The Hunt for Dark Matter with Neutrinos

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UW Madison Physics Colloquium

Coma Cluster

Outline

Motivation

Neutrino Telescopes and IceCube

Selected Searches

- Self-annihilating Dark Matter in the Galactic Halo
- Astrophysical Neutrinos and Dark Matter Decay
- Dark Matter Captured in the Sun

Conclusions and Outlook

Motivation

Coma Cluster

The Dark Matter Mystery

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

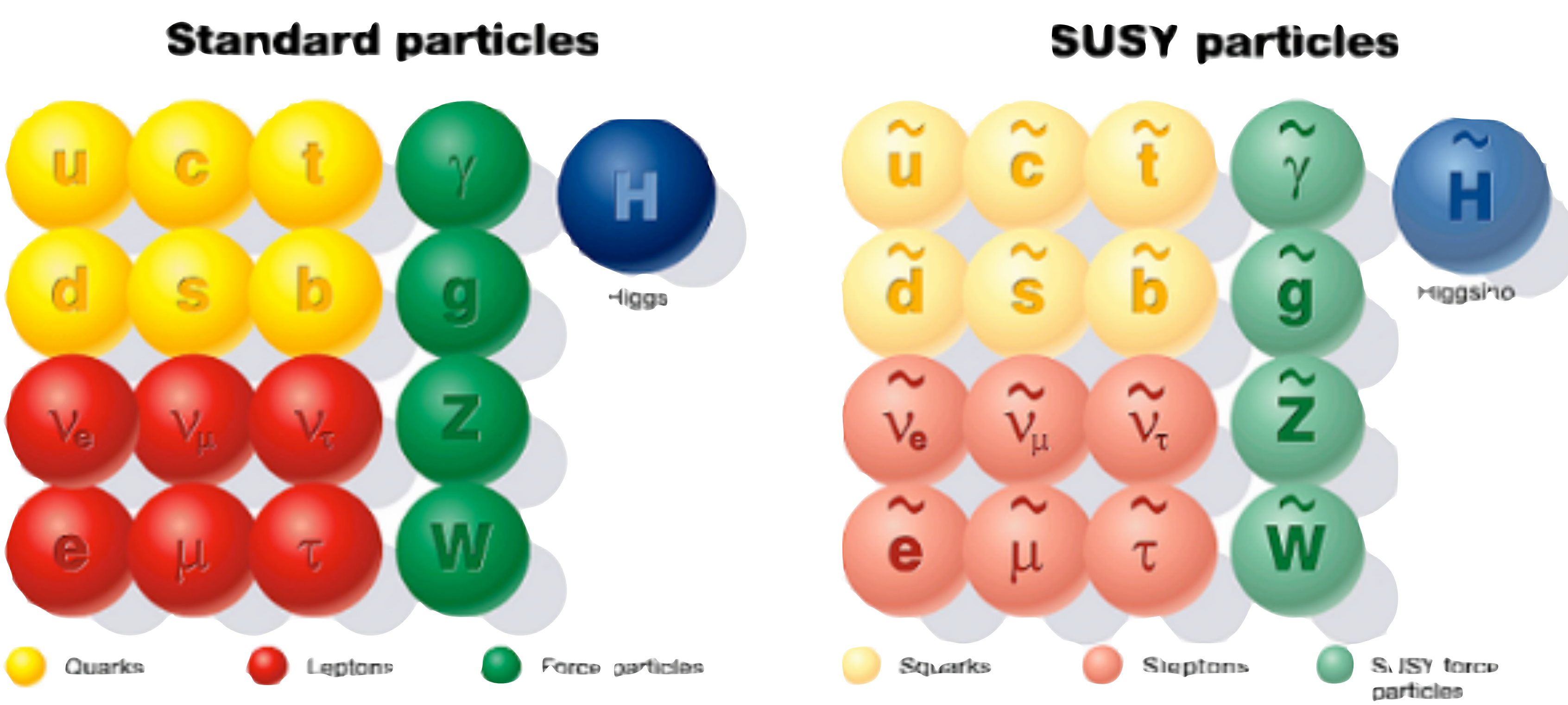
- Dark Matter already gravitationally “observed”, but ...
    - What is it ?
    - What are it’s properties ?

Weakly Interacting Massive Particle (χ)

- **Observational Evidence for Dark Matter points to**
  - Non-baryonic
  - Cold massive
  - Not strongly interacting
  - Stable (long lived)

  (Non-baryonic, Cold massive, Not strongly interacting: **WIMP**)

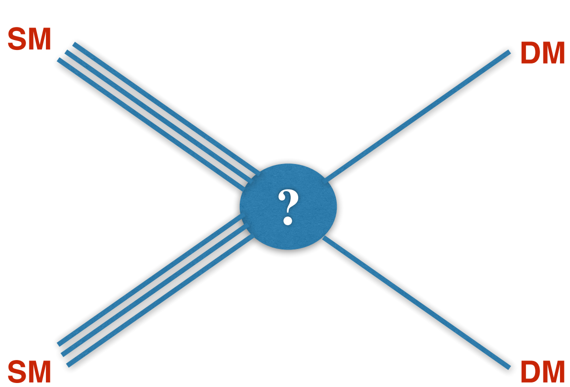
- **WIMPs often arise naturally in extensions to the Standard Model of Particle Physics: Supersymmetry, …**



Severe constraints on the WIMP hypothesis from collider searches, but still a good assumption as a generic dark matter candidate particle

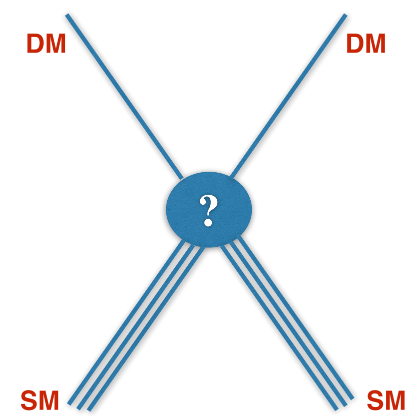
How to find dark matter ?

Make it !

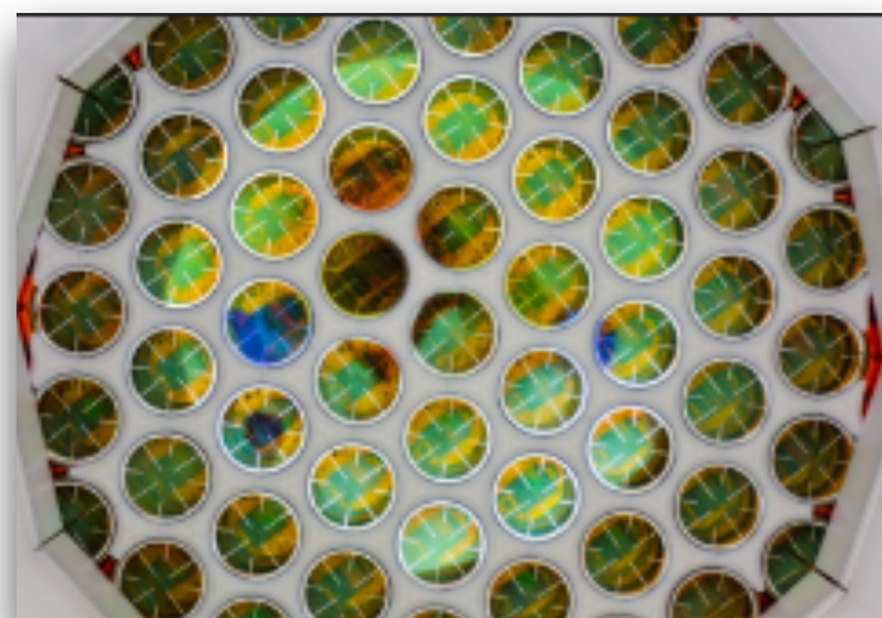


Collider

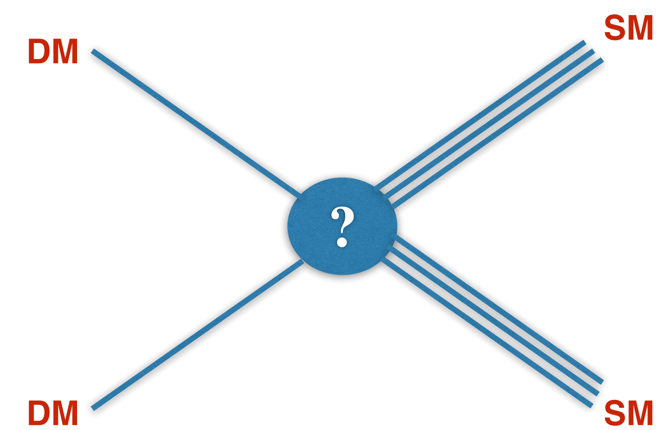
Shake it !



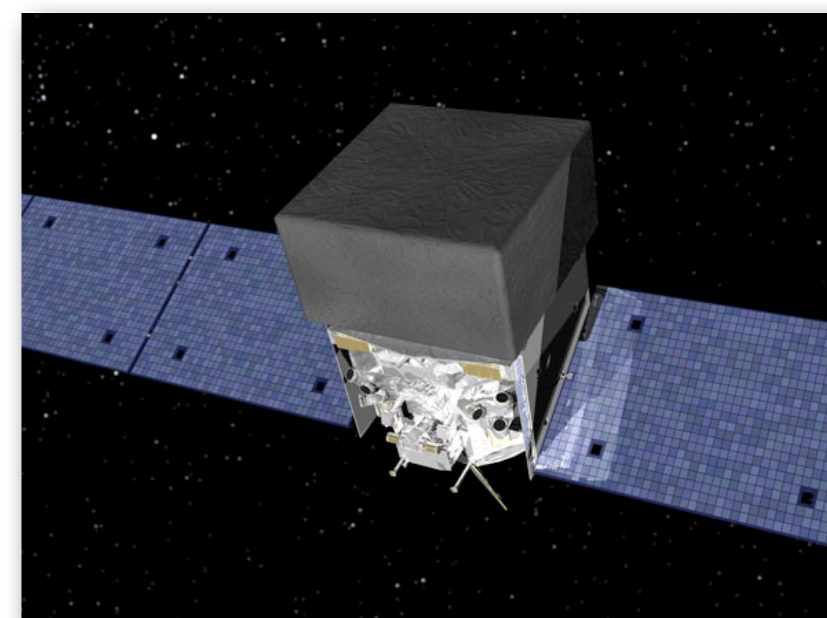
Direct



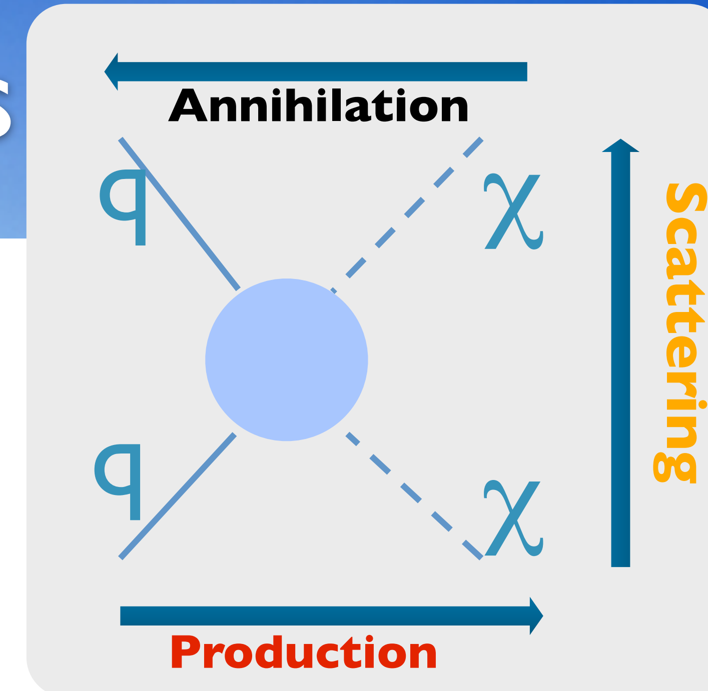
Break it !



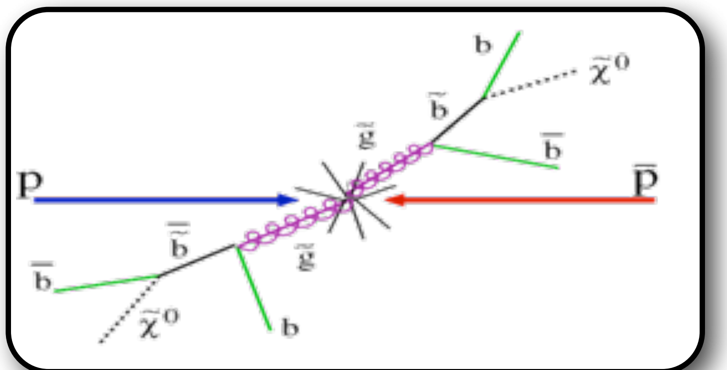
Indirect



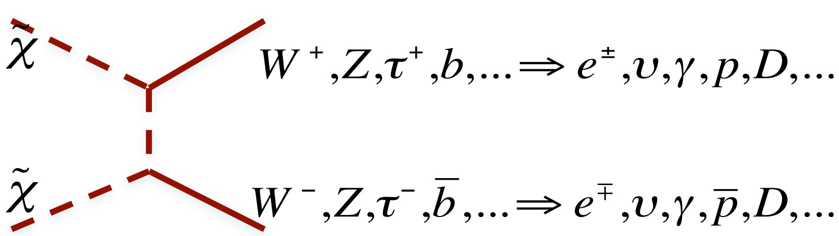
Role of Neutrinos

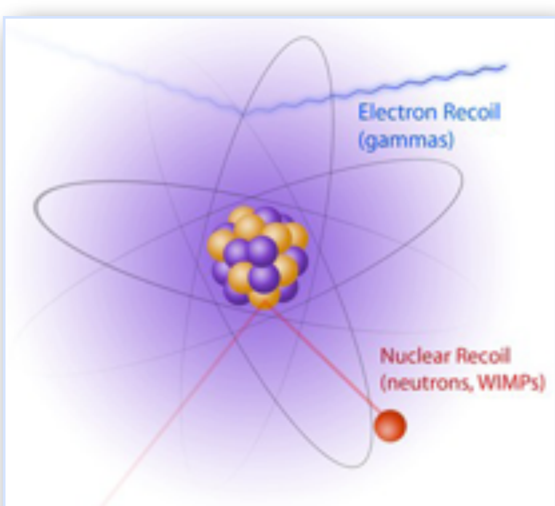


WIMP - Weakly Interacting Massive Particle



- **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

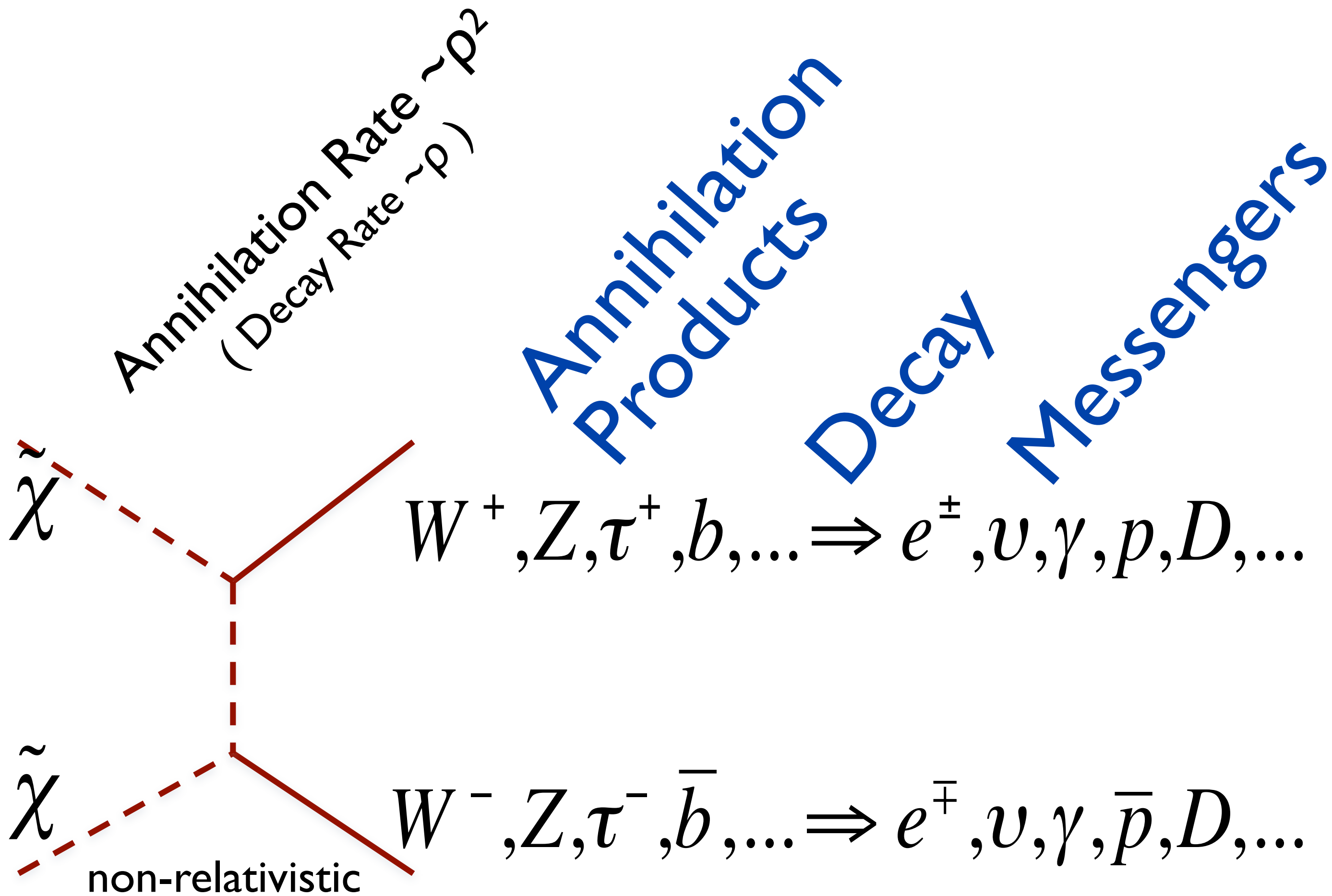
DM -Nucleon Scattering cross section

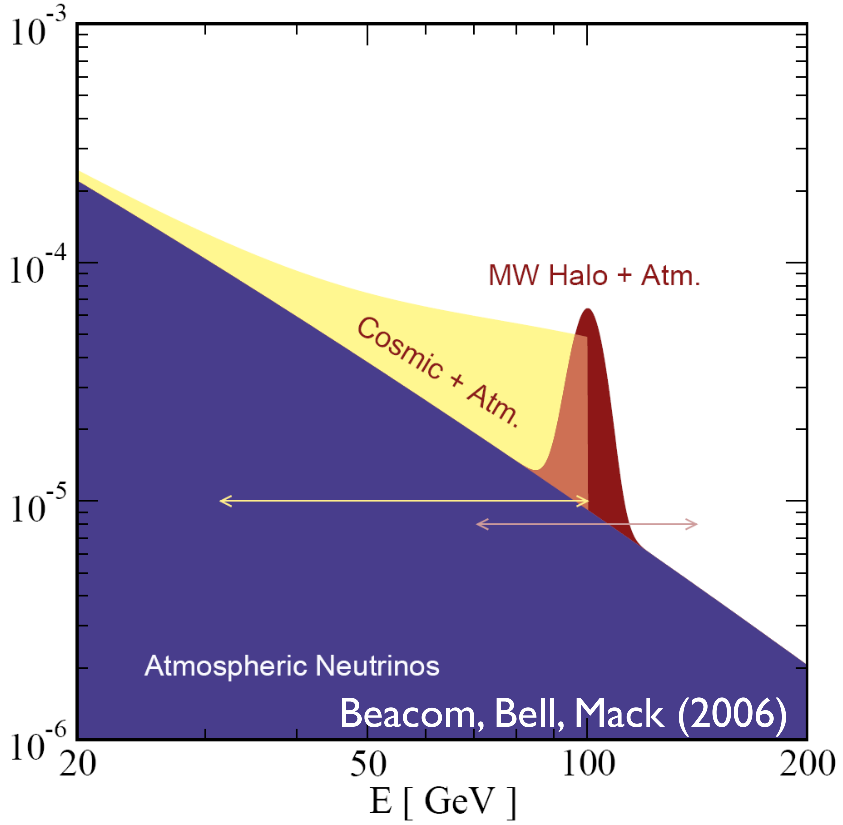
Dark Matter Signals

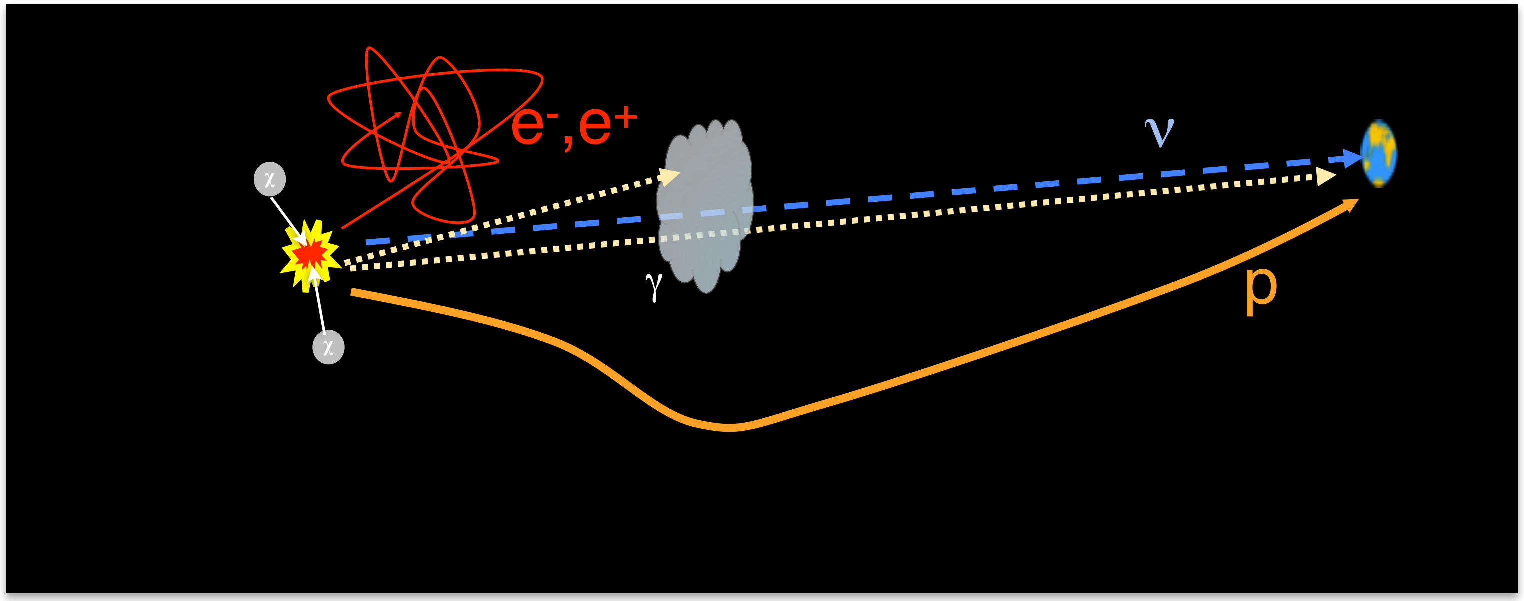
- Identify overdense regions of dark matter

  ⇒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

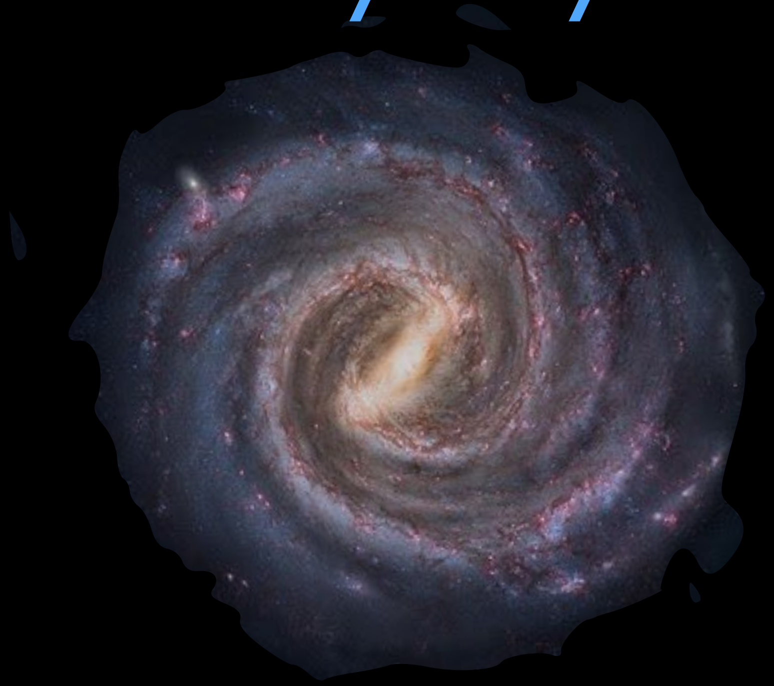




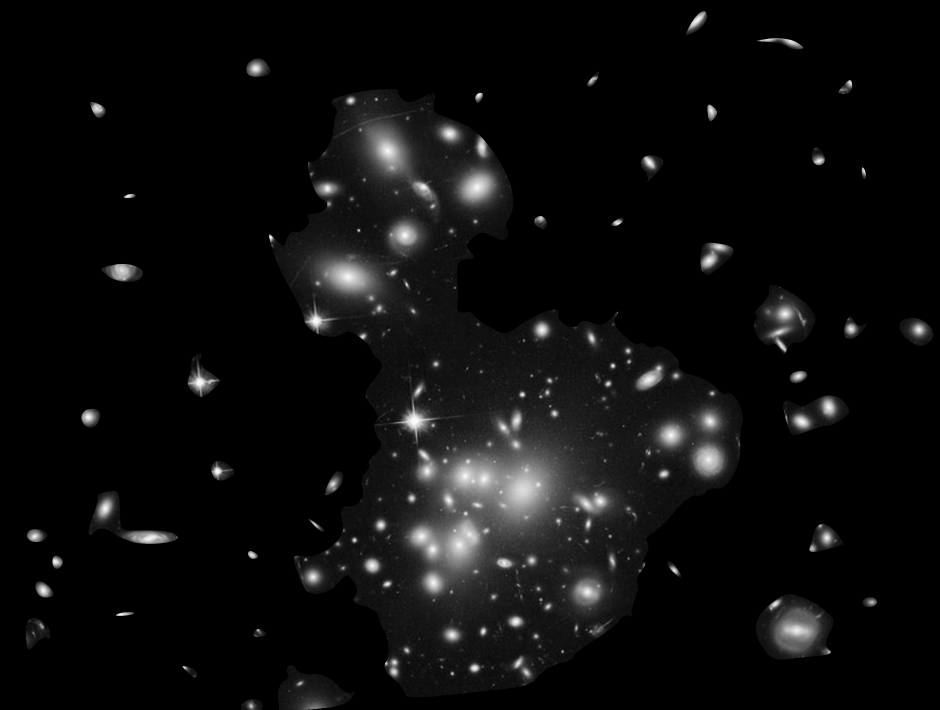


Dark Matter Targets

Milky Way



Galaxies



Galaxy clusters

dwarf spheroidal galaxy (dSph)

Image Credits:
ESA/Hubble Galaxy Cluster Abell 1689
ESO/Digitized Sky Survey 2 - Fornax dSph
M31 Andromeda

Dark Matter Distributions / Halo Profiles

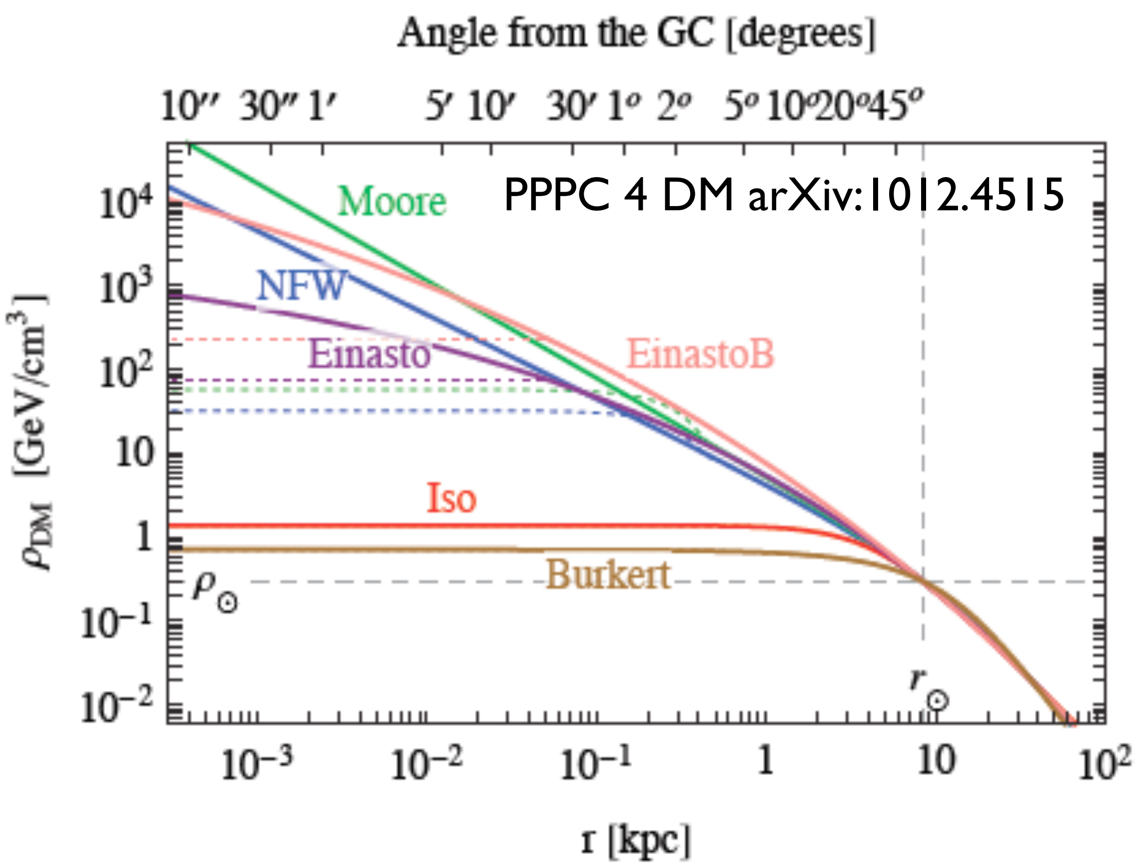
$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

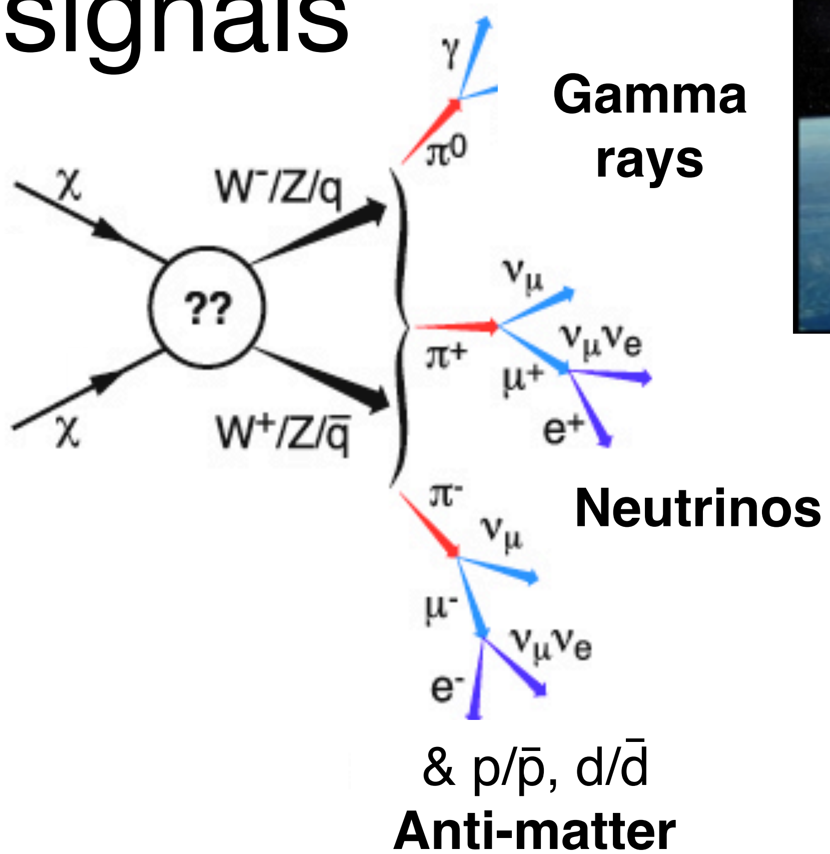
$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

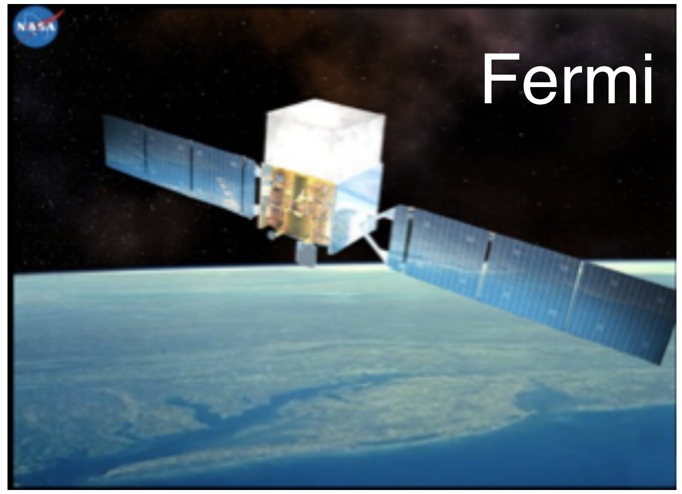


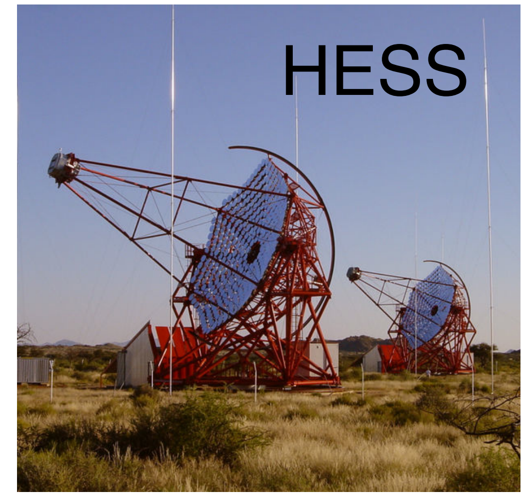
DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

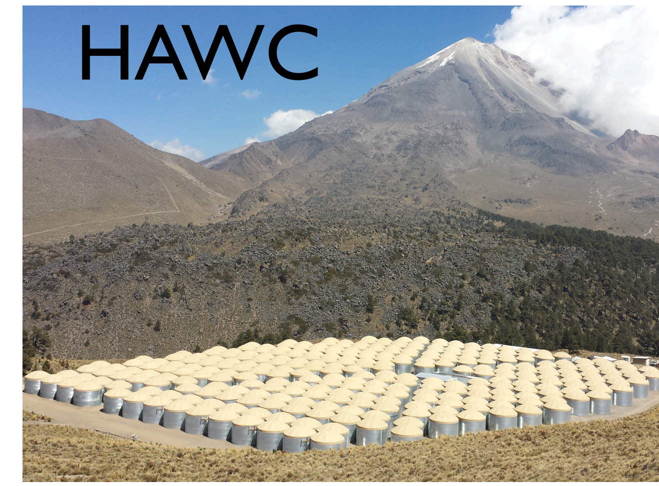
Indirect Detection of Dark Matter

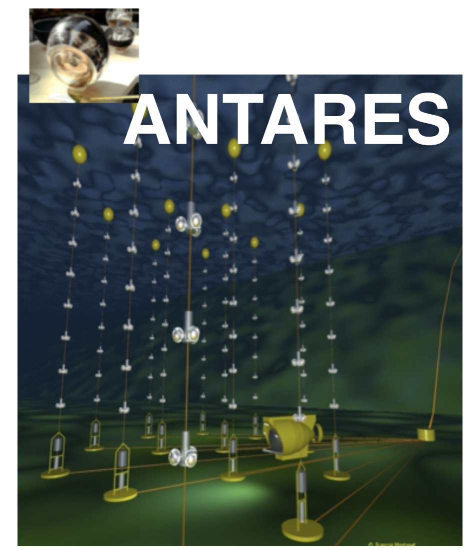
Annihilation signals

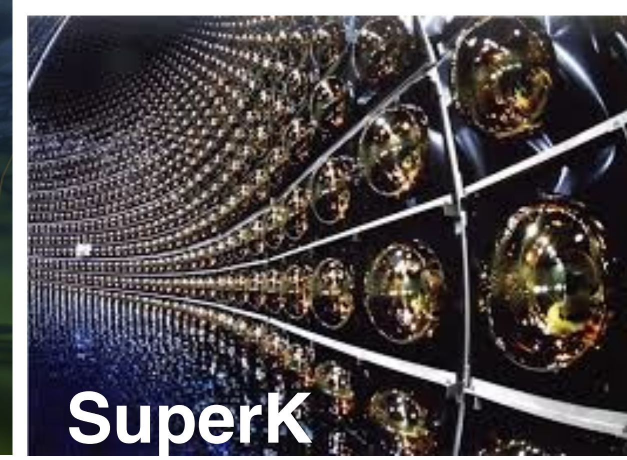












Indirect Dark Matter Searches

Extra-galactic

Small halo model dependence, boost factors

Diffuse flux, spectral feature

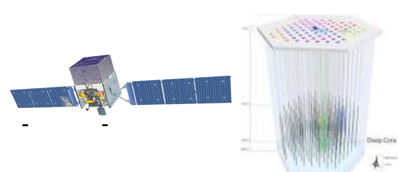
Signal weak compared to Galactic signal

Milky Way Halo

Large DM content, nearby source, O(10) larger flux than extra-galactic

Anisotropy

Relatively independent from DM halo profile

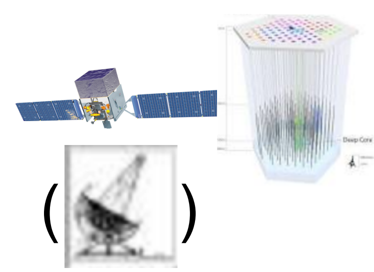


Galactic Center

Very dense DM accumulation, nearby source

Extended Source

Very strong dependence on DM density profile

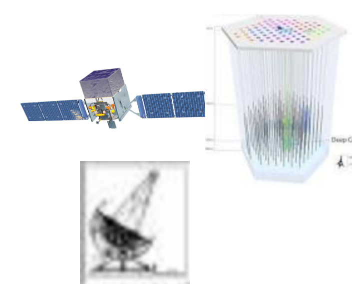


Dwarf Spheroidal

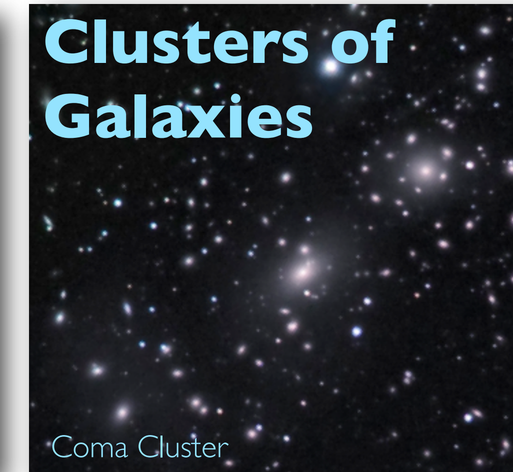
No astrophysical backgrounds

Point source

Cored profiles favored, less flux



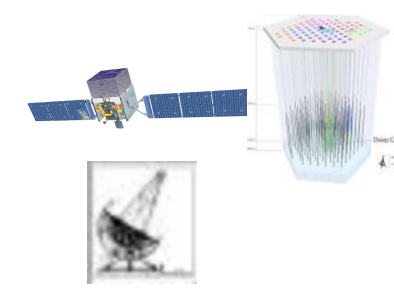
Clusters of Galaxies



Large DM content, high boost factors from sub structure

Extended source

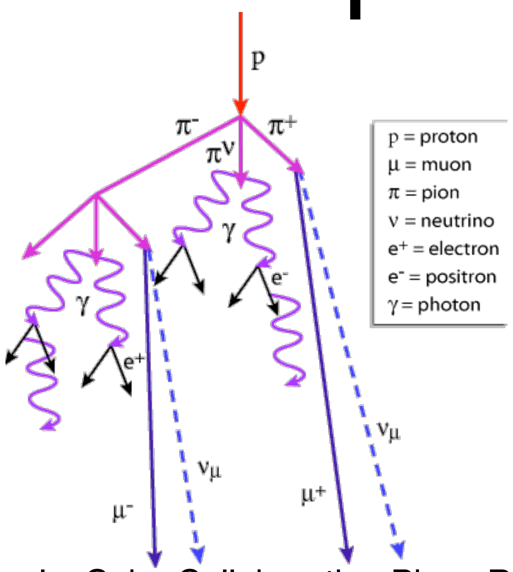
Understanding of boost factors



So far no evidence for dark matter annihilation signals detected with neutrino telescopes and gamma-ray observatories

Sources of High Energy Neutrinos

Atmospheric Neutrinos

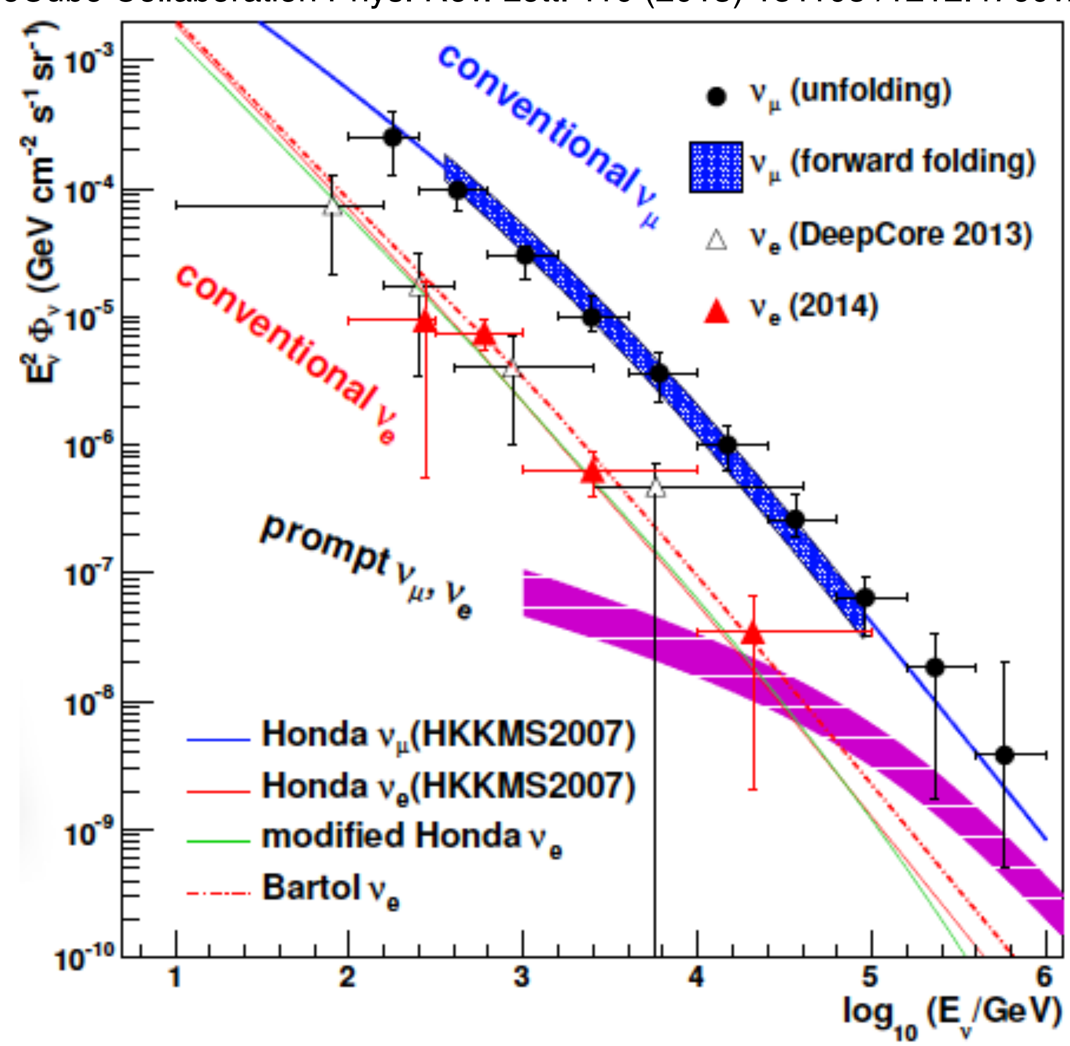


Cosmic rays interact in the upper atmosphere:

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

$\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \rightarrow e^{+} \nu_{e} \nu_{\mu} \nu_{\mu}$

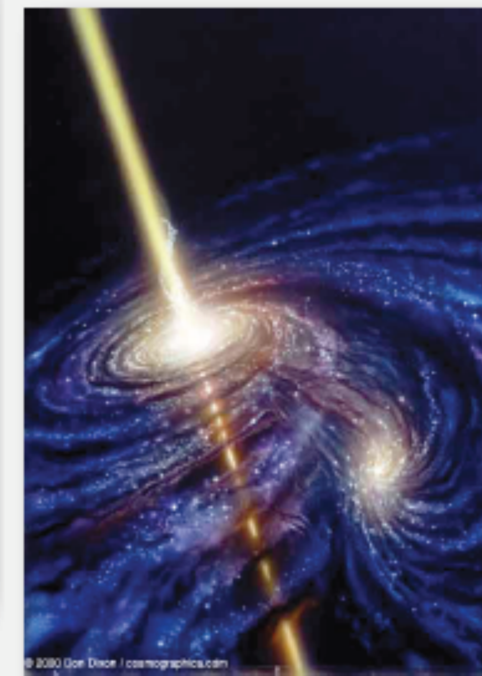
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



Astrophysical

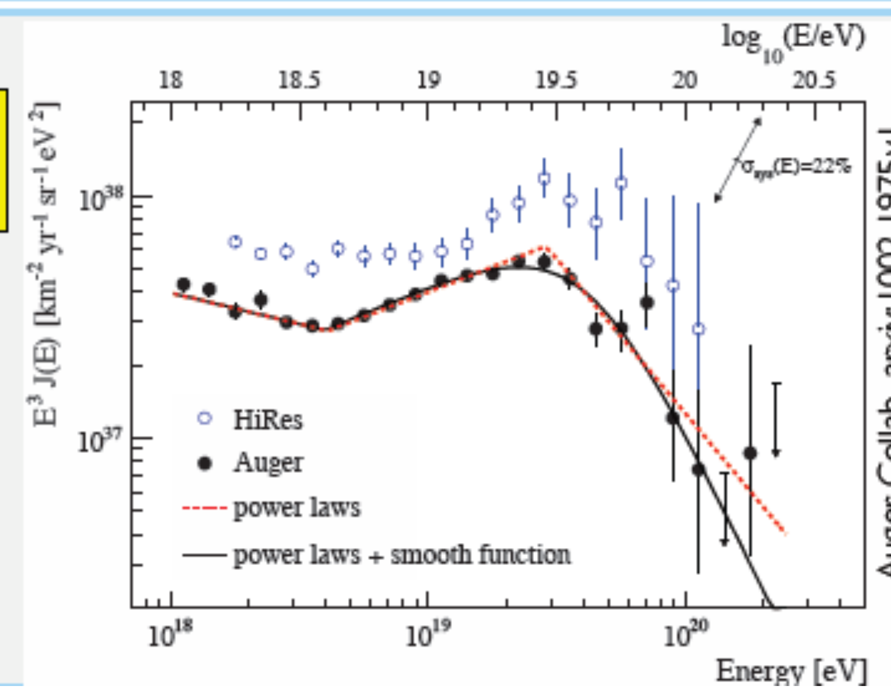
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Active Galactic Nuclei

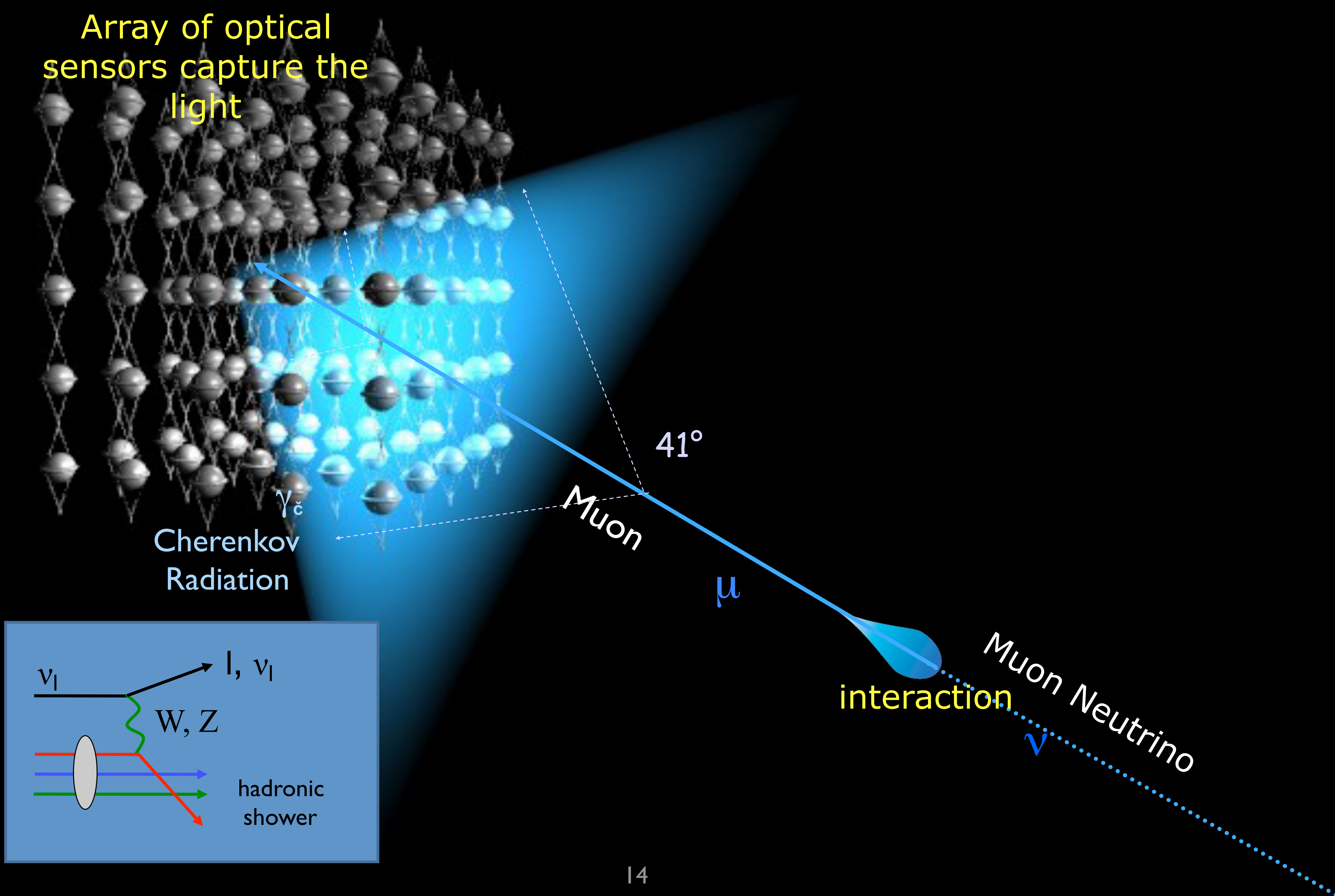


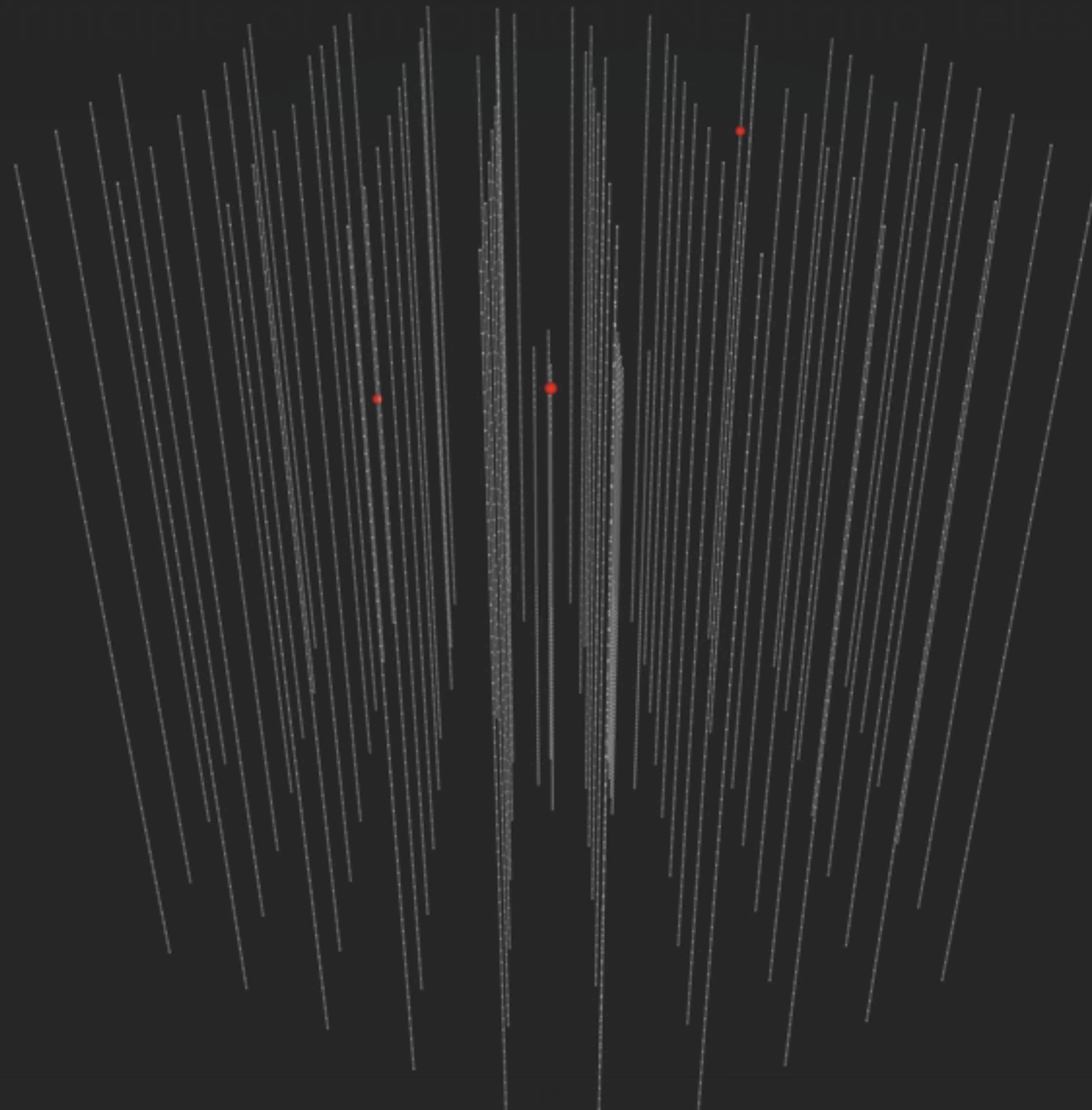
Gamma-ray Bursts

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



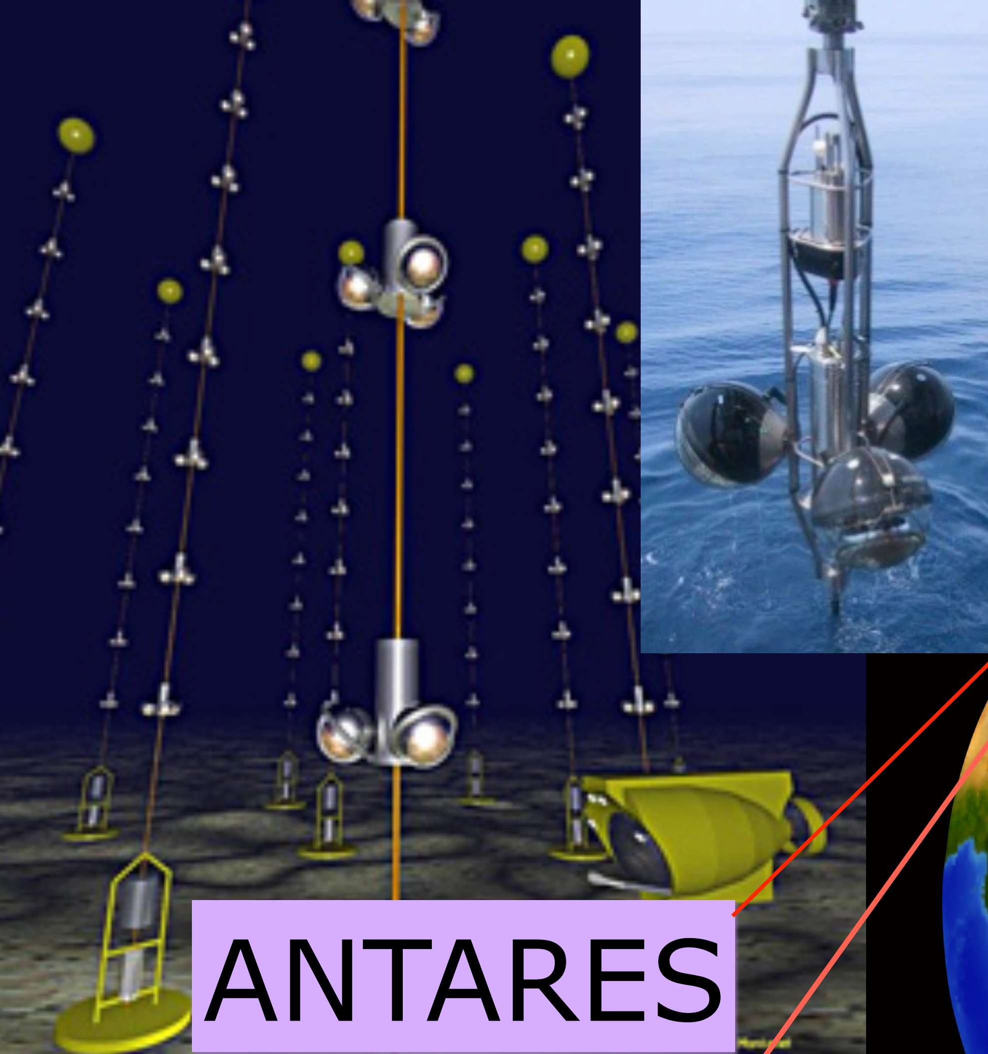
Principle of an optical Neutrino Telescope





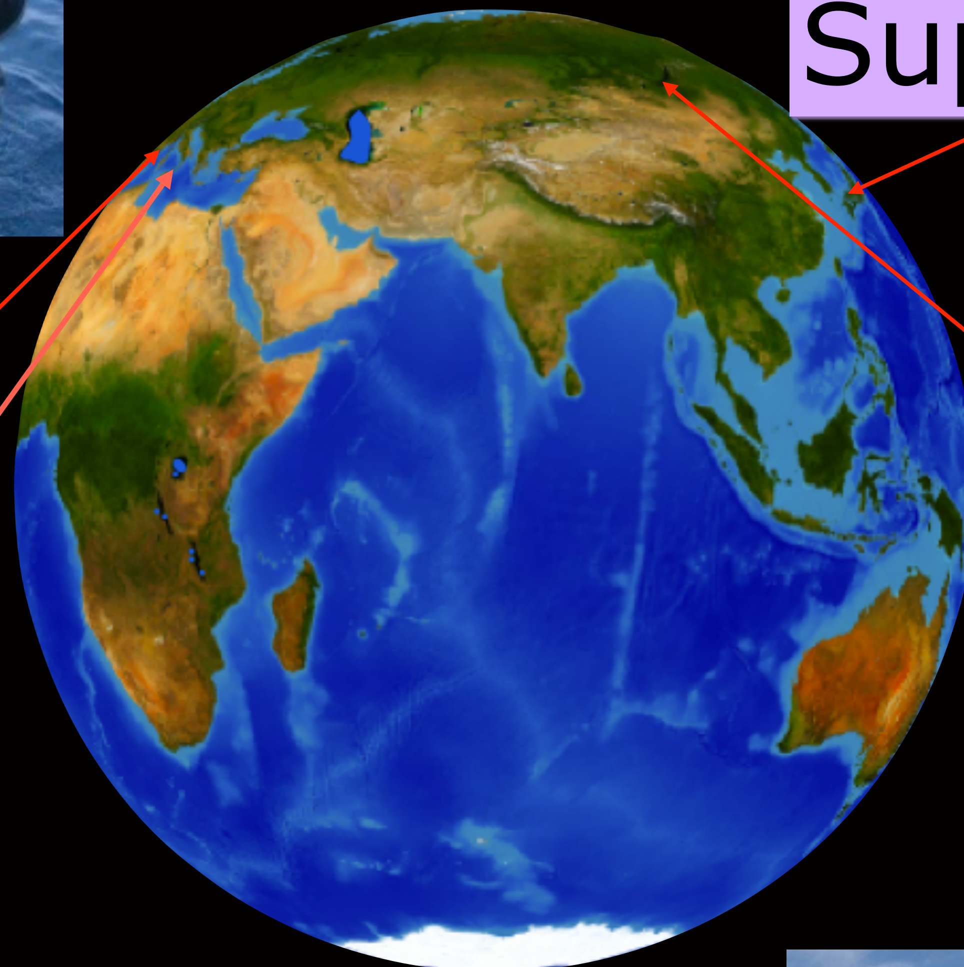
Neutrino Telescopes

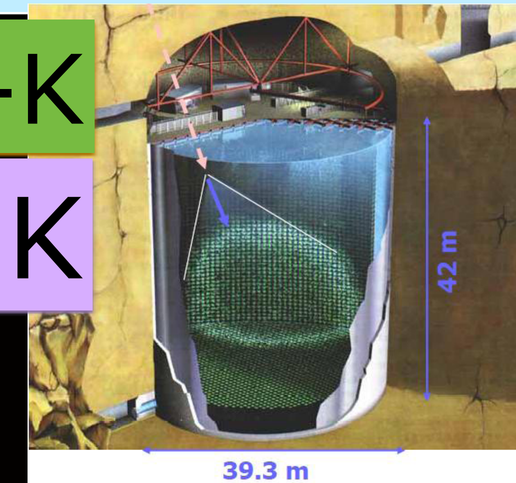
Large Water Cherenkov Neutrino Detectors




ANTARES

KM3Net





Hyper-K

Super-K

Lake Baikal

GVD

IceCube

Gen2/PINGU

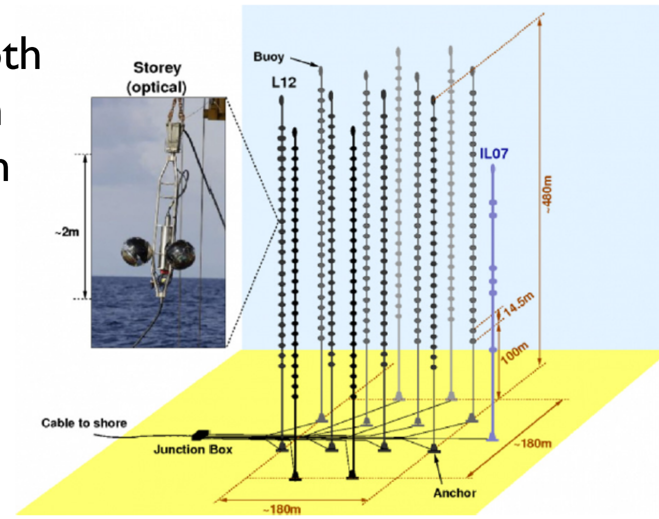
Active

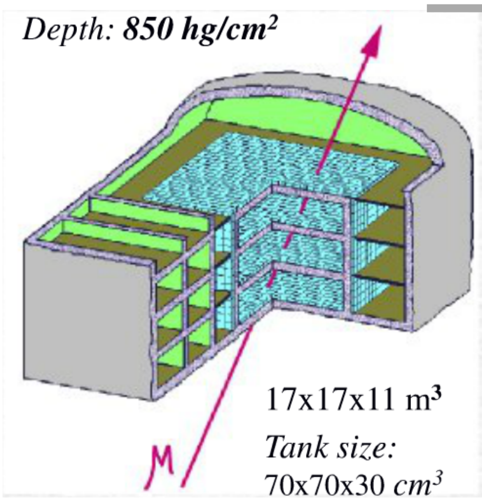
Construction

Planned

Neutrino Telescopes / Detectors

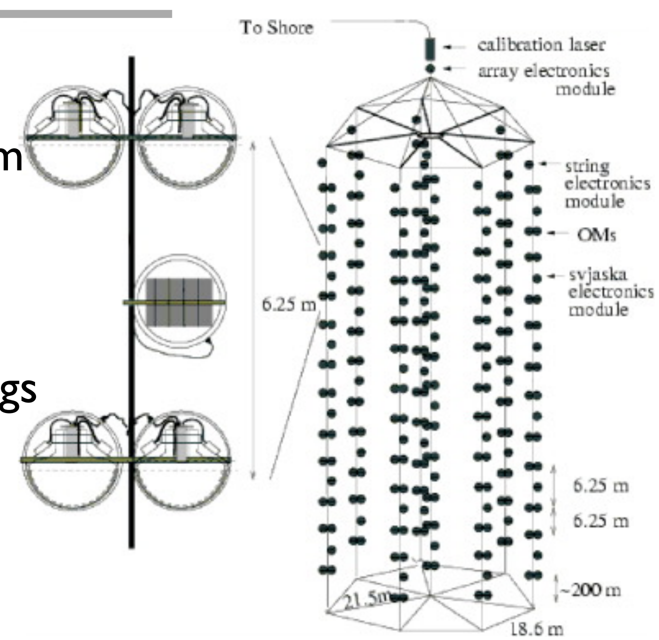
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10”PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



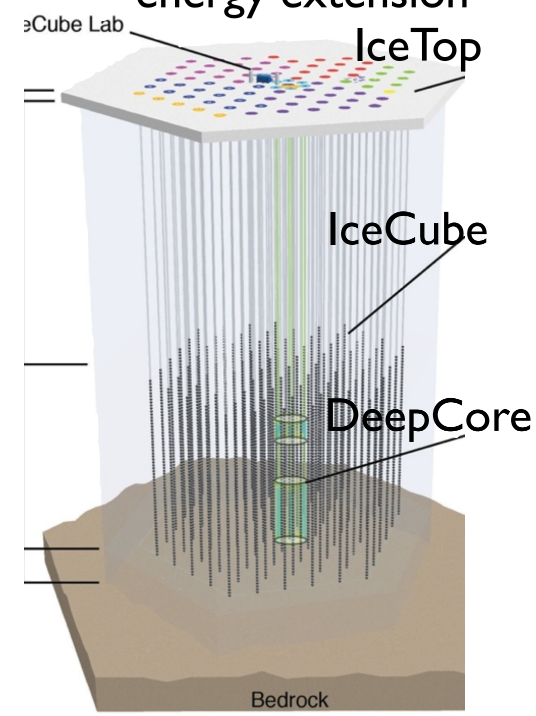


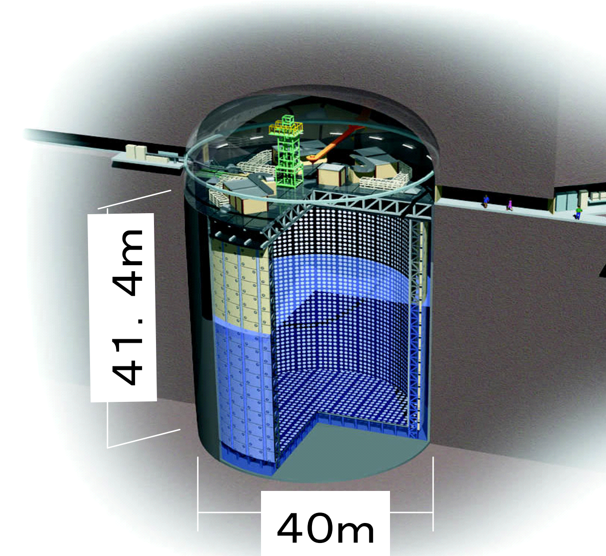
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- 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



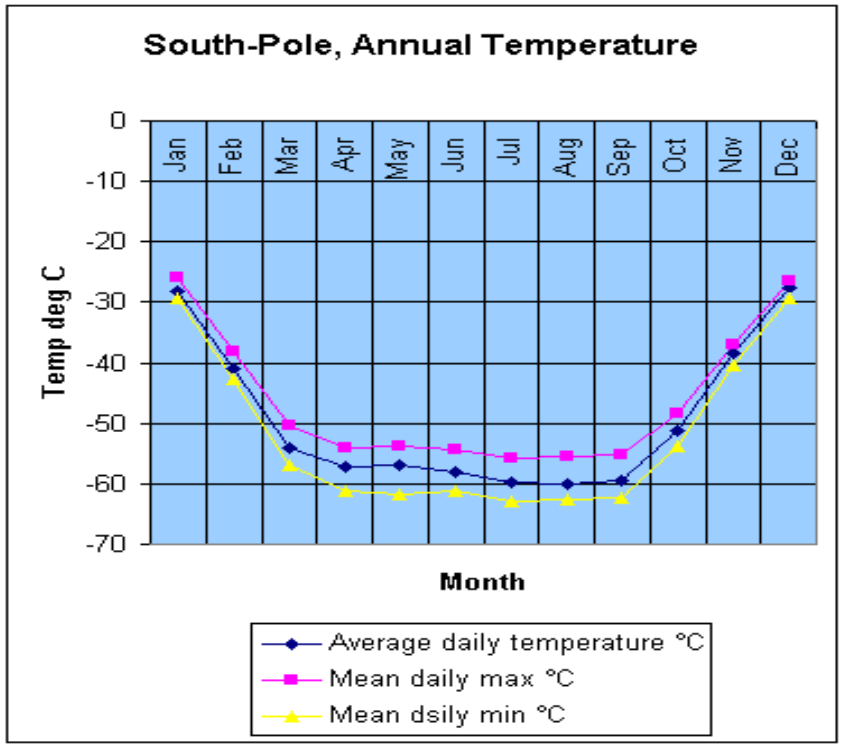
- **IceCube** at the Geographic South Pole
- 5160 10”PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km³
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension

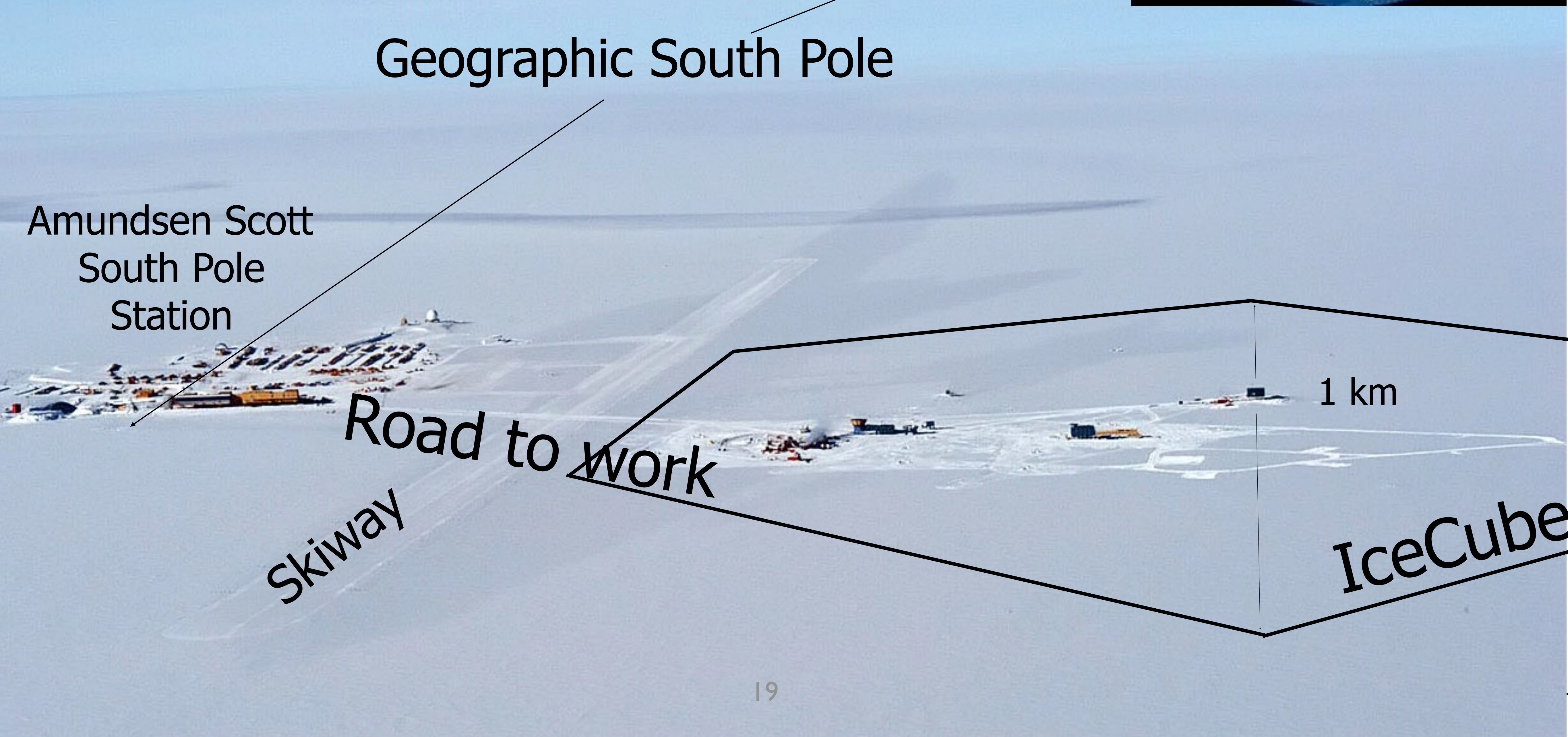




- **Super-Kamiokande** at Kamioka uses 11K 20” PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

Laboratory at the South Pole

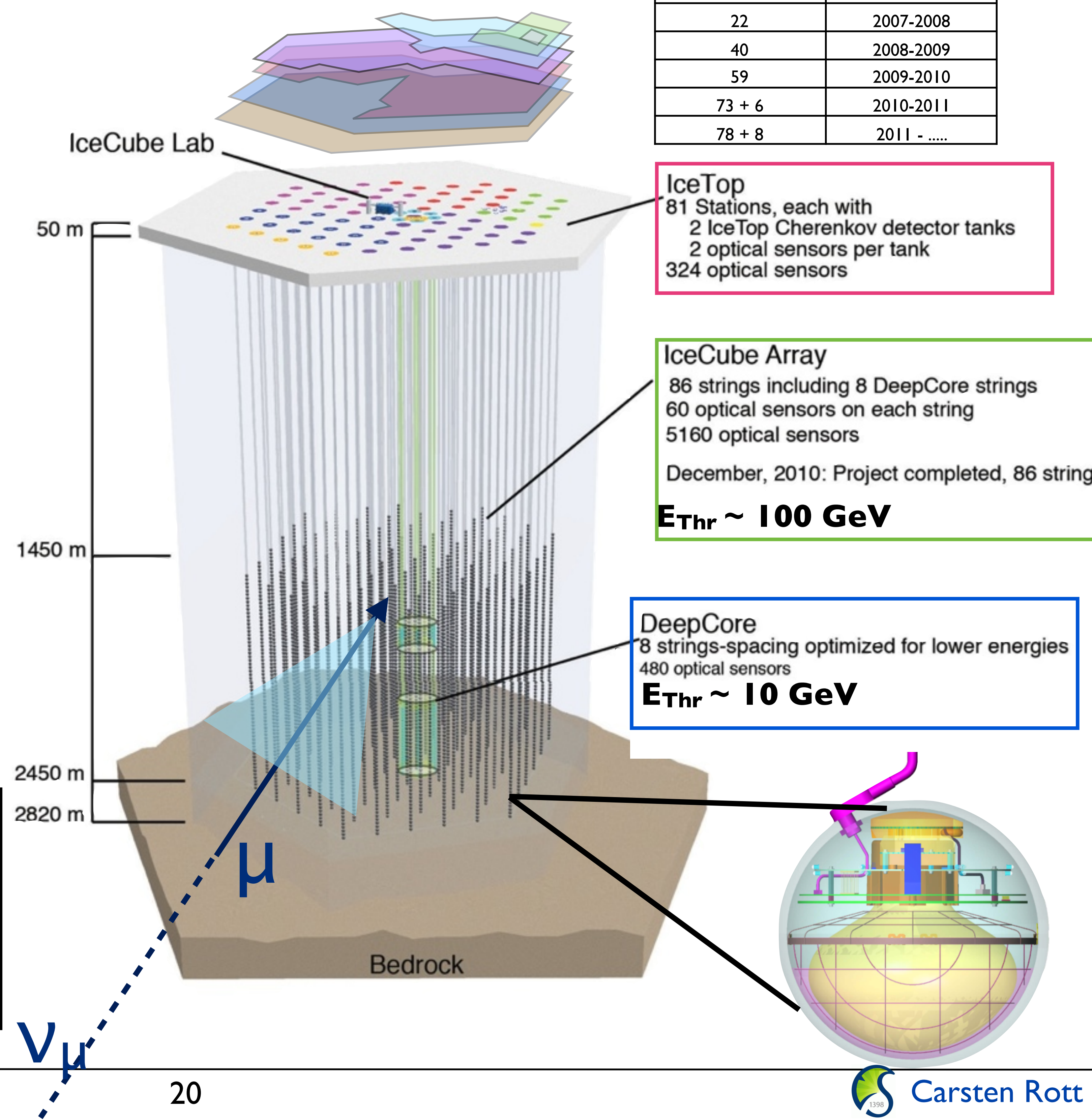




The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, data taking with full detector since May 2011
- 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°**

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
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RWTH Aachen
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Stony Brook University
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University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

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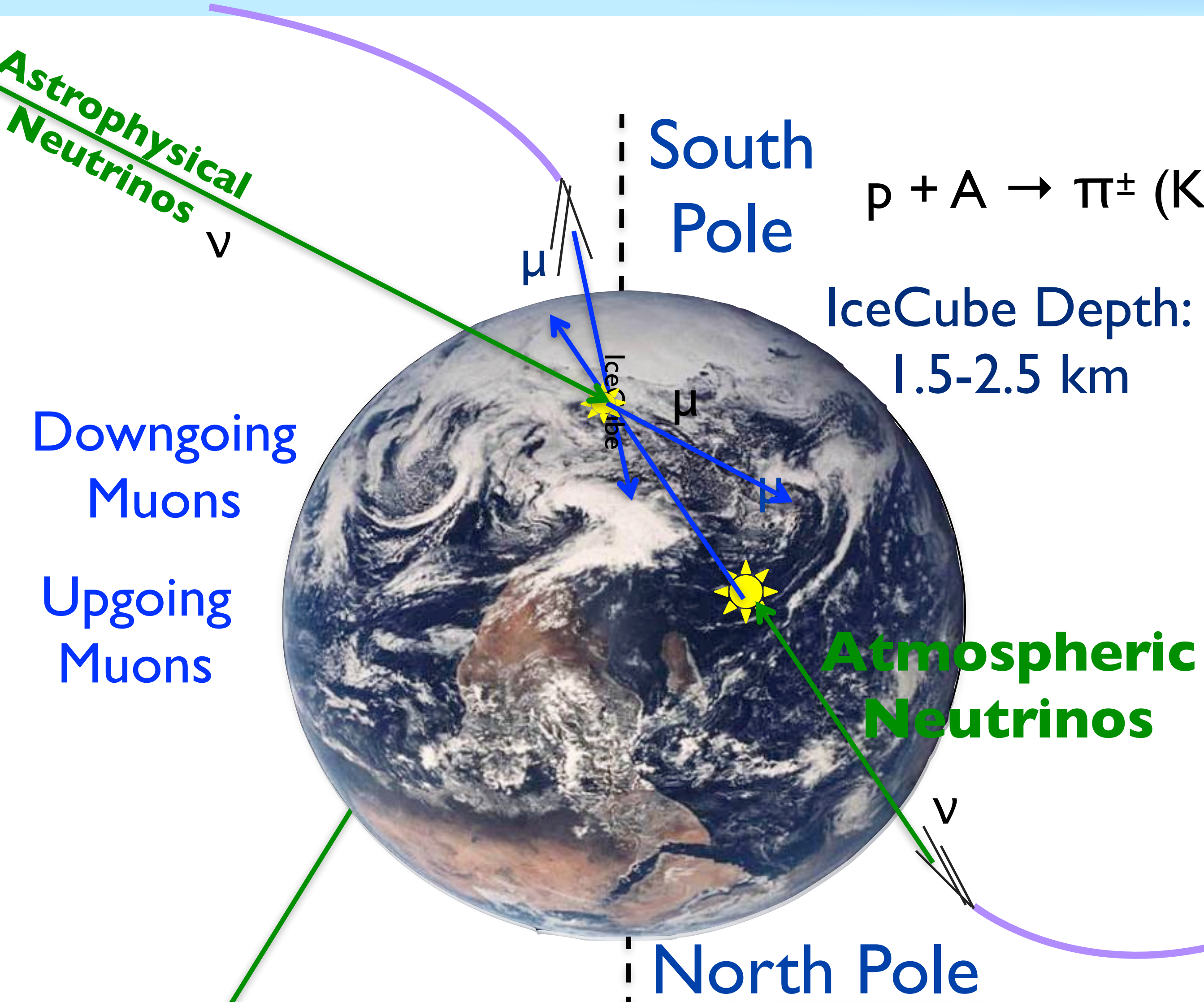
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science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

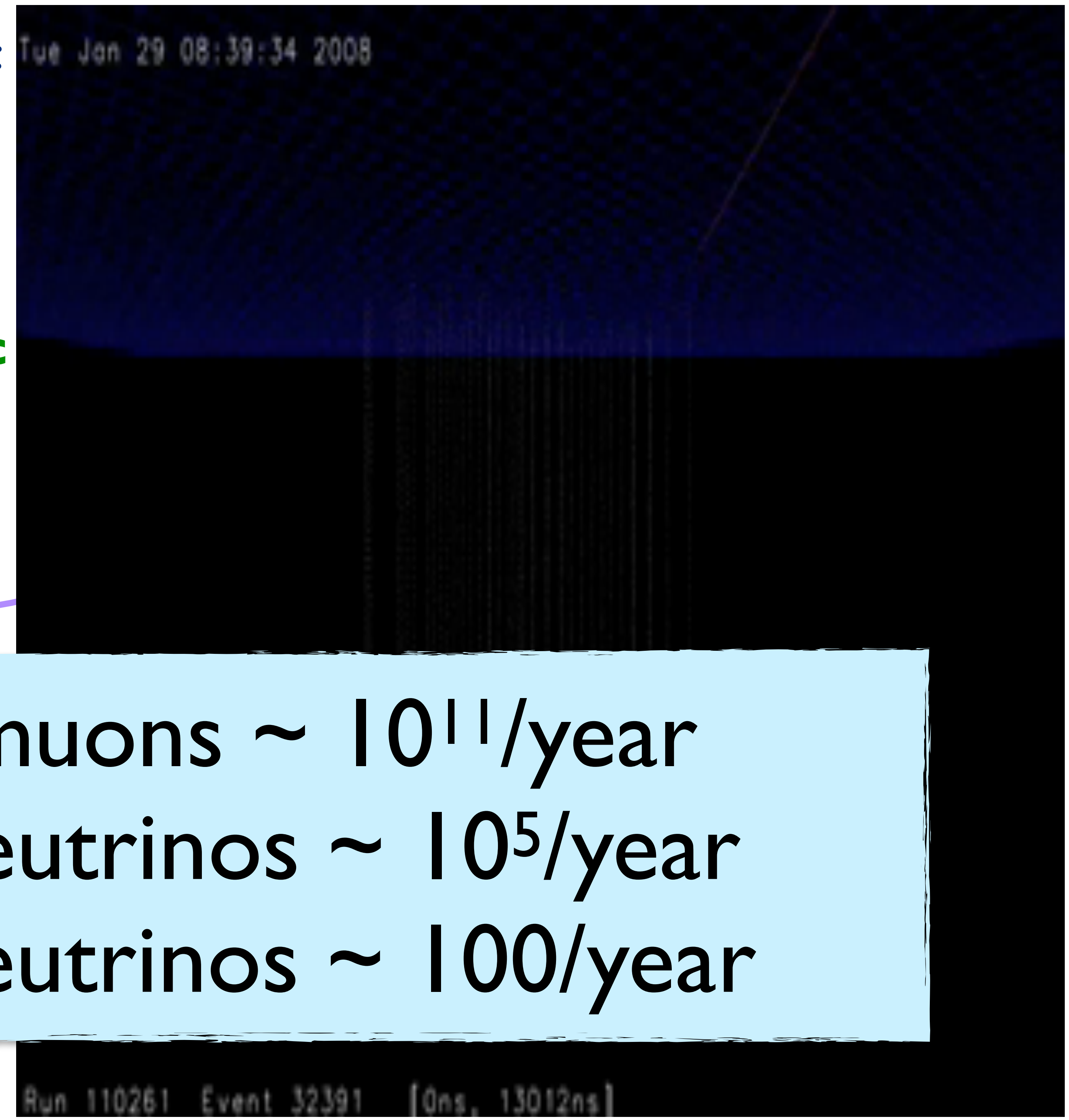
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Signals in IceCube



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

IceCube Depth: 1.5-2.5 km



Atmospheric muons ~ 10^{11}/year

Atmospheric neutrinos ~ 10^{5}/year

Astrophysical neutrinos ~ 100/year

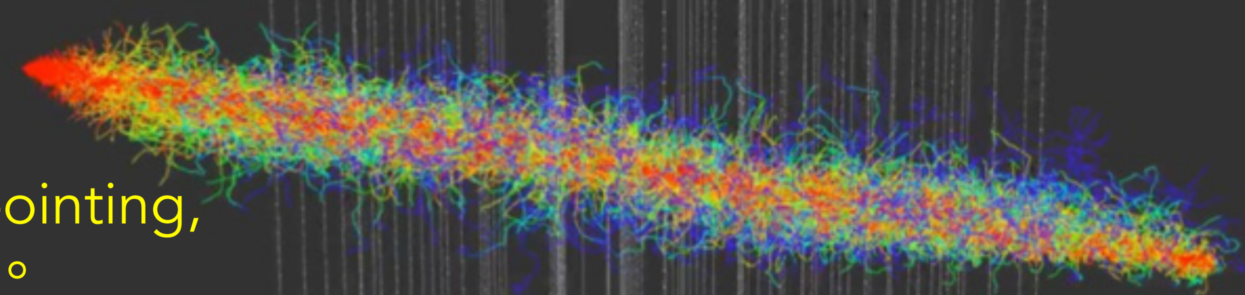
- U...
  "c...
- A...
  irreducible neutrino background to extra terrestrial neutrino fluxes

Event Topologies in IceCube

Track topology

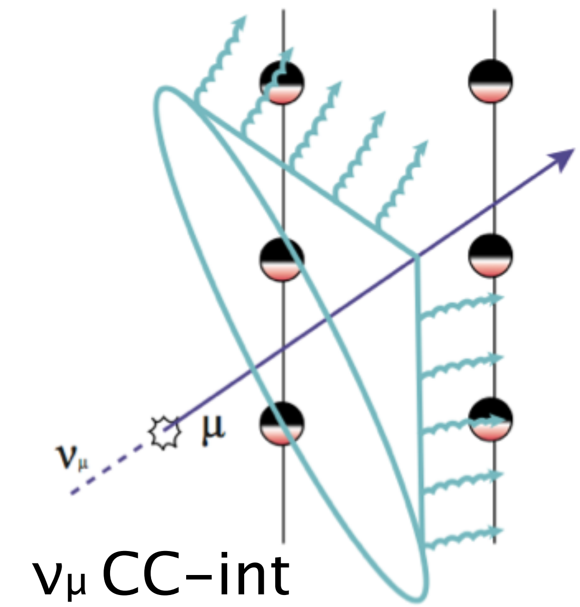
(e.g. induced by muon neutrino)

CC: ν_μ



Good pointing,
0.2° - 1°

Lower bound on energy for through-going events



ν_μ CC−int

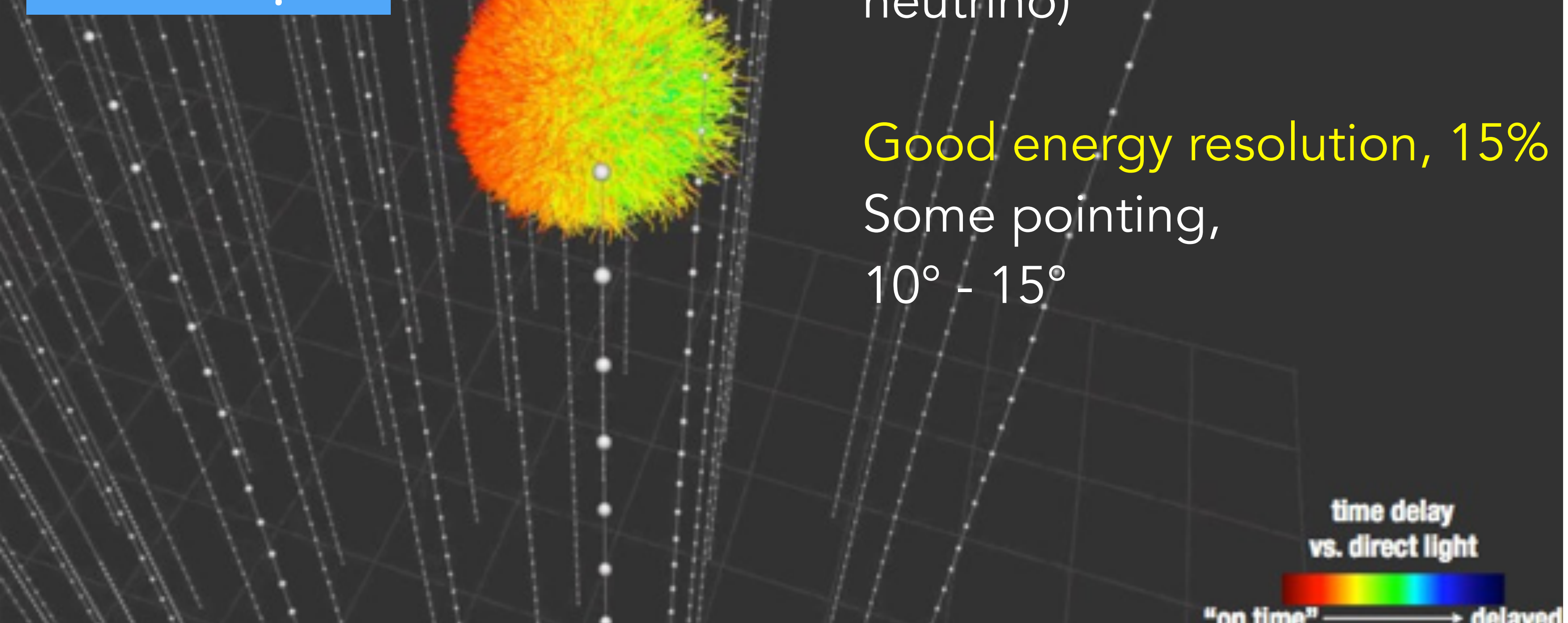
CC: ν_e ν_τ
NC: ν_e ν_μ ν_τ

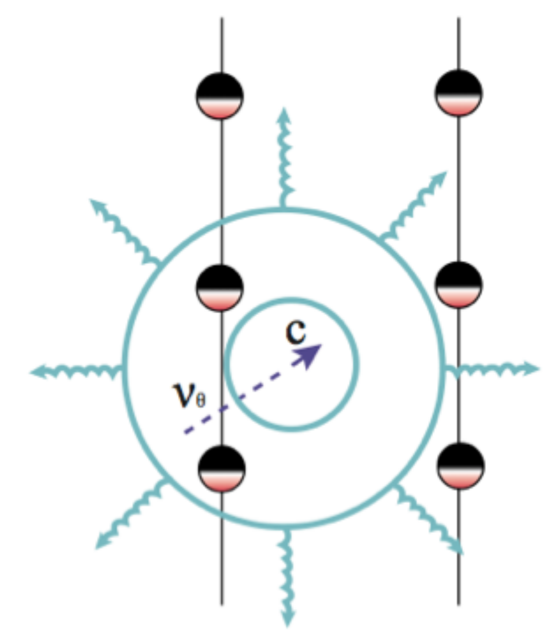
Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

Some pointing,
10° - 15°

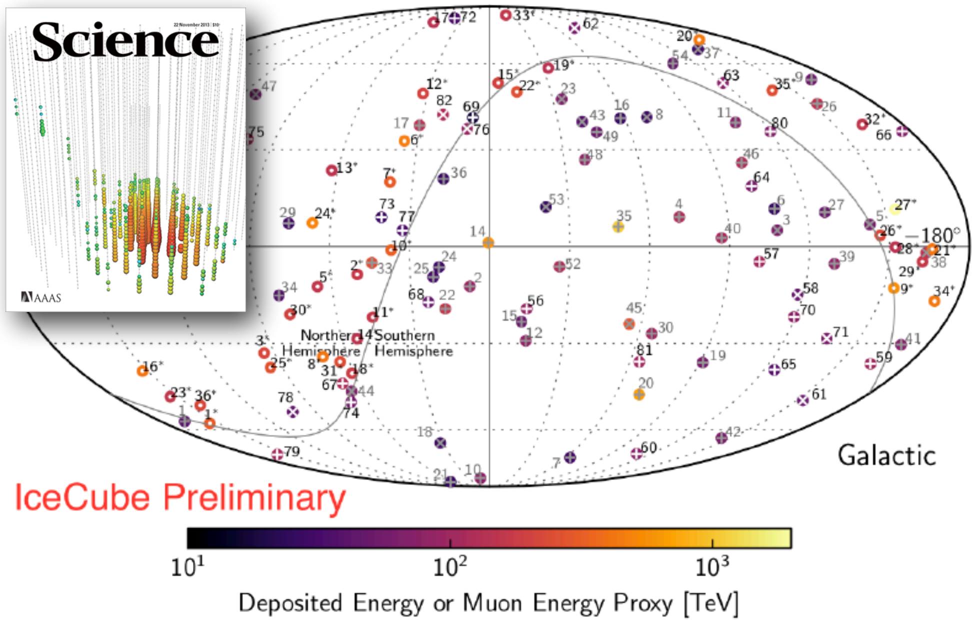




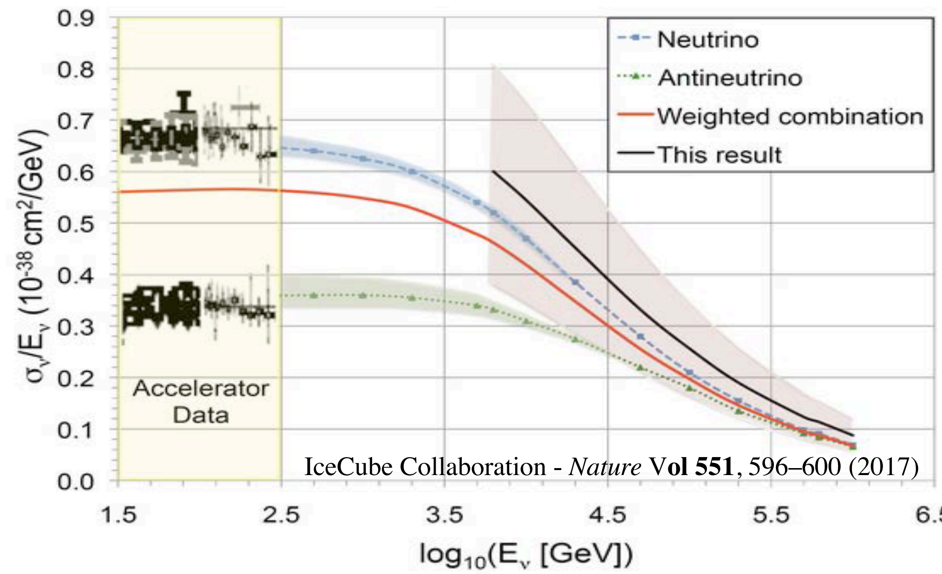
ν_e ν_τ CC−int & ν_i NC−int

IceCube Science

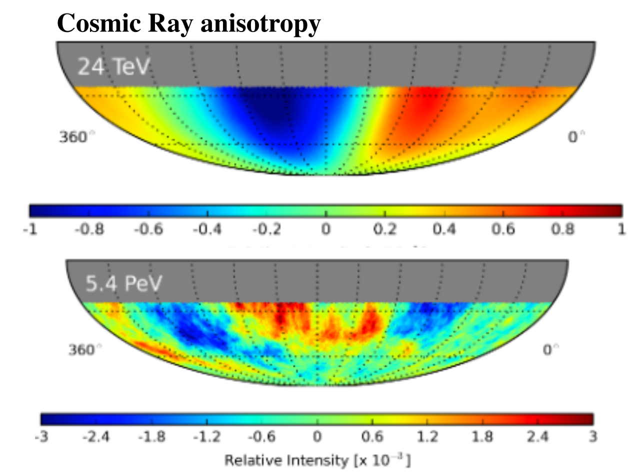
Astrophysical Neutrino Searches



Neutrino Tomography / Neutrino Cross Section Measurements

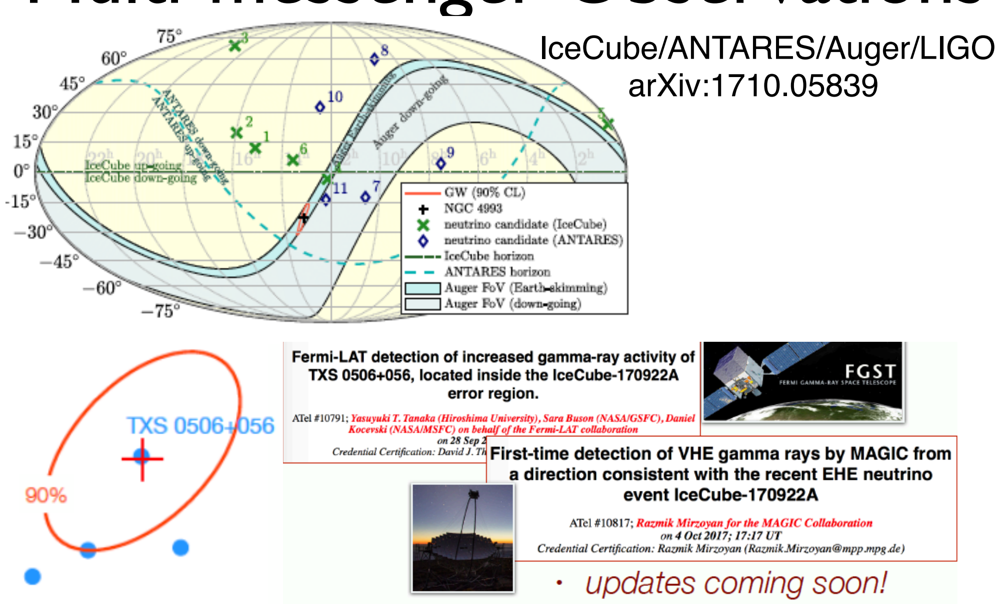


Cosmic Rays

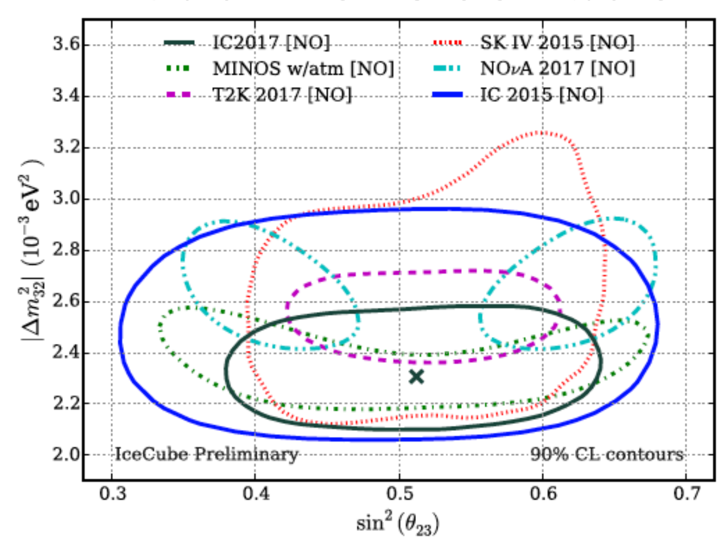


Astrophys.J. 826 (2016) no.2, 220

Multi-messenger Observations

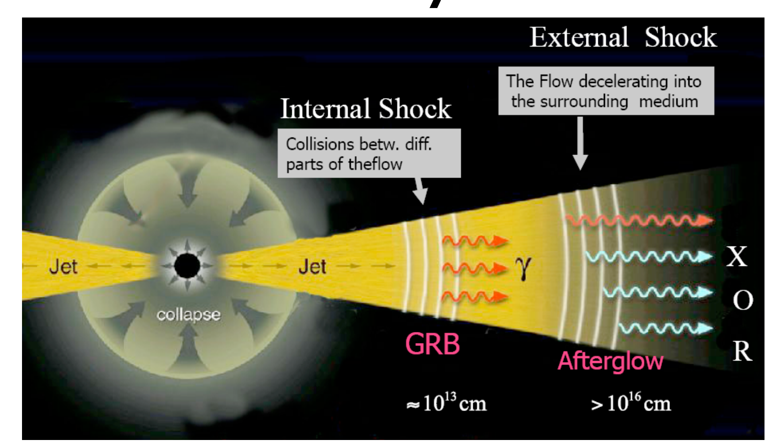


Neutrino Oscillations



IceCube Collaboration - arXiv:1707.07081

Gamma-ray bursts



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

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

Dark Matter Self-annihilations

$<\sigma_A v>$

Dark Matter in the Milky Way

Dark Matter Annihilation

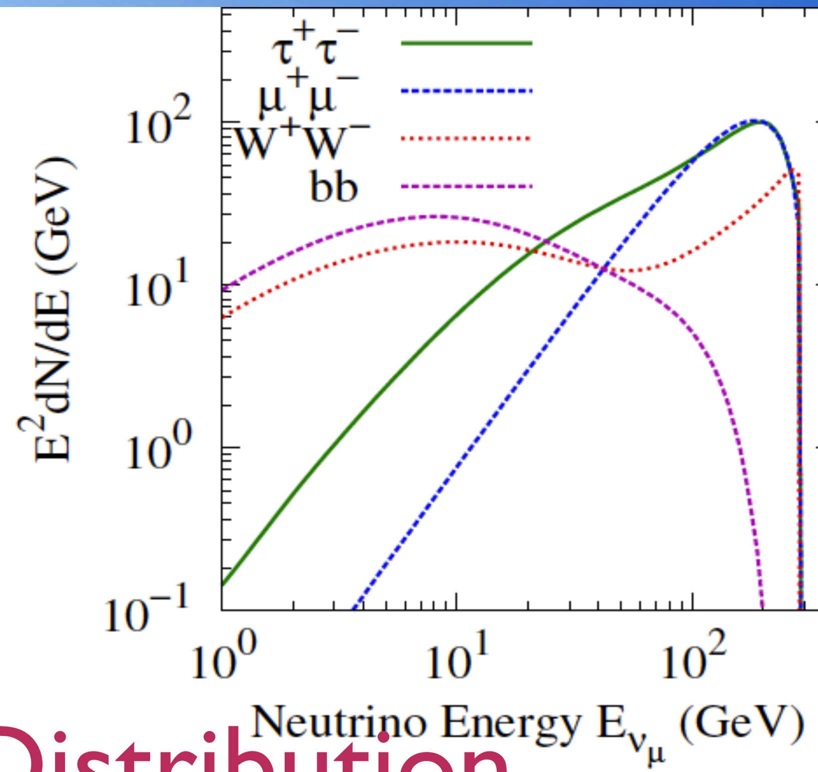
Measure Flux

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

=

Particle Physics

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



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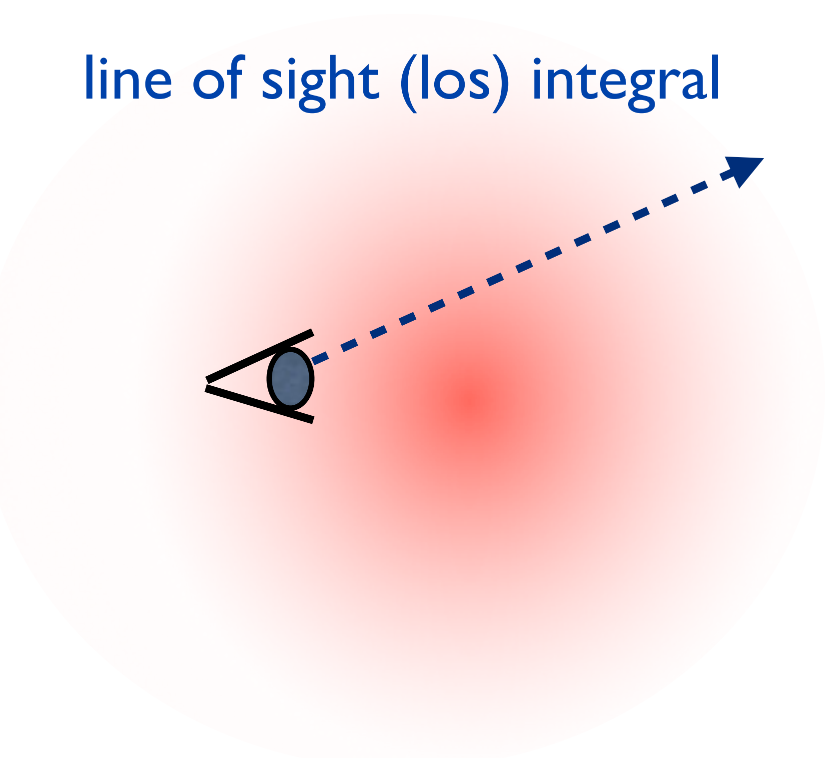
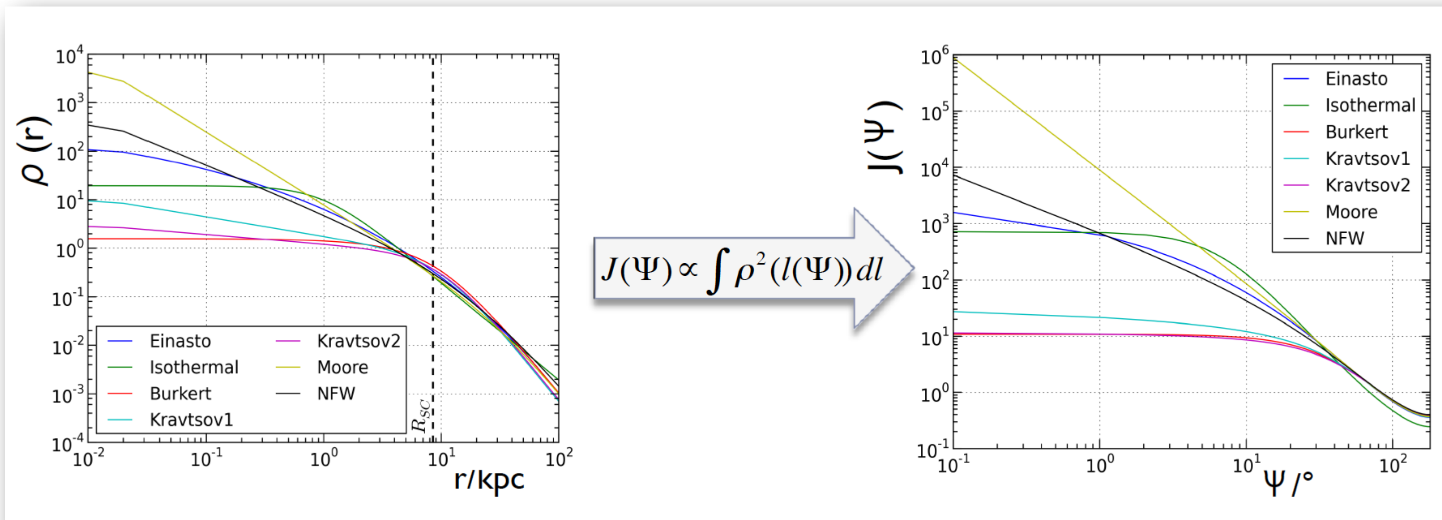
Dark Matter Distribution

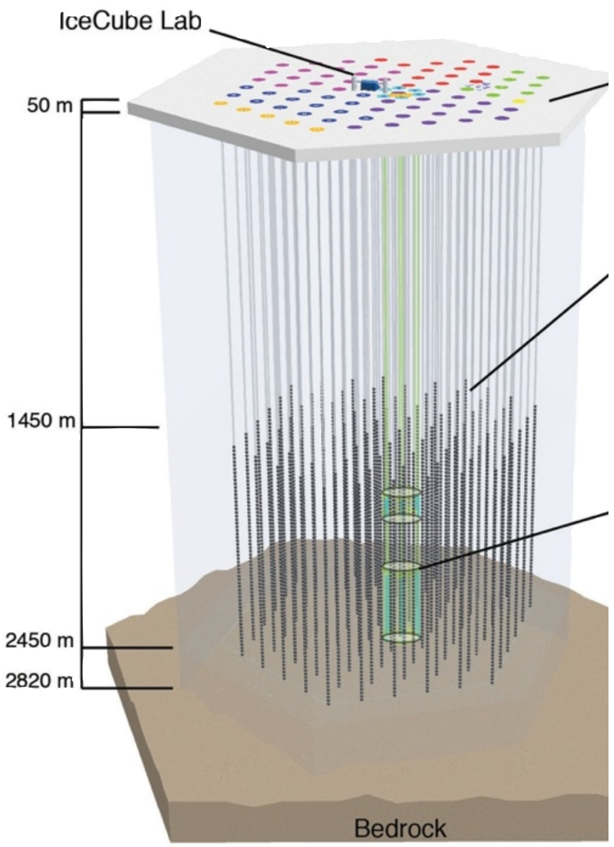
line of sight (los) integral

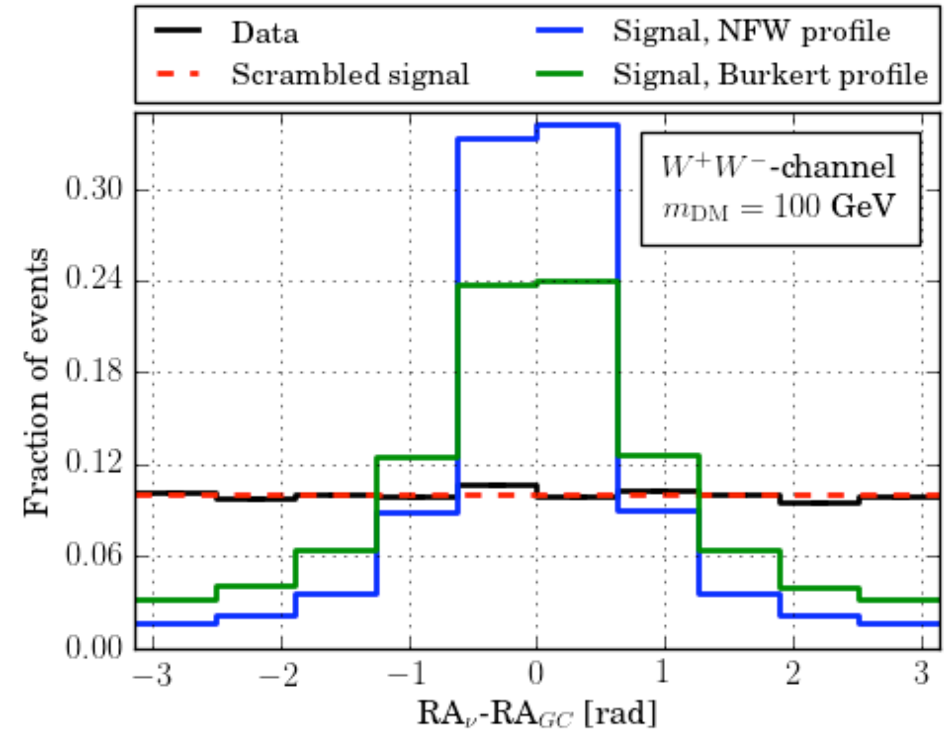


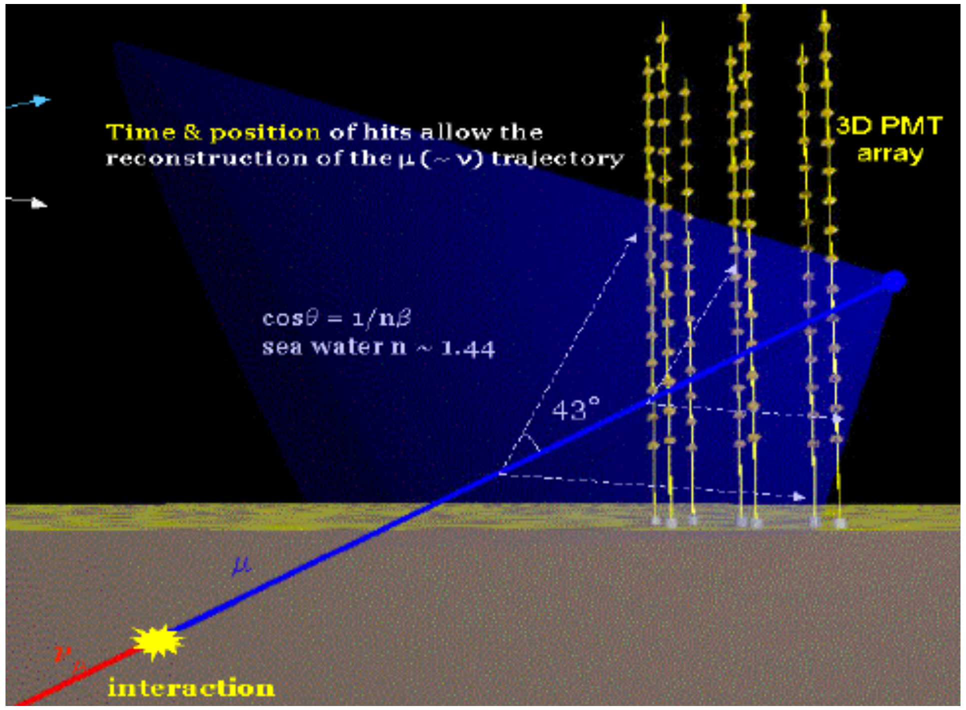
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\mathrm{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$

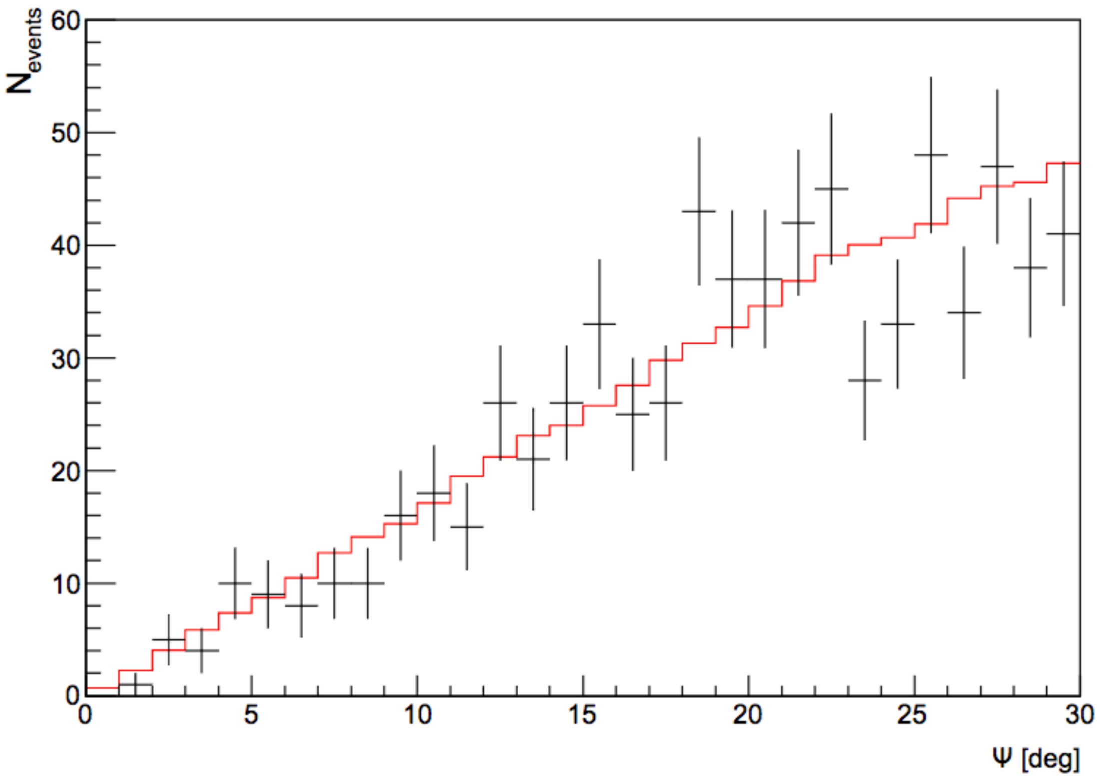


INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES









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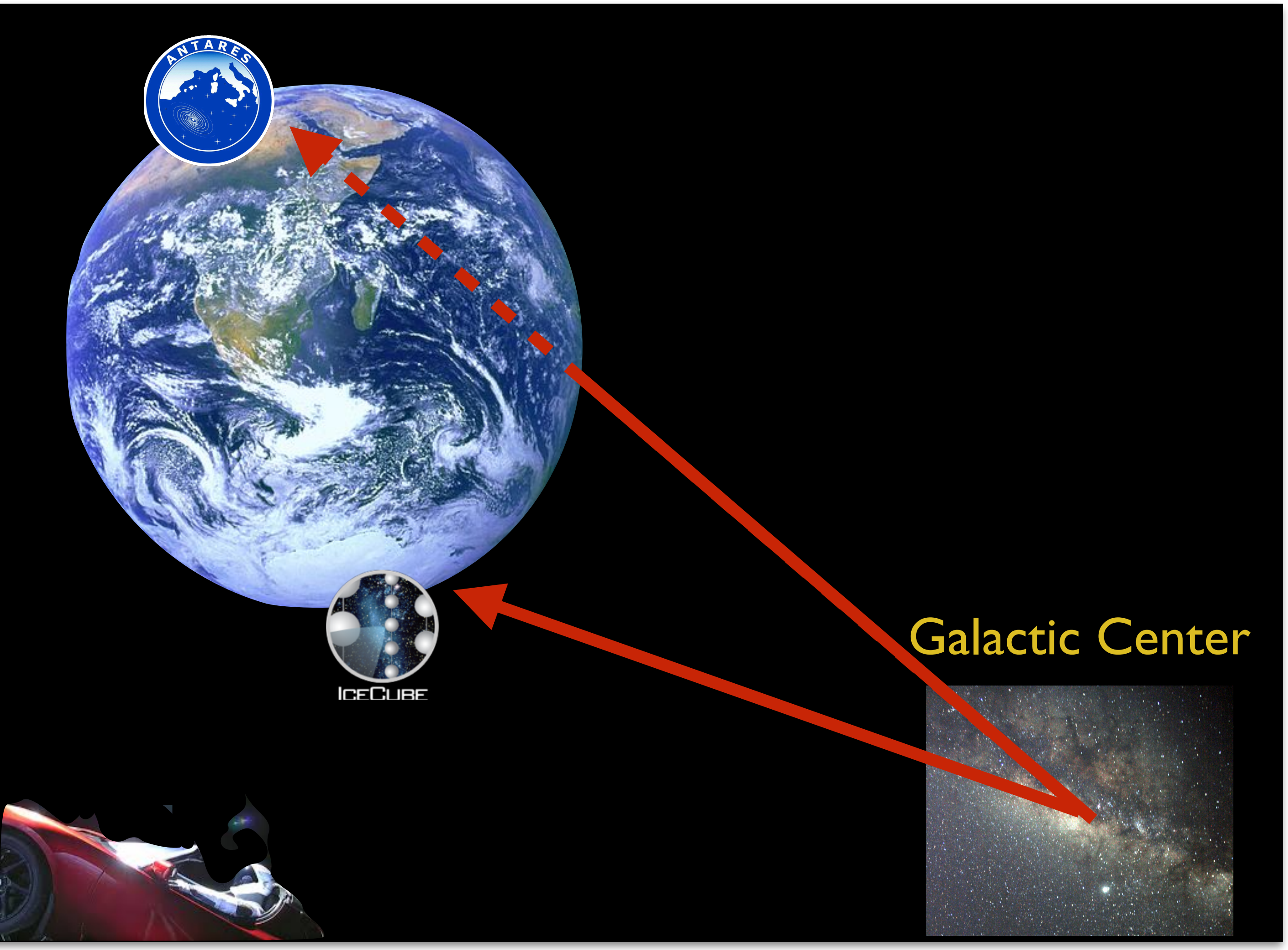
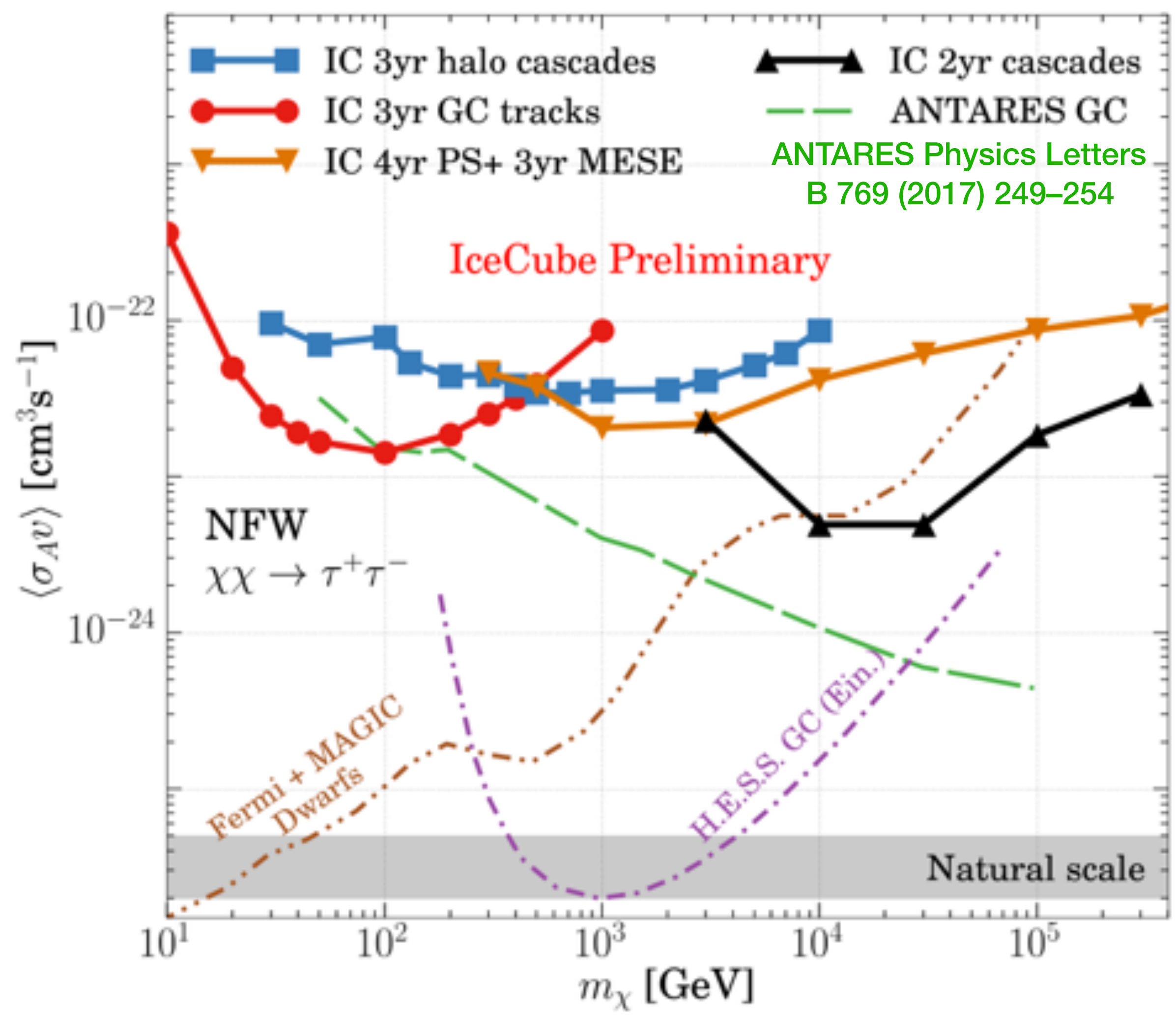


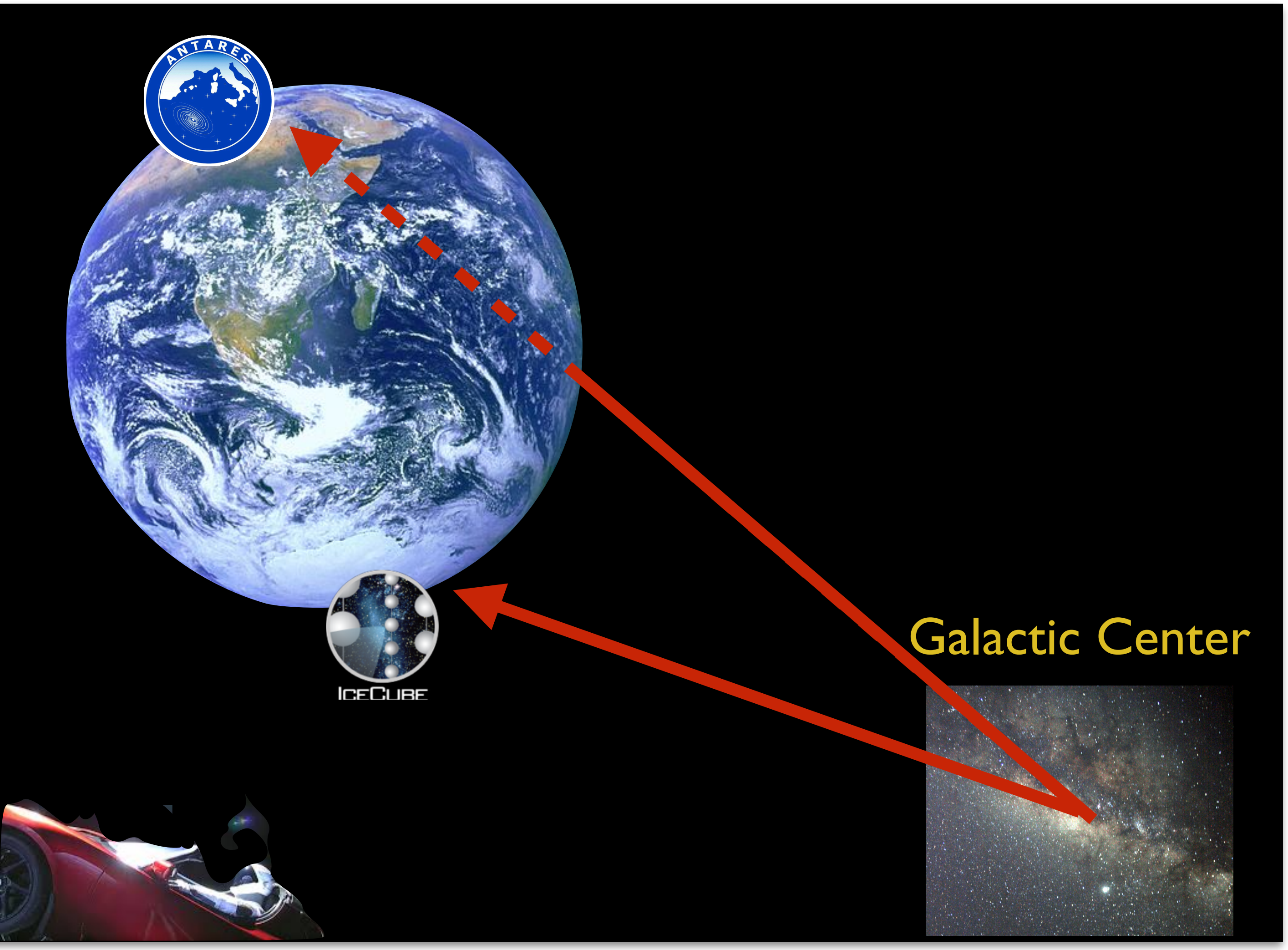
- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

Galactic Halo DM annihilation searches cover 10 GeV - 300 TeV Dark Matter masses with 4 analyses:

- ANTARES GC 2007 to 2015
- IceCube Galactic Halo Cascades 2yrs
- IceCube Galactic Center Tracks 4yrs (incl. 3yr MESE)
- IceCube Galactic Center Track 3yrs (low-energy)
  - IceCube [arXiv:1705.08103] Eur. Phys. J. C (2017) 77: 627



INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES



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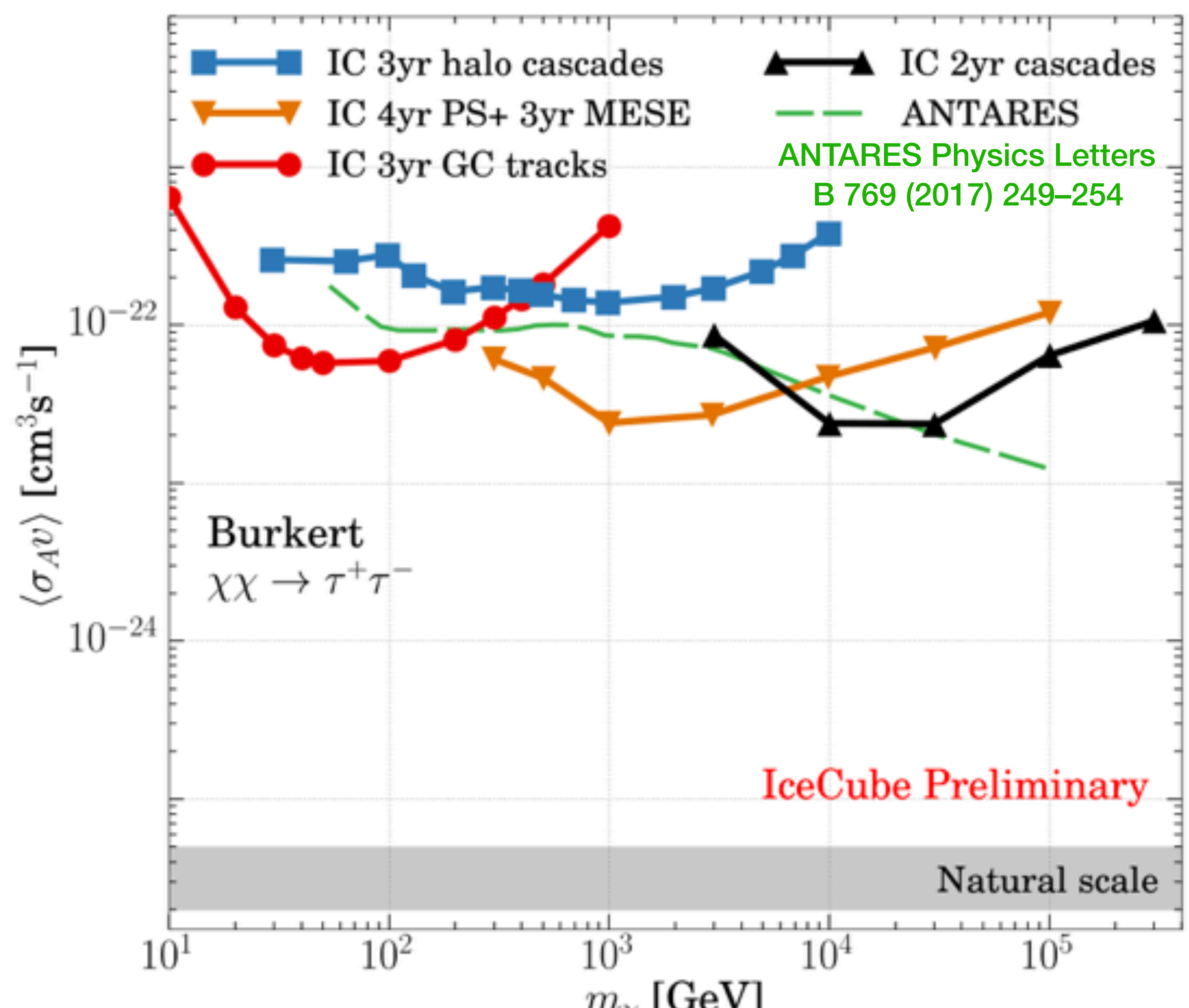
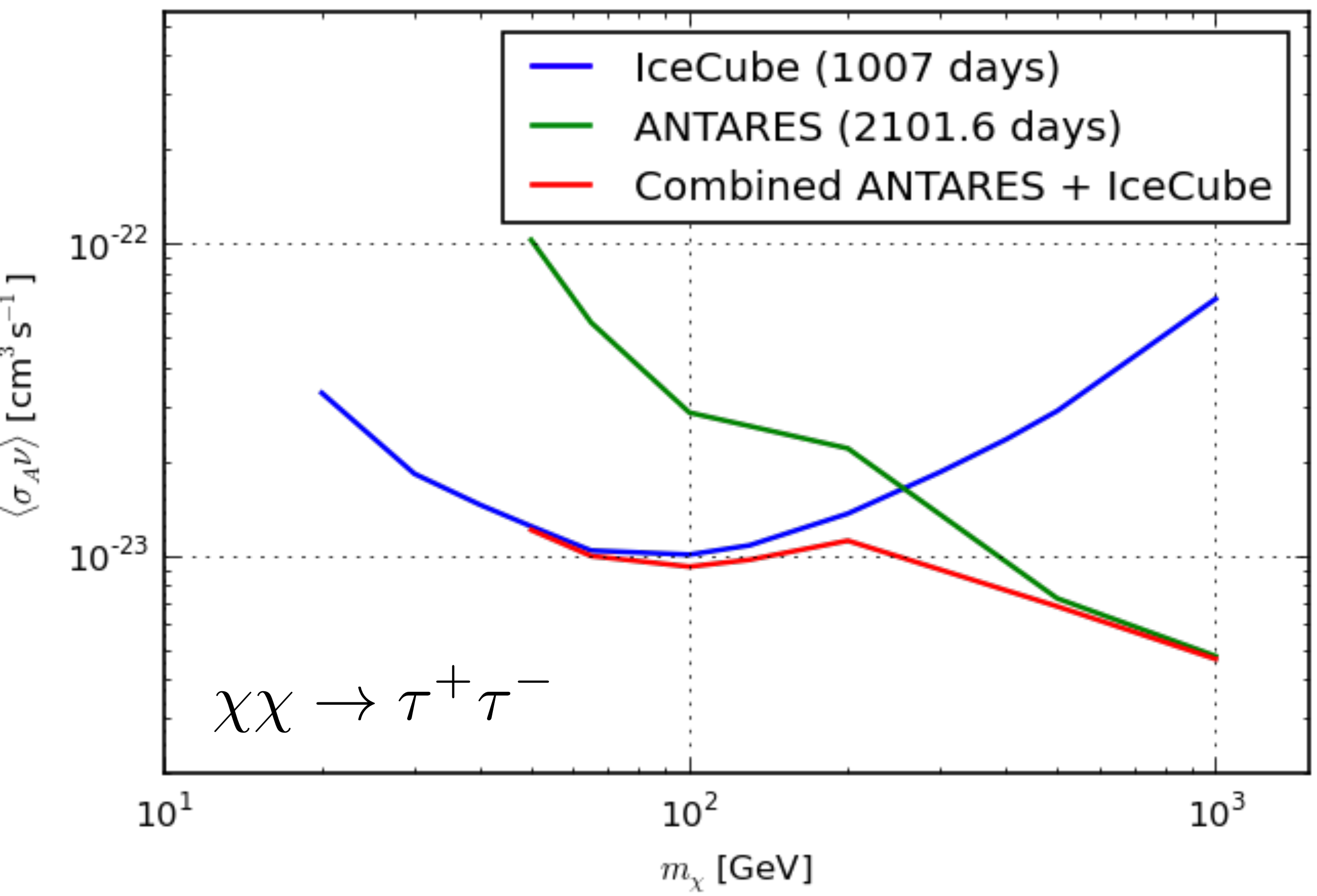
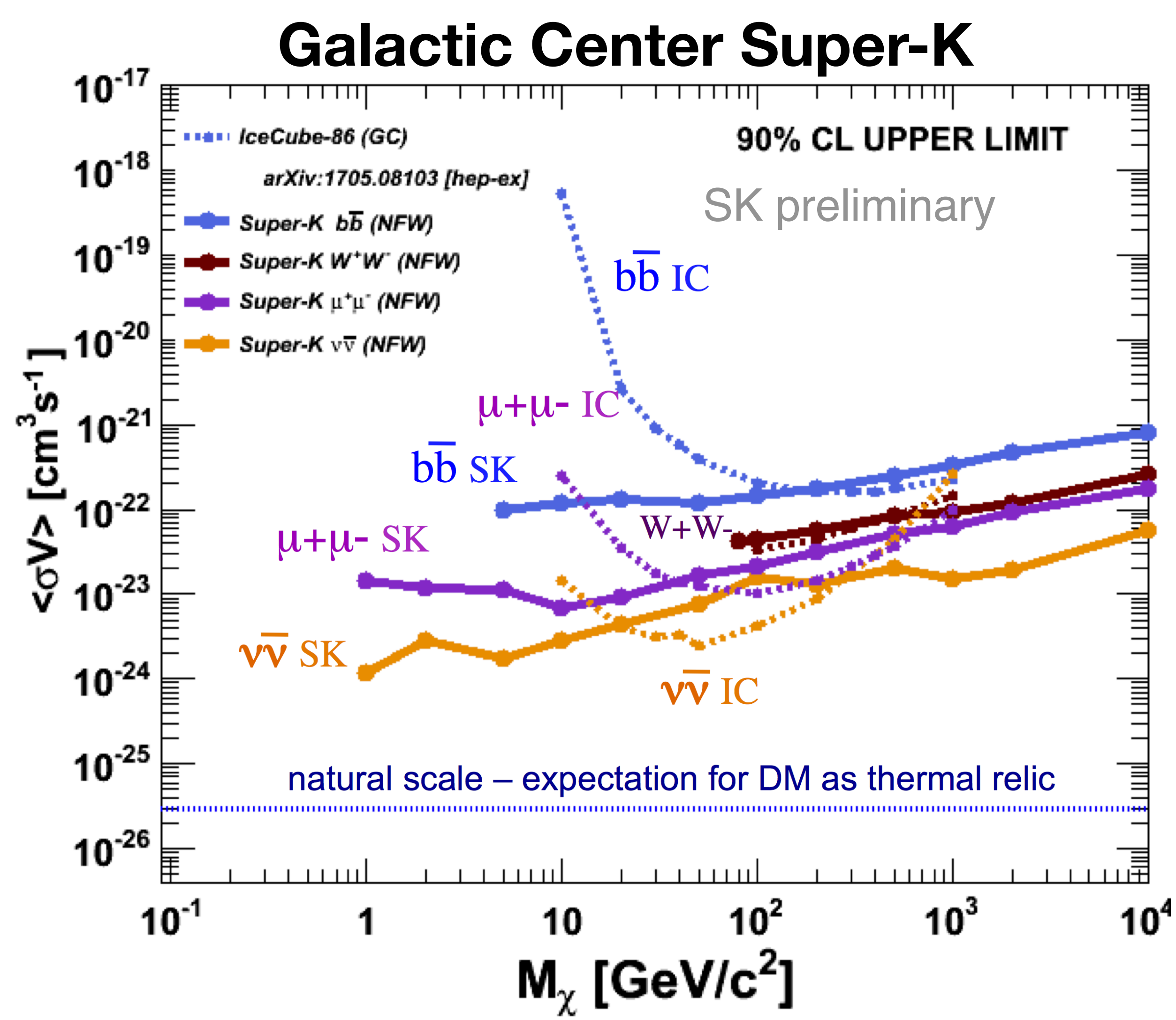


Galactic Center / Galactic Halo - IceCube/ ANTARES/Super-K

J.A. Aguilar Sánchez [ANTARES & IceCube] ICRC2017 (911)

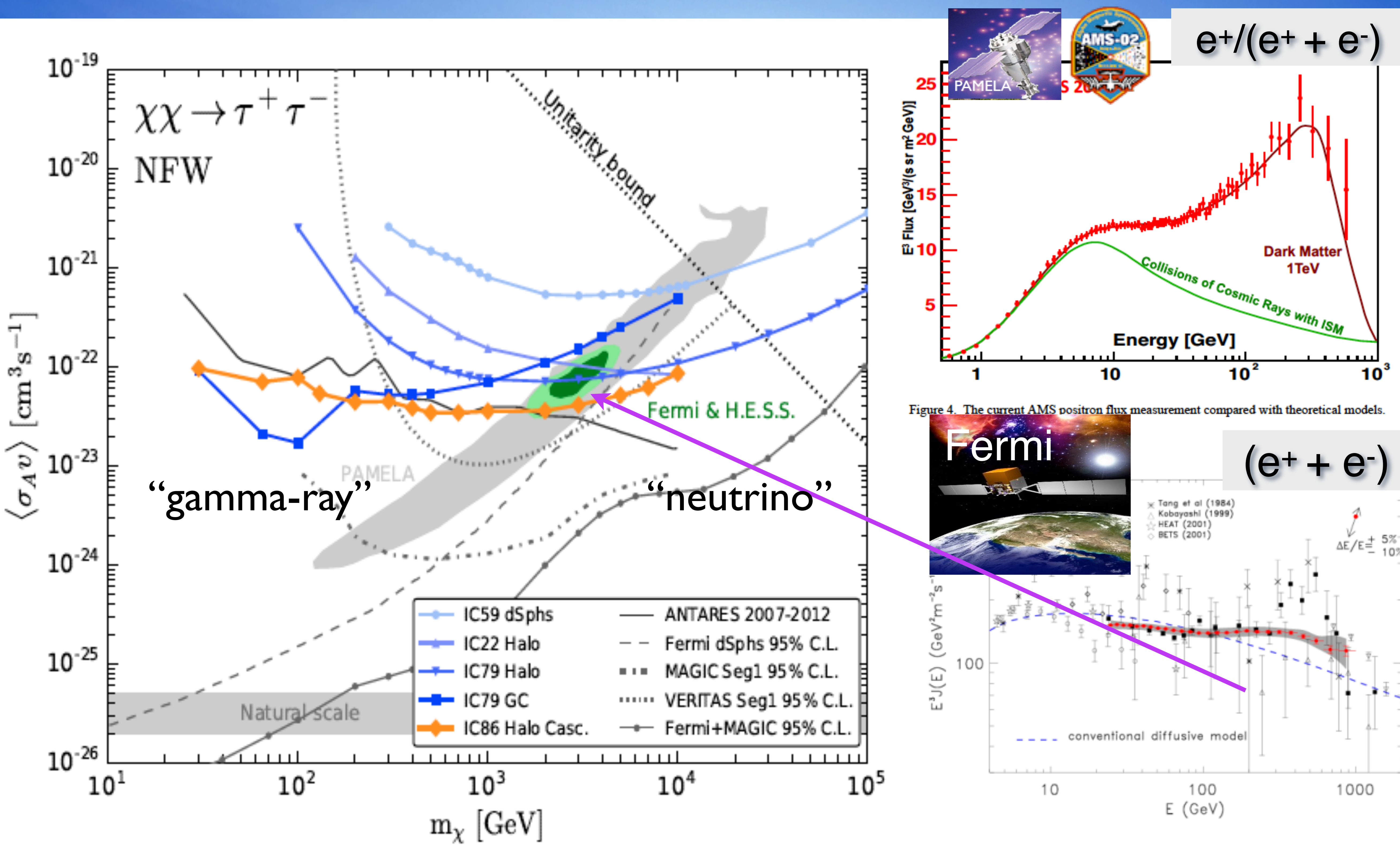


Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Center using IceCube and ANTARES

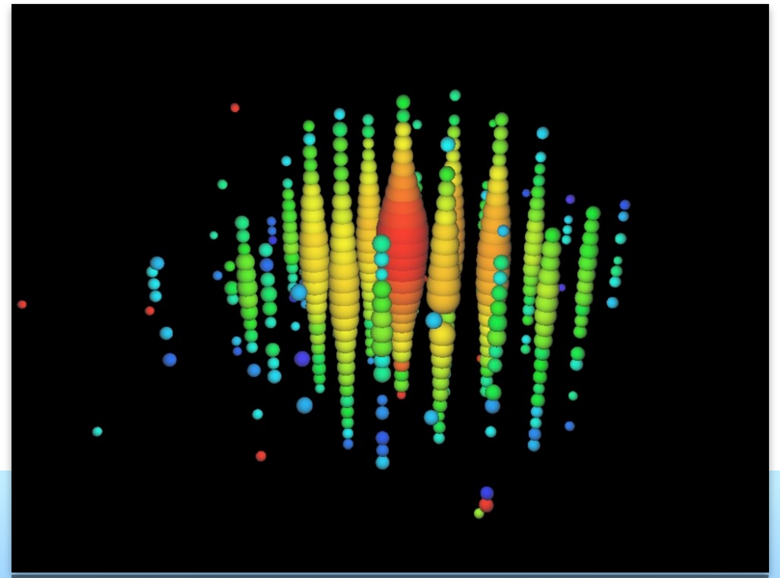


- Combined analysis enhances sensitivity in overlap region and helps to make analyses more comparable
- Very competitive result from Super-K for dark matter masses below a 100GeV

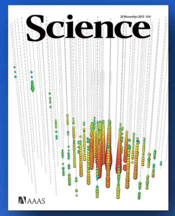
Neutrinos test lepton anomalies

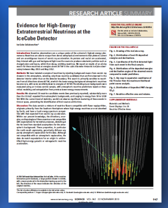


Neutrino Telescopes can probe models motivated by the observed lepton anomalies



Dark Matter Decay / Astro-physical Neutrinos

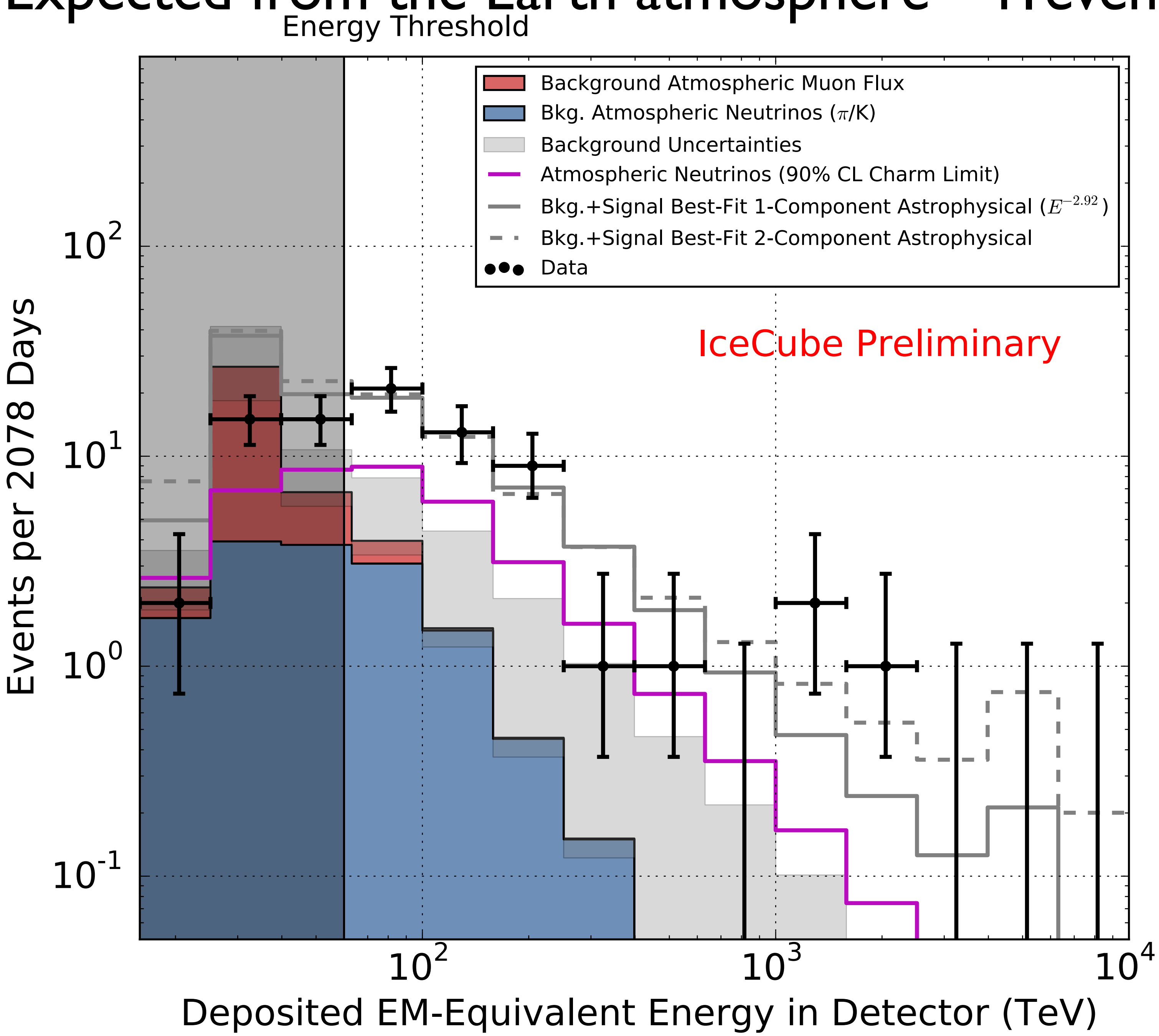


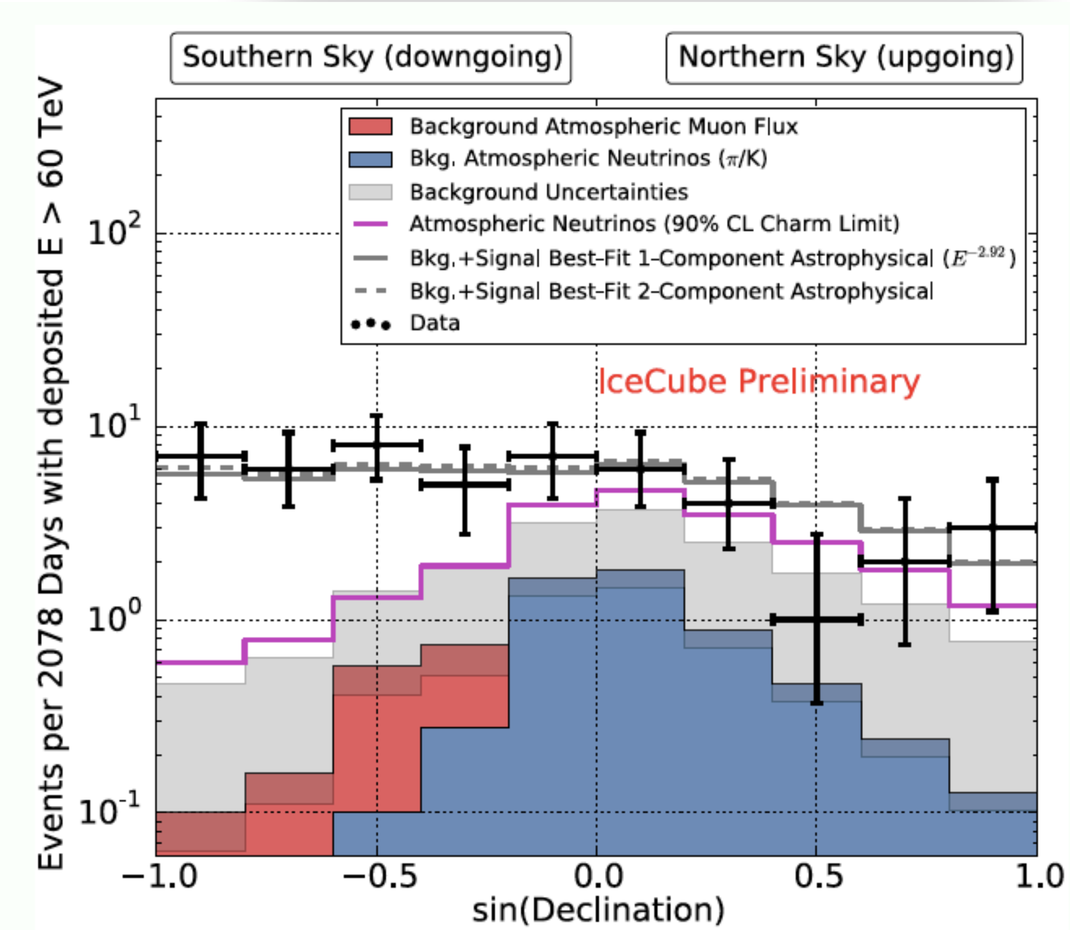


High-energy neutrino search 6years

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

Expected from the Earth atmosphere ~41events



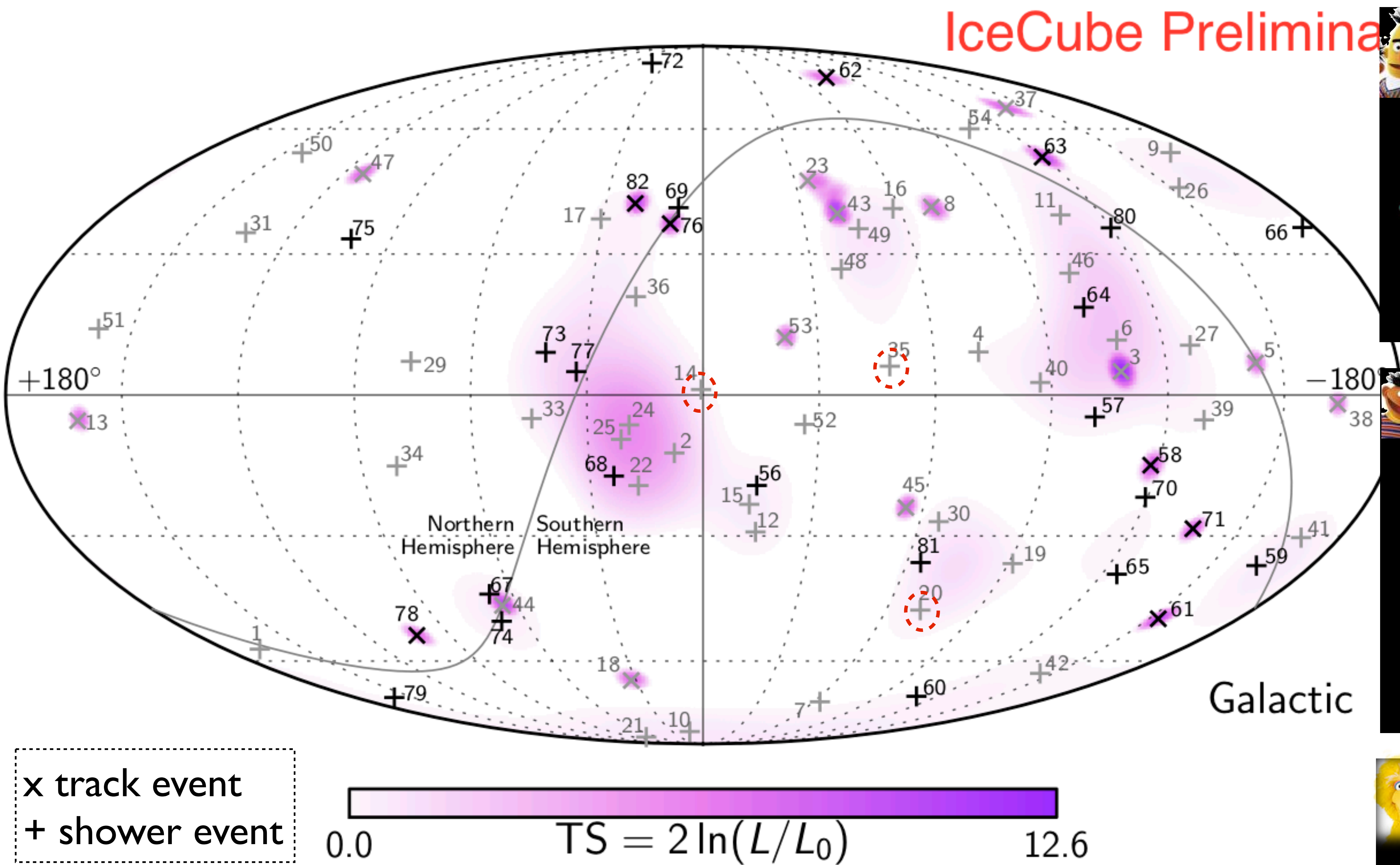


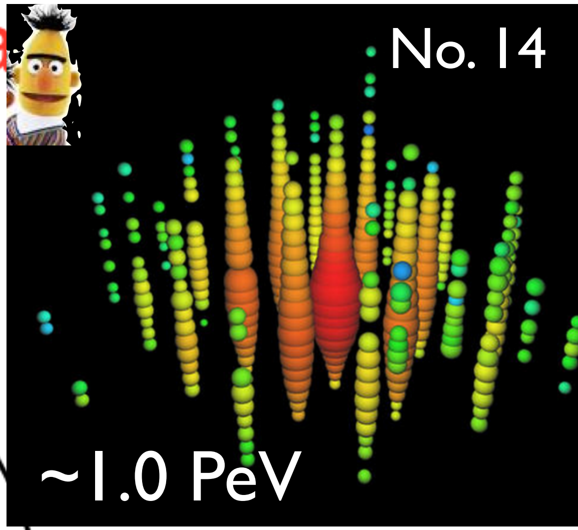
Best fit spectral index ($E^{-\gamma}$):
$\gamma=-2.92^{+0.33}_{-0.29}$

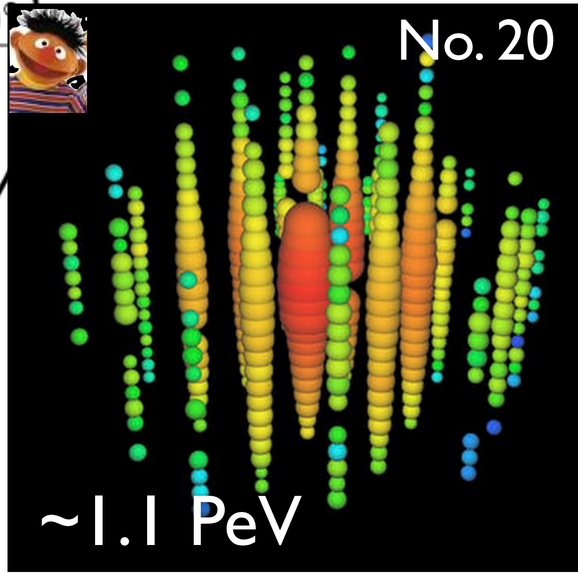
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

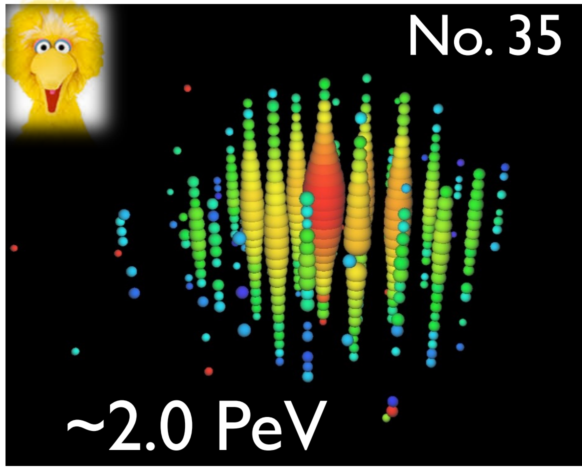
Skymap HESE-6yrs

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





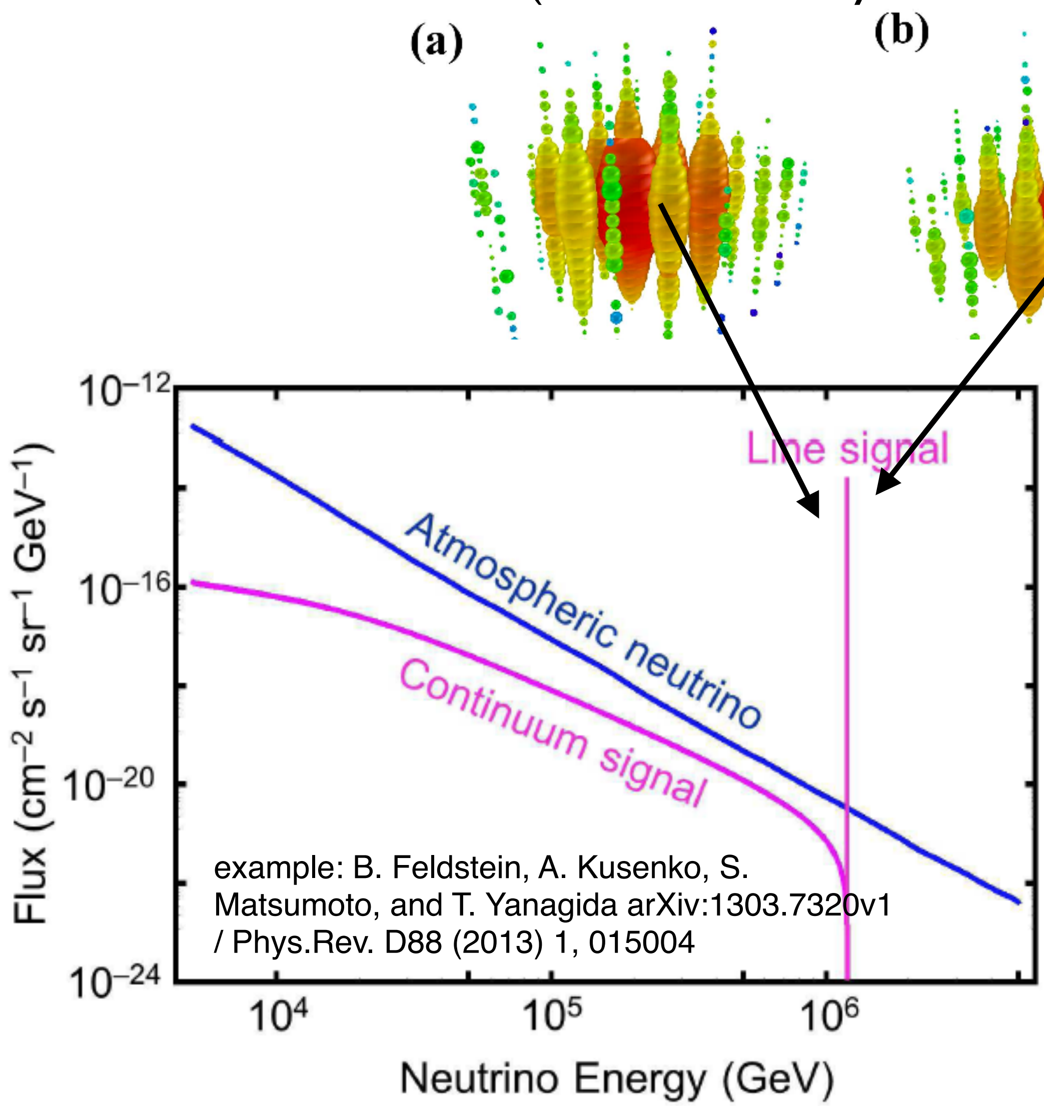




no significant clustering observed

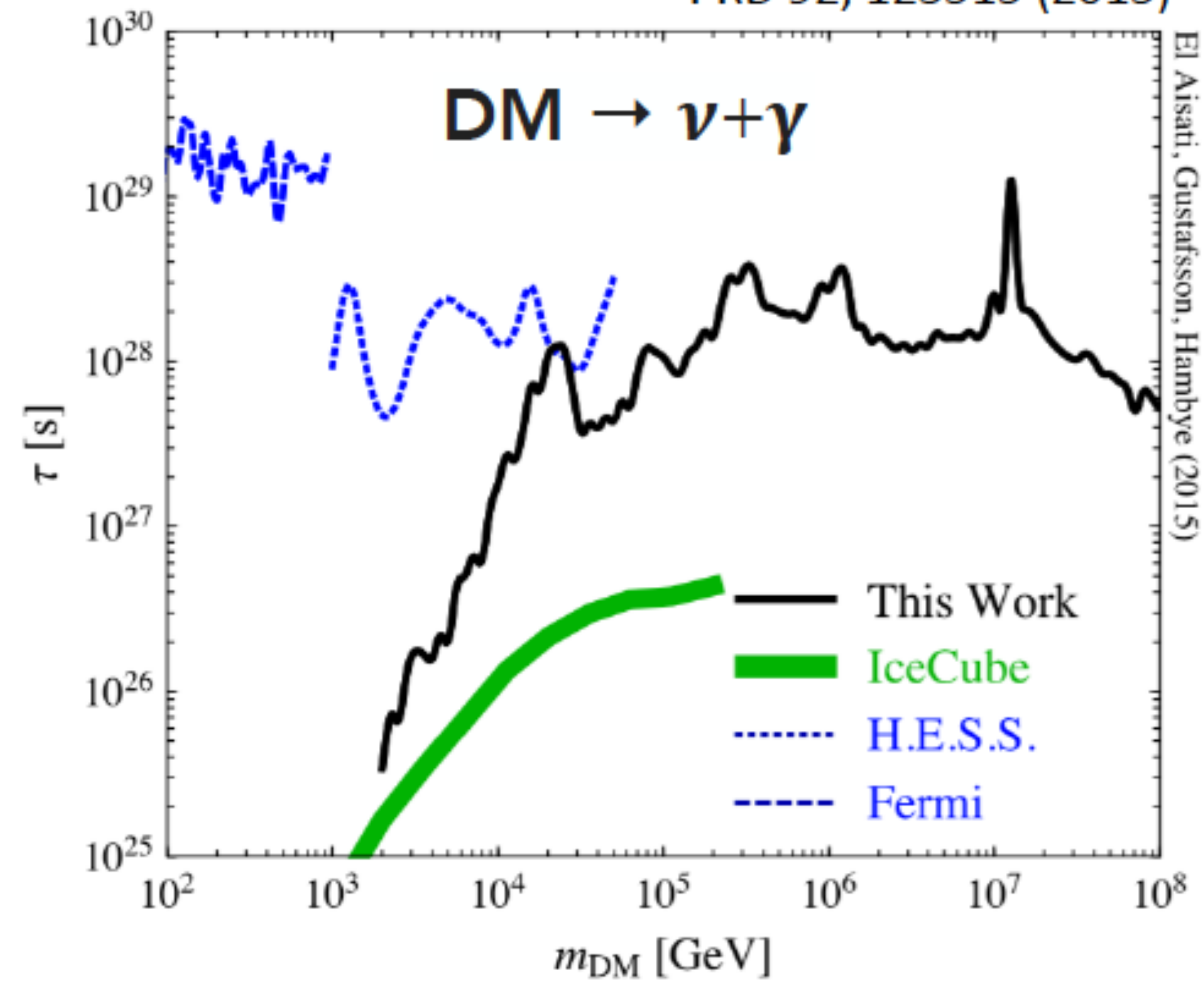
Heavy Dark Matter Decay

- 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).



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

Dedicated IceCube analysis can improve on these bounds …

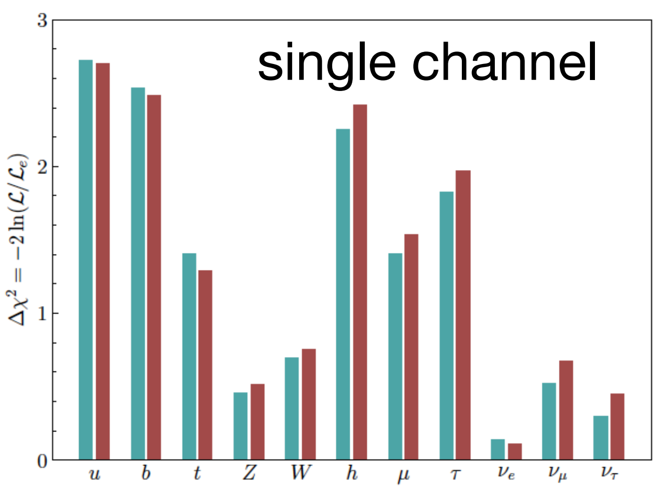
Heavy Decaying Dark Matter

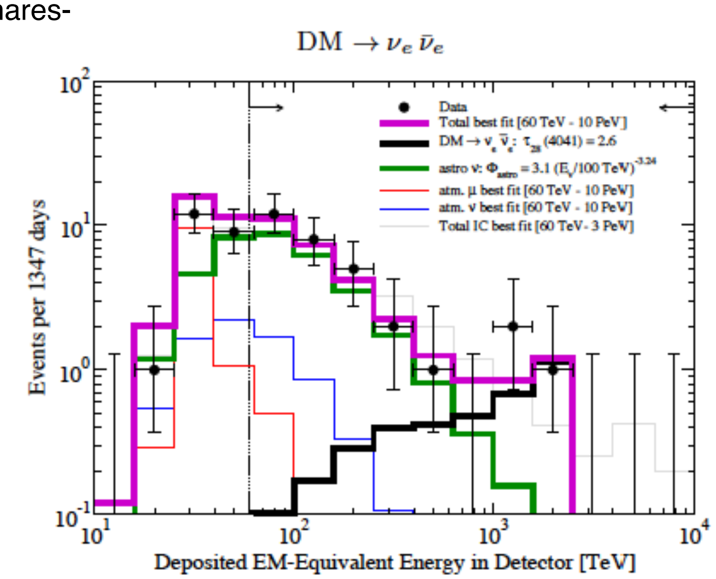
Could the observed neutrino flux be due to only dark matter decaying into multiple channels?

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

Take Galactic and Extra galactic contributions into account

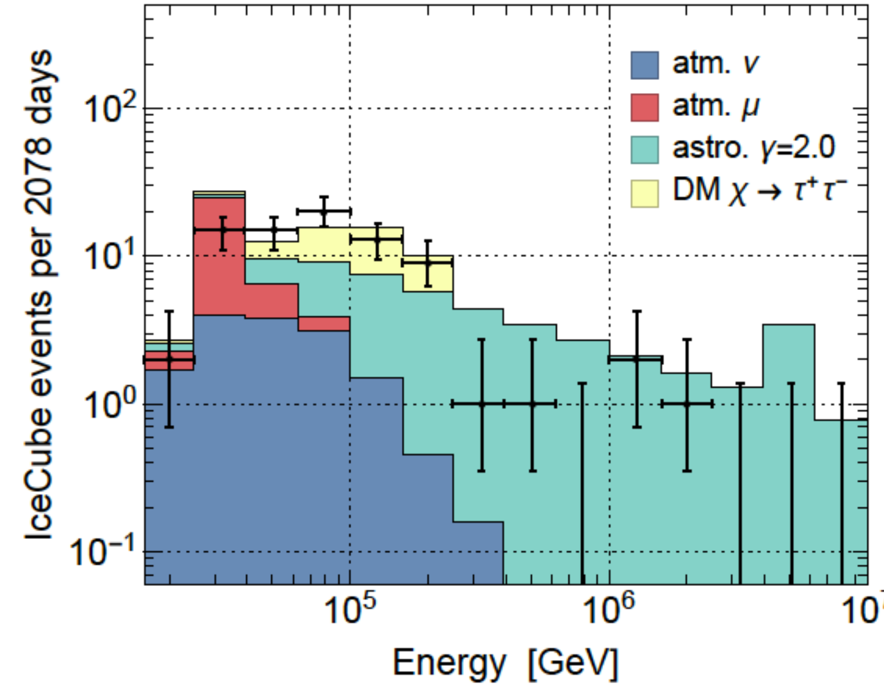
Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, arXiv:1706.05746

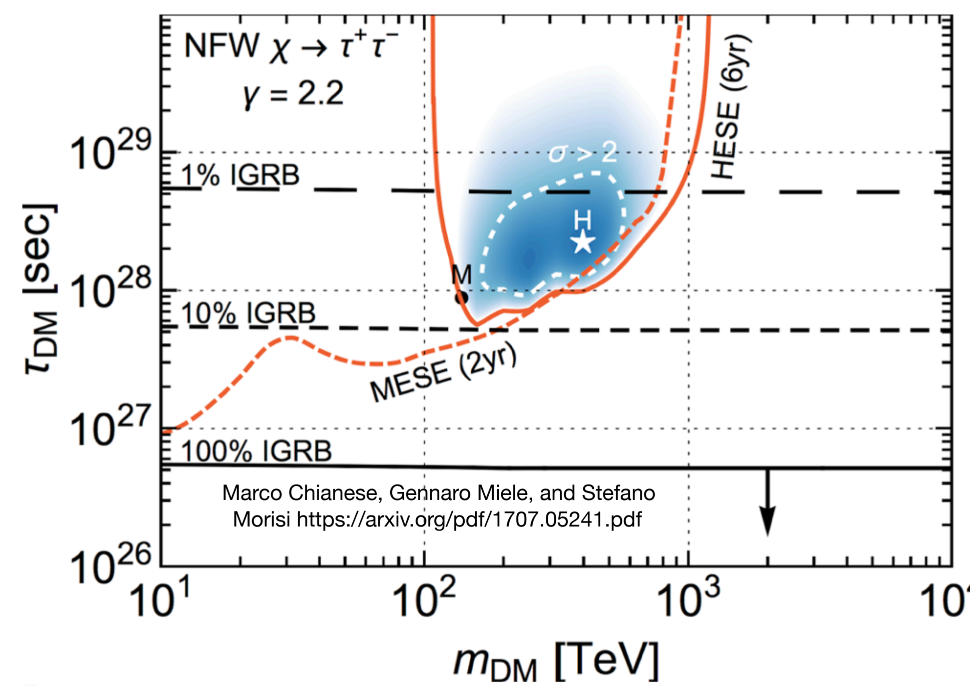




Find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay

Marco Chianese, Gennaro Miele, and Stefano Morisi
https://arxiv.org/pdf/1707.05241.pdf





Caution when interpreting HESE events:
- Earth absorption needs to be considered
- Outcome strongly depends on background assumption

Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034
Rott, Kohri, Park PRD92, 023529 (2015)
El Aisati, Gustafsson, Hambye 1506.02657

Dark Matter Decay with IceCube

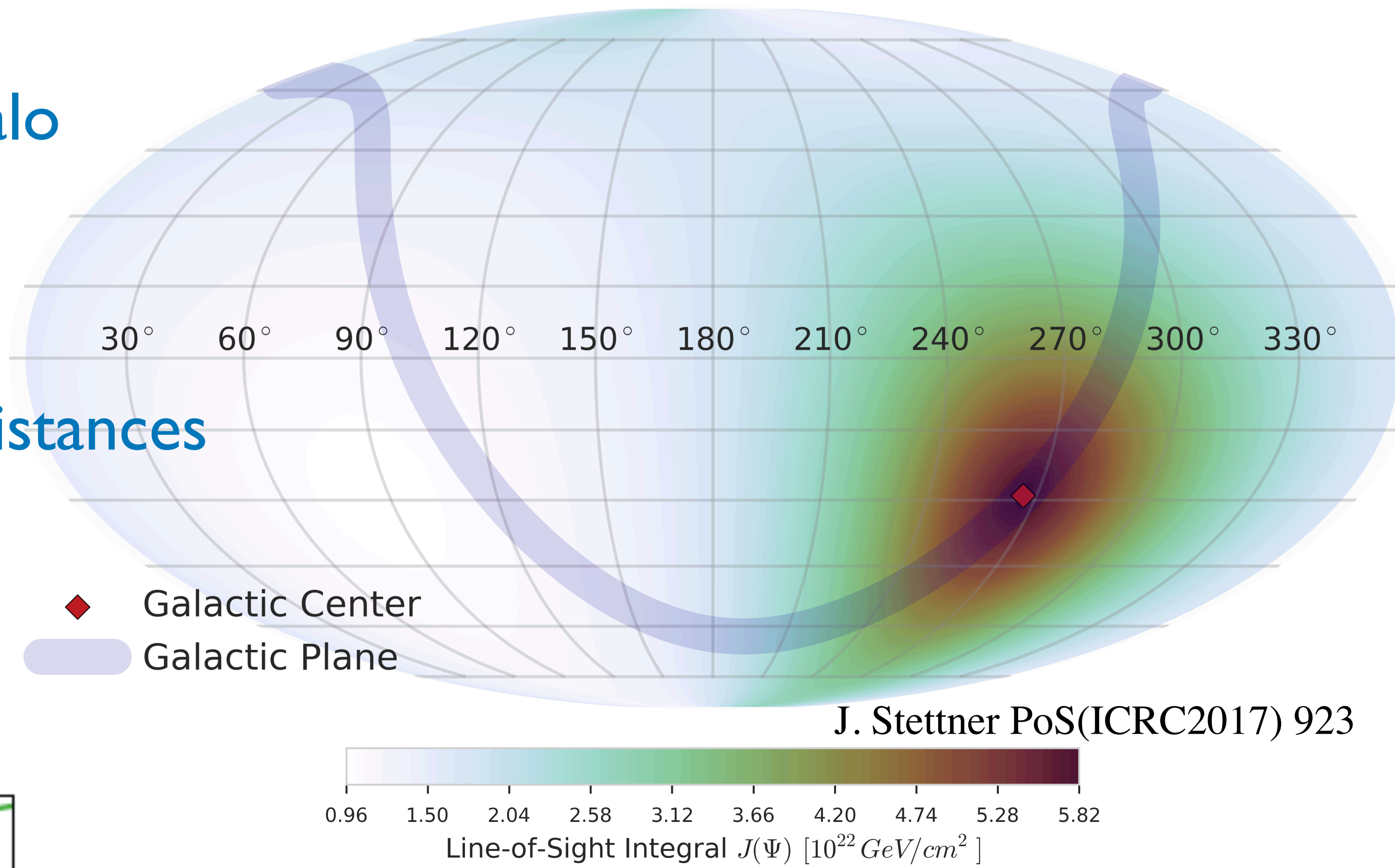
Two expected flux contributions:

- Dark Matter decaying in the Galactic Halo (Anisotropic flux + decay spectrum)

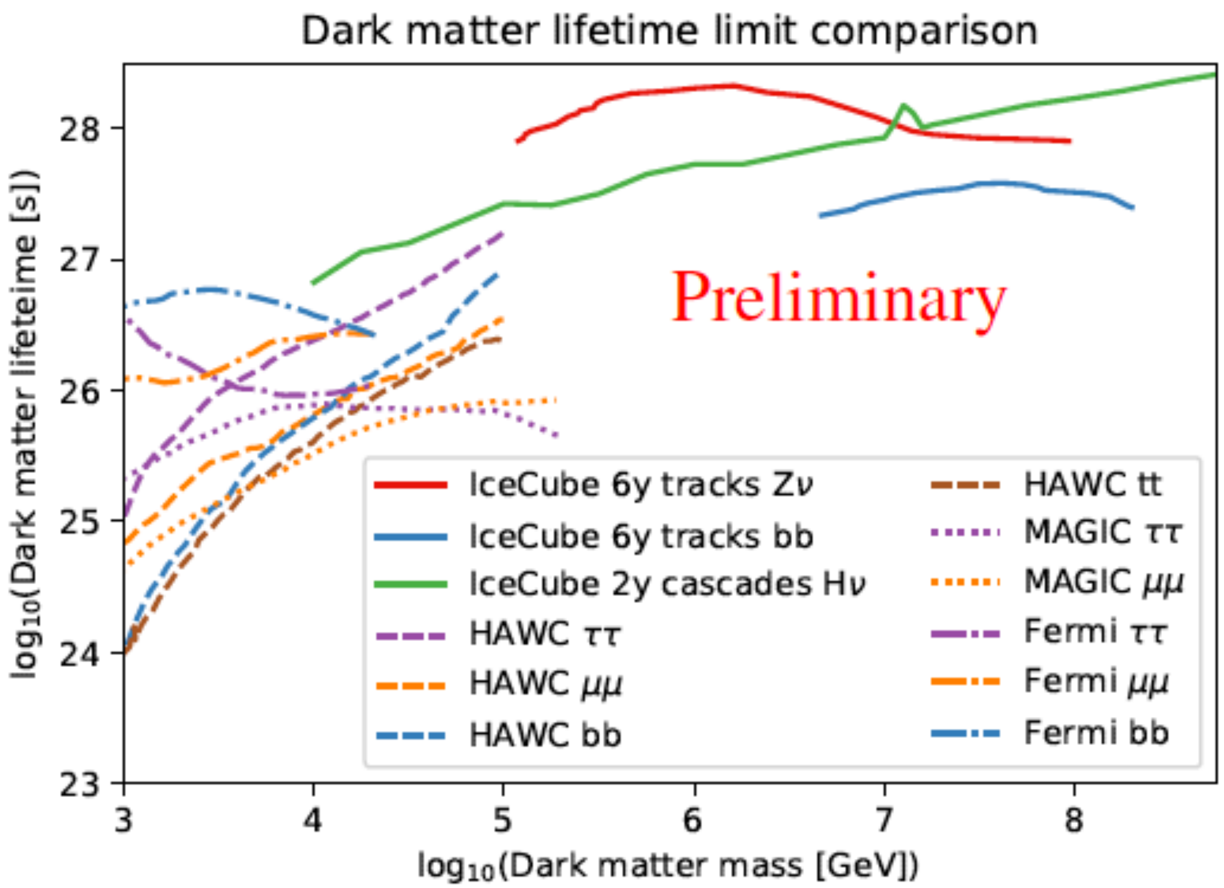
$$\frac{\mathrm{d}\Phi^{G}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\,\mathrm{d}s$$

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

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



J. Stettner PoS(ICRC2017) 923

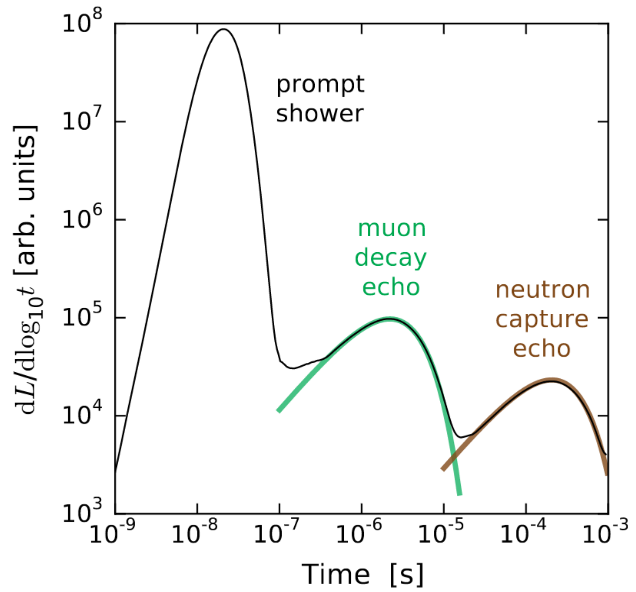


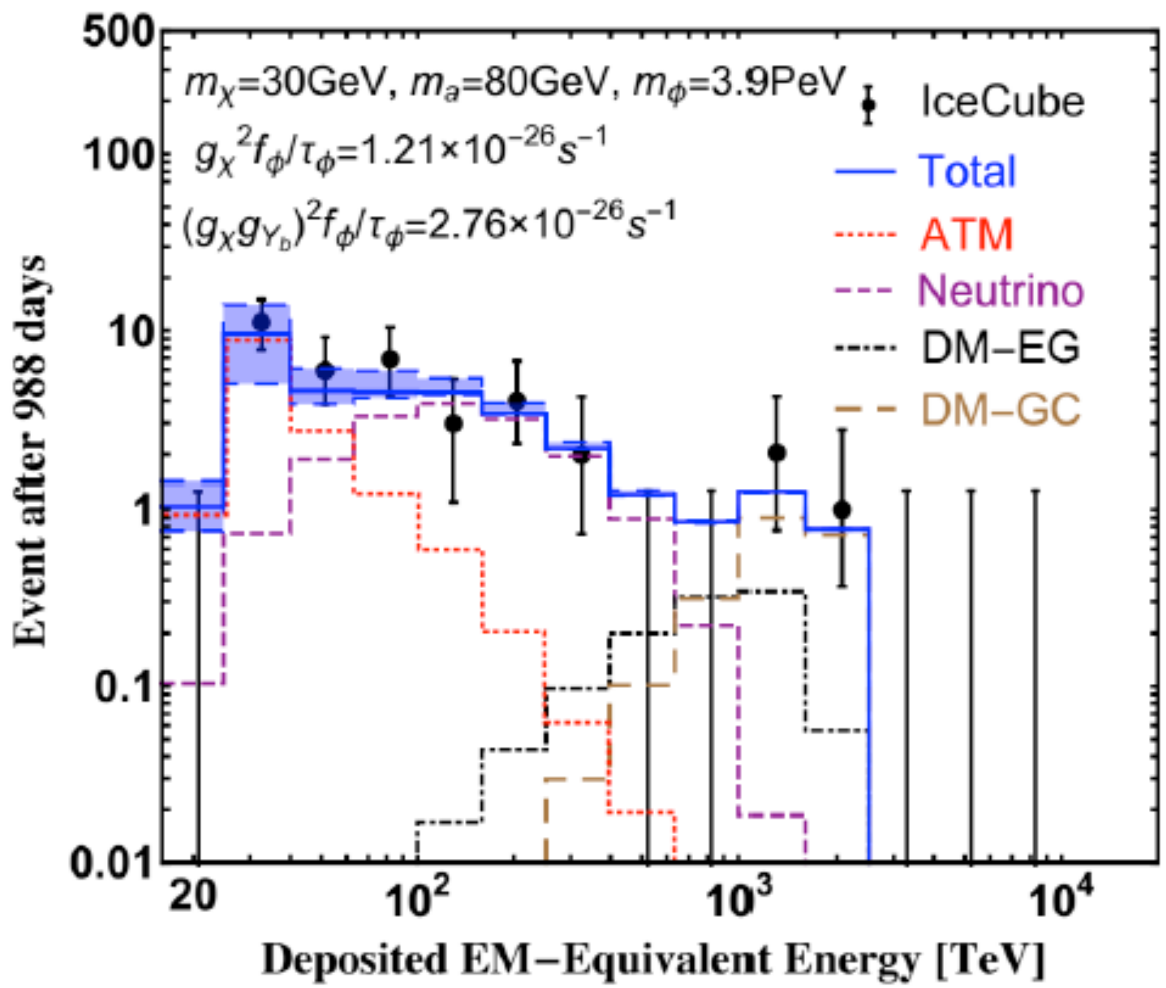
Test-Statistic: $TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM}=\infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$

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

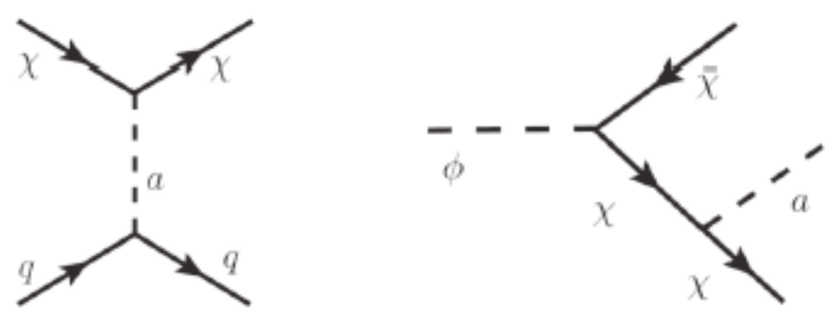
Boosted Dark Matter

- “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!



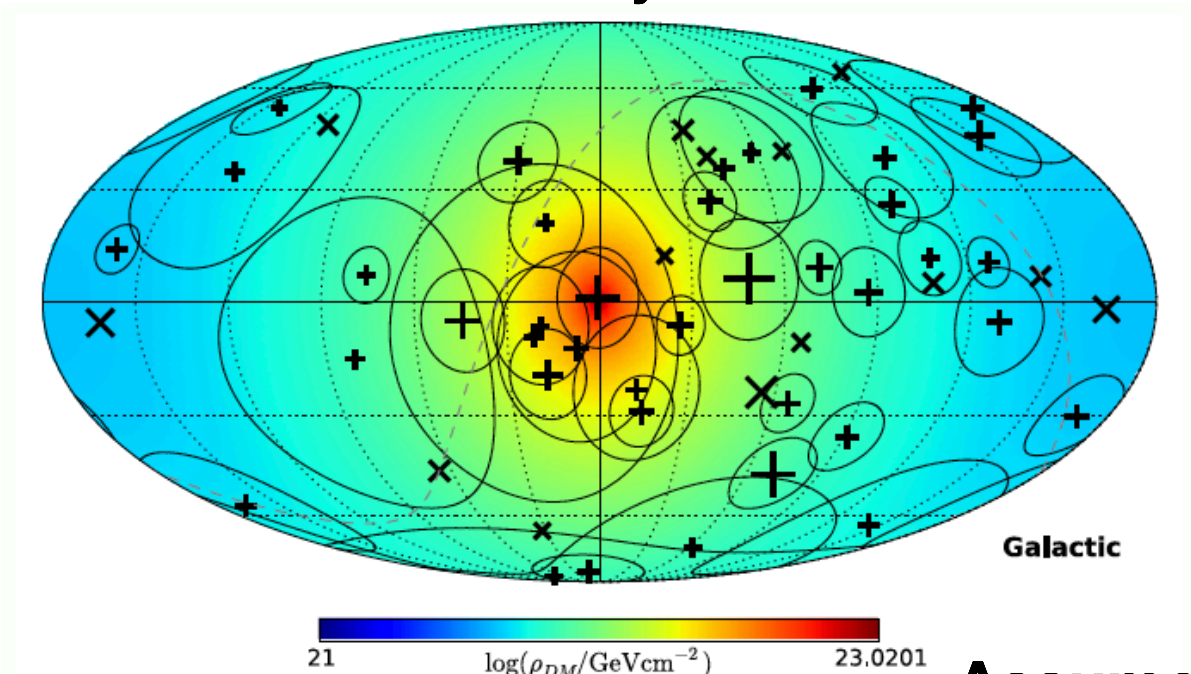
Recoil (only hadronic cascades)

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

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

[A. Kheirandish et al. arXiv:1703.00451]

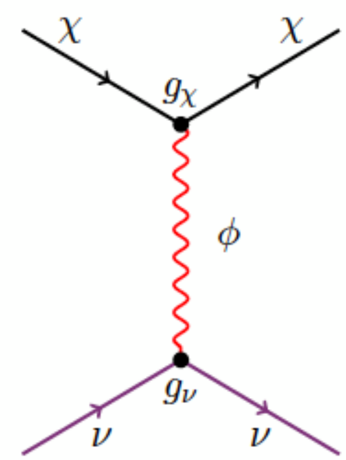
Dark Matter Column Density* as seen from Earth



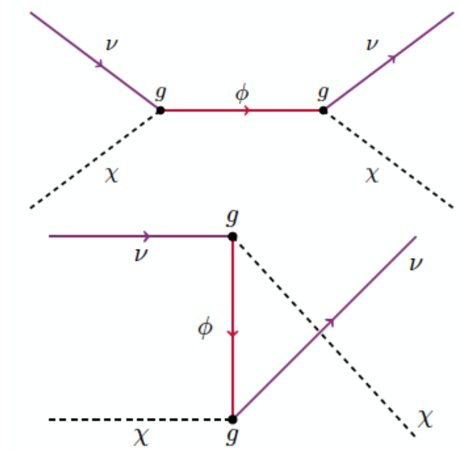
*Einasto Profile

Dark Matter - Neutrino Interaction

(1) Fermion DM, vector mediator

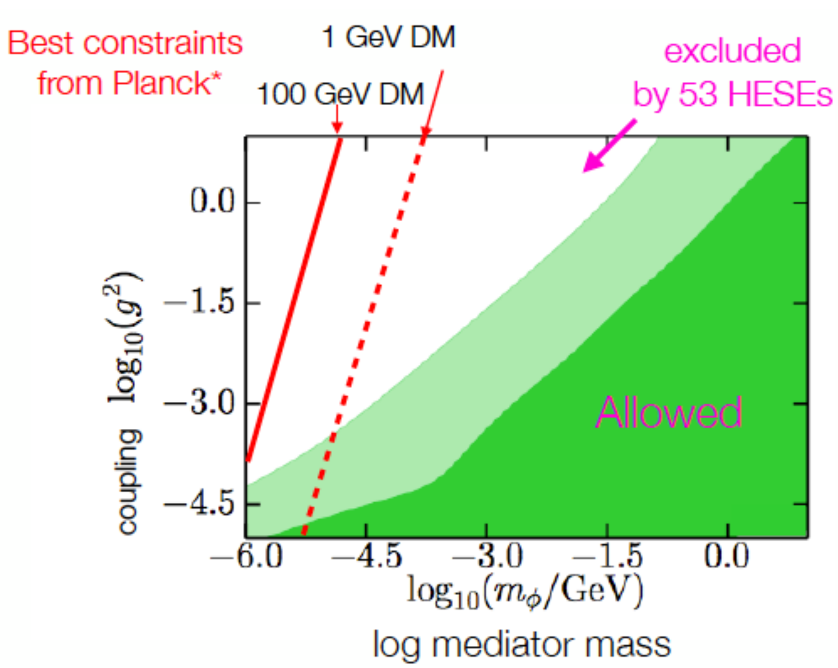


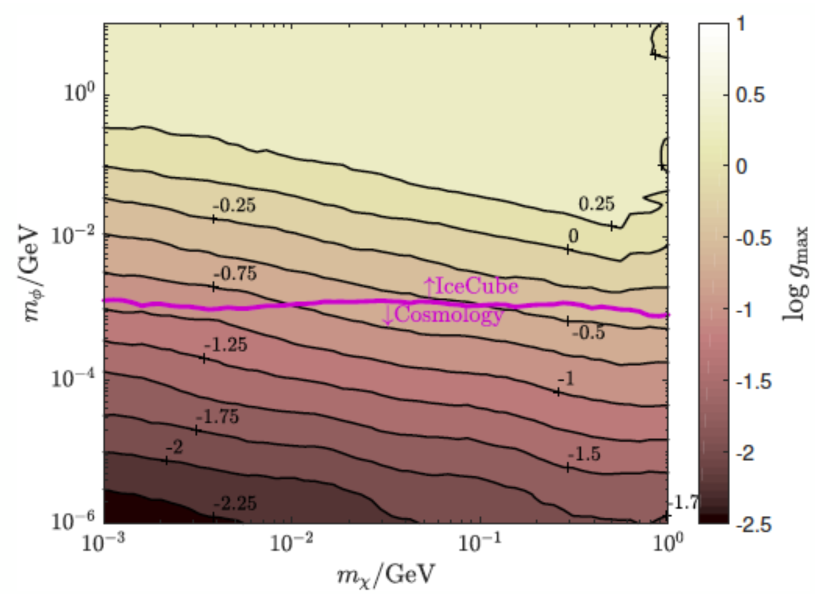
(2) Scale DM, ferminonic mediator

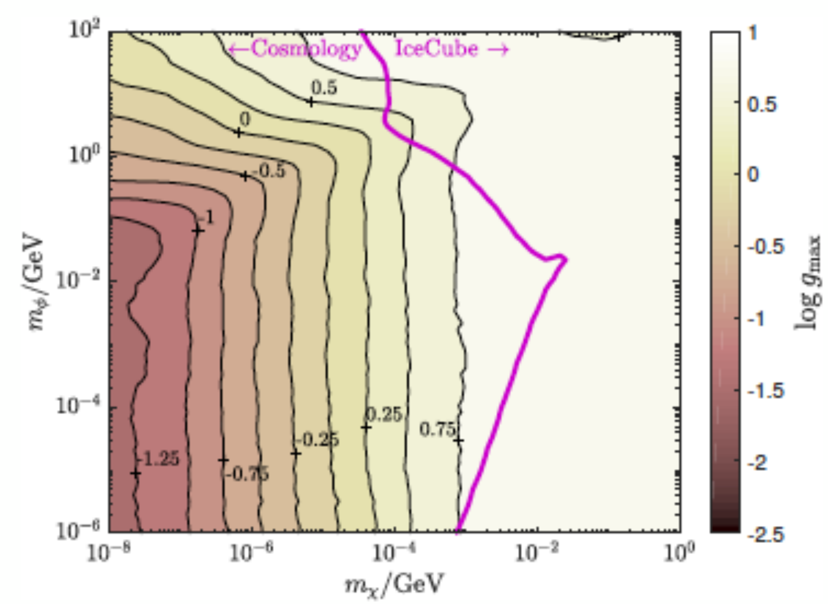


Assume:

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

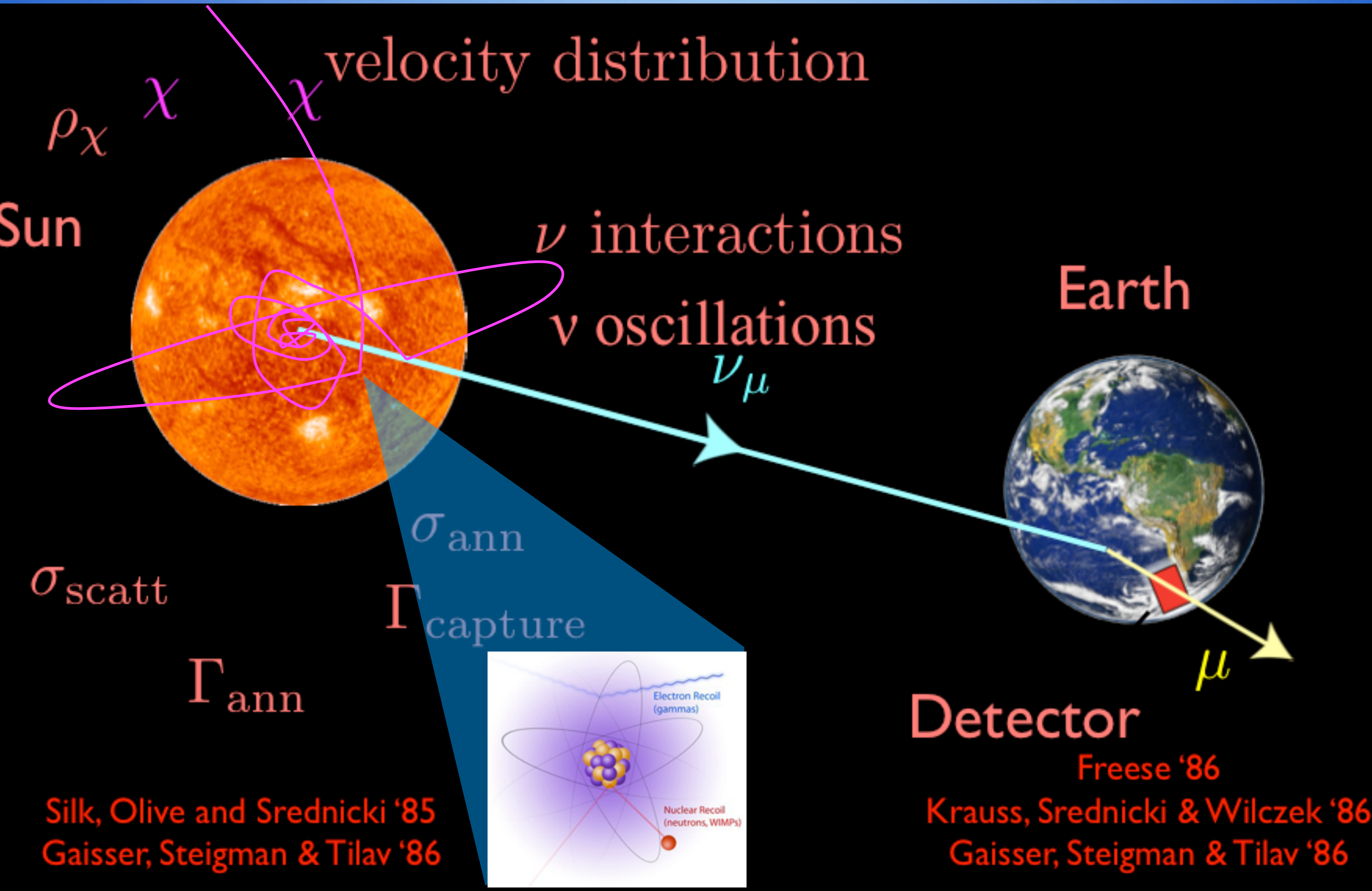






Dark Matter Capture in the Sun

Solar Dark Matter

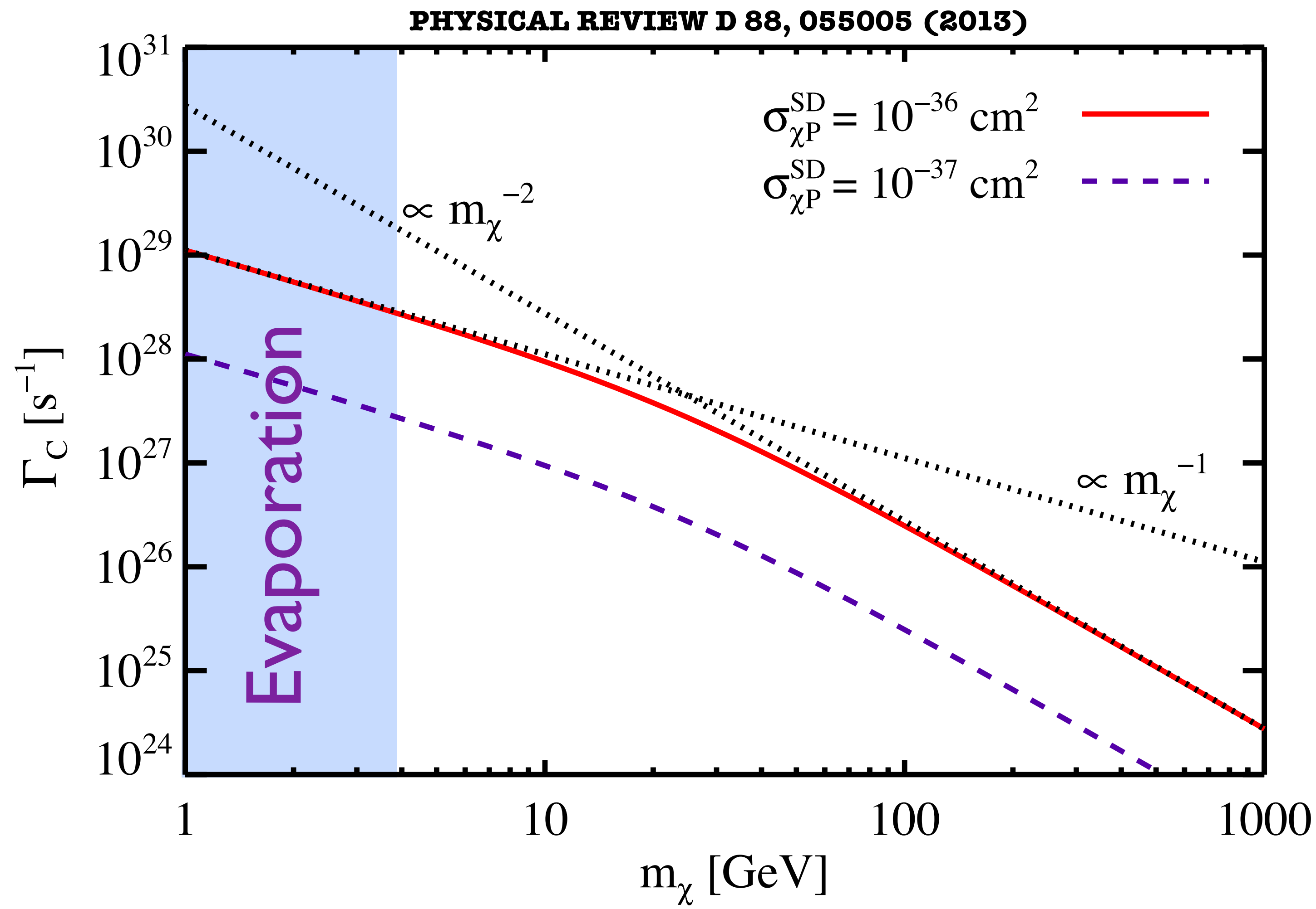


Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

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 $m_\chi >> m_A$

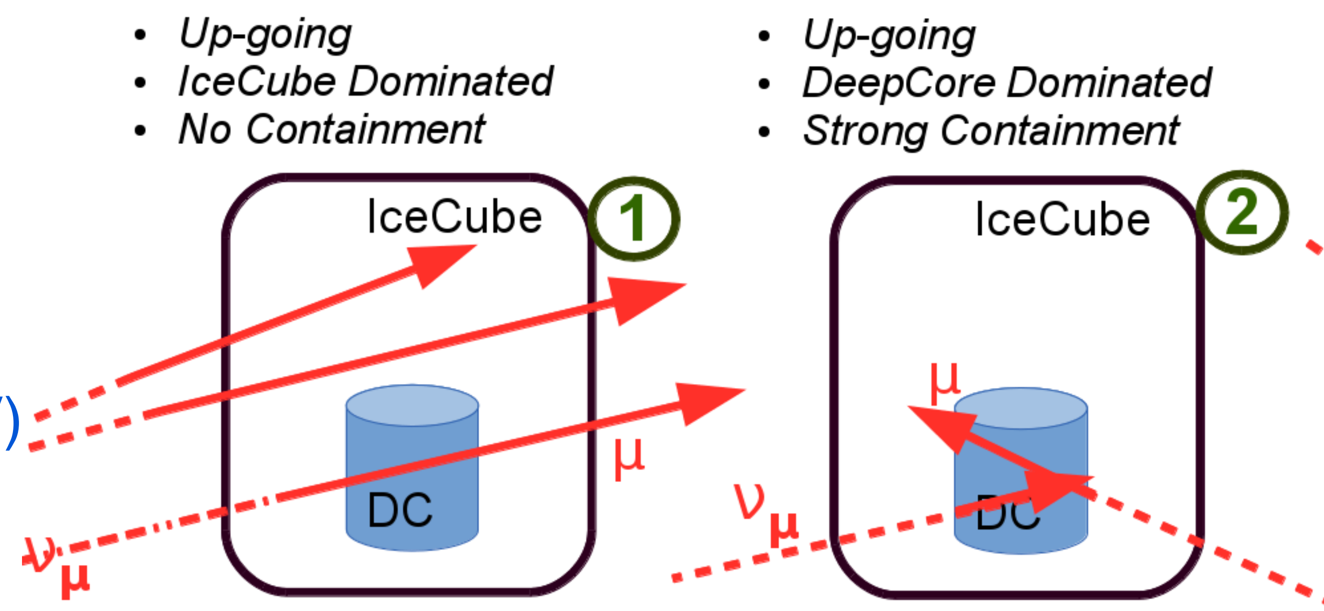
number density + kinematic suppression

m_A - is the target mass

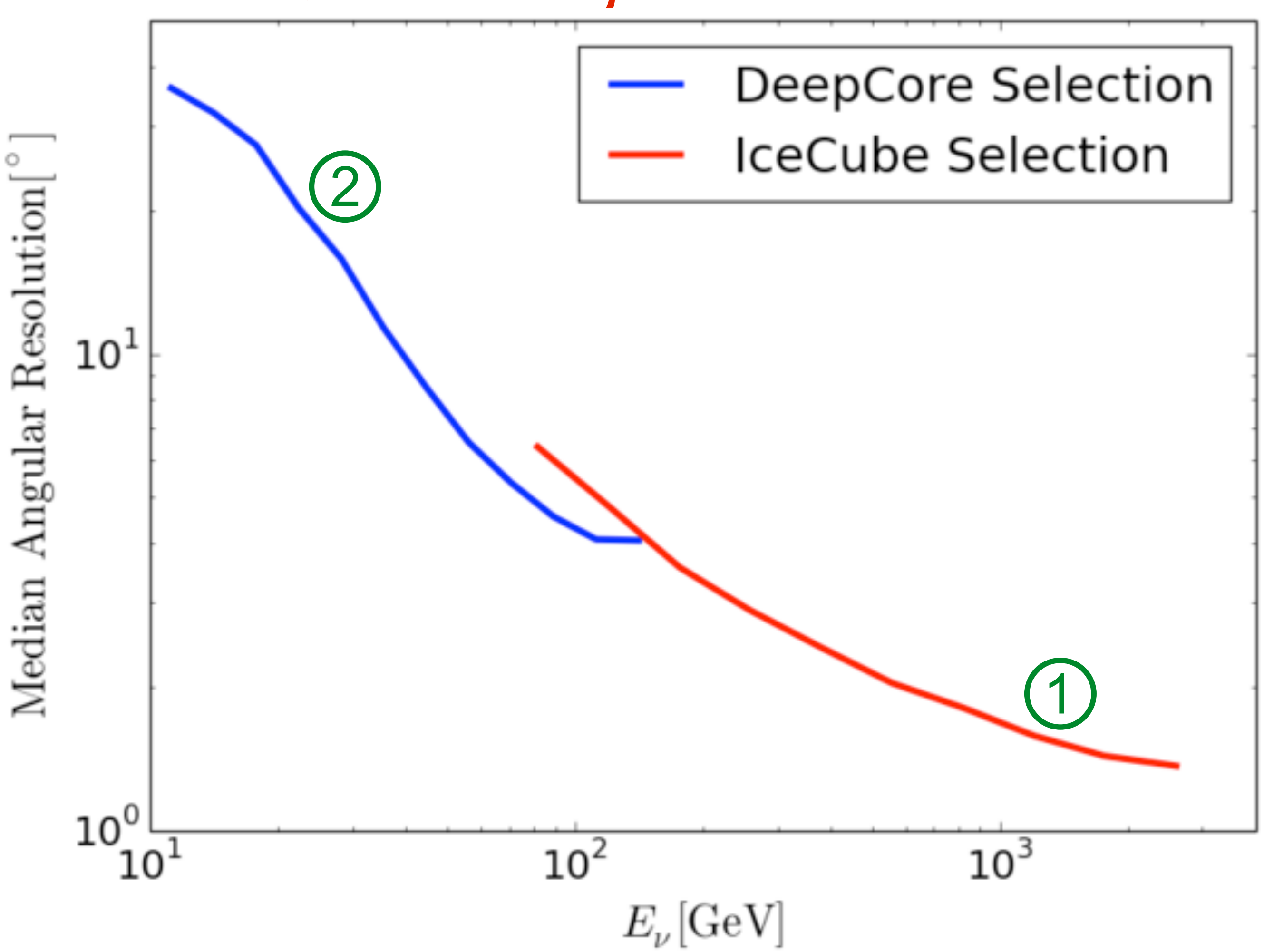
3yrs IceCube Solar WIMP Analysis

IceCubeColl., arXiv:1612.05949v1

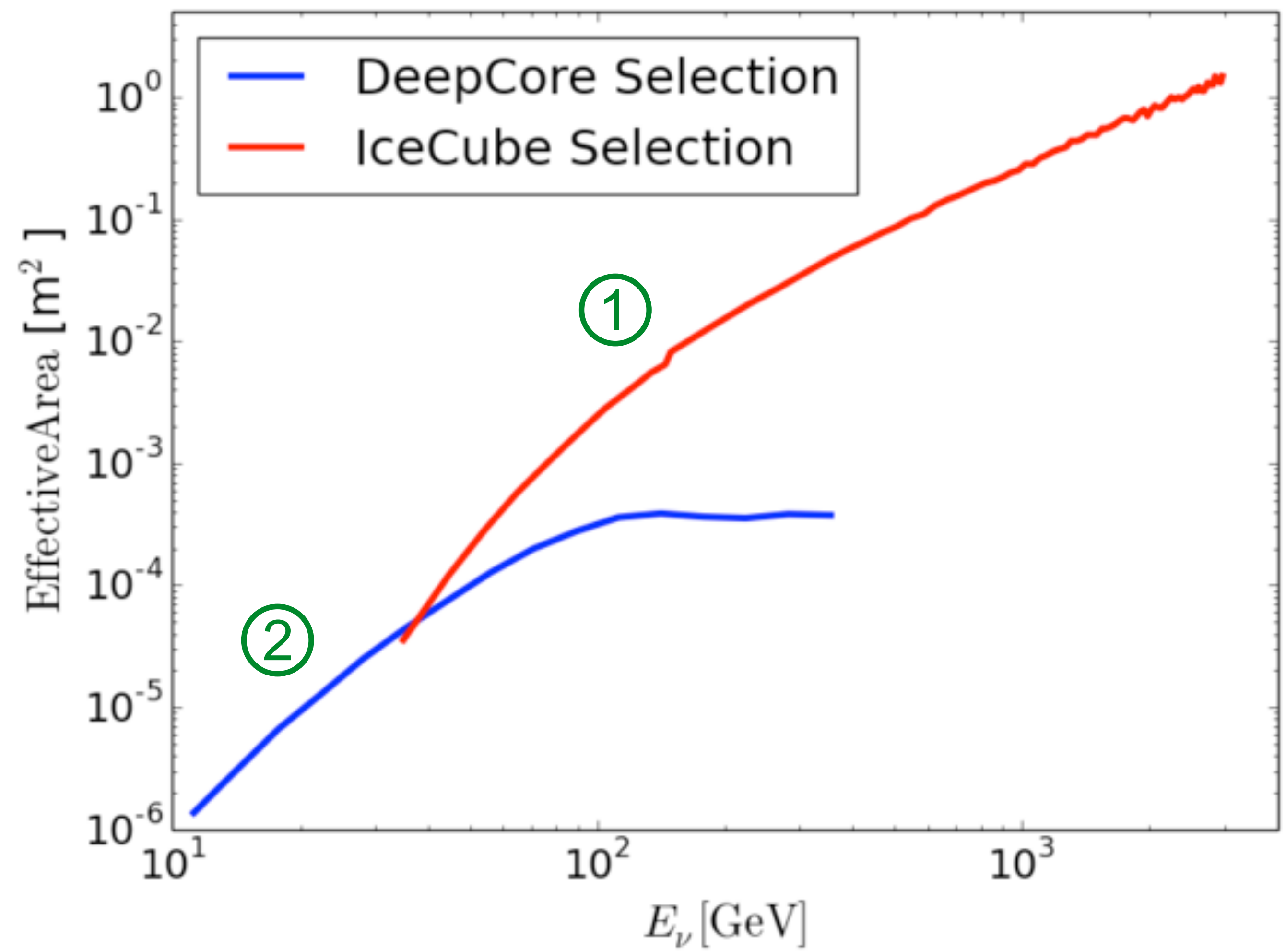
- Three years of data in 86-string configuration used (**May 2011 - May 2014**)
  - Only **up-going** events (Sun below the horizon) results in **532days of livetime**
- Two independent analysis performed
  - ① **IceCube**: Higher energy focus (m_χ > 100GeV)
  - ② **DeepCore**: Low-energy focus (m_χ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



Median angular resolutions

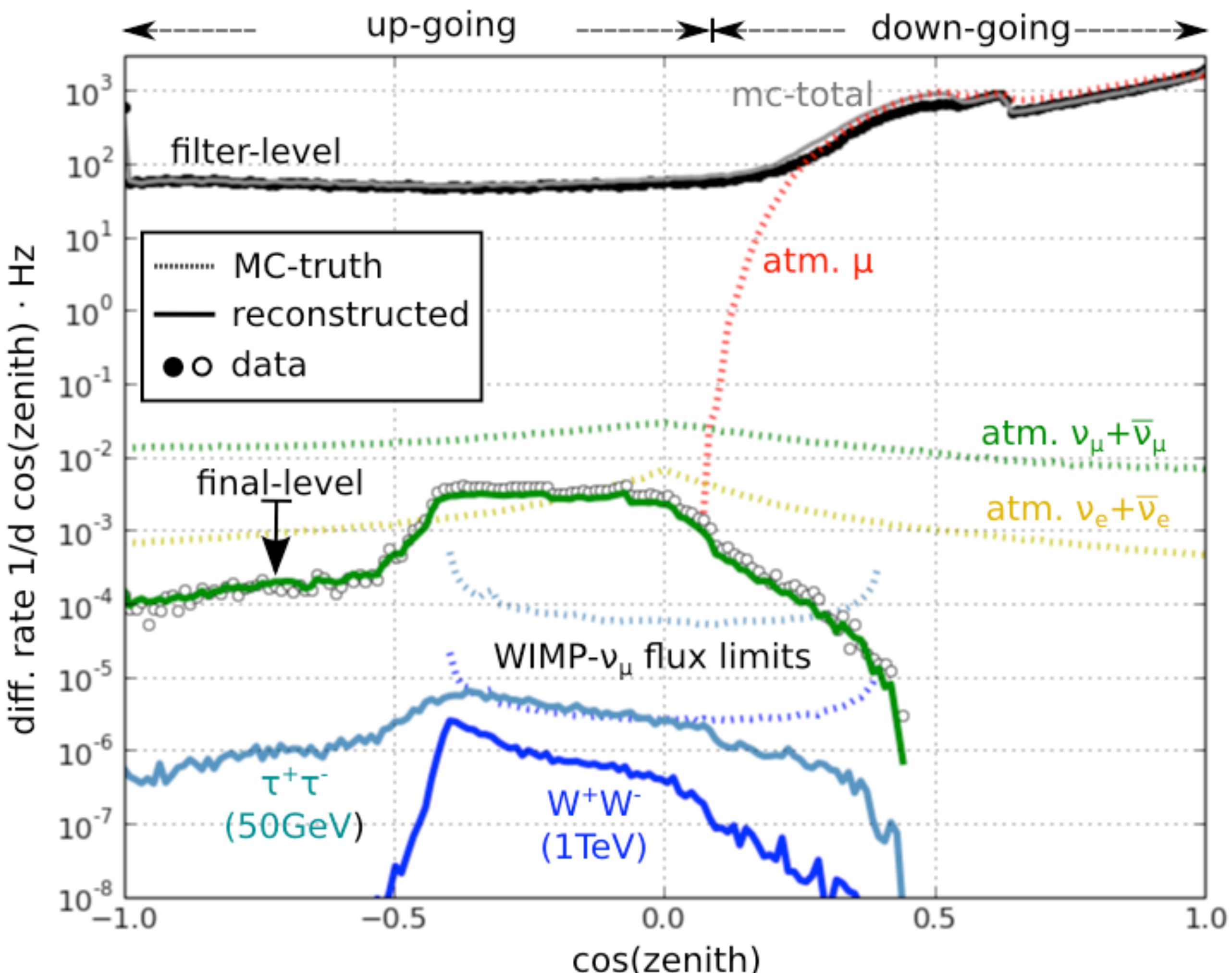


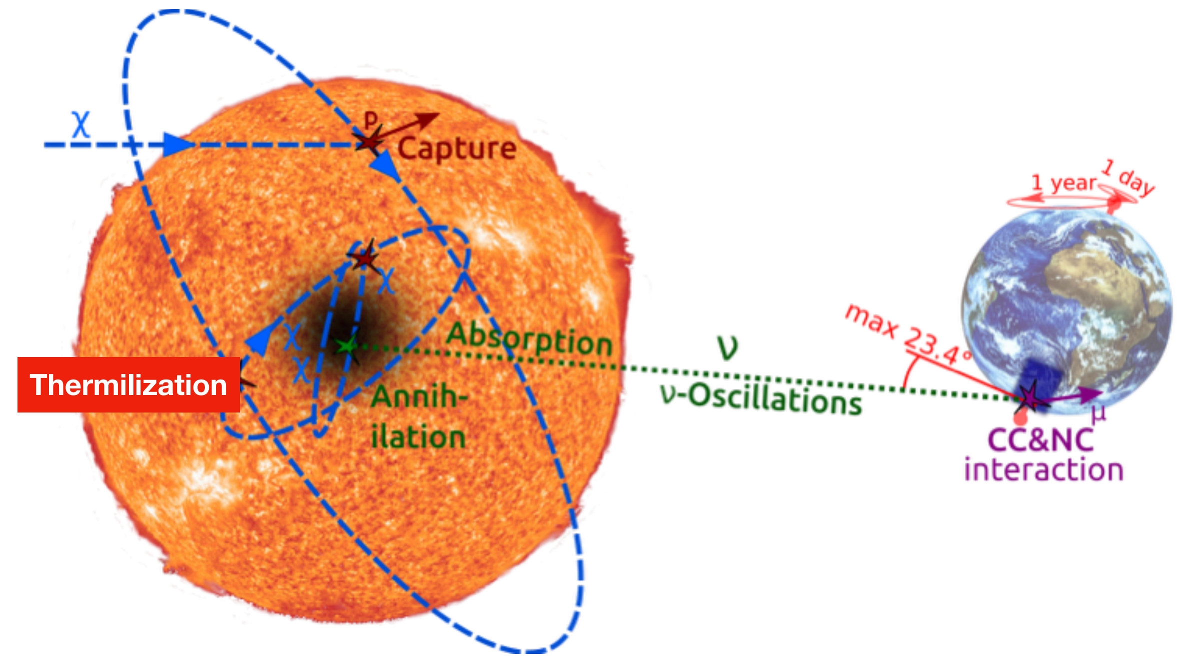
Effective Areas



Search for Dark Matter in the Sun

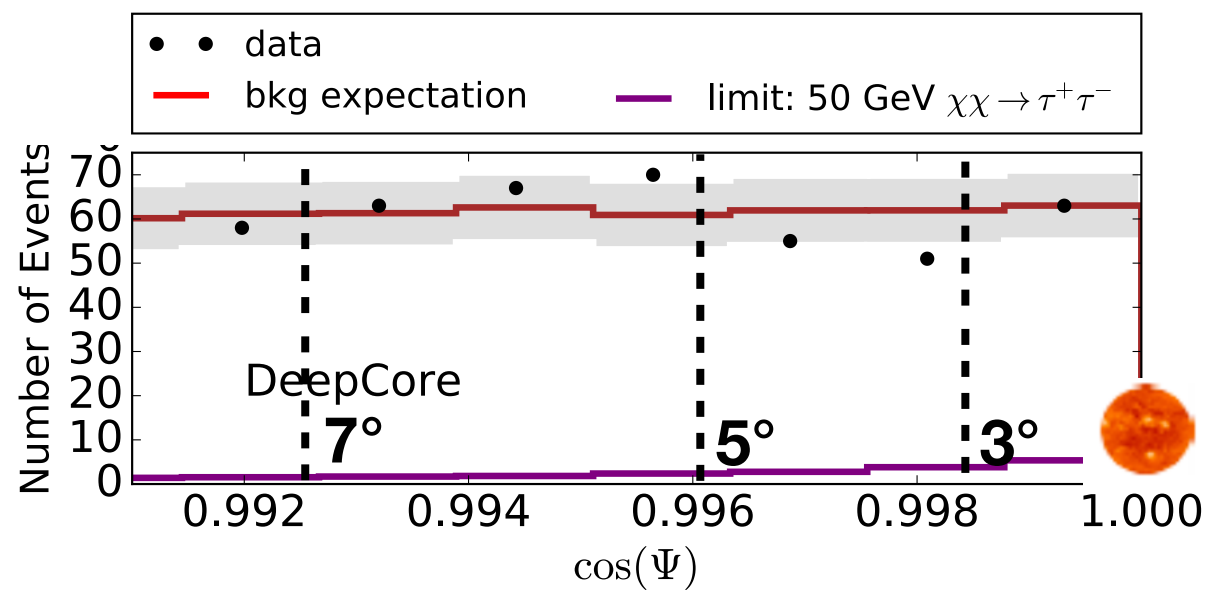
IceCubeColl., arXiv:1612.05949v1





Observed events

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



Signal pdf:

Spectral part

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

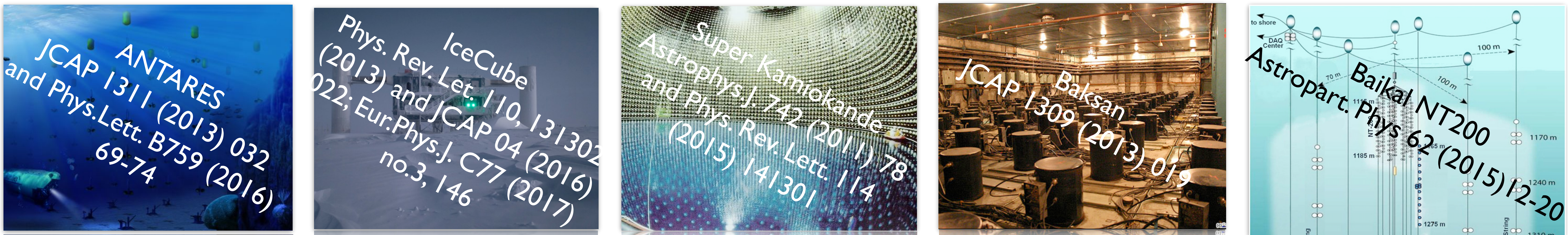
Monovariate Fisher Bingham distribution from directional statistics

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

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

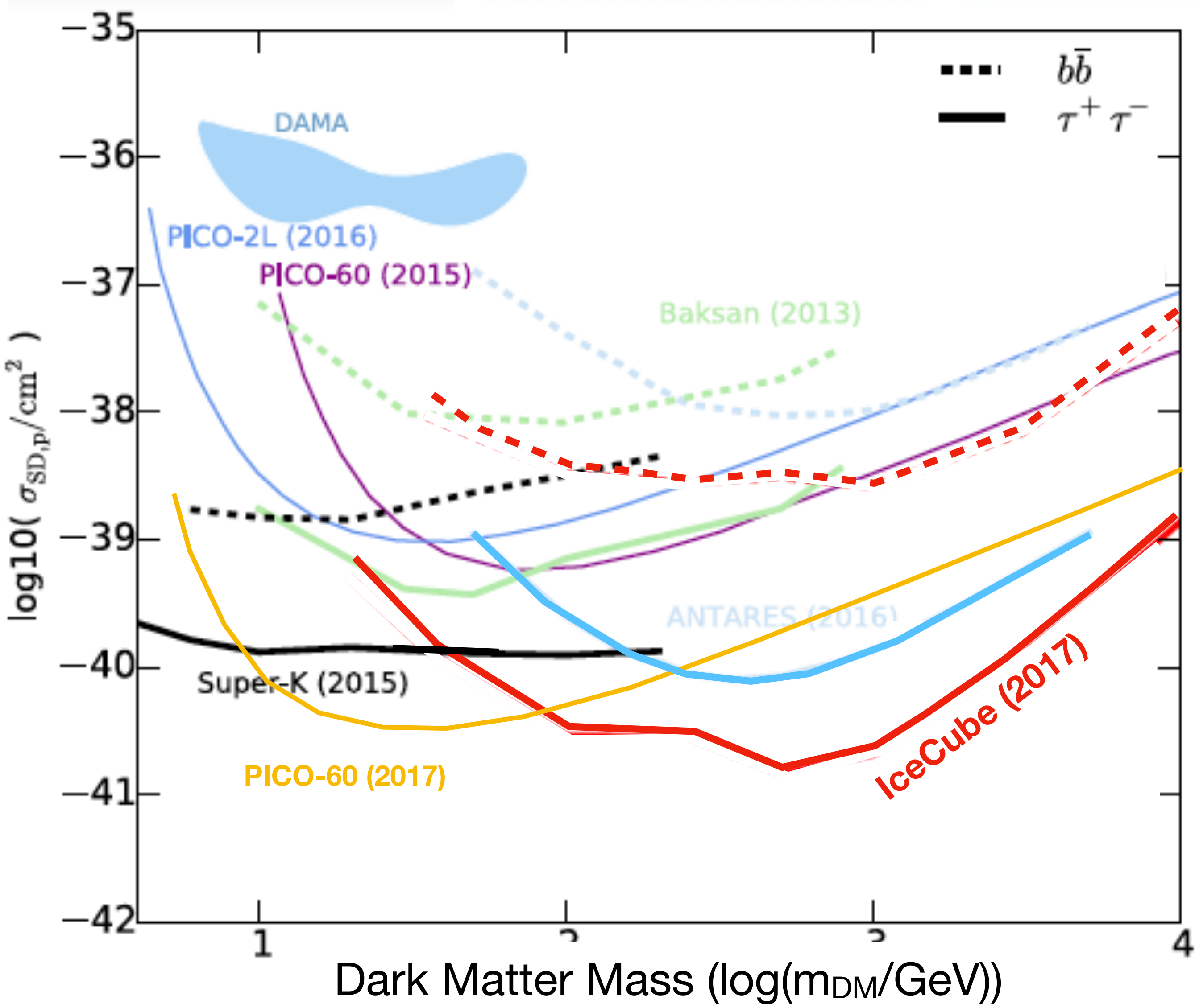
- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Observed events consistent with background only expectations

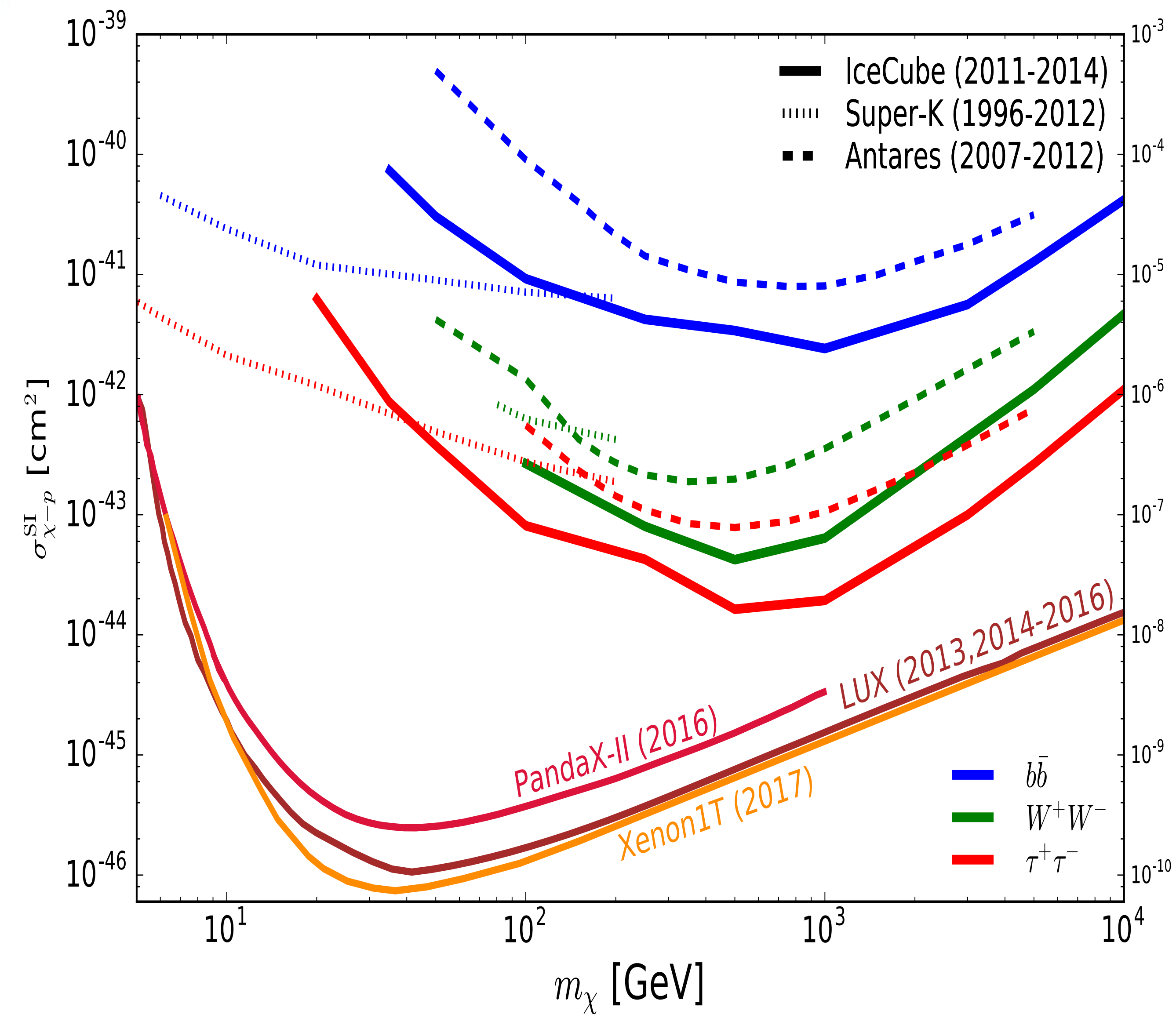
Solar Dark Matter Summary



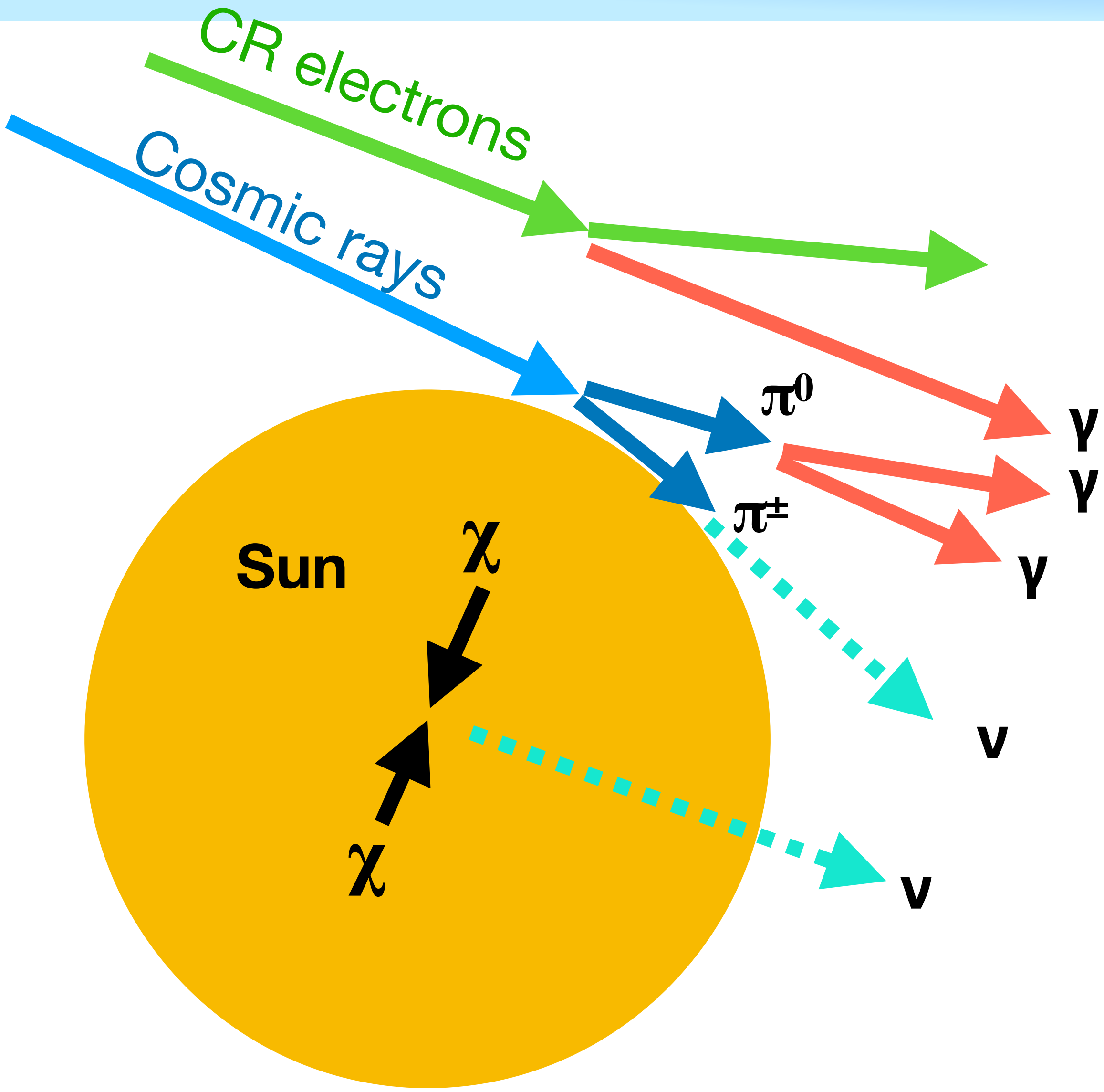
Spin-dependent scattering

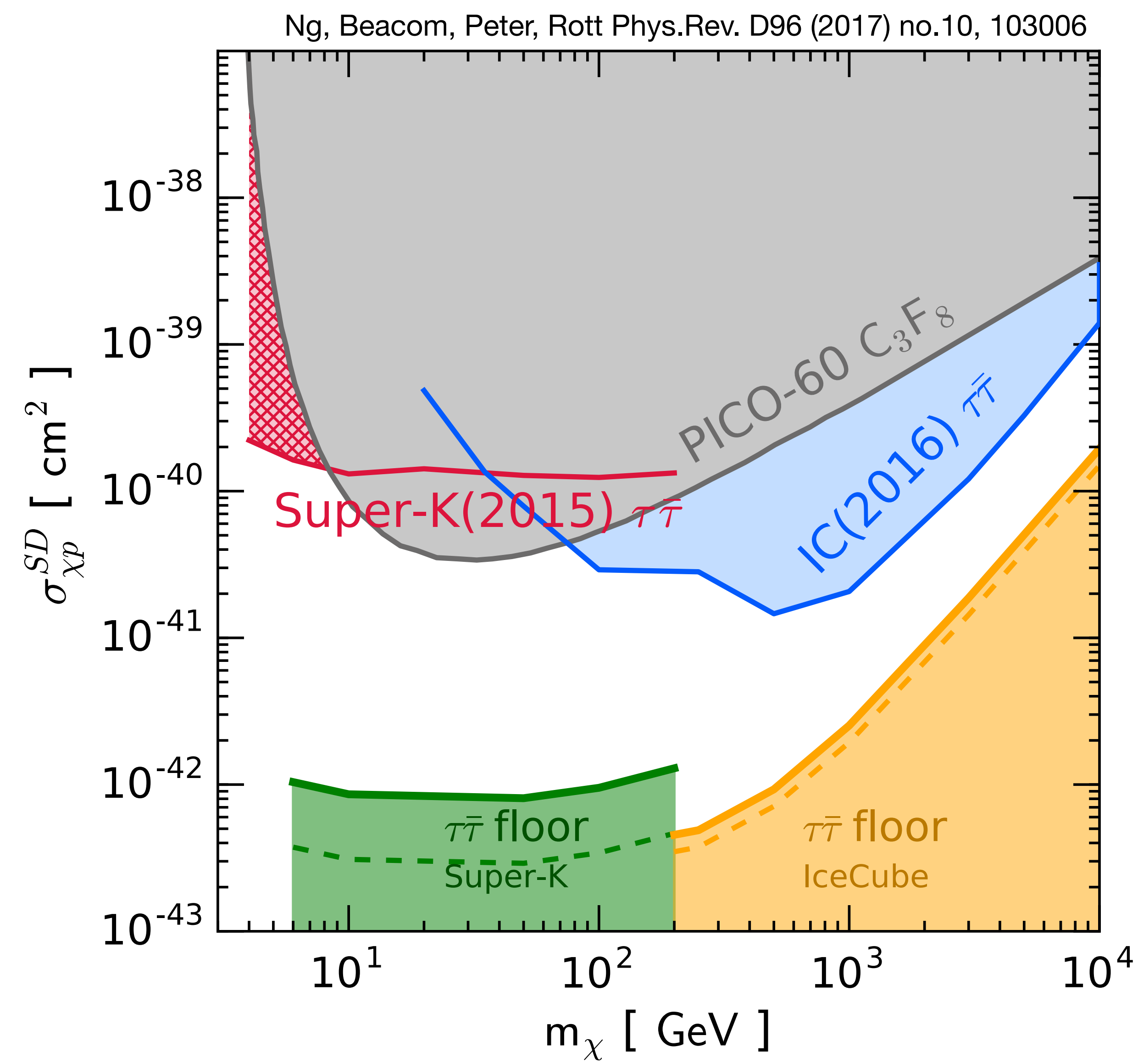
Spin-independent scattering





Solar Atmospheric Neutrino Background





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

Expect ~2events per year

Significant discovery potential

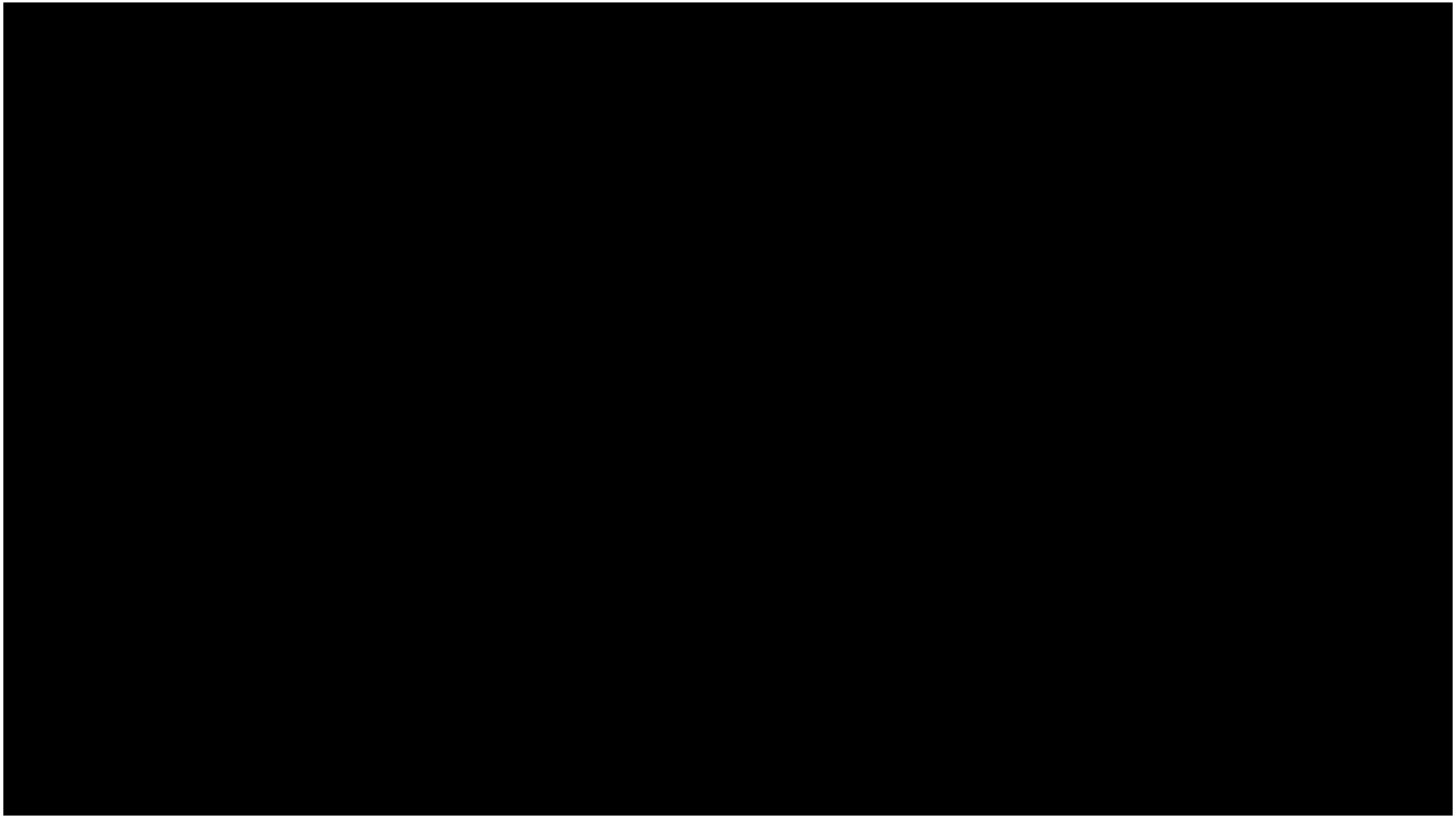
Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

- 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]

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/

Low Energy Neutrinos from the Sun

Low-Energy Neutrinos from the Sun

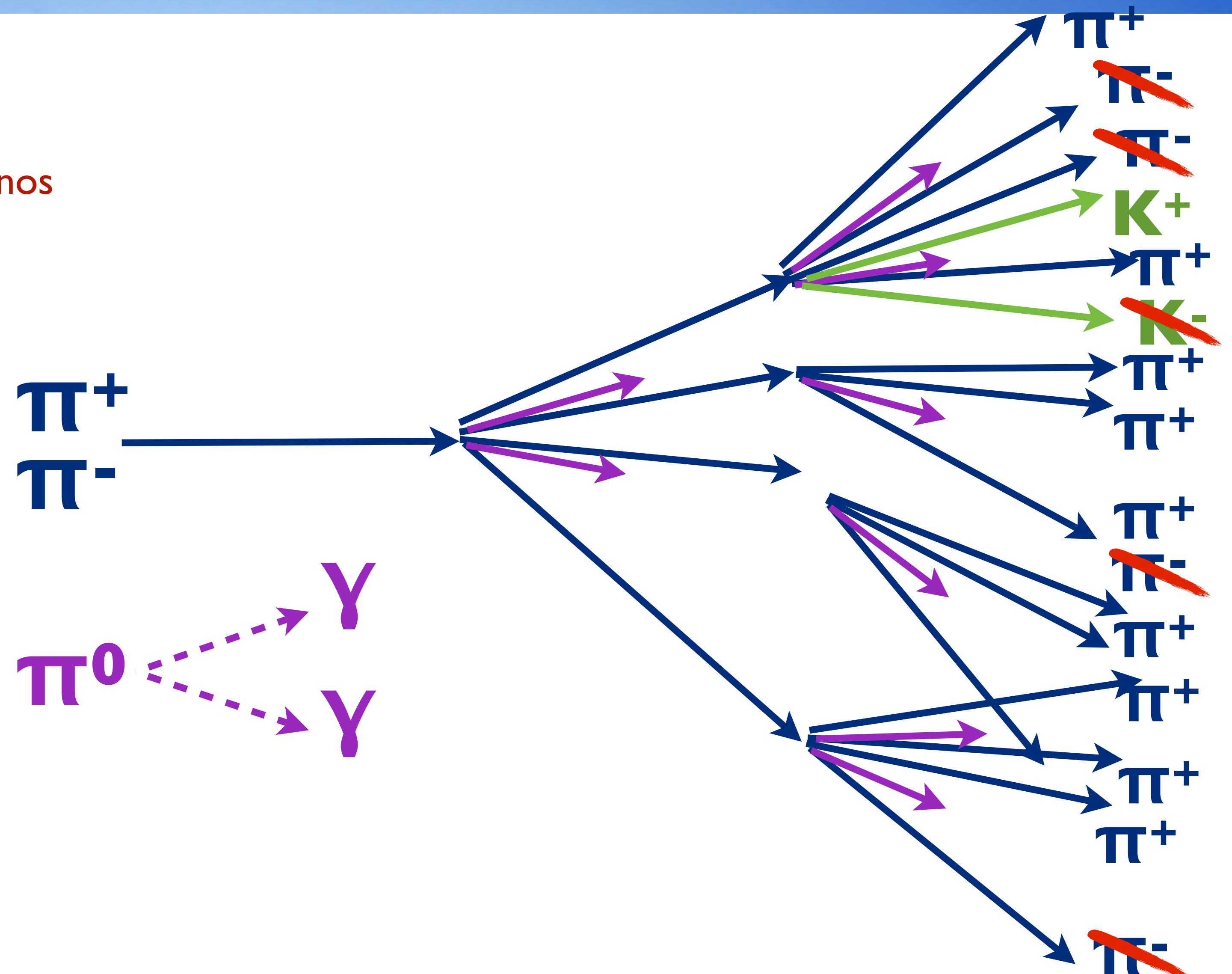
Possible annihilation channels:

qq,gg,cc,ss,bb,tt,W^+W^-, ZZ, $\tau^+\tau^-$,$\mu^+\mu^-$, $\nu\nu$, 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_ν= 29.8MeV

$K^+ \rightarrow \nu_\mu \mu^+$ E_ν=235.5MeV

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

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

π^0

- Lifetime too short to interact

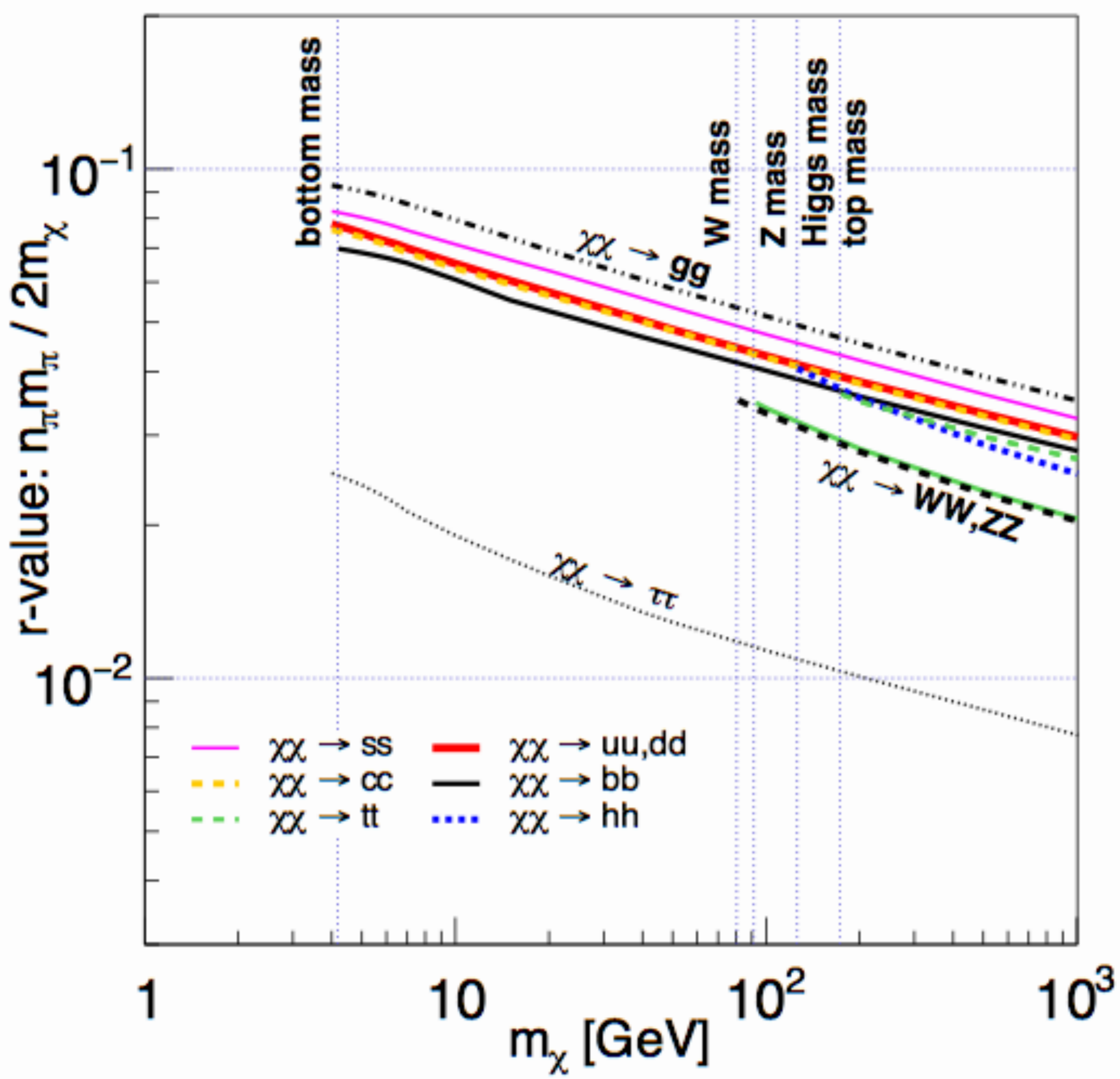
π^-

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

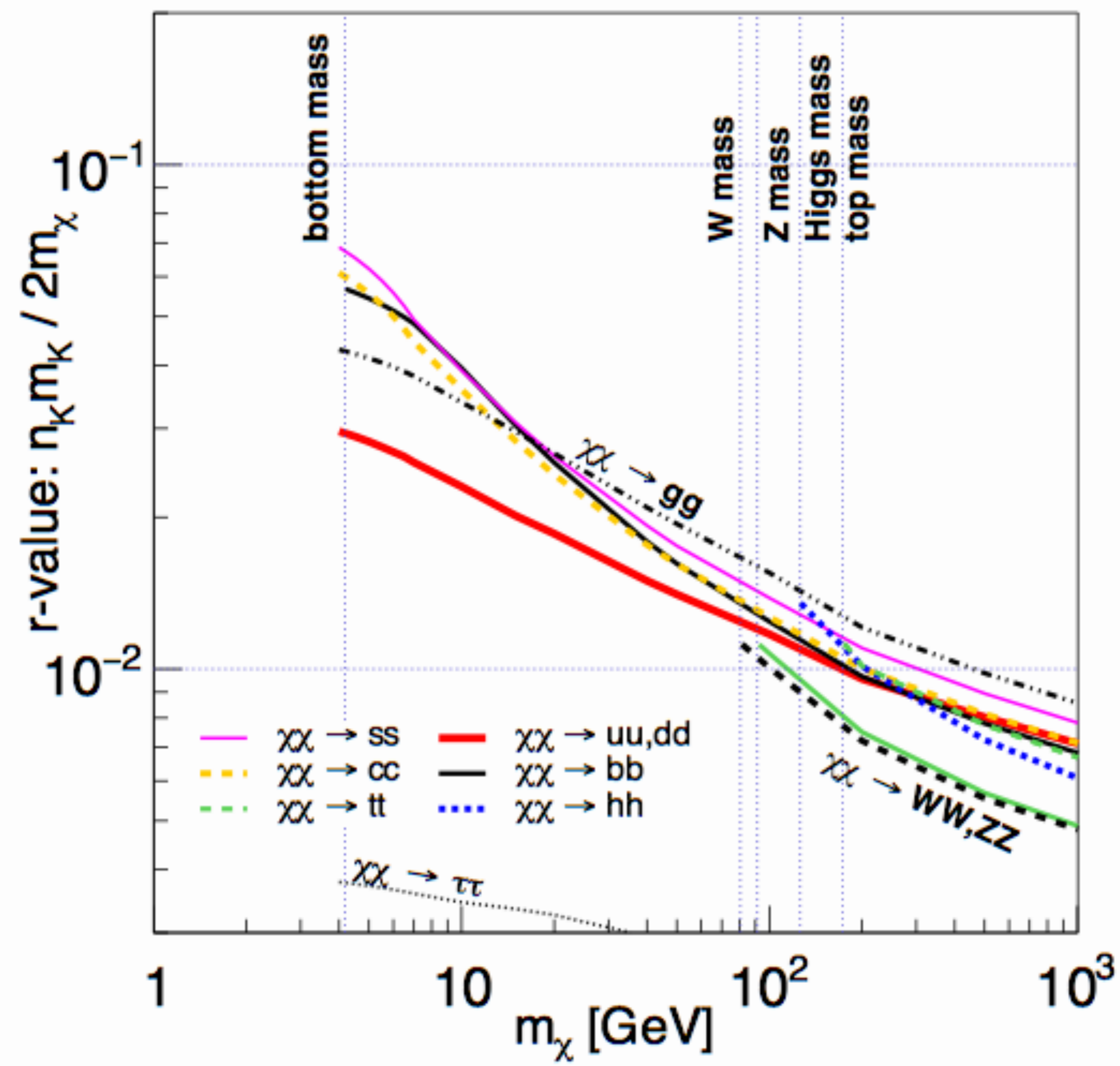
C.Rott, S.In, J.Kumar, D.Yaylali JCAP11(2015)039

Pion and Kaon yields

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

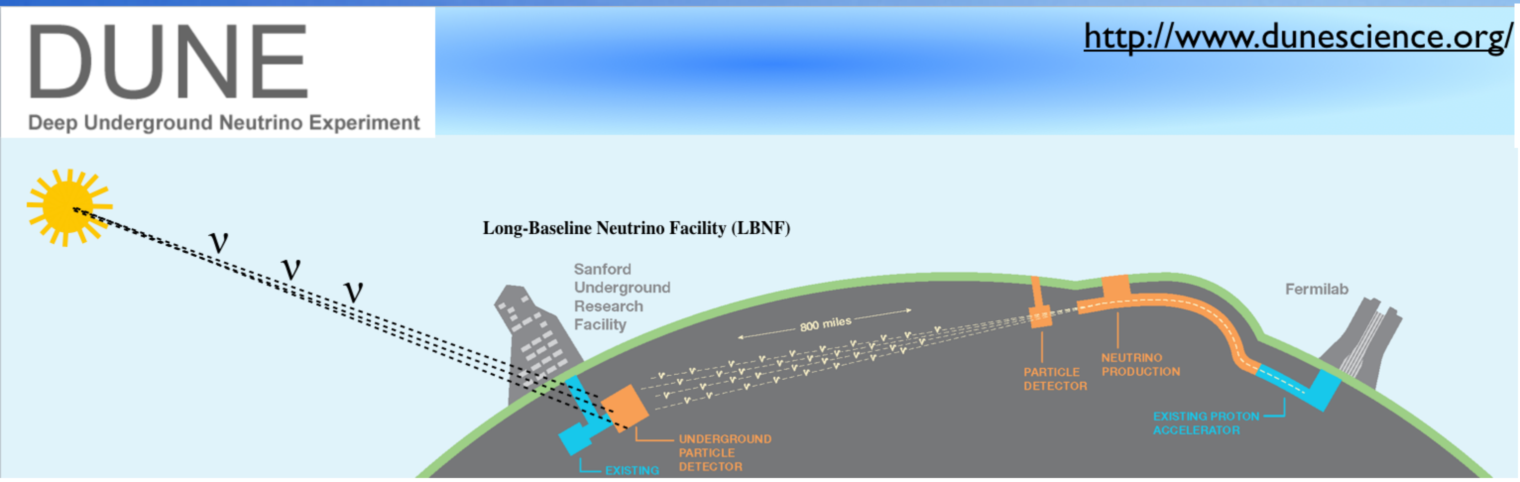


K^+ r-value - fraction of center-of-mass energy which goes into K^+

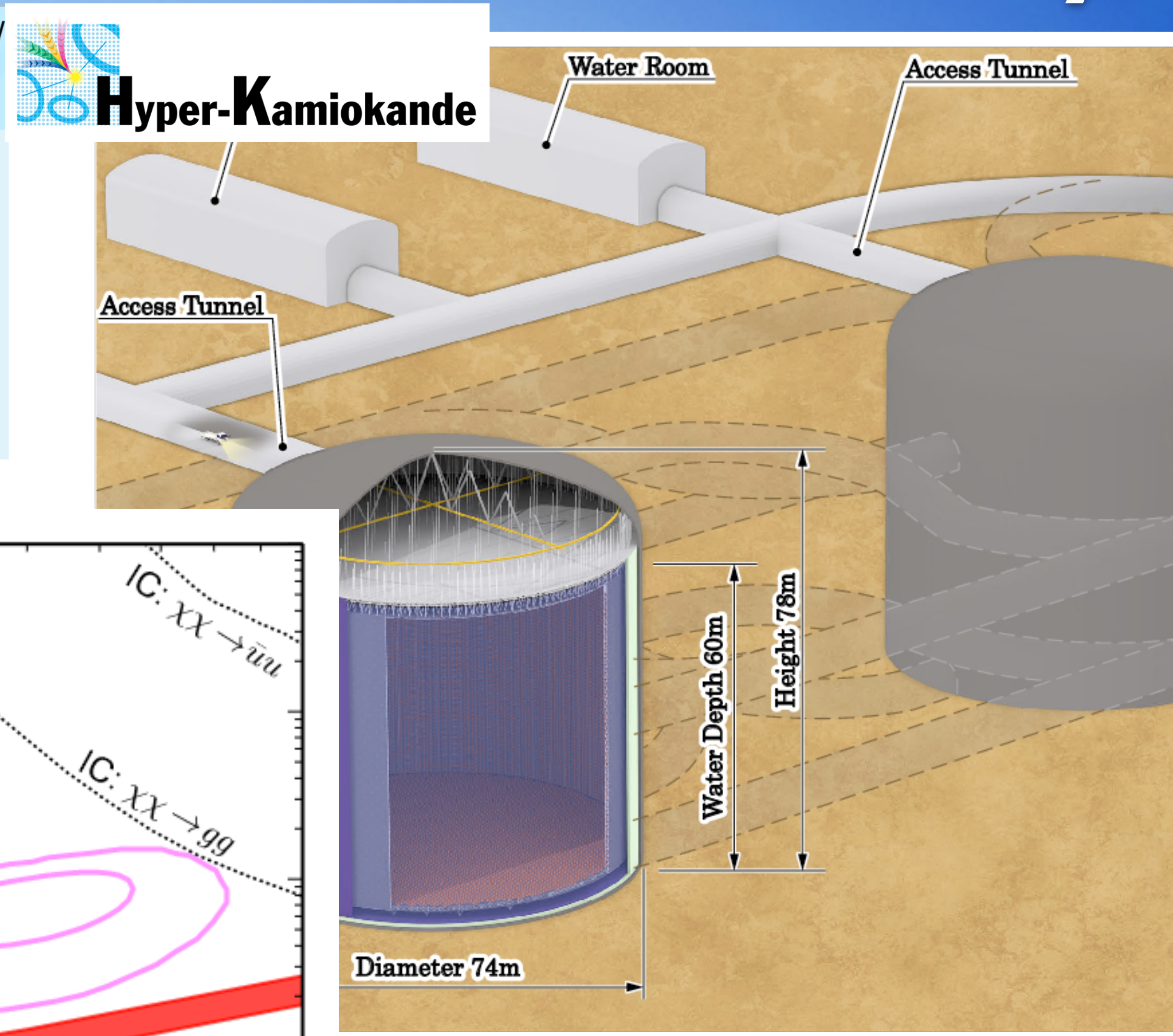


For low dark matter masses difference between flux from stopped pion and kaon decay at rest can be used to disentangle annihilation final states

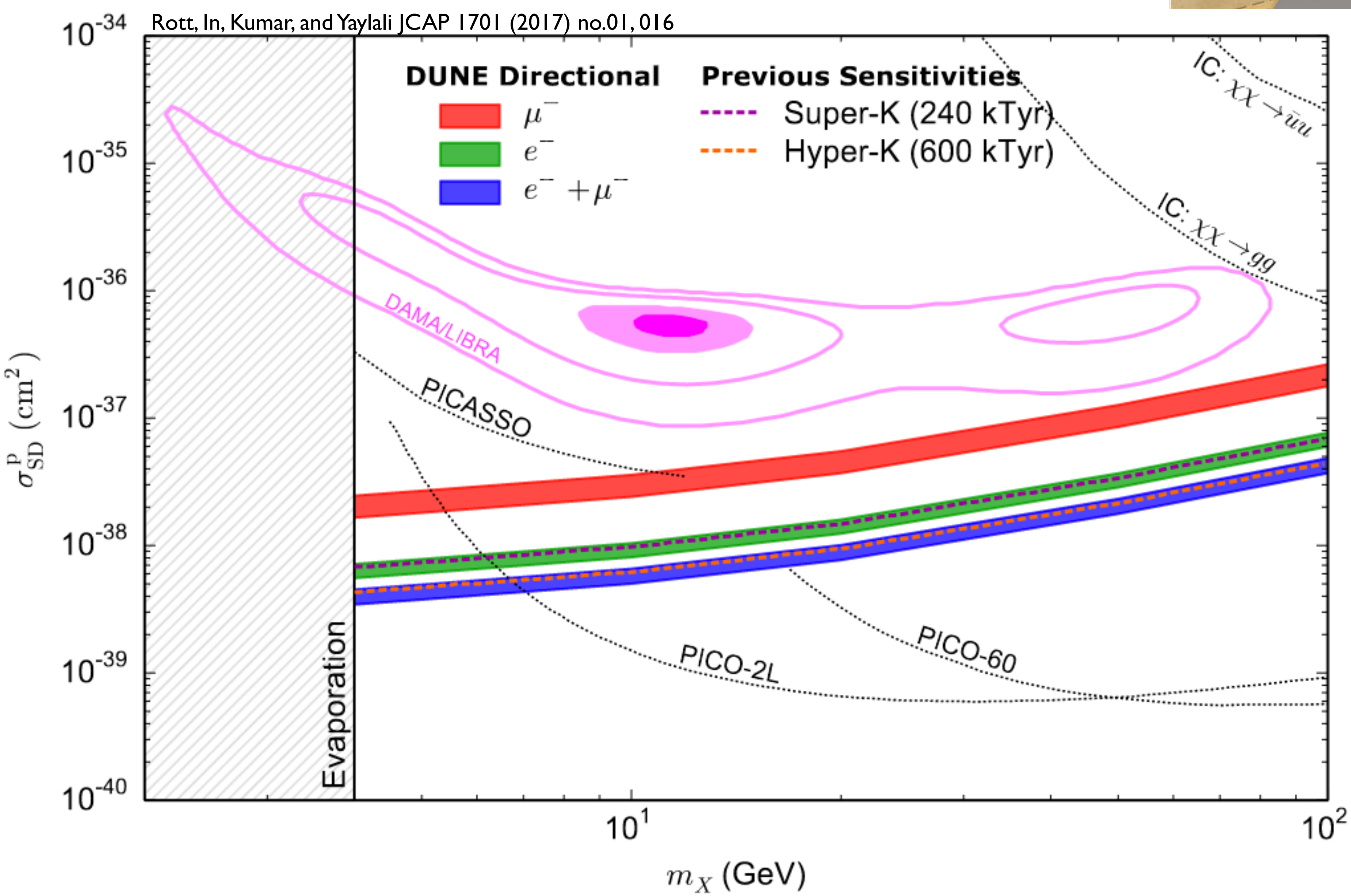
Sensitivity

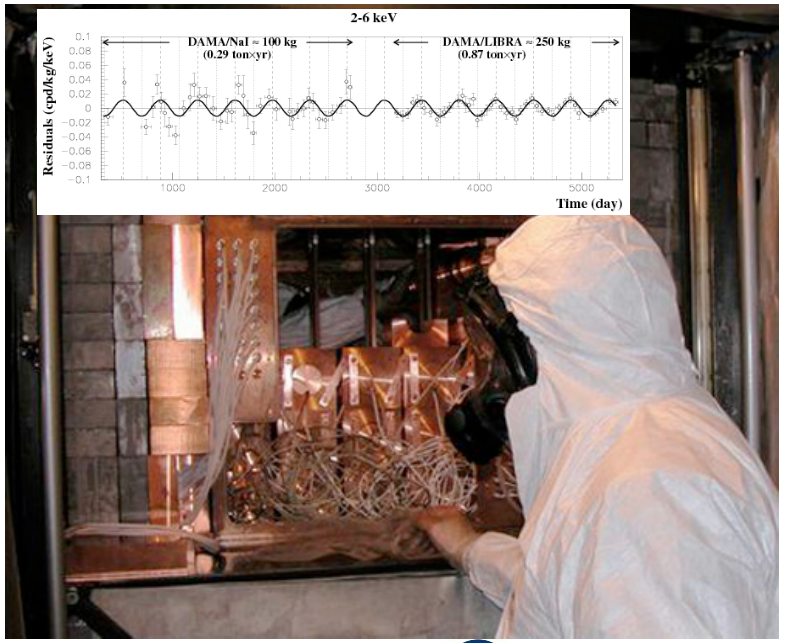


http://www.dunescience.org/



Rott, In, Kumar, and Yaylali JCAP 1701 (2017) no.01, 016

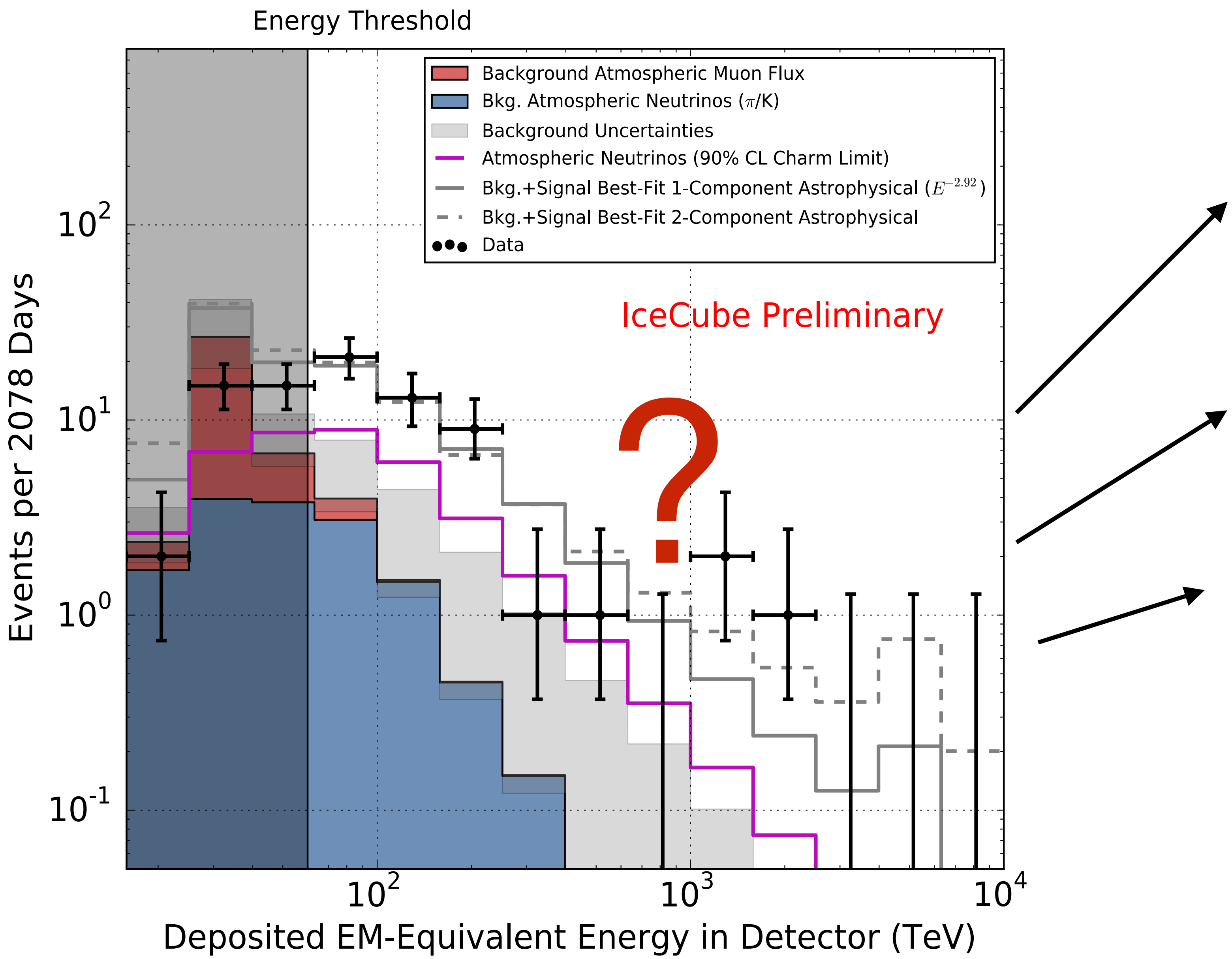




Future Plans for IceCube …

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 ?

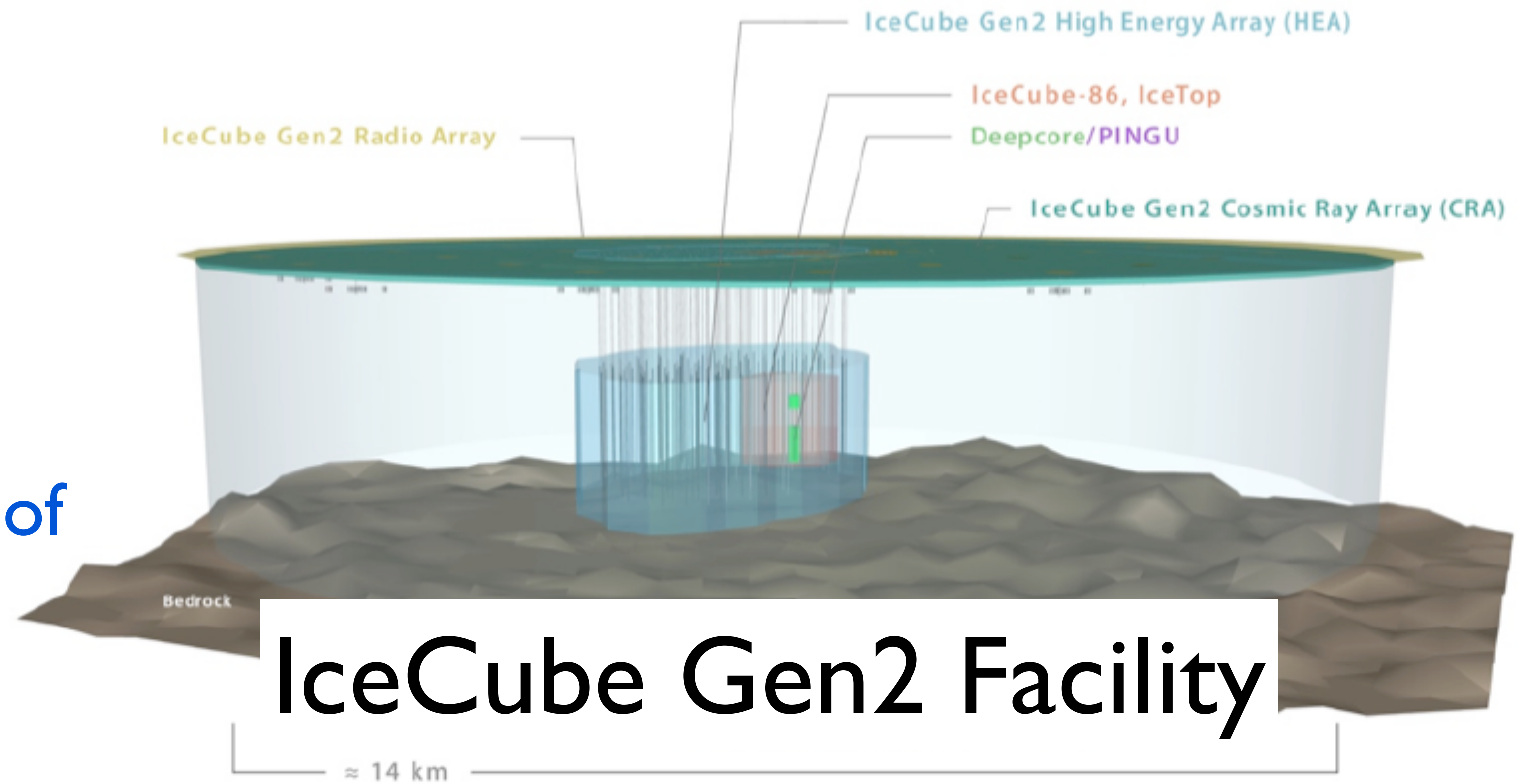


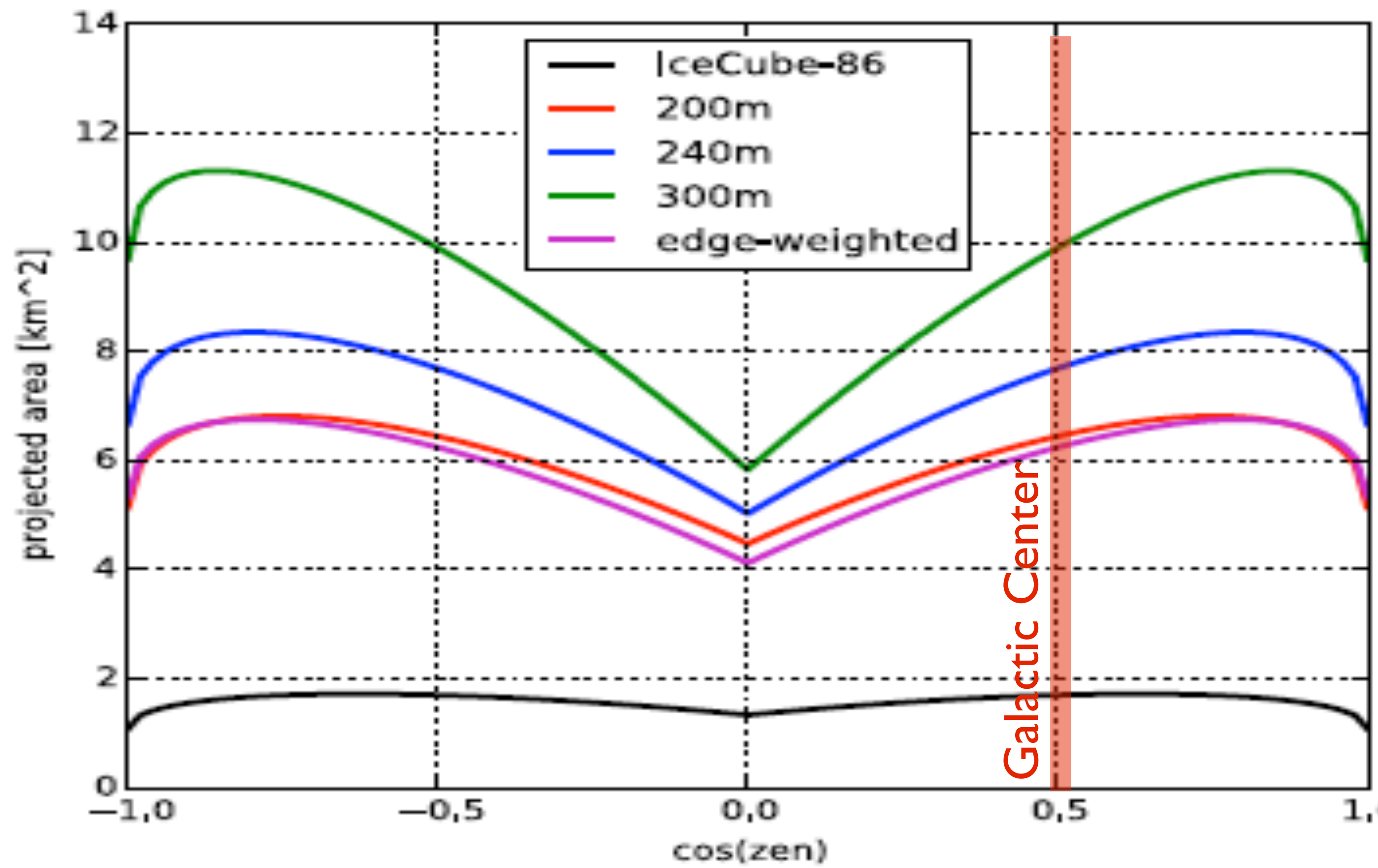
- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy right-handed neutrino dark matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and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

Next generation - IceCube Gen2 Facility

IceCube Gen2 arXiv:1412.5106

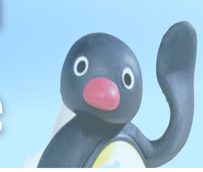
- IceCube has provided an amazing sample of astrophysical neutrino events, but interpretation is still limited by small statistics
    - Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
- Where are the point sources?
- What is the flavor composition?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



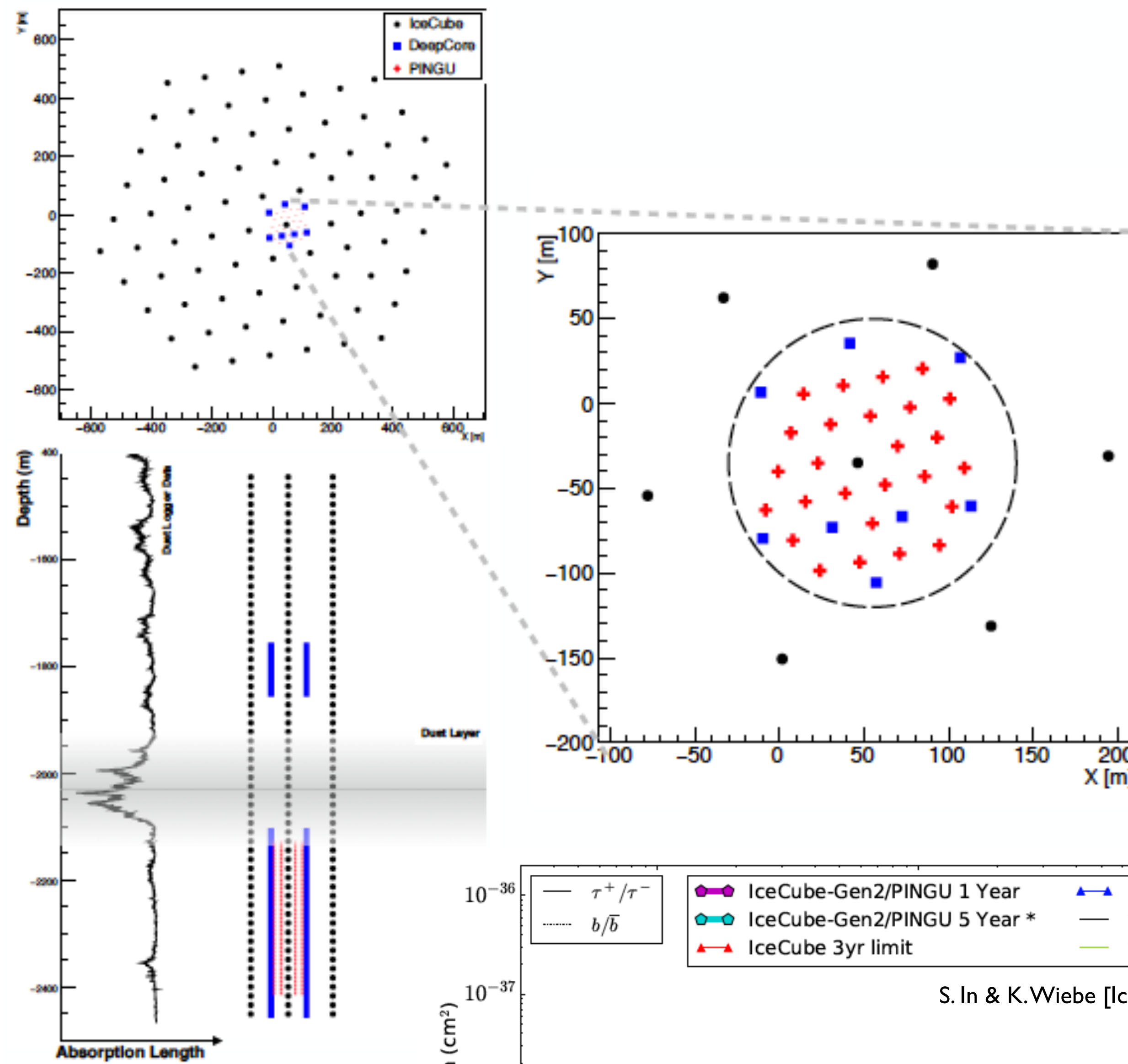


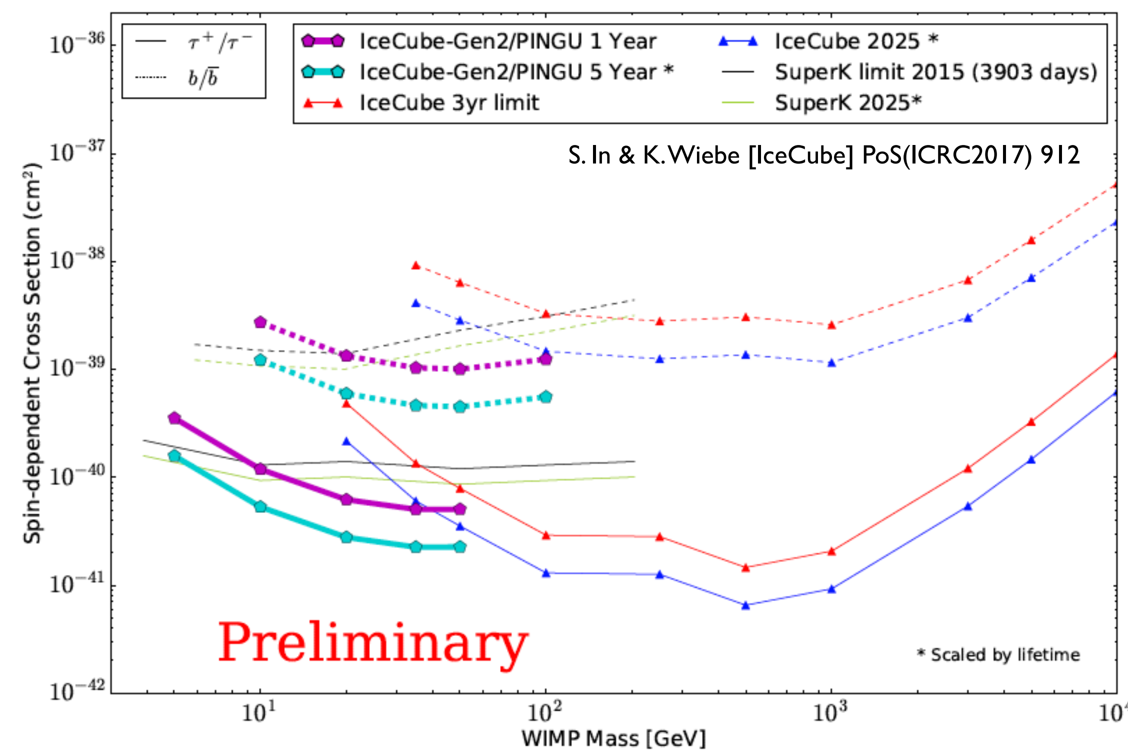
PINGU - Precision IceCube Next Generation Upgrade

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



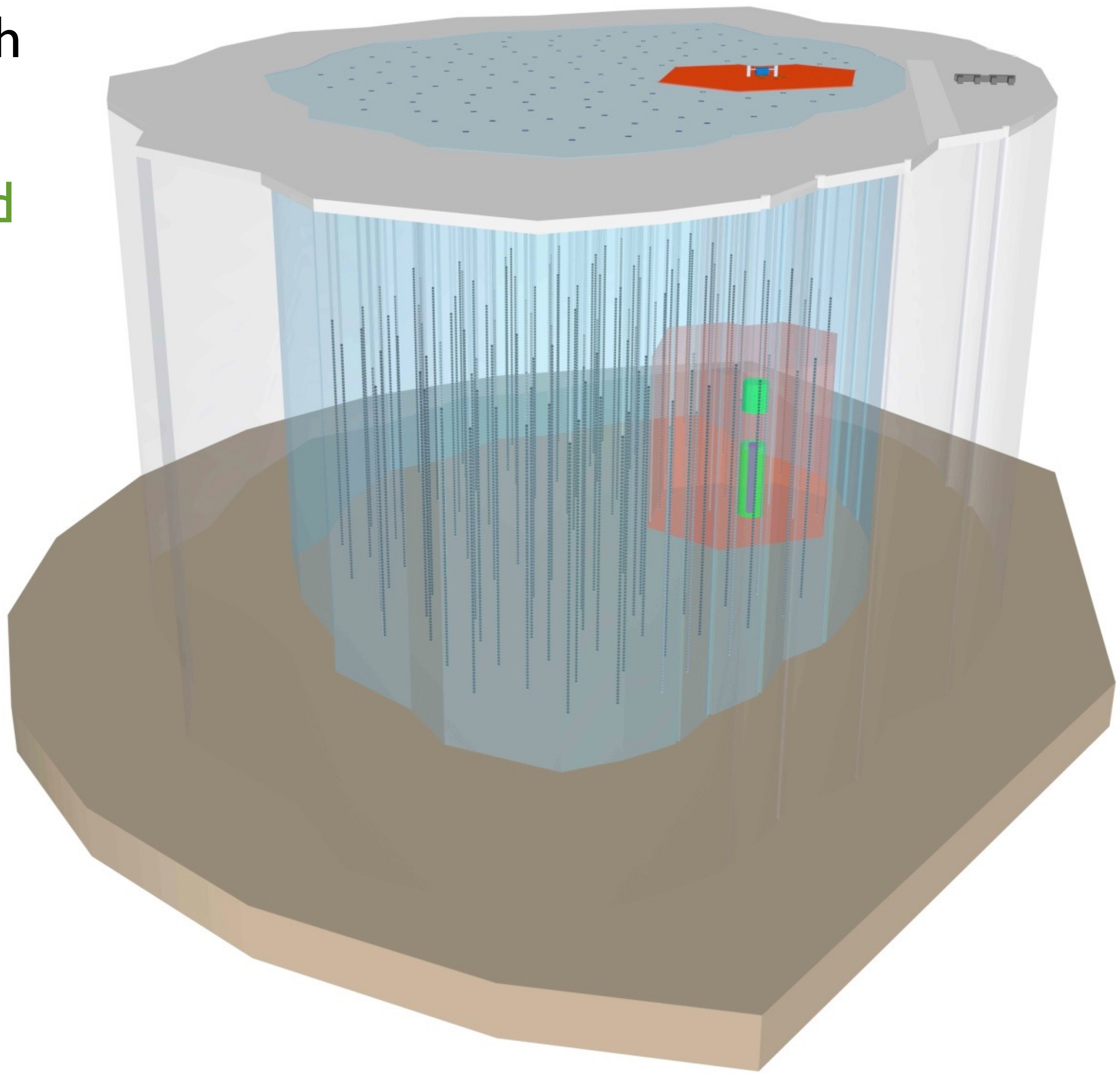
- PINGU upgrade plan
  - Instrument a volume of about 5MT with 20-26 strings
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, ...)
  - Test low mass dark matter models





Conclusions

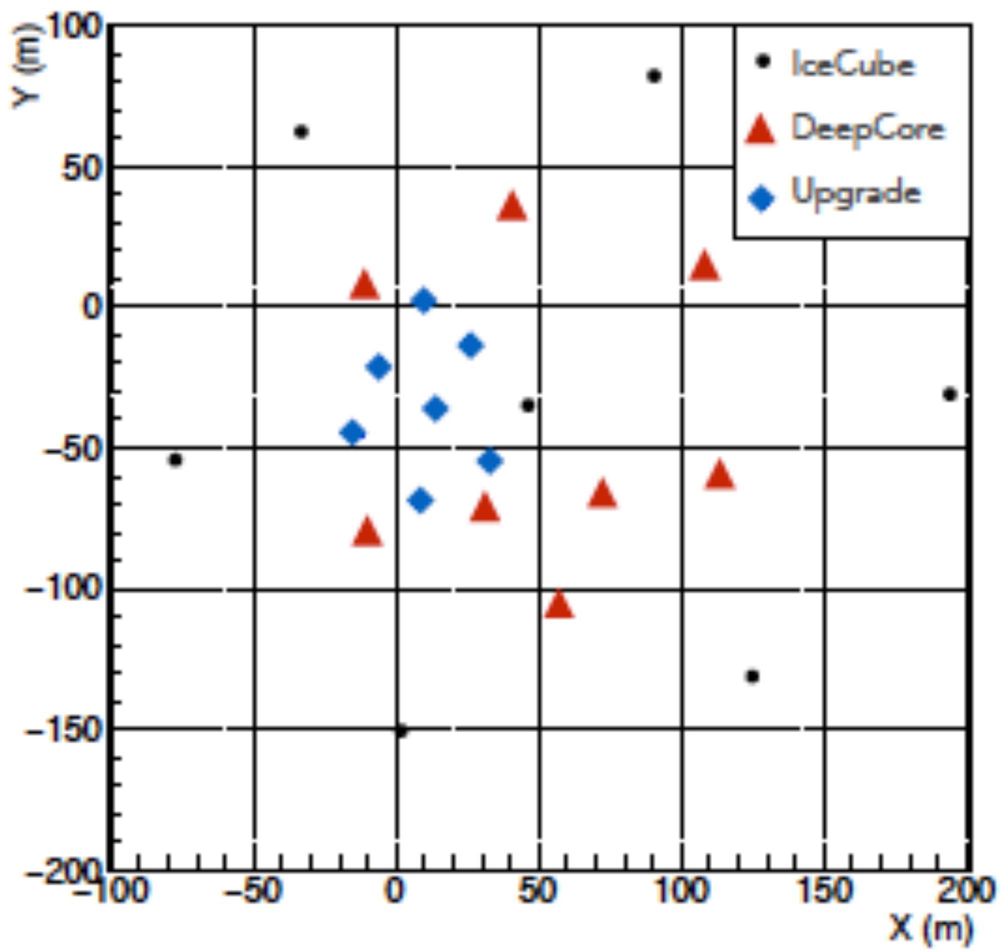
- Striking DM signatures might provide high discovery potential for indirect searches
- Models motivated by positron excess and gamma-ray observations can and have been tested with neutrino telescopes
- Lifetimes of heavy decaying dark matter can be constrained to 10^{28}s using neutrino signals
- Neutrino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

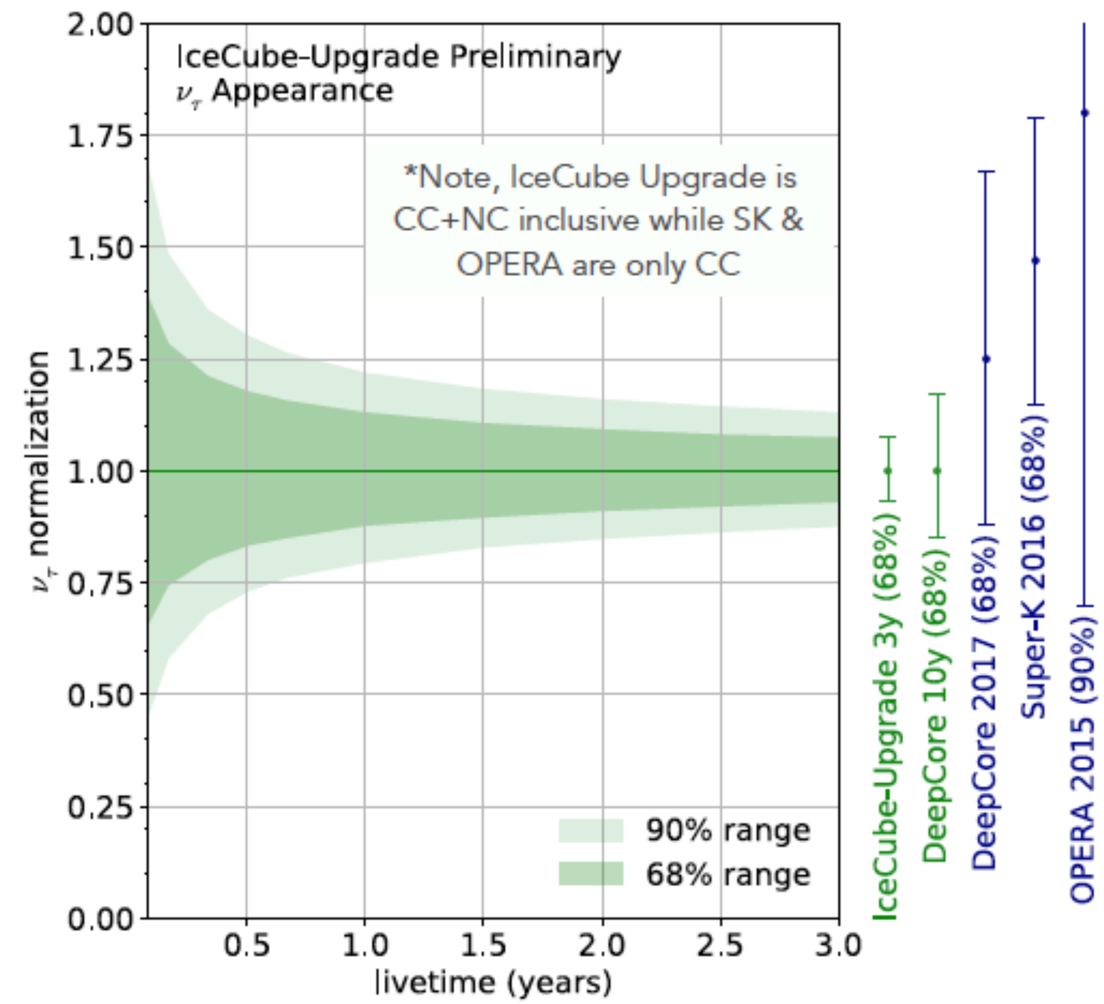


Thanks !

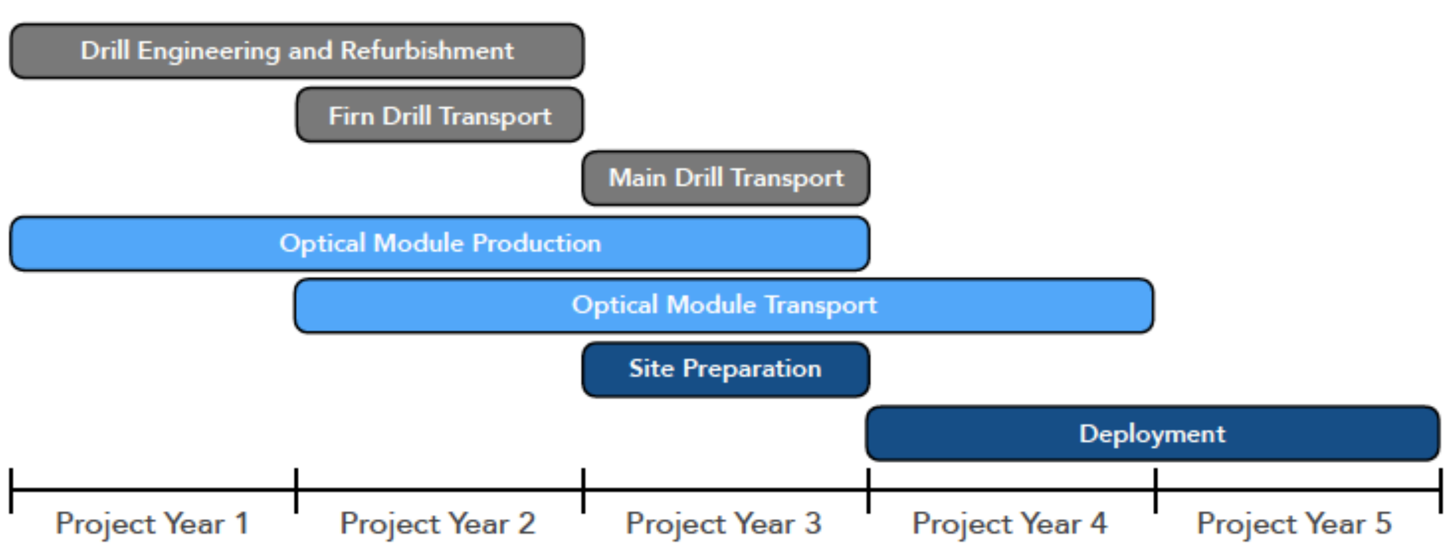
The IceCube Upgrade

"The IceCube Upgrade" ~7strings



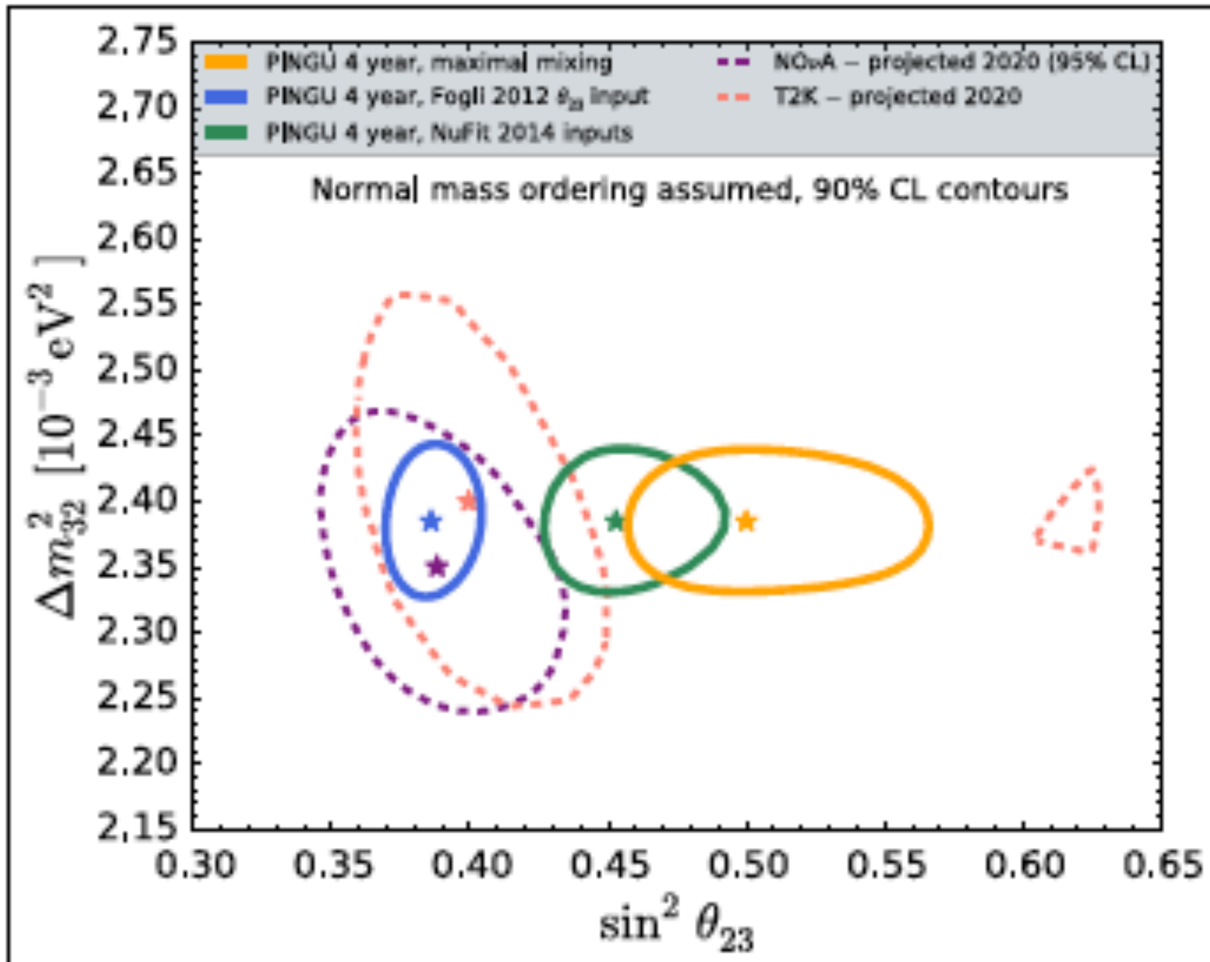


First step to restart South Pole activities
- Tau neutrino appearance
- Calibration devices
- Platform to test new technologies



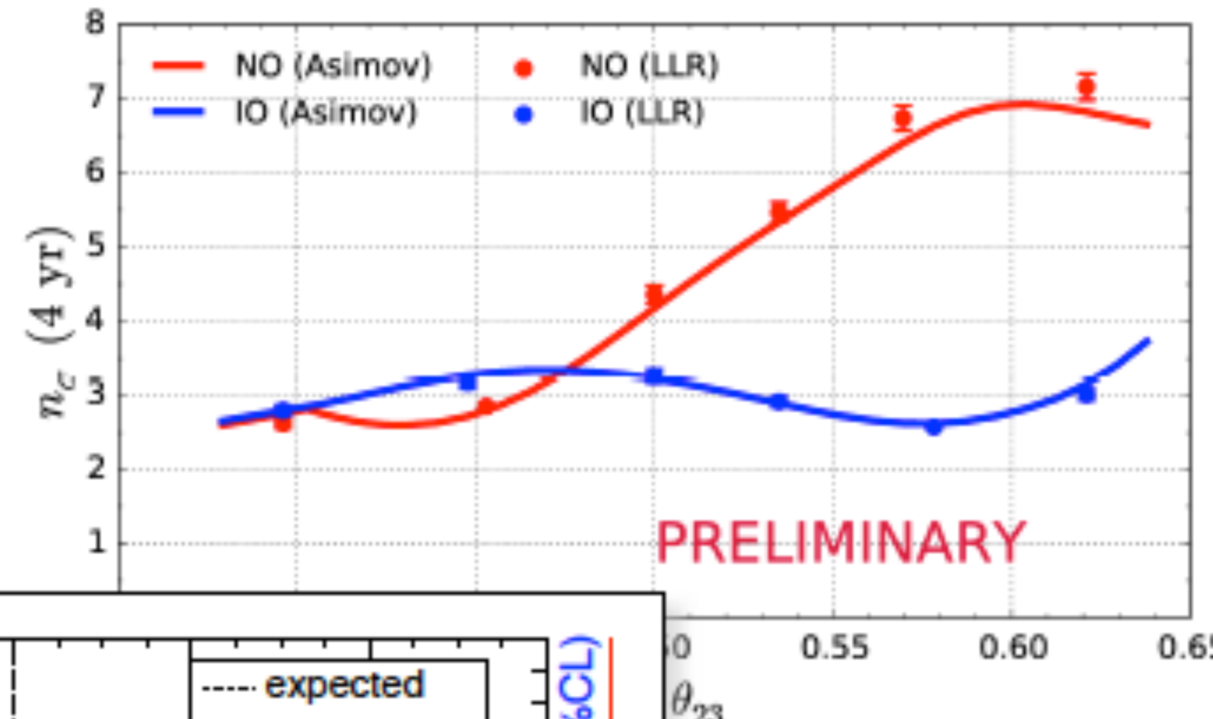
see also:
- PINGU LOI arXiv:1412.5106

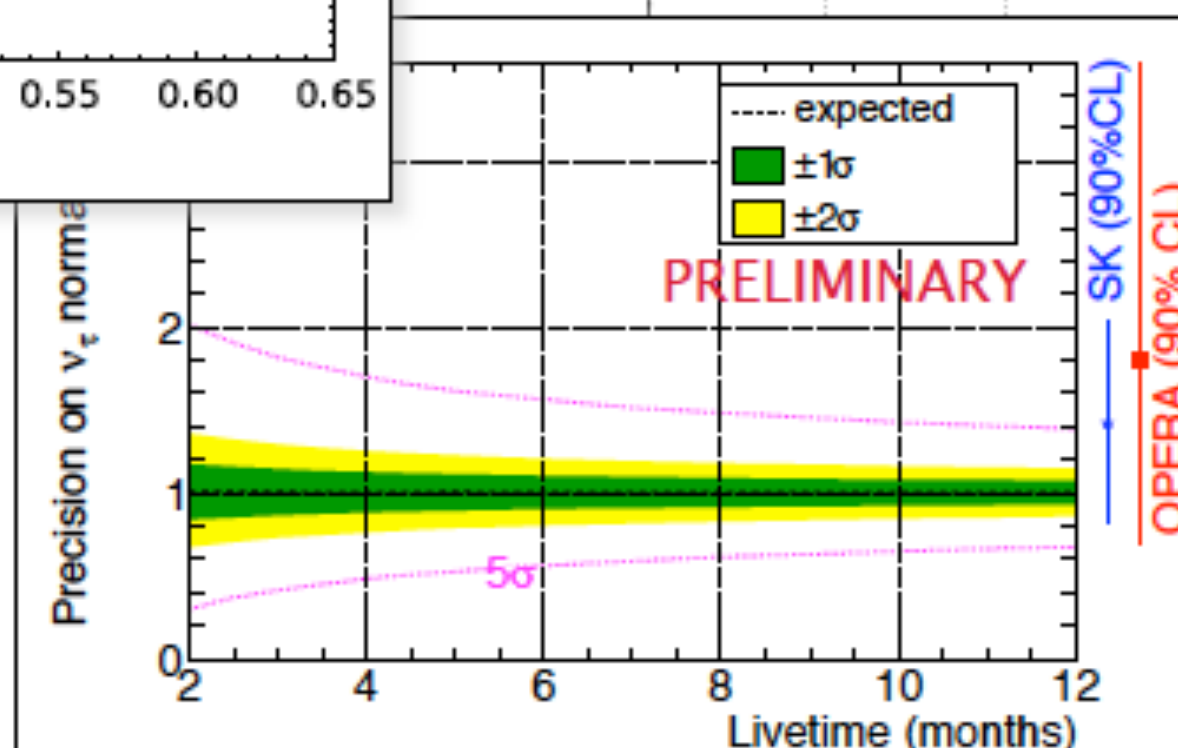
Neutrino Physics with PINGU



Measurement of mixing parameters with different method/energy range – Excellent sensitivity to octant of θ_{23}

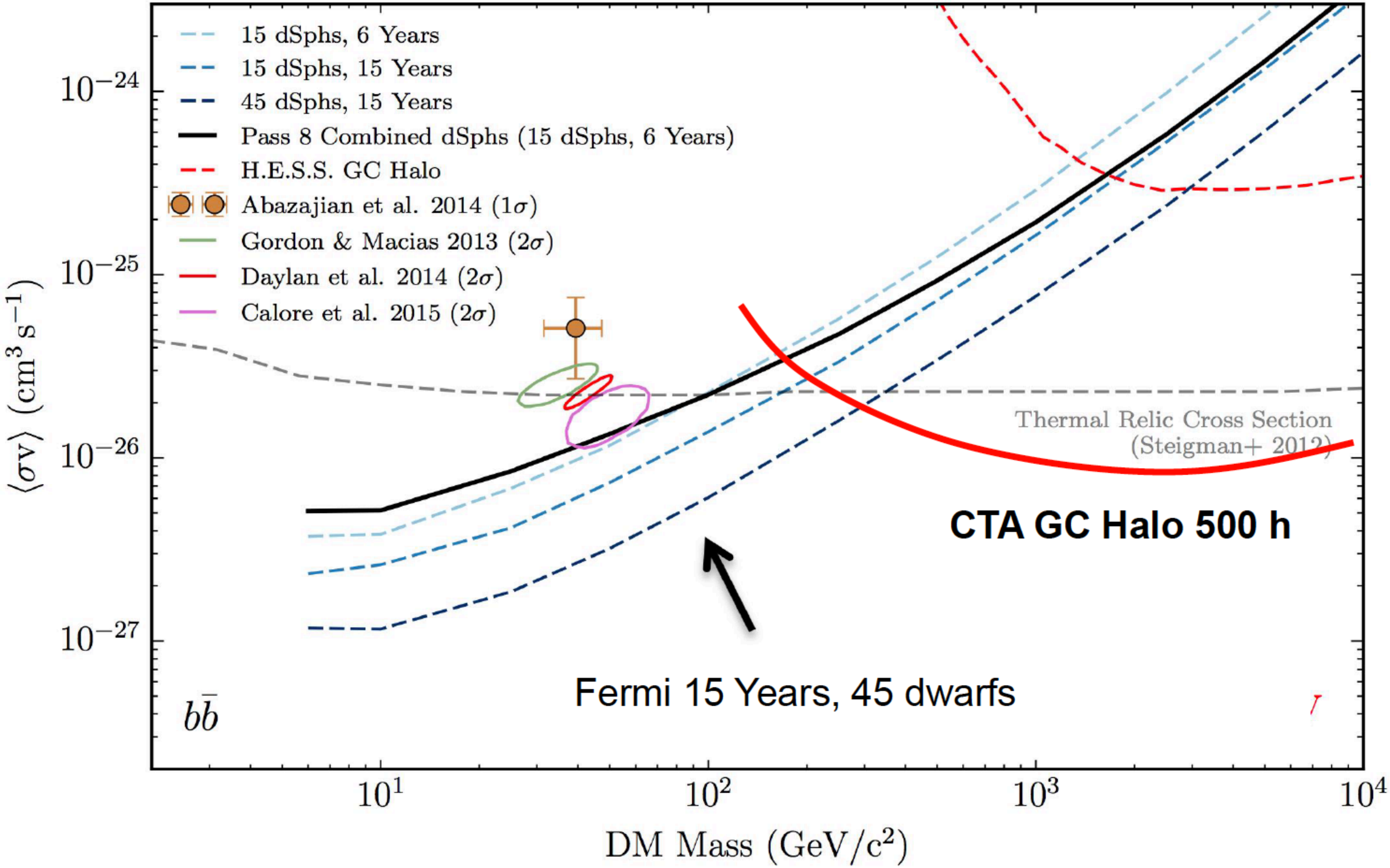
Determination of the neutrino mass ordering



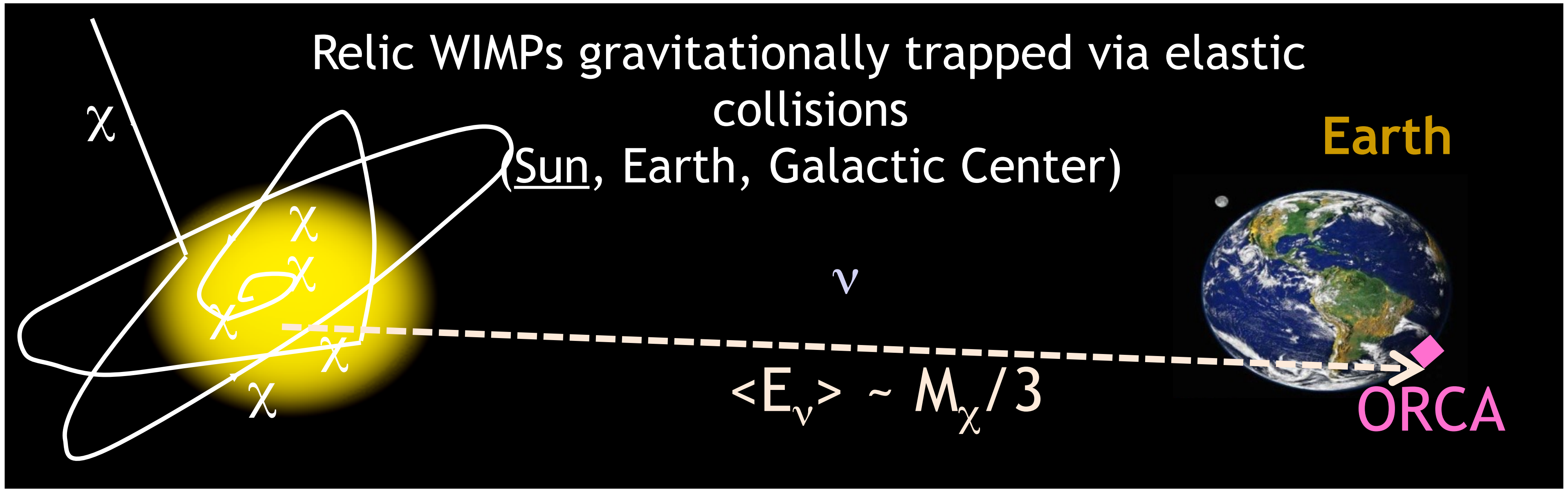


Precision measurement of ν_τ appearance – probe unitarity of PMNS matrix

CTA


15 dSphs, 6 Years
15 dSphs, 15 Years
45 dSphs, 15 Years
Pass 8 Combined dSphs (15 dSphs, 6 Years)
H.E.S.S. GC Halo
Abazajian et al. 2014 (1σ)
Gordon & Macias 2013 (2σ)
Daylan et al. 2014 (2σ)
Calore et al. 2015 (2σ)
Thermal Relic Cross Section
(Steigman+ 2012)
CTA GC Halo 500 h
Fermi 15 Years, 45 dwarfs
$b\bar{b}$
$\langle \sigma v \rangle$ (cm^3 s^{-1})
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4
DM Mass (GeV/c^2)

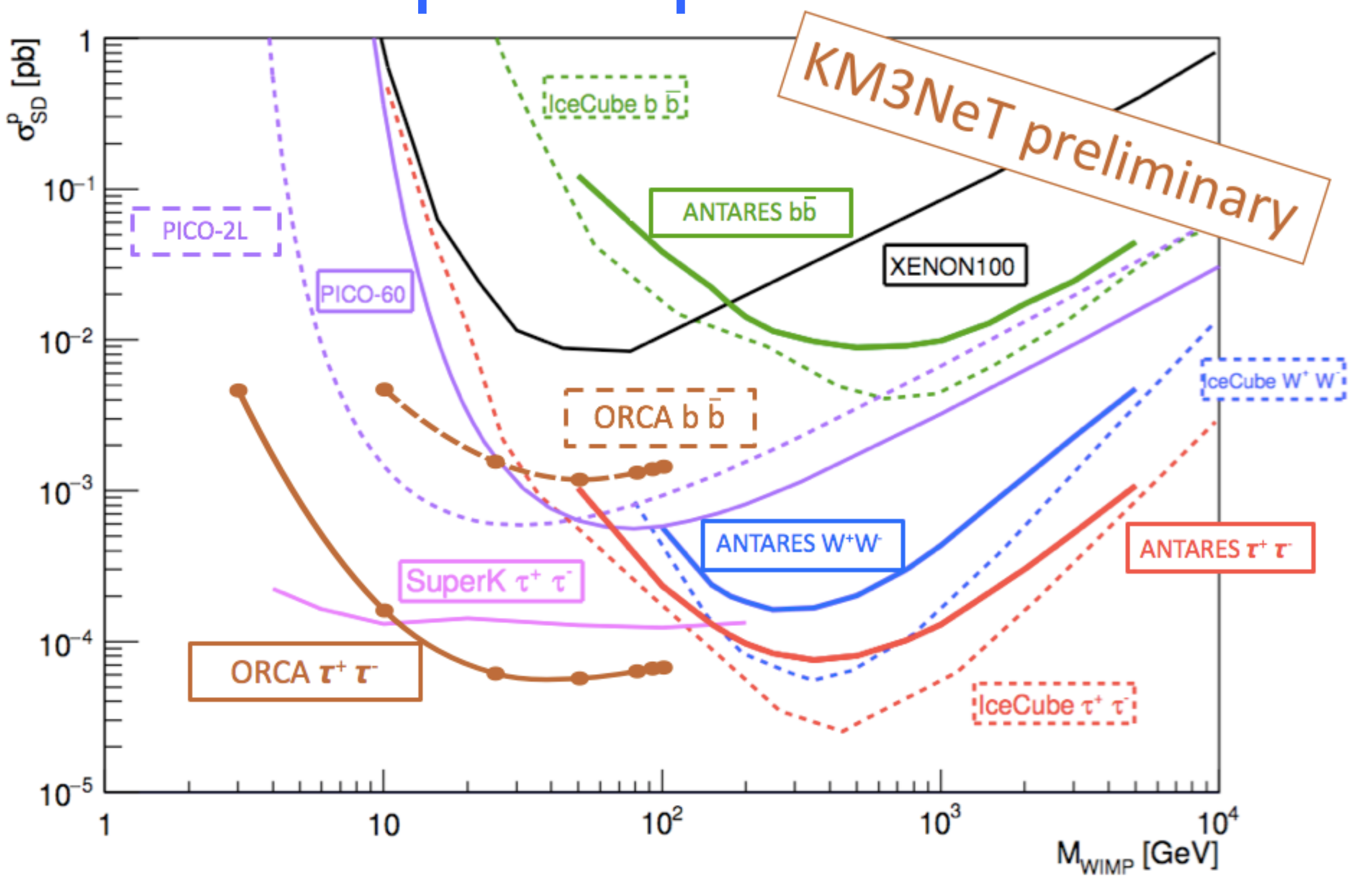
Indirect Detection of Dark Matter



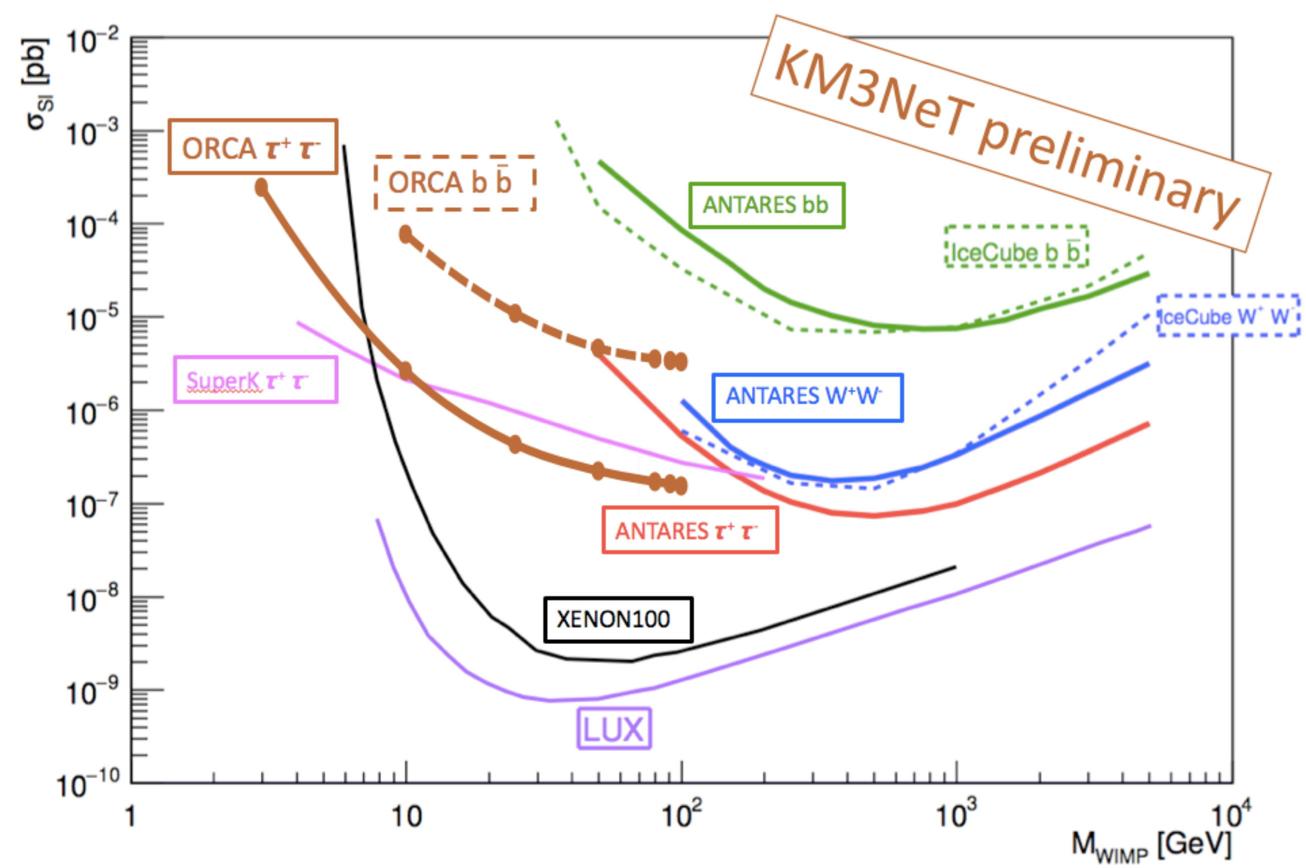
ORCA Schedule

- **Phase 1:**
  - **7 strings (funded)**
  - **operational by 2017/2018**
- **Phase 2:**
  - **115 strings (funding request ongoing)**
  - **operation by 2020**

Spin Dependent

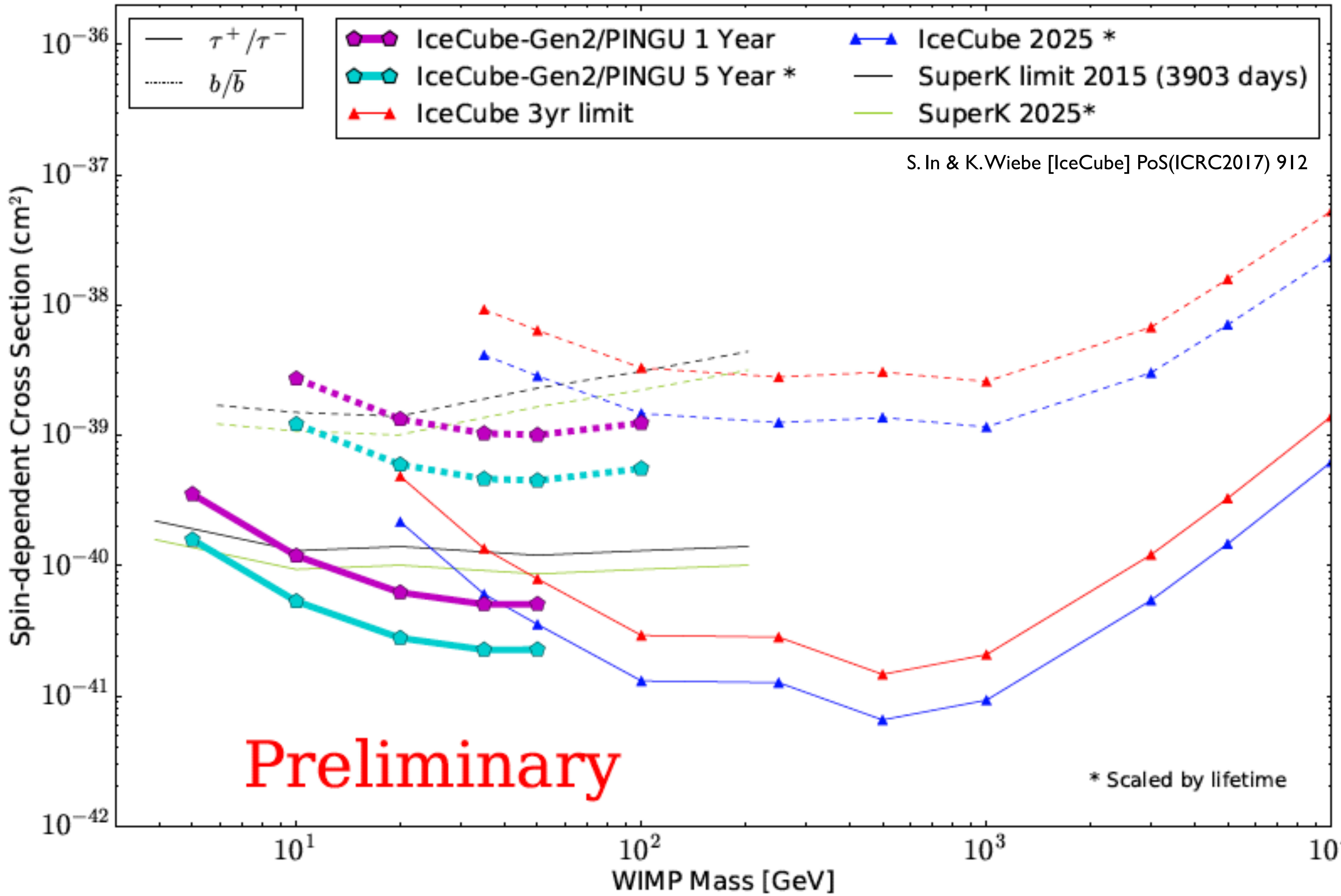


Spin Independent



ORCA 3 years - tracks+showers

PINGU DM Sensitivity



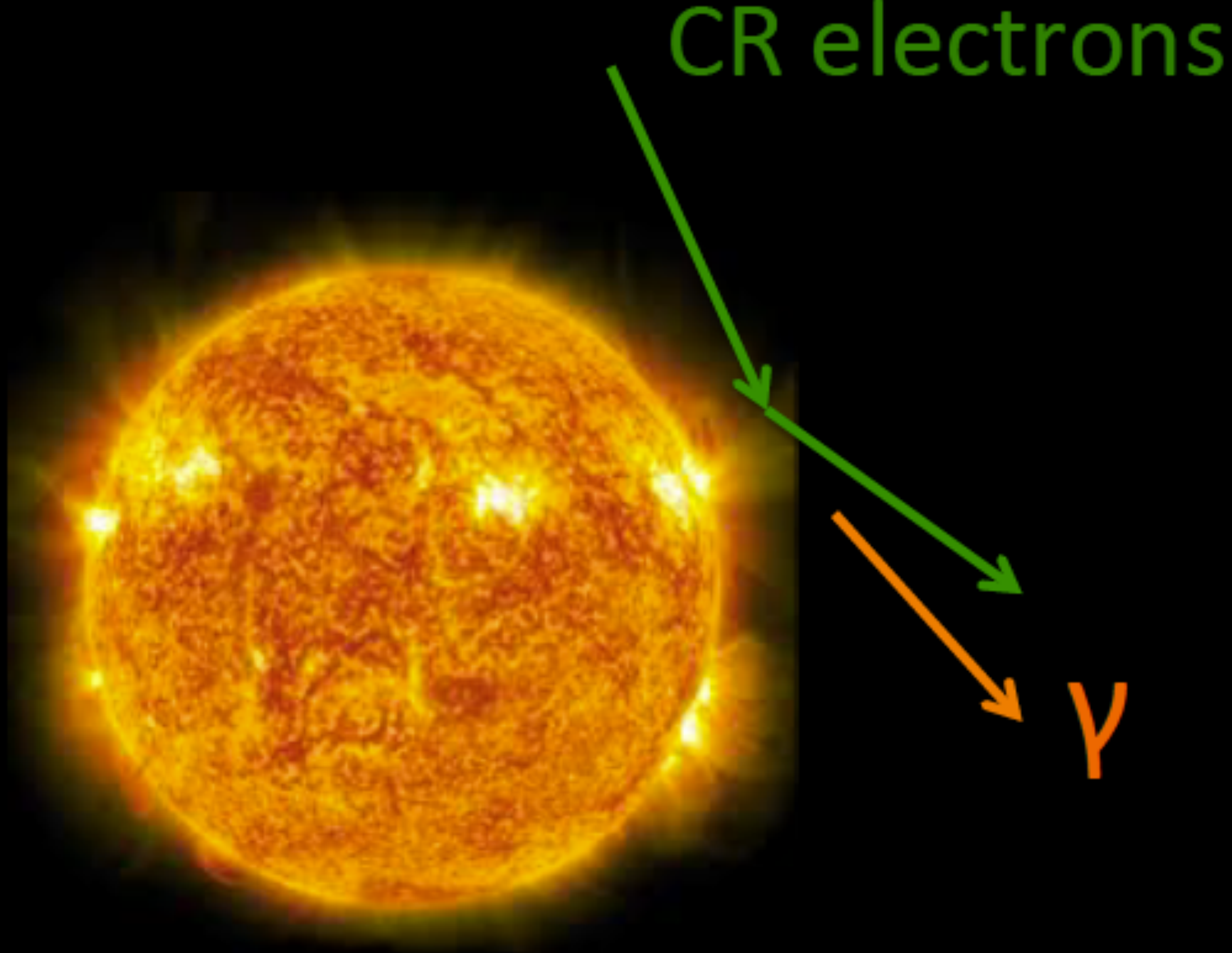
Solar Neutrino Floor

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

In preparation Ng, Beacom, Peter, Rott

Sun – Cosmic-Ray Beam Dump

- Leptonic

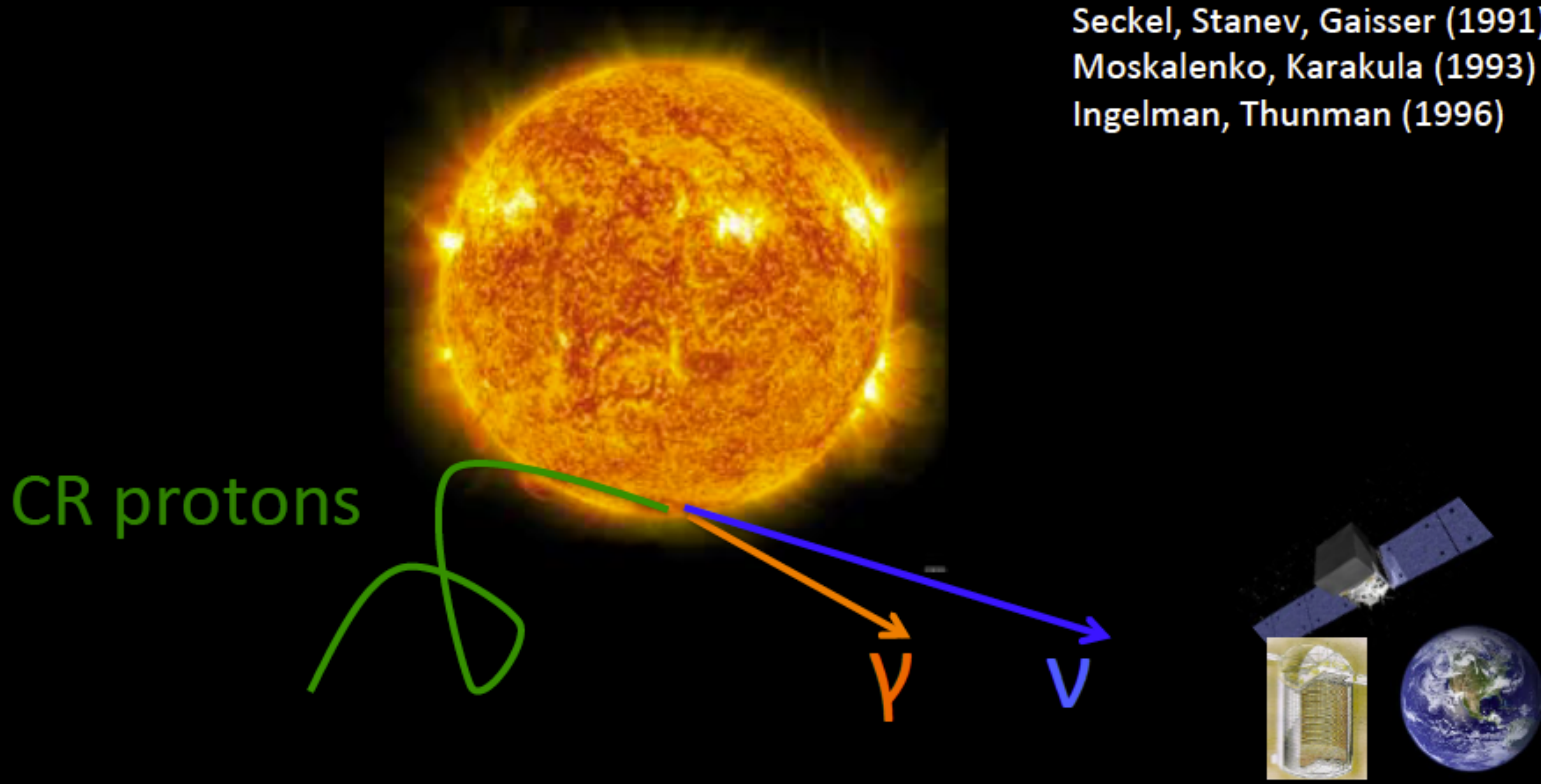


Moskalenko, Porter, Digel (2006)
Orlando, Strong (2007)

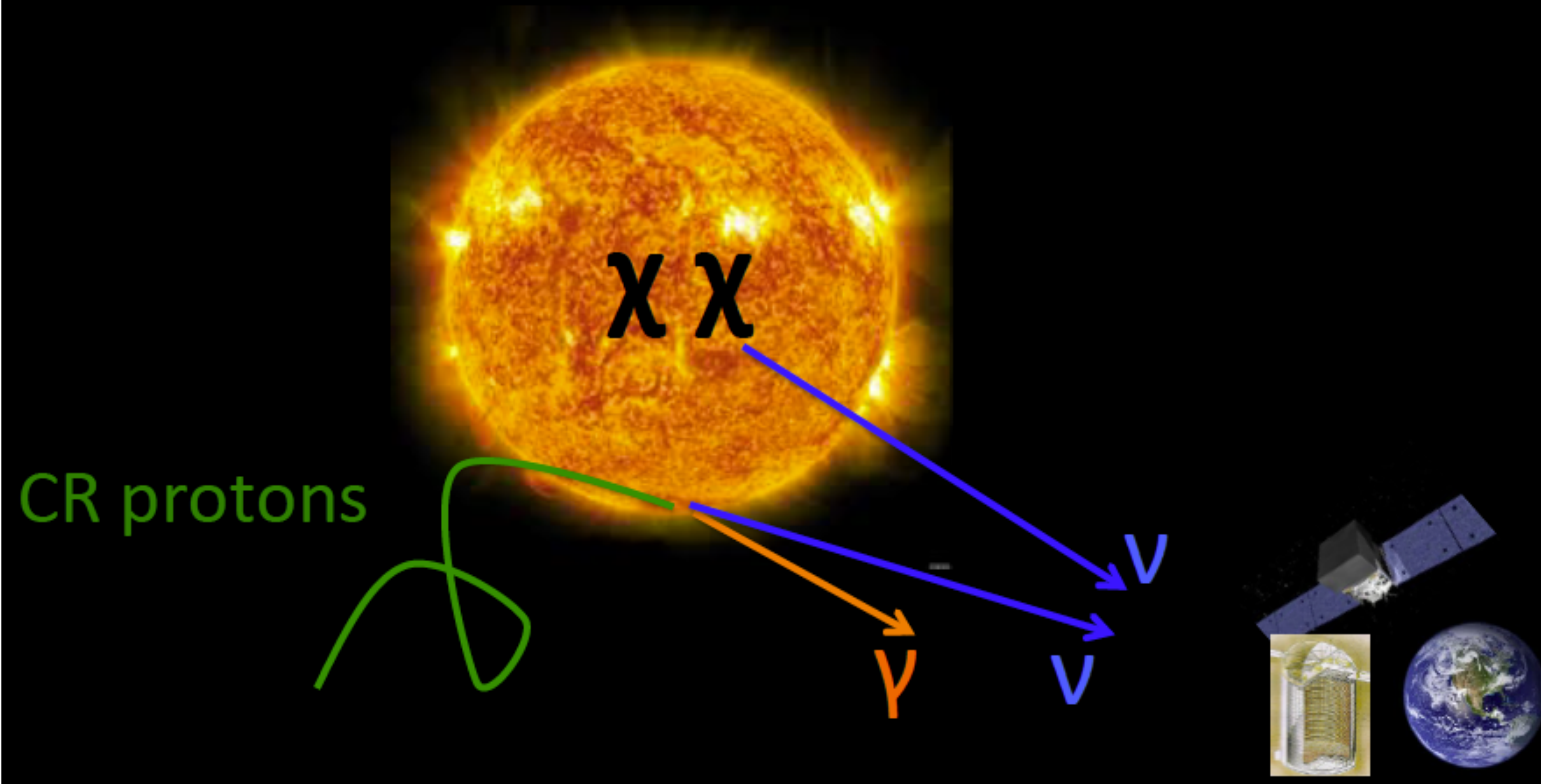
Sun – Cosmic-Ray Beam Dump

- Hadronic

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

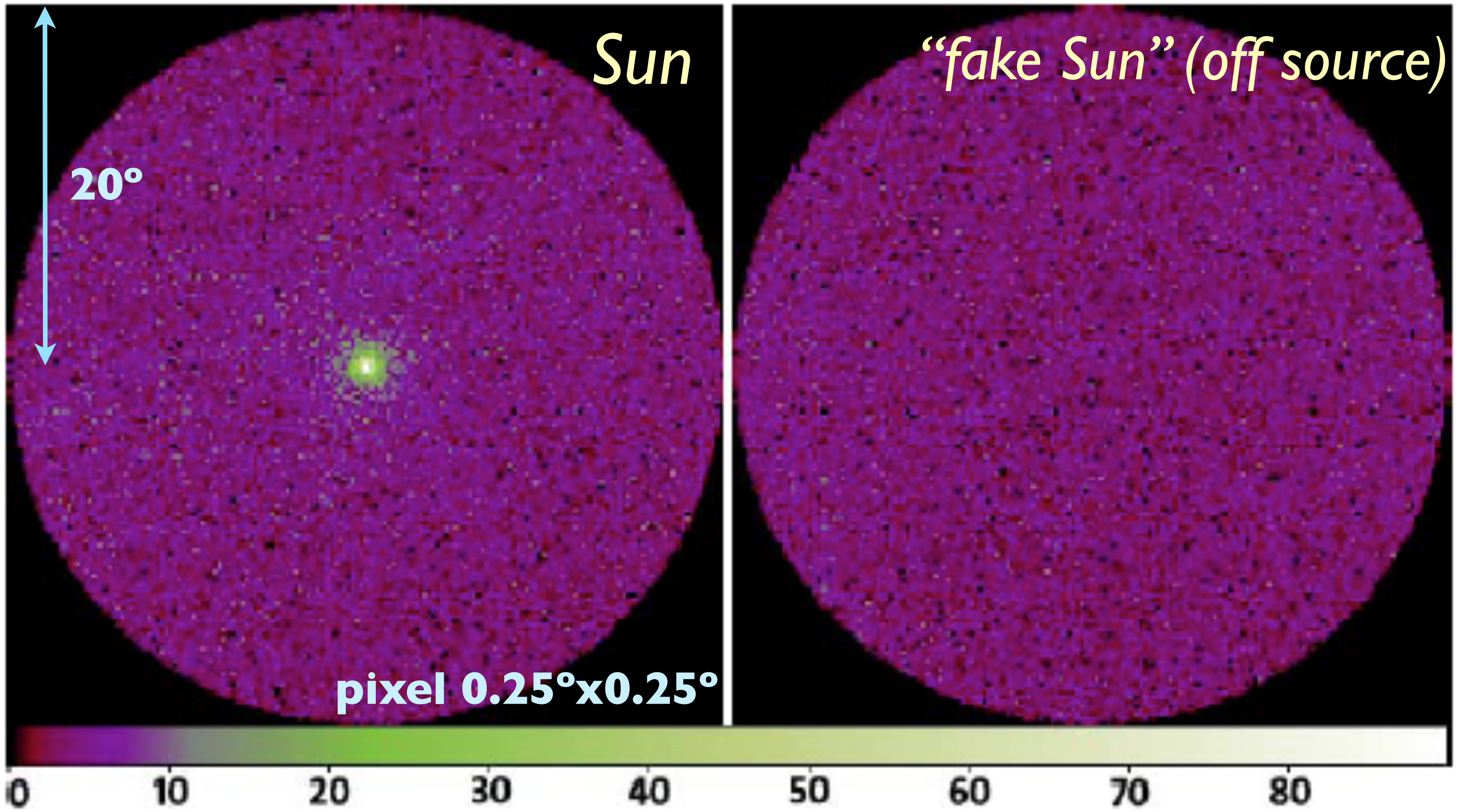


Cosmic Rays vs Dark Matter

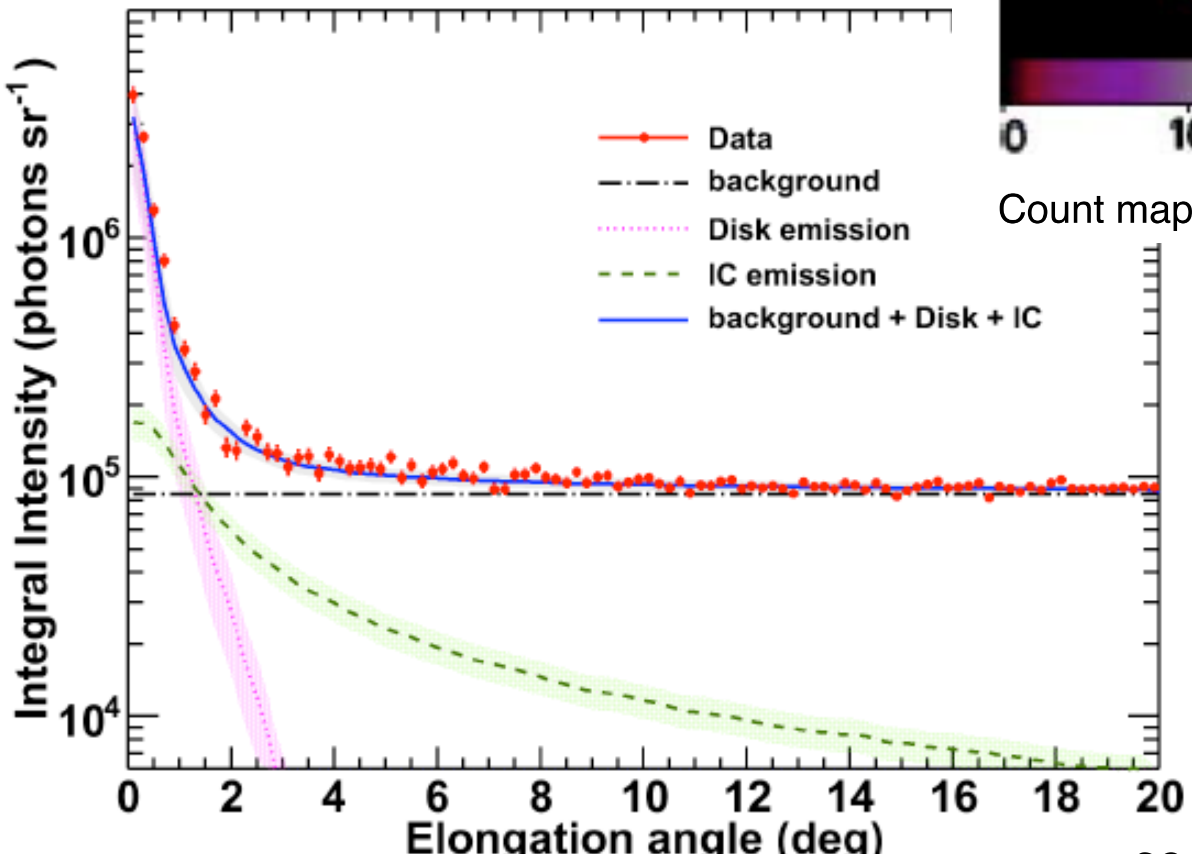


Gamma-ray's from the Sun

- 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

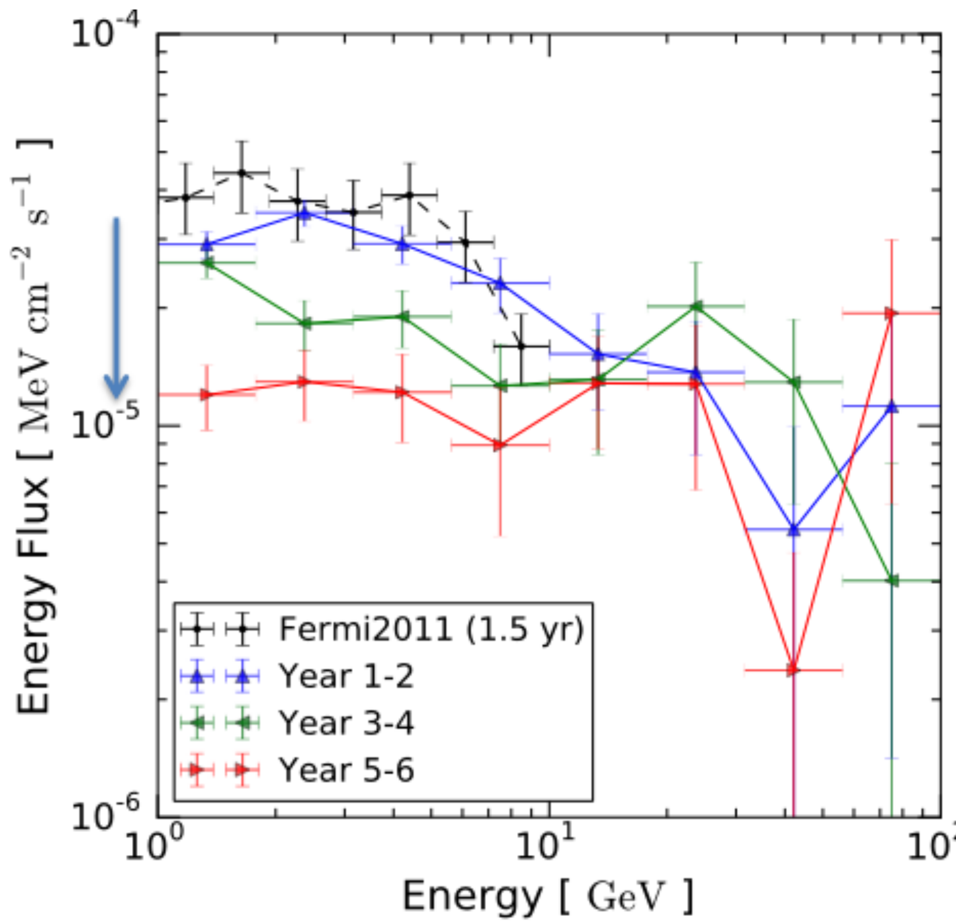


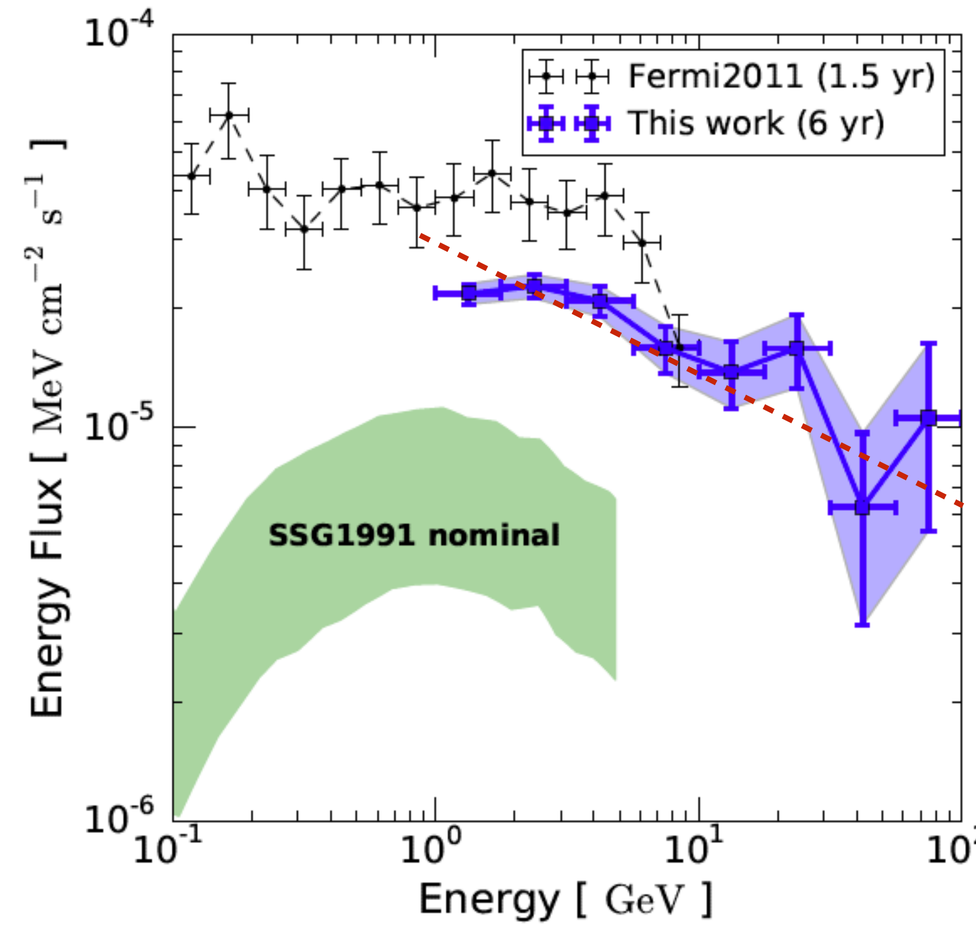
- Extended and disk emission is observed

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

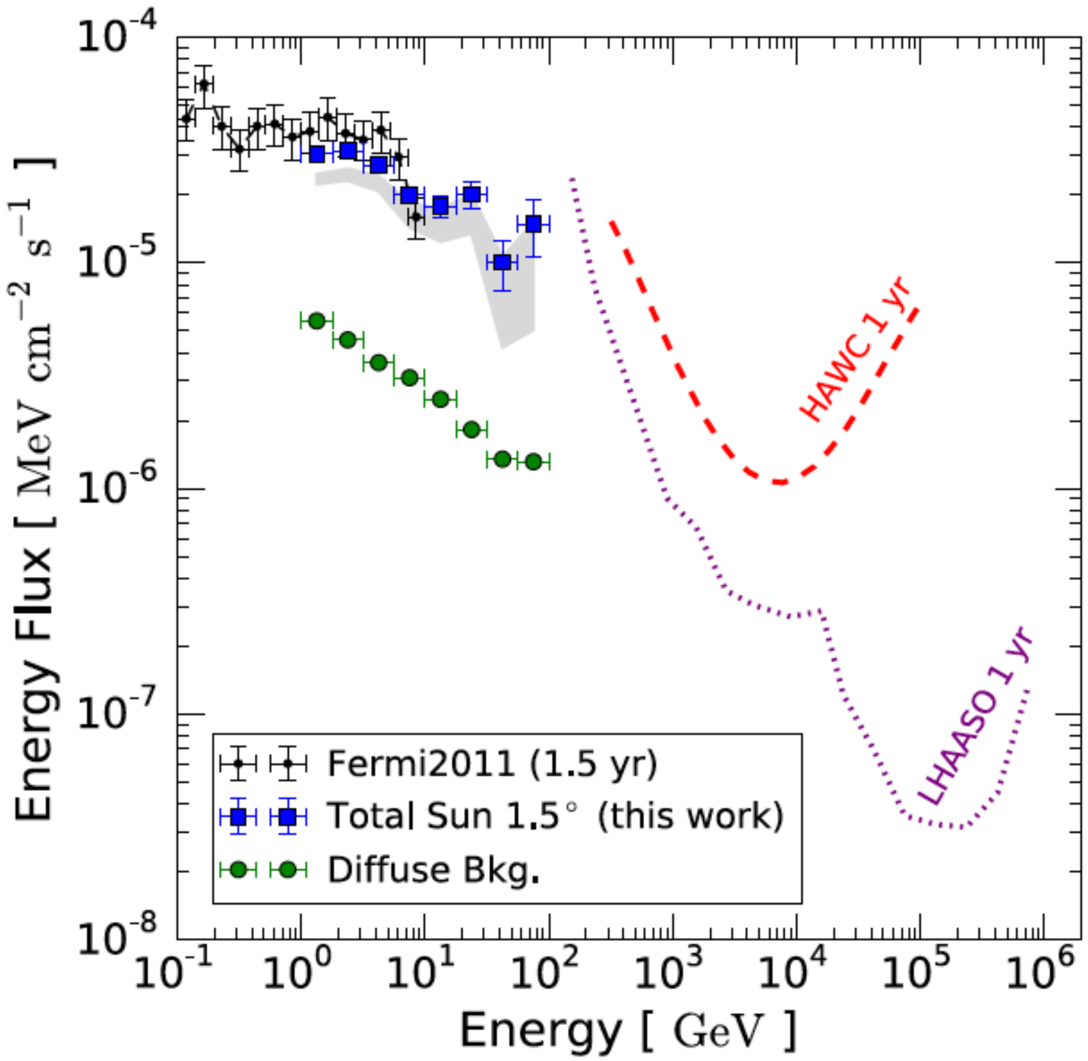




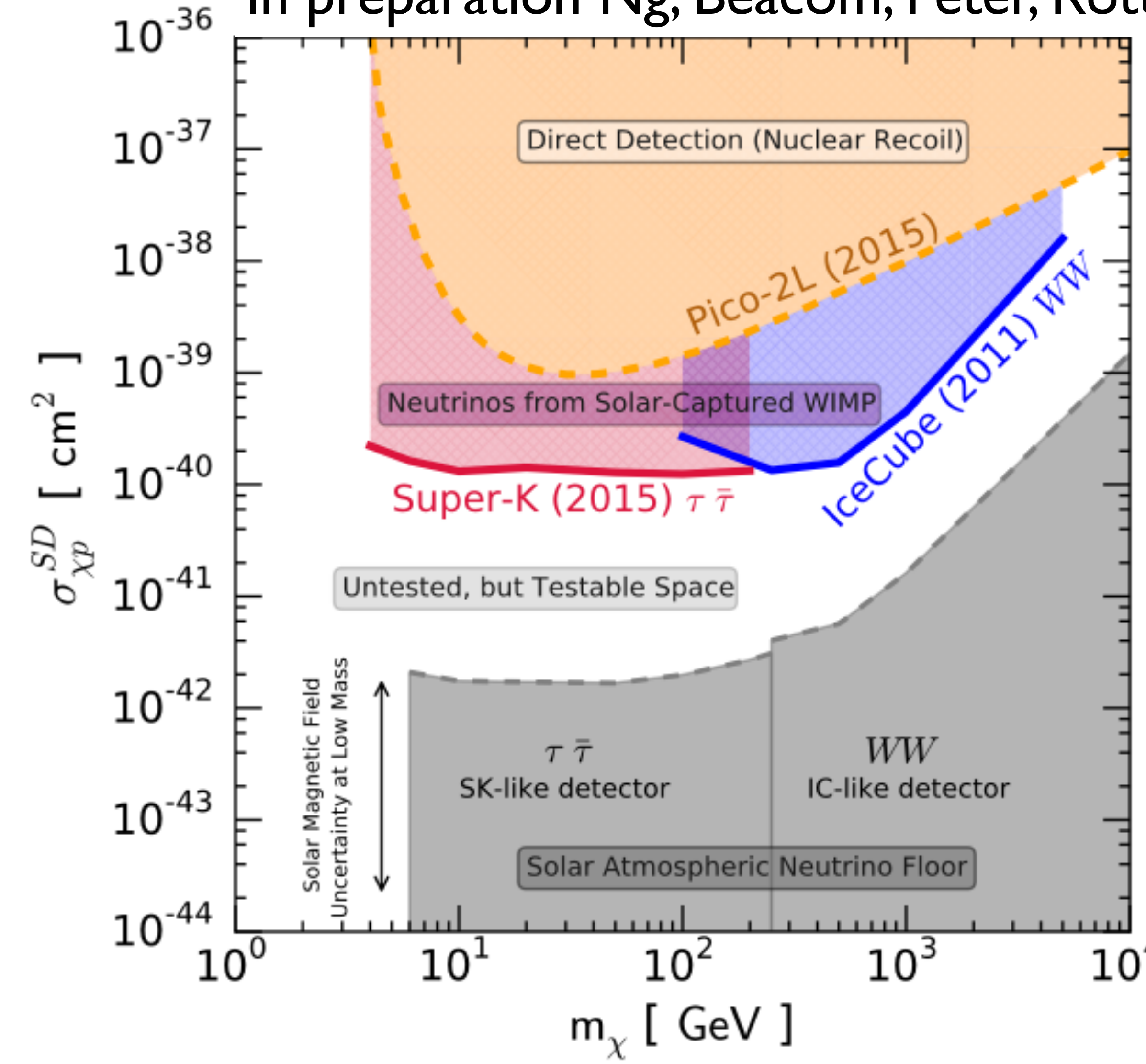
- Observed gamma-ray flux cannot be described by current models
- Significant time variation in solar-disk gamma-rays observed (<10GeV)
- Gamma-ray flux from the Sun extends beyond 100GeV

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

Gamma-ray's from the Sun



In preparation Ng, Beacom, Peter, Rott



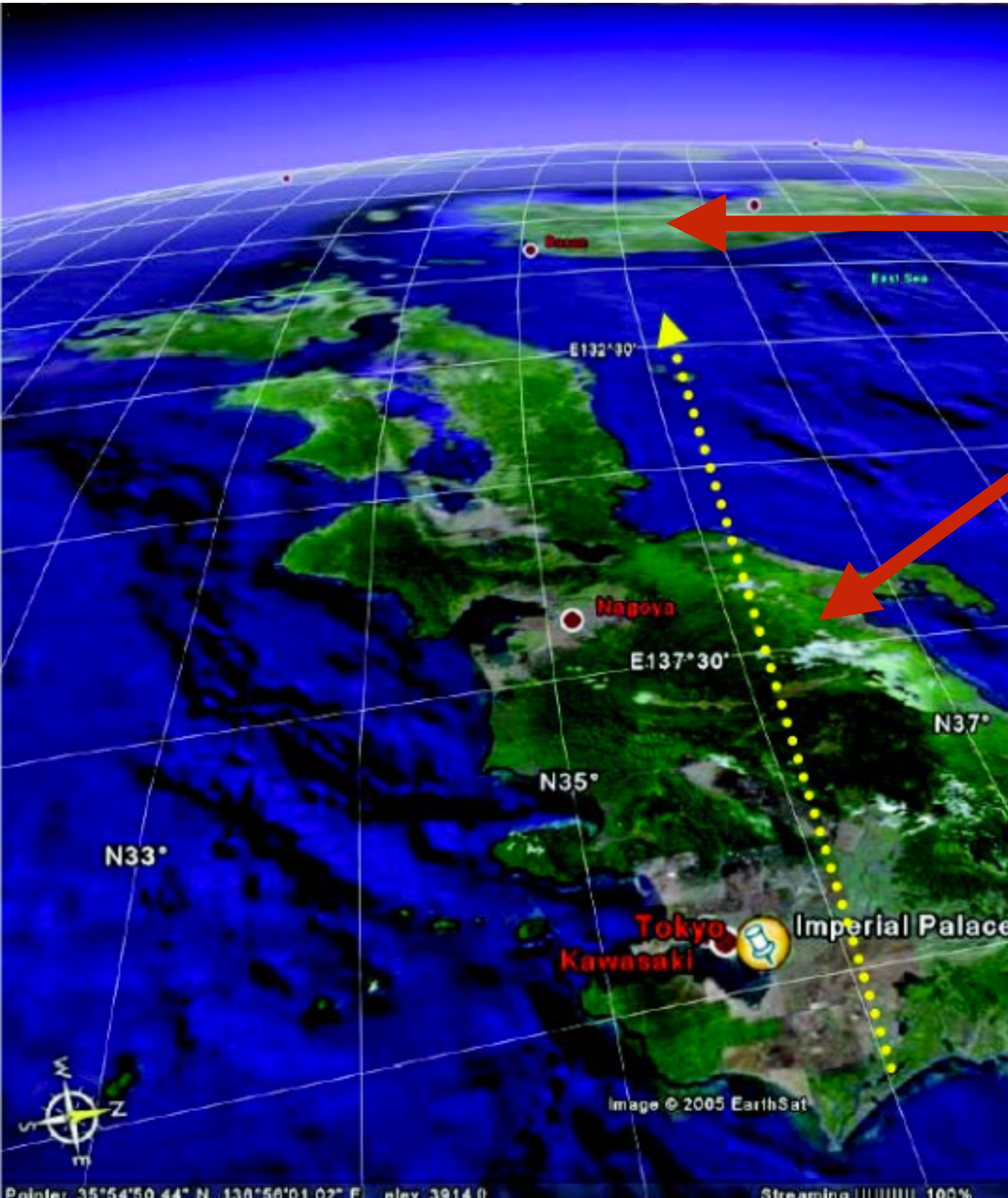
- Sun is a promising source for ground-based high altitude water Cherenkov detectors
- Background to dark matter search from the Sun, that soon will be relevant (and first high-energy neutrino point source ??)

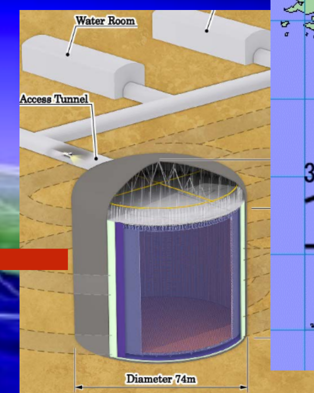
see K. Ng, J. Beacom, A. Peter, C. Rott PRD 2016

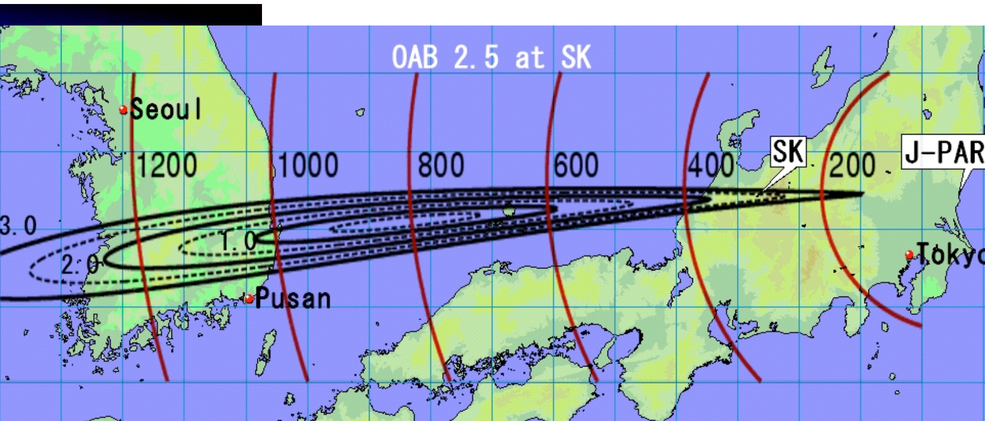
2nd Hyper-K Detector in Korea ?

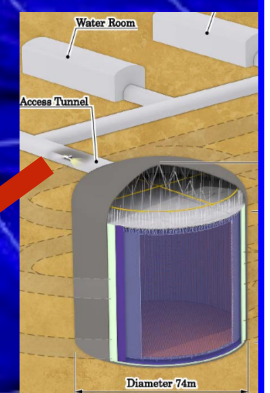
Hyper-Kamiokande Proto-Collaboration
arXiv:1611.06118

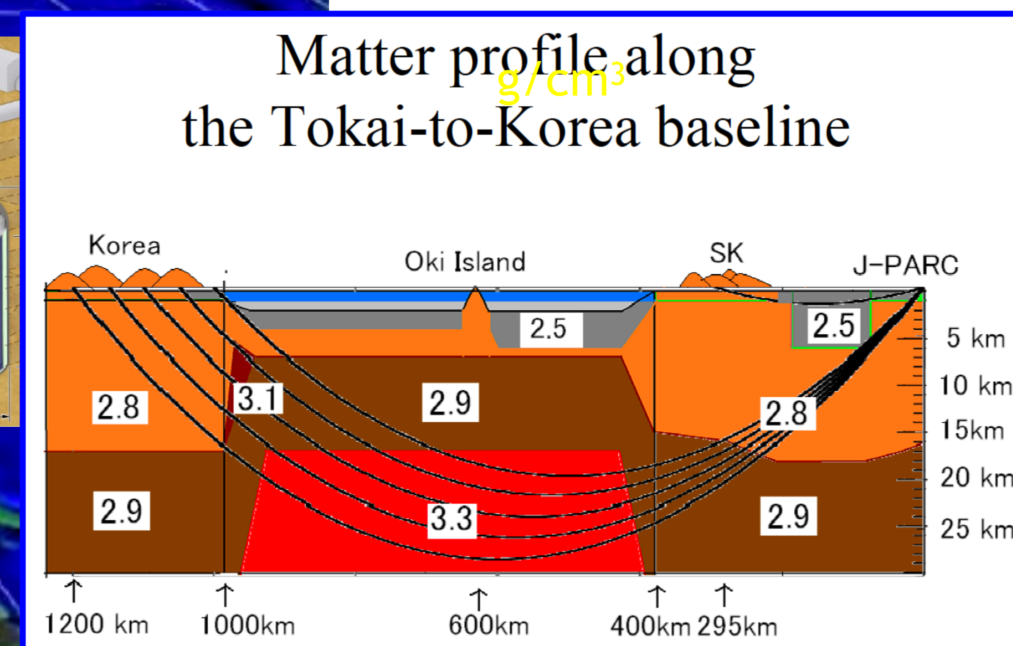
Tokai-to-Hyper-K & Korea (T2HKK)











Physics Potentials with the Second Hyper-Kamiokande Detector in Korea

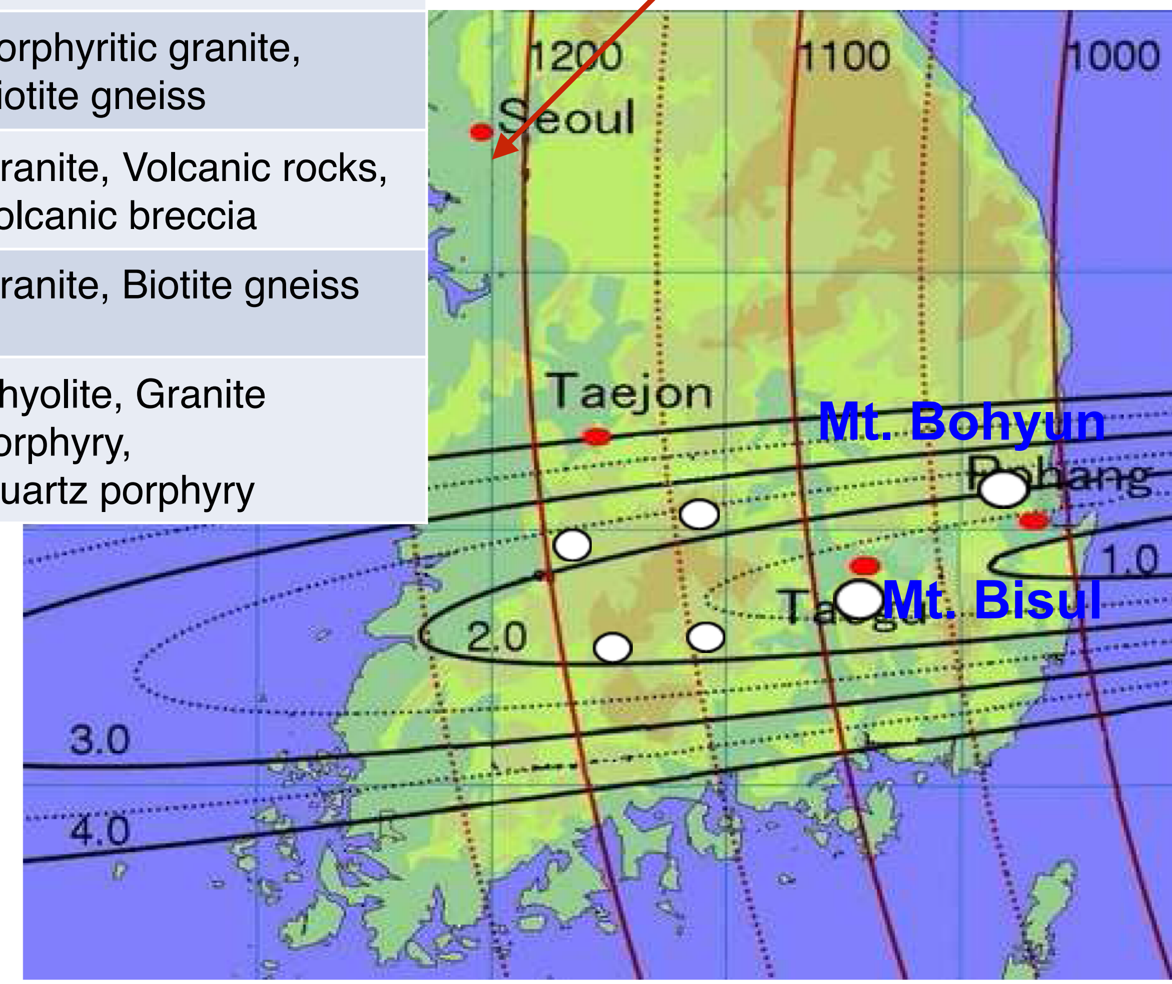
(Hyper-Kamiokande Proto-Collaboration)

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

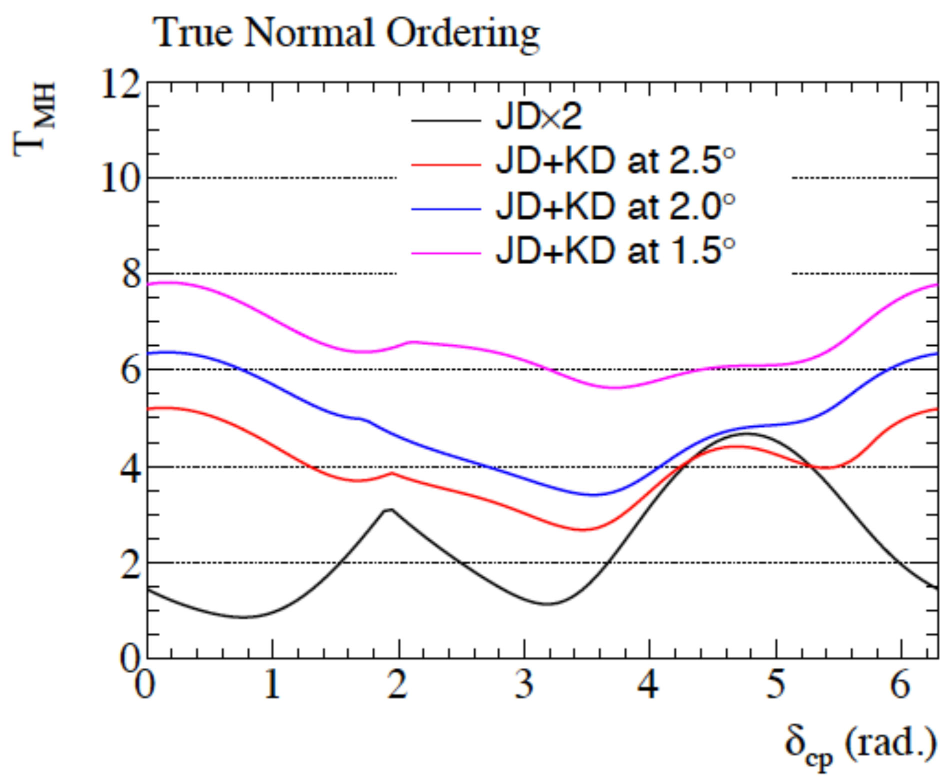
Site	OAB	Baseline	Height	Rock
Mt. Bisul	~1.3°	1088 km	1084 m	Granite porphyry, Andesitic breccia
Mt. Hwangmae	~1.8°	1140 km	1113 m	Flake granite, Porphyritic gneiss
Mt. Sambong	~1.9°	1180 km	1186 m	Porphyritic granite, Biotite gneiss
Mt. Bohyun	~2.2°	1040 km	1126 m	Granite, Volcanic rocks, Volcanic breccia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



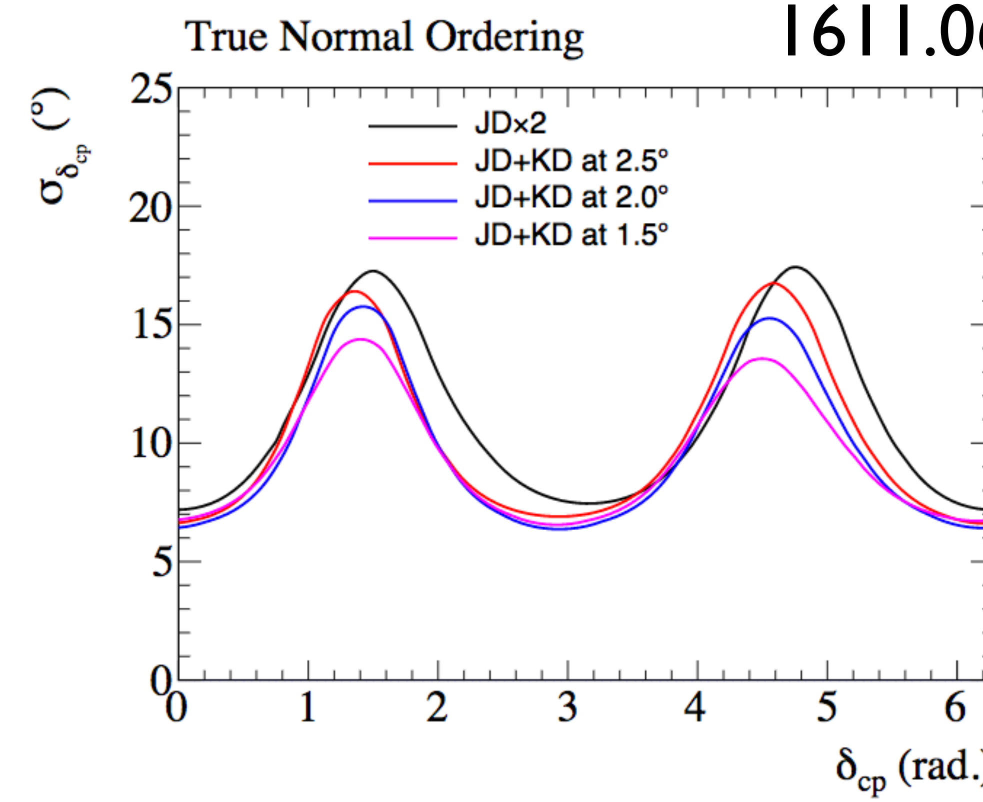
arXiv:1611.06118

- 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)



1611.06118



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

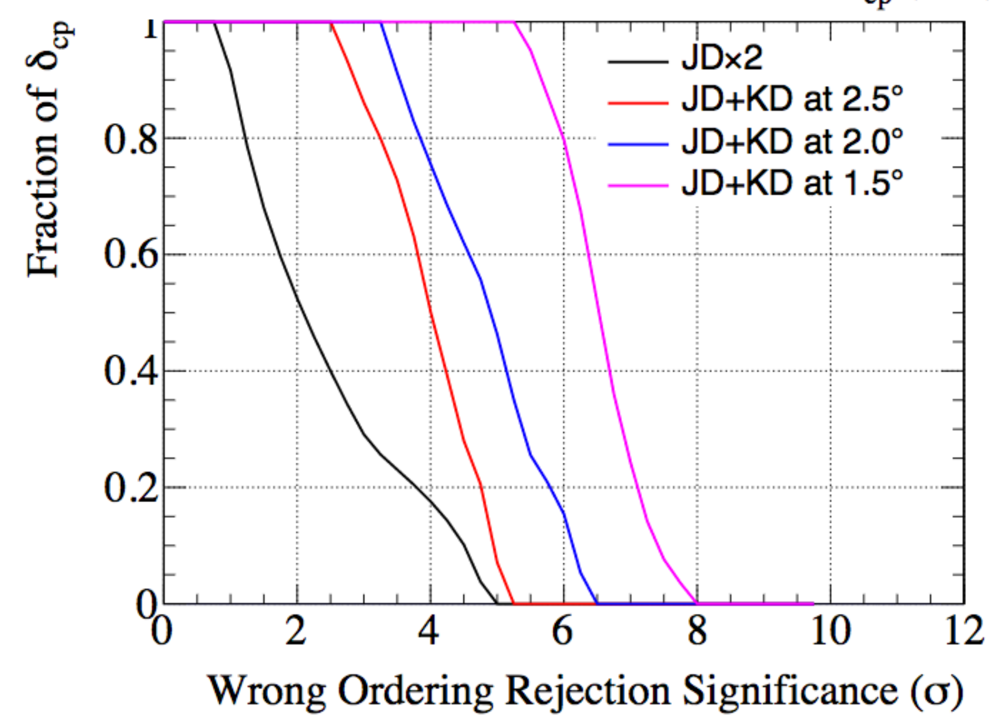


FIG. 19: The fraction of δ_{cp} values (averaging over the true mass ordering) for which the wrong hierarchy can be rejected with a given significance or greater.