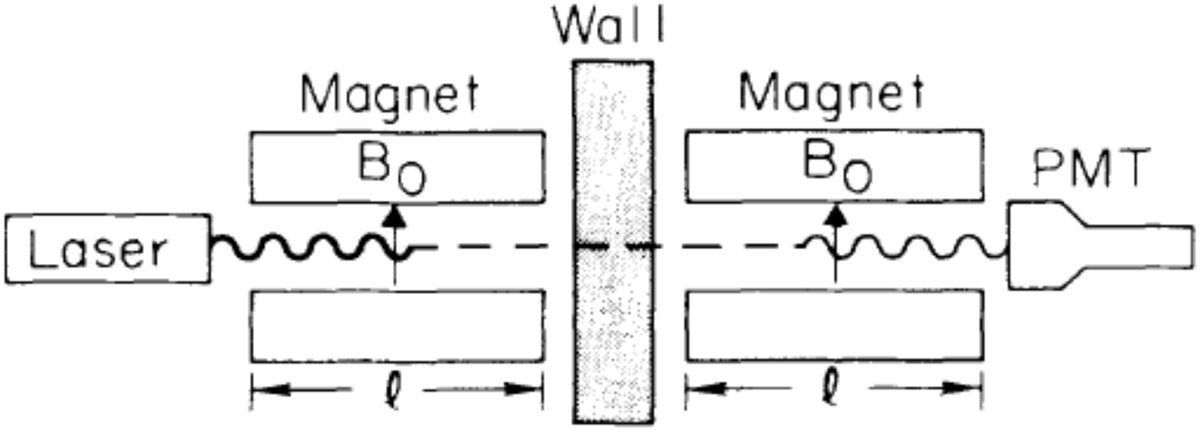
- Resonance occurs when the wavelength λ and/or the cavity length L are tuned such that integer number of wavelengths fits inside the cavity. Then a standing wave builds up as the beam is recycled.

- The power recycling factor is 1/η where η=total power lost per pass.
  - This determines the resonance bandwidth and the cavity lifetime.

- kW power is easy. aLIGO now shooting for 100 kW.

# Application 1: Use lots of photons to search for rare photon-photon scattering processes mediated by axion-like or Higgs-like particles

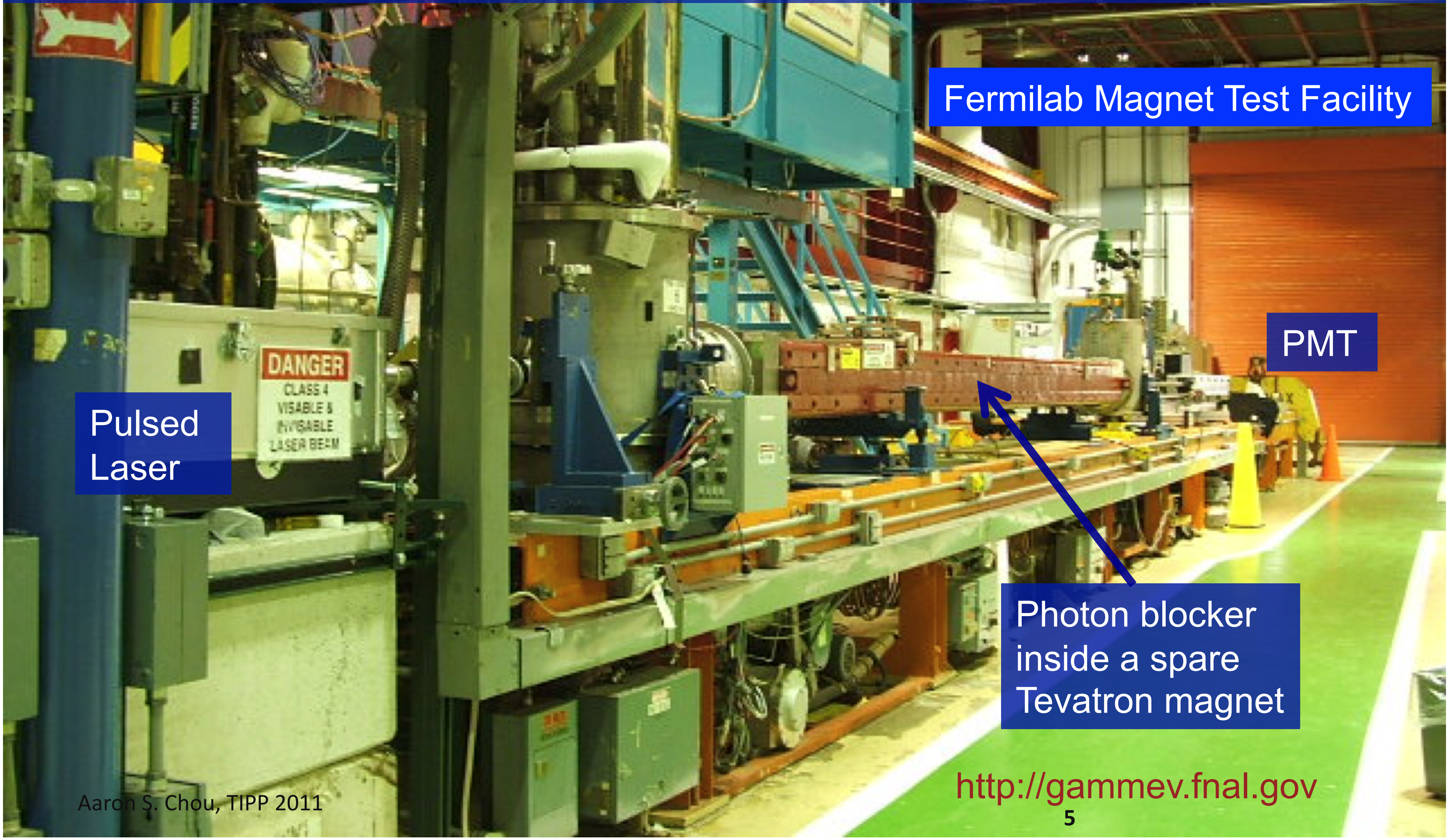




$$P_{\text{regen}} \approx \left(\frac{1}{4} g^2 B^2 L^2\right)^2$$

# **GammeV**: Shining light through walls

- FNAL collaboration with U.Michigan, New York U., U.Chicago, Cambridge U.
- World's best laboratory limit on axion-photon coupling, PRL 2008.
- World's best limit on meV-mass hidden-sector vector bosons, PRD 2008 (Ahlers, et.al).
- Chameleon afterglow search, PRL 2009, PRL 2011.



Fermilab Magnet Test Facility

PMT

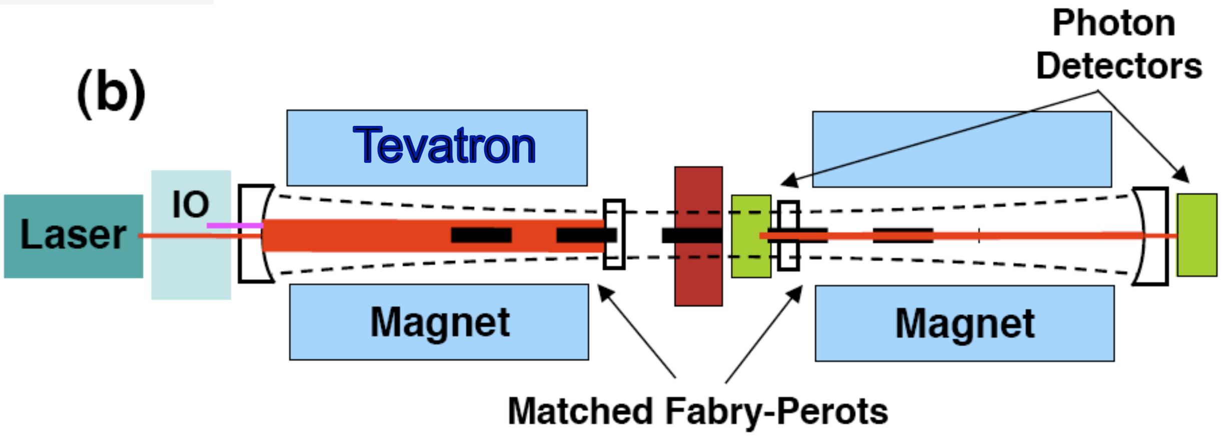
Pulsed Laser

Photon blocker inside a spare Tevatron magnet

http://gammev.fnal.gov

# Resonantly-enhanced axion-photon regeneration

Hoogeveen, Ziegenhagan,
Nucl. Phys B(1990);
Sikivie, Tanner, van Bibber, PRL (2007);
Mueller, Sikivie, Tanner, PRD (2009);

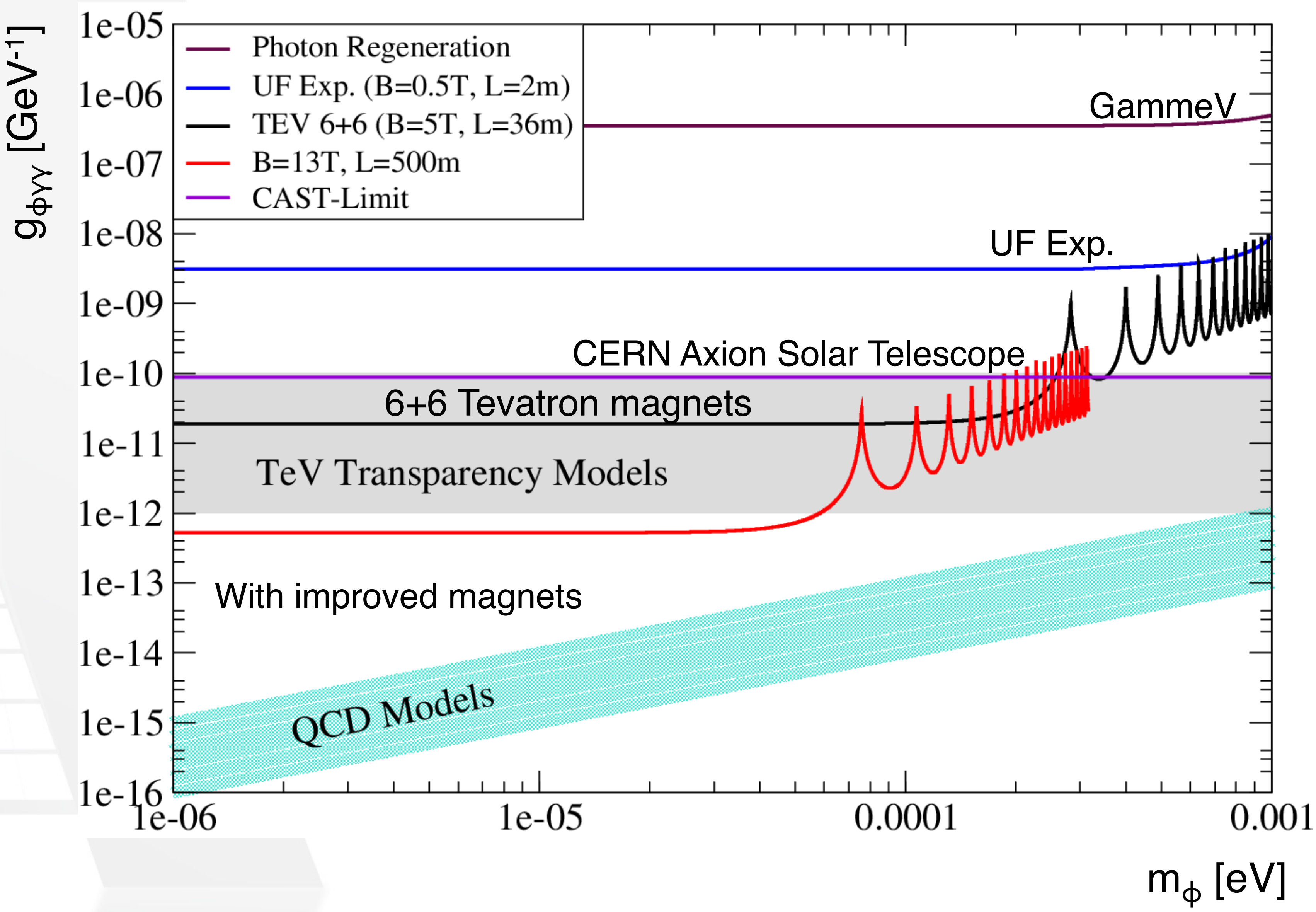


Matched Fabry-Perot cavities shape the axion beam and resonantly enhance the axion-photon transition probability. Light leaks coherently from the bright cavity into the dark cavity.

Rate enhanced by Finesse $F^2 \approx 10^{10}$ **This is huge!!!**

$$g_{\text{limit}} \propto \left( \frac{dN_{\text{laser}}}{dt} \cdot T_{\text{integration}} \right)^{-1/4} (BL)^{-1} \mathcal{F}^{-1/2}$$

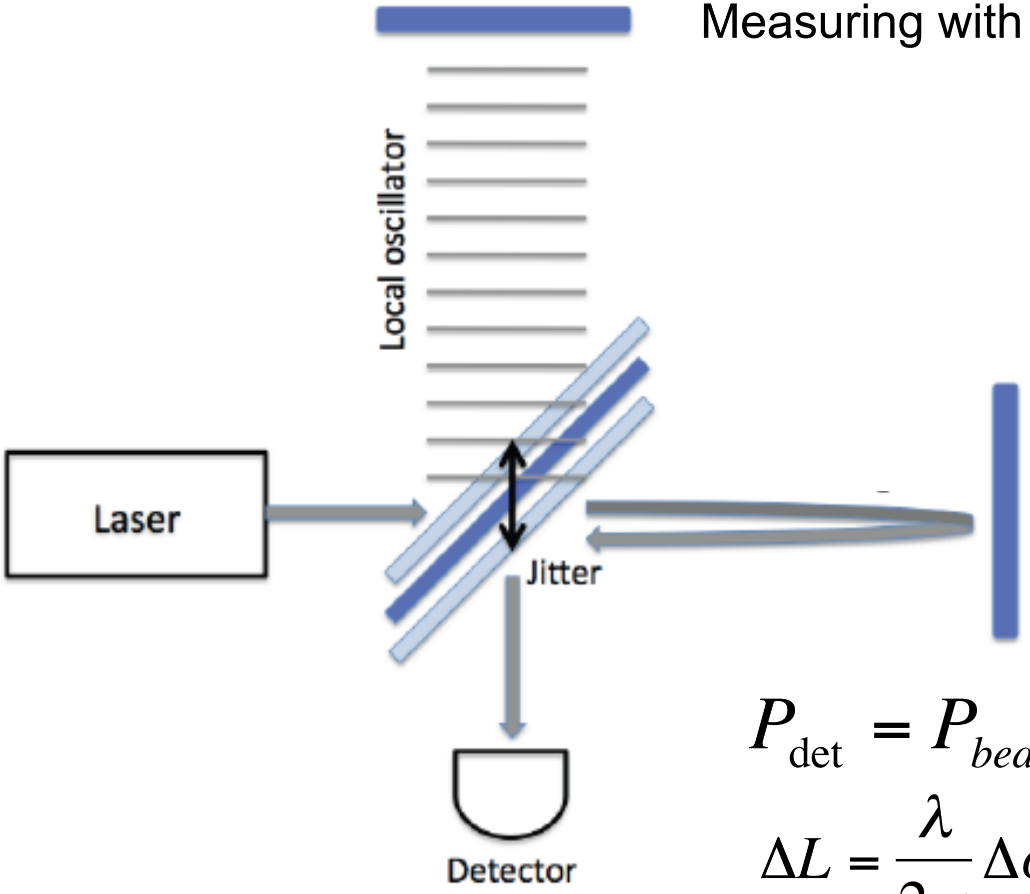
# Resonant regeneration discovery potential



Aaron S. Chou, TIPP 2011

# 2. Ultra-precise position measurements, holometry

# Application 2: Use lots of photons to make precise position measurements, e.g. of a beamsplitter position



Each Nd:YAG photon has position resolution 1064 nm.

Measuring with N photons gives resolution: $\frac{1064\,nm}{\sqrt{N}}$

$$P_{\det} = P_{beamsplitter} \times \sin^2(\Delta\phi/2)$$

$$\Delta L = \frac{\lambda}{2\pi}\Delta\phi$$

# Laser interferometers are already probing space-time at the TeV scale = $10^{-18}$ m

GEO-600 (Hannover)

Craig Hogan, Beyond Center workshop, January 2010

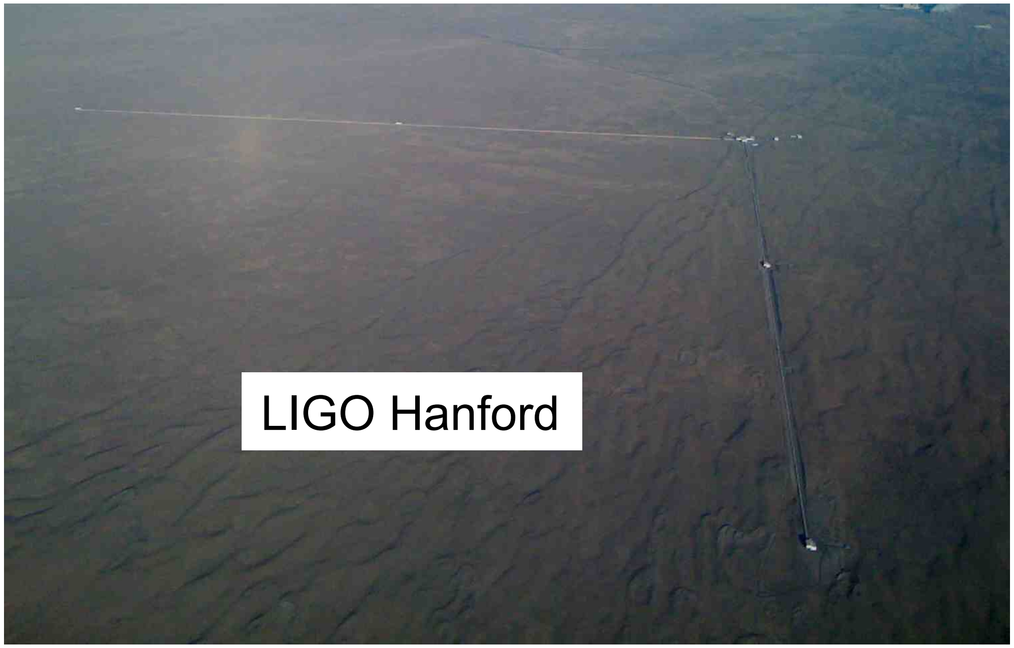
$\Delta N \times \Delta \phi = 1/2$

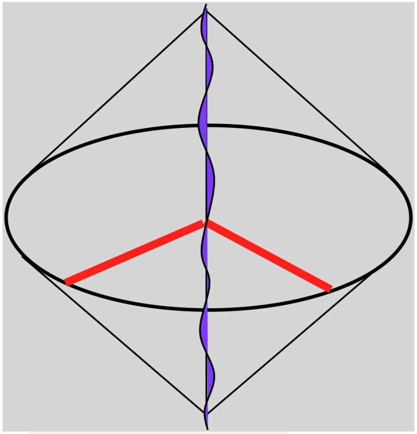
Shot noise limited sensitivity:
10 kW ←→ dN/dt = $10^{23}$ Υ/s

$$PSD_{\Delta\phi} = \sqrt{\frac{2}{dN/dt}} = 4.5 \times 10^{-12}\, rad/\sqrt{Hz}$$

$$PSD_{\Delta x} = PSD_{\Delta\phi} \cdot \frac{\lambda}{2\pi} = 7 \times 10^{-19}\, m/\sqrt{Hz}$$

**A 10 kW coherent photon beam probes the TeV scale in 1 second of integration.**



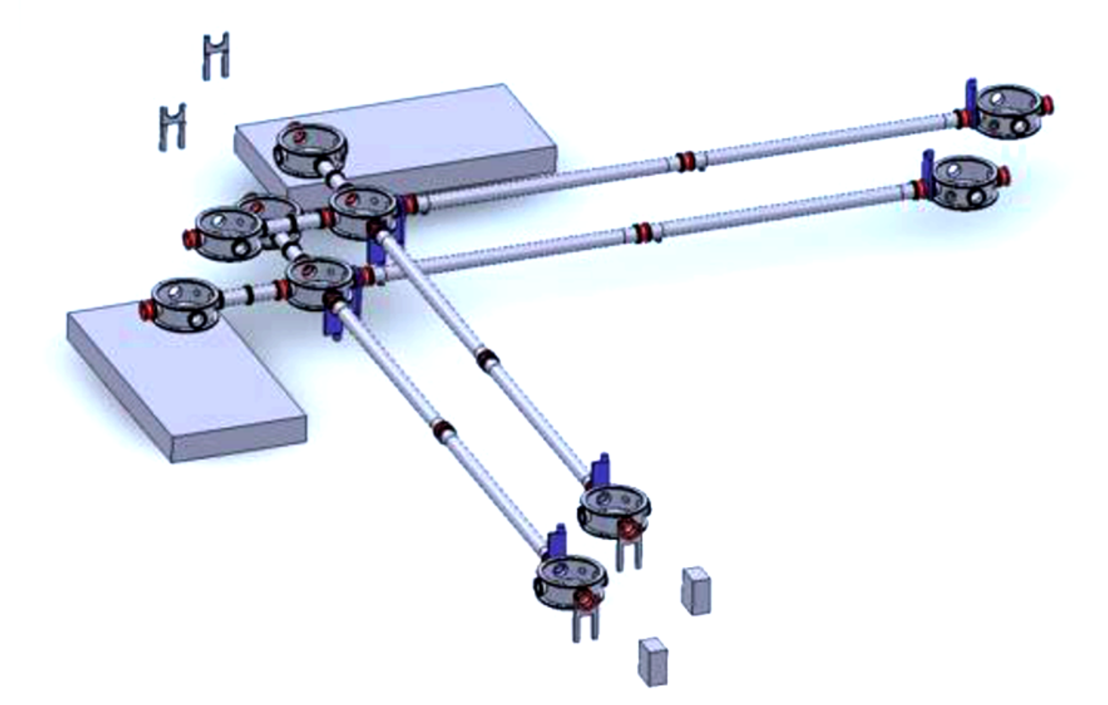


# The Fermilab Holometer:

## Interferometer probe of the quantum structure of space-time at the Planck scale $10^{19}$ GeV

- Fermilab:
  - A. S. Chou (co-PI, acting project manager), H.Glass, G. Guiterrez, C. Hogan, J. Steffen, C. Stoughton, R. Tomlin, J. Volk, W. Wester.
- MIT LIGO:
  - S. Waldman, R. Weiss
- U.Chicago
  - S. Meyer (co-PI), R. Lanza, L. McCuller
- U. Michigan LIGO
  - D. Gustafson

Dual, 40m long interferometers



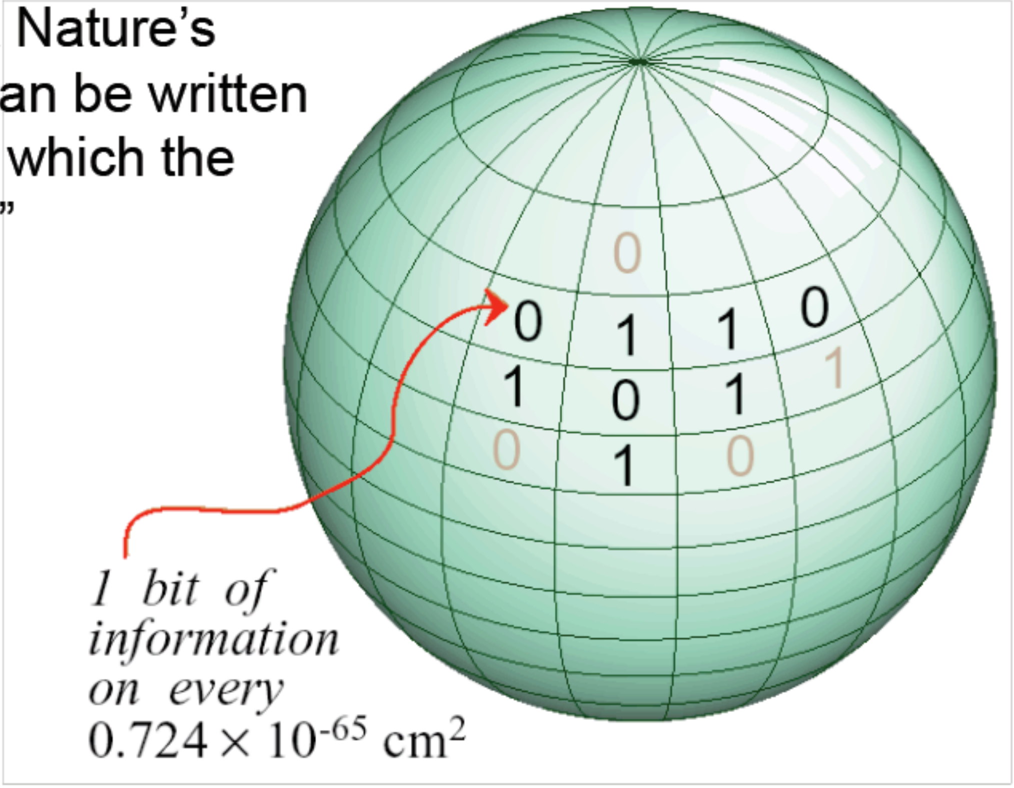
# Bekenstein-Hawking black hole entropy suggests that our world is holographic

Susskind, ‘t Hooft

$$S_{BH} = A_{BH} \times (M_{pl}/2)^2 = A_{BH}/(2\ \lambda_{pl})^2$$

“This is what we found out about Nature’s book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size.”

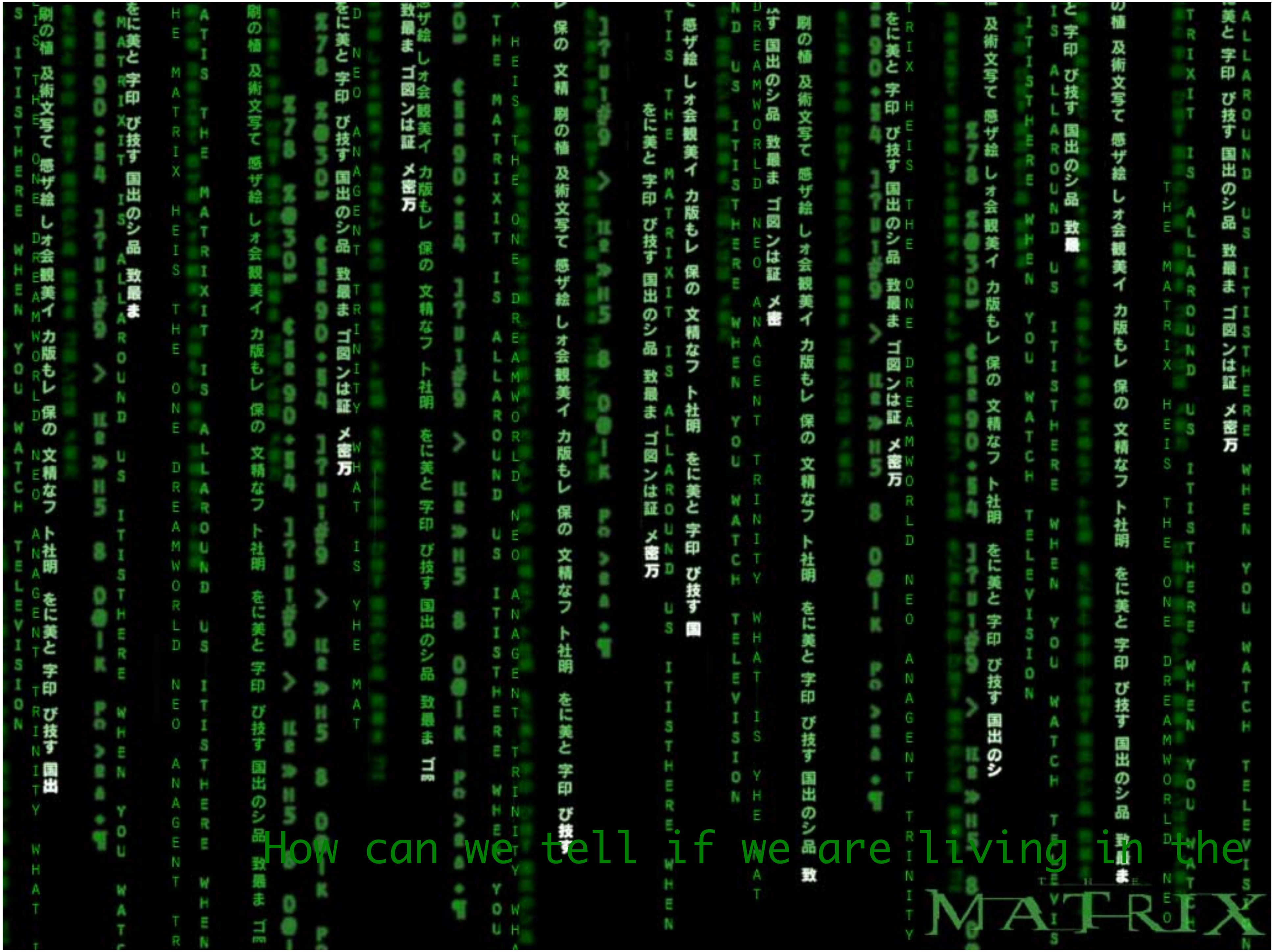
-Gerard ‘t Hooft



***Everything is written on 2D surfaces moving at the speed of light***

R. Bousso

The shocking thing is not holography, but rather the bandwidth limit….



How can we tell if we are living in the

# A holographic world is blurred by diffraction

WEEKLY NEWS IDEAS INNOVATION THE BEST JOBS IN SCIENCE

NewScientist

YOU ARE A HOLOGRAM

...projected from the edge of the universe

CAULDRON OF CREATION
DID LIFE ORIGINATE IN SULPHURIC ACID?

THE UPSIDE OF DOWN
Why misery is good for you

STARRY STARRY NIGHT
Save our astronomical heritage

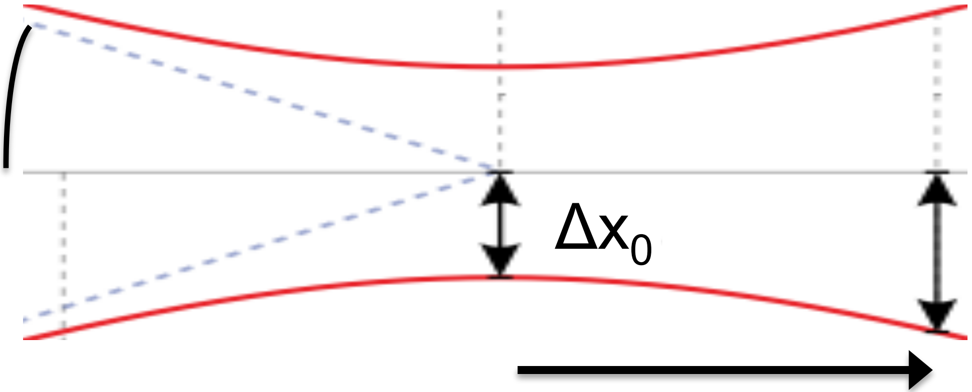
Can we detect this blurriness
in our apparently 3-dim world?

# Holograms are fuzzy—let's look for diffraction

C. Hogan (2010)

- Suppose that transverse space-time coordinate information is encoded on some carrier wave of maximum frequency $M_{pl}$ or minimum wavelength $\lambda_{pl} = 1/M_{pl}$.

- **Then space-time coordinates must be fuzzy, and the fuzziness will grow with time** as the carrier wave undergoes classical diffraction due to Heisenberg.



$\Delta\theta = \Delta p_t/p$
$= \lambda_{pl}/(4\pi\Delta x_0)$

$\Delta x_0$

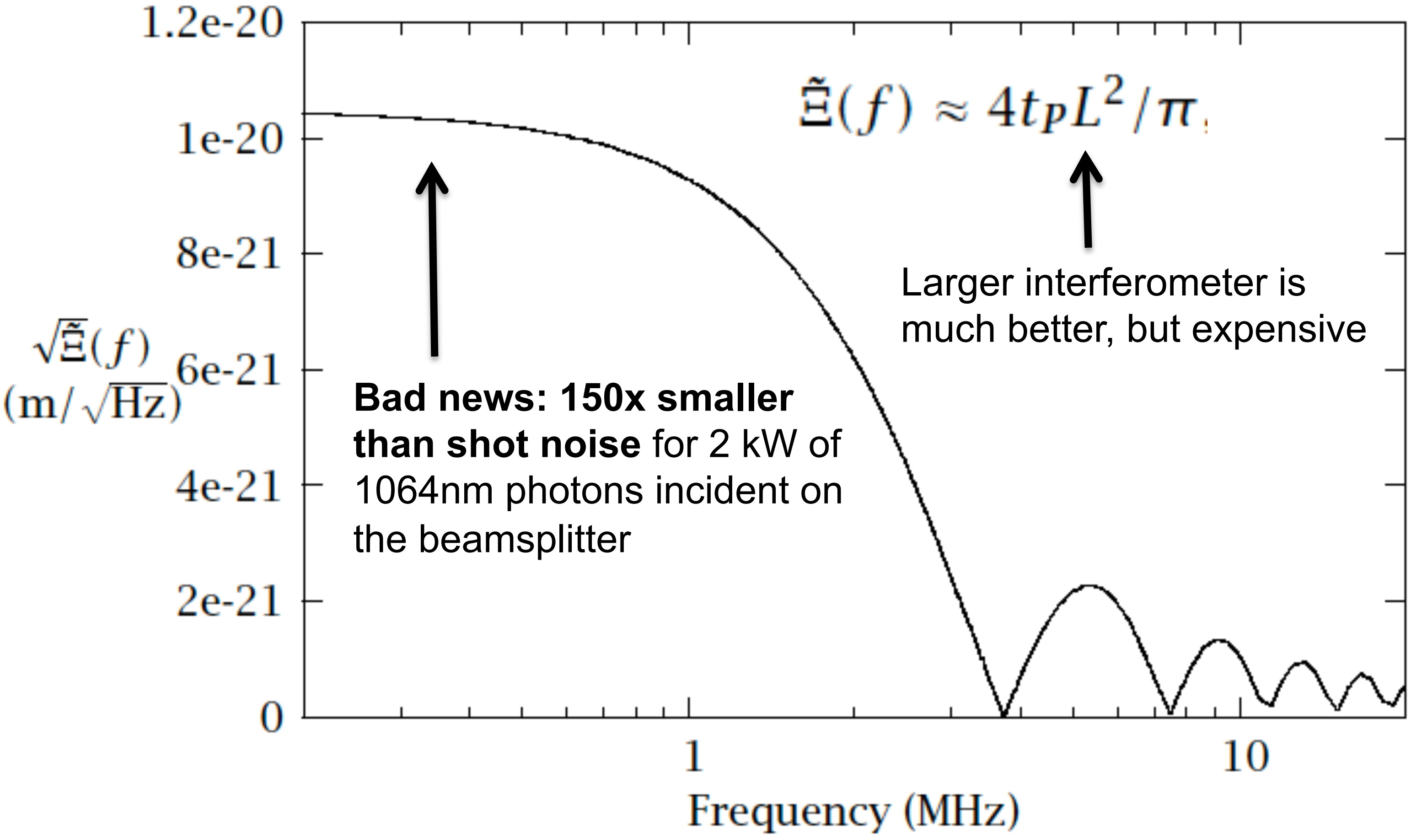
After some algebra:

$$\Delta x \geq \sqrt{\lambda_{pl} L / 2\pi}$$

Travel distance L or travel time of
carrier wave of wavelength $\lambda_{pl}$

Diffraction over a large "lever arm" L can amplify microscopic effects, including Planck scale effects!

# For a 40m interferometer, the diffractive effect amplifies the beamsplitter position uncertainty to $10^{-20}$ m/rtHz



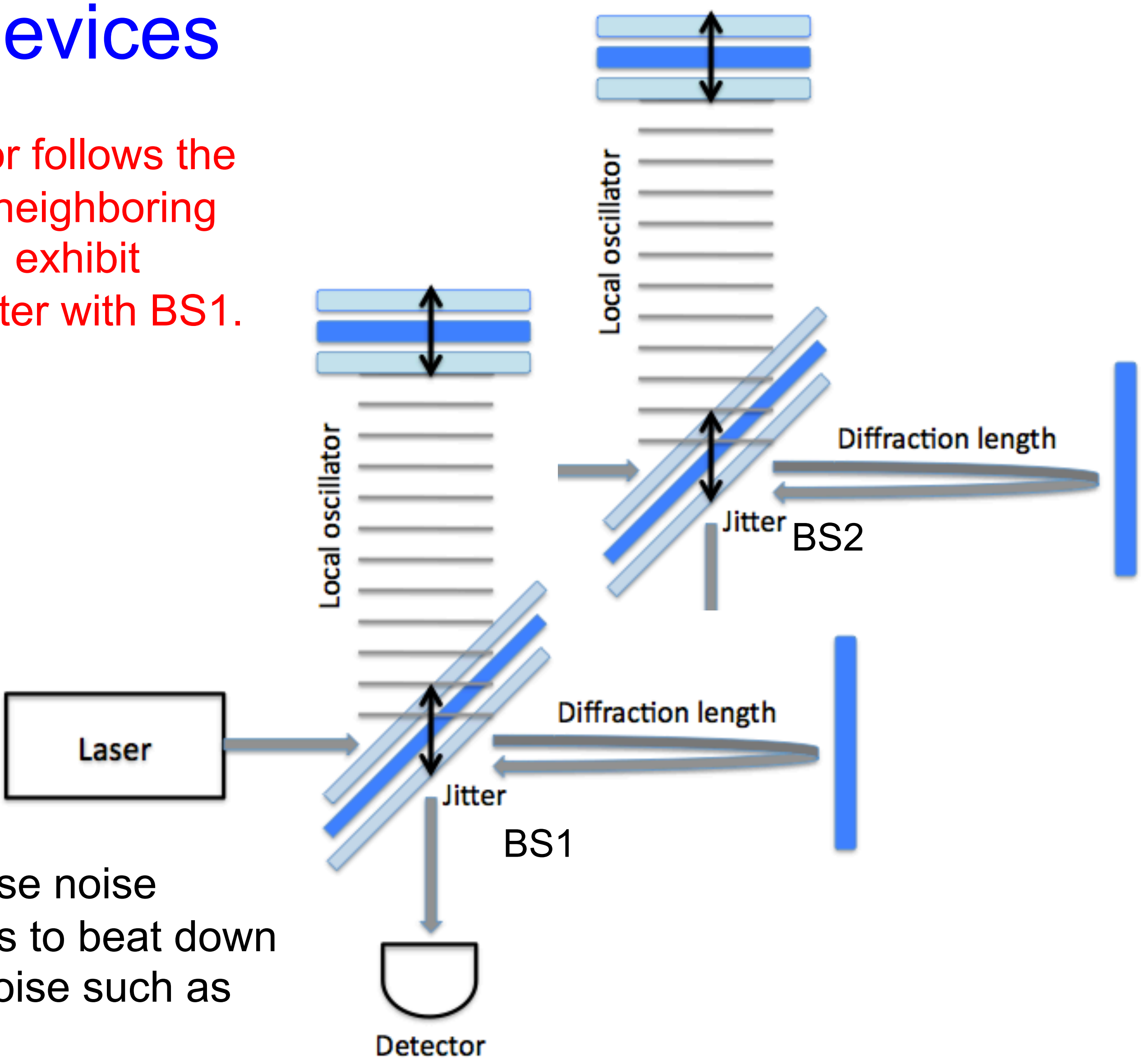
**Bad news: 150x smaller than shot noise** for 2 kW of 1064nm photons incident on the beamsplitter

Larger interferometer is much better, but expensive

Prediction from Craig Hogan, Fermilab Holometer proposal

# Utilize correlation between position jitter in neighboring devices

- Just as the end mirror follows the beamsplitter BS1, a neighboring beamsplitter BS2 will exhibit partially correlated jitter with BS1.



Cross-correlate the phase noise between the two devices to beat down random, uncorrelated noise such as shot noise.

# Cross-correlating two signals

Uncorrelated noise power is reduced as sqrt(time)

Correlated noise power stays constant

$$(\phi_1 X \phi_2)_N = \frac{(\delta\phi_n)^2}{\sqrt{\frac{t_{obs}}{\tau_{sample}}}} + (\delta\phi_{Hogan})^2$$

$$\tau_{\text{sample}} = c/2L = 270 \text{ ns}$$

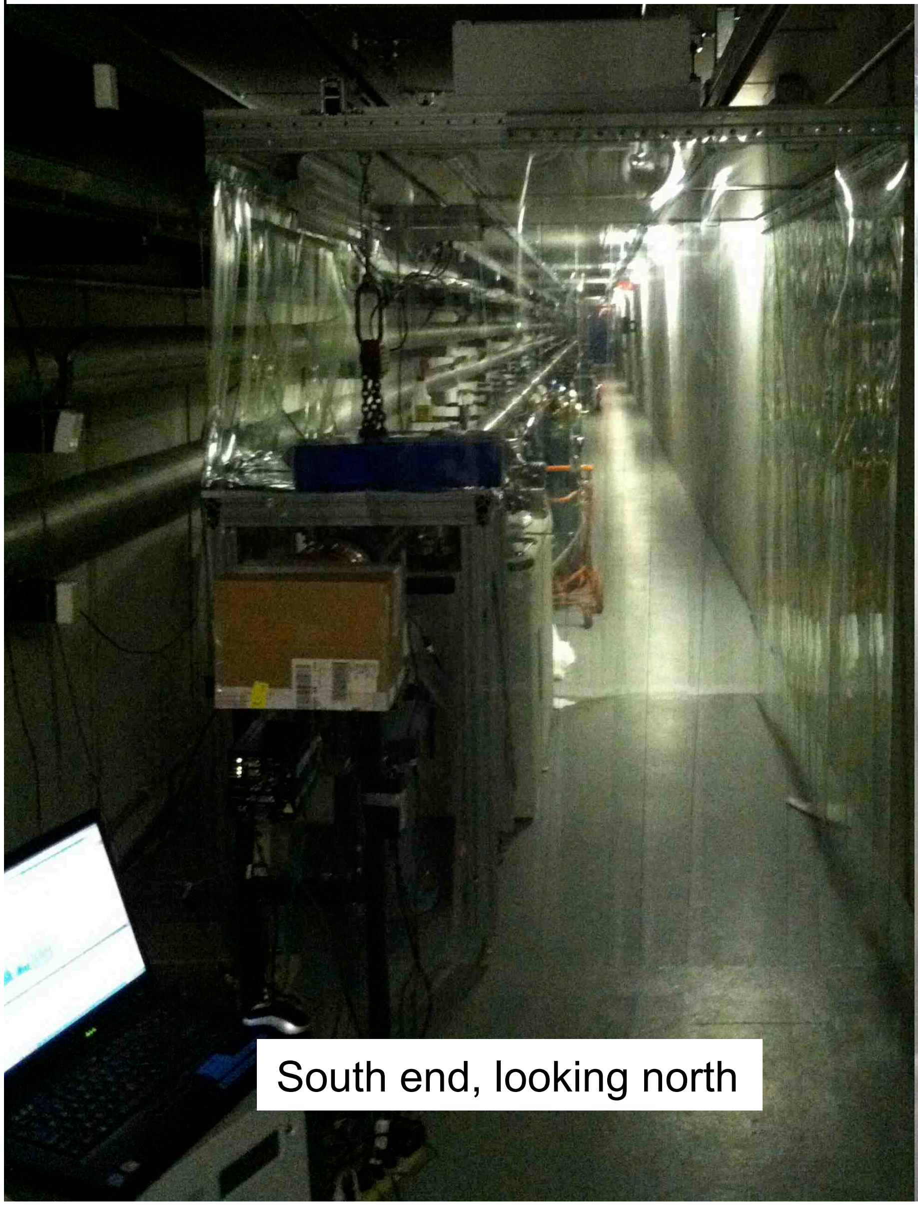
to resolve 2 MHz bandwidth

Required integration time for 1-sigma

$$\boxed{t_{obs} > \tau_{sample}\left(\frac{(\delta\phi_n)^2}{(\delta\phi_{Hogan})^2}\right)^2}$$

# Experimental progress at FNAL

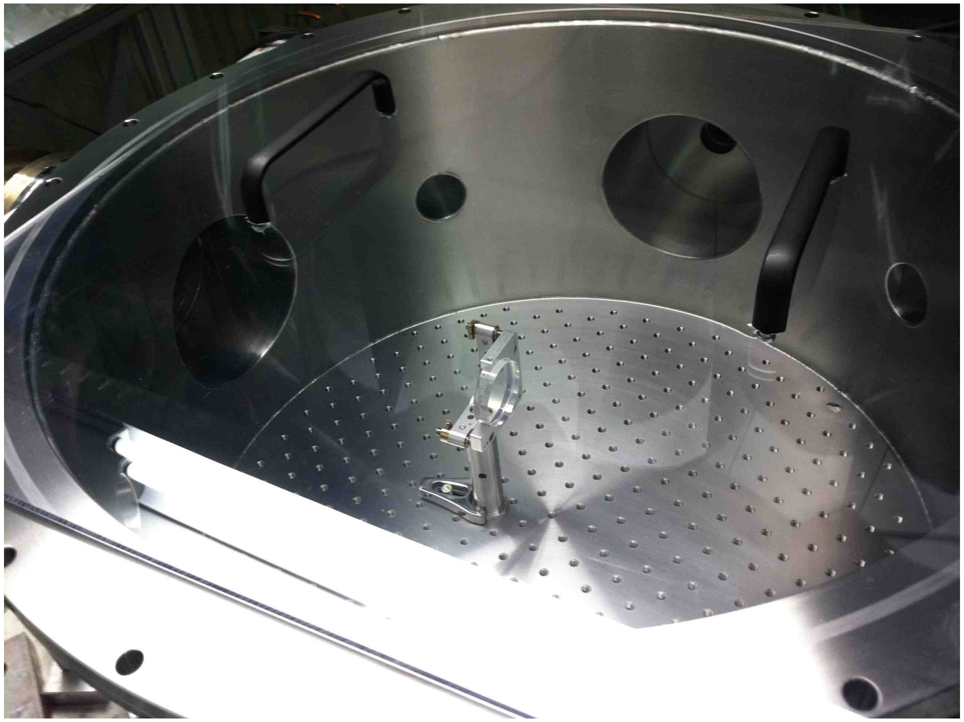
# 4/18/11: Completed installation of 40m long vacuum system at MP8.

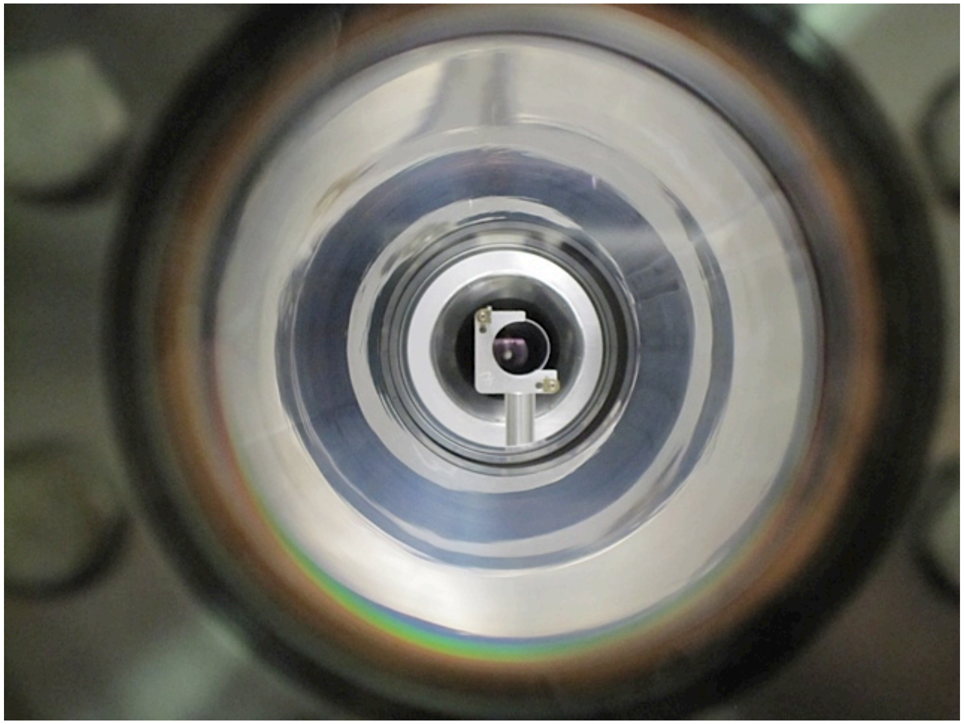


South end, looking north

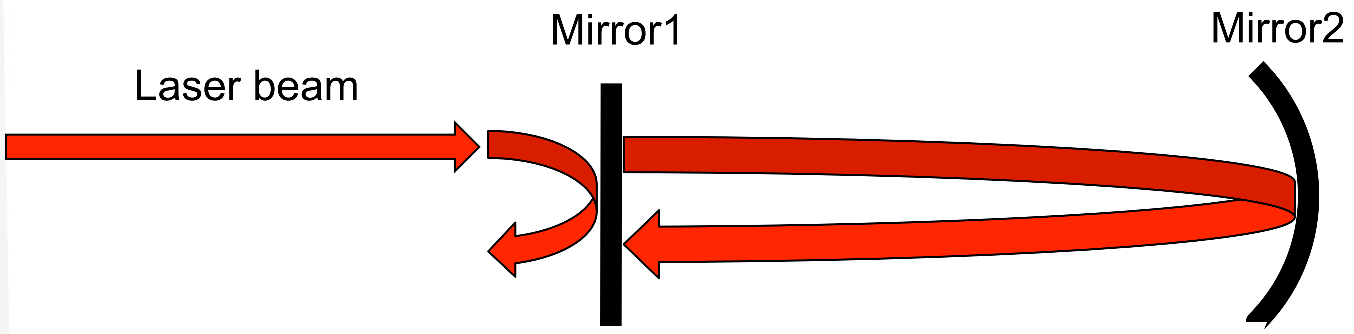
North end, looking south

# End station vacuum vessels hold custom optical cavity mirrors and eventually beamsplitters





# Pound Drever Hall Locking



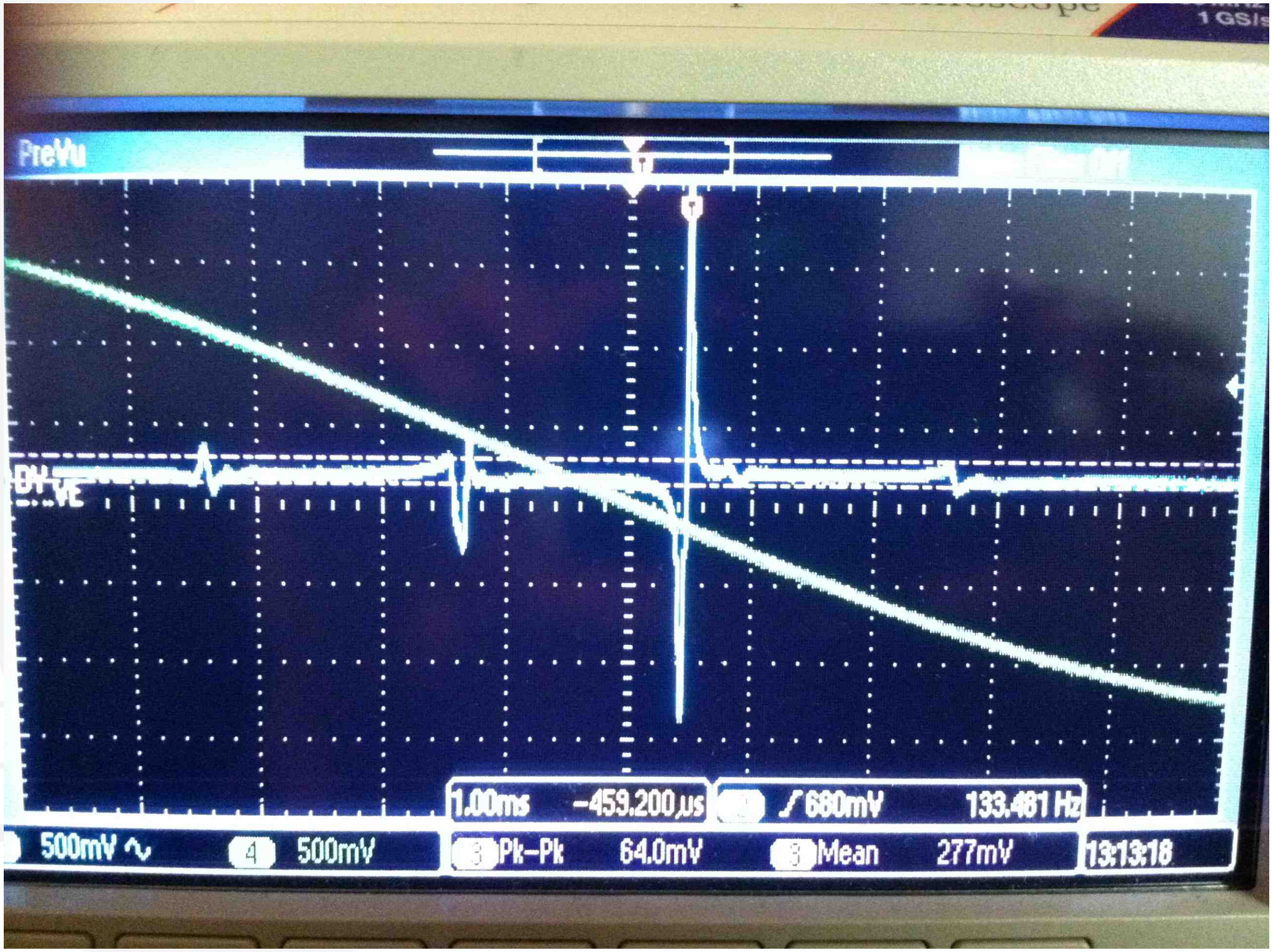
Measure the length of the cavity by looking at the coherent interference between:

A) Light that reflects directly from the (partially transmissive) injection mirror and
B) Light near resonance that makes a roundtrip in the cavity and leaks back out

Lock condition:

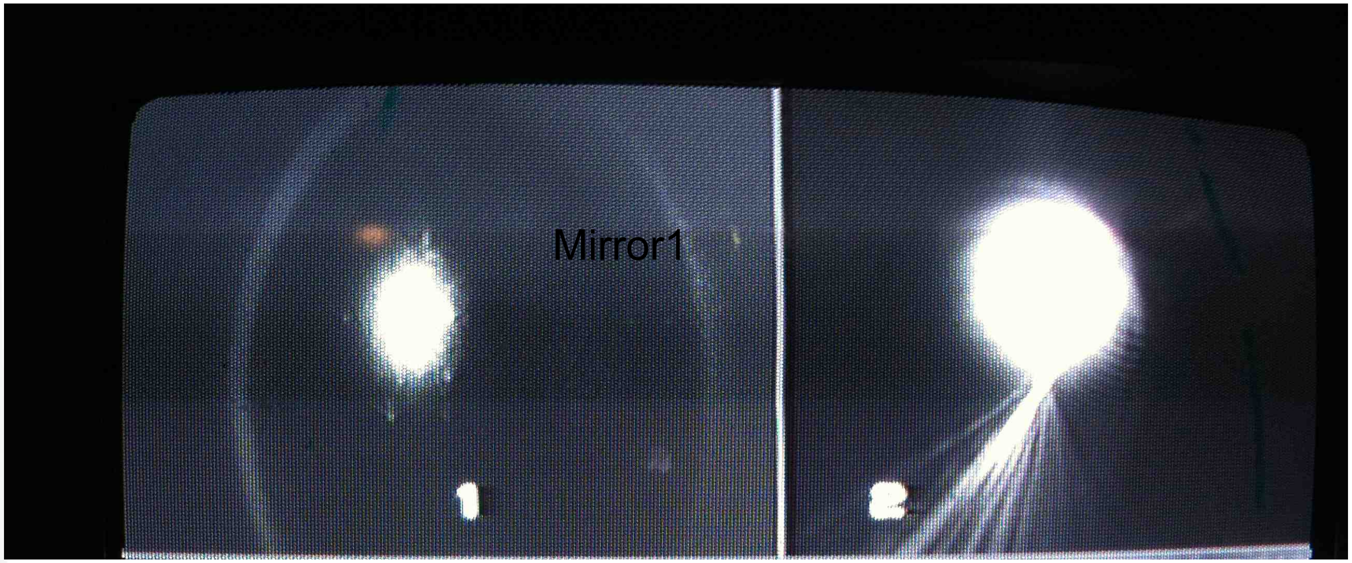
Zero phase difference when cavity length = integer number of ½ wavelengths.

Pound-Drever-Hall technique gives a **signed error signal** for detecting instantaneous mismatches between the laser frequency and the cavity resonance and applying feedback corrections.



# R&D cavity locked on Gaussian fundamental mode.

Spot on input mirror



Spot on end mirror

A 40m long standing wave with $8\times10^7$ nodes!
Initial optics recycle the beam 20 times before dumping it.
Cavity lock stability demonstrated in an 18 hour run.

Custom optics procurements are underway to improve power recycling to 1 kW power for the Fermilab holometer.

**Next step: build first 40m power recycled interferometer for the holometer.**

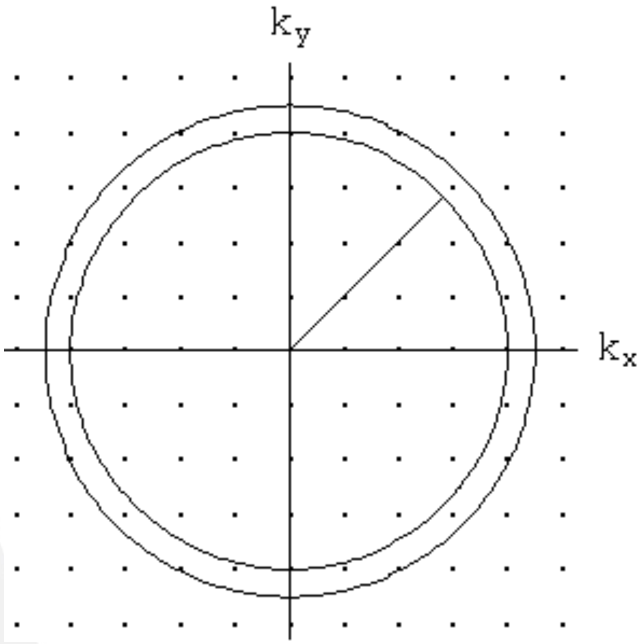
# 3. Probing the vacuum

# What do we know about the zero-point energy of the vacuum?

- Summing ½ photon per mode over the density of states of a particle in a Hubble-sized box overestimates the vacuum energy density by at least 60 orders of magnitude

$\frac{1}{2}\hbar\omega$

per mode of particles in a box

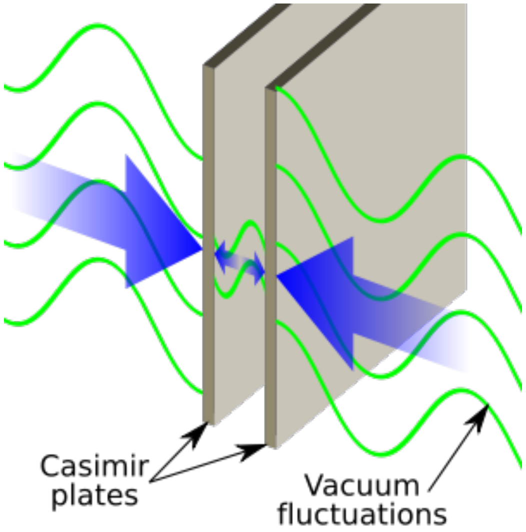


Integral from the Hubble scale to at least the electroweak scale gives predicted vacuum energy $(\mathrm{TeV})^4$.

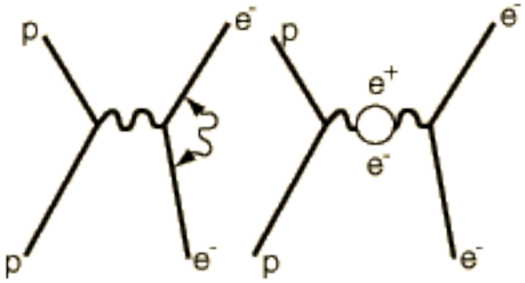
The observed cosmological vacuum energy is $(\mathrm{meV})^4$.

# What else do we know about vacuum energy?

- Casimir force measurements tell us that this energy is really there, in that it causes real, observable forces.
  - It is therefore hard to believe that gravity would not see it.

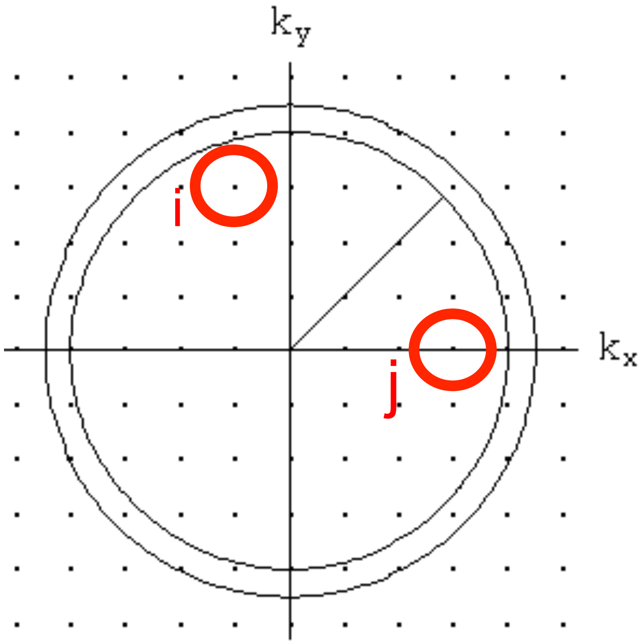


- Quantum field theory successfully predicts the Lamb shift, running of coupling constants, etc., by integrating over all of the plane wave states.
  - The accounting of states *appears* to be correct.



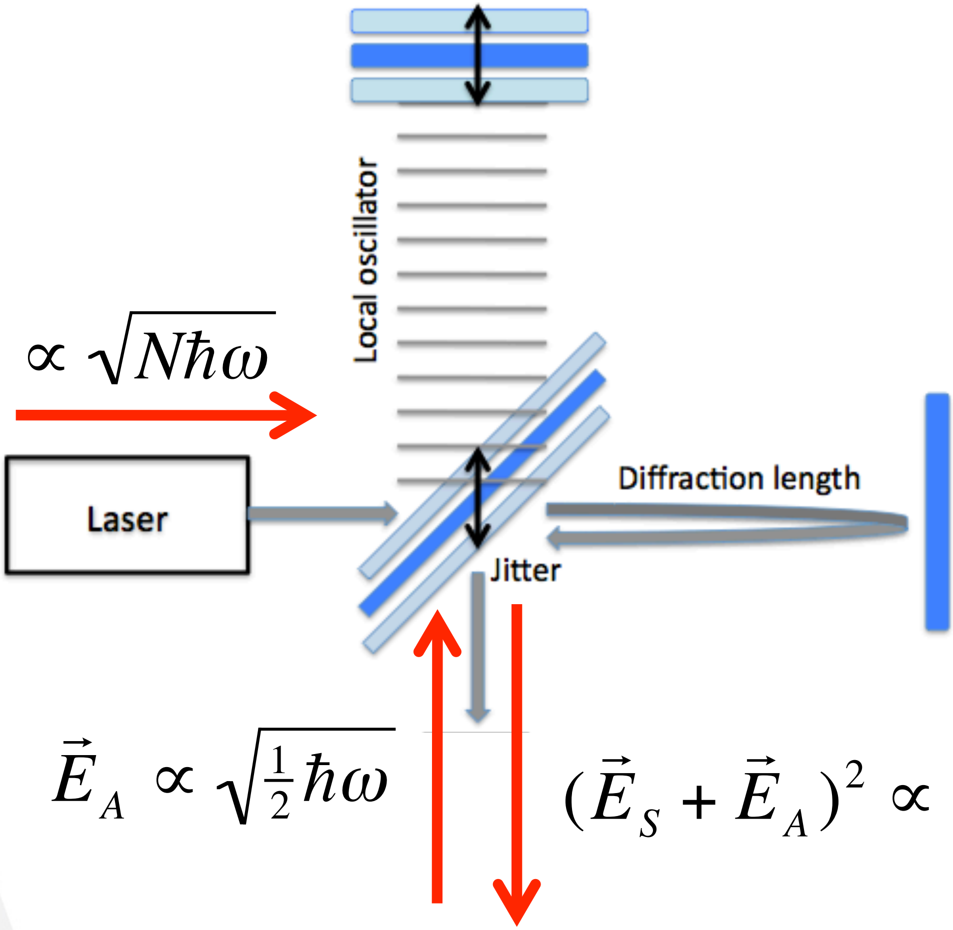
# Could it be that some of these Fock states are not distinct?

- What if state i and state j are somehow really the same underlying state so that we are overcounting when making a monotonic sum of zero-point energies?



Maybe QFT loop integrals are fooled by destructive interference of contributions from these states when they are mistakenly treated as distinct.

# Carlton Caves' description of shot noise as beating of a signal oscillator with the ½ photon vacuum state



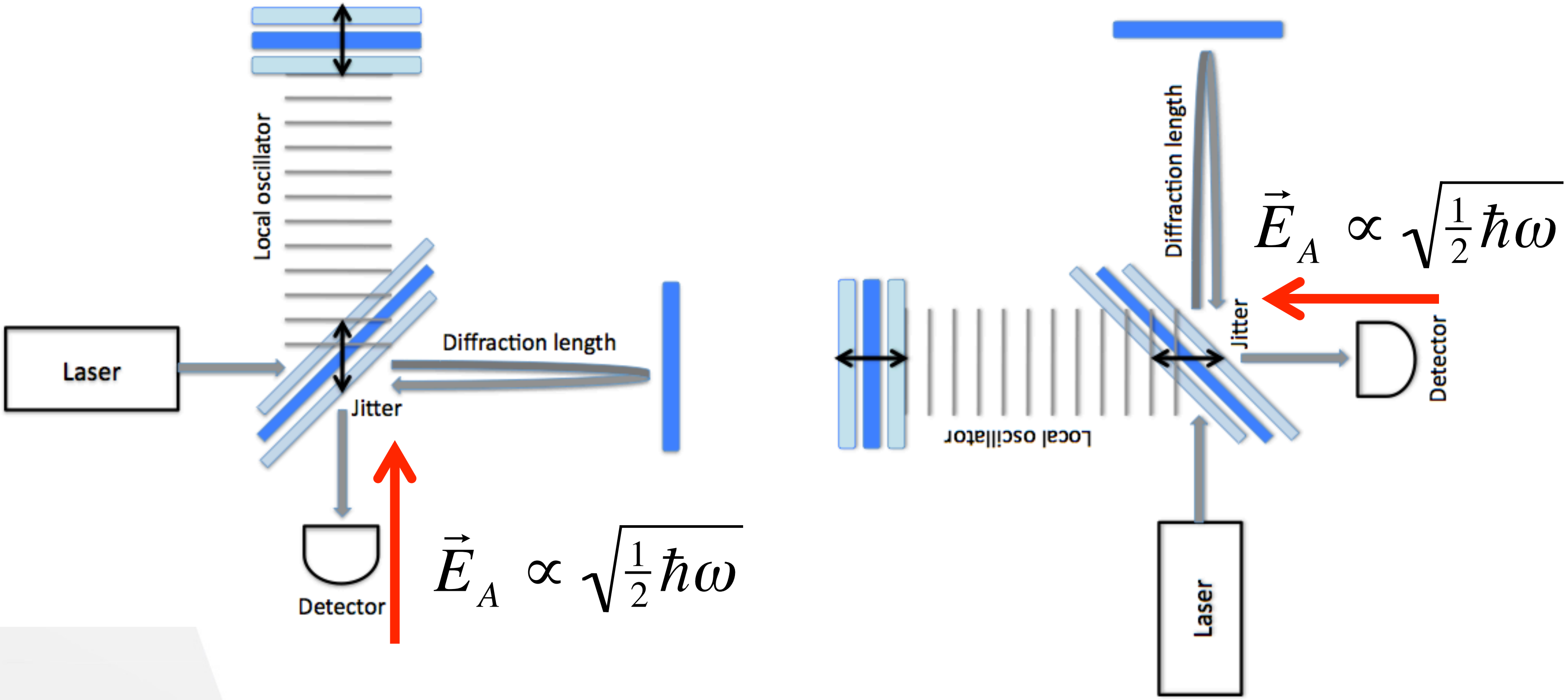
$$\vec{E}_S \propto \sqrt{N\hbar\omega}$$

$$\vec{E}_A \propto \sqrt{\tfrac{1}{2}\hbar\omega}$$

$$(\vec{E}_S + \vec{E}_A)^2 \propto (N + \sqrt{2N} + \tfrac{1}{2})\hbar\omega$$

Measured shot noise will also depend on relative random phase between $E_S$ and $E_A$

# How well do we know that shot noise in two “independent” interferometers is uncorrelated???



$$\vec{E}_A \propto \sqrt{\tfrac{1}{2}\hbar\omega}$$

$$\vec{E}_A \propto \sqrt{\tfrac{1}{2}\hbar\omega}$$

High speed cross-correlation electronics of the holometer will allow us to search for correlated shot noise in various geometric configurations of two devices.

# Uses for intense coherent optical beams

- Searches for exotic, rare scattering processes
  - $10^{24}$ photons/s
- Precision position measurements
  - $10^{-18}$ m/rtHz shot-noise-limited resolution
  - Can integrate down shot noise when searching for correlated signals with long coherence time
- Probing the quantum vacuum?