New Initiatives in Fermilab Particle Astrophysics

(a.k.a. non-accelerator physics)

Aaron S. Chou
Wilson Fellow, FNAL

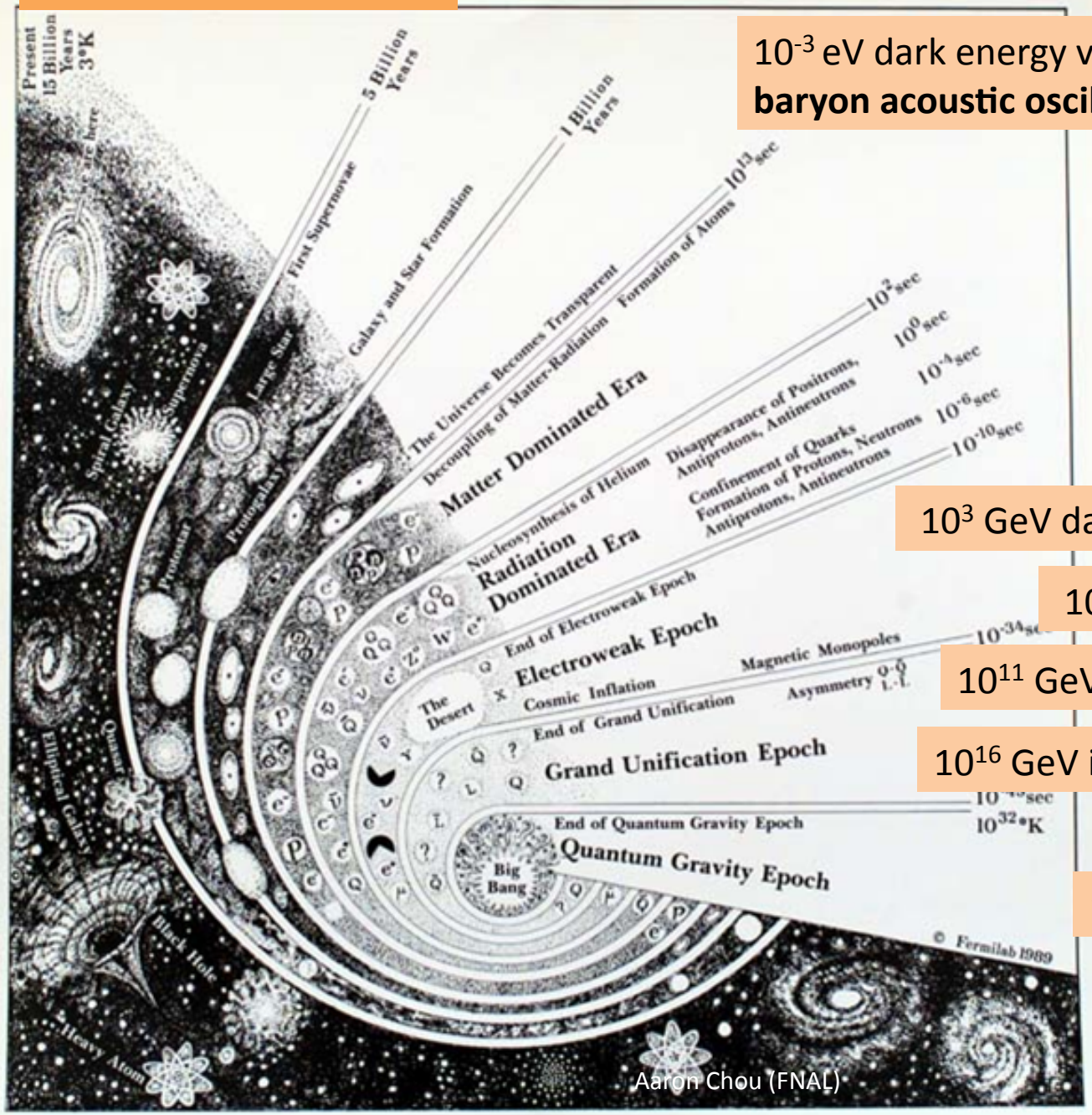
2010 Fermilab Users Meeting

Fermilab

Energy scales of interest

- Hubble: $H_0 = 10^{-33}$ eV
- Dark Energy: $M_{DE} = (\rho_{DE})^{1/4} = 10^{-3}$ eV = sqrt($H_0 \times M_{pl}$) new inflaton?
- Electroweak: $M_{EW} = 10^{3}$ GeV ≈ sqrt($M_{DE} \times M_{pl}$), WIMPs?
- Peccei-Quinn: $f_{PQ} = 10^{9}$-10^{13} GeV Axion DM? TeV transparency?
- Gravity-mediated SUSY: $M_{gSUSY} = 10^{11}$ GeV = sqrt($M_{EW} \times M_{pl}$)
- Grand Unification: $M_{GUT} = 10^{15}$ GeV ≈ sqrt($H_I \times M_{pl}$) Inflation scale?
- Gravity: $M_{pl} = 10^{19}$ GeV

Topics for this talk



10^{-3} eV dark energy via SDSS, DES, laser search, **baryon acoustic oscillations**, etc.

10^{3} GeV dark matter direct detection

10^{5} GeV **cosmic ray showers**

10^{11} GeV **axion-photon oscillations**

10^{16} GeV inflation via **CMB B-modes**

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

Probing the 10^{-3} eV dark energy scale
via baryon acoustic oscillations

The Cylinder Radio Telescope Consortium

- Jeff Peterson (CMU)
- Kevin Bandura,
- Bruce Taylor
- Jim McGee
- Blake Conaugher
- Florence Liu
- Deena Kim
- Bruce McWilliams

- Uros Seljak (U. C Berkeley)

- Peter Timbie (U. Wisc.)

- Scott Dodelson (FNAL)
- John Marriner
- Chris Stoughton
- Hee Jong Seo
- Dave McGinnis

- Tzu-Ching Chang (IAA Taipei)

- Kris Sigurdson (UBC)
- Ben Wang

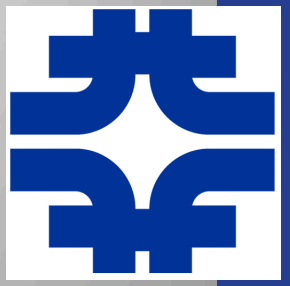
- Ue-LI Pen (CITA)
- Gojko Vujanovic

- Hassane Darhmouai (AUI)
- Ahmed Legrouri
- Hassan Bourhous
- Rachid Benmouktar

- Christope Yeche (CEA)
- Christohpe Magneville
- Jim Rich
- 2 FTE engineer

- Reza Ansari (LAL)
- Marc Moniez
- 2 FTE engineer

- Jon Bunton (CSIRO)



Carnegie Mellon

ICTP

the David & Lucile Packard FOUNDATION

جامعة الأخوين
AL AKHAWAYN UNIVERSITY

IN2P3

cea

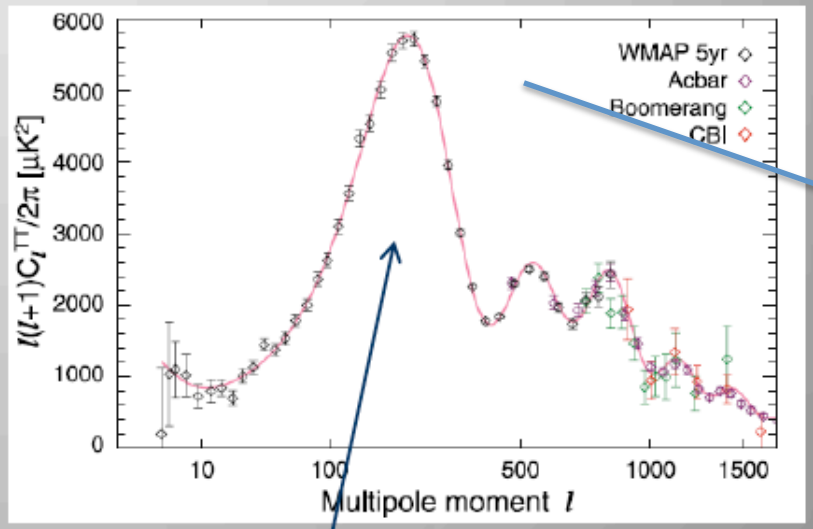
CITA ICAT

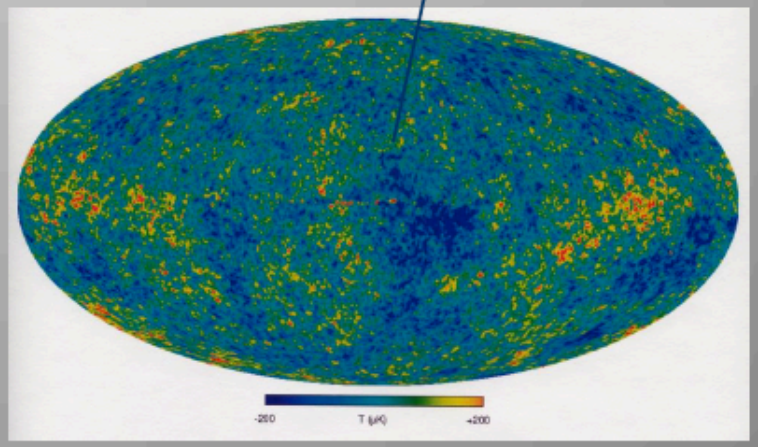
CSIRO

Baryon Acoustic Oscillations

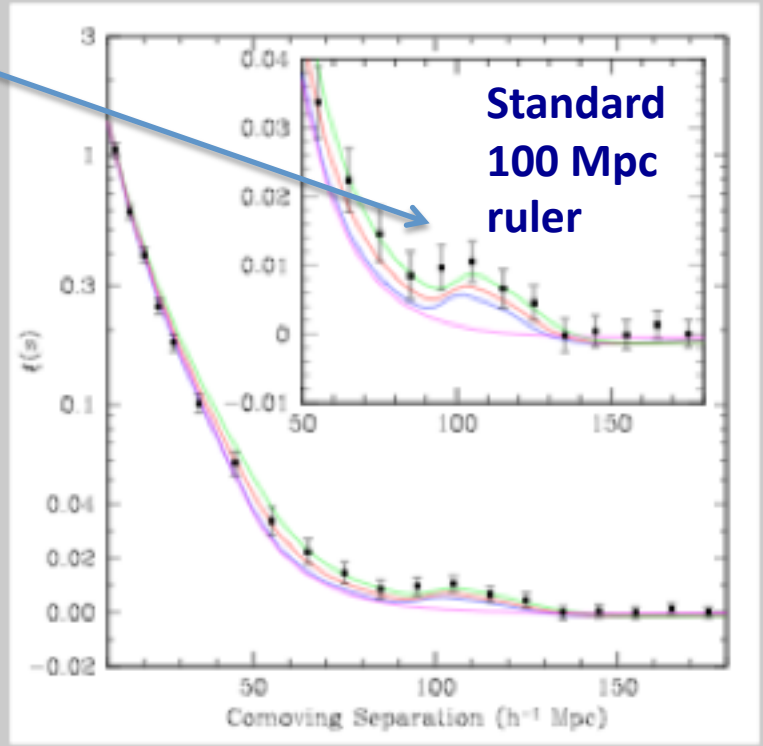
- The 1st CMB acoustic peak is imprinted on the dark matter distribution and visible in the distribution of baryons which fall into the resulting potential wells.

WMAP5 and other, Nolta et al (2008)





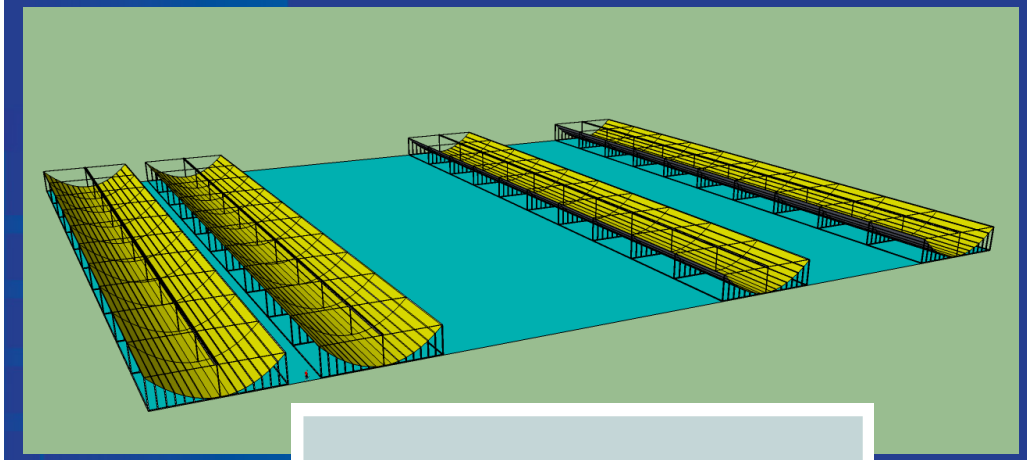
47k LRGs (SDSS)

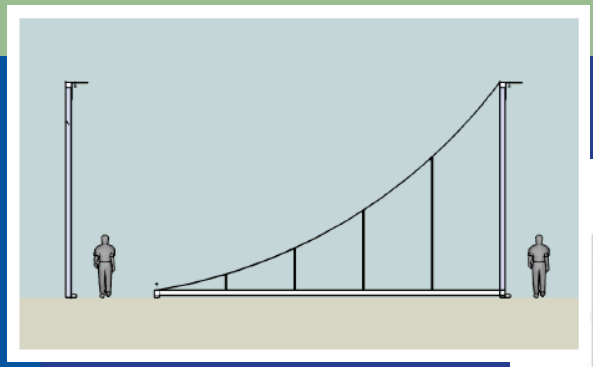


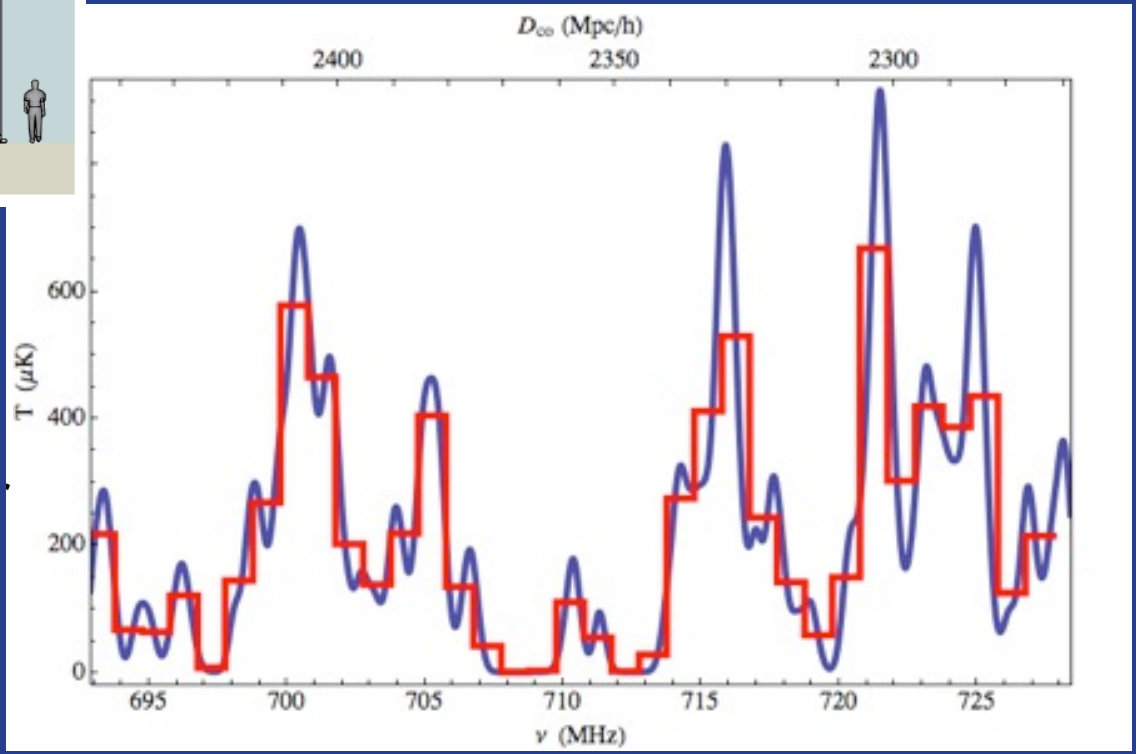
Eisenstein et al 2005

ou (FN

Dark energy by Fourier transforming the sky



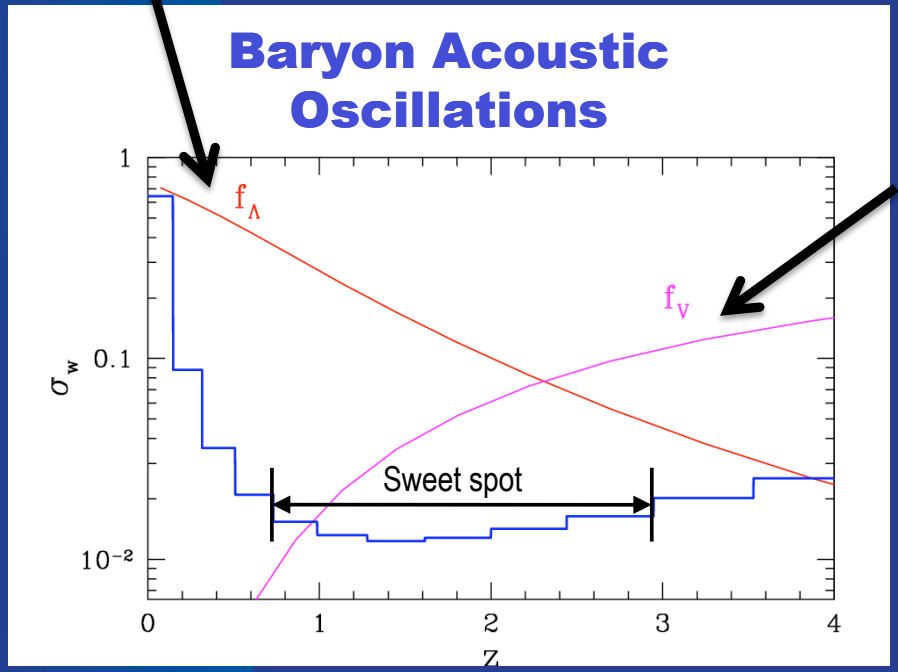




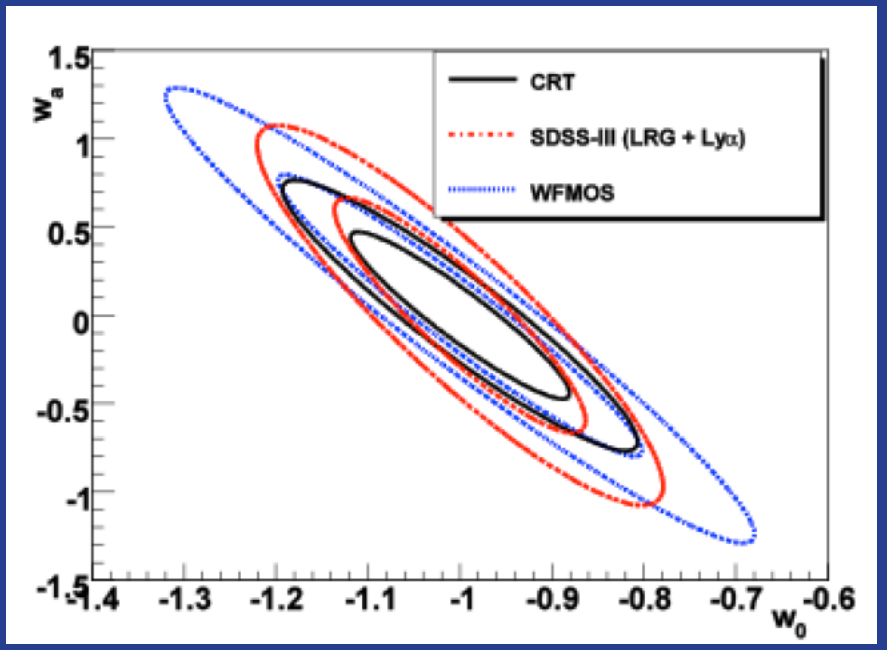
- BAO give a standard ruler of 100Mpc length.
- Detect BAO via (redshifted) 21 cm emission of neutral Hydrogen.
- Measure angular scale vs redshift to map out of the expansion history of the universe.
  - CMB = snapshot
  - BAO = movie

Sensitivity to vacuum energy

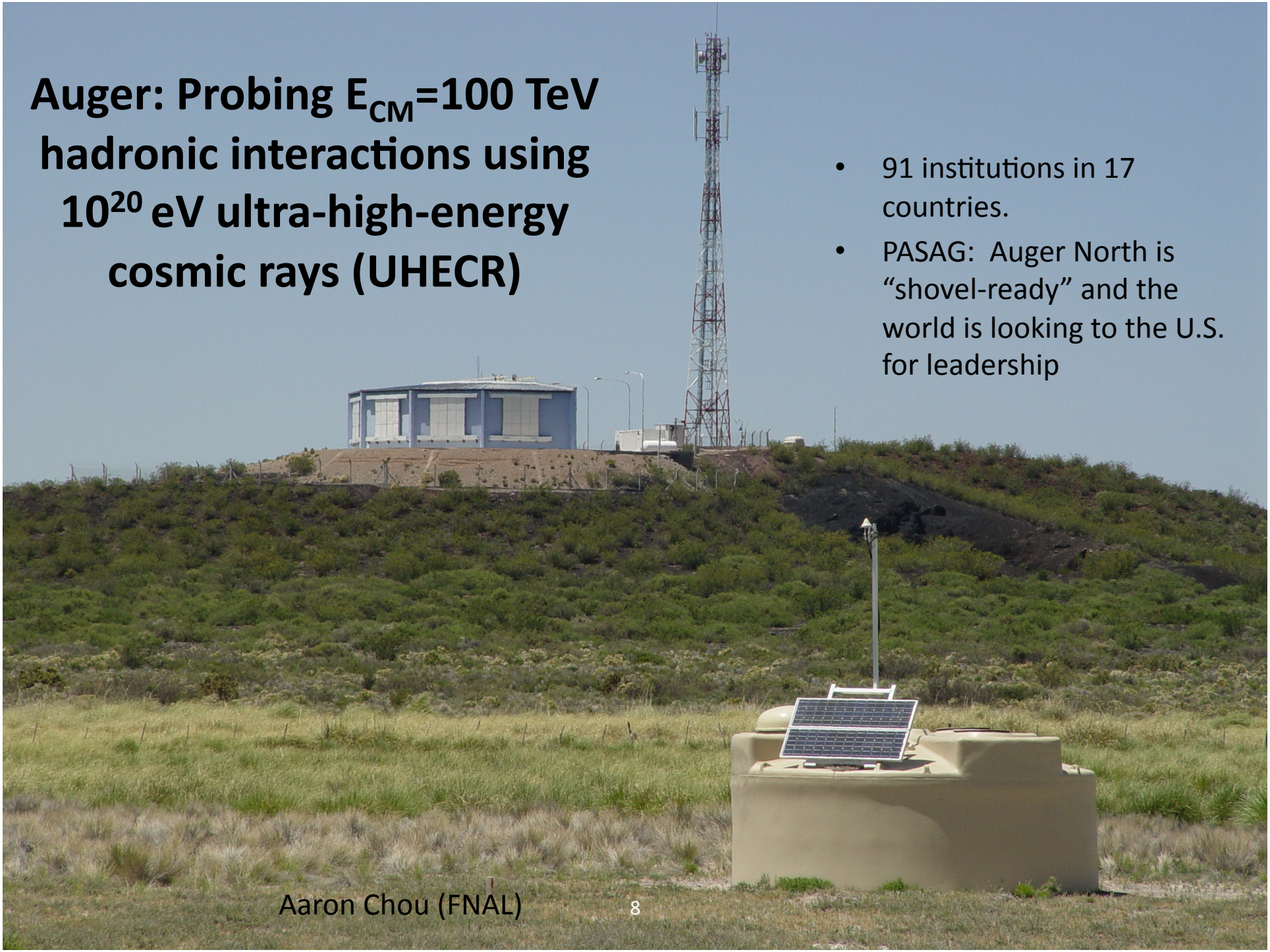
Large Ω_{vacuum}



High statistics

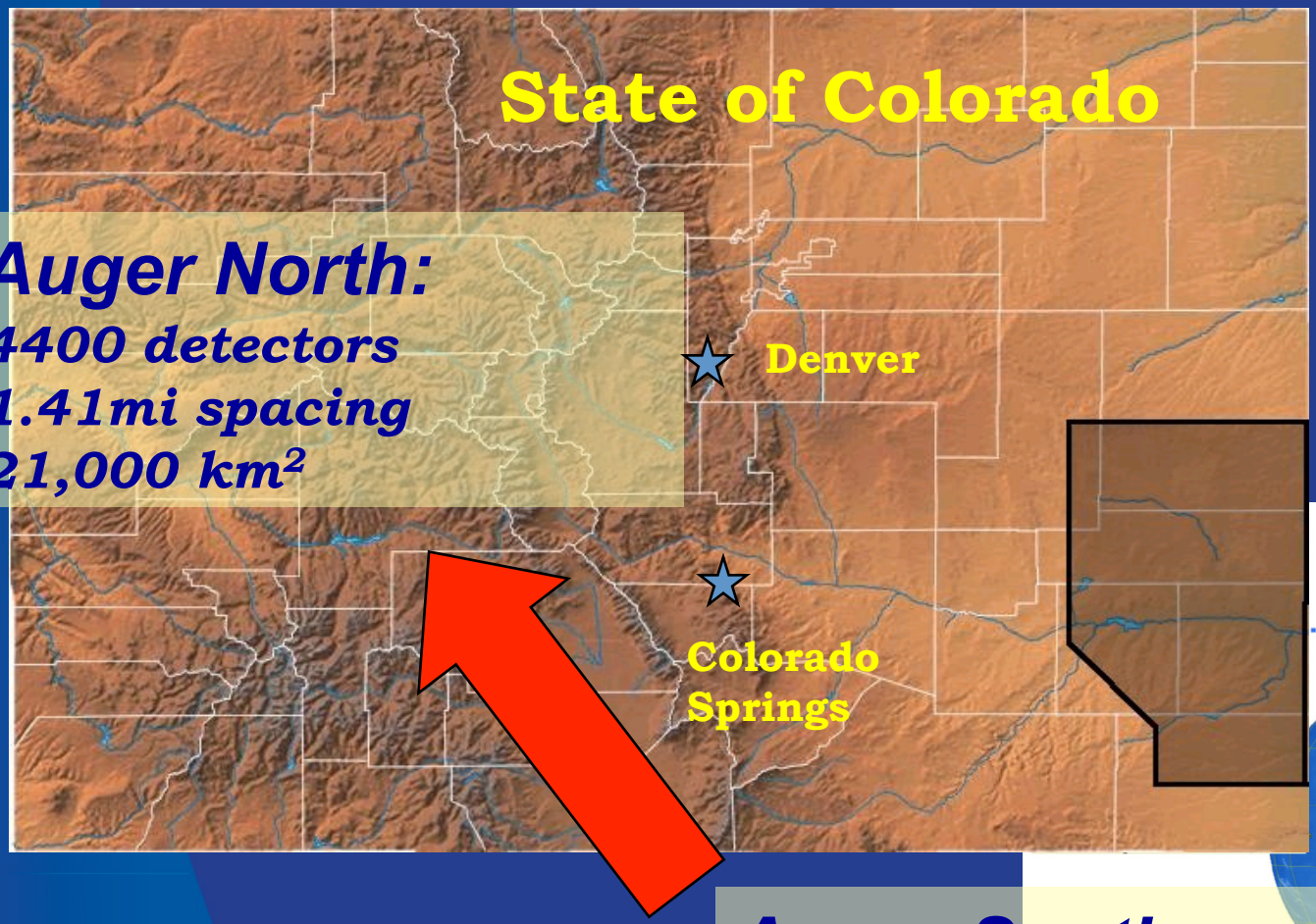


Auger: Probing E_{CM}=100 TeV hadronic interactions using 10^{20} eV ultra-high-energy cosmic rays (UHECR)



- 91 institutions in 17 countries.
- PASAG: Auger North is "shovel-ready" and the world is looking to the U.S. for leadership

Auger North will provide 7x the data rate and Northern hemisphere coverage for a variety of UHECR studies

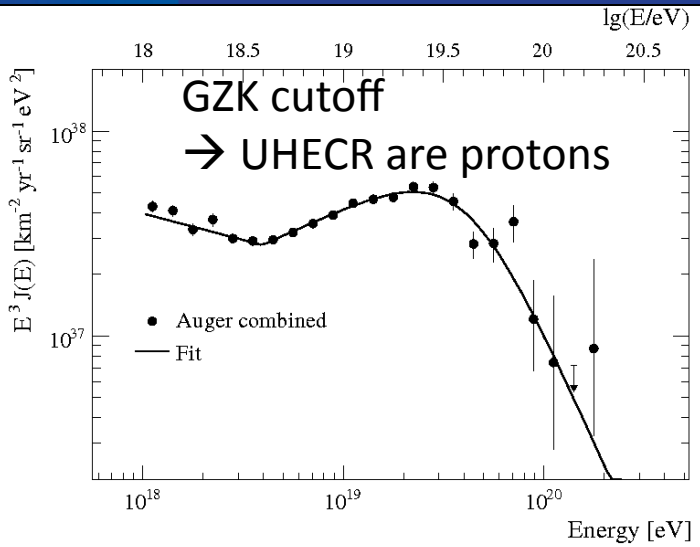


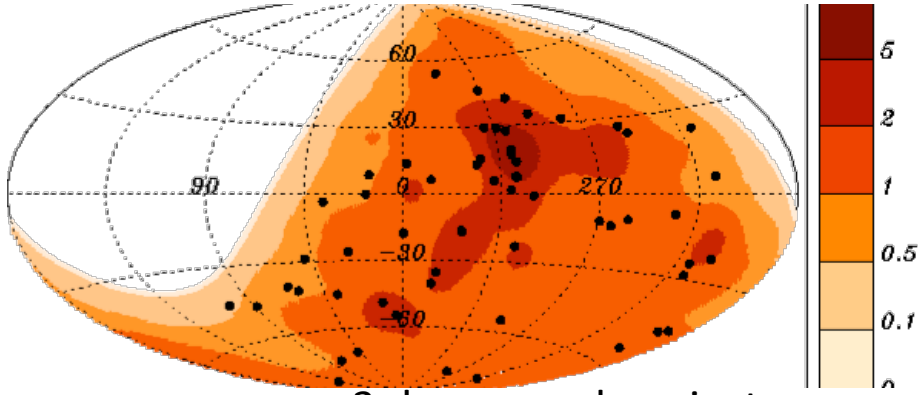
Auger North:
4400 detectors
1.41mi spacing
21,000 km²

Auger South:
1600 detectors
1.5 km Spacing
3000 km²

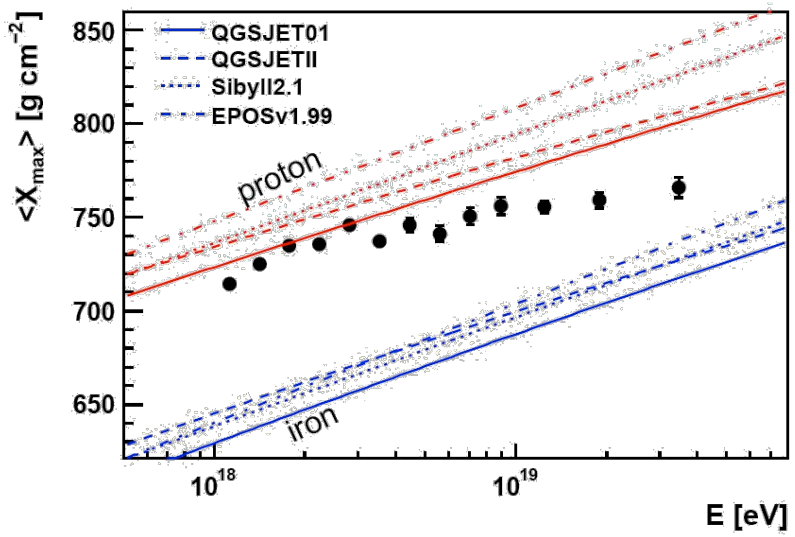
to scale

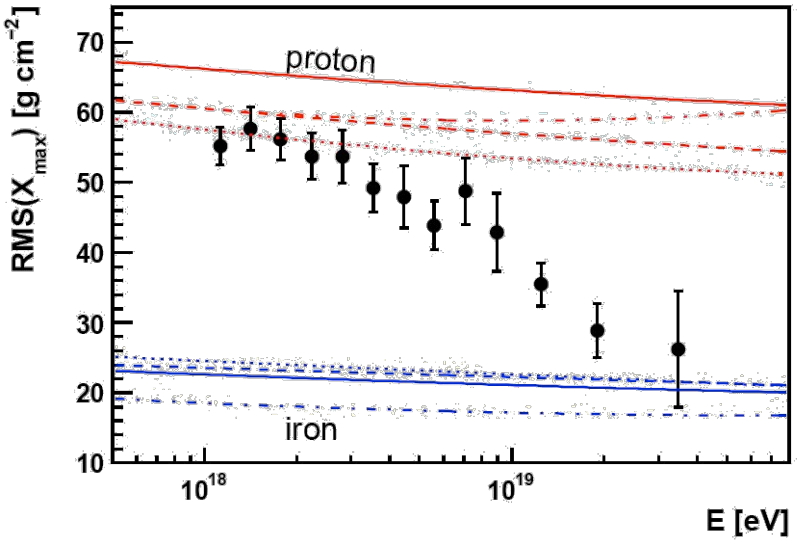
A New Puzzle in Ultra-High-Energy Cosmic Rays





3 degree scale anisotropy
→ UHECR are protons

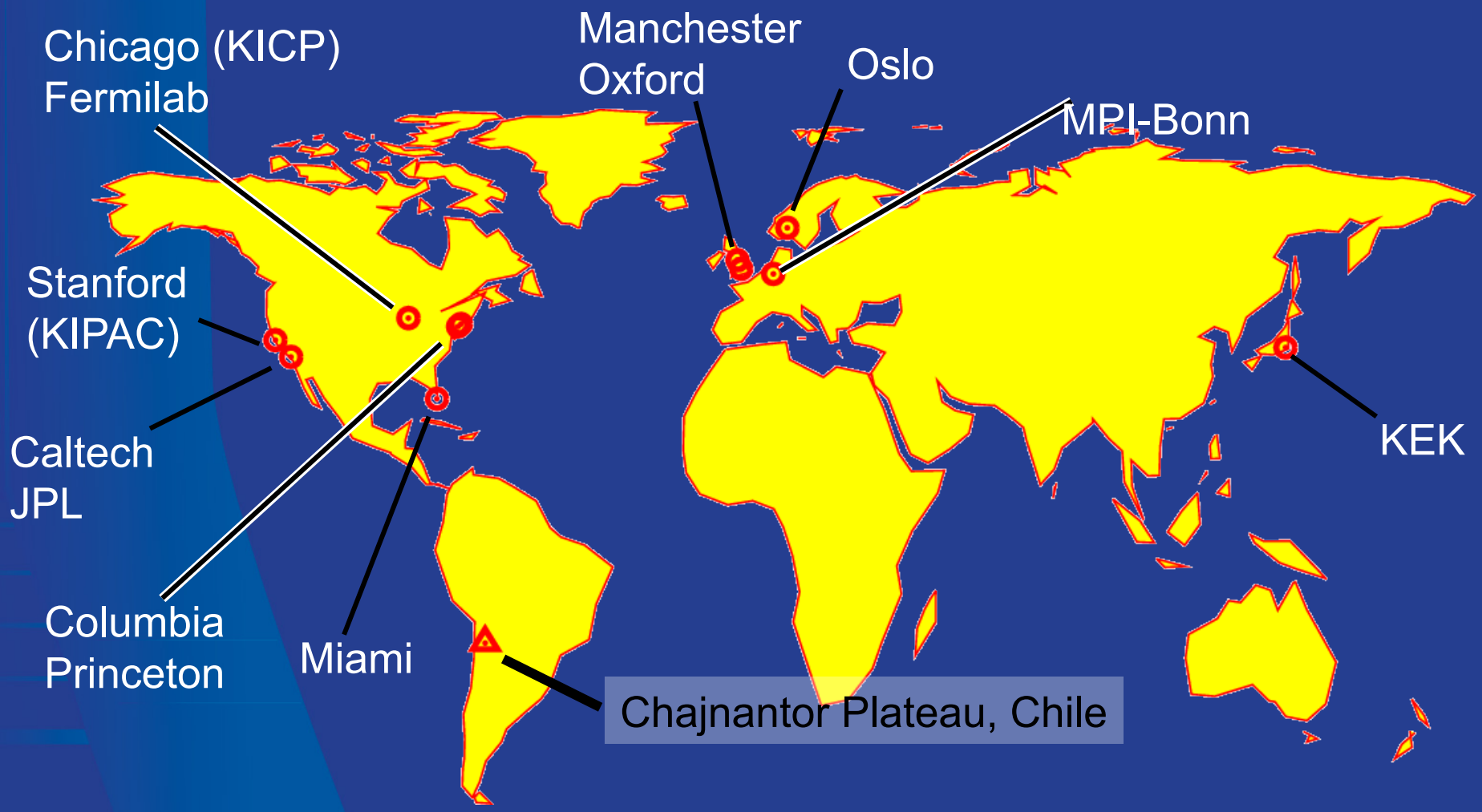




Small shower penetration depth implies unusually large cross section, and variability in depth is unusually low → **New interaction physics at 100 TeV or UHECR are Fe nuclei???**

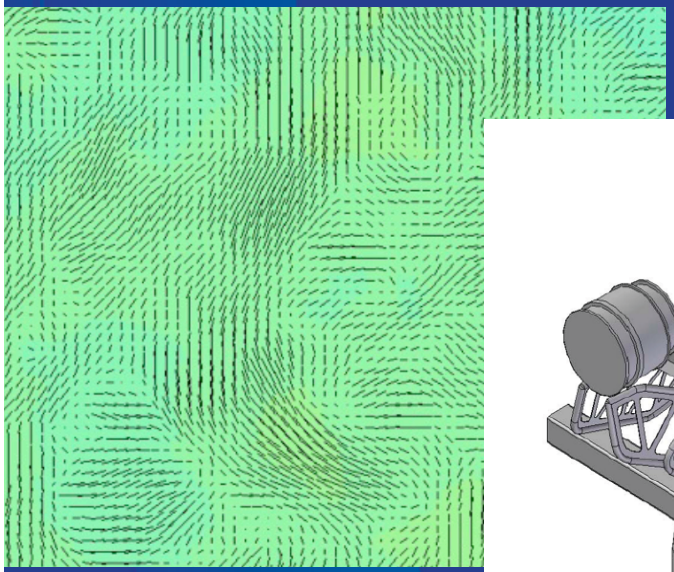
Probing the 10^{16} GeV scale:

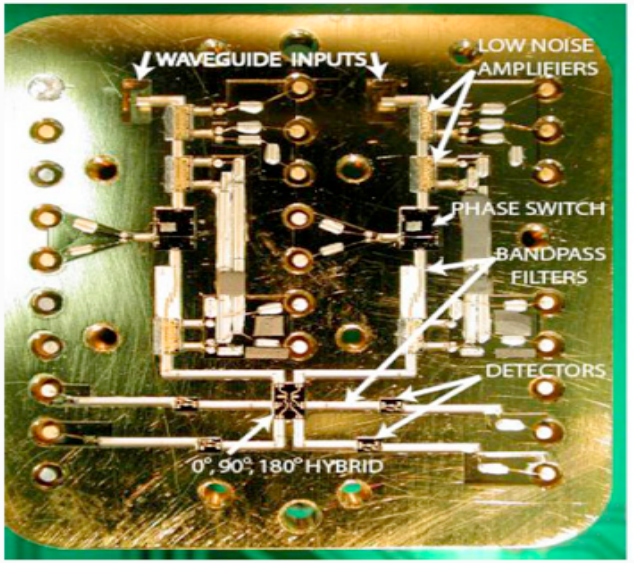
QUIET: Search for B-mode polarization in the CMB

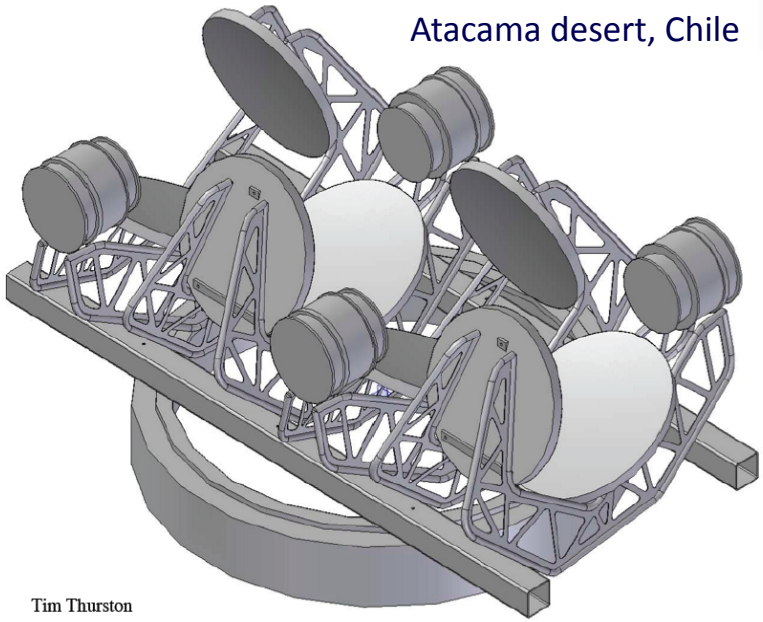


Coherent detection of polarized microwaves

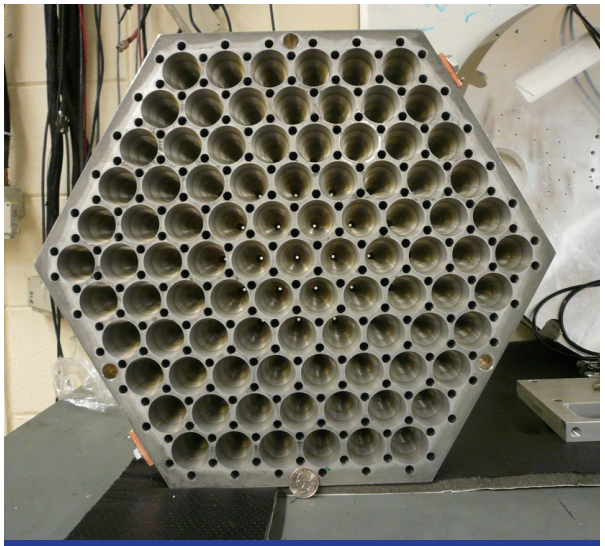
- Curl-like patterns imprinted on the sky from primordial gravitational waves
- Power spectrum amplitude directly measures the energy scale of cosmological inflation







Atacama desert, Chile

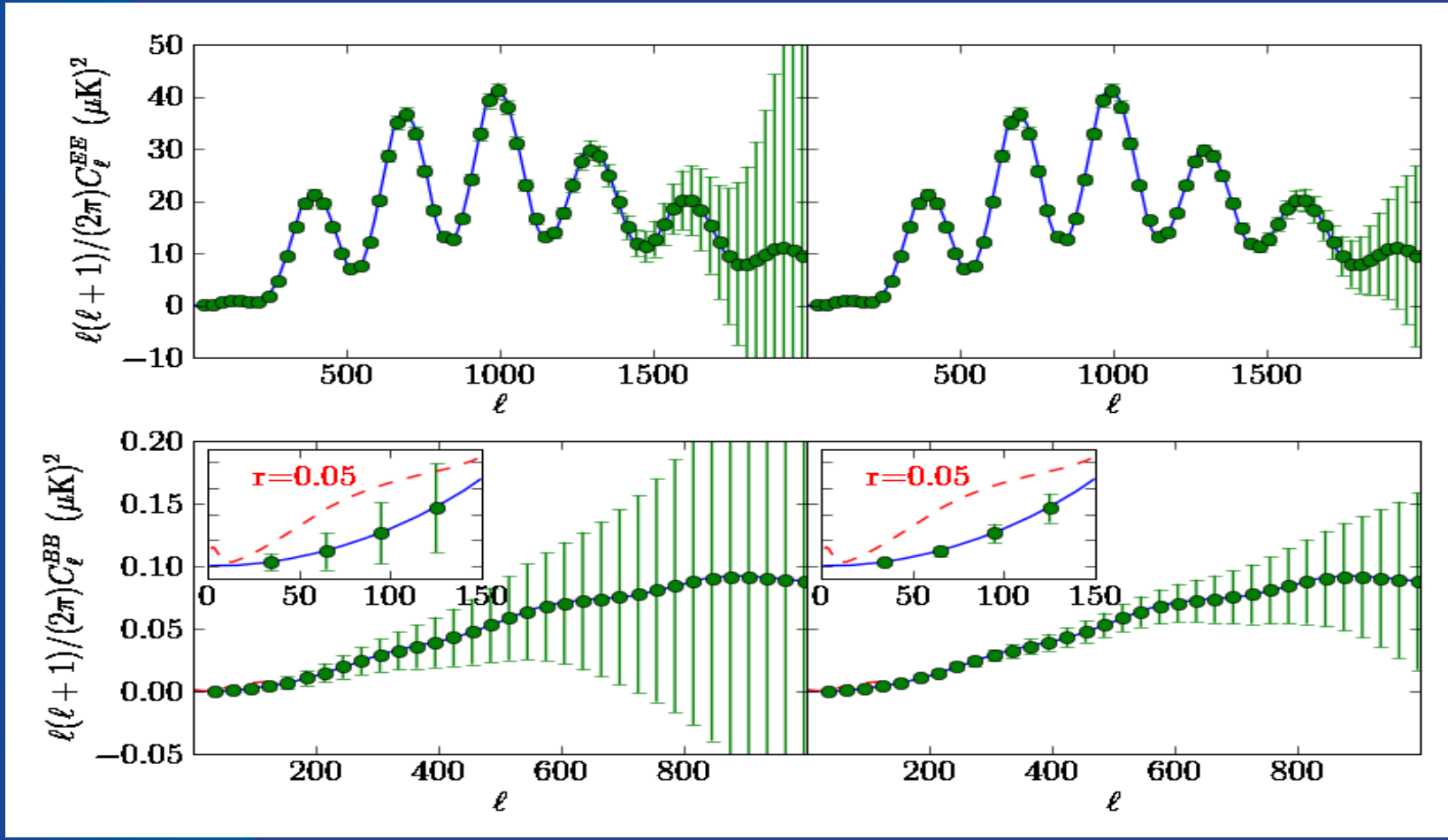


QUIET Phase-II (1600 pixels)

Current* Performance

(noise, duty cycle, 1/f)

Likely Improvements



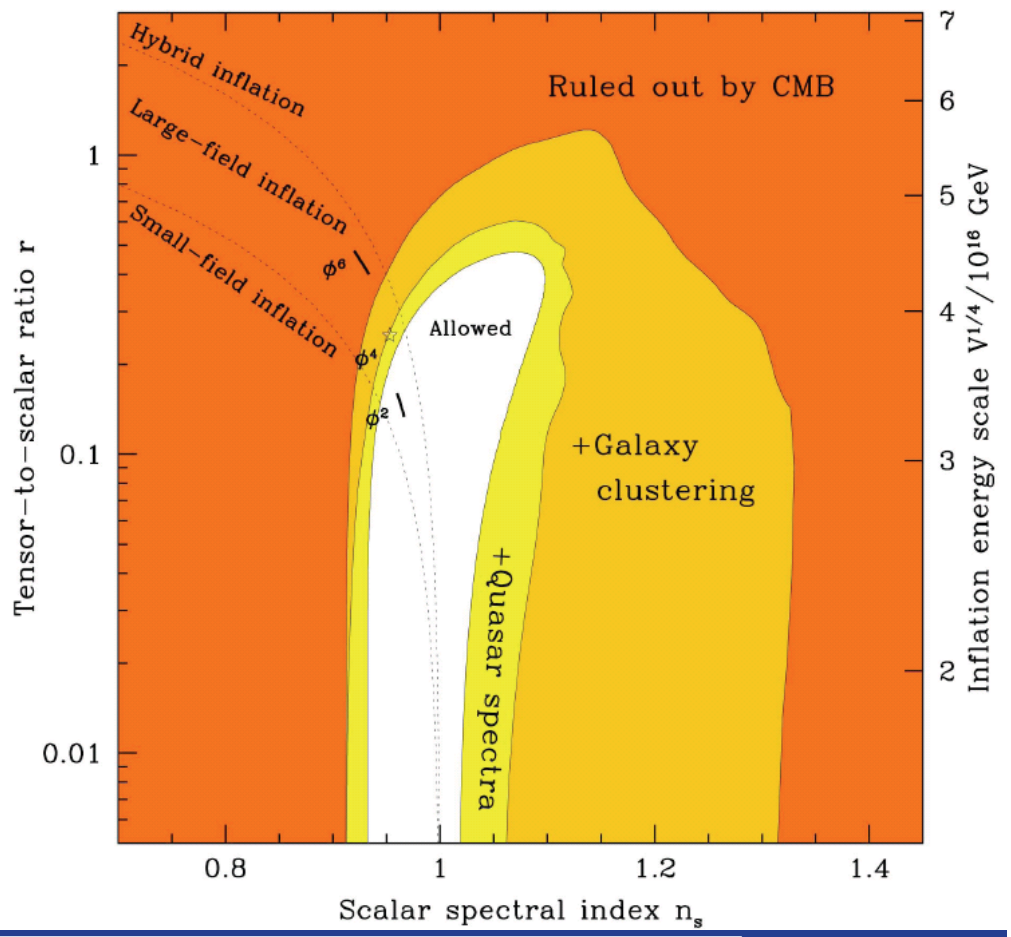
Sensitivity to the tensor/scalar ratio :

0.018 Δr 0.005

Amplitude of B-mode signal tied to physics of inflation

Tensor/scalar ratio teaches us about the GUT scale physics driving inflation.

$$r = 0.1\left(\frac{V^{1/4}}{3\times 10^{16} GeV}\right)^4$$



PASAG recommends HEP support of QUIET 2 under all budget scenarios.

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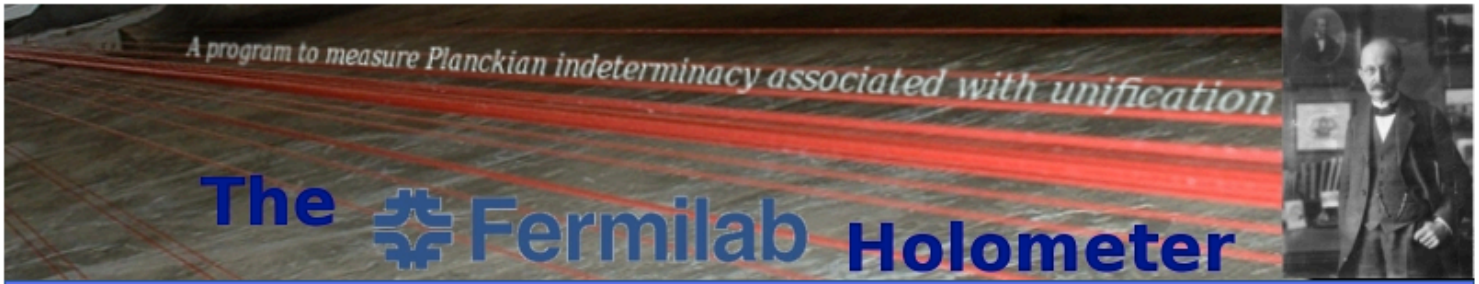
Interferometer probe of the Planck scale 10^{19} GeV



Fermi National Accelerator Laboratory

Aaron Chou, Craig Hogan (Project Scientist), Erik Ramberg, Jason Steffen, Chris Stoughton, Ray Tomlin, William Wester

Massachusetts Institute of Technology

Sam Waldman, Rainer Weiss

University of Chicago

Stephan Meyer

University of Michigan

H. Richard Gustafson

California Institute of Technology

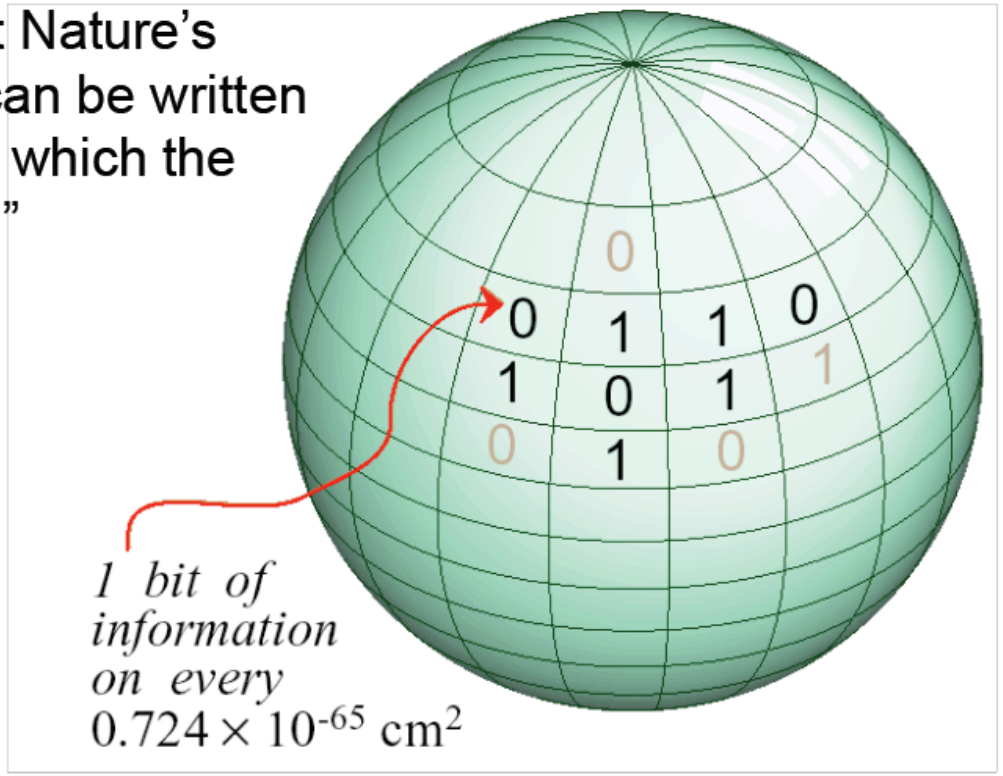
Stanley Whitcomb

Bold idea from black hole physics: the world is a hologram

Entropy $S = M_{pl}^2$ 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

Are there experimental consequences of this idea?

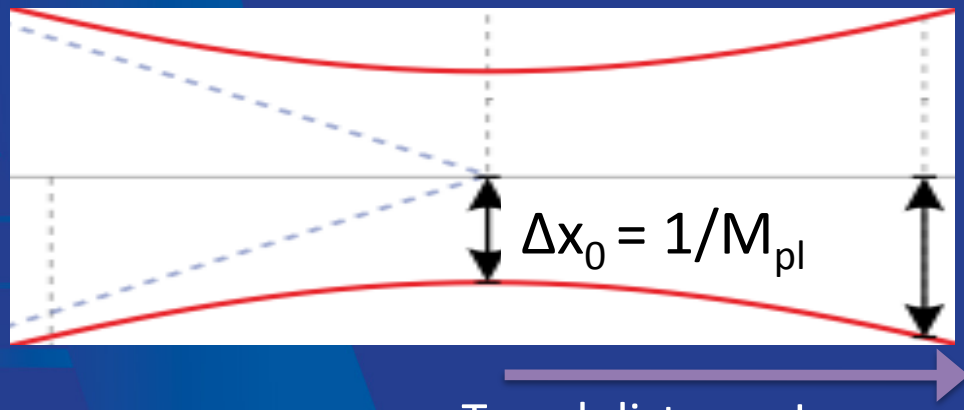
Specific idea (Hogan): add a new commutator

- If information stored on surface ***area***, not volume, let's postulate a new commutator of ***transverse*** position operators:

$$[x,y] = 1/M_{pl}^2$$ for a wave travelling along z.

- Since commutators specify phase space volume per degree of freedom, this corresponds to the black hole entropy formula

- The resulting initial minimum uncertainty in transverse coordinates x, y naturally grows due to ***diffraction*** in standard quantum mechanics: $[x, p_x]>1/2$, $[y, p_y]>1/2$

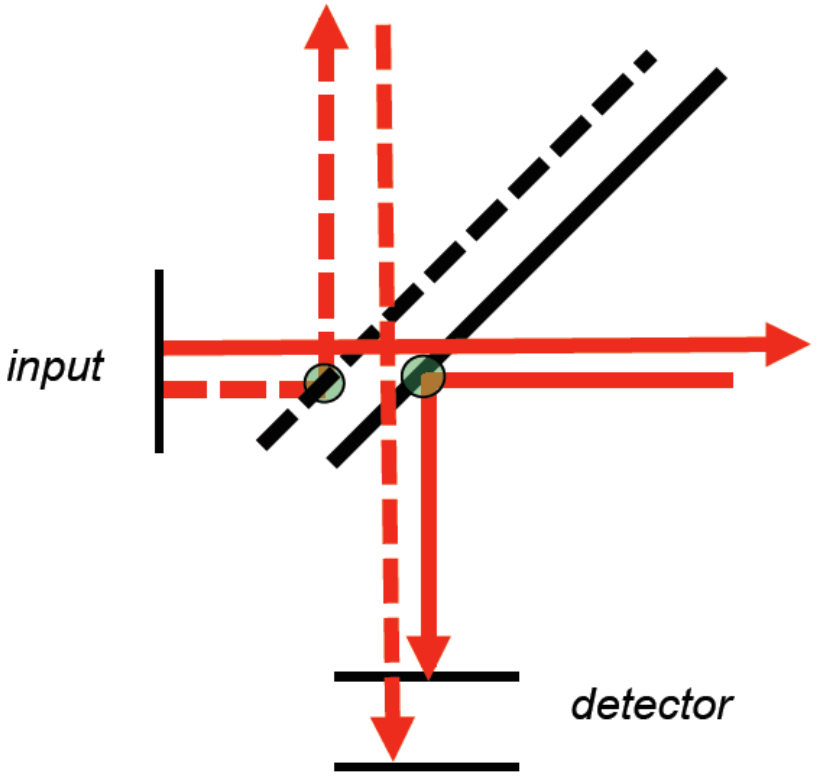


Initial size of the transverse position uncertainty = 10^{-33} cm

Let this uncertainty grow over a nice long lever arm between two measurements of the same transverse position into something detectable (10^{-15} cm for L=40m).

Holographic noise in a Michelson interferometer

Jitter in beamsplitter position leads to fluctuations in measured phase



Range of jitter depends on arm length:

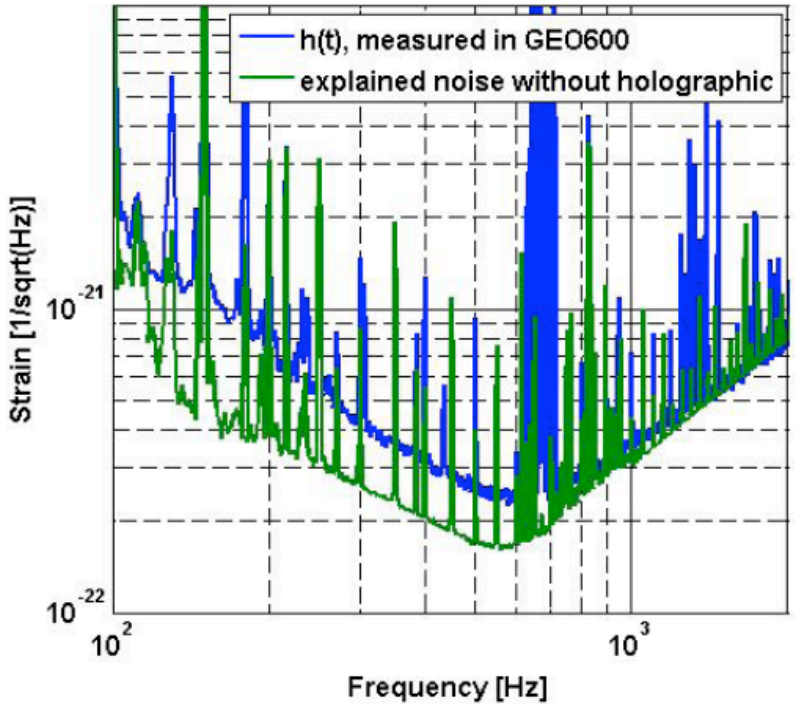
$$\Delta x^2 = \lambda_P L$$

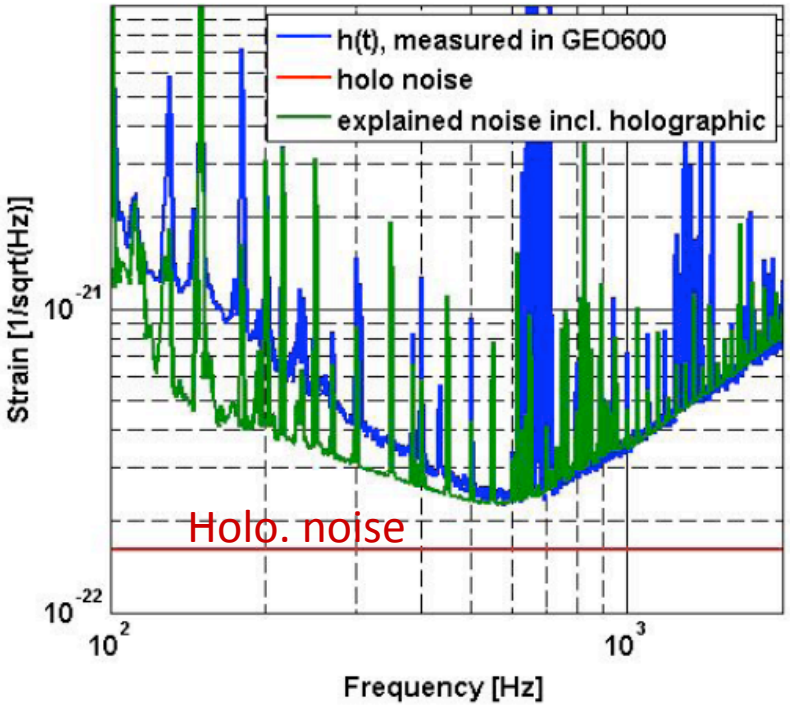
- **New effect predicted, with no free theoretical parameters!**
- **The resulting phase noise is detectable!**

GEO-600 (Hannover)

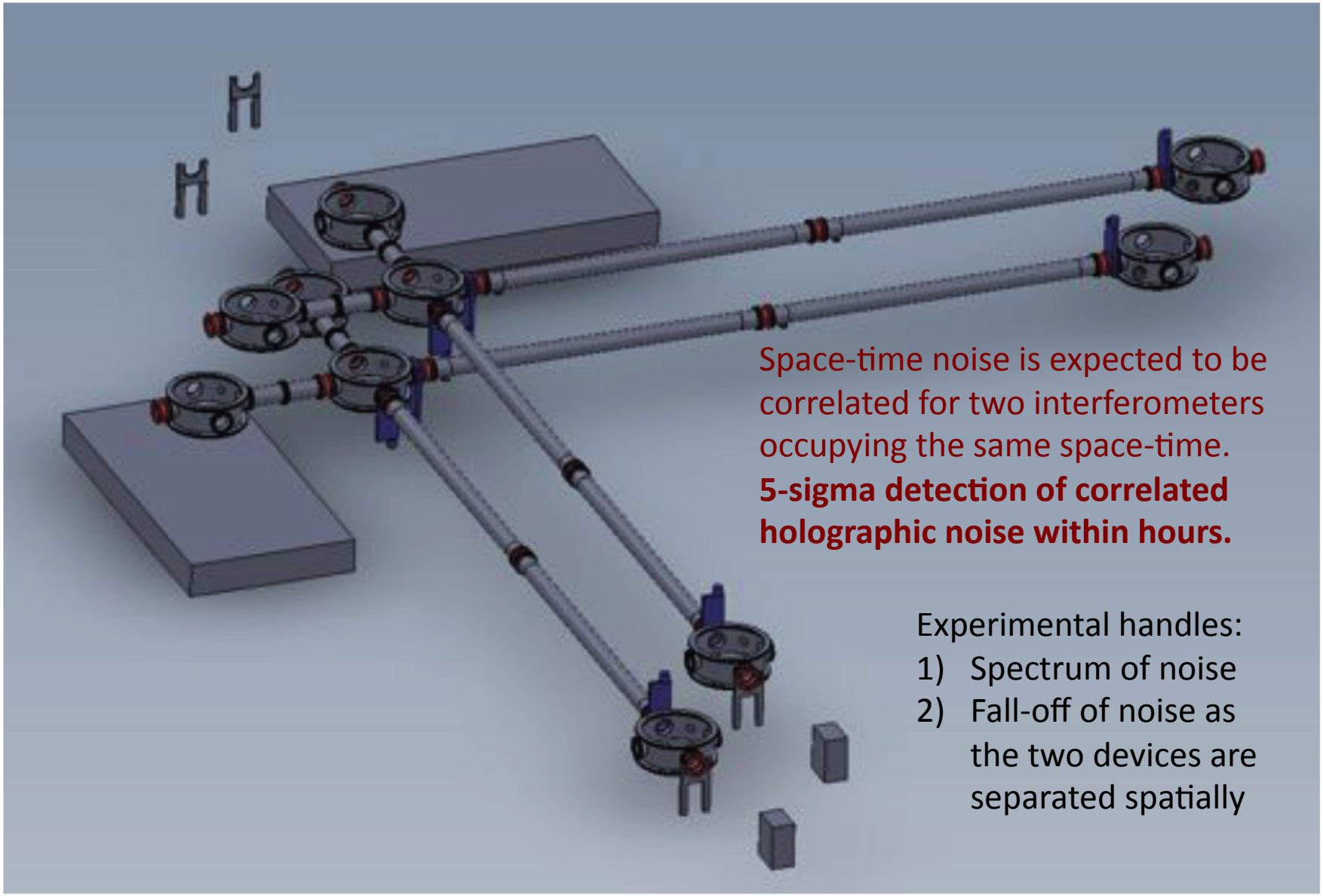
Craig Hogan, Beyond Center workshop, January 2010 33

Encoding of space-time coordinates at Planck wavelength gives i**rreducible noise** in gravitational wave interferometers, **possibly already detected by GEO600** (Hogan)





The Proposed 40m Fermilab Holometer



Space-time noise is expected to be correlated for two interferometers occupying the same space-time.
5-sigma detection of correlated holographic noise within hours.

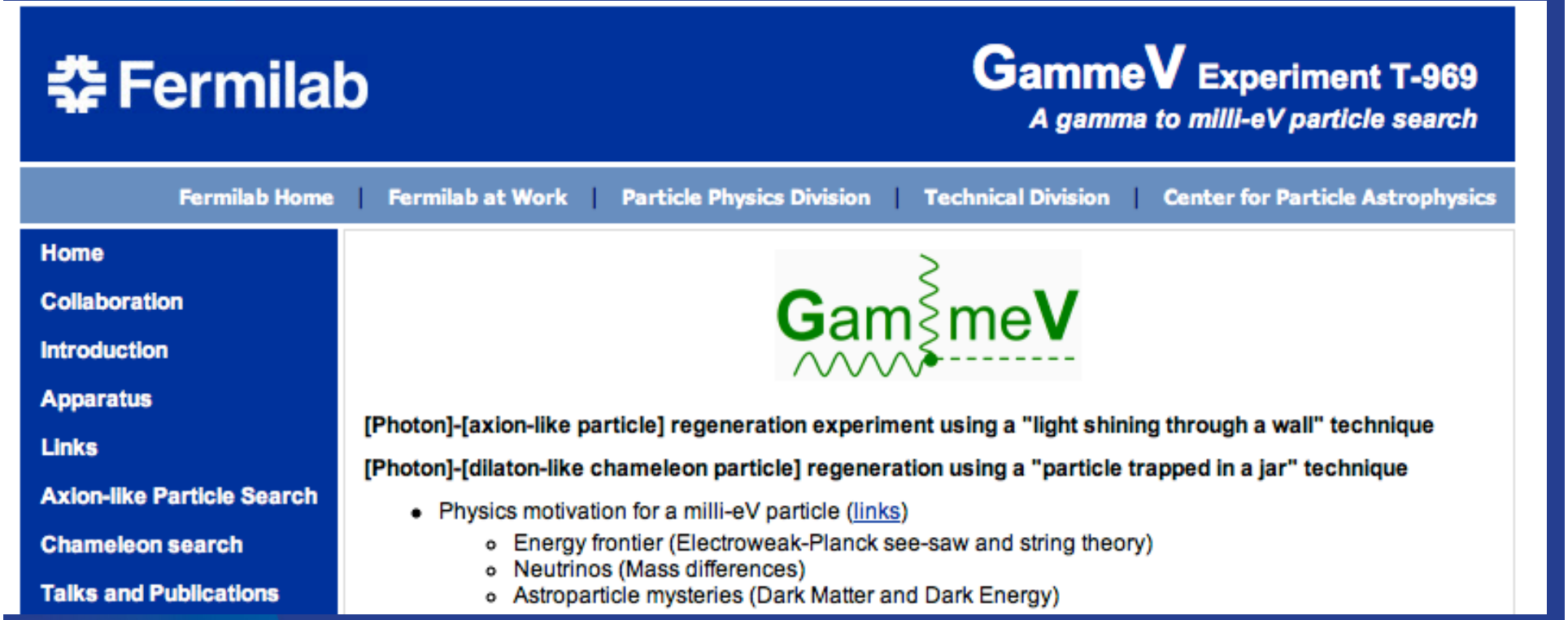
Experimental handles:

1) Spectrum of noise
2) Fall-off of noise as the two devices are separated spatially

History of interferometry

Michelson and team in suburban Chicago, winter 1924, with partial-vacuum pipes of 1000 by 2000 foot interferometer, measuring the rotation of the earth

Probing the 10^{11} GeV scale with lasers

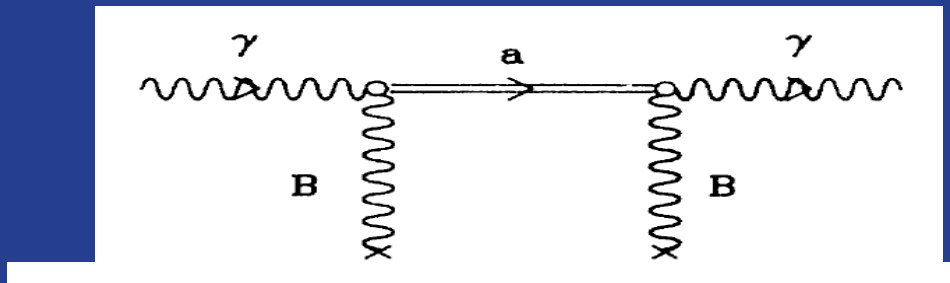


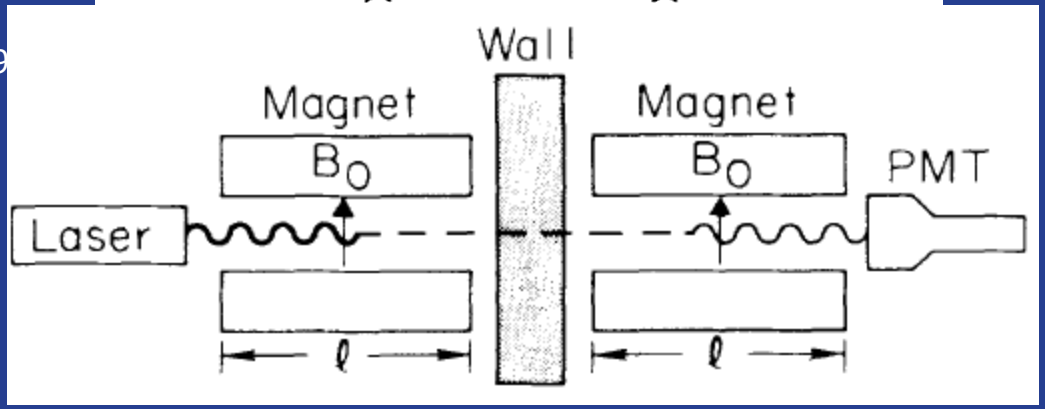
- Chameleon Search (CHASE):
  - Fermilab, U.Chicago, Cambridge
- Resonantly Enhanced Axion-Photon Regeneration (REAPER):
  - Fermilab, U.Florida, U.Michigan, Naval Postgraduate school

Axion search: Light shining though walls

Experimental configuration inspired by a Feynman diagram.

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



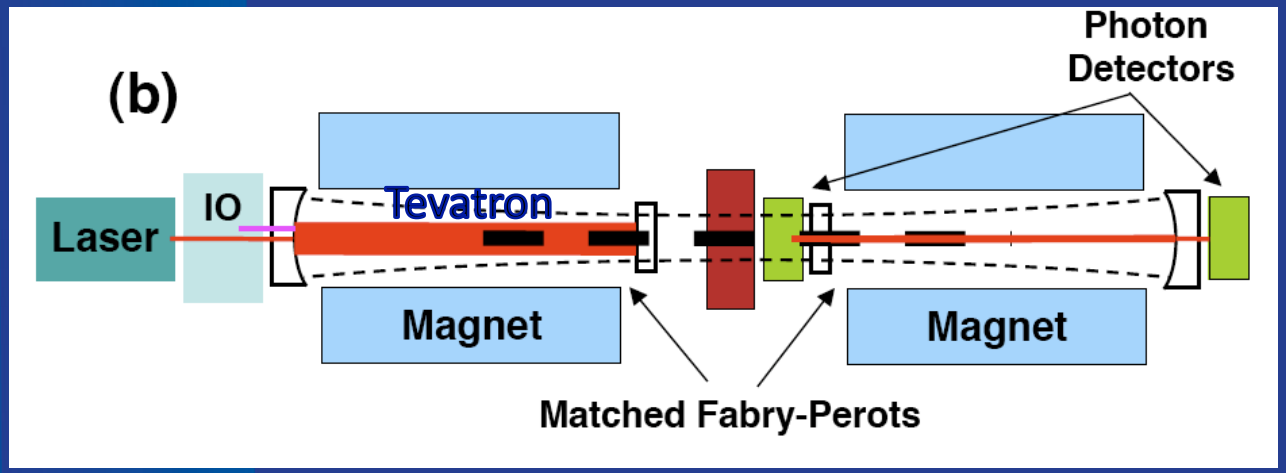


$$P_{\text{regen}} \approx \left(\frac{1}{4} g^2 B^2 L^2\right)^2$$

g=coupling constant

Cost scales linearly with sensitivity.
How to achieve orders of magnitude improvement???

A game-changer: Cavity-enhanced photon-axion conversion



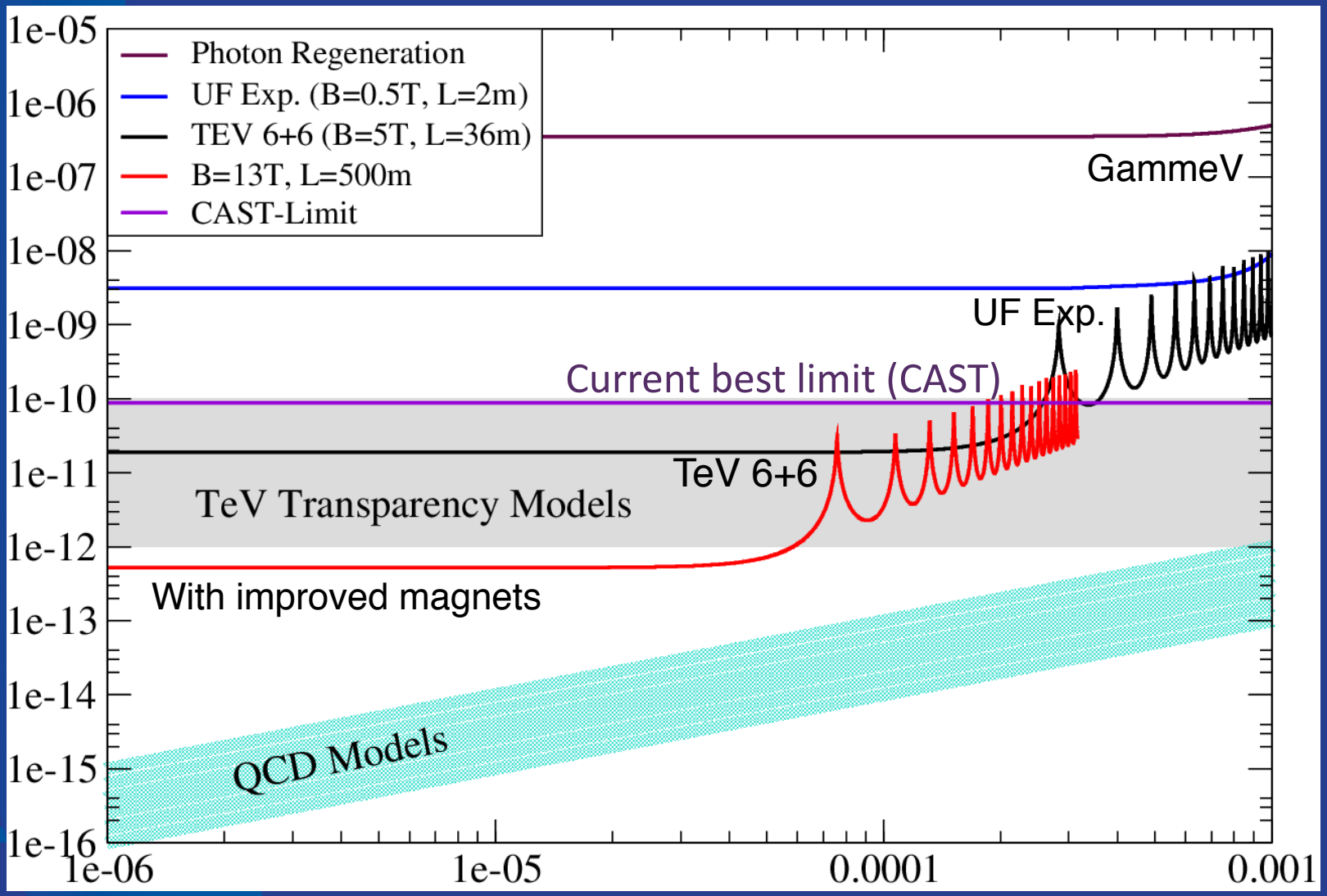
Matched Fabry-Perot cavities shape the axion beam and resonantly enhance the axion-photon transition probability. Light leaks coherently from the bright cavity into the dark cavity.

In other words to detect a weak spring constant coupling two oscillators, just jack up the Q of each oscillator! Shake one and watch the other one move.

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

Possible to improve GammeV limit by 4 orders of magnitude using 40m long strings of **existing spare Tevatron magnets**.

Resonant regeneration discovery potential



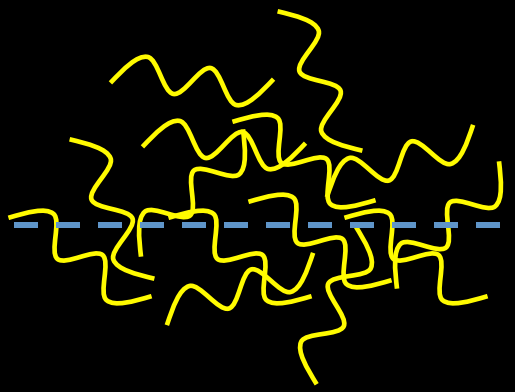
We are sensitive to an interesting region of coupling

Anomalous transparency of the universe to VHE and UHE gamma rays observed by HESS, VERITAS, MAGIC, Whipple, HiRes, can be explained by mixing of photons with axion-like particles.

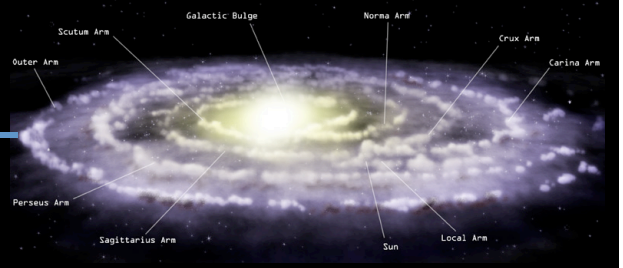
Hooper, Serpico, 2007
De Angelis, Mansutti, Roncadelli, 2007
Simet, Hooper, Serpico, 2008
Fairbairn, Rashba, Troitsky, 2009

$\text{Prob}(\gamma \leftrightarrow \phi) \approx (gBL/2)^2$

Cosmic ray accelerator
$BL = 10^{20}$ eV



Milky Way
$BL = 6.4\mu G\ 4kpc = 3\ 10^{19}$ eV



- If $g \approx 1/(BL) = 10^{-11}\ \text{GeV}^{-1}$, then high energy gamma rays can penetrate the opaque wall of background photons by efficiently converting into axions at the source, and then efficiently reconverting into photons in the galaxy.

Summary

- The Fermilab Center for Particle Astrophysics has plans to do great (and diverse) science!
- These projects are being planned in close collaboration with and in response to proposals from university groups and the larger scientific community.
- **A wide range of interesting energy scales from 10^{-3} eV to 10^{19} GeV will be probed.**