The Search for Neutrinos with the IceCube Neutrino Observatory



Jon Dumm, UMN

Cosmology Lunch Seminar

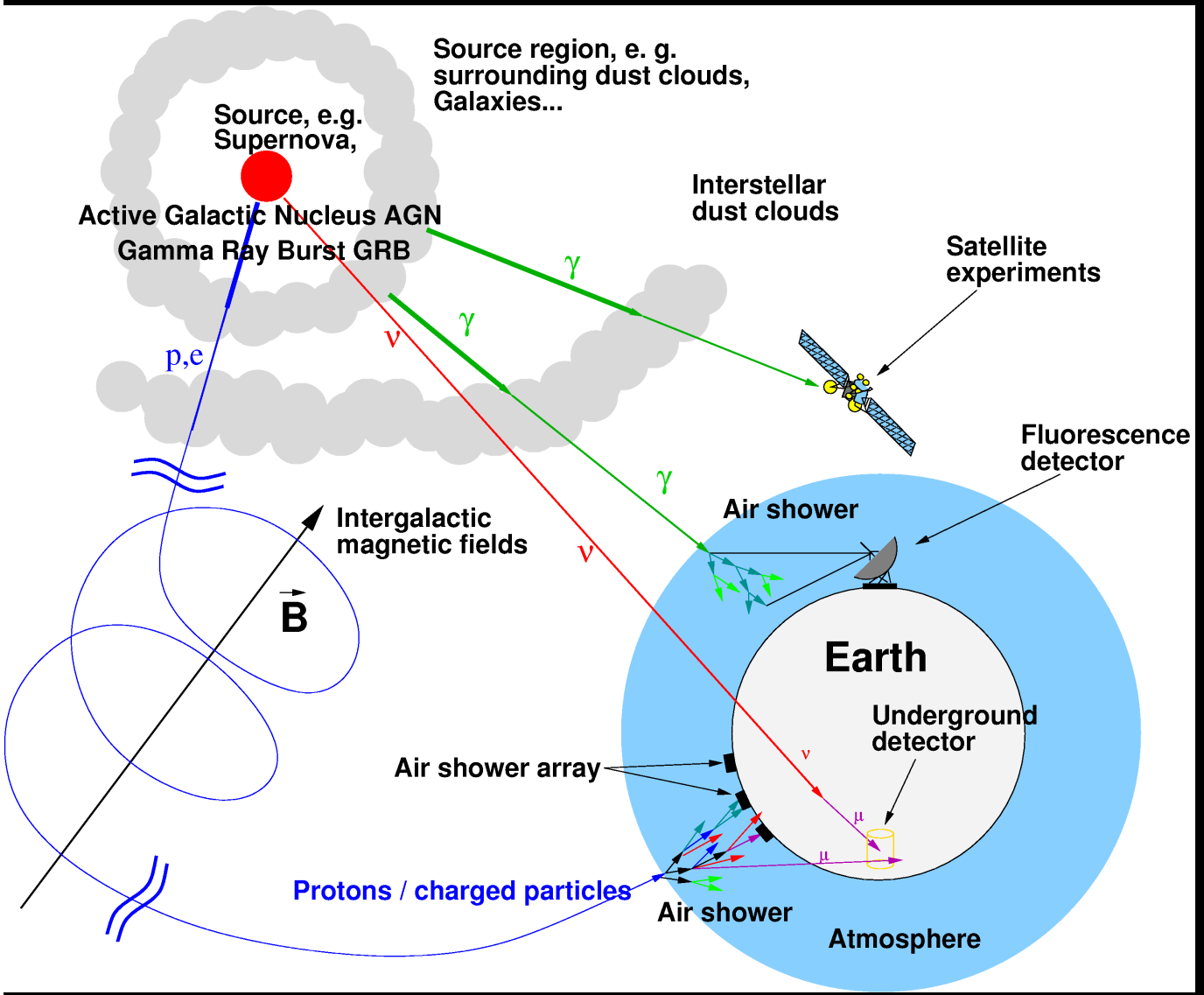
Oct 24, 2011


TOSTRH
ICECUBE

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



Neutrinos as Cosmic Messengers

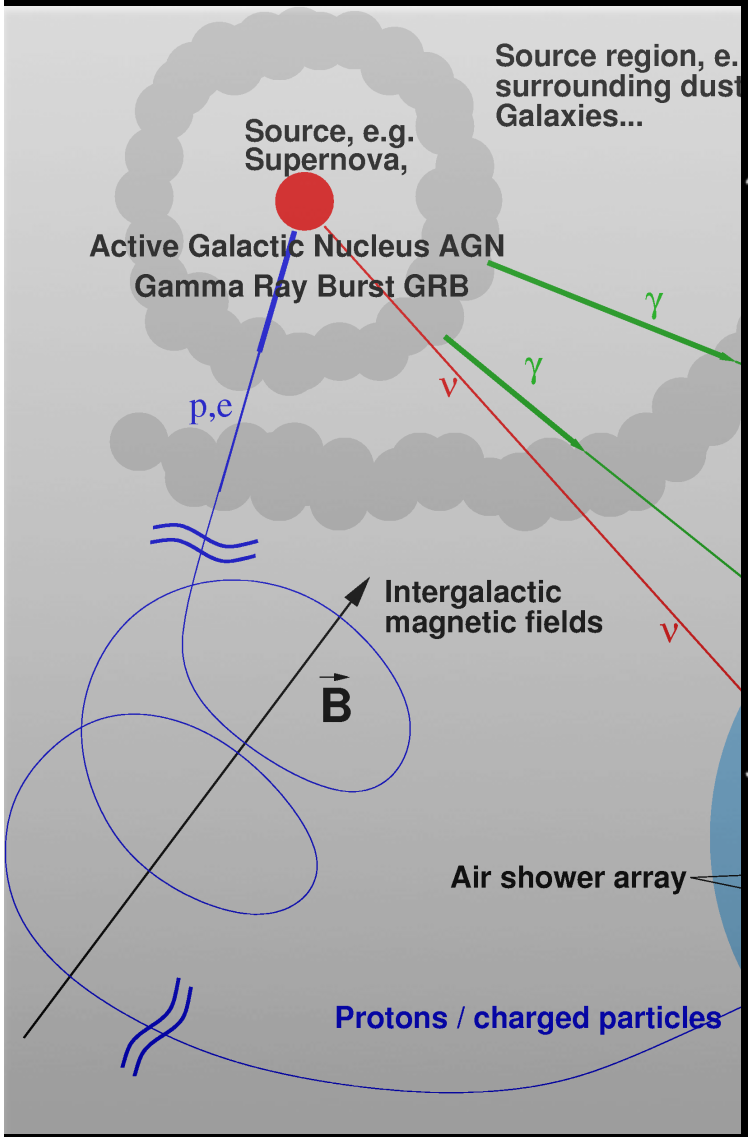


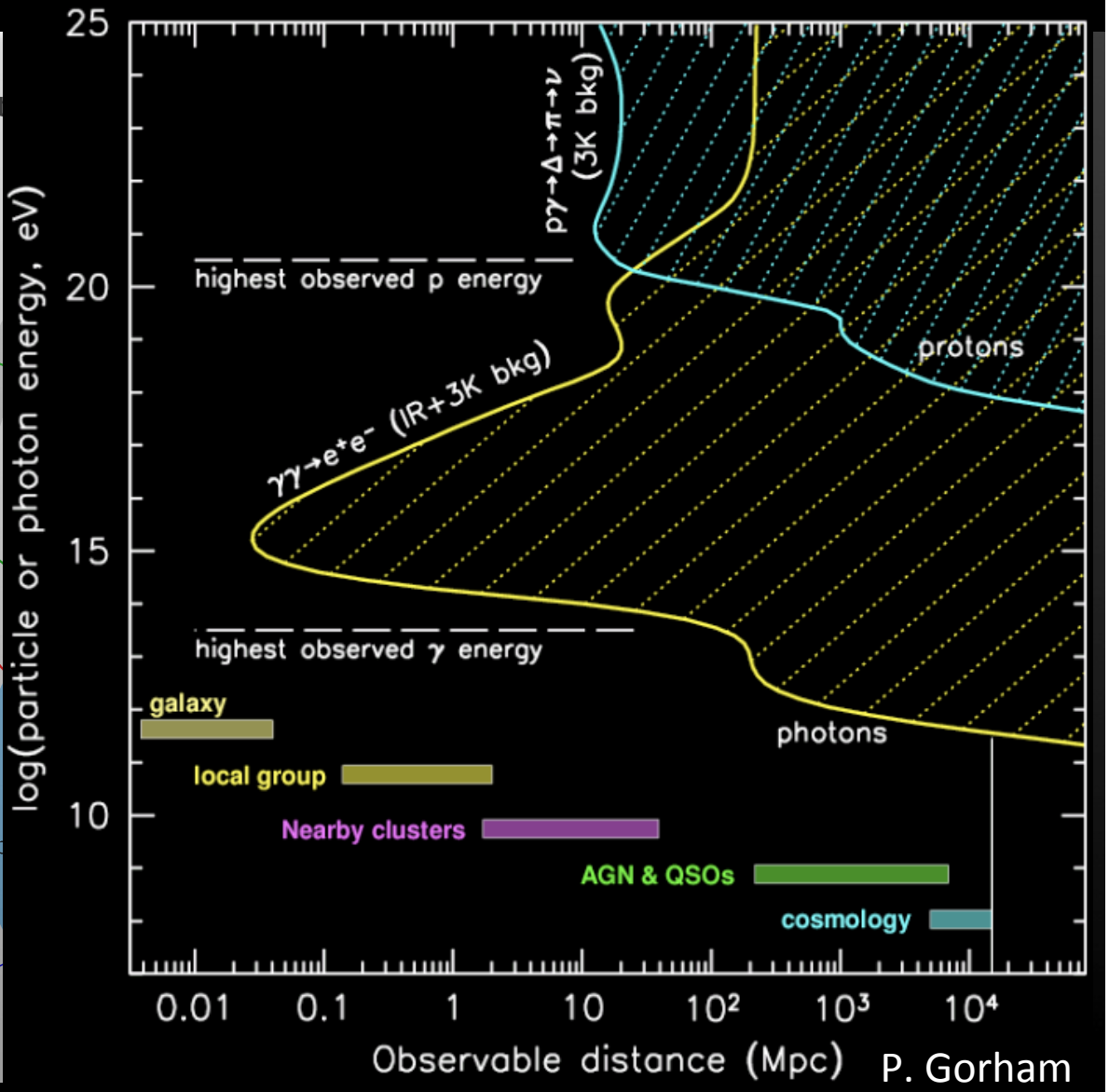
γ *Photons:* easily absorbed by CMB and IR backgrounds.

p *Protons:* deflected by magnetic fields.

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

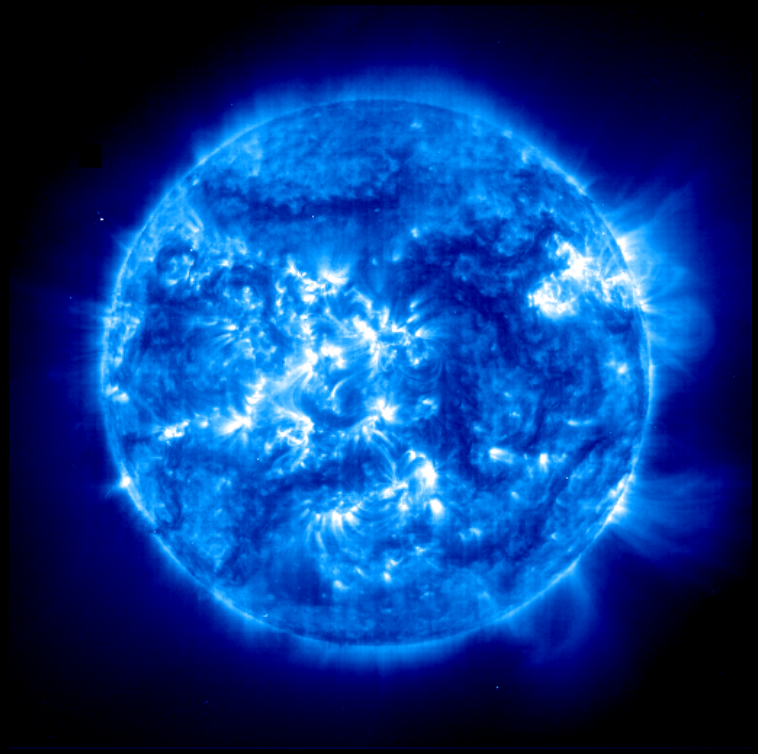
Neutrinos as Cosmic Messengers

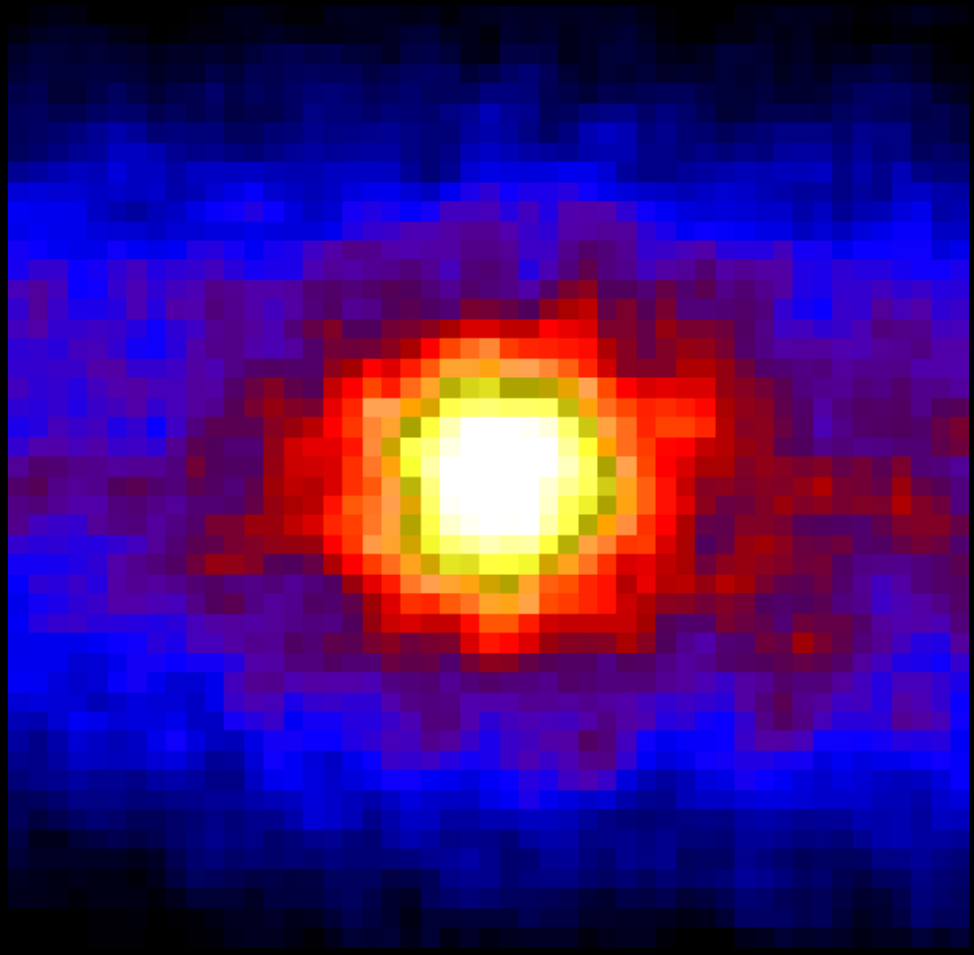




P. Gorham

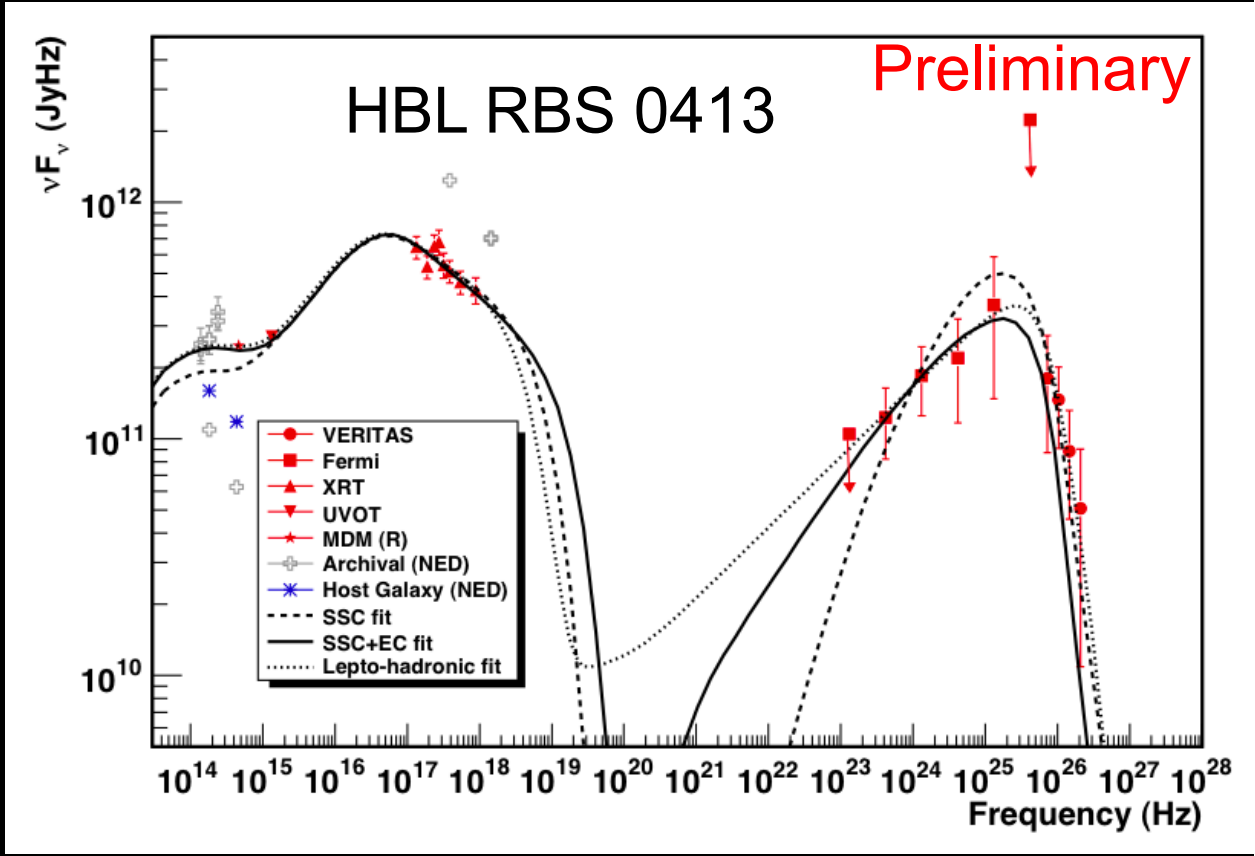
Multi-messenger Astronomy Is a Reality





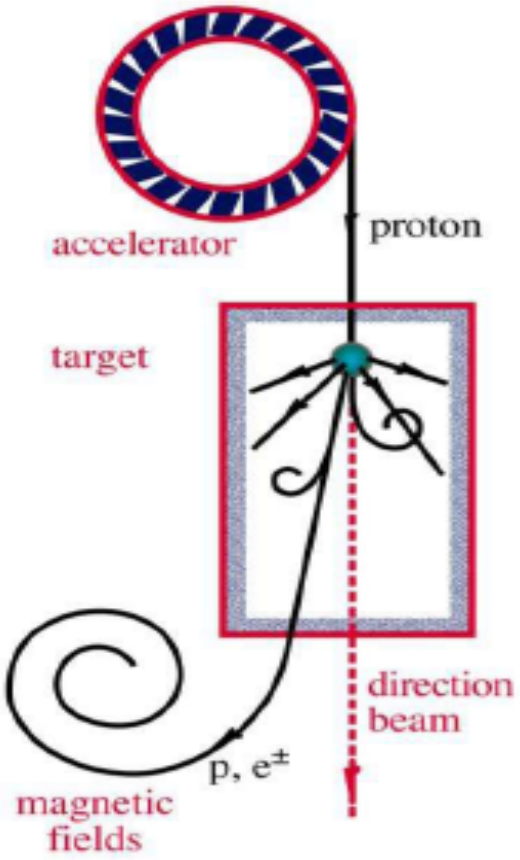
Blazar Spectral Energy Distribution

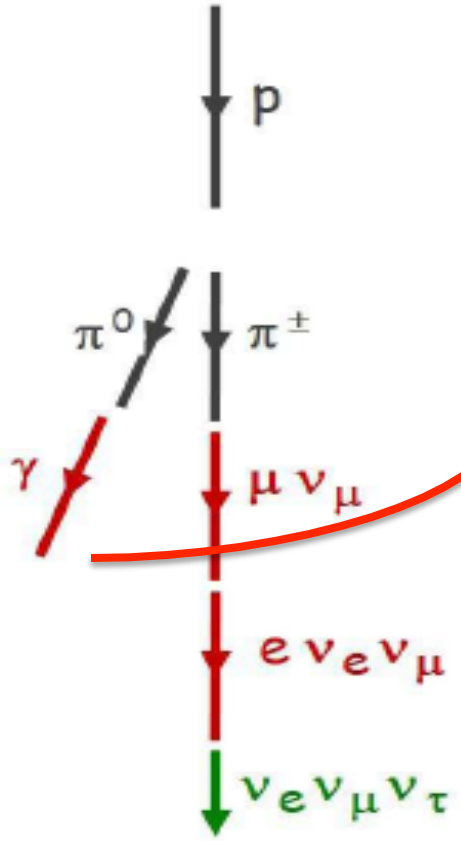
- Typical double-humped SED
- Low frequency emission from e^+,e^- synchrotron
- High frequency?
  - Self-Compton
  - External-Compton
  - Hadronic



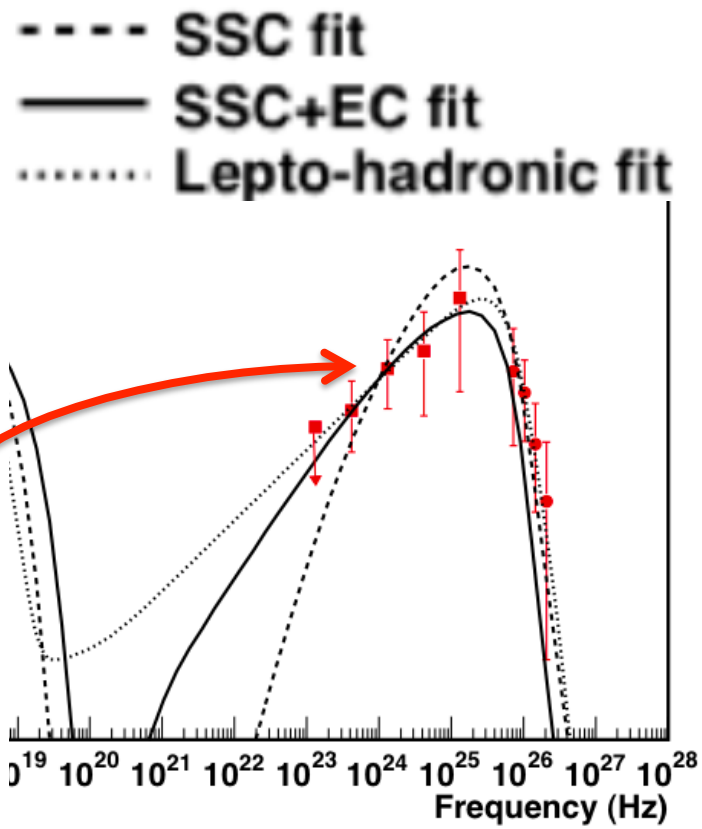
Blazar Spectral Energy Distribution

Hadronic beam dump scenario



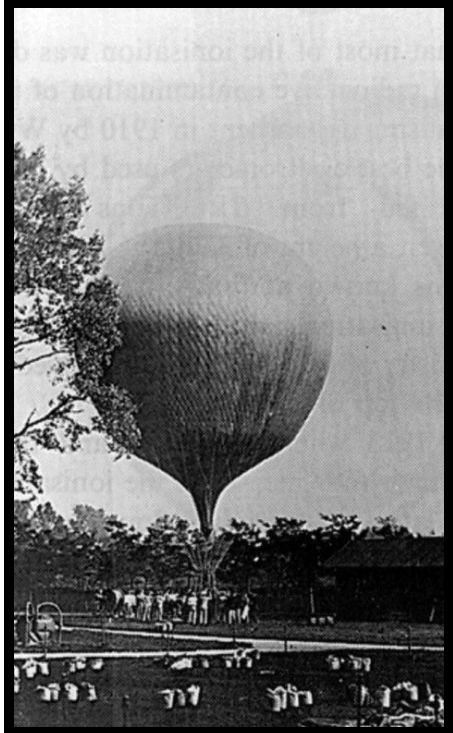


Preliminary



A hadronic component in the jet leads to neutrinos!

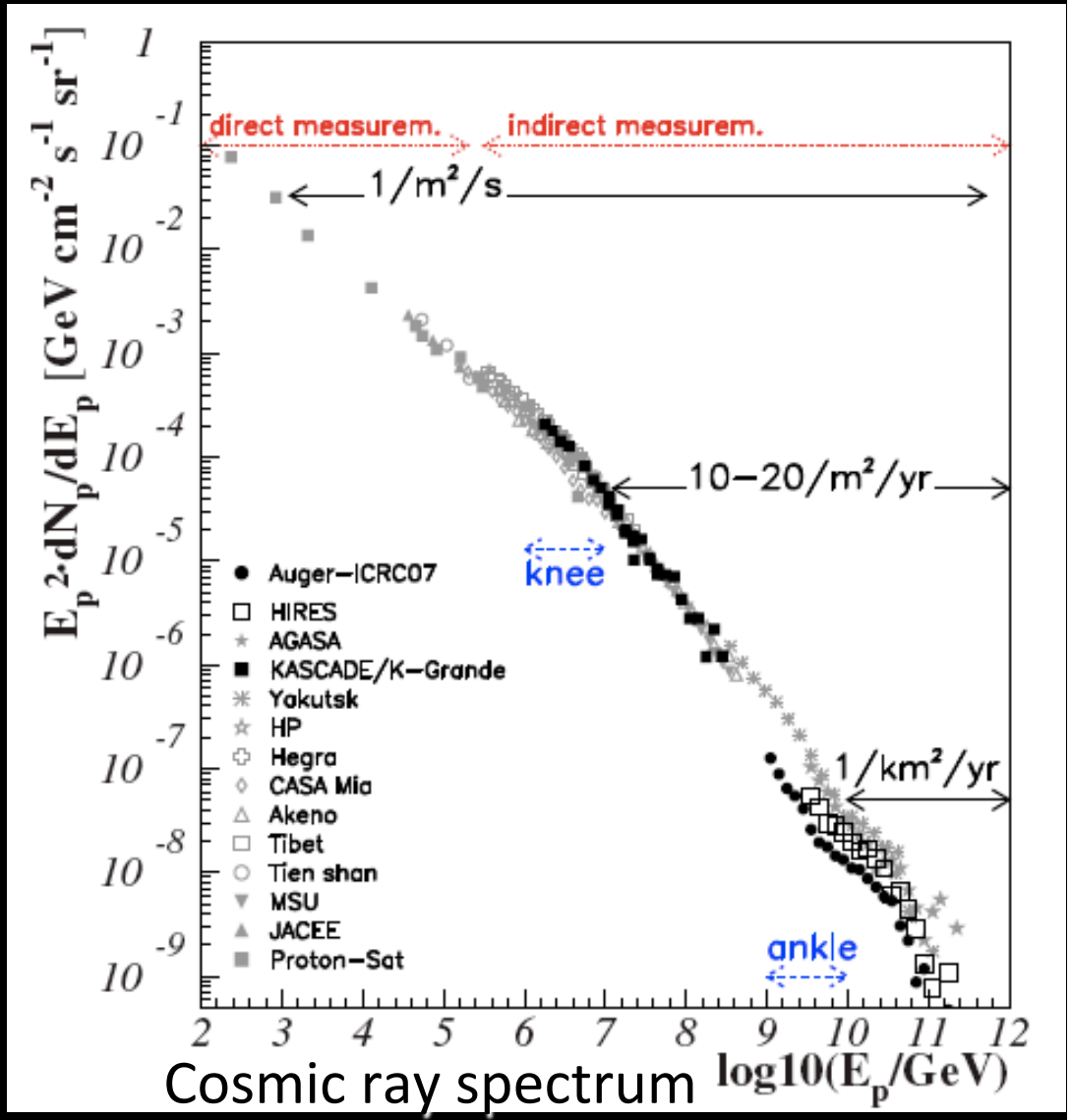
Cosmic Rays: a 100 year-old mystery



Balloon flights
1911-1913



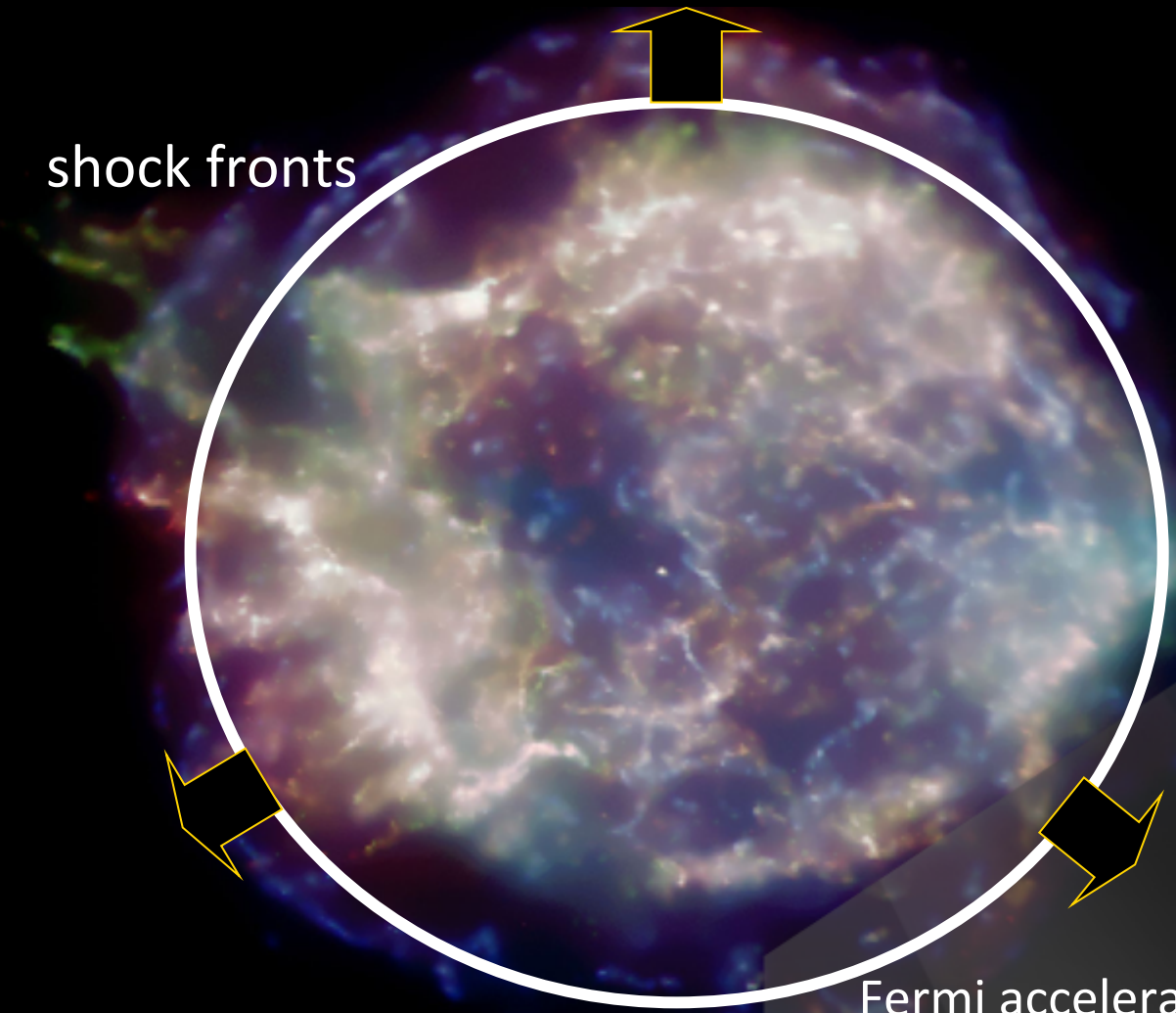
Victor Hess
Nobel Prize
1936



Cosmic ray spectrum

- Power law over many decades
- Origin Uncertain

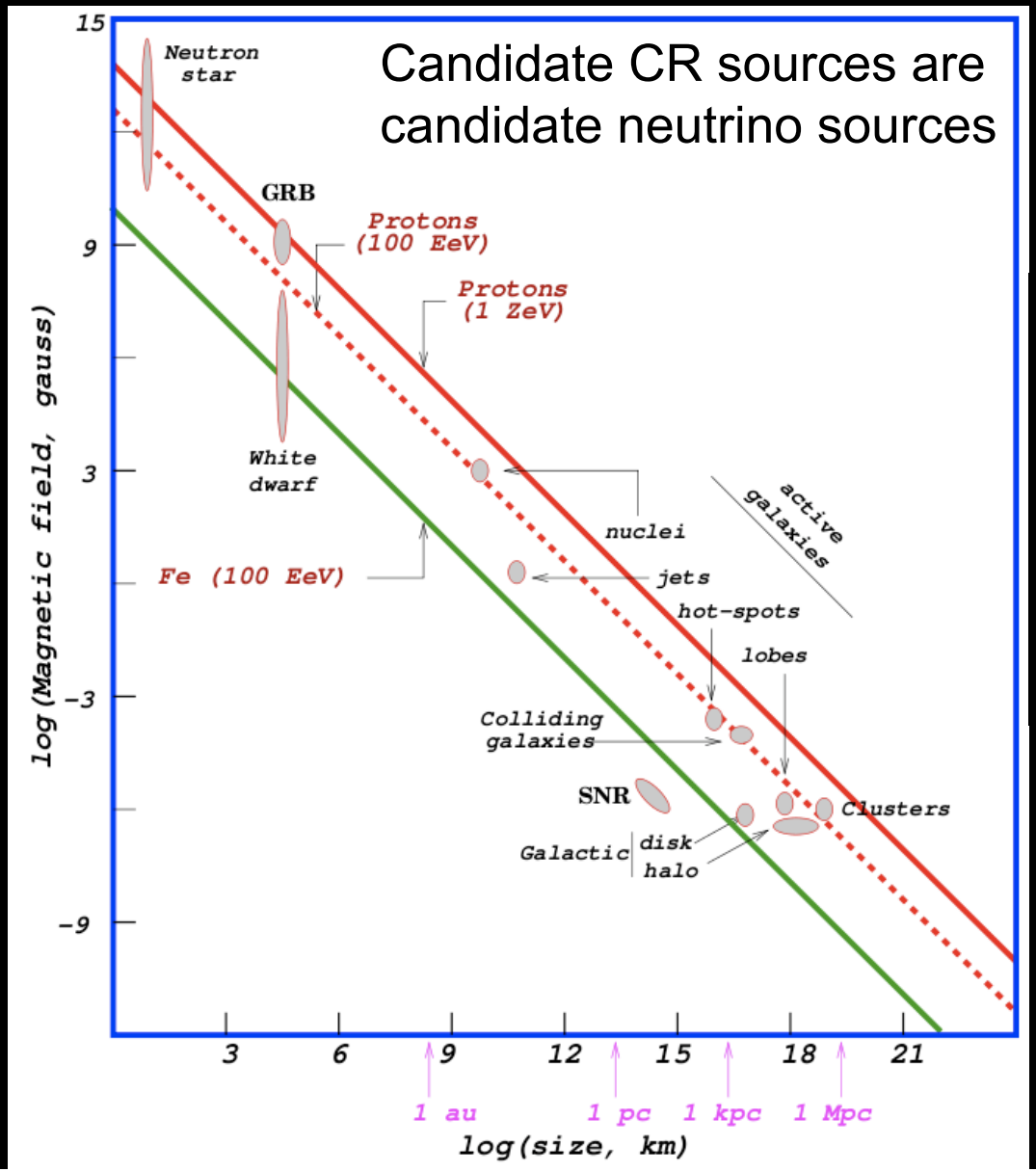
Cas A Supernova Remnant in X-rays



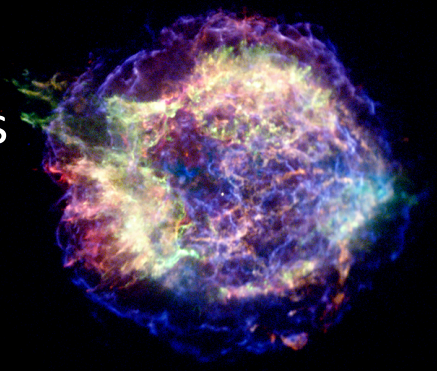
Fermi acceleration when particles reflected across shock fronts, contained by high B-fields

Jon Dumm

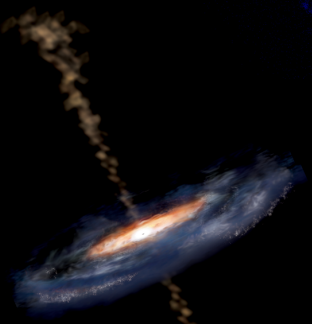
What Are the Cosmic Ray Sources?



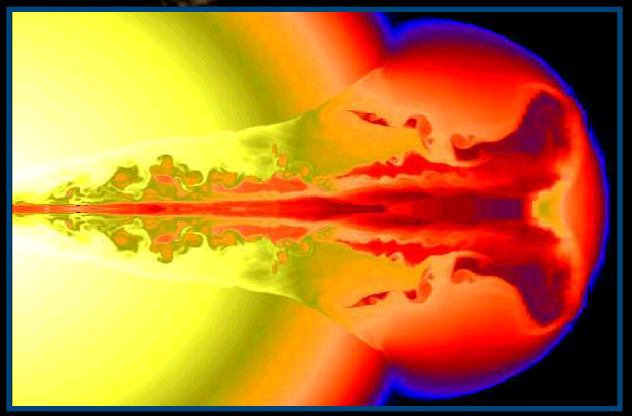
SN Remnants



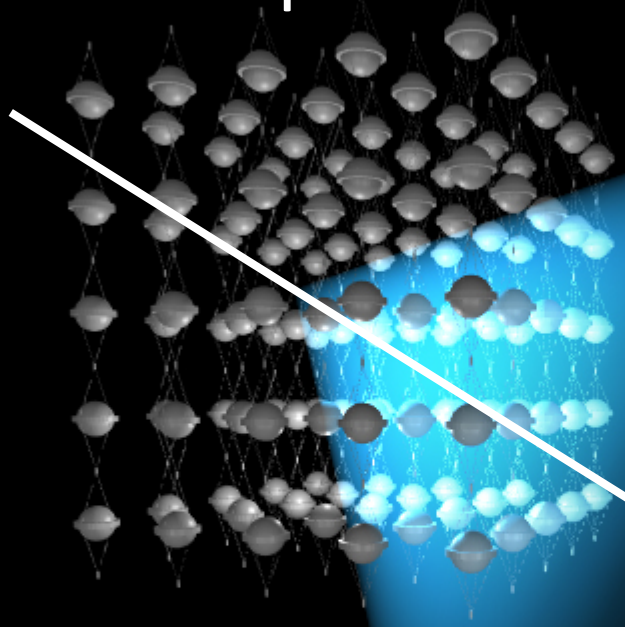
AGN



GRB

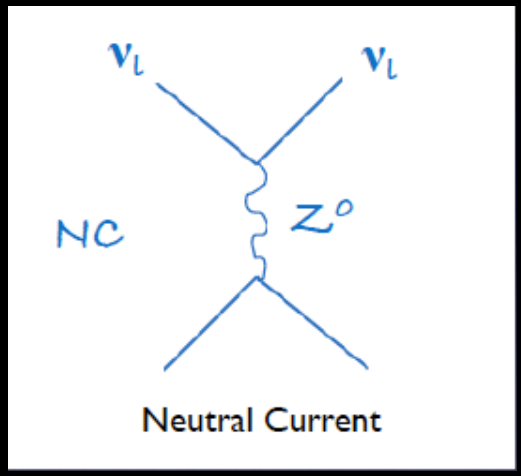


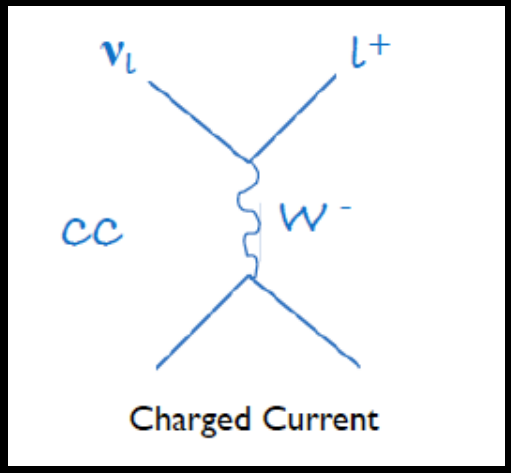
Concept of a Neutrino Telescope



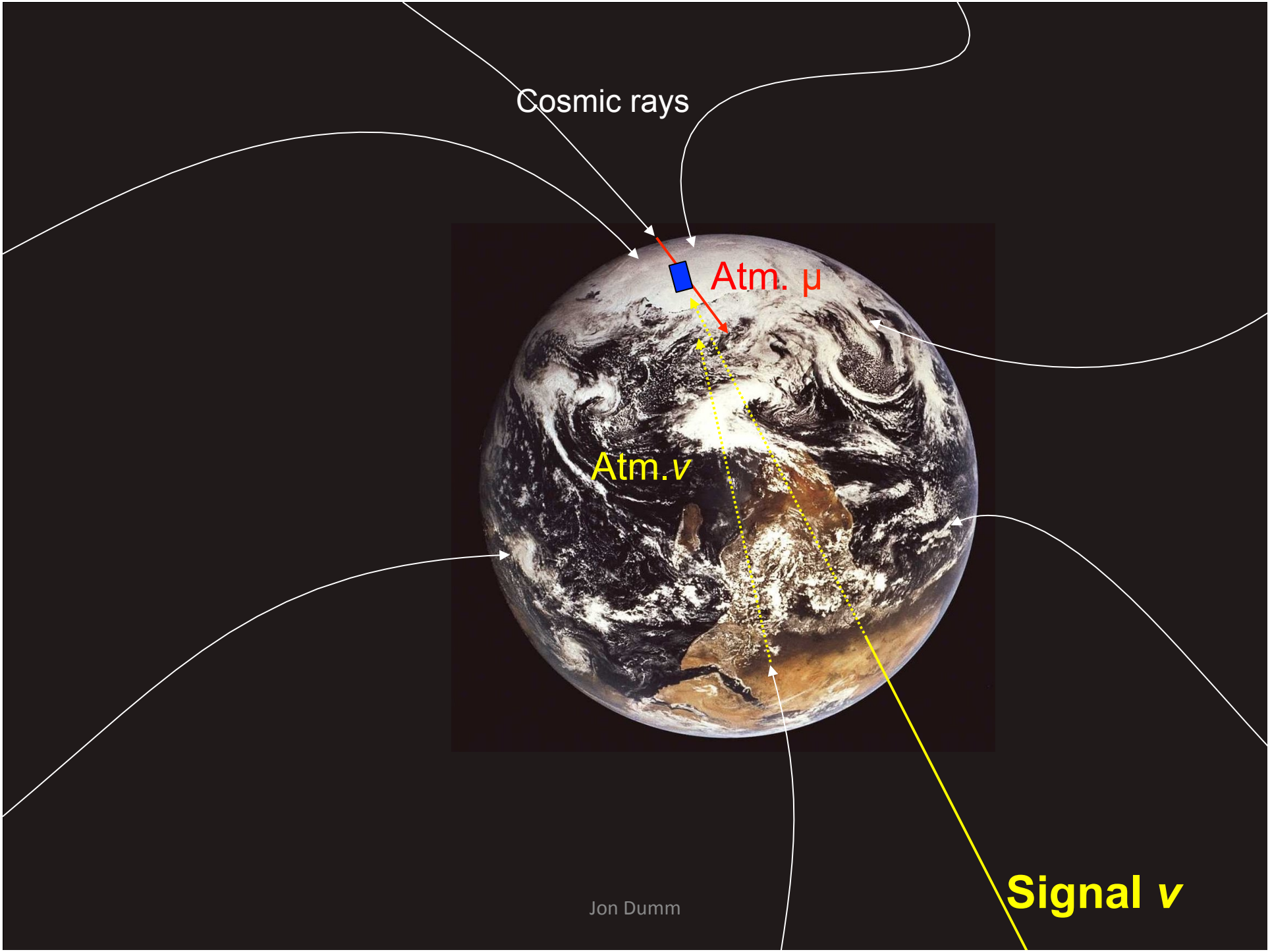
μ

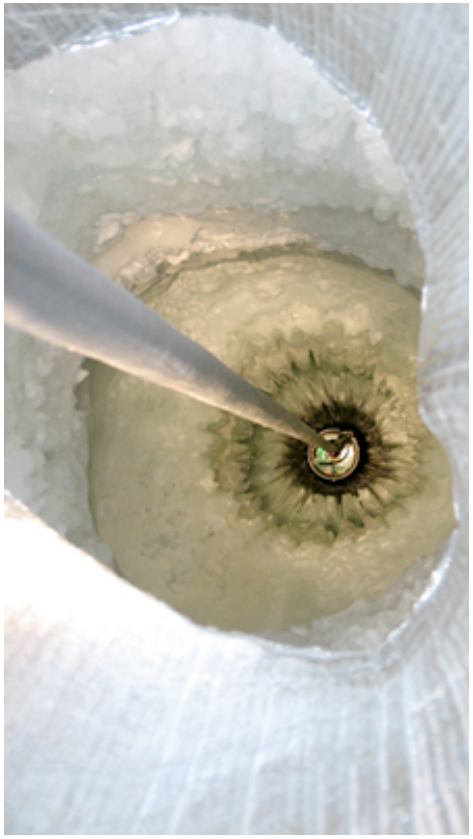
ν

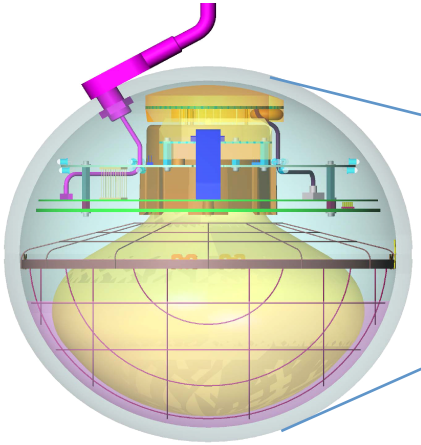




- Look for by-products of neutrino interactions
- 3D array of PMTs
  - Large, transparent medium
- From timing of Cherenkov light, reconstruct neutrino direction


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





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

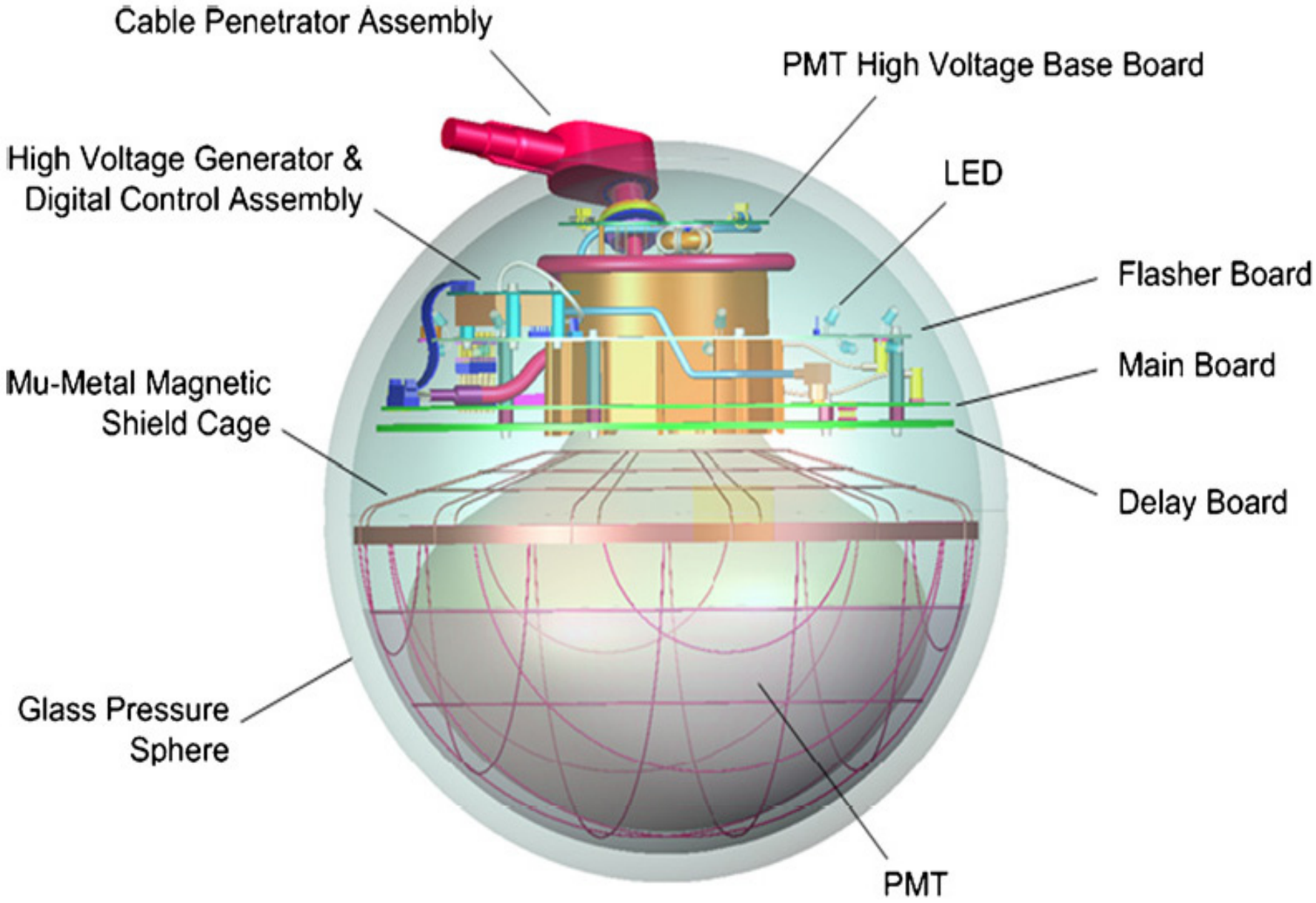
Deep Core
6 Strings - Optimized for lower energies
360 Optical Sensors

Eiffel Tower
324 m

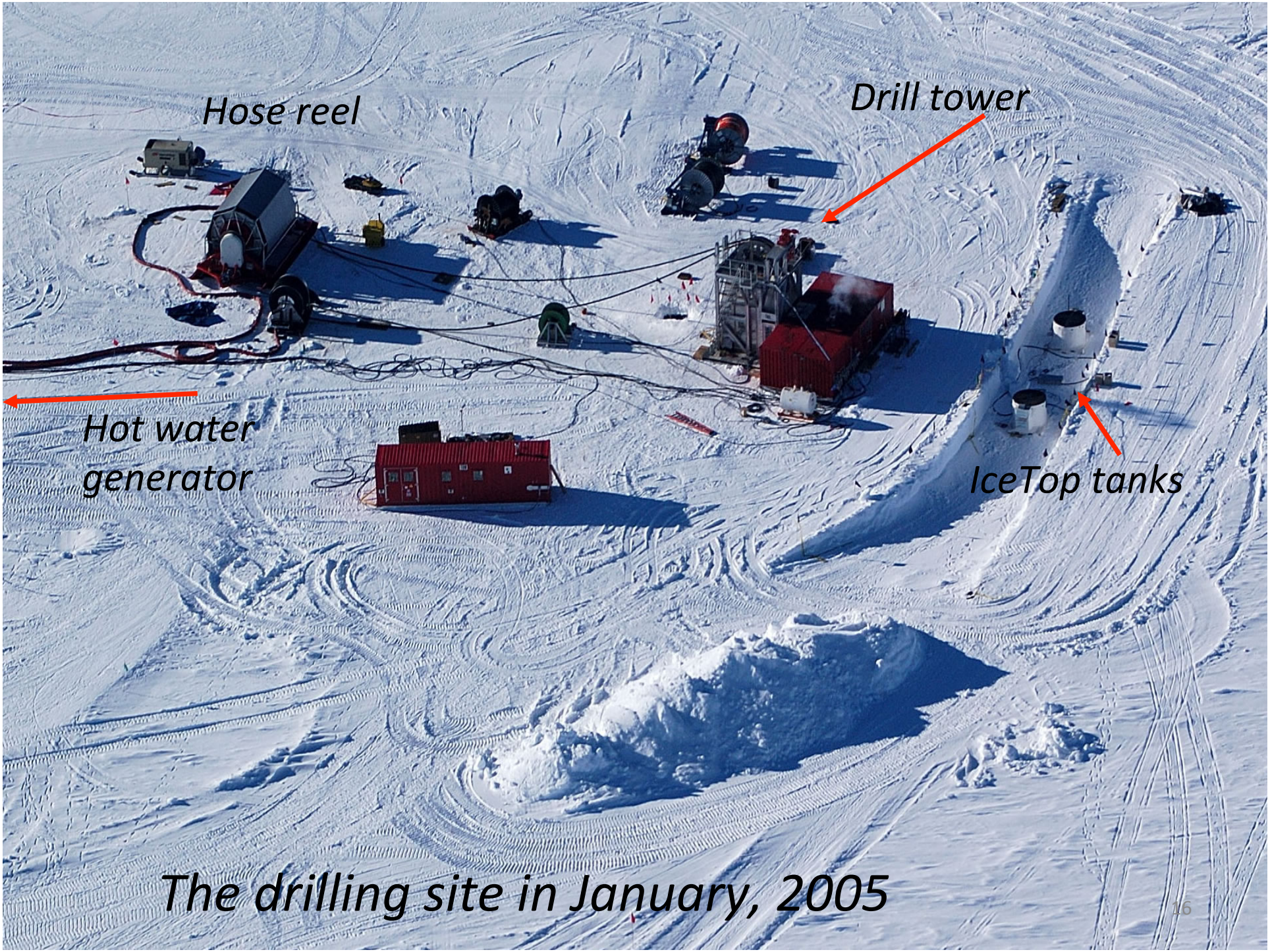
2450 m

2820 m

Bedrock



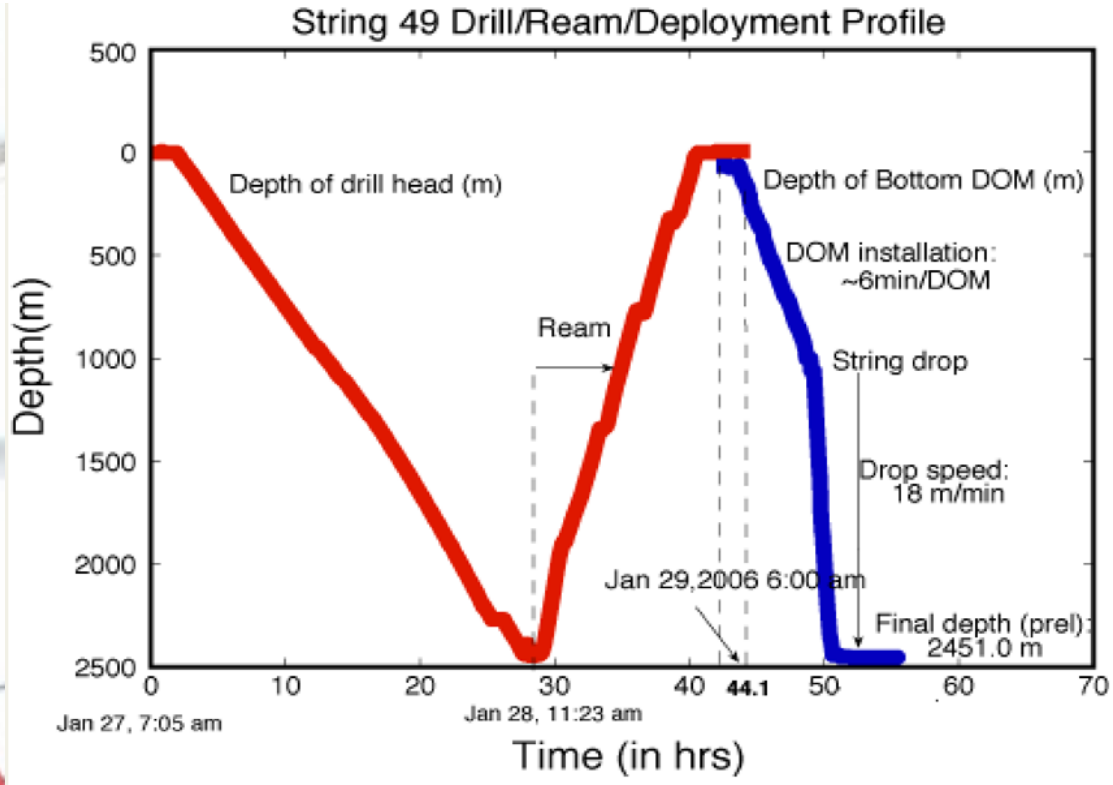
A schematic view of an IceCube digital optical module.



The drilling site in January, 2005


HOLE "L"

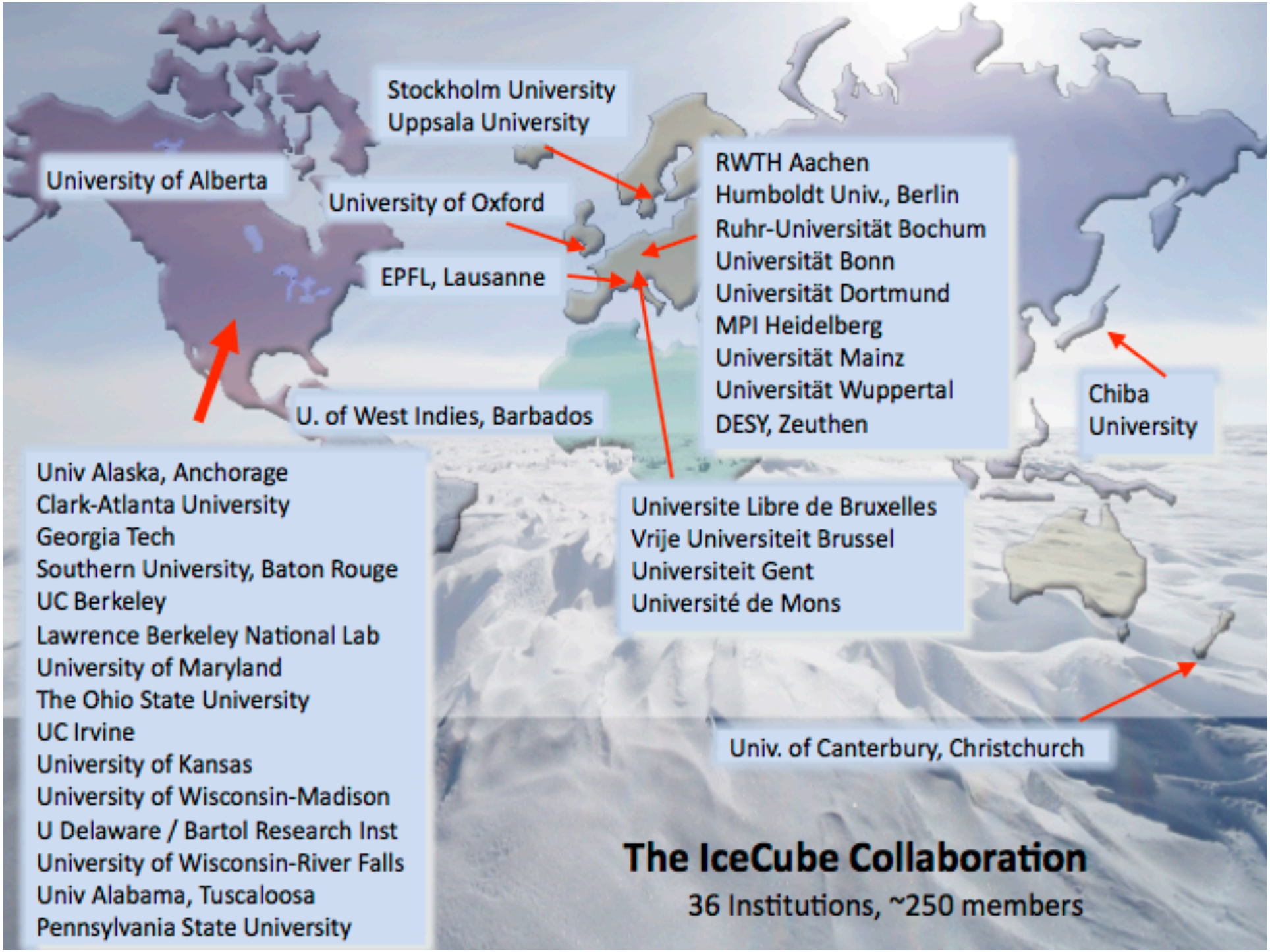



String 49 Drill/Ream/Deployment Profile
Depth(m)
500
0
500
1000
1500
2000
2500
Depth of drill head (m)
Depth of Bottom DOM (m)
DOM installation:
~6min/DOM
Ream
String drop
Drop speed:
18 m/min
Jan 29,2006 6:00 am
Final depth (prel):
2451.0 m
0
10
20
30
40
44.1
50
60
70
Jan 27, 7:05 am
Jan 28, 11:23 am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








Stockholm University
Uppsala University
University of Alberta
University of Oxford
EPFL, Lausanne
RWTH Aachen
Humboldt Univ., Berlin
Ruhr-Universität Bochum
Universität Bonn
Universität Dortmund
MPI Heidelberg
Universität Mainz
Universität Wuppertal
DESY, Zeuthen
Chiba University
U. of West Indies, Barbados
Univ Alaska, Anchorage
Clark-Atlanta University
Georgia Tech
Southern University, Baton Rouge
UC Berkeley
Lawrence Berkeley National Lab
University of Maryland
The Ohio State University
UC Irvine
University of Kansas
University of Wisconsin-Madison
U Delaware / Bartol Research Inst
University of Wisconsin-River Falls
Univ Alabama, Tuscaloosa
Pennsylvania State University
Universite Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons
Univ. of Canterbury, Christchurch
The IceCube Collaboration
36 Institutions, ~250 members

IceCube performance

DOM survival rate: ~98%

Low noise rates: ~500Hz

High duty cycle: >96%

Full 86-string detector installed and operated for almost 1 year

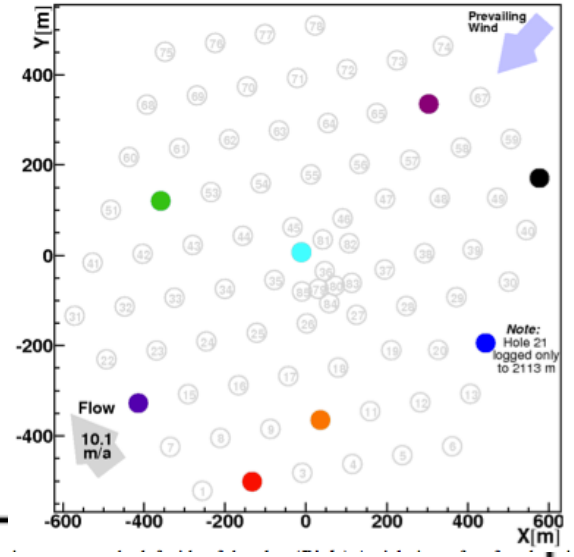


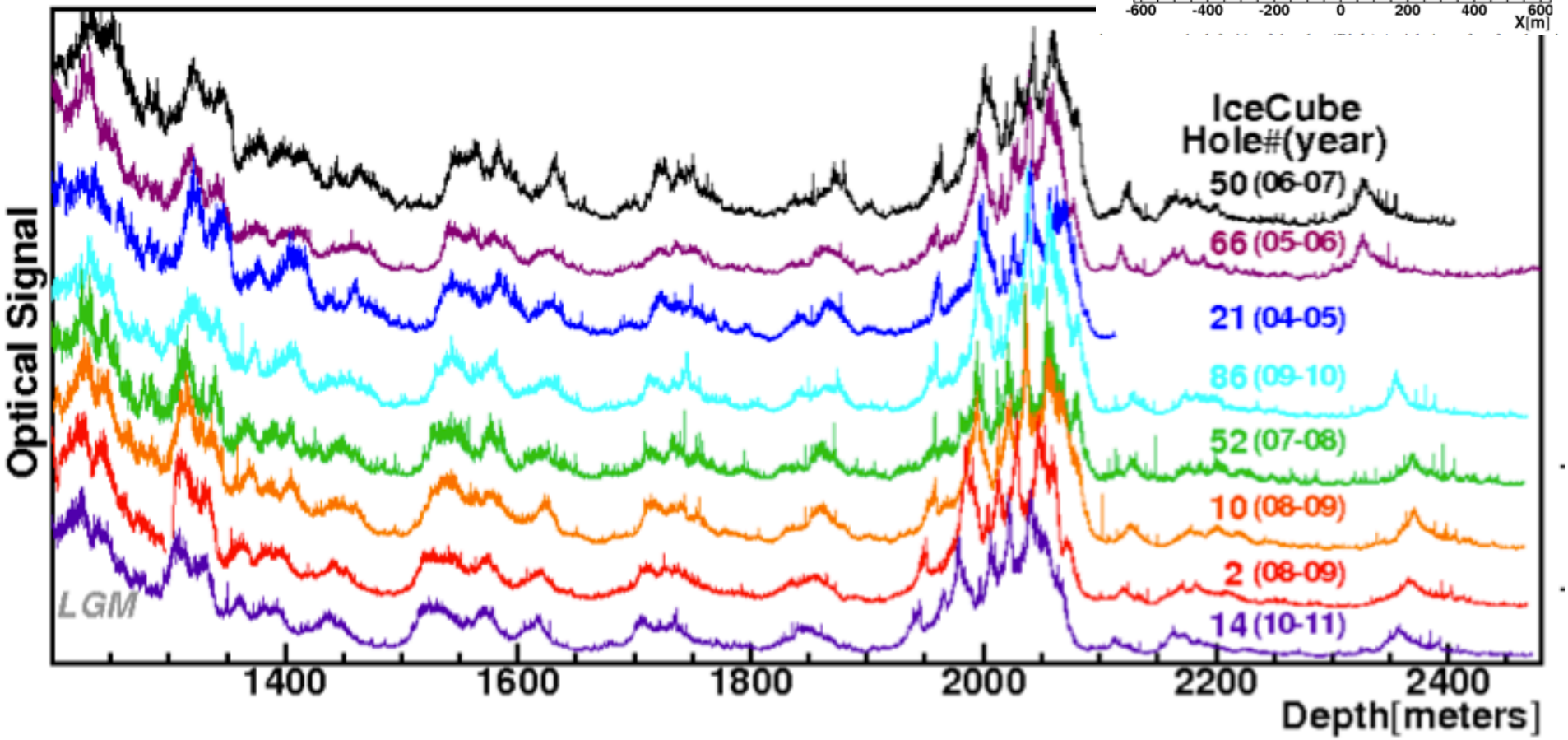
Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1900 Hz	160 / day
IC86	2011	~365 days	2800 Hz	220 / day

Optical Properties of Ice

A ‘dust-logger’ is sent down many holes

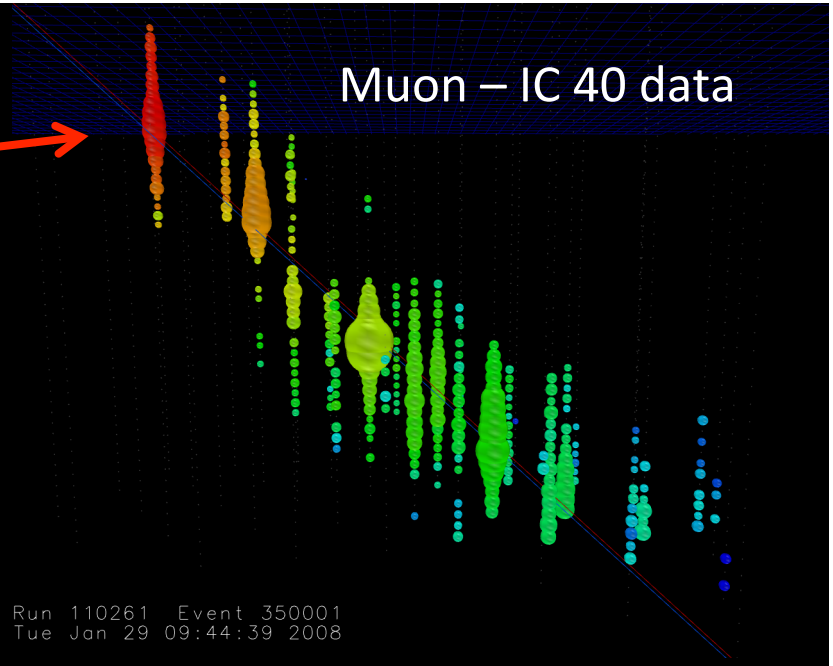
Sends out a laser pulse and monitors reflected optical signal

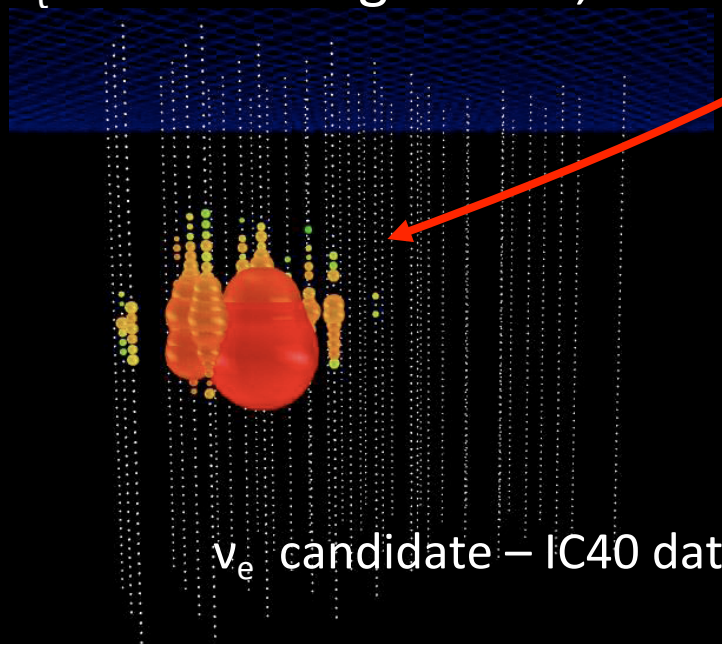




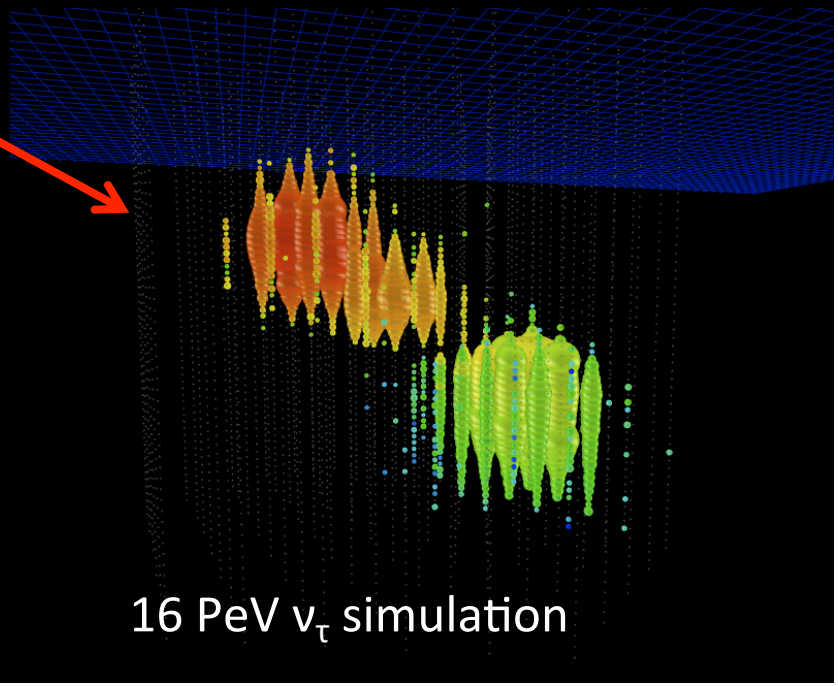
Event Topologies

- 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

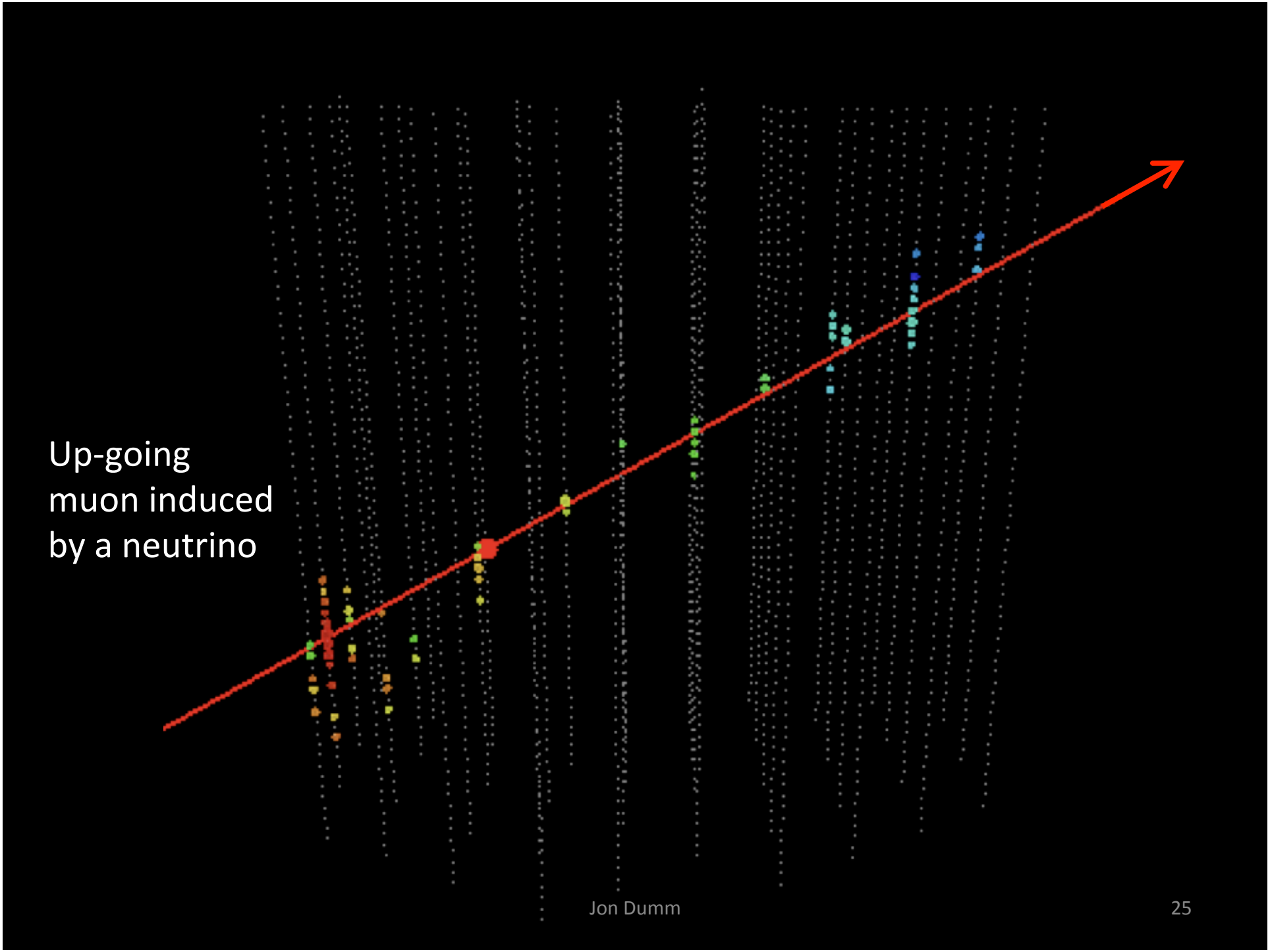


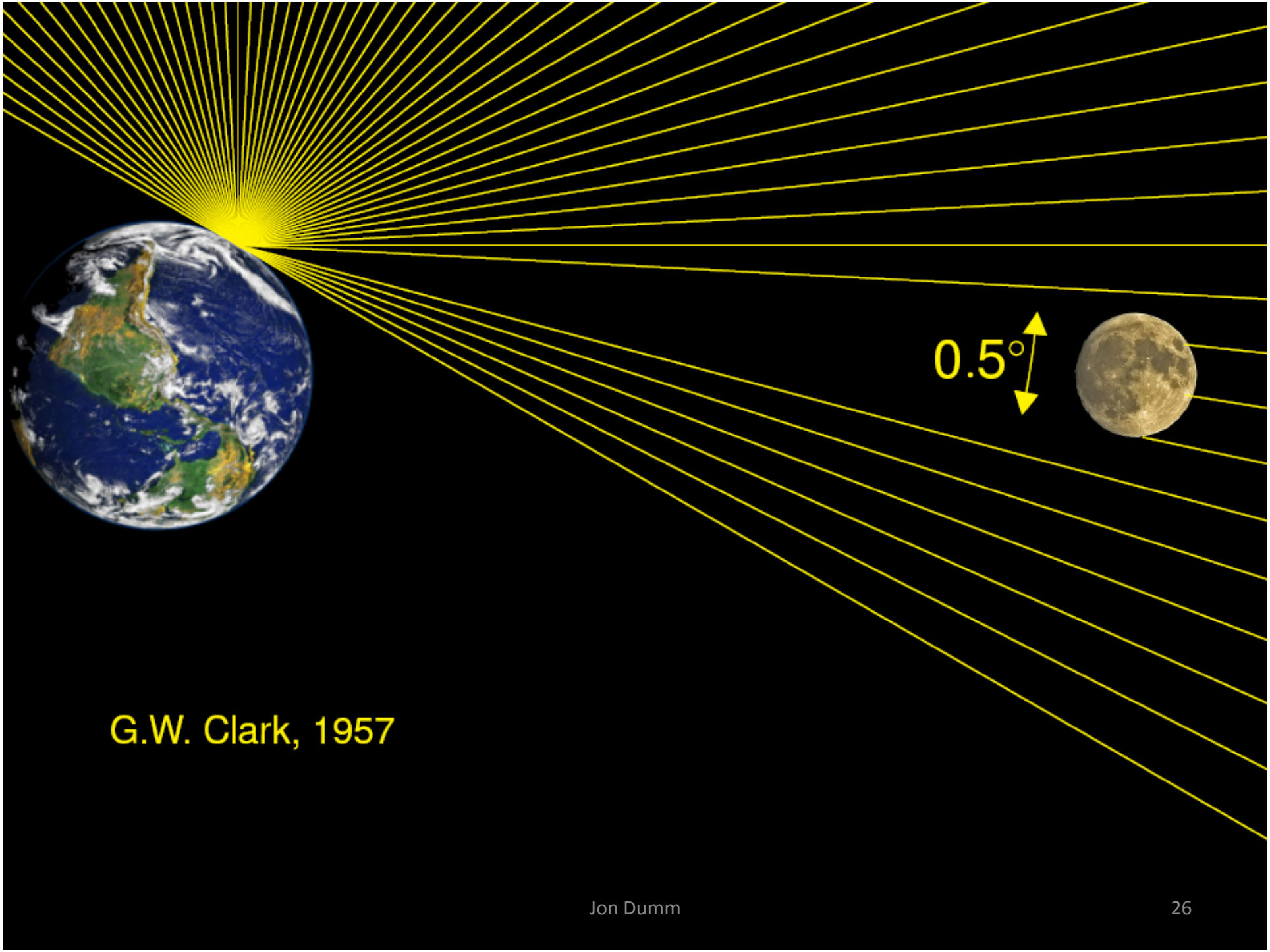


ν_e candidate – IC40 data



16 PeV ν_τ simulation

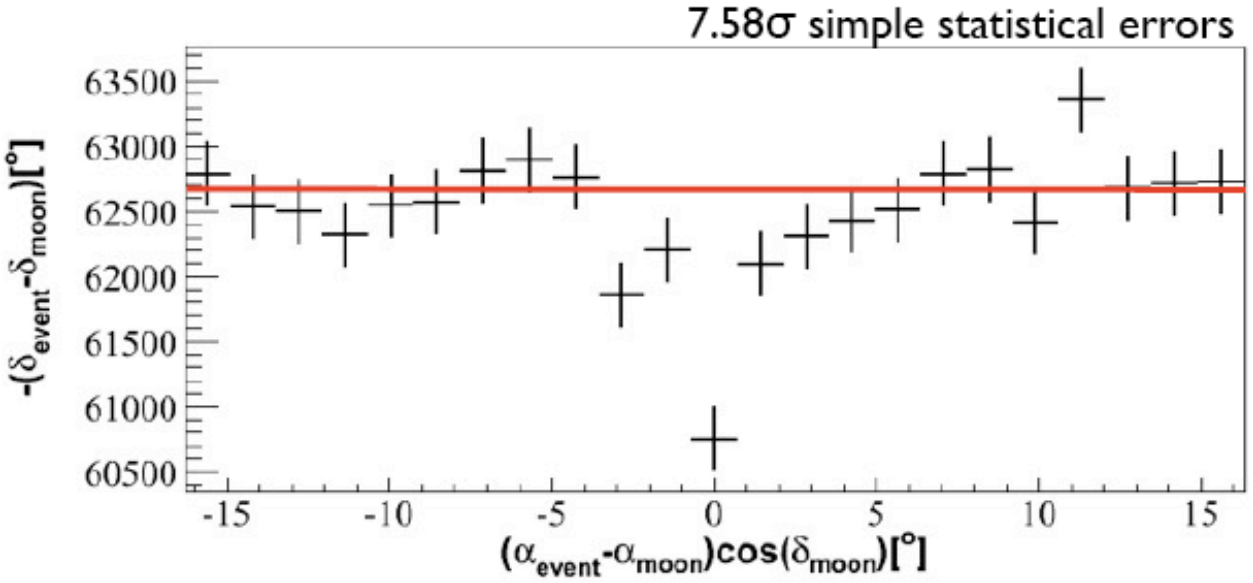

Up-going
muon induced
by a neutrino

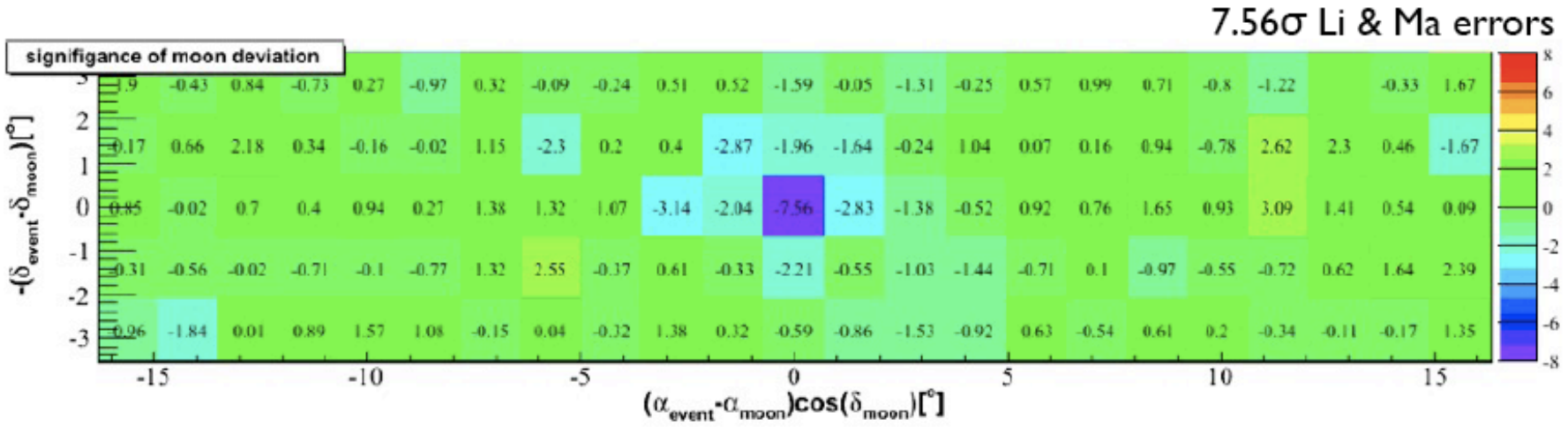

0.5°
G.W. Clark, 1957

Pointing Verification with the Moon -
The Standard Anti-Candle

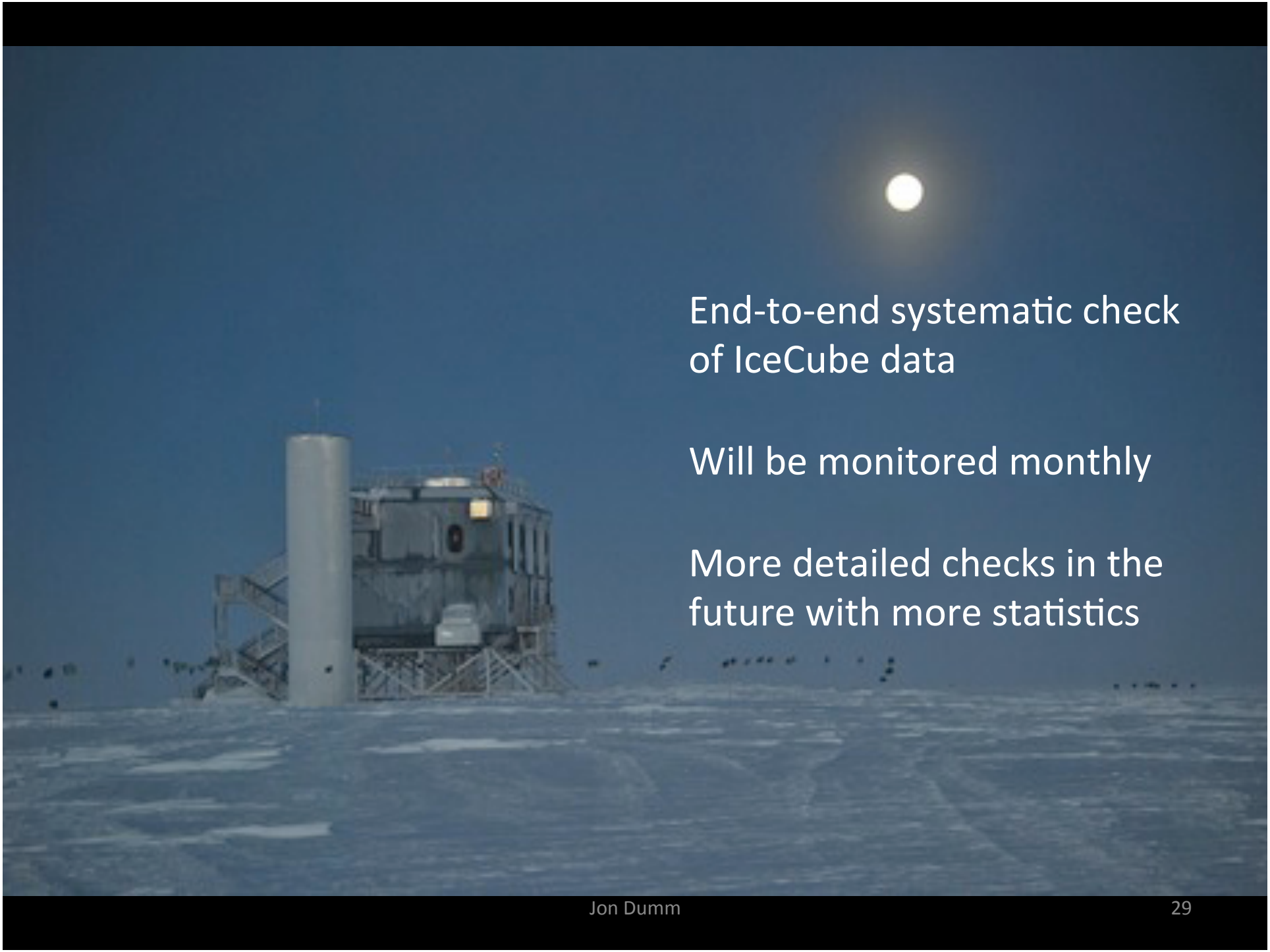
IceCube-40 strings (2009)

Deficit in agreement with Monte Carlo expectations

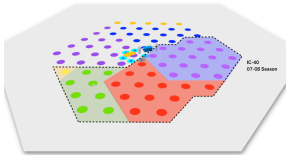






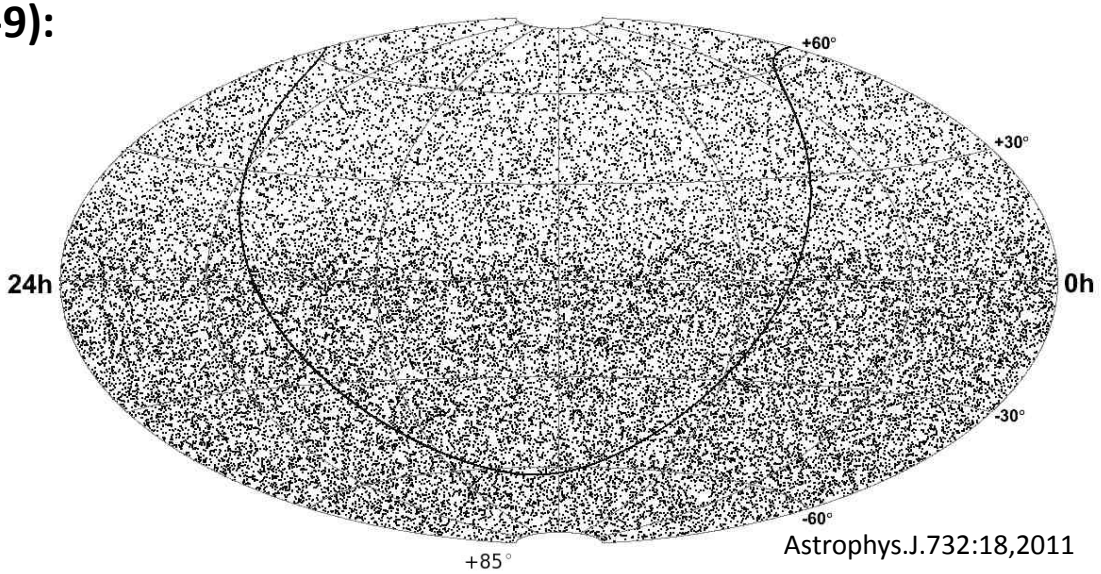

End-to-end systematic check of IceCube data
Will be monitored monthly
More detailed checks in the future with more statistics

IceCube 40 + IceCube 59-string Point Source Search



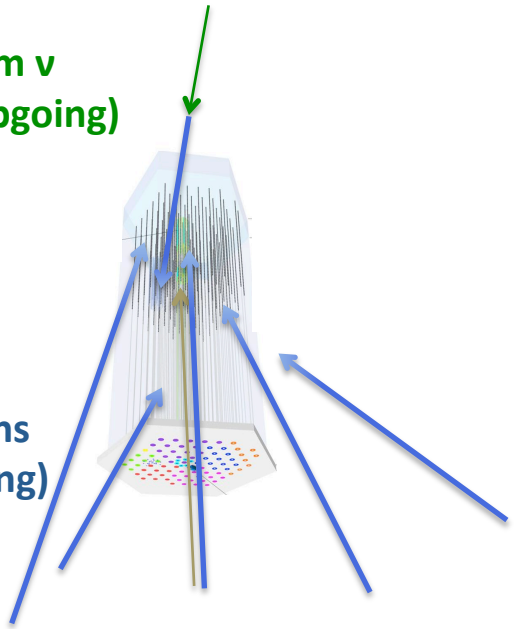
IceCube 40 strings (2008-9):

375 days livetime

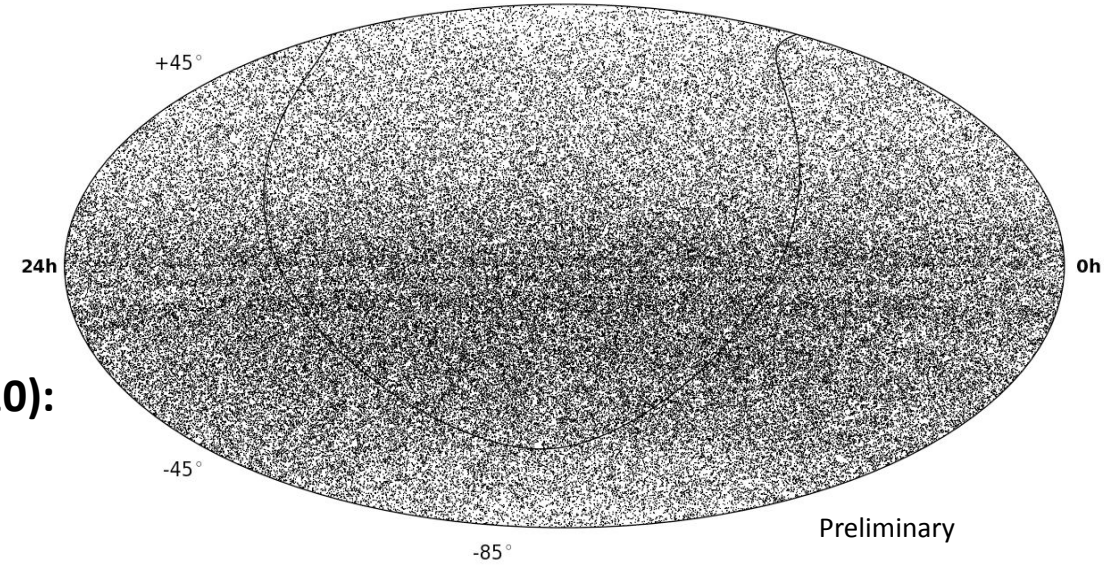


Astrophys.J.732:18,2011

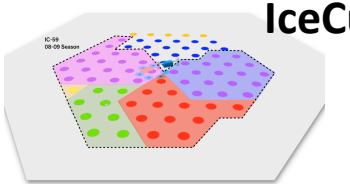
Atm ν (upgoing)



Atm muons (downgoing)



Preliminary



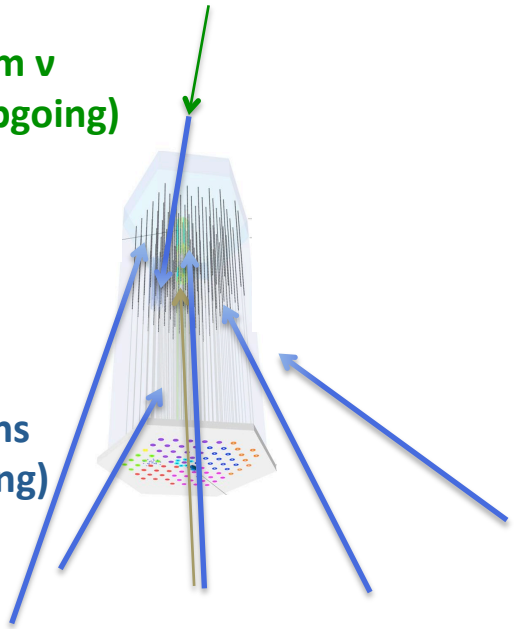
IceCube 59 strings (2009-10):

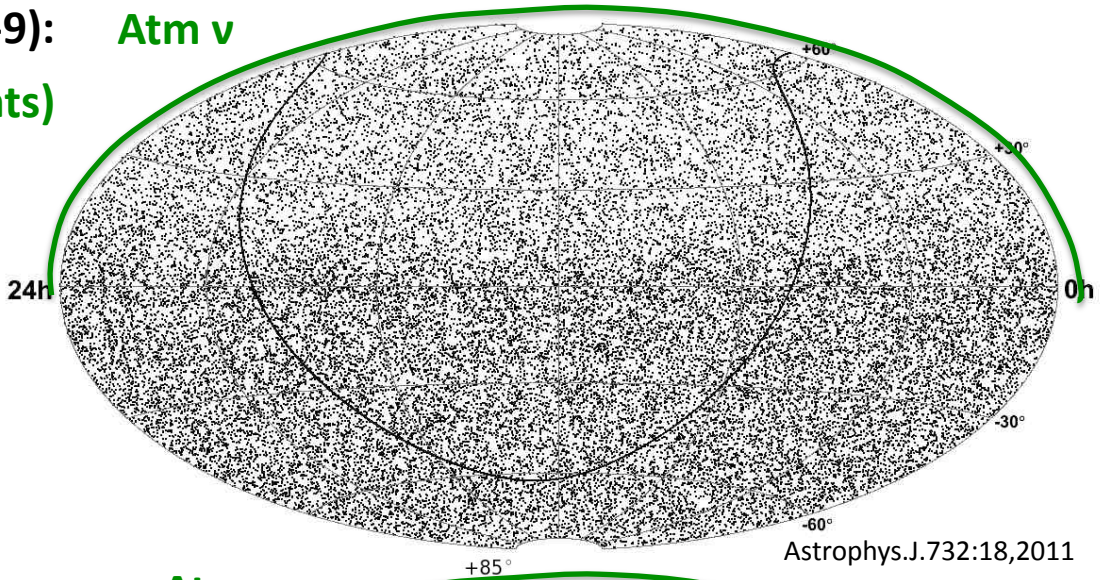
348 days livetime

IceCube 40 + IceCube 59-string Point Source Search

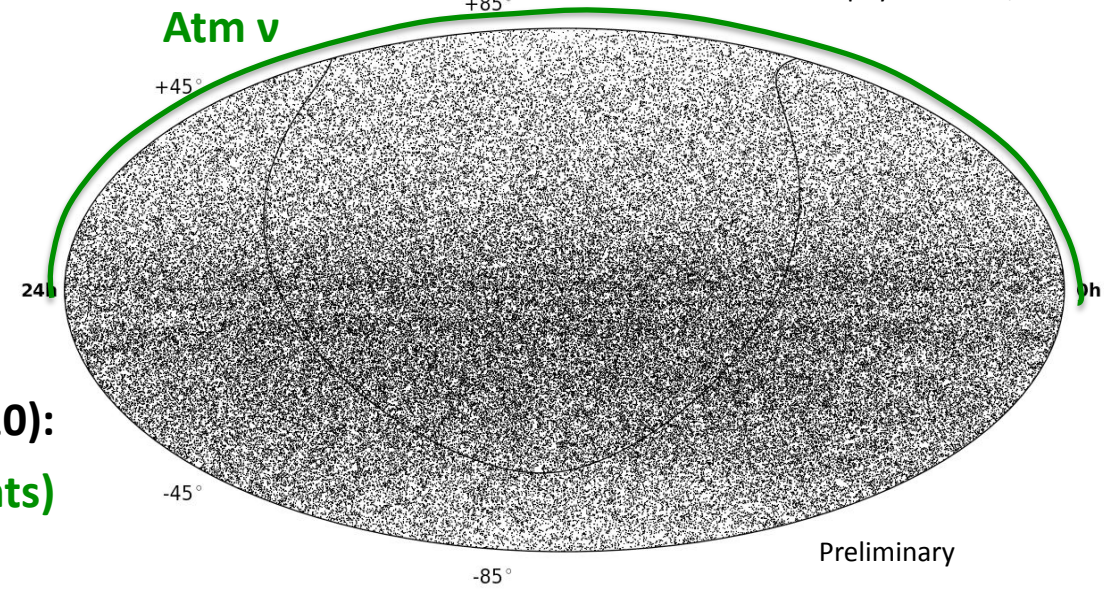
IceCube 40 strings (2008-9):

14,121 upgoing (ν candidate events)





Astrophys.J.732:18,2011



Preliminary

IceCube 59 strings (2009-10):

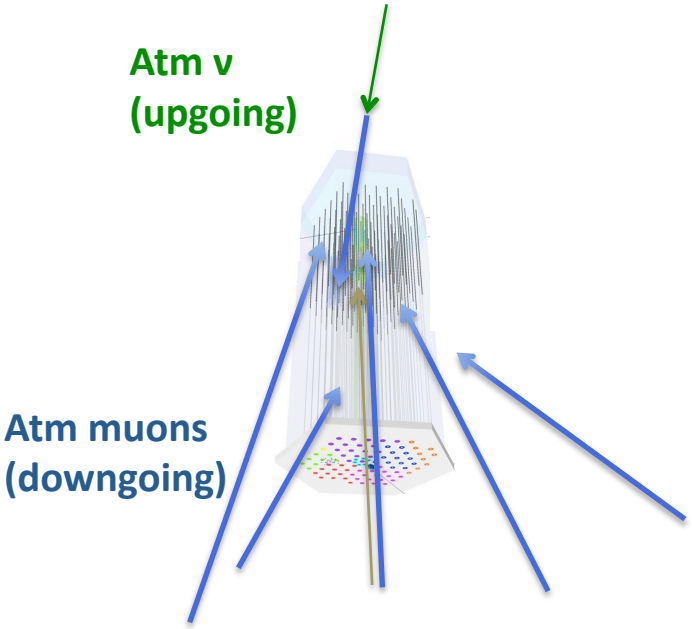
43,339 upgoing (ν candidate events)

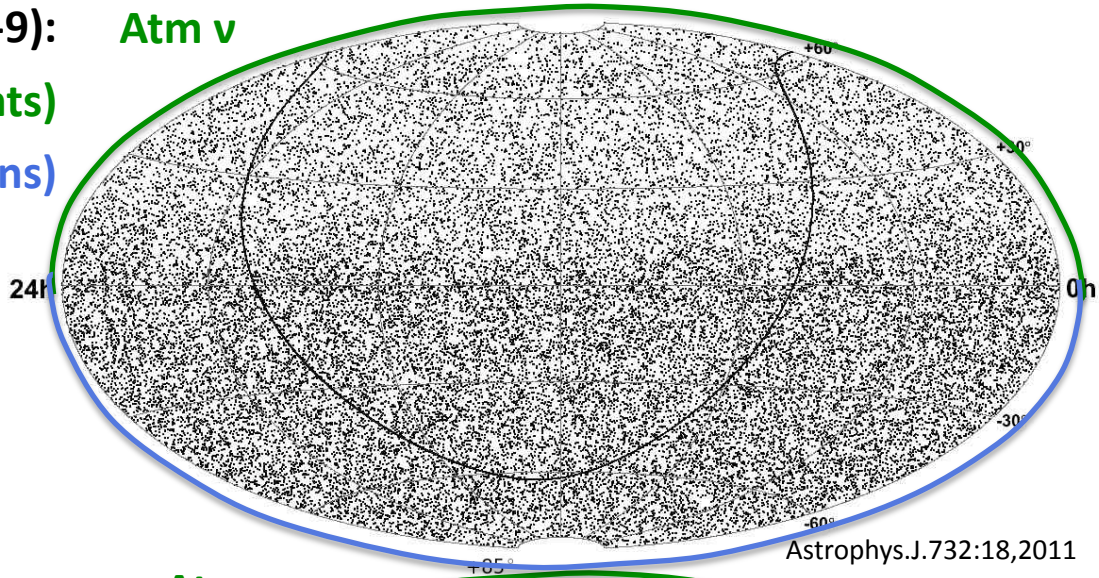
IceCube 40 + IceCube 59-string Point Source Search

IceCube 40 strings (2008-9):

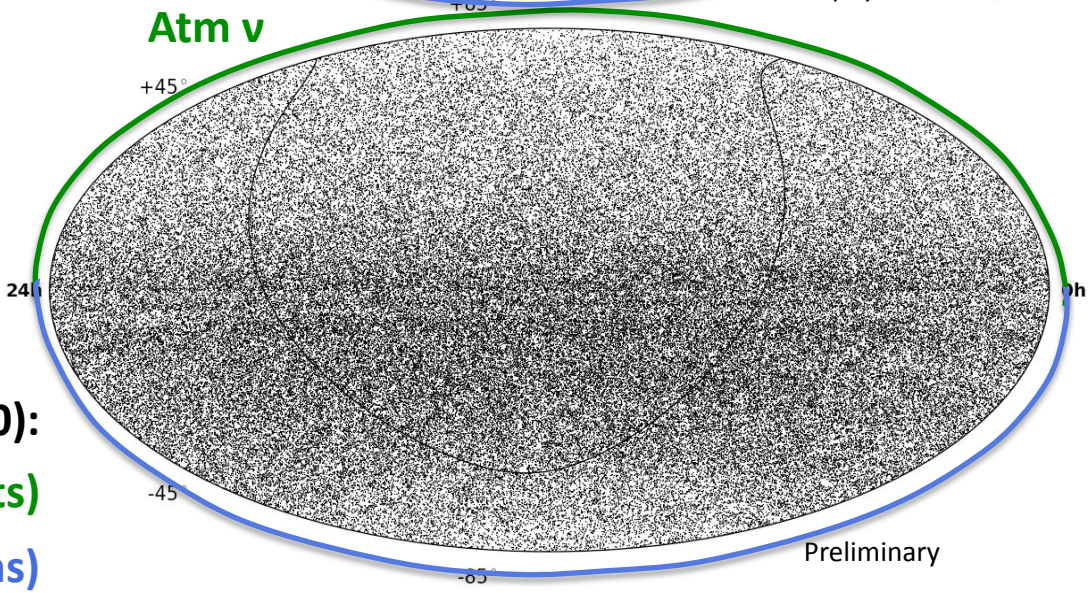
14,121 upgoing (ν candidate events)

22,779 downgoing (HE CR muons)





Astrophys.J.732:18,2011



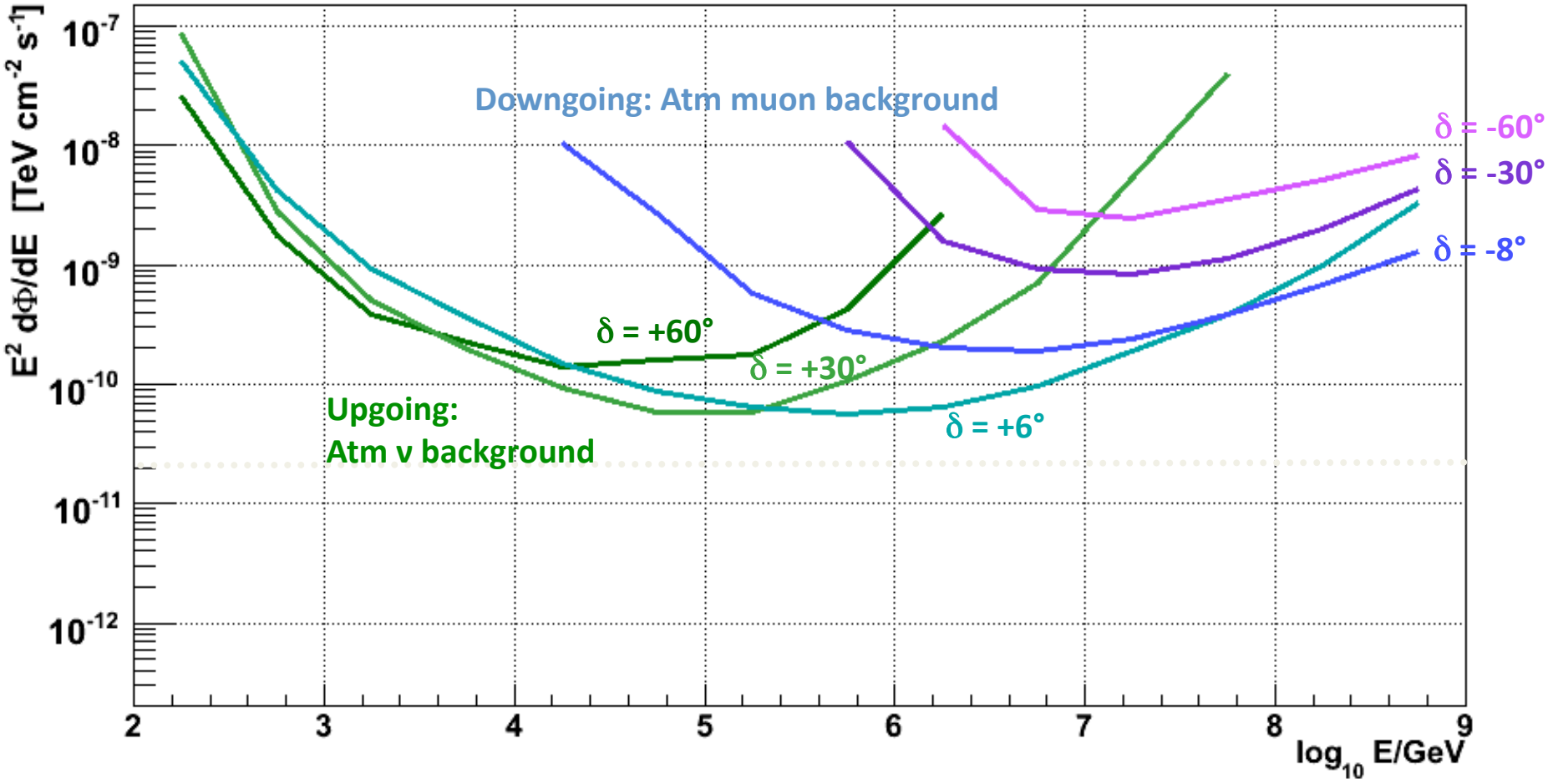
Preliminary

IceCube 59 strings (2009-10):

43,339 upgoing (ν candidate events)

64,230 downgoing (HE CR muons)

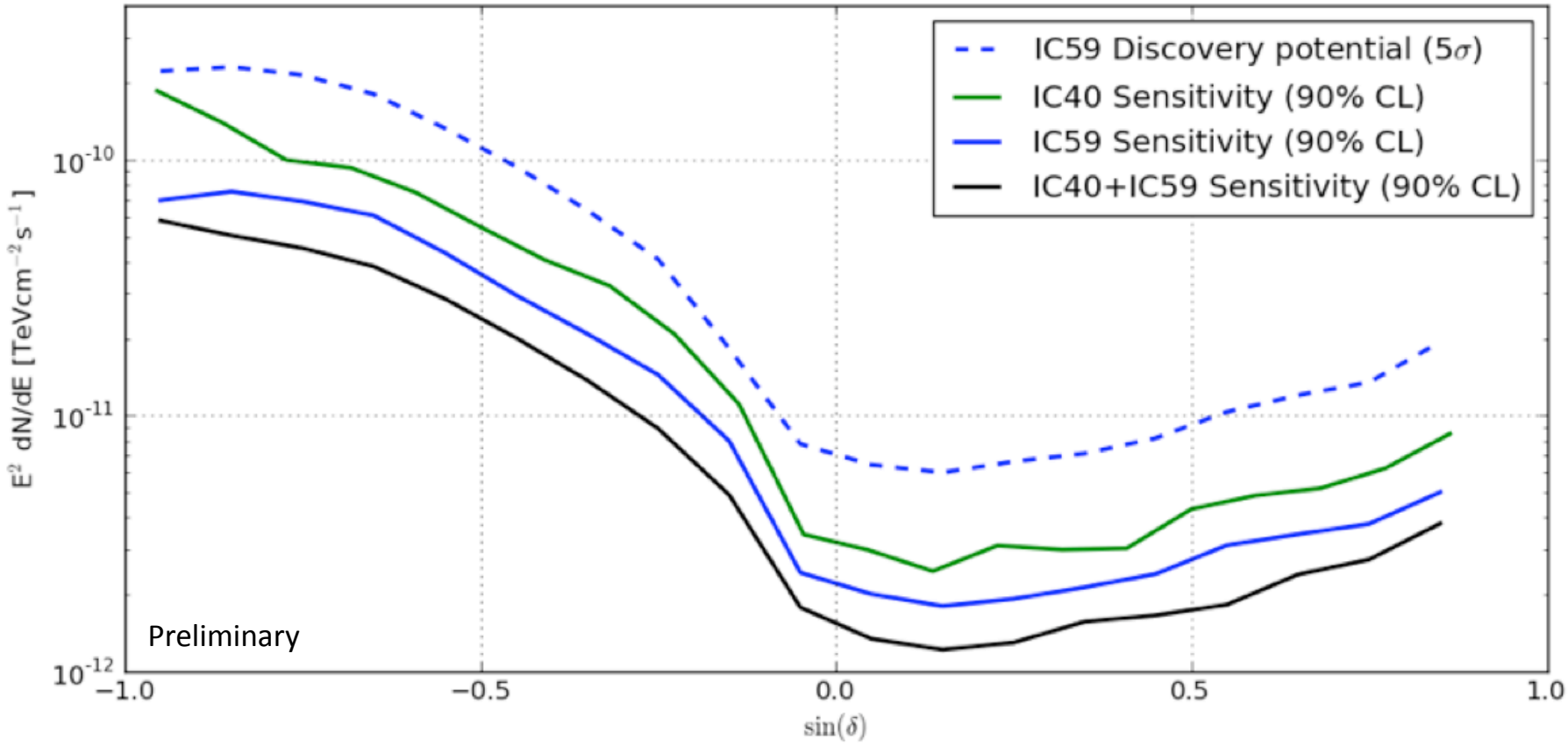
Differential Sensitivity Dependence on Direction



IC40 Differential 5σ Discovery Potentials

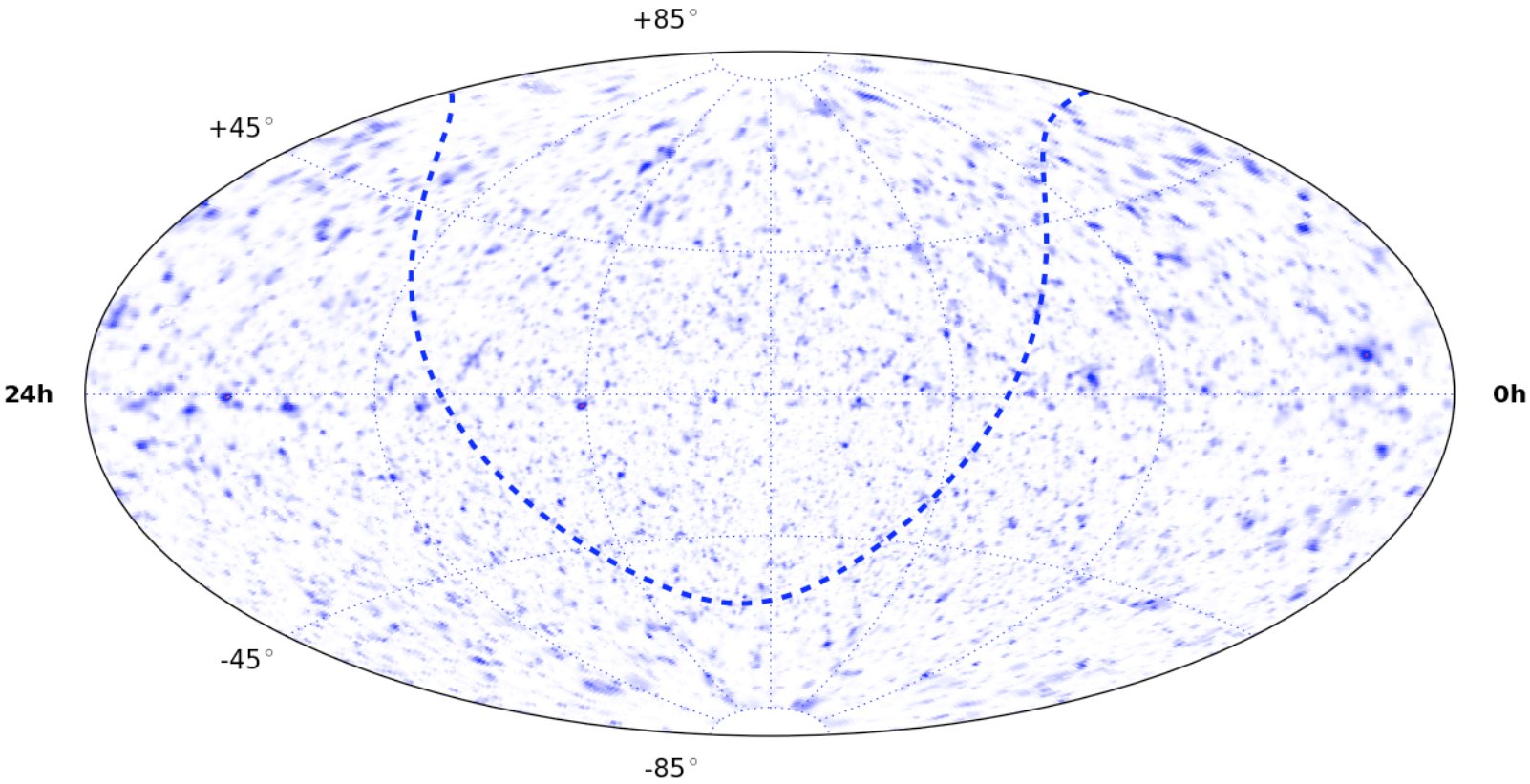
(for E^{-2} signal injected in 1/2 decades of energy)

IceCube 40 + IceCube 59 E^{-2} Sensitivity

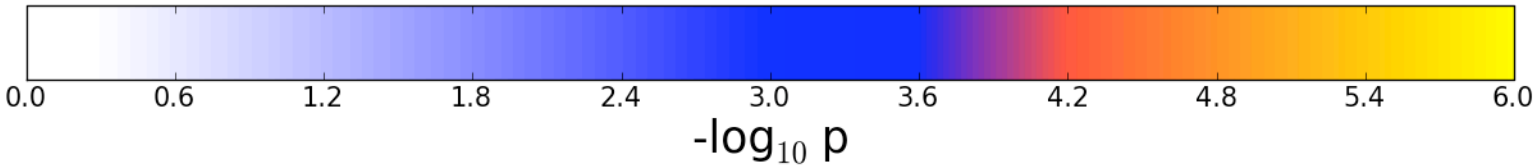


J. A. Aguilar et al., ICRC 2011

Results: Joint IC40+IC59 Point Source Skymap



Preliminary

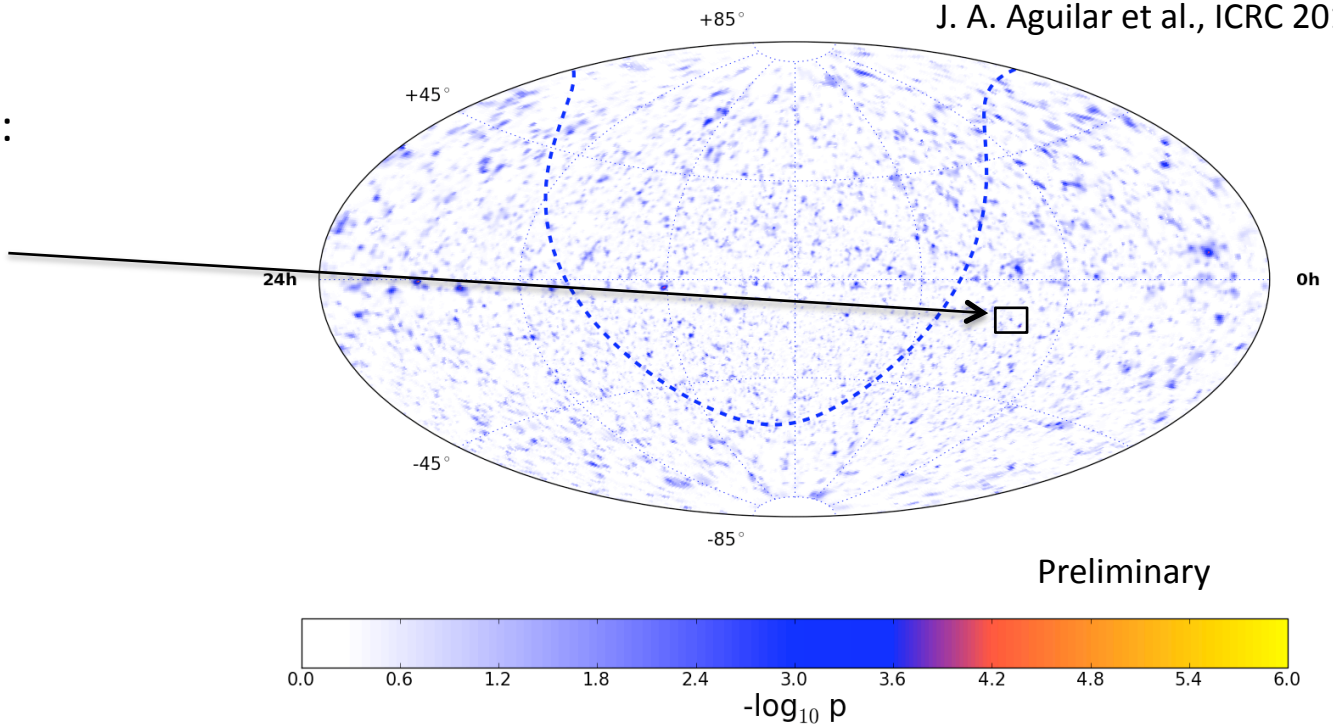


J. A. Aguilar et al., ICRC 2011

Results: Joint IC40+IC59 Point Source Skymap

J. A. Aguilar et al., ICRC 2011

Most significant spot:
r.a. = 75.45°
dec. = -18.15°
n_s = 18.3
γ = -3.9
-$\log_{10}$ p-value = 4.65



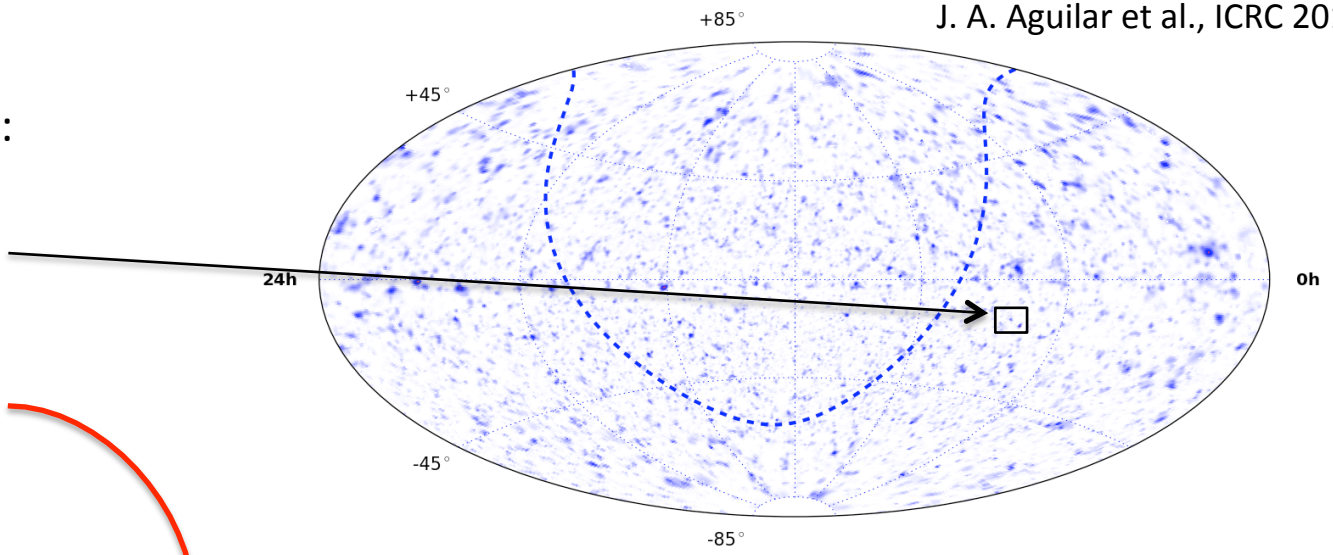
$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-|\vec{x}_i - \vec{x}_s|^2/2\sigma_i^2} \cdot P(E_i|\gamma)$$

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

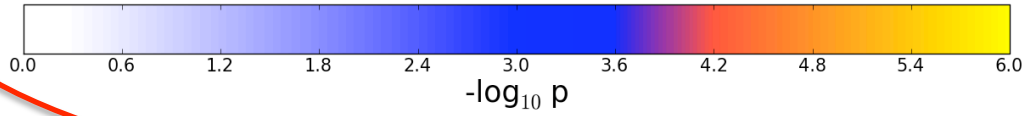
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J. A. Aguilar et al., ICRC 2011

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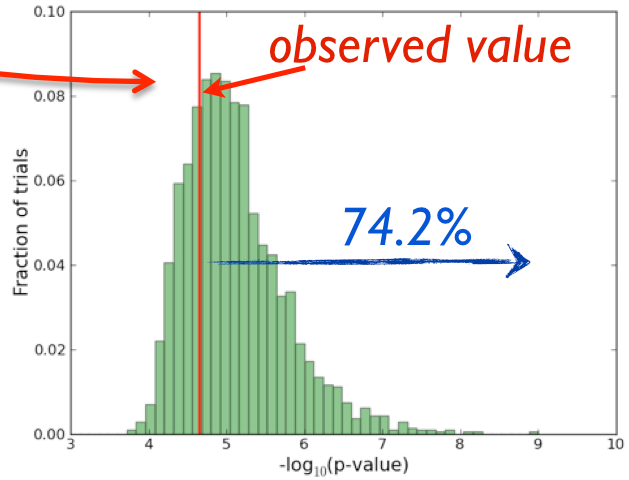


Preliminary

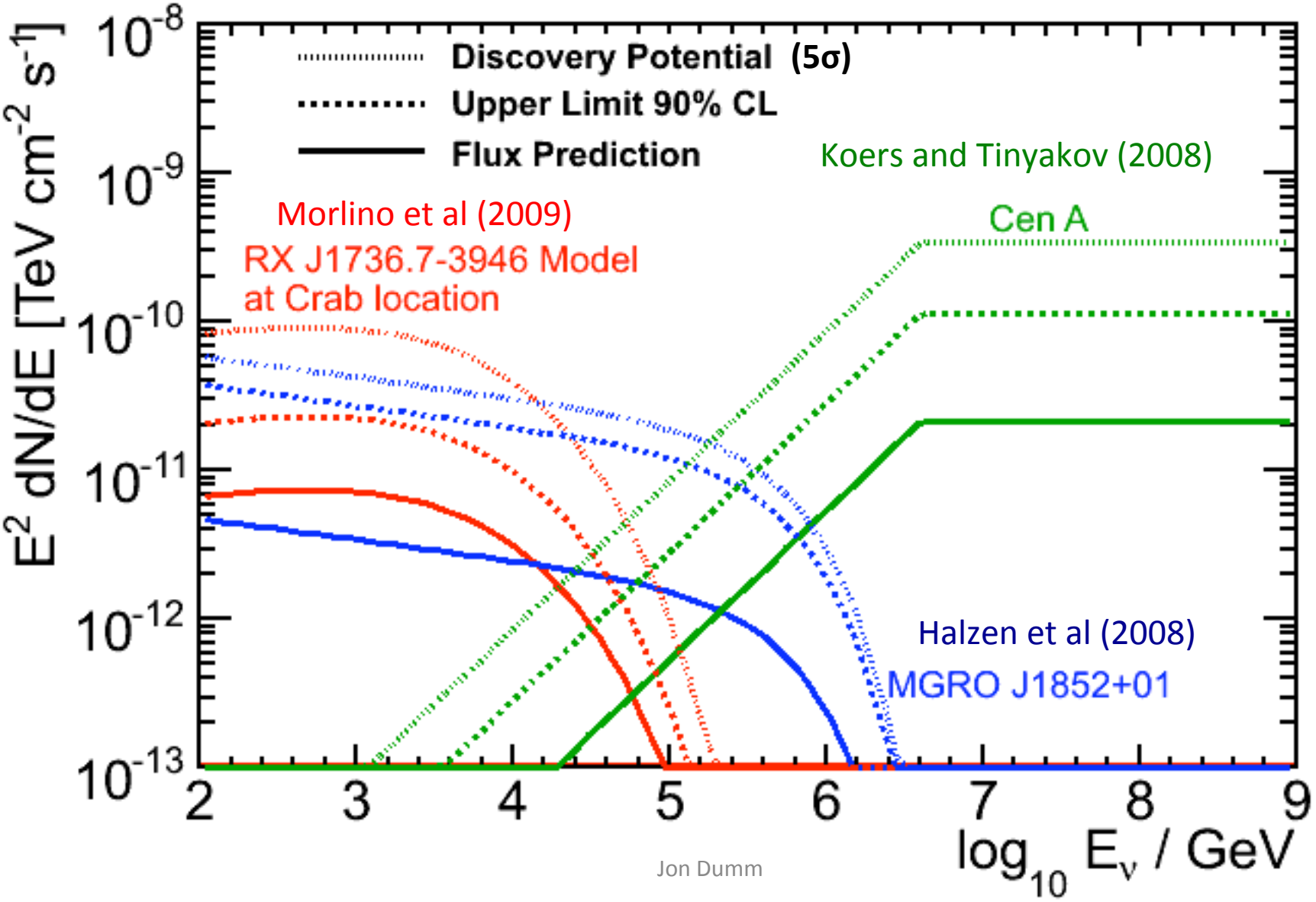


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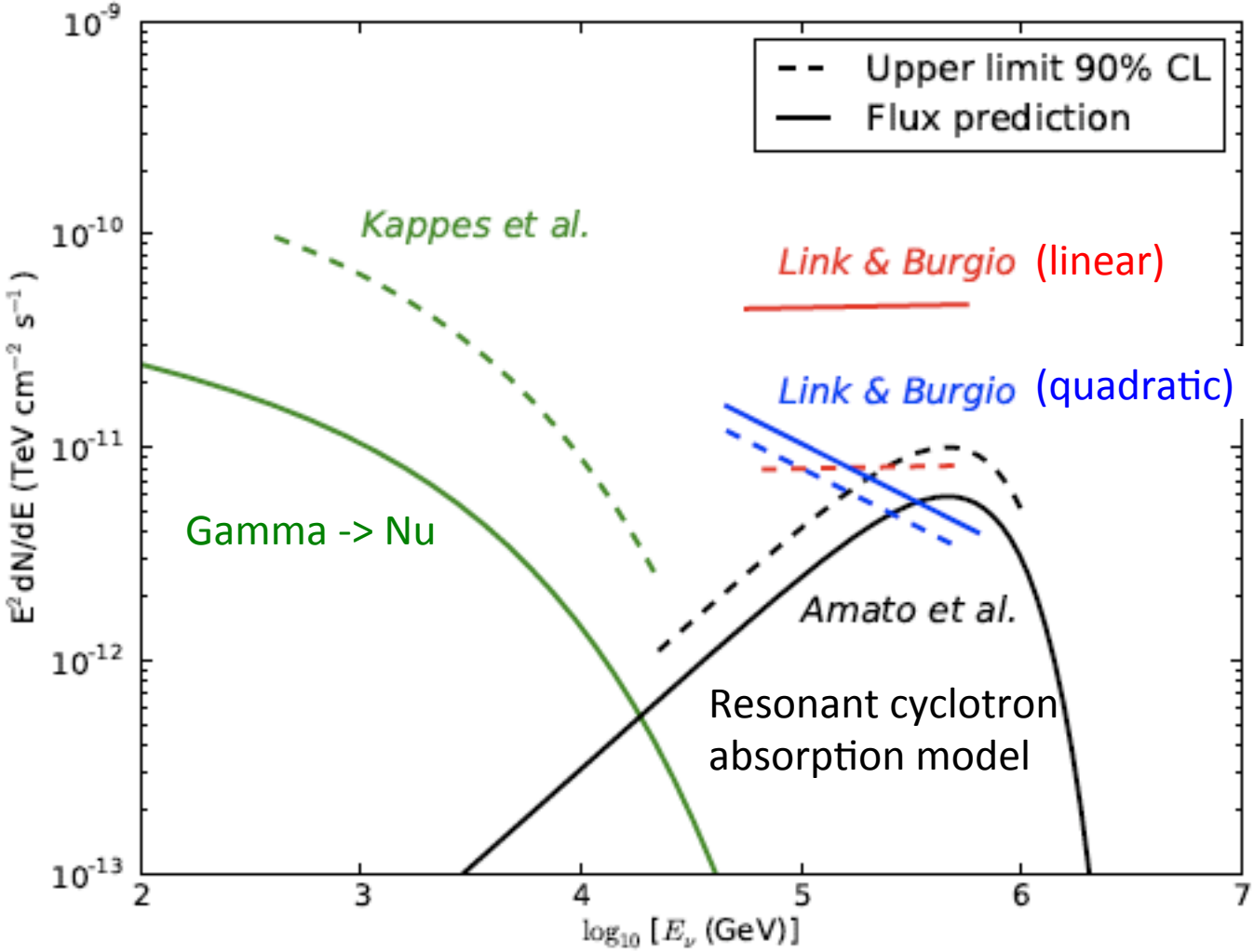
$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$



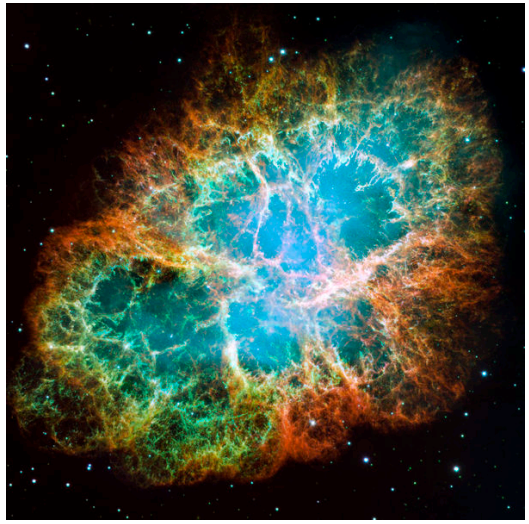
Model Testing - 40 strings

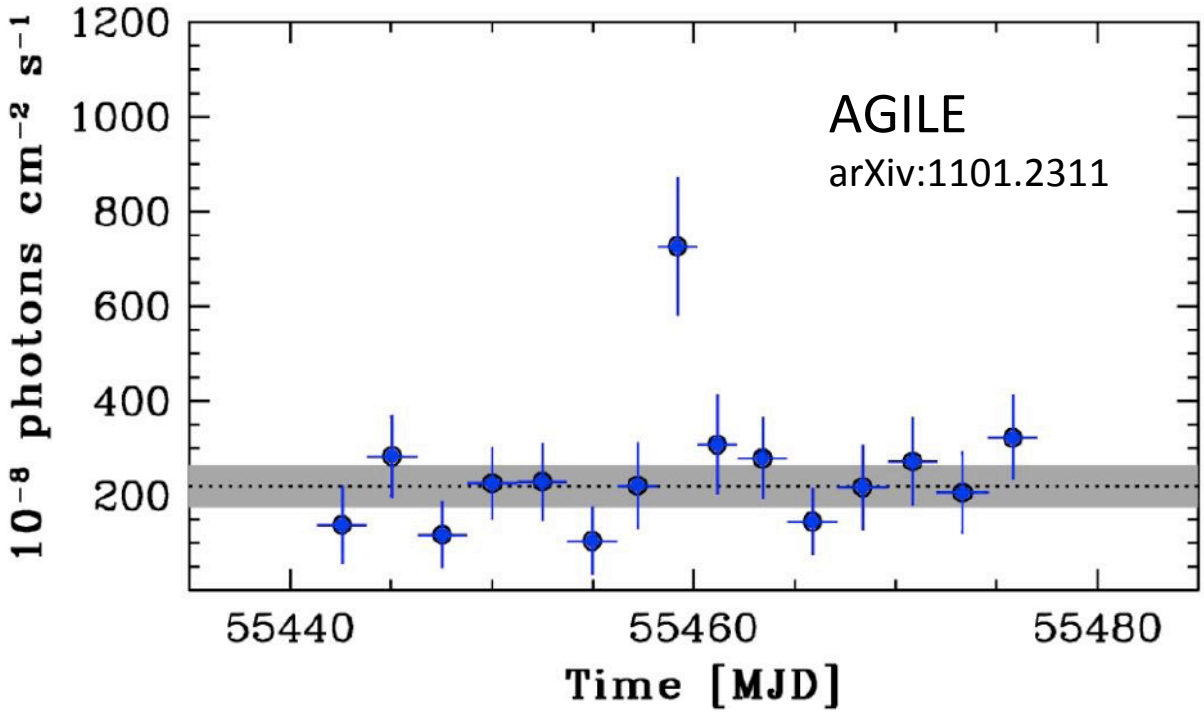


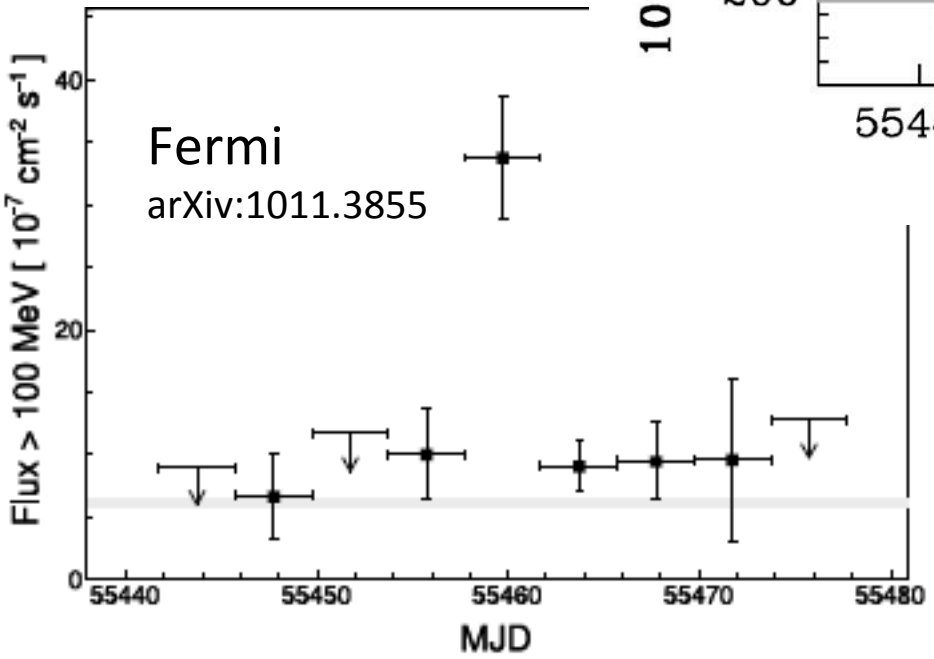
Model Testing: Crab Nebula - 40 strings



The Crab: A Standard Candle?



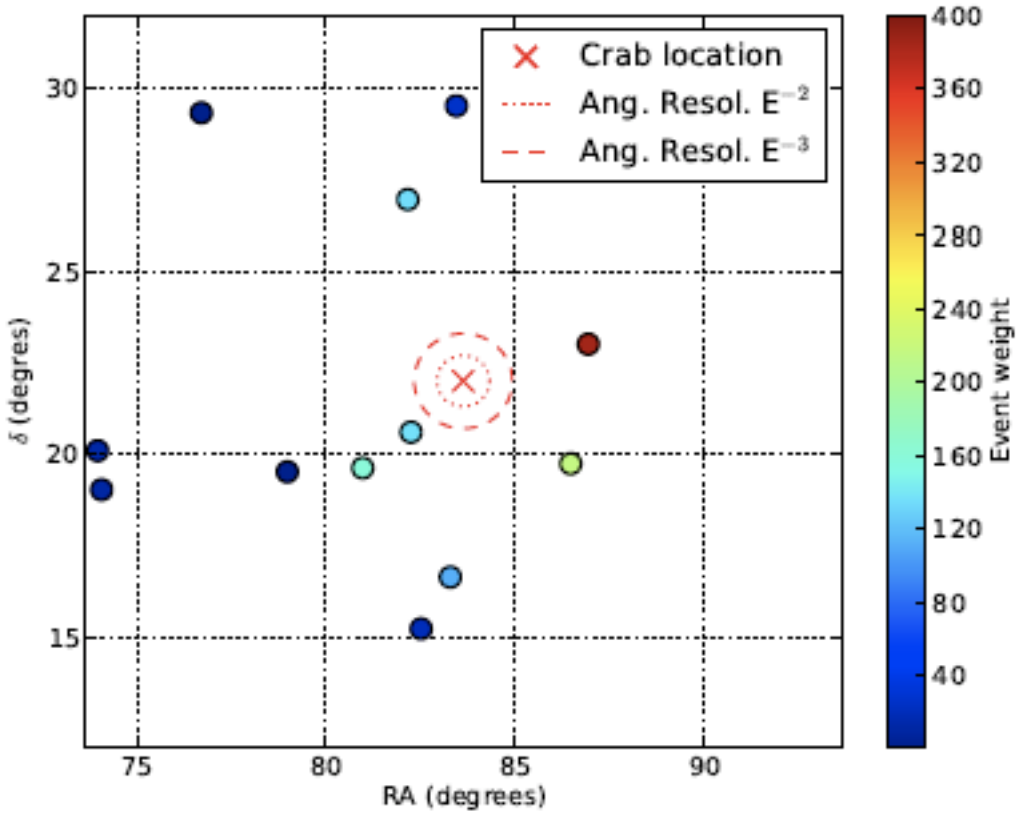




Last September: Crab Nebula flared to ~3-6 times its average flux for several days

Confirmed by ARGO in TeV but not HESS/VERITAS

IceCube 79-string Crab Flare Results



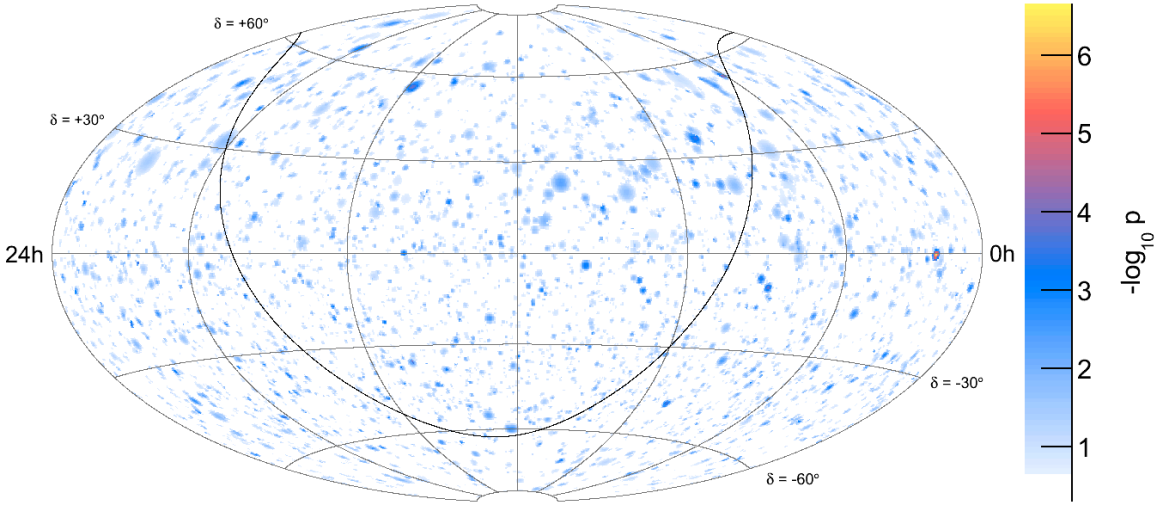
- We performed a dedicated, 'fast' unblinding for this Crab flare
- Resulted in an under-fluctuation – no signal

Preliminary:
Paper in progress

Time-Dependent All-Sky Search (IceCube-59)



M Baker et al., ICRC 2011



Preliminary

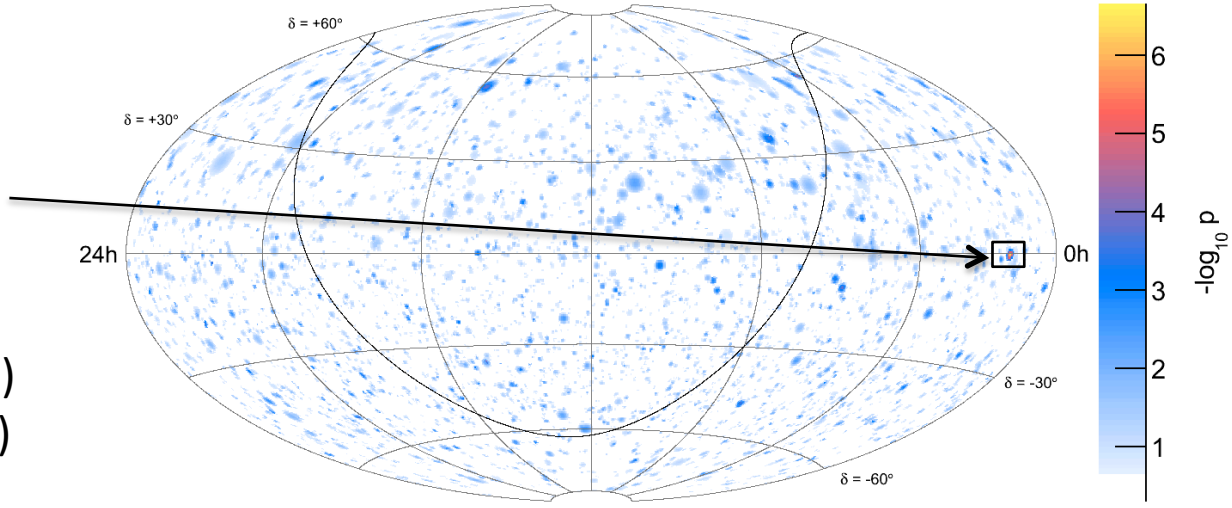
$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-|\vec{x}_i - \vec{x}_s|^2/2\sigma_i^2} \cdot P(E_i|\gamma) \cdot \frac{1}{\sqrt{2\pi}\sigma_T} e^{-(t_i - T_0)^2/2\sigma_T^2}$$

$$\mathcal{L}(n_s, \gamma, \sigma_T, T_0) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \sigma_T, T_0) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

Time-Dependent All-Sky Search (IceCube-59)

M Baker et al., ICRC 2011

Most significant spot:
r.a. = 21.35°
dec. = -0.25°
n_s = 14.5
γ = -3.9
σ_T = 5.5 days (FWHM 13 days)
T_0 = 55259 MJD (2010 Mar. 4)
-$\log_{10}$ p-value = 6.69



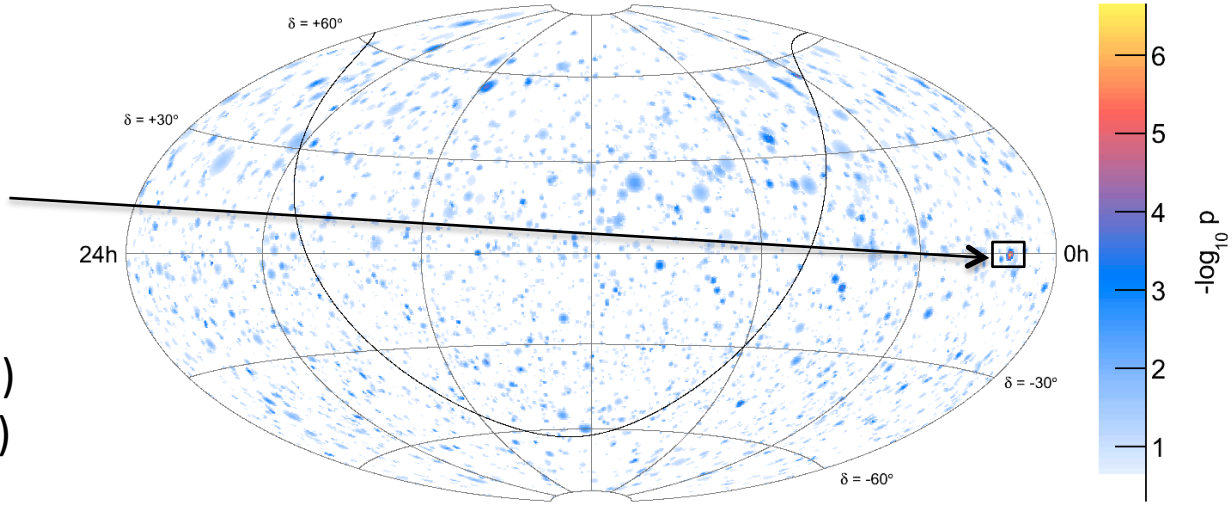
Preliminary

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Time-Dependent All-Sky Search (IceCube-59)

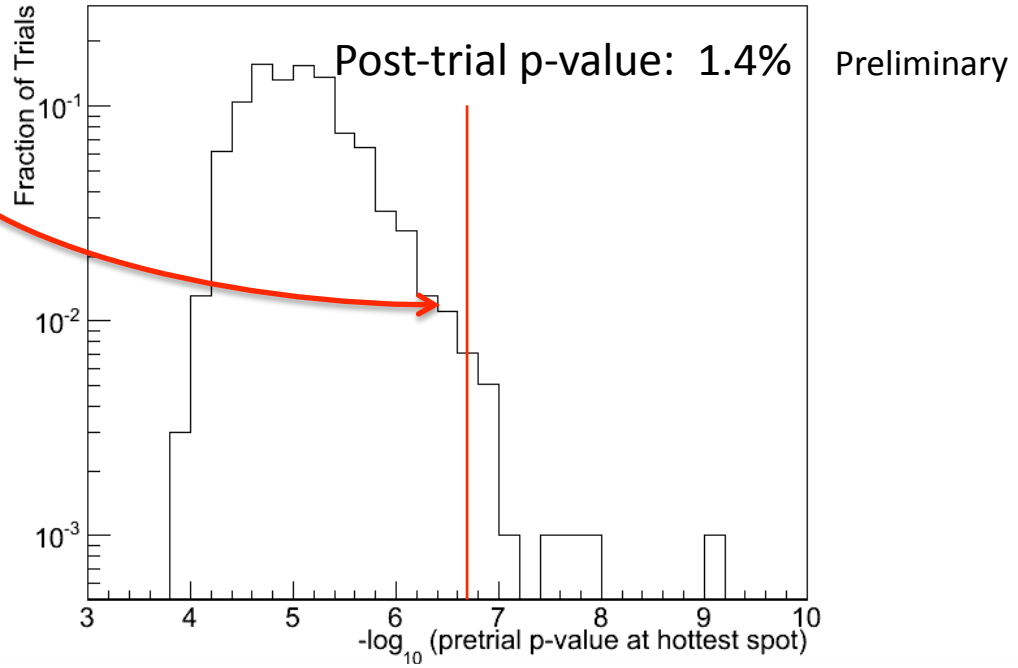
M Baker et al., ICRC 2011



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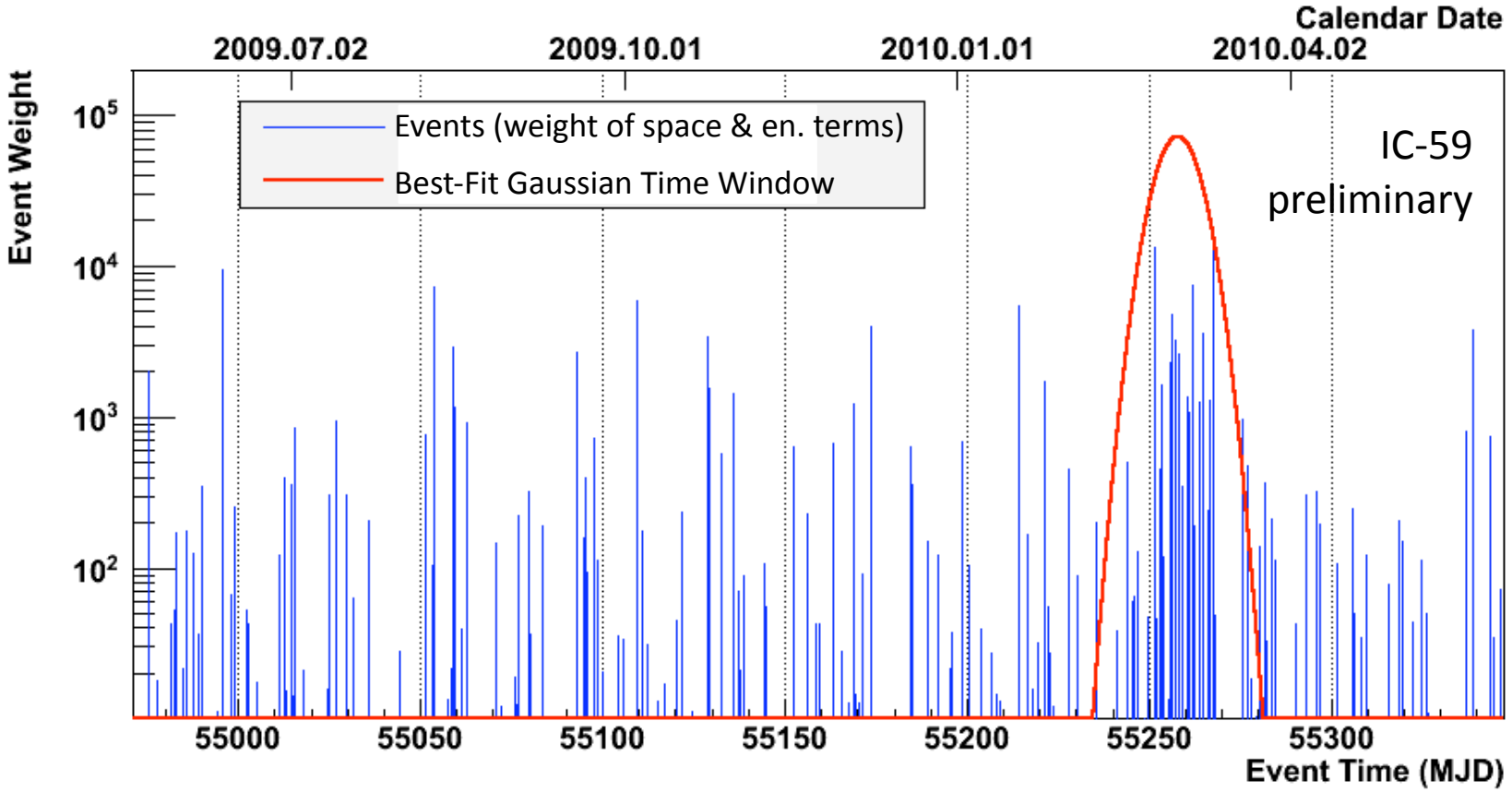
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$$\mathcal{L}(n_s, \gamma, \sigma_T, T_0) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \sigma$$



Time-Dependent All-Sky Search (IceCube-59)

M Baker et al., ICRC 2011



Most significant spot: r.a. = 21.35° dec. = -0.25°

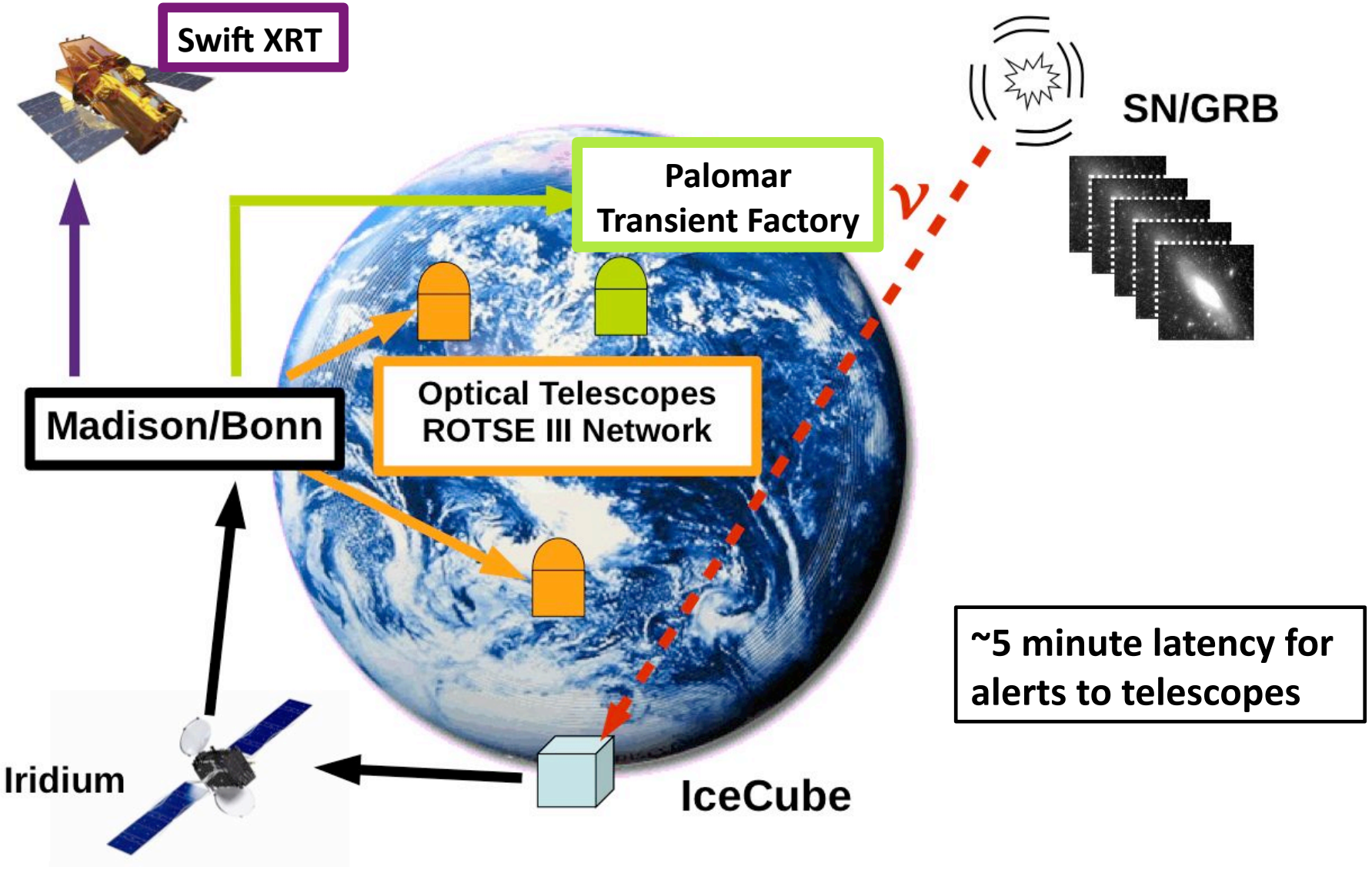
n_s = 14.5

γ = -3.9

σ_T = 5.5 days (FWHM 13 days)

T_0 = 55259 MJD (2010 Mar. 4)

IceCube Optical and X-Ray Follow-Up Programs



IceCube Optical Follow-Up Program



Reduce Background - by **6 orders of magnitude** at South Pole:

~ **2 kHz detector trigger level** (cosmic ray muons)

Use fast online reconstructions and event selections

~ 2 mHz (atmospheric neutrinos)

Generate Alerts – select **Multiplets:**

Two (or more) events arriving:

- within **100 seconds,** and
- with angular separation of **< 4°**

Rate of multiplets due to atm. bkg. **~ 25 per year**

or, with **tighter cuts** for < 25 per year

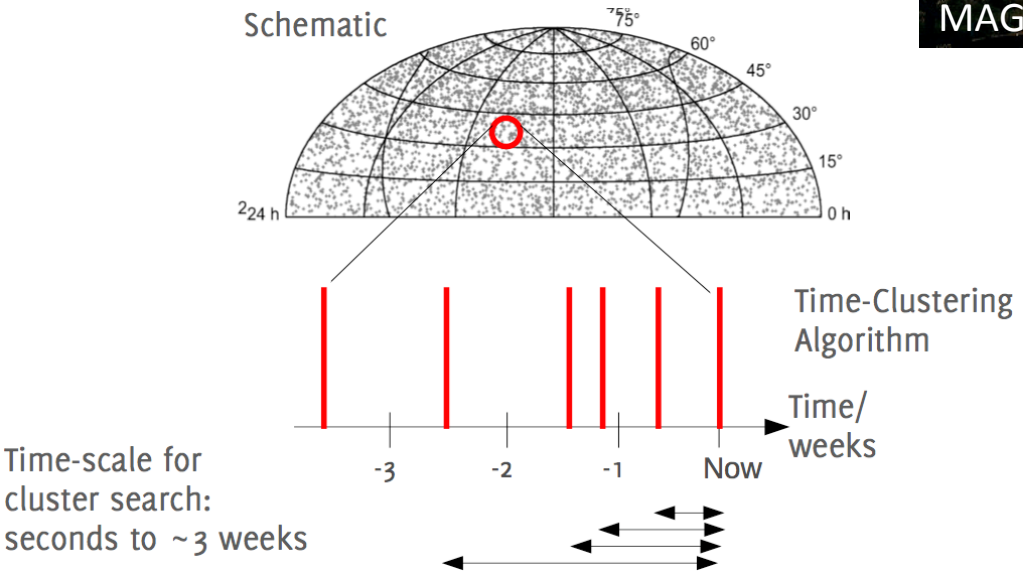
Neutrino-Triggered Target of Opportunity Program

Same online stream as Optical Follow-Up, But:

- monitors **specific list of variable sources**
- evaluates on **sliding scale, up to 3-weeks** (typical of e.g. AGN flares)
- send ~ one to few alerts per year

Operating with MAGIC, VERITAS since summer 2011





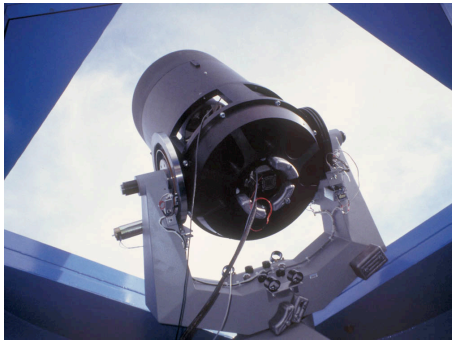


R. Franke, E. Bernardini et al., ICRC 2011

Current IceCube Burst Follow-Up Programs

Telescope	Approx. Alert Rate	IceCube Triggered since
ROTSE	**30 alerts / yr**	**Dec. 2008**
Palomar Transient Factory	**10 alerts / yr**	**Jul. 2010**
Swift XRT	**7 alerts / yr**	**Feb. 2011**

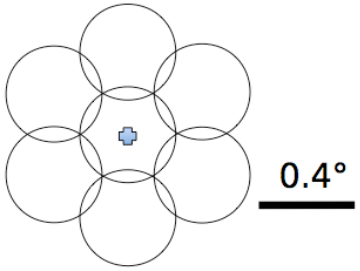
FoV: 1.85° x 1.85°
Limiting Magnitude: 18.5

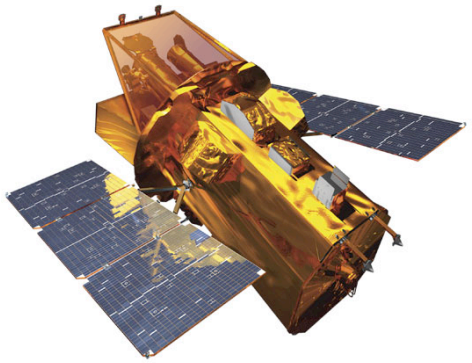


FoV: 3.5° x 2.3°
Limiting Magnitude: 20.6



Tiled observations to match IceCube PSF



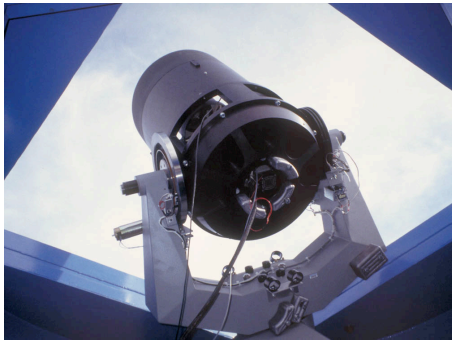


IceCube Optical Follow-Up Program

Telescope	Approx. Alert Rate	IceCube Triggered since
ROTSE	**30 alerts / yr**	**Dec. 2008**

FoV: 1.85° x 1.85°

Limiting Magnitude: 18.5



2008 Dec. 16 – 2009 Dec. 31 (IceCube 40- and 59-string configurations)

31 IceCube alerts forwarded to ROTSE
-5 too close to sun
-7 too close to galactic plane
-2 good data not collectable
= 17 good optical follow-ups

When ROTSE receives alert: Prompt observation – thirty 60 sec exposures
Follow-up observations – each night, next 14-24 nights

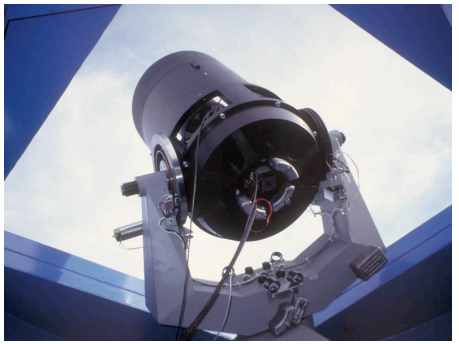
Analysis: Image subtraction to find optical SN counterpart

IceCube Optical Follow-Up Program

Telescope	Approx. Alert Rate	IceCube Triggered since
ROTSE	**30 alerts / yr**	**Dec. 2008**

FoV: 1.85° x 1.85°

Limiting Magnitude: 18.5



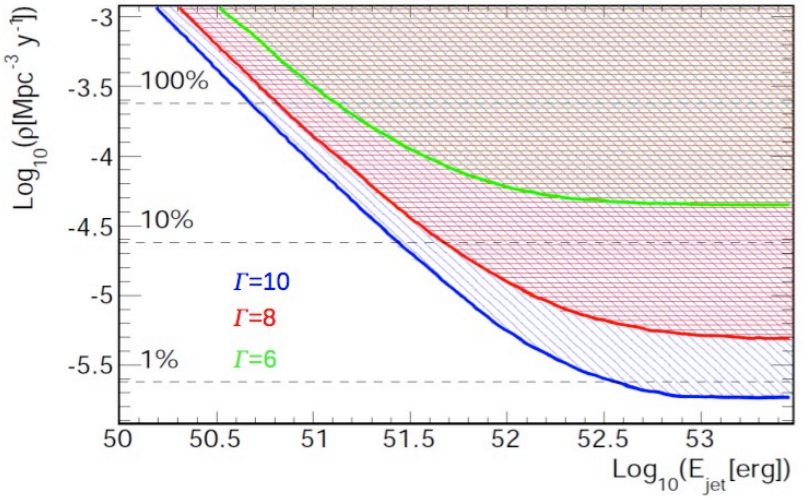
No optical counterpart observed.

First limits on hadronic jet production in core-collapse SNe jet derived.

A. Franckowiak et al., ICRC 2011

Limit on core collapse supernova (CCSN) jet model (90% confidence level) depending on:

- jet energy E_{jet}
- Lorentz boost factor Γ
- rate of CCSN with jets ρ

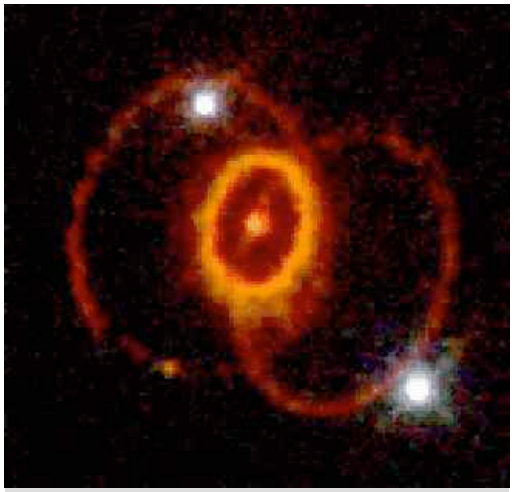


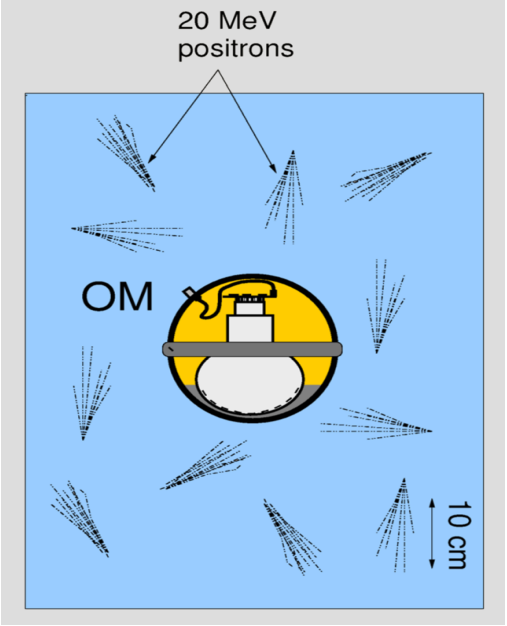
Preliminary

Stringent limits for higher boost factors in soft jet model:

< 7.8% of all SNe have a jet with Γ=10 and a typical jet energy of $E = 3 \cdot 10^{51}$ erg.

Supernova MeV Neutrino Detection in IceCube





Burst of low-energy (MeV) neutrinos
from core collapse supernovae

Neutrinos interact in the ice:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

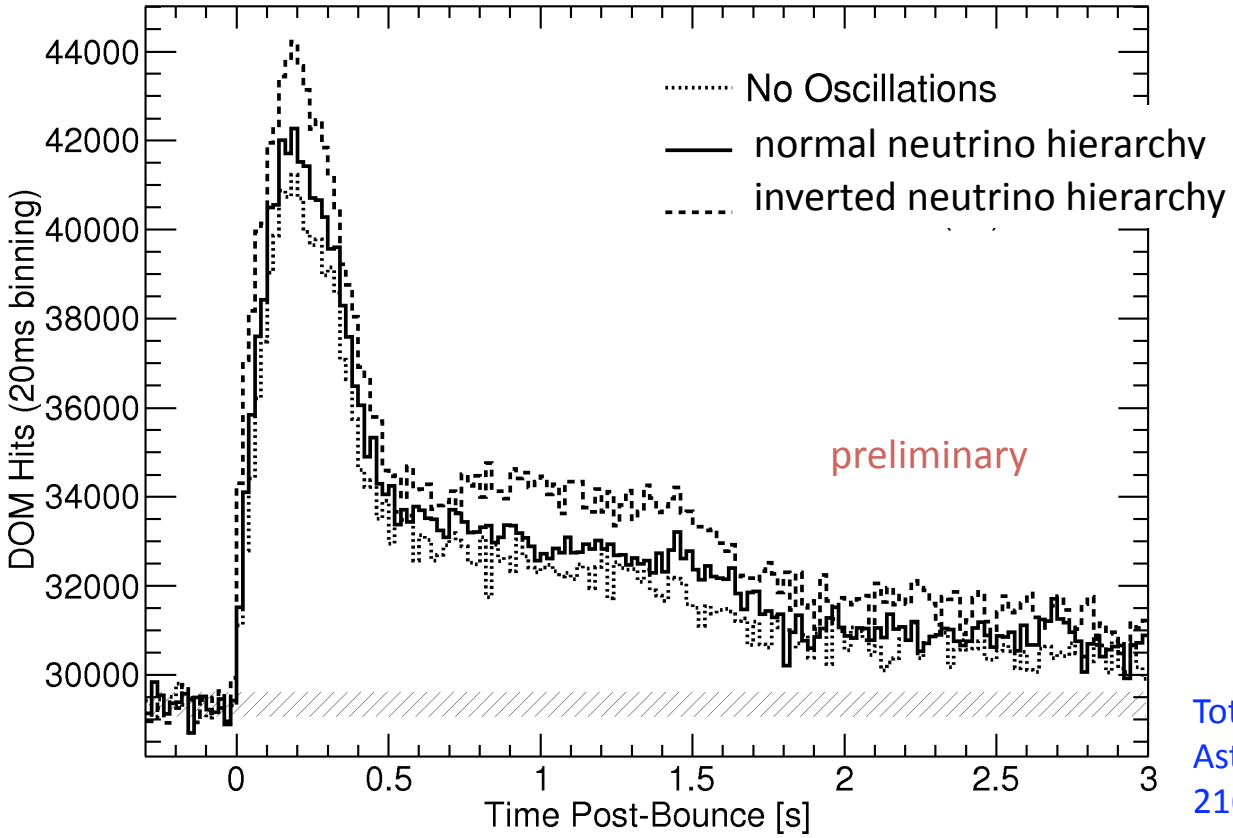
The produced positron is emitted almost isotropically

Short paths of ~25 MeV positrons do not create detectable “tracks.” But their Cherenkov emission increases the **noise rate**.

Example: SN MeV Neutrino Detection in IceCube

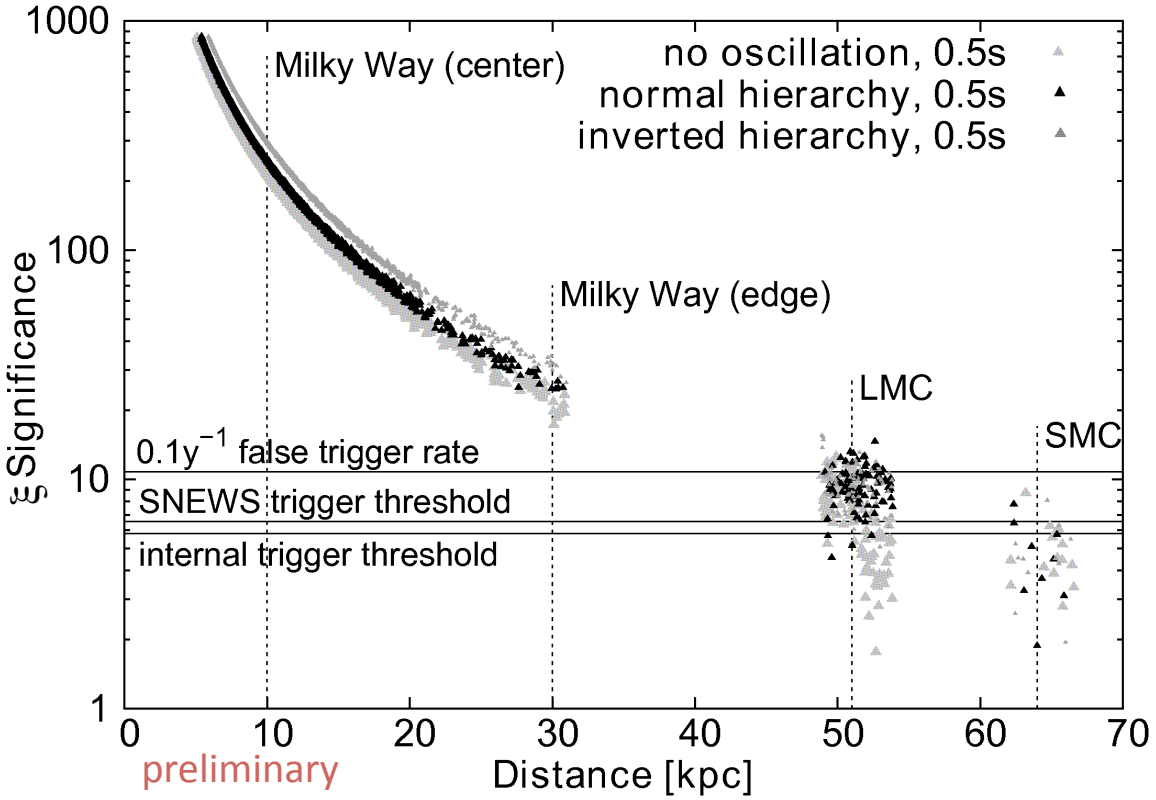
Lawrence Livermore model, 10 kpc distance (e.g. a SN at galactic center)

IceCube Monte Carlo with time-dependent energy spectra incorporated



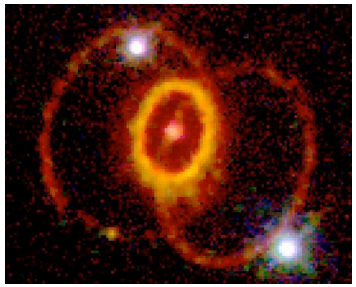
Totani et al.
Astrop. Phys. 496, 216 (1998)

Sensitivity / Reach of SN Detection



ξ > 25 in Galaxy

ξ ~ 3-10 in Magellanic clouds



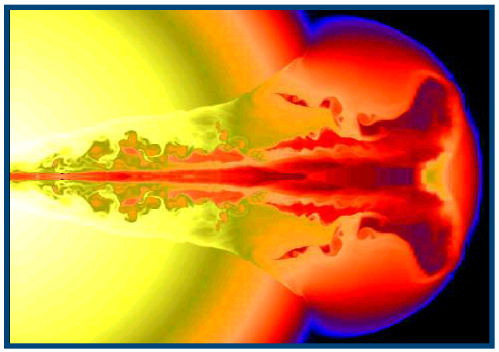
SN 1987A in Large Magellanic Cloud

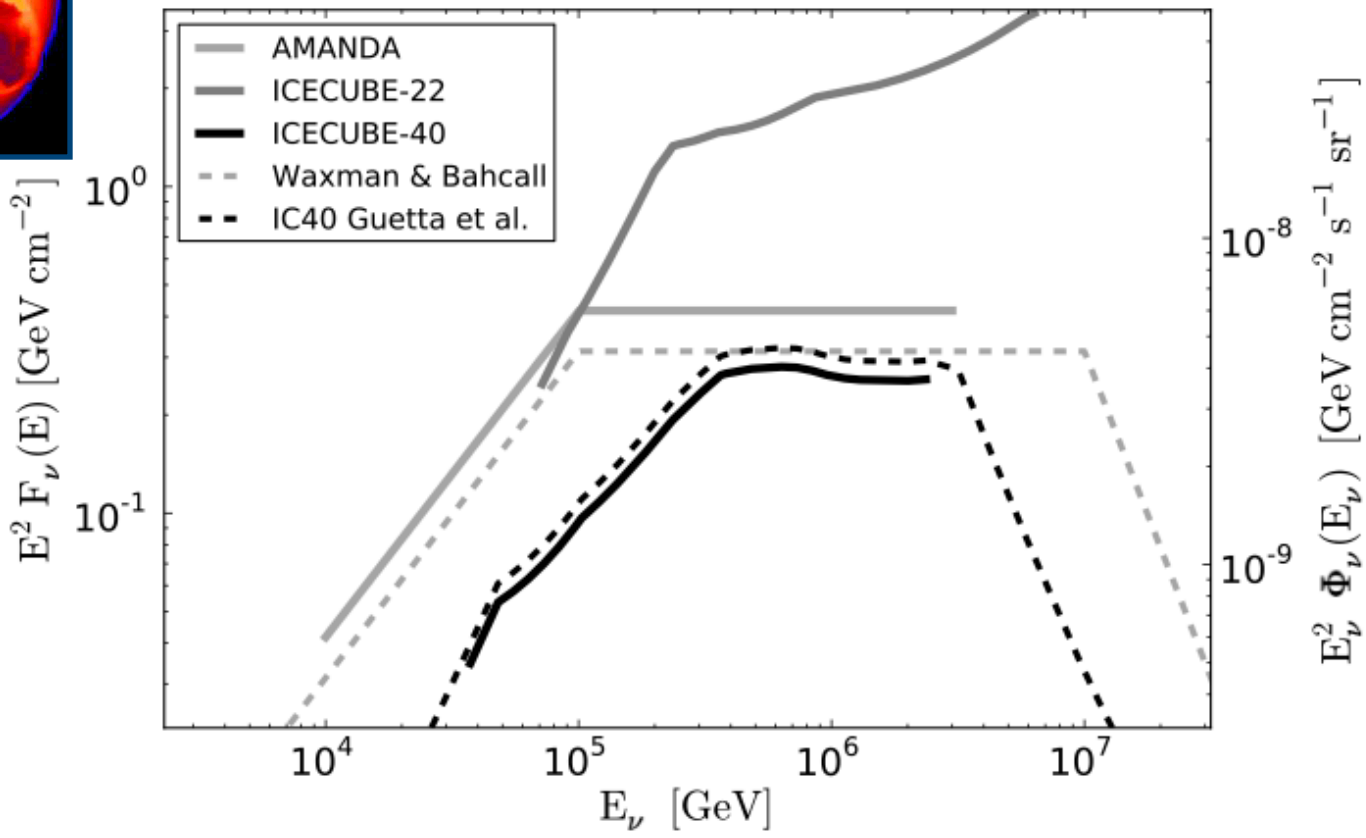
Since 2009:

IceCube sending real-time datagrams to SNEWS SuperNova Early Warning System

Gamma Ray Bursts as the sources of Cosmic Rays?

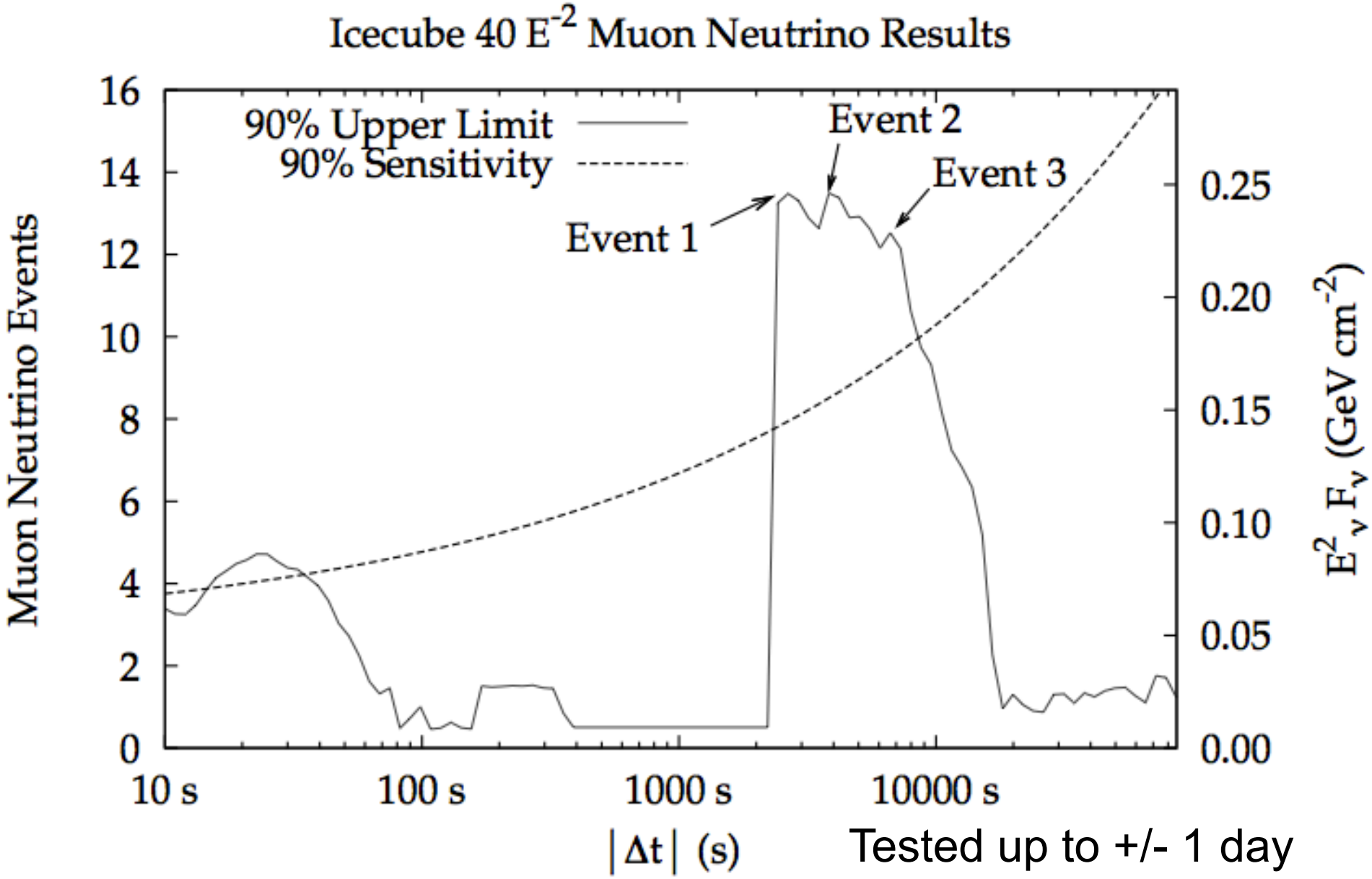
Fermi and Swift burst alerts are analyzed for coincident neutrinos in IC





Beginning to rule out GRBs as CR sources with ½ of IC

Gamma Ray Bursts as the sources of Cosmic Rays?



Tested up to +/- 1 day of GRB

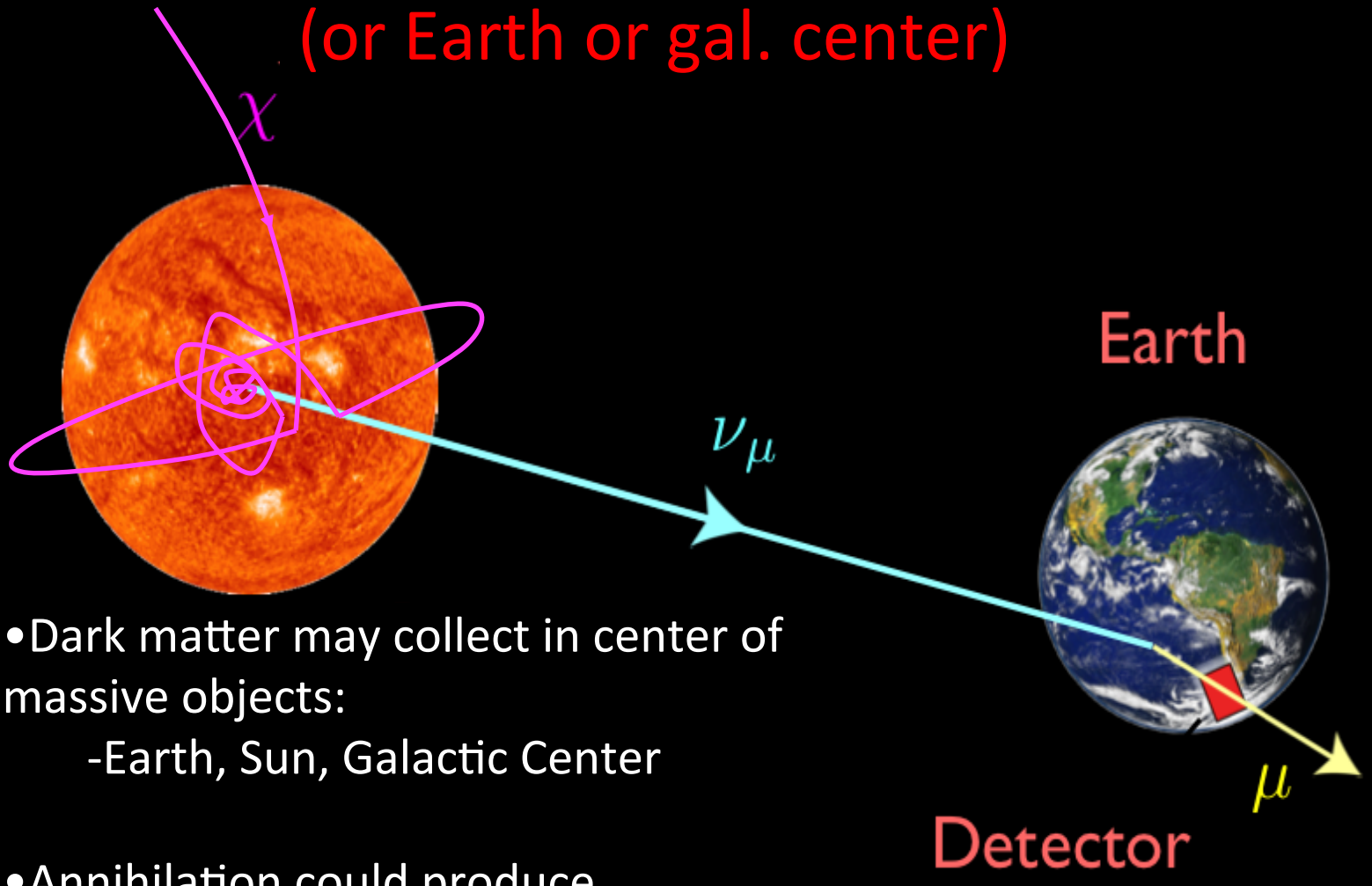
Neutrinos continue to surprise!

Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light $(v\text{-}c)/c = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$.

Posted 3 weeks ago on arXiv…
But we also have SN1987a neutrinos that arrived on time…

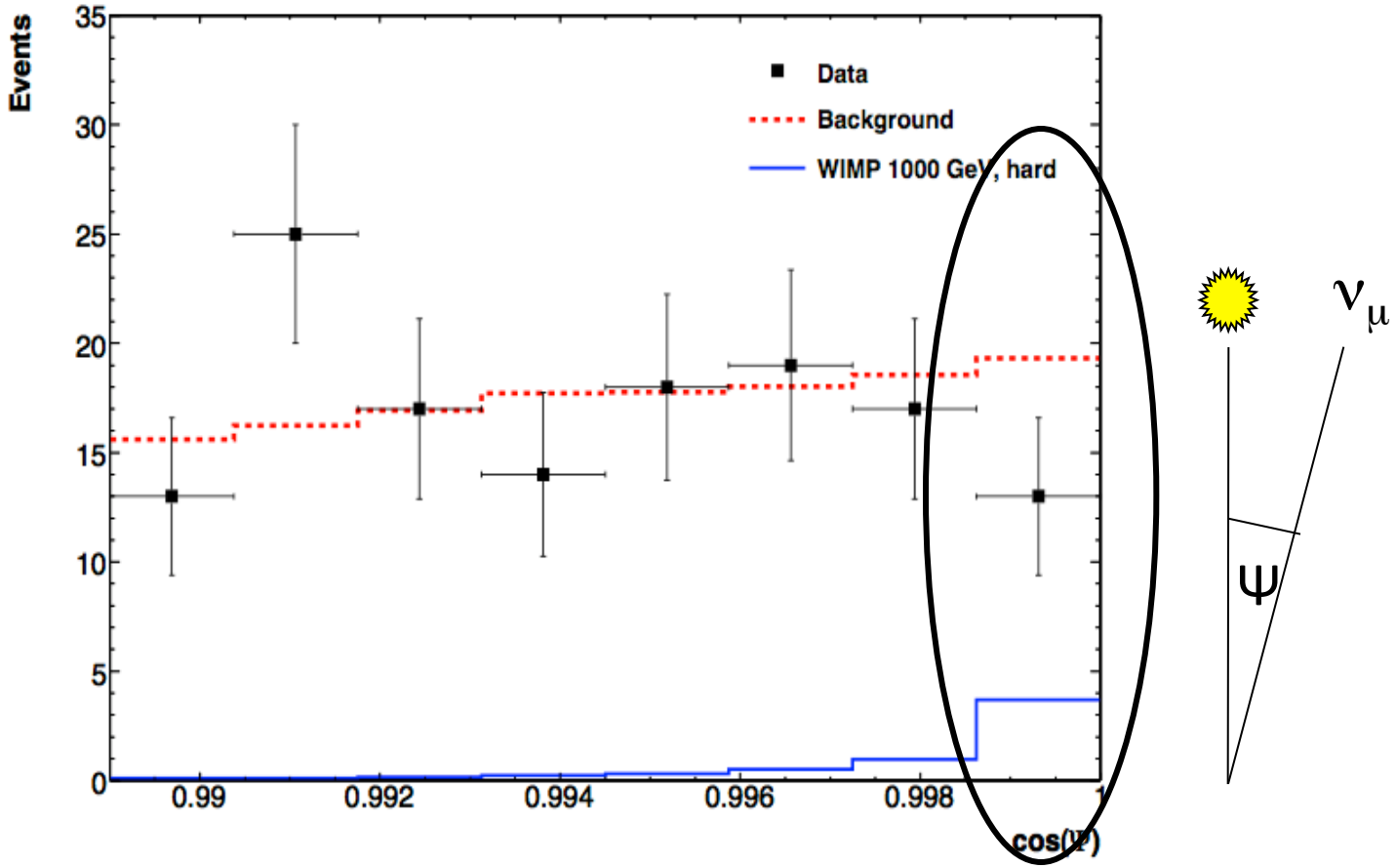
Indirect Detection of Dark Matter:
HE Neutrinos from the sun
(or Earth or gal. center)



- Dark matter may collect in center of massive objects:
  - -Earth, Sun, Galactic Center

- Annihilation could produce neutrinos, observable by IceCube

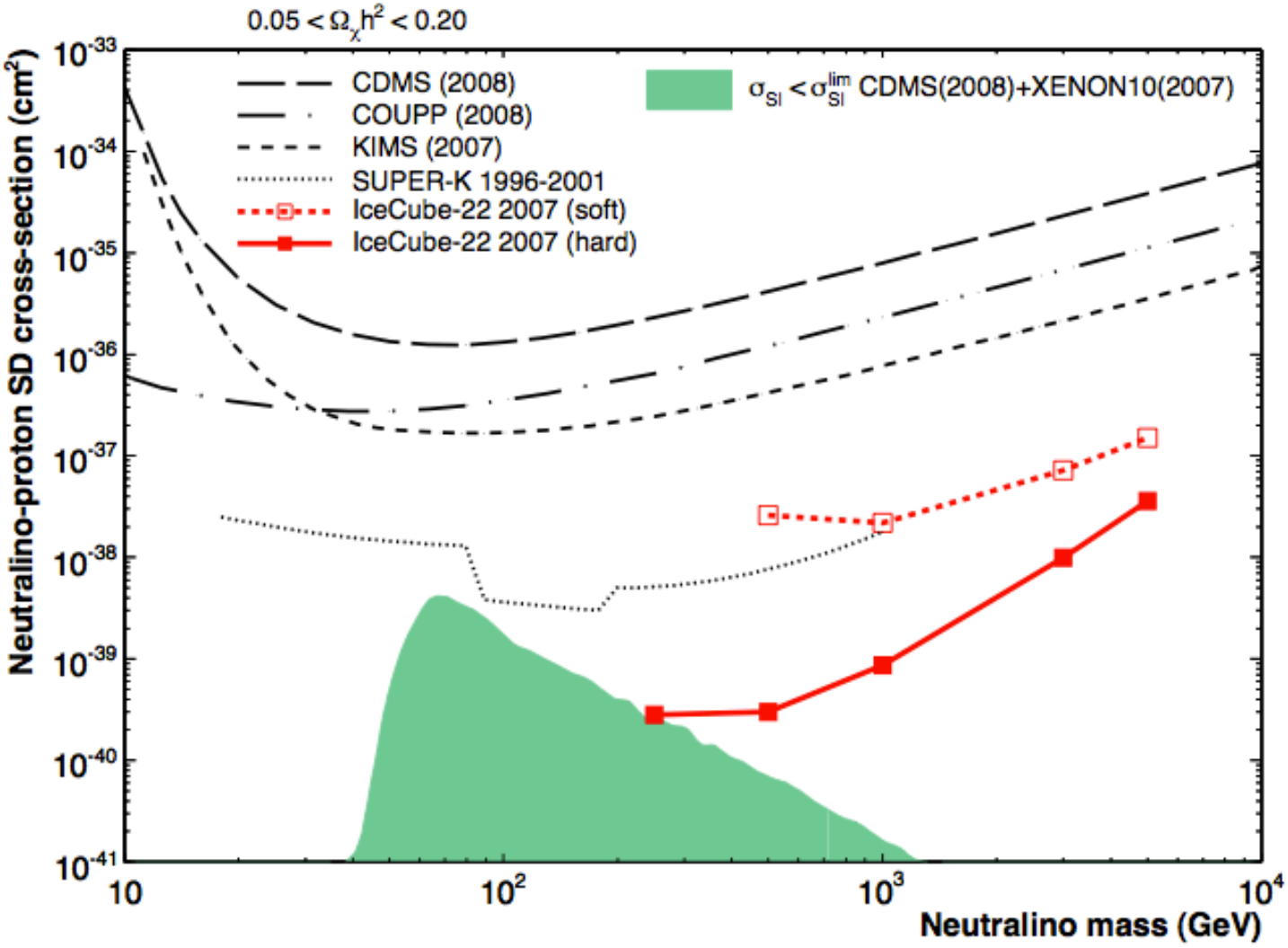
Indirect Detection of Dark Matter:
HE Neutrinos from the sun



Observation consistent with expectation from atmospheric neutrinos⇒upper limit

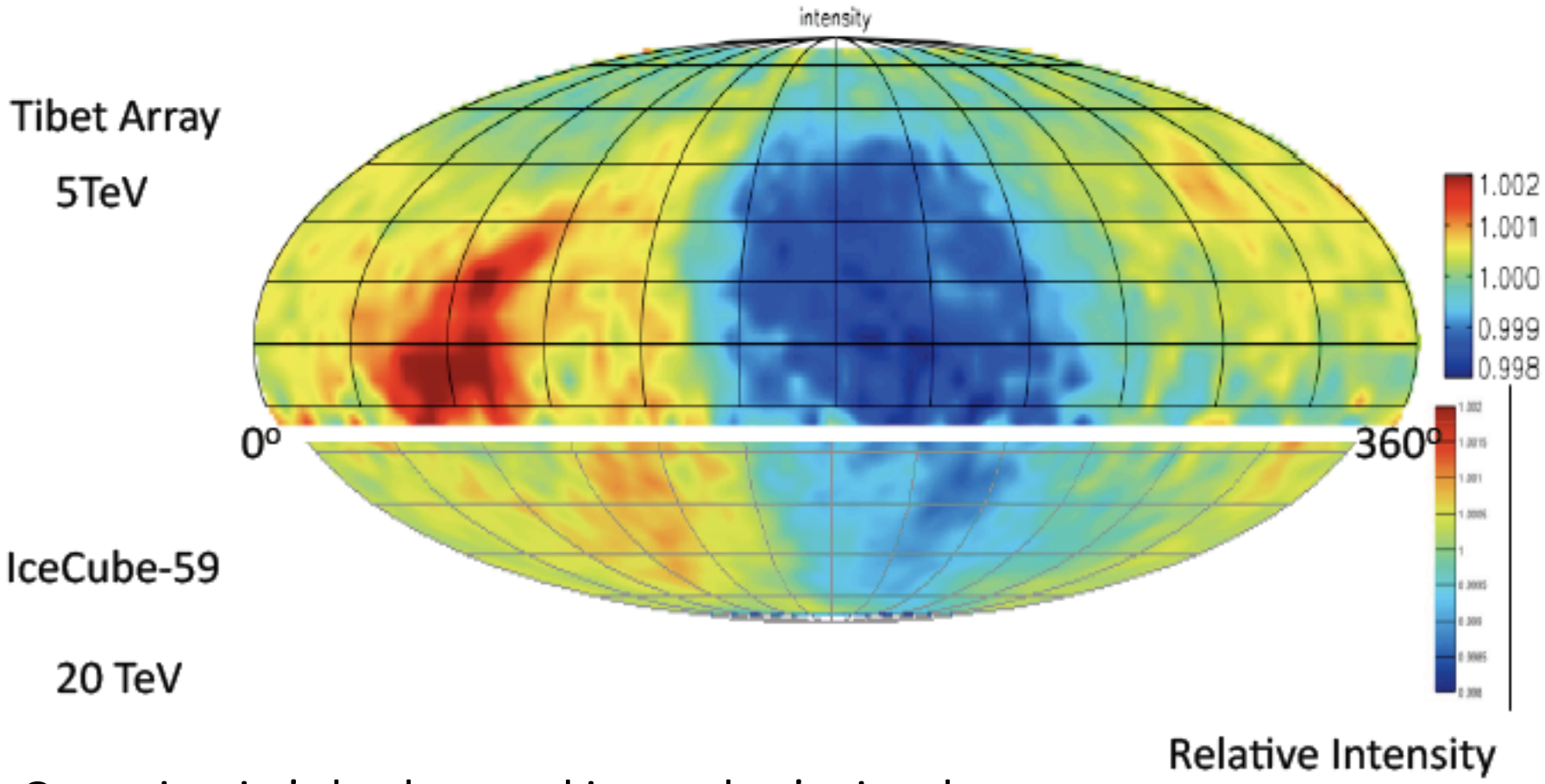
Abbasi et al., PRL, 2009

Indirect Detection of Dark Matter:
HE Neutrinos from the sun

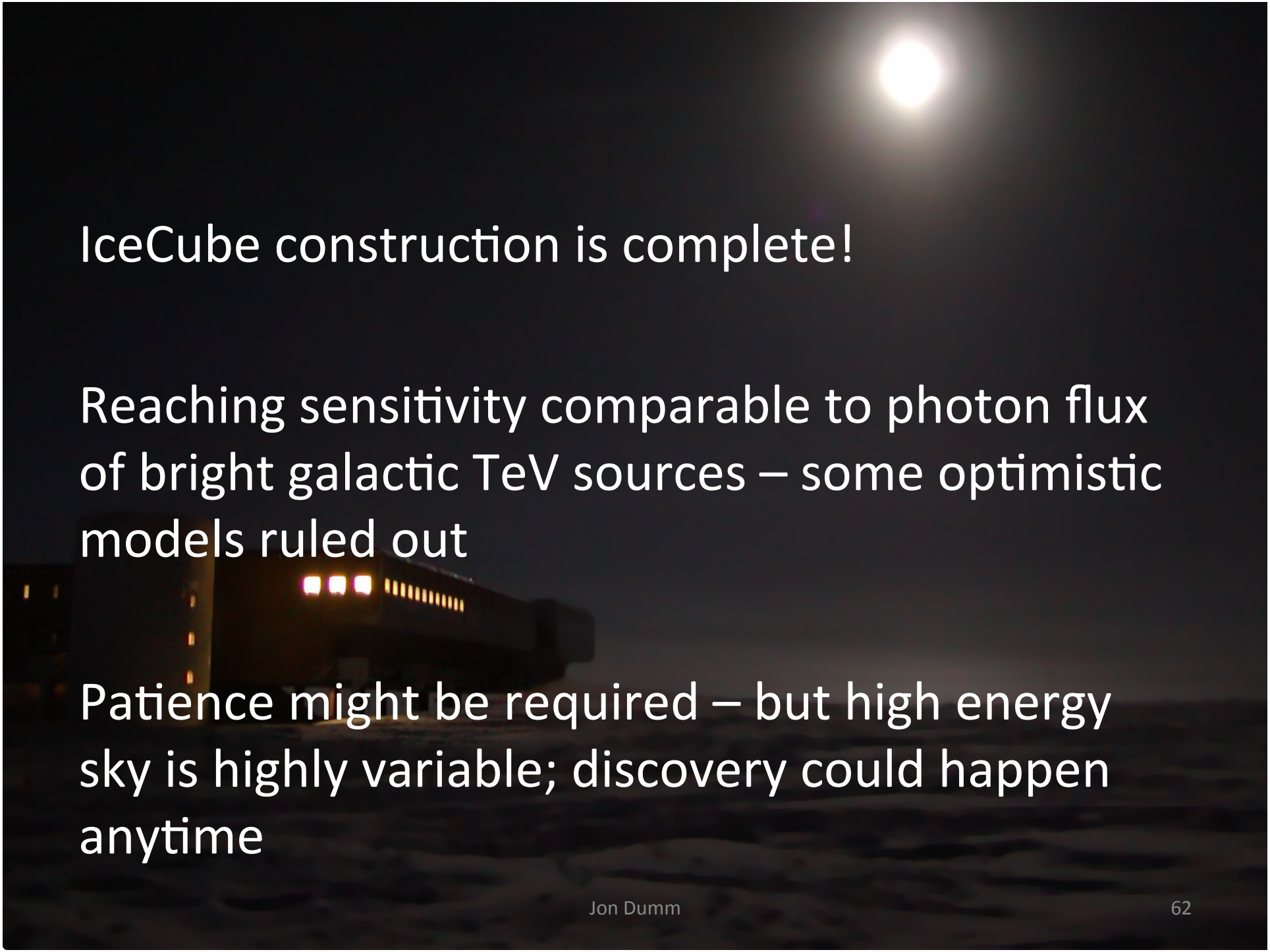


Abbasi et al., PRL, 2009

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?



IceCube construction is complete!

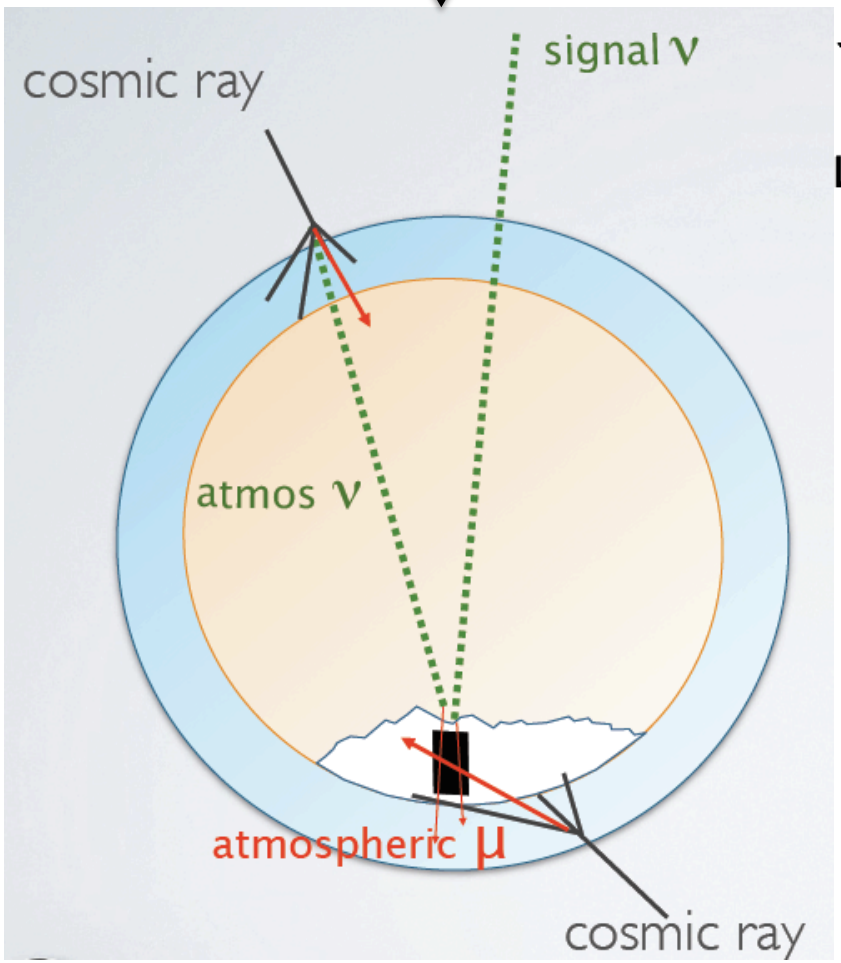
Reaching sensitivity comparable to photon flux of bright galactic TeV sources – some optimistic models ruled out

Patience might be required – but high energy sky is highly variable; discovery could happen anytime

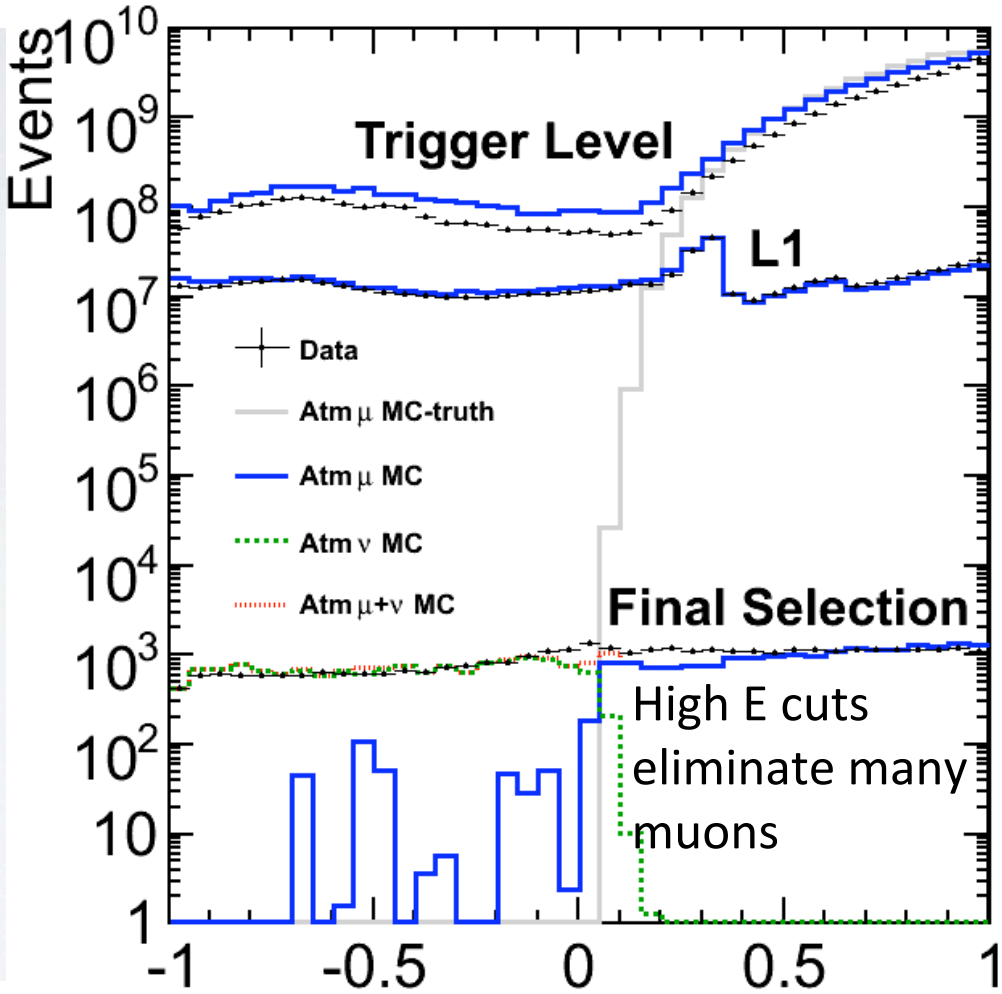
Backup Slides

Backgrounds

cos θ = -1



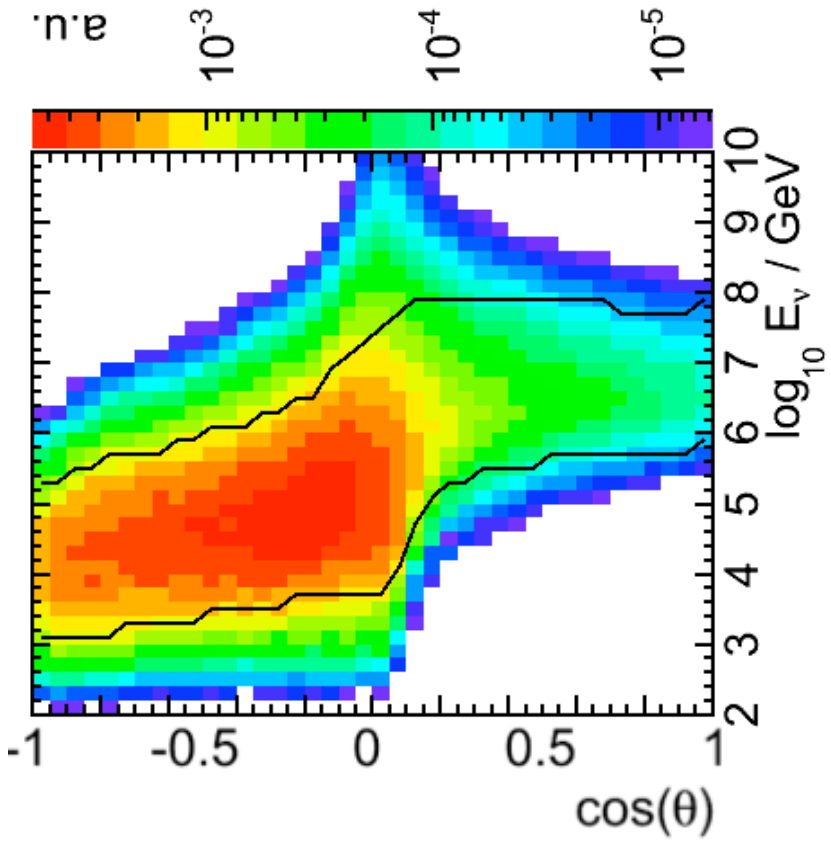
cos θ = +1



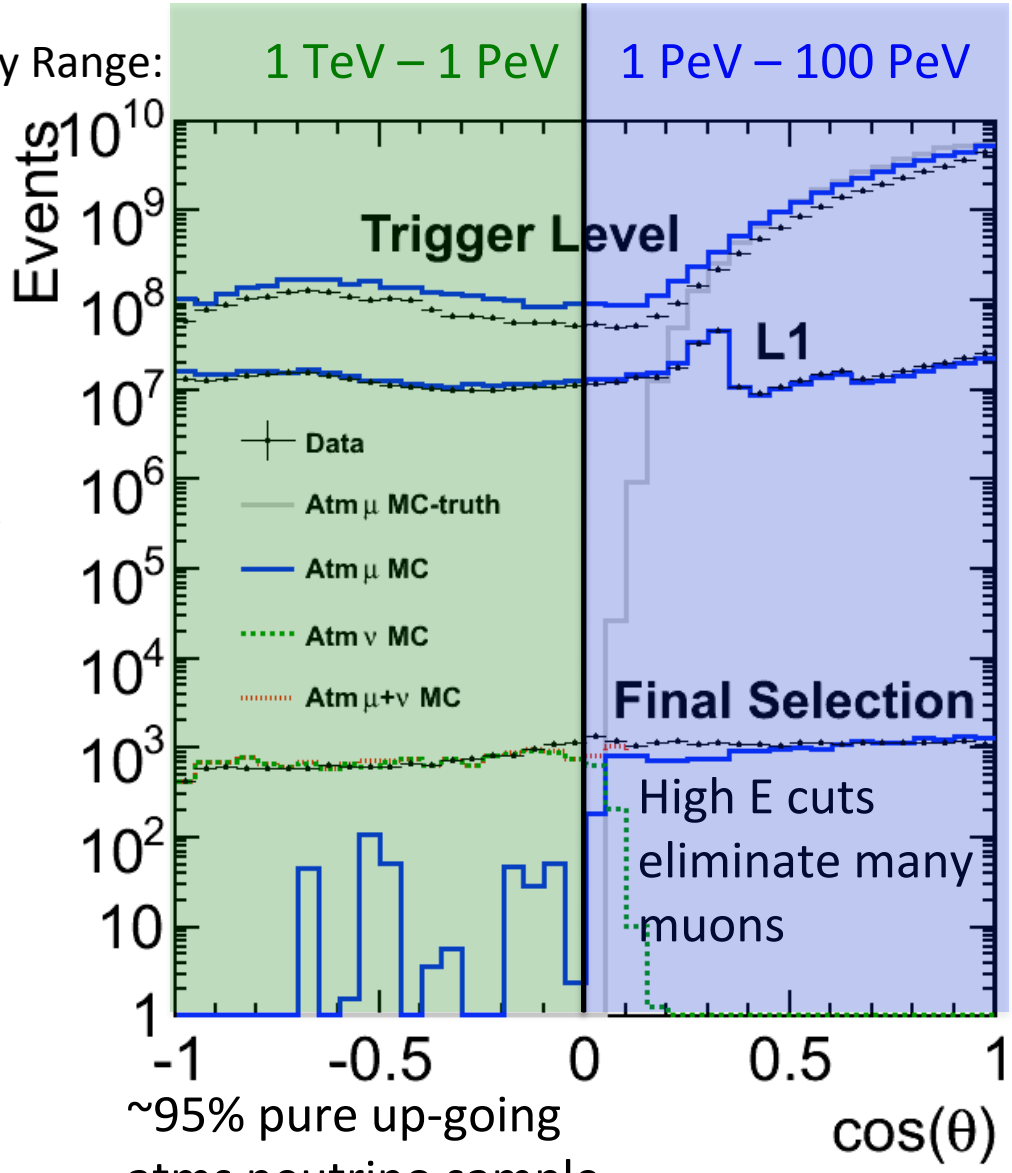
~95% pure up-going
atms neutrino sample

Backgrounds

Sensitivity Energy Range:

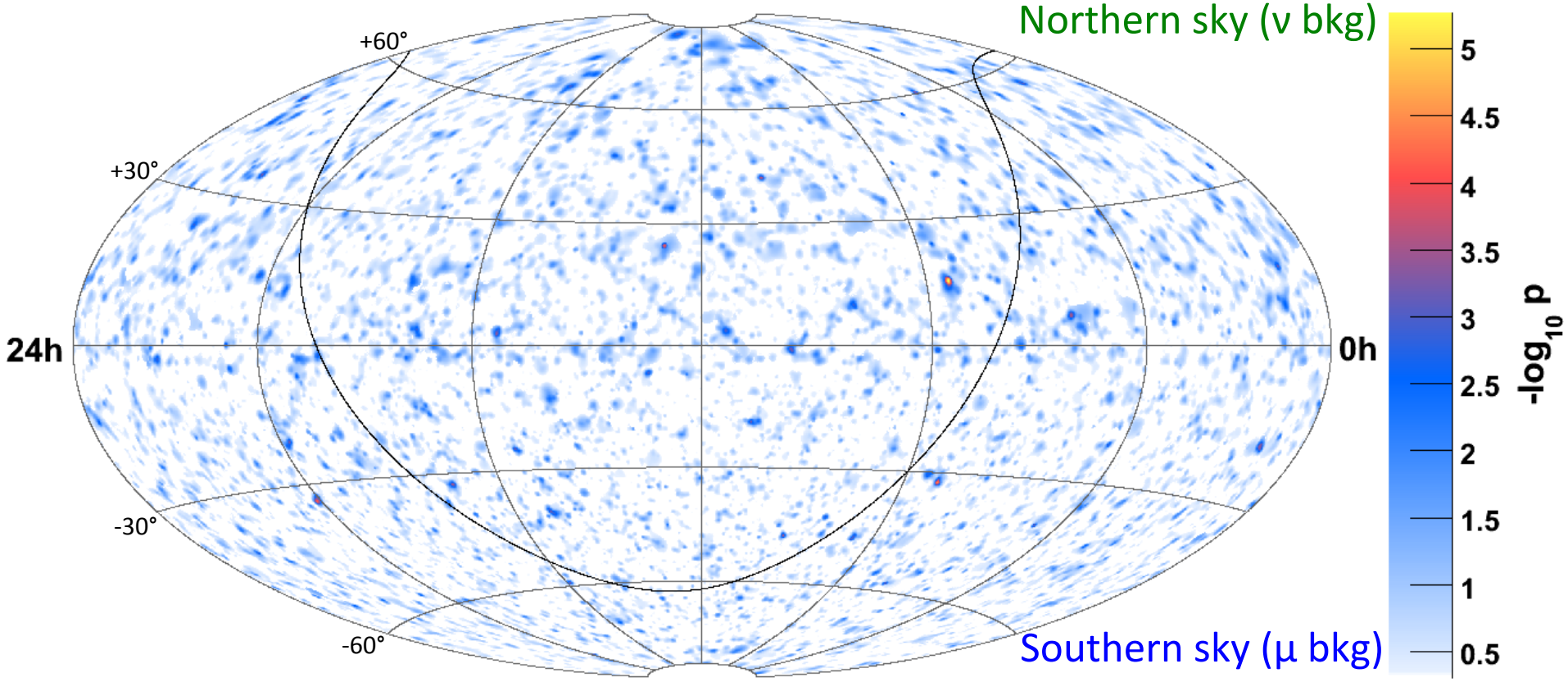


E^{-2} neutrino signal with 90% containment intervals



~95% pure up-going atms neutrino sample

40-string All-Sky Results



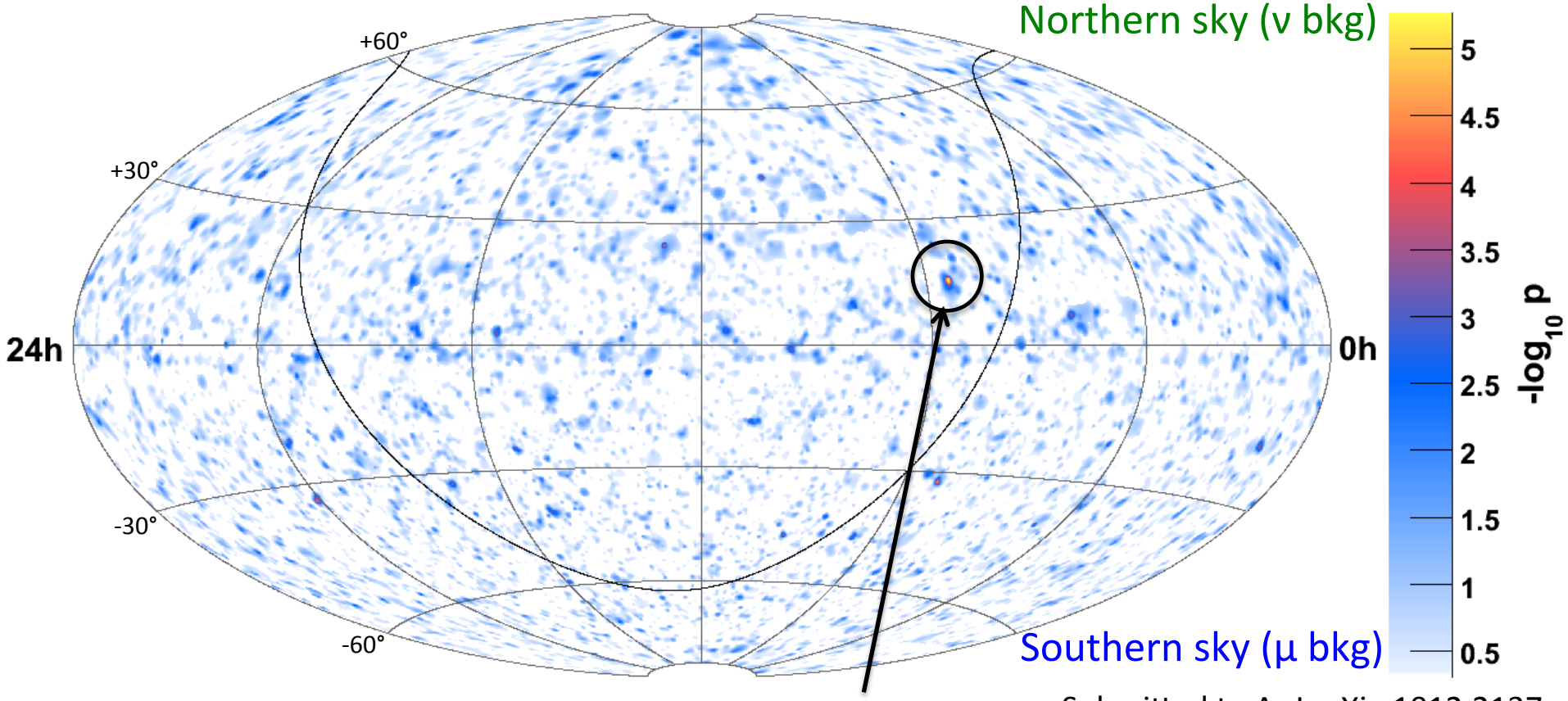
Accepted by ApJ arXiv:1012.2137

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

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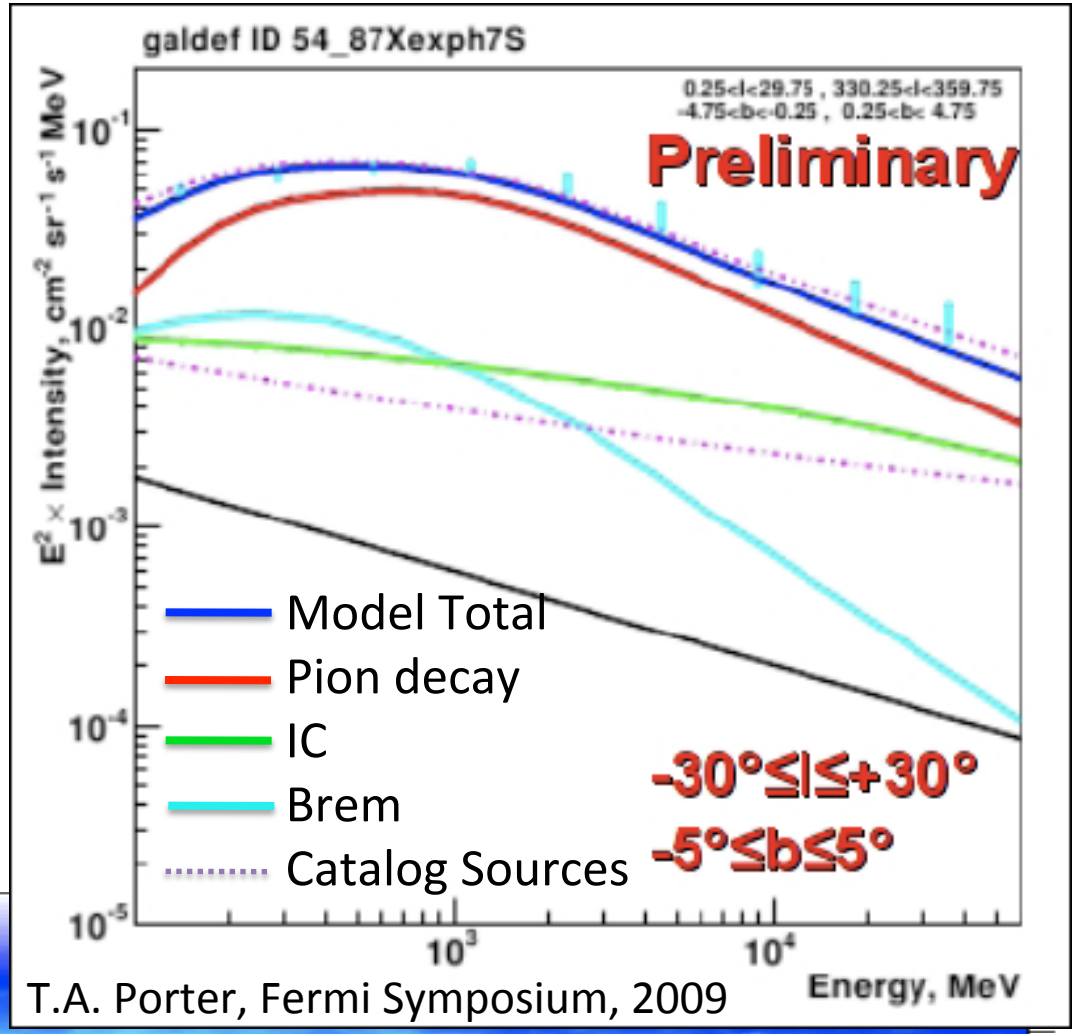
In background simulated trials (scrambling data in r.a.), an equal or greater excess occurs by chance 1817/10000 times.
=> **all-sky final p-value is 18%, not significant**

Fermi LAT GP Observations

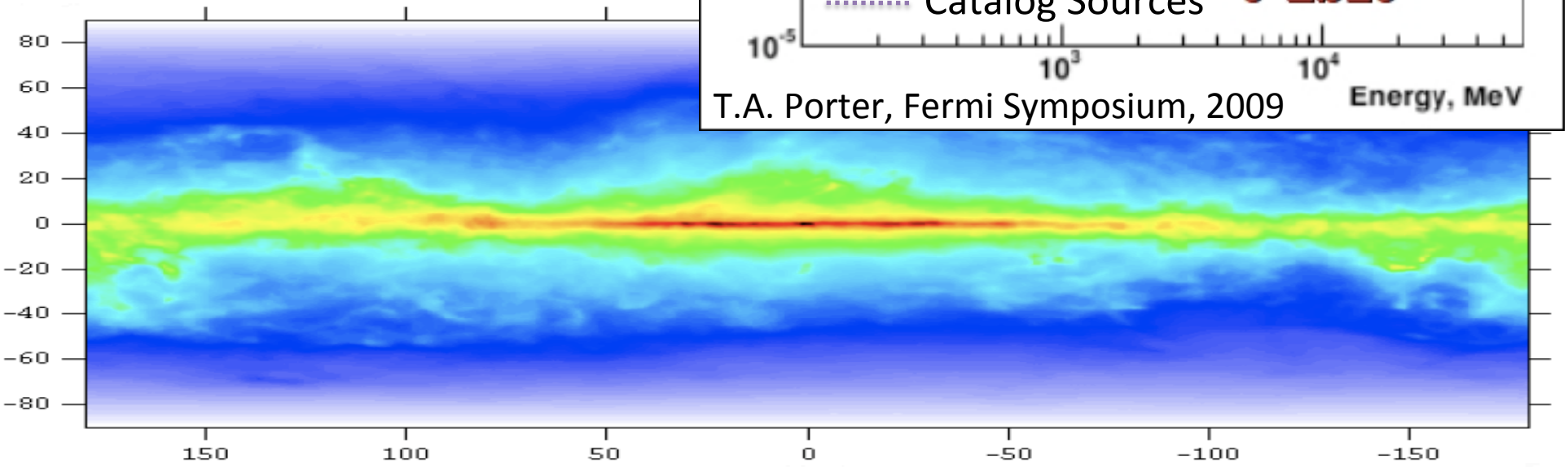
- Gamma rays mostly from pion decay

  (GalProp model)

- Neutrinos α Gammas



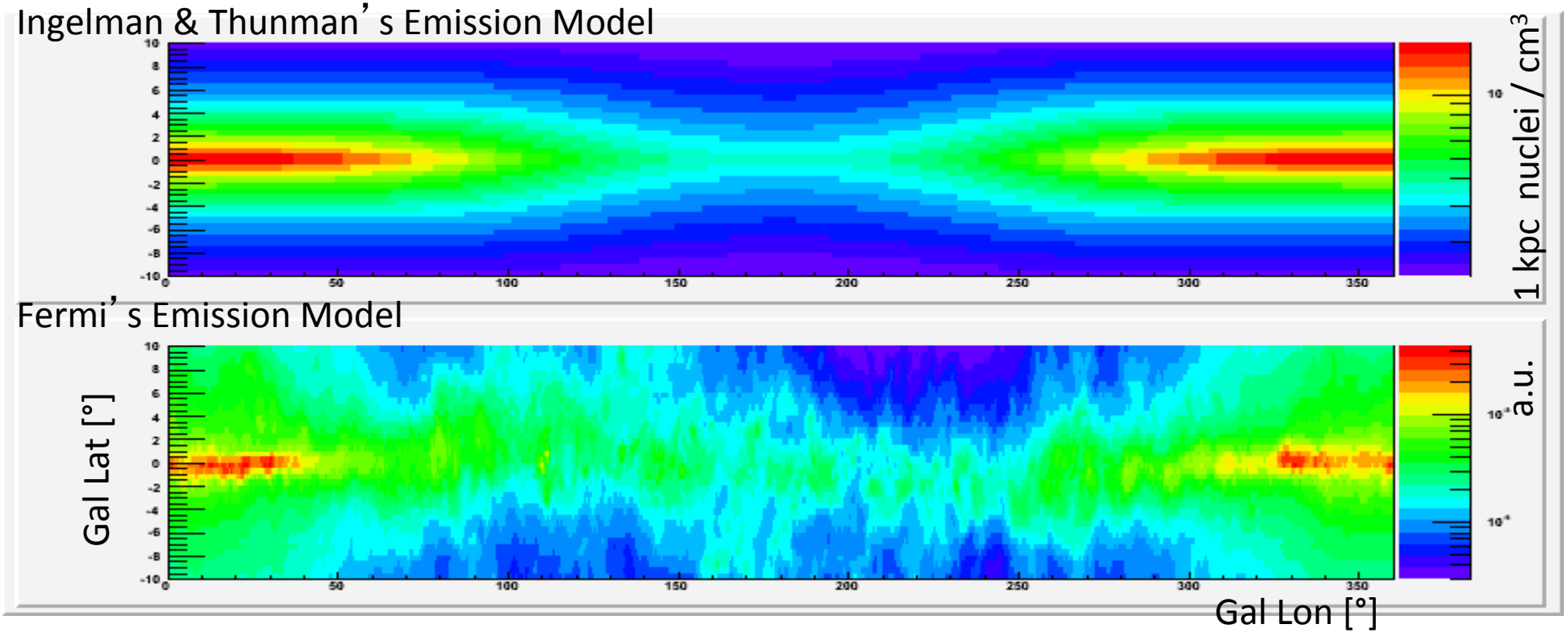
T.A. Porter, Fermi Symposium, 2009



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?)

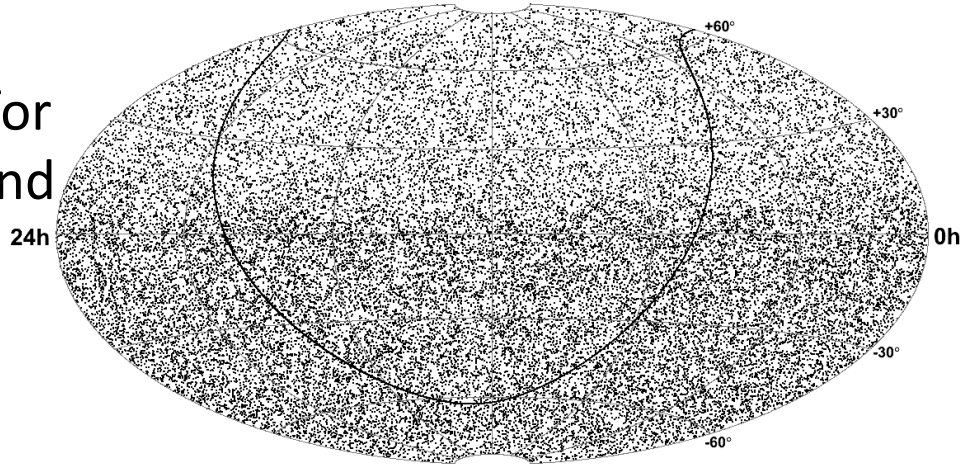
- Foreseeable to detect GP in **5-10 years** (with some effort)
- An important foreground to understand

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 . . .**

The Point Source Analysis in Words

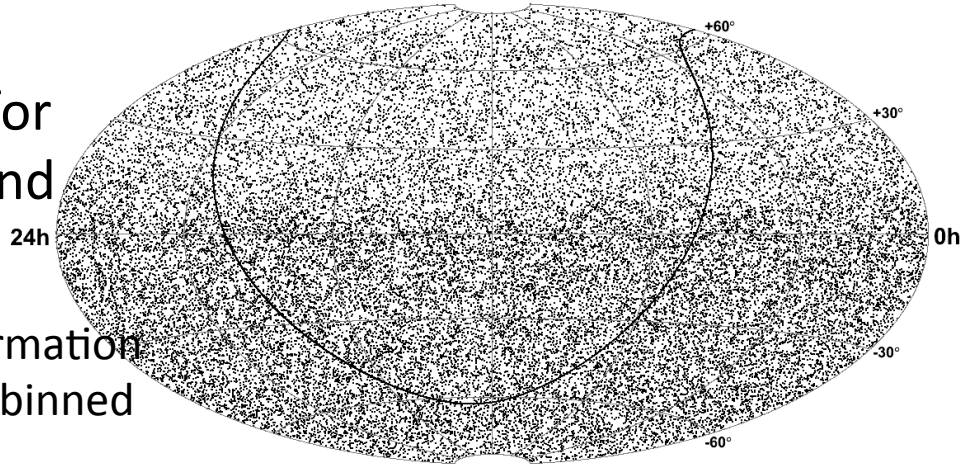
- Determine observables useful for separating signal and background
  - Space (θ, Φ)
  - Energy
  - (Time)



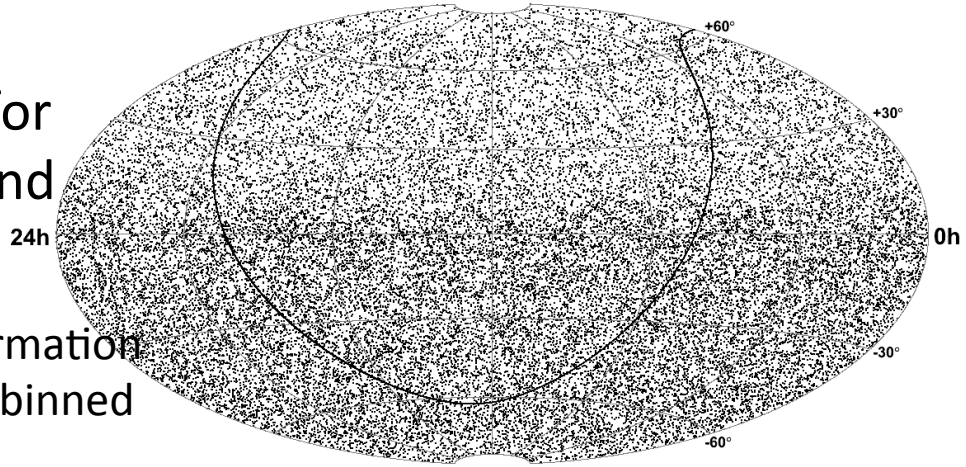
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Inherent loss of information when you cut, e.g. a binned analysis



The Point Source Analysis in Words

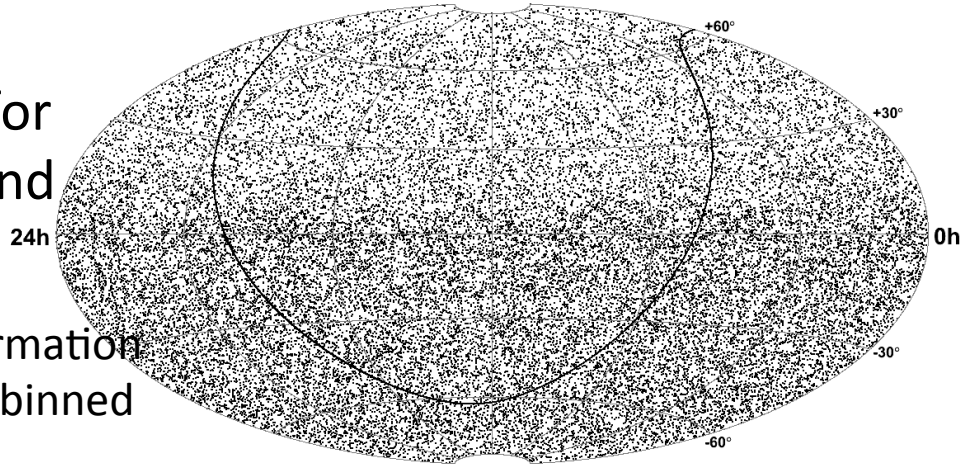


- Determine observables useful for separating signal and background
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Inherent loss of information when you cut, e.g. a binned analysis

- 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



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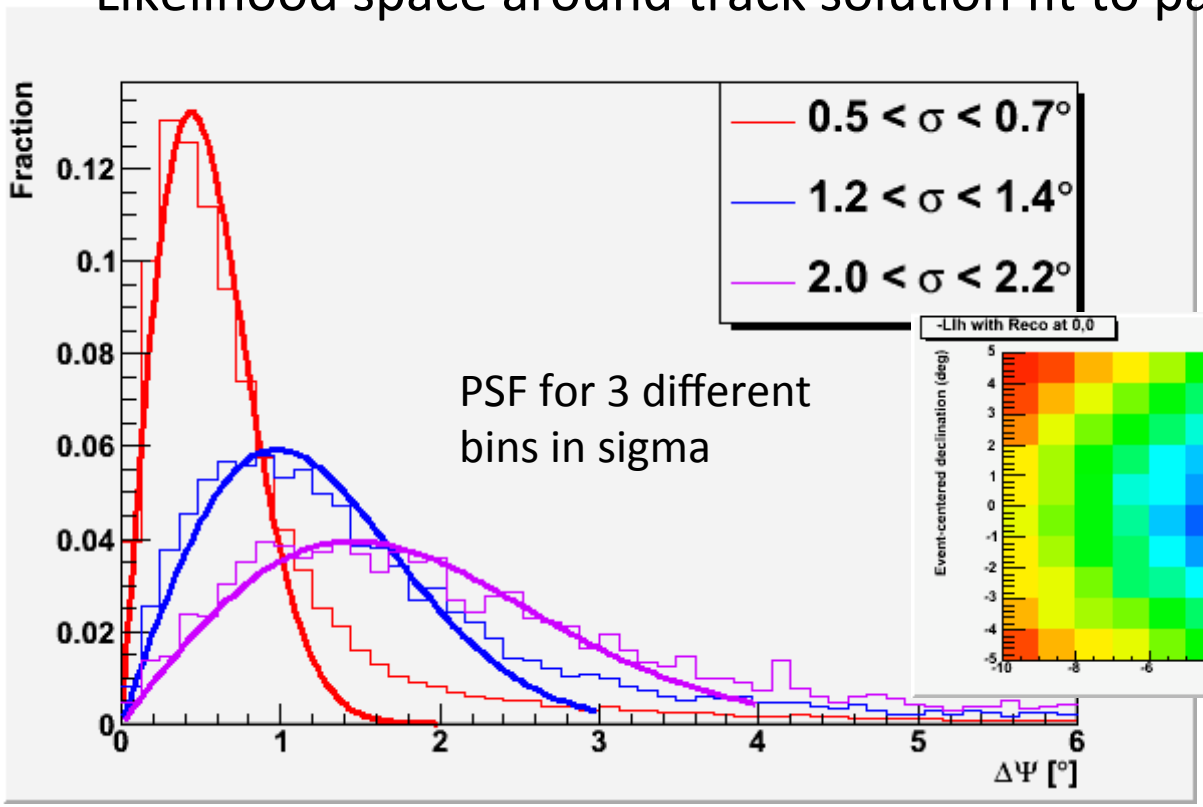
- Perform Maximum Likelihood fit for best mixture of signal and background
  - Extract astrophysical parameters

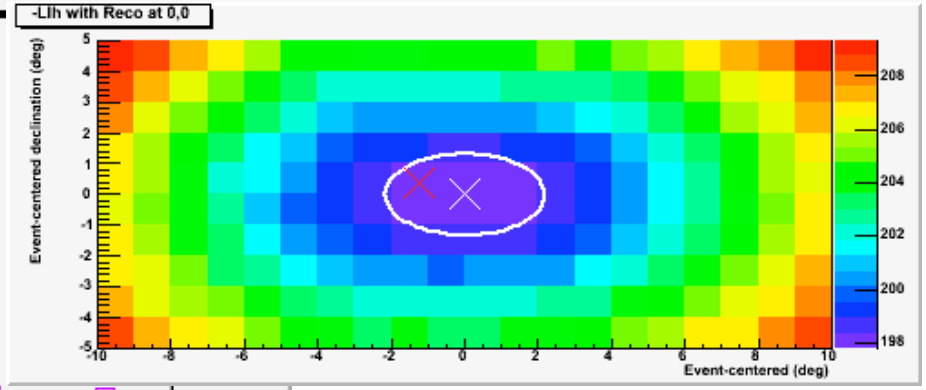
Maximum Likelihood Analysis with Energy

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





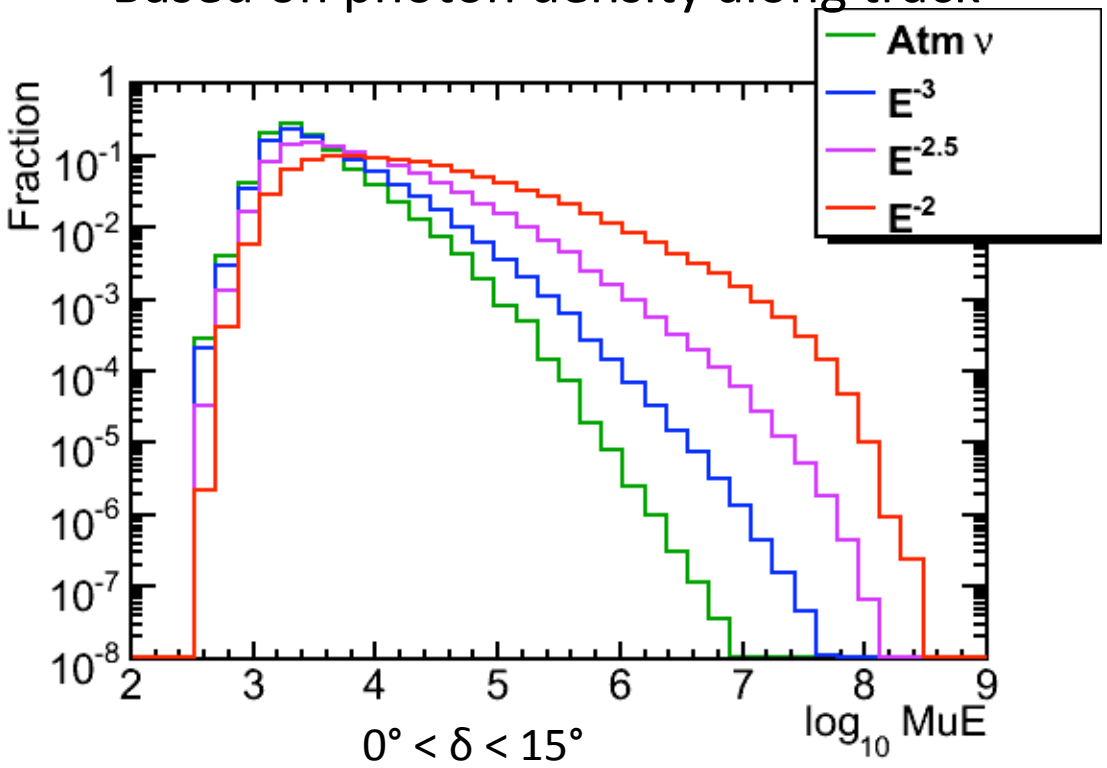
Median PSF = 0.7°

Maximum Likelihood Analysis with Energy

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

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

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Maximum Likelihood Analysis with Energy

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

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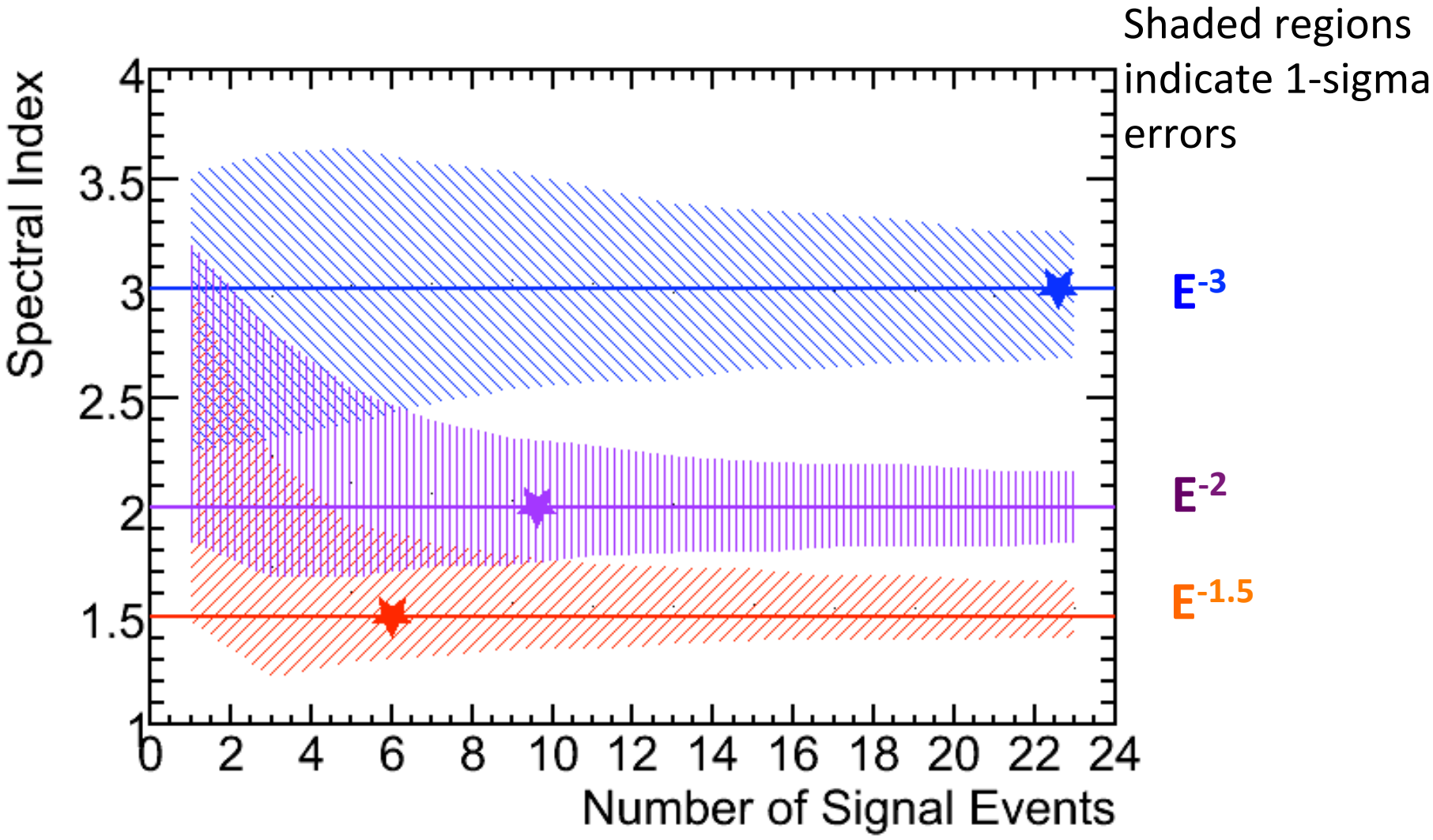
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Estimates which maximize the Llh

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

Spectral Reconstruction



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

Systematic Errors

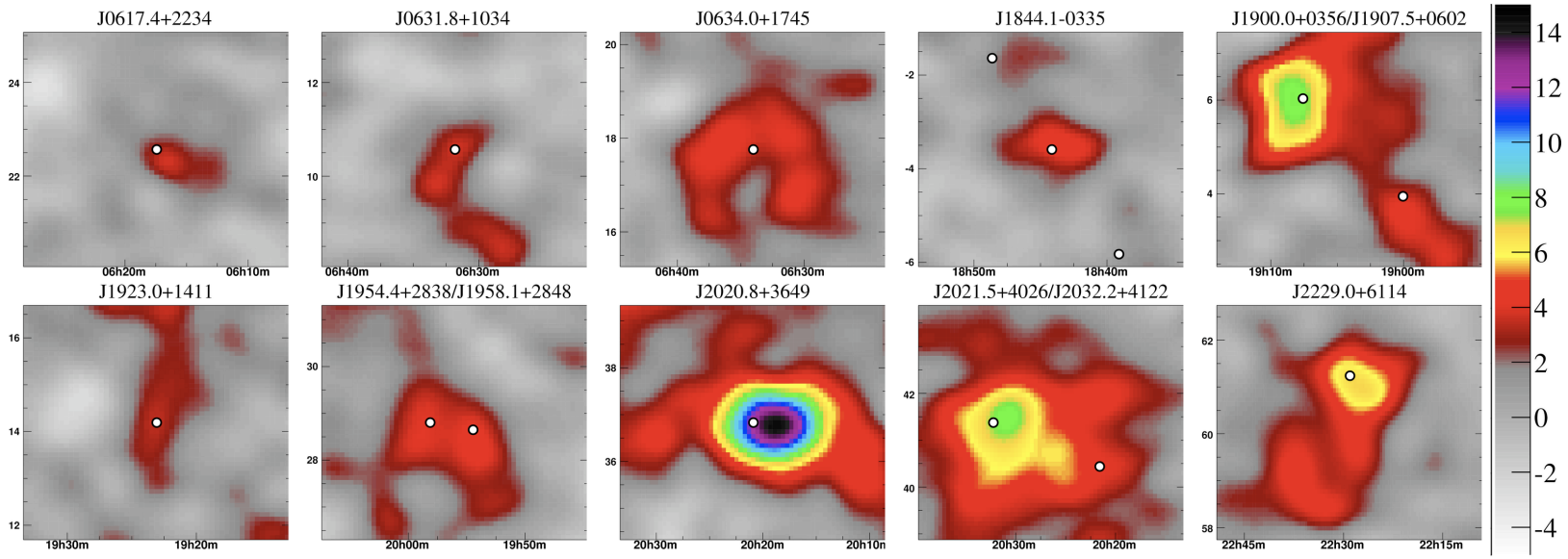
Error Source	Resulting error in signal efficiency
Optical properties of ice	11%
DOM sensitivity	9%
ν cross section, μ energy loss	8%

•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

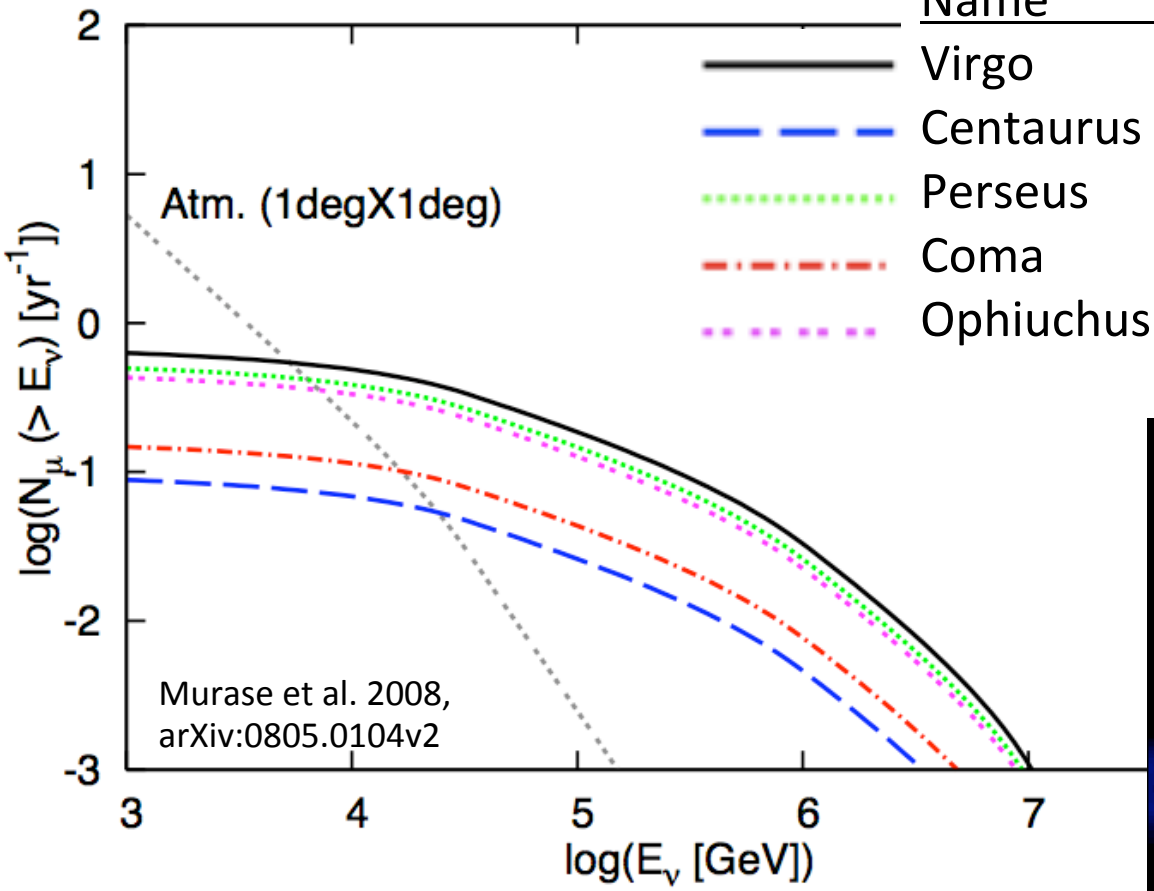
Milagro-Fermi Sources: the GeV – TeV connection



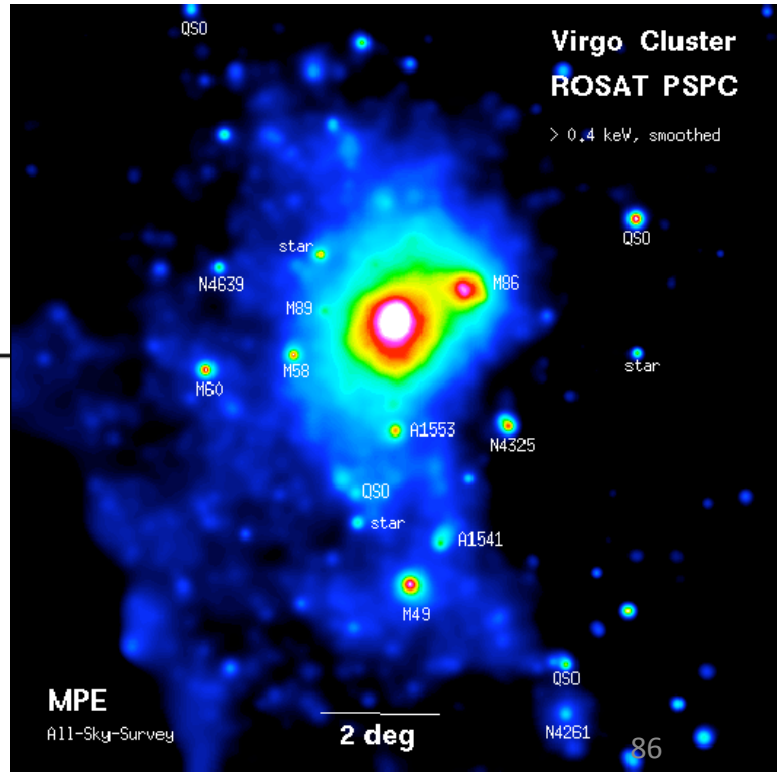
- Milagro showed that many Fermi GeV gamma ray sources extend to TeV
- Sources are a mix: SNR, pulsars, PWN, unidentified
- Great example of how knowing which sources to **stack** can help!
- Stacking in likelihood analysis: break signal PDF into sum of many pieces

Abdo et al. 2009, arXiv:0904.1018v3

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



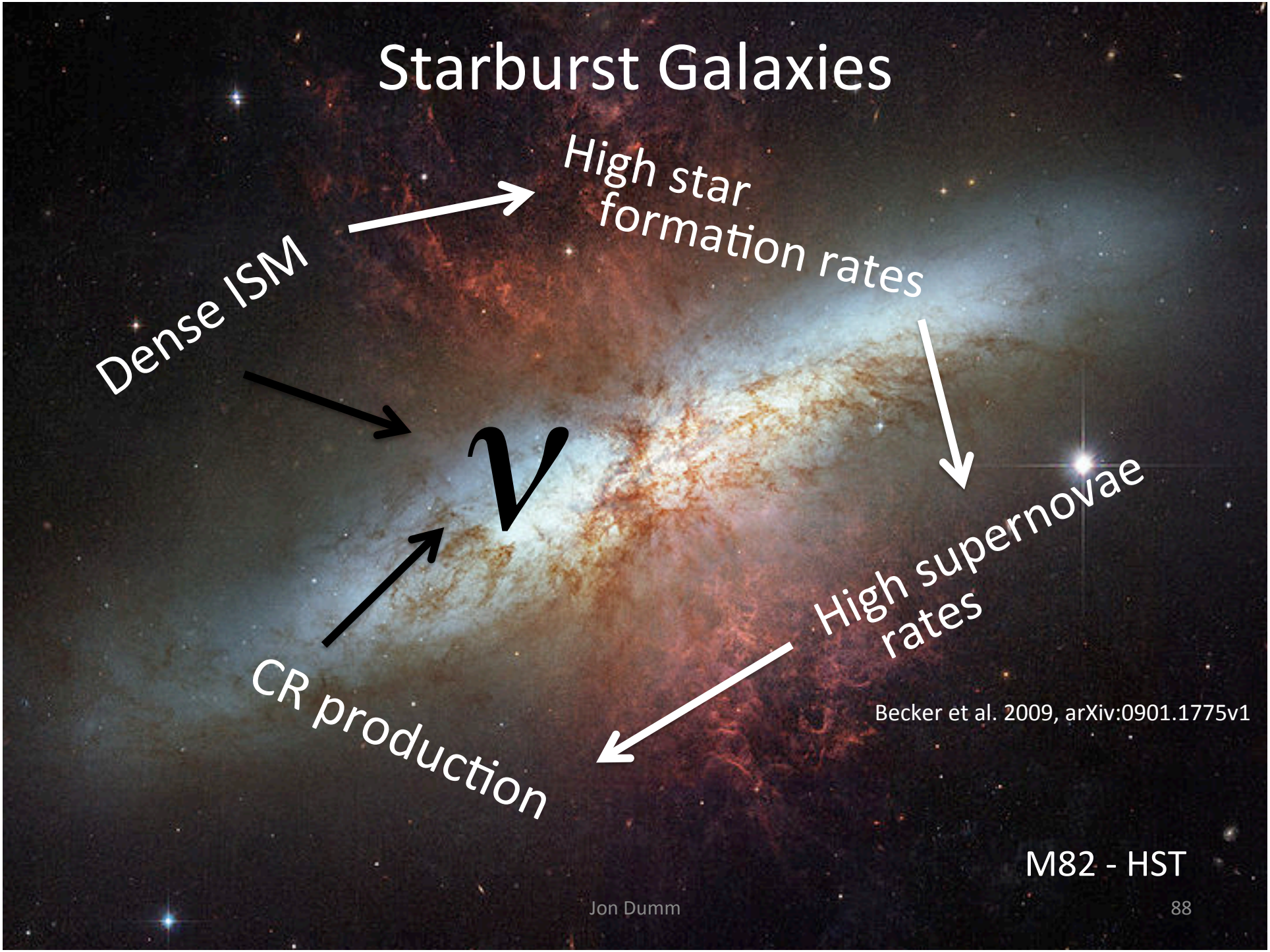
- Small magnetic fields but large accretion shock radii. Could be origin of UHE CRs
- CR distribution highly uncertain – several spatial models considered

Nearby Clusters of Galaxies

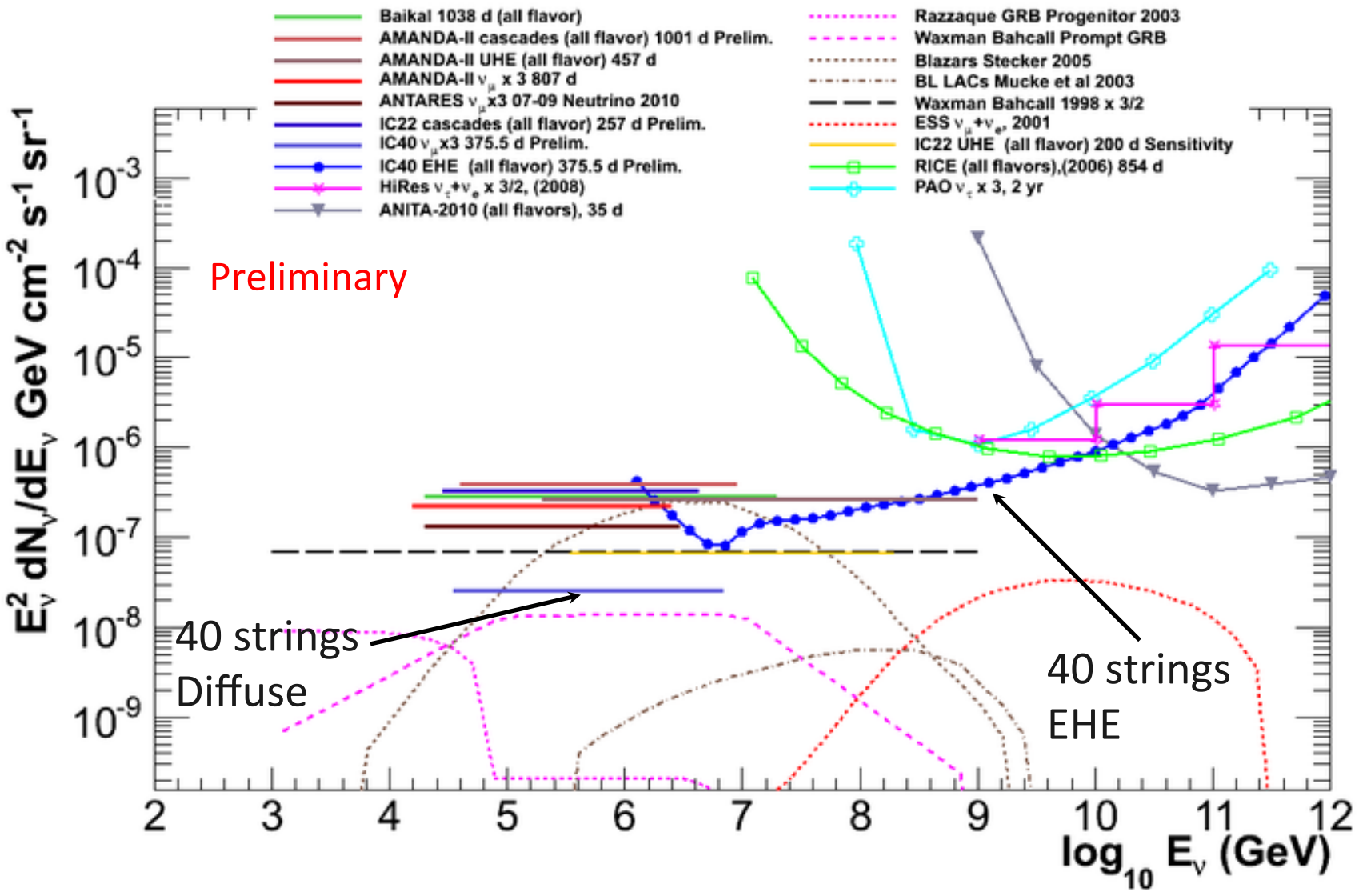
CR Distribution Model	Upper Limits (40-strings)
Uniform inside shock radius	7.8 * prediction
Uniform inside virial radius	12.0 * prediction
Trace hot gas (X-rays)	13.2 * prediction
Central AGN Model	6.0 * prediction

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

Murase et al. 2008, arXiv:0805.0104v2


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

Diffuse Flux Models and Limits



Diffuse Astrophysical Model Tests

