
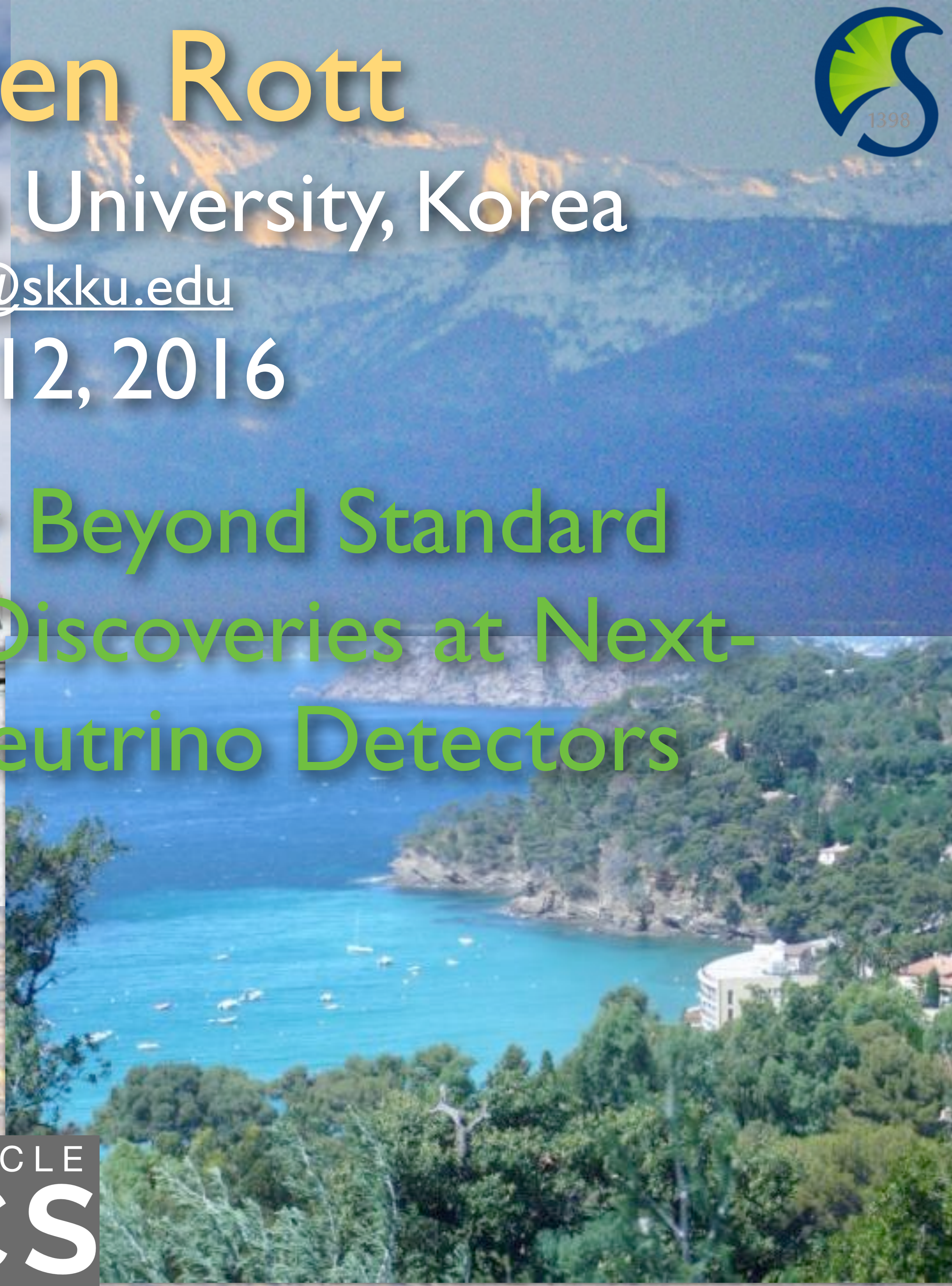

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Dec 12, 2016

Prospects for Beyond Standard Model Physics Discoveries at Next-generation Neutrino Detectors

UCI Seminar

THEORETICAL PARTICLE

UCI PHYSICS

Coma Cluster

Outline

Motivation

Neutrino Telescopes

Selected Searches

- Dark Matter and Astrophysical Neutrinos
- Dark Matter Captured in the Sun
- Solar Neutrino Floor

Conclusions and Outlook

Motivation

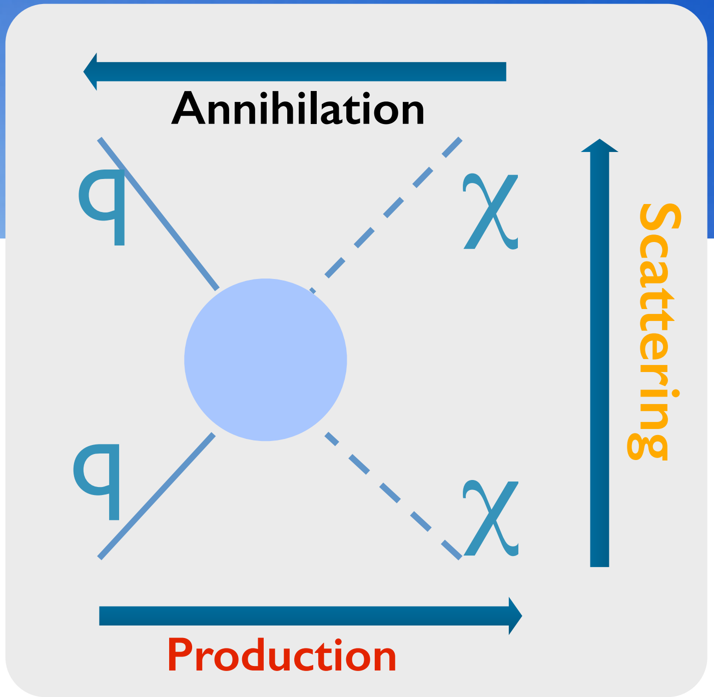
The Dark Matter Mystery

Coma Cluster

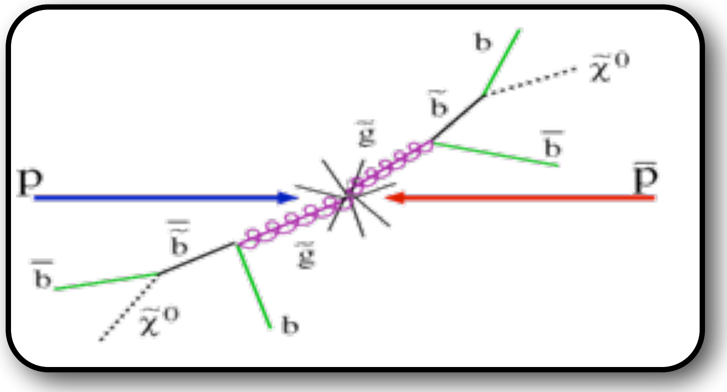
- Since Zwicky observed the Coma cluster evidence has hardened
  - Structure formations - Cosmological simulations
  - Gravitational lensing
  - Rotation curves
  - Cosmic microwave background
  - ...

- Dark Matter already gravitationally “observed”, but ...
  - What is it ?
  - What are it’s properties ?

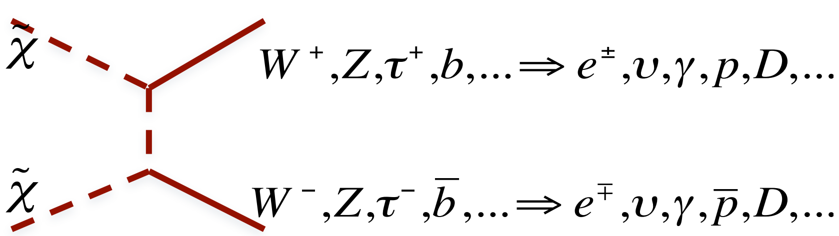
Role of Neutrinos

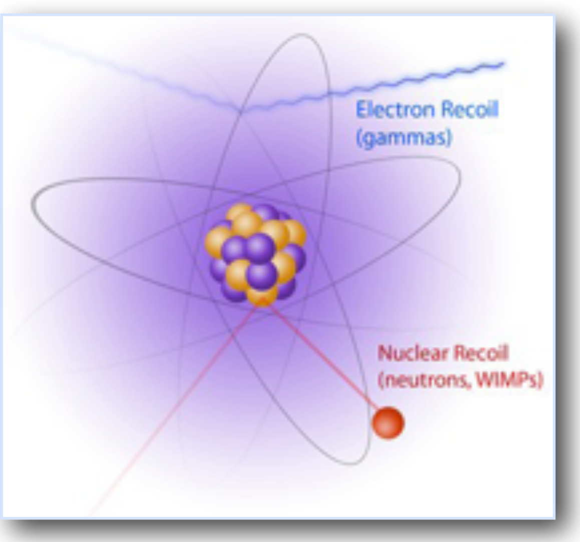


WIMP - Weakly Interacting Massive Particle



- Production
  - Colliders
- Indirect Searches
  - Dark Matter Decay
  - Annihilation of Dark Matter in Galactic Halo, ...
    - Gamma-rays, electrons, neutrinos, anti-matter, ...
  - Annihilation signals from WIMPs captured in the Sun (or Earth)
    - Neutrinos
- Direct Searches
  - WIMP scattering of nucleons → Nuclear recoils





Dark Matter Lifetime

Dark Matter Self-annihilation cross section

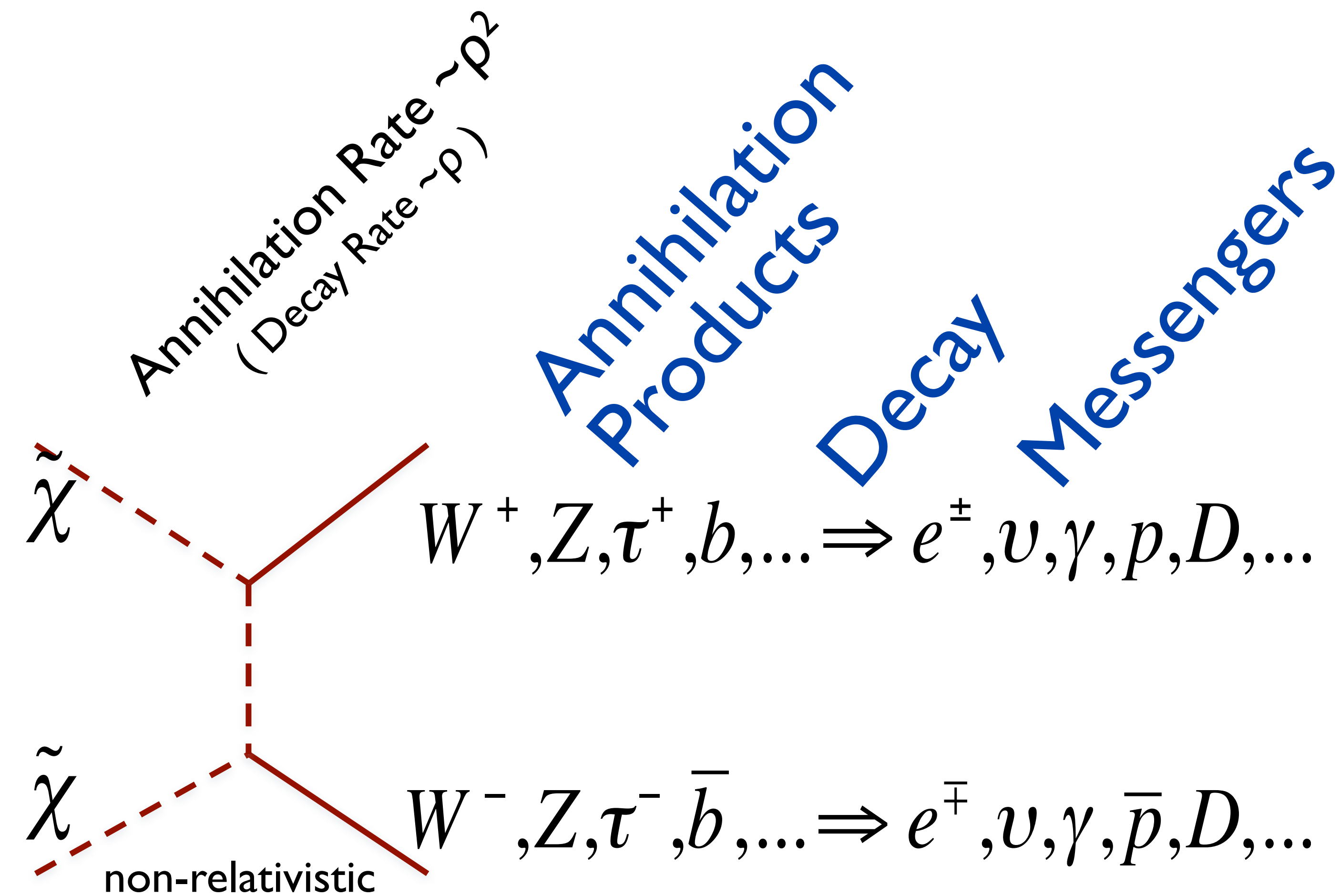
DM -Nucleon Scattering cross section

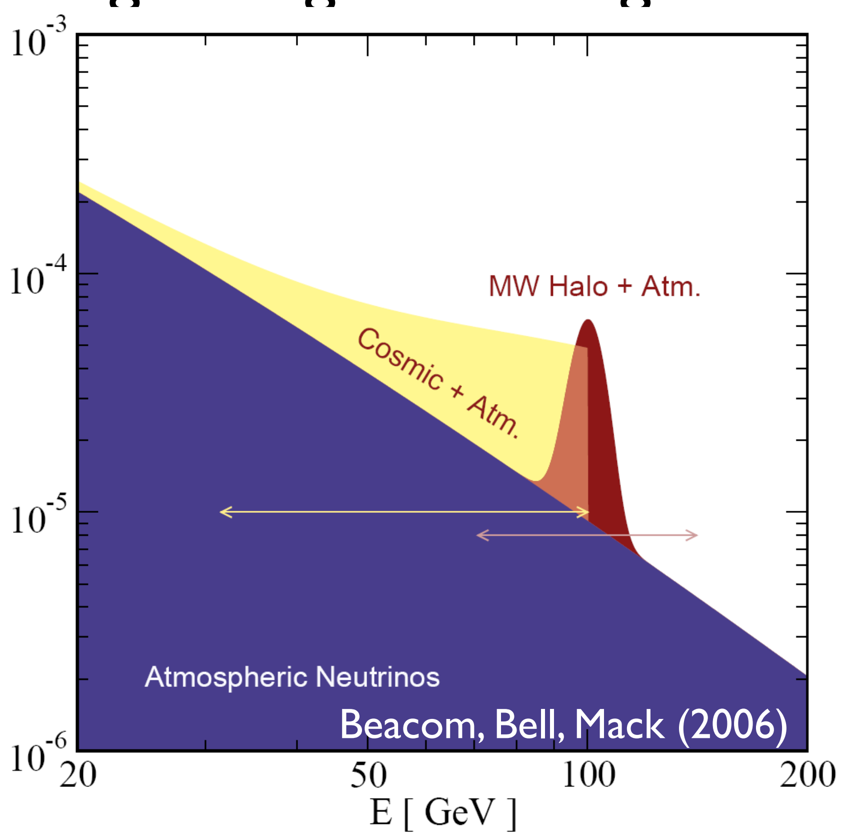
Dark Matter Signals

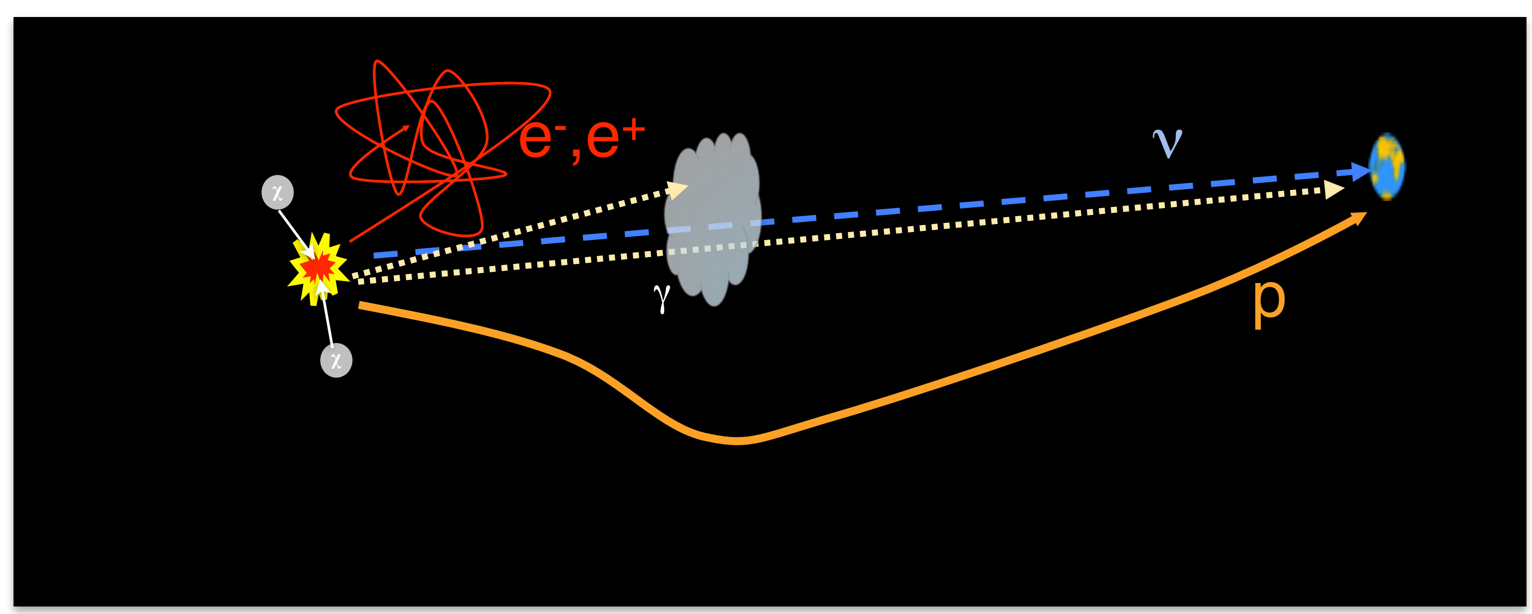
- Identify overdense regions of dark matter

  ⇒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

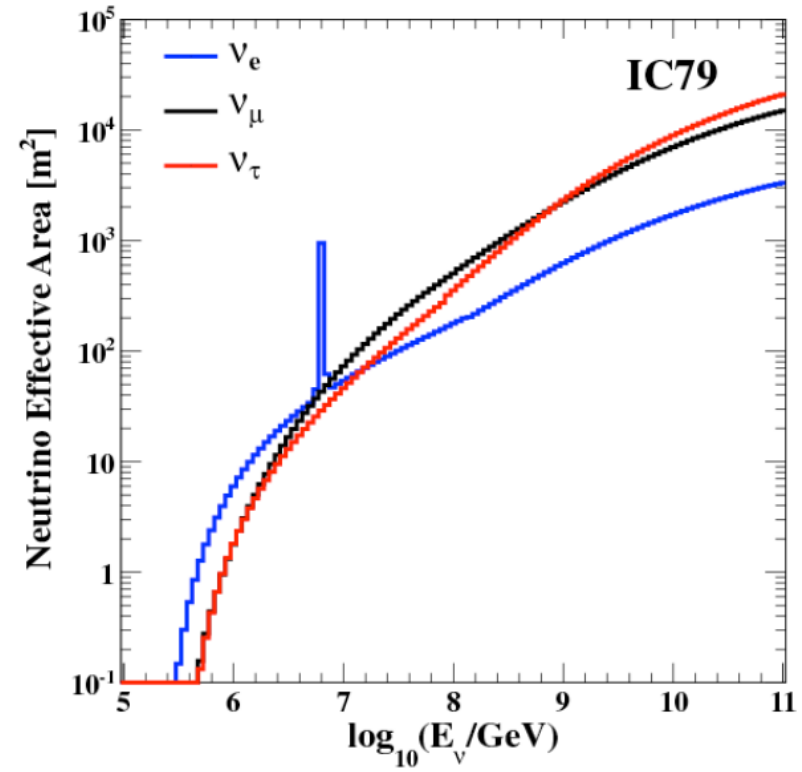


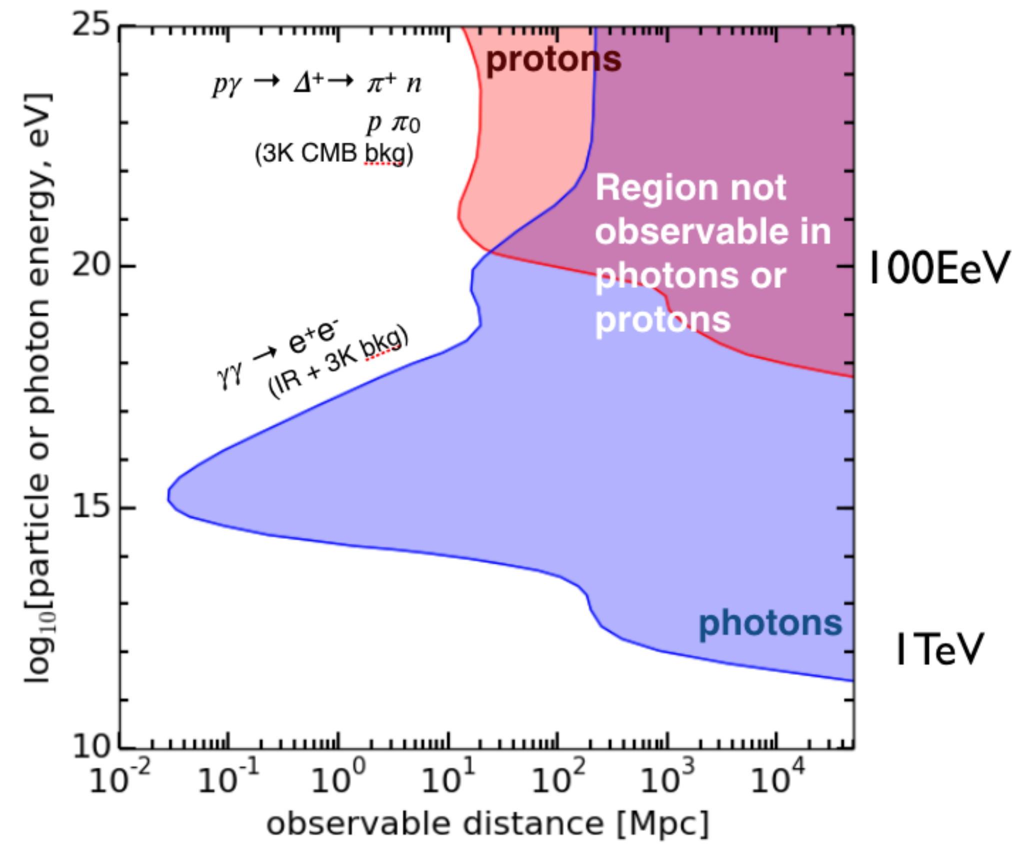




Why Neutrinos

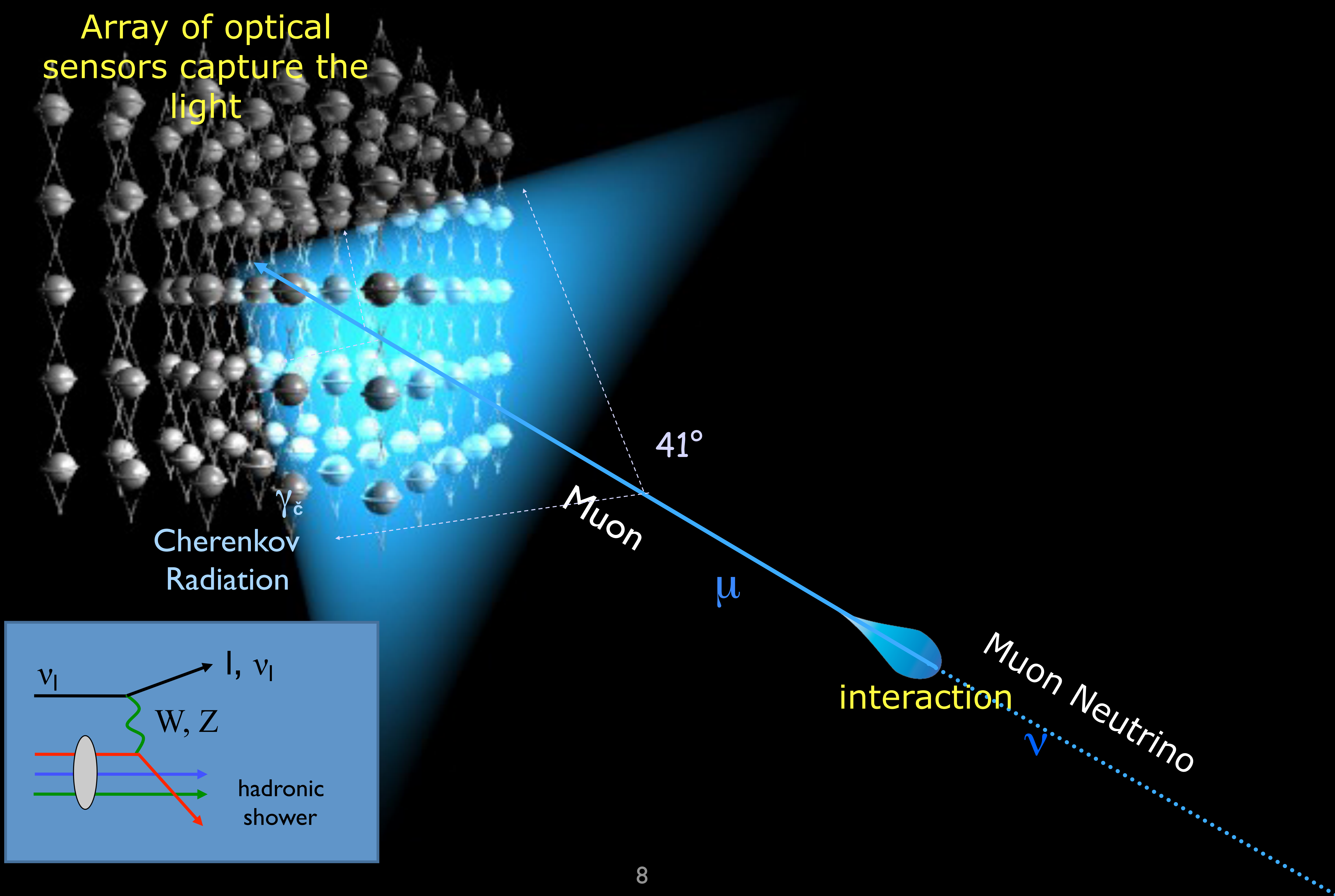
- Low mass DM (<1TeV)
  - Least detectable signal, most conservative bound (Beacom et al. 2006)
  - Confirm or rule out "signals" in observed in other channels
- High mass DM
  - Most detectable channel, discovery potential
  - Observe entire Universe with spectral information retained
  - Neutrino effective area increases with energy, better flavor ID, better angular resolution
  - Negligible atmospheric backgrounds, effectively use angular information
    - Spectral features more "visible"

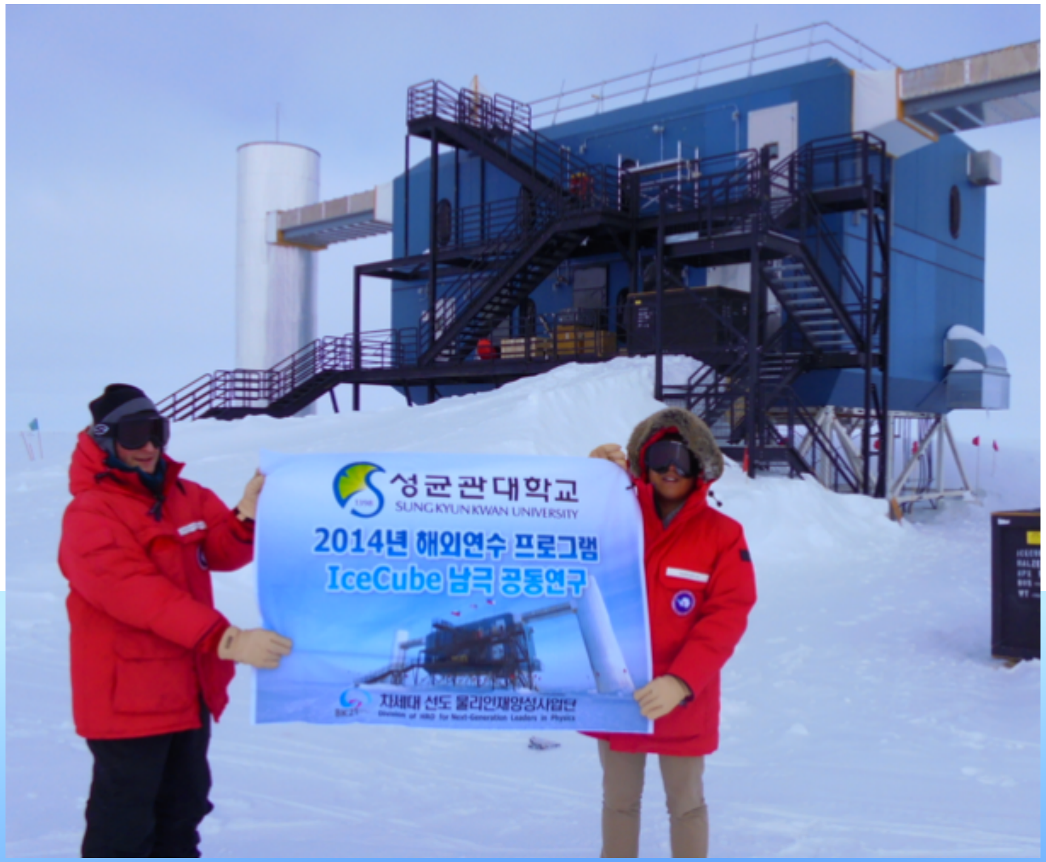




Neutrino telescopes naturally observe the entire sky, data is for "free"

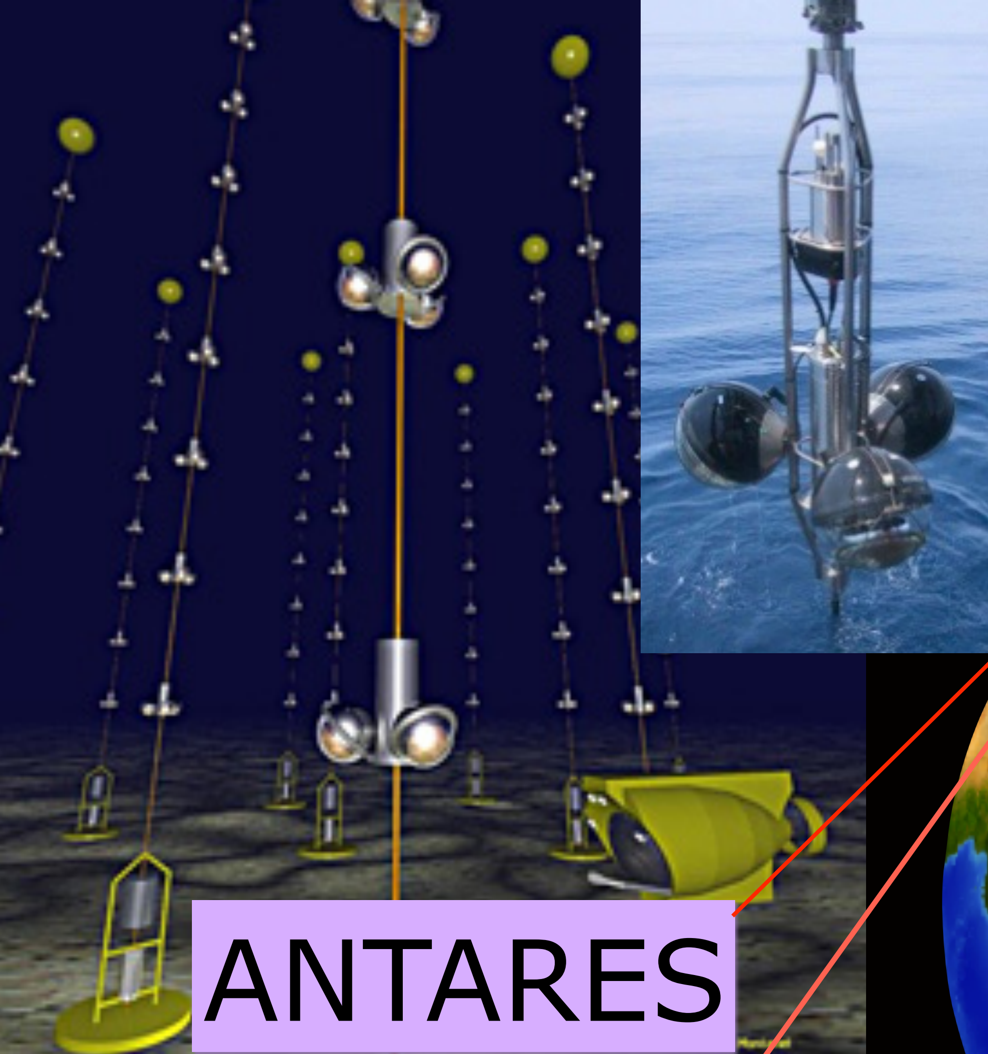
Principle of an optical Neutrino Telescope





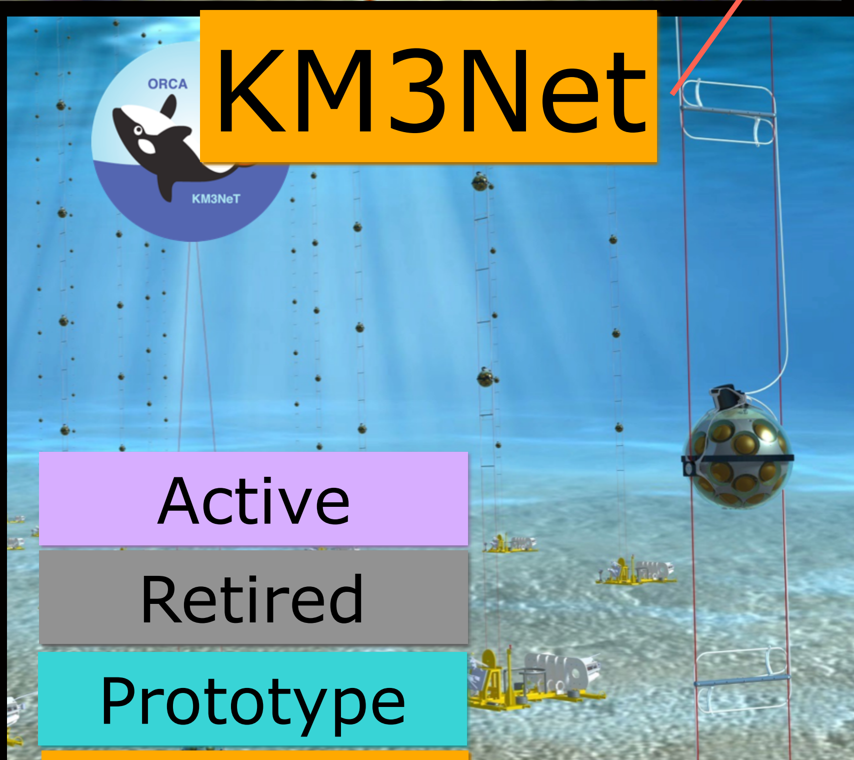
Neutrino Telescopes

Large Water Cherenkov Neutrino Detectors



ANTARES

KM3Net



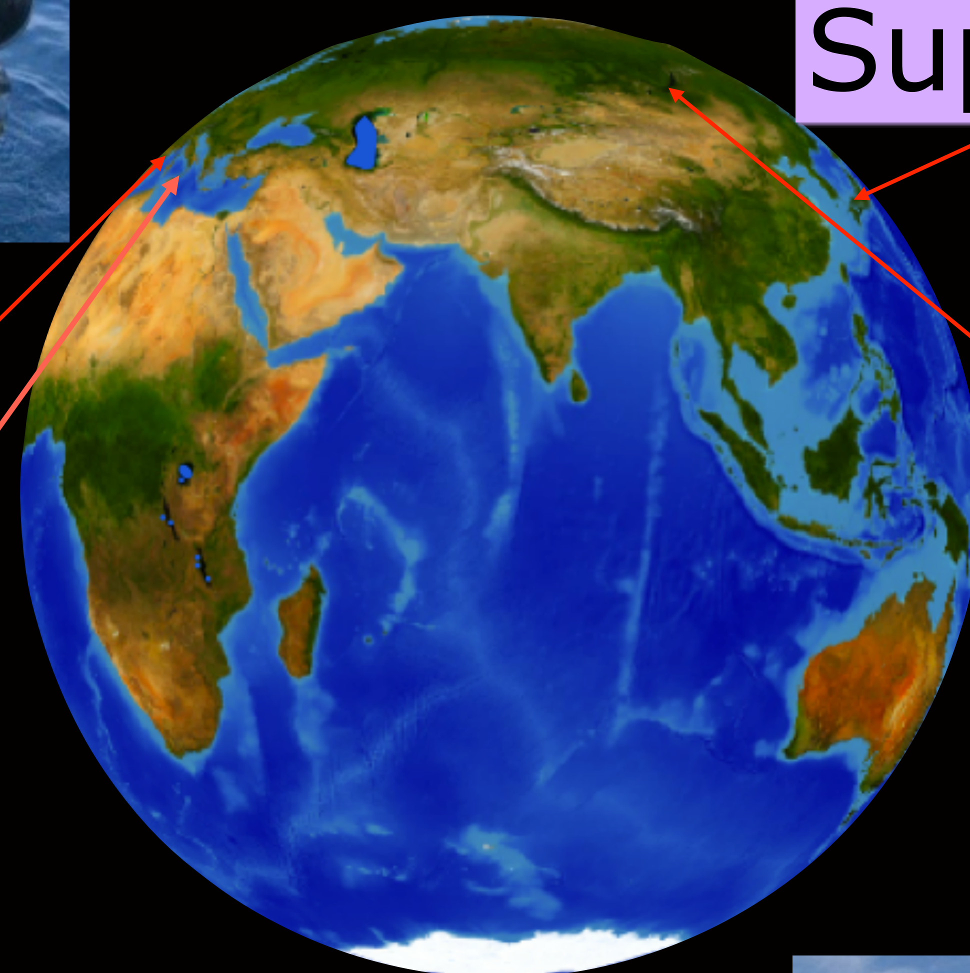
Active

Retired

Prototype

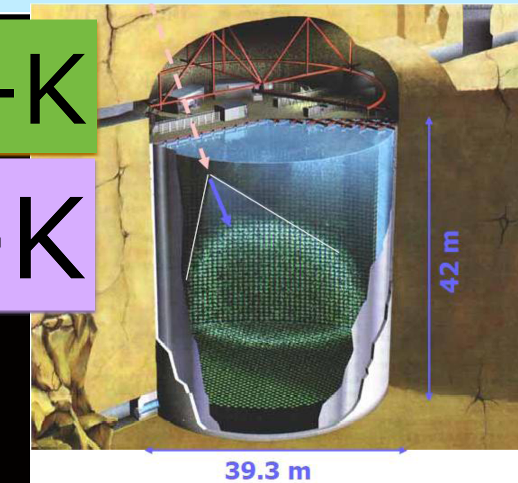
Construction

Planned



Hyper-K

Super-K



Lake Baikal

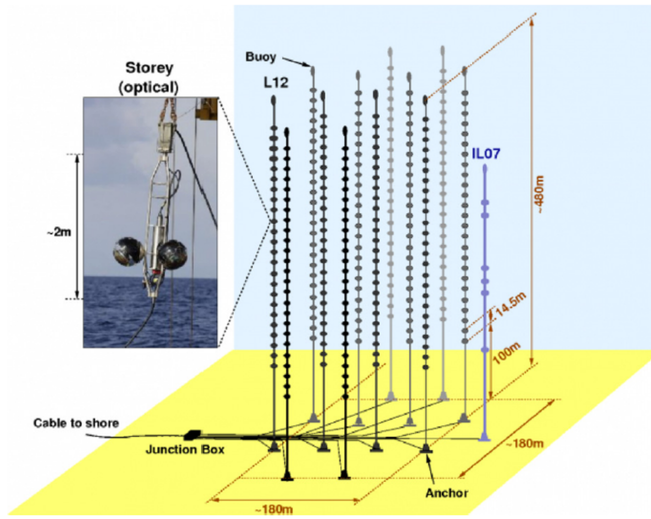
GVD

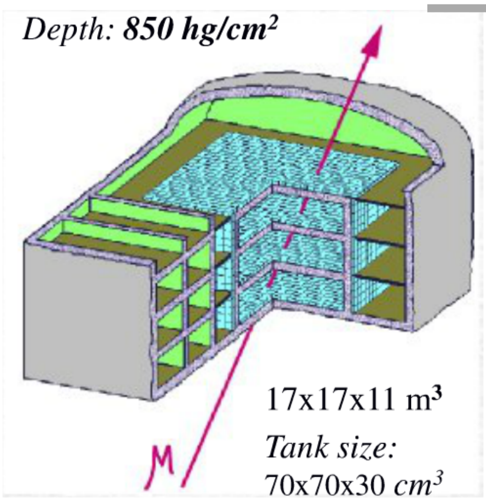
IceCube

Gen2/PINGU

Neutrino Telescopes / Detectors

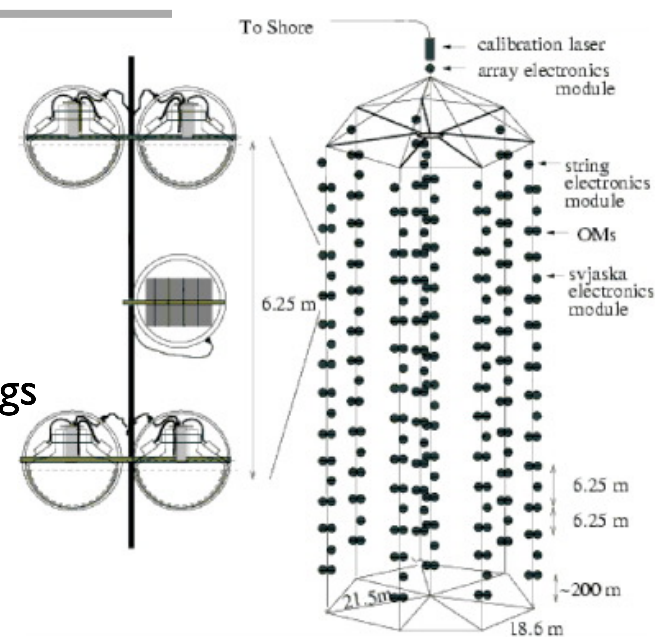
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



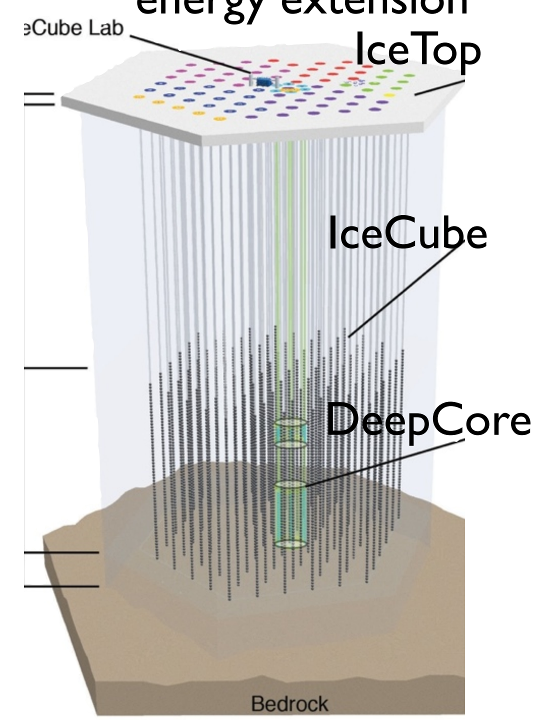


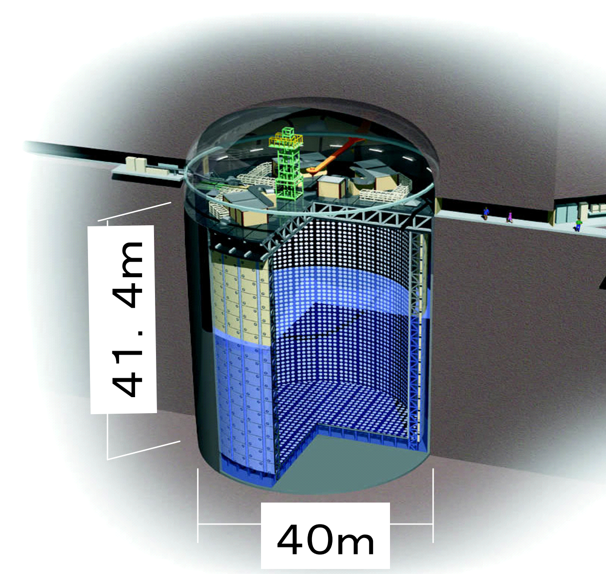
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- Lake **Baikal**, Siberia, at a depth 1.1 km NT36 in 1993
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length



- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km³
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension



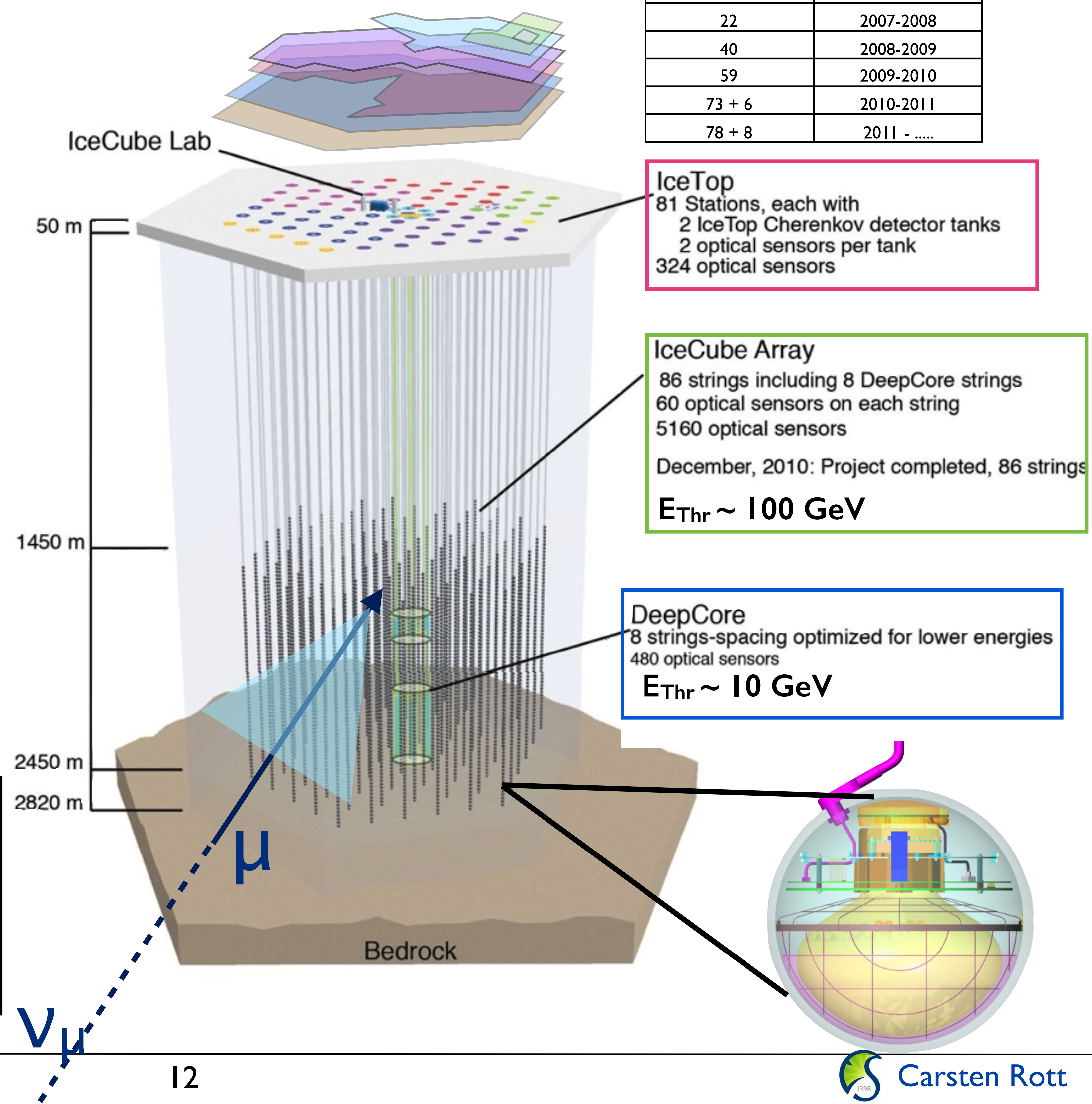


- **Super-Kamiokande** at Kamioka uses 11K 20" PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

The IceCube Neutrino Telescope

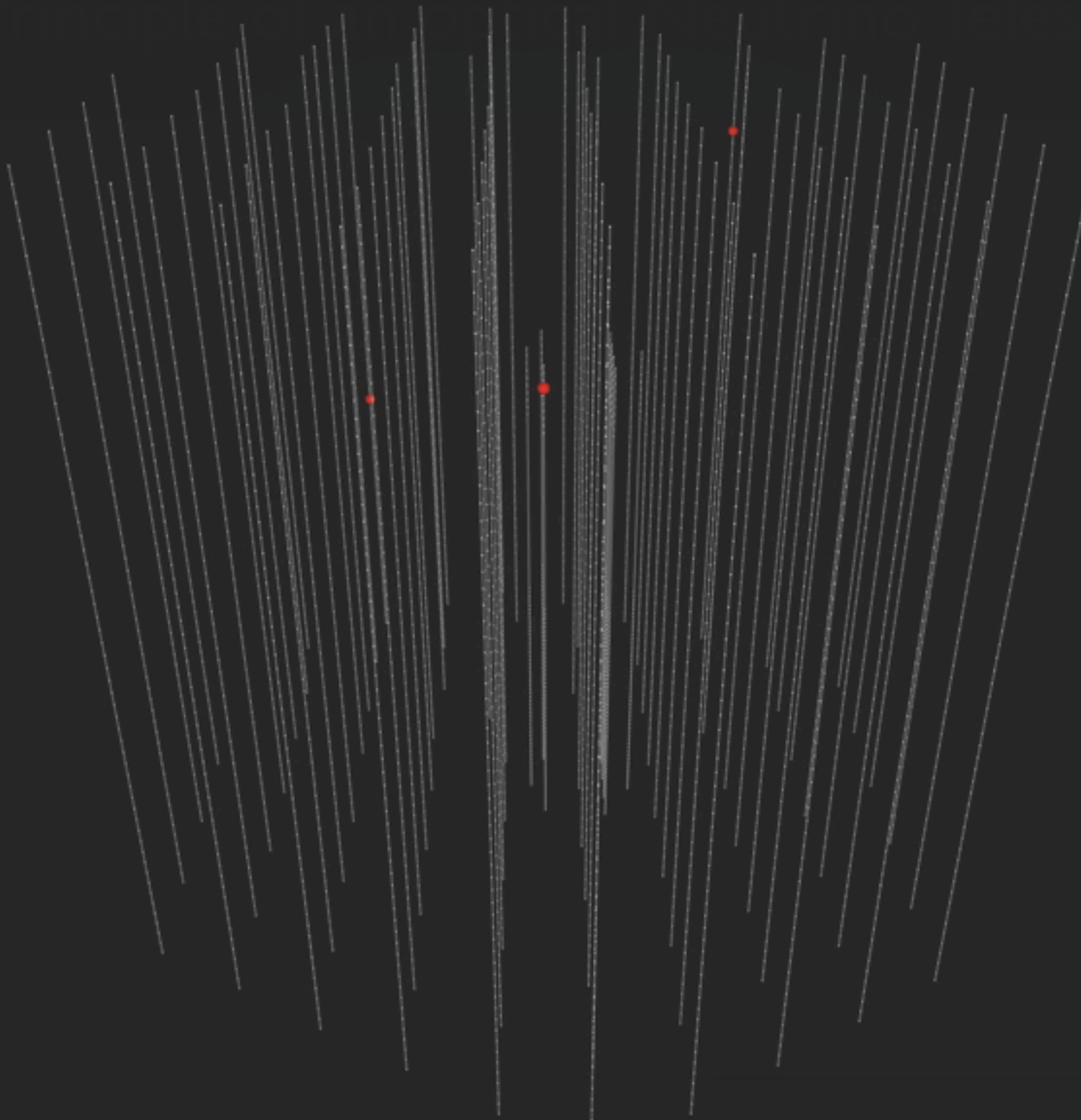
- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Data acquired during the construction phase has been analyzed
- Neutrinos are identified through Cherenkov 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 - .....



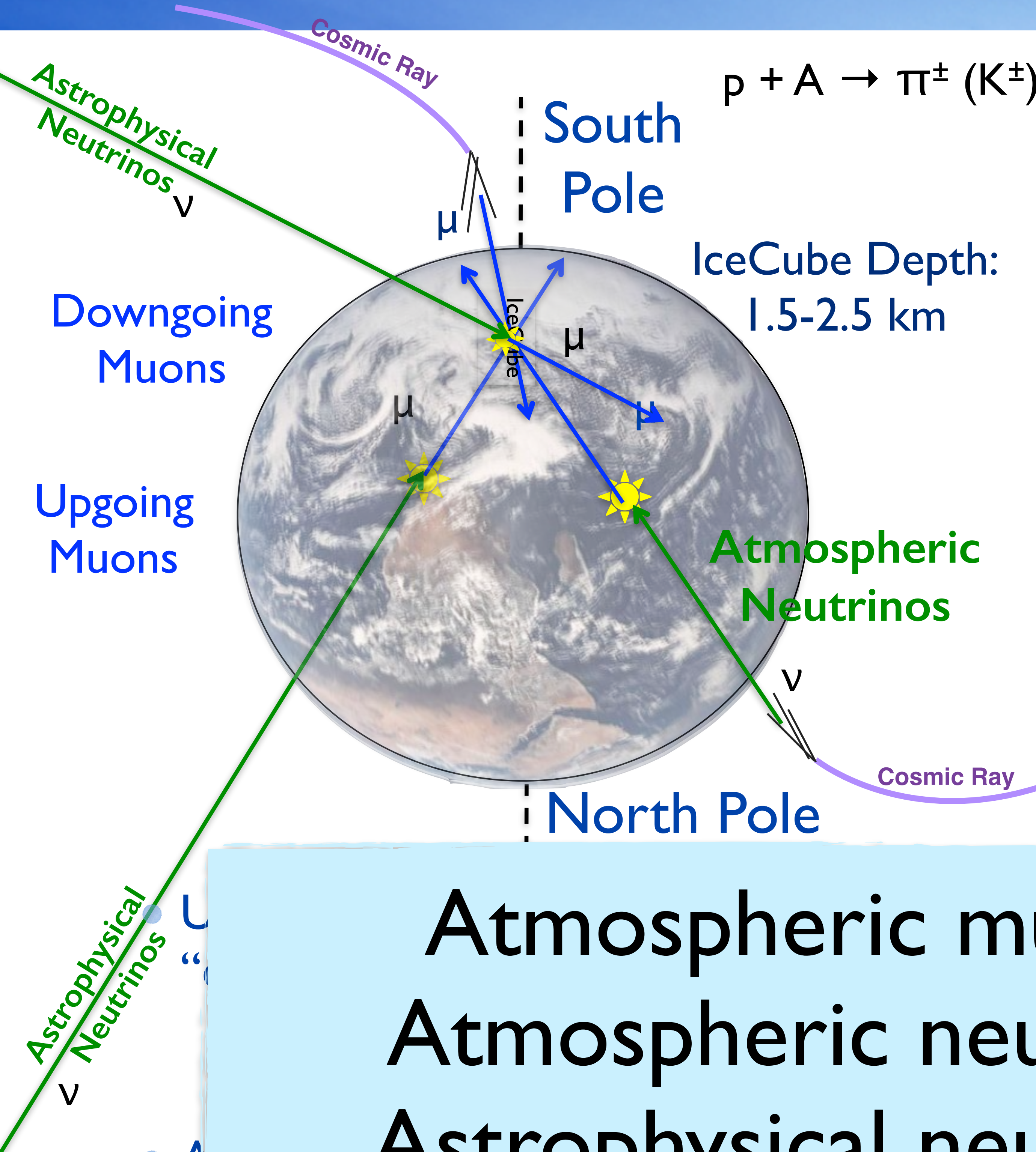
Dark Matter Searches

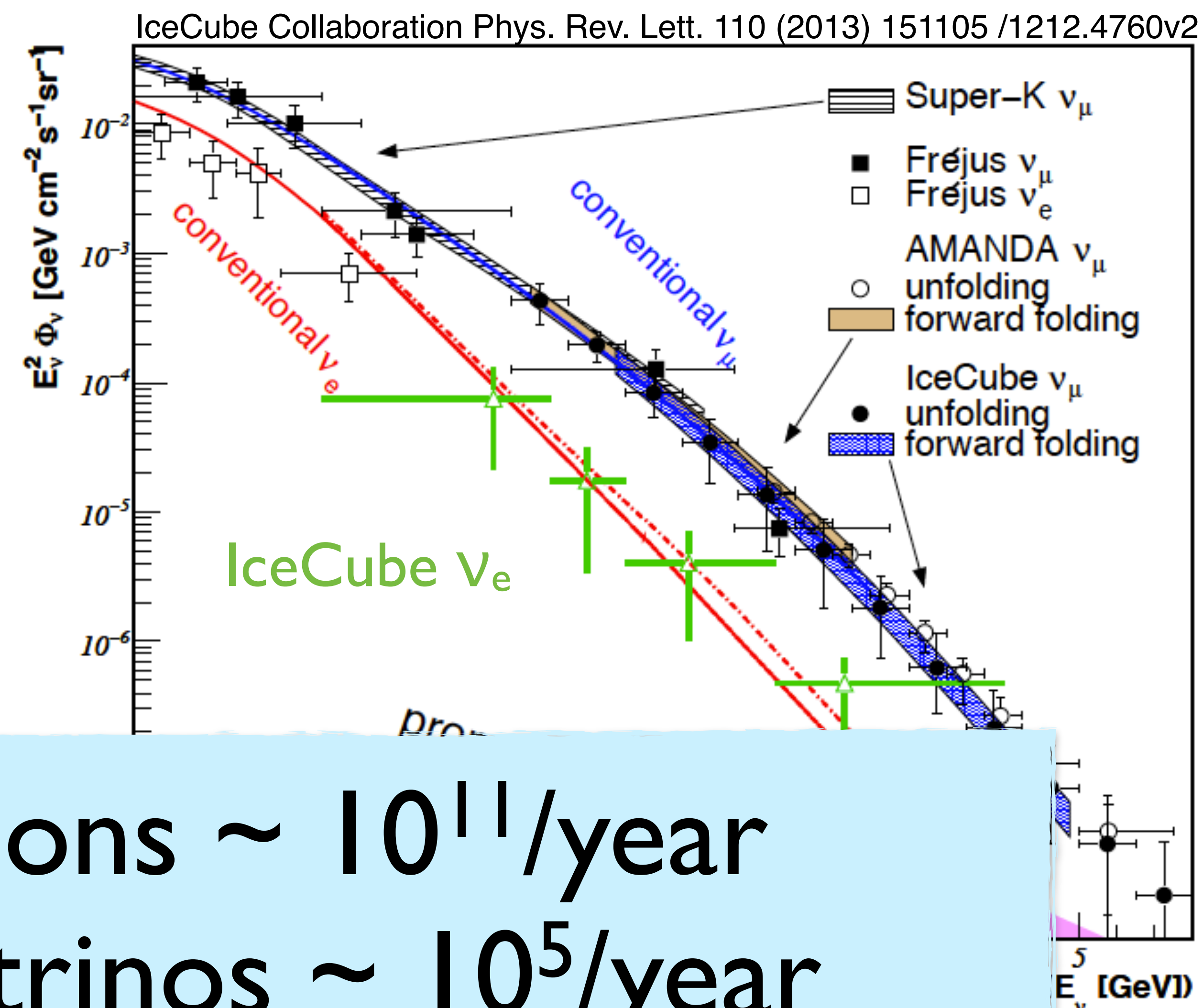
- Galactic Center is 29° above the horizon
- Sun is at +/- 23°



Signals in IceCube

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





Atmospheric muons ~ 10^{11}/year

Atmospheric neutrinos ~ 10^{5}/year

Astrophysical neutrinos >100/year

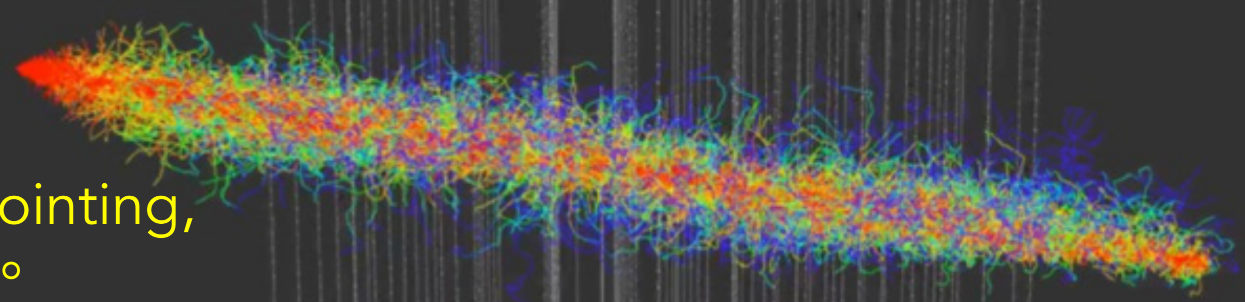
- U… “…
- A… irreducible neutrino background to extra terrestrial neutrino fluxes

Event Topologies in IceCube

Track topology

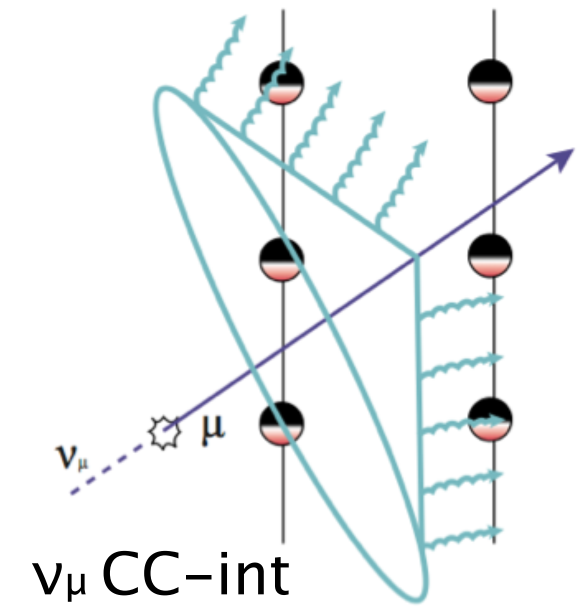
(e.g. induced by muon neutrino)

CC: ν_μ



Good pointing,
0.2° - 1°

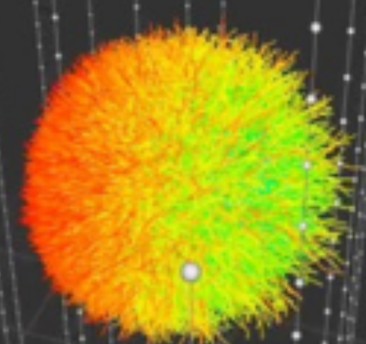
Lower bound on energy for through-going events



ν_μ CC−int

CC: ν_e ν_τ

NC: ν_e ν_μ ν_τ

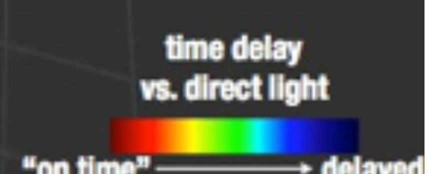


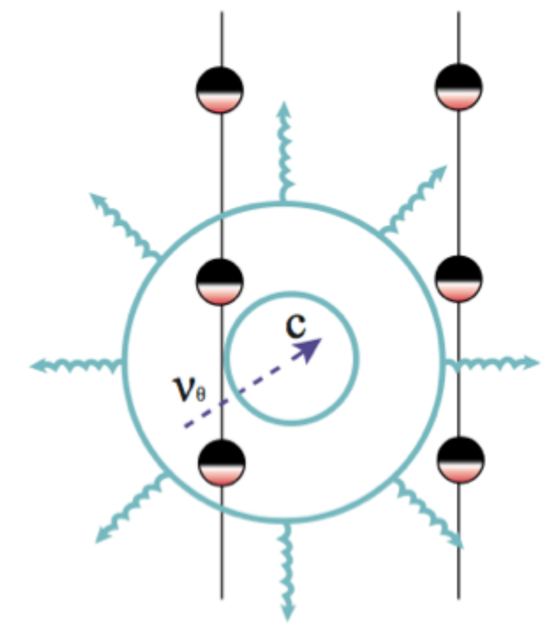
Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

Some pointing,
10° - 15°





ν_e ν_τ CC−int & ν_i NC−int

Dark Matter Self-annihilations

$<\sigma_A v>$

Dark Matter in the Milky Way

Dark Matter Annihilation

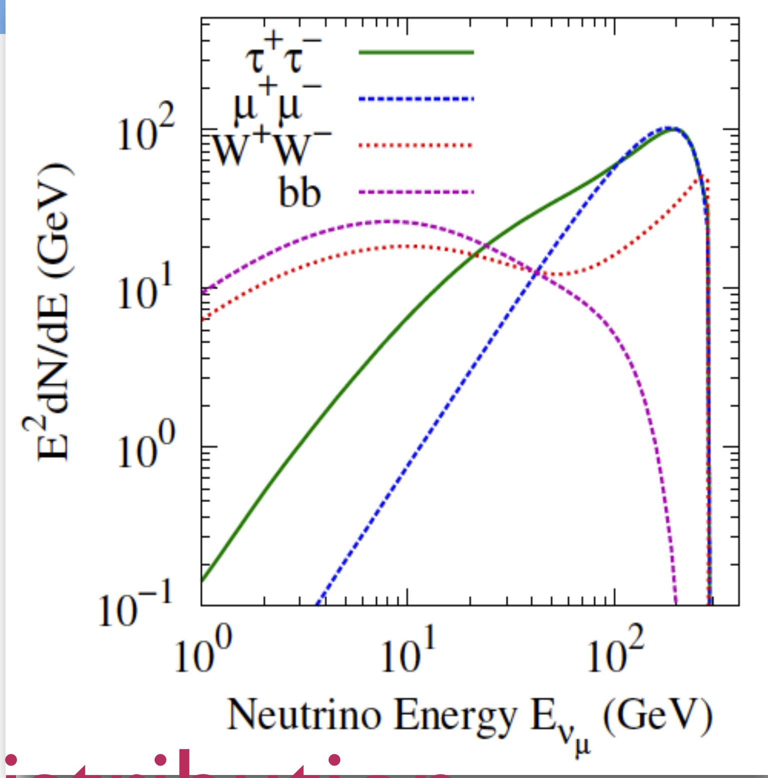
Measure Flux

$$\frac{d\Phi}{dE}(E,\phi,\theta)$$

=

Particle Physics

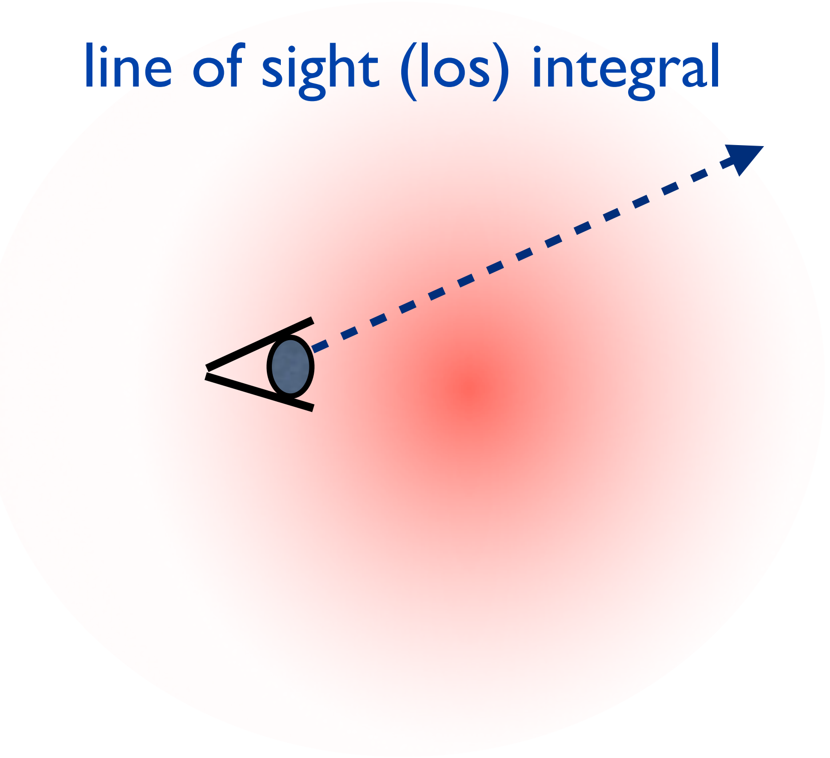
$$\frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f$$



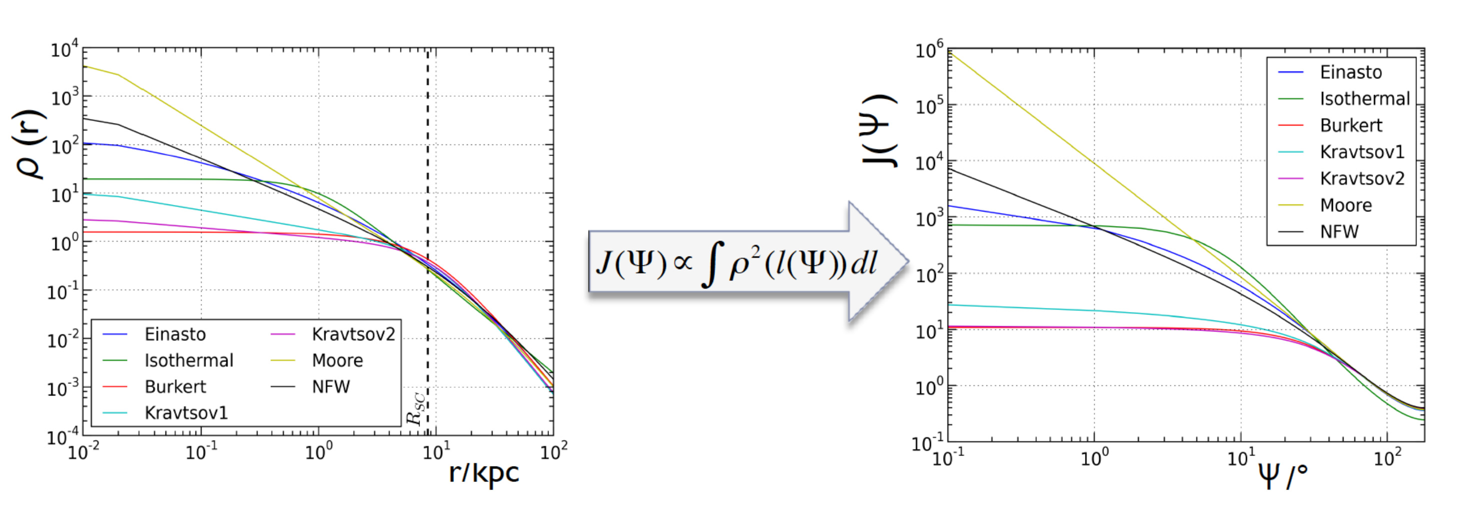
x

Dark Matter Distribution

line of sight (los) integral

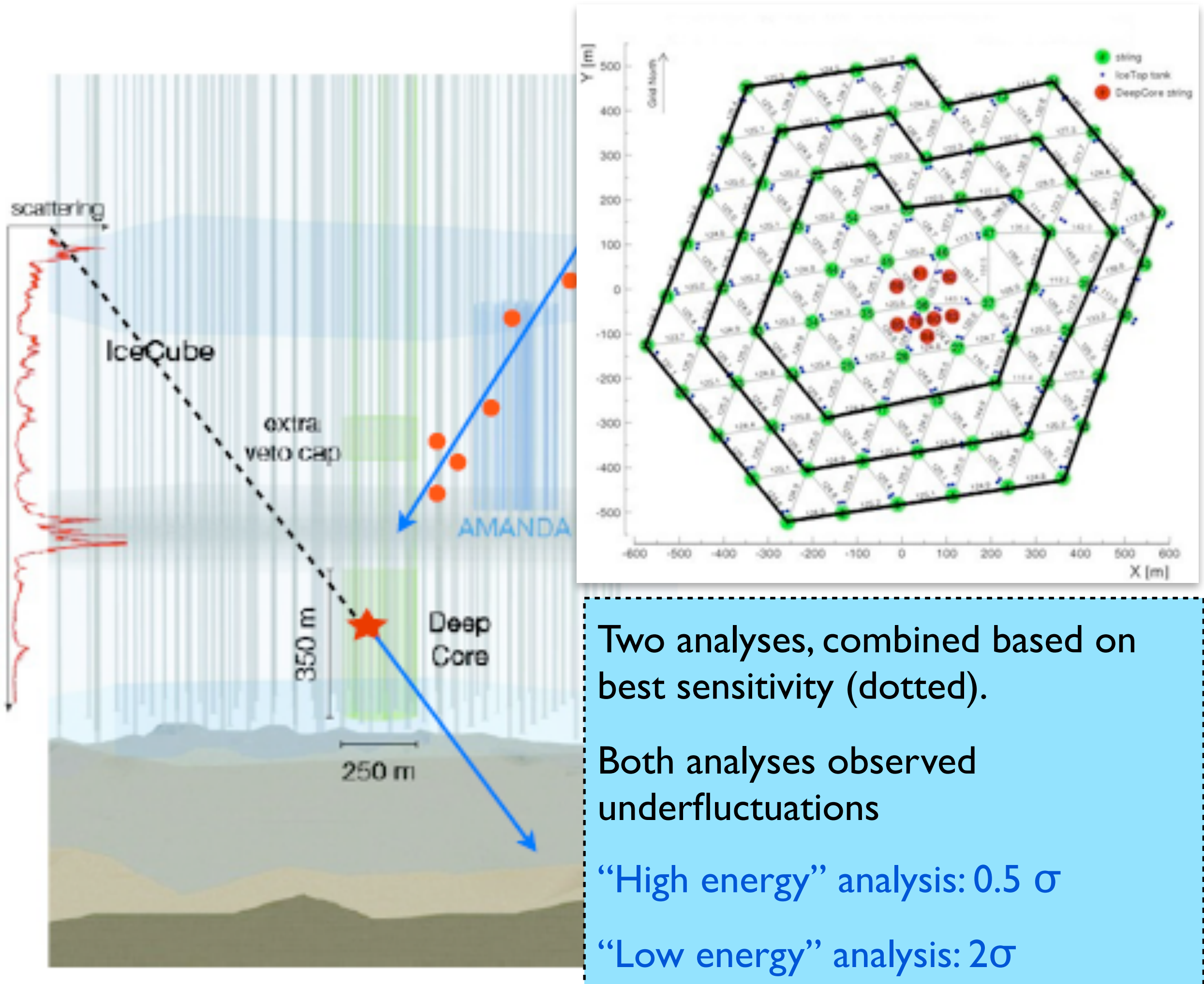


$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\mathrm{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



Galactic Center

Use IceCube external strings as a veto:
- 3 complete layers around DeepCore (~ 375m)
- Full sky sensitivity: access to southern hemisphere

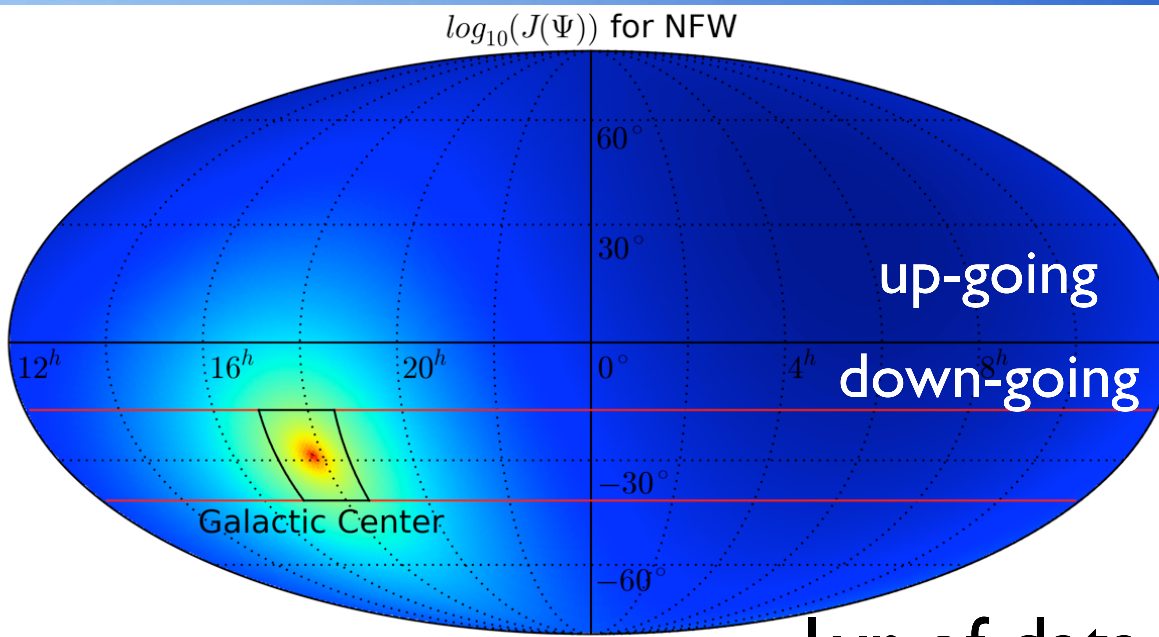


Two analyses, combined based on best sensitivity (dotted).

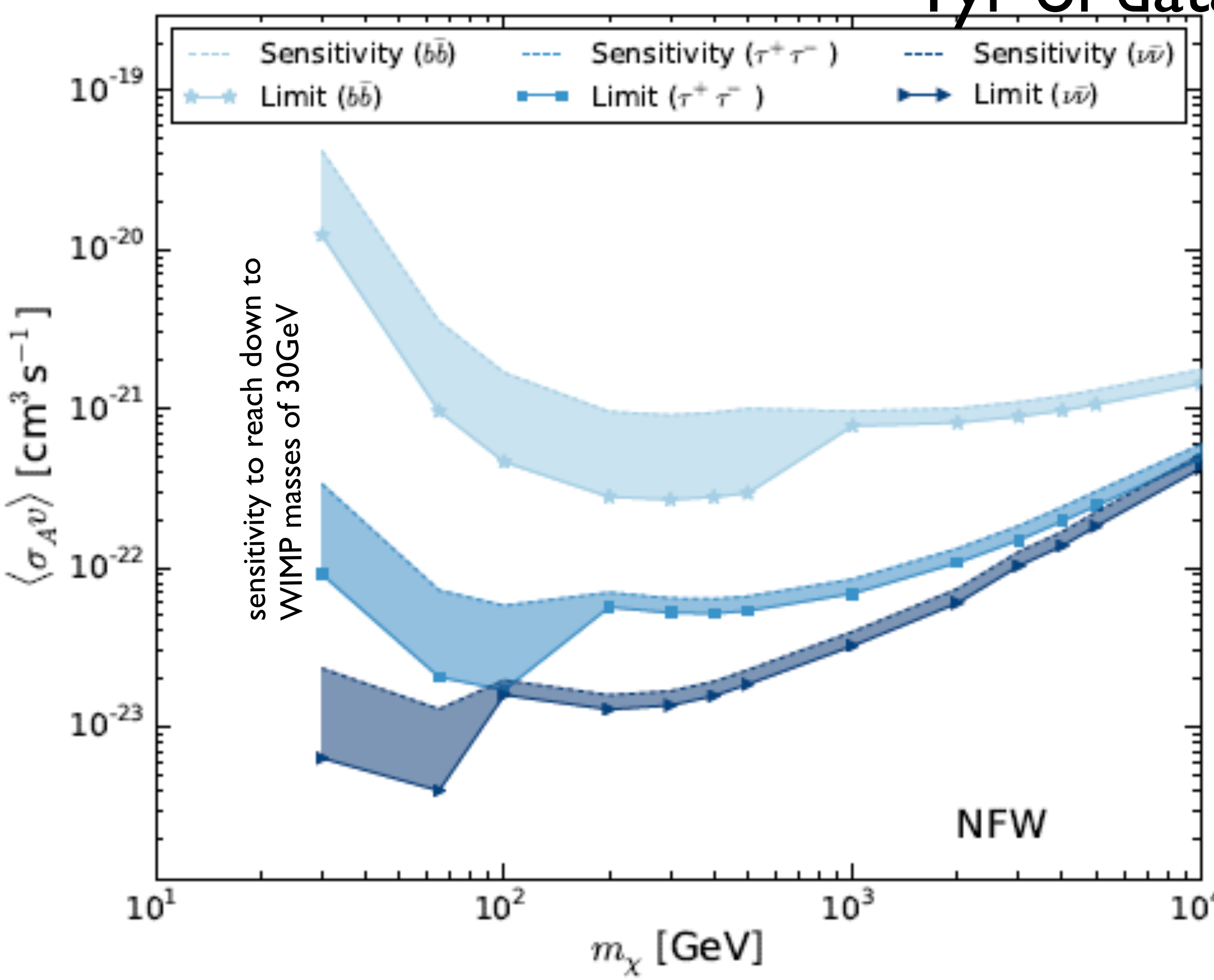
Both analyses observed underfluctuations

"High energy" analysis: 0.5 σ

"Low energy" analysis: 2σ

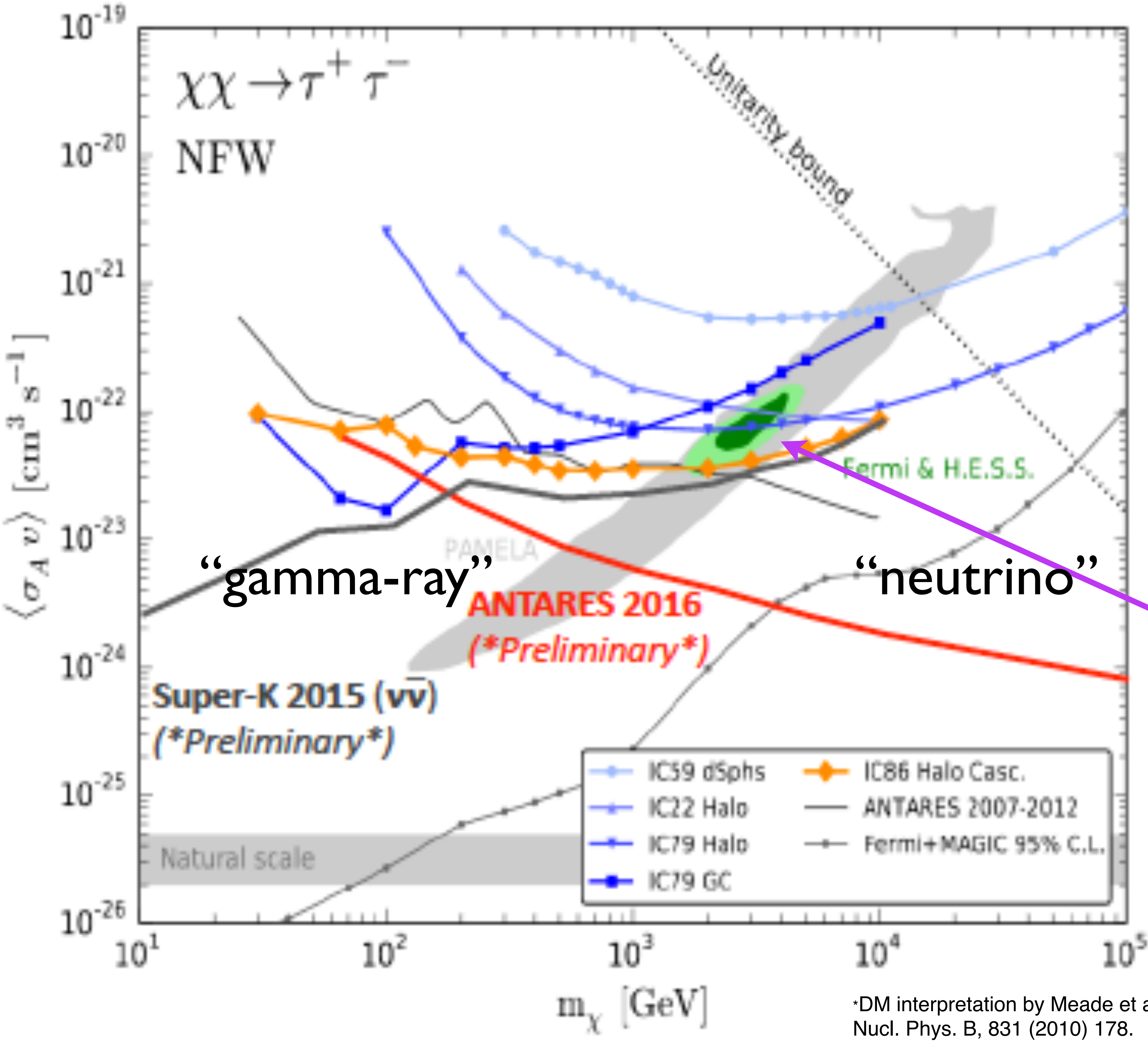


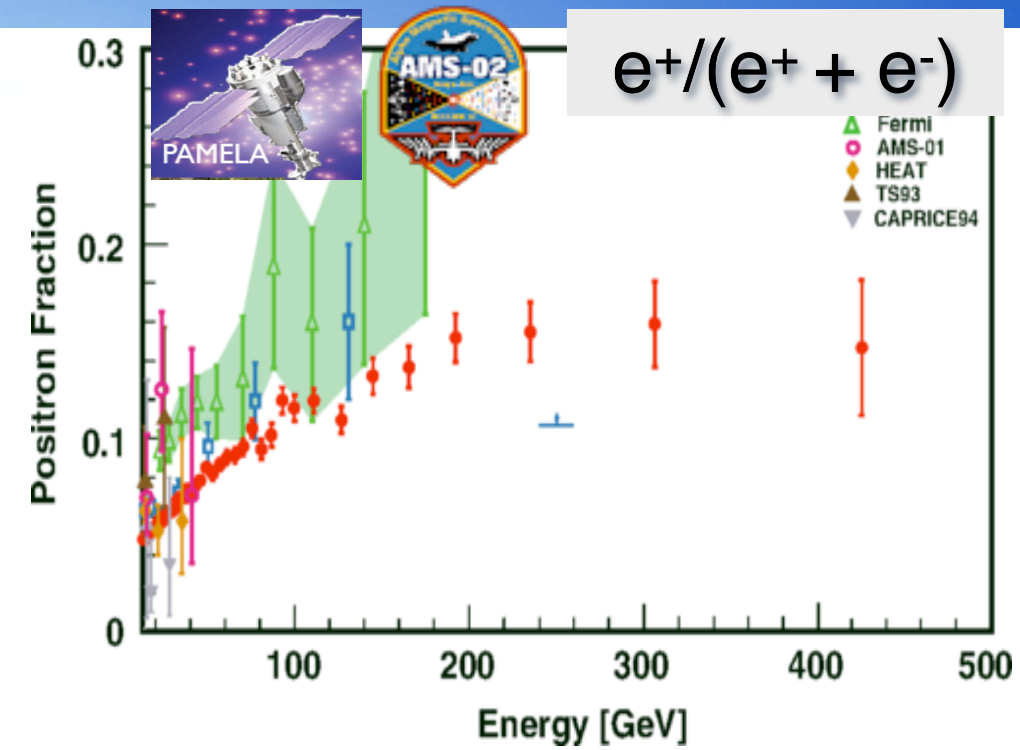
1yr of data

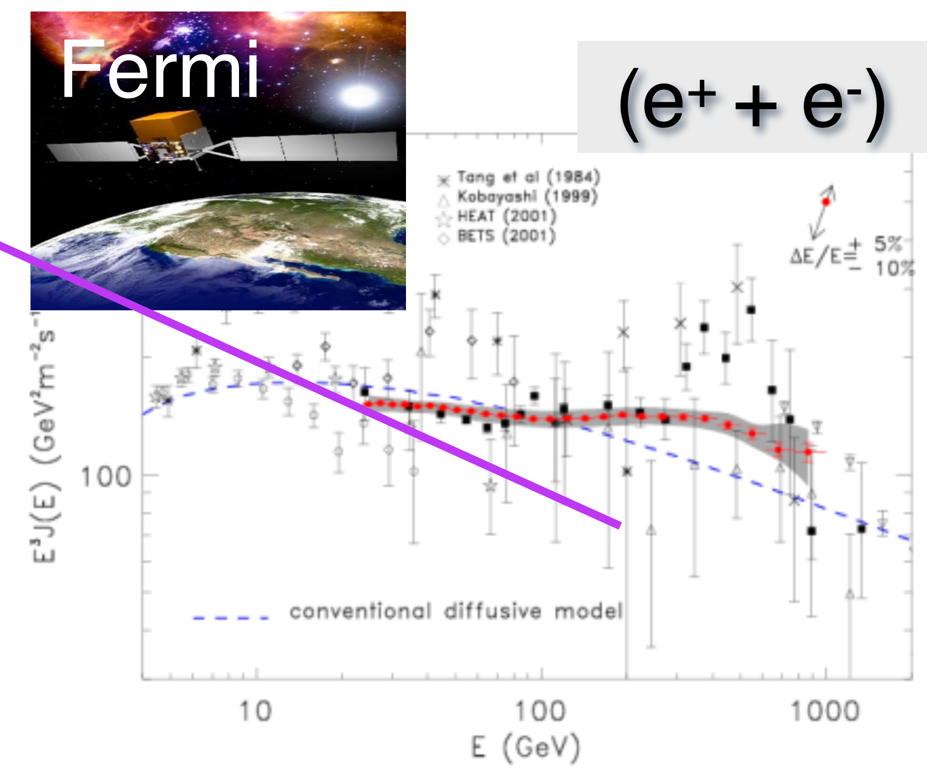


Separate Low energy and High energy optimizations:
GC is above the horizon
→ Fiducial volume in central strings
→ refined muon veto from surrounding layers
Use scrambled data for background estimation

Neutrinos test lepton anomalies







*DM interpretation by Meade et al., Nucl. Phys. B, 831 (2010) 178.

Neutrino Telescopes can probe models motivated by the observed lepton anomalies

AMS-02 5years result

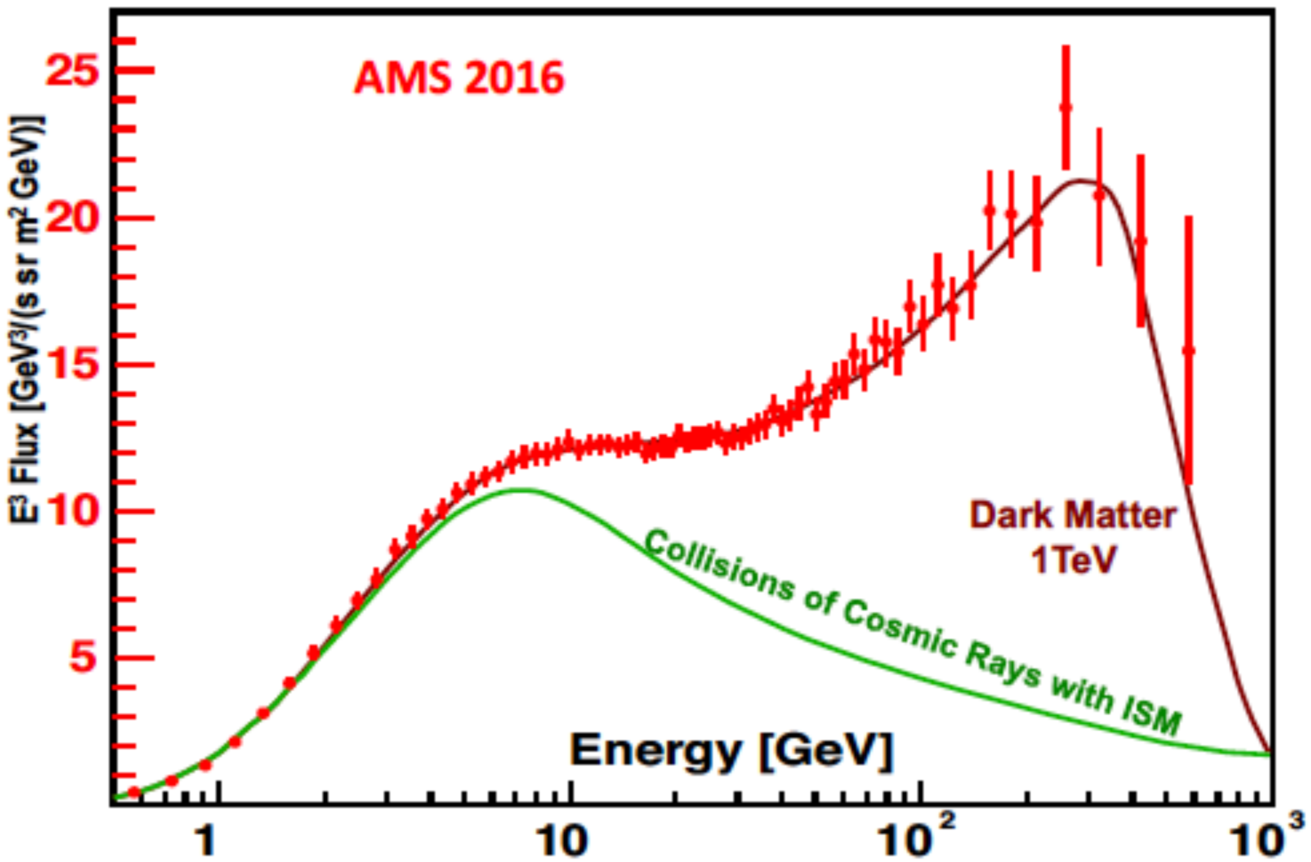


Figure 4. The current AMS positron flux measurement compared with theoretical models.

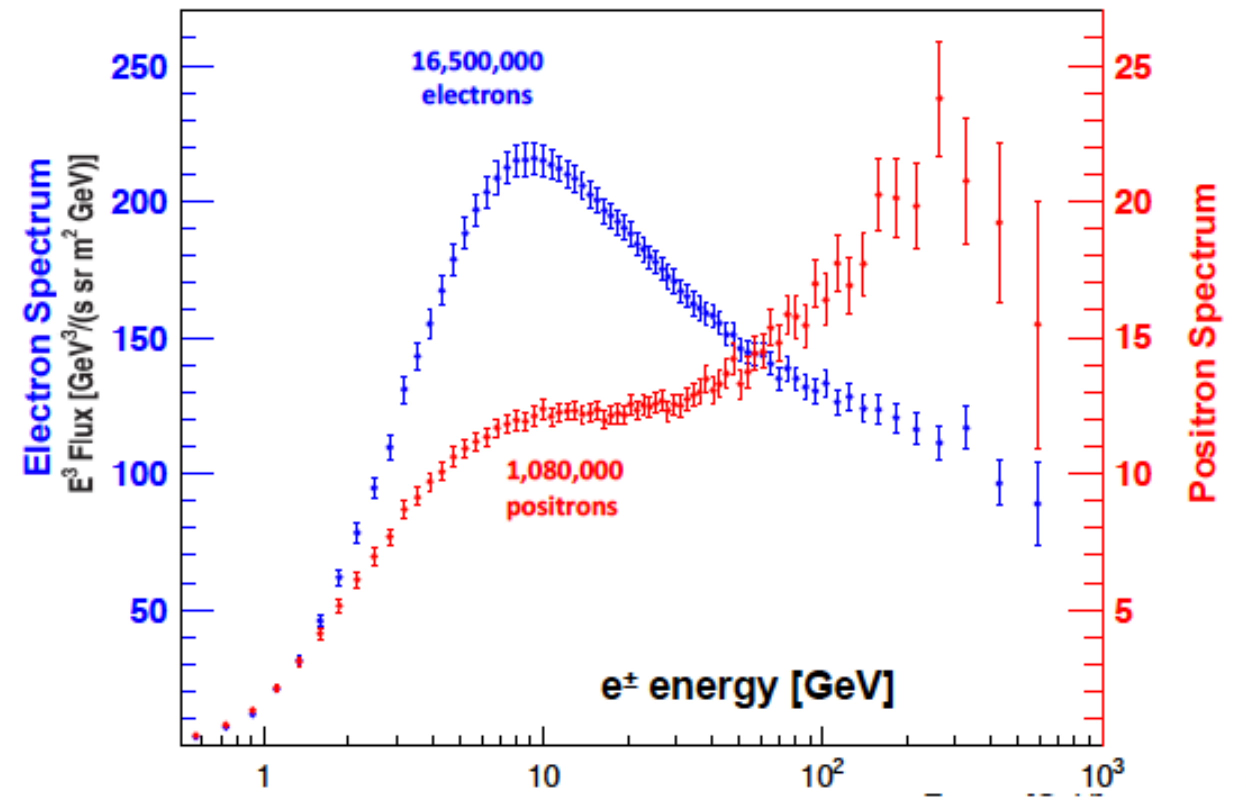
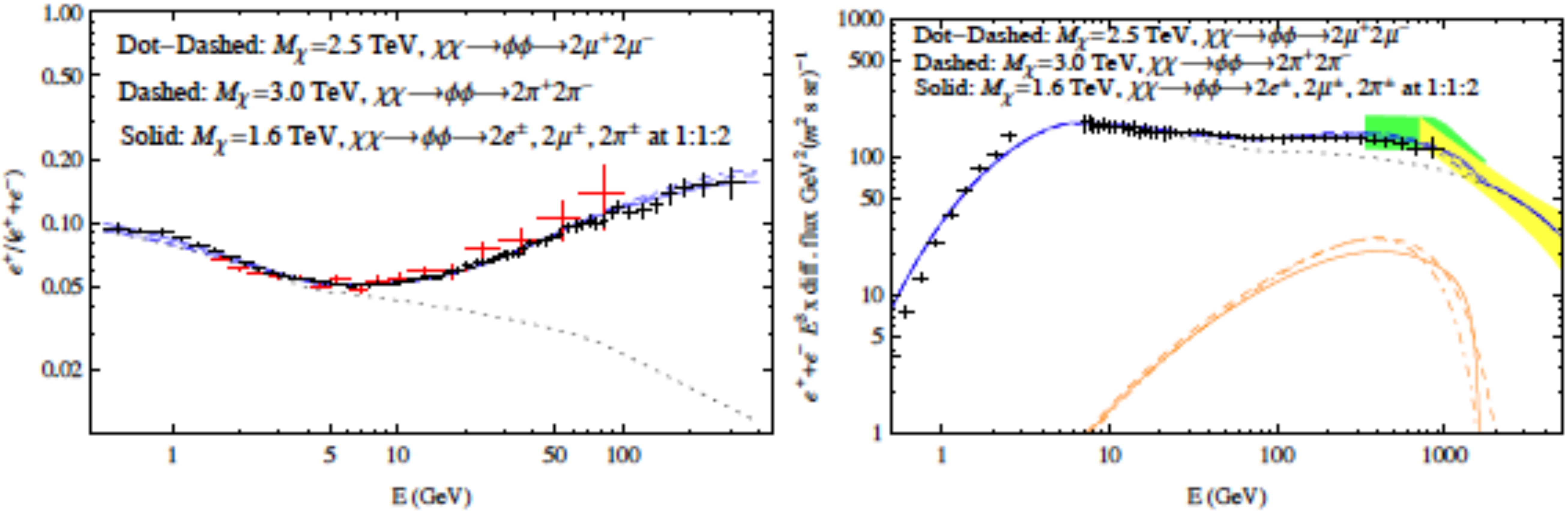


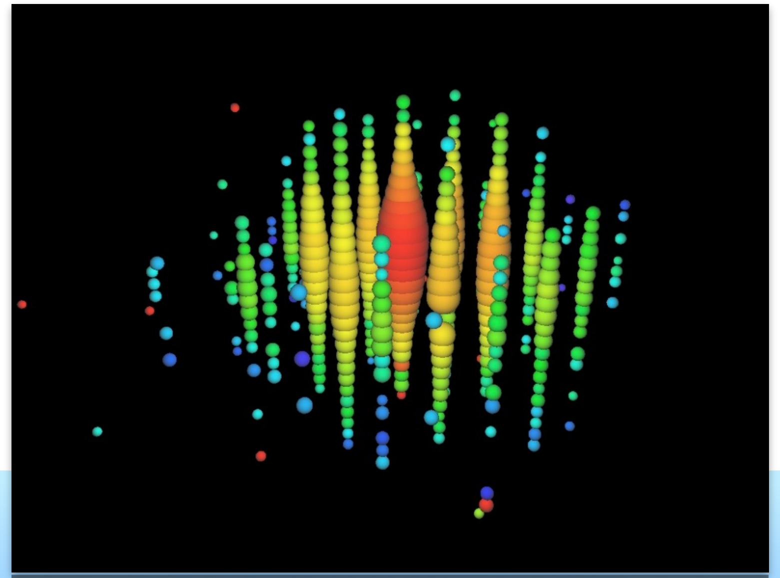
Figure 2. The electron flux and the positron flux are different in their magnitude and energy dependence.

What if it is dark matter ?

Example: Cholis & Hooper (2016)



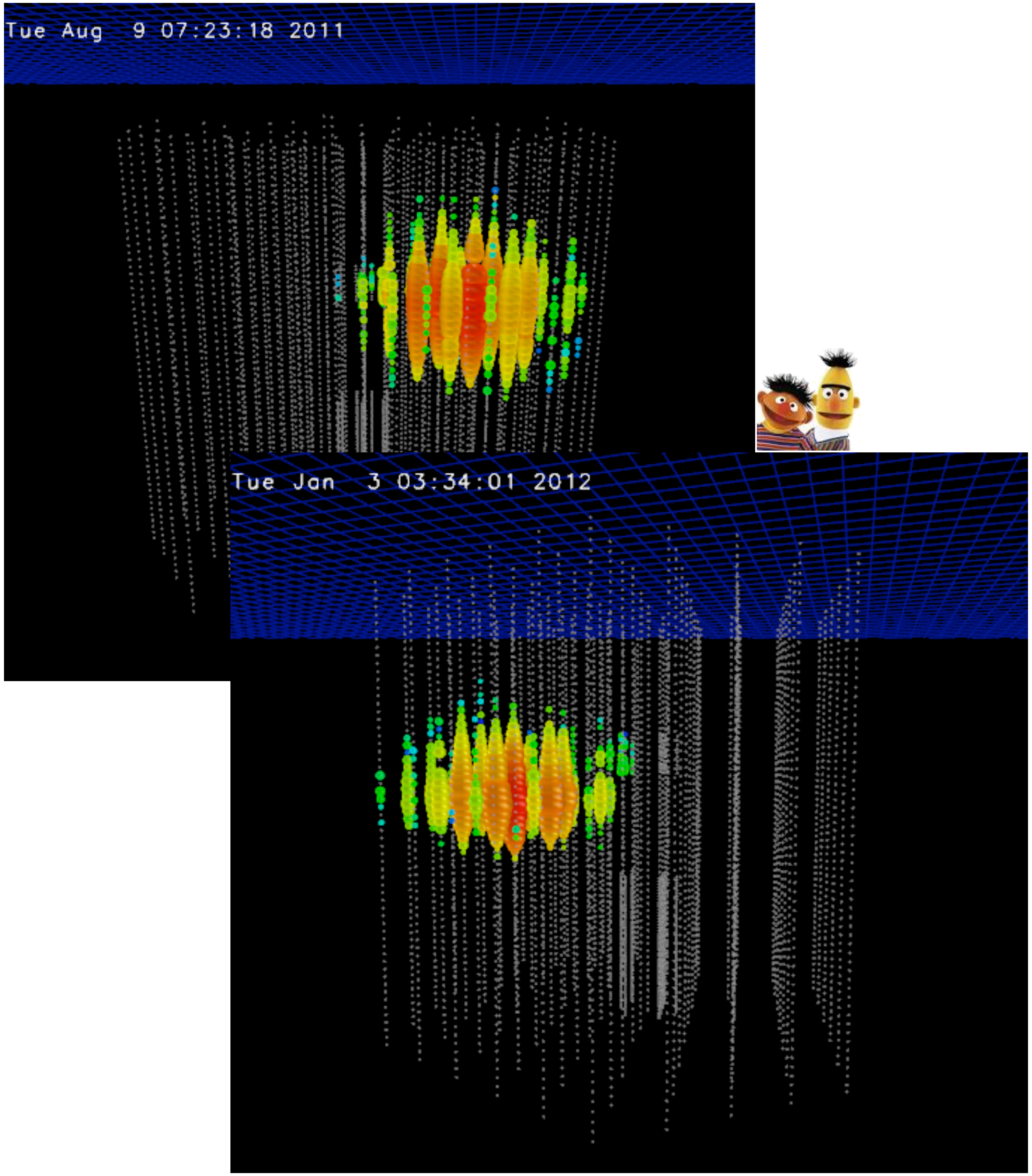
- Annihilation into e^+e^- or $\mu^+\mu^-$ disfavoured
- Typical masses 1-3TeV and cross sections ~10^{-23} - 10^{-24} cm^{3}s^{-1}
- Many scenarios well testable at neutrino telescopes !
  - Searches expanded to already underway



Dark Matter Decay / Astro-physical Neutrinos / Boosted Dark Matter / …

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 (→ 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 ...

Heavy Dark Matter

- Intriguing overlap in energy of the two 1 PeV cascade events of IceCube high energy event sample

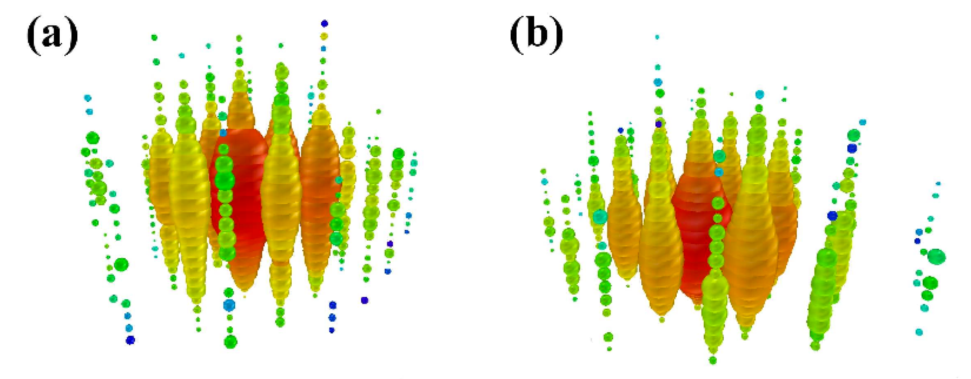


FIG. 4. The two observed events from (a) August 2011 and (b) January 2012. Each sphere represents a DOM. Colors represent the arrival times of the photons where red indicates early and blue late times. The size of the spheres is a measure for the recorded number of photo-electrons.

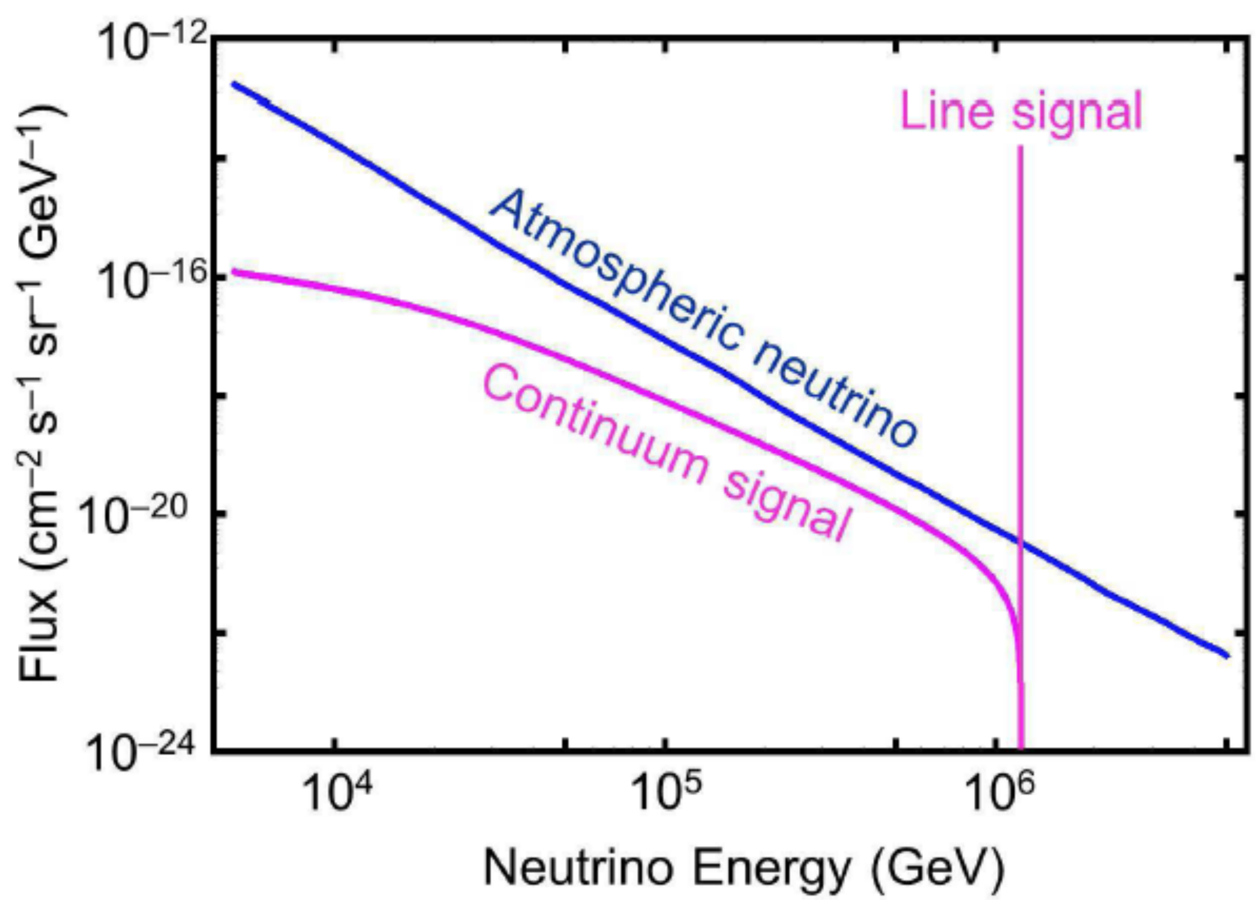
Could this be dark matter ?

example: B. Feldstein, A. Kusenko, S. Matsumoto, and T. Yanagida arXiv:1303.7320v1 / Phys.Rev. D88 (2013) 1, 015004

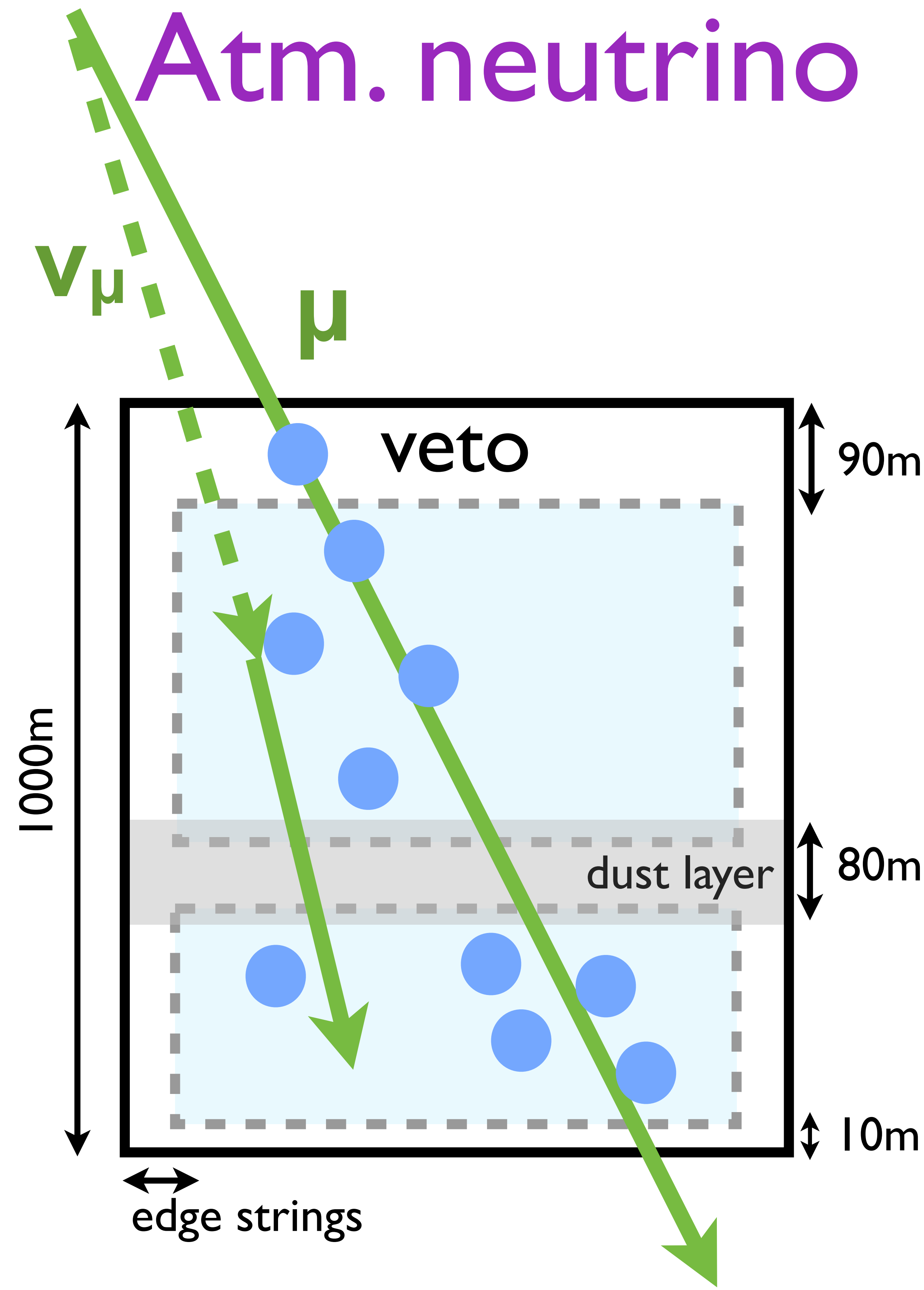
Evidence:
- 2.4PeV Dark Matter Particle mass
- Flux can be related to the lifetime τ_{DM}

$$\tau_{\mathrm{DM}} \simeq 1.9 N_\nu \times 10^{28}\ \mathrm{s}$$

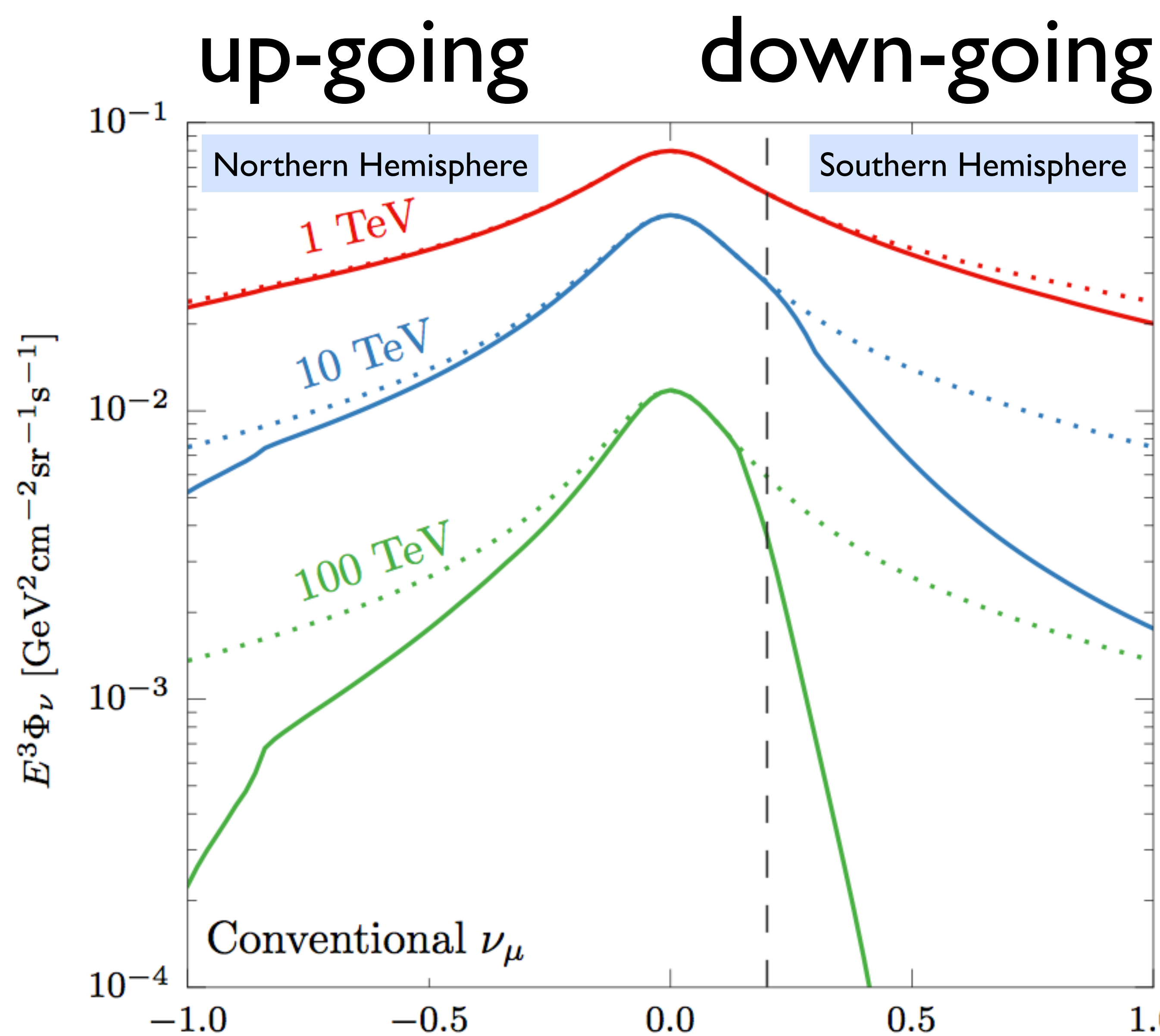
- Models
  - Singlet fermion in an extra dimension
  - Hidden Sector Gauge Boson
  - Gravitino Dark Matter with R-Parity Violation

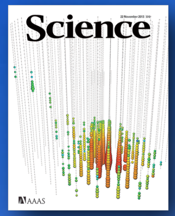


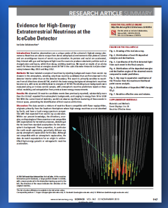
Veto and Self-veto



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



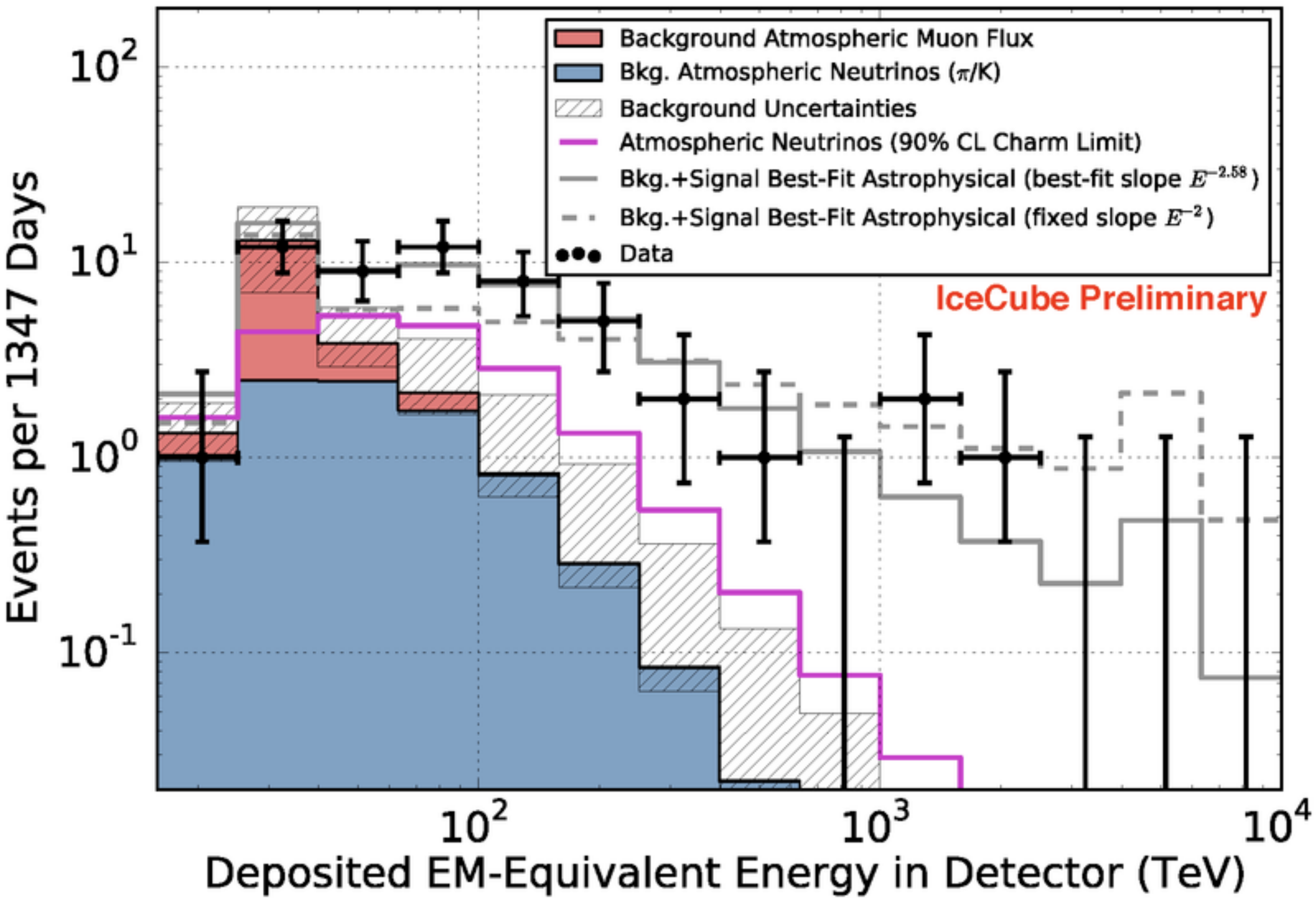




High-energy neutrino search 4yrs

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

Expectation from conventional atm. muons and neutrinos ~21.6



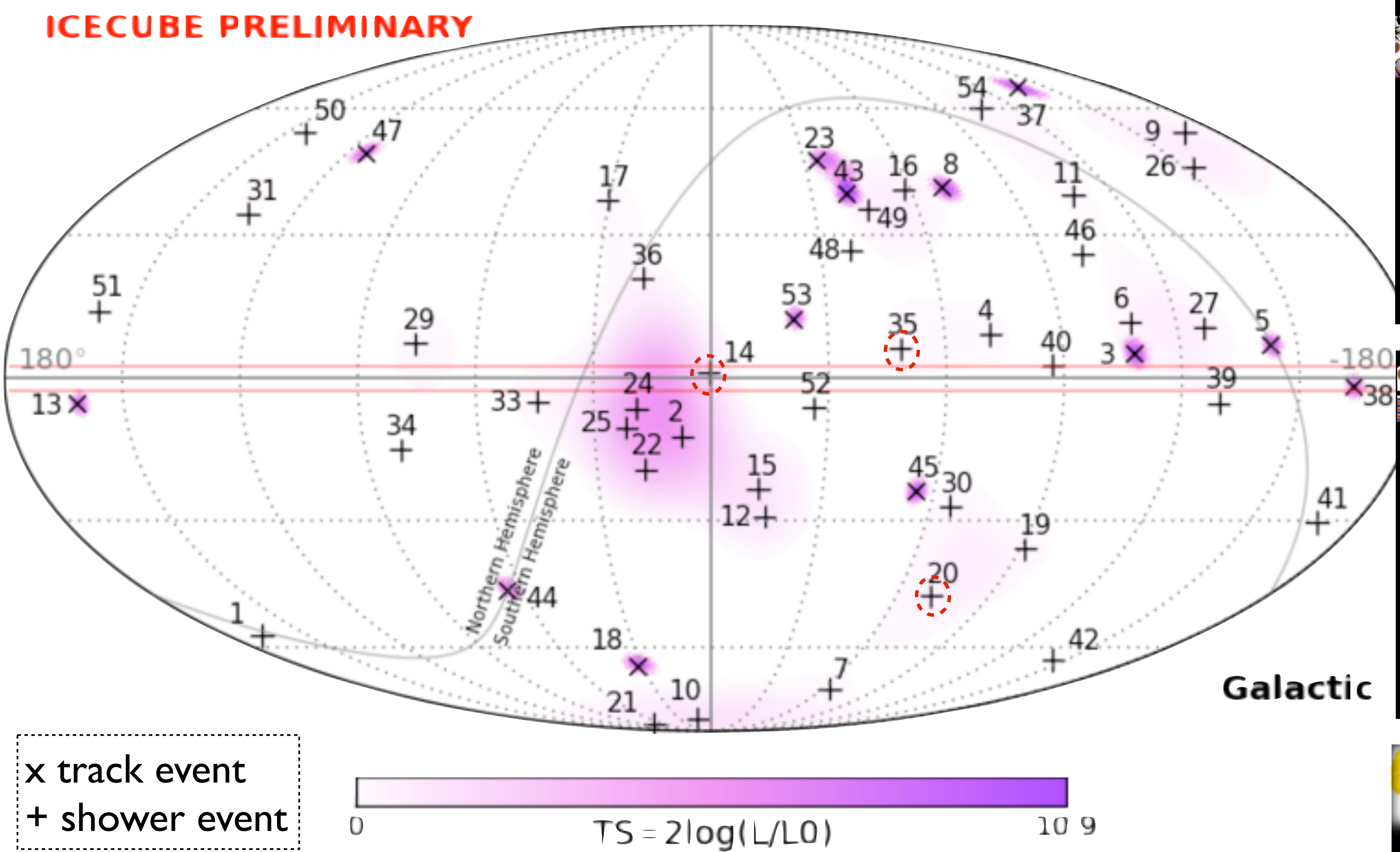
ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013),*
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

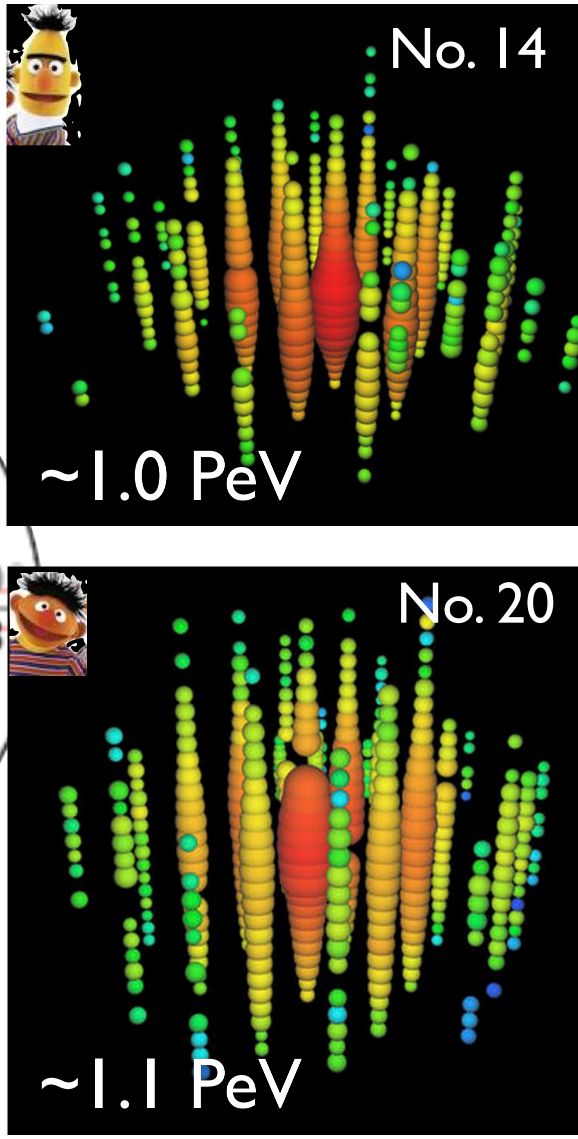
- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (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.

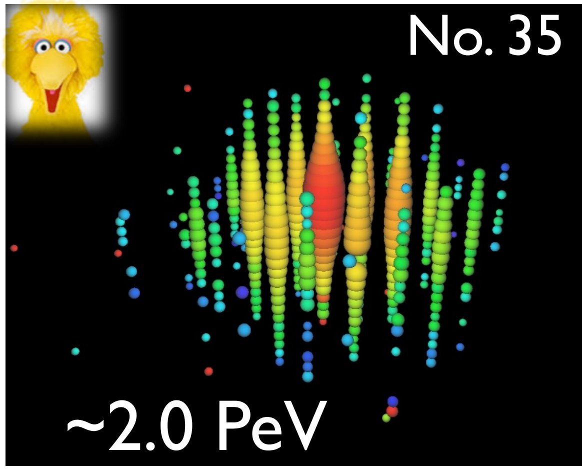
~7 sigma rejection of atmospheric-only hypothesis

Skymap HESE-4yrs

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





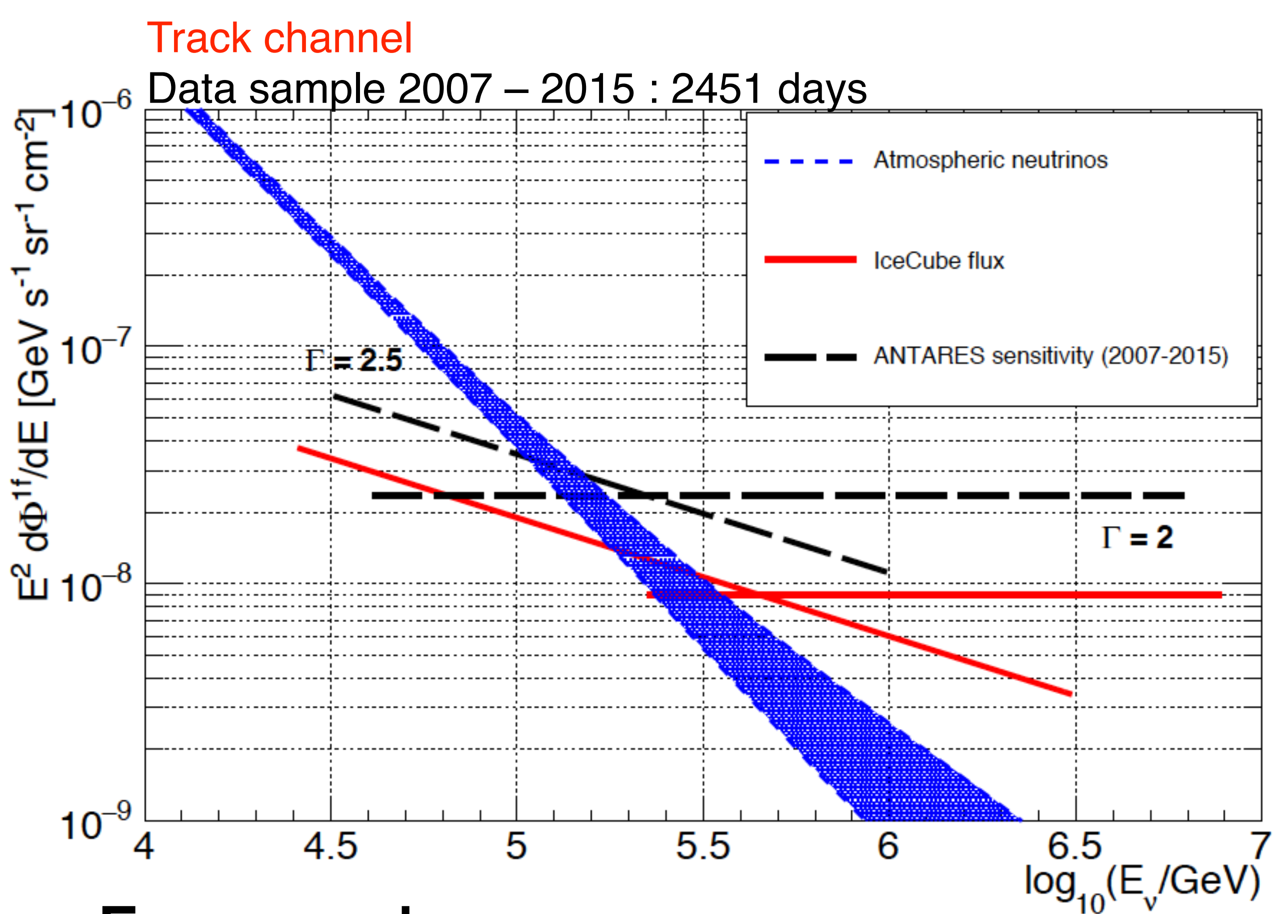


no significant correlations -- spacial or temporal

p-value for cascade events “clustering” 44%

Independent confirmation ?

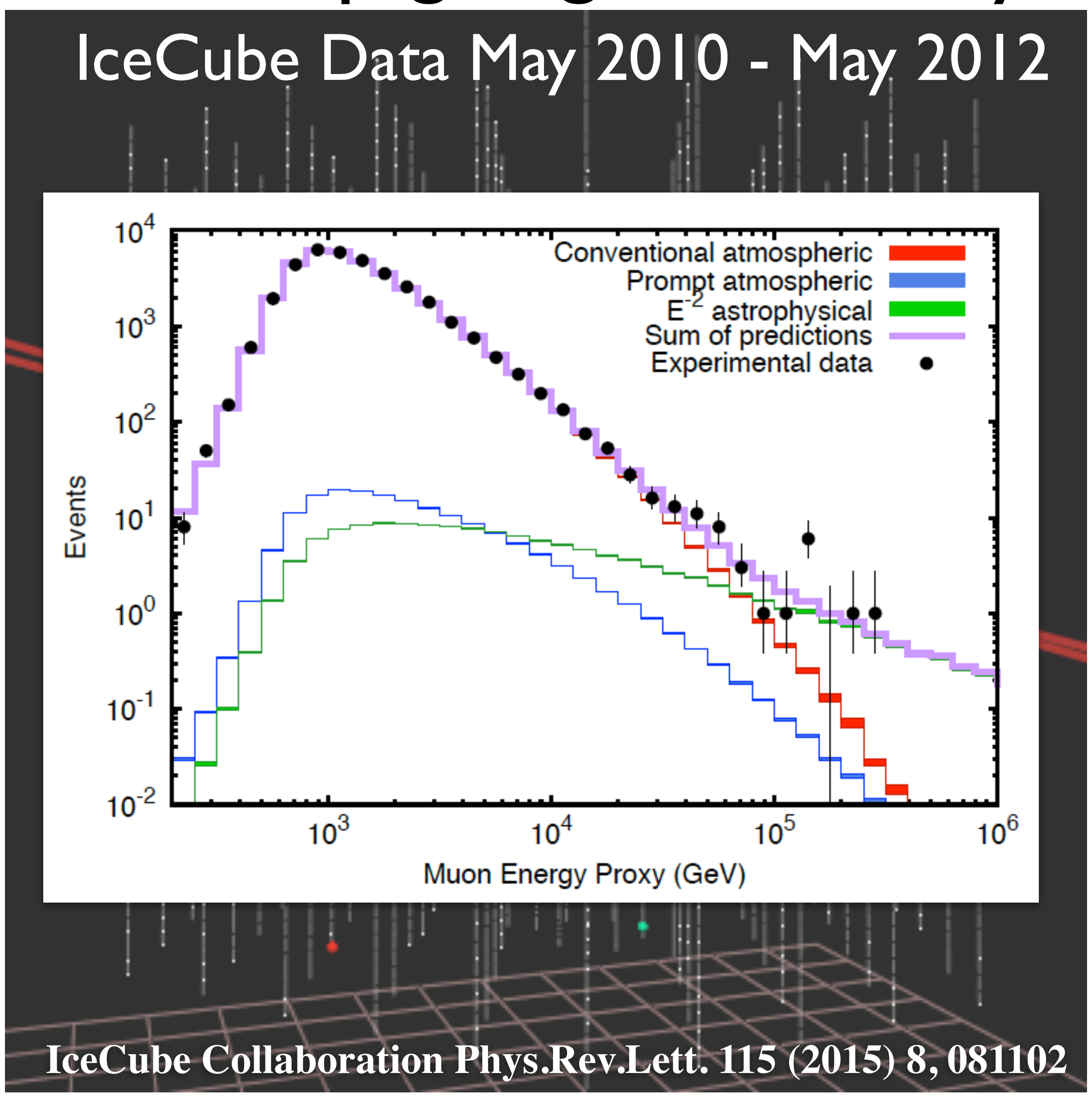
ANTARES Neutrino 2016



- Expected events:
  - Background: 13.5 ± 3
  - Astrophysical ~3
- Results:
  - Consistent with background
  - Consistent with IceCube

Observed 19 events

IceCube up-going muon analysis



Highest energy events are inconsistent with a hypothesis of solely terrestrial origin at **3.7σ**

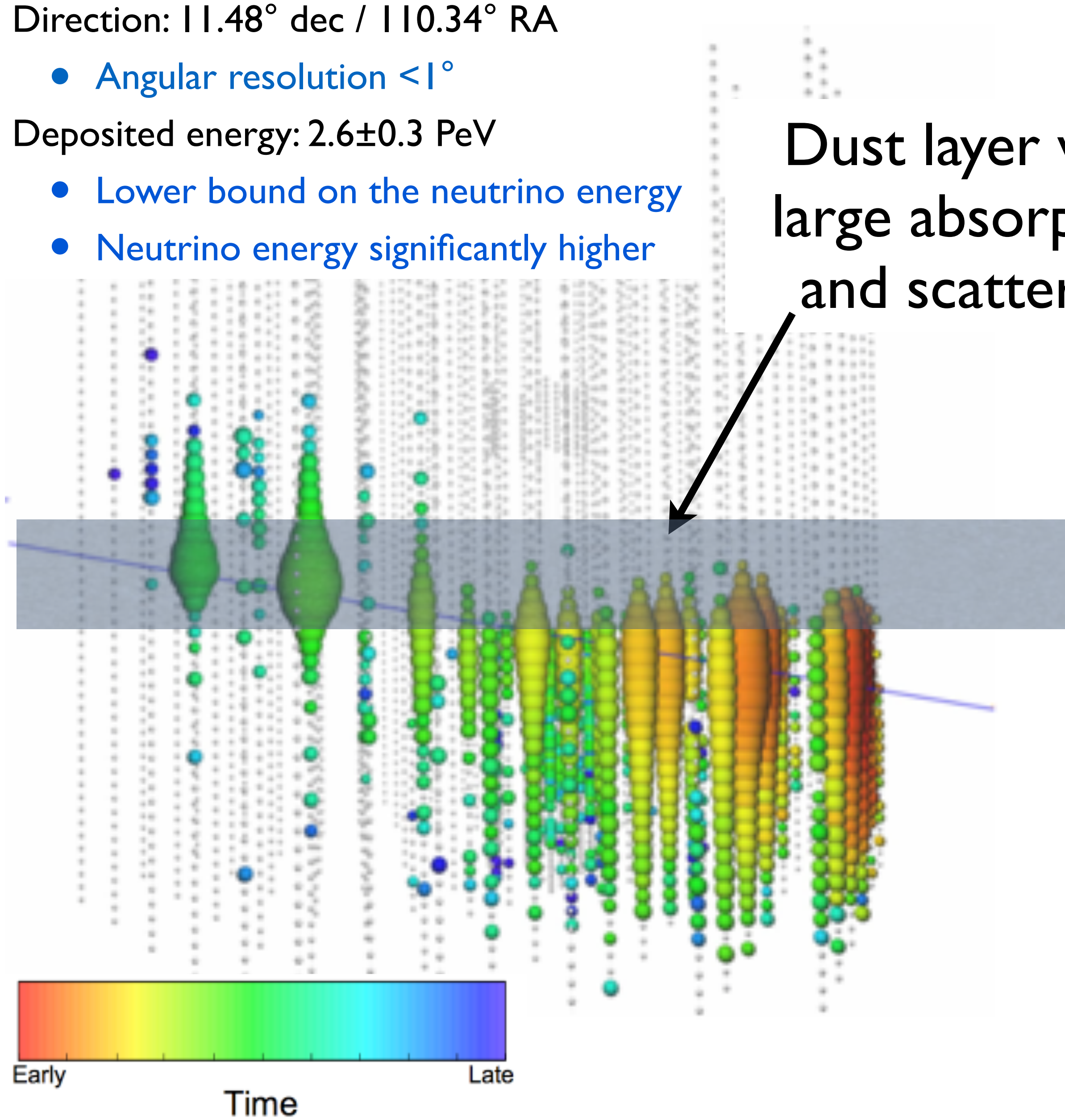
Best fit astrophysical flux consistent with High-Energy Starting Events

Normalization for E^{-2}: $0.99^{+0.4}_{-0.3}\ 10^{-8}\ E^{-2}$ GeV cm^{-2} s^{-1} sr^{-1}

Through-going muon tracks

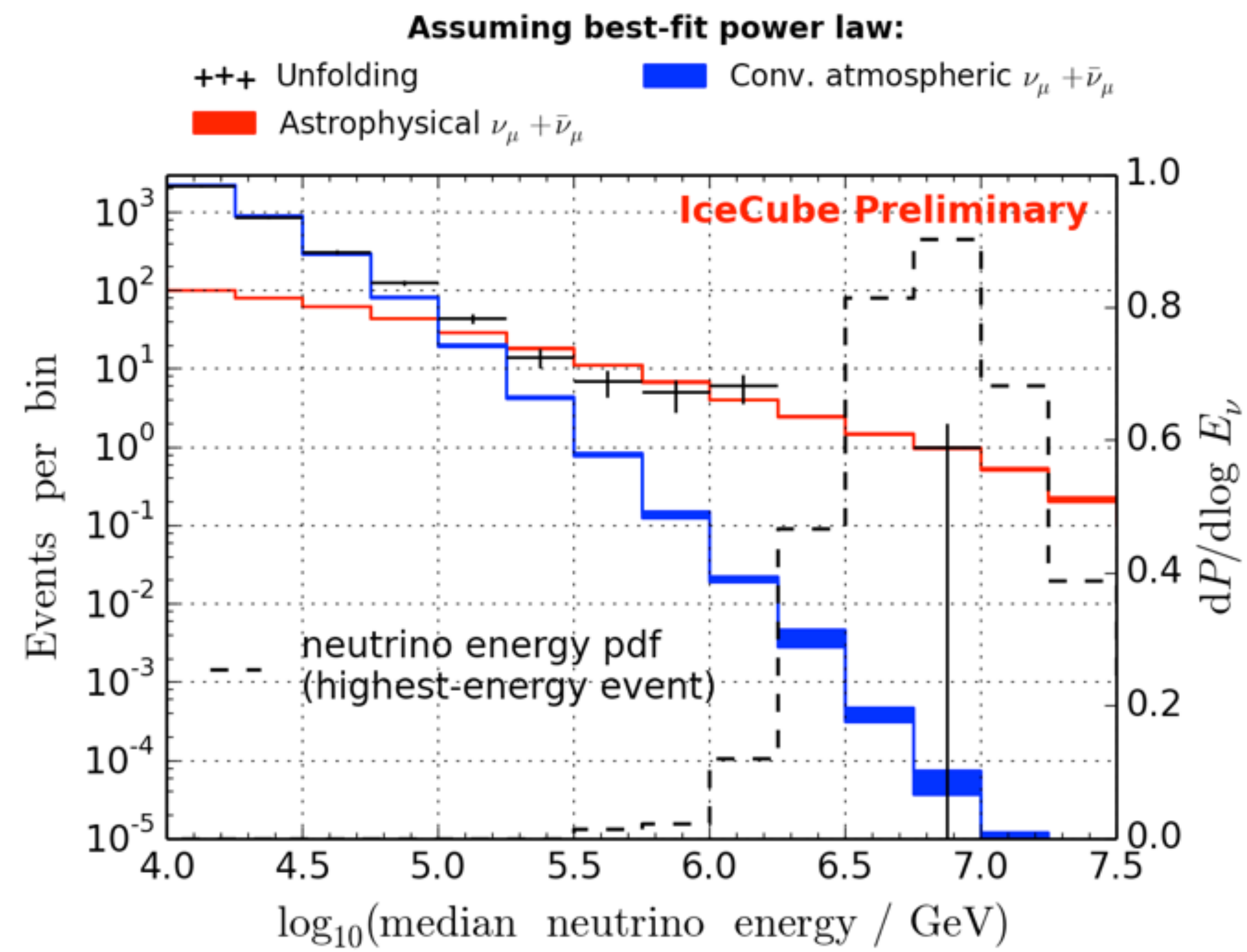
Up-going Track-like neutrino event
E_{dep}= 2.6 ±0.3 PeV

- Direction: 11.48° dec / 110.34° RA
  - Angular resolution <1°
- Deposited energy: 2.6±0.3 PeV
  - Lower bound on the neutrino energy
  - Neutrino energy significantly higher



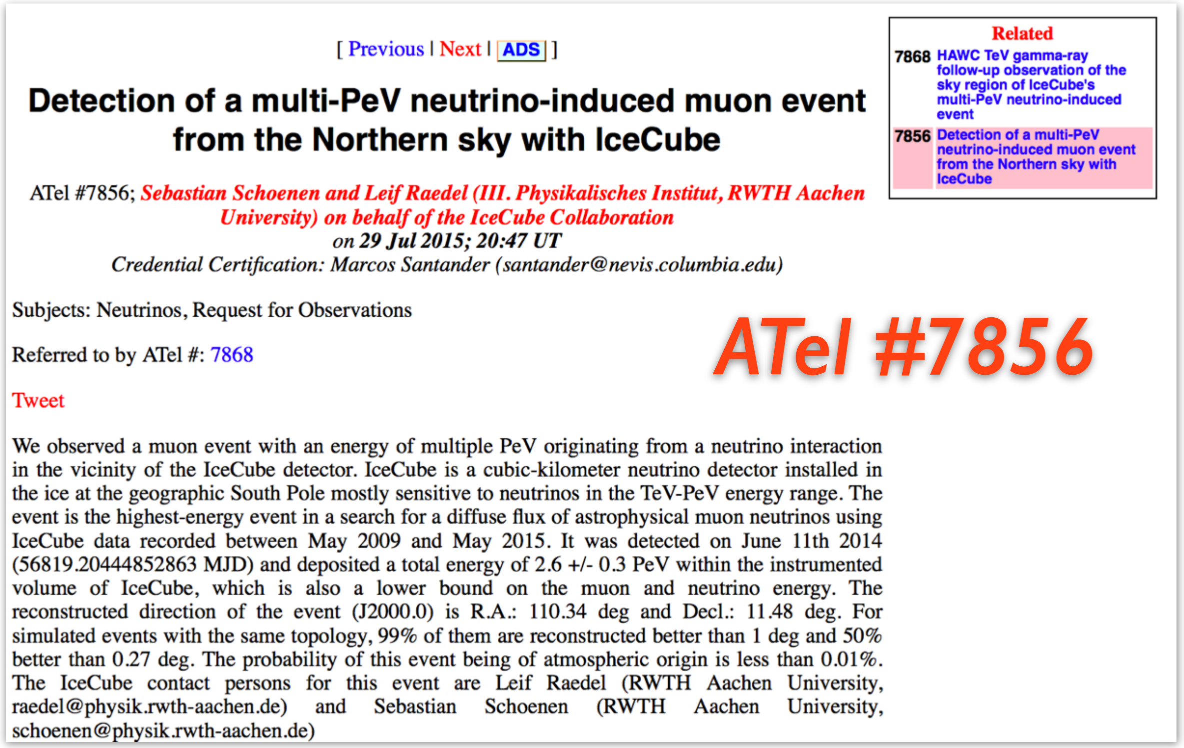
The event above was detected in IceCube on June 11, 2014. Image: IceCube Collaboration.

unfolded data assuming unbroken best-fit power law



5.6 sigma detection of astrophysical neutrinos with through-going muons analysis

2015


[Previous | Next | ADS]

Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856; *Sebastian Schoenen and Leif Raedel (III. Physikalisches Institut, RWTH Aachen University) on behalf of the IceCube Collaboration*
on 29 Jul 2015; 20:47 UT
Credential Certification: Marcos Santander (santander@nevis.columbia.edu)

Subjects: Neutrinos, Request for Observations

Referred to by ATel #: 7868

Tweet

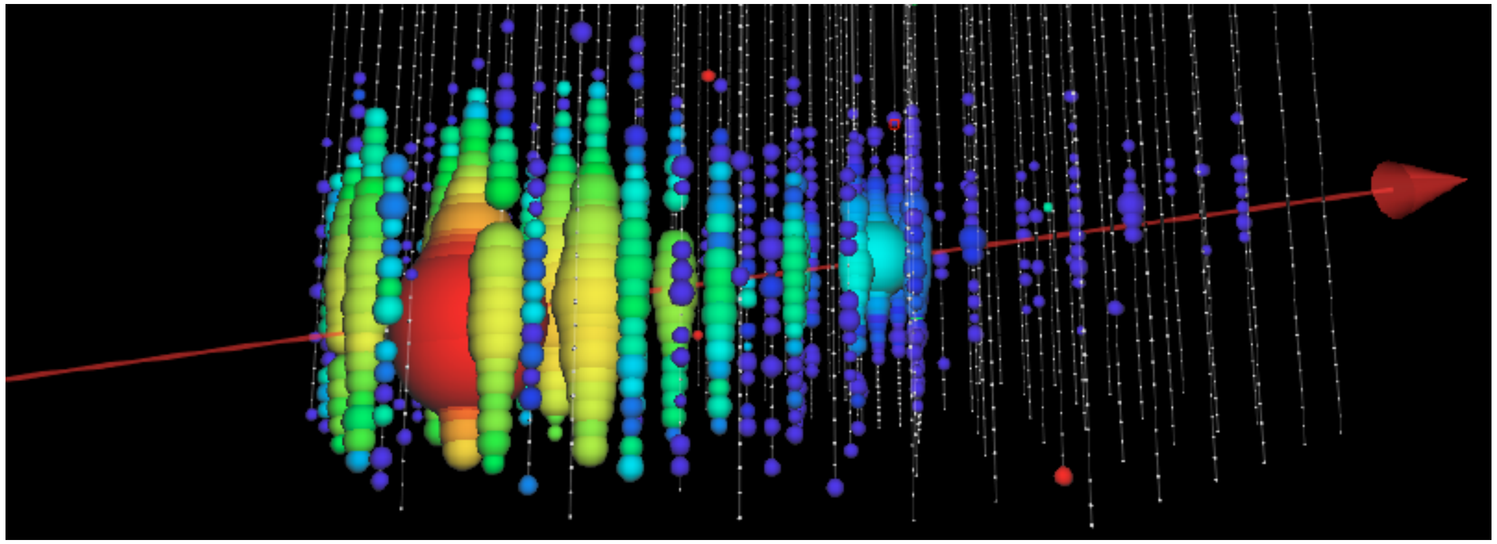
We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event is the highest-energy event in a search for a diffuse flux of astrophysical muon neutrinos using IceCube data recorded between May 2009 and May 2015. It was detected on June 11th 2014 (56819.20444852863 MJD) and deposited a total energy of 2.6 +/- 0.3 PeV within the instrumented volume of IceCube, which is also a lower bound on the muon and neutrino energy. The reconstructed direction of the event (J2000.0) is R.A.: 110.34 deg and Decl.: 11.48 deg. For simulated events with the same topology, 99% of them are reconstructed better than 1 deg and 50% better than 0.27 deg. The probability of this event being of atmospheric origin is less than 0.01%. The IceCube contact persons for this event are Leif Raedel (RWTH Aachen University, raedel@physik.rwth-aachen.de) and Sebastian Schoenen (RWTH Aachen University, schoenen@physik.rwth-aachen.de)

Related
7868 HAWC TeV gamma-ray follow-up observation of the sky region of IceCube's multi-PeV neutrino-induced event
7856 Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856

2016

more recent ICECUBE-160427A



Follow-ups to ICECUBE-160427A

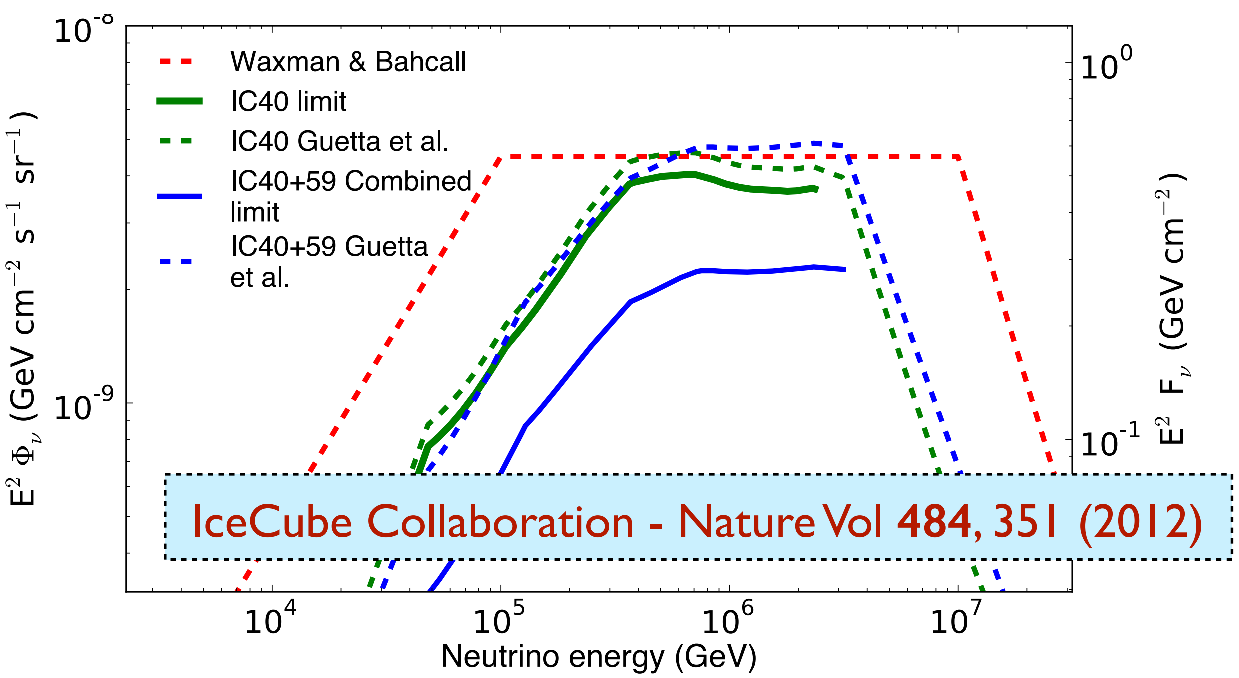
- GCN 19364 – Fermi Gamma-Ray Burst Monitor - No detection
- GCN 19360 – Fermi LAT – 5 unrelated blazars
- GCN 19361 – HAWC – no detection
- GCN 19362 – MASTER – no detection
- GCN 19377 – VERITAS – no detection
- GCN 19392 – iPalomar Transient Factory – 3 transients, all AGN
- GCN 19427 – FACT Cherenkov TeV Telescope – no detection
- GCN 19426 - Interplanetary Network – no detection
- GCN 19381 - Pan-STARRS - 7 SN candidates, one consistent with type Ic supernova.

See also https://gcn.gsfc.nasa.gov/amon.html http://gcn.gsfc.nasa.gov/gcn/gcn3/20247.gcn3

Origin of the high-energy neutrinos ?

Extra Galactic

Gamma Ray Burst



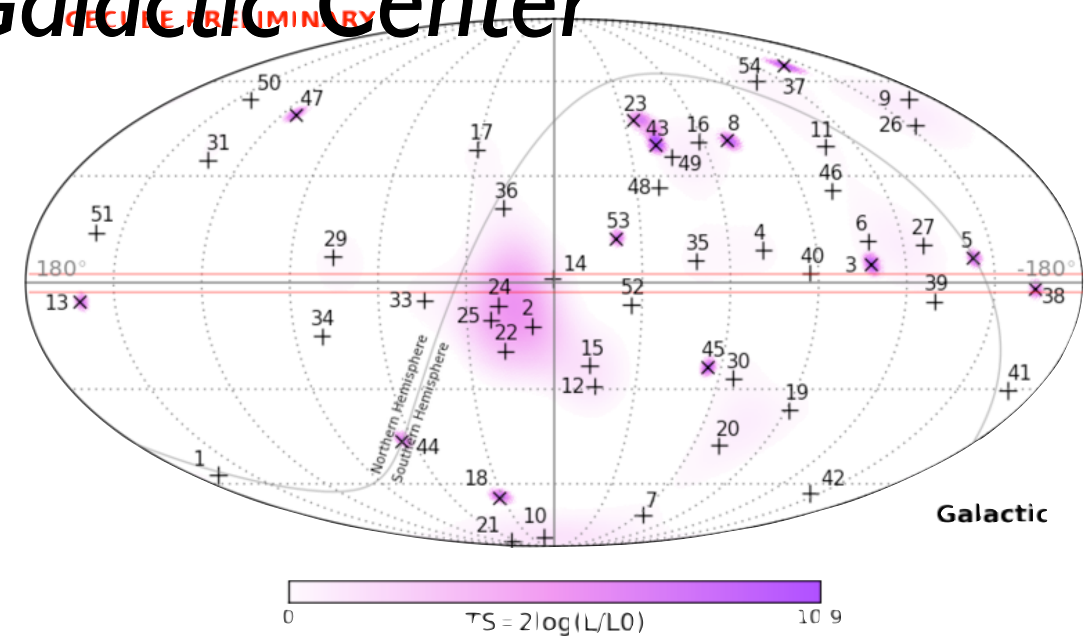
IceCube Collaboration - Nature Vol 484, 351 (2012)

Active Galactic Nuclei / Starburst Galaxies

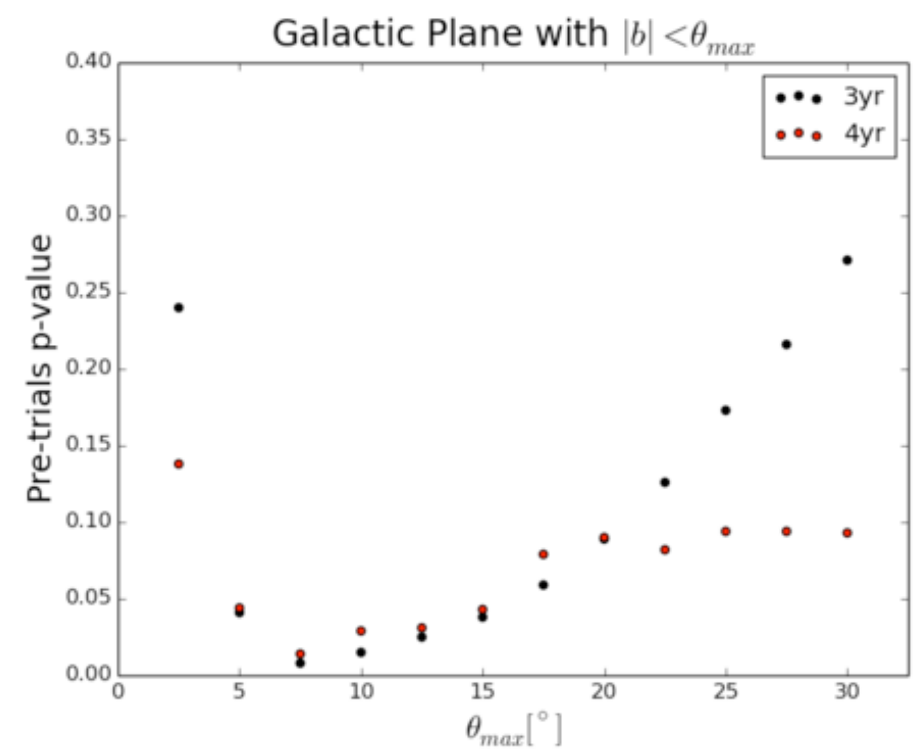
Starburst	M82	148.97	69.68	0.07	0.15
Radio	NGC 1275	49.95	41.51	0.0	–
Galaxies	Cyg A	299.87	40.73	0.9	0.03
	3C 123.0	69.27	29.67	0.0	–
	M87	187.71	12.39	0.0	–
	Cen A	201.37	-43.02	0.03	0.49

Galactic

Galactic Center



Galactic Plane



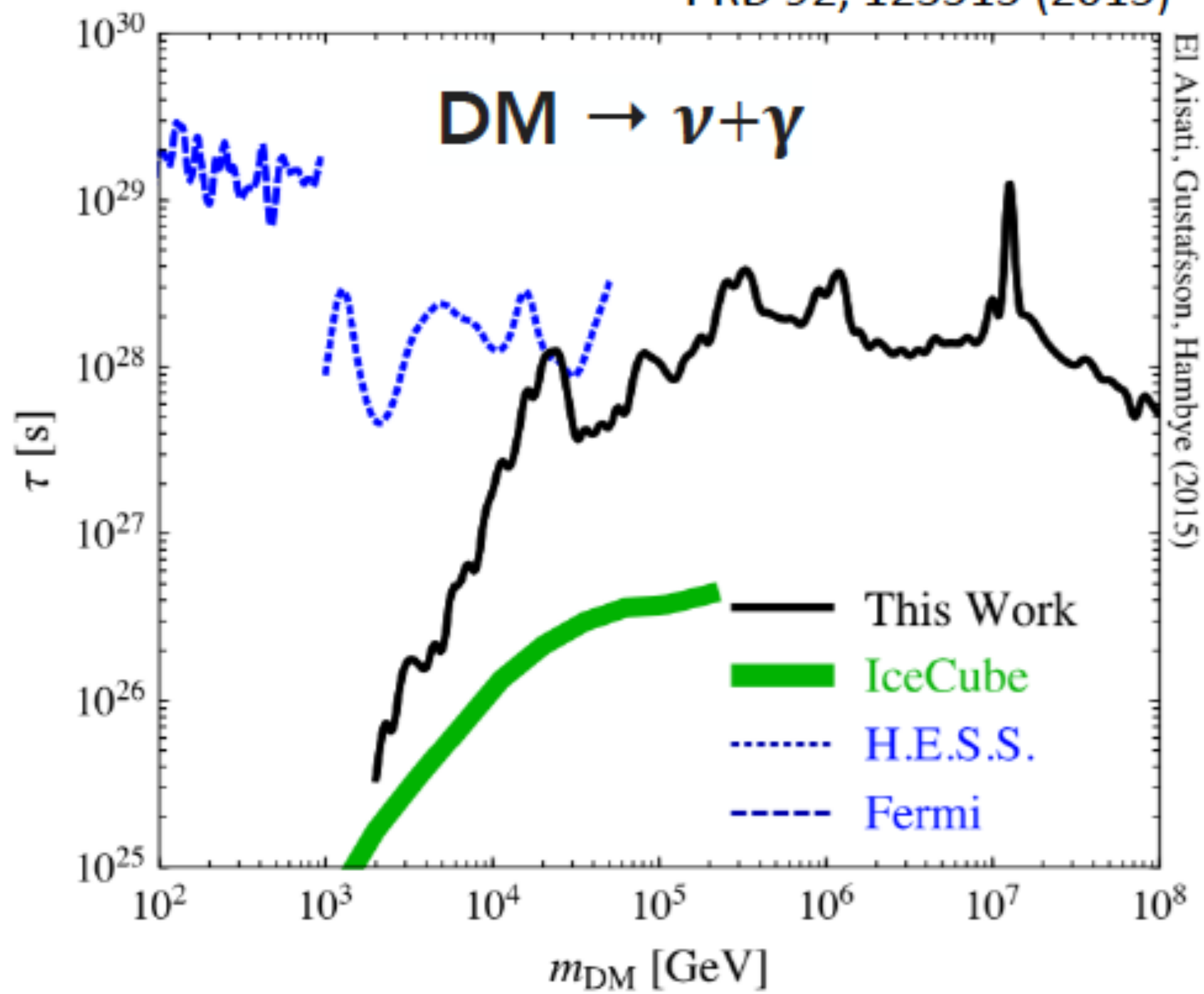
Heavy Dark Matter Decay

- 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).

Dedicated IceCube analysis should improve on these bounds
Analyses on-going

Bound on lifetime ~10^{28}s derived with IceCube data

PRD 92, 123515 (2015)



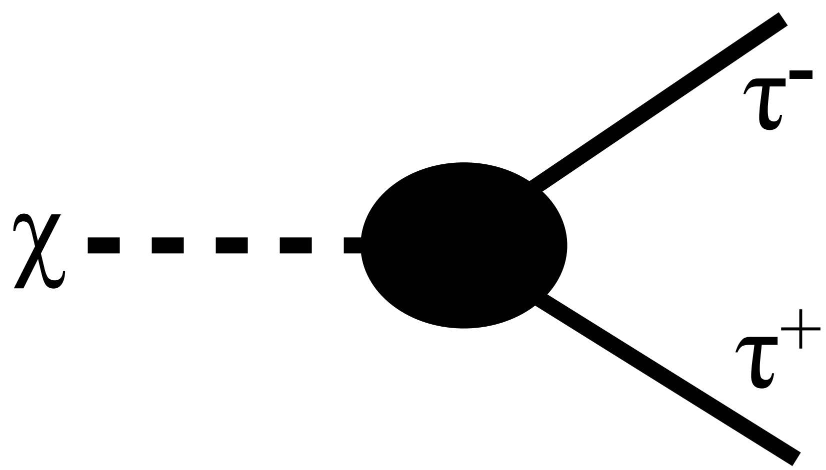
Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034
El Aisati, Gustafsson, Hambye 1506.02657

IceCube Collaboration Astrophys.J. 809 (2015) 1, 98

Flavor Ratio

- Global fit of several IceCube analyses
  - Variety of selection criteria for both shower-like and track-like events
  - Data are fit to three observables
    - Energy, zenith angle, event topology

Note that energy dependence needs to be considered ! Continuous spectrum vs injection at specific DM mass

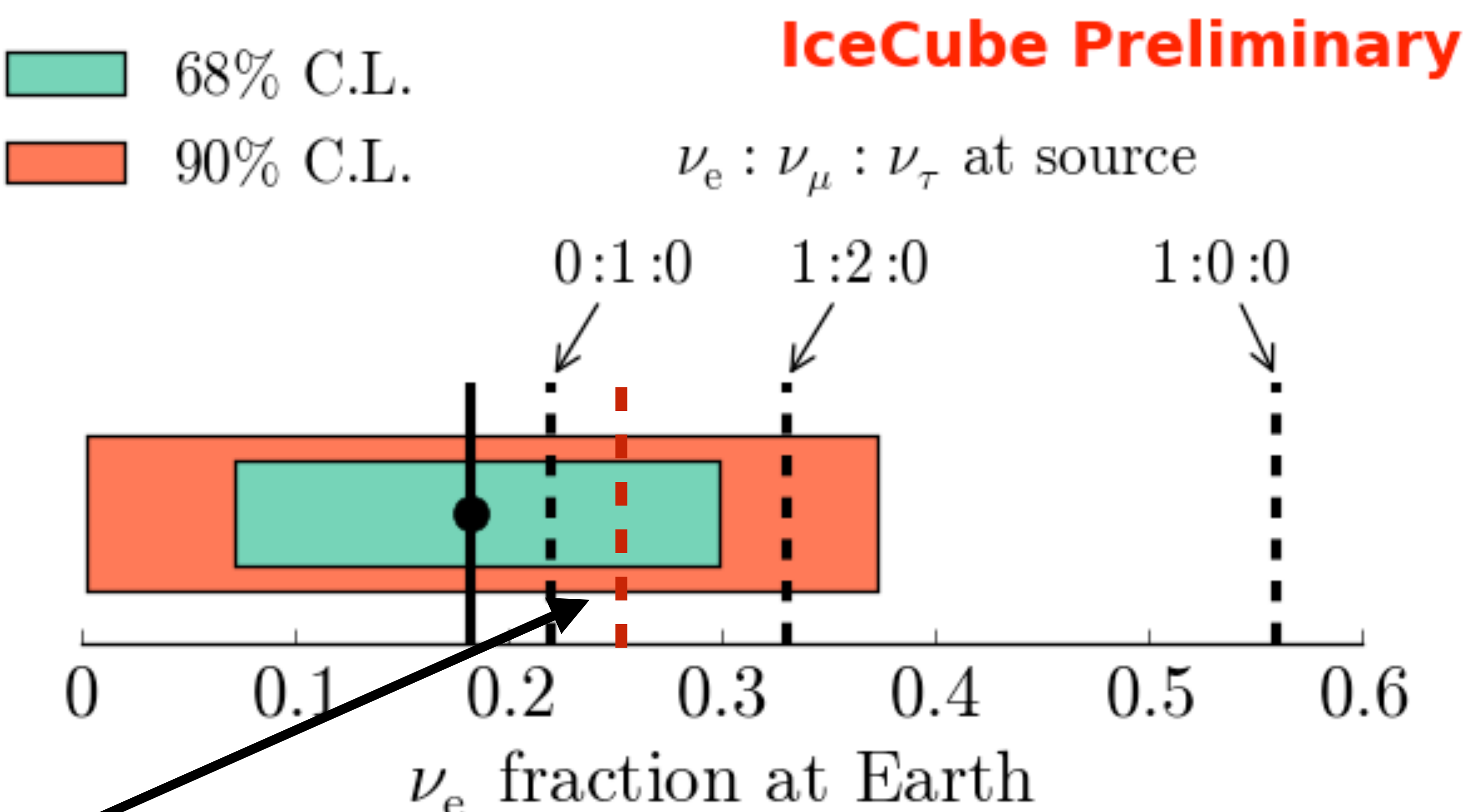


$\tau^- \rightarrow \nu_\tau + hadrons$ (64.8%)

$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^-$ (17.8%)

$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-$ (17.4%)

resulting flavor ratio 1:1:6

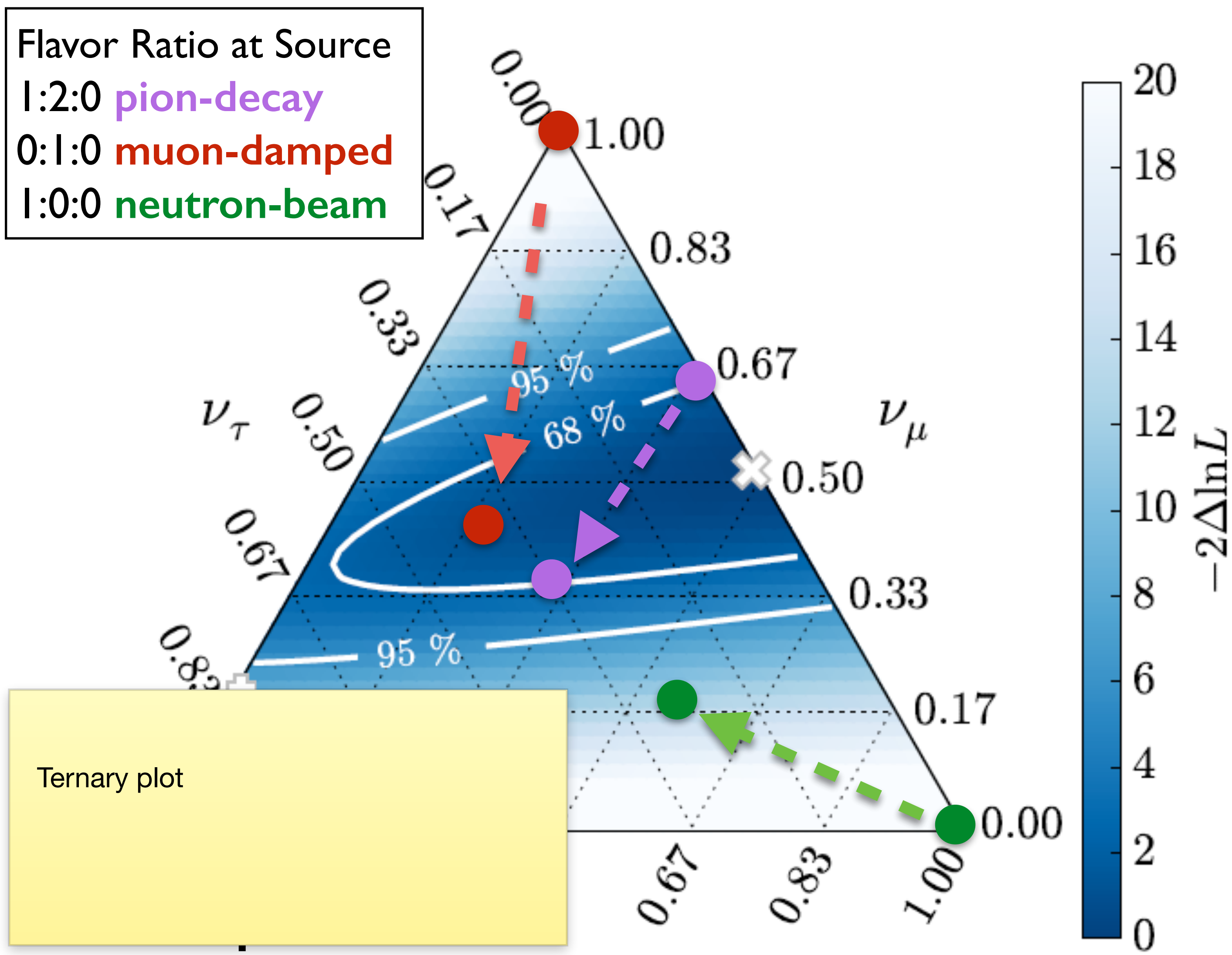


neutron-decay dominated source rejected at 3.6σ

Flavor Ratio

IceCube Collaboration Astrophys.J. 809 (2015) 1, 98

- Global fit of several IceCube analyses
  - Variety of selection criteria for both shower-like and track-like events
  - Data are fit to three observables
    - Energy, zenith angle, event topology



IceCube Collaboration Phys.Rev.Lett. 114 (2015) 17, 171102

Flavor ratio source and at Earth

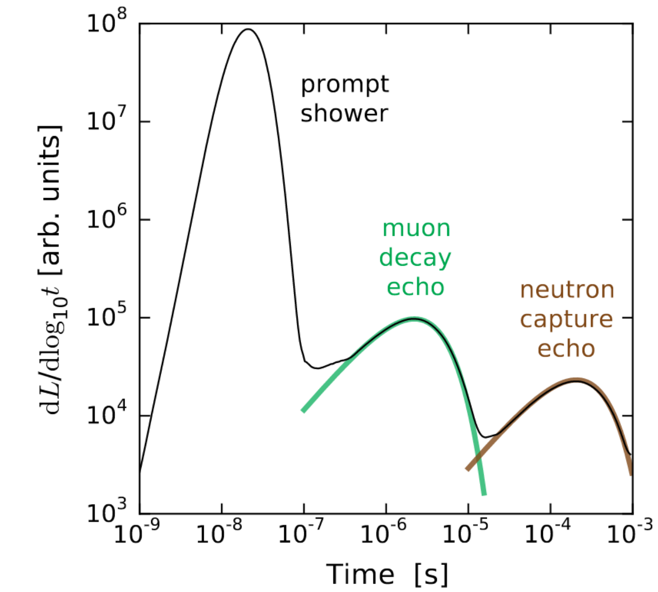
$\nu_e : \nu_\mu : \nu_\tau$

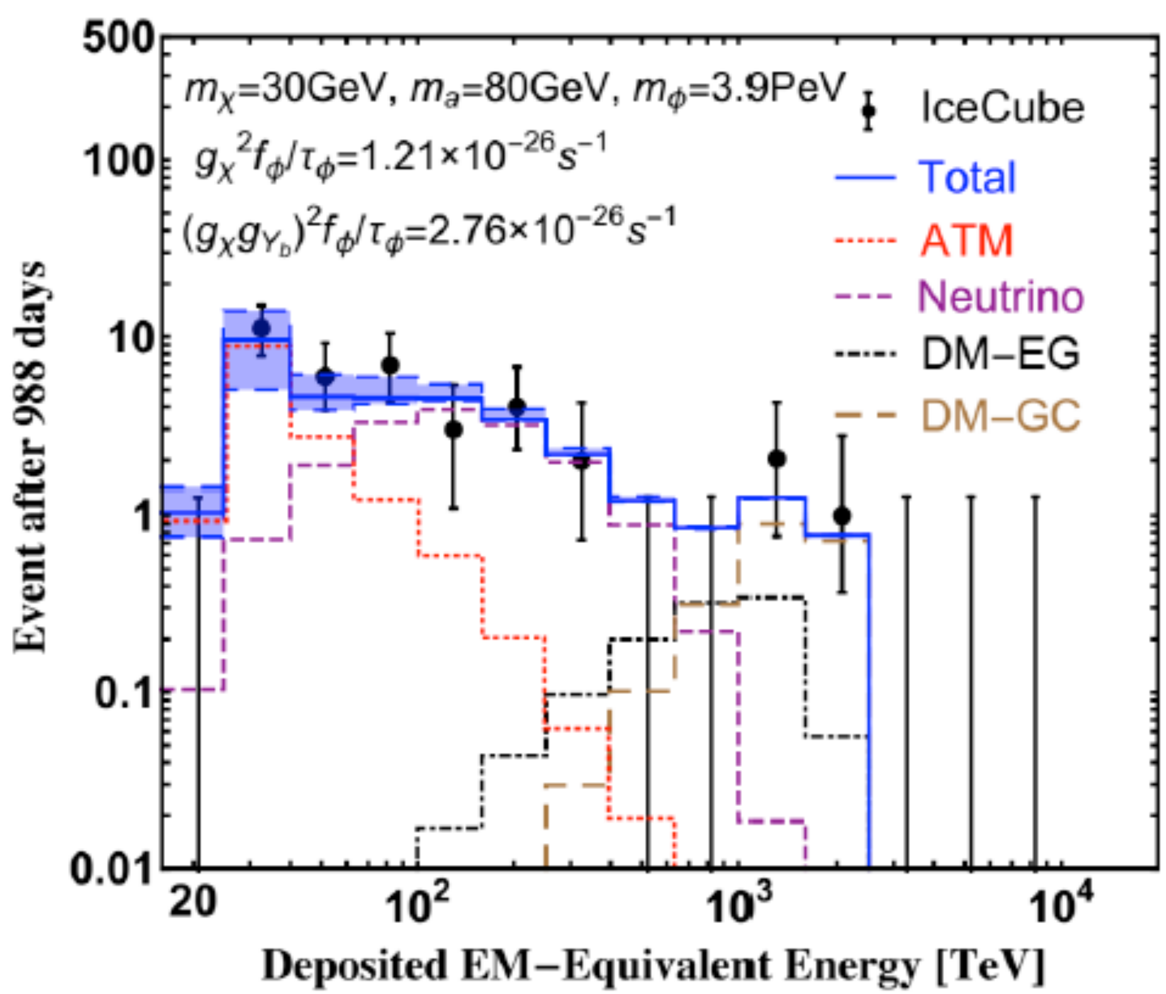
Source	Ratio at Source	Ratio at Earth
Pion decay	1:2:0	1:1:1
DM decay nunu	1:1:1	1:1:1
DM decay tau tau	1:1:6	2:3:3
DM decay bb	1:1:0	0.8:0.6:0.6

Boosted DM

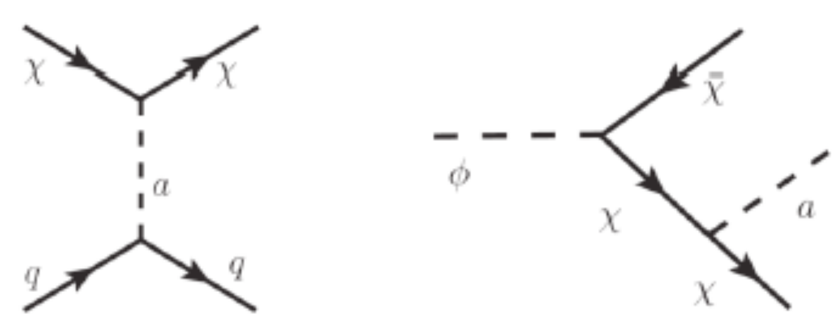
Boosted Dark Matter

- "Boosted Dark Matter Search"
  - Following search proposed by Kopp, Liu, Wan (2015)
  - using "Echo Technique" Li, Bustamante, Beacom (2016)





Very heavy dark matter particle ϕ decays to lighter stable dark matter χ →boost!



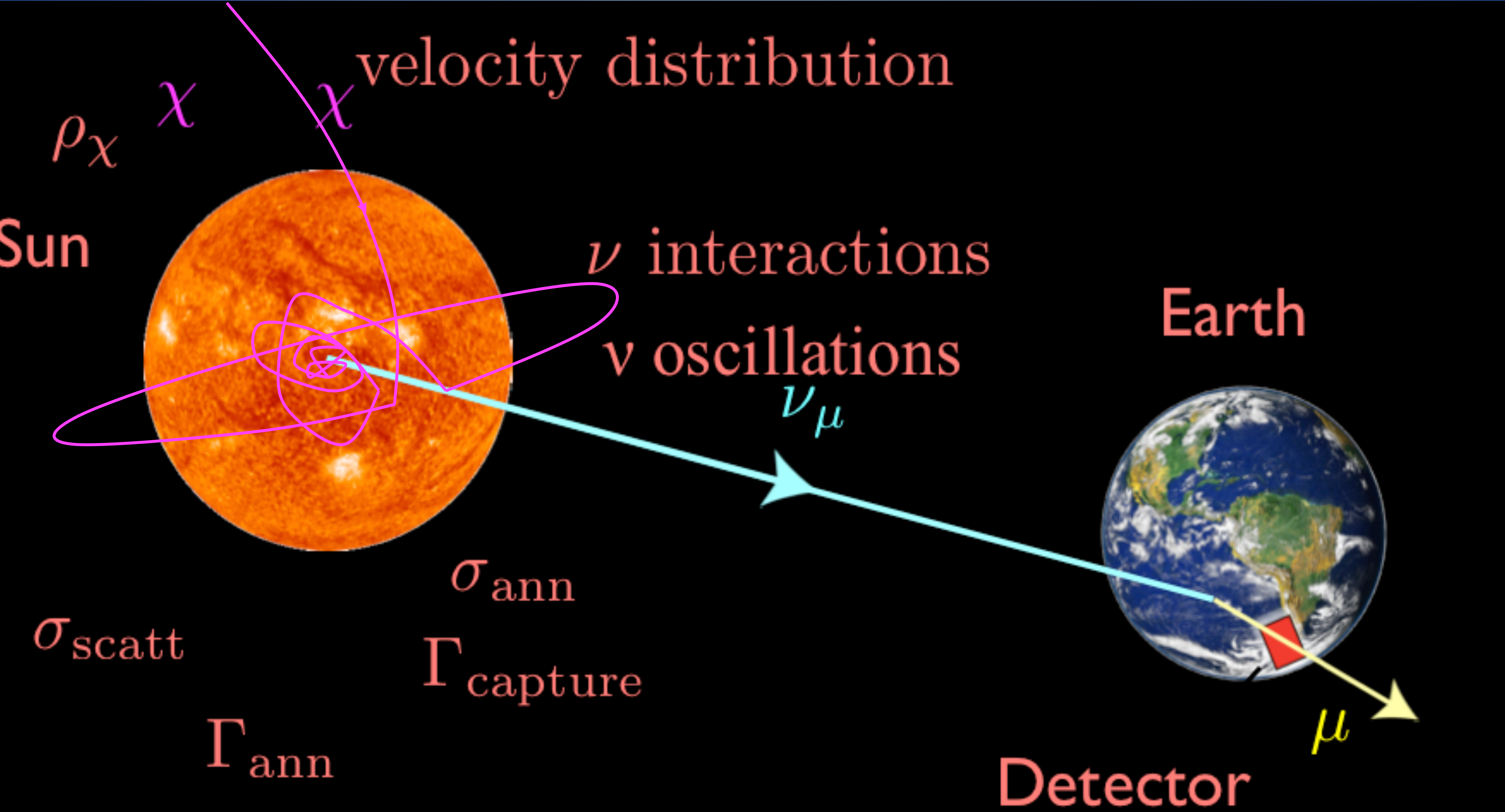
Recoil (only hadronic cascades)

$\phi \rightarrow \chi\,\bar{\chi}\,a,\ a \rightarrow b\,\bar{b}$
→ν's

May sound crazy, but is just an example for exotic interactions in IceCube detectable via recoil

Dark Matter Capture in the Sun

Solar WIMPs



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

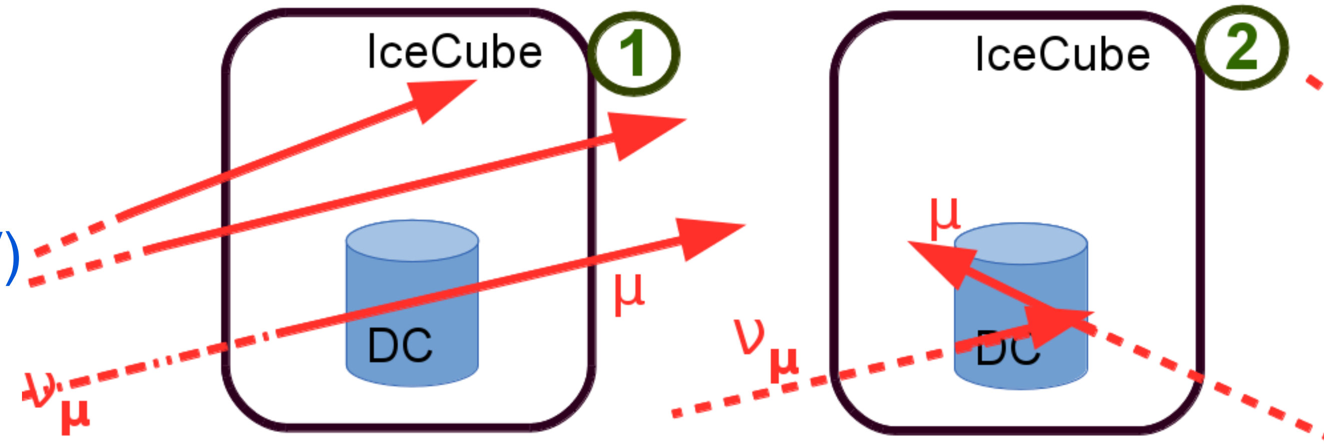
Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

3yrs IceCube Solar WIMP Analysis

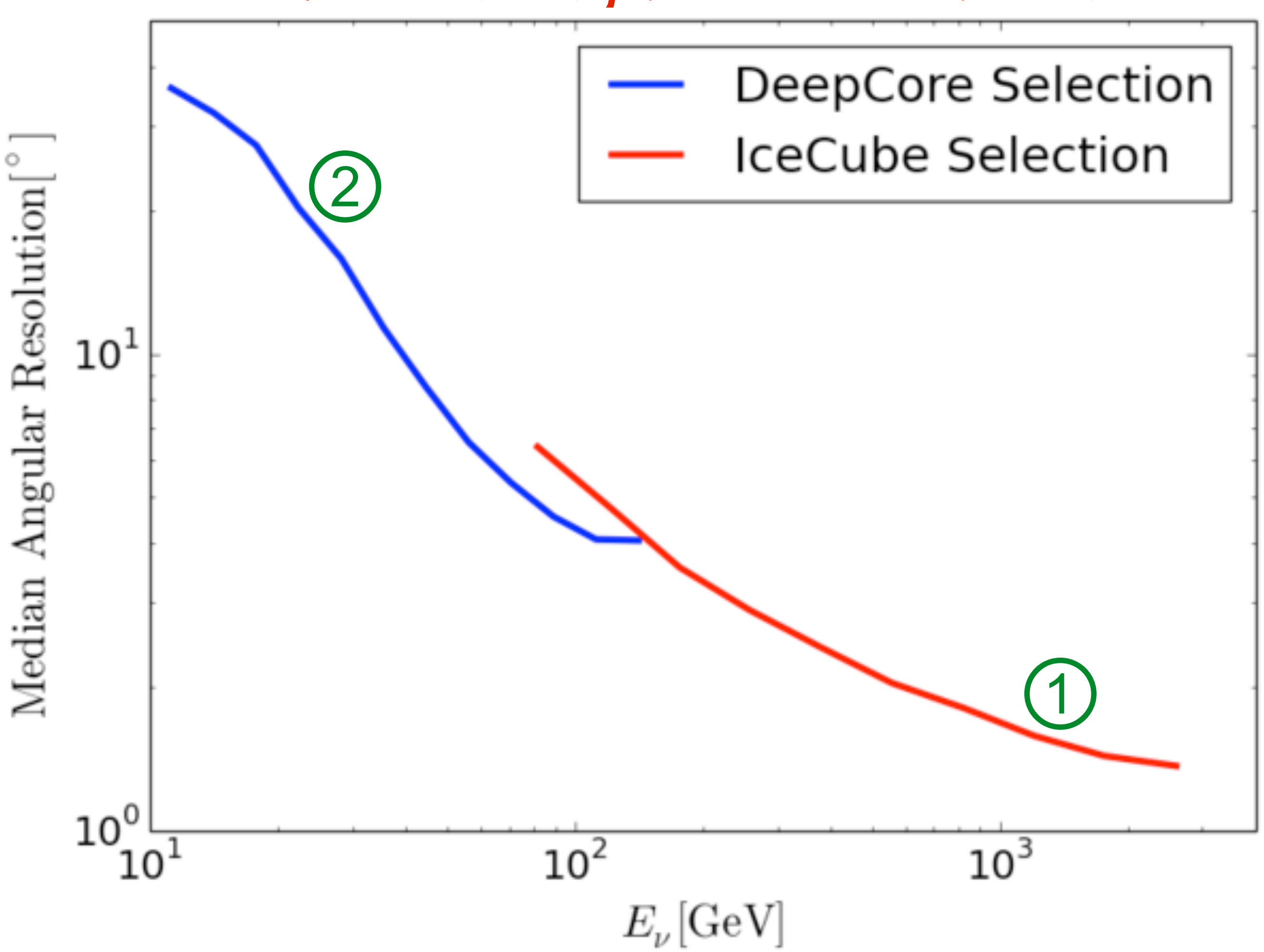
- Three years of data in 86-string configuration used (**May 2011 - May 2014**)
  - Only **up-going** events (Sun below the horizon) results in **532days of livetime**
- Two independent analysis performed
  - ① **IceCube**: Higher energy focus (m_χ > 100GeV)
  - ② **DeepCore**: Low-energy focus (m_χ = 30GeV - 100GeV)

- *Up-going*
- *IceCube Dominated*
- *No Containment*

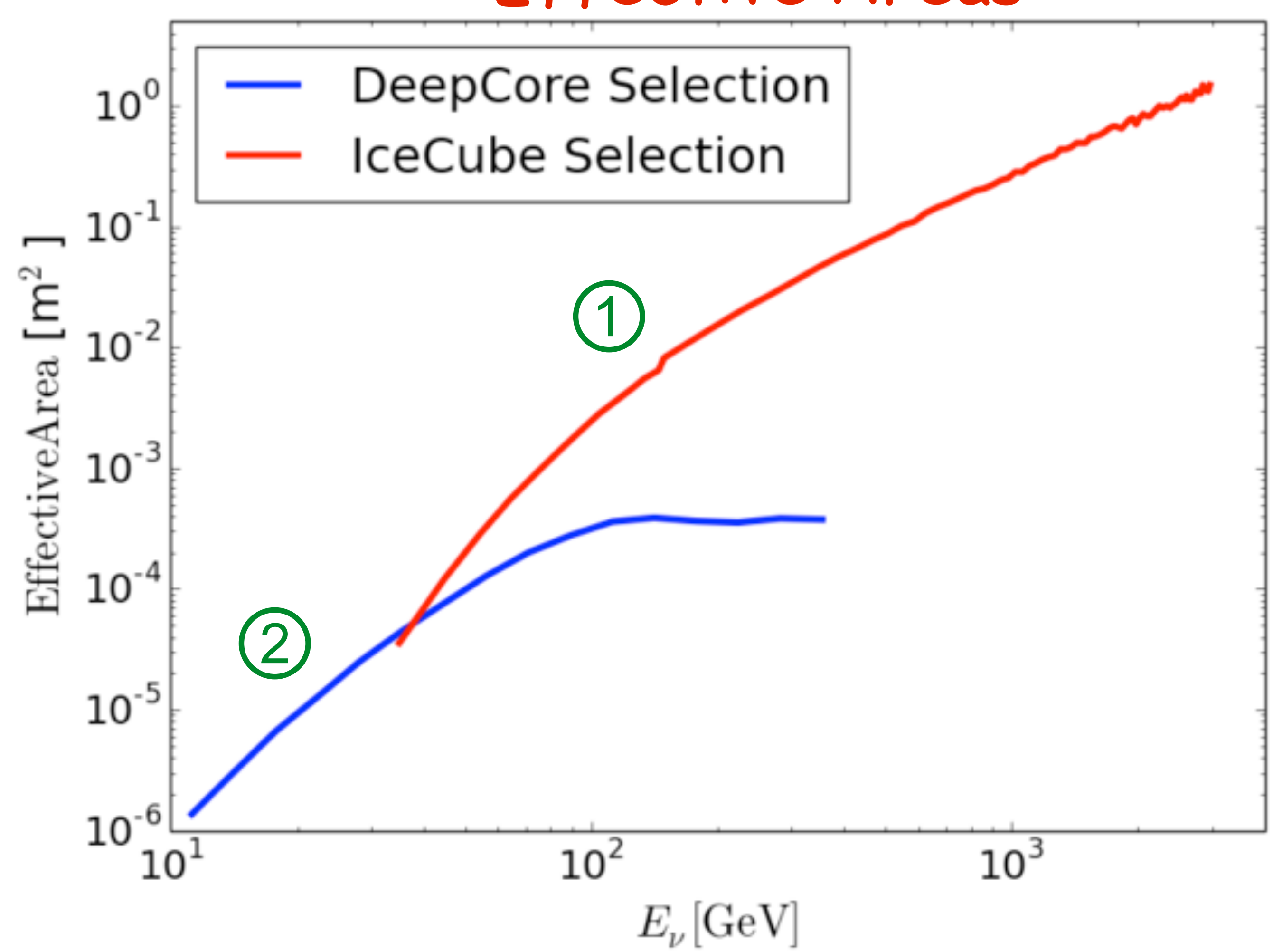
- *Up-going*
- *DeepCore Dominated*
- *Strong Containment*



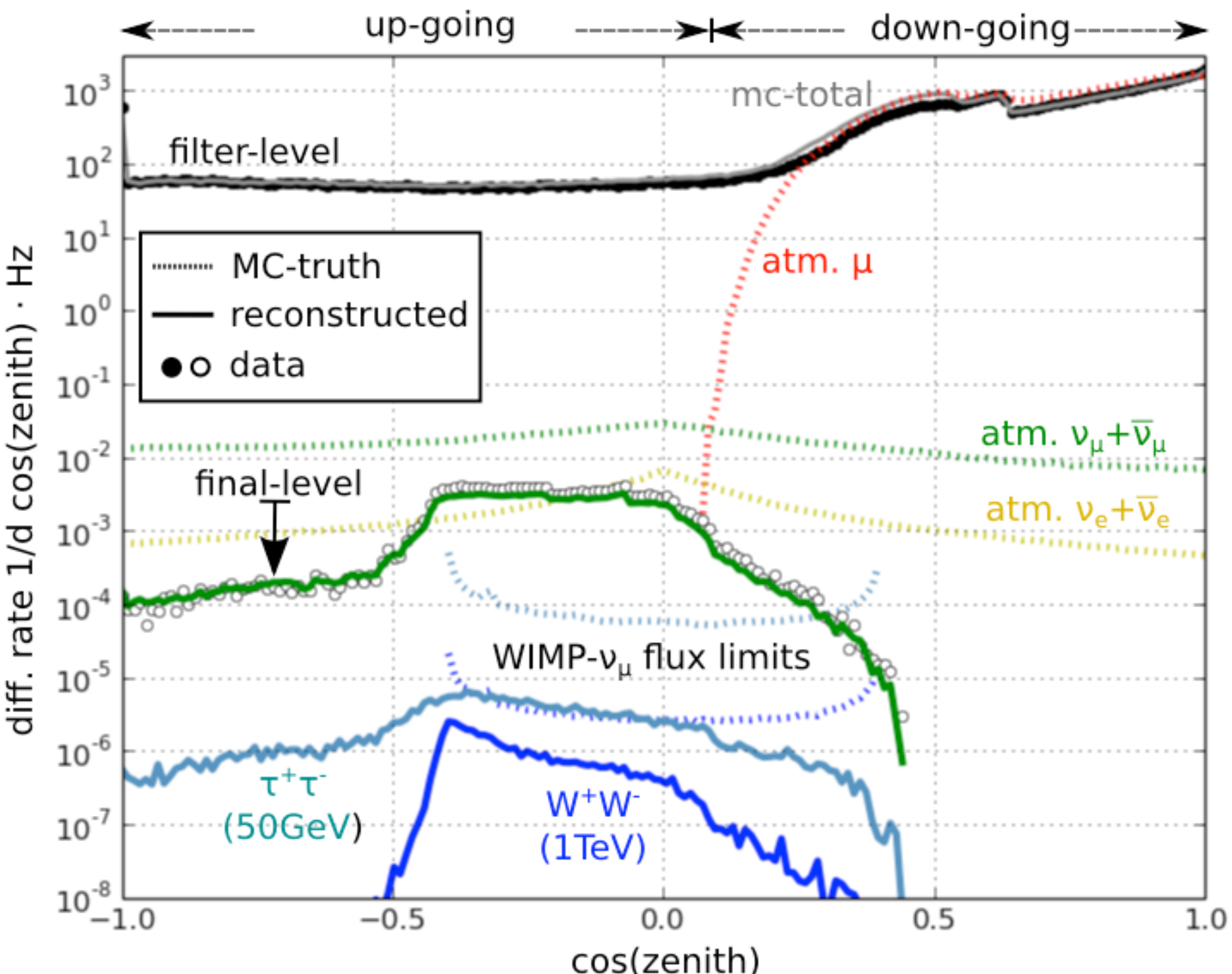
Median angular resolutions



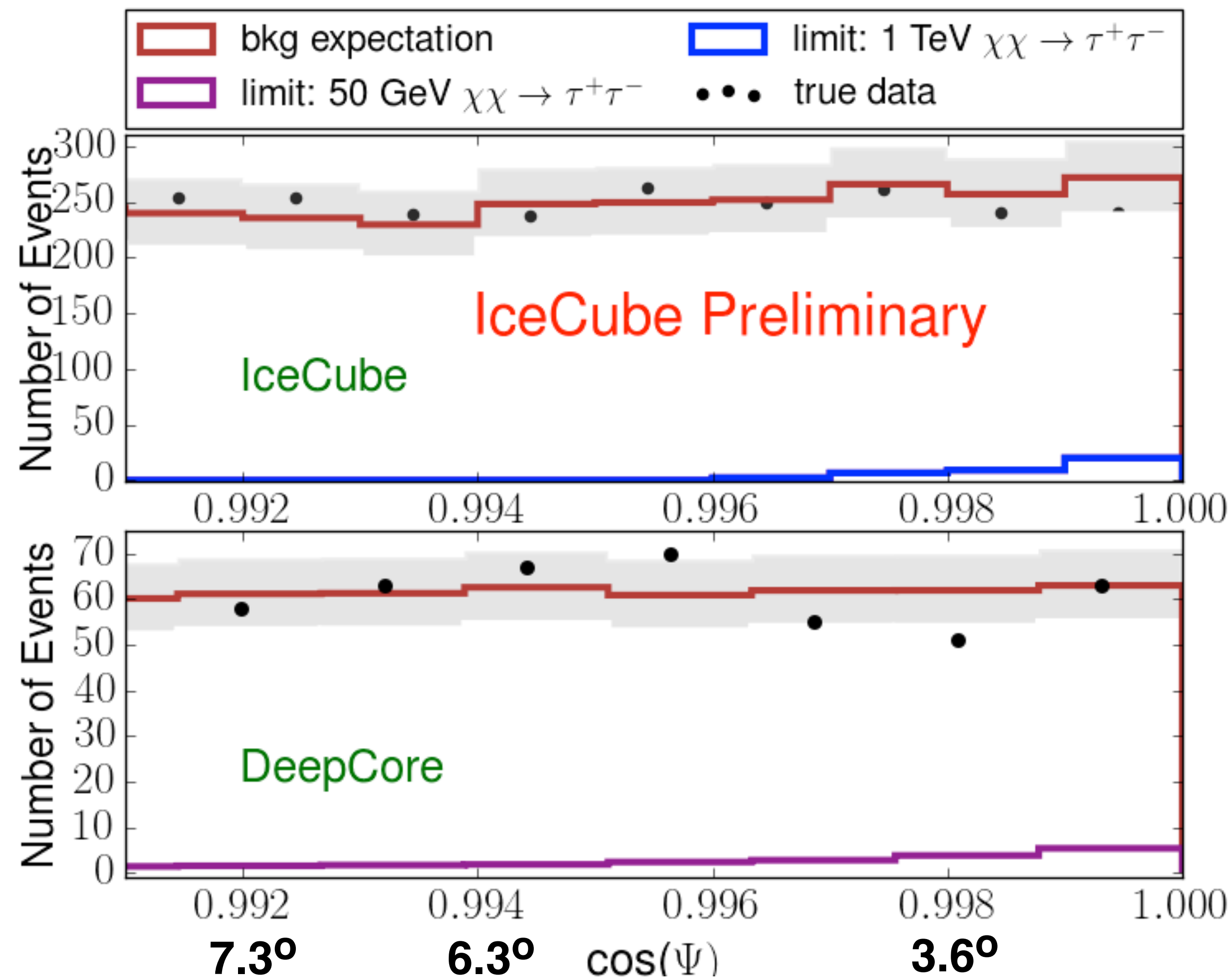
Effective Areas



3yrs IceCube Solar WIMP Analysis



Observed events

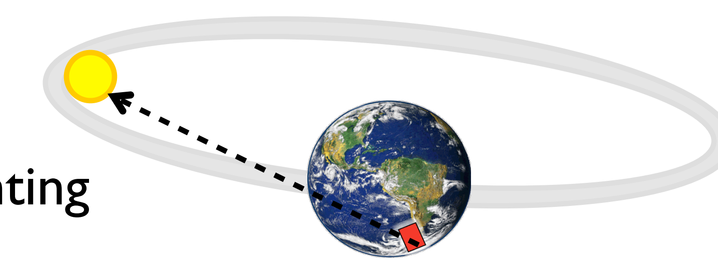


Signal pdf:

Spectral part

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

Monovariate Fisher Bingham distribution from directional statistics

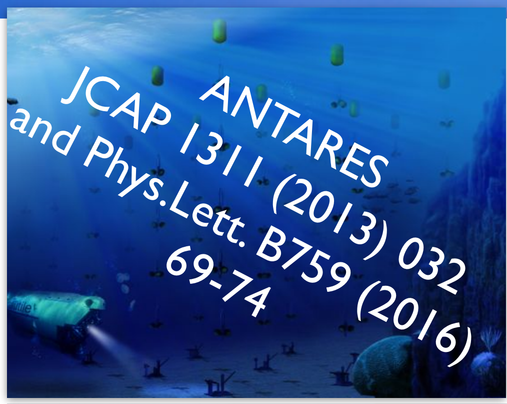


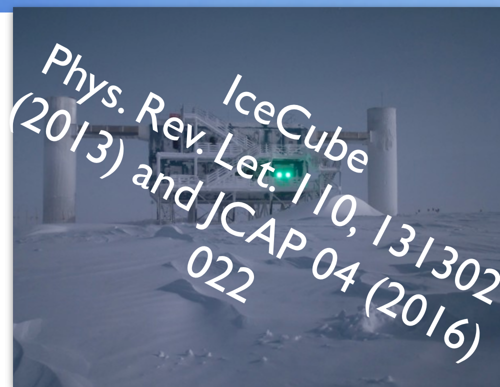
- Use track events for better pointing
- Search for an excess of events from the direction of the Sun
- Observed events consistent with background only expectations

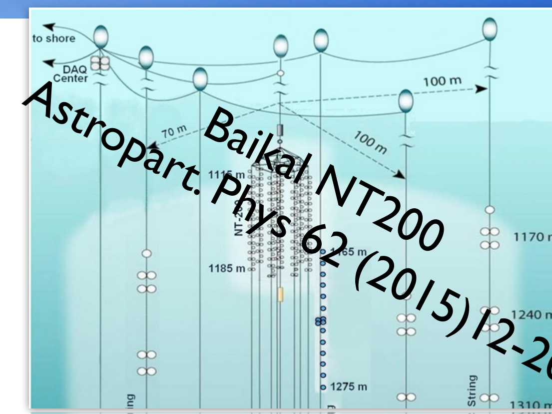
Background pdf: $\mathcal{B}_i(tx_i, E_i) = B(\delta_i) \times P(E_i|\phi_{\rm atm})$

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

Solar WIMPs Summary



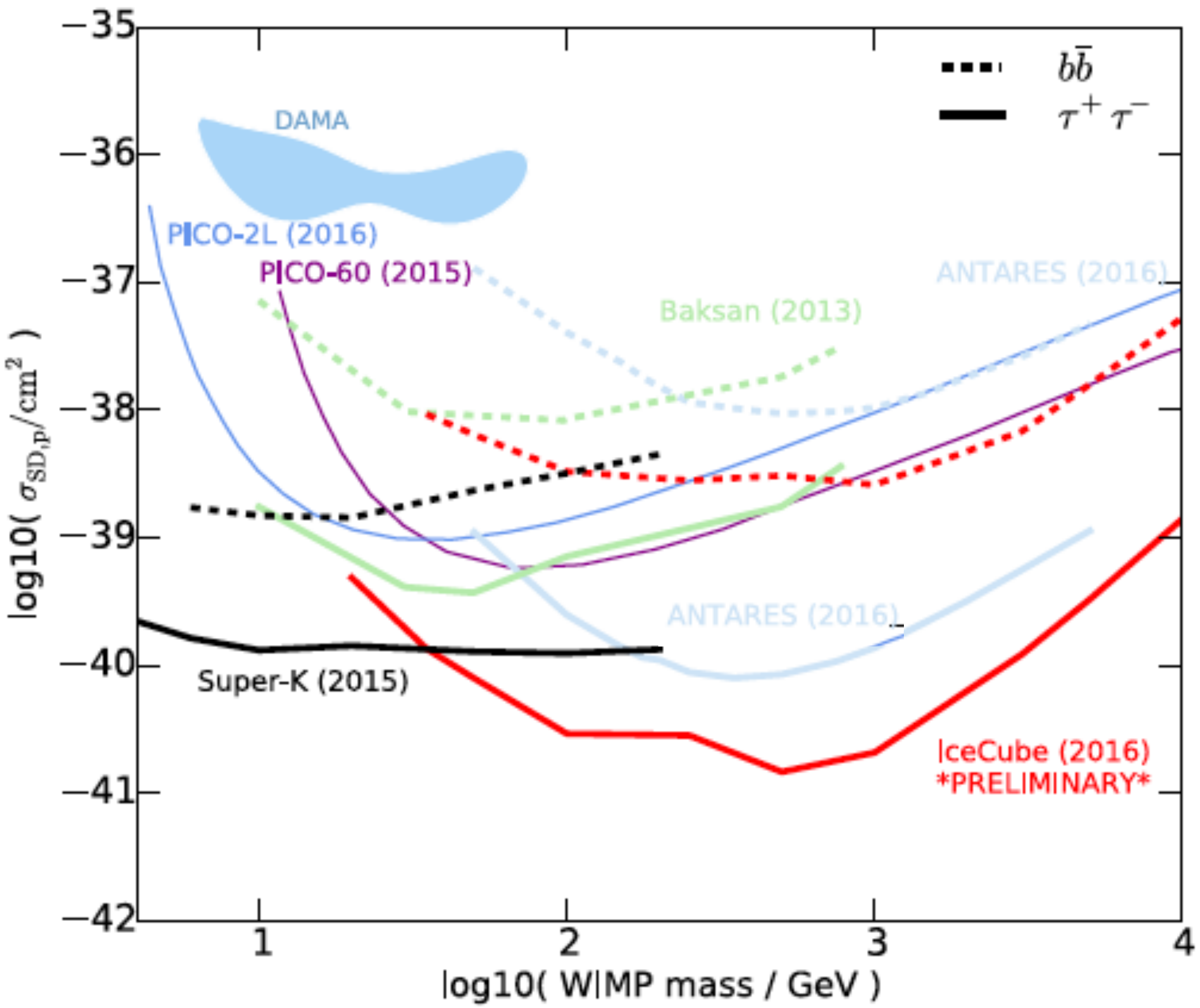


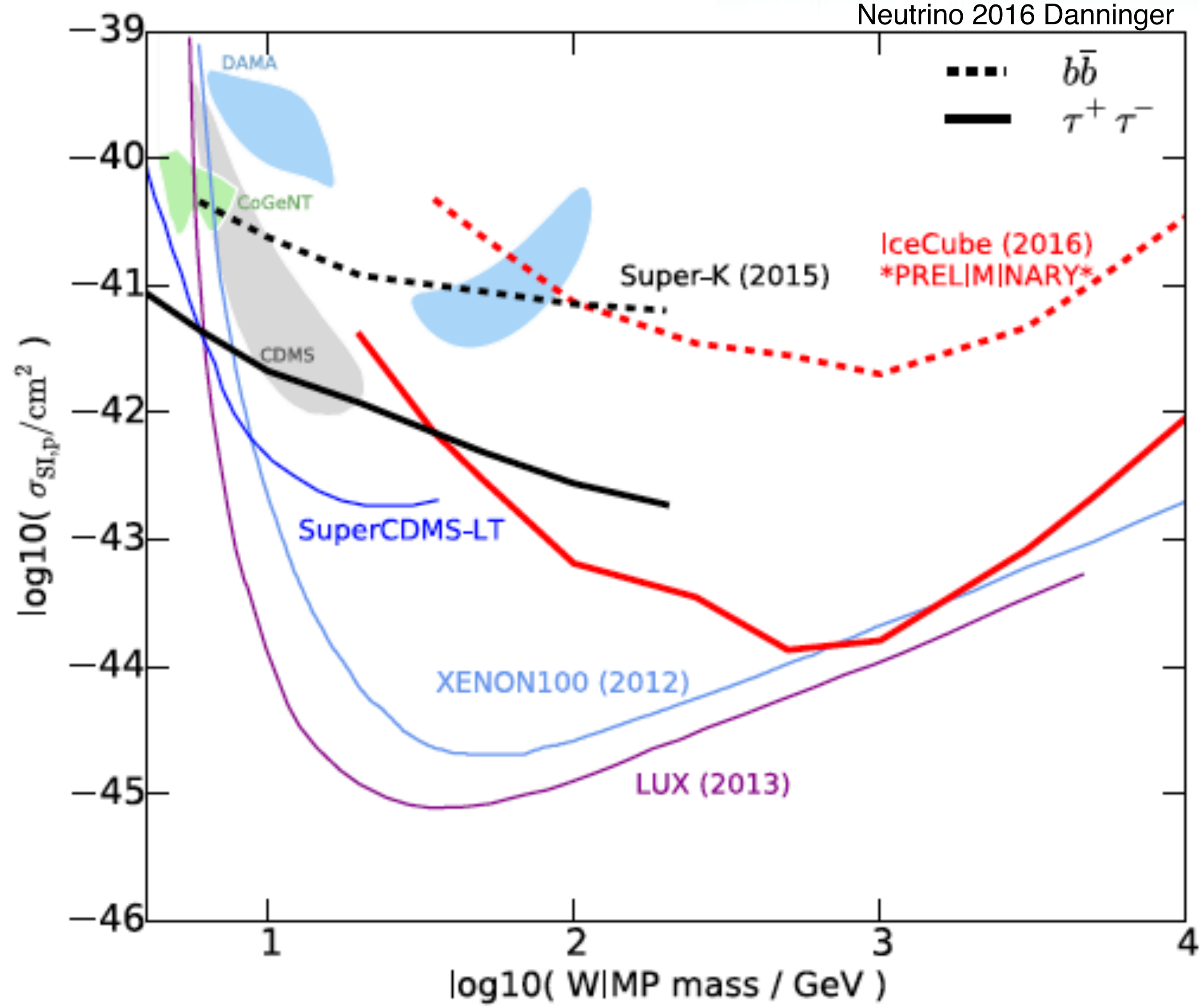


Spin-dependent scattering

Spin-independent scattering

Neutrino 2016 Danninger

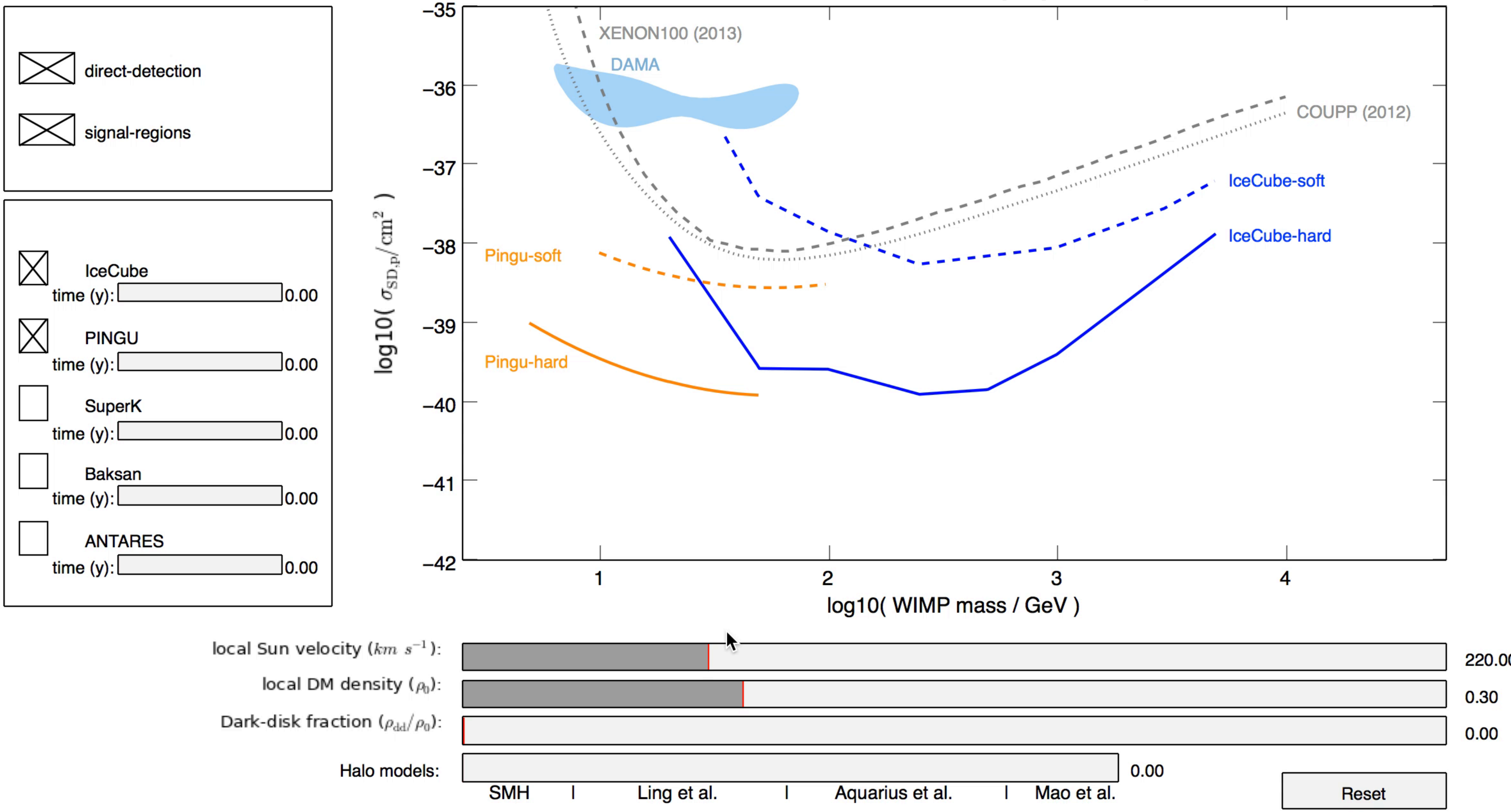




Impact of astrophysical uncertainties

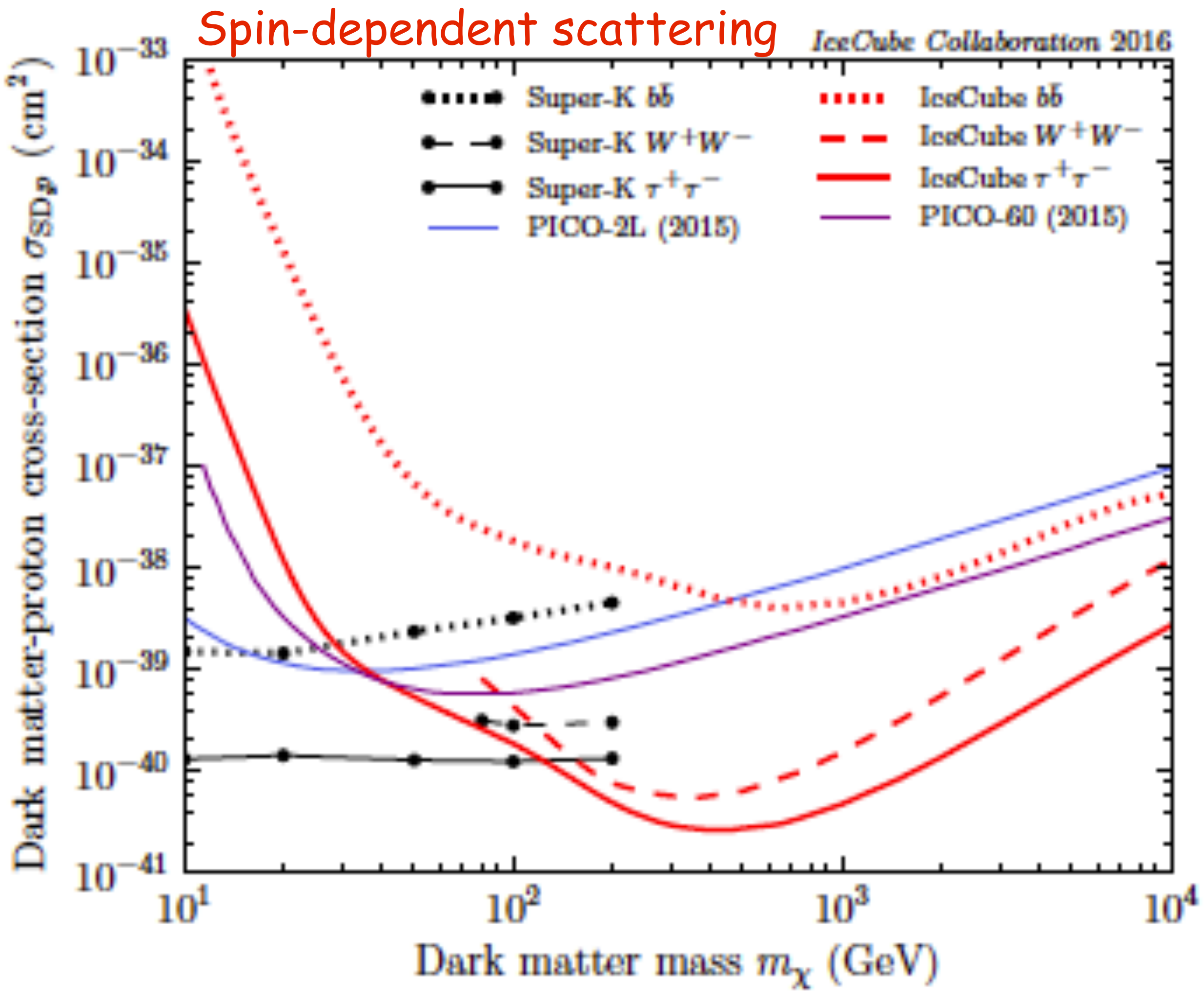
M. Danninger & C. Rott "Solar WIMPs Unraveled" – Physics of the Dark Universe (Nov 2014)

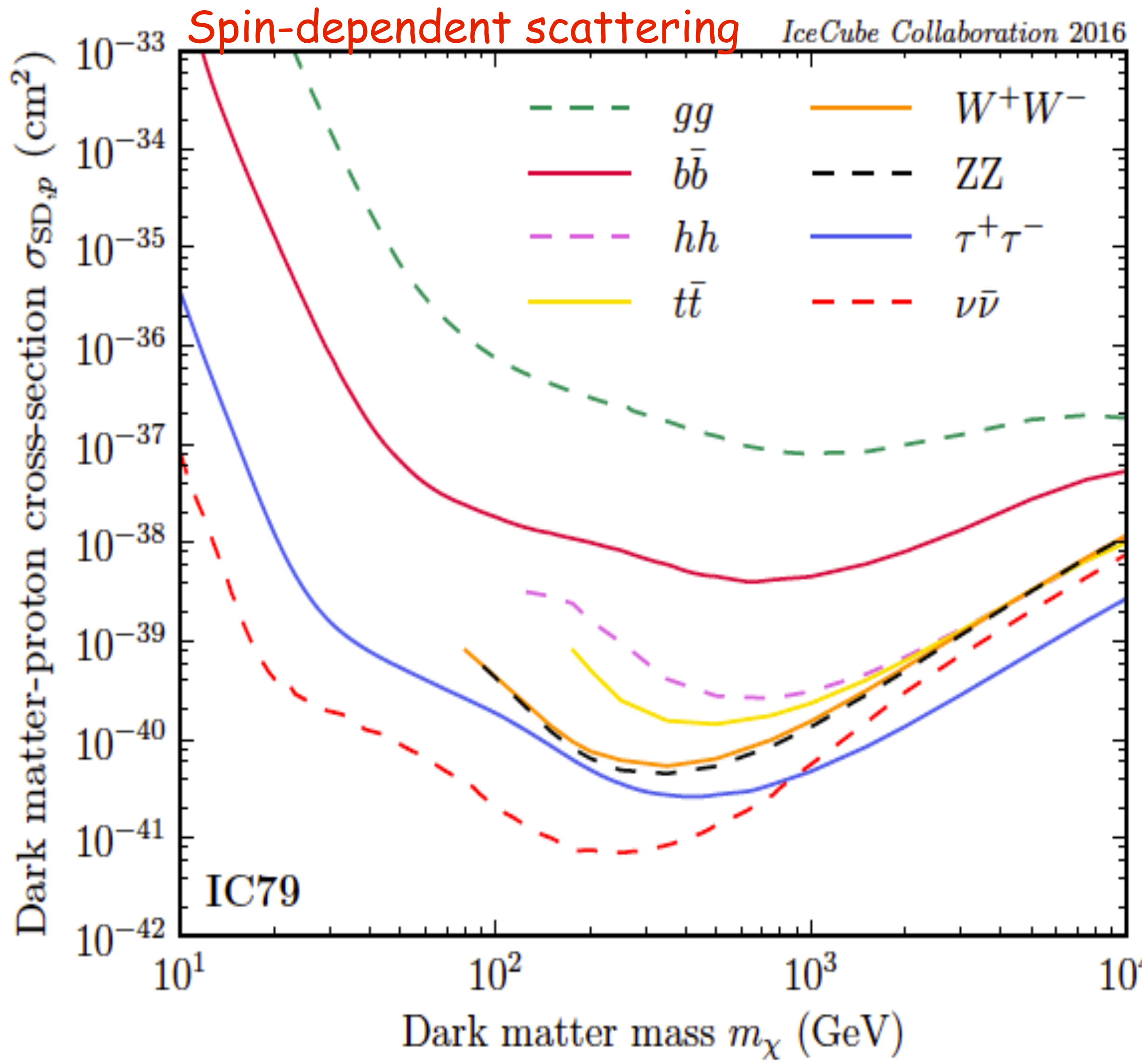
Interactive tool to study impact of astrophysical parameters

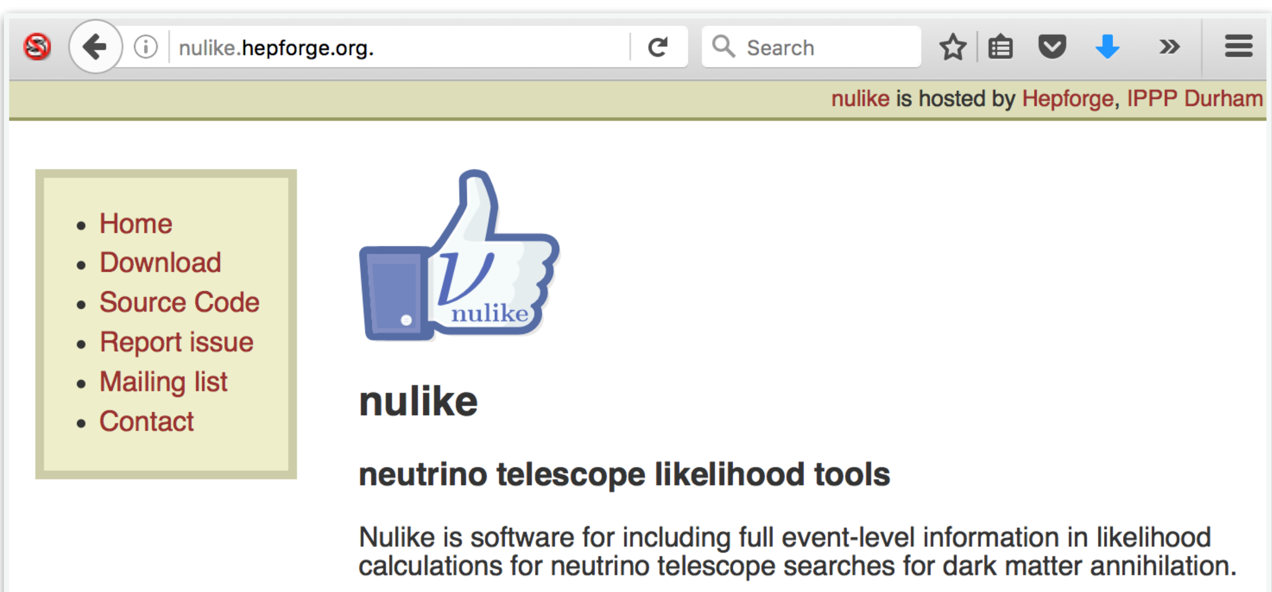


https://mdanning.web.cern.ch/mdanning/public/Interactive_figures/

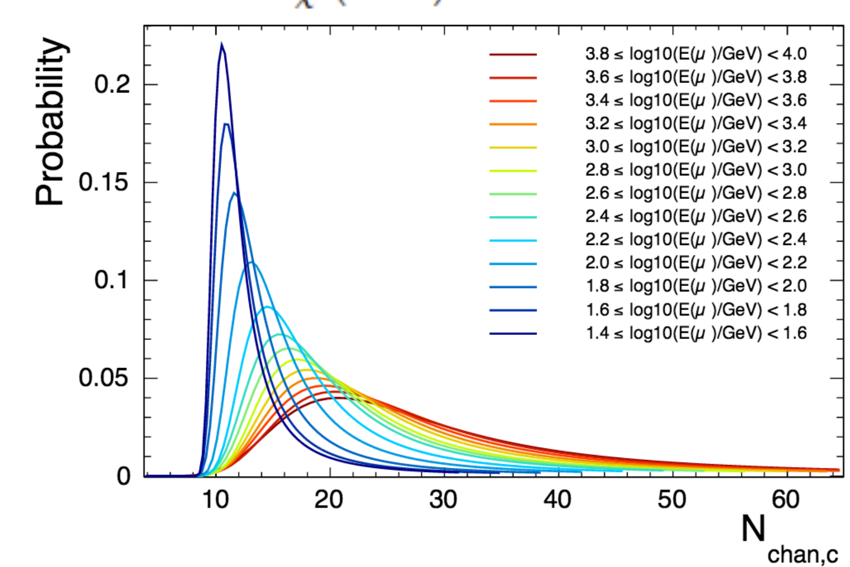
nulike







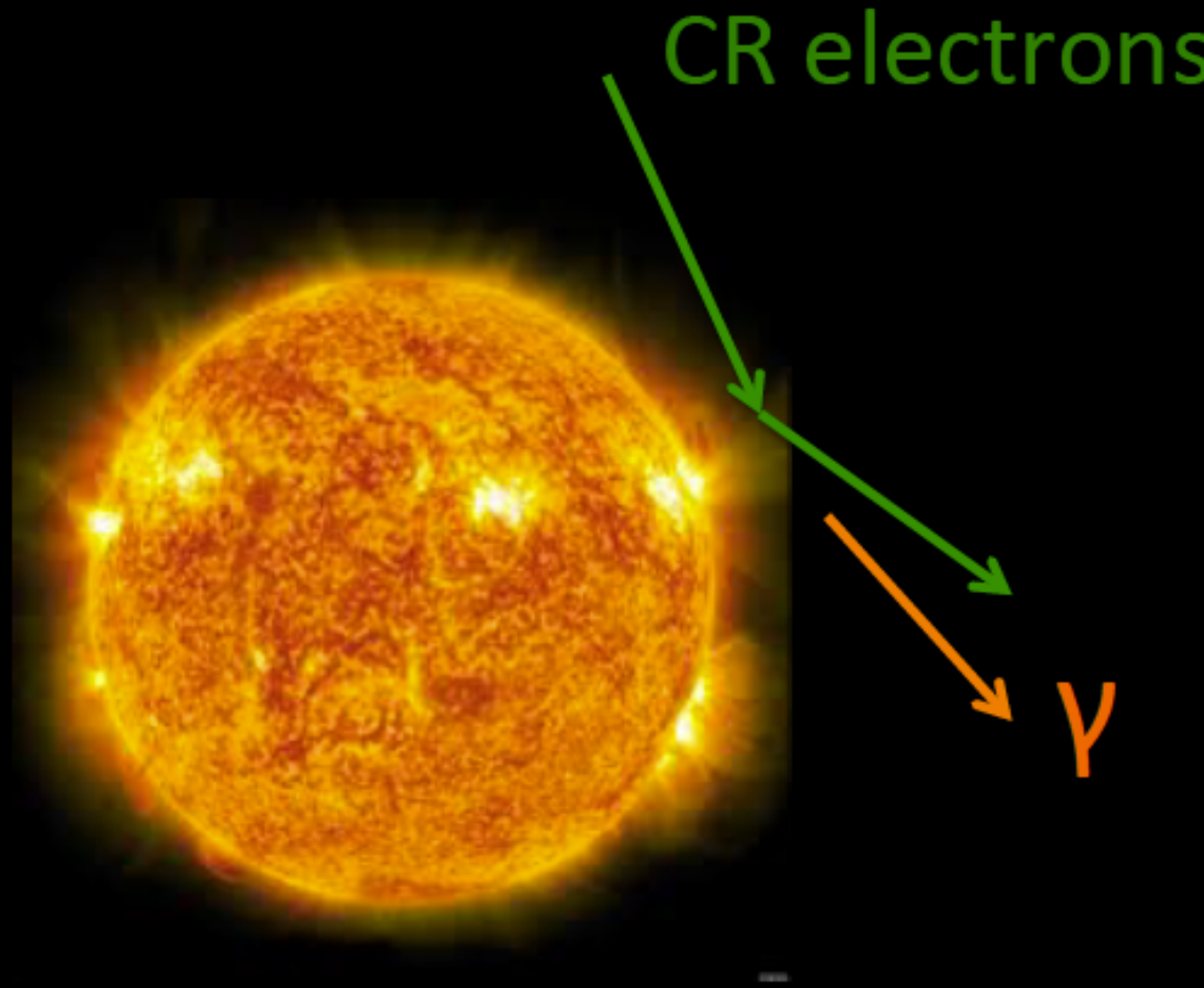
- Likelihood includes:
  - energy and directional information



Solar Neutrino Floor

Sun – Cosmic-Ray Beam Dump

- Leptonic

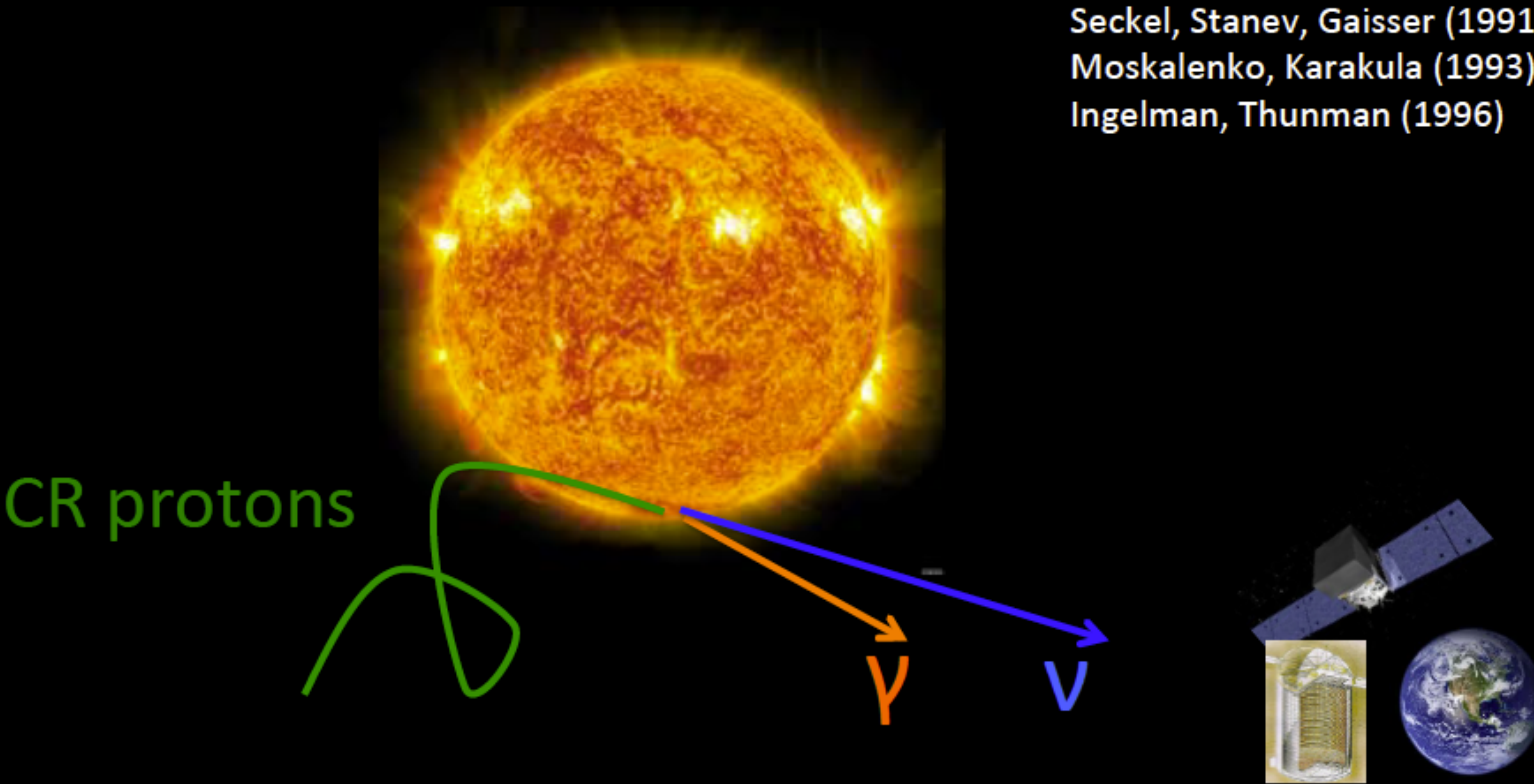


Moskalenko, Porter, Digel (2006)
Orlando, Strong (2007)

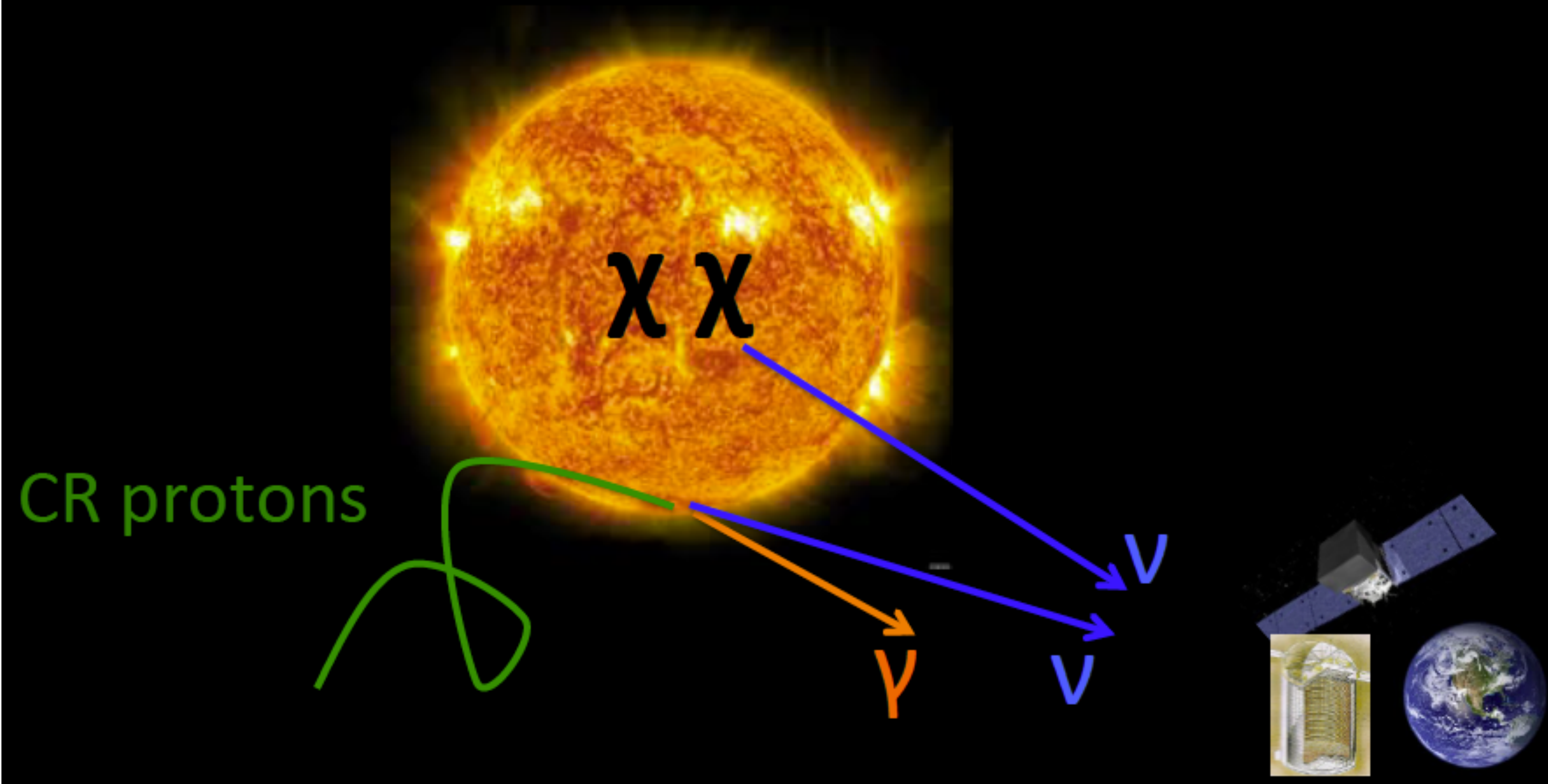
Sun – Cosmic-Ray Beam Dump

- Hadronic

Seckel, Stanev, Gaisser (1991)
Moskalenko, Karakula (1993)
Ingelman, Thunman (1996)

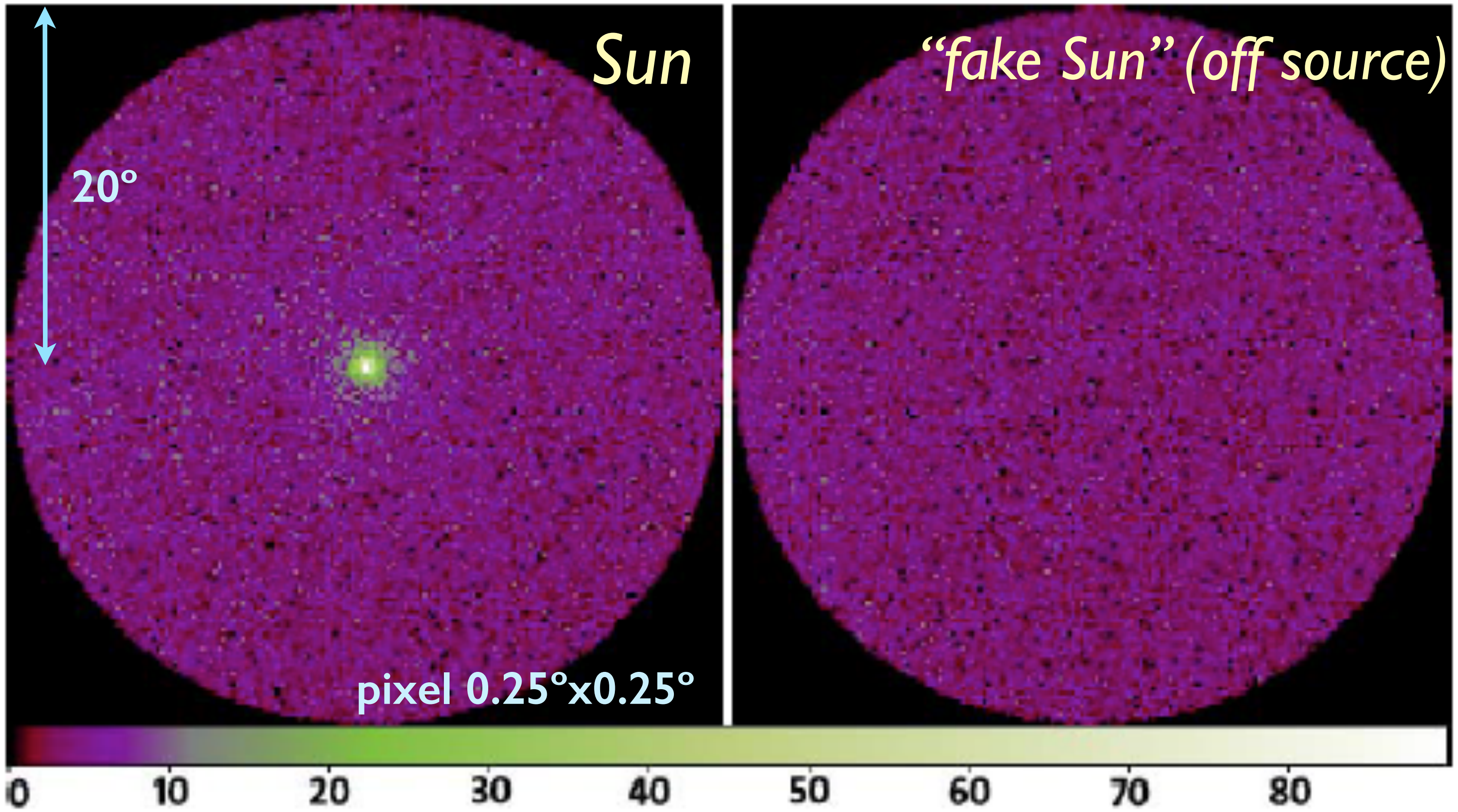


Cosmic Rays vs Dark Matter

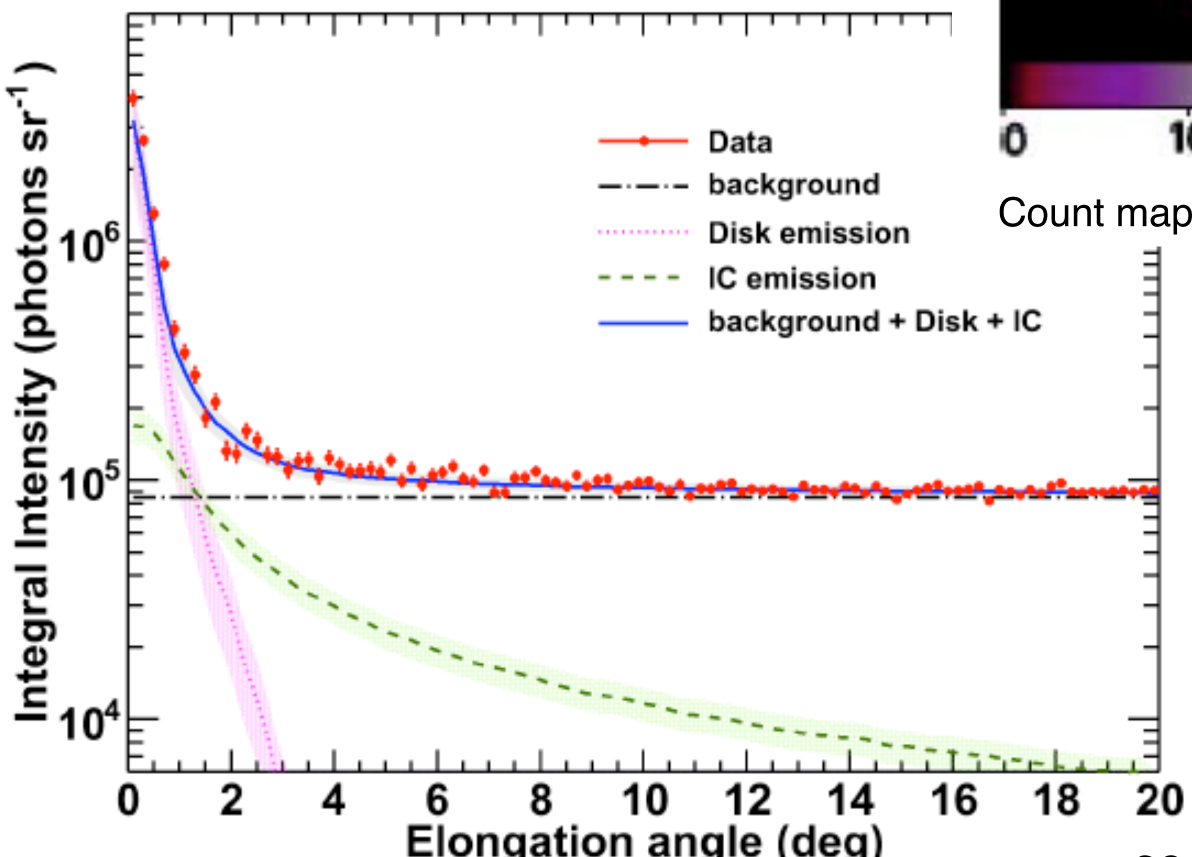


Gamma-ray's from the Sun

- 1.5 yrs of data during solar minimum
  - Aug 2008 - Feb 2010
- Standard Fermi analysis selection criteria



Count maps for events >100 MeV taken between August 2008 and February 2010

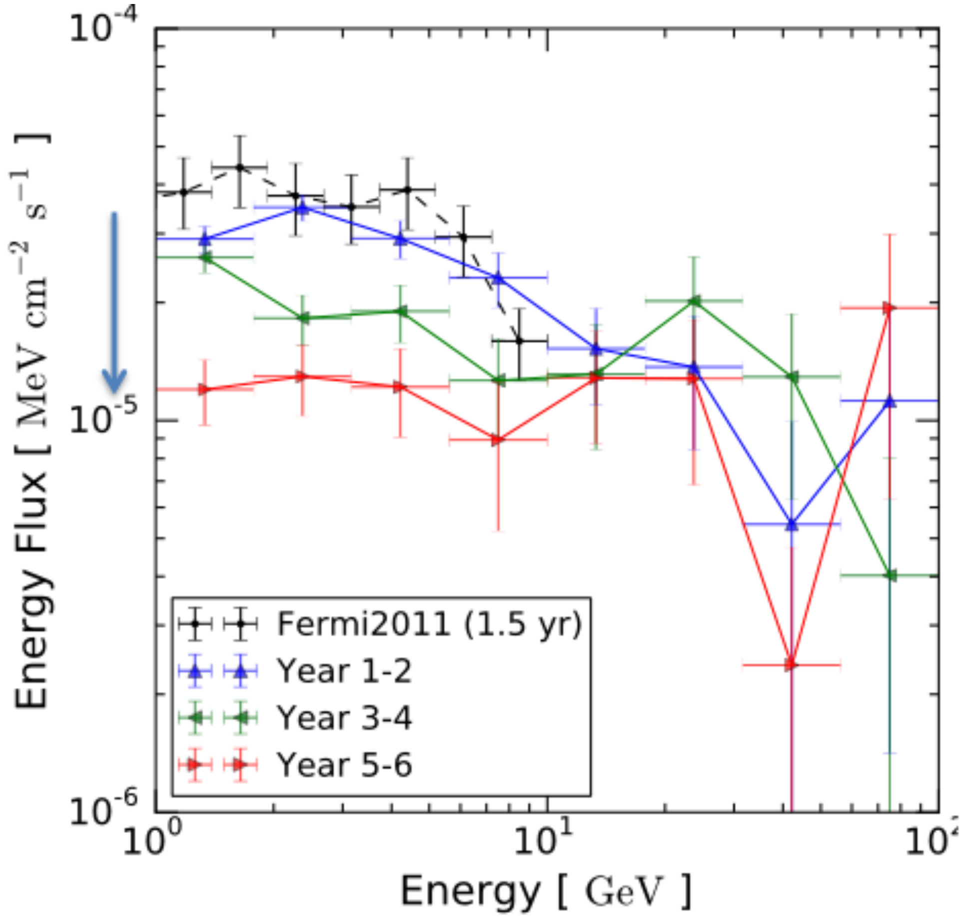


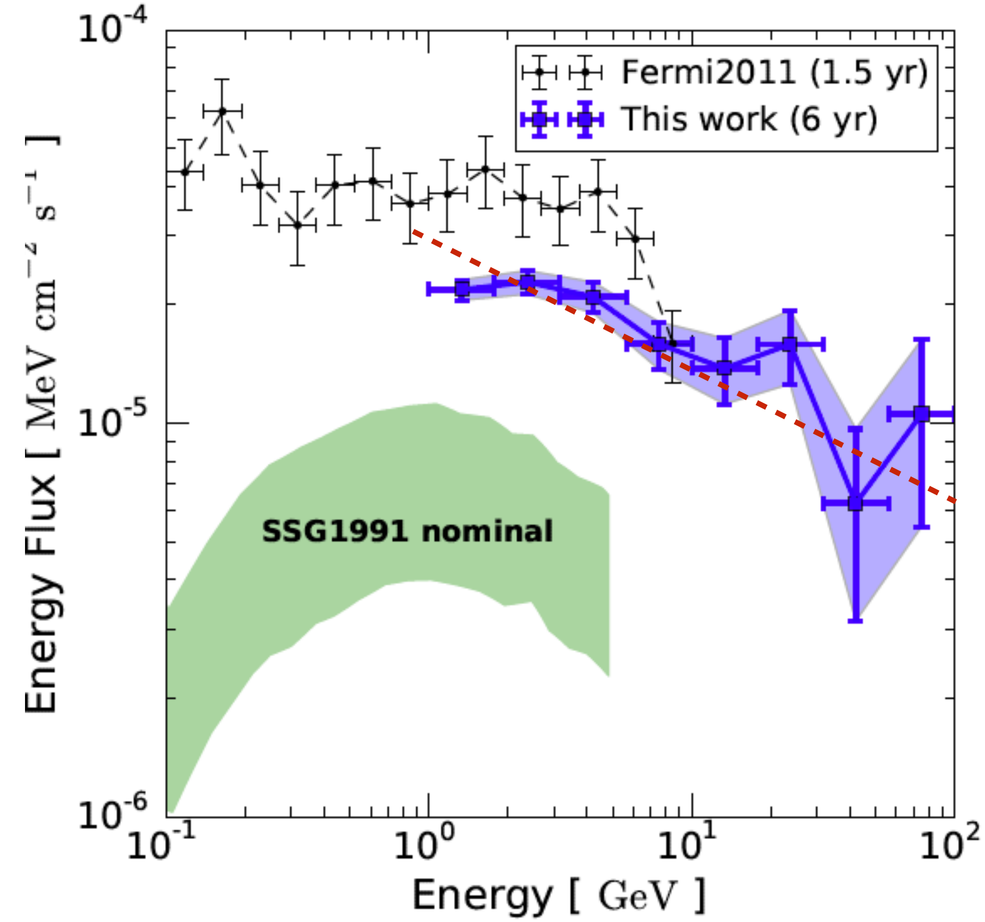
- Extended and disk emission is observed

see Fermi-LAT Collaboration: http://arxiv.org/pdf/1104.2093.pdf

Gamma-ray's from the Sun

- 6 yrs of data
  - Aug 2008 - Aug 2014
- Fermi science tools version v9r33p0

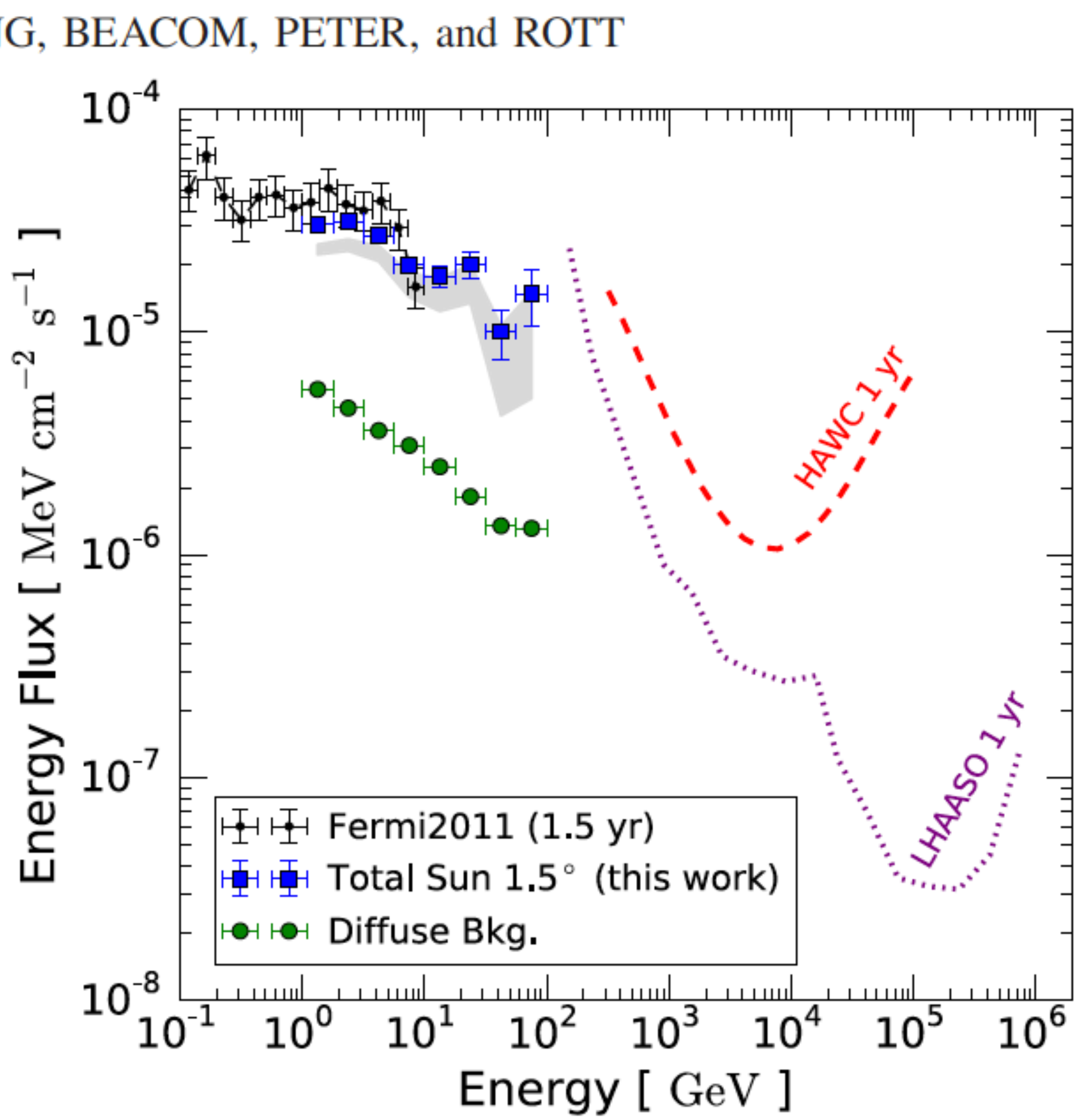


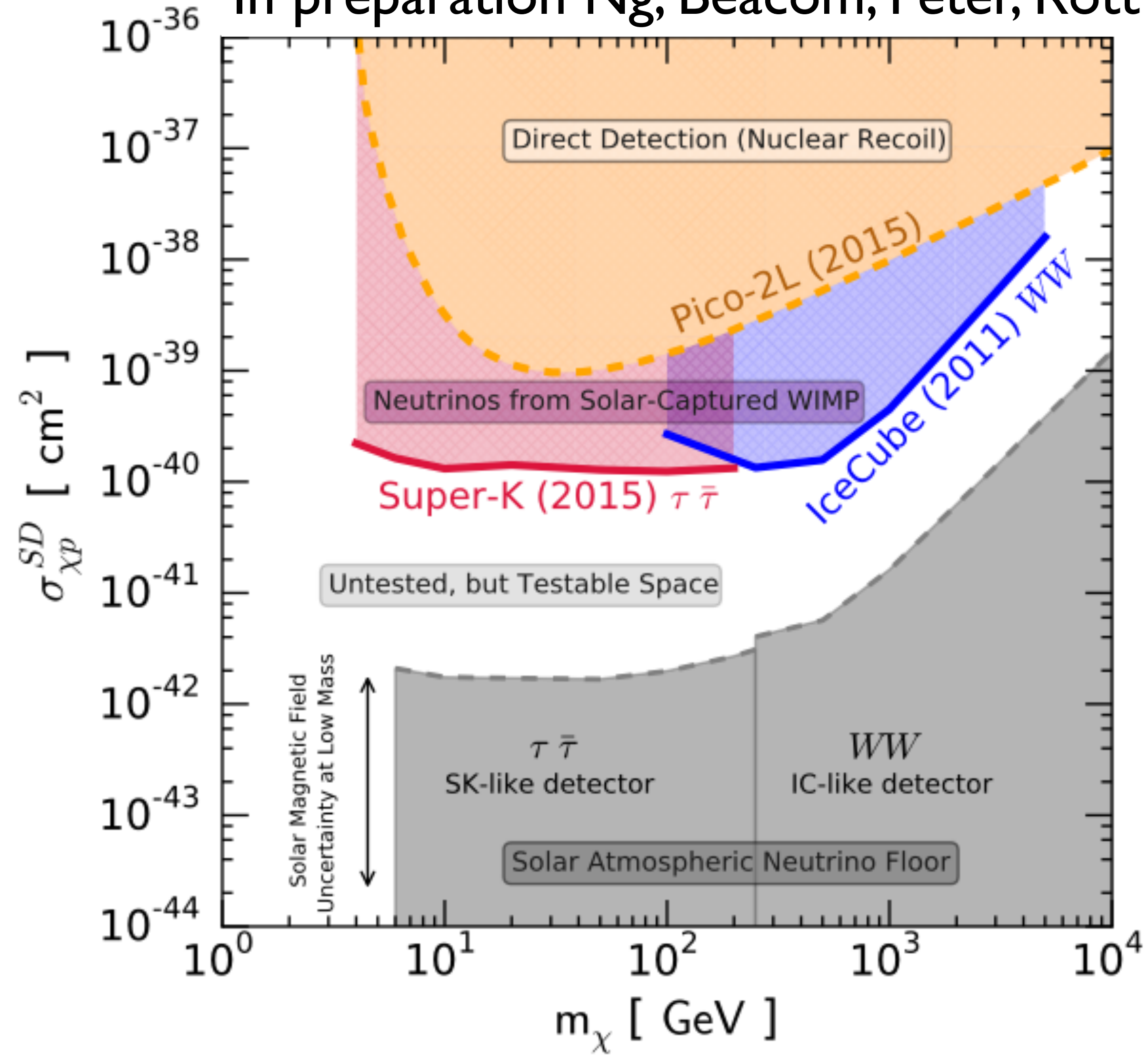


- Observed gamma-ray flux cannot be described by current models
- Significant time variation in solar-disk gamma-rays observed (<10GeV)
- Gamma-ray flux from the Sun extends beyond 100GeV

see K. Ng, J. Beacom, A. Peter, C. Rott PRD 2016

Gamma-ray's from the Sun



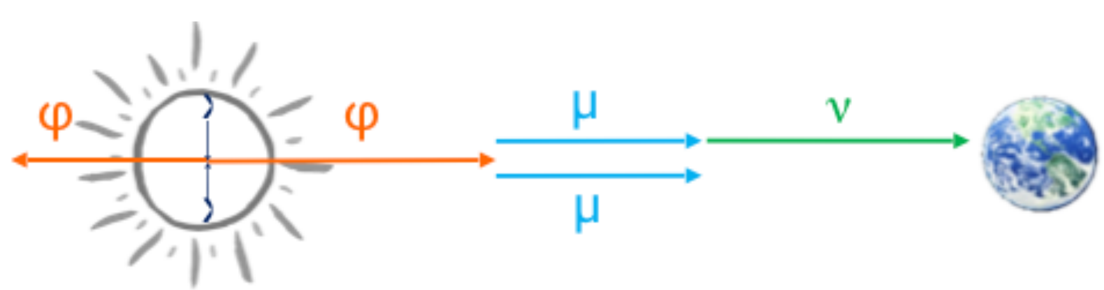


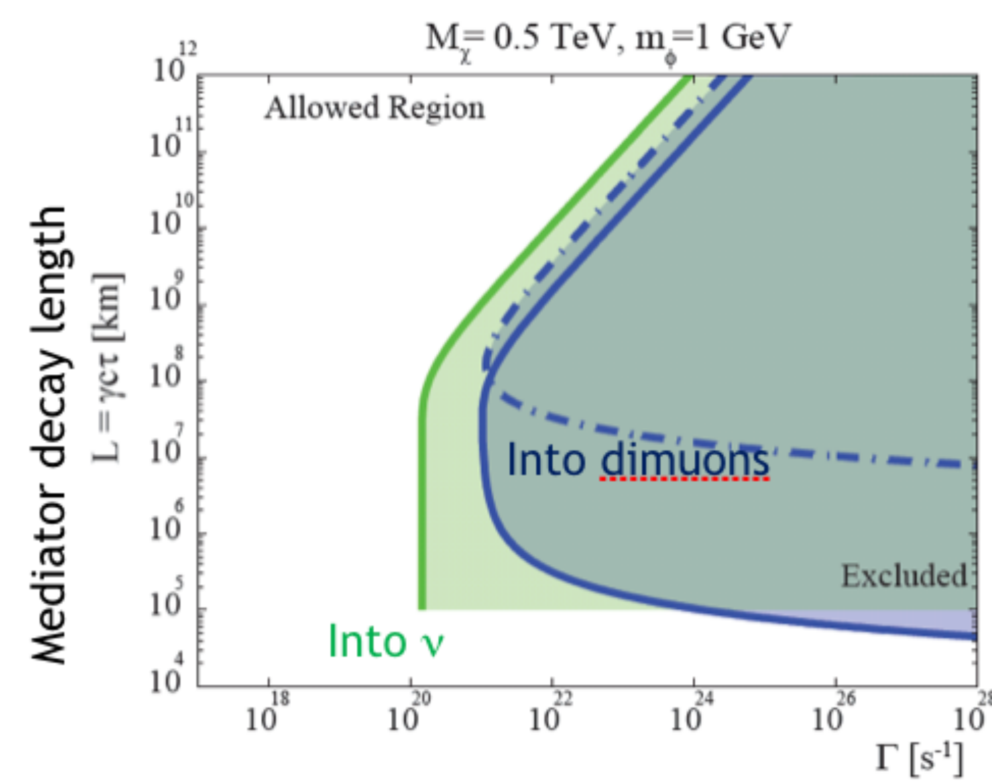
- Sun is a promising source for ground-based high altitude water Cherenkov detectors
- Background to dark matter search from the Sun, that soon will be relevant (and first high-energy neutrino point source ??)

see K. Ng, J. Beacom, A. Peter, C. Rott PRD 2016

Search for high-energy neutrinos from the Sun

- Absorption in the Sun relevant for neutrinos above 100GeV and signals severely attenuated above 1TeV
  - All Solar WIMP searches optimised on neutrino fluxes well below 1TeV
- Why search for high-energy neutrinos from the Sun ?
  - Test secluded dark matter scenarios
  - Solar disk neutrinos
  - Anything unexpected ?





Annihilation of DM in the Sun x Branching ratio

ANTARES Coll. JCAP 1605 (2016) no.05, 016

Low Energy Neutrinos from the Sun

C. Rott, J. Siegal-Gaskins, J.F.Beacom Physical Review D 88, 055005 (2013) (arXiv1208.0827)
C.Rott, S.In, J.Kumar, D.Yaylali JCAP11 (2015) 039

Low-Energy Neutrinos from the Sun

Possible annihilation channels:

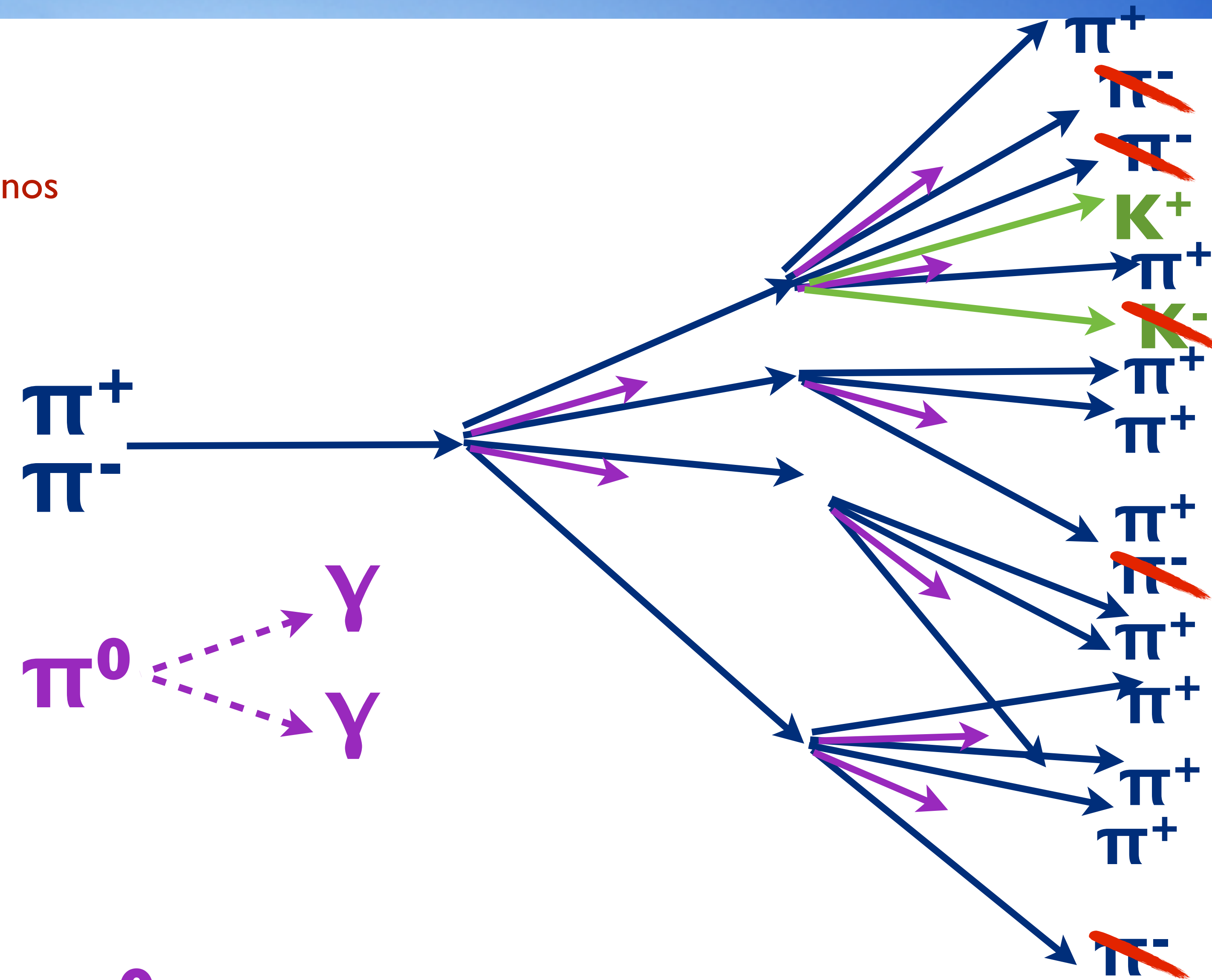
$q\bar{q}, gg, c\bar{c}, s\bar{s}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}, e^+e^-, \gamma\gamma$

few neutrinos

some "high energy" neutrinos in decays

⇒ basis of present day searches

dominant decay into hadrons



Charged pions and kaons decay at rest producing mono-energetic neutrinos

$\pi^+ \rightarrow \mu^+ \nu_\mu$ $E_\nu = 29.8\,\text{MeV}$

$K^+ \rightarrow \nu_\mu \mu^+$ $E_\nu = 235.5\,\text{MeV}$

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

π^0

- Lifetime too short to interact

π^-

- Interaction length short compared to losses
- Produces secondary particles in collision with protons
- Dominant energy loss term is π^0 production

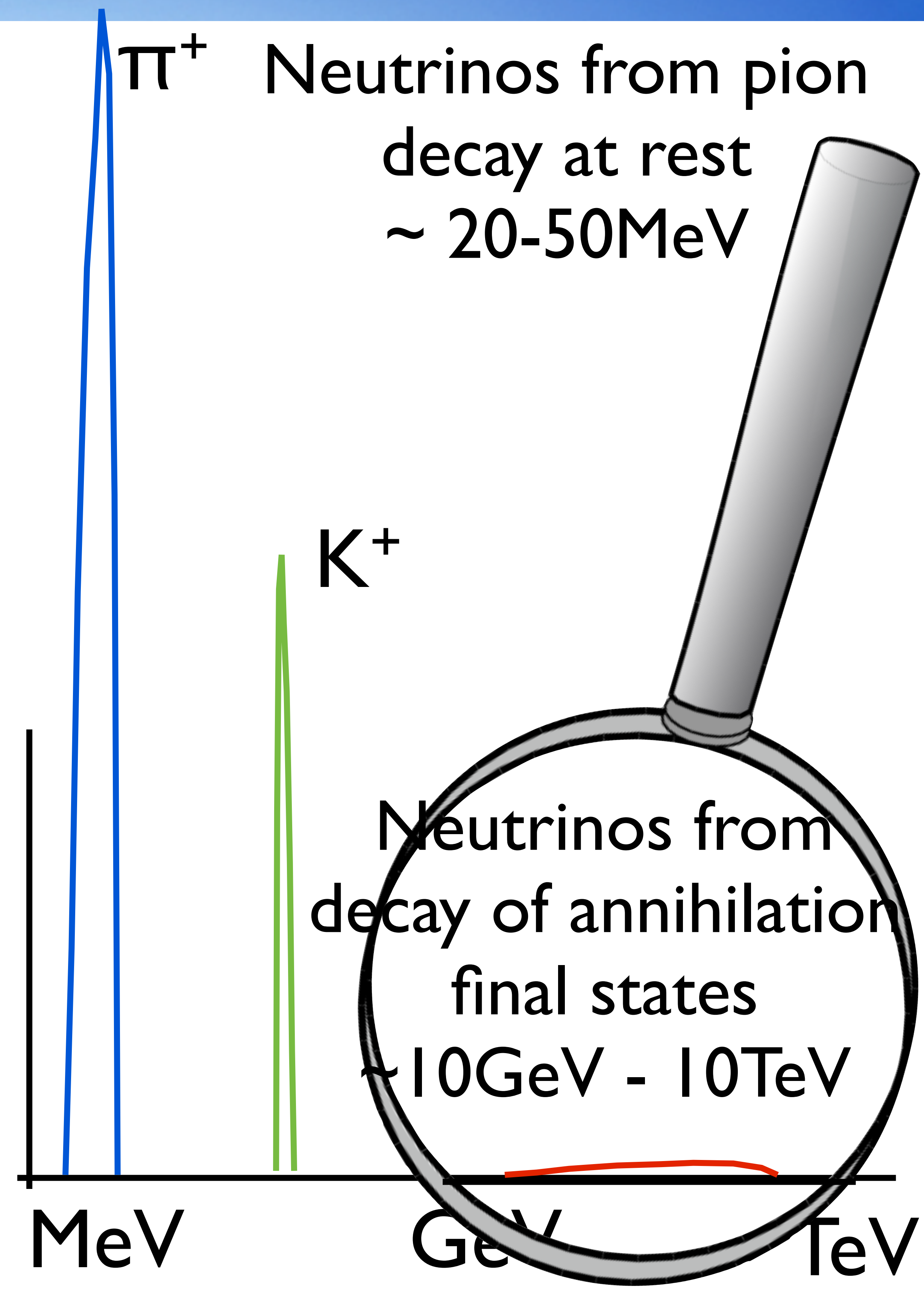
Neutrino signals - Example W-Boson

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

$\longrightarrow qq$ ~67%

Let's have a closer look at this:

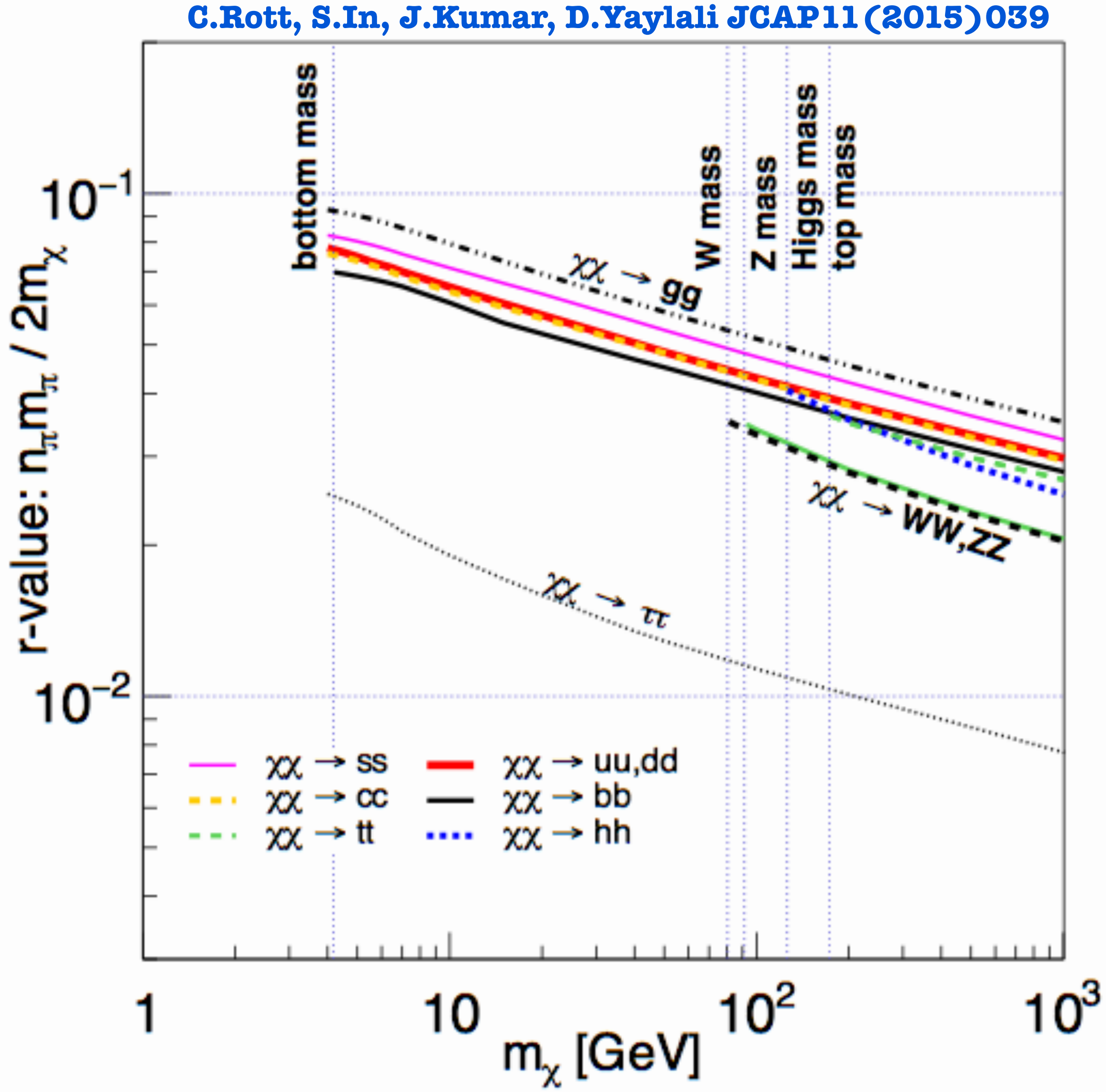
$e^+\nu_e$	1 high energy ν + em shower
$\mu^+\nu_\mu$	1 high energy ν + muon
$\tau^+\nu_\tau$	1 high energy ν + tau decay
qq	hadronic shower

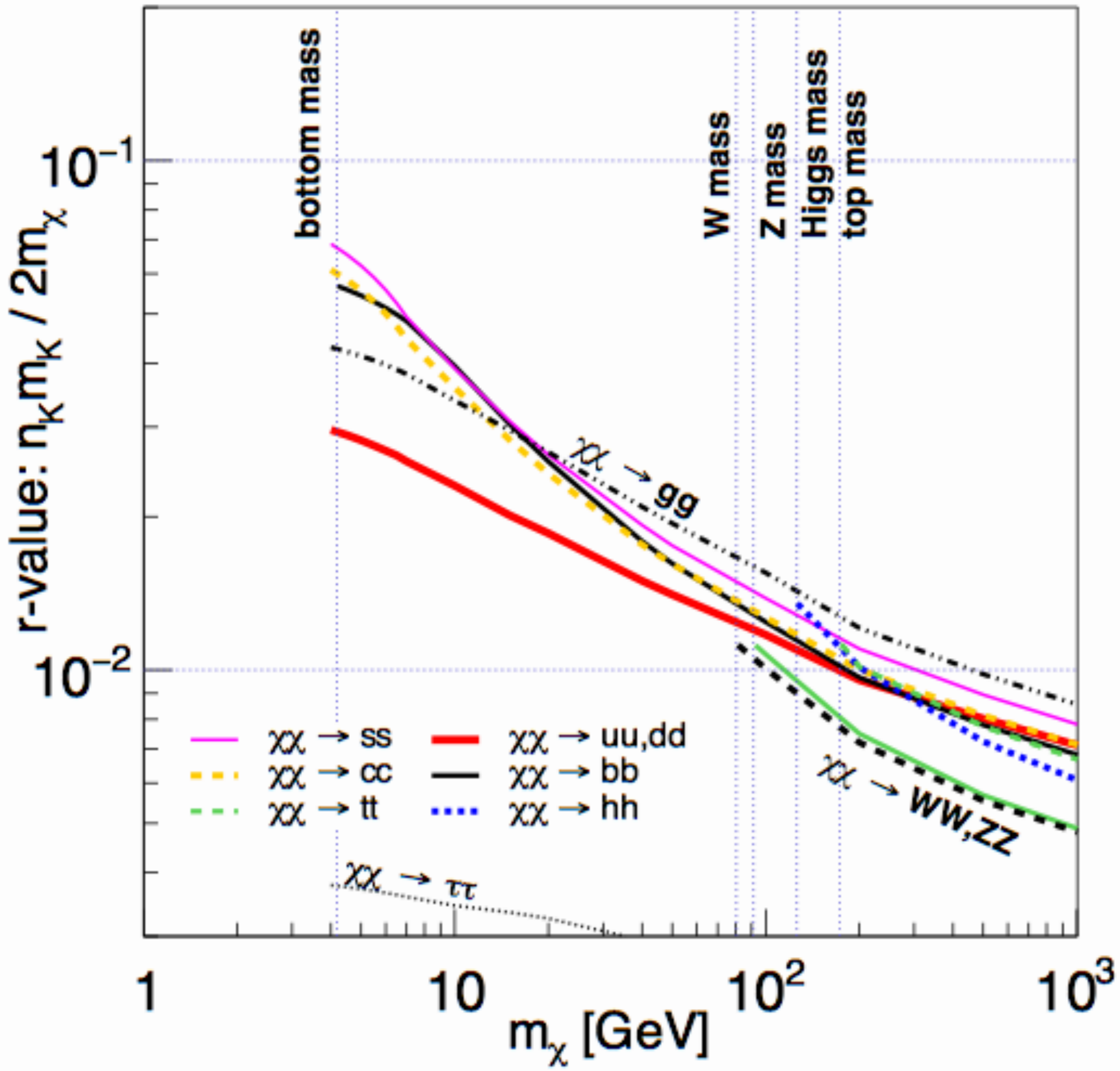


Pion and Kaon yields

π^+ r-value - fraction of center-of-mass energy which goes into π^+

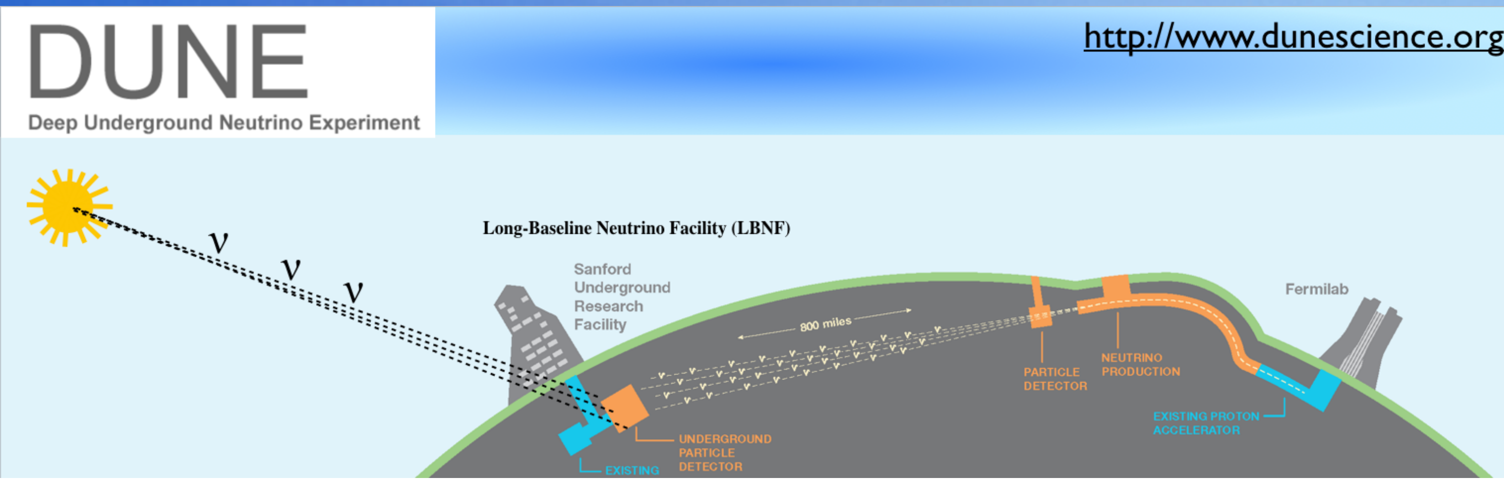
K^+ r-value - fraction of center-of-mass energy which goes into K^+

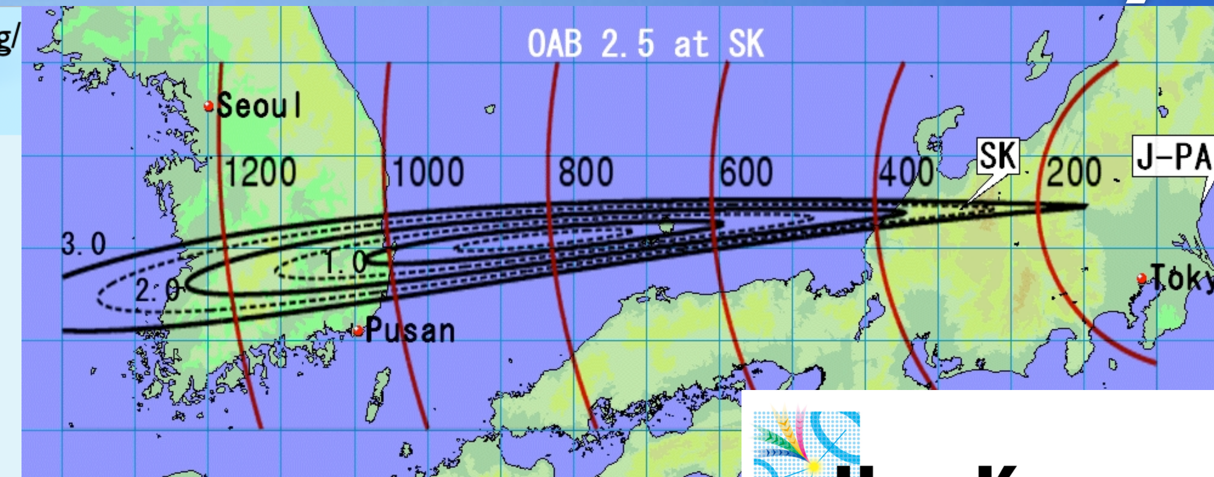


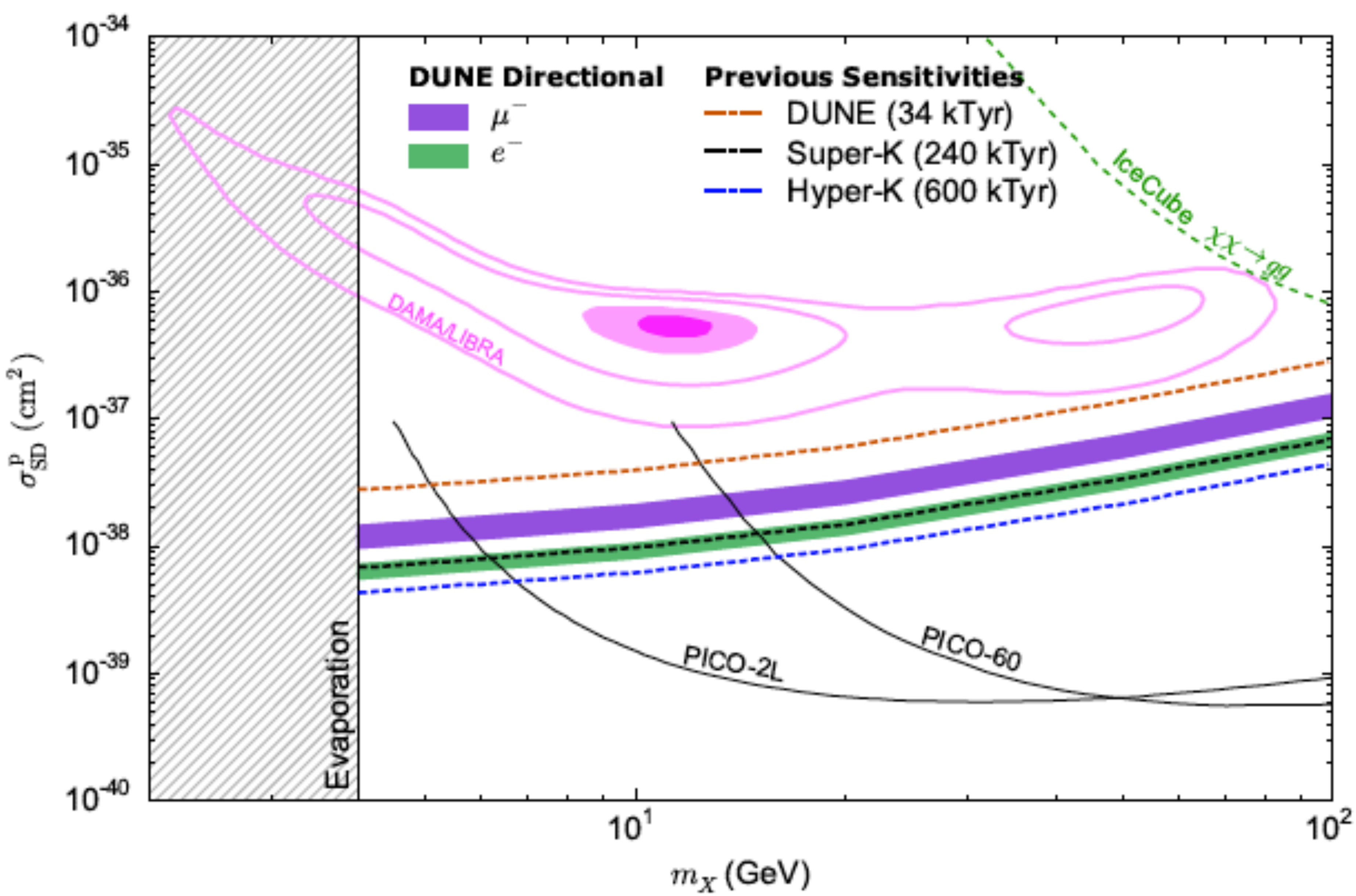


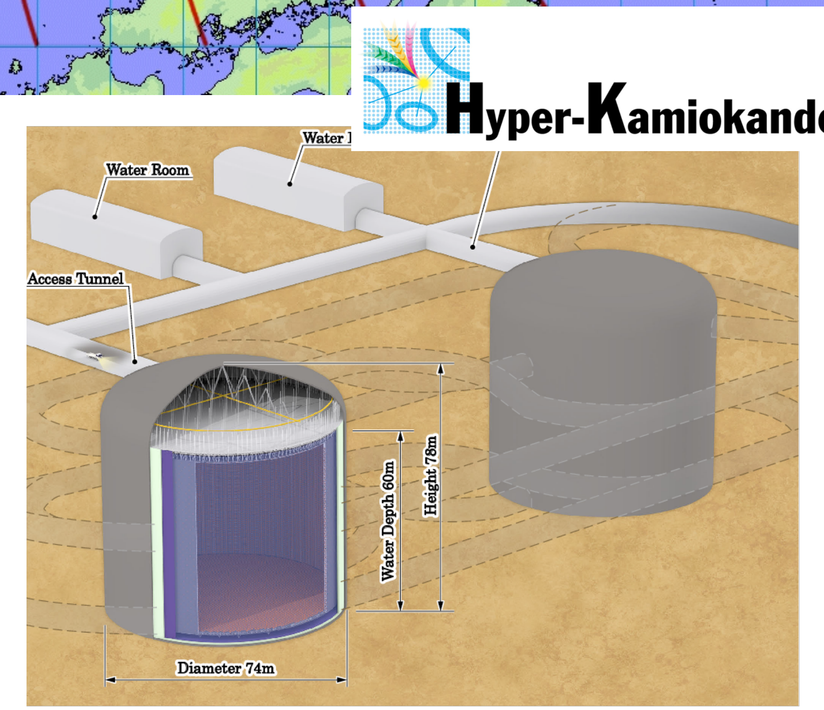
For low dark matter masses difference between flux from stopped pion and kaon decay at rest can be used to disentangle annihilation final states

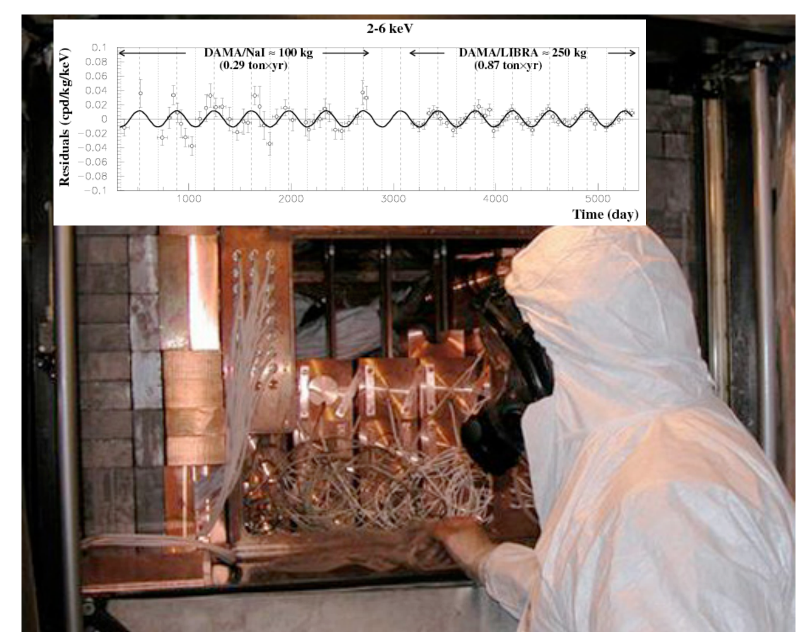
Sensitivity



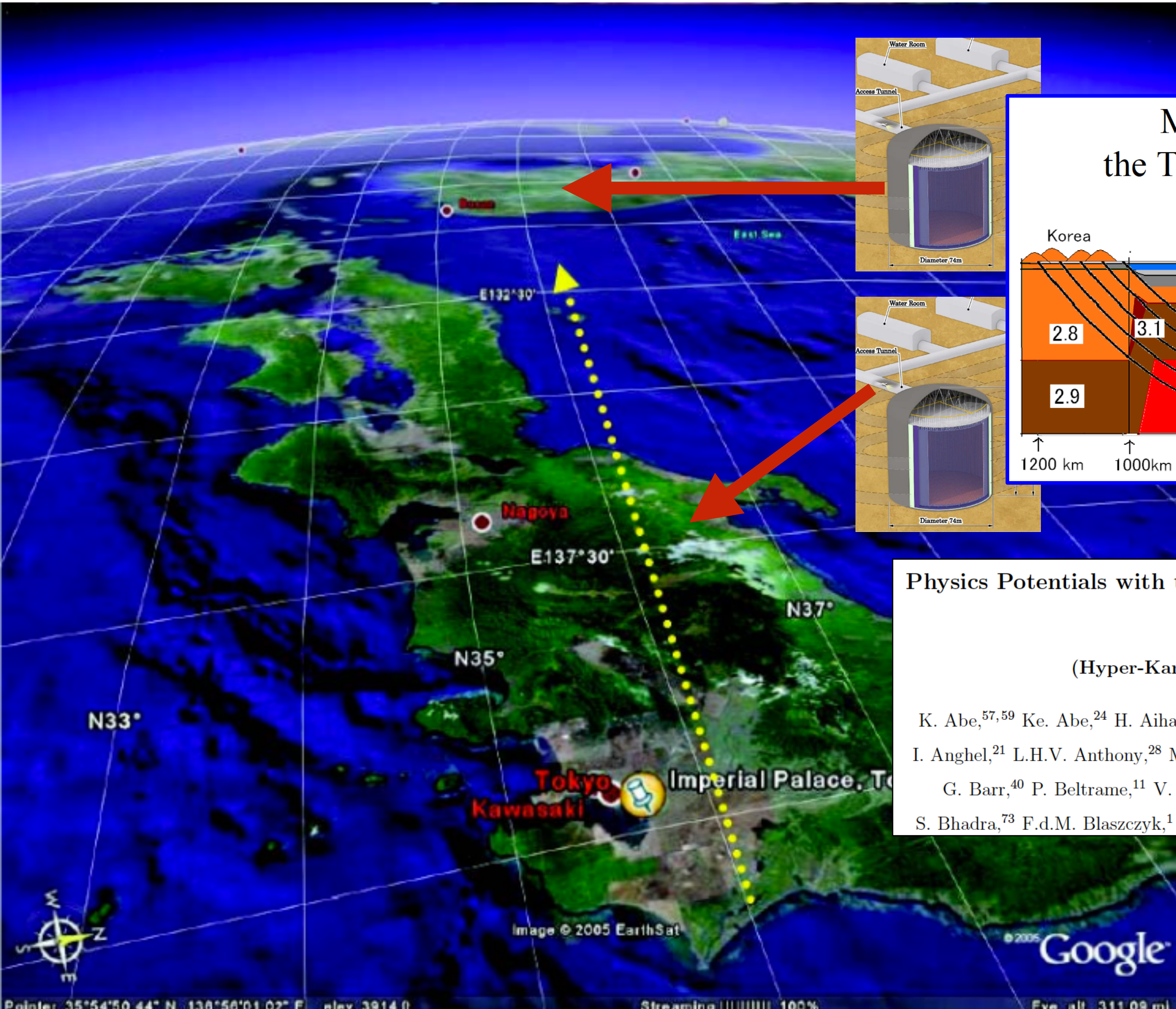


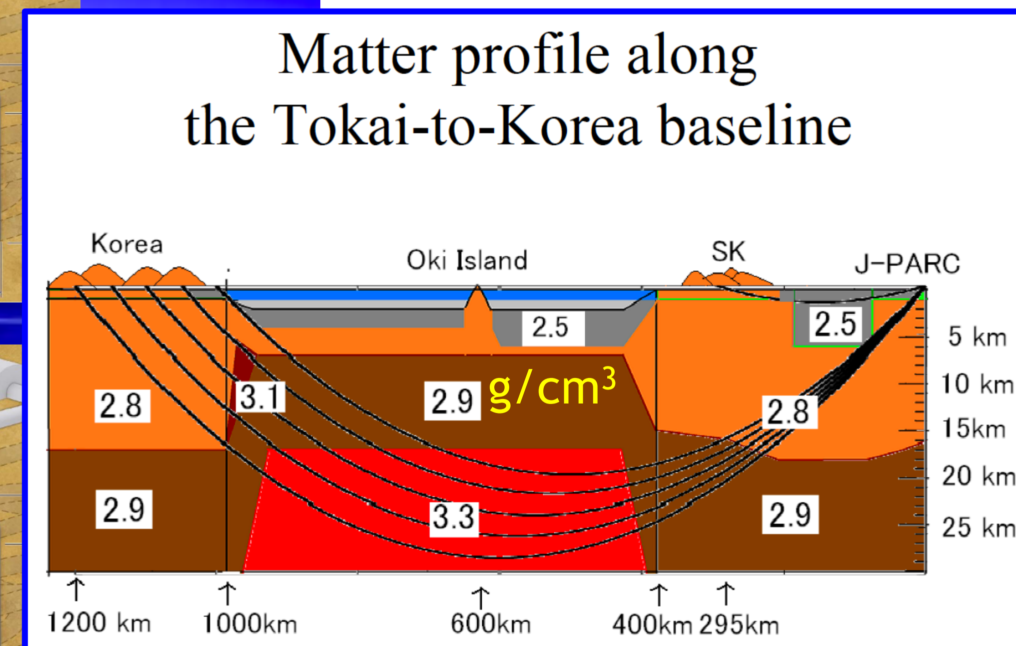






Tokai-to-Hyper-K & Korea (T2HKK)





Physics Potentials with the Second Hyper-Kamiokande Detector in Korea

(Hyper-Kamiokande Proto-Collaboration)

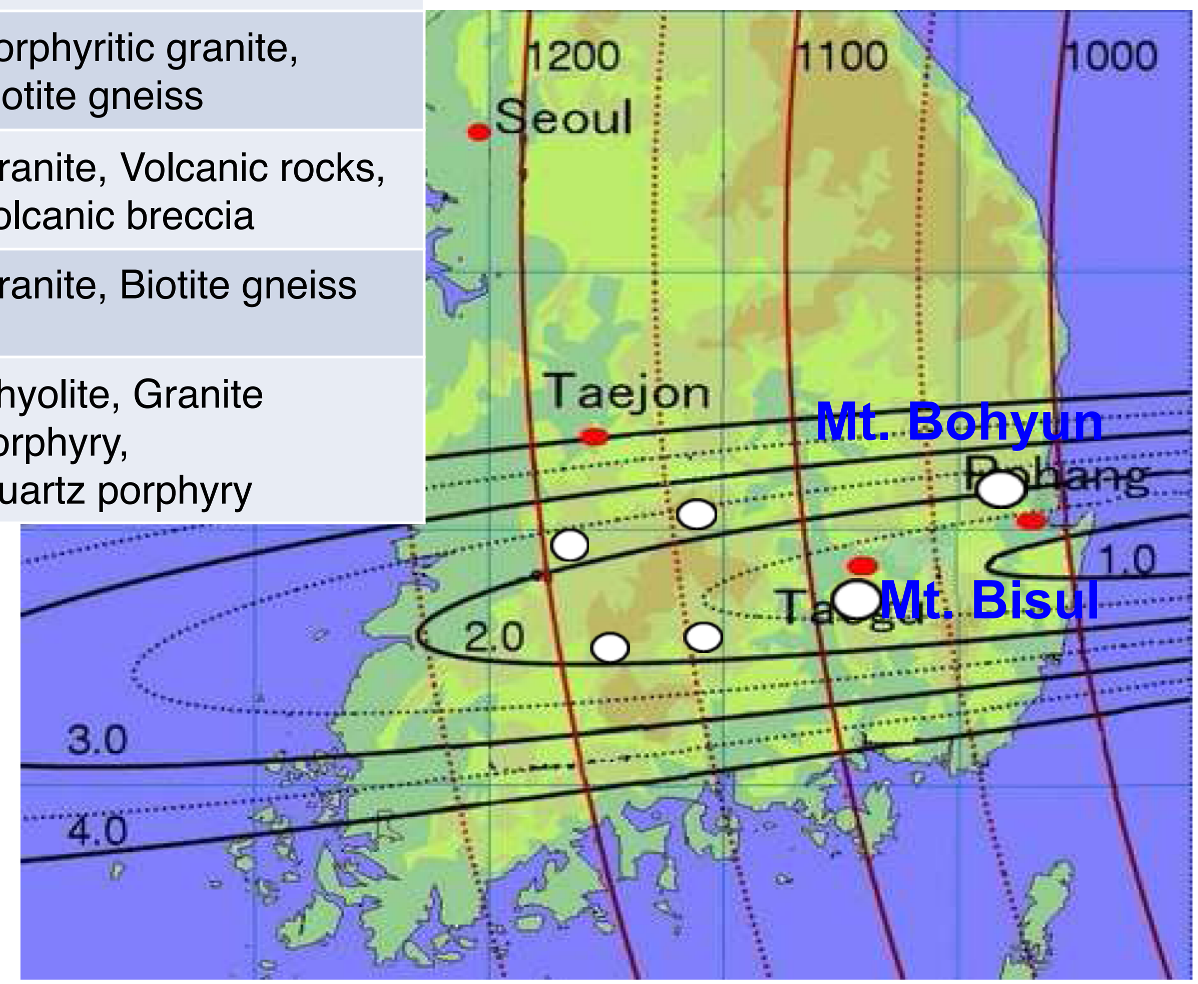
K. Abe,[57,59] Ke. Abe,[24] H. Aihara,[59,60] A. Aimi,[18] R. Akutsu,[58] C. Andreopoulos,[28,43] I. Anghel,[21] L.H.V. Anthony,[28] M. Antonova,[20] Y. Ashida,[25] M. Barbi,[44] G.J. Barker,[66] G. Barr,[40] P. Beltrame,[11] V. Berardi,[16] M. Bergevin,[3] S. Berkman,[2] T. Berry,[45] S. Bhadra,[73] F.d.M. Blaszczyk,[1] A. Blondel,[12] S. Bolognesi,[6] S.B. Boyd,[66] A. Bravar,[12]

arXiv:1611.06118

Candidate Sites in Korea

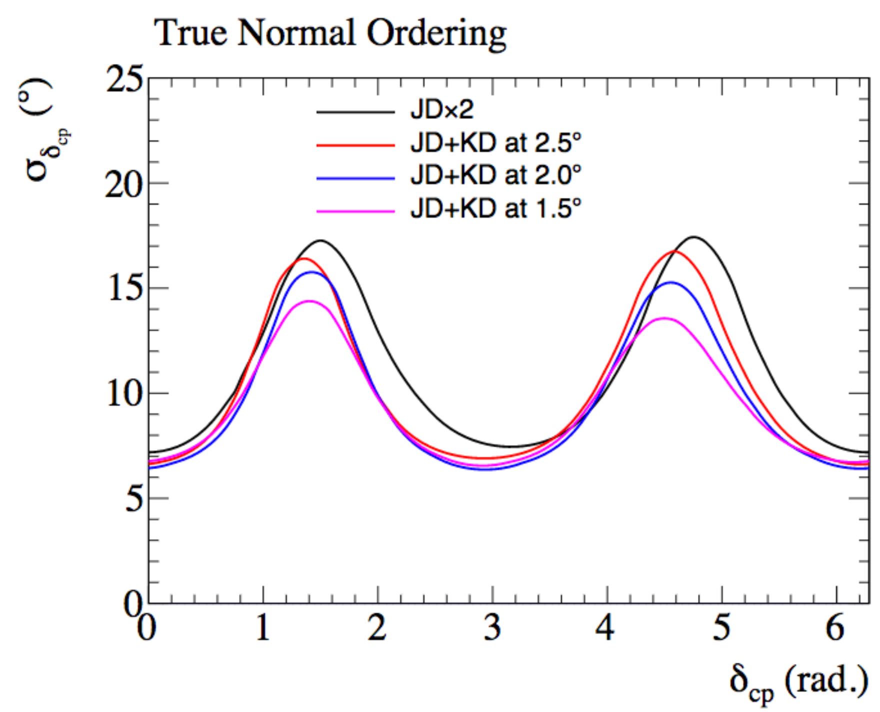
Site	OAB	Baseline	Height	Rock
Mt. Bisul	~1.3°	1088 km	1084 m	Granite porphyry, Andesitic breccia
Mt. Hwangmae	~1.8°	1140 km	1113 m	Flake granite, Porphyritic gneiss
Mt. Sambong	~1.9°	1180 km	1186 m	Porphyritic granite, Biotite gneiss
Mt. Bohyun	~2.2°	1040 km	1126 m	Granite, Volcanic rocks, Volcanic breccia
Mt. Minjuii	~2.2°	1140 km	1242 m	Granite, Biotite gneiss
Mt. Unjang	~2.2°	1190 km	1125 m	Rhyolite, Granite porphyry, Quartz porphyry

arXiv:1611.06118



- Baselines length 1,000 ~ 1,200 km
- Off axis angle 1.3° ~ 3°
- Considering tunnel entrance positions overburdens are expected to be greater than 820 m (2,200 m.w.e.)

Tokai-to-Hyper-K & Korea (T2HKK)



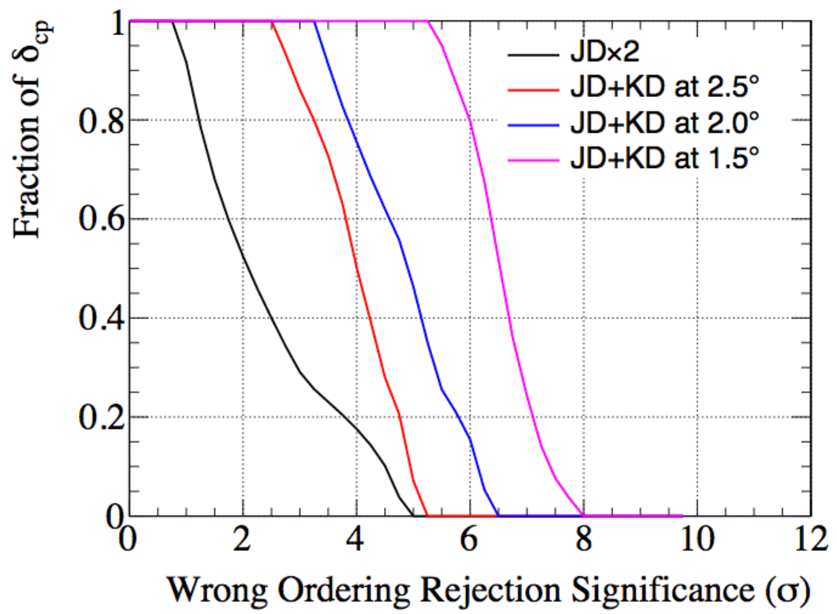
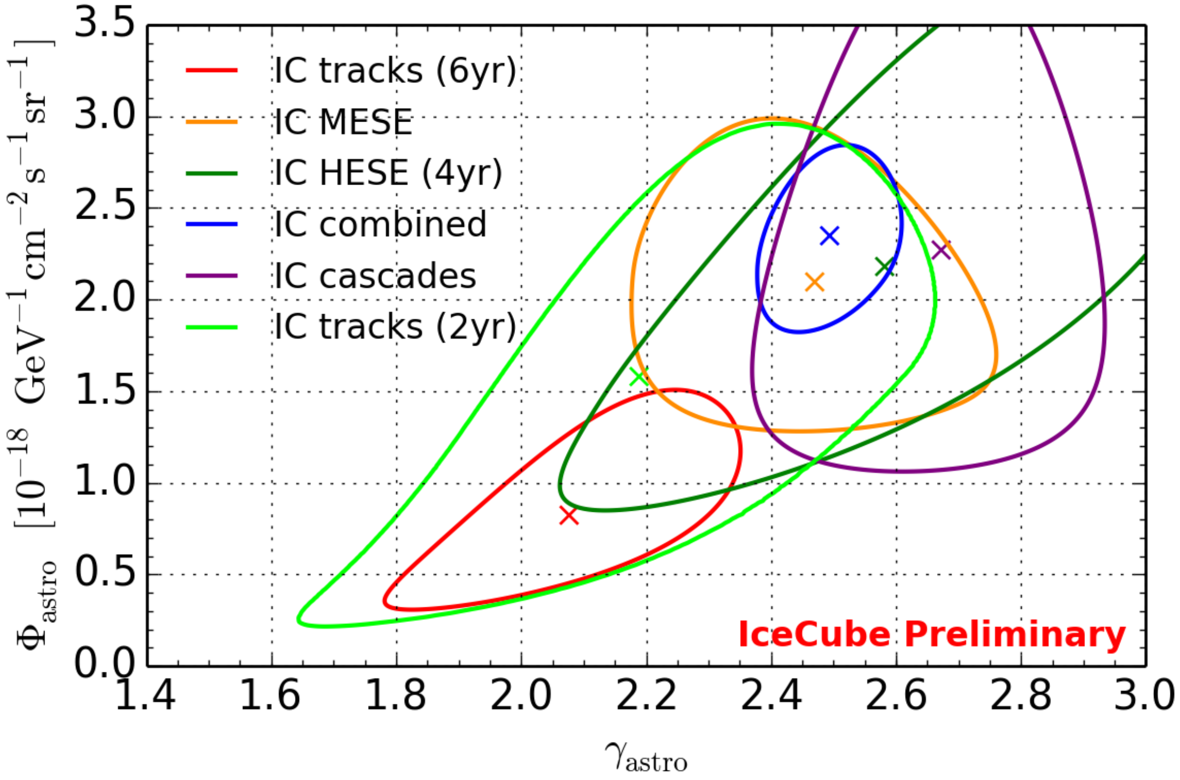


FIG. 19: The fraction of δ_{cp} values (averaging over the true mass ordering) for which the wrong hierarchy can be rejected with a given significance or greater.

- Improved CP Precision, Mass hierarchy, …
- Better control of systematics
- Potential site benefits (larger over burden)
- Non-standard neutrino interactions

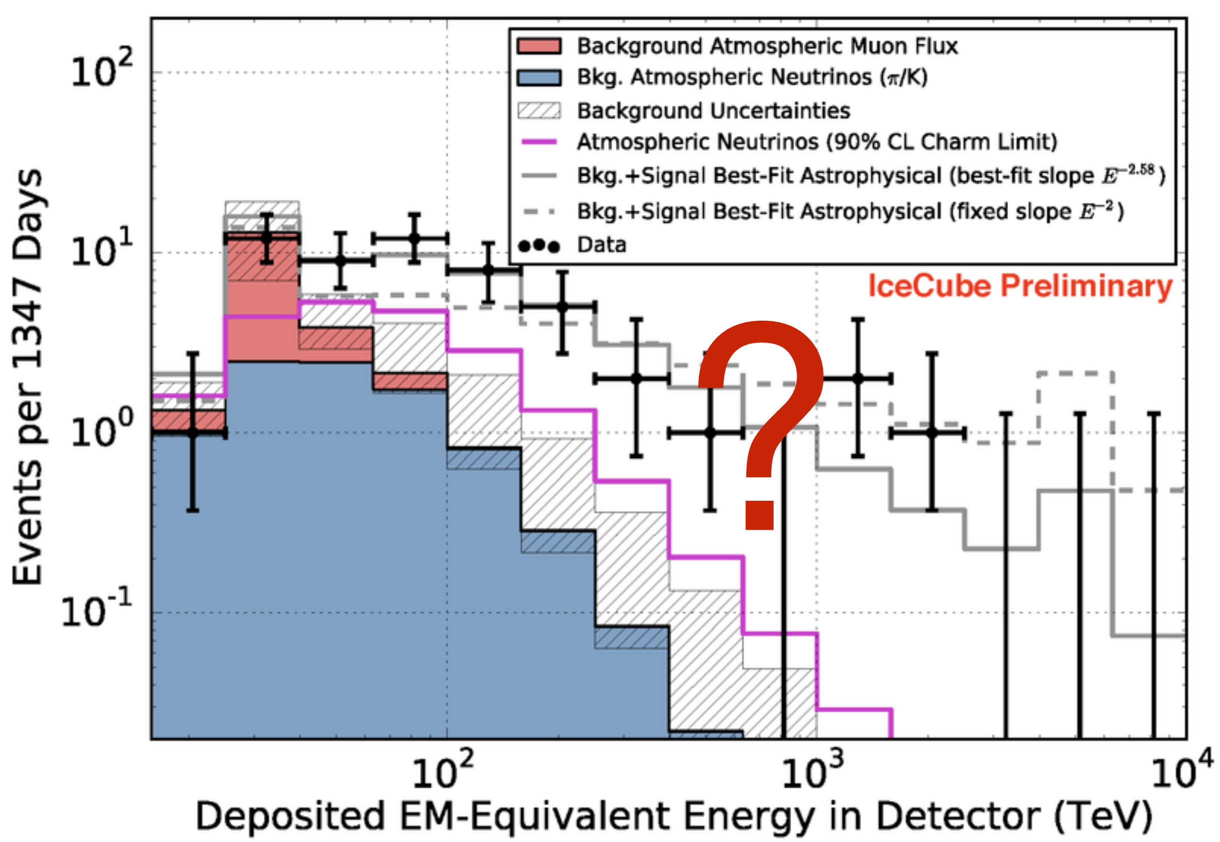
Future Plans

Beyond Standard Model Physics at the PeV scale



Intense interest in high-energy neutrino region

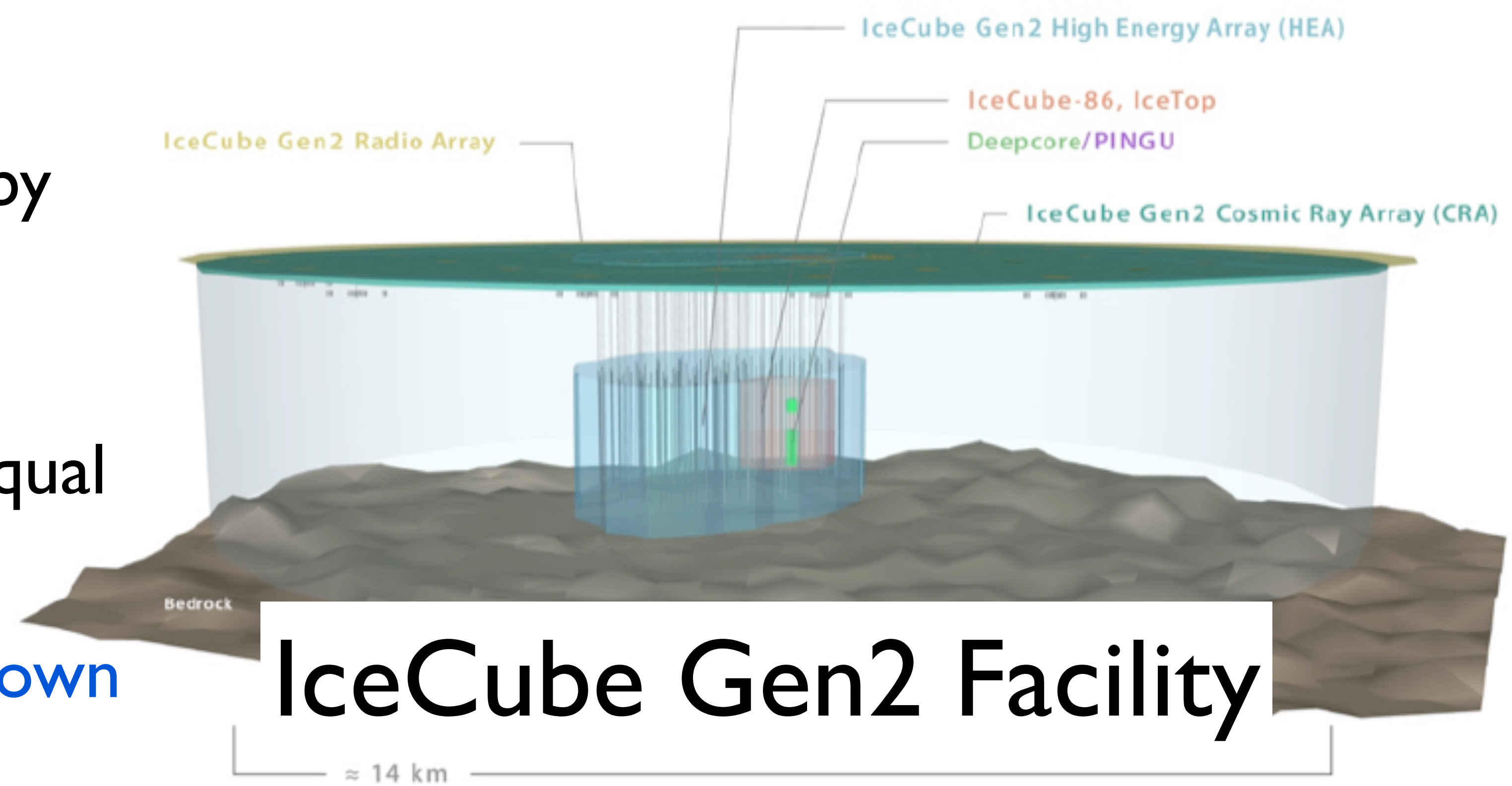
- Observations defy any simple explanation from a single generic source class
  - Multiple sources classes ?
  - Hints of new physics ?

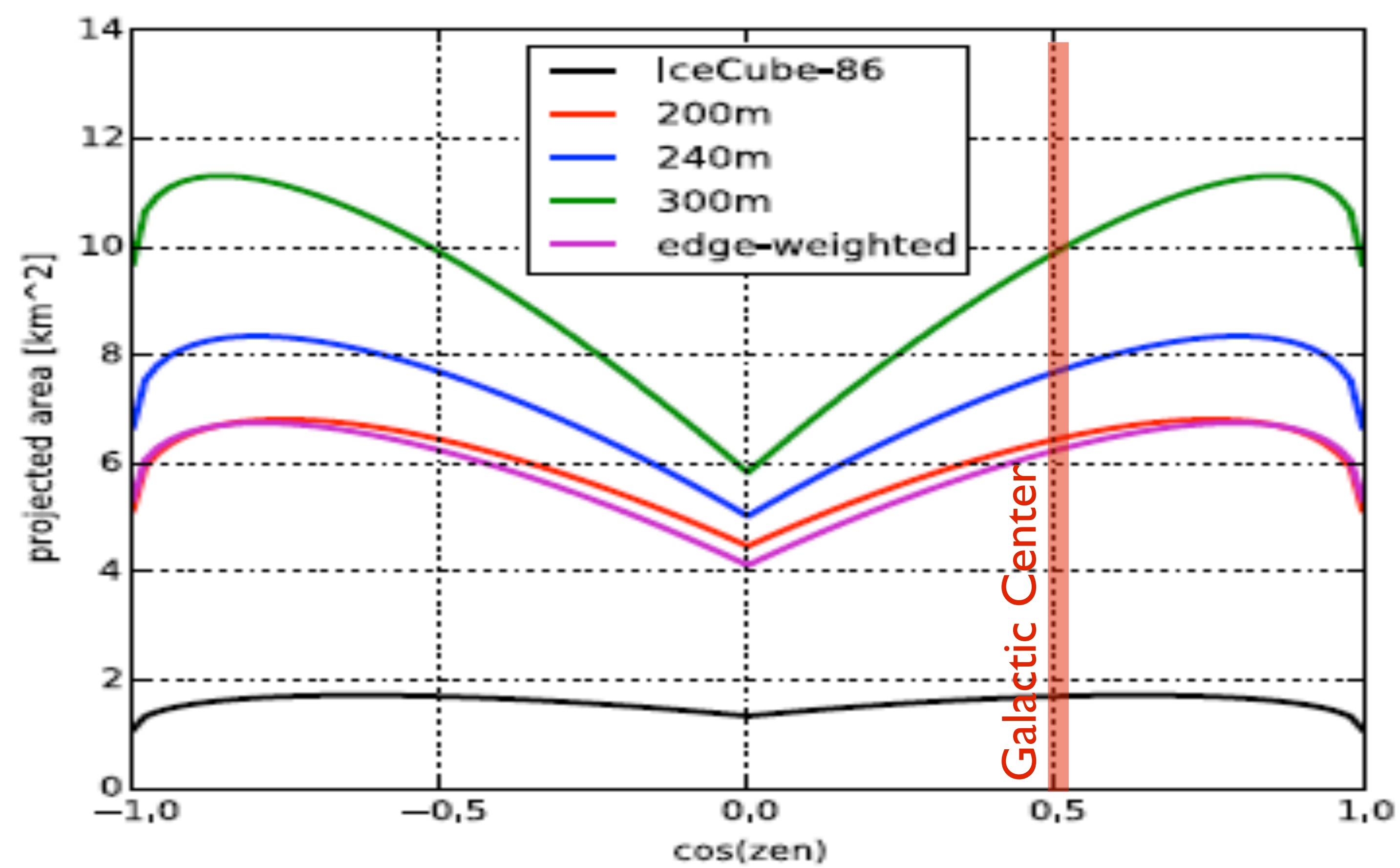


- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy right-handed neutrino dark matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and many-body decays
- Shadow dark matter
- Boosted Dark Matter
- …

Next generation - IceCube Gen2 Facility

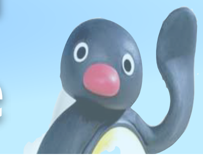
- IceCube has provided an amazing sample of events, but is still limited by the small number of events
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
    - So far non of the analyses has shown any evidence for point sources
- Where are the point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





PINGU - Precision IceCube Next Generation Upgrade

IceCube PINGU Collaboration arXiv:1401.2046



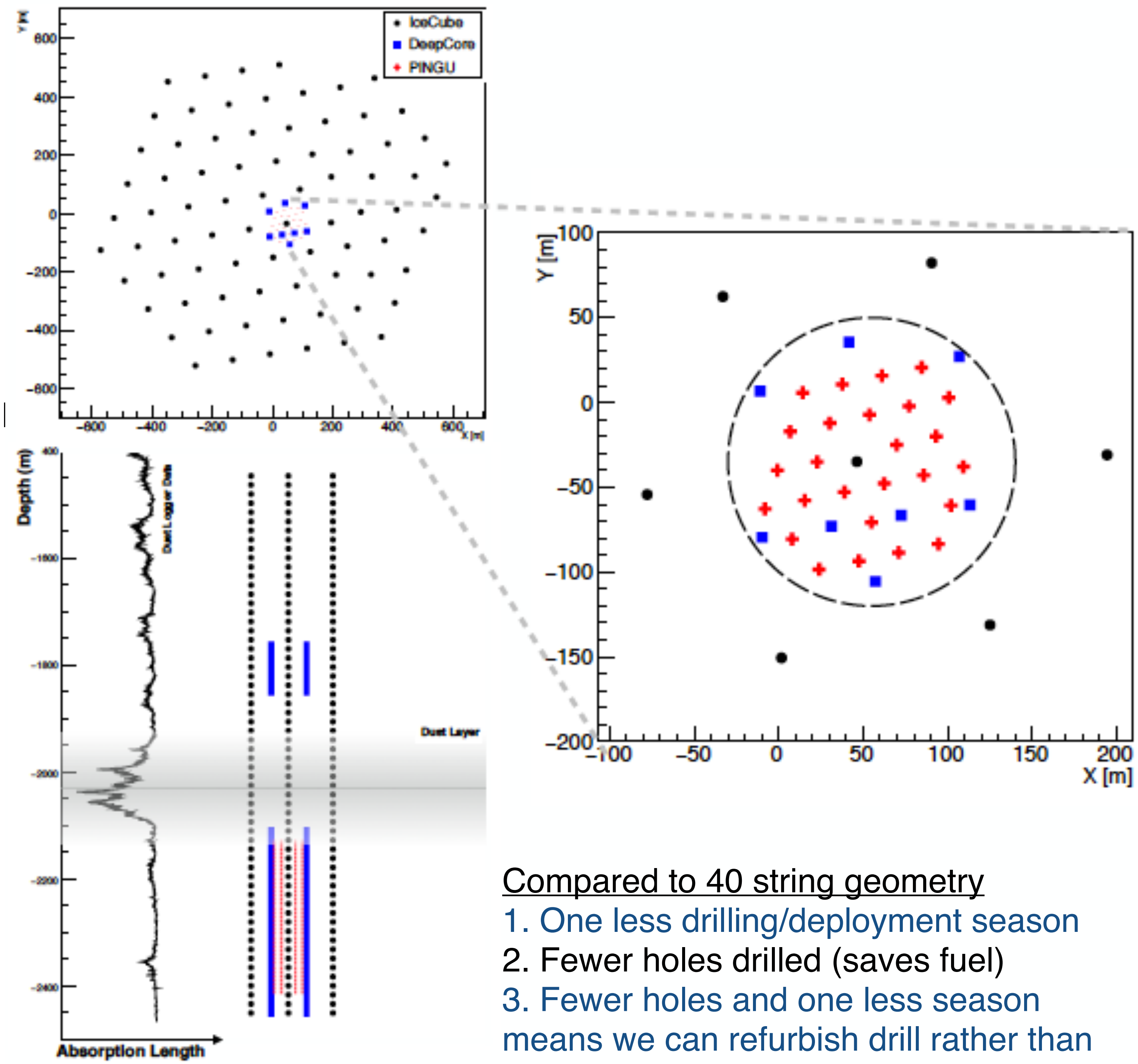
© [2011] The Pygos Group

- PINGU upgrade plan
  - Instrument a volume of about 5MT with 20-26 strings
  - 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

PINGU LOI to be updated shortly

Short version https://arxiv.org/pdf/1607.02671.pdf

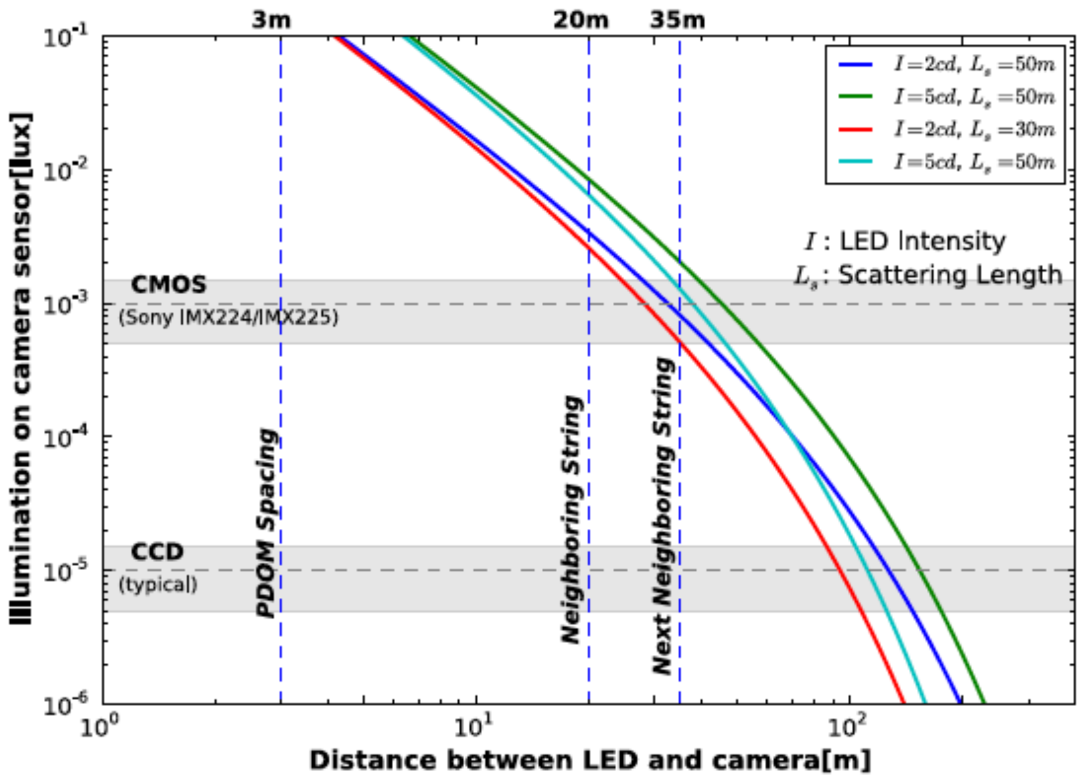
New PINGU Geometry

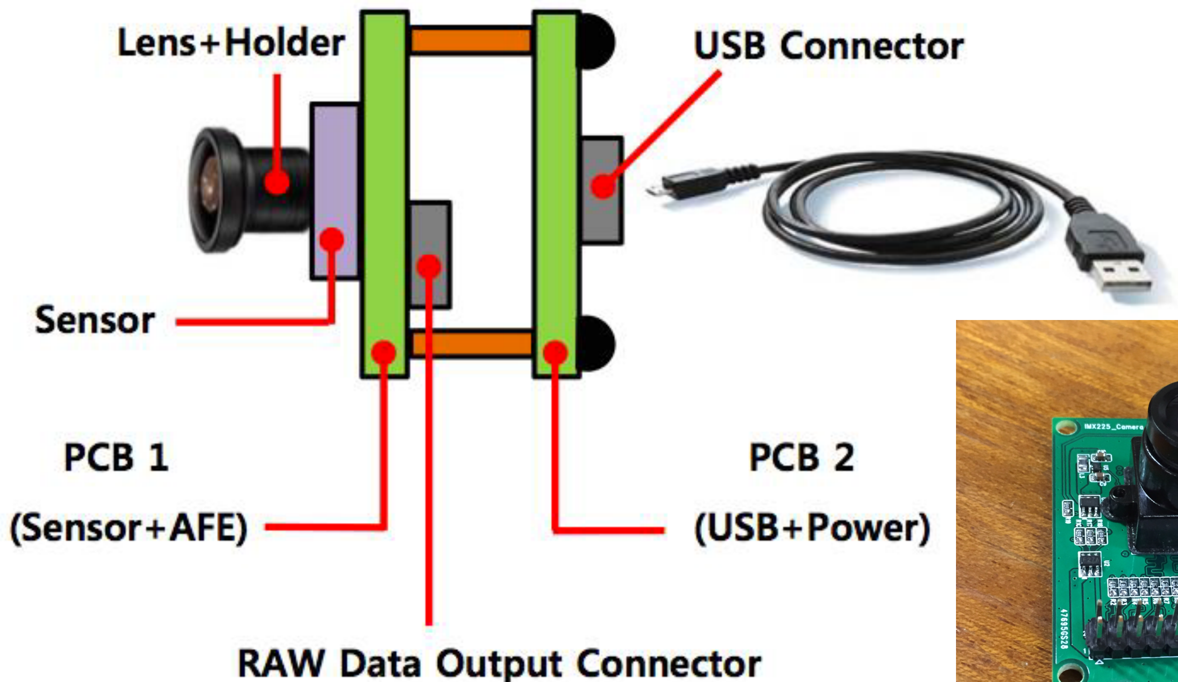


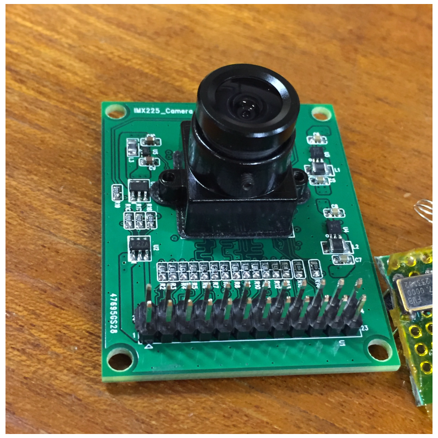
Compared to 40 string geometry

1. One less drilling/deployment season
2. Fewer holes drilled (saves fuel)
3. Fewer holes and one less season means we can refurbish drill rather than build a new one.

Ice Camera System





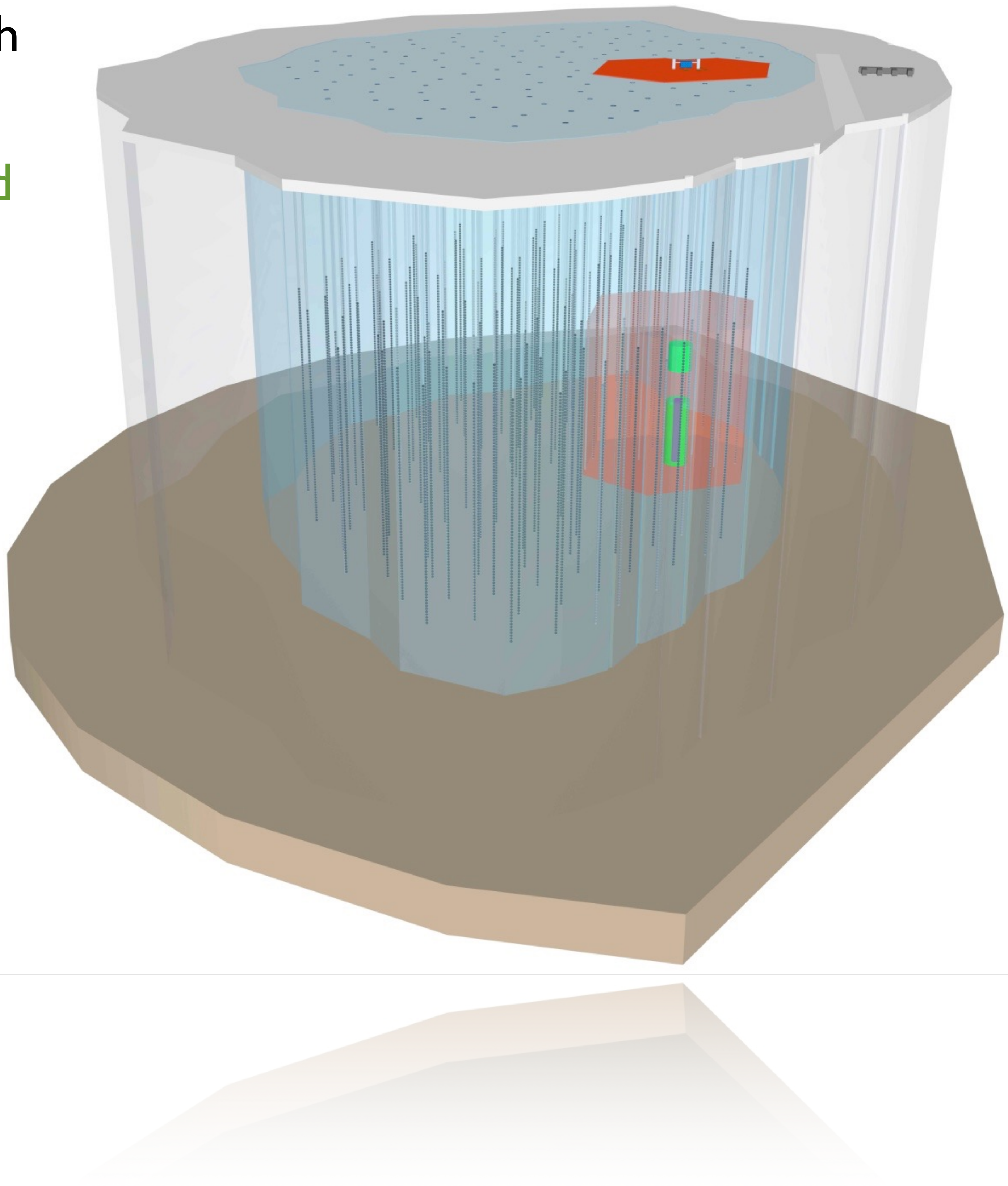


- Ice properties dominant source of sys. uncertainties for most analyses
- Low cost camera system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability

"Camera System to Study Properties of the Antarctic Ice"
D. Bose, M. Jeong, W. Kang, J. Kim, M. Kim, C. Rott.
ICRC Proceeding 2015 arXiv:1510.05228 [astro-ph.IM]

Conclusions

- Striking DM signatures might provide high discovery potential for indirect searches
- Models motivated by positron excess and gamma-ray observations can and have been tested with neutrino telescopes
- Lifetimes of heavy decaying dark matter can be constrained to 10^28s using neutrino signals
- Neutrino Telescopes provide world best limits on SD WIMP-Proton scattering cross section
- Neutrinos extremely sensitive to test low-mass WIMP scenarios at current and future detectors
- Efforts underway to expand searches beyond WIMP hypothesis …



Thanks !

Dark Matter Signal Expectation (Decay)

- Two components are expected: Galactic and Extra-galactic

	Galactic (G)	Extra-Galactic (EG)
Energy spectrum	Source spectrum	Redshifted
Angular distribution	Follows halo profile (line of sight integral)	Isotropic

$$\left.\frac{\mathrm{d}\phi_\beta^{\mathrm{G}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{dec.}} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\beta}{\mathrm{d}E_\nu} \int_0^\infty ds\, \rho_h \left[r\left(s,\ell,b\right)\right] ,$$

$$\left.\frac{\mathrm{d}\phi_\beta^{\mathrm{EG}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{dec.}} = \frac{\Omega_{\mathrm{DM}}\rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty dz\, \frac{1}{H\left(z\right)} \left.\frac{\mathrm{d}N_\beta}{\mathrm{d}E_\nu}\right|_{E'=E(1+z)}$$

Hubble expansion rate $H\left(z\right) = H_0 \sqrt{\Omega_\Lambda + \Omega_m \left(1+z\right)^3}$

see for example Chianese et al. (2016)

Dark Matter Signal Expectation (Annihilation)

- Two components are expected: Galactic and Extra-galactic

	Galactic (G)	Extra-Galactic (EG)
Energy spectrum	Source spectrum	Redshifted
Angular distribution	Follows halo profile (line of sight integral)	Isotropic

$$\left.\frac{\mathrm{d}J_\beta^{\mathrm{G}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{ann.}} = \frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi\, m_{\mathrm{DM}}^2}\frac{\mathrm{d}N_\beta}{\mathrm{d}E_\nu}\int_0^\infty ds\, \rho_h^2\left[r\left(s,\ell,b\right)\right]\,,$$

$$\left.\frac{\mathrm{d}J_\beta^{\mathrm{EG}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{ann.}} = \frac{1}{2}\frac{\langle\sigma v\rangle\,\left(\Omega_{\mathrm{DM}}\rho_c\right)^2}{4\pi\, m_{\mathrm{DM}}^2}\int_0^\infty dz\,\frac{B\left(z\right)\,\left(1+z\right)^3}{H\left(z\right)}\left.\frac{\mathrm{d}N_\beta}{\mathrm{d}E_\nu}\right|_{E'=E(1+z)}$$

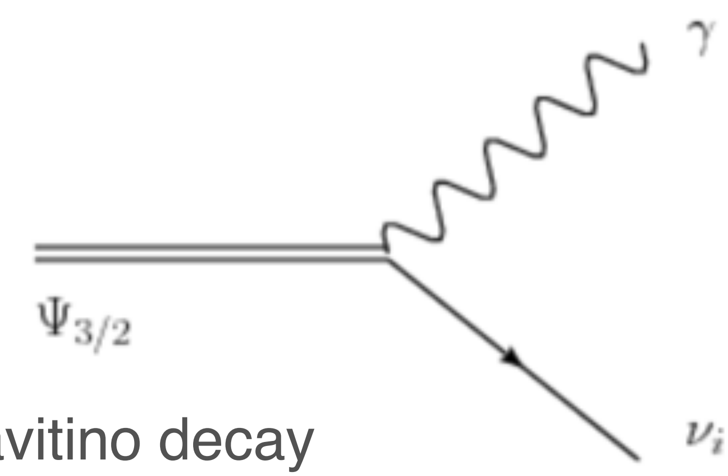
Hubble expansion rate $H\left(z\right) = H_0\sqrt{\Omega_\Lambda + \Omega_m\left(1+z\right)^3}$

see for example Chianese et al. (2016)

Sharp features

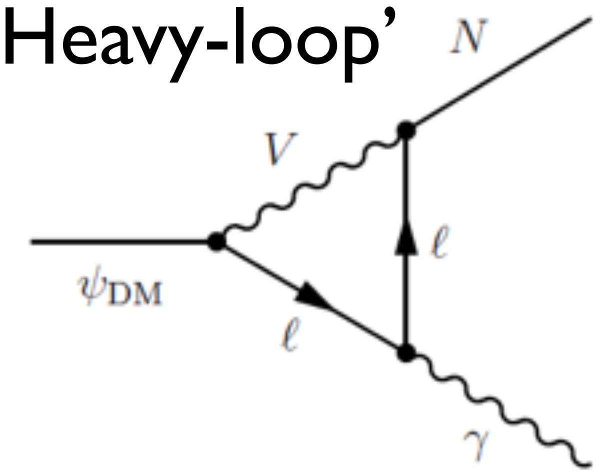
- Are sharp features theoretically motivated ?

Examples:

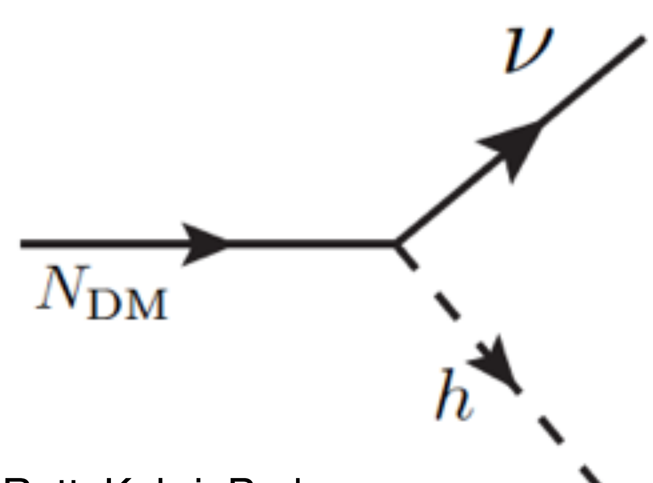


Gravitino decay

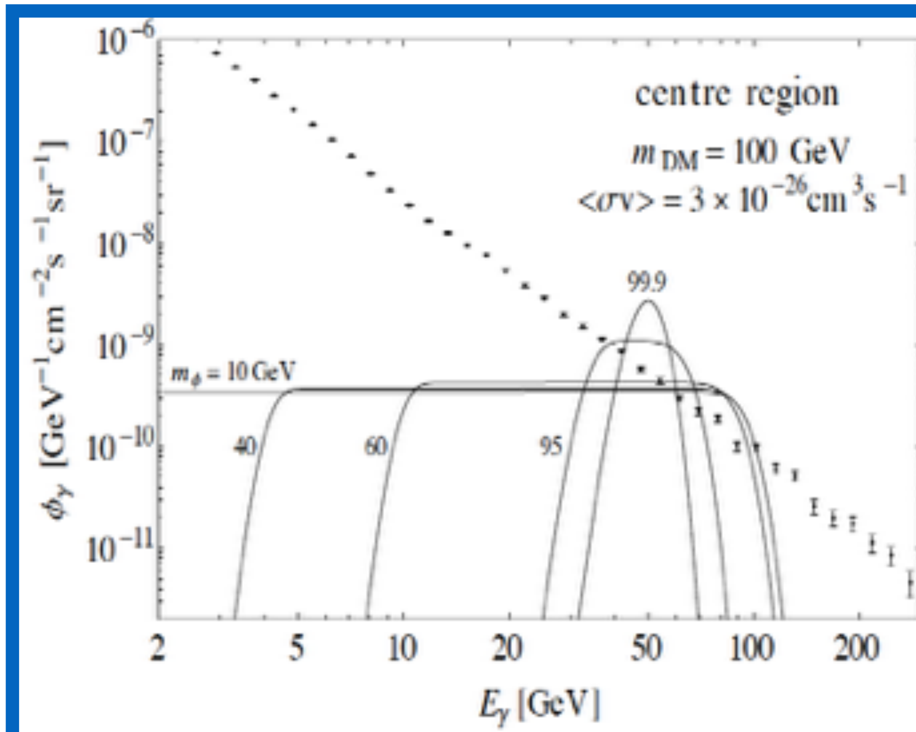
'Heavy-loop'



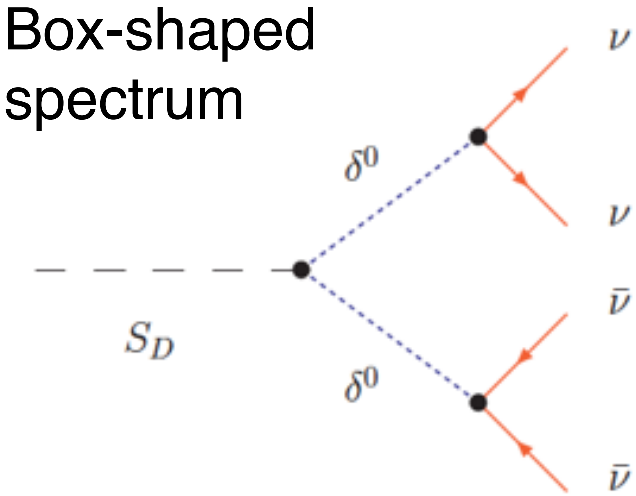
Garny, Ibarra, Tran, Weniger
JCAP 1101:032 (2011) [1011.3786]



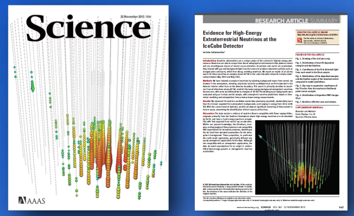
Rott, Kohri, Park
PRD 92, 023529 (2015)[1408.4575]



Box-shaped spectrum



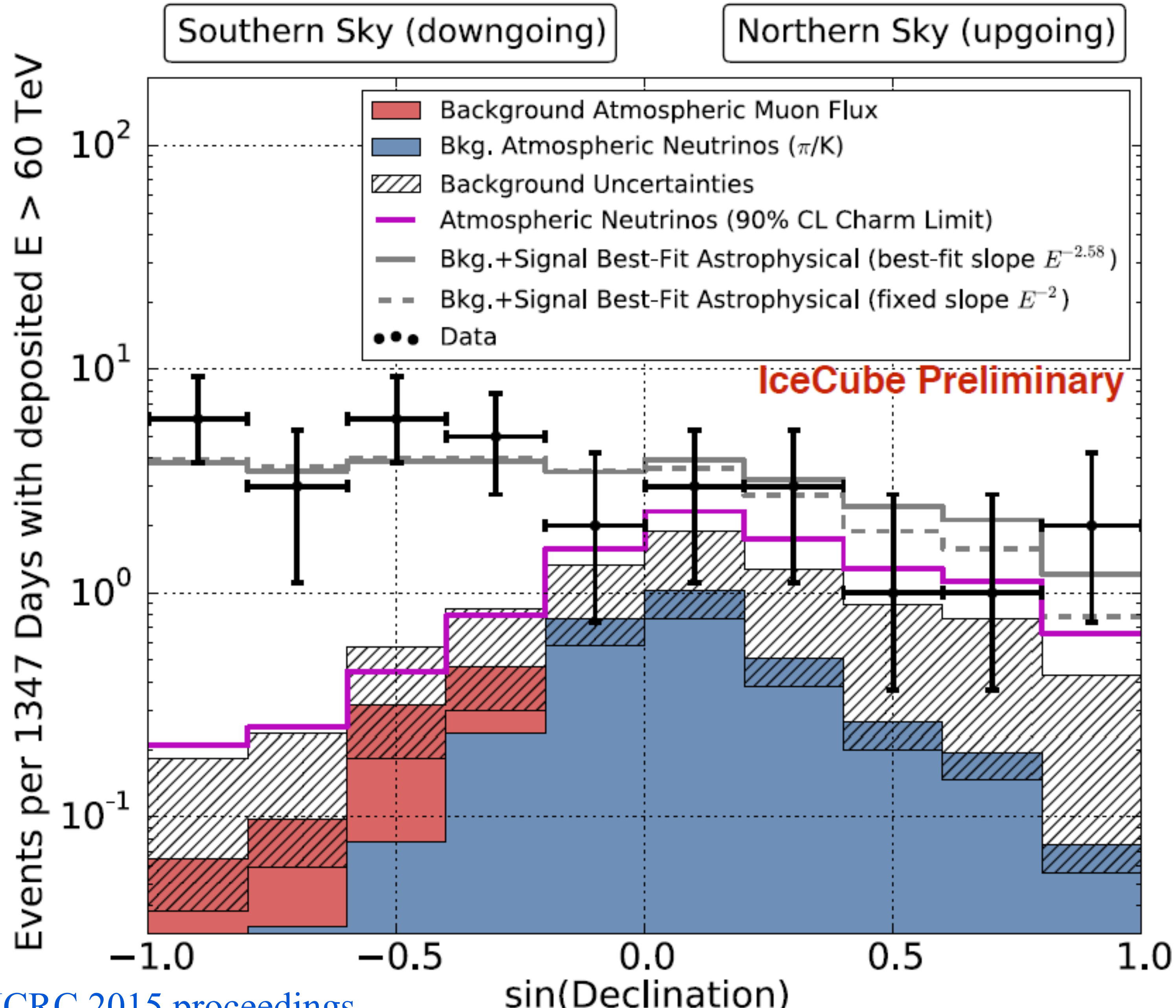
Guo, Wu Zhou,
PRD 81, 075014 (2010)



High-energy neutrino search 4yrs

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

Expectation from conventional atm. muons and neutrinos ~21.6



ICRC 2015 proceedings

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

IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

- 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 (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