An Atom Interferometric Sensor at Fermilab:
Searching for Ultralight Dark Matter Particles and Probing the Very Early Universe via Primordial Gravitational Waves

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Fermilab and Stanford

Collaborative proposal between Stanford and Fermilab for a 100-meter Atom Interferometer Test-bed on site.

Will be part of the "White Paper" submission for the recent DOE workshop on "Cosmic Visions", March 24-26, 2017 at University of Maryland – "MAGIS-100"

(Fermilab's Aaron Chou and Stanford's Peter Grahame were the Co- Chairs for this session on laboratory-scale experiments)

WHY Fermilab?

Precision Neutrino science in deep underground facilities a Core Competency of Fermilab.

An vertical underground shaft a few kilometers long already exists at the Sanford Lab housing the DUNE experiment.

A 100 meter tall NuMI shaft already exists in the MINOS facility which can be carefully examined for an intermediate experiment.

Hence “dark” sector and gravitational wave background search using Atomic Beam Interferometers at Fermilab.

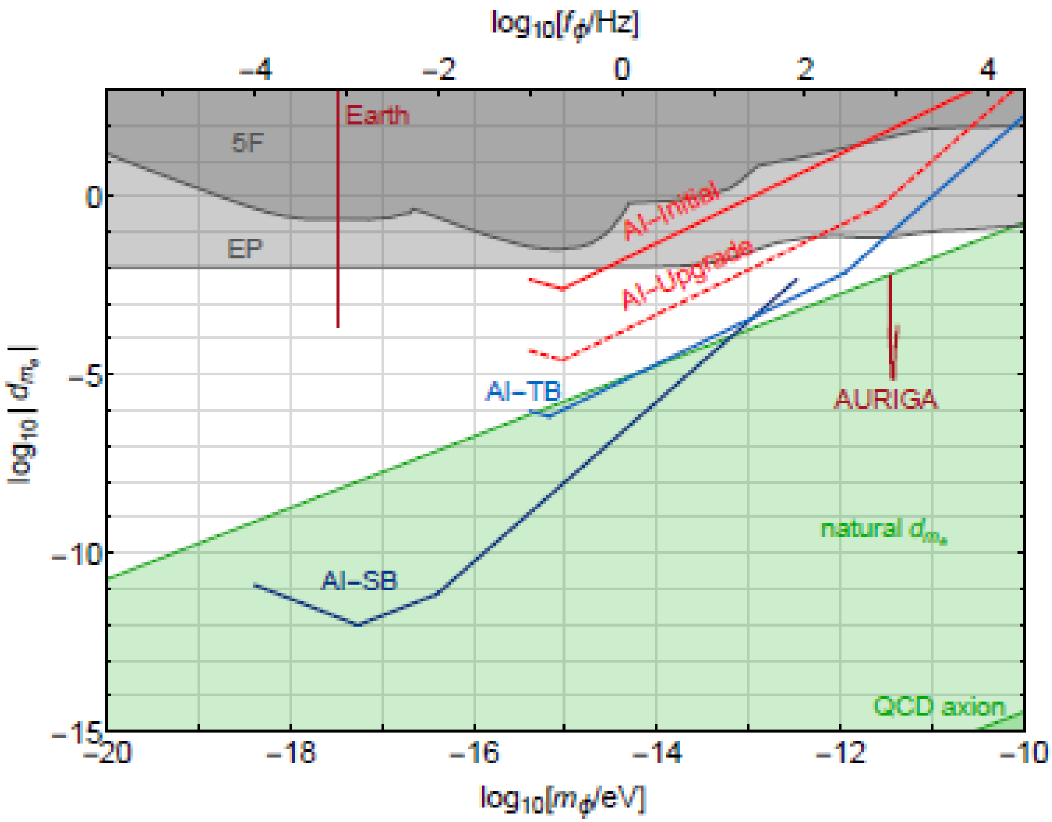
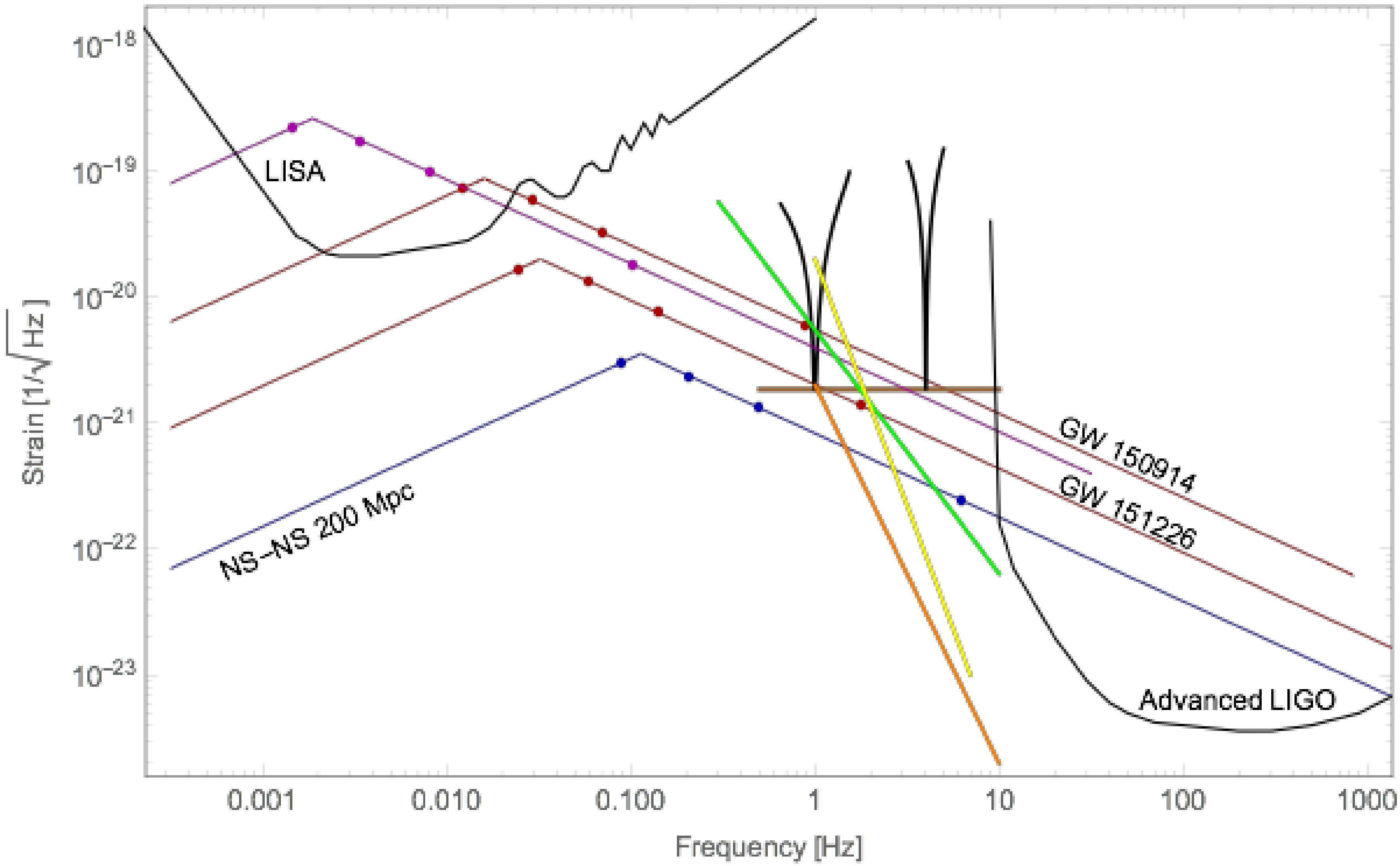
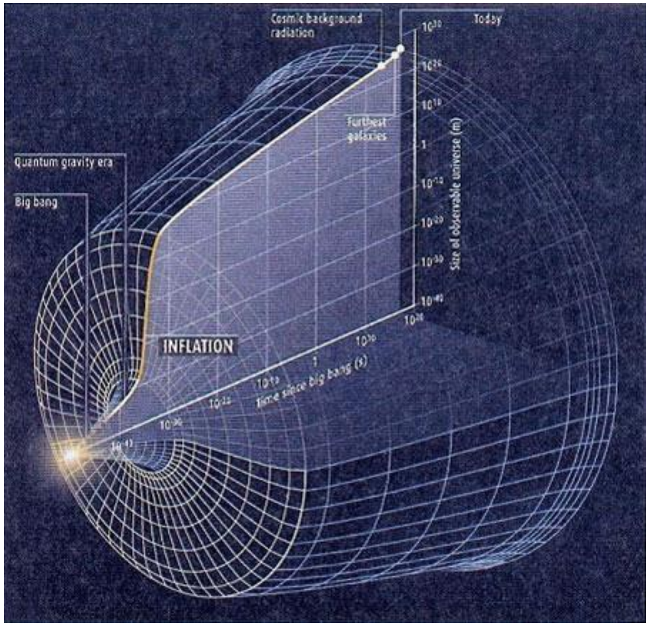


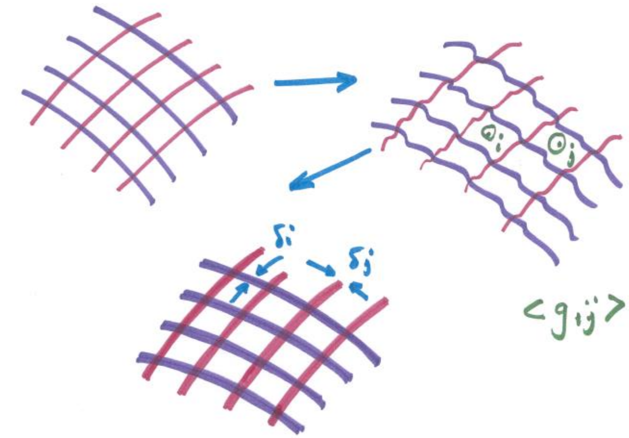
Figure 1: MAGIS-100 sensitivity to ultralight dark matter.

Projected Terrestrial GW Sensitivity MAGIS-100 Sweet spot (0.1 Hz- 10 Hz)



Stochastic Gravitational Radiation





- Uniformity and isotropy of space embodied in the “cosmological principle” often explained by the conjecture of “ cosmic inflation”
- At the end of the so-called inflationary period, the universe must have experienced a gravitational crunch, whose “tremors” must exist today as “stochastic” background gravitational waves;
- Can we design sensors to “feel” these gravitational tremors ?

MAGIS-100: Atom Interferometry for Ultra-light Dark Matter and Gravitational Waves from Early Universe

- **The MAGIS-100 proposal is an atom interferometric sensor that aims to search for ultralight dark matter and gravitational waves.**

- **Ultralight dark matter candidates with mass in the range 10 E -13 eV to 10 E -16 eV can cause time-varying atomic energy levels in the 0.1 Hz to 10 Hz frequency range that can be searched for with the proposed sensor.**

- **The MAGIS (Mid-band Atomic Gravitational wave Interferometric Sensor) detector is also sensitive to gravitational waves in this frequency range, which corresponds to frequencies between where LIGO and LISA operate. By operating in this mid-band, MAGIS can access an important frequency band in the gravitational wave spectrum that is otherwise not covered by existing and future detectors, and would thus be complementary to the LISA and LIGO detectors. The discovery potential in this frequency band appears exciting, ranging from observation of new astrophysical sources (e.g. black hole and neutron star binaries) to searches for cosmological sources of stochastic gravitational radiation in addition to the searches for dark matter.**

- **The source will look at primordial gravitational waves can discriminate between different models of early universe e.g. Inflationary' vs. 'oscillating' and various other models and can also point to the origin of very light particles as sources of 'dark' matter.**

- **The detector is based on a new kind of atomic sensor that is a hybrid between an atomic clock and an atom interferometer. Gravitational radiation is sensed through precise measurement of the light fight time between two distantly separated (atomic) inertial references. Time is recorded by the accumulation of phase by these atoms, which also serve as precise differential clocks.**

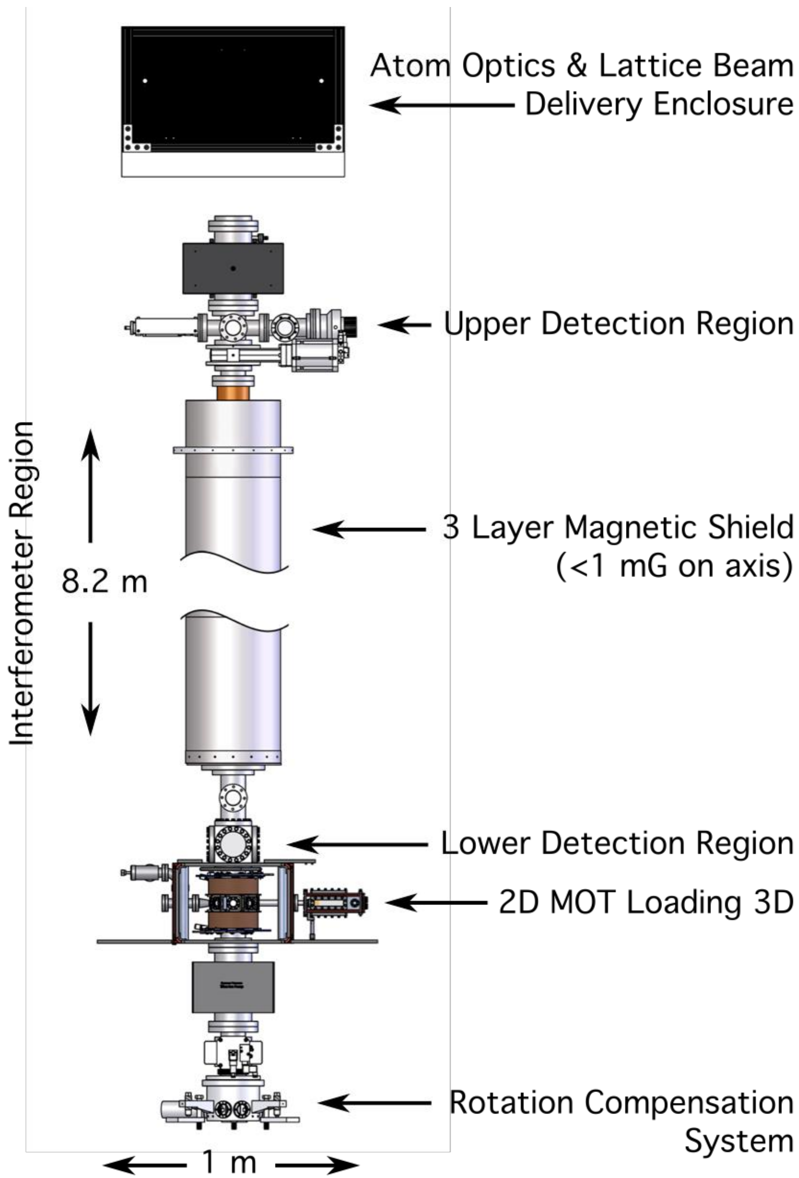
- **This same configuration is also sensitive to time-variations in the atomic energy levels caused by couplings to ultralight dark matter, since such energy level shifts change the phase accumulation by the separated atomic clocks .**

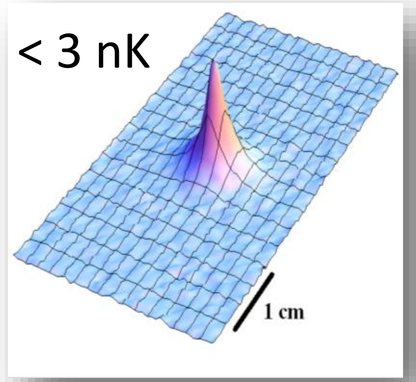
- **Current work is focused on building a small-scale (10-meter) prototype detector to demonstrate required detector performance characteristics, including laser noise suppression. Longer detector baselines are required to reach scientifically interesting strain sensitivity and dark matter couplings.**

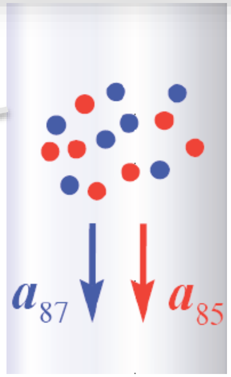
- **The MAGIS-100 proposal is a 100-meter long detector proposed to be located at Fermilab at the NuMI neutrino beam facility. The detector is to be build in an existing 100-meter vertical access shaft, with one atomic source at the top of the shaft and one midway down, allowing for over 3 seconds of free-fall time (this allows access to frequencies < 1 Hz). The initial detector will use state-of-the-art atom interferometry including 100 hk enhanced atom optics and an atom flux of 10 E 6 atoms/s. Planned upgrades include larger atom optics (1000 hk) and a larger atom flux of 10 E 8 atoms/s.**

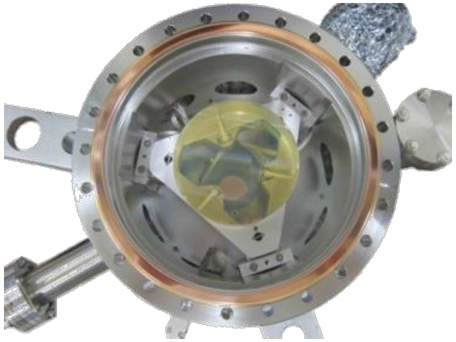
- **The detector cost estimate is $3 million, which includes hardware for the 100-meter detector as well as personnel for 3 years (not including possible retrofitting costs at the Fermilab site).**

10 meter scale atomic fountain at Stanford









Dark Energy and Gravitational Wave Detection with Accelerometers

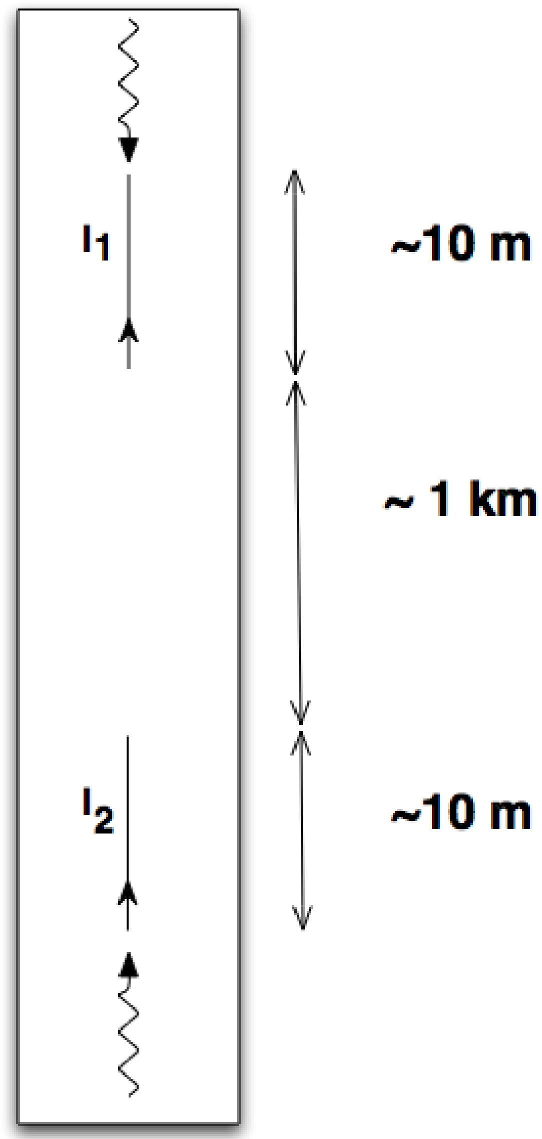
Gravitational waves @ 1 Hz could open the window for direct tests of cosmic inflation, frequency range inaccessible to LIGO/LISA. Atomic interferometers can also be sensitive detectors of "dark" energy.

EXAMPLE:

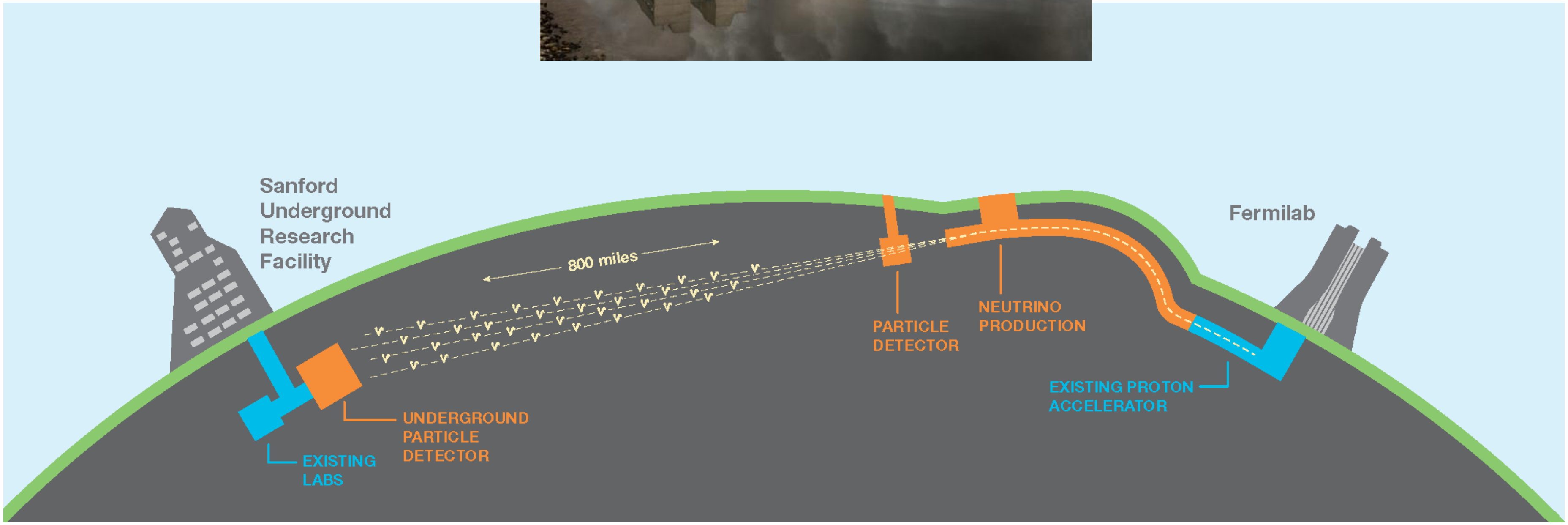
Two 10 m atom interferometers at either ends of a mine shaft. Both interferometers will be operated by common lasers. Signal scales with length ~ 1 km between interferometers.

Allows free fall time ~ 1s. Maximally sensitive in the 1 Hz band.

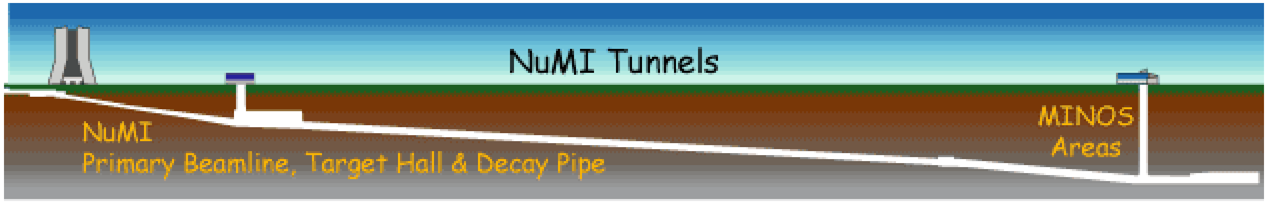
→ **POSSIBILITIES in the Sanford Lab where DUNE long-baseline neutrino experiment will be carried out by a global team using high powered beams from Fermilab sent to underground detectors with a vertical shaft of a few kilometers.**

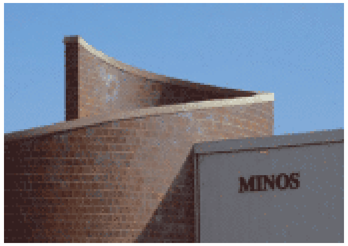


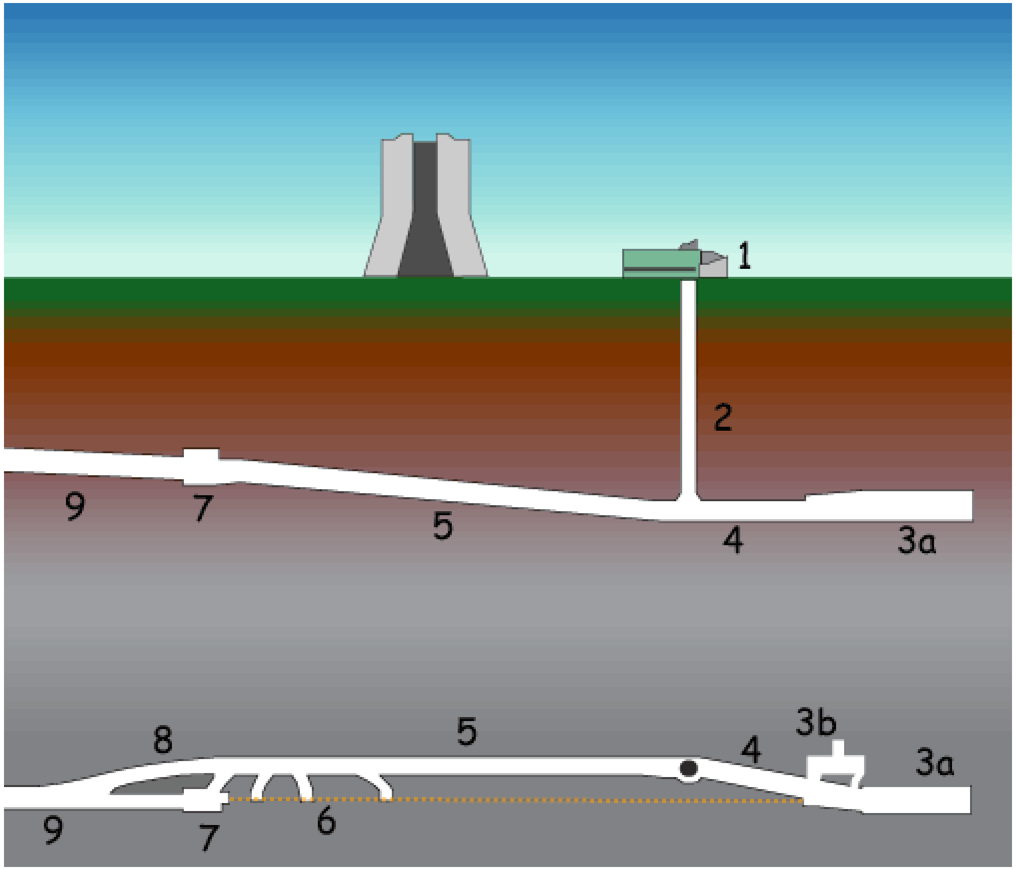
LBNF-DUNE @ Fermilab
houses 4 km vertical shaft



105 meter tall NuMI shaft in the MINOS







CHALLENGES:

Requirements/Backgrounds -- Systematic accounting of various noise sources

Vibrations in the Shaft: *Initial velocity of atoms, Newtonian Noise*

Magnetic Fields: *Gradients, Variations in time*

Environmental Newtonian Noise: *Fluid flow in pipes, gravity coupling*

Coriolis Effect: *Deflection, forces, phase-shifts*

Interactions with Neutrino Beam? *(Muons in NuMI still in beam, beam has large divergence)*

Vacuum Requirement

Laser Wave-front "jitter" noise *(equivalent to seismic noise in LIGO)*

Intrinsic Atomic Clock Stability 10^{-18} (currently) but projected to extend to 10^{-22} with 10^{8} free Sr atoms at 50 pK (as opposed to much fewer atoms bound in an optical lattice, thus raising 'shot' noise)

The team exploring/evaluating the potential for a 'reality' check

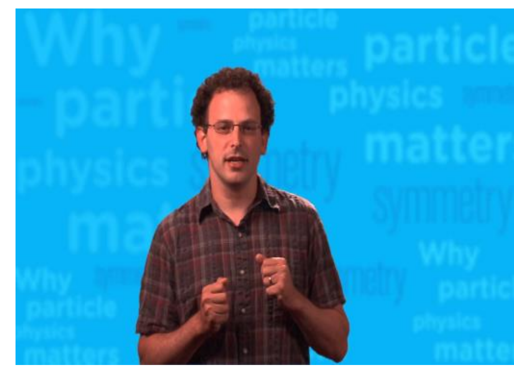
Mark Kasevich, Peter Graham and Jason Hogan, Stanford

Surjeet Rajendran, Berkeley

Jeremiah Mitchell, PhD student, NIU

Swapan Chattopadhyay, Fermilab/NIU

Joe Lykken Fermilab



Roni Harnik Fermilab