The IceCube Neutrino Telescope

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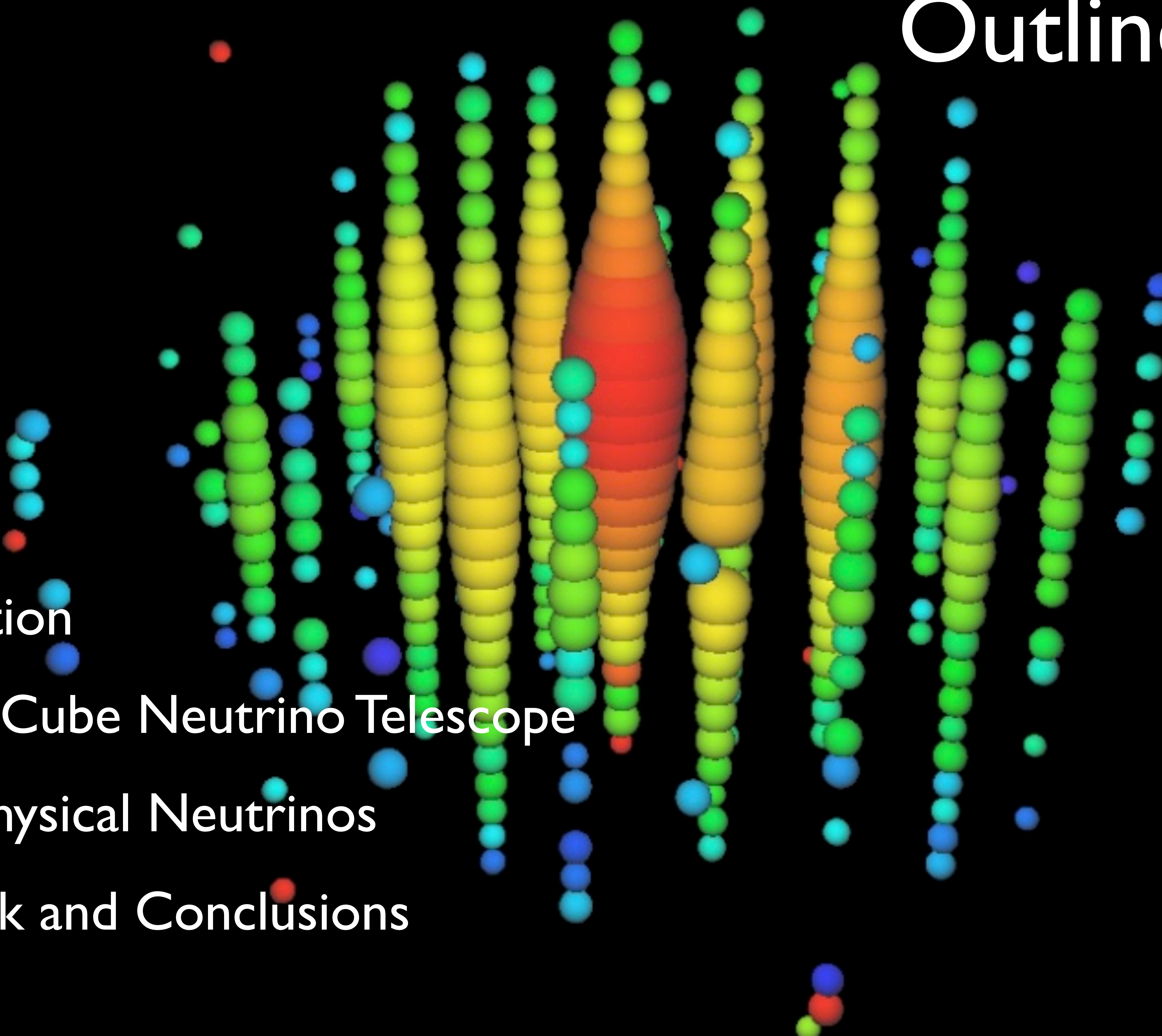
INHA UNIVERSITY

ICECUBE

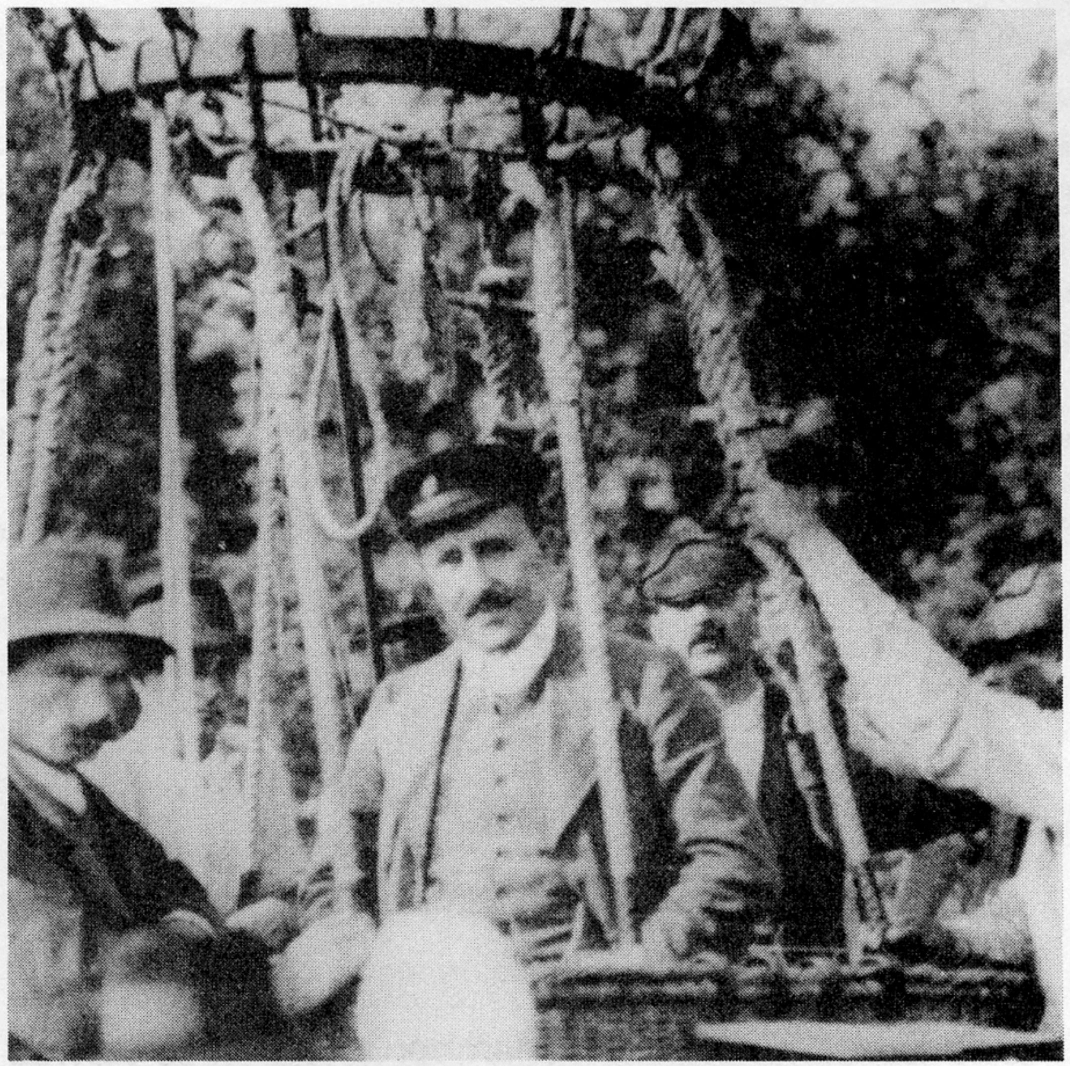
1398

Outline



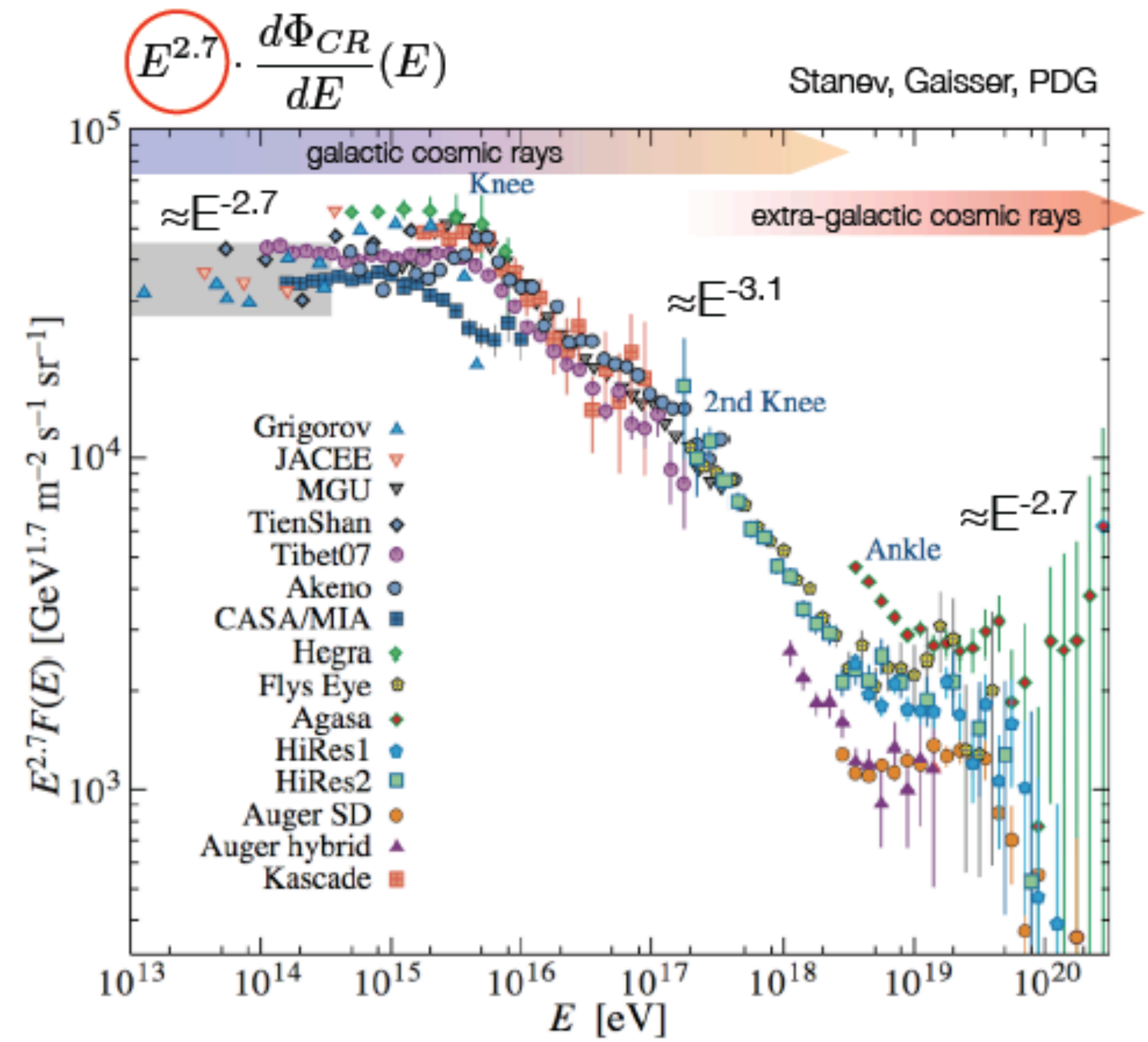
- Motivation
- The IceCube Neutrino Telescope
- Astrophysical Neutrinos
- Outlook and Conclusions

High Energy Cosmic Ray Mystery



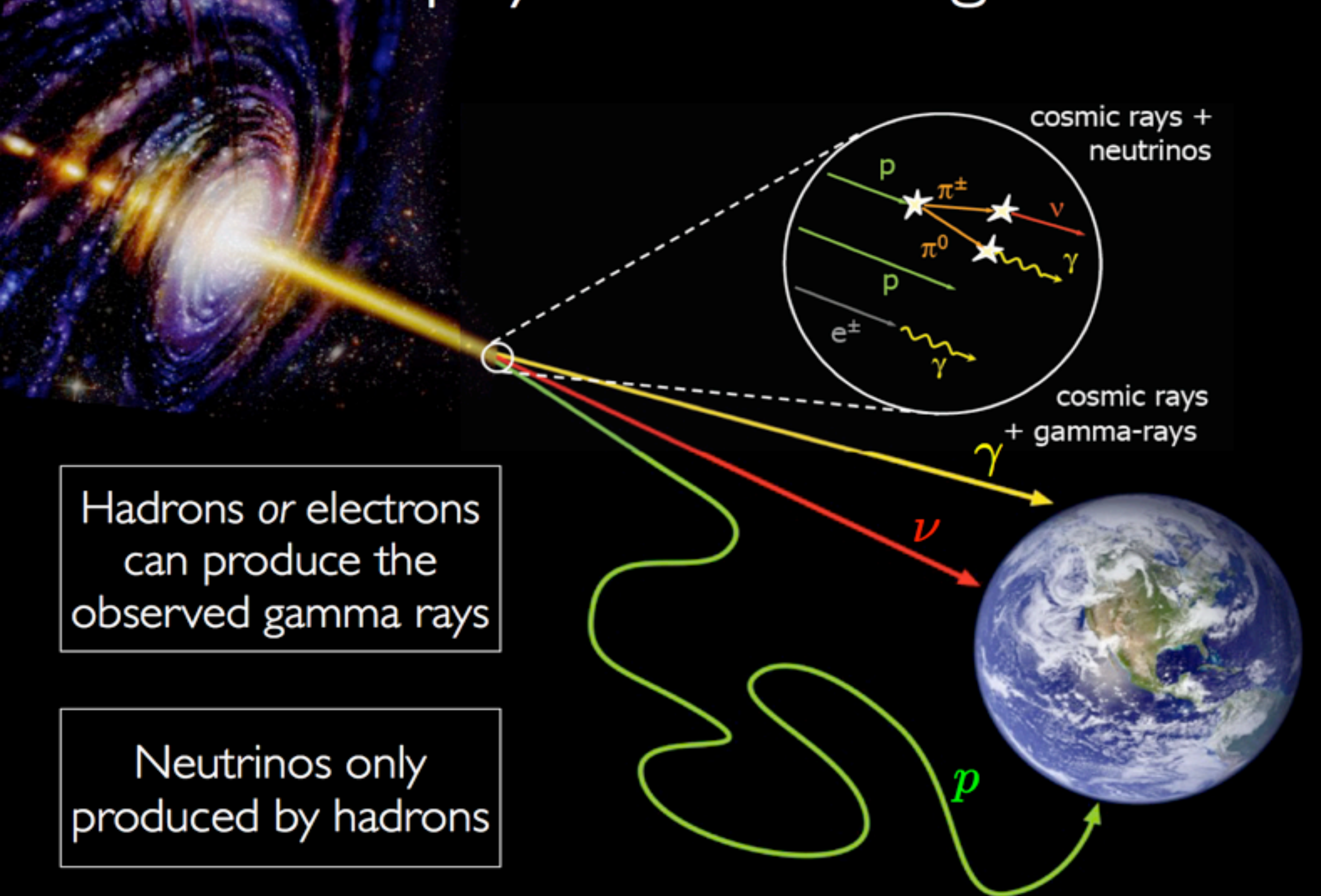
Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Böhmen.



- Where are they coming from ?
- What cosmic sources accelerate these particles to energies in the EeV range ?

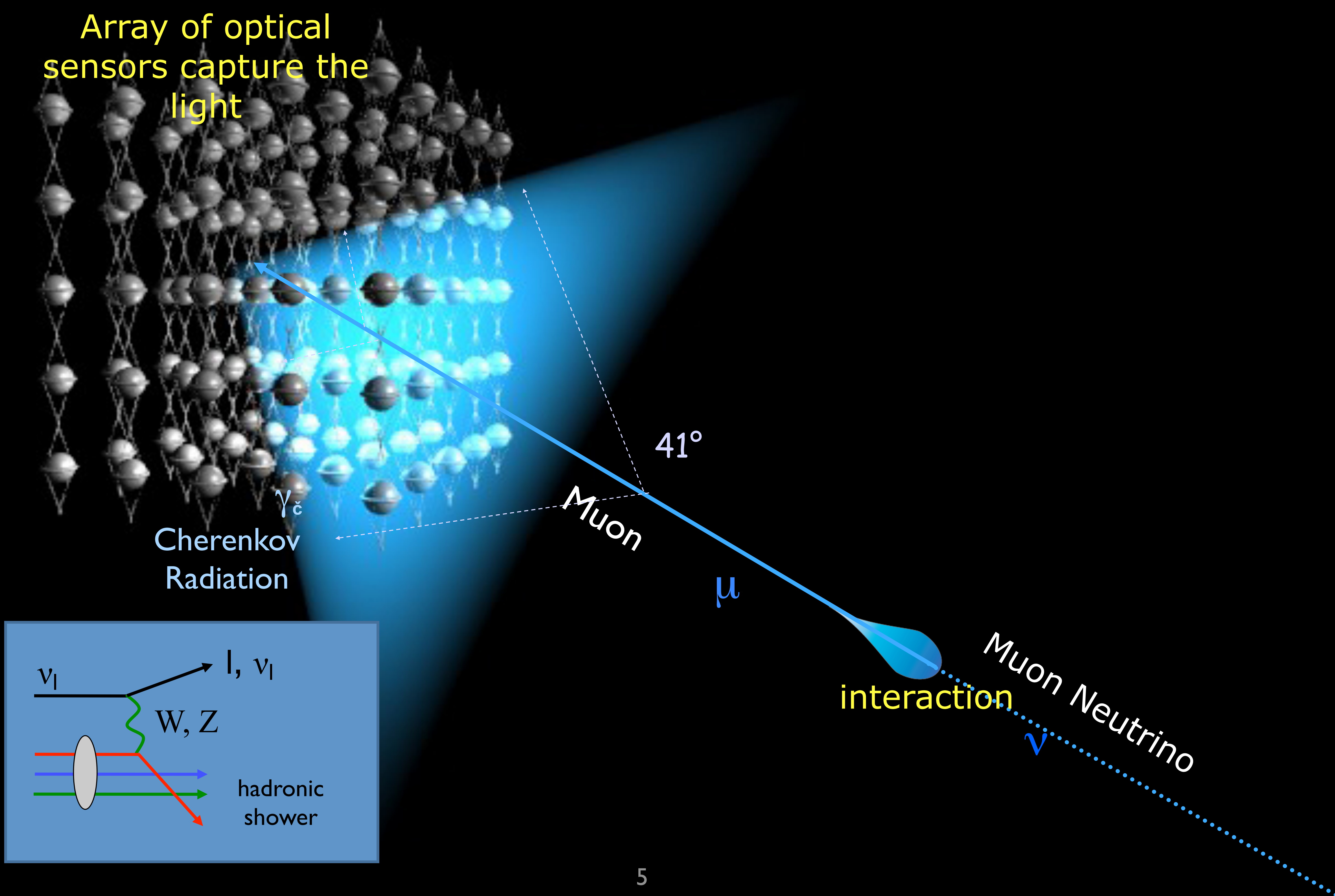
Astrophysical Messengers

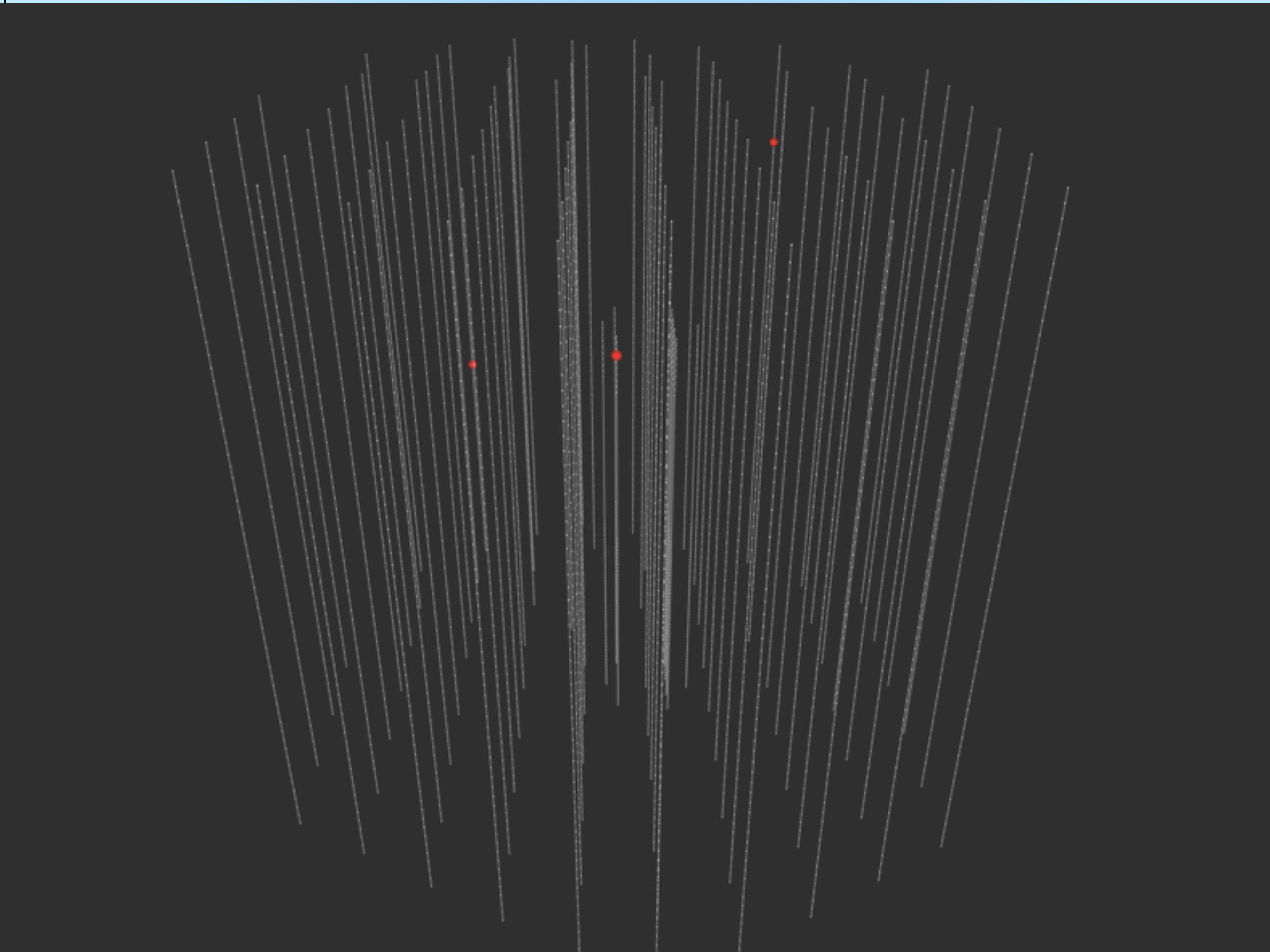


Hadrons *or* electrons can produce the observed gamma rays

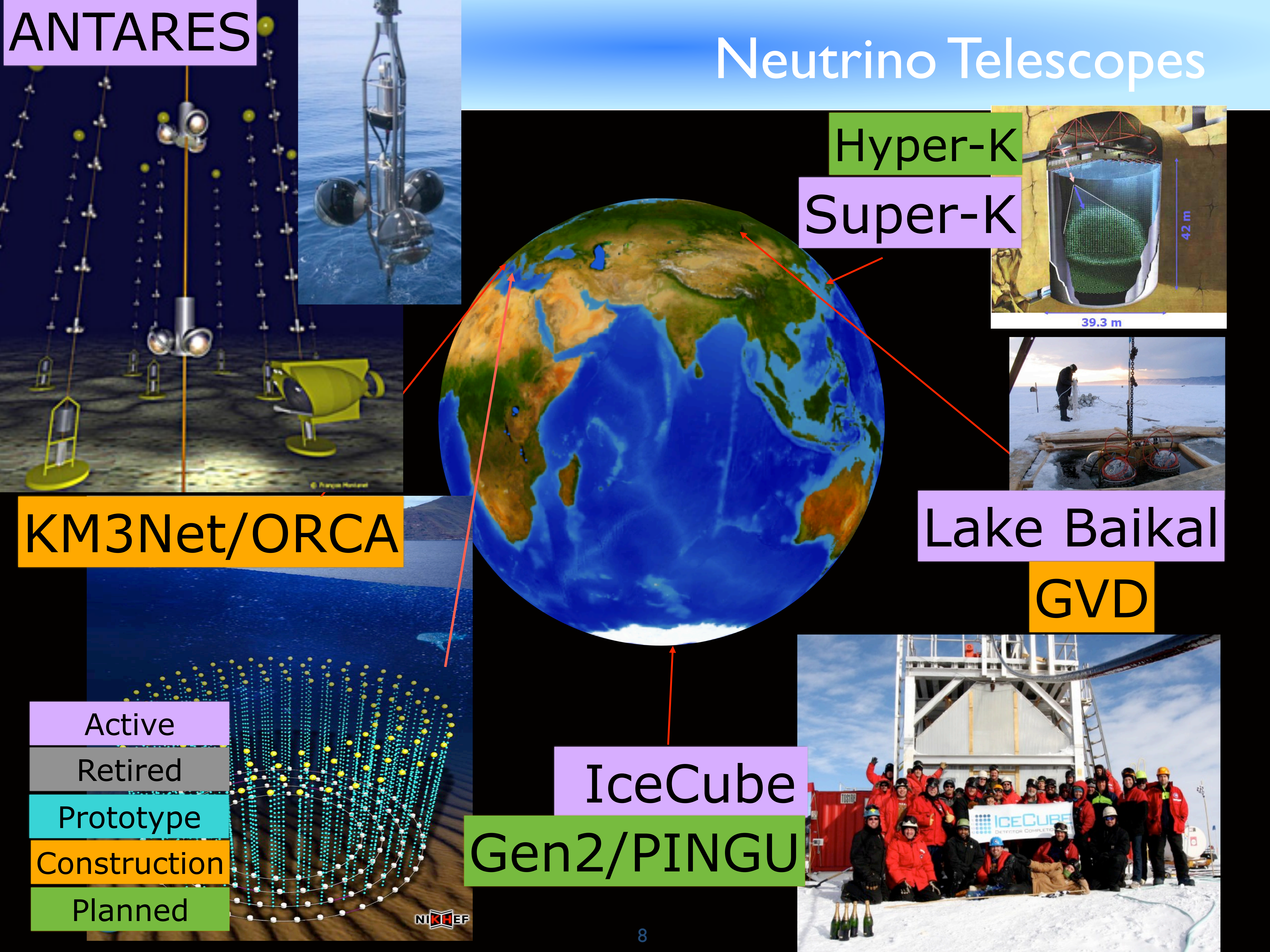
Neutrinos only produced by hadrons

Principle of an optical Neutrino Telescope

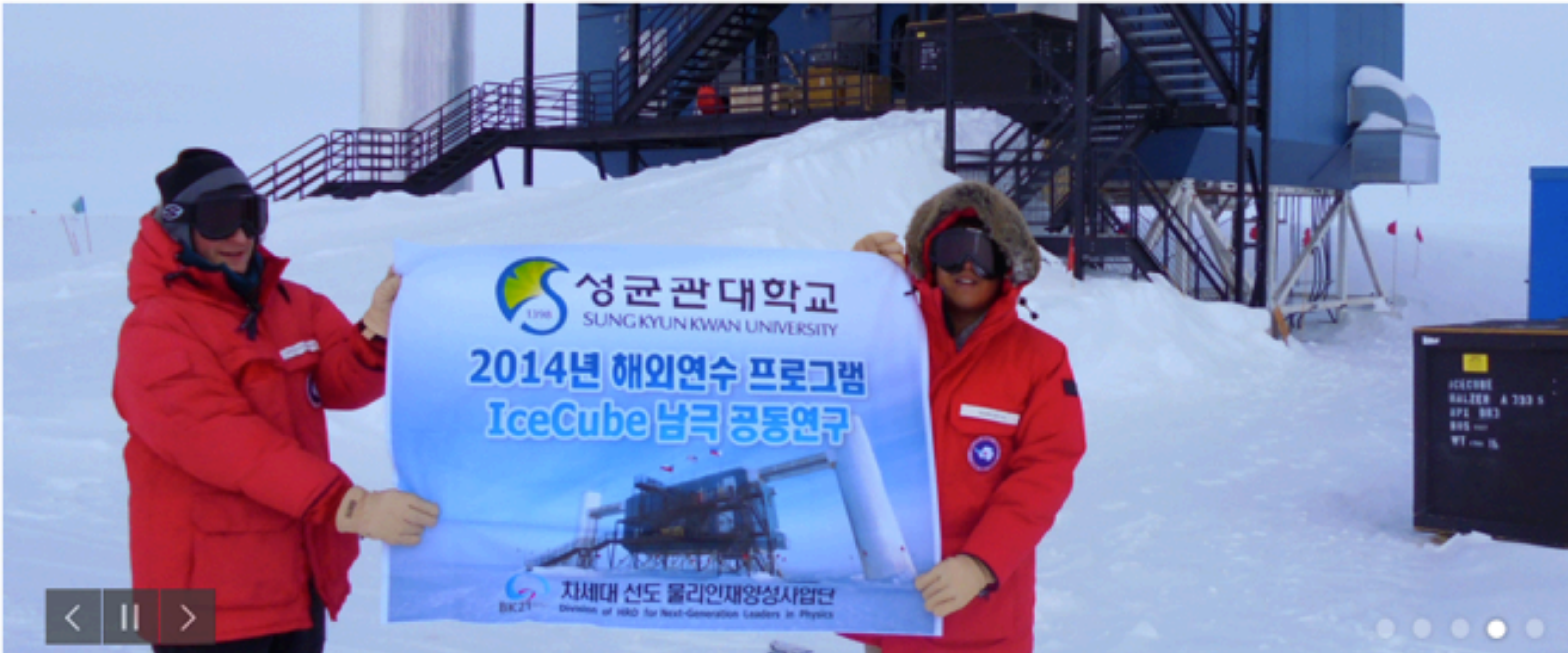




The IceCube Neutrino Telescope


Neutrino Telescopes
ANTARES
Hyper-K
Super-K
42 m
39.3 m
KM3Net/ORCA
Lake Baikal
GVD
IceCube
Gen2/PINGU
Active
Retired
Prototype
Construction
Planned
NIKHEF

The IceCube Neutrino Telescope



Brain Korea(BK) Project, Ice Cube Antartica Joint Reserch

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- Leading 'humanism Renaissance' by 617 years of ...
- The World cup star, Seol Kihyeon is retired, beco...
- Lee Wangeun, Chairman of Shinsung Solar Energ...

Notice
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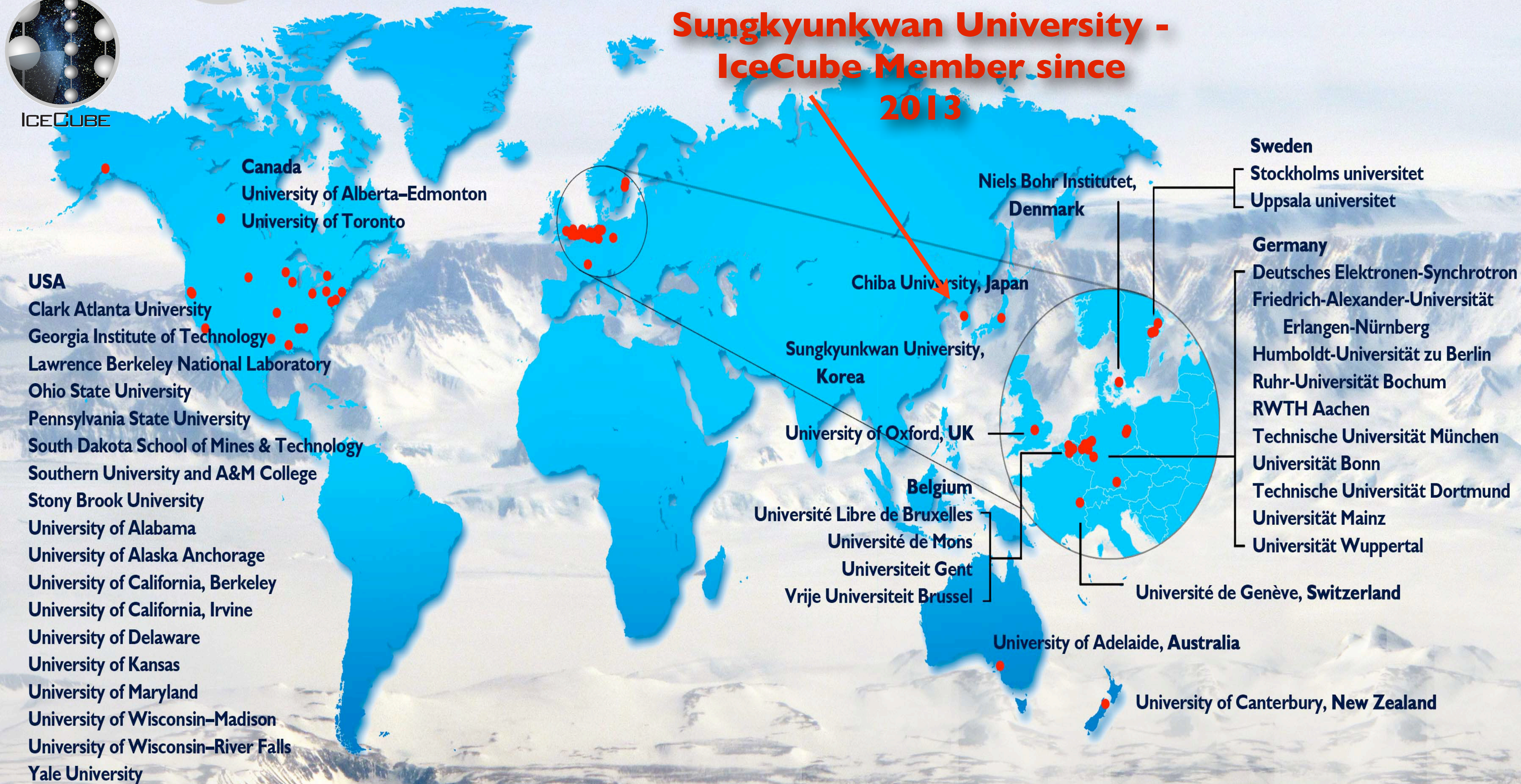
- Course lists of Dept. of Energy Science 2015 Sprin..
- Announcement to New International Students
- [Dormitory] 2015 Spring Myeongnyunhaksa Admi..

SKKU Reputation

SKKU News

Academics

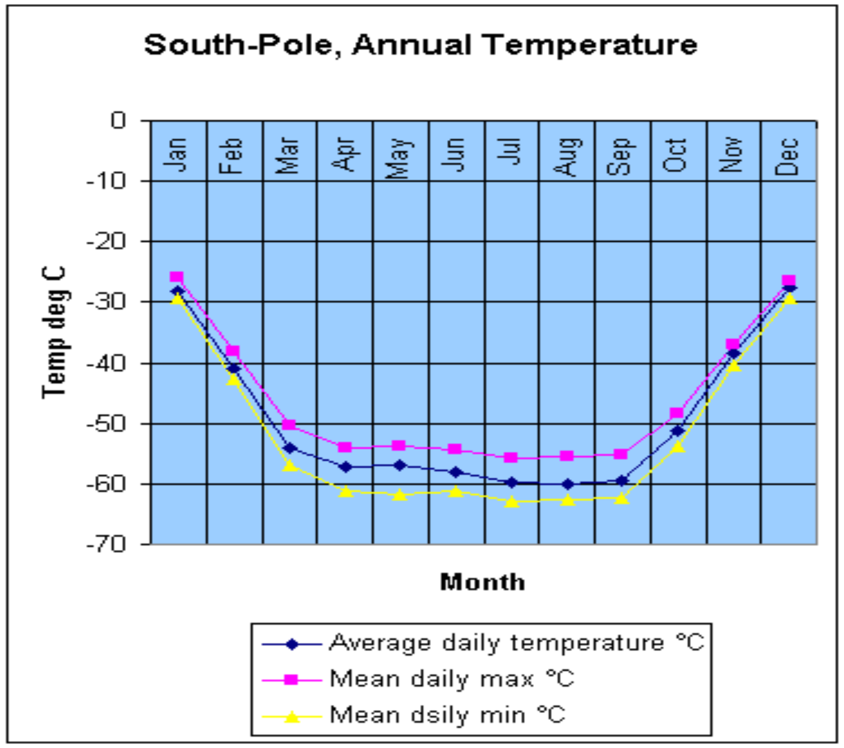
Sungkyunkwan University - IceCube Member since 2013

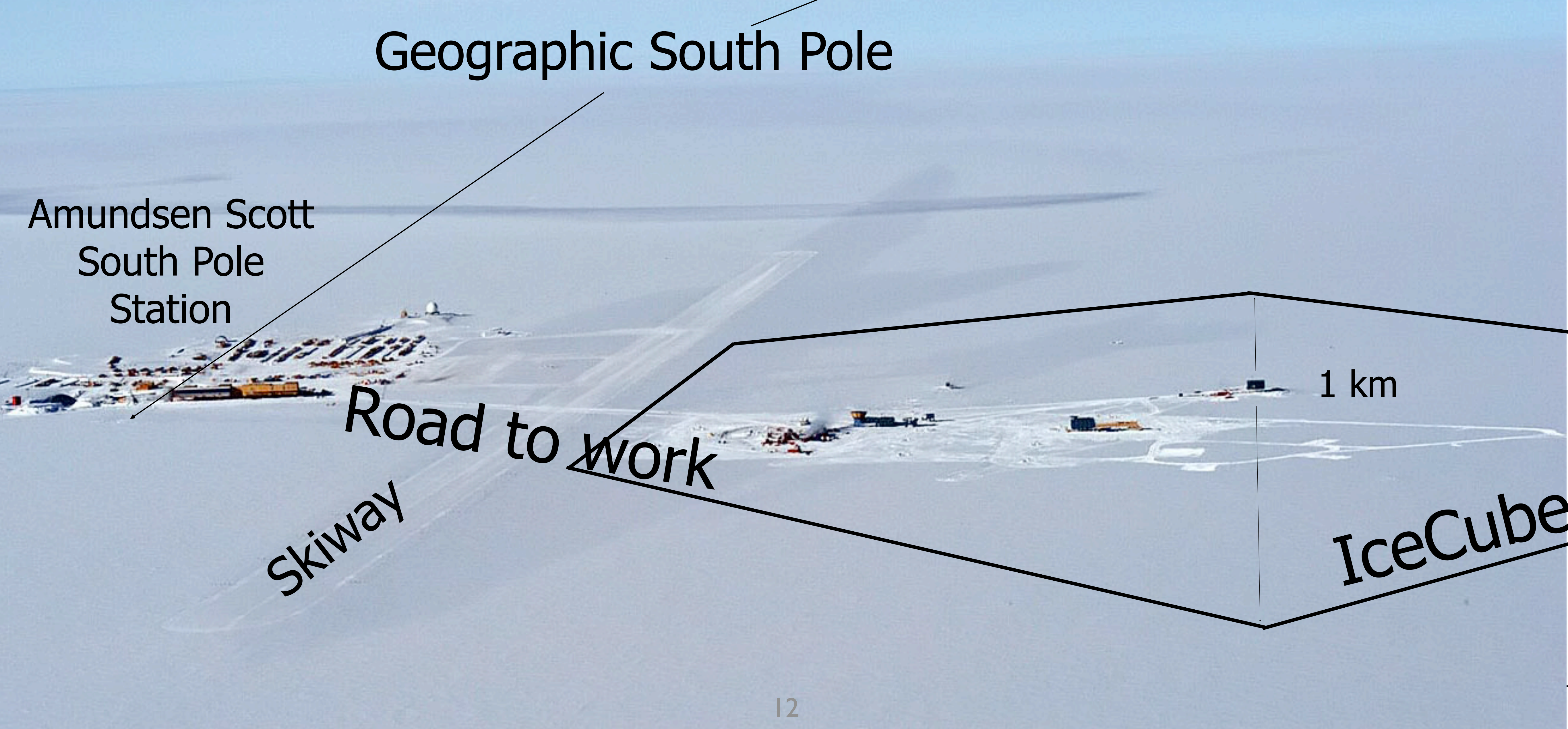


Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
National Research Foundation (NRF)

Laboratory at the South Pole





The IceCube Neutrino Telescope

Gigaton Neutrino Detector at the Geographic South Pole

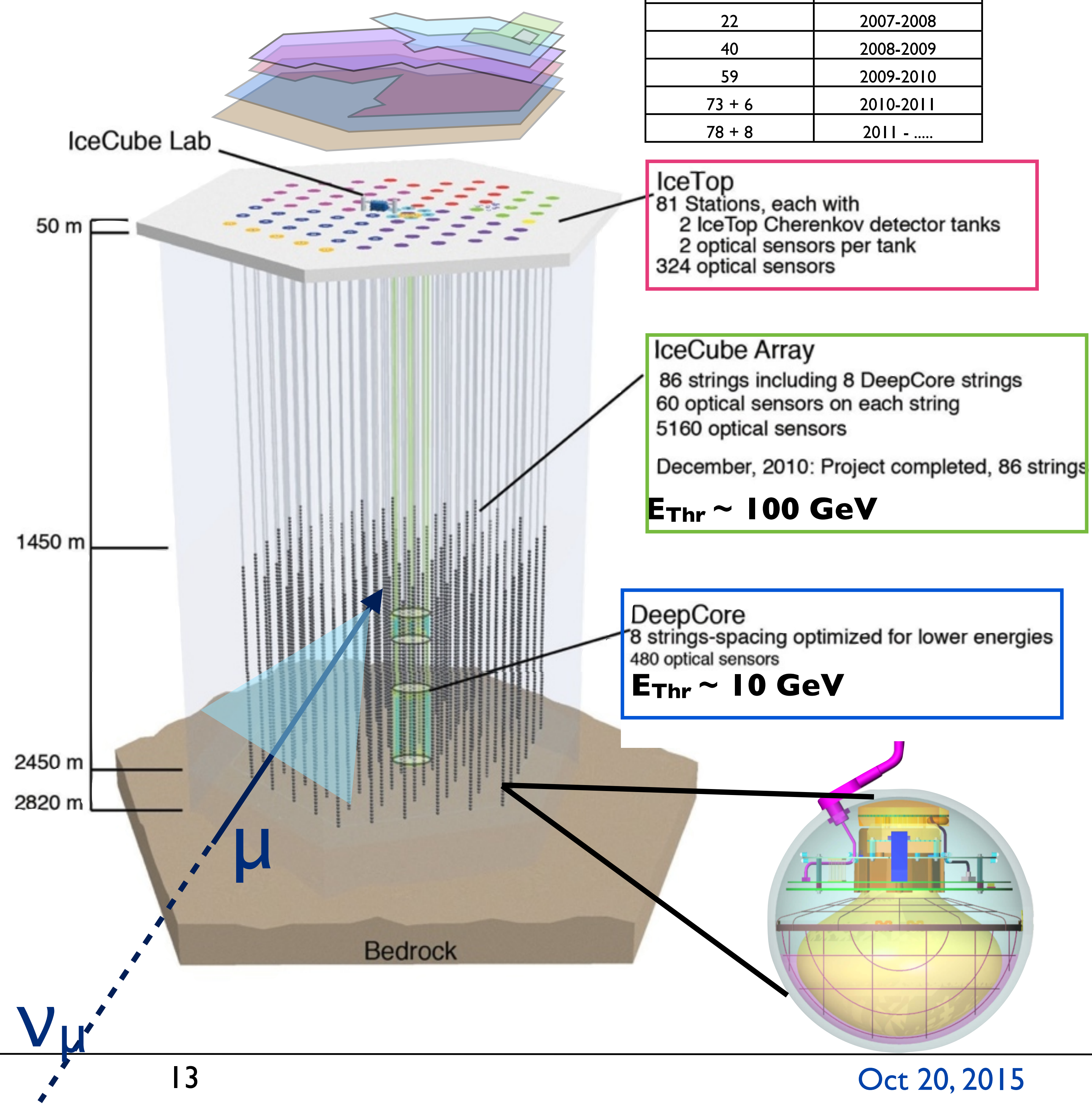
5160 Digital optical modules distributed over 86 strings

Completed in December 2010, start of data taking with full detector May 2011

Data acquired during the construction phase has been analyzed

Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

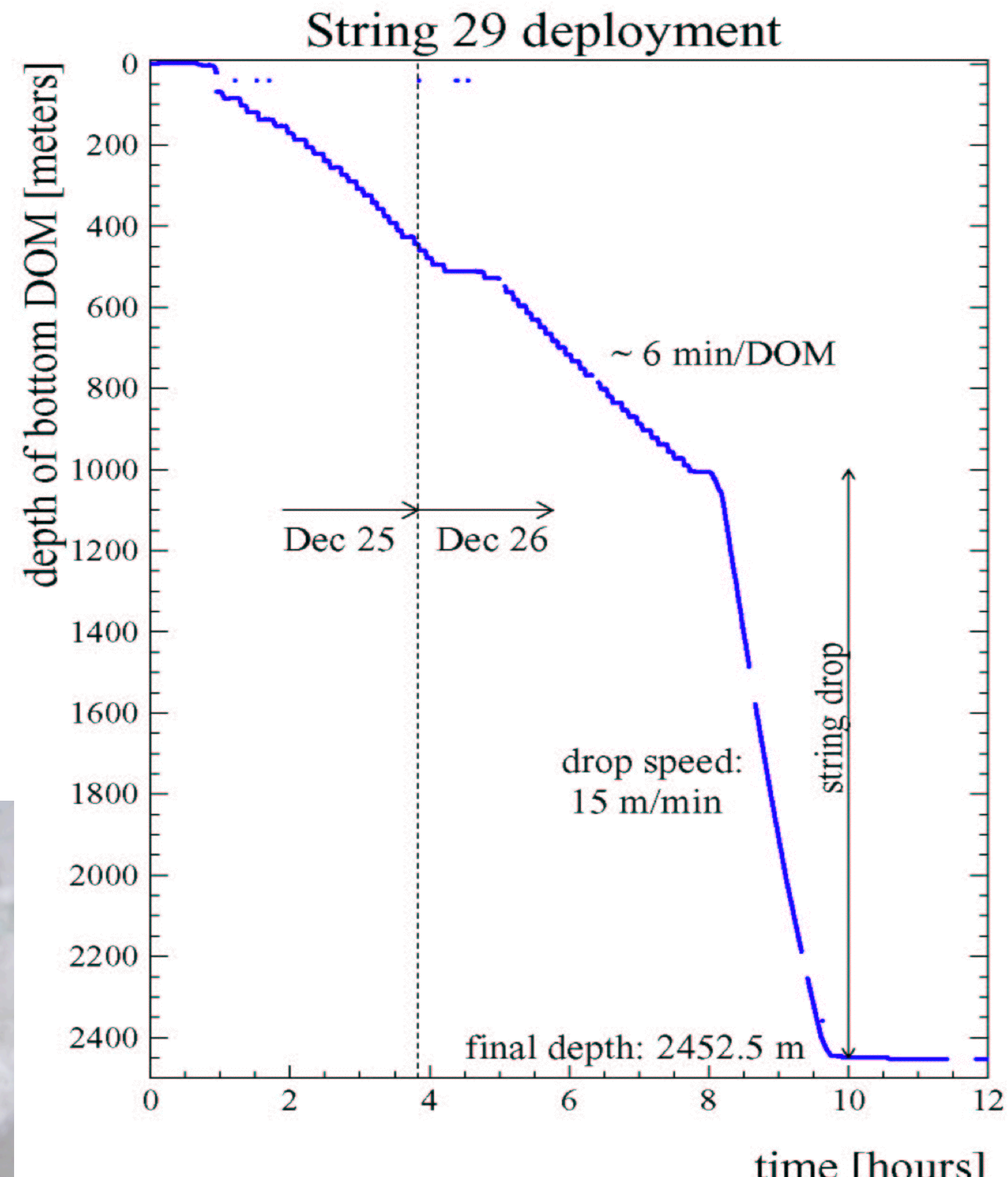
Strings	Dataset
1	2005-2006
9	2006-2007
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....



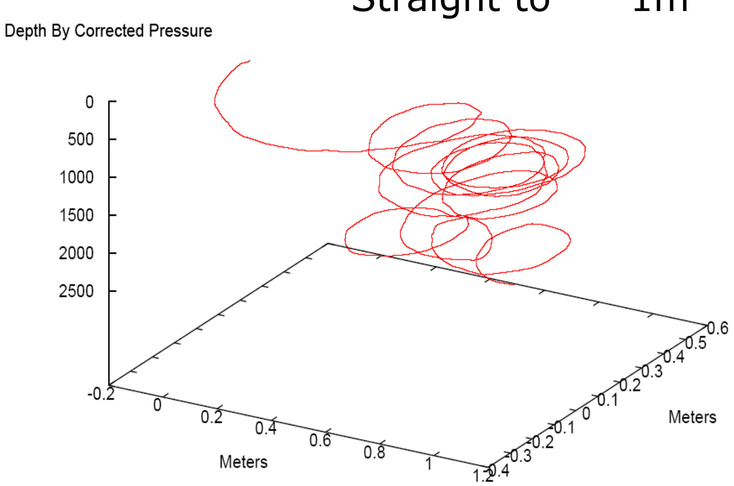
DOM @ SKKU

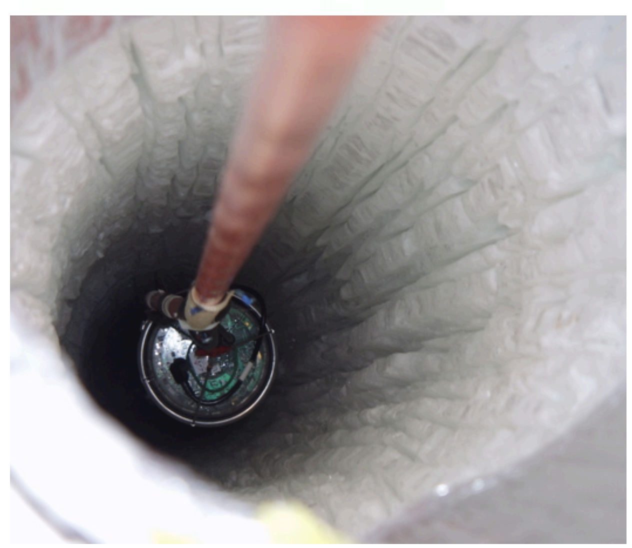
Photo: Ben Tibbets

Drilling & Deployment



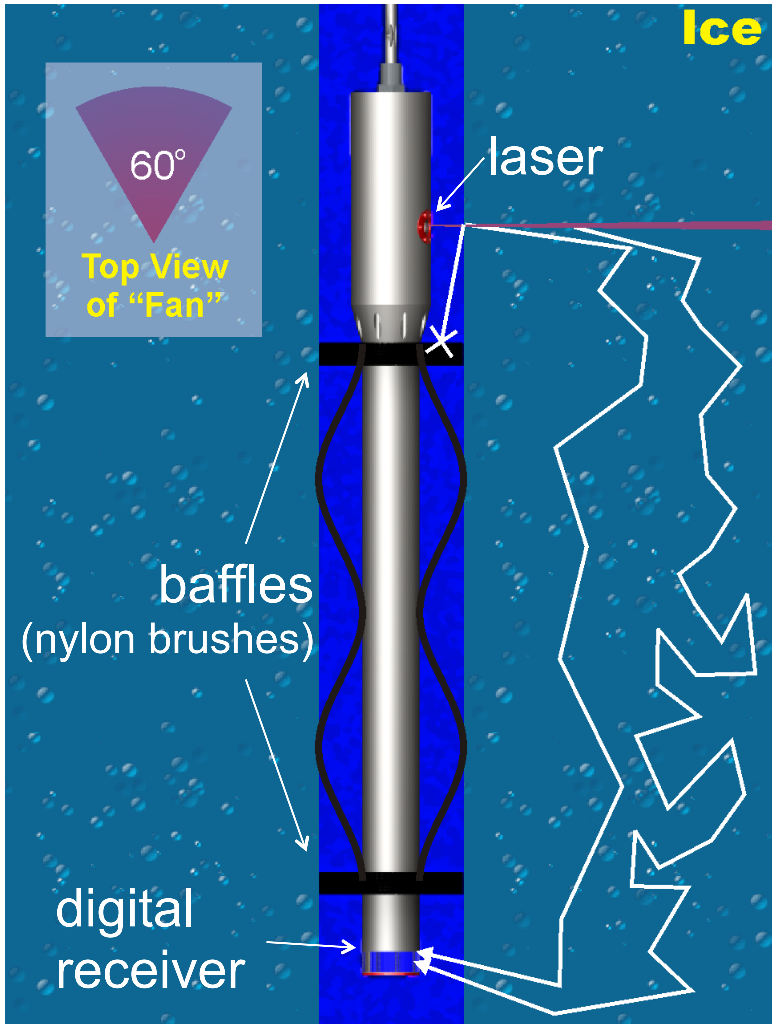
- Hole size ~60cm
- Depth ~2.5km
- Straight to 1m





Drilling to 2500 m < 40h
String deployment ~ 12h

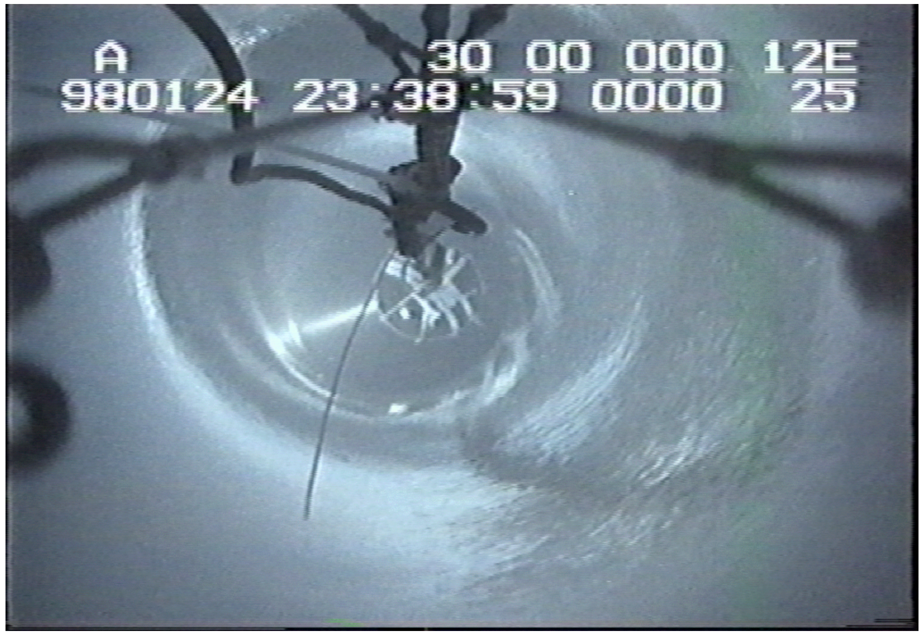
The Ice

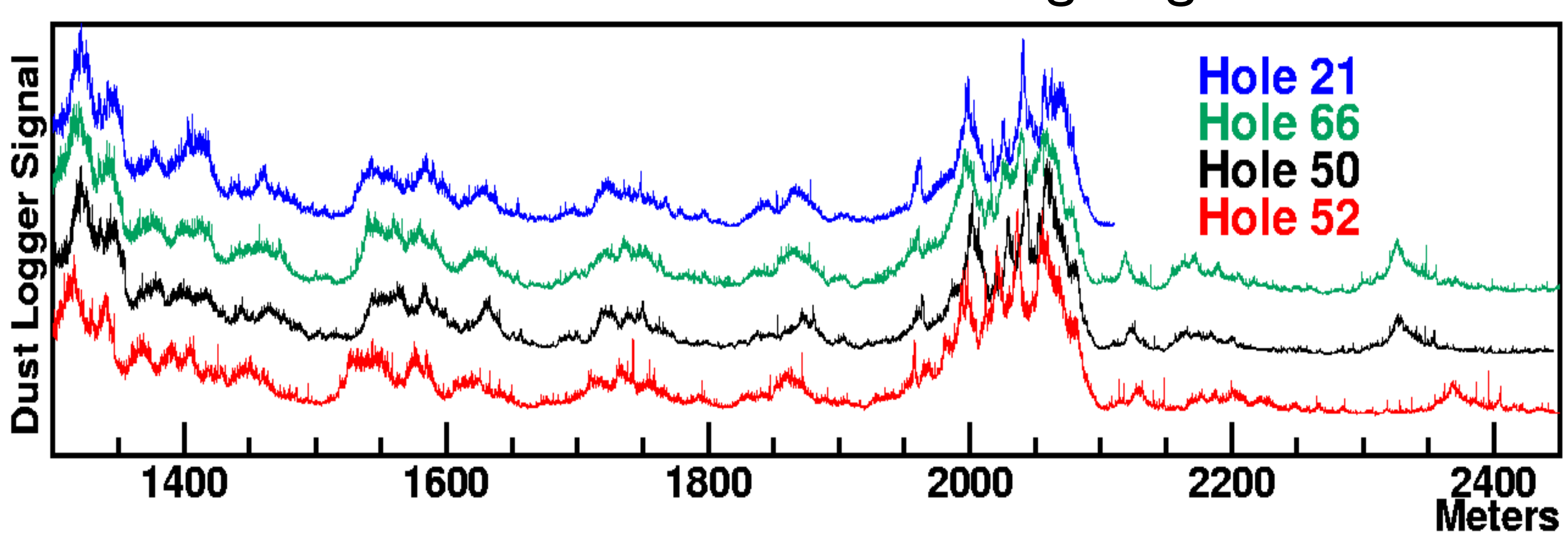


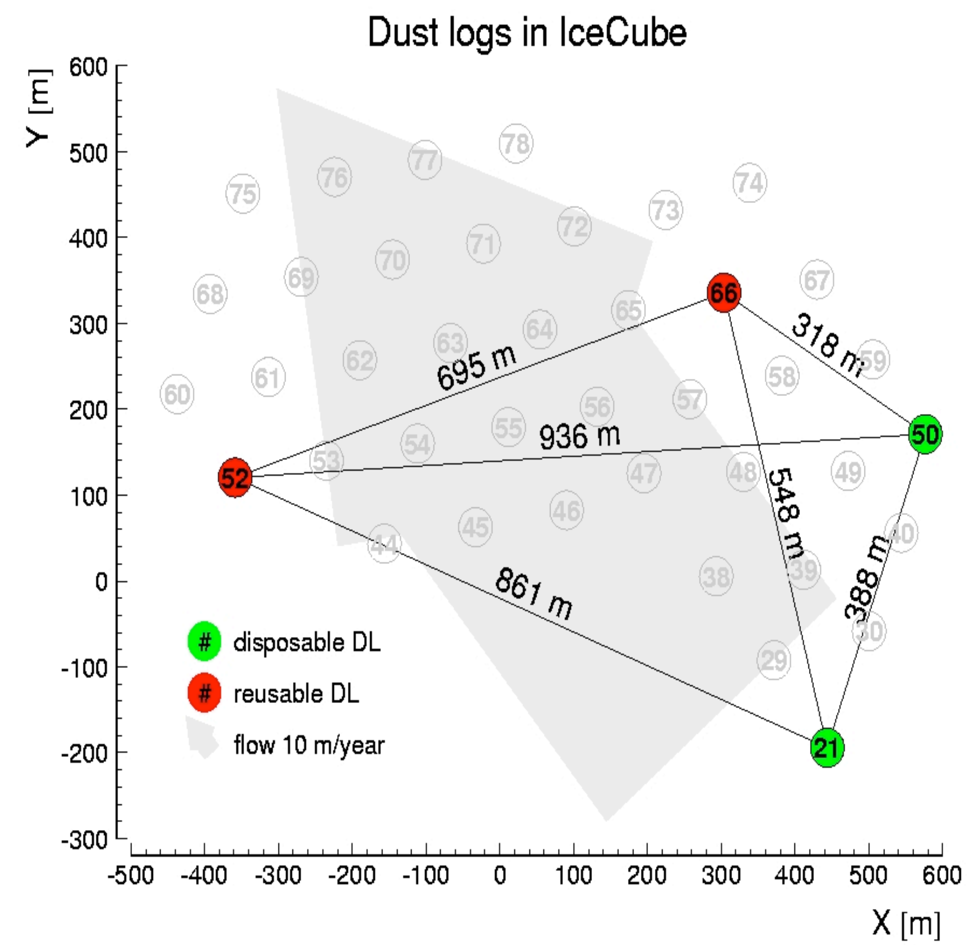
Major calibration efforts resulted in a very precise understanding of the ice surrounding the IceCube detector

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - One pair of Camera DOMs

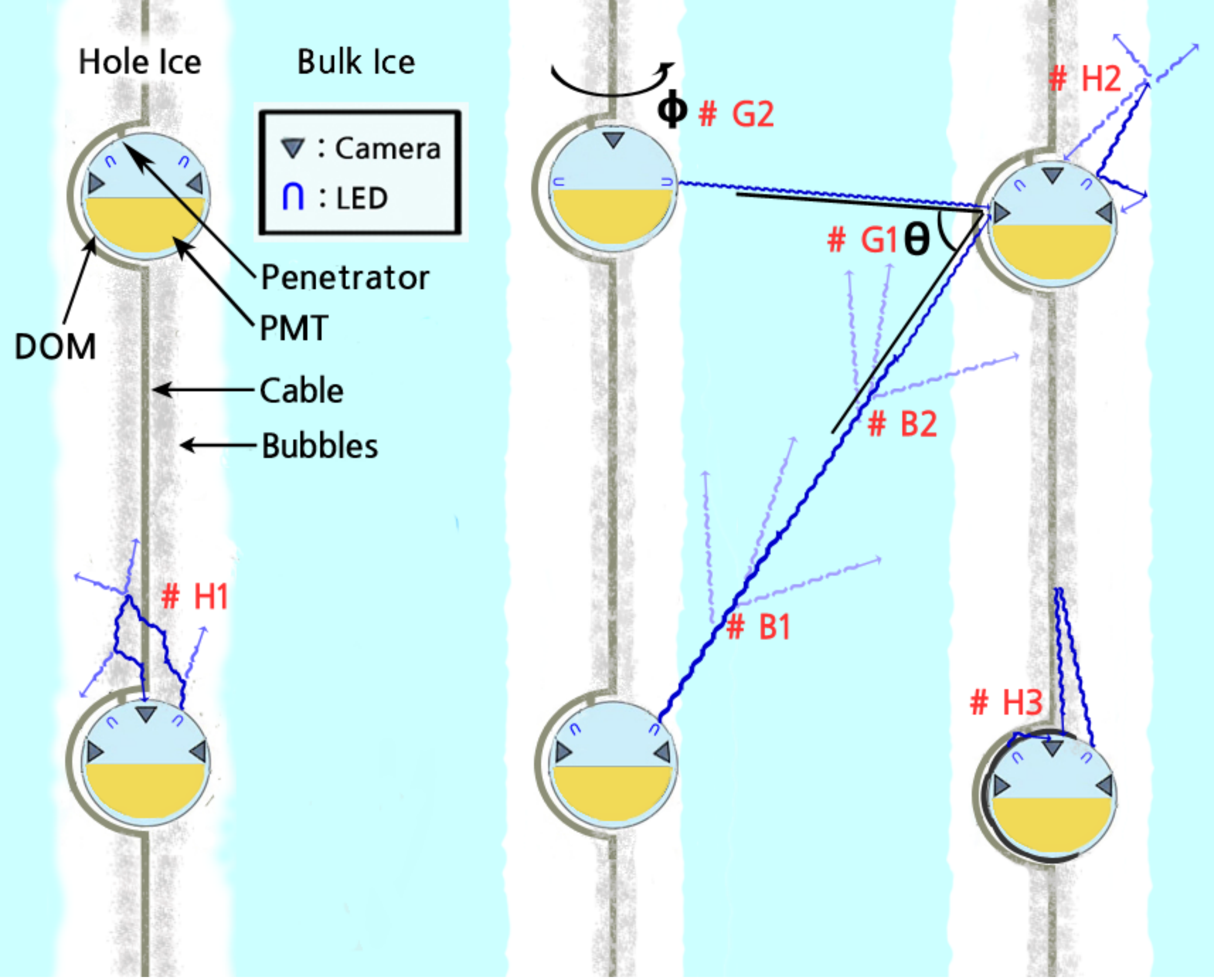
absorption length ~ 210m
scattering length ~20-40m

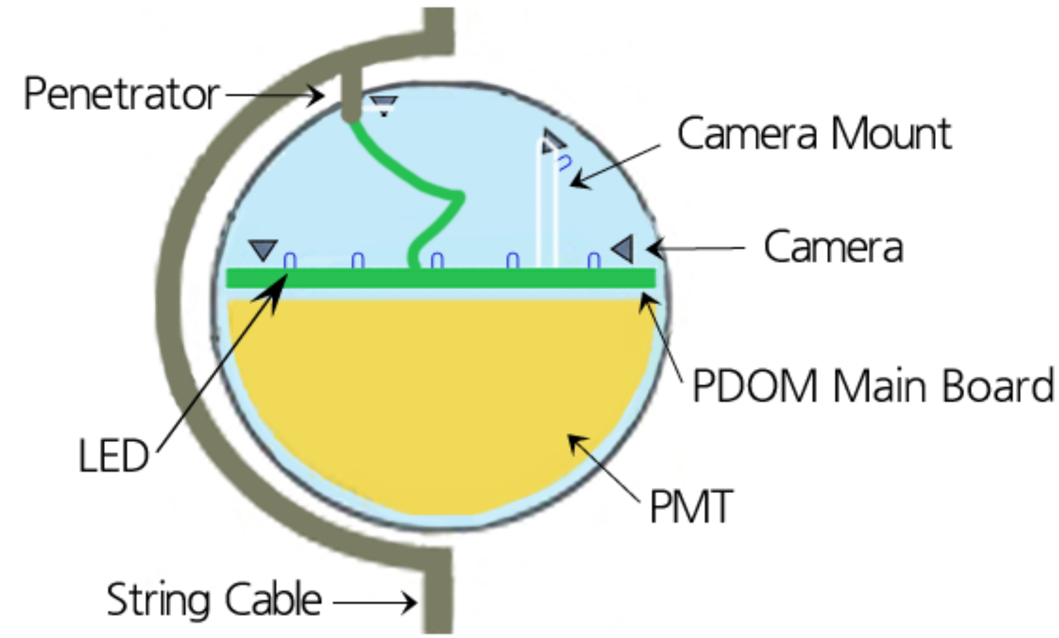




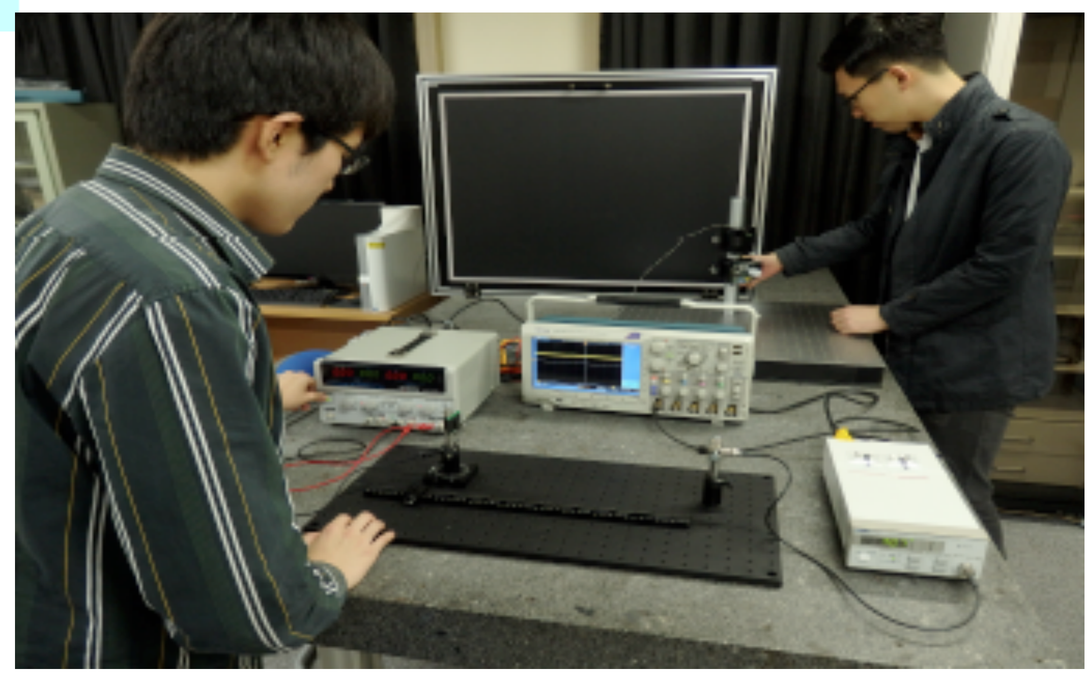


SKKU Camera Team

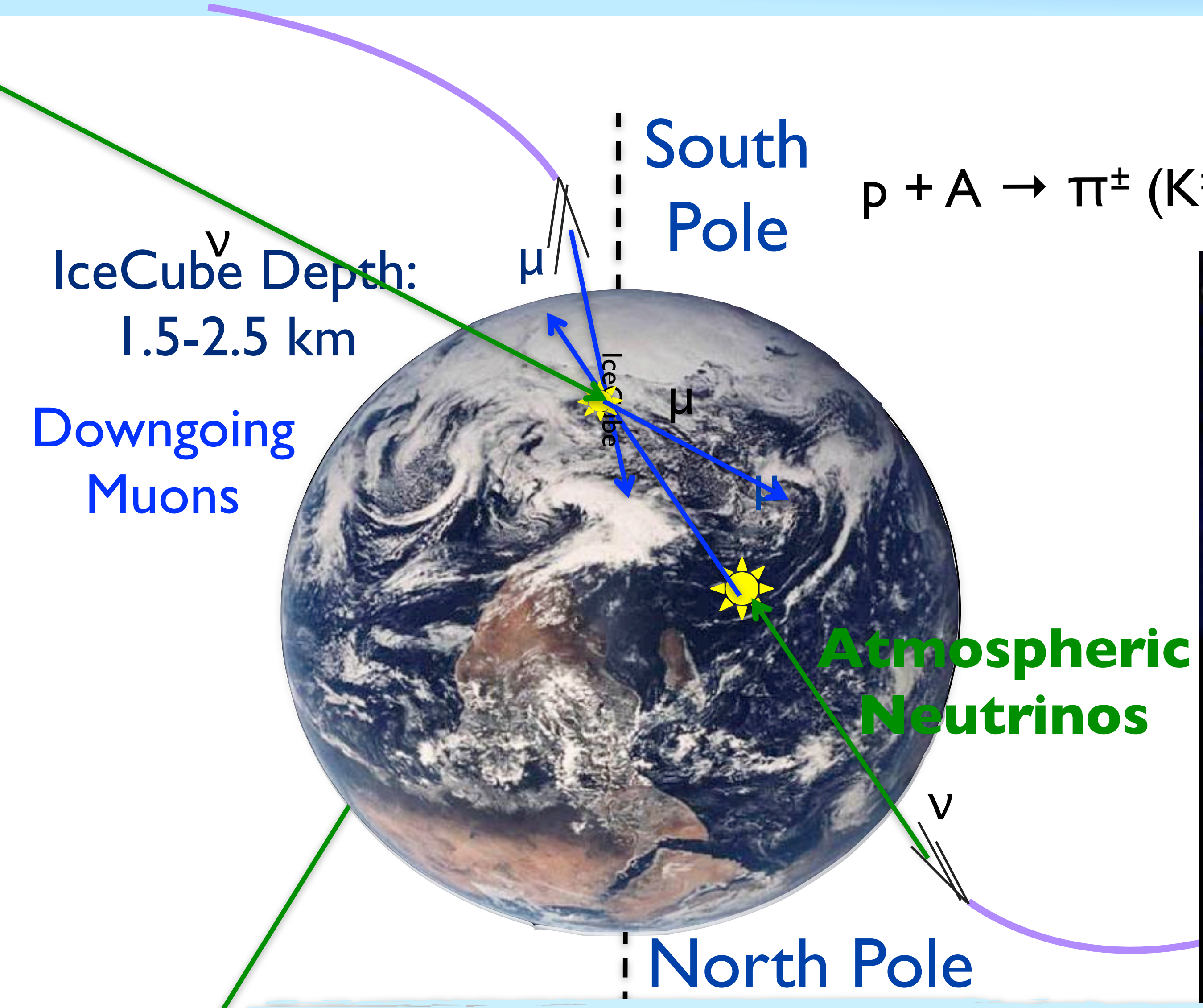


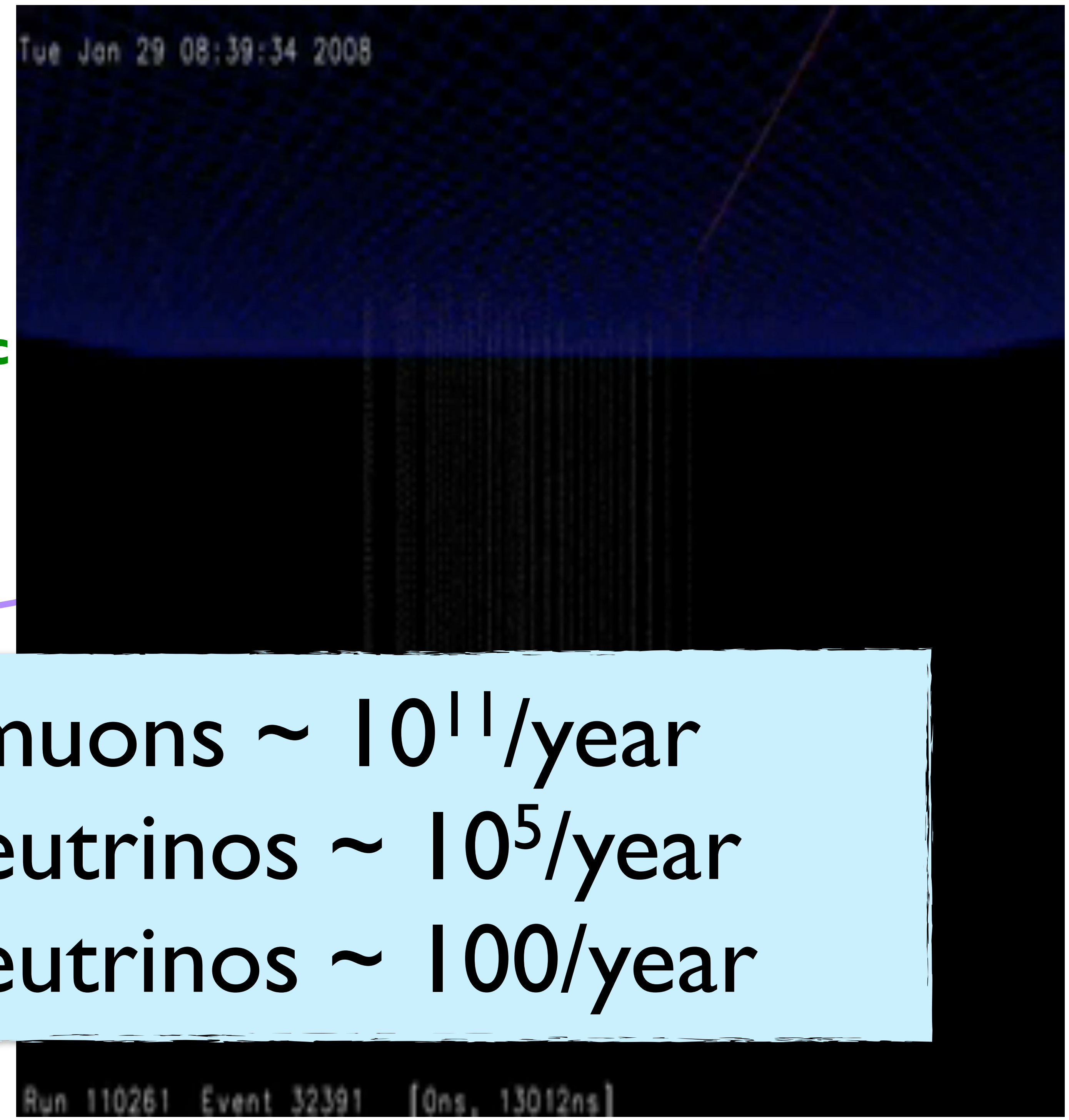


(#H1) Hole ice survey
(#H2) Mapping of hole shape
(#H3) Cable position and orientation
(#B1) Transmission and scattering at hole/bulk ice interface
(#B2) Light attenuation and scattering in the bulk ice
(#G1) DOM geometry
(#G2) Orientation of DOM



$p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons ... $\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \rightarrow e^{+} \nu_{e} \nu_{\mu} \nu_{\mu}$



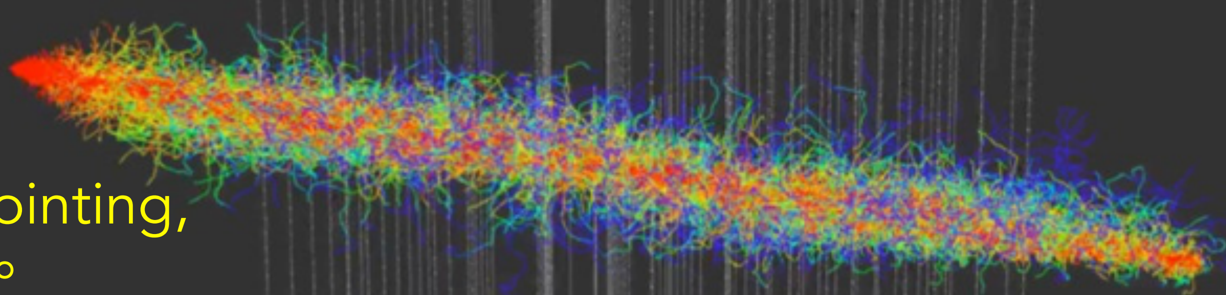


Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
Astrophysical neutrinos ~ 100/year

irreducible neutrino background to
extra terrestrial neutrino fluxes

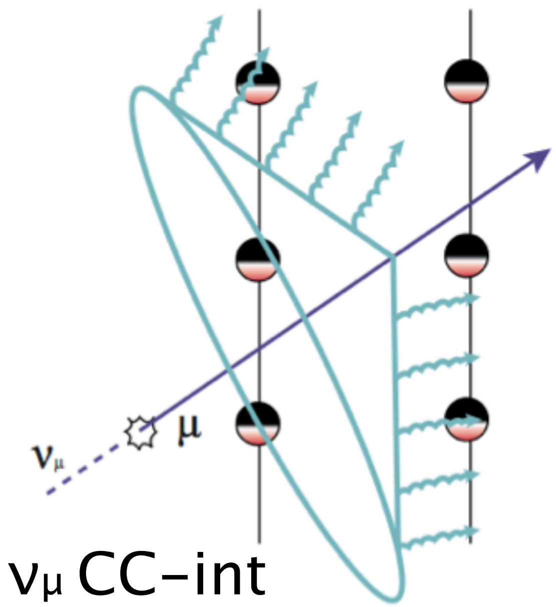
Event Topologies in IceCube

Track topology
(e.g. induced by muon neutrino)



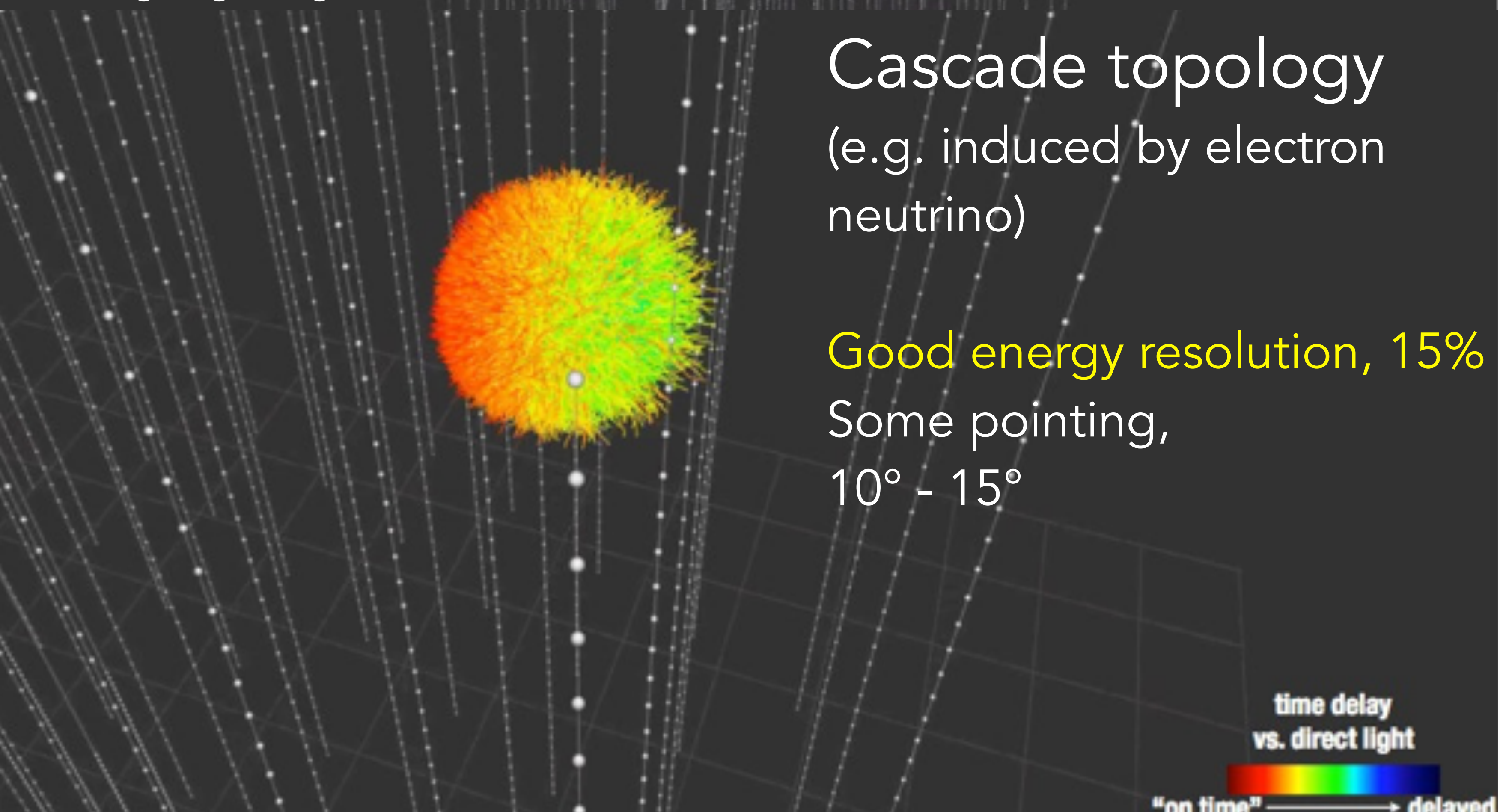
Good pointing,
0.2° - 1°

Lower bound on energy for through-going events



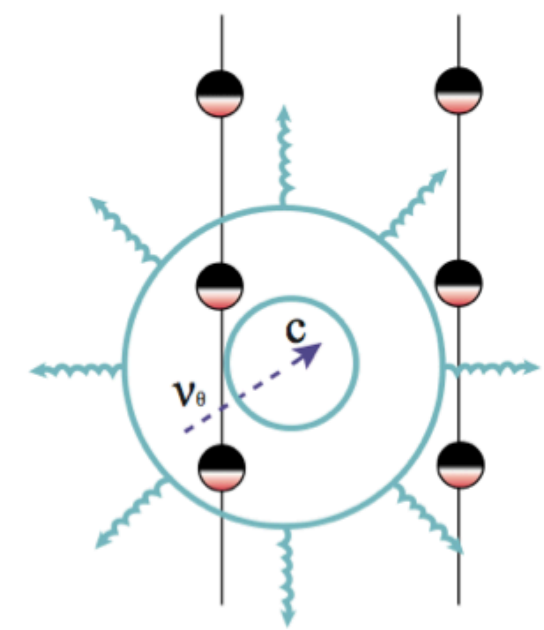
ν_μ CC–int

Cascade topology
(e.g. induced by electron neutrino)



Good energy resolution, 15%

Some pointing,
10° - 15°

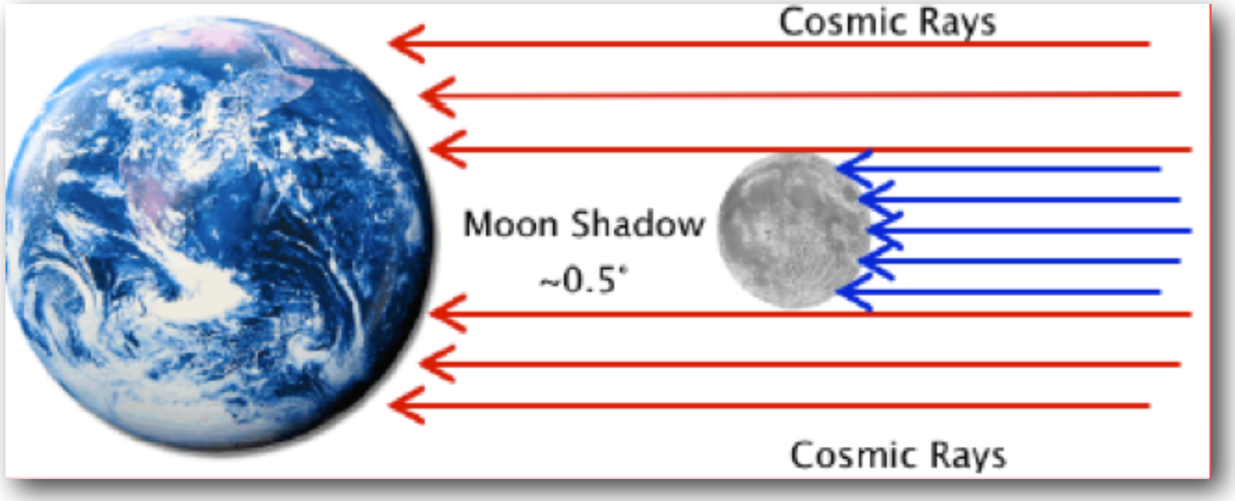


ν_e ν_τ CC–int & ν_i NC–int

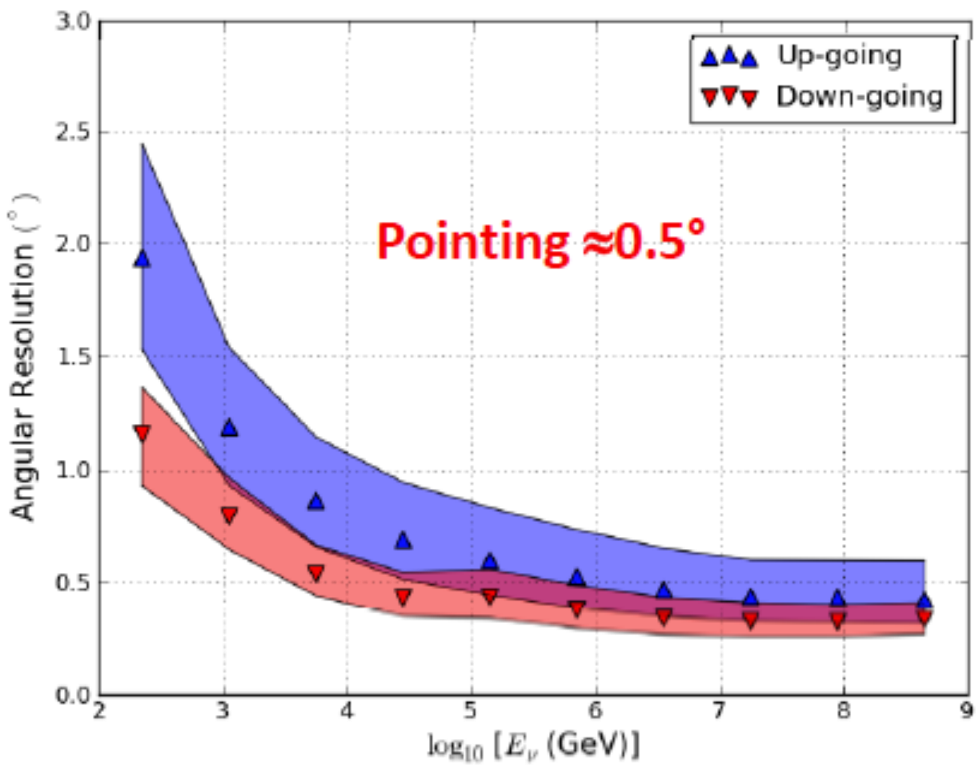
Calibration and Performance

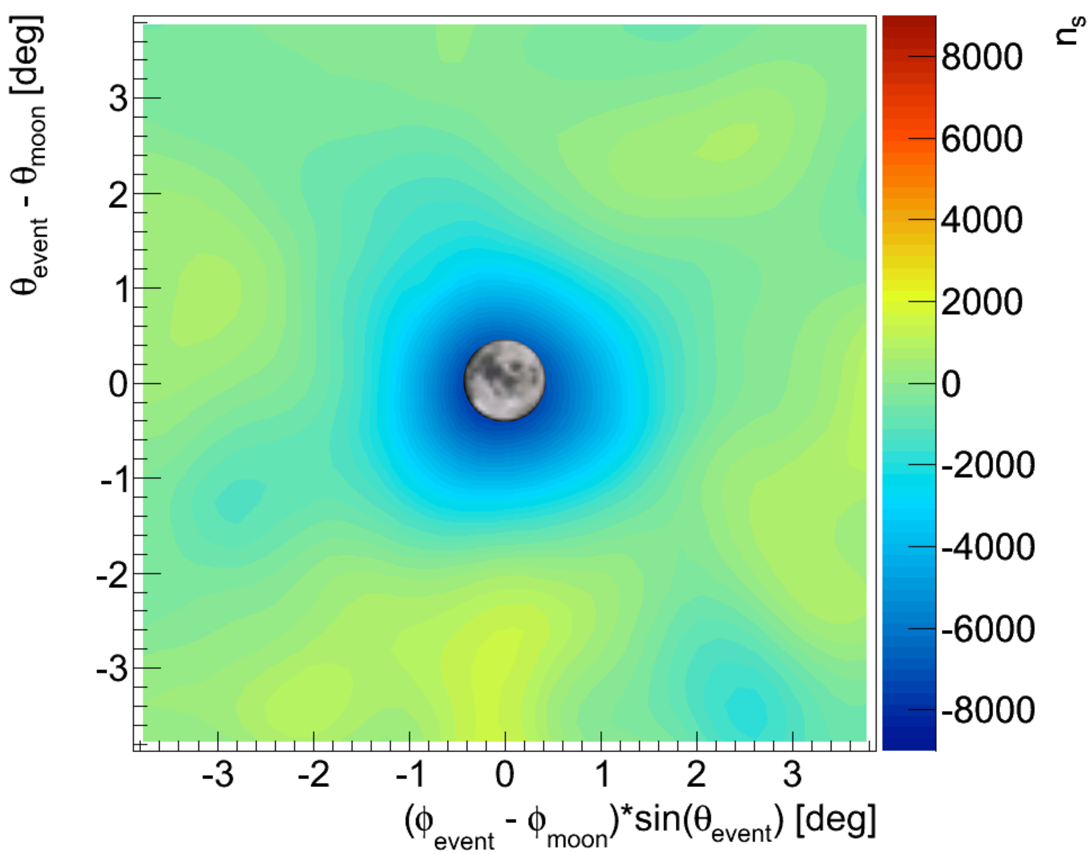
Physical Review D89 (2014) 102004

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - Moon Shadow
  - Atmospheric Neutrinos
  - Minimum-ionizing Muons



- Moon blocks cosmic rays - Observed muon deficit 14σ significance
  - systematic pointing error <0.1°

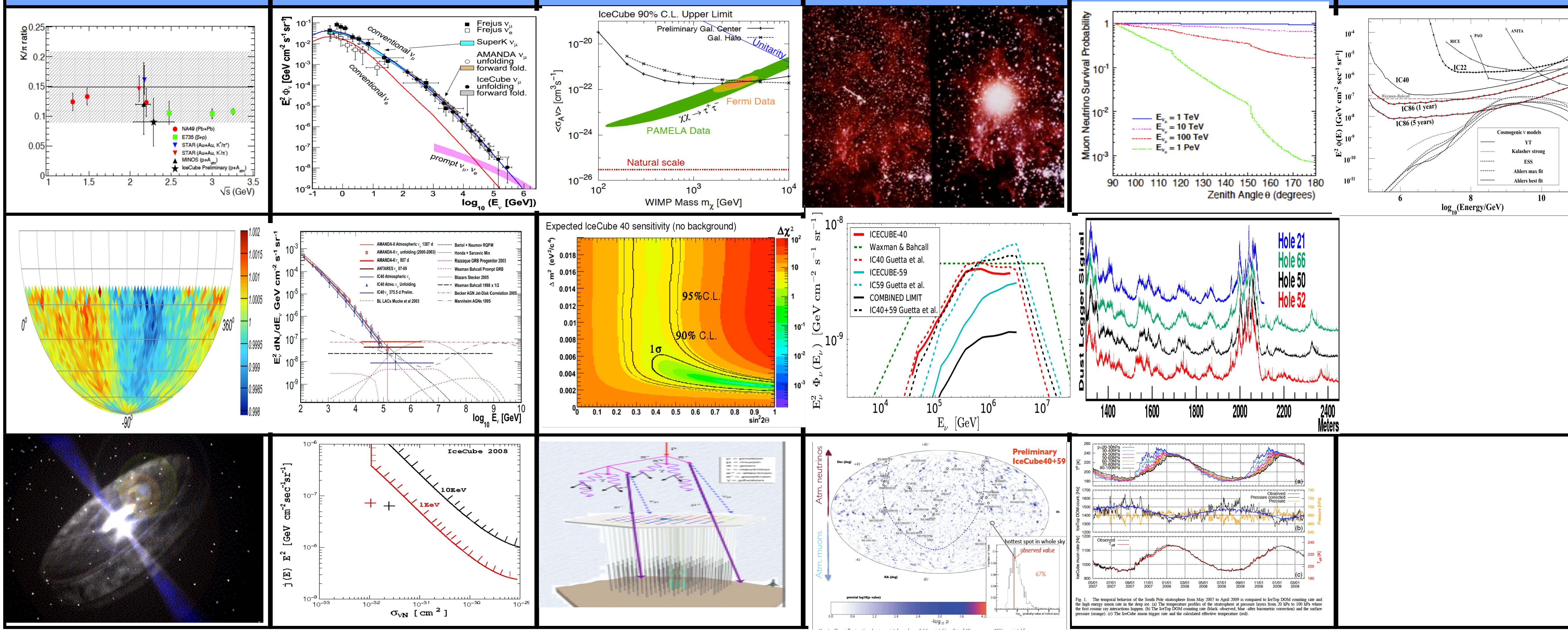




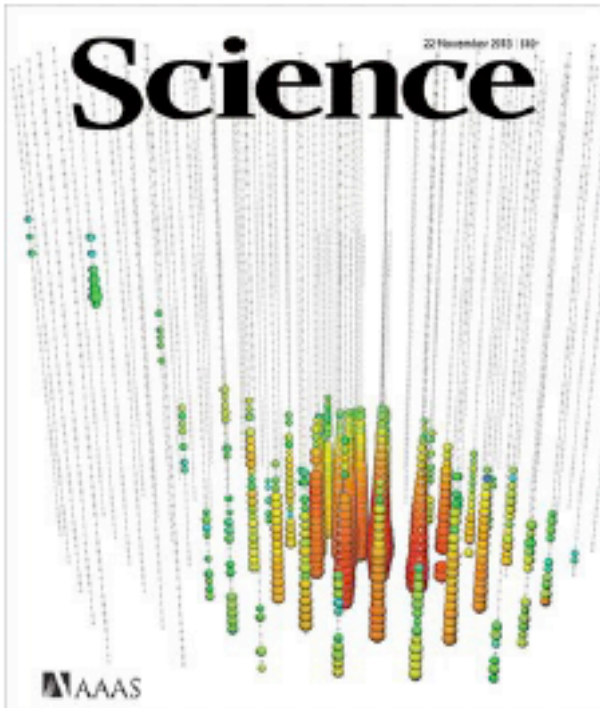
Physics Potential and Selected Results

IceCube Science

Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology



Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos



Recently detected High Energy Neutrinos of Astrophysical Origin

Science 342, 1242856 (2013)

Phy. Rev. Lett. 113, 101101 (2014)

physicsworld
BREAKTHROUGH OF THE YEAR 2013

Physics World
Breakthrough of the Year 2013

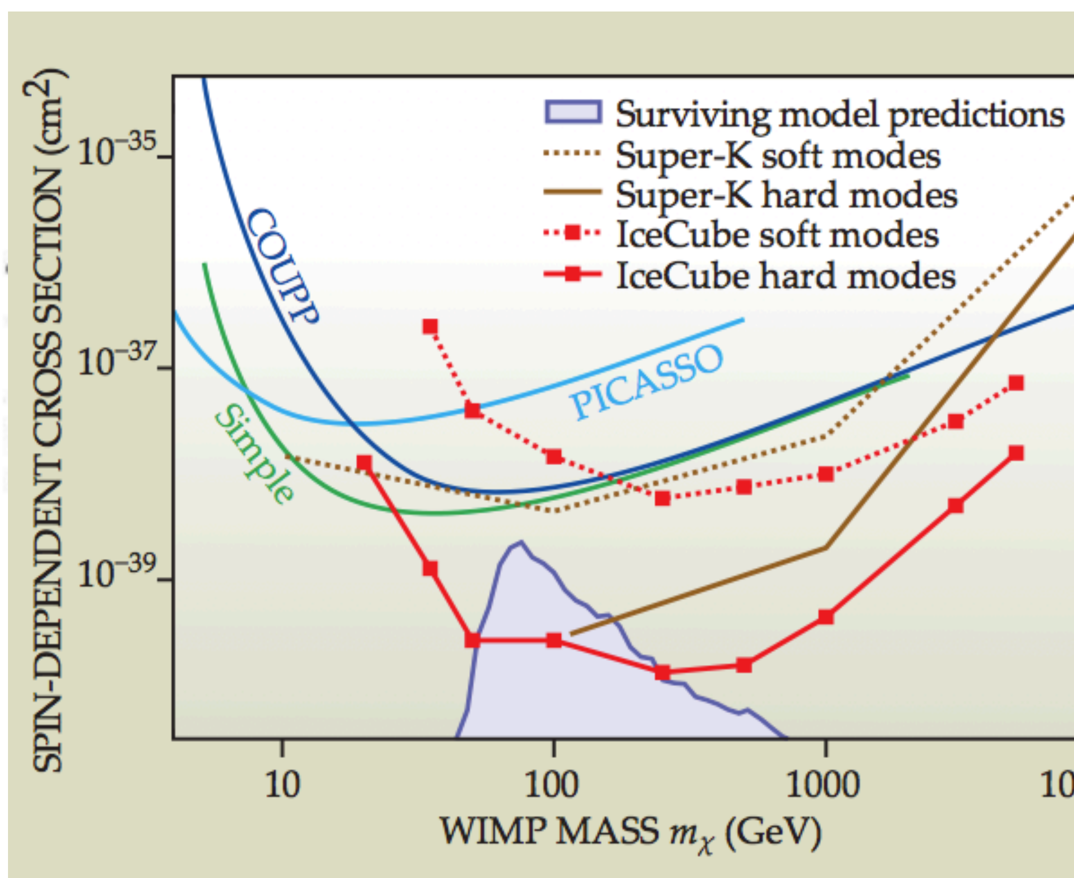
The *Physics World* Breakthrough of the Year is awarded for physics research published in 2013 and the decision is based on the following criteria:

- Fundamental importance of research
- Significant advance in knowledge
- Strong connection between theory and experiment
- General interest to all physicists

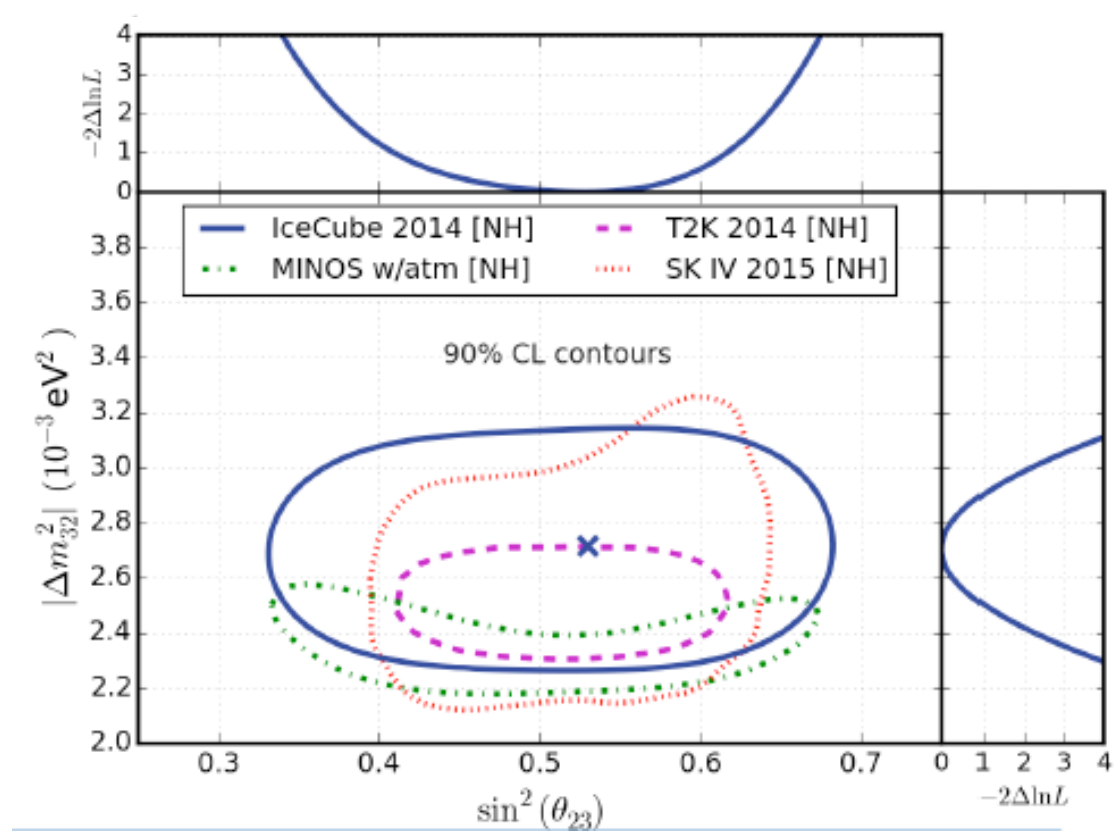
This is to certify that the *Physics World* Breakthrough of the Year has been given to

The IceCube South Pole Neutrino Observatory

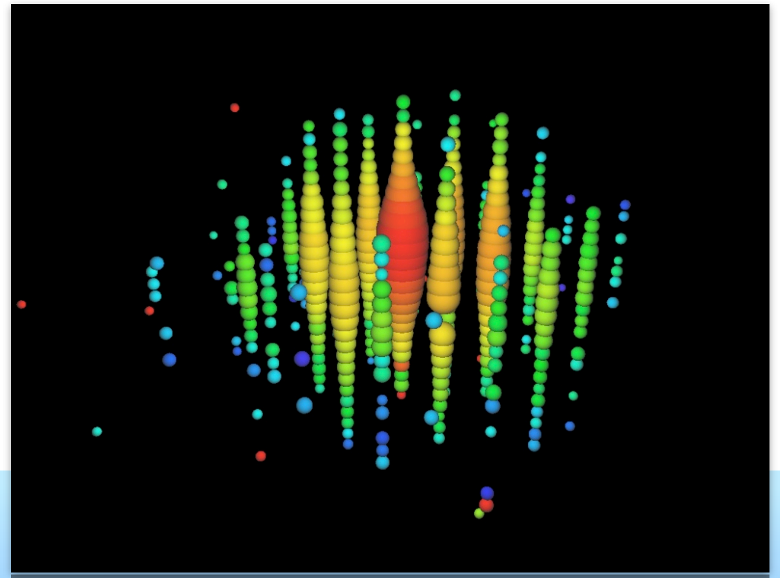
for making the first observations of high-energy cosmic neutrinos



Phys. Today 66(5), 14 (2013)



[IceCube, Phys.Rev.D91:072004 (2015)]



Astro-physical Neutrino Search

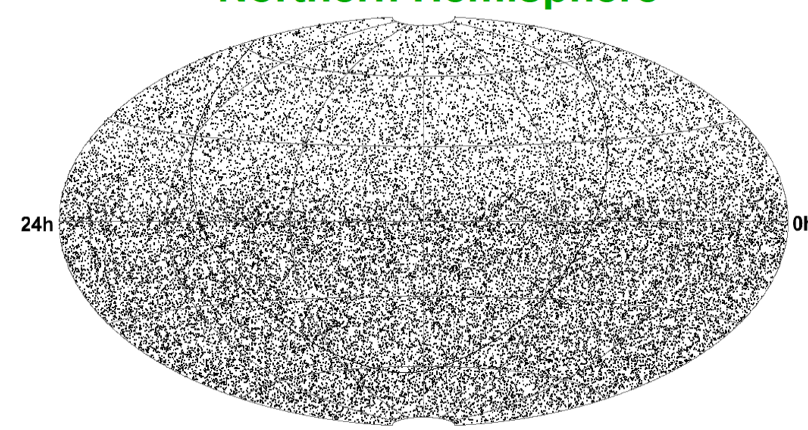
Finding Astrophysical Neutrinos

- How to overcome the large atmospheric neutrino background
- We need to rely on statistical methods to pick out neutrinos from this mess
  - Do neutrinos cluster anywhere in space, time, or arriving in coincidence with astronomical events or objects ?
  - Do we see any spectral features ?

1. Point Source

single dominant source

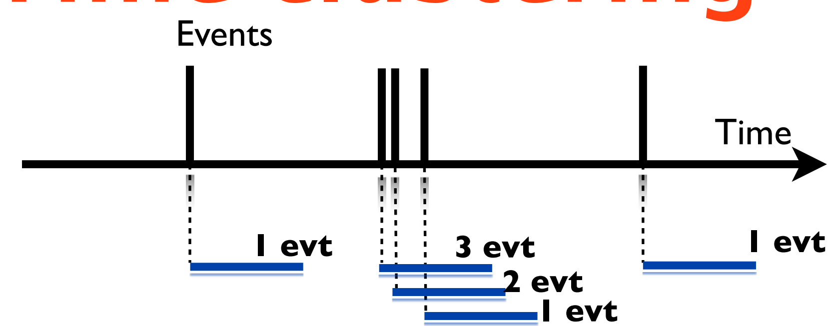
Northern Hemisphere



Southern Hemisphere

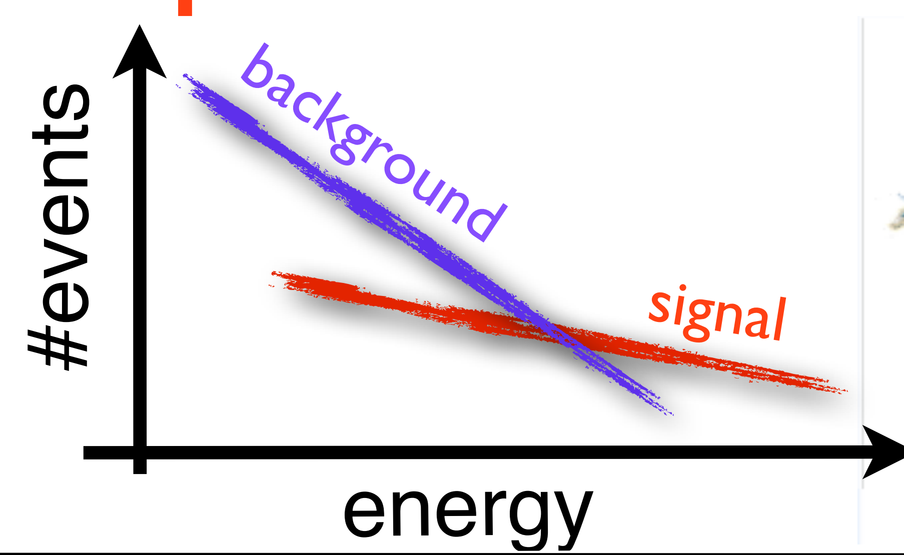
2. Time clustering

transient source



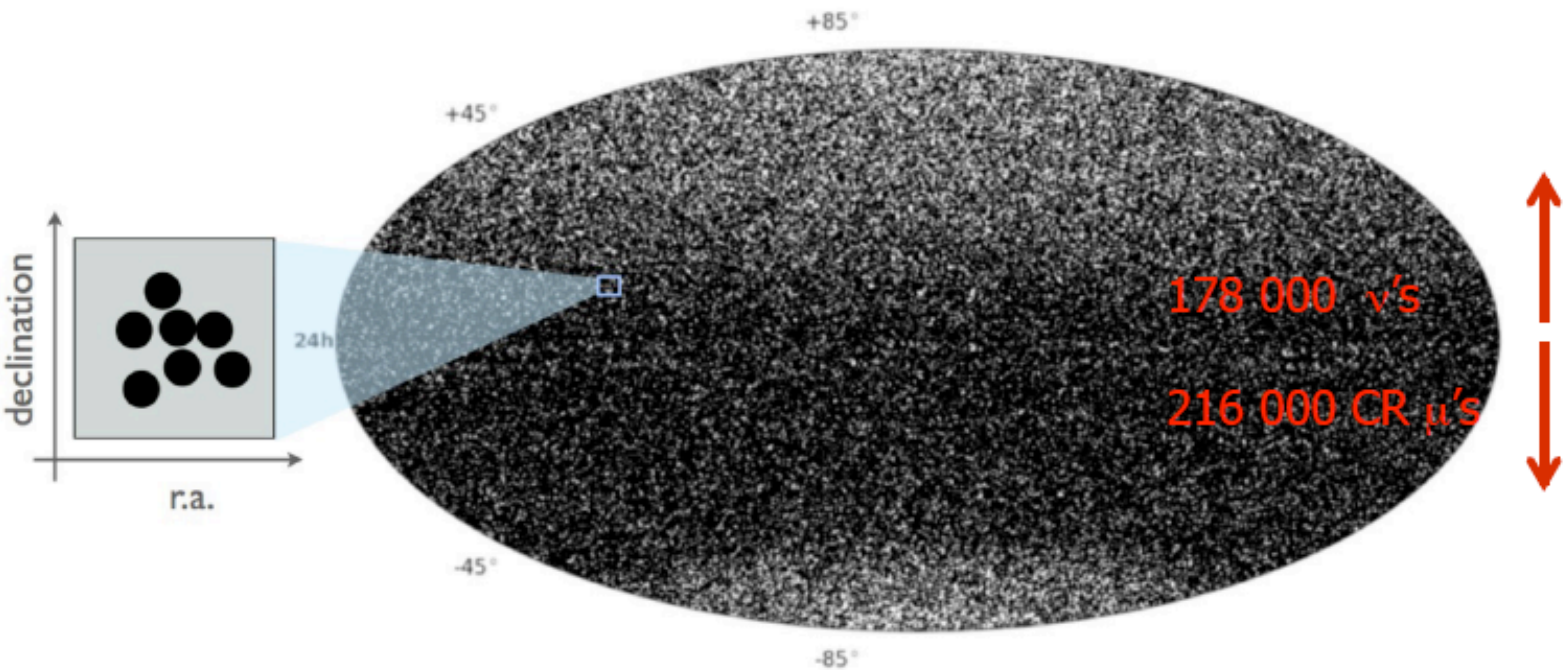
3. Spectral feature

cumulative flux



Point Source Search

- looser optimization
- background estimated off source at similar declination
- unbinned maximum likelihood test for a fine grid of potential sources



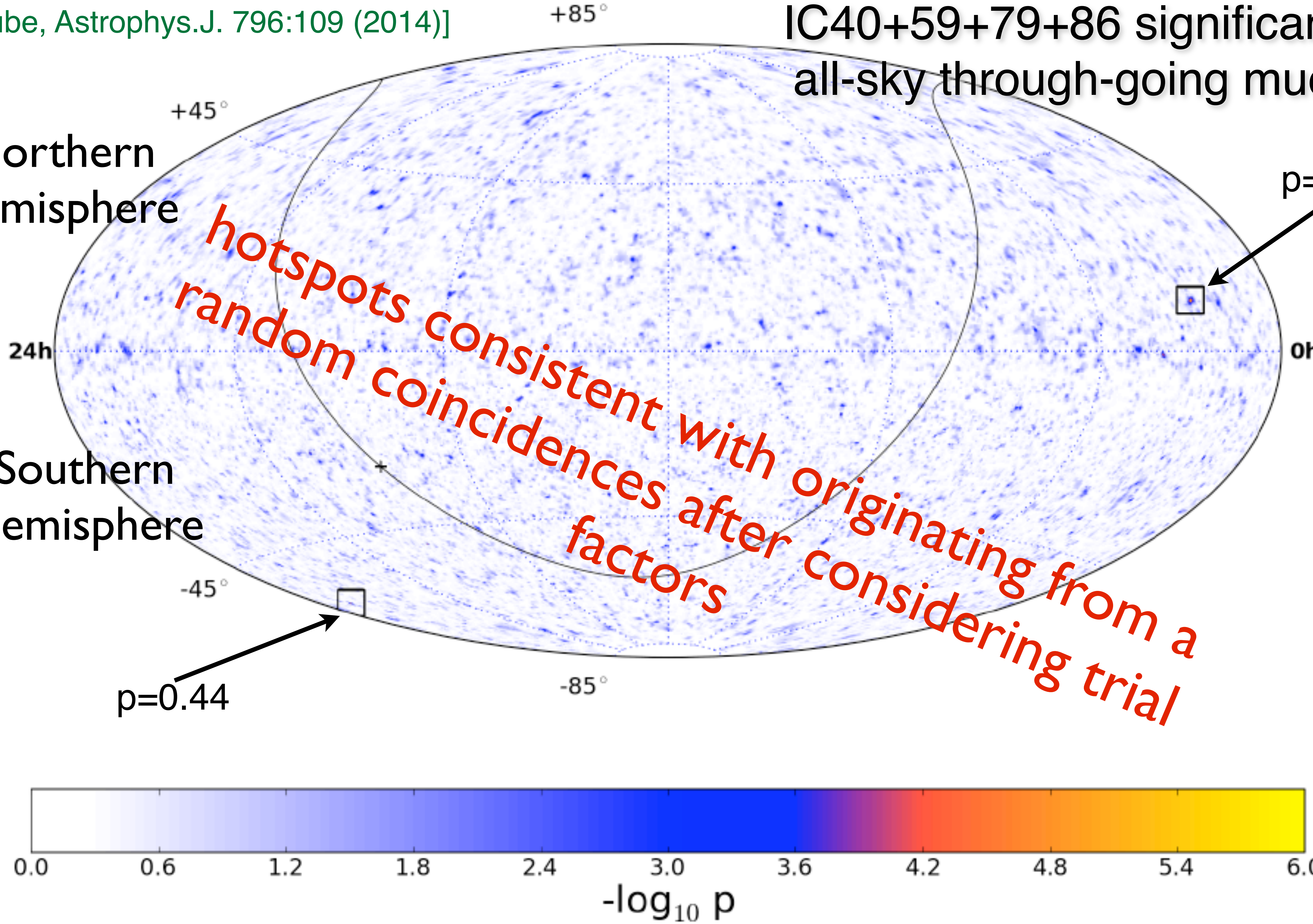
search for significant clustering of events above random background

[IceCube, Astrophys.J. 796:109 (2014)]

IC40+59+79+86 significance:
all-sky through-going muons

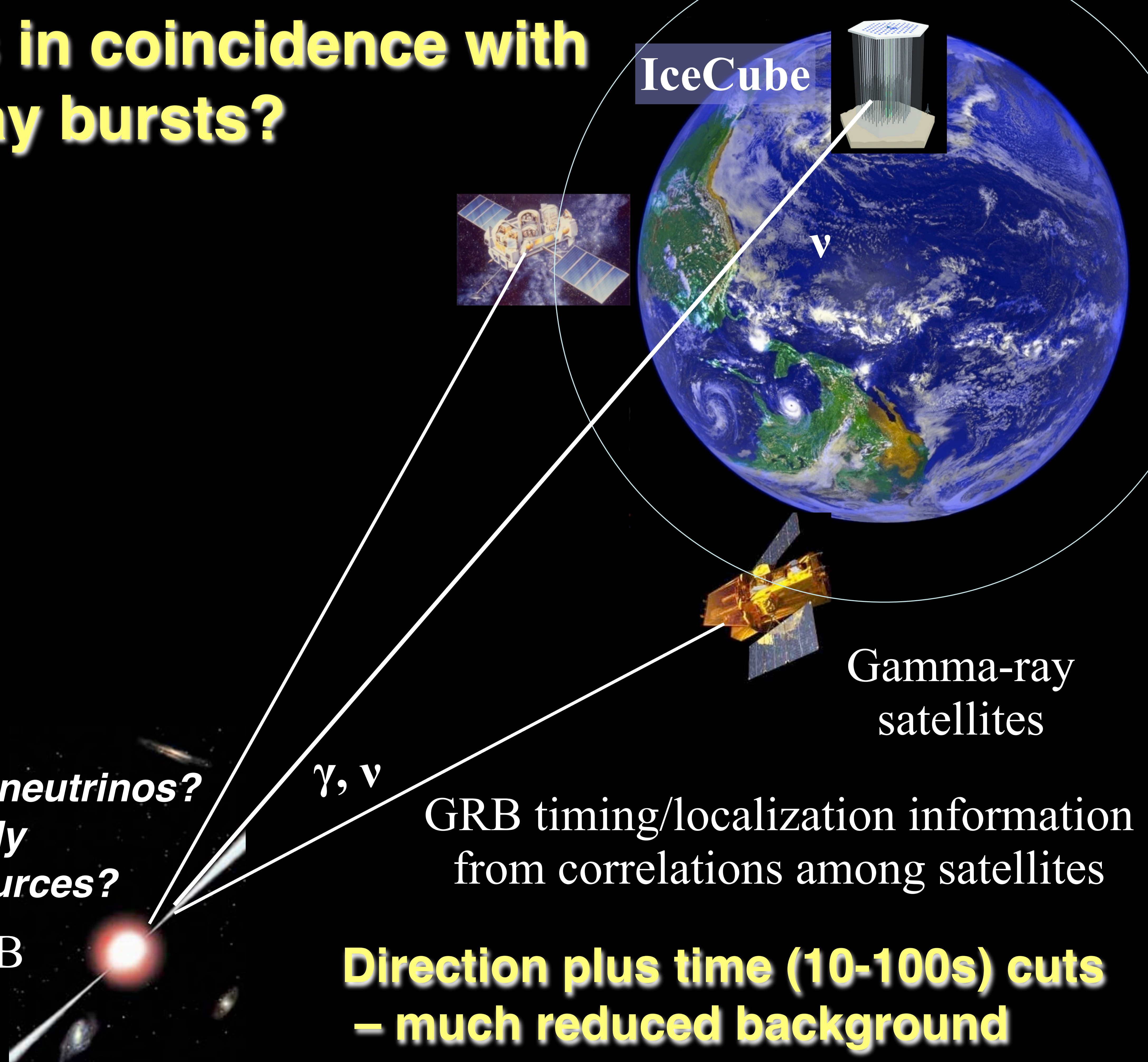
Northern Hemisphere

Southern Hemisphere



hotspots consistent with originating from a random coincidences after considering trial factors

Neutrinos in coincidence with gamma-ray bursts?



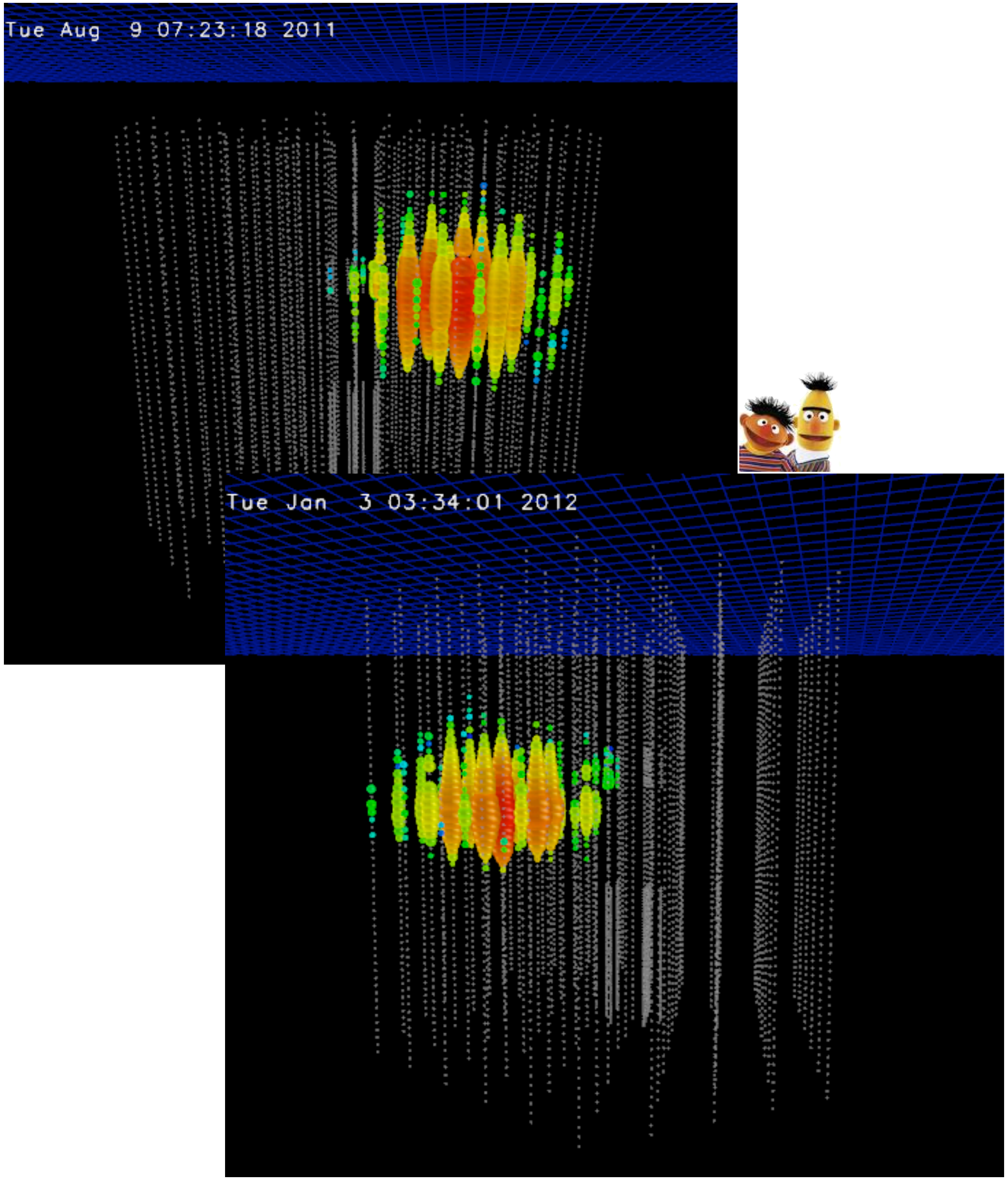
Where are the neutrinos? Are GRBs really cosmic ray sources?

GRB timing/localization information from correlations among satellites

Direction plus time (10-100s) cuts – much reduced background

Search for highest energy neutrinos

IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356

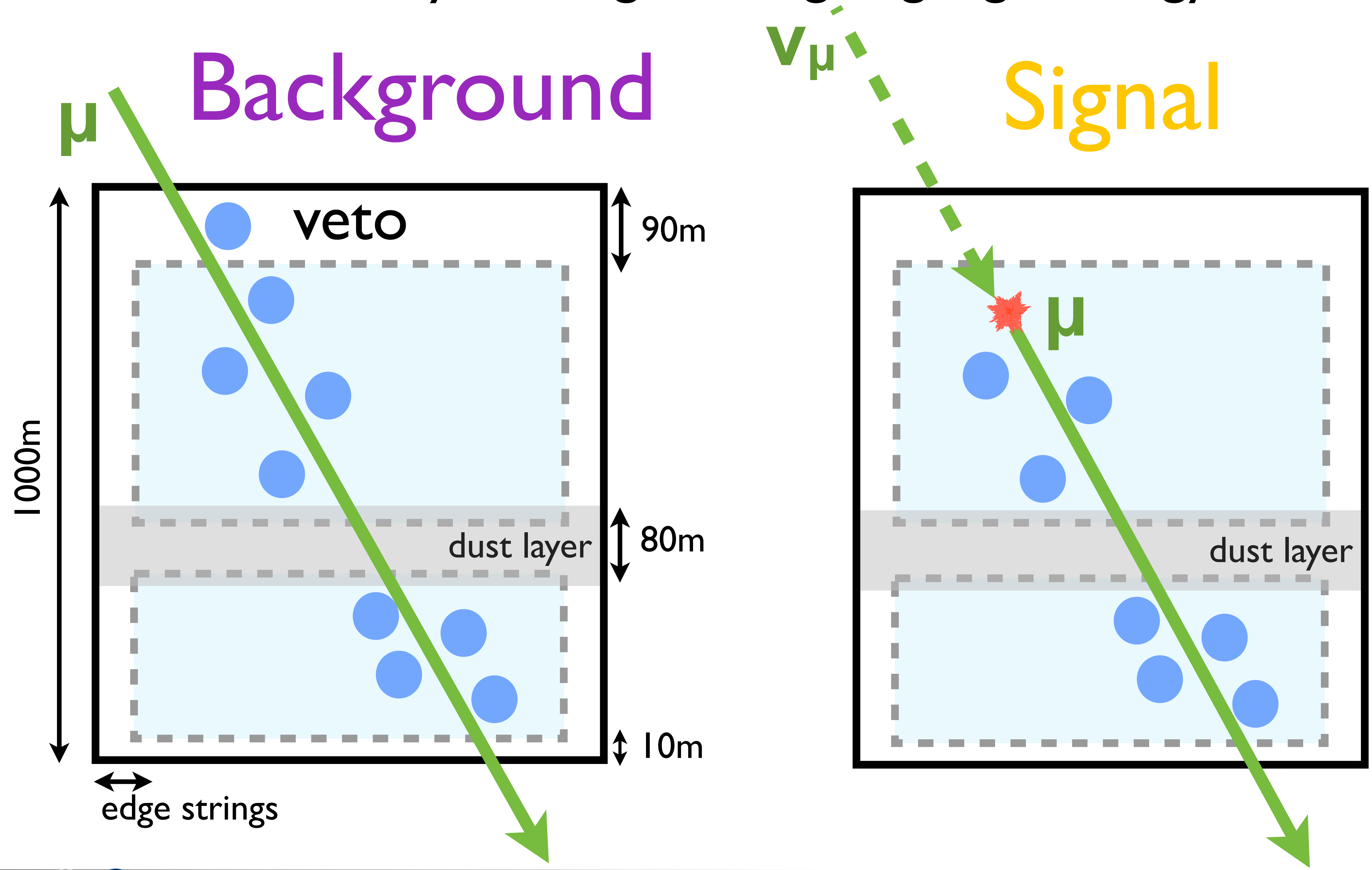


Dataset / Results
(670days of IC79/IC86 data)
expected 0.08 events
observed 2 events ($\rightarrow$ 2.7σ)

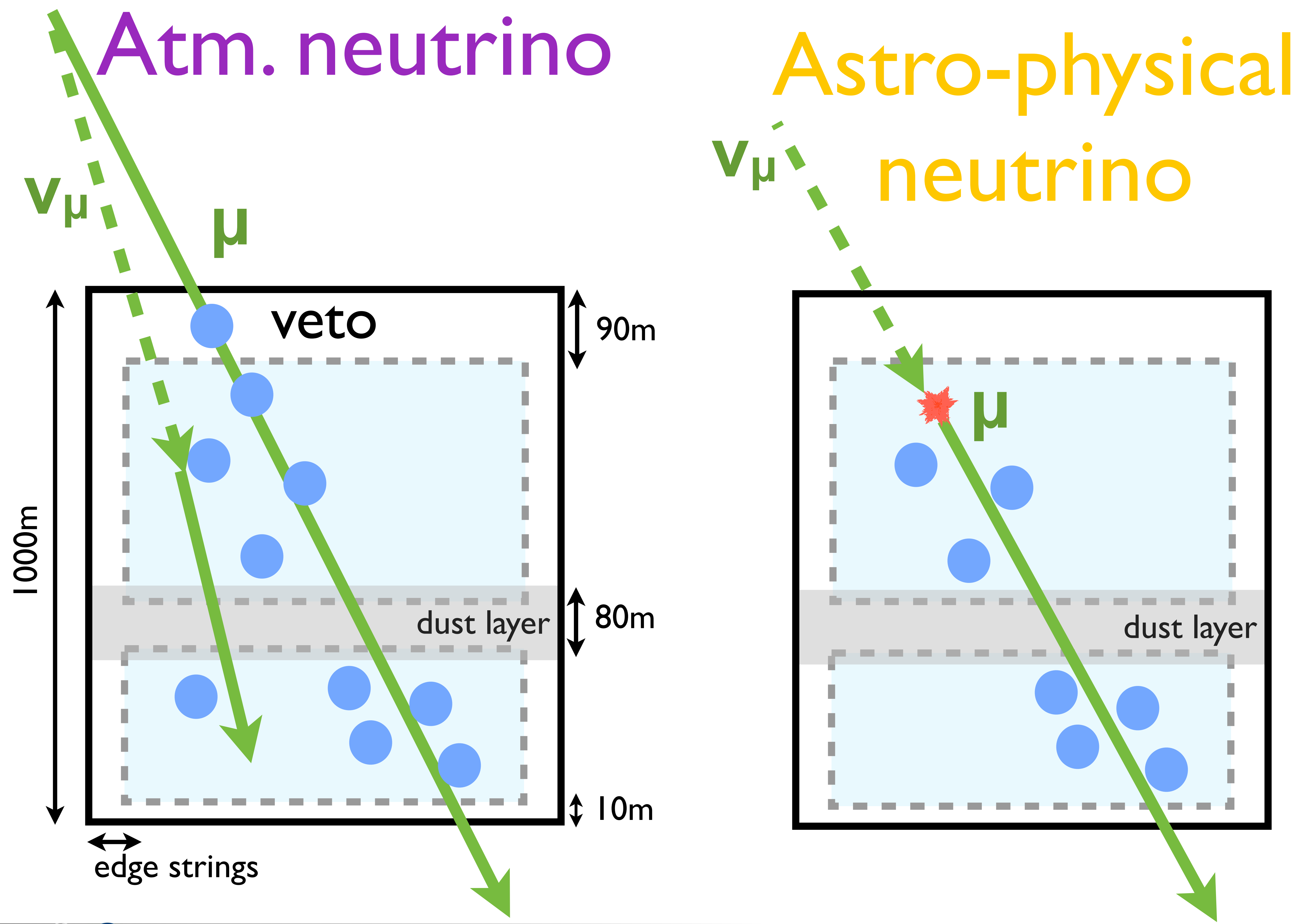
- Ernie ~1.15 PeV (~$1.9 \cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~$1.7 \cdot 10^{-4}$J)
- Energy is the visible energy of the cascade, could originate from NC event, ν_τ CC, or ν_e CC
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

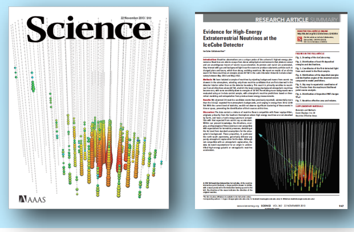
Ernie & Bert are not GZK, but ...

- Probe the energy region of about 30TeV to 1PeV, all flavors and all directions, by vetoing down-going high-energy muons



Veto and Self-veto

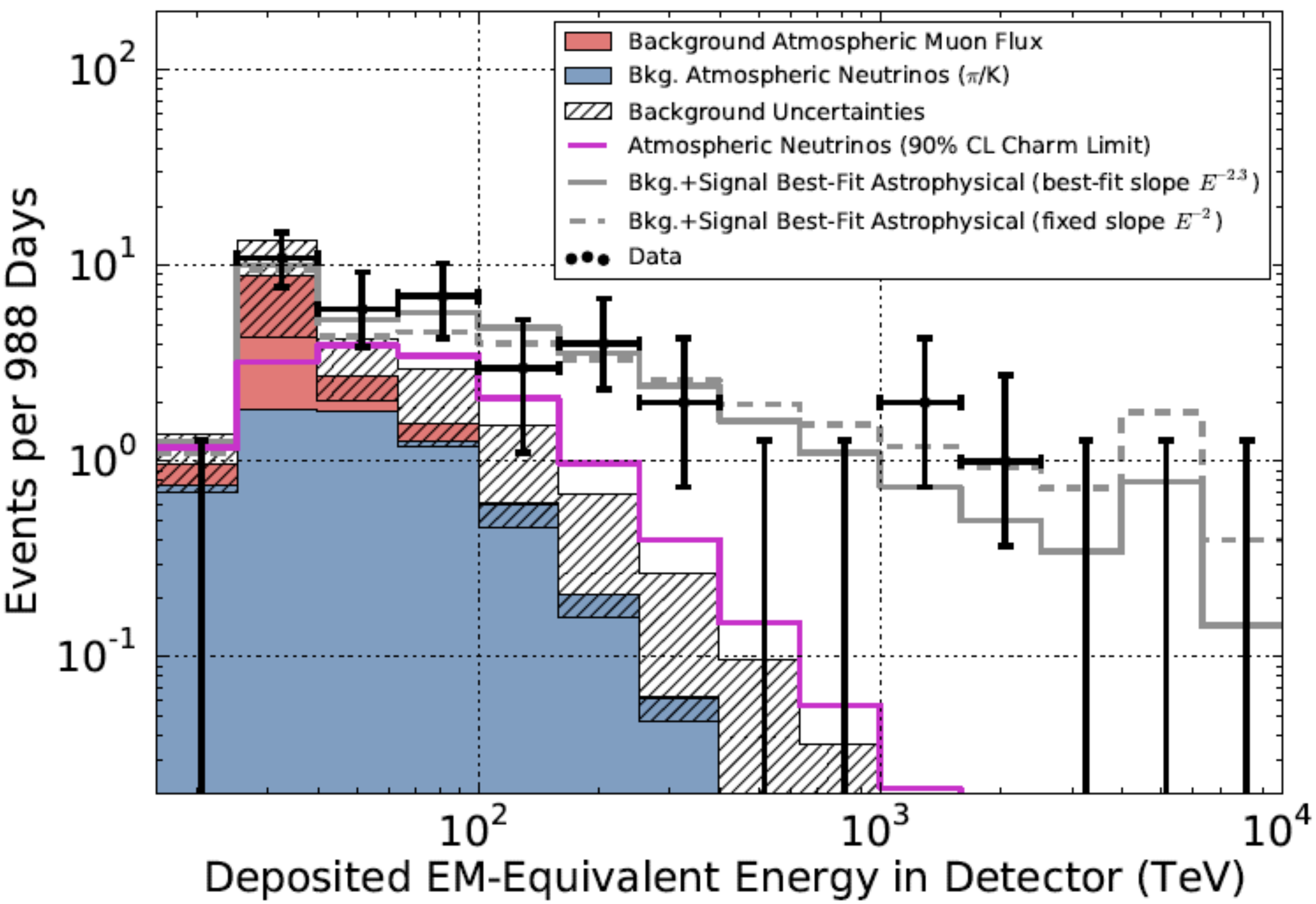




High-energy neutrino search 3yrs

37 events (9 track-like, 28 showers) observed

Expectation from conventional atm. muons and neutrinos ~15.0



- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (8.4±4.2), Conv. Neutrino ($6.6^{+5.9}_{-1.6}$),
- Over 60 TeV < E < 2000 TeV, the spectrum consistent with E^{-2} or $E^{-2.3}$
- E^{-2} spectrum predicts too may neutrinos above ~2 PeV. So, a cutoff or steeper spectrum needed.

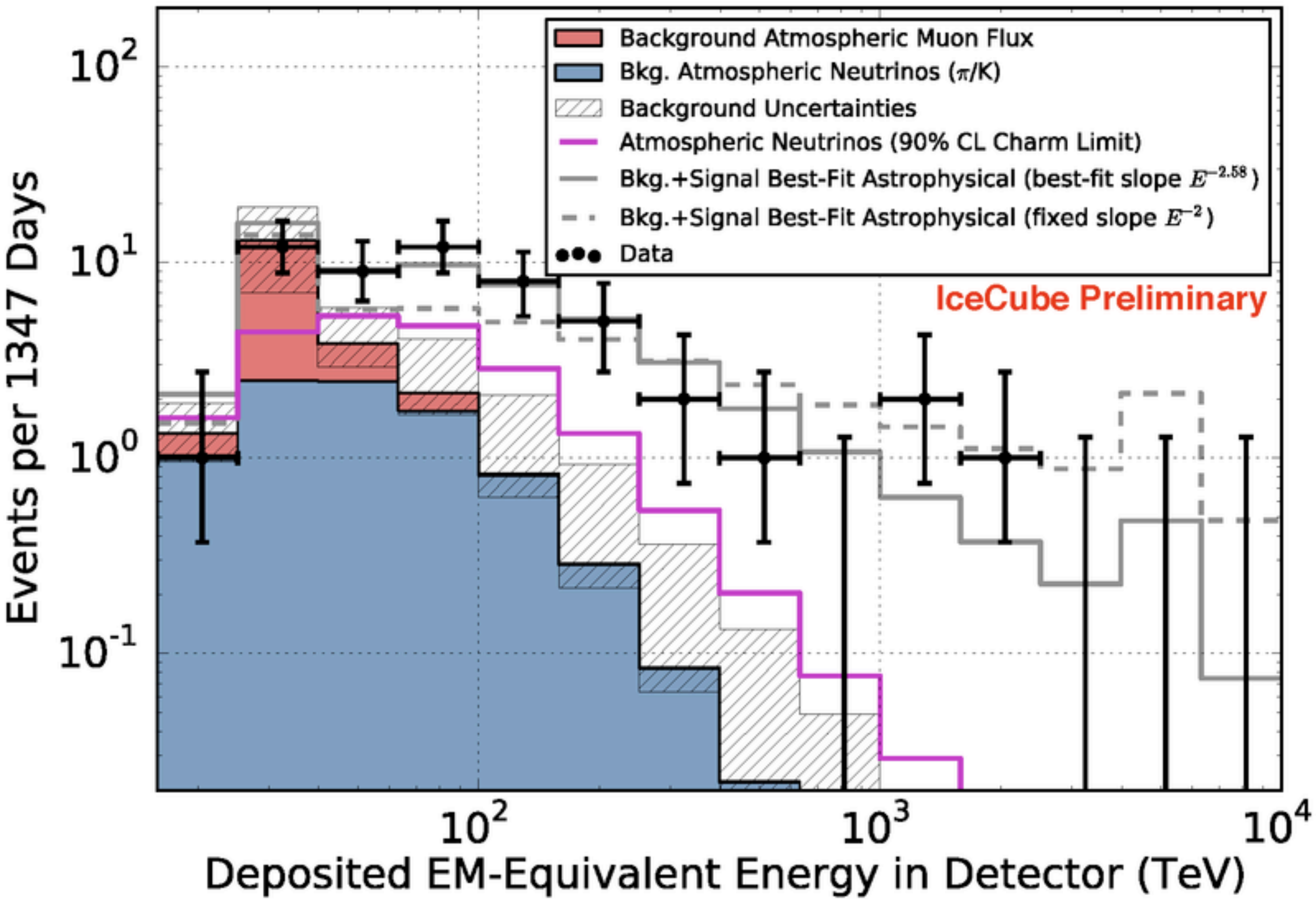
5.7 sigma rejection of atmospheric-only hypothesis

IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

High-energy neutrino search 4yrs

54 events (15 track-like, 39 showers) observed

Expectation from conventional atm. muons and neutrinos ~21.6



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- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (12.6±5.1), Conv. Neutrino ($9.0^{+8.0}_{-2.2}$),
- Over 60 TeV < E < 2000 TeV, the spectrum best fit with $E^{-2.58}$
- E^{-2} spectrum predicts too may neutrinos above ~2 PeV. So, a cutoff or steeper spectrum needed.

~7 sigma rejection of atmospheric-only hypothesis

forthcoming ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

Excitement about High-Energy Neutrino Discovery

International Balzan Prize Foundation

Search

Astroparticle Physics including neutrino and gamma-ray observation

Francis Halzen

Belgium/USA

ITALIANO DEUTSCH FRANÇAIS ENGLISH

For his unparalleled accomplishments which have led to the construction of the large IceCube Neutrino Observatory in the south polar ice, a facility that has opened up a new window into the Universe through the study of cosmological high-energy neutrinos.

Hilldale and Gregory Breit Distinguished Professor at the University of Wisconsin-Madison and Director of its Institute for Elementary Particle Physics Research

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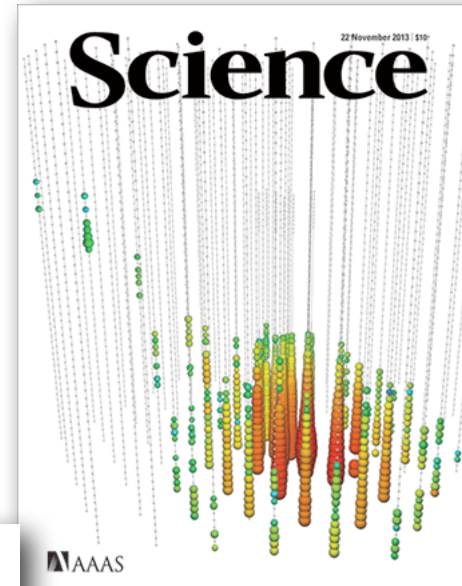
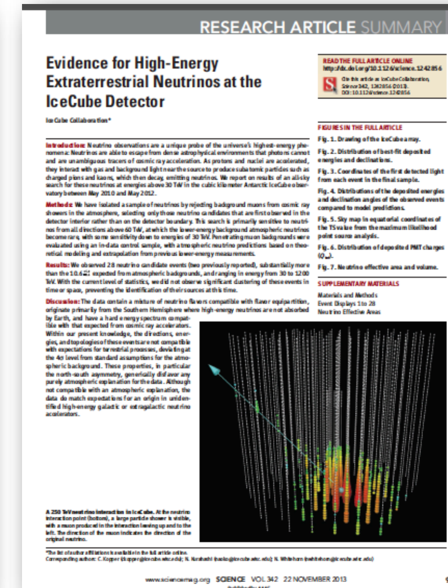




〈이 기사는 2014년 01월 06일자 신문 23면에 게재되었습니다.〉

"한국 '세계적 리더' 될 좋은 기회"

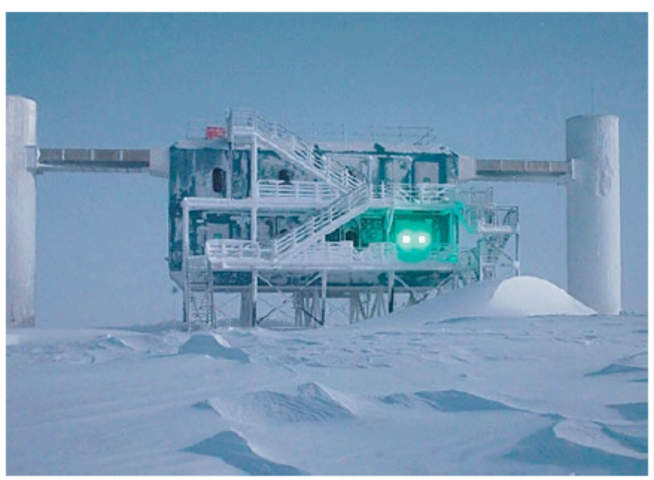
기초과학 투자 의지 활발, 한국에 새 연구 터전 둥지.. 연구자·학생 영입해 연구

▲아이스큐브 암흑물질 탐색팀의 책임자인 성균관대학교 카르스텐 로트 교수가 빙하 속 구형 디텍터를 활용해 중성미자를 하는 과정에 대해 설명하고 있다.

"지금은 중성미자 천체입자물리학계에 가장 흥미로운 시기다. 한국 과학계가 지금 이 새로 에 적극적으로 참여한다면 리더 그룹으로 자리잡을 수 있다."

우주서 날라온 '유령입자' 뭔가봤더니

디지털타임스 | 기사입력 2013-11-24 20:51 | 최종수정 2013-11-25 11:33

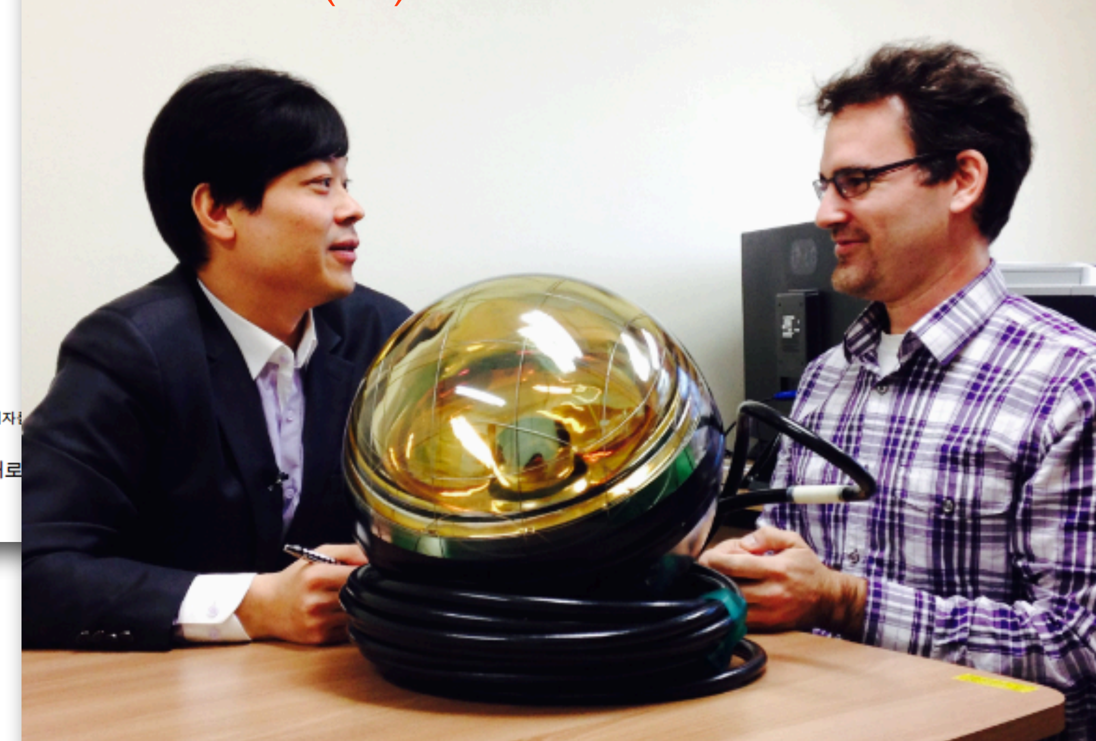


아이스큐브 공동연구팀, 남극서 초고에너지 중성미자 최초로 포착

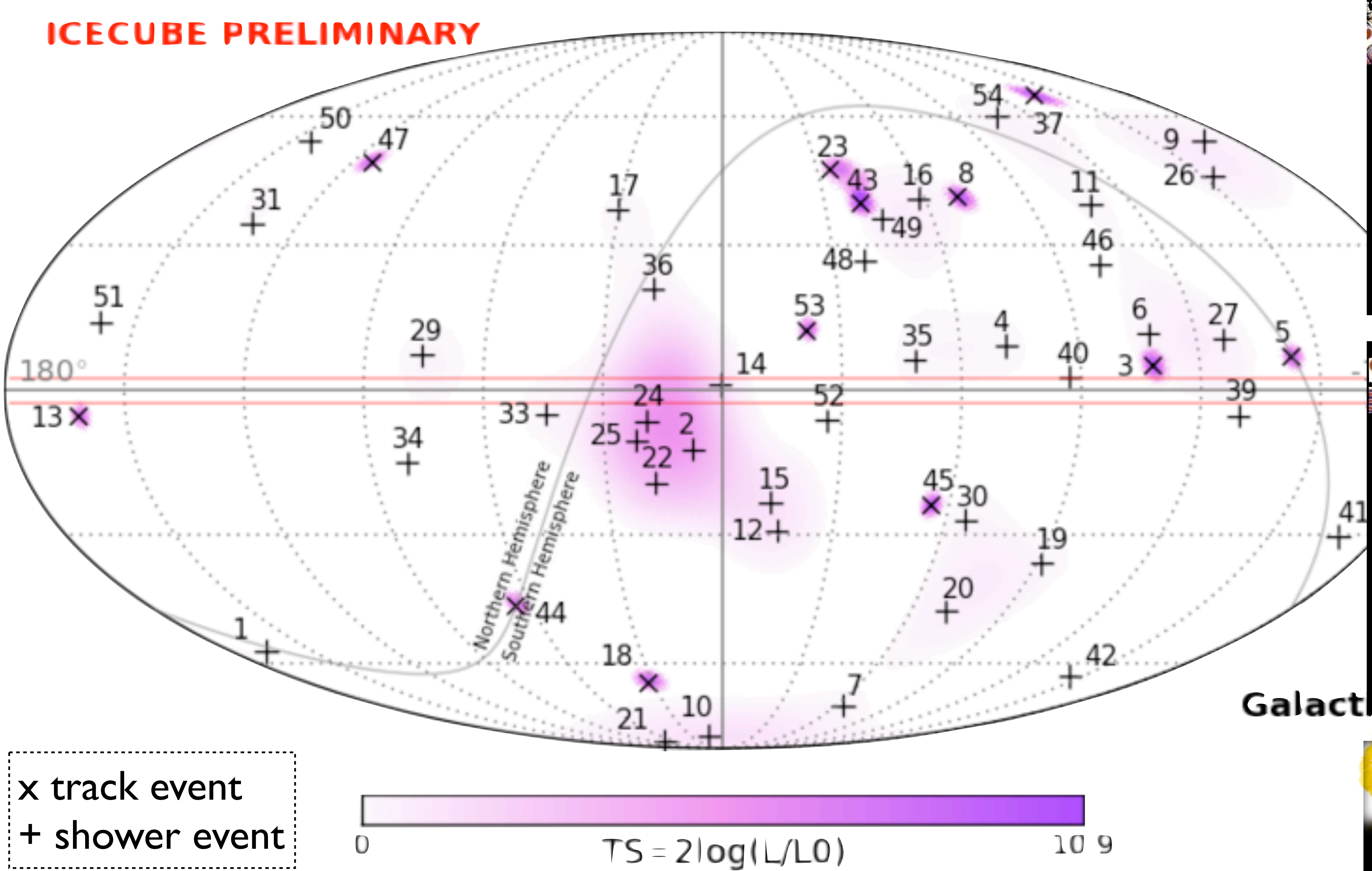
남극 얼음 깊이 설치된 연구장치에서 우주로부터 날아온 초고에너지 중성미자가 최초로 포착됐다.

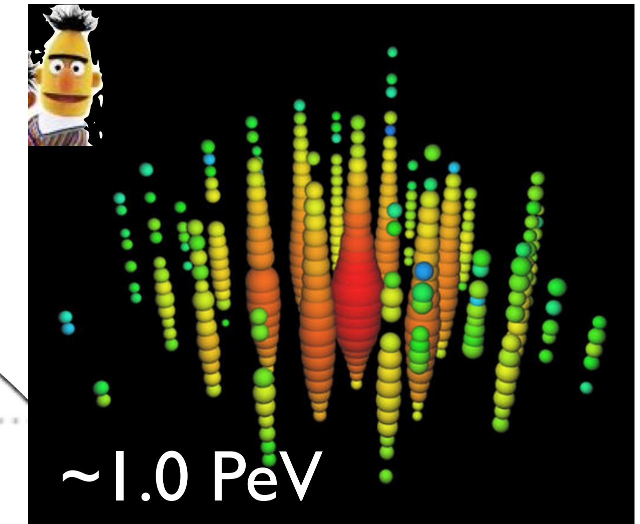
세계 11개국 39개 기관 200여명의 연구자로 구성된 '아이스큐브' 국제공동 연구팀은 남극 얼음층에서 우주로부터 날아온 초고에너지 중성미자의 흔적을 최초로 포착, 세계적인 과학저널인 사이언스에 22일 발표했다. 국내에서는 카르스텐 로트 성균관대 물리학과 교수가 연구에 참여했다.

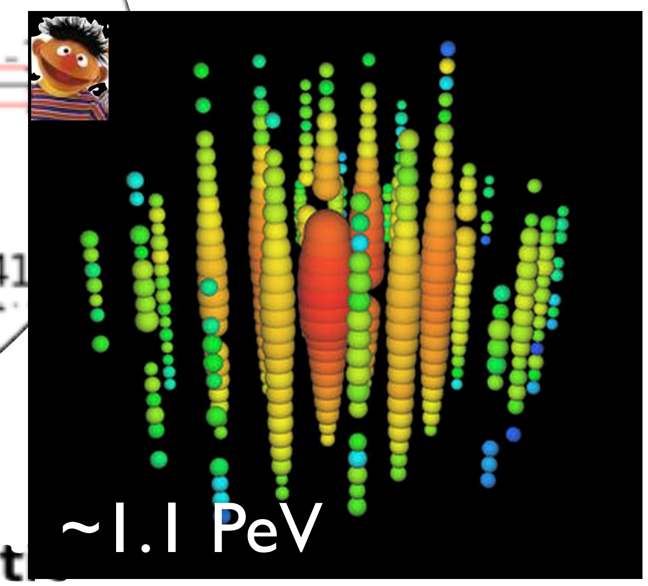
YTN Science (TV)

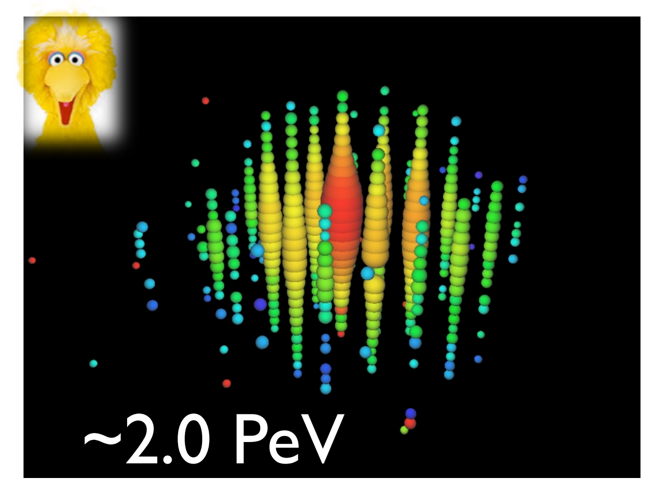


Skymap HESE-4yrs









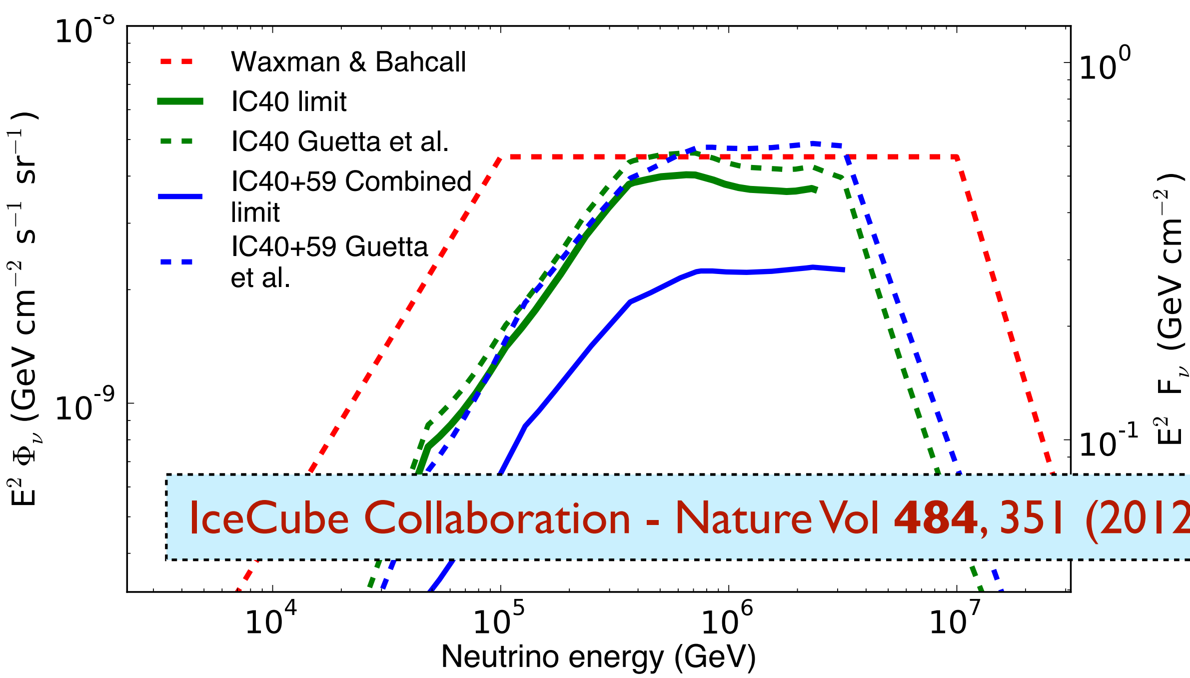
no significant correlations -- spacial or temporal

p-value for cascade events "clustering" 18%

Origin of the high-energy neutrinos ?

Extra Galactic

Gamma Ray Burst



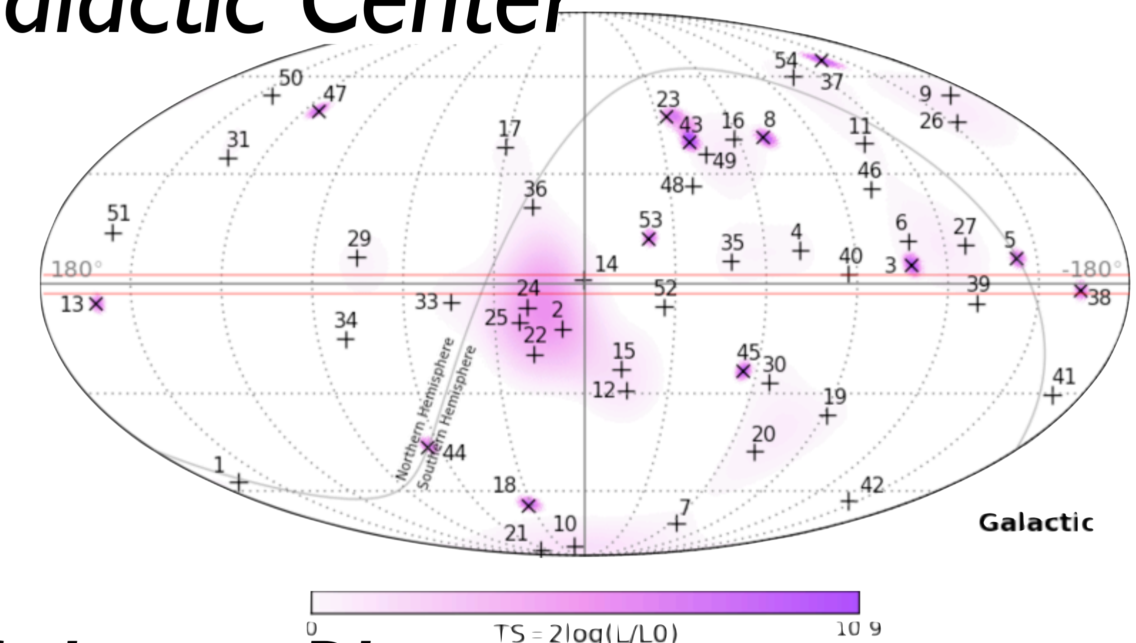
IceCube Collaboration - Nature Vol **484**, 351 (2012)

Active Galactic Nuclei / Starburst Galaxies

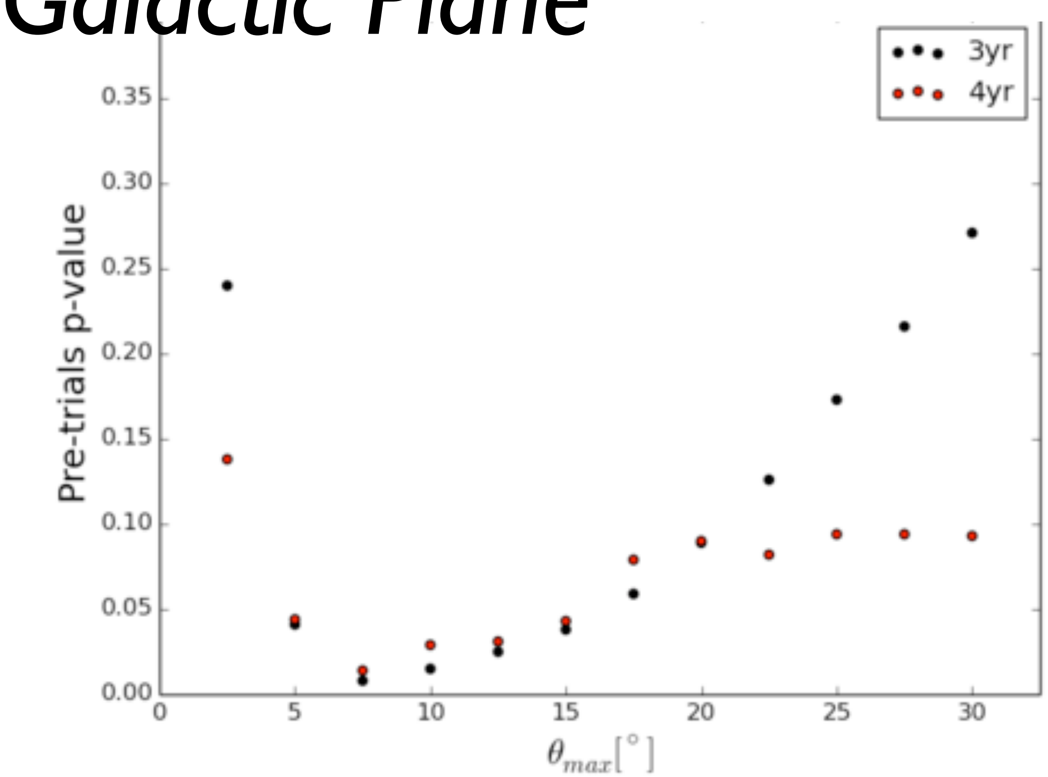
Starburst	M82	148.97	69.68	0.07	0.15
Radio Galaxies	NGC 1275	49.95	41.51	0.0	–
	Cyg A	299.87	40.73	0.9	0.03
	3C 123.0	69.27	29.67	0.0	–
	M87	187.71	12.39	0.0	–
	Cen A	201.37	-43.02	0.03	0.49

Galactic

Galactic Center



Galactic Plane

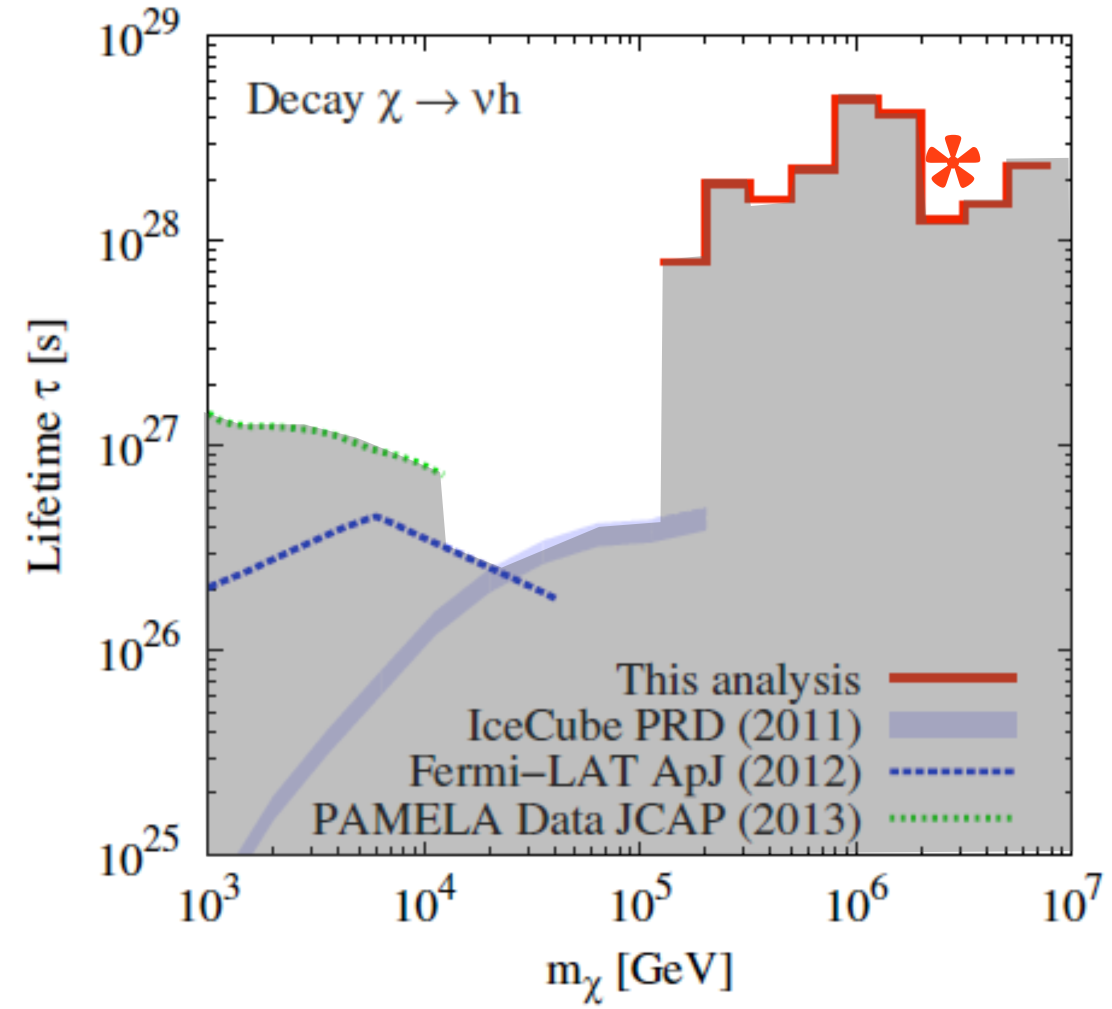


Heavy Dark Matter

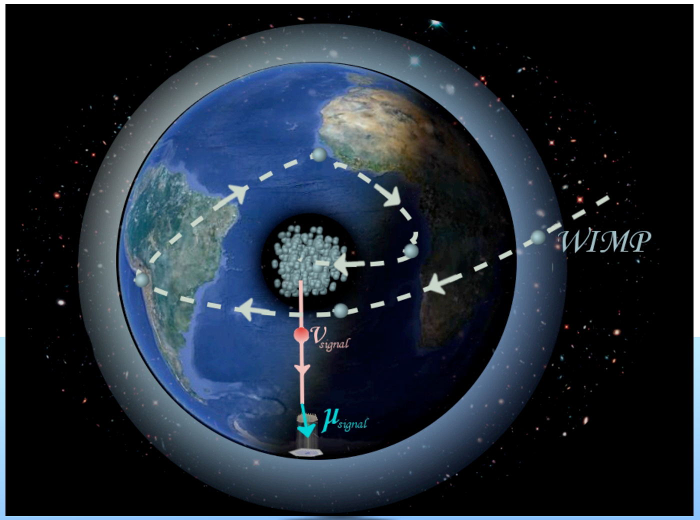
- Heavy Decaying Dark Matter (example $\chi \rightarrow \nu h$)
- focus on most detectable feature (neutrino line)
- Backgrounds steeply falling with energy, highest energy events provide best sensitivity
- Continuum and spacial distribution could help identify a signal
- Bounds from Fermi-LAT and PAMELA derived from search for bb annihilation channel (dominant decay channel of Higgs).

Bound on lifetime $\sim 10^{28}$s

Rott, Kohri, Park PHYS. REV. D 92, 023529 (2015)

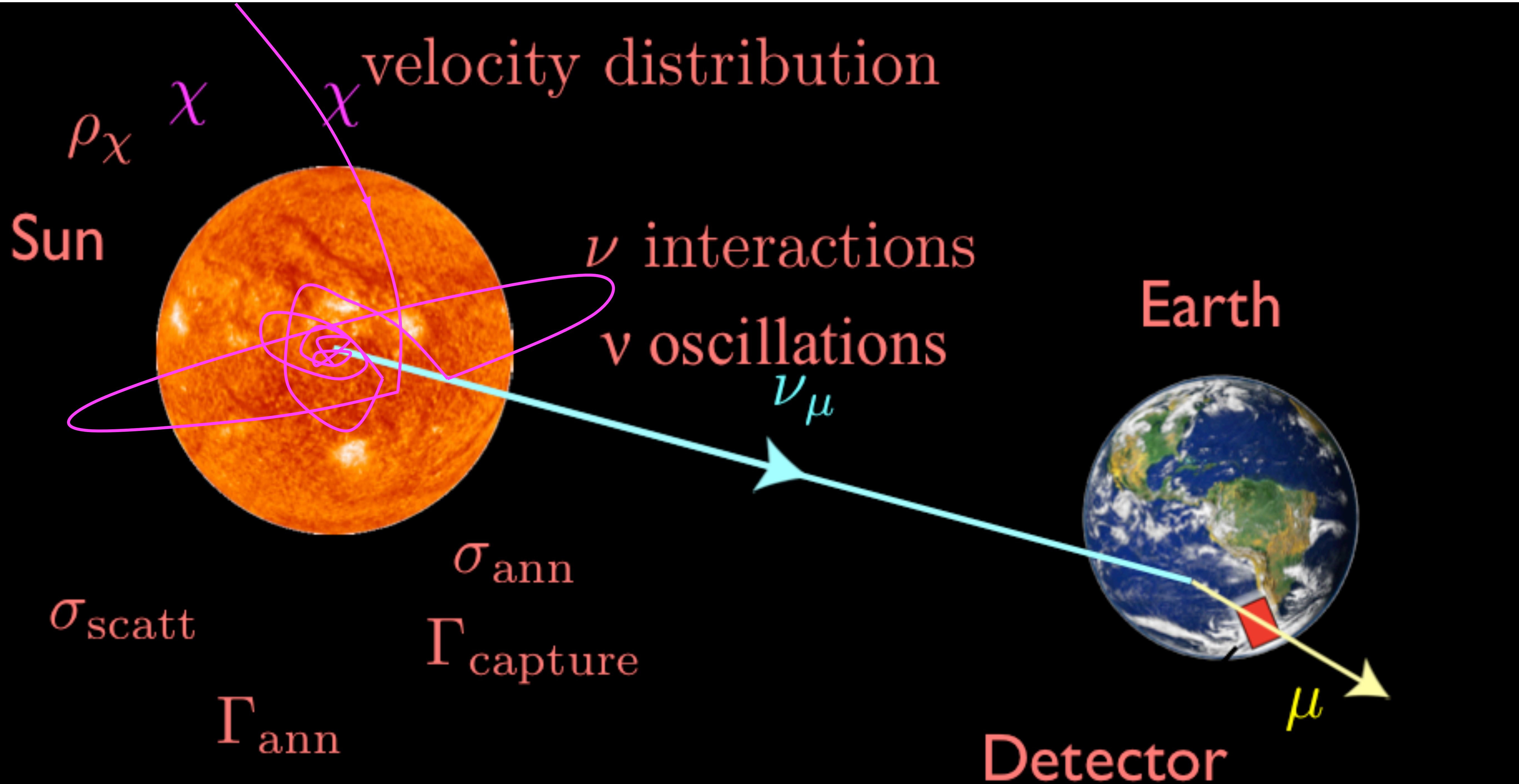


Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034



Dark Matter

Solar WIMP Signal



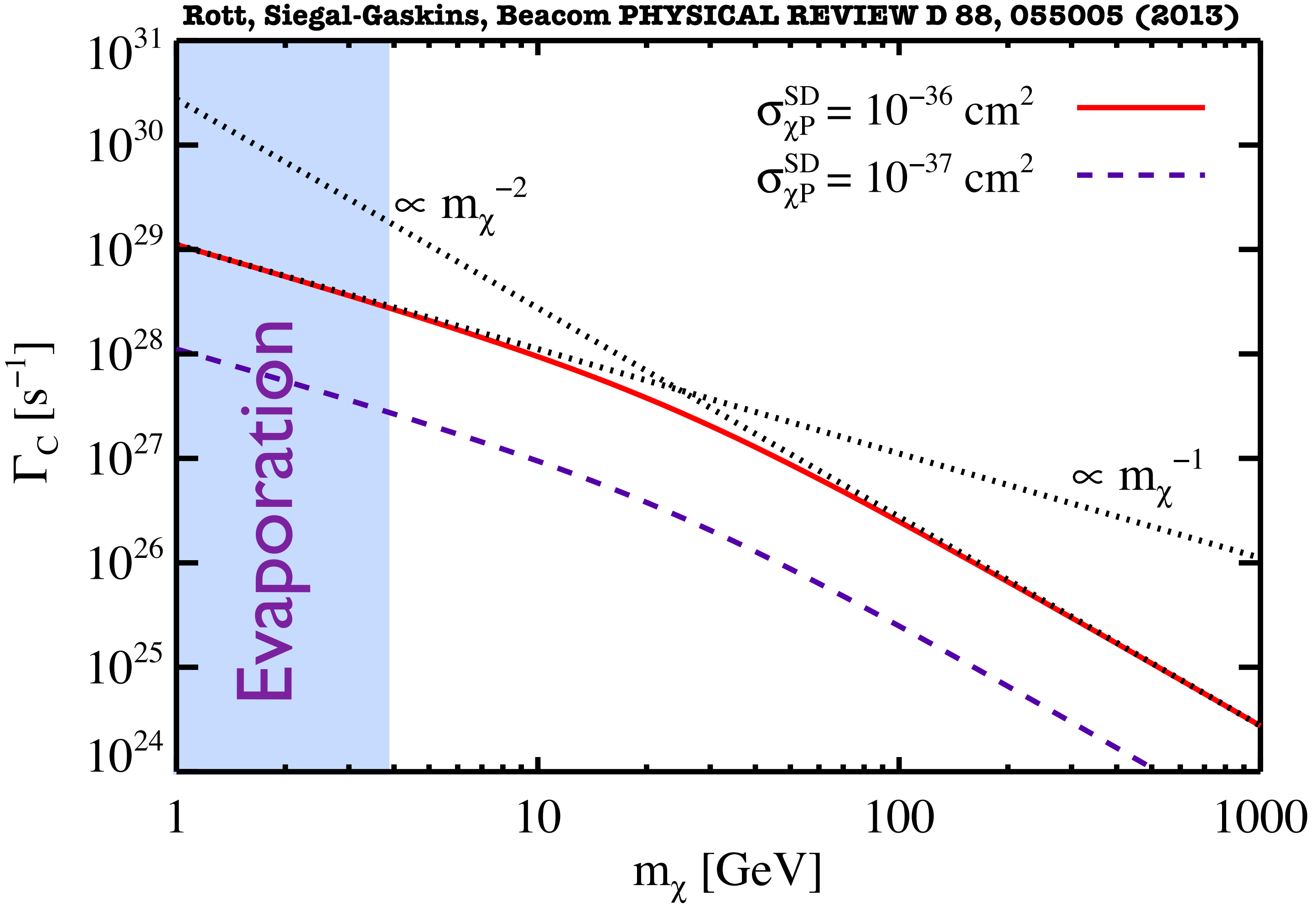
Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Solar WIMP Capture

- WIMPs can get gravitationally captured by the Sun
  - Capture rate, Γ_C ,depends on WIMP-nucleon scattering cross section
- Dark Matter accumulates and starts annihilating
  - → Only neutrinos can make it out
- Equilibrium: The capture rate regulates the annihilation rate ($\Gamma_A = \Gamma_C/2$)
  - The neutrino flux only depends on the WIMP-Nucleon scattering cross section

Rott, Siegal-Gaskins, Beacom PHYSICAL REVIEW D 88, 055005 (2013)



The capture rates scales as:

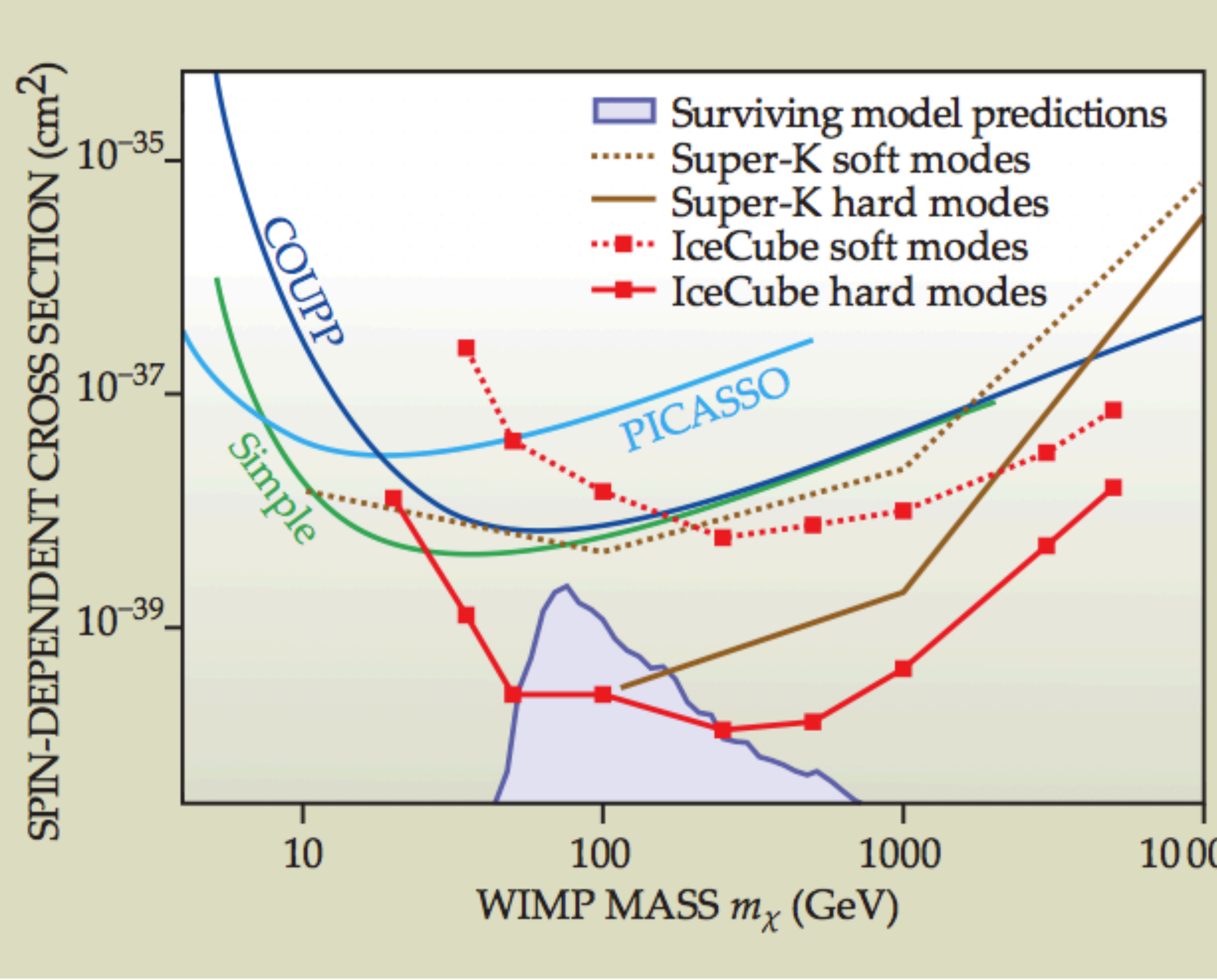
$\Gamma_C \sim \rho_\chi m_\chi^{-1} \sigma_A$ for $m_\chi \sim m_A$

$\Gamma_C \sim \rho_\chi m_\chi^{-2} \sigma_A$ for $m_\chi >> m_A$

number density + kinematic suppression

m_A - is the target mass

IceCube Result



Phys. Today 66(5), 14 (2013)

Neutrino bounds extremely competitive with Dark Matter direct detection

&

Can test models beyond the reach of LHC

Low Energy Neutrinos from the Sun

Low-Energy Neutrinos from the Sun

Possible annihilation channels:

qq,gg

don

the absorption of stopped negative pions. They are captured into atomic orbits and emit x rays until they reach a sufficiently small radius (because of their large rest mass) to interact with the nuclear medium. At this point they disappear as pions and their rest mass appears as various reaction fragments. Because the available energy is small, the dominance of the delta resonance in this process is no longer assured but, because of the internal momenta of the nucleons, neither can contributions from the delta be ruled out entirely.

Ch

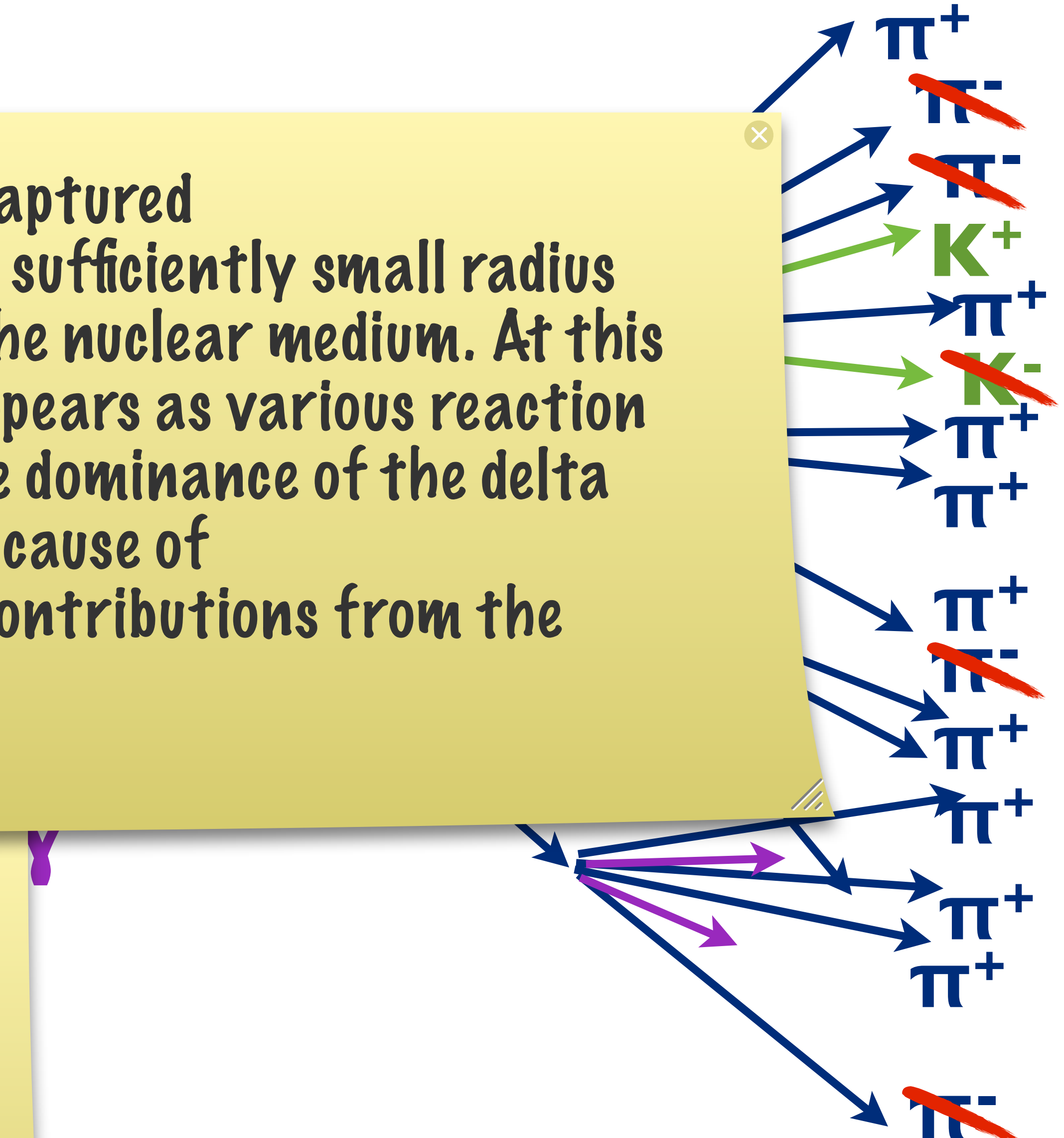
deca

mon

π^+

K^+

For high-energy charged pions, the hadronic interaction length in the Sun is short compared to the decay and continuous energy-loss lengths, so the number of pions increases in each generation of the hadronic shower until loss processes dominate at low energies energies.



ifetime too short to interact

teraction length short compared to losses

- Produces secondary particles in collision with protons
- Dominant energy loss term is π^0 production

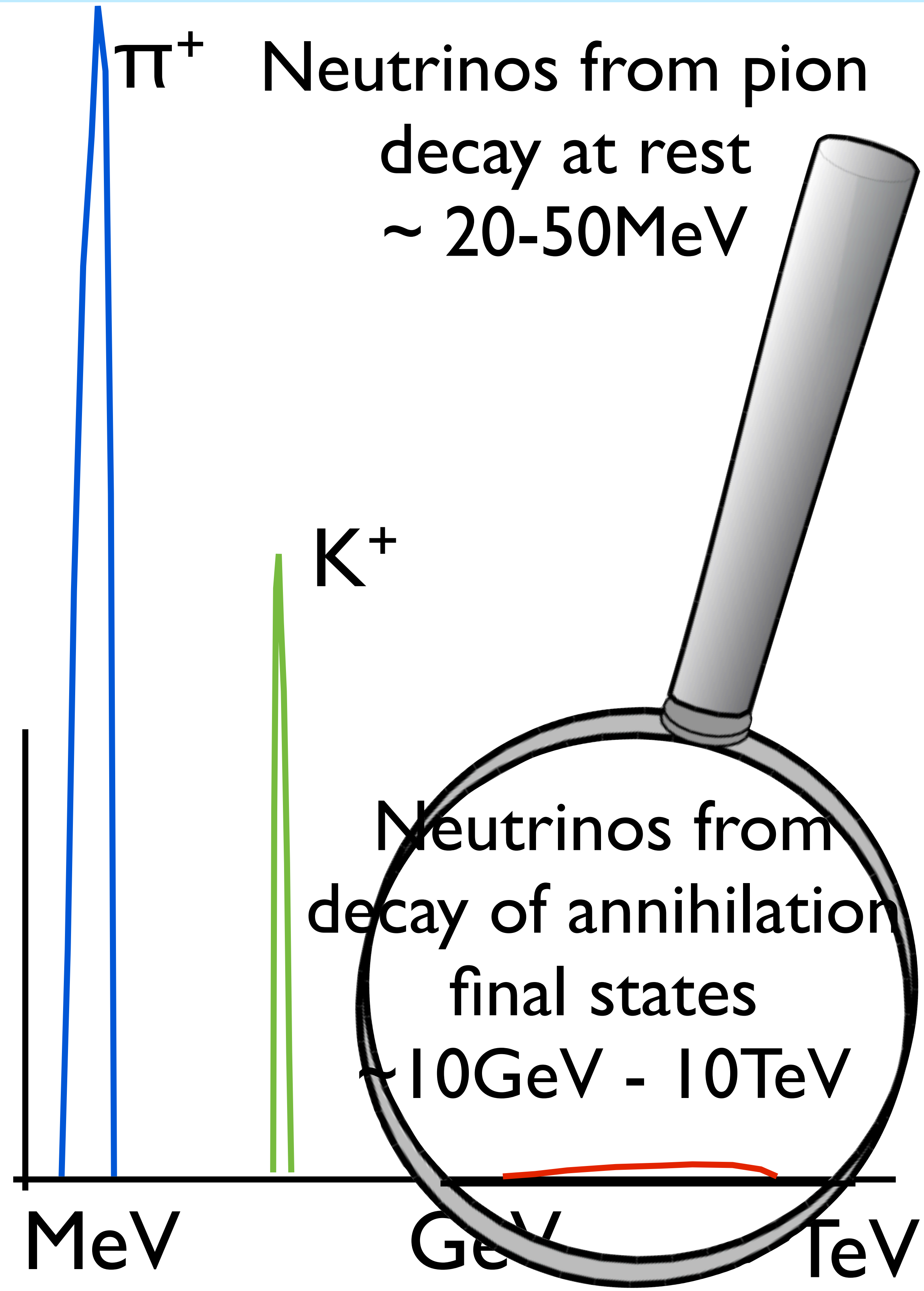
Neutrino signals - Example W-Boson

$W^+ \longrightarrow e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau$ ~33%

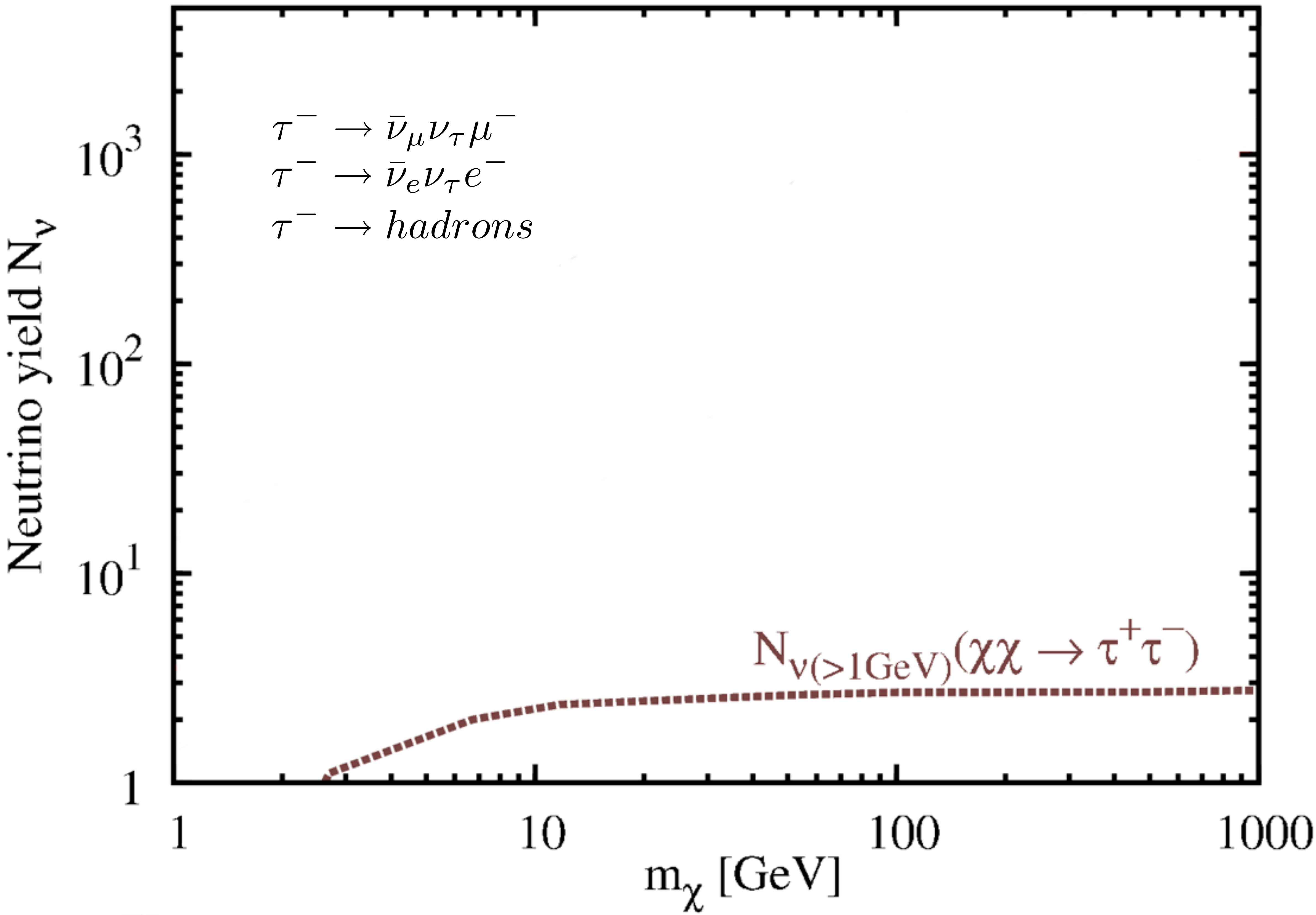
$\longrightarrow qq$ ~67%

Let's have a closer look at this:

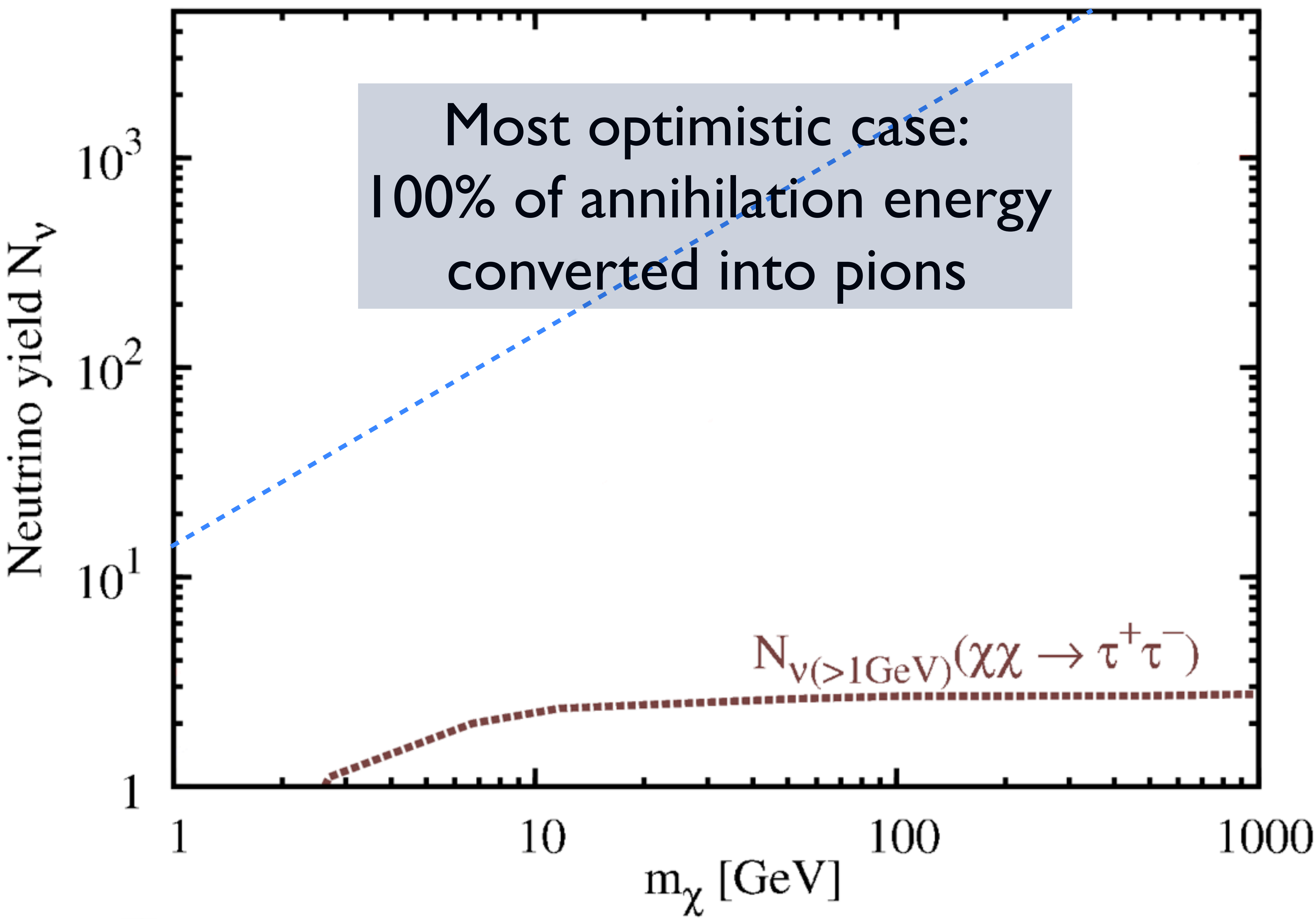
$e^+\nu_e$	1 high energy ν + em shower
$\mu^+\nu_\mu$	1 high energy ν + muon
$\tau^+\nu_\tau$	1 high energy ν + tau decay
qq	hadronic shower



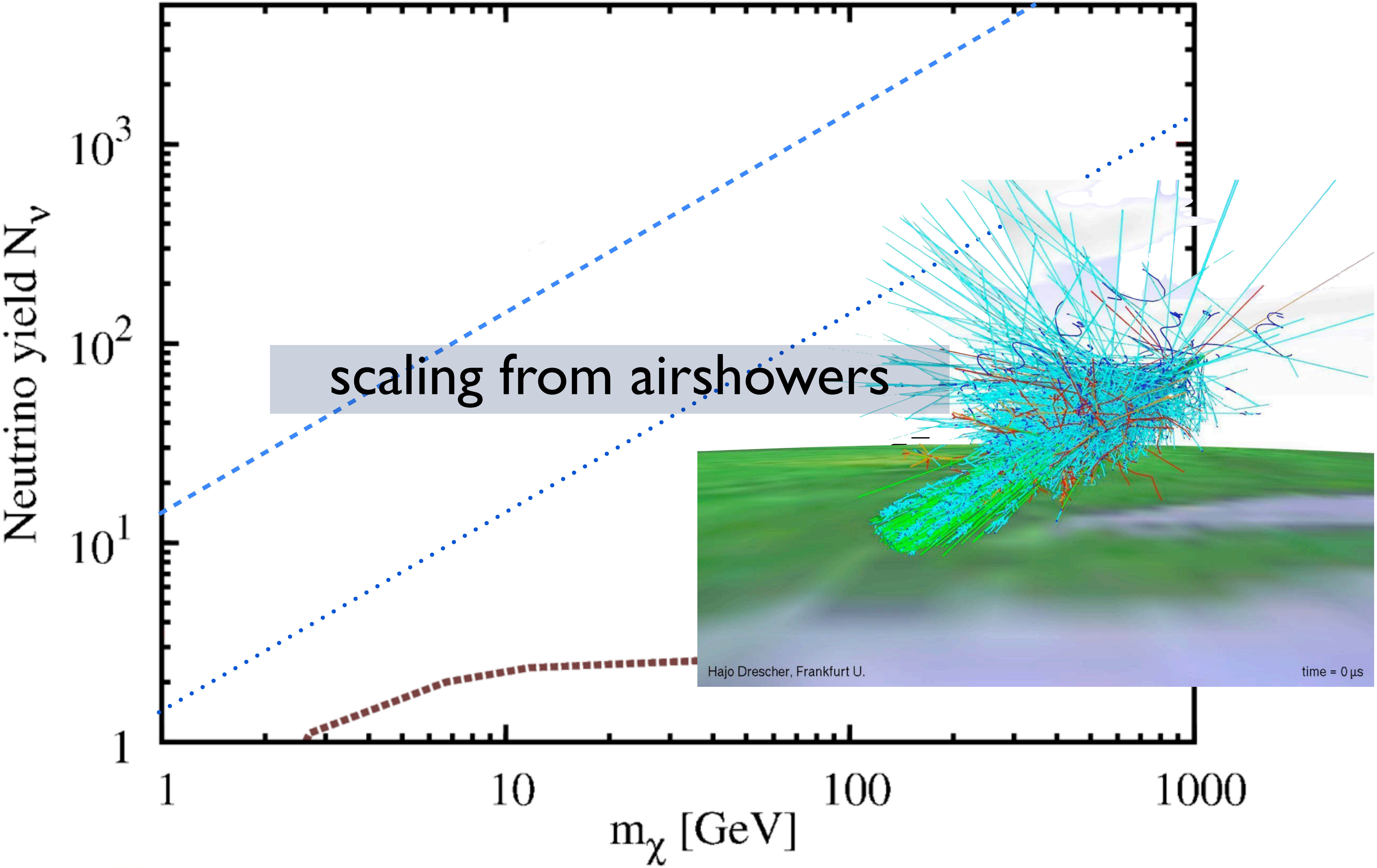
What is the Neutrino yield ?



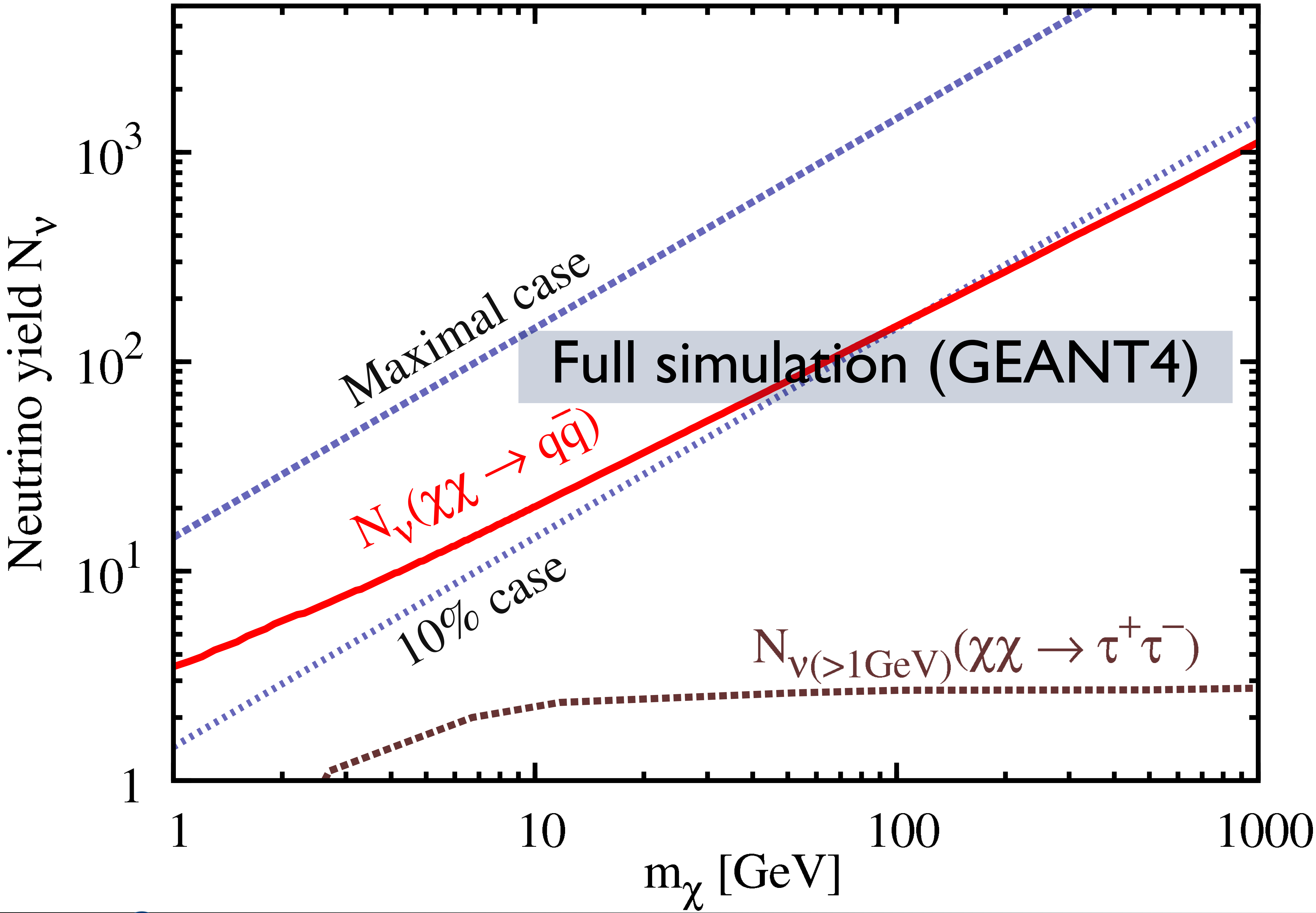
What's the Neutrino yield ?



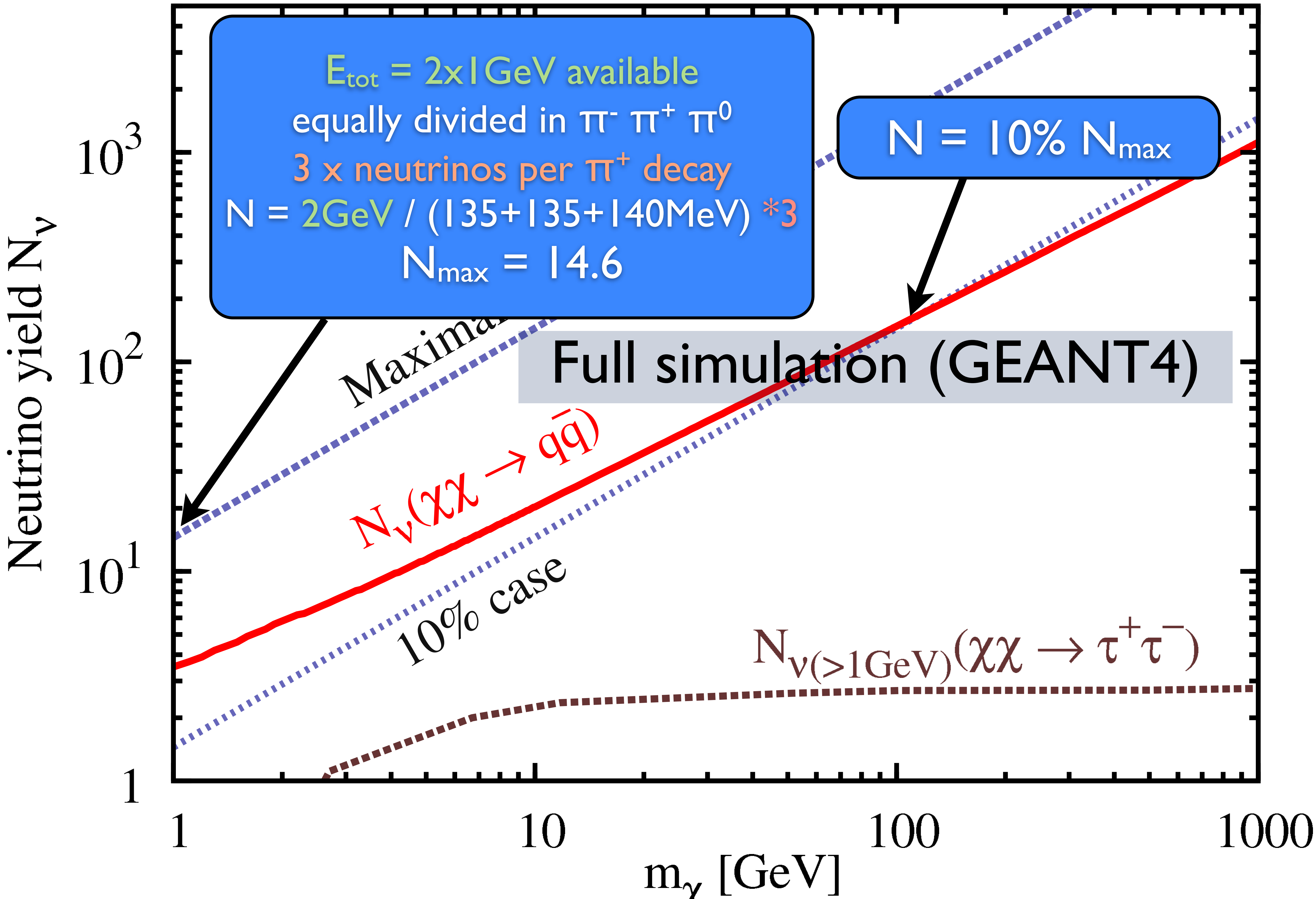
What's the Neutrino yield ?



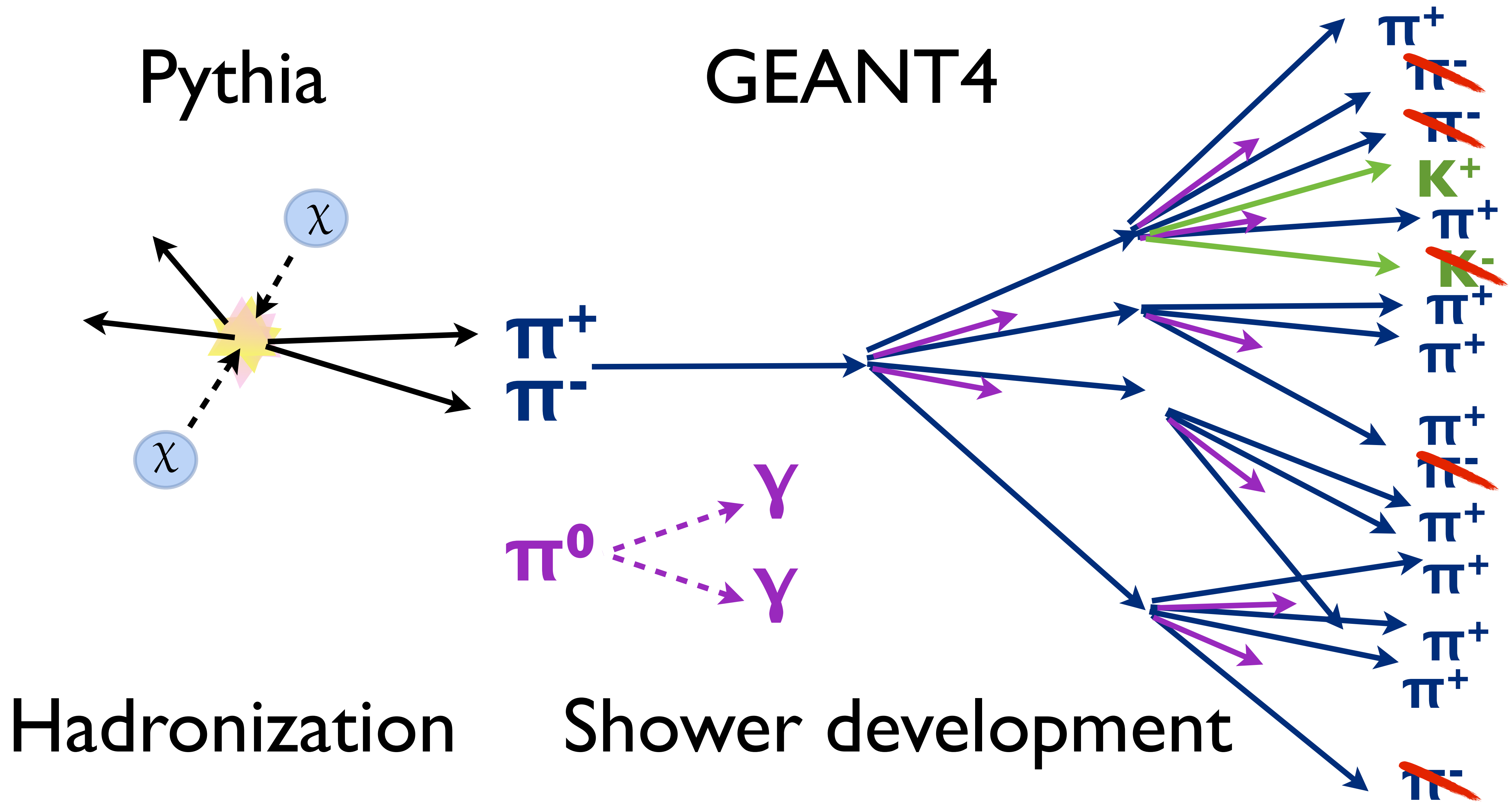
Neutrino yield



Neutrino yield



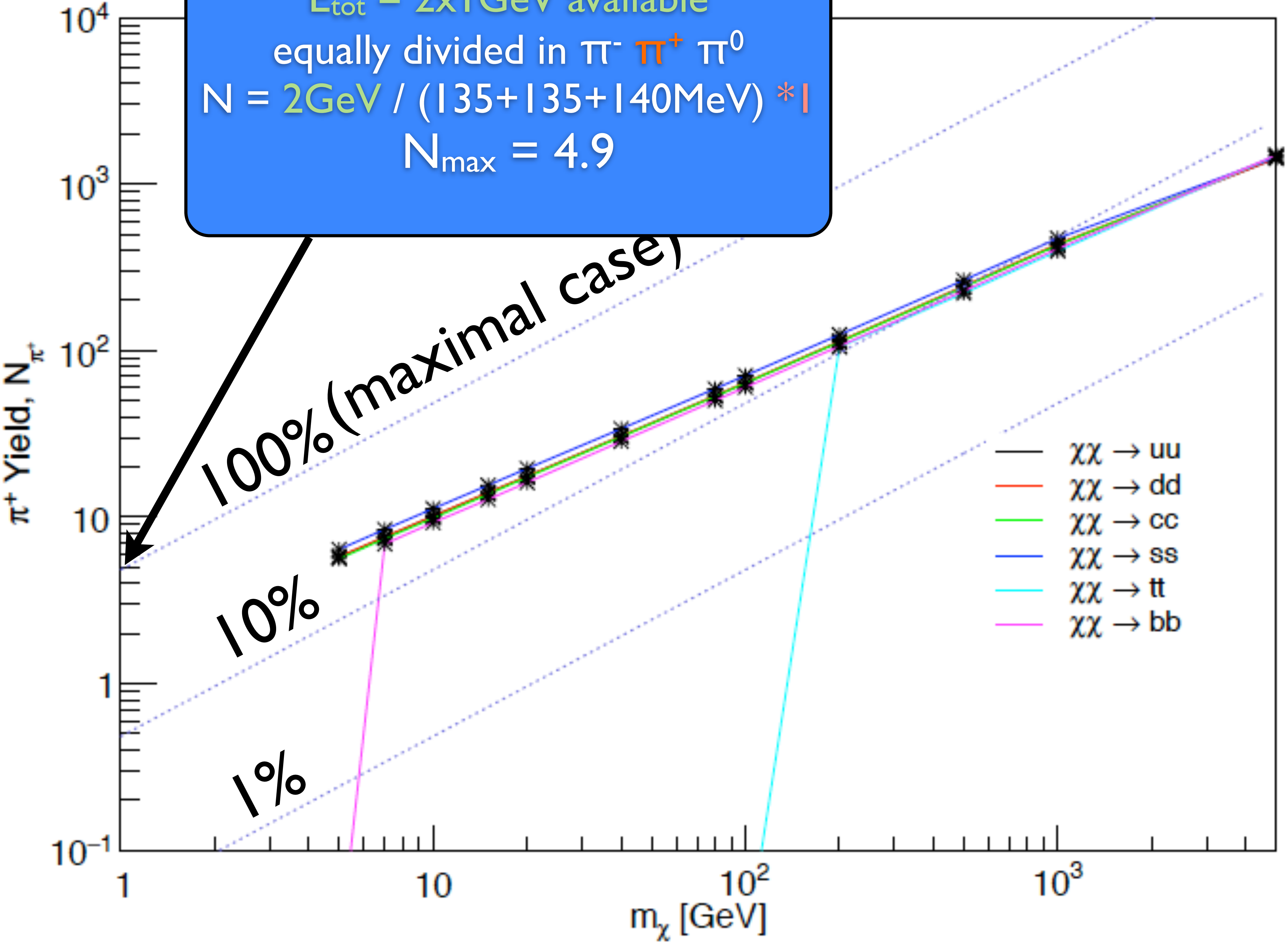
Pion and kaon yield



- Simulation to determine pion and kaon yields per channel
- Define r-value as the fraction of center-of-mass energy that goes into pions (π^+) or kaons(K^+) decaying at rest.

pi+ yield

E_{tot} = 2x1GeV available
equally divided in π^- π^+ π^0
N = 2GeV / (135+135+140MeV) *1
N_{max} = 4.9



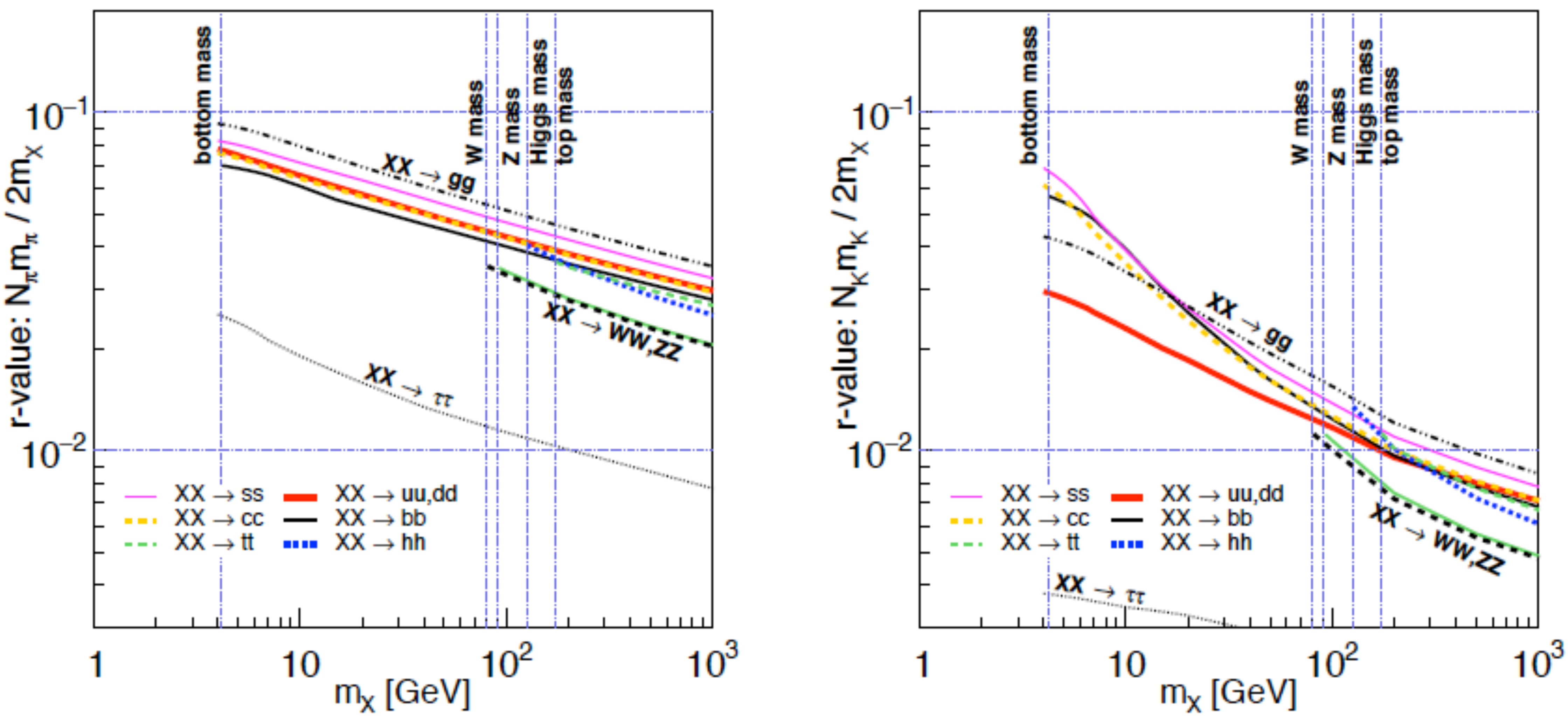
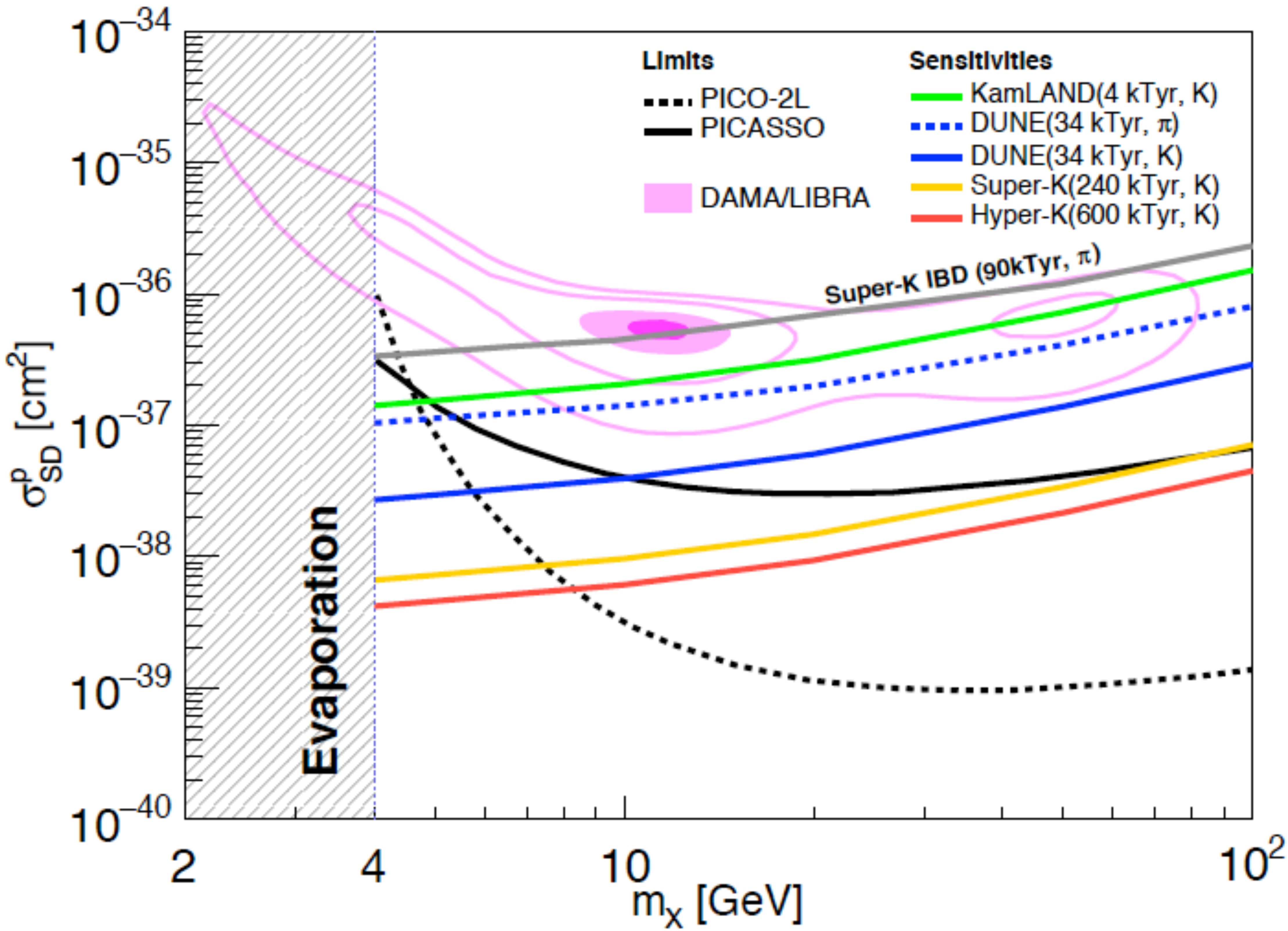
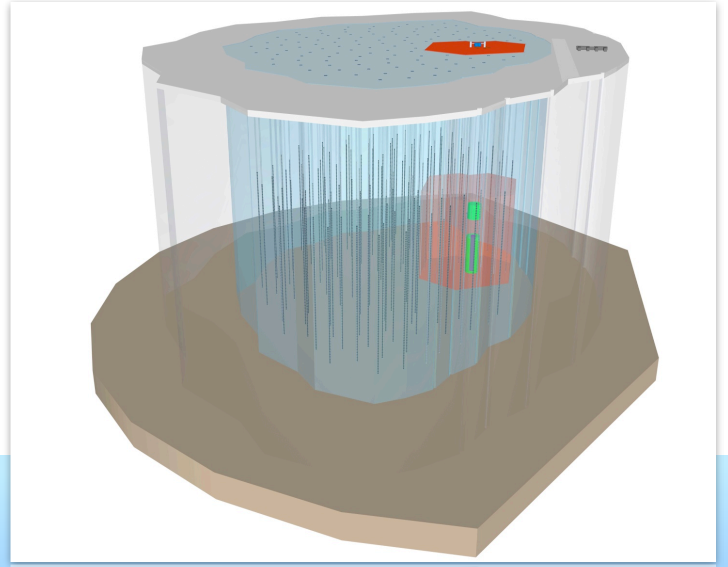


FIG. 1. Fraction of the energy produced in dark-matter annihilation which is converted to stopped π^+ (left) and K^+ (right), $r_{\pi,K}$. These fractions are then used to calculate the number of monoenergetic neutrinos produced in DM annihilation. These fractions were calculated by simulating DM annihilation to hadrons in PYTHIA, then simulating the showering of the hadrons as they propagate through the solar medium using GEANT, as discussed in the text.

Sensitivity

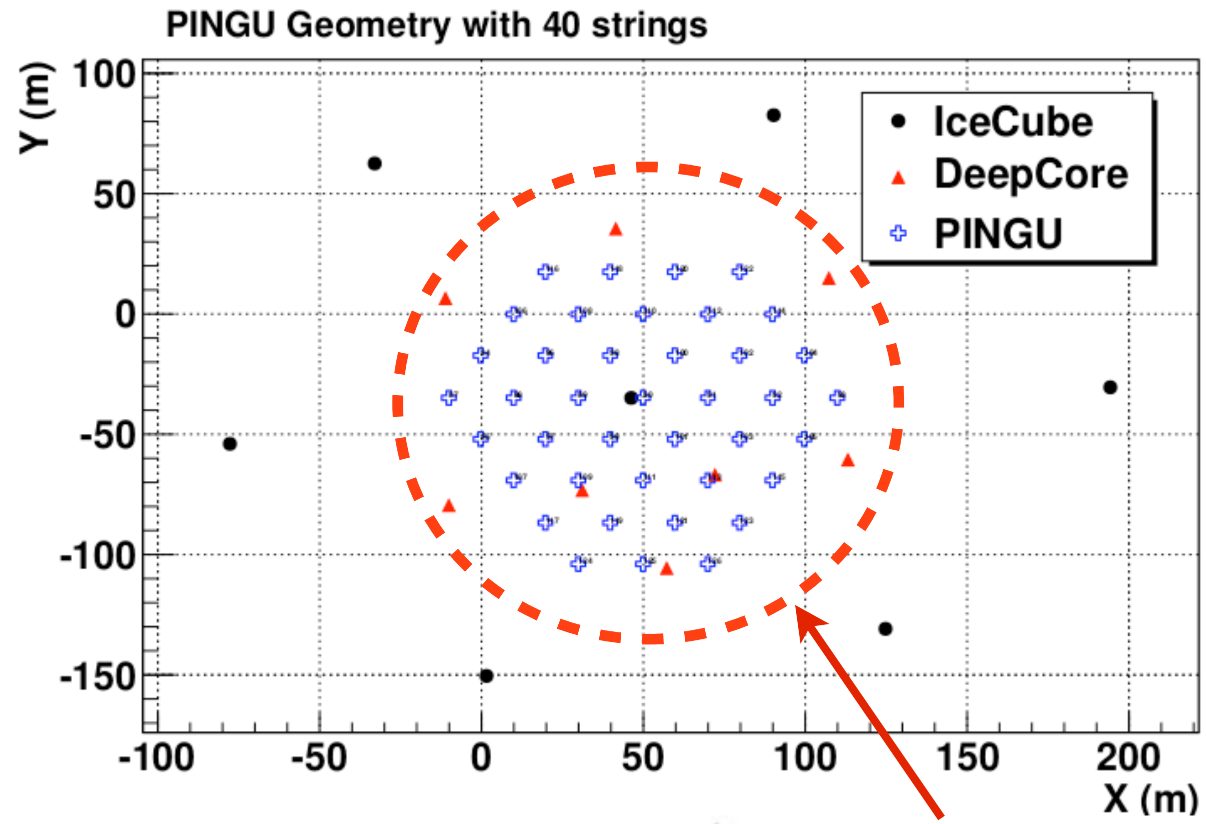




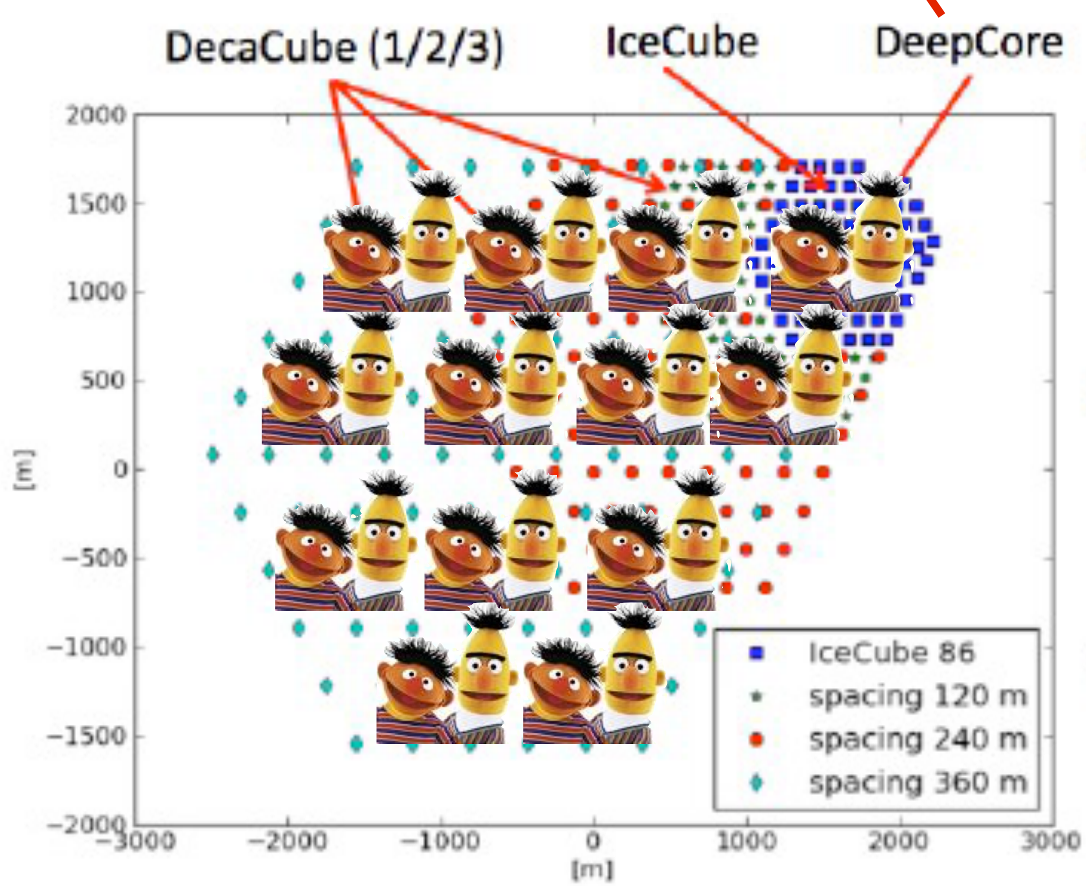
Future Plans

Future of IceCube

- Precision physics with ~GeV threshold



- Large volume: acquire high statistics astrophysical neutrino sample



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

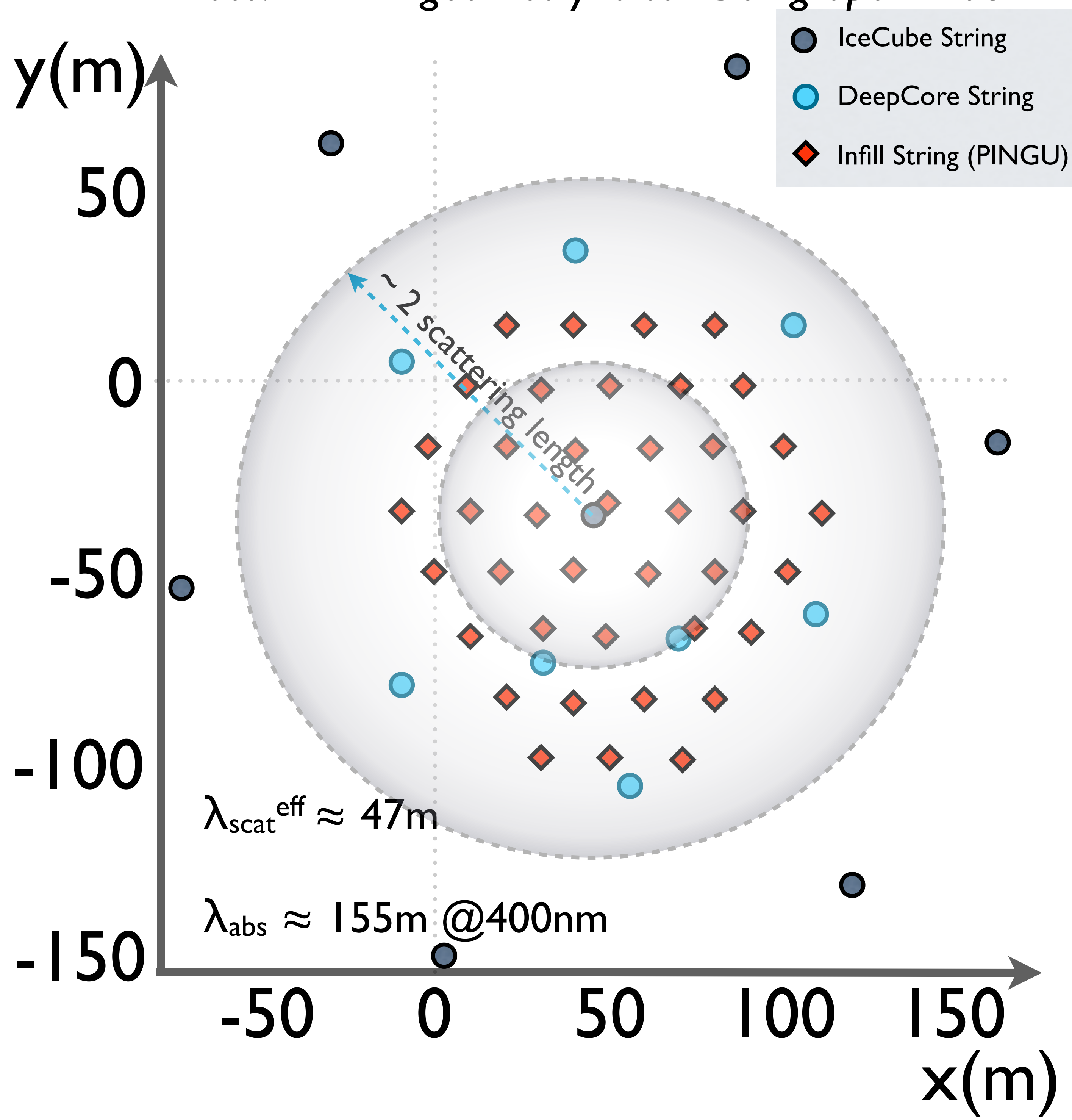
Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

PINGU - Precision IceCube Next Generation Upgrade

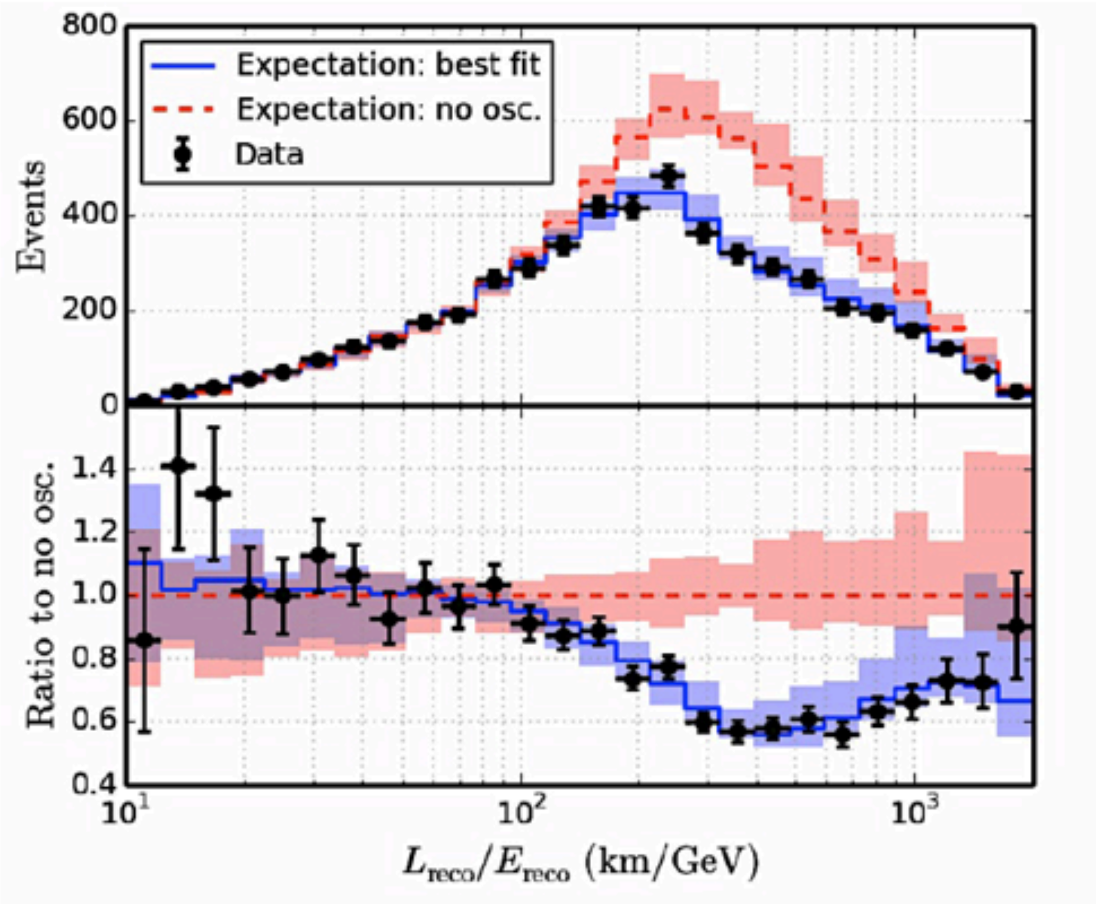
- PINGU upgrade plan
  - Instrument a volume of about 5MT with ~40 strings each containing 96 optical modules
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, ...)
  - Test low mass dark matter models

An example PINGU geometry (40 strings)

Note: PINGU geometry is still being optimized



IceCube Neutrino Oscillations



- select
  - starting events
  - clear μ tracks
  - rely on direct photons

- 5174 events observed cf. 6830 expected if no oscillation

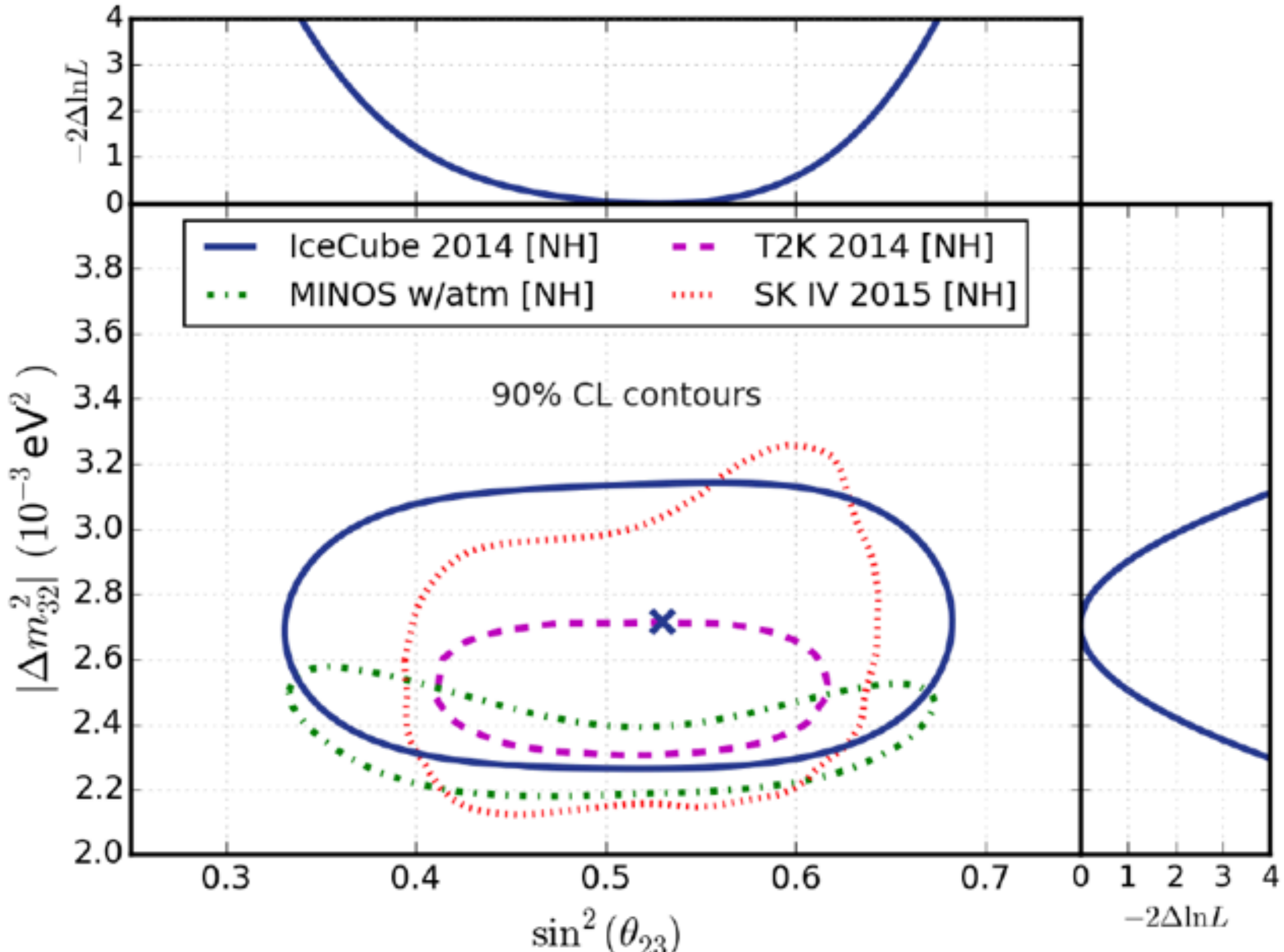
- perform 2D fit in *E* and *cos(θ)*

[IceCube, Phys.Rev.D91:072004 (2015)]

- competitive result (3 years)

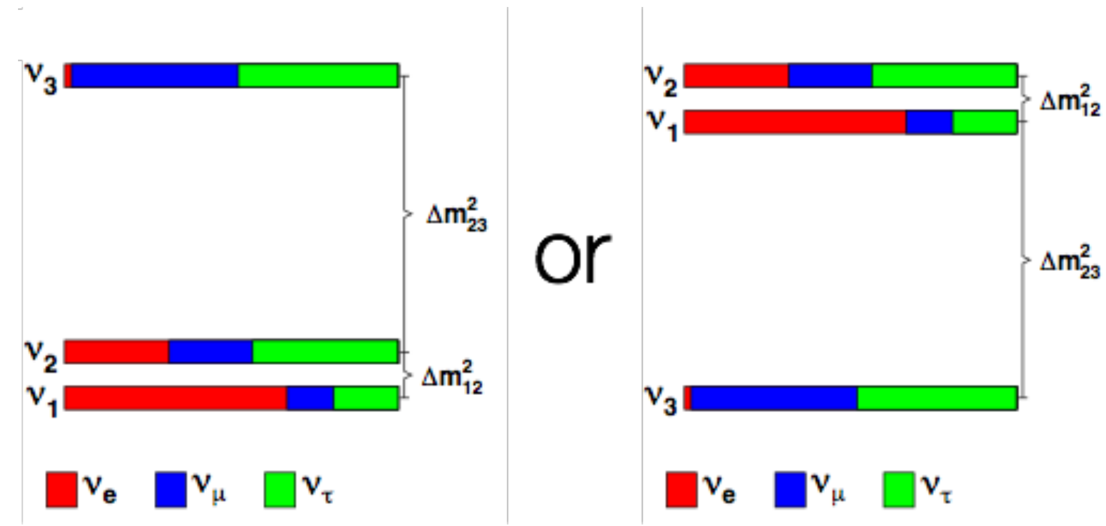
- will improve further

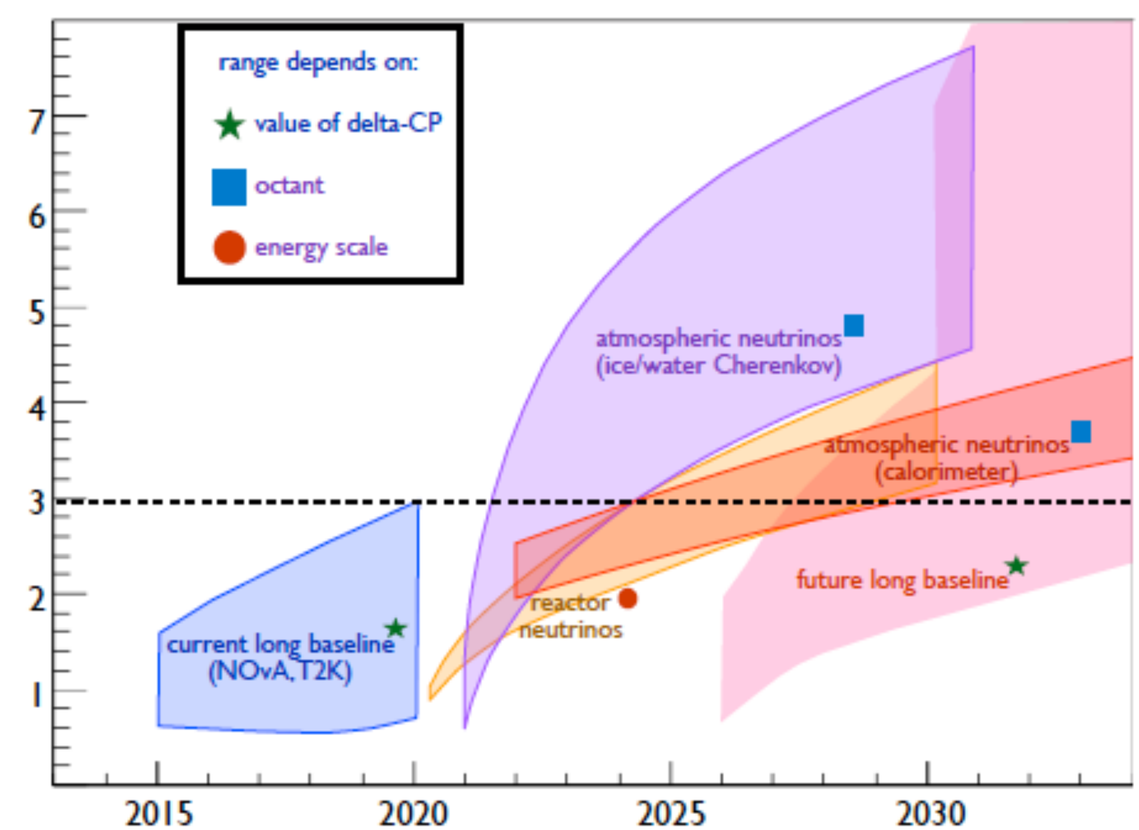
$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$



Advantages of PINGU

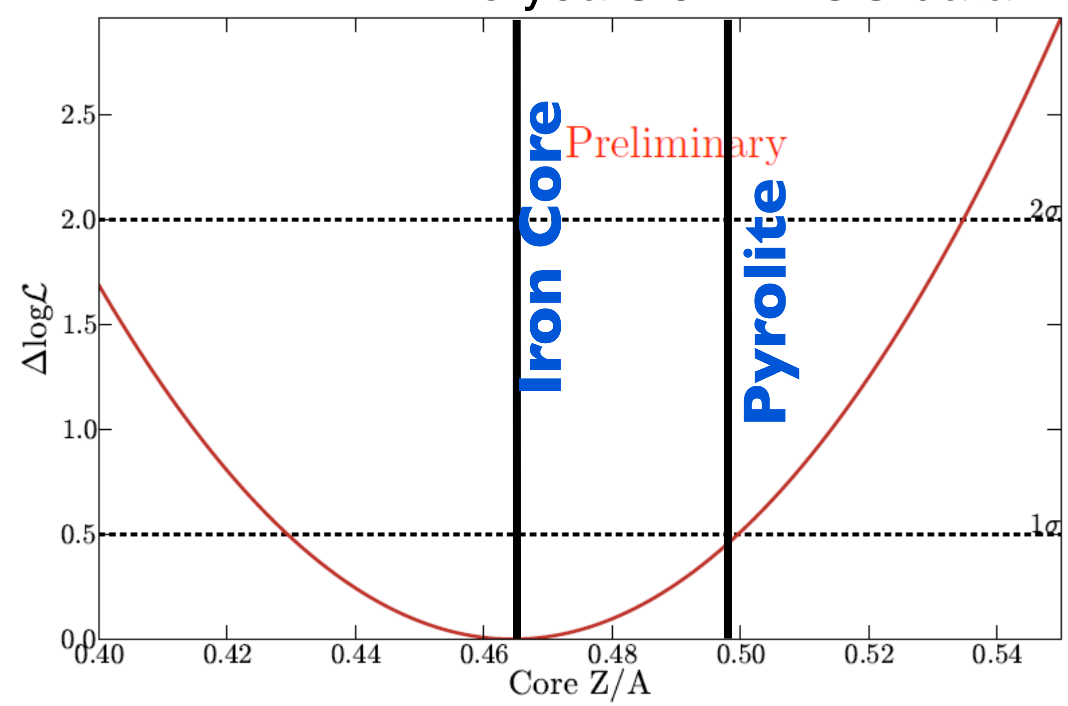
- Well-established detector and construction technology (low risk)
- Relatively low cost: ~$10M design/startup plus ~ $1.25M per string
- Rapid schedule
  - 3 seasons (first deployments in 2017/2018 ?)
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Multipurpose detector: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ice/ water Cherenkov detectors
- PINGU LOI released *arXiv:1401.2046*
  - update this Fall

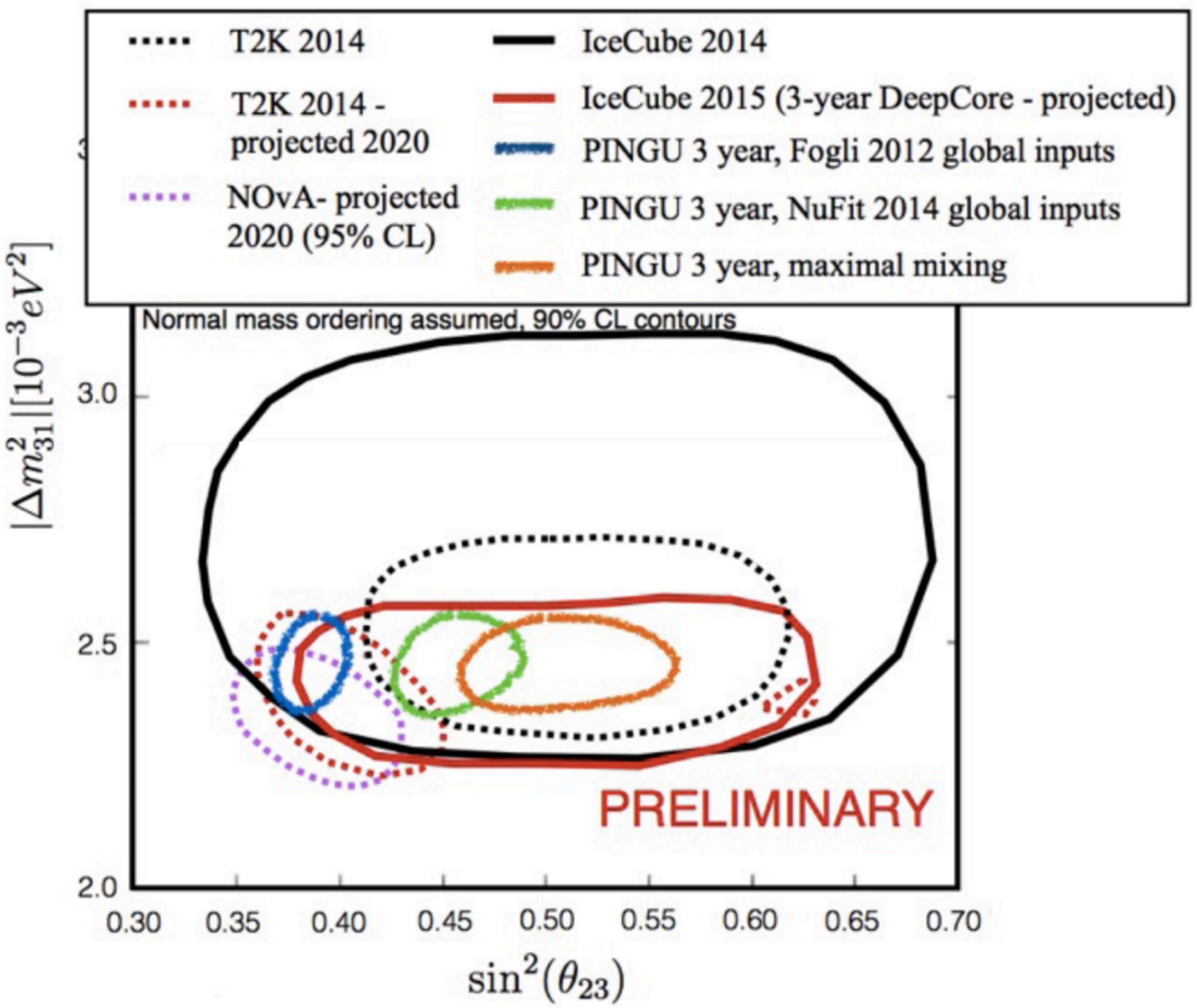




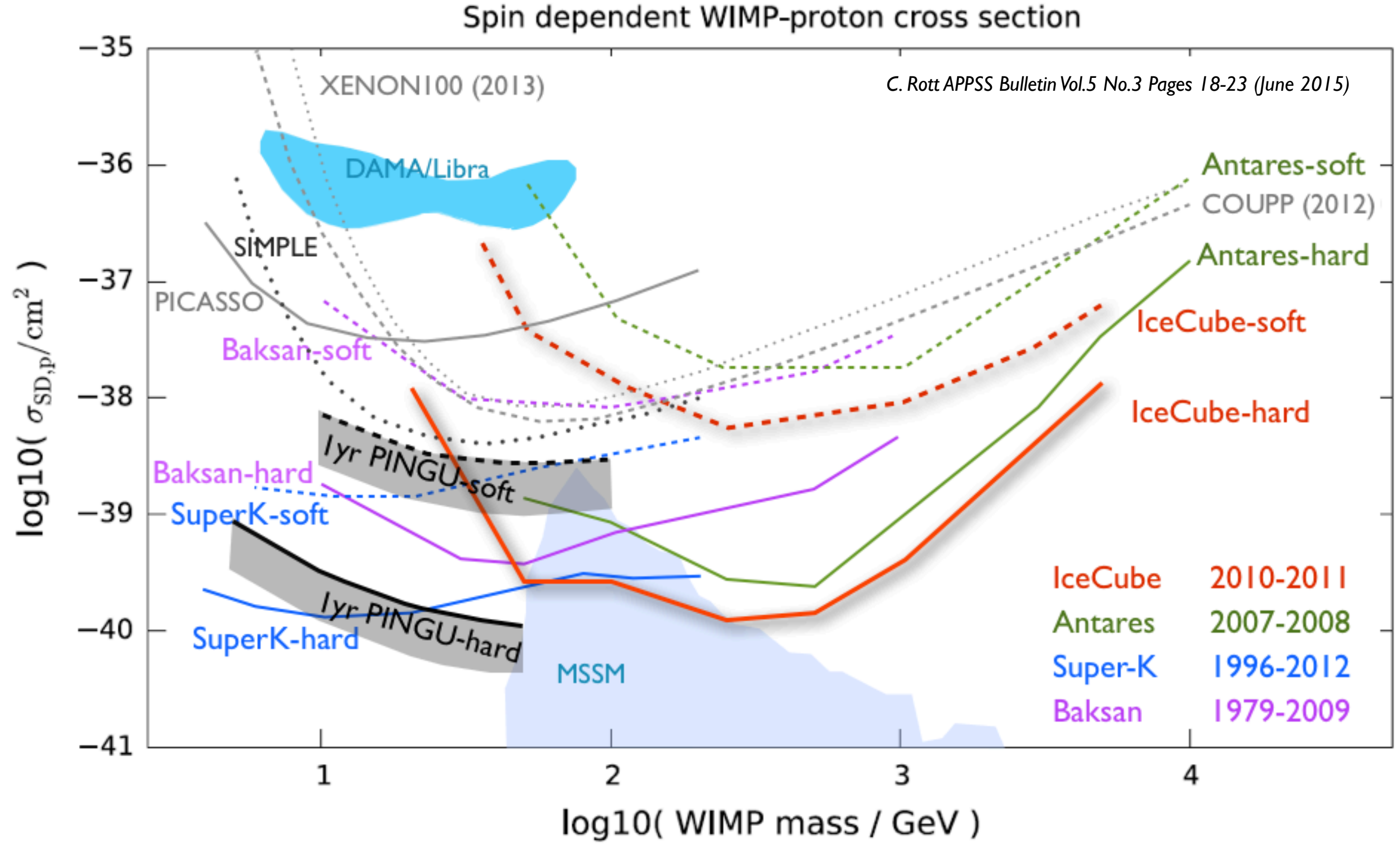
- <u>Multipurpose detector</u>: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...

5 years of PINGU data

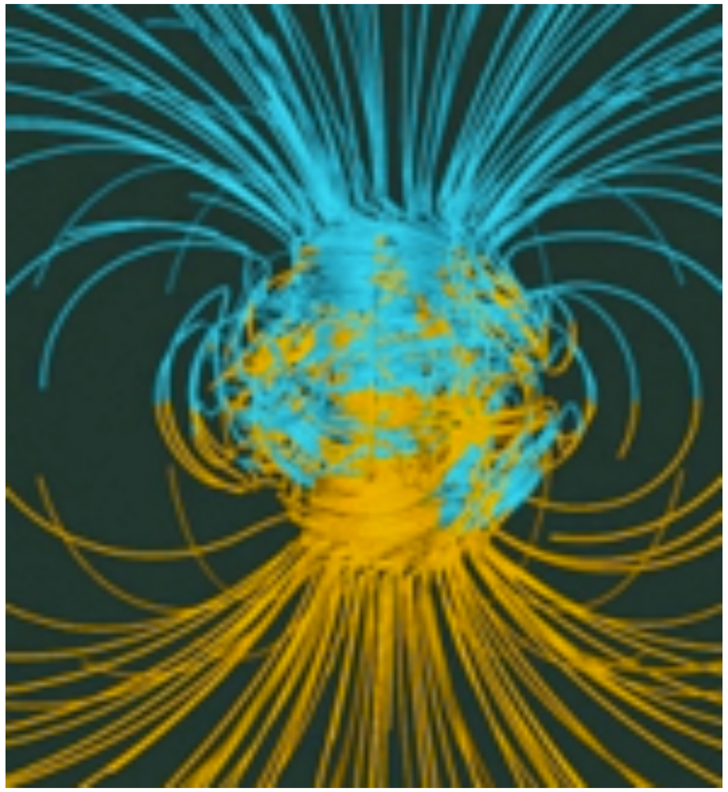


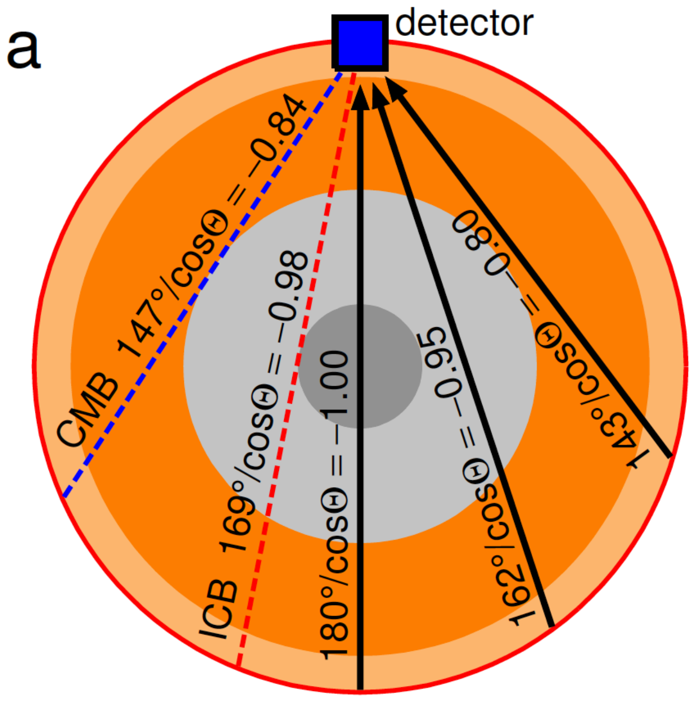


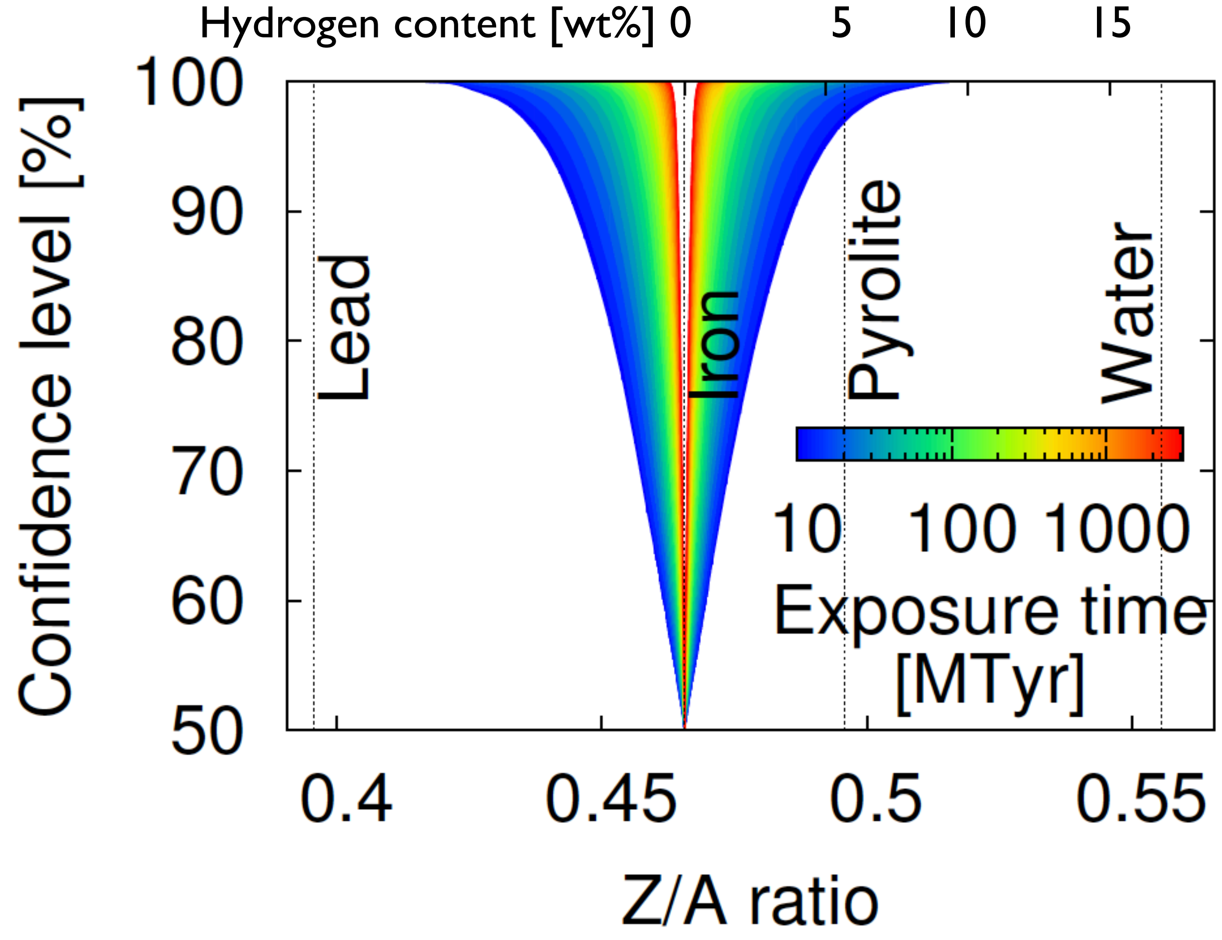
Spin dependent WIMP-proton cross section

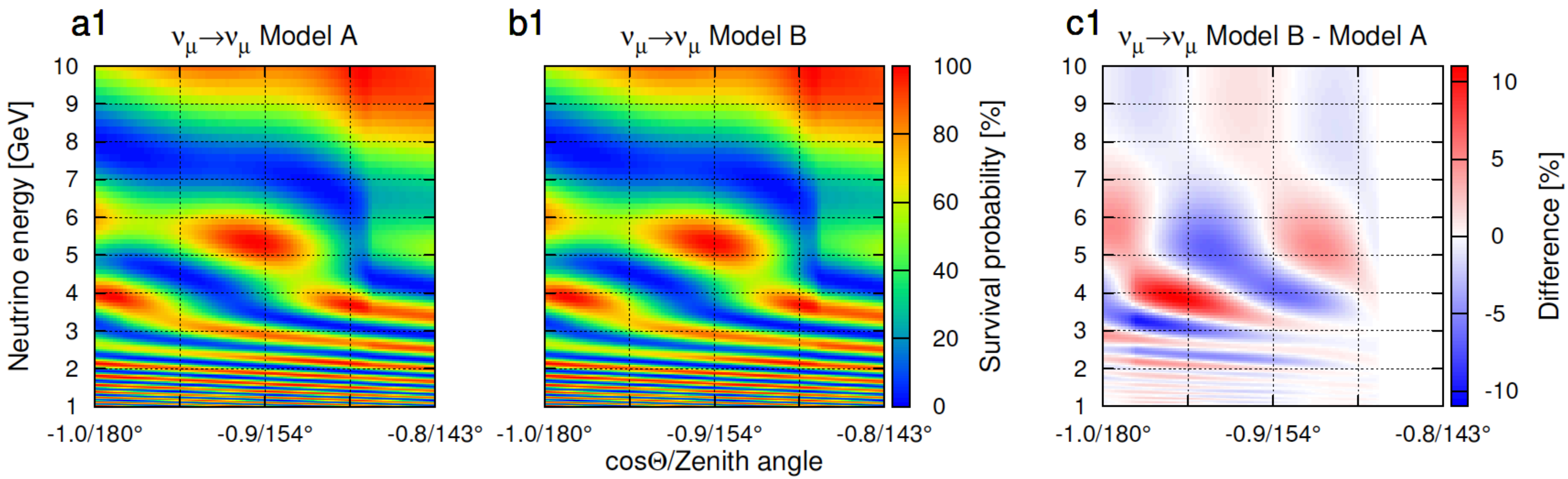


Neutrino Tomography



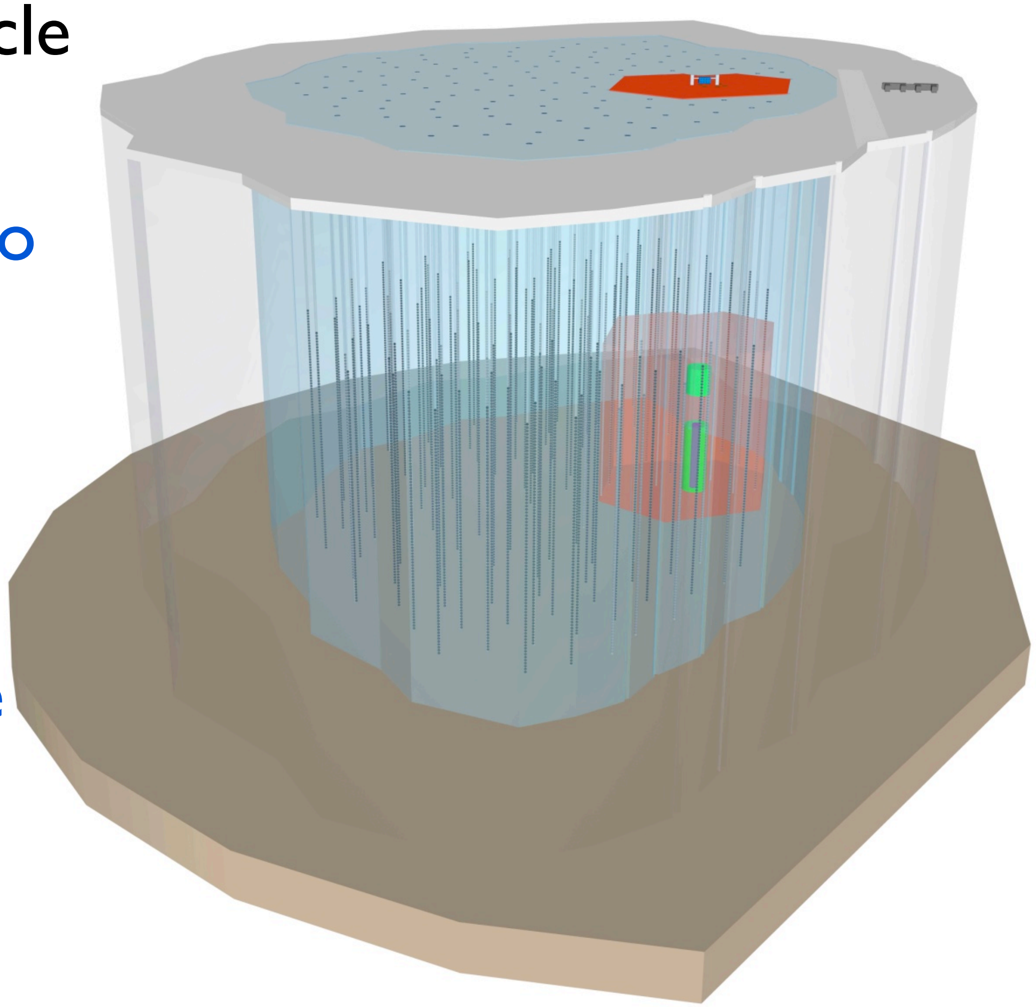






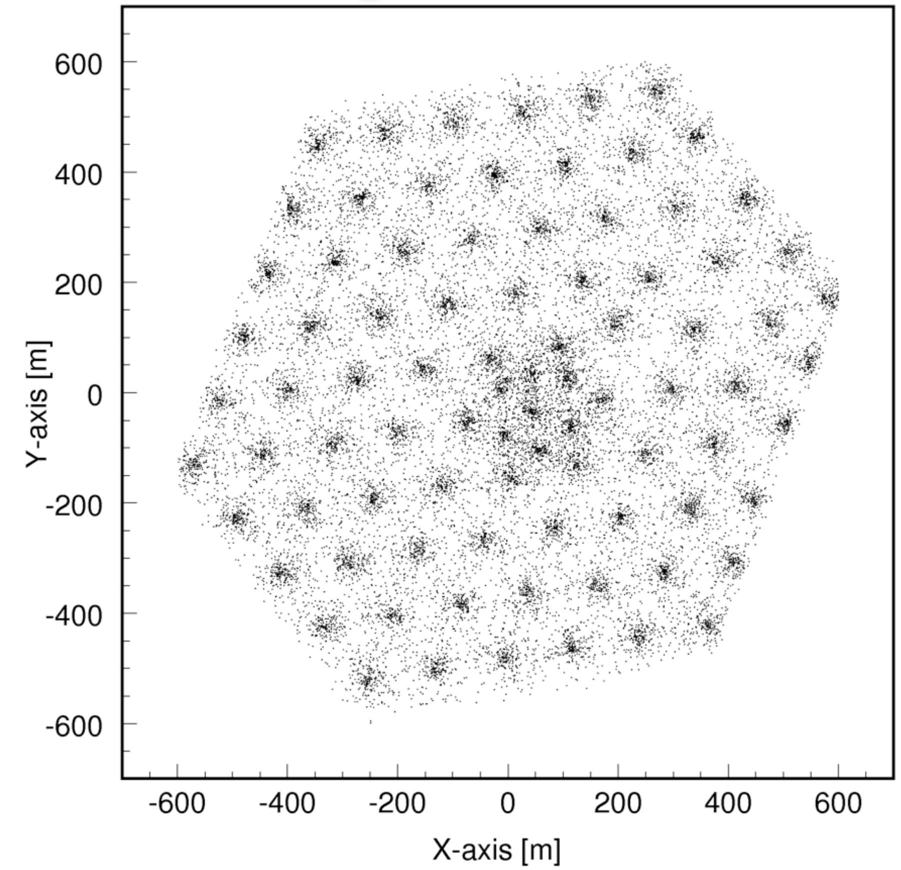
Conclusions

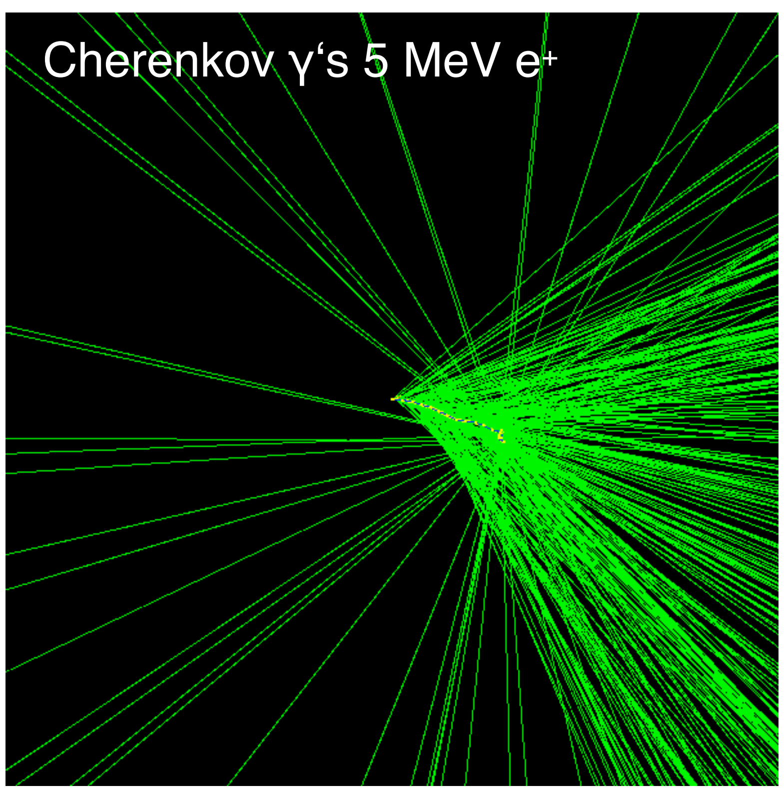
- IceCube has reigned in a new era in astro-particle physics
    - What's the origin of the high-energy neutrino excess ?
    - Let's find out !
- Great prospect for future upgrades
    - PINGU in-fill aims at creating a large volume detector with a threshold of few GeV
    - High-energy extension for PeV neutrinos
- Opportunity for unexpected discoveries !
    - Dark Matter
    - Galactic Supernova
        - Axions
        - Neutrino Oscillation Parameters

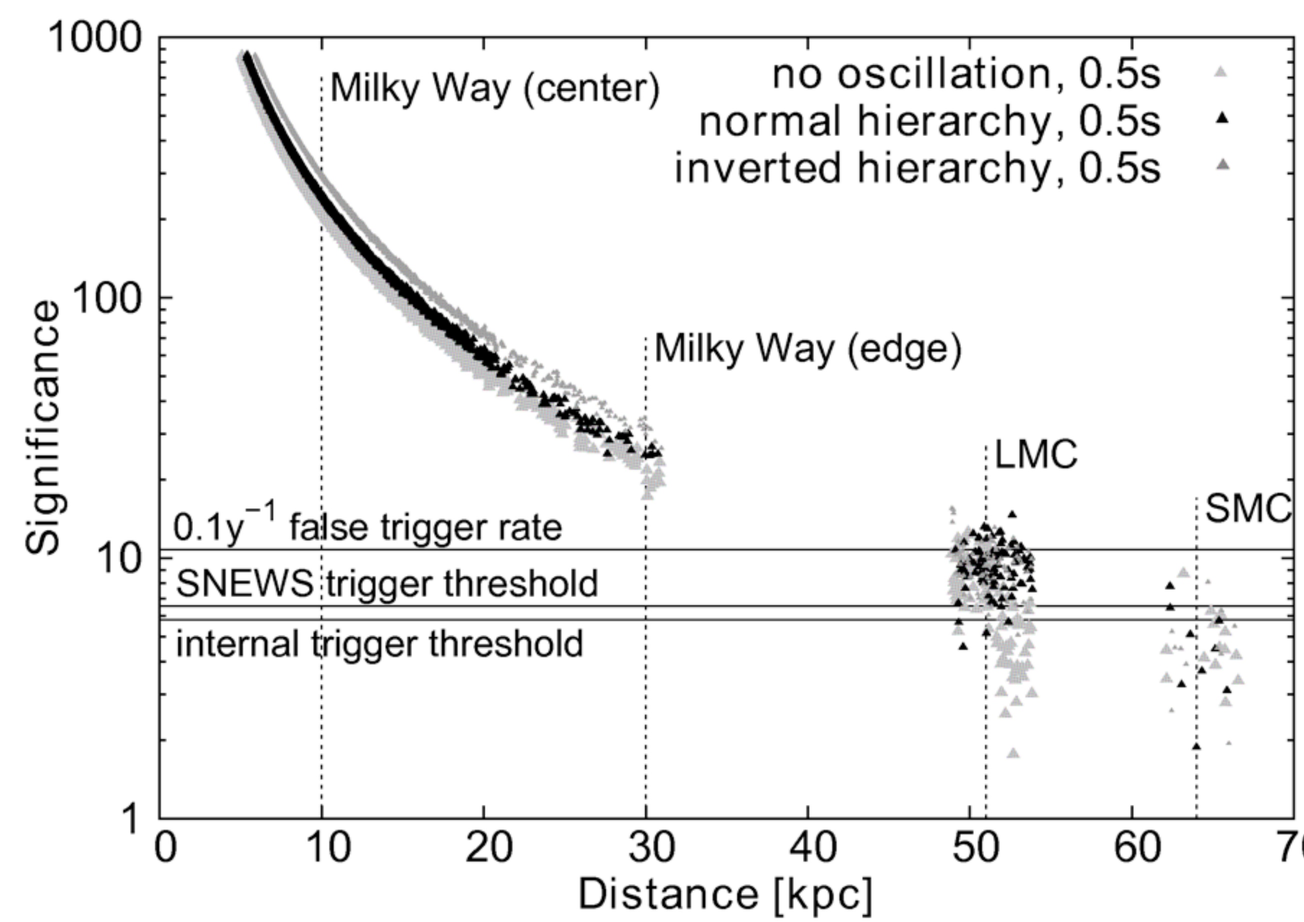



Thanks !

Galactic Supernova







IceCube graduate student Seongjin In awarded the Korean Global PhD Fellowship

By Sílvia Bravo, 30 Sep 2015 10:00 AM

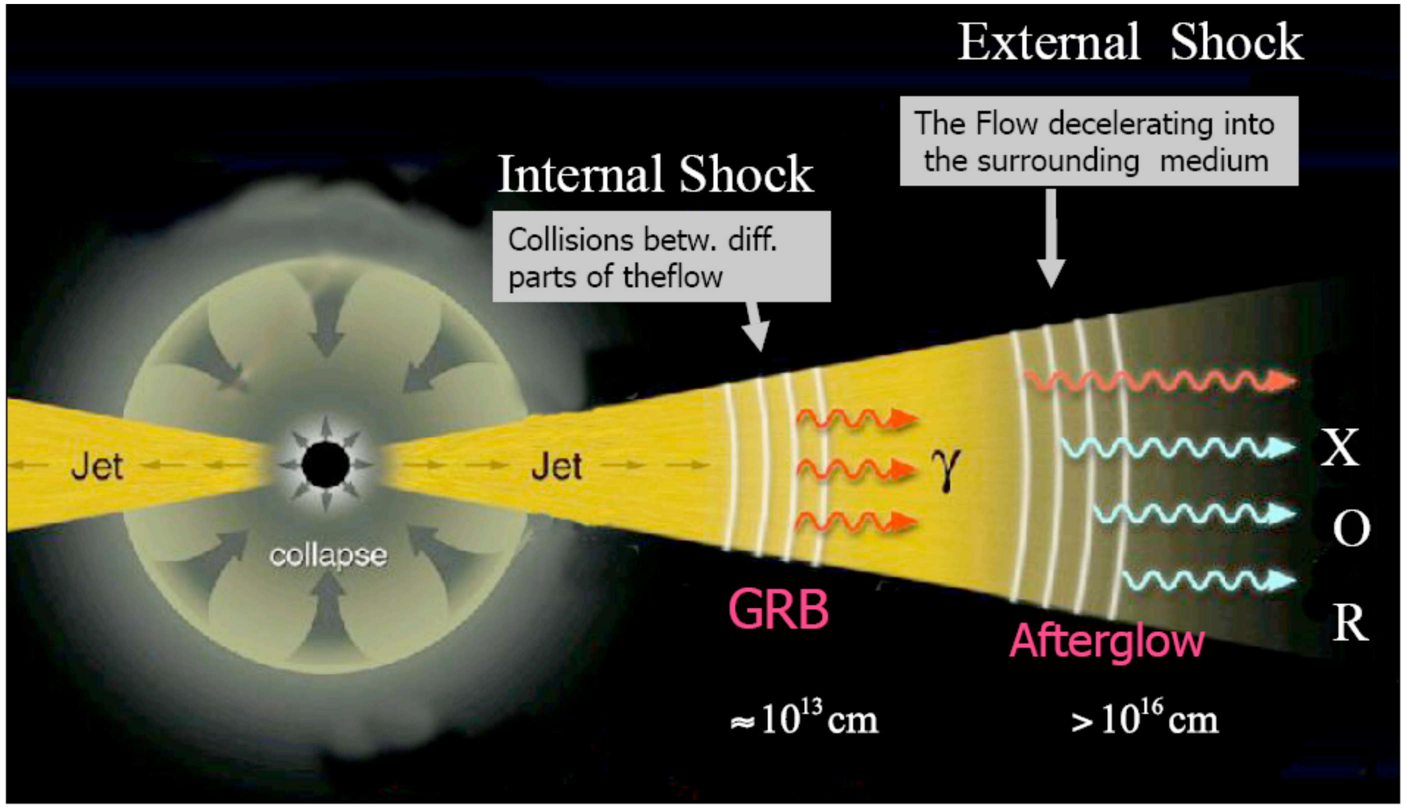
Like G+1

Seongjin In at the Pole. Image: Seongjin In, IceCube.

The National Research Foundation of Korea has awarded Seongjin In, a graduate student at Sungkyunkwan University (SKKU) and known as Jin within the IceCube community, with a 2015 Global PhD Fellowship (GPF). The selection committee selected his research proposal, highlighting his enthusiasm about exploring the universe from Antarctica. The fellowship was announced in July and will provide funds for his salary, travel, and research expenses until completion of his PhD.

GPF is the biggest and most competitive fellowship for graduate students in Korea. "It's really an honor to be one of the awardees, especially since only two proposals were accepted in experimental astrophysics," explains Jin. "But it was not only my achievement. Prof. Rott and Dr. Bose at SKKU, together with the IceCube team, provided guidance and support for my application."

Transient Search GRBs

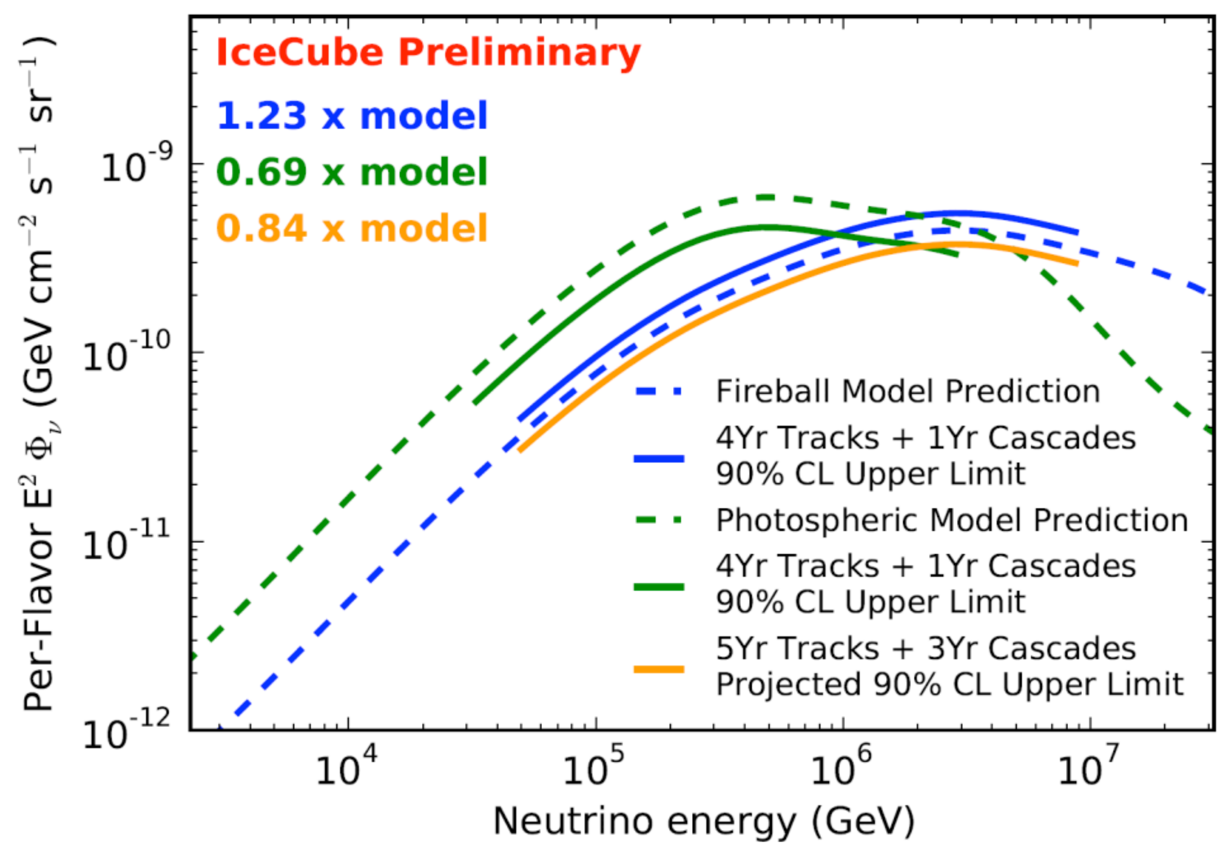


IC40 data **2008-2009** (117 GRBs in northern sky) and **IC59** data **2009-2010** (98 GRBs in the northern and 85 from southern sky) analyzed. **No coincidence found**

IceCube Collaboration - Nature Vol **484**, 351 (2012)

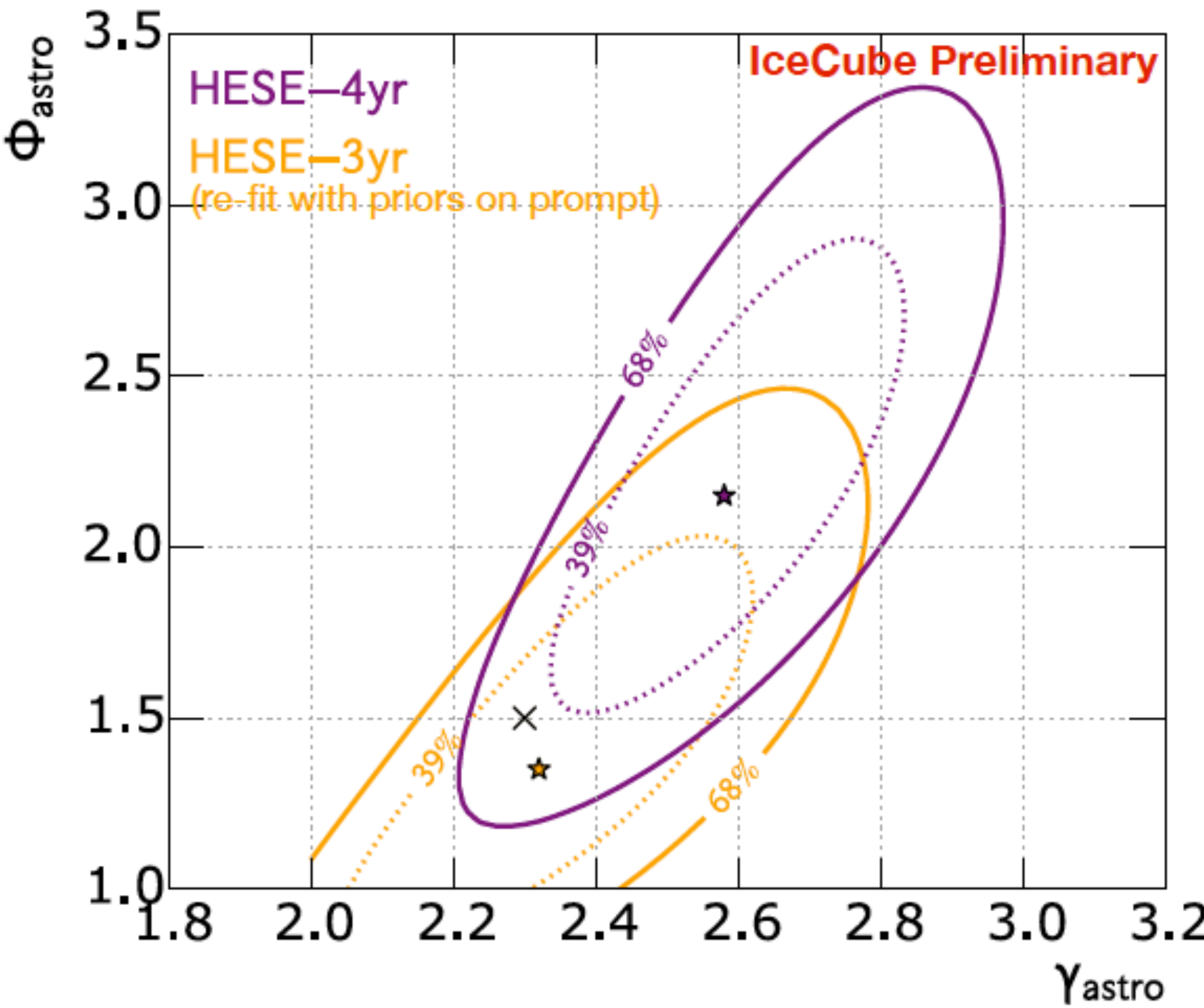
Burst data from Fermi-BAT and Swift provide precise time stamp and location

- upgoing ν_μ track search – 506 bursts in 4yrs
- all-flavor cascade search – 257 bursts in 1yr



Difficult to attribute diffuse neutrino flux with GRB bounds

Spectral index and flux



Contour plot in spectral index vs. normalization at 100TeV

HESE-4yrs best fit flux:
$E^2\Phi$ = ~2.2 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

Spectral index has steepened
(no new PeV events but relatively large number in TeV)