New Initiatives in Particle Astrophysics (a.k.a. non-accelerator physics)

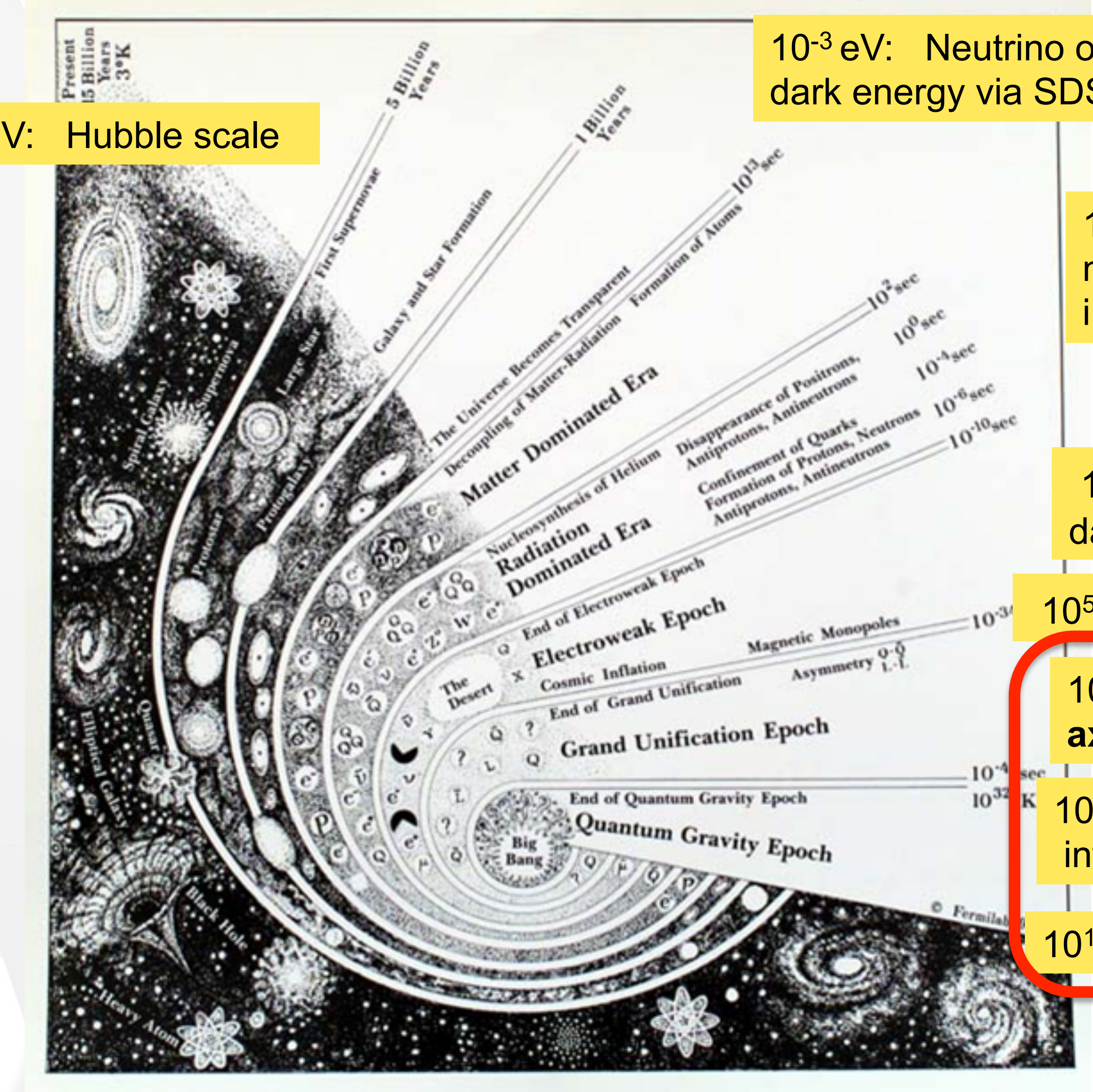
Aaron S. Chou
Wilson Fellow, FNAL

DOE KA13 Review
September 29, 2010

1. Optical Cavity Experiments (REAPR axion search, Holometer)
2. Solid Xenon Detector R&D (Solar axions, etc.)
3. Cosmic Microwave Background Polarization (QUIET Phase 2)

Fermilab

New experiments to probe the highest energy scales



10^{-33} eV: Hubble scale

10^{-3} eV: Neutrino oscillations.
dark energy via SDSS, DES, laser search, etc

1 eV-1 GeV: Chemistry, nuclear physics, strong interactions

10^{3} GeV: Tevatron, LHC, dark matter direct detection

10^{5} GeV: cosmic ray showers

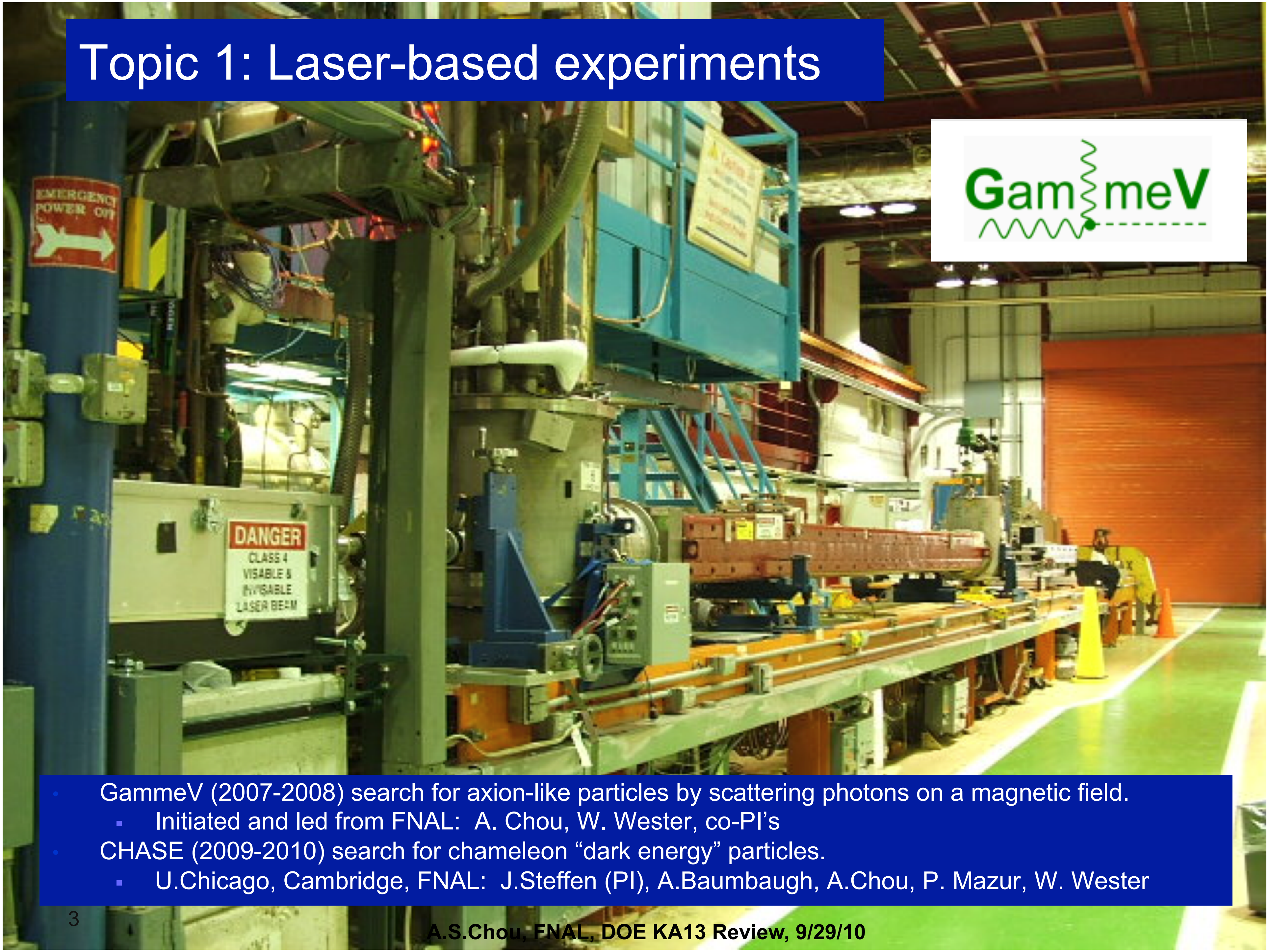
10^{11} GeV: **solar axions, axion-photon oscillations**

10^{16} GeV: 0νββ search, inflation via **CMB B-modes**

10^{19} GeV: **holographic noise**

Topic 1: Laser-based experiments

GammeV

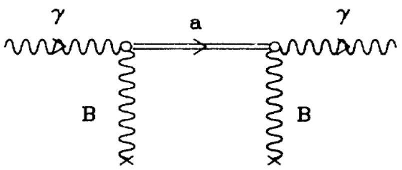


- GammeV (2007-2008) search for axion-like particles by scattering photons on a magnetic field.
  - Initiated and led from FNAL: A. Chou, W. Wester, co-PI’s
- CHASE (2009-2010) search for chameleon “dark energy” particles.
  - U.Chicago, Cambridge, FNAL: J.Steffen (PI), A.Baumbaugh, A.Chou, P. Mazur, W. Wester

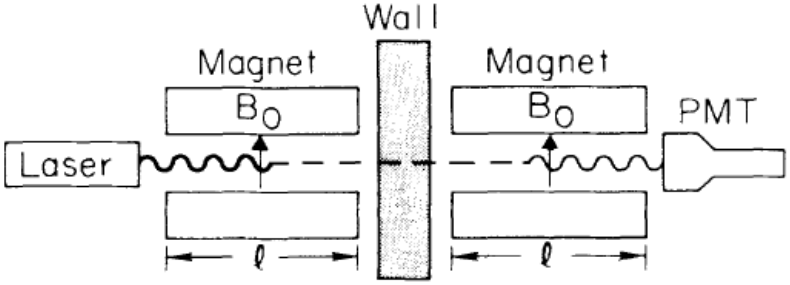
Search for axion-like particles (pseudo-Nambu-Goldstone bosons) by shining light through walls

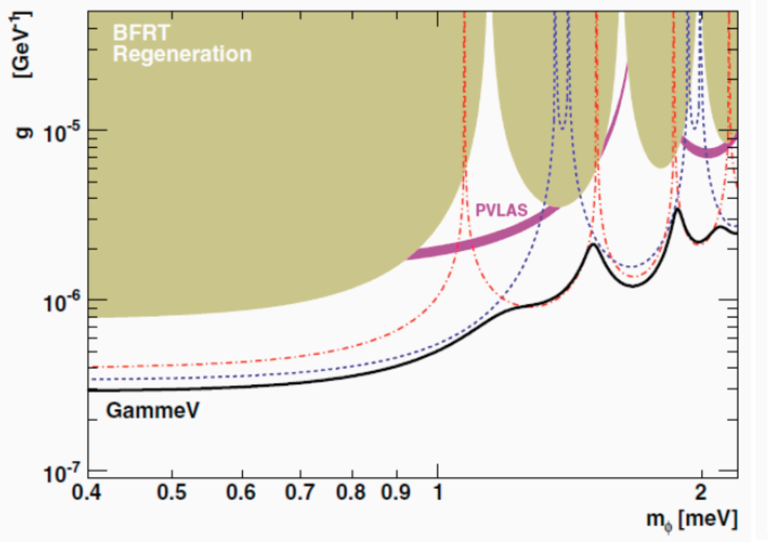
Experimental configuration inspired by a Feynman diagram.

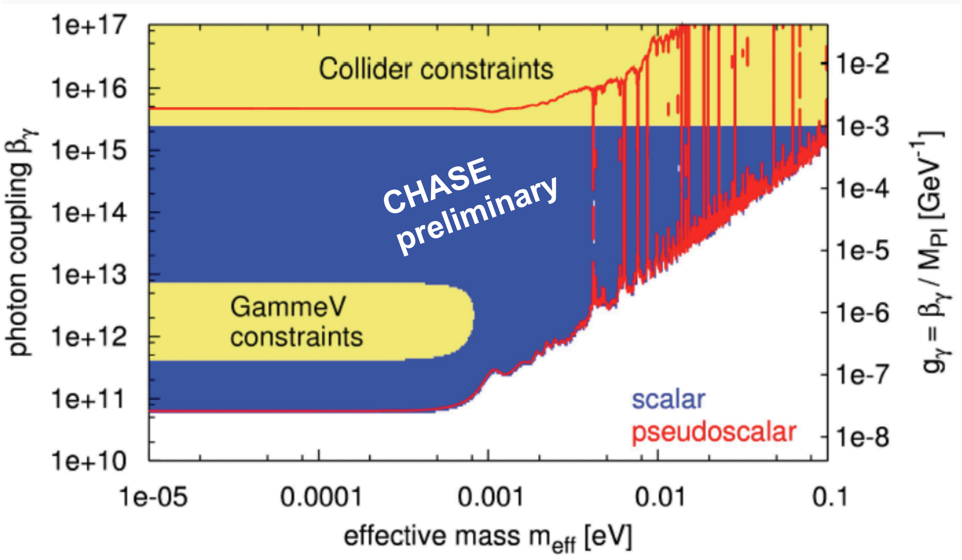
Van Bibber, et. al., PRL 59, 759 (1987) **(+ Steve Koonin)**



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





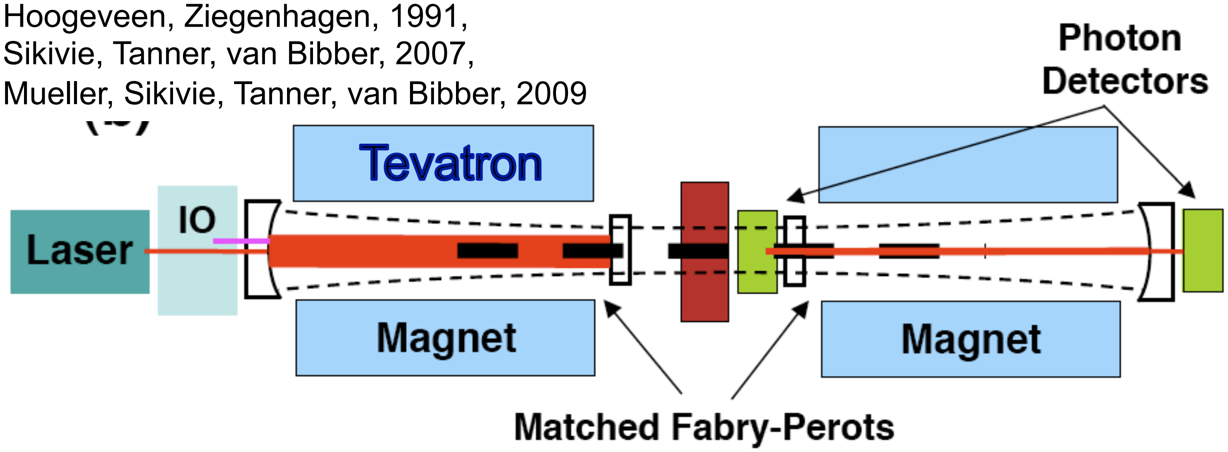


GammeV program at FNAL produced two Physical Review Letters (so far), 100 citations, >40 presentations, 3 postdocs → tenure-track positions.

REAPR: Resonantly Enhanced Axion Photon Regeneration

Collaboration with U.Florida, U.Michigan, Naval Postgraduate School.
OJI grant to A. Chou.

Hoogeveen, Ziegenhagen, 1991,
Sikivie, Tanner, van Bibber, 2007,
Mueller, Sikivie, Tanner, van Bibber, 2009

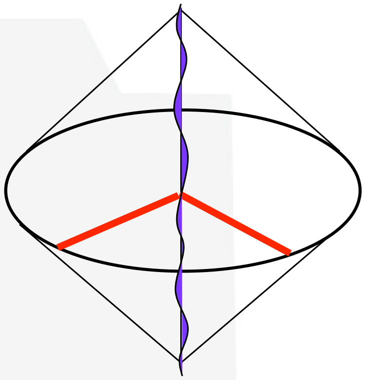


Place matched Fabry-Perot cavities around each magnet.

1st cavity recycles the photons and creates an intense axion beam.
2nd cavity serves as a high-Q resonant detector for regenerated photons.

Signal rate increases as the square of cavity Q:
with 10^5 bounces, the rate increases by 10^{10} !

Improve GammeV sensitivity to coupling by 4 orders of magnitude to the **10^{11} GeV** scale, using 40m long cavities enclosing **existing spare Tevatron magnets**.



The Fermilab Holometer:

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

- Fermilab:
  - A. Chou (co-PI, acting project manager), C. Hogan, E. Ramberg, J. Steffen, C. Stoughton, R. Tomlin, J. Volk, W. Wester. (<2 FTE scientists)
- MIT LIGO:
  - S. Waldman, R. Weiss
- U.Chicago
  - S. Meyer (co-PI)
- U. Michigan LIGO
  - D. Gustafson
- Caltech LIGO
  - S.Whitcomb

Large overlap in both scientific staff and R&D topics with the FNAL axion group.

Co-develop 40m optical cavities for the two experiments.
The large recycled photon flux (up to 10^{24} photons/s) can be used either for searches for rare events or to make precise position measurements.

The Holographic Principle

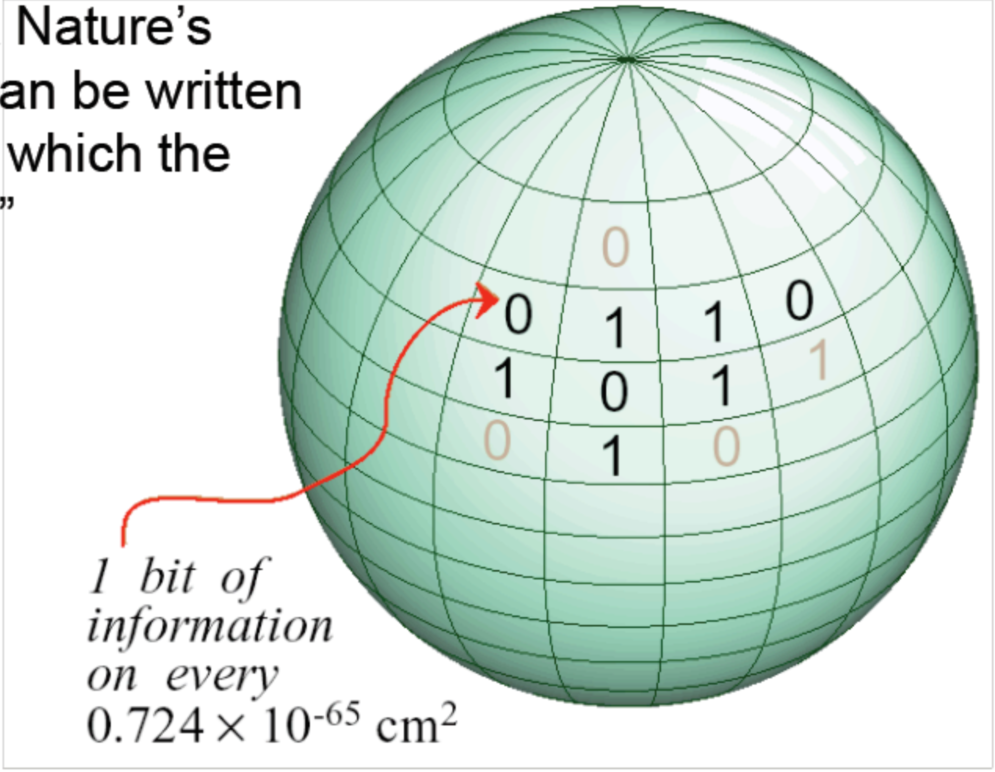
Black hole entropy $S = M_{pl}^2 \text{ Area} / 4$

“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

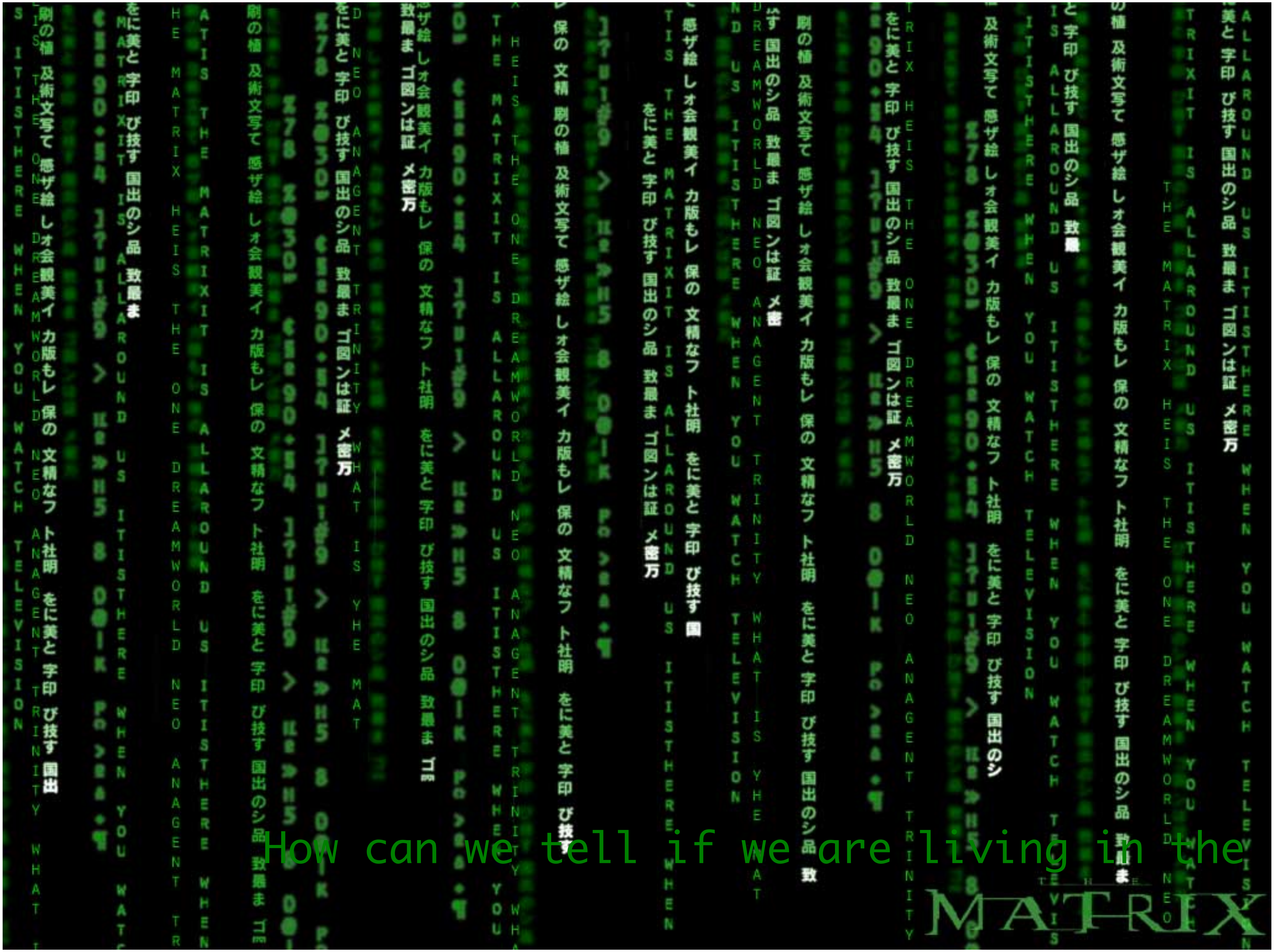
Everything is written on 2D surfaces moving at the speed of light

R. Bousso



1 bit of information on every $0.724 \times 10^{-65}\ \text{cm}^2$

Our apparently 3D world is actually 2D and has a bandwidth limit ?!?!

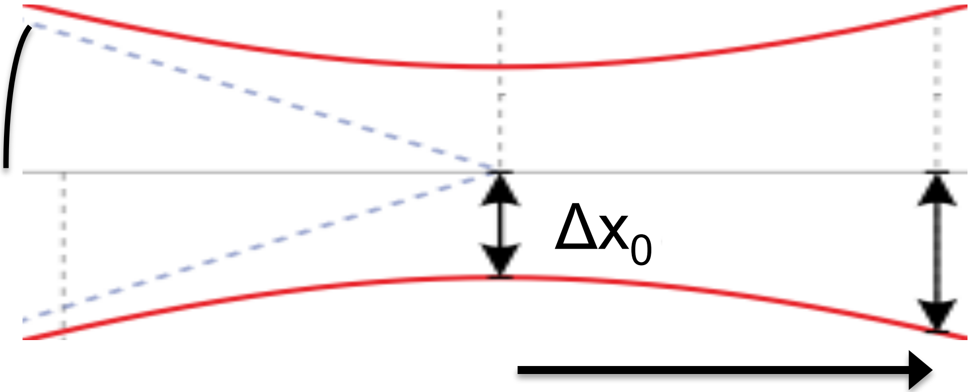


How can we tell if we are living in the

Hogan: Holograms are fuzzy—let's look for diffraction

- 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.

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



After some algebra:

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

Travel distance L or travel time of carrier wave of wavelength λ_{pl}

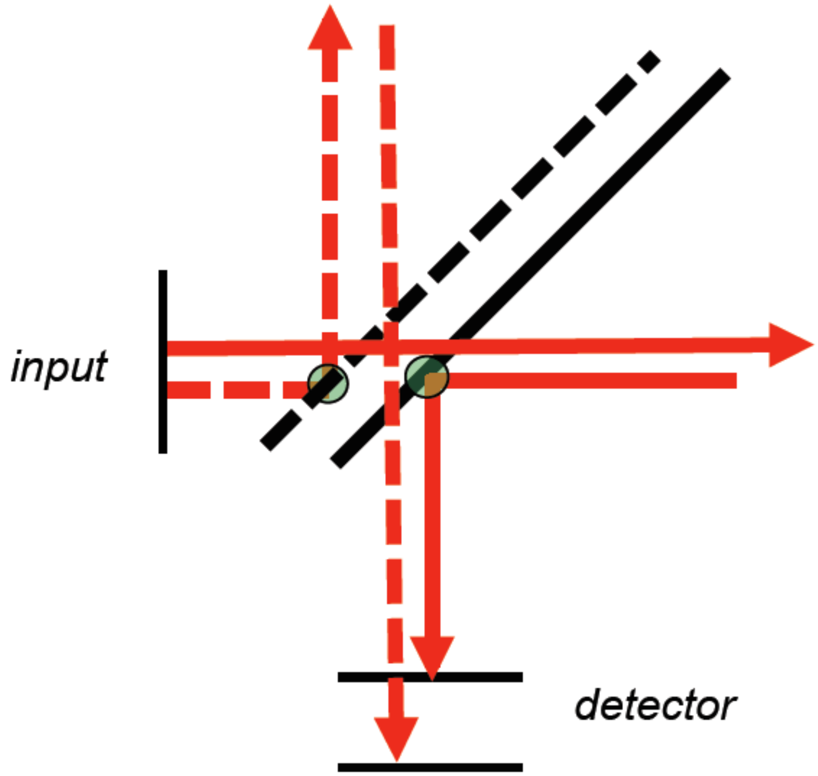
Diffraction over a large "lever arm" L can amplify microscopic effects, including Planck scale effects!

Holographic noise in a Michelson interferometer

Beam comes in, samples the beamsplitter position, goes down the arms and back.

In this time interval, the space-time coordinates *underneath* the beamsplitter have grown uncertain due to the diffractive effect.

This apparent jitter of the beamsplitter position gives irreducible phase noise in the interferometer.

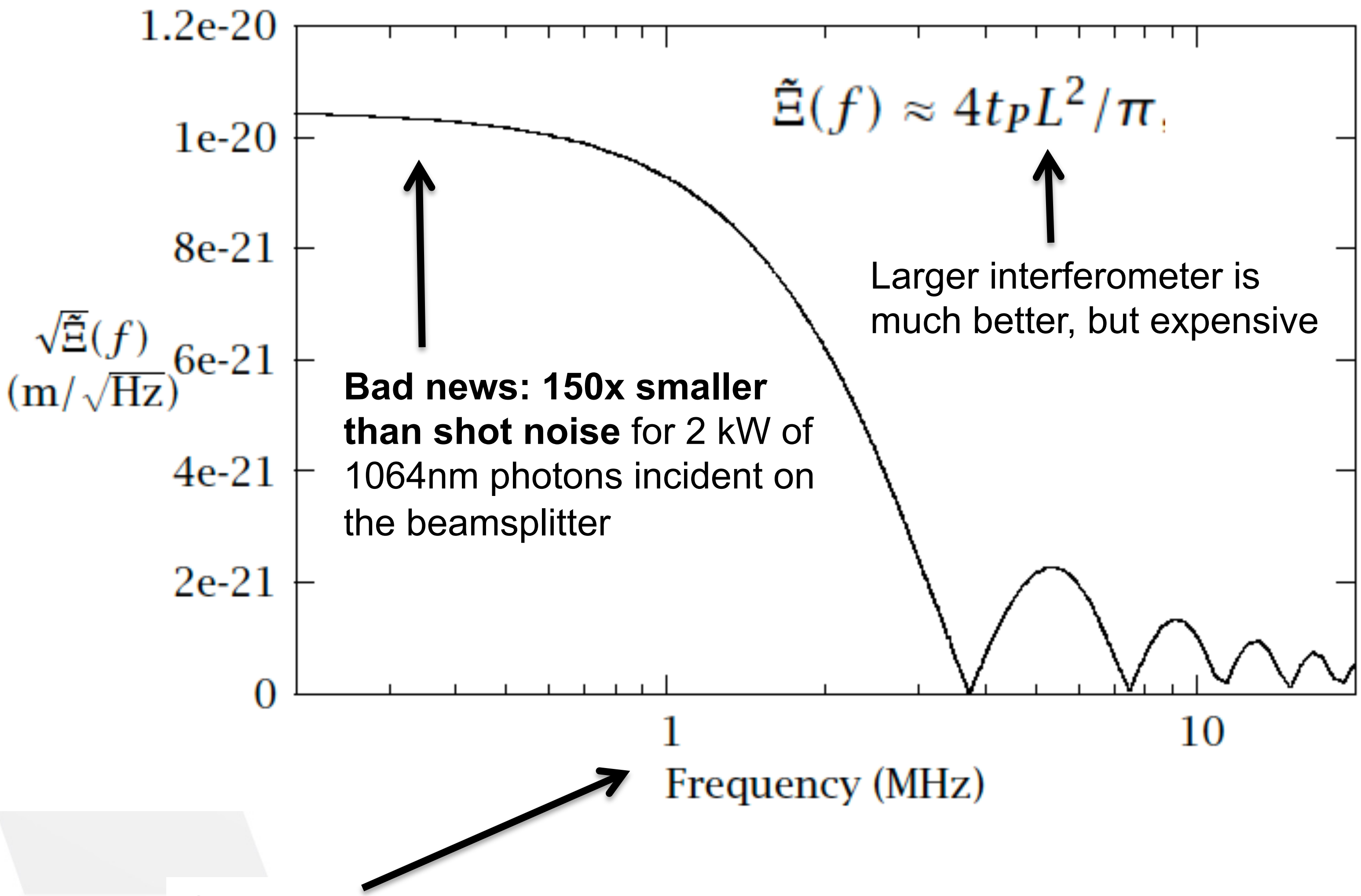


Range of jitter depends on arm length:

$$\Delta x^2 = \lambda_P L$$

- **New jitter of space-time predicted, with no free theoretical parameters.**
- **The resulting Planck-suppressed phase noise is tiny, but detectable!**

Characteristic frequency spectrum of the holographic noise in a 40m cavity-enhanced interferometer

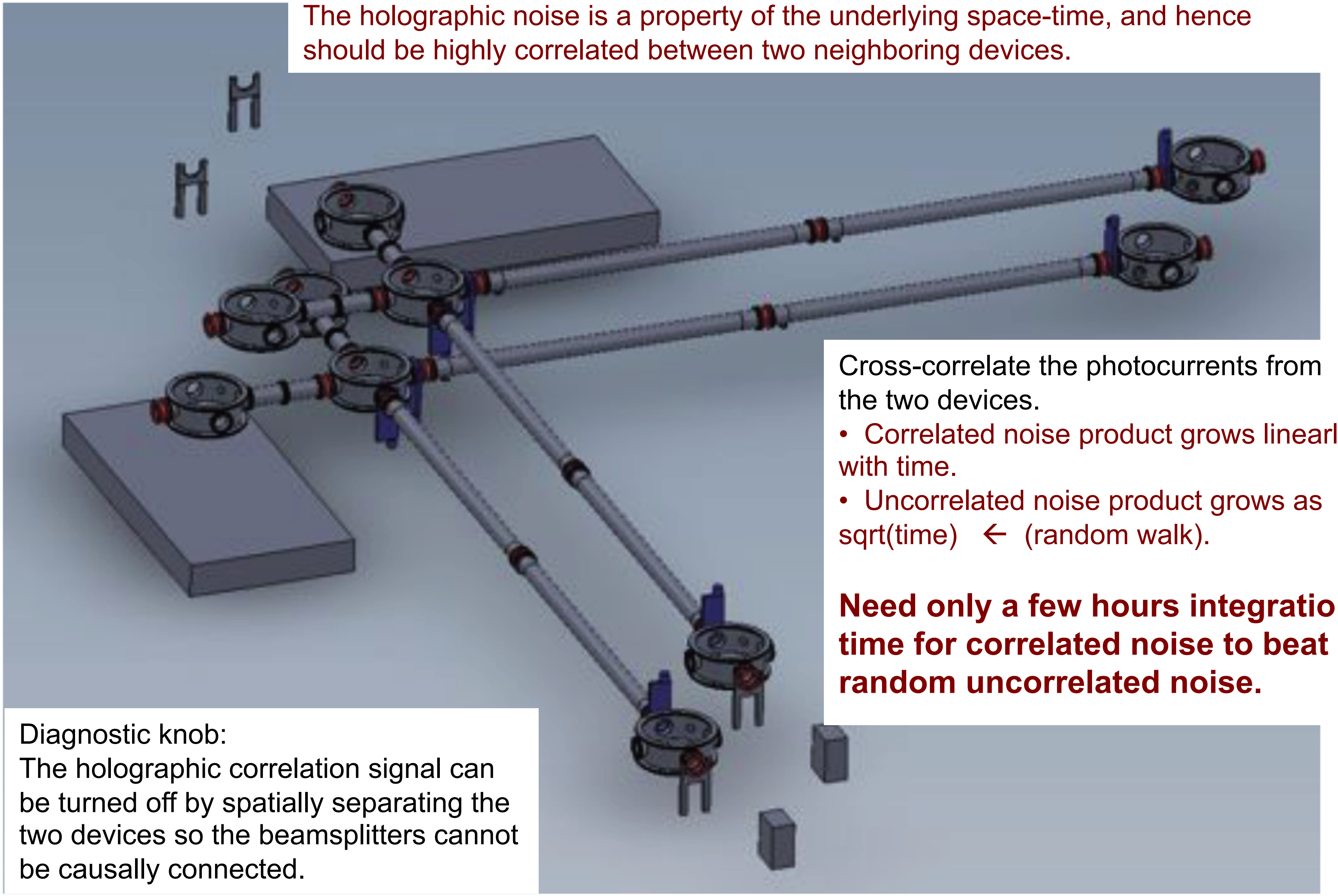


Larger interferometer is much better, but expensive

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

Good news: No seismic background at MHz, only RF.

The Proposed 40m Fermilab Holometer



The holographic noise is a property of the underlying space-time, and hence should be highly correlated between two neighboring devices.

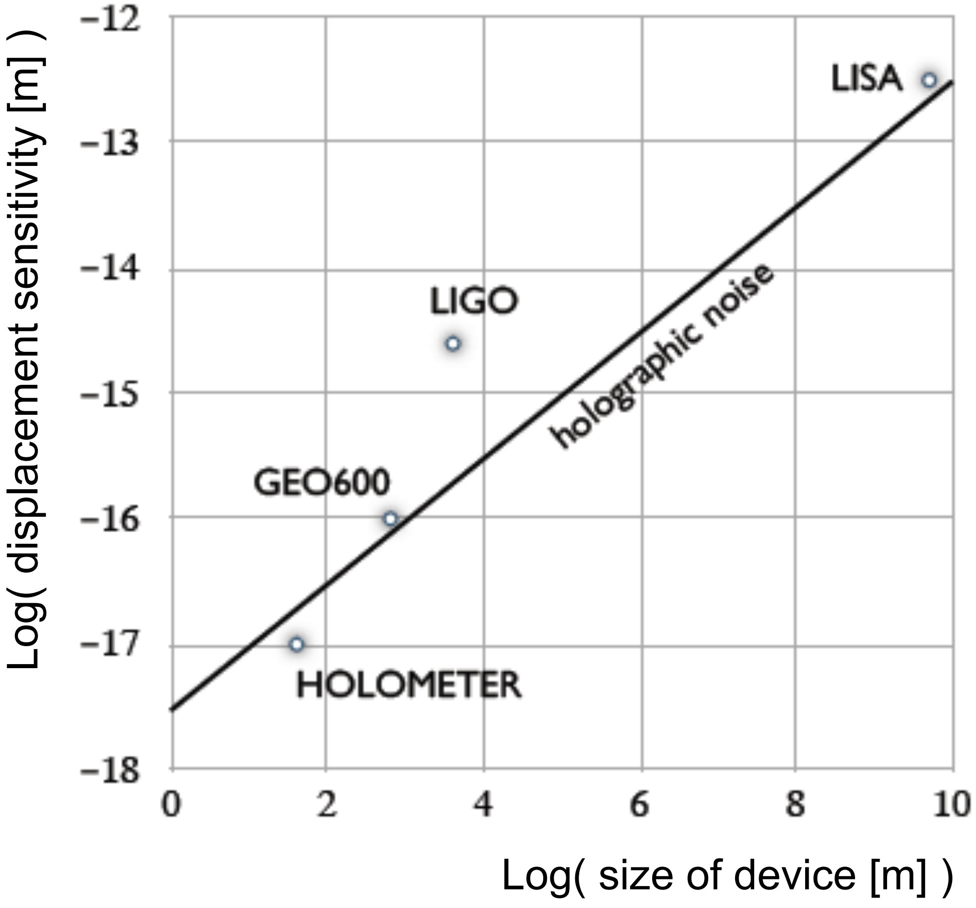
Cross-correlate the photocurrents from the two devices.

- Correlated noise product grows linearly with time.
- Uncorrelated noise product grows as sqrt(time) ← (random walk).

Need only a few hours integration time for correlated noise to beat random uncorrelated noise.

Diagnostic knob:
The holographic correlation signal can be turned off by spatially separating the two devices so the beamsplitters cannot be causally connected.

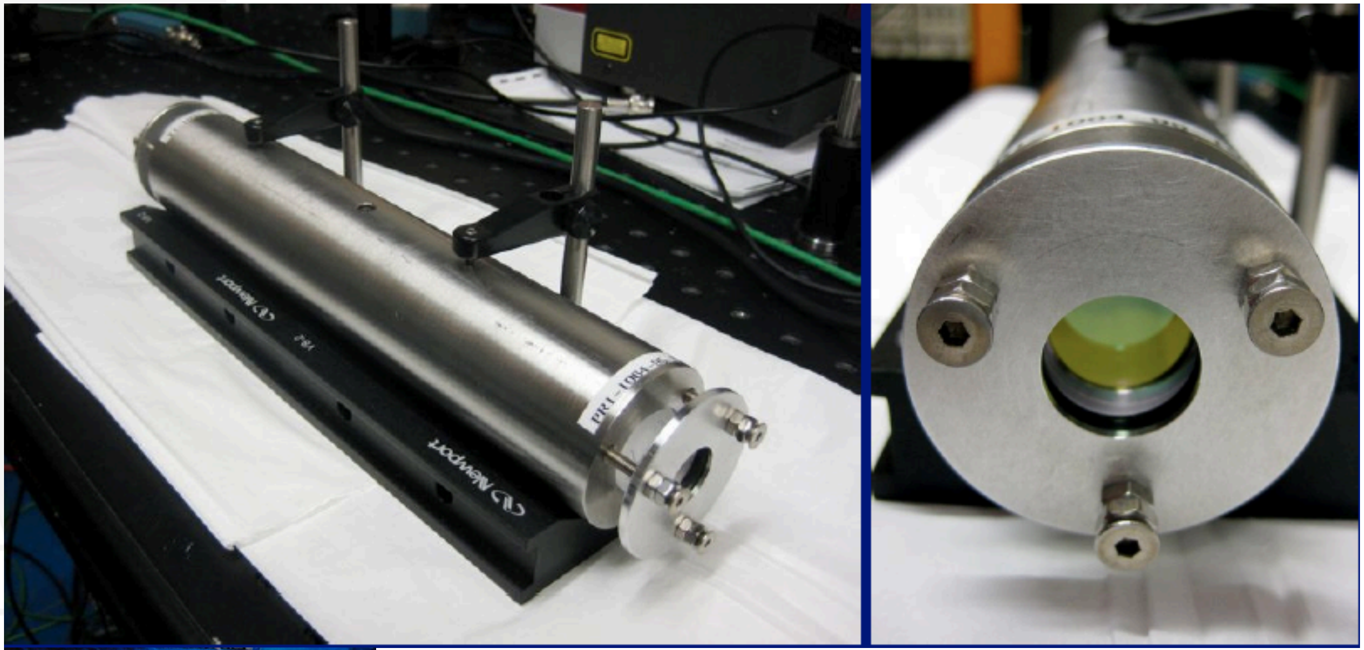
The holometer design is optimized to detect holographic *shear* noise, as opposed to devices optimized to detect the gravitational wave *strain* signal

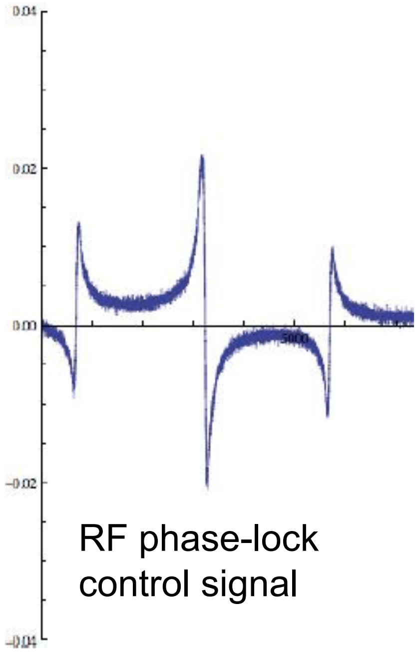


The holometer can be built for a tiny fraction of the cost of existing interferometers (which do not have the required sensitivity to see this new phenomenon).

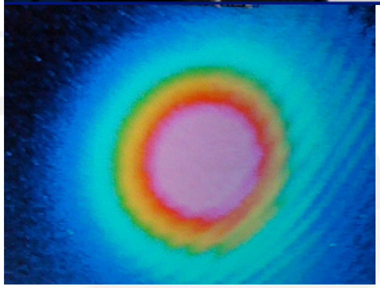
Current effort in optical cavity R&D

- Collaboration with university colleagues from LIGO on tabletop cavity and interferometer prototypes to demonstrate precision RF feedback control and optical measurement techniques





RF phase-lock control signal



Student project to develop stable frequency reference cavity.
Phase-lock between the laser and optical cavity is robust!
Fringe-locking of power-recycled interferometer also demonstrated.

Optical Cavity Test Bench (A. Chou, PI)
T-1007 in Fermilab Test Beam Program

- 40m long vacuum system in an unused meson beamline
- This has become the largest safety-interlocked laser lab at FNAL
- General-purpose facility for long baseline optical beams

Test custom optics.

Testbed for devices developed by university colleagues (PZT actuated mirror mounts, data acquisition electronics, etc.)

Develop control systems for full-scale cavities and interferometers needed for future experiments.

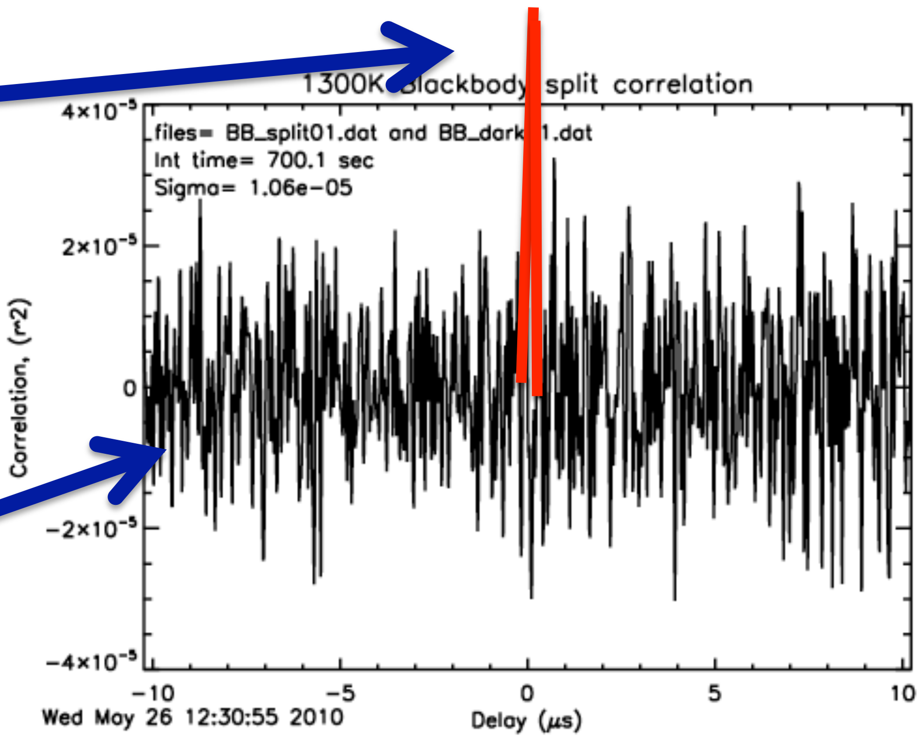
MIT physicist S.Waldman, conducting cavity tests in new FNAL laser lab

Collaborative effort for electronics development

- Funded by U.Chicago Strategic Collaborative Initiative grant awarded to S. Meyer (U.Chicago), A. Chou, and C. Stoughton (FNAL)
  - 90 MHz digital data acquisition system
  - Digital feedback control to piezo actuators on the laser and mirror mounts
  - **To be tested at FNAL 40m cavity facility**

Expected **holographic cross-correlation signal** between two photodiodes plotted vs delay time between the two data streams.

Actual cross-correlation data taken with the digital DAQ.



Why Fermilab?

Natural cost advantages by leveraging equipment and capabilities of a national lab.
Available beamlines, magnets, cryogenics, clean vacuum assembly areas, technical expertise in all of these

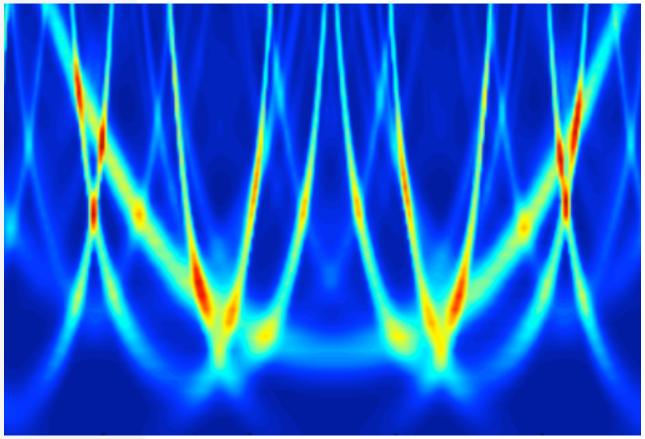
Local scientific expertise and desire to perform these experiments.
Demonstrated record of success.

Near-term plans for optical cavity experiments

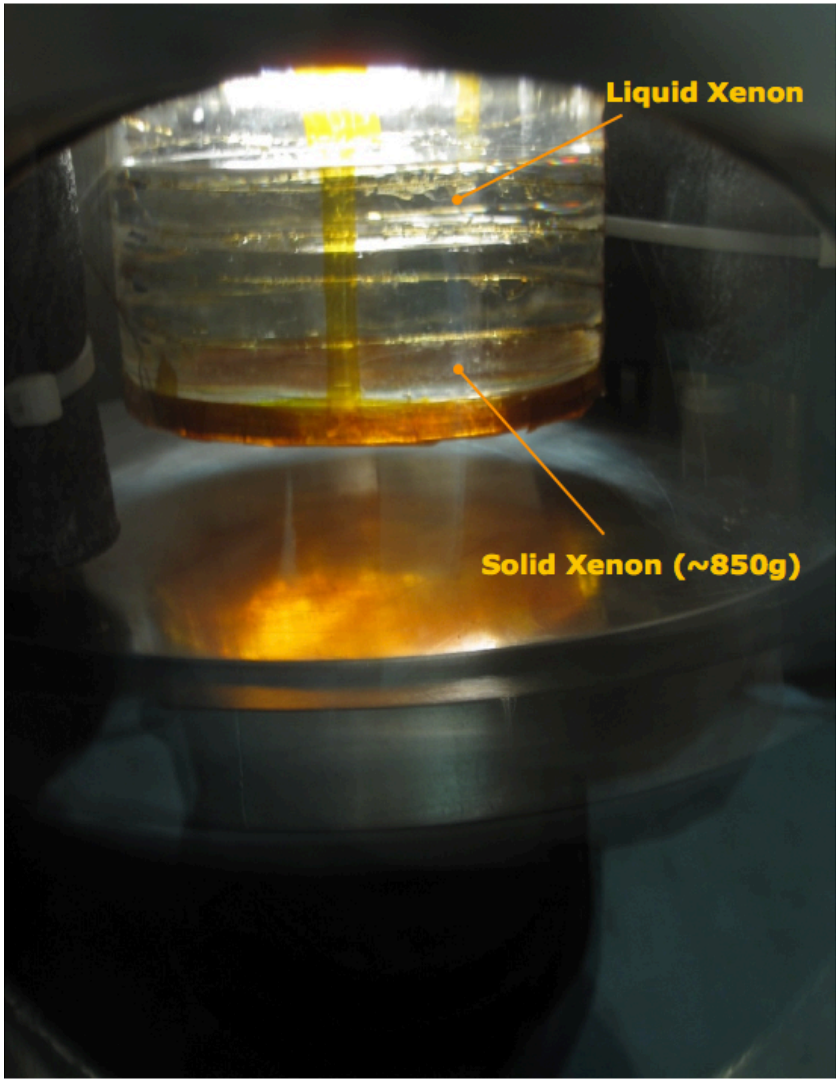
- 2010: Continued KA13-supported scientific effort on optical cavity R&D
- 2011: Seek KA13 (sub-MIE level) funding for construction of the Holometer + continued scientific support
- 2011-2012: Build and operate the Holometer, discover Planck-scale microphysics

- Possible schedule for the axion search
  - 2012-: Pending successful R&D program and reviews, begin commissioning of REAPR axion search using spare Tevatron magnets and equipment from the Holometer.
  - Current R&D effort at universities is coordinated with 40m cavity development at FNAL:
    - cavity assembly/alignment jig and prototype experiment at UFlorida,
    - shot-noise-limited single photon detection at UMichigan.

Topic 2: Solid Xenon Detector R&D (J.Yoo, Wilson Fellow)



PRL cover image:
CDMS solar axion search (Germanium)



Solid Xenon

- High mass, low backgrounds.
- Bragg scattering → improved solar axion search
- More scintillation light (solid > liquid)
  → low threshold WIMP detection

R&D Phase I & II

- Detector concept invented at Fermilab
  - KA15 generic detector R&D
- Demonstrated optically transparent solid xenon
- Scintillation light & ionization readout in progress
- **Utilize FNAL infrastructure from liquid Argon TPC facilities.**

Topic 3: QUIET-II

The Search for B-Mode Polarization in the Cosmic Microwave Background Using Coherent HEMT Detectors

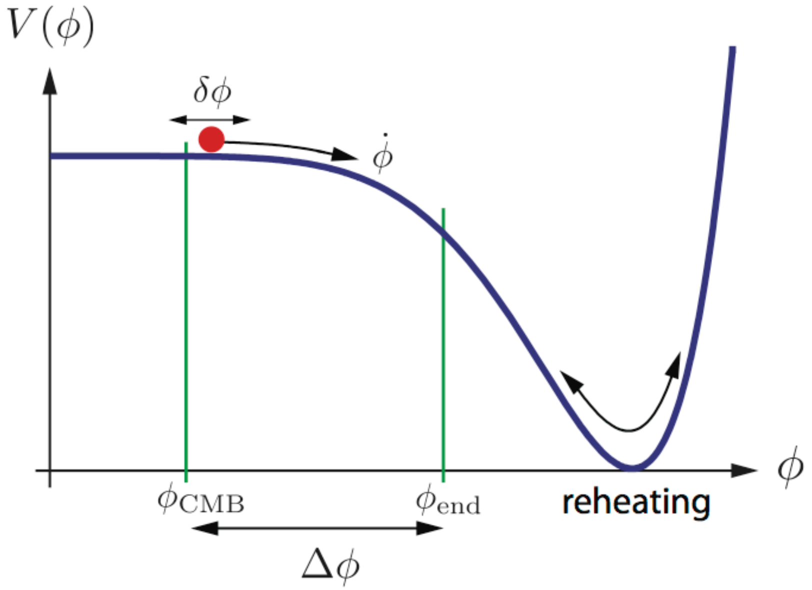
QUIET-I apparatus at
Chajnantor Plateau
(5612 m ASL), Chile

**Caltech, Chicago, Columbia,
Fermilab, KEK, JPL,
Manchester, Miami, Michigan,
MPI, Oslo, Oxford, Princeton,
SLAC, Stanford**

2 Fermilab Scientists:
DeJongh, Nguyen

Probing the Inflationary Potential at the 10^{16} GeV scale

Tensor fluctuations of the metric (ie. gravity waves) in the inflationary era are ***encoded*** in the polarization of the CMB. A ***curl*** (or B-mode) polarization pattern is generated.



B-mode power spectrum tells the energy scale of inflation

$$V^{1/4} = 3.3\times 10^{16}\times r^{1/4}\ \mathrm{GeV}$$

μK resolution gives sensitivity to the 10^{16} GeV scale

The QUIET Experiment

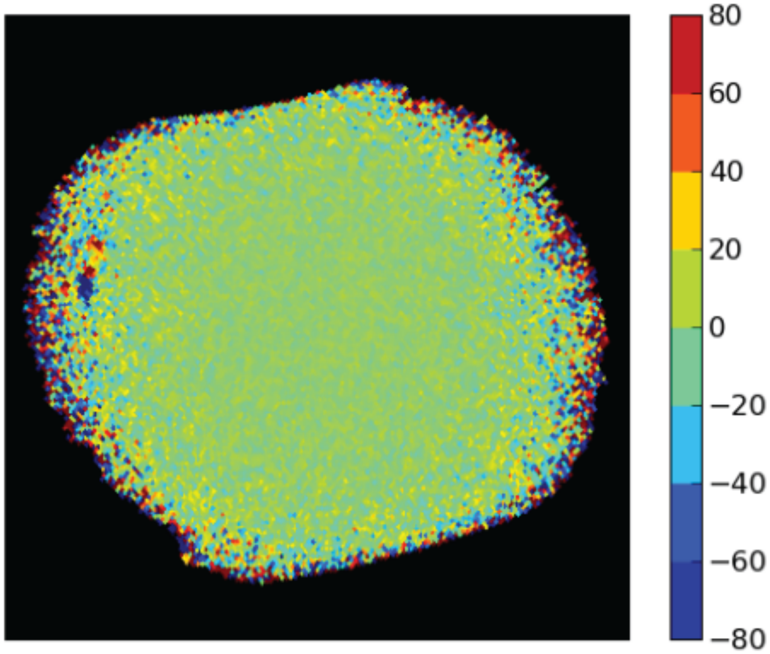
QUIET-I is currently collecting 91 GHz data till Dec 2010.

Publication of 40 GHz data is imminent.

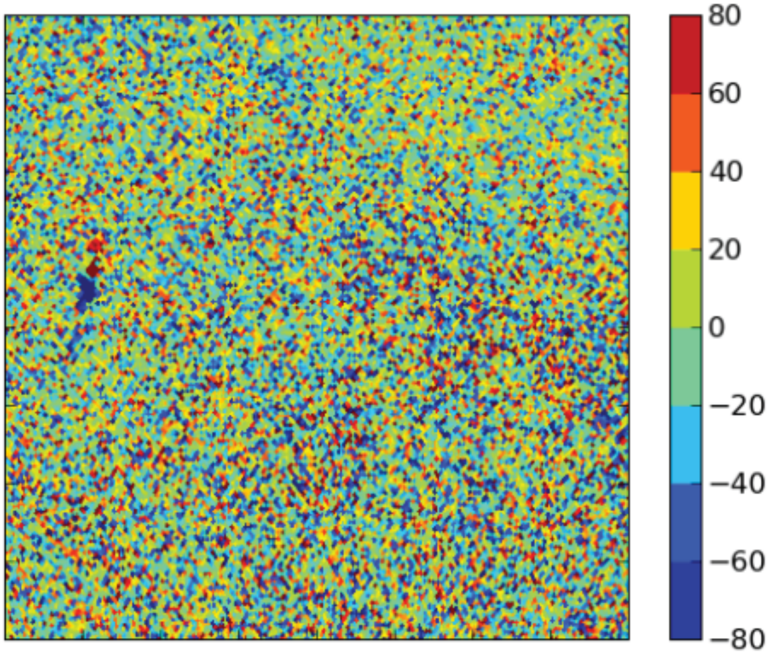
~15x more detectors proposed for QUIET-II

QUIET-II Awaiting Approval from NSF

QUIET 40 GHz polarization map (600 hours)



WMAP 5 years

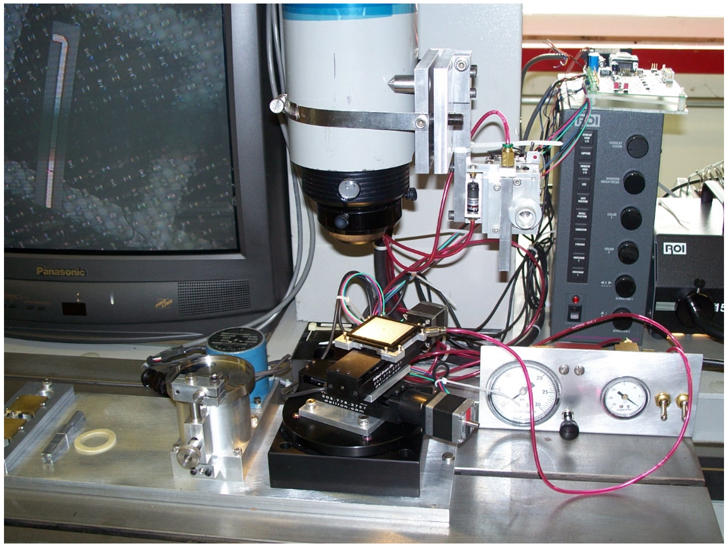


Fermilab's Proposed Role in QUIET Phase II

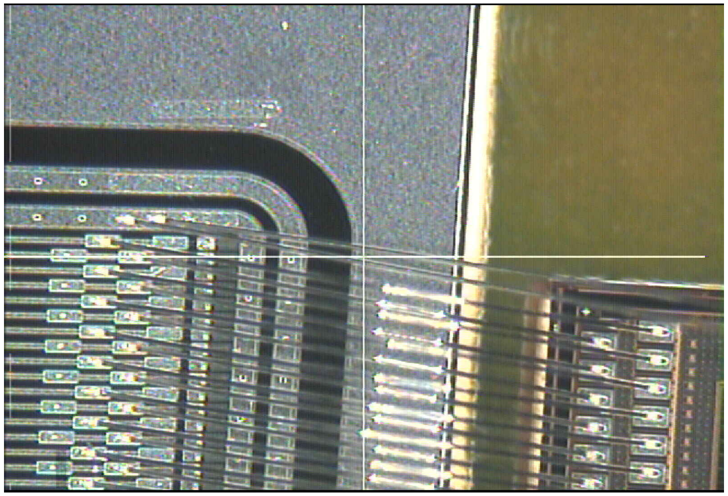
Mass production, assembly and testing of ~1500 modules at FNAL silicon detector facility.
Utilizes existing facilities and capabilities of FNAL.
Solves a critical need of the QUIET experiment.

Calibration hardware.
Commissioning of a cryostat.
Vacuum Window Engineering needed for large diameter cryostat.

Automated Die Bonding



Automated wirebonding



Current Activities

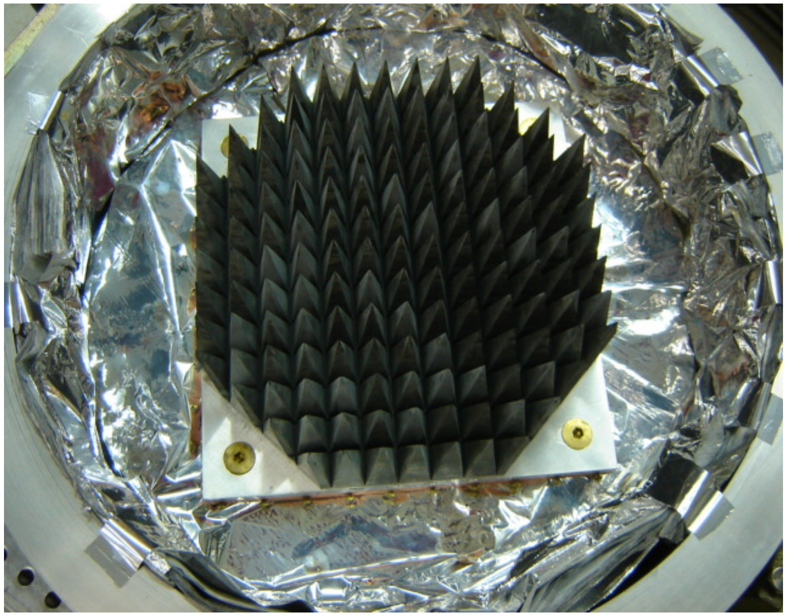
Collaboration to improve modules (noise temperature, crosstalk, etc.), with potential to reduce total project cost.

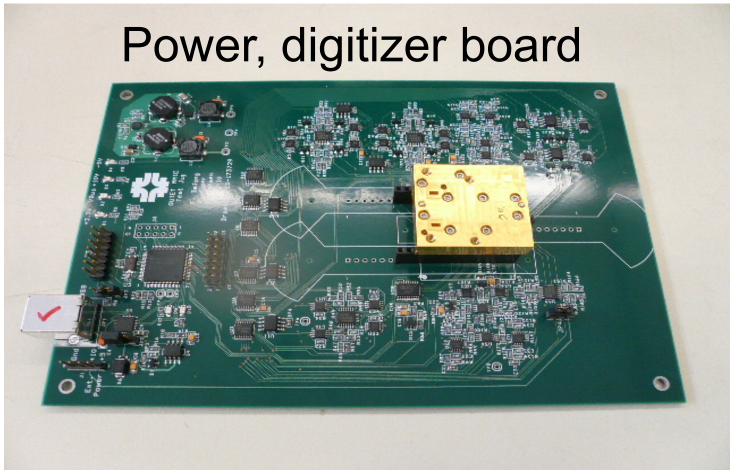
KISS/Caltech (Lead), Chicago, Fermilab,
JPL, KEK,
Manchester, SLAC,
and Stanford.

<u>Fermilab Contributions</u>

Support Electronics
Calibration Tools
Precision Machining
Final Testing

20 Kelvin Black Body Load for Module Testing




Power, digitizer board

Summary

- The Fermilab Center for Particle Astrophysics is planning future experiments in close collaboration with the external scientific community.

- Three experiments currently under development will probe the highest energy scales up to 10^{19} GeV.

  - **Planck-suppressed quantum phenomena** can be accessed via
    - Long diffraction baseline + lots of photons (Holometer)
    - High primordial energy density + low noise photon detection (QUIET)
  - **Ultraweak bosonic scattering cross-sections** can be detected using
    - Coherent excitation of high-Q resonances + lots of photons (REAPR).
    - Coherent Bragg scattering on crystals (solid xenon R&D)

- Keep costs low by utilizing existing infrastructure, expertise at FNAL.

- Request continued KA13 support for FNAL scientist effort in developing these new projects, which may be submitted for future KA13 Field Work Proposals when ready.