Title: Searching for Quantum Gravity with the IceCube Neutrino Observatory

Date: Oct 23, 2012 02:00 PM

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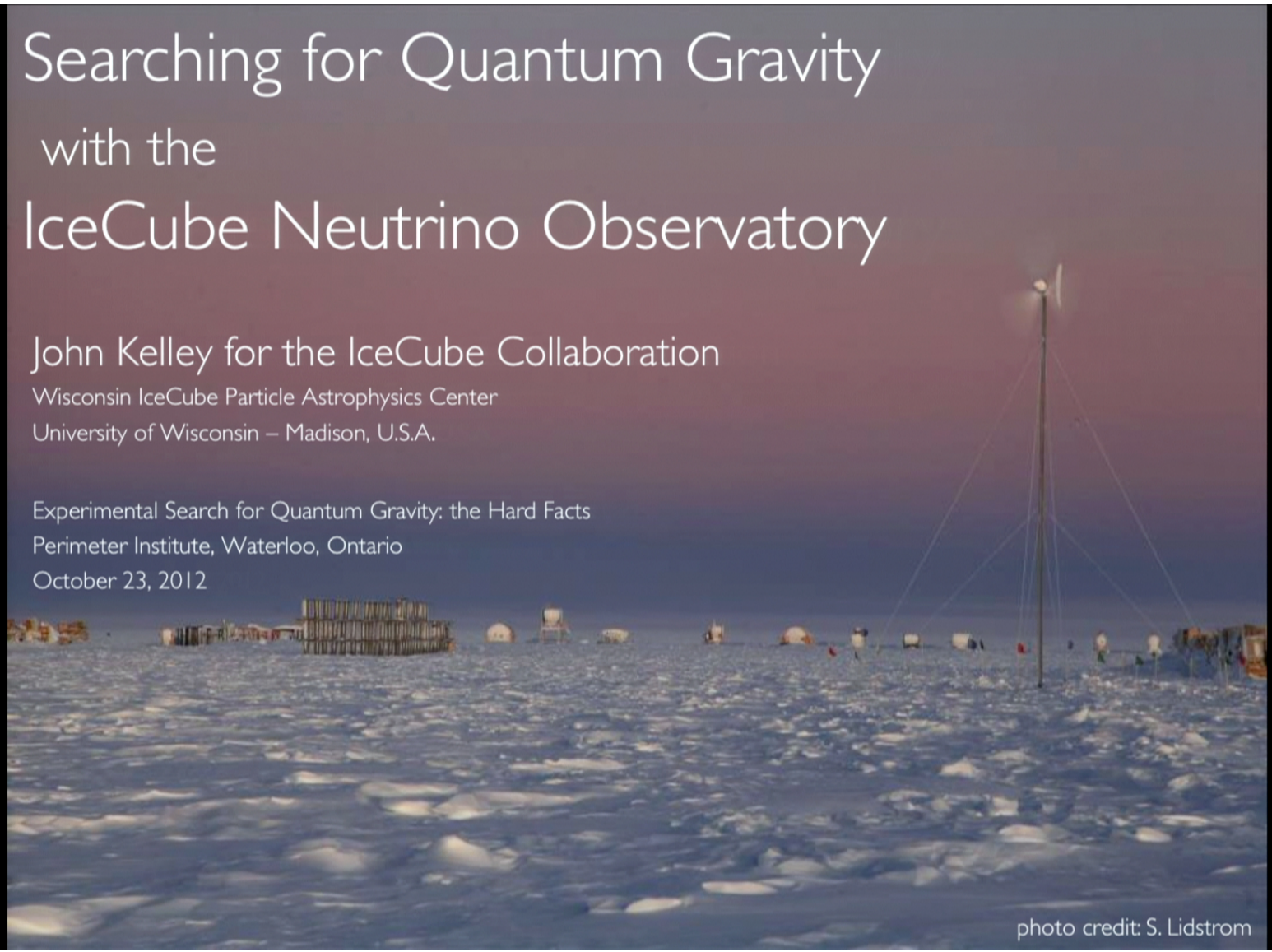
Abstract: The IceCube Neutrino Observatory is a cubic-kilometer-scale neutrino detector built into the ice sheet at the geographic South Pole. Completed in December 2010, the detector consists of an array of photomultiplier tubes deployed along 86 cables ("strings") at depths of 1450 to 2450 m, as well as the IceTop air shower array of surface Cherenkov tanks. IceCube is detecting atmospheric neutrinos of energies above approximately 100 GeV at a rate of ~6 per hour, and is currently searching for extraterrestrial neutrinos from cosmic ray accelerators. A measurement of the atmospheric neutrino spectrum can be used to search for possible phenomenological signatures of quantum gravity (QG), such as violations of Lorentz invariance or quantum decoherence, and I present limits we have set on these phenomena in the neutrino sector. To extend the search for QG to much higher energies and cosmological baselines, we require an extraterrestrial neutrino source. In this context, I report on the status of our searches for neutrinos from gamma-ray bursts and from cosmic-ray interactions with the microwave background ("cosmogenic" neutrinos).

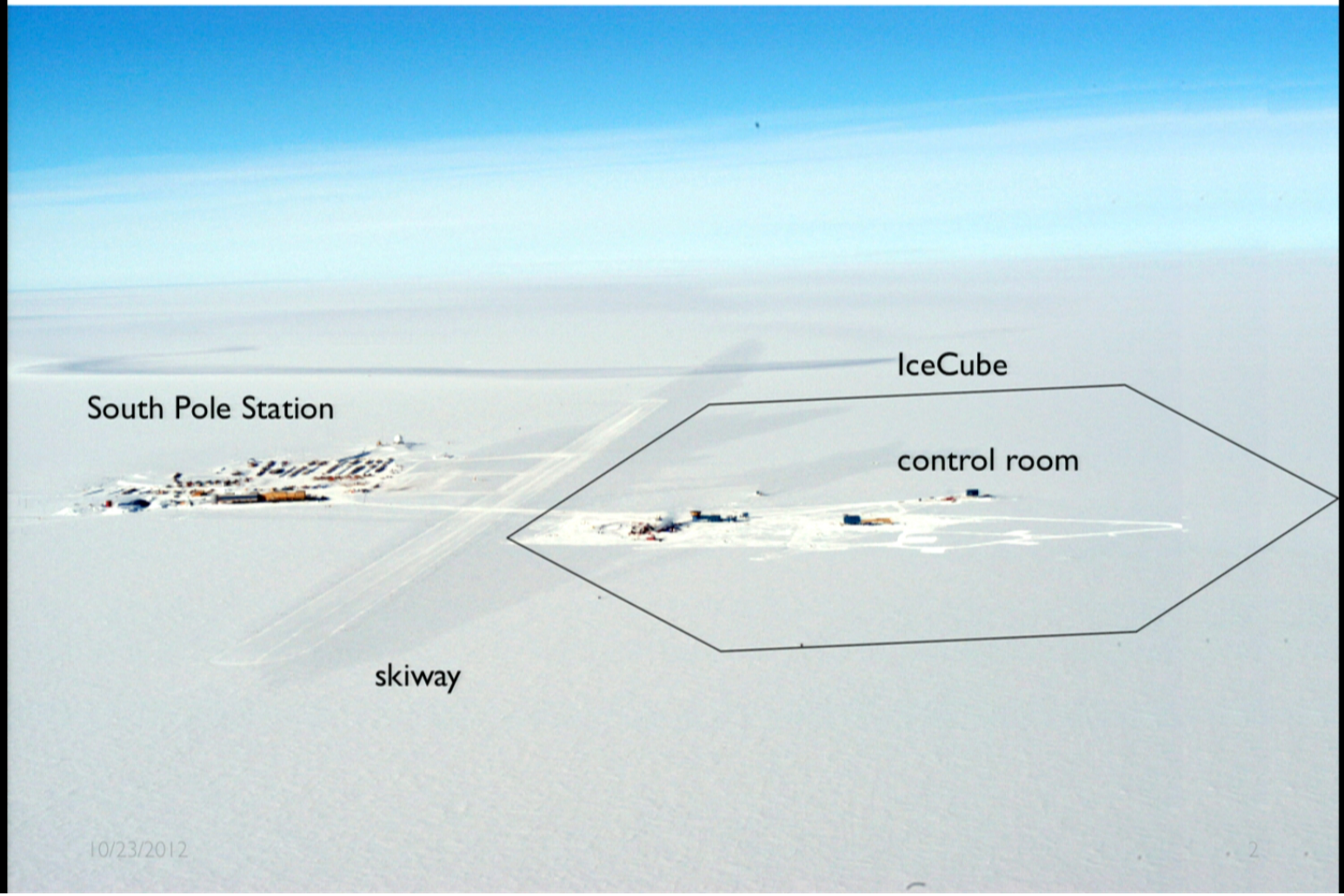
Searching for Quantum Gravity with the IceCube Neutrino Observatory

John Kelley for the IceCube Collaboration
Wisconsin IceCube Particle Astrophysics Center
University of Wisconsin – Madison, U.S.A.

Experimental Search for Quantum Gravity: the Hard Facts
Perimeter Institute, Waterloo, Ontario
October 23, 2012



IceCube from the Air



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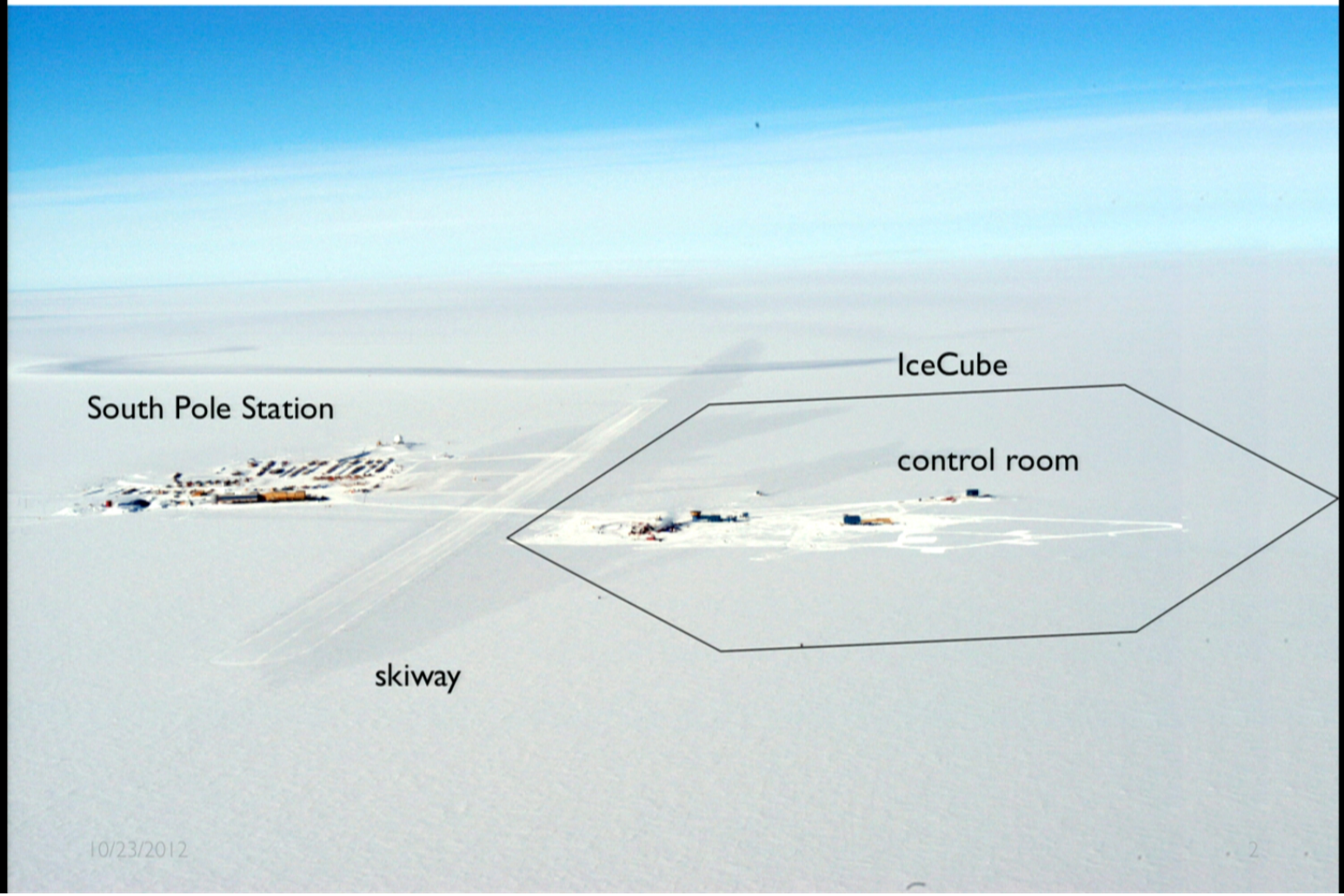
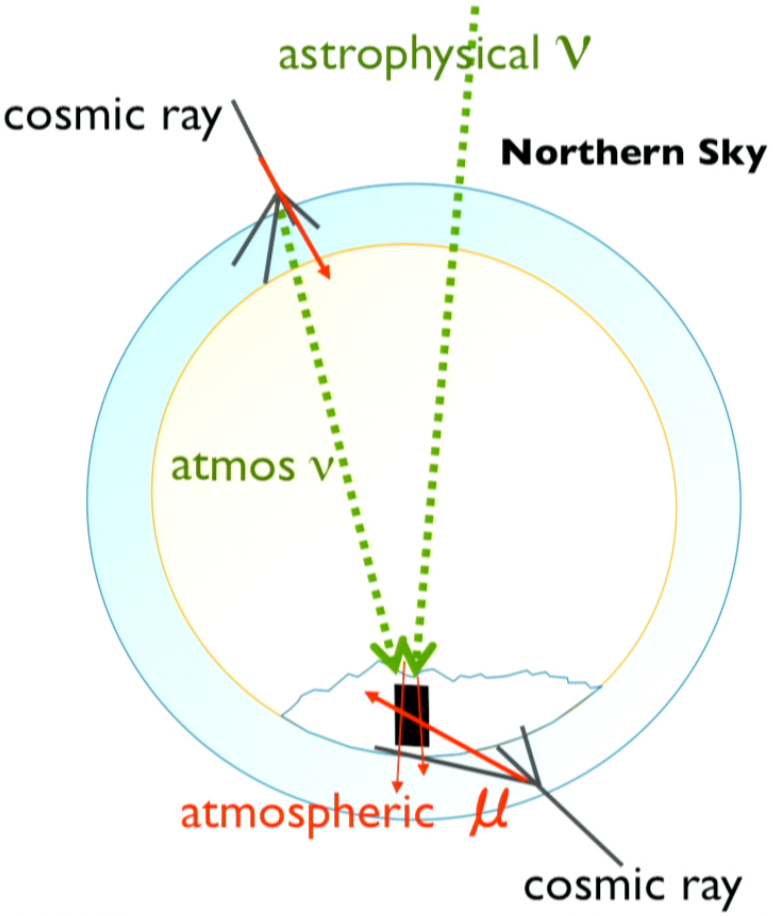
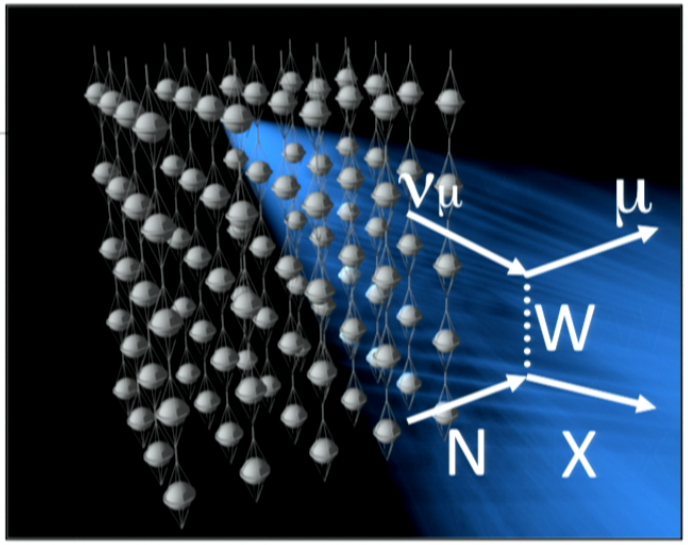
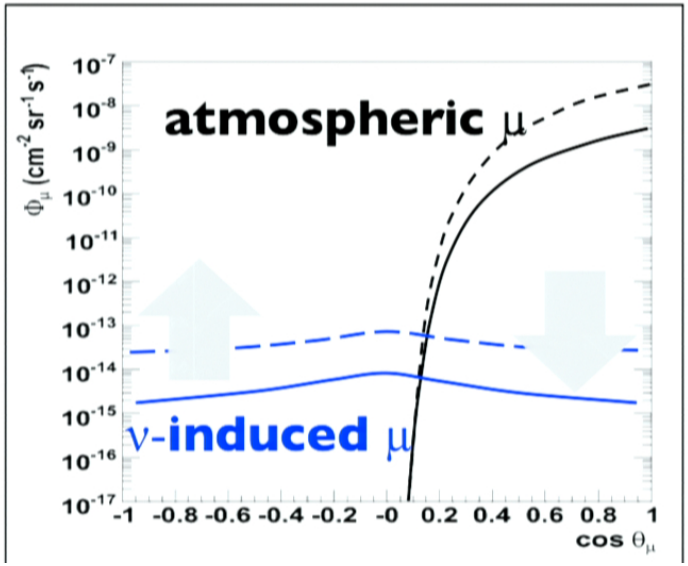


Detection Principle







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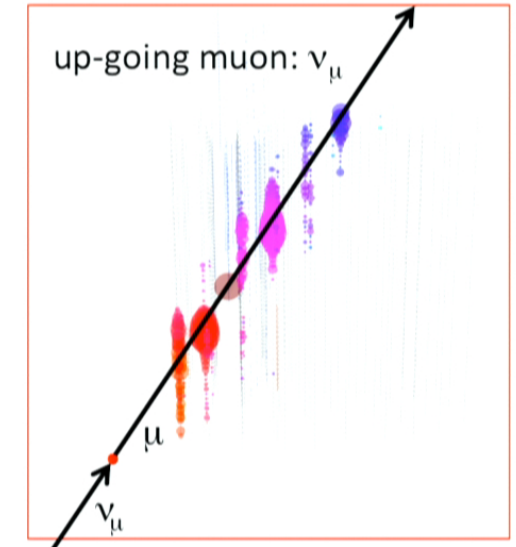
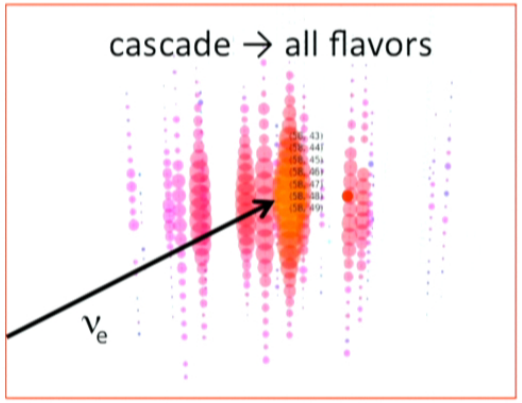
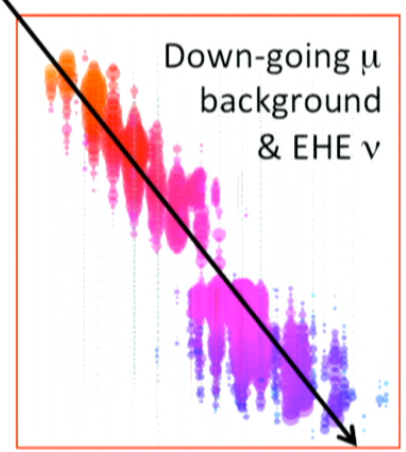
Event Signatures

Positions, times, and amplitudes of Cherenkov light deposition: neutrino direction + energy



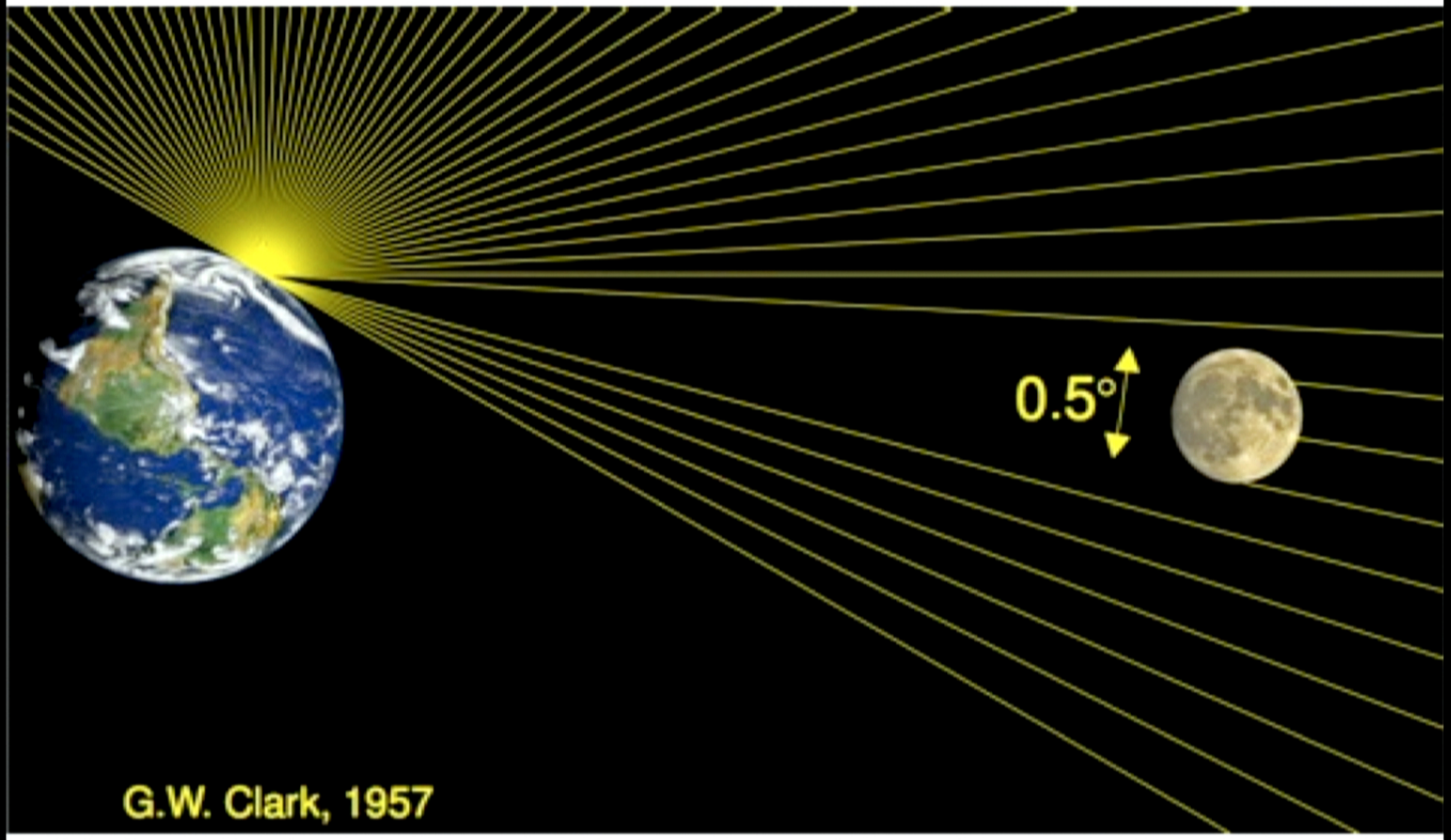




Relevant energy ranges:

- atmospheric neutrinos: dominant below 100 TeV
- "prompt" nu from atmospheric charm: ~300 TeV
- cosmic-ray accelerators: > 100 TeV
- cosmogenic neutrinos: ~10^6 TeV

Shadow of the Moon



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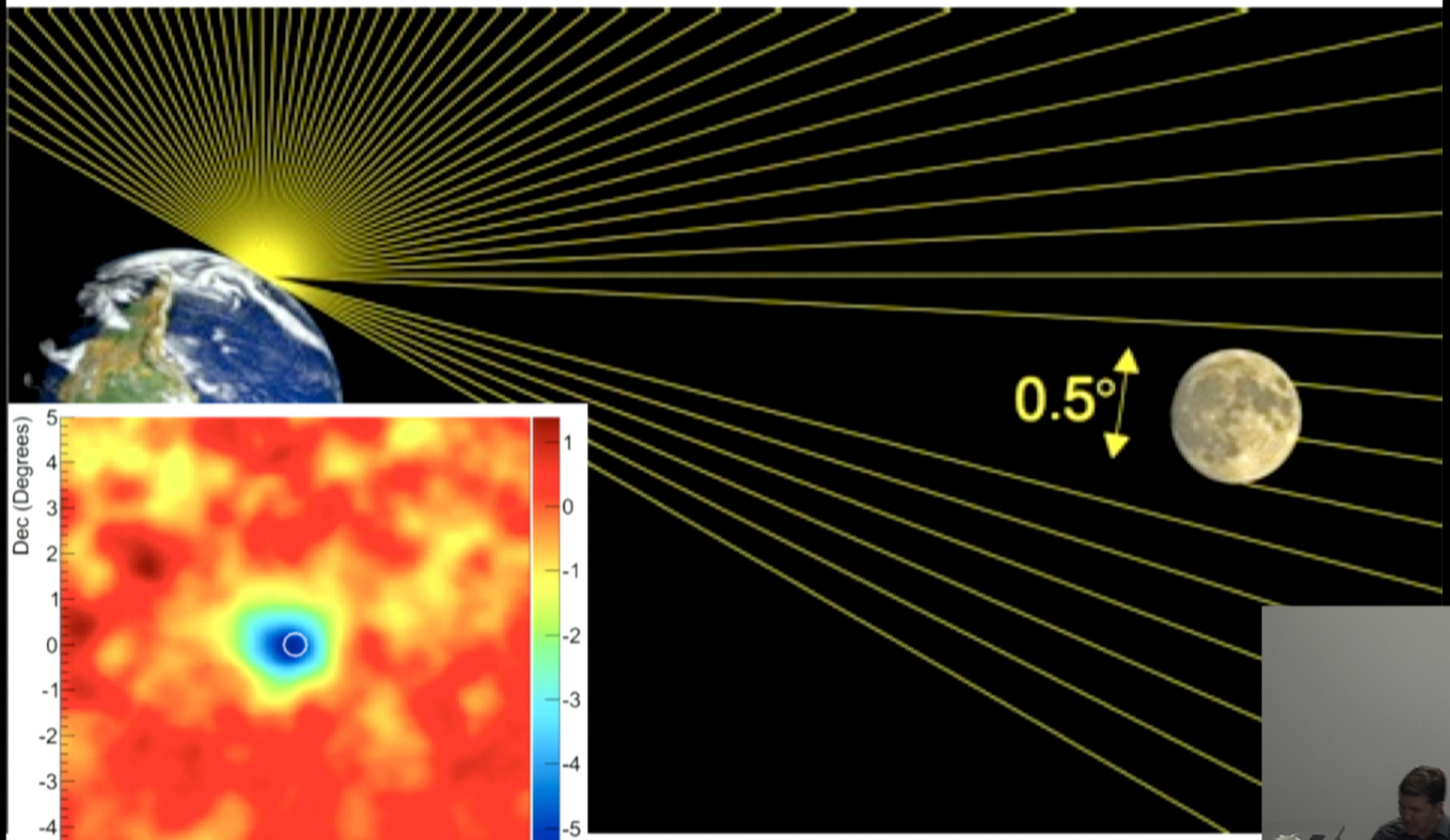

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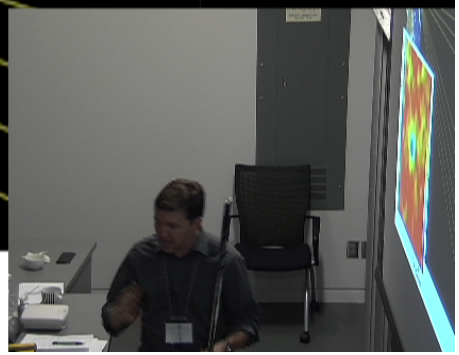
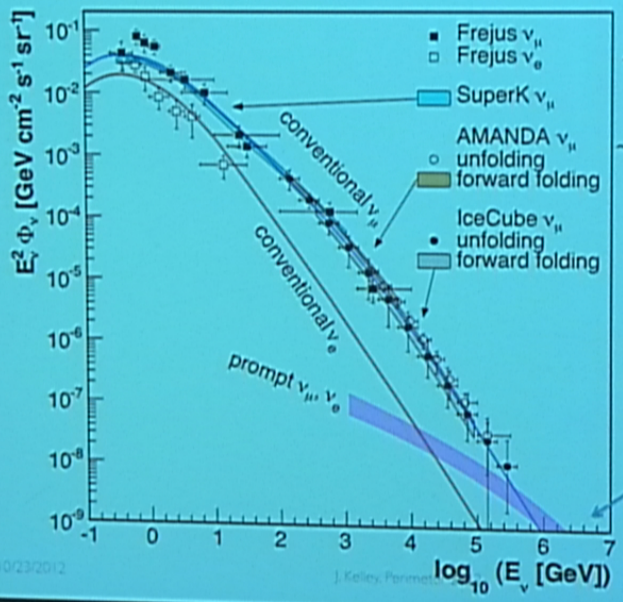


Atmospheric Neutrino Spectra



~4 atm. neutrinos / day in AMANDA-II

~200 atm. neutrinos / day in IceCube

neutrino point sources?
diffuse high-energy flux?
cosmogenic neutrinos?

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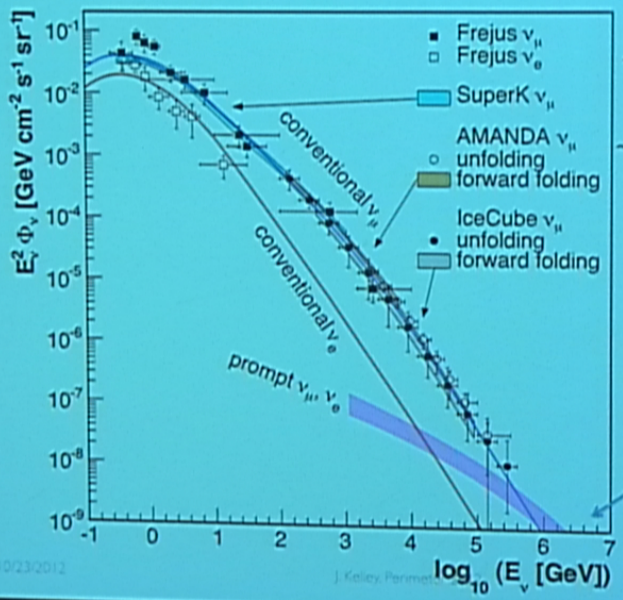

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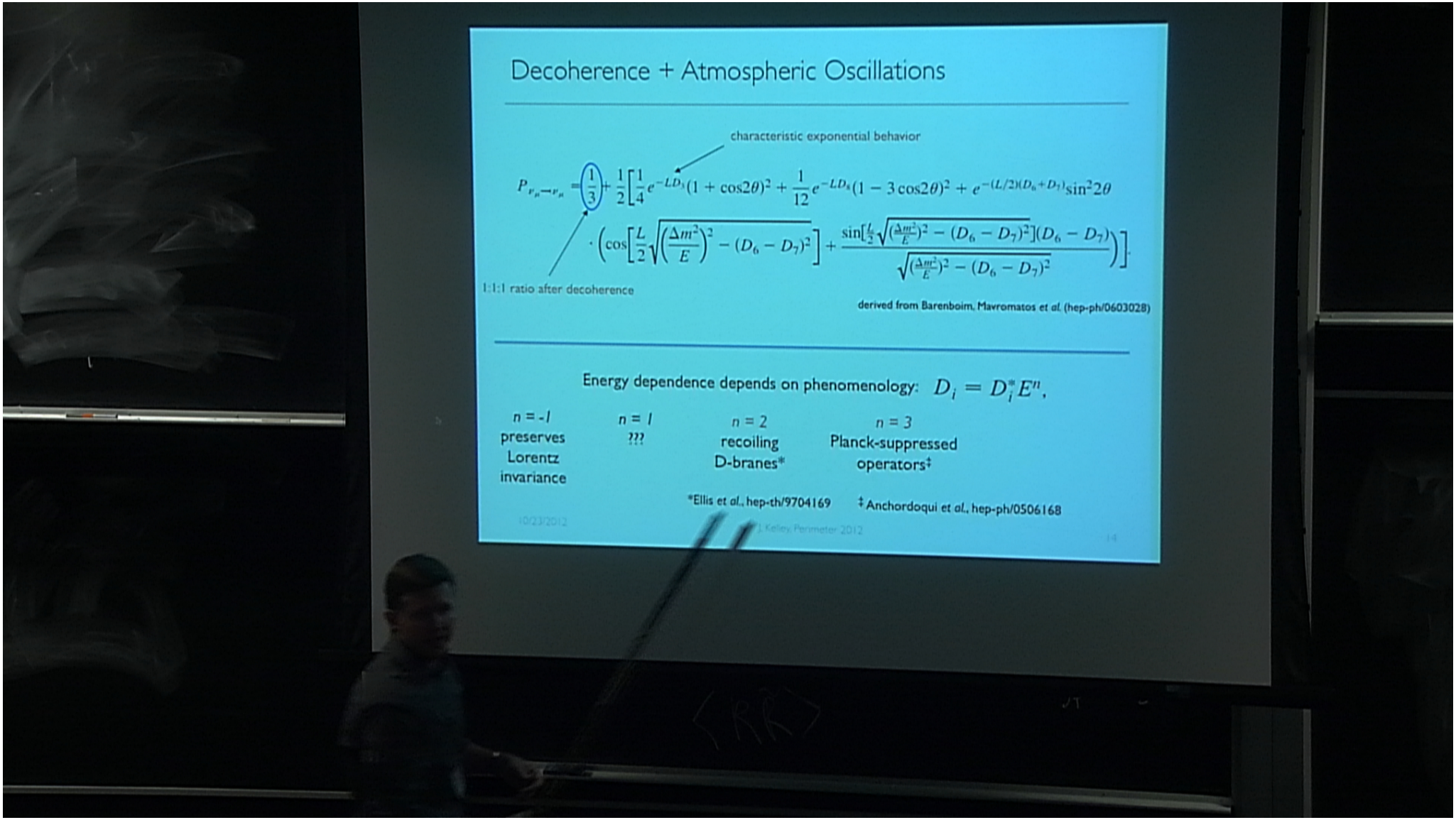
Decoherence + Atmospheric Oscillations
characteristic exponential behavior
$P_{\nu_\mu \to \nu_\mu} = \frac{1}{3} + \frac{1}{2}\left[\frac{1}{4}e^{-LD_3}(1+\cos 2\theta)^2 + \frac{1}{12}e^{-LD_8}(1-3\cos 2\theta)^2 + e^{-(L/2)(D_6+D_7)}\sin^2 2\theta \cdot \left(\cos\left[\frac{L}{2}\sqrt{\left(\frac{\Delta m^2}{E}\right)^2 - (D_6-D_7)^2}\right] + \frac{\sin\left[\frac{L}{2}\sqrt{\left(\frac{\Delta m^2}{E}\right)^2 - (D_6-D_7)^2}\right](D_6-D_7)}{\sqrt{\left(\frac{\Delta m^2}{E}\right)^2 - (D_6-D_7)^2}}\right)\right]$
1:1:1 ratio after decoherence
derived from Barenboim, Mavromatos et al. (hep-ph/0603028)
Energy dependence depends on phenomenology: $D_i = D_i^* E^n$,
n = -1 preserves Lorentz invariance
n = 1 ???
n = 2 recoiling D-branes*
n = 3 Planck-suppressed operators‡
*Ellis et al., hep-th/9704169
‡ Anchordoqui et al., hep-ph/0506168
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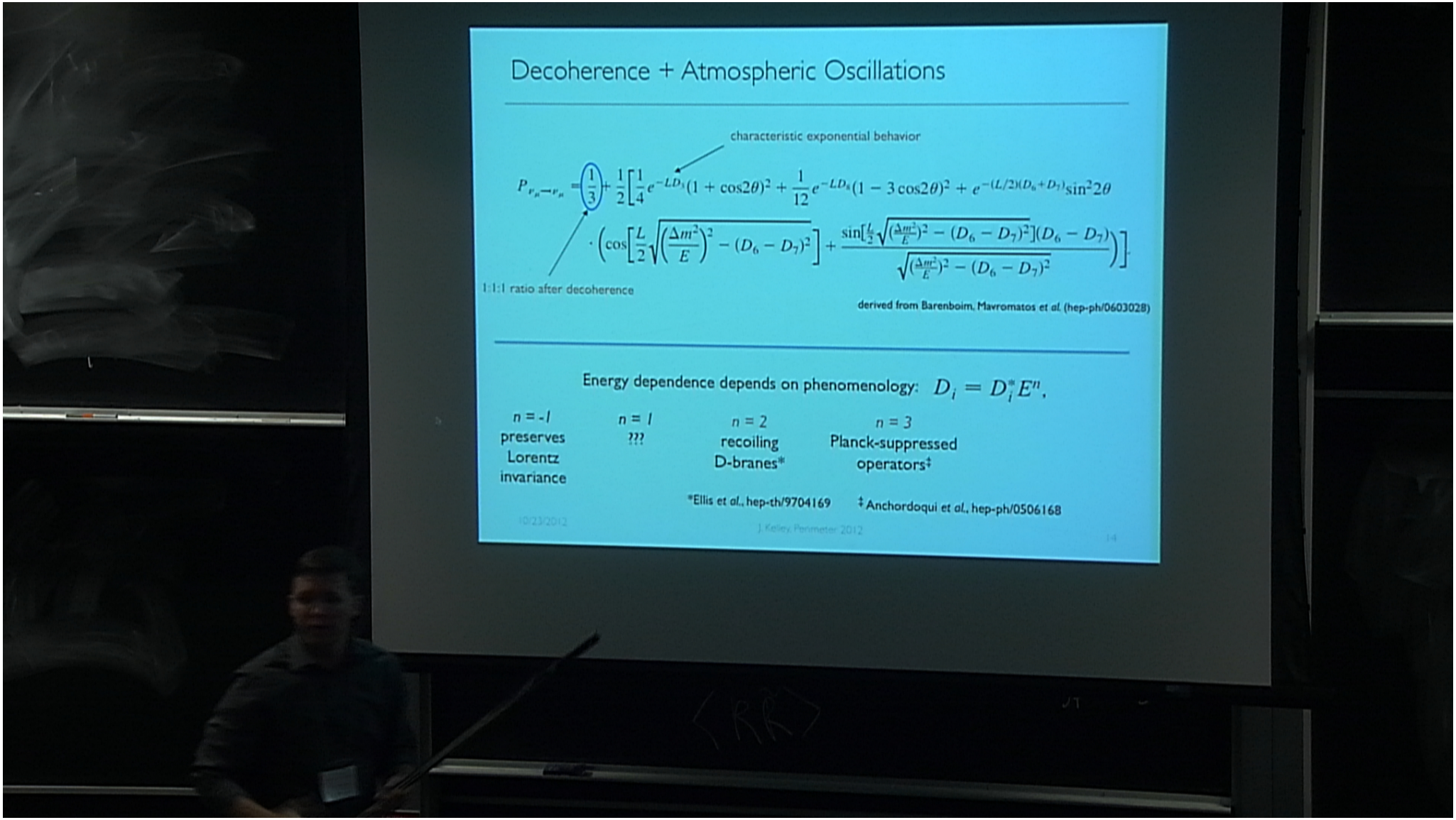
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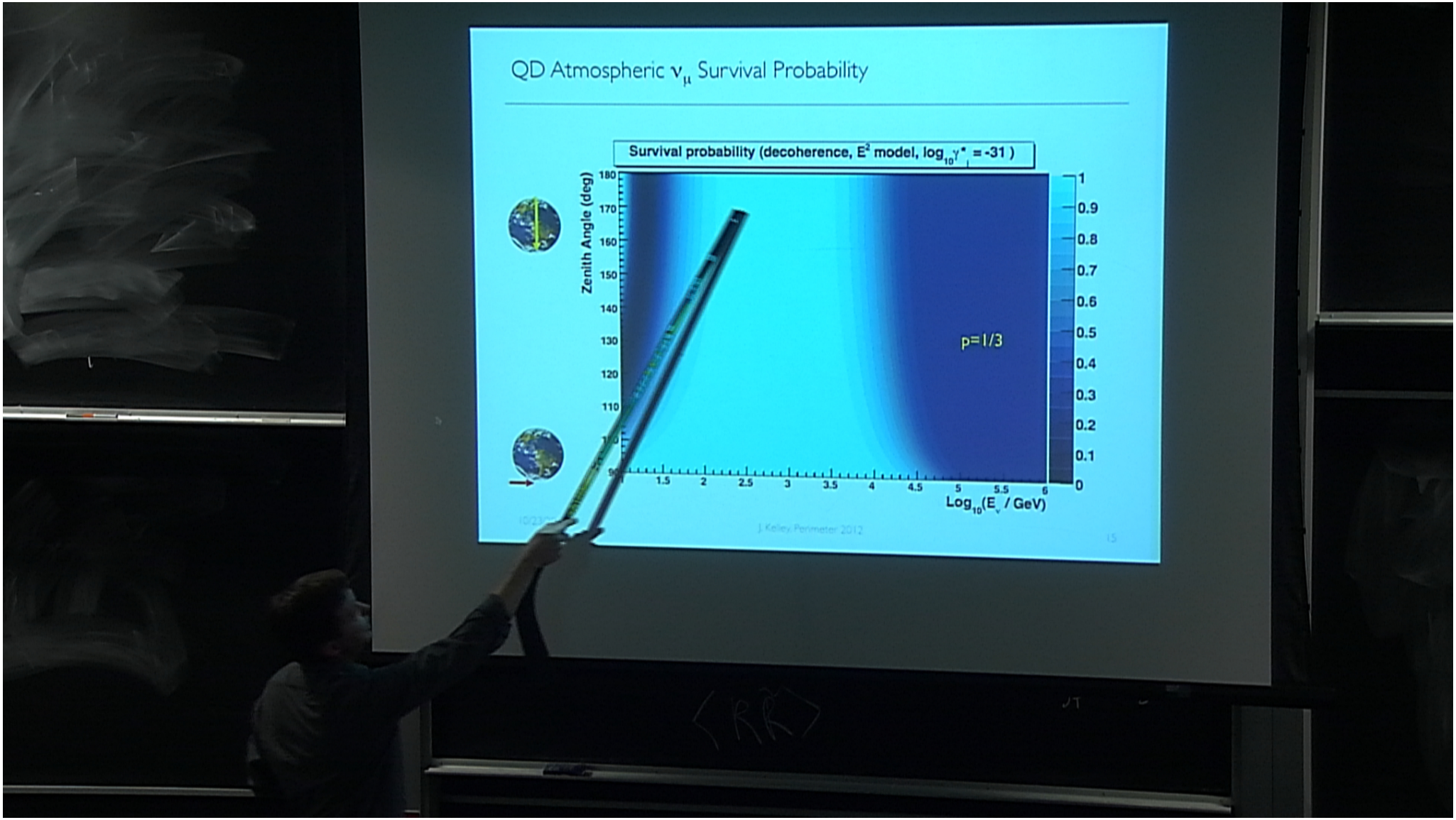
QD Atmospheric ν_μ Survival Probability
Survival probability (decoherence, E^2 model, $\log_{10}\gamma^*_\perp = -31$)
Zenith Angle (deg)
180
170
160
150
140
130
120
110
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
$\text{Log}_{10}(E_\nu / \text{GeV})$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
p=1/3
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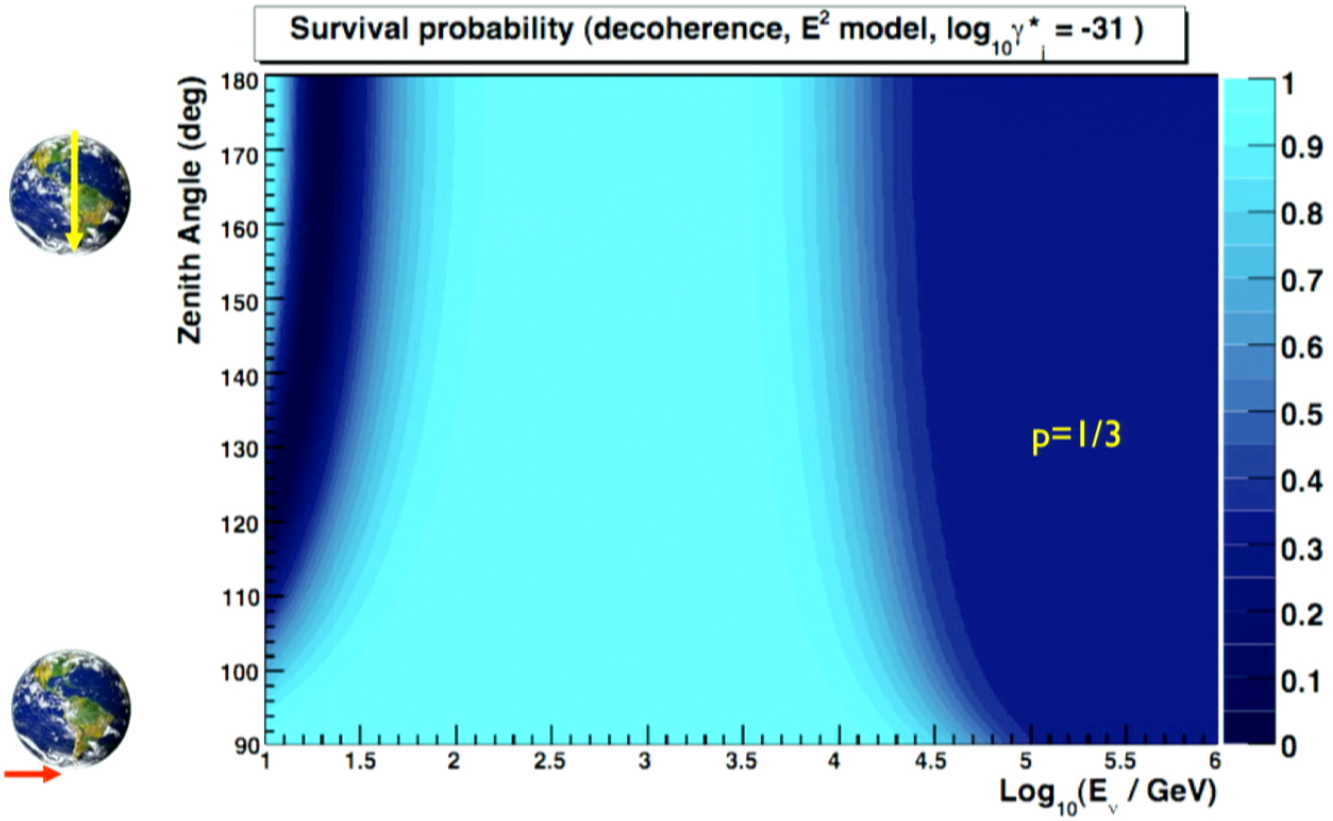

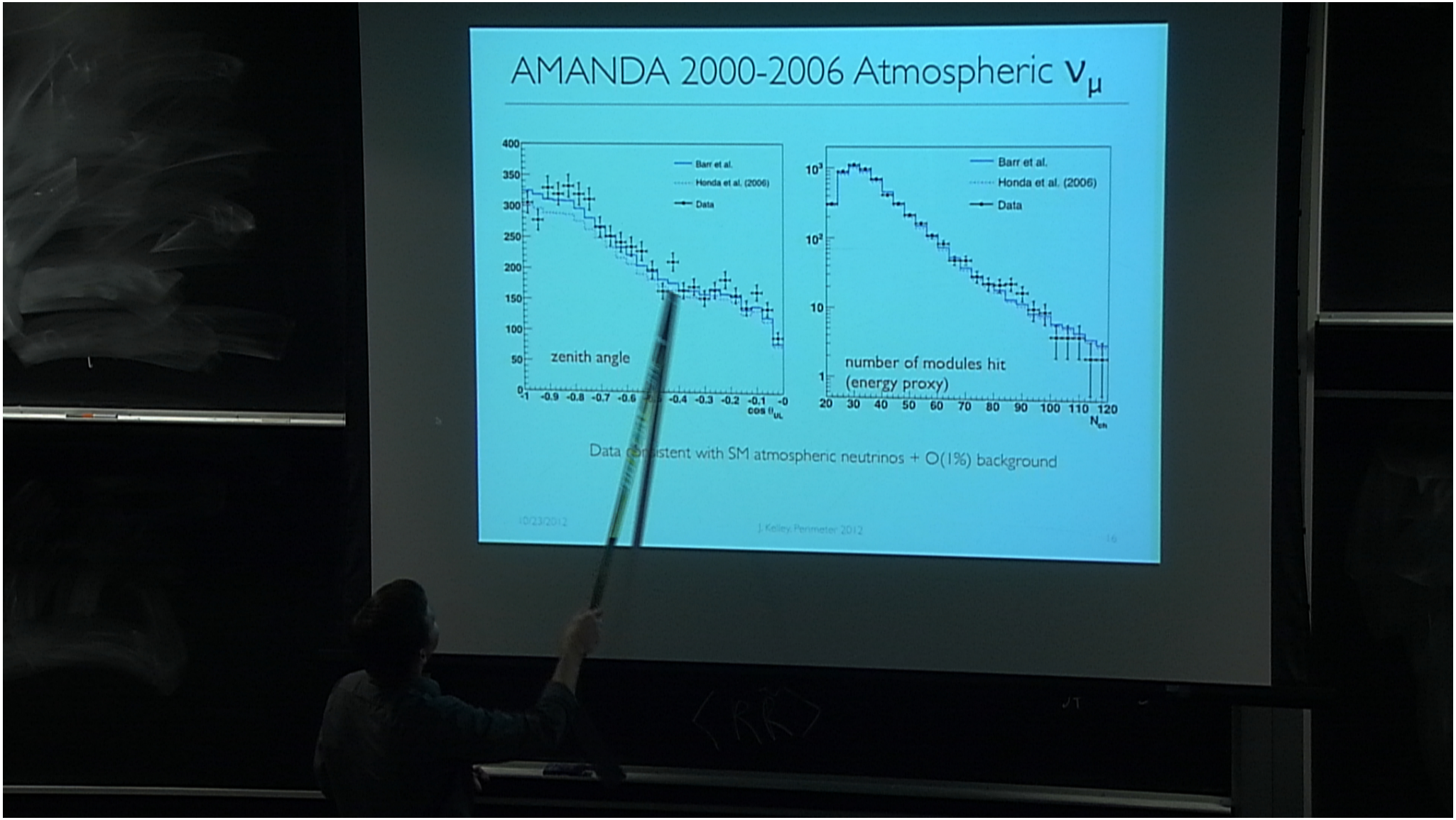
AMANDA 2000-2006 Atmospheric ν_μ
Barr et al.
Honda et al. (2006)
Data
zenith angle
$\cos\theta_{UL}$
Barr et al.
Honda et al. (2006)
Data
number of modules hit
(energy proxy)
N_{ch}
Data consistent with SM atmospheric neutrinos + O(1%) background
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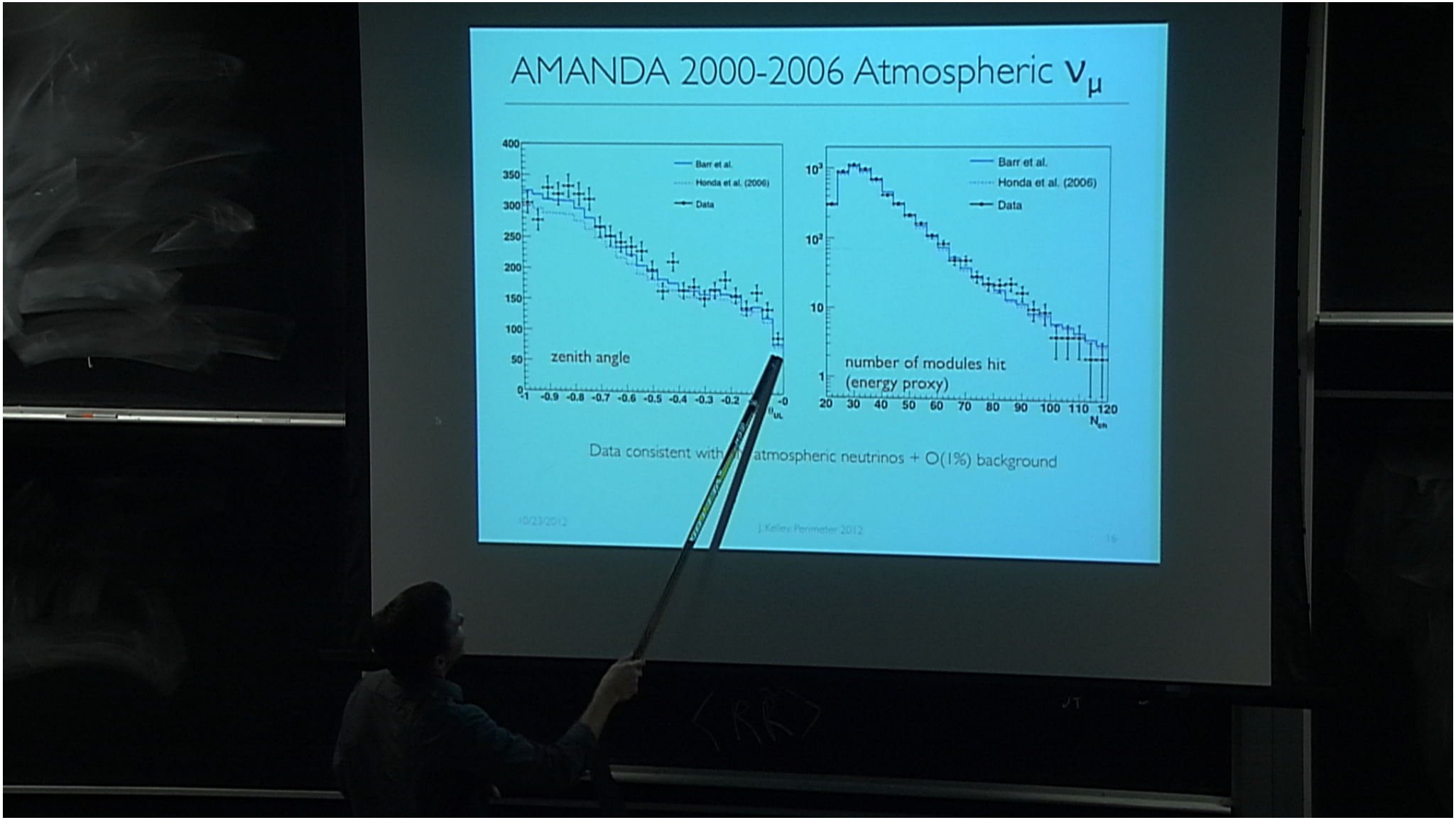
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10/23/2012
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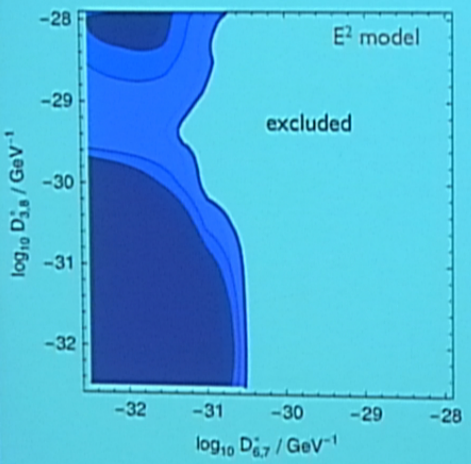
Results: Limit on Quantum Decoherence



- SuperK limit‡ (2-flavor):

  $\gamma_i < 0.9 \times 10^{-27}$ GeV^{-1} (90% CL)

  ‡ Lisi, Marrone, and Montanino, PRL 85 6 (2000)

- This analysis:

  $D^*_i < 1.3 \times 10^{-31}$ GeV^{-1} (90% CL)

  Abbasi *et al.*, PRD **79**, 102005 (2009)

- QG expectation? d^* of O(1) where

$$D = D^* E_\nu^n = d^* \frac{E_\nu^n}{M_{\rm Pl}^{n-1}}.$$

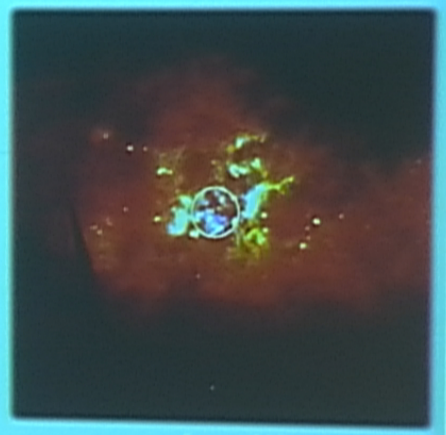
Limit for n=2: $d^* < 1.6 \times 10^{-12}$

Similar methods can be used to set limits on violation of Lorentz invariance

Other Possibilities

Astrophysical neutrino sources would provide even more powerful probes of QG

- Electron antineutrino decoherence from, say, Cygnus OB2 (see Anchordoqui *et al.*, hep-ph/0506168)
- But "standard" sources: degeneracy with 1:1:1 flavor ratio from standard oscillations
- Distortions in high-energy neutrino spectra?
- Time delays from GRBs?



Cygnus OB2 region
courtesy of J. Knoedlseder

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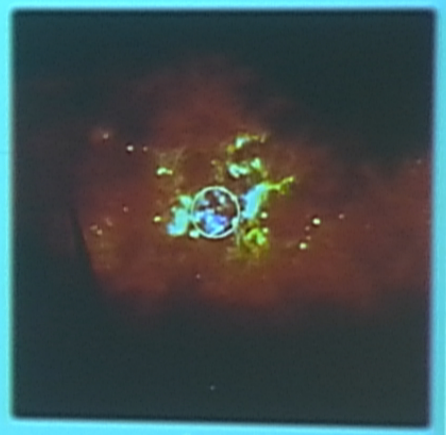

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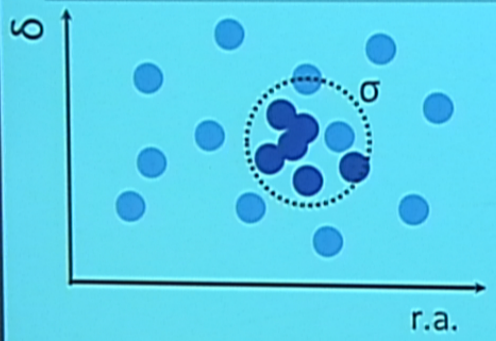
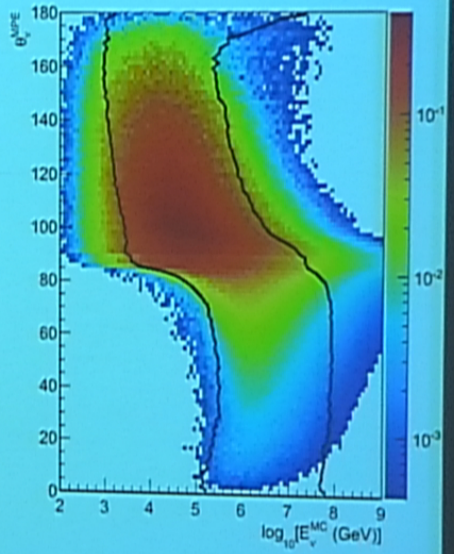
Neutrino Point Source Searches



- Unbinned likelihood search to search for time-independent clustering
- Covers both hemispheres (different backgrounds, energy regimes)



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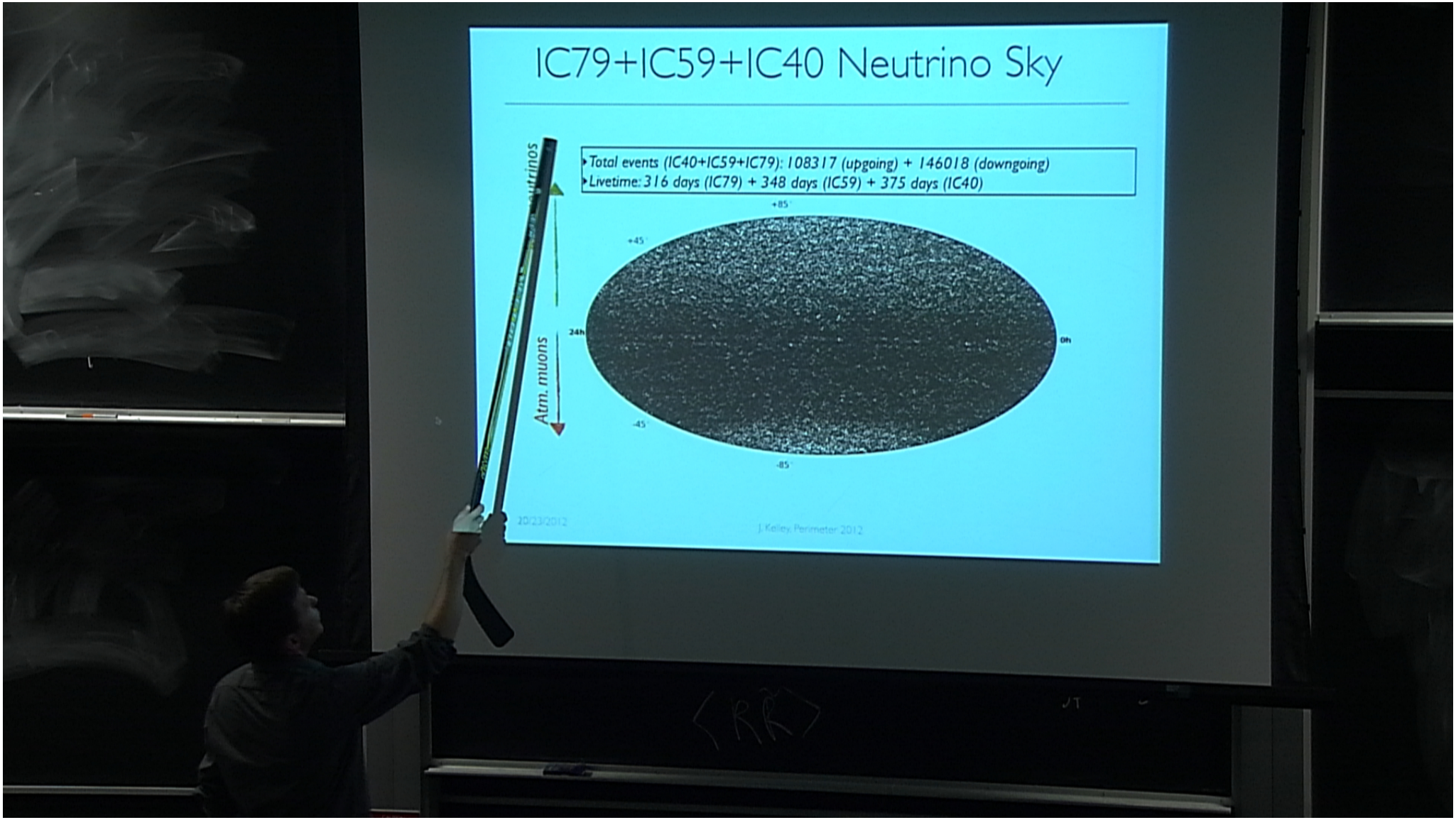
IC79+IC59+IC40 Neutrino Sky
Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)
Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)
Atm. muons
+85°
+45°
24h
0h
-45°
-85°
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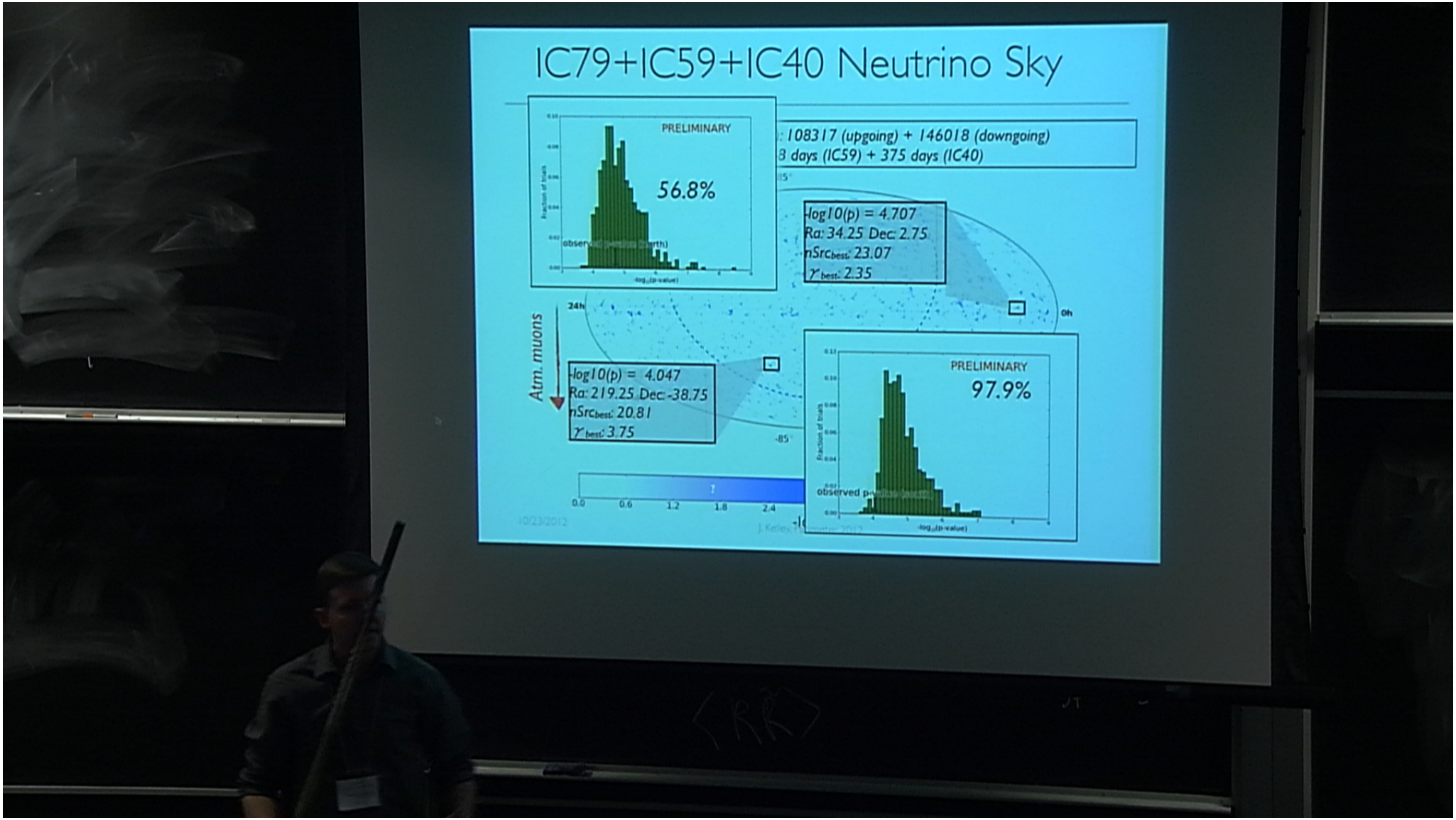
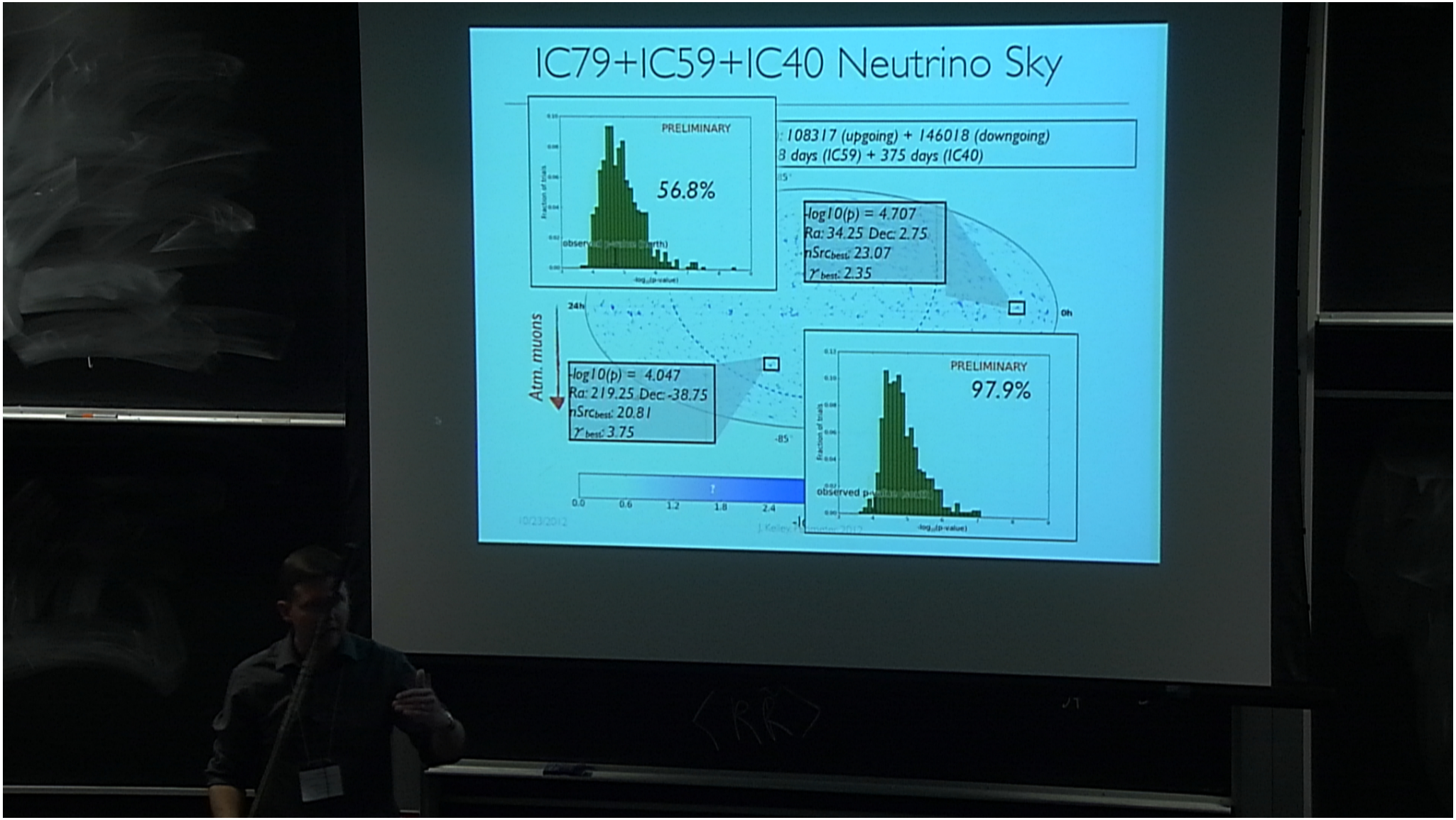

IC79+IC59+IC40 Neutrino Sky
PRELIMINARY
56.8%
108317 (upgoing) + 146018 (downgoing)
3 days (IC59) + 375 days (IC40)
-log10(p) = 4.707
Ra: 34.25 Dec: 2.75
nSrc best: 23.07
γ best: 2.35
Atm. muons
-log10(p) = 4.047
Ra: 219.25 Dec: -38.75
nSrc best: 20.81
γ best: 3.75
PRELIMINARY
97.9%
0.0
0.6
1.2
1.8
2.4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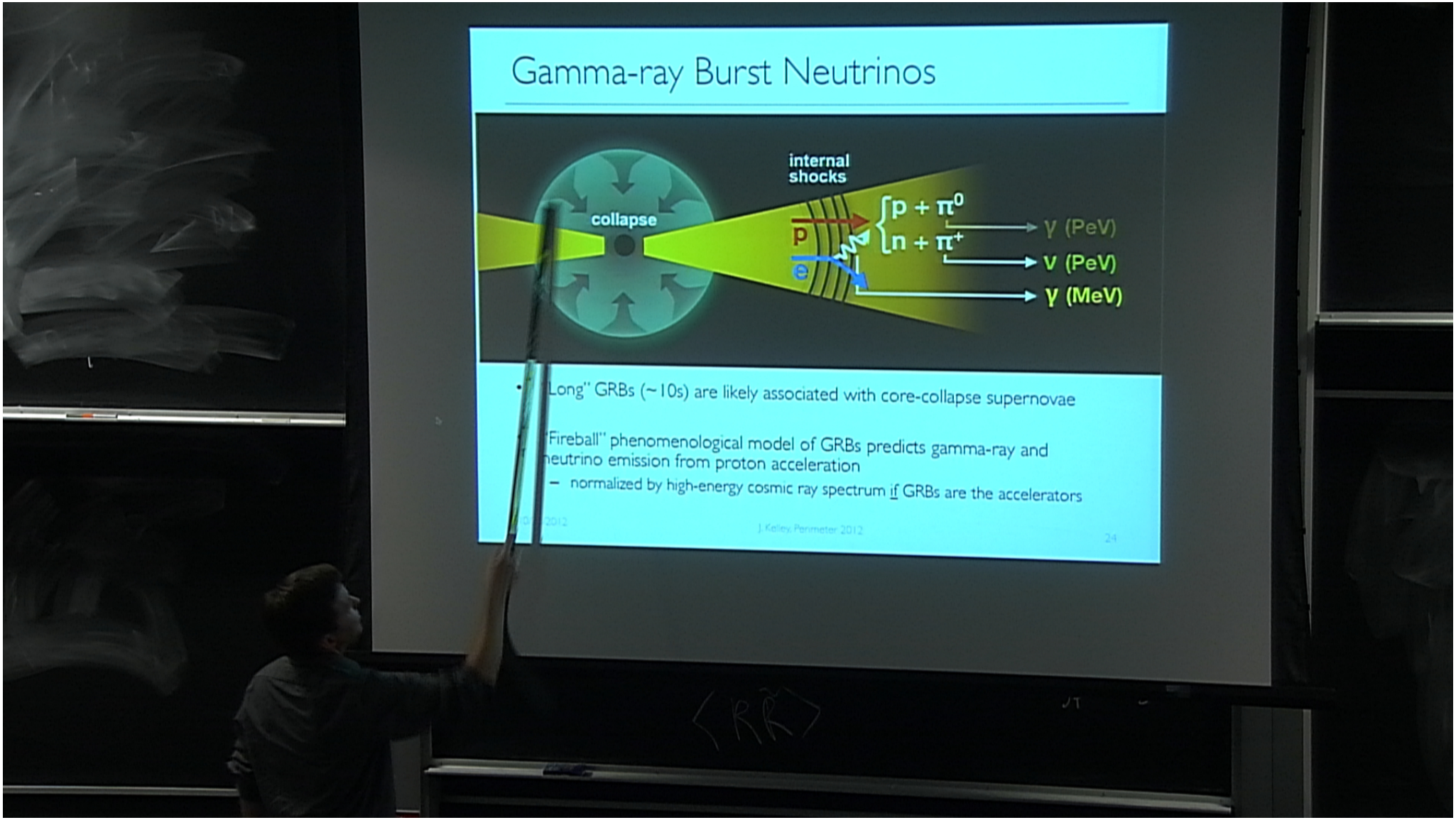
Gamma-ray Burst Neutrinos
internal shocks
collapse
p
e
p + π0
n + π+
γ (PeV)
ν (PeV)
γ (MeV)
Long" GRBs (~10s) are likely associated with core-collapse supernovae
Fireball" phenomenological model of GRBs predicts gamma-ray and neutrino emission from proton acceleration
– normalized by high-energy cosmic ray spectrum if GRBs are the accelerators
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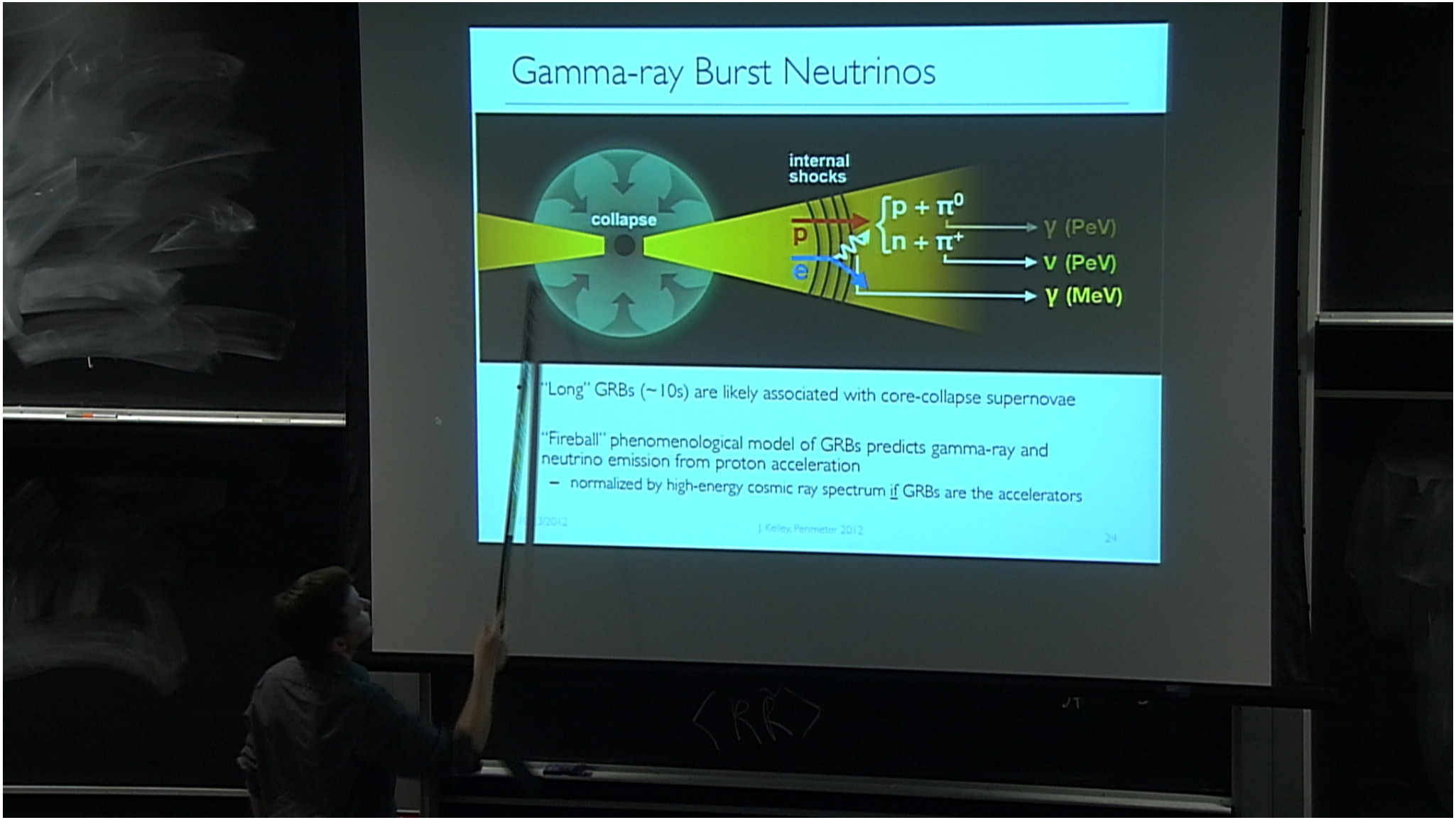
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3/2012
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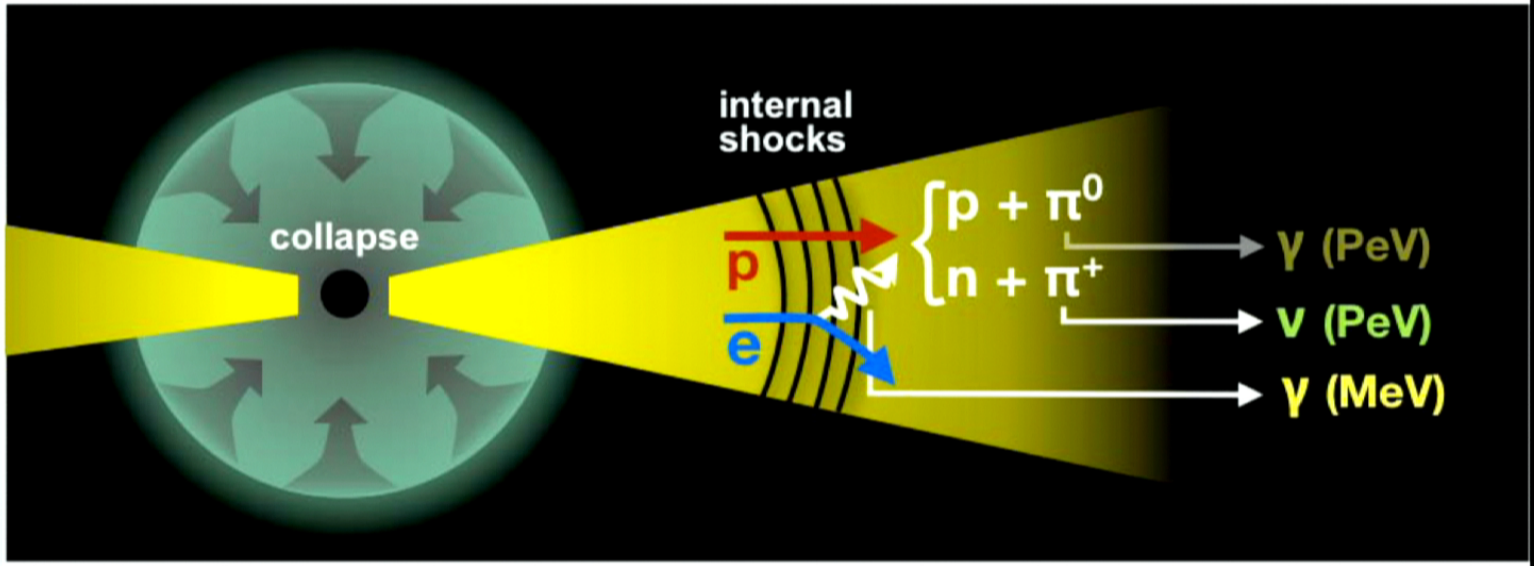

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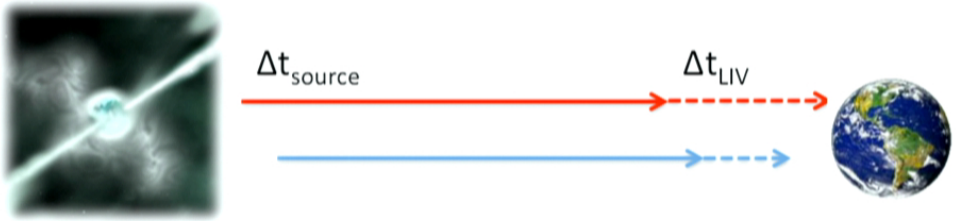
- "Fireball" phenomenological model of GRBs predicts gamma-ray and neutrino emission from proton acceleration
  - normalized by high-energy cosmic ray spectrum if GRBs are the accelerators

GRB Neutrinos as a Probe of QG

Lorentz violation, dispersion of: $E^2 = p^2 + m^2 \pm E^2(\frac{E}{\xi E_{Planck}})^n \pm \ldots$

time delay / advance of $\Delta t_{LIV} \simeq \frac{1+n}{2}(\frac{d}{c})(\frac{E}{\xi E_{Planck}})^n$

GRB neutrinos: large d and high E!



Benefits: possibly larger distances, higher energies with neutrinos than photons

Challenges: source physics (intrinsic delays up to O(1000) seconds) and energy measurement
Other challenge: have to detect the neutrinos first!

- U. Jacob and T. Piran, *Nature Phys.* **3**, 87 (2007)
- M.C. Gonzalez-Garcia and F. Halzen, *JCAP* **0702**, 008 (2007)
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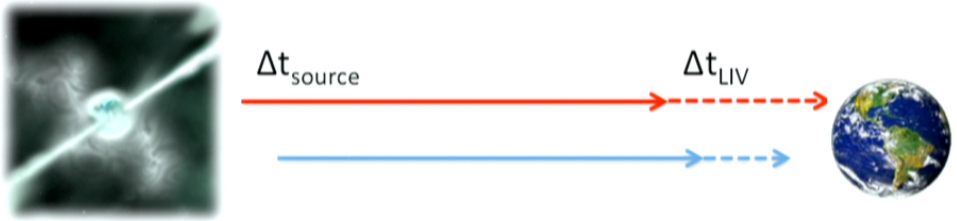

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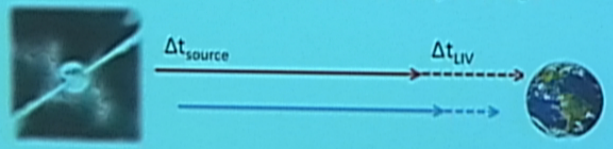

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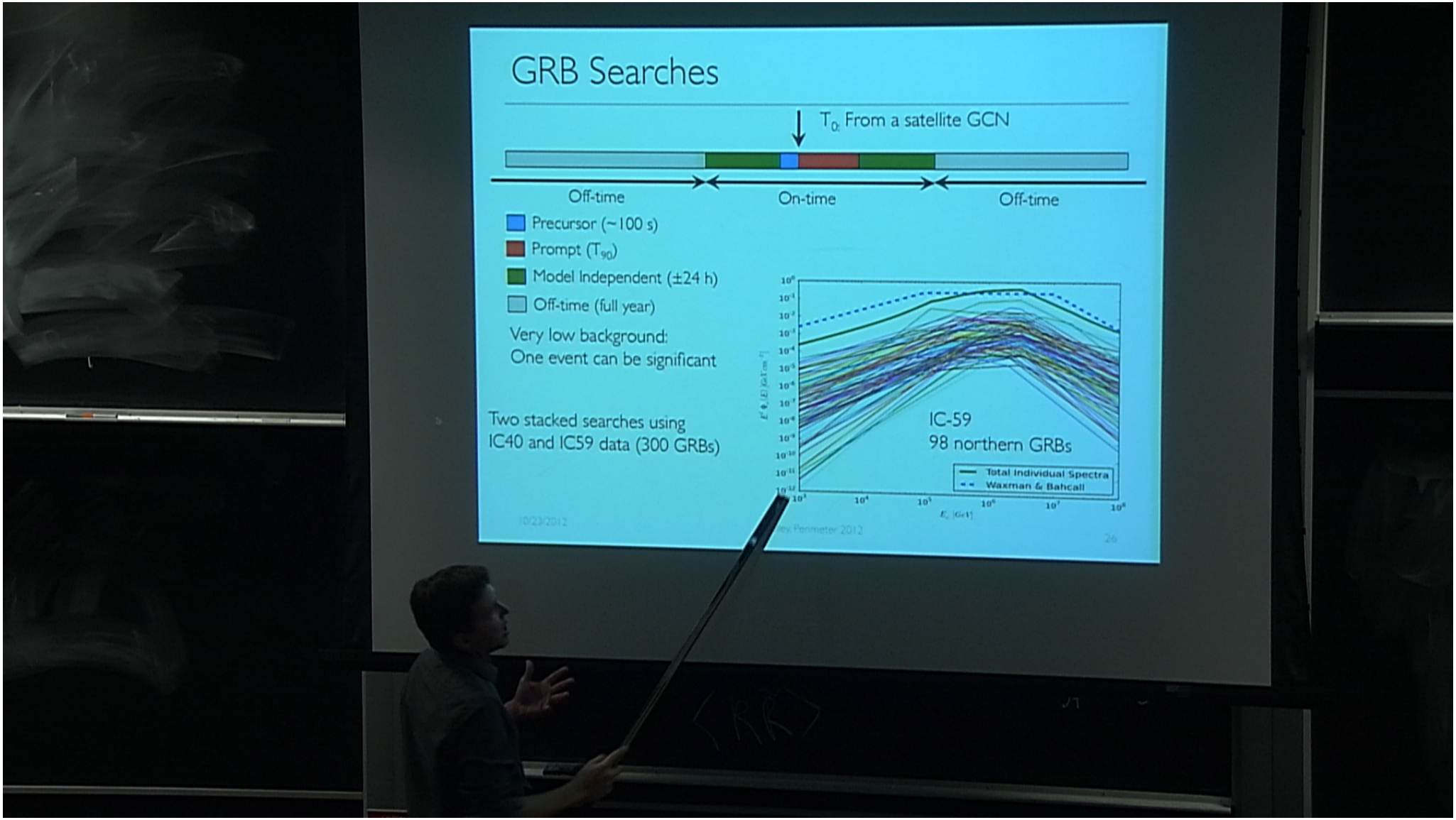
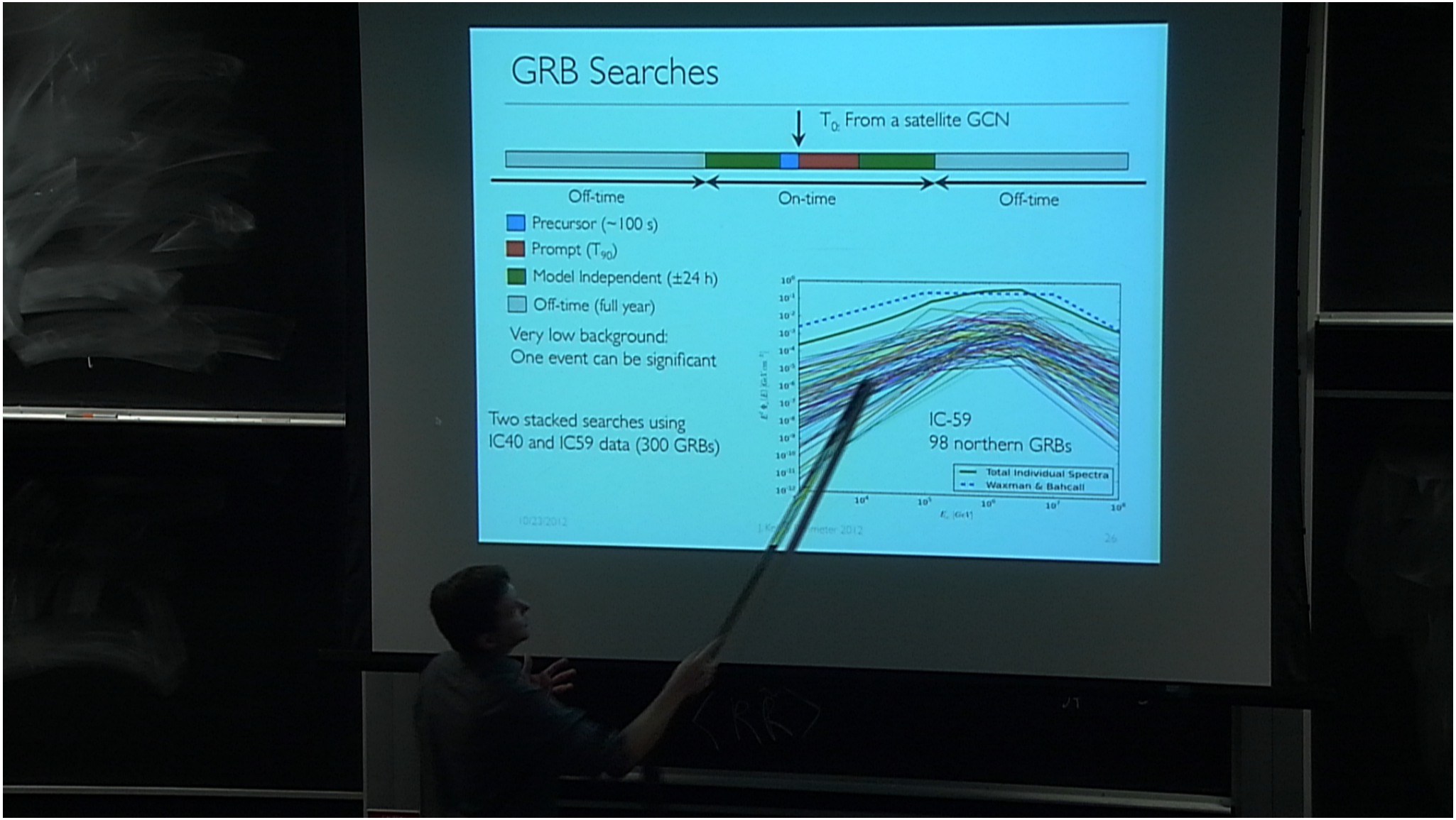
Challenges: source physics (intrinsic delays up to O(1000) seconds) and energy measurement

Other challenge: have to detect the neutrinos first!

- U. Jacob and T. Piran, *Nature Phys.* **3**, 87 (2007)
- M.C. Gonzalez-Garcia and F. Halzen, *JCAP* **0702**, 008 (2007)
- G. Amelino-Camelia and L. Smolin, *Phys. Rev. D* **80**, 084017 (2009)


GRB Searches
T0: From a satellite GCN
Off-time
On-time
Off-time
Precursor (~100 s)
Prompt (T90)
Model Independent (±24 h)
Off-time (full year)
Very low background:
One event can be significant
Two stacked searches using
IC40 and IC59 data (300 GRBs)
IC-59
98 northern GRBs
Total Individual Spectra
Waxman & Bahcall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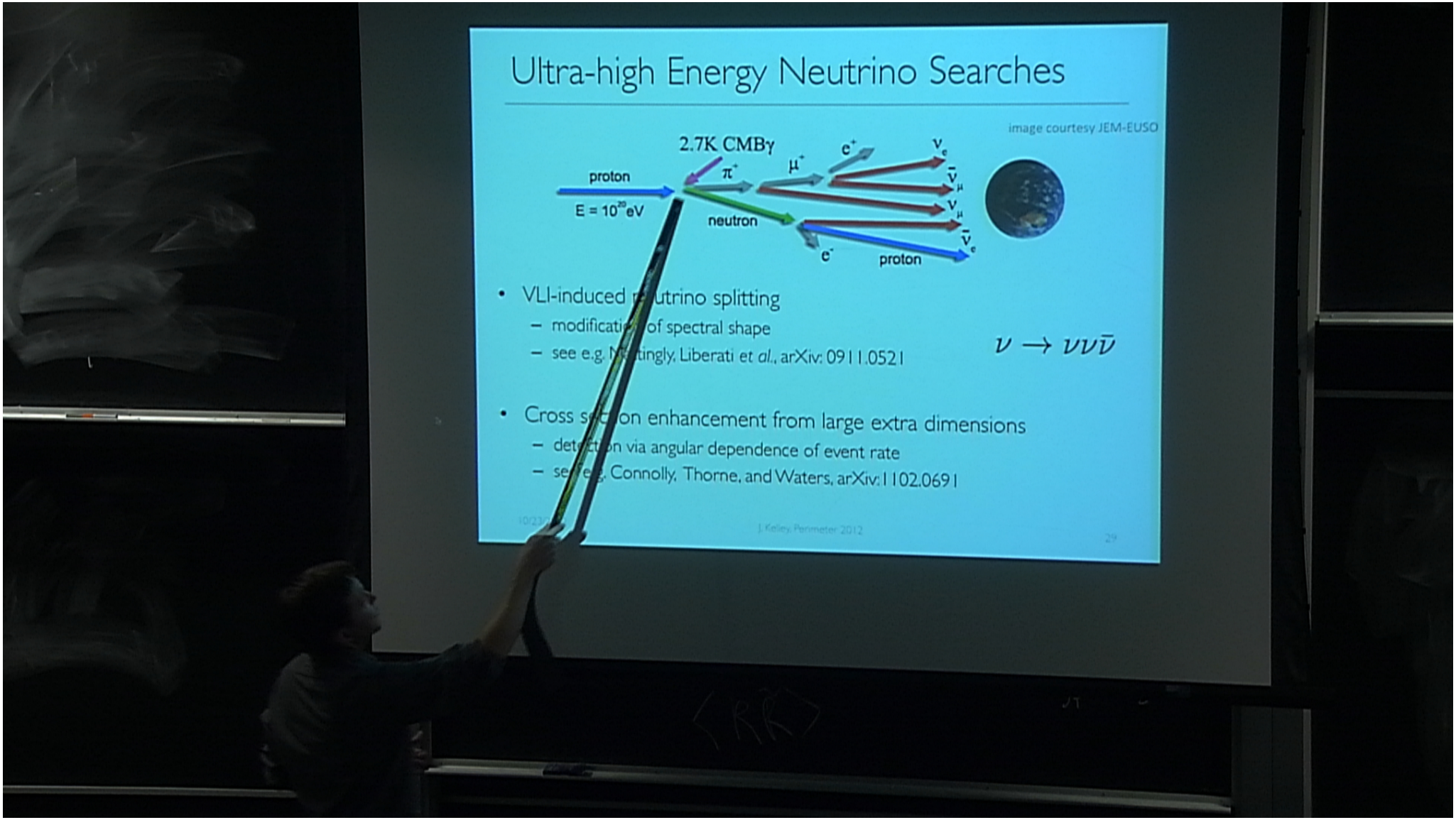
Ultra-high Energy Neutrino Searches
image courtesy JEM-EUSO
2.7K CMBγ
proton
E = 10^20 eV
neutron
proton
• VLI-induced neutrino splitting
– modification of spectral shape
– see e.g. Mattingly, Liberati et al., arXiv: 0911.0521
$\nu \rightarrow \nu\nu\bar{\nu}$
• Cross section enhancement from large extra dimensions
– detection via angular dependence of event rate
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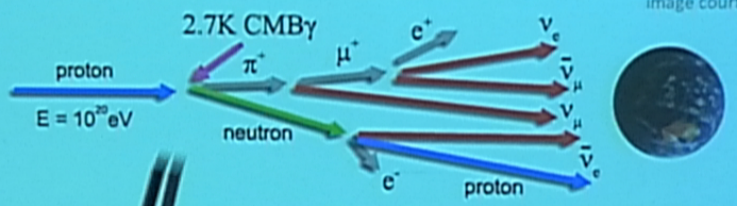
J. Kelley, Perimeter 2012

Ultra-high Energy Neutrino Searches

image courtesy JEM-EUSO



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  - see e.g. Mattingly, Liberati *et al.*, arXiv: 0911.0521

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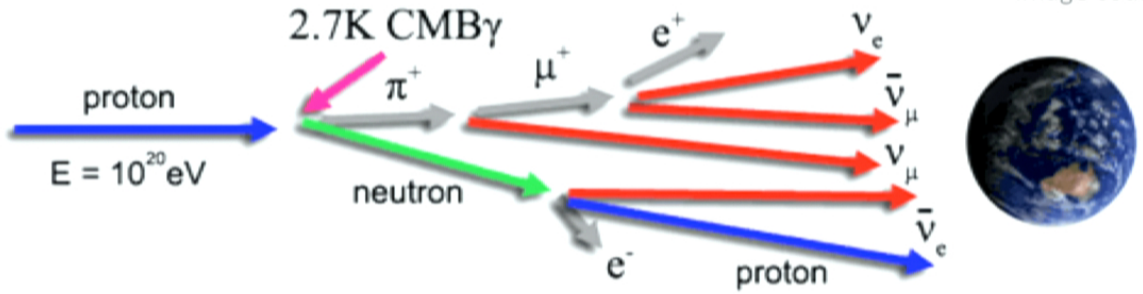

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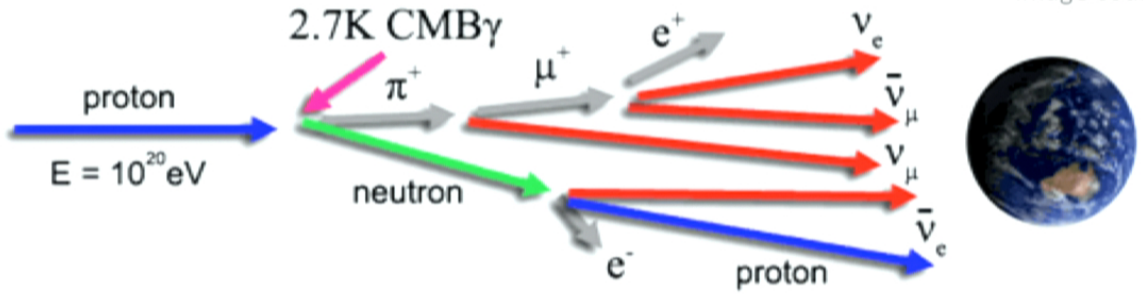

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The Neutrino Connection

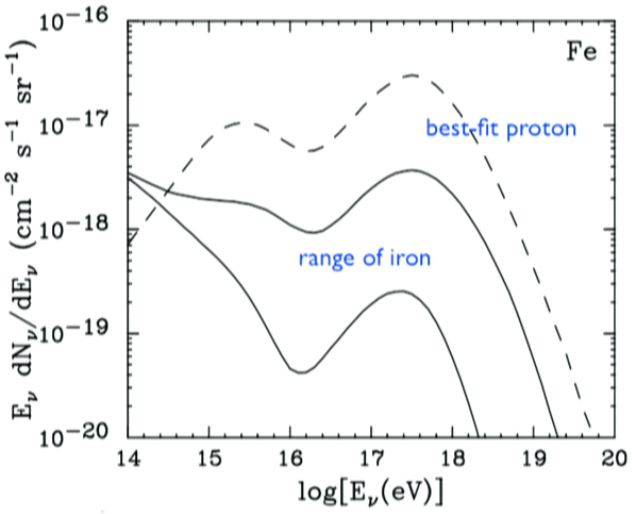
- GZK process also produces UHE neutrinos!

$$p\gamma \rightarrow n\pi^{+} \rightarrow n\mu + \nu_{\mu}$$

- Nuclei will tend to photodisintegrate first (reduced flux)

- Neutrino measurement could confirm GZK nature of CR suppression

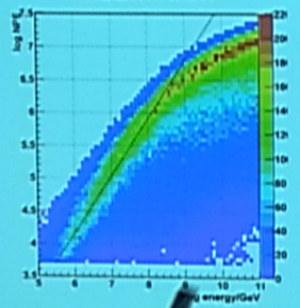
GZK neutrino flux models



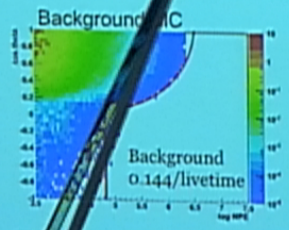
Anchordoqui *et al.*, PRD **76** 123008 (2007)

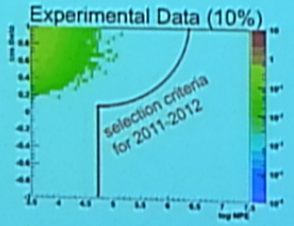
IceCube EHE Neutrino Search

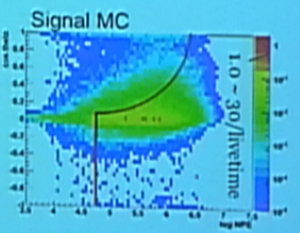
PRELIMINARY



- May 2010 – May 2012 (672.7 days livetime)
- Primary selection criterion: high "NPE"
- Track reconstruction quality removes corner-clippers, coincident CR events







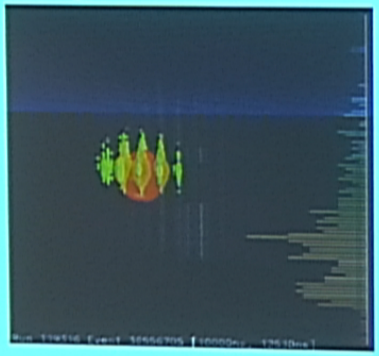
J. Kelley, Perimeter 2012

see also first IceCube upper limits: Phys. Rev. D 82, 072003 (2010)

Neutrino Candidates

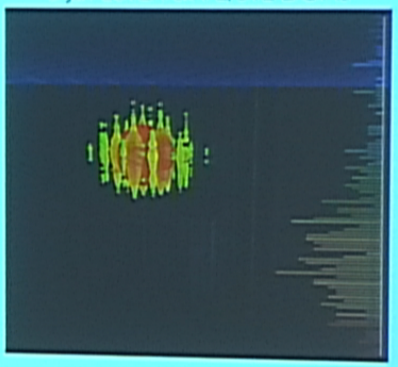
Two cascade events in unblinded data sample (background estimation: 0.14 events; 2.36 σ)

9 Aug. 2011: 70k PE, 354 DOMs



"Bert" ~1100 TeV

3 Jan 2012: 96k PE, 312 DOMs



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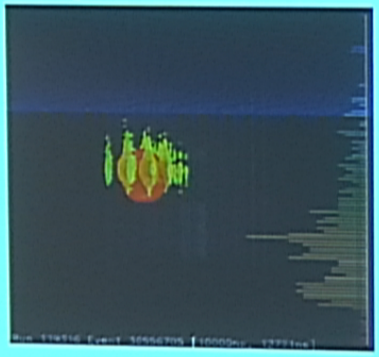

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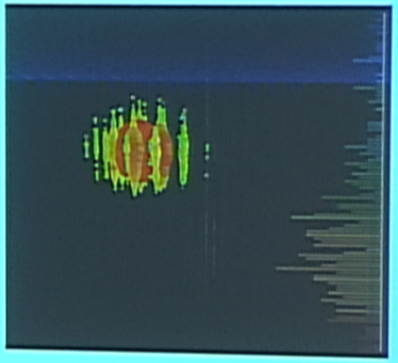

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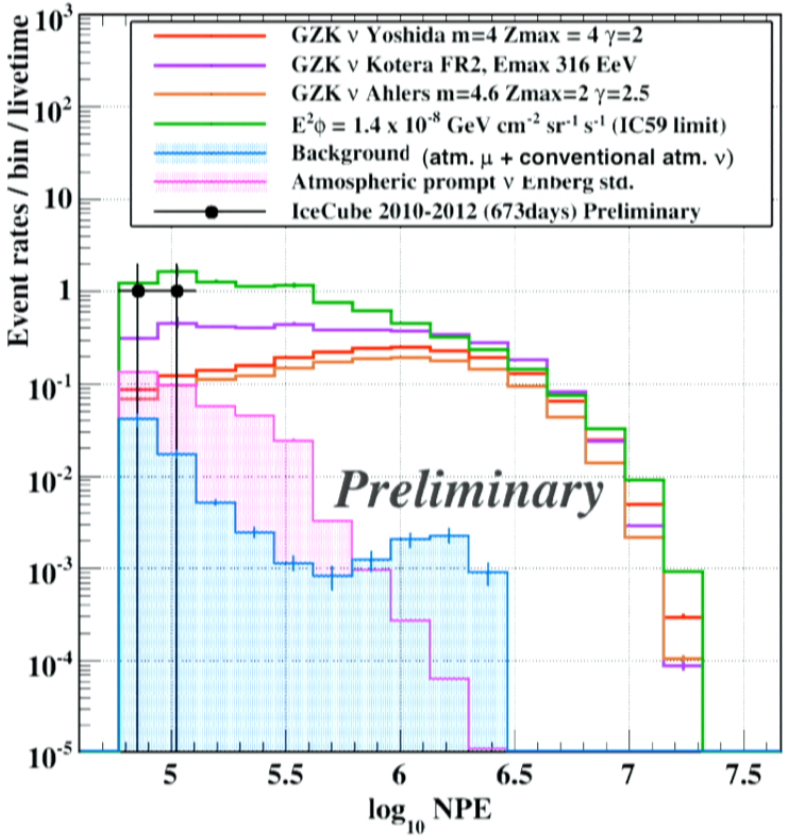
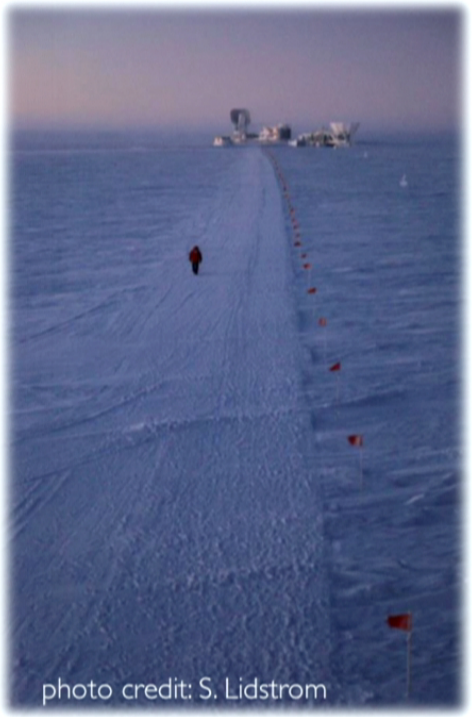
PRELIMINARY

Event Brightness



- No indication that they are background cosmic-ray muons
- Analysis of energy, directions ongoing
- Follow-up analysis in progress
  - extend to lower energies
  - veto downgoing atmospheric neutrinos
  - all flavors

Conclusions and outlook



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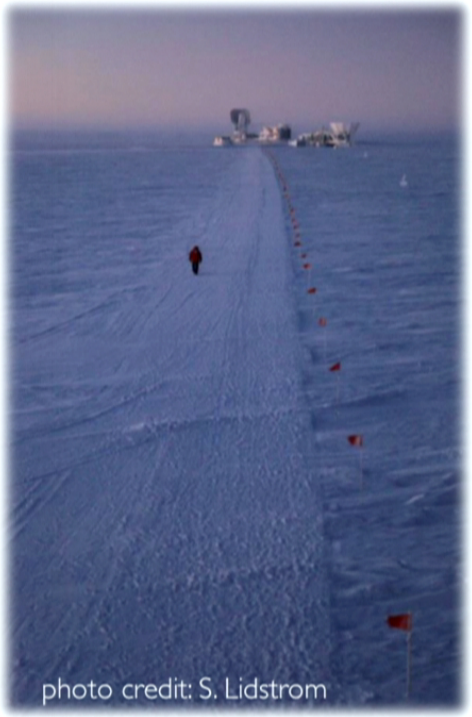

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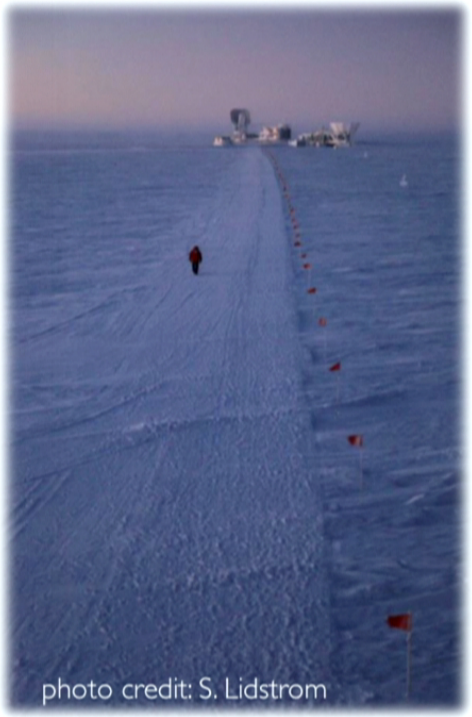

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