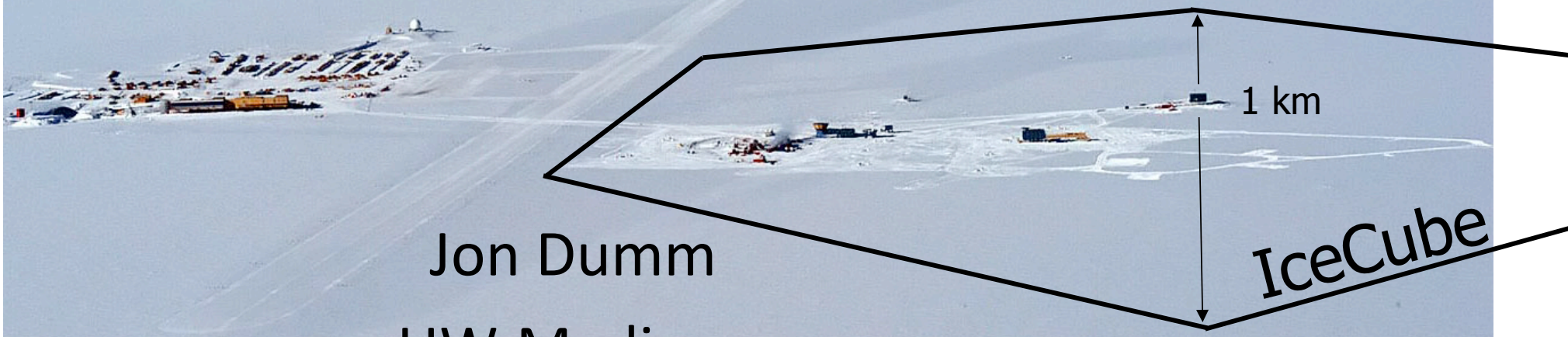
A Search for Point Sources with the IceCube Neutrino Observatory



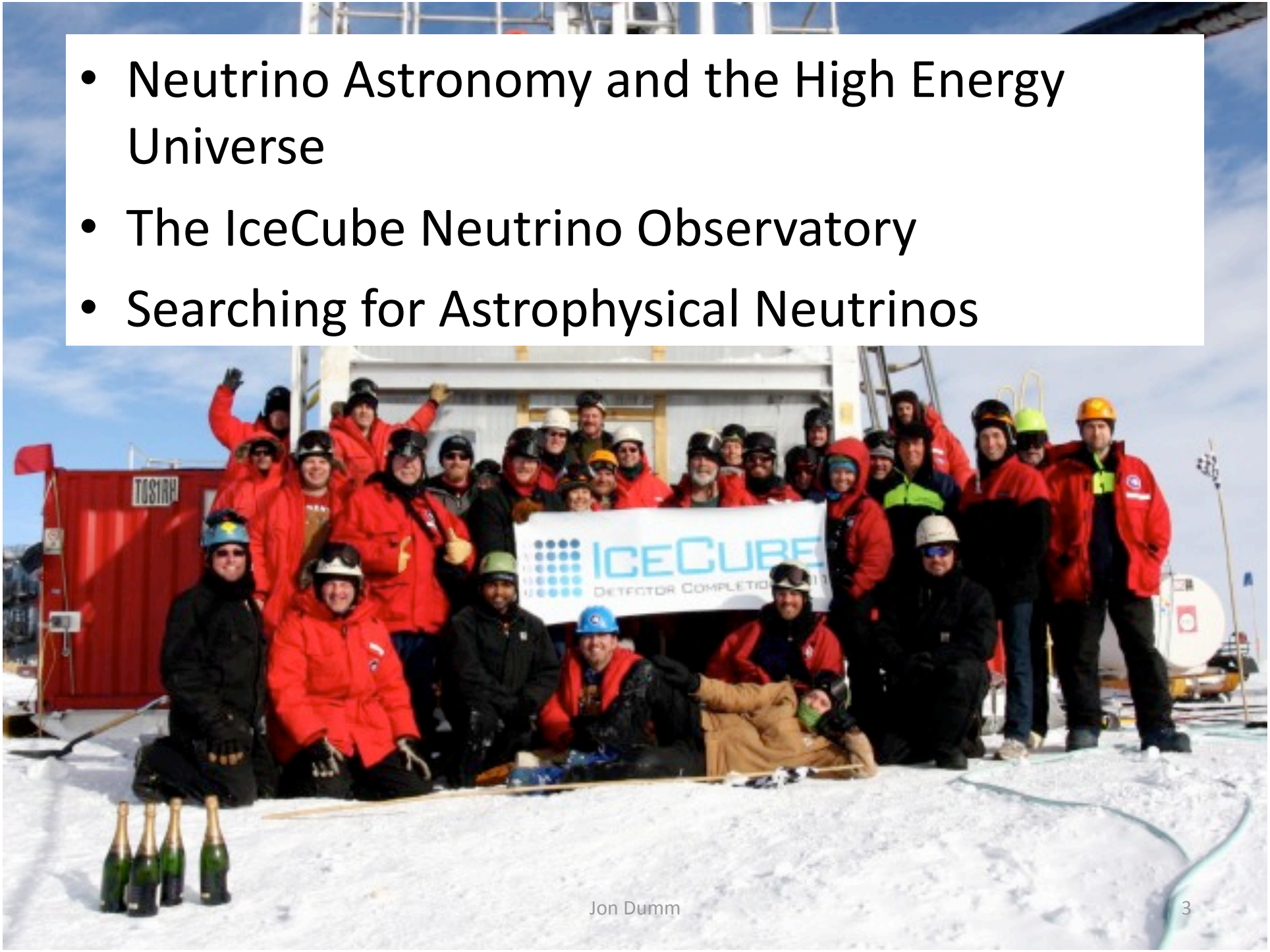
Jon Dumm

UW-Madison

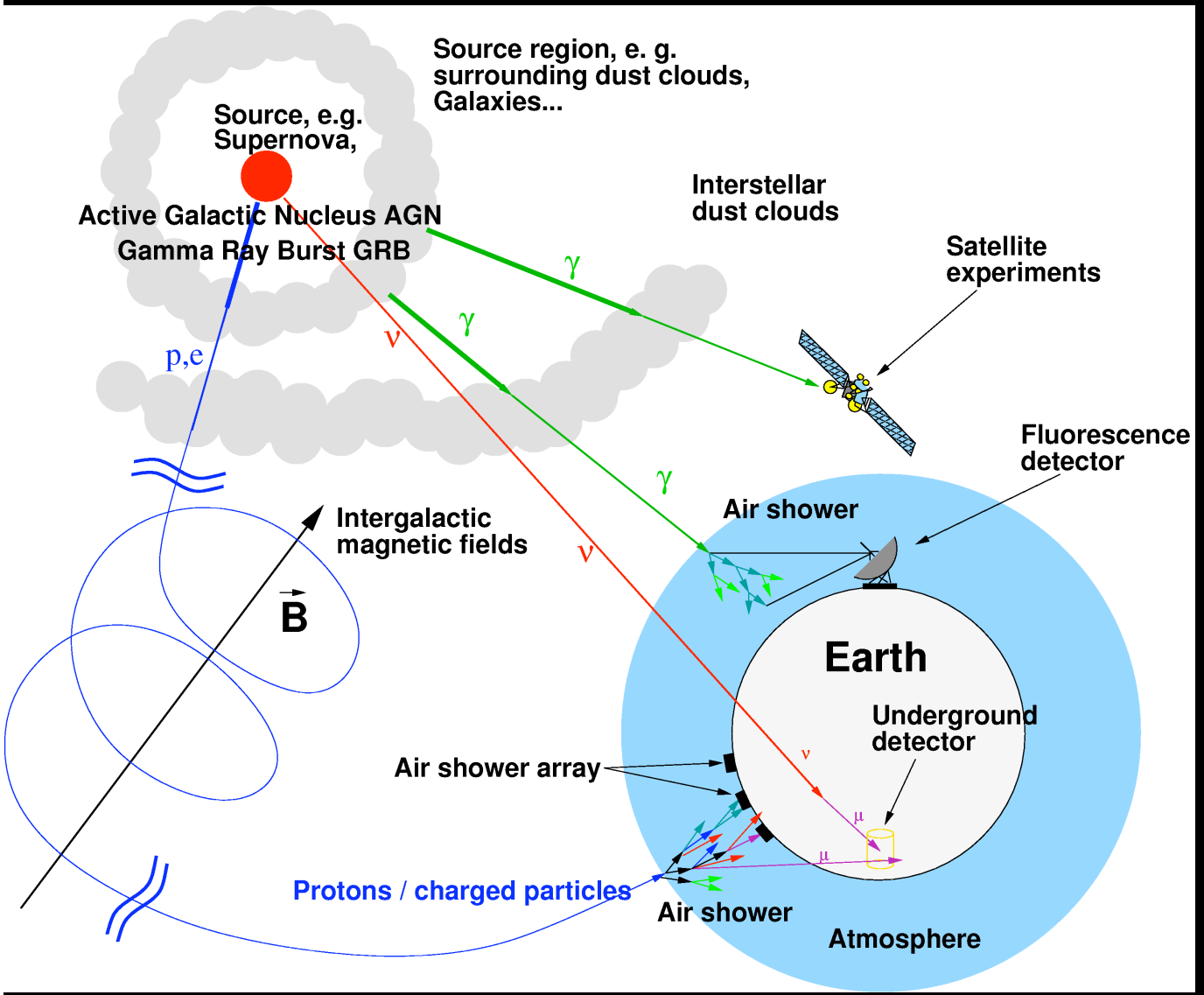
Feb 24, 2011


TOSTRH
ICECUBE

- Neutrino Astronomy and the High Energy Universe
- The IceCube Neutrino Observatory
- Searching for Astrophysical Neutrinos



Neutrinos as Cosmic Messengers

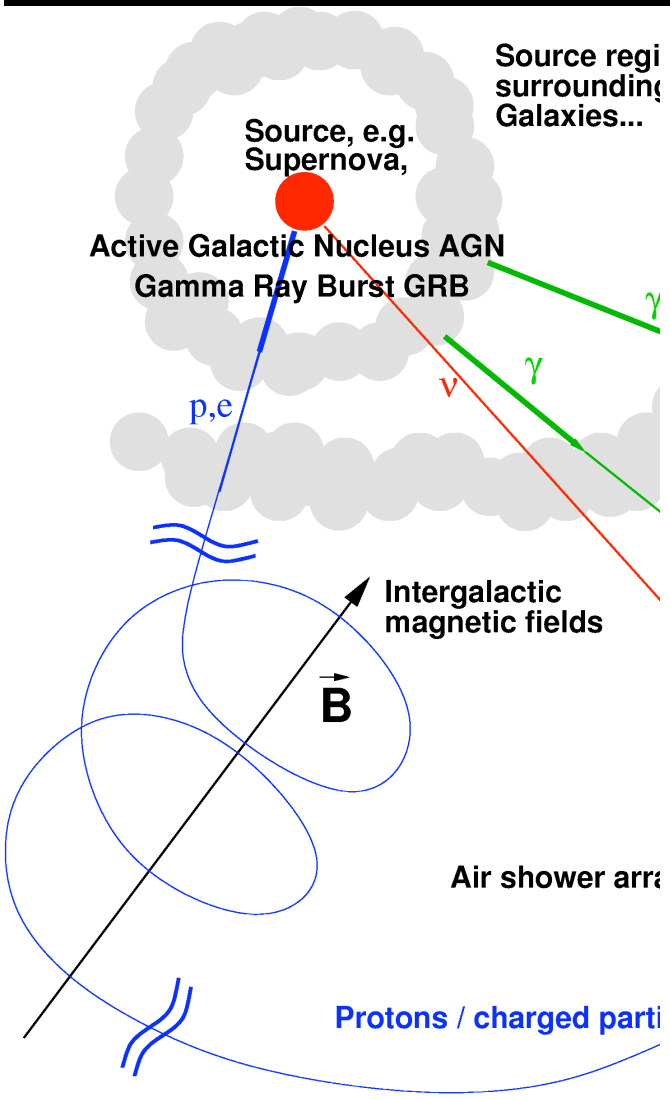


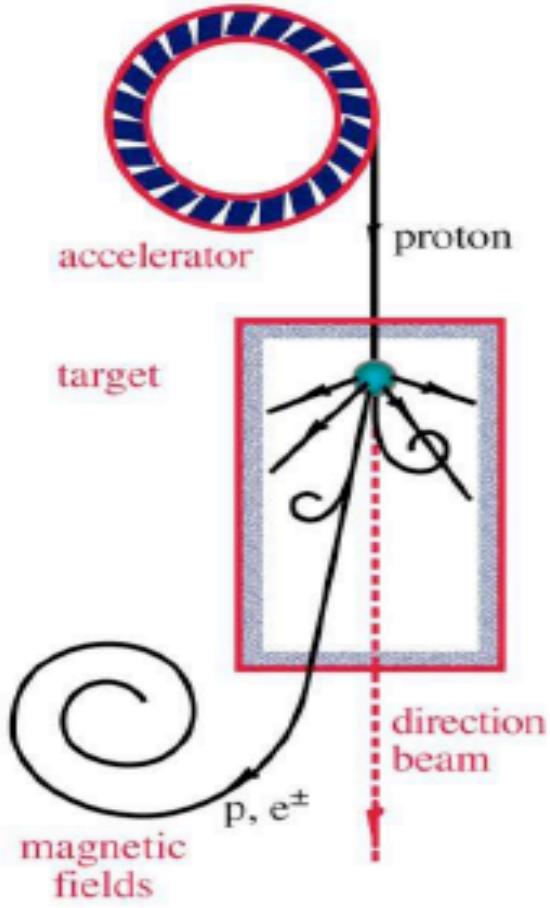
γ *Photons:* easily absorbed by CMB and IR backgrounds.

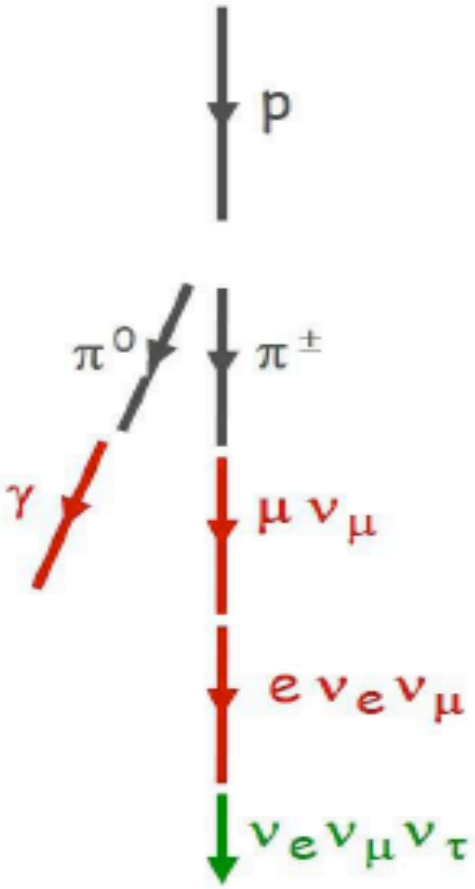
p *Protons:* deflected by magnetic fields.

ν *Neutrinos:* not deflected by magnetic fields. Low interaction cross-section.

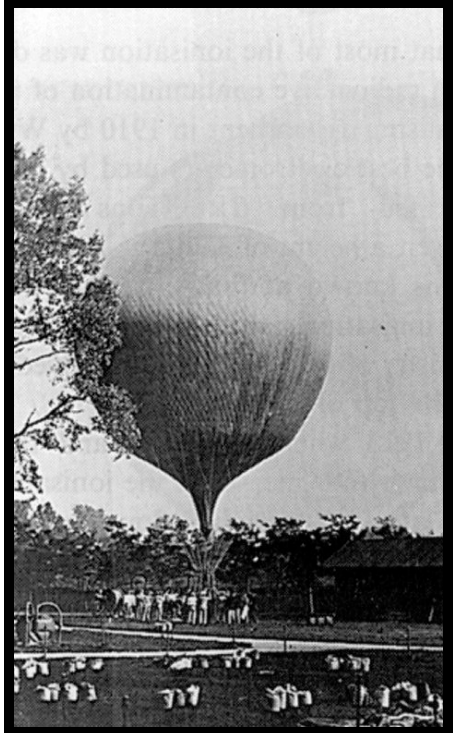
Neutrinos as Cosmic Messengers







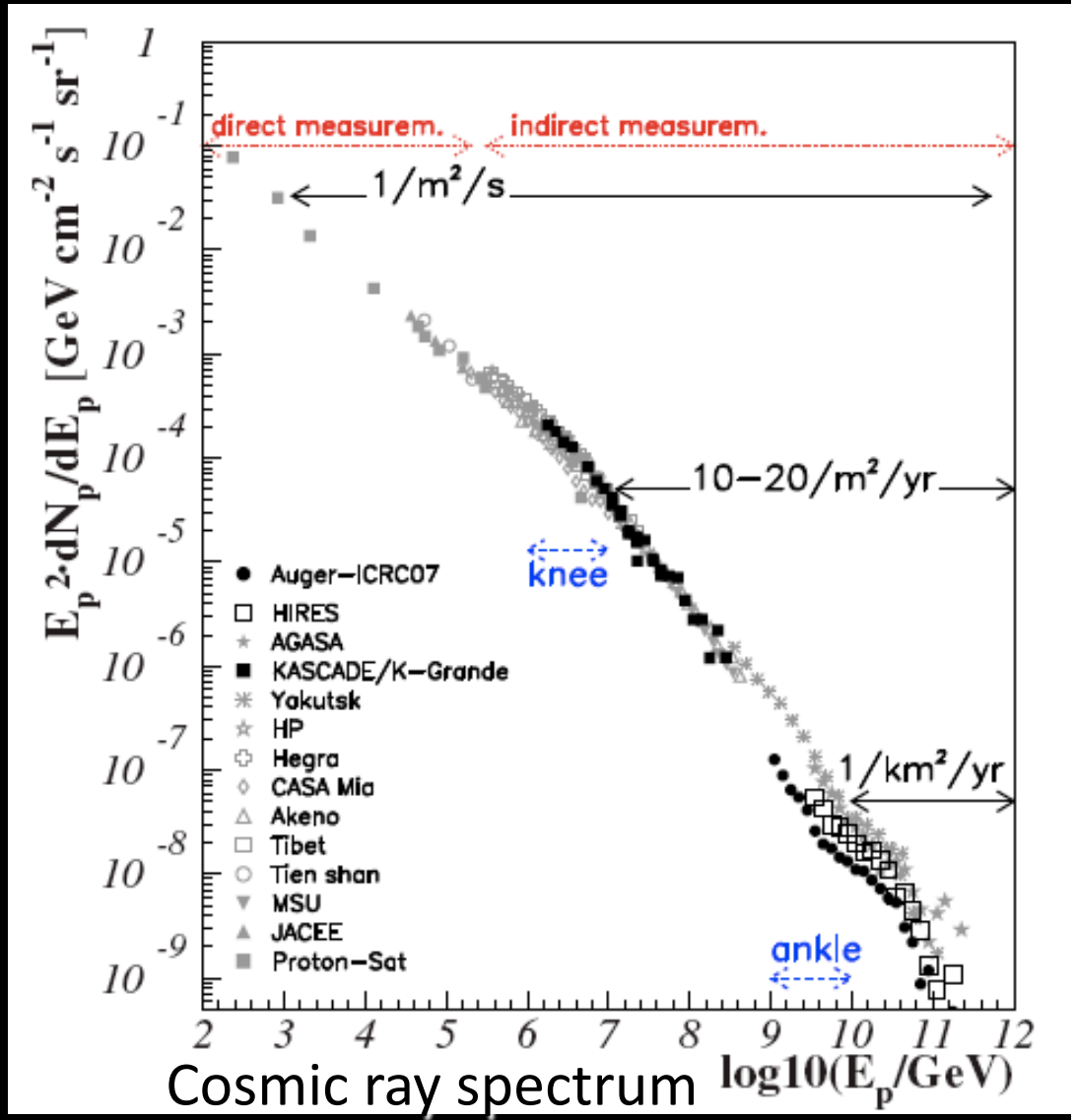
Cosmic Rays: a 100 year-old mystery



Balloon flights
1911-1913



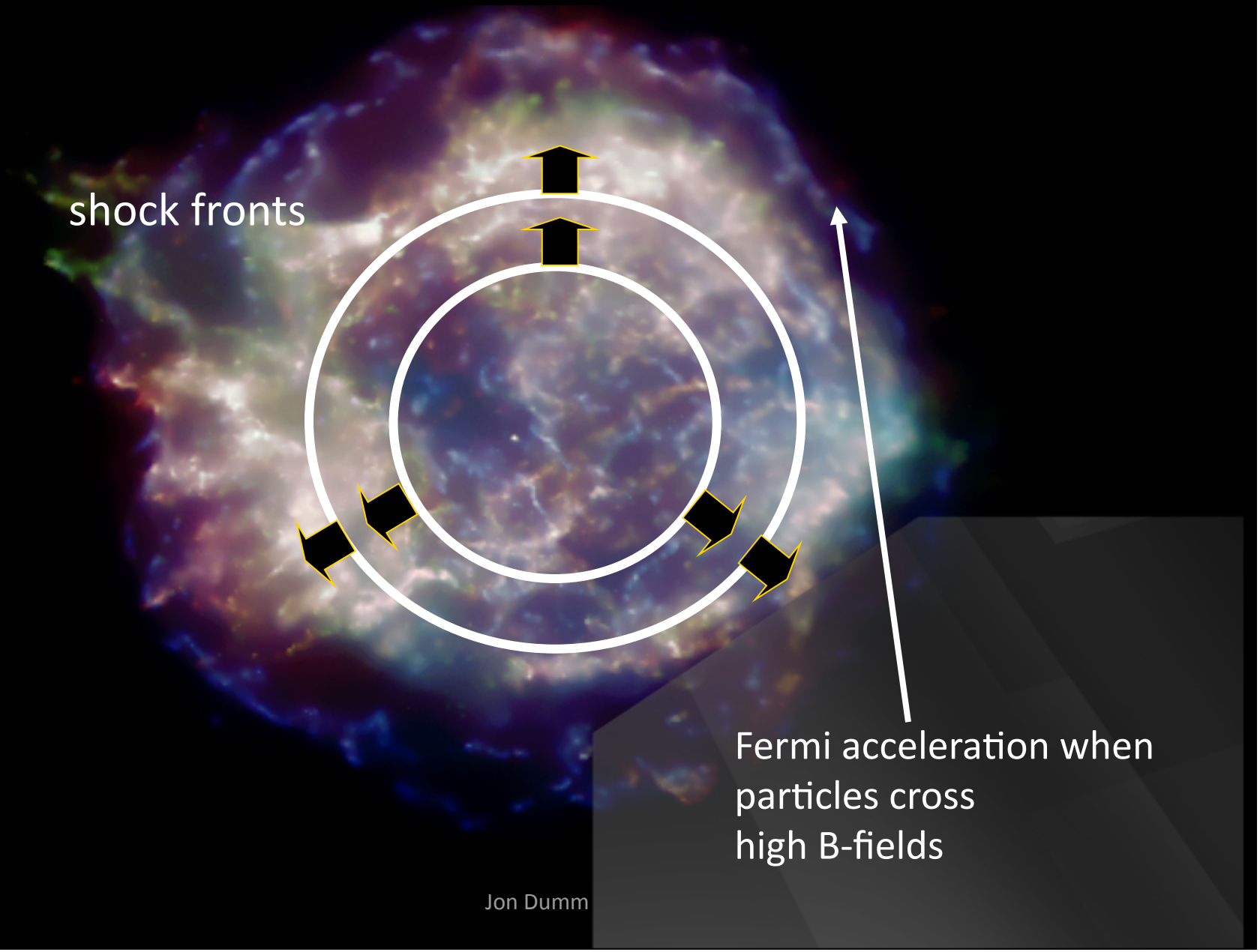
Victor Hess
Nobel Prize
1936



Cosmic ray spectrum

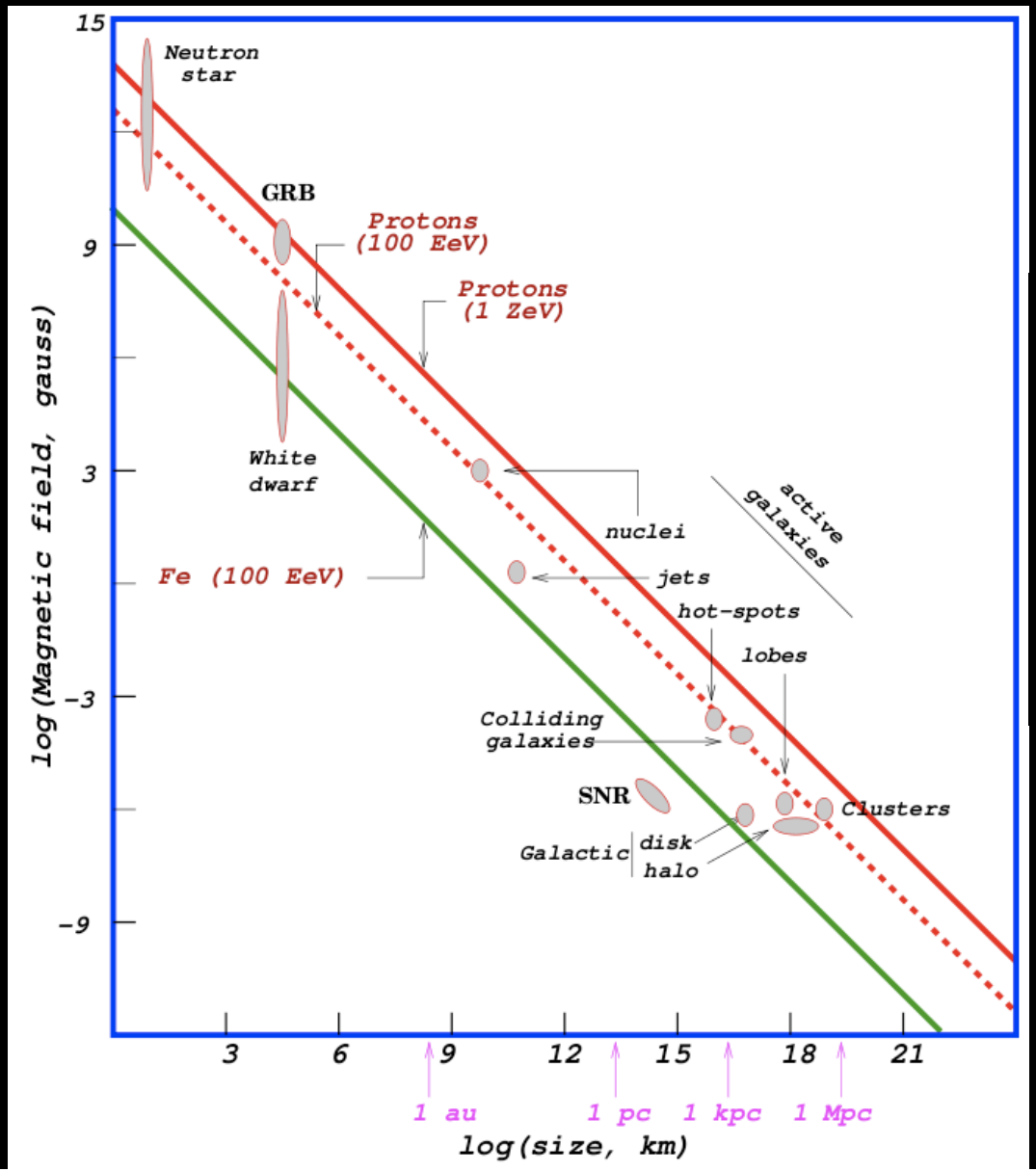
- Power law over many decades
- Origin Uncertain

Cas A Supernova Remnant in X-rays

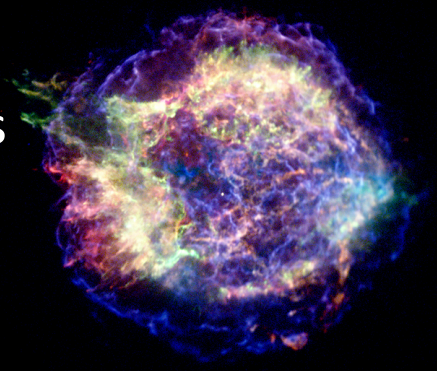


Jon Dumm

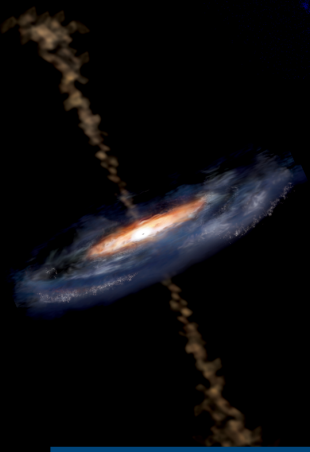
What Are the Cosmic Ray Sources?



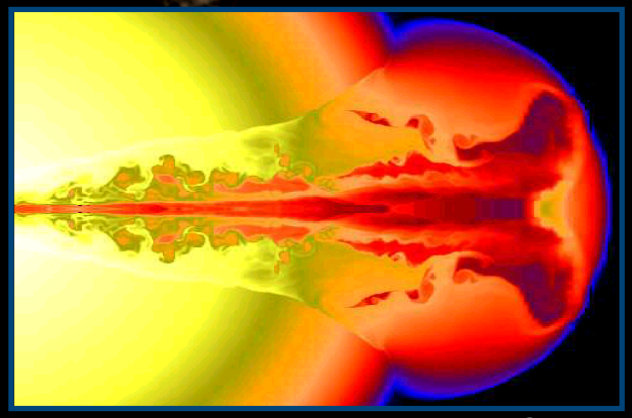
SN Remnants



AGN

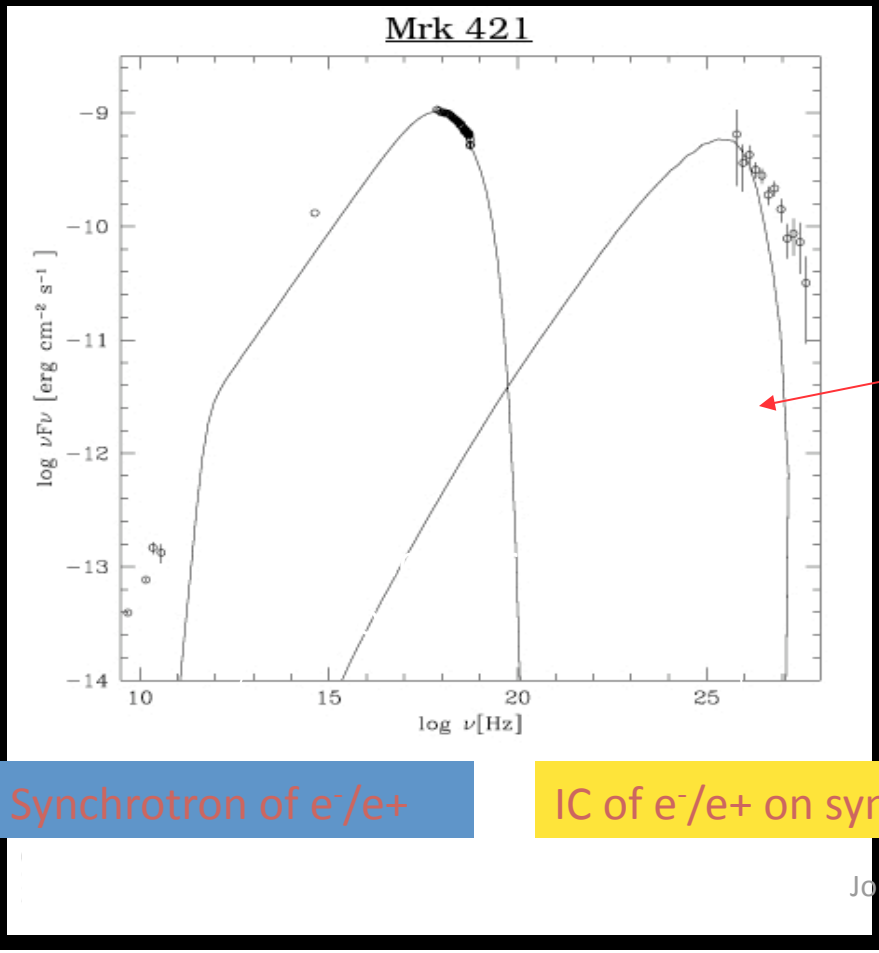


GRB



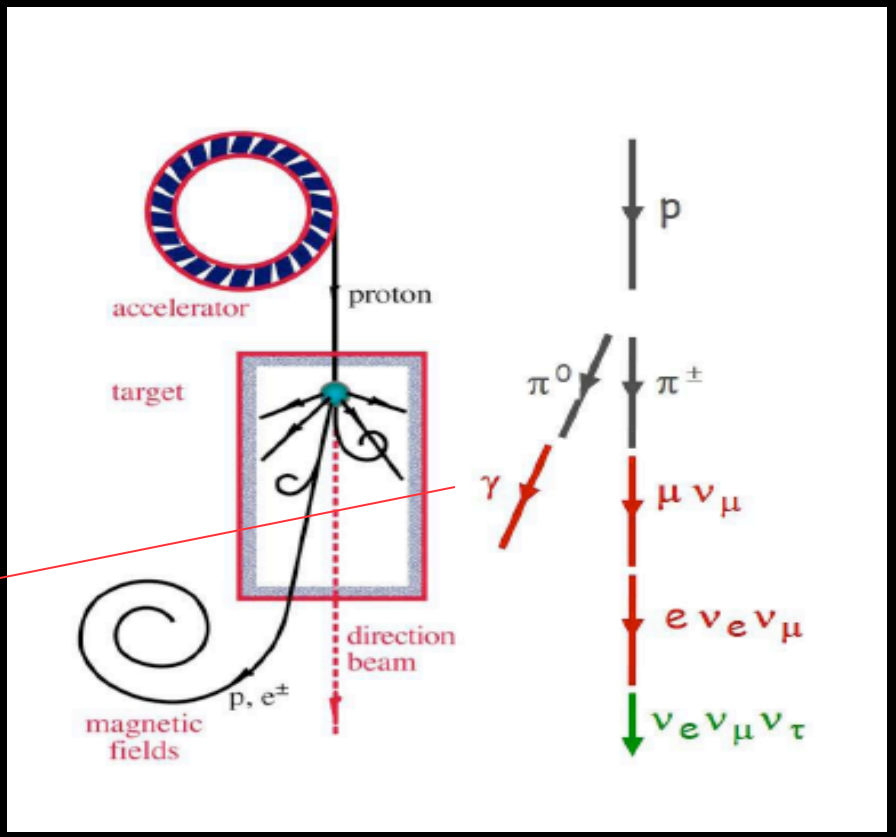
Blazar Spectral Energy Distribution

- Typical double-humped SED
- Separated by 8-10 orders of mag.
- Only small correlation



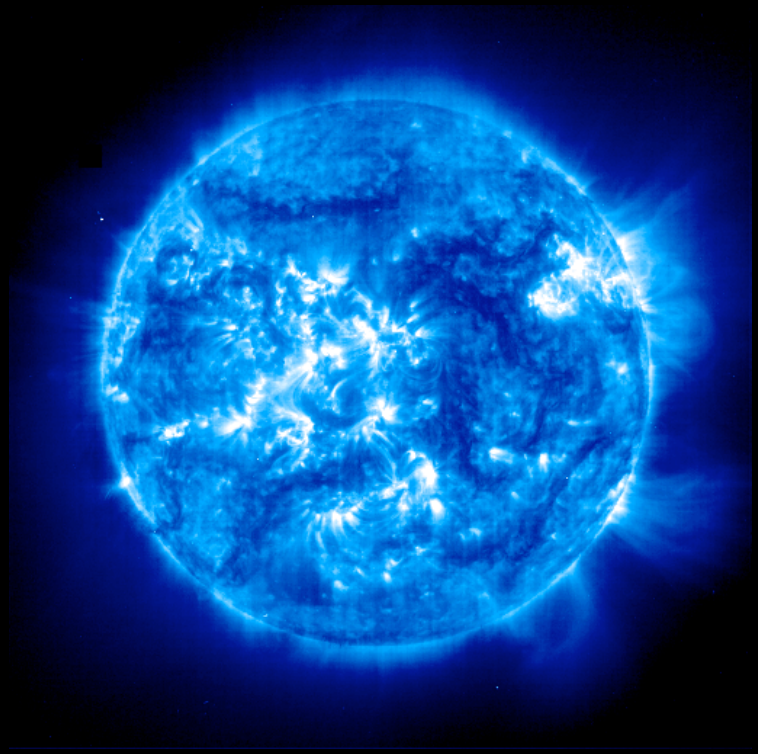
Synchrotron of $e^-/e+$

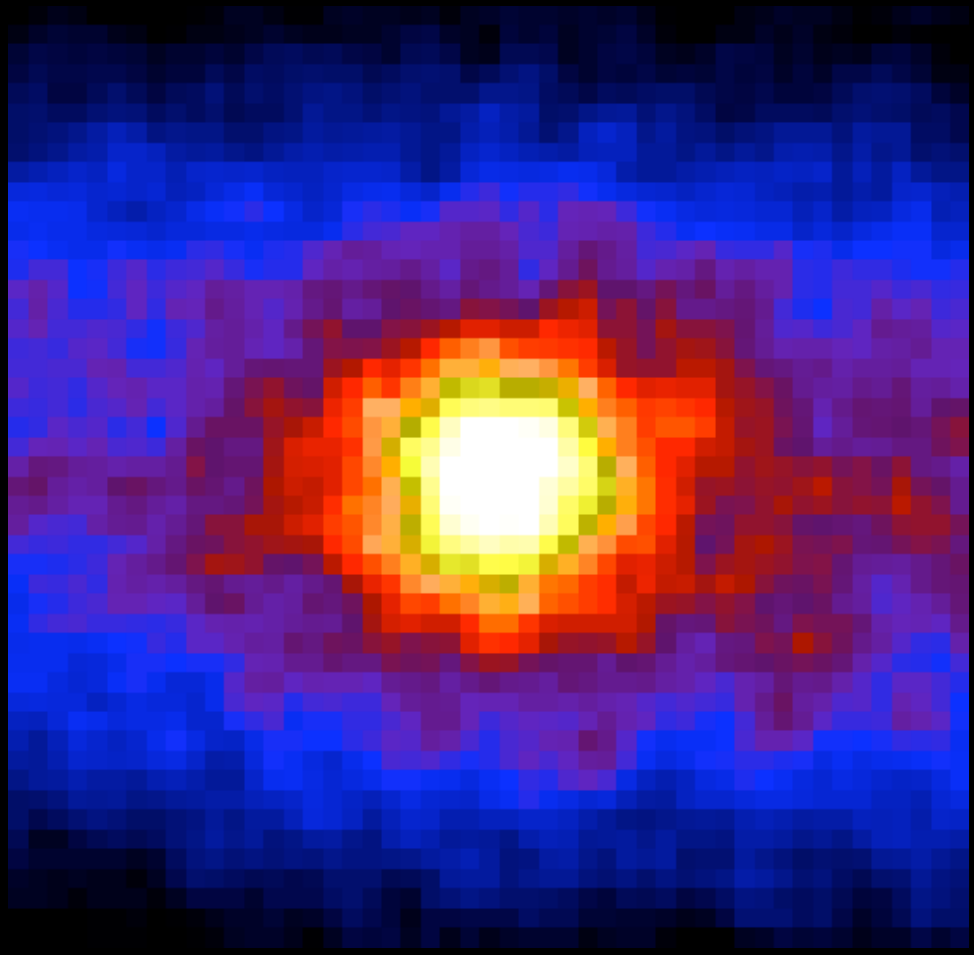
IC of $e^-/e+$ on synch. γs



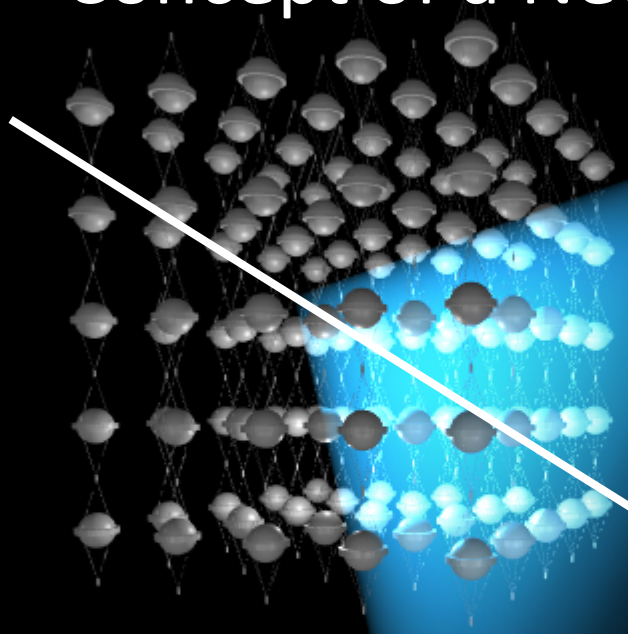
A hadronic component in the jet leads to neutrinos!

Multi-messenger Astronomy Is a Reality



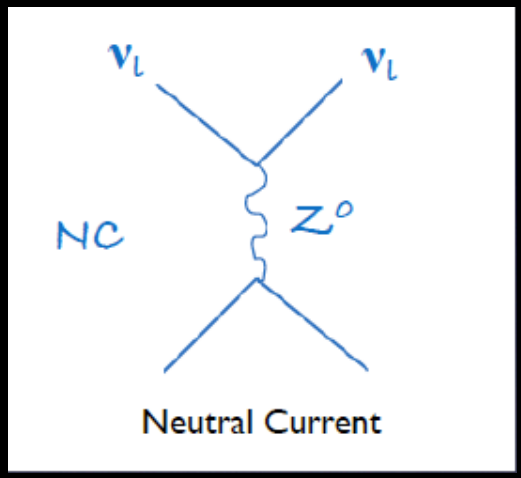


Concept of a Neutrino Telescope

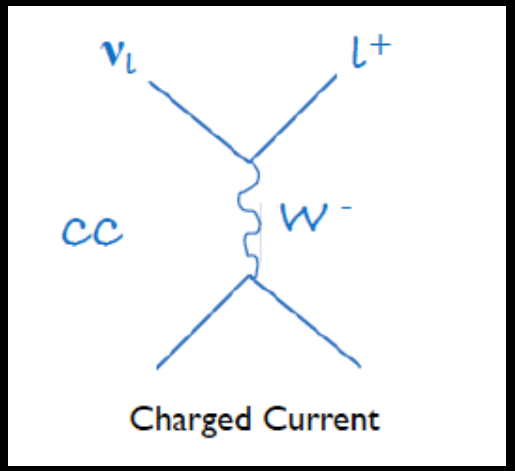


μ

ν



Neutral Current



Charged Current

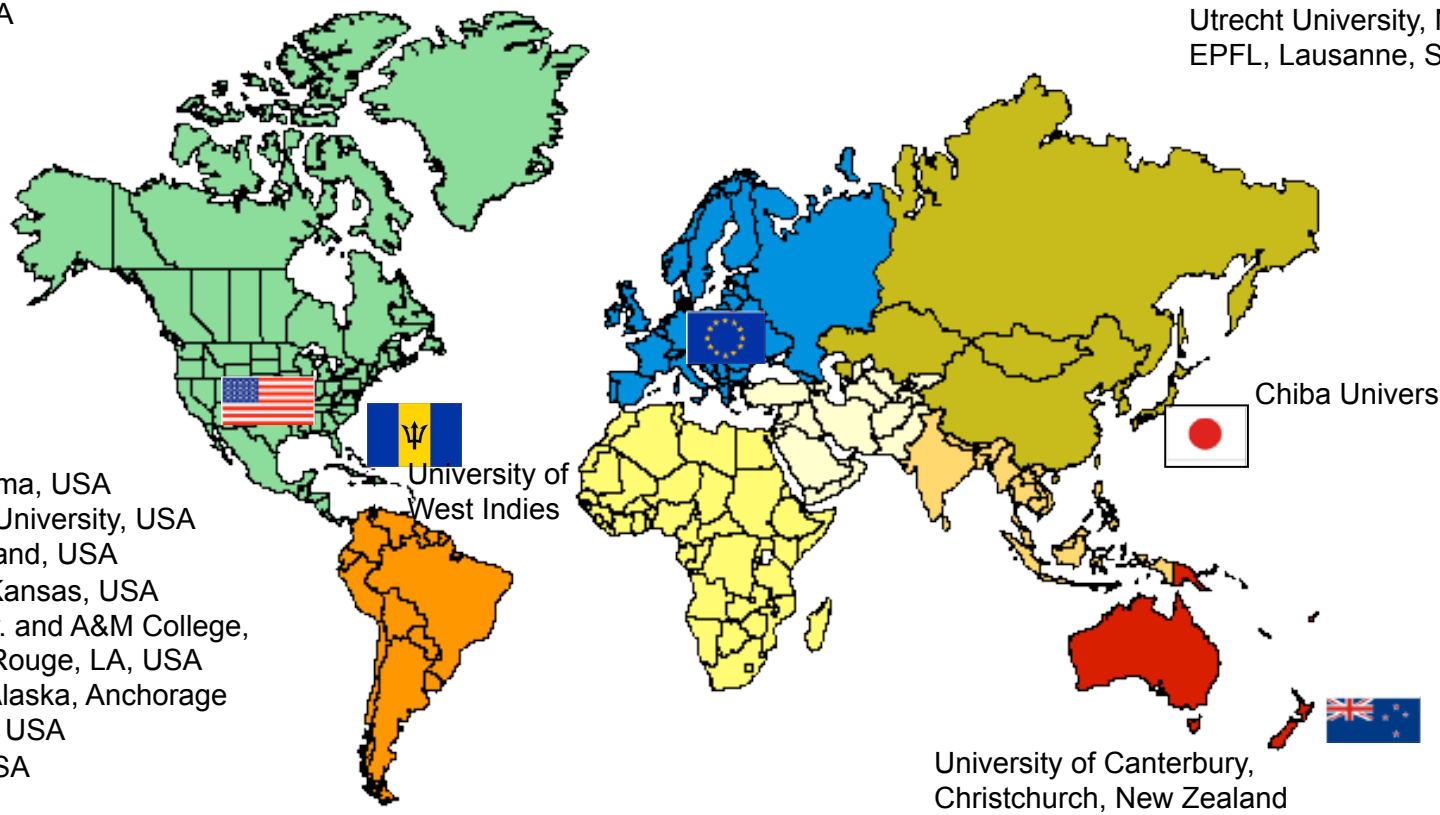
- Look for by-products of neutrino interactions
- 3D array of PMTs
  - Large, transparent medium
- From timing of Cherenkov light, reconstruct neutrino direction

IceCube Collaboration

Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany

Humboldt Universität, Germany
MPI, Heidelberg
Ruhr-Universität, Bochum
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Netherlands
EPFL, Lausanne, Switserland



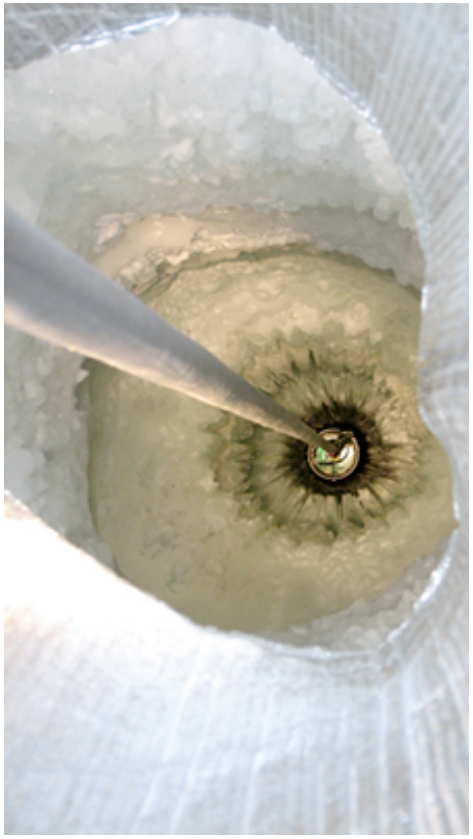
Chiba University, Japan

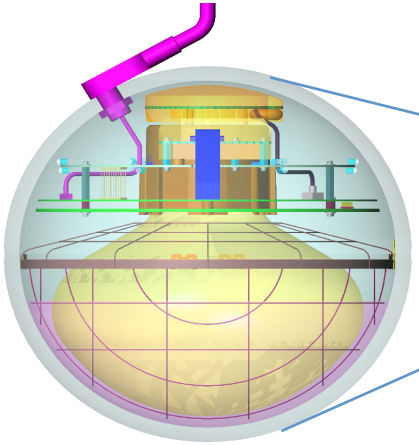
University of West Indies

Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College,
Baton Rouge, LA, USA
University of Alaska, Anchorage
Georgia Tech, USA
Ohio State, USA

University of Canterbury,
Christchurch, New Zealand

36 collaborating institutions





Digital Optical Module (DOM)

IceCube Lab

IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors

50 m

2010: 79 strings in operation
2011: Project complettion, 86 strings

IceCube In-Ice Array
86 Strings, 60 Sensors each
5160 Optical Sensors

1450 m

AMANDA-II Array
Precursor to IceCube

Deep Core
6 Strings - Optimized for lower energies
360 Optical Sensors

Eiffel Tower
324 m

2450 m

2820 m

Bedrock

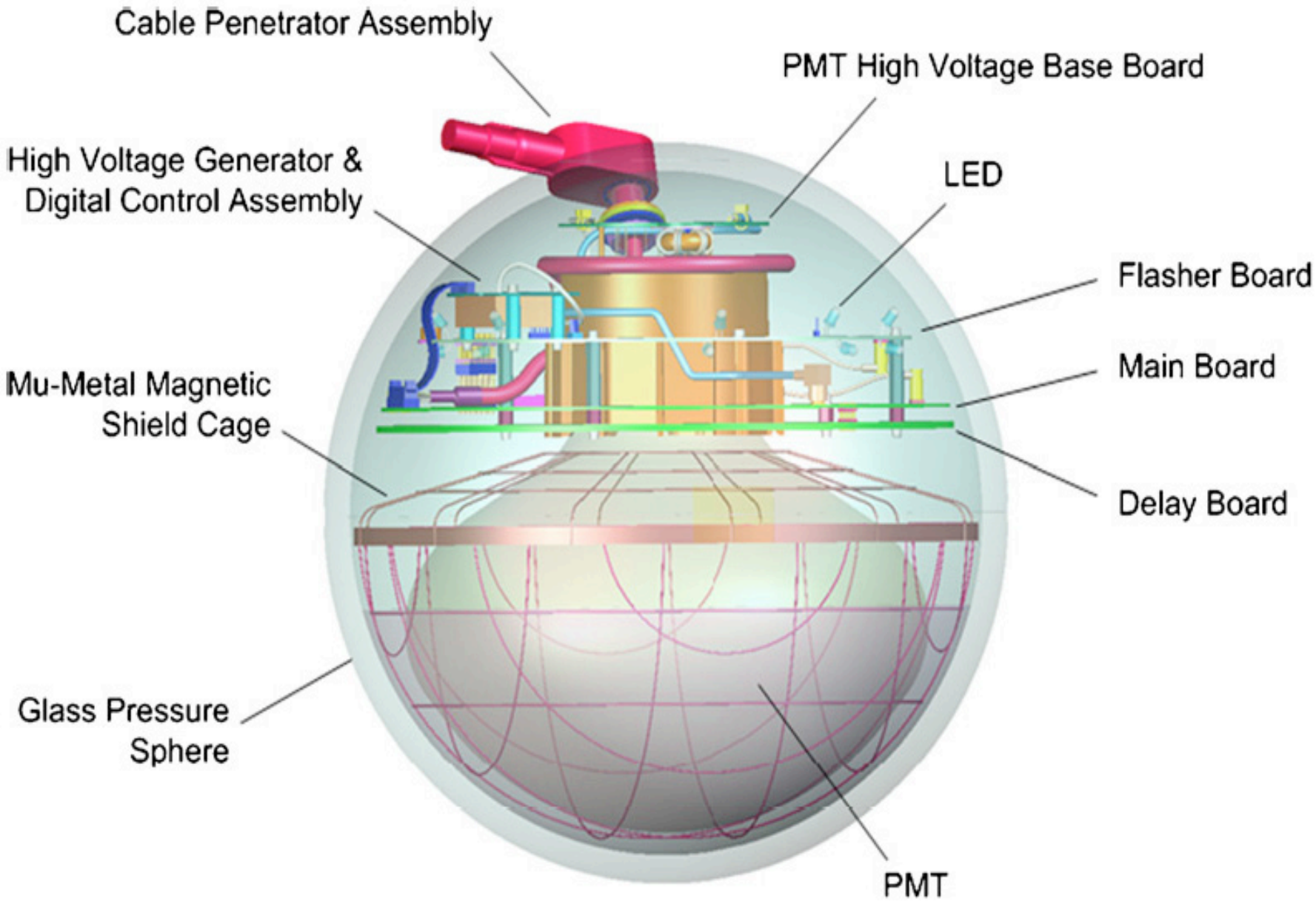
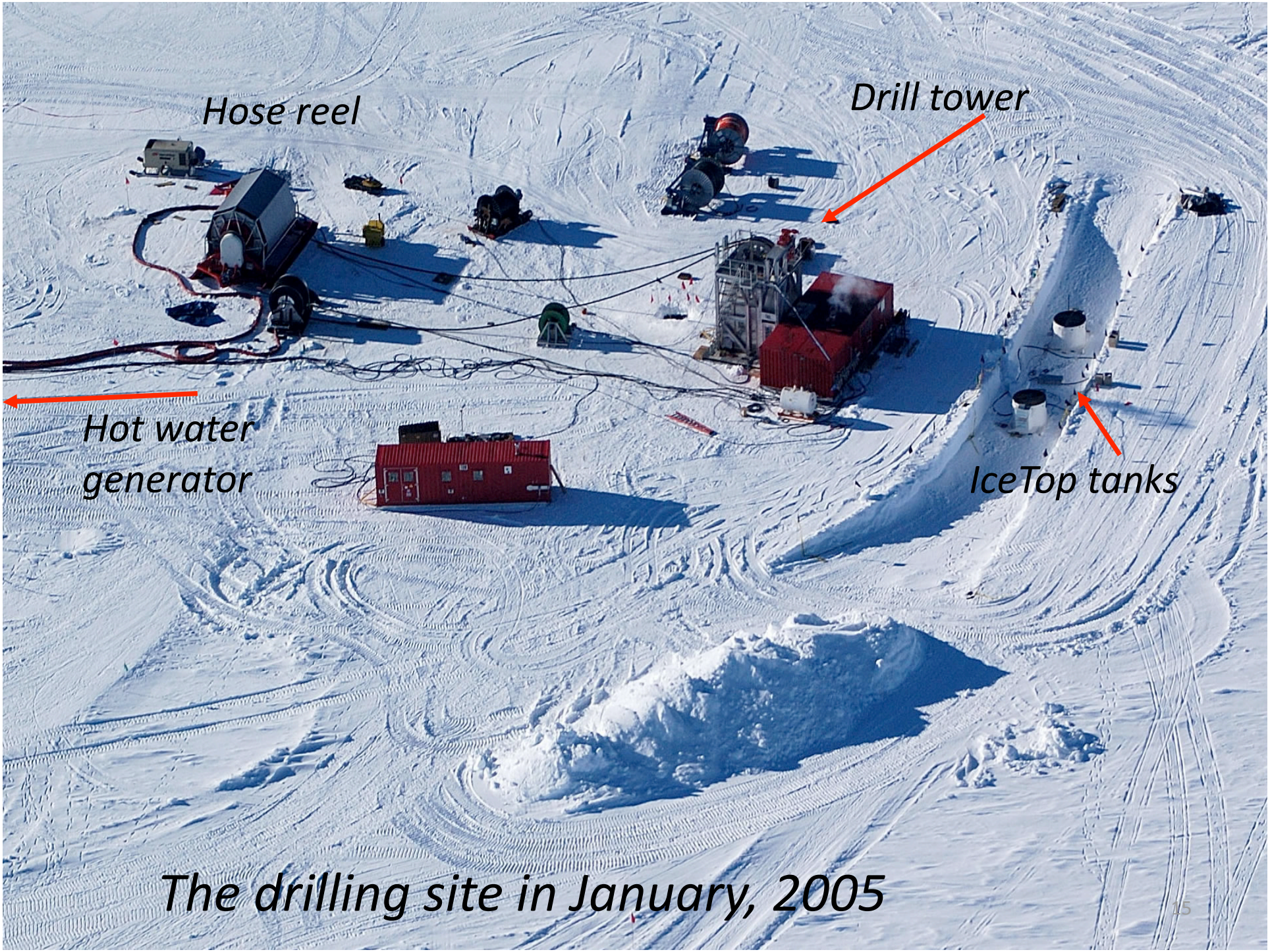
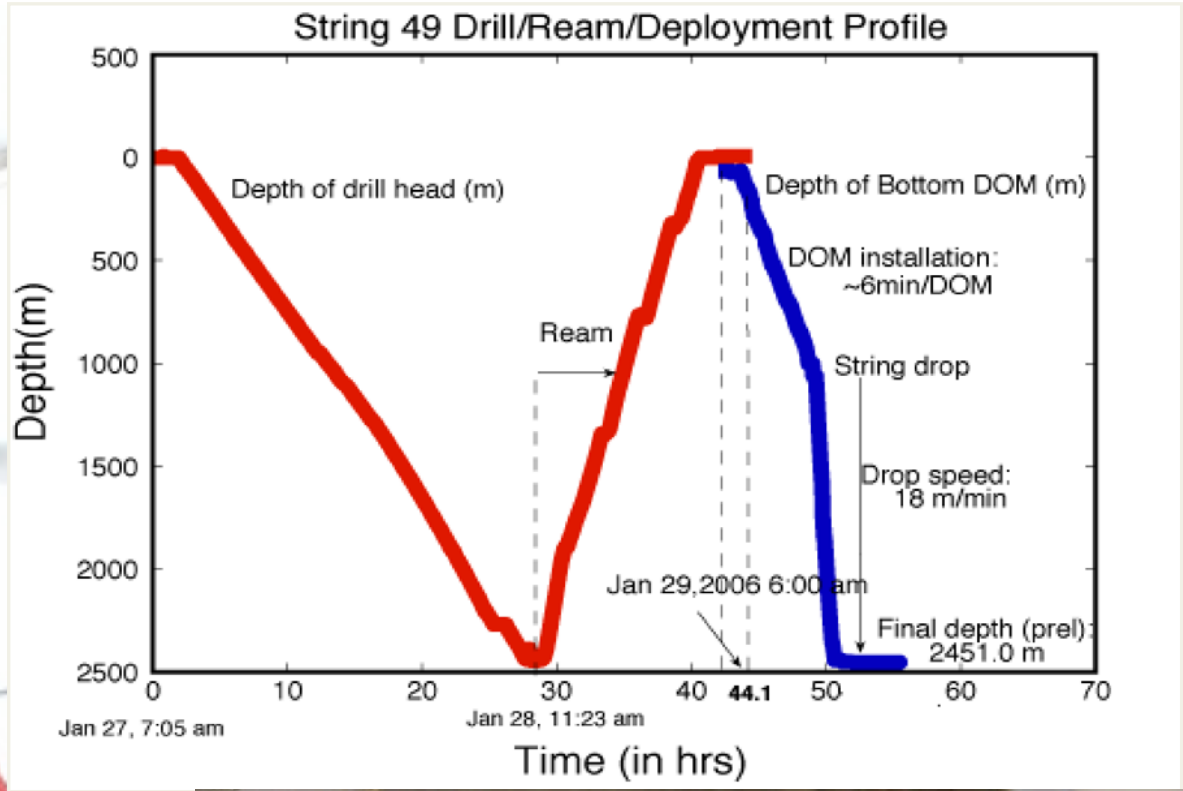


Fig. 3. A schematic view of an IceCube digital optical module.



The drilling site in January, 2005




String 49 Drill/Ream/Deployment Profile
Depth(m)
500
0
500
1000
1500
2000
2500
Depth of drill head (m)
Depth of Bottom DOM (m)
DOM installation:
~6min/DOM
Ream
String drop
Drop speed:
18 m/min
Jan 29,2006 6:00 am
Final depth (prel):
2451.0 m
0
10
20
30
40
44.1
50
60
70
Jan 27, 7:05 am
Jan 28, 11:23 am
Time (in hrs)



IceCube performance

DOM survival rate: ~98%

Low noise rates: ~500Hz

High duty cycle: >96%

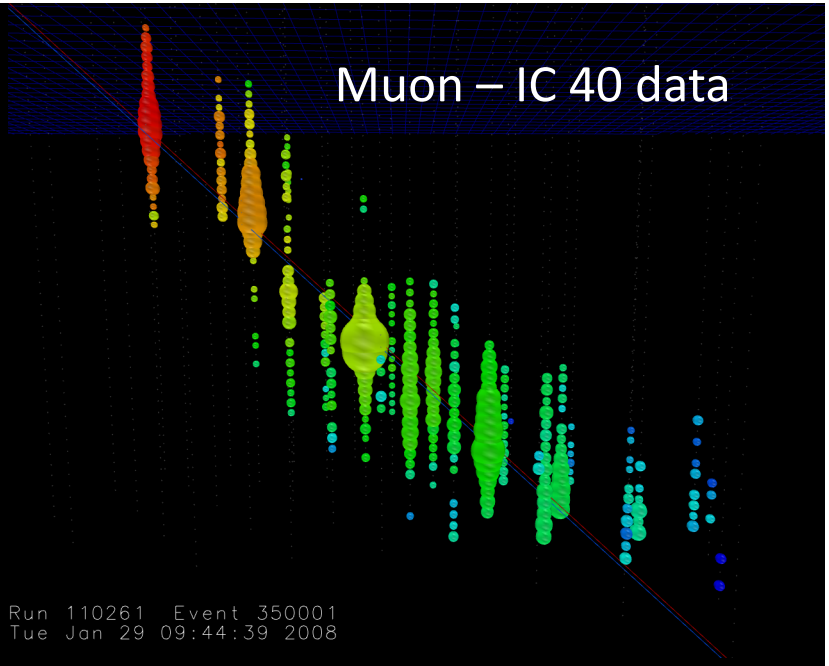
86-string configuration will be running in a couple of weeks!

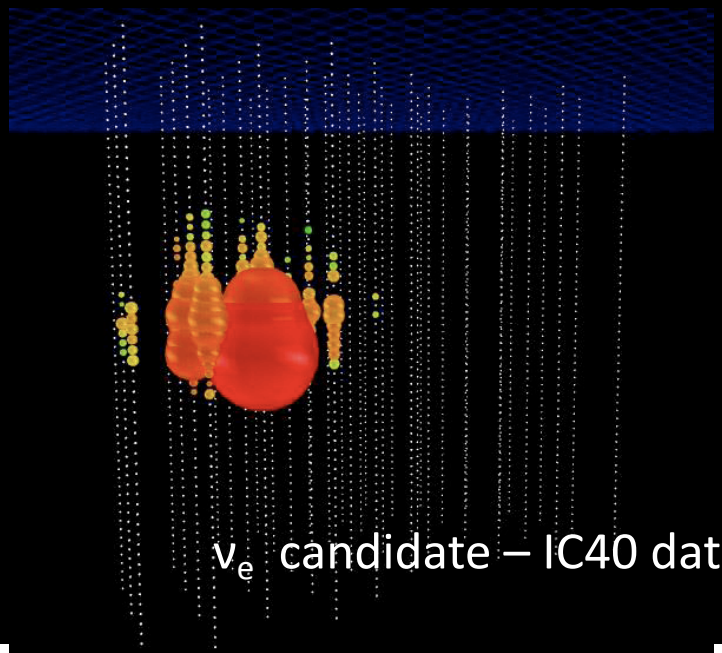


Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1900 Hz	160 / day
IC86	2011	~365 days	2300 Hz	220 / day

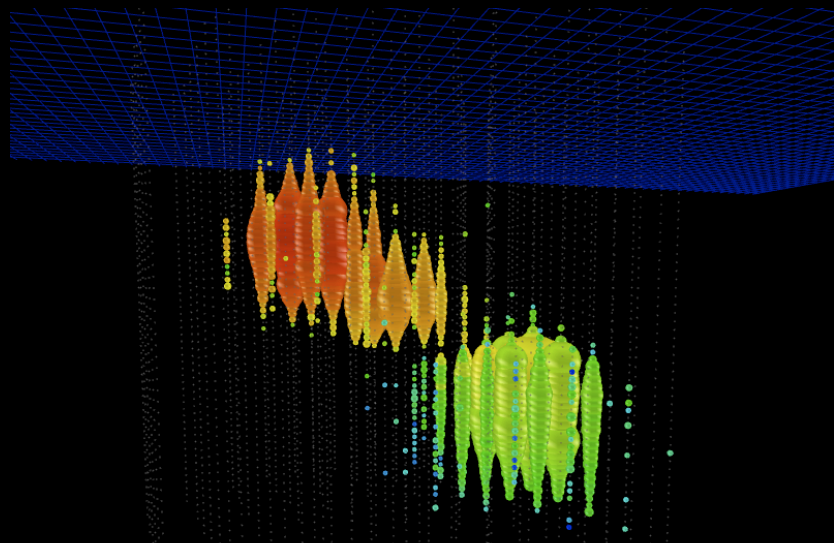
Event Topologies

- ν_μ produce μ tracks
  - Angular Res ~ 0.7^0
  - Energy Res log(E)~0.3
- ν_e CC, ν_x NC create showers
  - ~ point sources, 'cascades'
  - Eres log(E)=0.1-0.2
- ν_τ double bang events, others



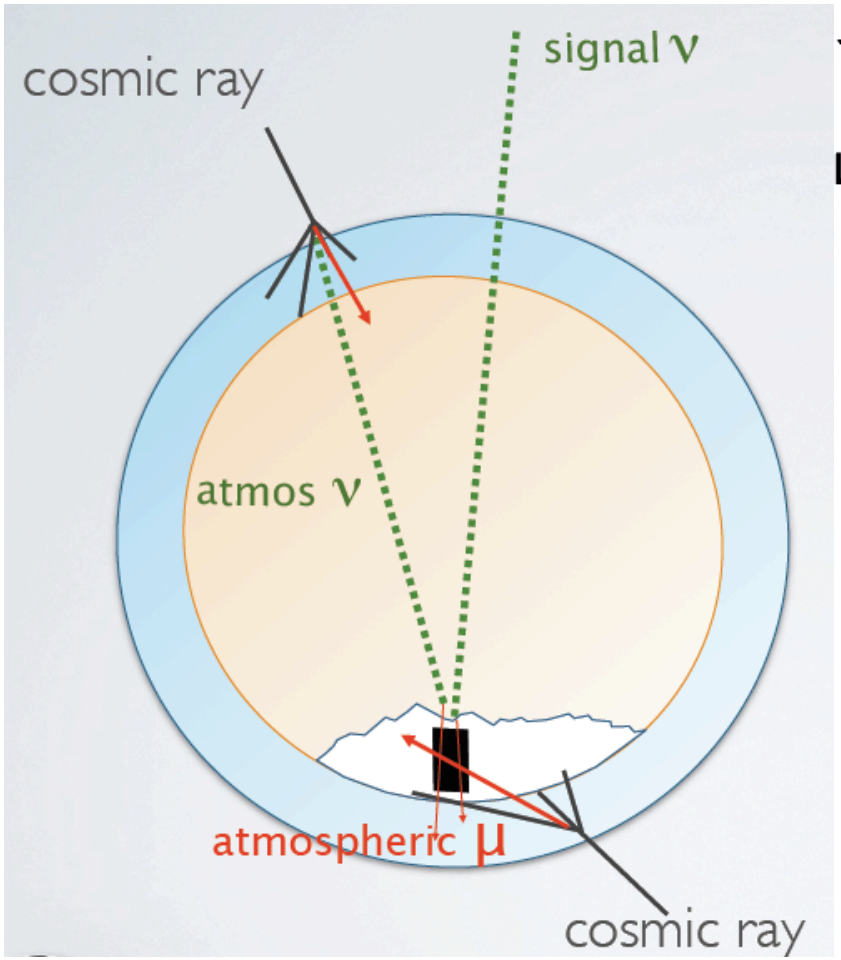


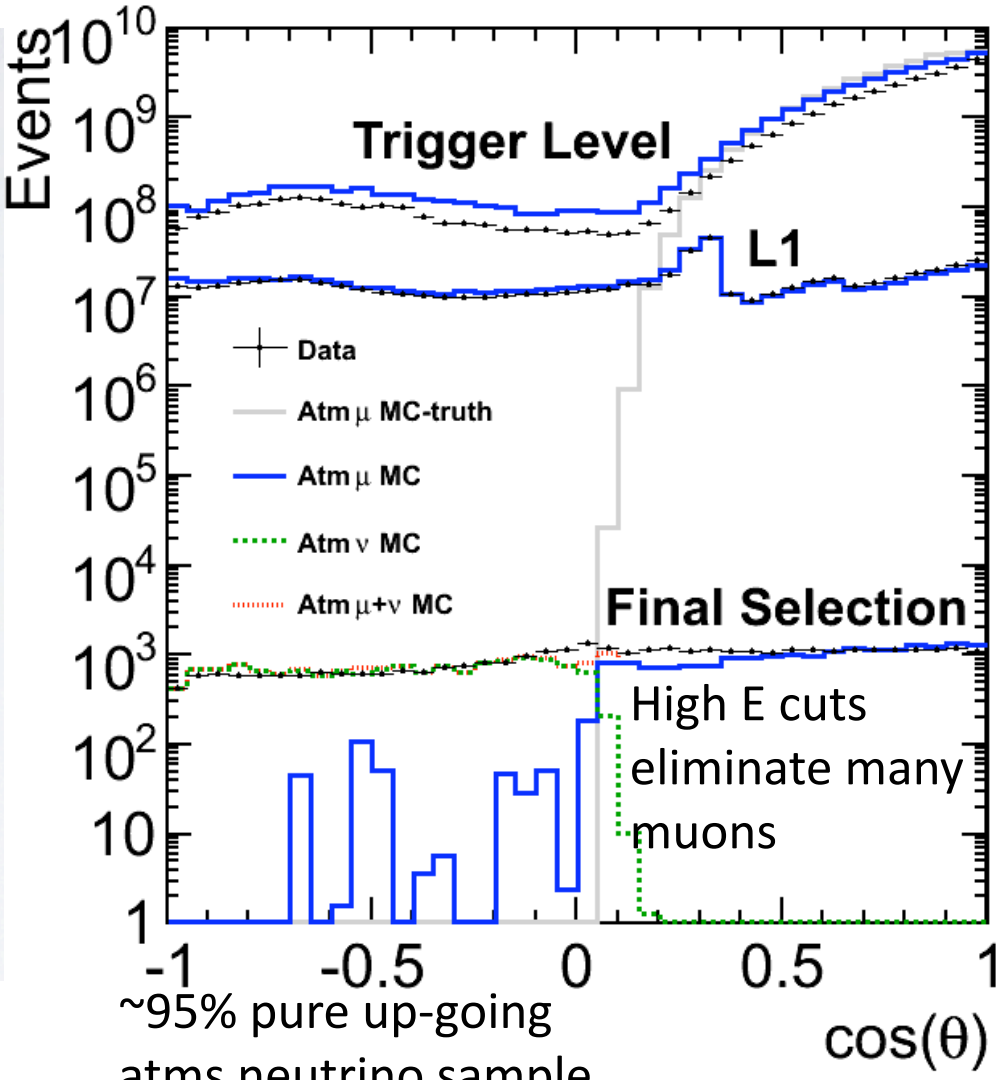
ν_e candidate – IC40 data



16 PeV ν_τ simulation

Backgrounds



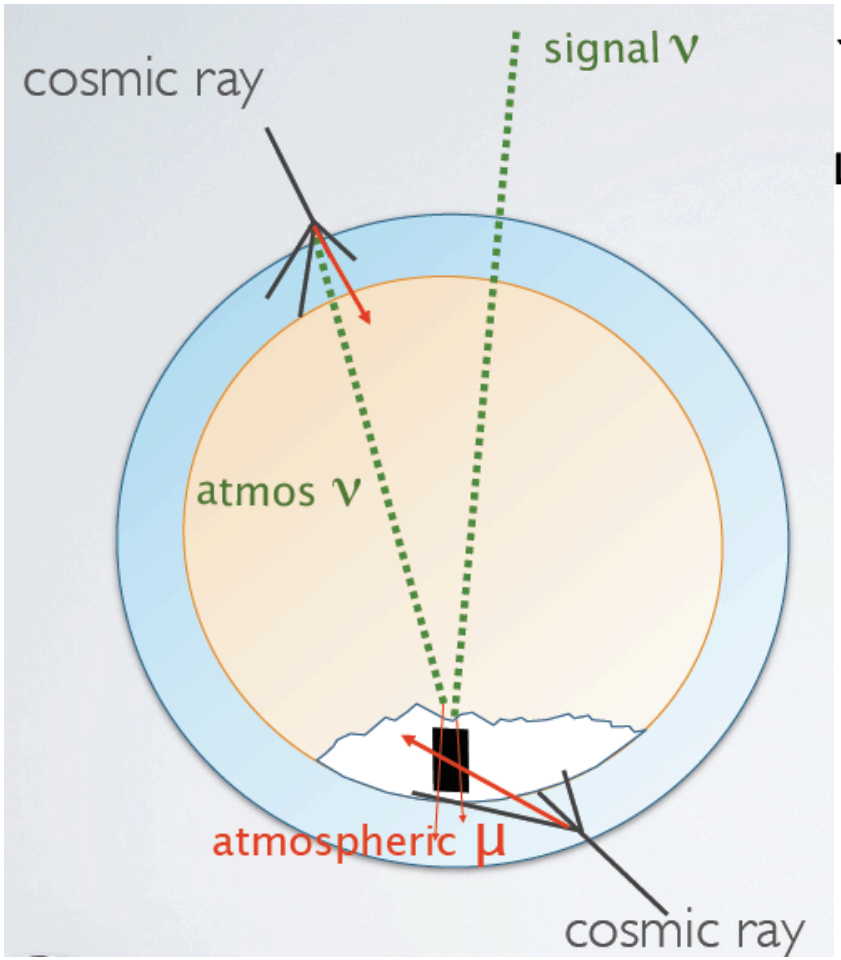


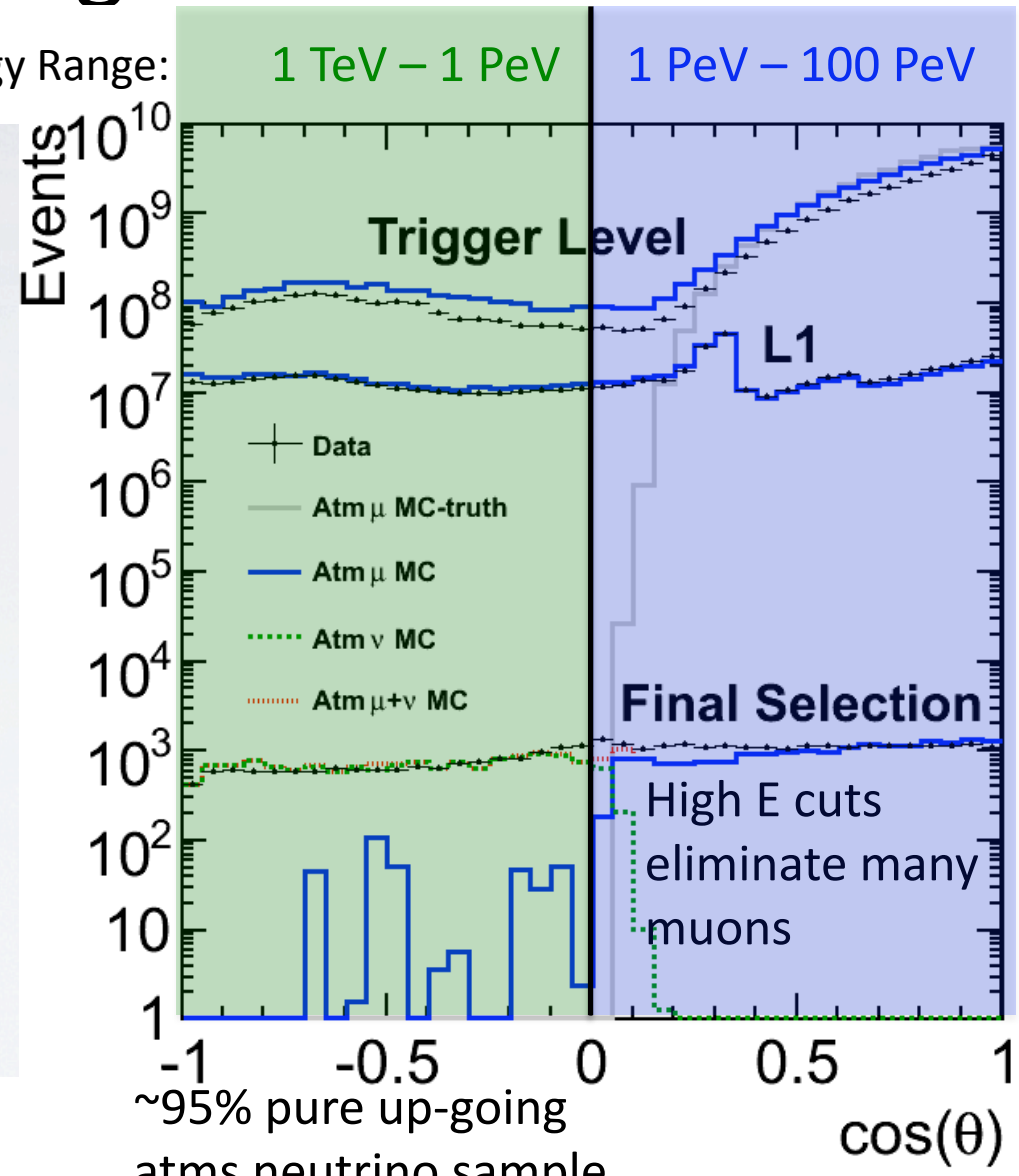
High E cuts eliminate many muons

~95% pure up-going atms neutrino sample

Backgrounds

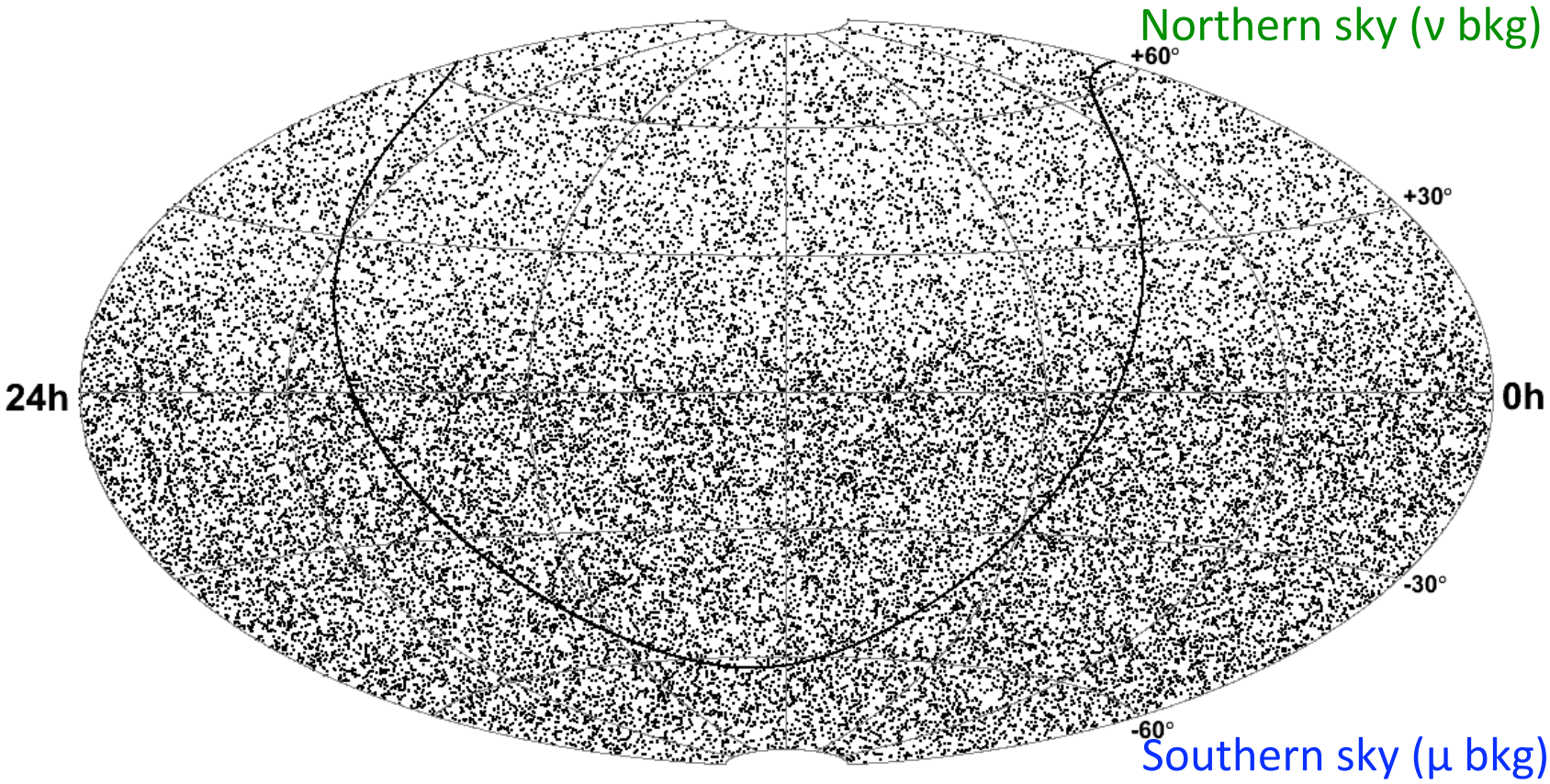
Sensitivity Energy Range: 1 TeV – 1 PeV | 1 PeV – 100 PeV





~95% pure up-going atms neutrino sample

40-string All-Sky Event Map



Livetime = 375.5 days

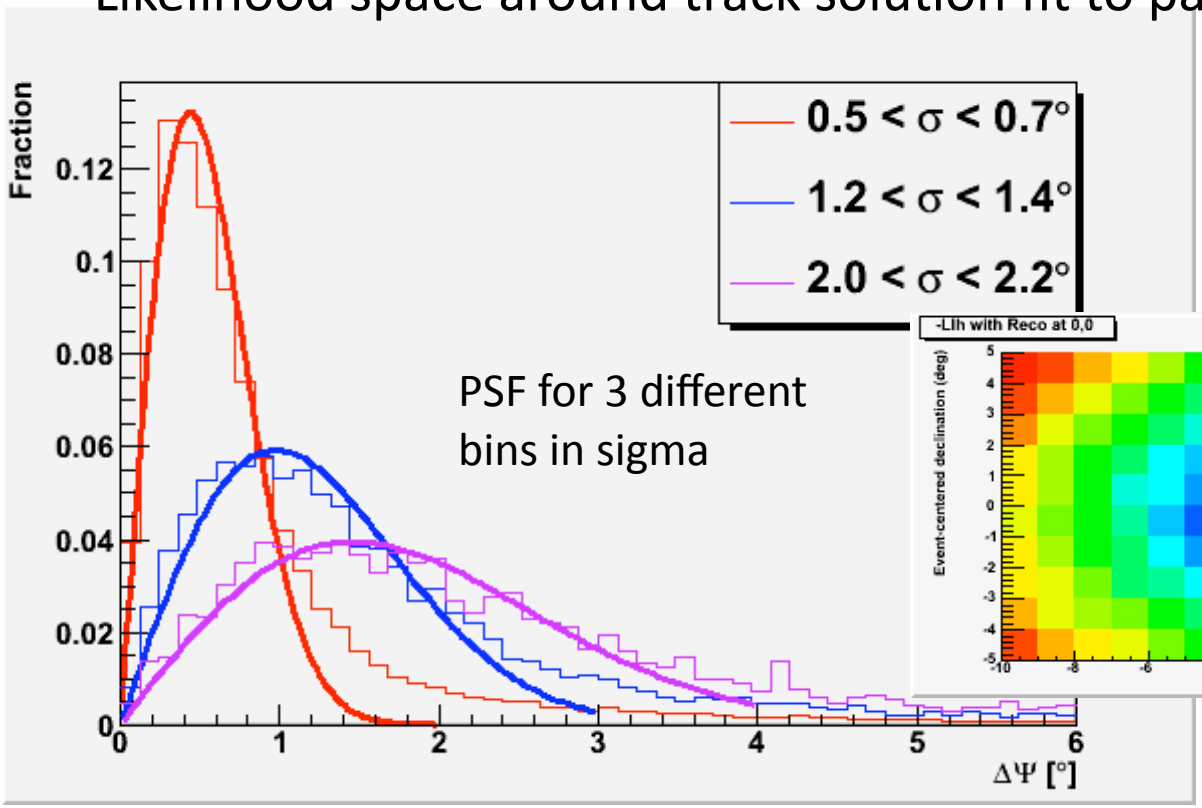
Events = 36900
(14121 up-going,
22779 down-going)

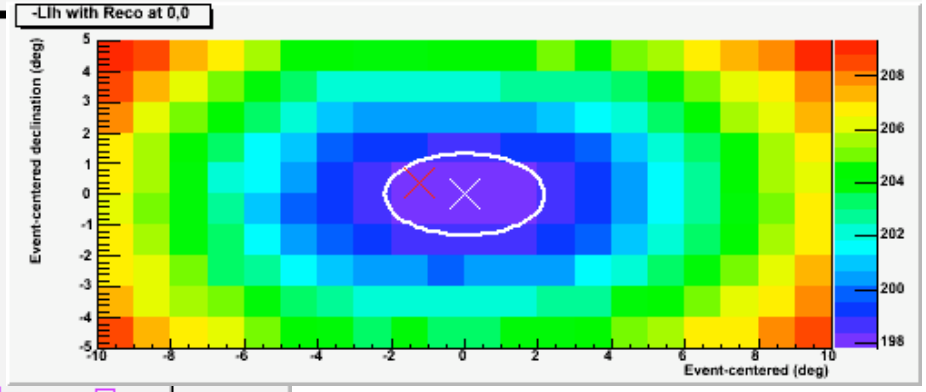
Maximum Likelihood Analysis with Energy

Signal PDF: $$S(\vec{x}_i, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2}\exp\left(\frac{-|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right) P_{SigMue}(E_i \mid \delta_i, \gamma)$$

PSF modeling:

Likelihood space around track solution fit to paraboloid: width = σ





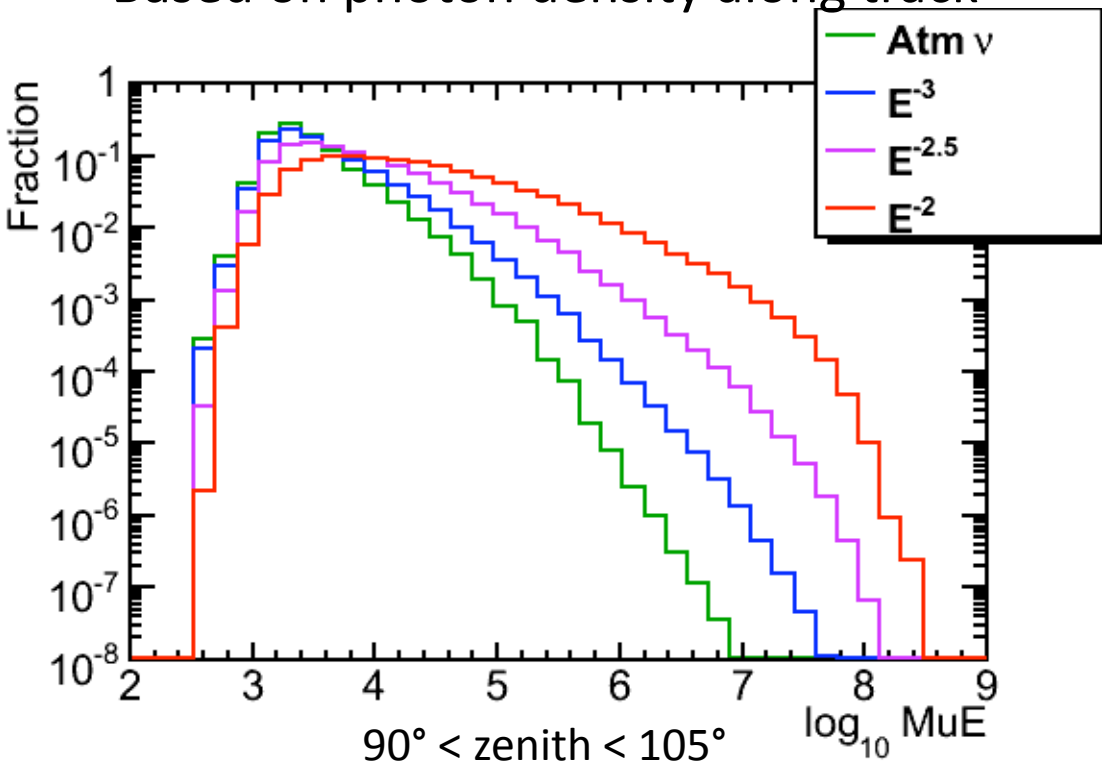
Median PSF = 0.7°

Maximum Likelihood Analysis with Energy

Signal PDF: $$S(\vec{x}_i, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2}\exp\left(\frac{-\left|\vec{x}_i - \vec{x}_s\right|^2}{2\sigma_i^2}\right) P_{SigMue}\left(E_i \mid \delta_i, \gamma\right)$$

Spectral modeling:

Based on photon density along track



Maximum Likelihood Analysis with Energy

Signal PDF: $$S(\vec{x}_i, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2}\exp\left(\frac{-\left|\vec{x}_i - \vec{x}_s\right|^2}{2\sigma_i^2}\right) P_{SigMue}\left(E_i \mid \delta_i, \gamma\right)$$

Background PDF: $$B(\vec{x}_i, E_i) = P_{BckDec}(\vec{x}_i) P_{BckMue}(E_i, \delta_i)$$ Data used for background

Maximum Likelihood Analysis with Energy

Signal PDF: $$S(\vec{x}_i, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2}\exp\left(\frac{-\left|\vec{x}_i - \vec{x}_s\right|^2}{2\sigma_i^2}\right) P_{SigMue}\left(E_i \mid \delta_i, \gamma\right)$$

Background PDF: $$B(\vec{x}_i, E_i) = P_{BckDec}(\vec{x}_i) P_{BckMue}(E_i, \delta_i)$$ Data used for background

Partial Probability: $$P_i(\vec{x}_i, E_i, \gamma, n_s) = \frac{n_s}{n_{tot}} S(\vec{x}_i, E_i, \gamma) + (1 - \frac{n_s}{n_{tot}}) B(\vec{x}_i, E_i)$$

Maximum Likelihood Analysis with Energy

Signal PDF: $$S(\vec{x}_i, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2}\exp\left(\frac{-\left|\vec{x}_i - \vec{x}_s\right|^2}{2\sigma_i^2}\right) P_{SigMue}\left(E_i \mid \delta_i, \gamma\right)$$

Background PDF: $$B(\vec{x}_i, E_i) = P_{BckDec}(\vec{x}_i) P_{BckMue}(E_i, \delta_i)$$ Data used for background

Partial Probability: $$P_i(\vec{x}_i, E_i, \gamma, n_s) = \frac{n_s}{n_{tot}} S(\vec{x}_i, E_i, \gamma) + (1 - \frac{n_s}{n_{tot}}) B(\vec{x}_i, E_i)$$

Likelihood: $$L(\gamma, n_s) = \prod_i P_i(\vec{x}_i, E_i, \gamma, n_s)$$

Maximum Likelihood Analysis with Energy

Signal PDF: $$S(\vec{x}_i, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2}\exp\left(\frac{-\left|\vec{x}_i - \vec{x}_s\right|^2}{2\sigma_i^2}\right) P_{SigMue}\left(E_i \mid \delta_i, \gamma\right)$$

Background PDF: $$B(\vec{x}_i, E_i) = P_{BckDec}(\vec{x}_i) P_{BckMue}(E_i, \delta_i)$$ Data used for background

Partial Probability: $$P_i(\vec{x}_i, E_i, \gamma, n_s) = \frac{n_s}{n_{tot}} S(\vec{x}_i, E_i, \gamma) + (1 - \frac{n_s}{n_{tot}}) B(\vec{x}_i, E_i)$$

Likelihood: $$L(\gamma, n_s) = \prod_i P_i(\vec{x}_i, E_i, \gamma, n_s)$$

Log Likelihood Ratio (test statistic): $$\log\lambda = \log\left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)}\right)$$

Estimates which maximize the Llh

Maximum Likelihood Analysis with Energy

Signal PDF: $$S(\vec{x}_i, E_i, \gamma) = \frac{1}{2\pi\sigma_i^2}\exp\left(\frac{-\left|\vec{x}_i - \vec{x}_s\right|^2}{2\sigma_i^2}\right) P_{SigMue}\left(E_i \mid \delta_i, \gamma\right)$$

Background PDF: $$B(\vec{x}_i, E_i) = P_{BckDec}(\vec{x}_i) P_{BckMue}(E_i, \delta_i)$$ Data used for background

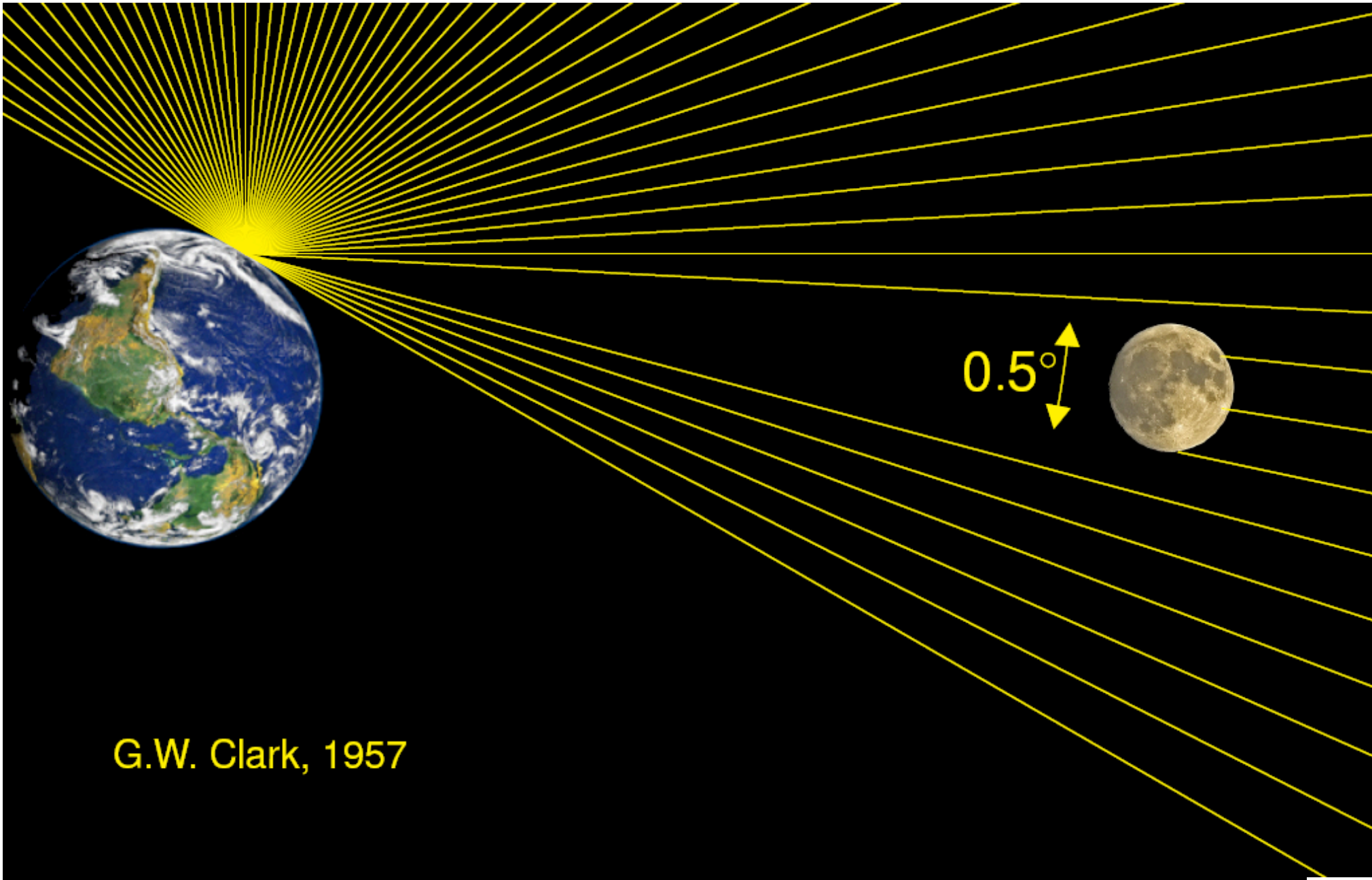
Partial Probability: $$P_i(\vec{x}_i, E_i, \gamma, n_s) = \frac{n_s}{n_{tot}} S(\vec{x}_i, E_i, \gamma) + (1 - \frac{n_s}{n_{tot}}) B(\vec{x}_i, E_i)$$

Likelihood: $$L(\gamma, n_s) = \prod_i P_i(\vec{x}_i, E_i, \gamma, n_s)$$

Log Likelihood Ratio (test statistic): $$\log\lambda = \log\left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)}\right)$$

Estimates which maximize the Llh

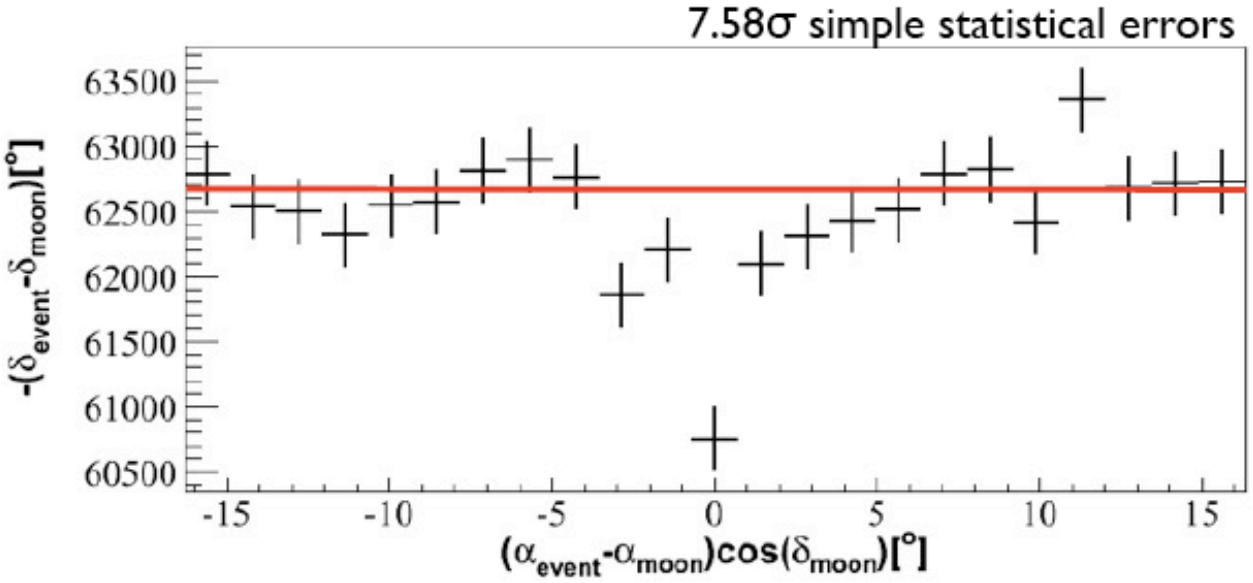
Reliable results: Blind analysis, background from data, p-values from scrambling

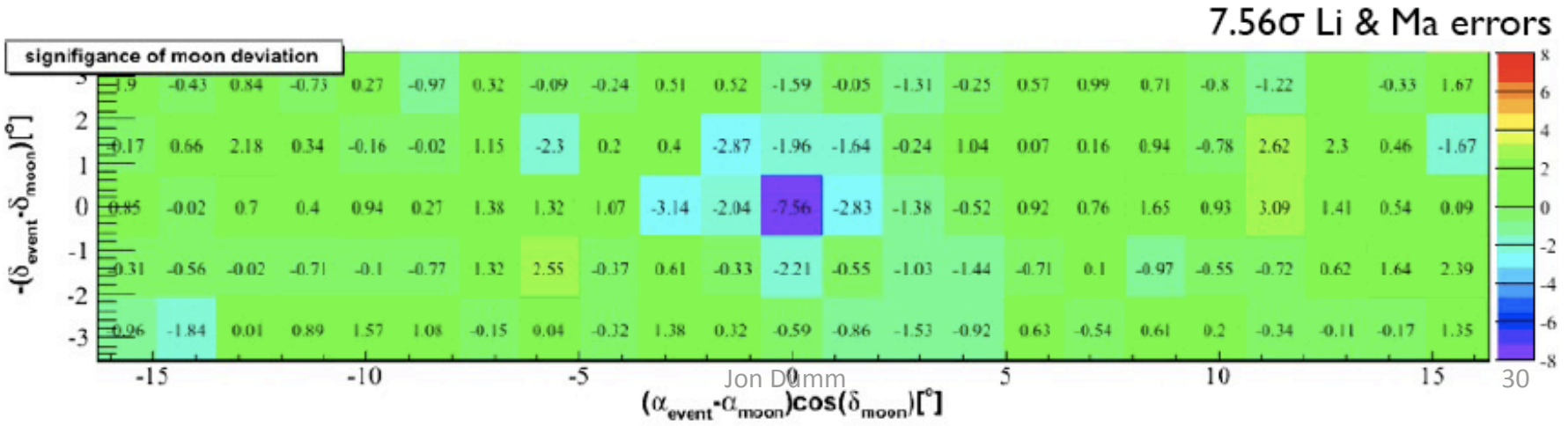

0.5°
G.W. Clark, 1957

Pointing Verification with the Moon -
The Standard Anti-Candle

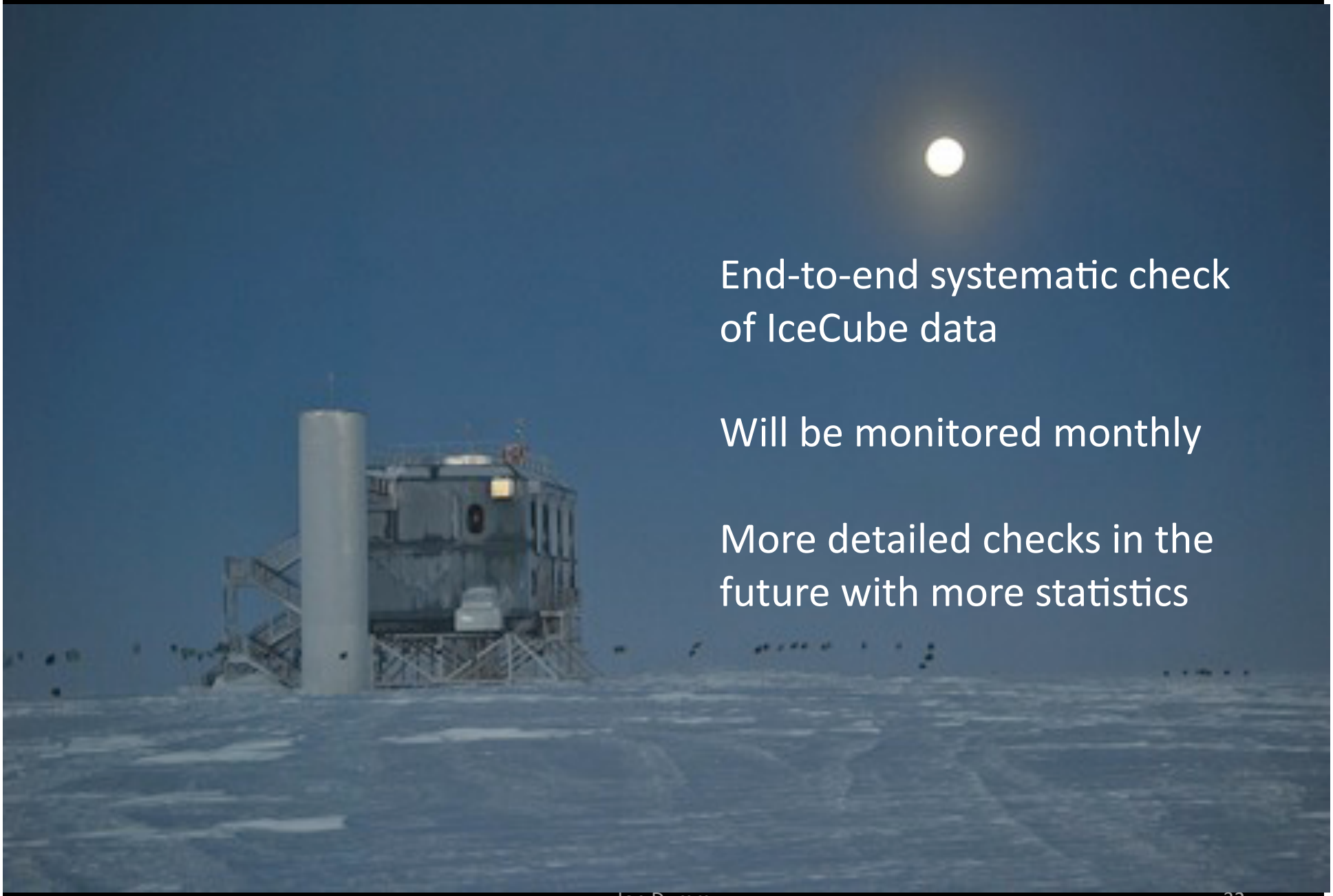
IceCube-40 strings (2009)

Deficit in agreement with expectations

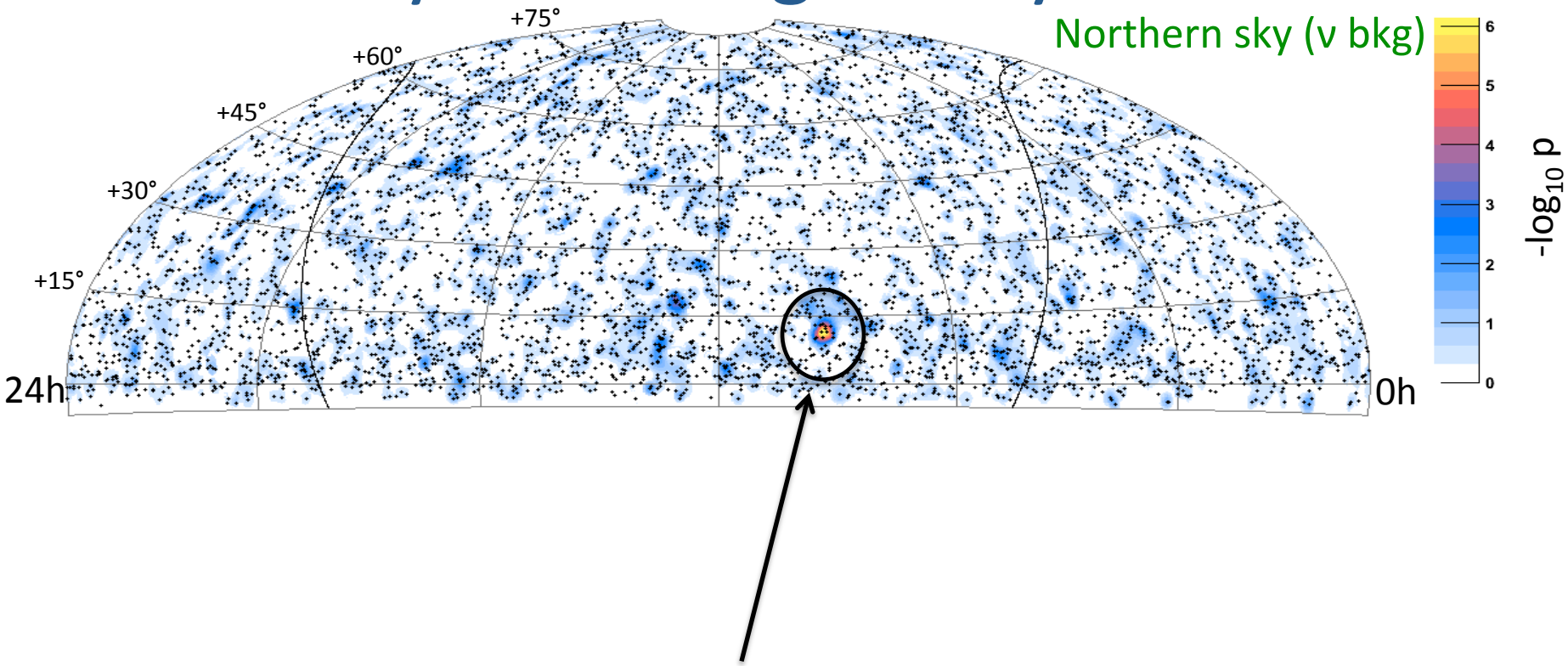







End-to-end systematic check of IceCube data
Will be monitored monthly
More detailed checks in the future with more statistics

Previously: 22-string all-sky results

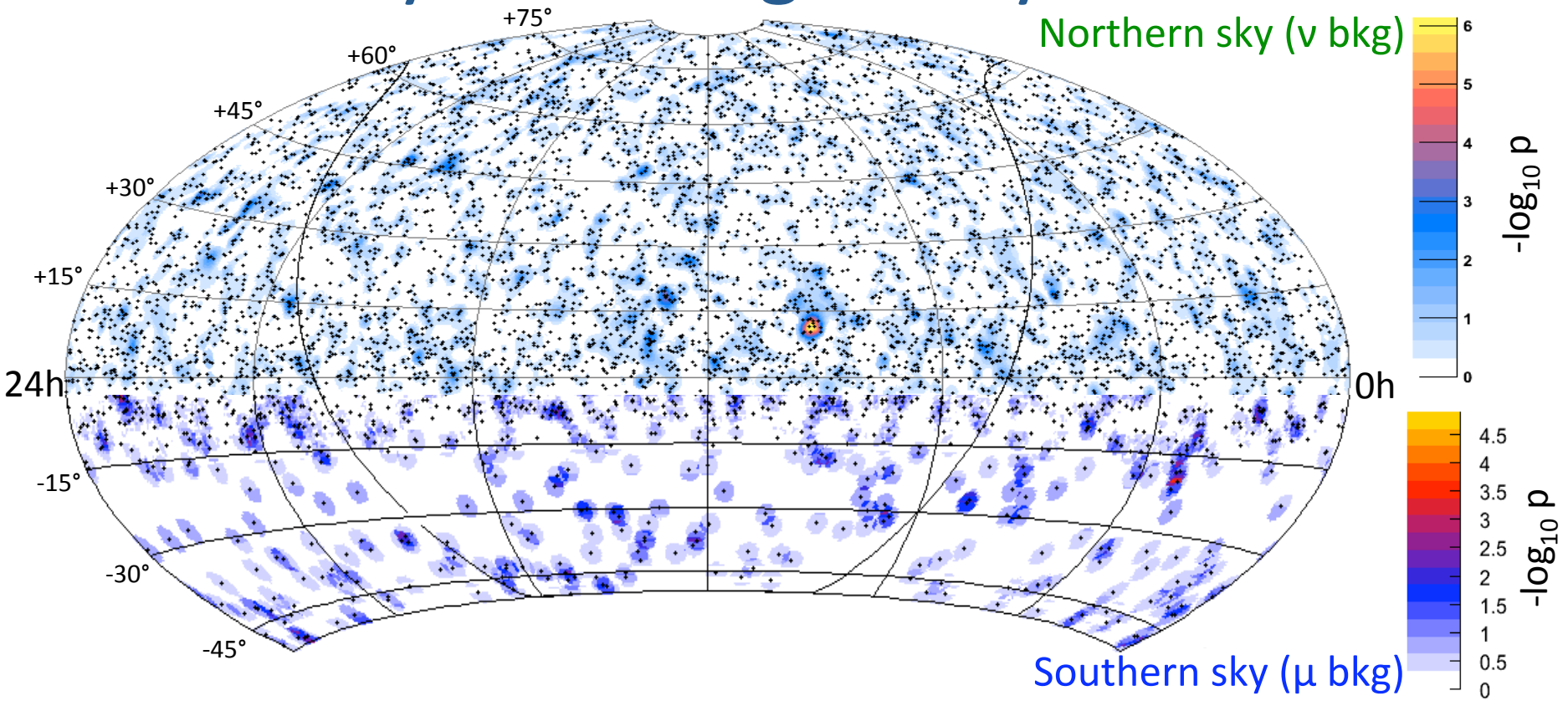


Hottest spot found at r.a. 153.4° , dec. 11.4°

Post-trials p-value of analysis is ~ 1.34% (2.2 sigma) ...

ApJL 70, 47 (2009)

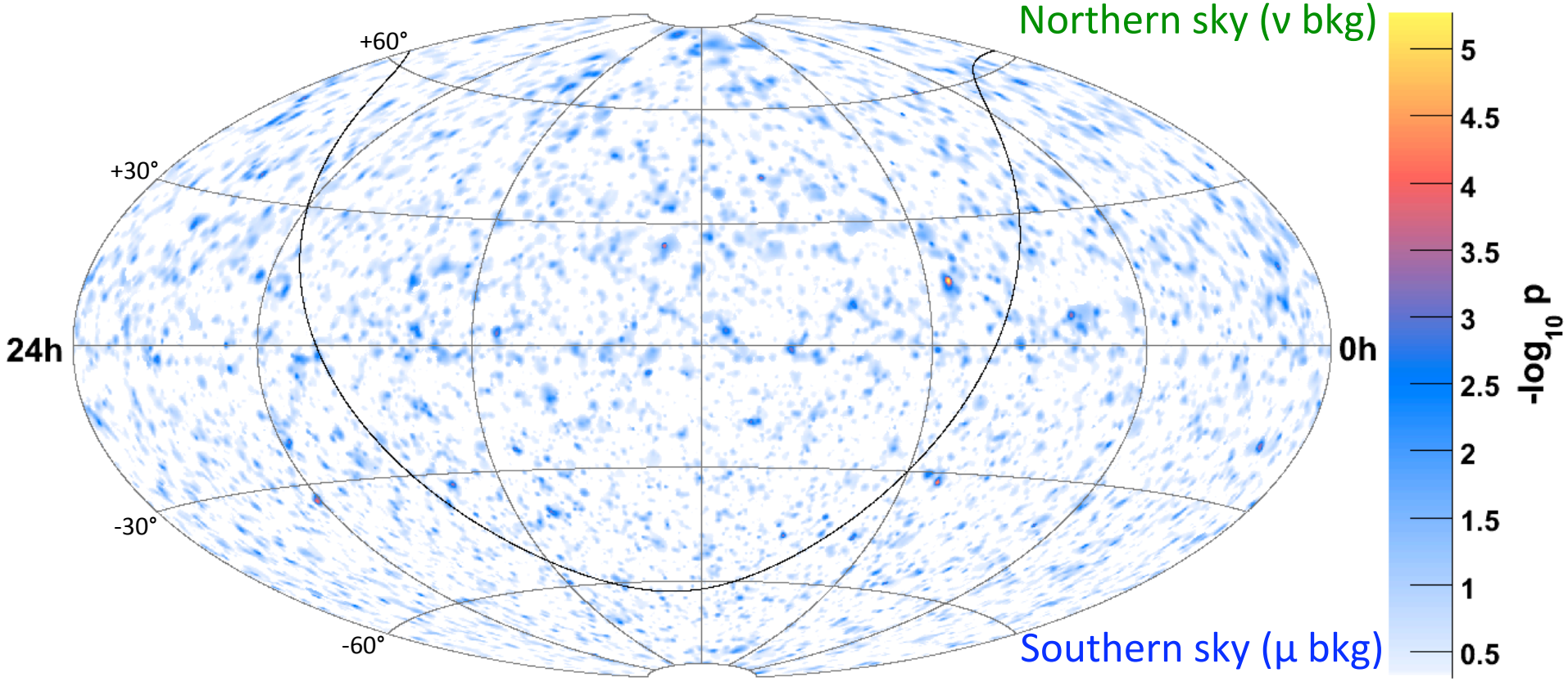
Previously: 22-string all-sky results



First IceCube analysis extended to -50° dec

PRL 103, 221102 (2009)

40-string All-Sky Results



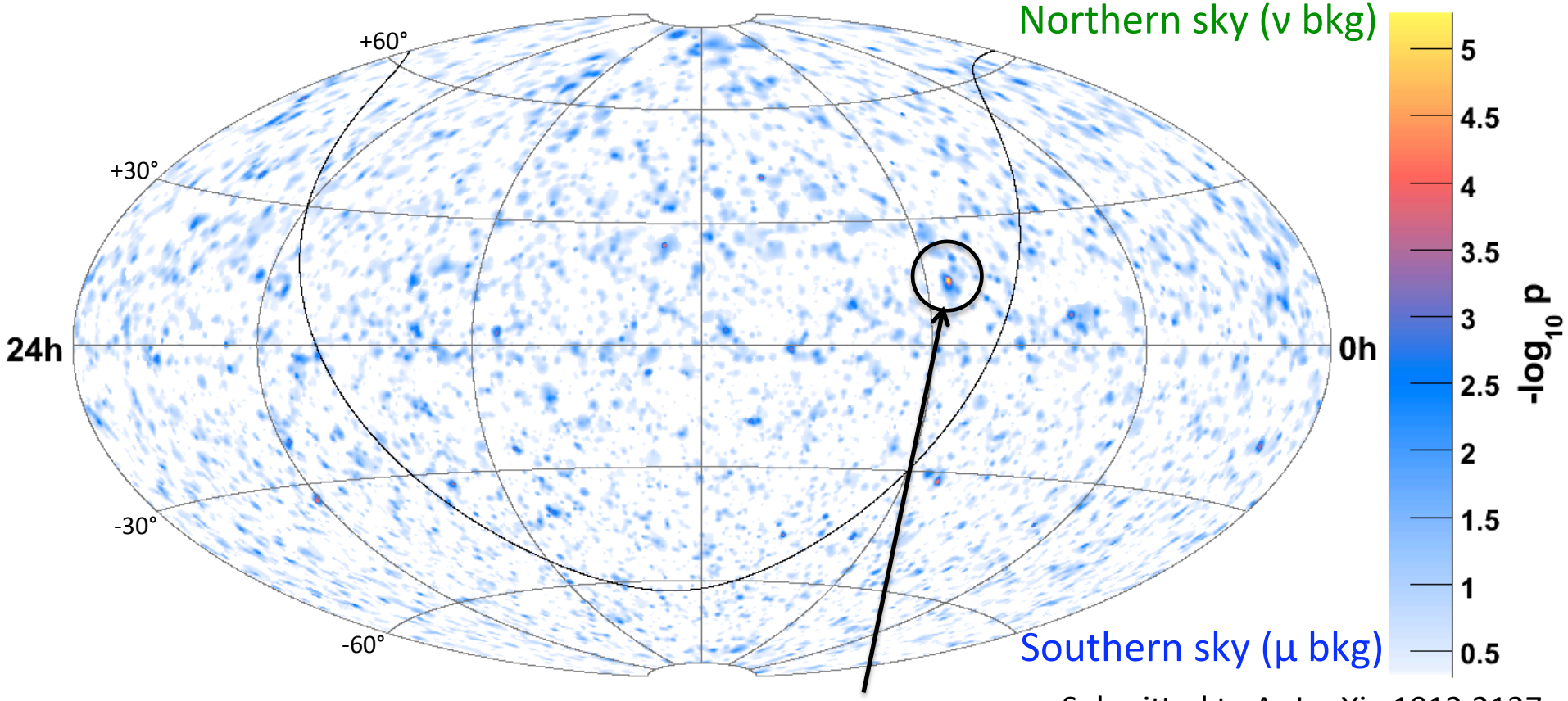
Submitted to ApJ arXiv:1012.2137

Hottest location in the all-sky search is:
Ra=113.75°, Dec=15.15°

Livetime = 375.5 days

Events = 36900
(14121 up-going,
22779 down-going)

40-string All-Sky Results



Submitted to ApJ arXiv:1012.2137

Hottest location in the all-sky search is:
Ra=113.75°, Dec=15.15°

Livetime = 375.5 days

Events = 36900
(14121 up-going,
22779 down-going)

In background simulated trials (scrambling data in r.a.), an equal or greater excess occurs by chance 1817/10000 times.
=> **all-sky final p-value is 18%, not significant**

40-string Source List Results

Northern Sky **Sources:**

Highest significance comes from southern sky (see next slide)

P-values >=0.5 (downward fluctuations) are given as "---"

Source Name	Ra , Dec (deg)	p-value
Cyg_OB2	(308.083, 41.510) :	---
MGRO_J2019+37	(305.220, 36.830) :	0.44
MGRO_J1908+06	(286.976, 6.269) :	---
Cas_A	(350.850, 58.815) :	---
IC443	(94.179, 22.529) :	---
Geminga	(98.476, 17.770) :	0.48
Crab_Nebula	(83.633, 22.014) :	---
1ES_1959+650	(299.999, 65.149) :	---
1ES_2344+514	(356.770, 51.705) :	---
3C66A	(35.673, 43.043) :	0.24
H_1426+428	(217.136, 42.672) :	---
BL_Lac	(330.680, 42.278) :	0.23
Mrk_501	(253.468, 39.760) :	0.42
Mrk_421	(166.114, 38.209) :	0.14
W_Comae	(185.382, 28.233) :	---
1ES_0229+200	(38.202, 20.287) :	0.18
M87	(187.706, 12.391) :	---
S5_0716+71	(110.473, 71.343) :	---
M82	(148.967, 69.680) :	0.40
3C_123.0	(69.268, 29.671) :	0.44
3C_454.3	(343.491, 16.148) :	---
4C_38.41	(248.815, 38.135) :	0.46
PKS_0235+164	(39.660, 16.620) :	0.14
PKS_0528+134	(82.735, 13.532) :	---
PKS_1502+106	(226.104, 10.494) :	---
3C_273	(187.278, 2.052) :	---
NGC_1275	(49.951, 41.512) :	---
Cyg_A	(299.868, 40.734) :	0.44
IC-22_maximum	(153.375, 11.375) :	---

22-string hottest spot is now a downward fluctuation →

←

…Southern Sky sources continue on next slide…

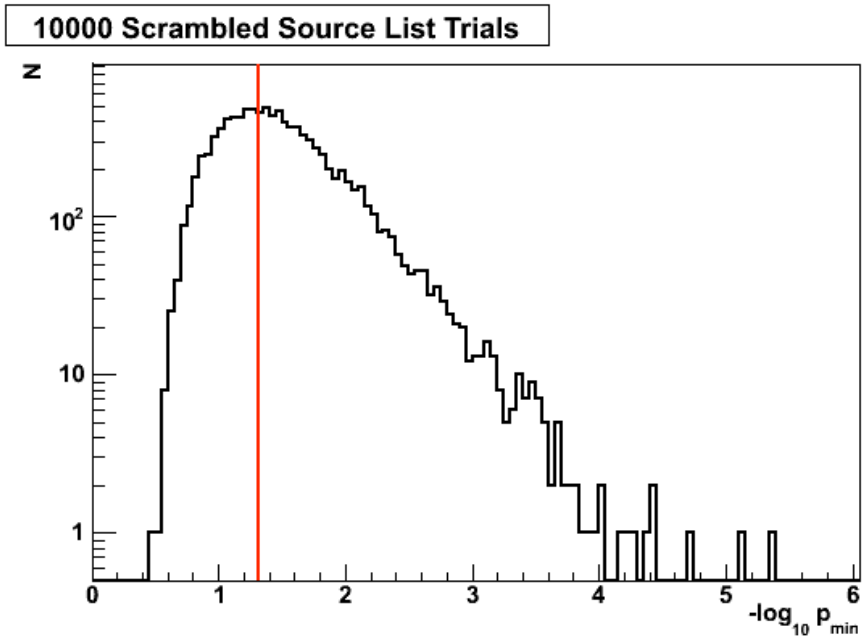
40-string Source List Results (cont.)

Southern Sky **Sources:**

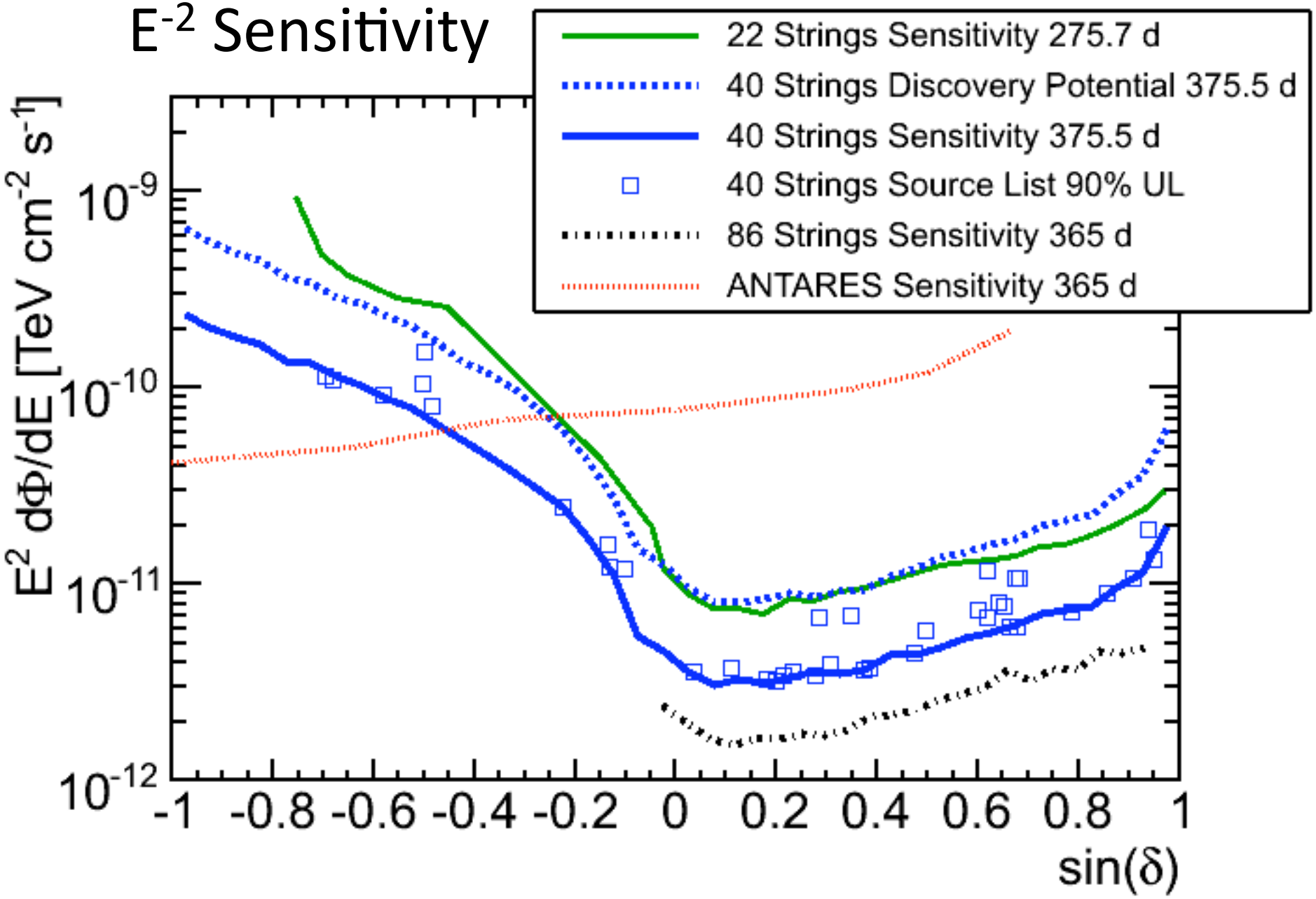
Highest significance from list of 39 sources comes from PKS 1622-297

Source Name	Ra , Dec (deg)	p-value
Sgr_A*	(266.417, -29.008) :	0.44
PKS_0537-441	(84.710, -44.086) :	---
Cen_A	(201.365, -43.019) :	---
PKS_1454-354	(224.361, -35.653) :	---
PKS_2155-304	(329.717, -30.225) :	0.32
PKS_1622-297	(246.525, -29.857) :	0.048
QSO_1730-130	(263.261, -13.08) :	---
PKS_1406-076	(212.235, -7.874) :	0.39
QSO_2022-077	(306.420, -7.640) :	---
3C279	(194.050, -5.790) :	0.12

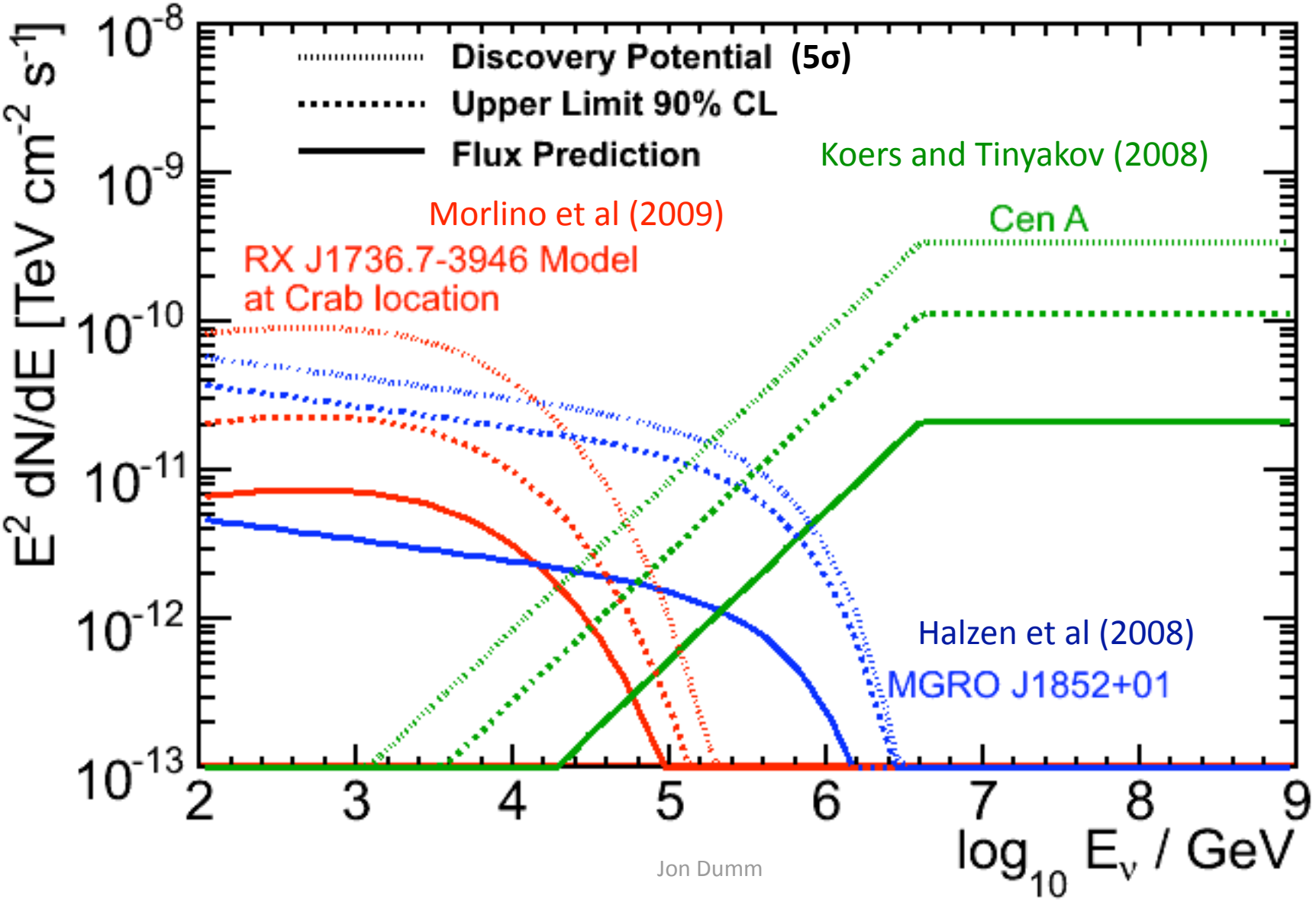
*Pretrial p-value of 4.8% or less for any of the 39 sources happens in 62% of scrambled skymaps
-> **source list final p-value = 62%**



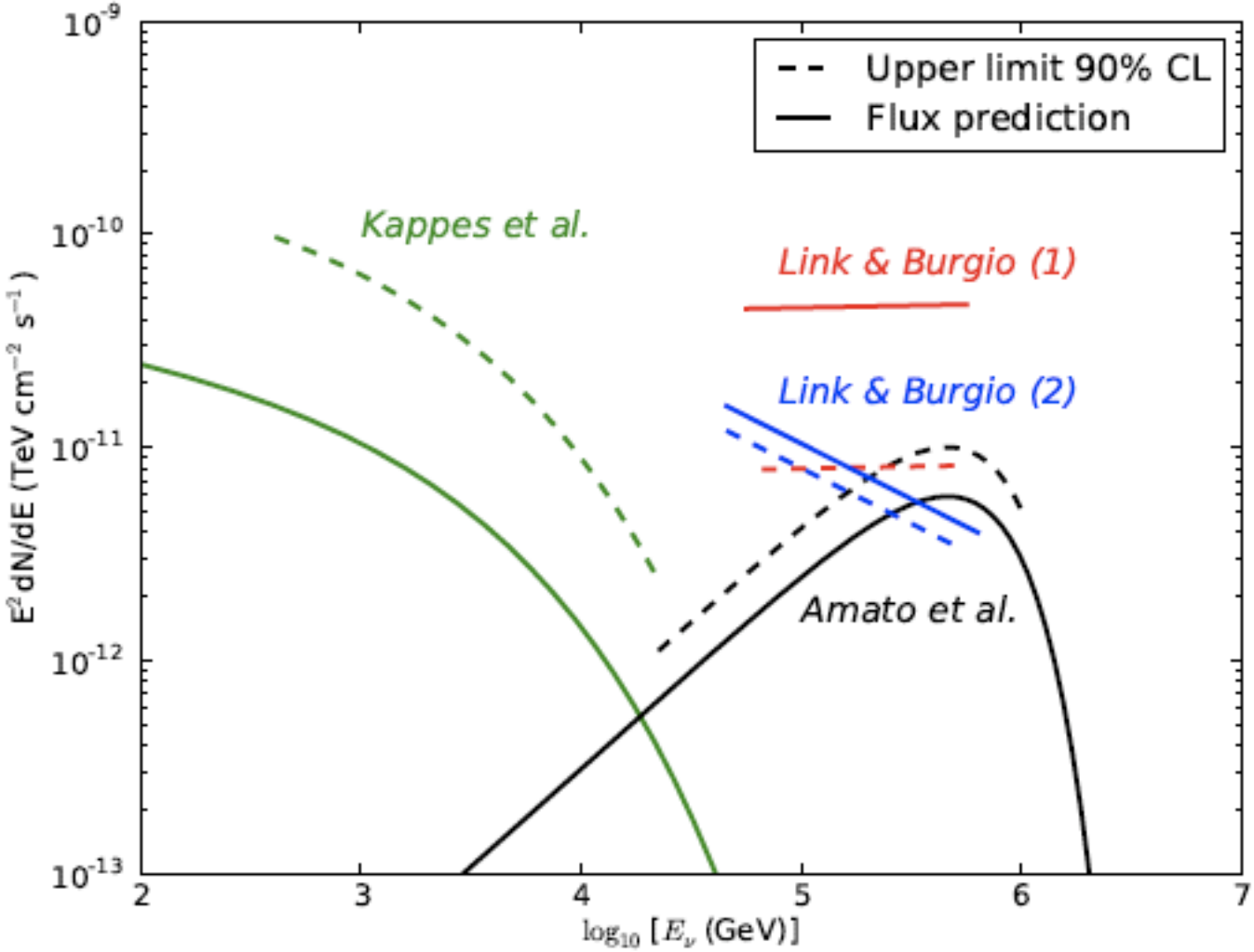
E^{-2} Sensitivity



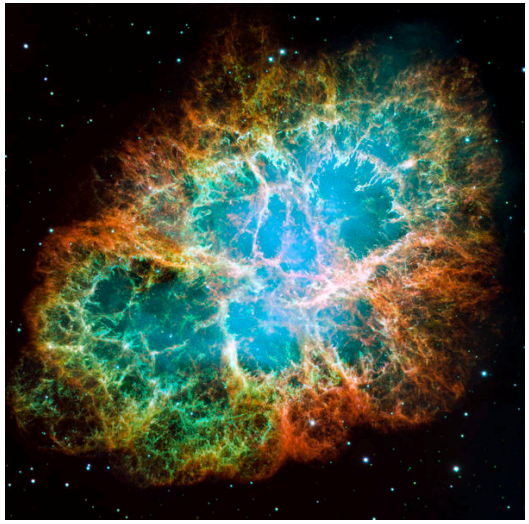
Model Testing - 40 strings

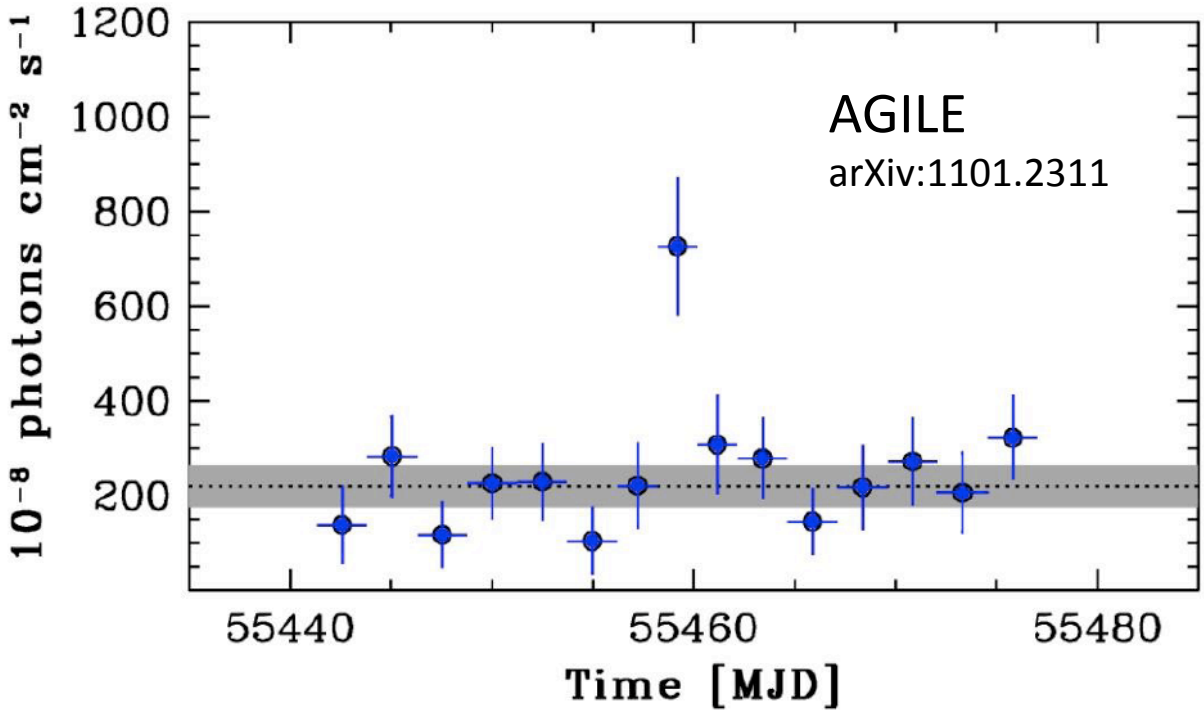


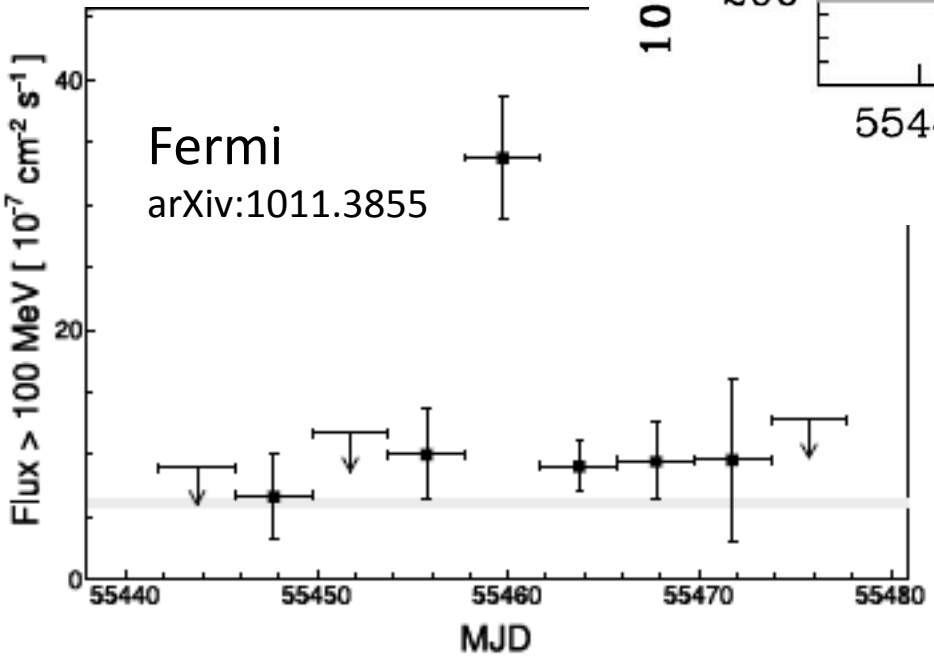
Model Testing: Crab Nebula - 40 strings



The Crab: A Standard Candle?



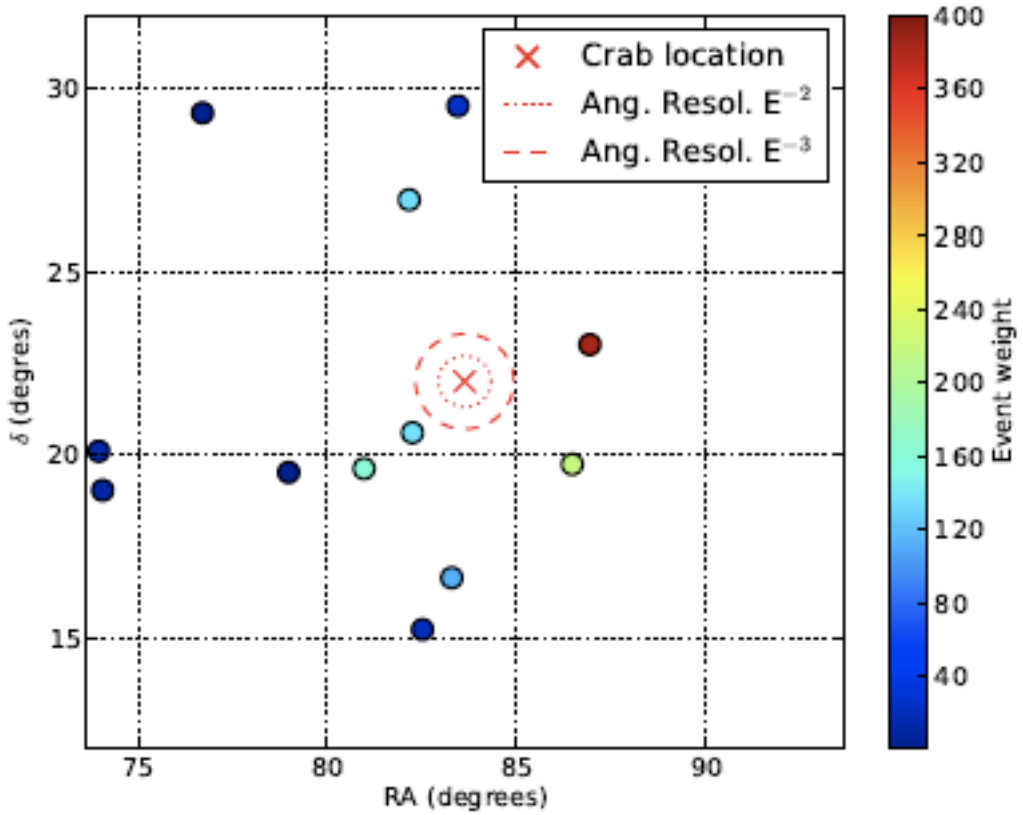




Last September: Crab Nebula flared to ~3-6 times its average flux for several days

Confirmed by ARGO in TeV but not HESS/VERITAS

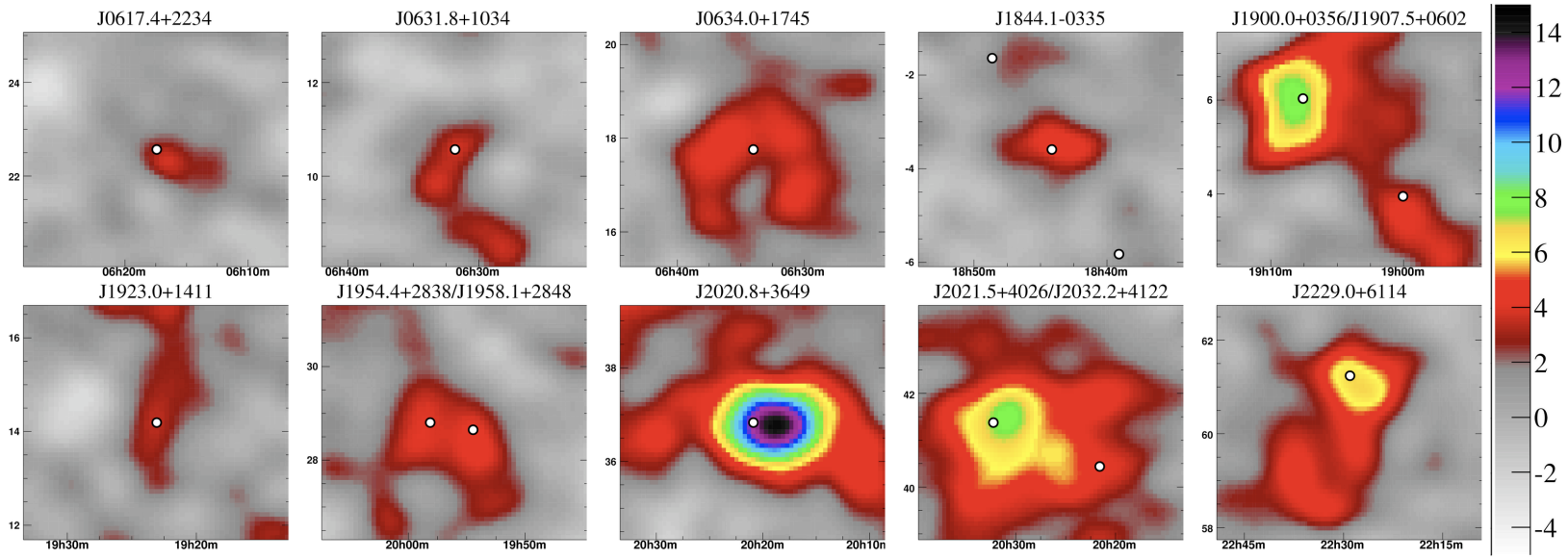
IceCube 79-string Crab Flare Results



- We performed a dedicated, 'fast' unblinding for this Crab flare
- Resulted in an under-fluctuation – no signal

Preliminary:
Paper in progress

Milagro-Fermi Sources: the GeV – TeV connection

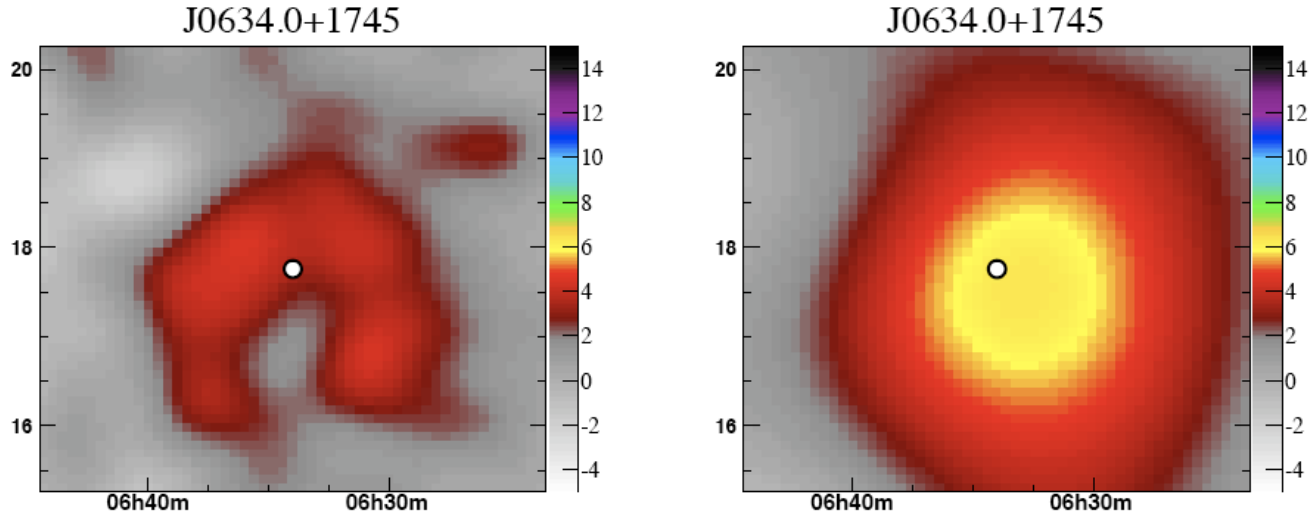


- Milagro showed that many Fermi GeV gamma ray sources extend to TeV
- Sources are a mix: SNR, pulsars, PWN, unidentified
- Great example of how knowing which sources to **stack** can help!

Abdo et al. 2009, arXiv:0904.1018v3

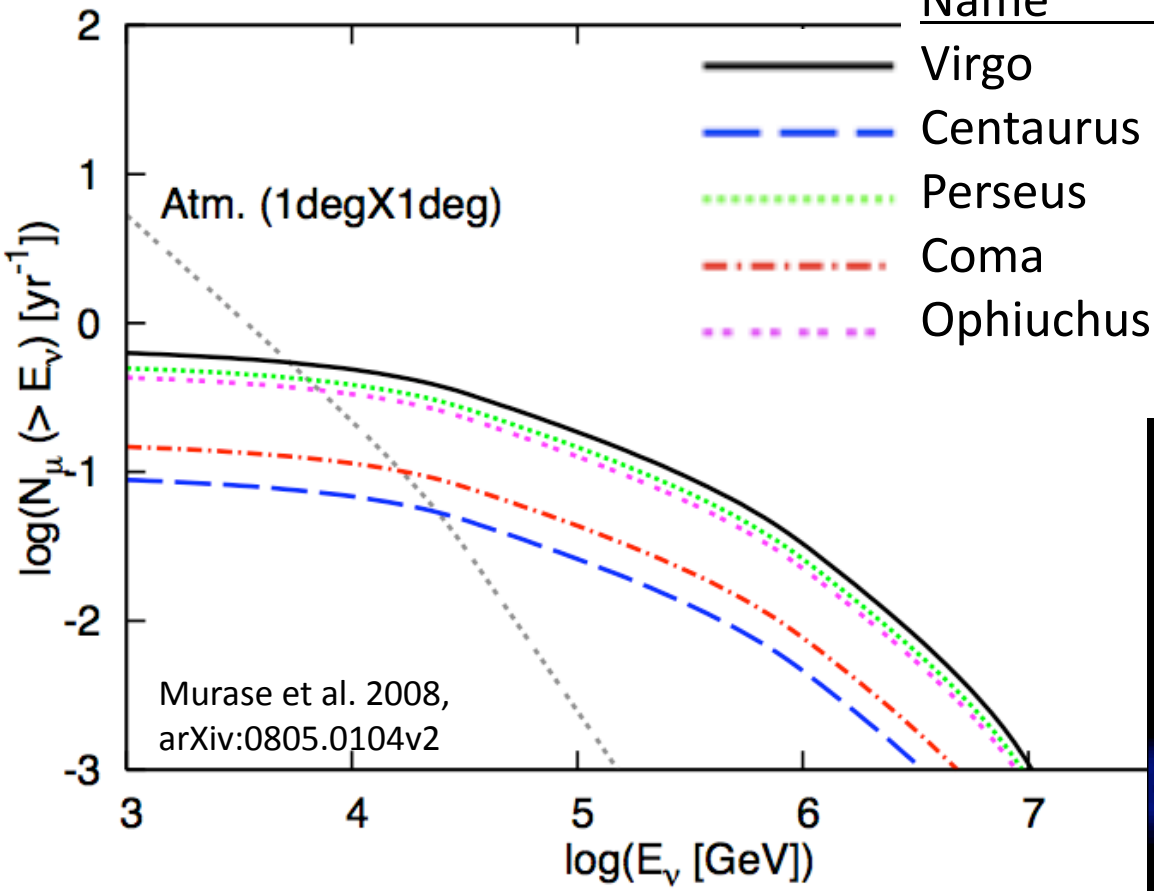
Spatially Extended Sources

- Geminga: Milagro significance maps before and after smearing by a 1° source extension

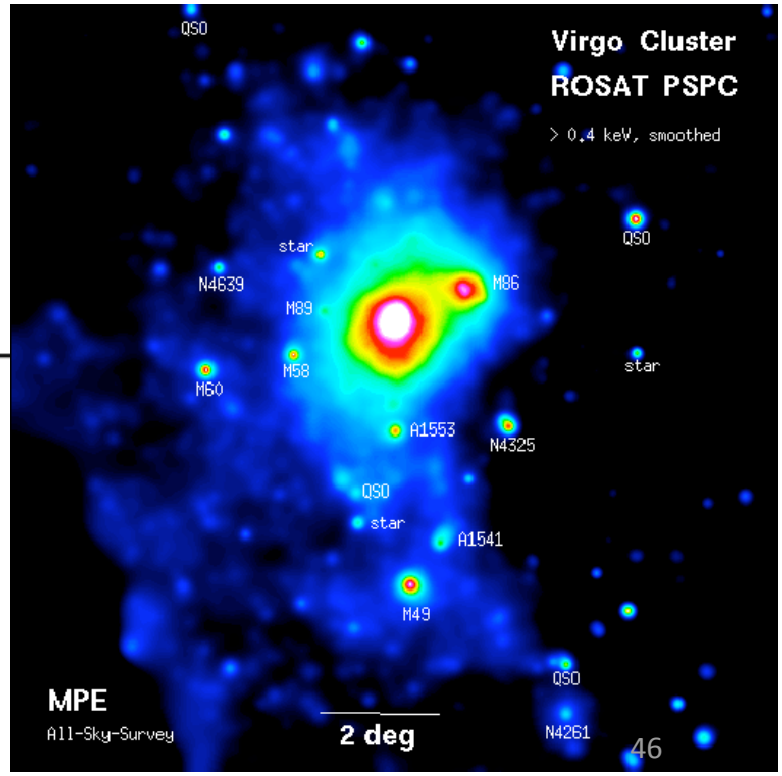


- CRs must be accelerated and interact to produce pions (-> gamma rays + neutrinos)
- Convolve source distribution with PSF in likelihood

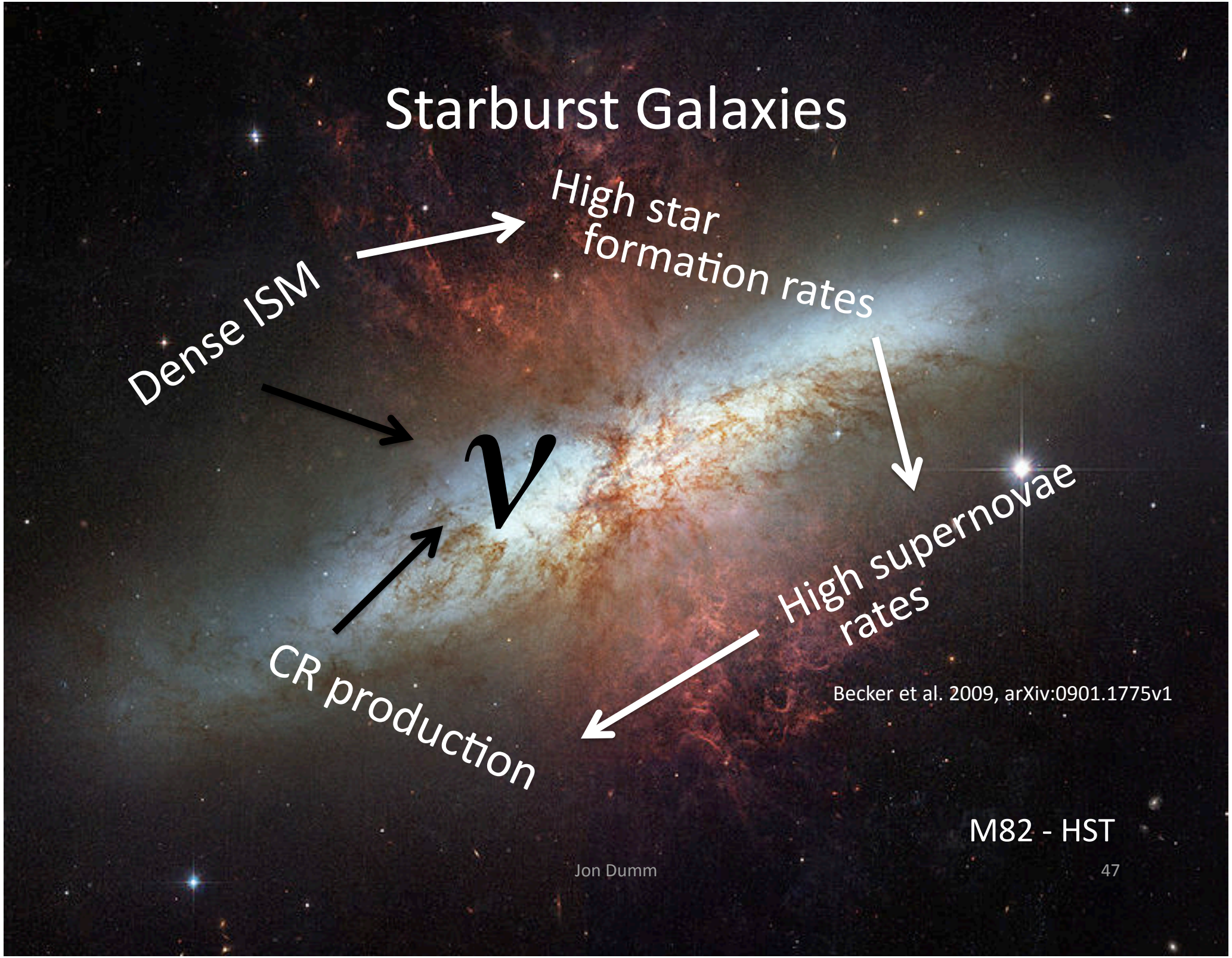
Nearby Clusters of Galaxies



Name	Size (°)	RA(°)	Dec(°)
Virgo	6.7	186.6	12.7
Centaurus	1.6	193.2	-41.3
Perseus	1.4	50.0	41.5
Coma	1.3	195.0	28.0
Ophiuchus	1.3	247	-24.5



- Small magnetic fields but large accretion shock radii. Could be origin of UHE CRs
- CR distribution highly uncertain – several spatial models considered


Starburst Galaxies
High star formation rates
Dense ISM
ν
High supernovae rates
CR production
Becker et al. 2009, arXiv:0901.1775v1
M82 - HST

Three Stacking Searches

Stacked Sources (# of sources)	P-value from scrambling	Fit Number of Source Events	Spectral Index
Milagro (17)	32%	7.6	-2.6
Starburst (127)	100%	0.0	--
Clusters (5)	78%	1.8	-3.9

E^{-2} events required for 5σ (P=50%) discovery: 20.2, 37.5, 15.7, respectively

Nearby Clusters of Galaxies

CR Distribution Model	Upper Limits (40-strings)
Uniform inside shock radius	7.8 * prediction
Uniform inside virial radius	12.0 * prediction
Trace hot gas (X-rays)	13.2 * prediction
Central AGN Model	6.0 * prediction

Could begin to rule out CR acceleration models within the next couple of years of data taking

Murase et al. 2008, arXiv:0805.0104v2

Stacking 6 Milagro SNR

IC40 Stacking Search	Med. Sensitivity	90% Upper Limit
Milagro 6 SNR	2.9 * prediction	7.2 * prediction

- 3.0 events predicted by flux from Halzen, Kappes, O'Murchadha (2008), best fit was 15 signal events over background

p-values of 6 Milagro SNR stacked searches:

AMANDA 7-yr	22-strings	40-strings
20%	27%	1%

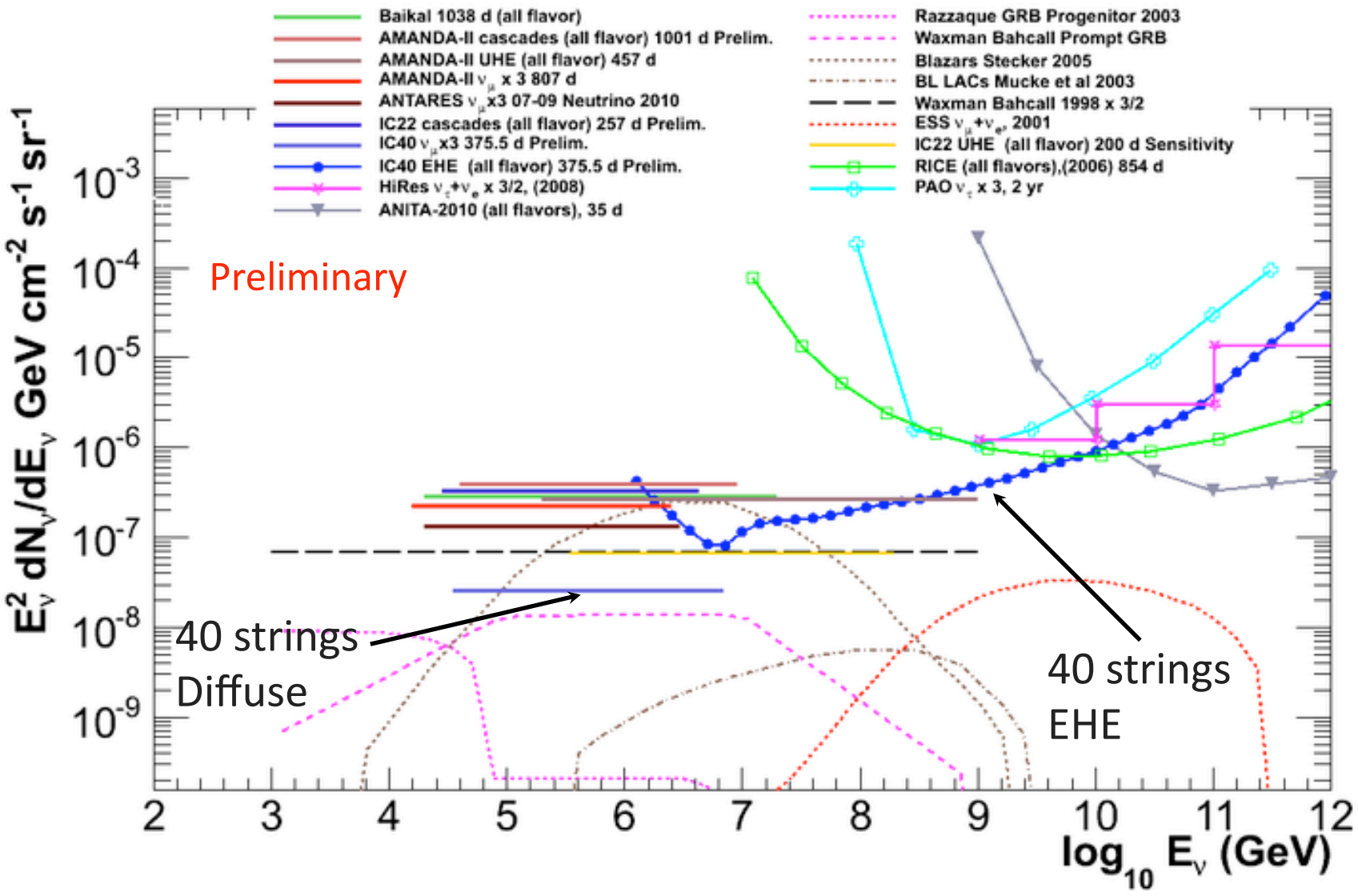
(a posteriori)

Other Recent IceCube Results

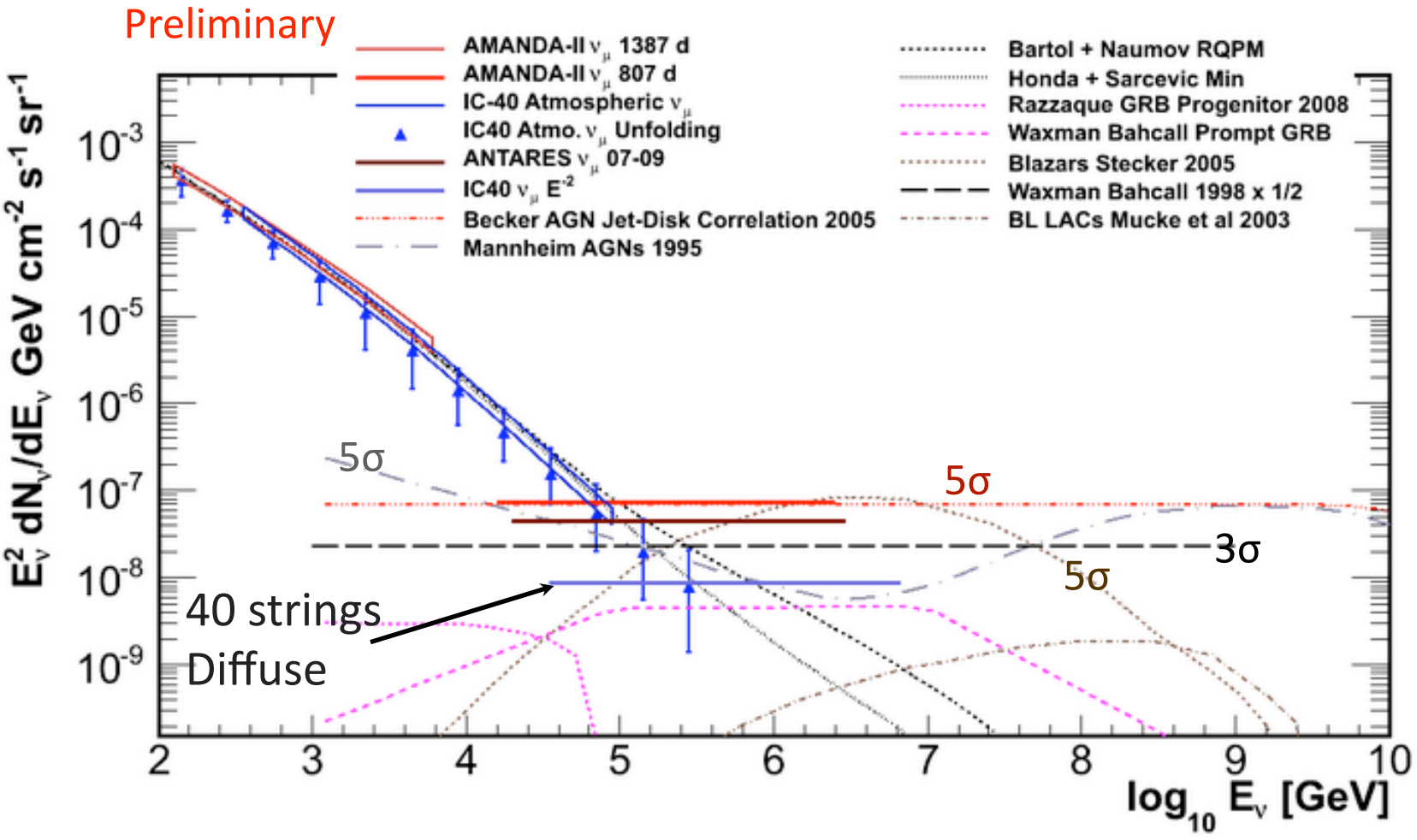
- Diffuse Neutrino Search → Under-fluctuation
- Gamma Ray Bursts → Under-fluctuation
- WIMPs (Solar, Gal. Halo) → Under-fluctuation

- Cosmic Ray Anisotropy → TeV cosmic rays have anisotropy at 0.2%

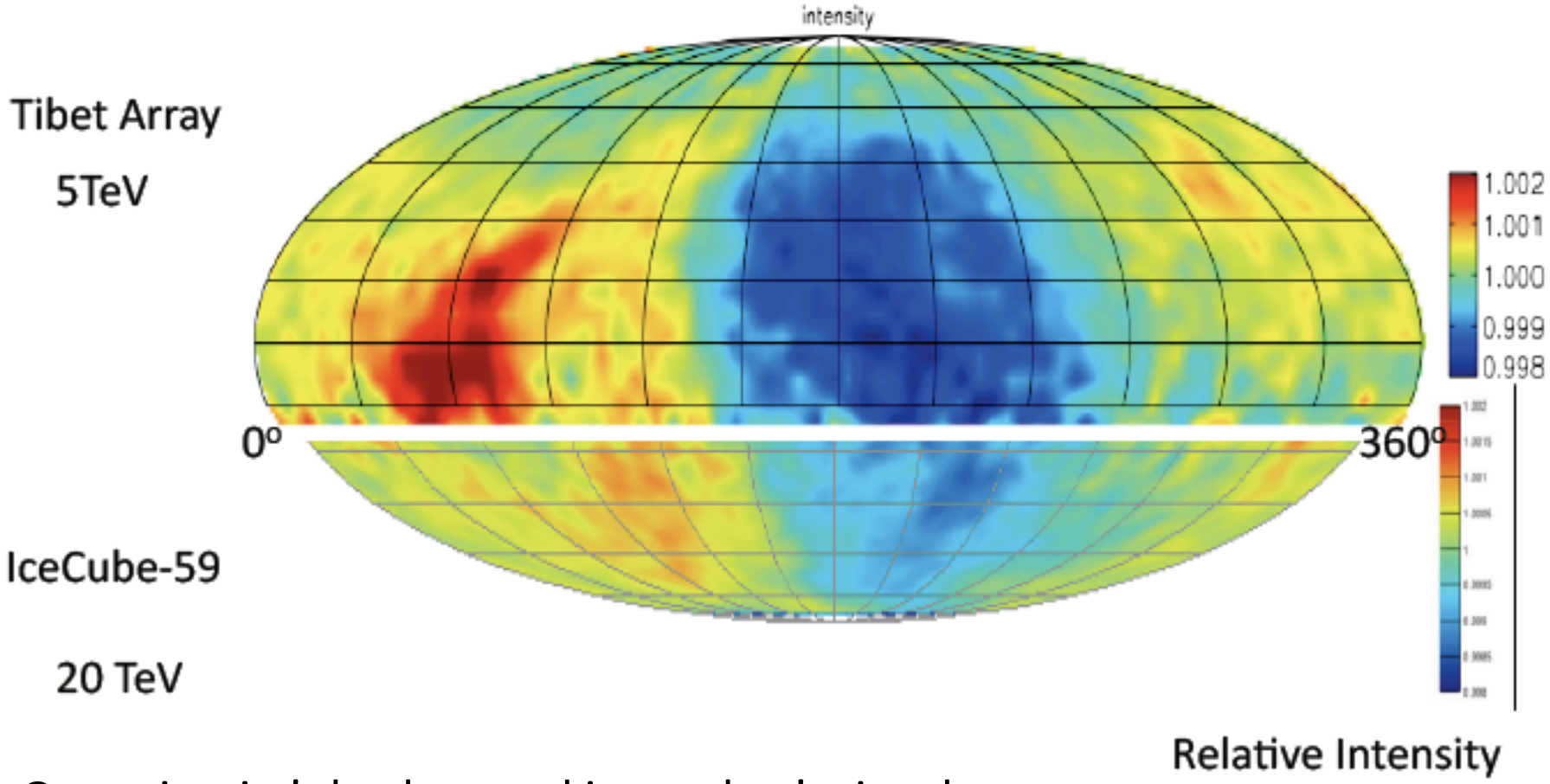
Diffuse Flux Models and Limits



Diffuse Astrophysical Model Tests



Large-scale CR Anisotropy



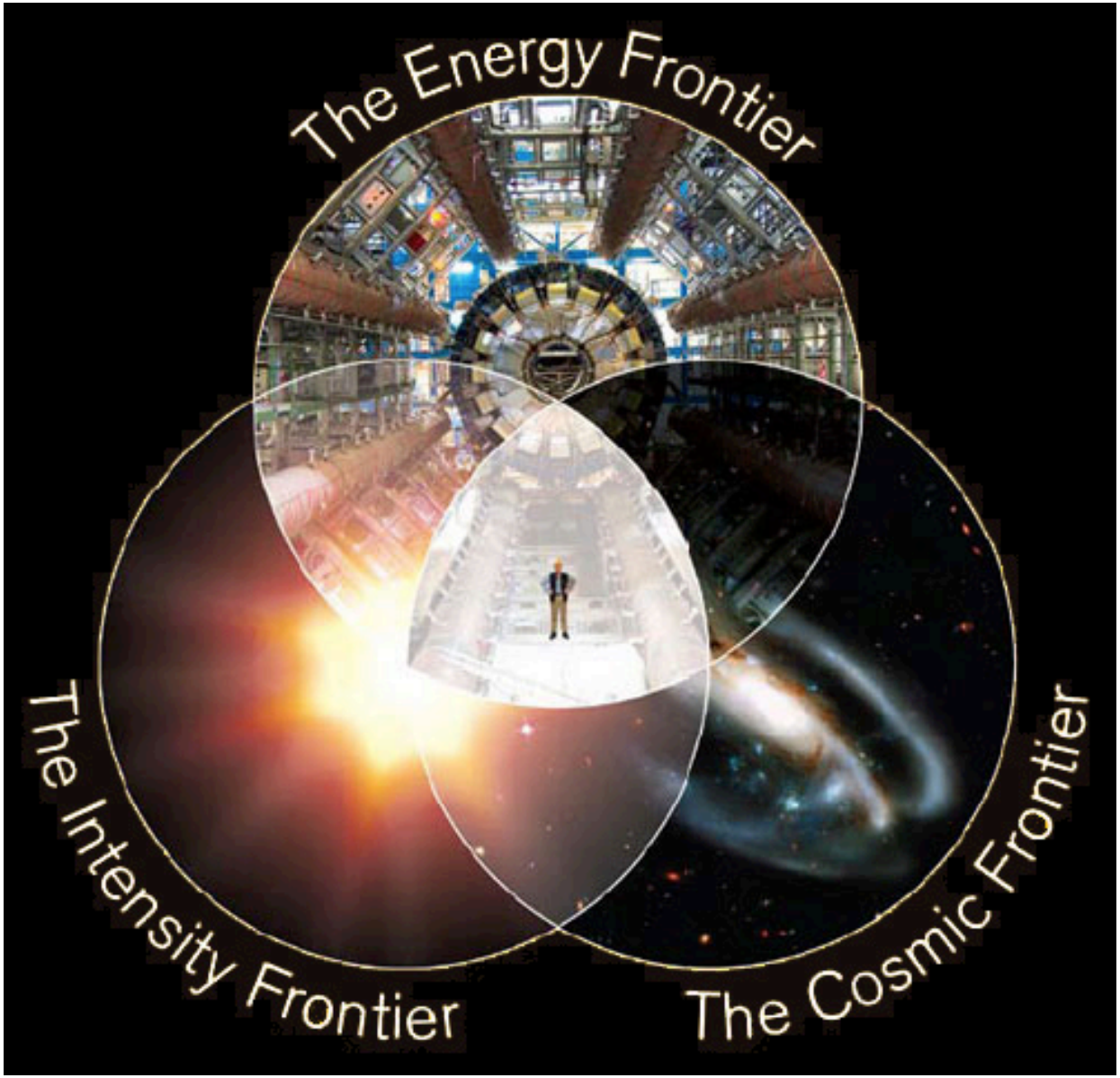
- One scientist's background is another's signal
- In agreement with continuation of anisotropy in the north
- Nearby magnetic fields, CR sources?
- Not consistent with Compton Getting

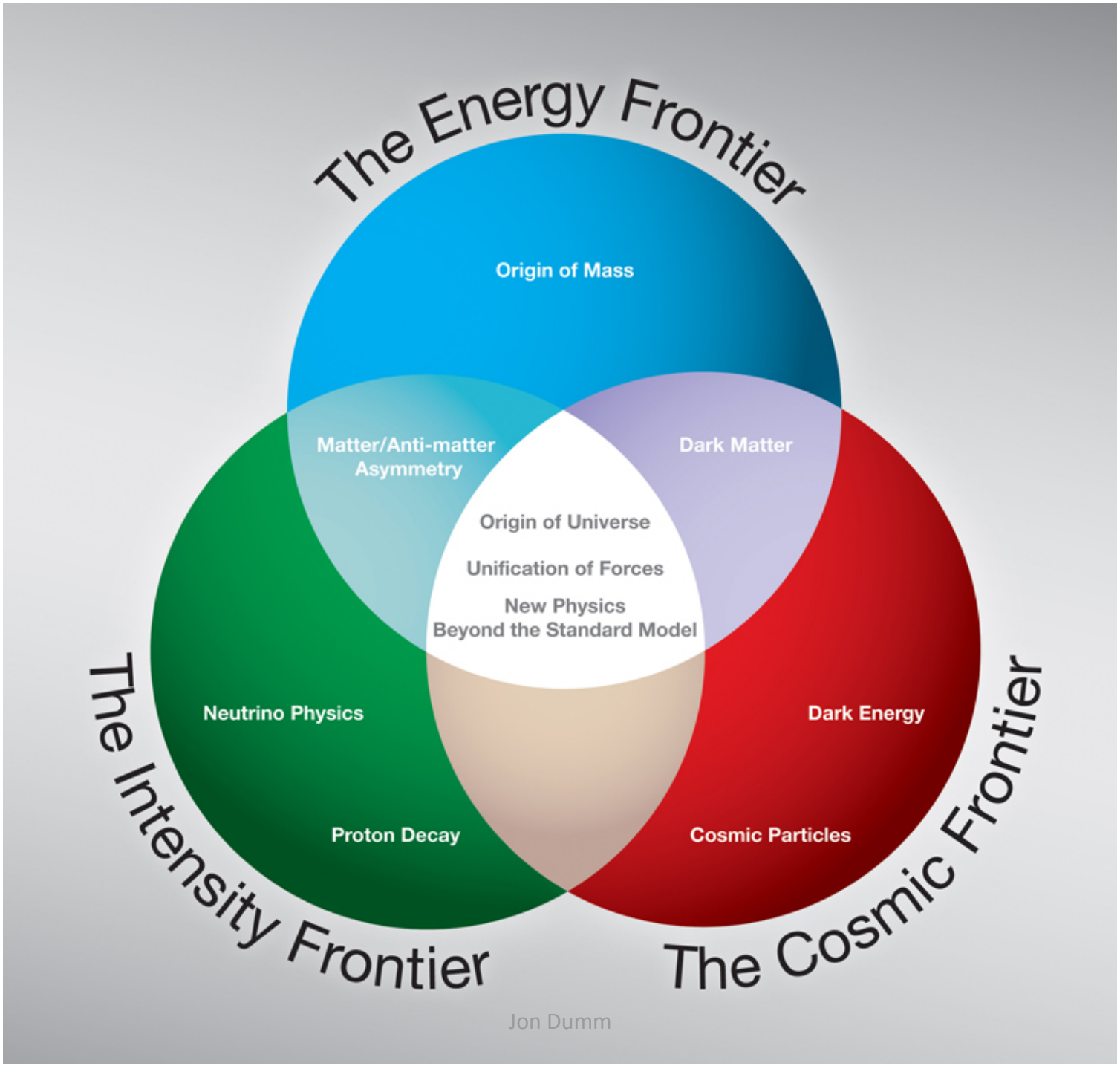
Conclusions

- IceCube construction is complete!
- So far, no evidence found for any signal
  - Upper limits already begin to rule out some astrophysical scenarios
- 40-string data being published,
  59-string analysis underway,
  79-string data processing,
  86-string detector being commissioned

Backup Slides

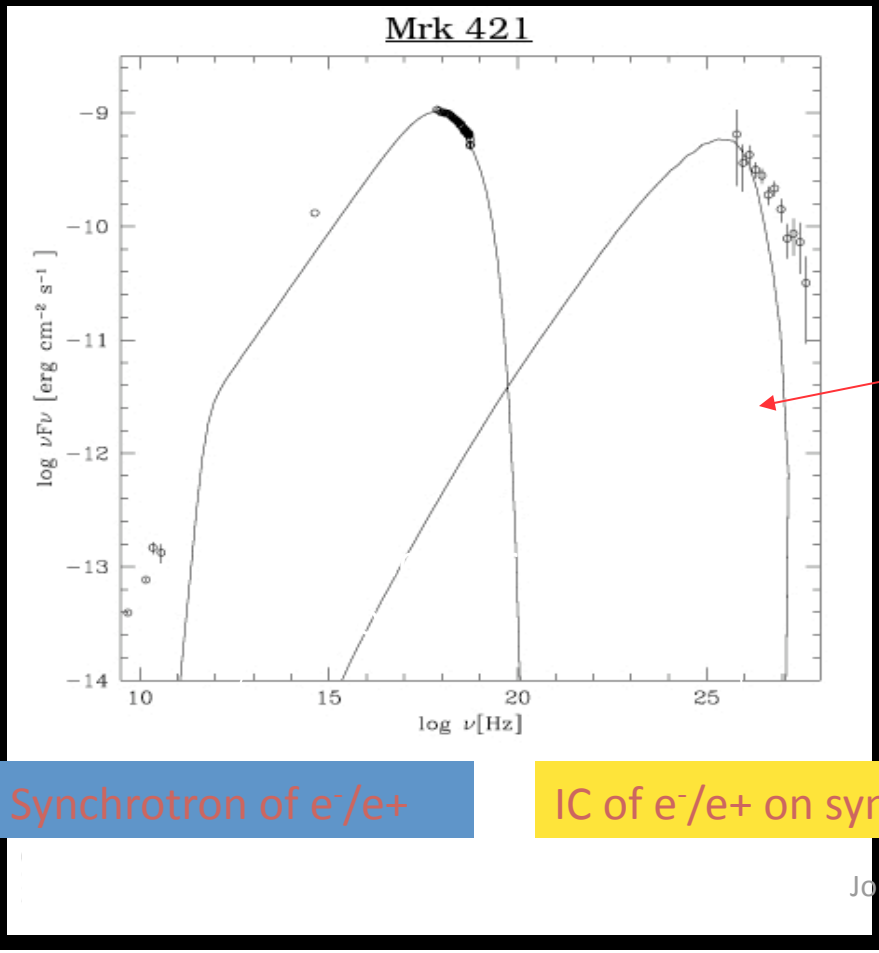
Particle Physics Today:
Three Frontiers of Science




The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

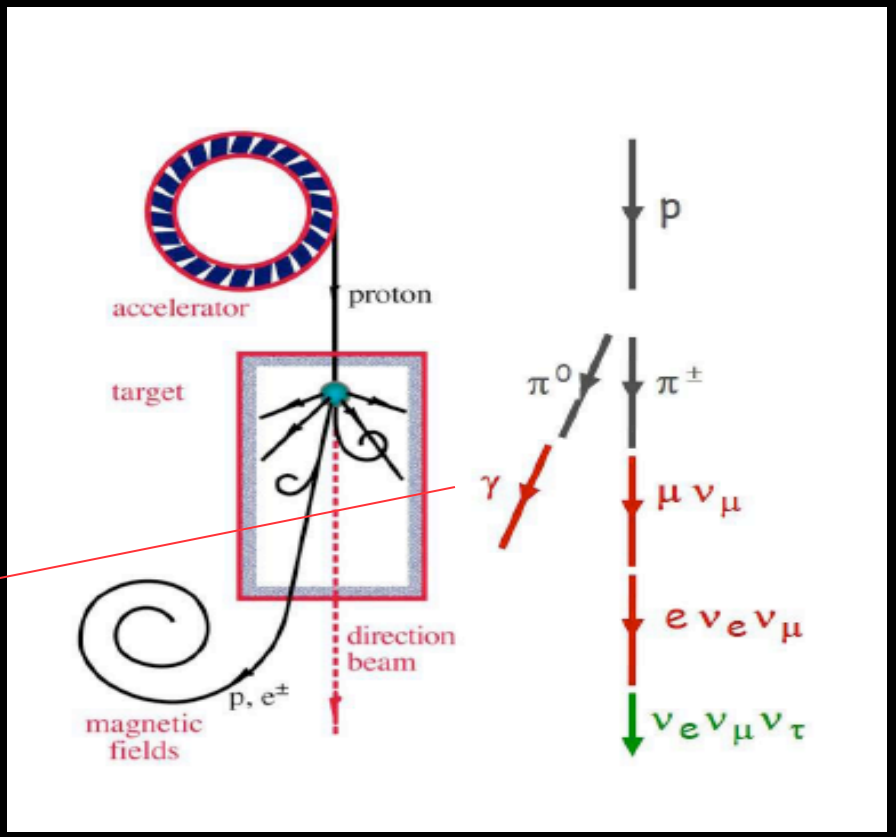
Blazar Spectral Energy Distribution

- Typical double-humped SED
- Separated by 8-10 orders of mag.
- Only small correlation



Synchrotron of $e^-/e+$

IC of $e^-/e+$ on synch. γs

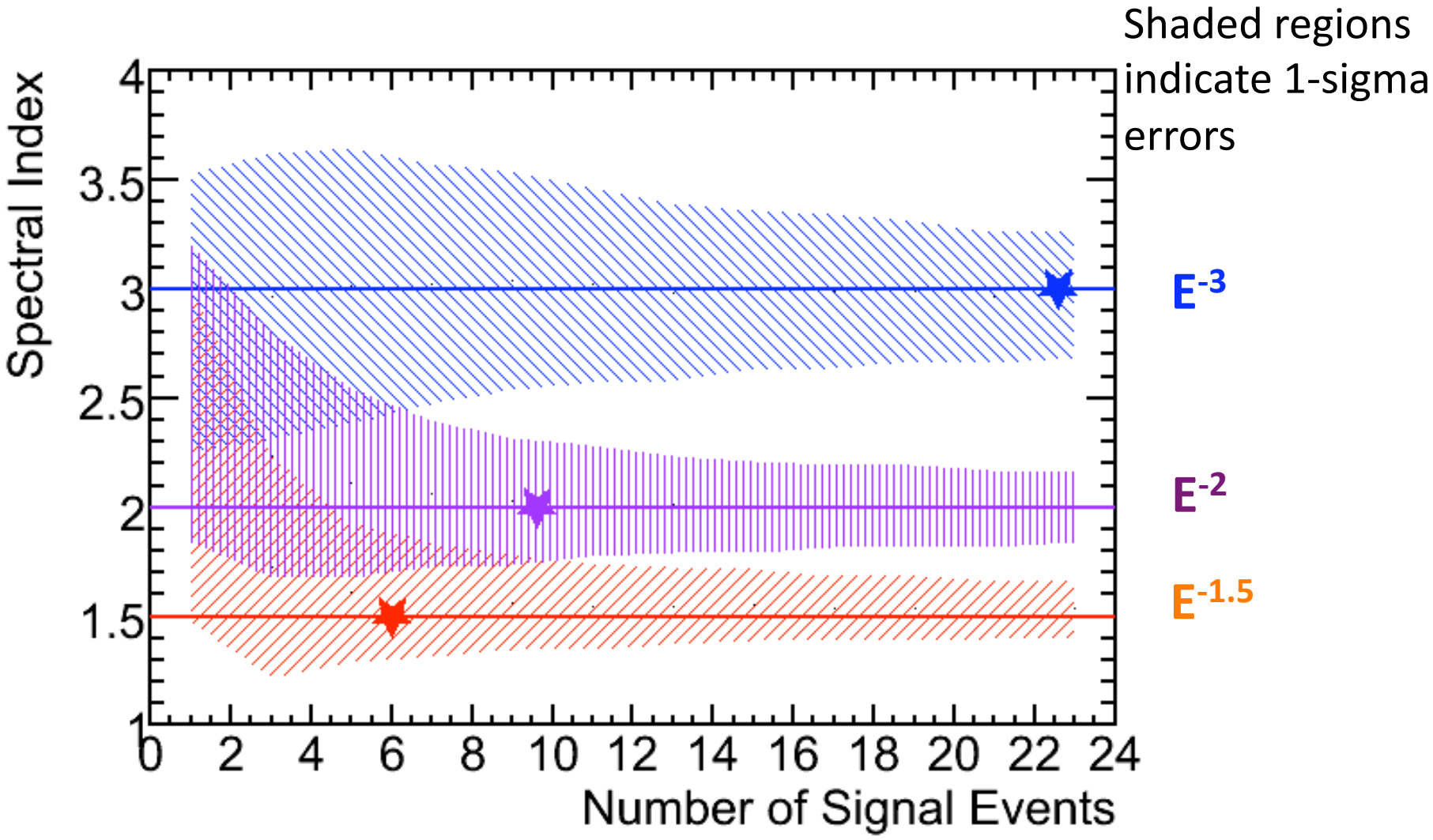


A hadronic component in the jet leads to neutrinos!

Telescope	User	Date	Intended Use	Discovery
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio Galaxies
Microwave	Penzias & Wilson	1965	Radio astronomy, communications	3K cosmic background
X-ray	Gicacconi et. al.	1965	Sun, moon	Neutron Stars, accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
Gamma rays	Military	1960(?)	Thermonuclear explosions	Gamma Ray Bursts

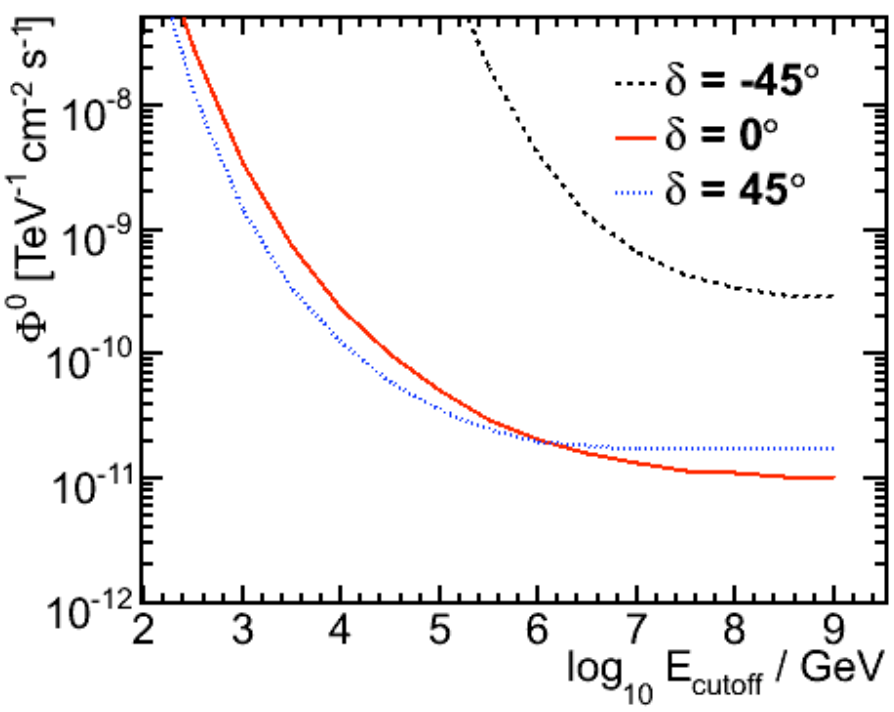
Moral of the story: **expect the unexpected . . .**

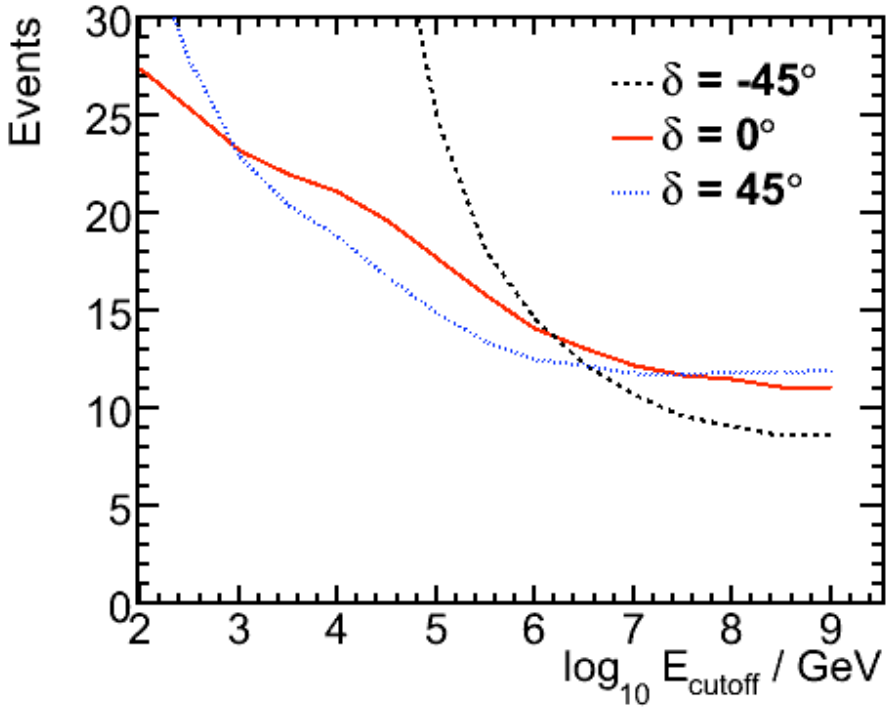
Spectral Reconstruction



Spectral resolution is about 0.3 when enough events are present for a discovery (stars)

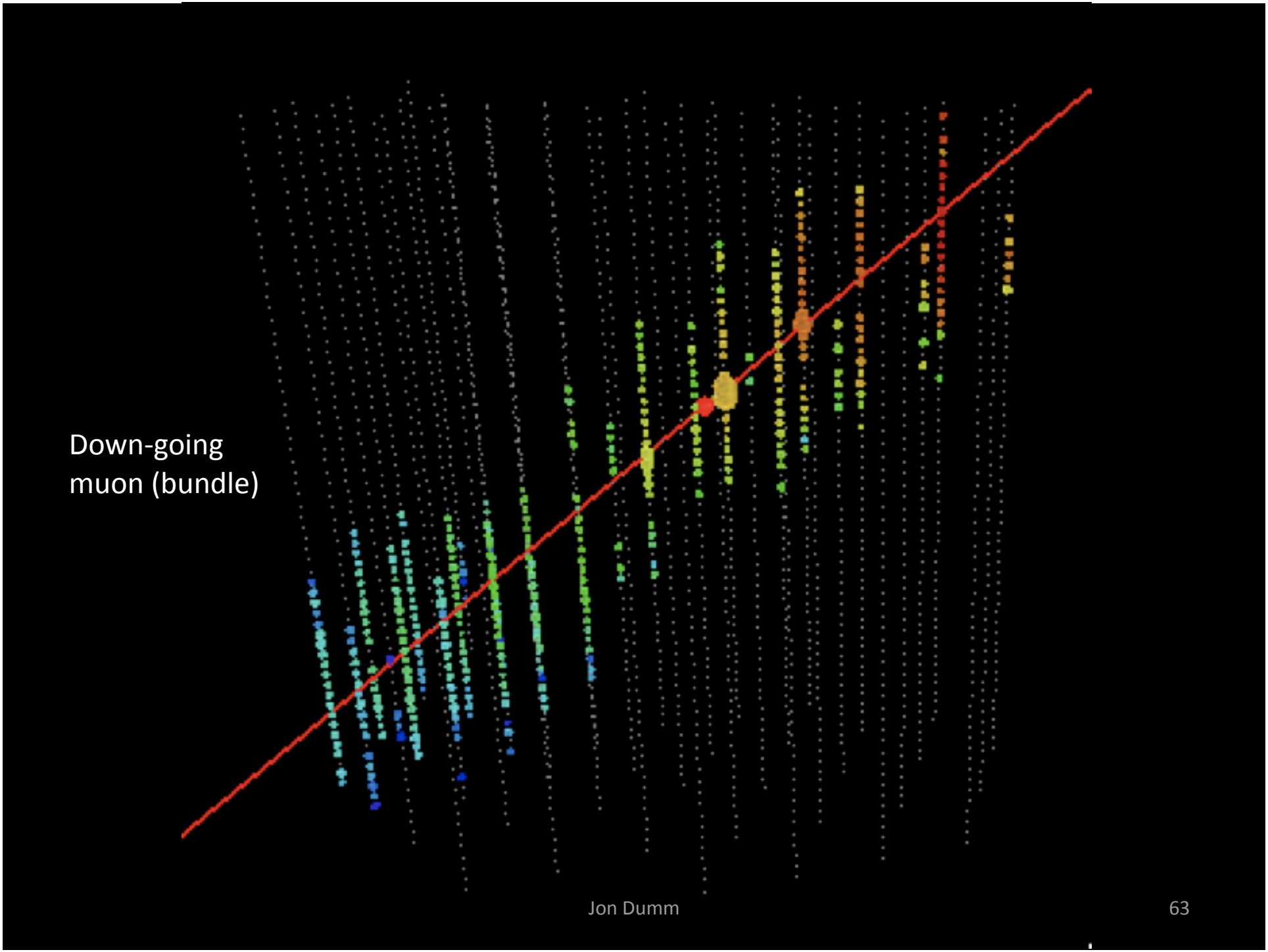
Discovery Potential for Cutoff Spectra

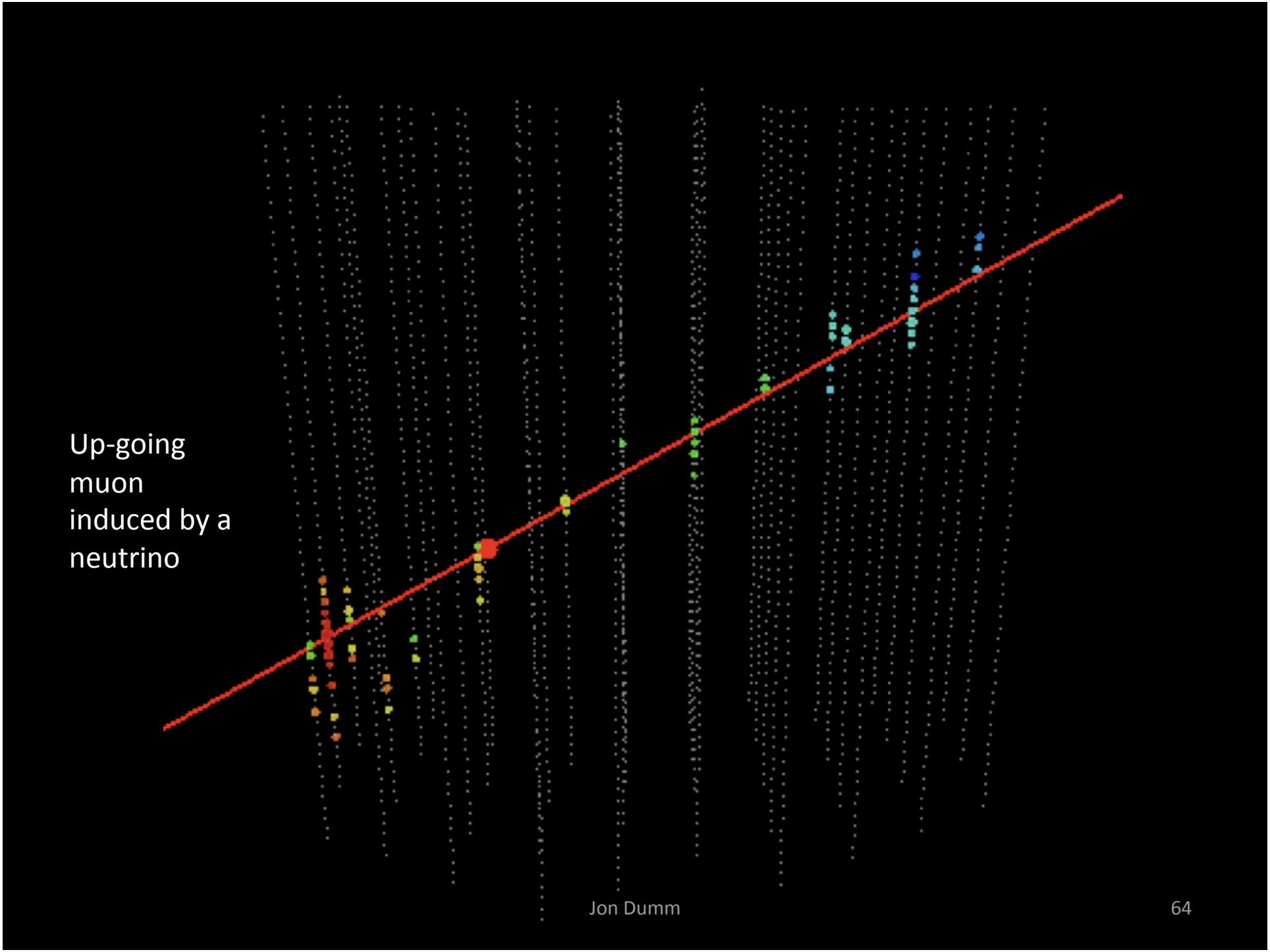




Cutoff spectra parameterized as:

$$d\Phi / dE = \Phi^0 E^{-2} \exp(-E / E_{cutoff})$$


Down-going
muon (bundle)


Up-going
muon
induced by a
neutrino

Second Astrophysical Neutrinos: SN1987A

- **99% of binding energy goes into νs in a core collapse**
- *Neutronization*, ~10 ms 10^{51} erg $e^- + p \rightarrow n + \nu_e$
- *Thermalization:* ~10 s 3×10^{53} erg $e^- + e^+ \rightarrow \bar{\nu} + \nu$

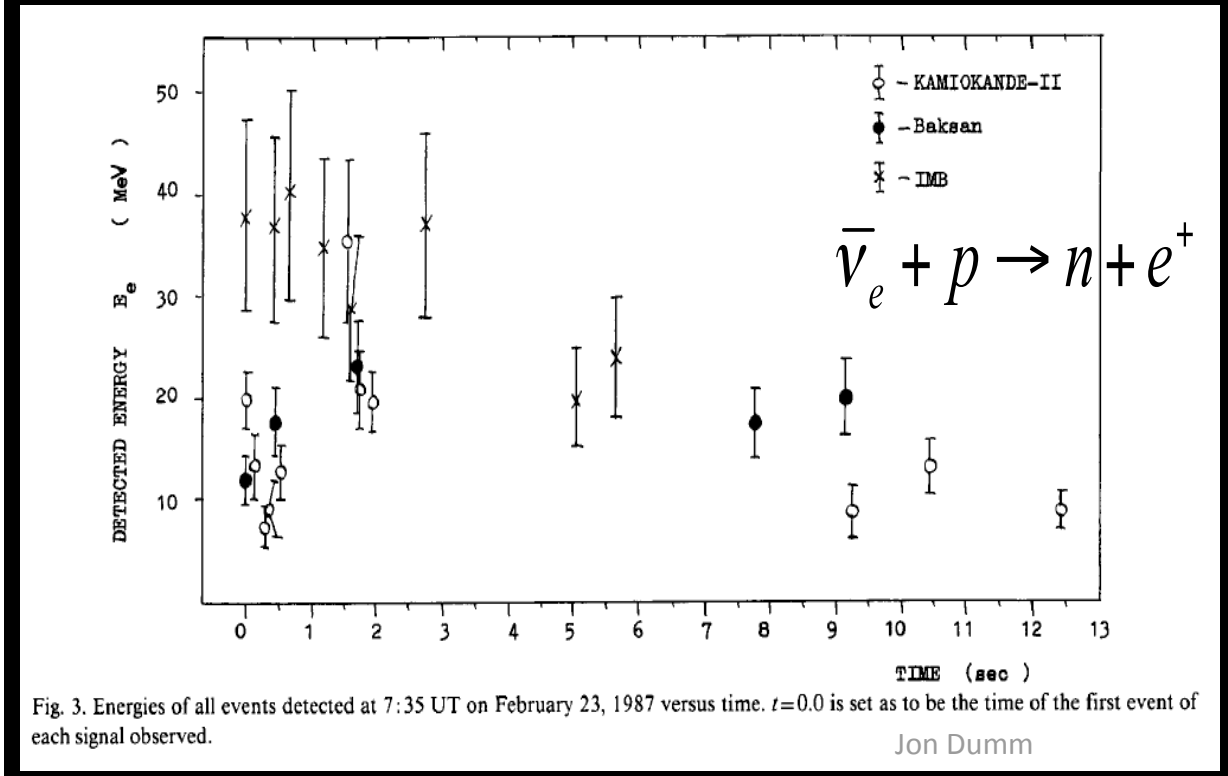
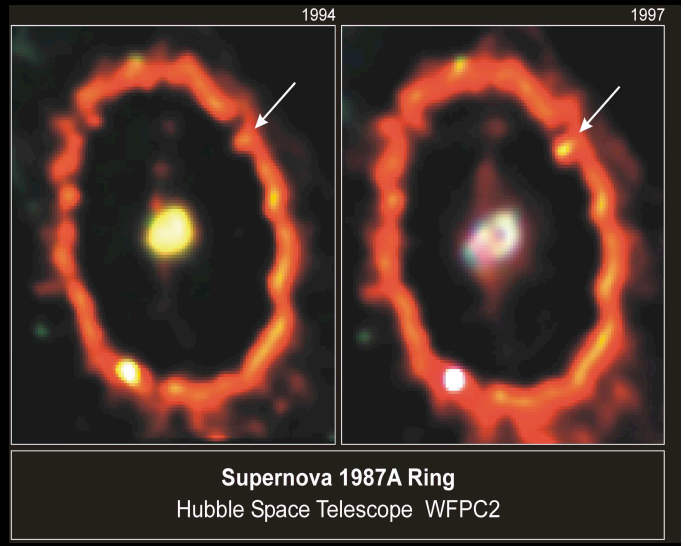


Fig. 3. Energies of all events detected at 7:35 UT on February 23, 1987 versus time. $t=0.0$ is set as to be the time of the first event of each signal observed.

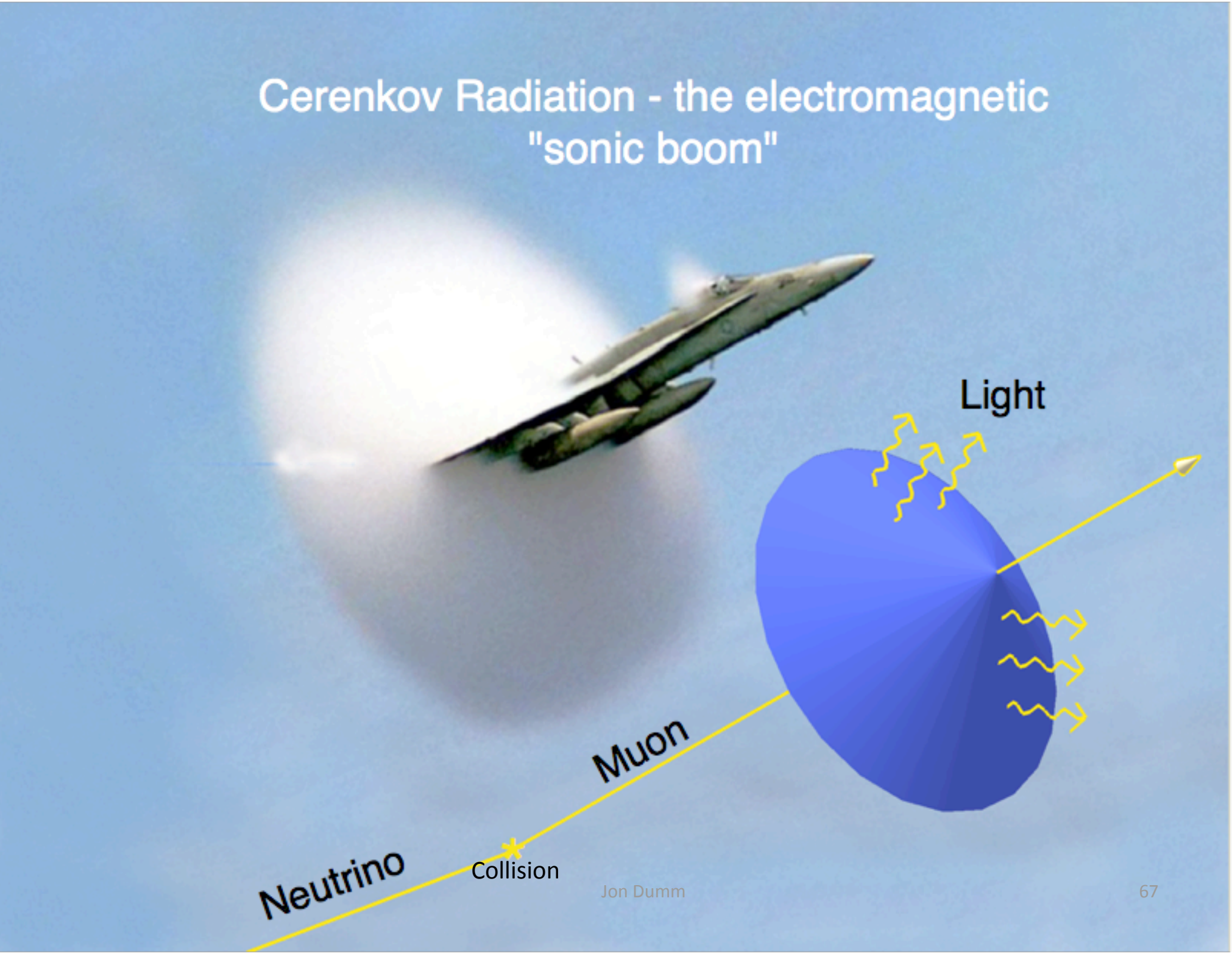


The Point Source Analysis in Words

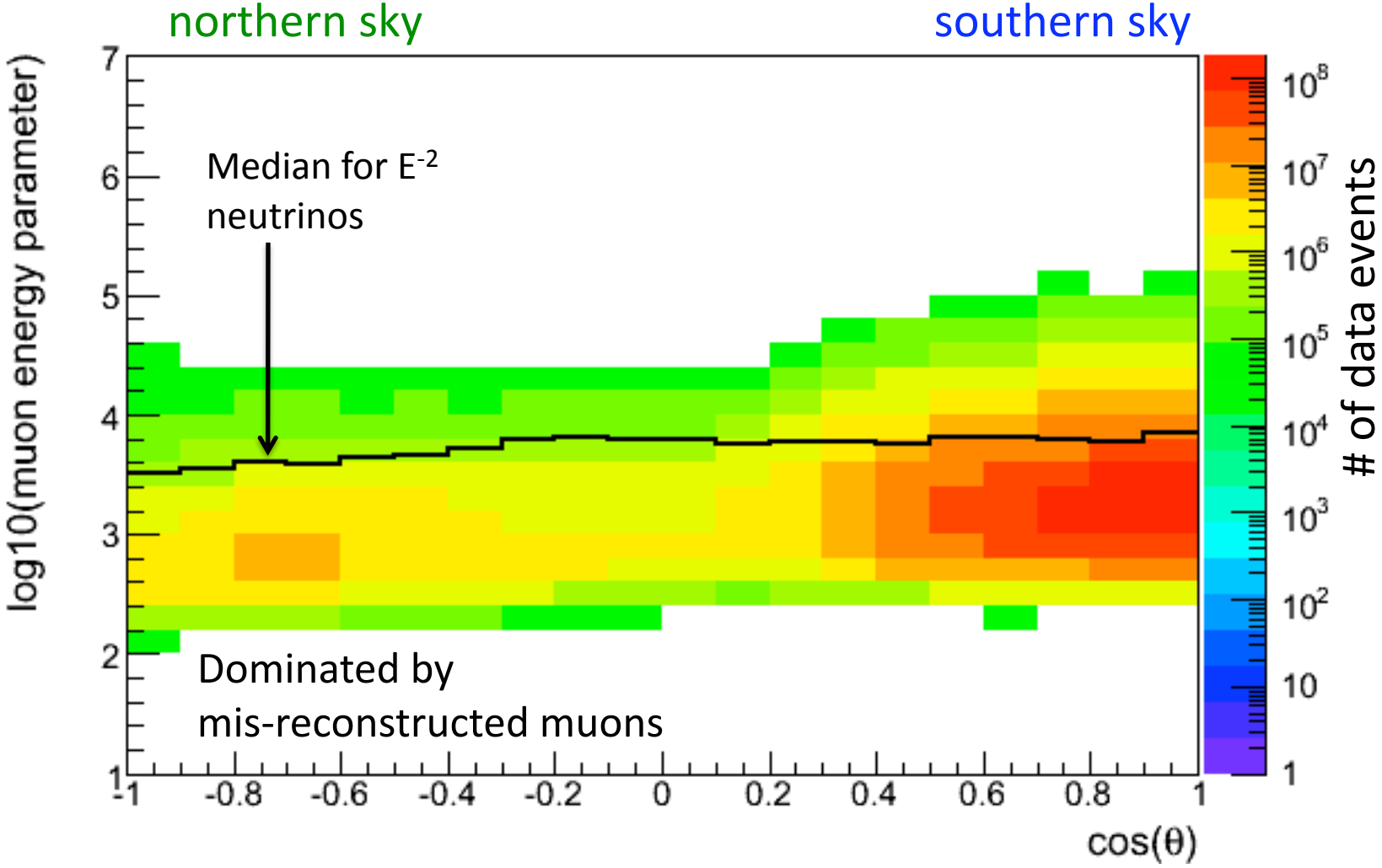
- Determine observables useful for separating signal and background
  - Space (θ, Φ)
  - Energy
  - (Time)

- Build PDFs for how signal and background are distributed for these observables
  - Under null hypothesis all data are background (atmospheric neutrinos and muons)
  - Simulation used for PSF and Energy

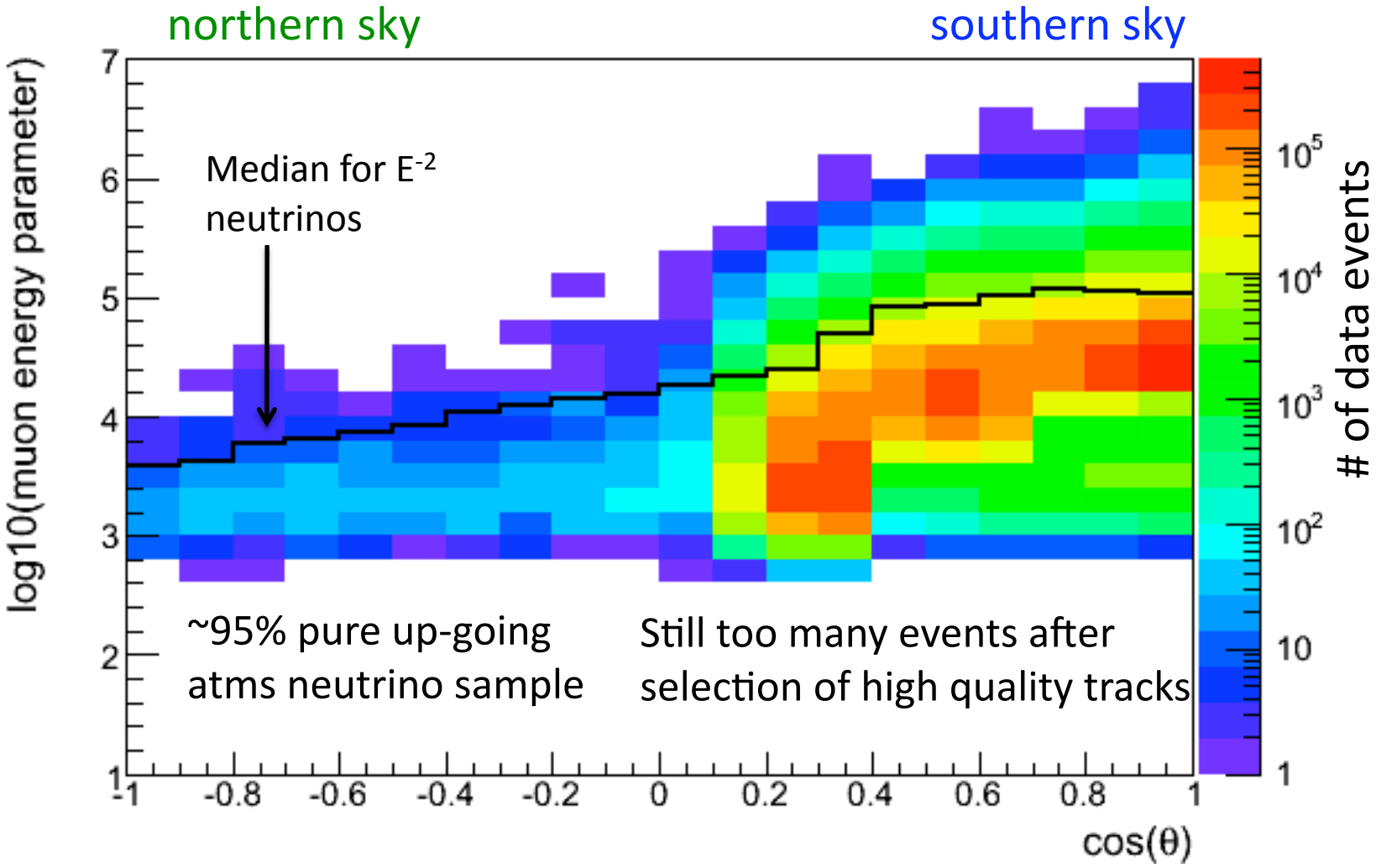
- Fit for best mixture of signal and background
  - Extract astrophysical parameters


Cerenkov Radiation - the electromagnetic "sonic boom"
Light
Muon
Neutrino
Collision

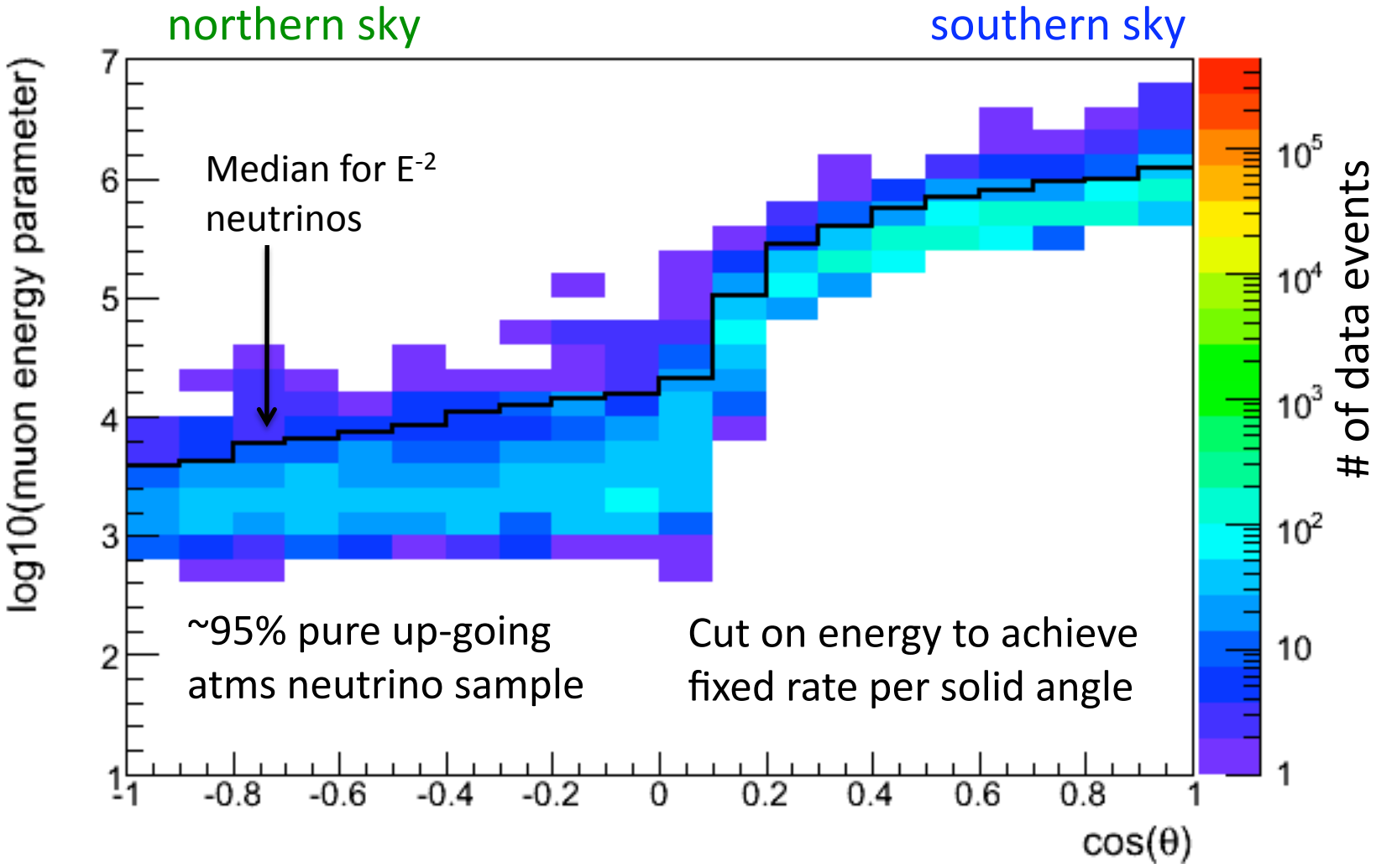
Energy vs Zenith – Trigger Level



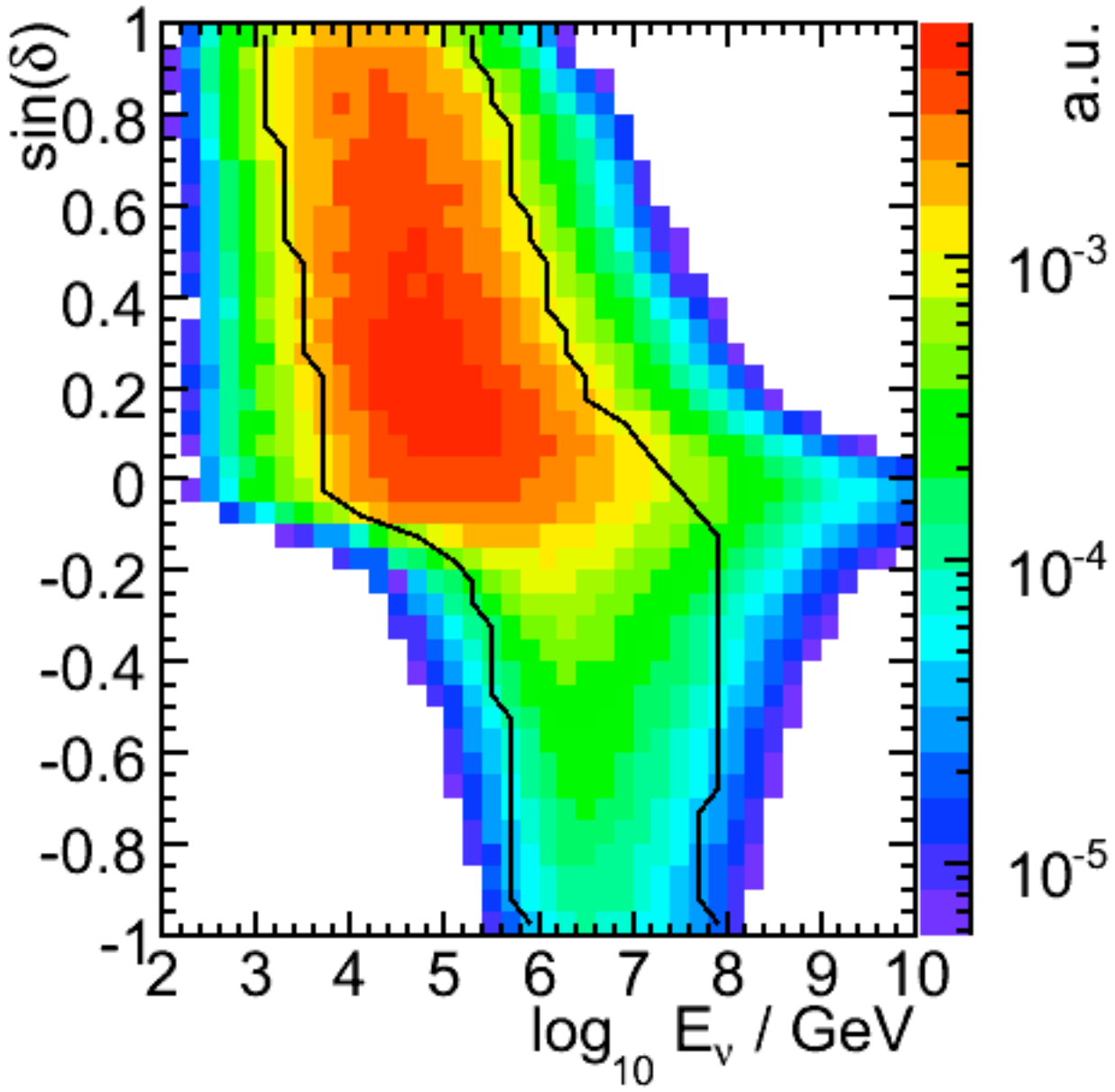
Energy vs Zenith – Quality Cuts



Energy vs Zenith – Quality + Energy Cuts

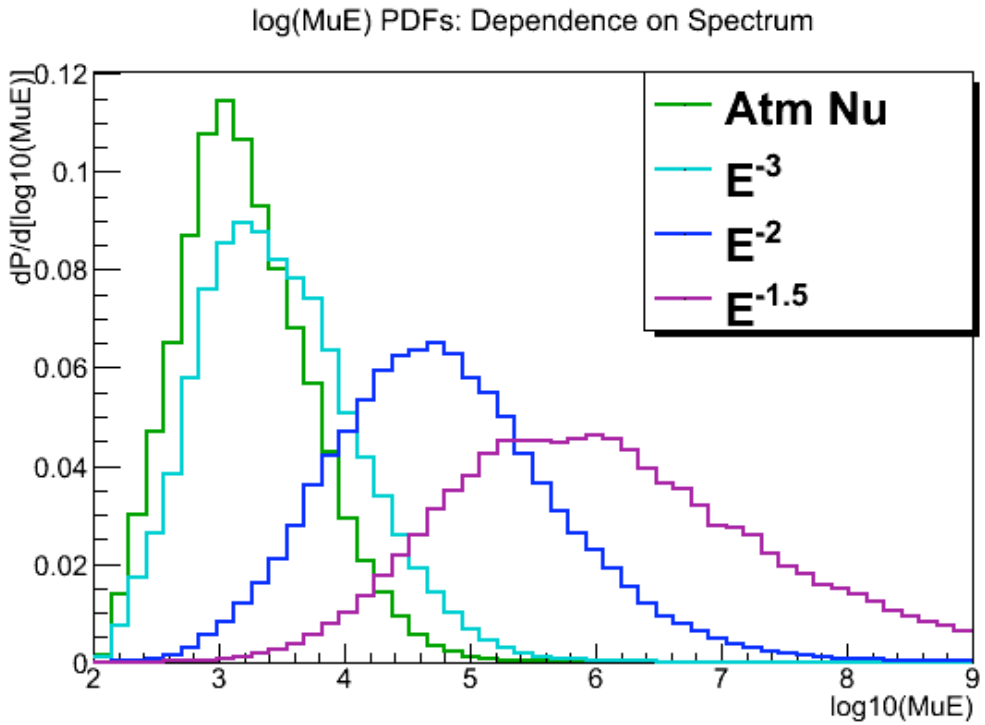


Energy of E^{-2} Signal



Search Method

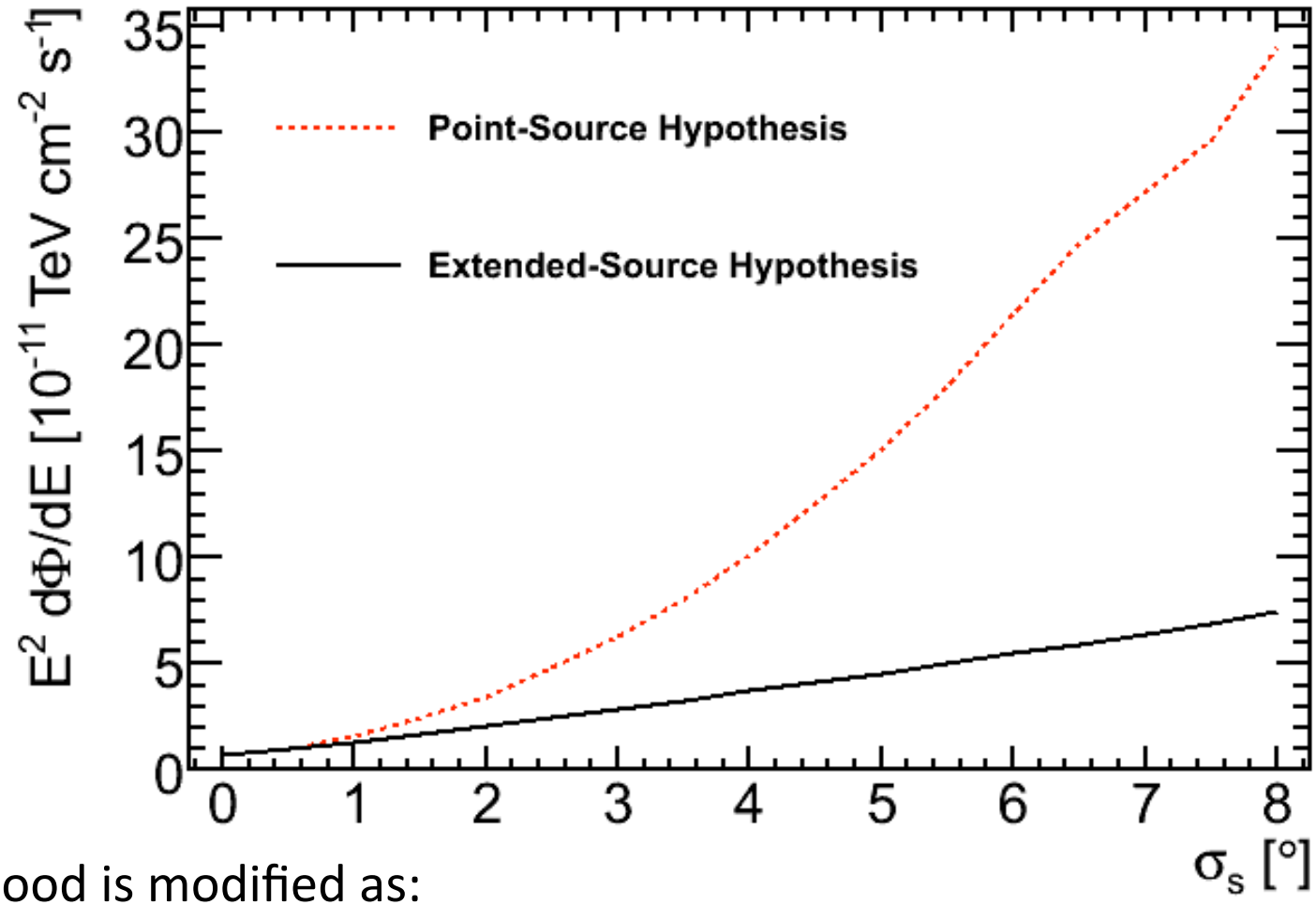
- Unbinned maximum likelihood search
  - Directional clustering → Median PSF for E^{-2} neutrino spectrum:
    0.7° in northern sky
    0.5° in southern sky
  - Energy



Robust results:

- Blind analysis
- Background pdfs drawn from data
- Final significance comes from scrambling data in r.a.

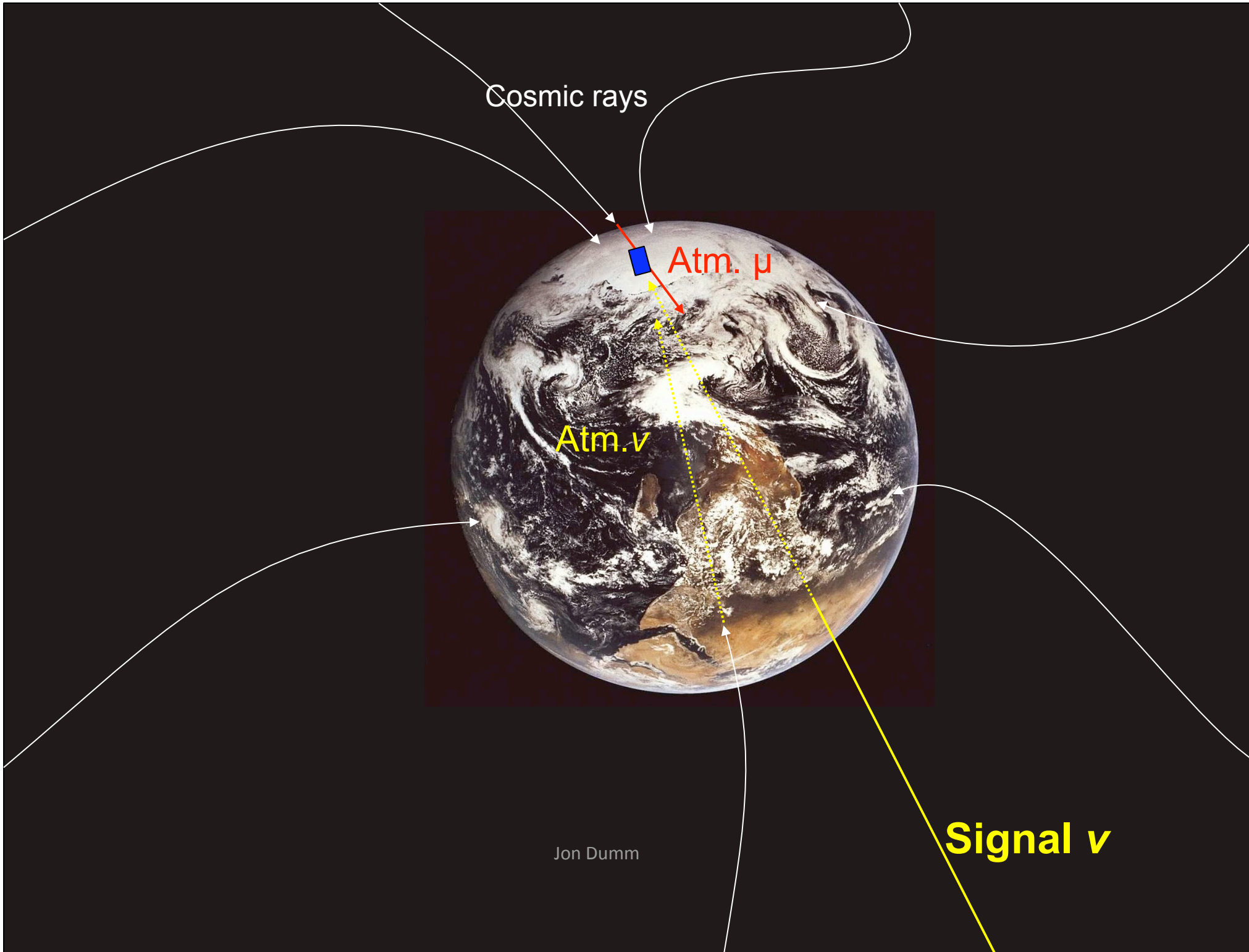
Extended Search Performance - 2D Gaussian Source PDF



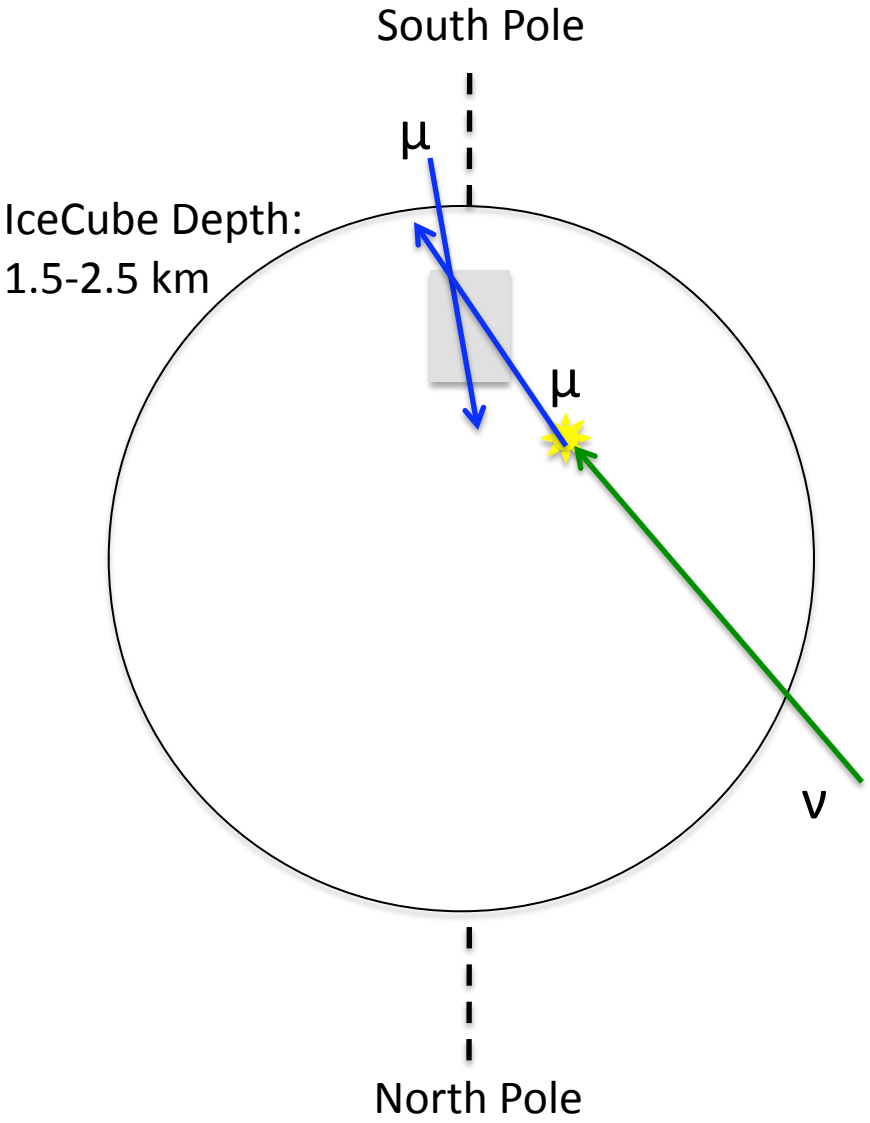
Likelihood is modified as:

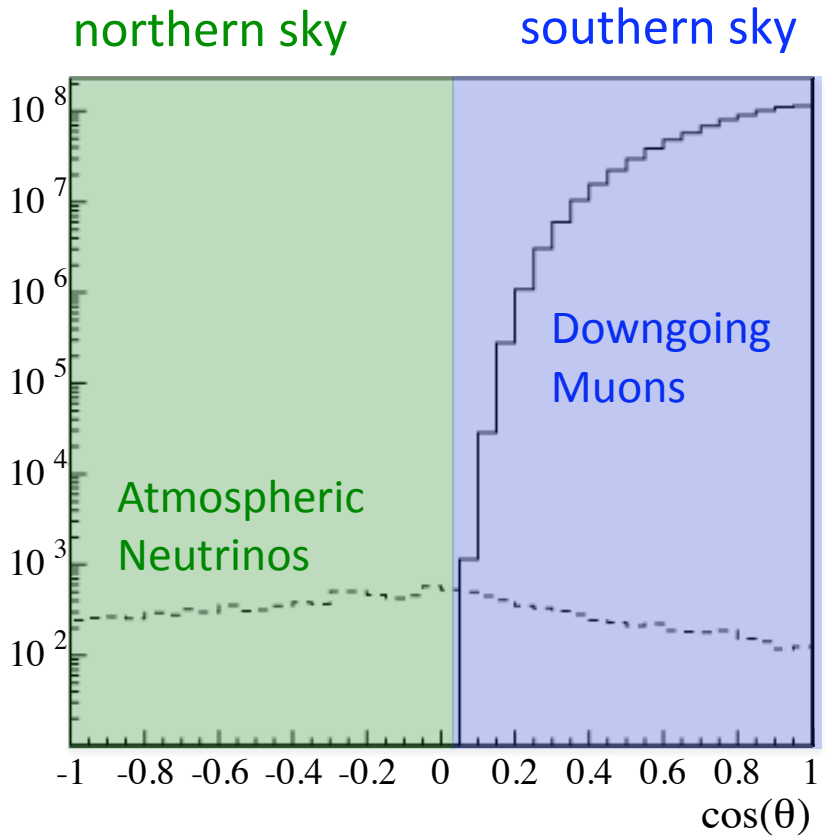
$\sigma_{PSF} \rightarrow \sigma_{conv} = \sqrt{(\sigma_{PSF}^2 + \sigma_s^2)}$

Source Extension


Cosmic rays
Atm. μ
Atm.ν
Signal ν
Jon Dumm

Backgrounds





Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube