The Search for Dark Matter with Neutrinos

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TD Lee Institute Seminar

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Outline

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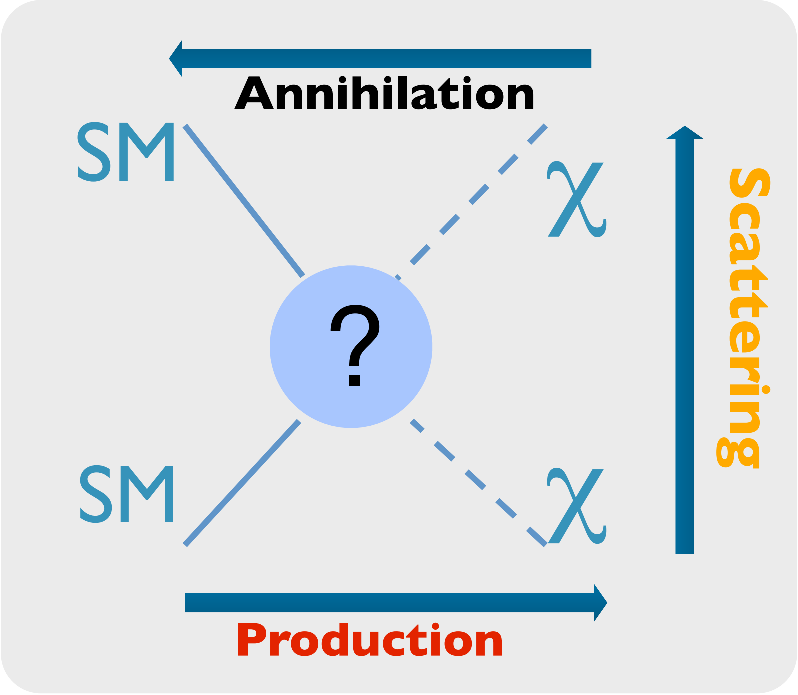
- Motivation
- Search for self-annihilating or decaying dark matter
- Probing neutrino DM interactions with astrophysical neutrinos
- Dark Matter capture in the Sun
- Solar Atmospheric Neutrino Sensitivity Floor
- Outlook & Conclusions

Motivation

Role of Neutrinos in Dark Matter Searches



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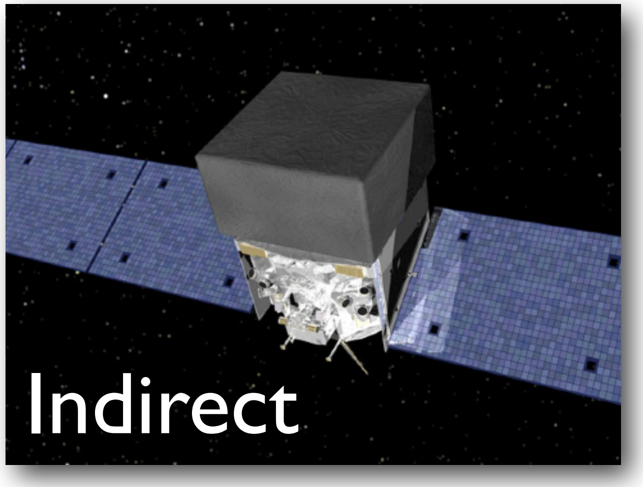

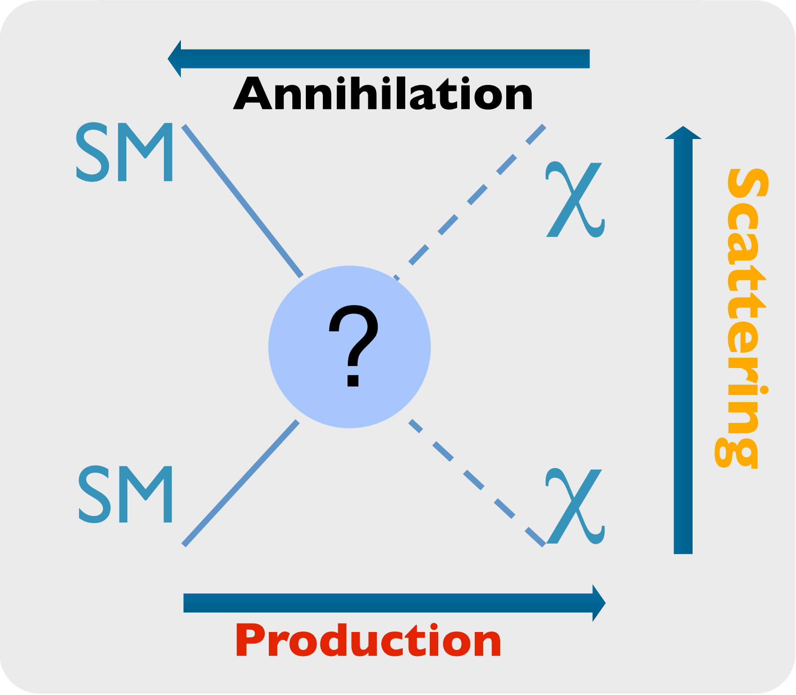

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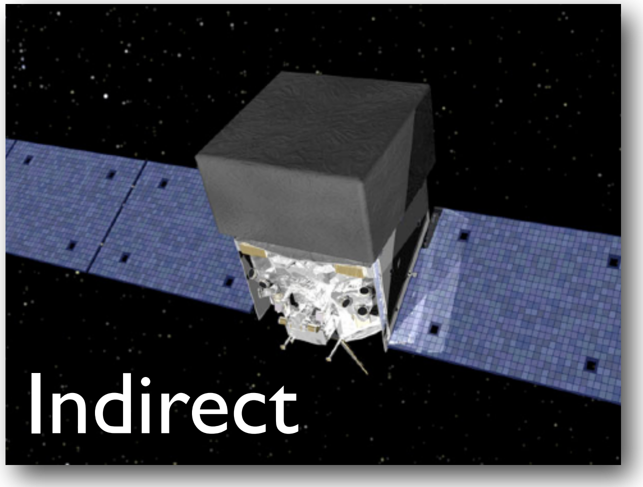

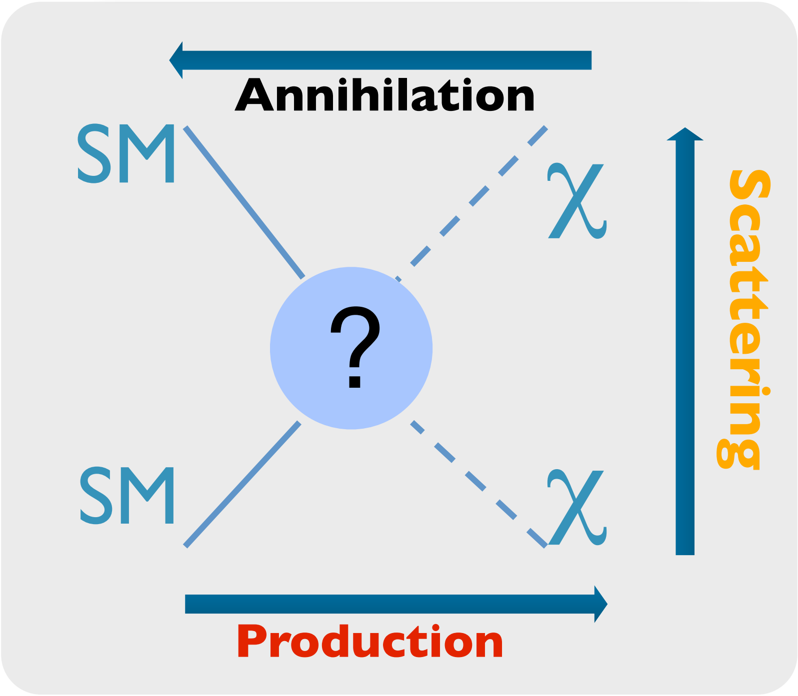

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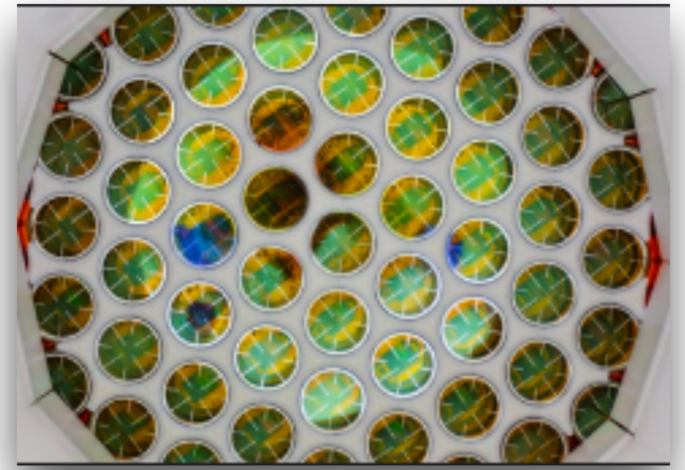

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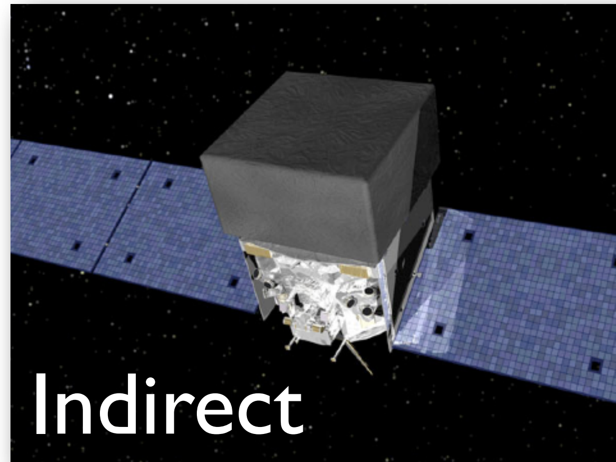

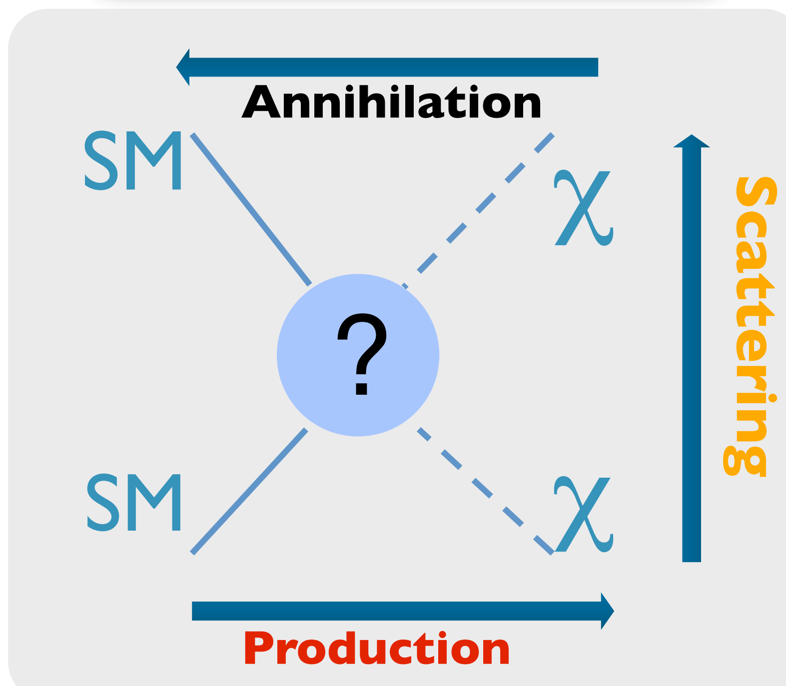

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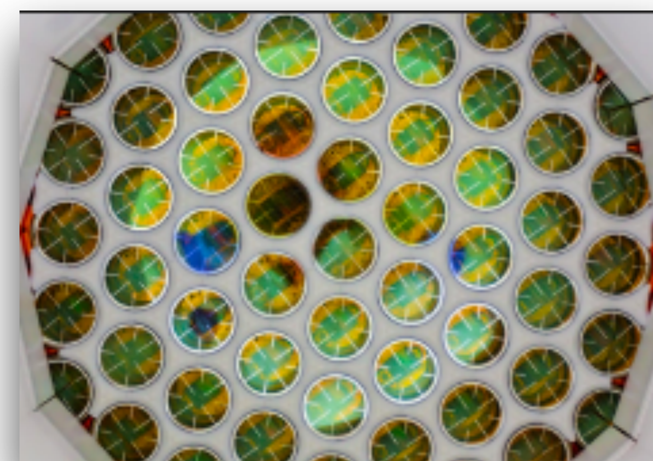

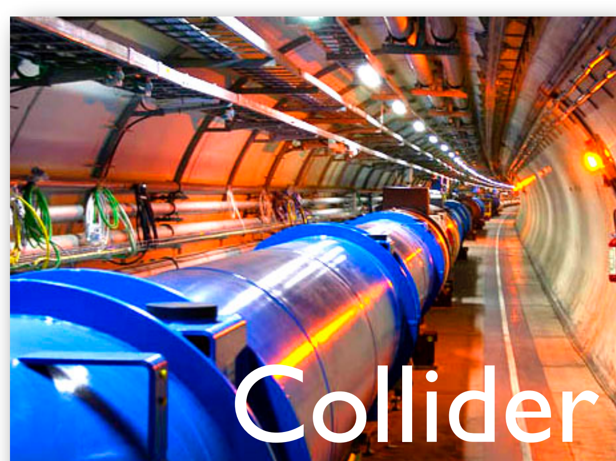

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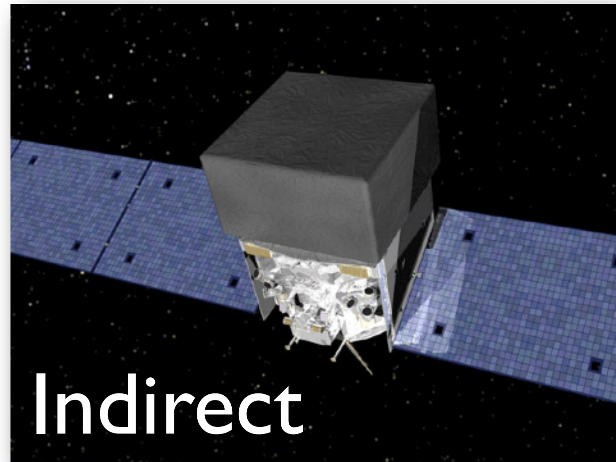
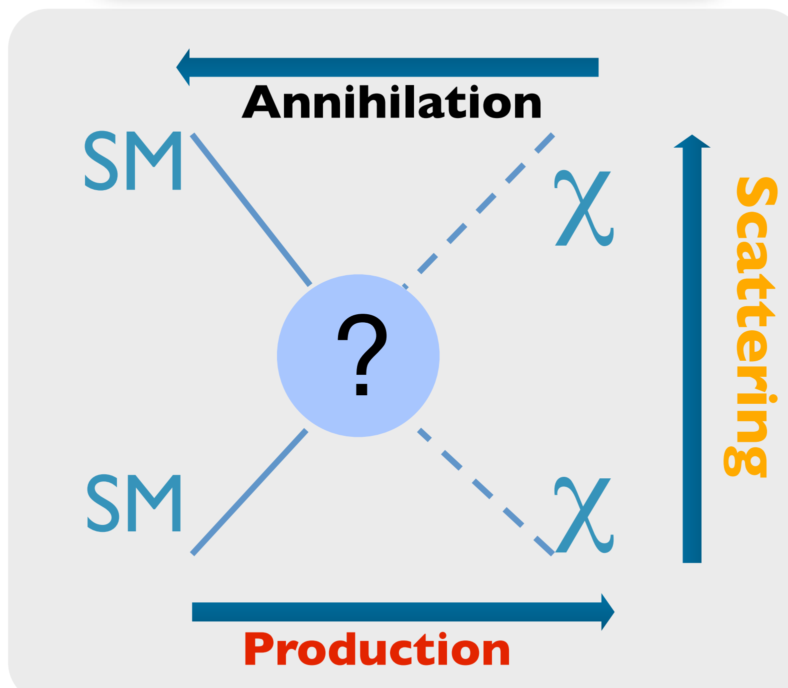


Neutrinos from

…



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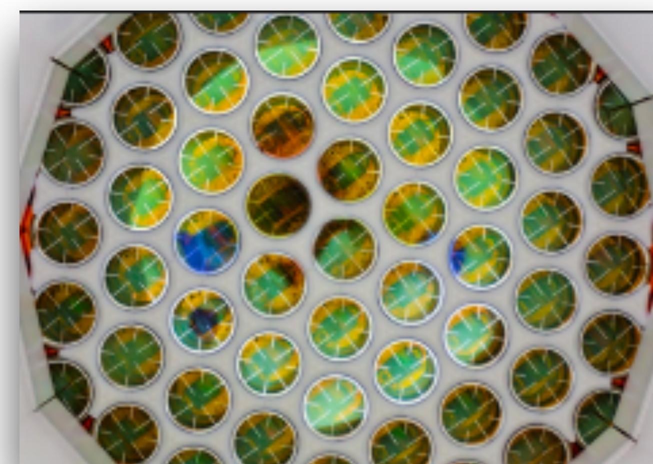

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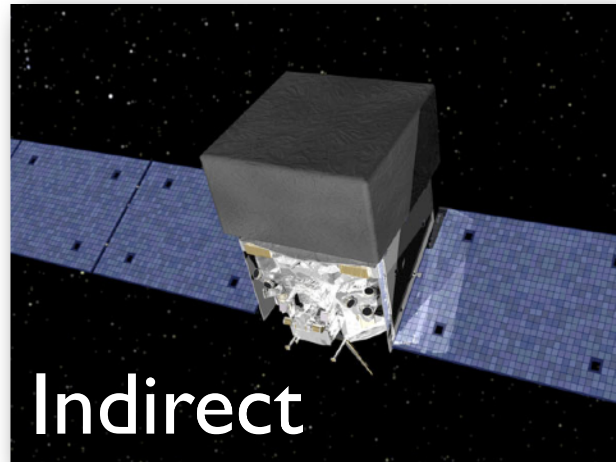

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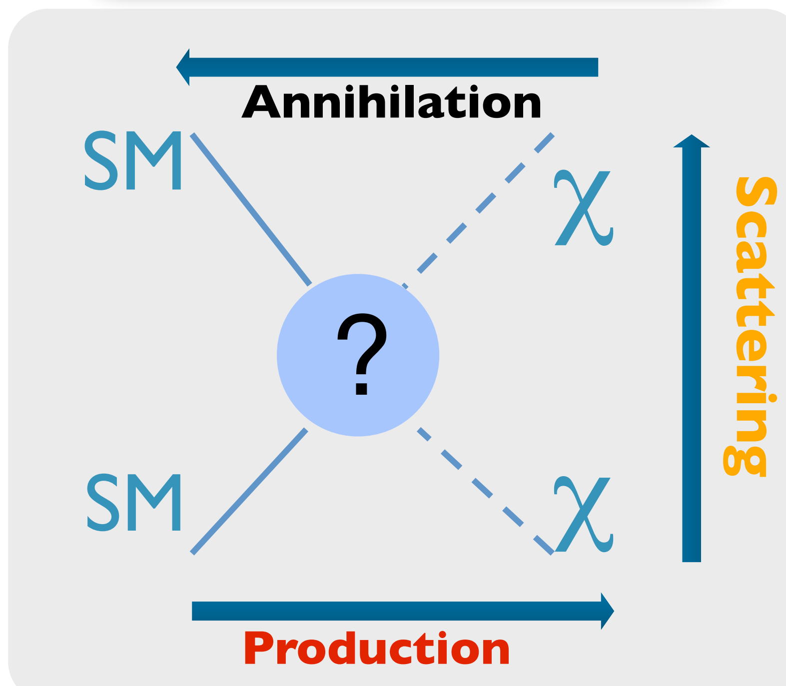

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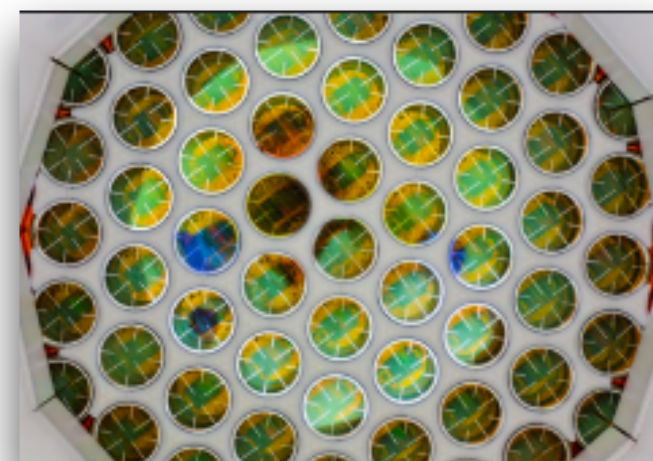

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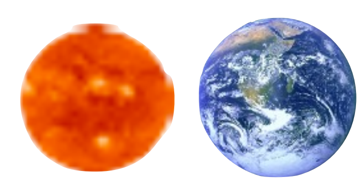

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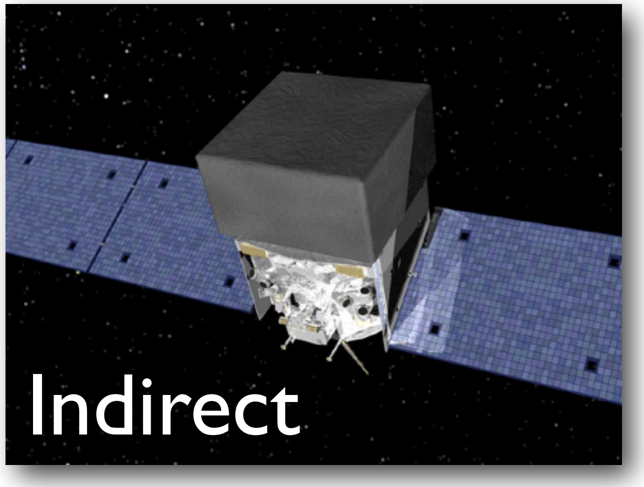

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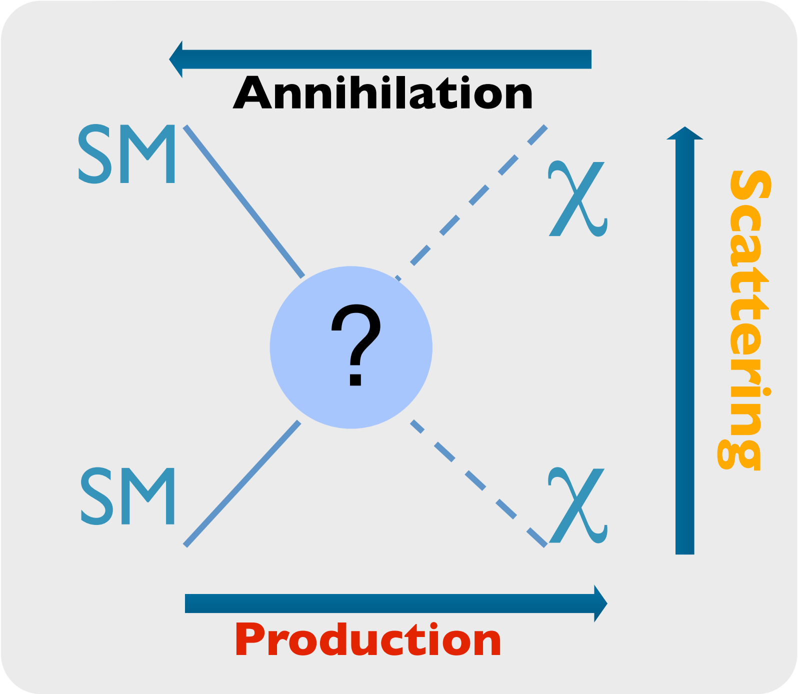

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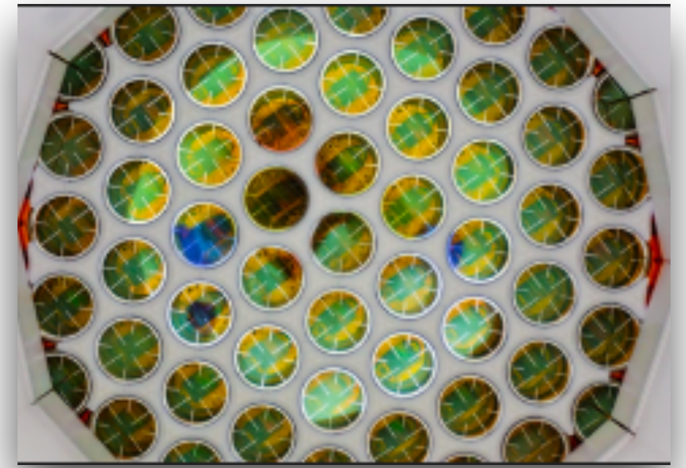

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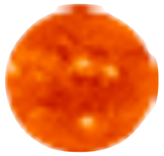
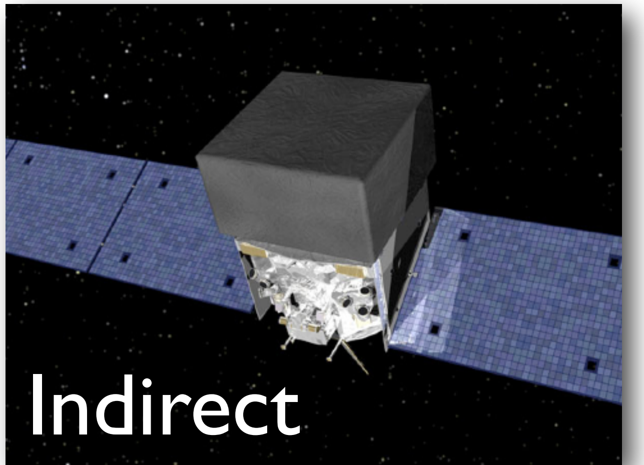


Role of Neutrinos in Dark Matter Searches

The case for Neutrinos



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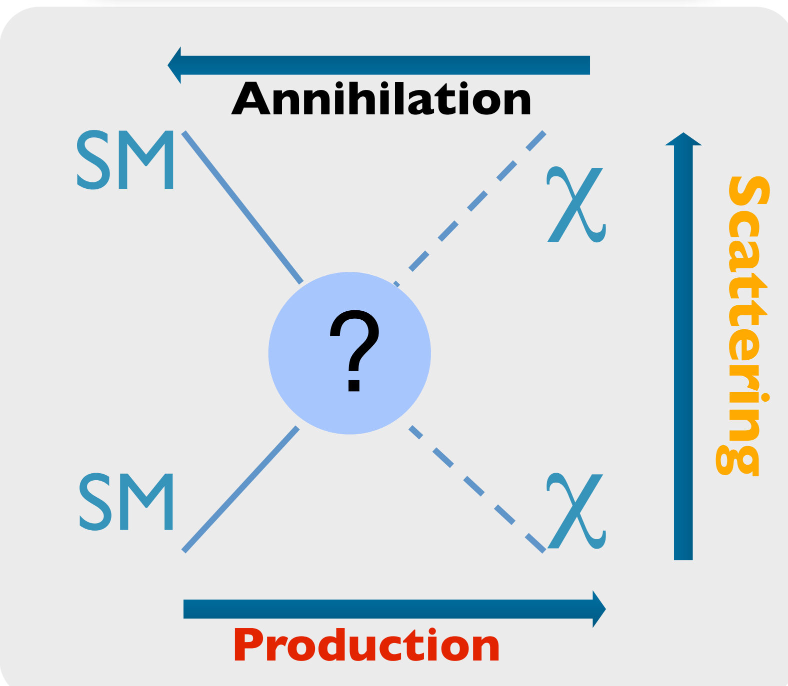

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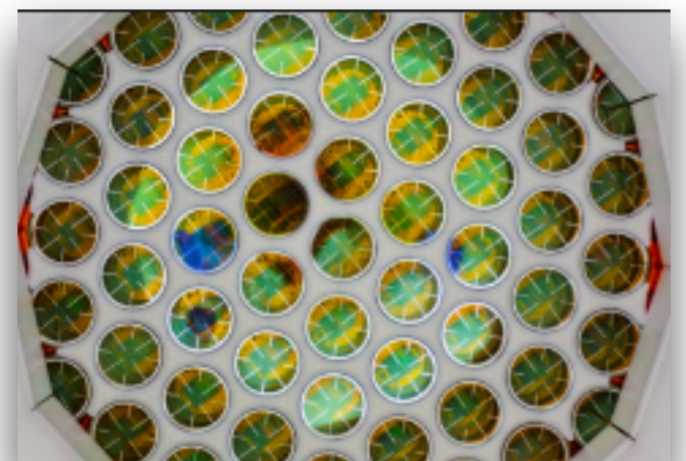

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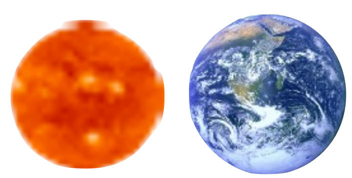

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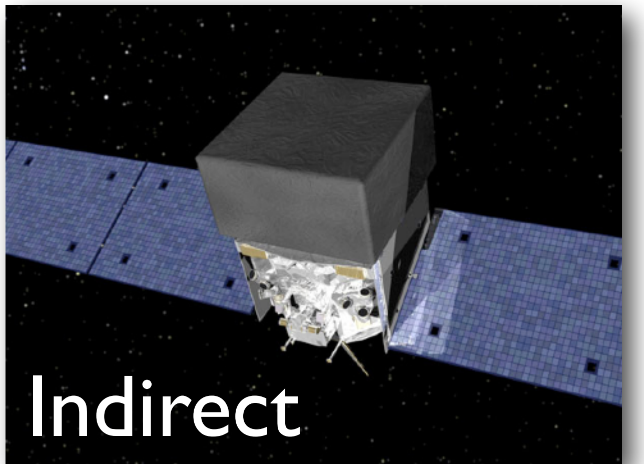

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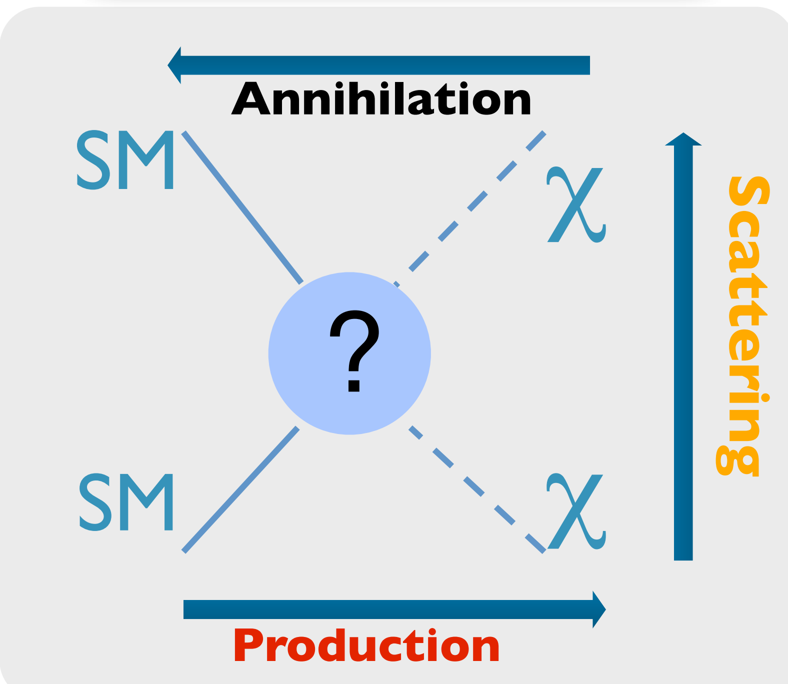

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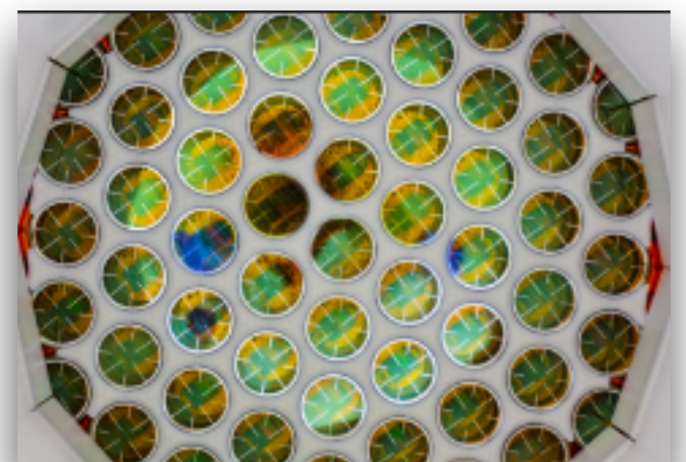

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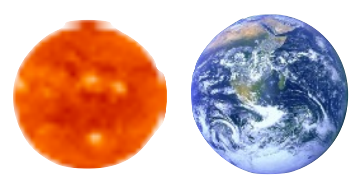
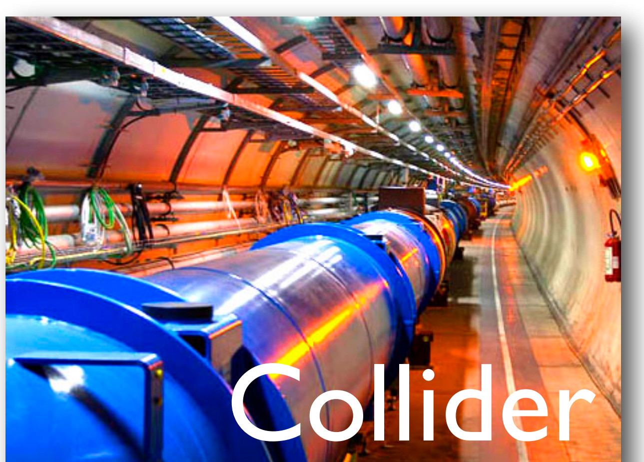


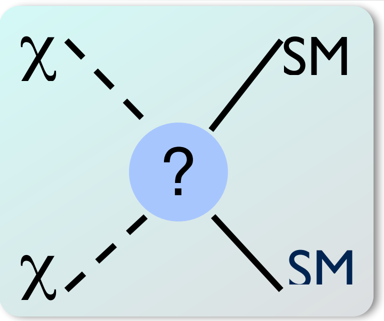


The case for Neutrinos

- Search for signals from the Galaxy, etc.
  - Probe DM self-annihilation cross section or lifetime (for decaying DM)
- Search for signals of dark matter captured in the Sun (and Earth)
  - Probe DM-Nucleon scattering
- Neutrino detectors naturally observe the entire sky (all-sky coverage)
- Neutrino detection efficiency rises with energy, and angular resolution improves

Signatures of Dark Matter in Neutrino Detectors

Channel | **Type of Search** | **Typical Sources** | **Measures**



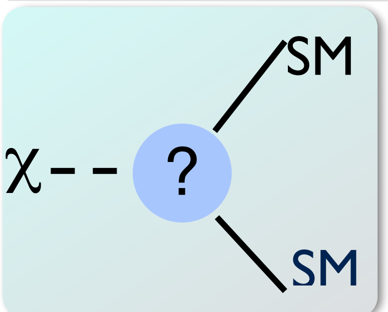
DM Annihilation searches

ν from SM particle decay, direct neutrinos helicity suppressed

- Galactic Center
- Galactic Halo
- Dwarf Spheroidals
- Galaxy clusters
- …

Self-annihilation cross section **<σv>**

DM Mass $\mathbf{m}_\chi$ (Branching fractions)



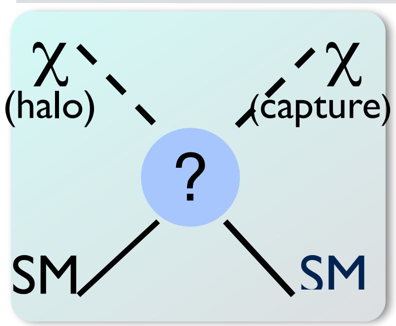
DM Decay searches

ν from SM particle decay or directly produced

- Extragalactic
- Galactic Halo
- Galaxy clusters
- …

DM Lifetime τ_χ

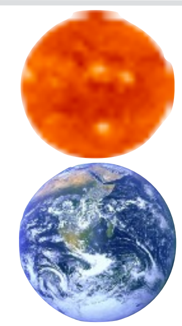
DM Mass $\mathbf{m}_\chi$ (Branching fractions)



DM Nucleon scattering

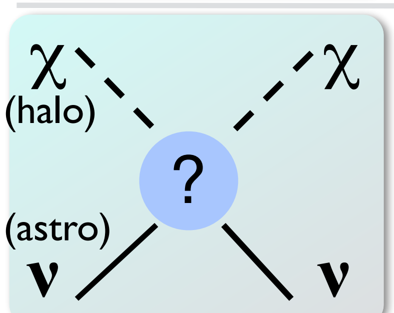
Following χ capture, annihilation. Once annihilation and capture in balance (equilibrium) - no dependence on **<σv>**

- Sun
- Earth



DM-Nucleon scattering cross section σ^{SD} / σ^{SI}

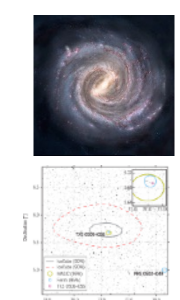
DM Mass $\mathbf{m}_\chi$ (Branching fractions)



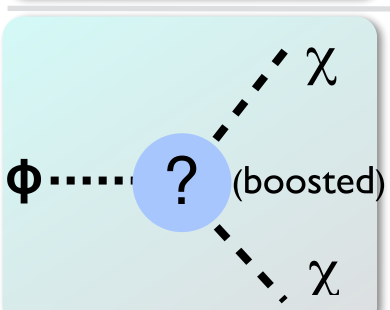
Neutrino DM scattering

Astrophysical ν scatter off χ from Galactic halo - resulting in anisotropy

- Milky Way Halo
- Distant Source



Combination of coupling strength **g** and masses $\mathbf{m}_\phi$ $\mathbf{m}_\chi$



Boosted DM

Highly boosted χ from the decay or annihilation of a heavy DM particle $\mathbf{m}_\phi$ interacts directly in the detector

- Galactic Center
- Sun
- …

DM Lifetime τ_χ

… or self-annihilation cross section **<σv>**

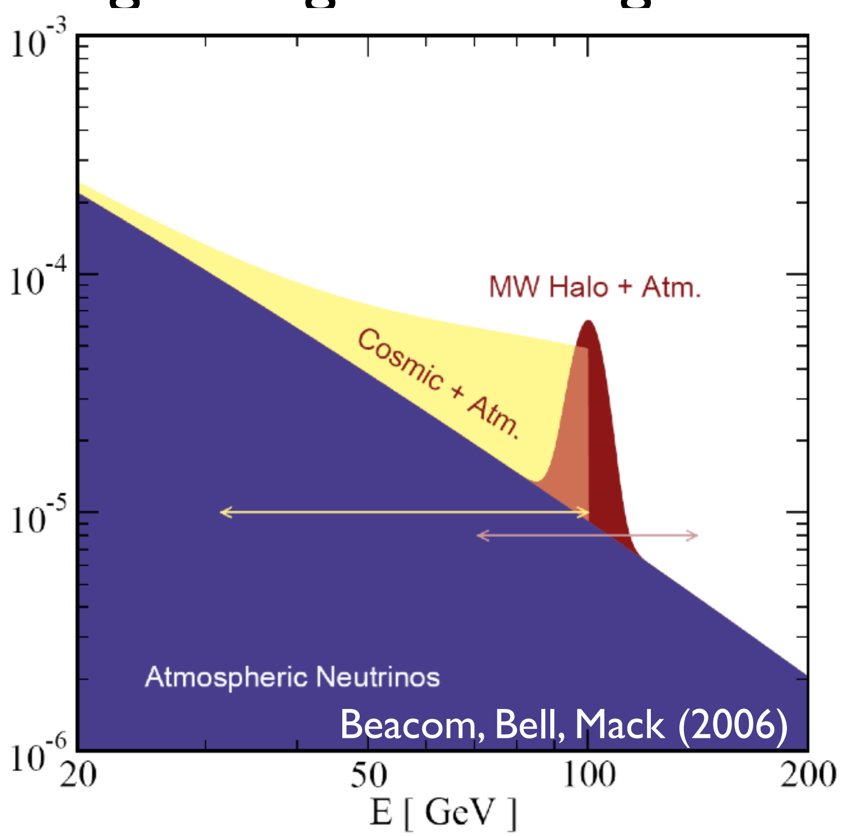
DM mass $\mathbf{m}_\phi$

Dark Matter Signals

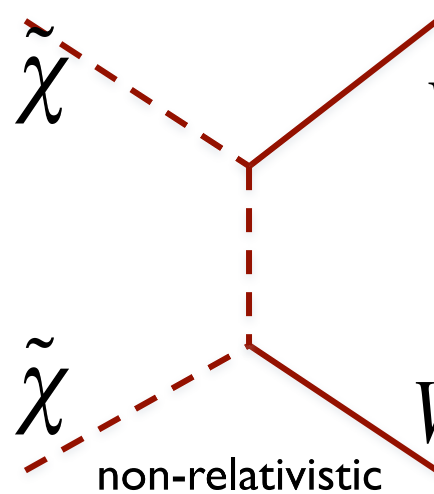
- Identify overdense regions of dark matter

  ⇒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

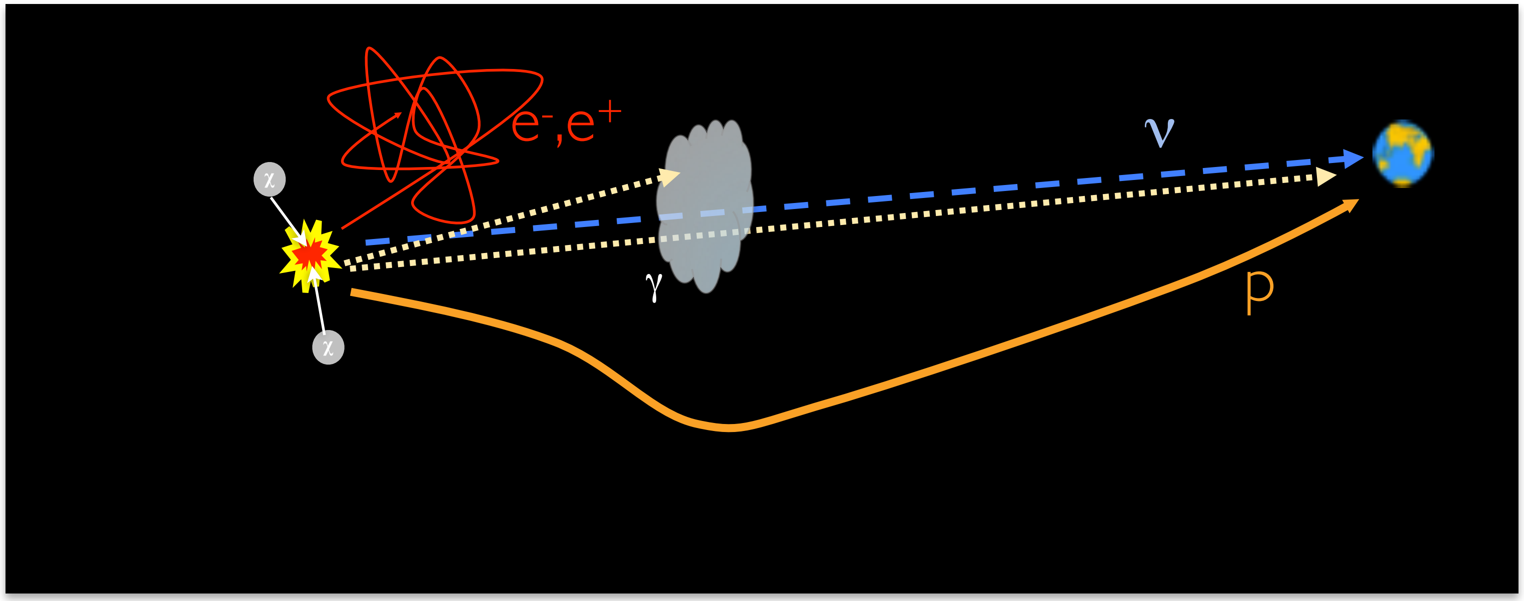


Annihilation Rate ~ρ^2
(Decay Rate ~ρ)



$$W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \upsilon, \gamma, p, D, \ldots$$

$$W^-, Z, \tau^-, \bar{b}, \ldots \Rightarrow e^\mp, \upsilon, \gamma, \bar{p}, D, \ldots$$



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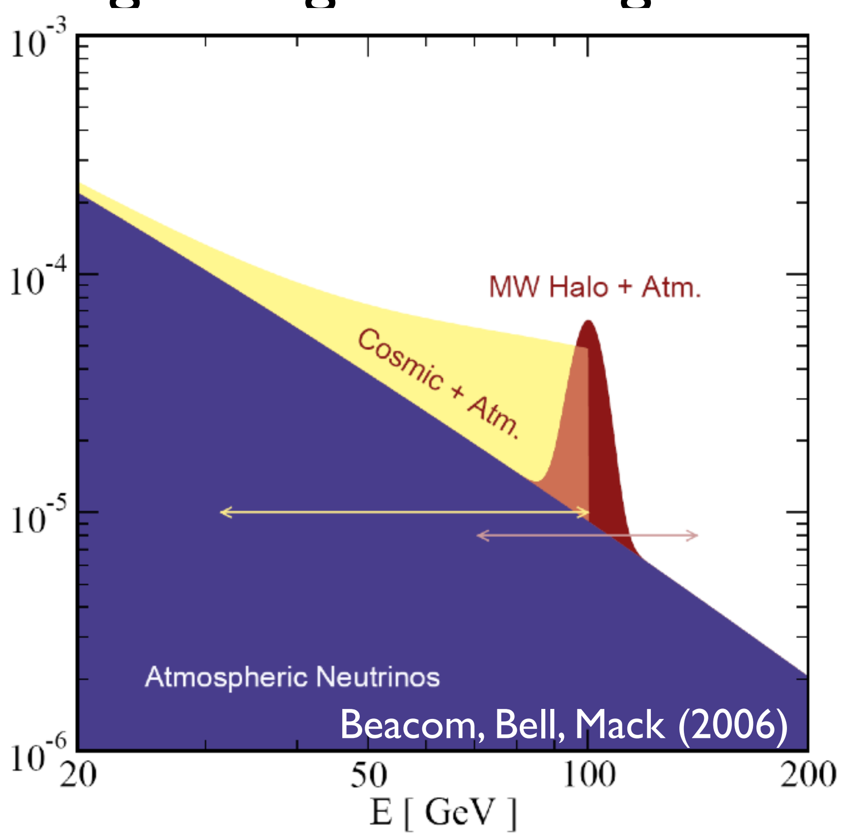
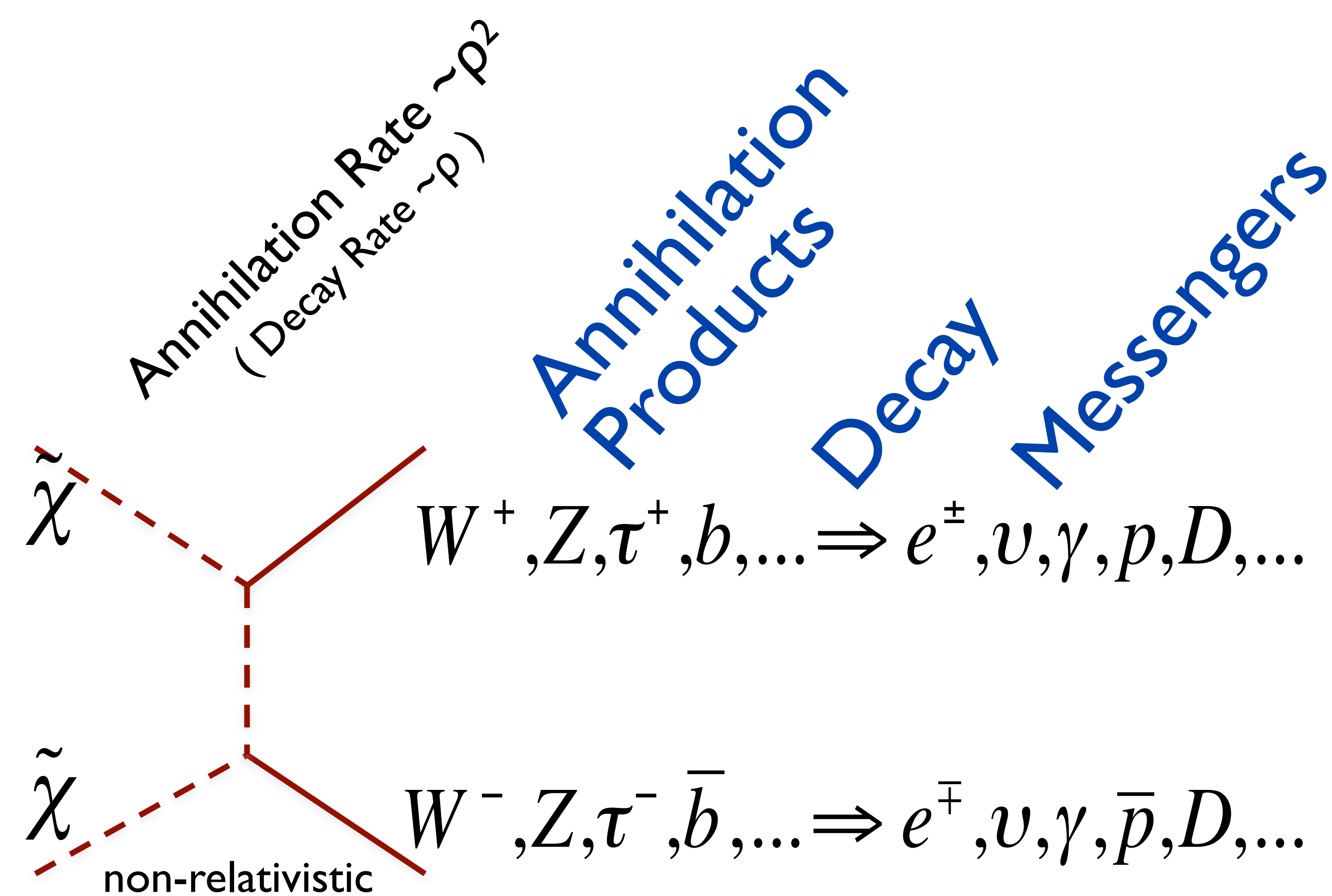
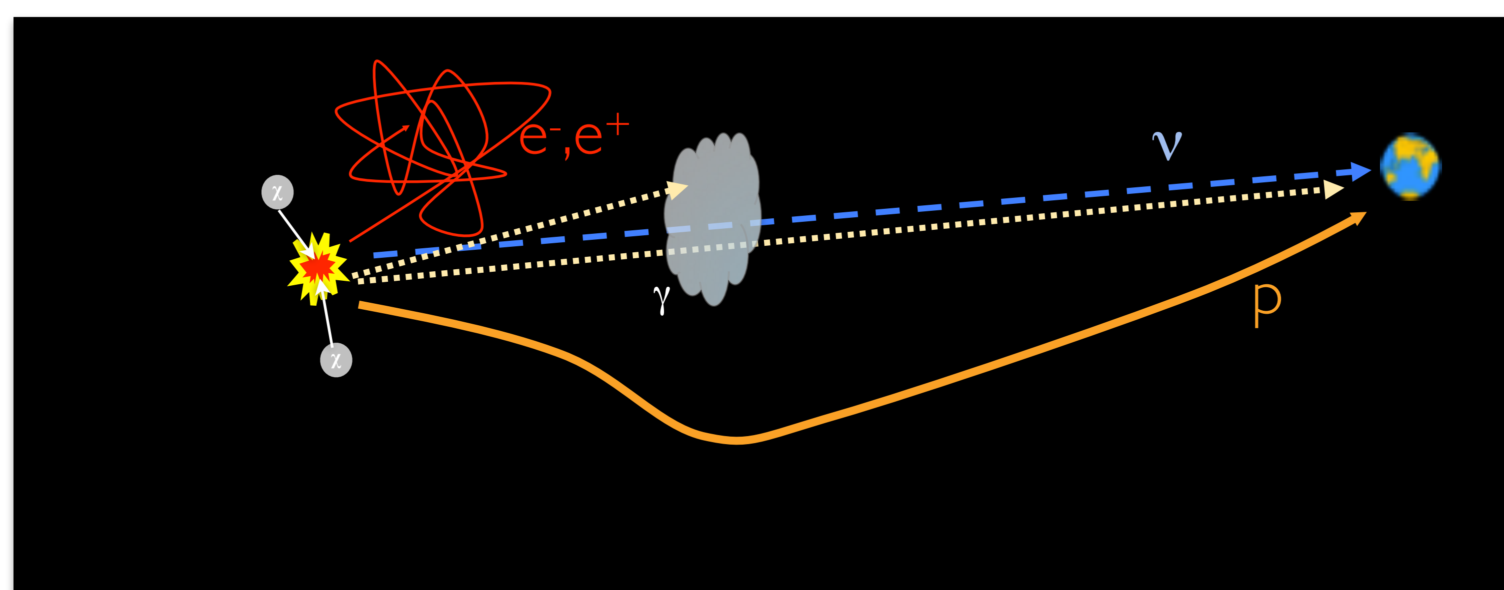
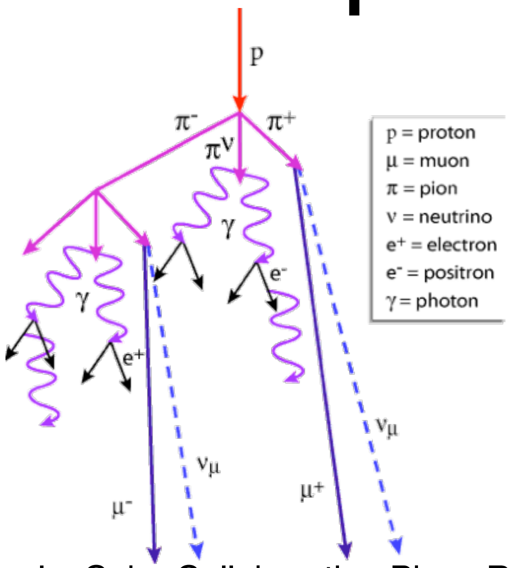






Sources of High Energy Neutrinos

Atmospheric Neutrinos

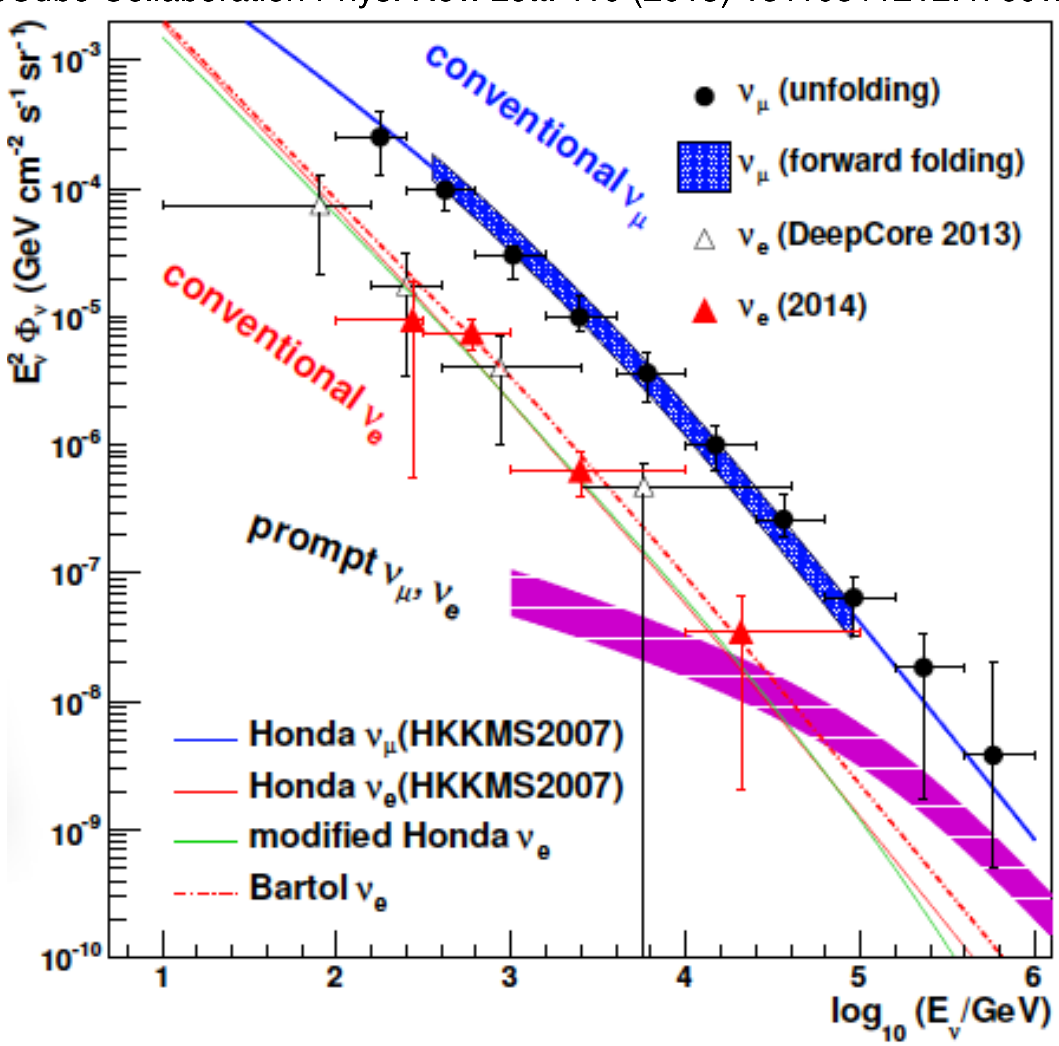


Cosmic rays interact in the upper atmosphere:

$p + A \rightarrow \pi^{\pm}\ (K^{\pm})$ + 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

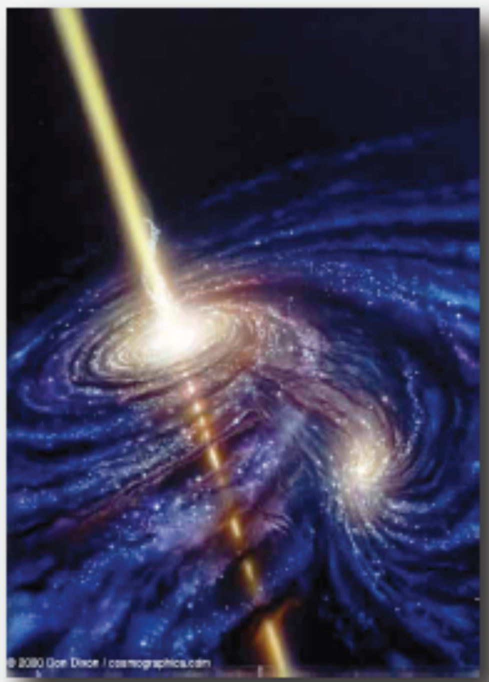


Astrophysical

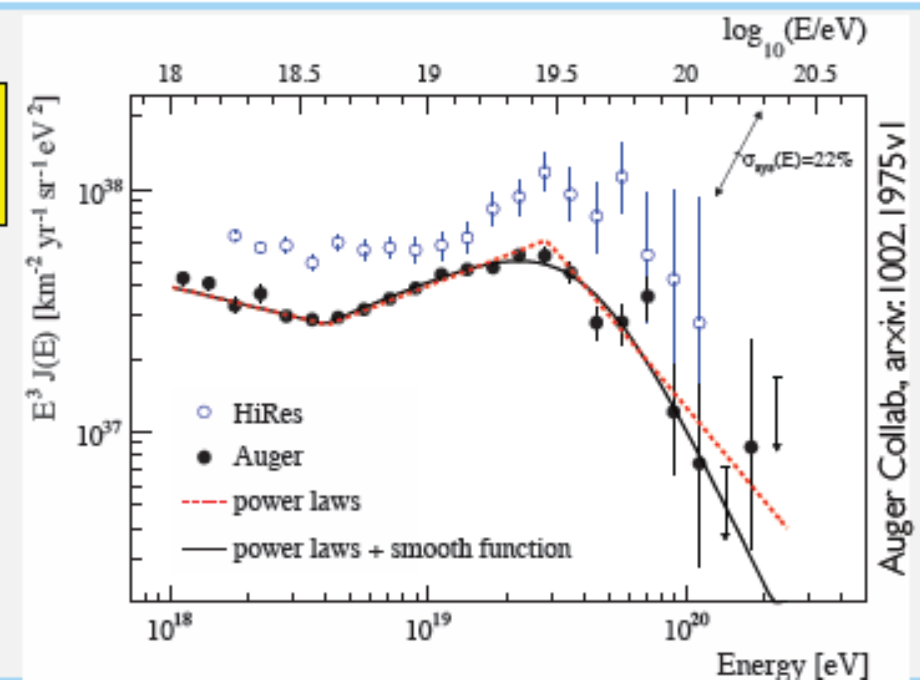
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Gamma-ray Bursts

Active Galactic Nuclei

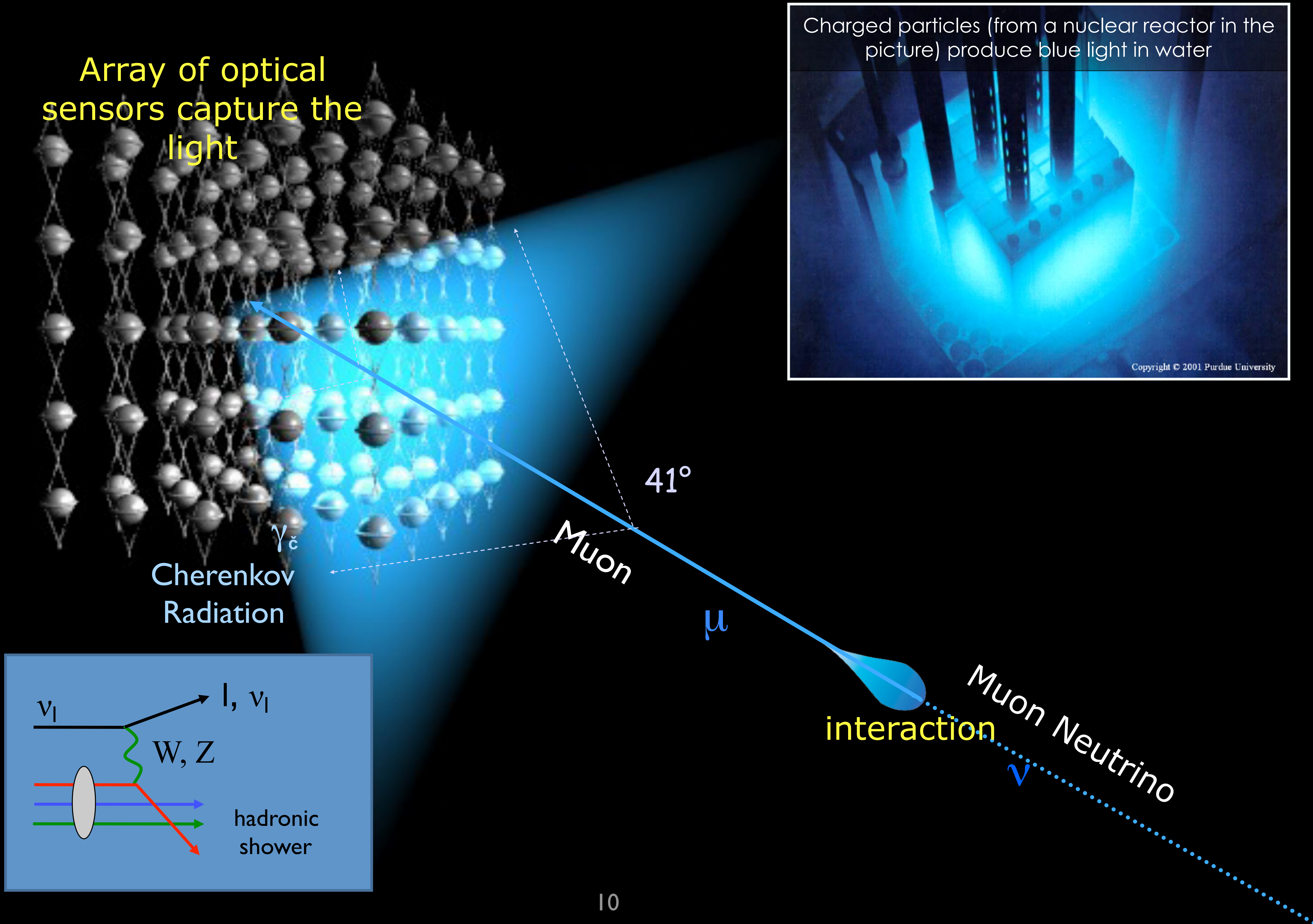


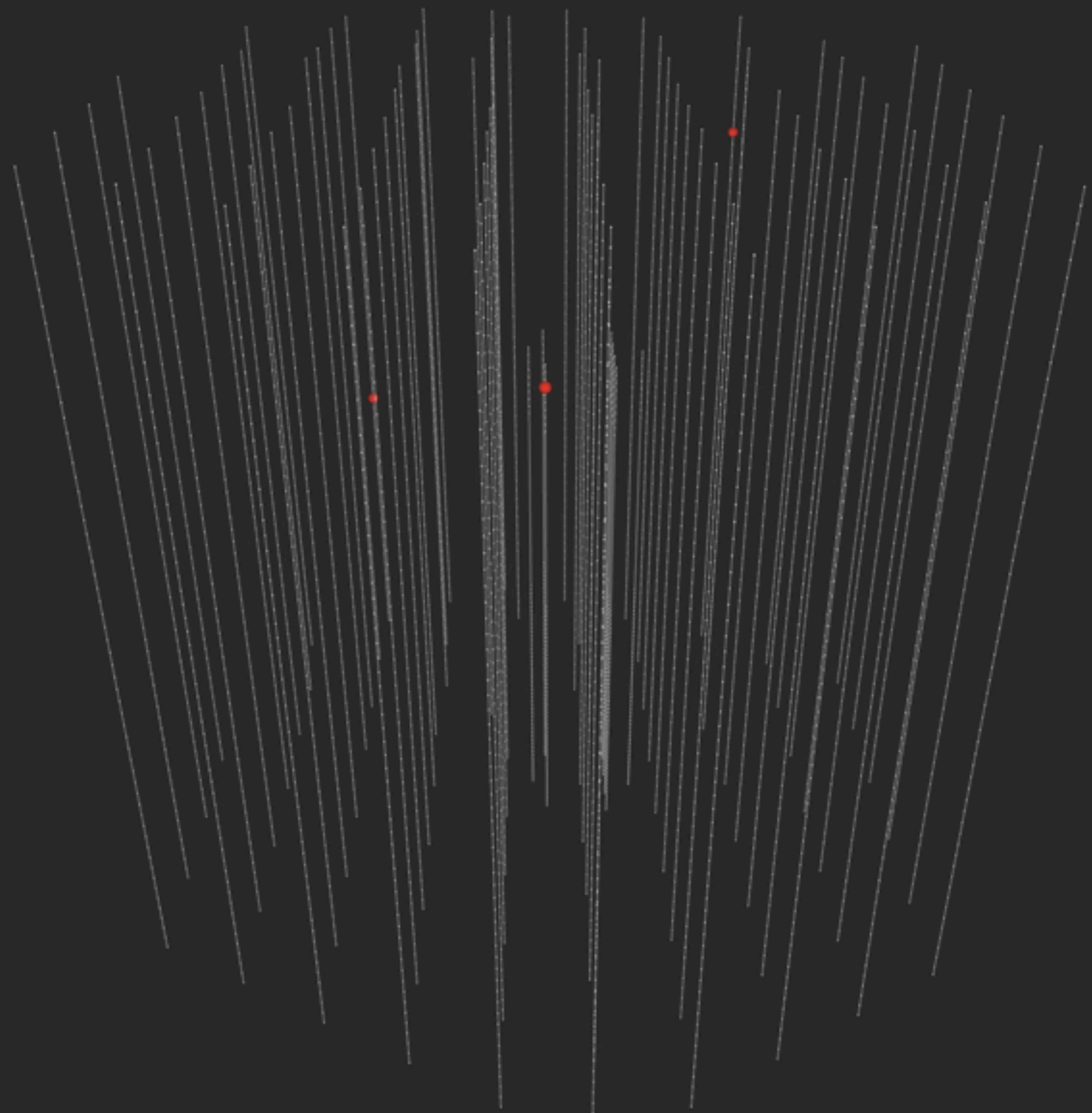
$p+\gamma_{3K} \rightarrow \Delta^{+}$ (GZK)

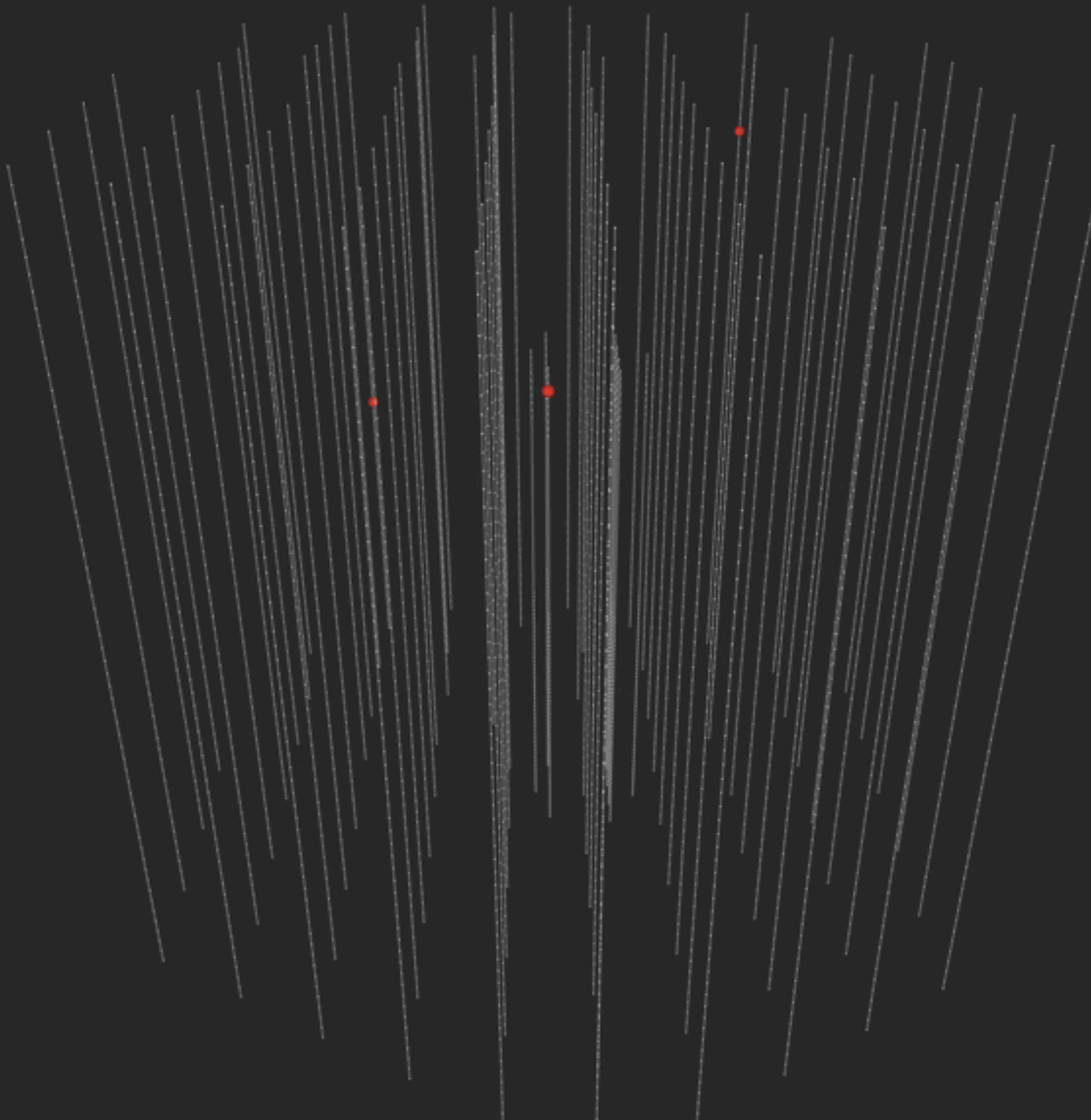


Auger Collab, arxiv:1002.1975v1

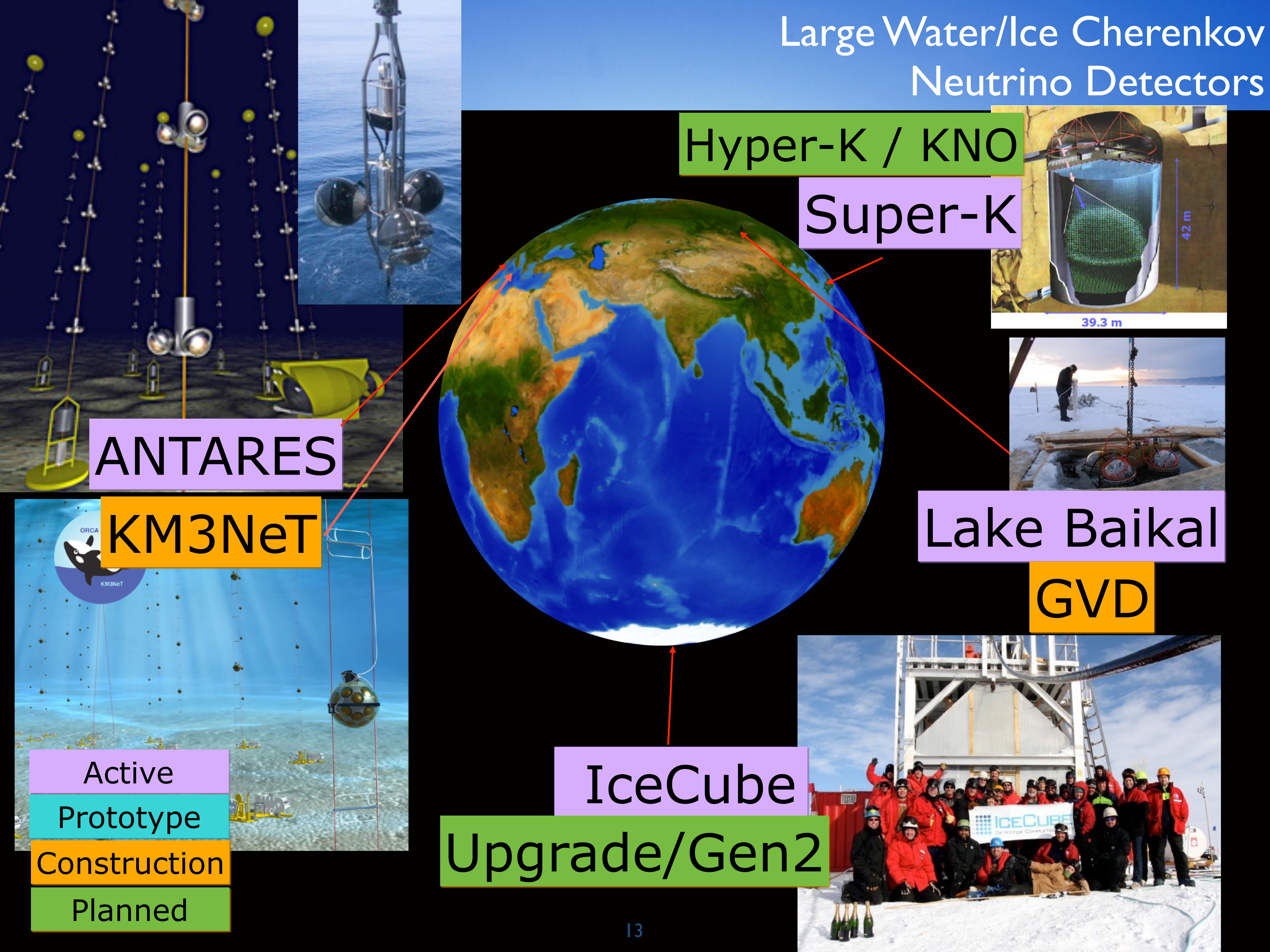
Principle of an optical Neutrino Telescope



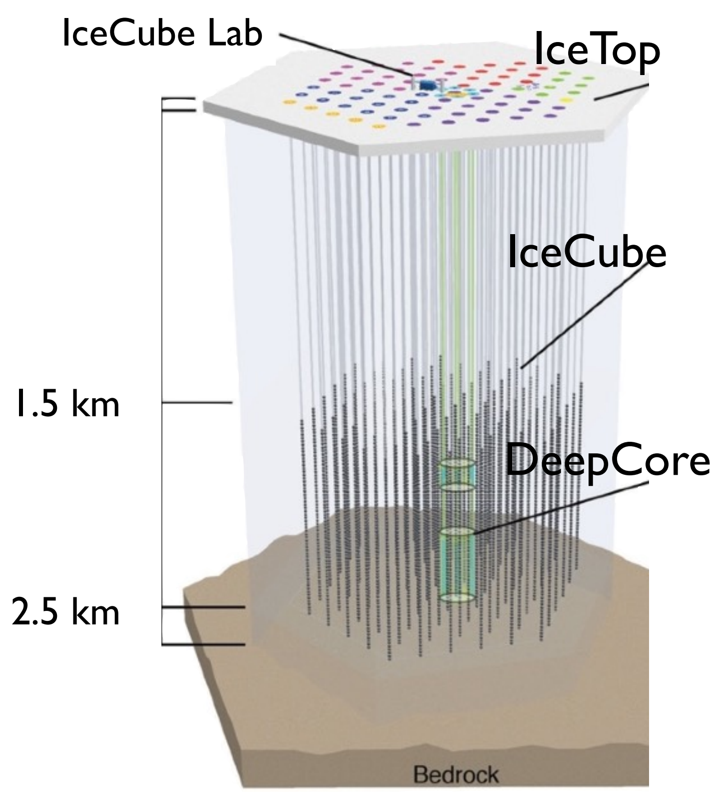


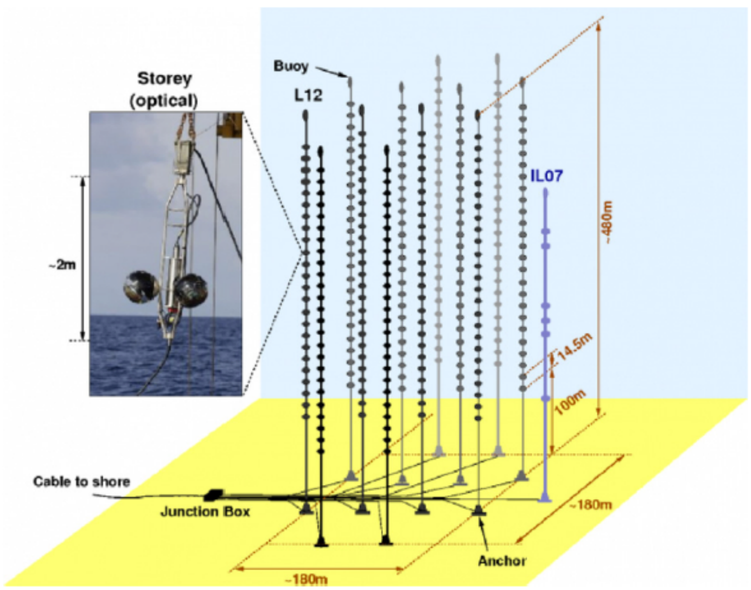


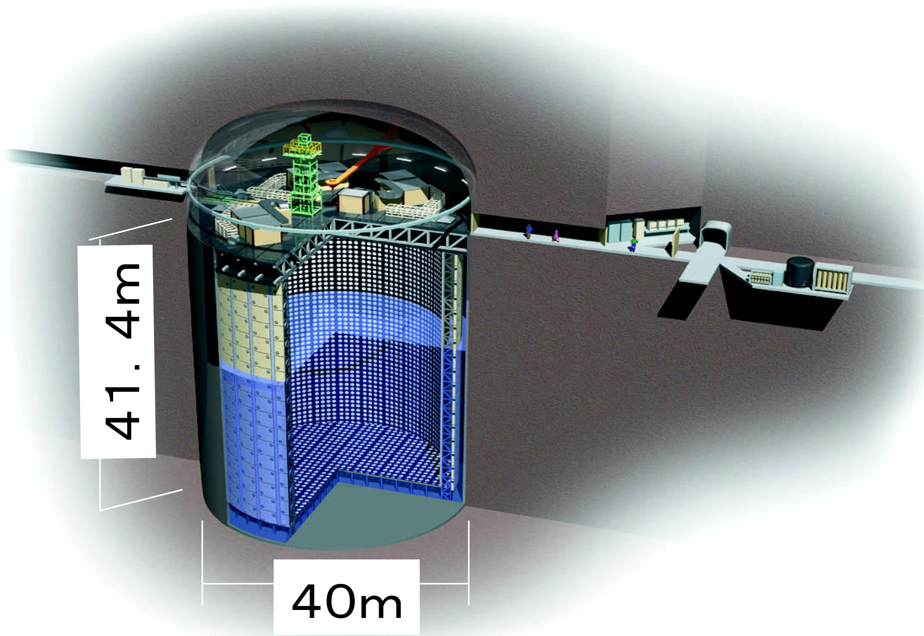
Neutrino Telescopes and IceCube



Large Water/Ice Cherenkov
Neutrino Detectors
Hyper-K / KNO
Super-K
42 m
39.3 m
ANTARES
KM3NeT
ORCA
Lake Baikal
GVD
IceCube
Upgrade/Gen2
Active
Prototype
Construction
Planned







- **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

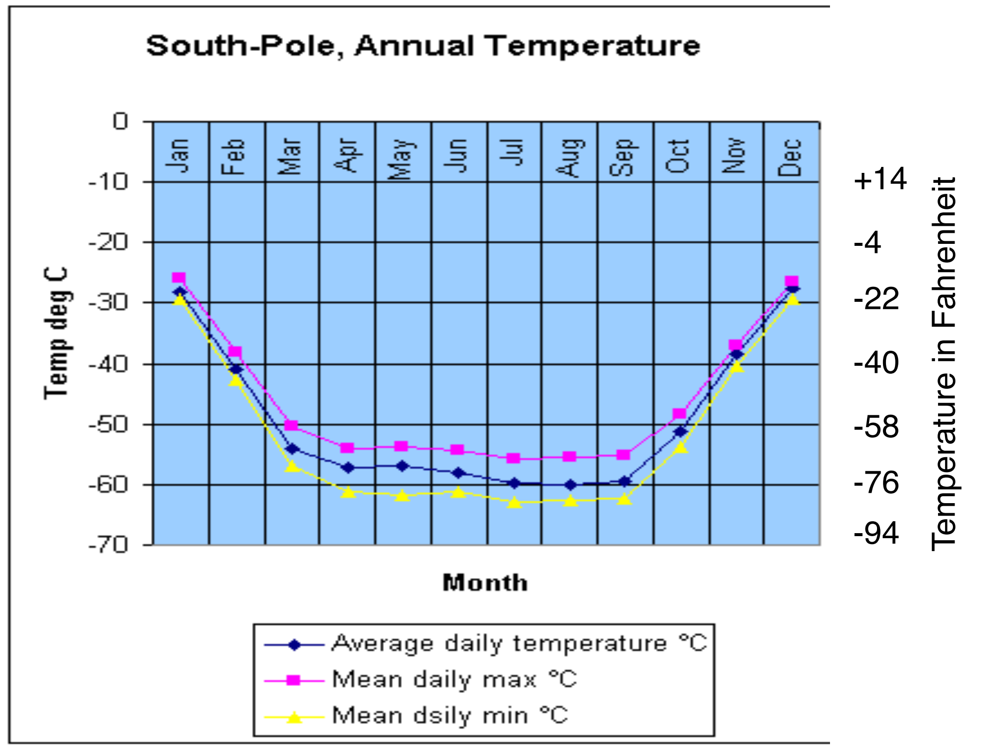
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008 ; Phyiscs data taking since 2007

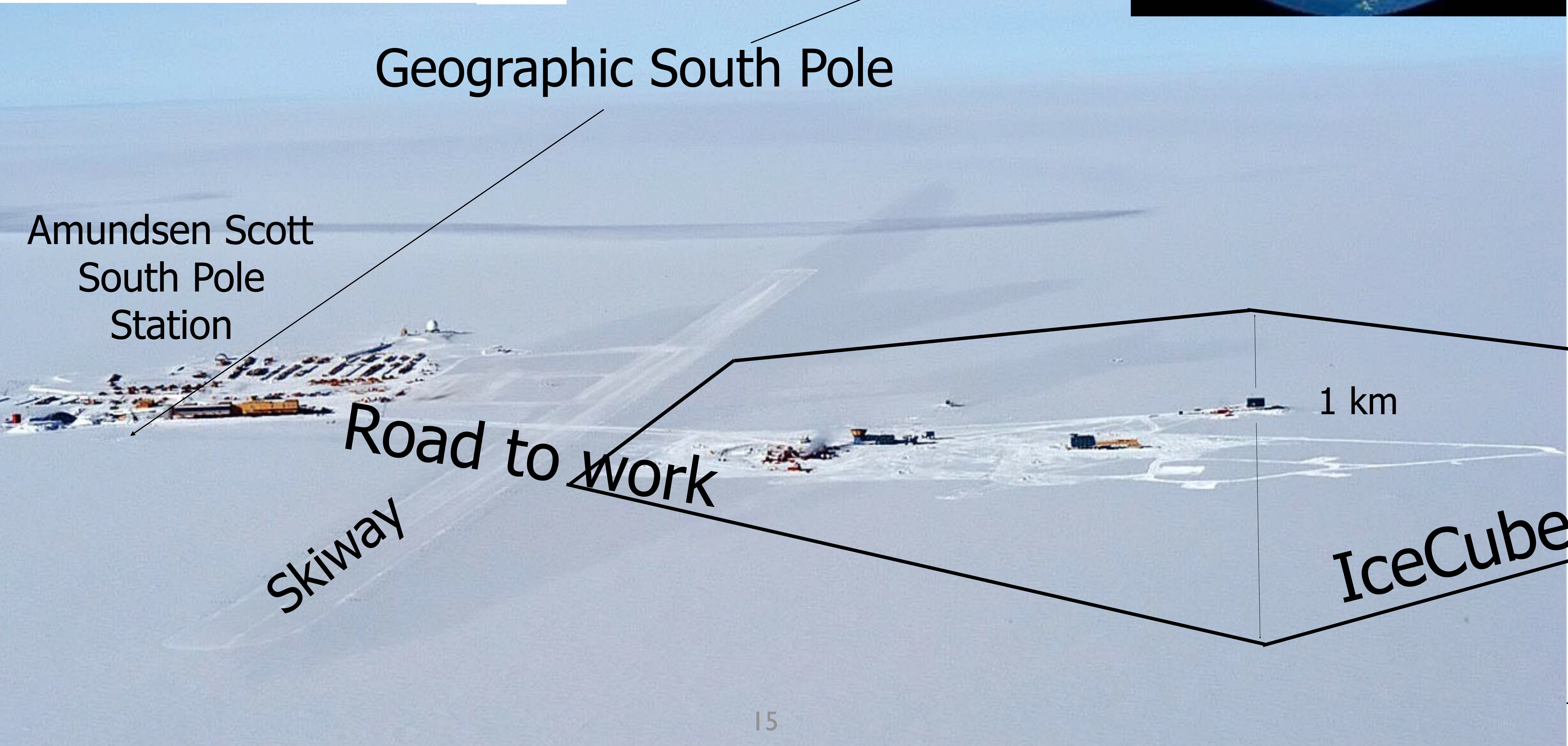
- **Super-Kamiokande** at Kamioka uses 11K 20" PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

Detect Cherenkov light from neutrino interaction products

Main backgrounds: Atmospheric neutrino, atmospheric muons (down-going)

Laboratory at the South Pole





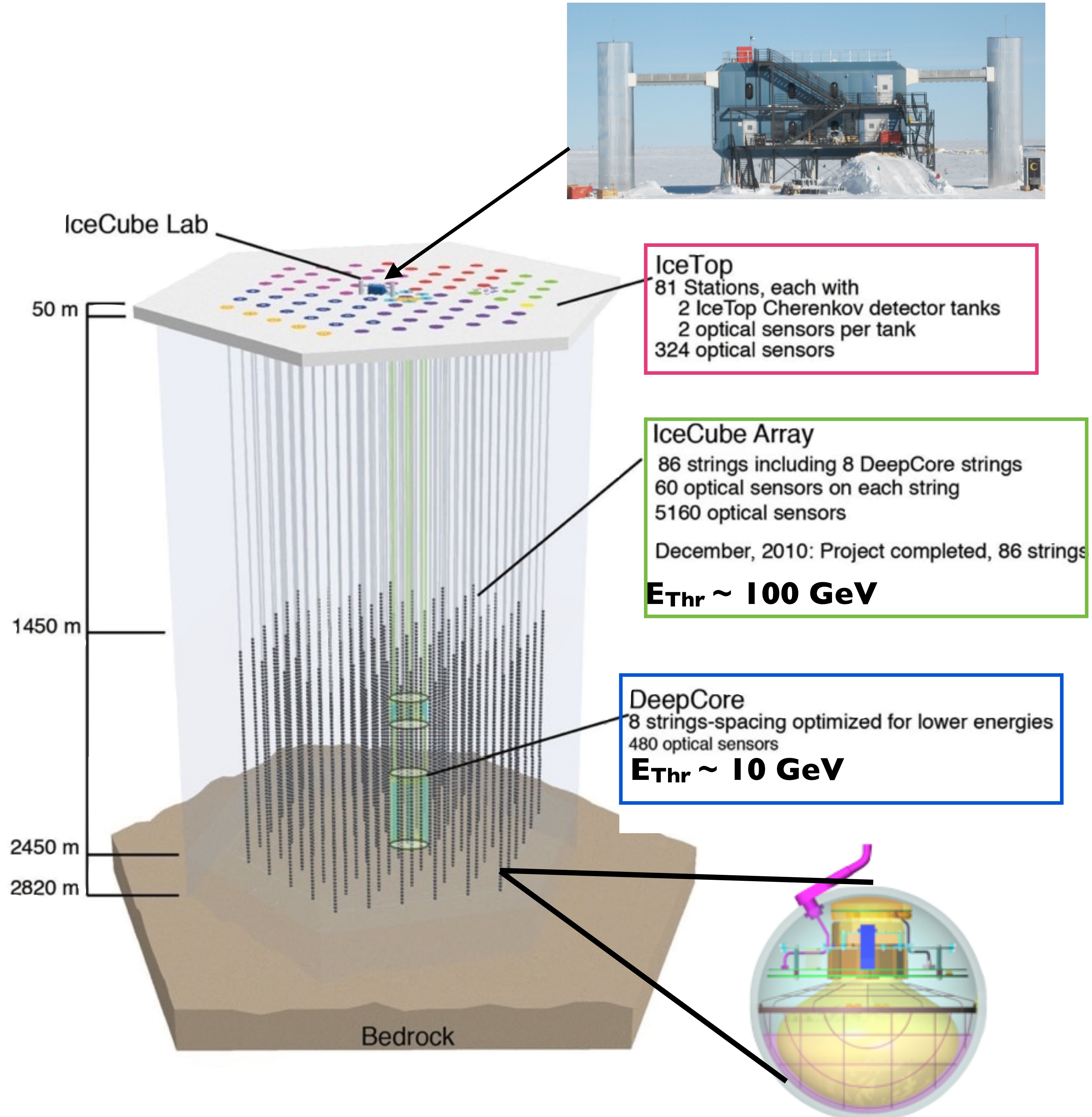
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010
- Extremely stable: >99% uptime and 98% of sensor modules in perfect condition !
- 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



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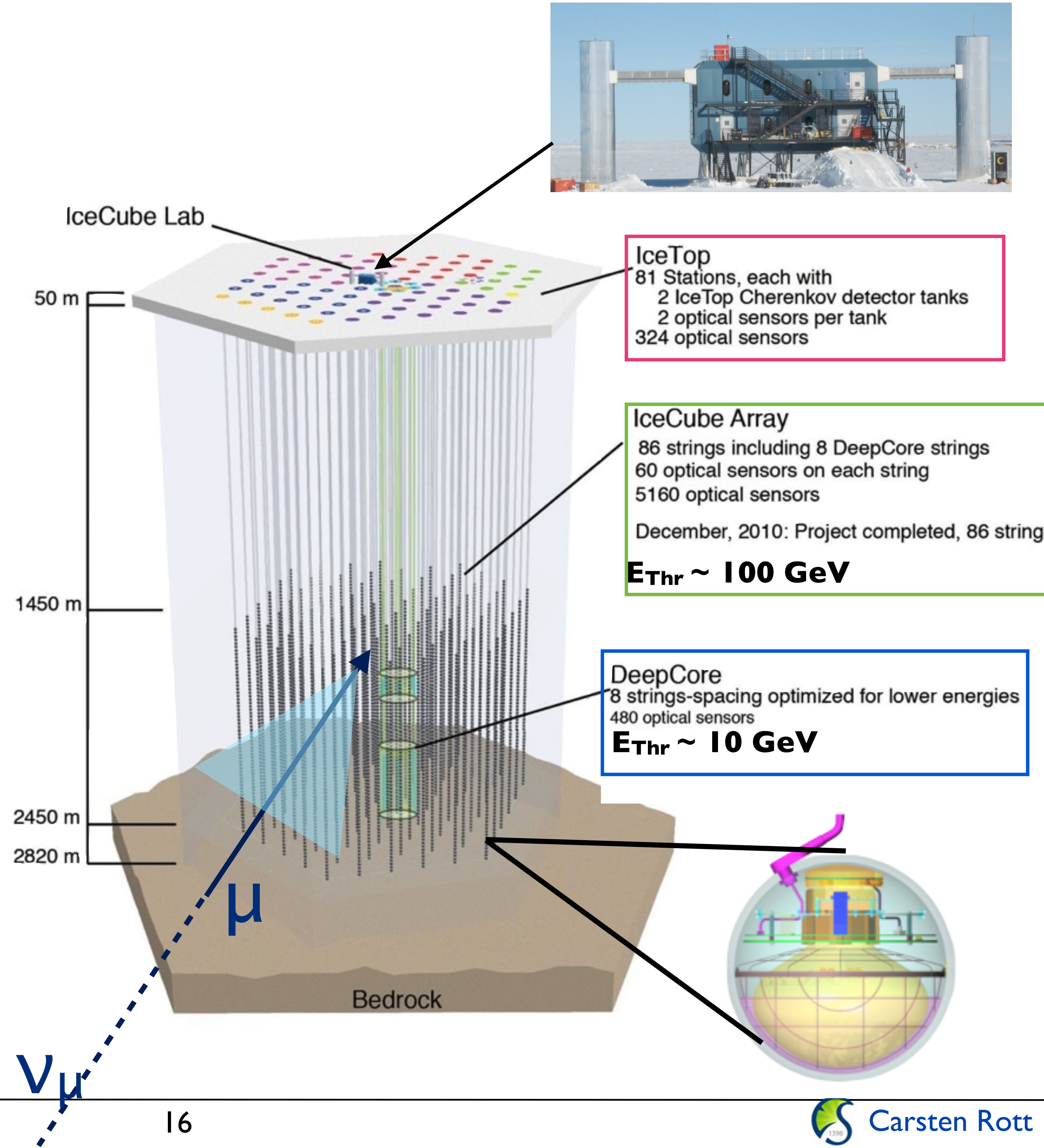

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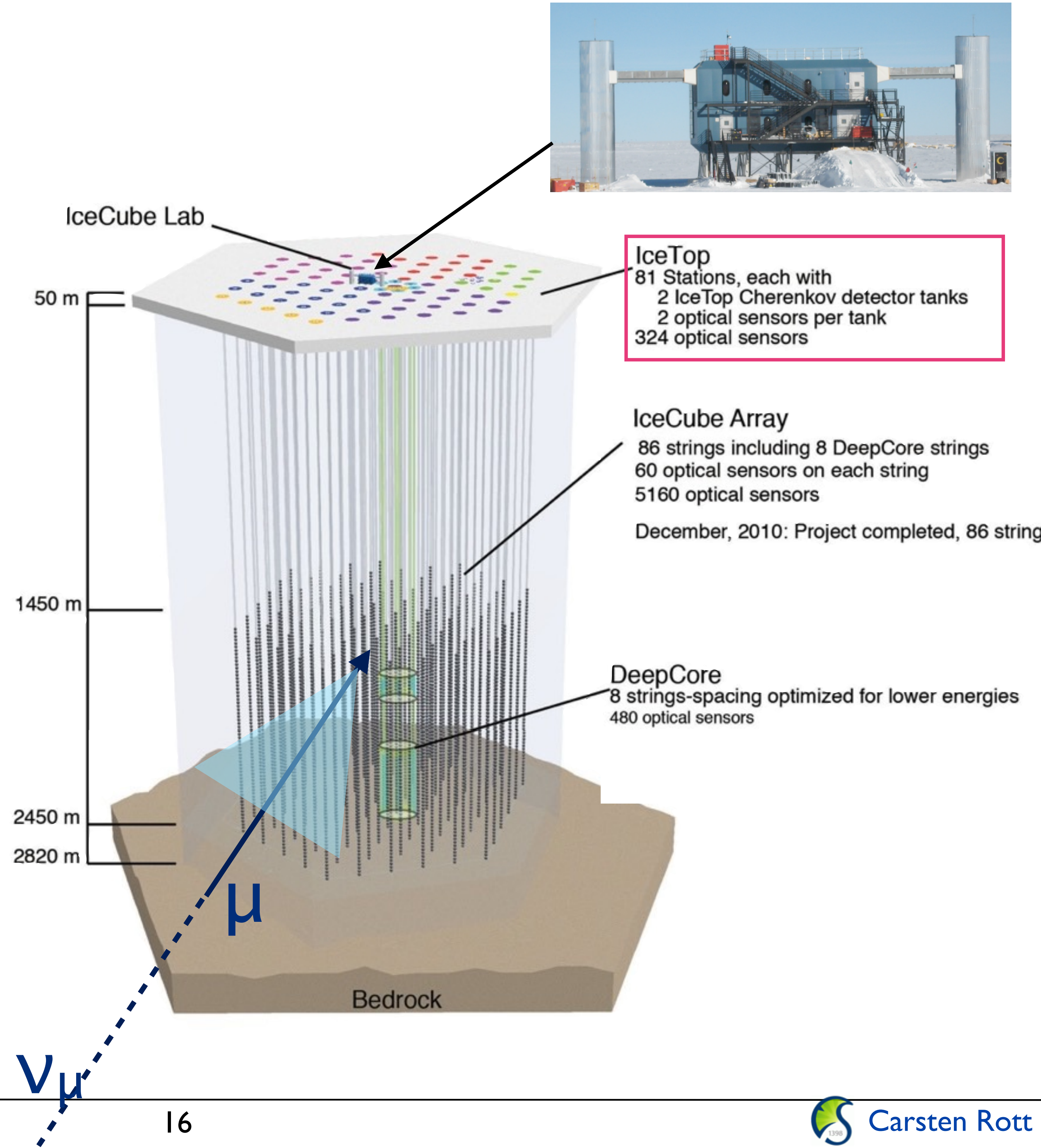
- Extremely stable: >99% uptime and 98% of sensor modules in perfect condition !
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice


〈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



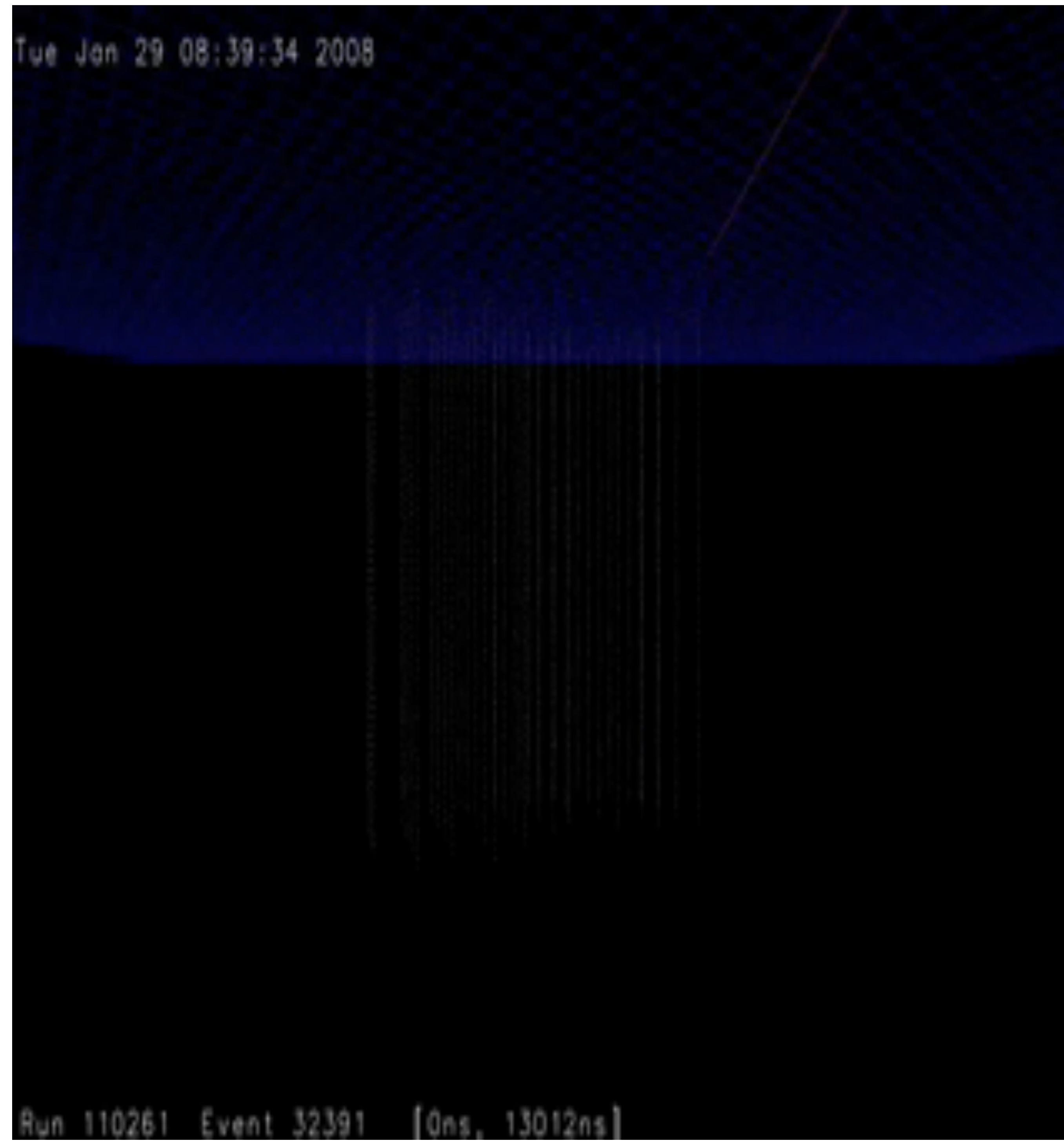
Signals in IceCube

South Pole

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

IceCube Depth:
1.5-2.5 km

Downgoing
Muons



North Pole

- Up-going events can be used to obtain "clean" neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

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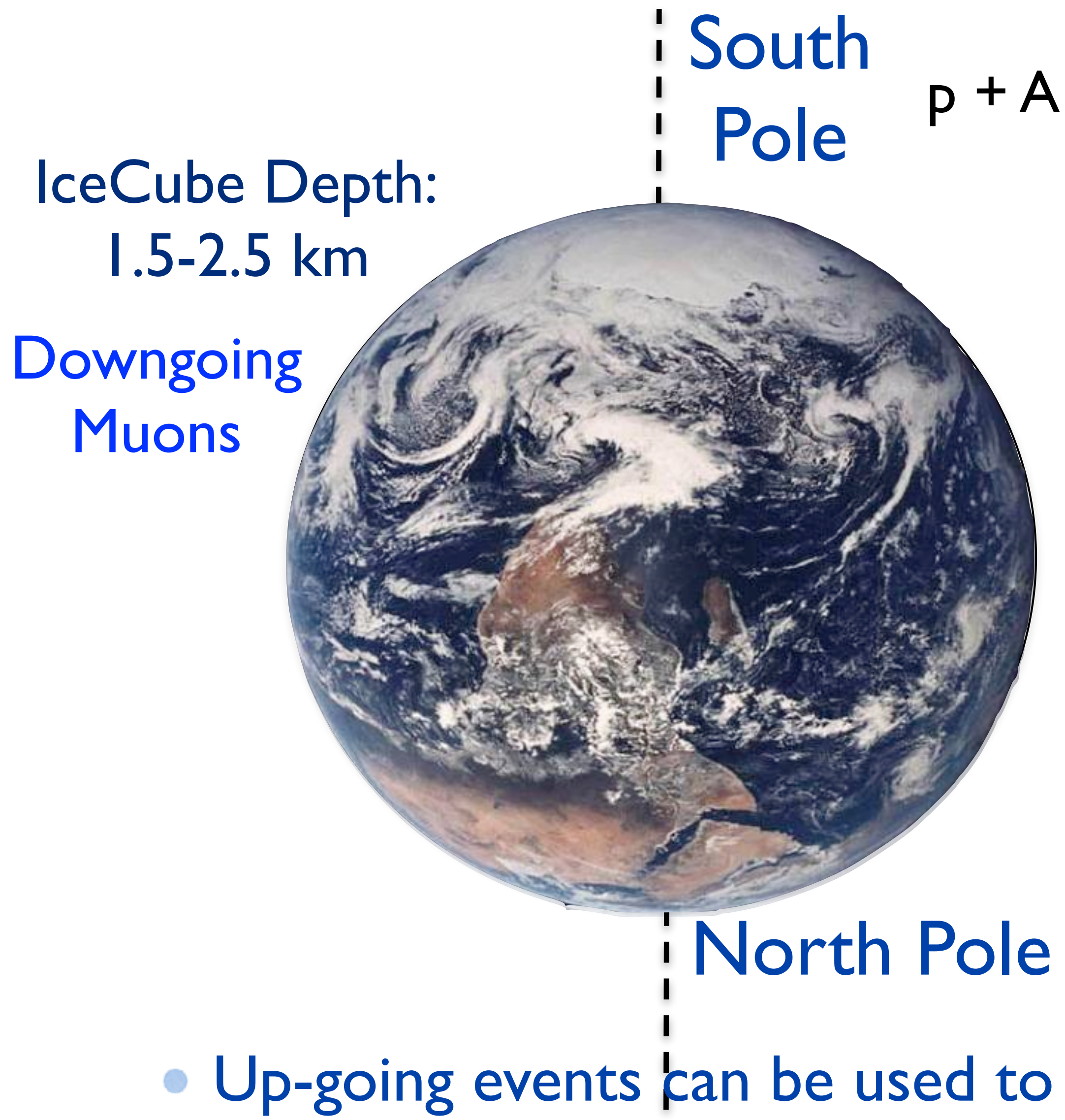

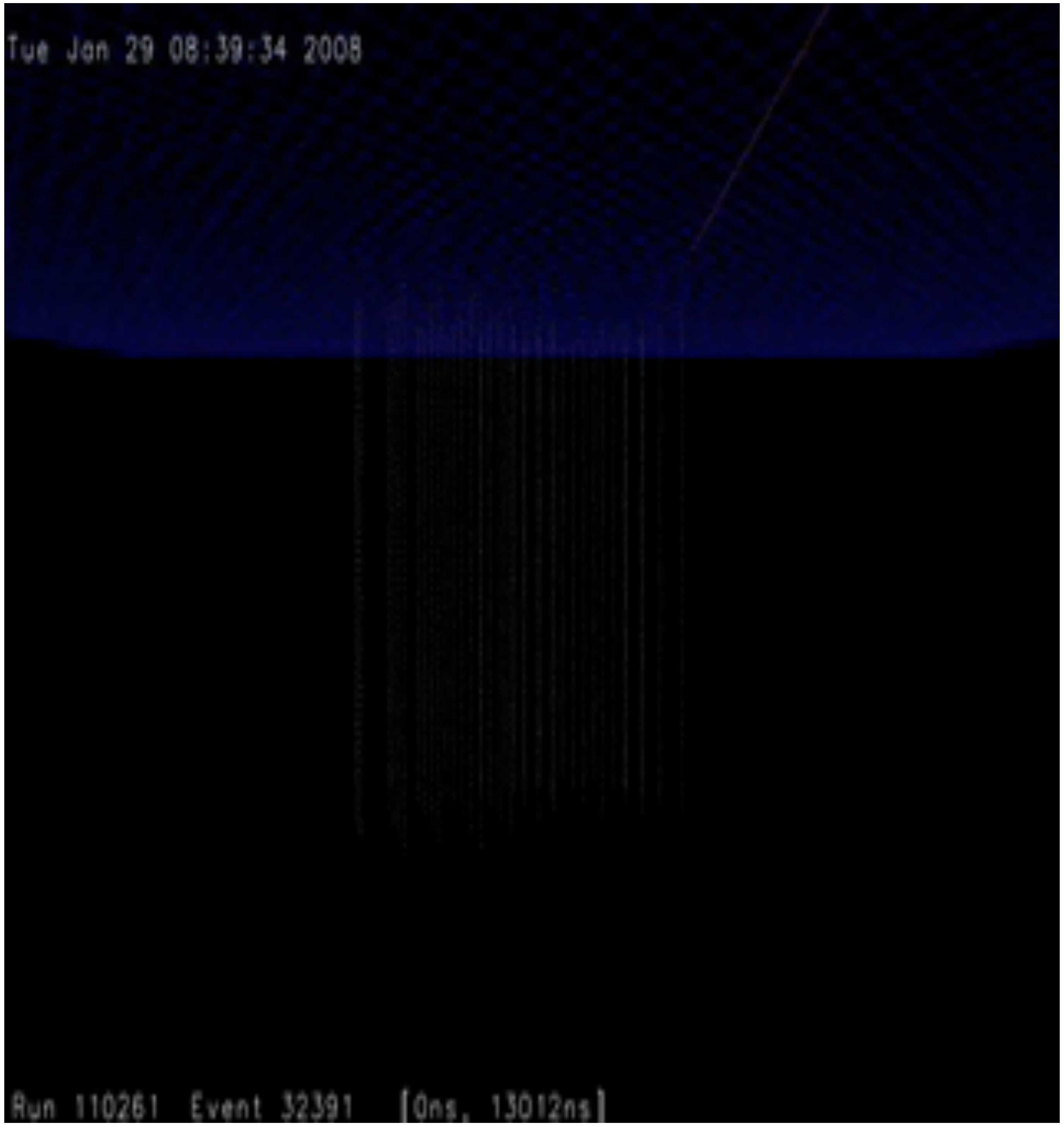

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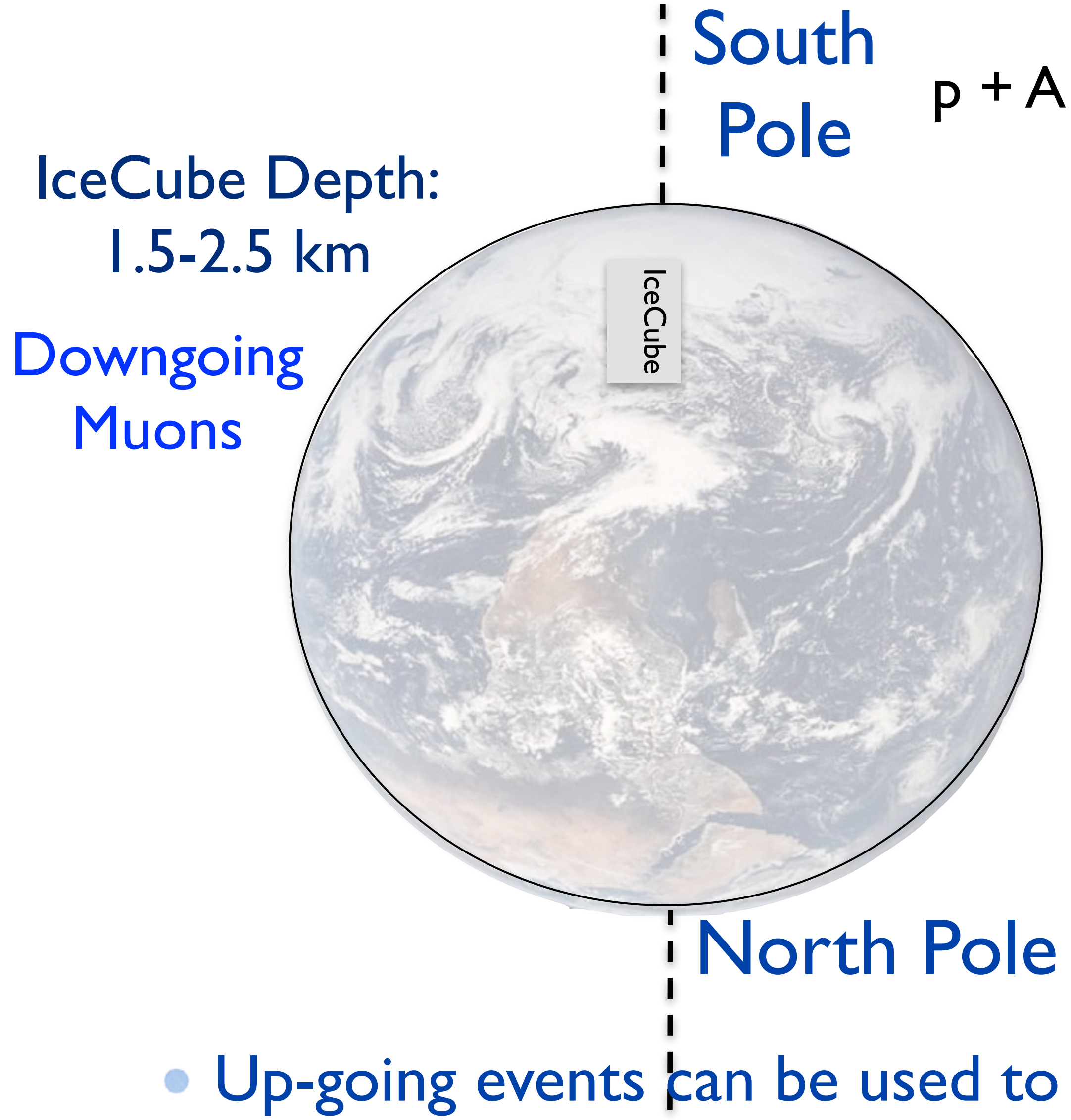

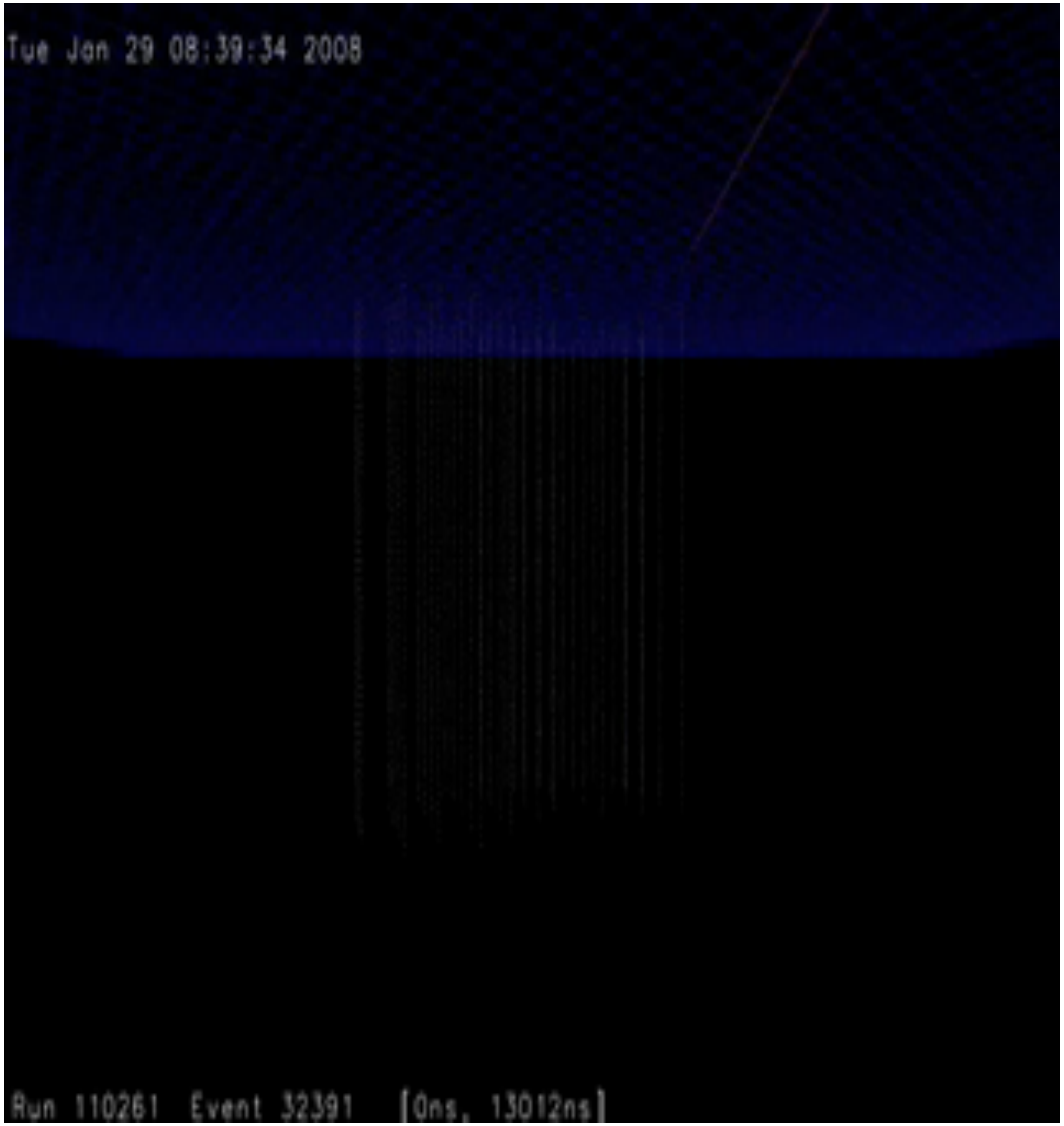

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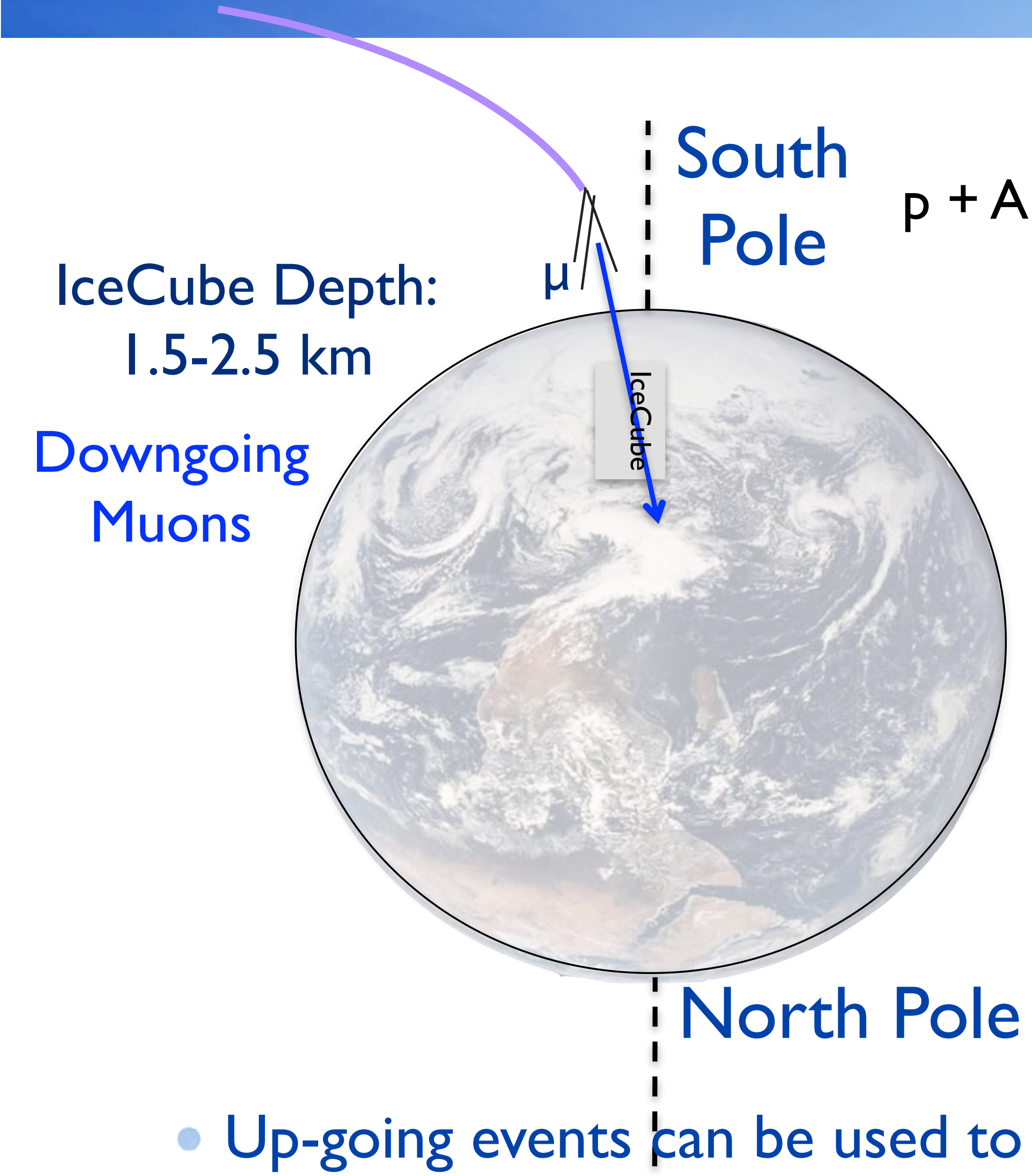

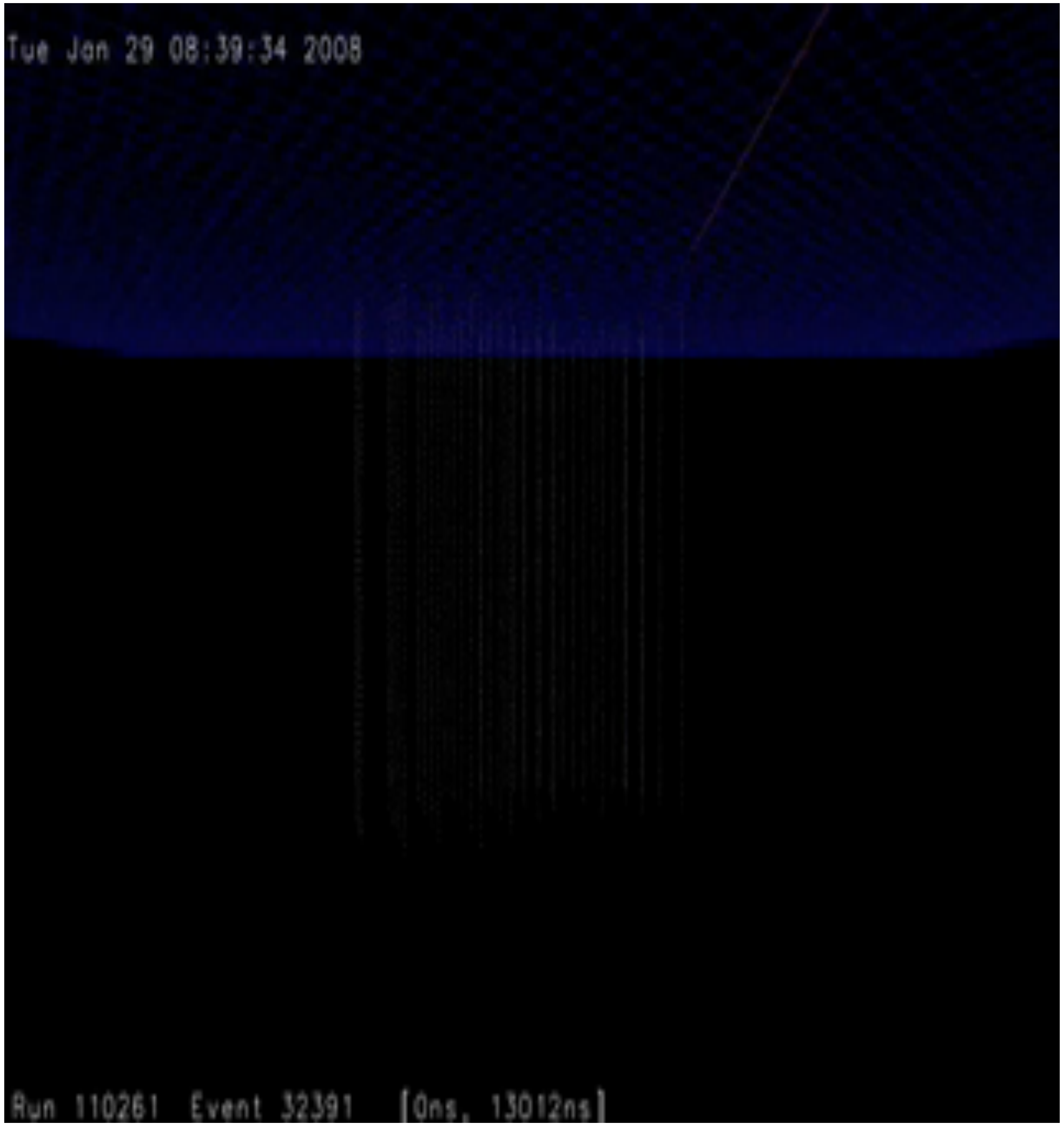

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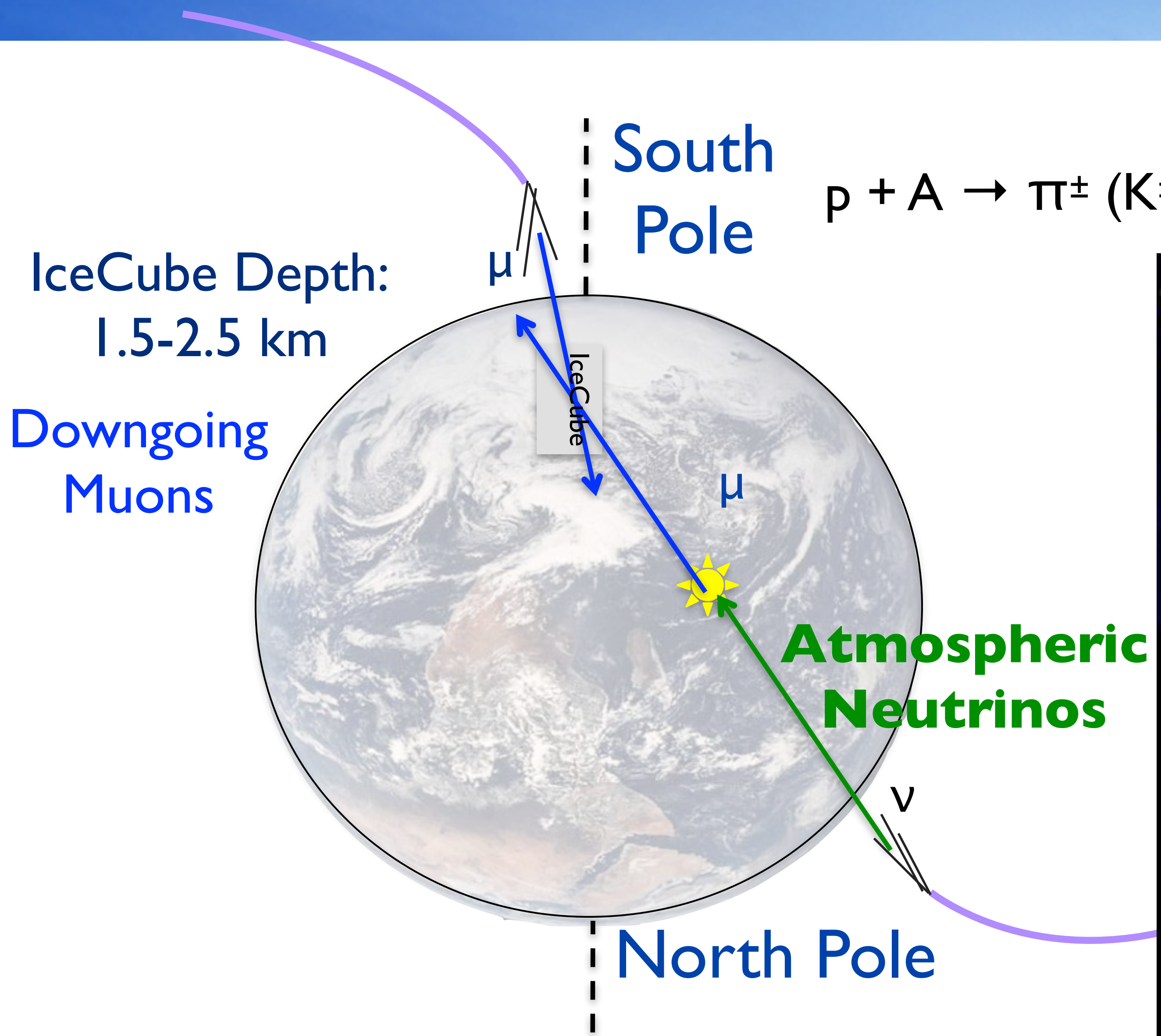

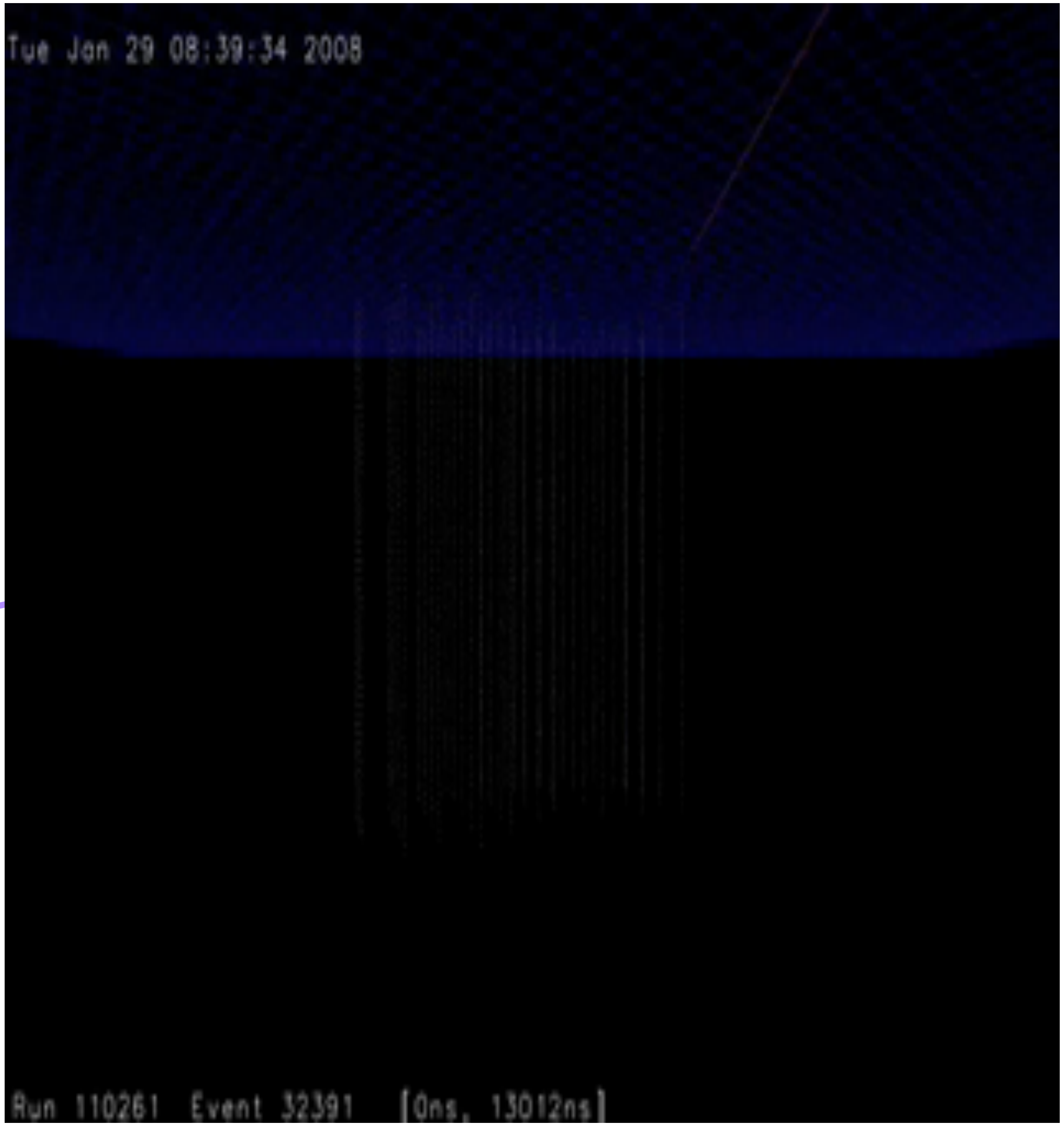

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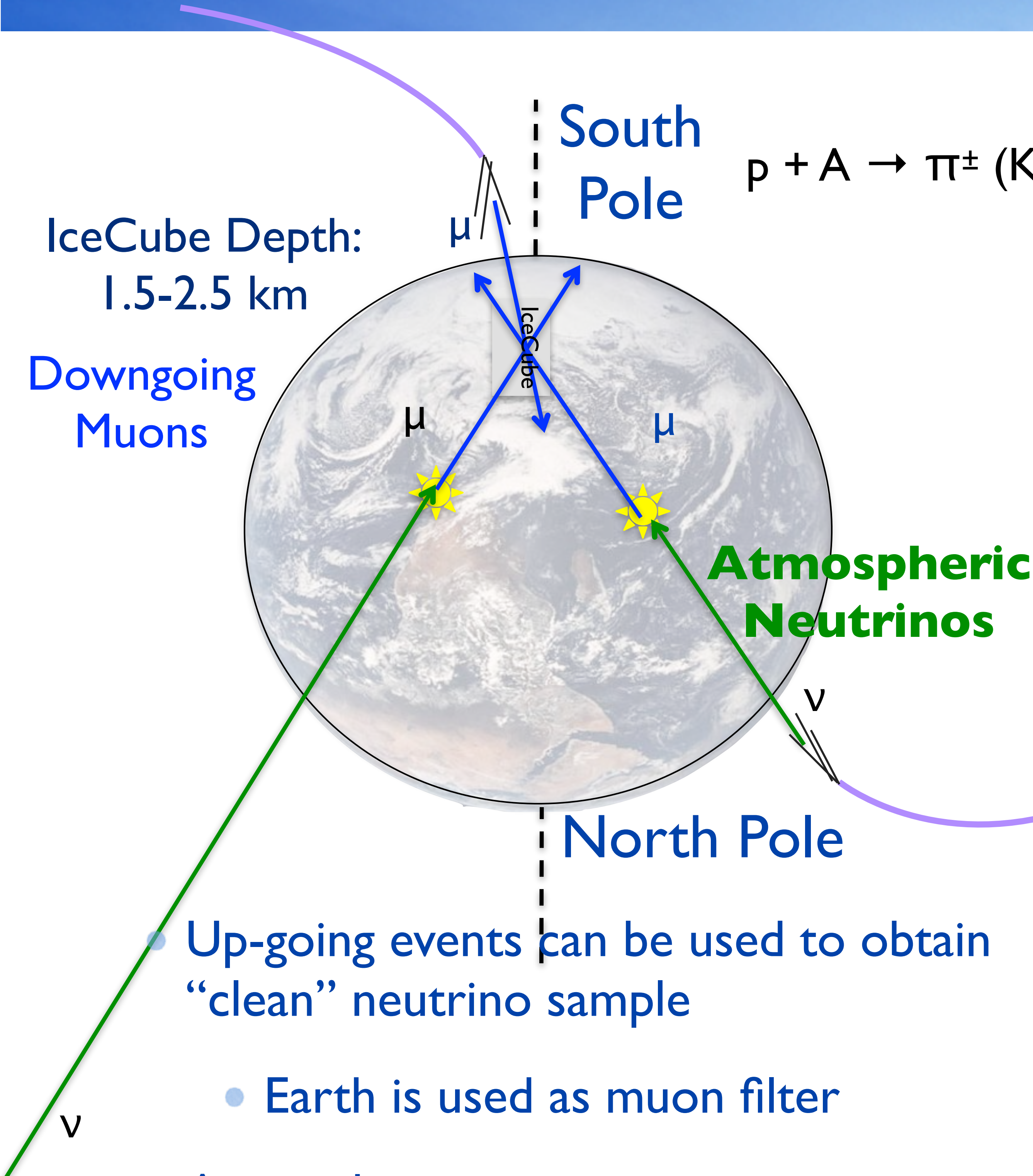

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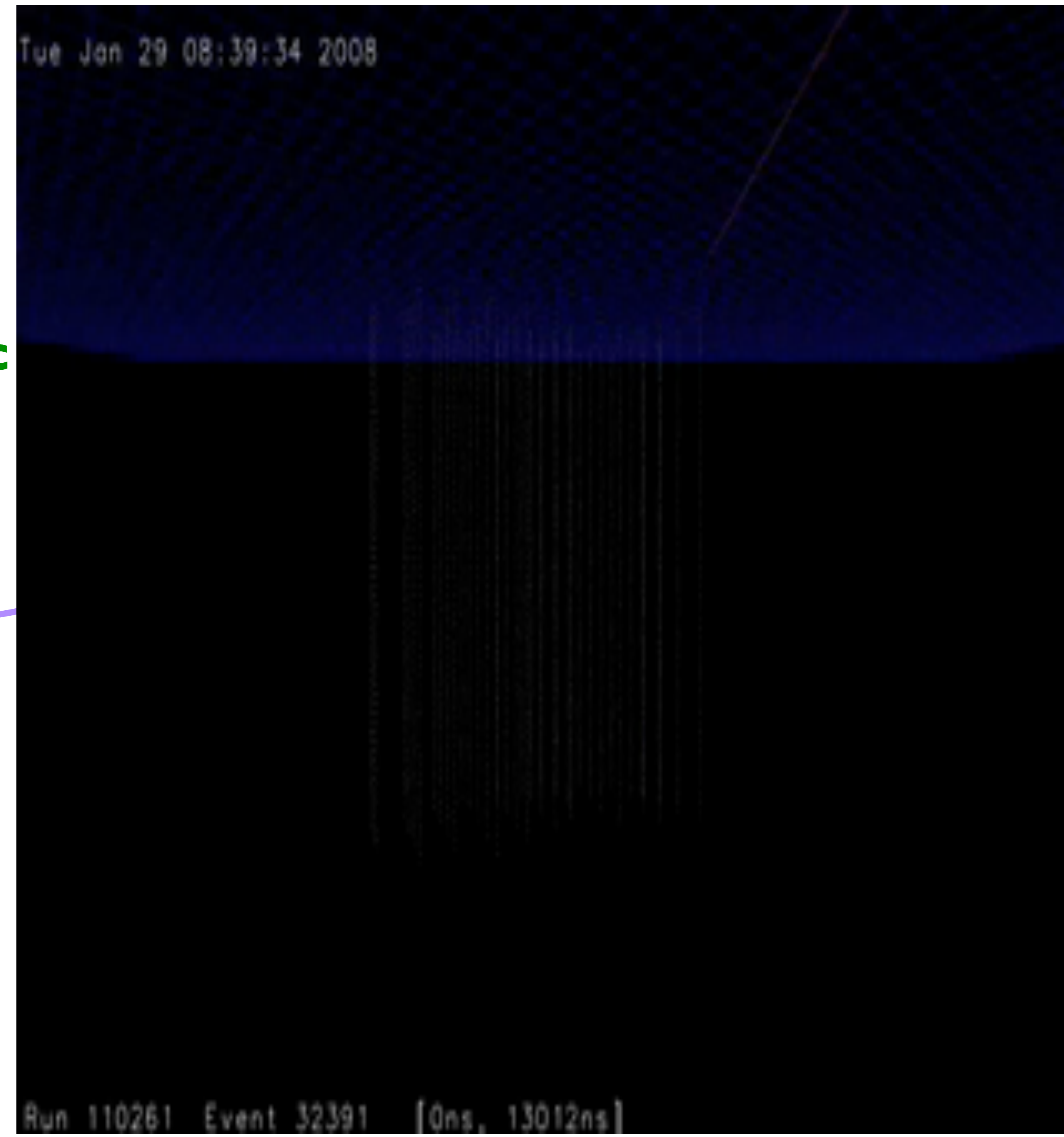

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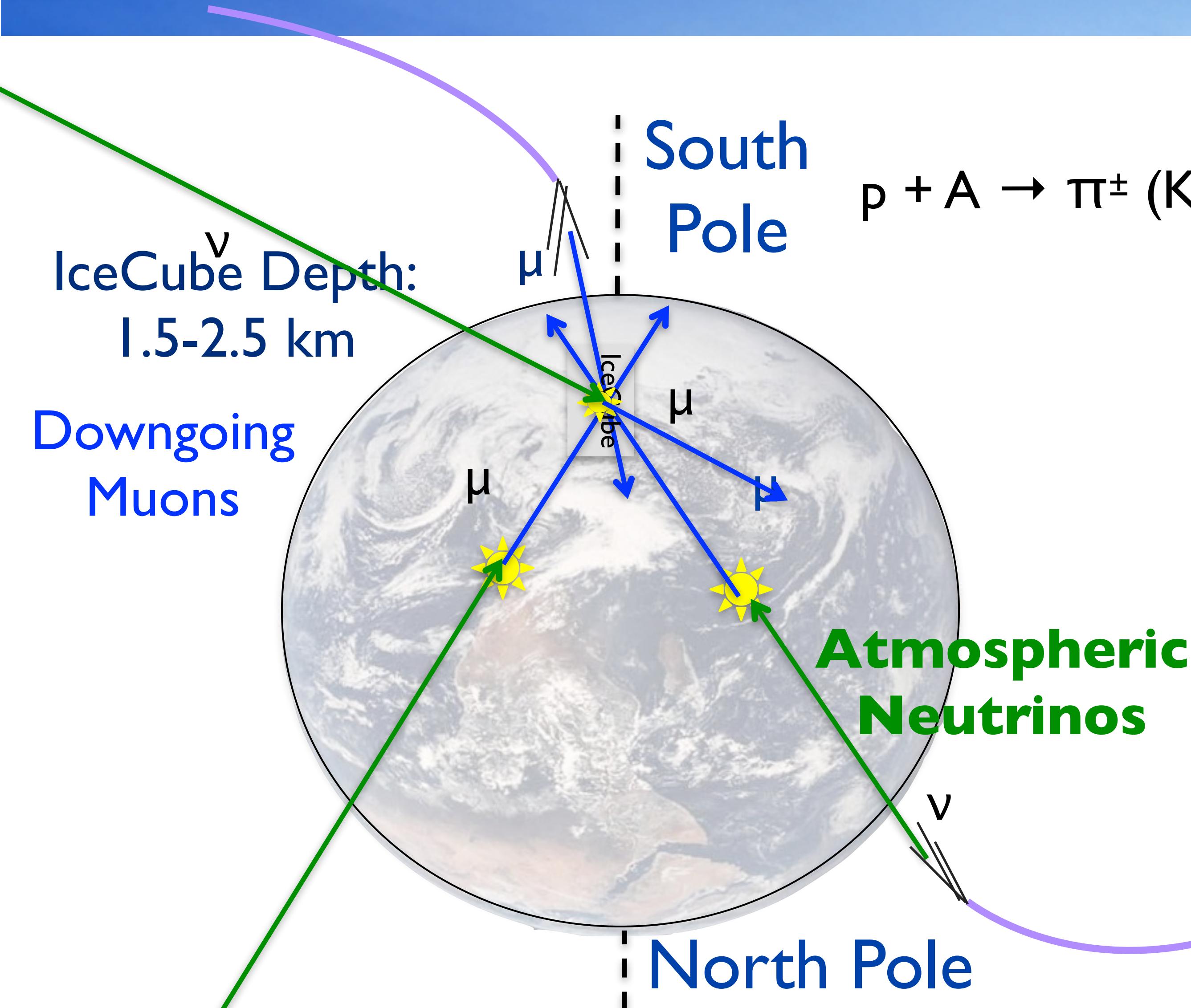

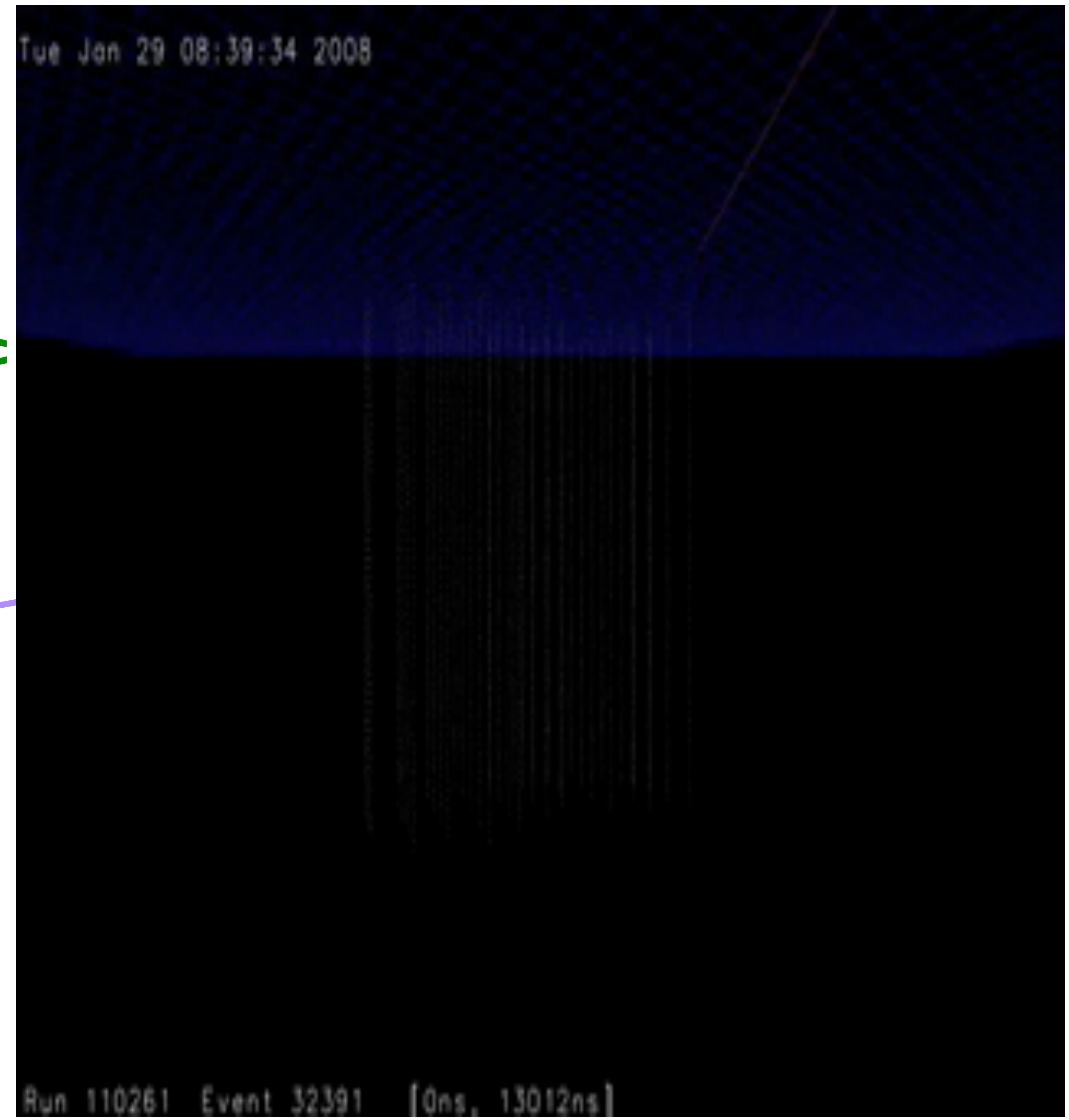

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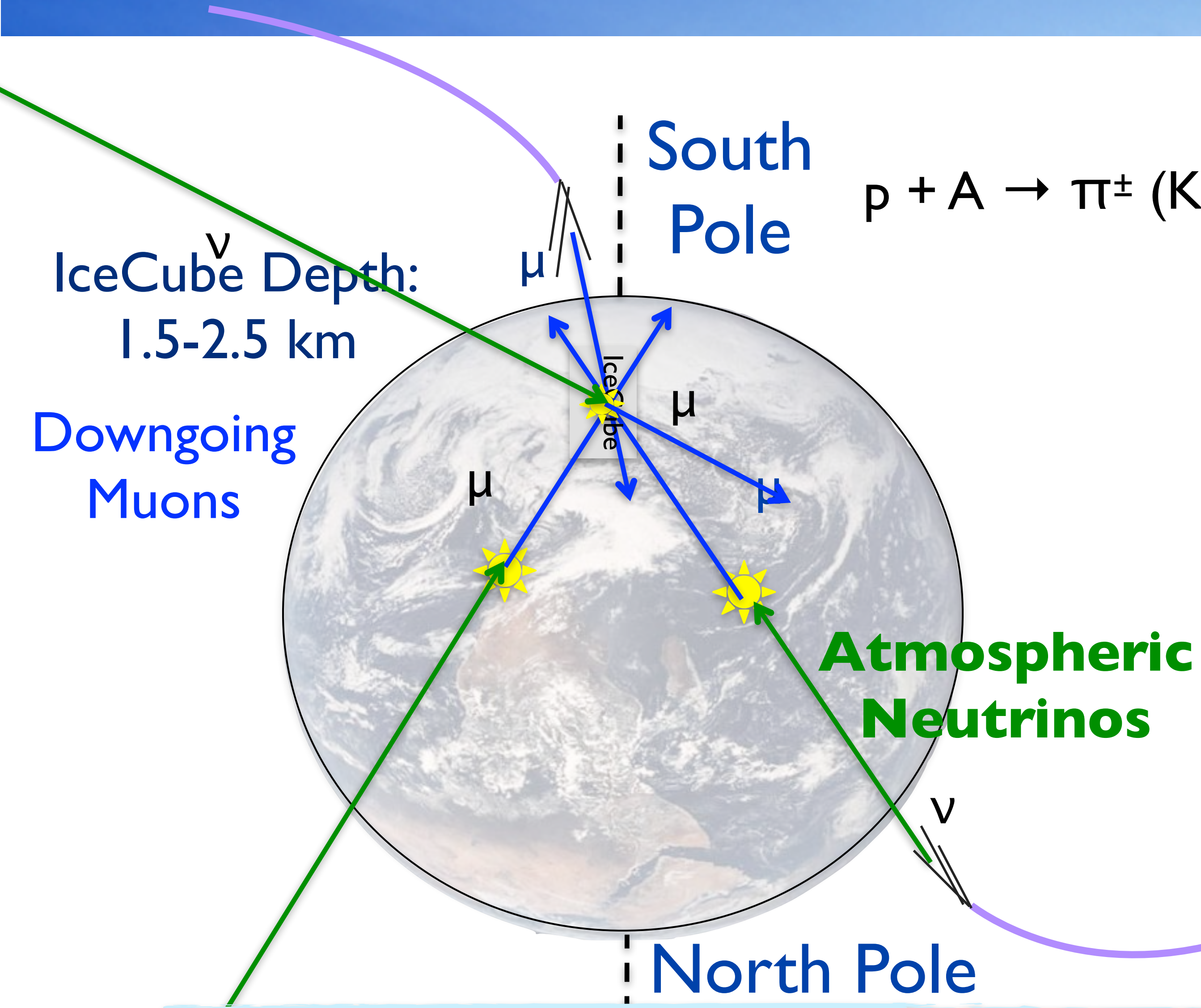
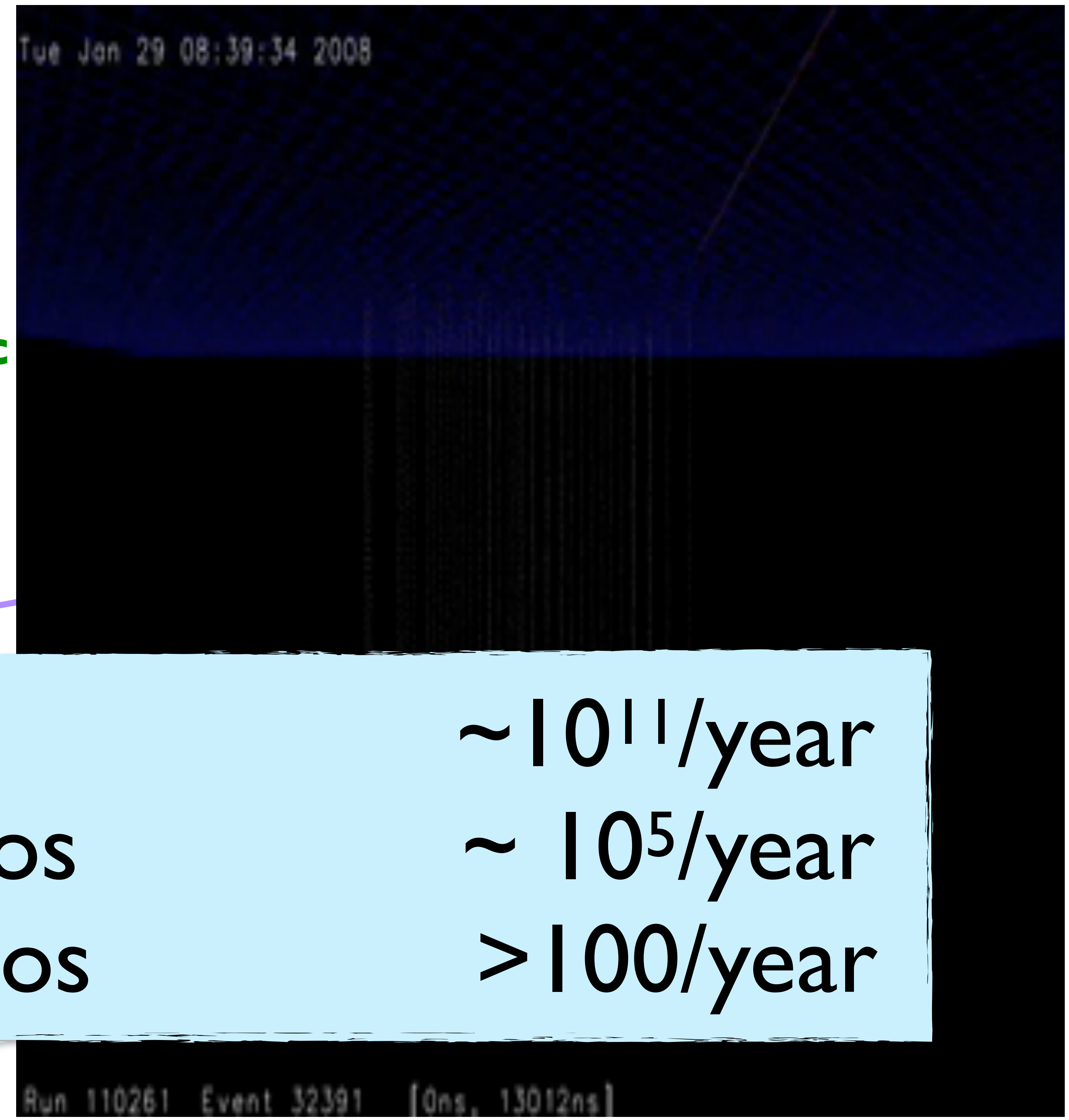


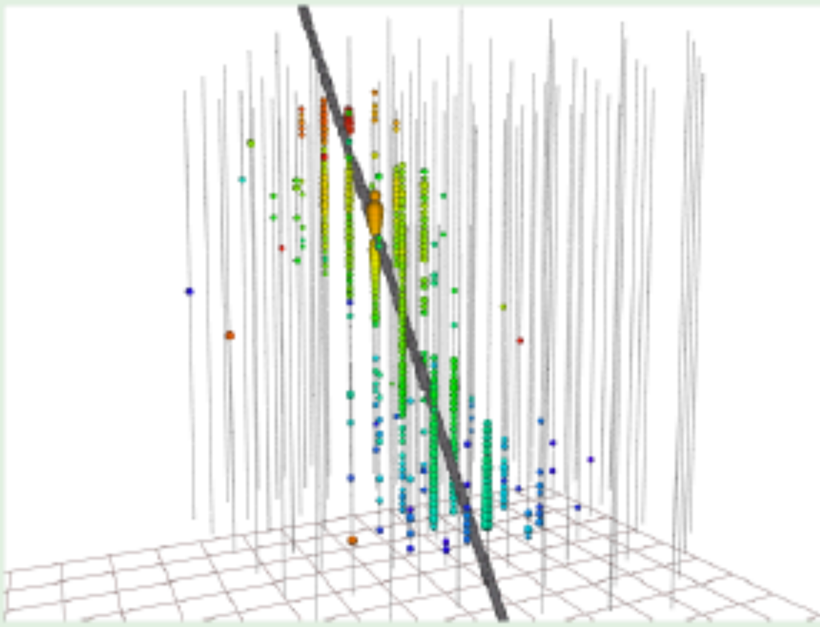


Atmospheric muons	~10^{11}/year
Atmospheric neutrinos	~ 10^{5}/year
Astrophysical neutrinos	>100/year

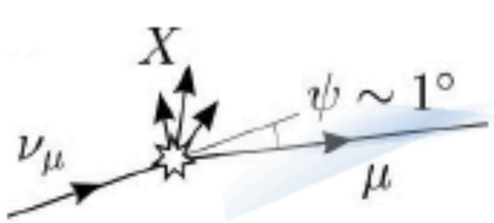
extra terrestrial neutrino fluxes

Event topologies in IceCube

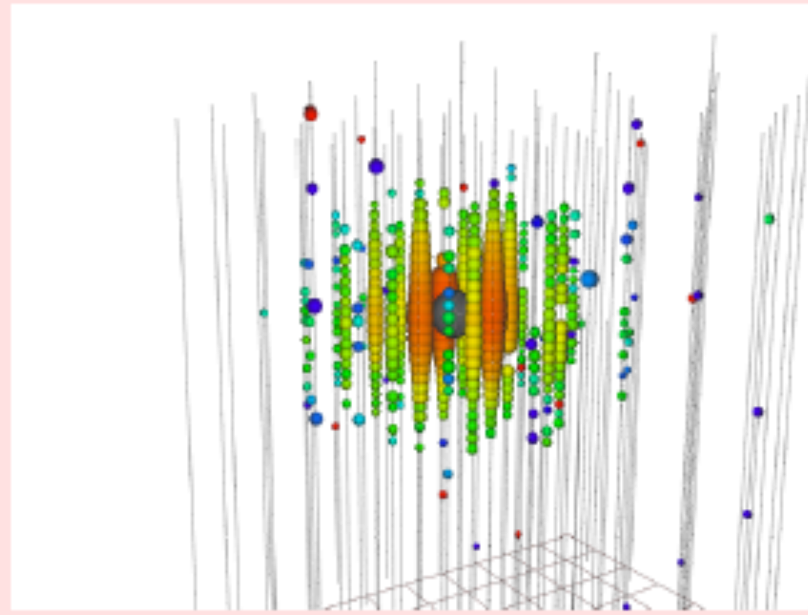
Track



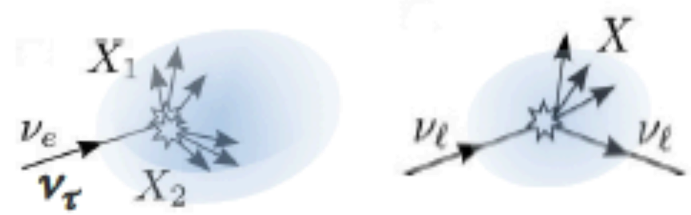
- Muon tracks (CC ν_μ)
- Resolution $< 1°$
- Large energy uncertainties



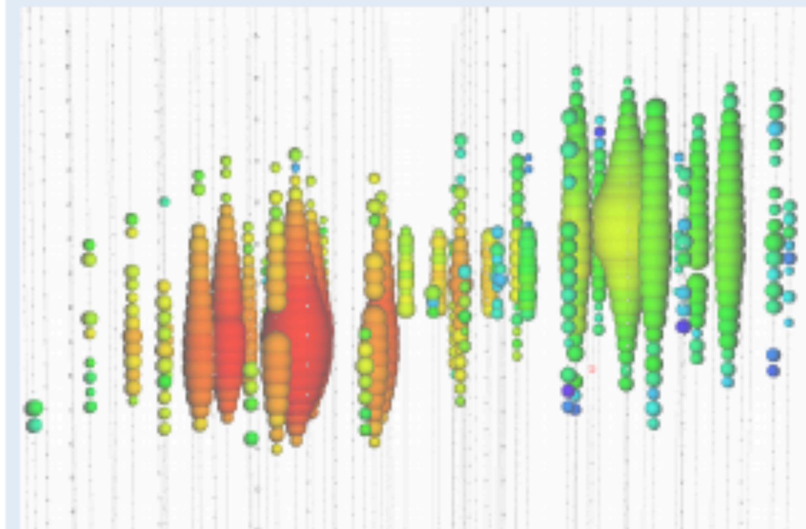
Cascade



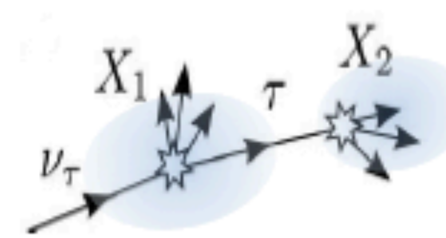
- NC or ν_e/ν_τ
- Resolution $\approx 15° - 20°$
- Energy resolution $\delta E/E \approx 15\%$



Double-bang



- High energy ν_τ (>100 TeV)
- Not observed yet



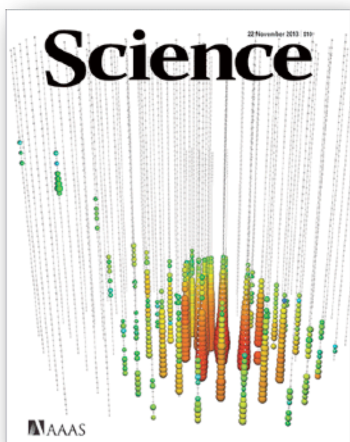
amount of light in detector ∝ ν energy

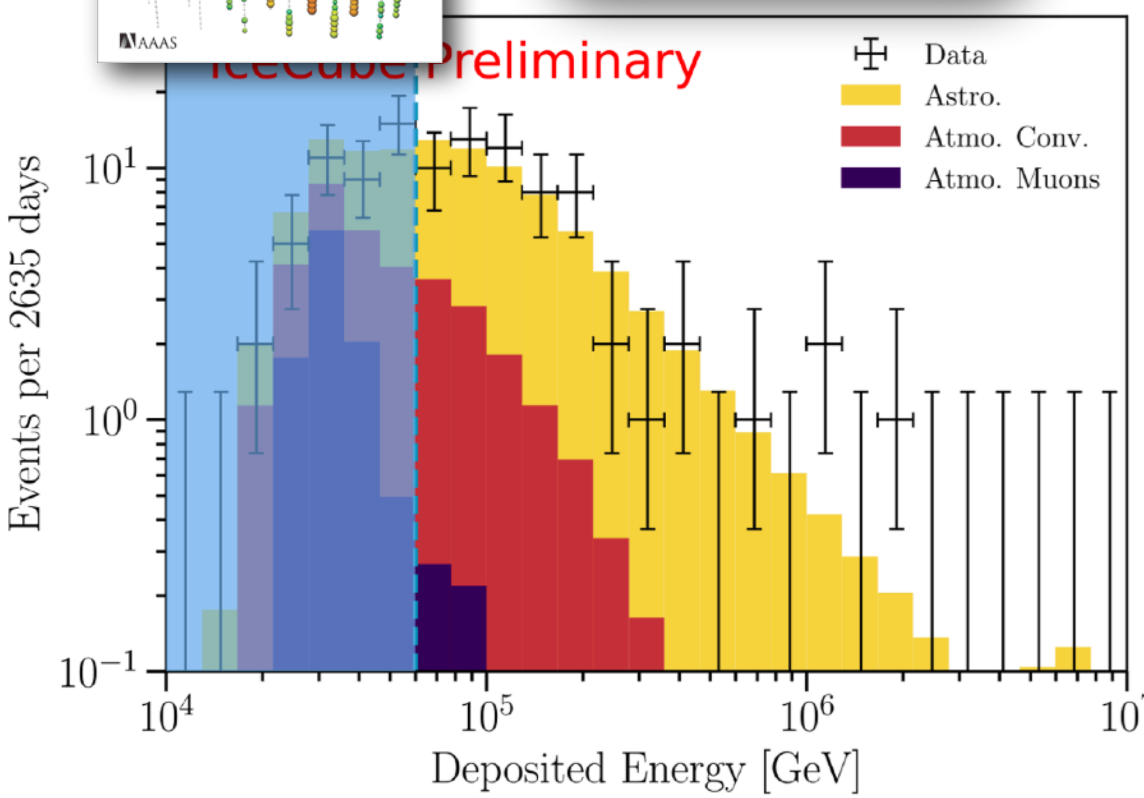
New Window to the Universe !

2002

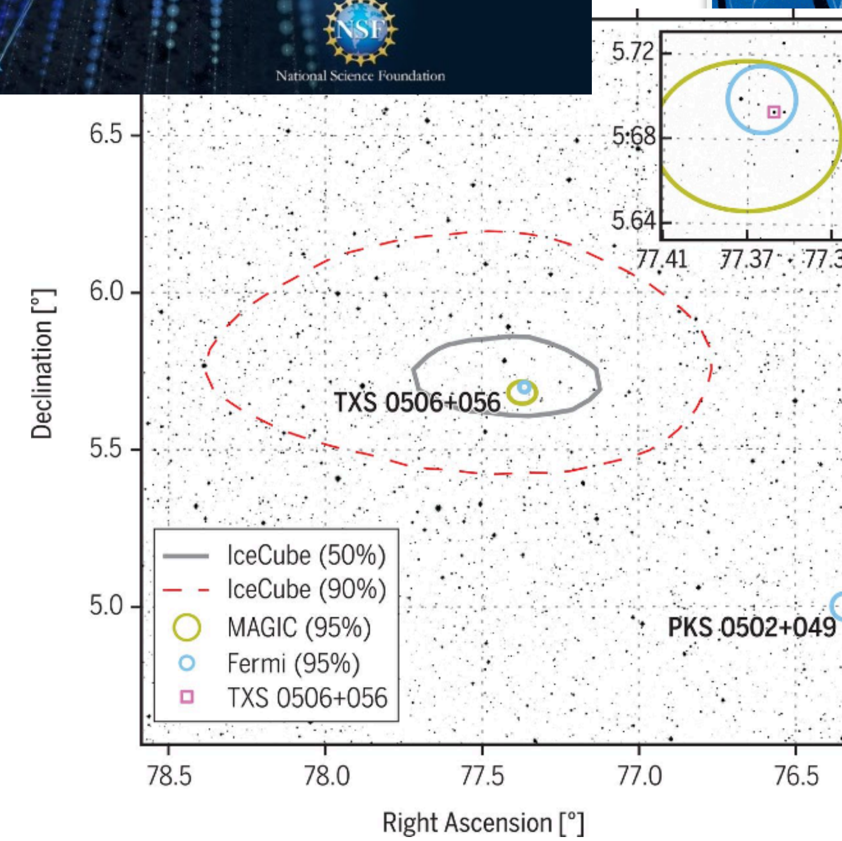
Following the observation of supernova burst neutrinos in 1987, *neutrino astronomy is becoming a reality quickly now …*

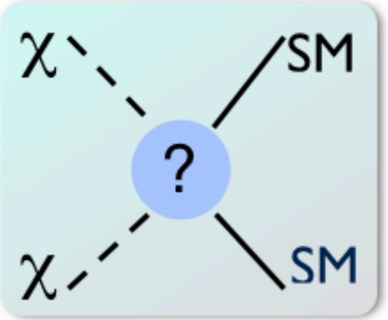
2013 Discovery of diffuse astrophysical neutrino flux





2018 Neutrino multi-messenger astroparticle physics





DM Annihilation searches

ν from SM particle decay, direct neutrinos helicity suppressed

- Galactic Center
- Galactic Halo
- Dwarf Spheroidals
- Galaxy clusters
- …

Self-annihilation cross section **<σv>**

DM Mass $\mathbf{m}_\chi$ (Branching fractions)

Dark Matter Self-annihilations

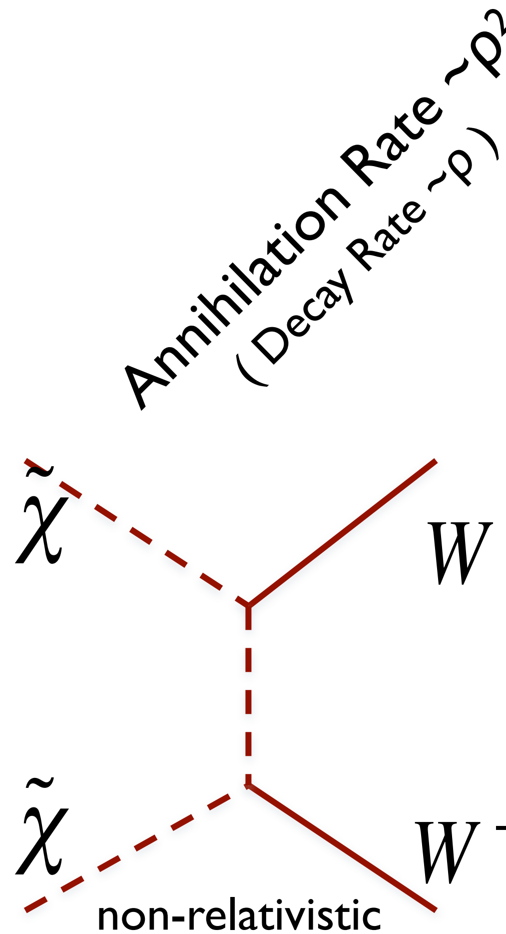
$<\sigma_A v>$

Dark Matter Signals

- Identify overdense regions of dark matter

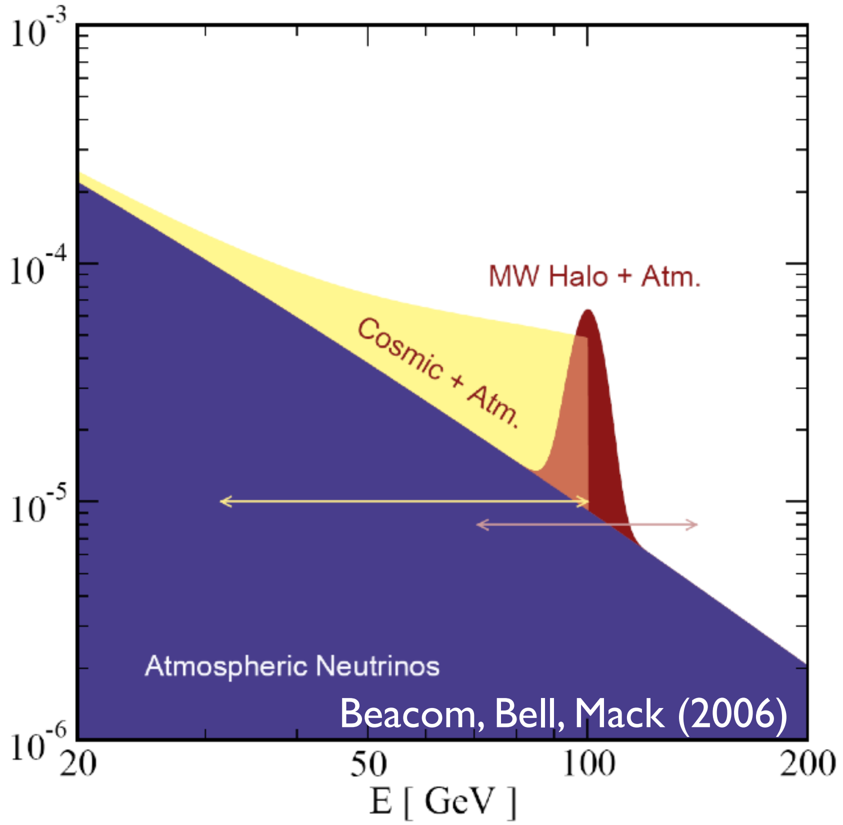
  ⇒self-annihilation can occur at significant rates

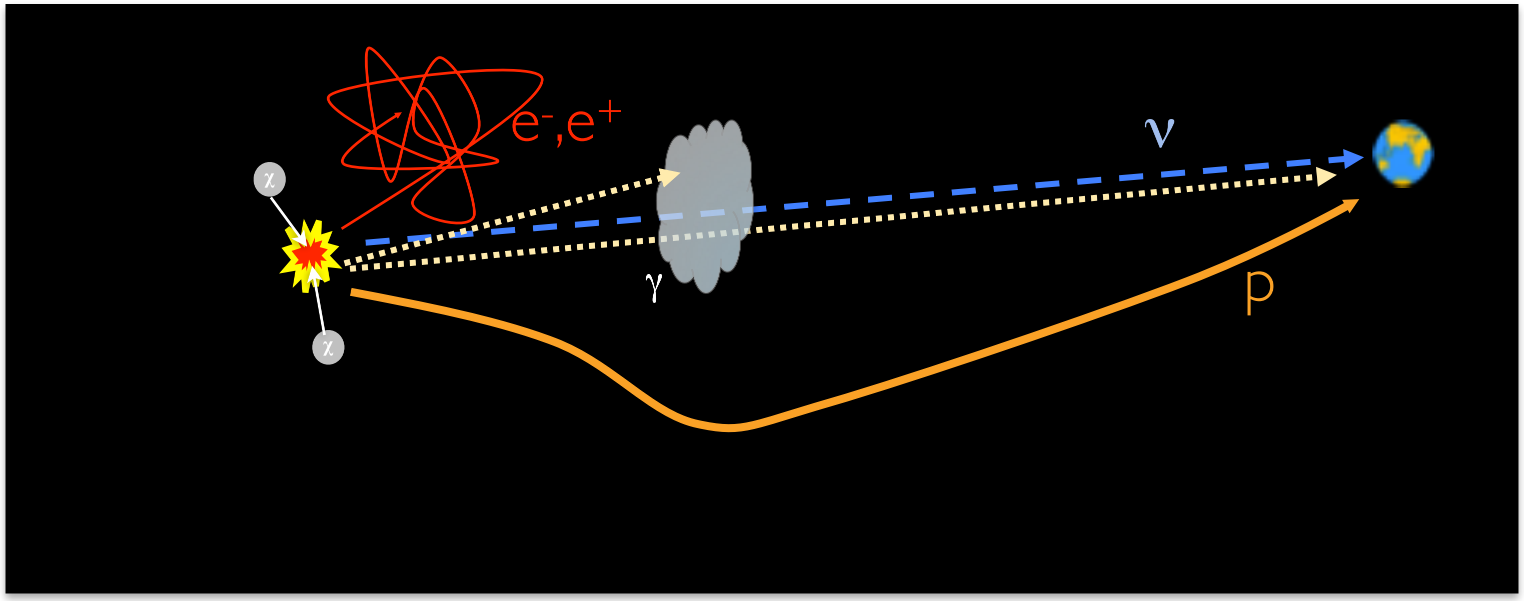
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds



$$\tilde{\chi} \quad W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \upsilon, \gamma, p, D, \ldots$$

$$\tilde{\chi} \quad W^-, Z, \tau^-, \bar{b}, \ldots \Rightarrow e^\mp, \upsilon, \gamma, \bar{p}, D, \ldots$$





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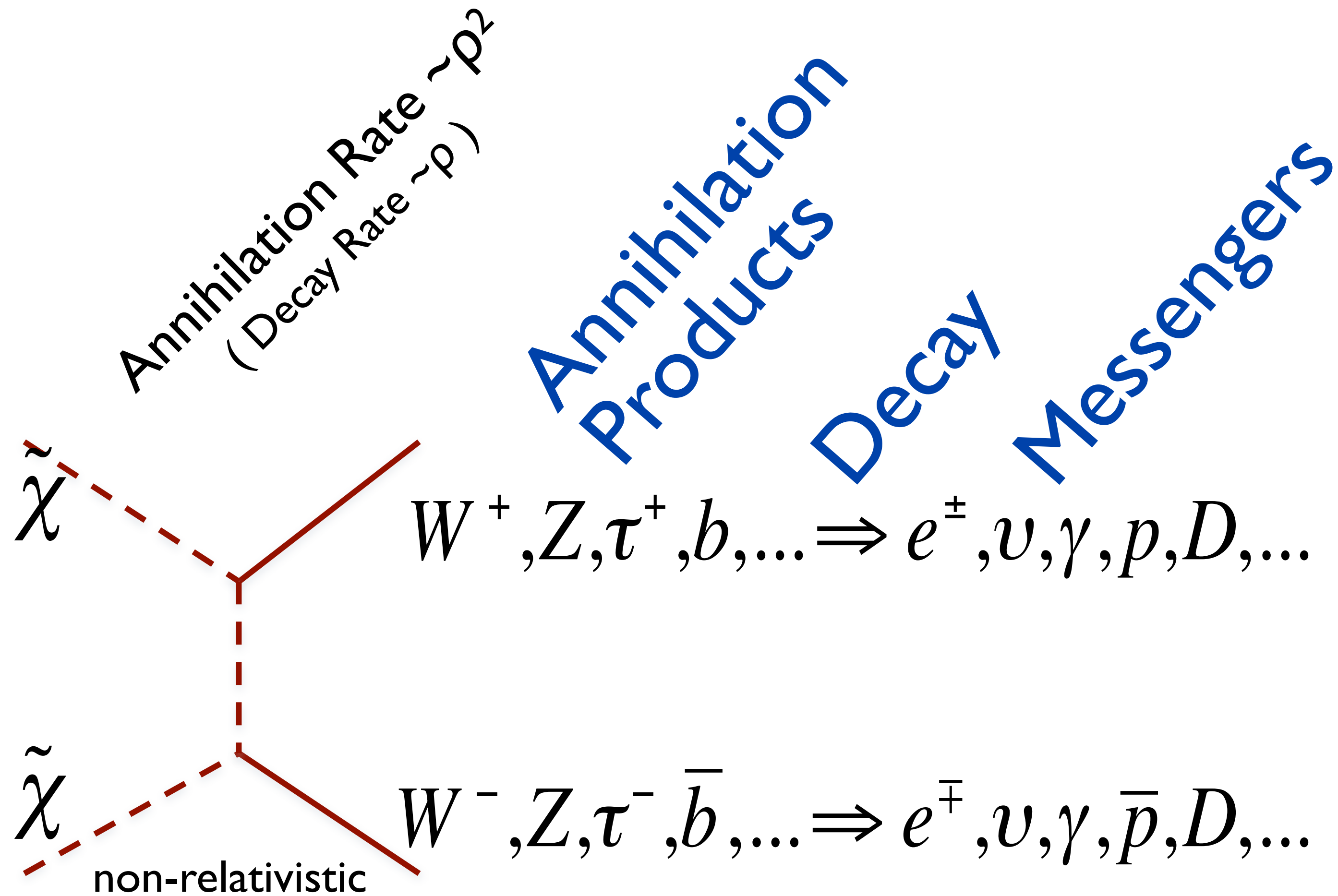
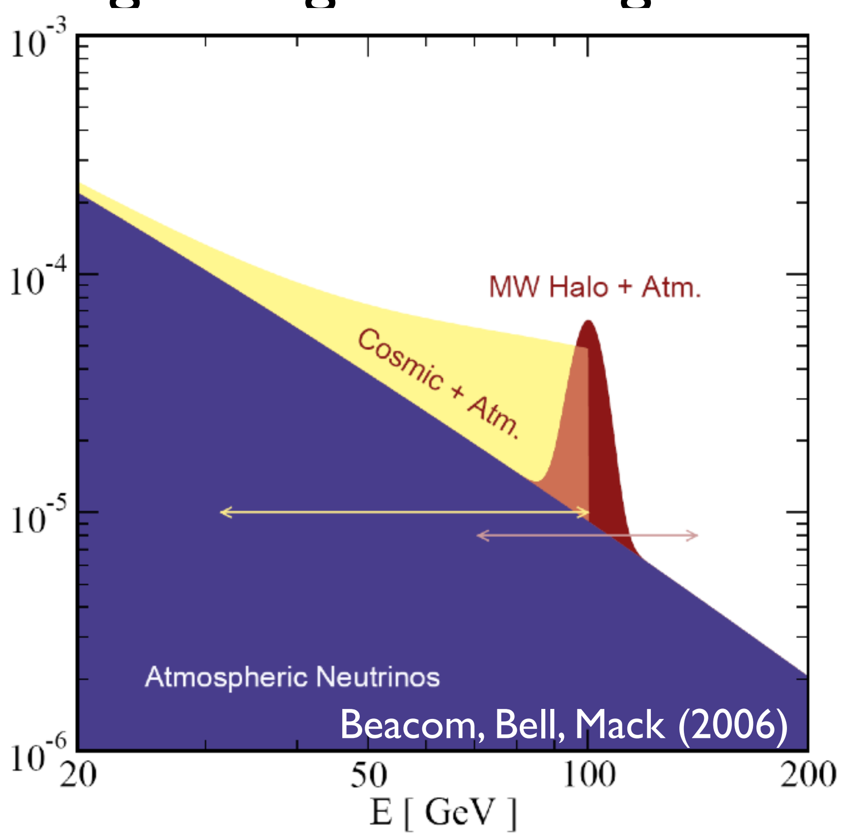
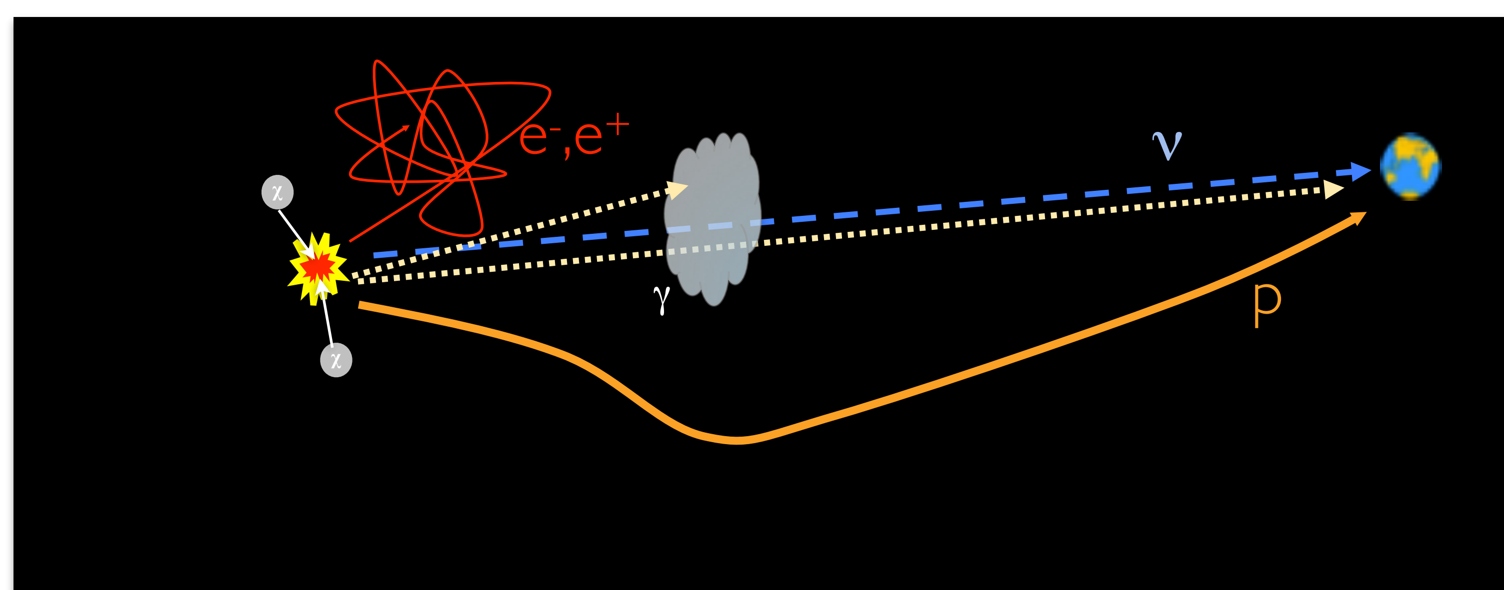


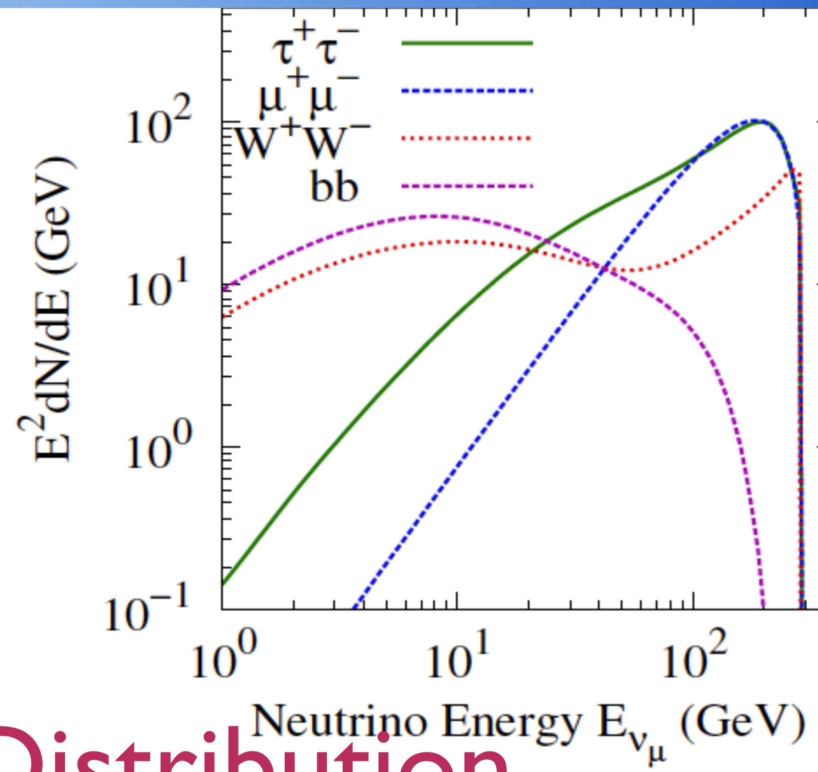




Dark Matter Annihilation

Measure Flux = **Particle Physics** × **Dark Matter Distribution**

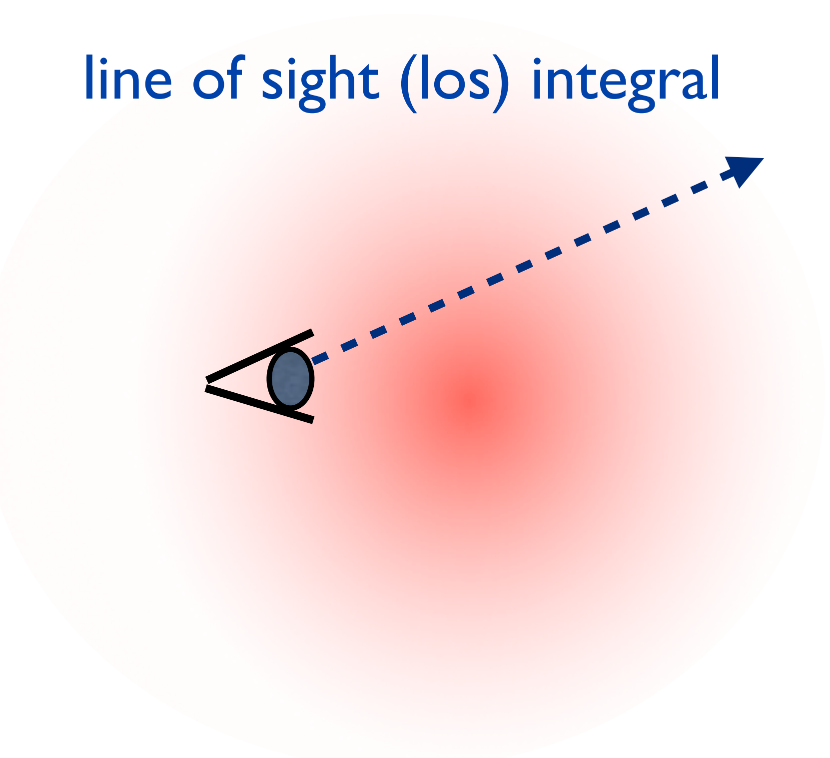
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f$$

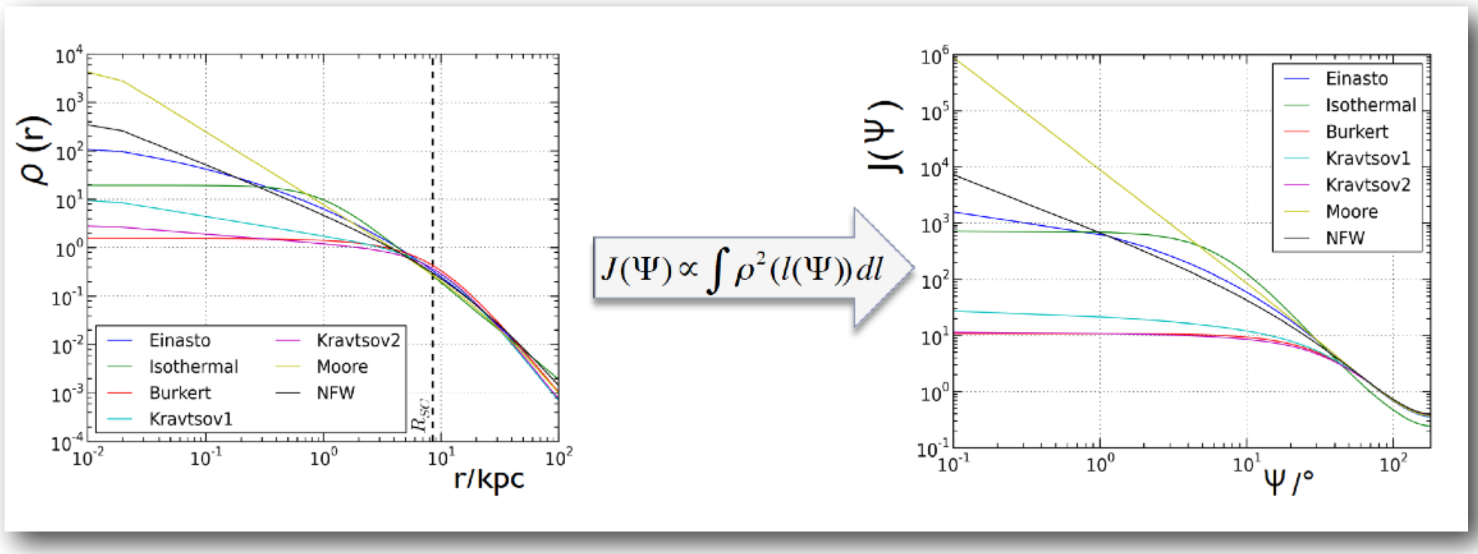


×

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

line of sight (los) integral





Dark Matter Annihilation

Measure Flux

Particle Physics

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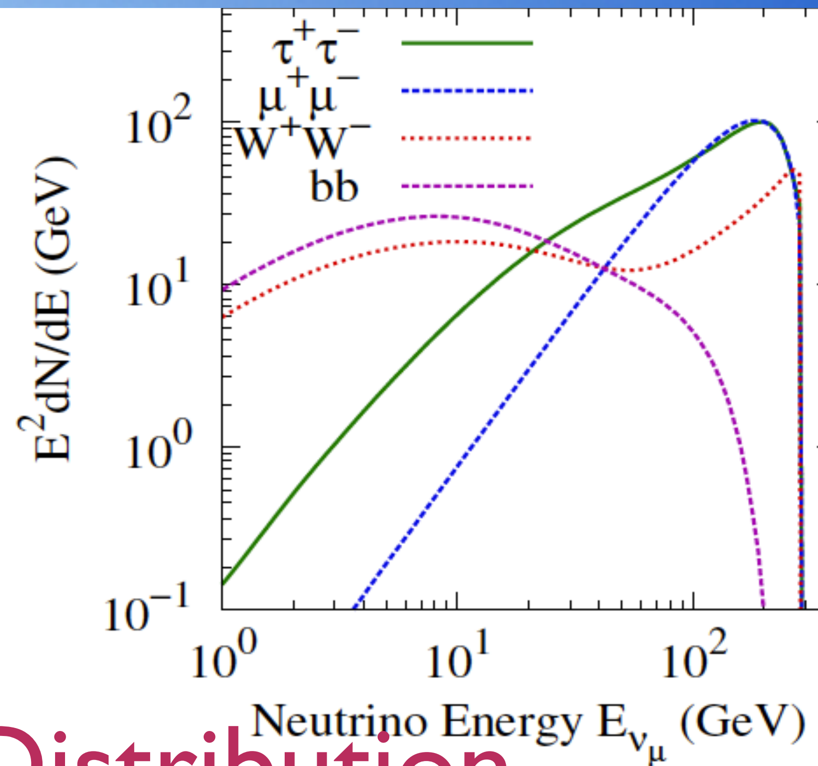
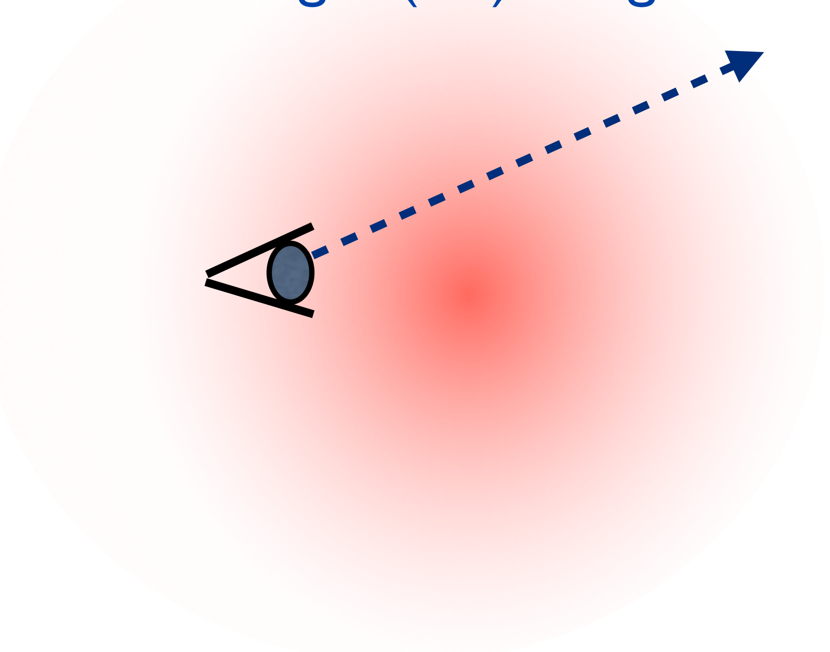


×

Dark Matter Distribution

line of sight (los) integral



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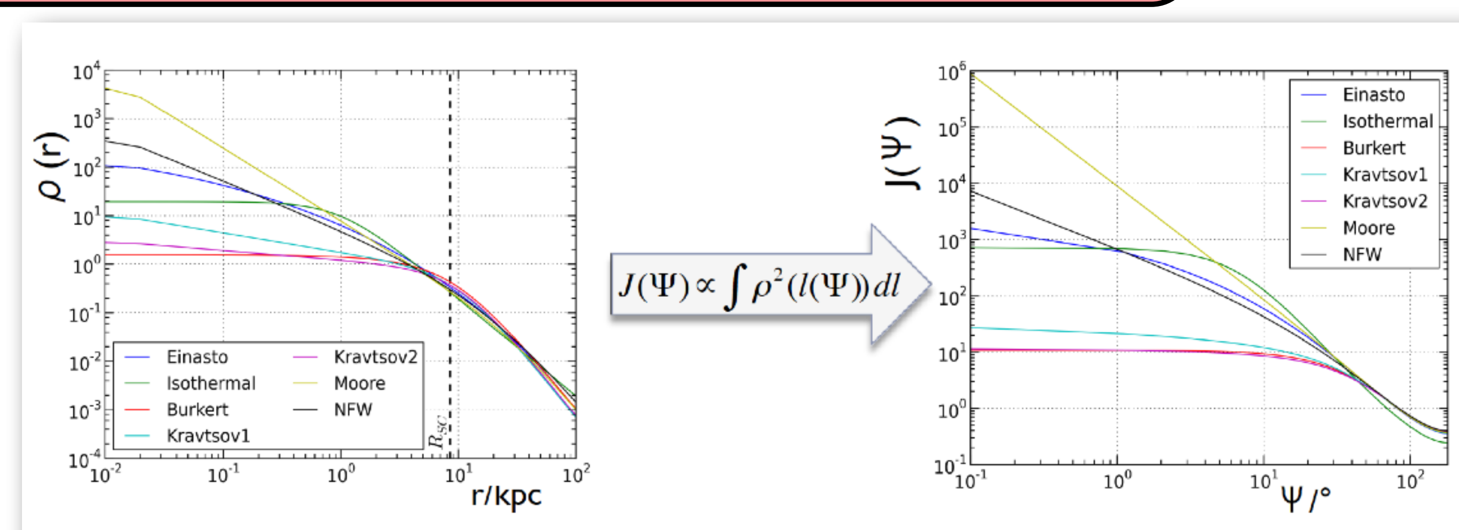
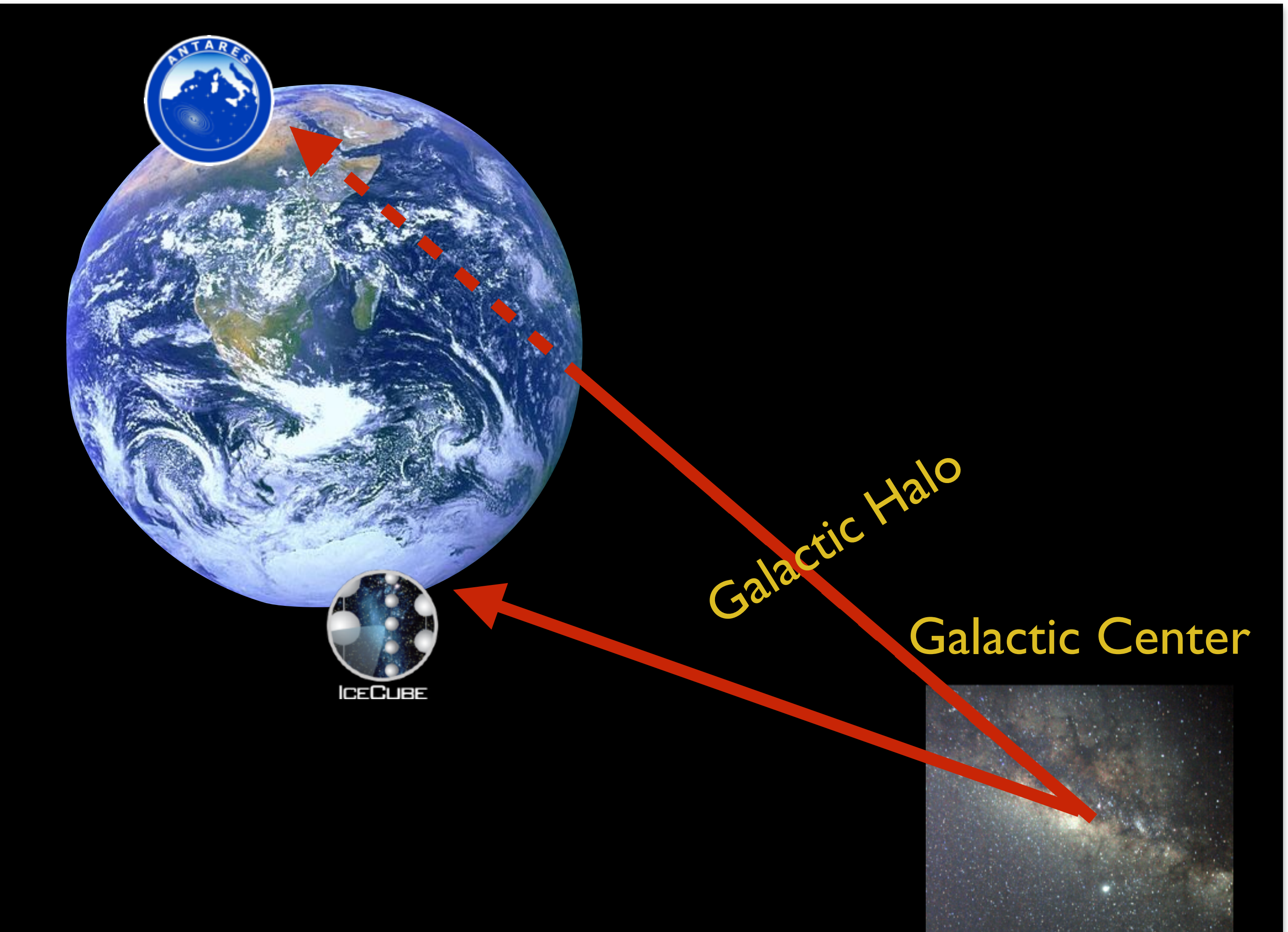
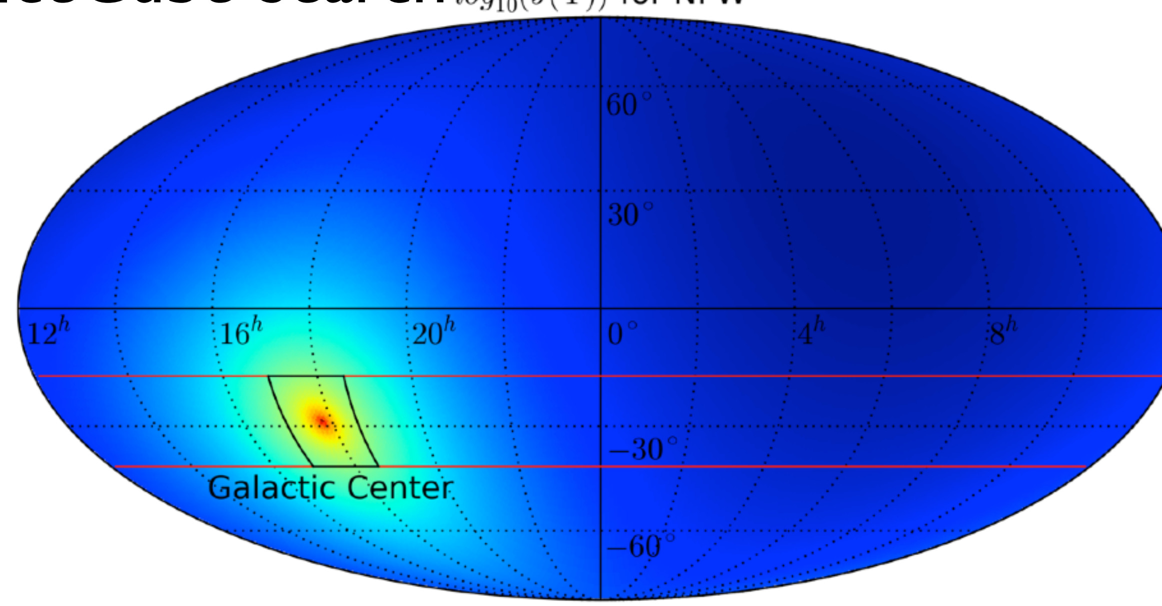


INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES



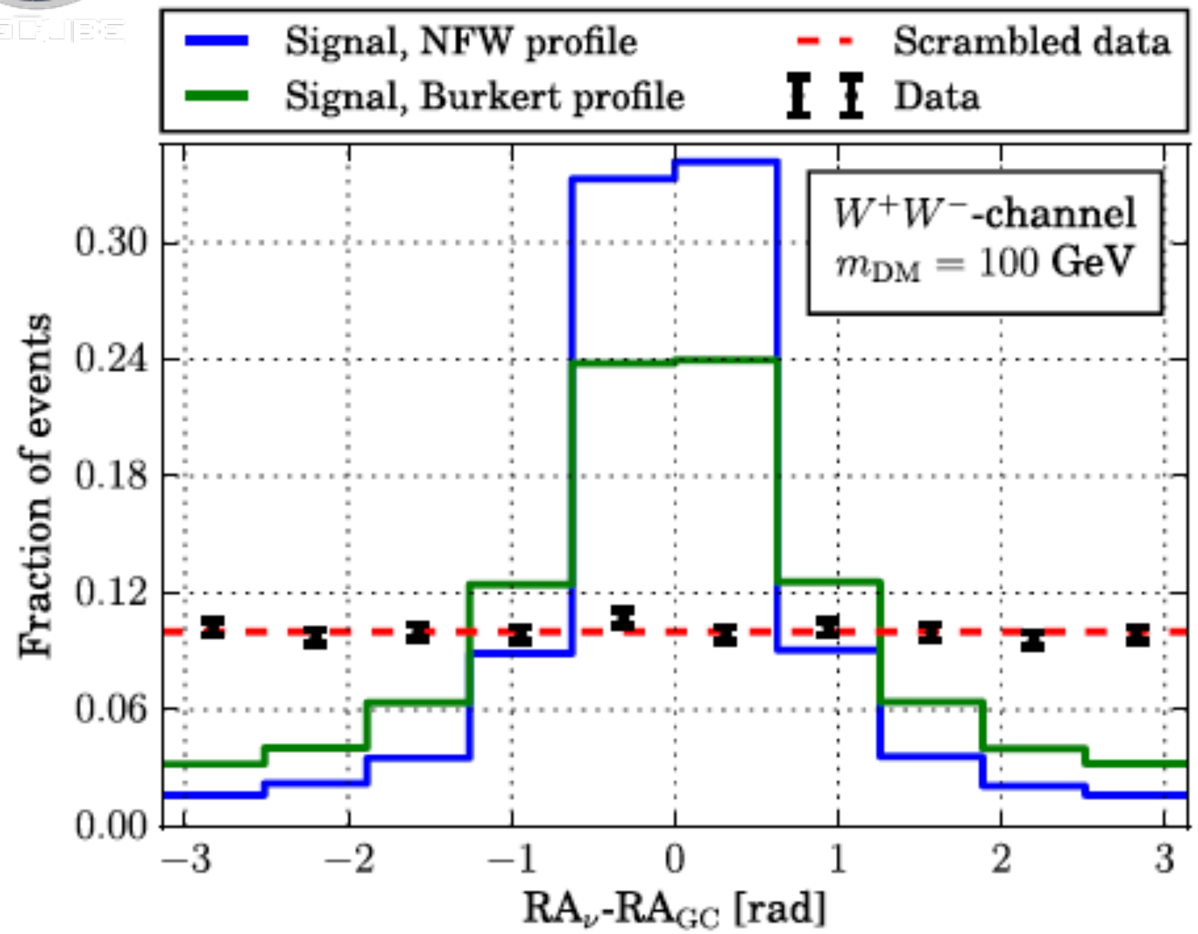
IceCube Search



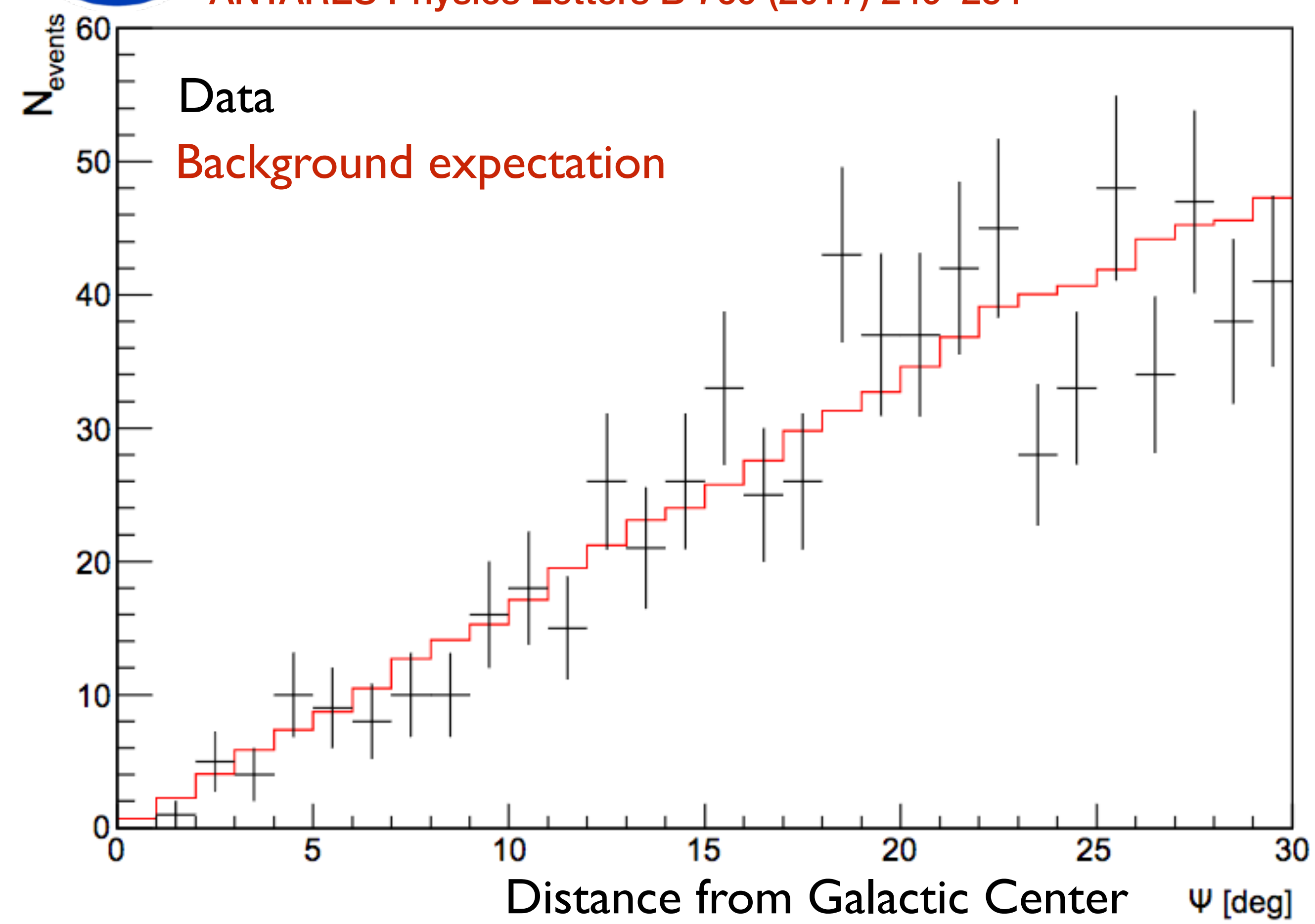
- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

IceCube Eur. Phys. J. C (2017) 77: 627



ANTARES Physics Letters B 769 (2017) 249–254



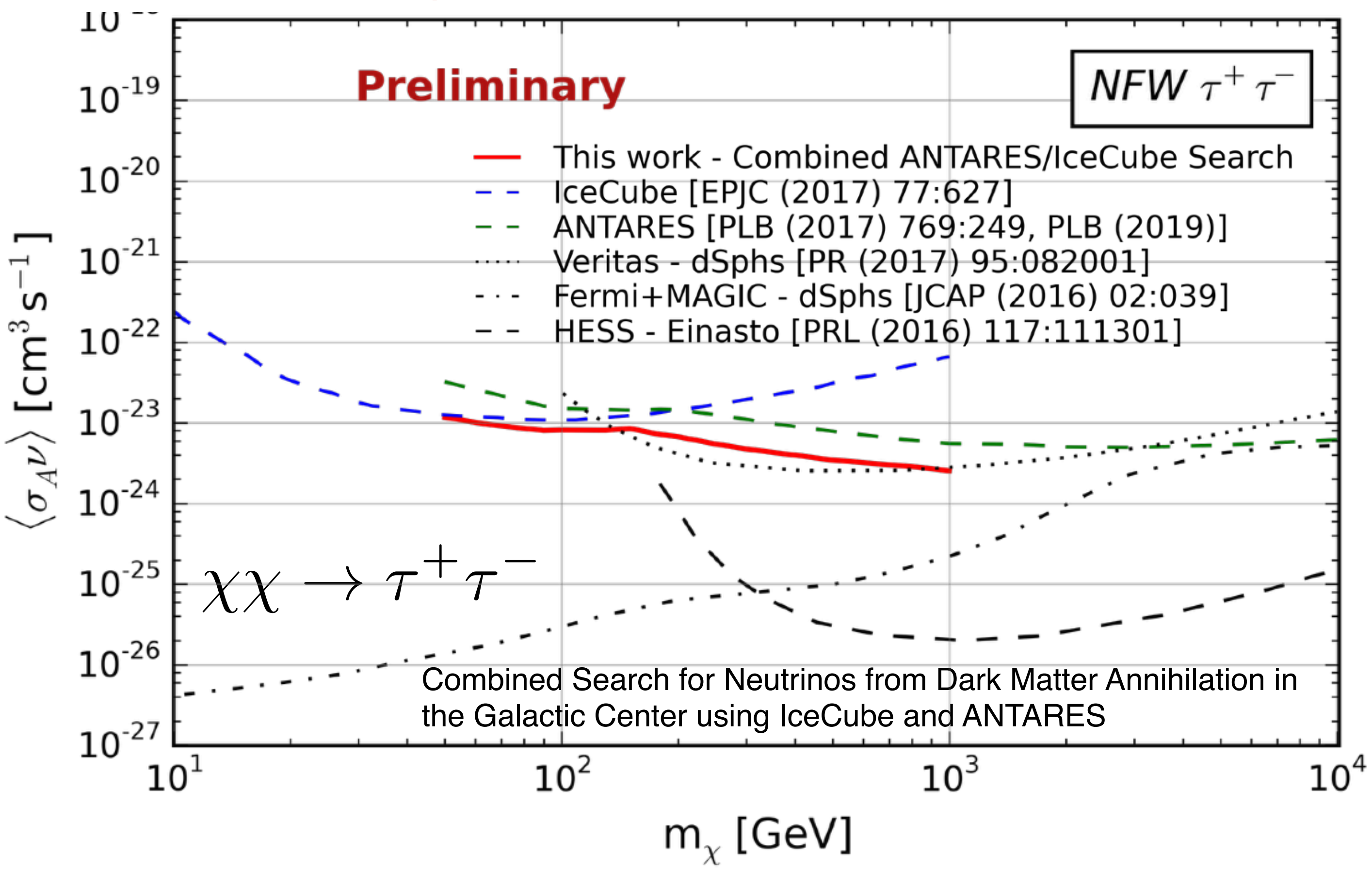
Search for DM annihilation in the Galactic Halo (IceCube) and Galactic Center (ANTARES)

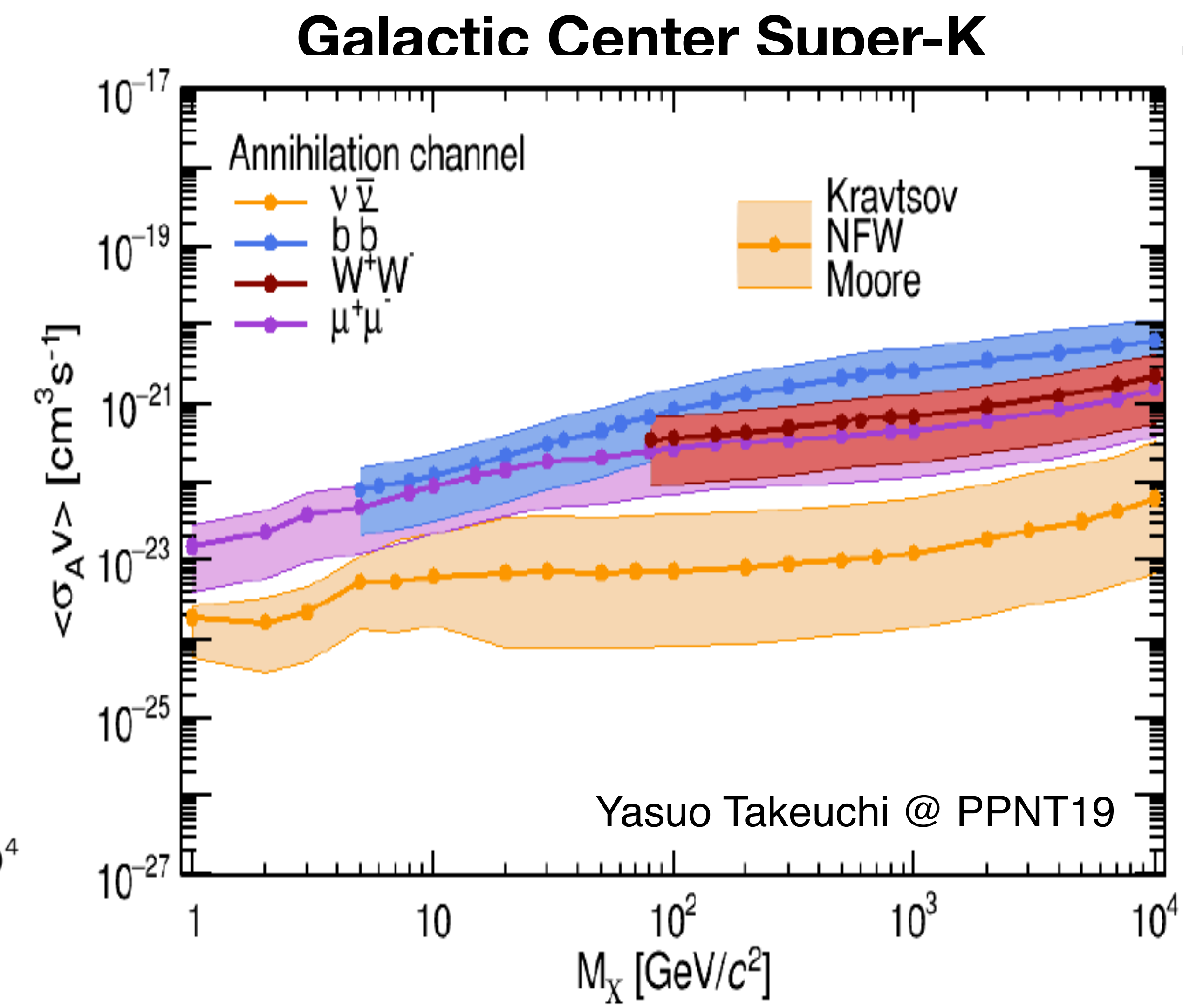
Observations consistent with background expectations

Galactic Center / Galactic Halo - IceCube/ ANTARES/Super-K

Nadège Iovine [ANTARES & IceCube] PoS(ICRC2019) 1177

ANTARES/IceCube Combined Exclusion Limit





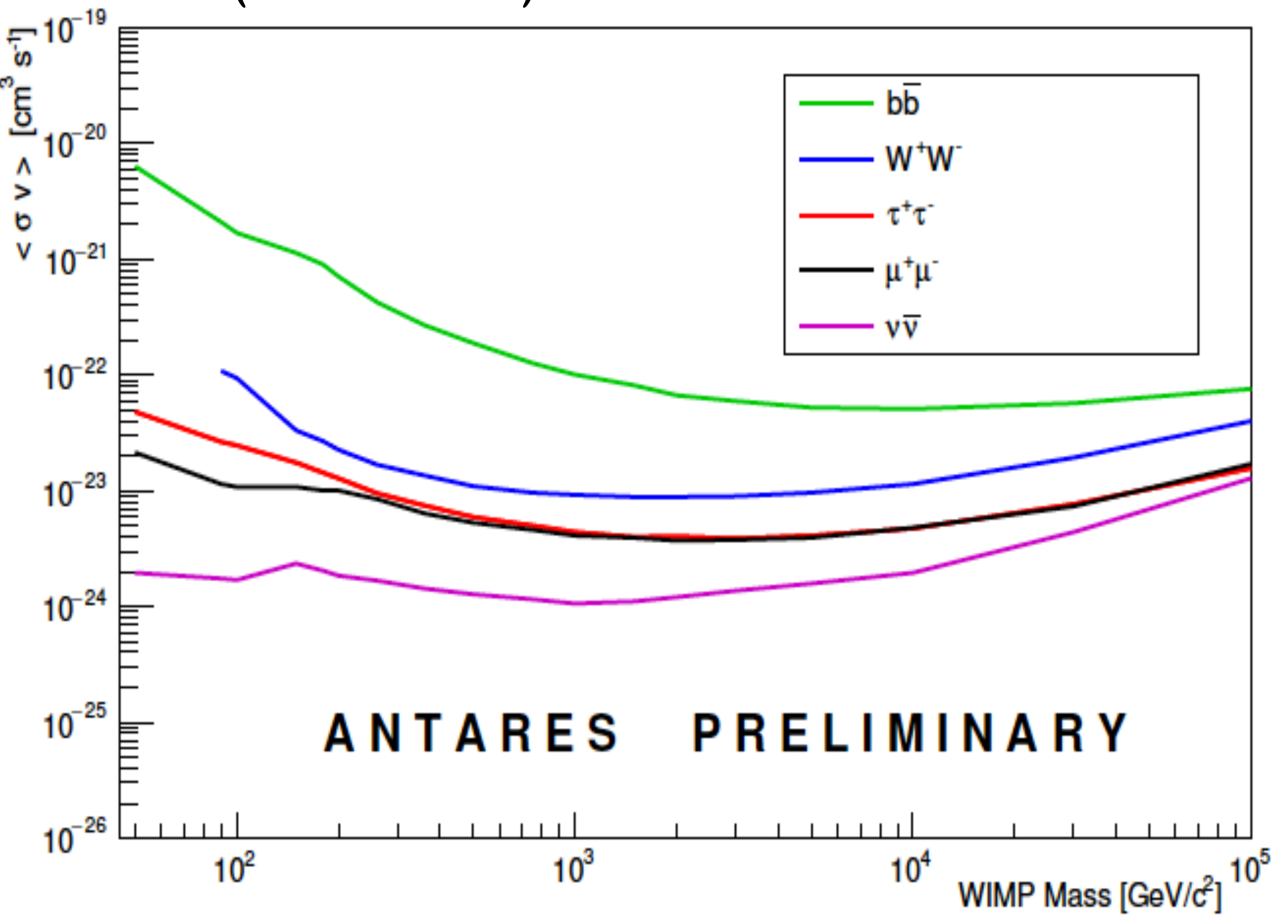
- Combined analysis enhances sensitivity in overlap region and helps to make analyses more comparable
- Very competitive result from Super-K for dark matter masses below a 100GeV

Neutrino searches have been important test to probe models motivated by observations with other messengers (example the cosmic-ray positron excess (PAMELA, AMS-02, …))

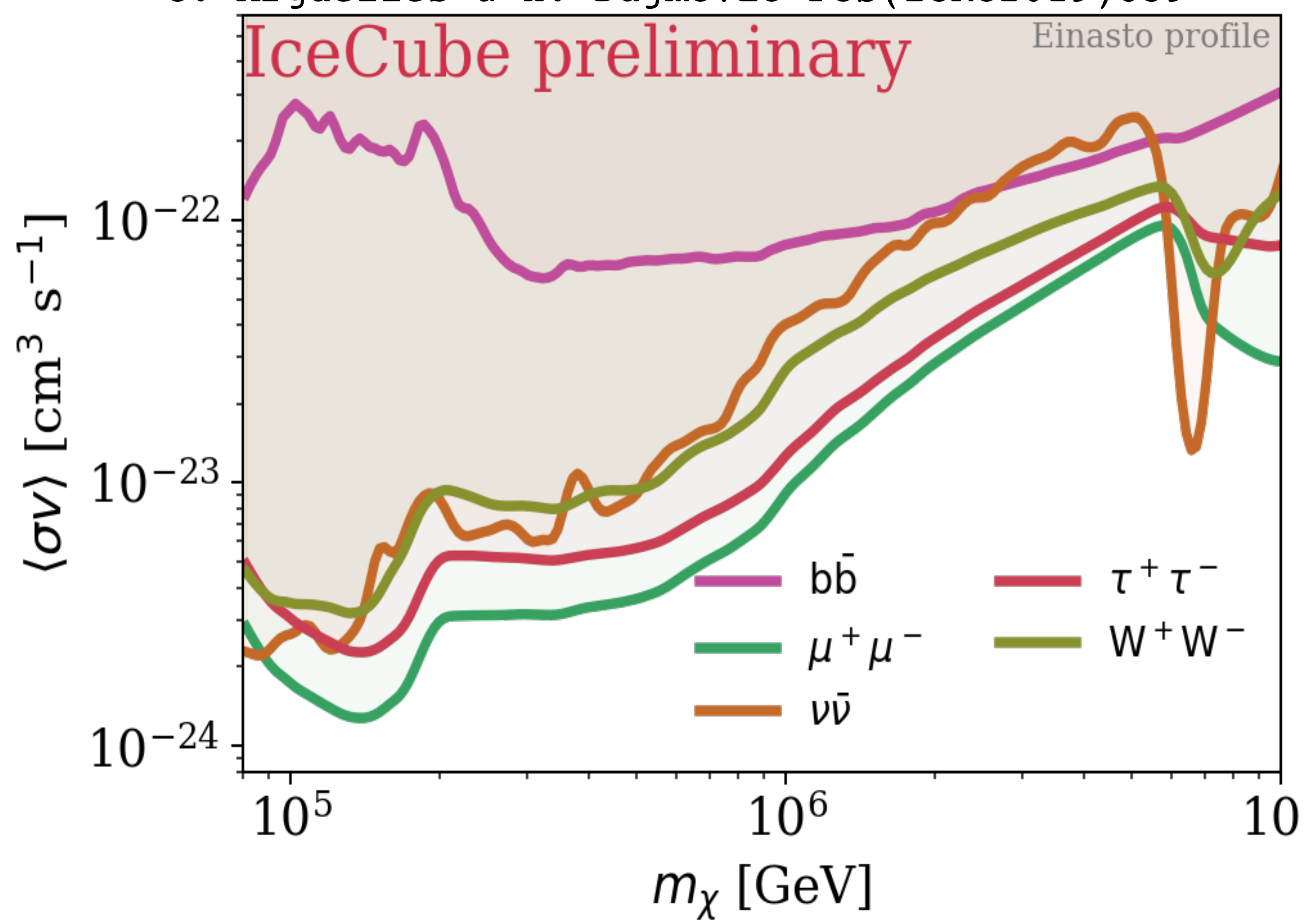
Low mass DM difficult to probe with neutrinos - strong bounds from gamma-rays

Search DM Annihilation with IceCube's 7years HESE Sample

[ANTARES/KM3NeT Collaborations] PoS(ICRC2019)552

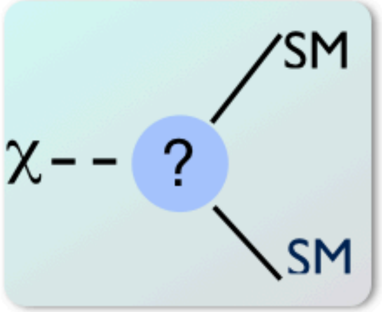


C. Arguelles & H. Dujmovic PoS(ICRC2019)839



- 11 years of ANTARES data
  - Upgoing muon tracks
- Improved statistics compared to previous searches

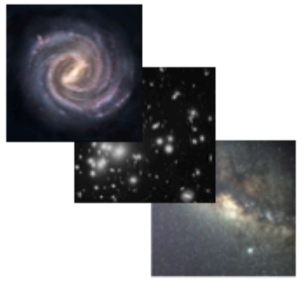
- 7 years of IceCube's HESE (High Energy Starting Events) Sample
  - Events with energies above >60TeV
- Binned likelihood analysis
- Improve neutrino bounds above 100TeV and extend to high masses



DM Decay searches

ν from SM particle decay or directly produced

- Extragalactic
- Galactic Halo
- Galaxy clusters
- …



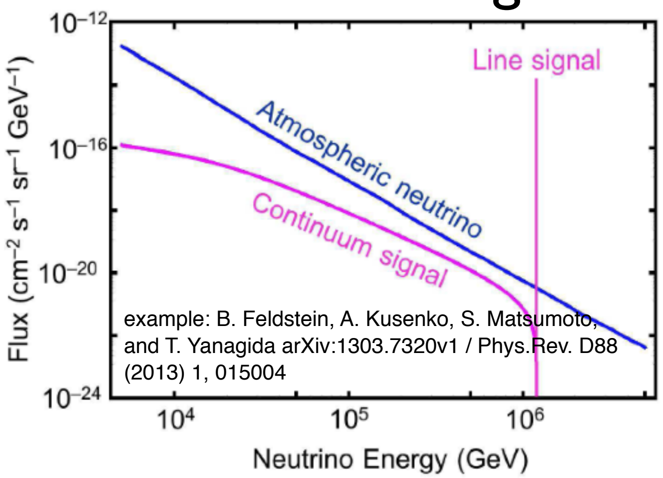
DM Lifetime τ_χ

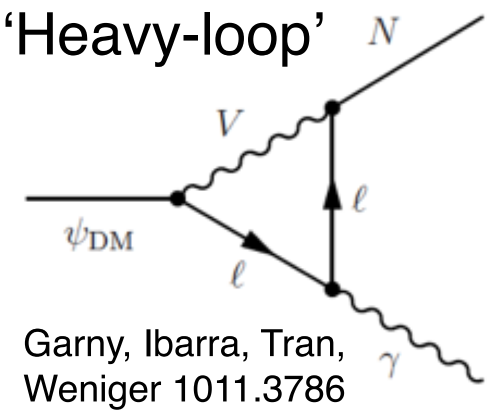
DM Mass $\mathbf{m}_\chi$
(Branching fractions)

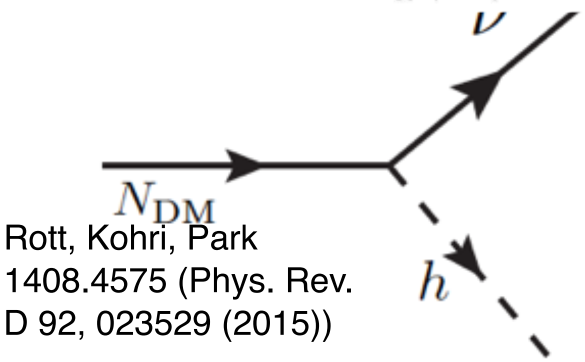
Dark Matter Decay

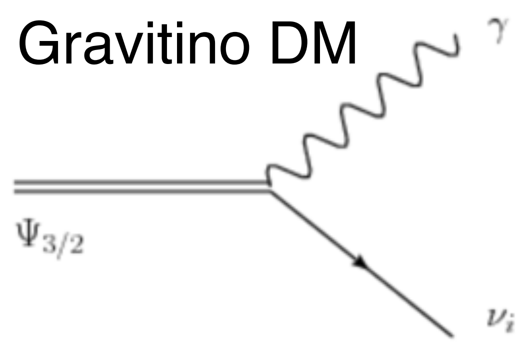
Heavy Dark Matter Decay

Decay process might produce mono-energetic neutrinos

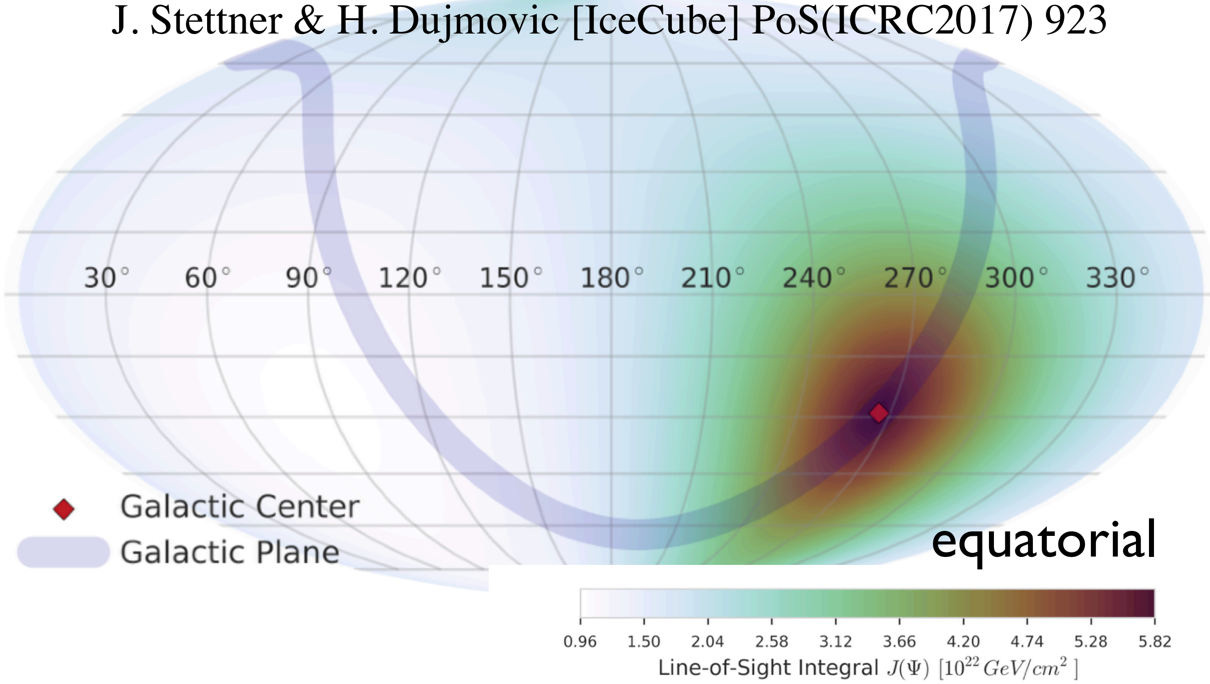








J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923



Two flux contributions: Galactic and Extra galactic

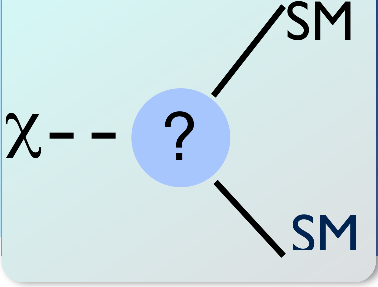
$$\frac{d\Phi_{DM,\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu}$$

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

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

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

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



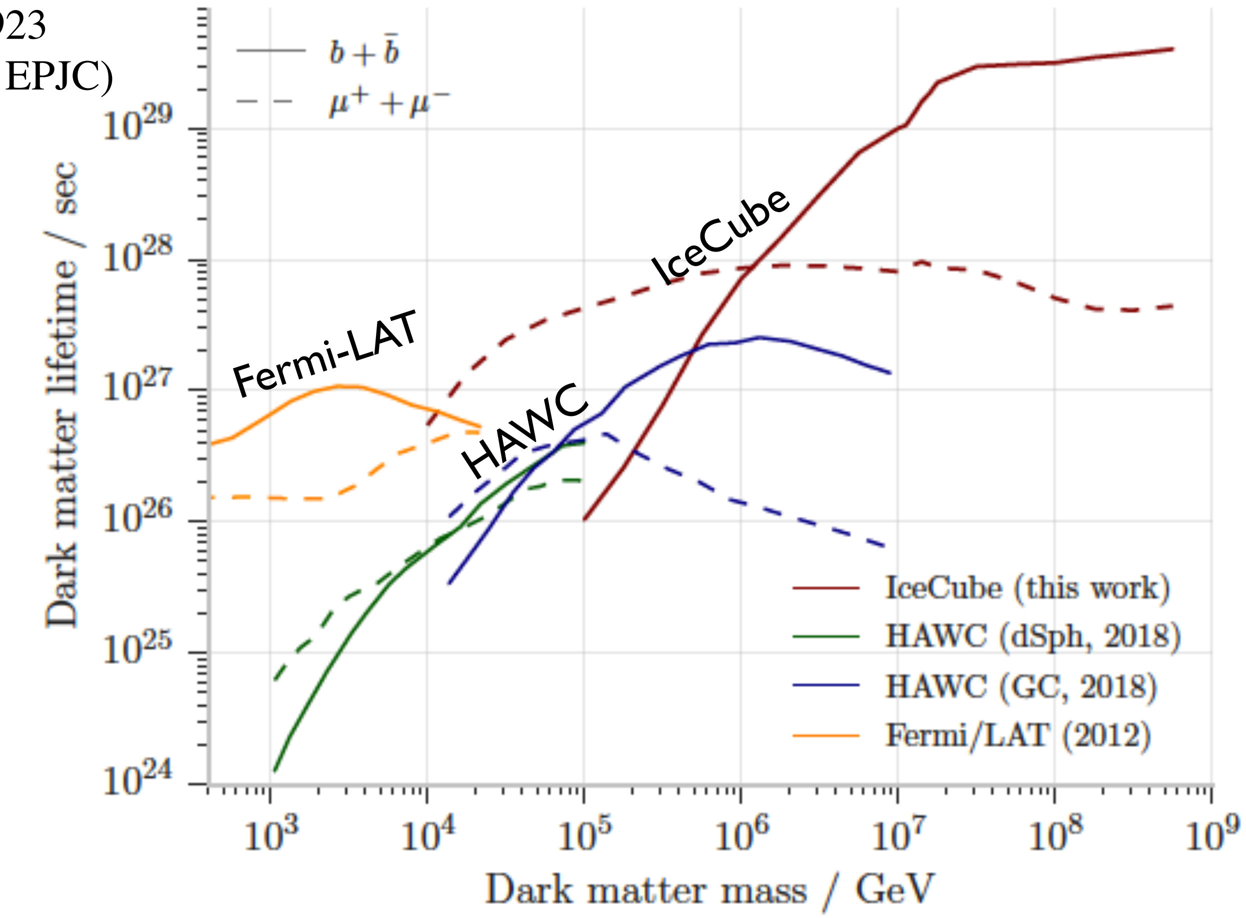
Dark Matter Decay with IceCube

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

- 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_ν > 100 TeV)	~ 10°
Energy uncertainty	~ 100%	~ 10%

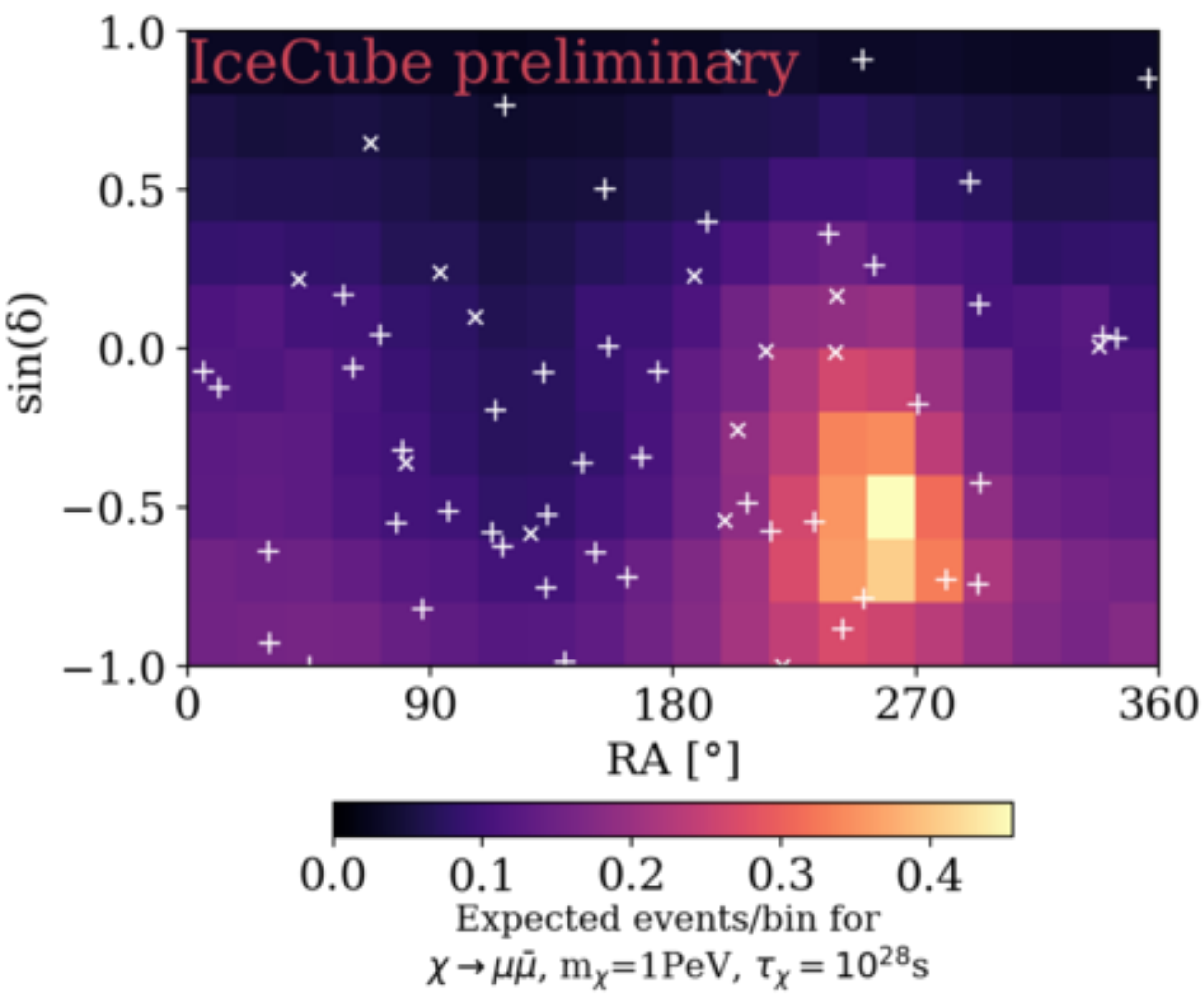
Test-Statistic: $$TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM} = \infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$$

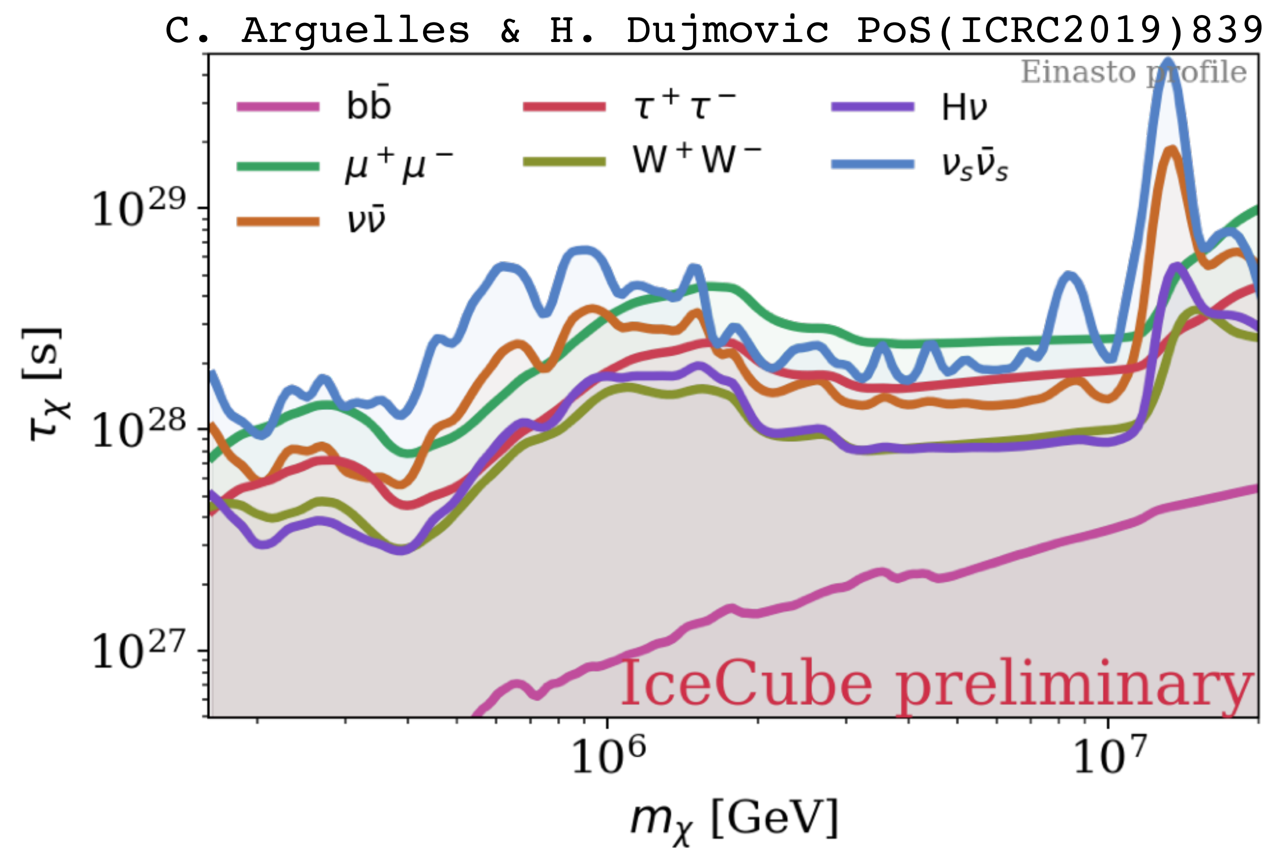


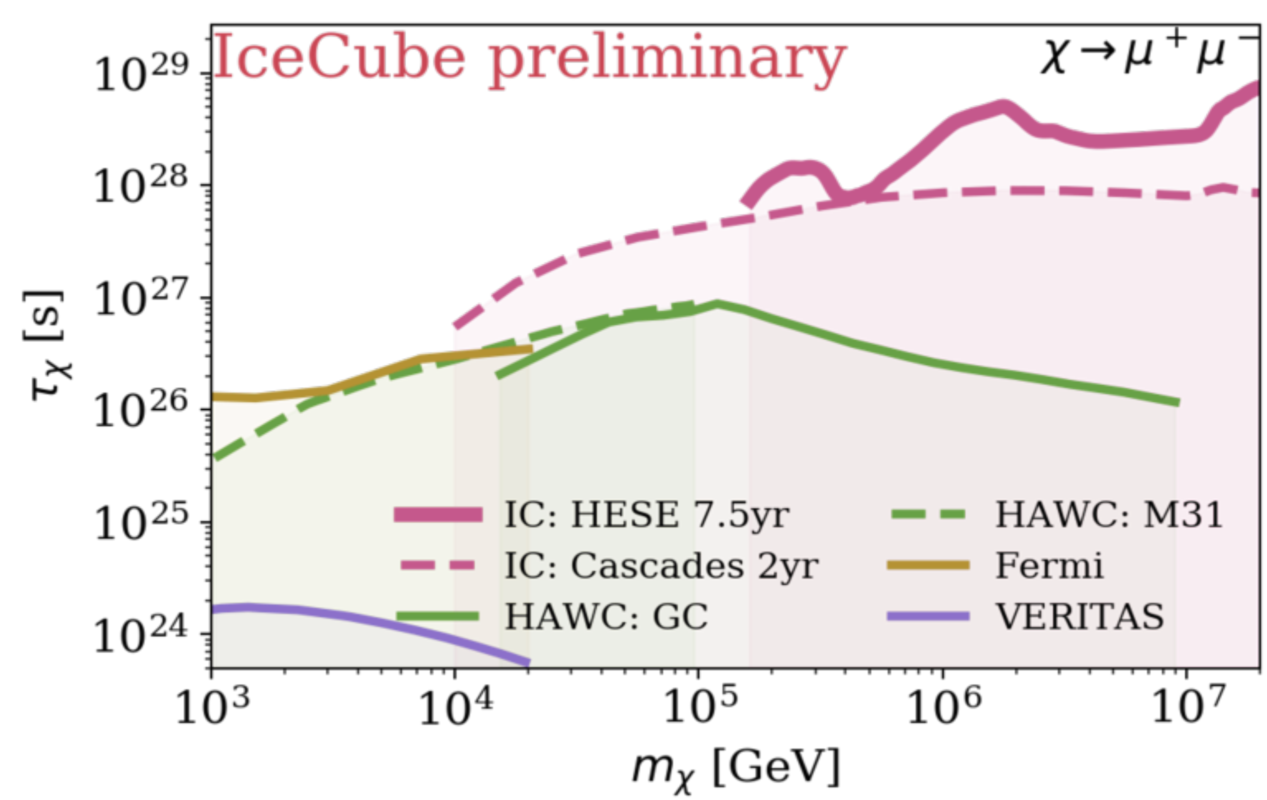
Bound on DM lifetime at ~10^{27}s obtained with IceCube data for m_{DM}>10TeV

- 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

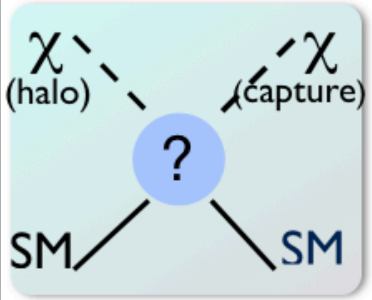
Search DM Decay with IceCube's 7years HESE Sample







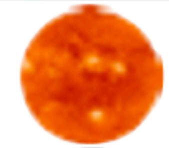
- 7 years of IceCube's HESE (High Energy Starting Events) Sample
  - Events with energies above >60TeV
- Binned likelihood analysis
- Most competitive limits above 100TeV for a large number of channel



DM Nucleon scattering

Following χ capture, annihilation.
Once annihilation and capture in balance (equilibrium) - no dependence on **<σv>**

- Sun
- Earth

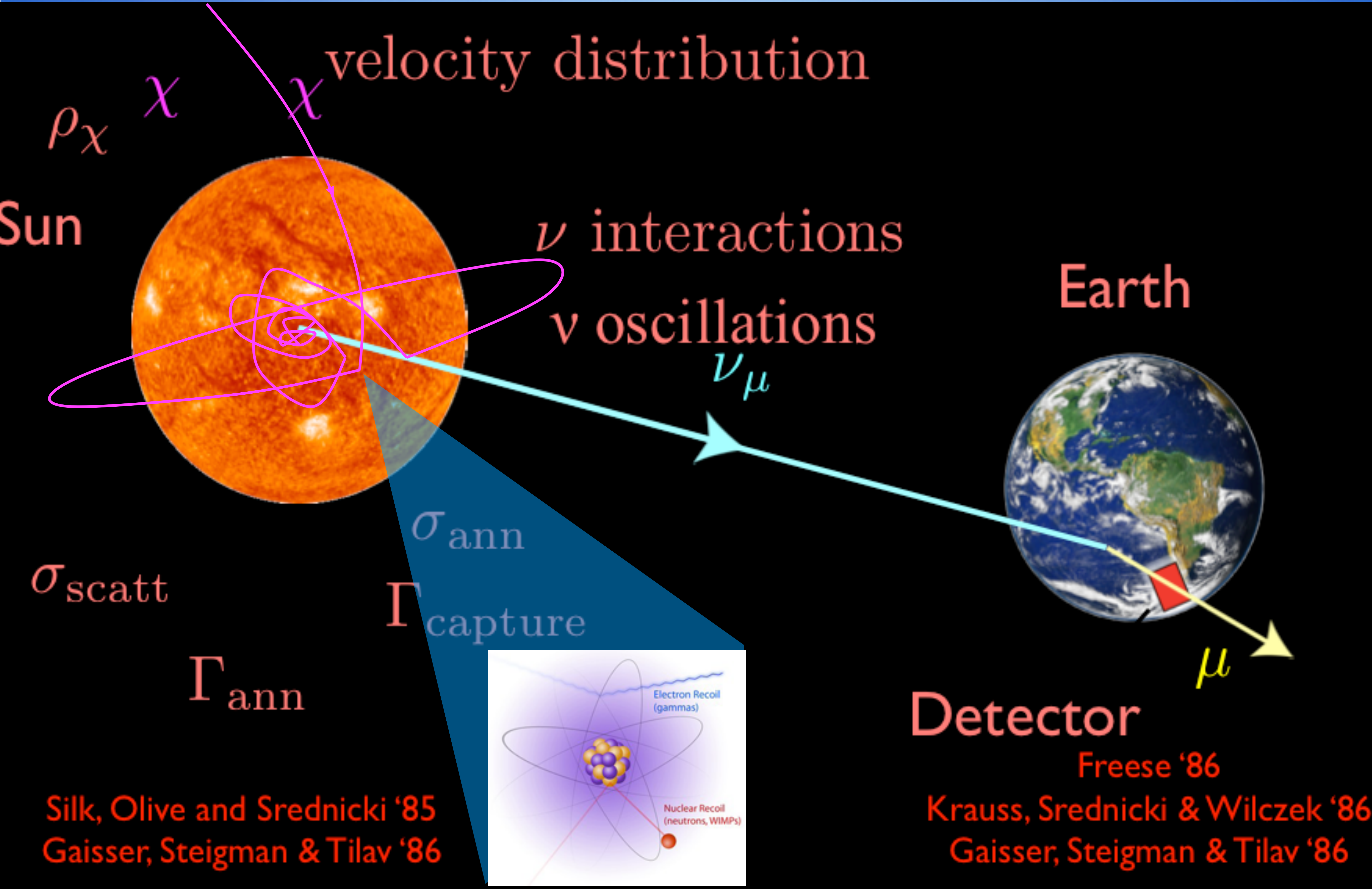


DM-Nucleon scattering cross section $\boldsymbol{\sigma}^{SD}$ / $\boldsymbol{\sigma}^{SI}$

DM Mass $\mathbf{m}_\chi$
(Branching fractions)

Dark Matter Capture in the Sun

Solar Dark Matter

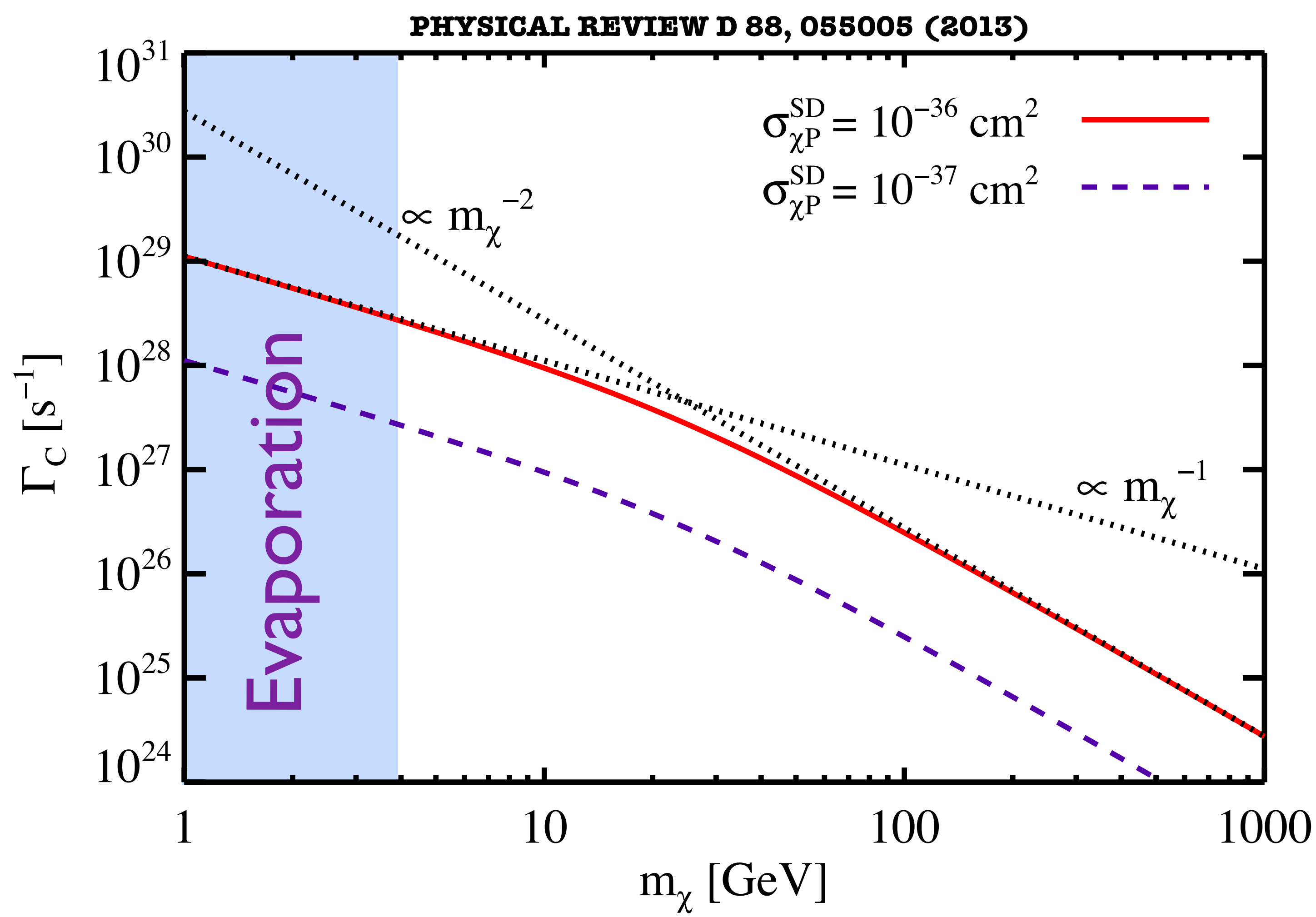


Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

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

Solar Dark Matter Capture

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



The capture rates scales as:

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

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

number density + kinematic suppression

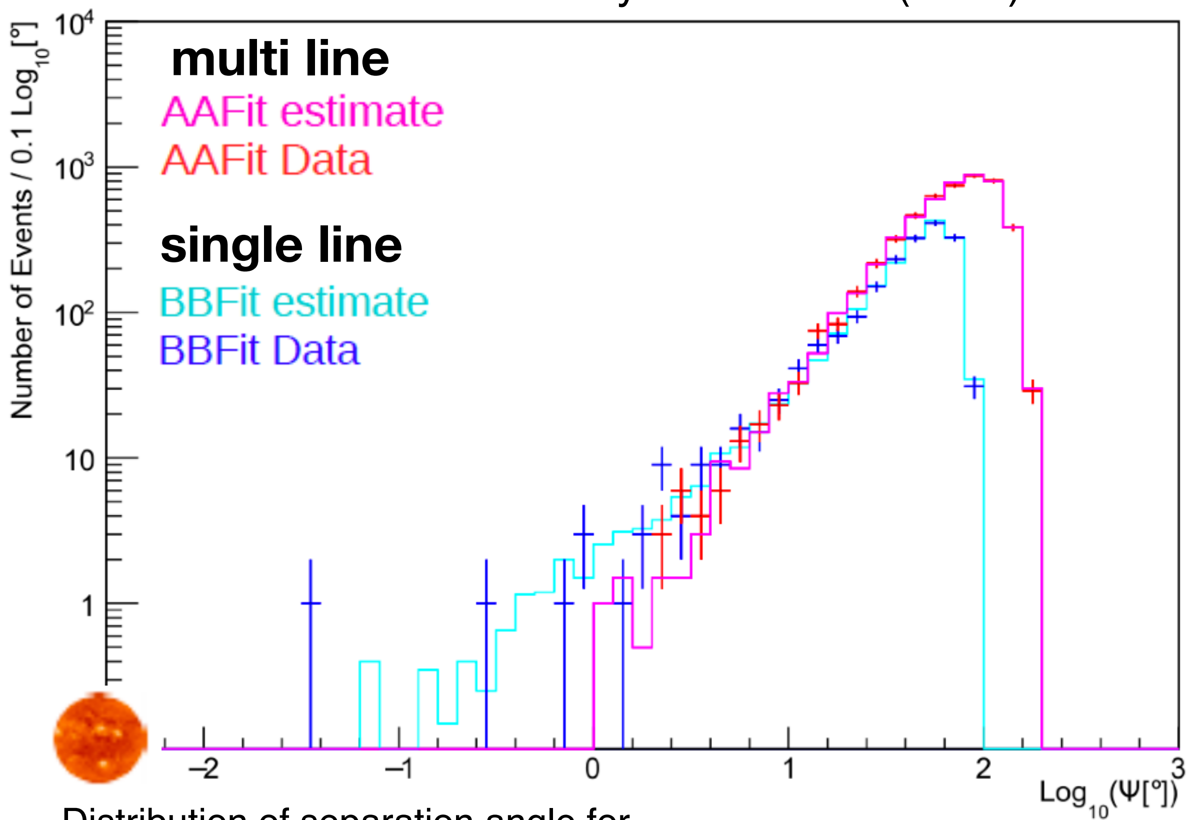
m_A - is the target mass

Evaporation limits searches for DM in the Sun to masses above 4GeV

Solar Dark Matter - IceCube/ANTARES

ANTARES

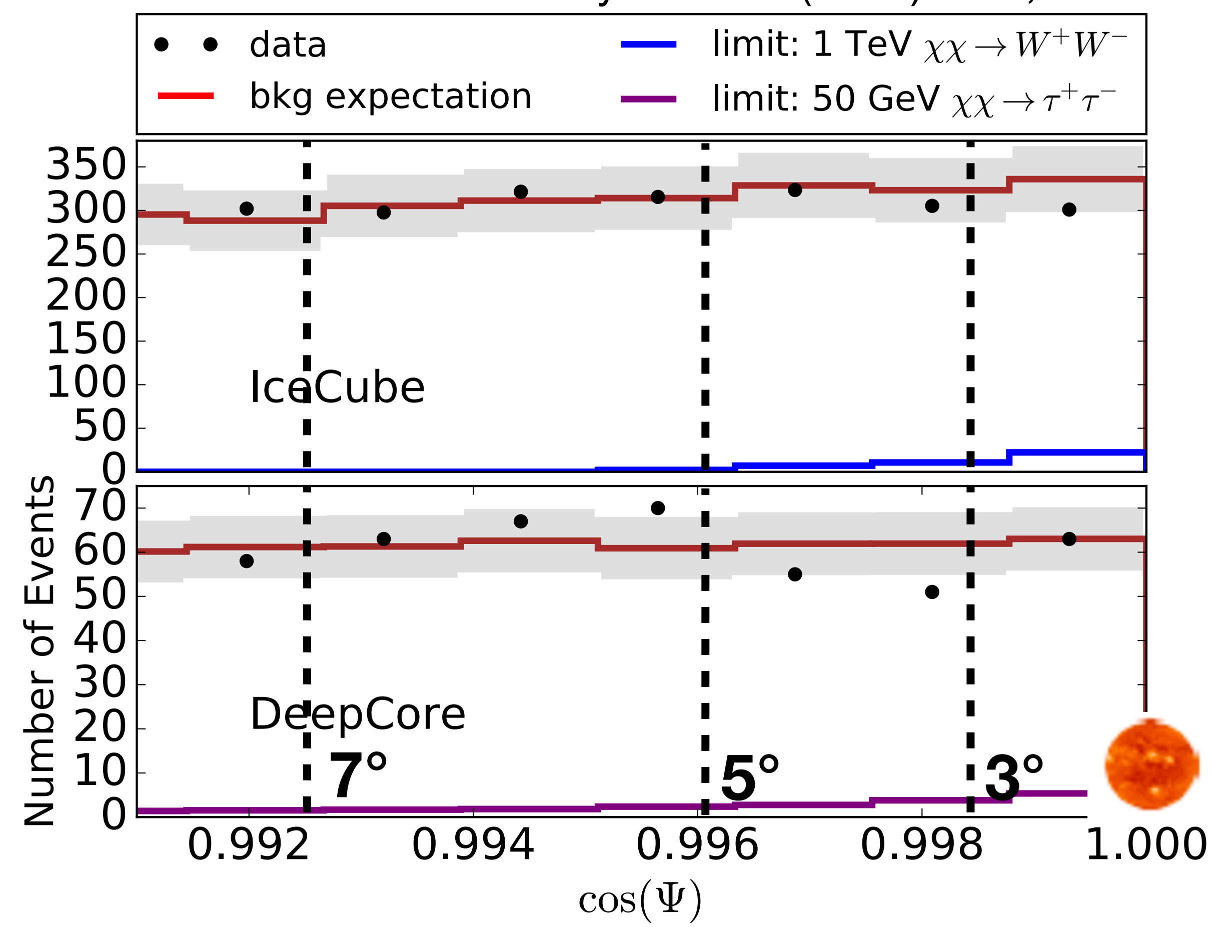
ANTARES - Phys.Lett. B759 (2016) 69-74



Distribution of separation angle for 2007-2012 ANTARES data

IceCube

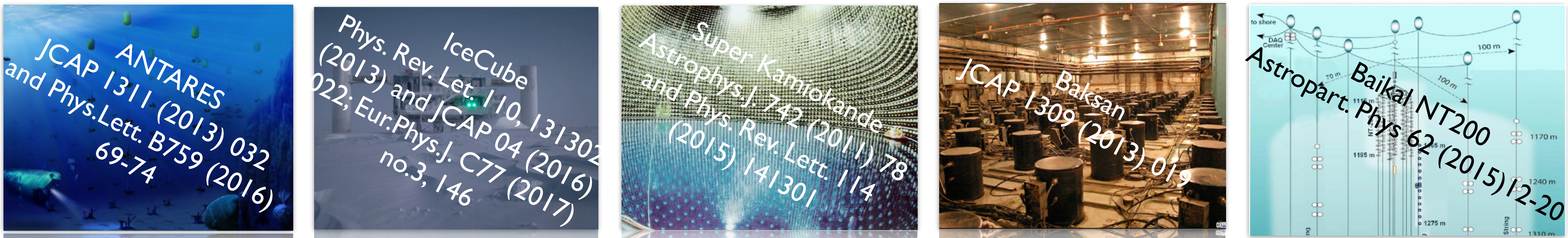
IceCube Eur.Phys.J. C77 (2017) no.3, 146



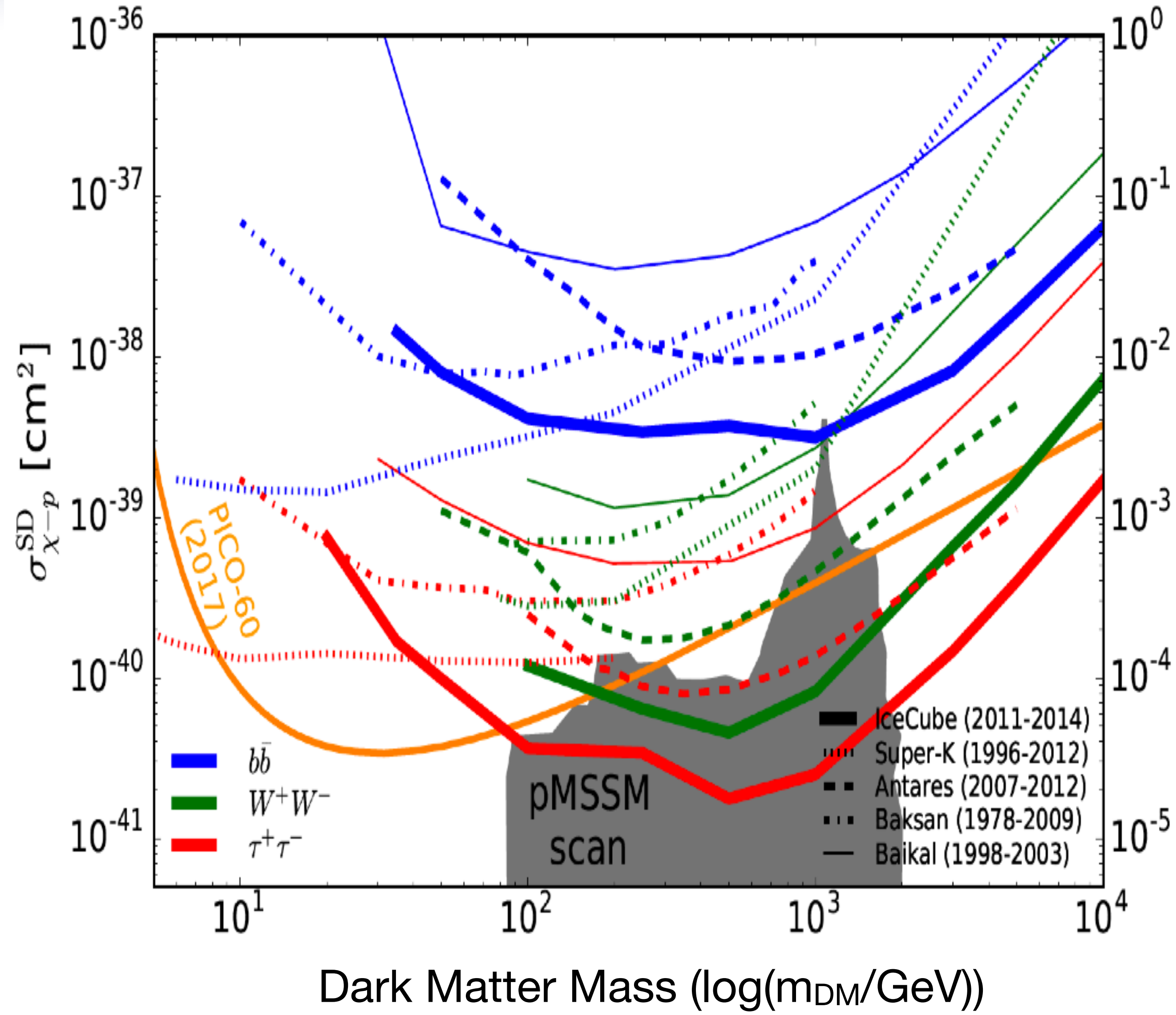
- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Energy and angular information taken into account

No excess observed - set limit …

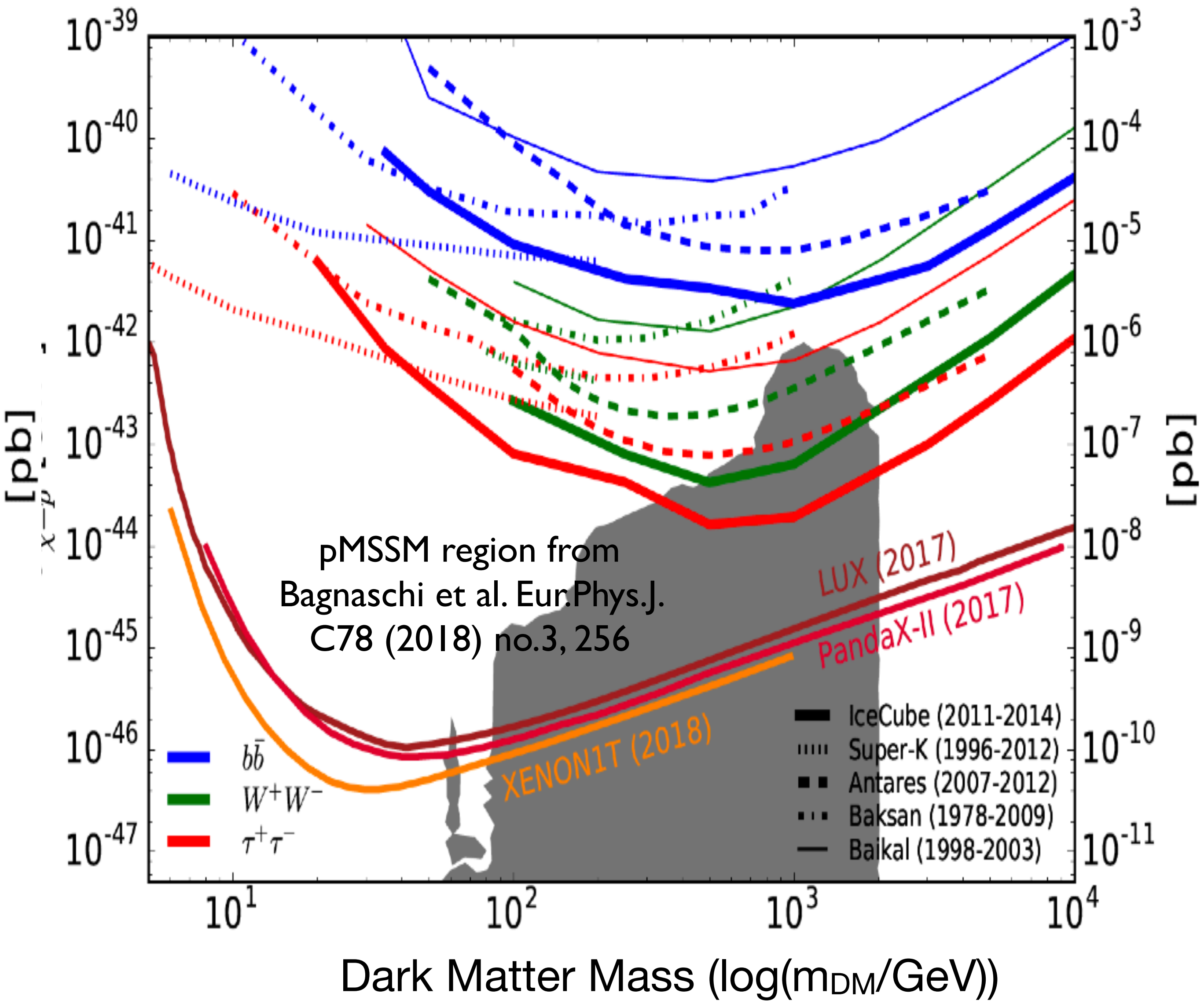
Solar Dark Matter Summary



Spin-dependent scattering



Spin-independent scattering

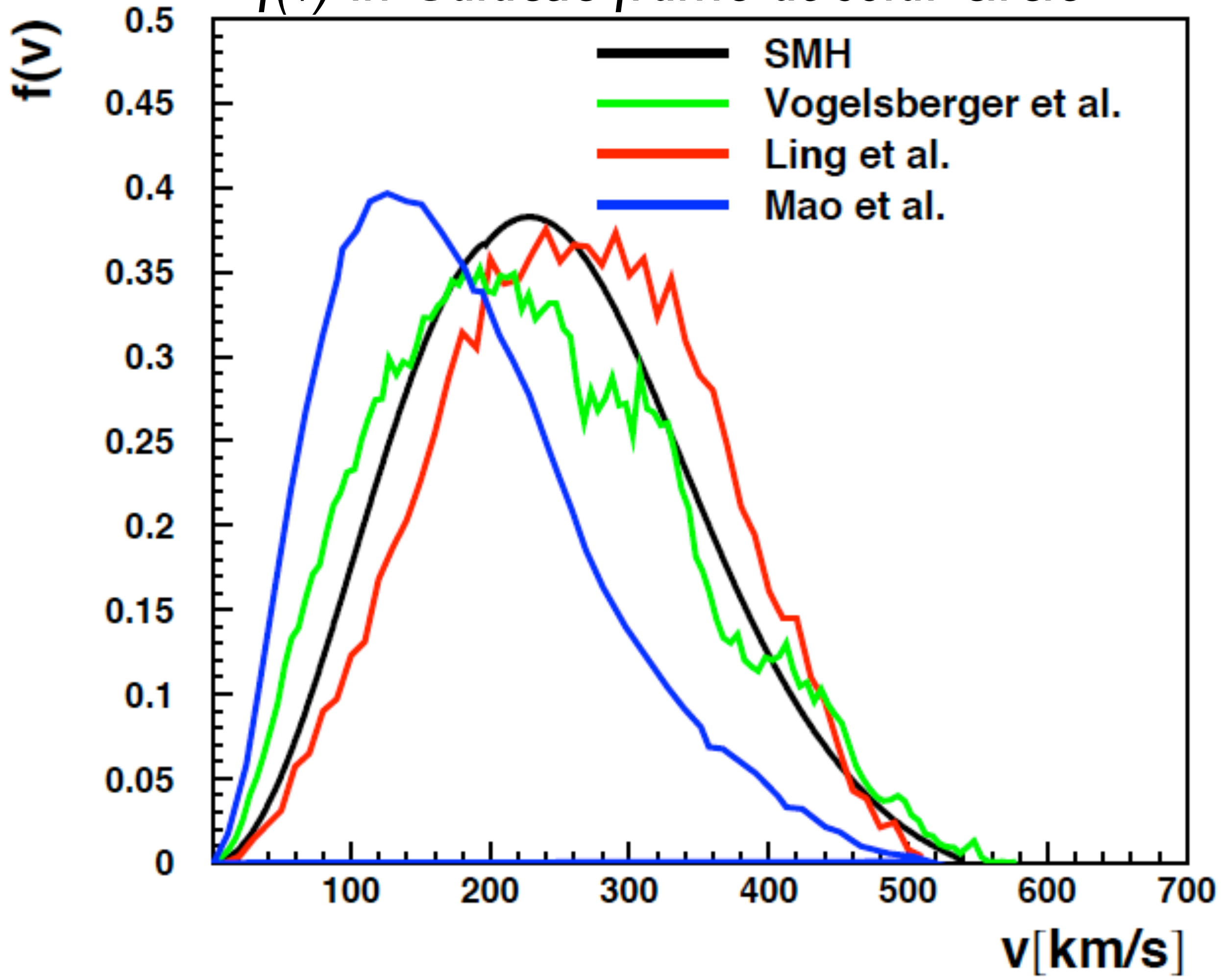


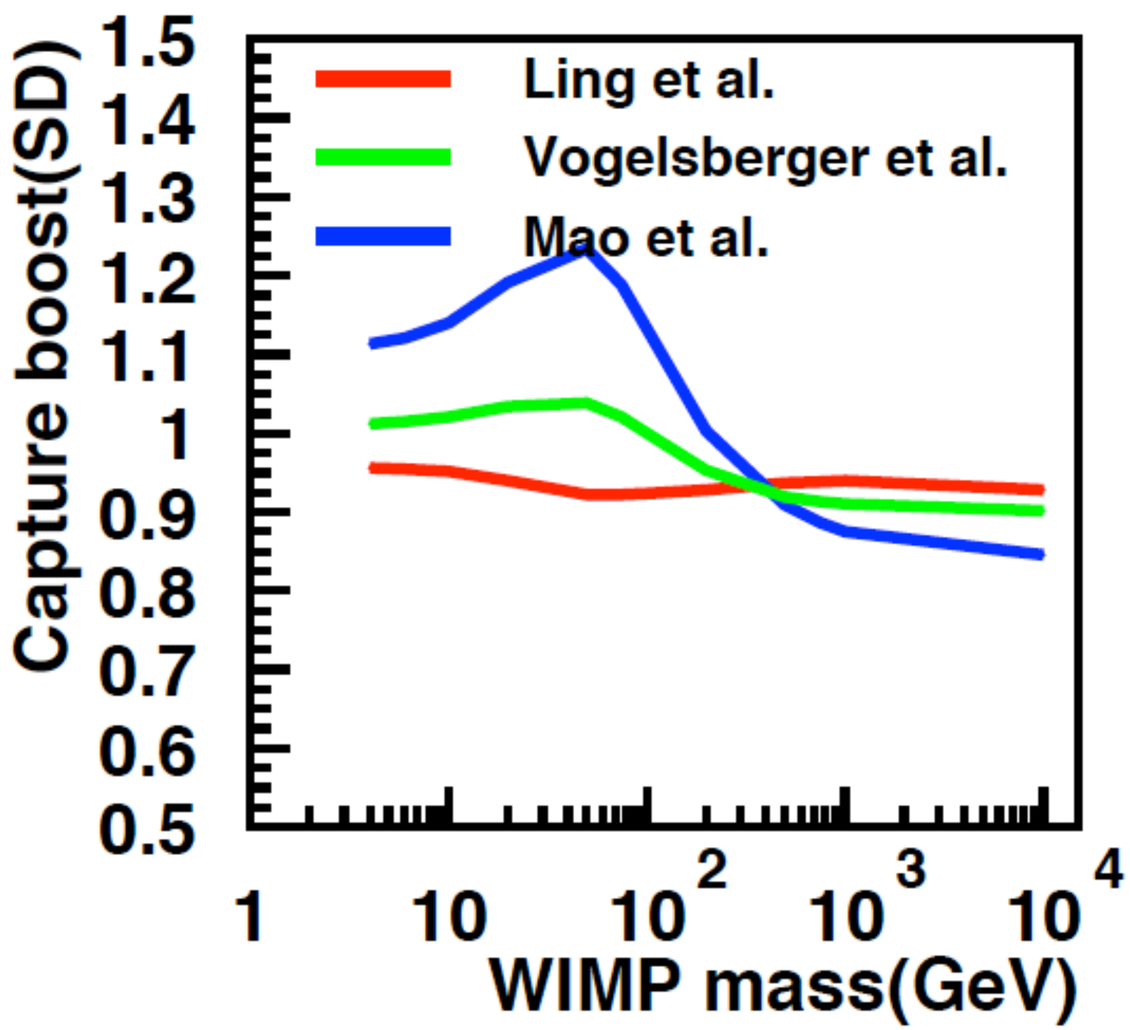
Impact of velocity distribution

- Explore the change in capture rate using different velocity distributions obtained from dark matter simulations

Choi, Rott, Itow JCAP 1405 (2014) 049

f(v) in Galactic frame at solar circle



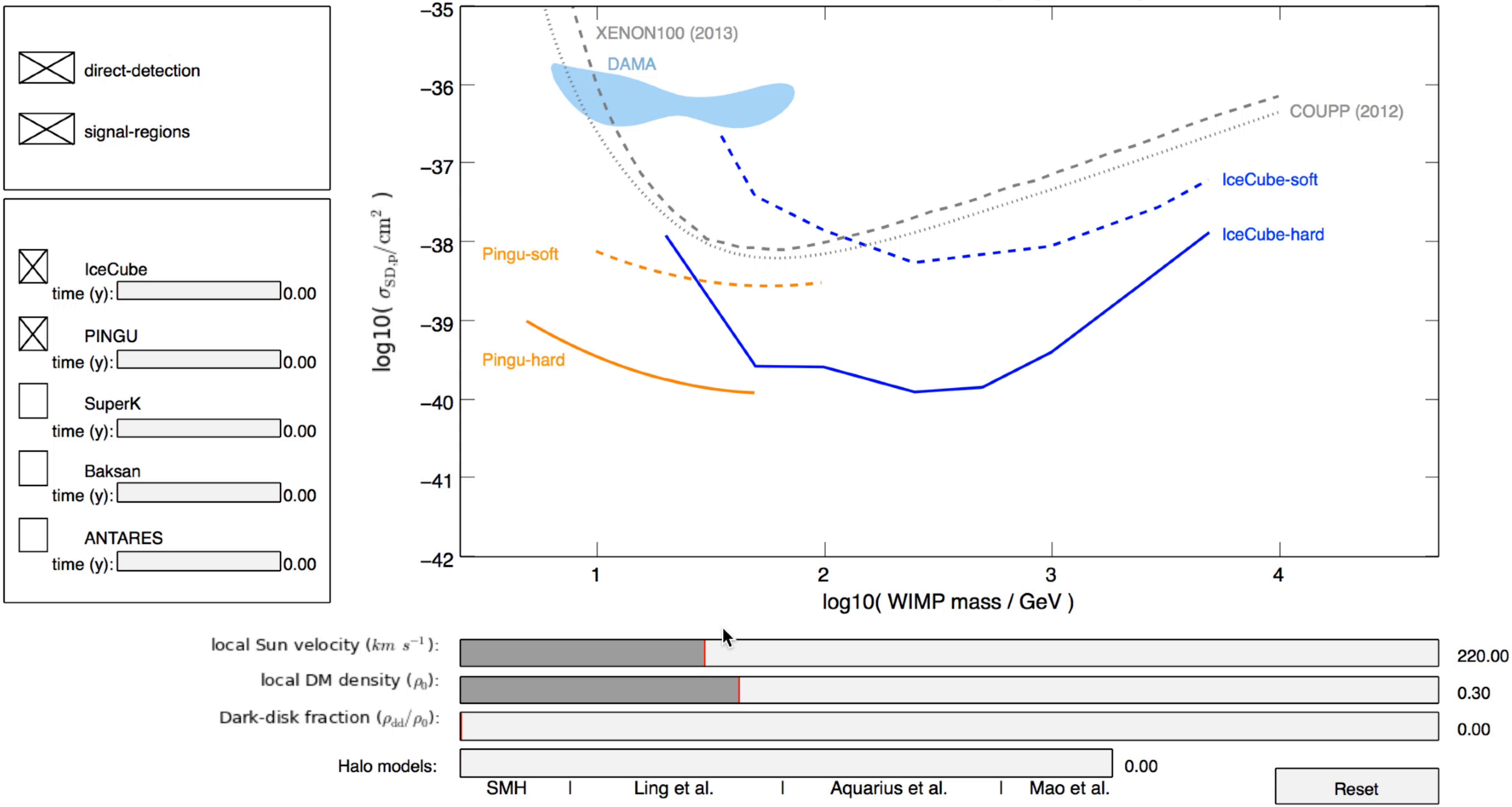


- A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%

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/

Impact of astrophysical uncertainties

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

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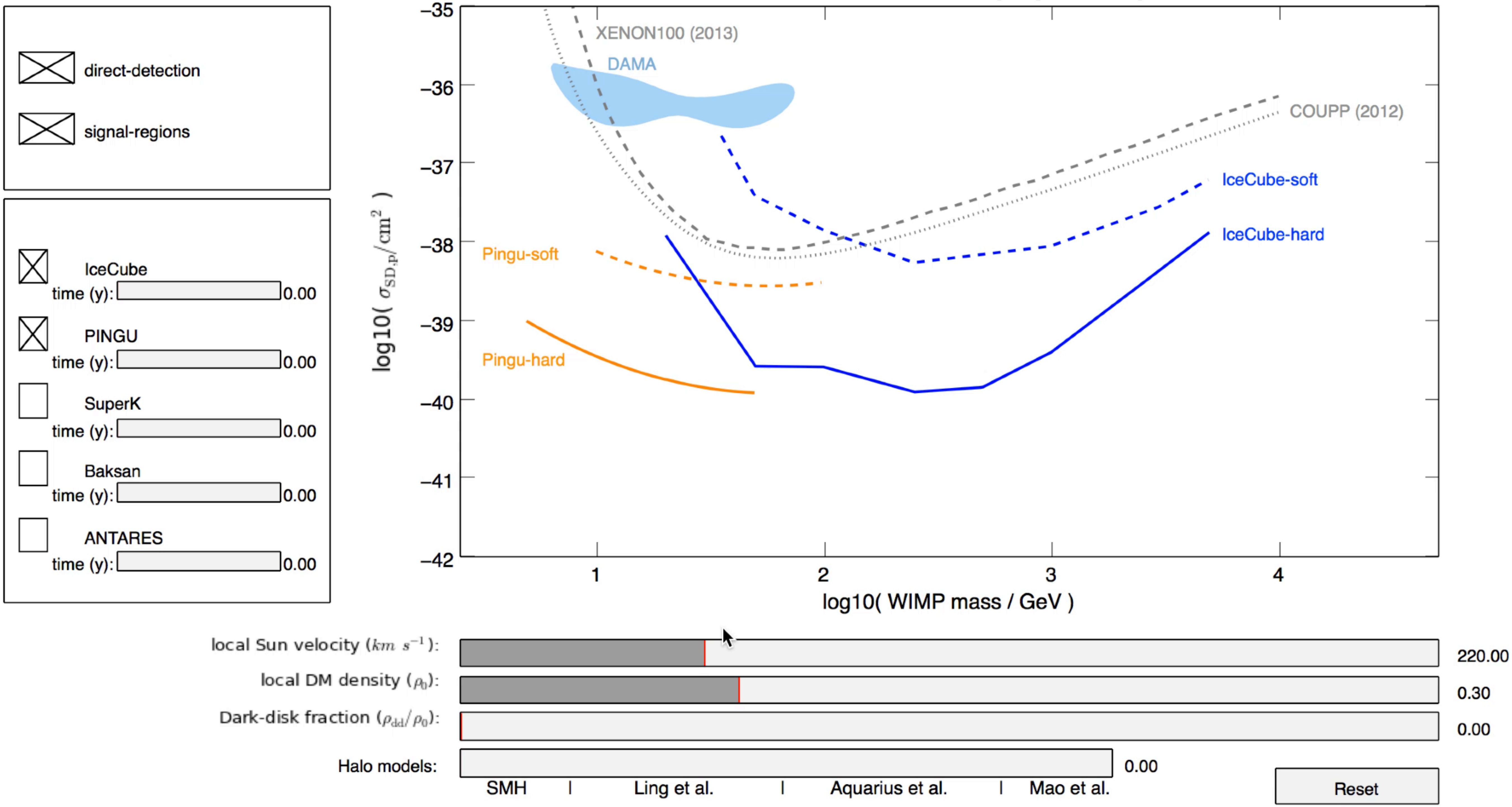
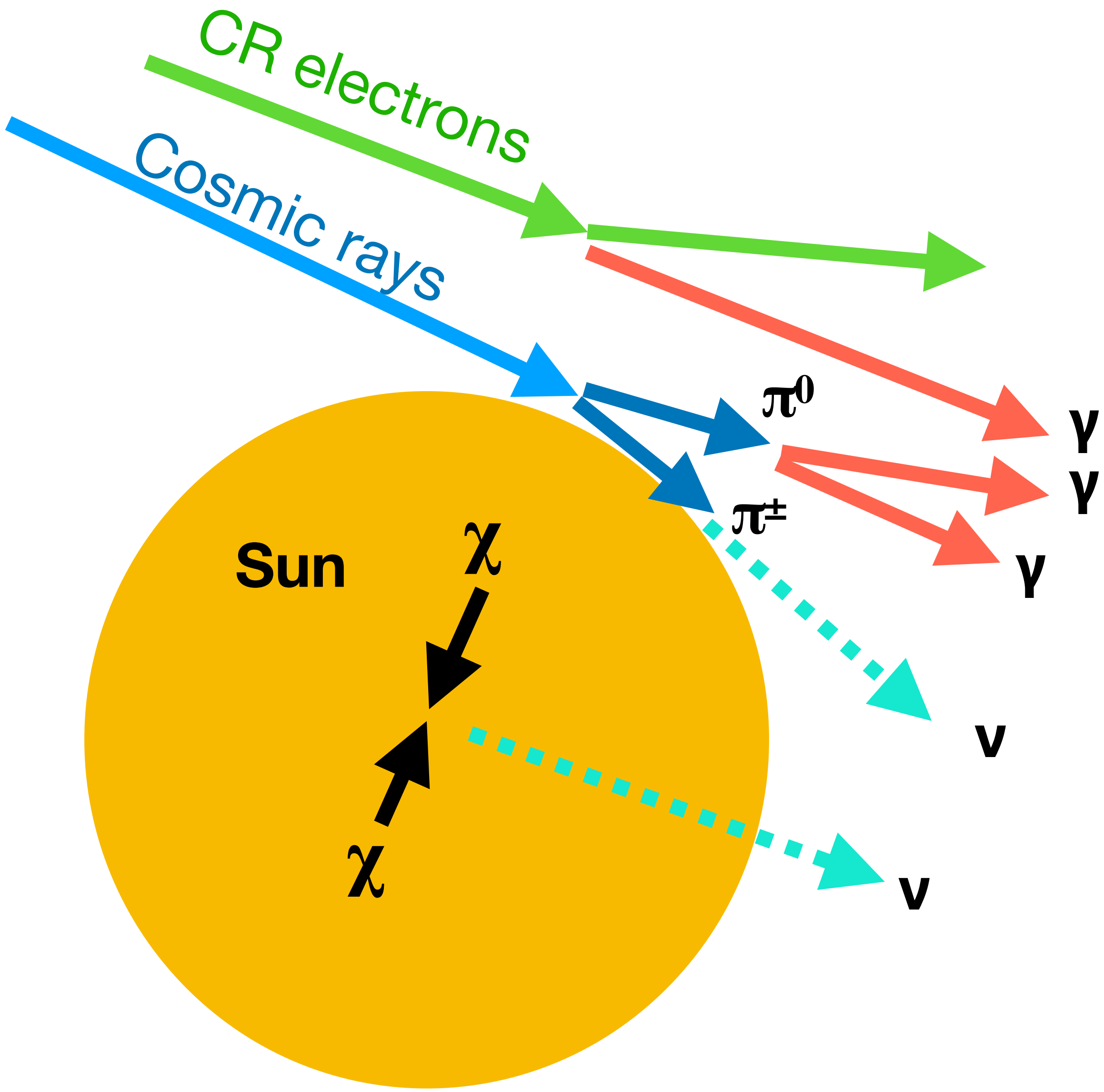


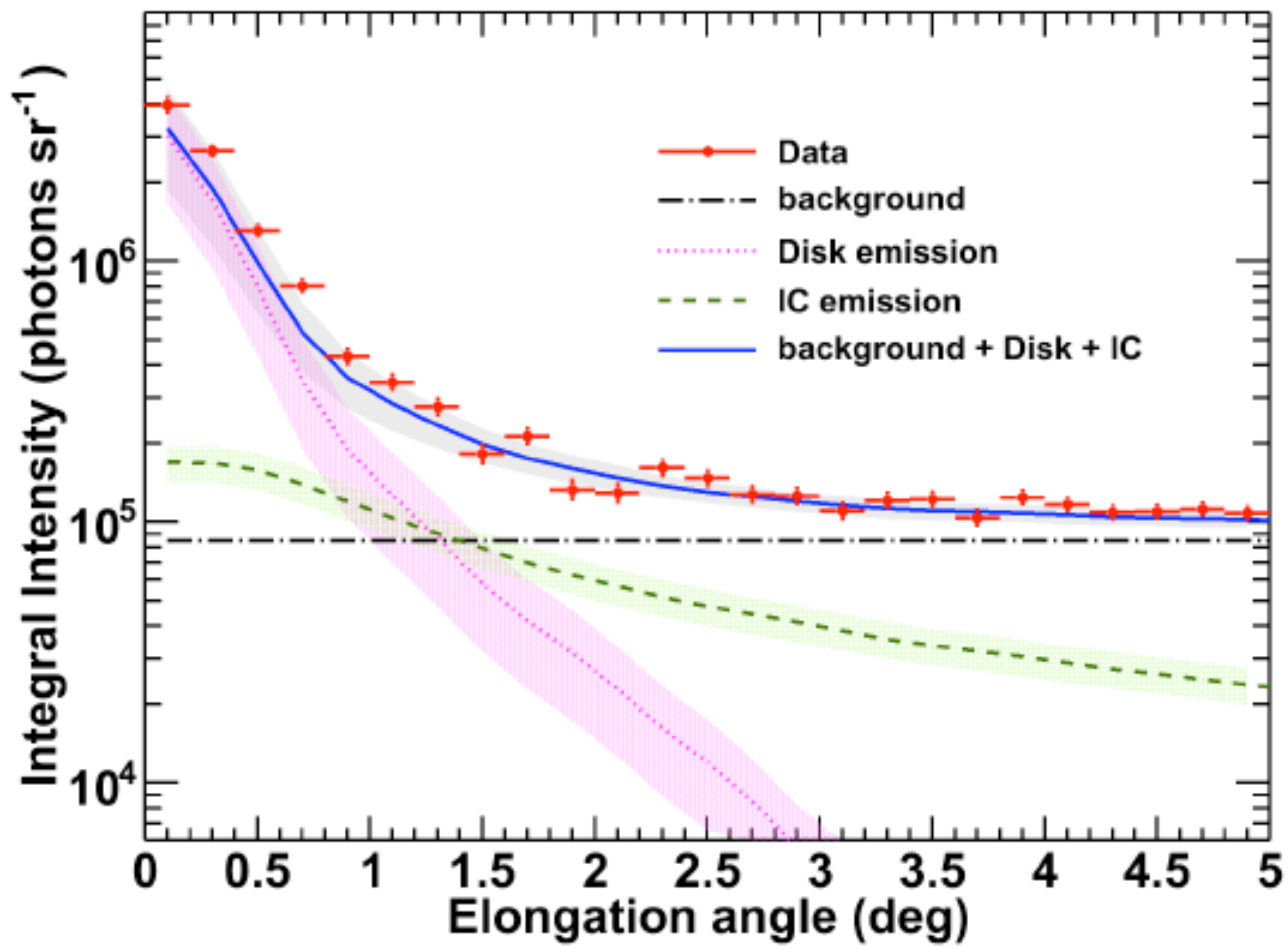
https://mdanning.web.cern.ch/mdanning/public/Interactive_figures/

Solar Atmospheric Neutrinos

Cosmic ray interactions with the Sun



see Fermi-LAT Collaboration: The Astrophysical Journal 734 (2011) 116 (arxiv:1104.2093)



- Cosmic ray interactions in the solar atmosphere produce gamma-rays and neutrinos
- Background to dark matter searches from the Sun that are becoming very relevant and also harbor the opportunity to detect a high-energy neutrino point source

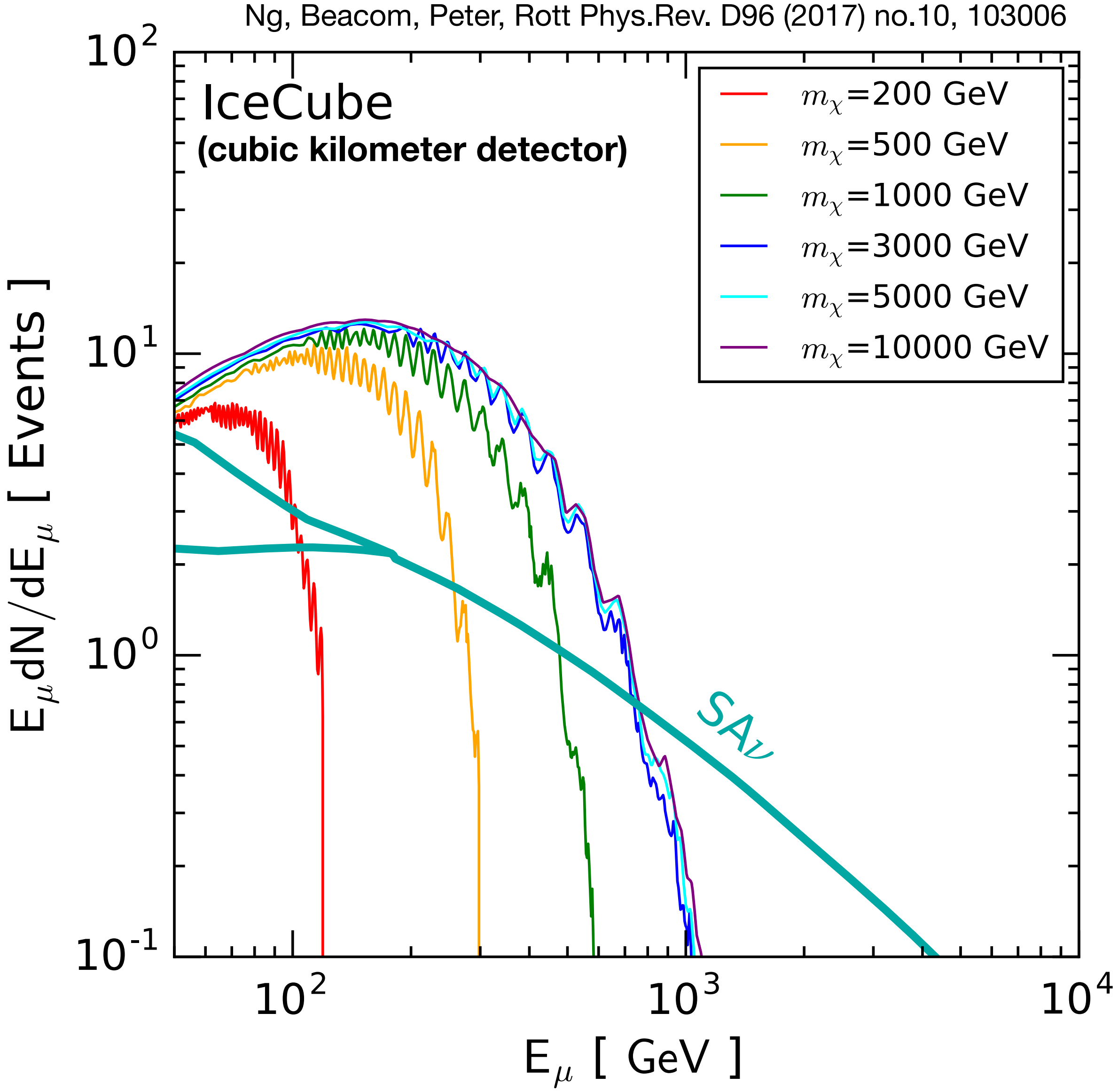
Leptonic

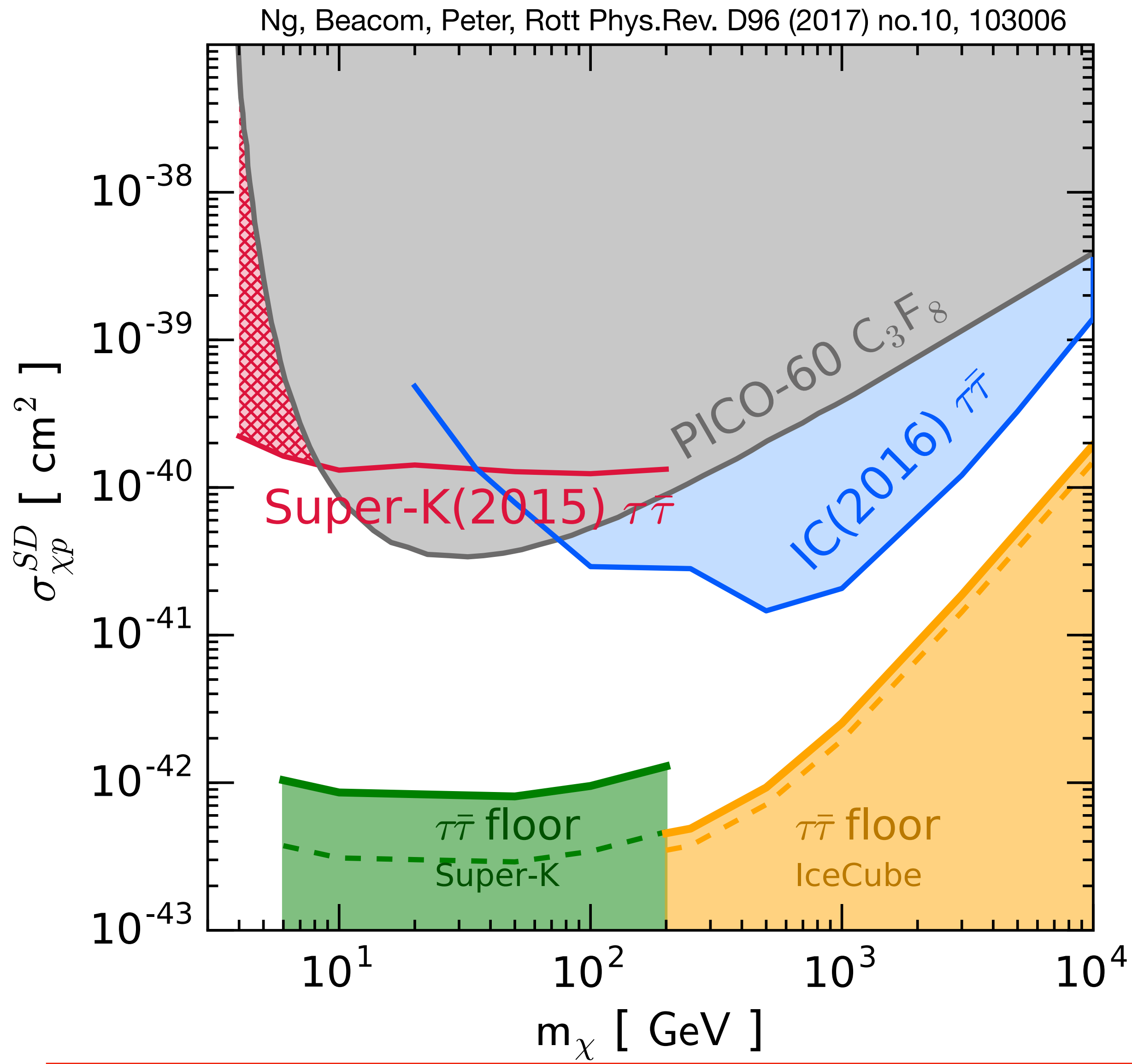
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

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

Cosmic background from the Sun





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

Expect ~2events per year at cubic kilometer detector

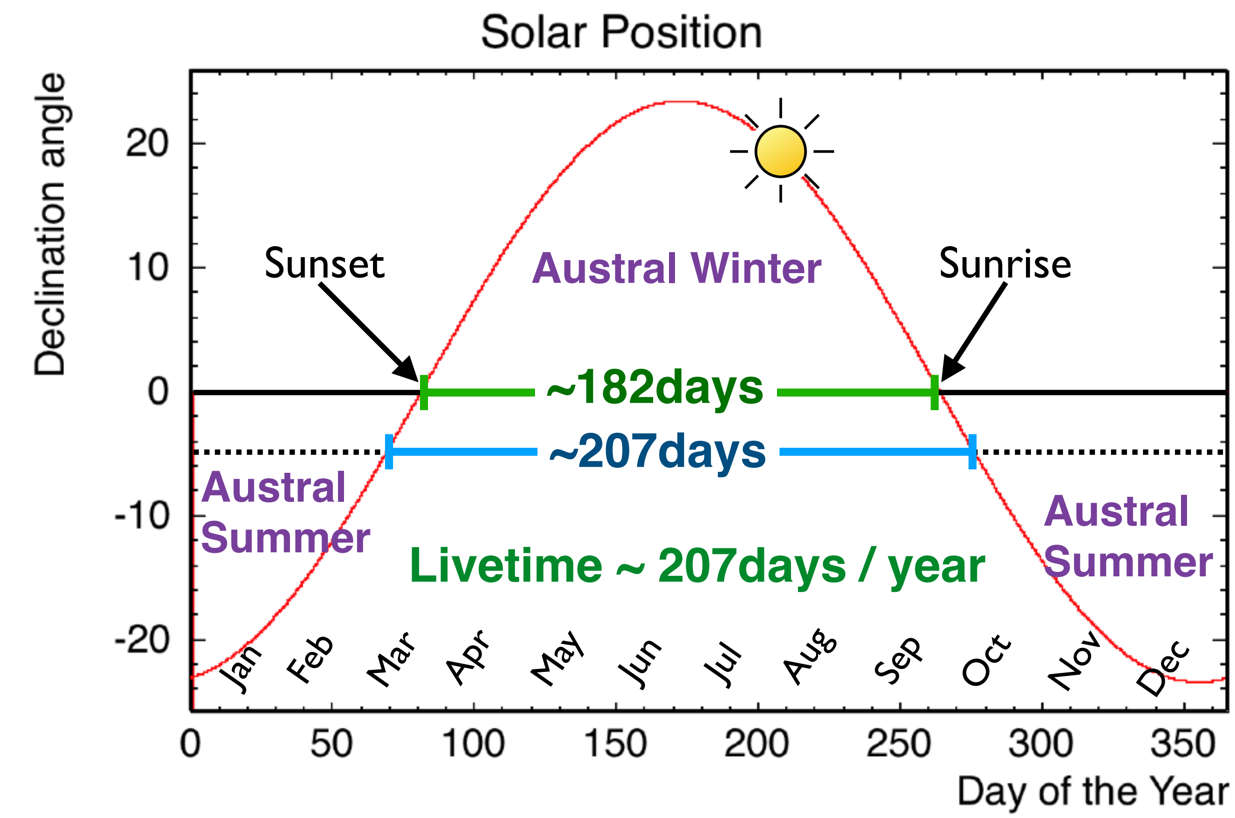
Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

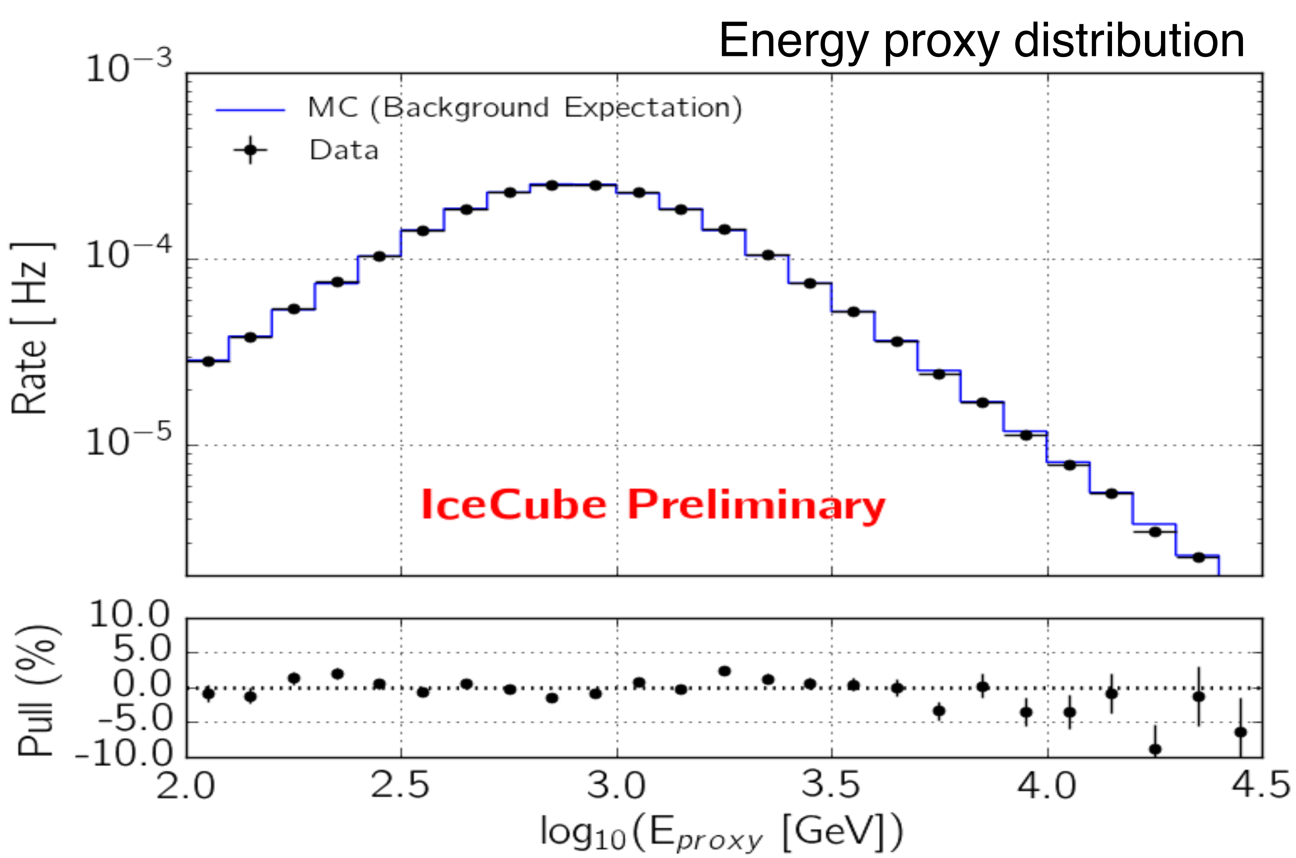
- C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]
- K. Ng, J. Beacom, A. Peter, C. Rott **Phys.Rev. D96 (2017) no.10, 103006** [arXiv:1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, **JCAP 2017 .06 (2017), p. 033**, arXiv: 1704.02892 [astro-ph.HE]
- M. Masip **Astropart.Phys. 97 (2018) 63-68** [arXiv: 1706.01290]

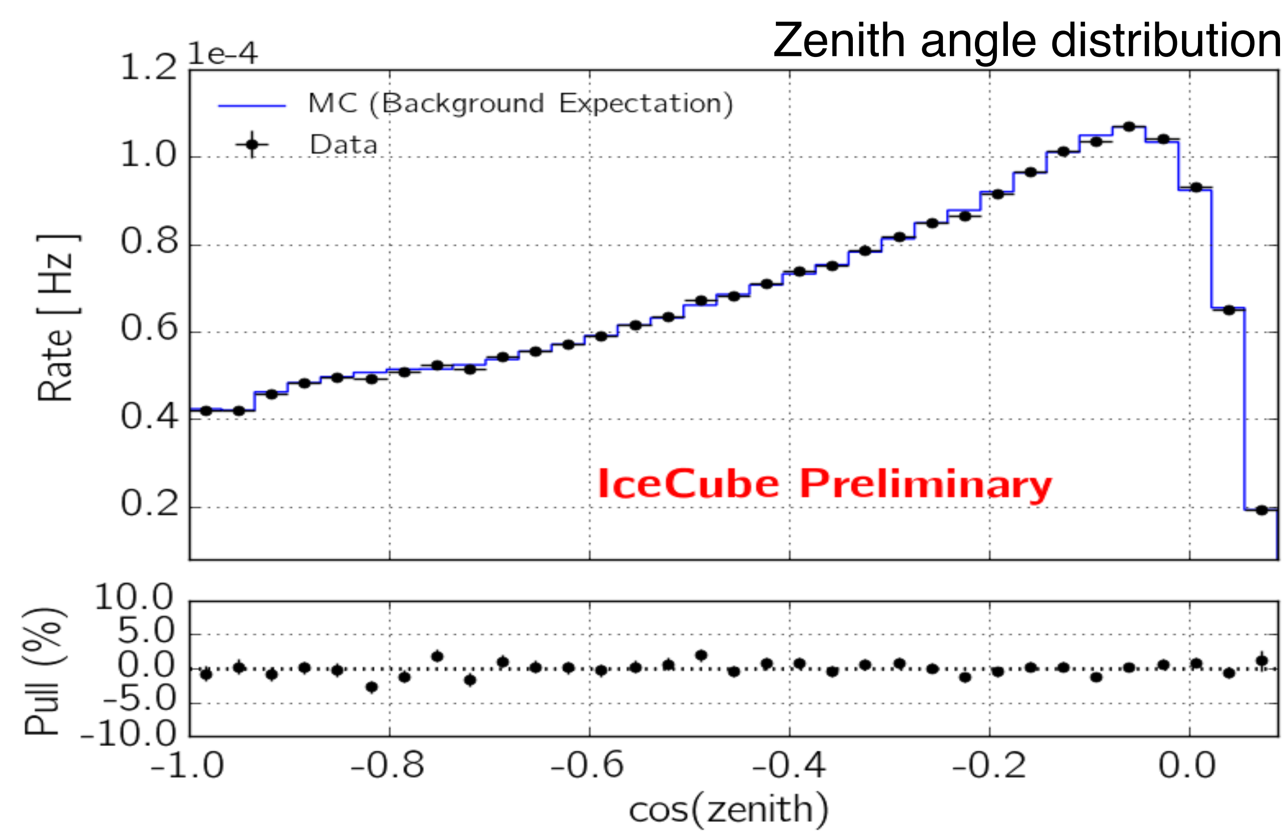
Experimental IceCube Search S. In & C. Rott ICRC2017 (965)

Data sample

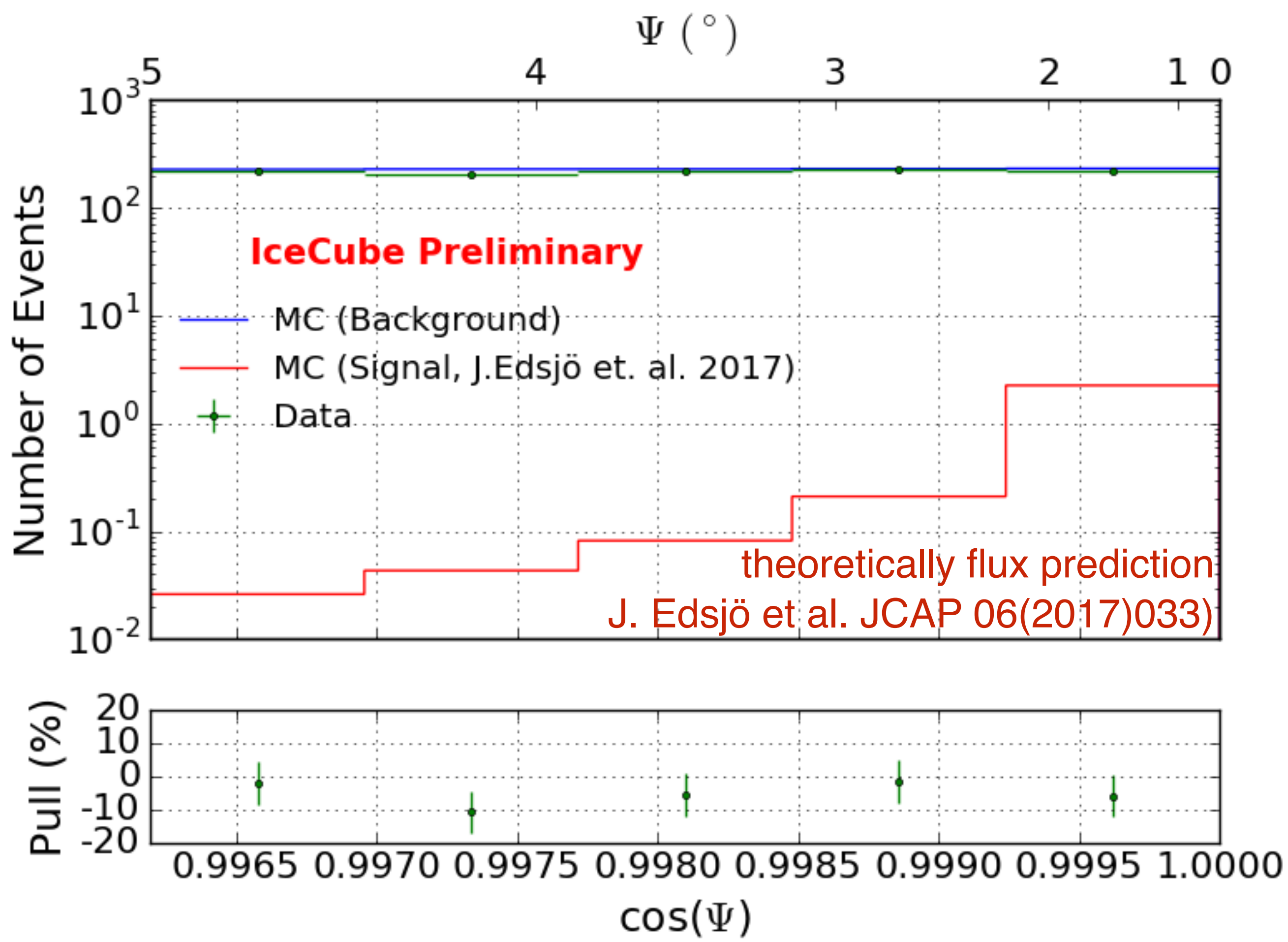
- The analysis utilizes data collected over a 7 year period (May 31, 2010 - May 18, 2017)
  - Up-going muon neutrino candidate events are selected using the well established IceCube point source analysis selection procedure
  - We only consider events from the winter season when the Sun is below the horizon (δ=[-5°,23°]). This results in a total analysis livetime of 1420.73 days.

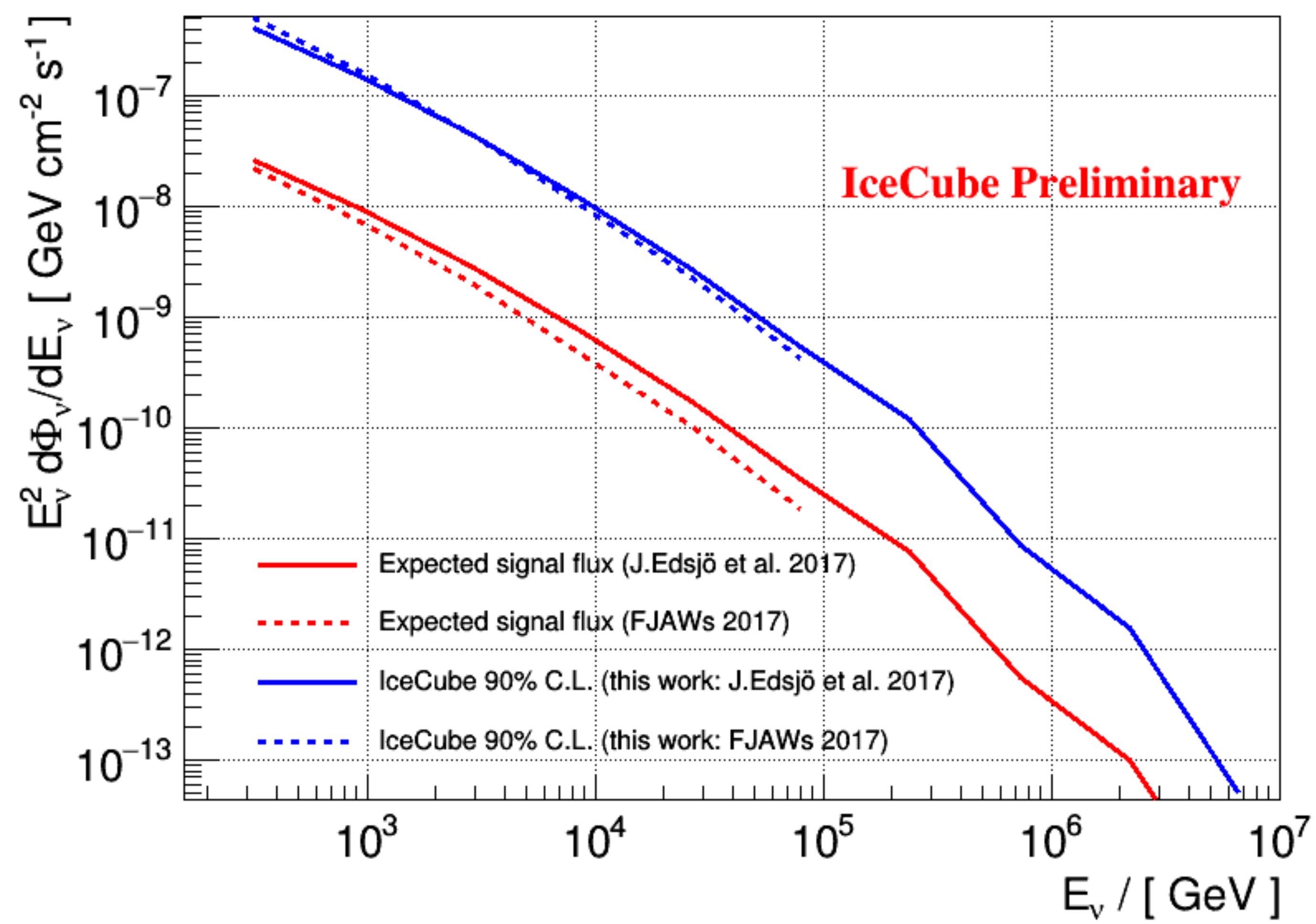






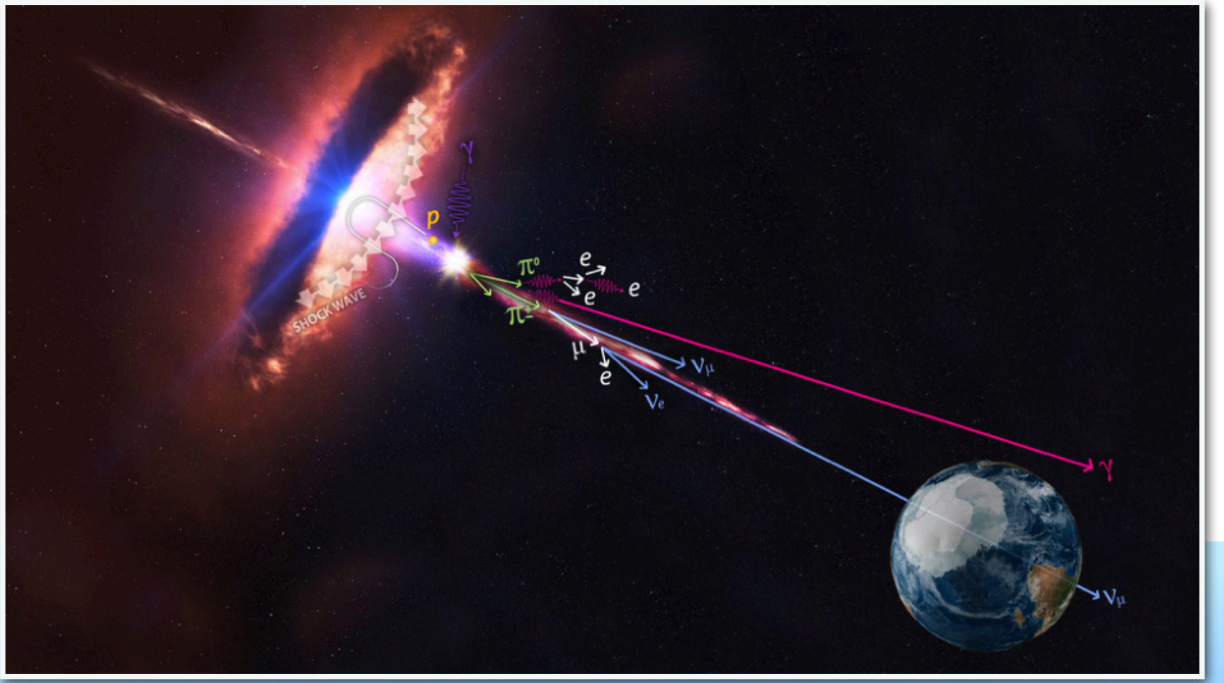
Result





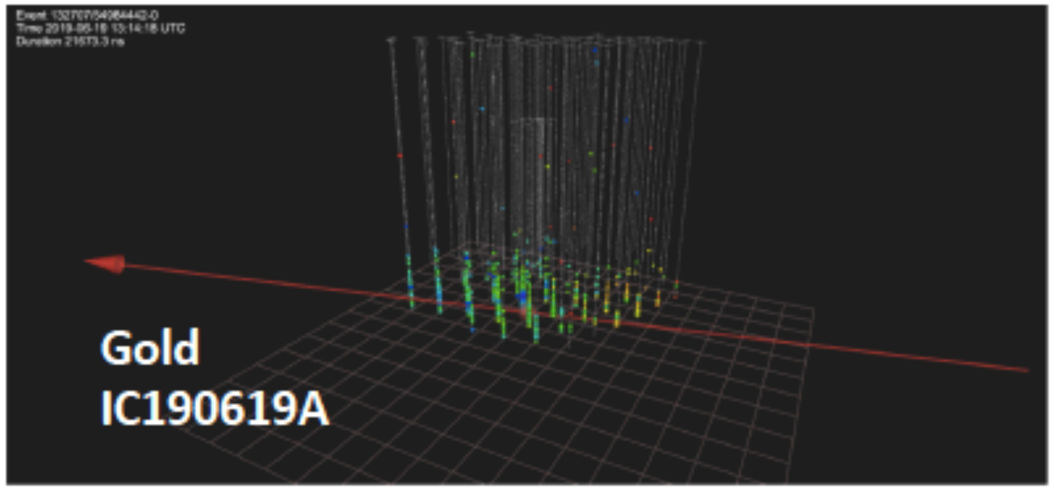
- No excess of events observed
  - Proceeded to set bound on the neutrino flux from the Sun

Systematic	Size
DOM efficiency	12%
Ice properties	4%
Source distribution	4%
Cosmic ray shadow	2%
Total	**13%**



Multi-messenger Neutrino Astronomy and IceCube-170922A

IceCube Realtime Alerts

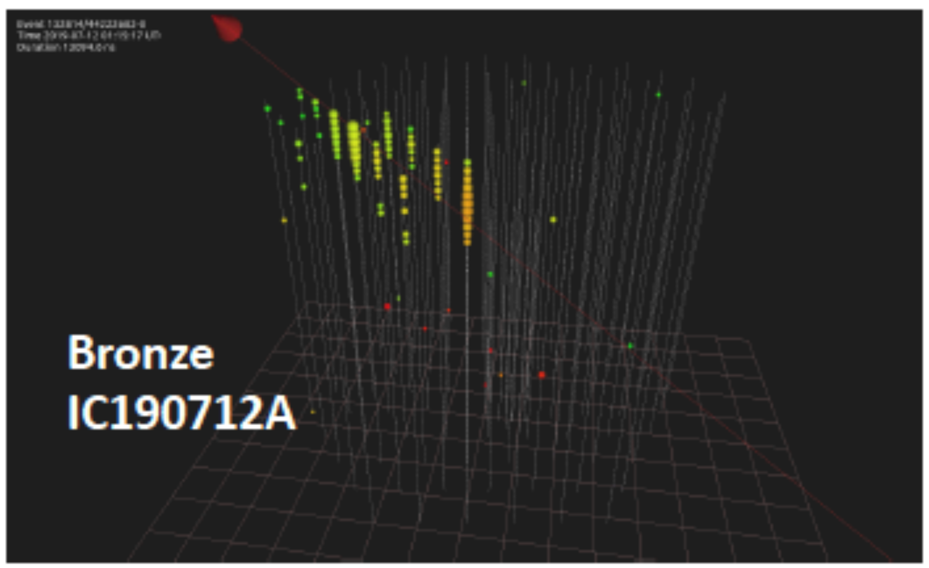


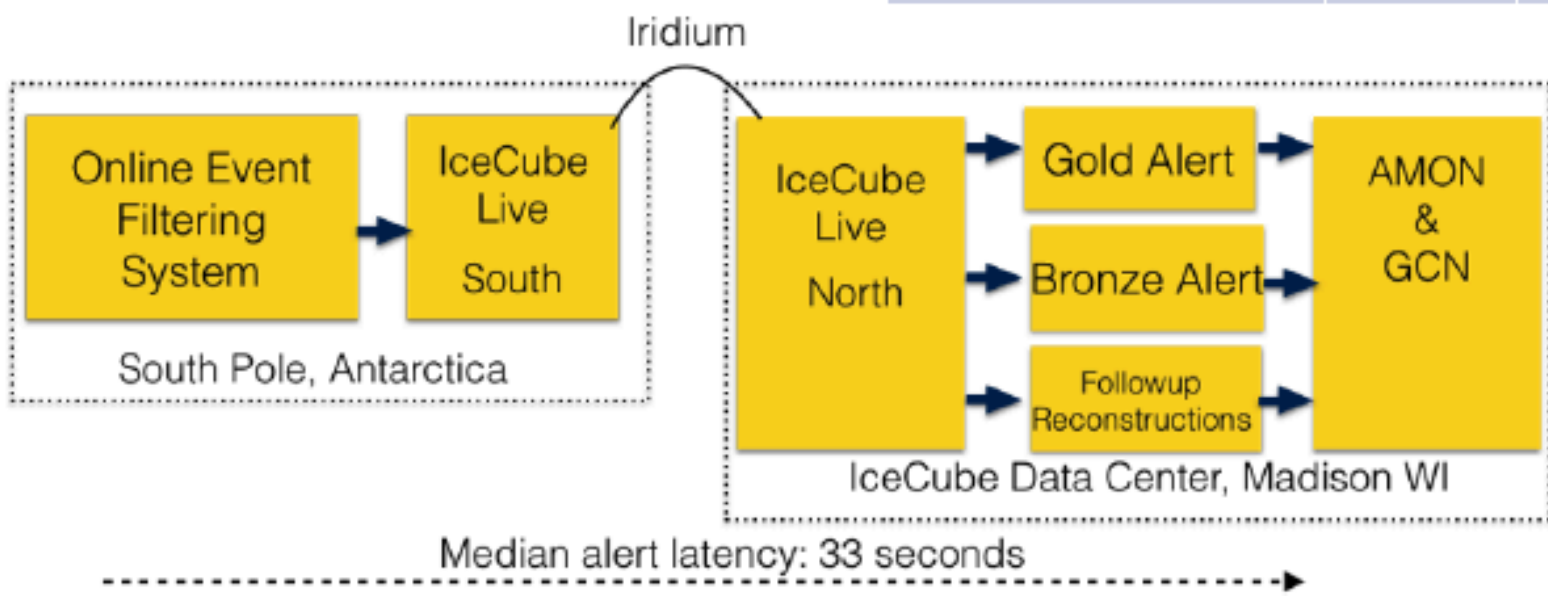
IceCube sending alerts since April 2016
Updated alerts as of June 2019

Initial GCN Notice followed by GCN Circular with updated reconstruction

C. Tung NU9b

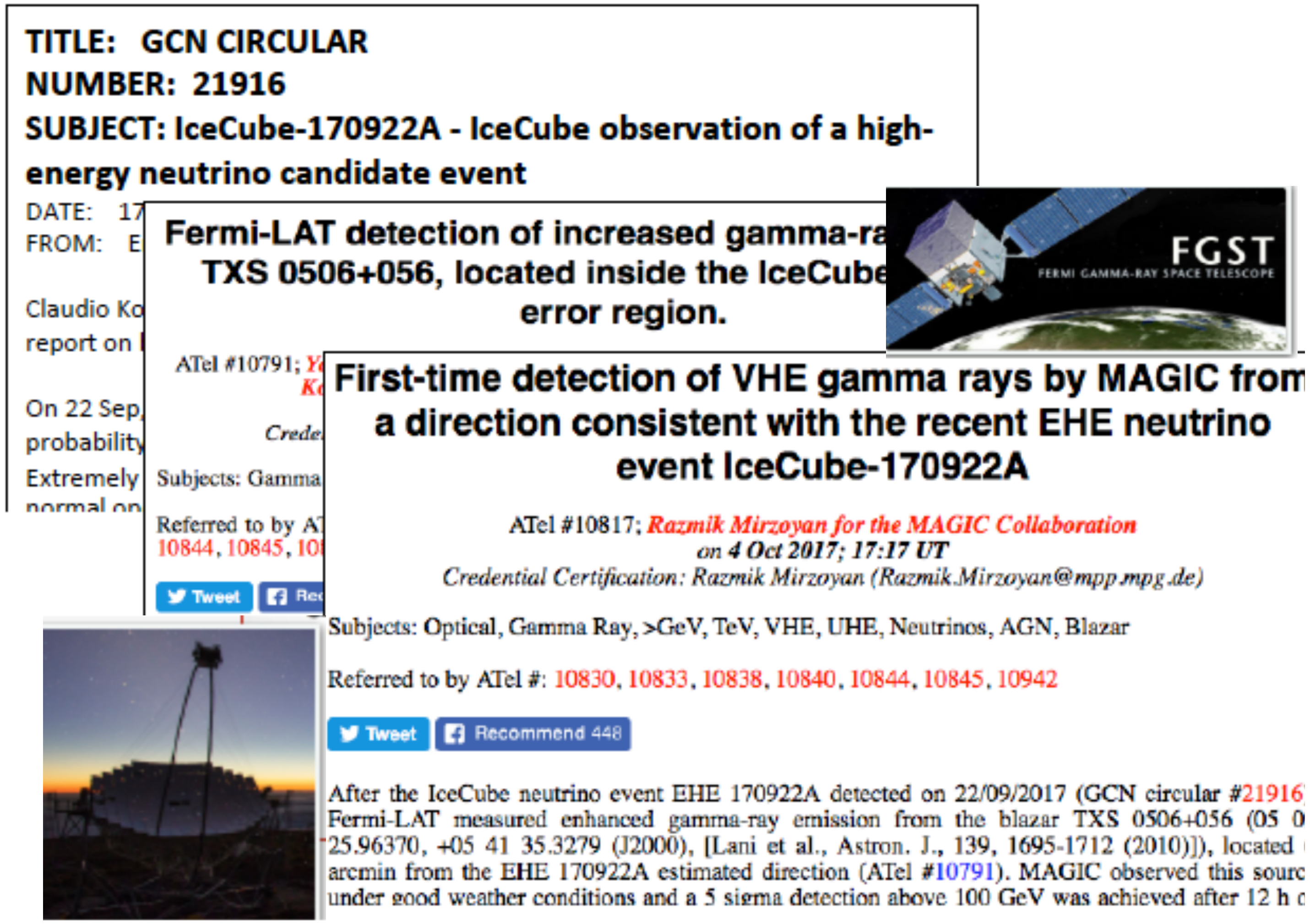
Updated alerts	Gold	Bronze
Signalness	> 50%	>30%
Expected signal/yr	6.6	2.8
Expected bkgd/yr	6.1	14.7





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

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 AT
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)

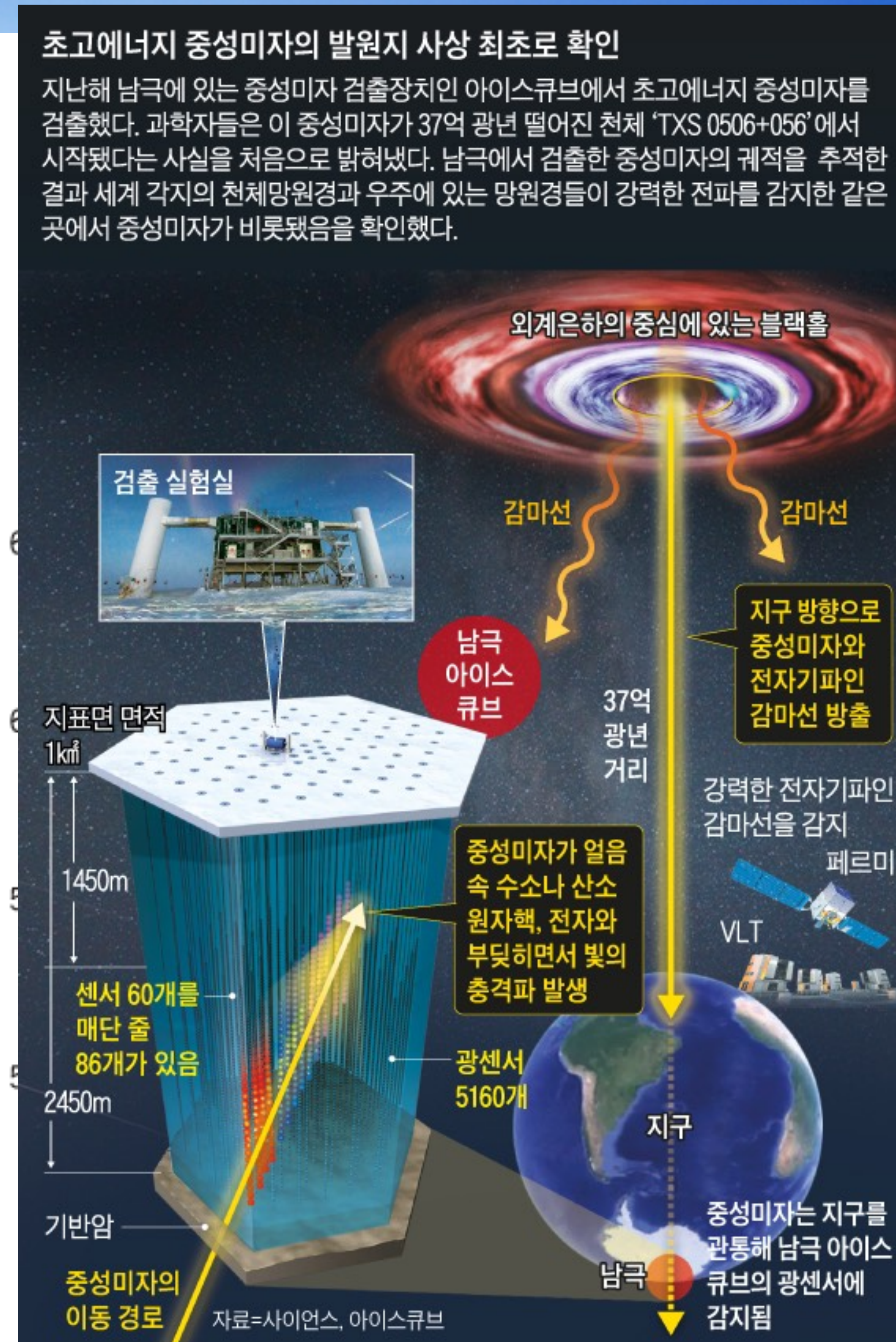
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

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 0 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this sourc under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h c

- 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



Astropart. Phys. 92 (2017) 30

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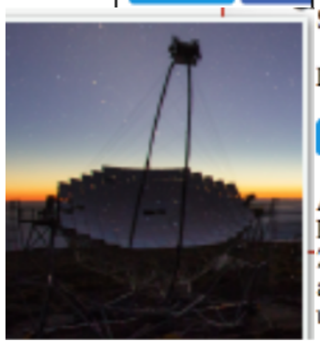

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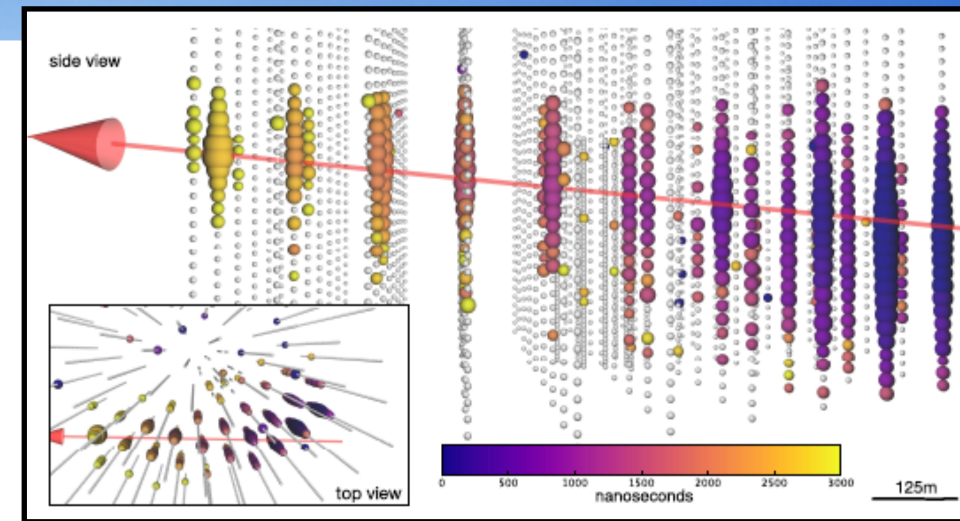
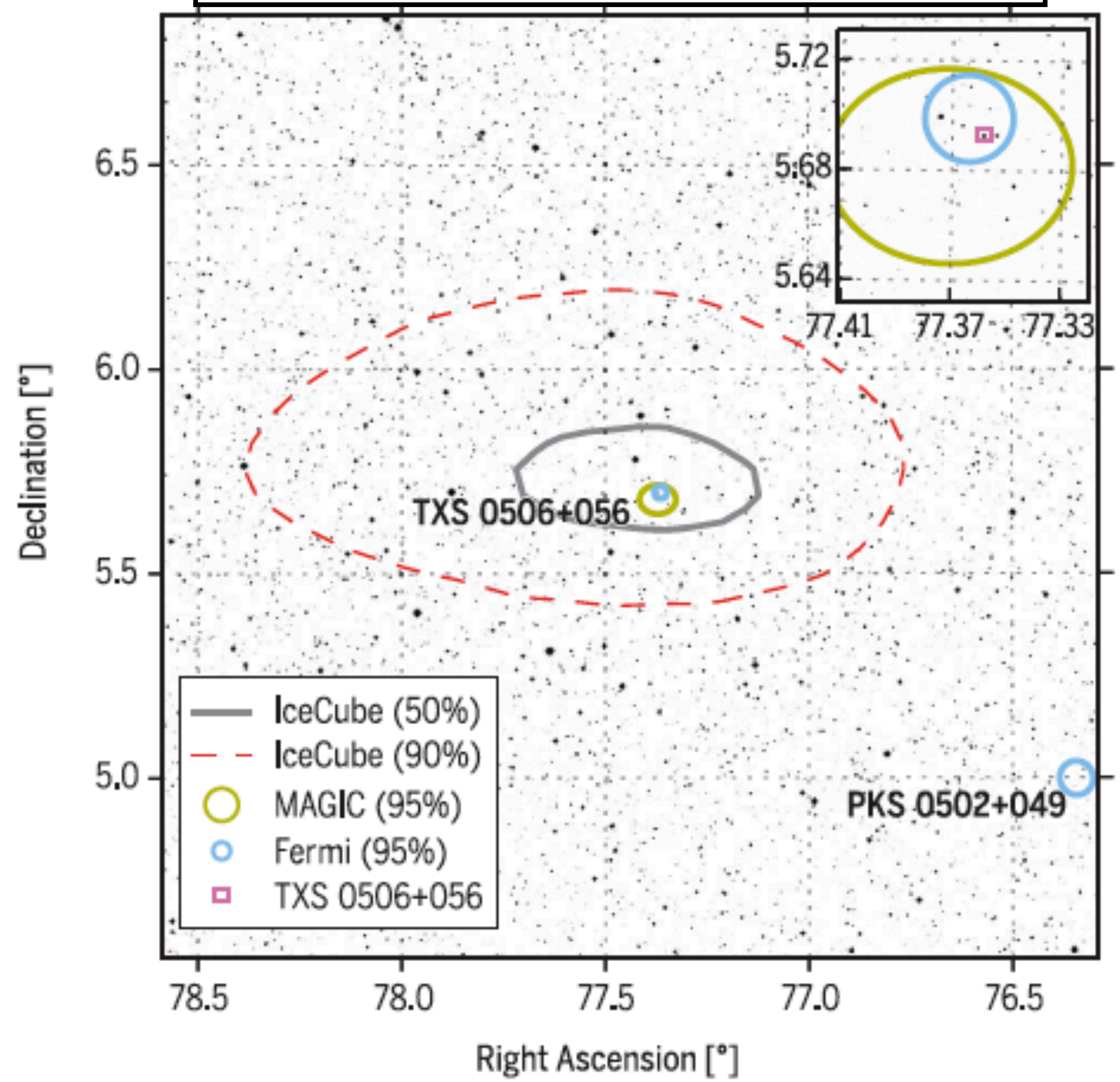




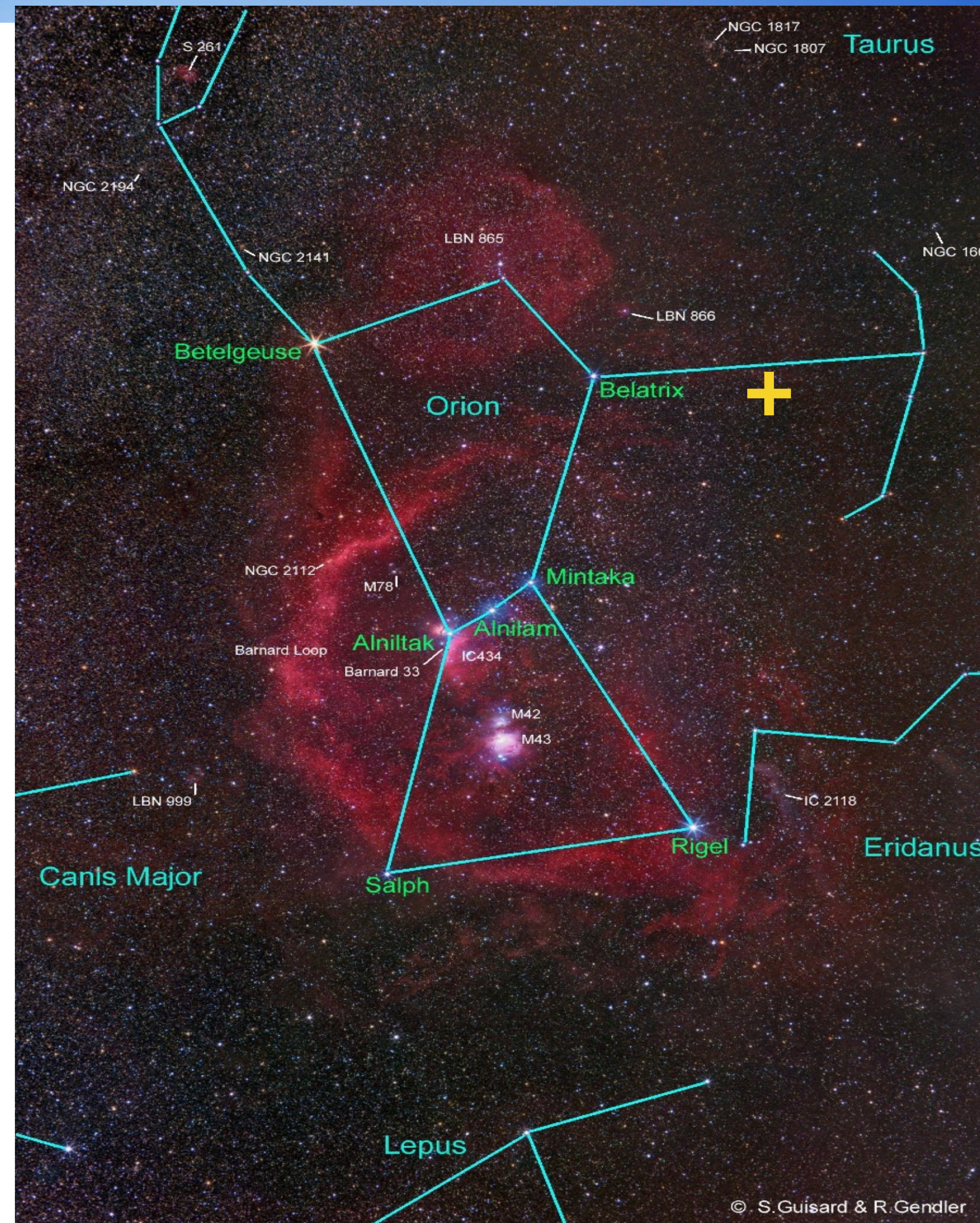
(Science 361, eaat1378 (2018))

IceCube-170922A

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

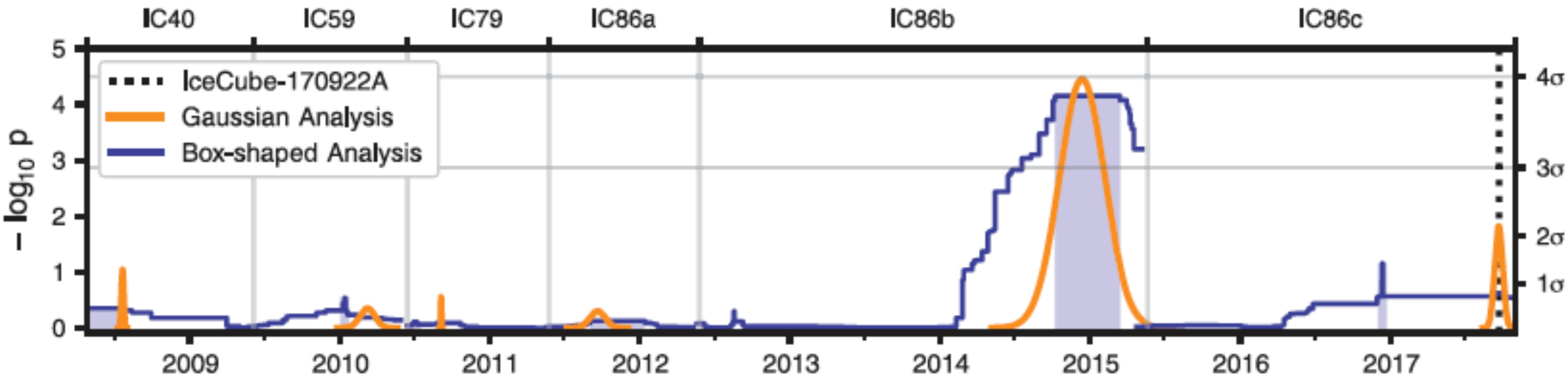
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

- Chance probability of a Fermi-IceCube coincident observation: ~3σ (determined based on the historical IceCube sample and known Fermi-LAT blazars)
- Time-integrated neutrino spectrum is approximately $E^{-2.1}$
- TXS 0506+056 redshift determined to be z=0.3365 (S. Paiano et al. ApJL 854.L32(2018))
- Time-average luminosity about an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605

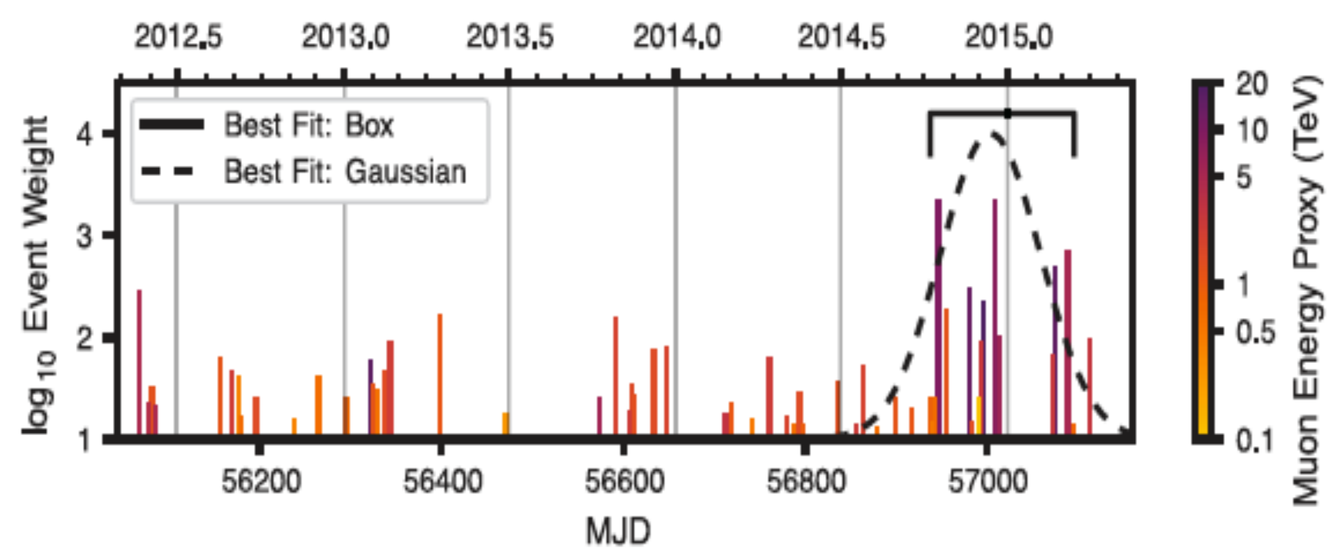


Science 361 (6398), 147-151.

IceCube-170922A

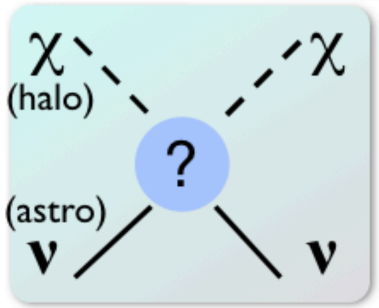


- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)



Time-independent weight of individual events during the IC86b period.

However: Maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV [IceCube Astrophys.J. 835 (2017) no.1, 45]



Neutrino DM scattering

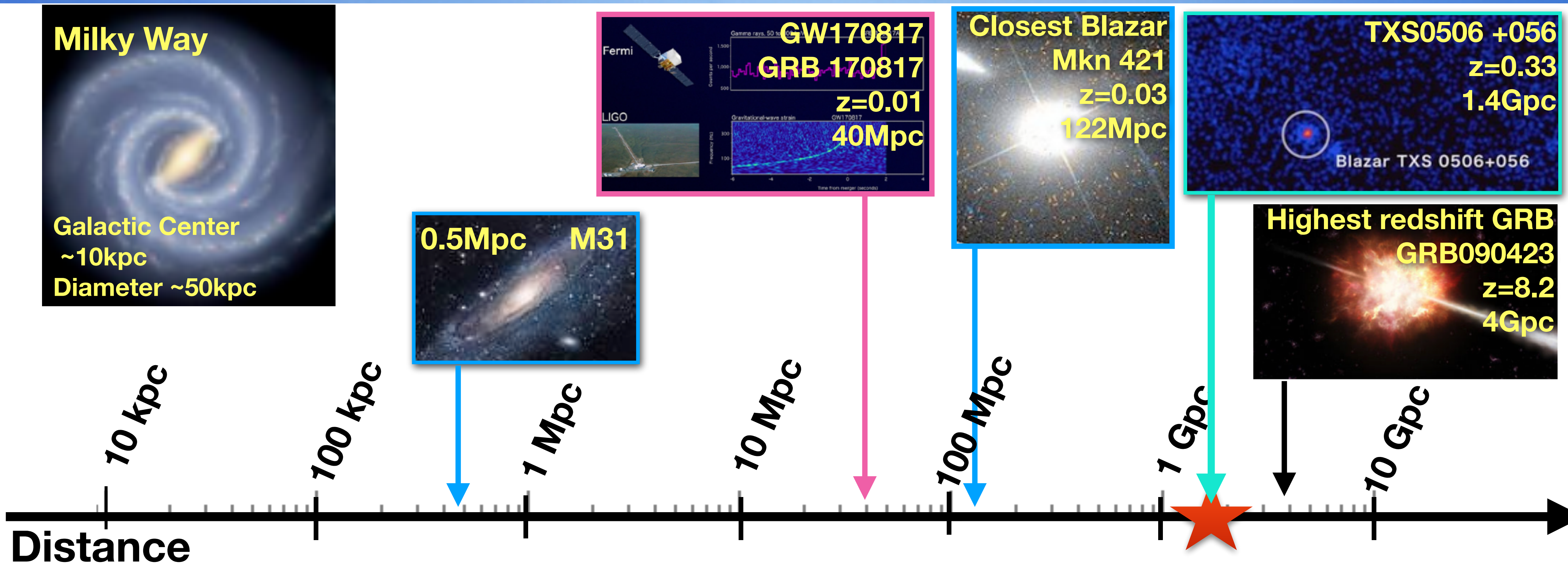
Astrophysical ν scatter off χ from Galactic halo - resulting in anisotropy

- Milky Way Halo

Combination of coupling strength **g** and masses $\mathbf{m_\phi}$ $\mathbf{m_\chi}$

Neutrino-Dark Matter Scattering

Distance scales …



Neutrinos

Cosmic Rays

GZK cut-off (E~5·10^{19}eV)
d~50 Mpc

Gamma-rays (@1TeV)

← Gamma-rays (@1PeV)

Gamma-rays interact with EBL and CMB

Gravitational waves

↑ LIGO sensitivity

1 pc = 3.26 ly

Choi, Kim, Rott PRD 99, 083018 (2019)

The interaction of neutrinos with dark matter in the Universe can suppress the flux of neutrinos along the path from the astrophysical source to the Earth

$$\Phi = \Phi_0 e^{-\int_{\rm path} \sigma n(\mathbf{x}) dl}$$

The suppression depends on the scattering cross section between DM and neutrinos and as well as the DM number density along the path.

The observation of neutrinos imply that

$$\int_{\rm path} \sigma n(\mathbf{x}) dl \lesssim 1$$

Choi, Kim, Rott PRD 99, 083018 (2019)

Dissipation of Neutrino flux from IC170922A

DM is non-relativistic
sigma is constant

$$\int_{\text{path}} \sigma n(\mathbf{x}) dl = \int_{los} n(z)\sigma dl + \int_{los} \sigma n_{\text{gal}}(\mathbf{x}) dl,$$

$$= \frac{\sigma}{M_{\text{dm}}} \left(\int_{los} \rho(z) dl + \int_{los} \rho_{\text{gal}}(\mathbf{x}) dl \right)$$

[Kelly, Machado, 2018]
[Alvey, Fairbairn, 2019]

cosmological DM

$$\rho(z) = \rho_0 (1+z)^3$$
$$\rho_0 \simeq 1.3 \times 10^{-6}\ \text{GeV}/\text{cm}^3$$

$$L = 1420\ \text{Mpc}$$

$$\int_{los} \rho(z)\, dl = \int \rho(z) \frac{cdt}{dz} dz, \quad \simeq 7.2 \times 10^{21}\ \text{GeV}/\text{cm}^2,$$

Galactic DM

$$\rho_{\text{gal}}(\mathbf{x}) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

$$\rho_s = 0.184\ \text{GeV}/\text{cm}^3$$
$$r_s = 24.42\ \text{kpc}$$

$$\int_{los} \rho_{\text{gal}}(\mathbf{x}) dl \simeq 3.8 \times 10^{22}\ \text{GeV}/\text{cm}^2$$

Choi, Kim, Rott PRD 99, 083018 (2019)

Requiring less than 90% suppression of the flux $\int \sigma n dl \lesssim 2.3$

$$\frac{\sigma}{M_{\rm dm}} \lesssim 2.3 \times \left(\rho_0 L + \int_{los} \rho_{\rm gal}(\mathbf{x}) dl\right)^{-1}$$

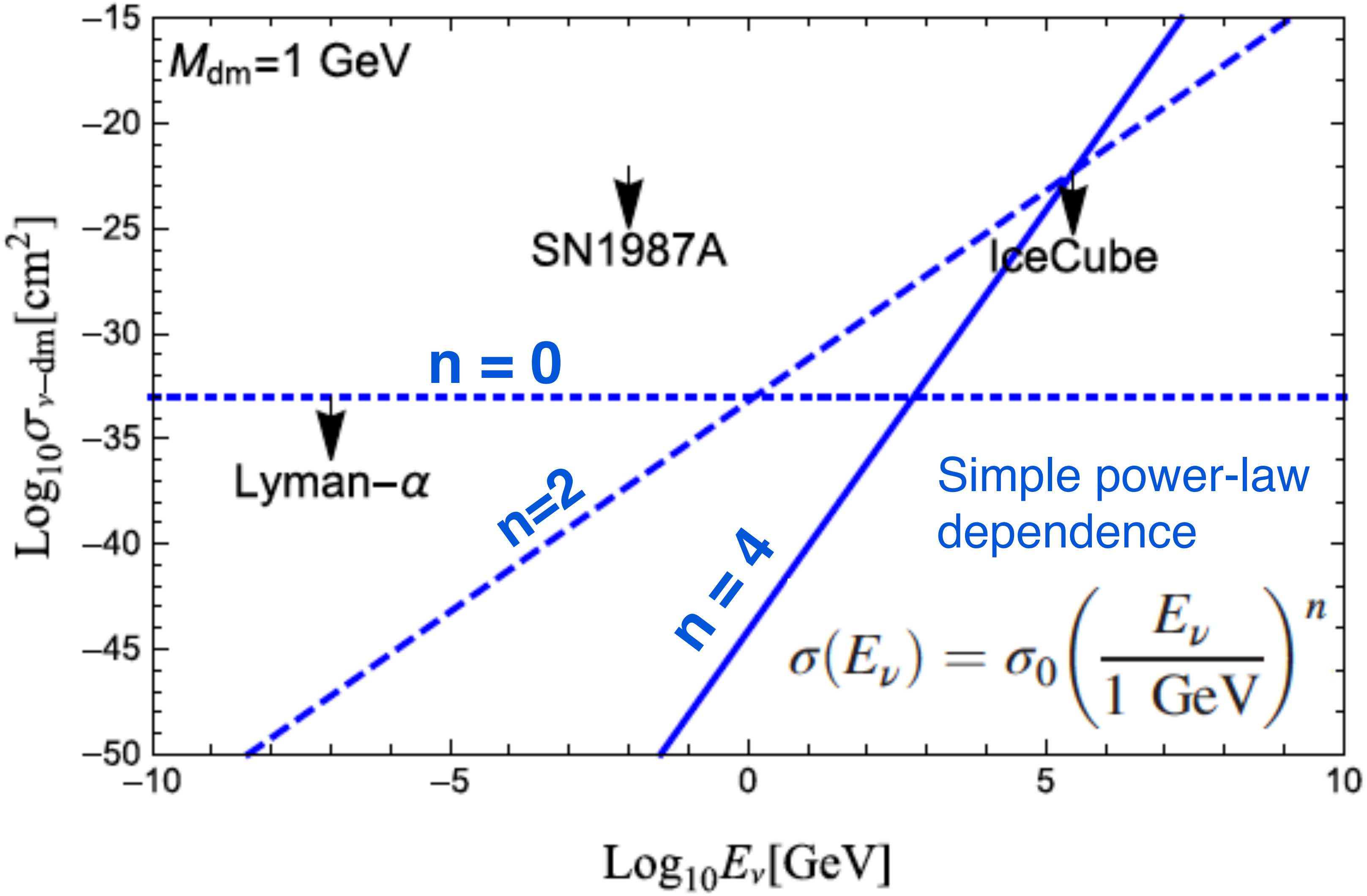
We obtain the upper bound on the cross section/mass as

$$\sigma / M_{\rm dm} \lesssim 5.1 \times 10^{-23}\,{\rm cm}^2/\,{\rm GeV} \quad \text{at} \quad E_\nu = 290\,{\rm TeV}$$

$$\frac{\sigma}{M_{\rm dm}} \lesssim 2.3 \times \left(\rho_0 L + \int_{los} \rho_{\rm gal}(\mathbf{x}) dl\right)^{-1} \simeq 5.1 \times 10^{-23}\,{\rm cm}^2/\,{\rm GeV} \quad \text{at} \quad E_\nu = 290\,{\rm TeV}$$

Energy dependence of the constraint

Choi, Kim, Rott PRD 99, 083018 (2019)



The strongest constraint depends on the form of cross section

$$\sigma_0/M_{\text{dm}} \lesssim 10^{-33}\,\text{cm}^2/\,\text{GeV} \quad \text{for} \quad n = 0,$$
$$\sigma_0/M_{\text{dm}} \lesssim 6.3\times 10^{-34}\,\text{cm}^2/\,\text{GeV} \quad \text{for} \quad n = 2,$$
$$\sigma_0/M_{\text{dm}} \lesssim 7.5\times 10^{-45}\,\text{cm}^2/\,\text{GeV} \quad \text{for} \quad n = 4.$$

CMB / Lyman-α constraint:

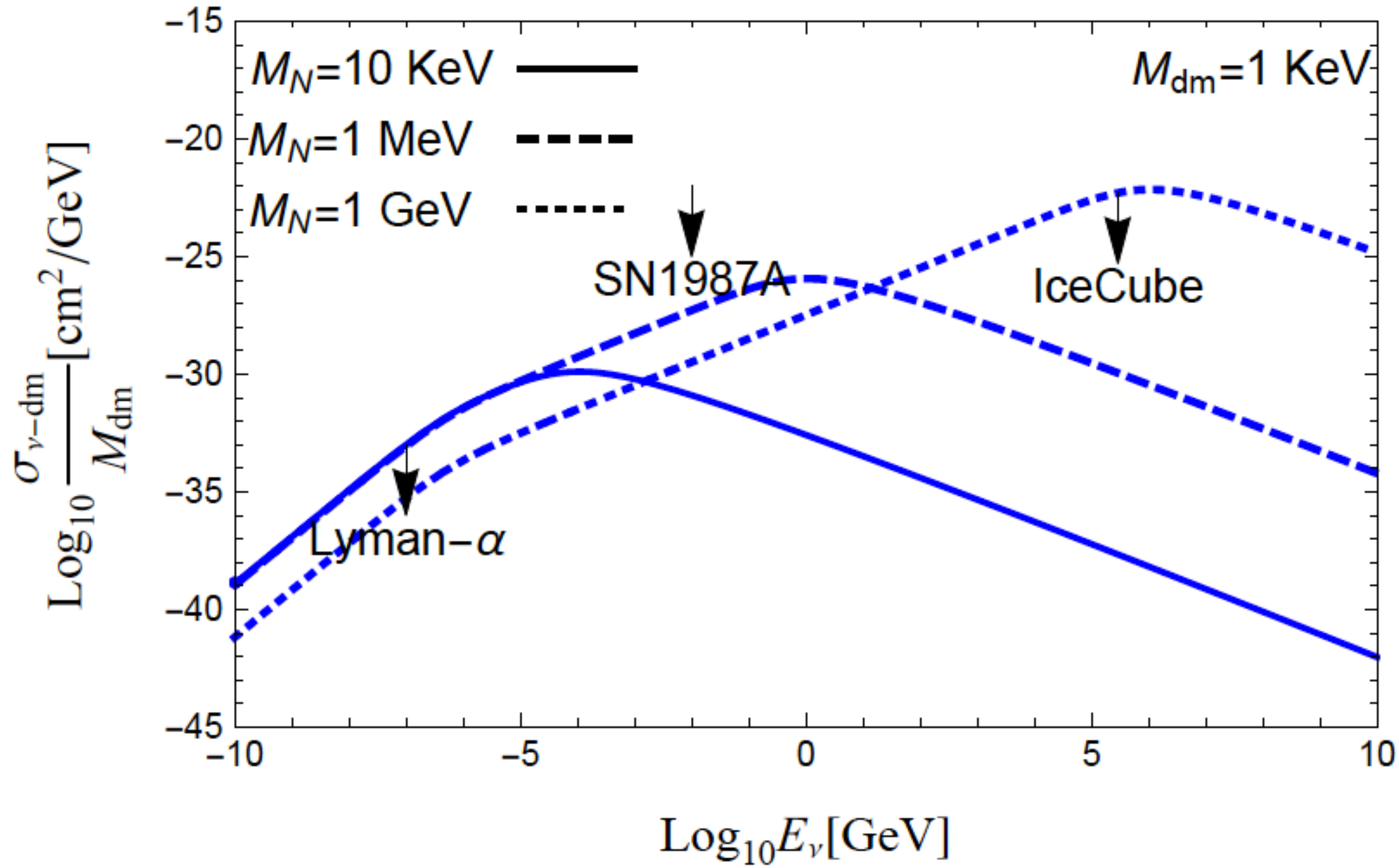
small scale suppression of the density fluctuation that has been caused before the last scattering of photons, when the neutrino energy was around 100 eV

Choi, Kim, Rott PRD 99, 083018 (2019)

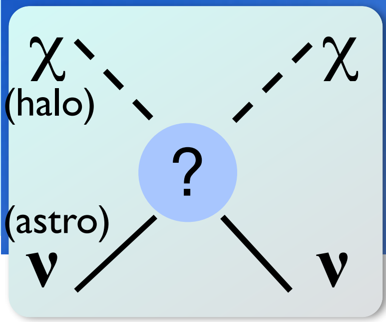
$$\mathcal{L}_{\rm int} = -g\chi\overline{N}\nu_L + {\rm h.c.}$$

χ dark matter

N massive fermion



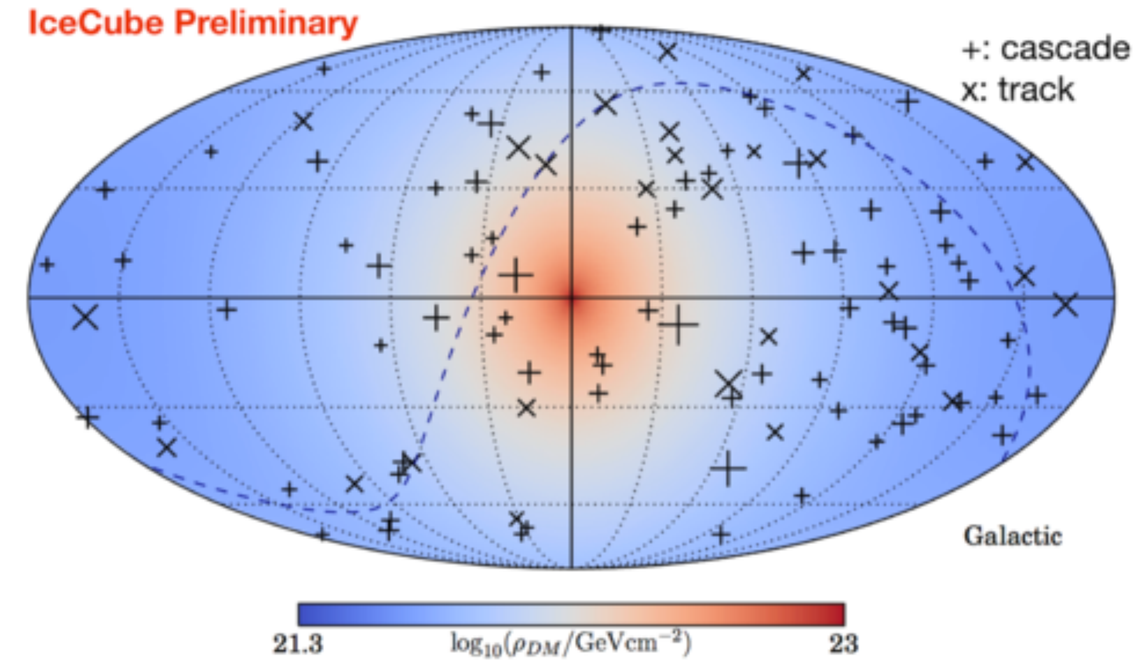
Probing dark matter neutrino interactions with HESE 7.5yrs and Galactic Halo



[C. A. Argüelles, A. Kheirandish A. C. Vincent Phys.Rev.Lett. 119 (2017) no. 20, 201801 (arXiv:1703.00451)]

Dark Matter - Neutrino Interaction

- Scattering of high energy astrophysical neutrinos on DM in the Galactic halo can lead to a deficit of high energy neutrinos
  - Neutrino-DM interactions mediated by a scalar or vector mediator f.
  - Limits on coupling constant, g, possible by measuring the isotropy of the HE neutrino flux

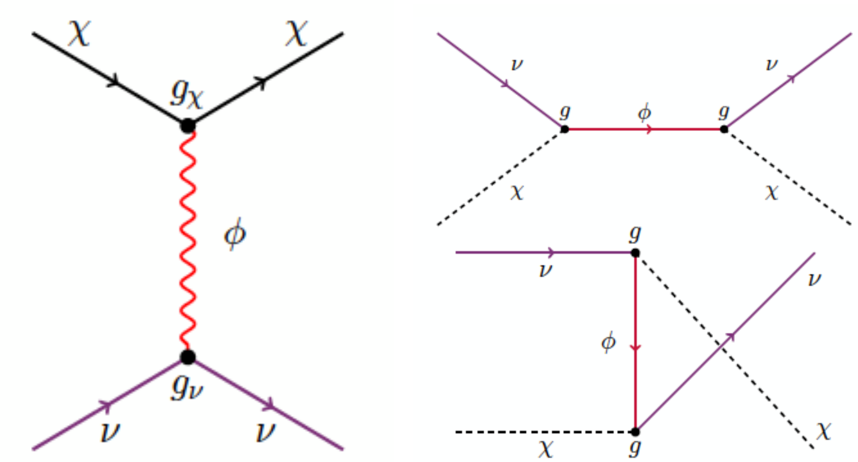


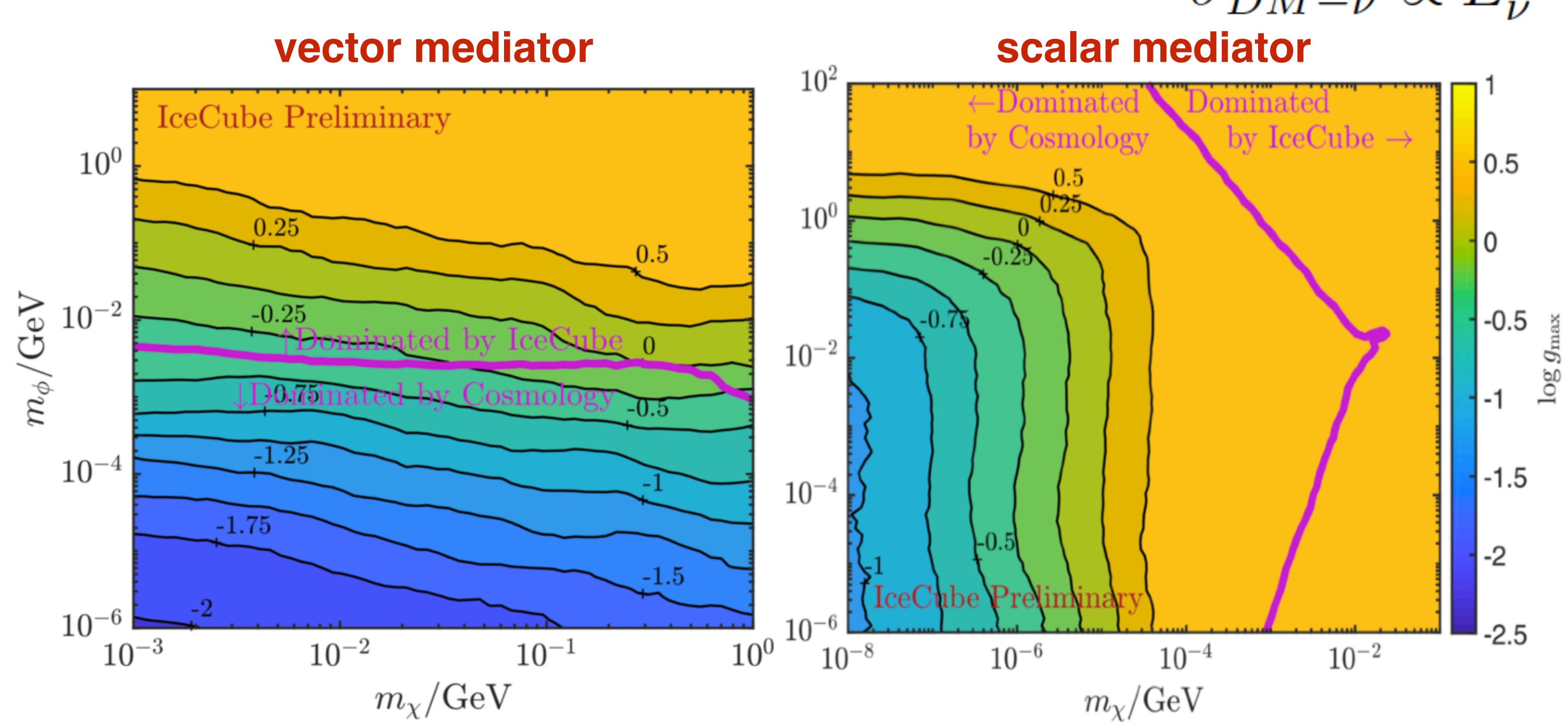
Assume:

$$\sigma_{DM-\nu} \propto E_\nu^2$$

(1) Fermionic DM, vector mediator

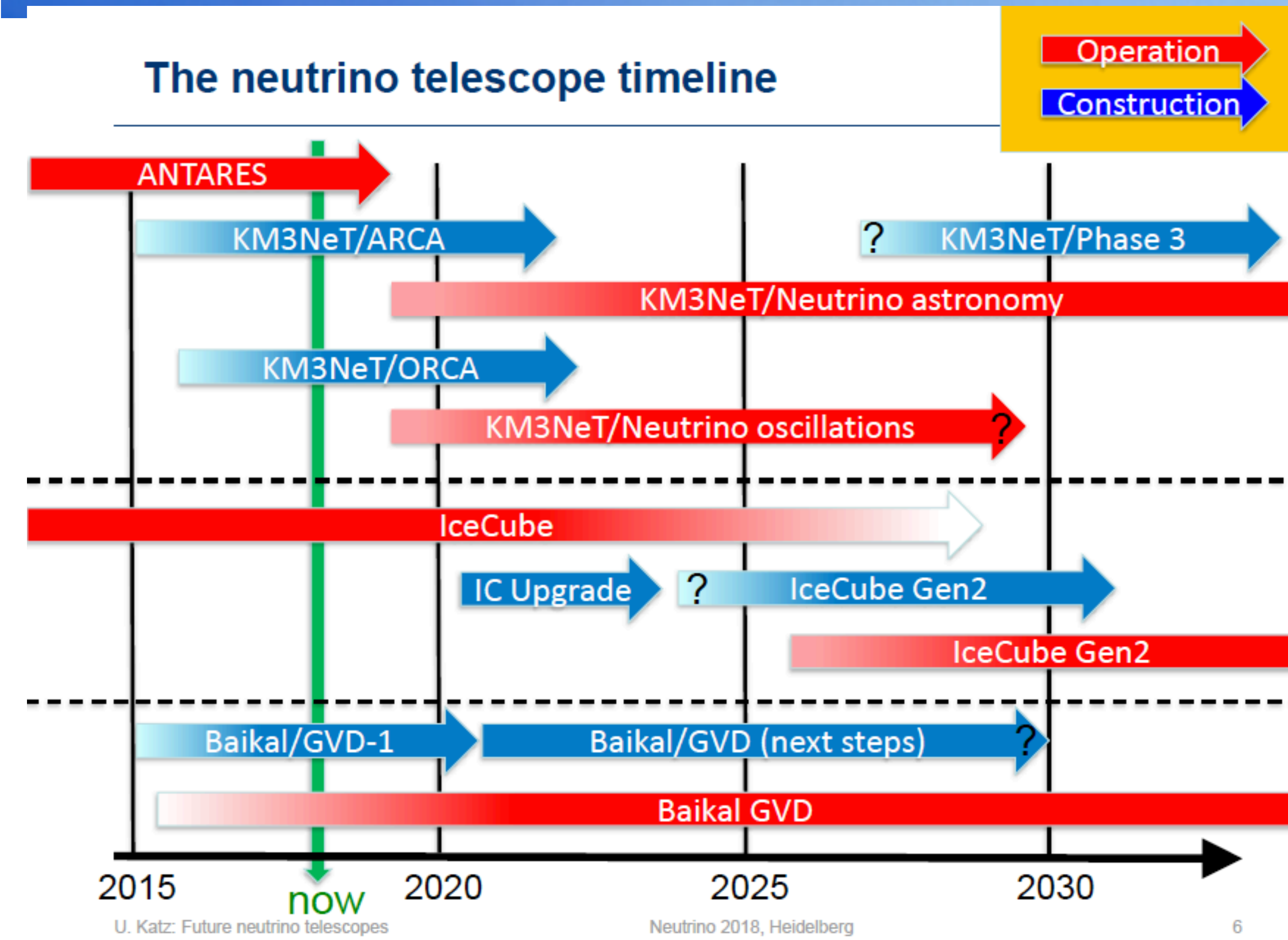
(2) Scalar DM, ferminonic mediator

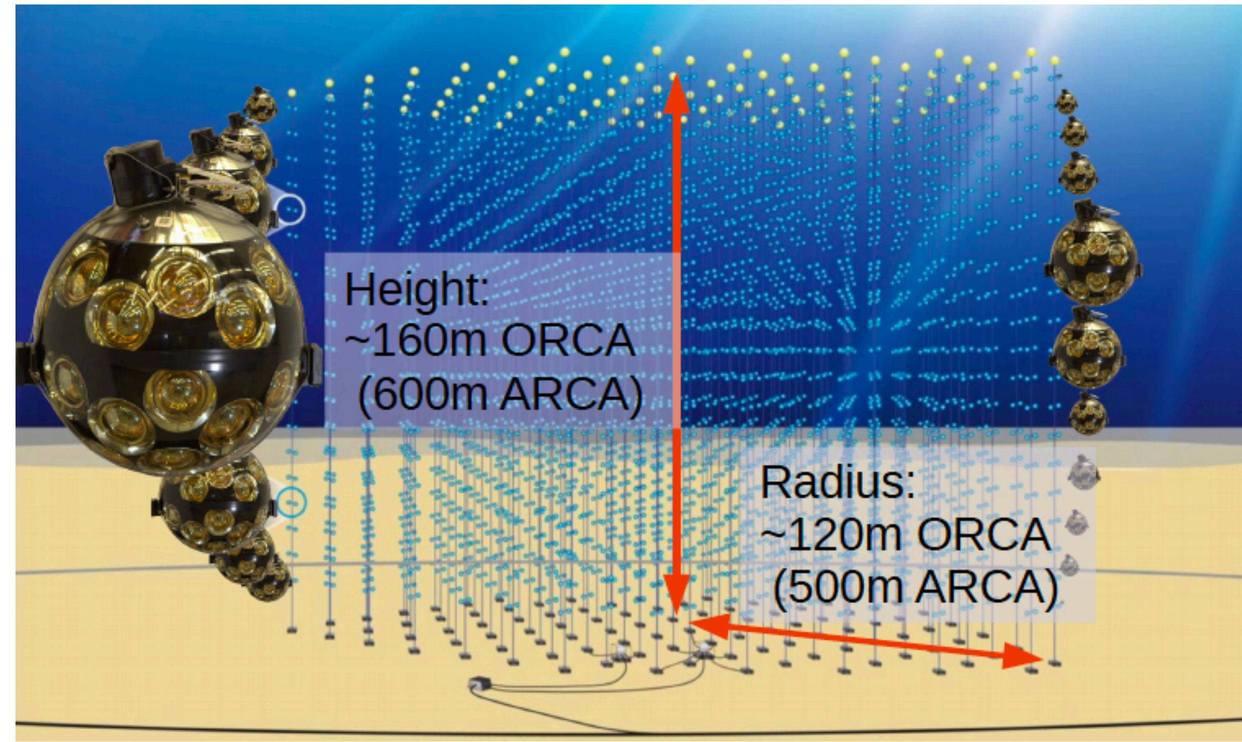


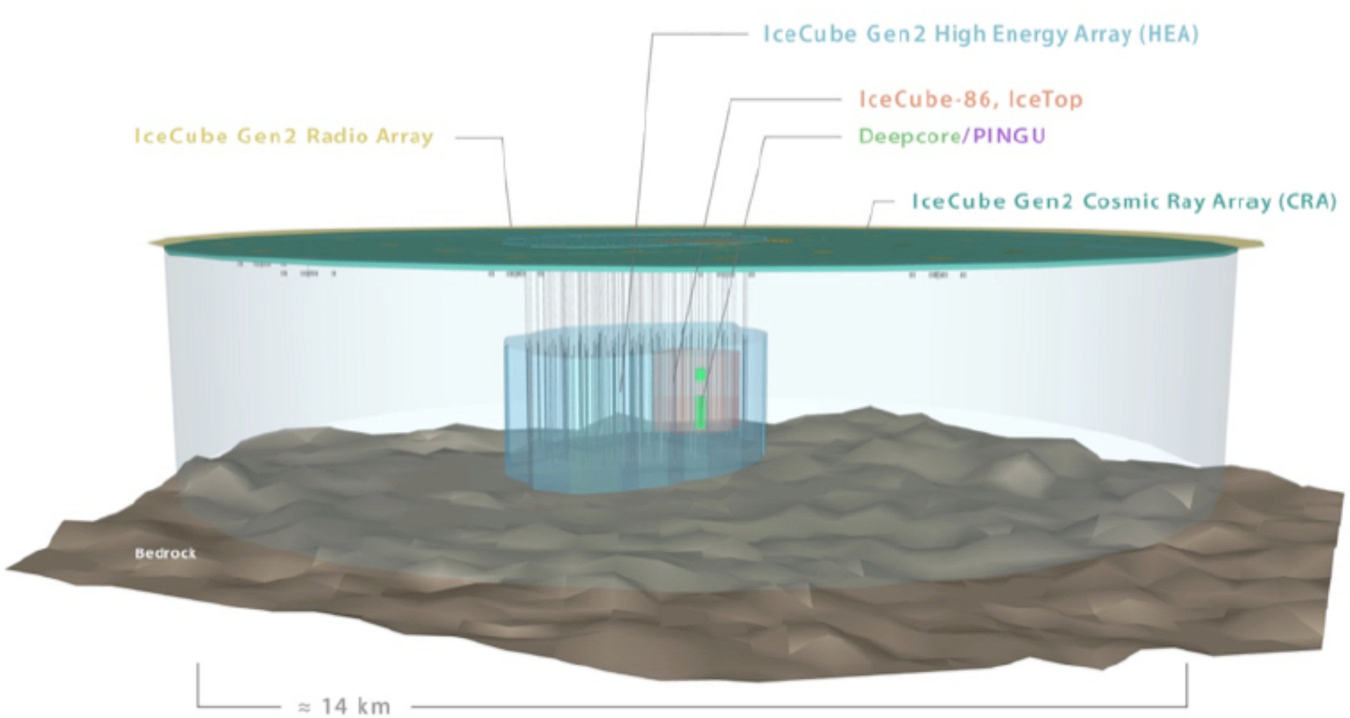


Outlook

Neutrino telescope landscape expanding quickly





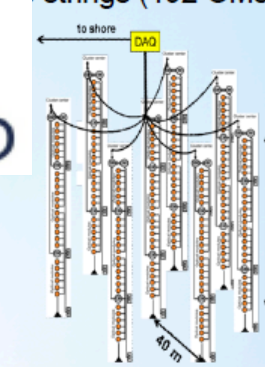


BAIKAL-GVD

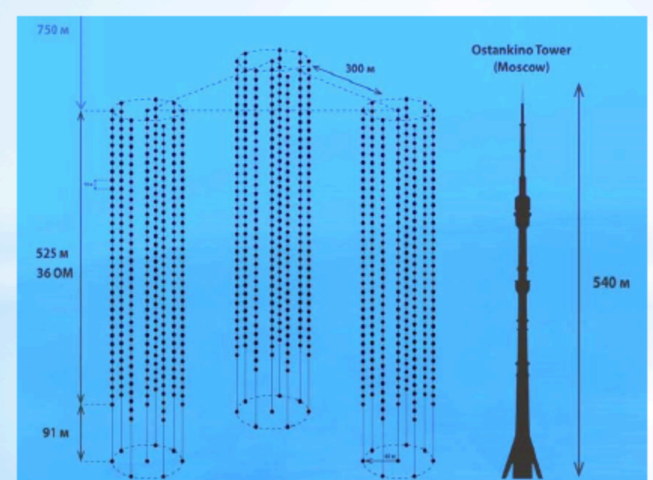
hern latitudes

2015: «Dubna»

strings (192 OMs)

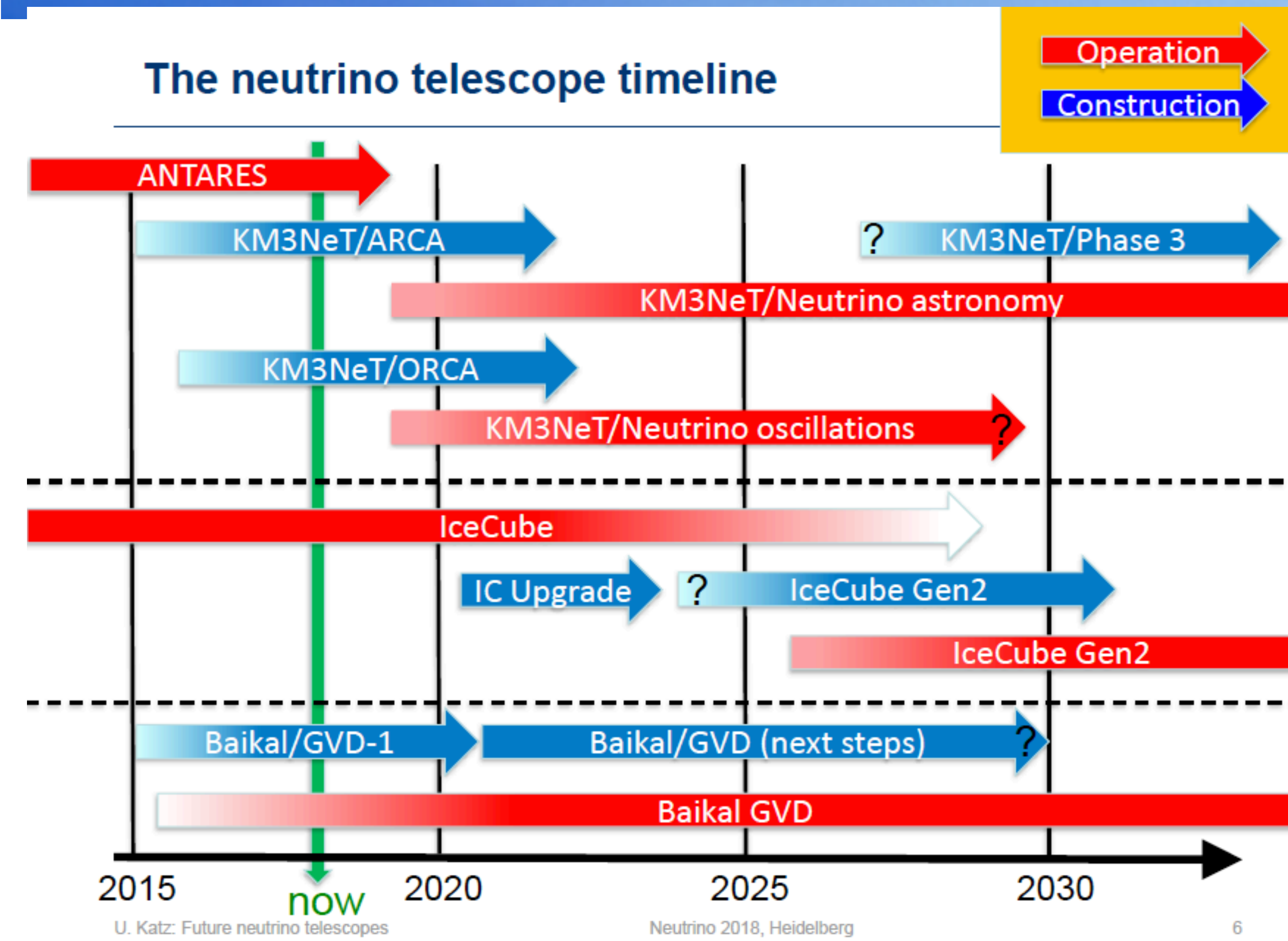


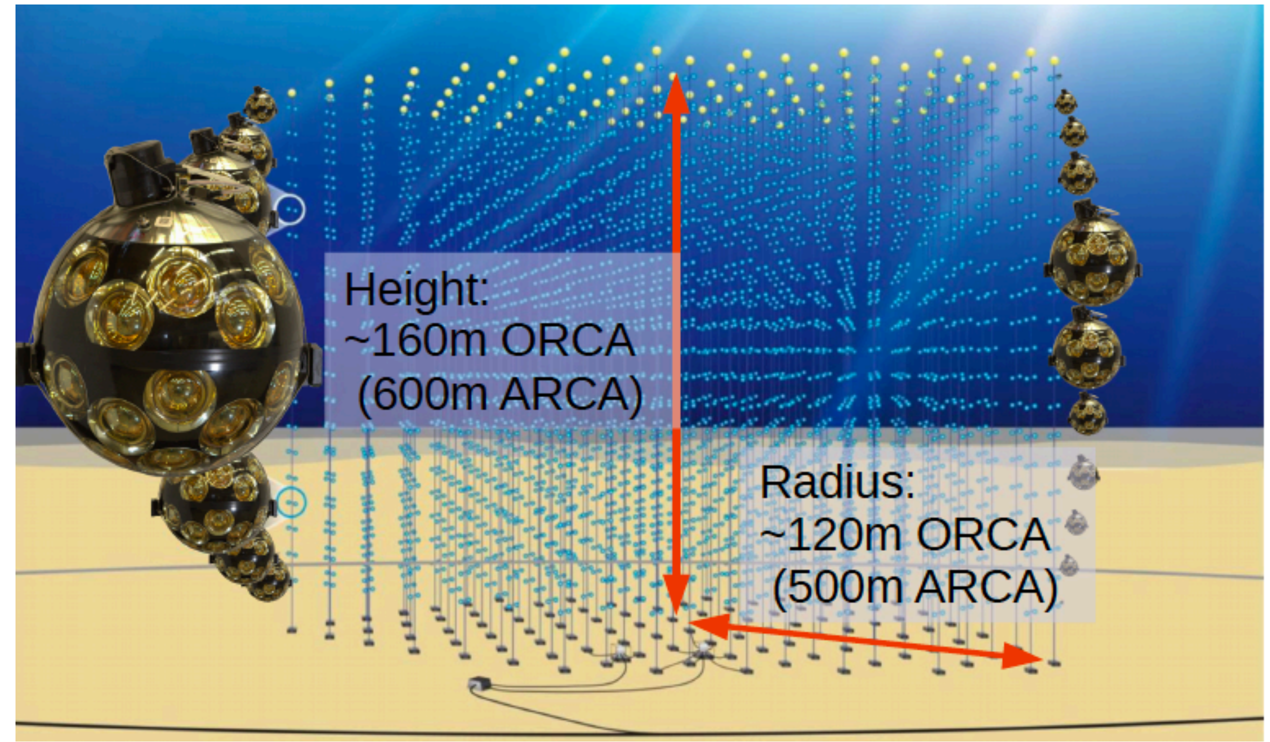
2018: Data taken with three Baikal-GVD clusters

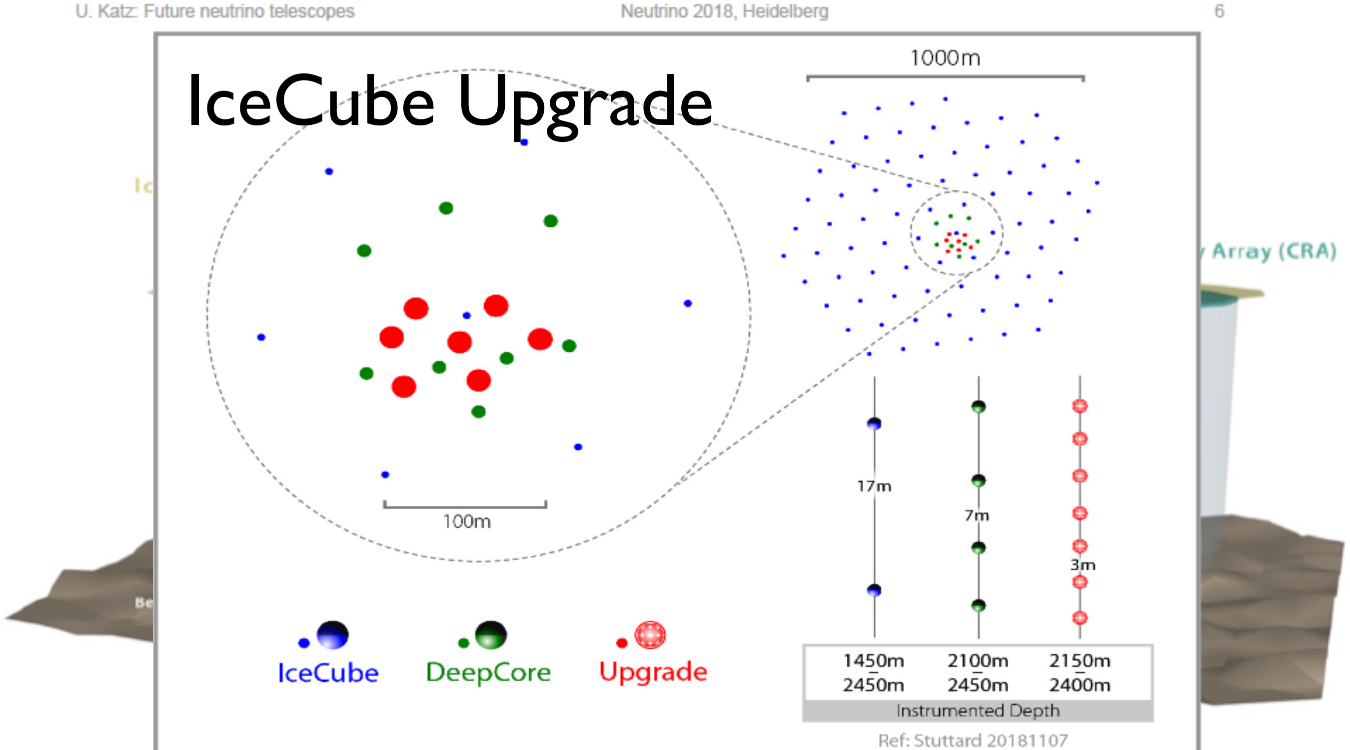


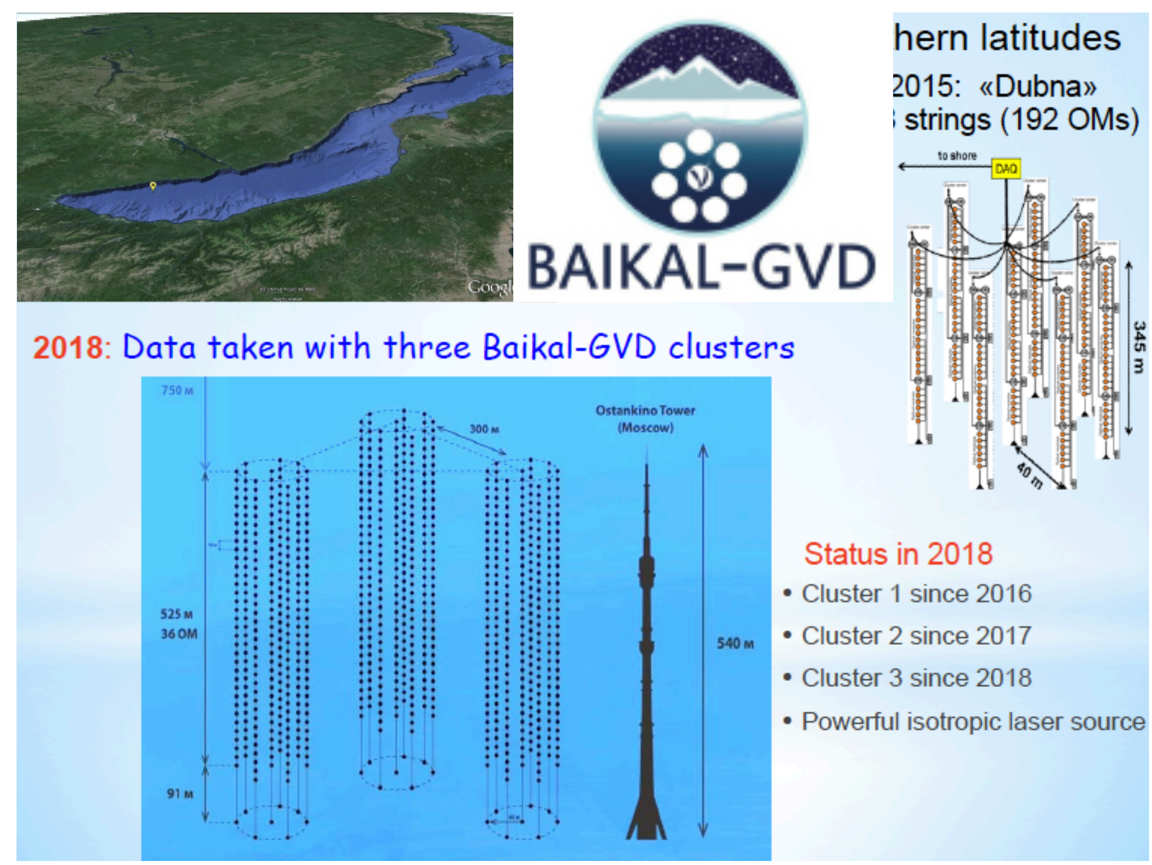
Status in 2018
- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source

Neutrino telescope landscape expanding quickly

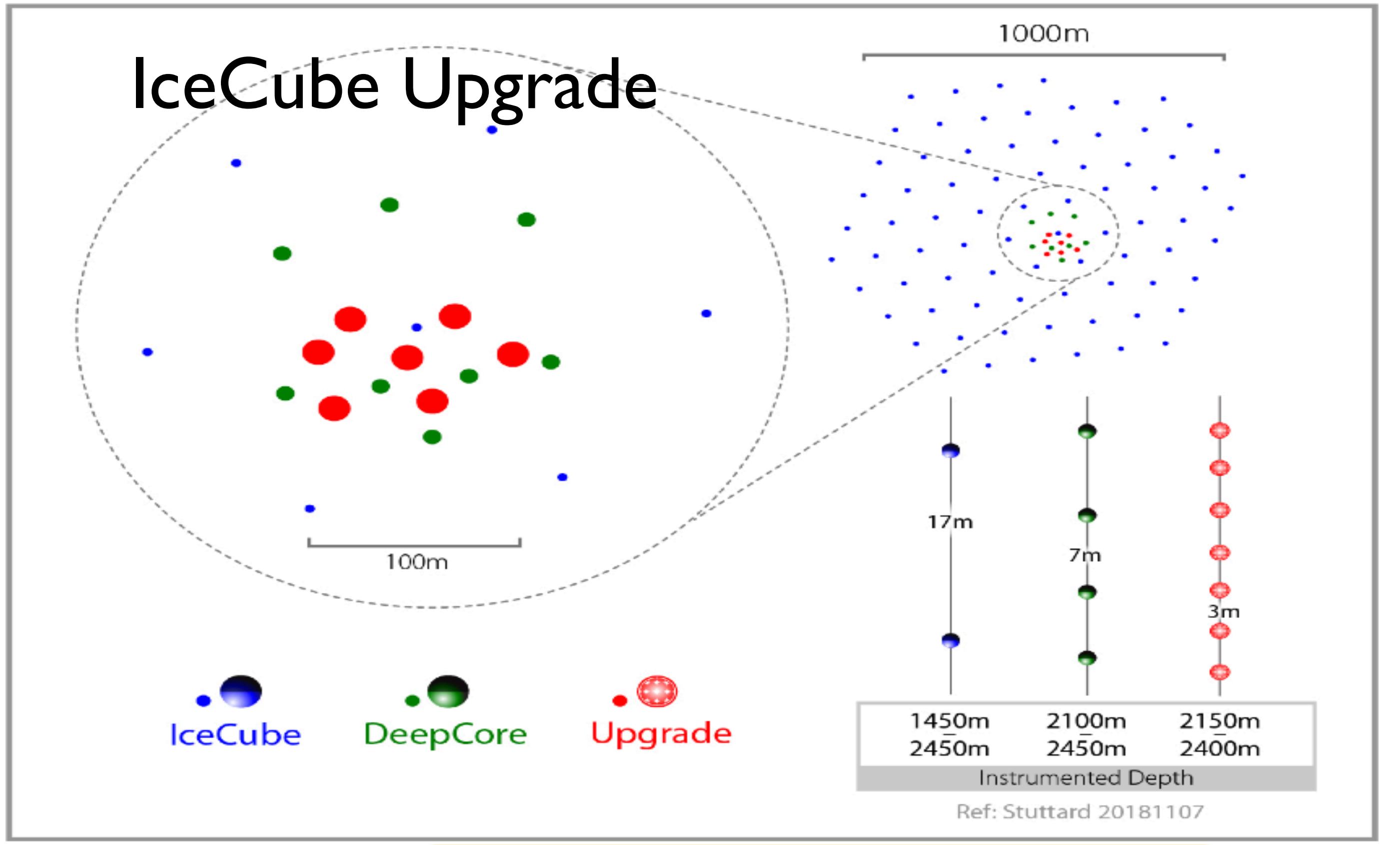








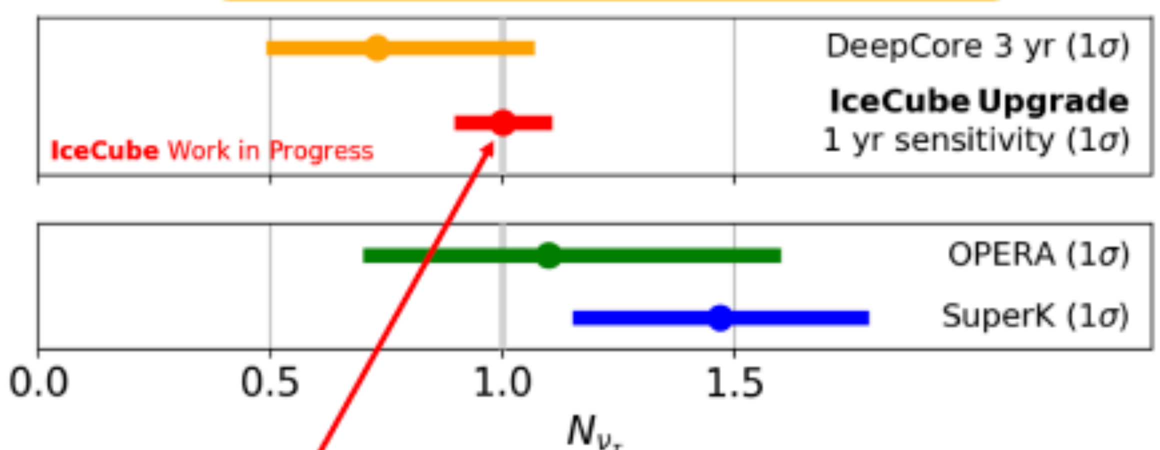
IceCube Upgrade



The IceCube Upgrade

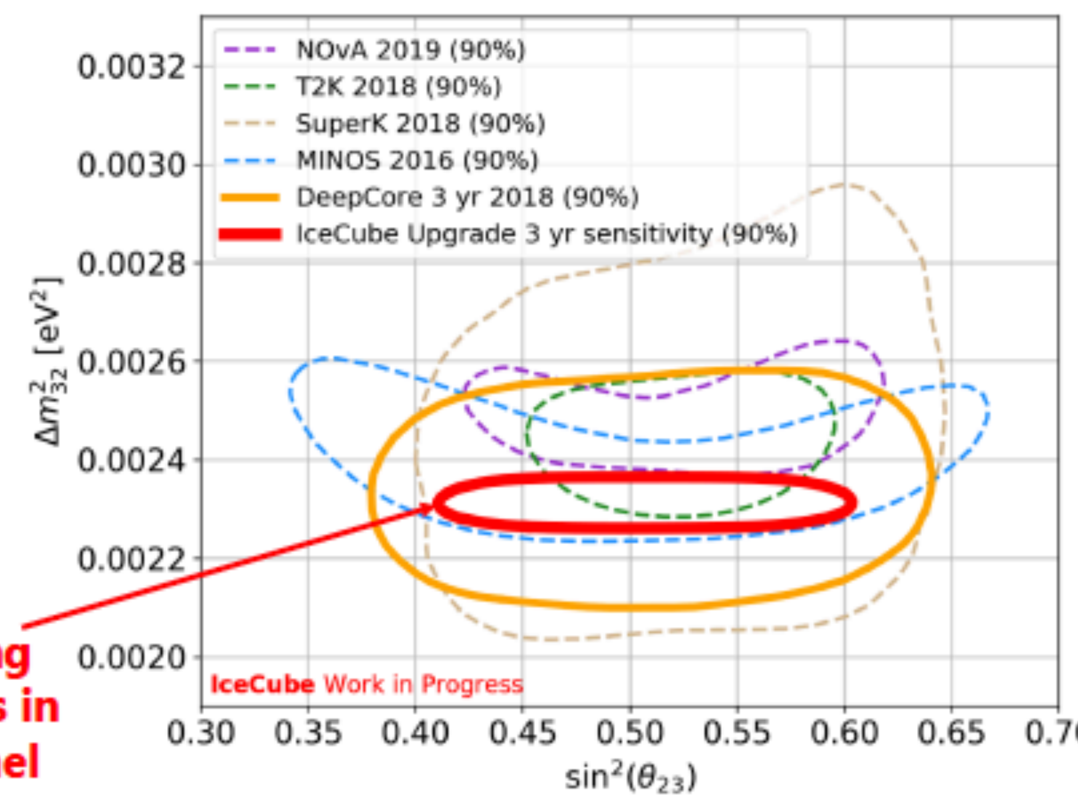
- NSF has funded a $30M extension to IceCube
  - Deployment in 2022/2023
- 700 multi-PMT sensors
- Improved ice calibration

ν_τ appearance sensitivity (1 yr)



10% precision after 1 year
(6% after 3 years)

ν_μ disappearance sensitivity (3 yr)



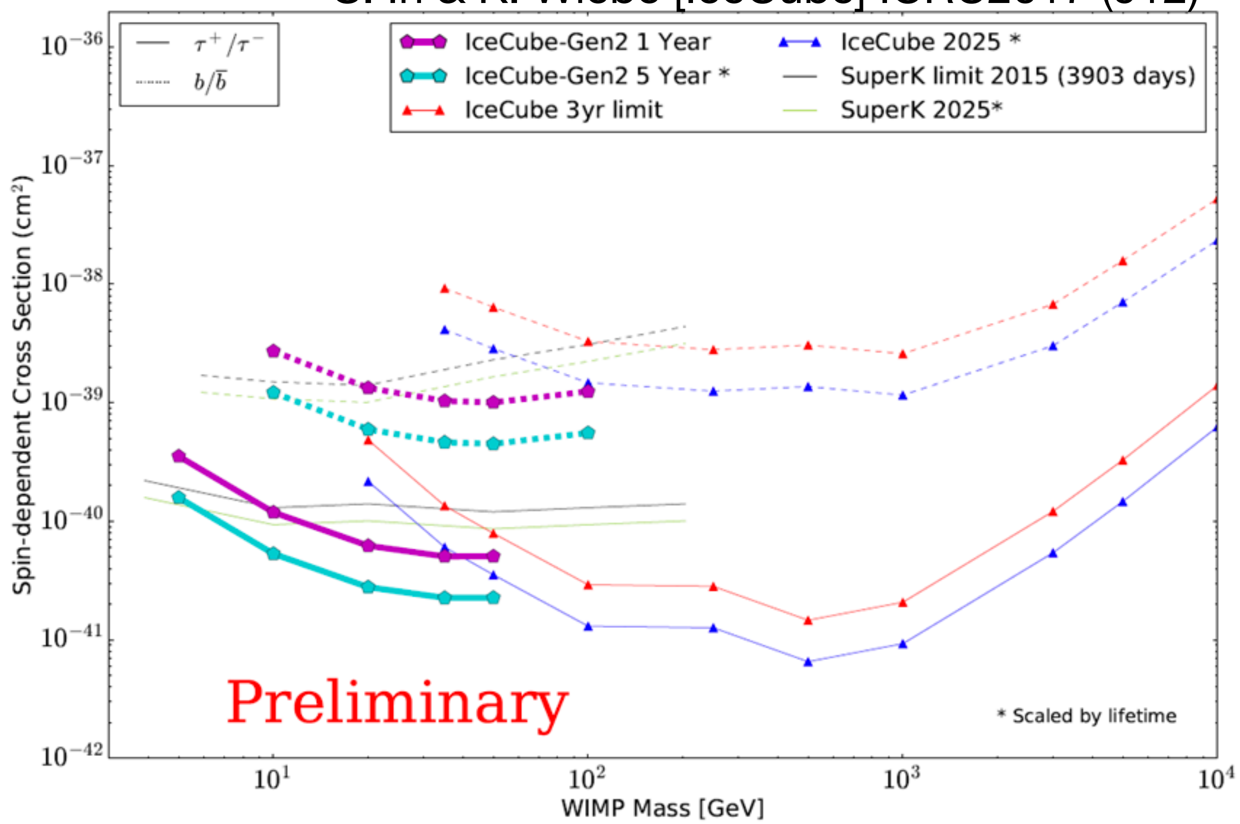
Competitive with long baseline experiments in disappearance channel

IceCube PINGU Collaboration arXiv:1401.2046
Short version https://arxiv.org/pdf/1607.02671.pdf

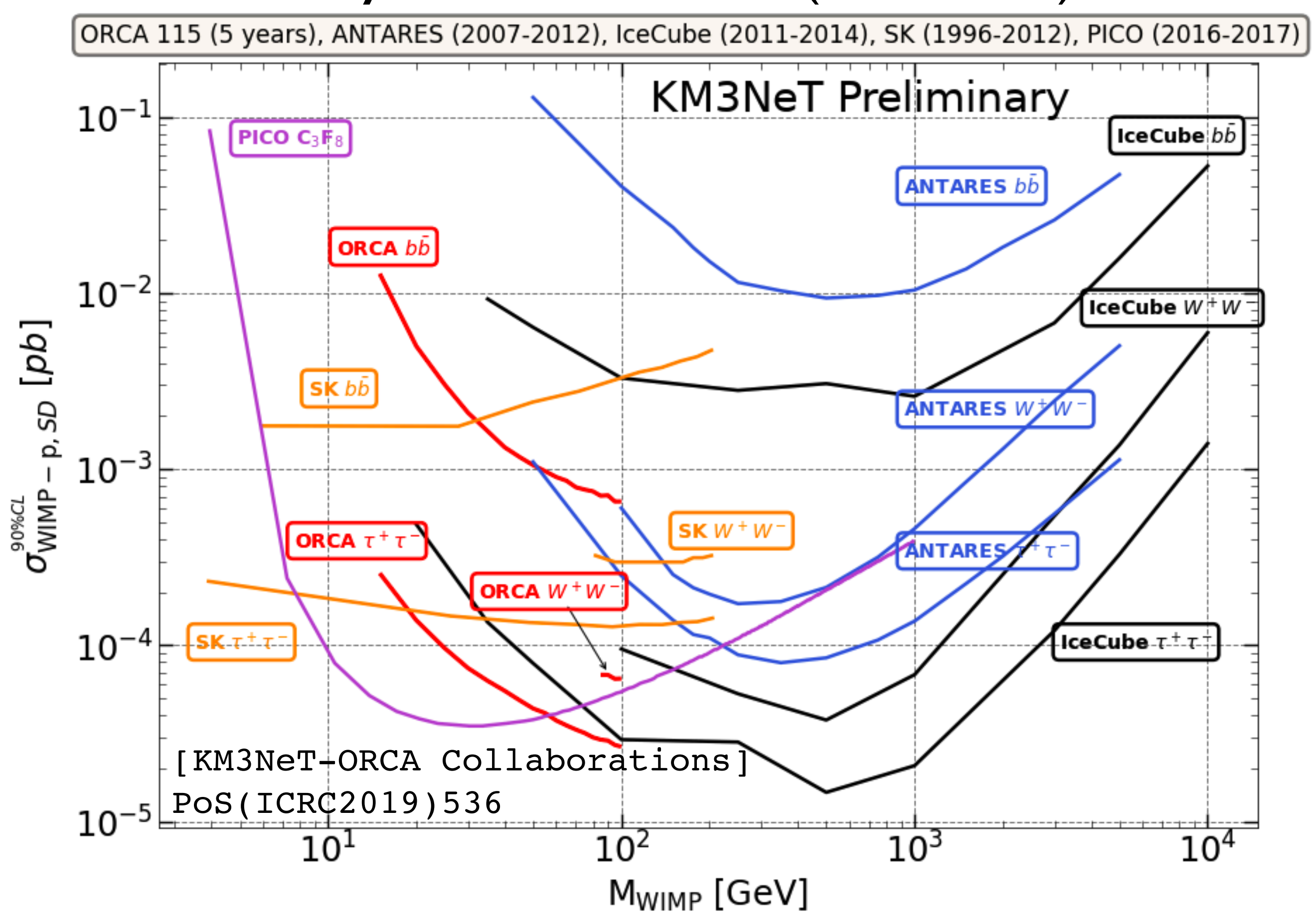
Next generation neutrino detectors

IceCube-Gen2 (IceCube-Upgrade)

S. In & K. Wiebe [IceCube] ICRC2017 (912)



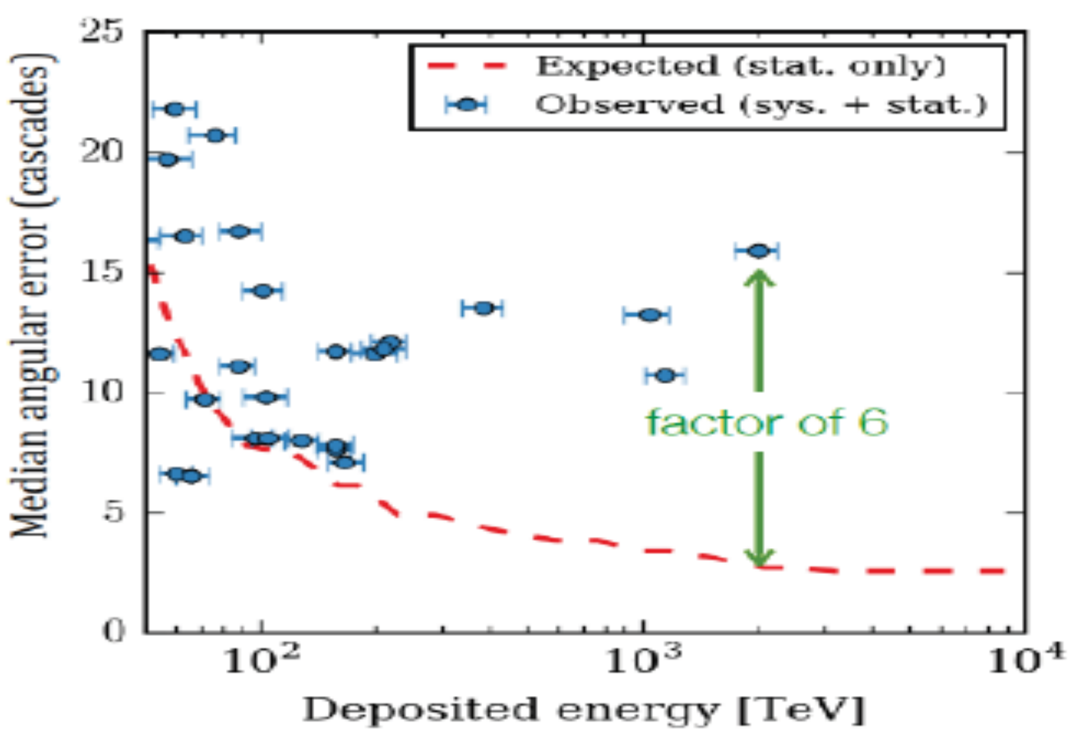
5 years of ORCA (115 lines)



- IceCube Upgrade (to be deployed 2022/2023) and ORCA (under construction) will be able to improve Solar Dark Matter sensitivity for masses below 100GeV
- IceCube recalibration campaign will result in improved limits for higher dark matter masses

Ice Camera System

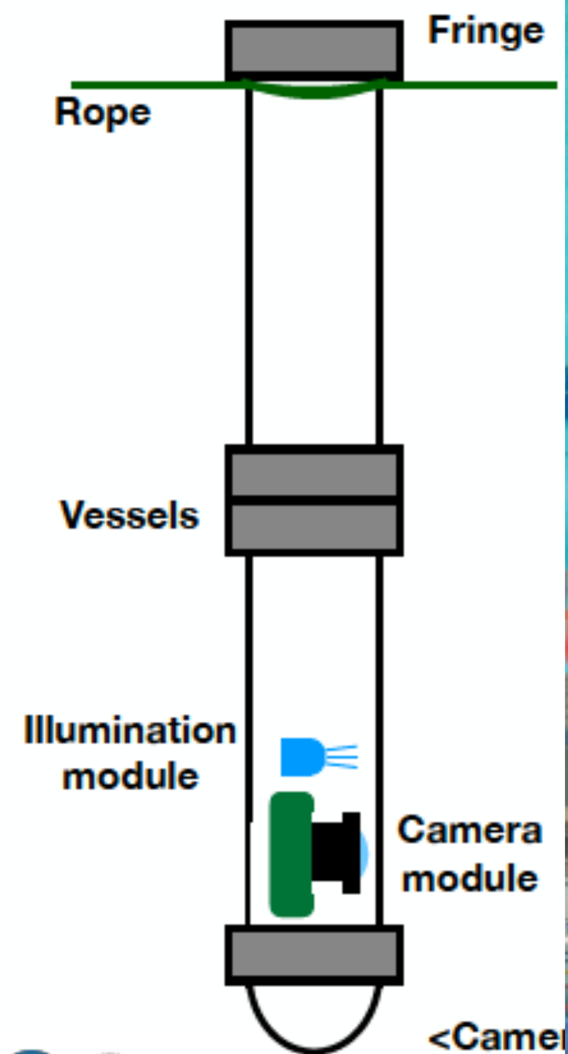
- Ice properties dominant source of sys. uncertainties for most analyses
- Solution: SKKU ice camera system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability

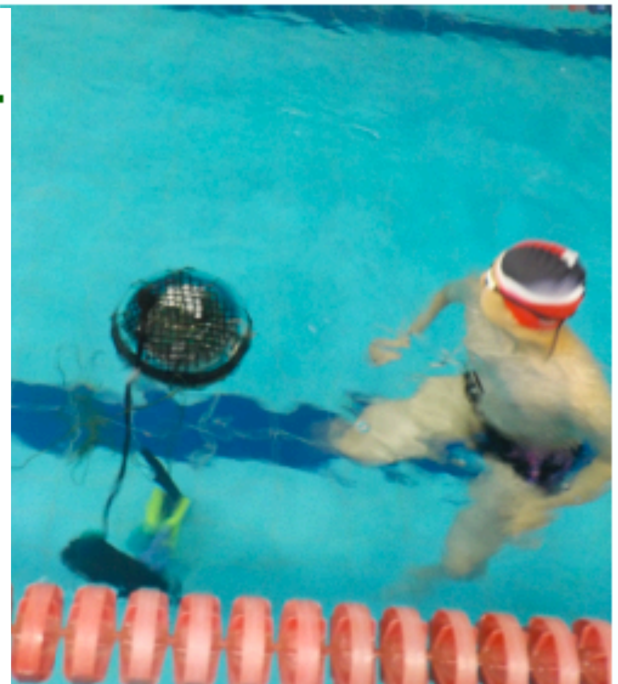


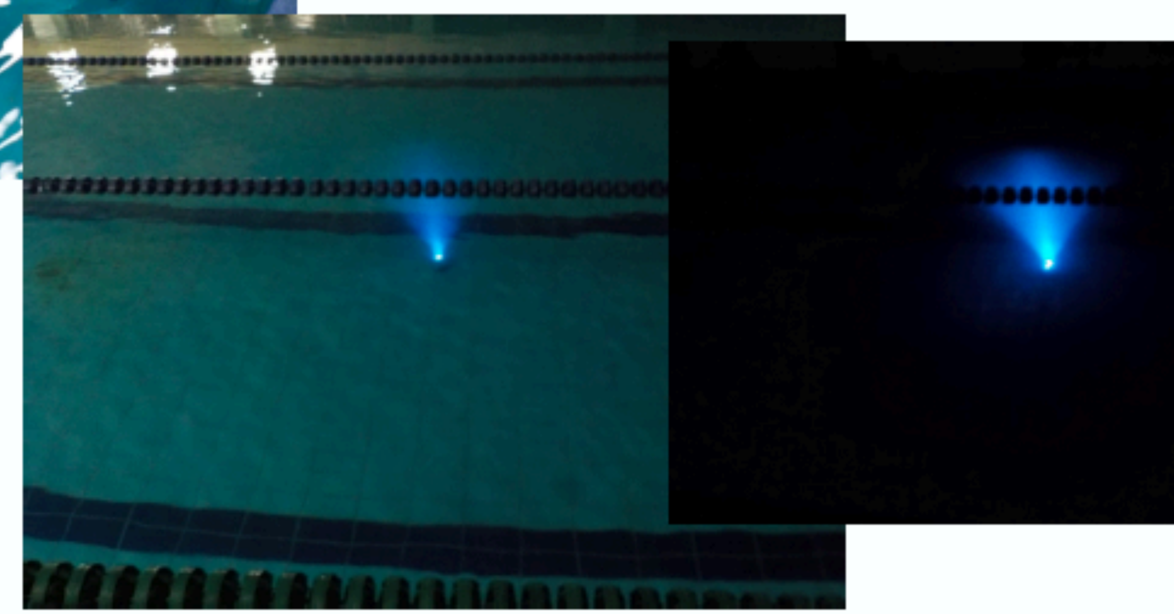
Camera system key to comprehensive understanding of the detector medium
—> Retroactively analyze more than 10 years of IceCube data with substantially improved angular and energy resolution

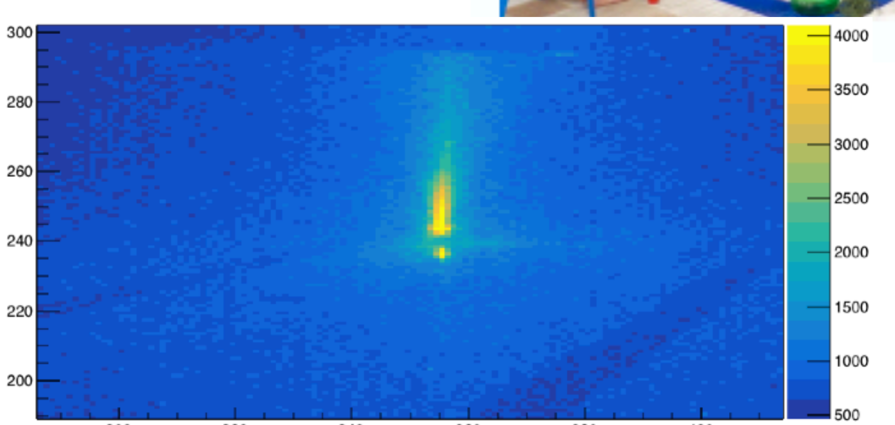
Improved sensitivity for astrophysical source detection through better calibration

Camera testing …





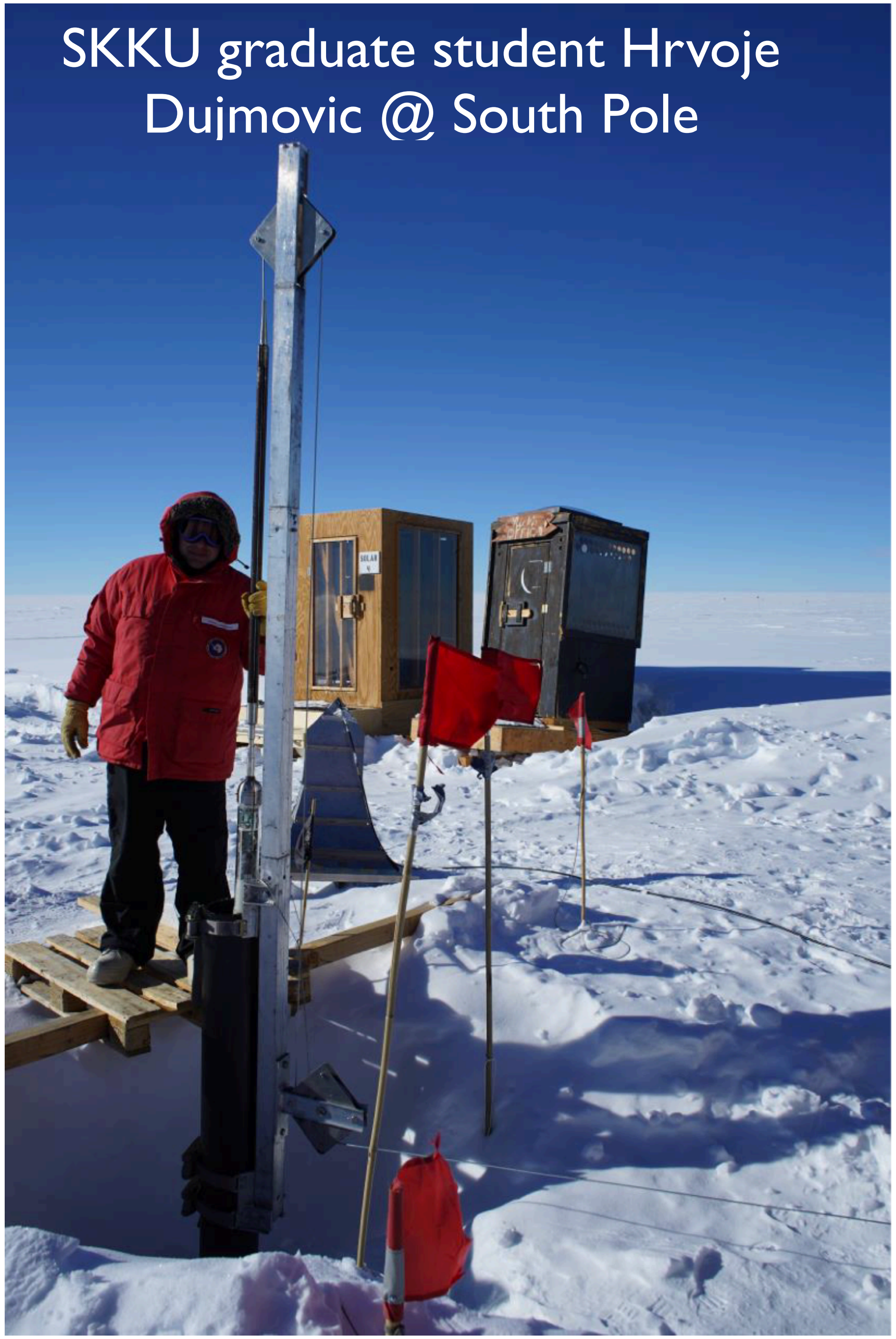


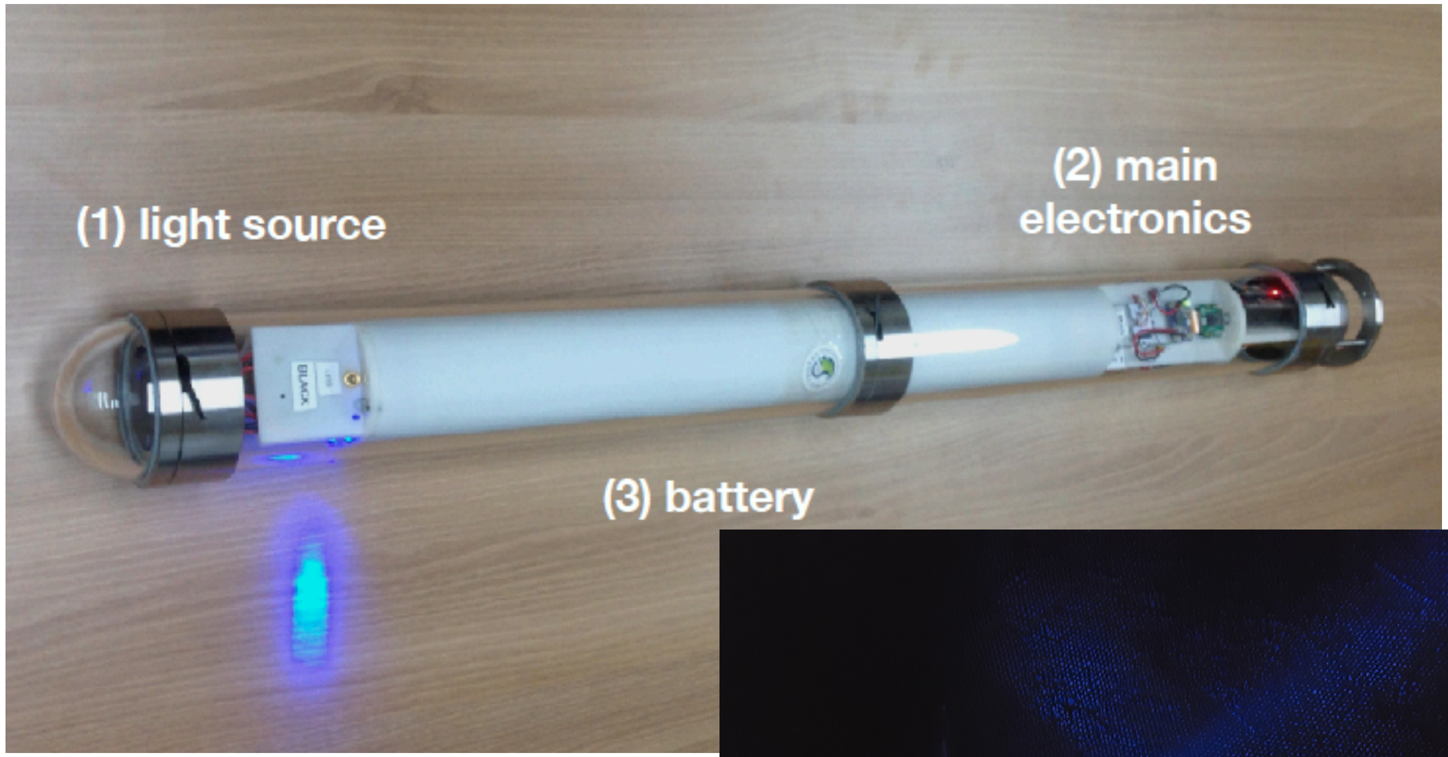


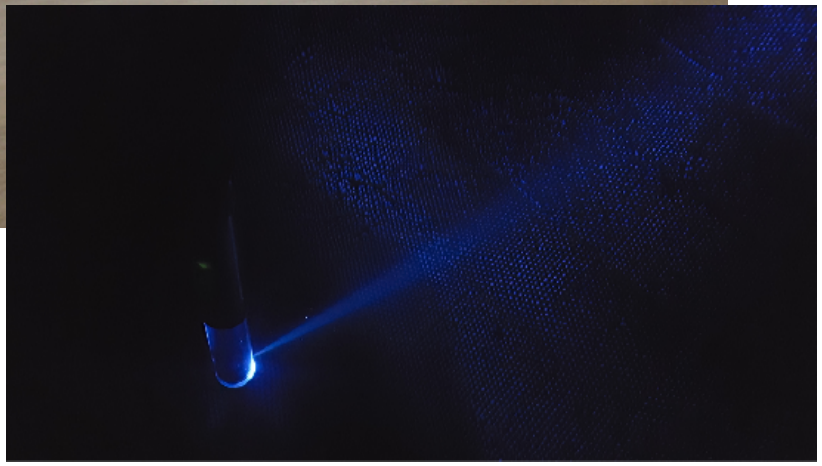
Geometry measurements of order ~10cm at 25m distances

Scattering cones clearly visible - scattering length measurements

SpiceCore Camera System







- SPICE Core camera system was successfully deployed in January 2019 (one 7h deployment to the maximal depth of 1695m)
- Several hundred images taken - image analysis on-going
- Platform to test camera systems for integration into next-generation optical sensor modules

Conclusions

- Striking signatures provide high discovery potential for indirect searches for dark matter with neutrinos
- Stringent limits on dark matter self-annihilation cross section set using neutrino telescopes
- Lifetimes of heavy decaying dark matter has be constrained to 10^{28}s using neutrino signals
- Neutrino Telescopes/Detectors provide world best limits on the Spin-Dependent Dark Matter-Proton scattering cross section
- A new neutrino floor for solar dark matter searches has been calculated and might be observable in the near future
- Neutrino telescope landscape rapidly expanding providing new opportunities for BSM physics searches

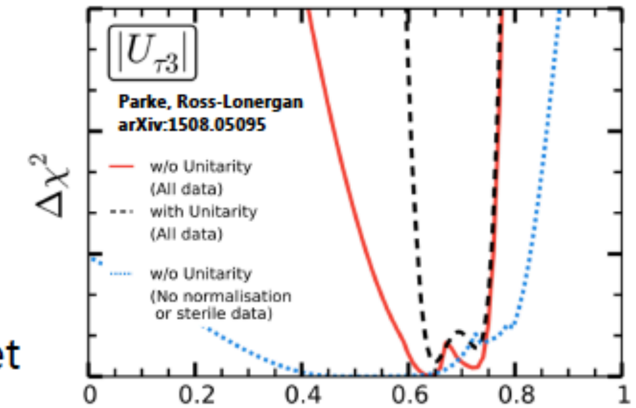
Backup

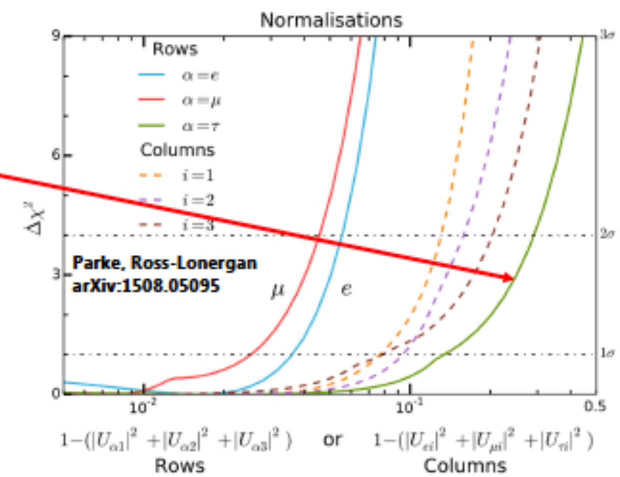
IceCube - PMNS Unitarity

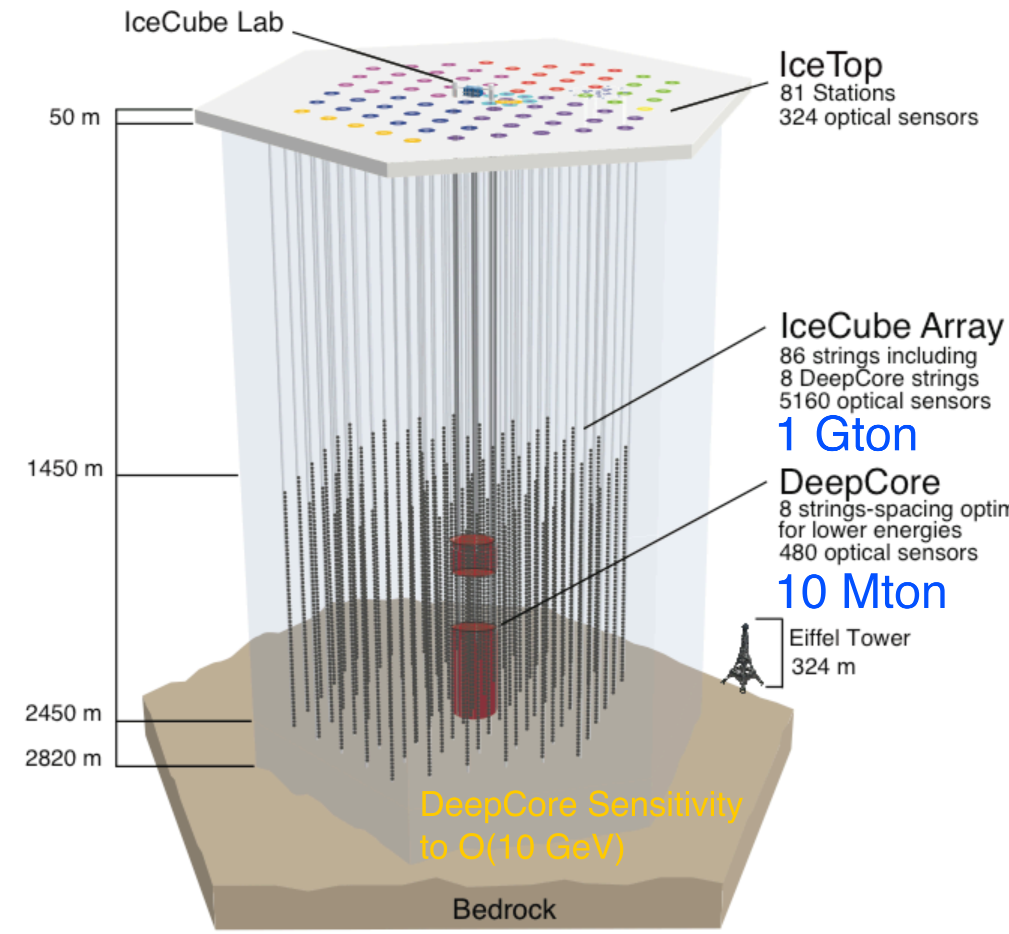
PMNS unitarity

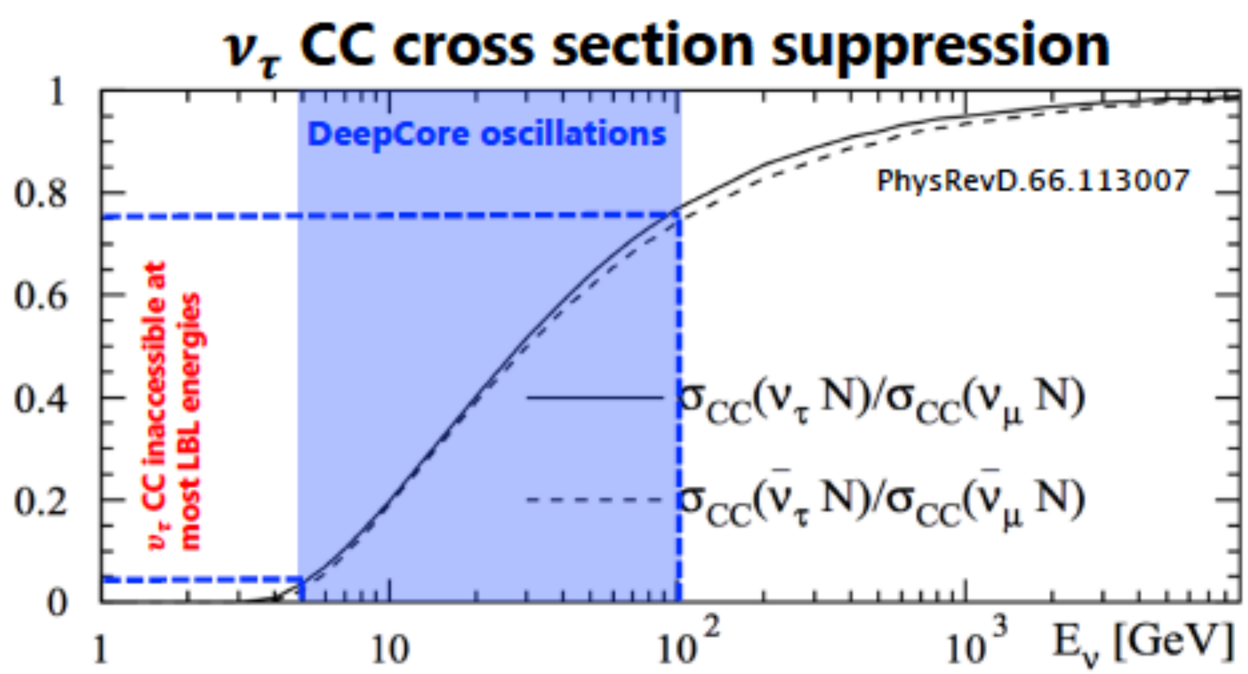
- **PMNS** mixing matrix is **unitary** in standard oscillation picture
  - e.g. mixing between the 3 known neutrino flavours
- Additional (sterile?) states → 3x3 matrix is subset of full unitary matrix
- Test unitarity by measuring 3x3 matrix elements
  - **ν_τ elements least well measured**

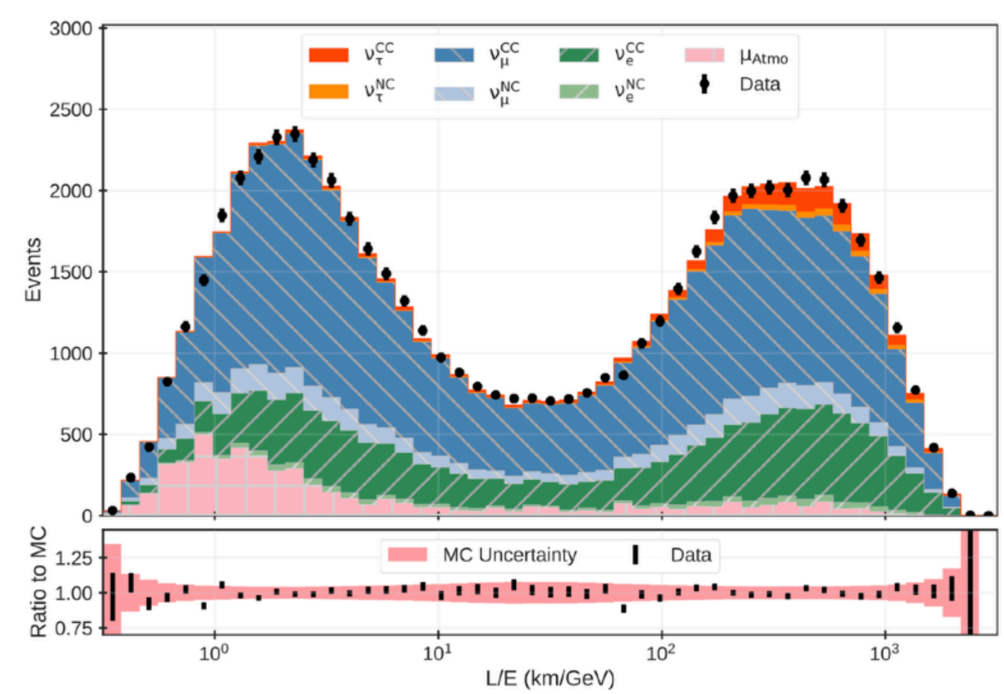
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ & \vdots & & \ddots \end{pmatrix}}^{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$









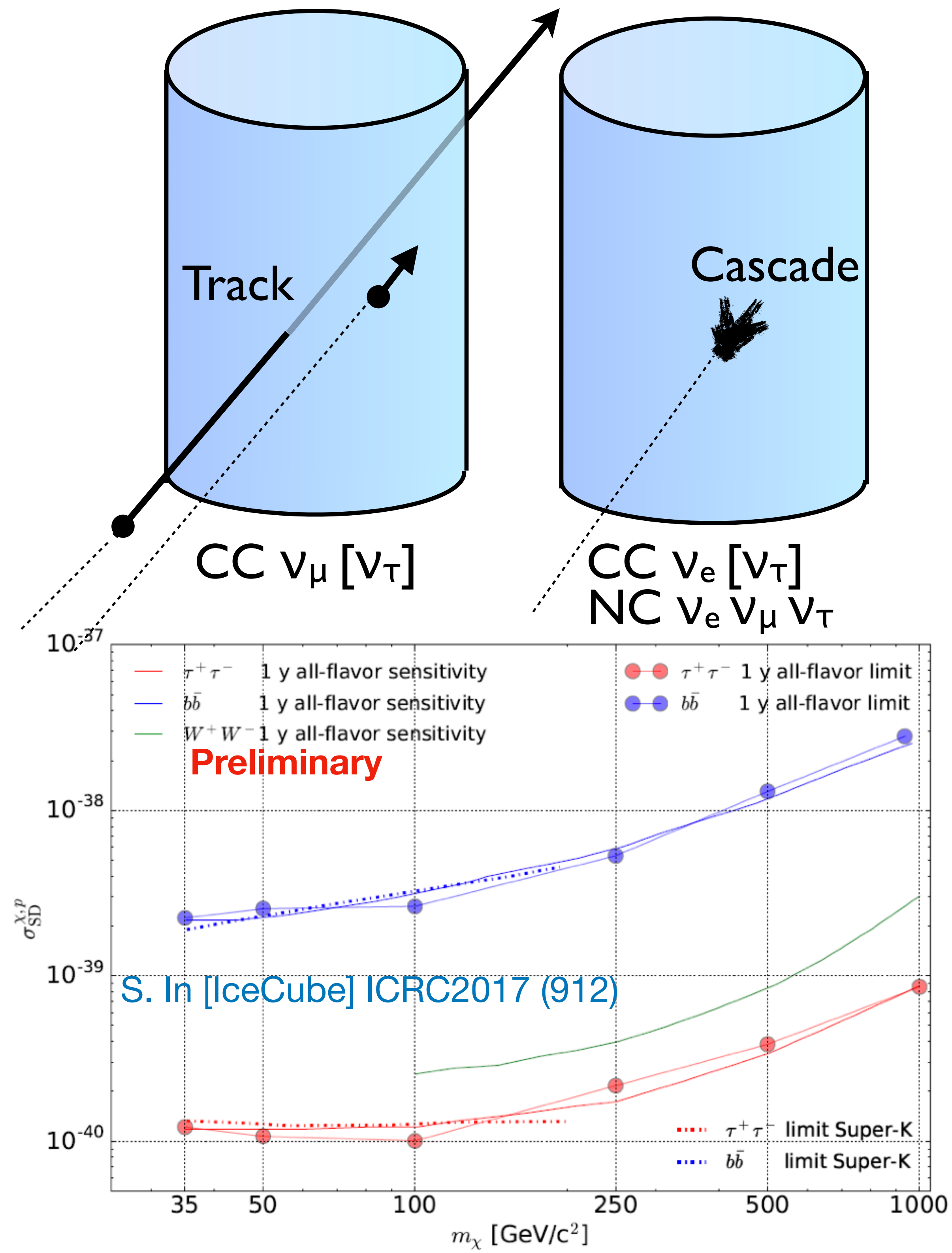


Solar Dark Matter - IceCube/ANTARES

- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section

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

All flavor Solar WIMP - IceCube



Solar WIMPs
- ANTARES - Phys.Lett. B759 (2016) 69-74
- IceCube Eur.Phys.J. C77 (2017) no.3, 146
- S. In and K. Wiebe [IceCube] ICRC2017 (912)

Solar Dark Matter - IceCube/ANTARES

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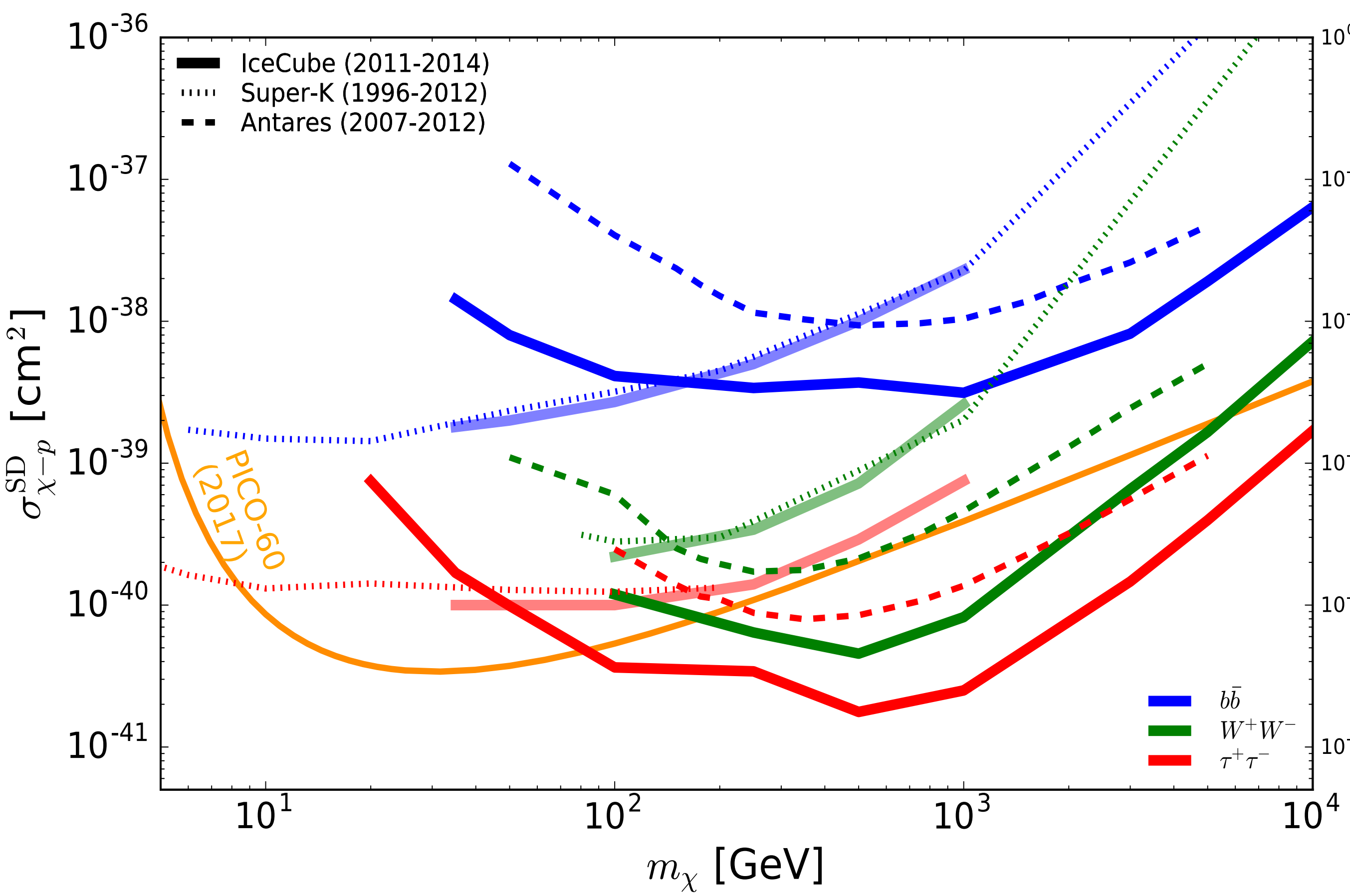

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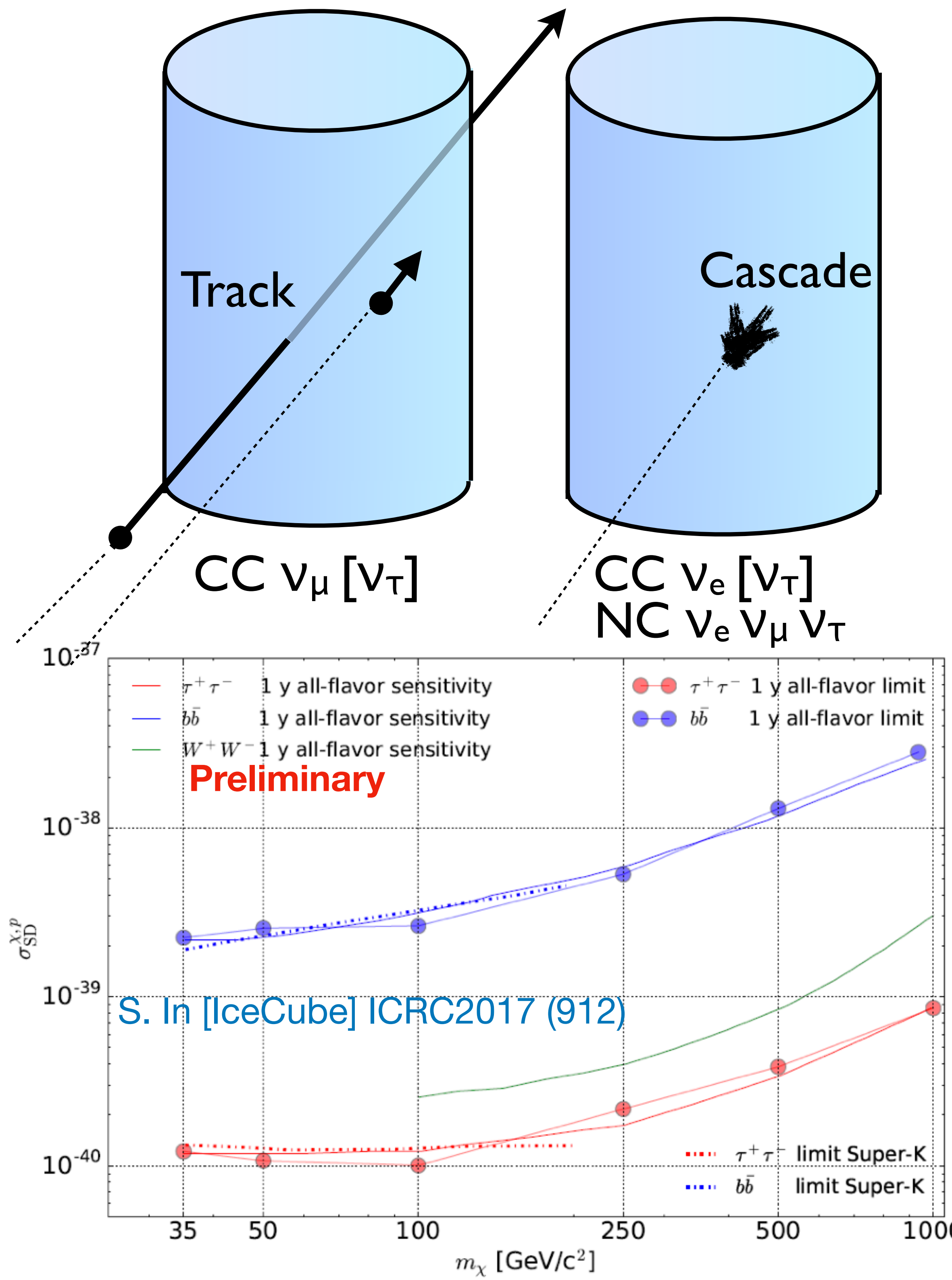
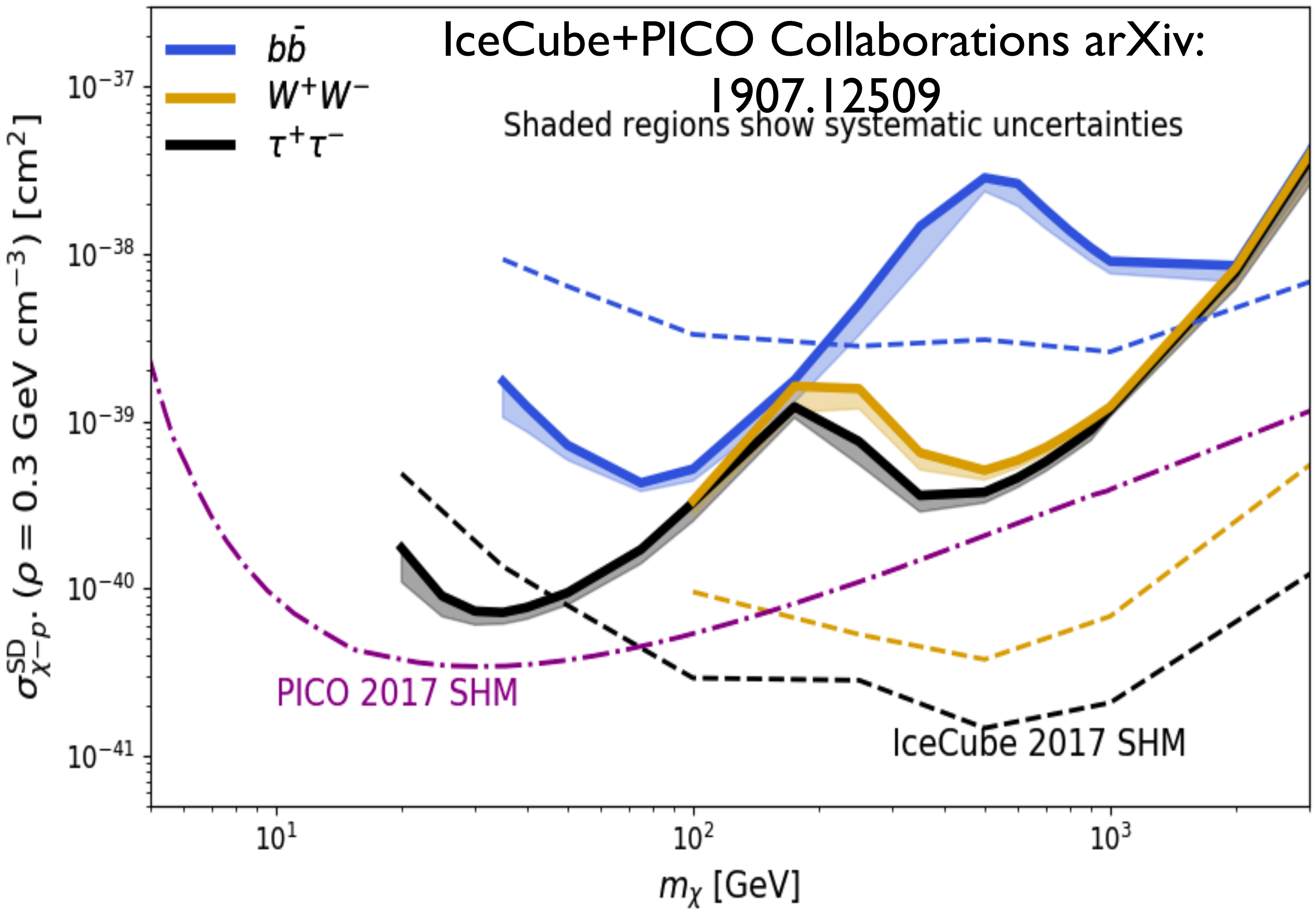


S. In [IceCube] ICRC2017 (912)

PICO-IceCube Combined Limit



Combines data from

- PICO-60 C_3F_8 superheated bubble chamber experiments - 1167 kg-days
- IceCube 3years data

Exploit the complementarity of direct and indirect searches (see F. Ferrer, A. Ibarra and S. Wild, JCAP1509, no. 09, 052(2015))

Halo Model independent bound (Extremely conservative, decomposing the velocity distribution in dark matter streams with fixed velocity)

Standard method to compute bounds assuming Standard Halo Model (SHM) of an isotropic Maxwellian velocity distribution