IceCube - A new Window to the Universe

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중앙대학교

CHUNG-ANG UNIVERSITY

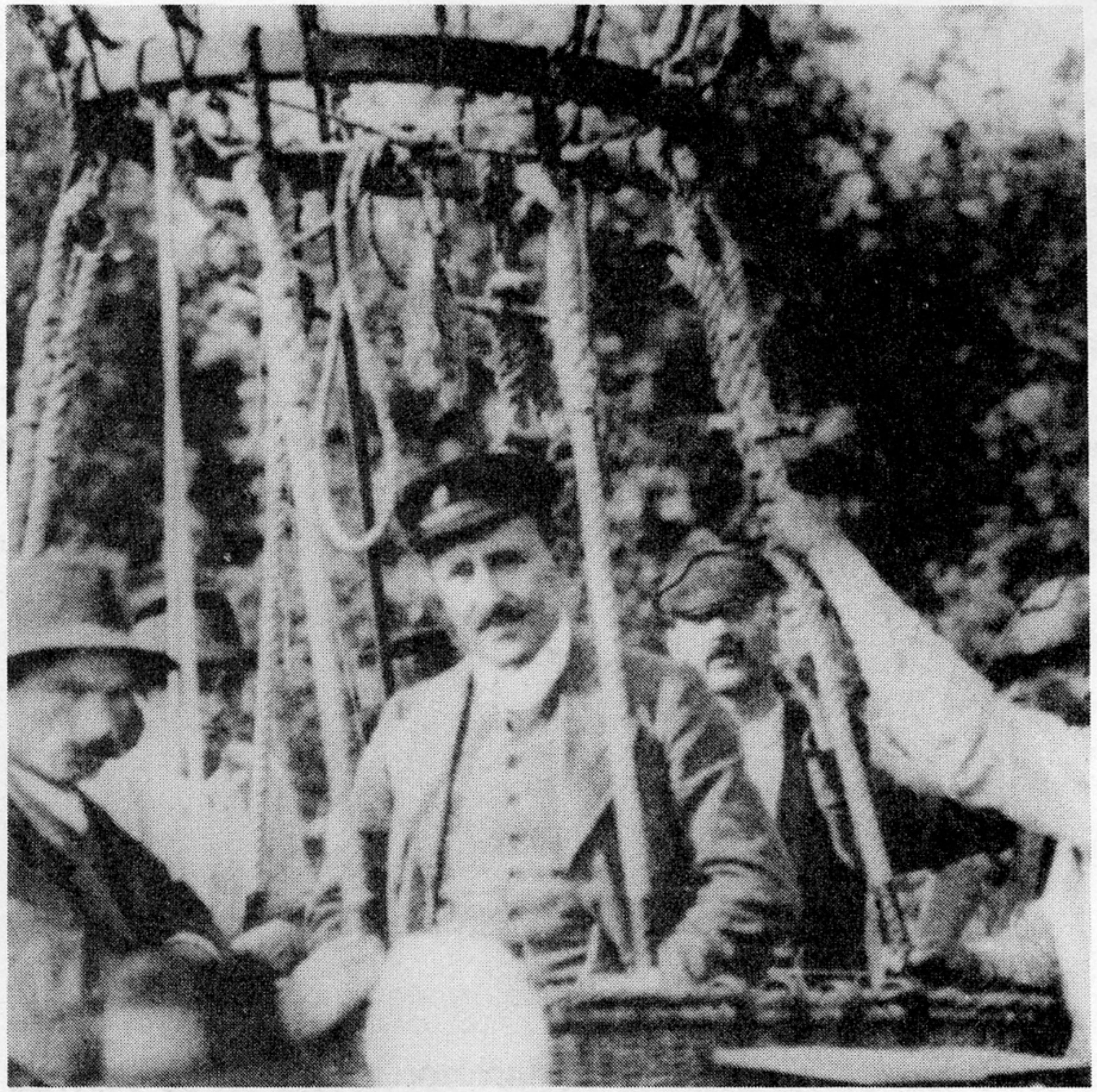
Physics Colloquium

Outline

- Motivation
- Neutrino Telescopes and IceCube
- Search for Dark Matter
- Search for Astrophysical Neutrinos
- Outlook and Conclusions

The Cosmic Ray Mystery

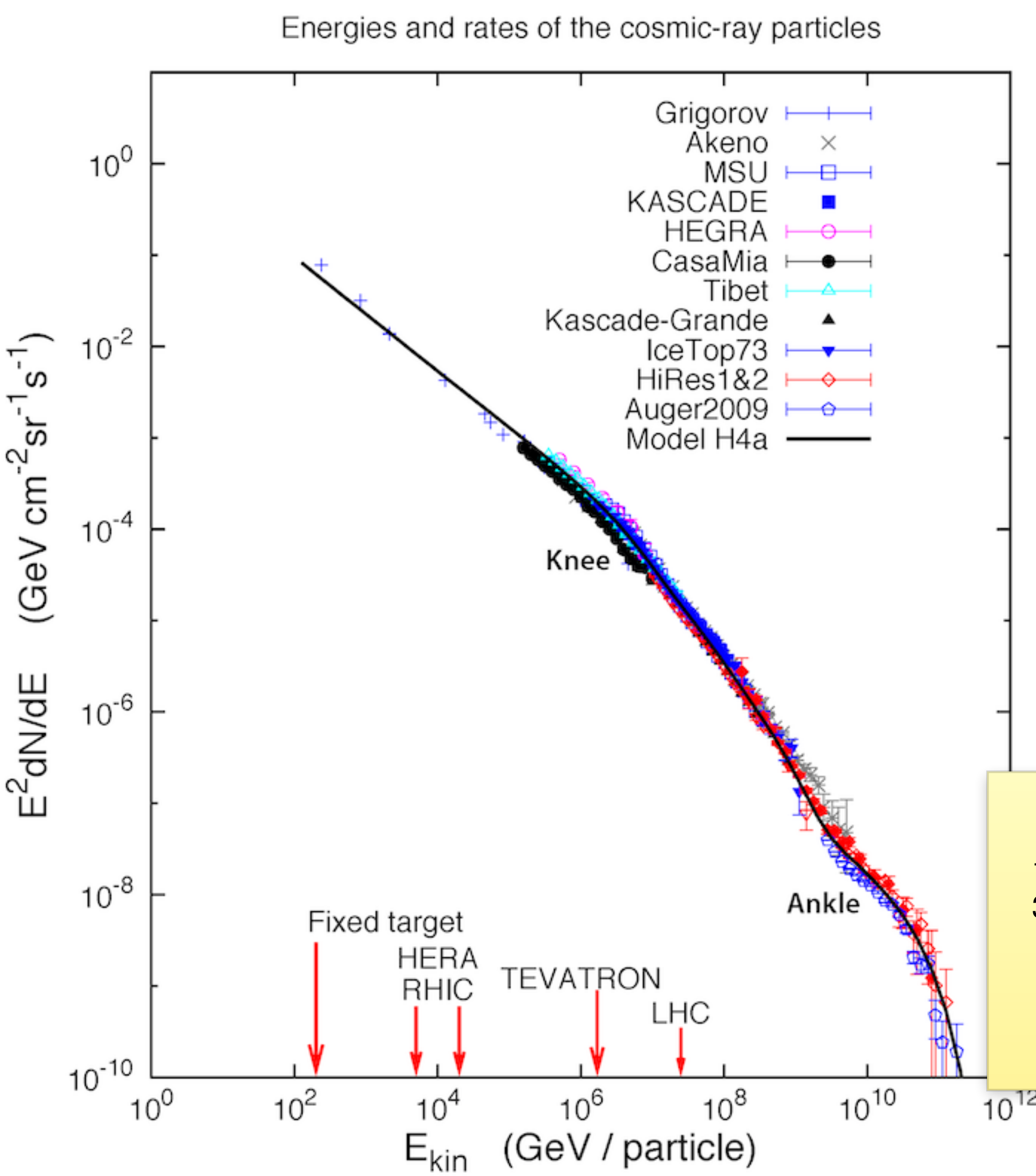
Victor Hess



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.

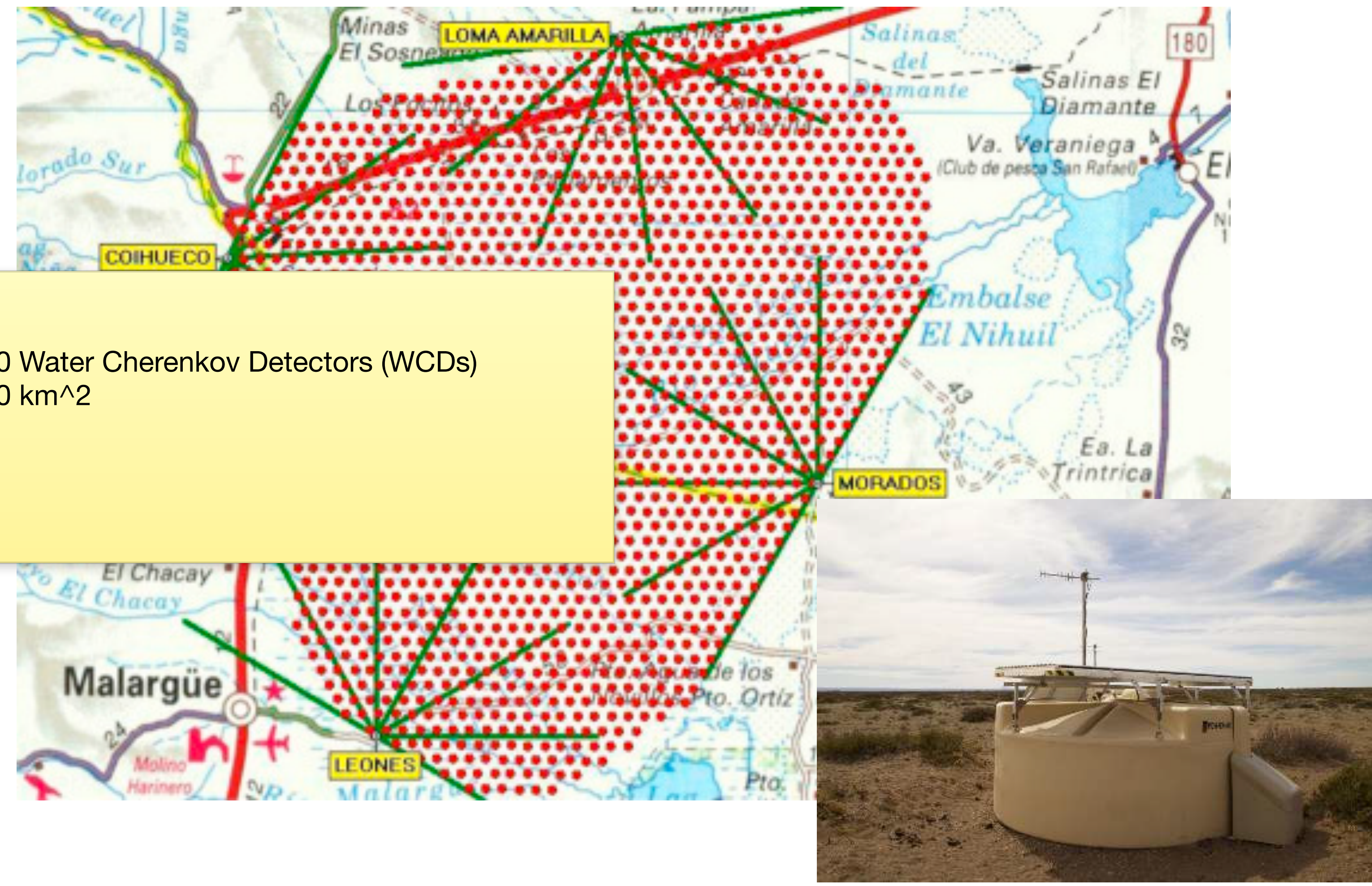
Cosmic rays



Cosmic rays have been observed with energies up to 10^{20}eV (100EeV) or 10^7 LHC beam energies

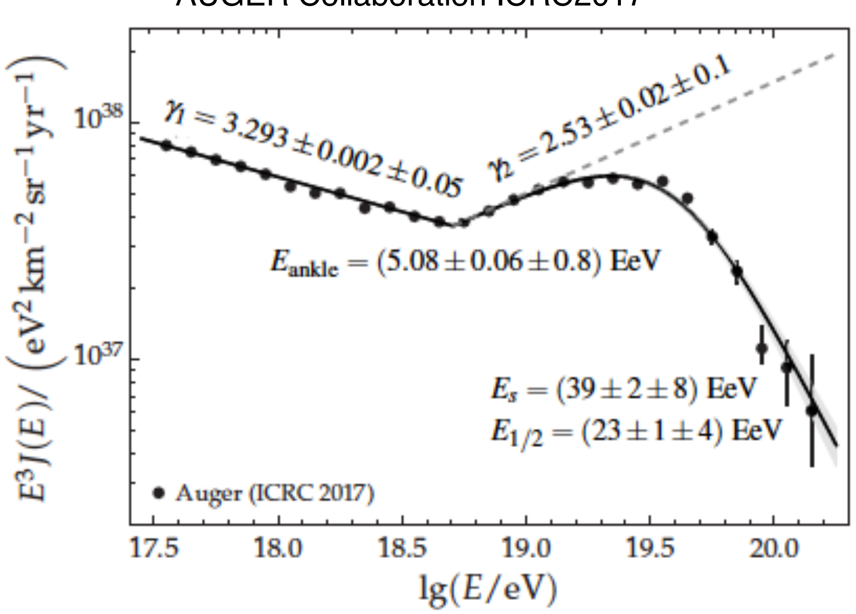
AUGER

Malargüe, Mendoza

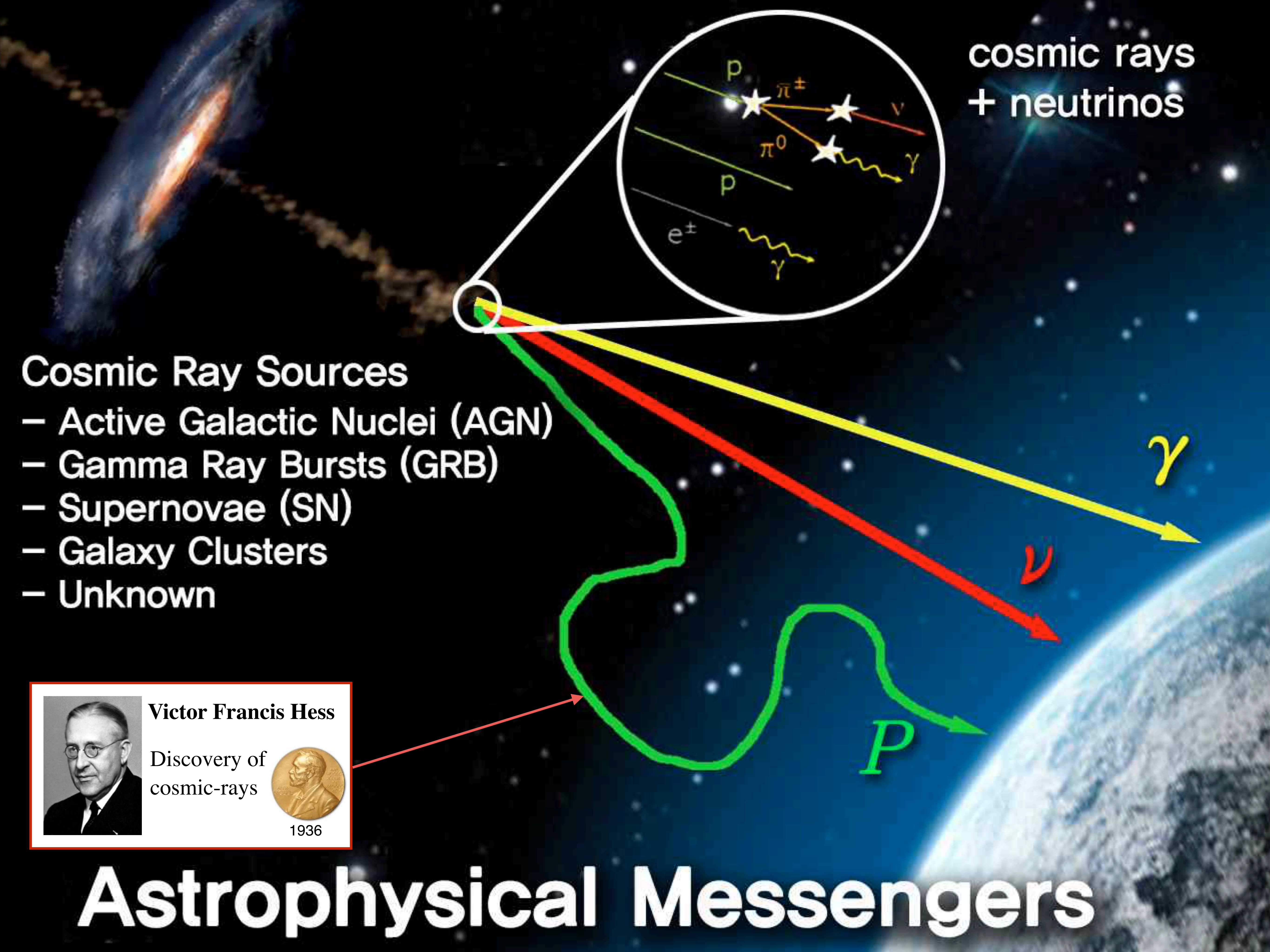


1600 Water Cherenkov Detectors (WCDs)
3000 km^2

AUGER Collaboration ICRC2017

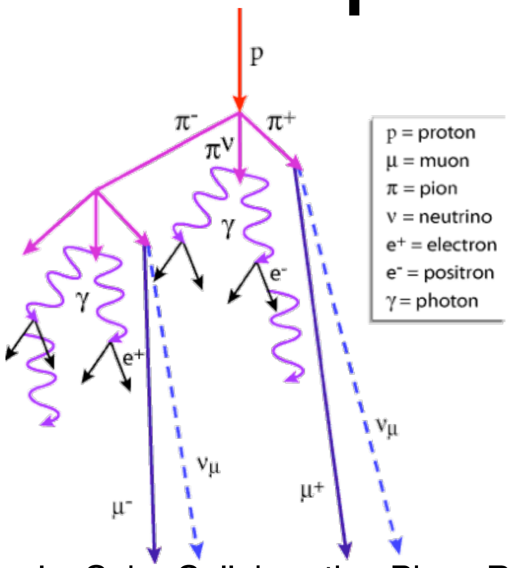


- Cosmic ray spectrum extremely well measured (TA, Auger, …)
- Where are they coming from ?
- What cosmic sources accelerate these particles to energies well beyond that reached at LHC ?


cosmic rays
+ neutrinos
p
$\pi^{\pm}$
ν
π^0
γ
p
$e^{\pm}$
γ
Cosmic Ray Sources
– Active Galactic Nuclei (AGN)
– Gamma Ray Bursts (GRB)
– Supernovae (SN)
– Galaxy Clusters
– Unknown
γ
ν
P
Victor Francis Hess
Discovery of
cosmic-rays
1936
Astrophysical Messengers

Sources of High Energy Neutrinos

Atmospheric Neutrinos

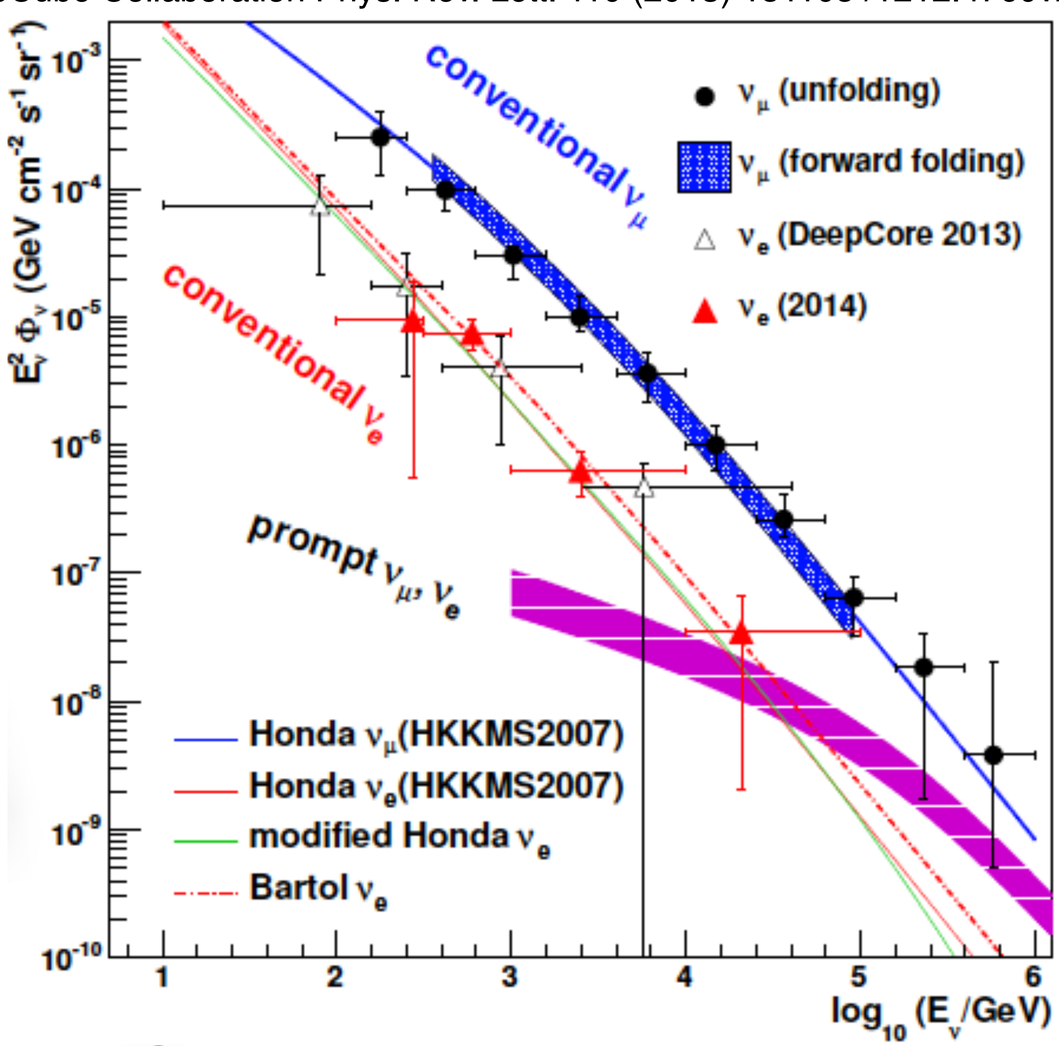


Cosmic rays interact in the upper atmosphere:

$p + A \rightarrow \pi^\pm\ (K^\pm)$ + other hadrons ...

$\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\nu_\mu\nu_\mu$

IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2

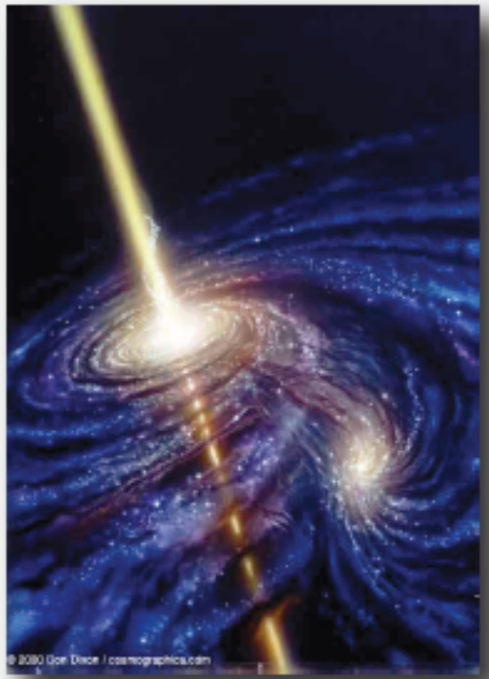


Astrophysical

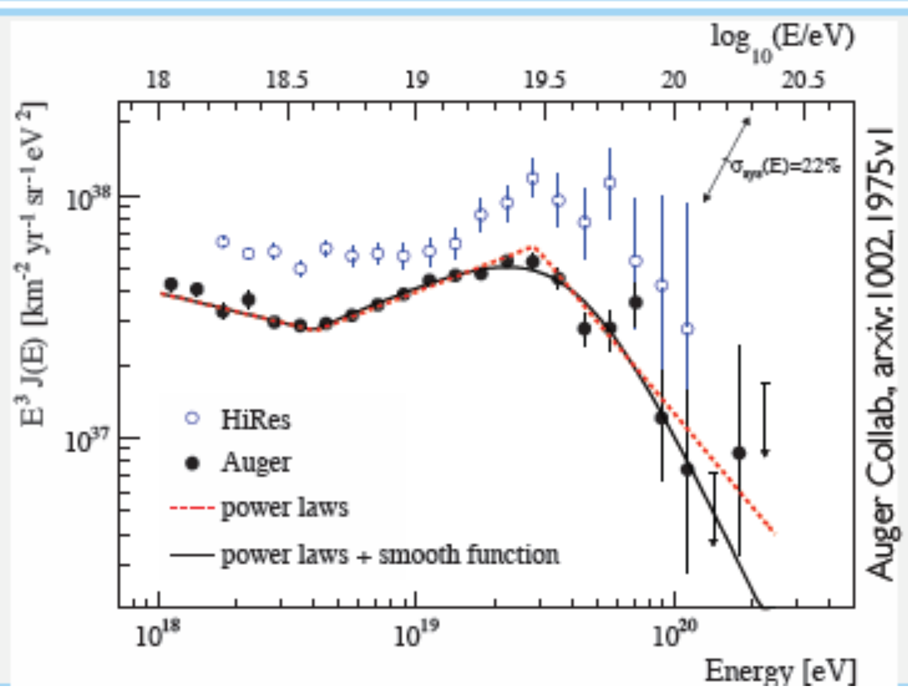
$p + (p,\gamma) \rightarrow \pi^\pm \rightarrow \nu$

Gamma-ray Bursts

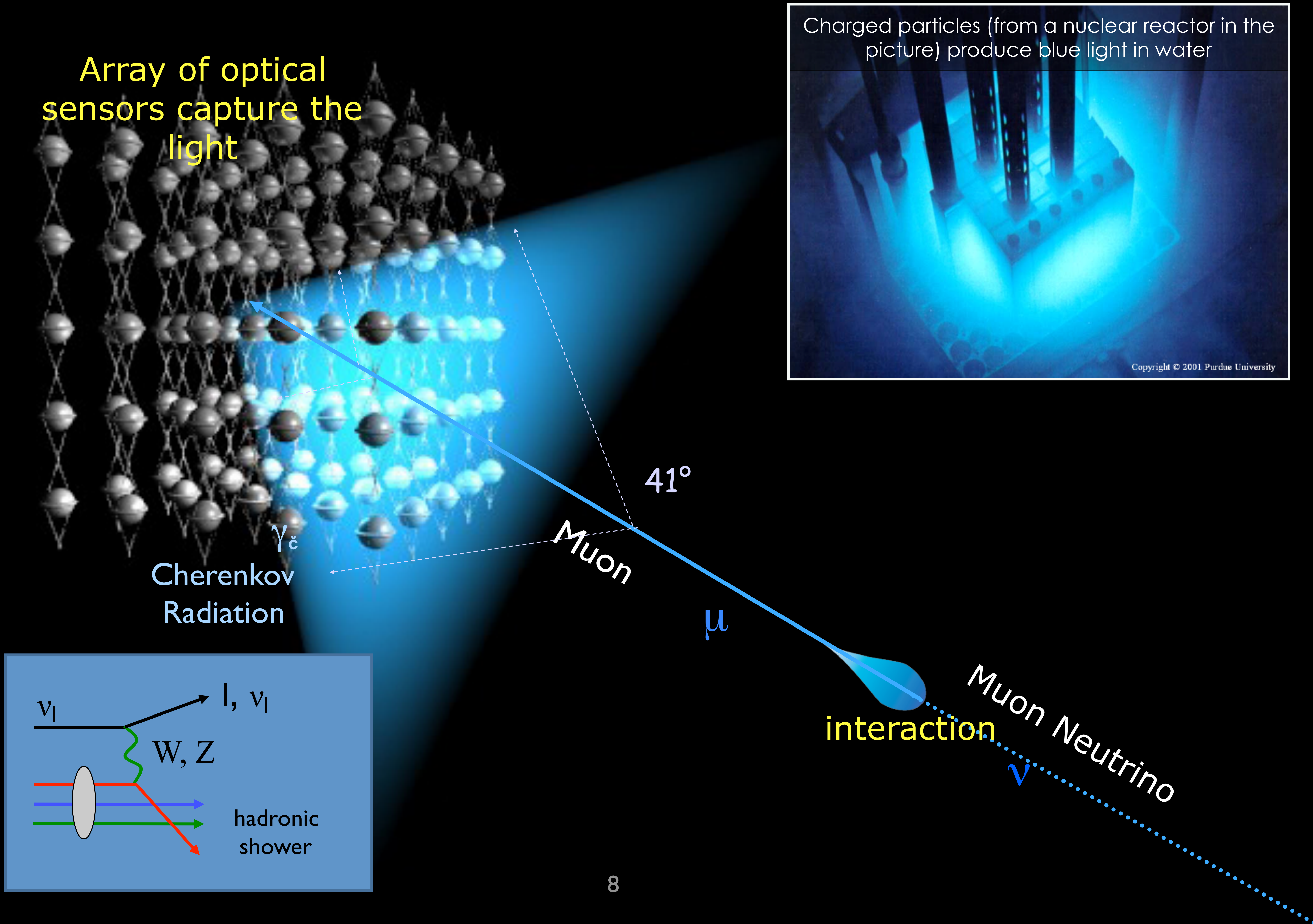
Active Galactic Nuclei

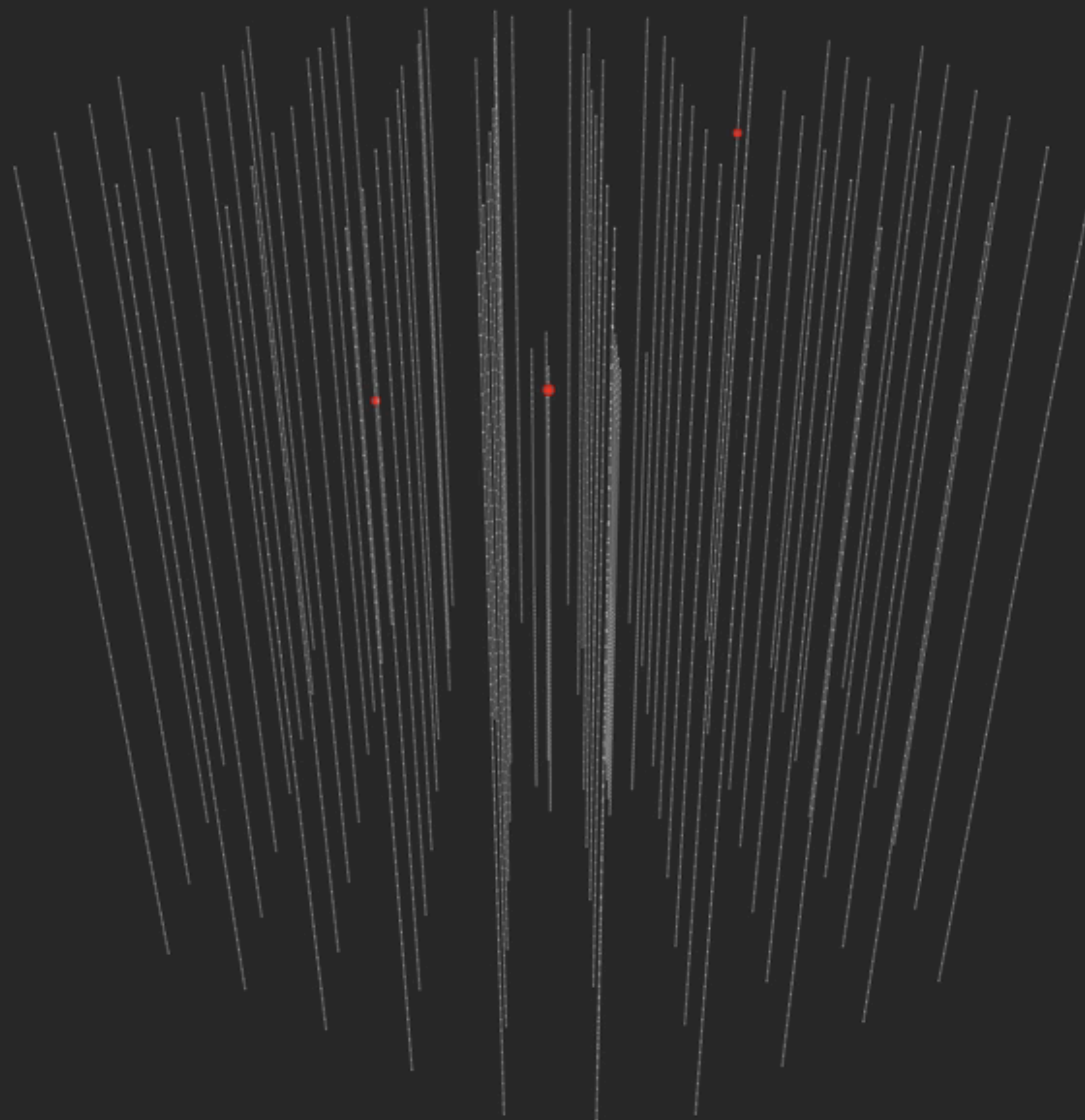


$p+\gamma_{3K} \rightarrow \Delta^+$ (GZK)



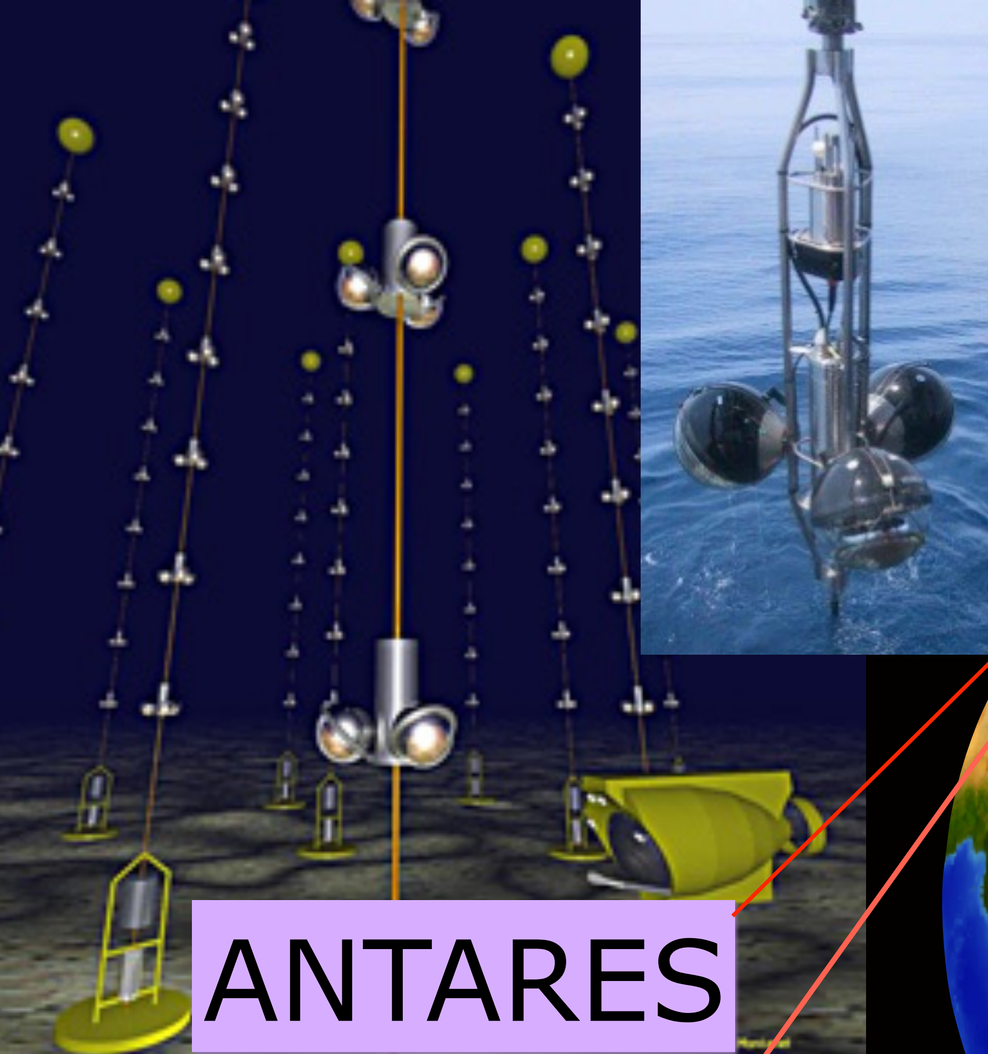
Principle of an optical Neutrino Telescope

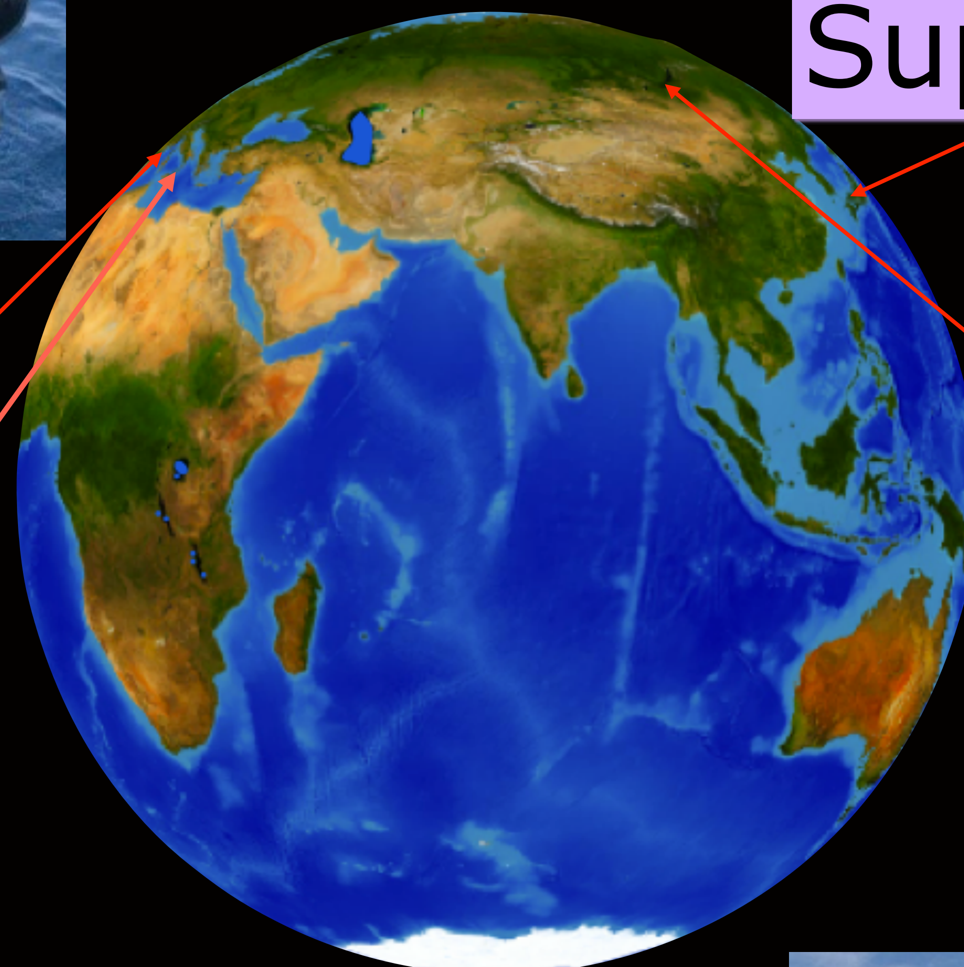


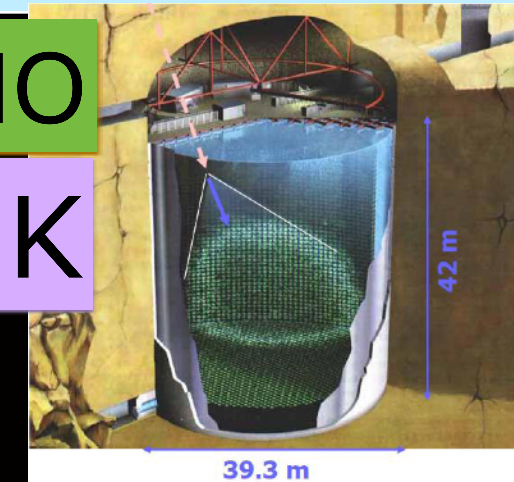


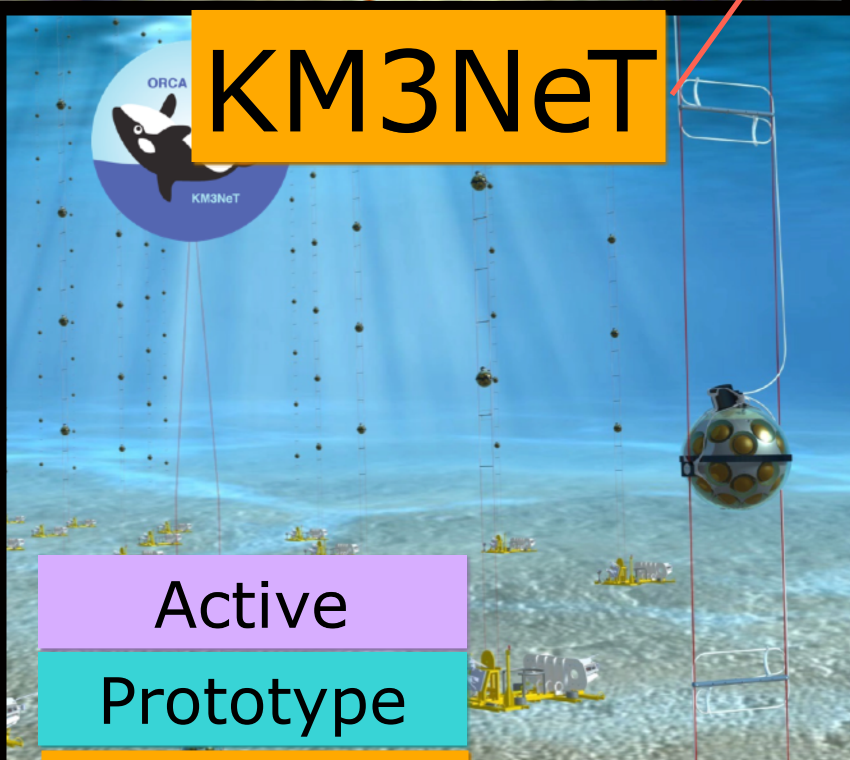
Neutrino Telescopes and IceCube

Large Water/Ice Cherenkov Neutrino Detectors









Hyper-K / KNO

Super-K

ANTARES

KM3NeT

Lake Baikal

GVD

IceCube

Gen2/PINGU

Active

Prototype

Construction

Planned

Sungkyunkwan University
since 2013

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität
Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität Dortmund
Technische Universität München
Universität Münster
Universität Mainz
Universität Wuppertal

JAPAN
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Sungkyunkwan University

SWEDEN
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Uppsala Universitet

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Université de Genève

UNITED KINGDOM
University of Oxford

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Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
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University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

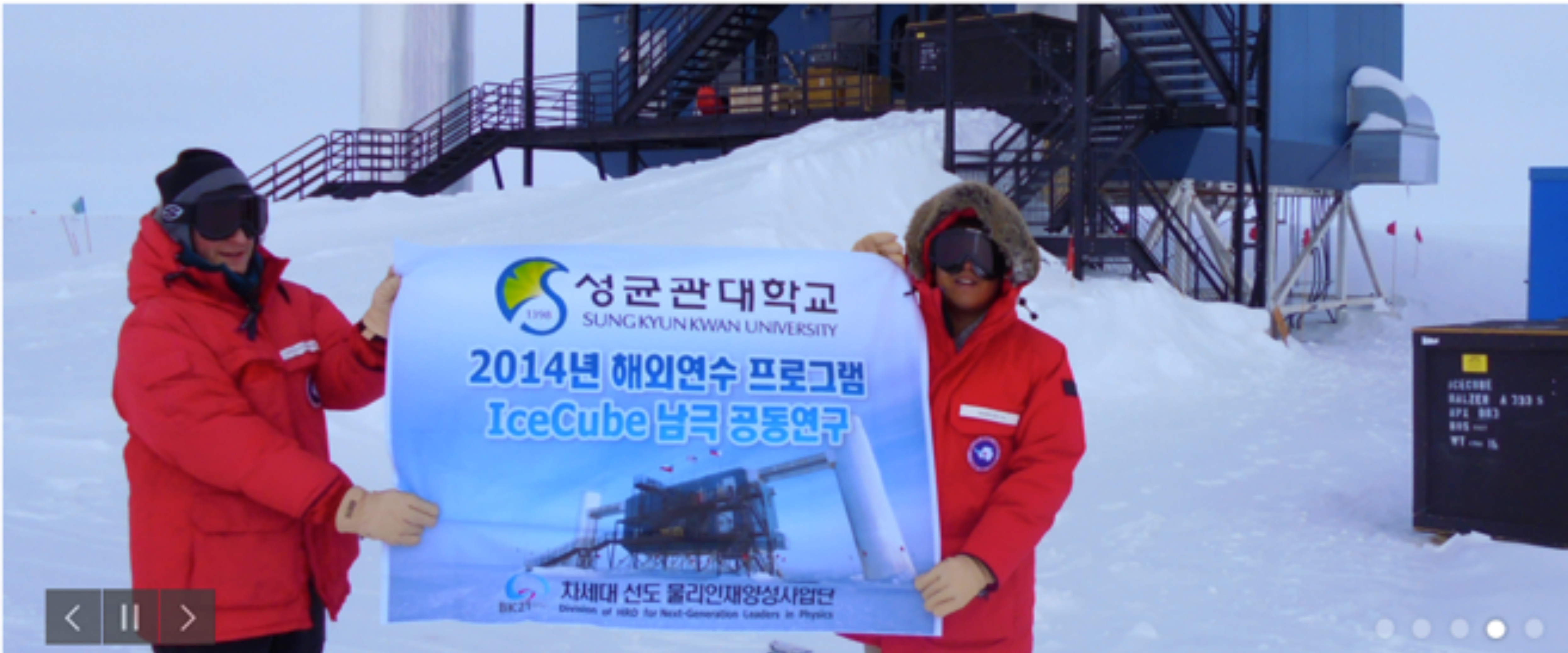
FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and 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)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

SUNG KYUN KWAN UNIVERSITY (SKKU)

SEARCH GO



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

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

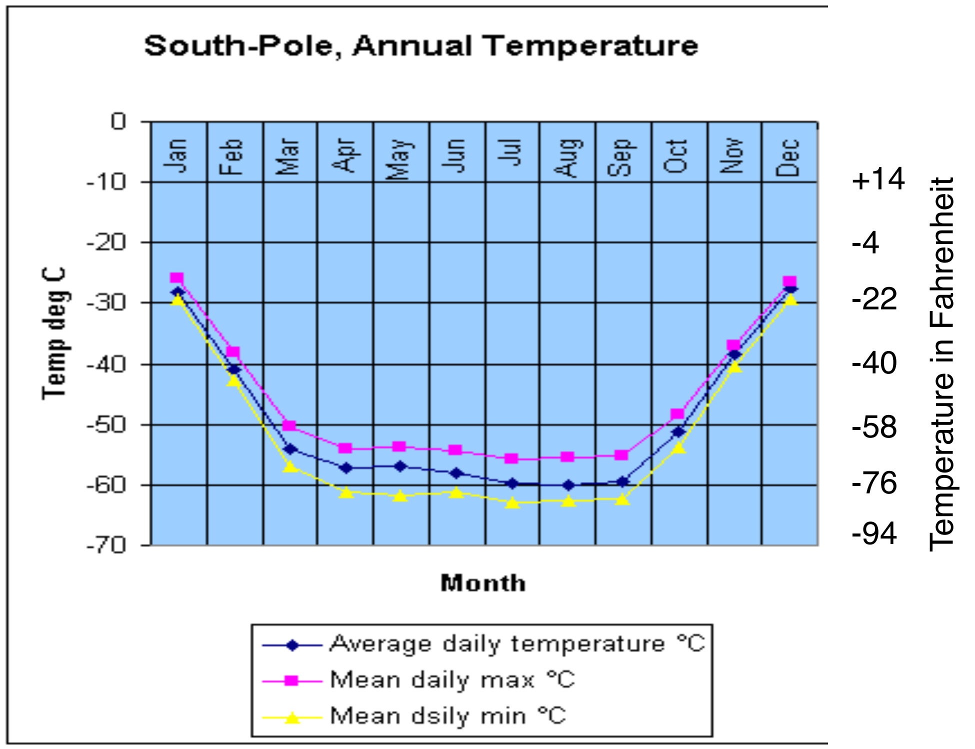
SKKU Reputation

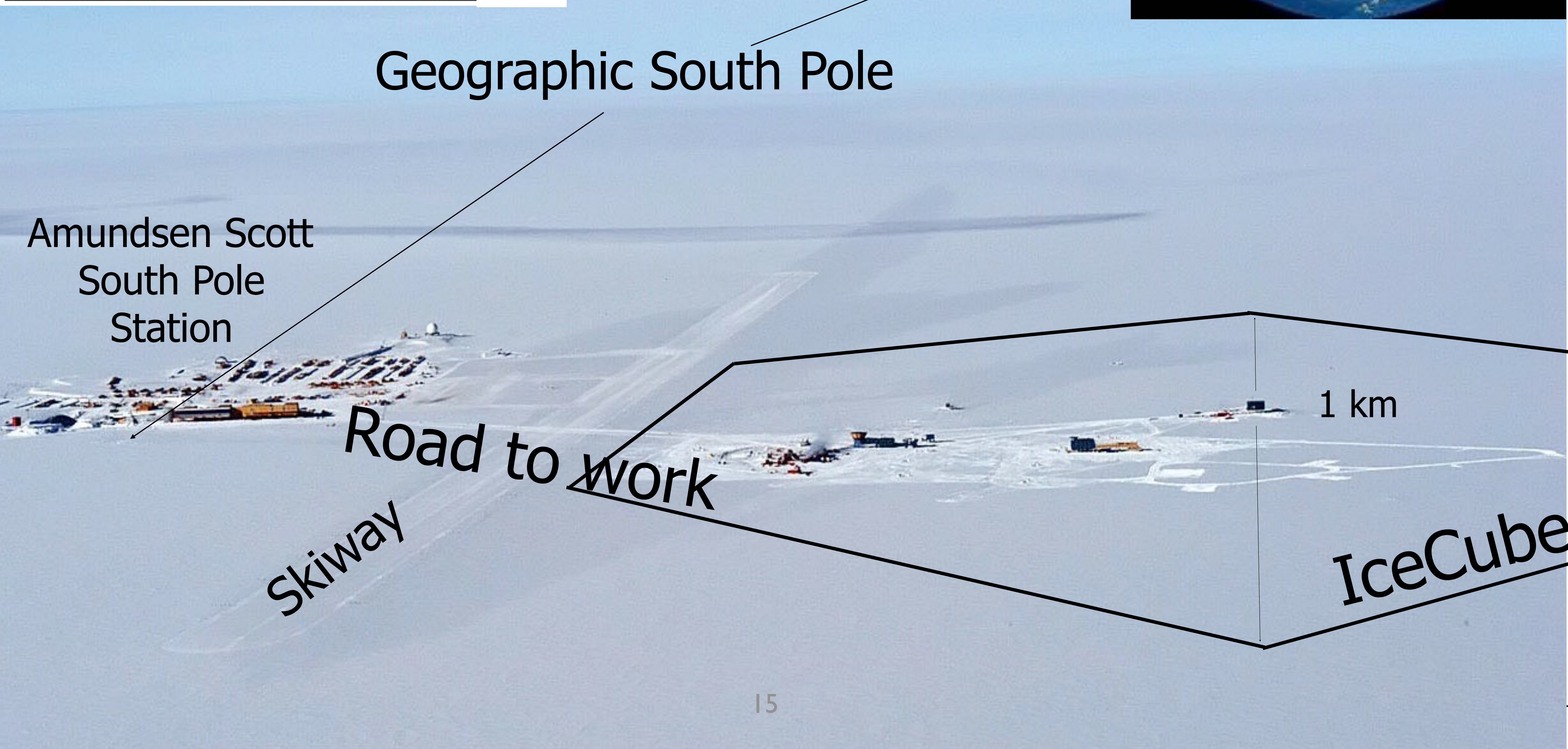
SKKU News

Academics


TEX

Laboratory at the South Pole





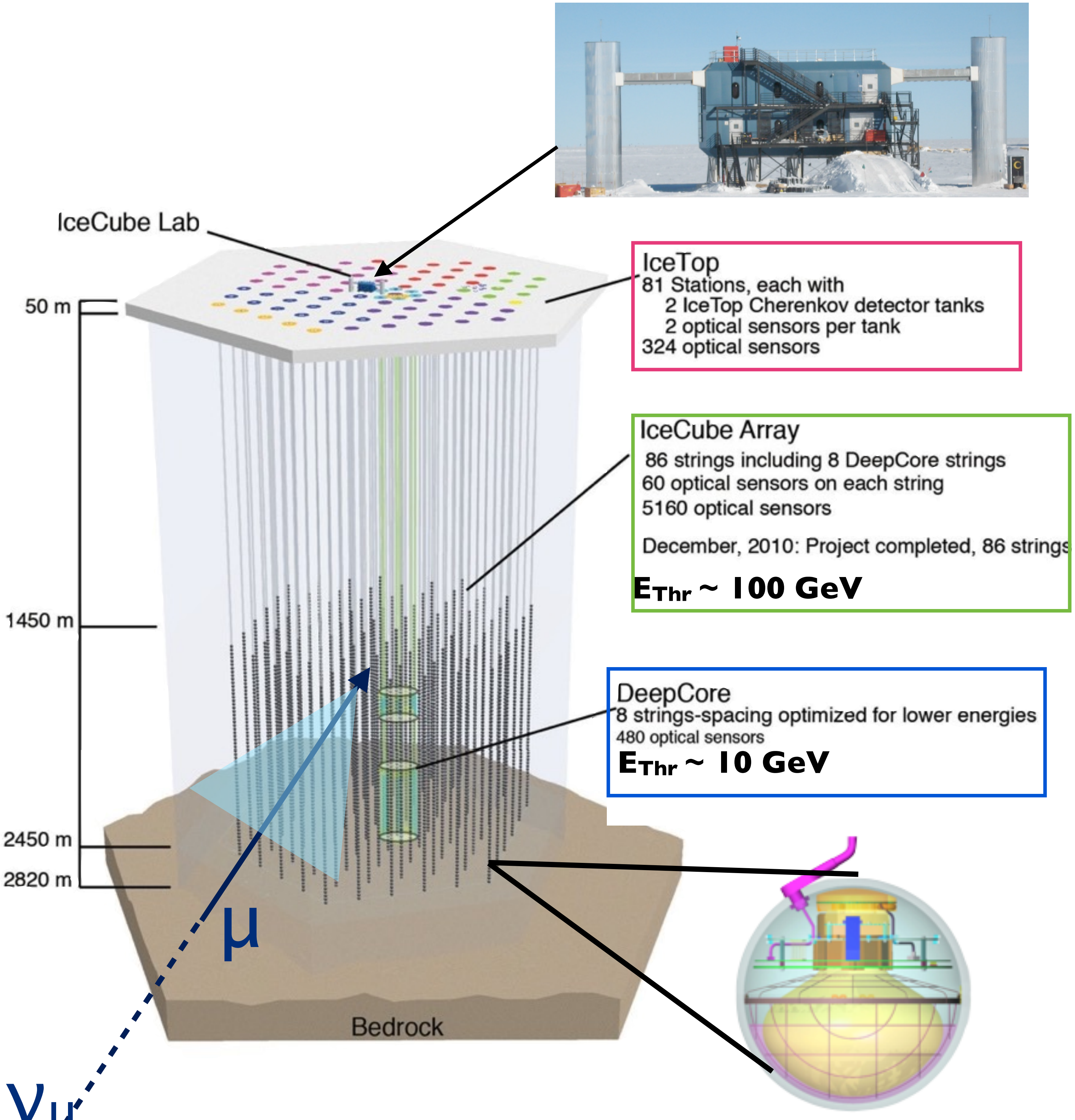
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Detector completed in December 2010 after 7 years construction
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice


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

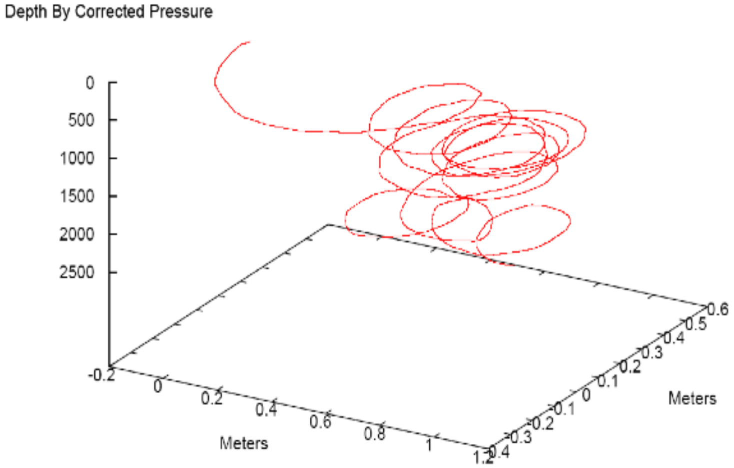
"한국 '세계적 리더' 될 좋은 기회"

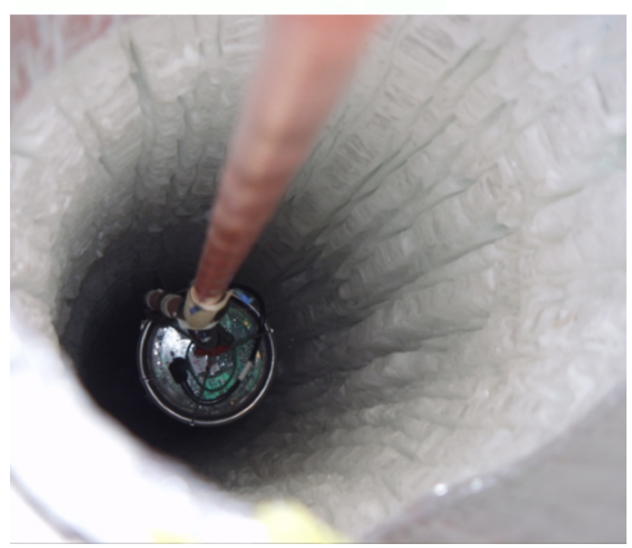
기초과학 투자 의지 활발, 한국에 새 연구 터전 둥지.. 연구자-학생 영입해 연구

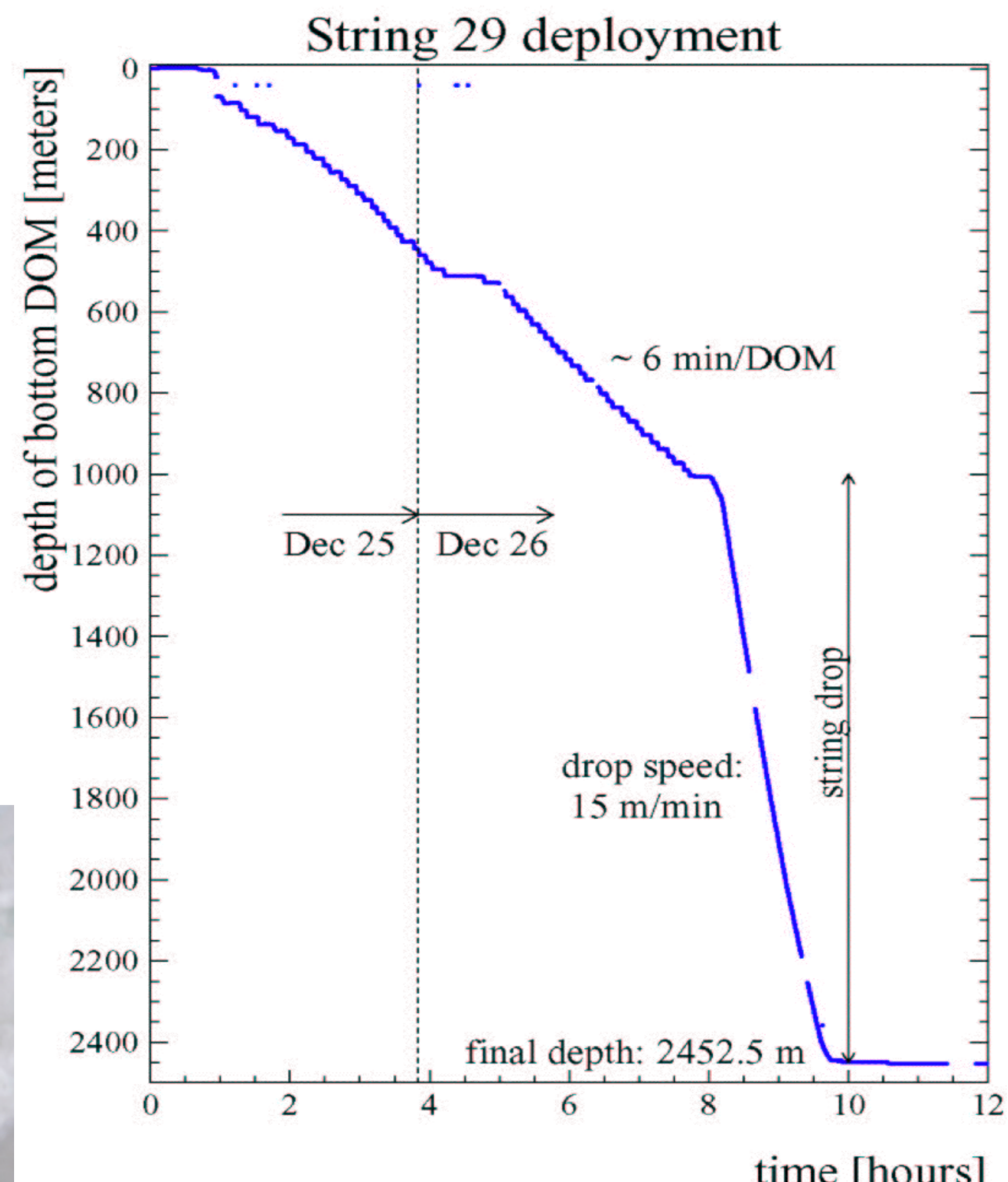


Drilling & Deployment

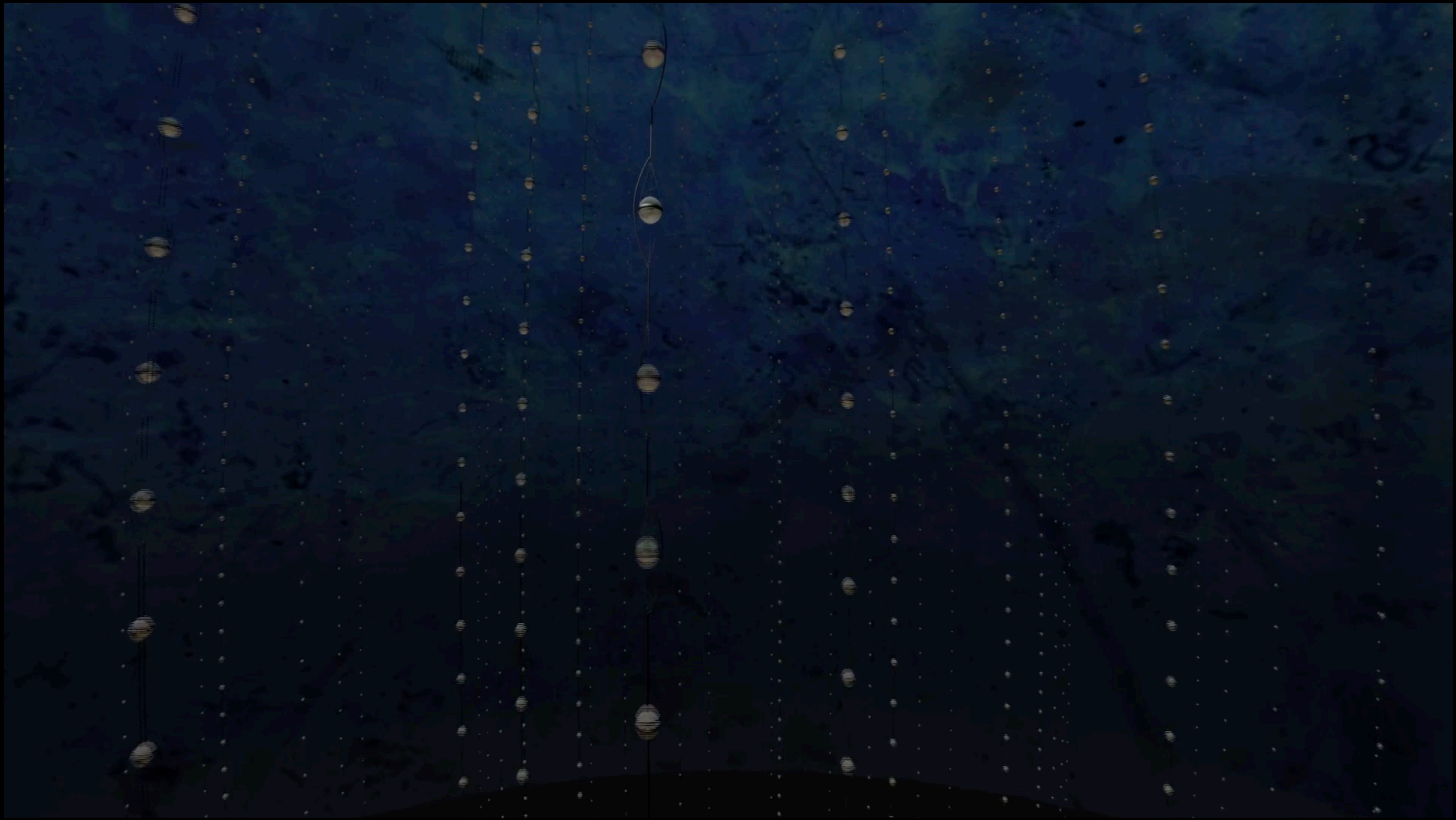
- Hole size ~60cm
- Depth ~2.5km
- Straight to 1m



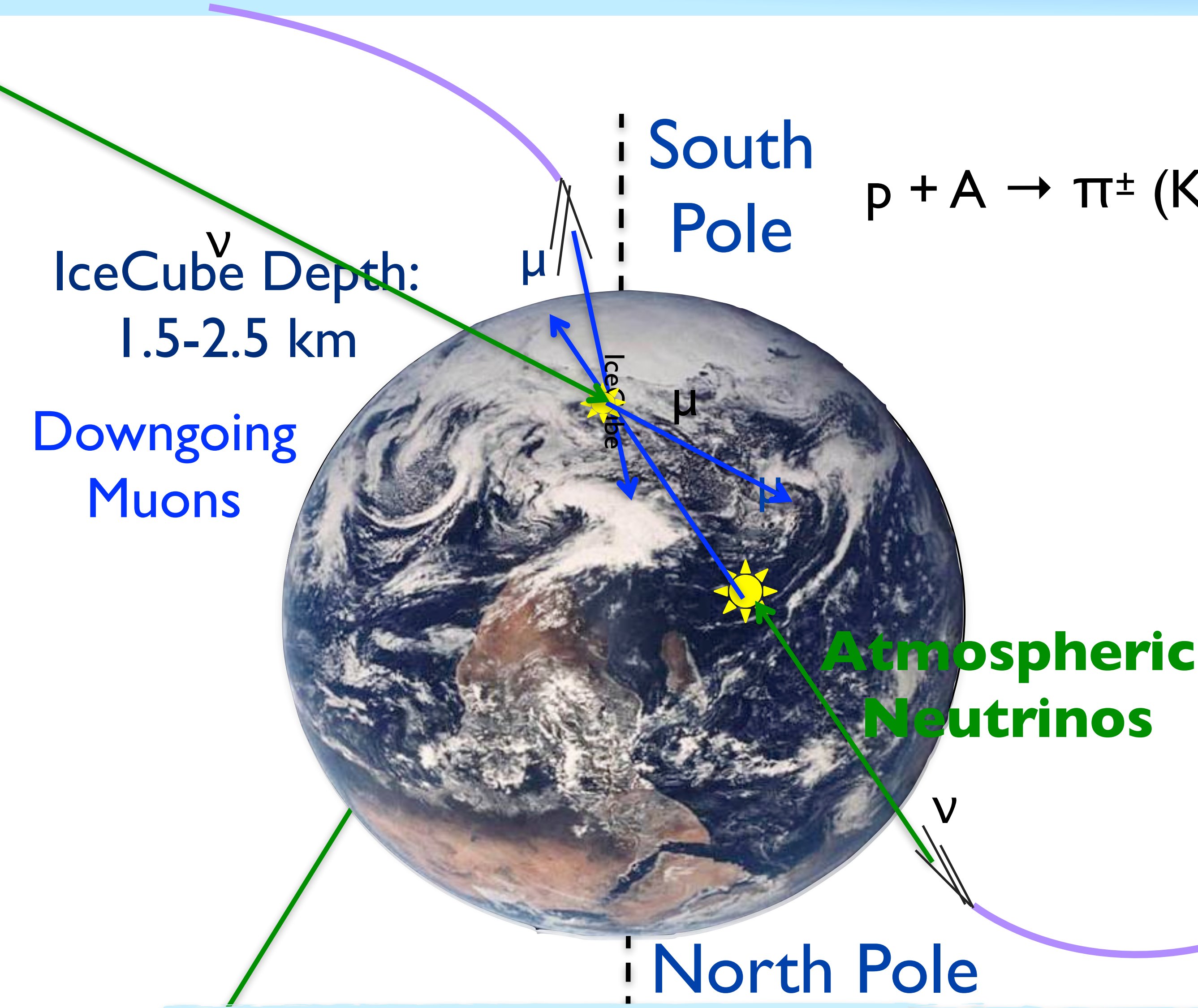


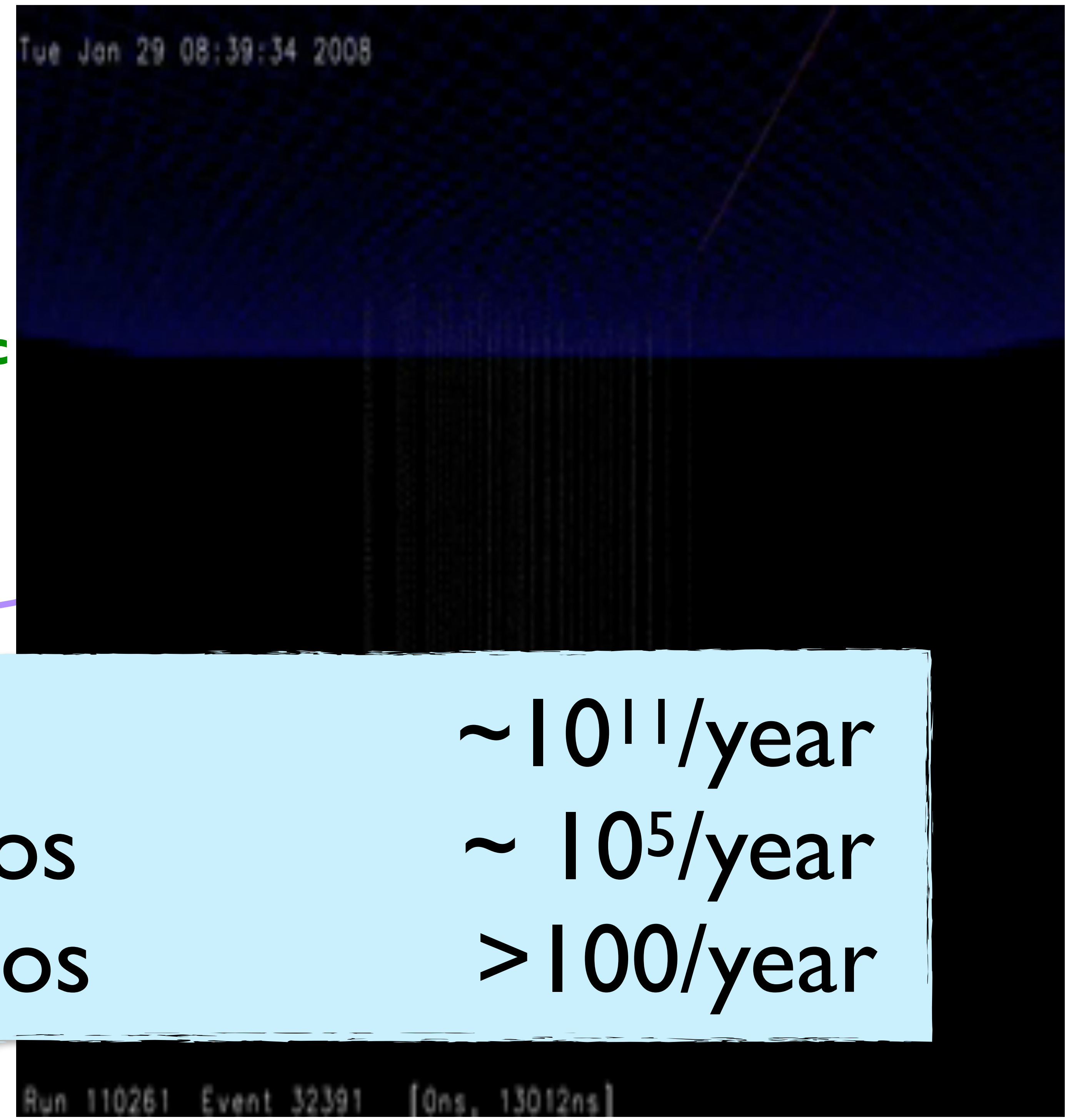


Drilling to 2500 m < 40h
String deployment ~ 12h



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





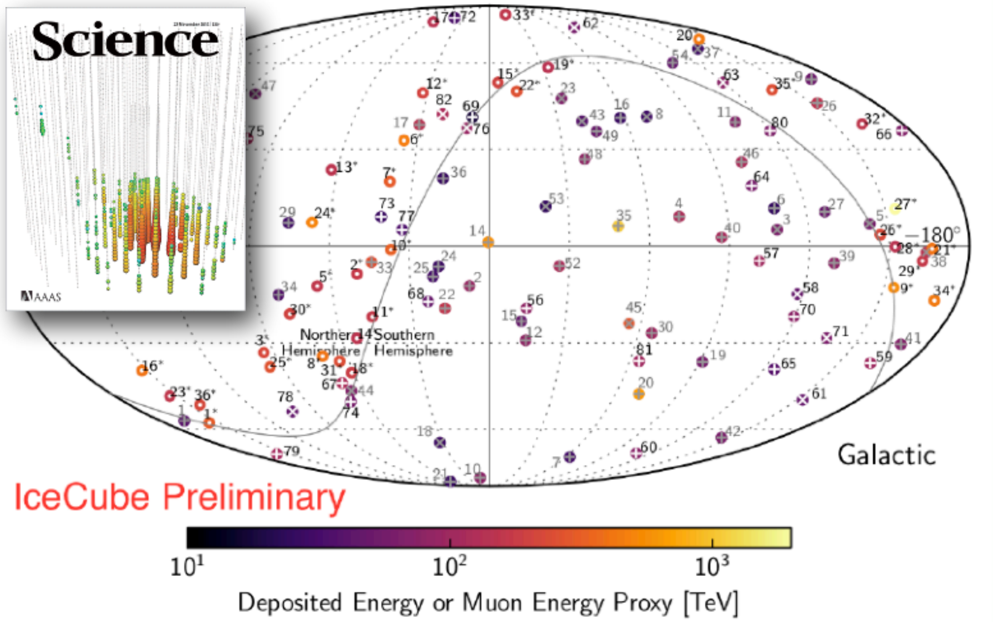
Atmospheric muons	$\sim 10^{11}$/year
Atmospheric neutrinos	$\sim 10^{5}$/year
Astrophysical neutrinos	>100/year

extra terrestrial neutrino fluxes

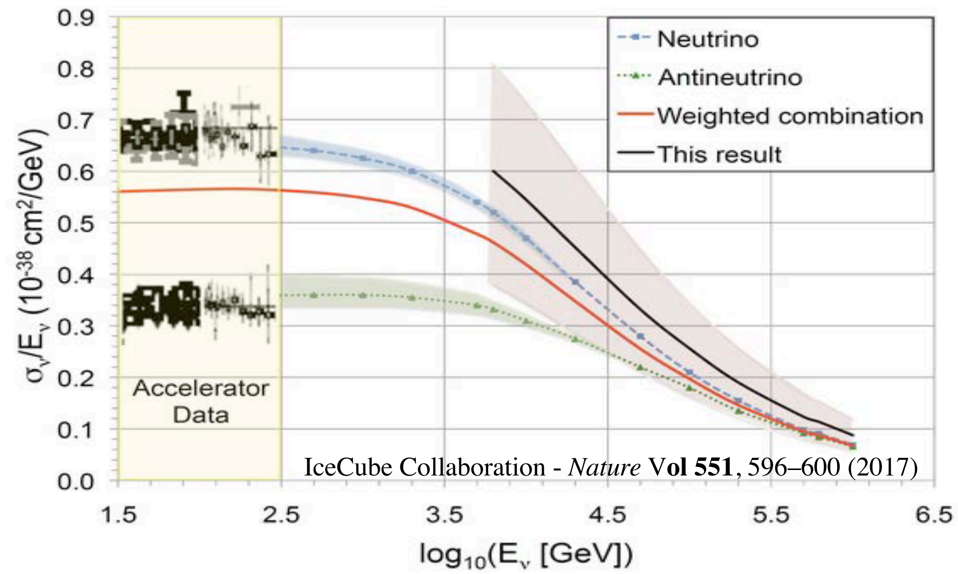
Physics Potential and Selected Results

IceCube Science

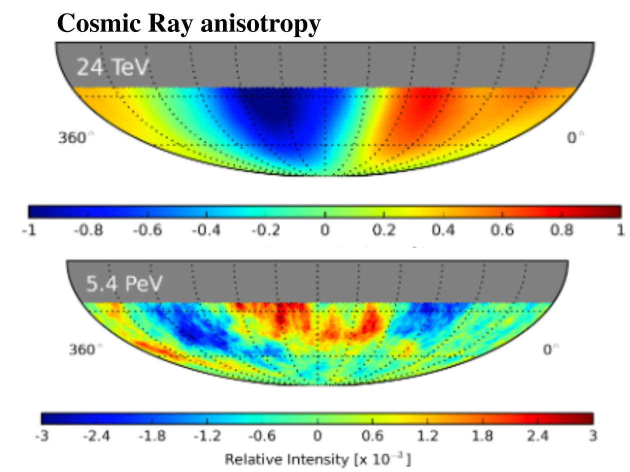
Astrophysical Neutrino Searches



Neutrino Tomography / Neutrino Cross Section Measurements



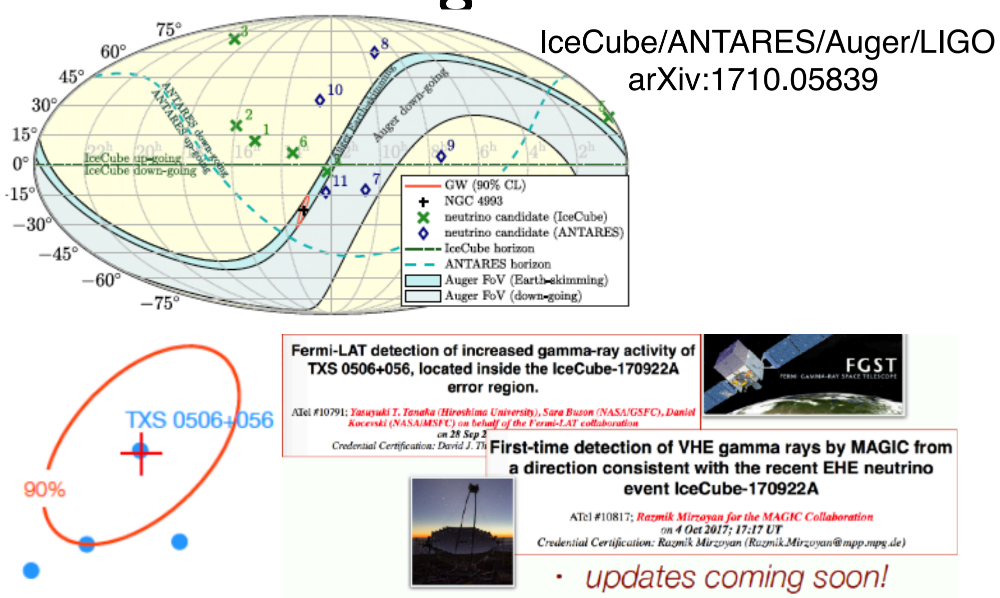
Cosmic Rays



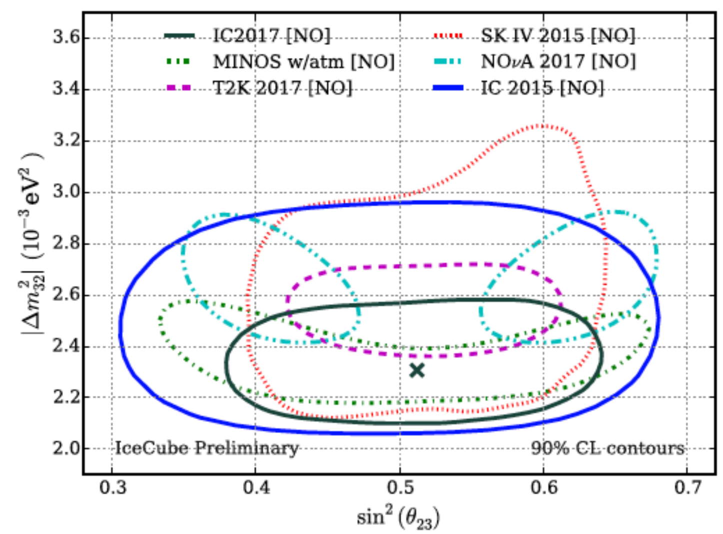
Astrophys.J. 826 (2016) no.2, 220

Multi-messenger Observations

IceCube/ANTARES/Auger/LIGO arXiv:1710.05839

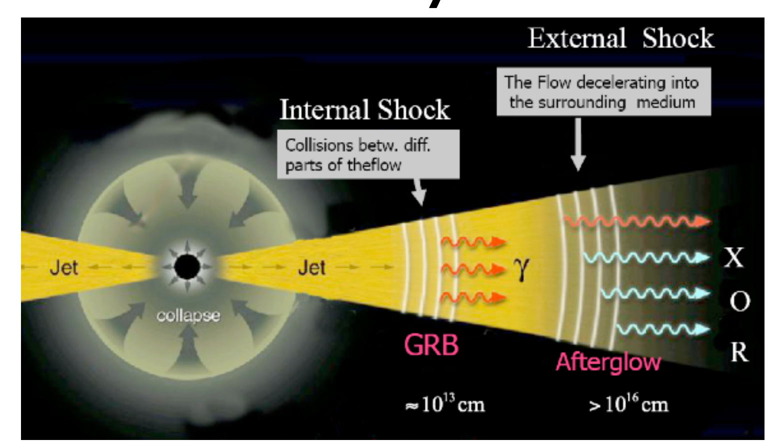


Neutrino Oscillations



IceCube Collaboration - arXiv:1707.07081

Gamma-ray bursts



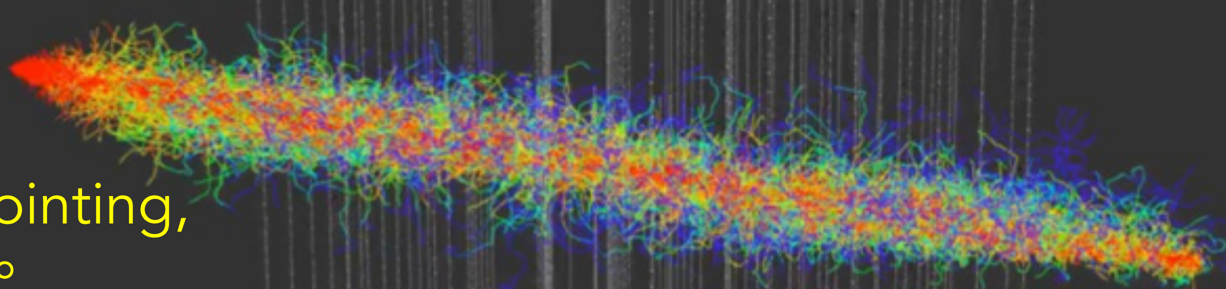
IceCube Collaboration - Nature Vol **484**, 351 (2012)

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

Typical Event Topologies in IceCube

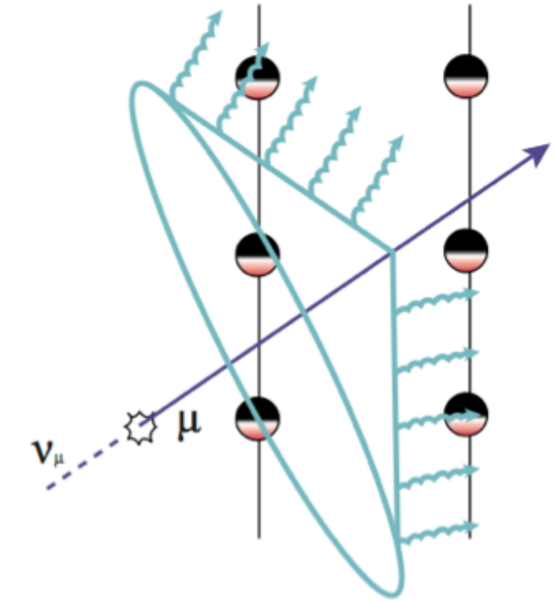
Track topology

(e.g. induced by muon neutrino)

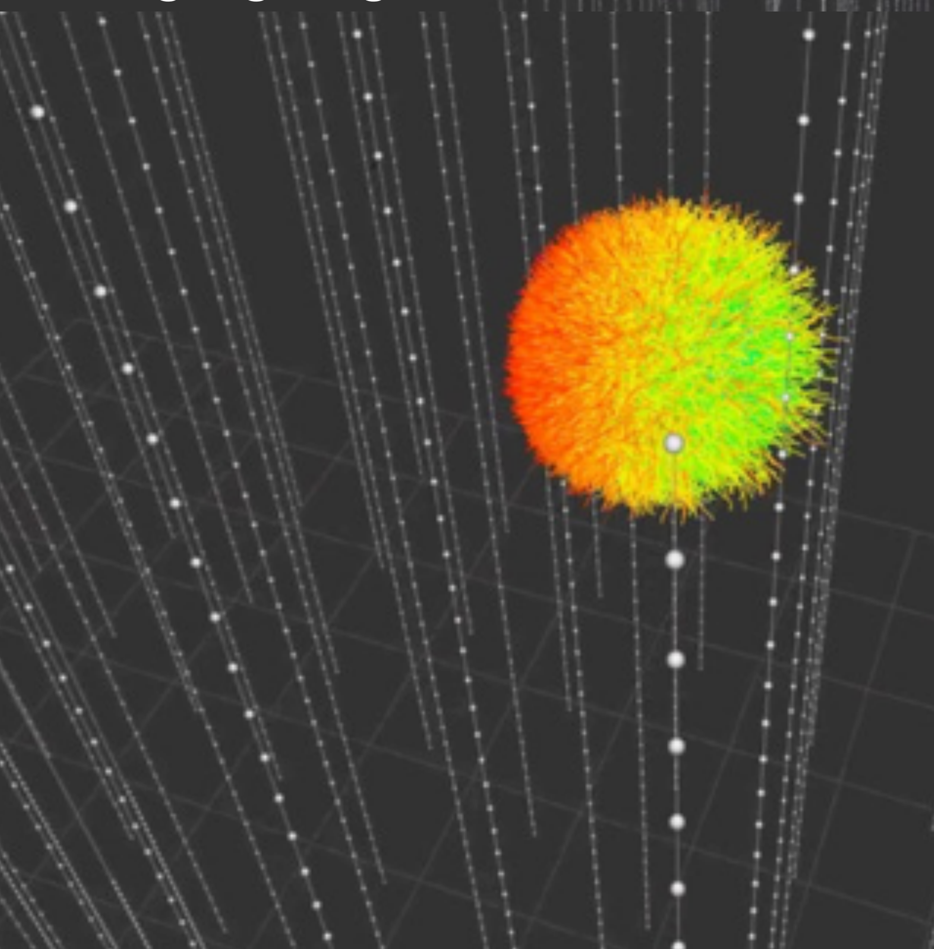


Good pointing,
0.2° - 1°

Lower bound on energy for through-going events



Muon Neutrino ν_μ

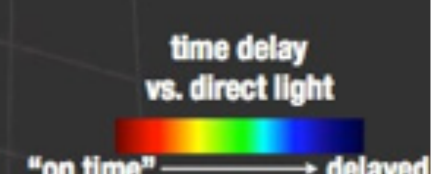


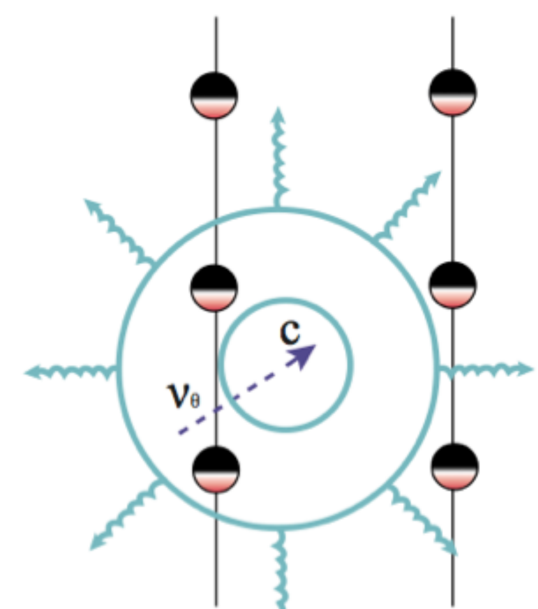
Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

Some pointing,
10° - 15°



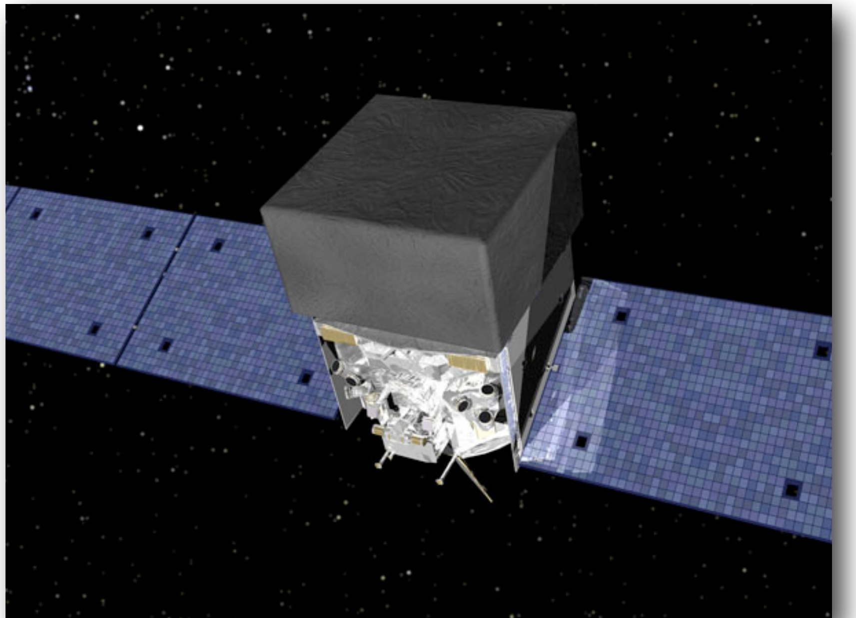


Electron Neutrino ν_e
or Tau Neutrino ν_τ

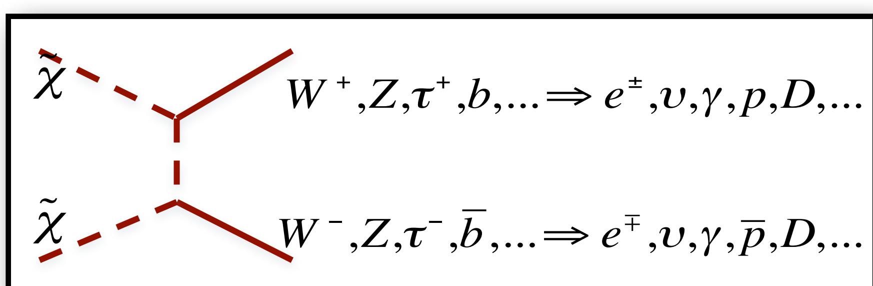
Search for Dark Matter

Synergy

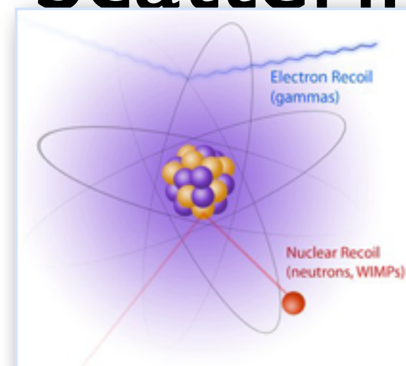
Indirect



Annihilation / Decay



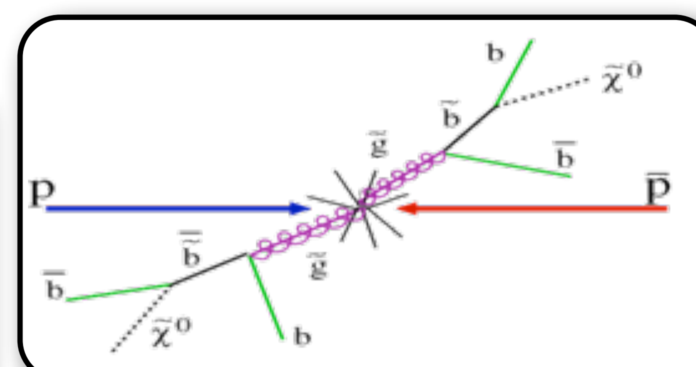
Scattering



Direct

?

Production



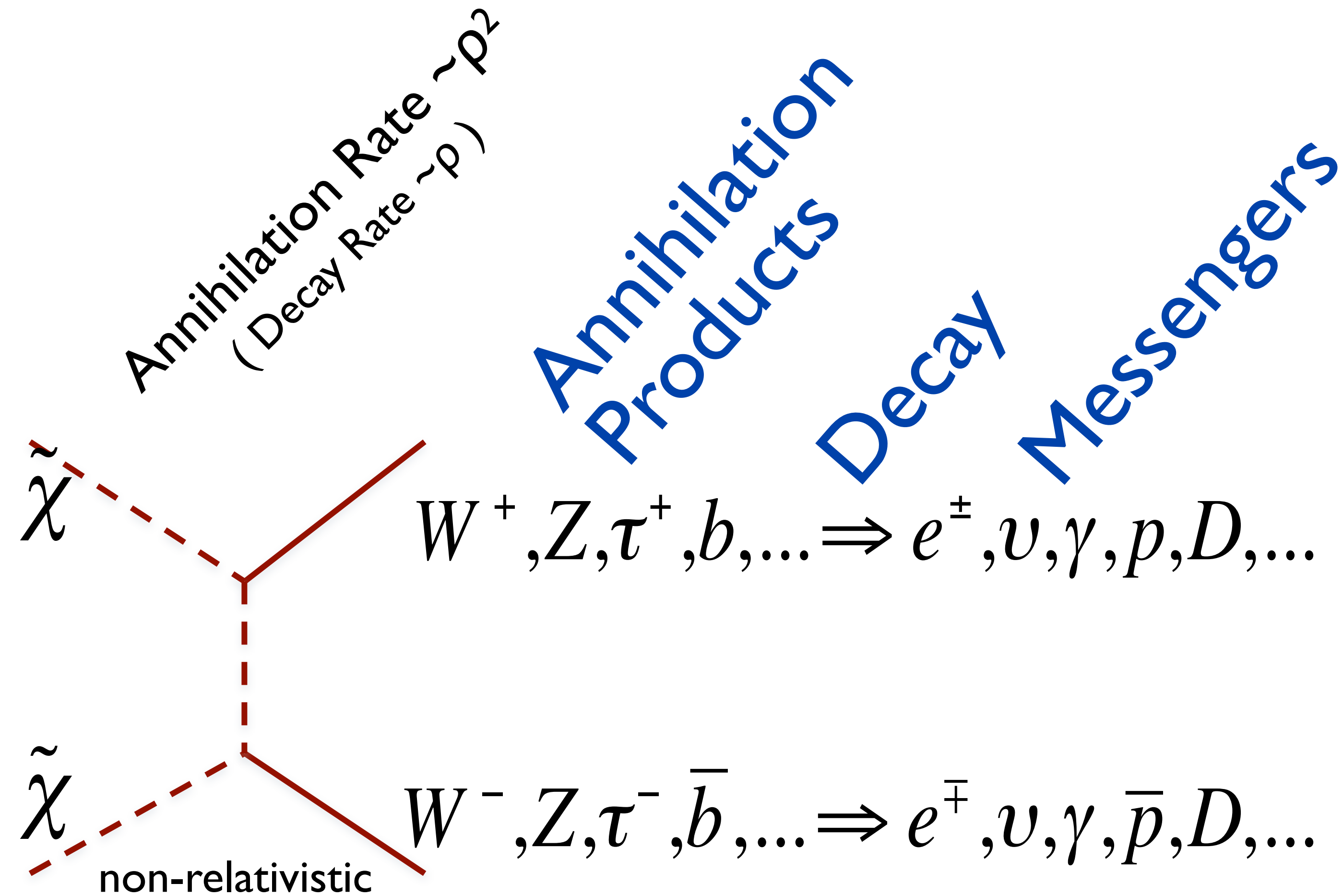
Collider

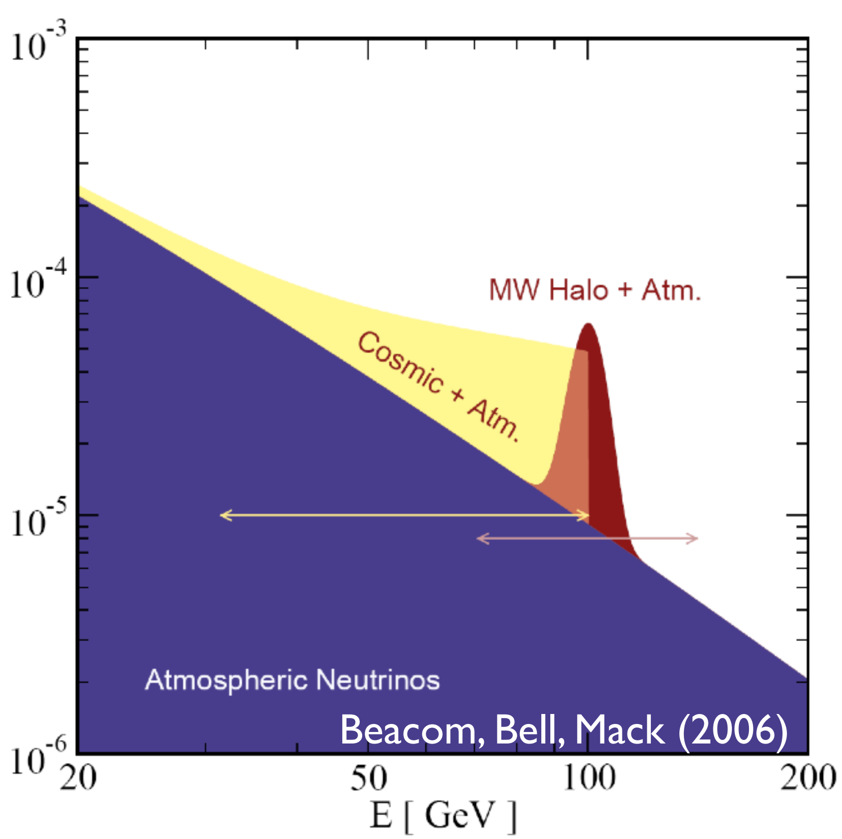
Dark Matter Signals

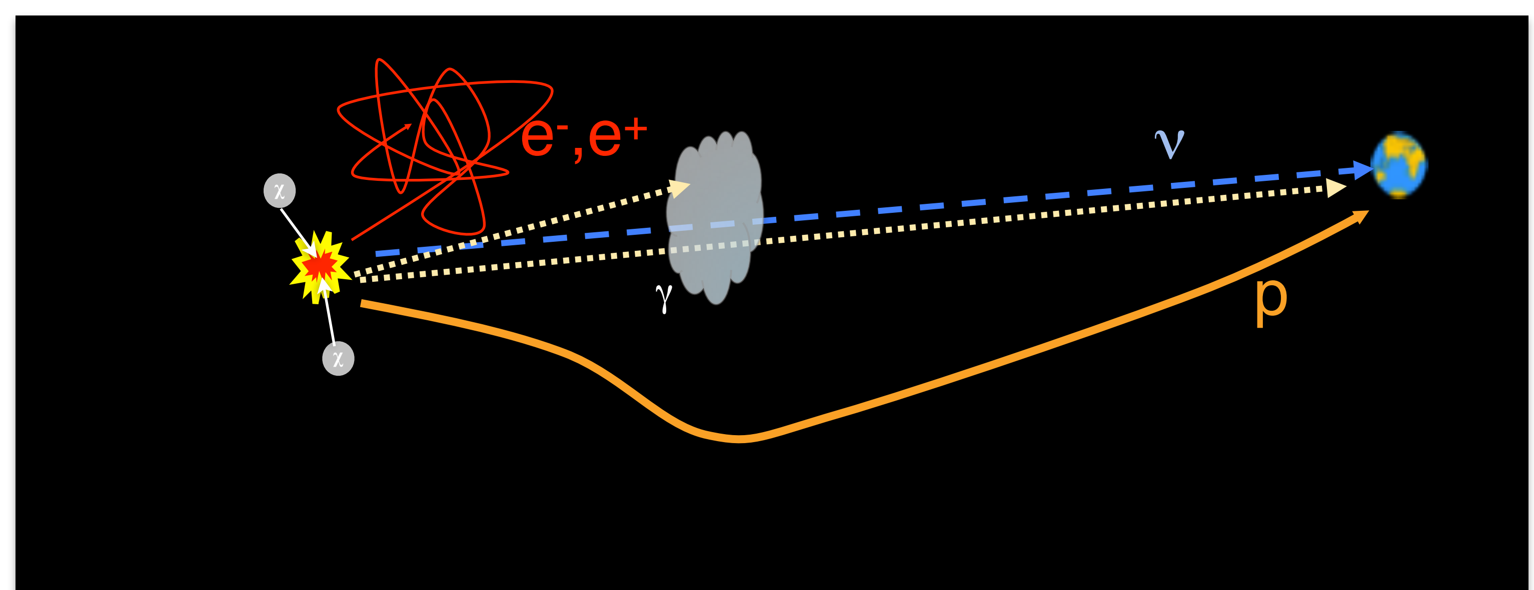
- Identify overdense regions of dark matter

  ⇒self-annihilation can occur at significant rates

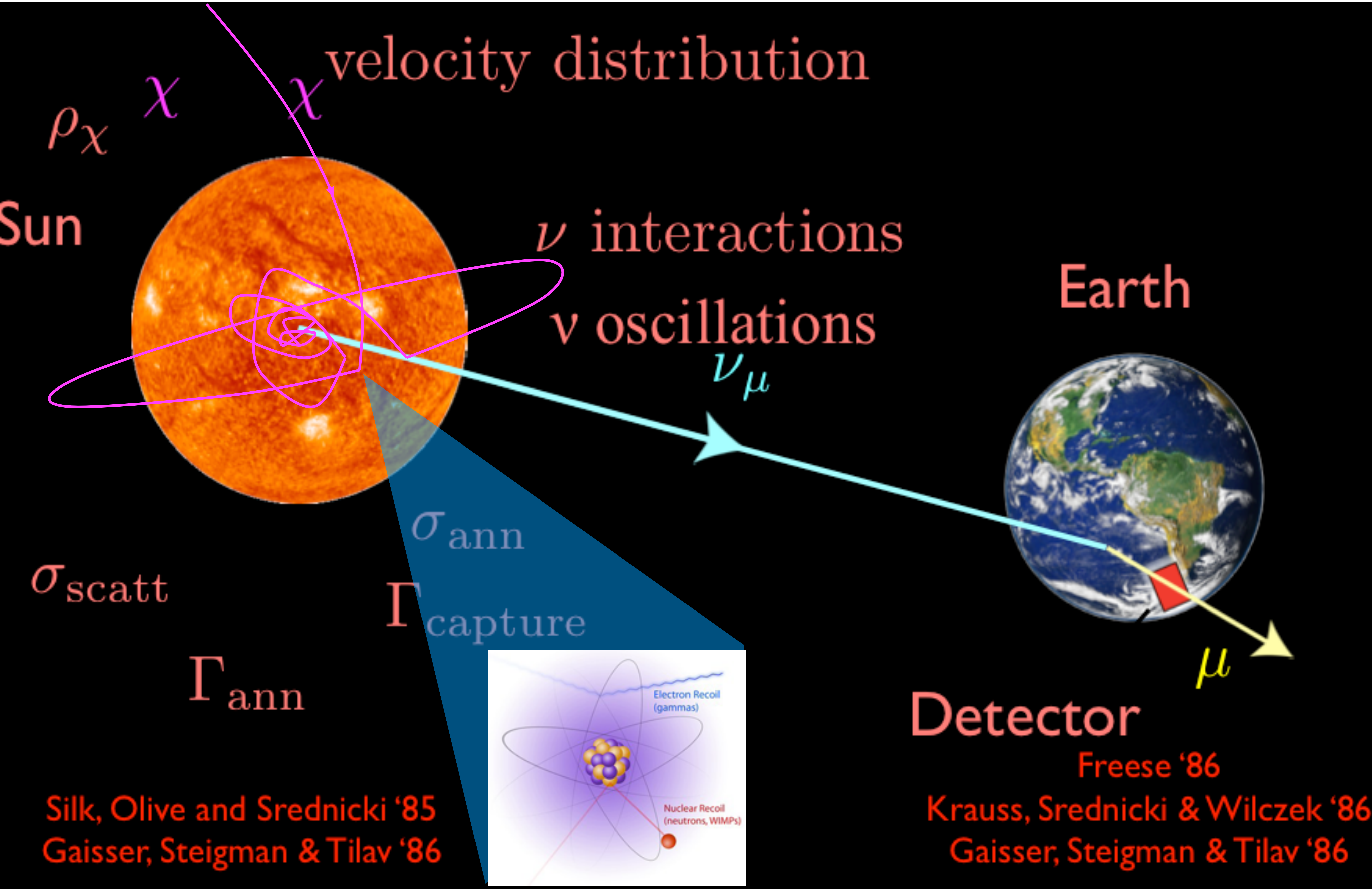
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds

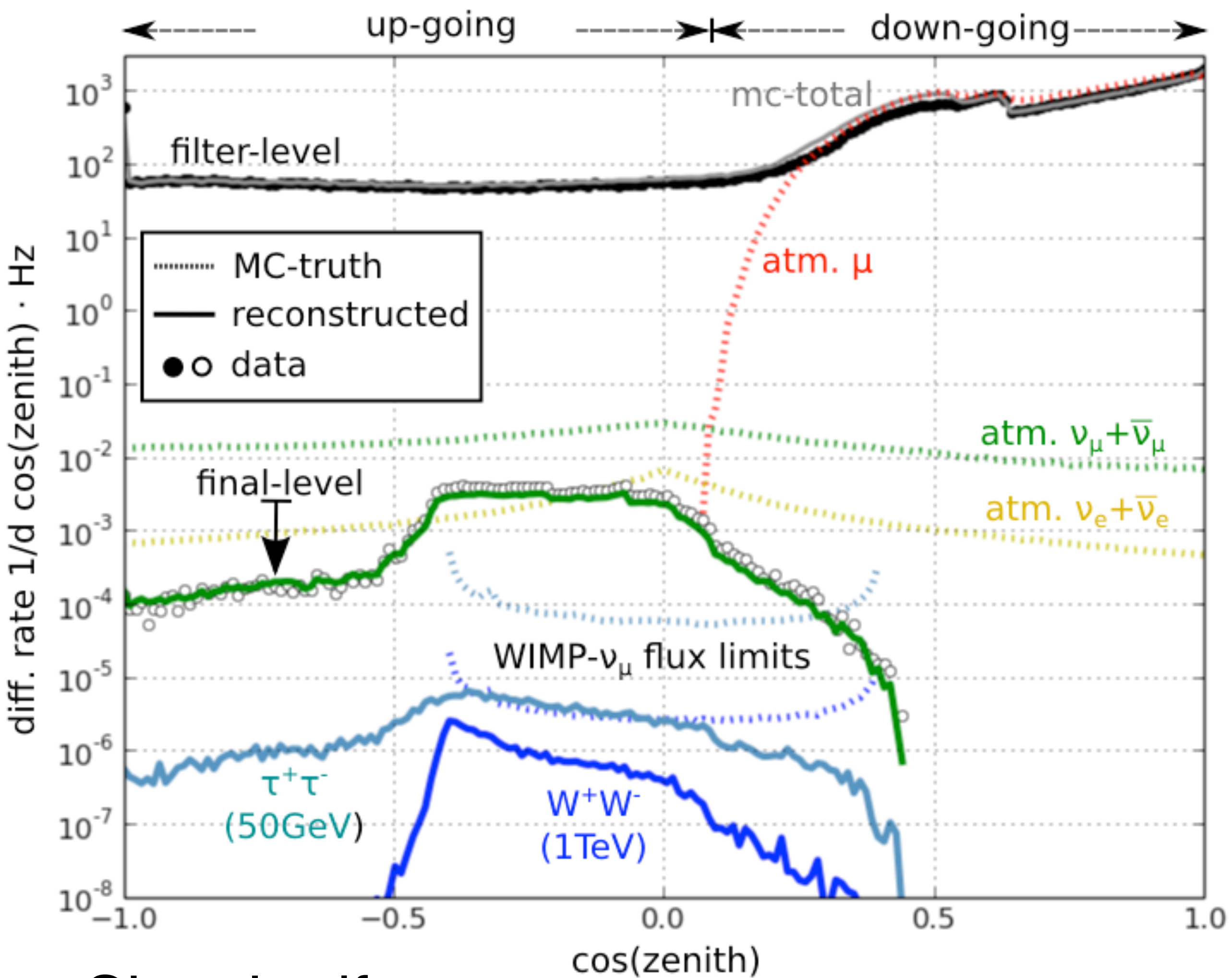




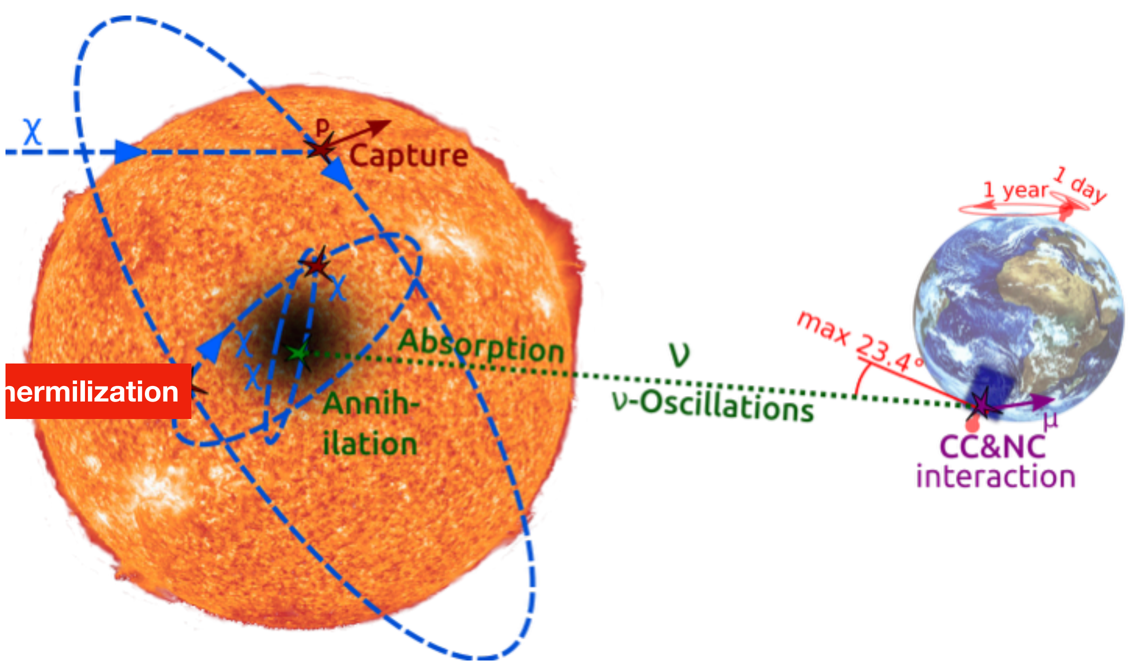


Solar Dark Matter





Search for Dark Matter in the Sun



Signal pdf:

Spectral part

$$S_i(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, E_i, m_\chi, c_{\rm ann}) = \mathscr{K}(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, \kappa_i) \times \mathscr{E}_{m_\chi, c_{\rm ann}}(E_i)$$

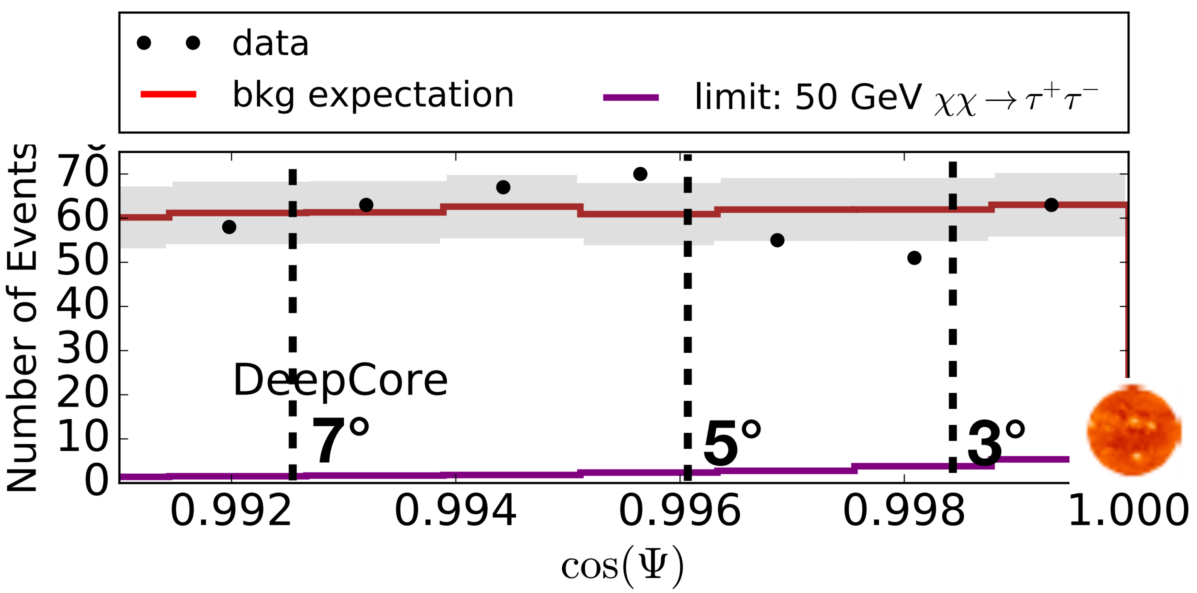
Monovariate Fisher Bingham distribution from directional statistics

Background pdf: $\mathscr{B}_i(tx_i, E_i) = B(\delta_i) \times P(E_i|\phi_{\rm atm})$

Likelihood: $\mathscr{L}(n_s) = \prod_N \left(\frac{n_s}{N} S_i + (1 - \frac{n_s}{N})\mathscr{B}_i\right)$

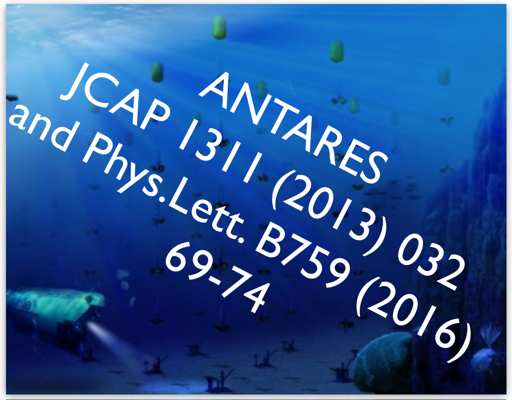
Observed events

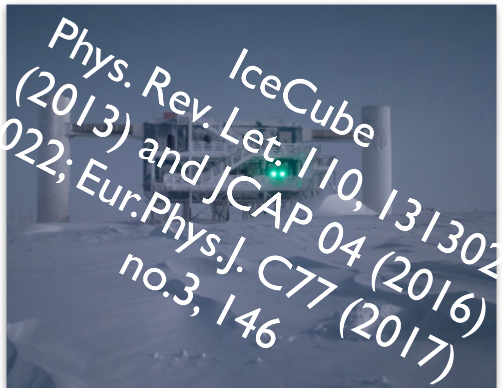
IceCube Eur.Phys.J. C77 (2017) no.3, 146

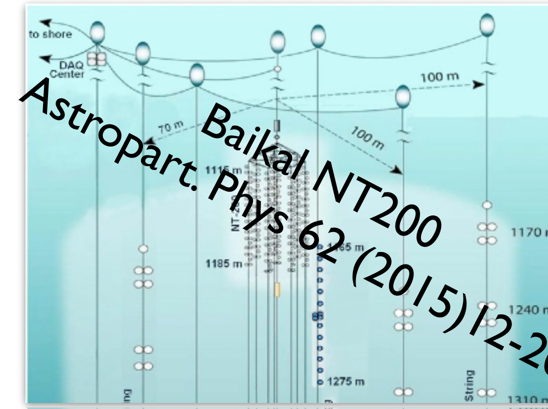


- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Observed events consistent with background only expectations

Solar Dark Matter Summary

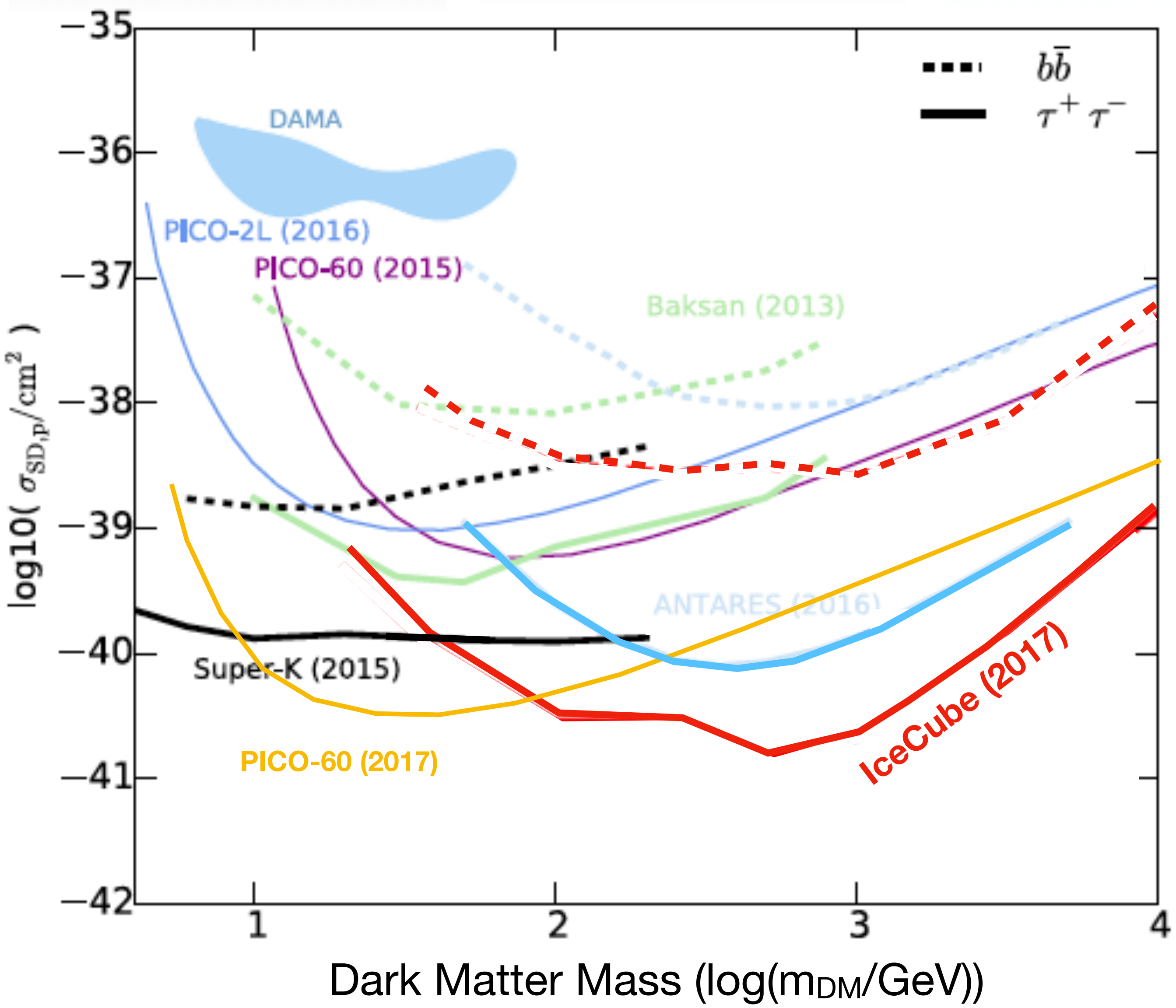


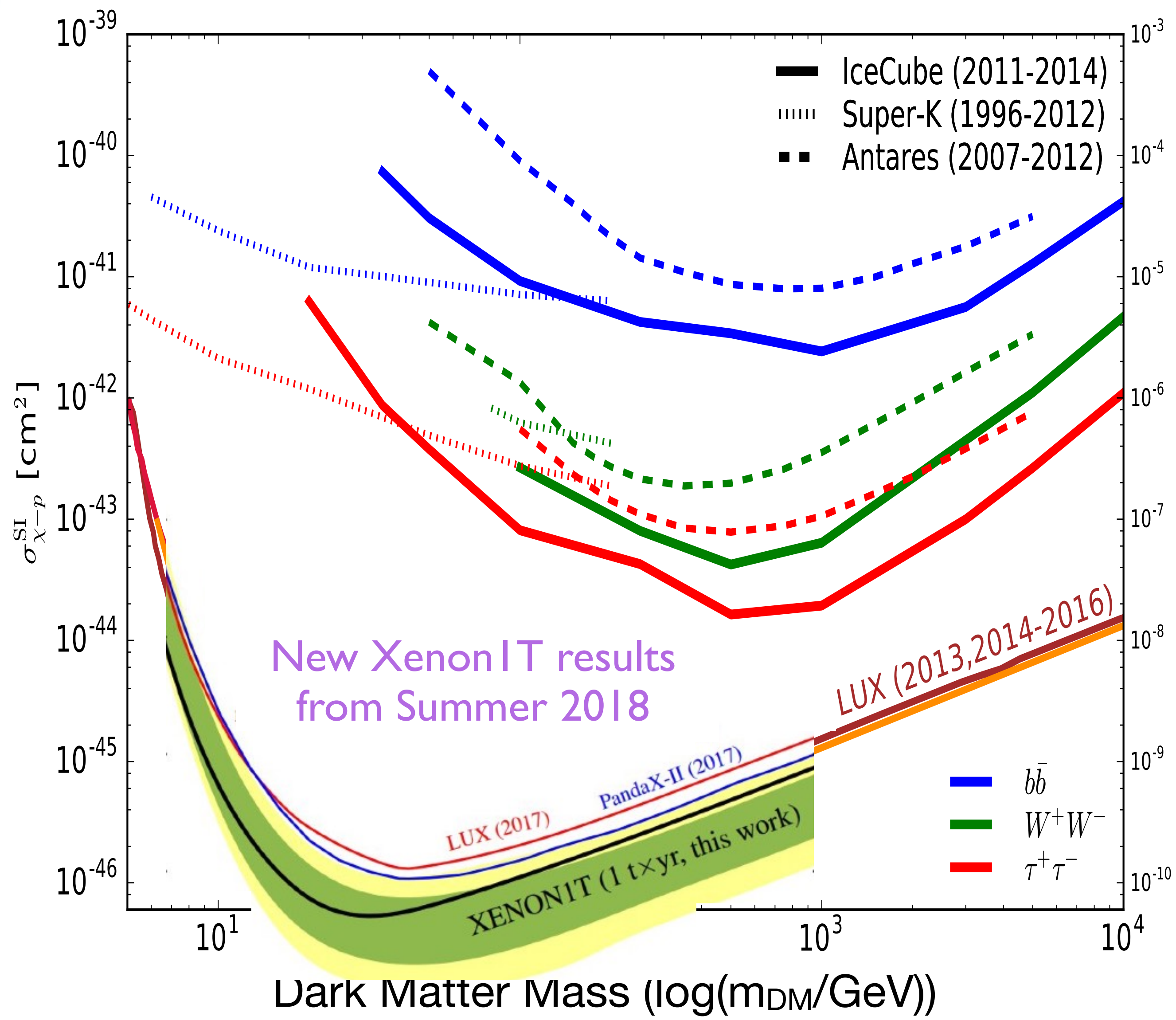




Spin-dependent scattering

Spin-independent scattering

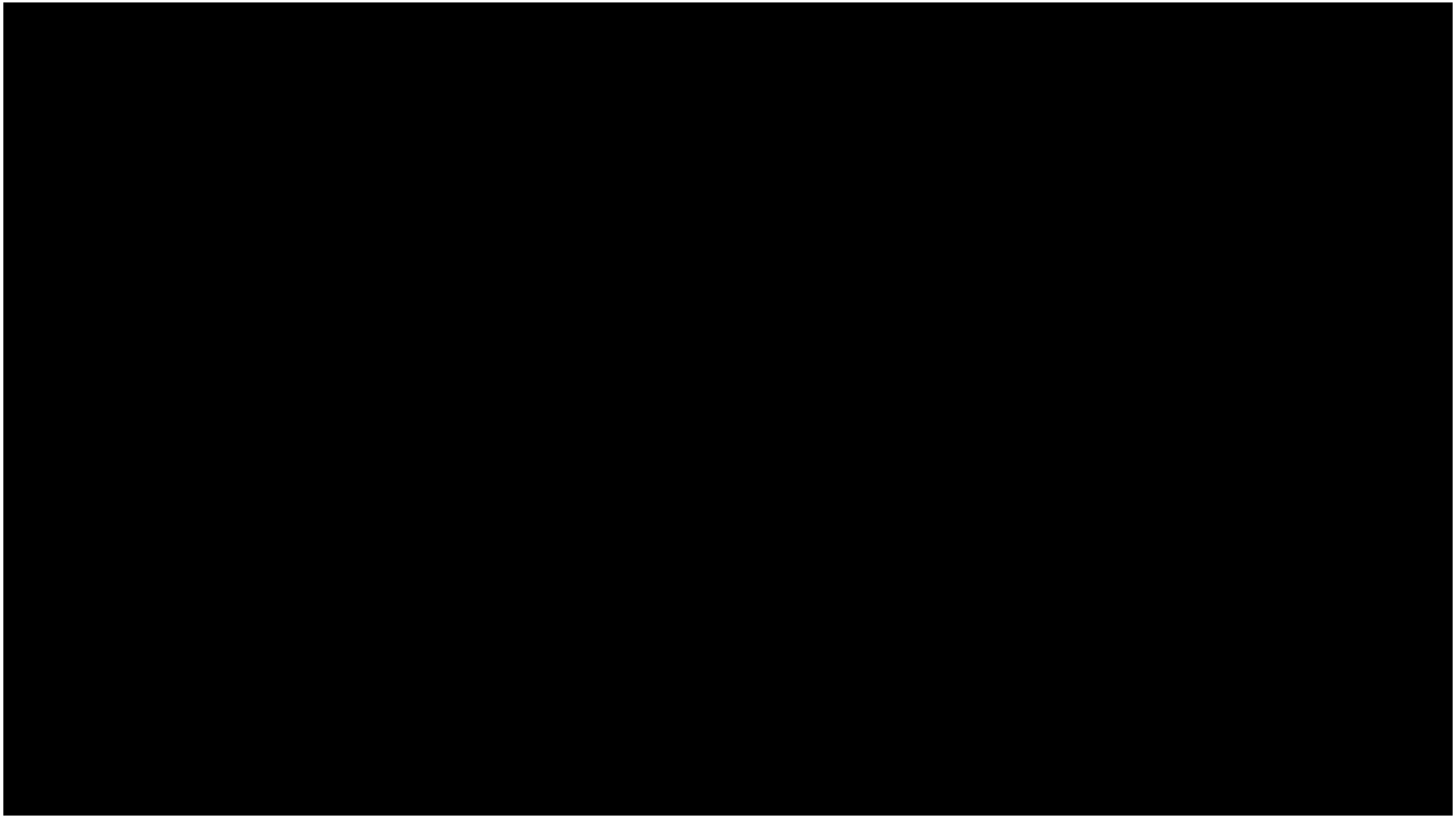




Impact of astrophysical uncertainties

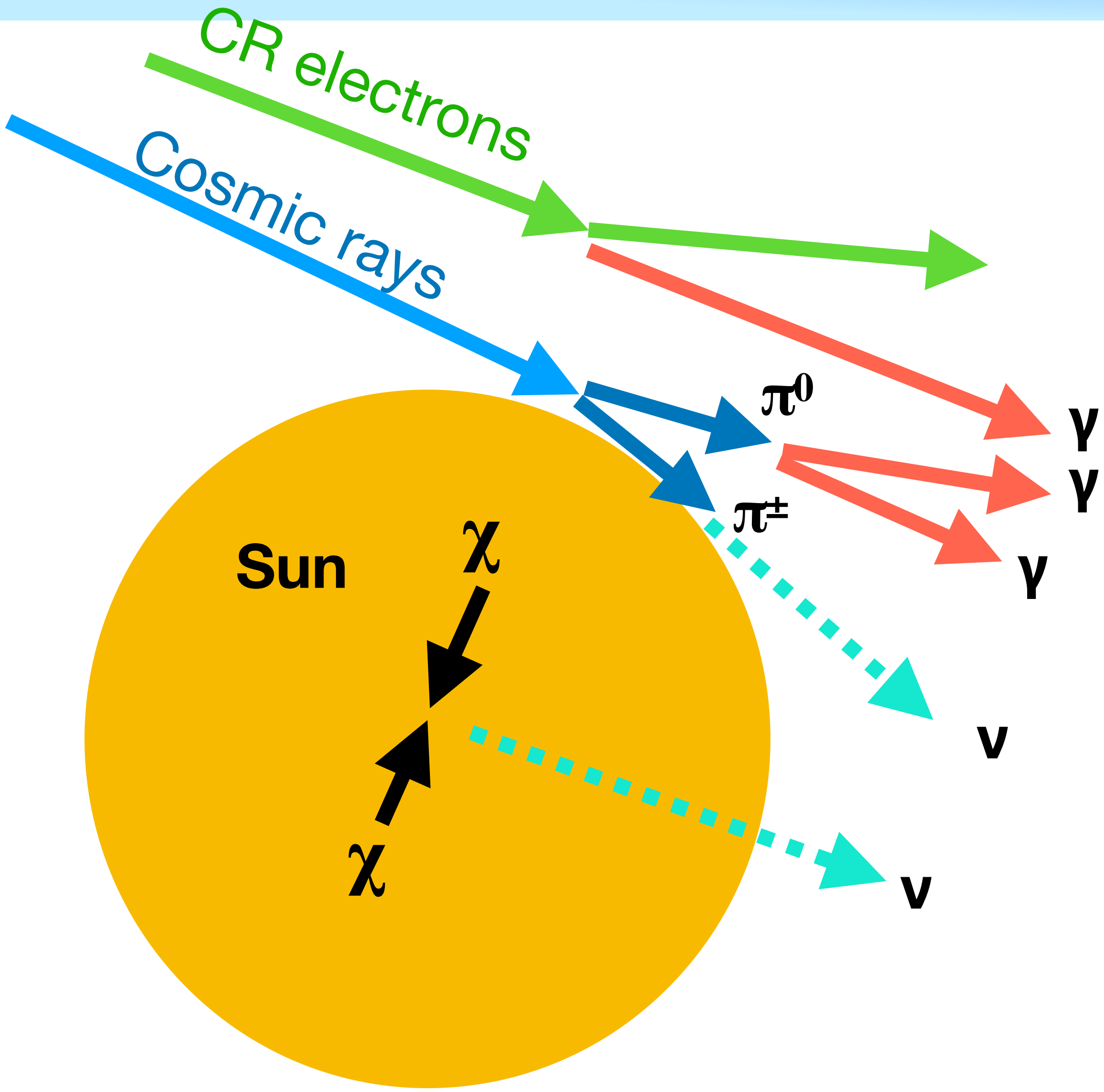
M. Danninger & C. Rott "Solar WIMPs Unraveled" -- Physics of the Dark Universe (Nov 2014)

Interactive tool to study impact of astrophysical parameters

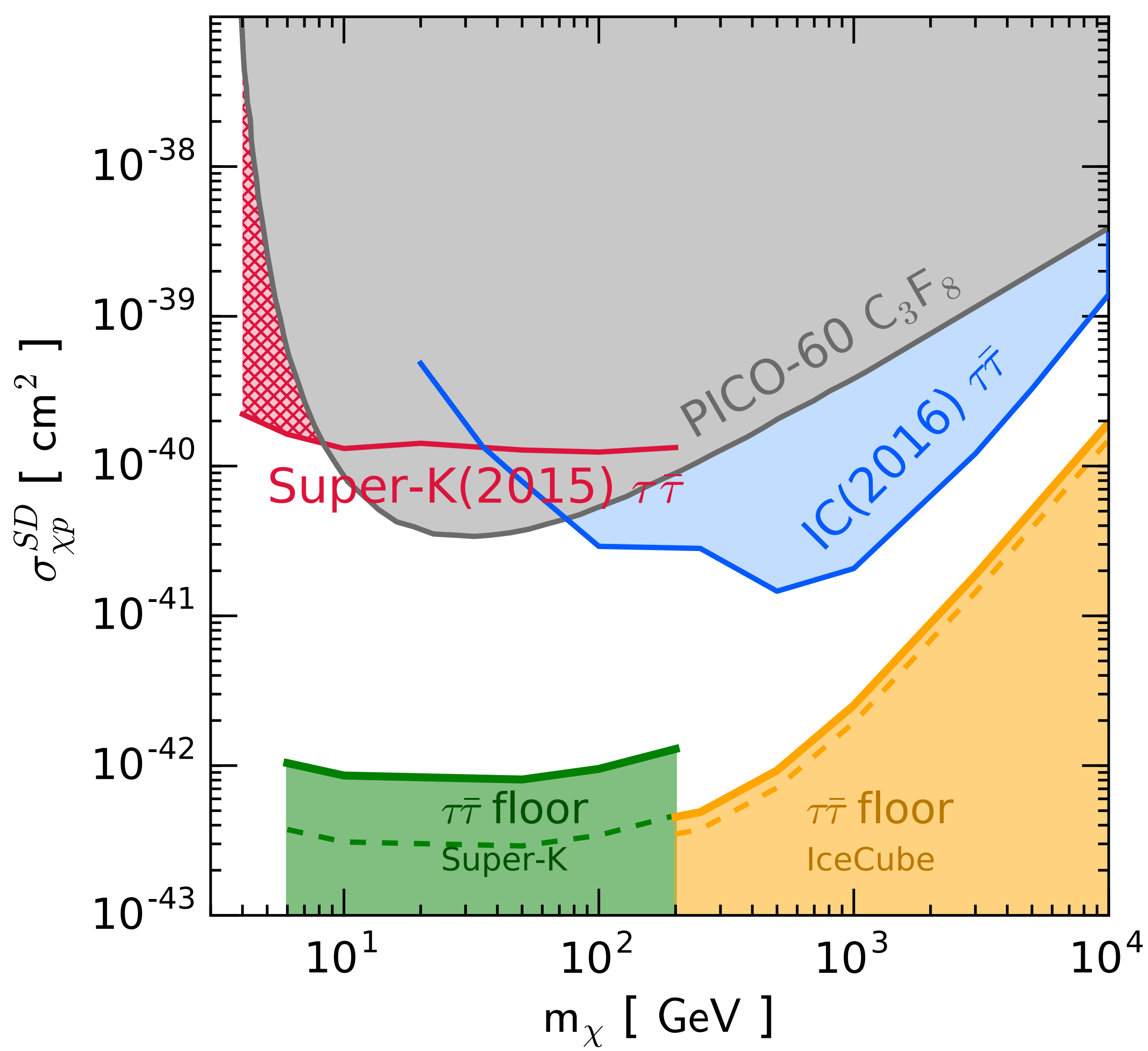


https://mdanning.web.cern.ch/mdanning/public/Interactive_figures/

Solar Atmospheric Neutrino Background



Ng, Beacom, Peter, Rott Phys.Rev. D96 (2017) no.10, 103006



- Solar Atmospheric give a new background to solar dark matter search
- However, energy spectrum expected to be different
- DM annihilation neutrinos significantly attenuated above a few 100GeV

Expect ~2events per year

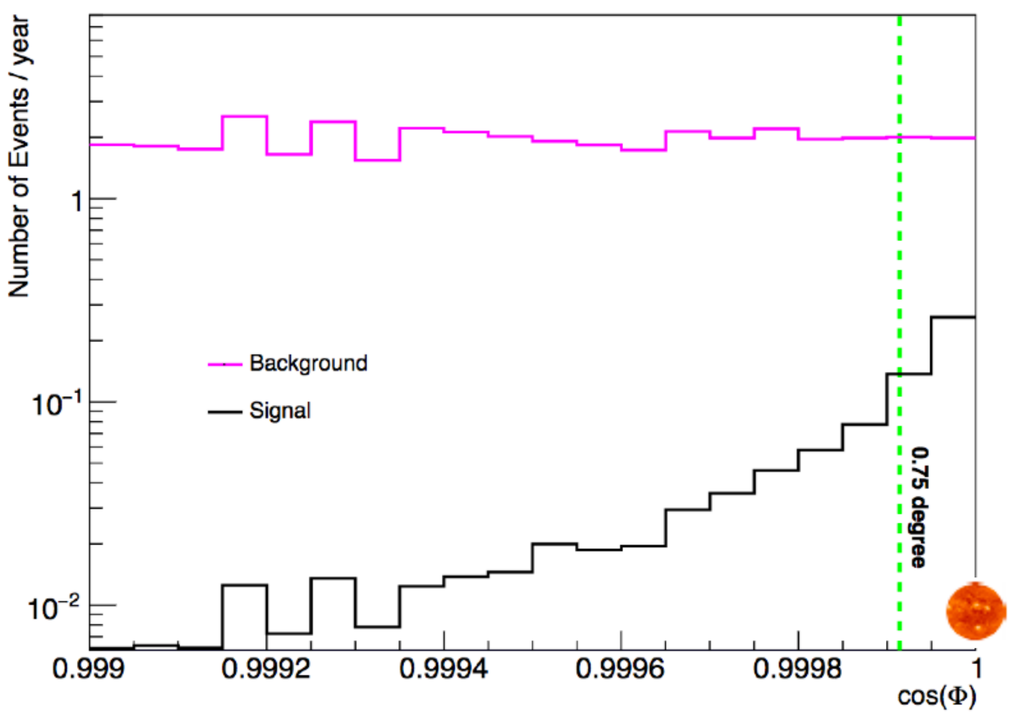
Significant discovery potential

Recent works on the Solar Atmospheric Neutrino Floor

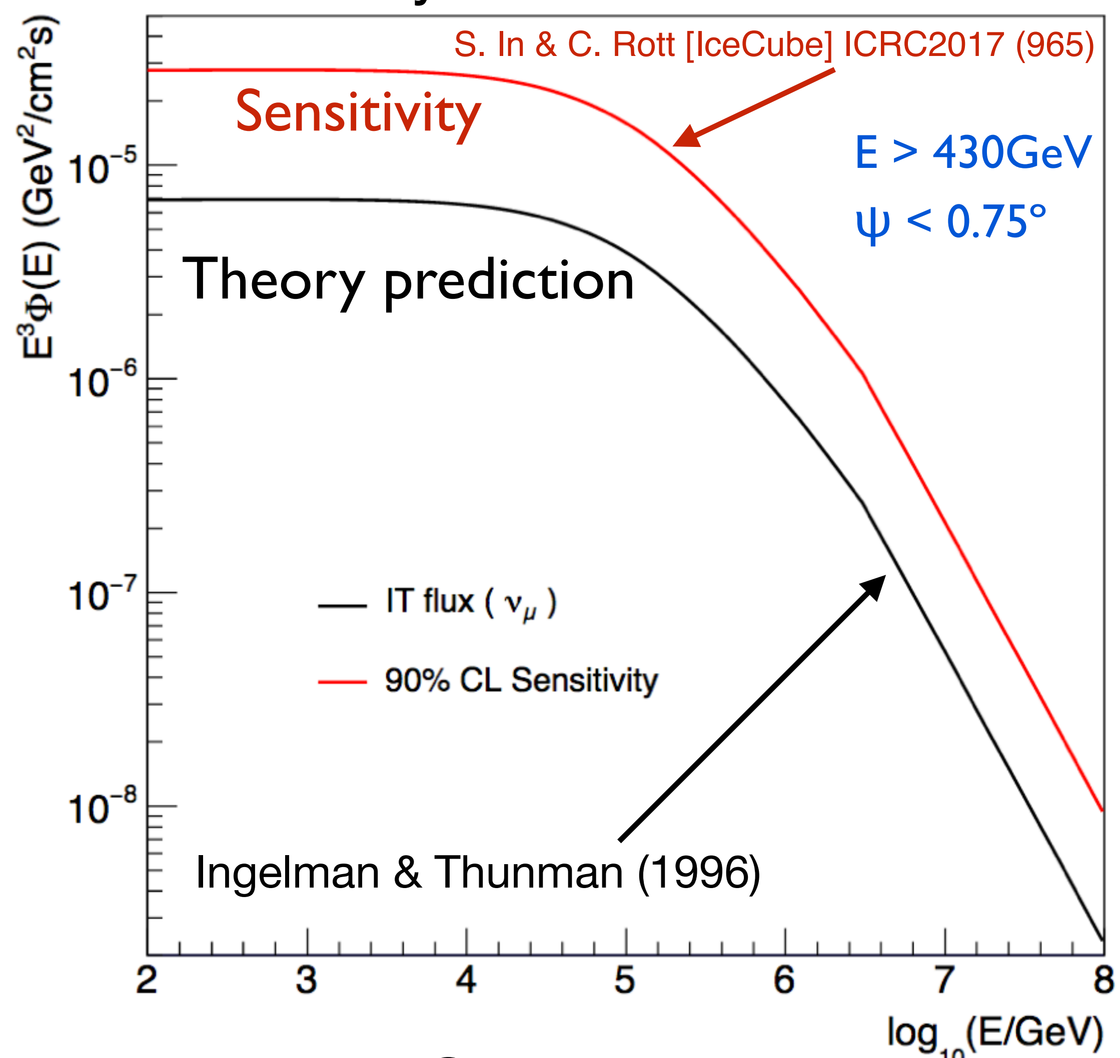
- Argüelles et al. [astro-ph/1703.07798]
- Ng et al. [astro-ph/1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, JCAP 2017 .06 (2017), p. 033, [astro-ph/1704.02892]
- M. Masip (2017), [hep-ph/1706.01290]

Solar Atmospheric Neutrino Search

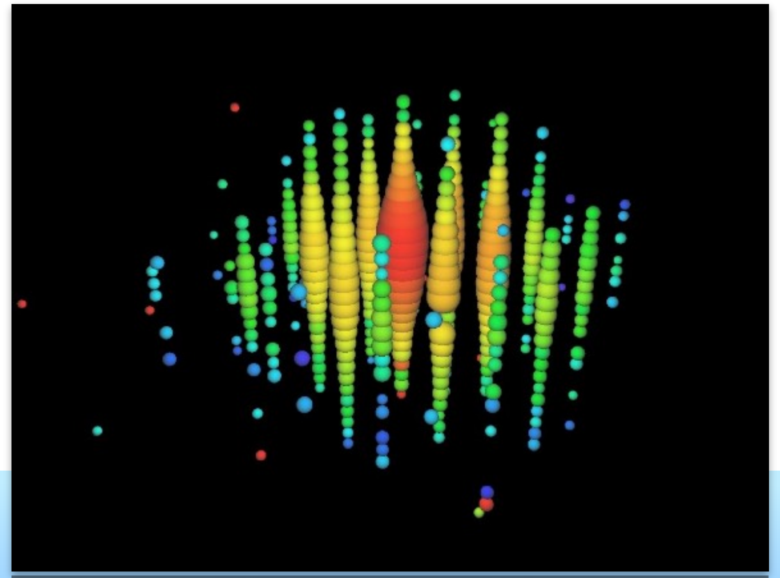
- Experimental searches have started at
  - Off-source data for background prediction
  - Cosmic-ray Sun shadow needs to be included as systematic uncertainty



Sensitivity Solar Atm. Neutrinos



- Solar Atmospheric neutrinos might be observable with IceCube
- Observing solar atmospheric neutrinos is important for:
  - Understanding solar magnetic fields;
  - Cosmic ray propagation in the inner solar system;
  - Improving models of cosmic ray interactions in the solar atmosphere;
  - Finding a high-energy neutrino point source
  - Better understand the background for dark matter searches



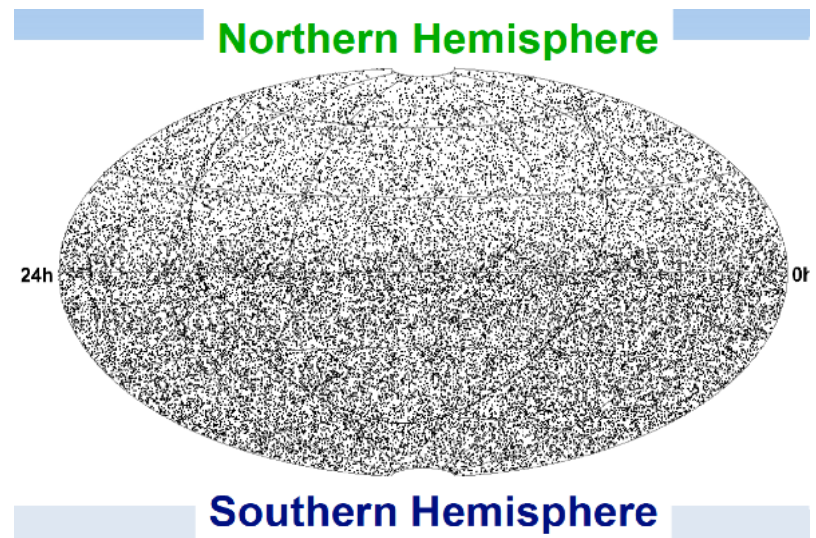
Astro-physical Neutrino Search

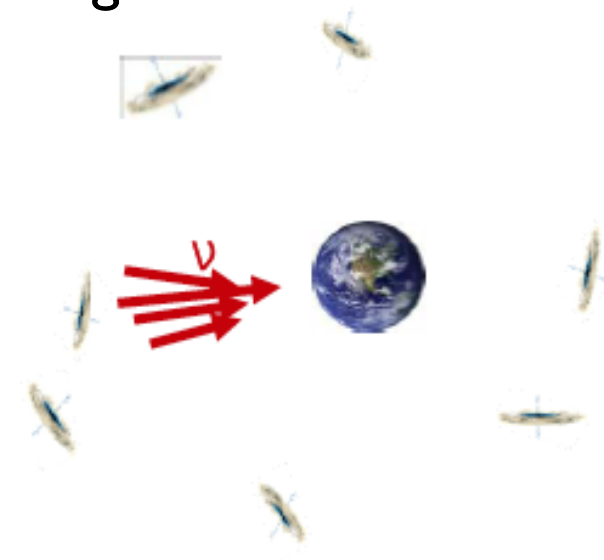
Finding Astrophysical Neutrinos

- 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

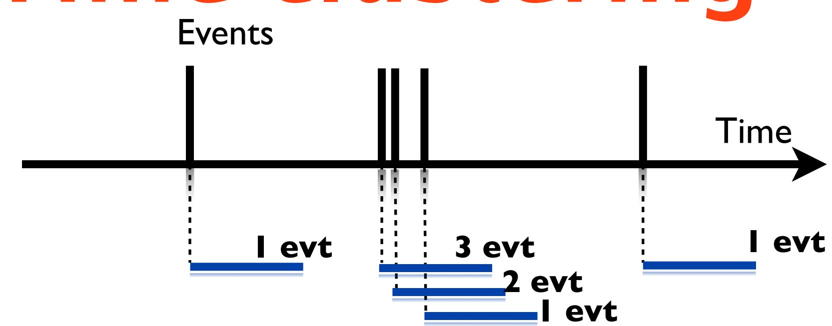
single dominant source





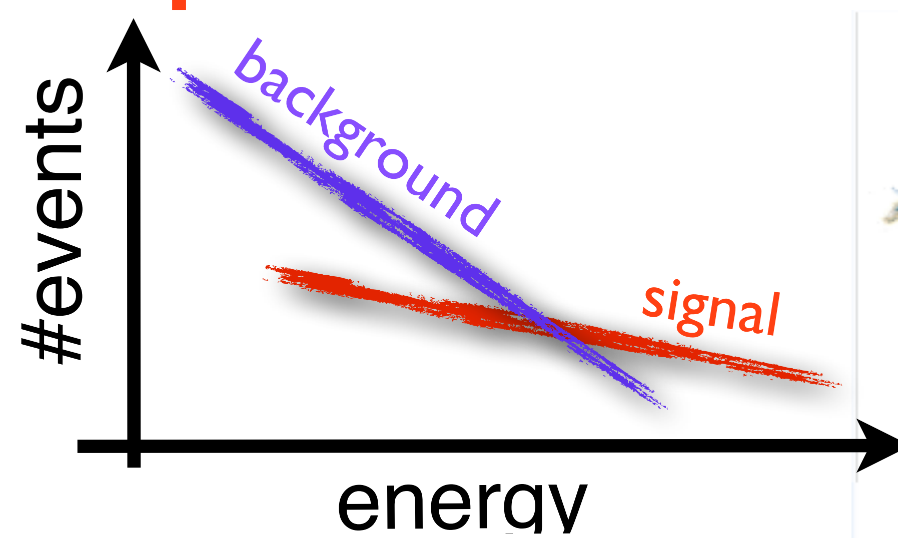
2. Time clustering

transient source

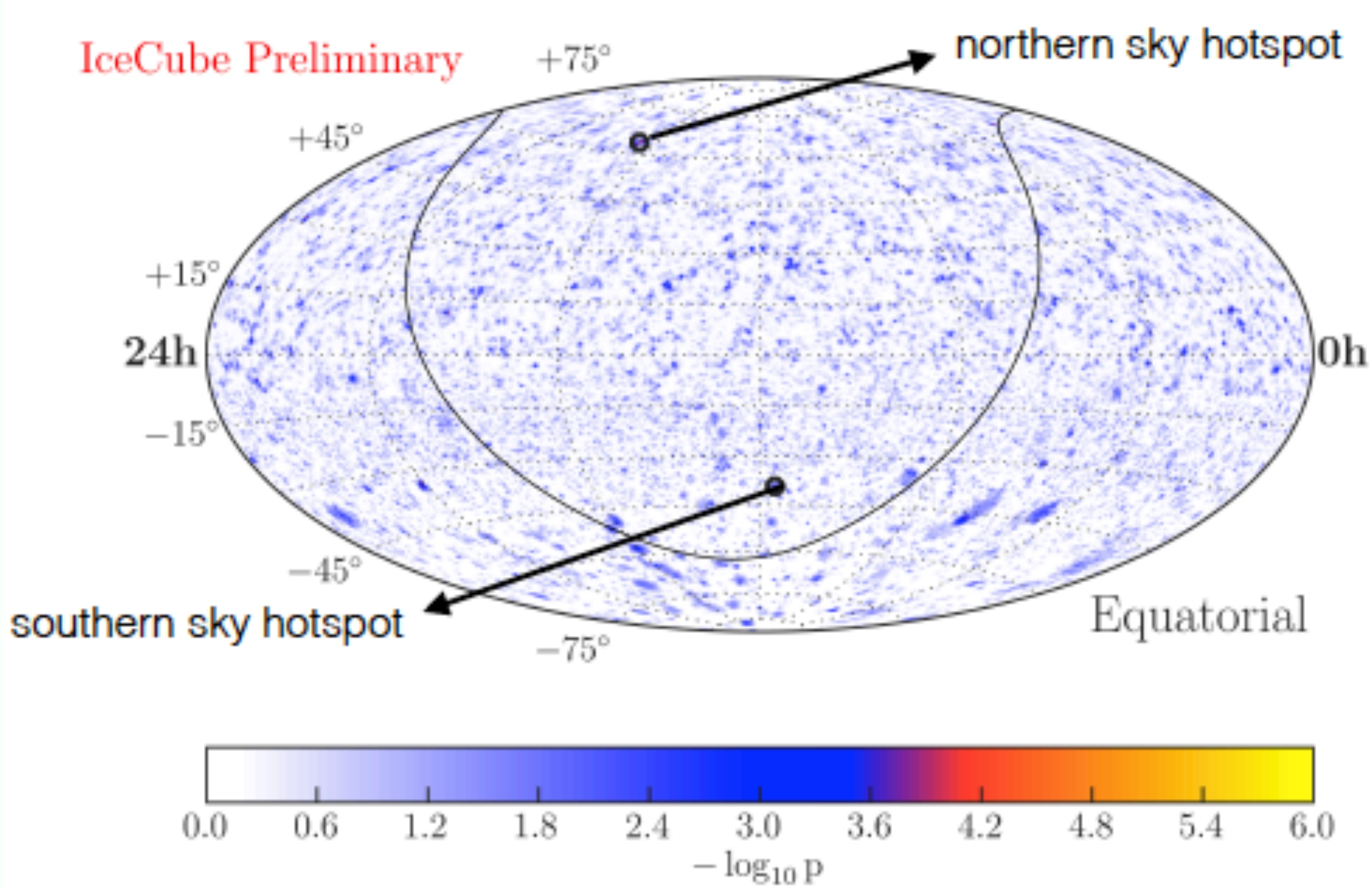


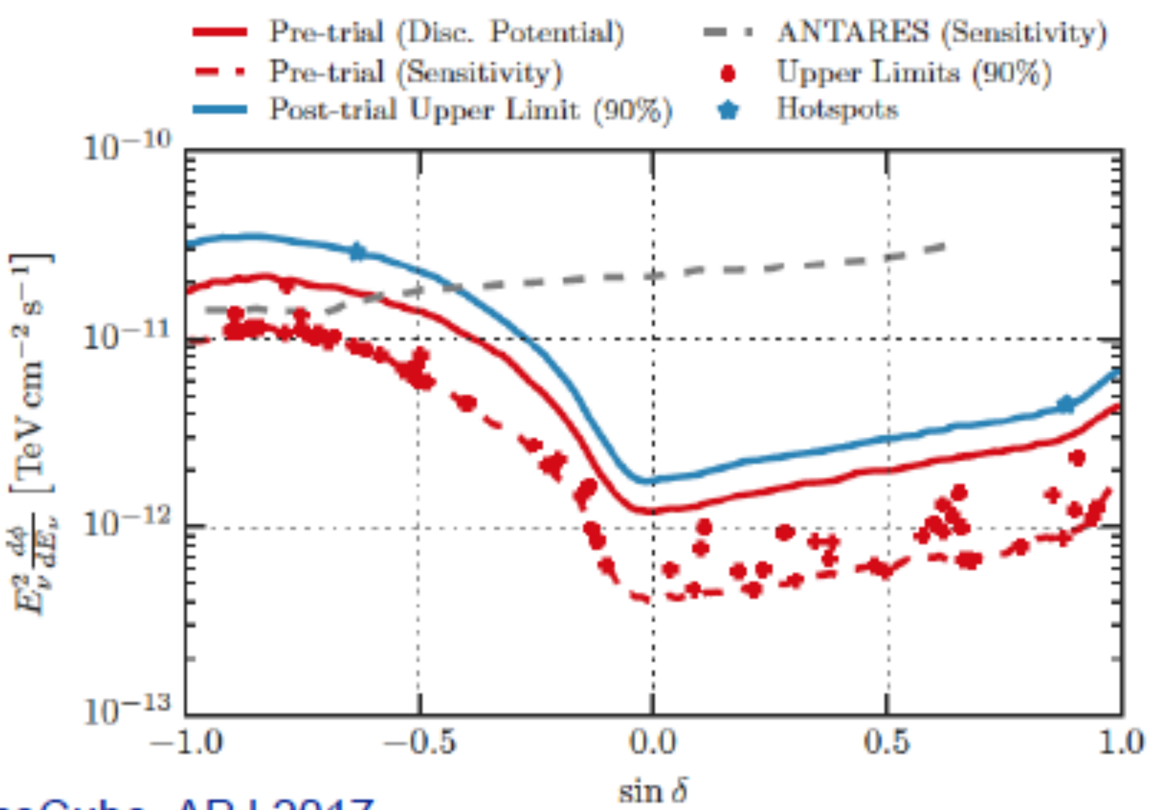
3. Spectral feature

cumulative flux



Point Source Search





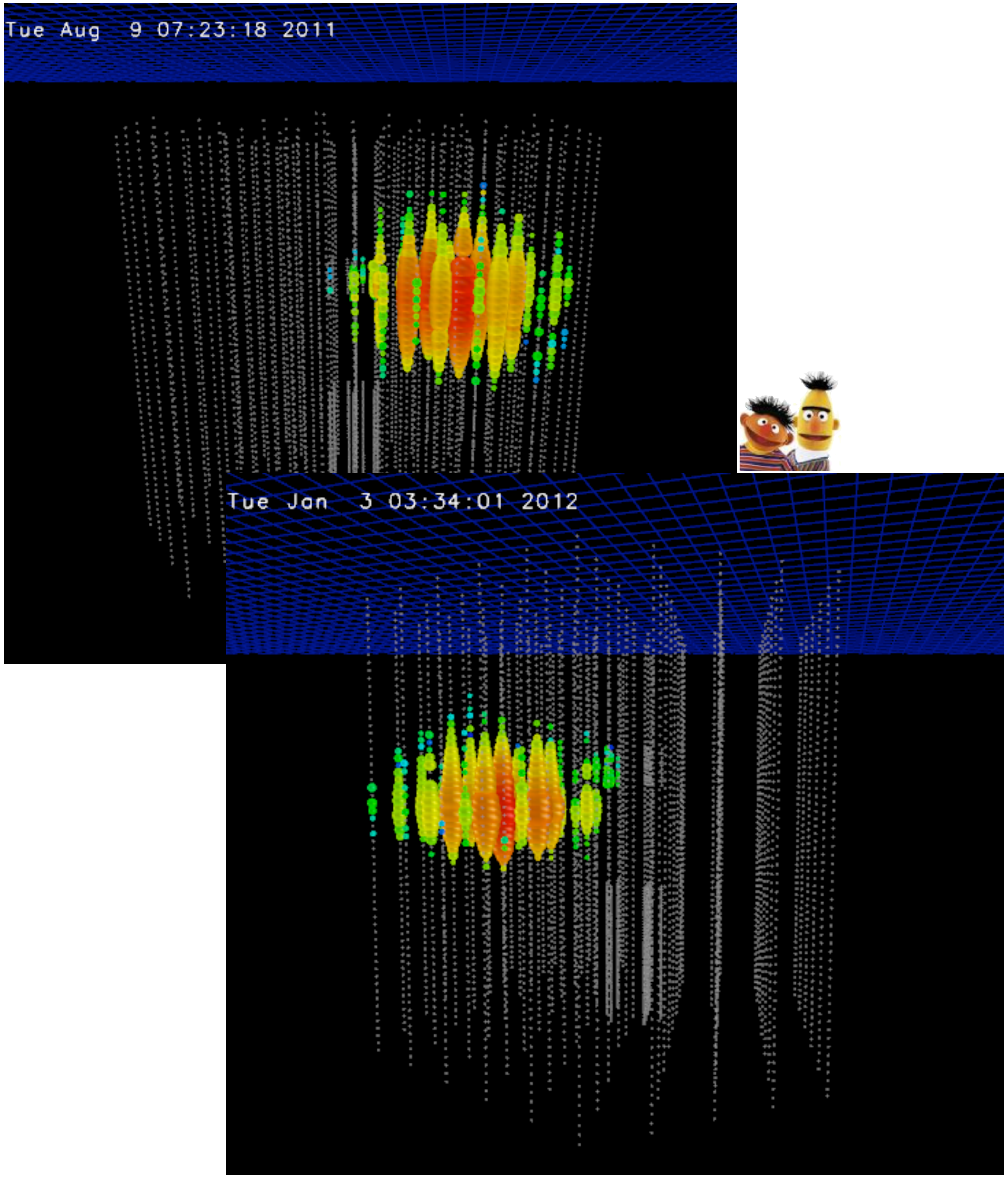
IceCube, APJ 2017

IceCube Searched for
- point sources
- extended sources
- catalog of sources
- diffuse Galactic emission

- No point/extended source found yet.
- No correlation with source catalogs found.

Search for highest energy neutrinos

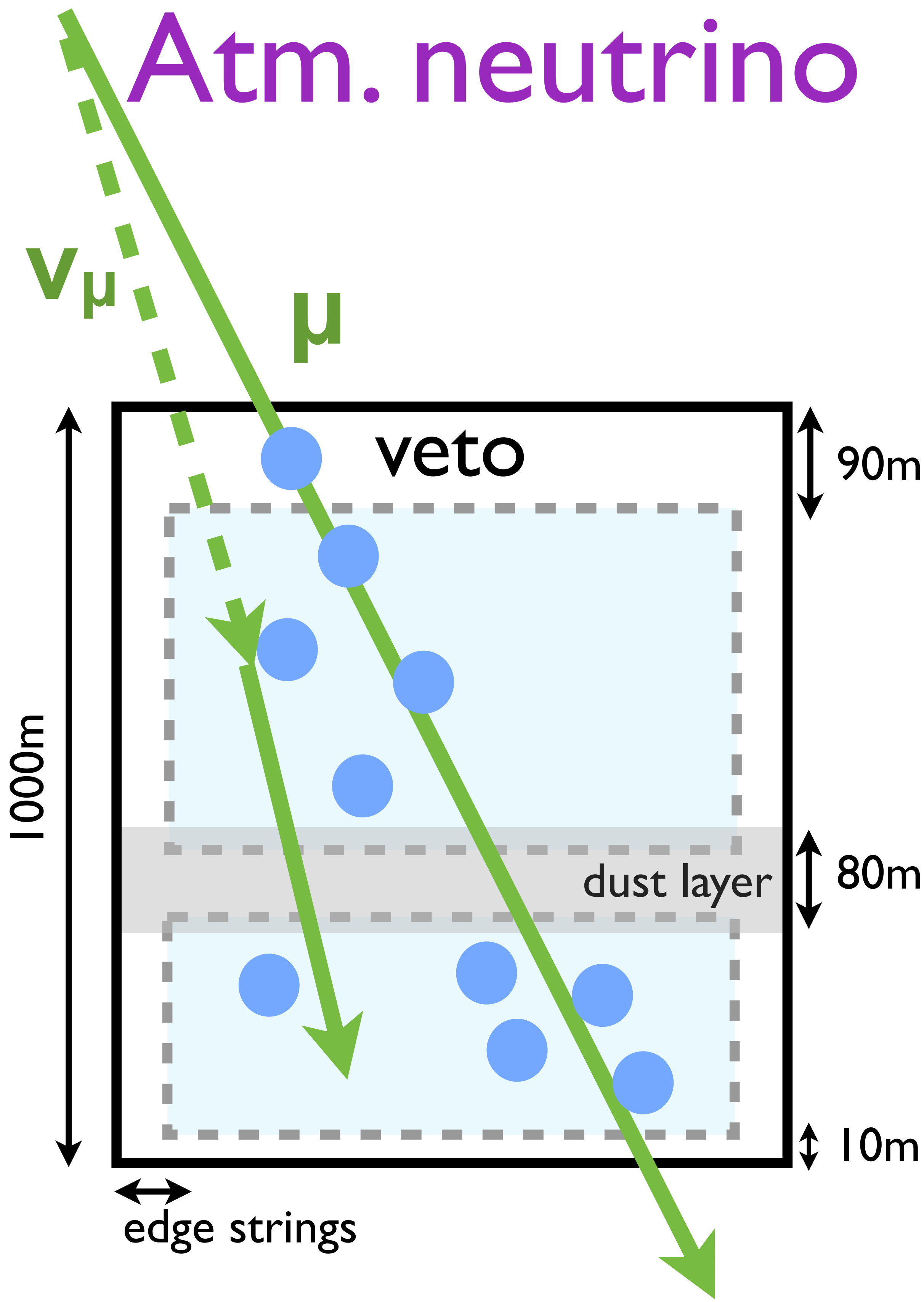
IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356



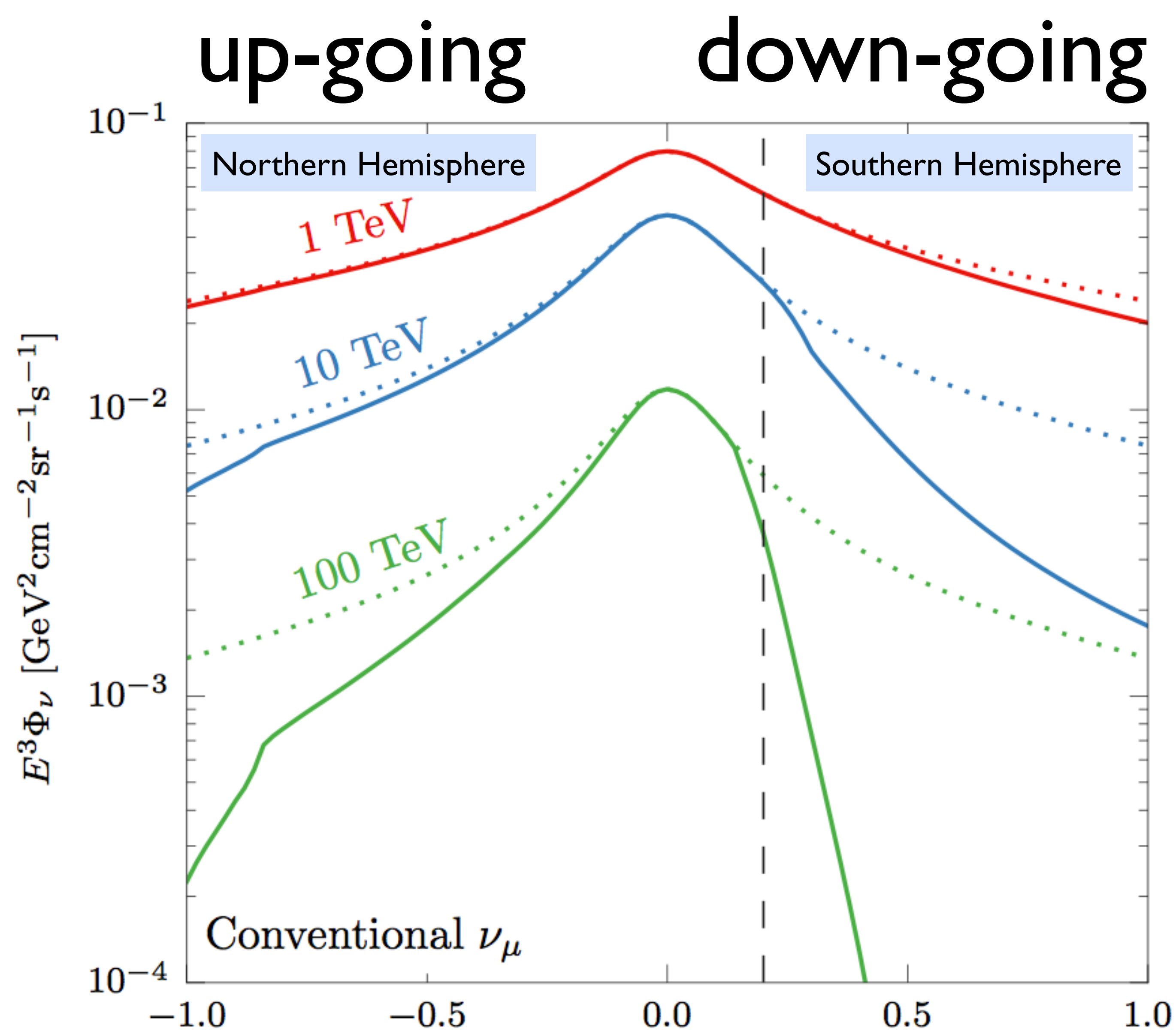
In two years of data expect 0.08 events at high energies, but observed 2 events !!

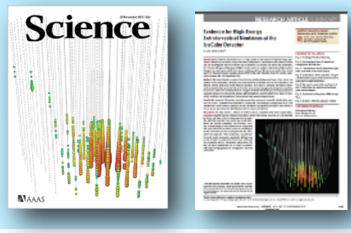
- Ernie ~1.15 PeV (~1.9 $\cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~1.7 $\cdot 10^{-4}$J)
- Topology of the events - cascades
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

Veto and Self-veto



Down-going high-energy neutrinos can be nearly background free identified as astro-physical neutrinos

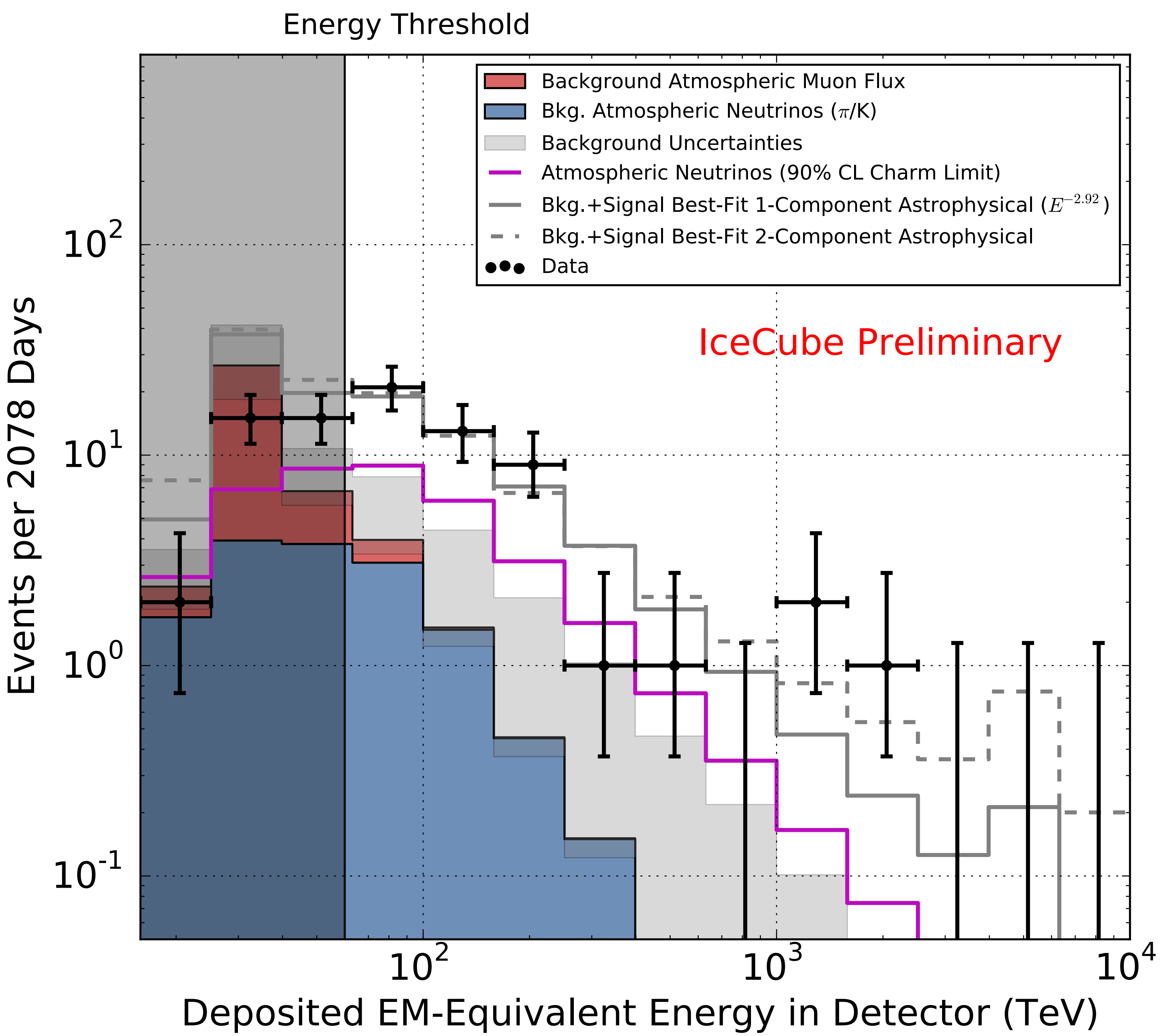


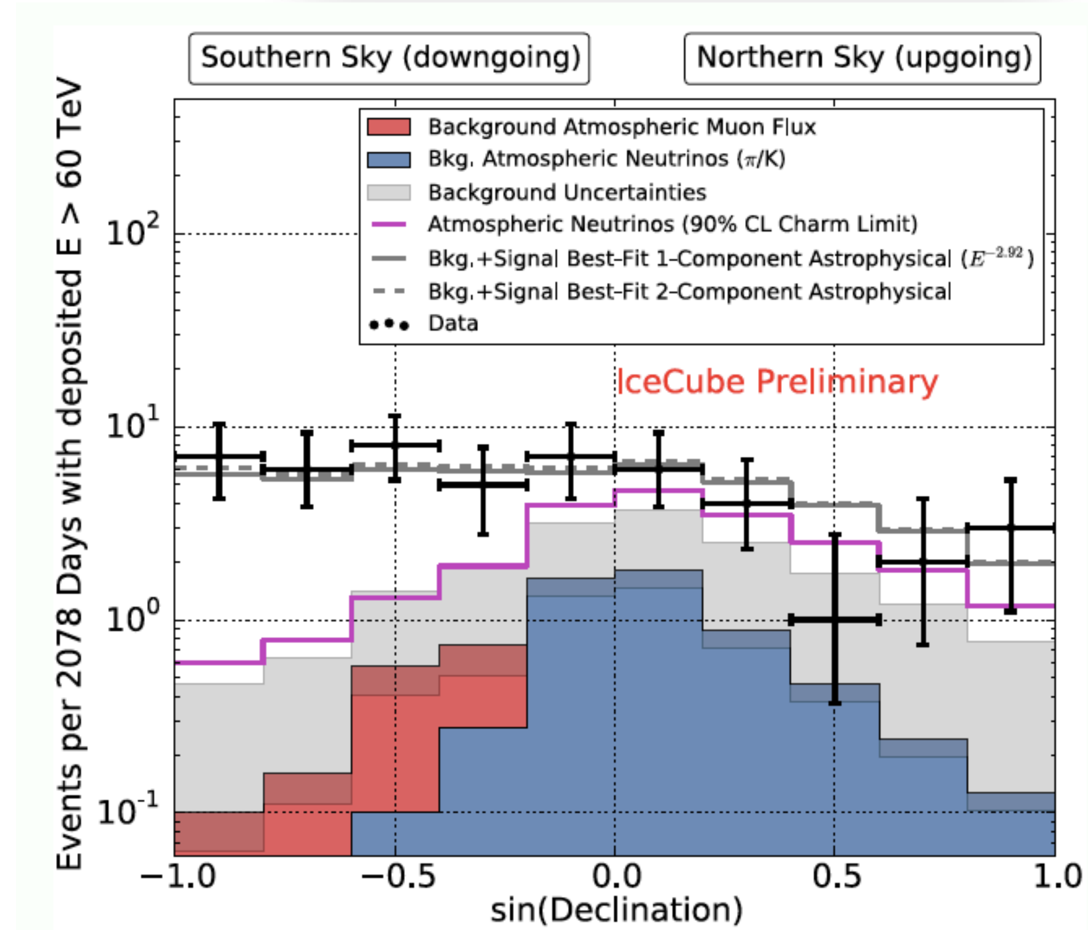


High-energy neutrino search 6years

HESE 6yrs 80 events (track-like & showers) observed

Expected from the Earth atmosphere ~41events

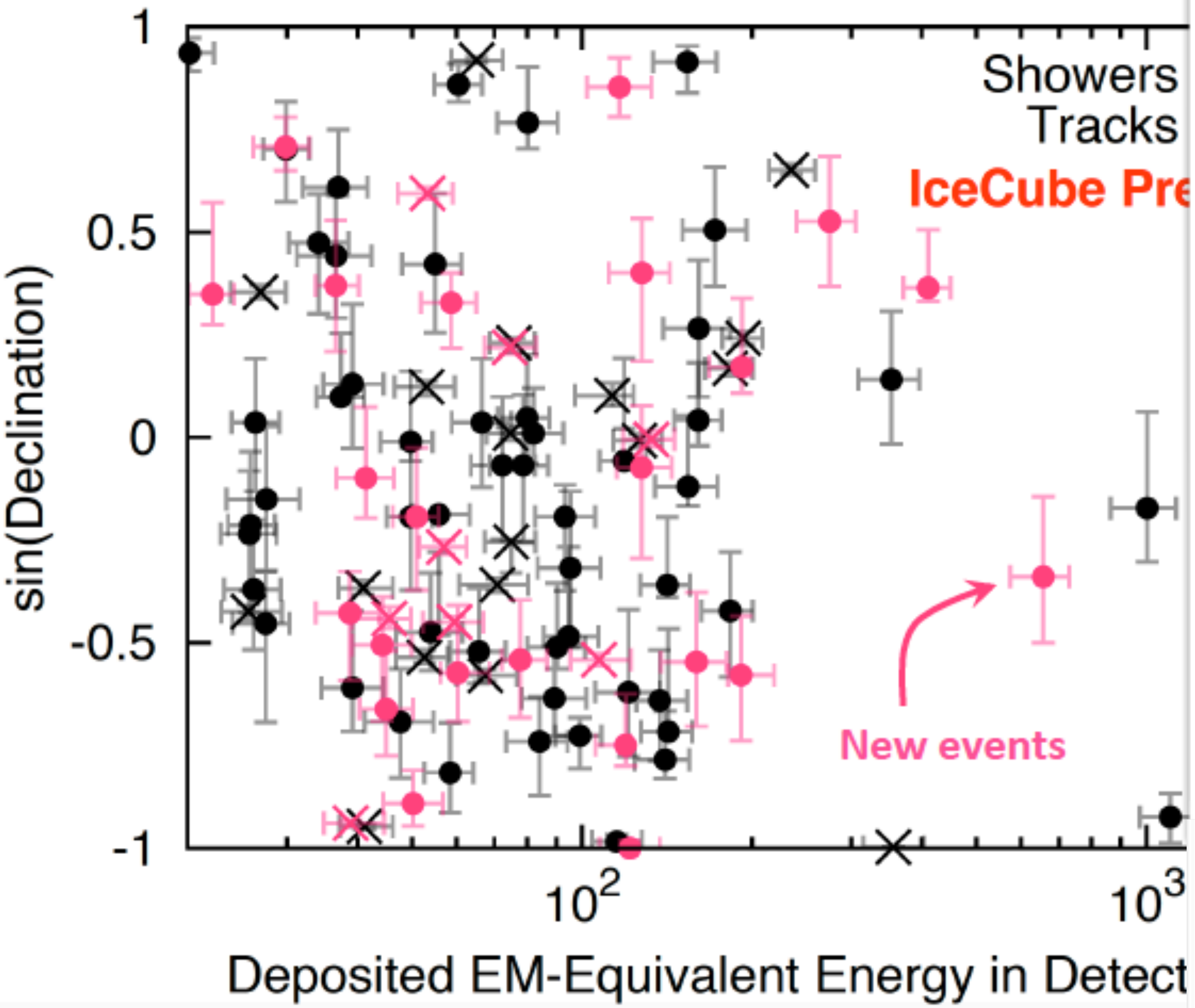




Best fit spectral index ($E^{-\gamma}$):
$\gamma=-2.92^{+0.33}_{-0.29}$

HE

IceCube Collaboration, *Science* 342, 1242856 (2013)




Menü | Politik Meinung Wirtschaft Panorama Sport Kultur Netzwelt Wissenschaft mehr ▼

WISSENSCHAFT Schlagzeilen | Wetter | DAX 13.059,84 | TV-Programm | Abo

Nachrichten > Wissenschaft > Natur > Neutrinos > Neutrinos im IceCube-Experiment: Erde verschluckt Geisterteilchen

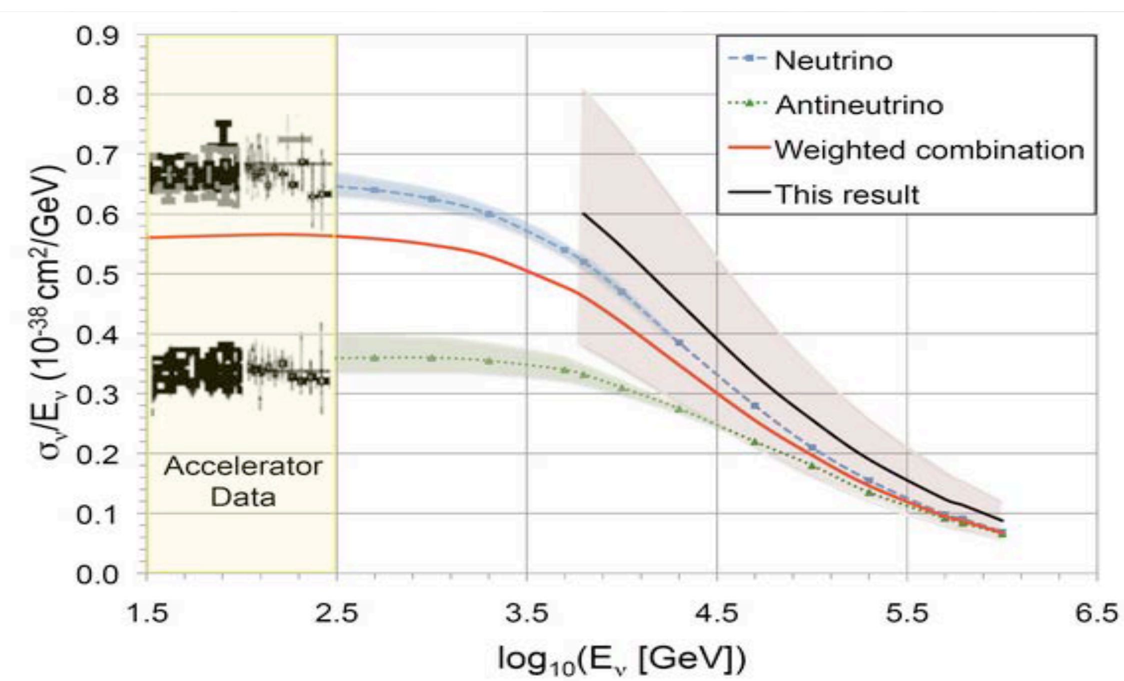
Neutrino-Experiment

Erde verschluckt geheimnisvolle Geisterteilchen

Neutrinos rasen weitgehend ungestört durchs All, weil sie fast nicht mit normaler Materie interagieren. Aber nur fast. Ausgerechnet unsere Erde ist ein effizienter Neutrino-Killer, wie ein Experiment beweist.

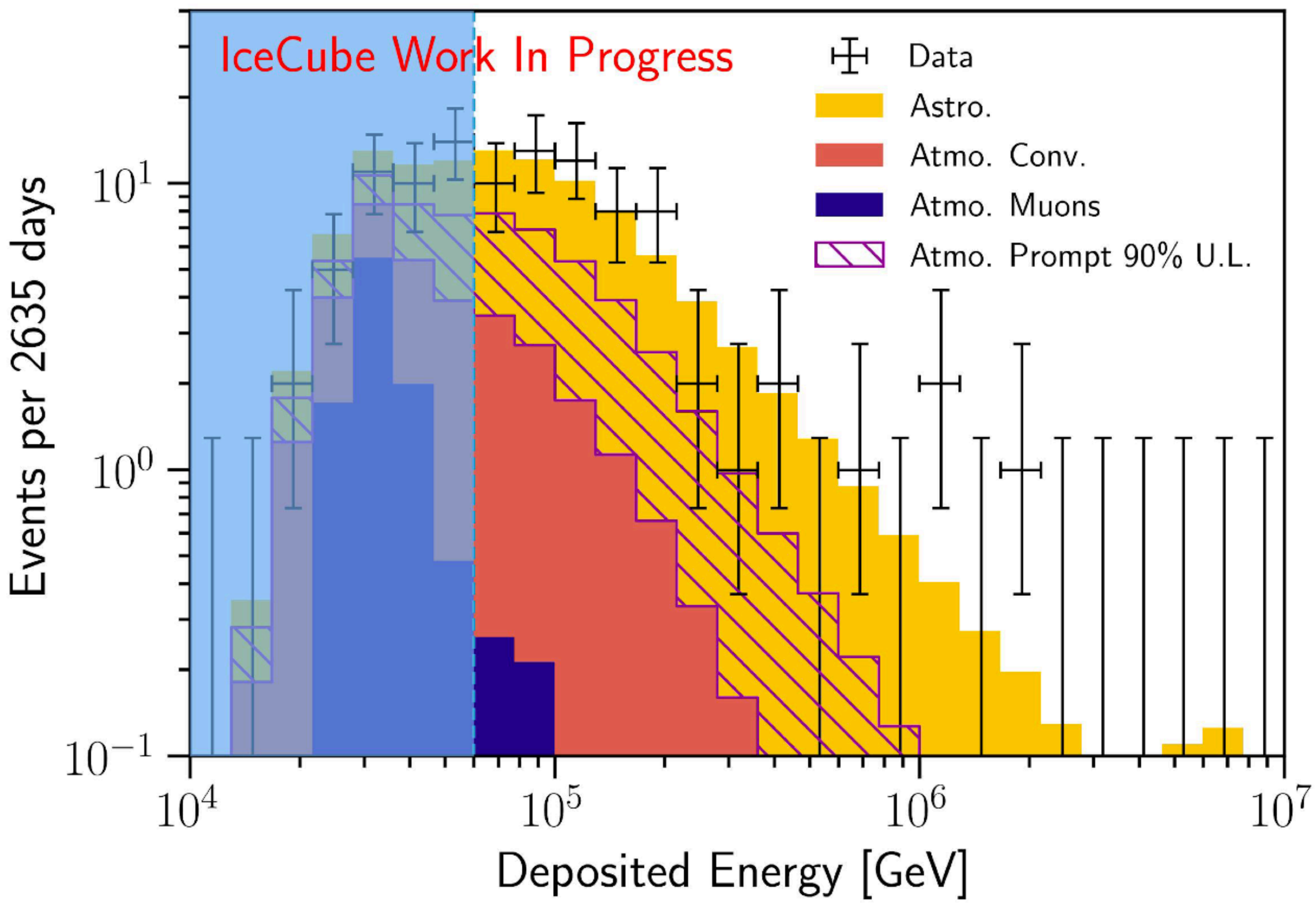
Von Christoph Seidler

Fotos



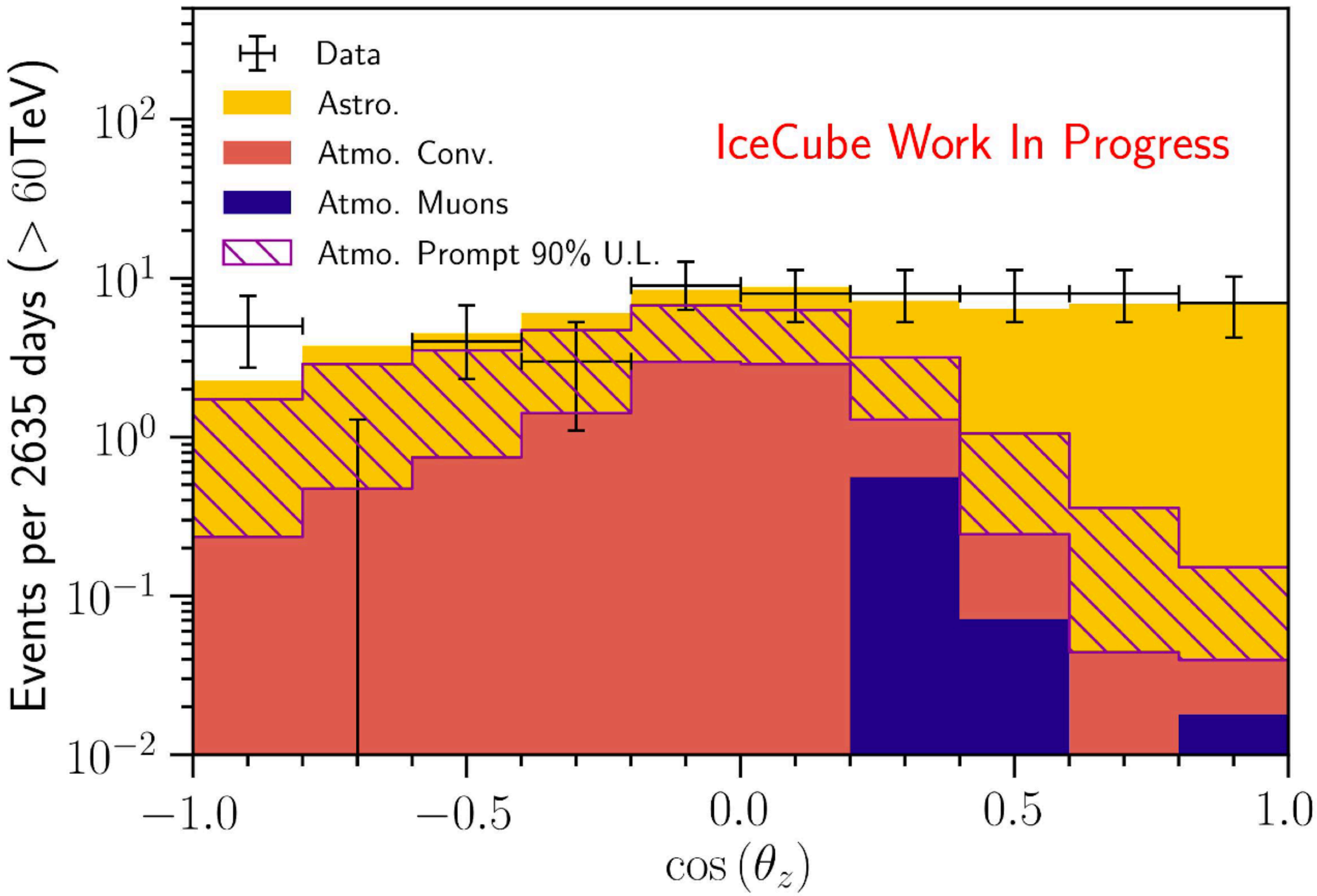
- Recently unblinded 1.5 additional years of data (new ca
- Topology ID added (Cascades, Tracks, Double Cascades
- Above 60TeV: 60 events - 17 new events in 2016/2017
- All energies: 102 events - 31 new events in 2016/2017 s

HESE 7.5years Energy spectrum



- Compatible with benchmark single power-law model.
- Best fit spectral index ($E^{-\gamma}$): $\gamma=2.91^{+0.33}_{-0.22}$
- $E^2\phi = 2.19^{+1.10}_{-0.55} \times 10^{-8} \times (E\ /\ 100\mathrm{TeV})^{-0.91}$ GeV cm^{-2} s^{-1} sr^{-1}

HESE 7.5yrs Zenith angle distribution



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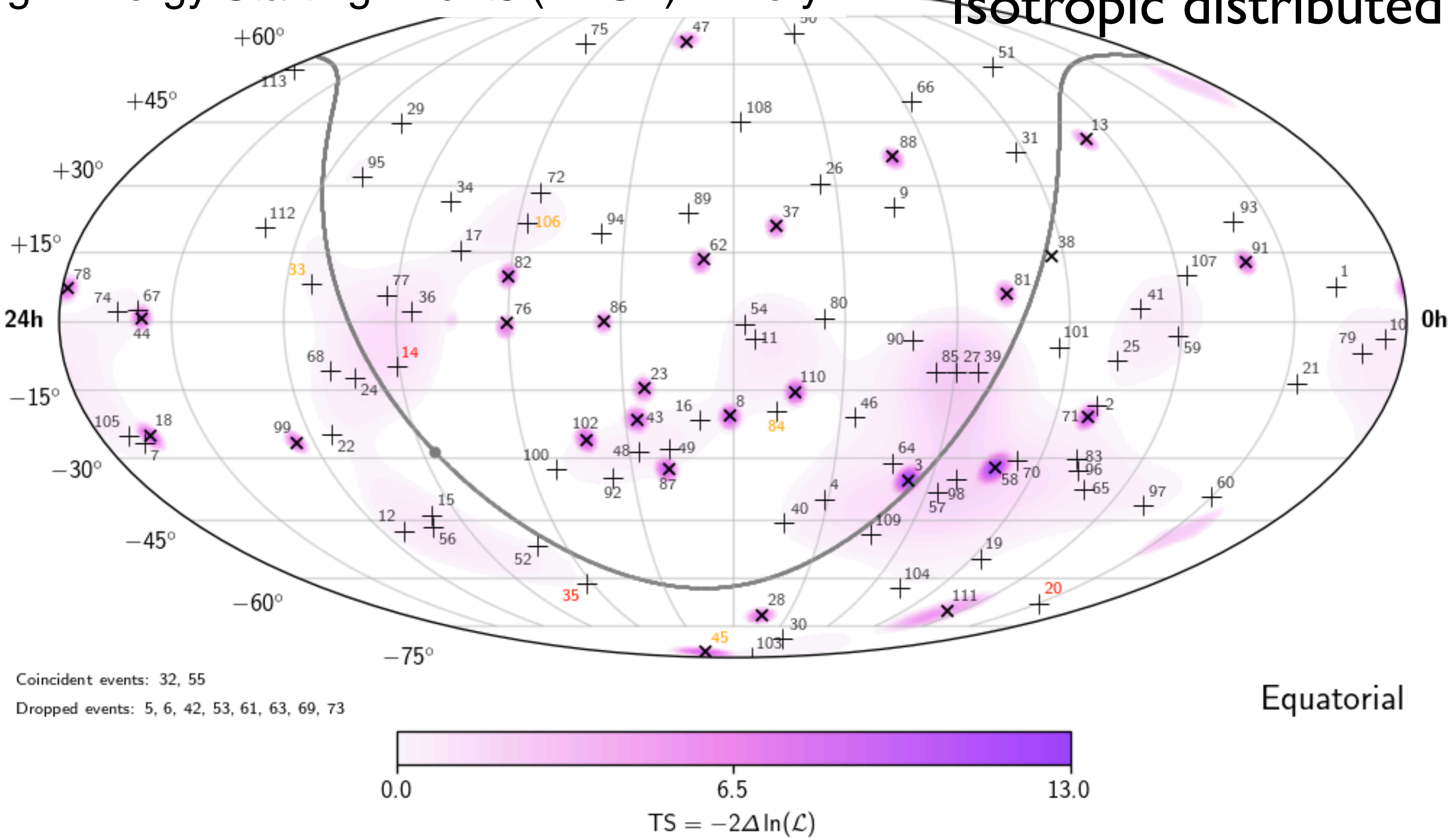
- $E^2\phi = 2.19^{+1.10}_{-0.55} \times 10^{-8} \times (E / 100\text{TeV})^{-0.91}$ GeV cm^{-2} s^{-1} sr^{-1}

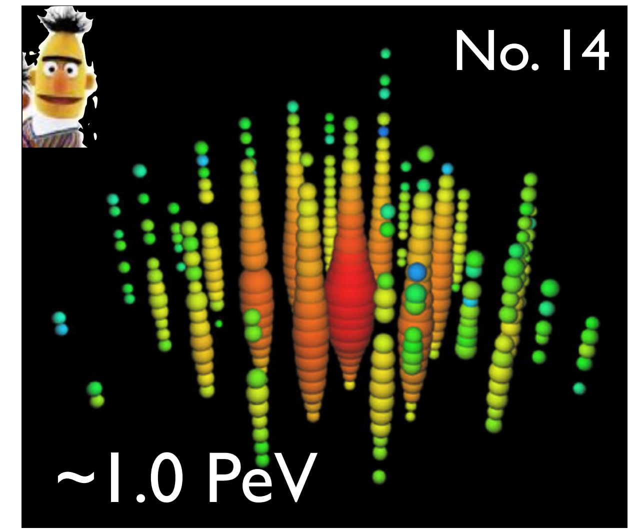
IceCube Collaboration, *Science* 342, 1242856 (2013)

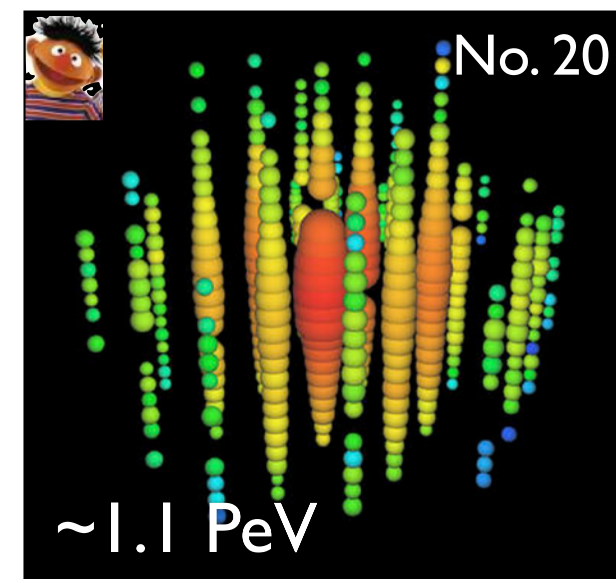
High-Energy Starting Events (HESE) – 7.5 yr

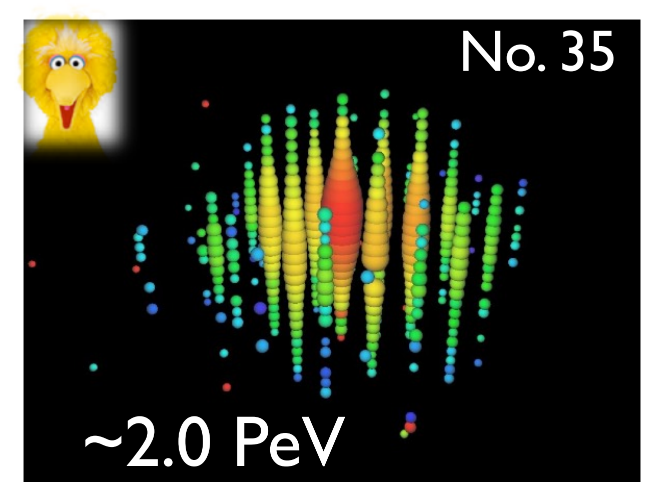
Isotropic distributed

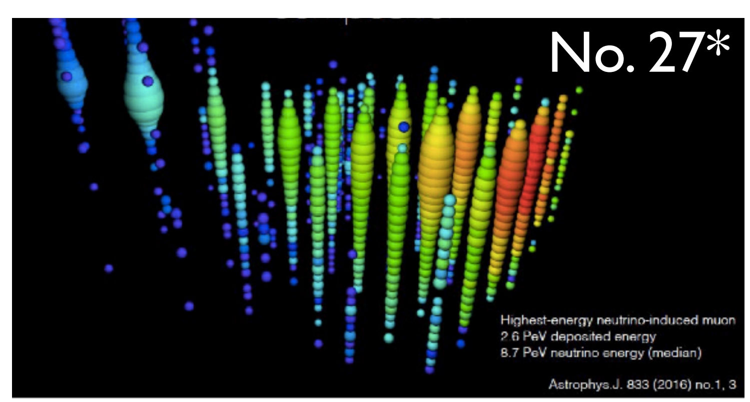


$E < 300\,\mathrm{TeV}$ $300\,\mathrm{TeV} < E < 1\,\mathrm{PeV}$ $1\,\mathrm{PeV} < E$





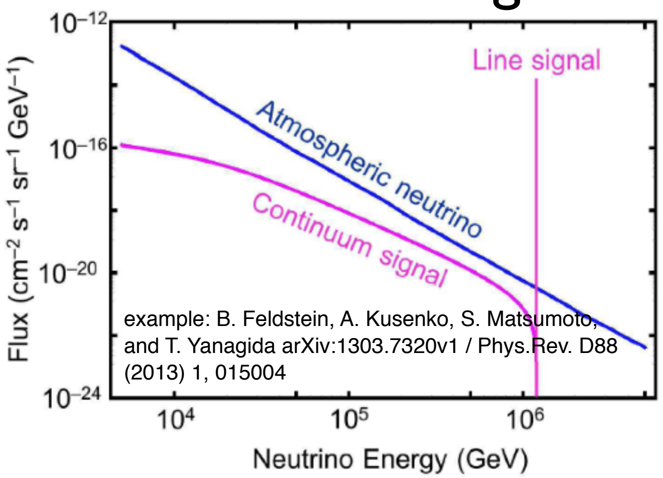




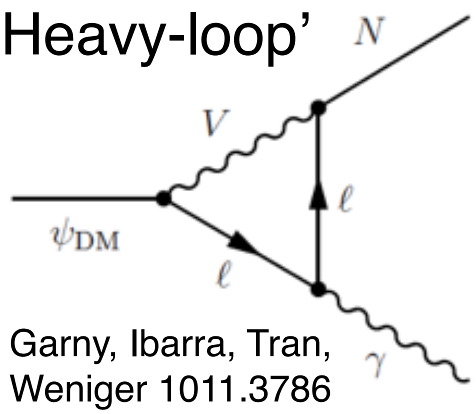
No evidence for point sources, nor a correlation with the galactic plane

Heavy Dark Matter Decay

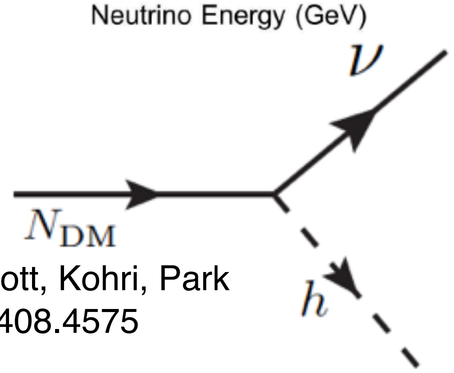
Decay process might produce mono-energetic neutrinos



‘Heavy-loop’

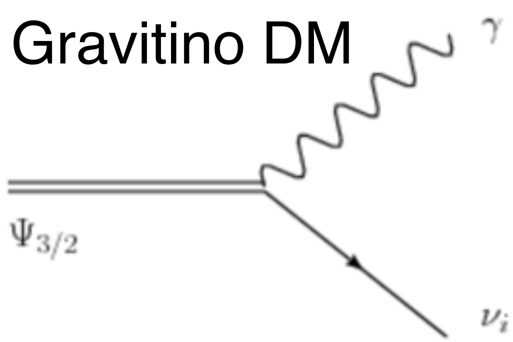


Garny, Ibarra, Tran, Weniger 1011.3786

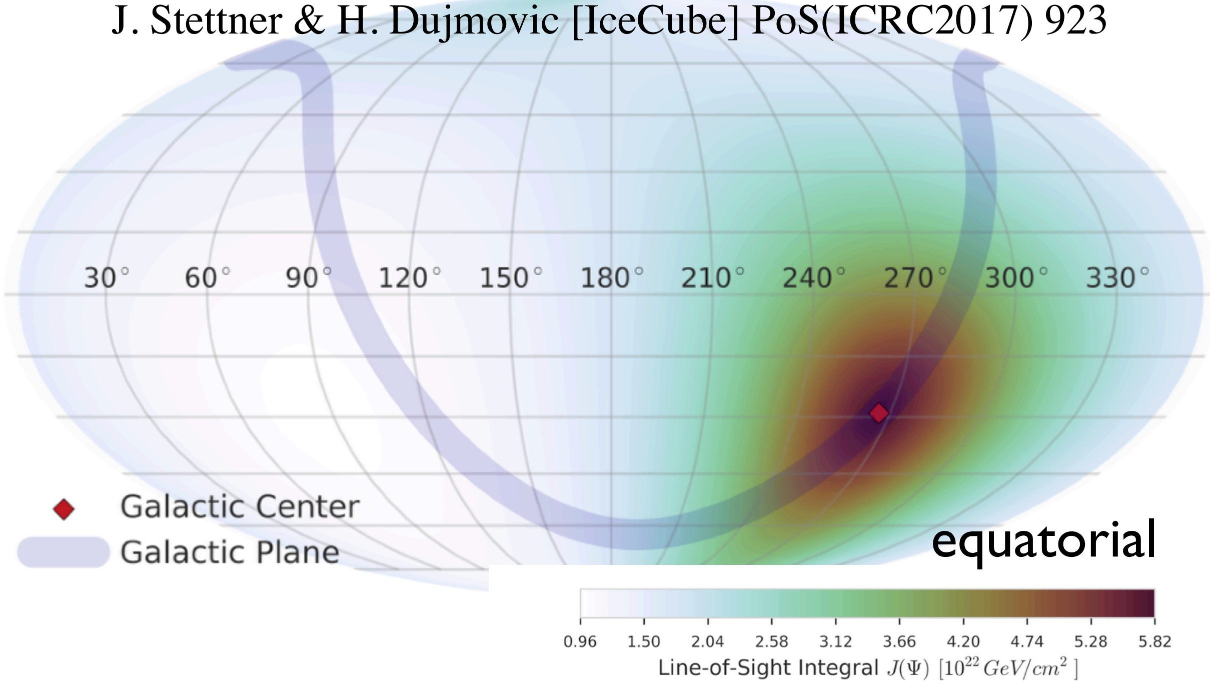


Rott, Kohri, Park 1408.4575

Gravitino DM



J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923



Two flux contributions: Galactic and Extra galactic

$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

- Characteristics of the signal components:
  - (1) Dark Matter decay in the Galactic Halo (Anisotropic flux + decay spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s$$

  - Dark Matter decay at cosmological distances (Isotropic flux + red-shifted spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} [(1+z)E_\nu]\, \mathrm{d}z$$

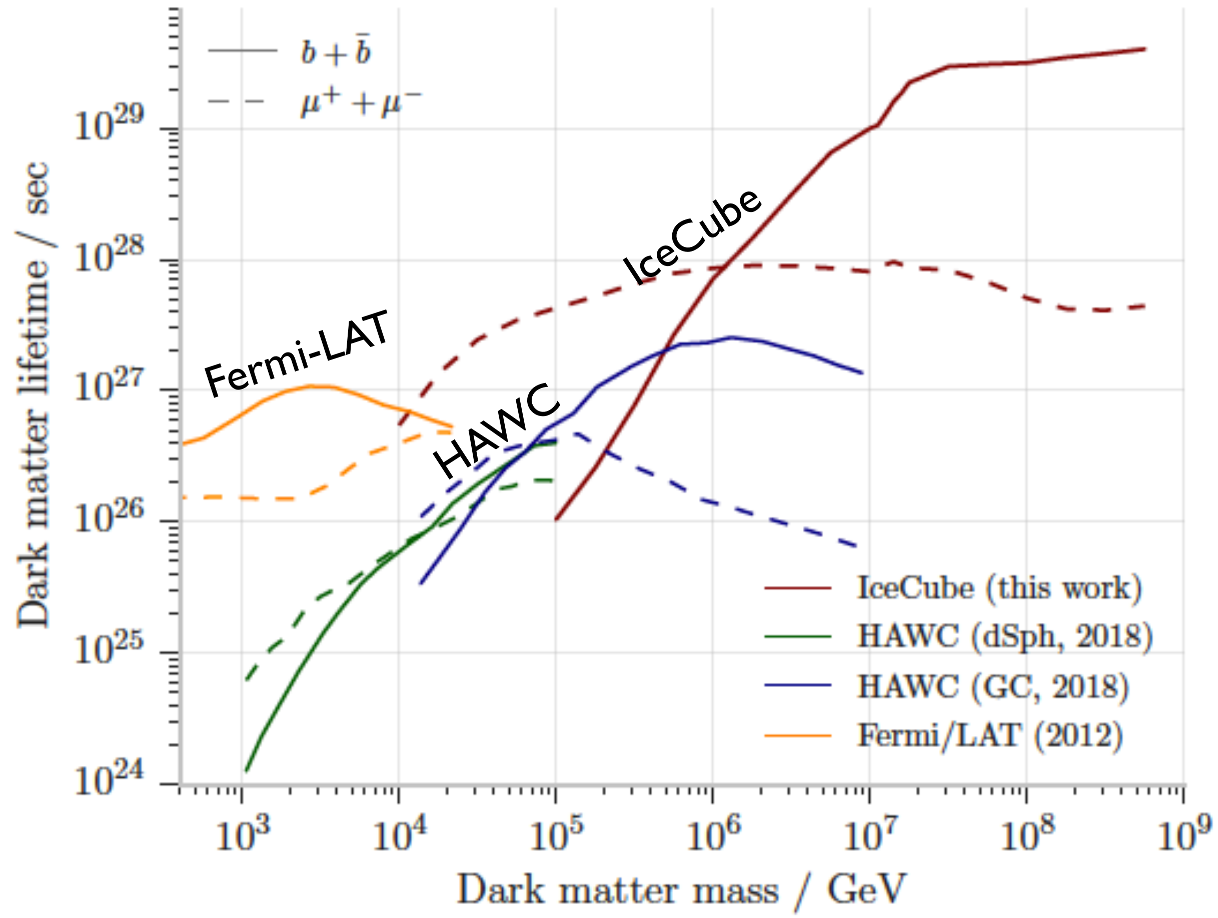
Dark Matter Decay with IceCube

J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923
IceCube Collaboration arXiv:1804.03848v1

- Two IceCube analyses have been performed on independent data samples
  - Track-like with six years of data
  - Cascade-like with two years of data

	Track-like	Cascade-like
Number of events	352,294	278
Livetime	2060 days	641 days
Sky coverage	North (zenith > 85°)	Full Sky
Atm. muon background	0.3%	10%
Median reconstr. error	$< 0.5°$ ($E_\nu > 100$ TeV)	$\sim 10°$
Energy uncertainty	$\sim 100\%$	$\sim 10\%$

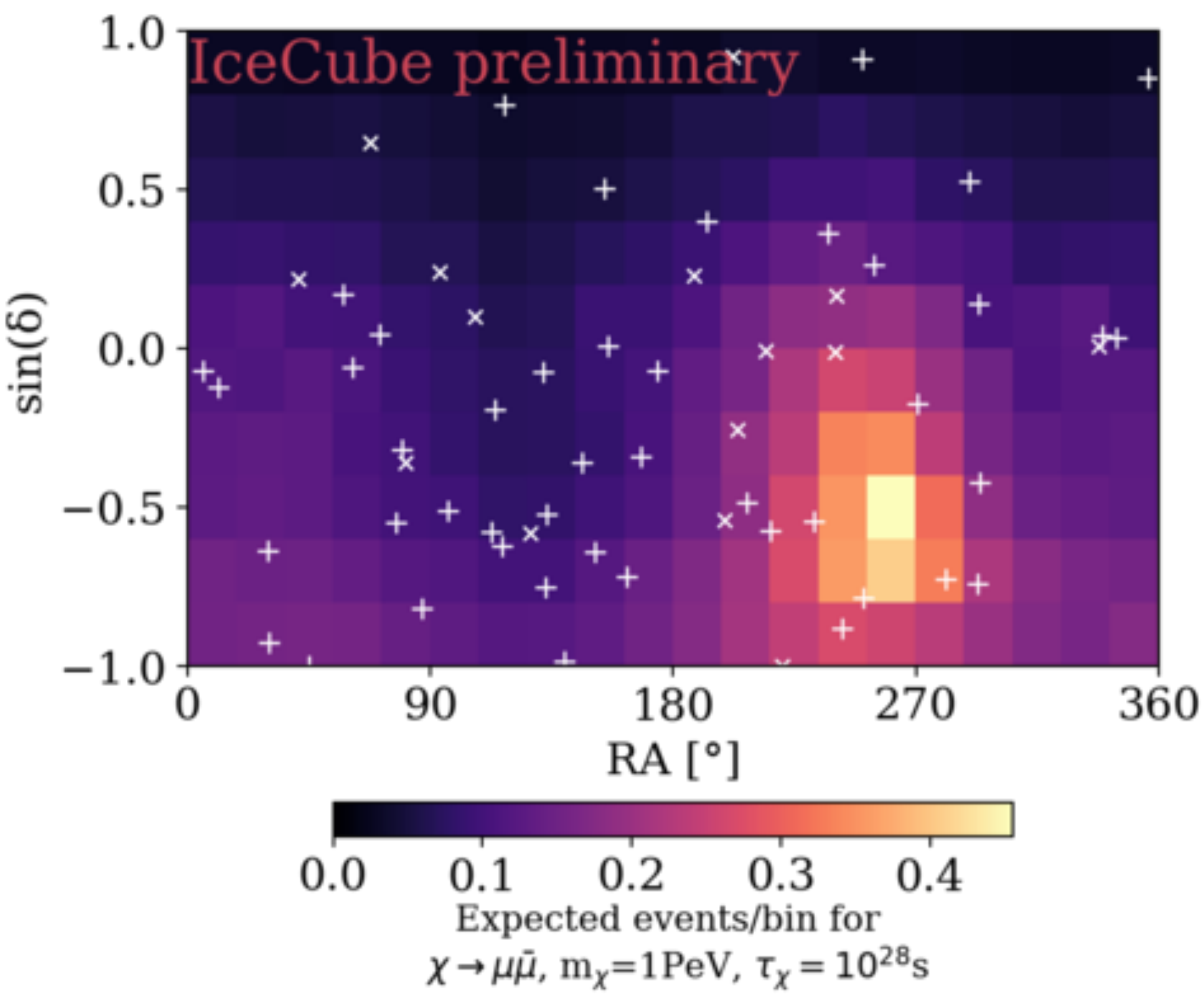
Test-Statistic: $$TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM} = \infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$$

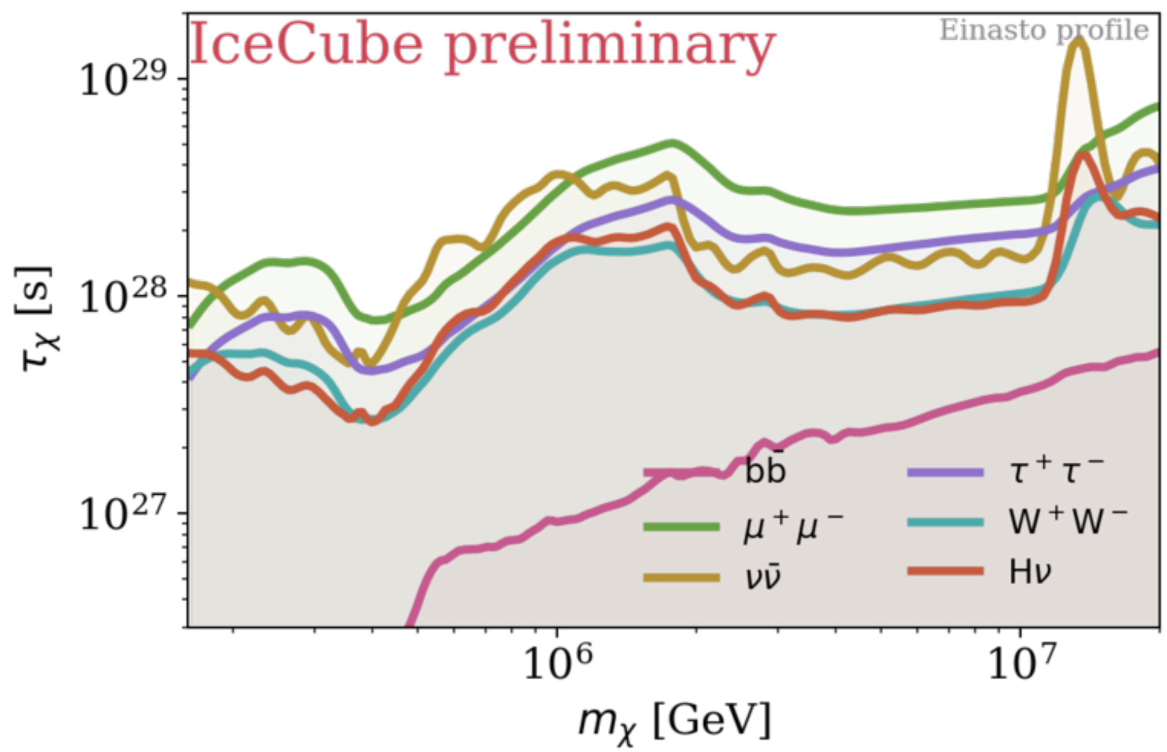


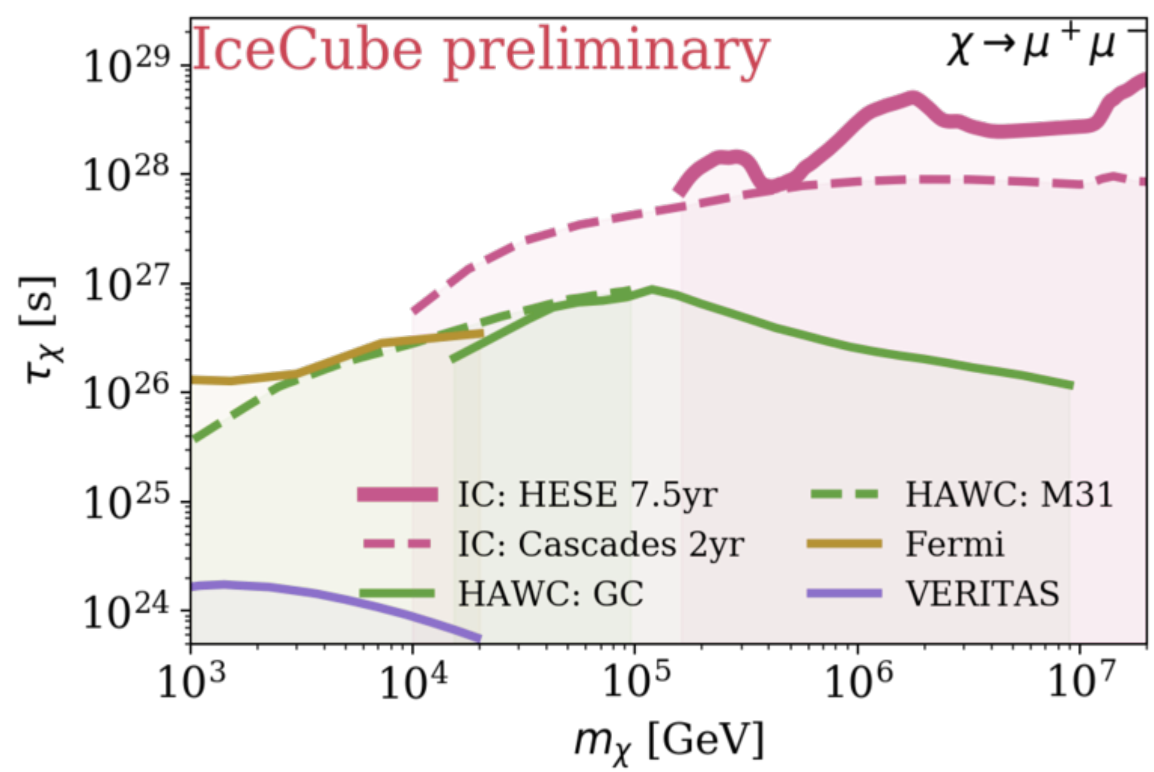
Bound on DM lifetime at ~10^{27}s obtained with IceCube data for m_{DM}>10TeV

- Dark matter alone cannot explain the observed astrophysical neutrino flux in IceCube
- Scenarios with a PeV neutrino line became less attractive with IceCube's observation of neutrino events well above this energy

Search DM Decay with IceCube's 7years HESE Sample







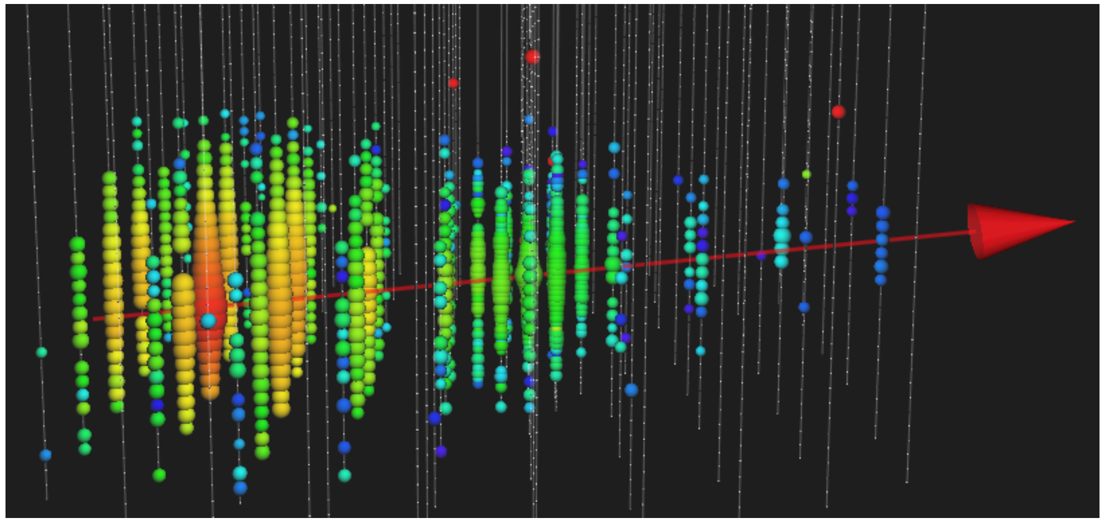
- 7 years of IceCube's HESE (High Energy Starting Events) Sample
  - Events with energies above >60TeV
- Binned likelihood analysis
- Most competitive limits above 100TeV for a large number of channel

IceCube-170922A

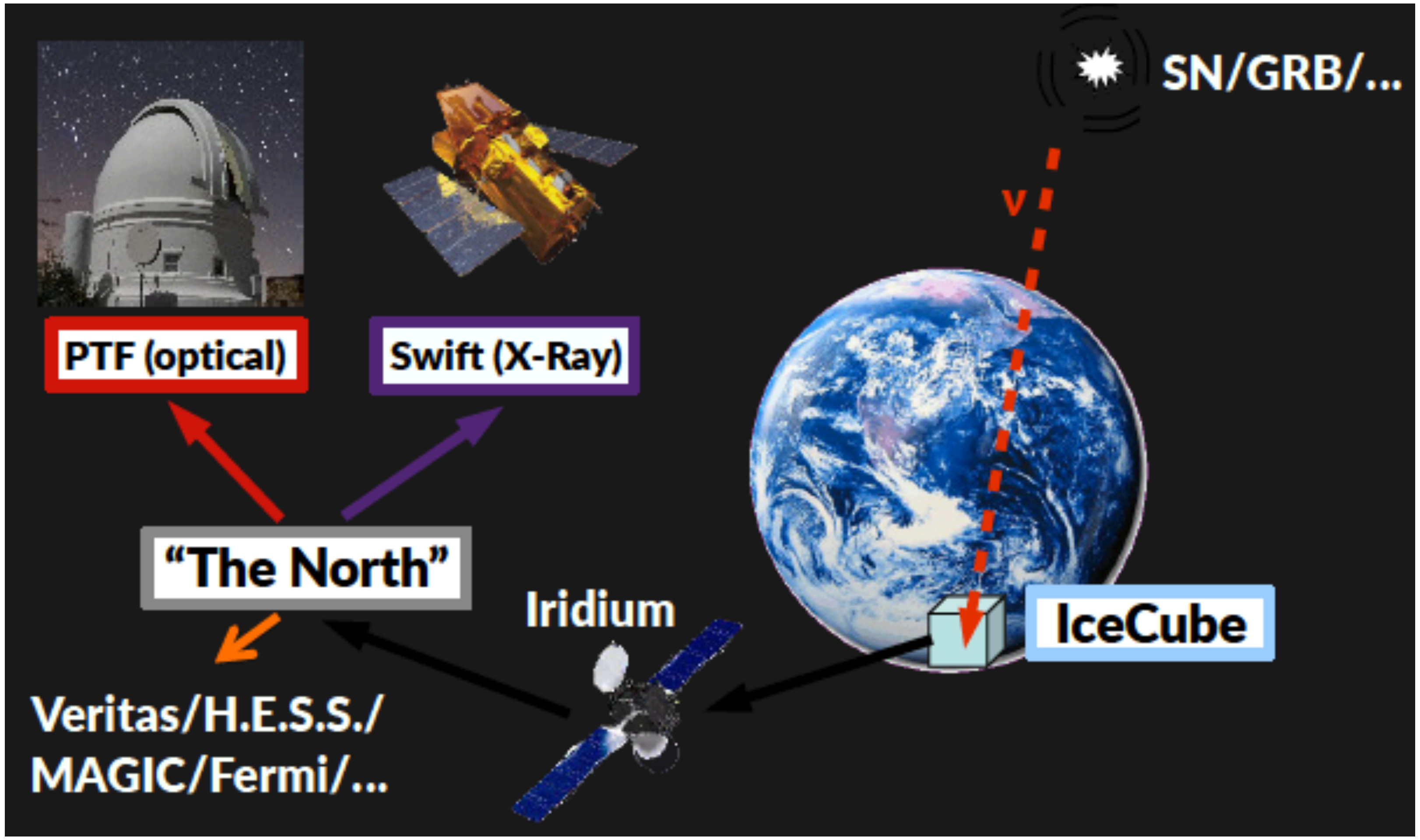
Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

IceCube-170922A & TXS 0506+056

- Real-time alerts. Since 04/2016, ≈6-8/yr
  - Latency ~2 min.
  - Improved selection summer 2018
    - Good angular resolution (0.5° - 2° 90% of events)
    - 50% astrophysical fraction



First public ν Alert: IceCube-160427



IceCube-170922A & TXS 0506+056

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17
FROM: E

Claudio Ko
report on

On 22 Sep
probability
Extremely
normal on

Fermi-LAT detection of increased gamma-ra TXS 0506+056, located inside the IceCube error region.

ATel #10791; Y
K

Crede

Subjects: Gamma

Referred to by A
10844, 10845, 10

Tweet Rec

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

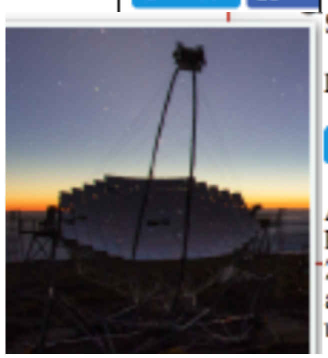
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of



- September 22, 2017: a neutrino alert issued by IceCube
- Fermi-LAT and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
- Very active multi-messenger follow-up from radio to γ-rays

(Science 361 (2018) 6398, eaat1378)

IceCube-170922A

TXS 0506+056 redshift of z = 0.3365

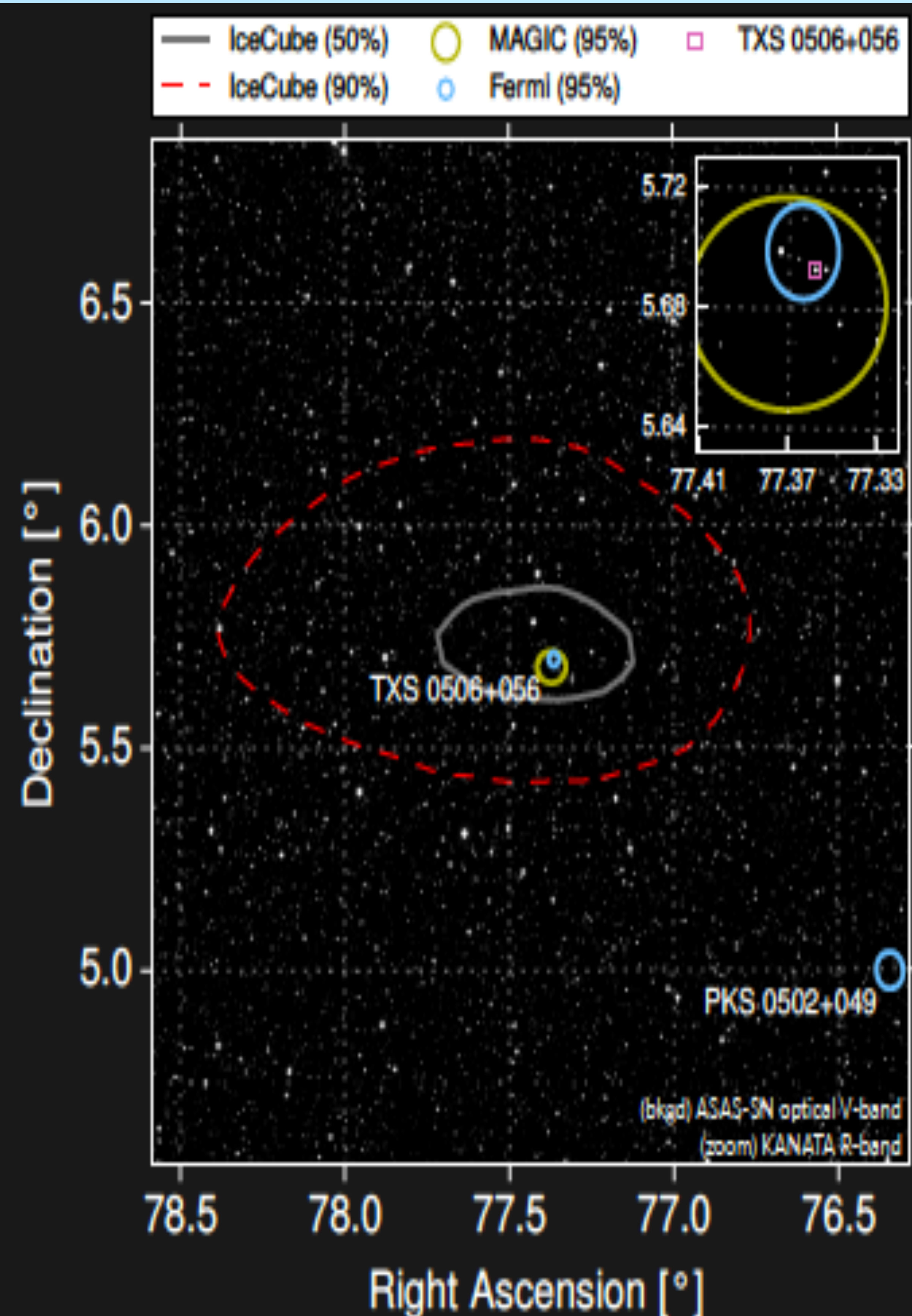
(S. Paiano et al. ApJL 854, L32 (2018).)

Time-averaged luminosity an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605

Time-integrated neutrino spectrum is approximately $E^{-2.1}$

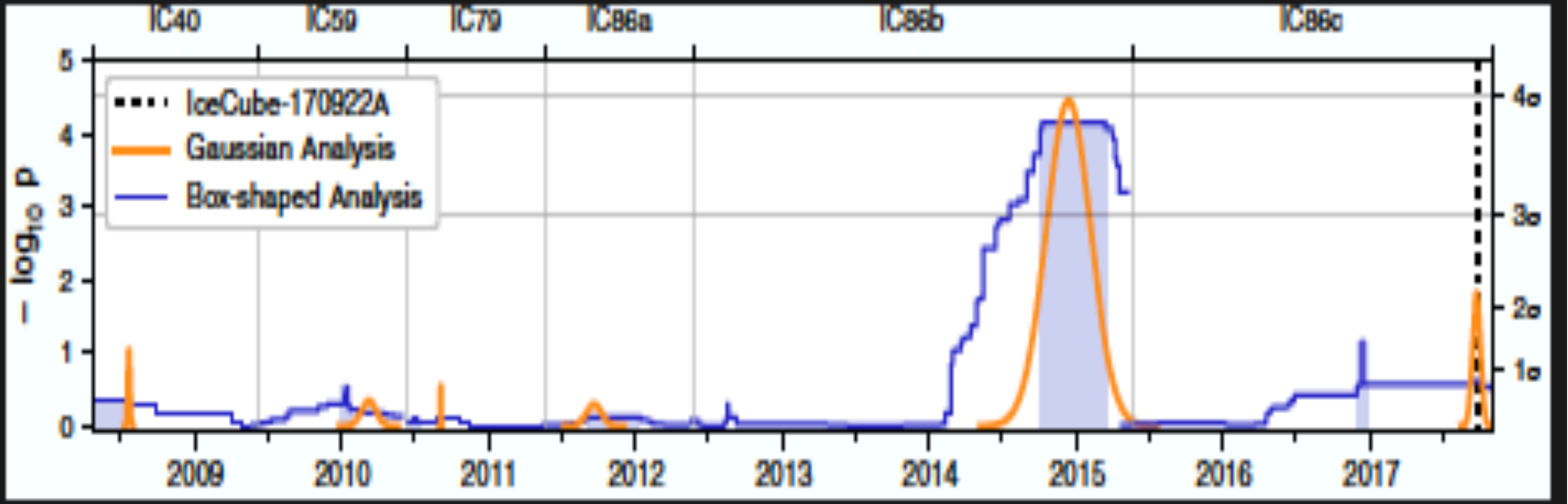
Chance probability of a Fermi-IceCube coincident observation: **3σ** level

(Significance determined using all known Fermi-LAT blazars and the historical data sample from IceCube.)

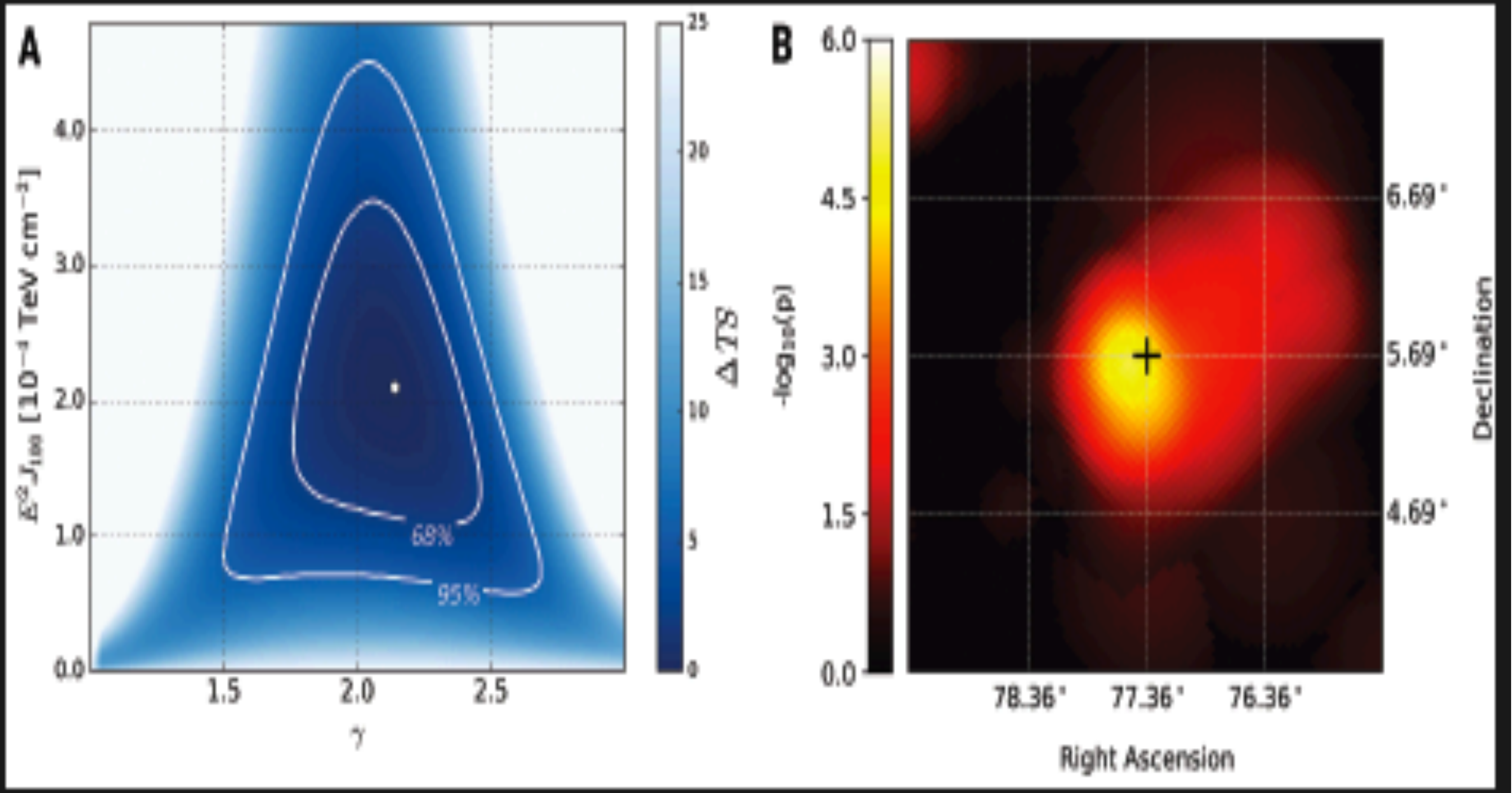


IceCube-170922A

IceCube evaluated 9.5 years of archival data in the direction of TXS 0506+056



13+5 events excess compared to background expectations (Sept 2014–March 2015)



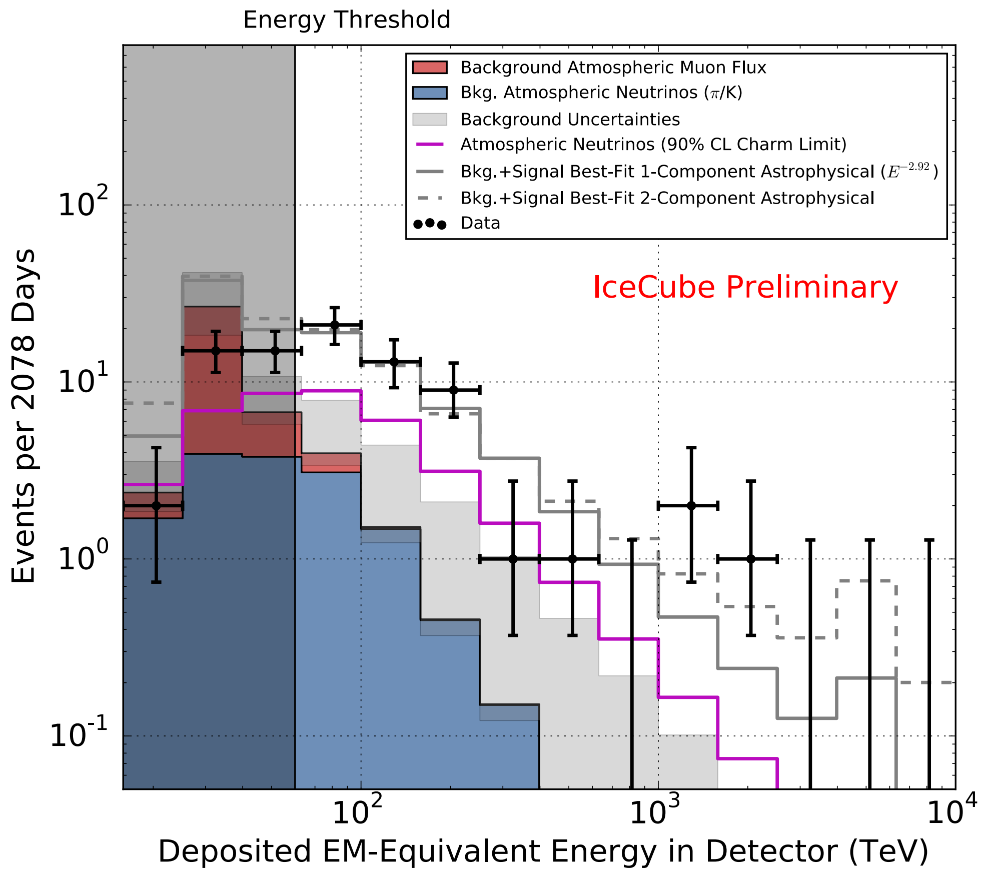
Inconsistent with bkg-only hypothesis at the **3.5σ** level

(In addition and independently of the previous 3σ when looking in this specific direction)

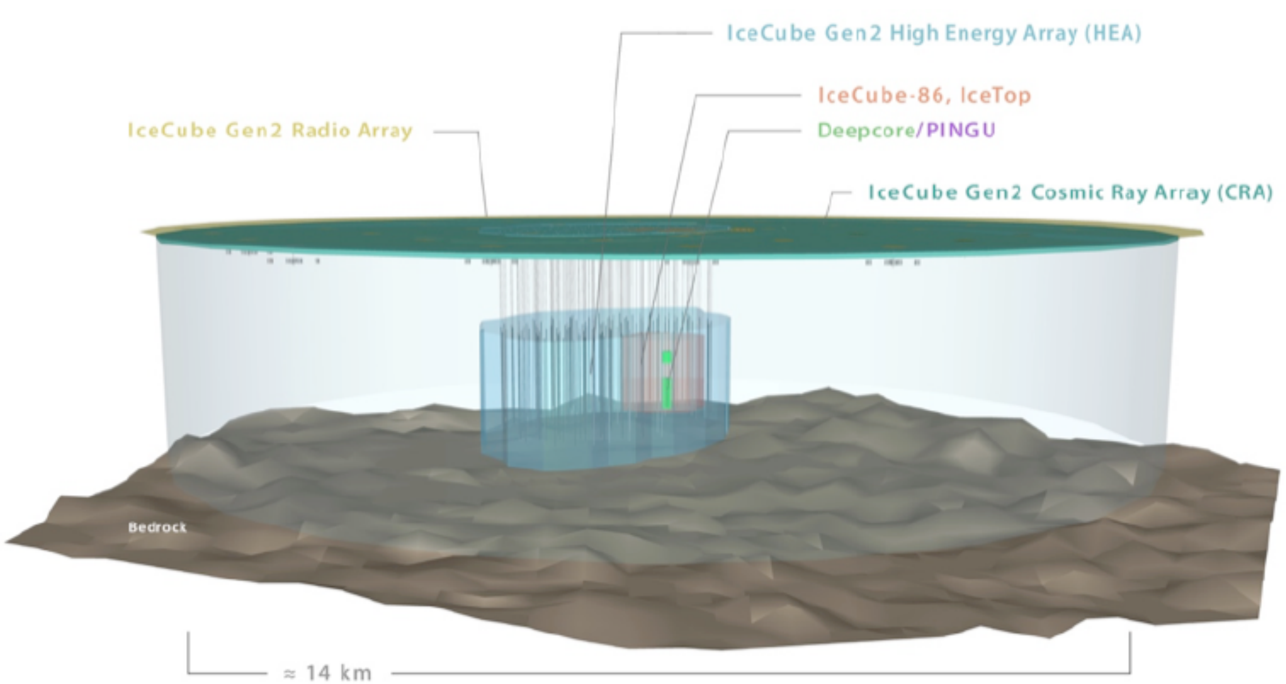
Future Plans

Next generation

- IceCube has provided an amazing sample of events, but is still statistics limited
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
  - So far non of the analyses has shown any evidence for point sources
- Where are the point sources?
- What is the flavor composition?
- What is the spectrum? Cutoff?
- Transients ?
- Multi-messenger physics?
- GZK neutrinos?
- New physics or something unexpected ?
- …

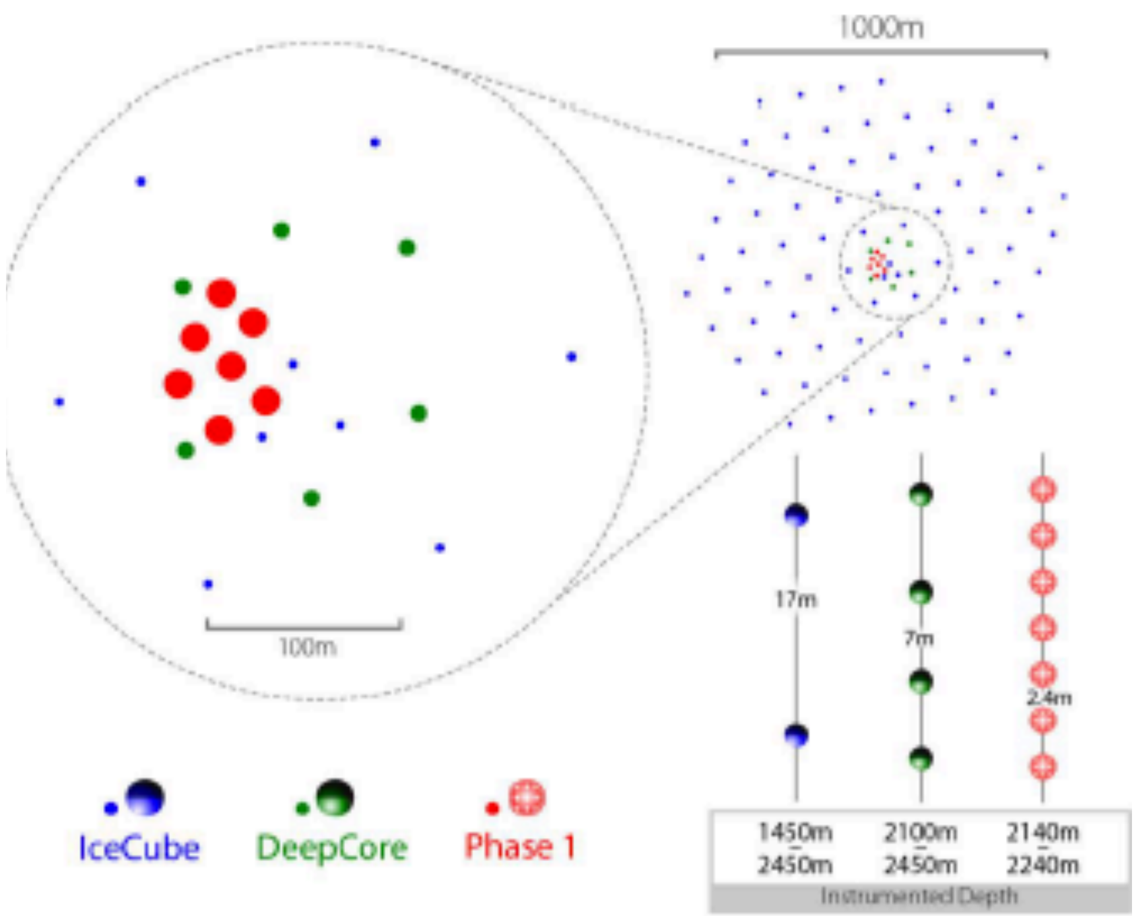


IceCube Gen2 Facility

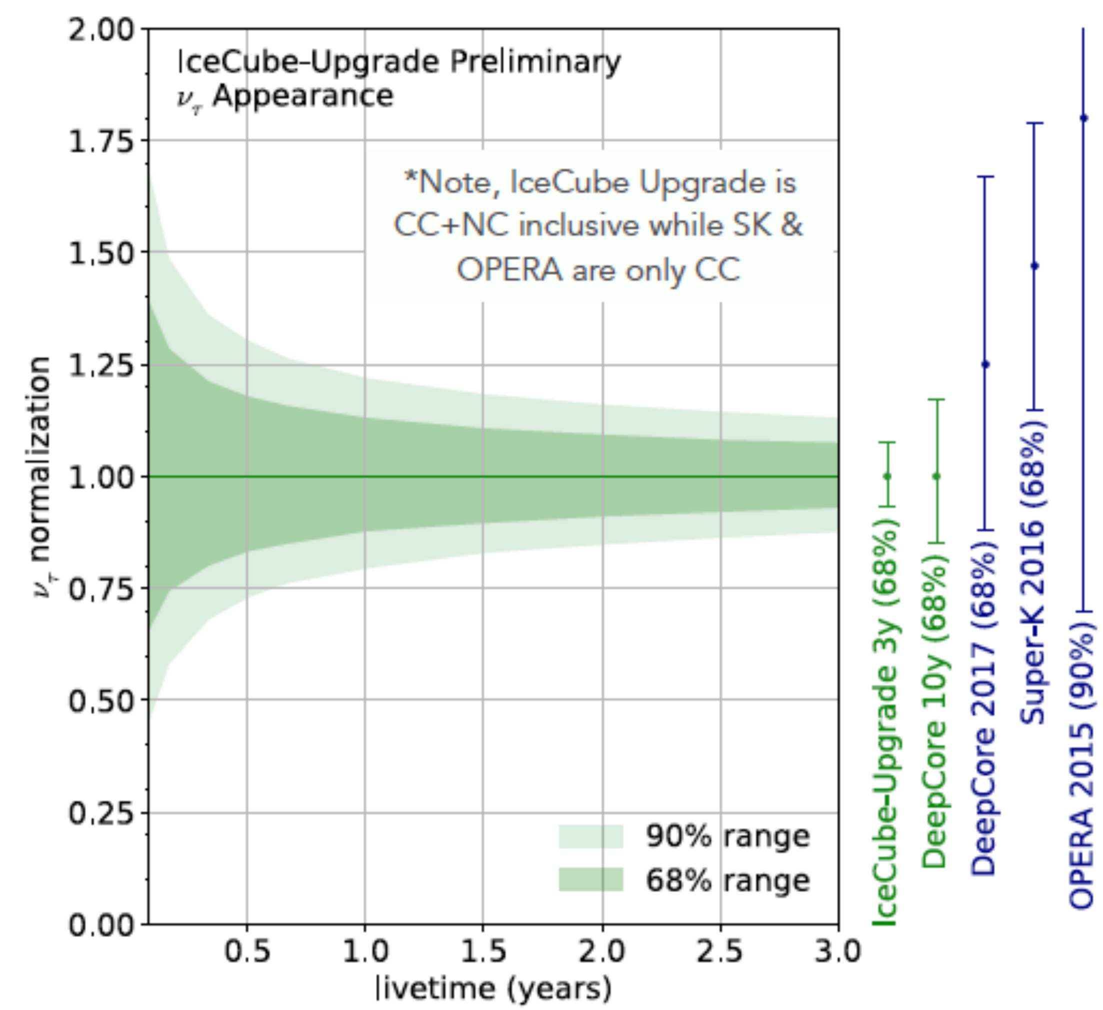


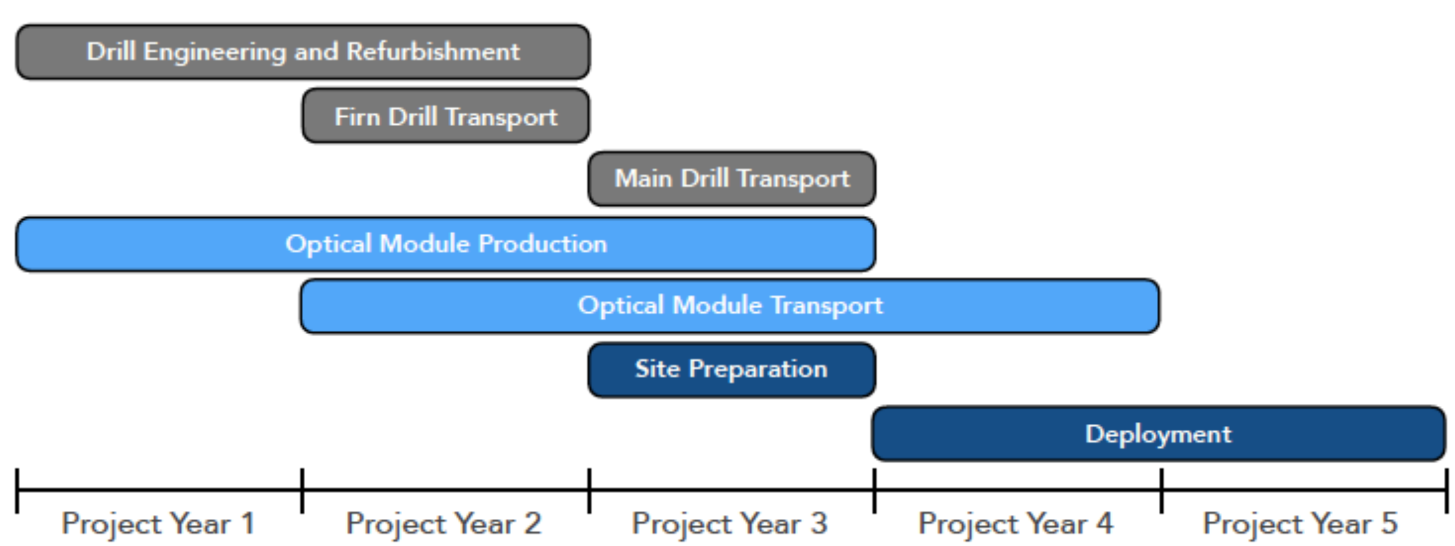
see also:
- PINGU LOI arXiv:1412.5106

The IceCube Upgrade



Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125

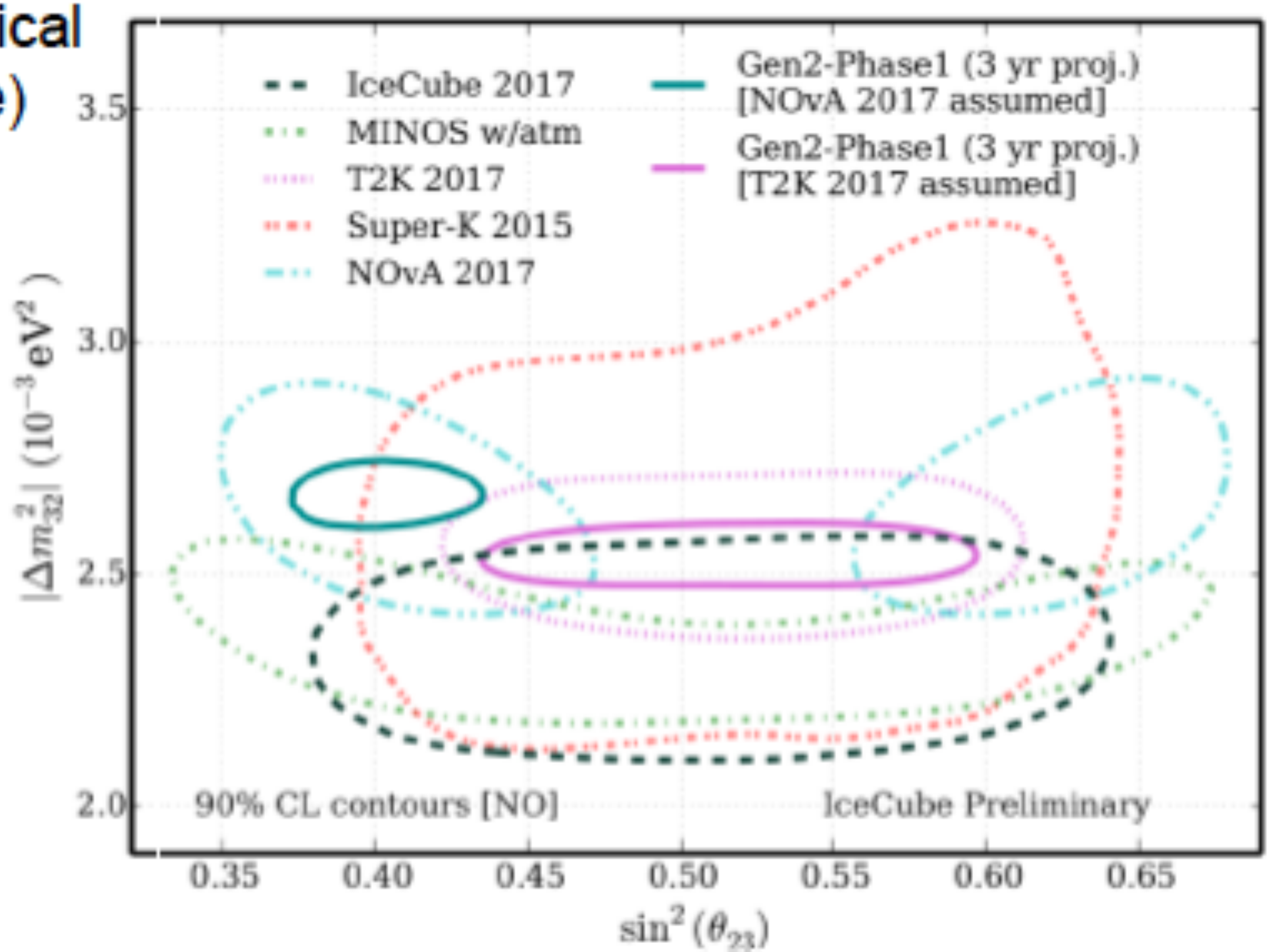




First step to restart South Pole activities
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Calibration devices
- Platform to test new technologies

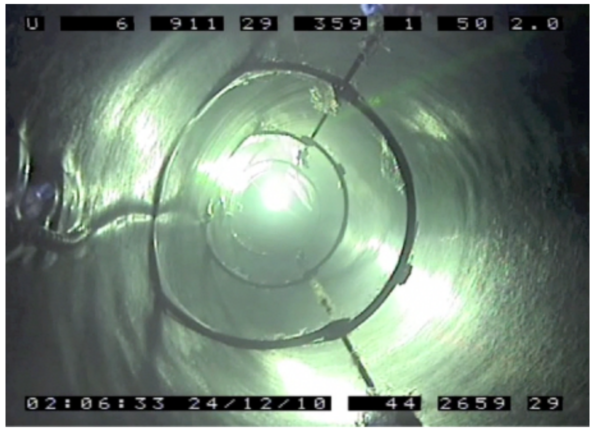
The IceCube Upgrade

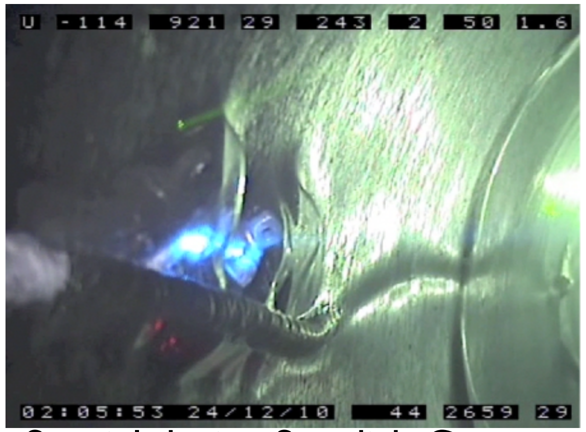
- Target $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Detect ν_τ events on a statistical basis (up-going, shower-like)
- Case study for IceCube Upgrade:
  - ~2500 ν_τ events / year
  - Drastically improve measurement of atmospheric mixing parameters
  - Chance to determine octant of θ_{23}
- Also possible with ORCA



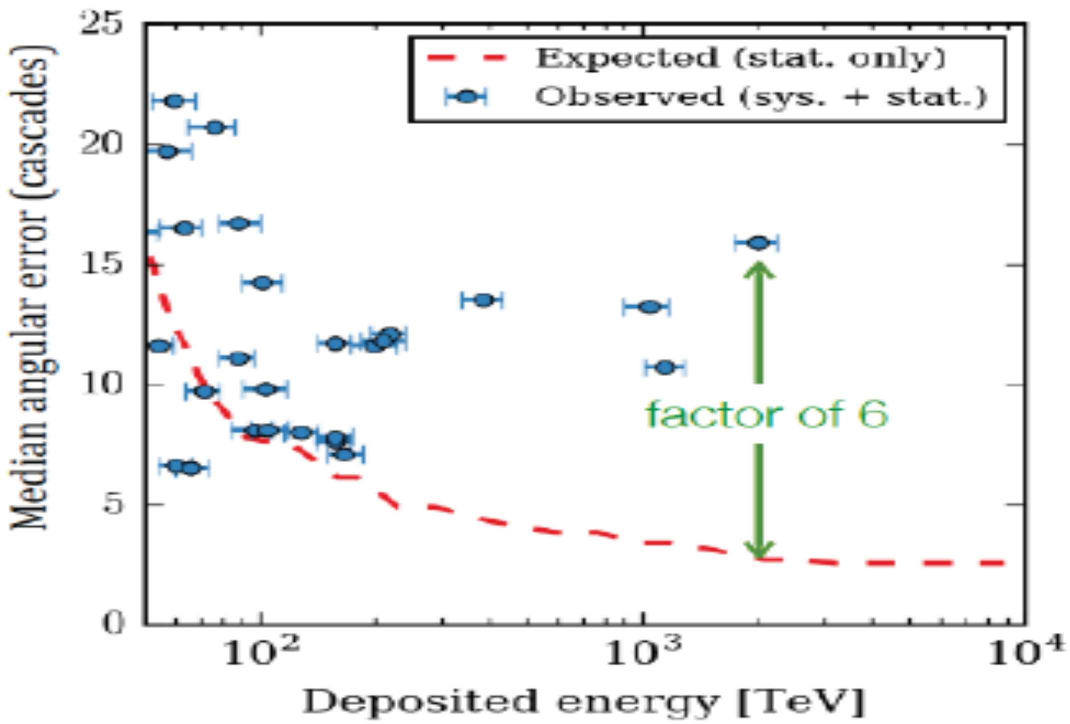
IceCube extremely competitive for neutrino oscillation parameter measurements using atmospheric neutrinos

Sungkyunkwan Ice Camera System





Special device Swedish Camera



- Ice properties dominant source of sys. uncertainties for most analyses
- Solution: SKKU ice camera system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability

Camera system key to comprehensive understanding of the detector medium
—> Retroactively analyze more than 10 years of IceCube data with substantially improved angular and energy resolution

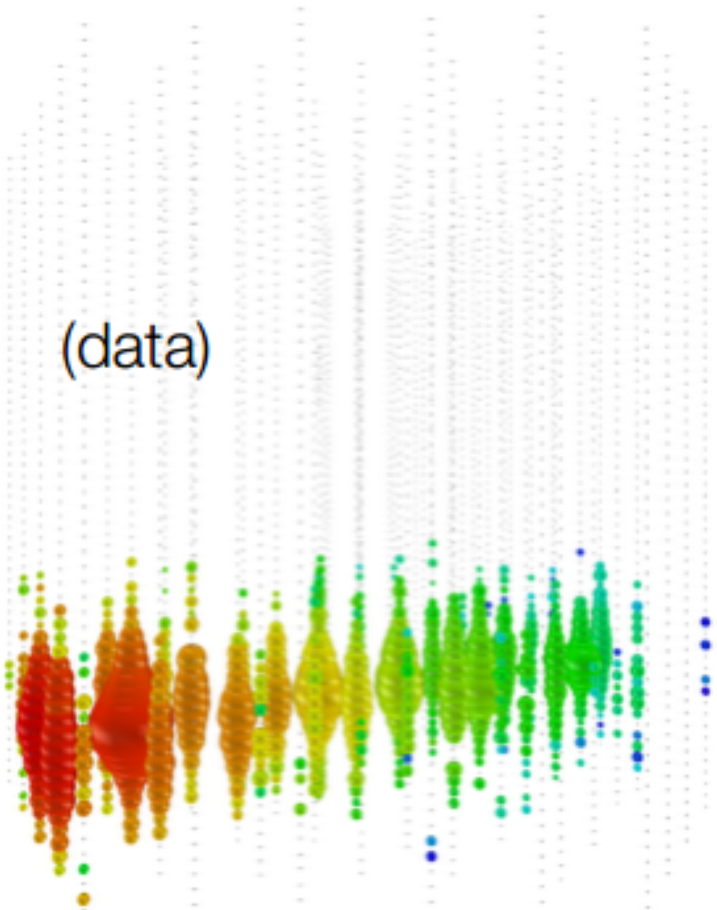
- High-energy astrophysical neutrinos have opened up a new window to the Universe
  - What's the origin of the high-energy neutrino
- Very strong bounds on dark matter scattering with nucleons
- Very diverse science program, IceCube turns out to be a treasure throve
- Neutrino astronomy is a central part of the multi messenger astroparticle physics field
- The IceCube Upgrade has just been approved and we can look forward to many exciting discoveries in the near future

Image:Stephan Richter, IceCube/NSF


Thanks

Event topologies

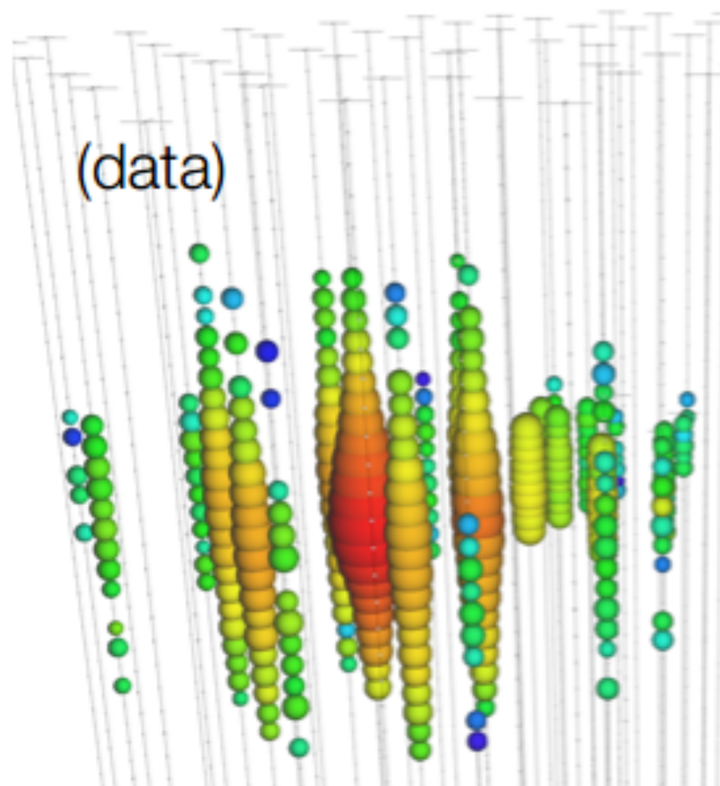
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

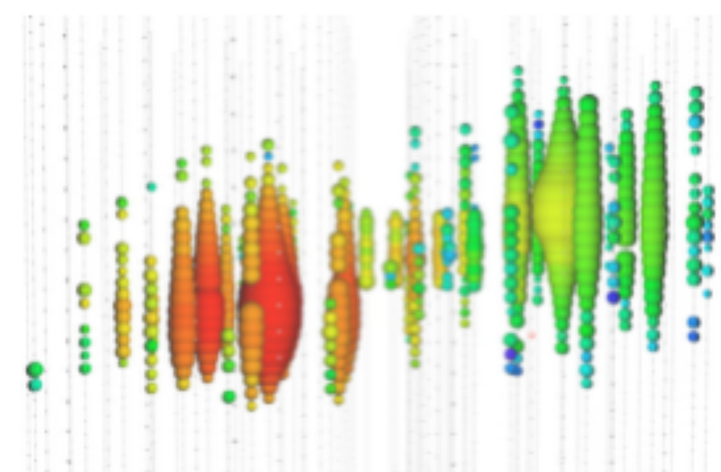
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

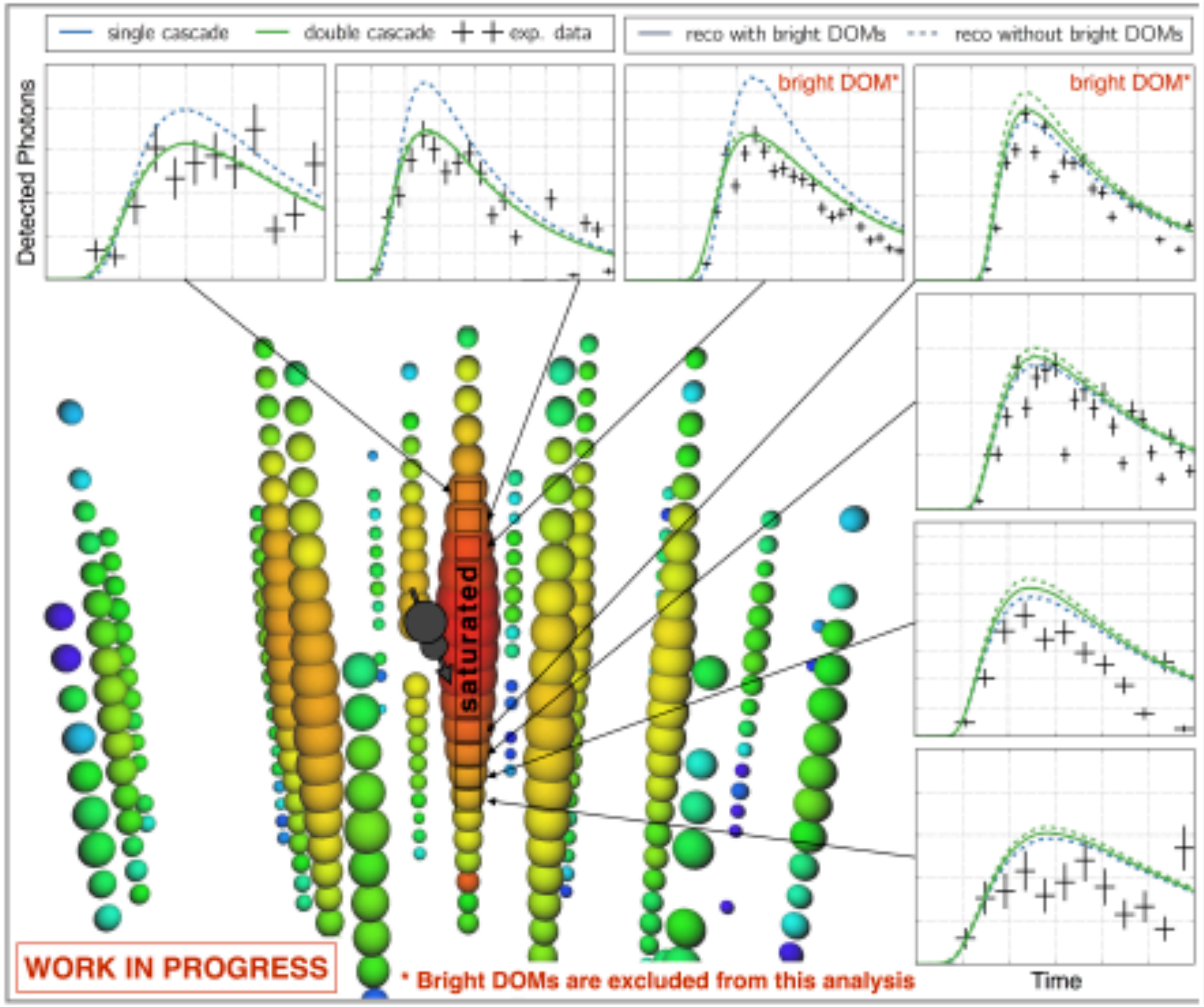
Charged-current ν_τ



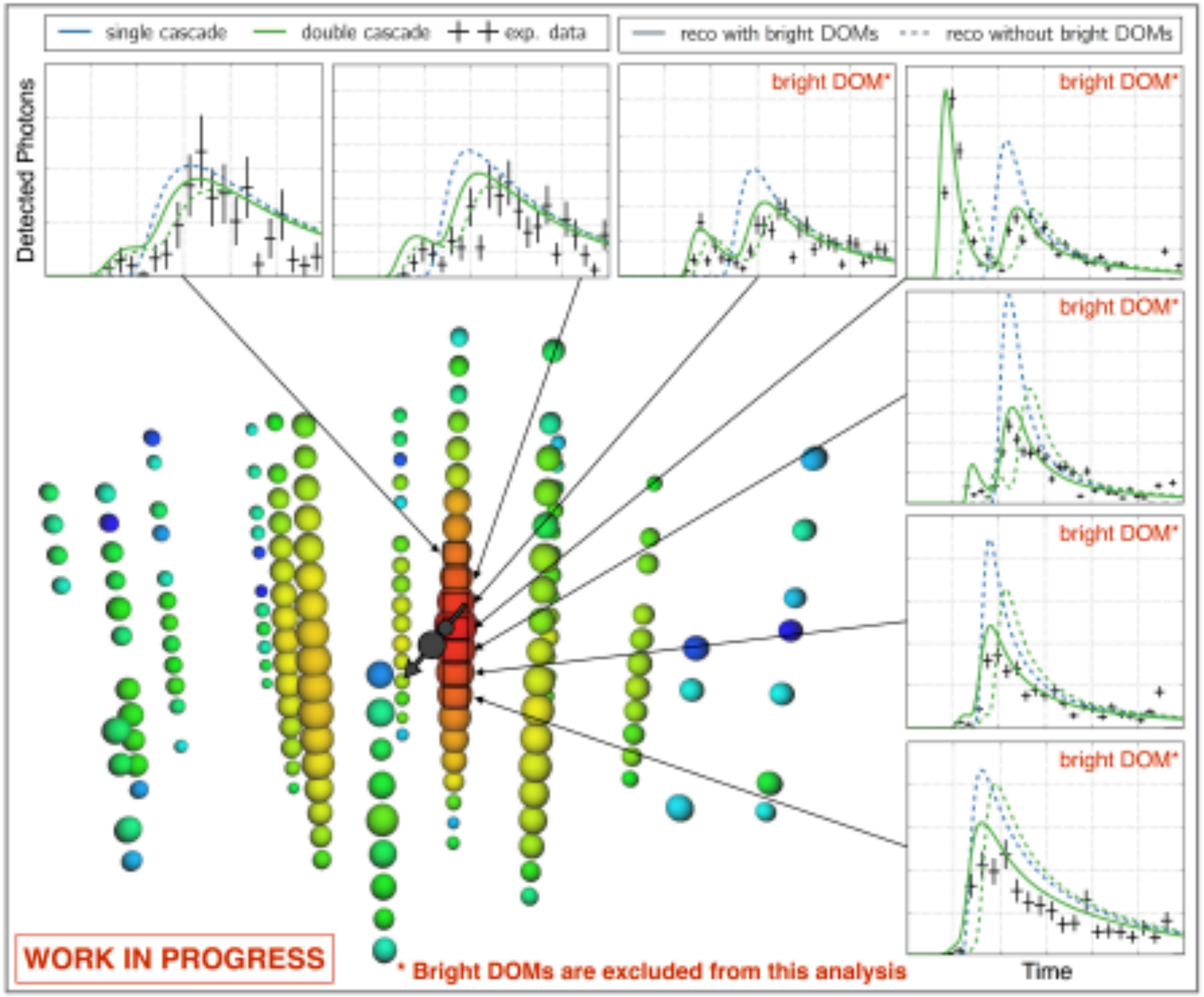
“Double-bang”

(none observed yet: τ decay length is 50 m/PeV)

HESE 7.5yrs Tau Search



Double cascade Event #1



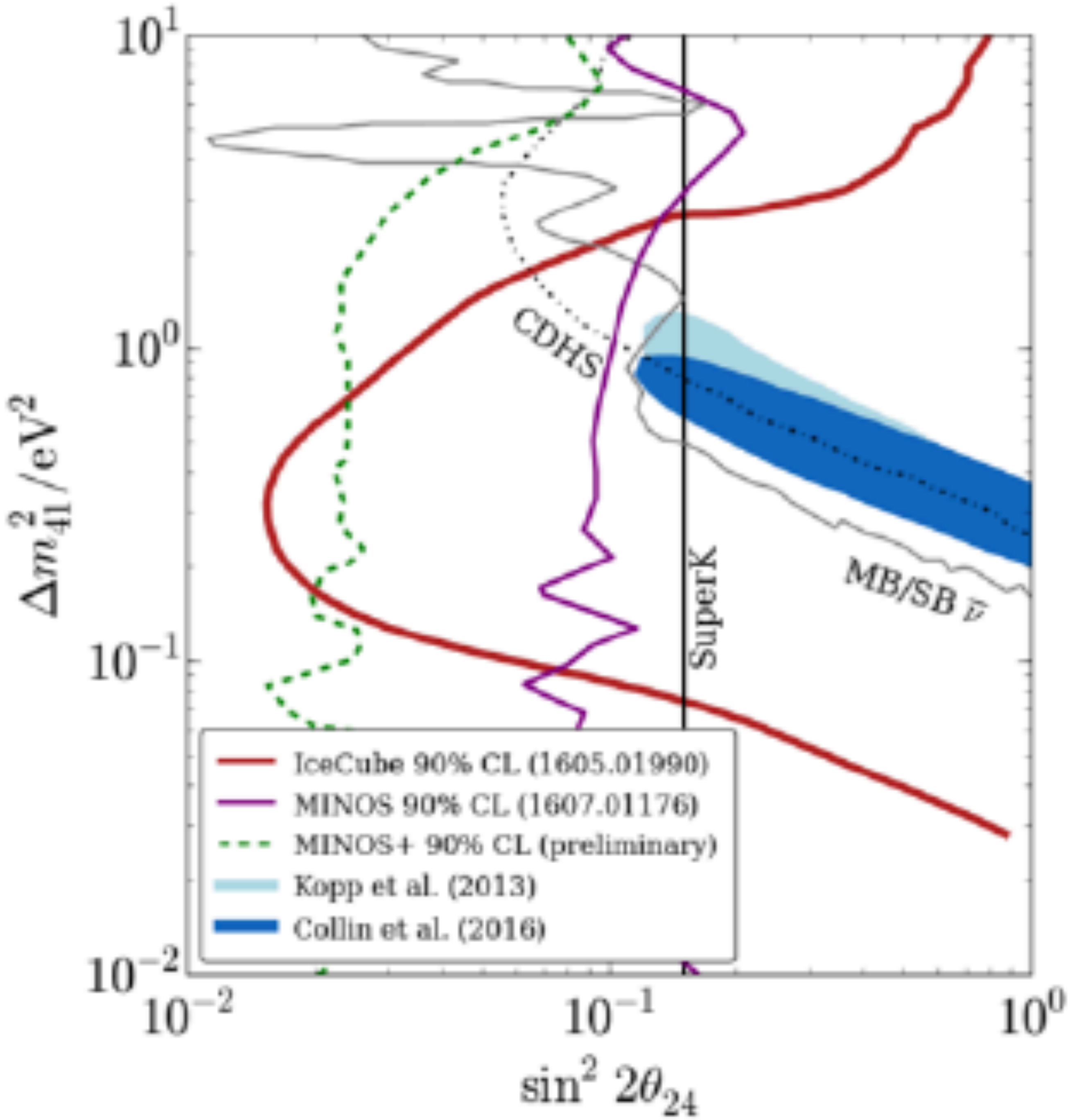
Double cascade Event #2

"Bright" DOMs not used in reconstruction
Direction and two reconstructed cascades shown in dark gray

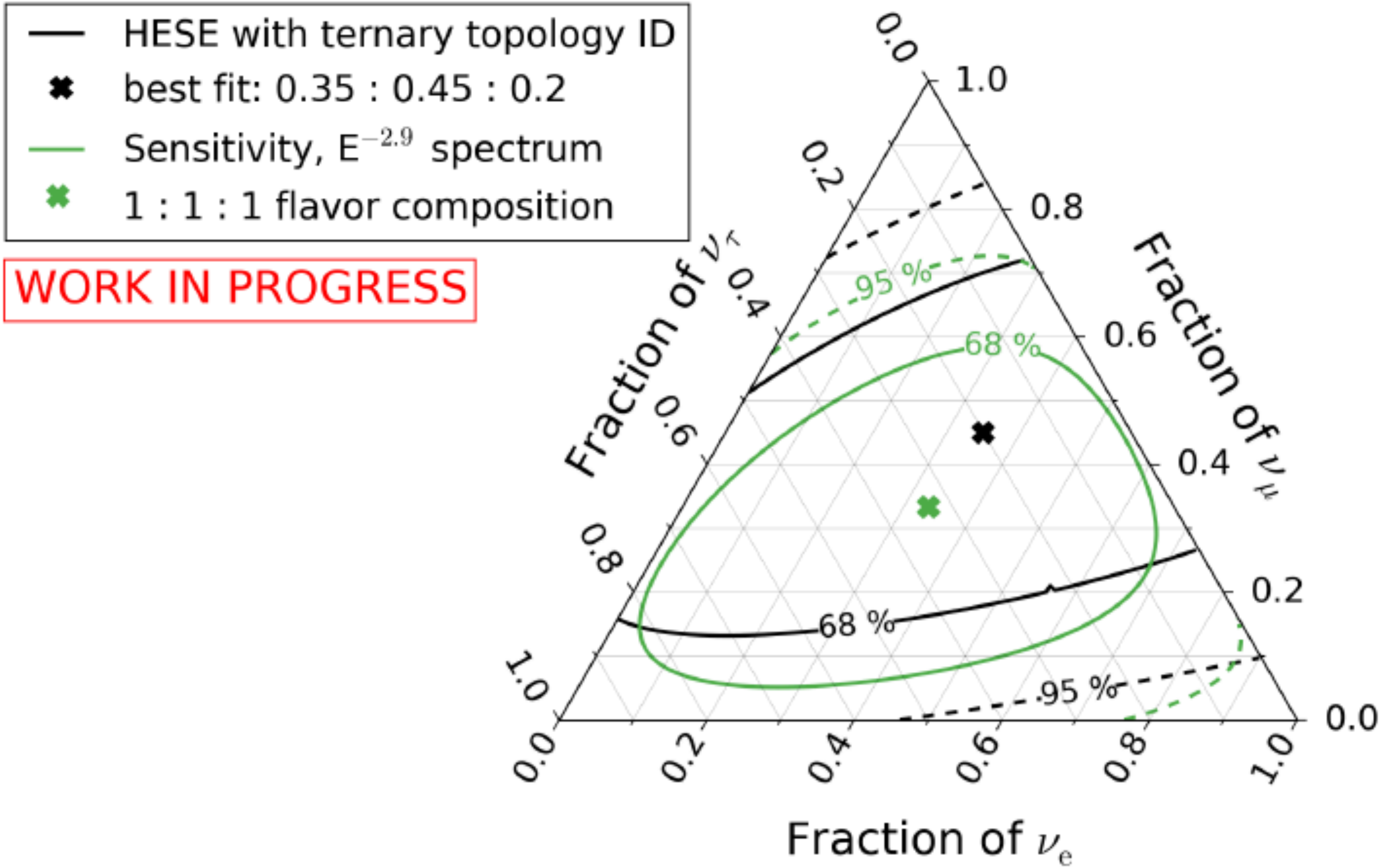
Sterile Neutrino Search

M. Aartsen et al. (IceCube), *Phys. Rev. Lett.* 117, 071801 (2016)

- 2016 IceCube result based on one year of data
  - $\Delta m^2_{41} > 0$ assumed (conservative: $\Delta m^2_{41} < 0$ would affect ν instead)
  - In tension with preferred region based on LSND, MiniBooNE data
  - Analysis of 7 year data set underway – additional statistics at high energy, improved systematics



HESE 7.5yrs Tau Search



WORK IN PROGRESS

IceCube Upgrade

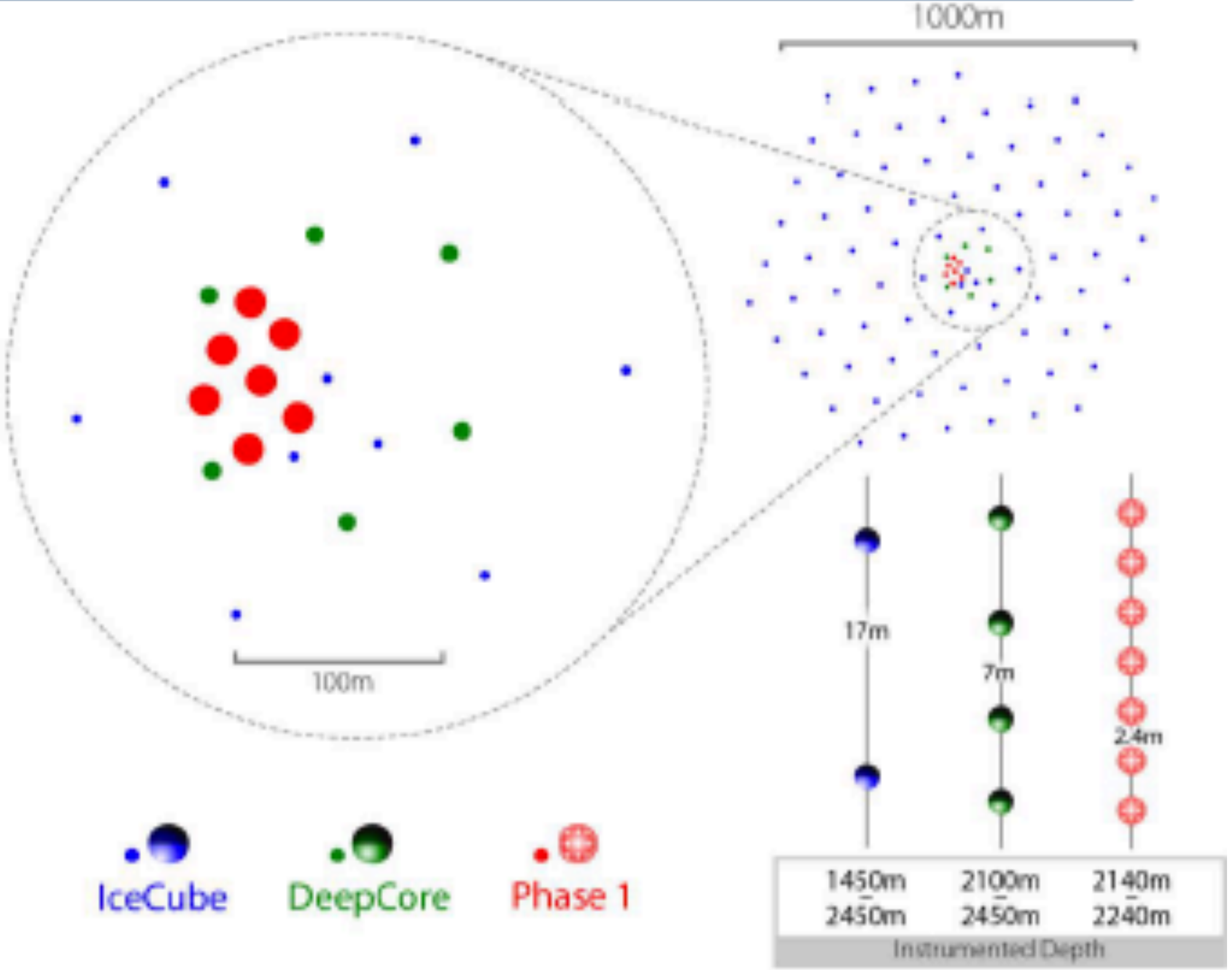
- Proposals pending with NSF (PHY mid-scale) and foreign partners
  - \$22.7M US plus \$12.8M from foreign partners
    - \$2M USD approved in Japan!
  - Significantly enhance detector performance – *retroactively* – for 10% incremental investment (with very low impact on ongoing cost of operations)
- Project-driven timeline:
  - Final engineering and design reviews in 2018-19
  - Instrumentation production and drill transport beginning in 2020
  - Drill integration and firn drilling at South Pole in 2021/22
  - Drilling and deployment in 2022/23, commissioning and integration in 2023

MICHIGAN STATE UNIVERSITY   Tyce DeYoung, Neutrino 2018   34

IceCube: next step = Upgrade

IceCube-Upgrade

- 7 additional strings in Deep Core domain, densely instrumented
- Objectives:
  - GeV neutrinos: τ appearance, Dark Matter, …
  - Improved understanding of ice properties → better precision, reduced systematic uncertainties
  - Opportunity to test new hardware developments
- Funding commitment expected very soon



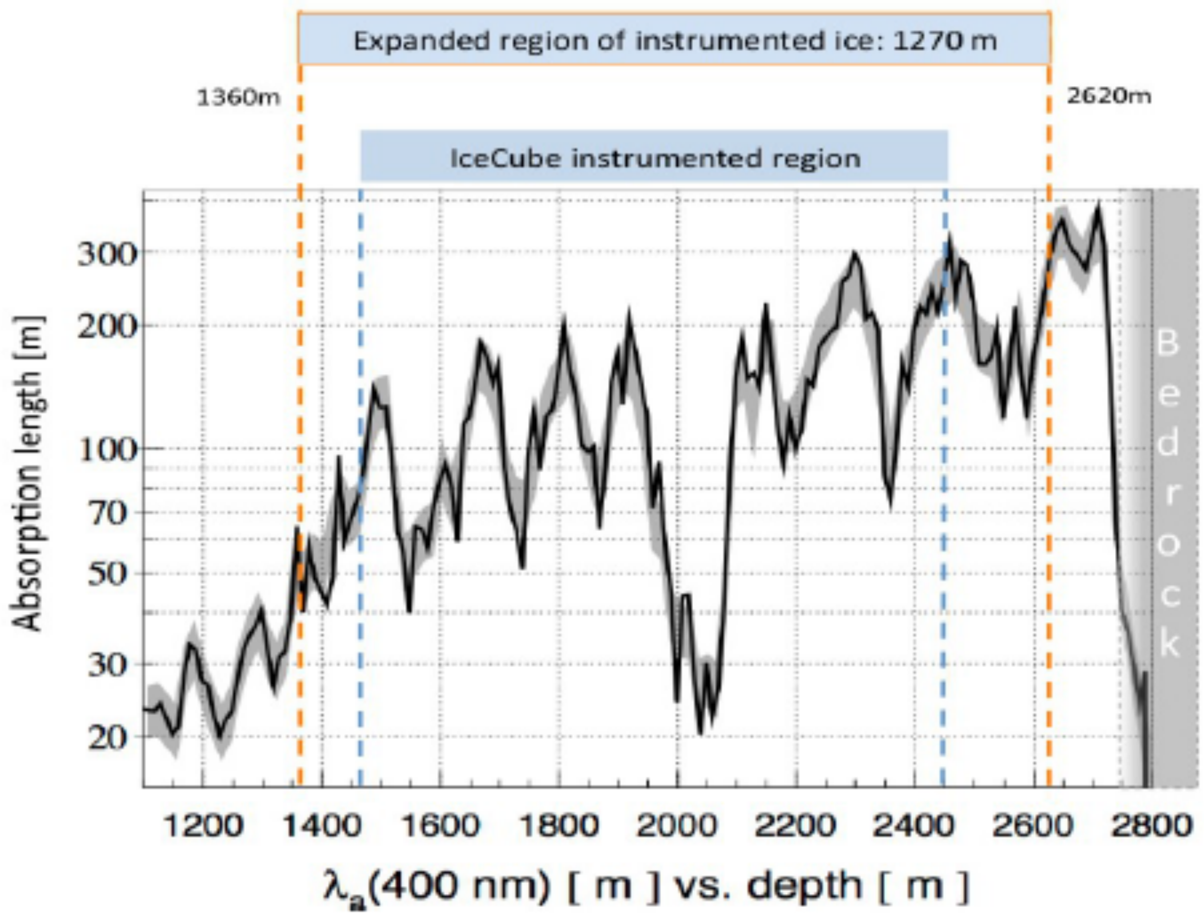
Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125

Deployment 2022/23 → time

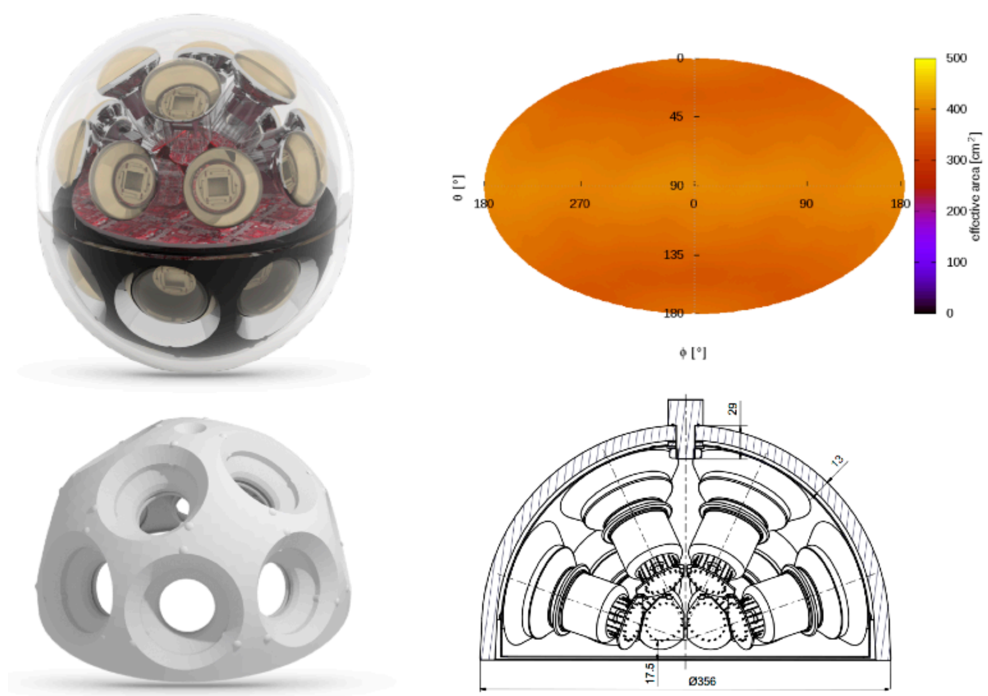
P[2/163] J. Evans

U. Katz: Future neutrino telescopes   Neutrino 2018, Heidelberg   26

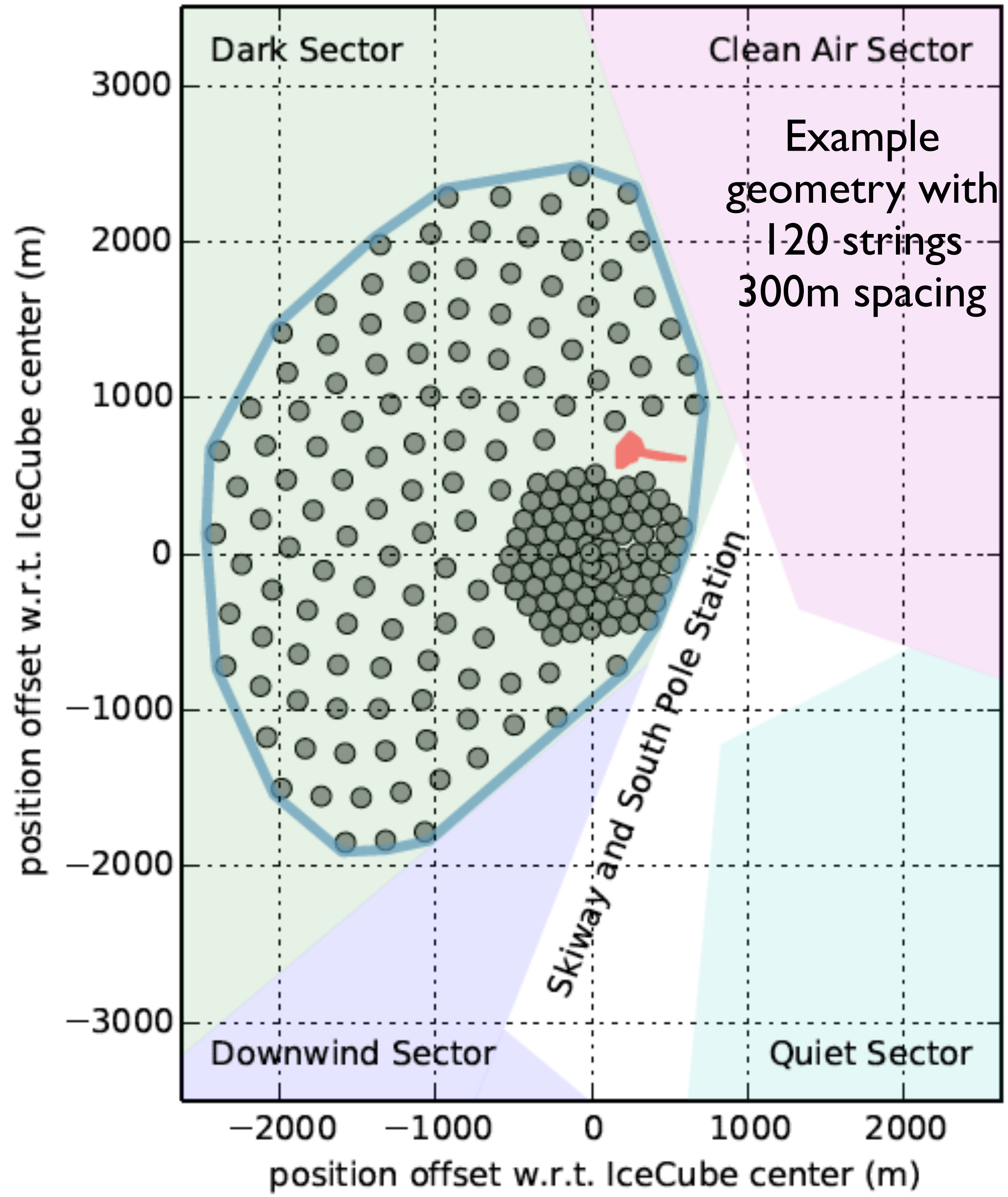
IceCube Gen2



Plan to use new sensor modules



IceCube Coll. Gen2 LOI [arXiv:1412.5106](https://arxiv.org/abs/1412.5106)



required that each event have fewer than three of its first 250 observed photoelectrons detected in the veto region. In addition, we required that the event produce at least 6000 photoelectrons overall