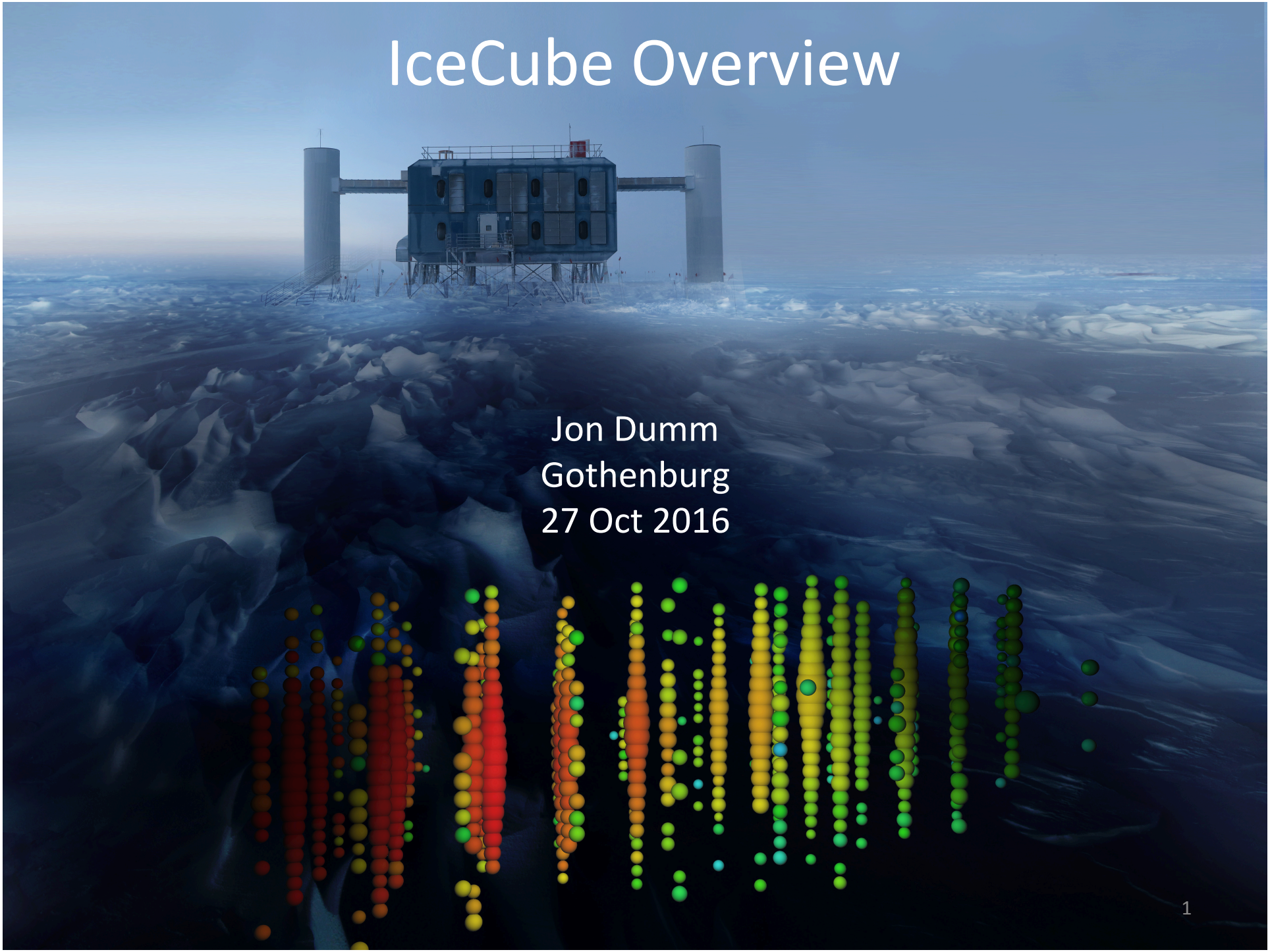
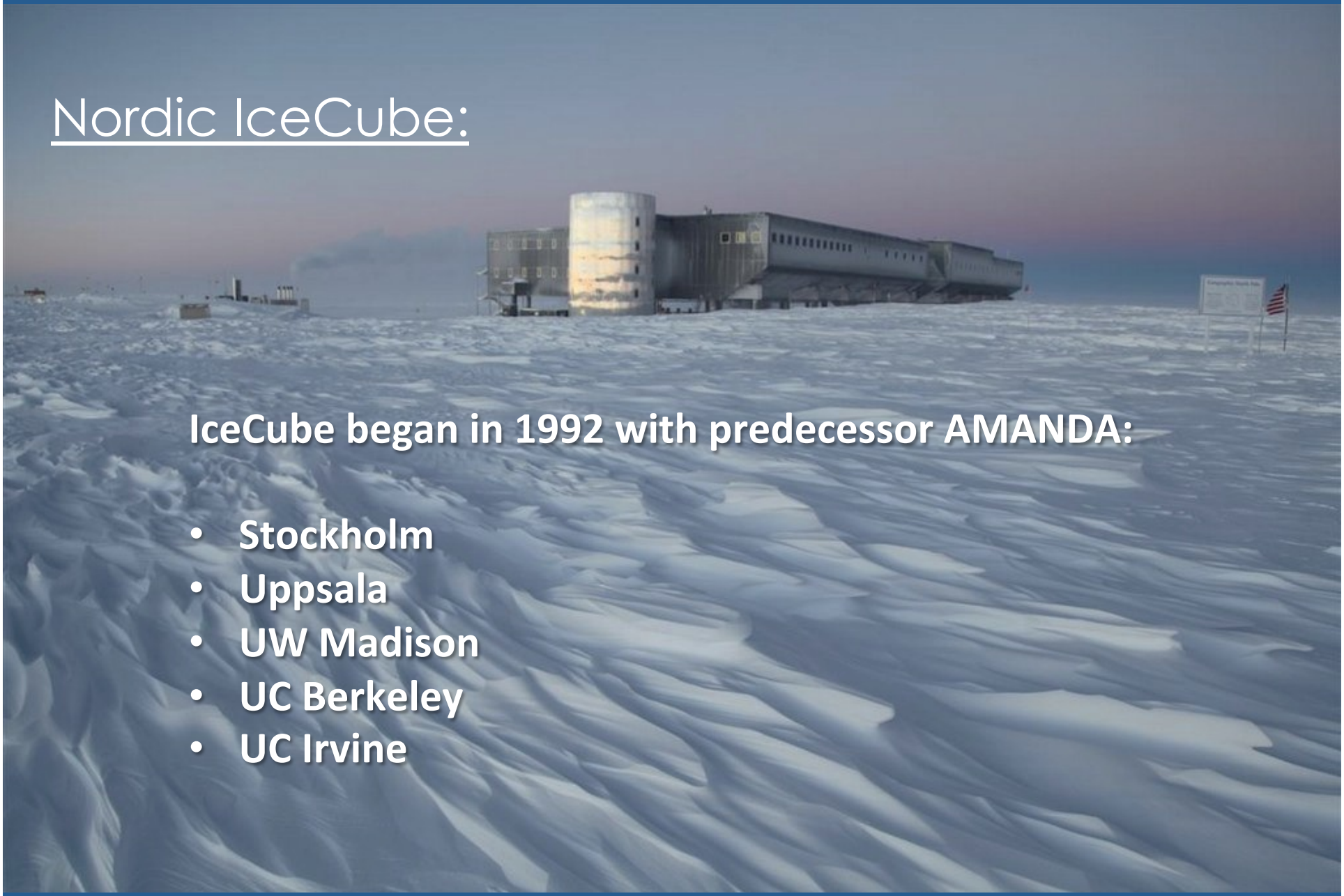
IceCube Overview



Jon Dumm
Gothenburg
27 Oct 2016

Nordic IceCube:



IceCube began in 1992 with predecessor AMANDA:

- **Stockholm**
- **Uppsala**
- **UW Madison**
- **UC Berkeley**
- **UC Irvine**

Photo: Sven Lidström

Nordic IceCube:



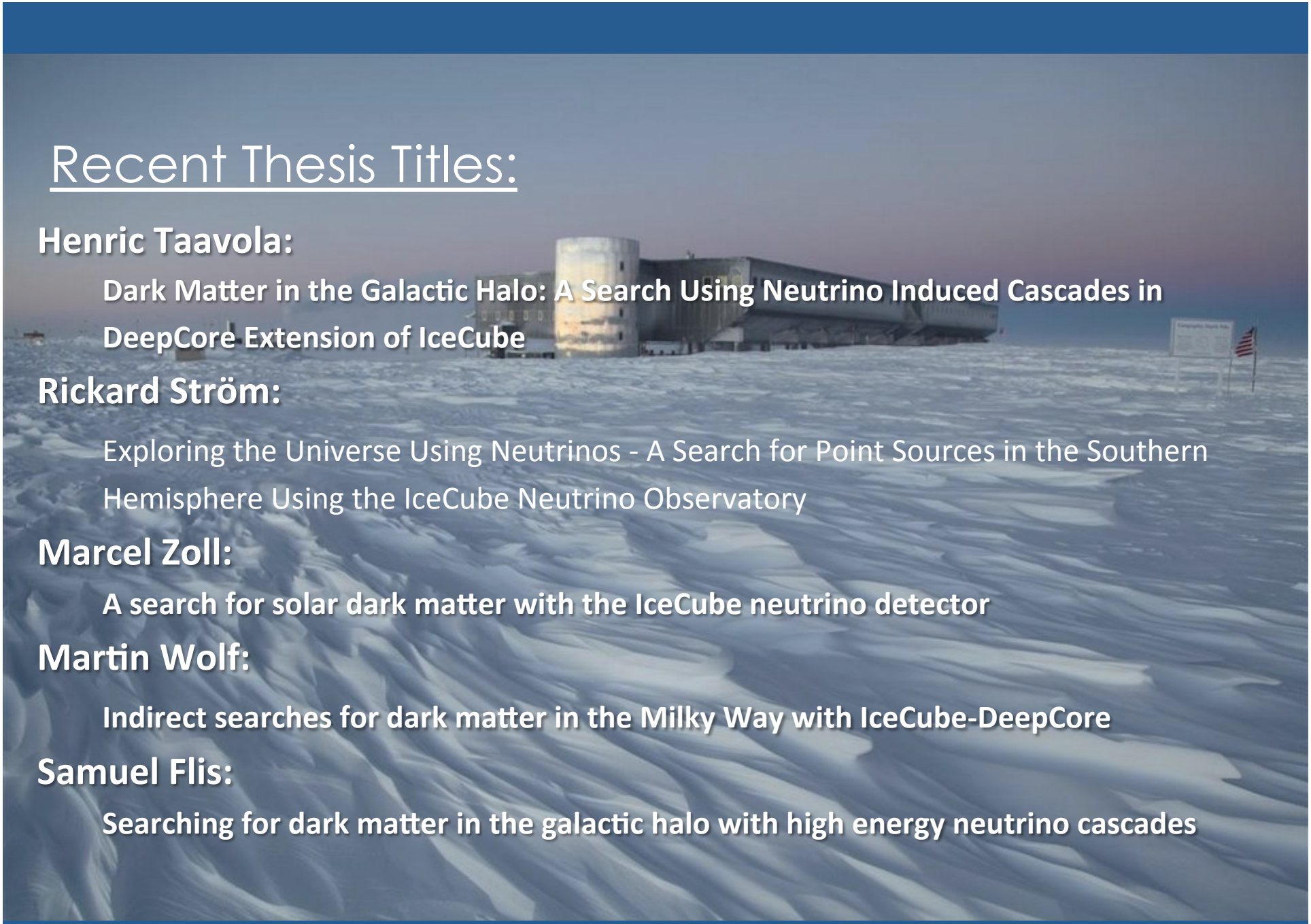
Uppsala University
Olga Botner
Allan Hallgren
Carlos de los Heros
Henric Taavola*
Rickard Ström*
Lisa Unger
Alexander Burgman

Stockholm University
Klas Hultqvist
Chad Finley
Christian Walck
Christian Bohm
Jonathan Dumm
Marcel Zoll*
Samuel Flis
Martin Wolf*
Maryon Ahrens

Niels Bohr Institute
Subir Sarkar
David Jason Koskinen
Mohamed Rameez
Morten Medici
Michael Larson
Eva Brottman Hansen*

* recent PhDs

Photo: Sven Lidström



Recent Thesis Titles:

Henric Taavola:

Dark Matter in the Galactic Halo: A Search Using Neutrino Induced Cascades in DeepCore Extension of IceCube

Rickard Ström:

Exploring the Universe Using Neutrinos - A Search for Point Sources in the Southern Hemisphere Using the IceCube Neutrino Observatory

Marcel Zoll:

A search for solar dark matter with the IceCube neutrino detector

Martin Wolf:

Indirect searches for dark matter in the Milky Way with IceCube-DeepCore

Samuel Flis:

Searching for dark matter in the galactic halo with high energy neutrino cascades

Photo: Sven Lidström

IceCube Collaboration

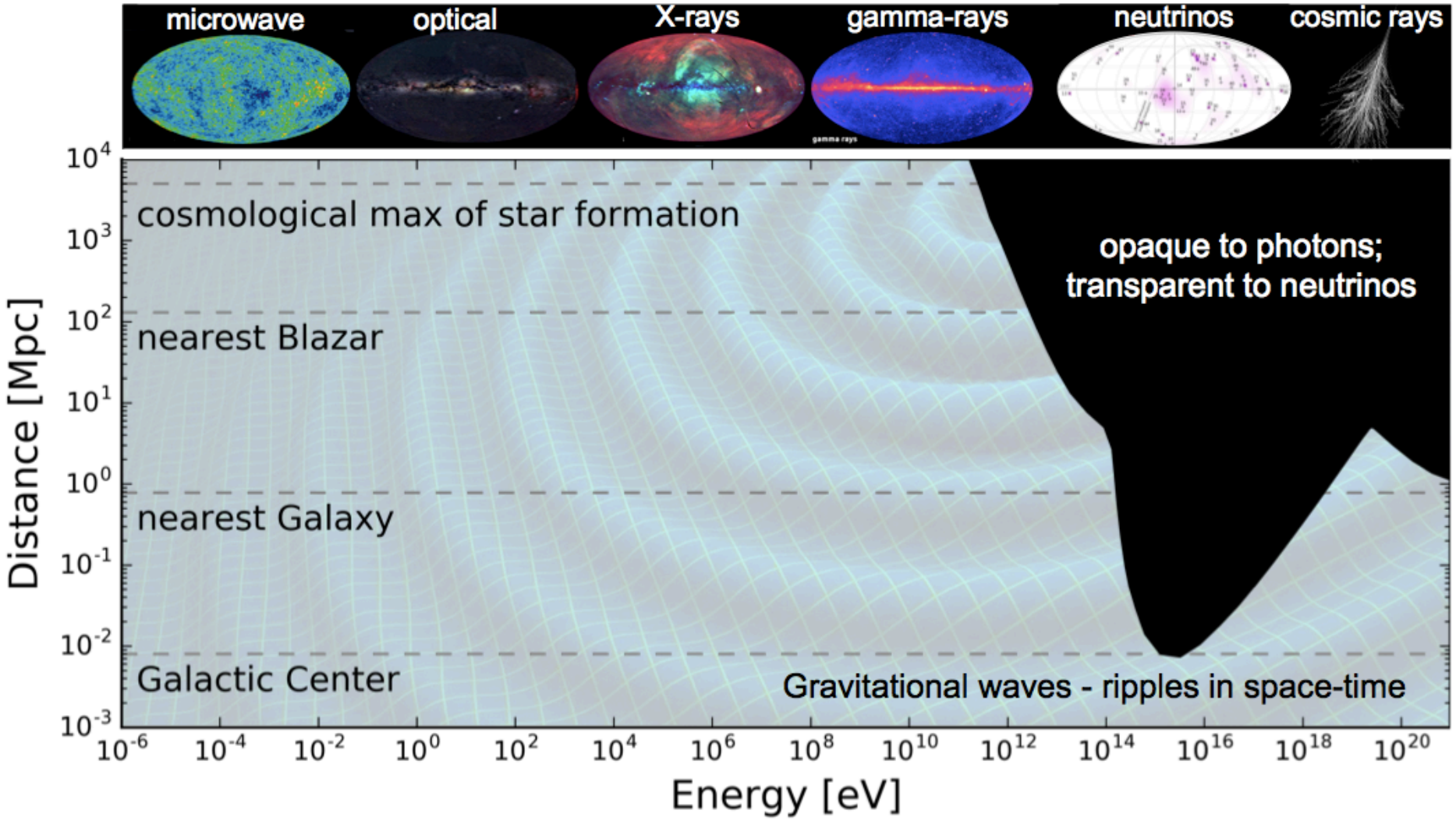
The Collaboration: 12 countries — 47 institutes — 300 scientists
(Main financial support from: USA, Germany, Sweden, Belgium)

Current Spokesperson (2013-2017): **Olga Botner** (Uppsala)

Largest neutrino telescope in the world
15x more sensitive than next competitor (ANTARES in Mediterranean)

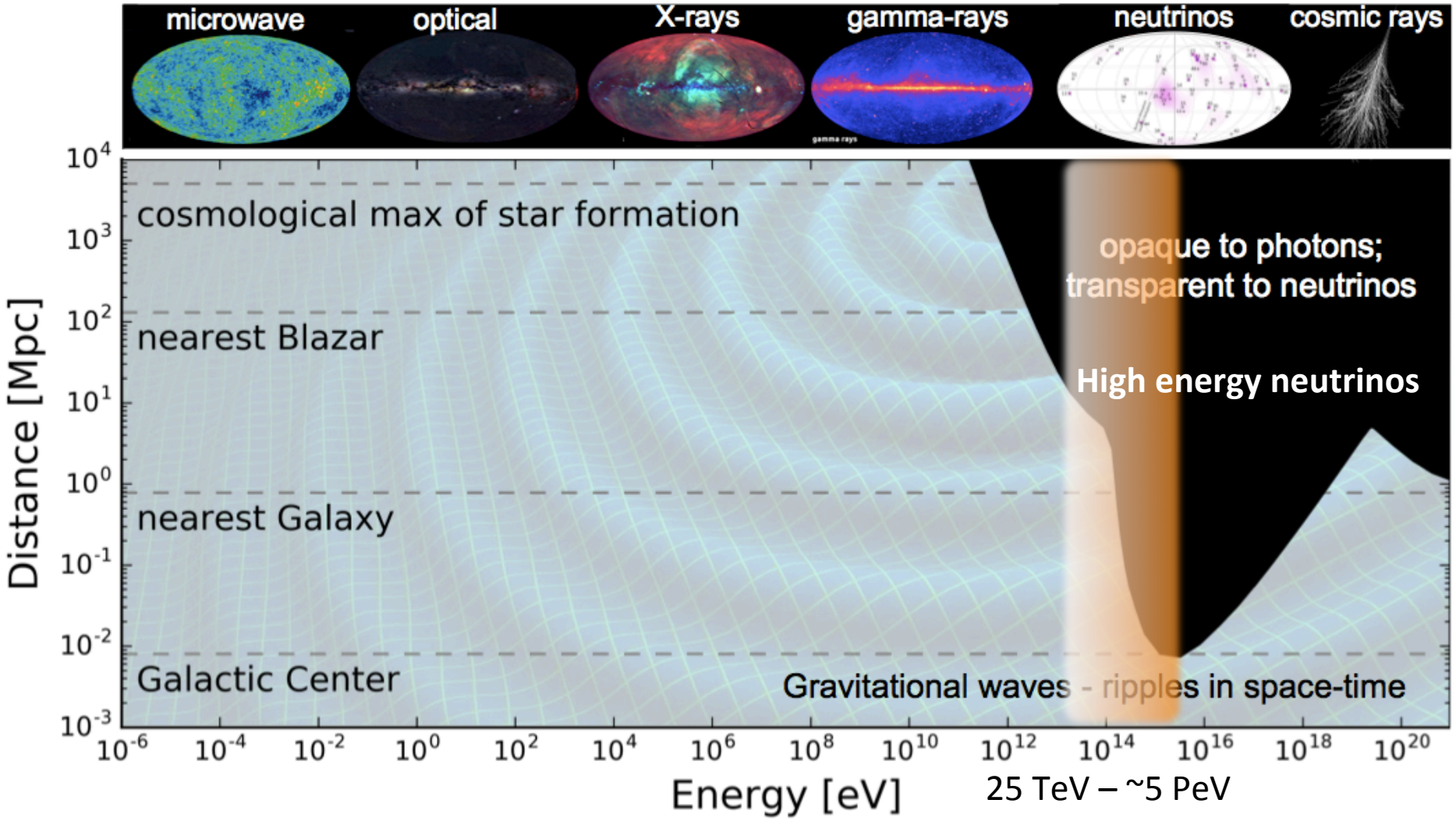


Multi-Messenger Astronomy Context



Marek Kowalski

Multi-Messenger Astronomy Context



Marek Kowalski

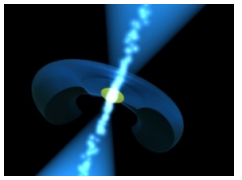
Neutrino Astroparticle Physics: IceCube's science goals
(SU, UU, and NBI core activities)

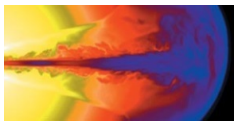
Astrophysics of the extreme Universe

Sources of cosmic rays => sources of neutrinos:

Analyses: point-sources, extended emissions, transients,
diffuse flux (i.e. integrated emission over history of universe)

Targets: Supernovae remnants, Active Galactic Nuclei,
Gamma Ray Bursts, Starburst Galaxies, Microquasars, …





Dark matter annihilation produces neutrinos

Analyses search for signal from: **Sun's core**, **Galactic Center**, **Galactic Halo**, Galaxy clusters and dwarf galaxies



Particle physics

Neutrino oscillations, neutrino mass ordering
Charm production in cosmic ray interactions
Violation of Lorentz invariance, quantum decoherence
Exotic searches: **magnetic monopoles**, …



Ultrahigh Energy Neutrinos from cosmic ray interactions with CMB



Cosmic ray physics energy spectrum, composition, anisotropy

Supernova in our galaxy (if one occurs)

IceCube Neutrino Observatory

IceTop: 1 km^2 surface array

86 strings

60 Optical Modules per string

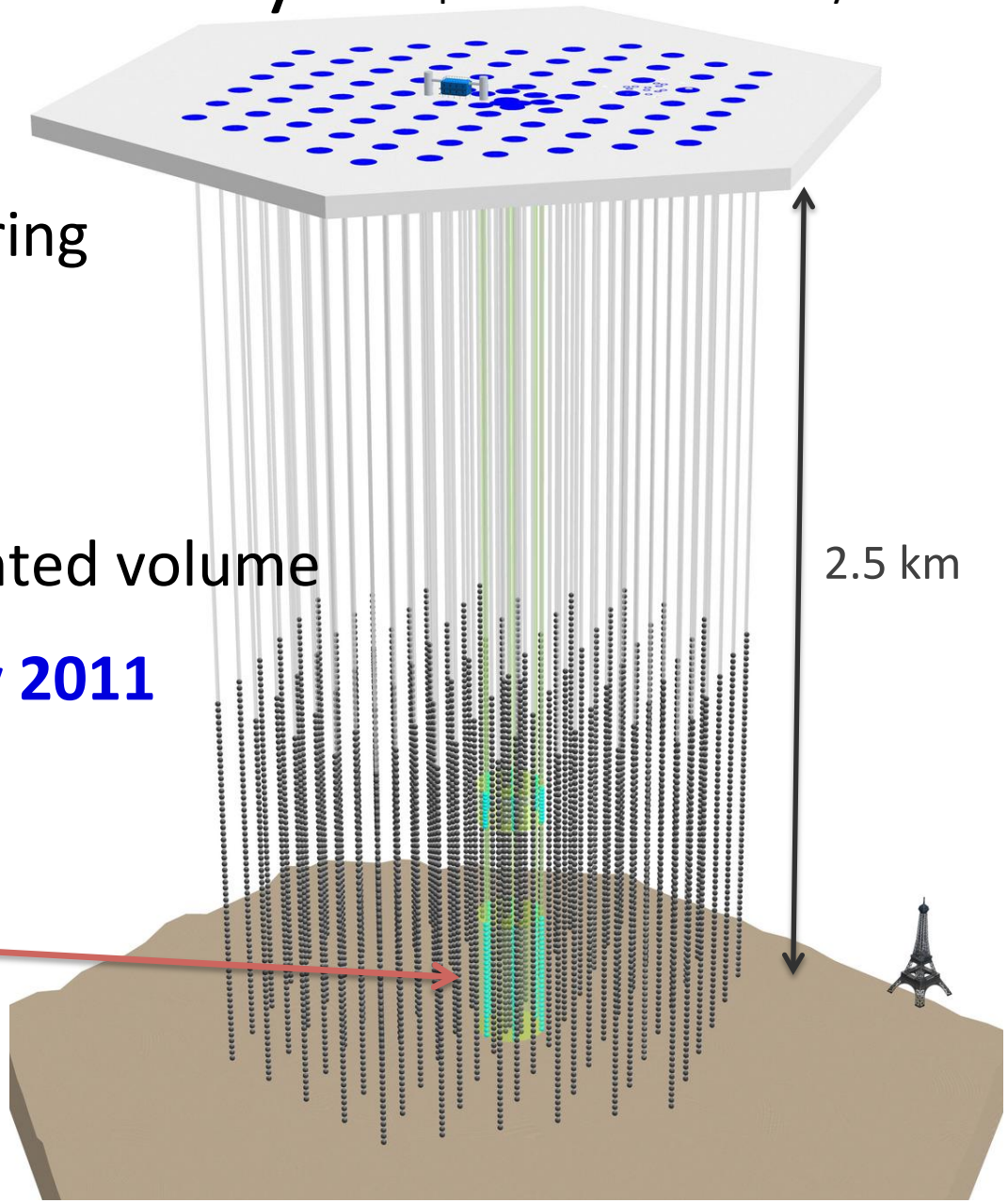
5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

Began full operations May 2011

DeepCore
Low-energy Extension

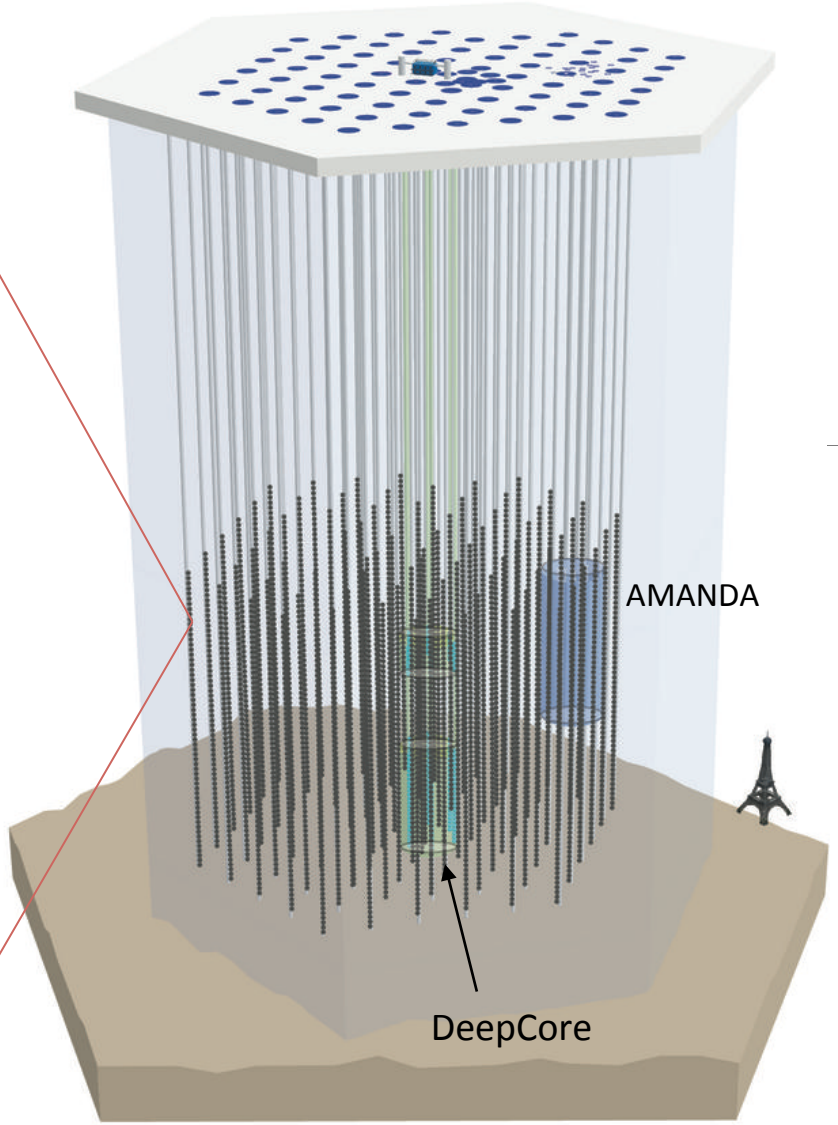
Dark Matter,
Neutrino Oscillations

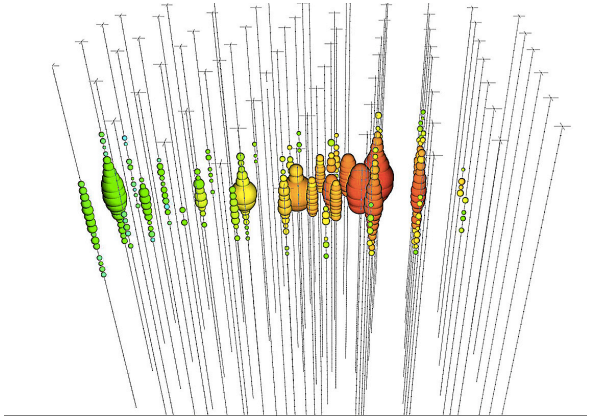


IceCube Neutrino Observatory

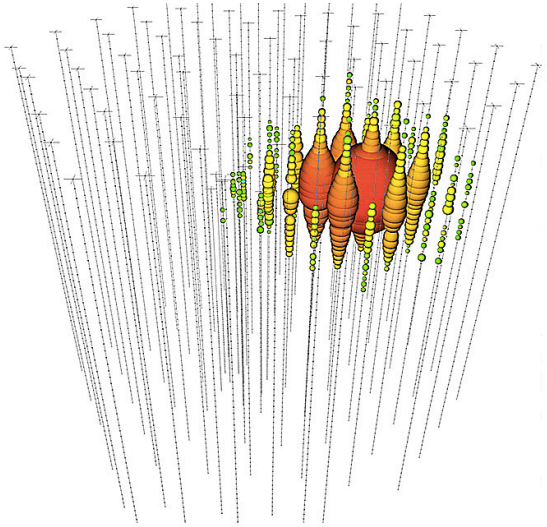
Digital Optical Module



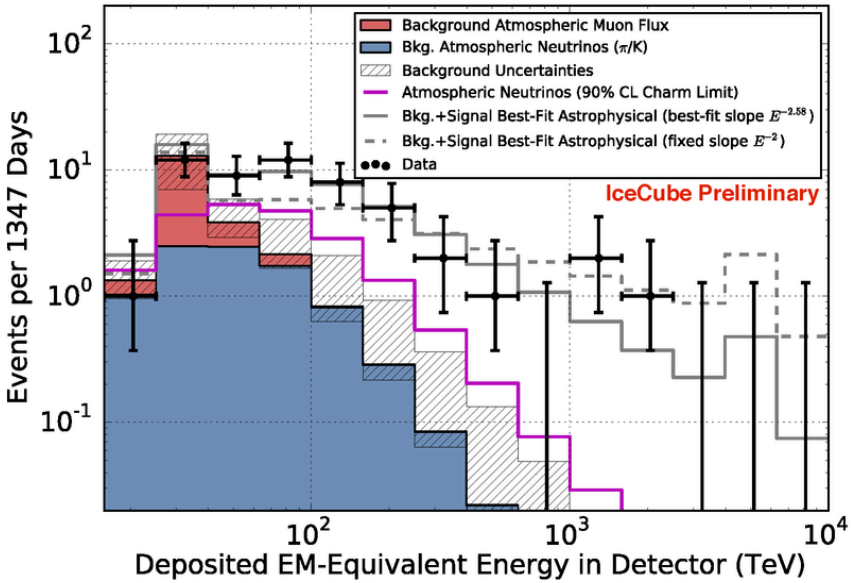


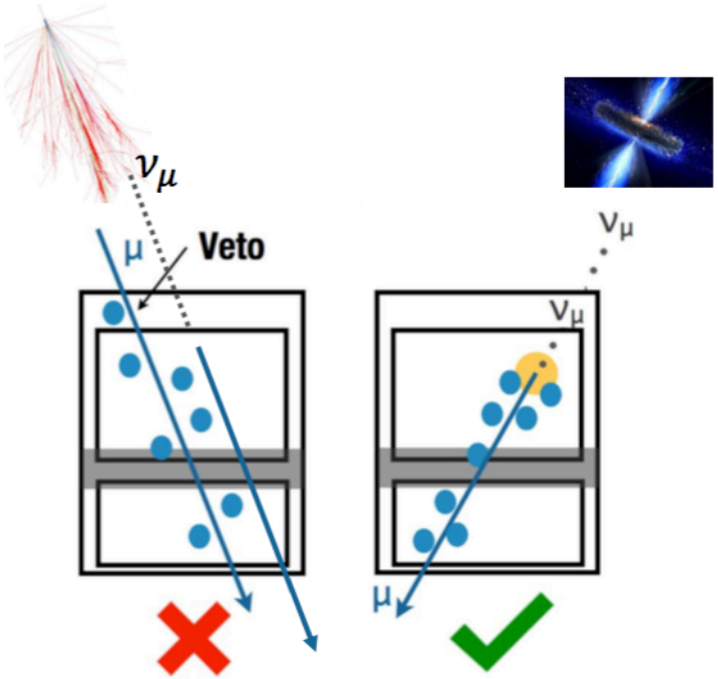


High Energy Neutrino Events



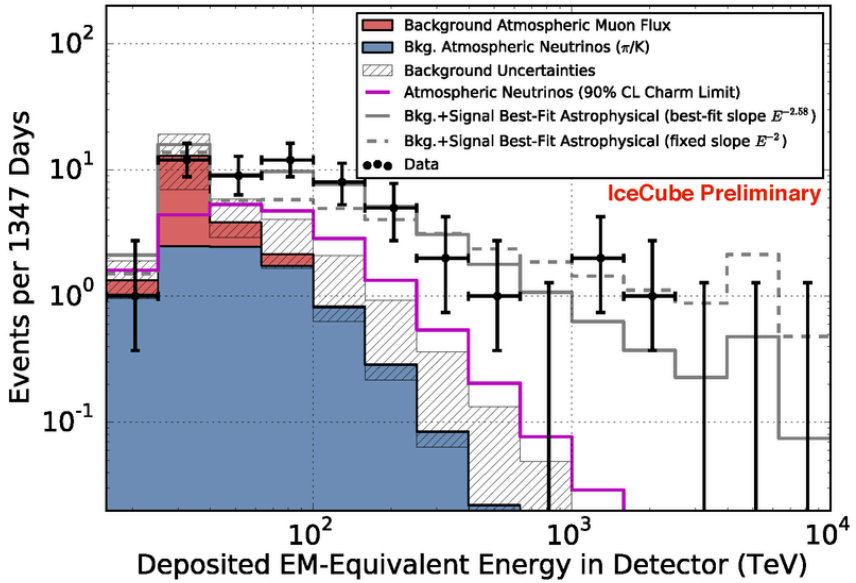
Astrophysical Neutrinos

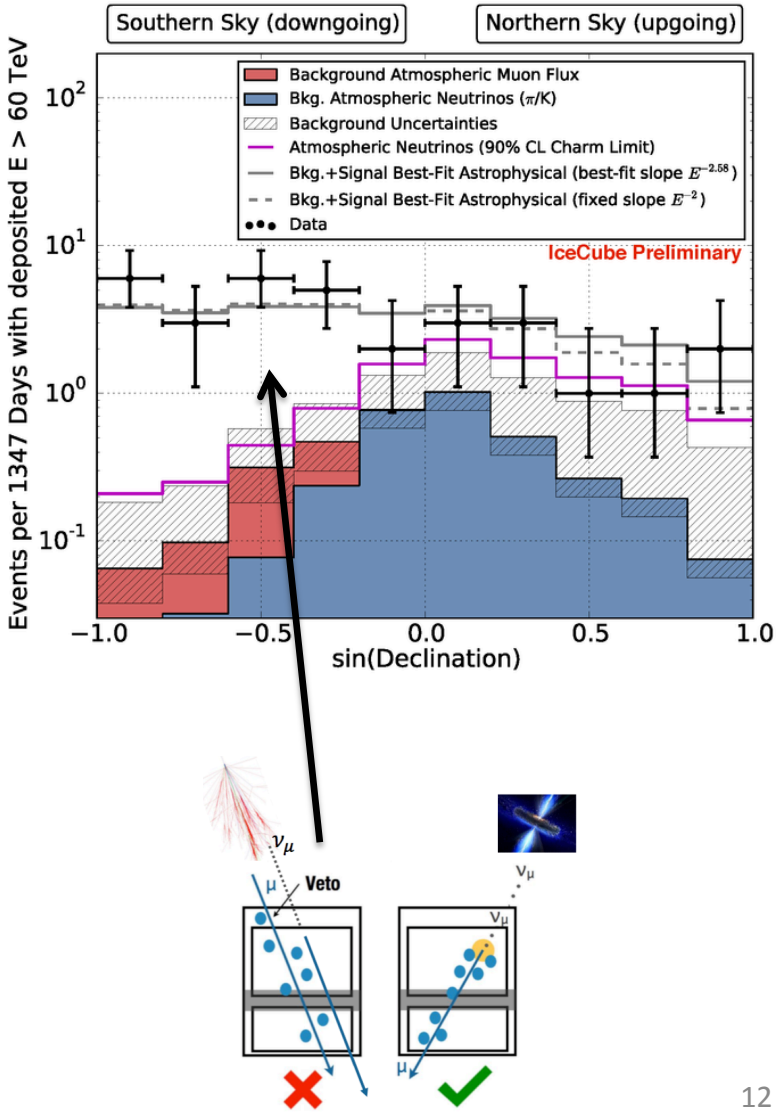




IceCube Collab. ICRC (2015)
update of Science (2013)

Astrophysical Neutrinos





2010 – 2014: **7σ**

<u>Veto studies:</u>

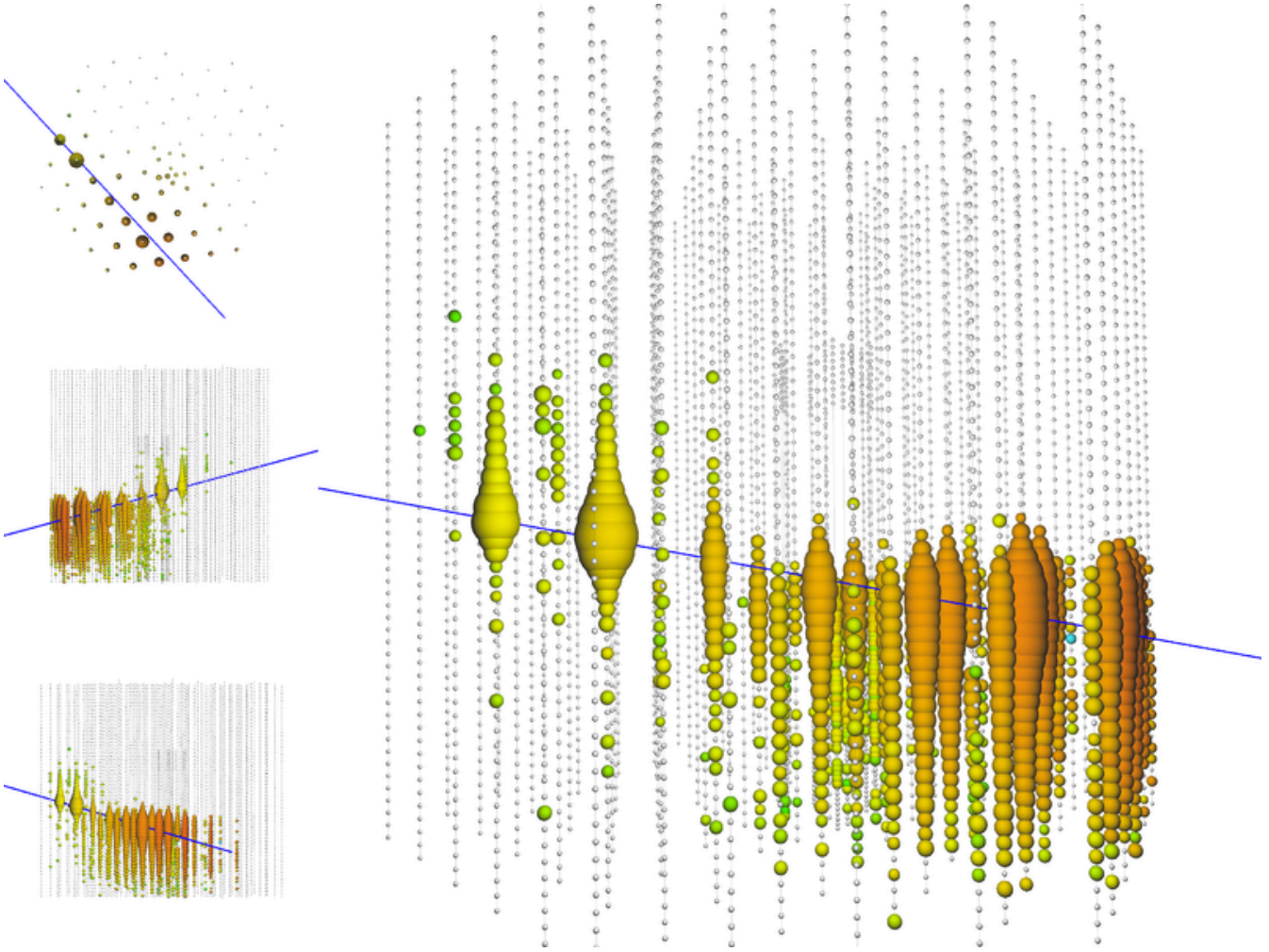
+ low background

– low signal statistics

IceCube Collab. ICRC (2015)
update of Science (2013)

Multi-PeV Neutrino

Take advantage of long muon range: More signal, more background



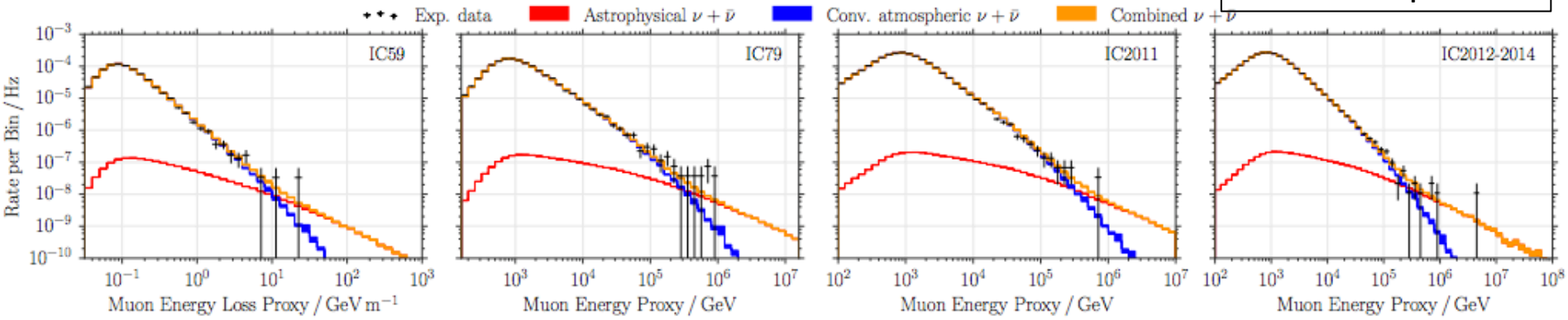
Deposited ~2 PeV in detector – likely 5 – 10 PeV neutrino!
Almost a discovery in itself! p = 0.005% from atmos. background

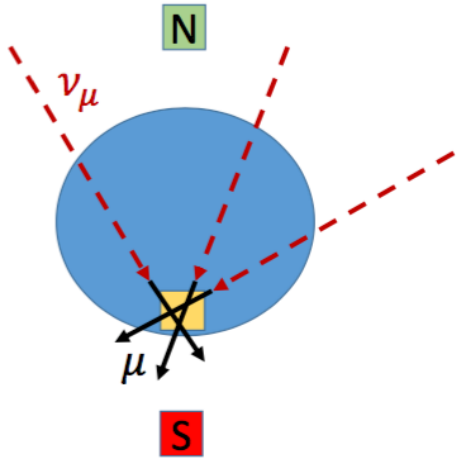
Through-going Astro Neutrinos

Through-going muon channel highly complementary to starting events

6 years of data analyzed – 6.0 σ

IceCube: ApJ 2016



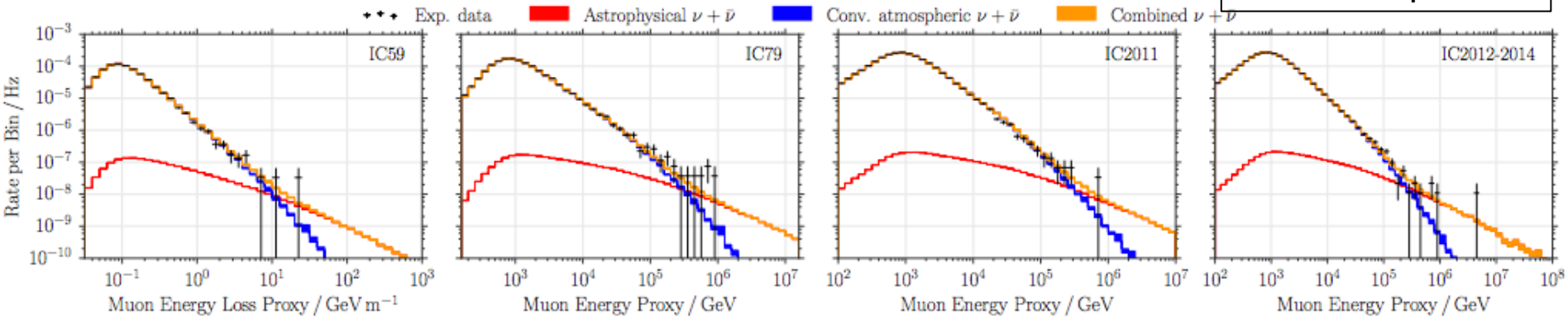


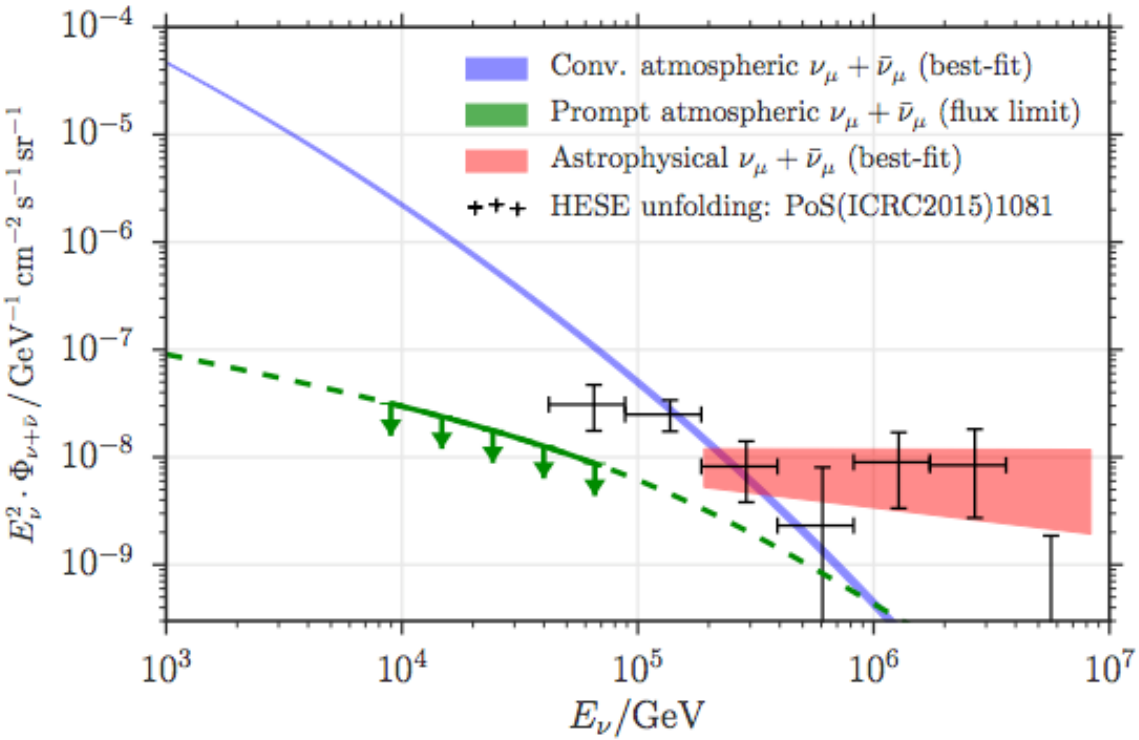
Through-going Astro Neutrinos

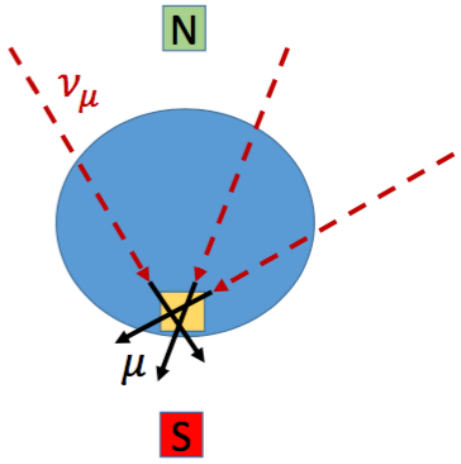
Through-going muon channel highly complementary to starting events

6 years of data analyzed – 6.0 σ

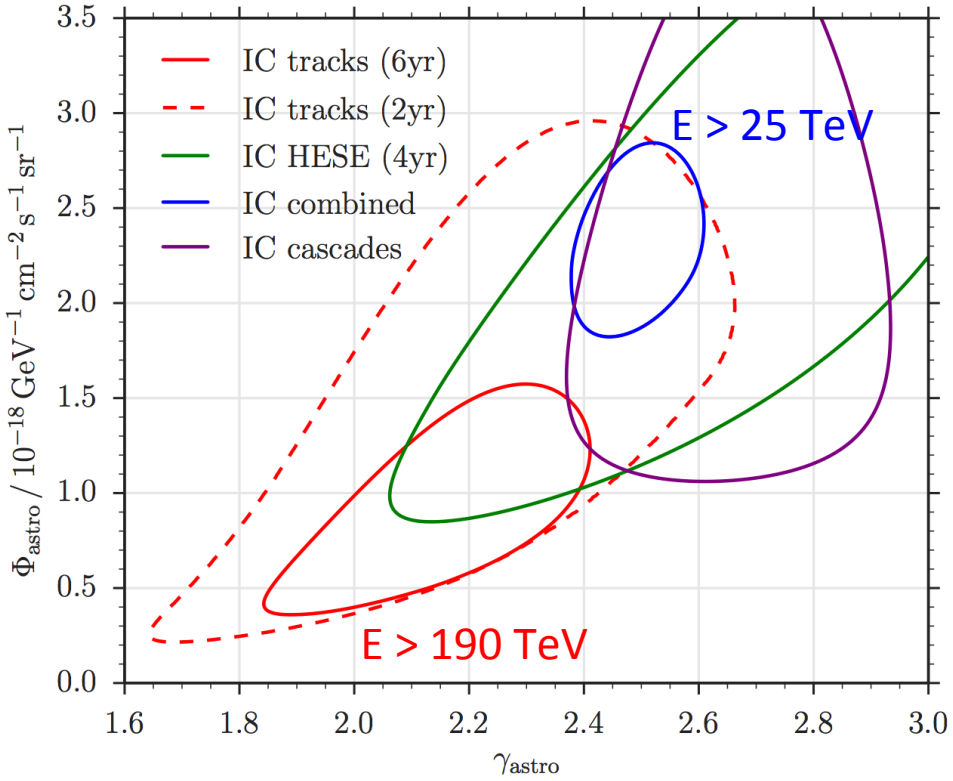
IceCube: ApJ 2016

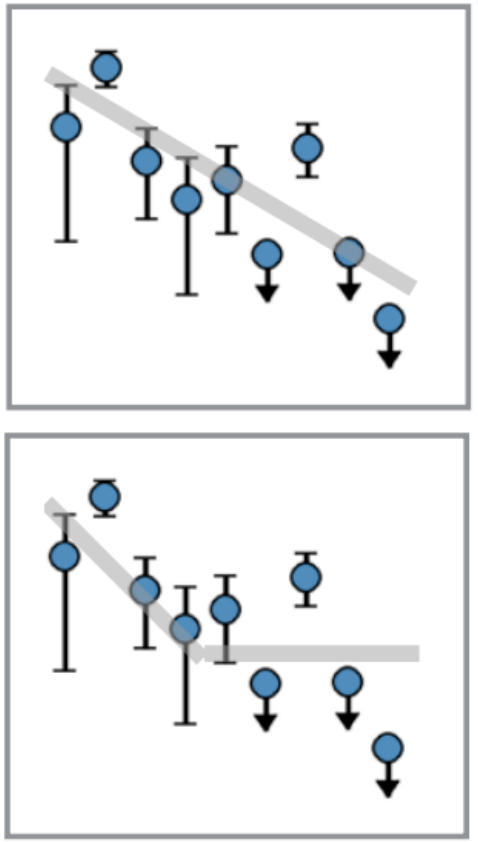






Spectral Analysis for Different Channels



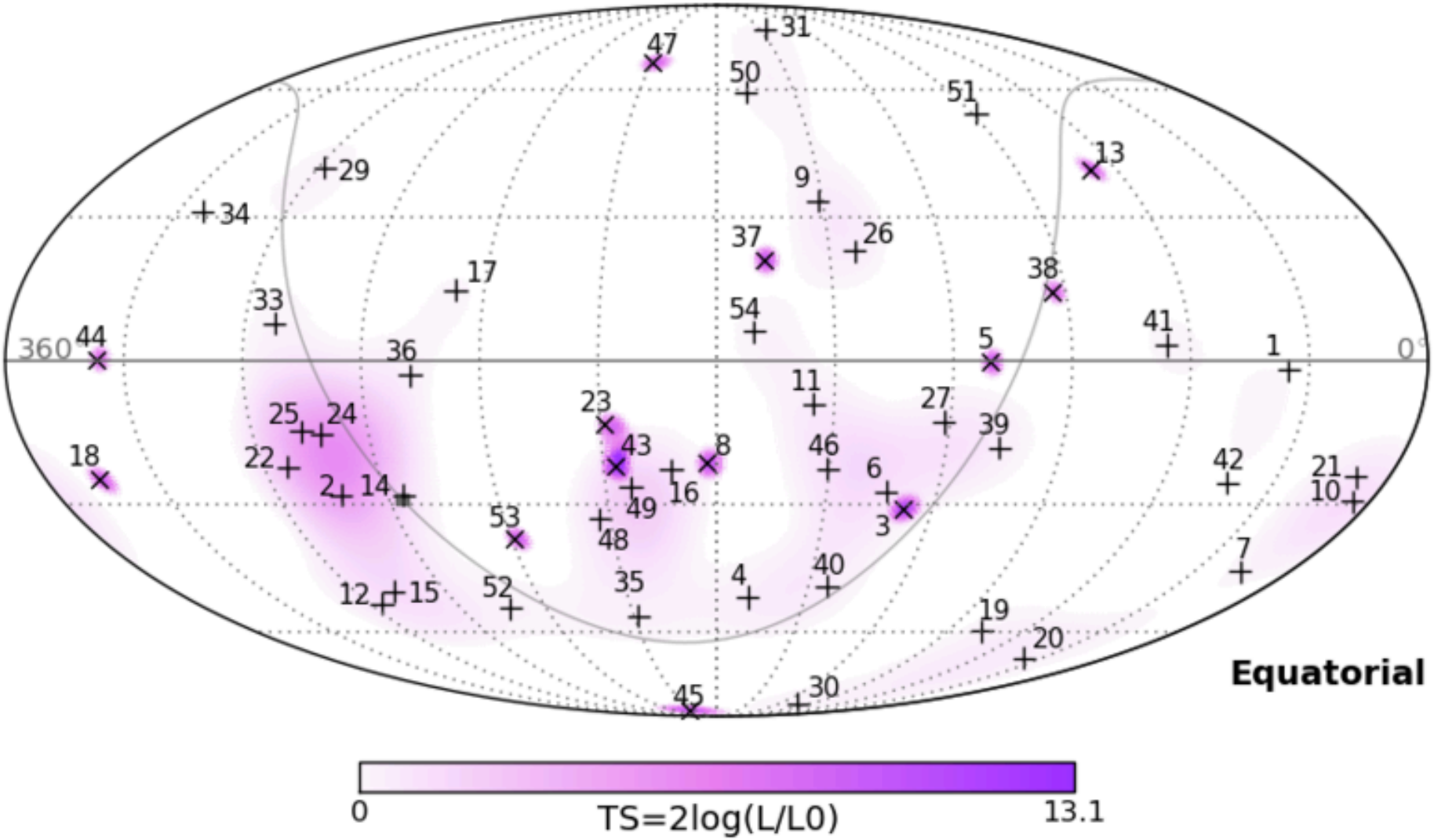


Combined spectral index: 2.50 ± 0.09
Starting events: 2.58 ± 0.25
Through-going tracks: 2.13 ± 0.13

Are we seeing a spectral break?
Channel sensitivity to hemispheres?

IceCube: ICRC 2015, PRD 2015, ApJ 2015, PRL 2014

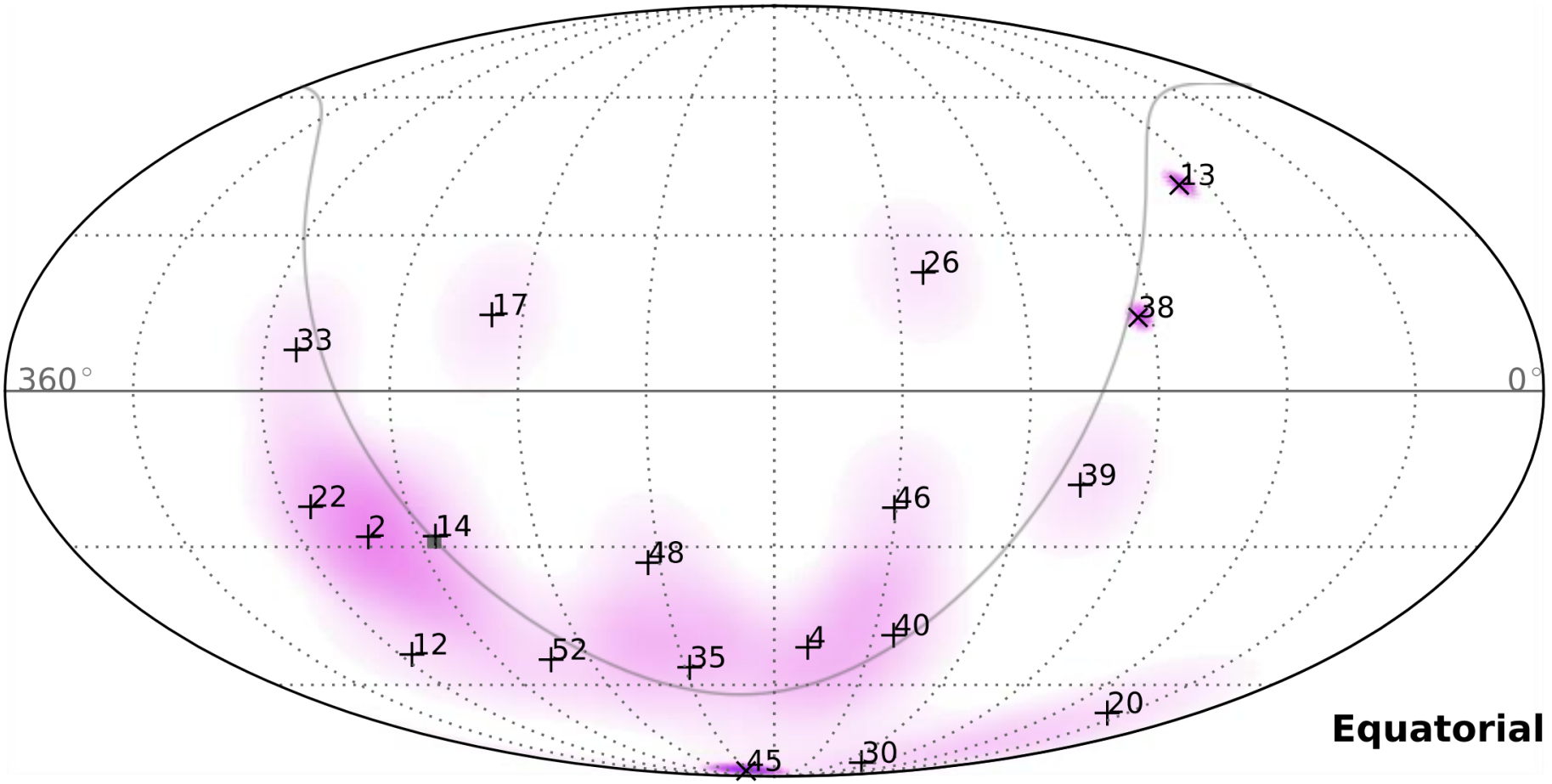
Starting Event Sky Map > 60 TeV



x : track-like

+ : shower-like

Starting Event Sky Map > 100 TeV

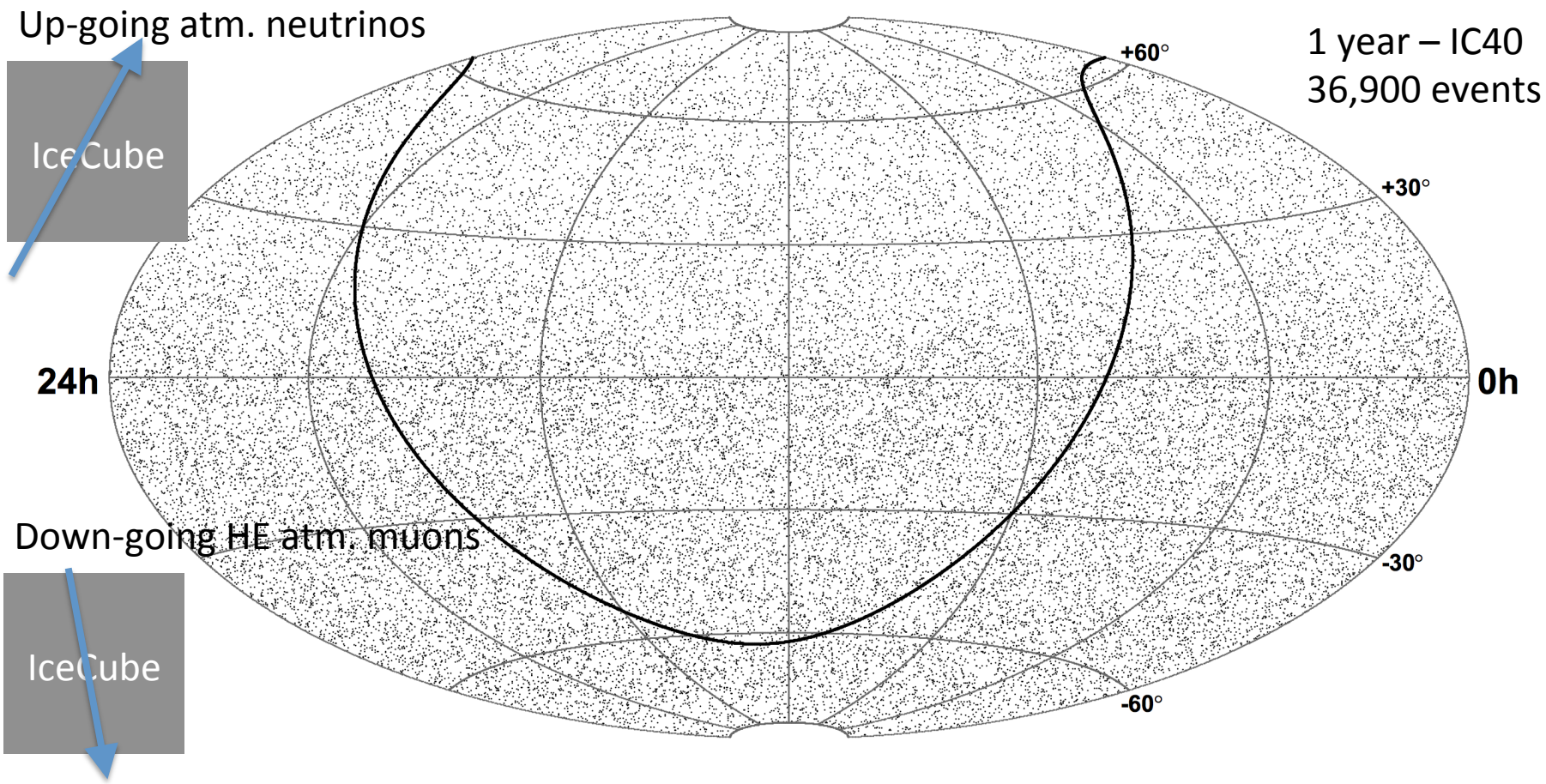




x : track-like
+ : shower-like

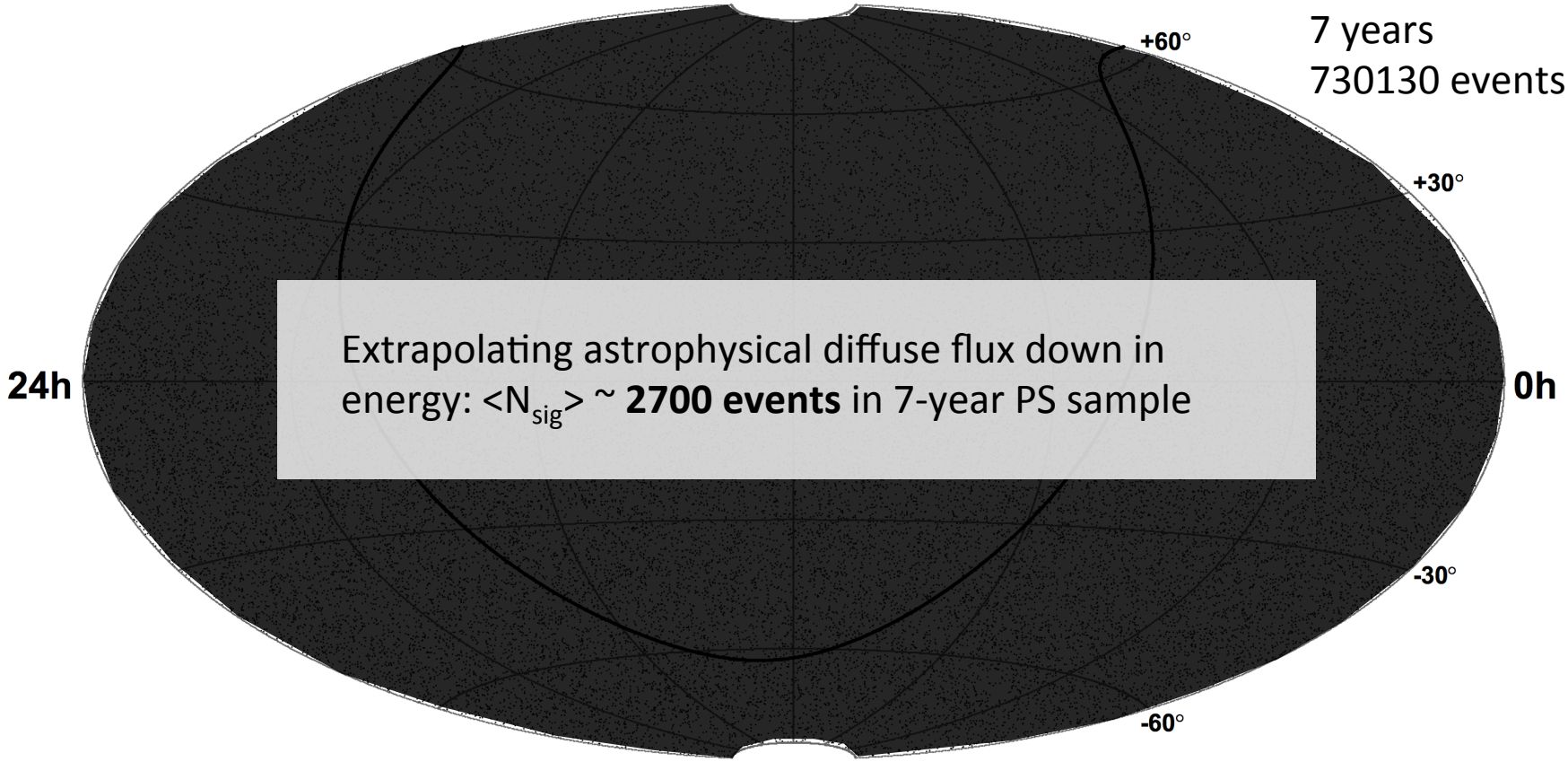
Neronov & Semikoz 2015 (arXiv: 1509.03522) claim >3 σ

Point Source Sample



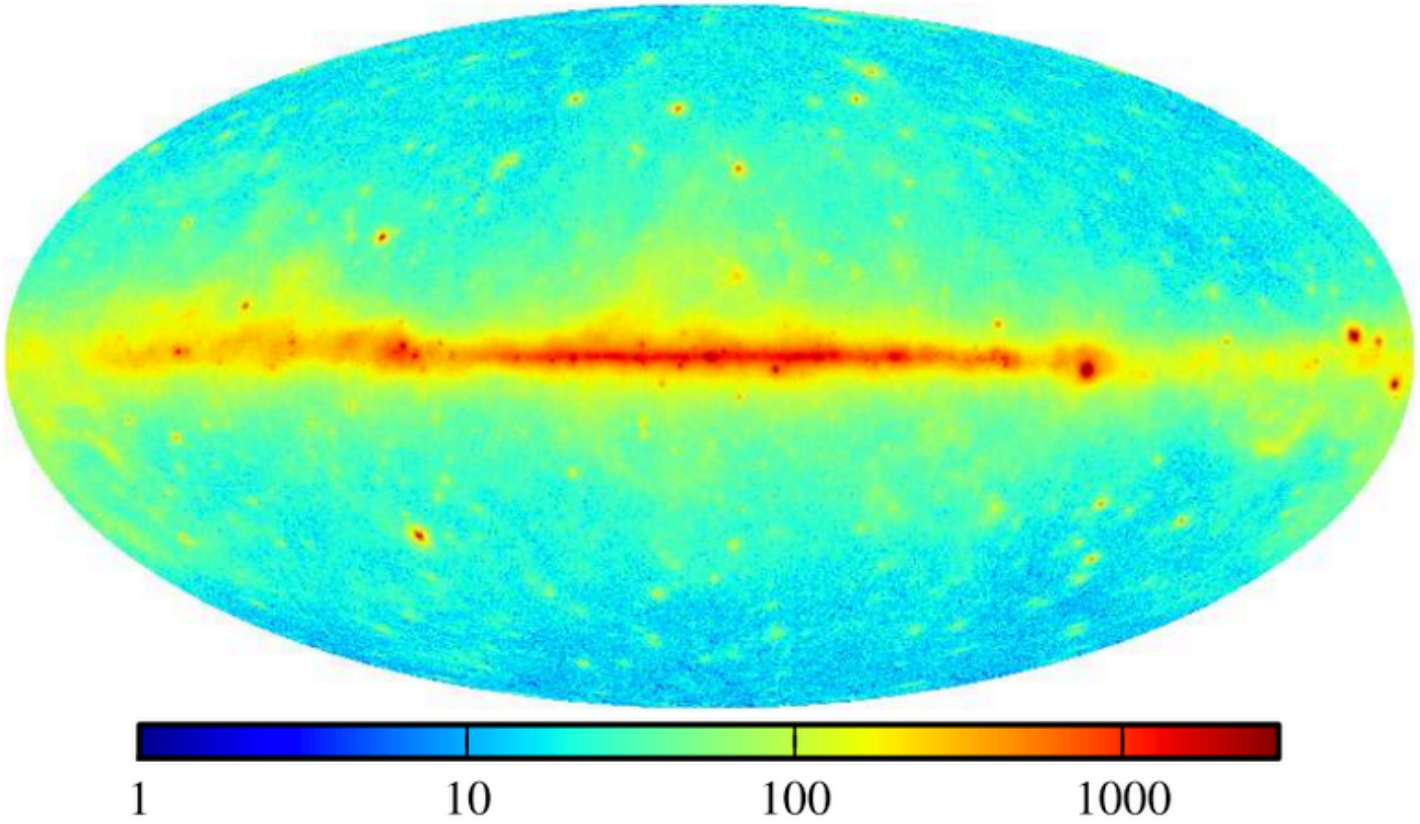
- Too many events to show full sample – 1-yr sample for illustration
- Can we find some ~hundreds of events distributed along the plane?

7 years of PS Data



- Too many events to show full sample – 40-string sample for illustration
- Can we find some ~hundreds of events distributed along the plane?

Raw Gamma-Ray counts > 100 MeV

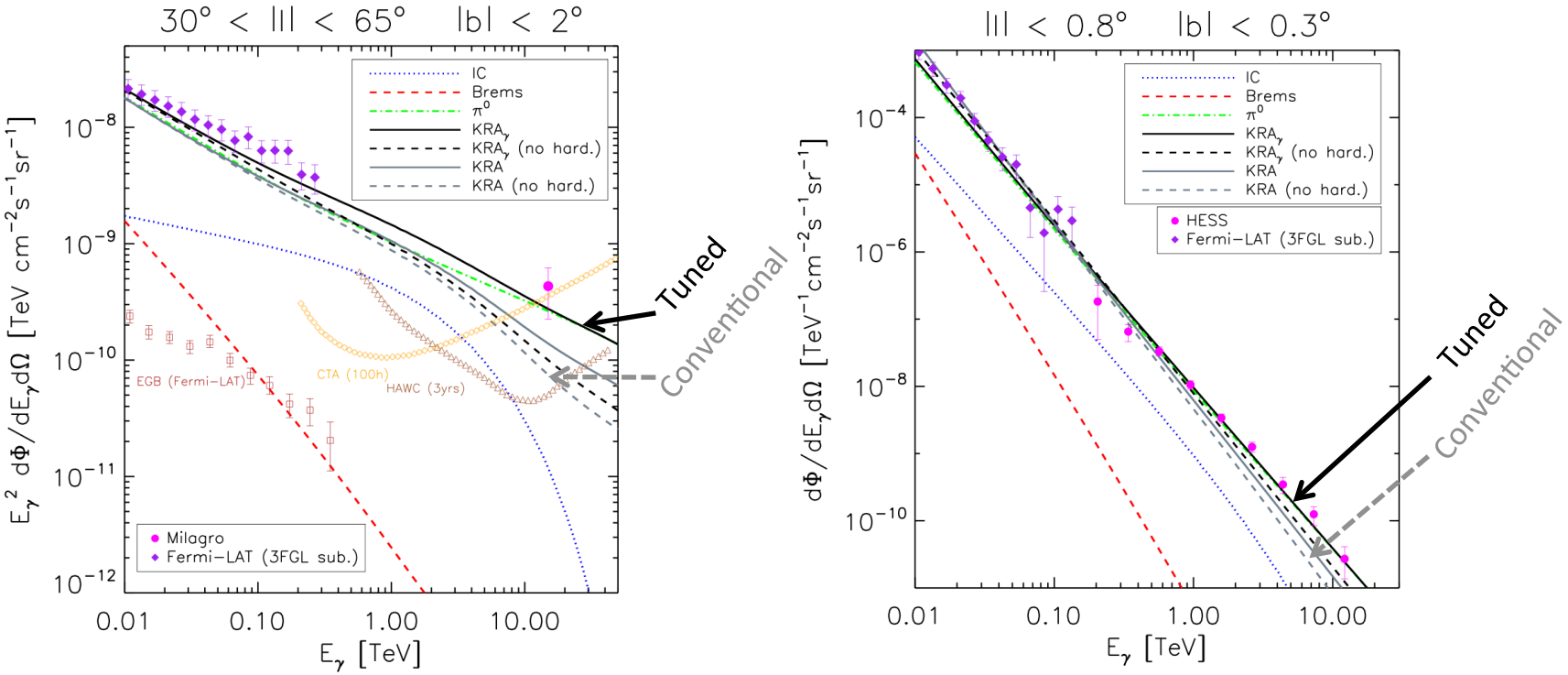


Dominant contribution of diffusive galactic gamma rays is from π^0 decay!

Gal Cosmic Ray Interactions

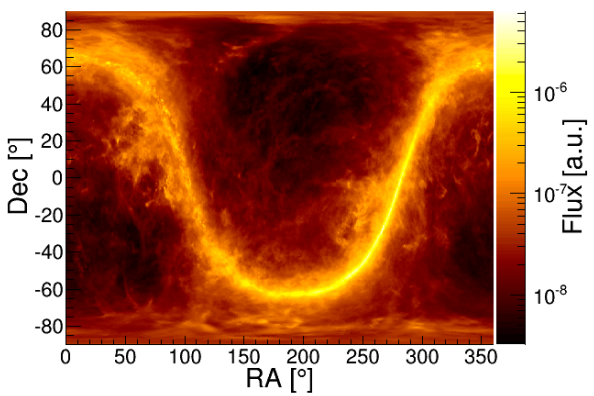
- Previous modeling assumed ~$E^{-2.7}$ CR spectrum uniform in galaxy
- Fermi+Milagro+HESS γ-ray data combined now allow us to build new models, allowing CR diffusion to change with galactic radius

γ-ray Models



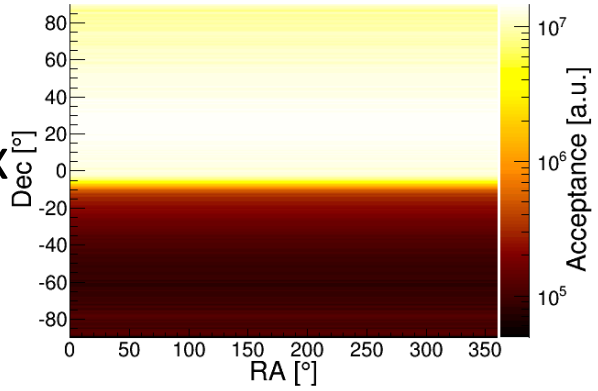
Gaggero et al 2015
arXiv:1504.00227

Max LH Spatial Template



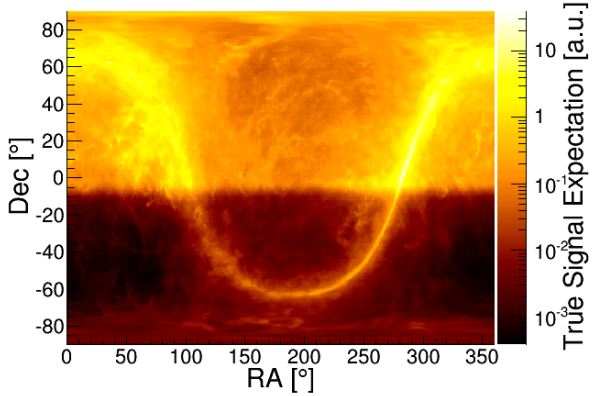
Gamma-ray Gal Plane π^0 Decay Map from *Fermi*-LAT

X



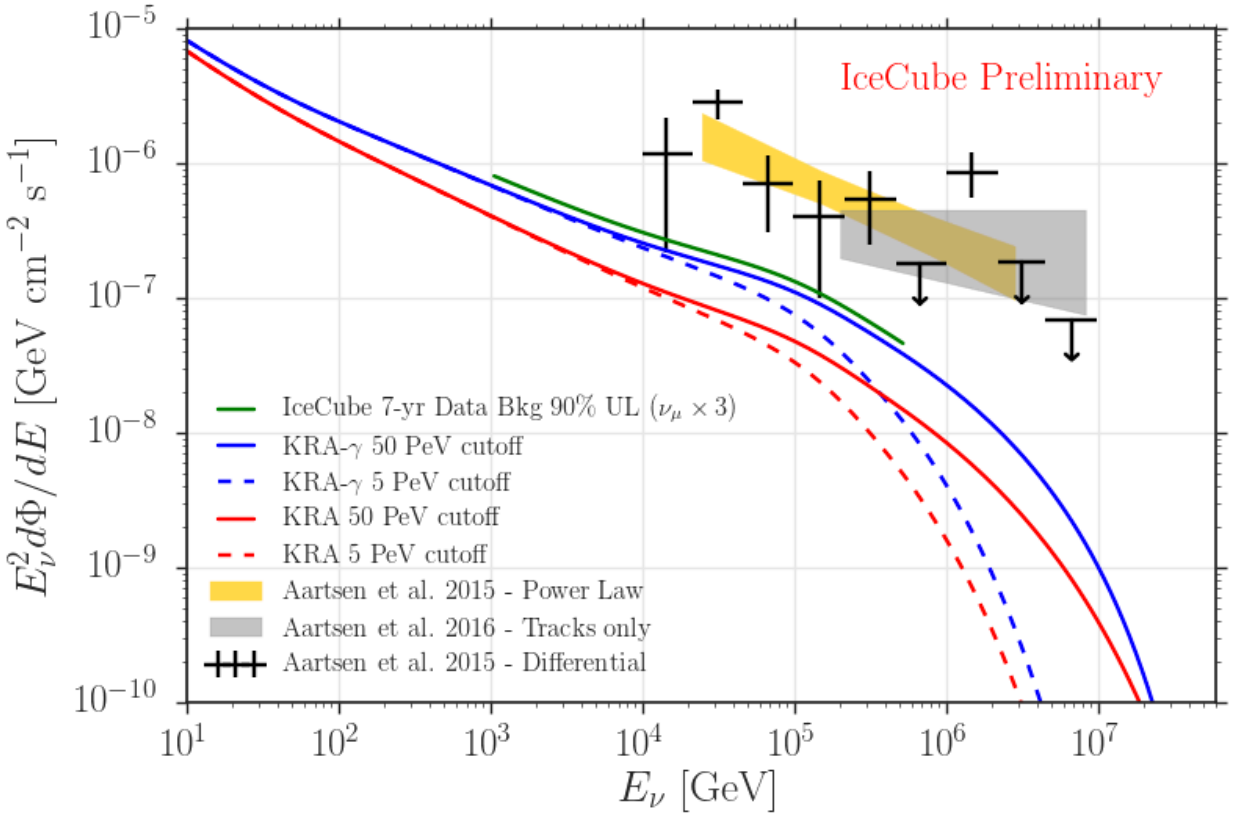
IceCube Acceptance (IC86 PS sample, $E^{-2.5}$)

=



Where we expect neutrinos

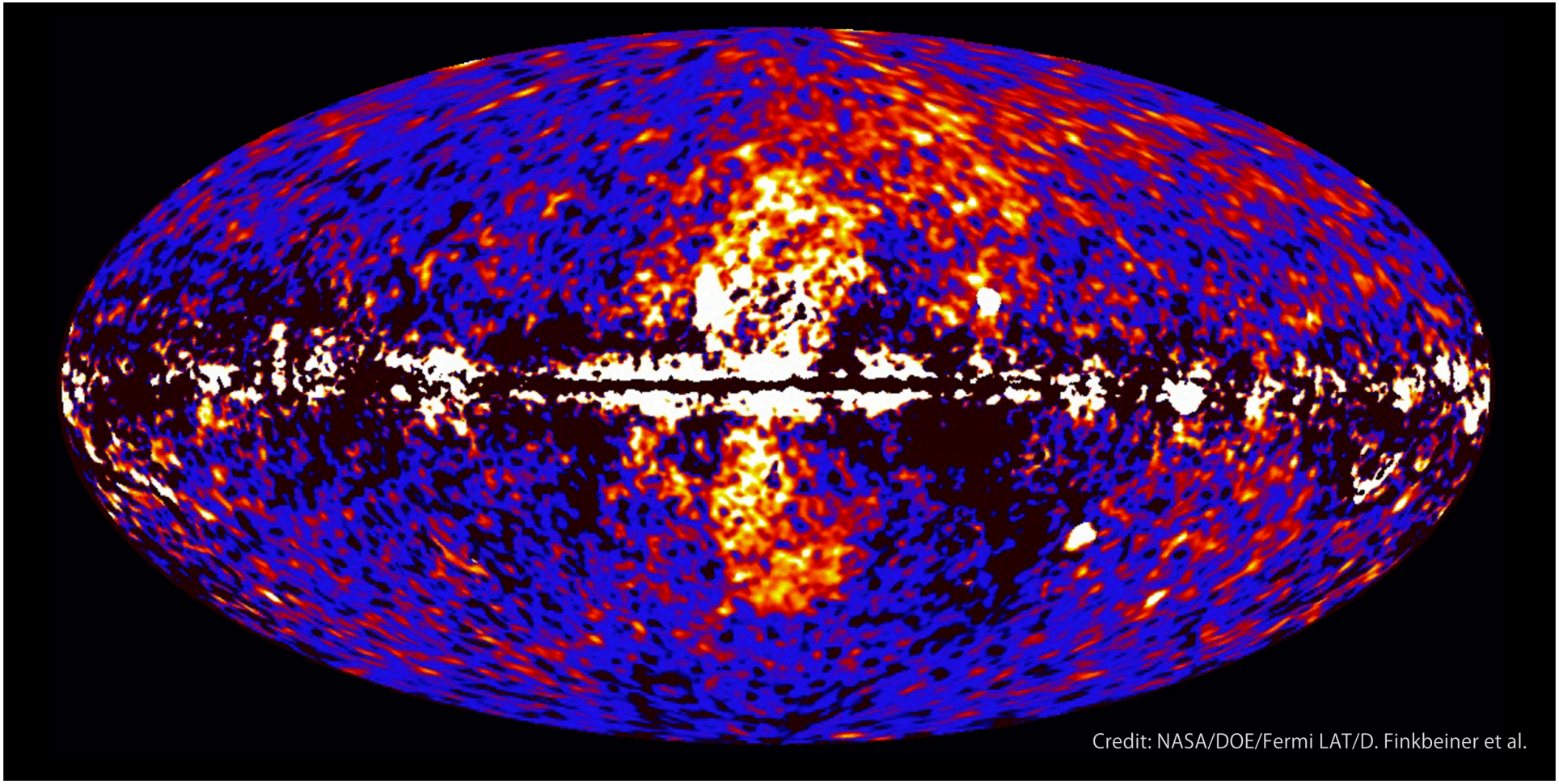
Gal Plane Predictions and Limits



- In 7 years of data we see small excess: ~150 events, p-value = 37%
- Upper limit is 120% of the most optimistic model prediction
  - Sensitivity is 78% of model
- Merging tracks + cascade channels
- **Joint analysis with ANTARES**

Analysis by Jon Dumm (SU)

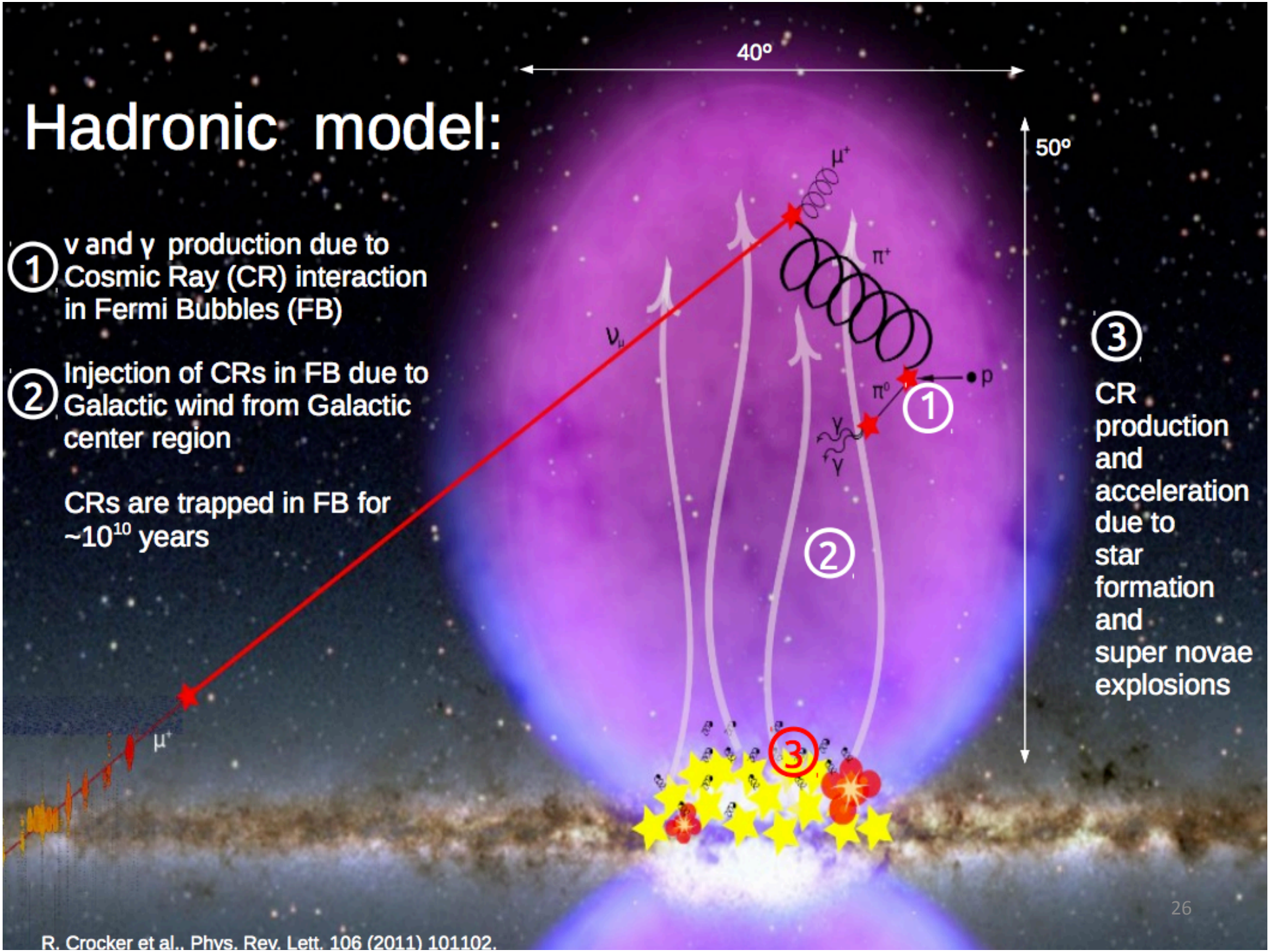
Fermi Bubbles



Visible in IceCube if **hadronic** in origin?

Analysis led by Lisa Unger (UU)

Hadronic model:



1. ν and γ production due to Cosmic Ray (CR) interaction in Fermi Bubbles (FB)

2. Injection of CRs in FB due to Galactic wind from Galactic center region

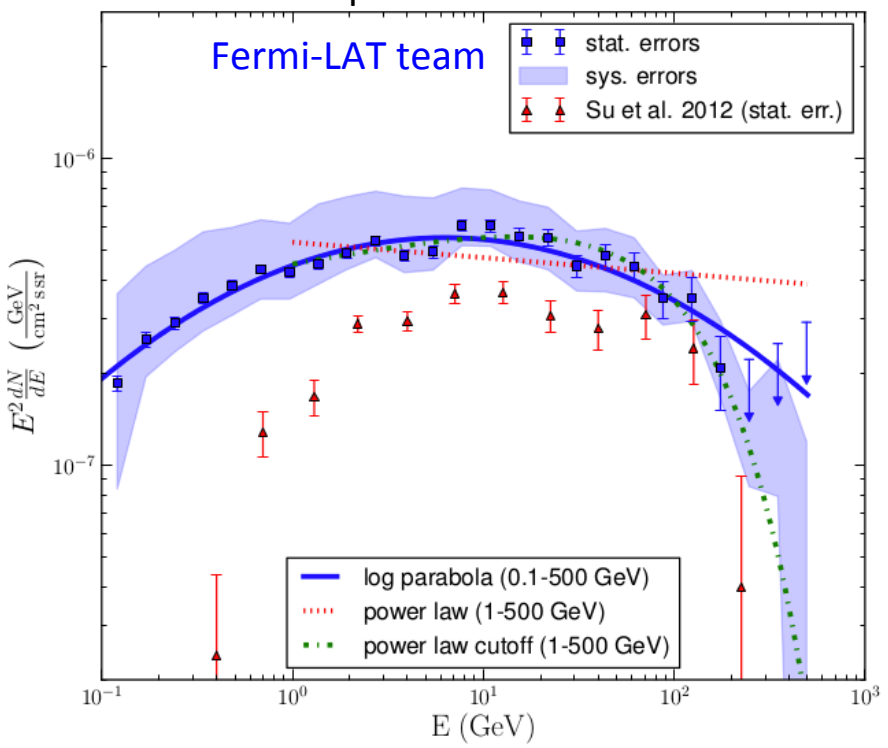
   CRs are trapped in FB for ~10^{10} years

3. CR production and acceleration due to star formation and super novae explosions

R. Crocker et al., Phys. Rev. Lett. 106 (2011) 101102.

Fermi Bubbles Spectrum

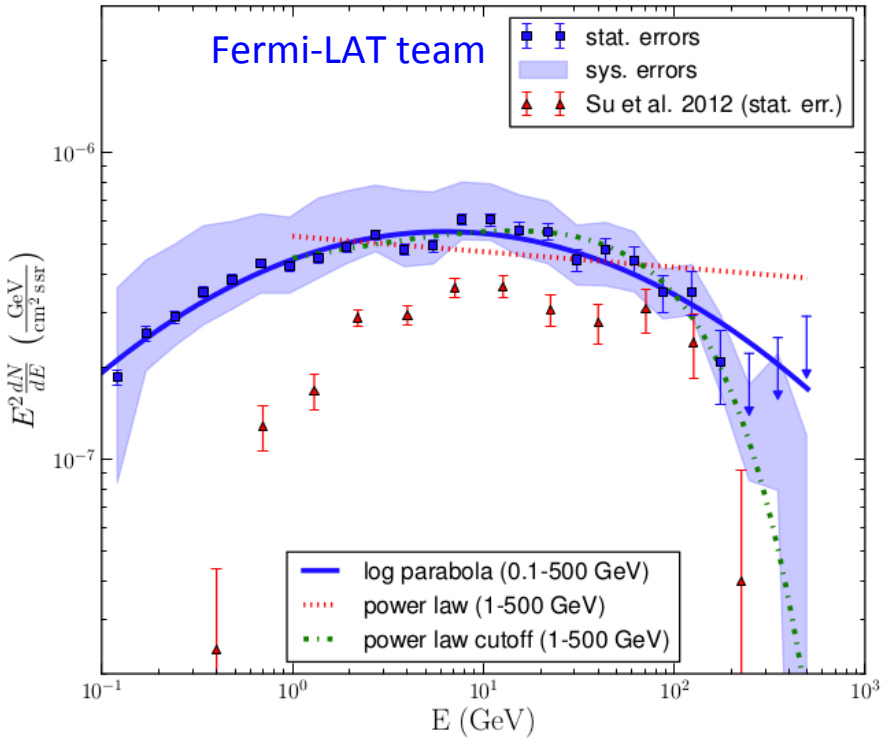
Fermi-LAT: ApJ. arXiv:1407.7905v1

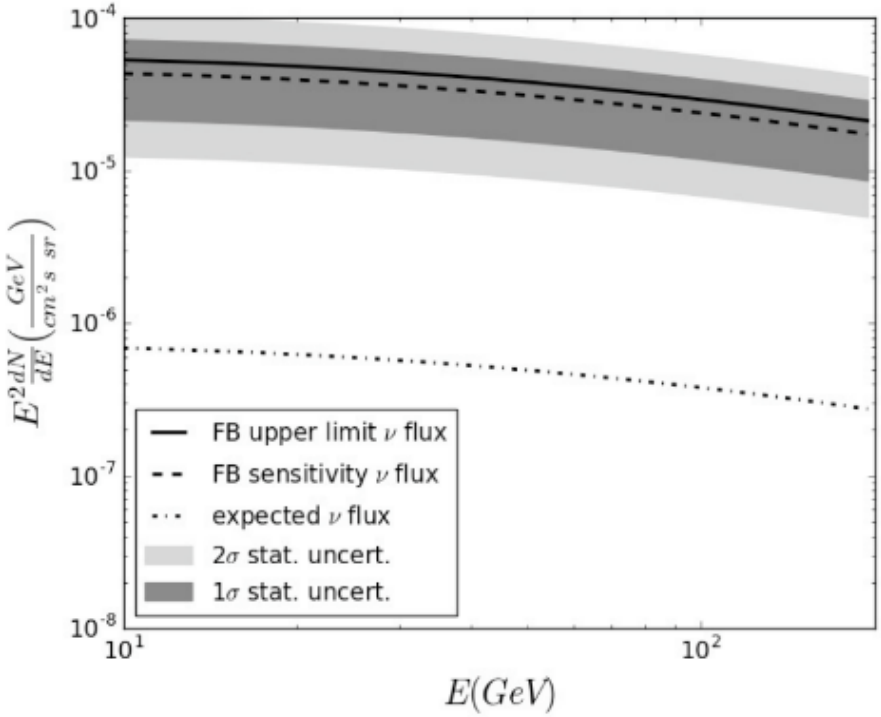


- Spectrum likely cuts off > ~100 GeV → Focus on low-energy contained cascade sample

Fermi Bubbles Spectrum

Fermi-LAT: ApJ. arXiv:1407.7905v1

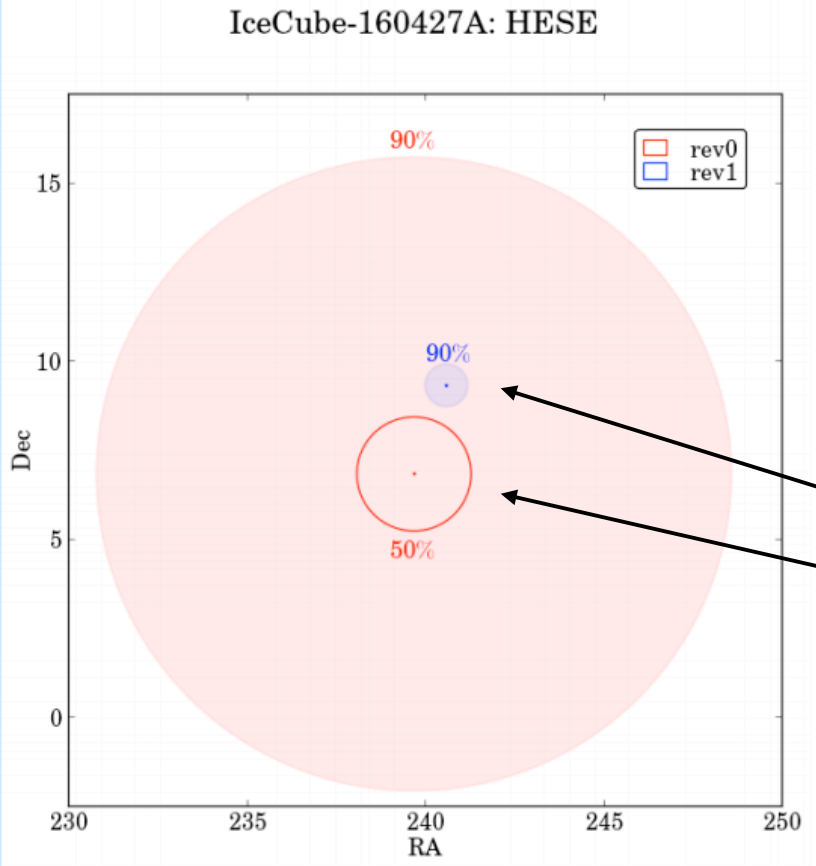




- Spectrum likely cuts off > ~100 GeV → Focus on low-energy contained cascade sample
- Sensitivity ~60 times higher than hadronic models predict
- 0.3 σ excess in unblinded results → Paper being drafted

Analysis led by Lisa Unger (UU)

First IceCube GCN Alerts!



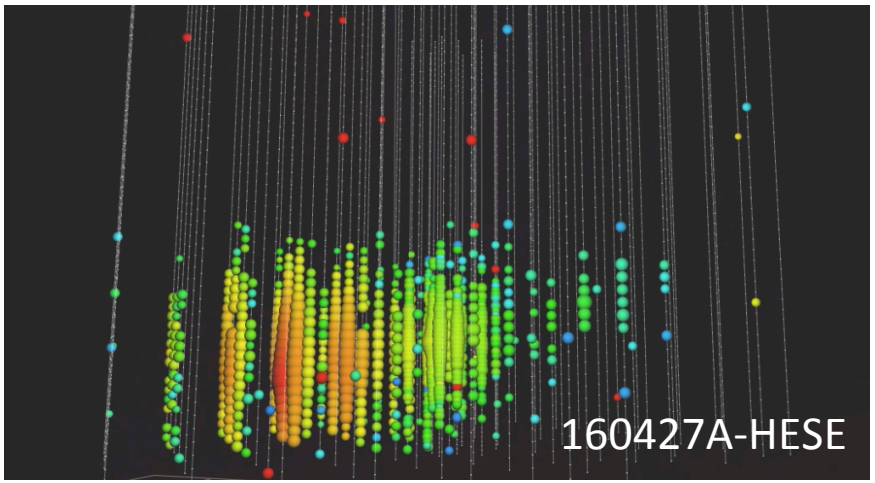
First public GCN neutrino alert sent last April

Follow ups: Optical (PanSTARRS, PTF)
Gamma-ray (VERITAS, H.E.S.S., MAGIC, FACT)

Track direction changed substantially
-Automatically updated in 1—2 hours!

Revision

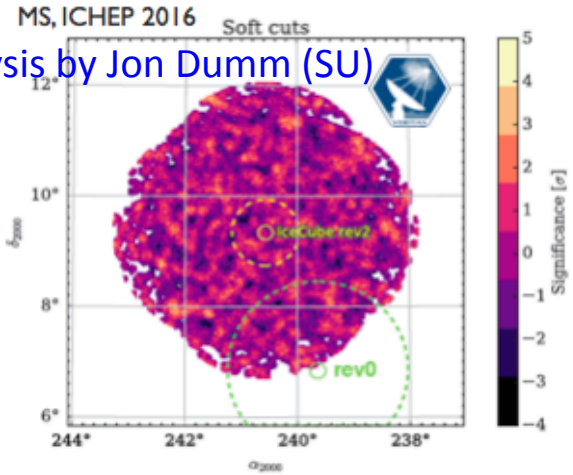
Original



Gamma-ray Followup

H.E.S.S.

★ automatic **follow-up < 2 min**
★ duration: 2h (full H.E.S.S.-II array)
2016-04-28: 18min (first position)
2016-04-29: 1.5h (updated position)
2016-04-30: 0.5h (updated position)
★ analysis in progress



Analysis by Jon Dumm (SU)

VERITAS

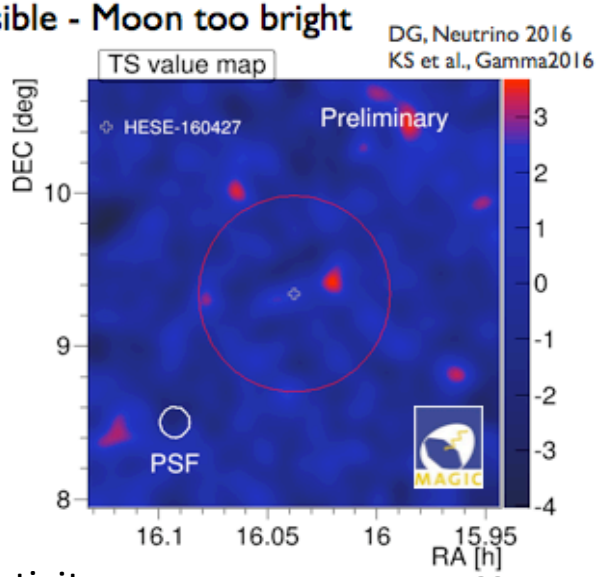
★ automatic **follow-up in 112s**
★ duration: 1.2 h (first) + 2 h (updated)
★ moonlight settings - reduced high-voltage
★ UL ~ few % C.U.

FACT

★ observed updated position
★ duration: 4.24 h
2016-04-28 2:00 – 4:32 UTC
2016-04-29 1:32 – 3:33 UTC
★ zd: 19 – 30°
★ moderate moon light
★ some clouds in the 1st night
★ weather fine in the 2nd night
★ no signal found

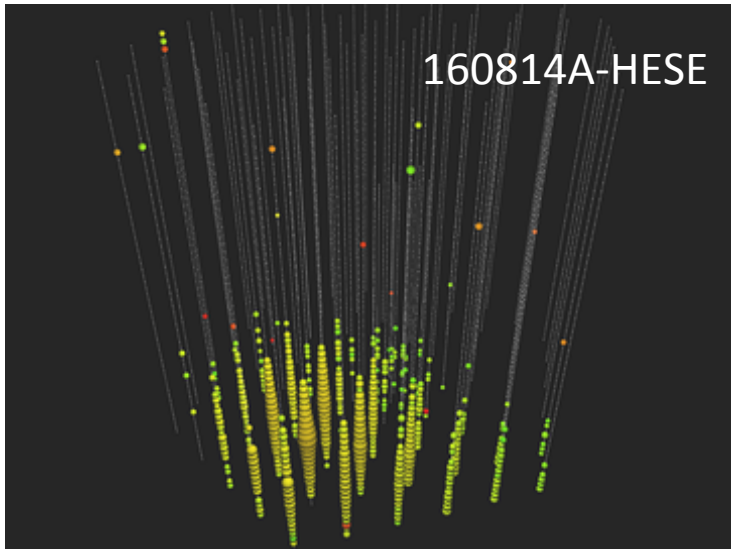
MAGIC

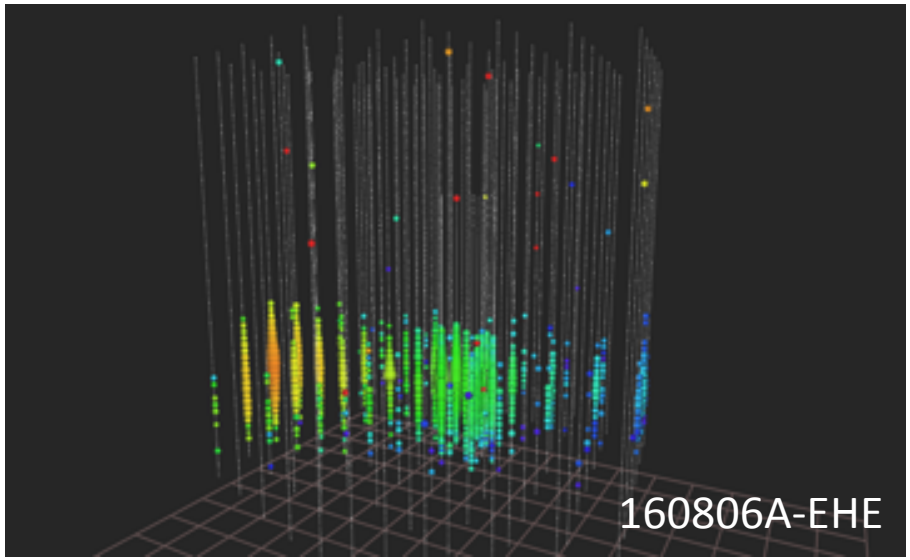
★ 2h data taken on 29/04/2016 with moderate moon (updated position)
★ night 27/28 Apr not possible - Moon too bright
★ zenith range: 18-26 deg
★ E threshold ~120 GeV
★ hot spot 0.3 deg away, significance: ~ 3.6 sigma (2.1 sigma after trials)
★ UL - analysis ongoing...

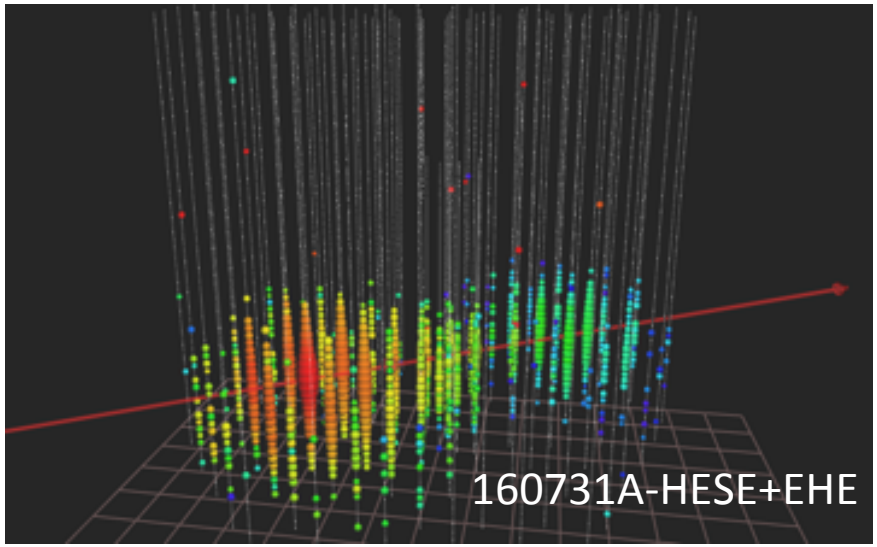


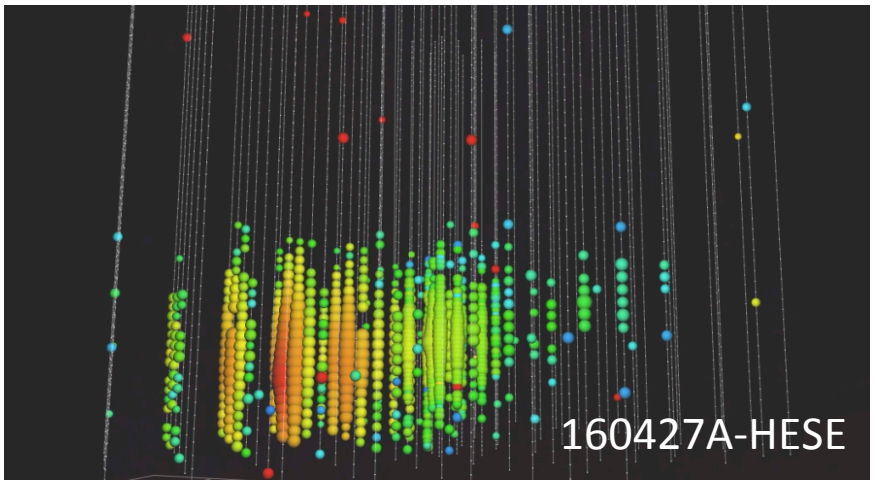
Fermi-LAT saw 5 blazars within error circle – no activity

Four HE Alerts So Far!





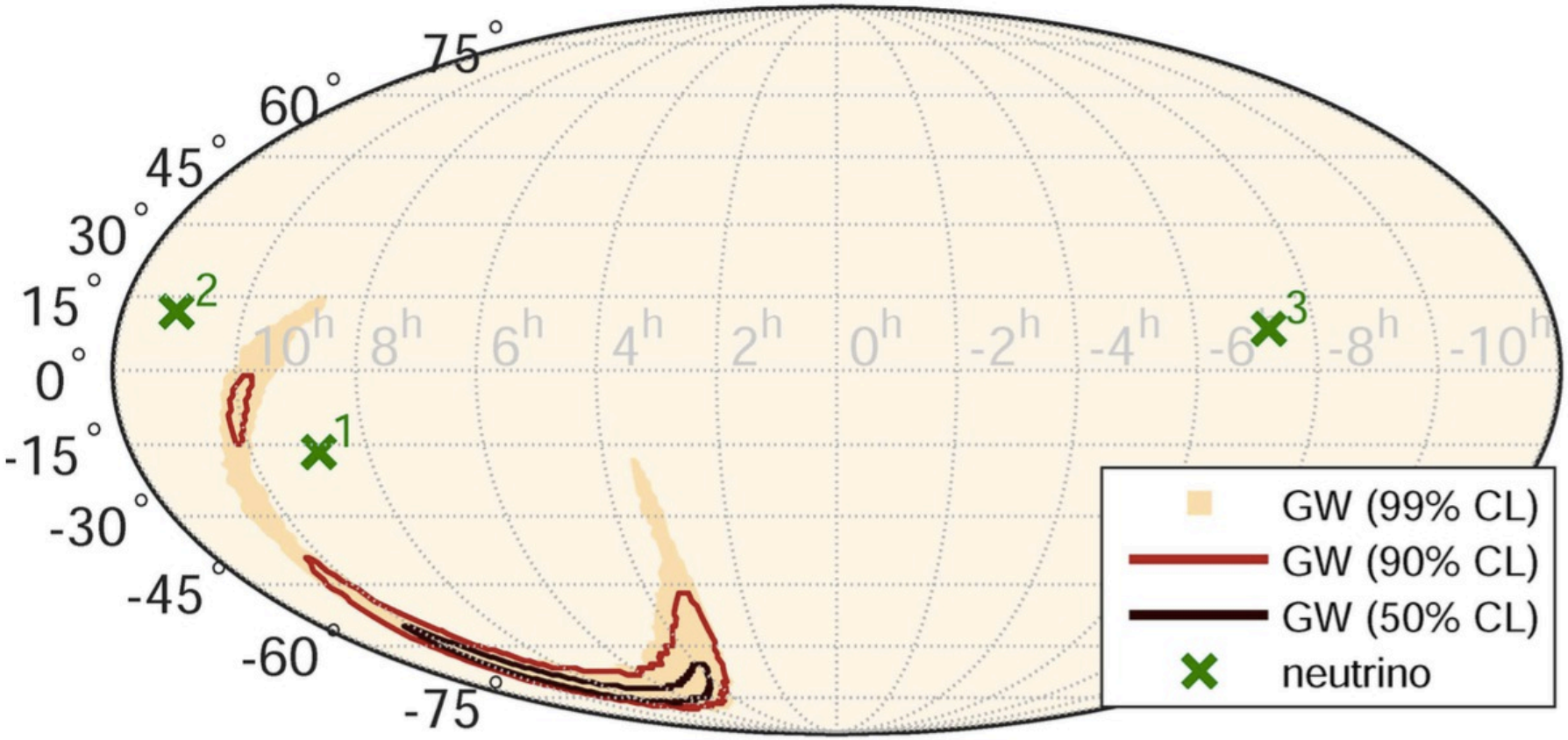




High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube

ANTARES Collaboration, IceCube Collaboration,
LIGO Scientific Collaboration, Virgo Collaboration
[arXiv:1602.05411]

±500 sec time window

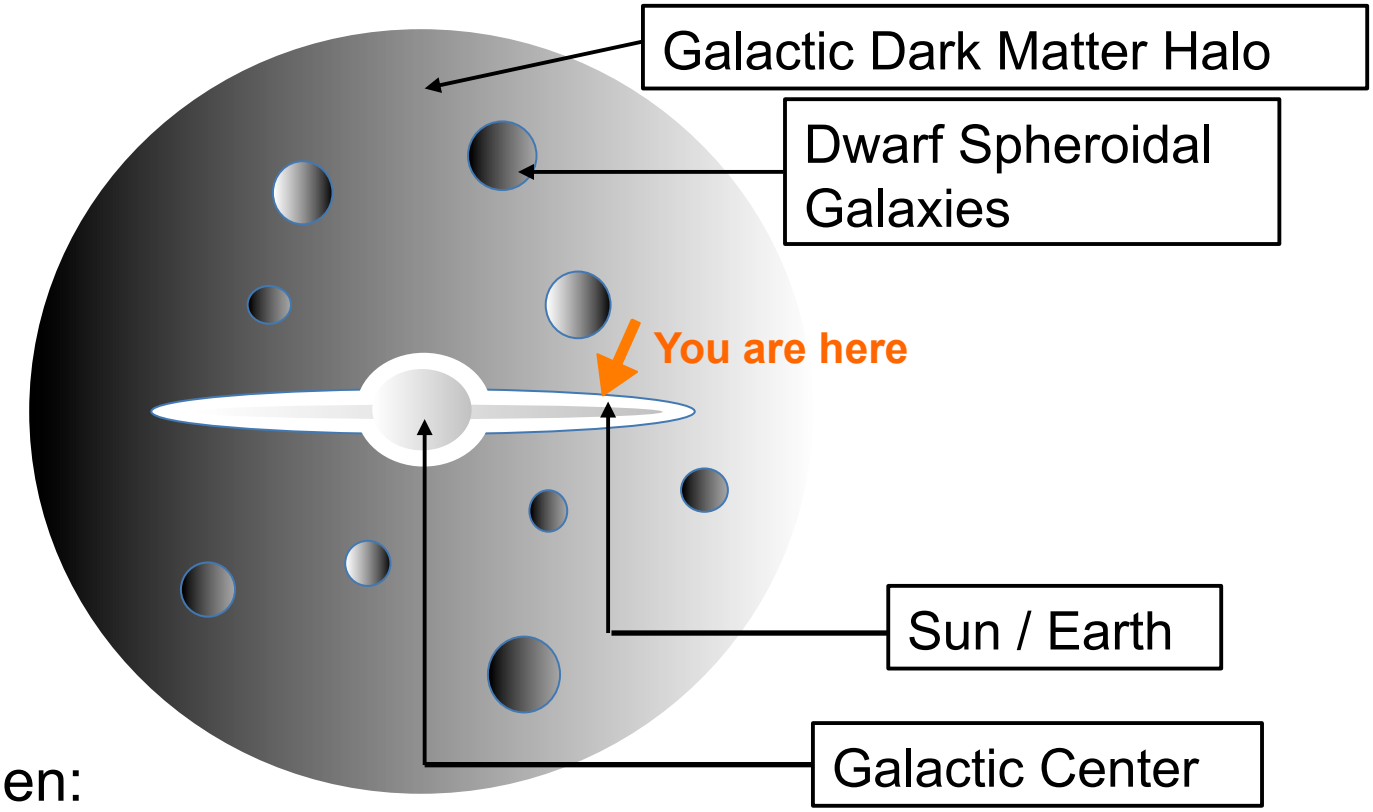


No HESE event in time window.
No SN alert in time window

IceCube uptime ~ 99%

Analysis efforts by Chad Finley (SU)

Indirect DM Searches with IceCube



Recently finished analyses in Sweden:

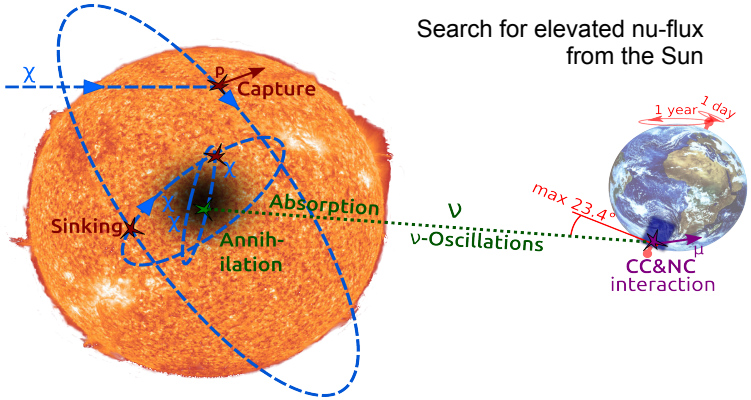
Analysis I : H. Taavola (Uppsala) PhD-defense Dec 4th 2015
DM in Galactic Halo with Low-energy cascades (DeepCore)

Analysis II : M. Wolf + S. Flis (Stockholm) EPJ C75 (2015) 10, 492
DM in Galactic Center with Low-energy tracks (DeepCore)

Analysis III: M. Zoll (Stockholm) ICRC 2015
DM in the Sun with tracks (IceCube + DeepCore)

Analysis IV: M. Wolf PhD-defense June 3rd 2016
DM in the Galactic Halo with tracks

Solar WIMP Analysis

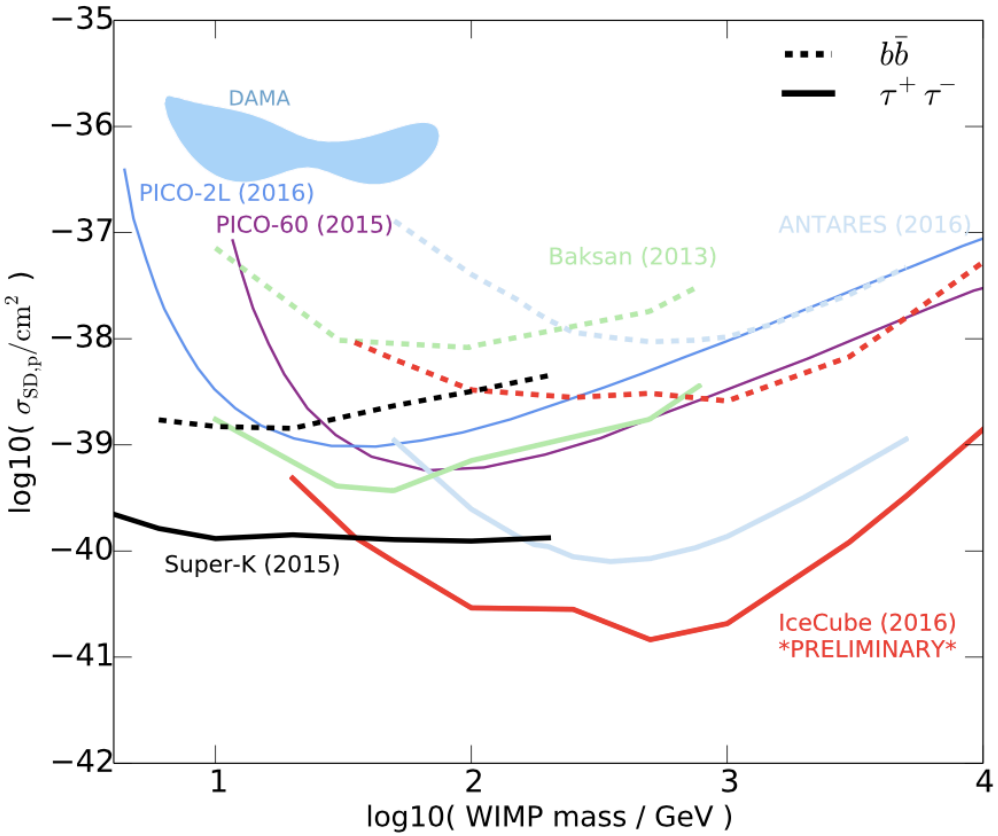


Search for elevated nu-flux from the Sun

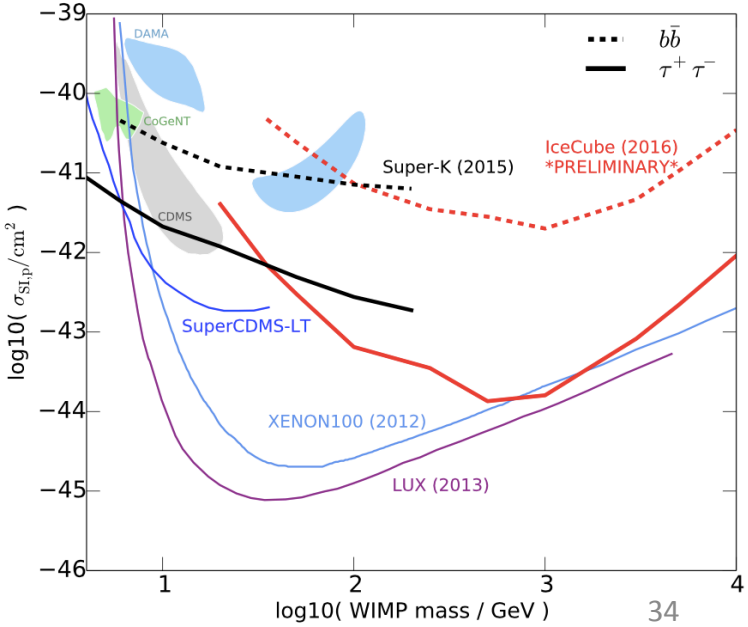
M. Zoll (SU)

PhD-defense Feb 29th 2016

World best limits for
SD WIMP-cross section m>100GeV
-Paper draft nearing completion

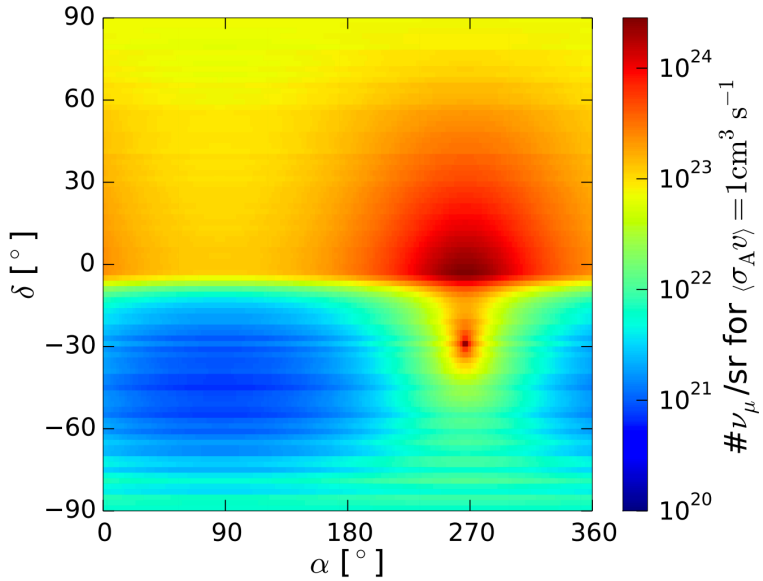


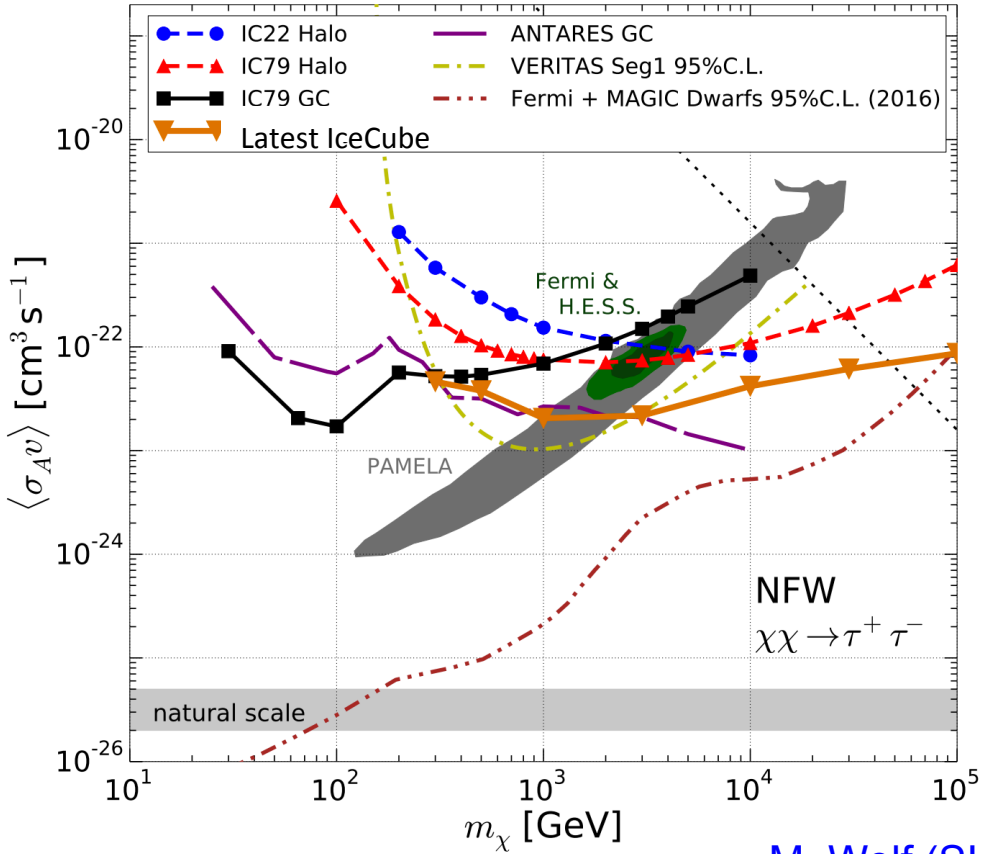
← Spin **Dependent**
Spin **Independent** ↓



Galactic DM Halo Analysis

IceCube view of NFW profile in tracks





Analysis explored: $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, $\mu^+\mu^-$, $\nu\bar{\nu}$
NFW vs Burkert

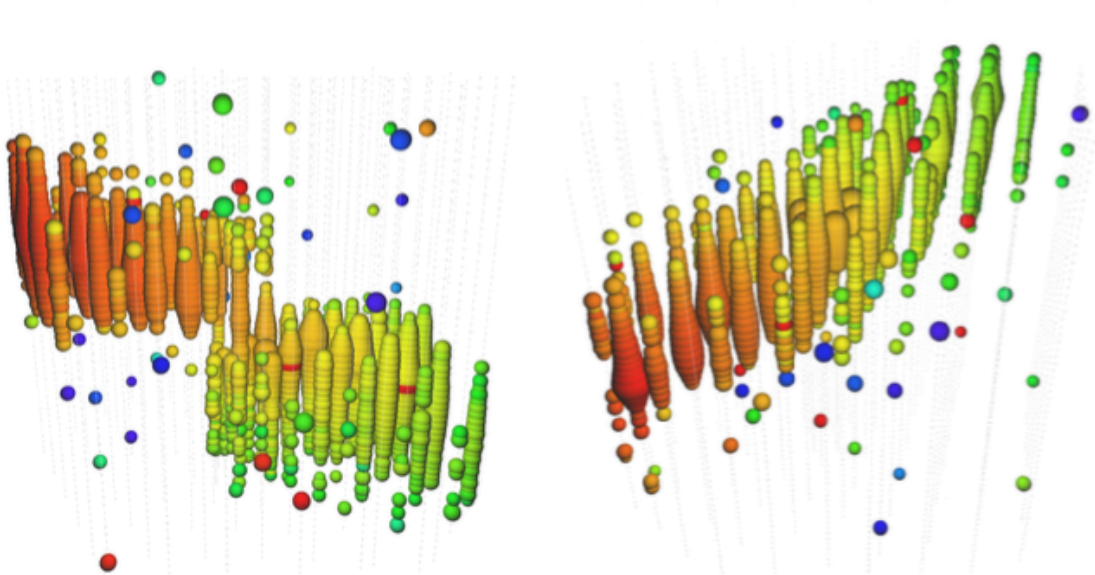
M. Wolf (SU)
PhD-defense June 3rd 2016

S. Flis (SU) finalizing complementary analysis in southern sky with starting events in southern sky

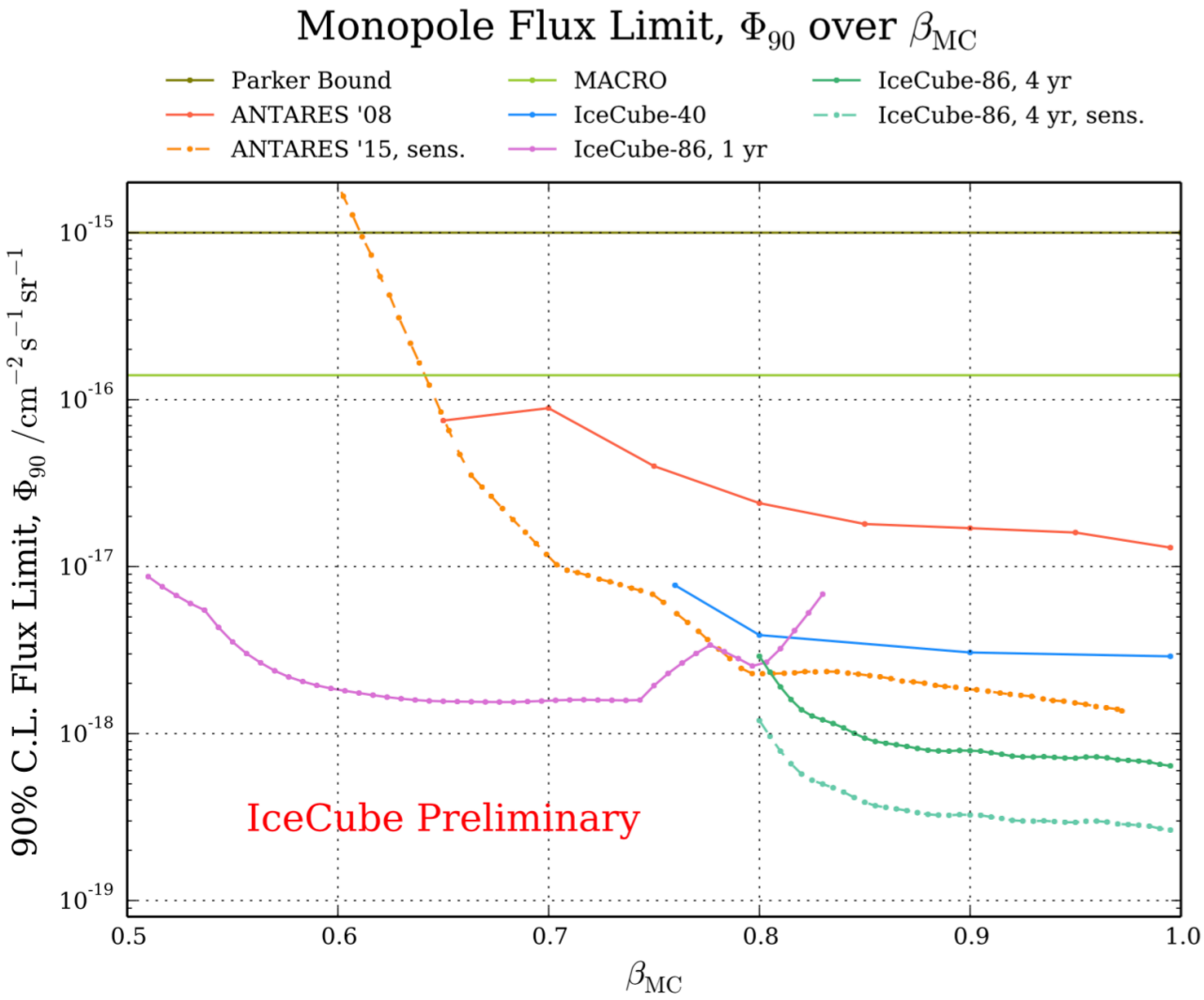
Magnetic Monopoles in IceCube

"... One of the safest bets that one can make about physics not yet seen."
-Joseph Polchinski

- Uppsala Analysis: Alexander Burgman
  - β region: $0.800 \leq \beta \leq 0.995$
  - Dominant energy loss: Direct Cherenkov Light
- First Step: Look for very bright tracks in existing UHE sample (GZK neutrinos)

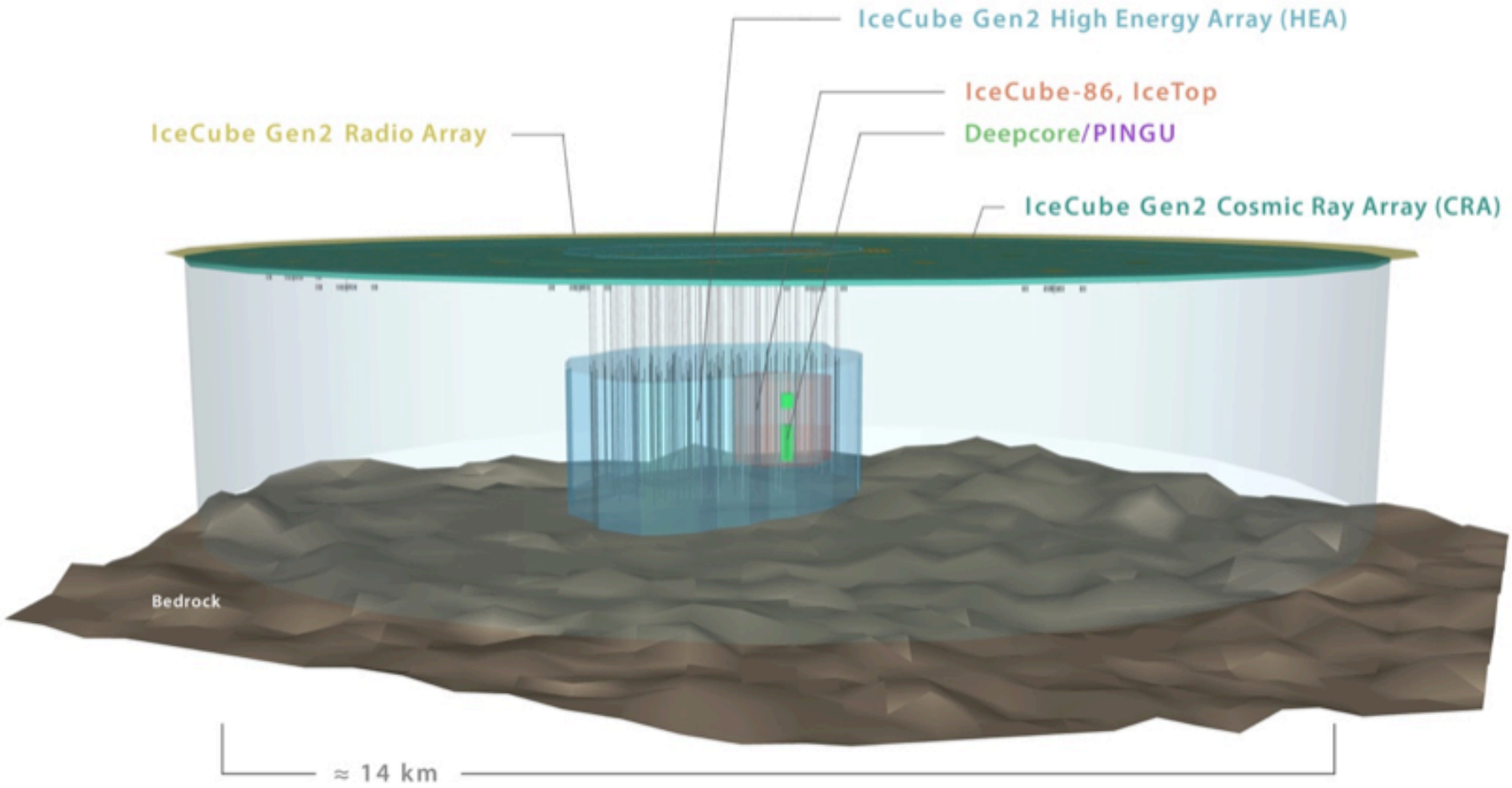


Magnetic Monopoles in IceCube

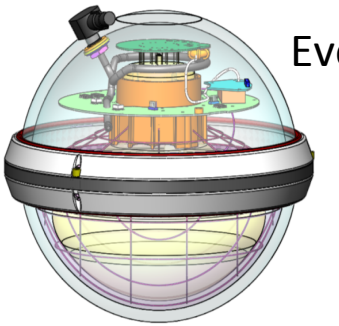


Next step: Characterize and eliminate astrophysical neutrinos (smoothness)

IceCube Gen2 Facility – Conceptual Design



Photodetection: the Options

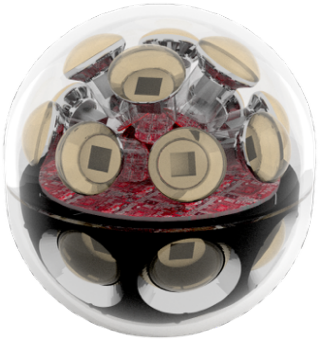


Evolve the **IceCube Digital Optical Module (DOM)**

- Well-tested, low risk

R&D: Multi-PMT "mDOM": 24 x 3" PMTs

- similar to KM3NeT design, test in PINGU
- suppress noise bkg with local coincidence
- uniform 4pi acceptance
- 2x eff. area as DOM @ similar price/ photocathode area





R&D: D-Egg Dual 8" PMT design

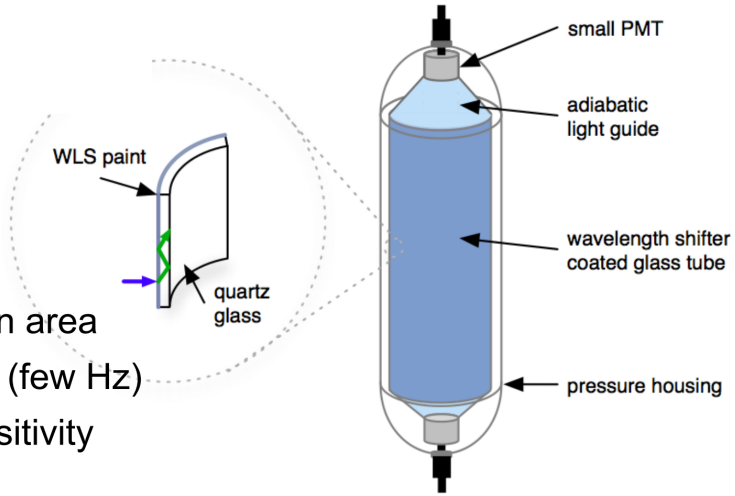
- includes testing better UV transparent glass

R&D: WOM - Wavelength-shifting Optical Module

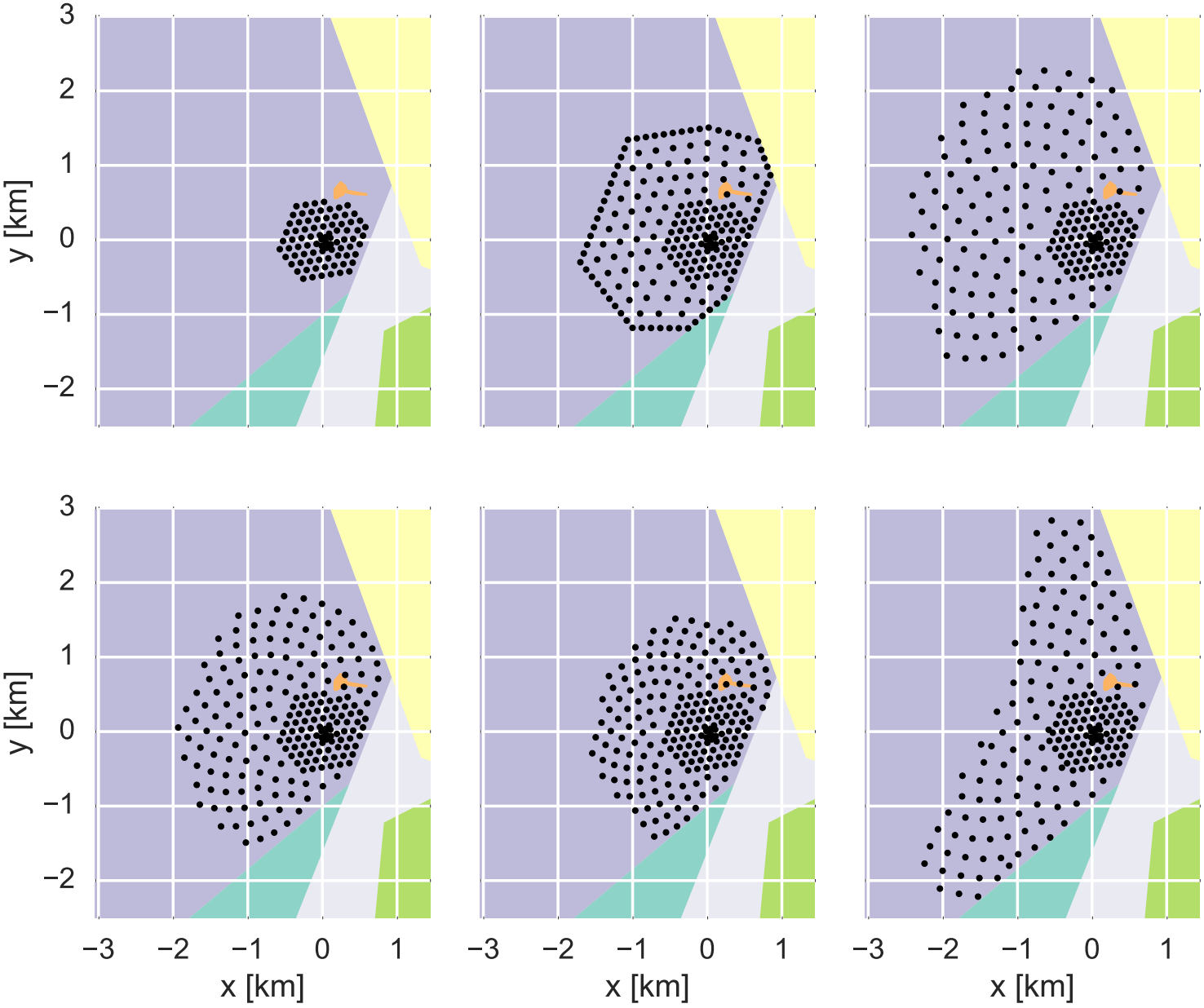
- light concentration with wavelength-shifting light guides
- large detection area increase
- ns timing not critical for HEA

Features

- large collection area
- low noise rate (few Hz)
- better UV sensitivity
- cost effective

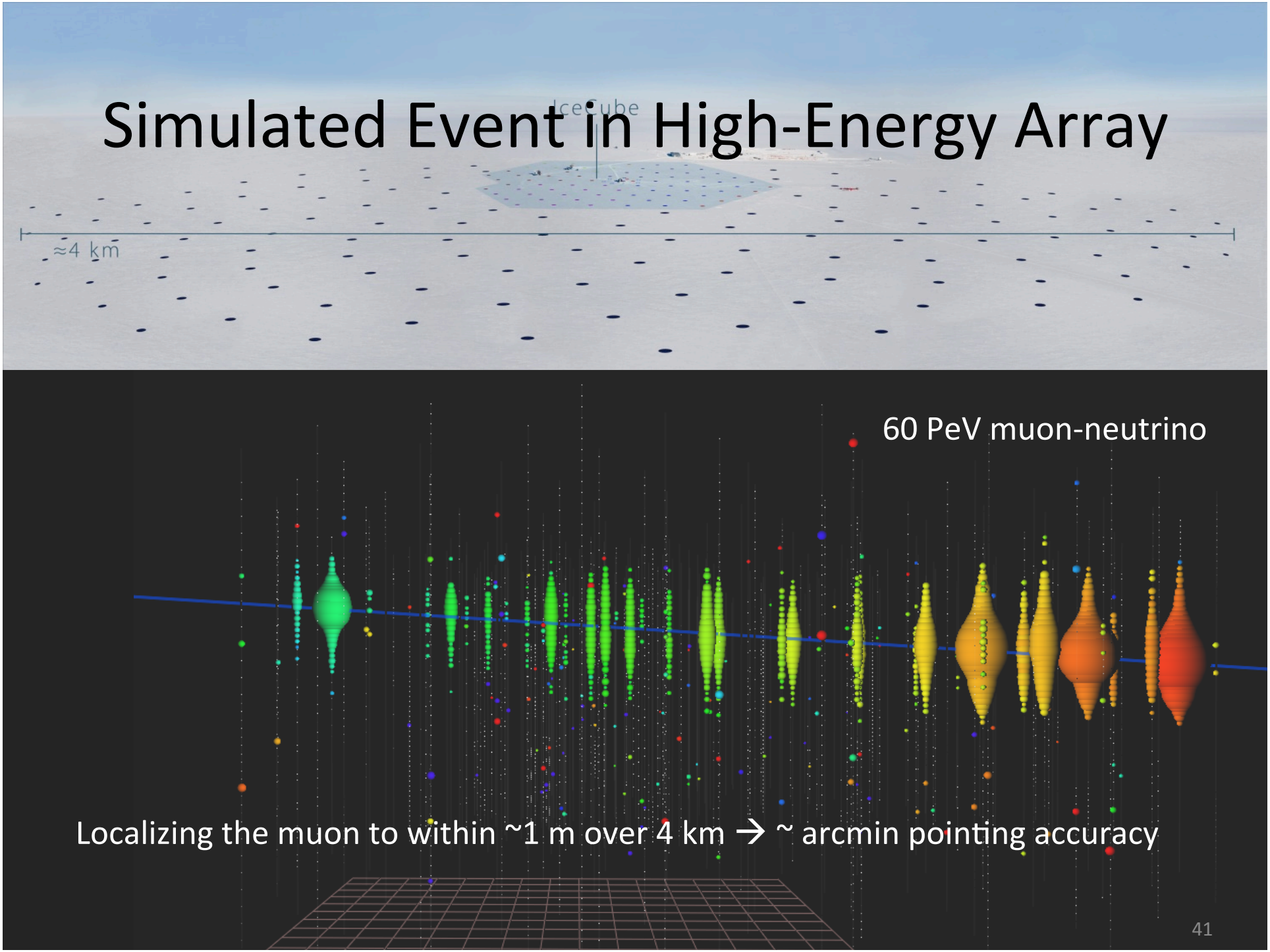


Geometries Currently Studied

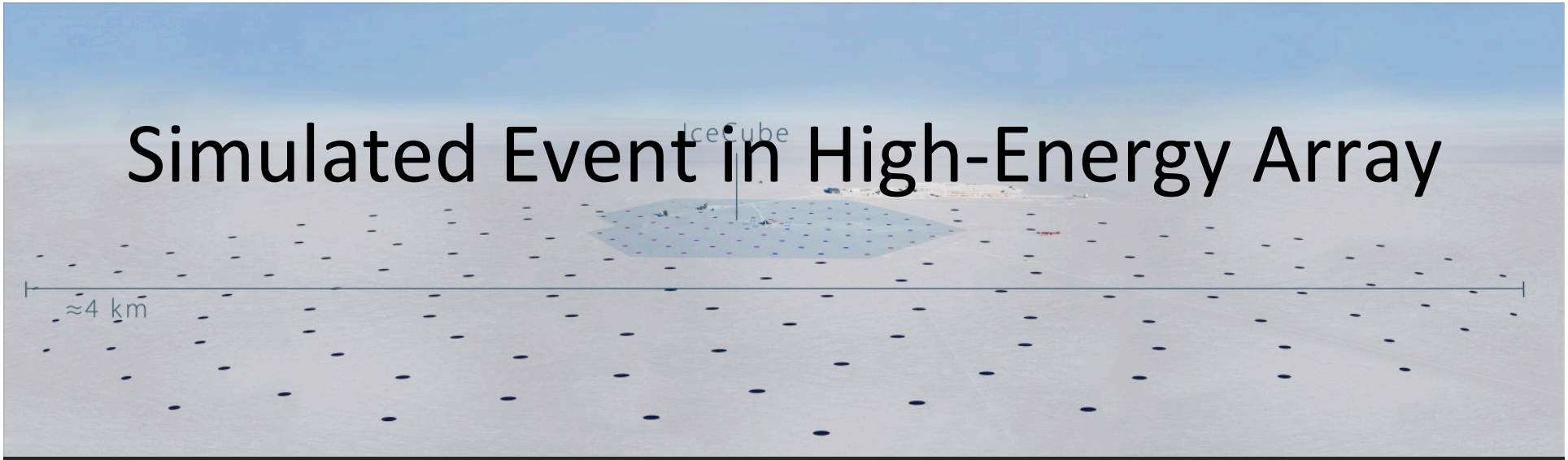


optimization studies by Samuel Flis (SU)

Simulated Event in High-Energy Array

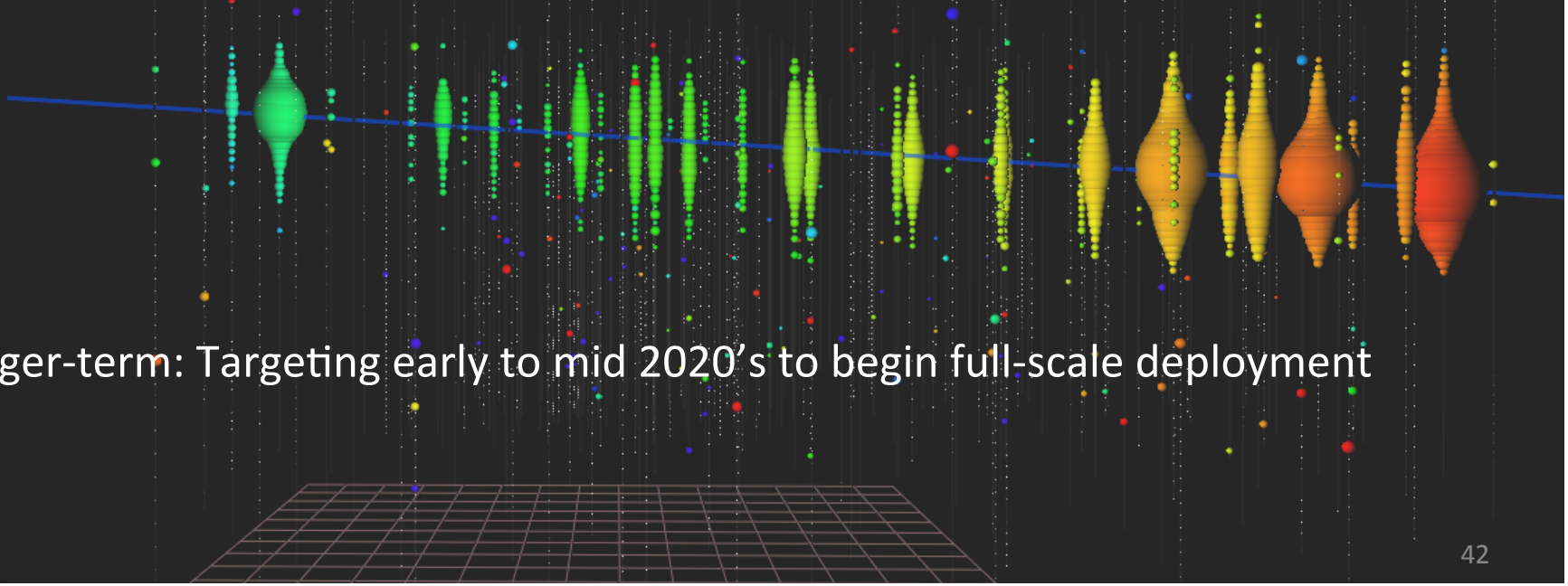


Simulated Event in High-Energy Array



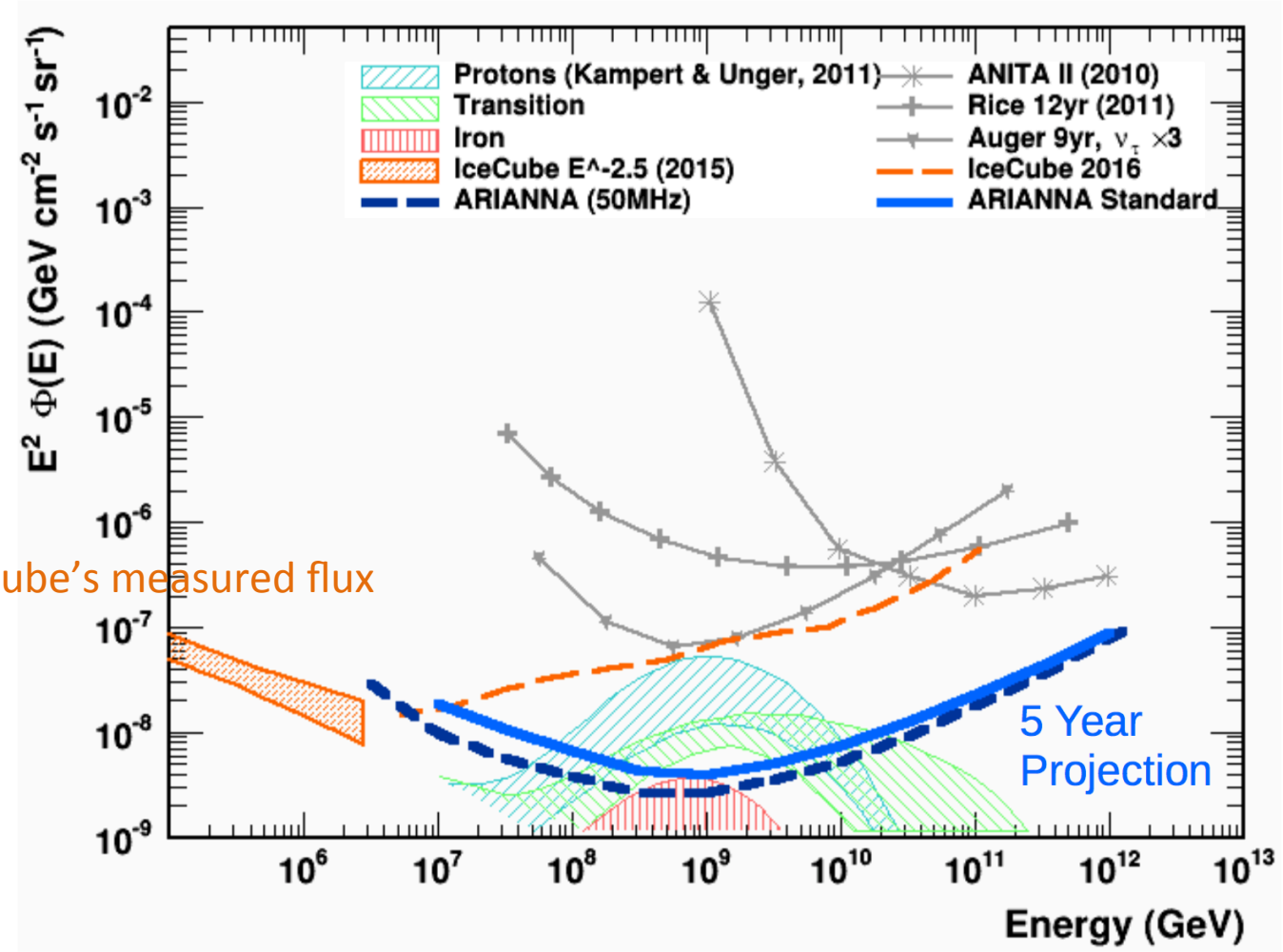
Near-term: NSF mid-scale instrumentation proposal with up to 7 new, close strings

- Funding by USA, Germany, and Canada
- Tau-neutrino appearance studies and tau double-bang studies



Longer-term: Targeting early to mid 2020's to begin full-scale deployment

Radio Detection of Neutrinos

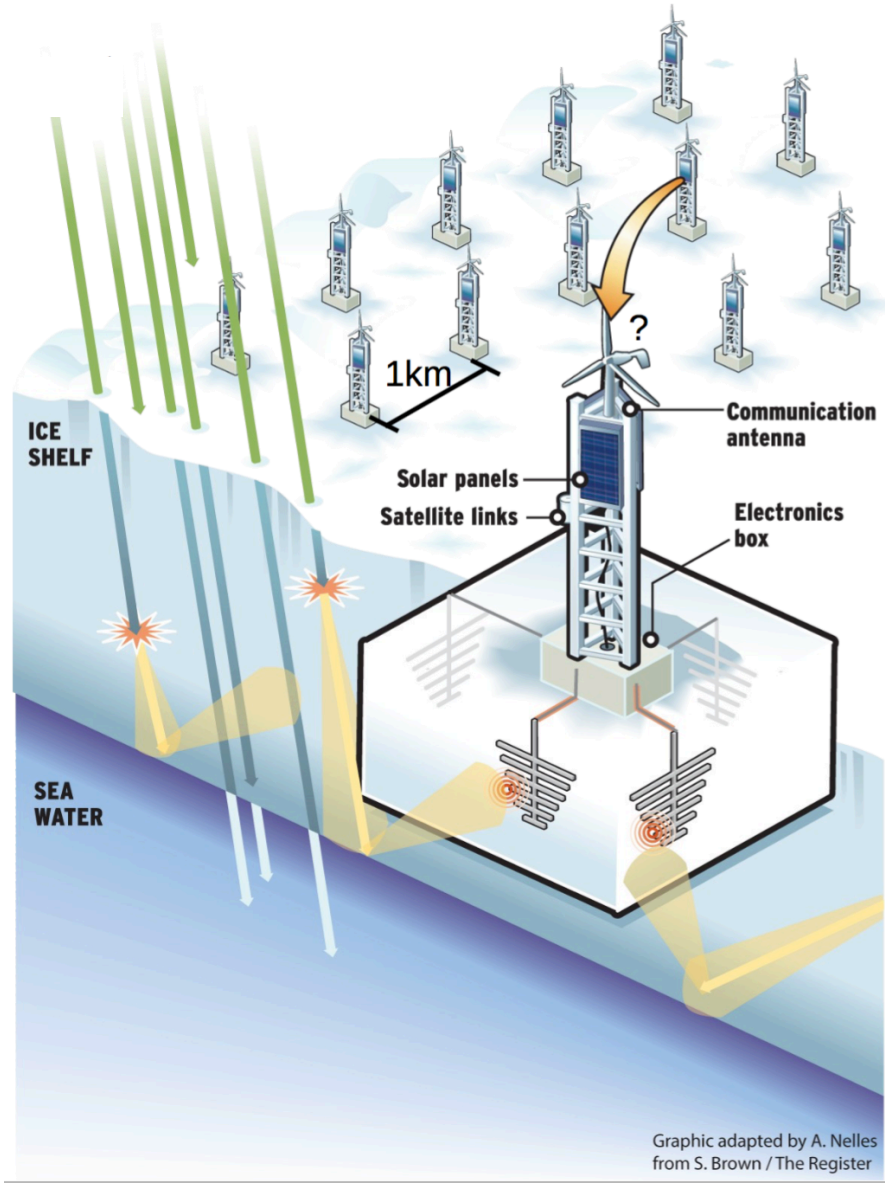


- Pursuing neutrinos from UHECR interactions with CMB requires new detection technique
- Radio arrays being pursued in China, Greenland, South Pole, and **Antarctic Ice Shelf (ARIANNA)**

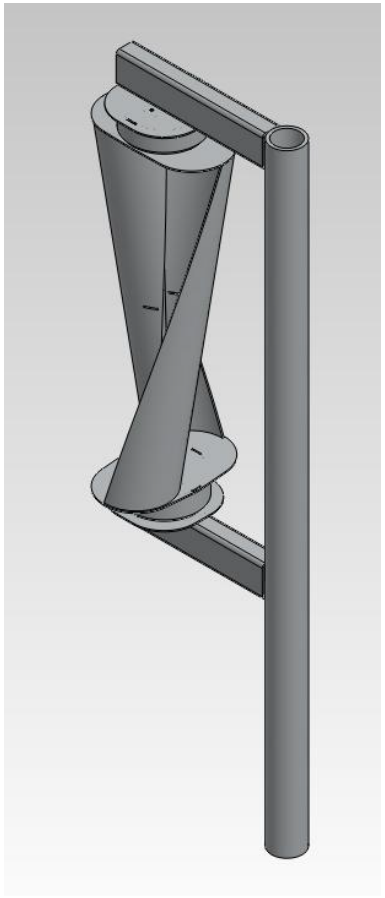
efforts by Allan Hallgren et al (UU)

ARIANNA Concept

- Large interaction volume
  - ~500 m thick ice shelf
- Signal reflection at ice/water interface allows for surface installation
- Radio-quiet environment means low trigger rate, allowing real-time data transfer over satellite radio
- Low power requirements allow for self-contained power system, autonomous operation
  - Solar in summer (Oct – Apr) proven eff. over two seasons
  - Testing wind turbines for winter







Wind Power at the ARIANNA site?

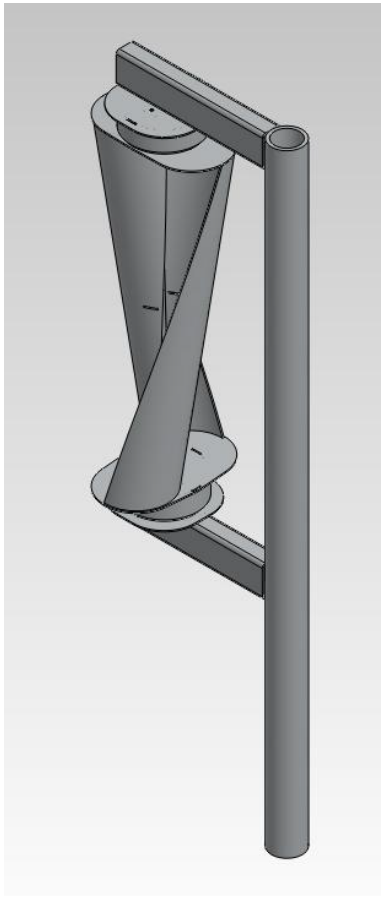
- Can we use wind power for rest of the year?
- Simulations using wind data show available wind power should be sufficient also with a relatively small turbine

- Earlier attempts failed, generated RF noise and turbines broke
  - Vertical axis turbines more robust and proper electronics to not generate noise needed
- A small robust commercial model "Antarctic" ruled out
  - Problematic interface with the battery management unit
  - Unit also somewhat too small to deliver good up-time.

- → Design and build a custom made turbine
  - Now under construction in UU workshop.
  - Field test by Prof. Hans Bernhoff, wind power expert.

efforts by Allan Hallgren et al (UU)





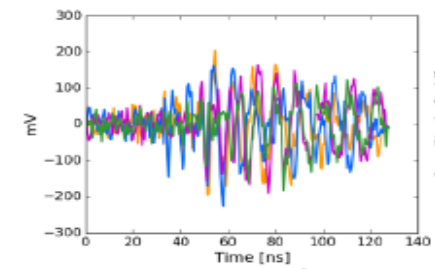
Wind Power at the ARIANNA site?

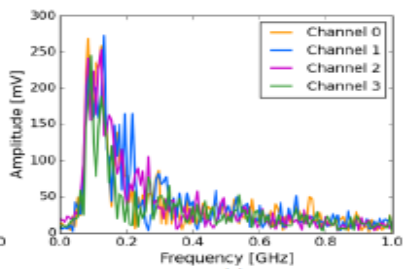


efforts by Allan Hallgren et al (UU)

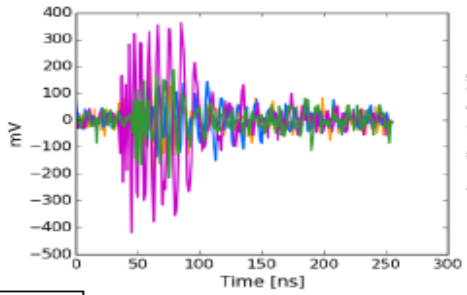
Cosmic ray detection
Calibration and science

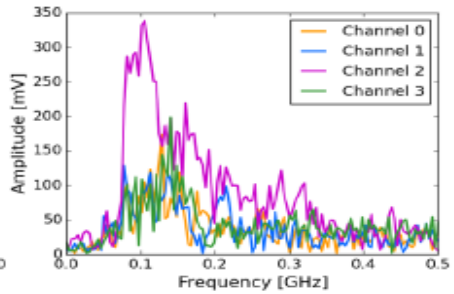
Simulation and reconstruction development ongoing
5 stations hit in cosmic ray event shown below
Clear Up/down separation and good pointing





1 km





Cosmic ray station
Upward pointing channels 2,3
Better low-frequency resolution
Signal detection in forward direction

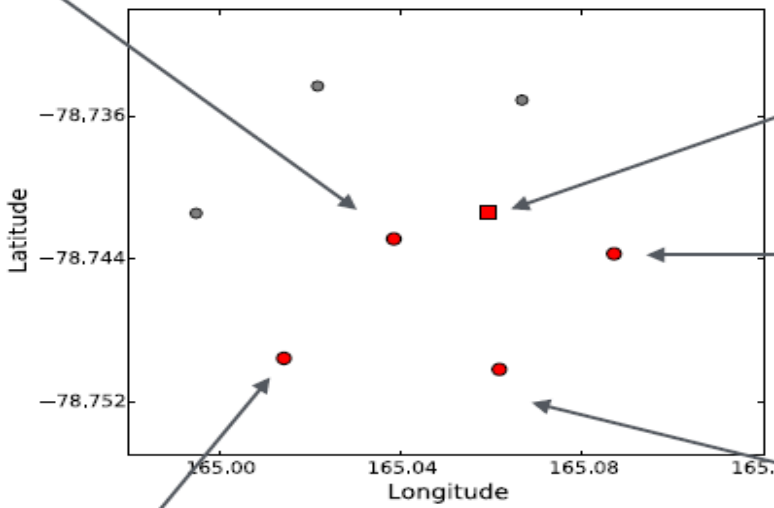
December 21st 2015
1450734371 UTC

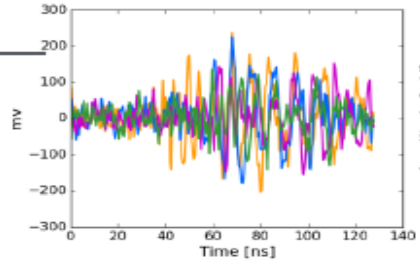
Four independent direction reconstructions

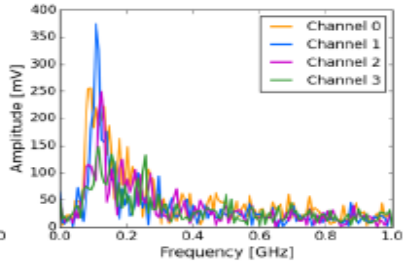
Azimuth = 47° +/- 2°

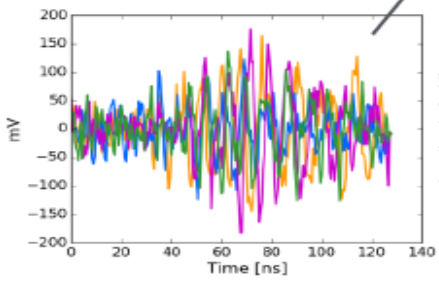
After Fresnel:
Zenith = 49° +/- 2°

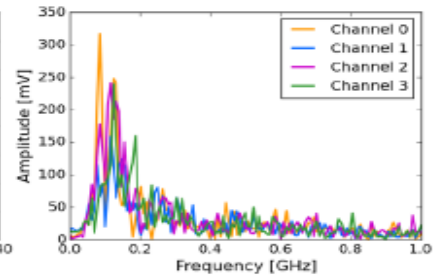
Before Fresnel:
Zenith = 75° +/- 3°

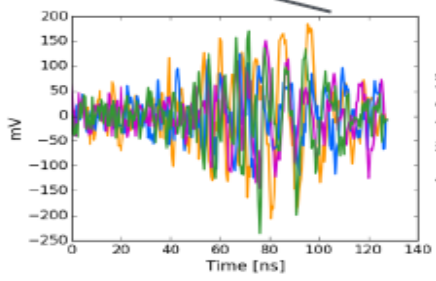


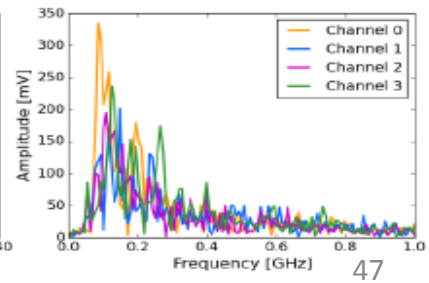












Summary

- Astrophysical neutrino flux is 3 years old
  - Increasingly better characterized with time
  - Still no sources and expected source classes **subdominant**:

  GRBs (1%), starbursts (<30%), blazars (<27%)
  - Neutrinos are giving us **unique** insight into (some) astrophysical process or processes

- Progress likely requires new hardware: IceCube-Gen2 Facility!
  - Will incorporate: dense infill (PINGU), extended in-ice array, expanded surface CR detector for veto, and likely radio

- SU and UU play a large role in IceCube
  - Diffuse flux, Point sources, Galaxy, Fermi bubbles, GW and gamma-ray transients, Solar DM, Gal DM halo, Monopoles, Radio detection

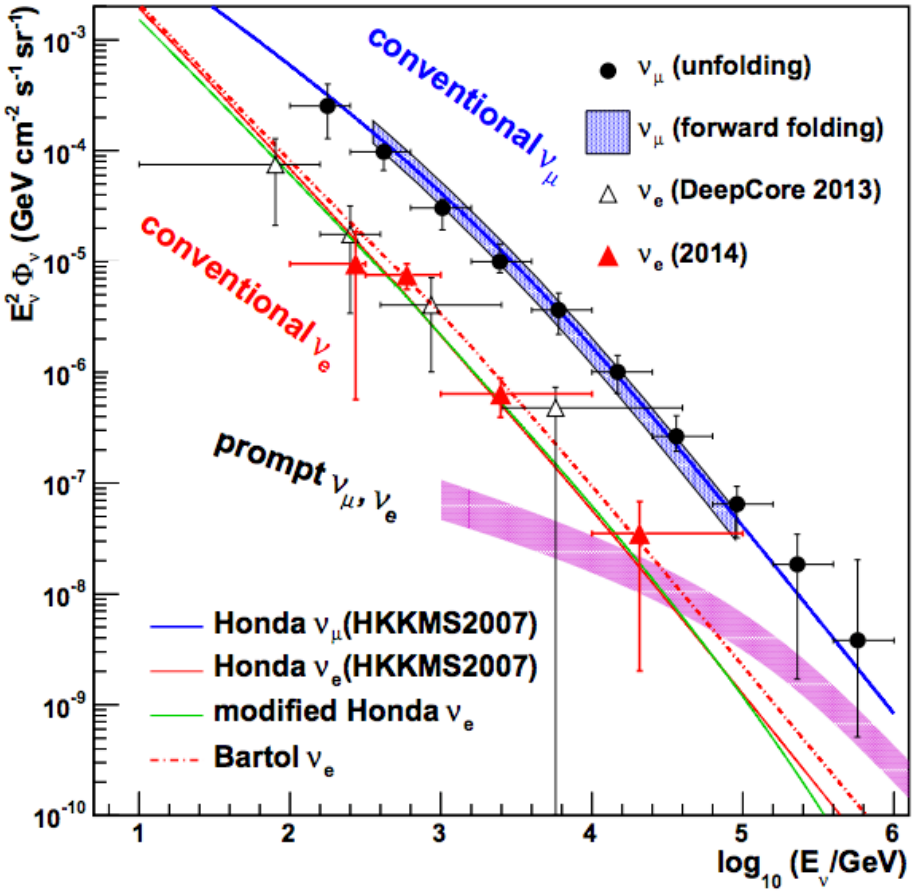
Backups

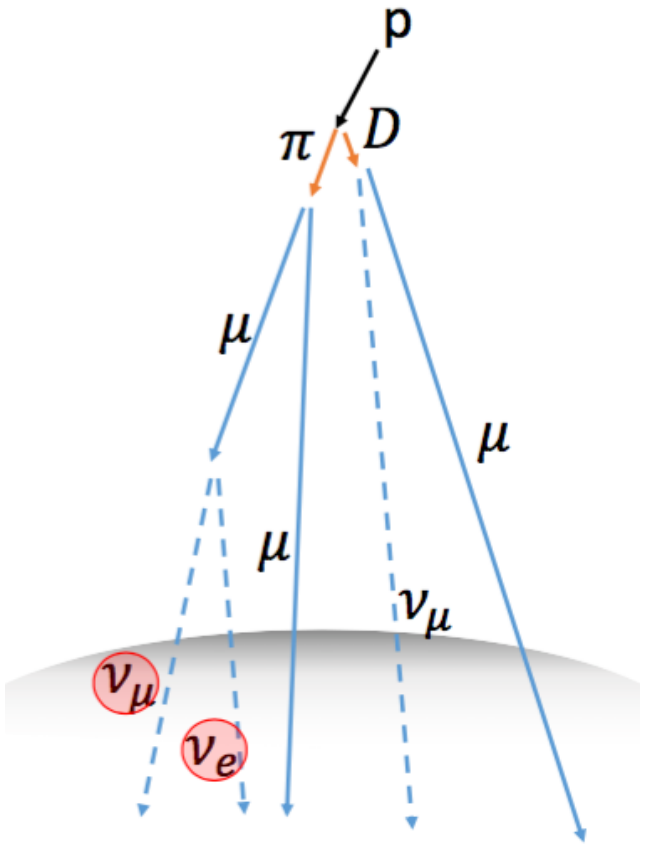
Atmospheric Neutrinos

Atmos

Muons: 3000 / sec

Neutrinos: 70 000 / yr

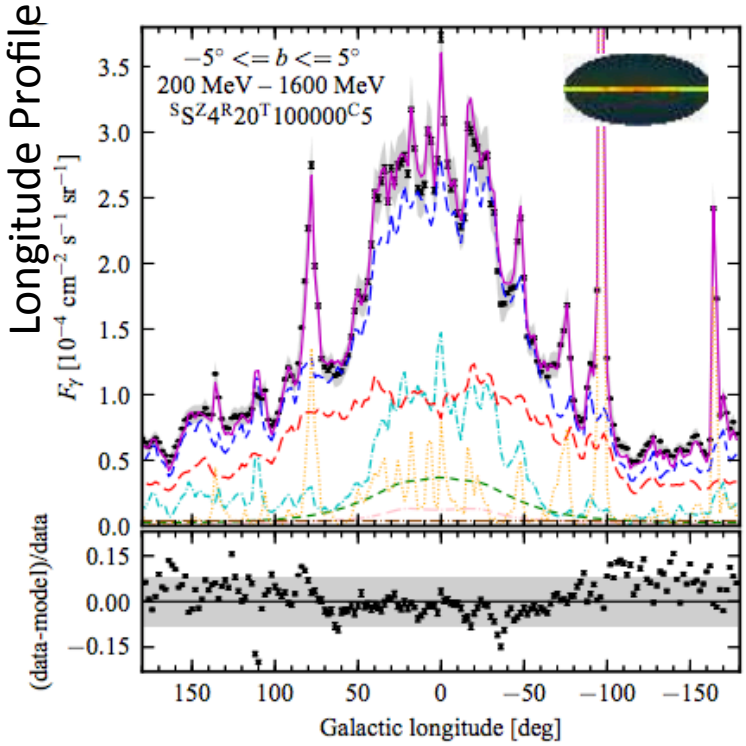


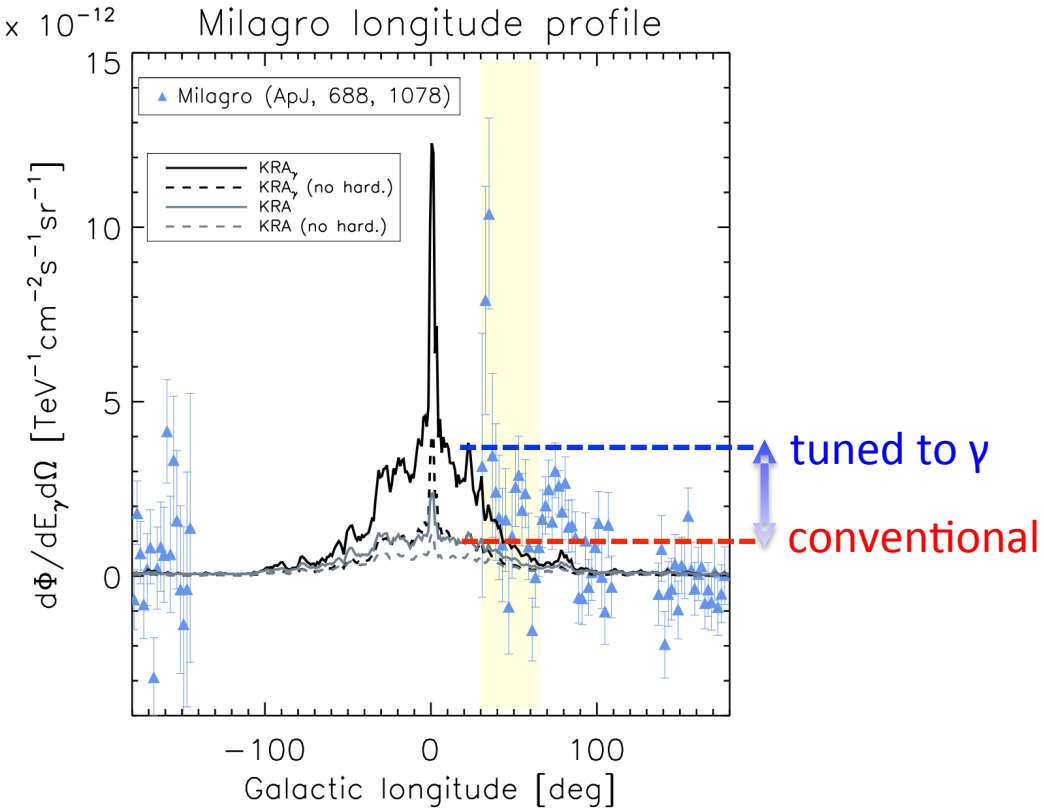


IceCube Collab. PRD 91, 022001 (2015)

Large Uncertainty in Inner Galaxy

Fermi Pion-decay profile in **red**





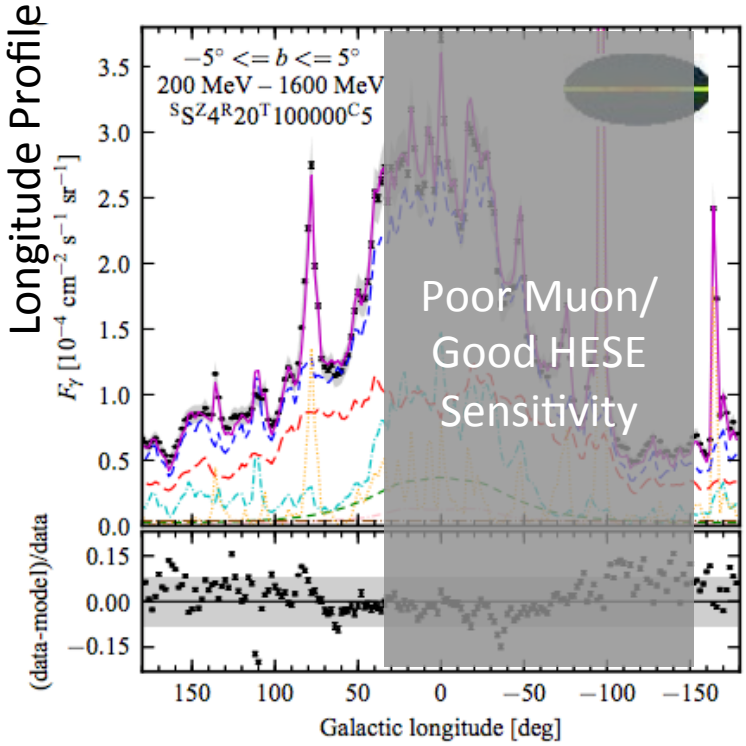
Large uncertainty in flux from inner galaxy!

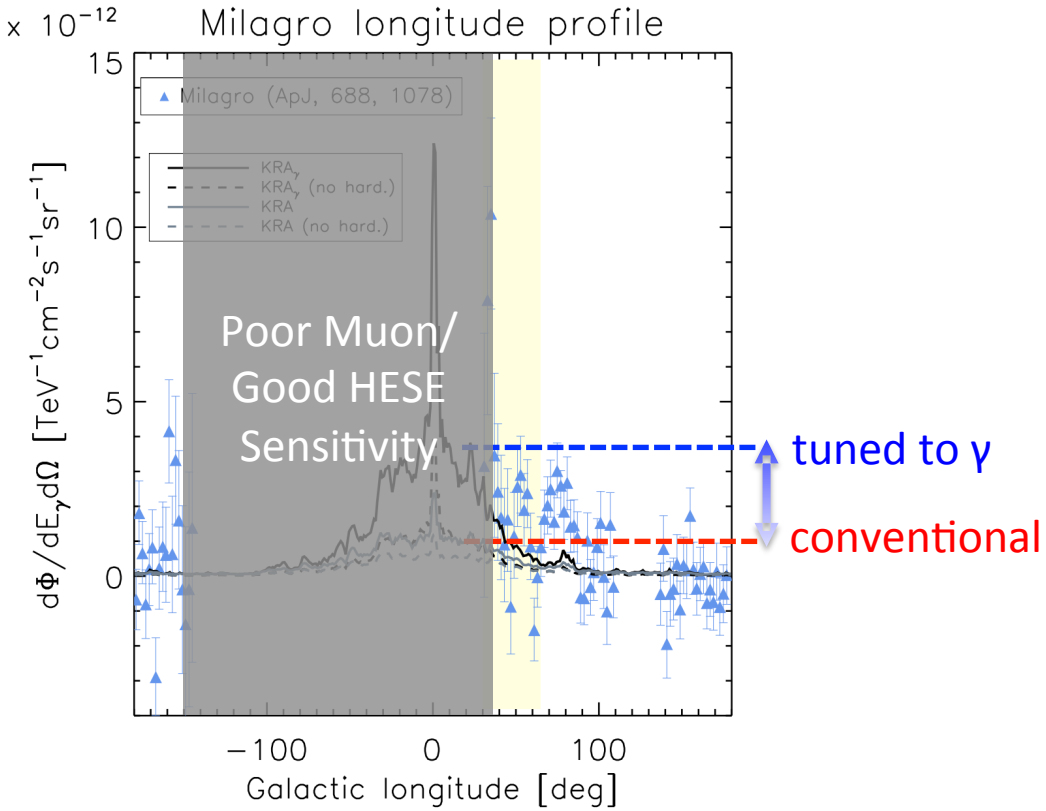
M. Ackermann et al 2011
arXiv:1202.4039v2

Gaggero et al 2015
1507.07796v1.pdf

Large Uncertainty in Inner Galaxy

Fermi Pion-decay profile in **red**





Large uncertainty in flux from inner galaxy!

M. Ackermann et al 2011
arXiv:1202.4039v2

Gaggero et al 2015
1507.07796v1.pdf

Indirect DM Searches with IceCube

Neutrino flux from DM annihilation:

Measured ν-flux

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E}(E,\theta,\phi)$$

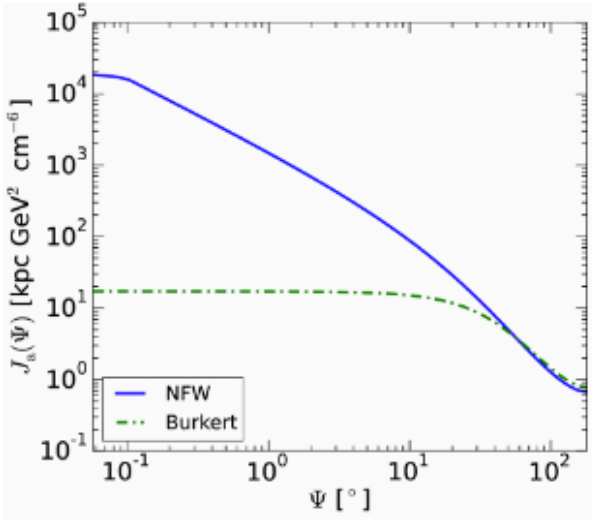
$=$

Particle Physics

$$\frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\sum_f \frac{\mathrm{d}N_\nu}{\mathrm{d}E}B_f$$

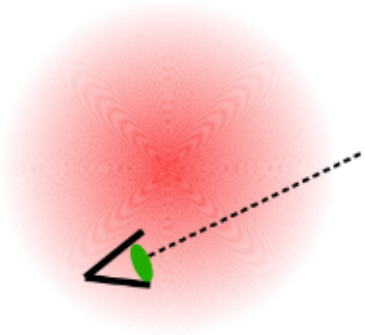
Setting upper limit on
DM self-ann. cross section

x



Dark Matter Distribution

$$\int_{\Delta\Omega(\theta,\phi)} \mathrm{d}\Omega' \int_{\mathrm{l.o.s.}} \mathrm{d}l(r,\phi')\rho^2(r(l,\phi'))$$

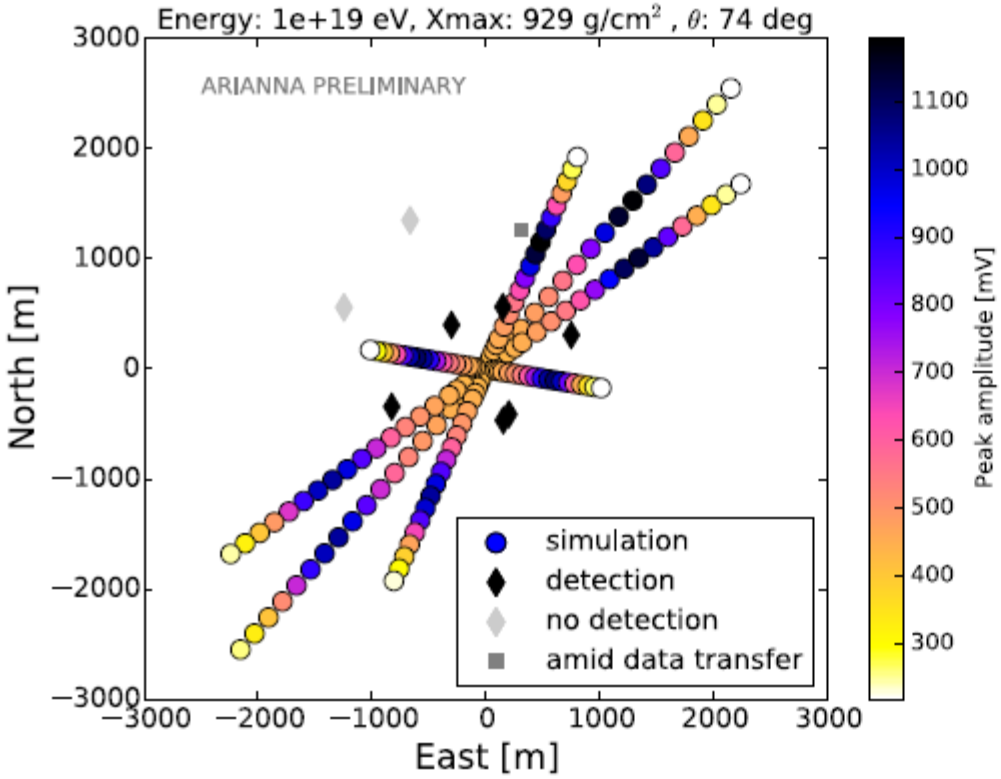


line of sight
(l.o.s)

ρ is defined by the DM density model,
e.g. NFW [APJ 462, 563 (1996)] or
Burkert [APJ 447, L25 (1995)]

and their parameter values, e.g. the local DM density

Air shower simulation



- Detected multiple coincidences: **horizontal showers**
- Full detector simulation and dedicated simulations for big events
- Experiment with method as tested in LOFAR and AERA
- Use polarization information
- Fully independent reconstruction of air shower parameters

Earlier contributions from Sweden

- Custom chip production.
  - 4 ch/chip 2 Gs/s, 256 samples/chan.
  - Used in improved electronics design (SST) for 2014 deployment.
  - Now used in all stations.
  - Remaining quantity sufficient for ~ 110 stations (8 chan/ station)
- Funding new batteries and charge controllers
- Antenna response measurements
- Alexander Burgman, Leif Gustafsson, Lisa Unger
- ……

