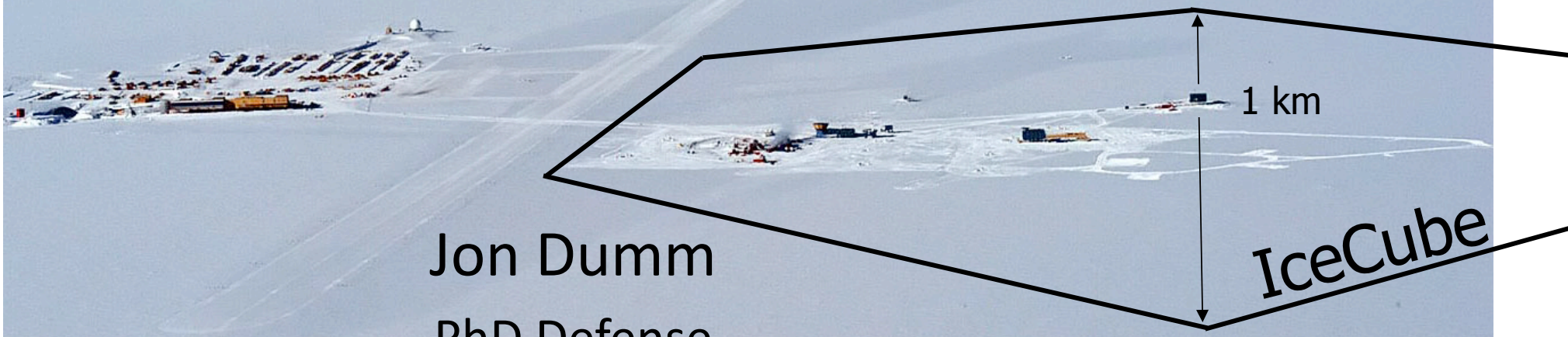
A Search for Point Sources with the IceCube Neutrino Observatory



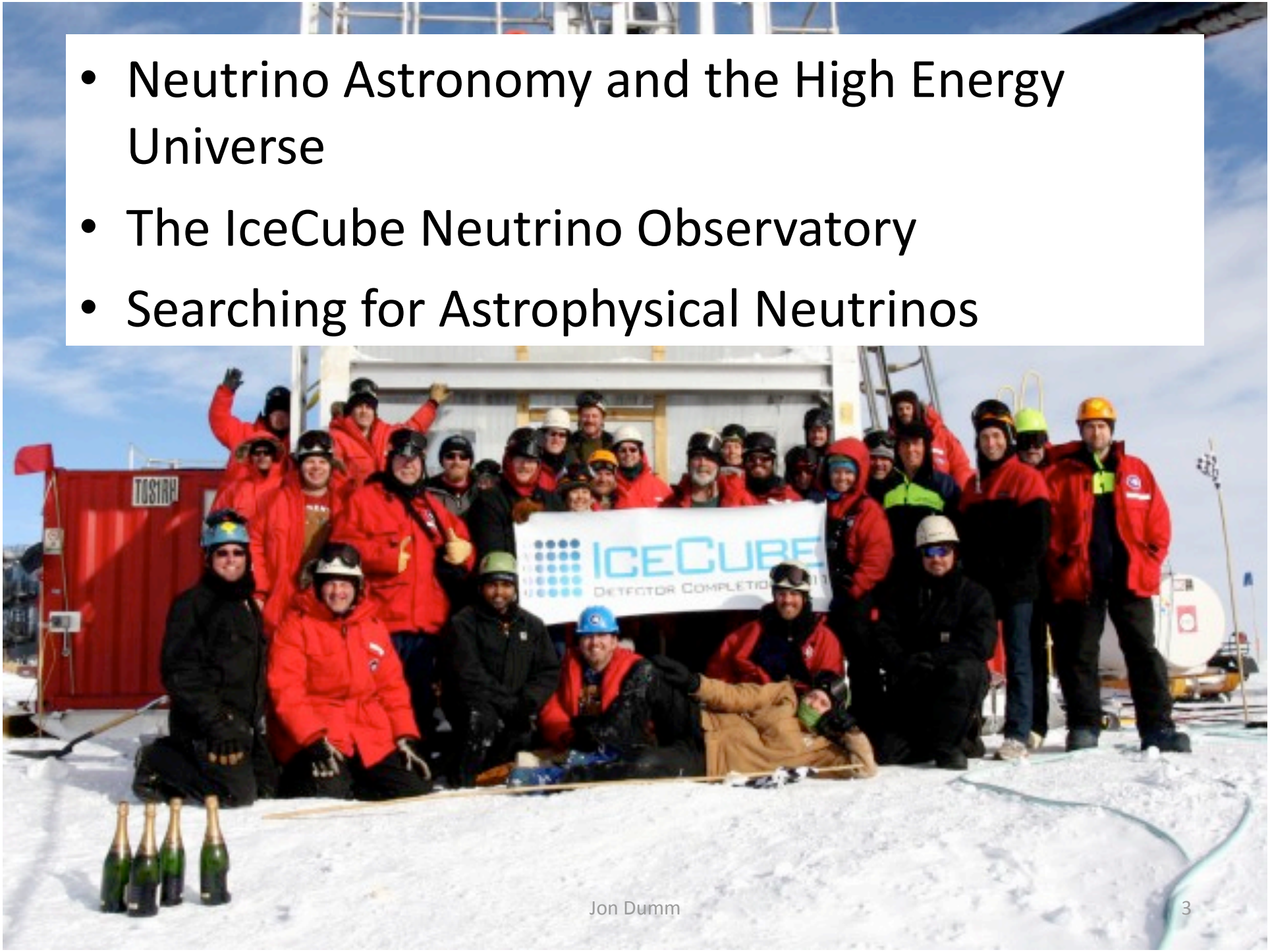
Jon Dumm

PhD Defense

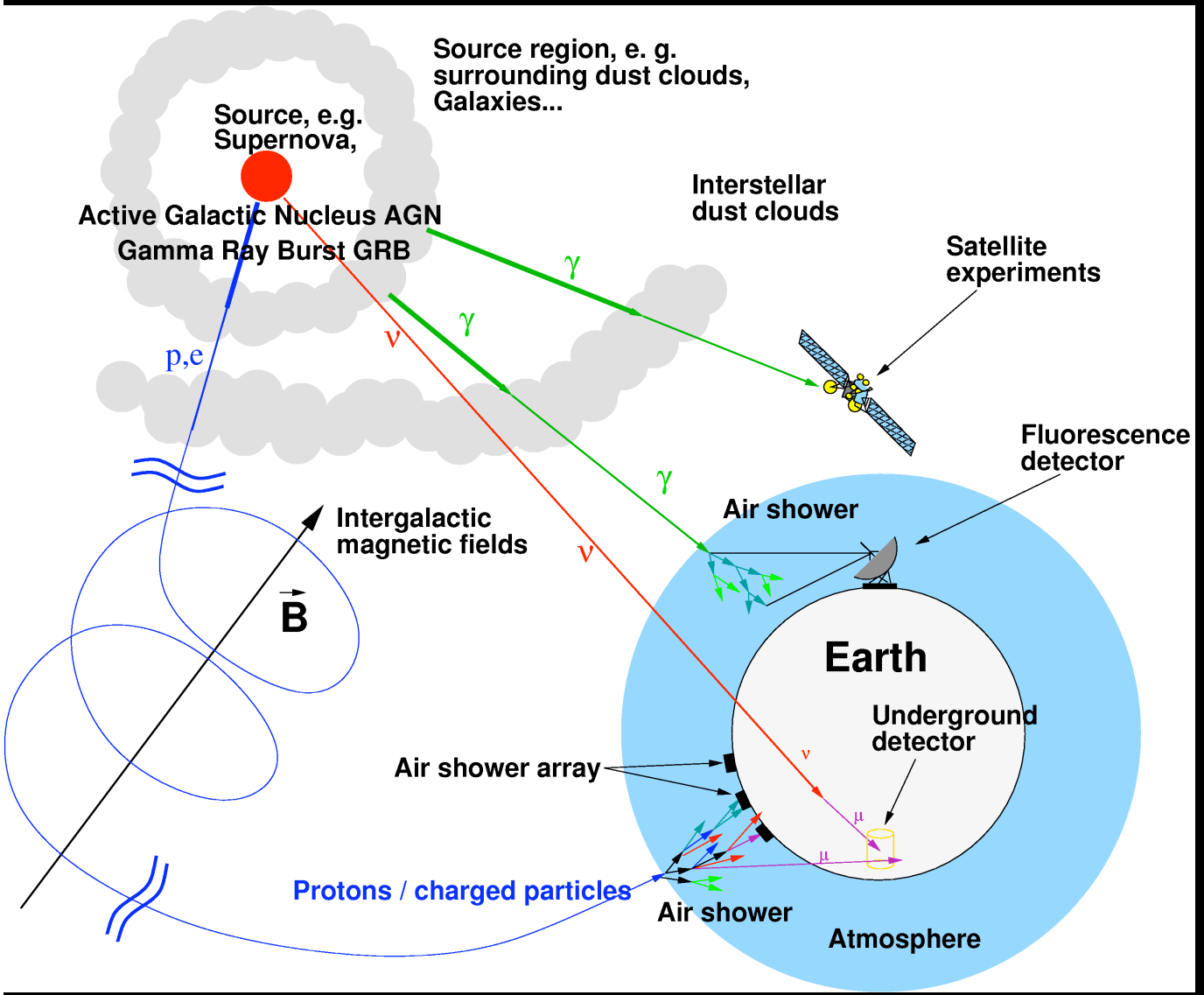
March 31, 2011


TOSTRH
ICECUBE

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



Neutrinos as Cosmic Messengers

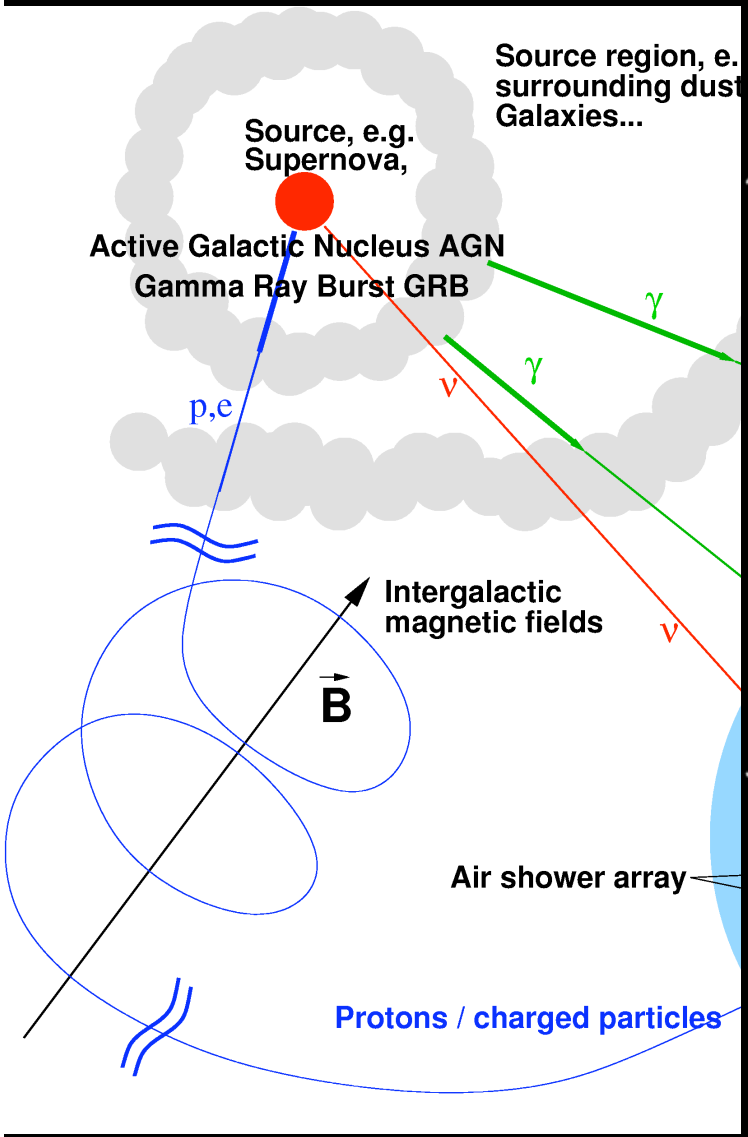


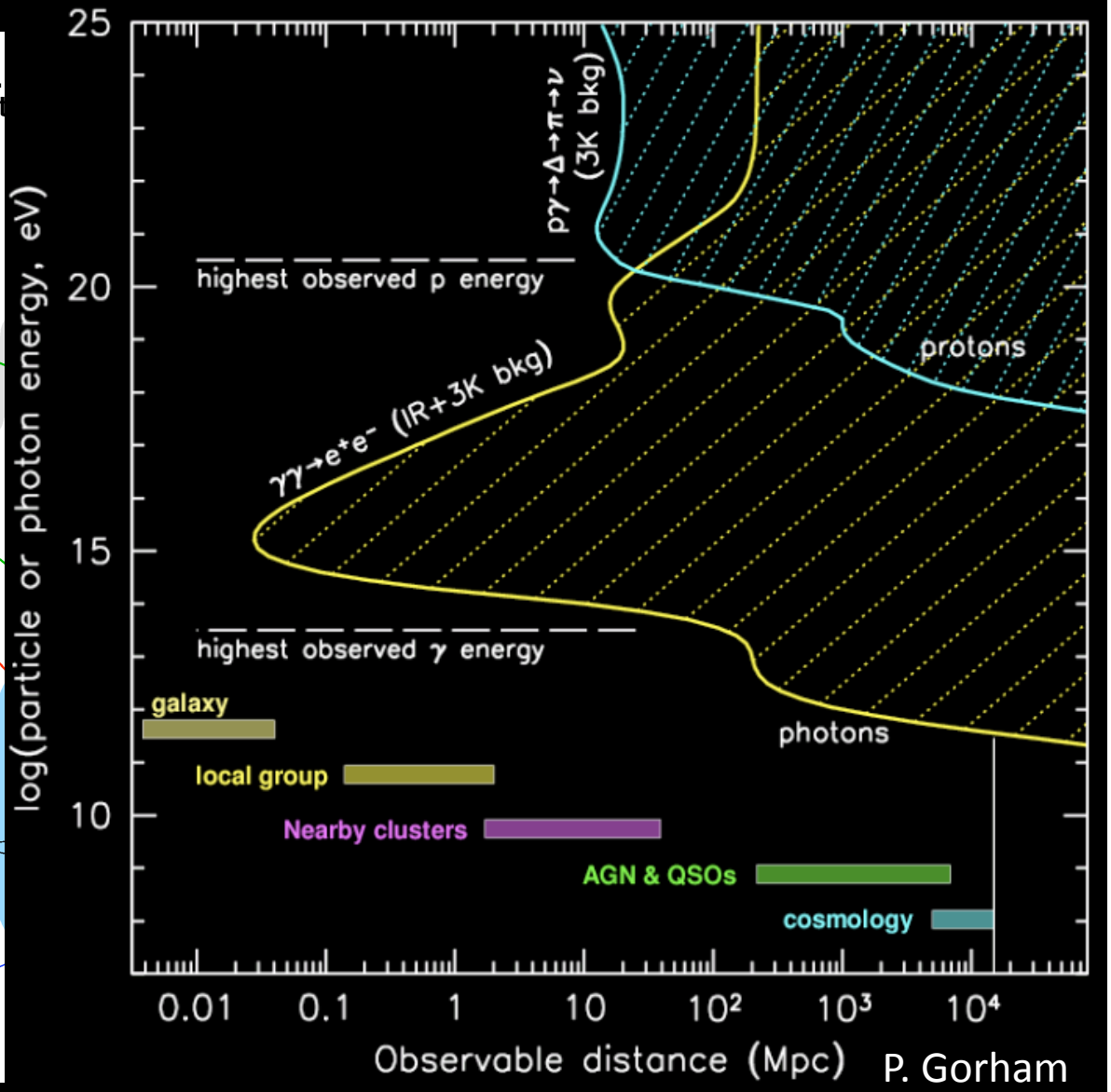
γ *Photons:* easily absorbed by CMB and IR backgrounds.

p *Protons:* deflected by magnetic fields.

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

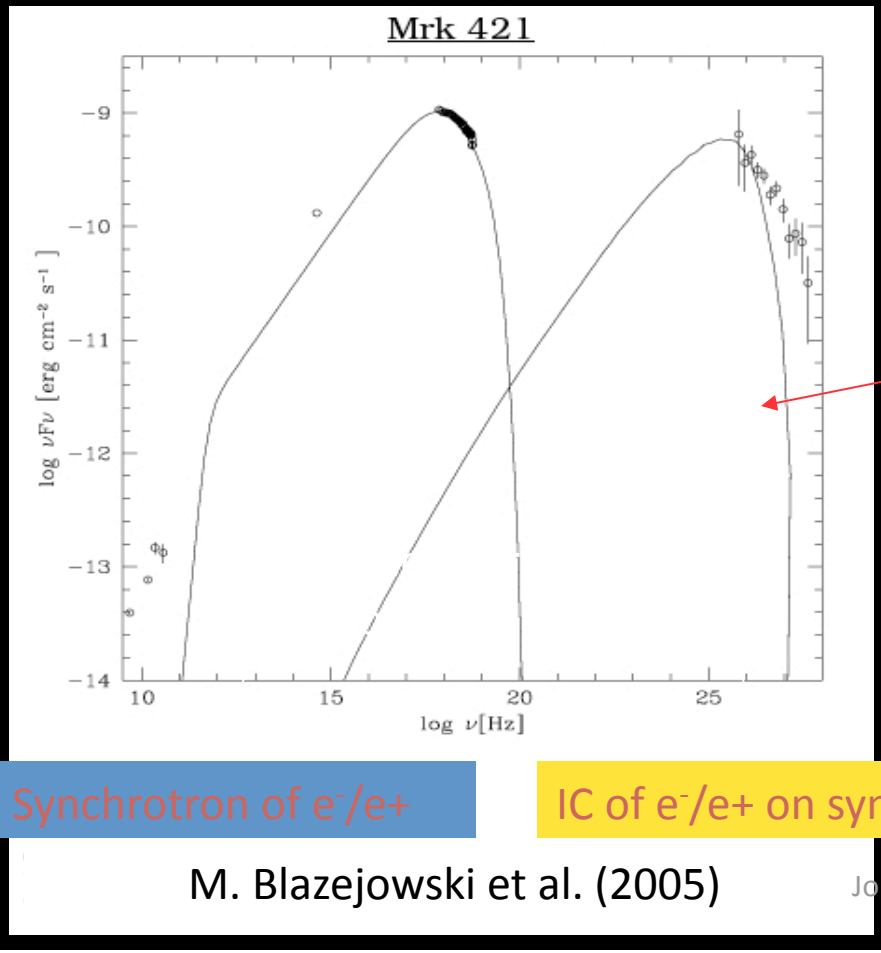
Neutrinos as Cosmic Messengers





Blazar Spectral Energy Distribution

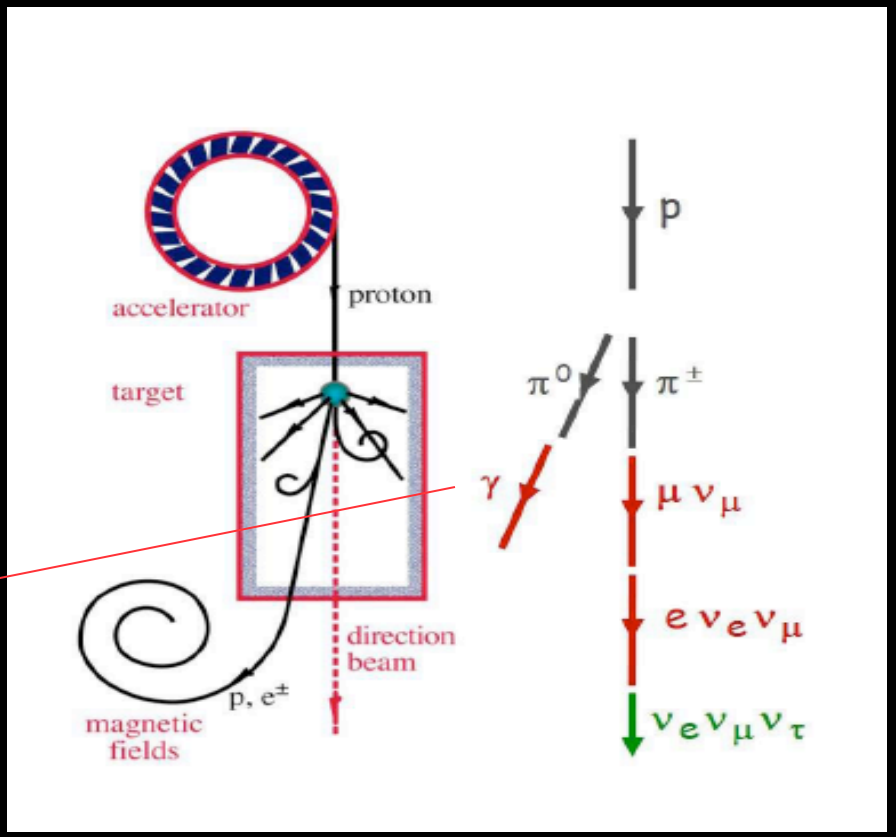
- Typical double-humped SED
- Separated by 8-10 orders of mag.
- Only small correlation



Synchrotron of $e^-/e+$

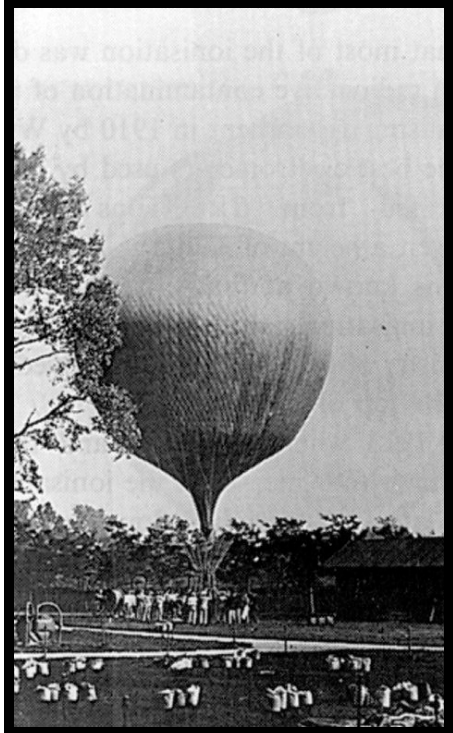
IC of $e^-/e+$ on synch. γs

M. Blazejowski et al. (2005)



A hadronic component in the jet leads to neutrinos!

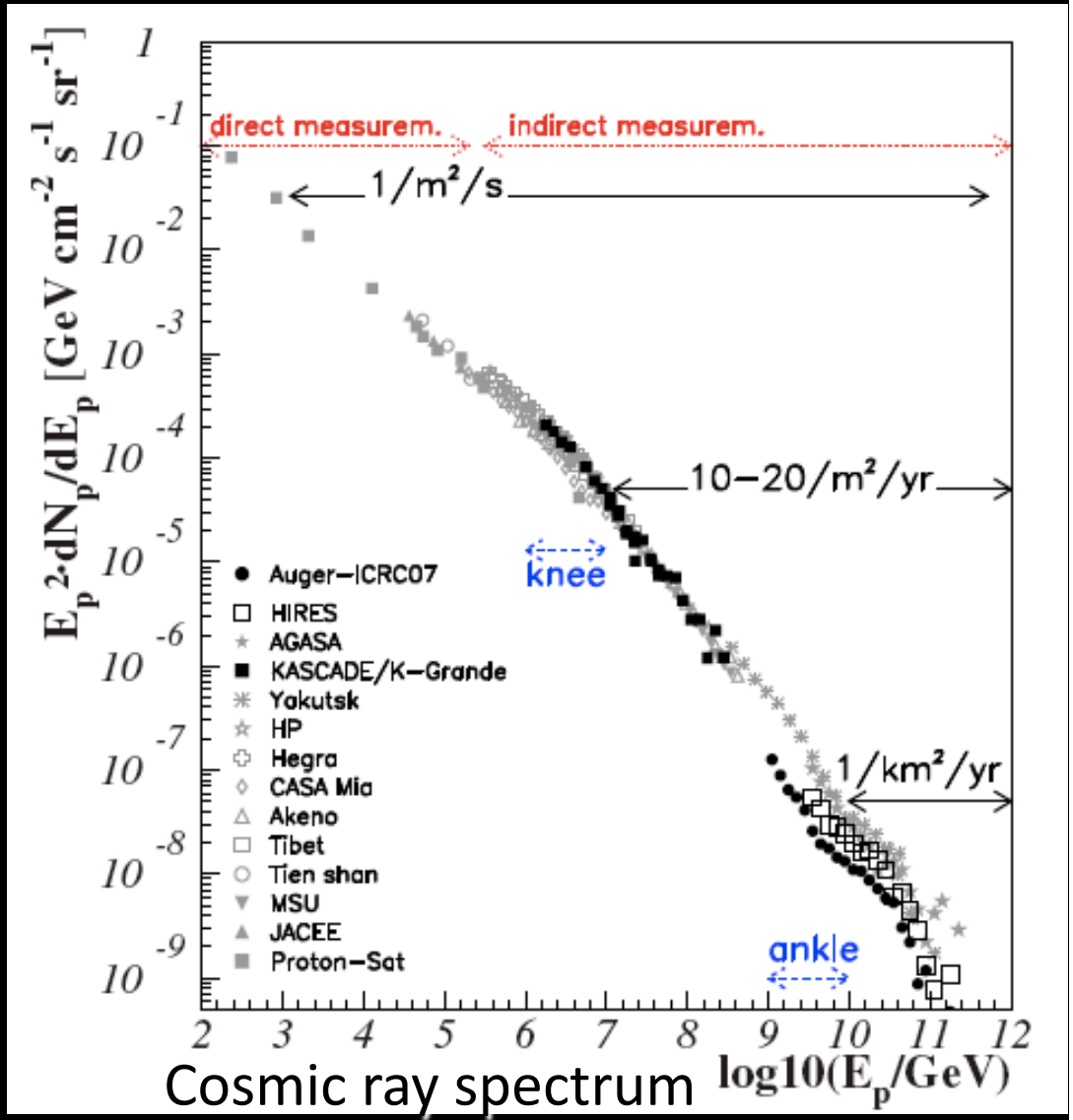
Cosmic Rays: a 100 year-old mystery



Balloon flights
1911-1913



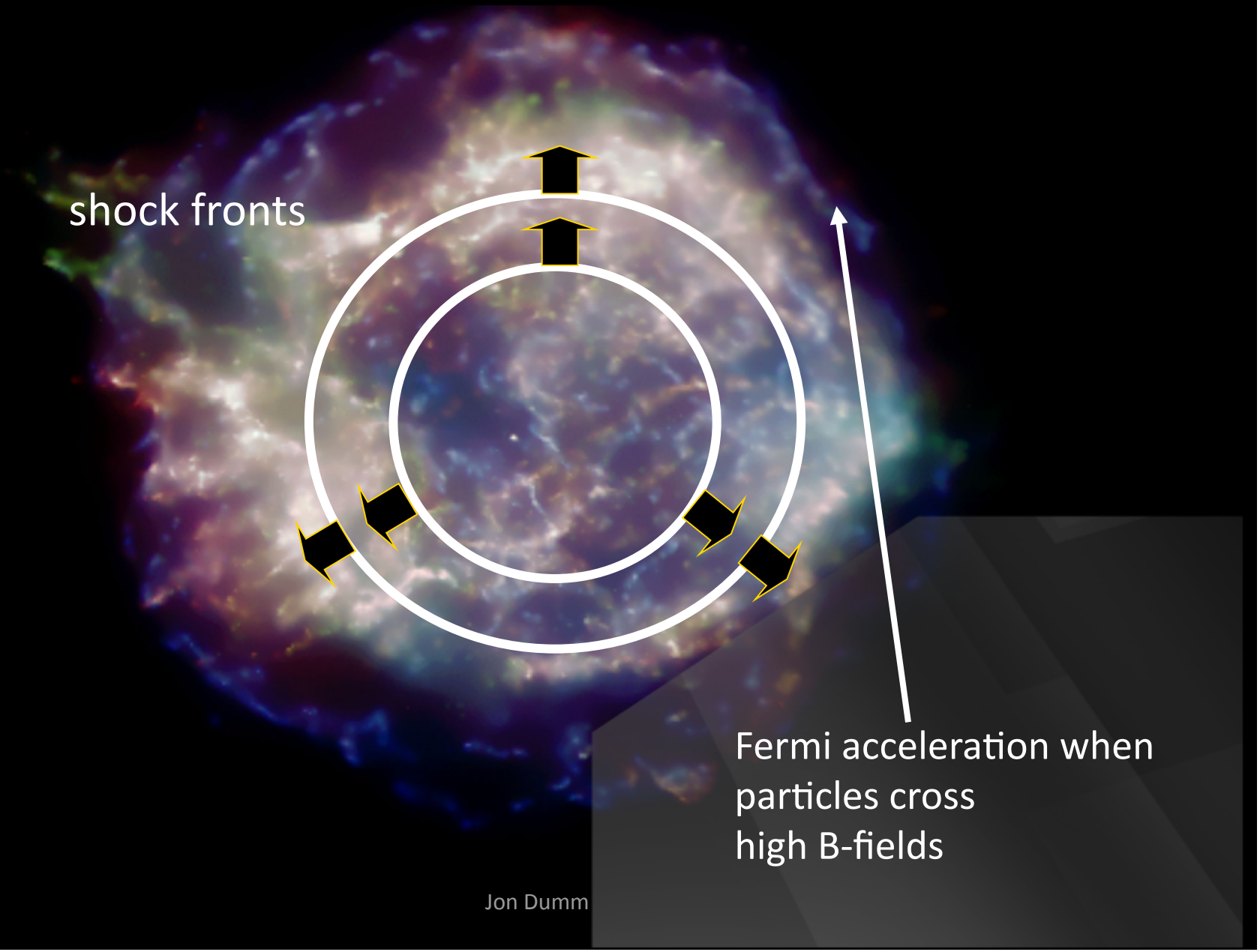
Victor Hess
Nobel Prize
1936



Cosmic ray spectrum

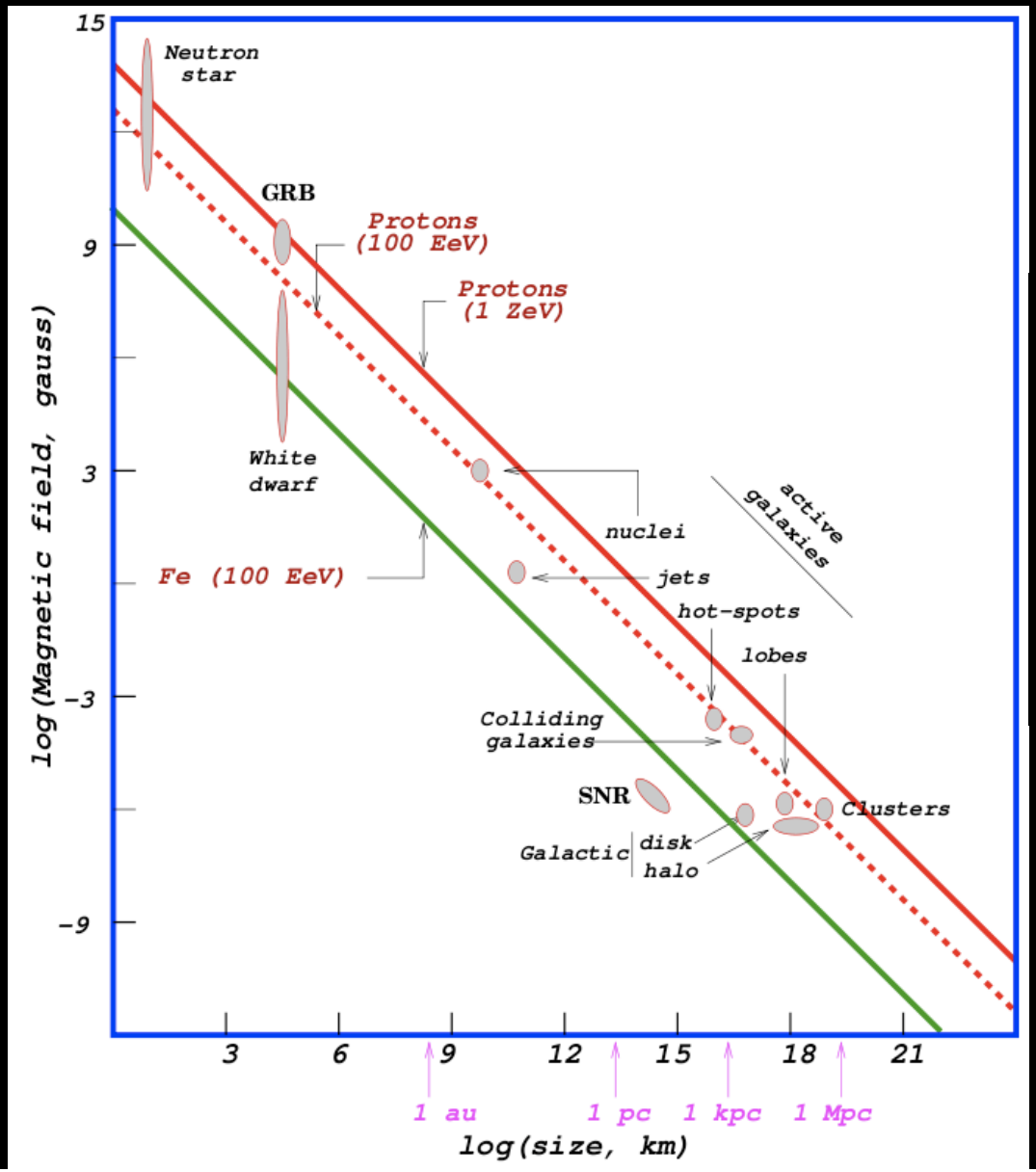
- Power law over many decades
- Origin Uncertain

Cas A Supernova Remnant in X-rays

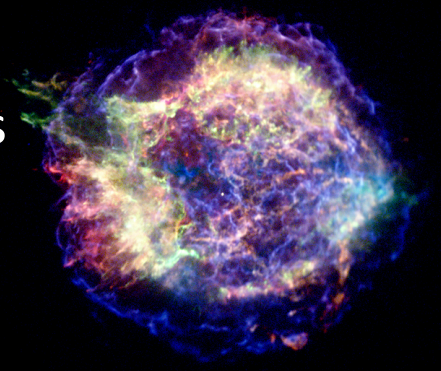


Jon Dumm

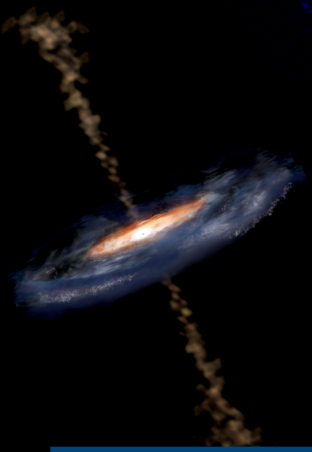
What Are the Cosmic Ray Sources?



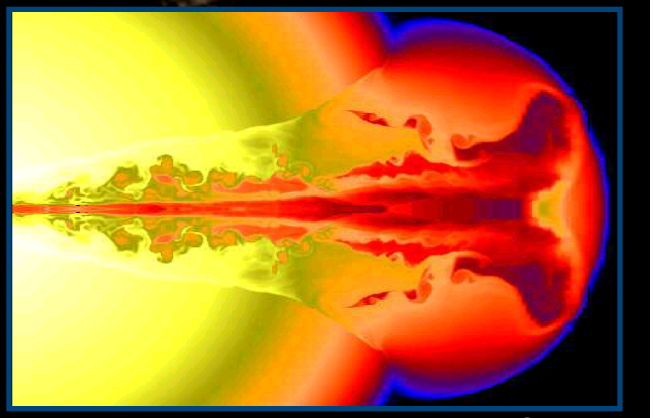
SN Remnants



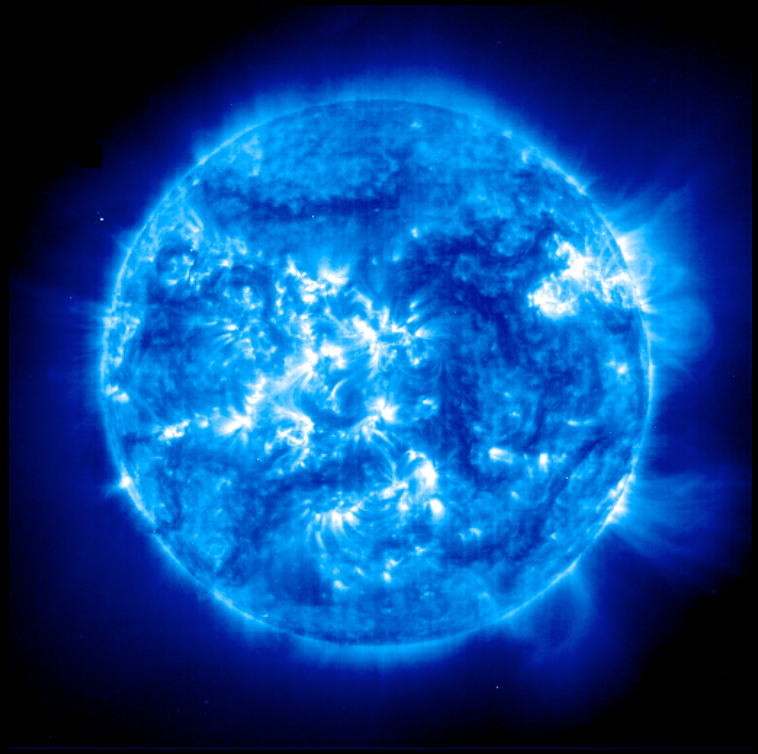
AGN

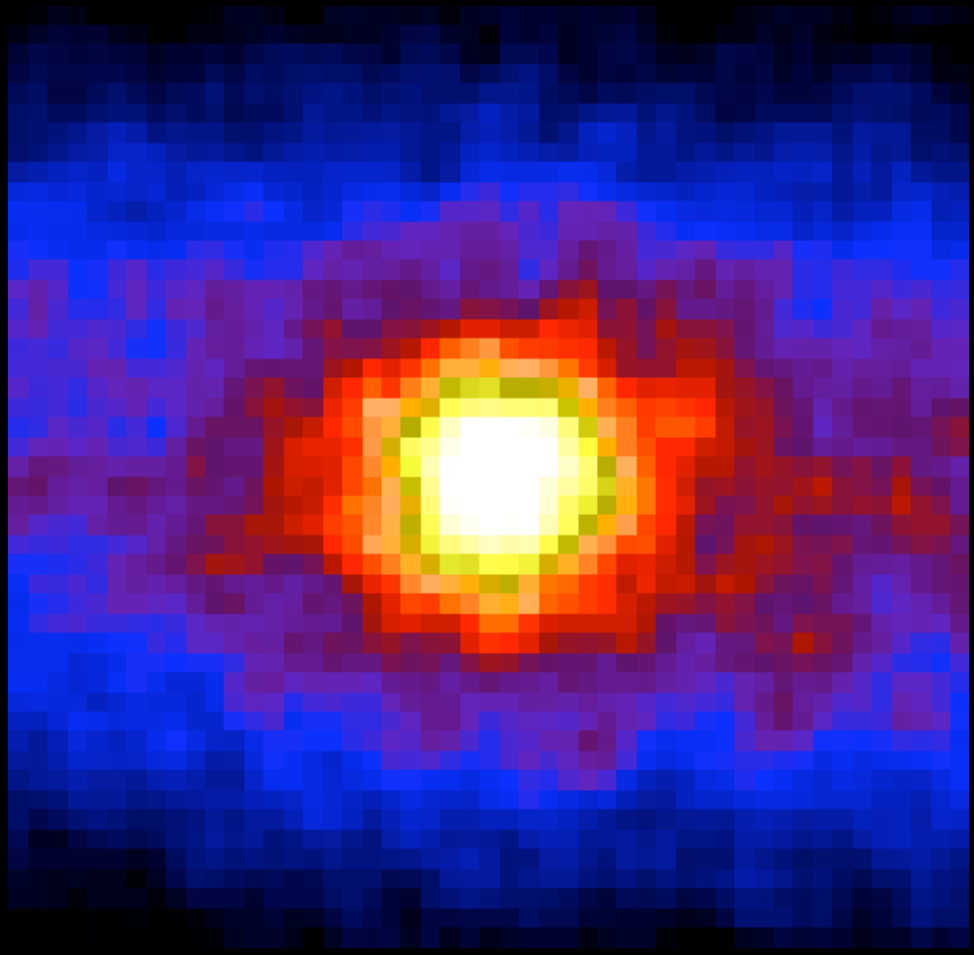


GRB

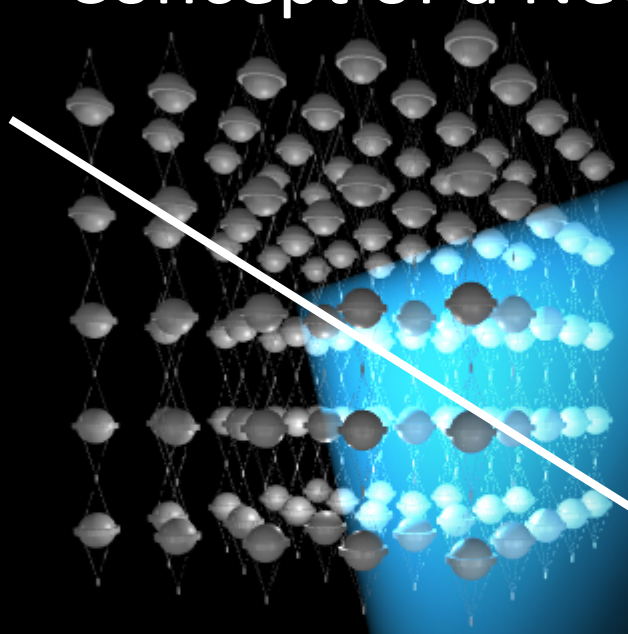


Multi-messenger Astronomy Is a Reality



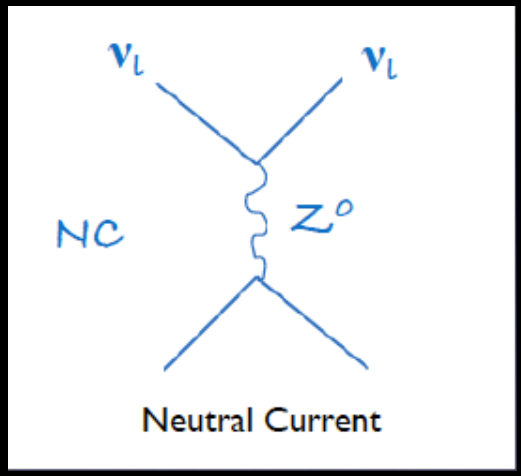


Concept of a Neutrino Telescope

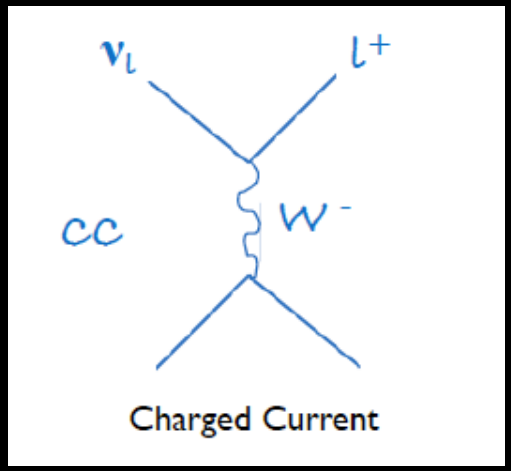


μ

ν



Neutral Current



Charged Current

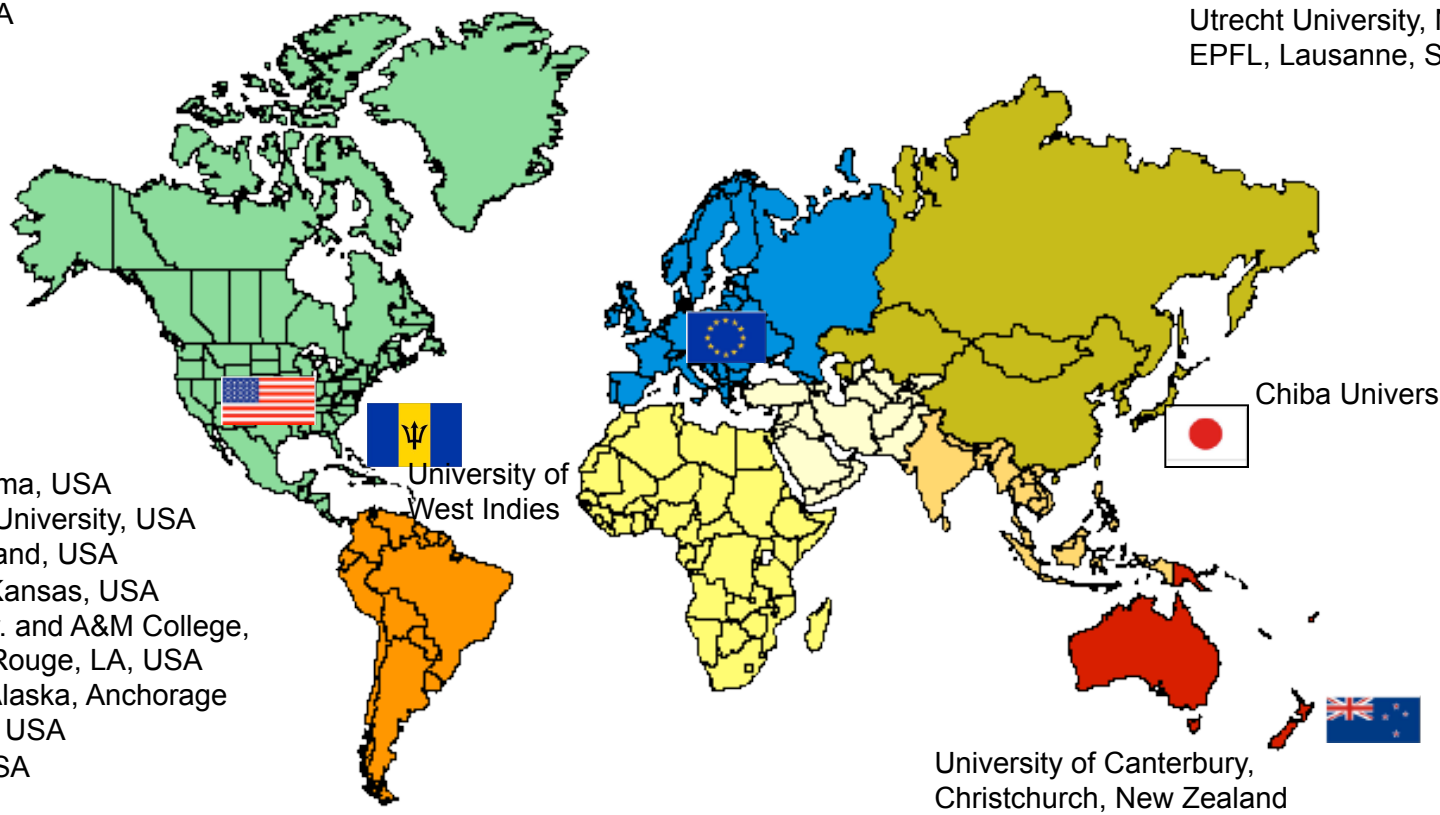
- Look for by-products of neutrino interactions
- 3D array of PMTs
  - Large, transparent medium
- From timing of Cherenkov light, reconstruct neutrino direction

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



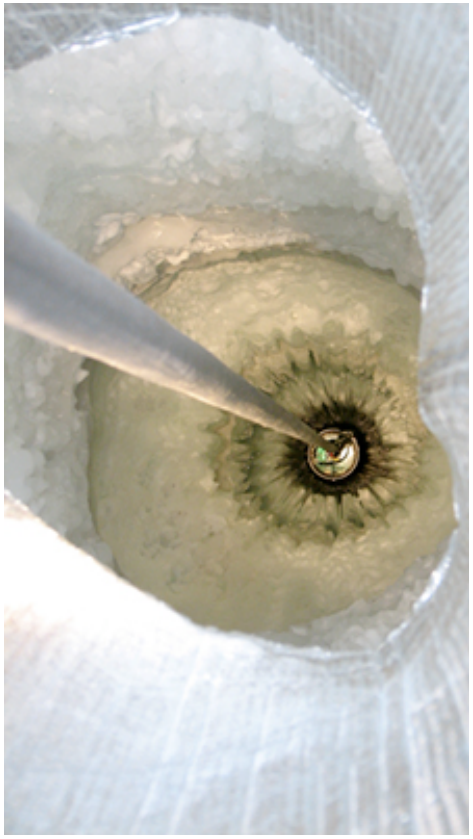
Chiba University, Japan

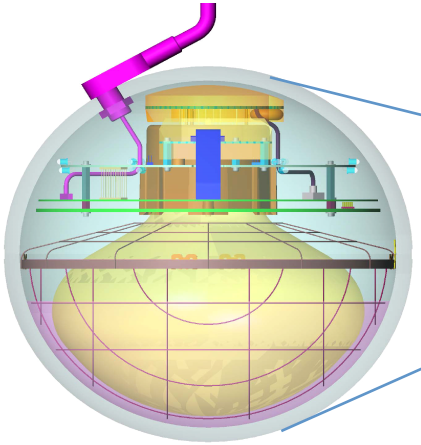
University of West Indies

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

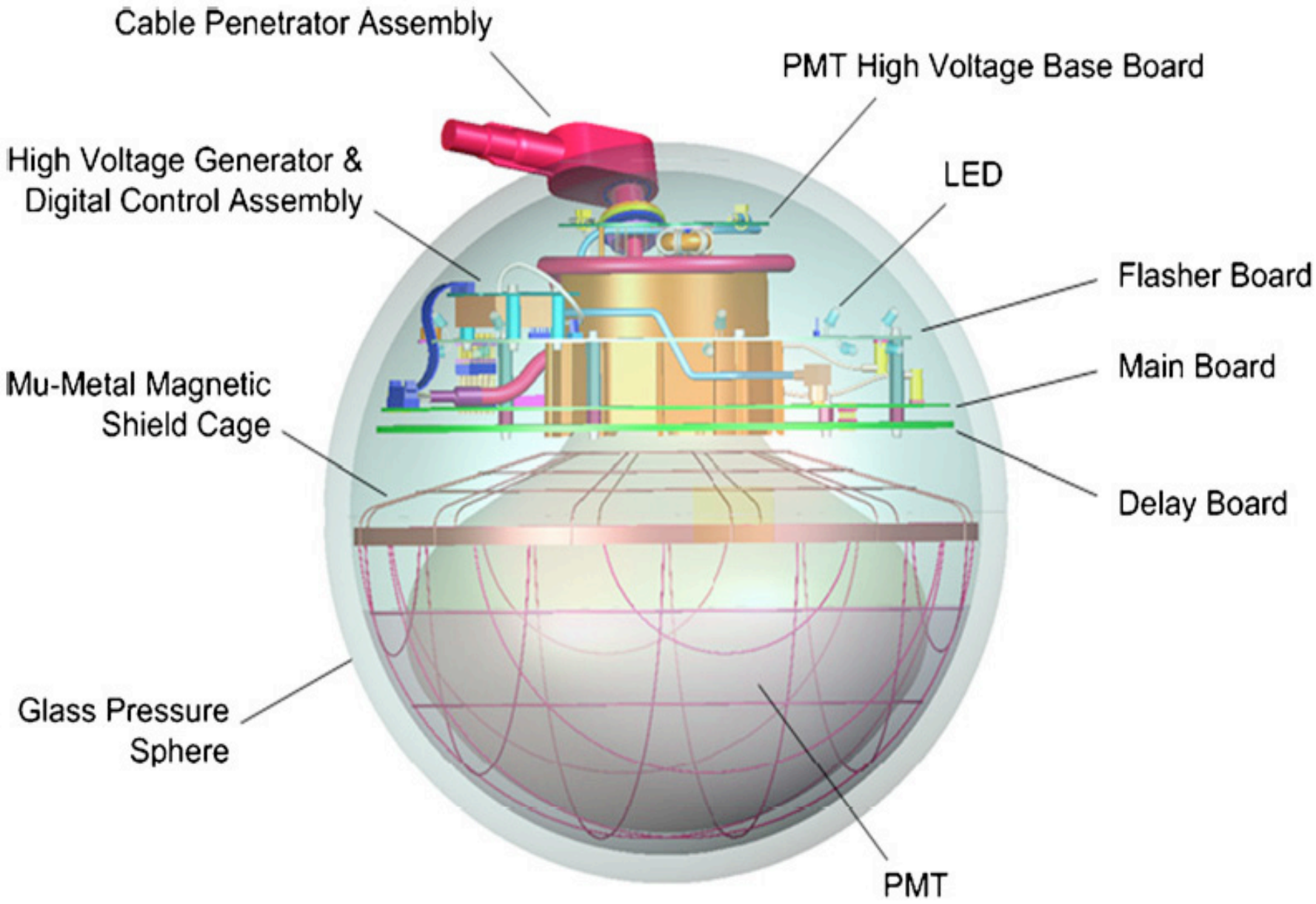
Deep Core
6 Strings - Optimized for lower energies
360 Optical Sensors

Eiffel Tower
324 m

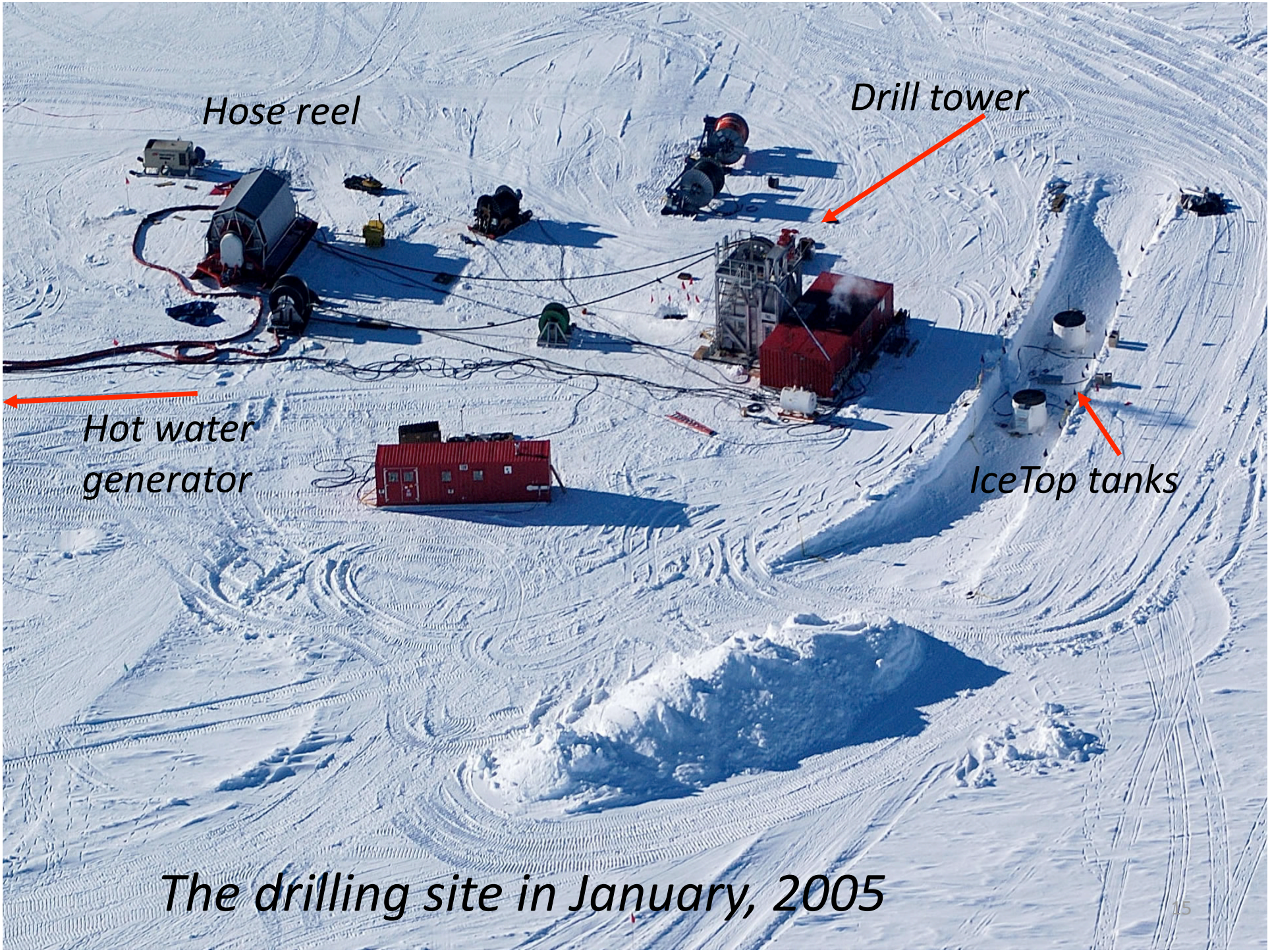
2450 m

2820 m

Bedrock

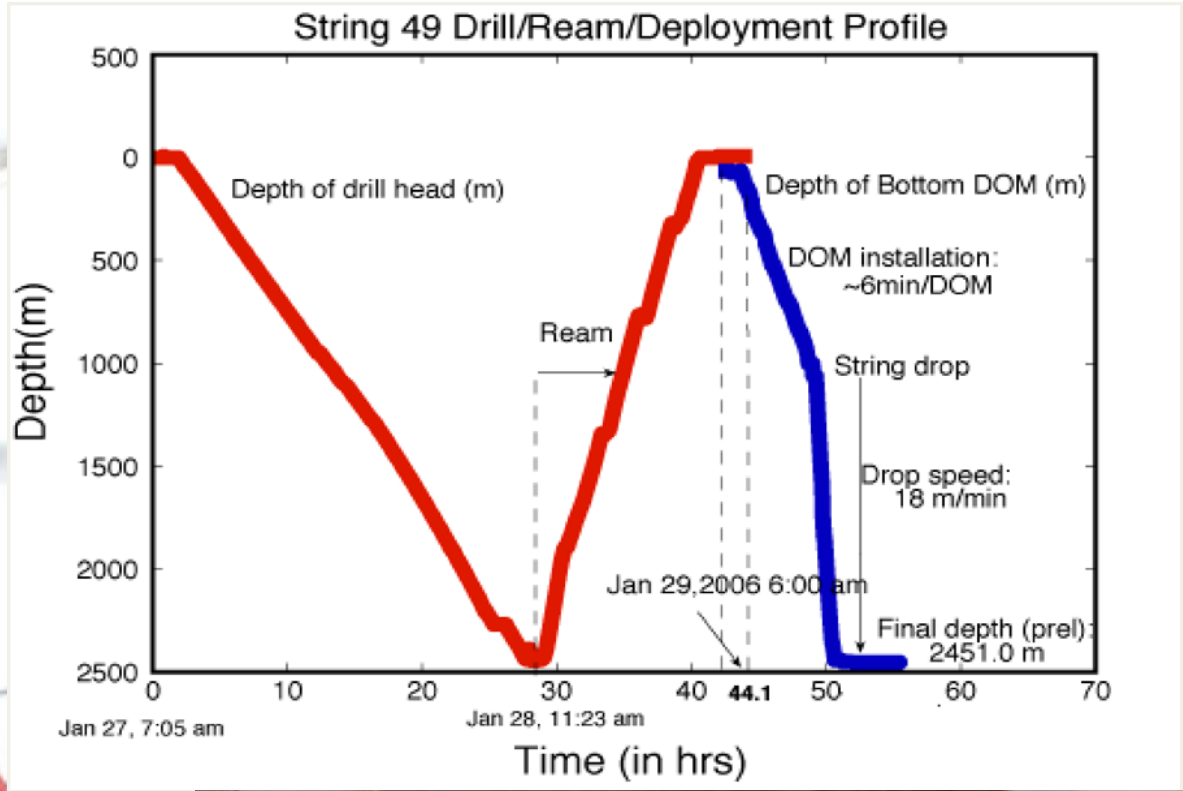


A schematic view of an IceCube digital optical module.



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%

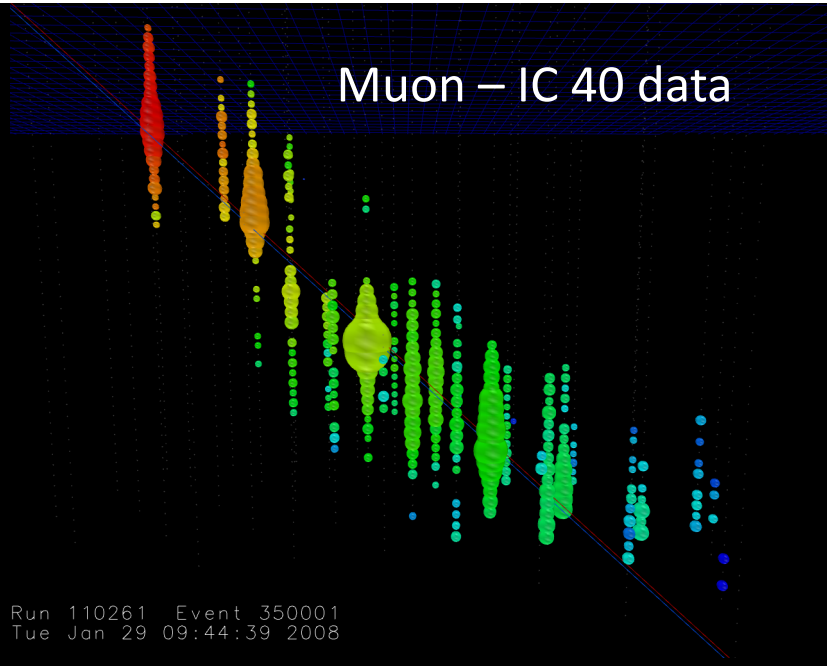
86-string configuration will be running in a couple of weeks!

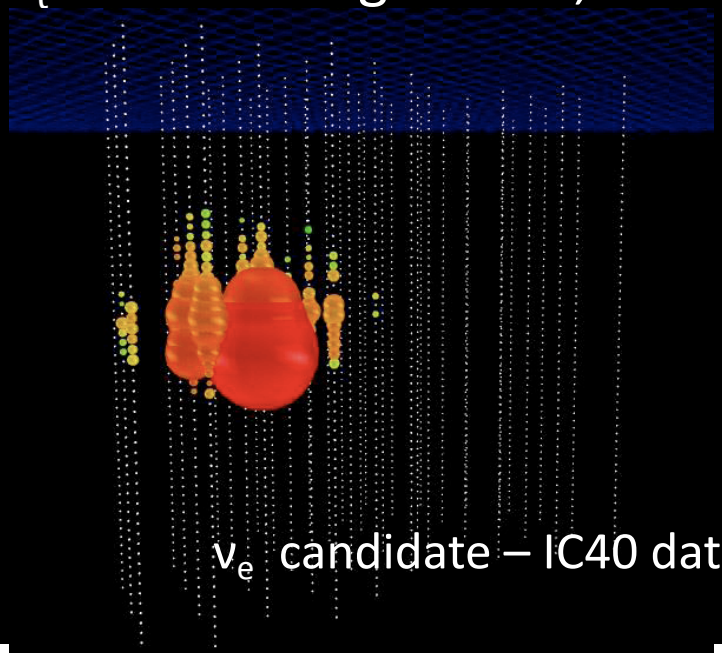


Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1900 Hz	160 / day
IC86	2011	~365 days	2800 Hz	220 / day

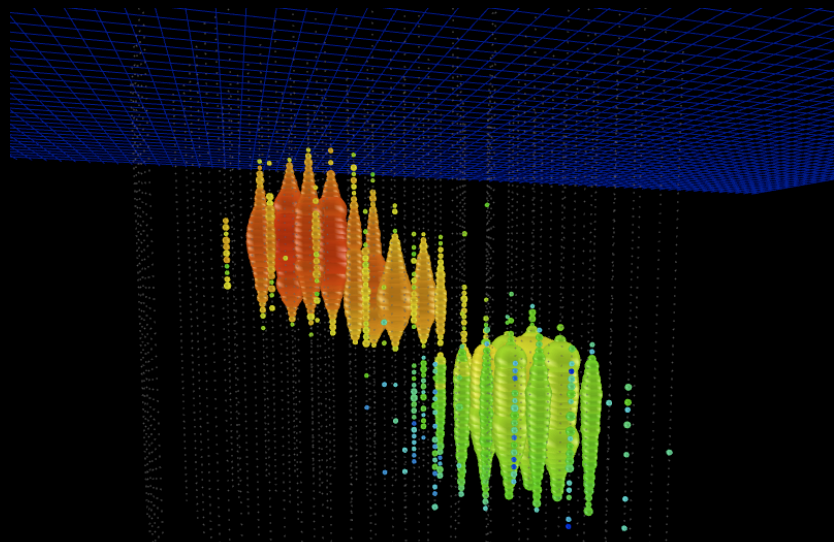
Event Topologies

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

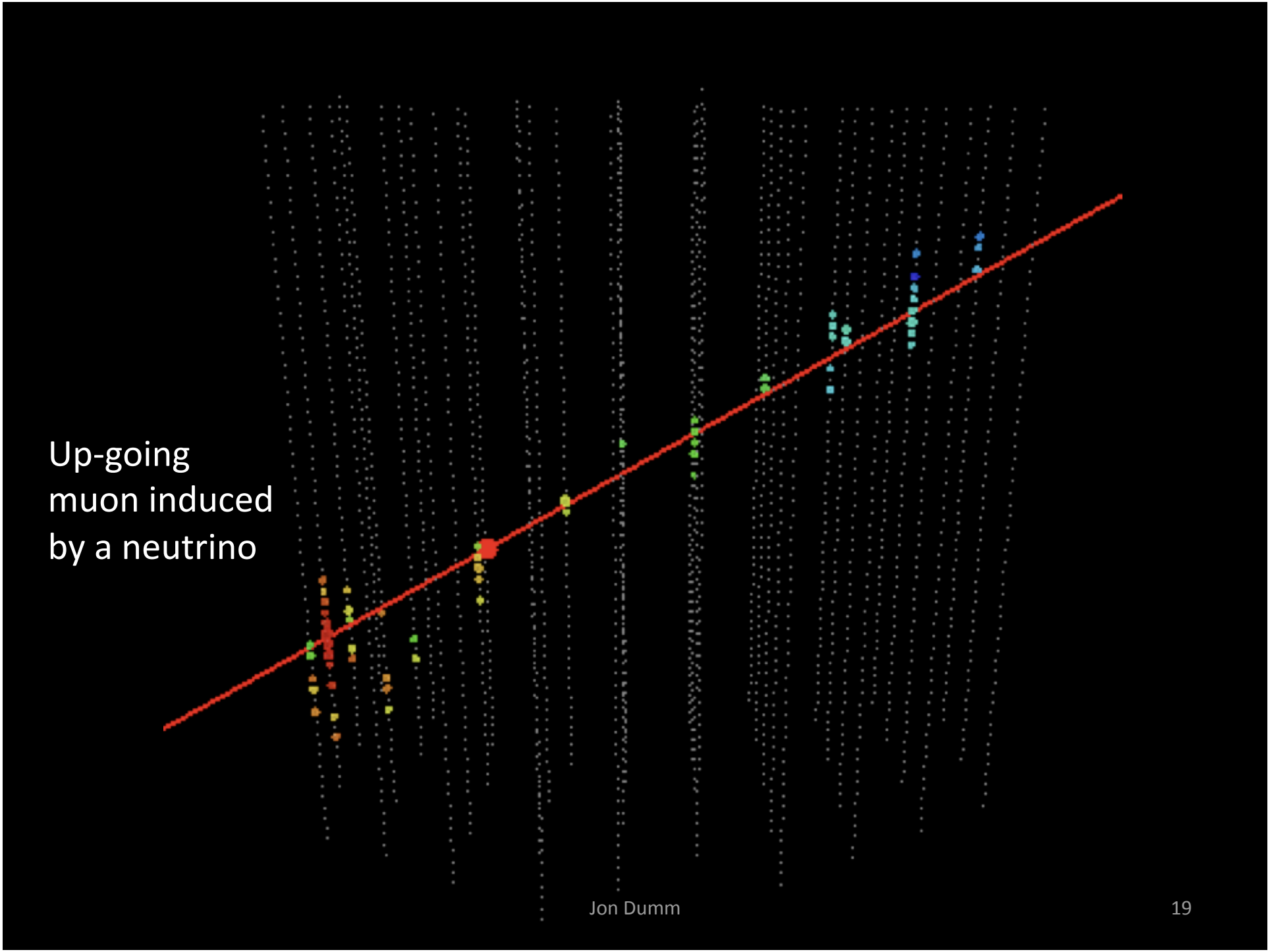




ν_e candidate – IC40 data

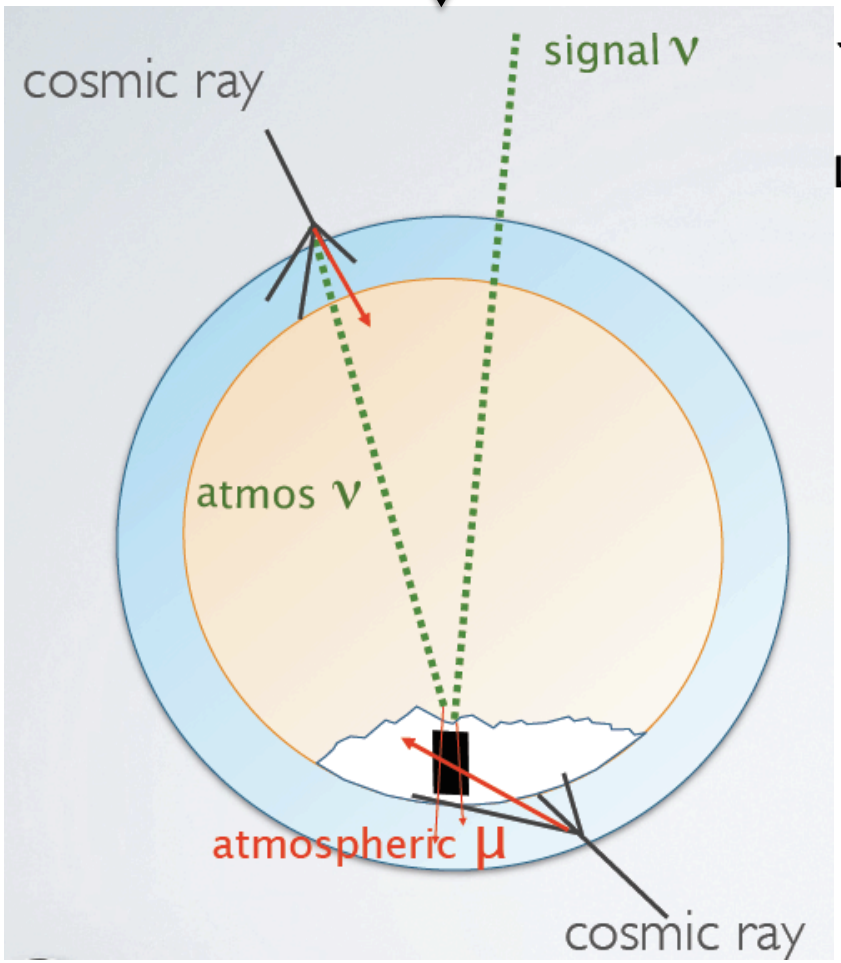


16 PeV ν_τ simulation

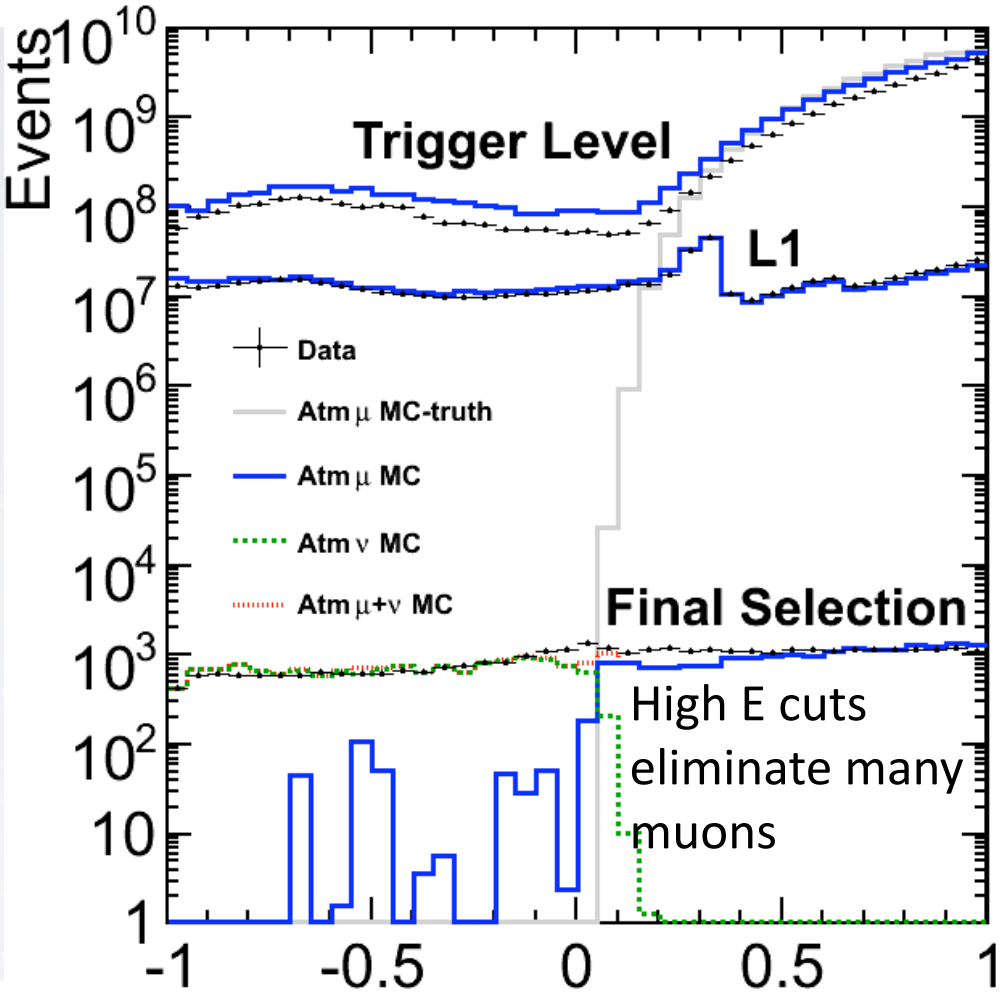

Up-going
muon induced
by a neutrino

Backgrounds

cos(θ) = -1



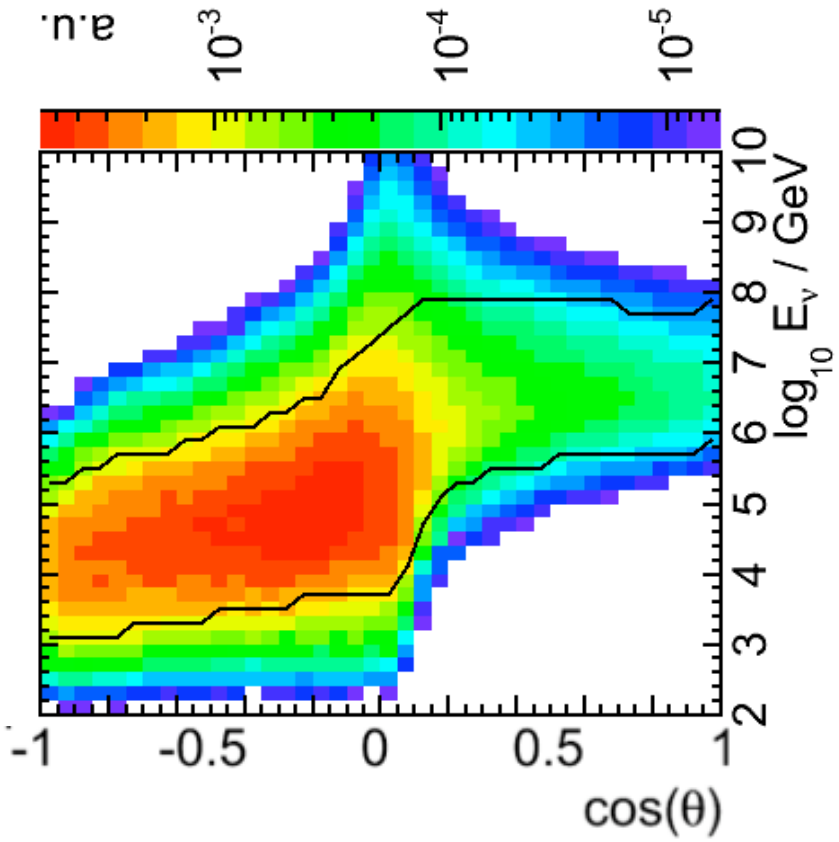
cos(θ) = +1



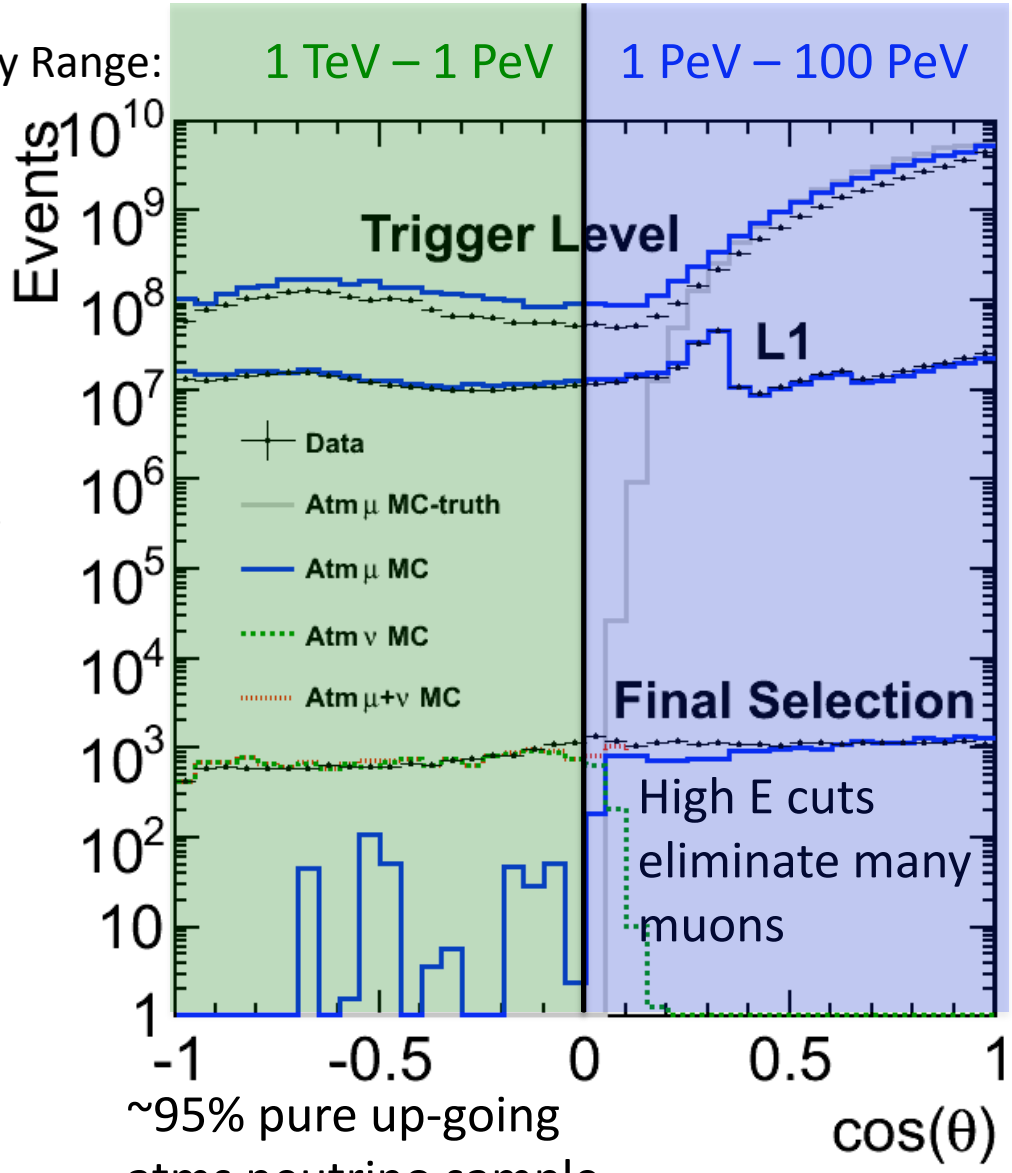
~95% pure up-going
atms neutrino sample

Backgrounds

Sensitivity Energy Range:

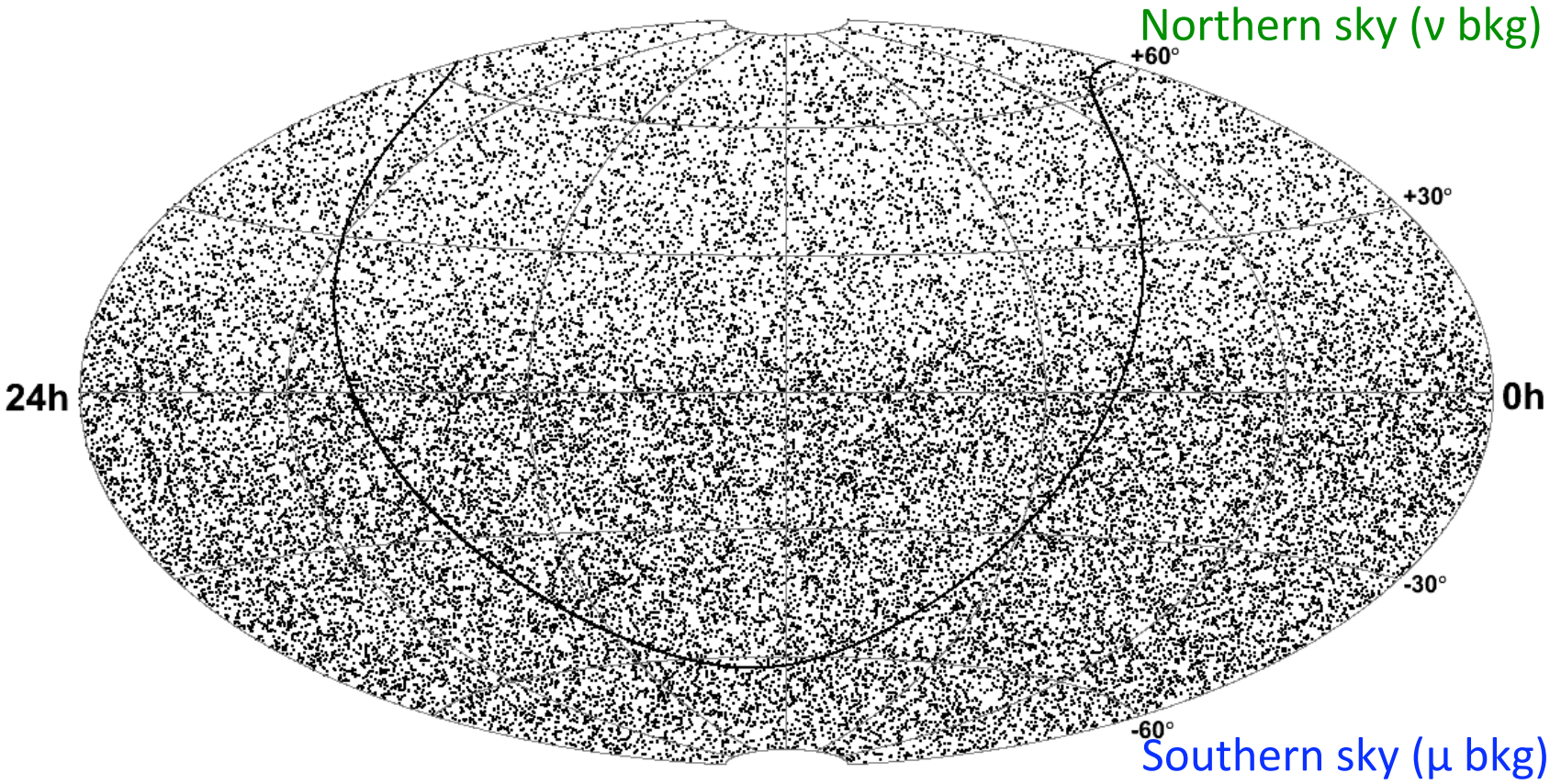


E^{-2} neutrino signal with 90% containment intervals



~95% pure up-going atms neutrino sample

40-string All-Sky Event Map

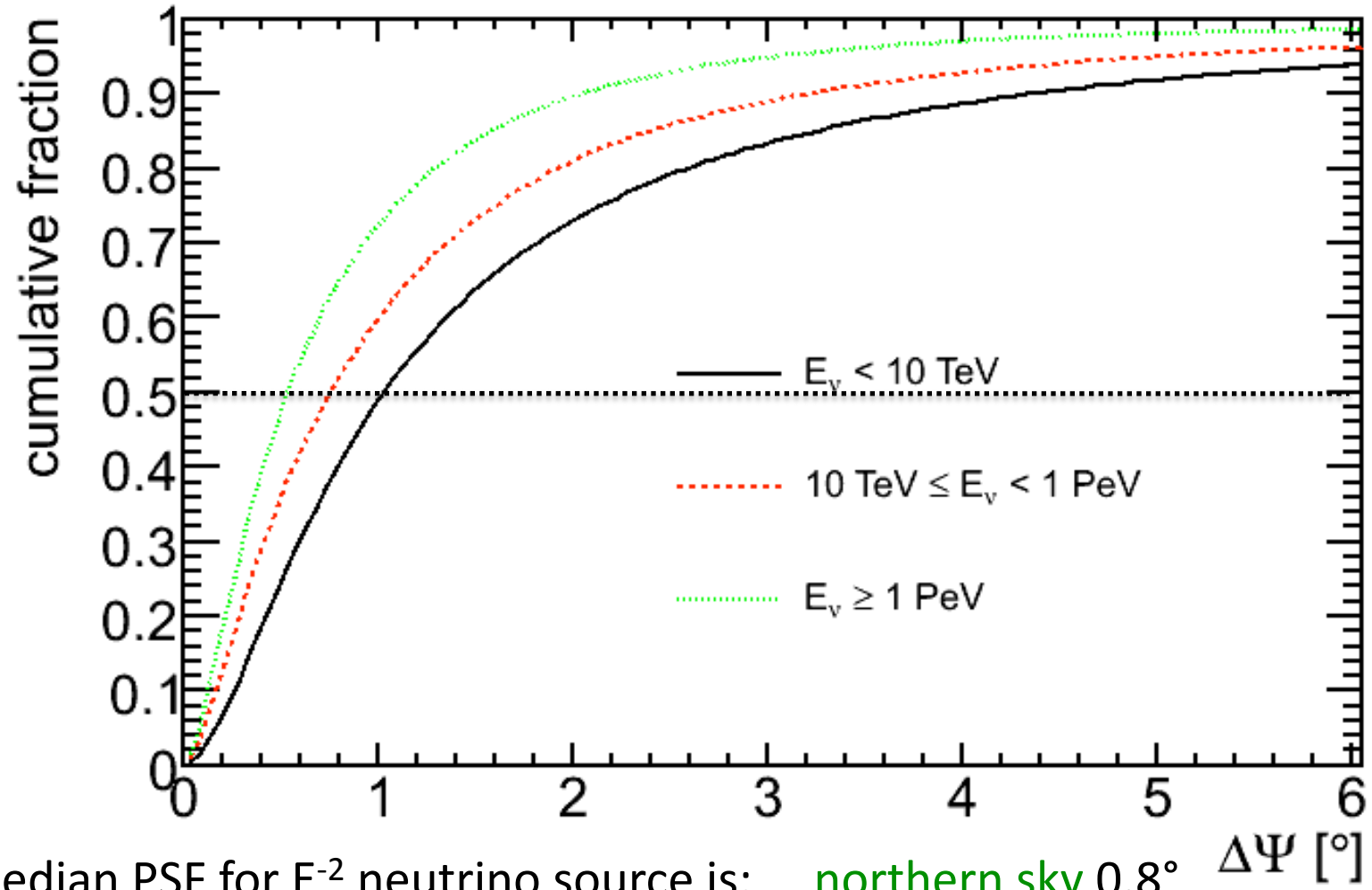


Livetime = 375.5 days

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

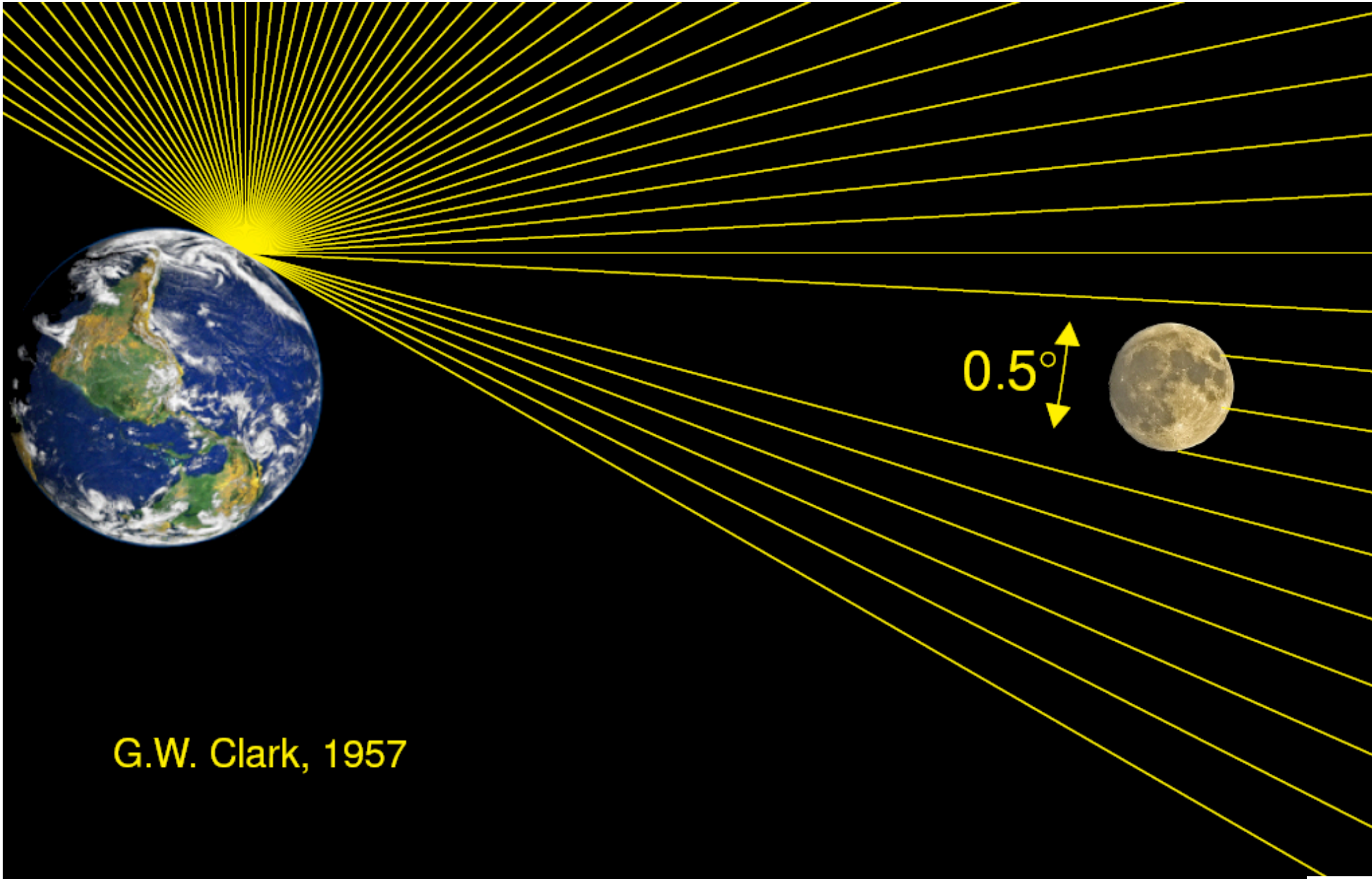
Angular Resolution

Angular difference between the neutrino and reconstructed muon



Median PSF for E^{-2} neutrino source is: northern sky 0.8°

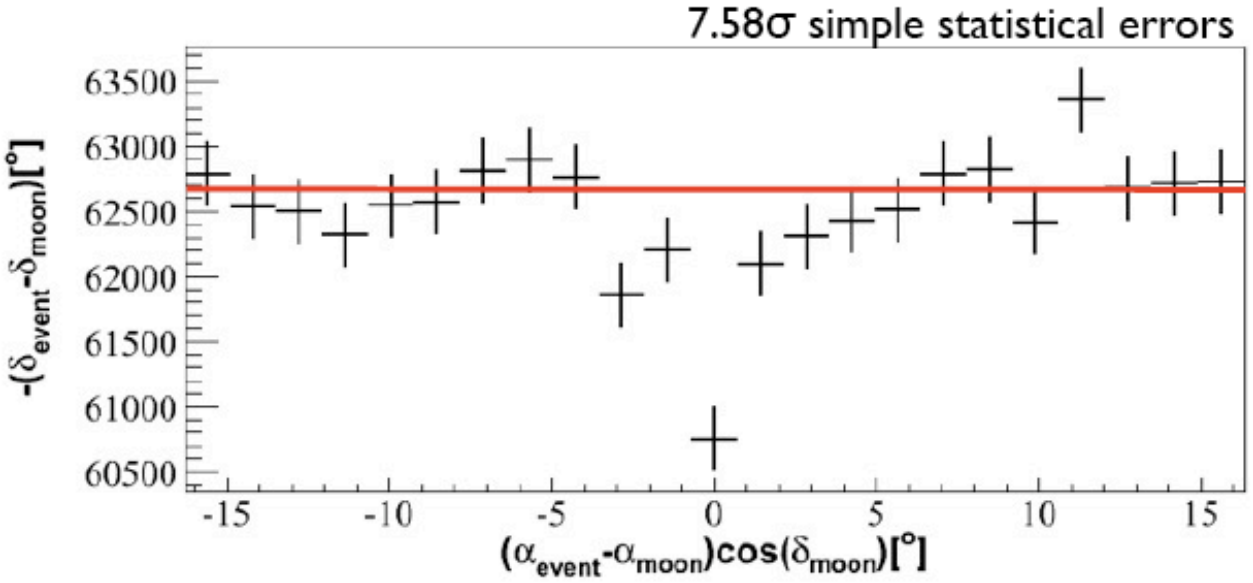
southern sky 0.6°

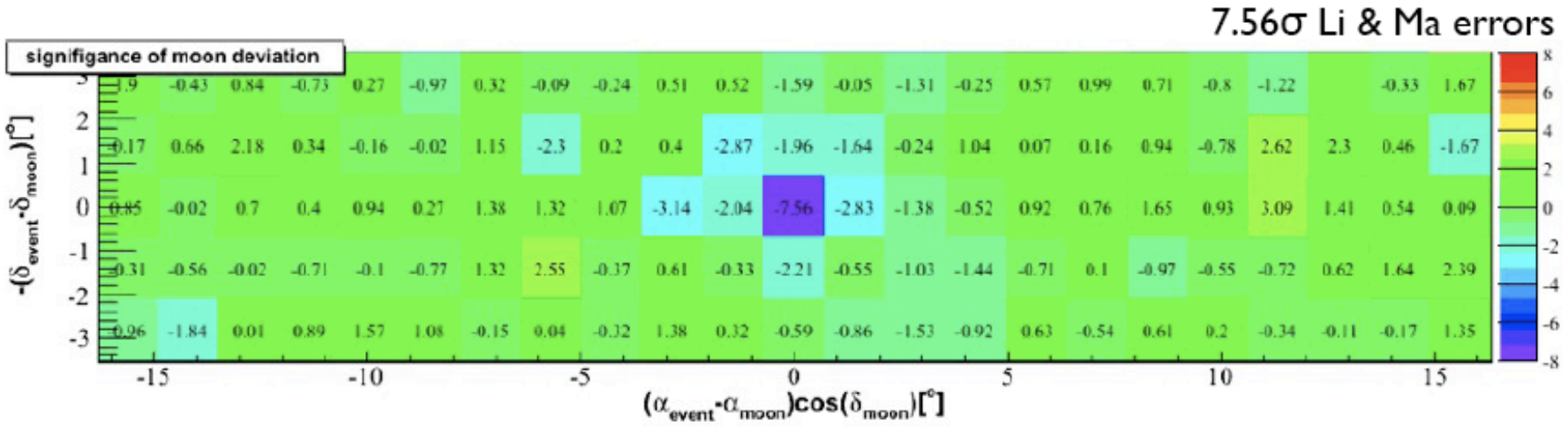

0.5°
G.W. Clark, 1957

Pointing Verification with the Moon -
The Standard Anti-Candle

IceCube-40 strings (2009)

Deficit in agreement with expectations



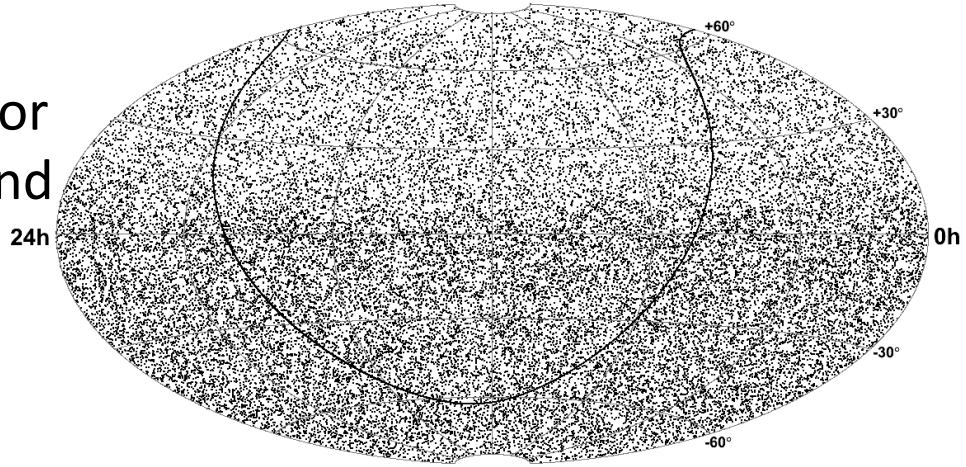





End-to-end systematic check of IceCube data
Will be monitored monthly
More detailed checks in the future with more statistics

The Point Source Analysis in Words

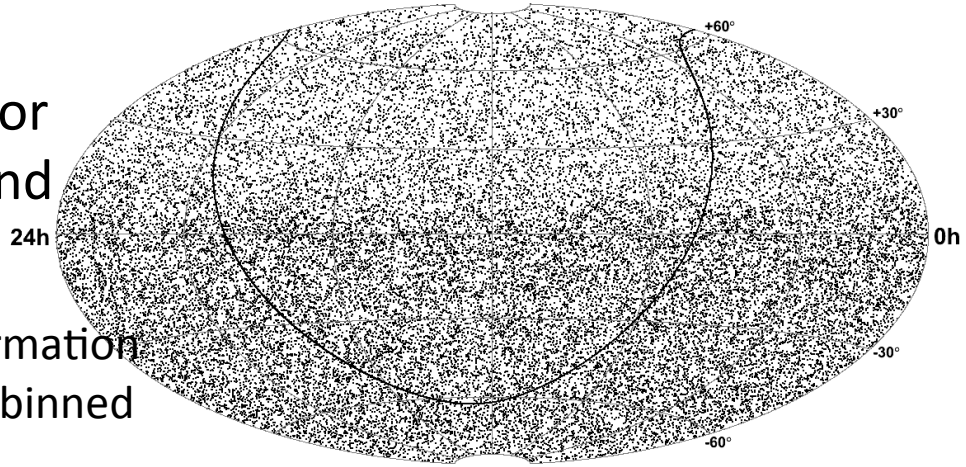
- Determine observables useful for separating signal and background
  - Space (θ, Φ)
  - Energy
  - (Time)



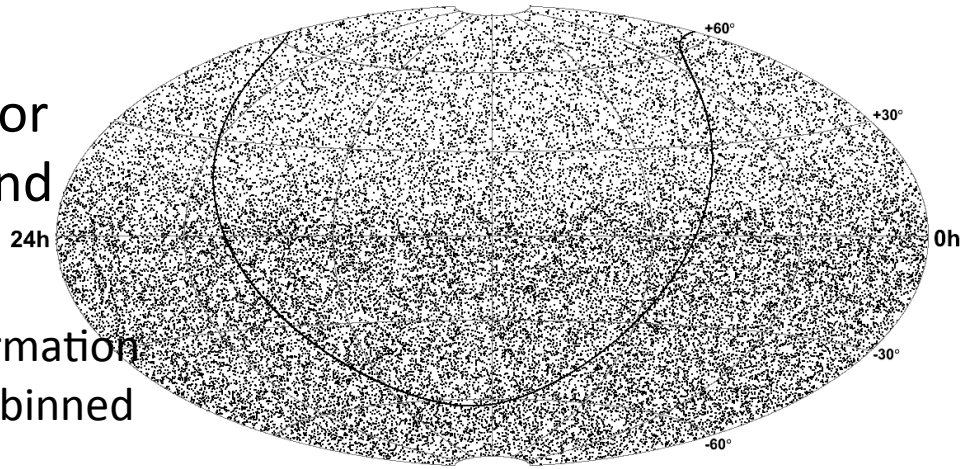
The Point Source Analysis in Words

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

Inherent loss of information when you cut, e.g. a binned analysis



The Point Source Analysis in Words

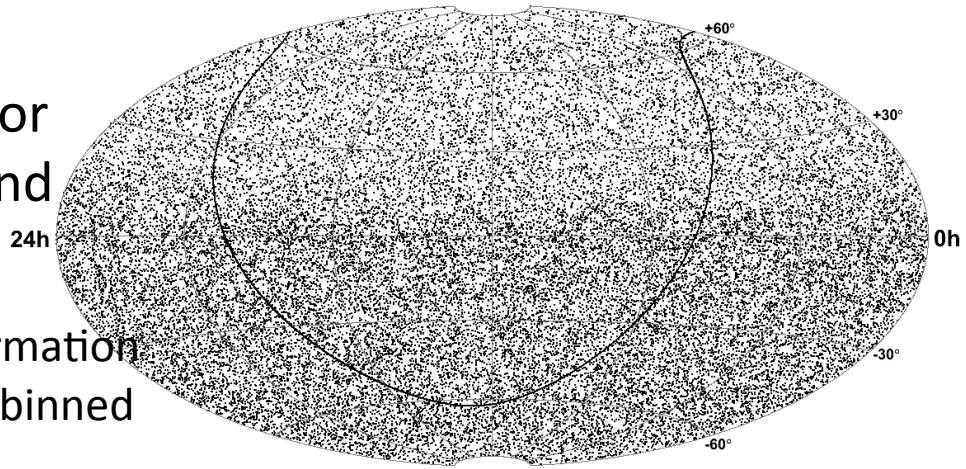


- Determine observables useful for separating signal and background
  - Space (θ, Φ)
  - Energy
  - (Time)

Inherent loss of information when you cut, e.g. a binned analysis

- 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 signal PDFs

The Point Source Analysis in Words



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

Inherent loss of information when you cut, e.g. a binned analysis

- Build PDFs for how signal and background are distributed for these observables
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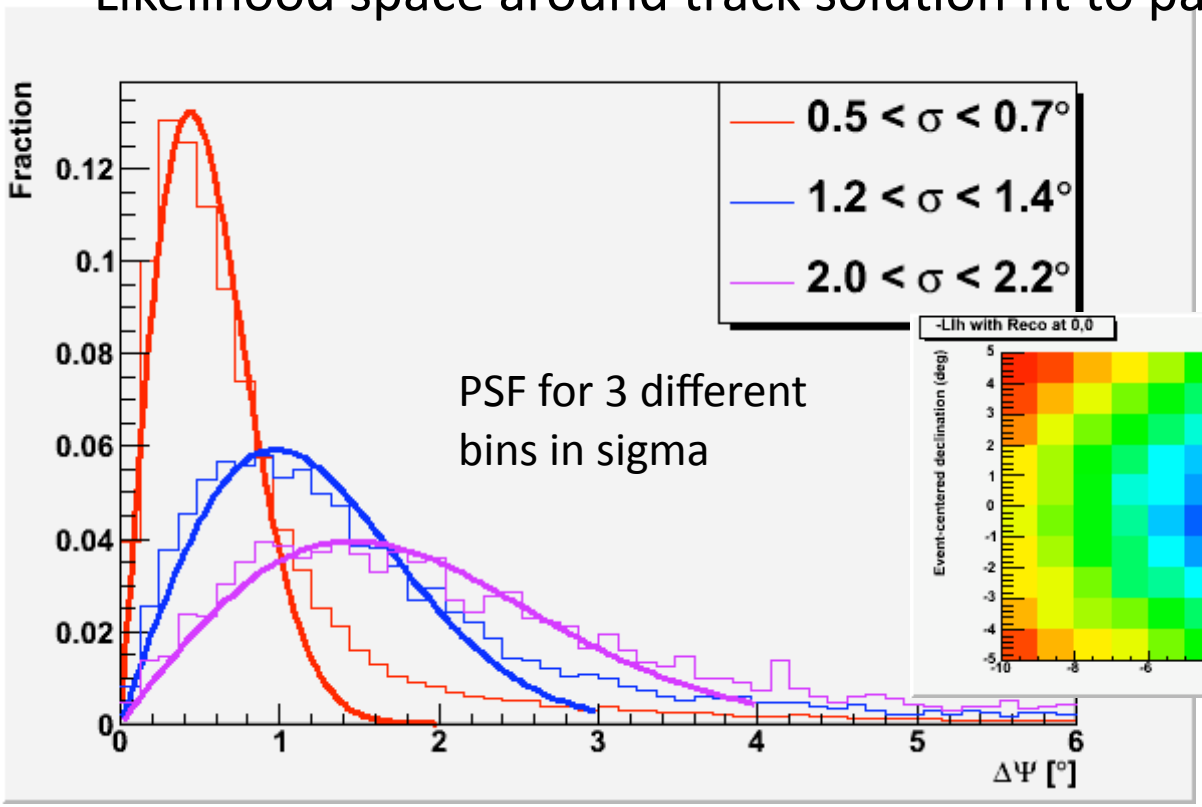
- Perform Maximum Likelihood fit for best mixture of signal and background
  - Extract astrophysical parameters

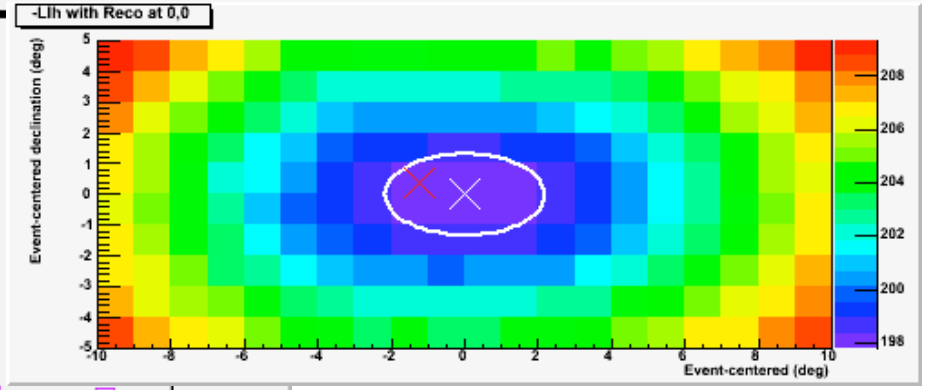
Maximum Likelihood Analysis with Energy

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

PSF modeling:

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





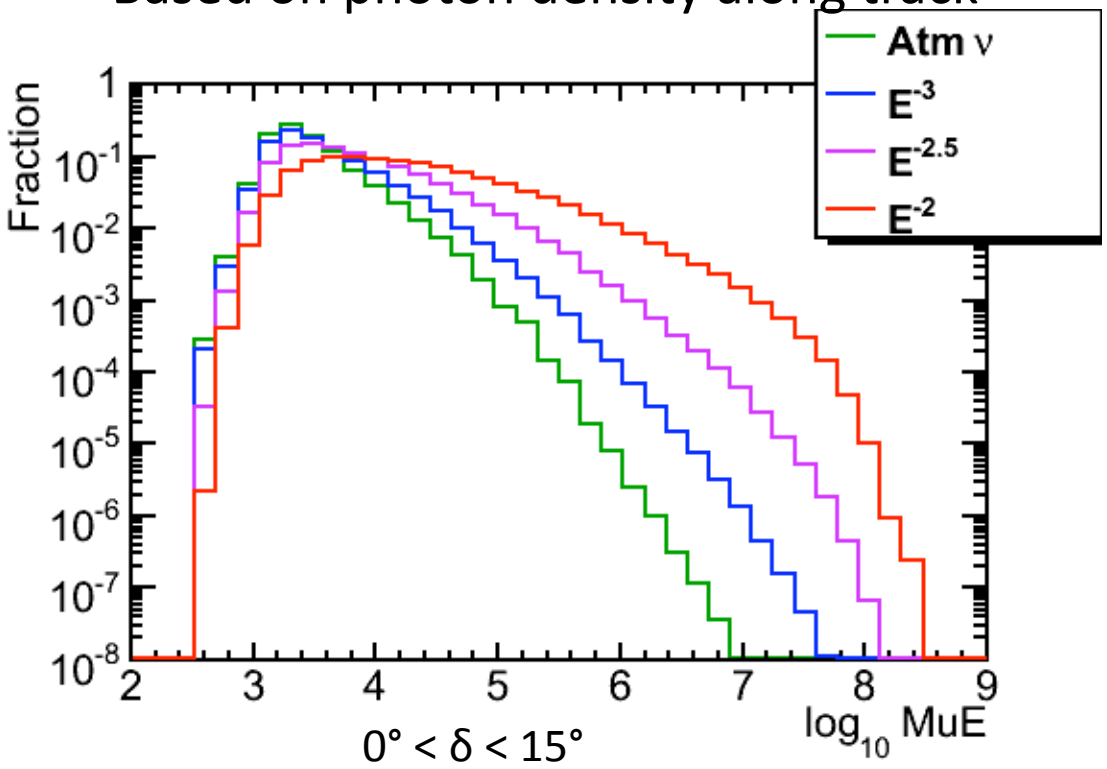
Median PSF = 0.7°

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

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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): $$TS = 2\log\left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)}\right)$$

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

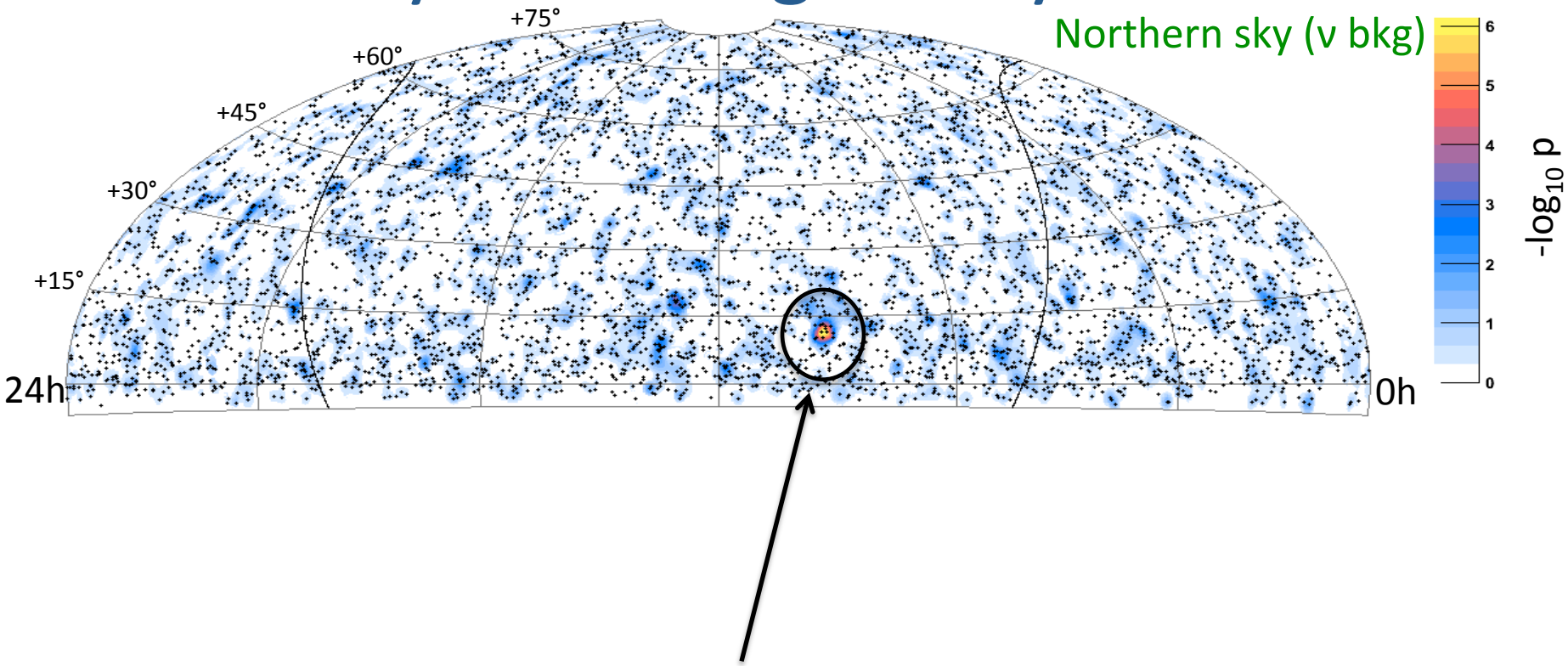
Likelihood: $$L(\gamma, n_s) = \prod_i P_i(\vec{x}_i, E_i, \gamma, n_s)$$

Log Likelihood Ratio (test statistic): $$TS = 2\log\left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)}\right)$$

Estimates which maximize the Llh

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

Previously: 22-string all-sky results

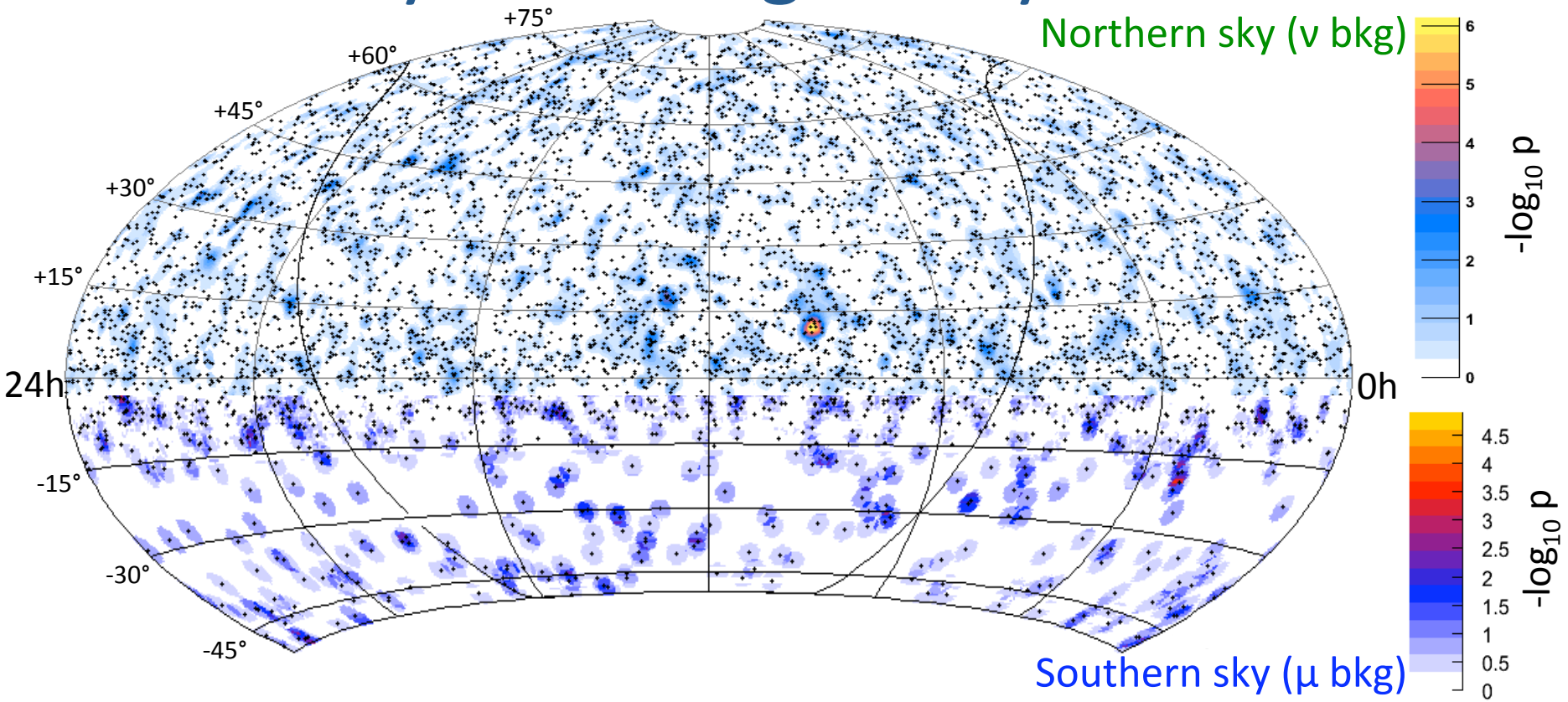


Hottest spot found at r.a. 153.4° , dec. 11.4°

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

ApJL 70, 47 (2009)

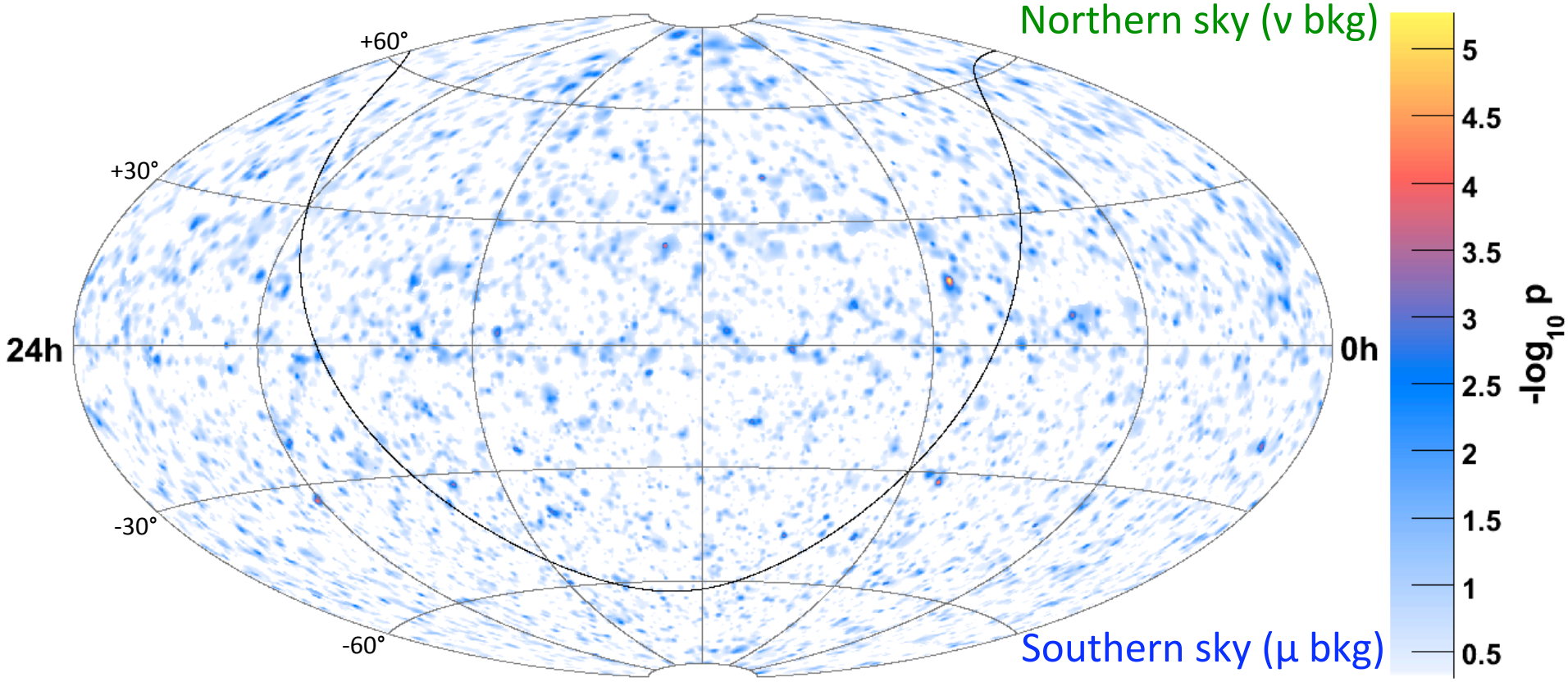
Previously: 22-string all-sky results



First IceCube analysis extended to -50° dec

PRL 103, 221102 (2009)

40-string All-Sky Results



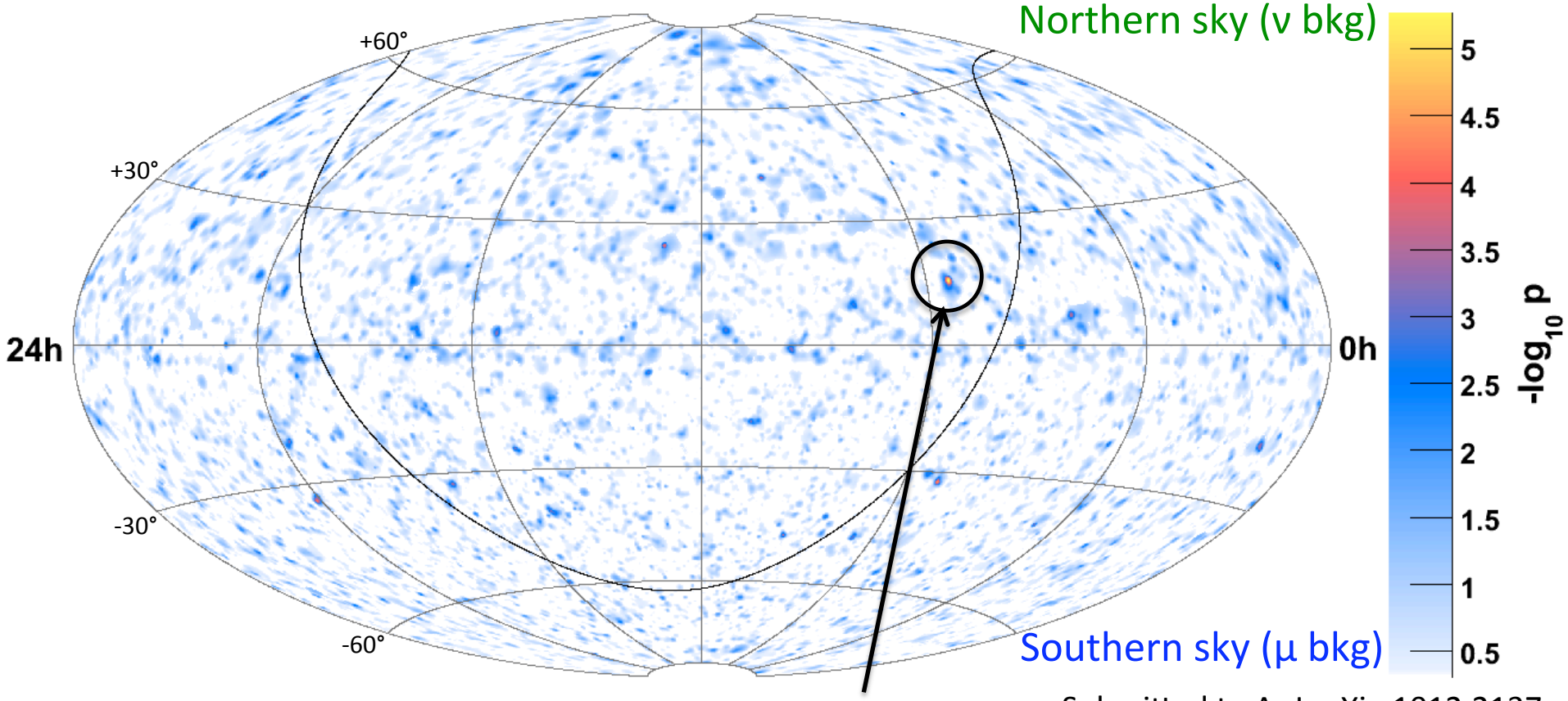
Accepted by ApJ arXiv:1012.2137

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…

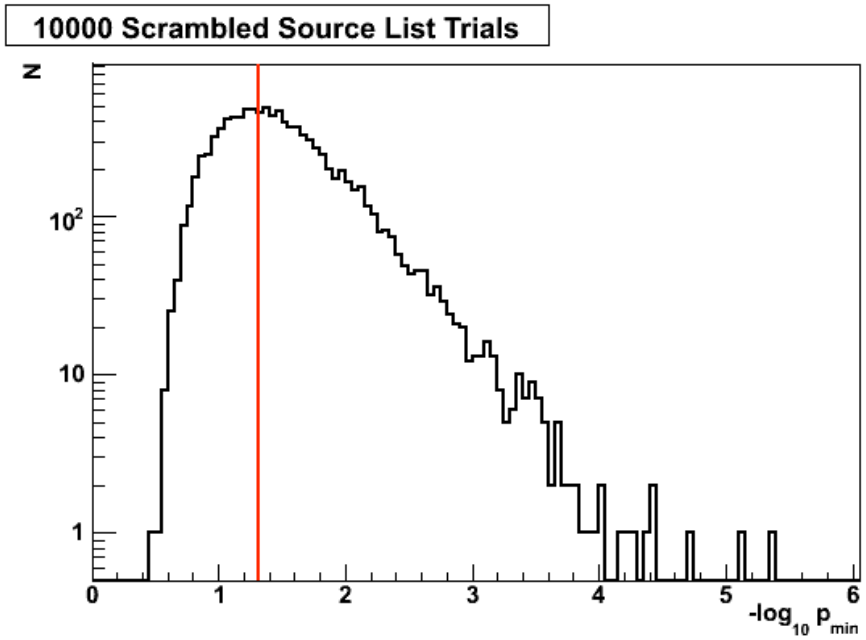
40-string Source List Results (cont.)

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%**



Systematic Errors

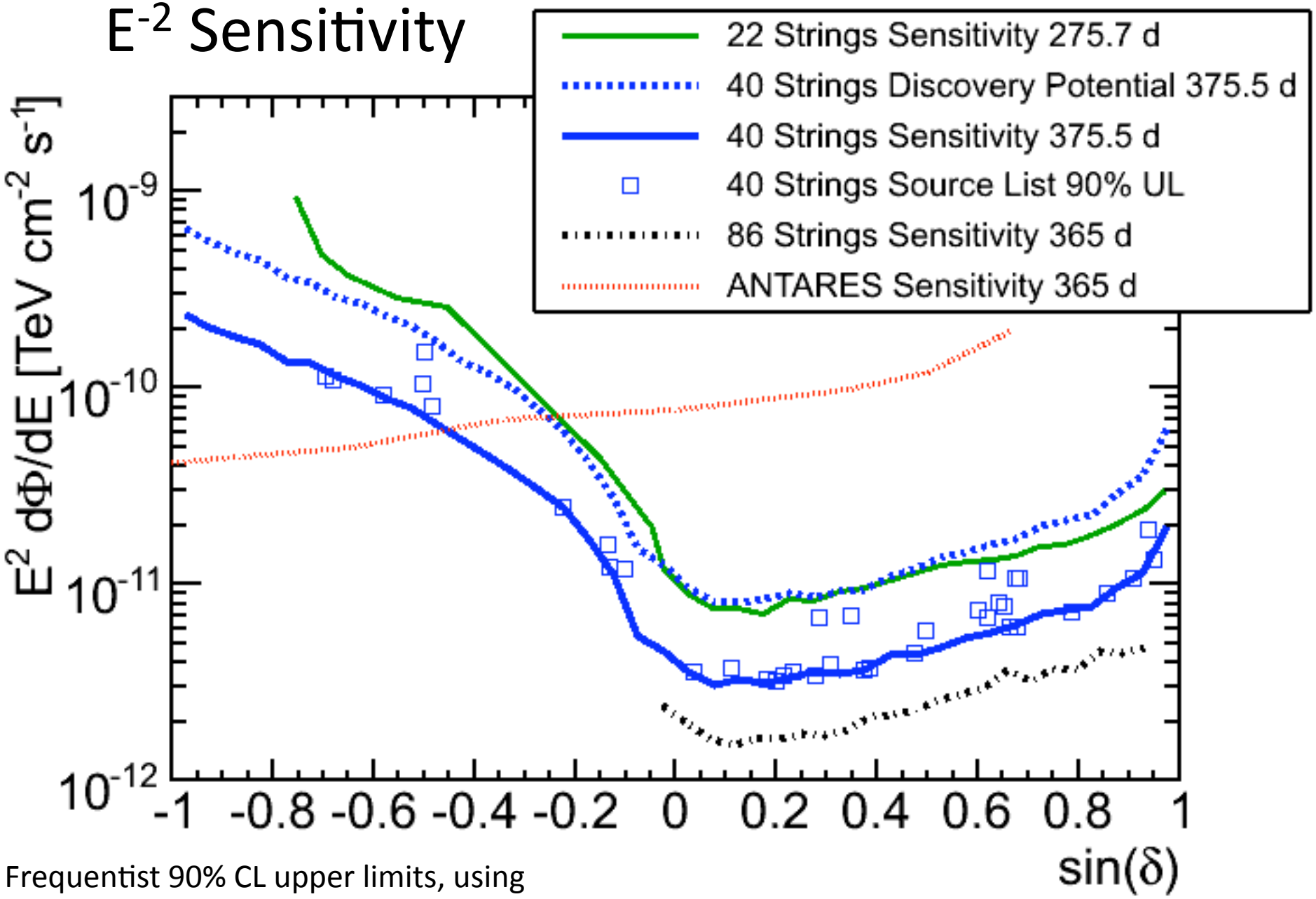
Error Source	Resulting error in signal efficiency
Optical properties of ice	11%
DOM sensitivity	9%
ν cross section, μ energy loss	8%

•Dedicated signal simulations are run where physical parameters are varied within their estimated error

•These simulations were used to determine the error on the signal efficiency of 16% (sum in quadrature)

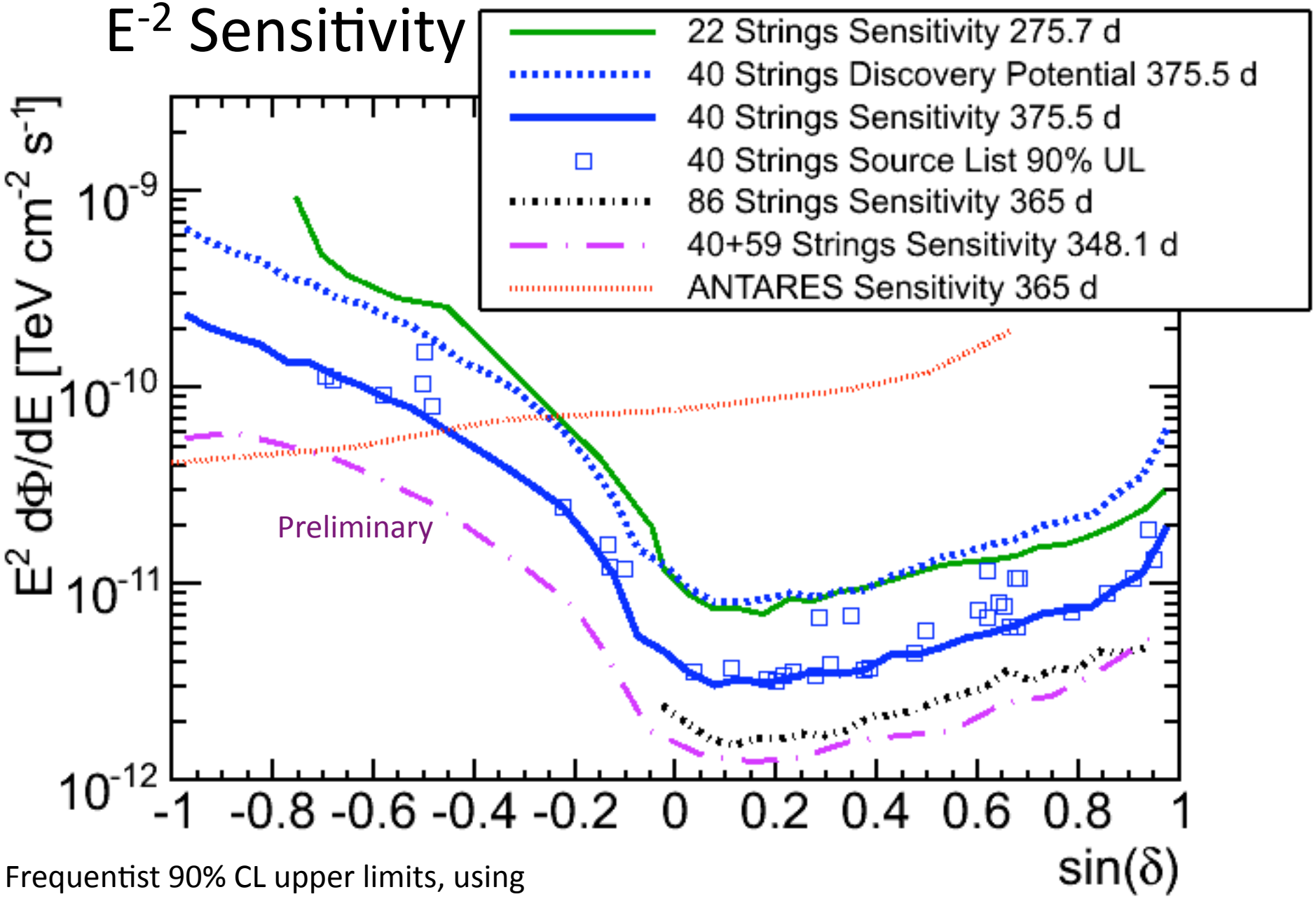
•These errors have been incorporated into the upper limits

E^{-2} Sensitivity



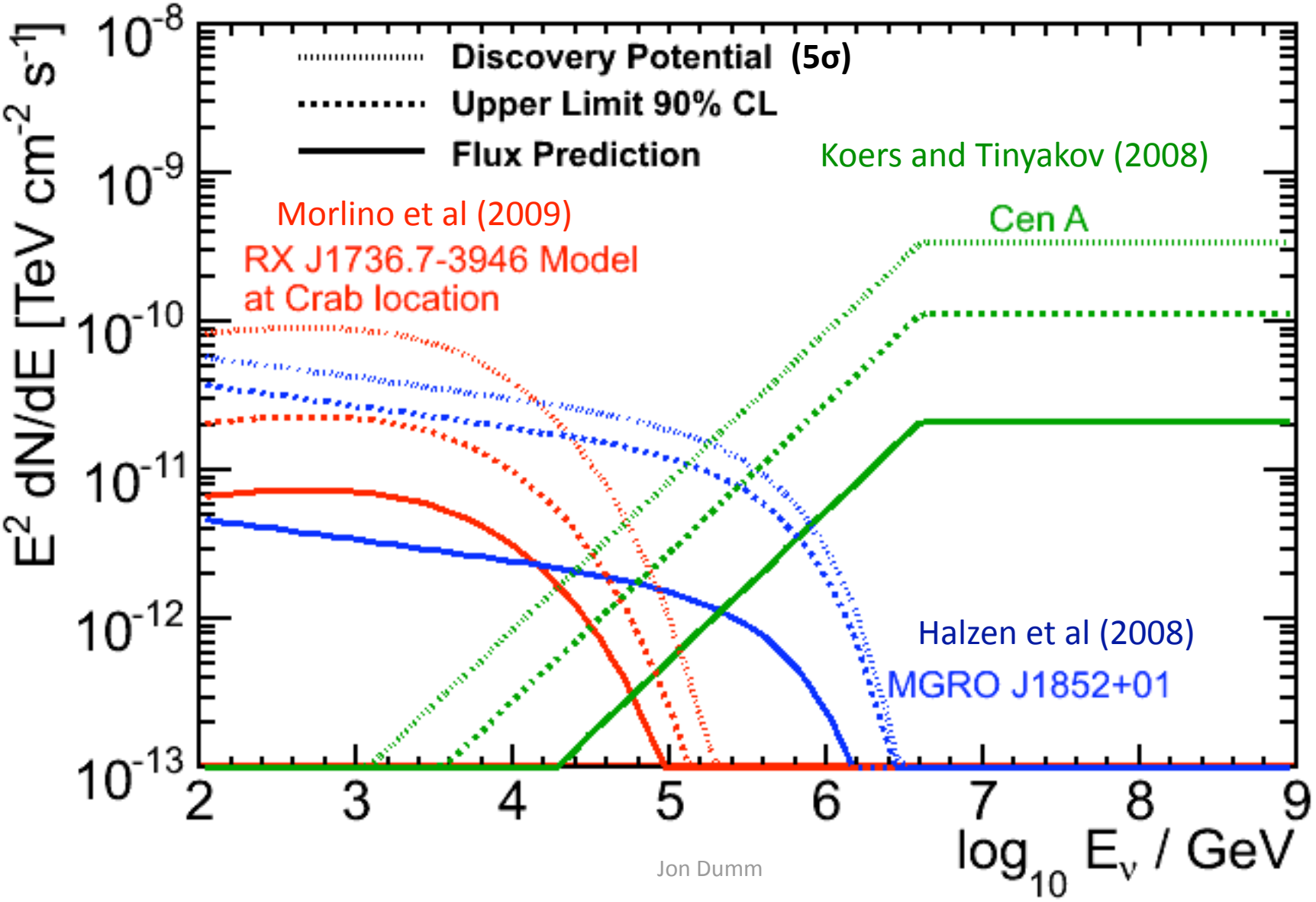
Frequentist 90% CL upper limits, using Feldman and Cousins ordering principle

E^{-2} Sensitivity

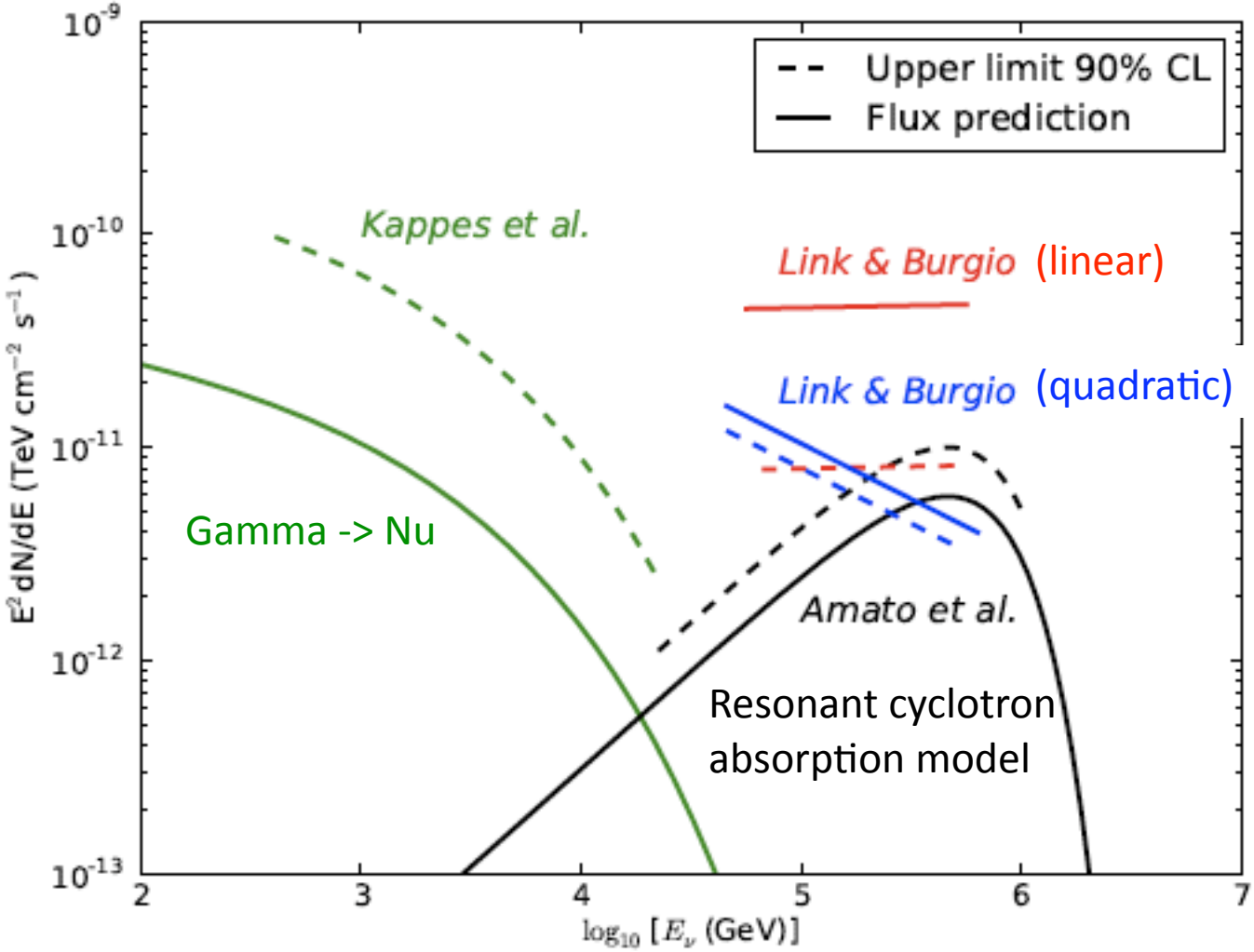


Frequentist 90% CL upper limits, using Feldman and Cousins ordering principle

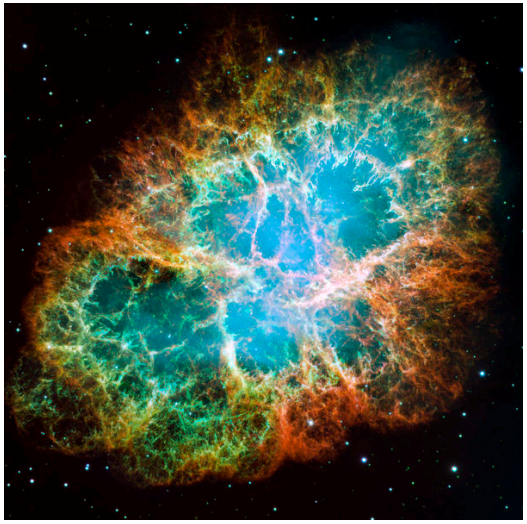
Model Testing - 40 strings

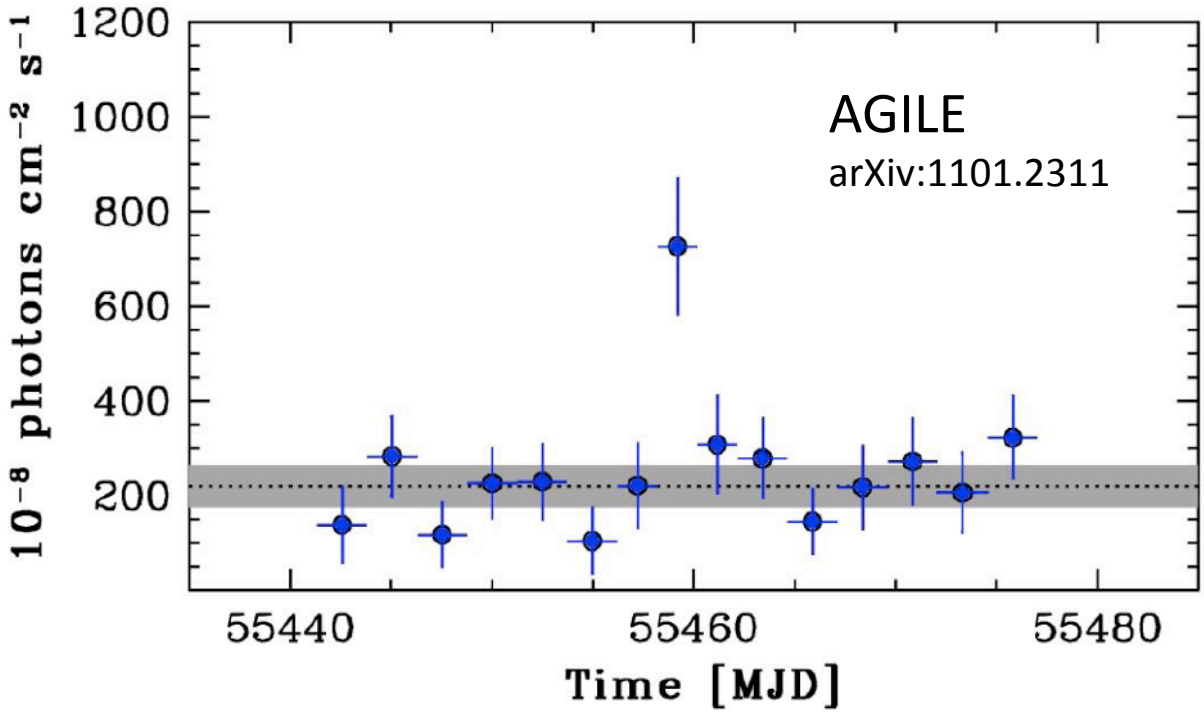


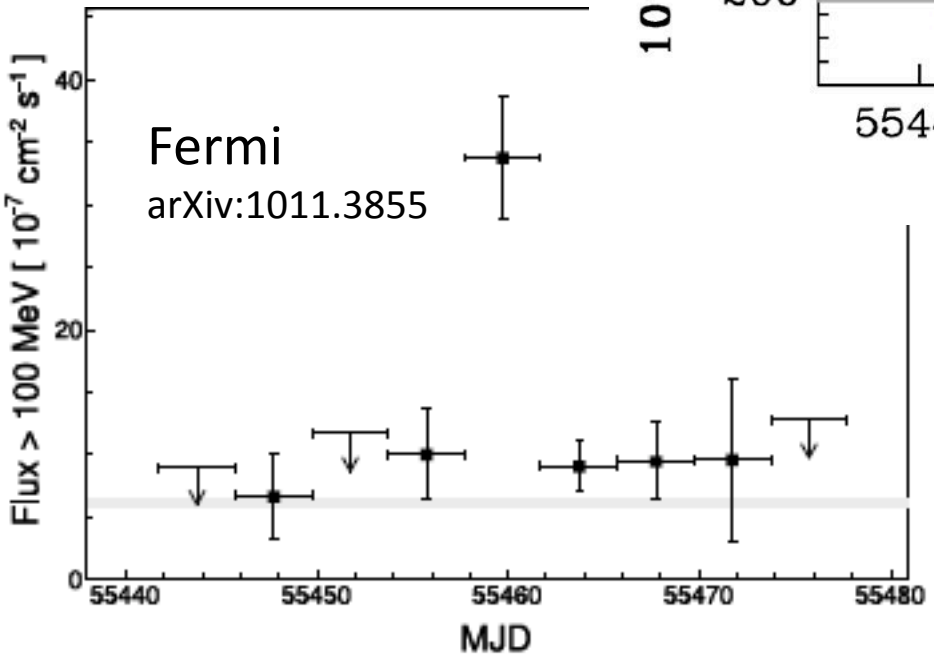
Model Testing: Crab Nebula - 40 strings



The Crab: A Standard Candle?



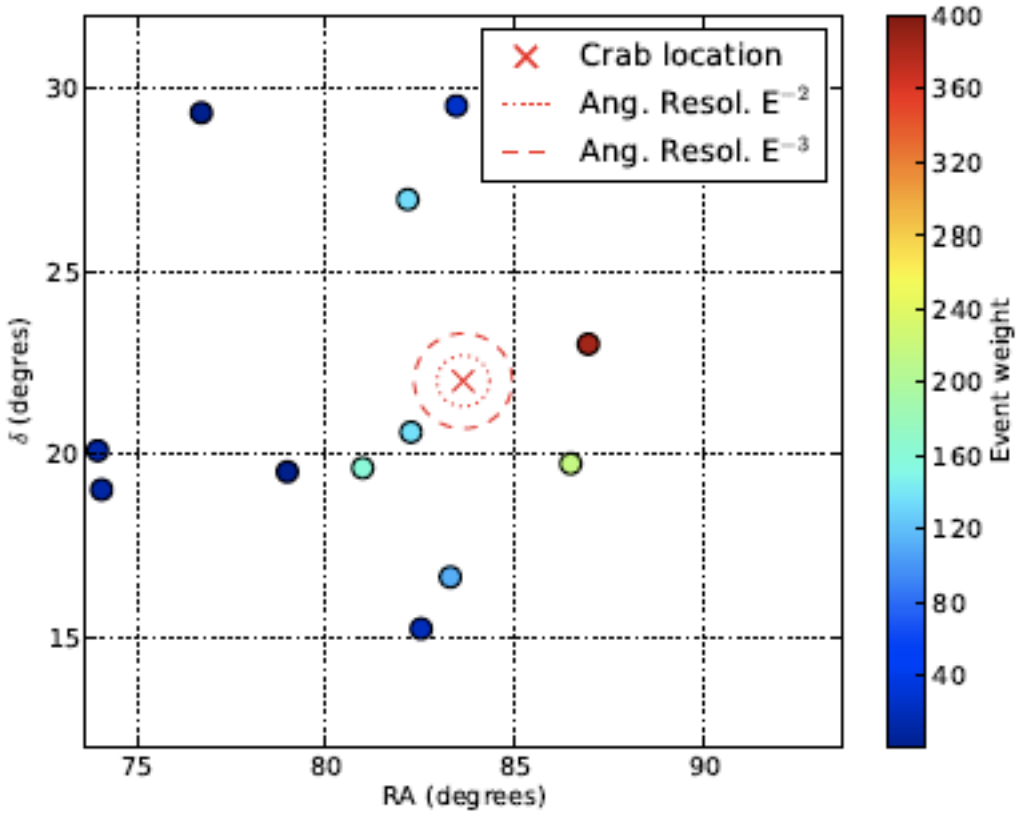




Last September: Crab Nebula flared to ~3-6 times its average flux for several days

Confirmed by ARGO in TeV but not HESS/VERITAS

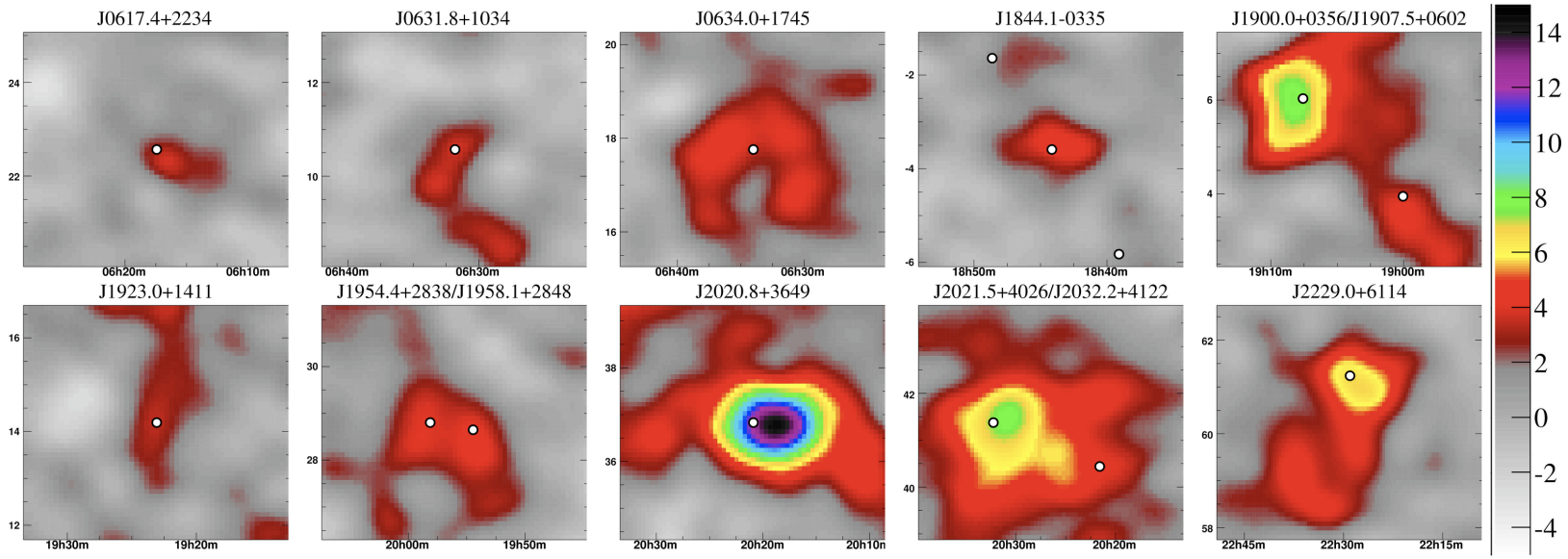
IceCube 79-string Crab Flare Results



- 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

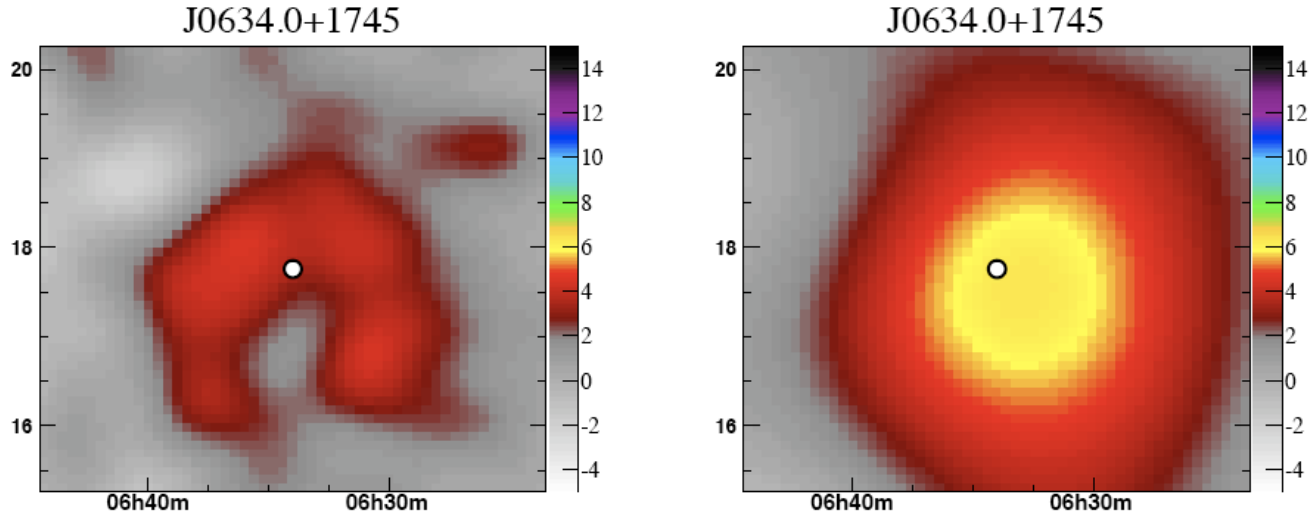


- Milagro showed that many Fermi GeV gamma ray sources extend to TeV
- Sources are a mix: SNR, pulsars, PWN, unidentified
- Great example of how knowing which sources to **stack** can help!
- Stacking in likelihood analysis: break signal PDF into sum of many pieces

Abdo et al. 2009, arXiv:0904.1018v3

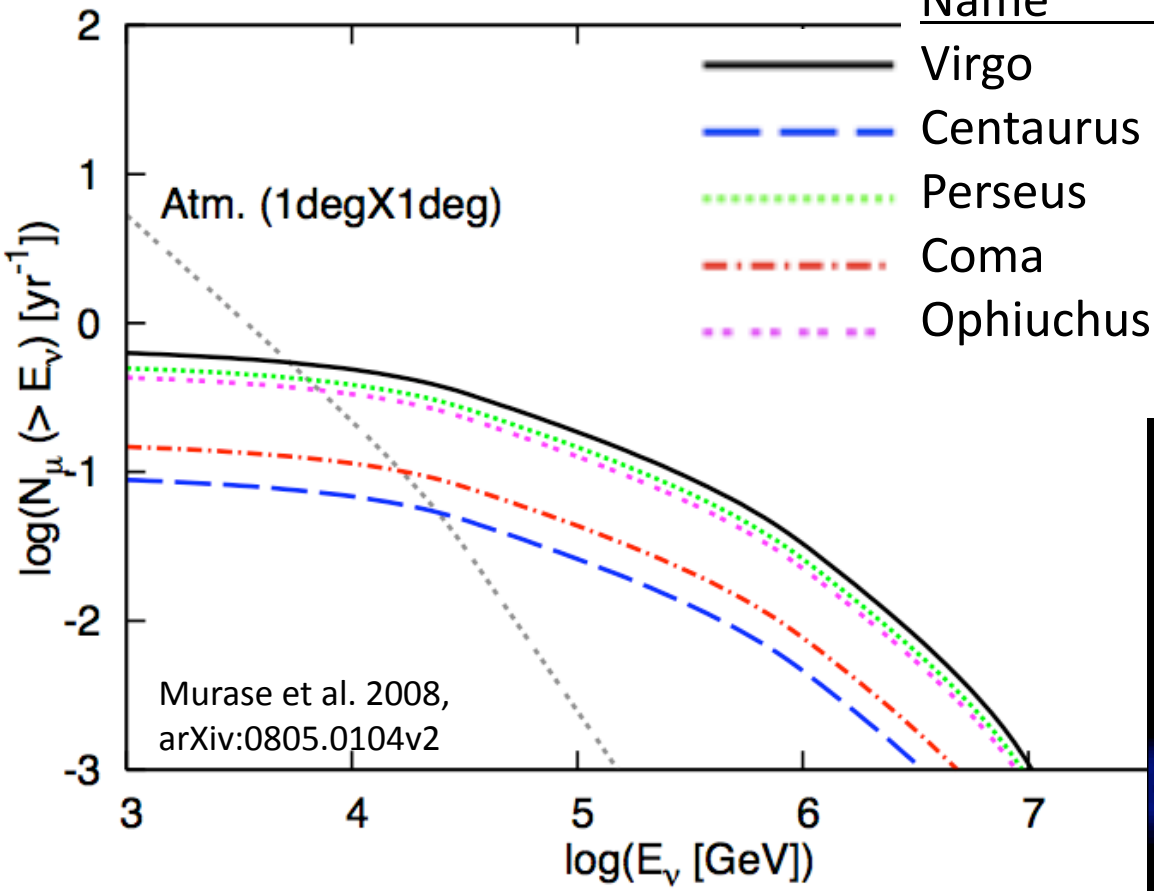
Spatially Extended Sources

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

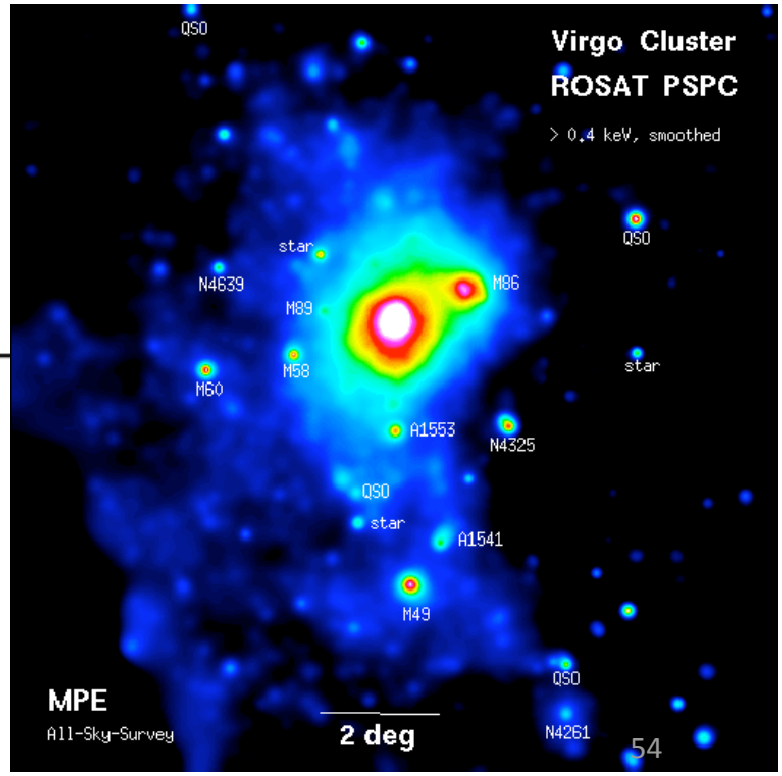


- CRs must be accelerated and interact to produce pions (-> gamma rays + neutrinos)
- Convolve source distribution with PSF in likelihood

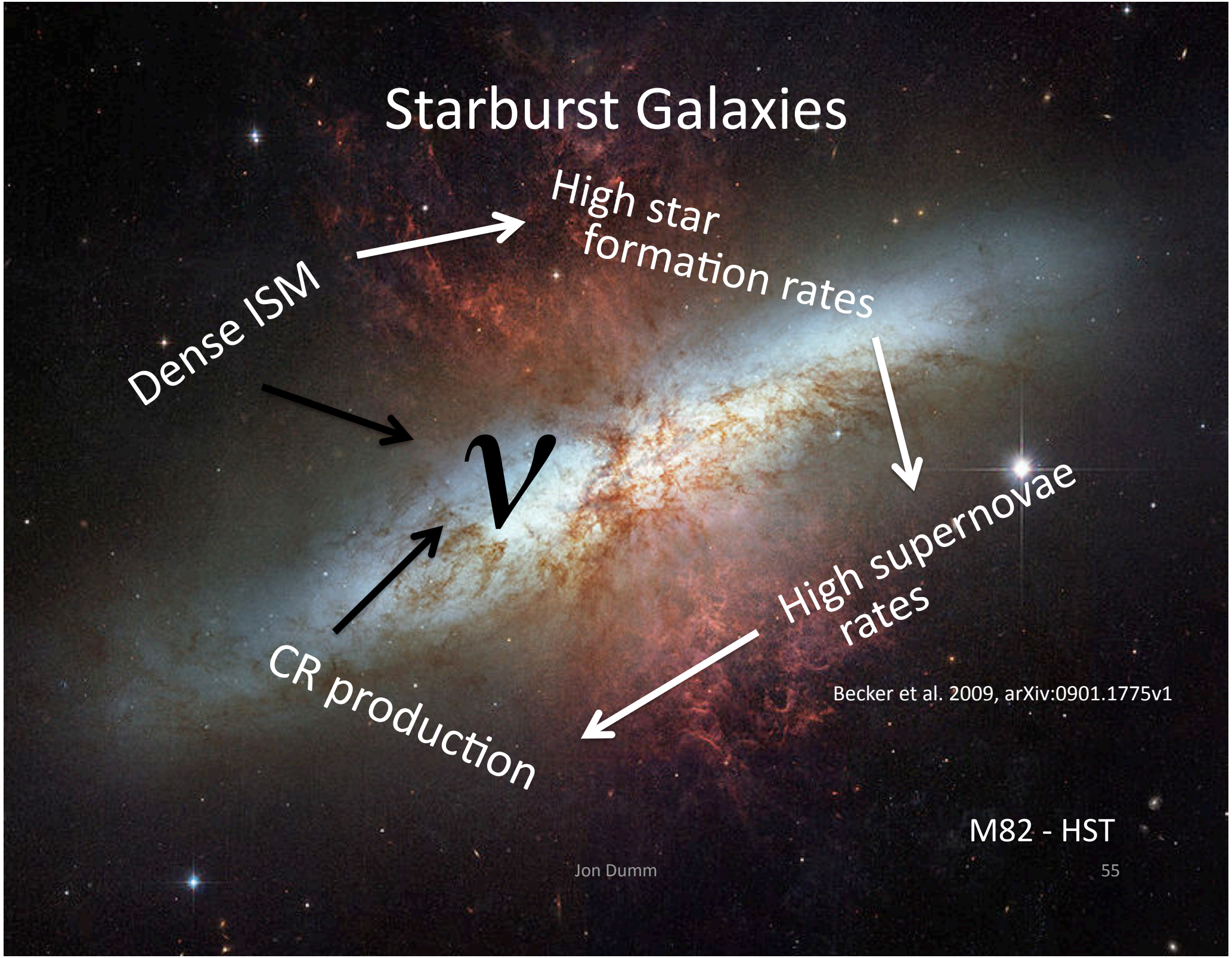
Nearby Clusters of Galaxies



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

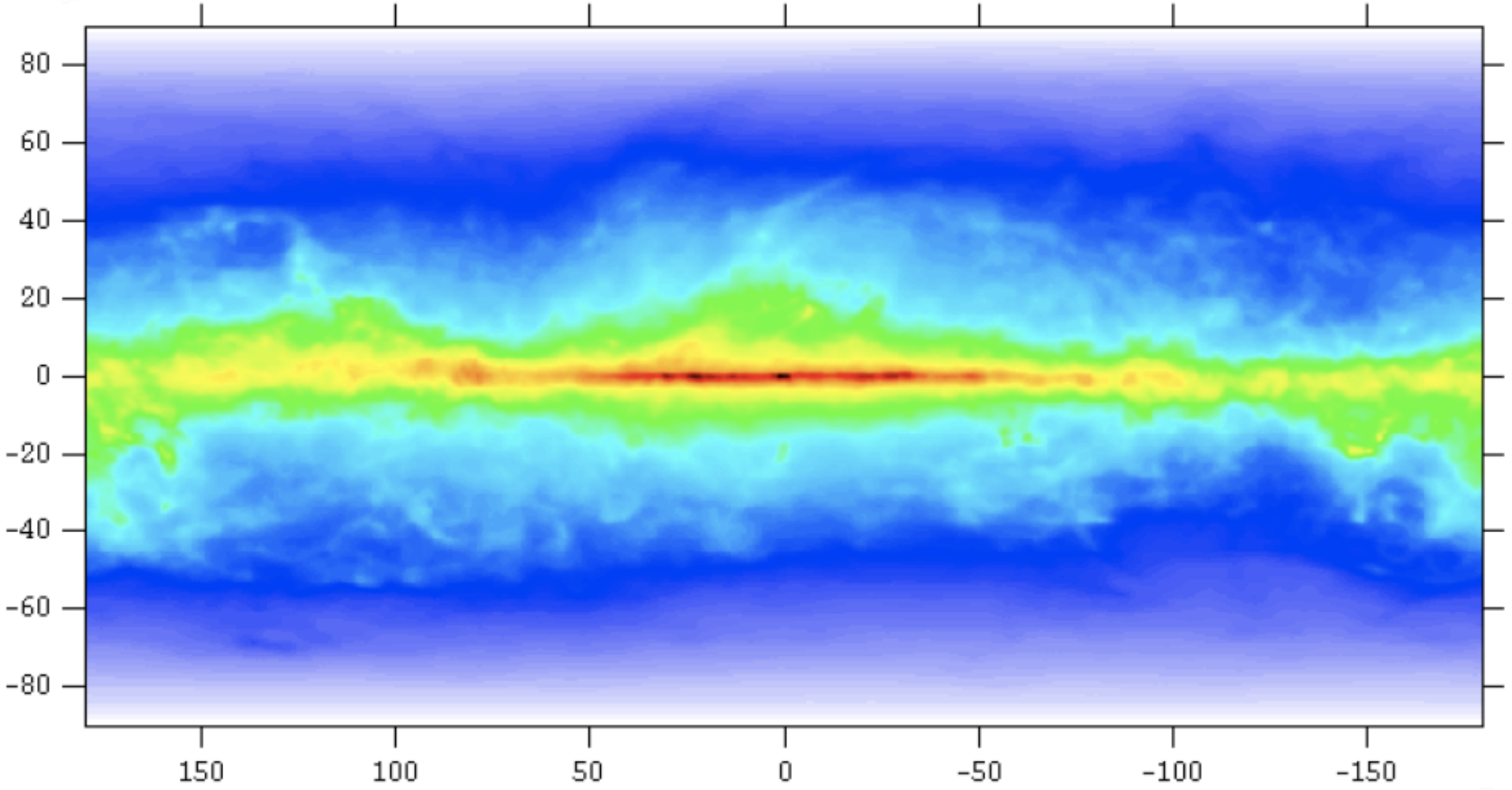
- 3.0 events predicted by flux from Halzen, Kappes, O'Murchadha (2008), best fit was 15 signal events over background

p-values of 6 Milagro SNR stacked searches:

AMANDA 7-yr	22-strings	40-strings
20%	27%	2%

(a posteriori)

Searching for Neutrinos from the Galactic Plane

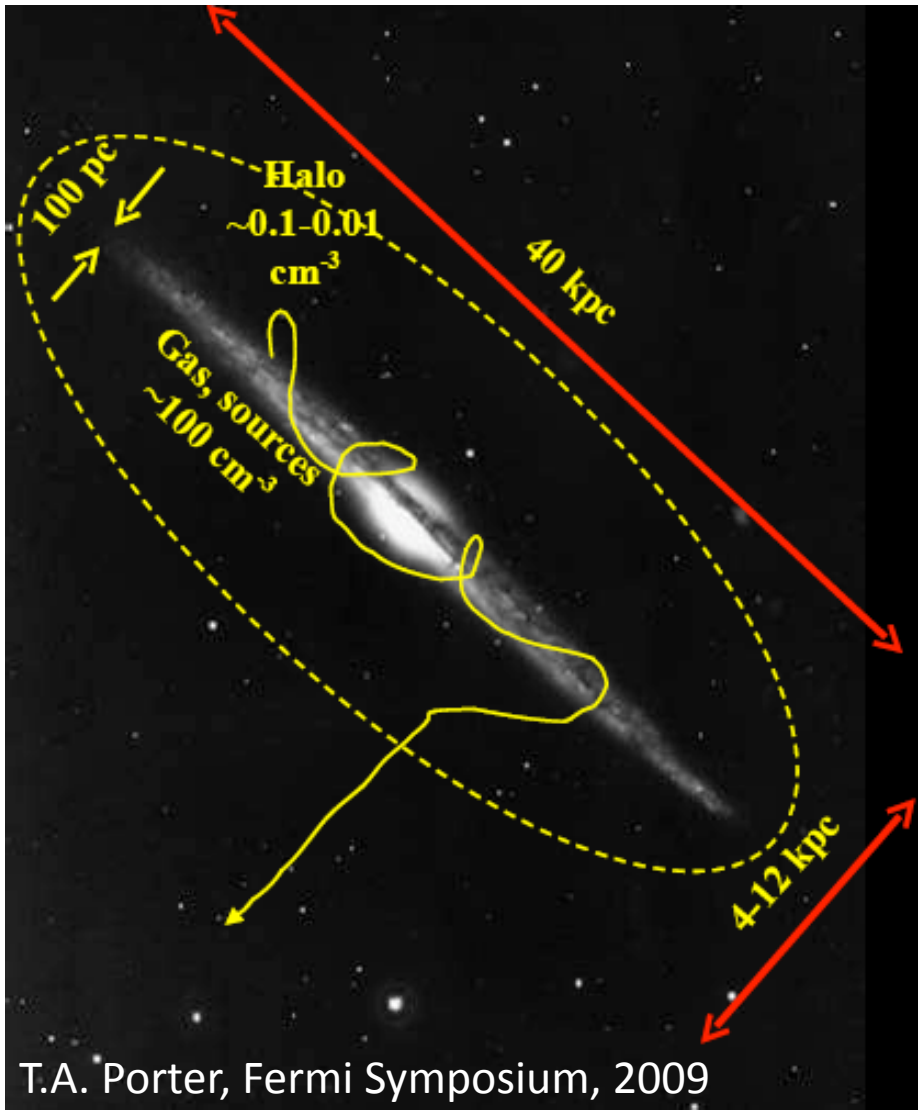


We can use a similar maximum likelihood technique to search for neutrinos from the Milky Way:

Change signal PDF to be based on a 2D map of neutrino emission

Origin of Diffuse GP Emission

- CRs diffuse in galaxy interacting with ISM -> gamma rays + neutrinos
  - 'guaranteed' flux of neutrinos, but small
- Modeling gammas + neutrinos possible
  - PYTHIA, SIBYLL and some assumptions about CR and ISM density
  - GalProp (no neutrinos yet)

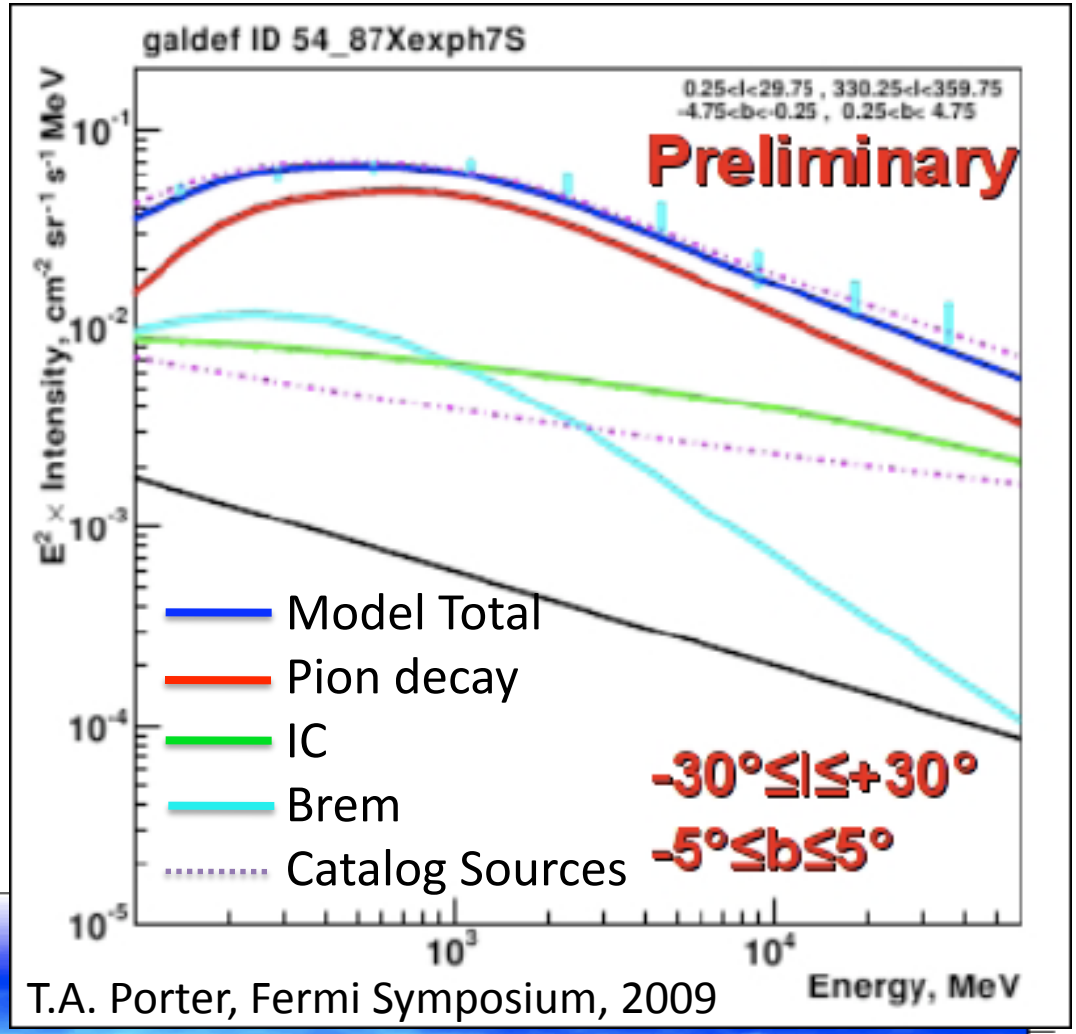


Fermi LAT GP Observations

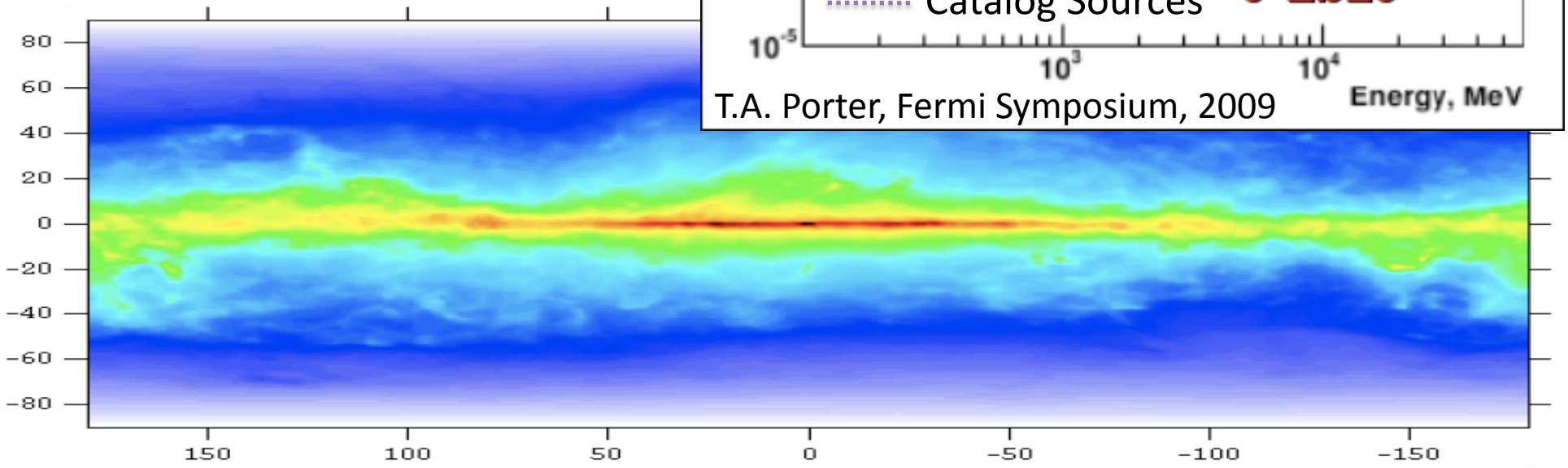
- Gamma rays mostly from pion decay

  (GalProp model)

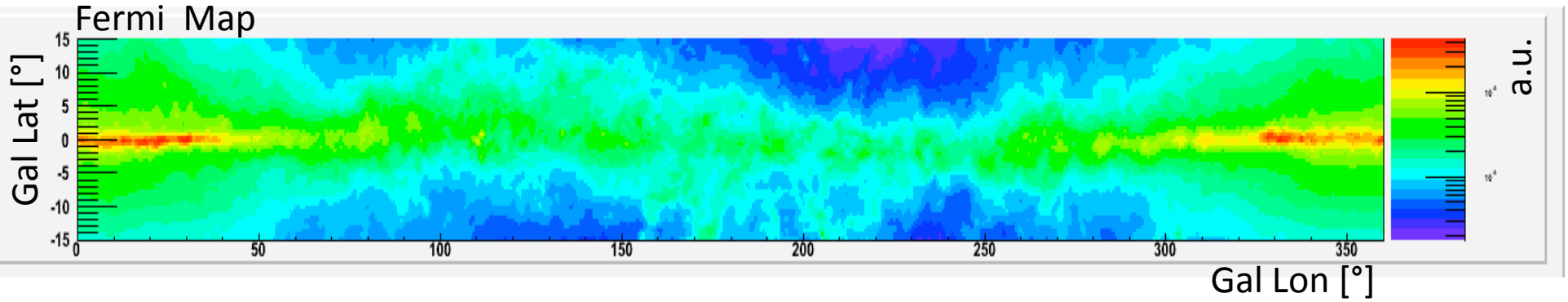
- Neutrinos α Gammas



T.A. Porter, Fermi Symposium, 2009



Fermi GP Model



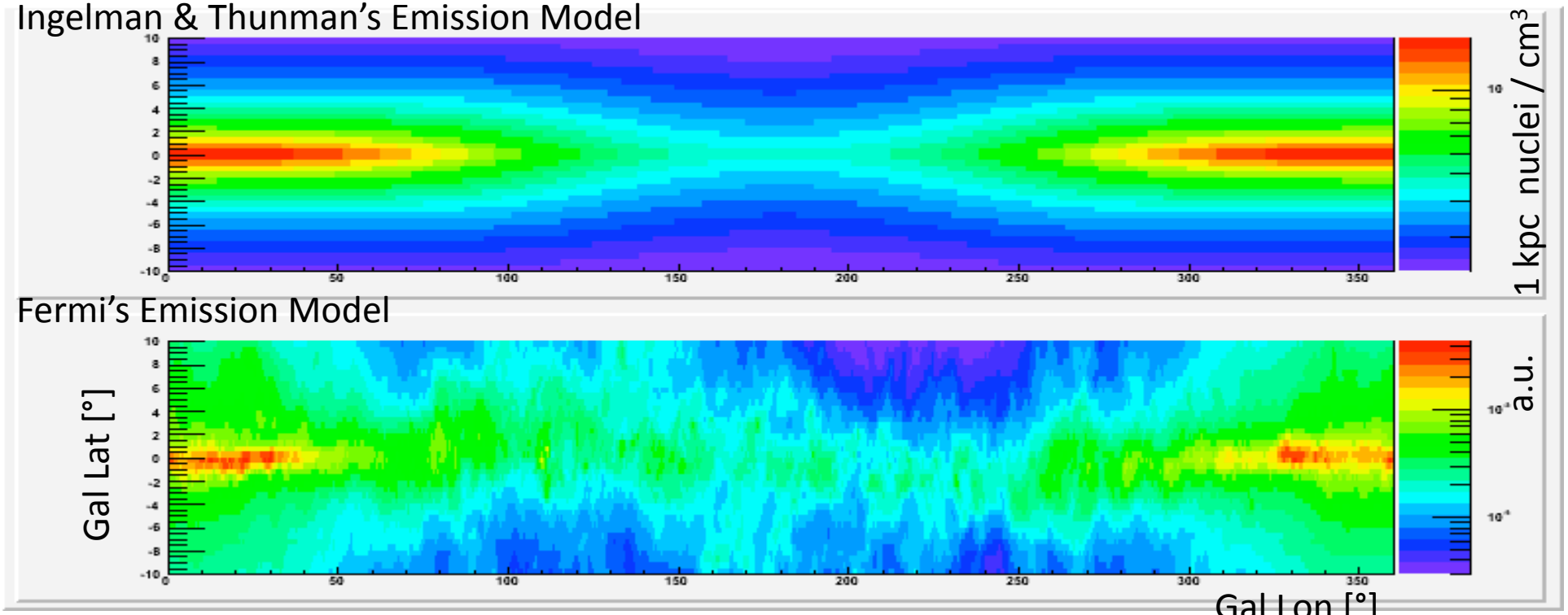
- We can take advantage of the fact that the gamma ray and neutrino emissions are proportional
- Above is GP model fit to Fermi data
  - Constructed from H1+CO(proxy for H2) maps
  - Point sources and isotropic (extra-gal) subtracted out
- Using the Fermi map convolved with detector response as signal PDF:

  Sensitivity = 64.6 events

Prediction by Ingelman & Thunman `96

- Simplified model of GP:
  - ρ_{ISM}=1 nuclei/cm^3 * exp(-h/0.26kpc)
  - CR flux throughout galaxy same as at Earth
- Prediction leads to 8 events in the 40-string PS sample (1/8th Sensitivity)

Oscillations accounted for



Neutrinos are being added to the GalProp simulation for a more accurate prediction!

Outlook

- Sensitivity will improve as ~√no. signal events
  - Being conservative, say IC86 gives 2x more events:

    ~32 yrs of IC86 before sensitivity reaches Ingelman & Thunman prediction

- Numerous possibilities to decrease that large number of years
  - enhanced low energy sensitivity in IceCube
    - Deep Core, veto CRs in southern sky
    - optimized cuts (~2x the 'point source sample' if PSF matters less)
  - combined analysis w/ ANTARES (KM3NeT)
  - any point sources in the GP contribute
  - (Potentially higher CR flux at >TeV than predicted in GalProp?)

- Foreseeable to detect GP in **5-10 years** (with some effort)
- An important foreground to understand

Conclusions

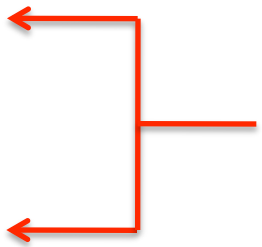
- IceCube construction is complete!
- So far, no evidence found for any signal
  - Upper limits already begin to rule out some astrophysical scenarios
- 40-string data being published
  - Provides the best >TeV astrophysical neutrino limits
- 59-string data being unblinded soon
- 86-strings in operation shortly!

Backup Slides

Why Look for Diffuse GP Emission?

- Properties of ISM
- Distribution of CRs

  (potentially origins of CRs)

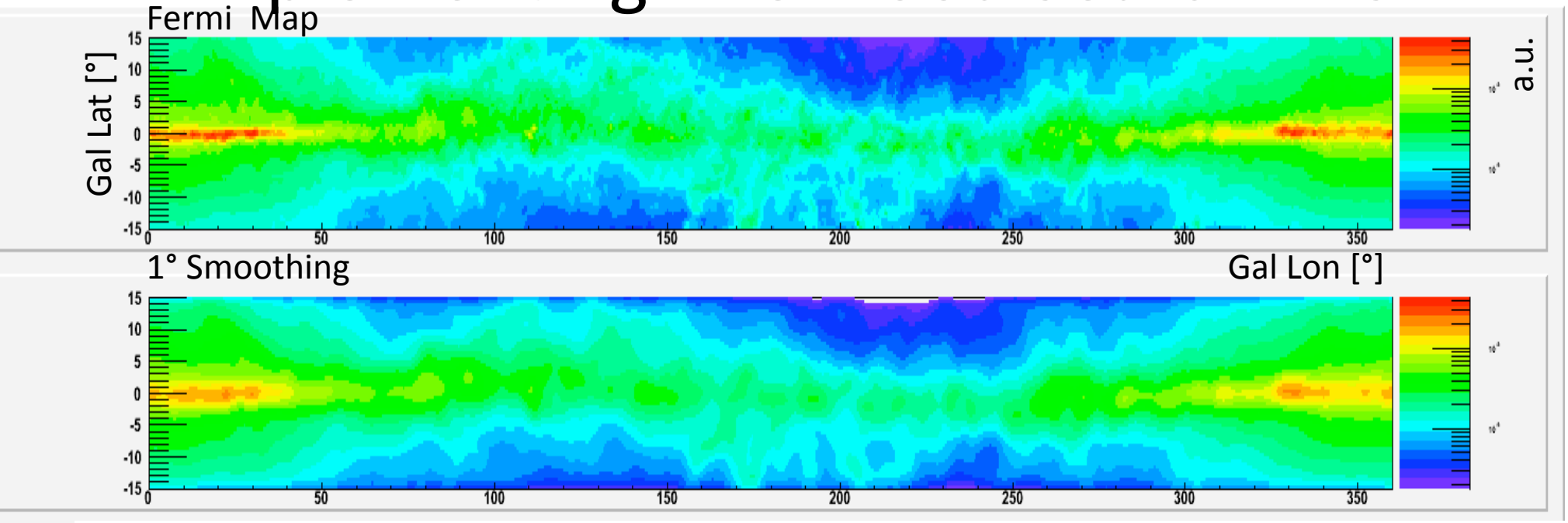


Gamma ray astronomy does these quite well (model dependent)

Many 'excesses' claimed in gamma ray astronomy

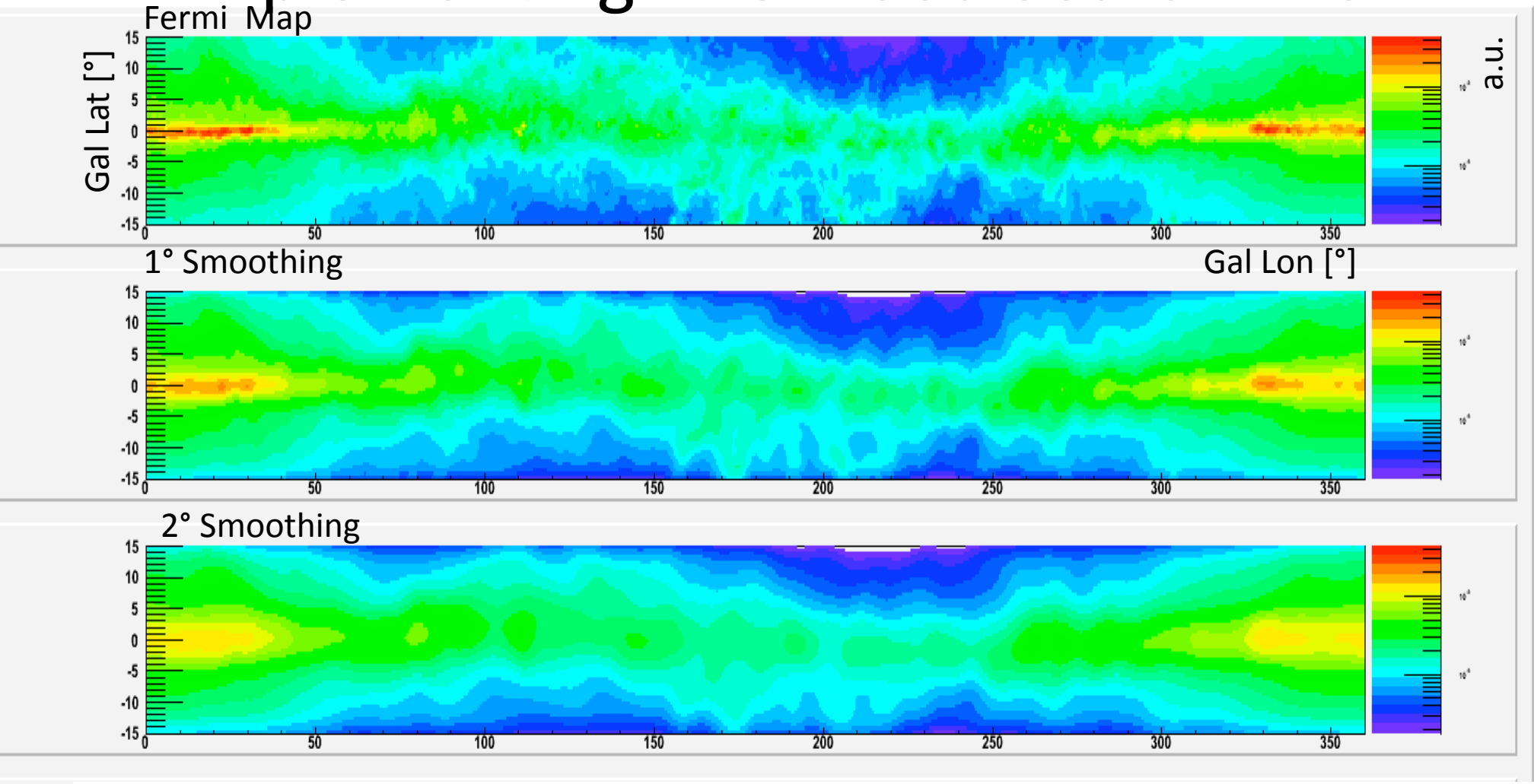
- **A foreground for many other searches**
  - See an excess from galactic center? Dark Matter or conventional CR interactions?
  - Measurement of prompt (charm) component of atmospheric flux needs to model or mask GP flux

Implementing Likelihood Search - PSF



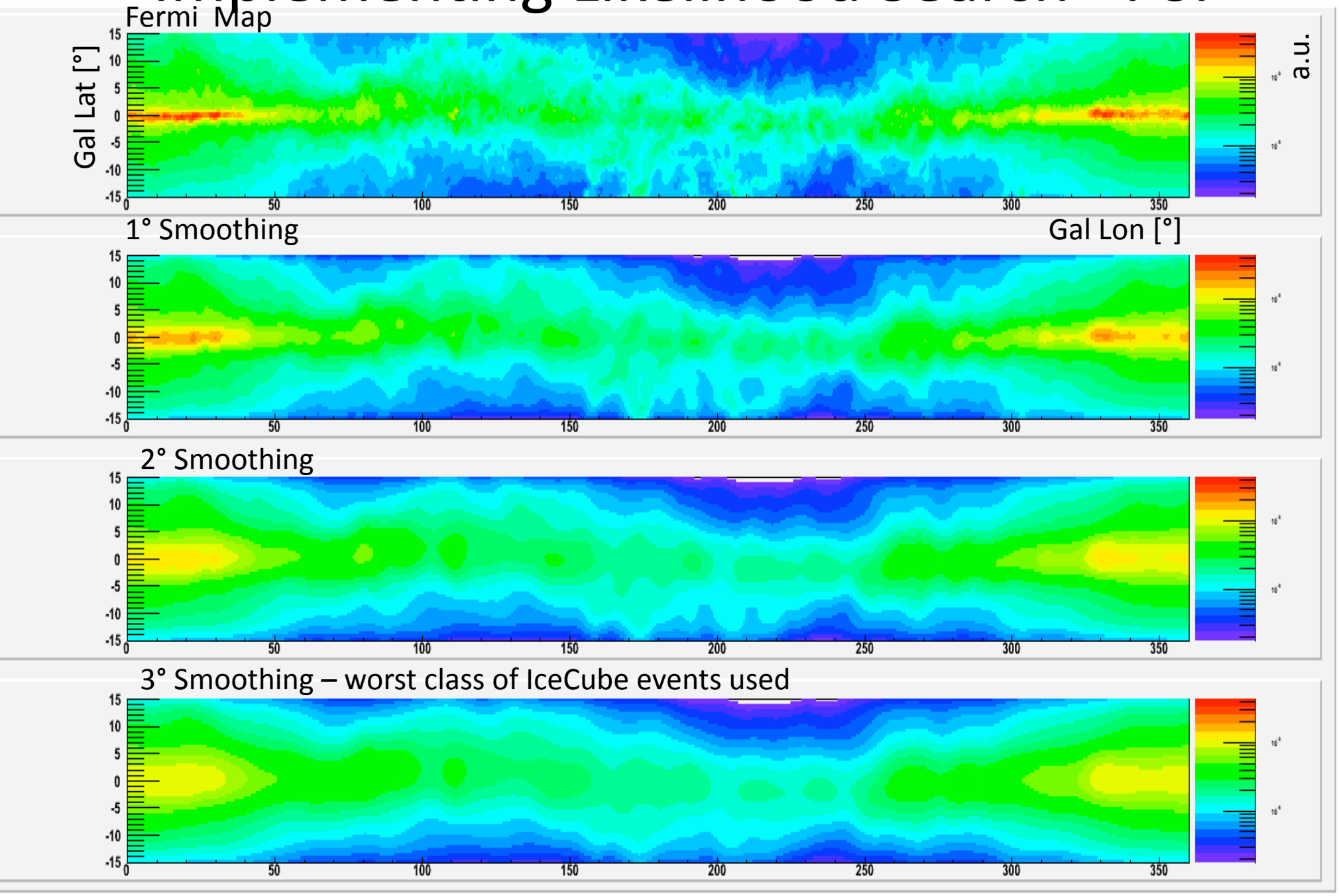
- The same model seen with IceCube's 'blurred' vision
  - average PSF for $E^{-2.7}$ is ~1°

Implementing Likelihood Search - PSF



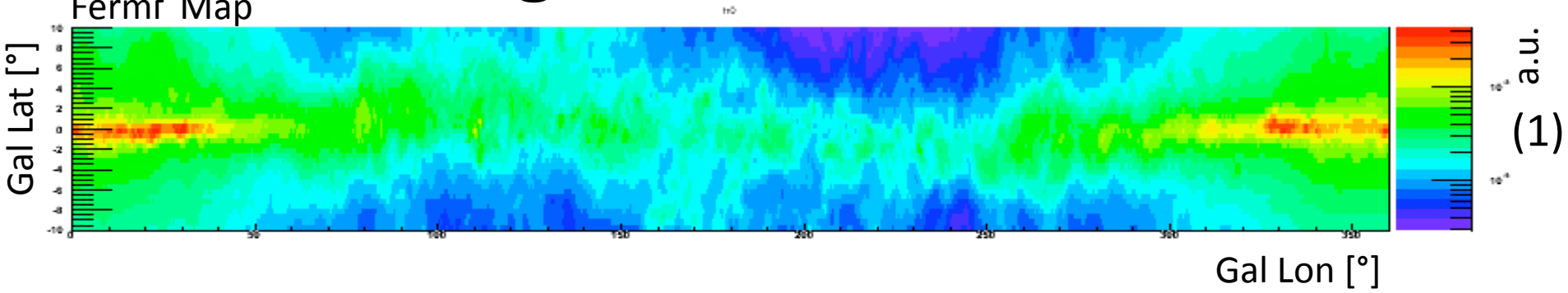
- Would like to use event-by-event reconstructed angular uncertainties up to 3°
  - Use 30 maps binned by 0.1° in sigma

Implementing Likelihood Search - PSF



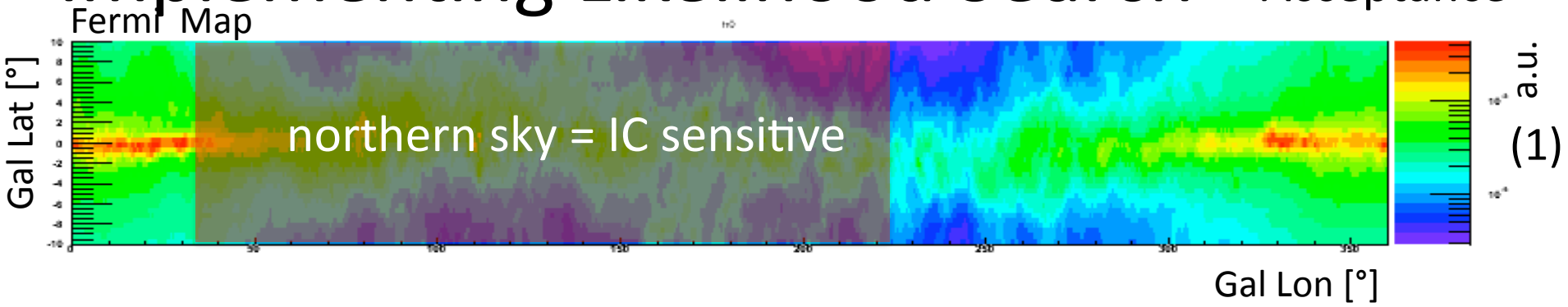
Implementing Likelihood Search - Acceptance

Fermi Map



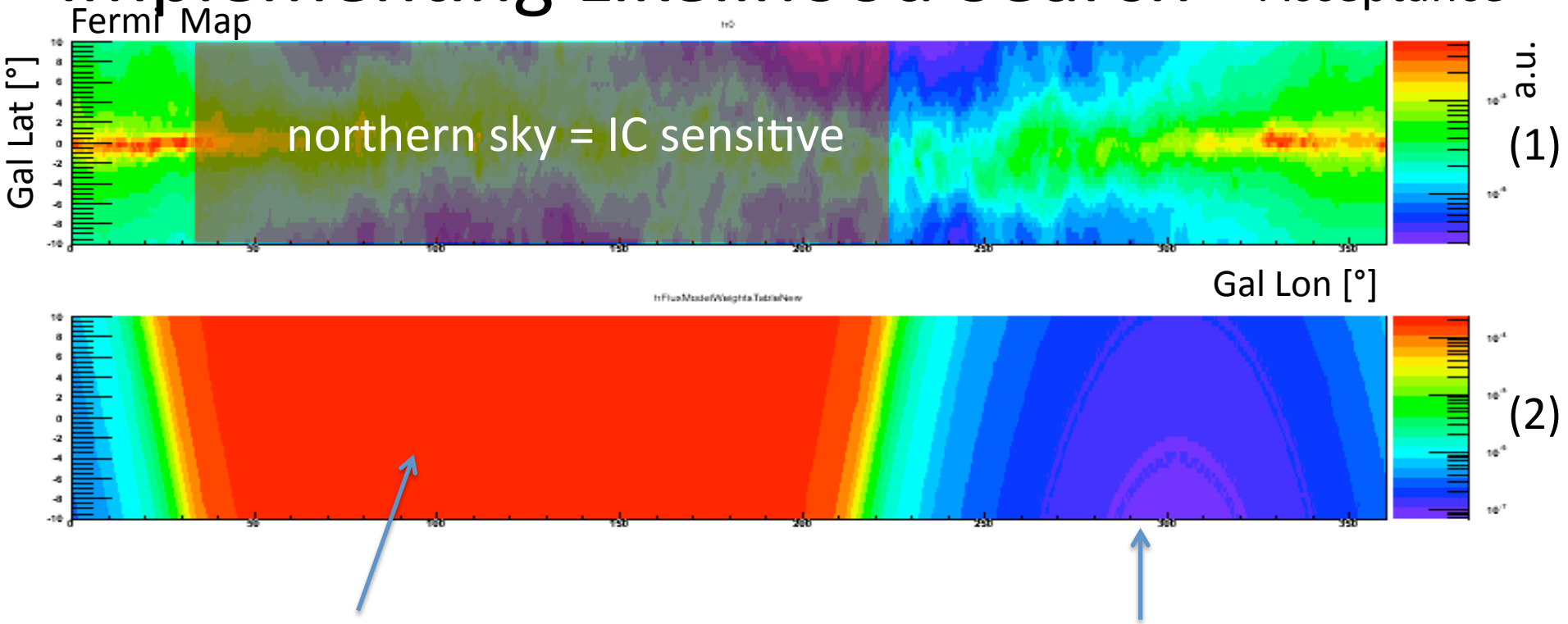
- The Fermi model above is our signal emission hypothesis

Implementing Likelihood Search - Acceptance



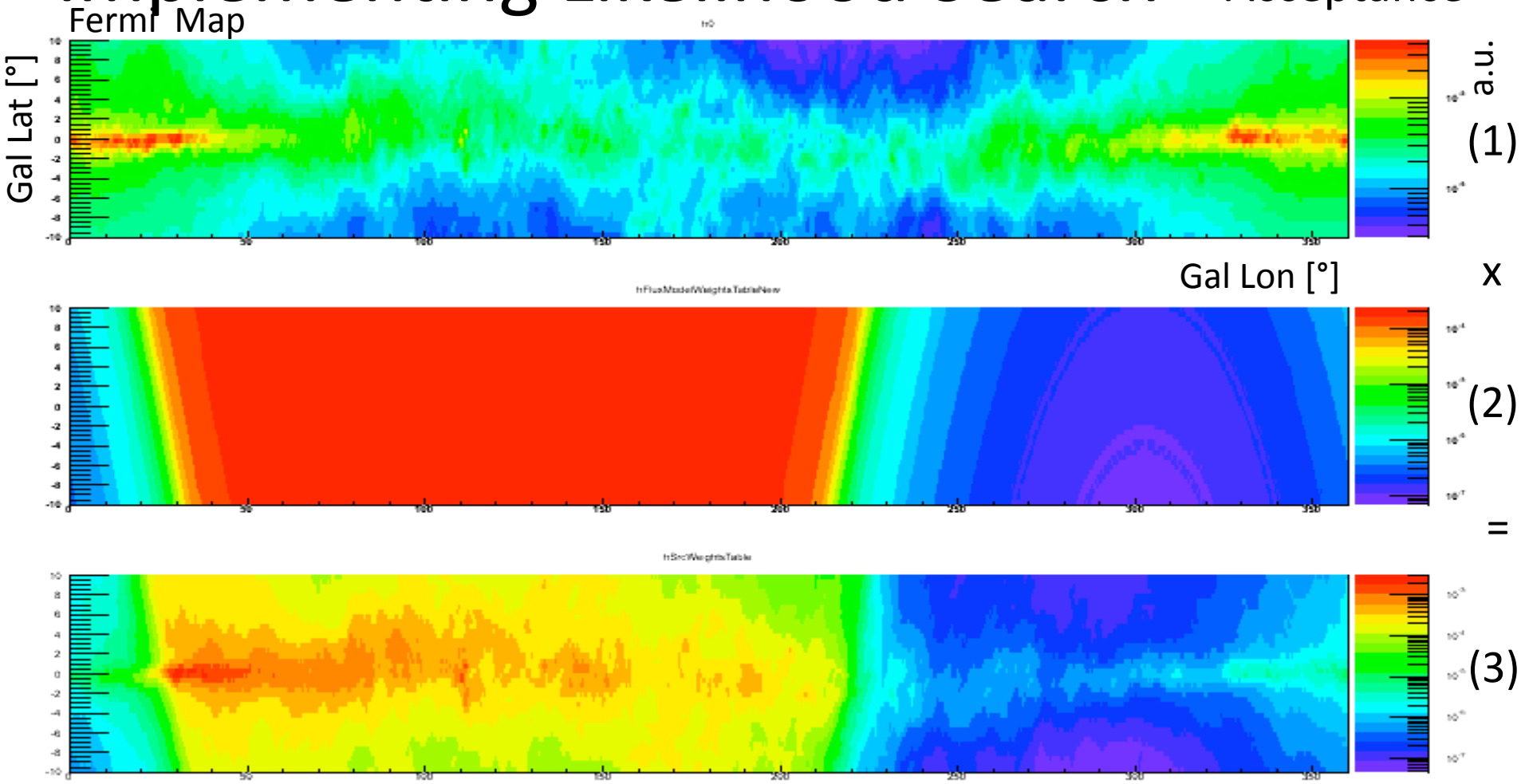
- The Fermi model above is our signal emission hypothesis
- Besides just PSF, we need to account for the detector relative acceptance
  - IceCube mostly sensitive between 33° and 213° galactic longitude

Implementing Likelihood Search - Acceptance



- IceCube's relative detector acceptance to an $E^{-2.7}$ flux of neutrinos, calculated using simulation for 40-strings
  - About 3 orders-of-magnitude between north and south

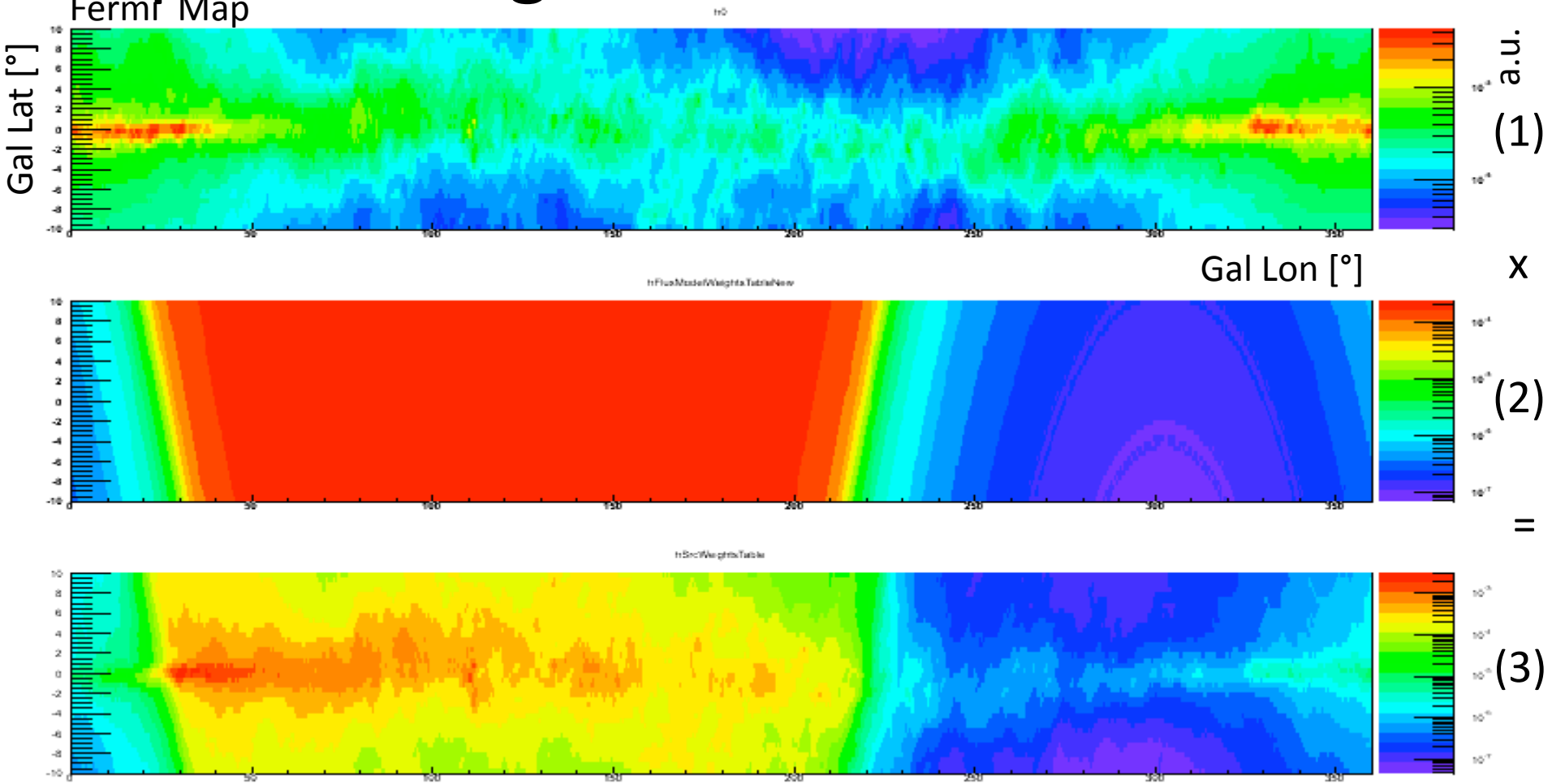
Implementing Likelihood Search - Acceptance



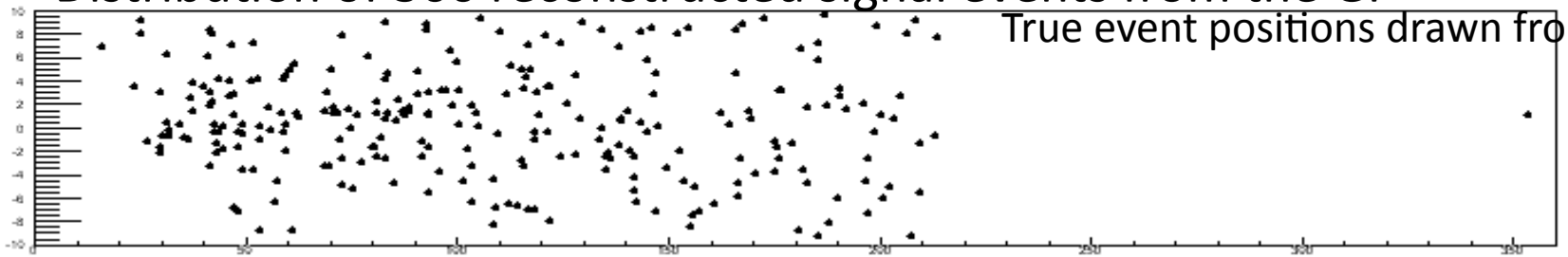
- Multiplying (1) and (2) gives (3), the true signal event distribution, before convolving with PSF

Implementing Likelihood Search - Acceptance

Fermi Map



Distribution of 500 reconstructed signal events from the GP



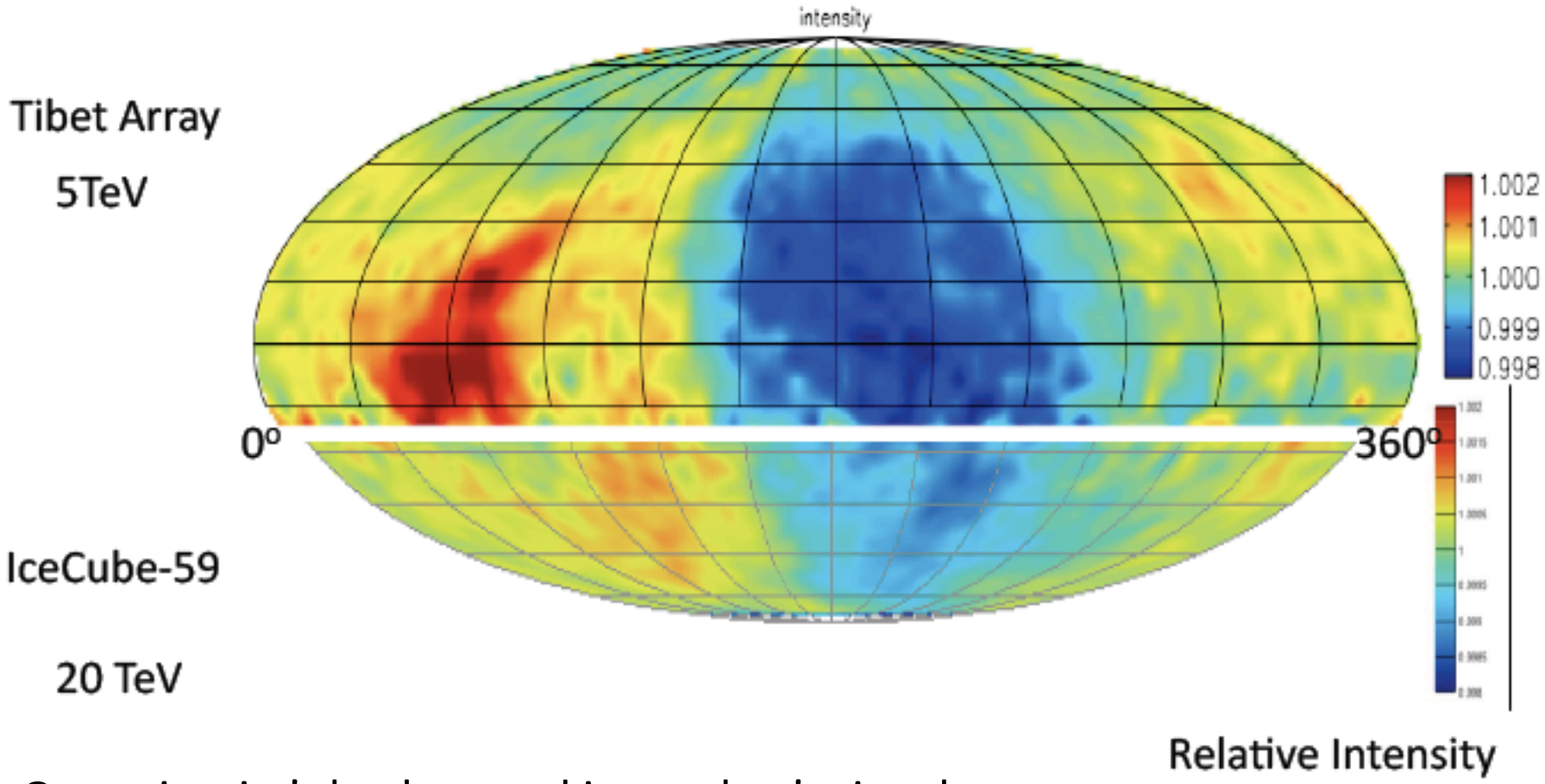
True event positions drawn from (3)

Other Recent IceCube Results

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

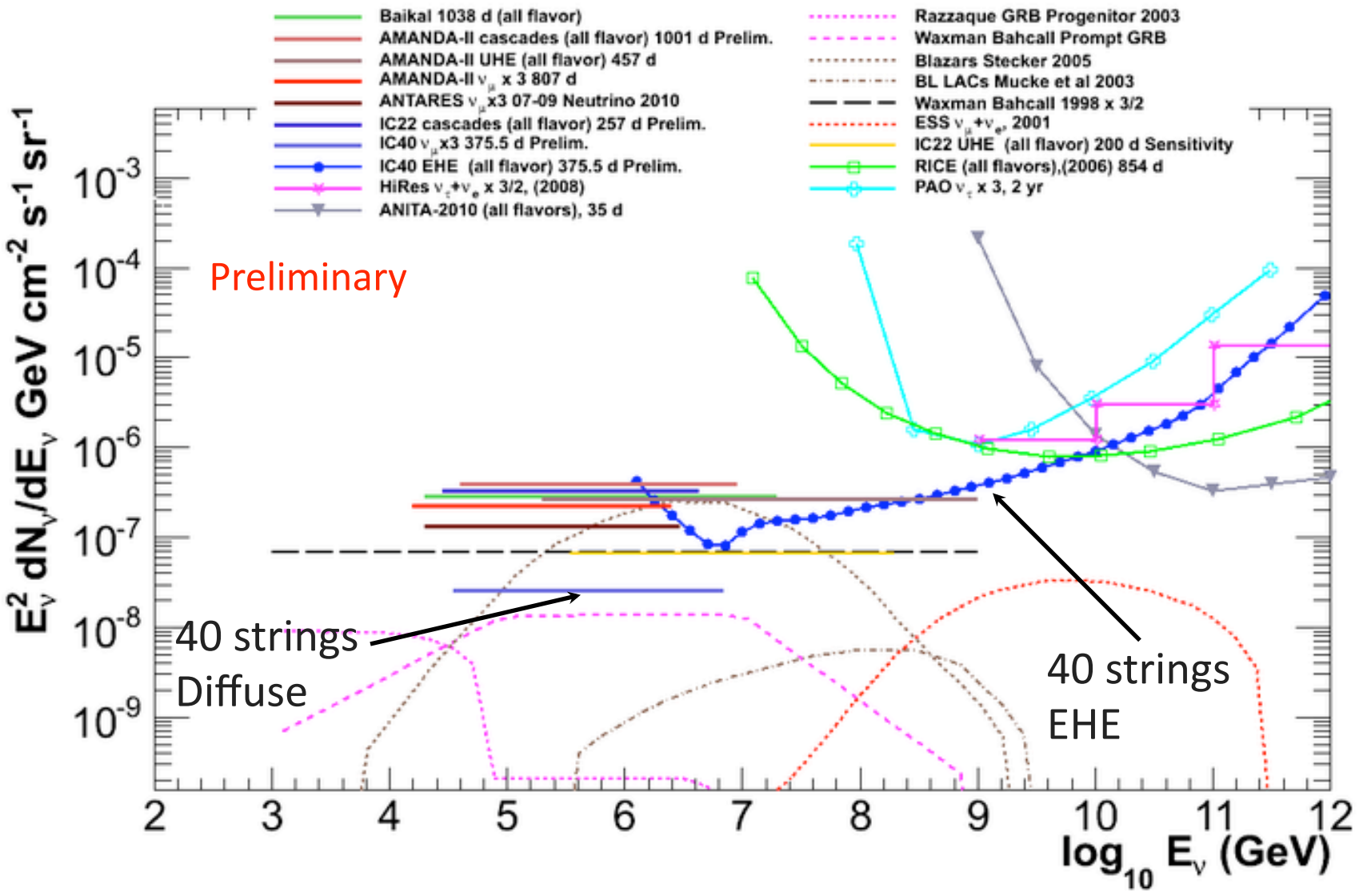
- Cosmic Ray Anisotropy → TeV cosmic rays have anisotropy at 0.2%

Large-scale CR Anisotropy

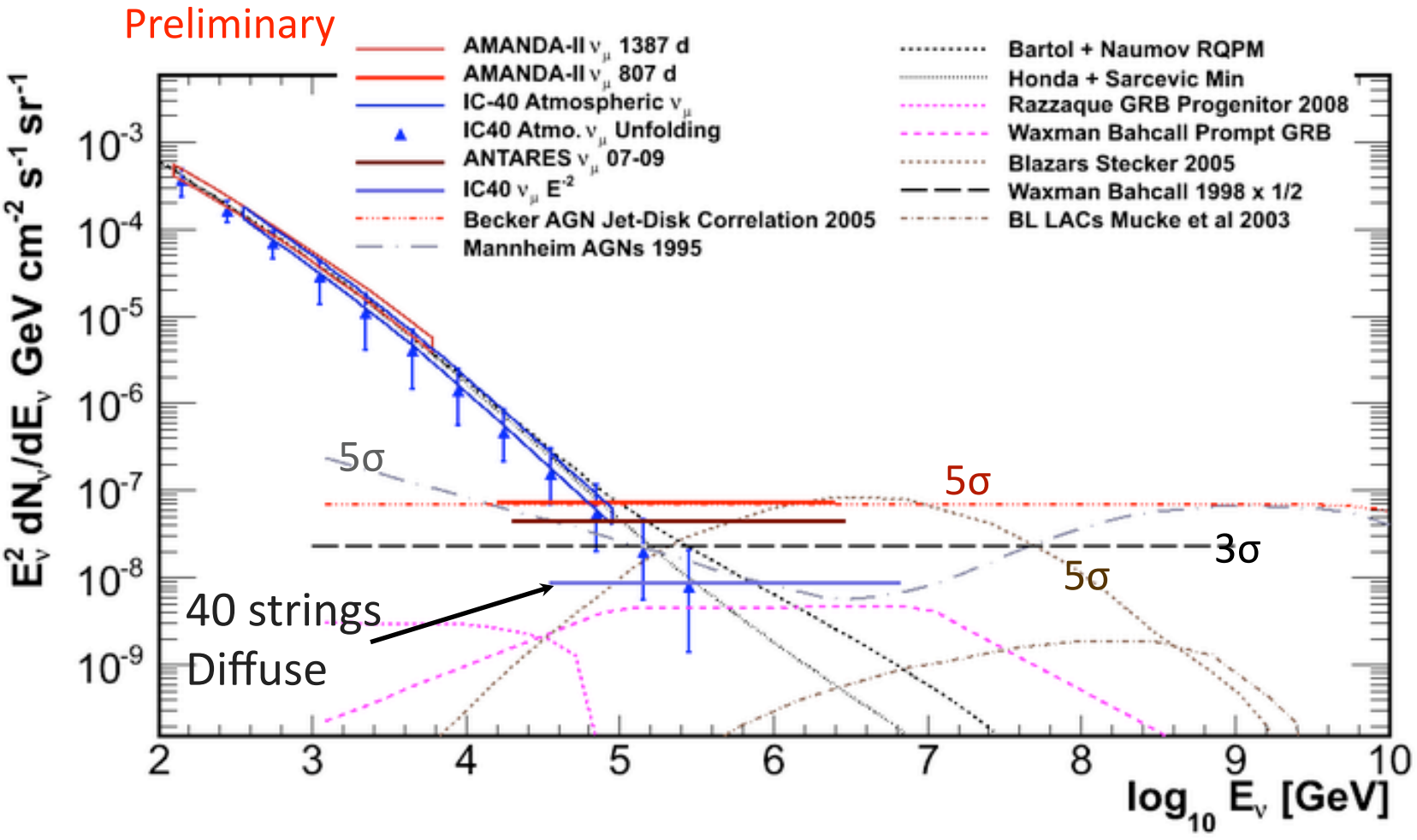


- One scientist's background is another's signal
- In agreement with continuation of anisotropy in the north
- Nearby magnetic fields, CR sources?
- Not consistent with Compton Getting

Diffuse Flux Models and Limits



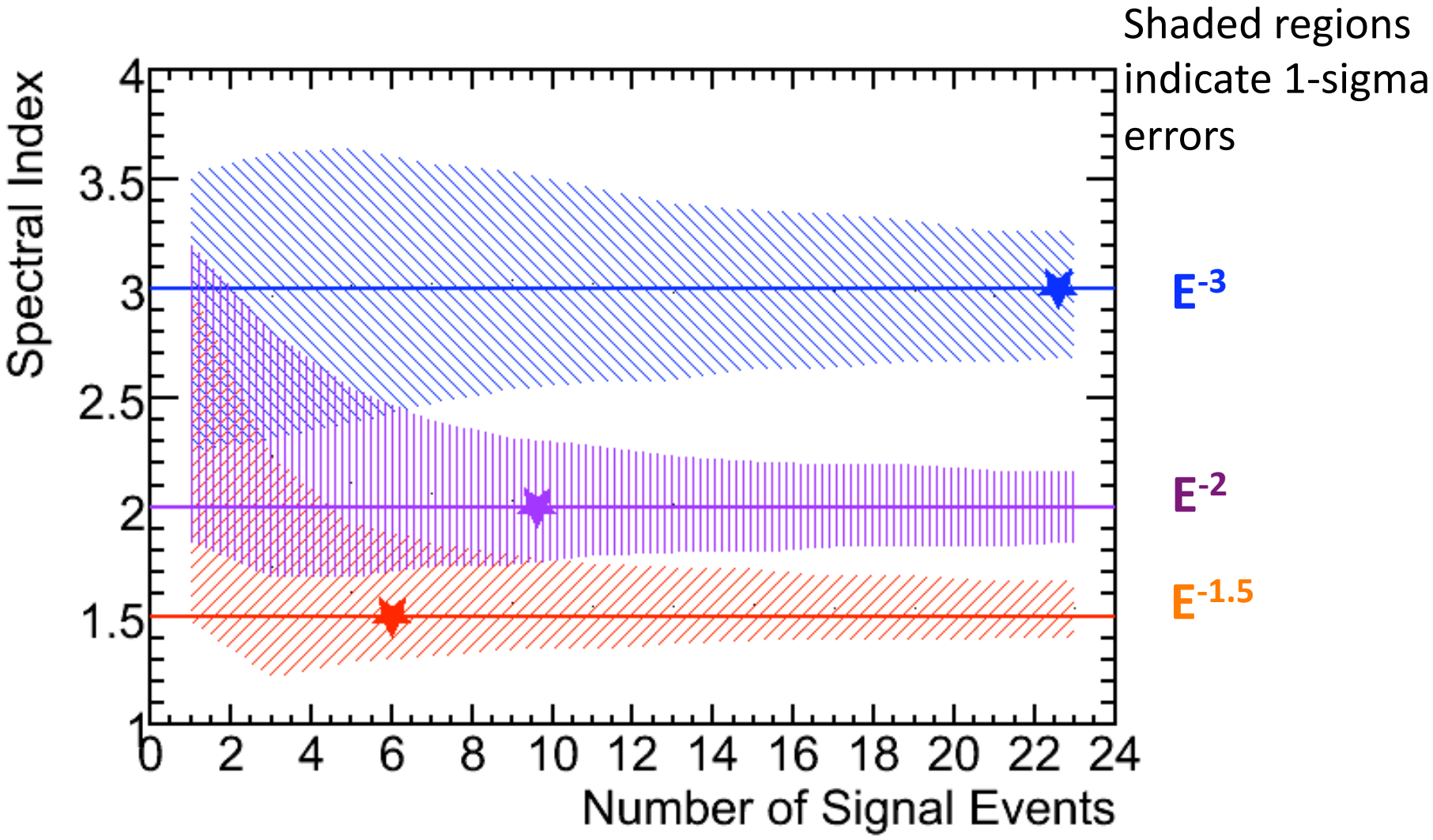
Diffuse Astrophysical Model Tests



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

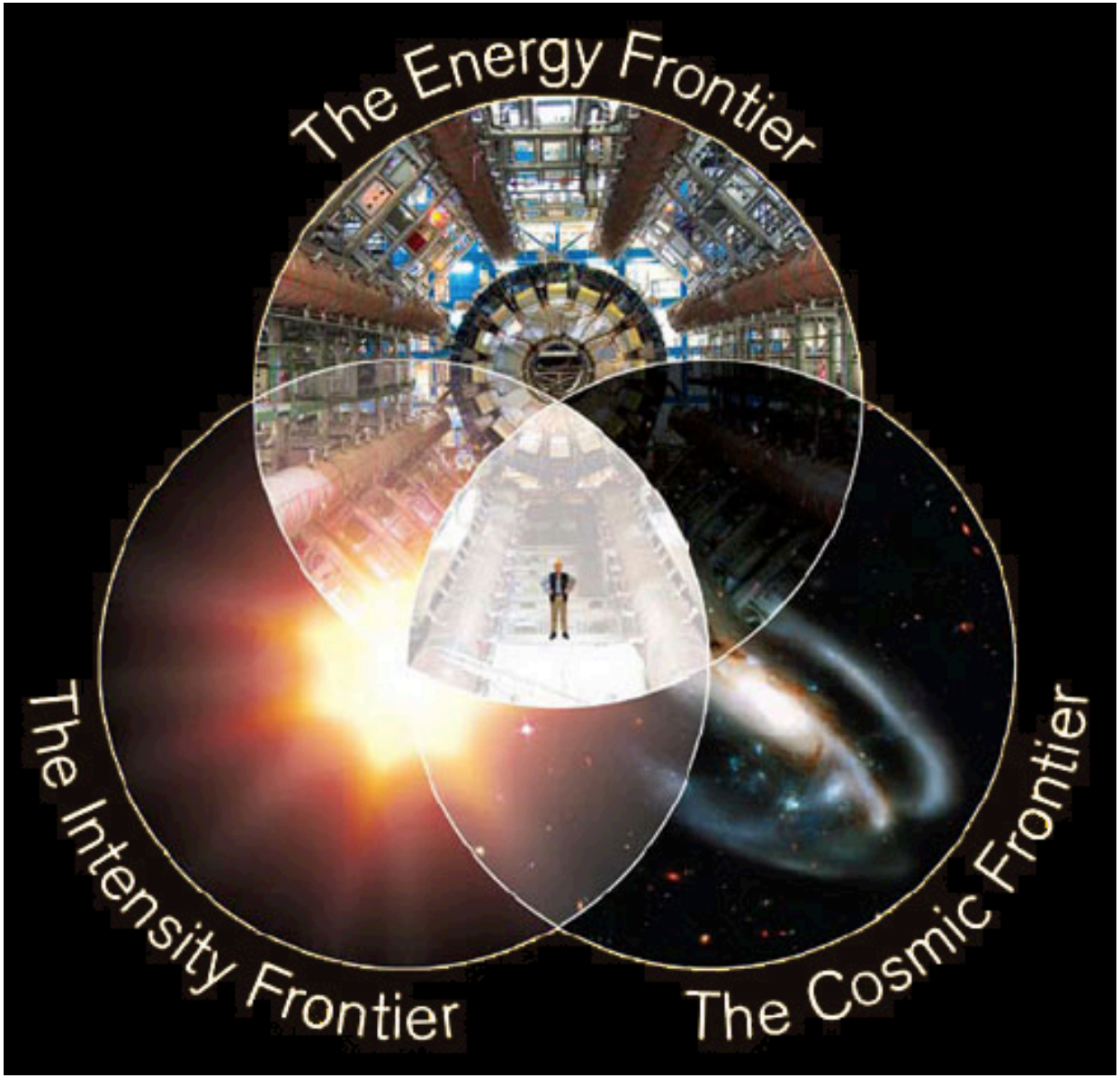
Moral of the story: **expect the unexpected . . .**

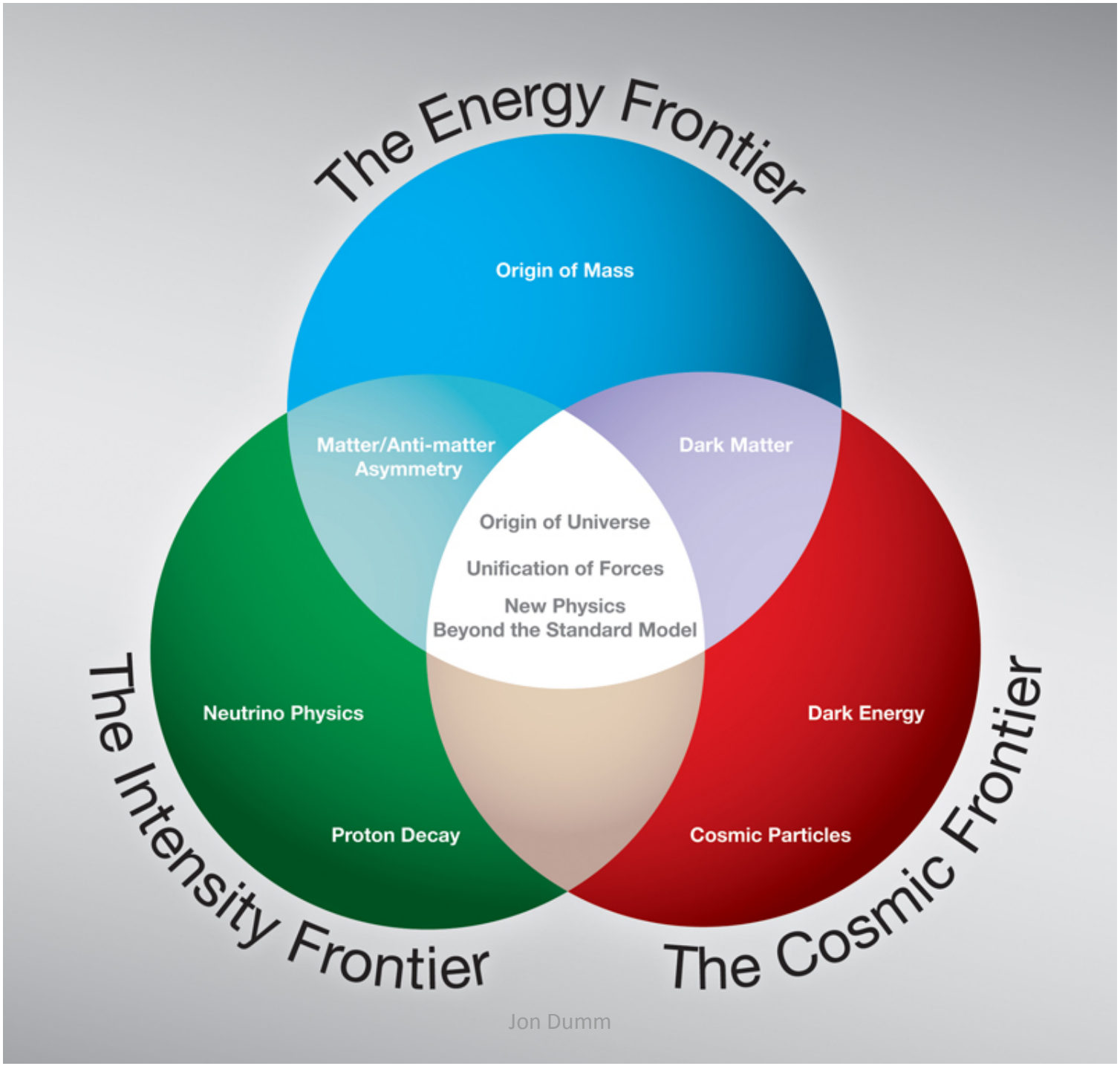
Spectral Reconstruction



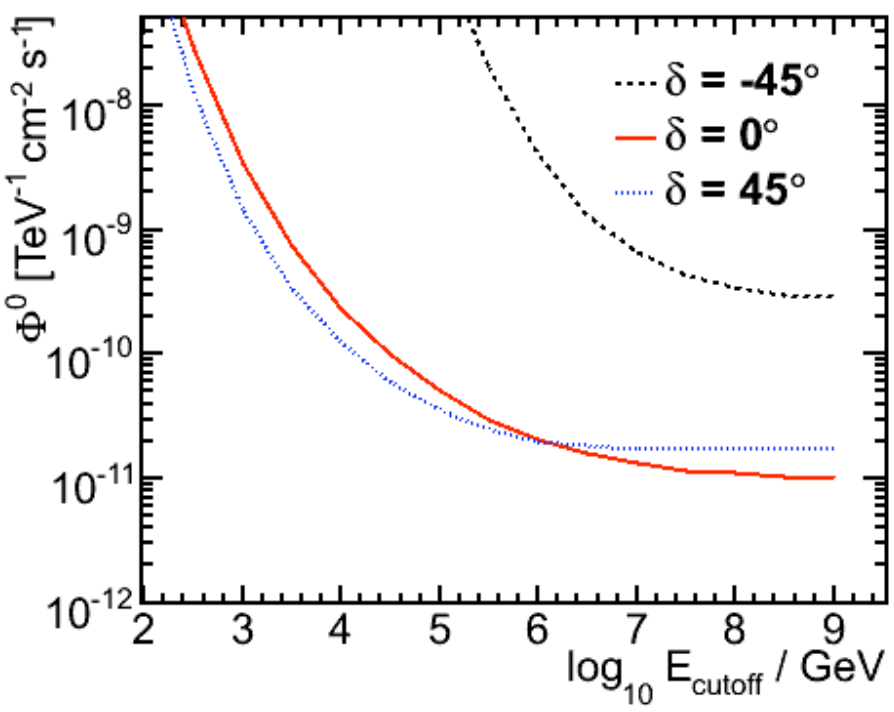
Spectral resolution is about 0.3 when enough events are present for a discovery (stars)

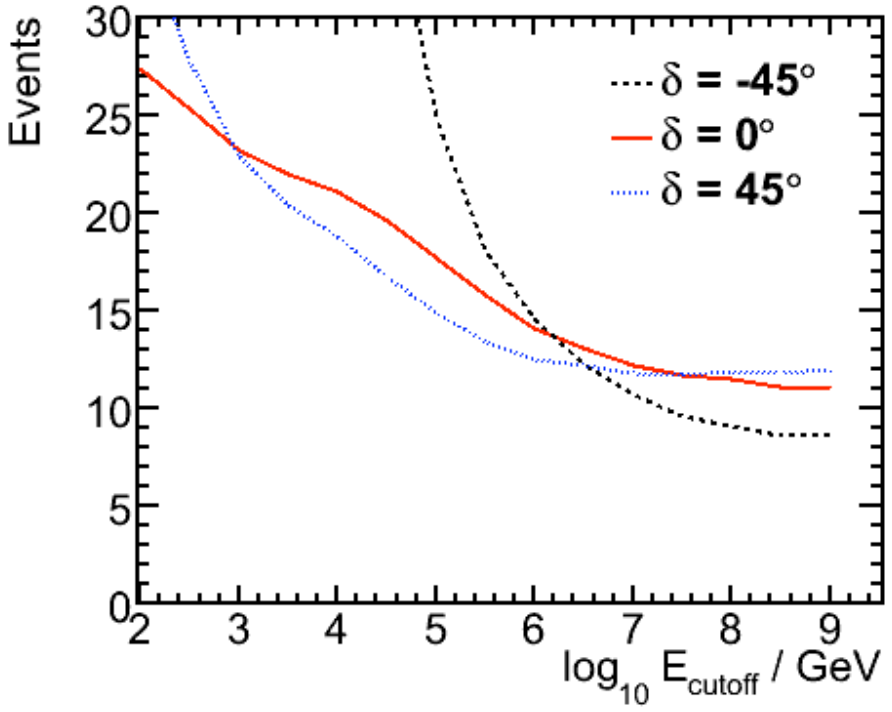
Particle Physics Today:
Three Frontiers of Science




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

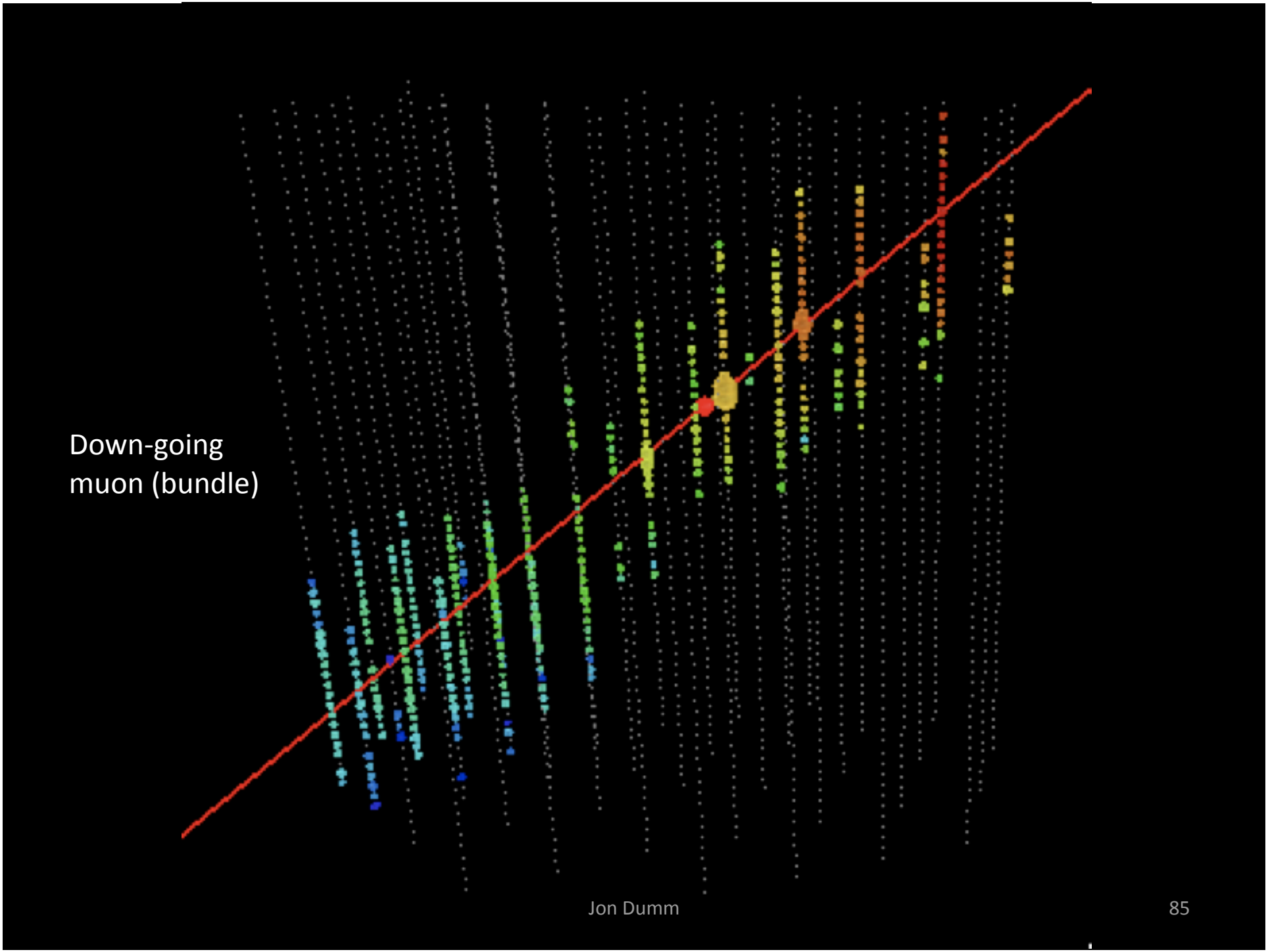
Discovery Potential for Cutoff Spectra

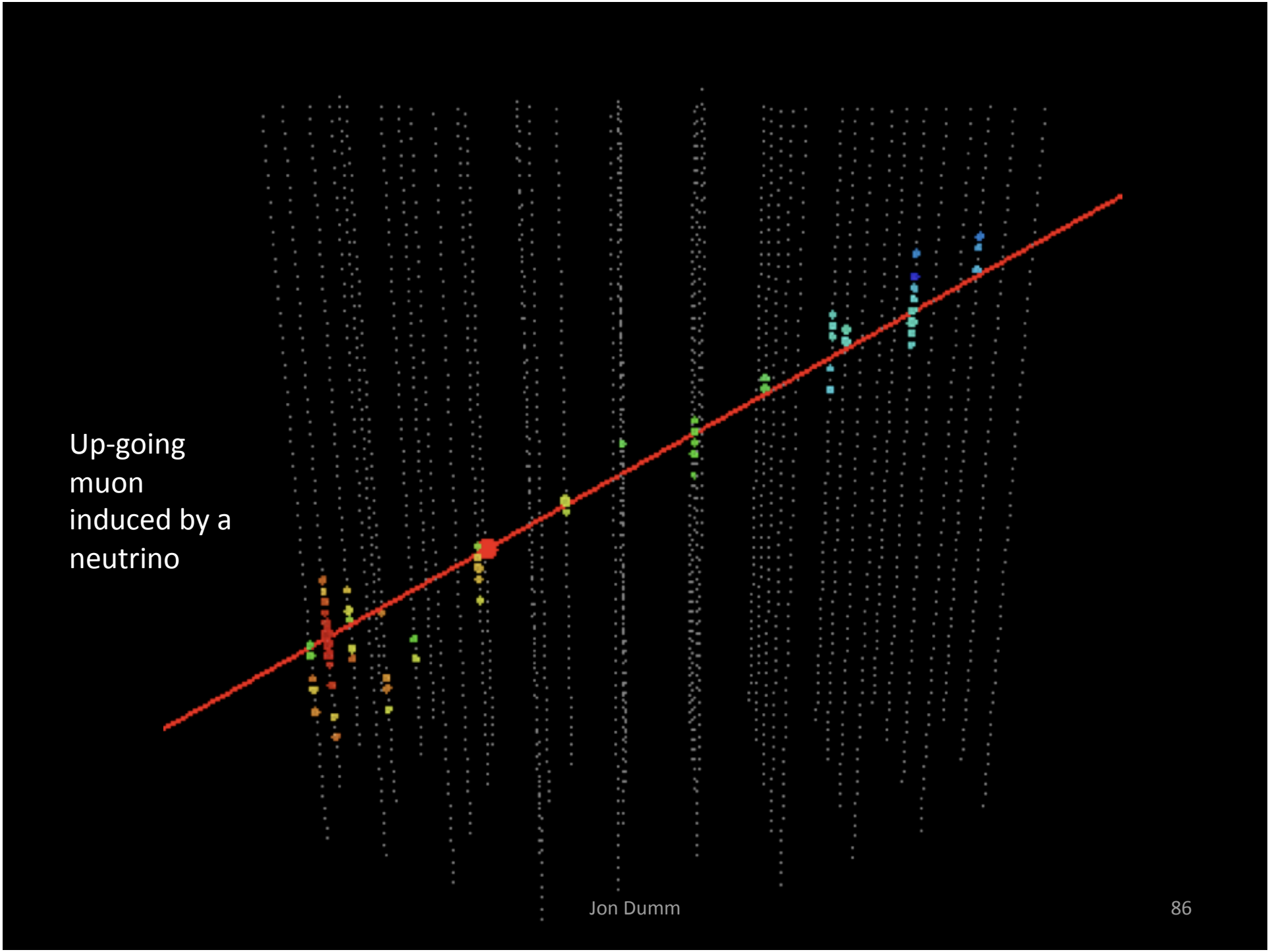




Cutoff spectra parameterized as:

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


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 $e^- + e^+ \rightarrow \bar{\nu} + \nu$

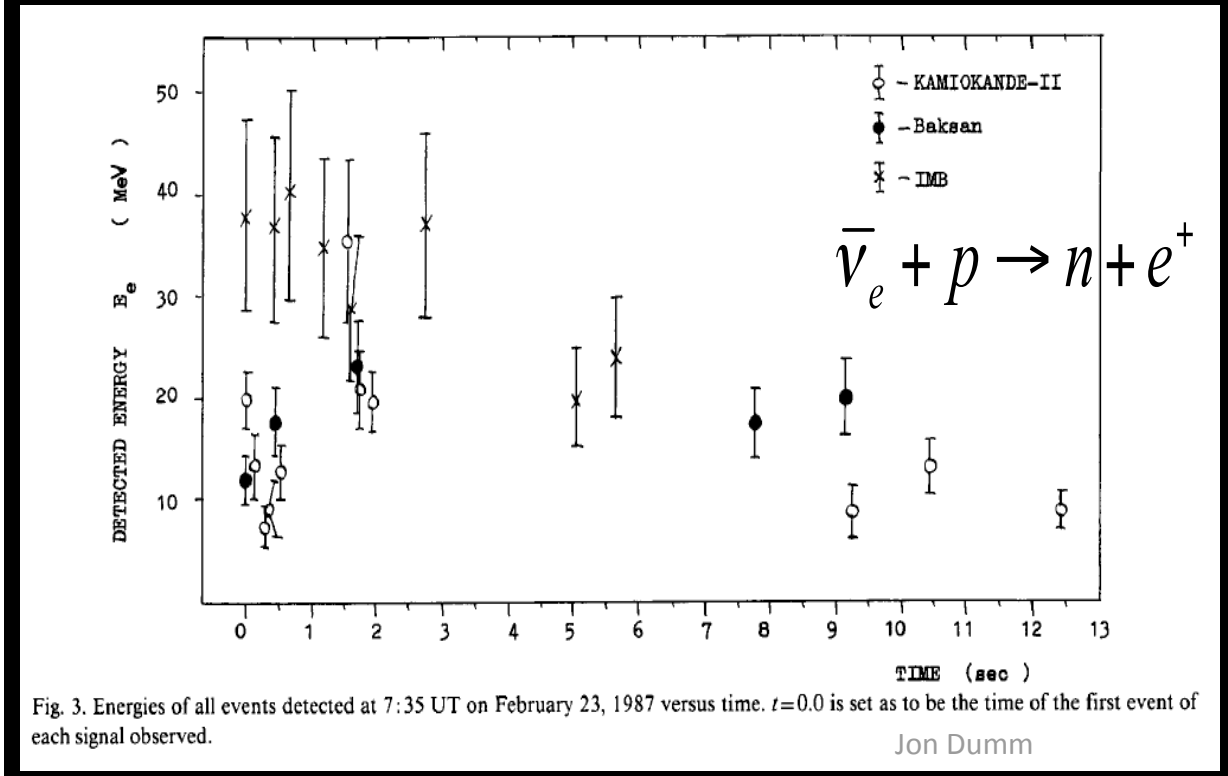
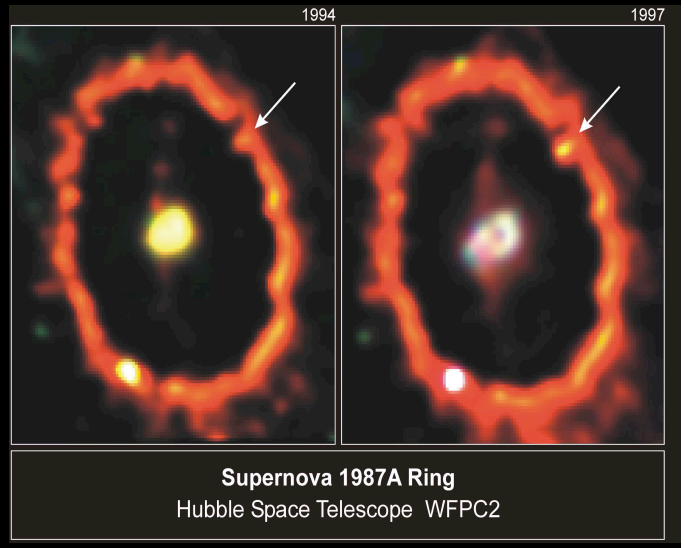
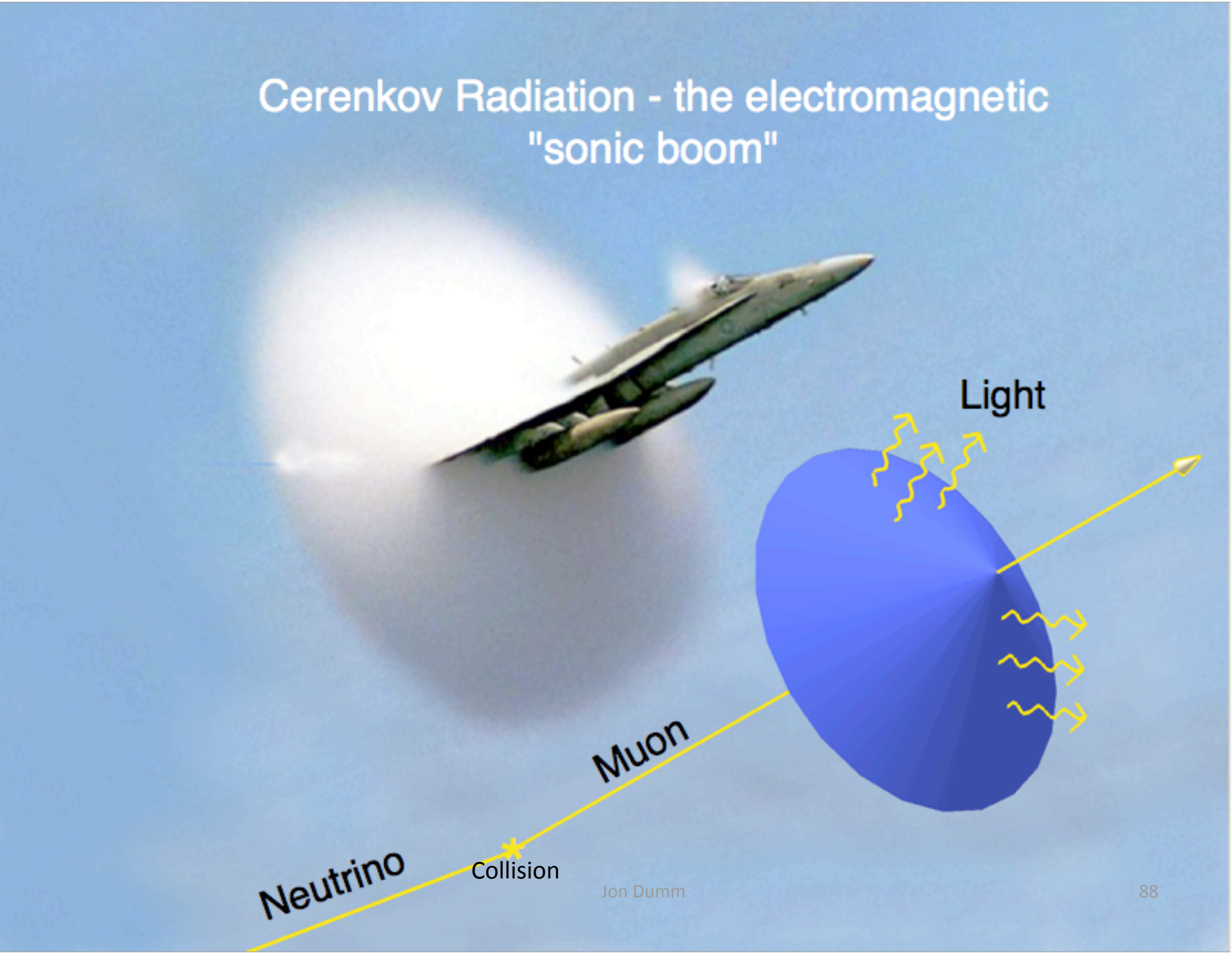
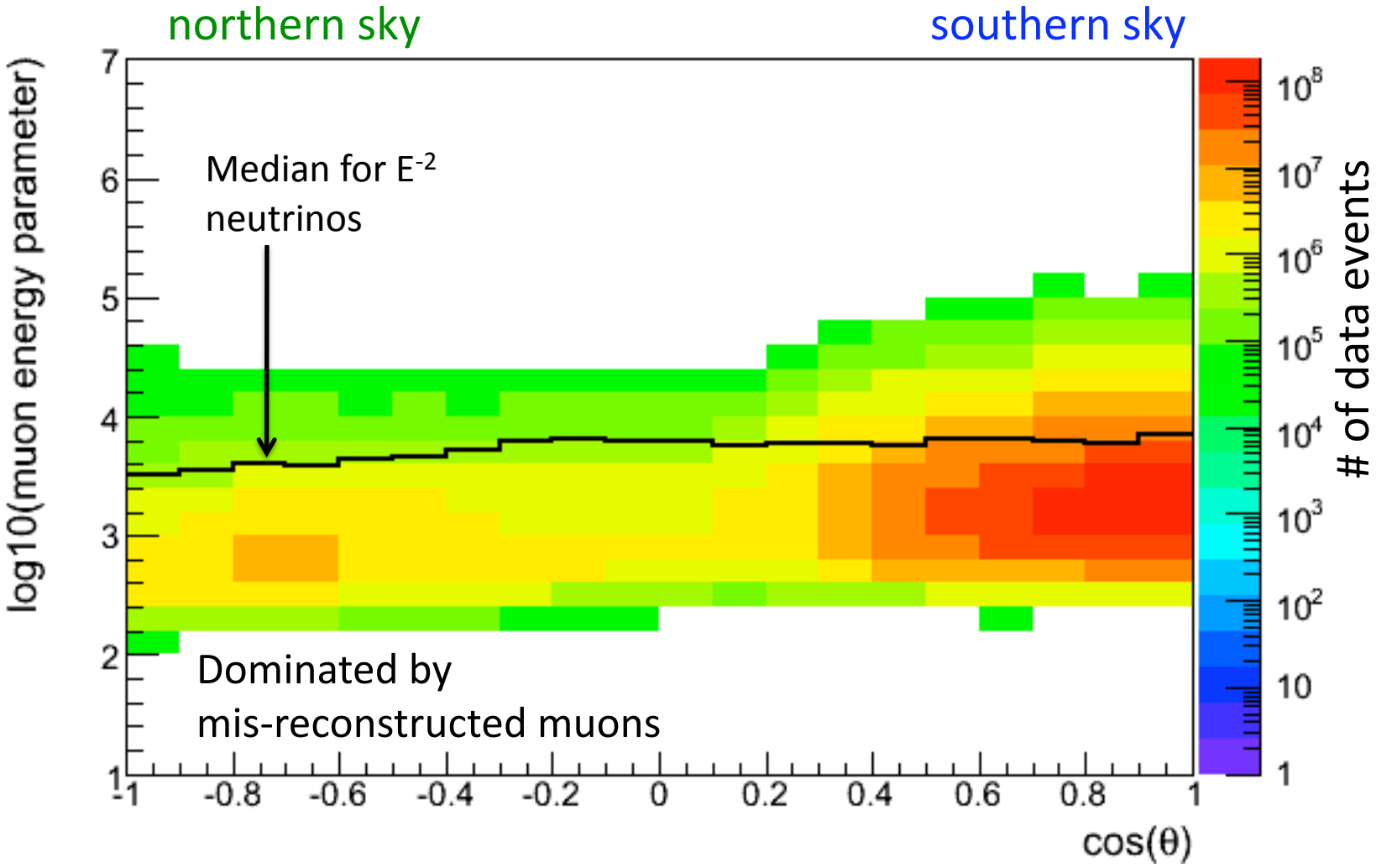


Fig. 3. Energies of all events detected at 7:35 UT on February 23, 1987 versus time. $t=0.0$ is set as to be the time of the first event of each signal observed.

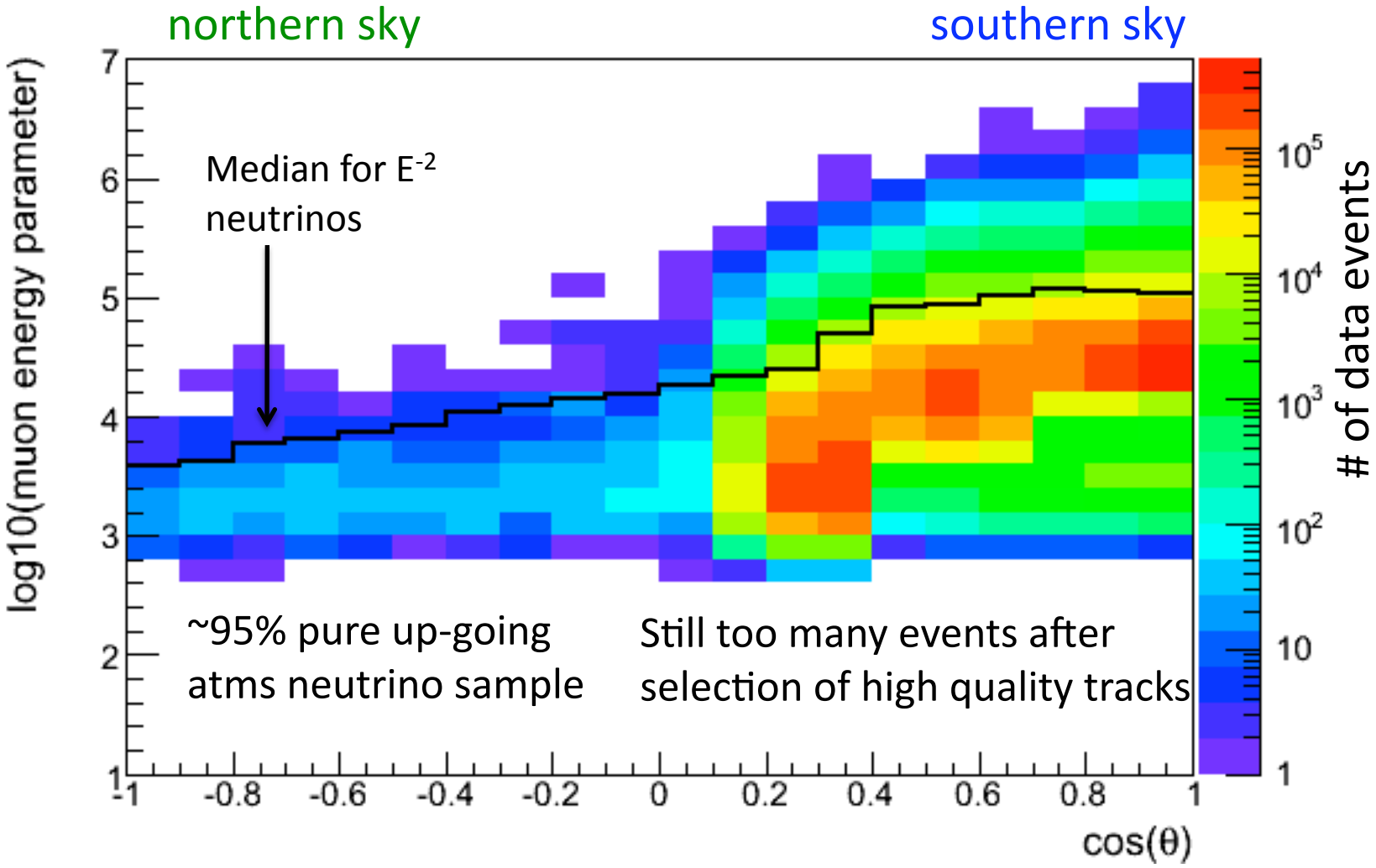



Cerenkov Radiation - the electromagnetic "sonic boom"
Light
Muon
Neutrino
Collision

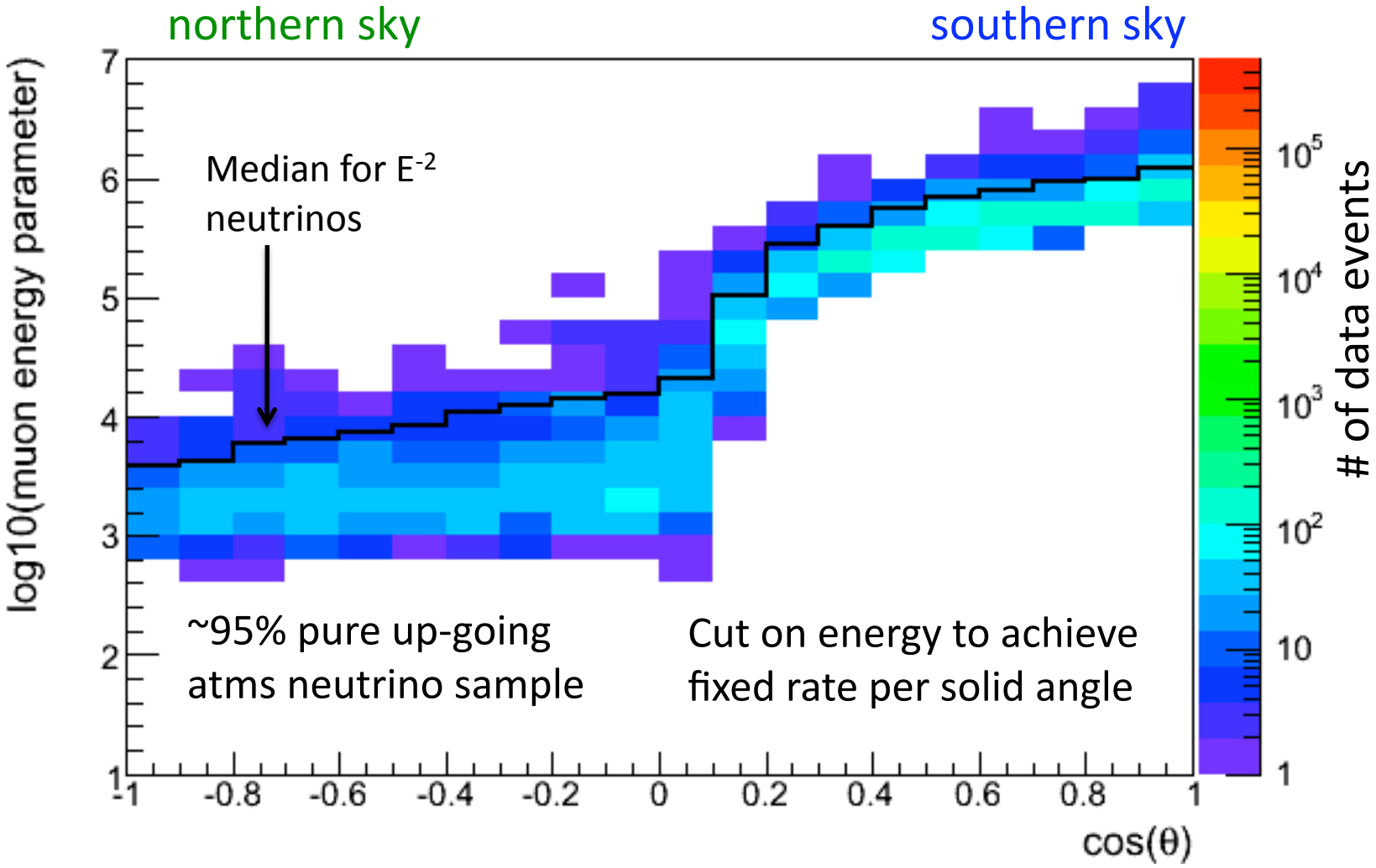
Energy vs Zenith – Trigger Level



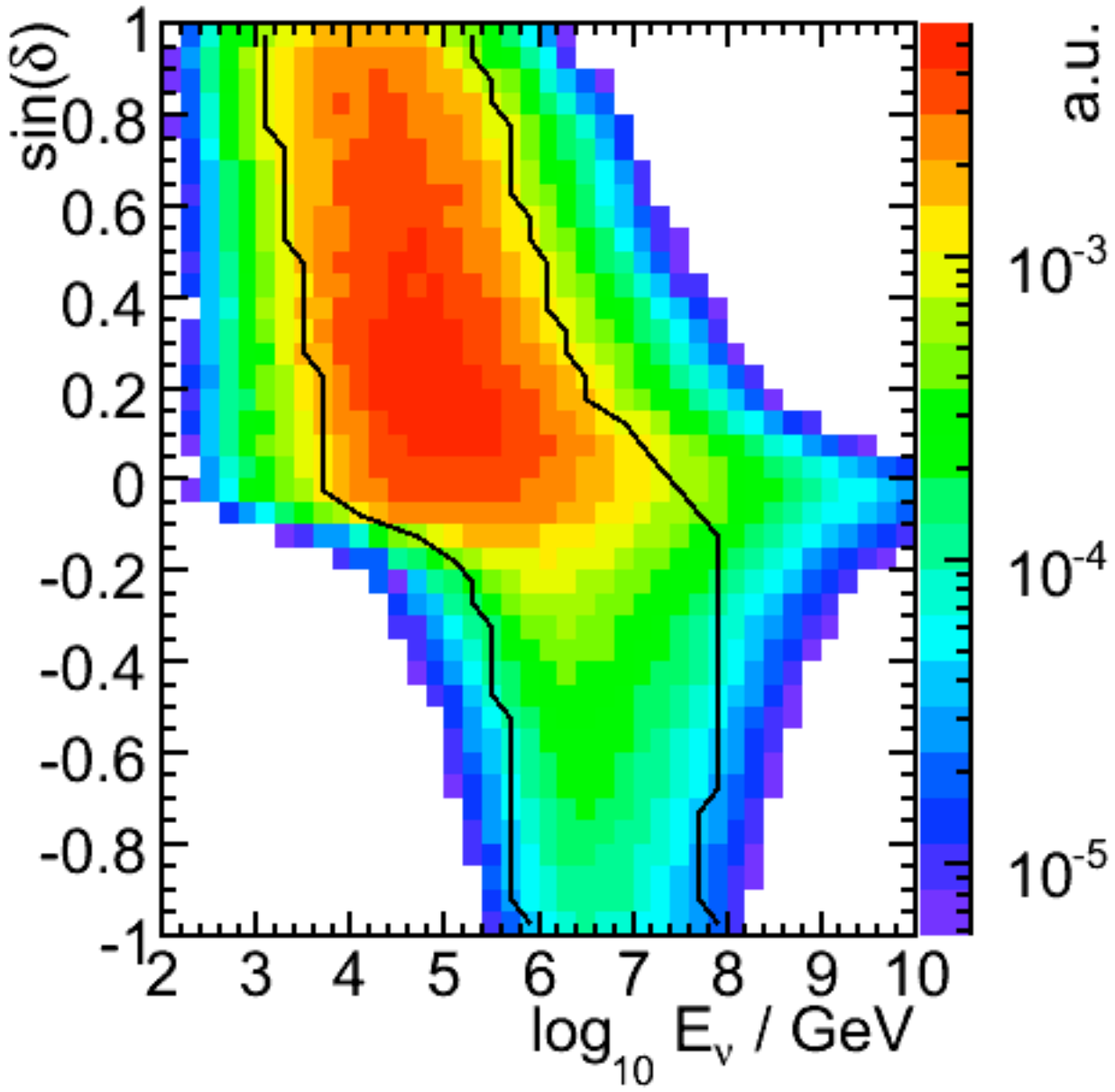
Energy vs Zenith – Quality Cuts



Energy vs Zenith – Quality + Energy Cuts

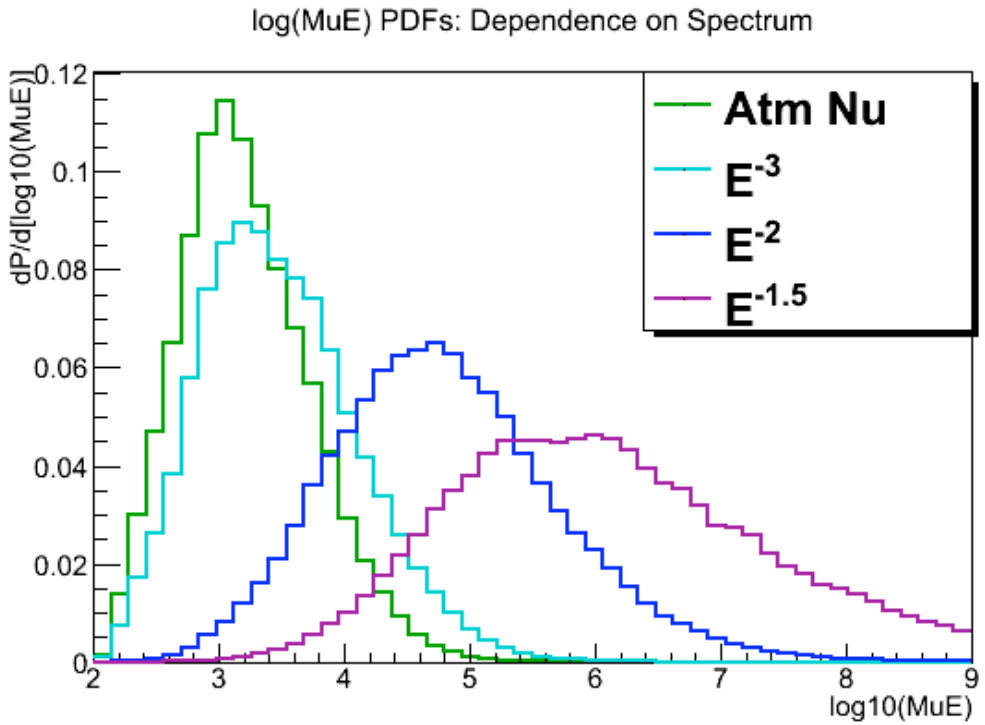


Energy of E^{-2} Signal



Search Method

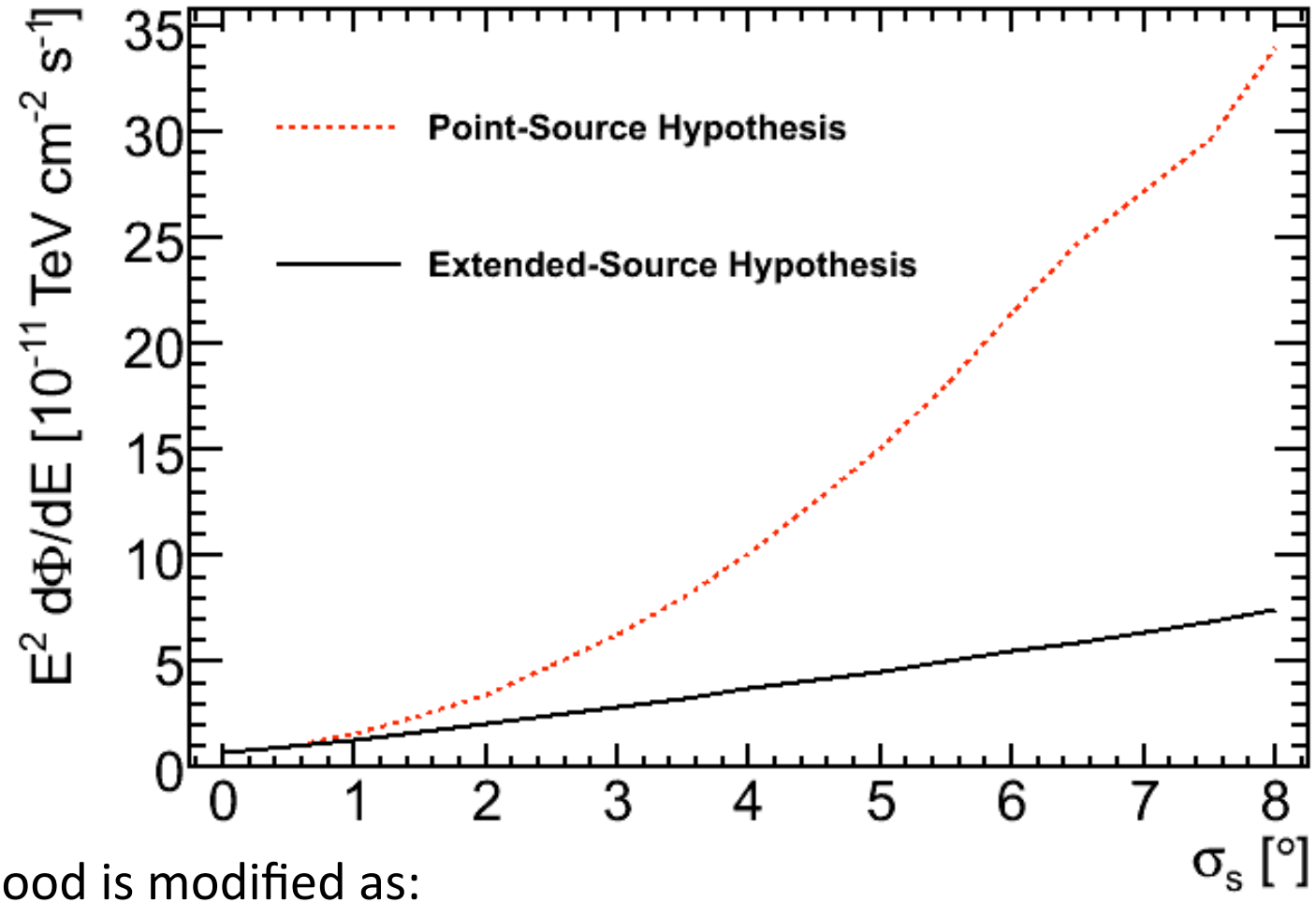
- Unbinned maximum likelihood search
  - Directional clustering → Median PSF for E^{-2} neutrino spectrum:
    0.7° in northern sky
    0.5° in southern sky
  - Energy



Robust results:

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

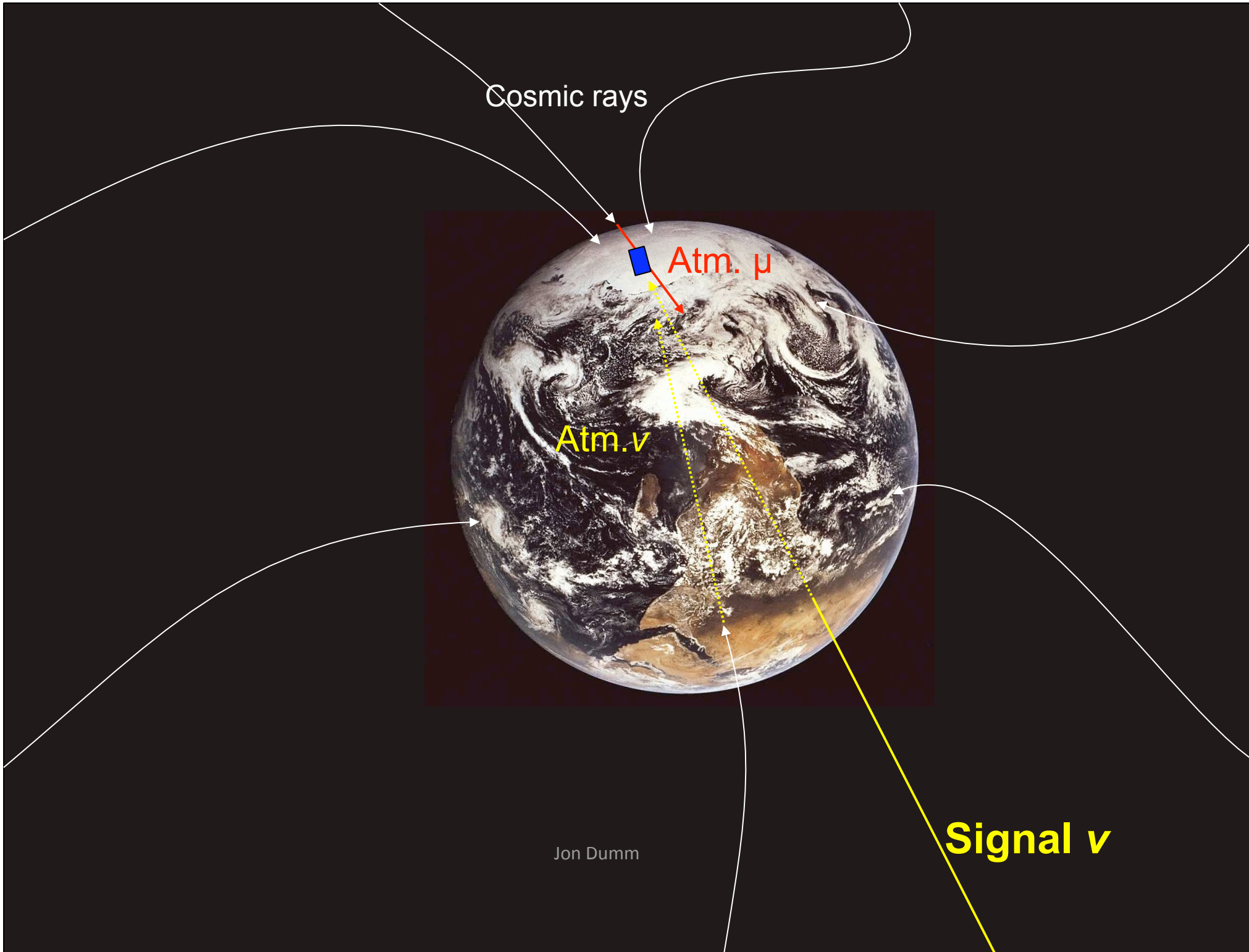
Extended Search Performance - 2D Gaussian Source PDF



Likelihood is modified as:

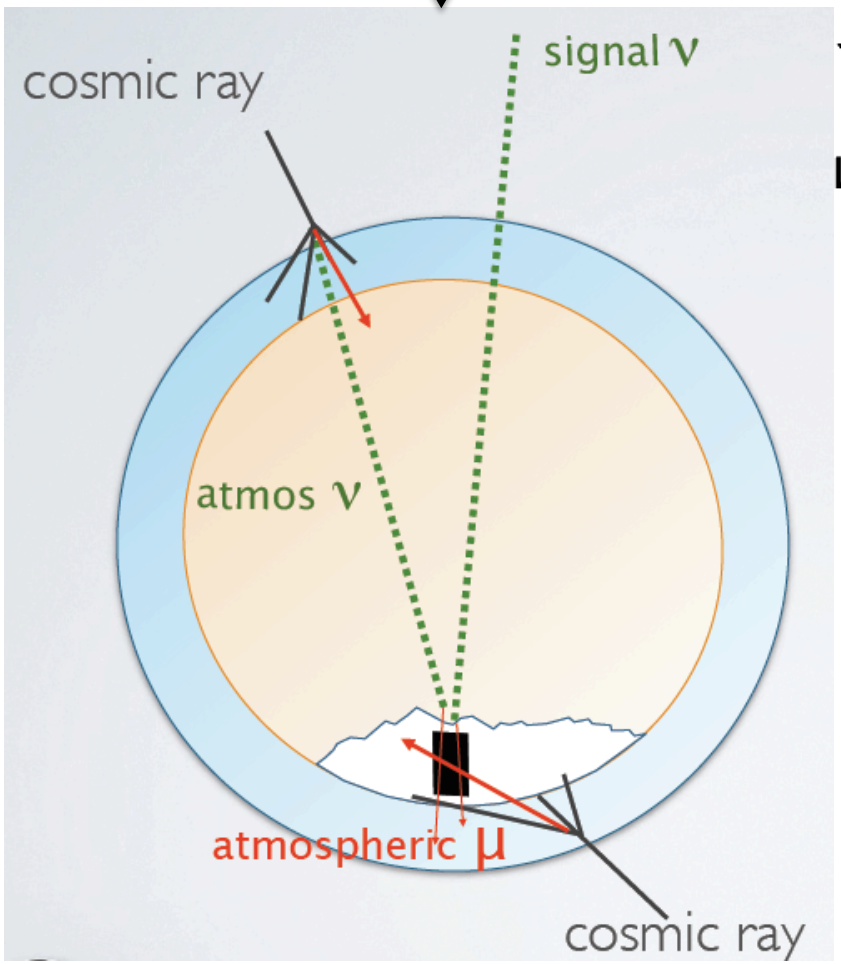
$\sigma_{PSF} \rightarrow \sigma_{conv} = \sqrt{(\sigma_{PSF}^2 + \sigma_s^2)}$

Source Extension


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

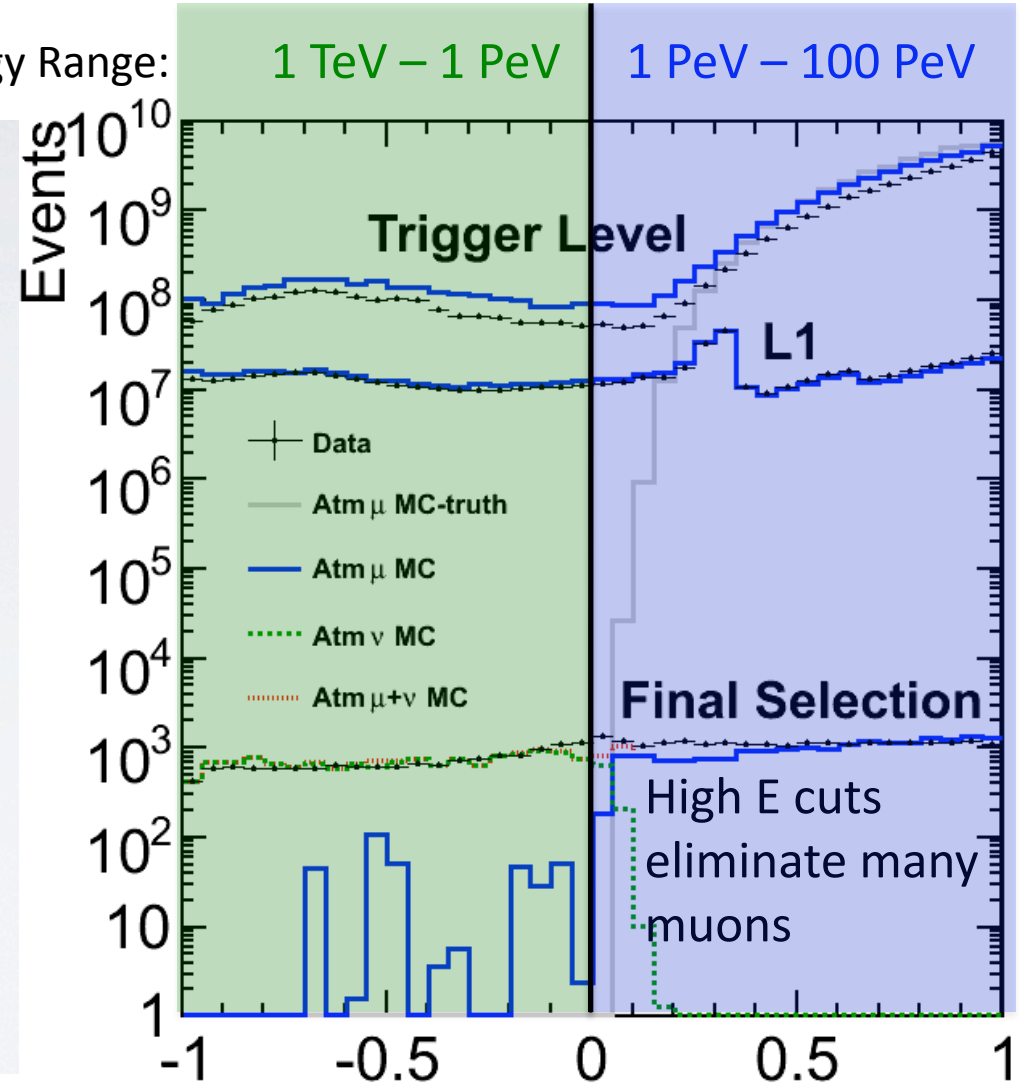
Backgrounds

cos(θ) = -1



cos(θ) = +1

Sensitivity Energy Range:



~95% pure up-going atms neutrino sample