Indirect Searches for Dark Matter with IceCube

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IFIC Seminar

Coma Cluster

Outline

Motivation

The IceCube Neutrino Telescope

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

The Dark Matter Mystery

Coma Cluster

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
    - ...

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The Dark Matter Mystery

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  - Rotation curves
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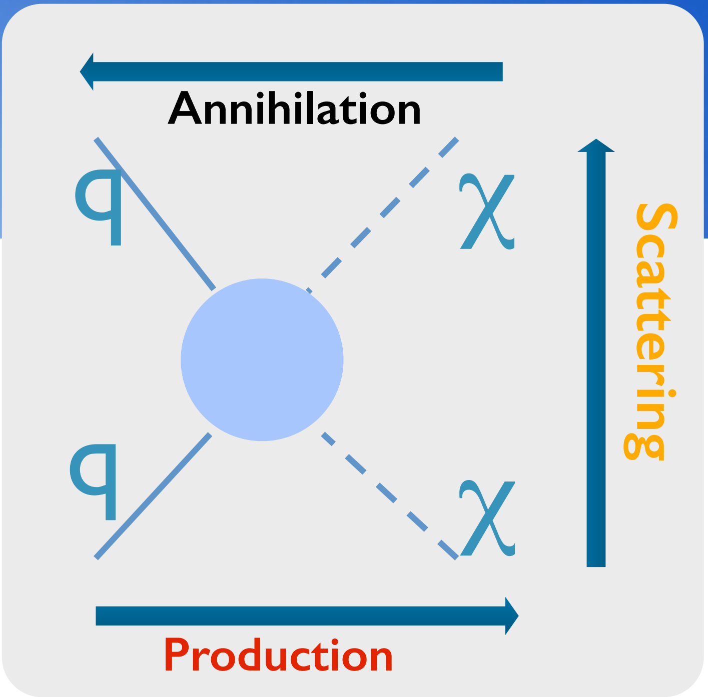
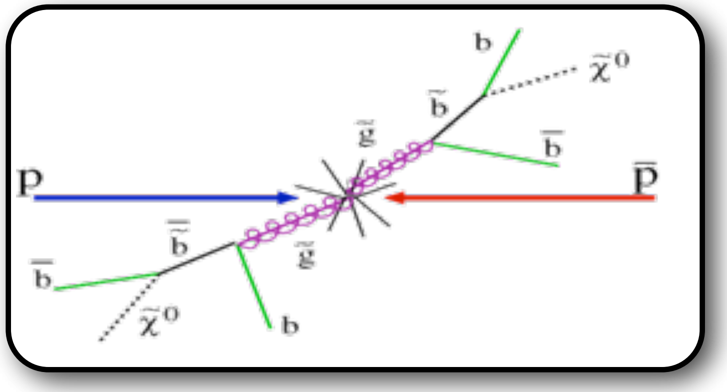
  - ...

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

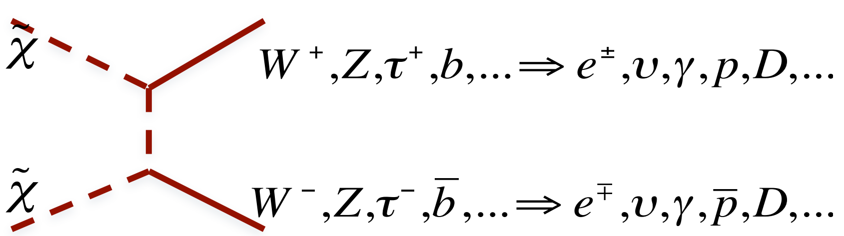
Role of Neutrinos

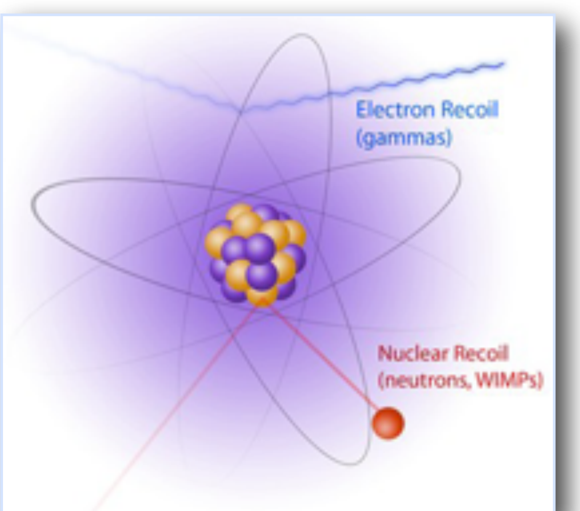


WIMP - Weakly Interacting Massive Particle



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



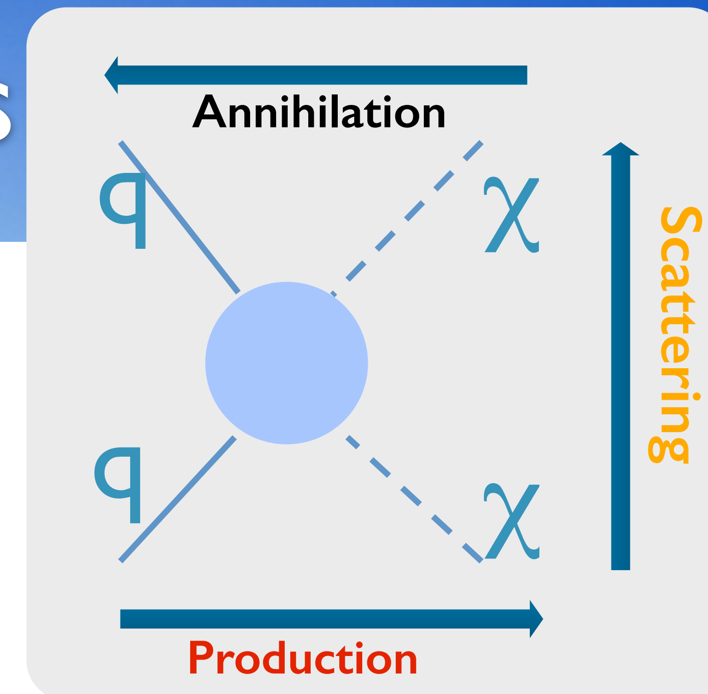


Dark Matter Lifetime

Dark Matter Self-annihilation cross section

DM -Nucleon Scattering cross section

Role of Neutrinos



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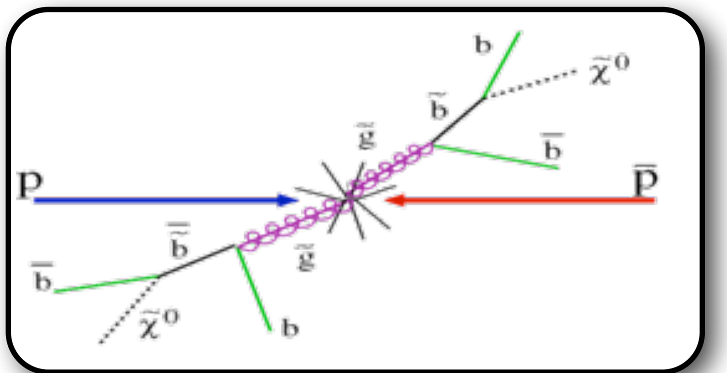

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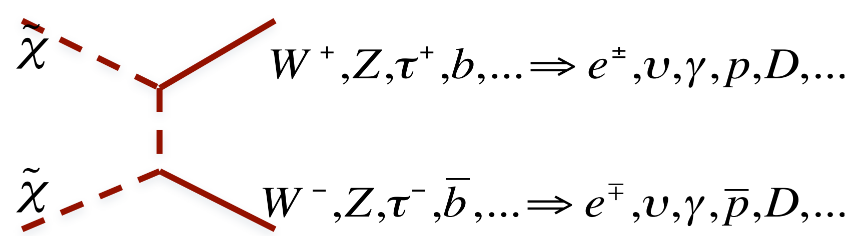

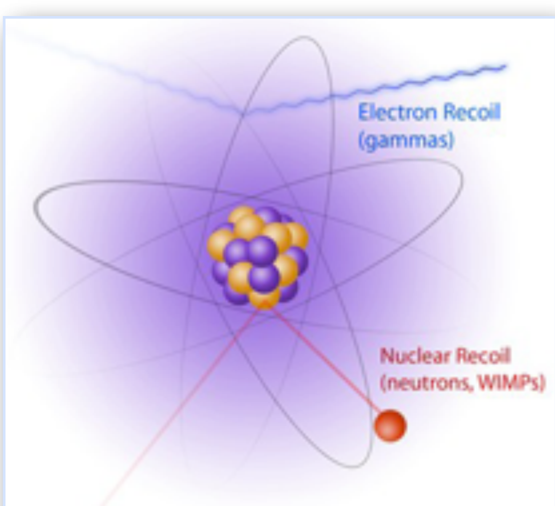

Dark Matter Lifetime

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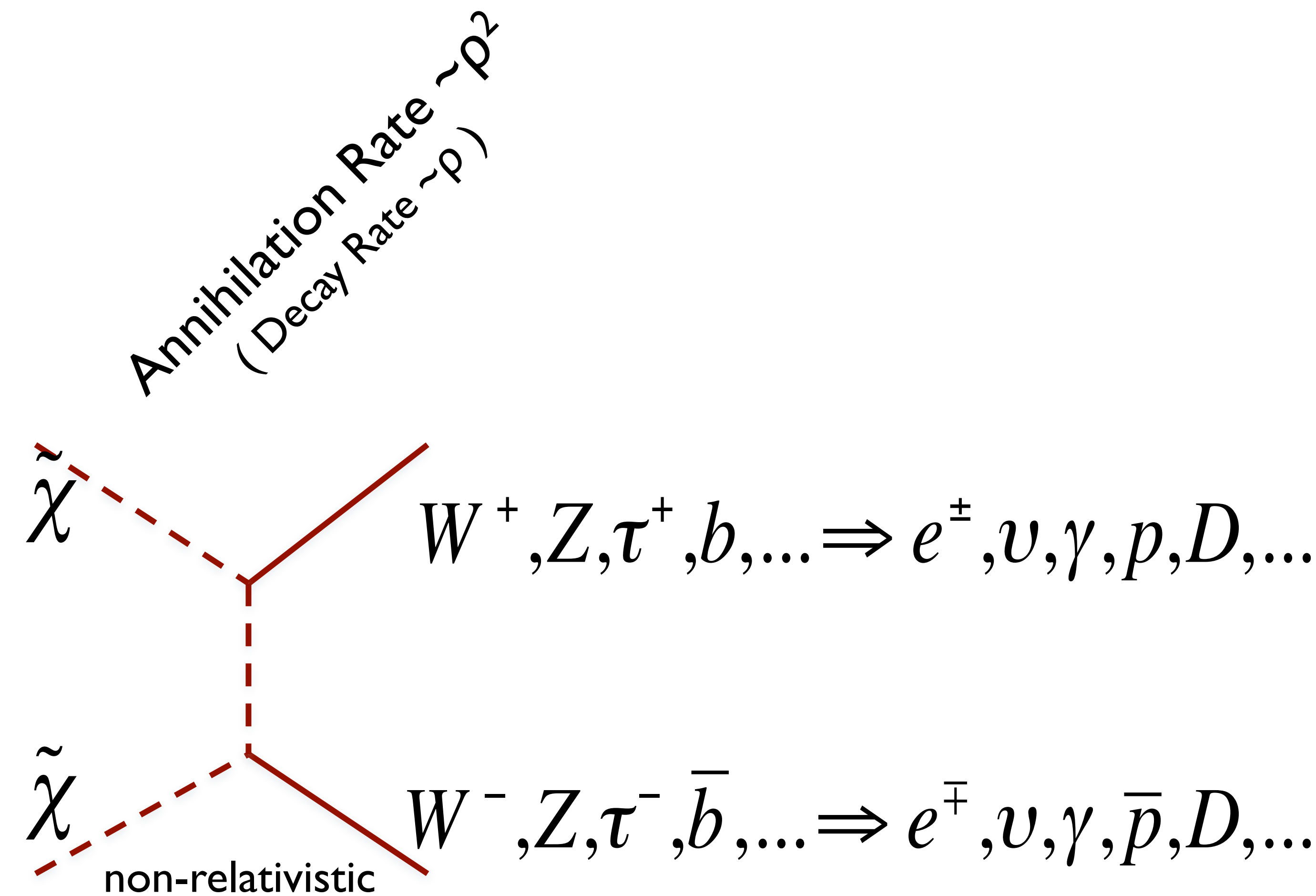
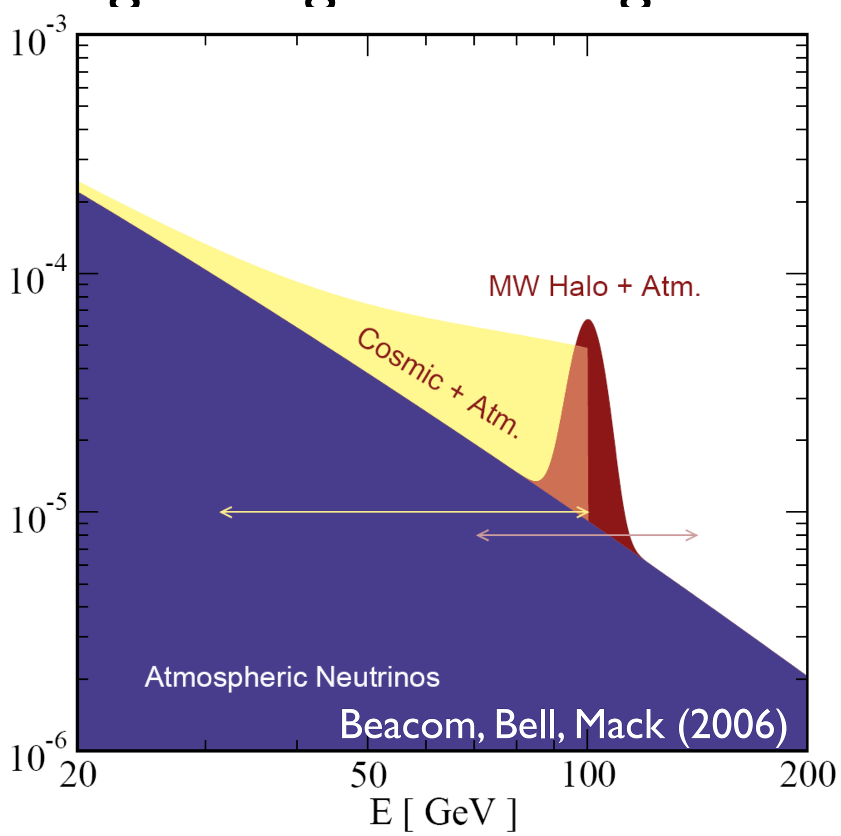
Dark Matter Signals

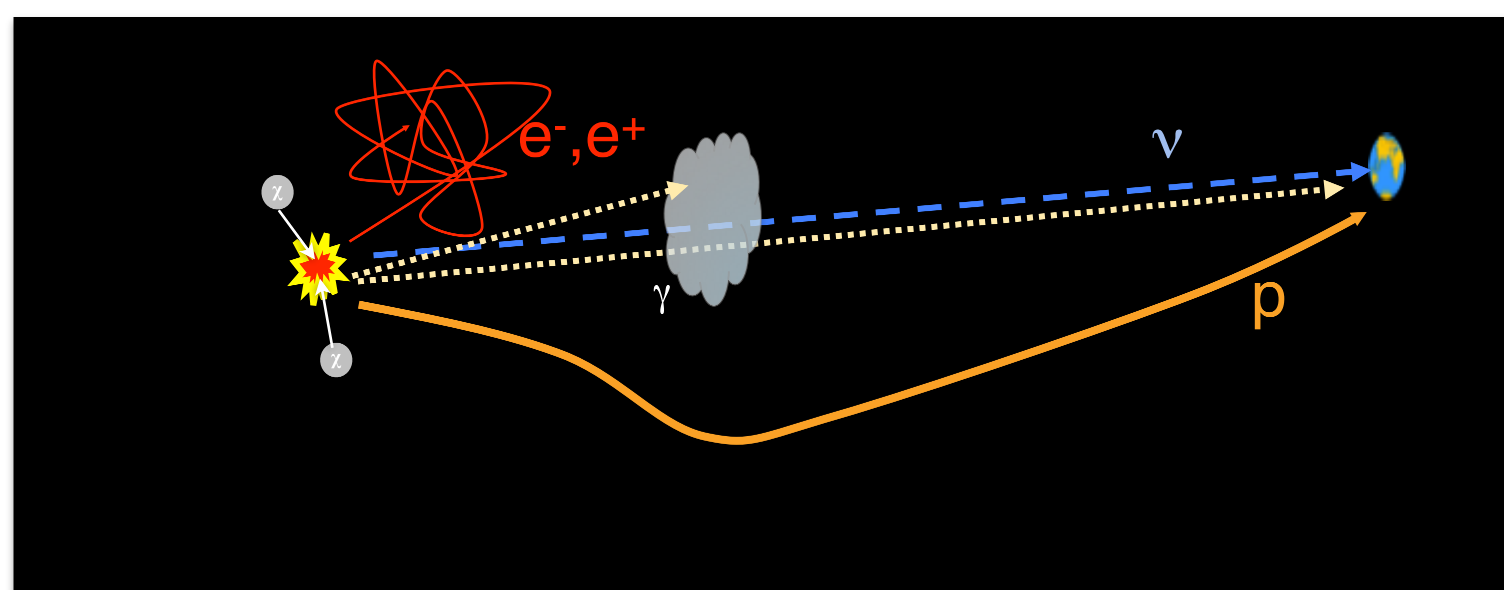
- Identify overdense regions of dark matter

  ⇒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







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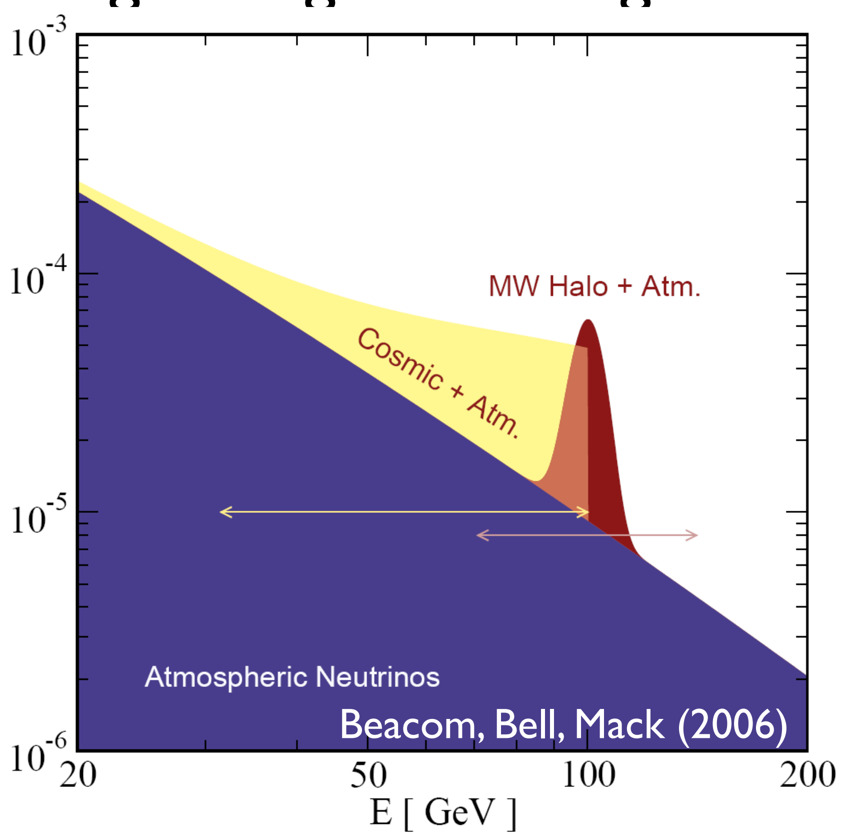
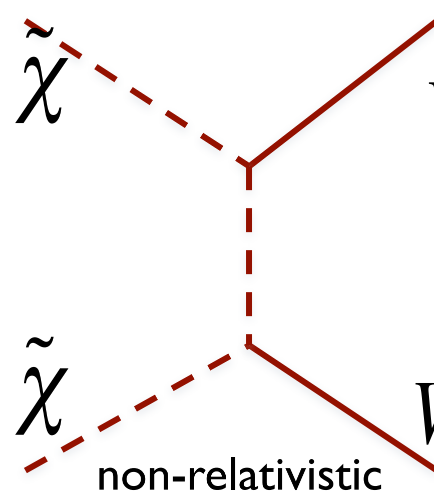


Annihilation Rate ~ρ^2 (Decay Rate ~ρ)

Annihilation Products

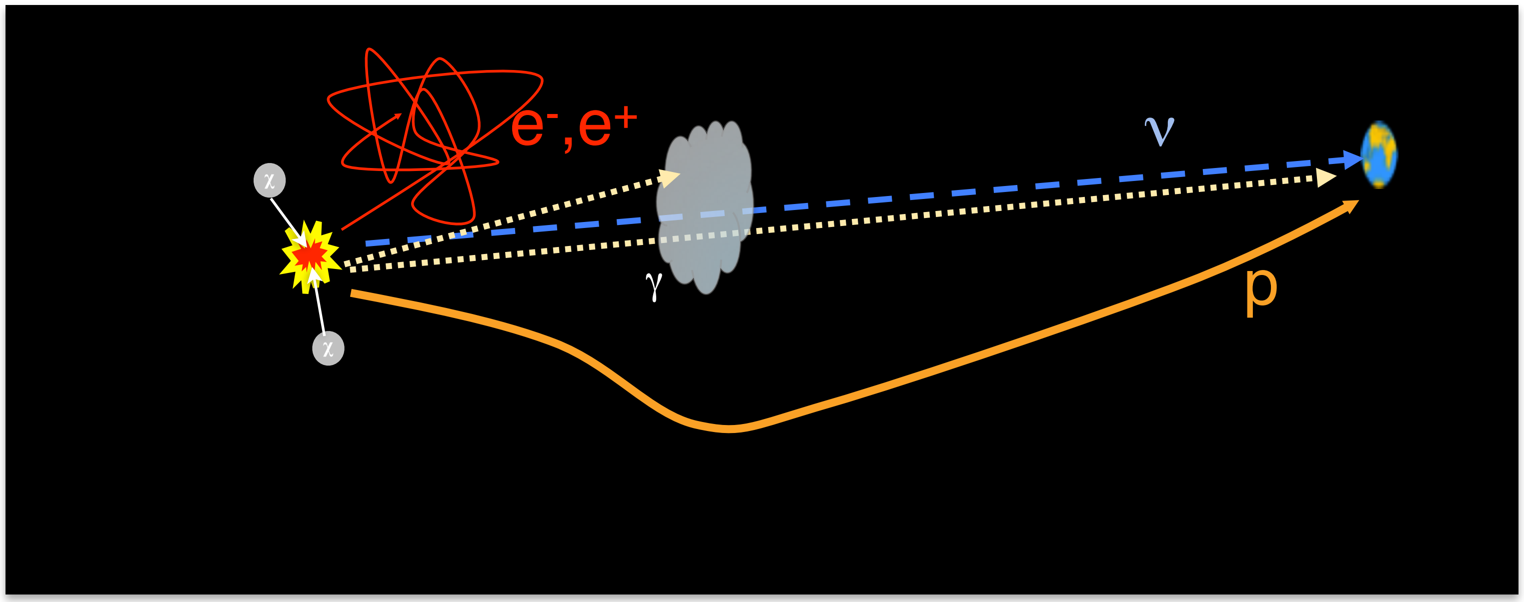
Decay

Messengers



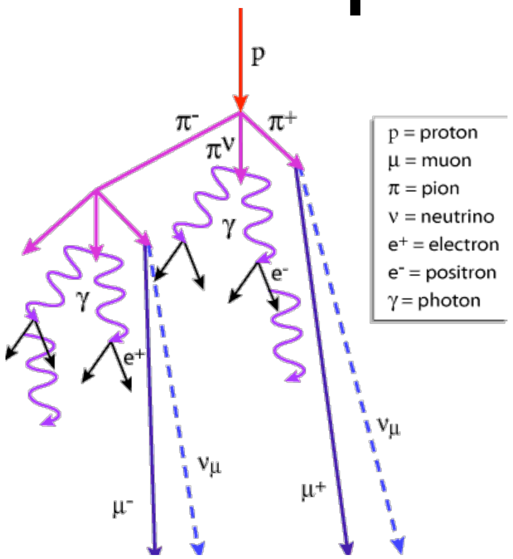
$$W^+, Z, \tau^+, b, \ldots \Rightarrow e^{\pm}, \upsilon, \gamma, p, D, \ldots$$

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



Sources of High Energy Neutrinos

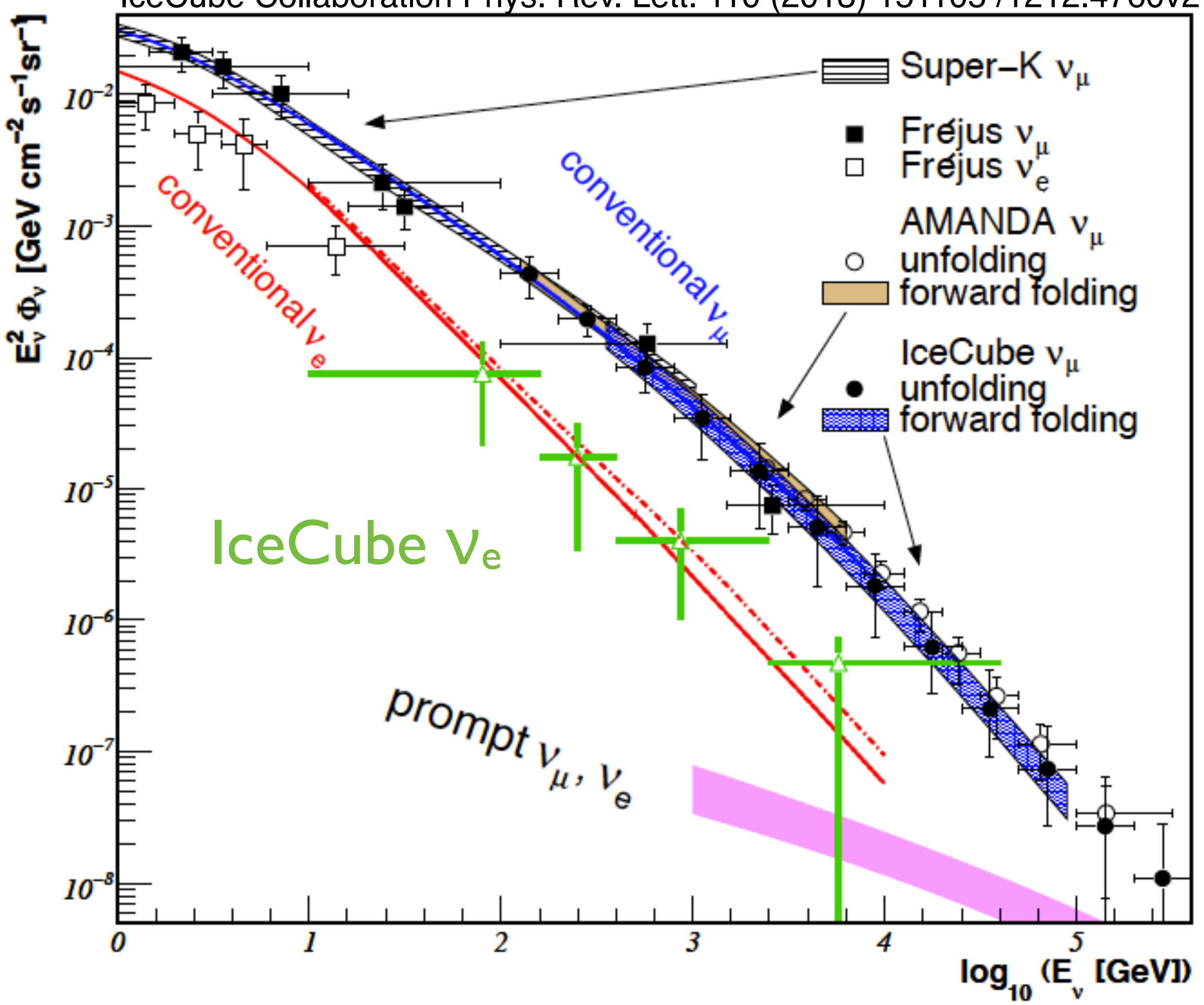
Atmospheric Neutrinos



Cosmic rays interact in the upper atmosphere:

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

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

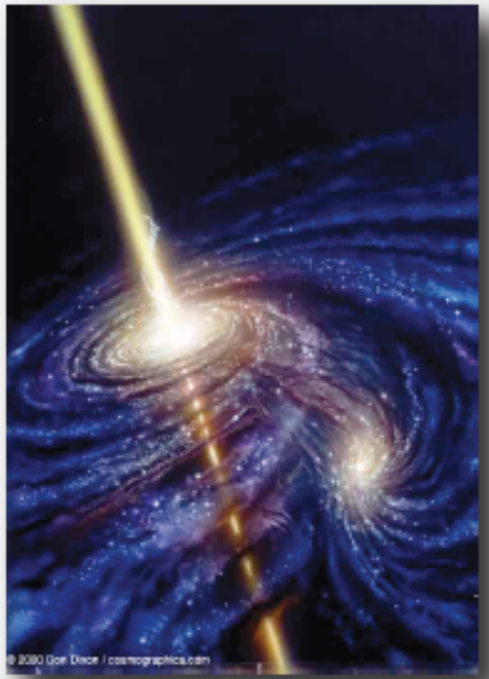


Astrophysical

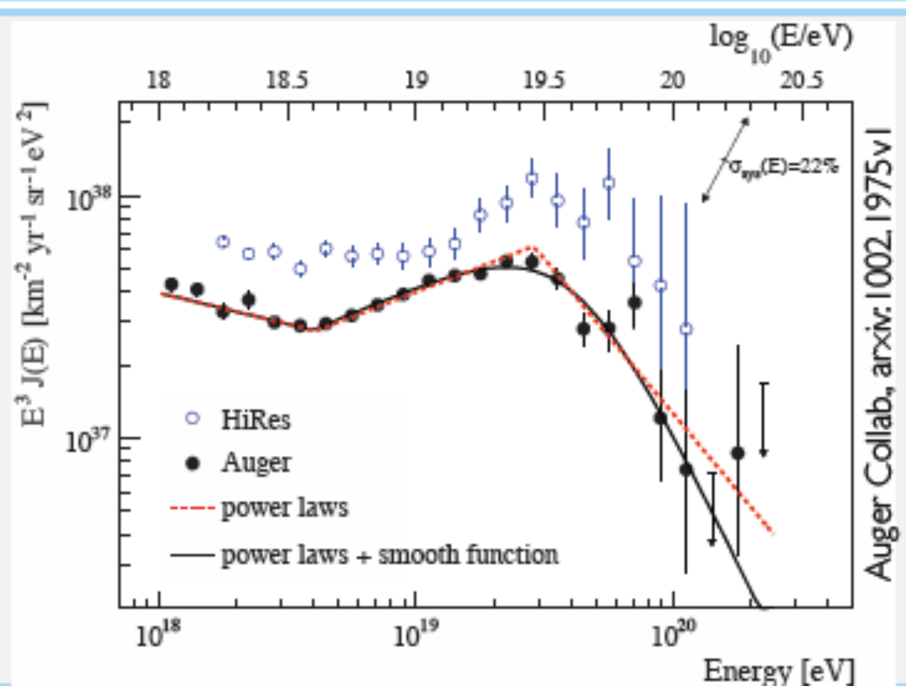
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Gamma-ray Bursts

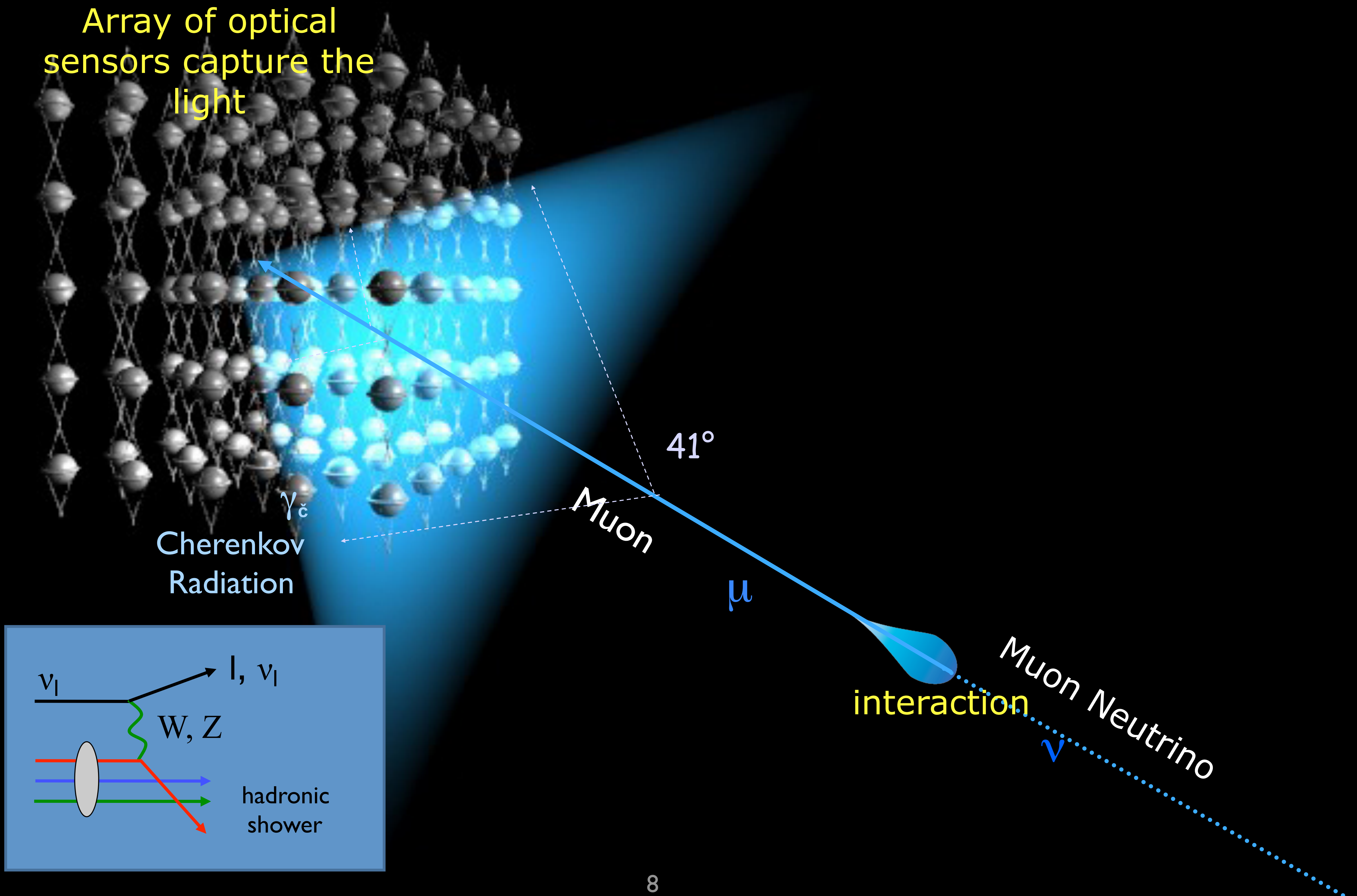
Active Galactic Nuclei

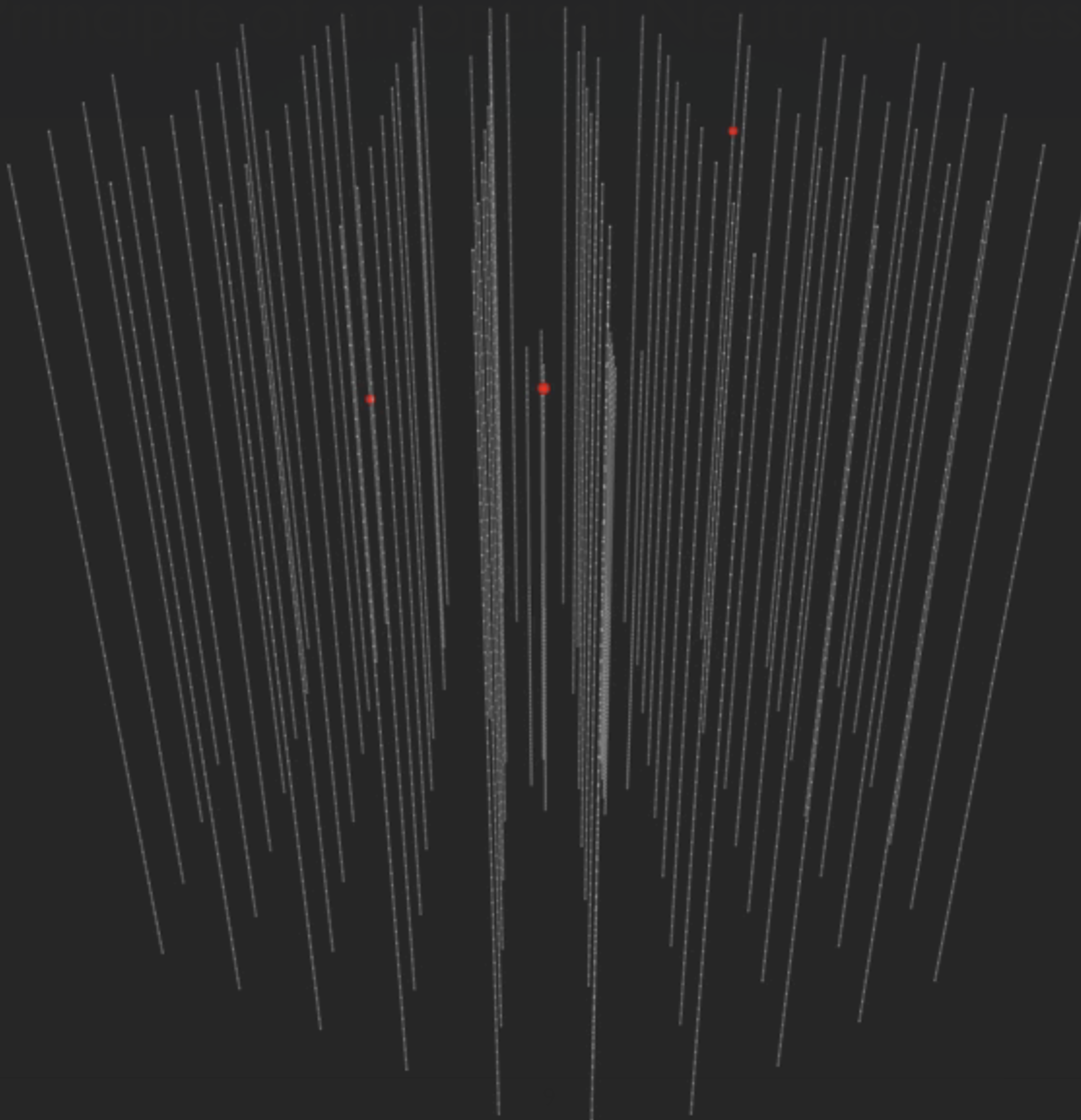


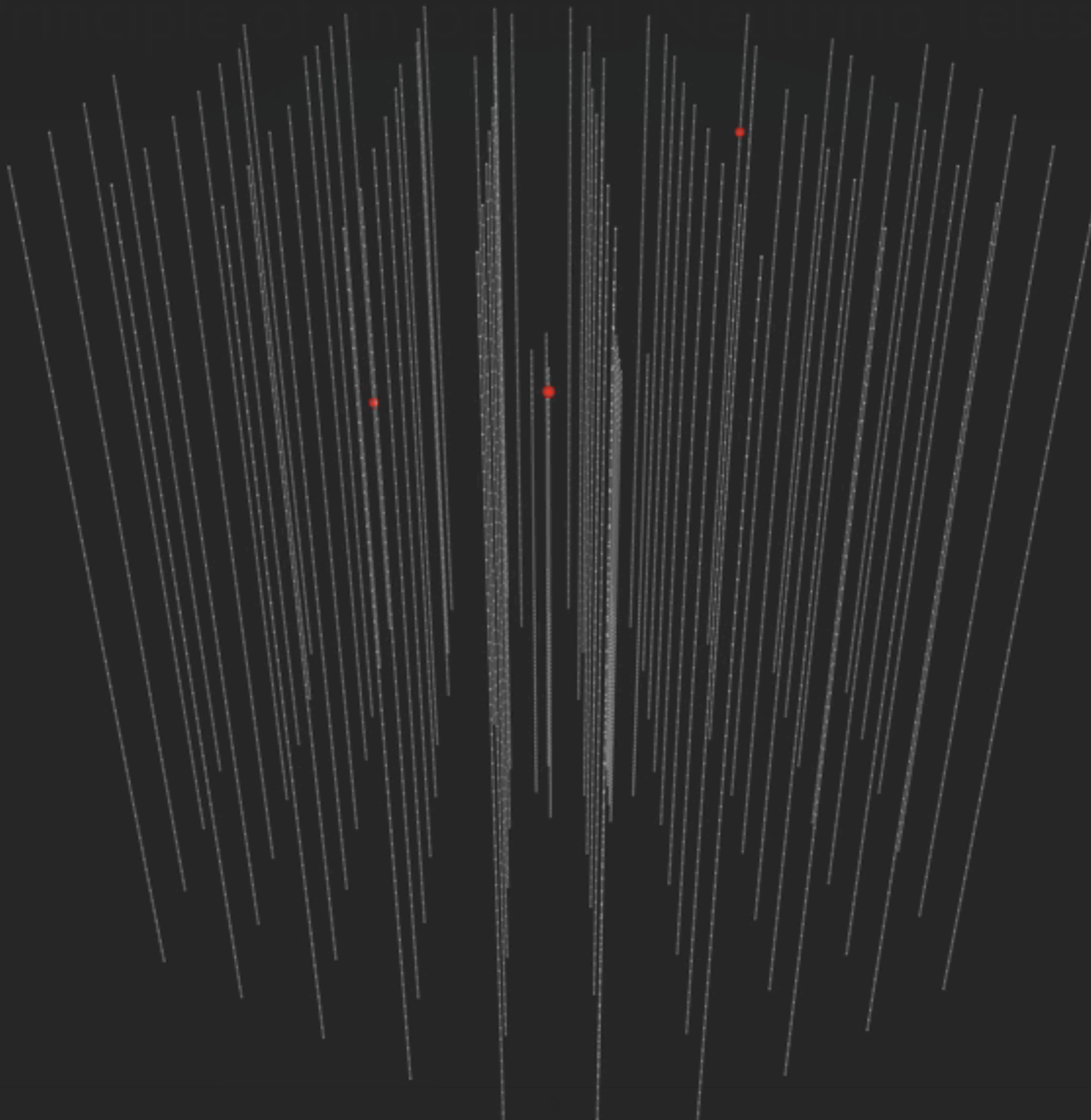
$p+\gamma_{3K} \rightarrow \Delta^+$ (GZK)

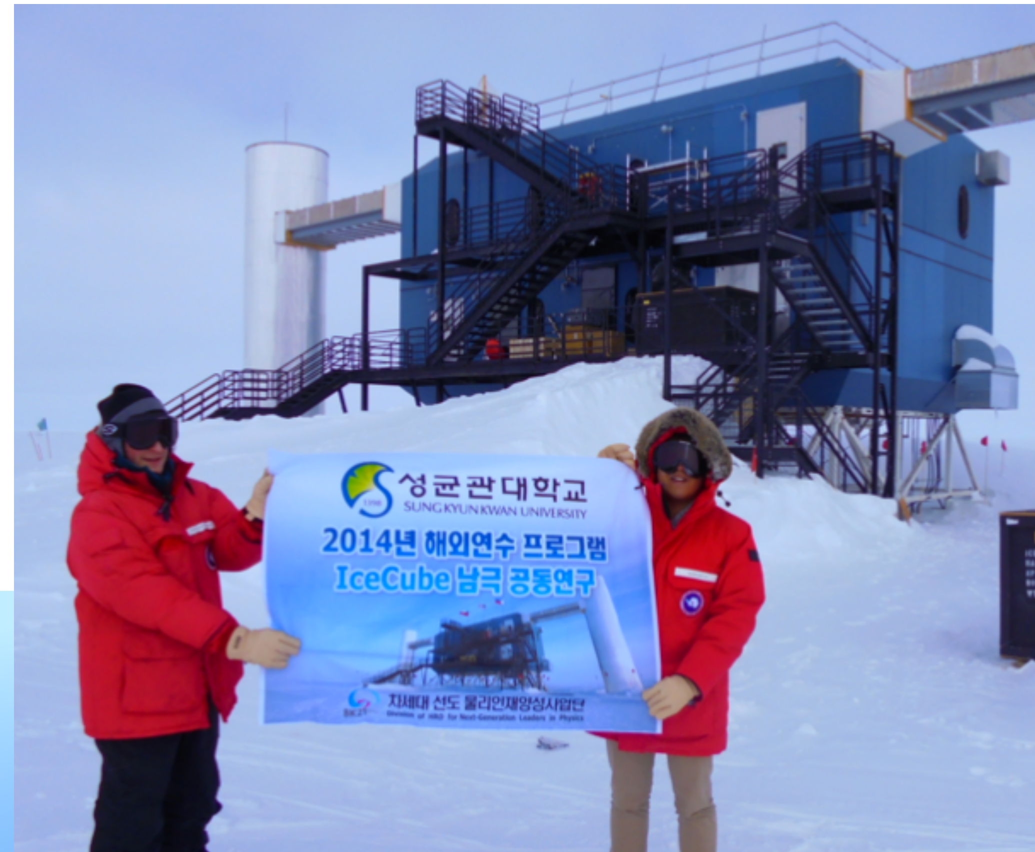


Principle of an optical Neutrino Telescope



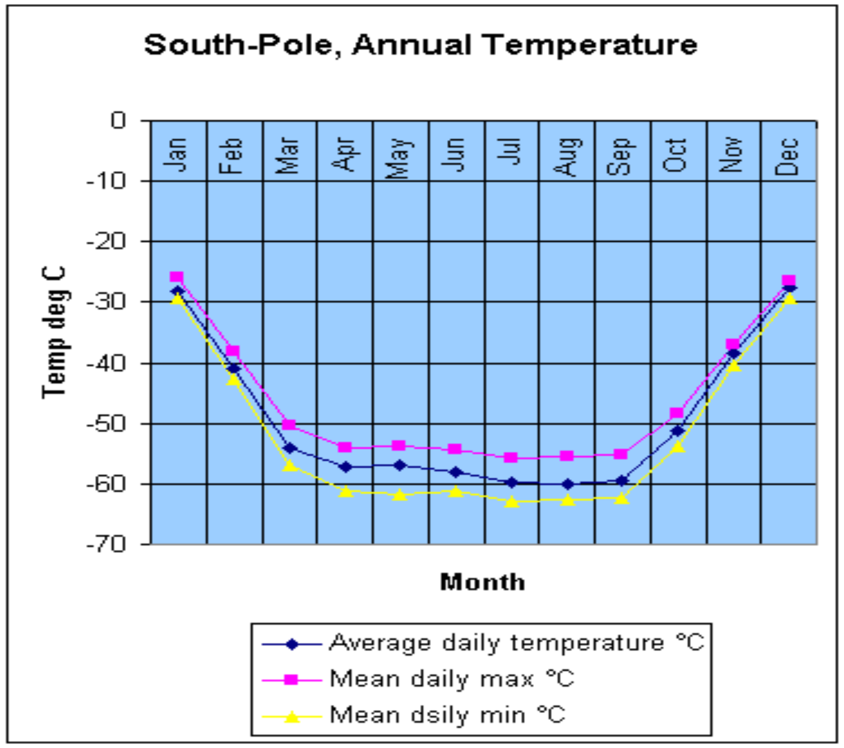


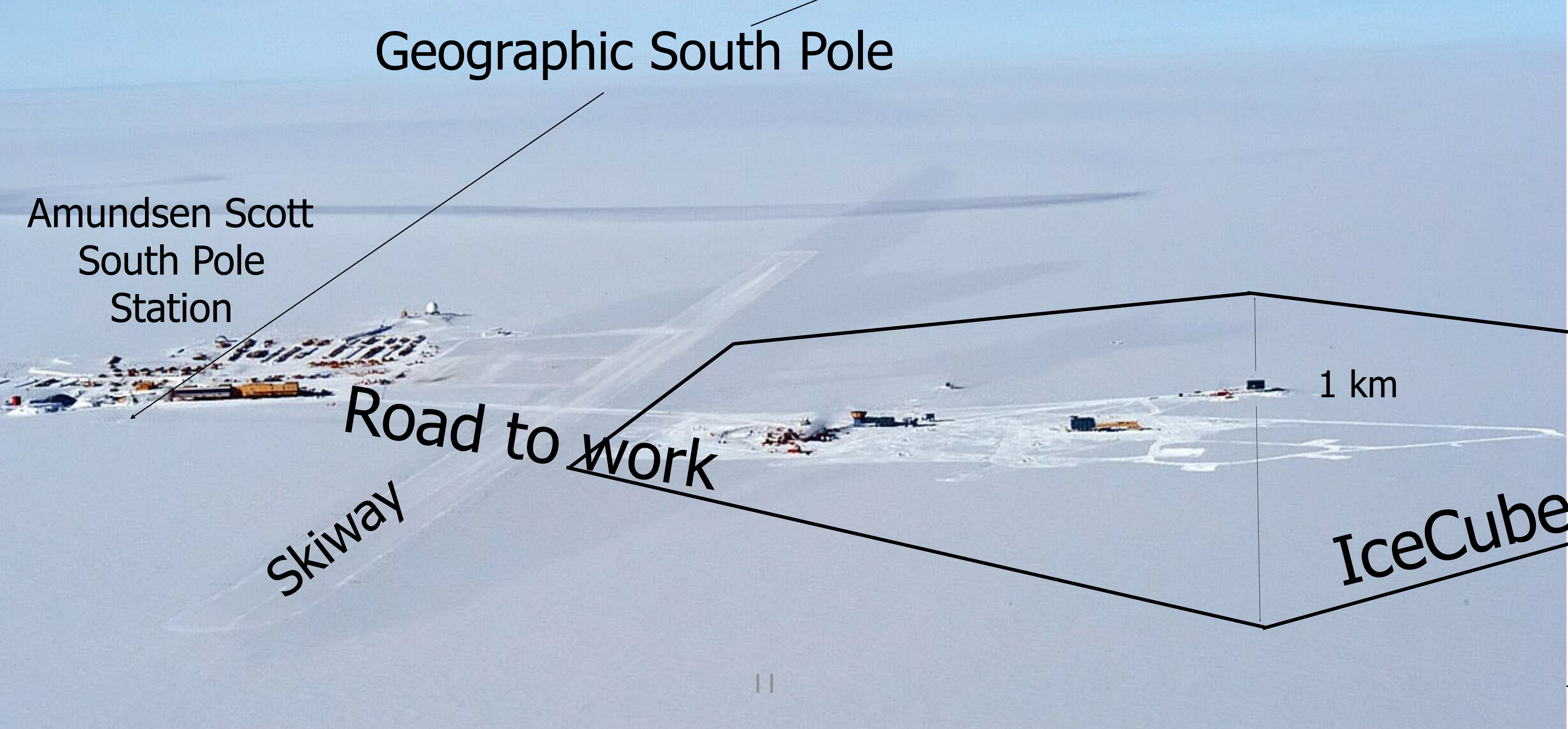




The IceCube Neutrino Telescope

Laboratory at the South Pole

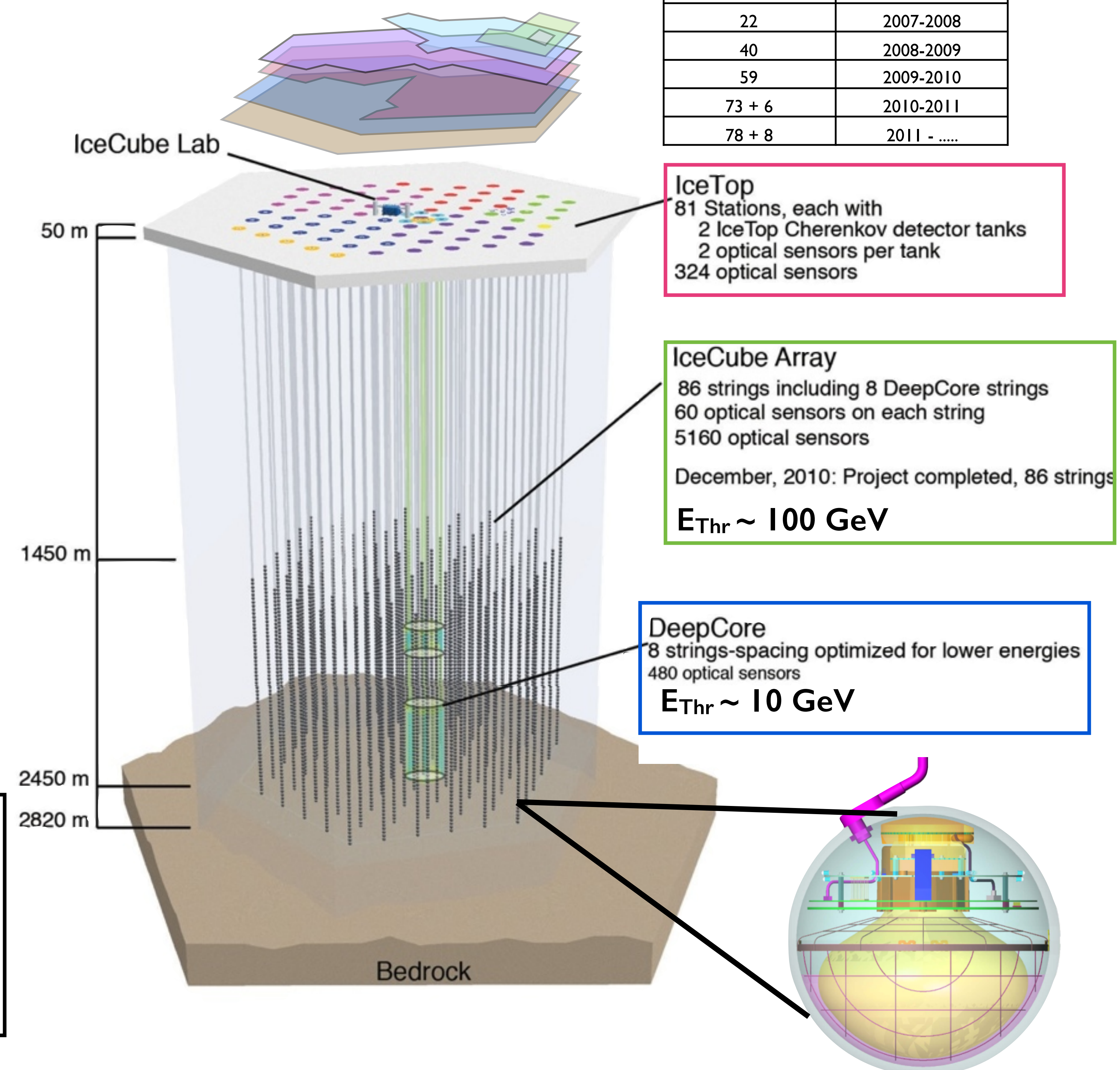




The IceCube Neutrino Telescope

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

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



Dark Matter Searches

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

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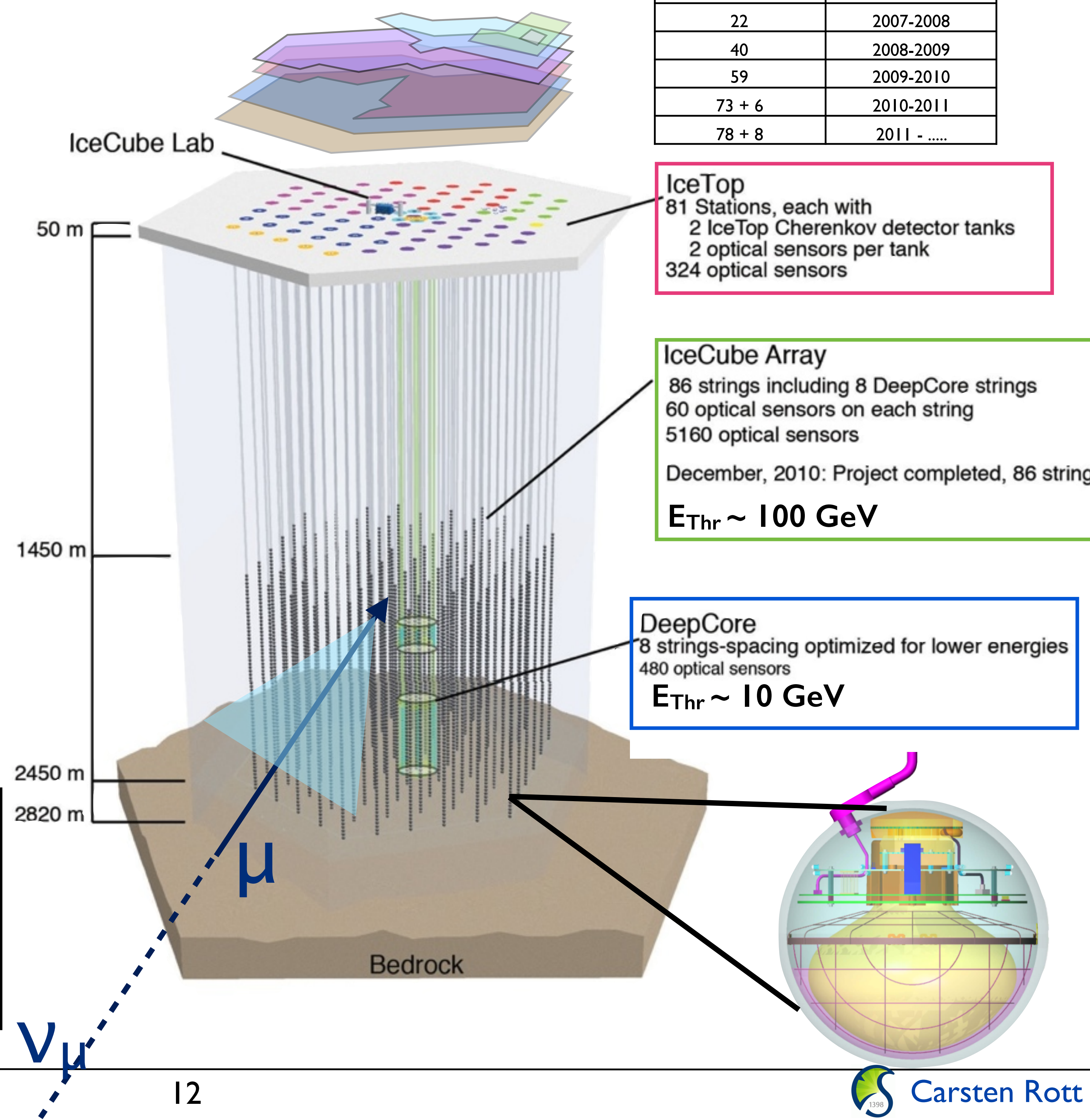

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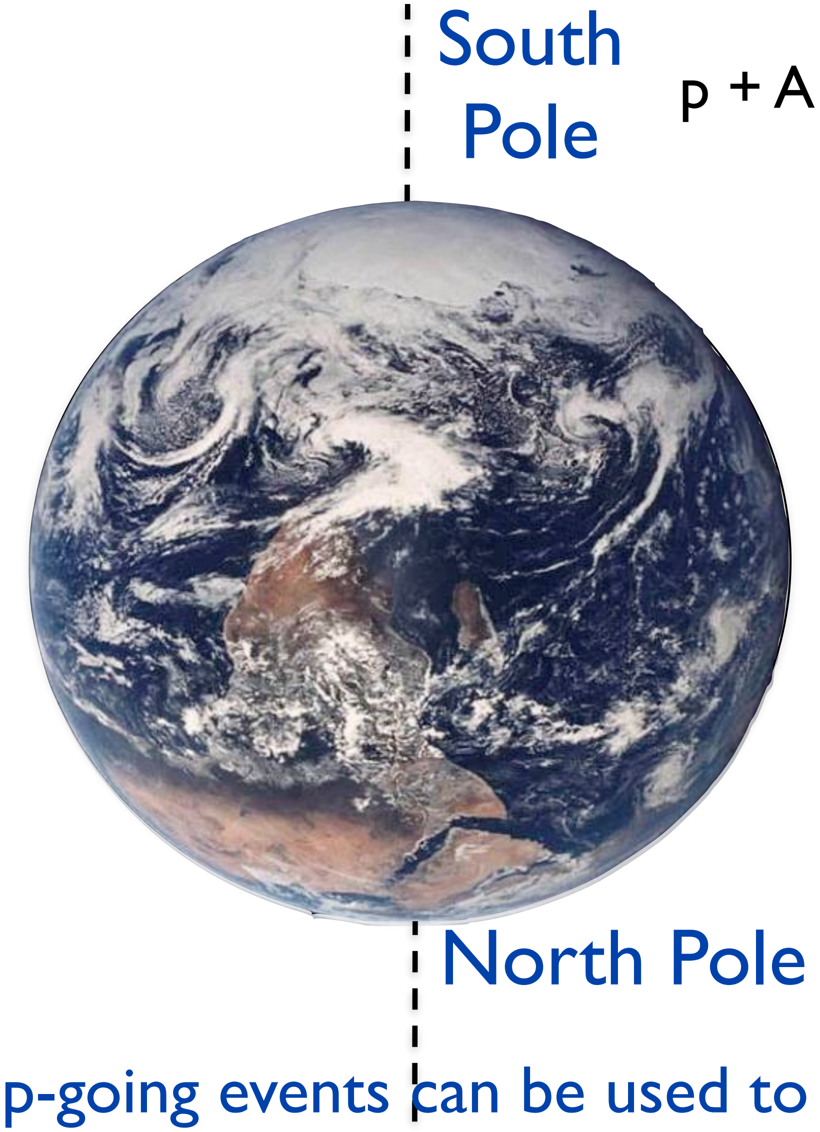
Signals in IceCube



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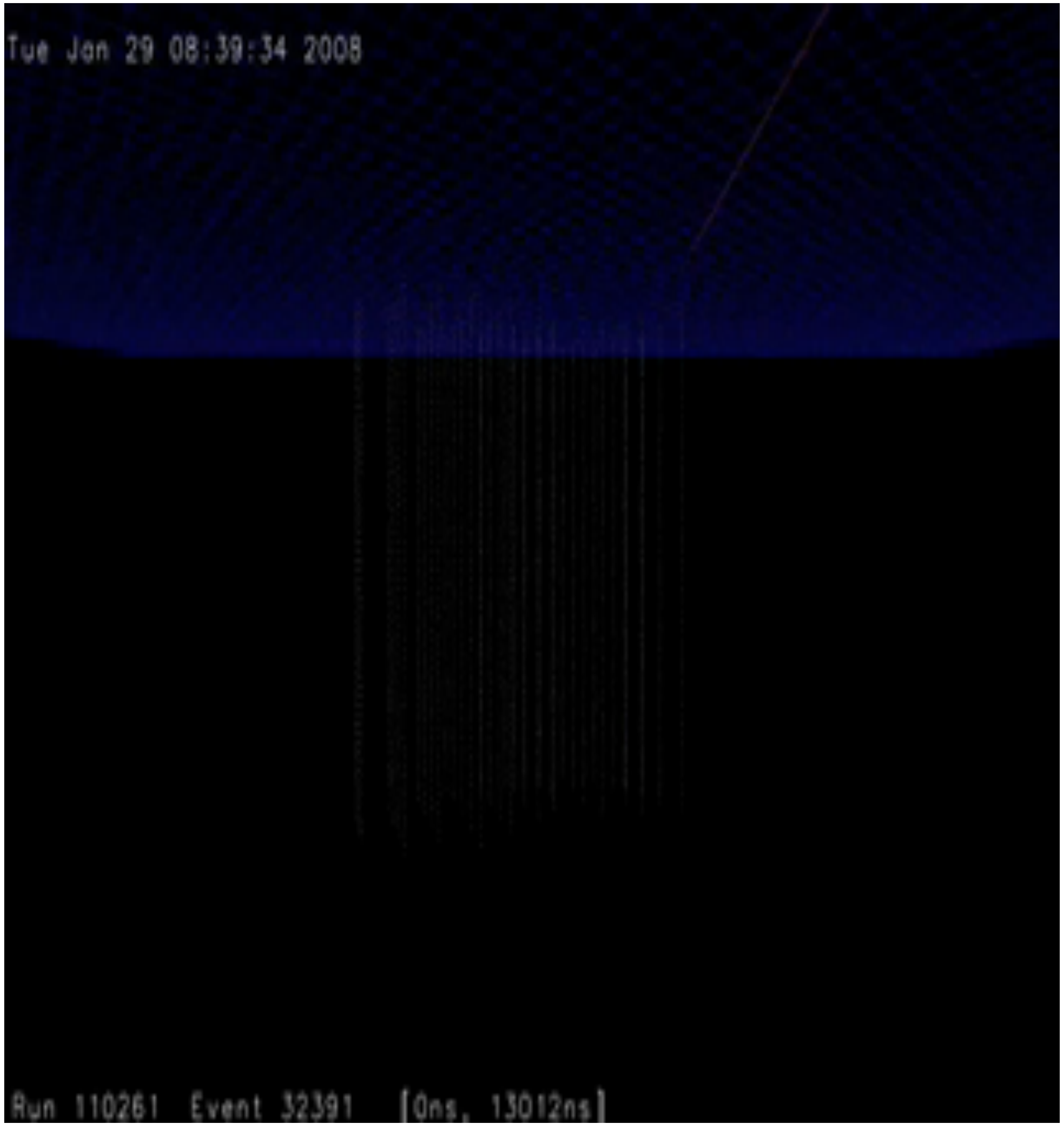

- Up-going events can be used to obtain "clean" neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

Signals in IceCube

South Pole

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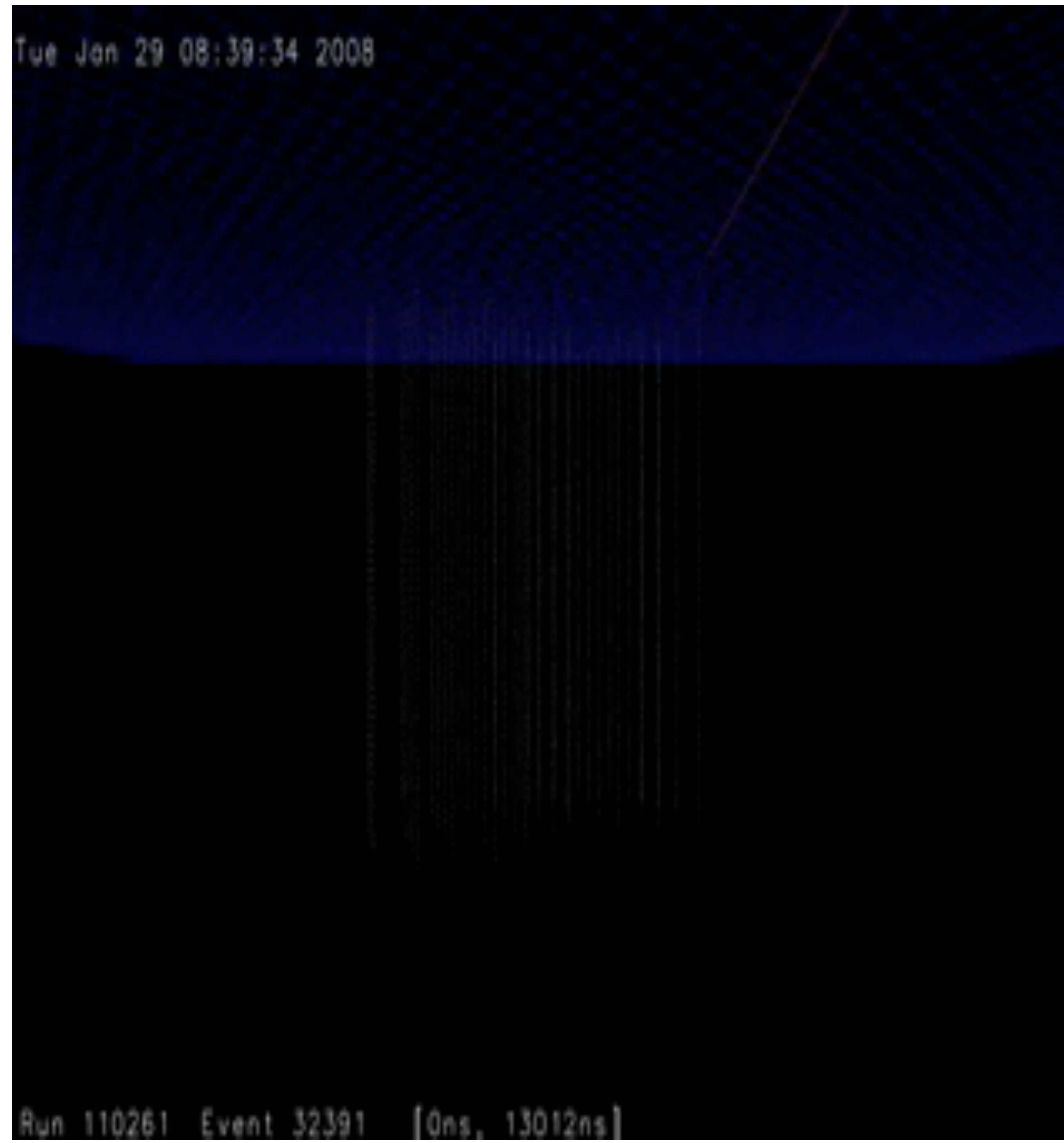
North Pole



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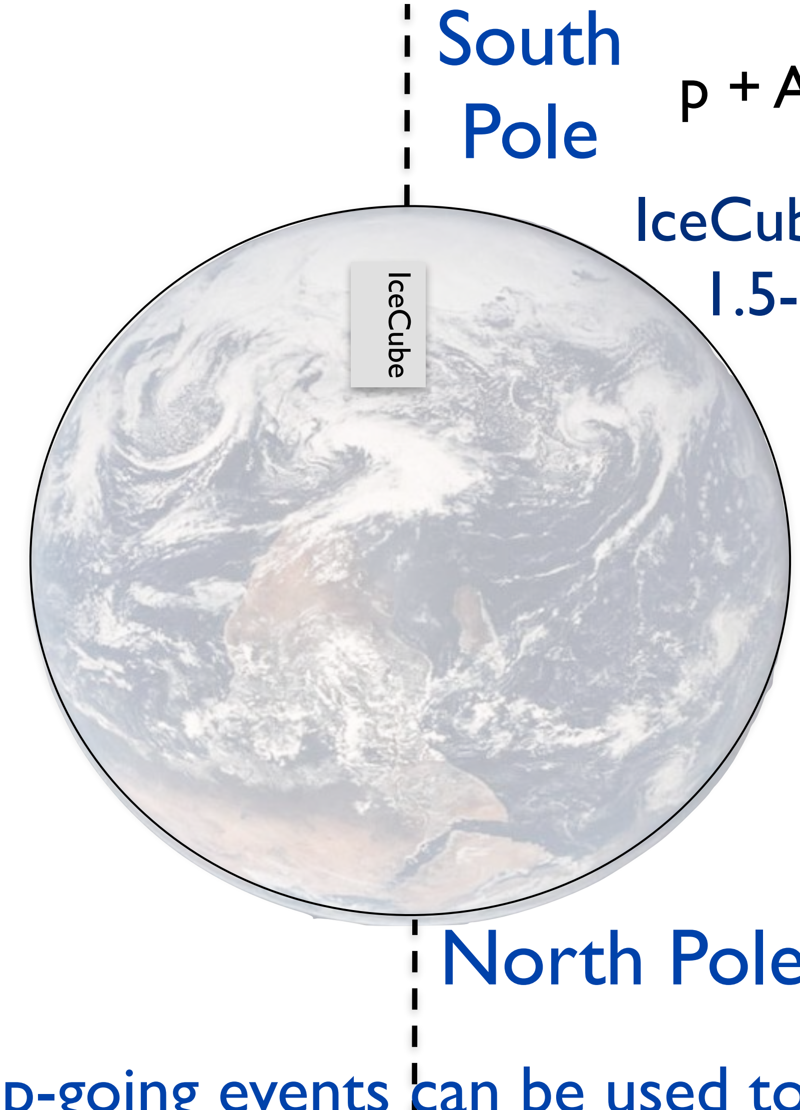
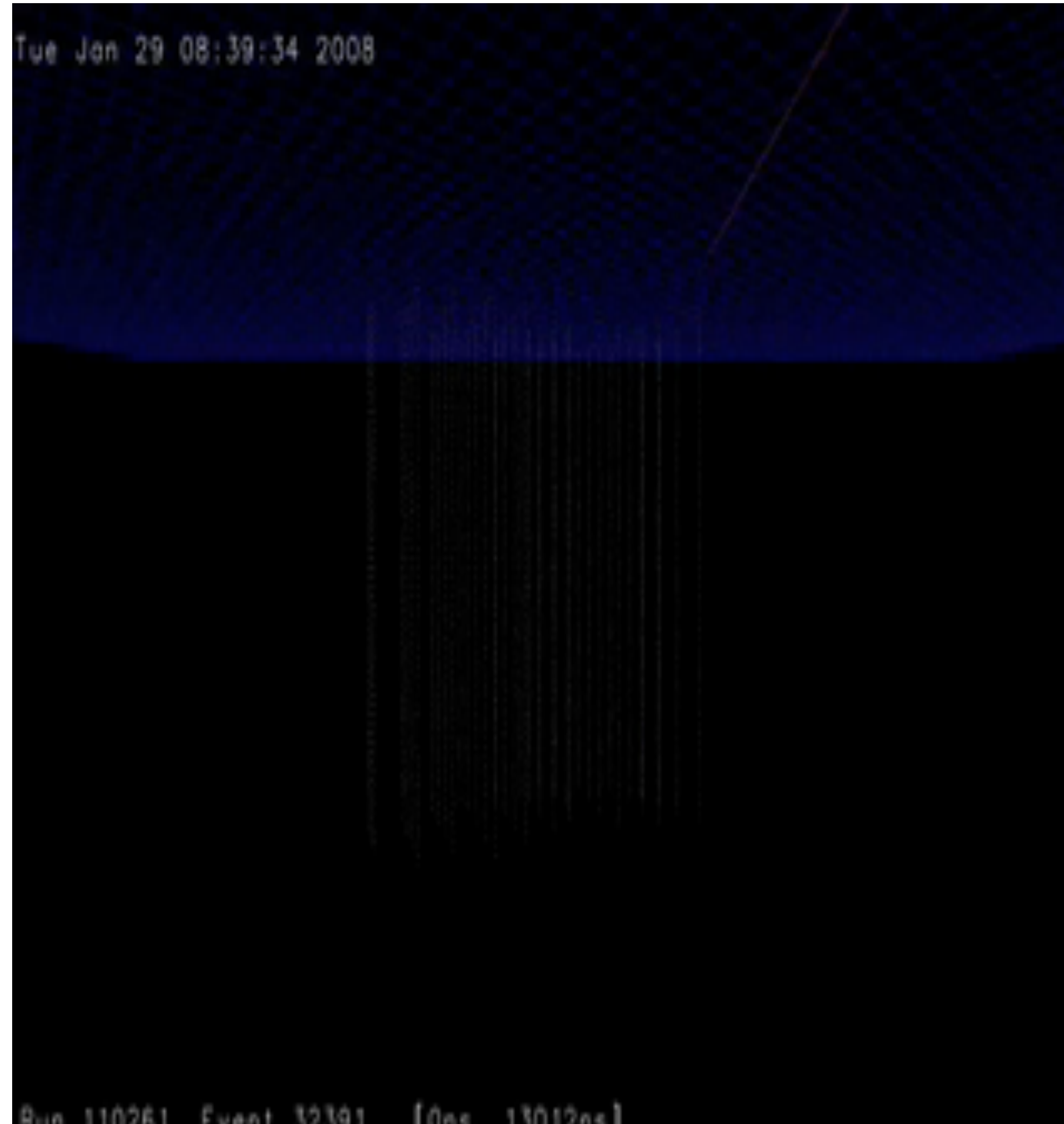


IceCube Depth:
1.5-2.5 km



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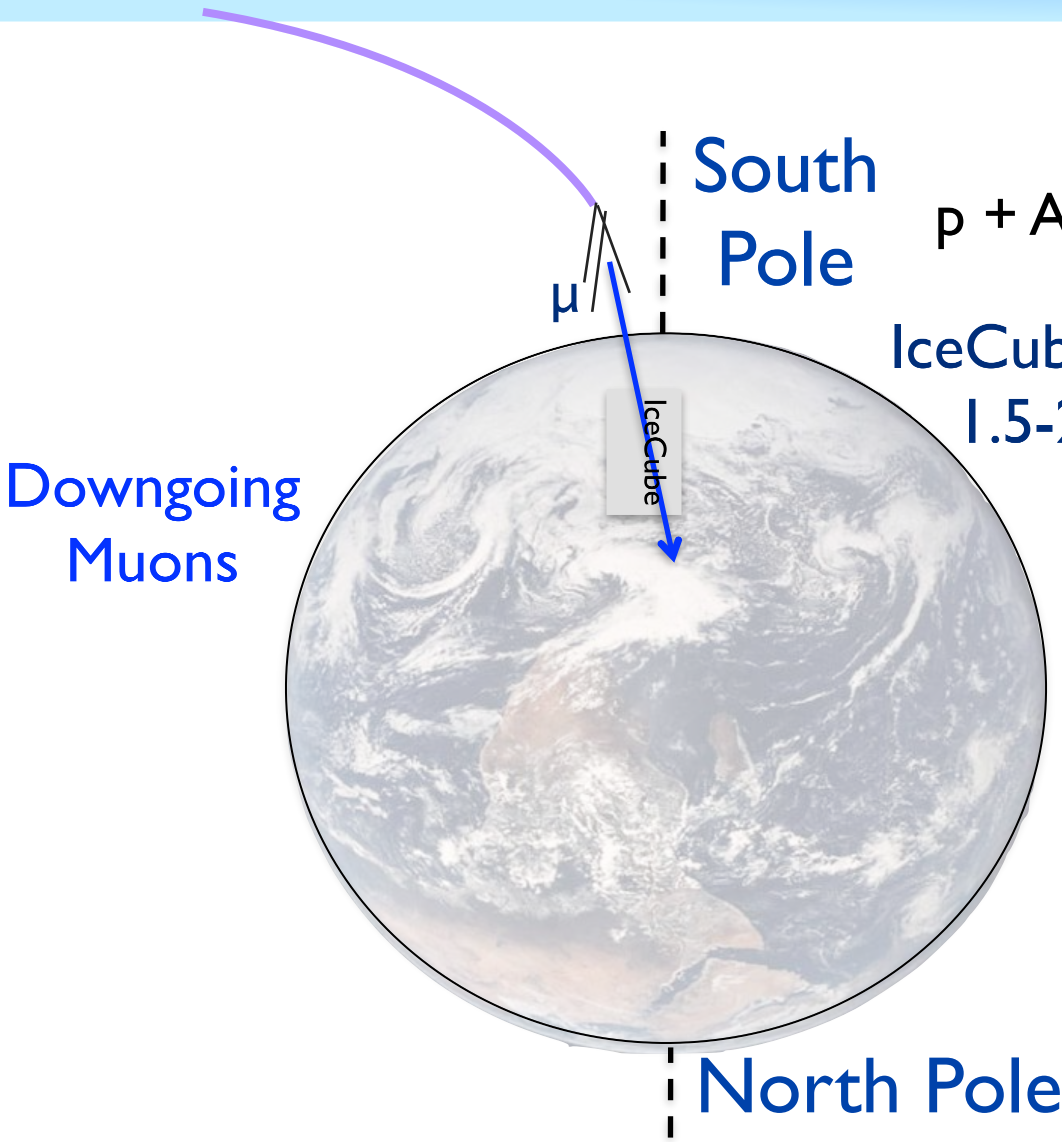

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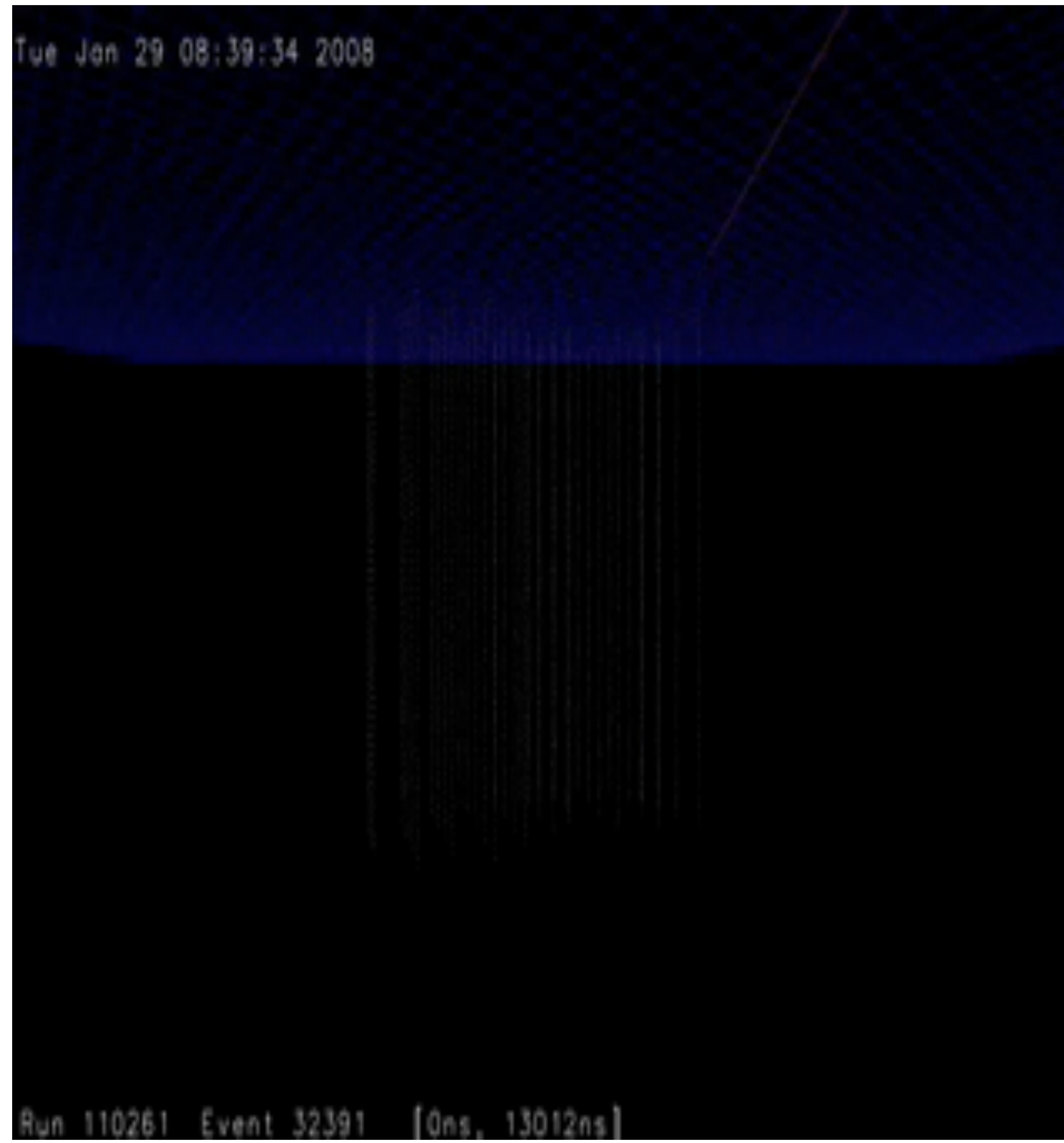

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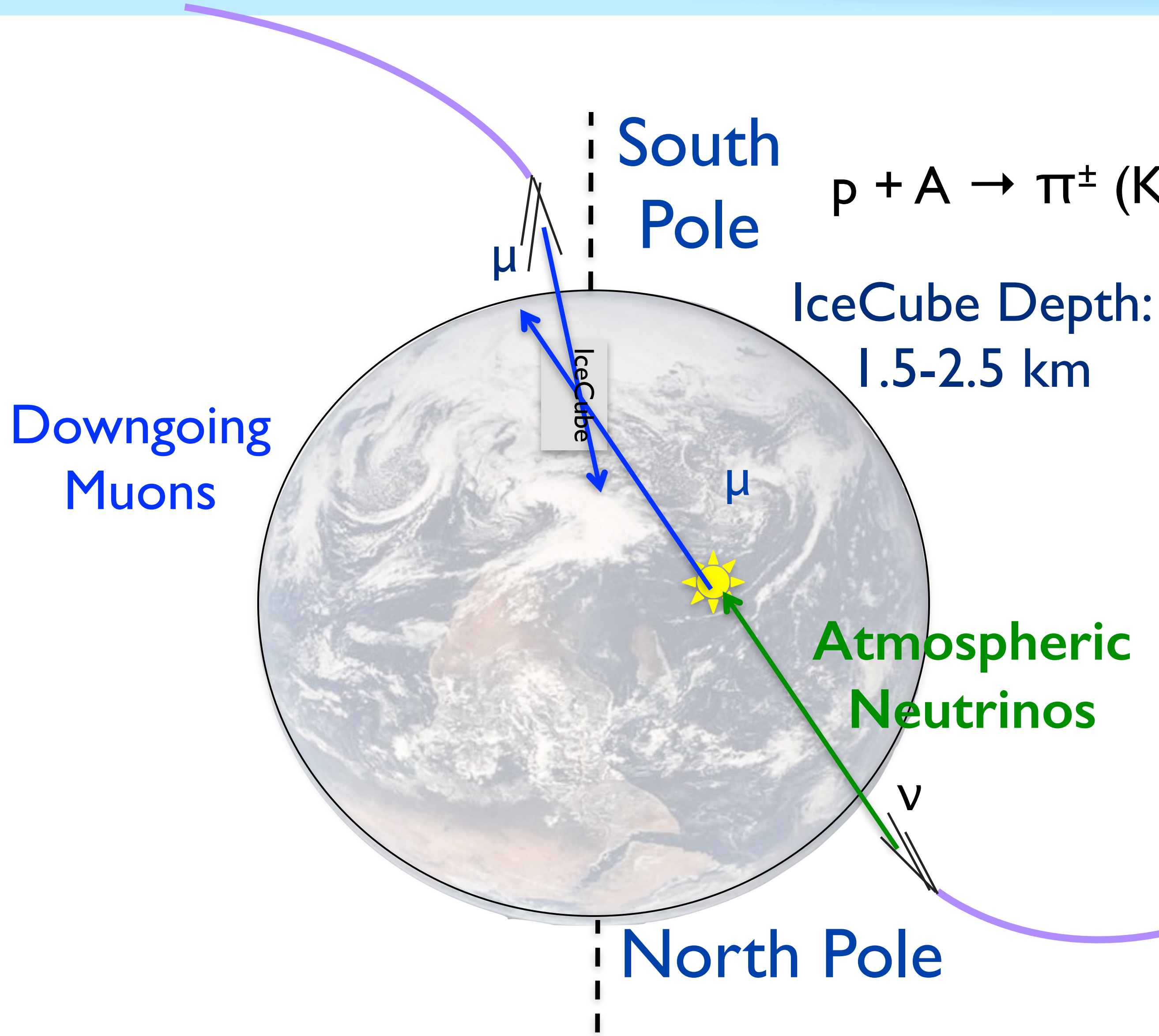

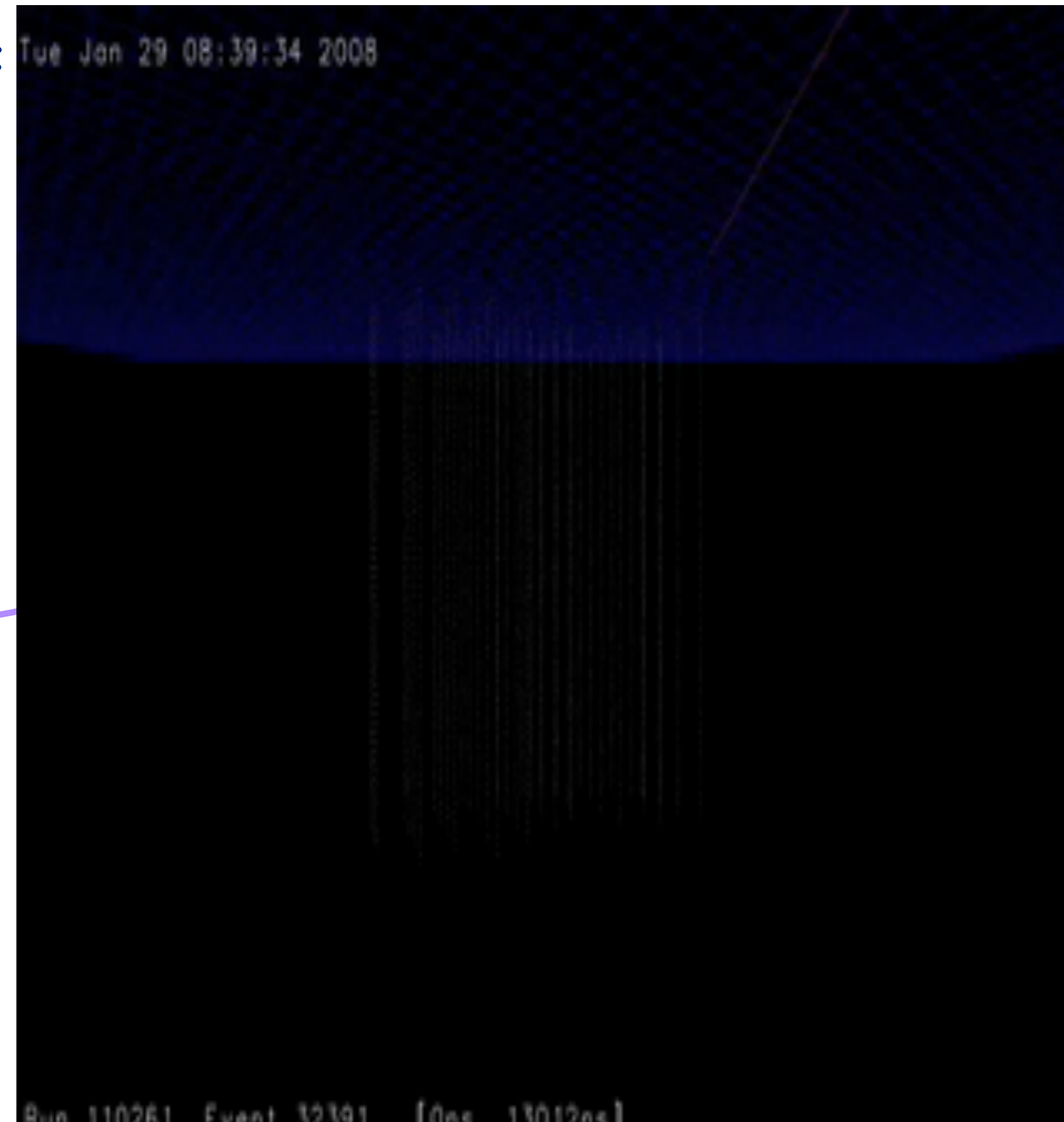

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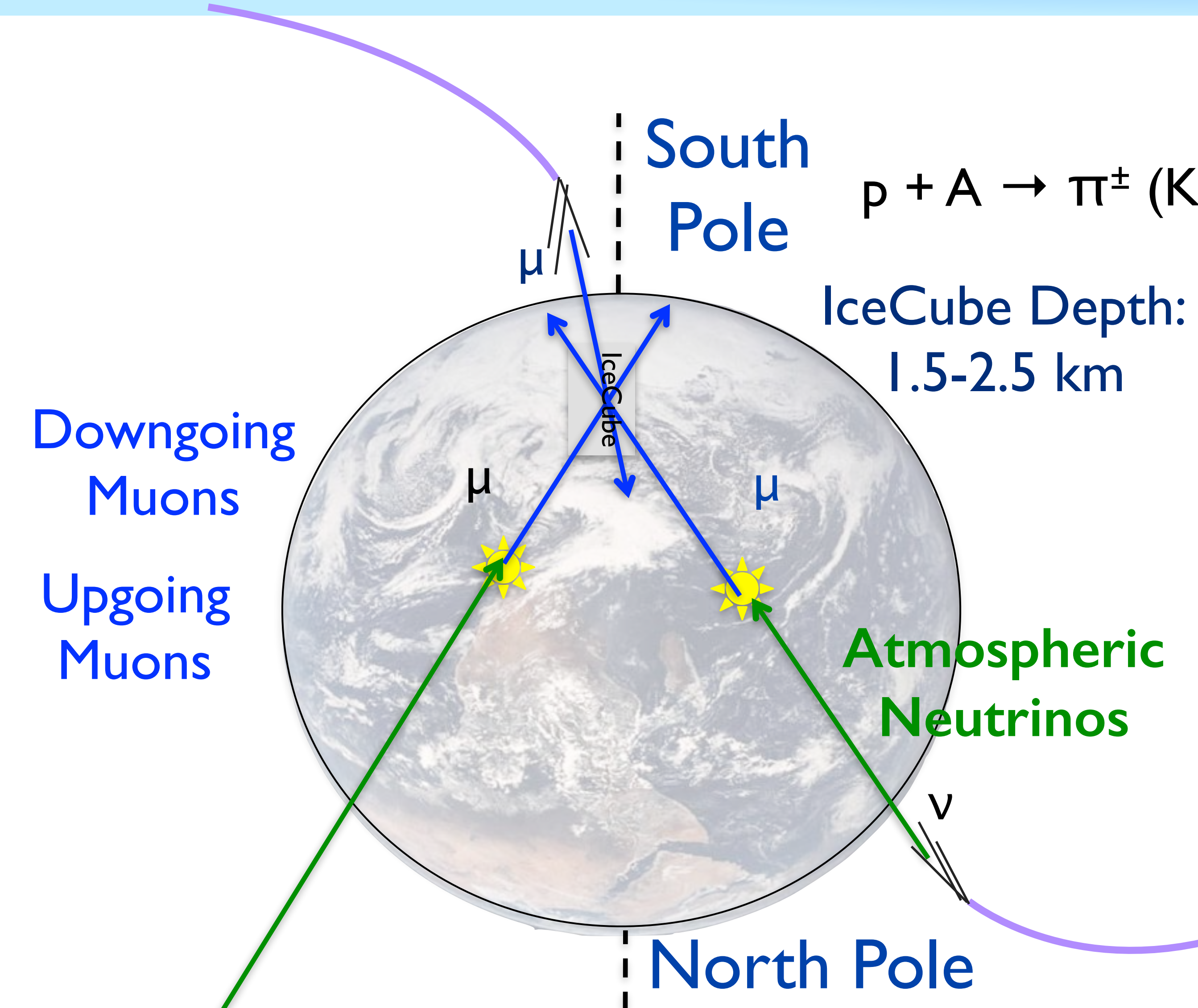

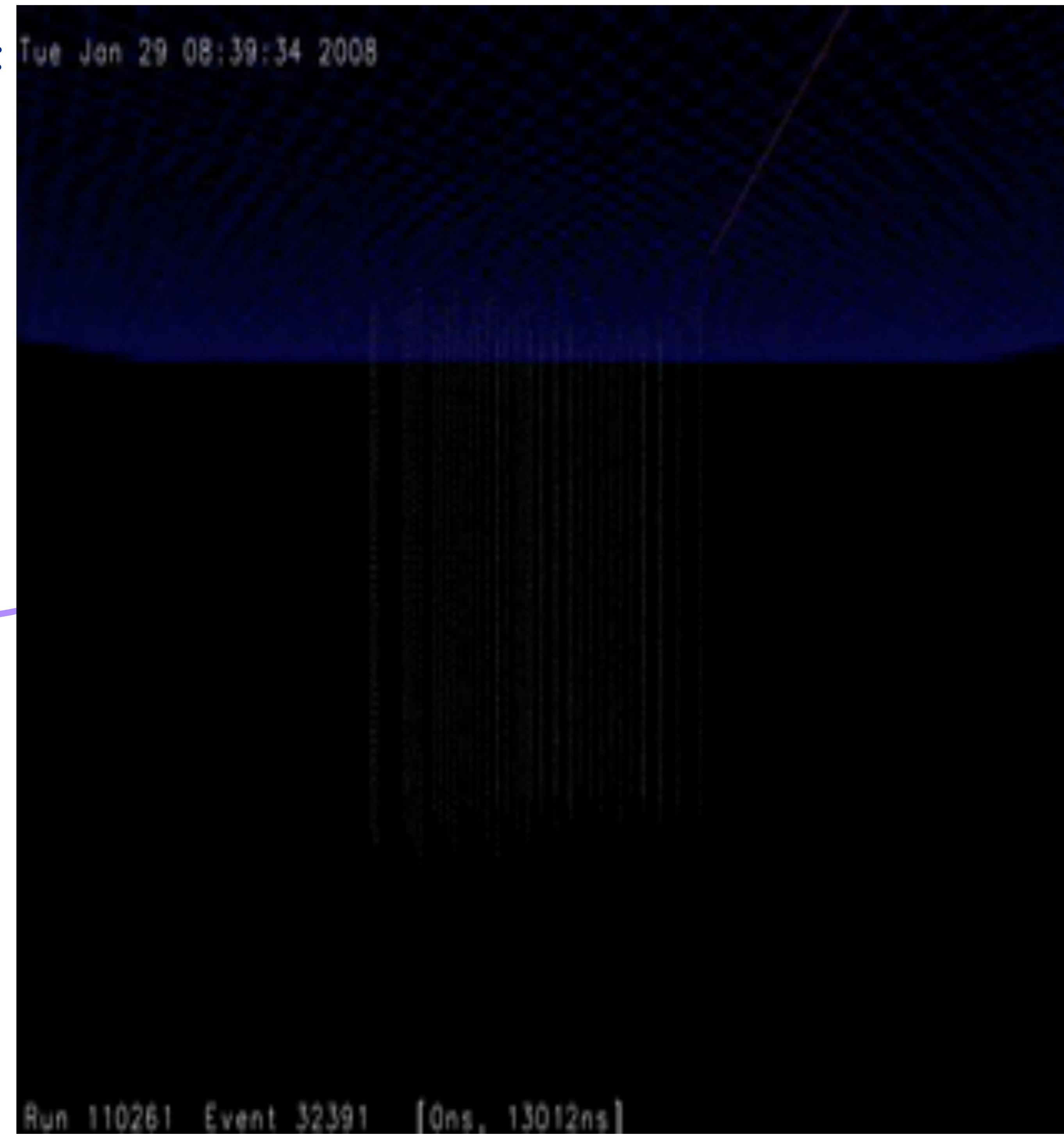

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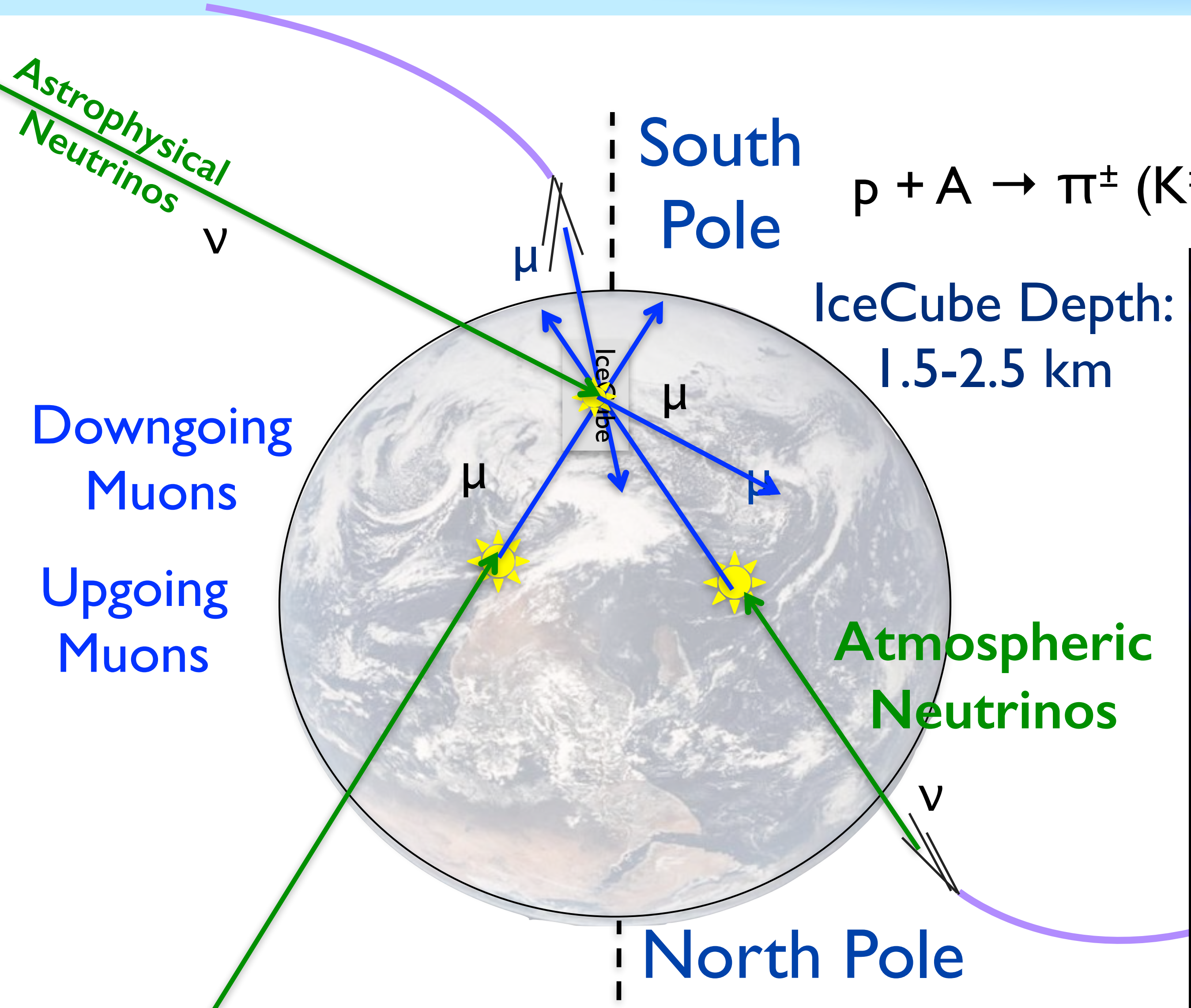

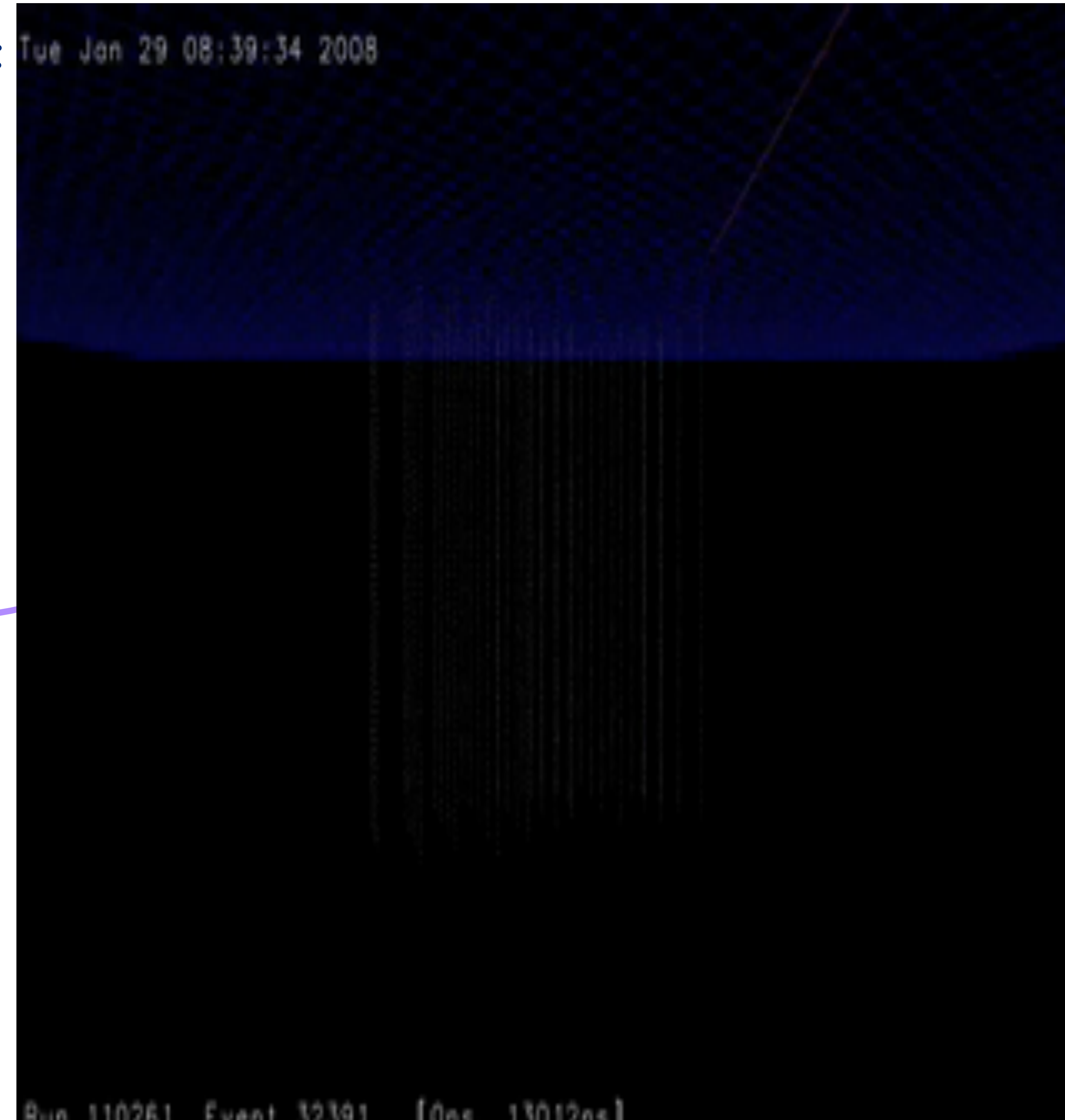

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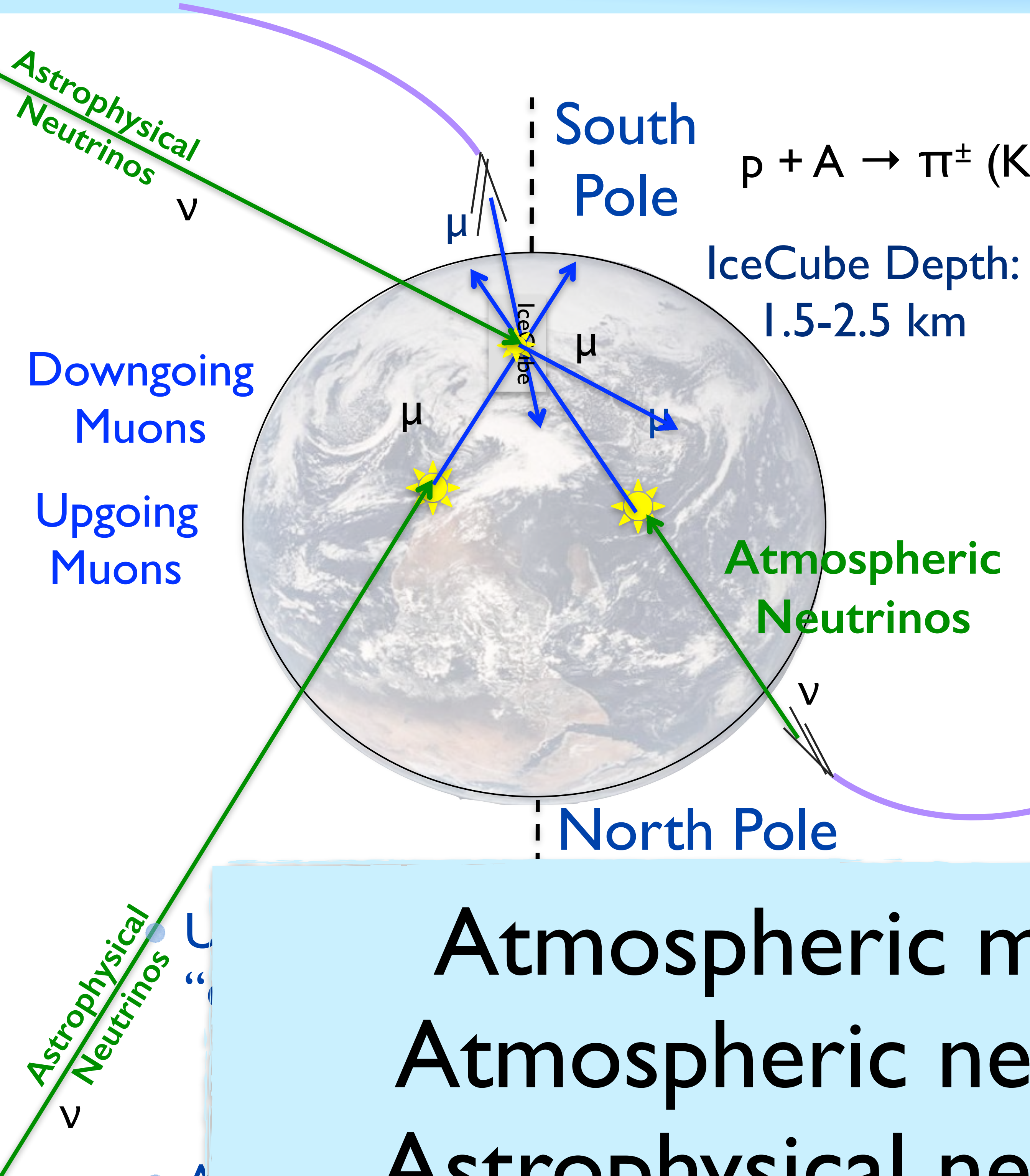
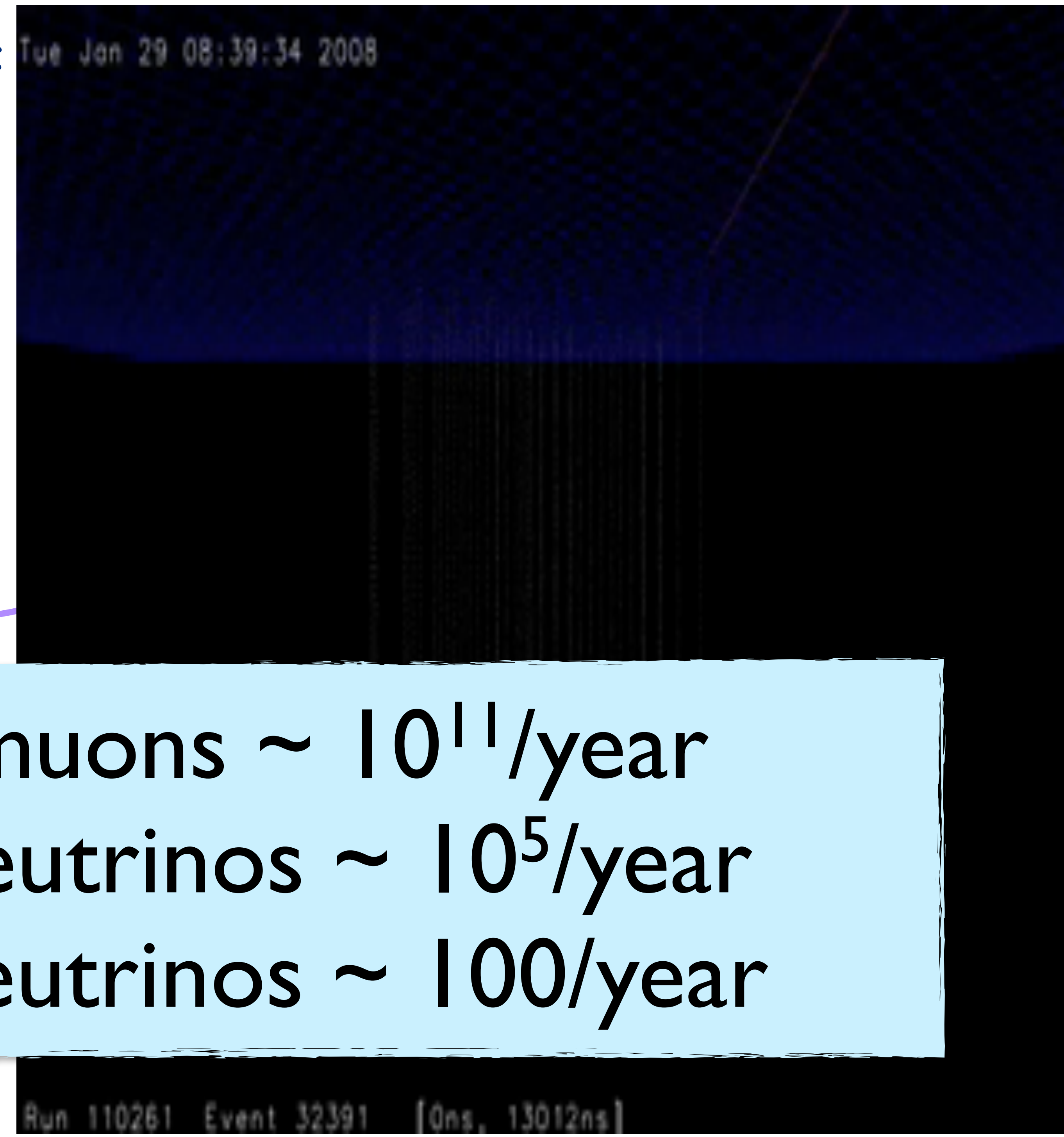




Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
Astrophysical neutrinos ~ 100/year

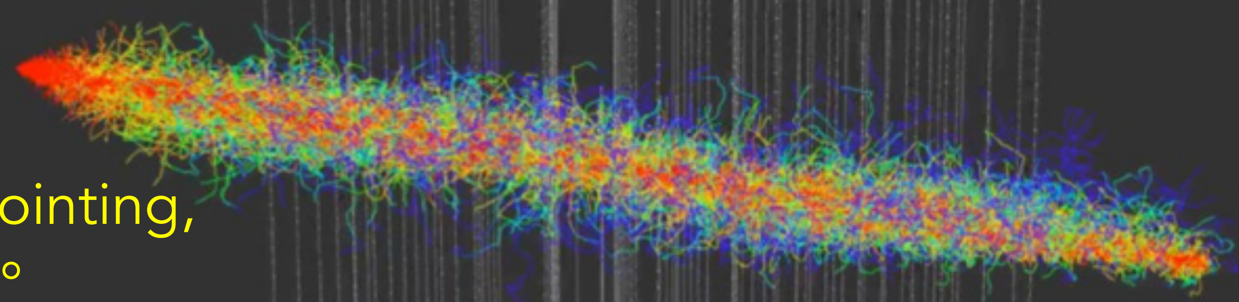
- U… "…
- A… irreducible neutrino background to extra terrestrial neutrino fluxes

Event Topologies in IceCube

CC: ν_μ

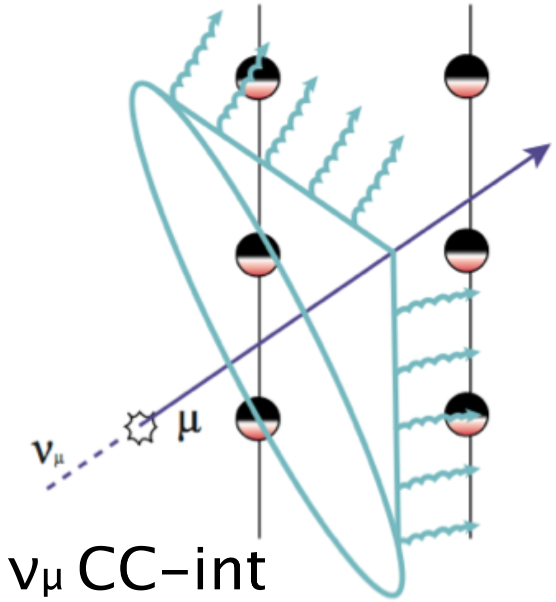
Track topology

(e.g. induced by muon neutrino)



Good pointing,
0.2° - 1°

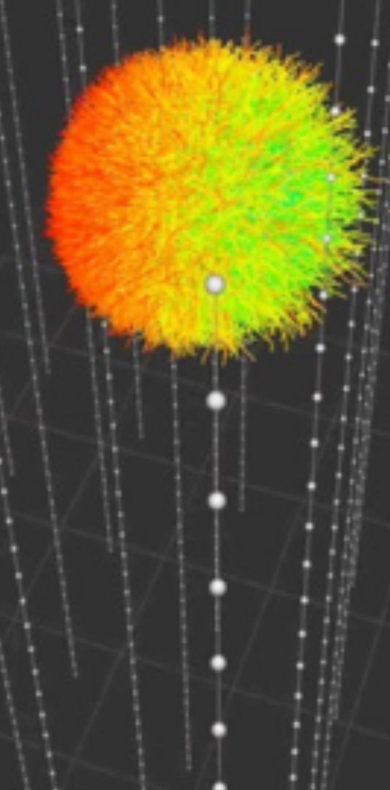
Lower bound on energy for through-going events



ν_μ CC−int

CC: ν_e ν_τ

NC: ν_e ν_μ ν_τ

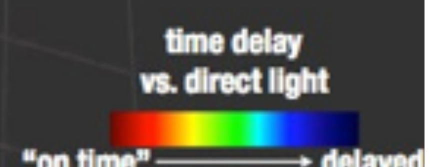


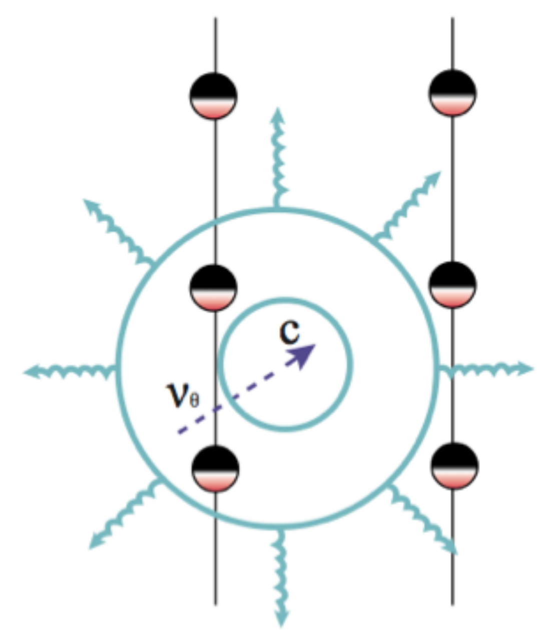
Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

Some pointing,
10° - 15°

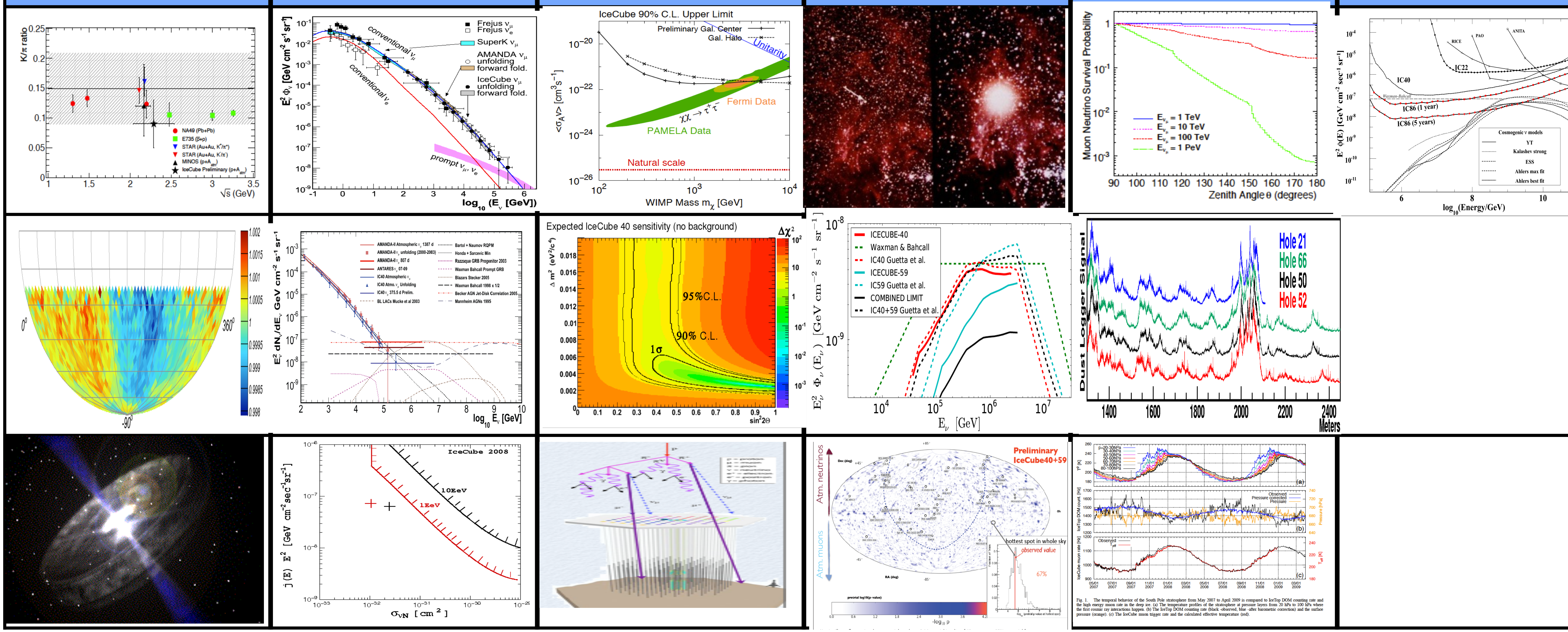




ν_e ν_τ CC−int & ν_i NC−int

IceCube Science

Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology



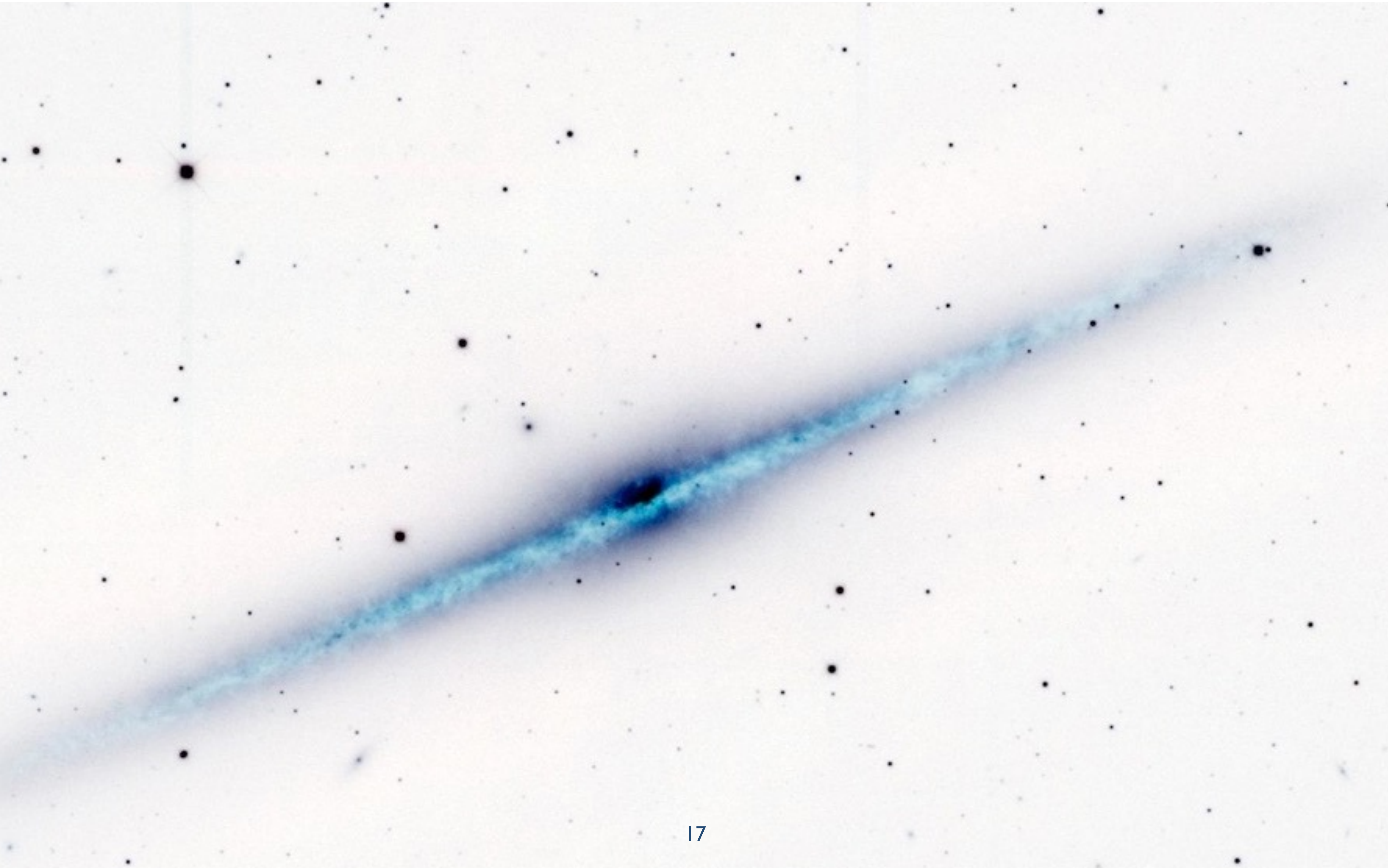
Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

Dark Matter Self-annihilations

$\langle\sigma_A v\rangle$

Dark Matter in the Milky Way

Dark Matter in the Milky Way



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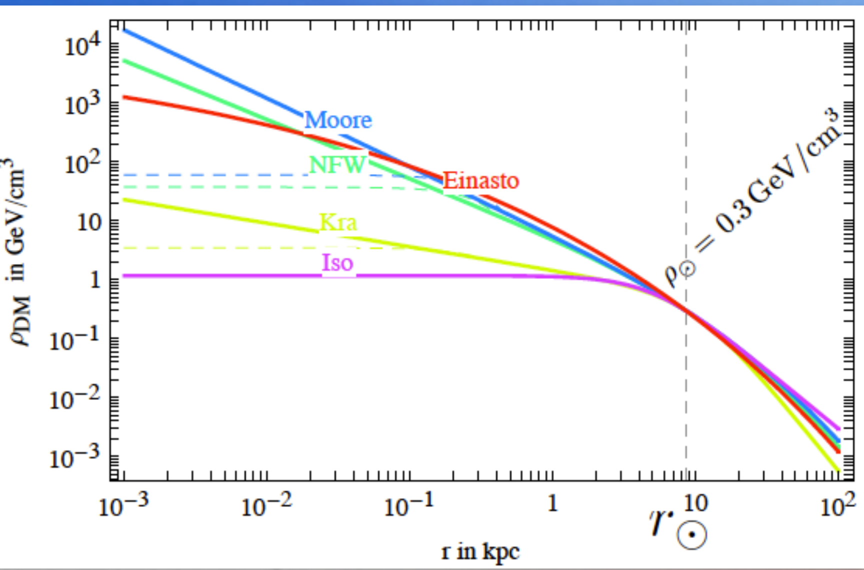

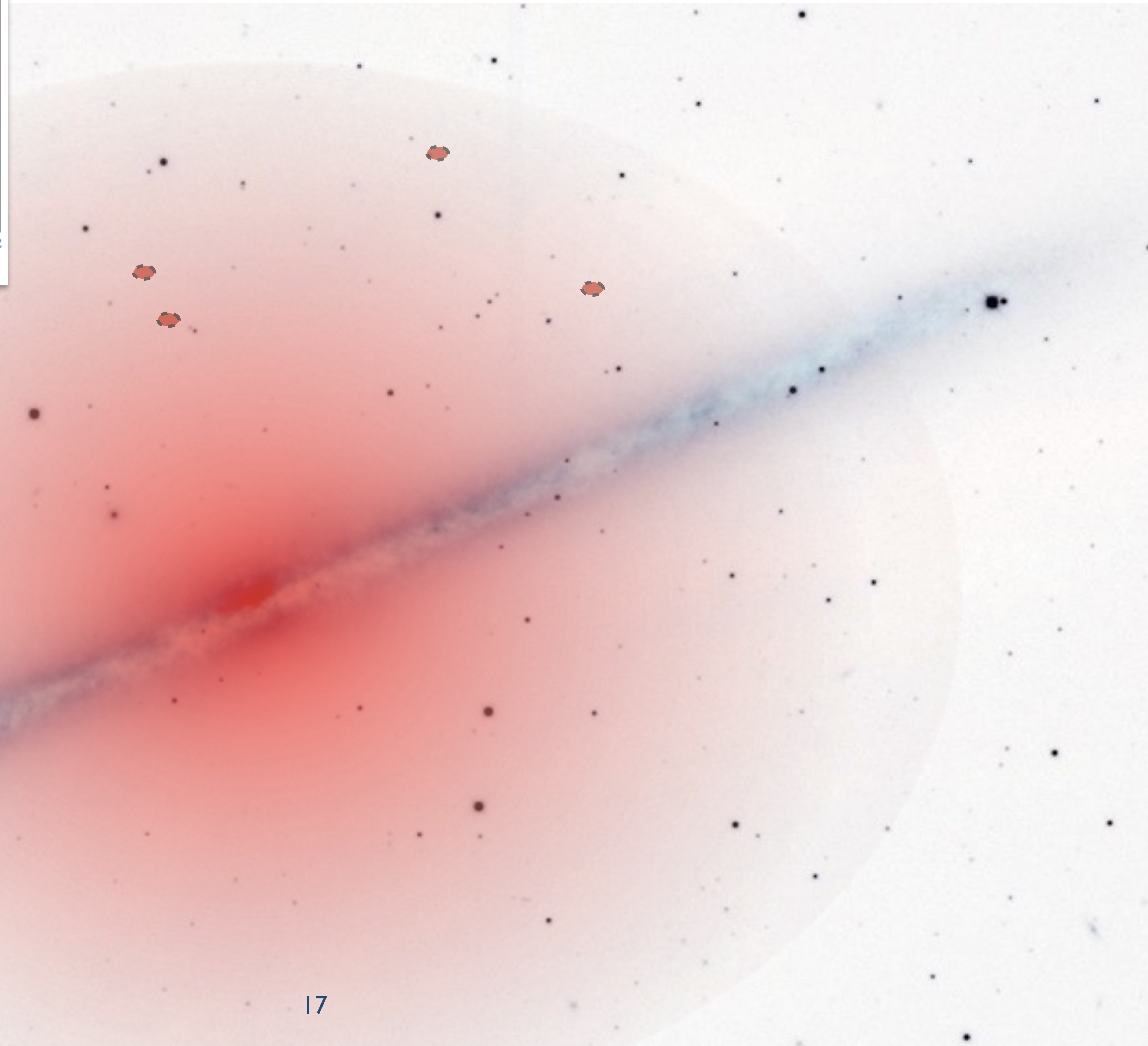

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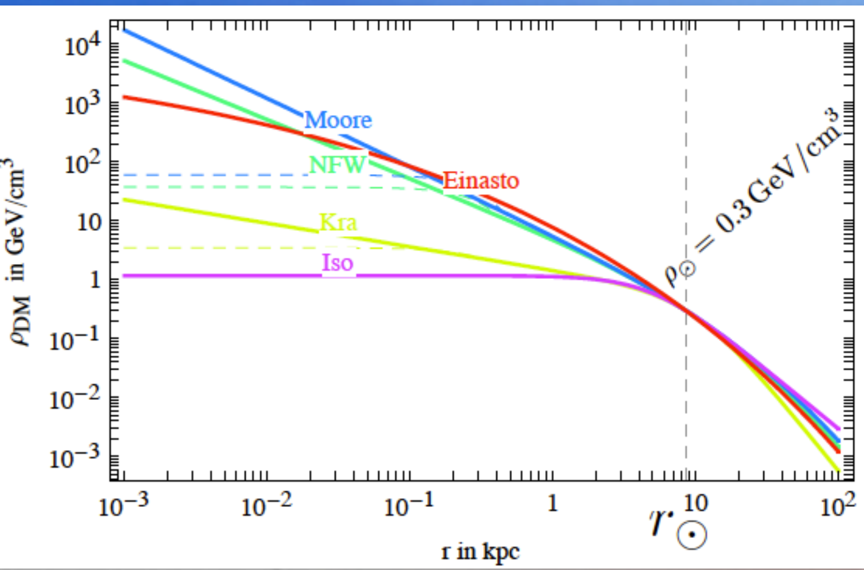

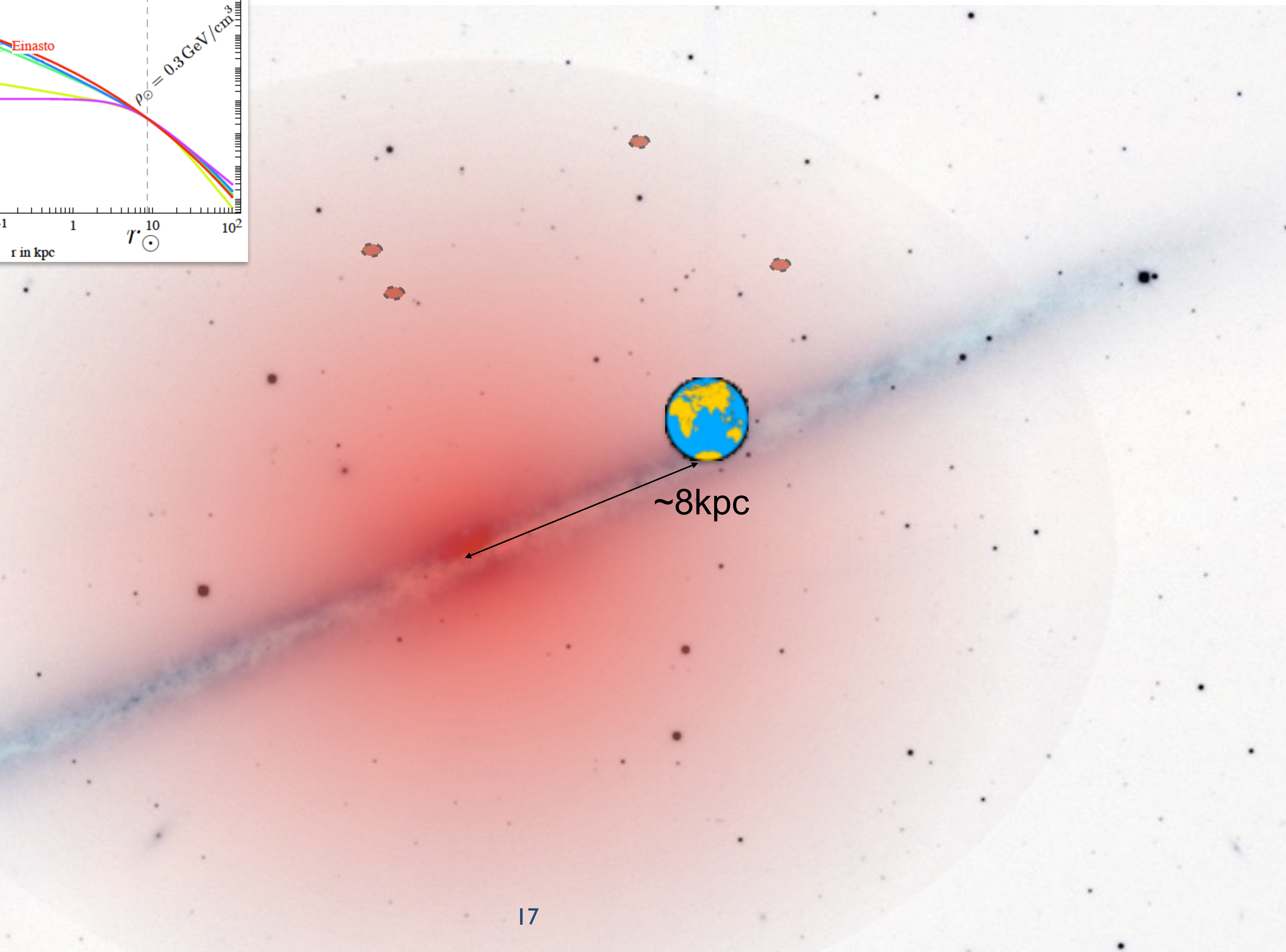

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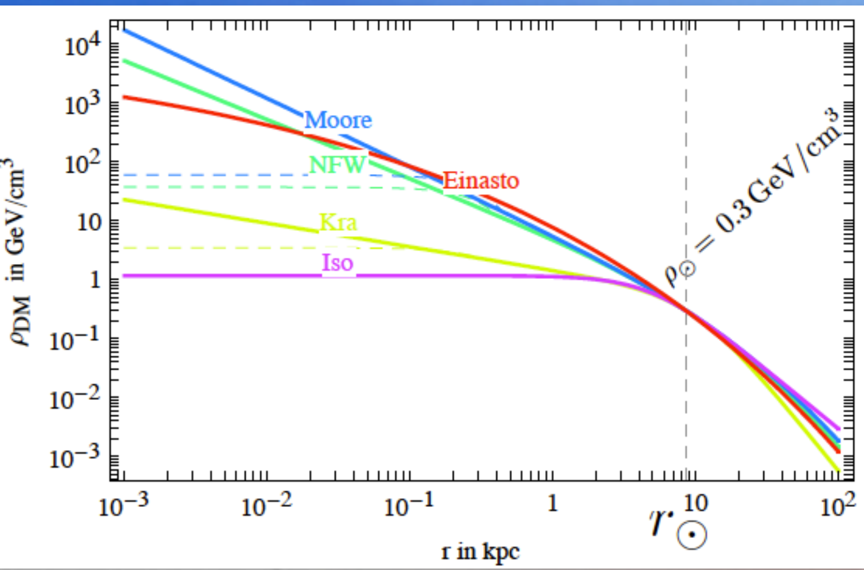
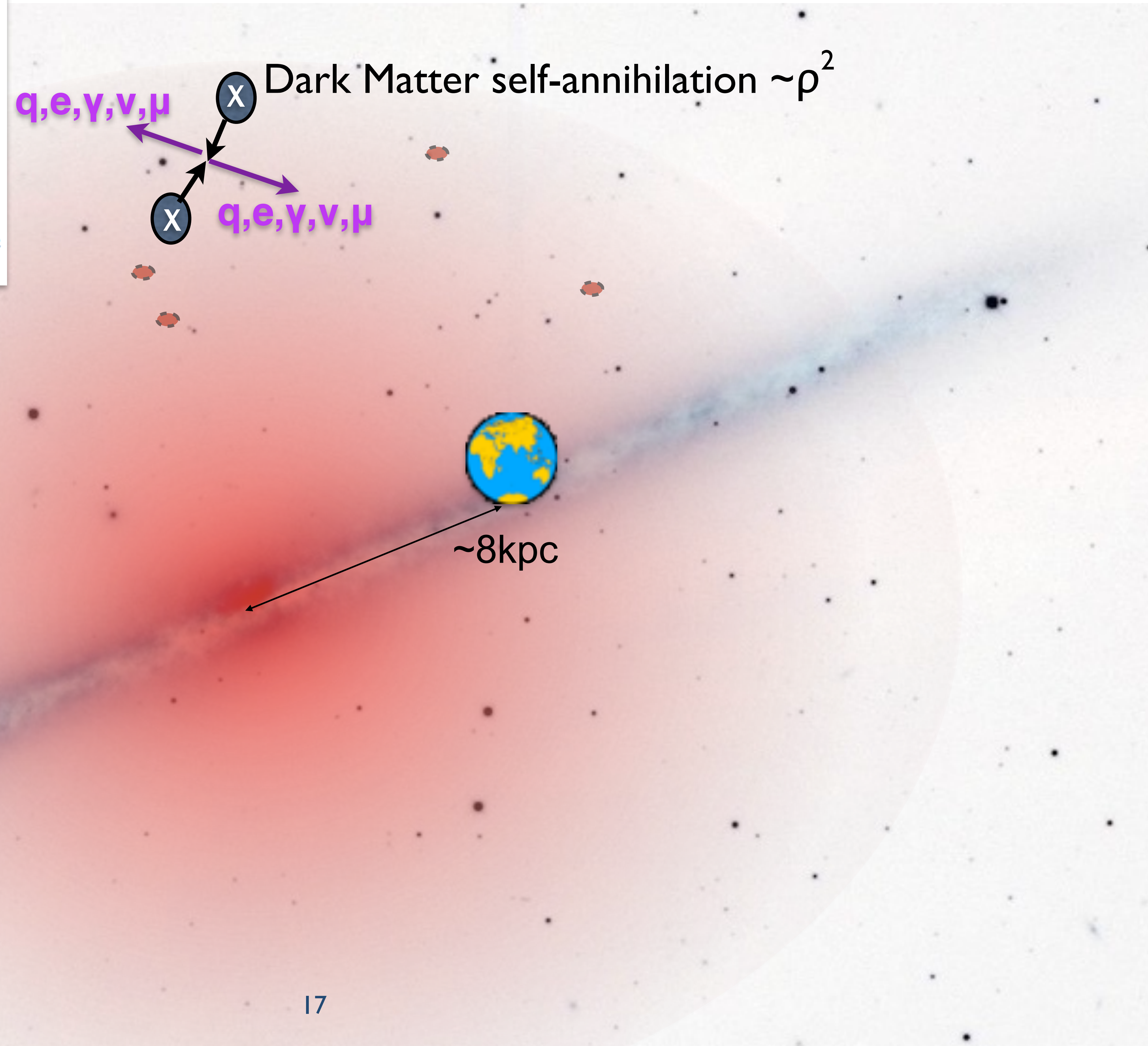
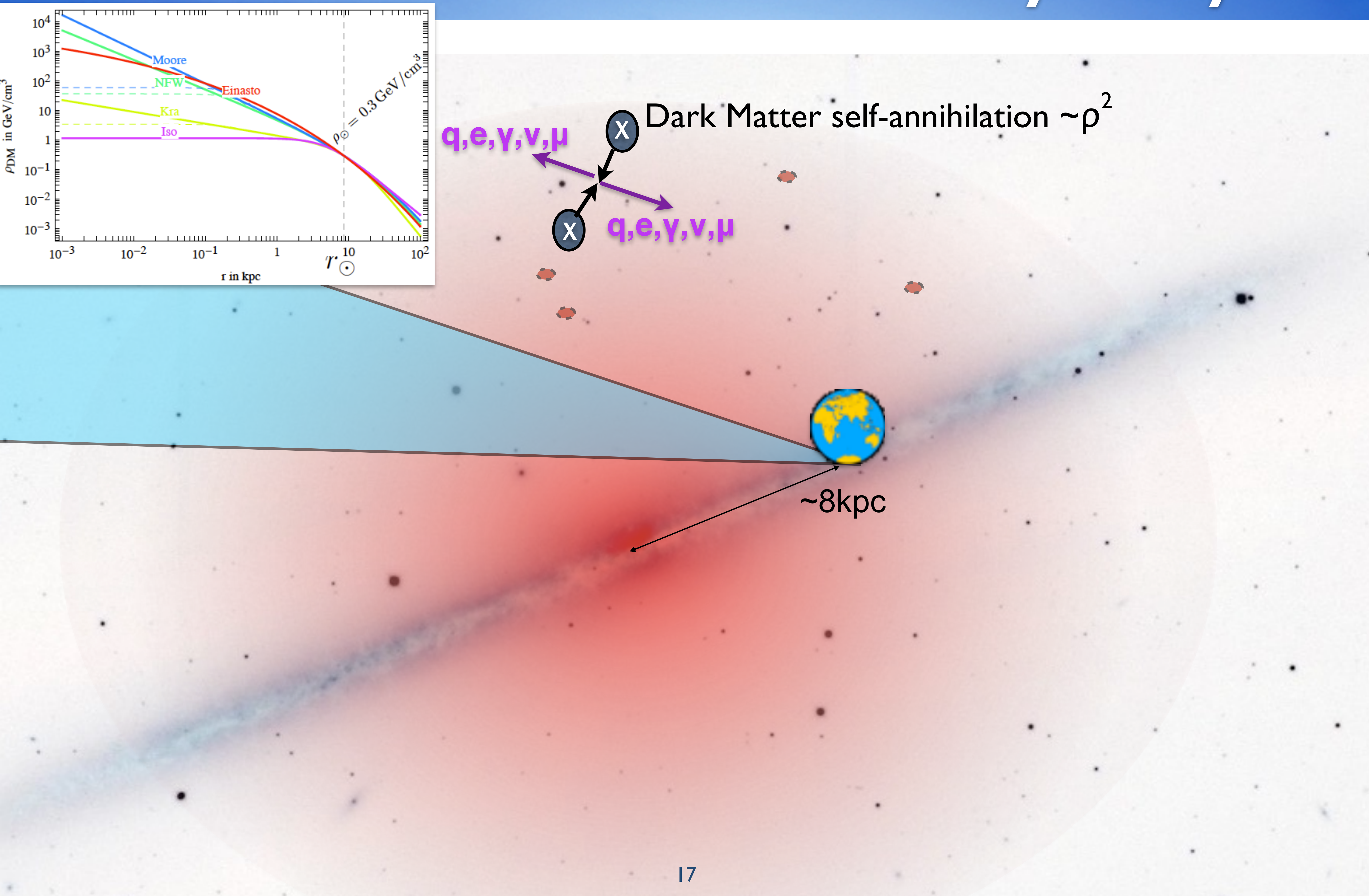
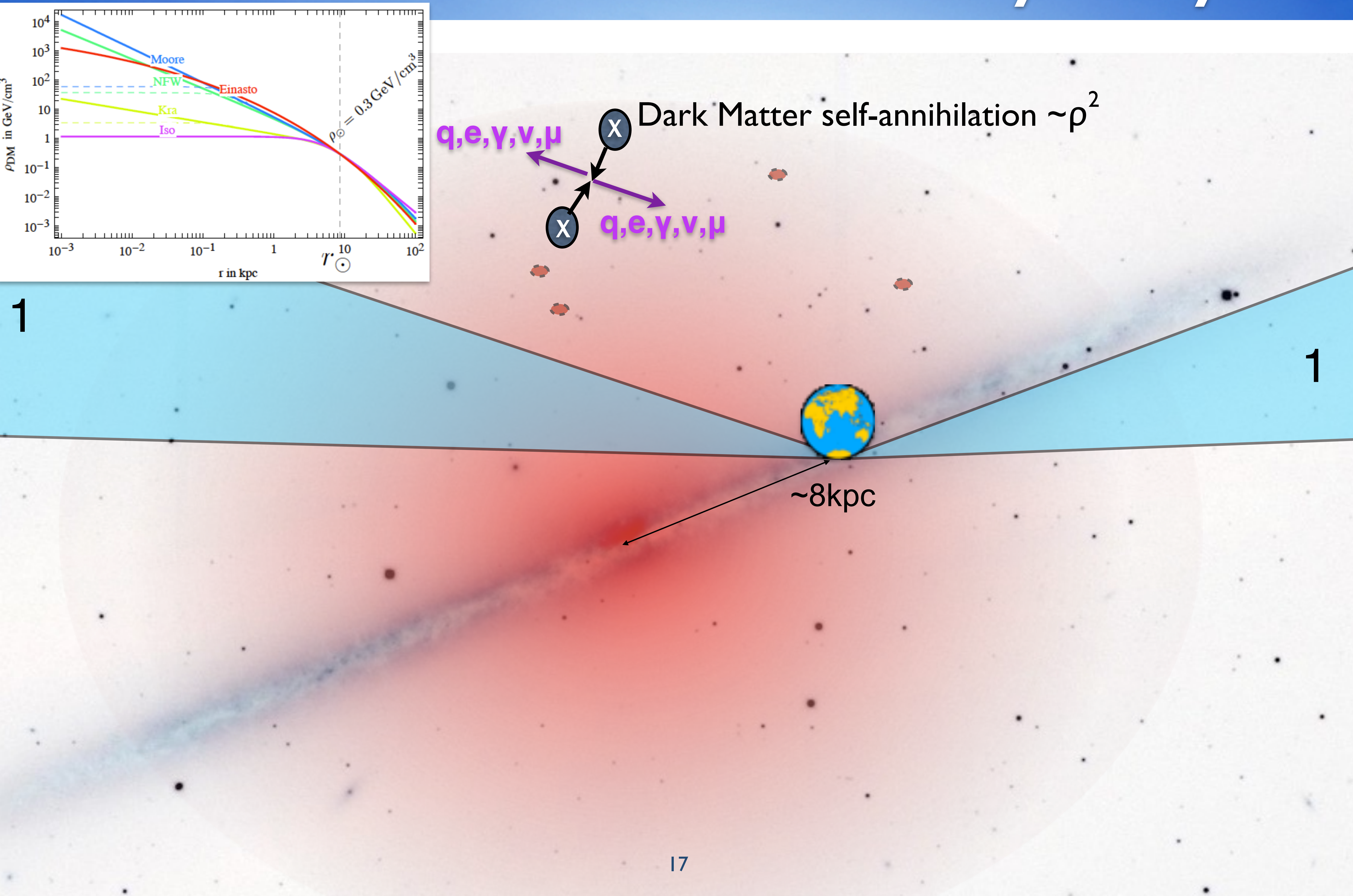




Dark Matter in the Milky Way



Dark Matter in the Milky Way



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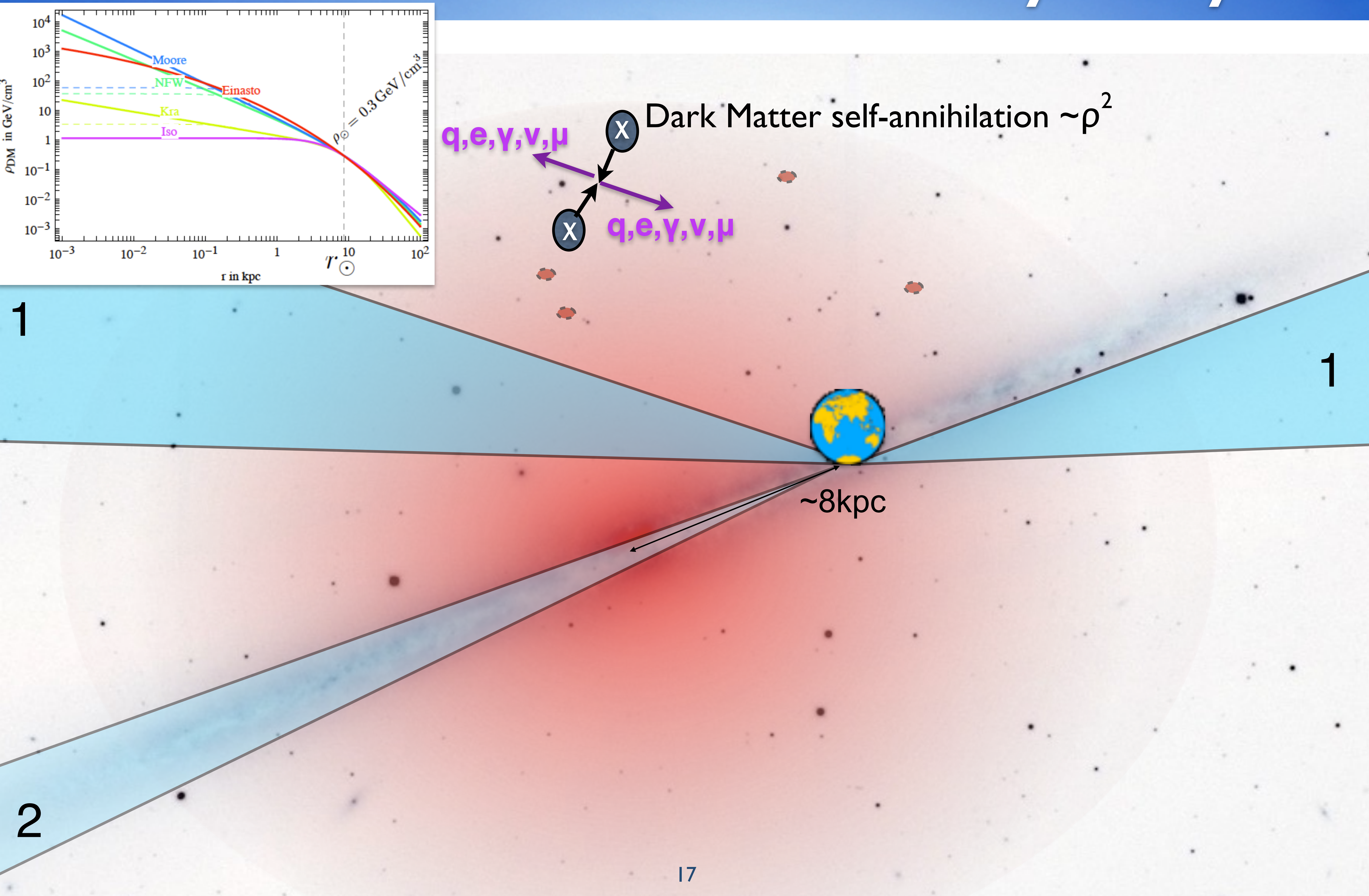

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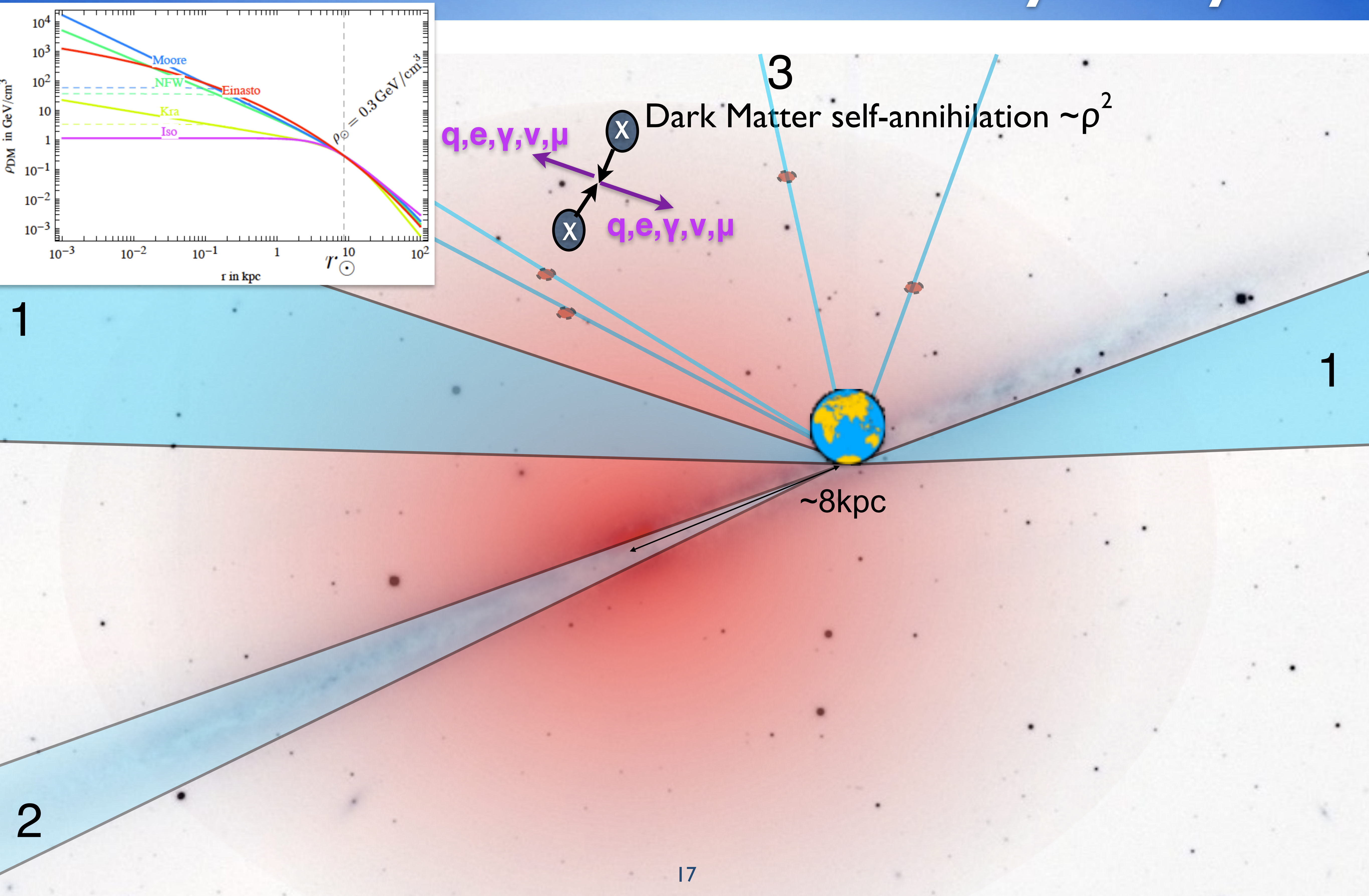
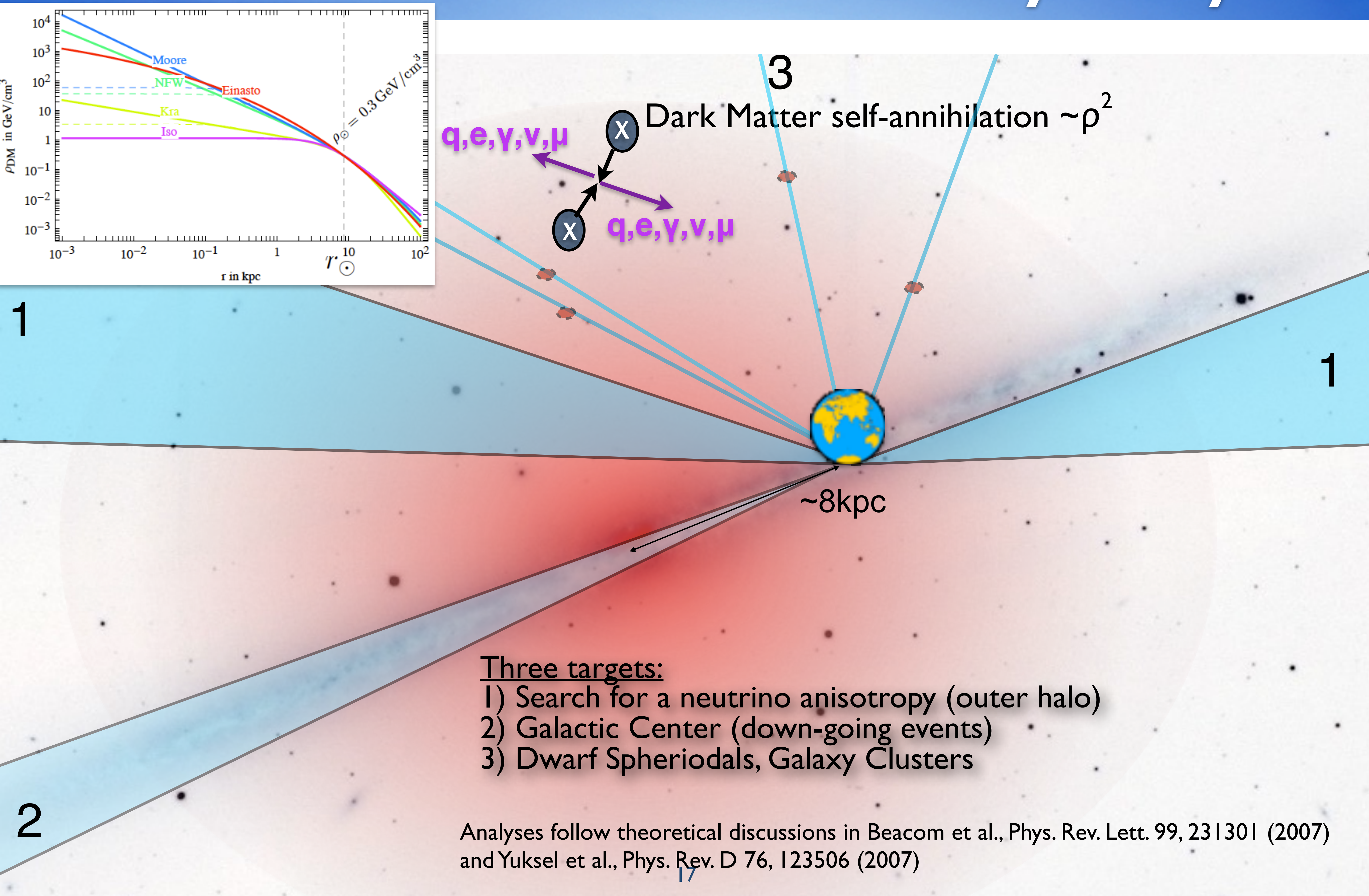


Dark Matter in the Milky Way

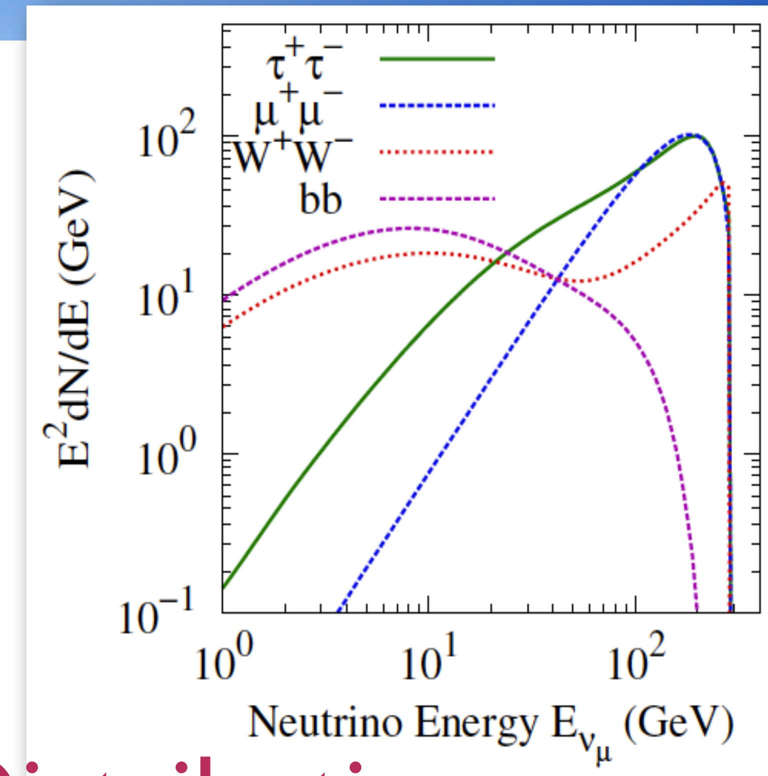


<u>Three targets:</u>

1) Search for a neutrino anisotropy (outer halo)
2) Galactic Center (down-going events)
3) Dwarf Spheriodals, Galaxy Clusters

Analyses follow theoretical discussions in Beacom et al., Phys. Rev. Lett. 99, 231301 (2007) and Yuksel et al., Phys. Rev. D 76, 123506 (2007)

Dark Matter Annihilation



Measure Flux

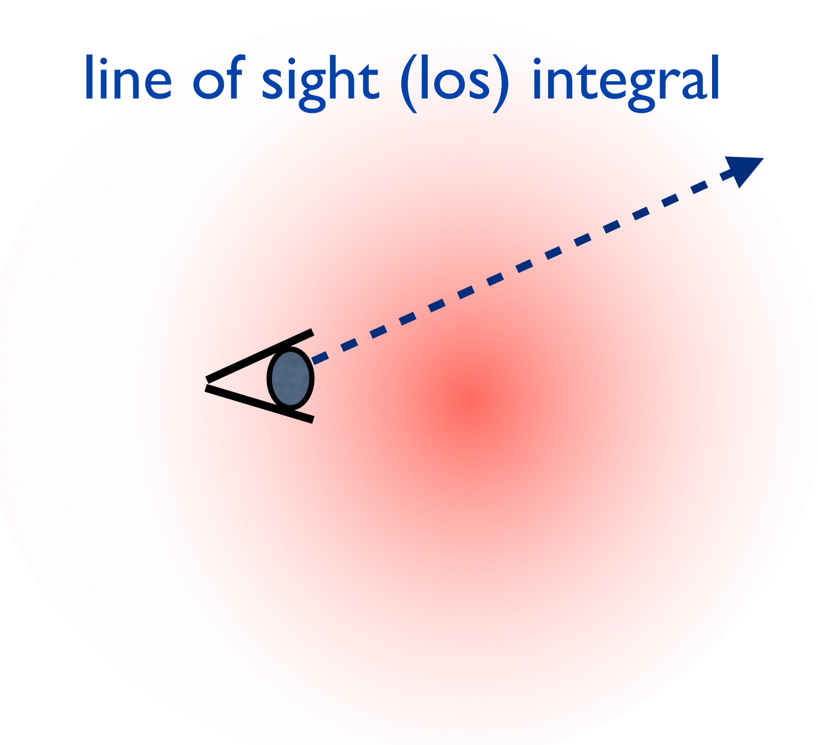
Particle Physics

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

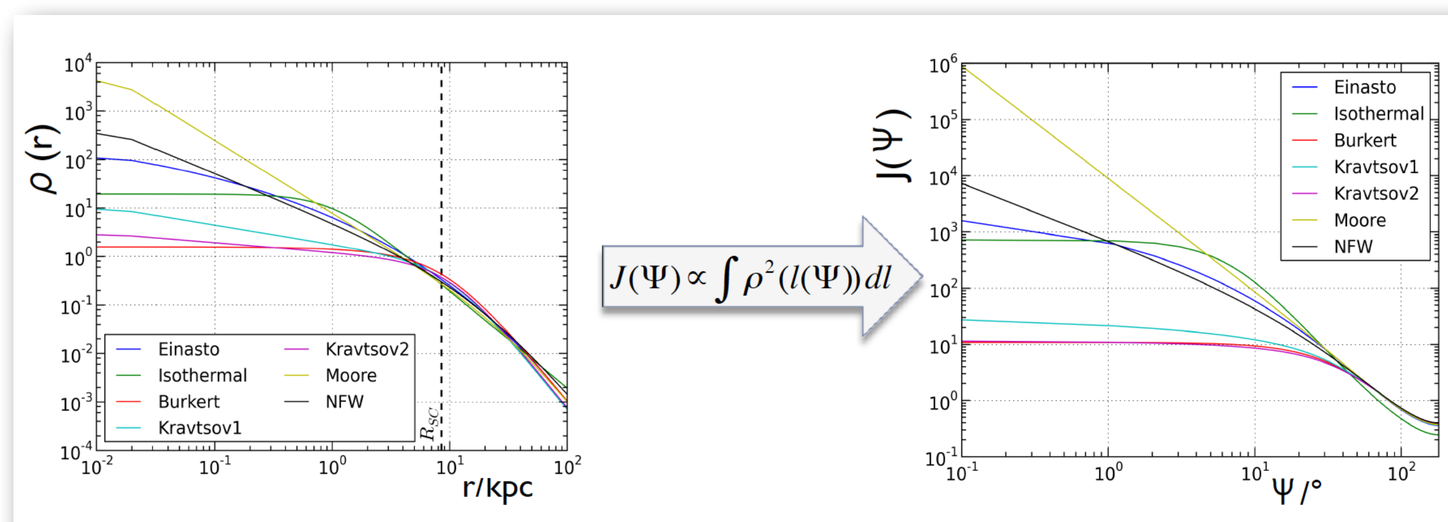
x

Dark Matter Distribution

line of sight (los) integral



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



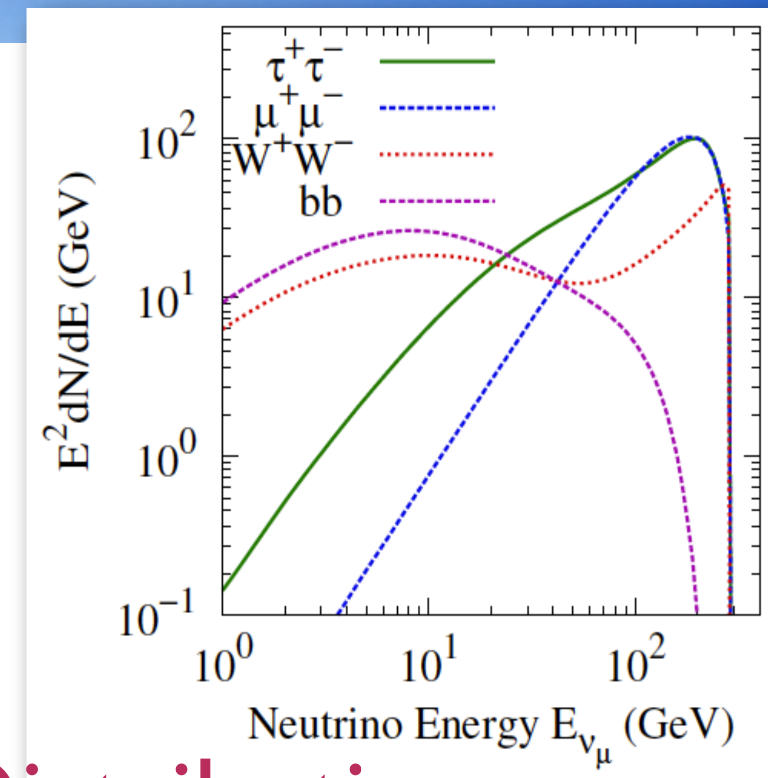
Dark Matter Annihilation

Measure Flux

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

Particle Physics

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



x

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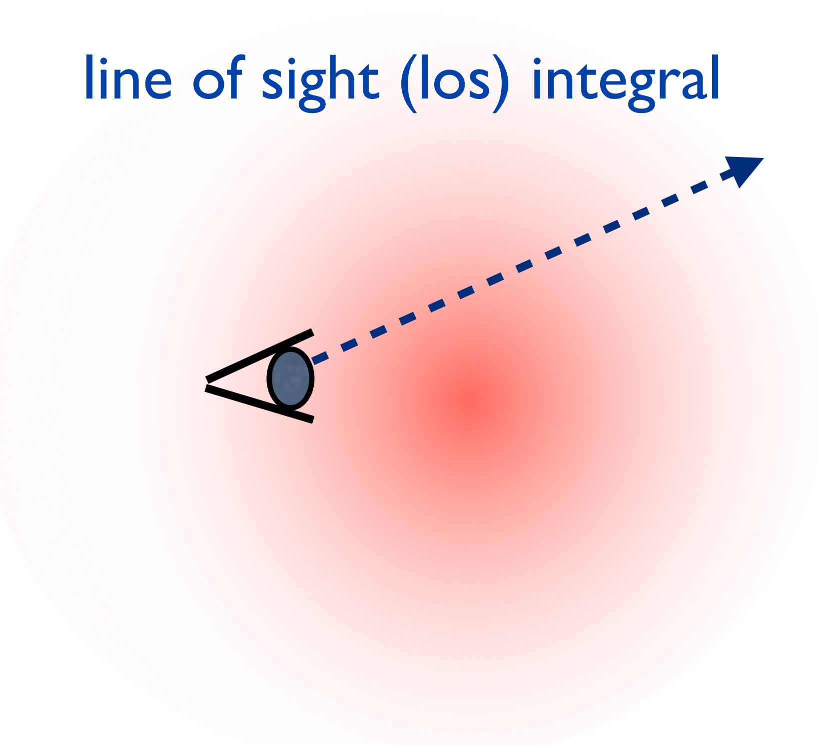
line of sight (los) integral



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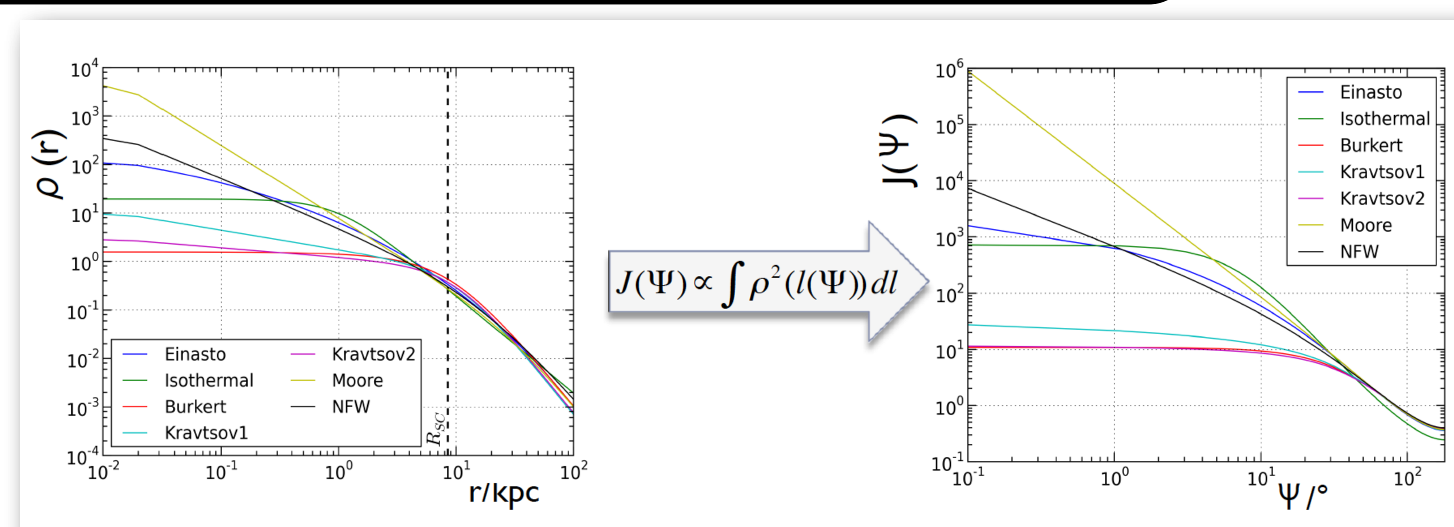
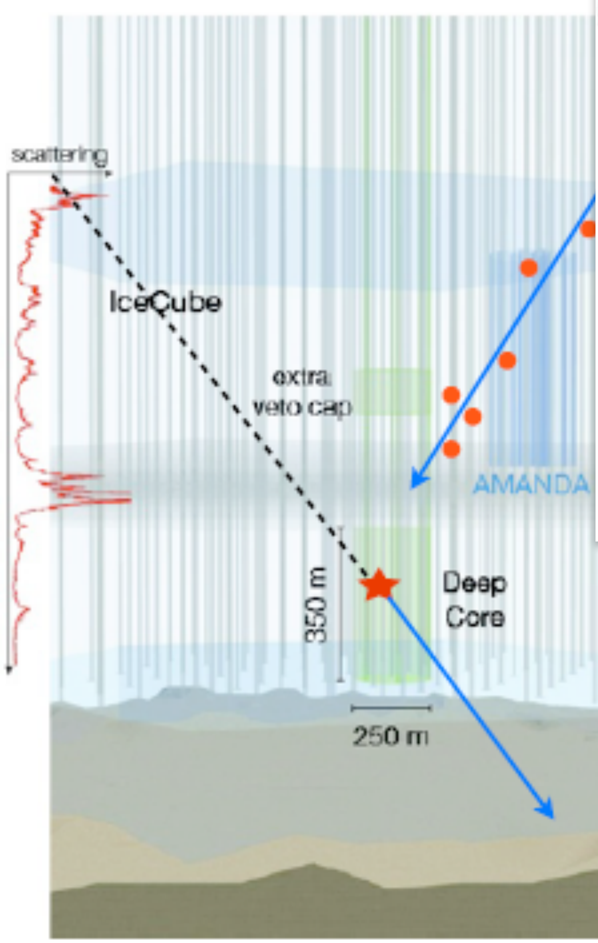
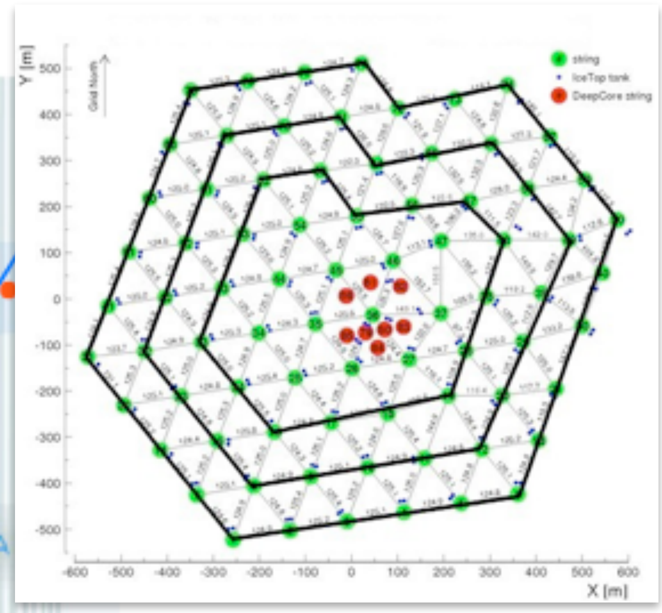


IceCube Collaboration
arXiv1505.07259
Eur.Phys.J. C75 (2015) 10, 492

Galactic Center

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



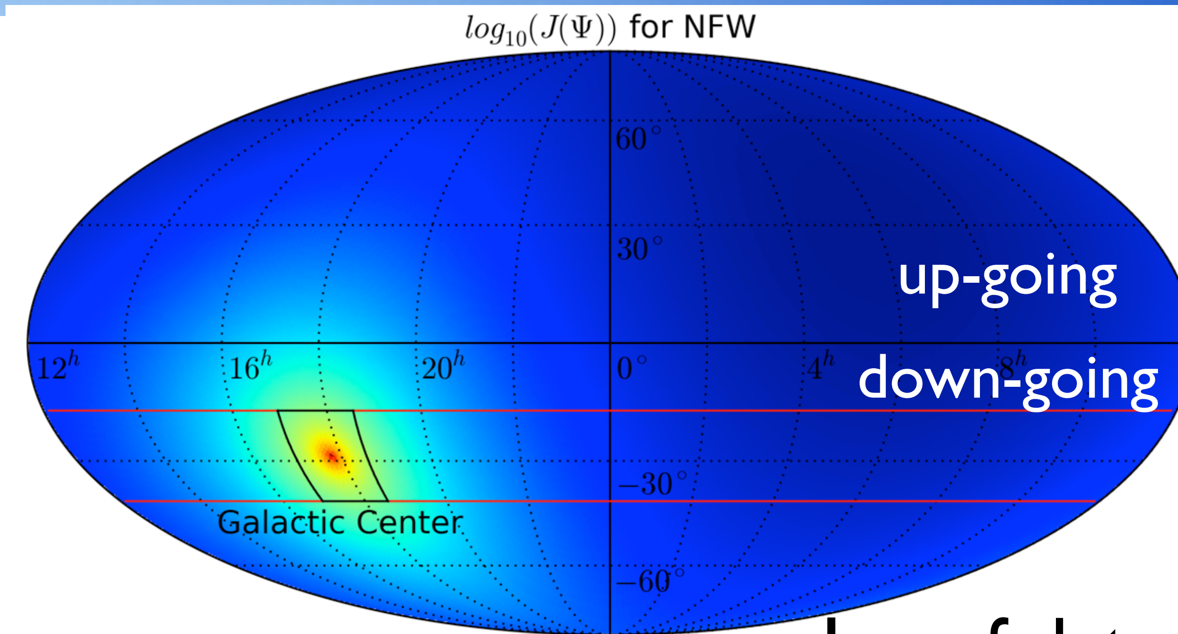


Two analyses, combined based on best sensitivity (dotted).

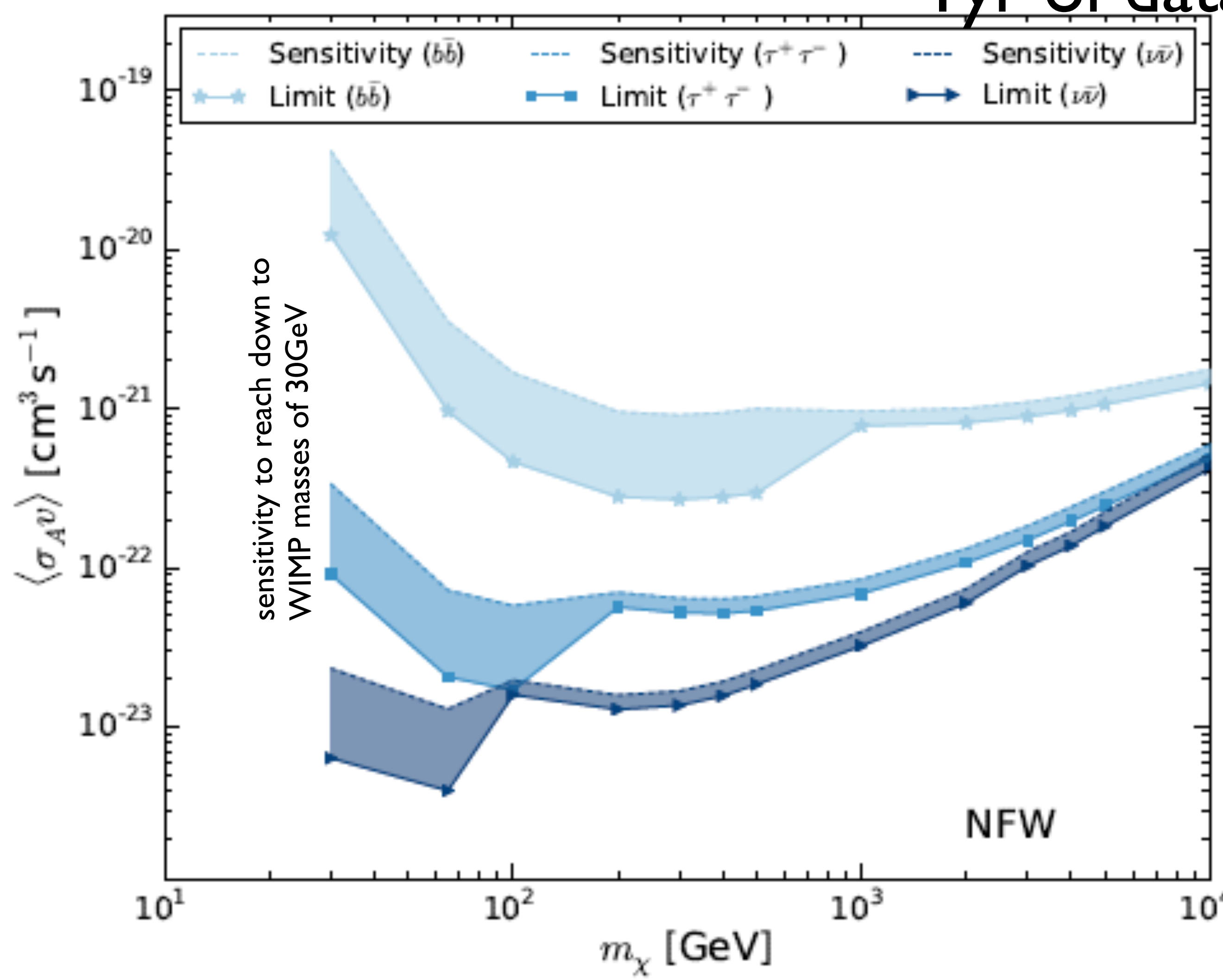
Both analyses observed underfluctuations

"High energy" analysis: 0.5 σ

"Low energy" analysis: 2σ

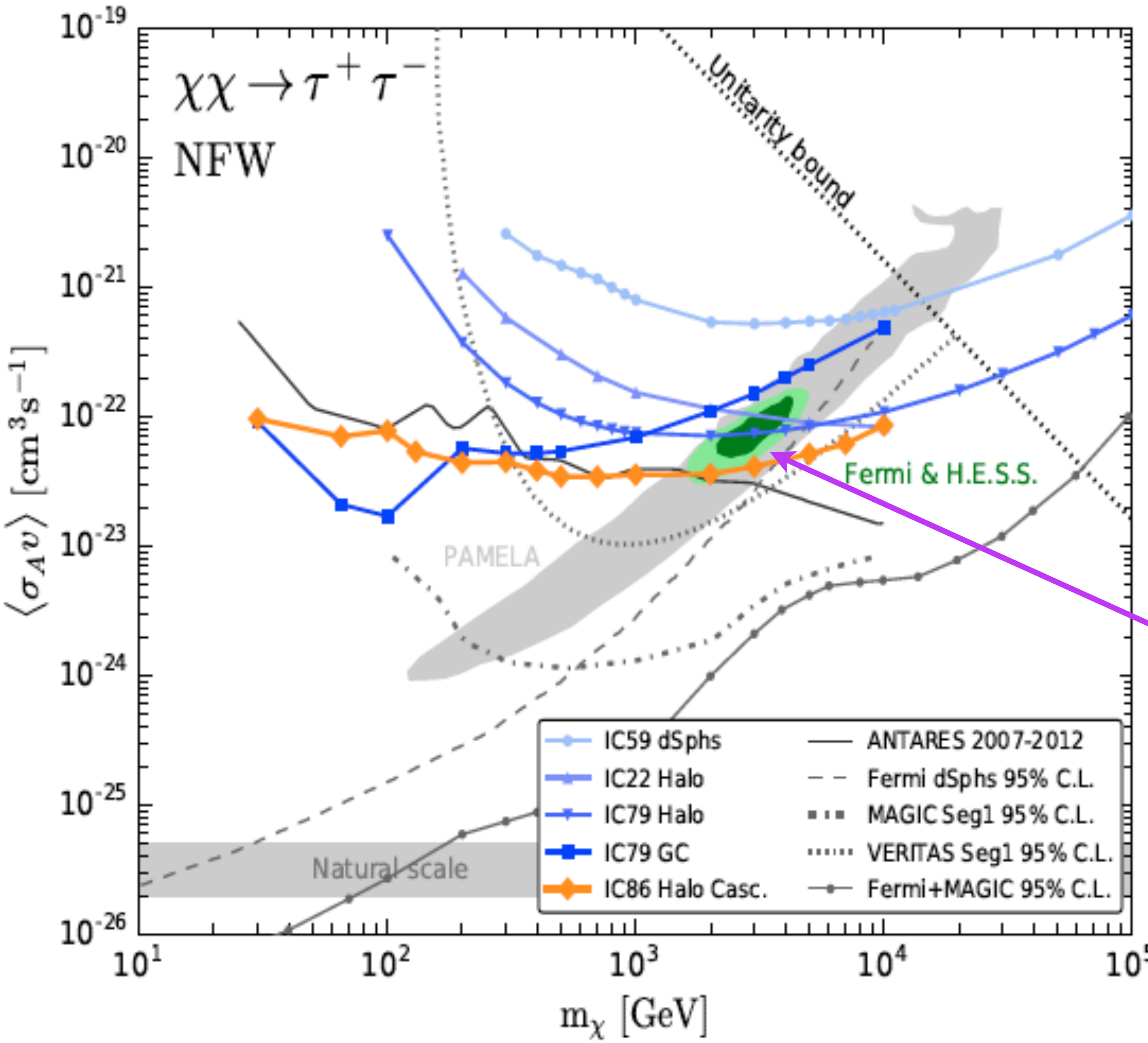


1yr of data



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

Neutrinos test lepton anomalies



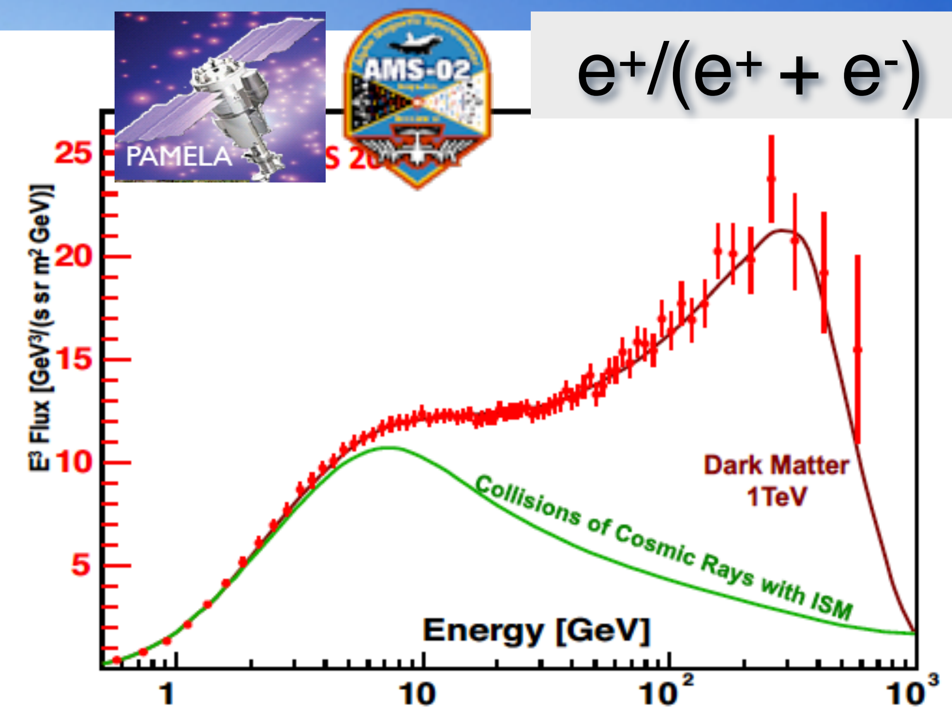
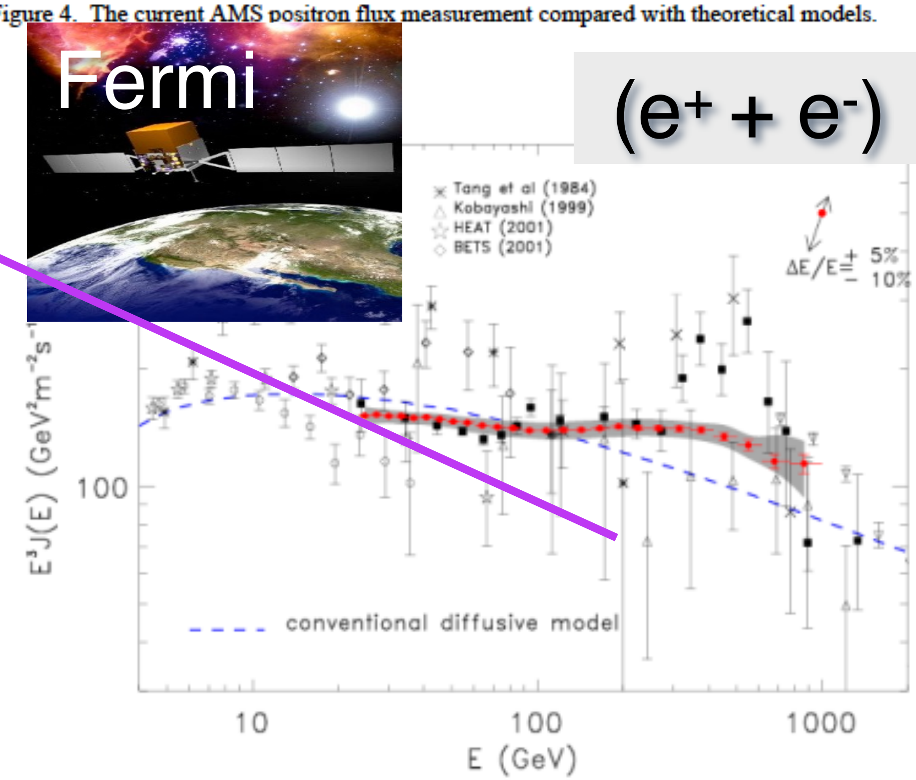
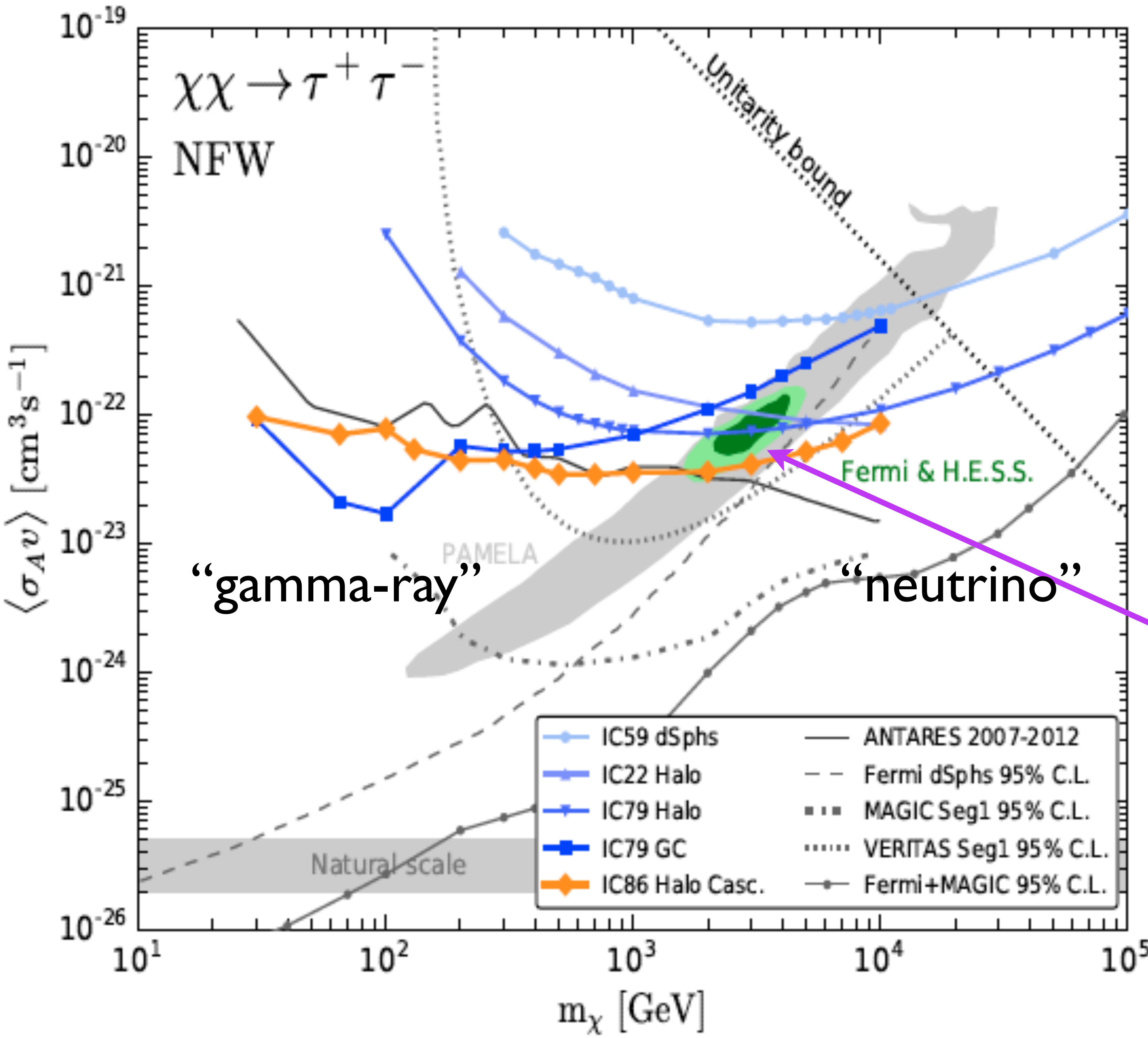


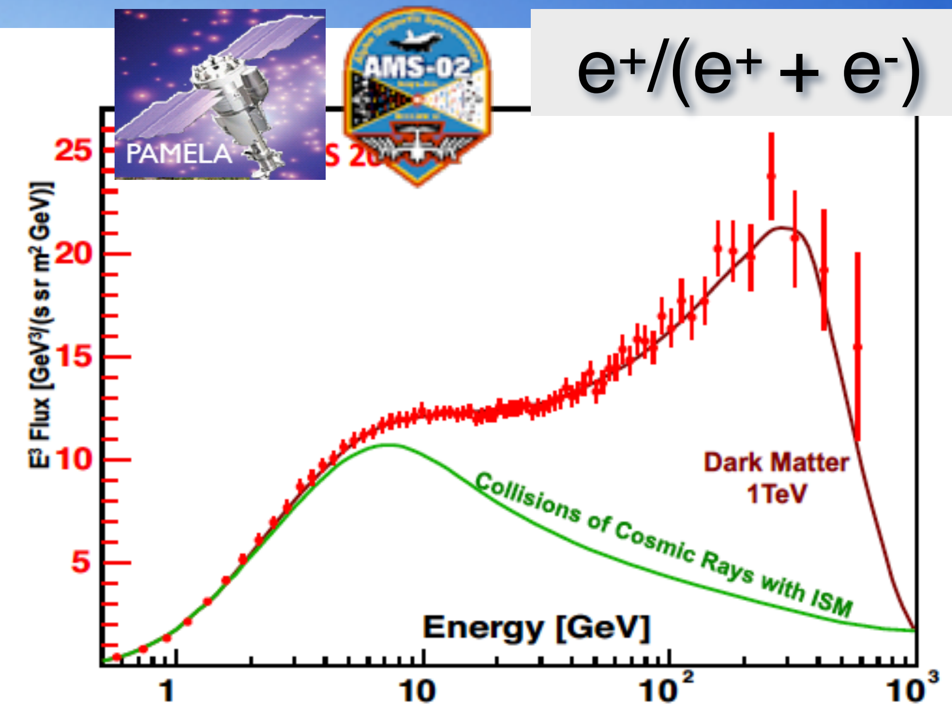
Figure 4. The current AMS positron flux measurement compared with theoretical models.



Neutrino Telescopes can probe models motivated by the observed lepton anomalies

Neutrinos test lepton anomalies





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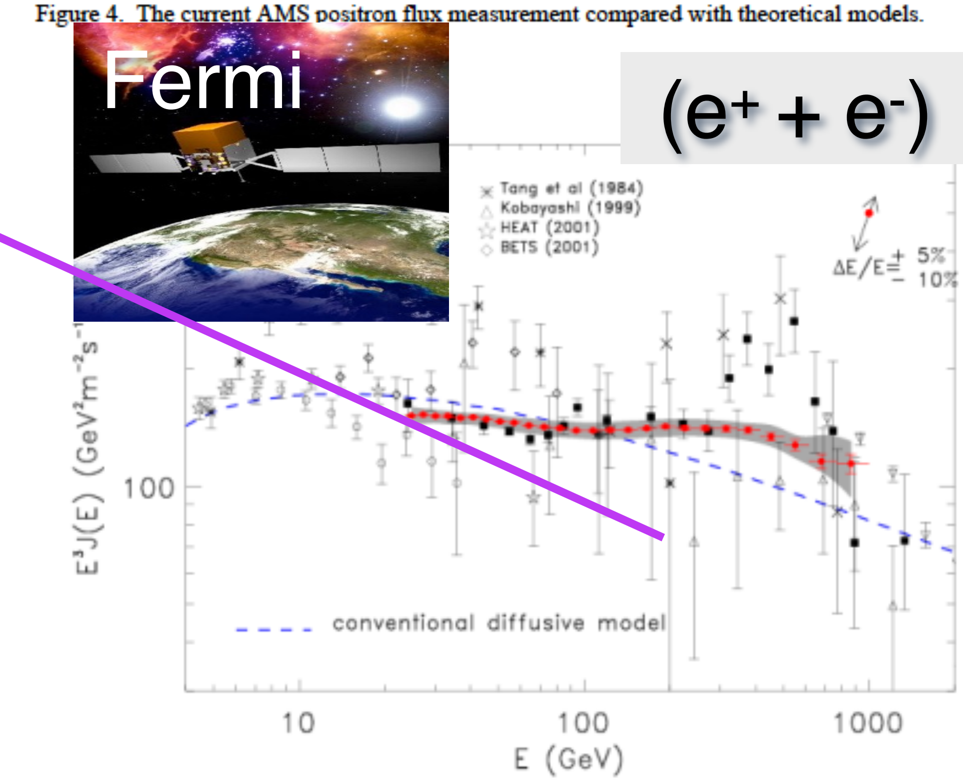

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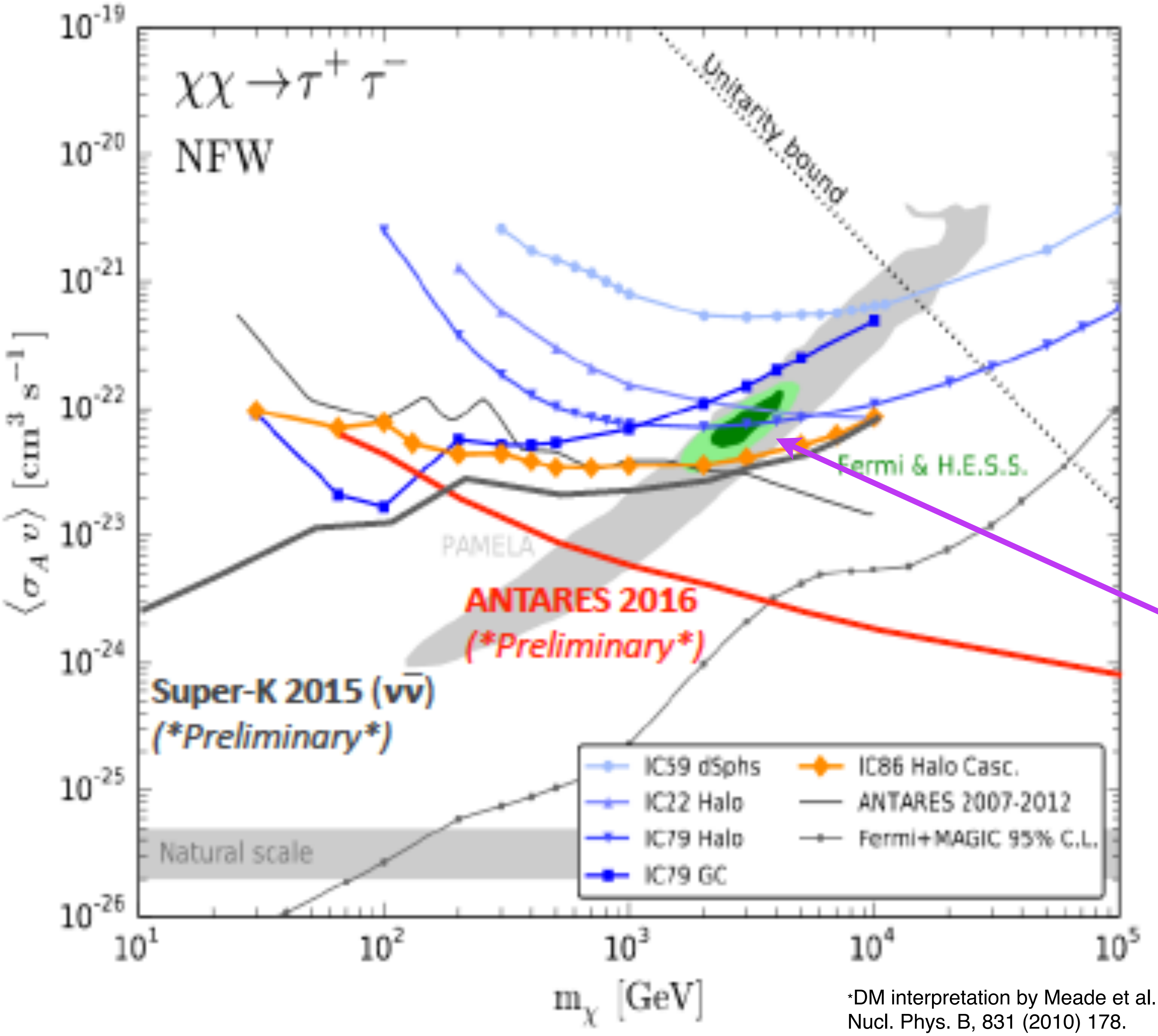


e+/(e+ + e-)

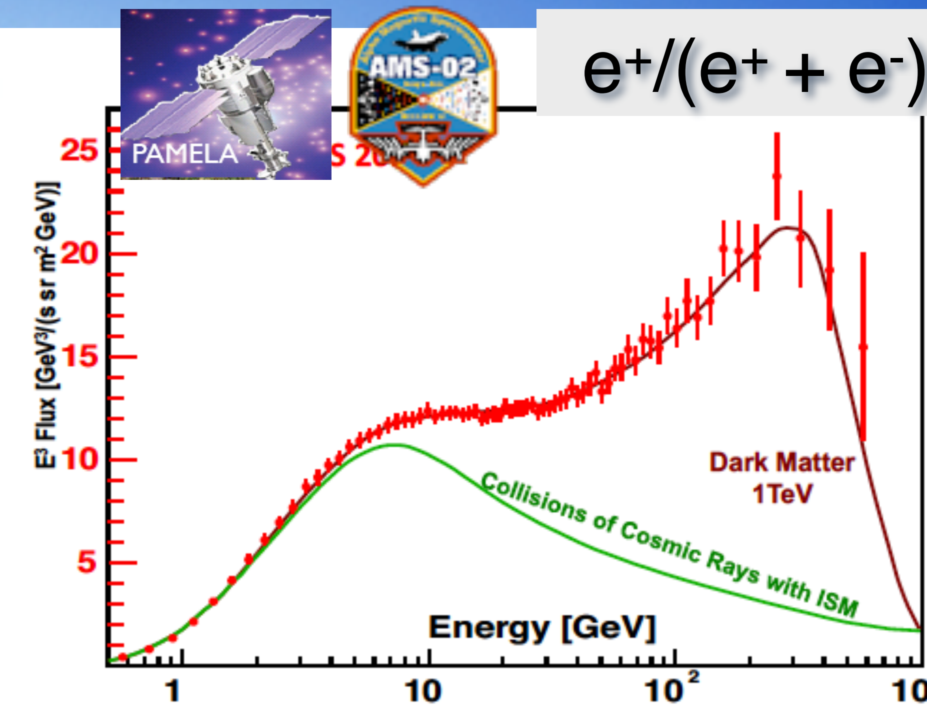
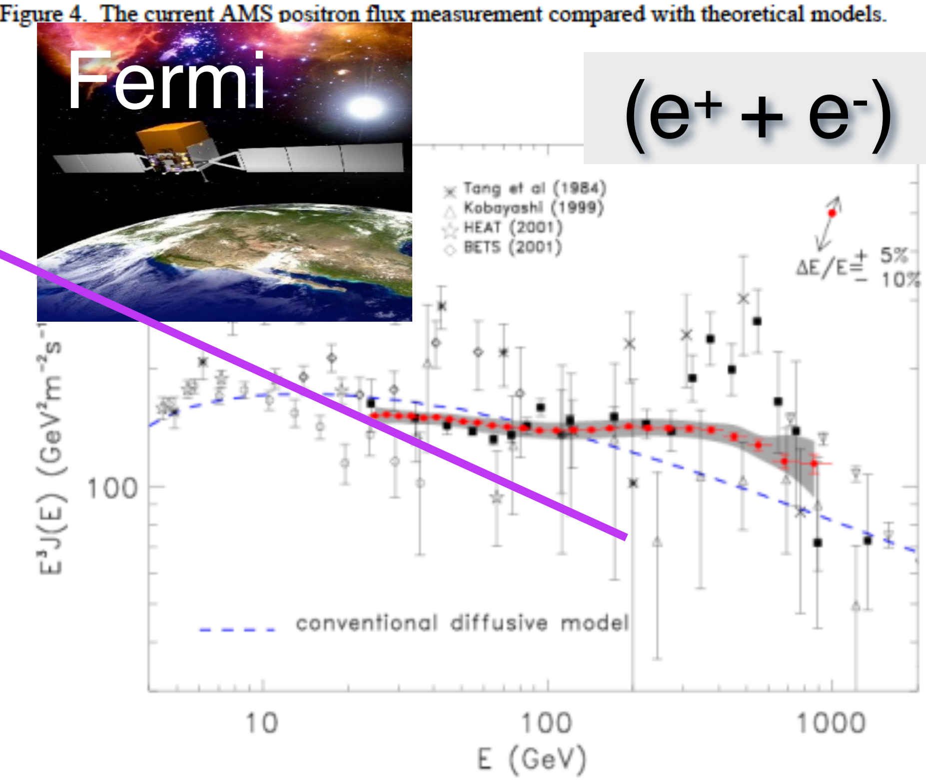


Figure 4. The current AMS positron flux measurement compared with theoretical models.

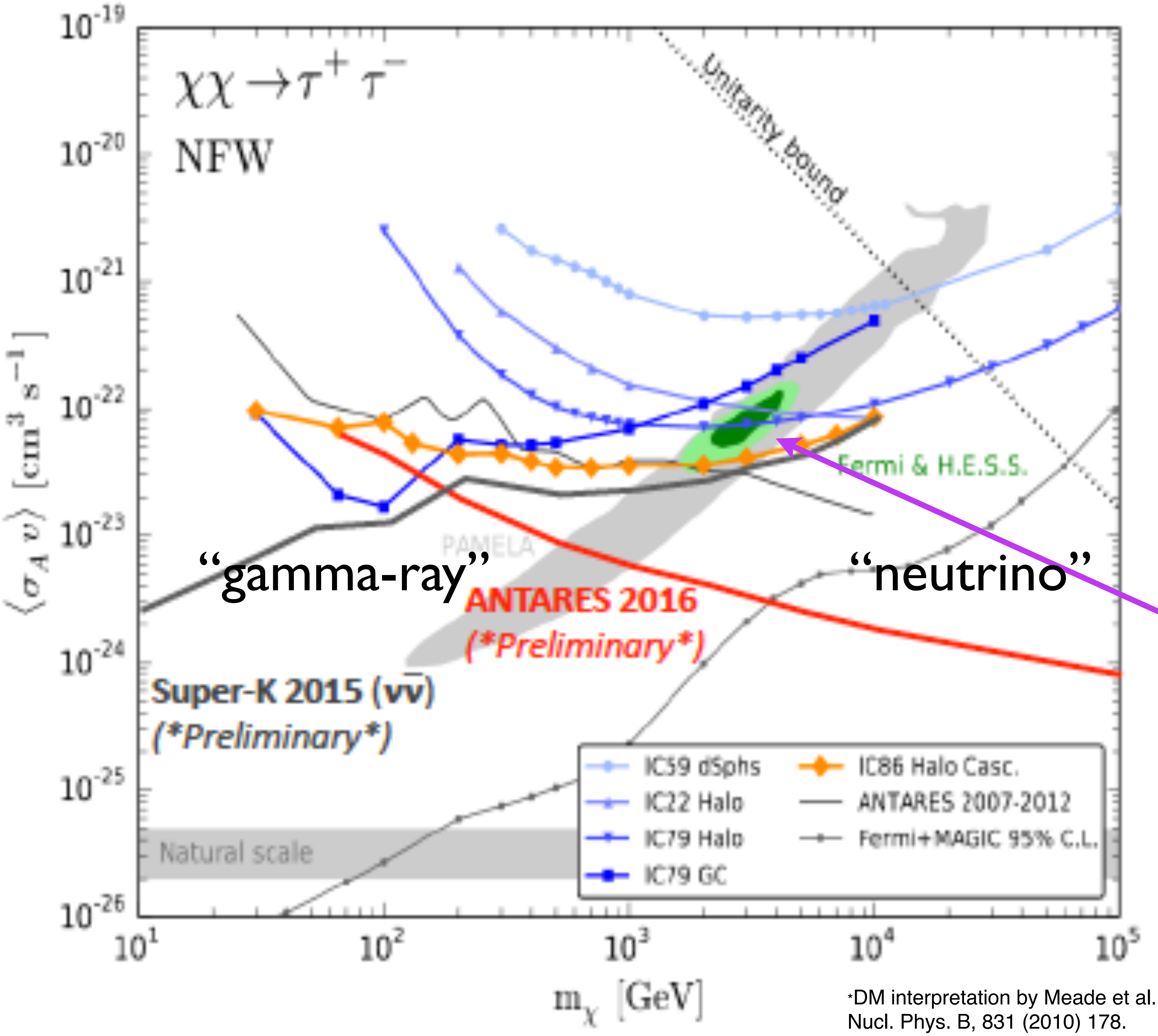
(e+ + e-)

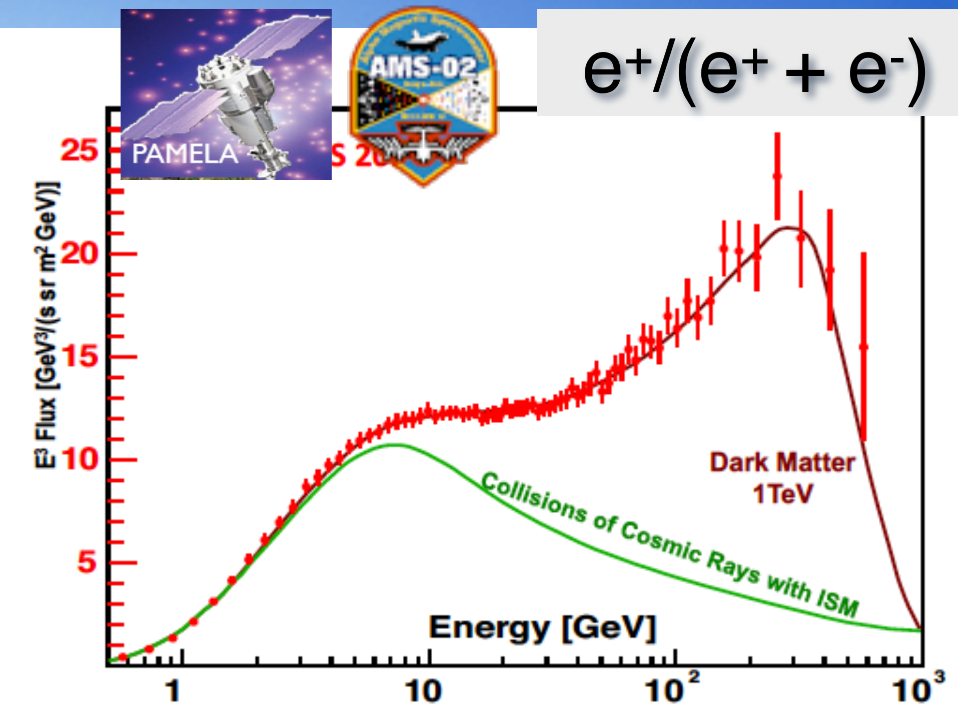


*DM interpretation by Meade et al., Nucl. Phys. B, 831 (2010) 178.

Neutrino Telescopes can probe models motivated by the observed lepton anomalies

Neutrinos test lepton anomalies





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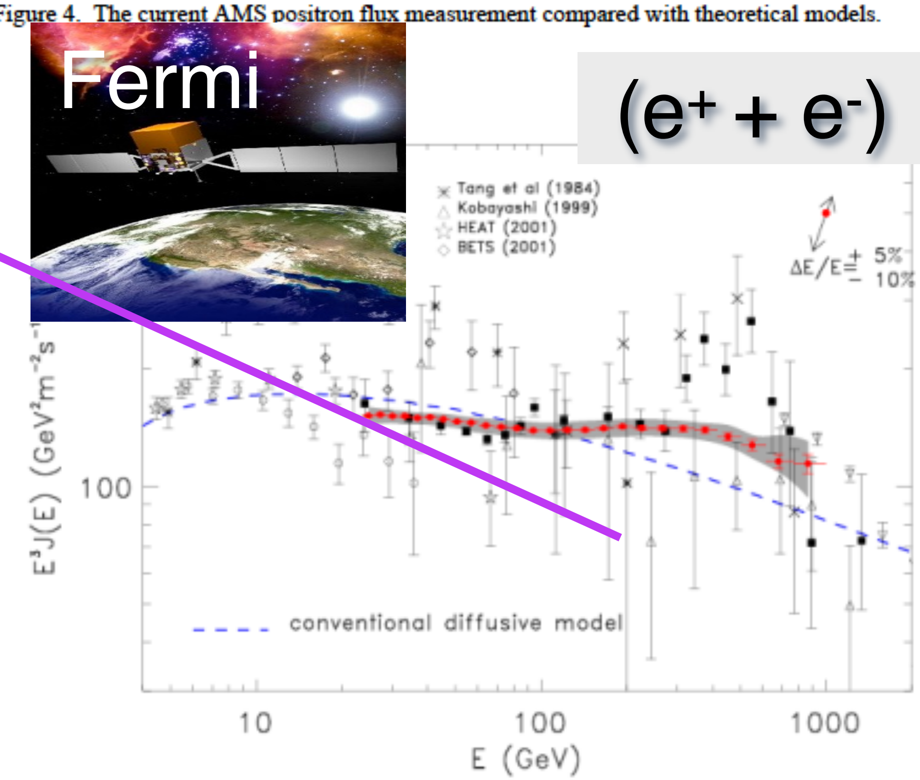

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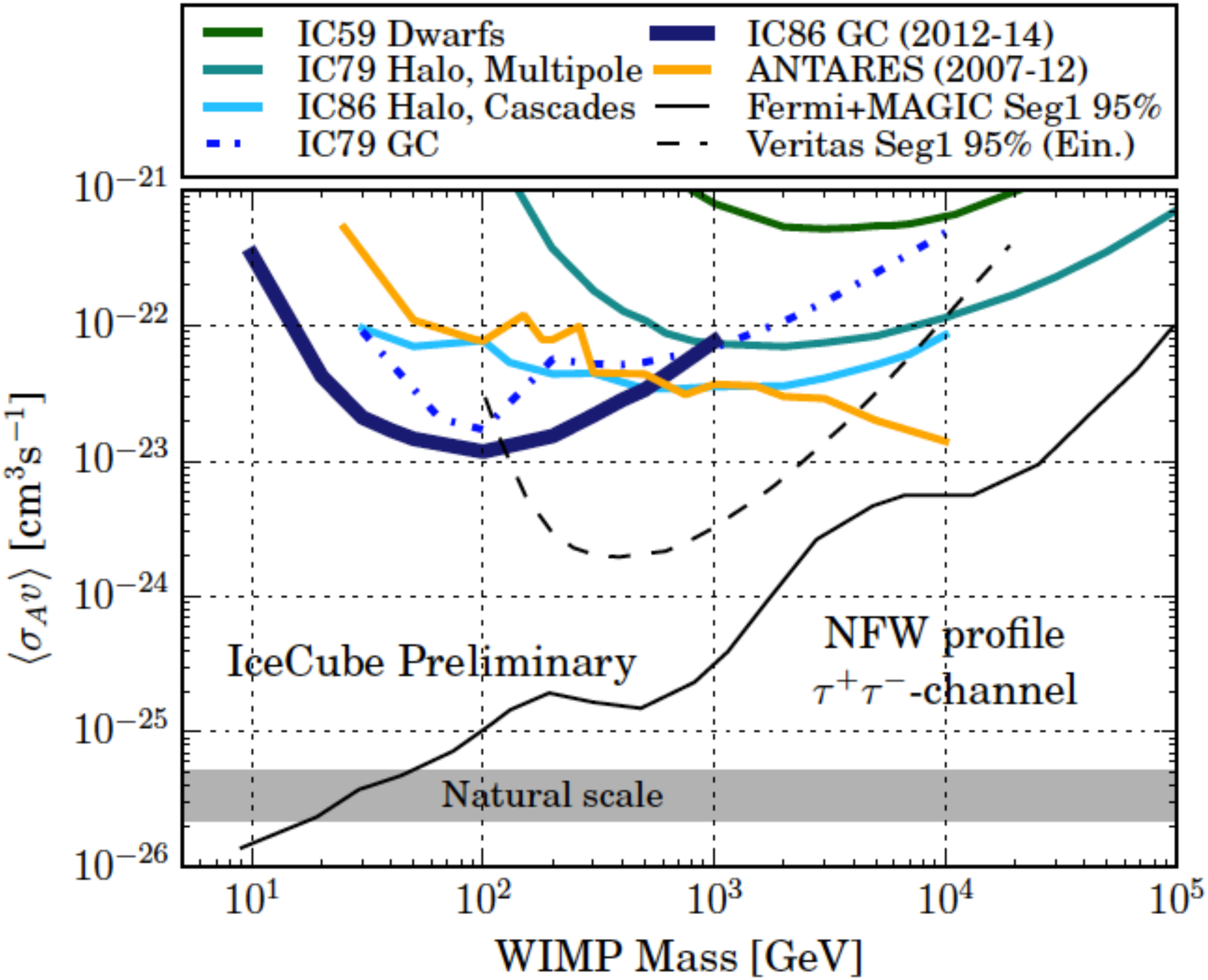
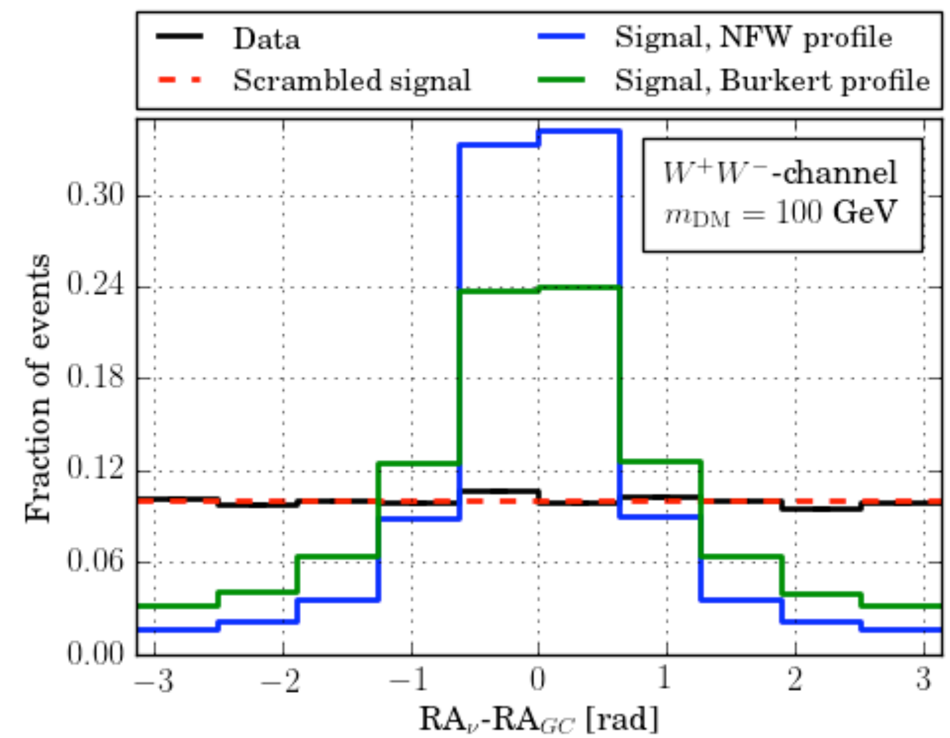
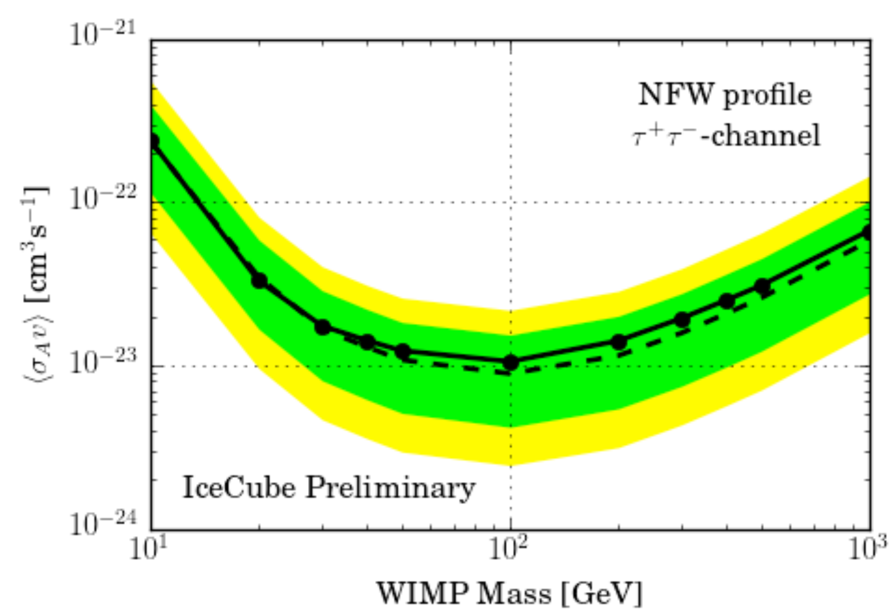
Neutrino Telescopes can probe models motivated by the observed lepton anomalies

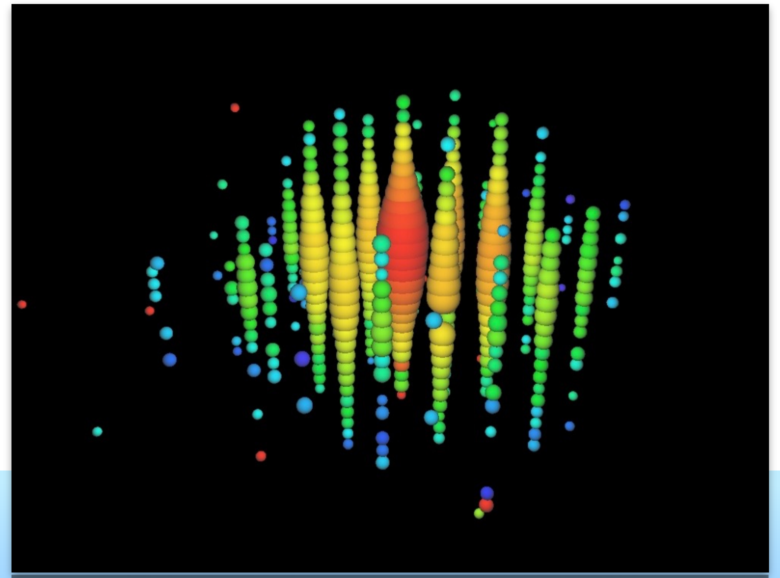
DeepCore Analysis



3 years of IceCube-DeepCore data



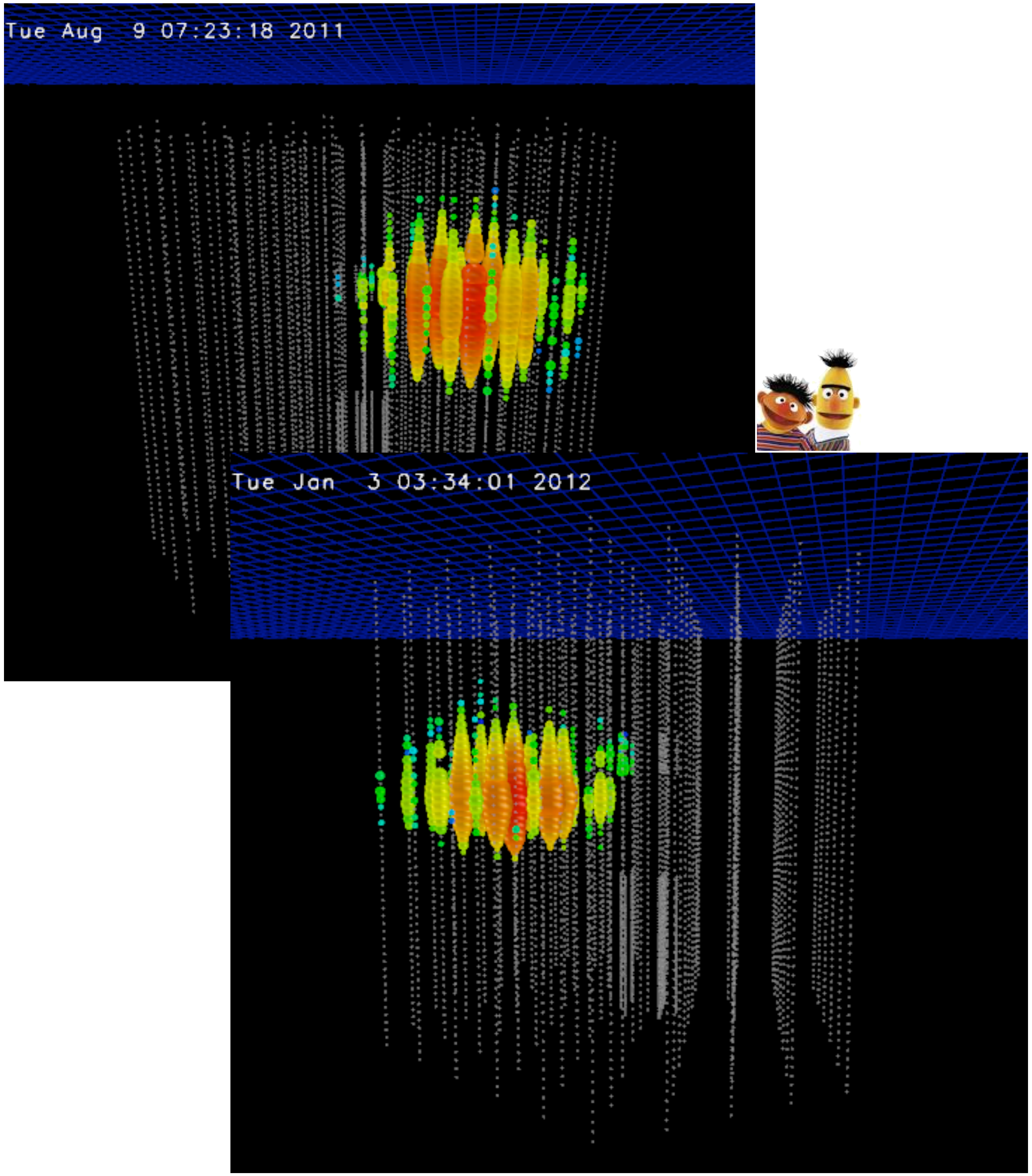




Dark Matter Decay / Astro-physical Neutrinos

Search for highest energy neutrinos

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



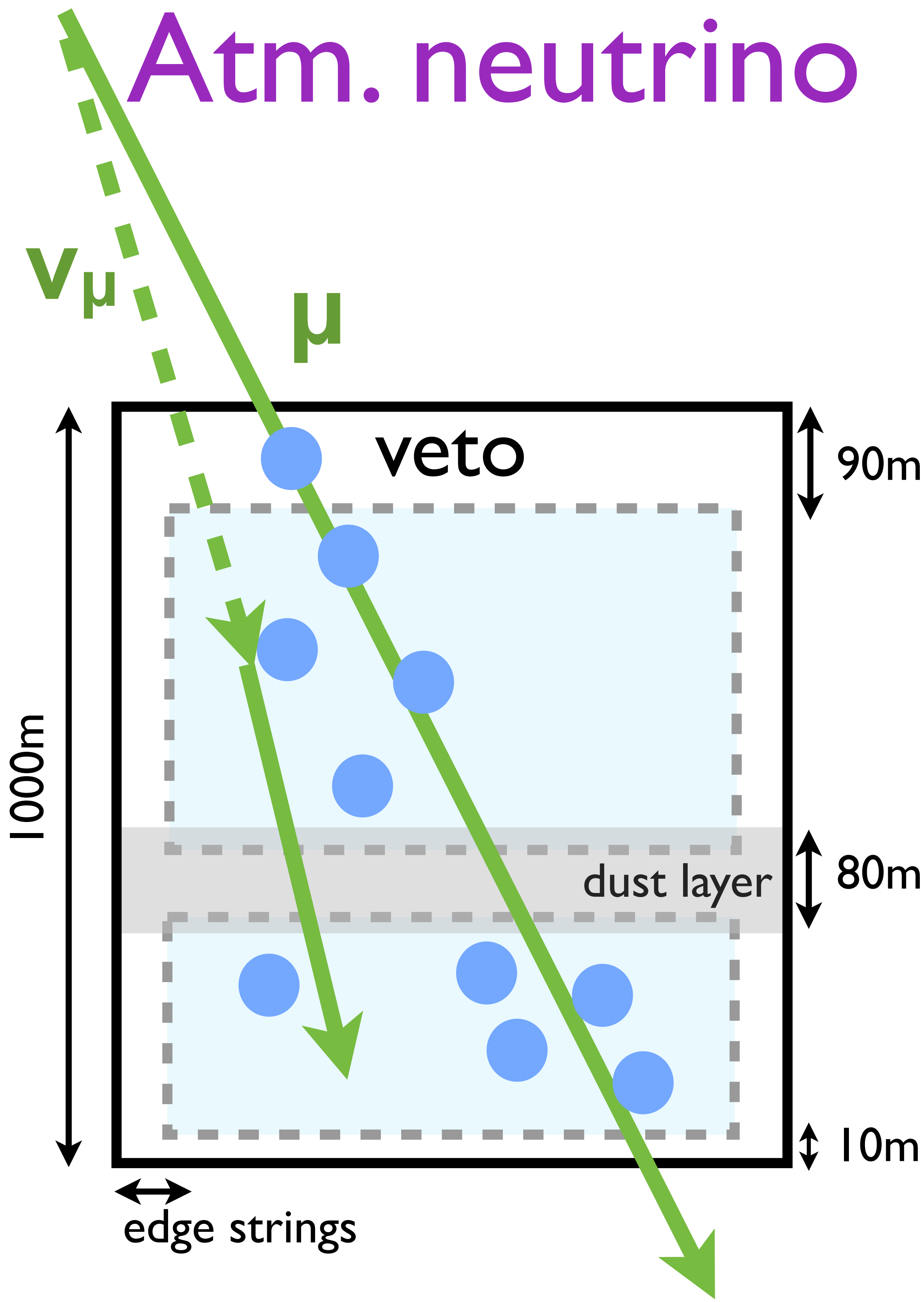
Dataset / Results
(670days of IC79/IC86 data)
expected 0.08 events
observed 2 events (→ 2.7σ)

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

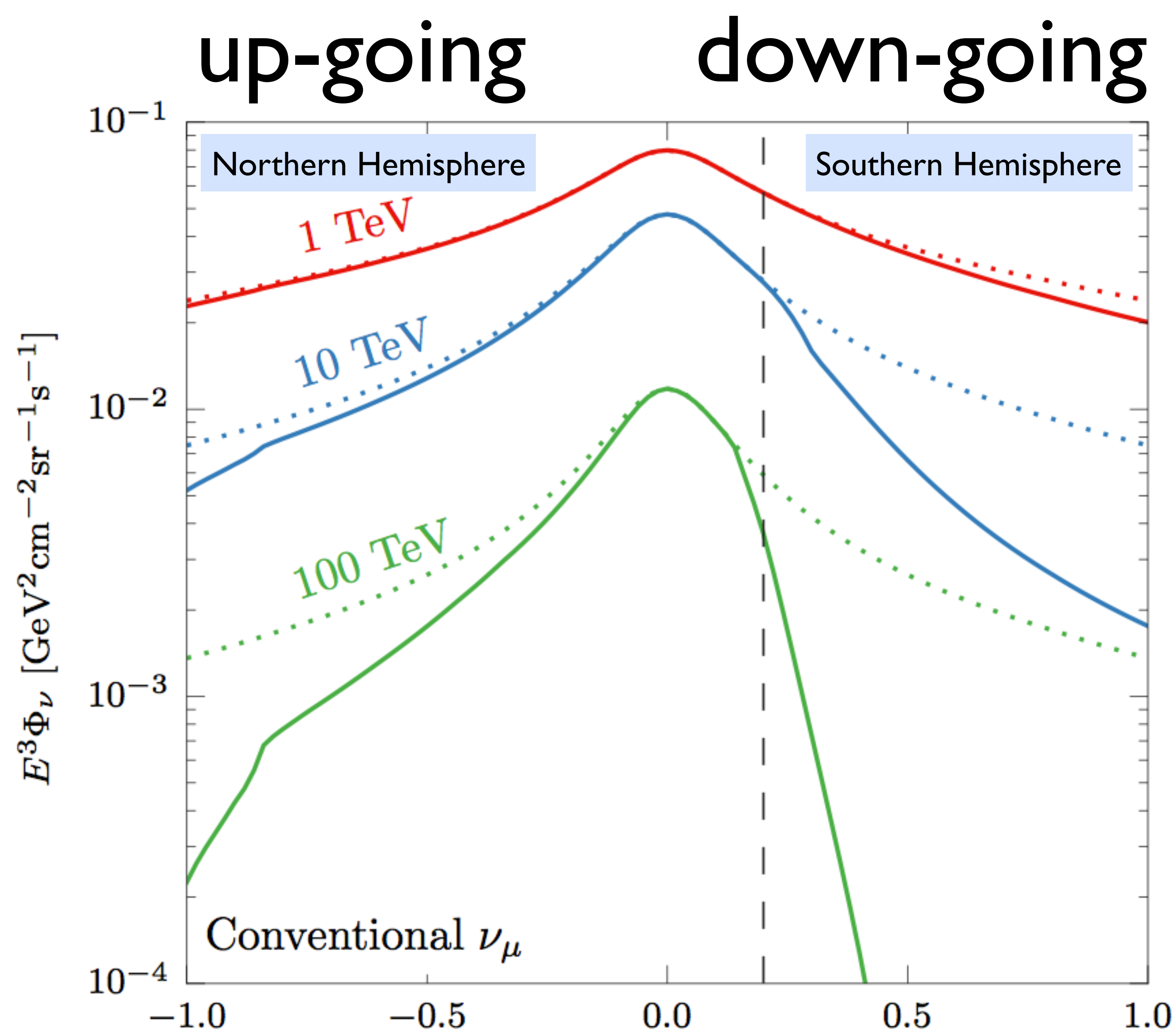
Ernie & Bert are not GZK, but ...

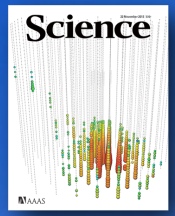
Veto and Self-veto

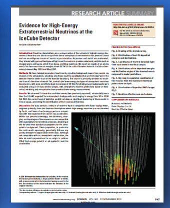
IceCube Collaboration **Phys.Rev. D91 (2015) no.2, 022001** (arxiv:1410.1749)



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



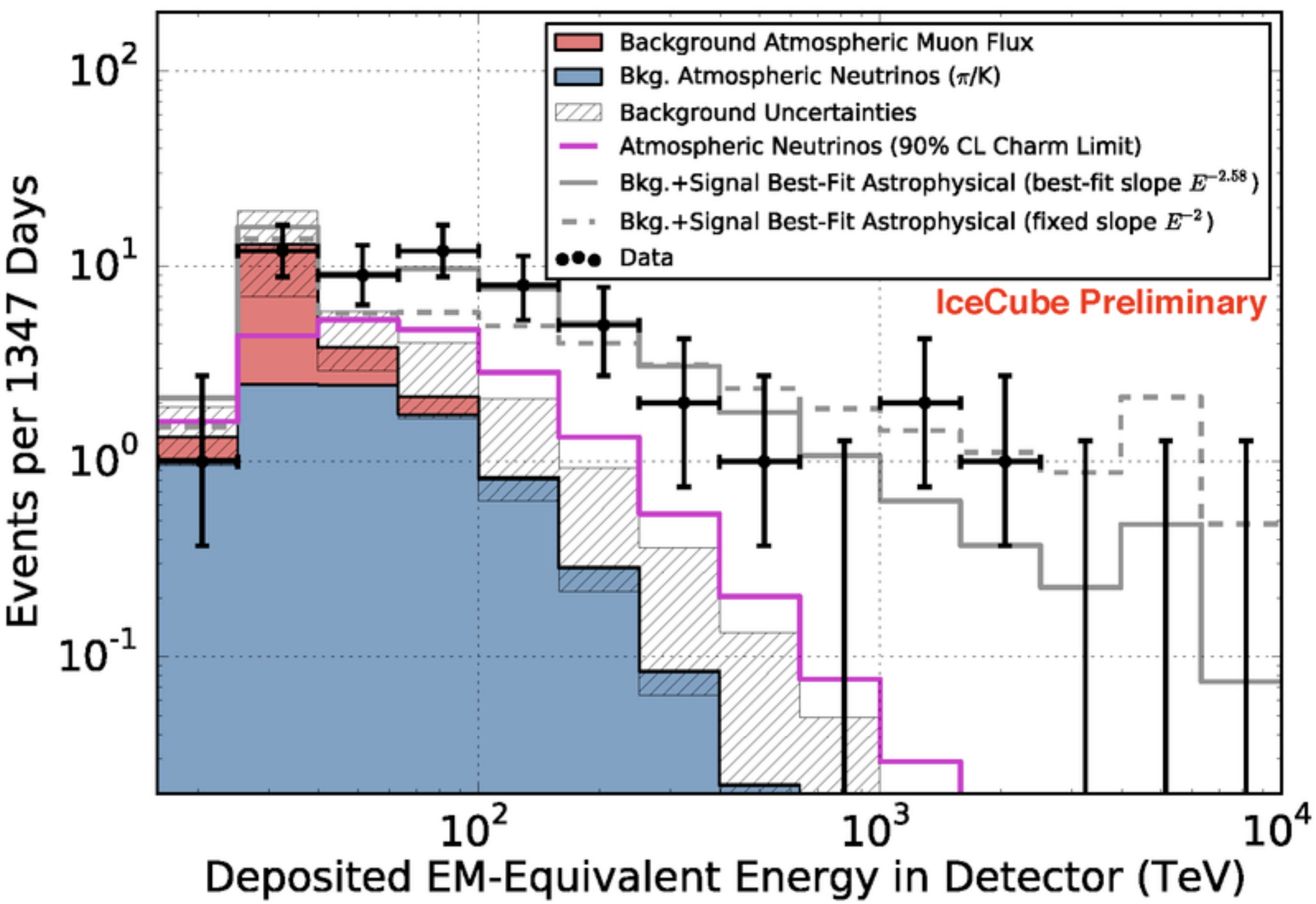




High-energy neutrino search 4yrs

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

Expectation from conventional atm. muons and neutrinos ~21.6



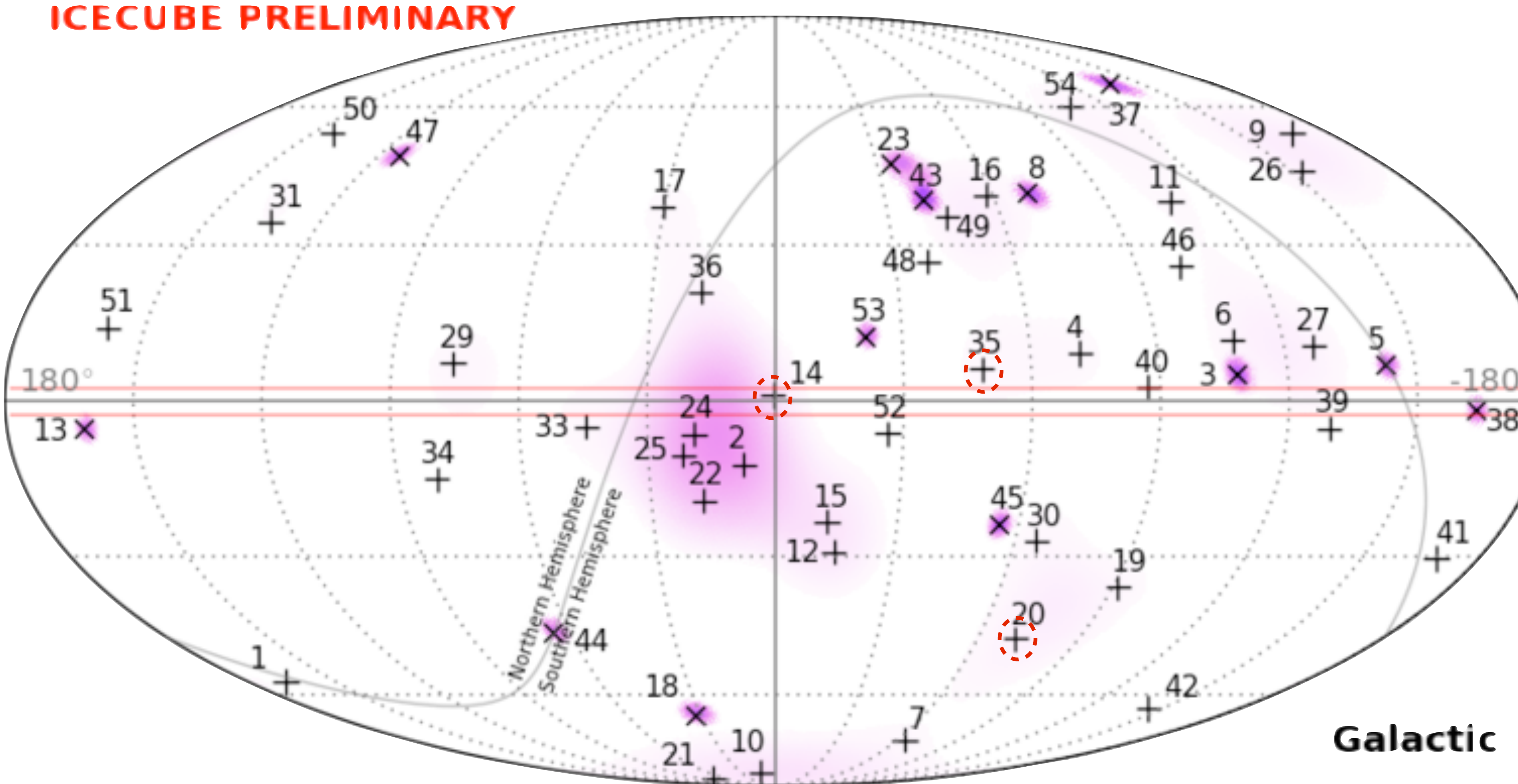
ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

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

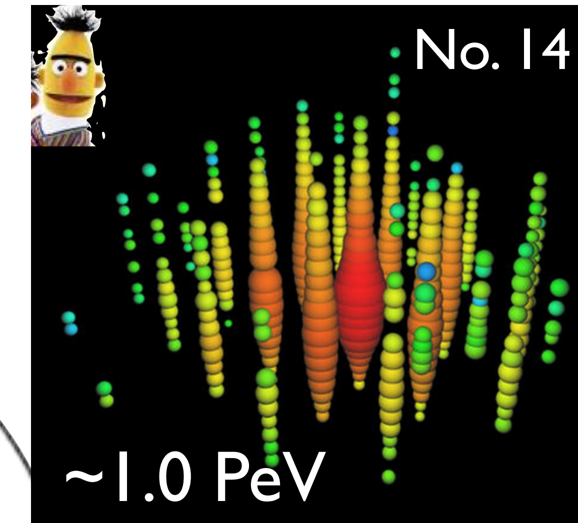
~7 sigma rejection of atmospheric-only hypothesis

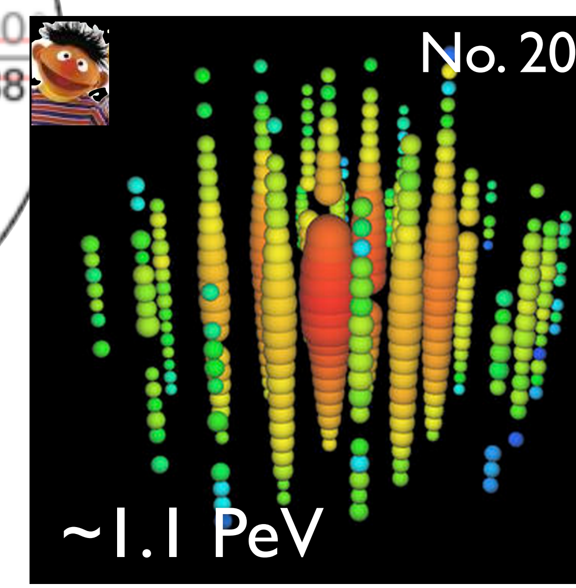
Skymap HESE-4yrs

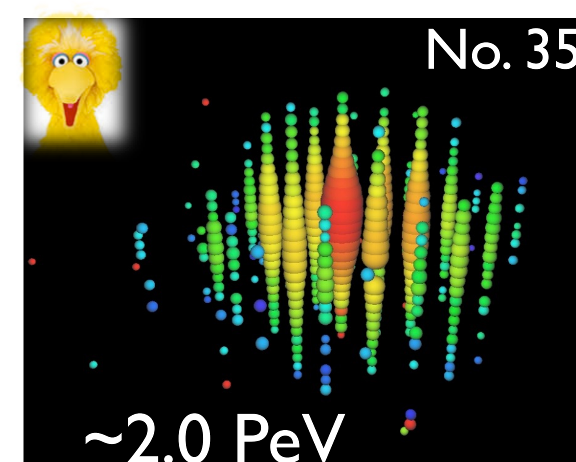
IceCube Collaboration, *Science* 342, 1242856 (2013)



x track event
+ shower event







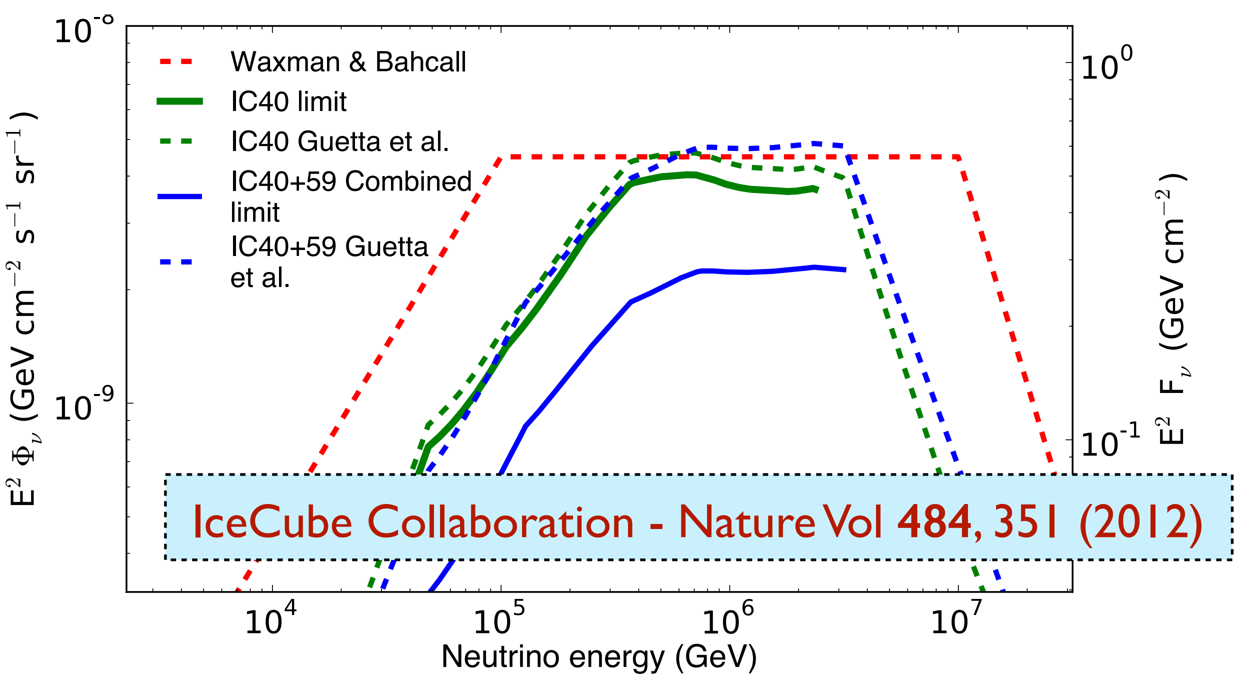
no significant correlations -- spacial or temporal

p-value for cascade events “clustering” 44%

Origin of the high-energy neutrinos ?

Extra Galactic

Gamma Ray Burst

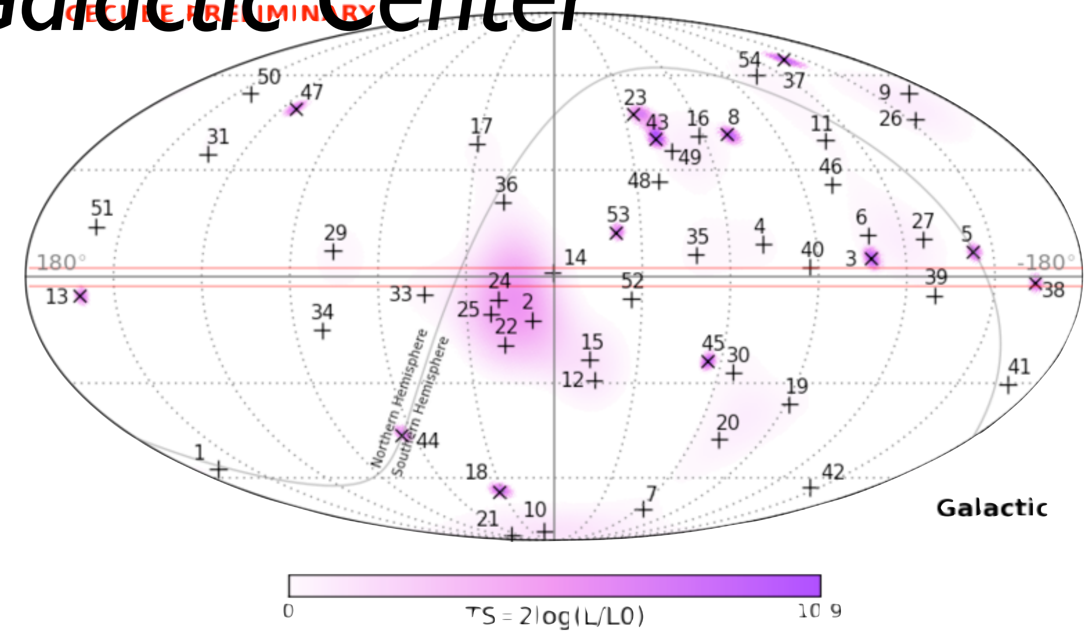


Active Galactic Nuclei / Starburst Galaxies

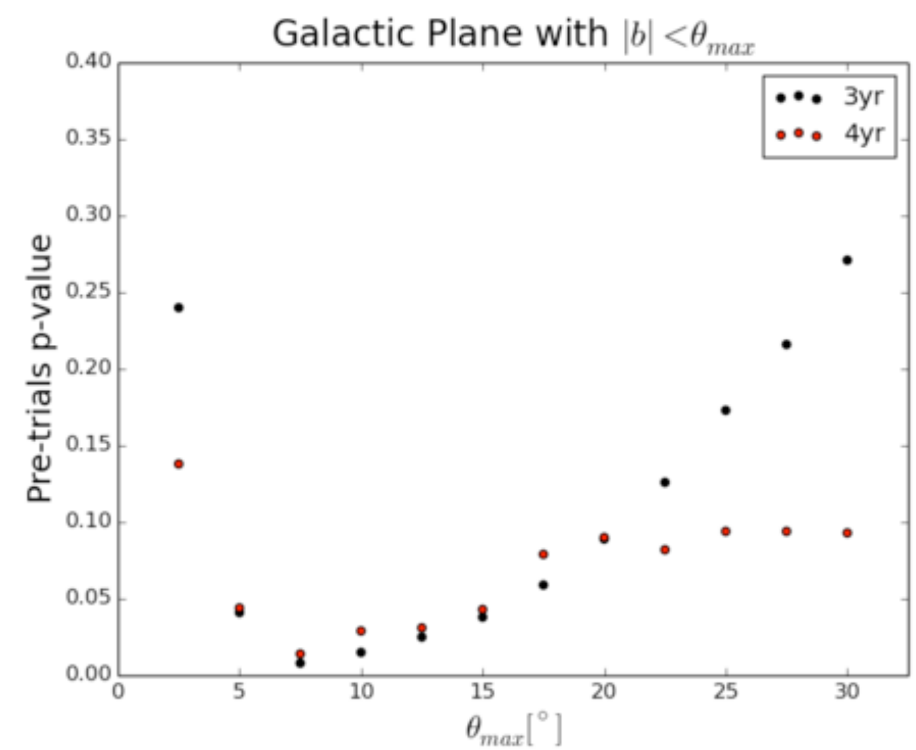
Starburst	M82	148.97	69.68	0.07	0.15
Radio	NGC 1275	49.95	41.51	0.0	–
Galaxies	Cyg A	299.87	40.73	0.9	0.03
	3C 123.0	69.27	29.67	0.0	–
	M87	187.71	12.39	0.0	–
	Cen A	201.37	-43.02	0.03	0.49

Galactic

Galactic Center



Galactic Plane



Heavy Dark Matter

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

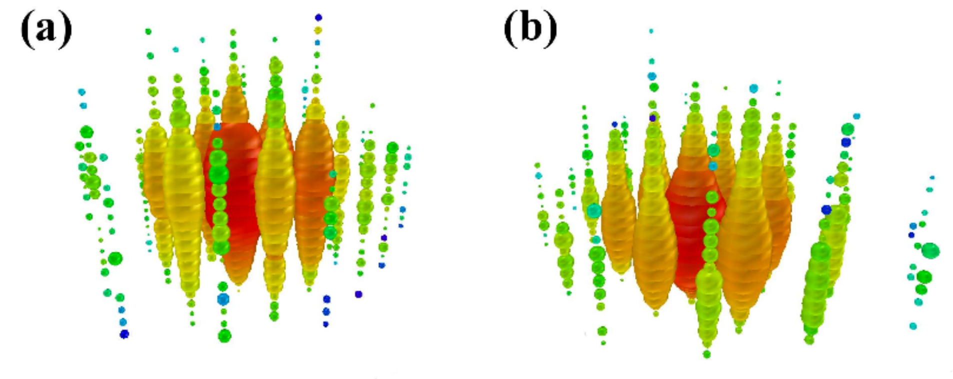


FIG. 4. The two observed events from (a) August 2011 and (b) January 2012. Each sphere represents a DOM. Colors represent the arrival times of the photons where red indicates early and blue late times. The size of the spheres is a measure for the recorded number of photo-electrons.

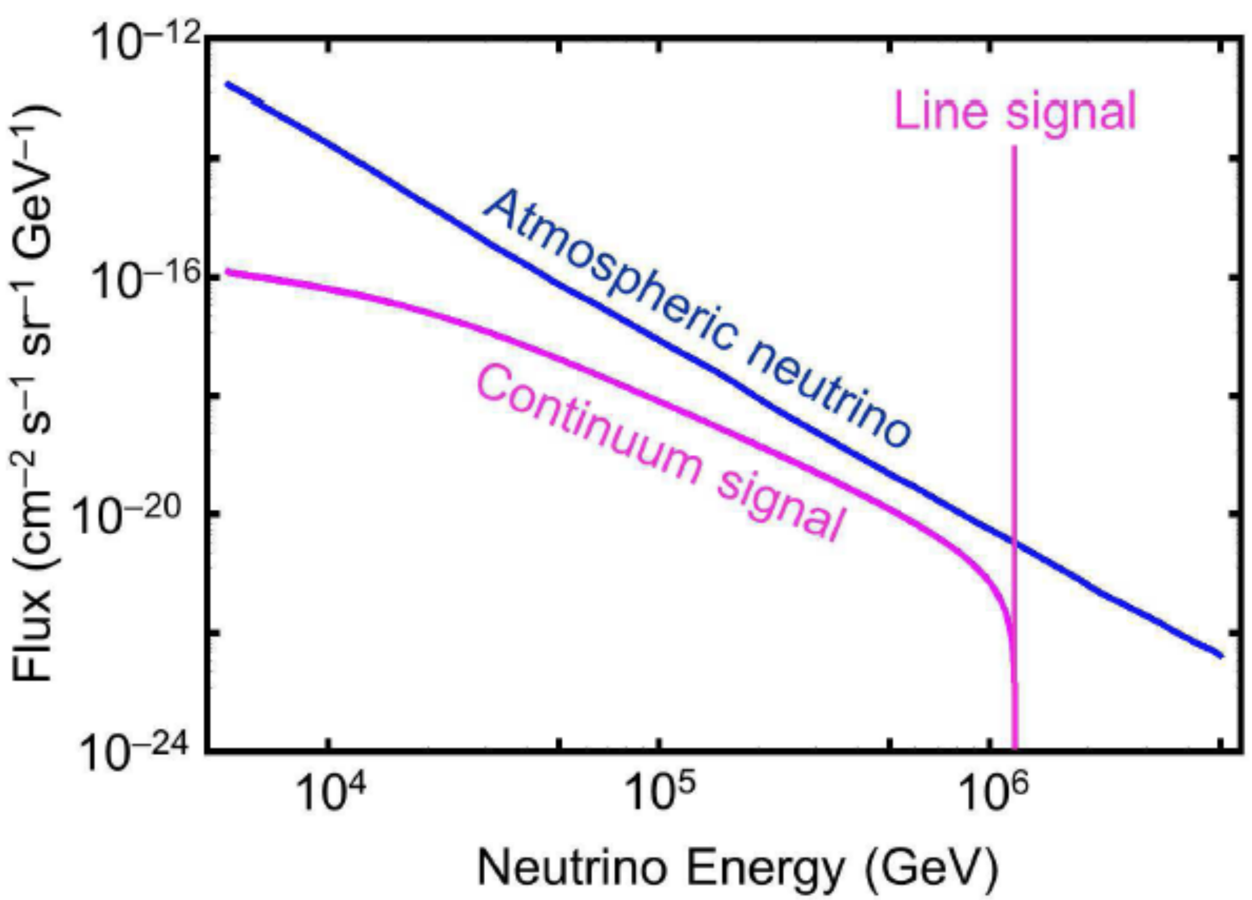
Could this be dark matter ?

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

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

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

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



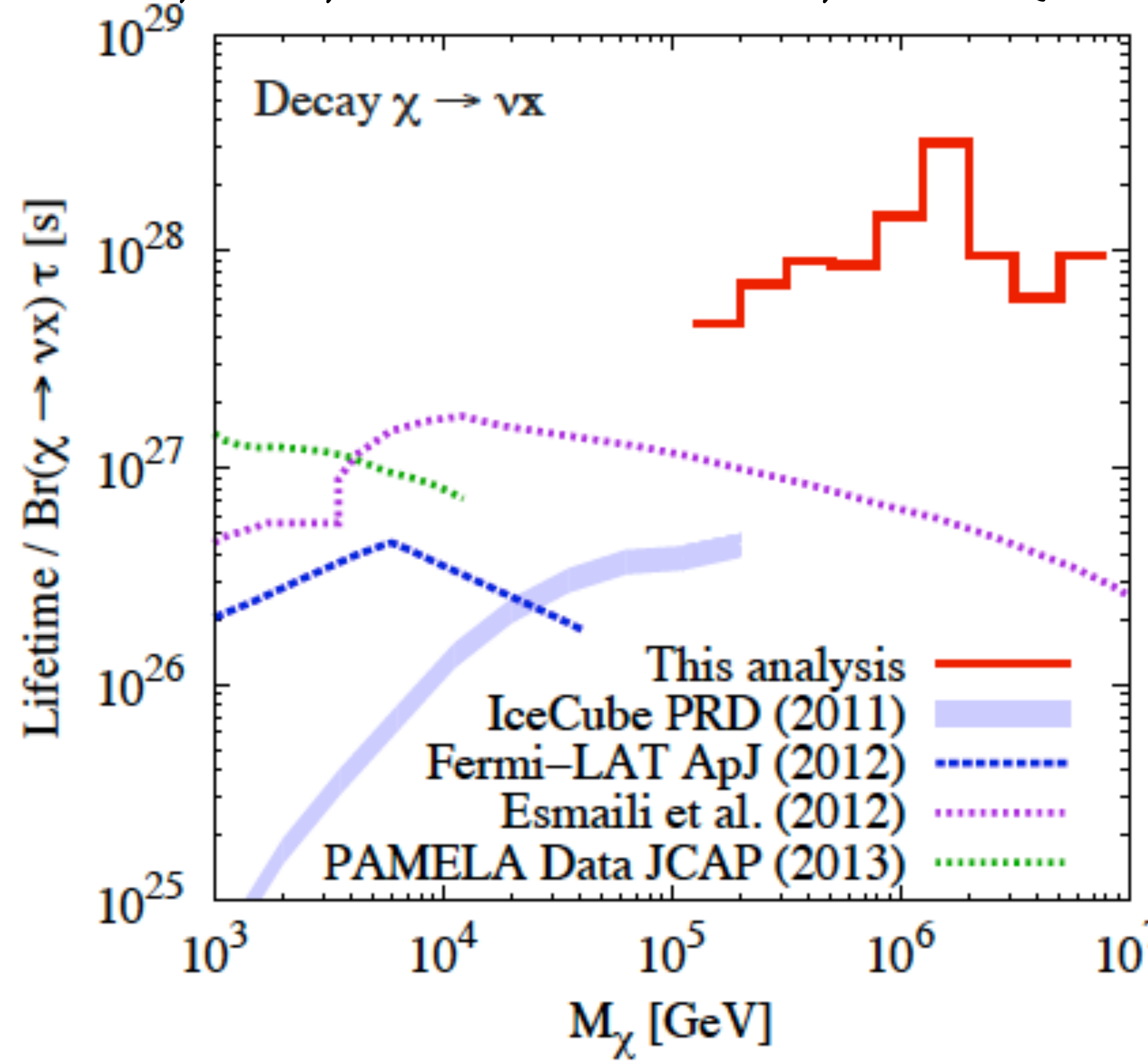
Heavy Dark Matter Decay

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

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

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

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



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

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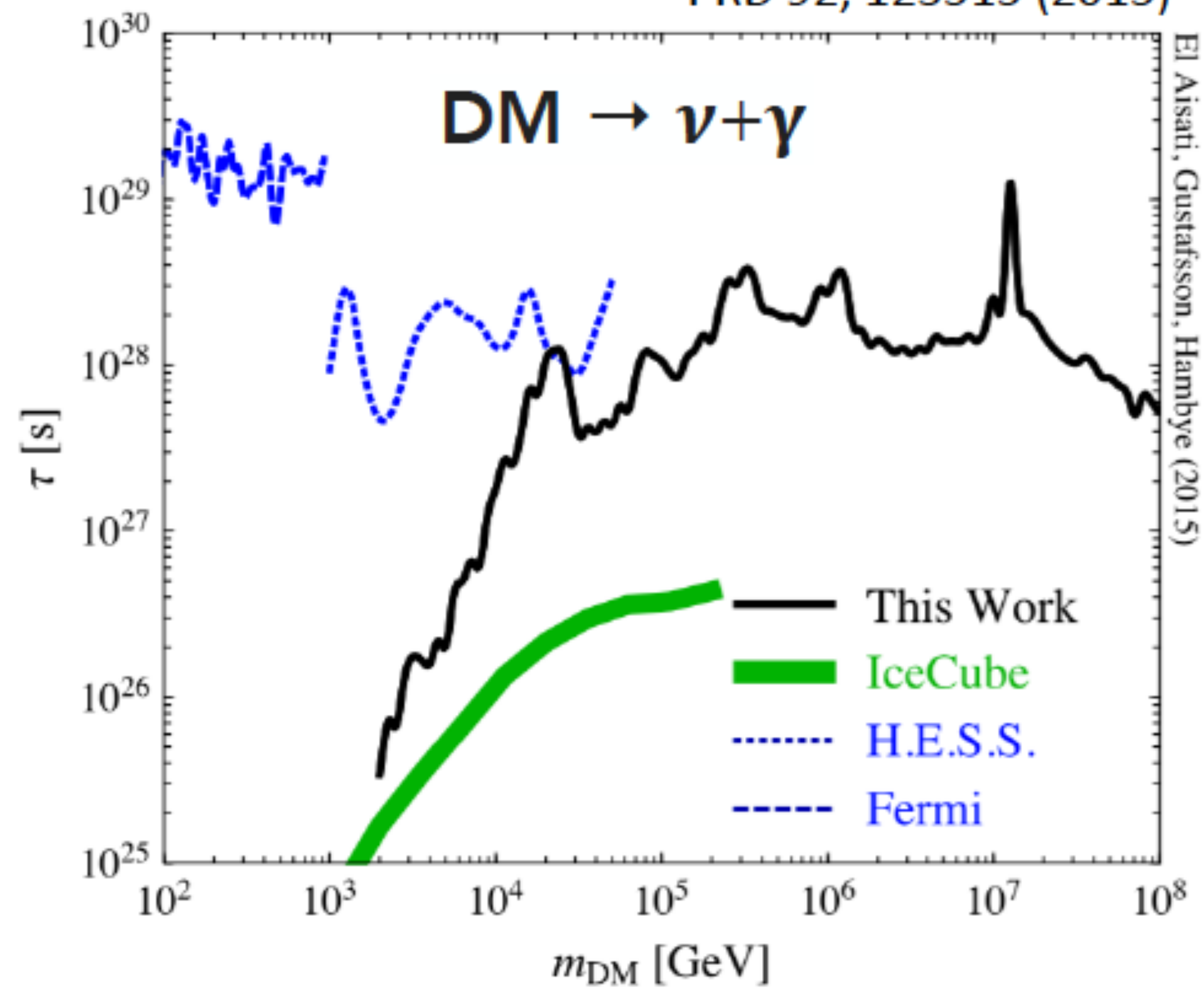
PRD 92, 123515 (2015)



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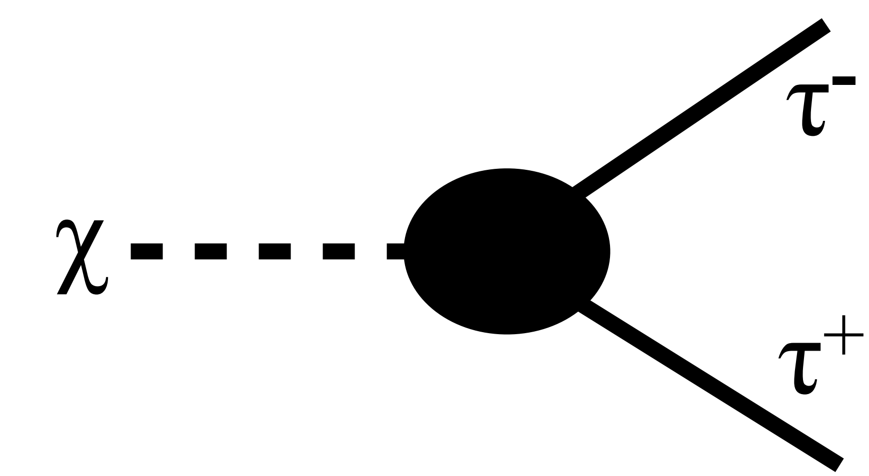
IceCube Collaboration Astrophys.J. 809 (2015) 1, 98

Flavor Ratio

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

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

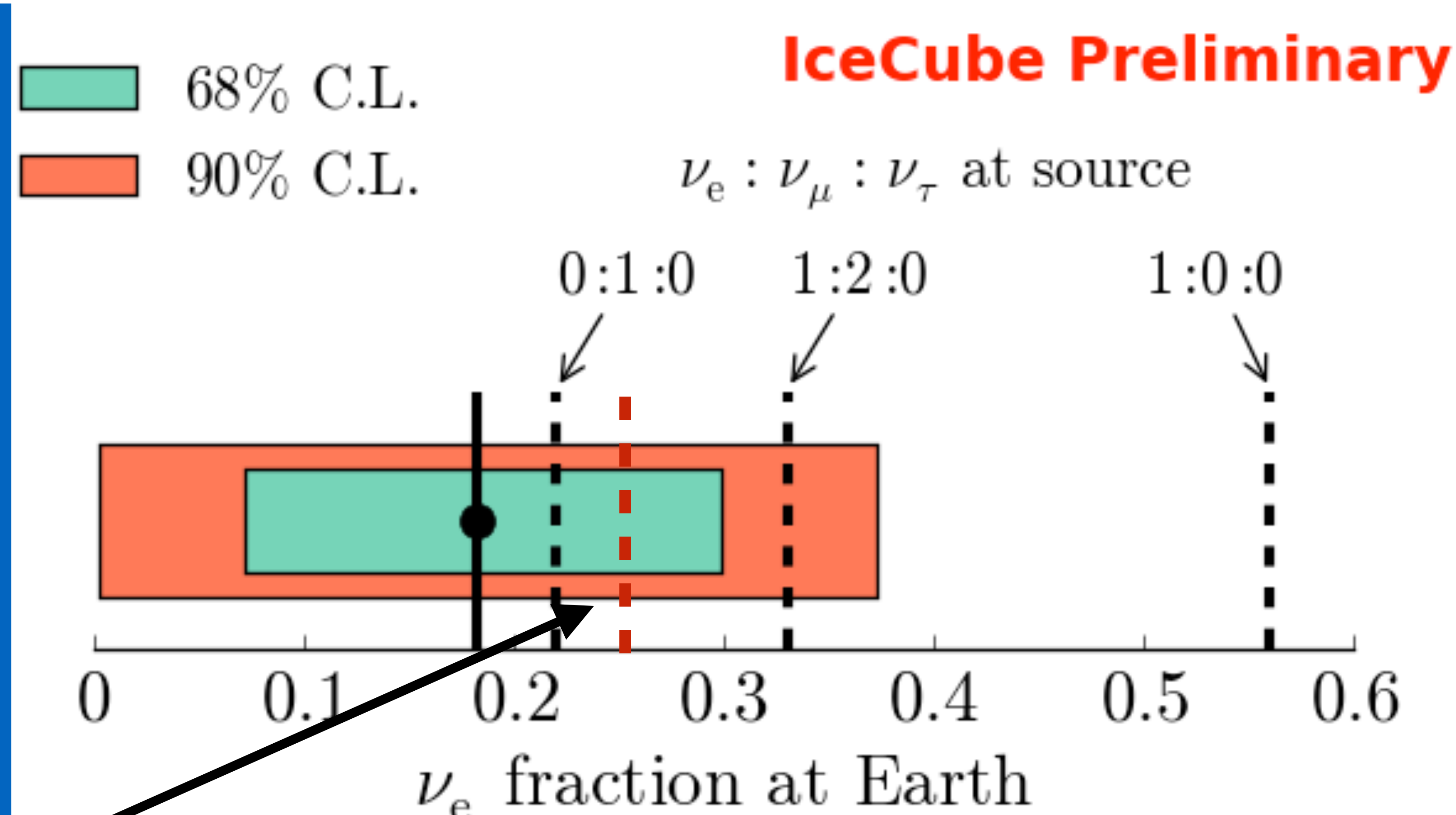


$\tau^- \rightarrow \nu_\tau + hadrons$ (64.8%)

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

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

resulting flavor ratio 1:1:6



neutron-decay dominated source rejected at 3.6σ

Flavor Ratio

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

- Global fit of several IceCube analyses
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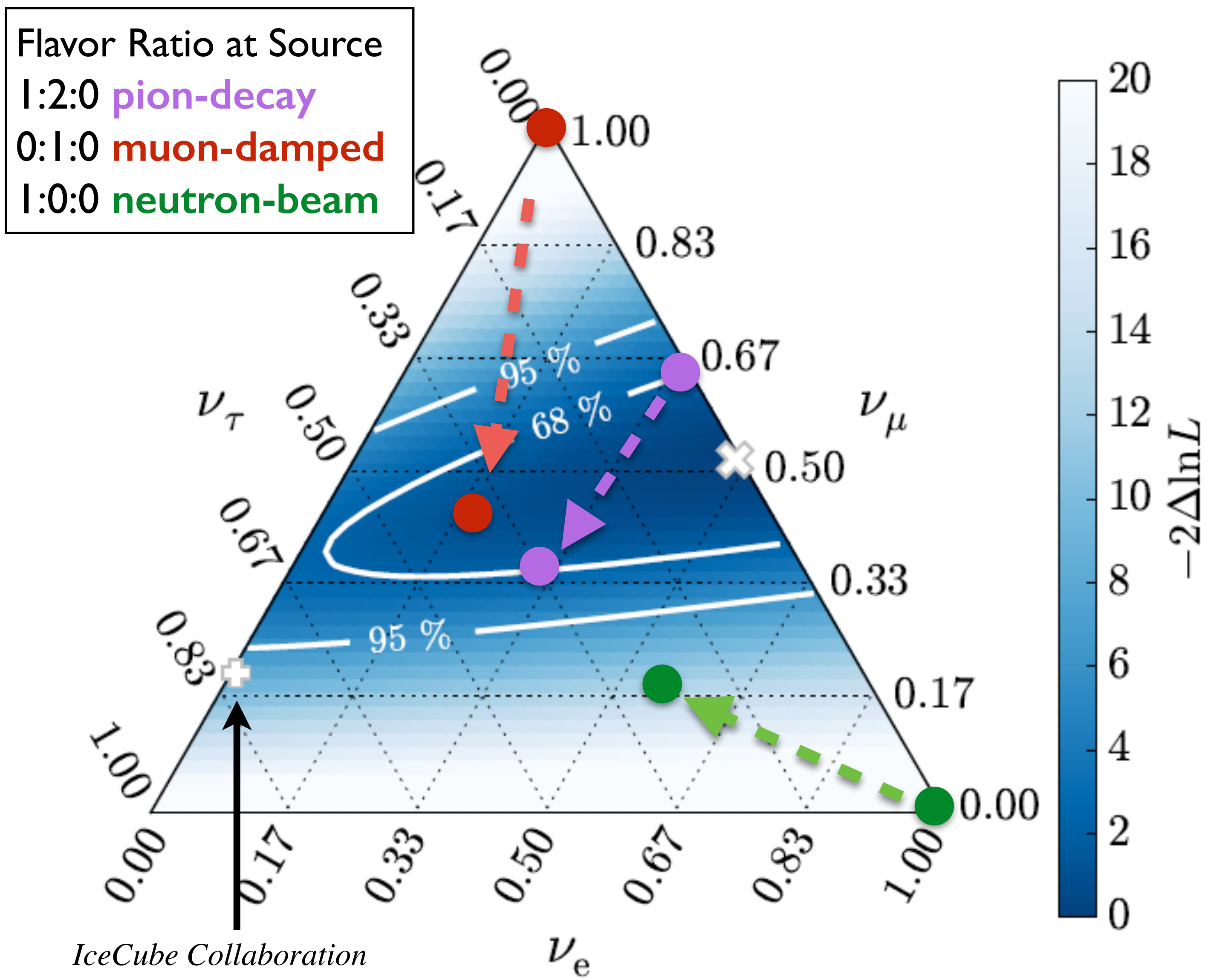


IceCube Collaboration
Phys.Rev.Lett. 114 (2015) 17, 171102

Flavor ratio source and at Earth

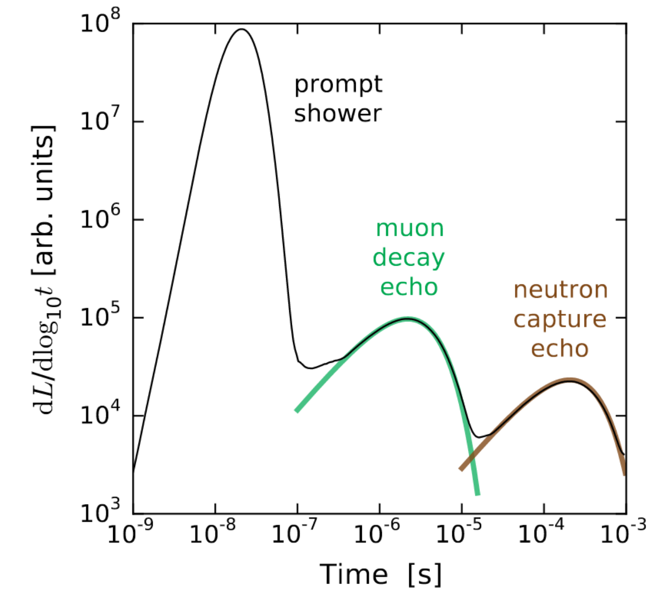
$\nu_e : \nu_\mu : \nu_\tau$

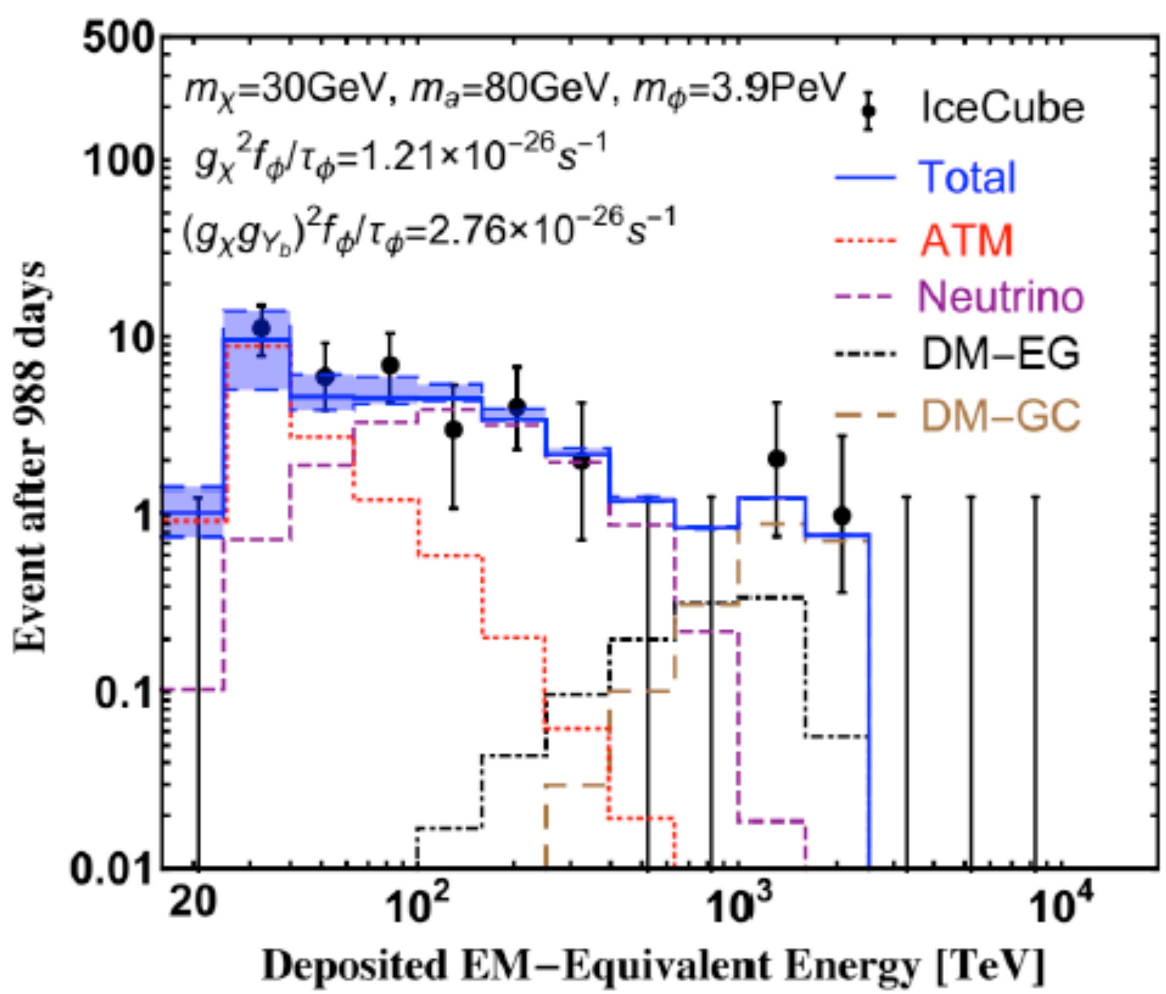
Source	Ratio at Source	Ratio at Earth
Pion decay	1:2:0	1:1:1
DM decay nunu	1:1:1	1:1:1
DM decay tau tau	1:1:6	2:3:3
DM decay bb	1:1:0	0.8:0.6:0.6

Boosted DM

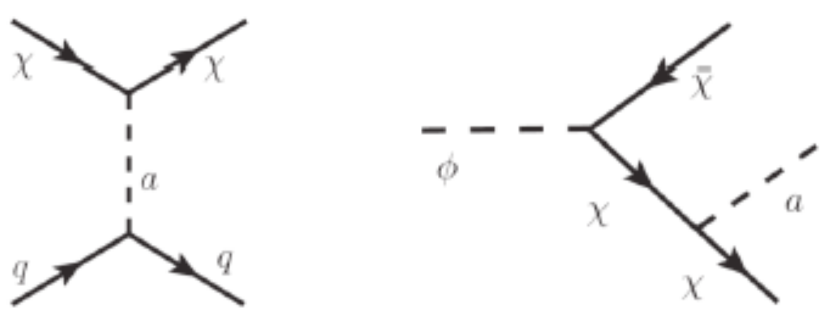
Boosted Dark Matter

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





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



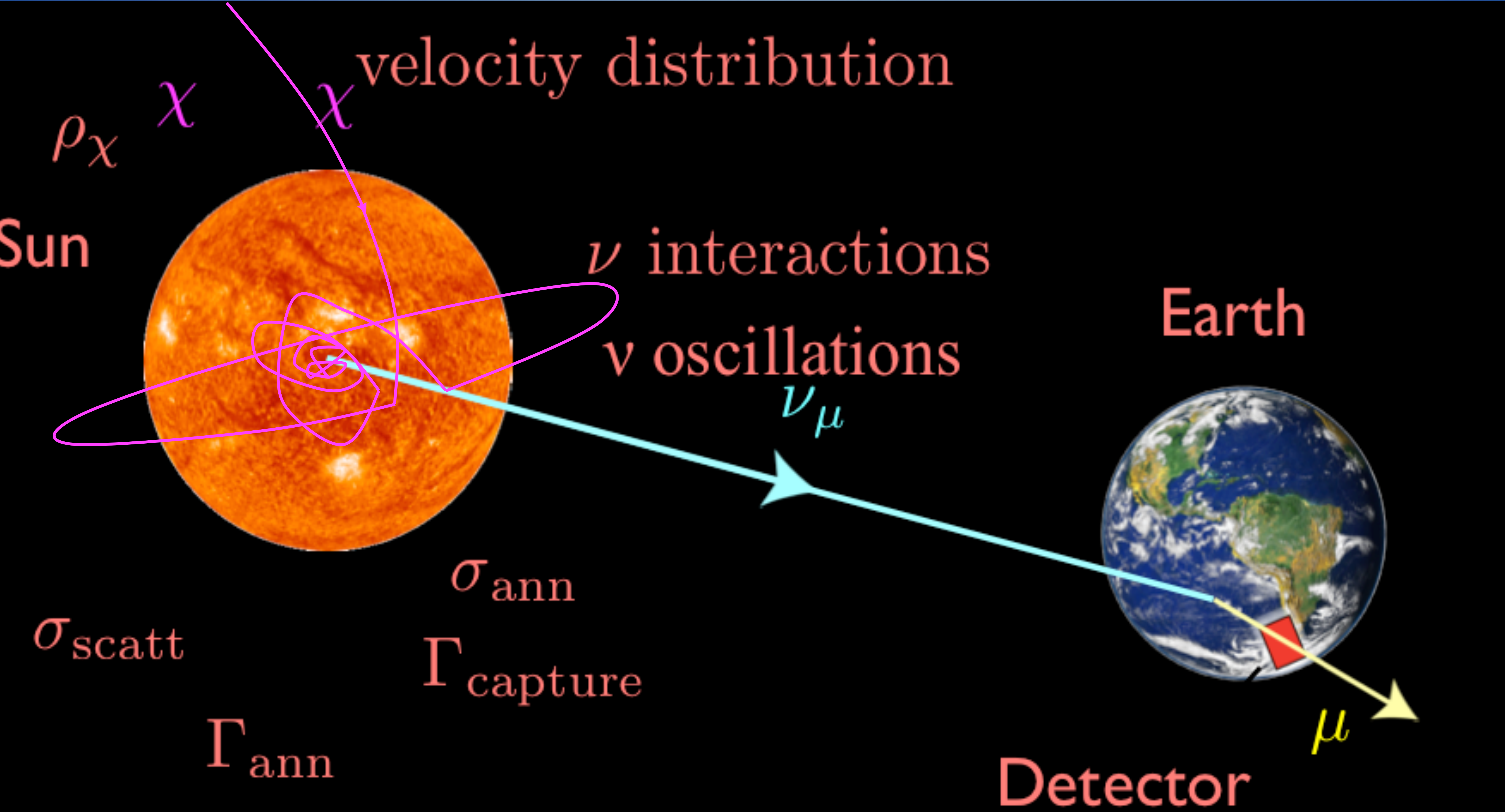
Recoil (only hadronic cascades)

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

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

Dark Matter Capture in the Sun

Solar WIMPs



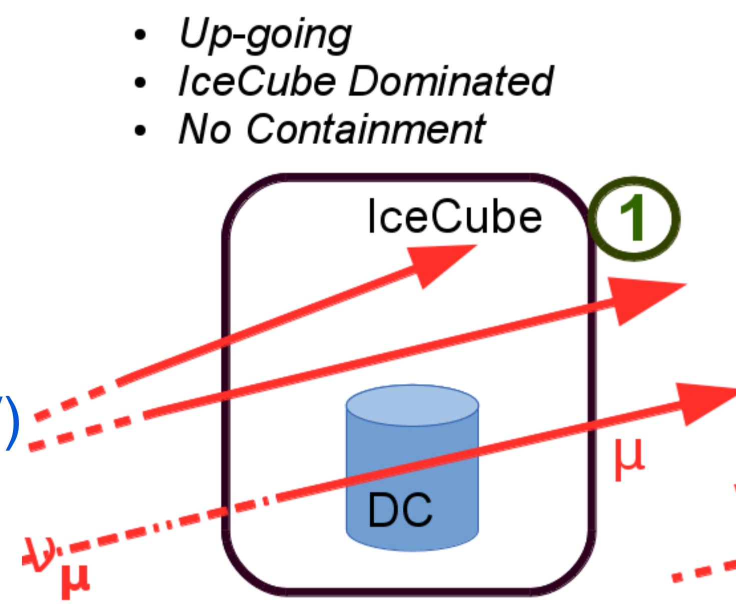
Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

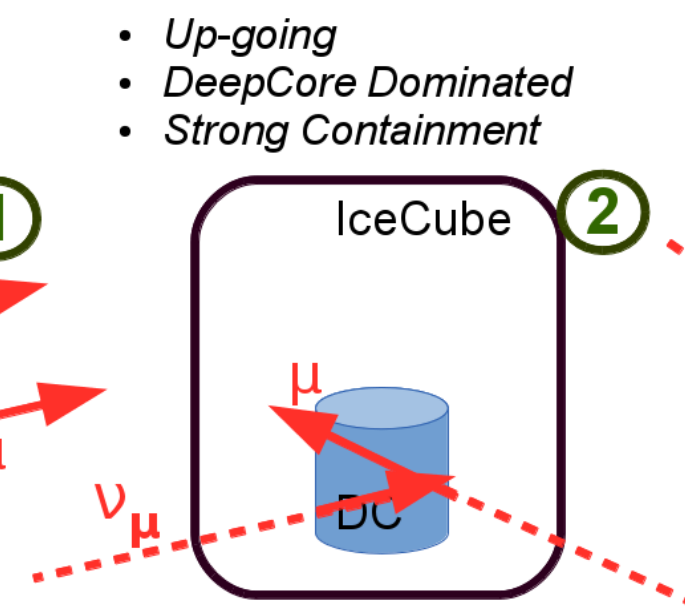
Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

3yrs IceCube Solar WIMP Analysis

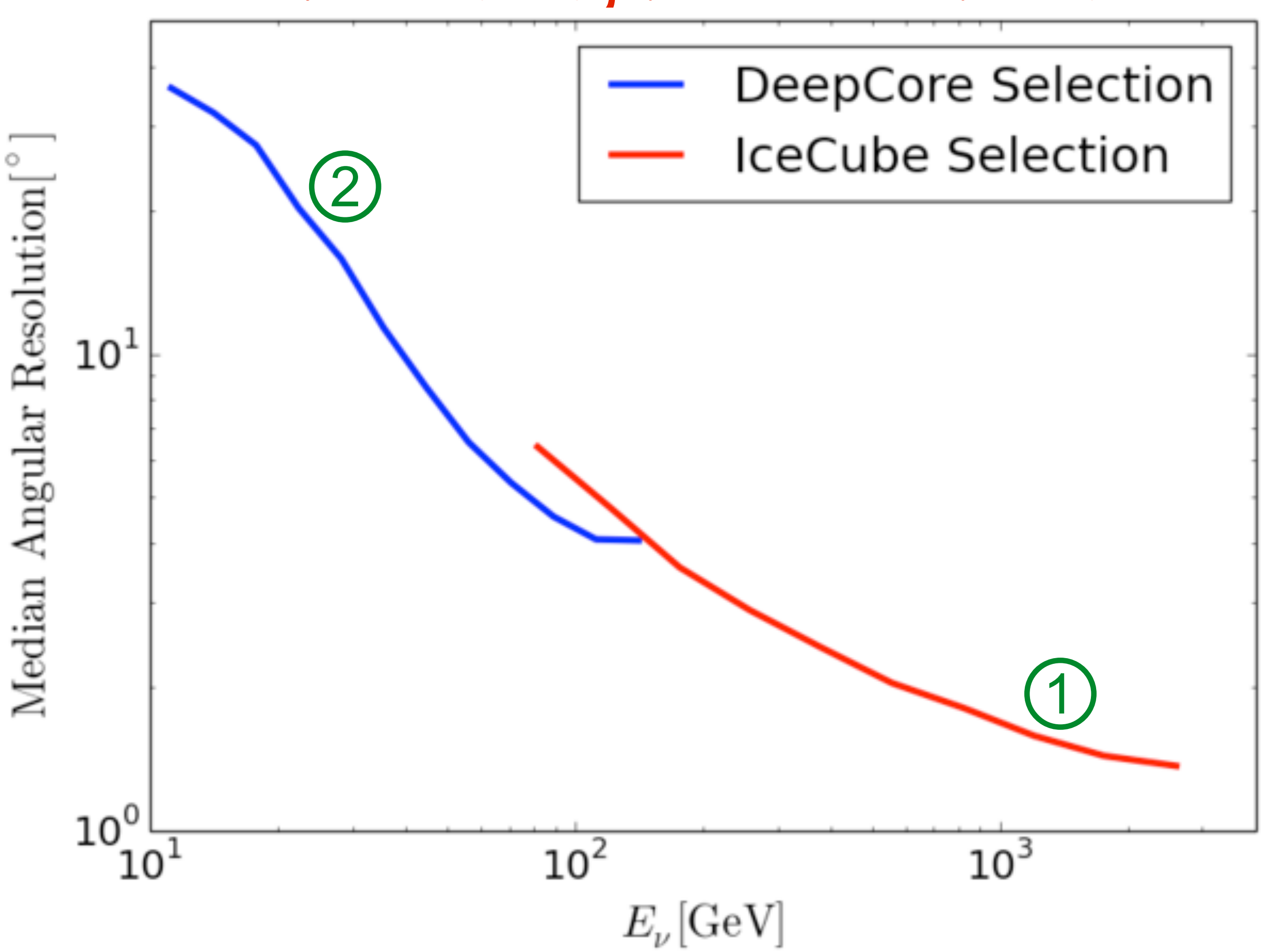
IceCubeColl., arXiv:1612.05949v1

- 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)

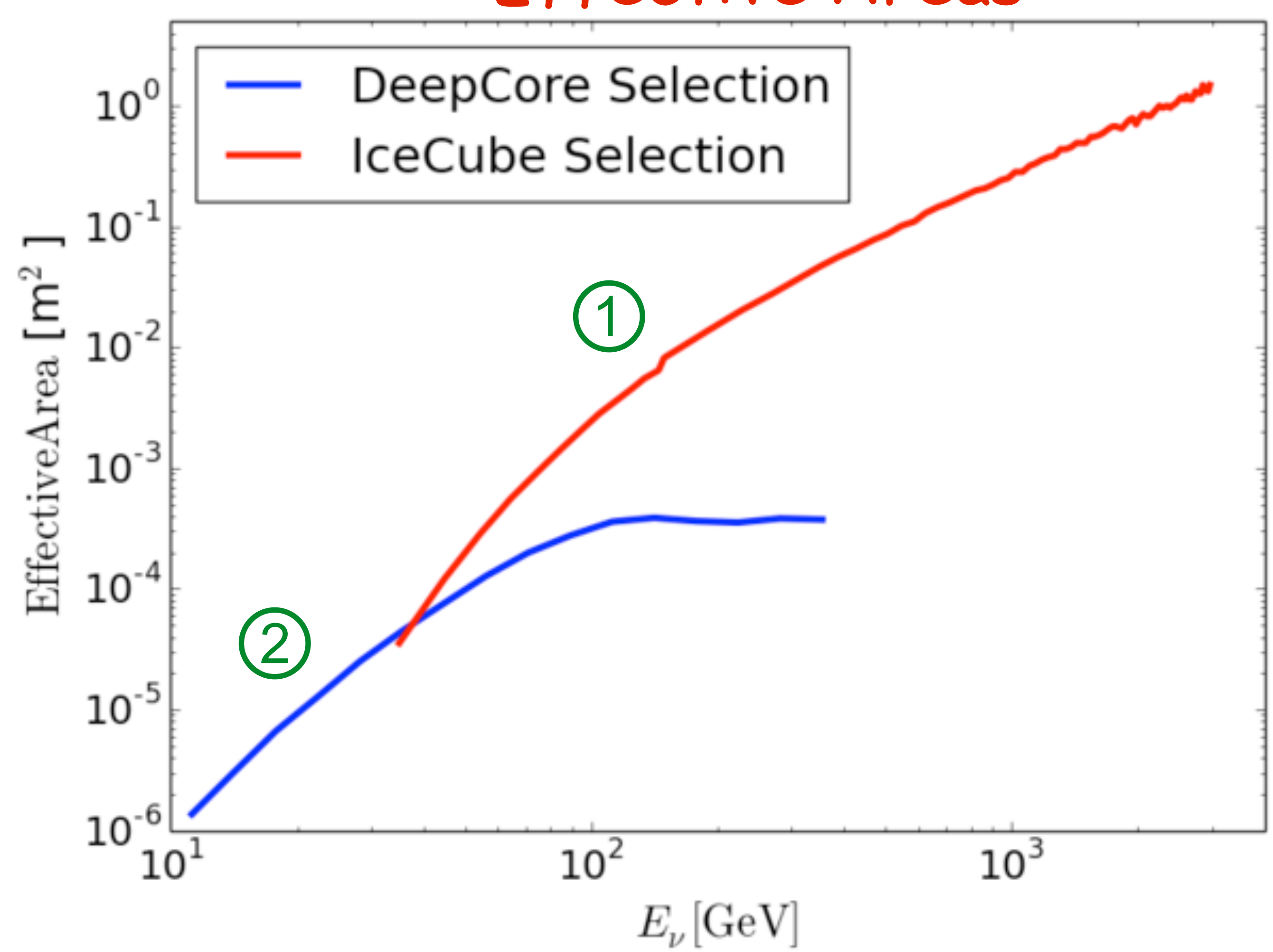




Median angular resolutions

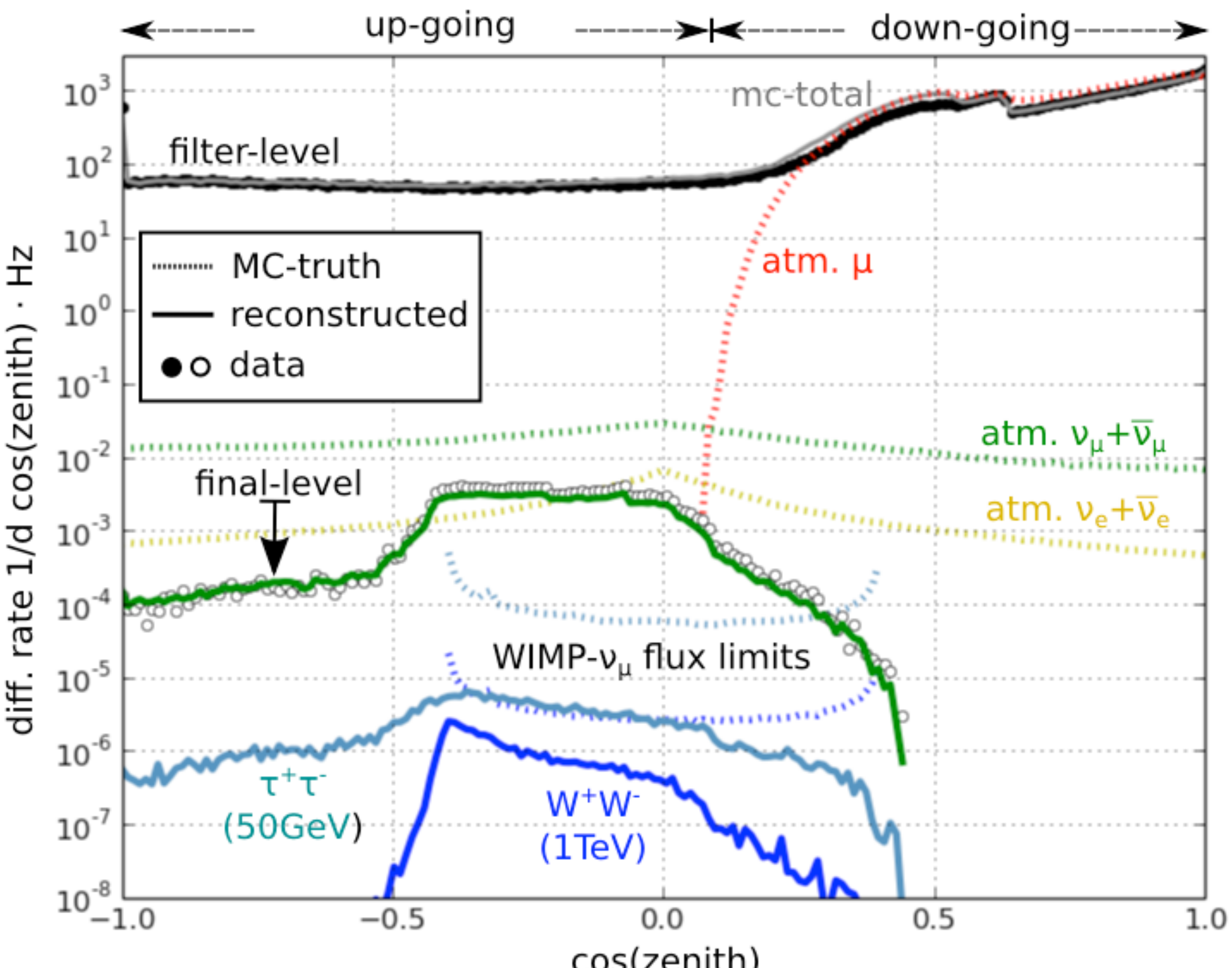


Effective Areas

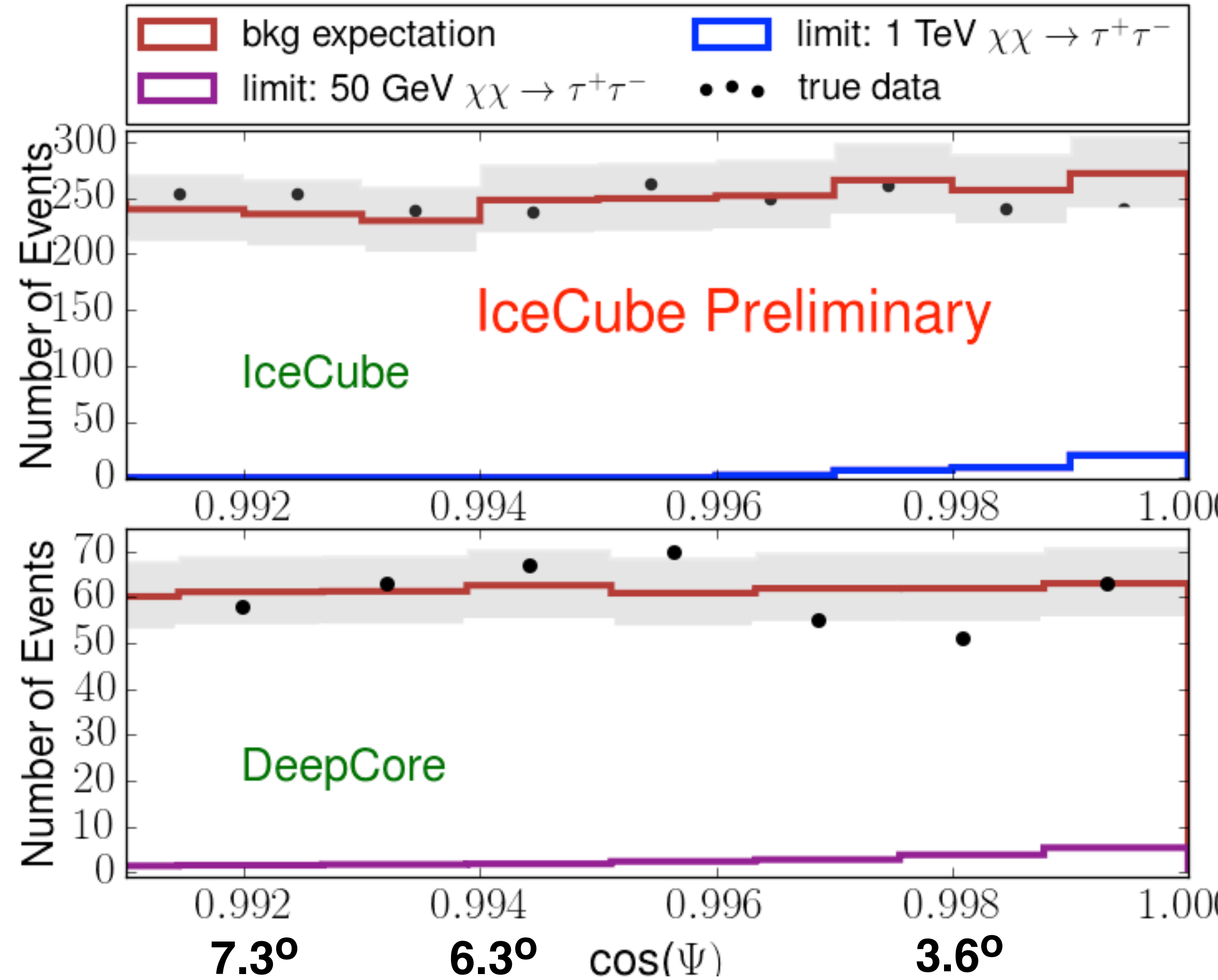


3yrs IceCube Solar WIMP Analysis

IceCubeColl., arXiv:1612.05949v1



Observed events



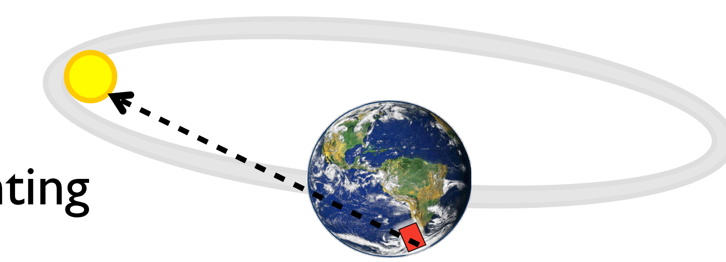
Signal pdf:

$$S_i(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, E_i, m_\chi, c_{\rm ann})$$

Spectral part

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

Monovariate Fisher Bingham distribution from directional statistics



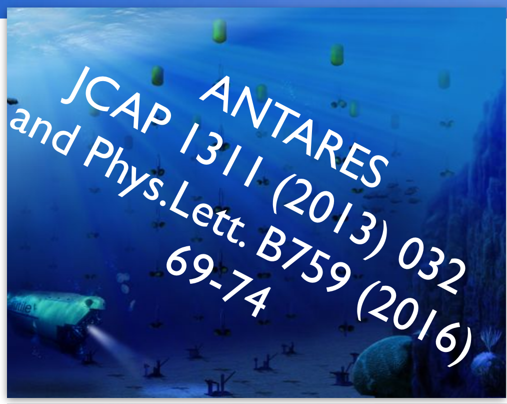
- Use track events for better pointing
- Search for an excess of events from the direction of the Sun
- Observed events consistent with background only expectations

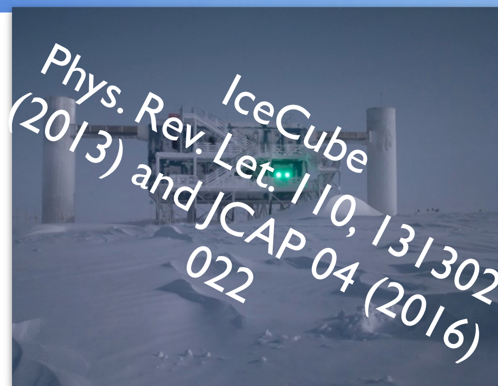
Background pdf: $\mathscr{B}_i(tx_i, E_i) = B(\delta_i) \times P(E_i|\phi_{\rm atm})$

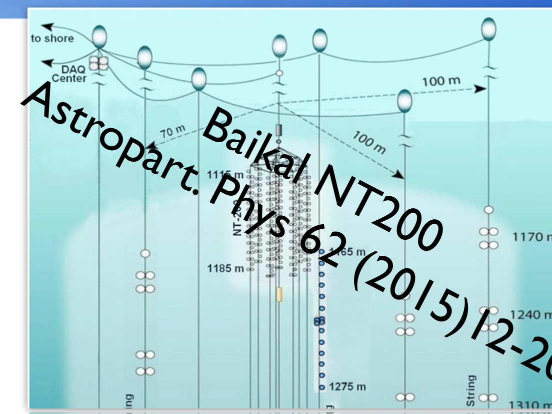
Likelihood: $\mathscr{L}(n_s) = \prod_N \left(\frac{n_s}{N} S_i + (1 - \frac{n_s}{N})\mathscr{B}_i\right)$

Solar WIMPs Summary

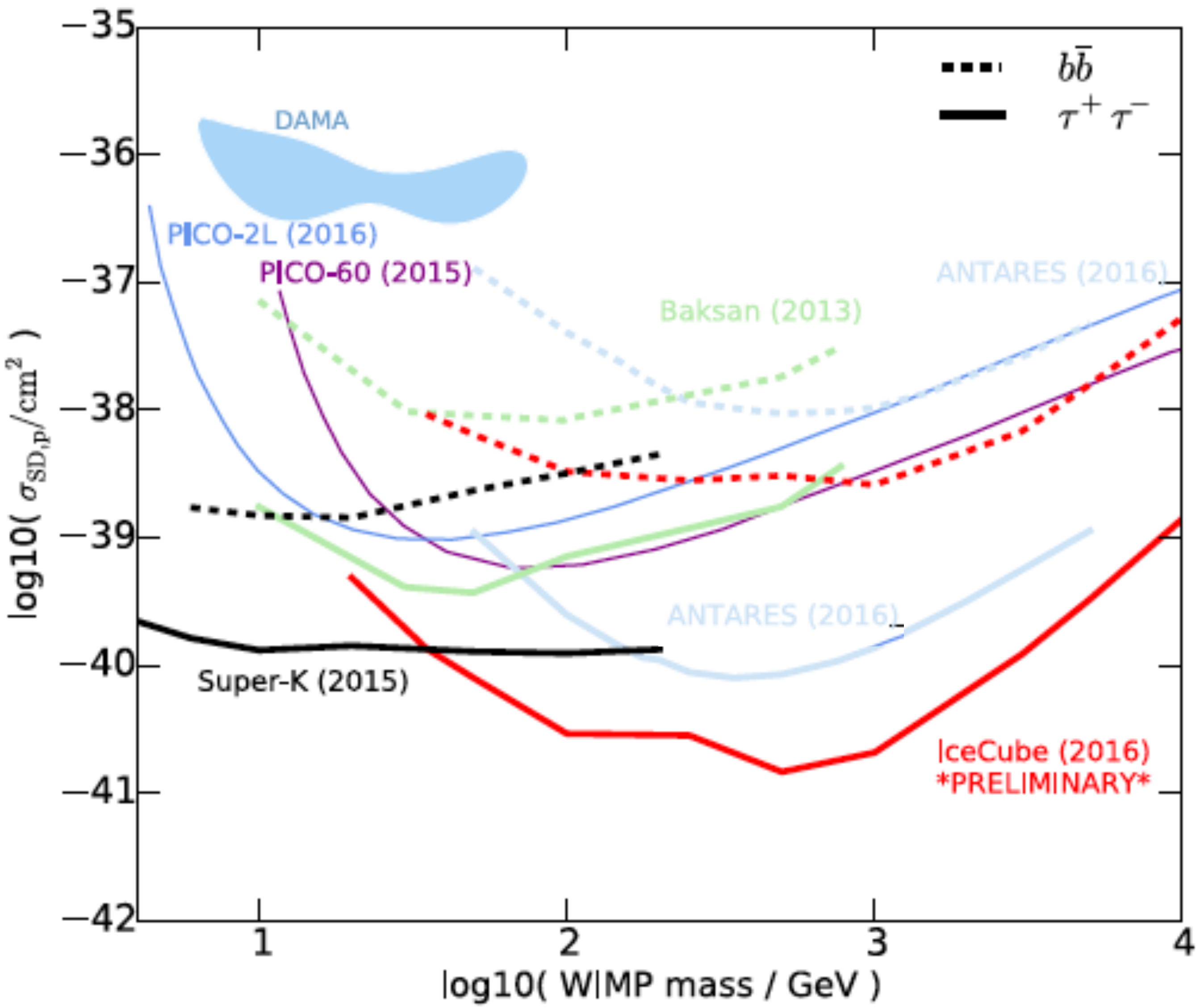
IceCubeColl., arXiv:1612.05949v1



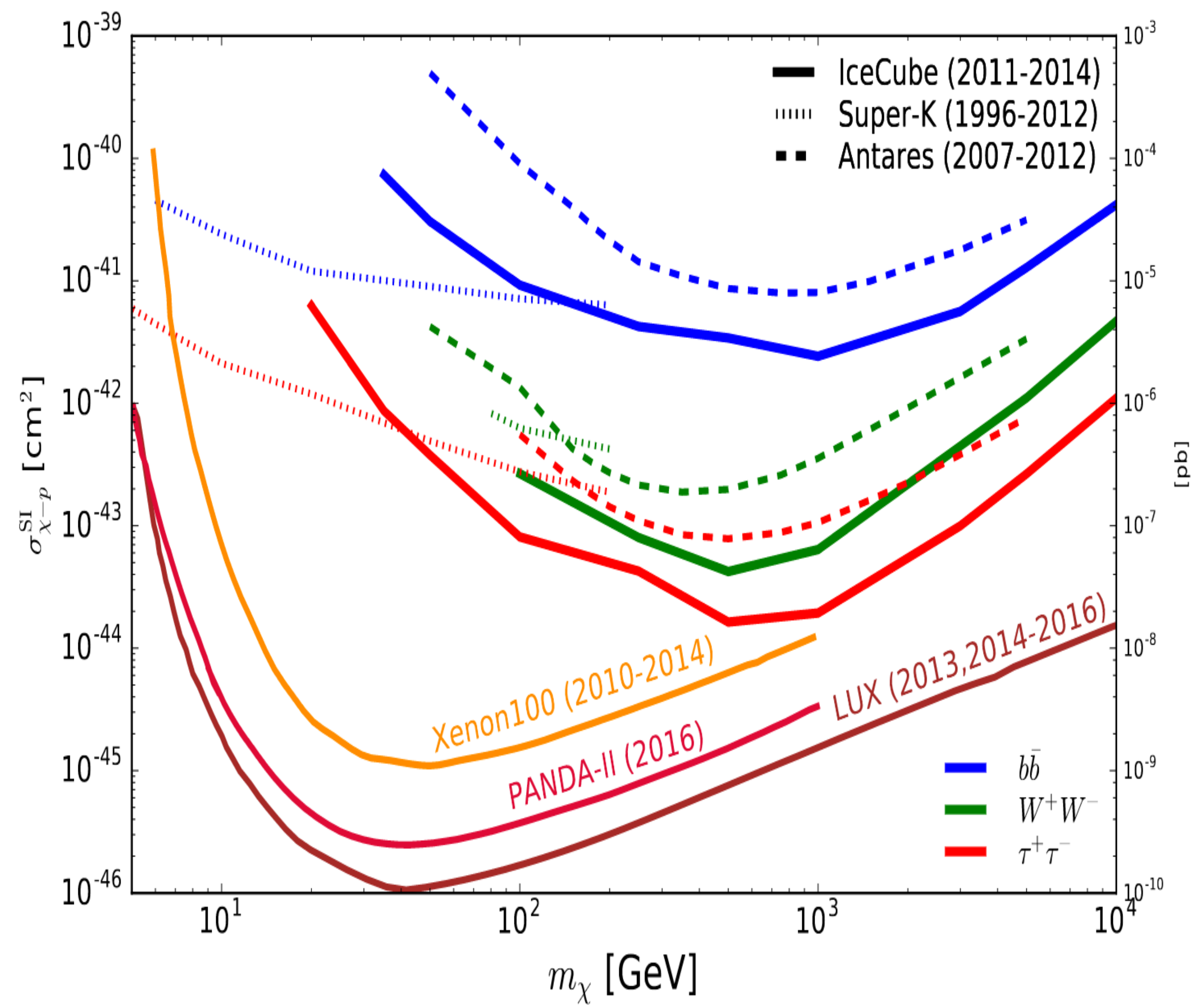




Spin-dependent scattering

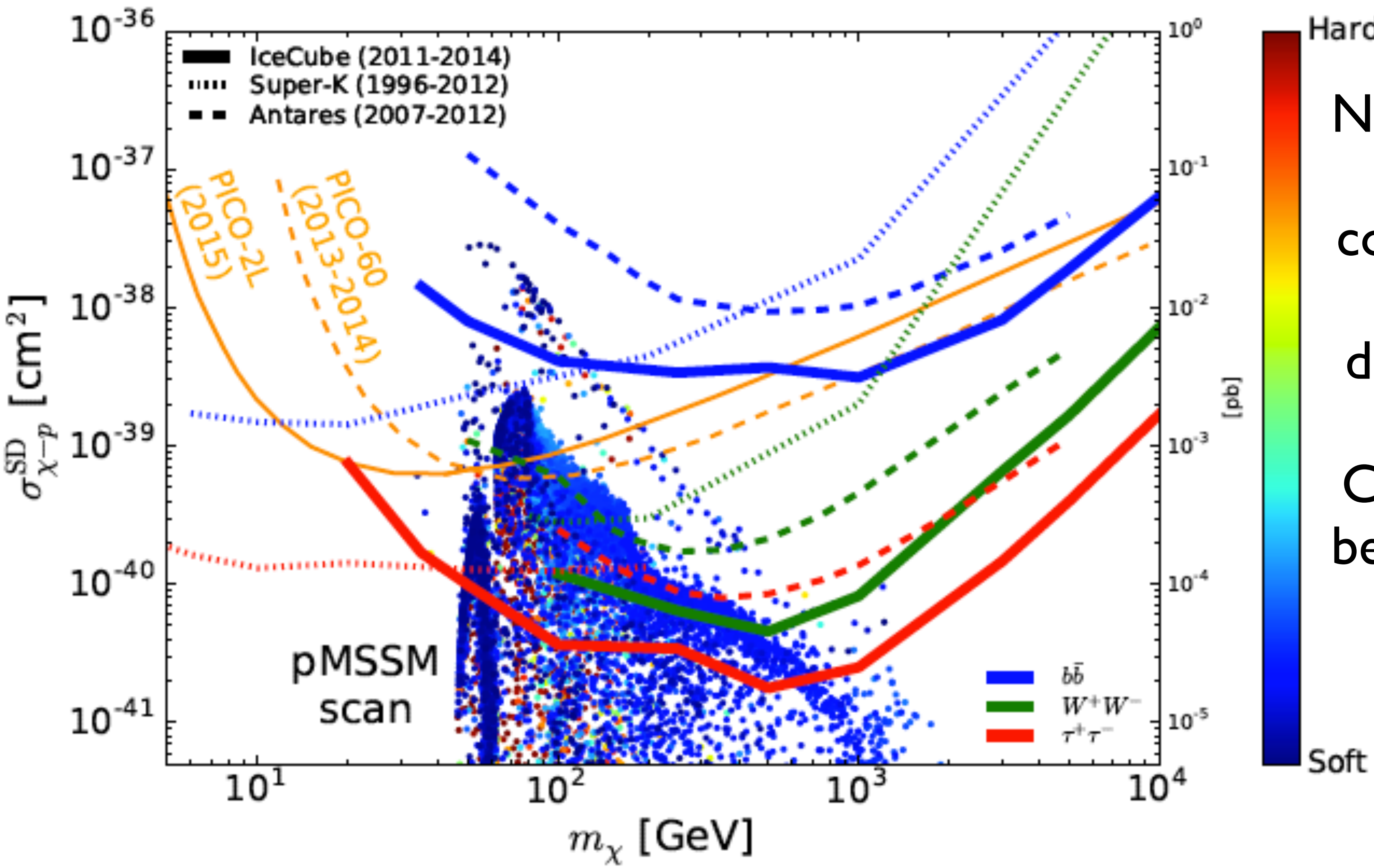


Spin-independent scattering



Solar WIMPs (Spin-dependent)

IceCubeColl., arXiv:1612.05949v1



Neutrino bounds extremely competitive with Dark Matter direct detection
&
Can test models beyond the reach of LHC

- pMSSM model scans
  - Hard / Soft defined by fraction of hard and soft final states

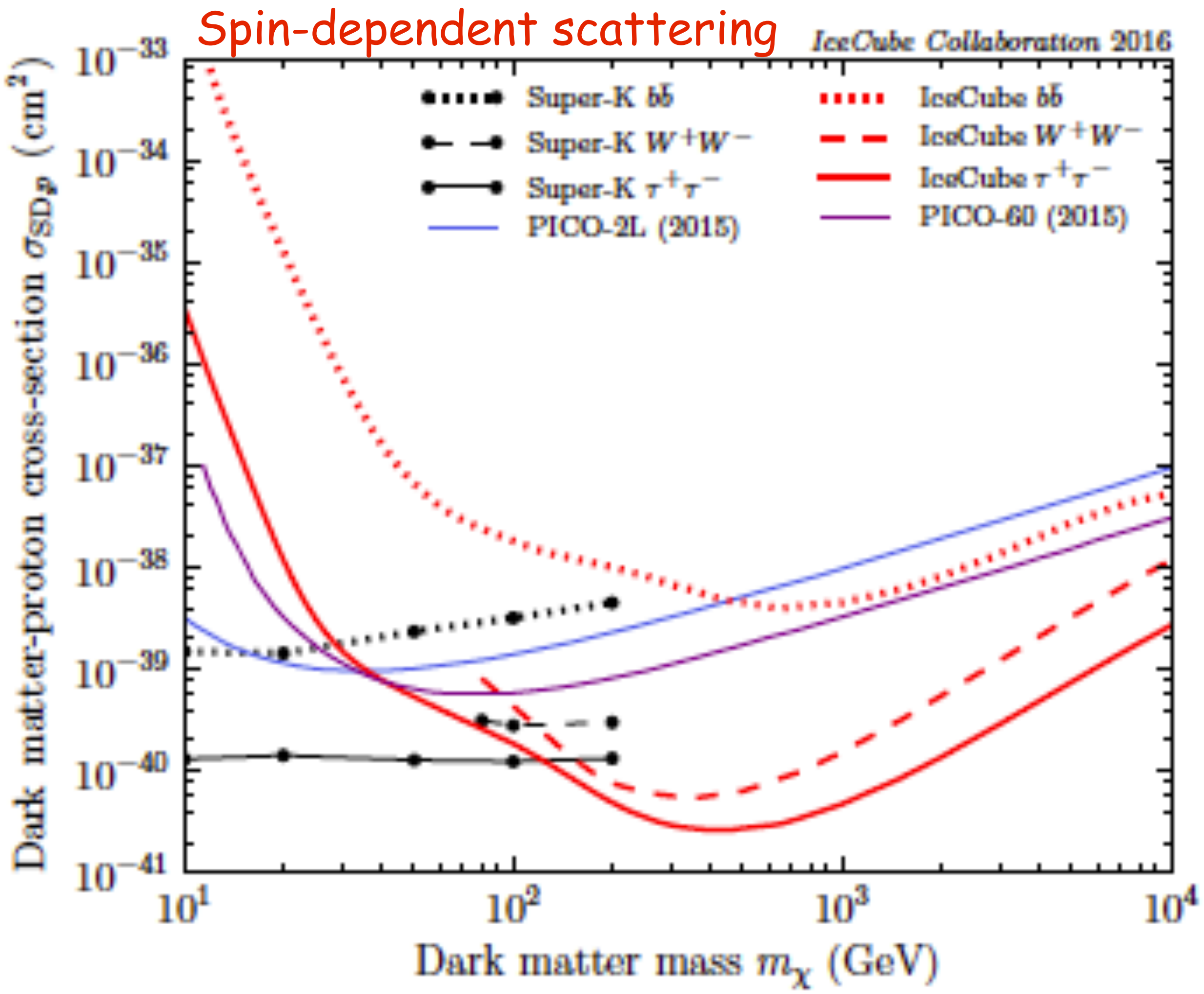
No evidence for dark matter

nulike

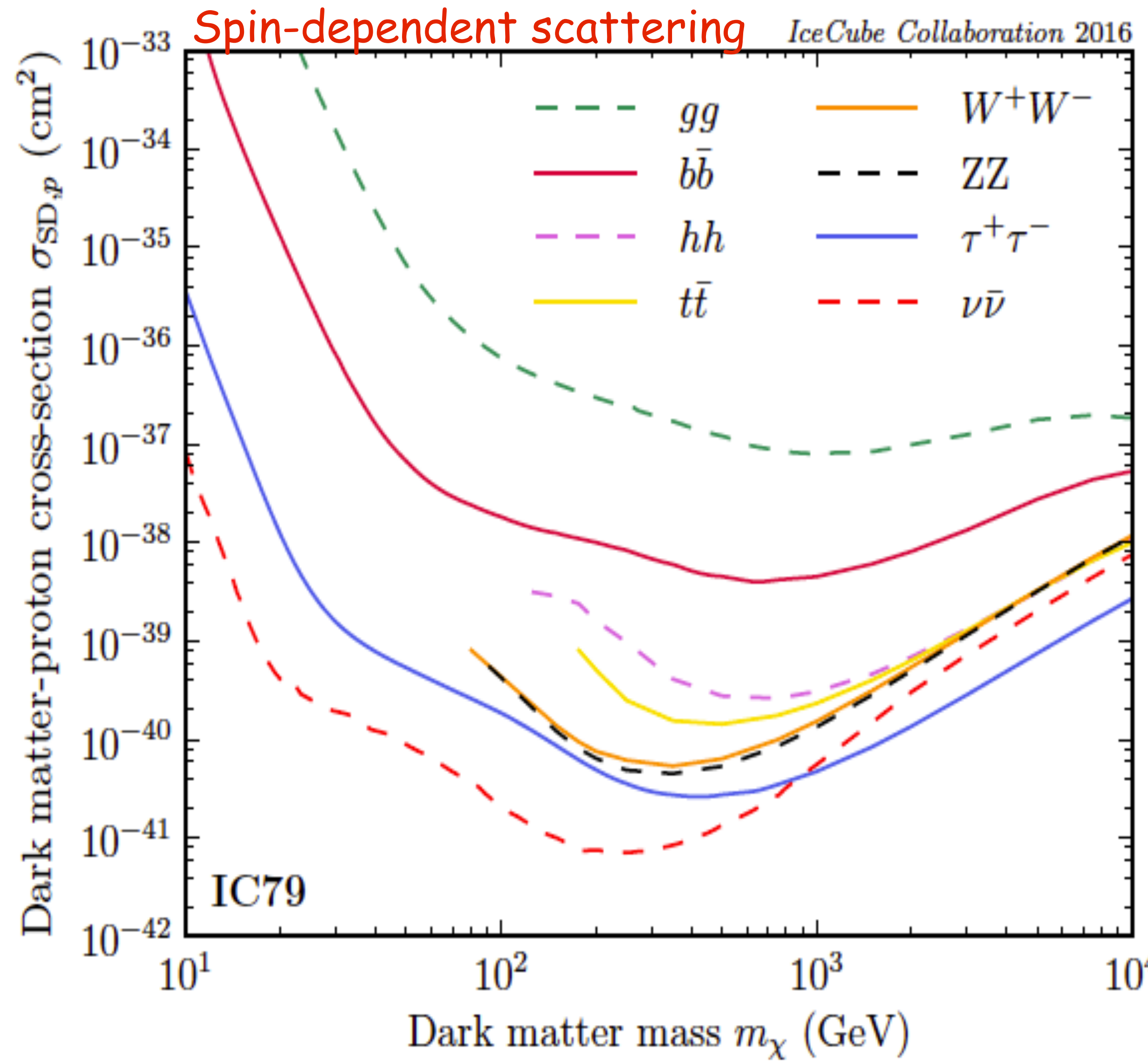
http://nulike.hepforge.org./

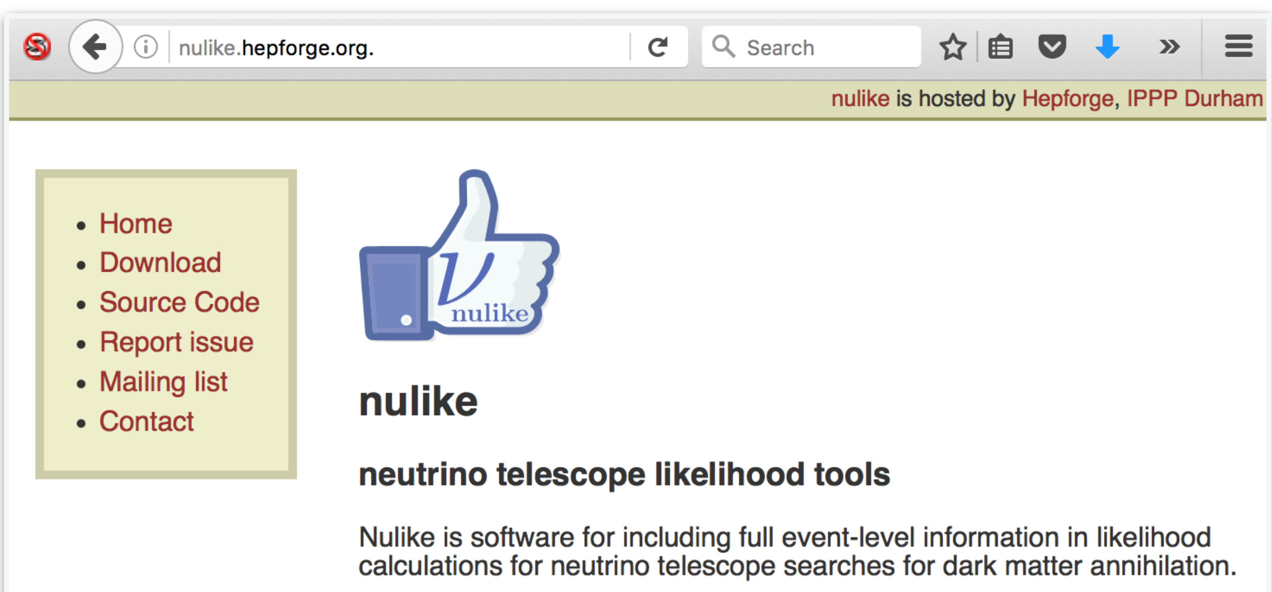
JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf

Spin-dependent scattering



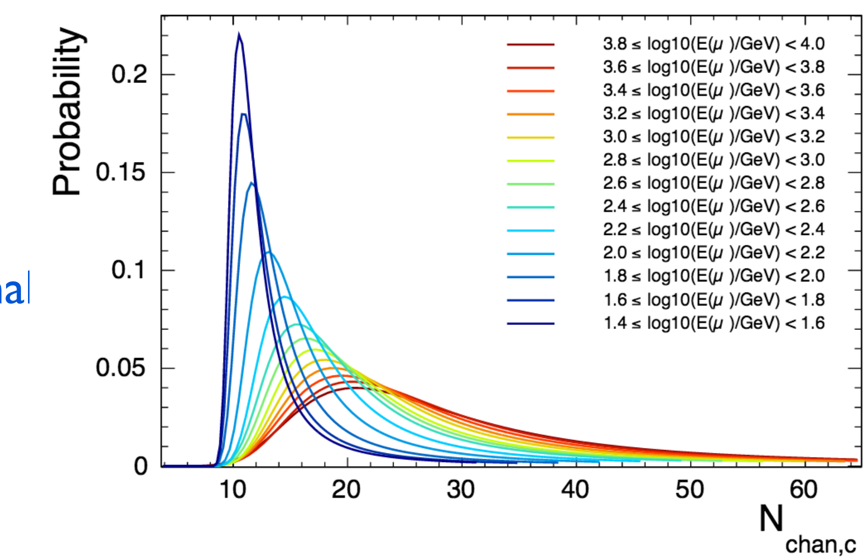
Spin-dependent scattering



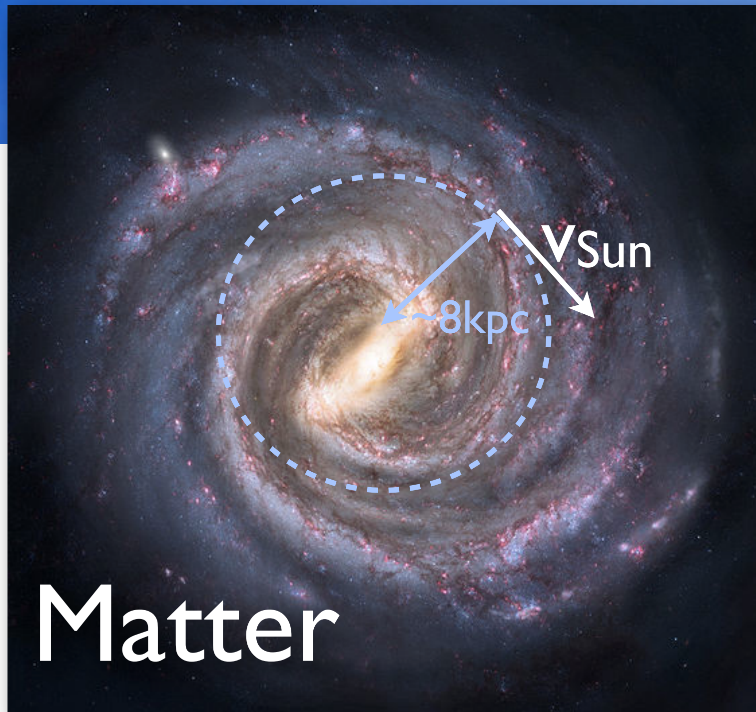


Likelihood includes:

- energy and directional information



Solar WIMP Capture



+

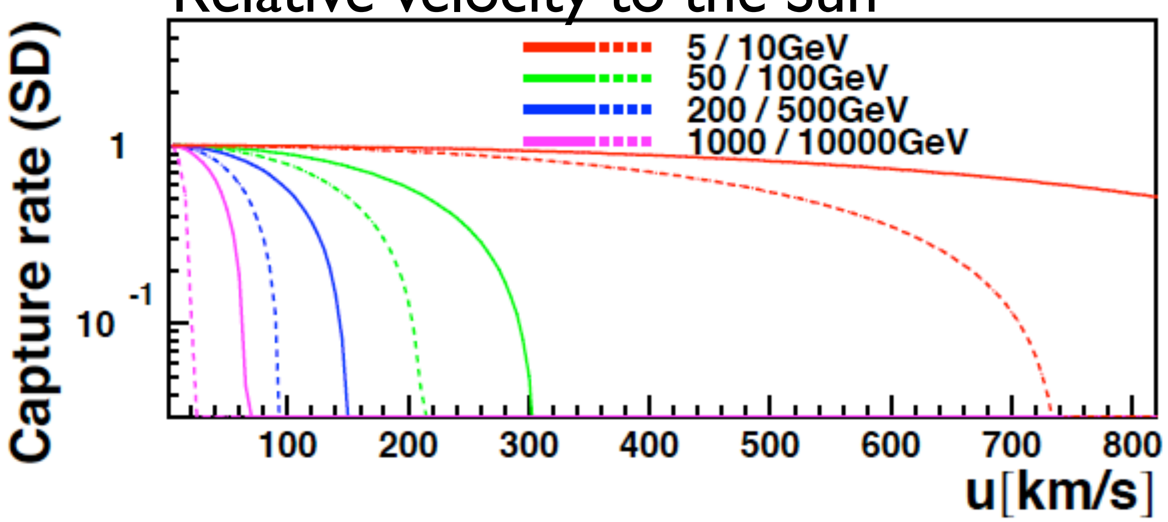
<u>Standard assumption</u>

DM isotropic with Maxwellian velocity distribution

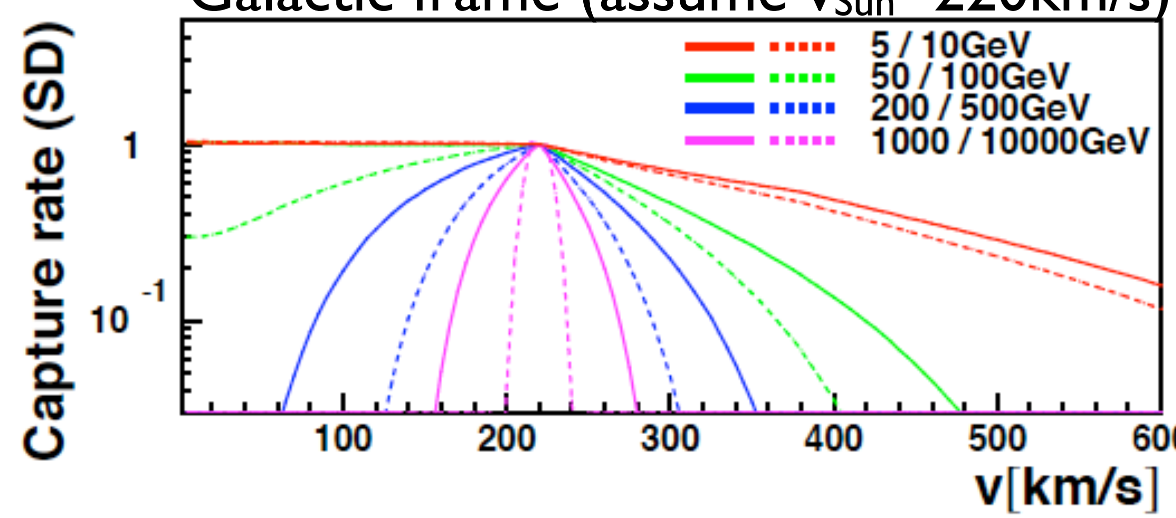
... consequence of a density profile $\rho(r) \propto r^{-2}$ of collisionless particles

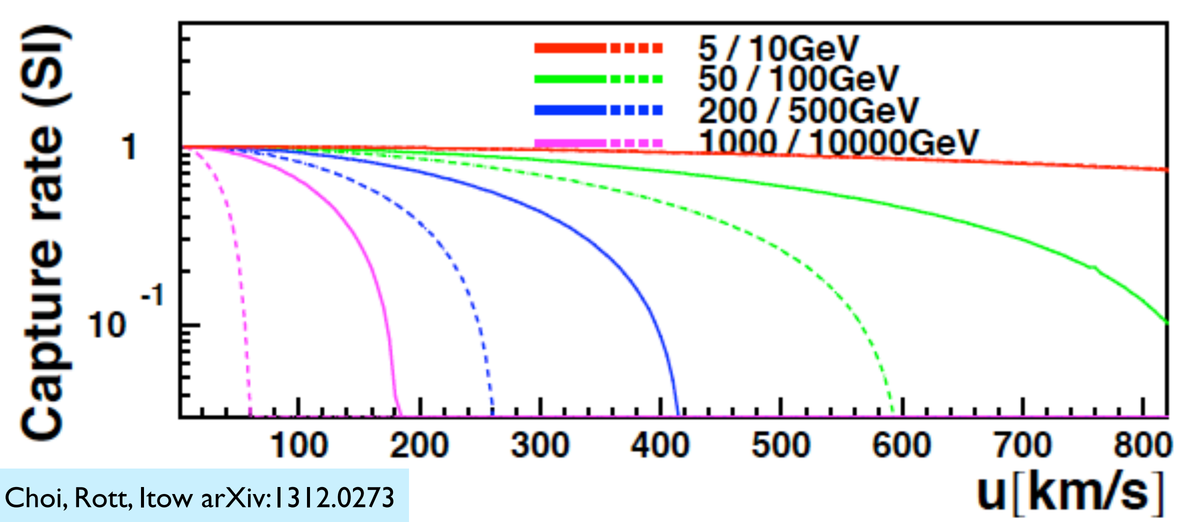
$$f(u) = \sqrt{\frac{3}{2\pi}} \frac{u}{v_\odot v_{\rm rms}} \left(\exp\left(-\frac{3(u-v_\odot)^2}{2v_{\rm rms}^2}\right) - \exp\left(-\frac{3(u+v_\odot)^2}{2v_{\rm rms}^2}\right)\right).$$

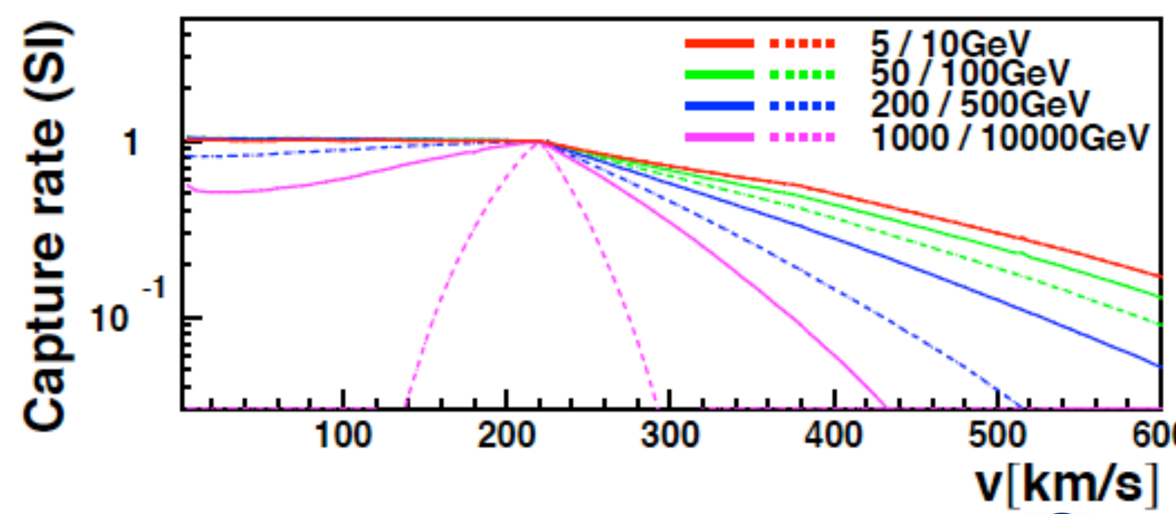
Relative velocity to the Sun



Galactic frame (assume v_{Sun}=220km/s)







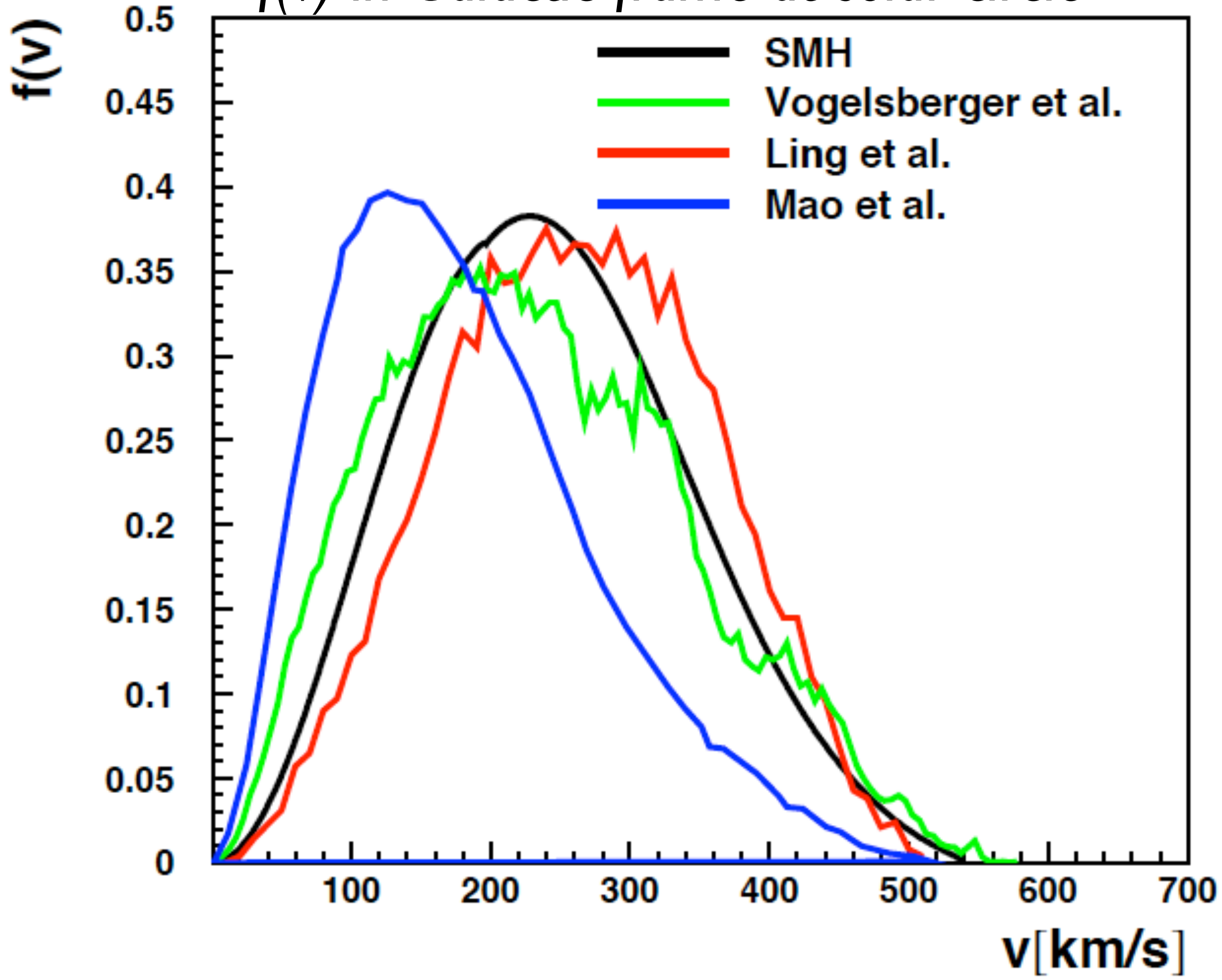
Choi, Rott, Itow arXiv:1312.0273

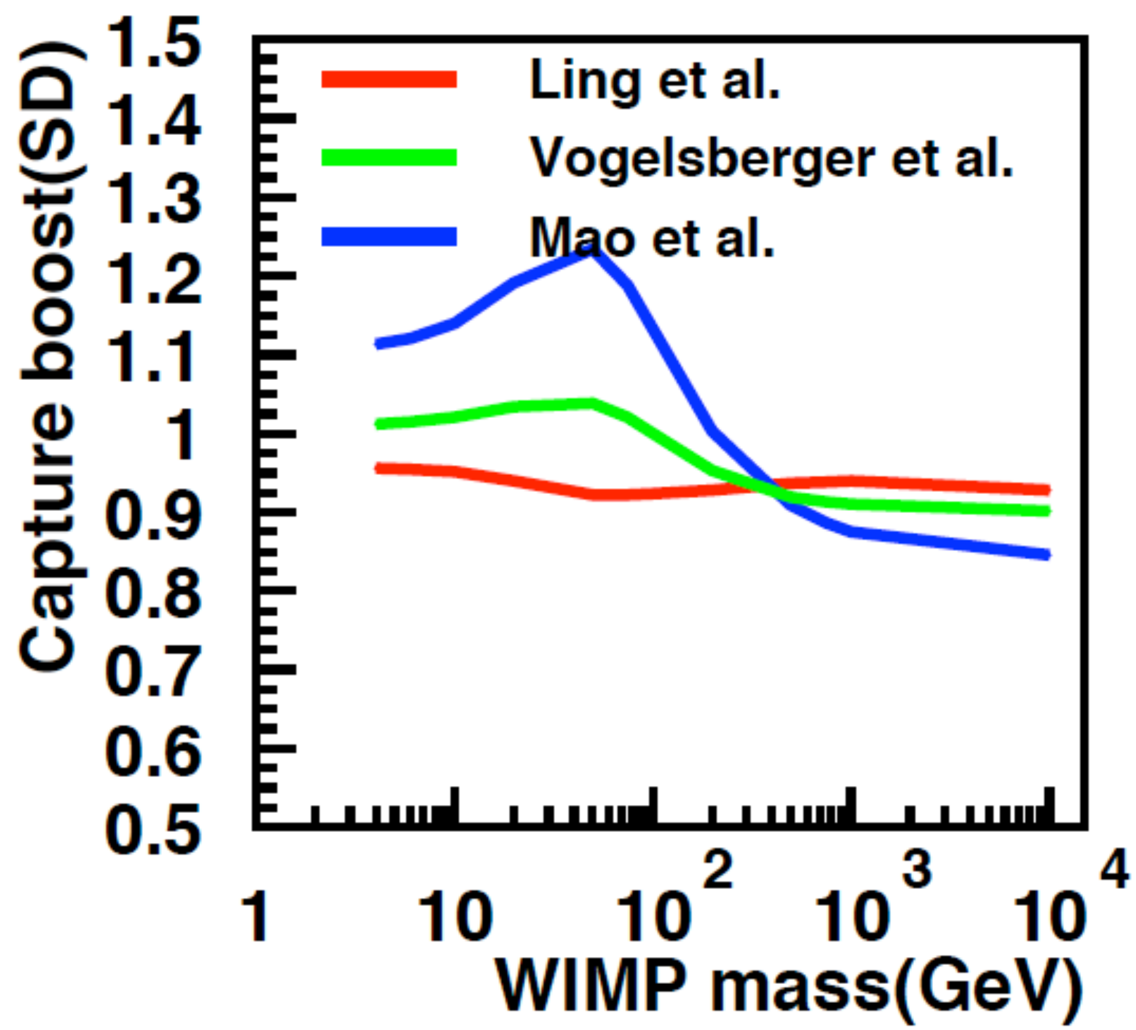
Impact of velocity distribution

- 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



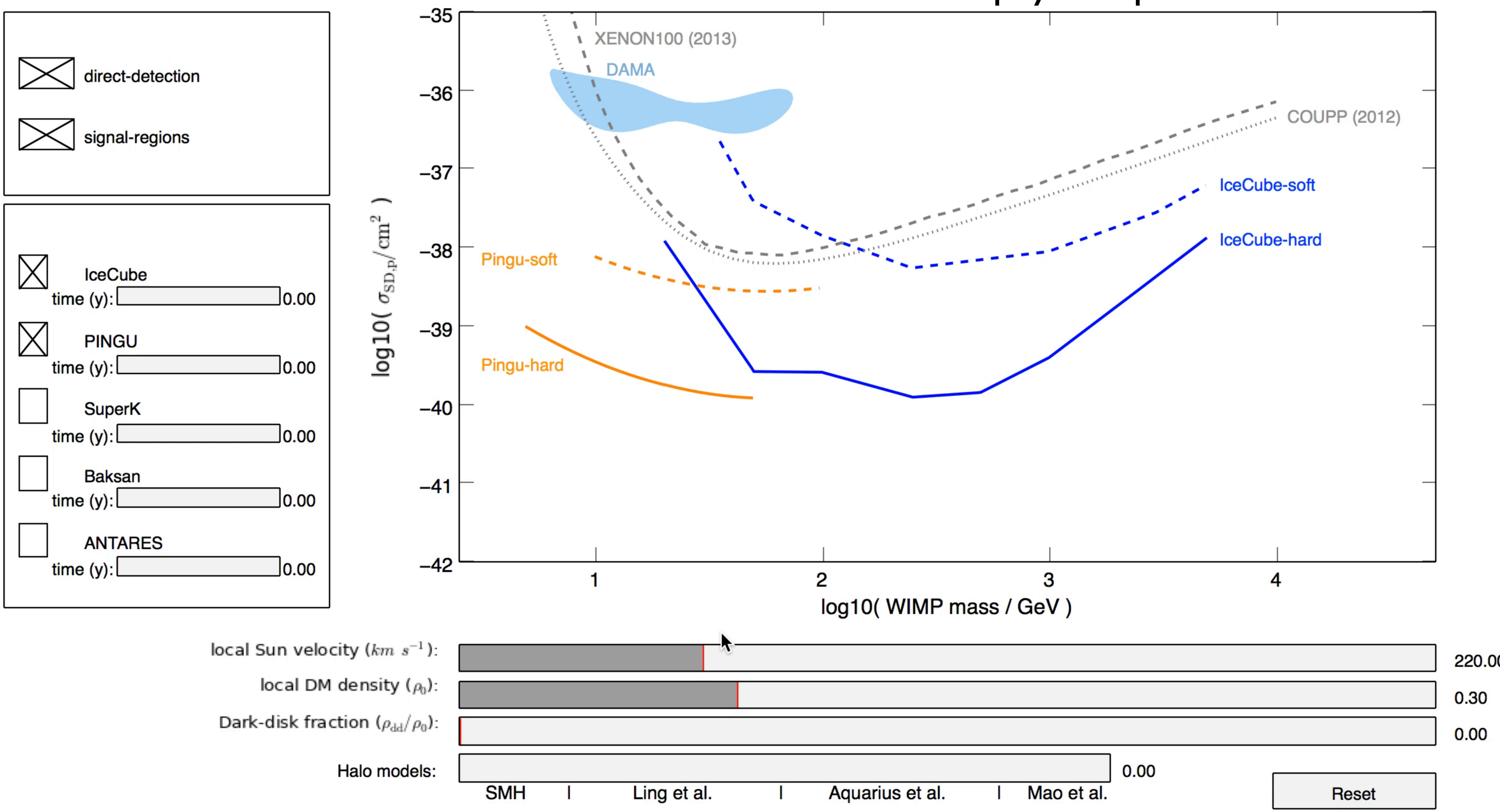


- A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%

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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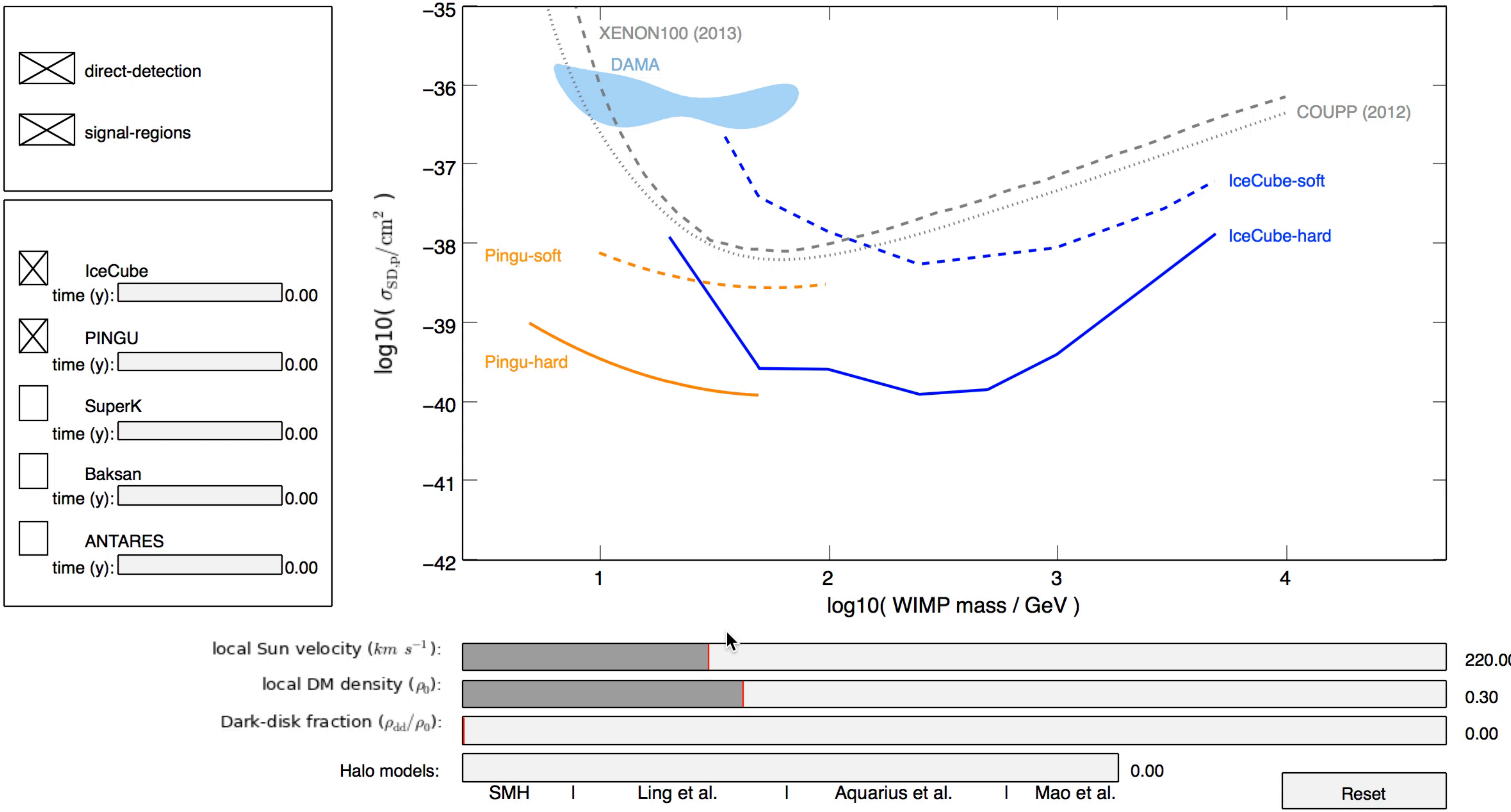
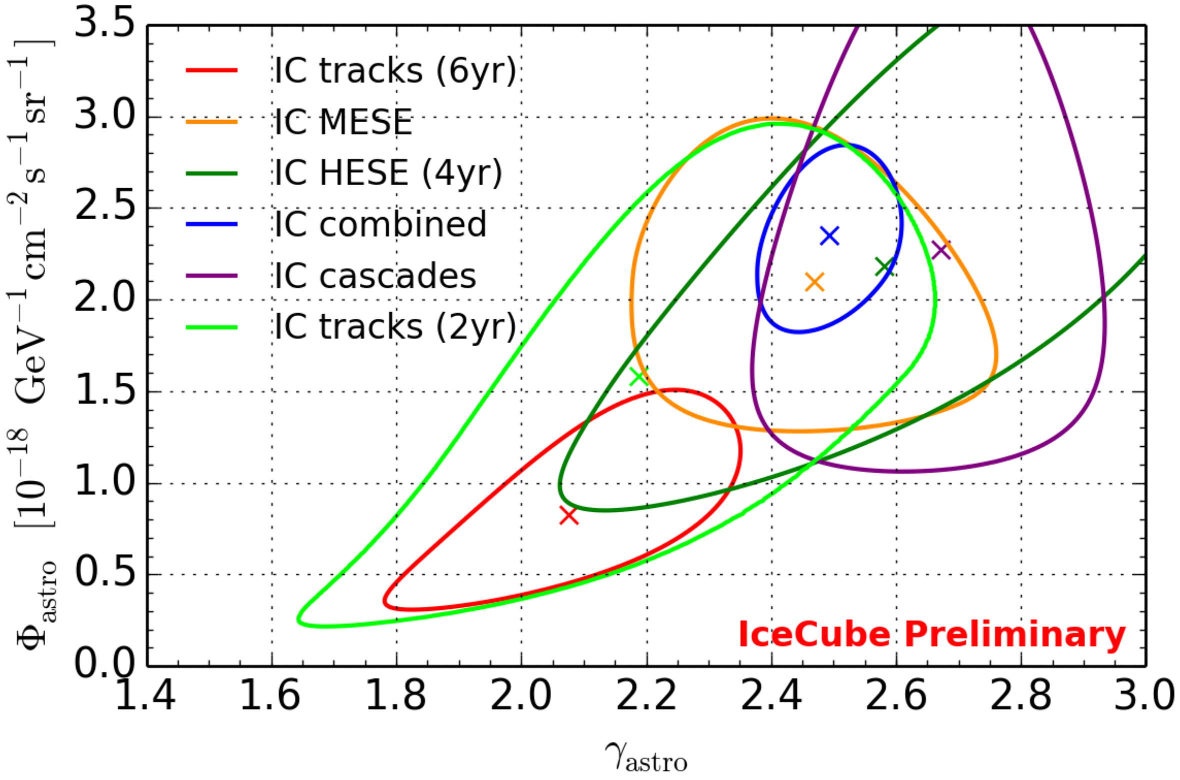


https://mdanning.web.cern.ch/mdanning/public/Interactive_figures/

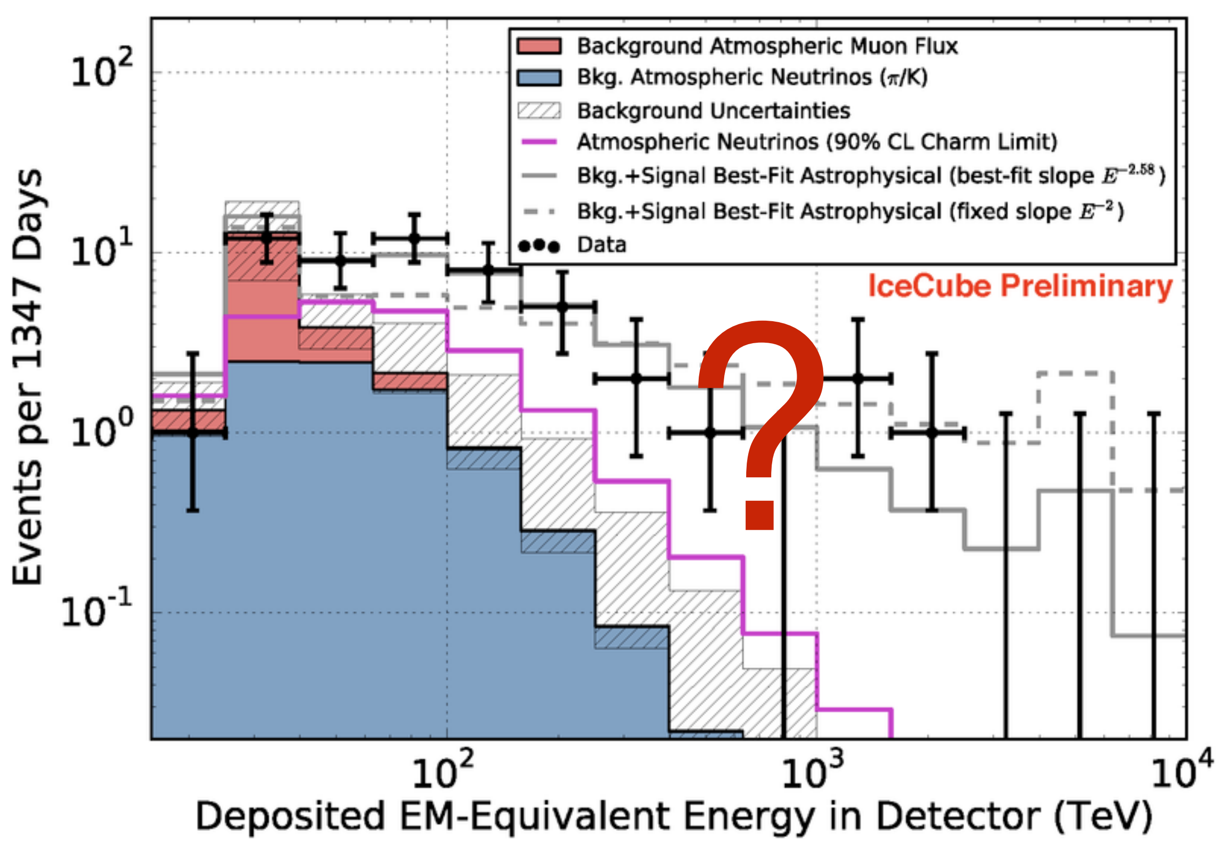
Future Plans for IceCube …

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 ?

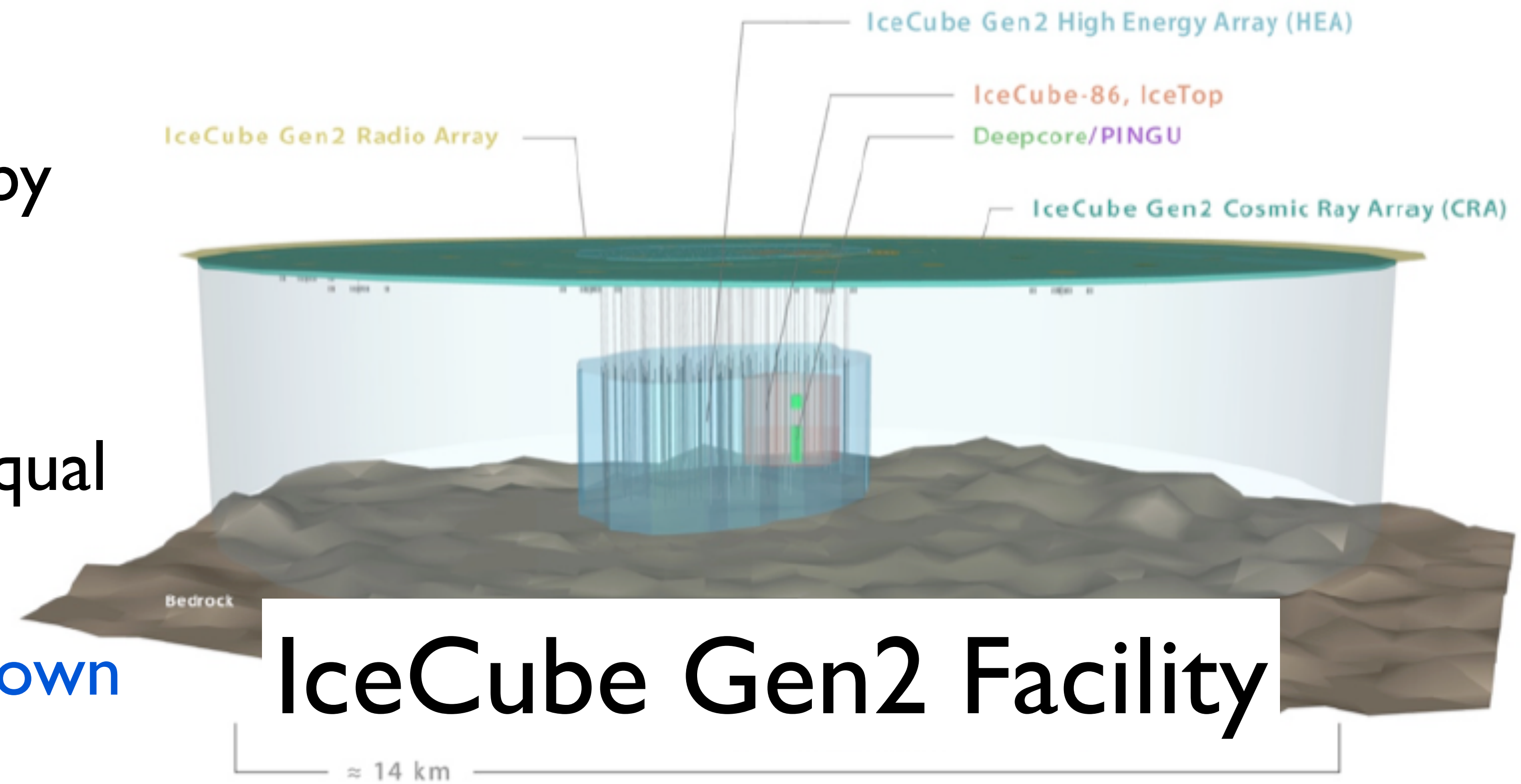


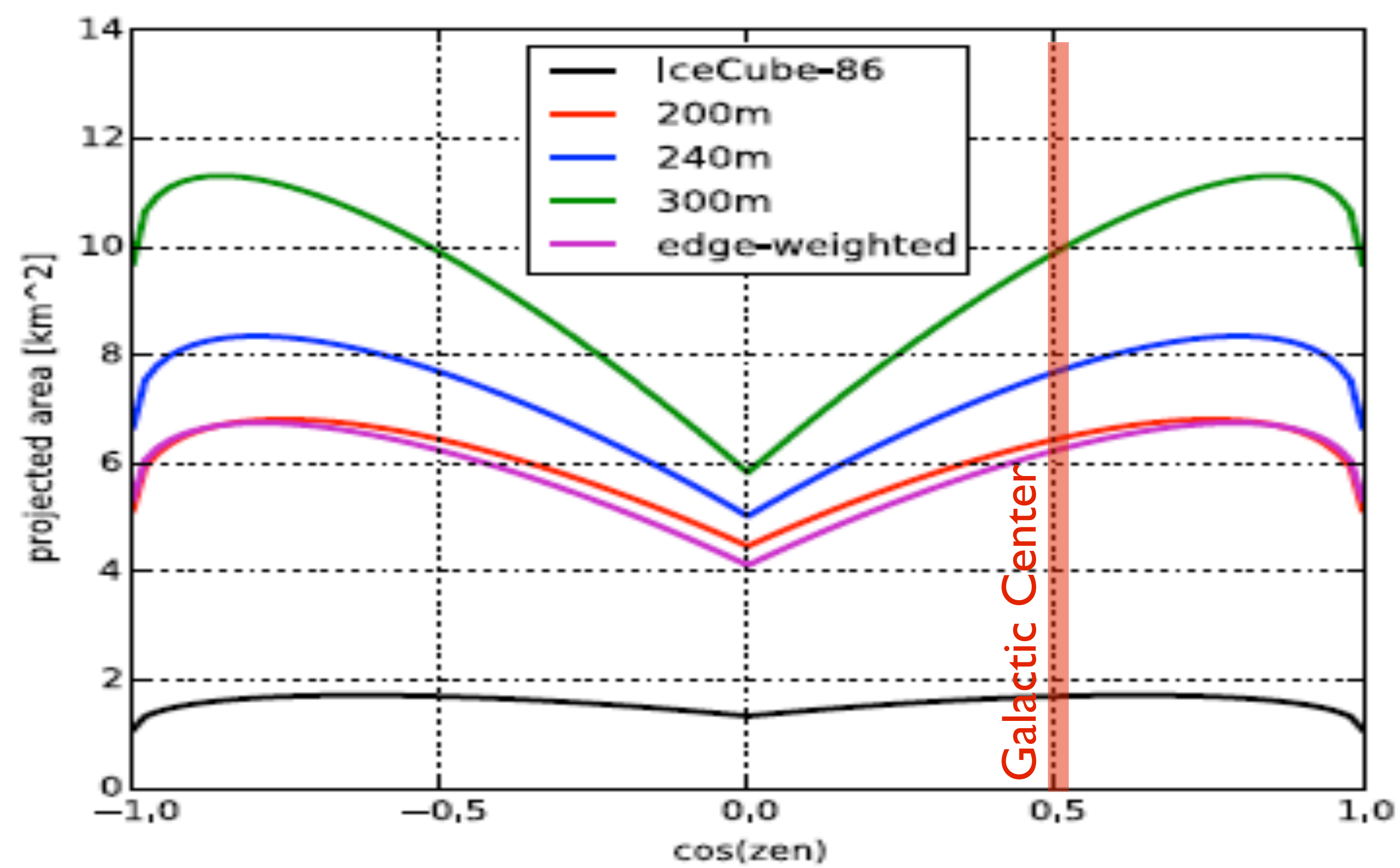
- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy right-handed neutrino dark matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and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

Next generation - IceCube Gen2 Facility

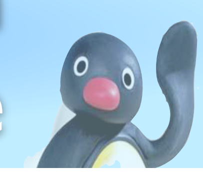
IceCube Gen2 arXiv:1412.5106

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





PINGU - Precision IceCube Next Generation Upgrade



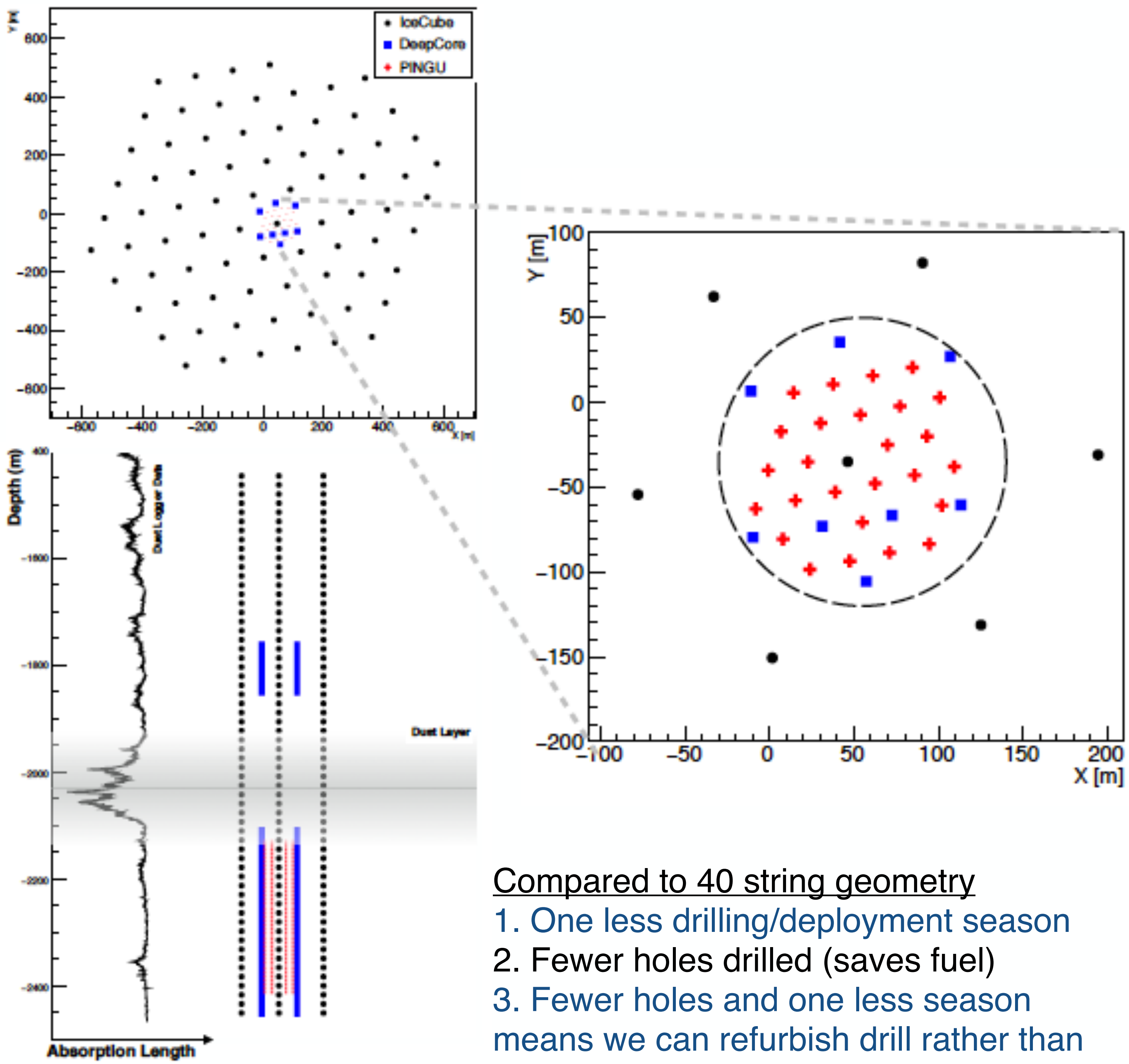
© [2011] The Pygos Group

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

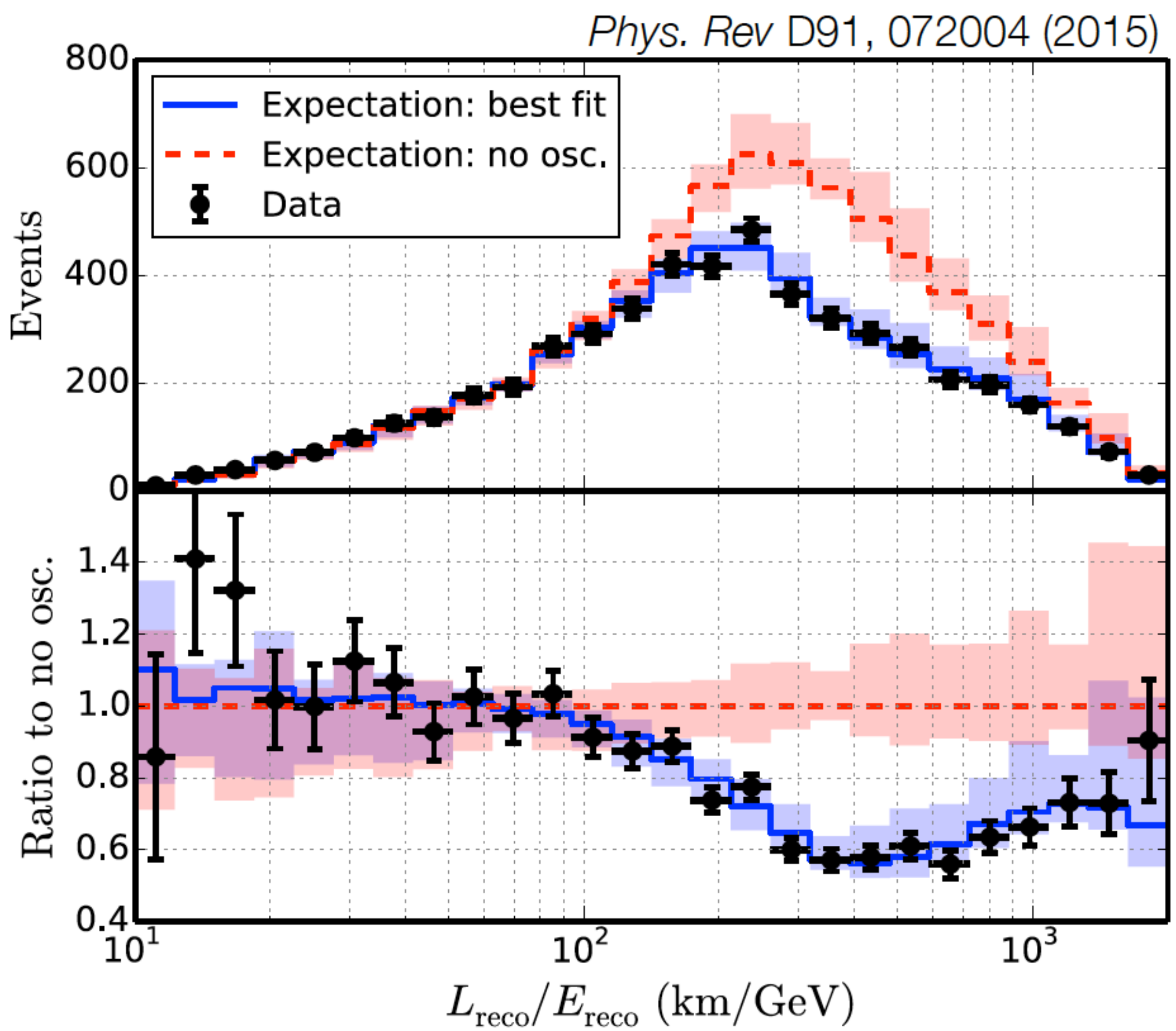
PINGU LOI to be updated shortly

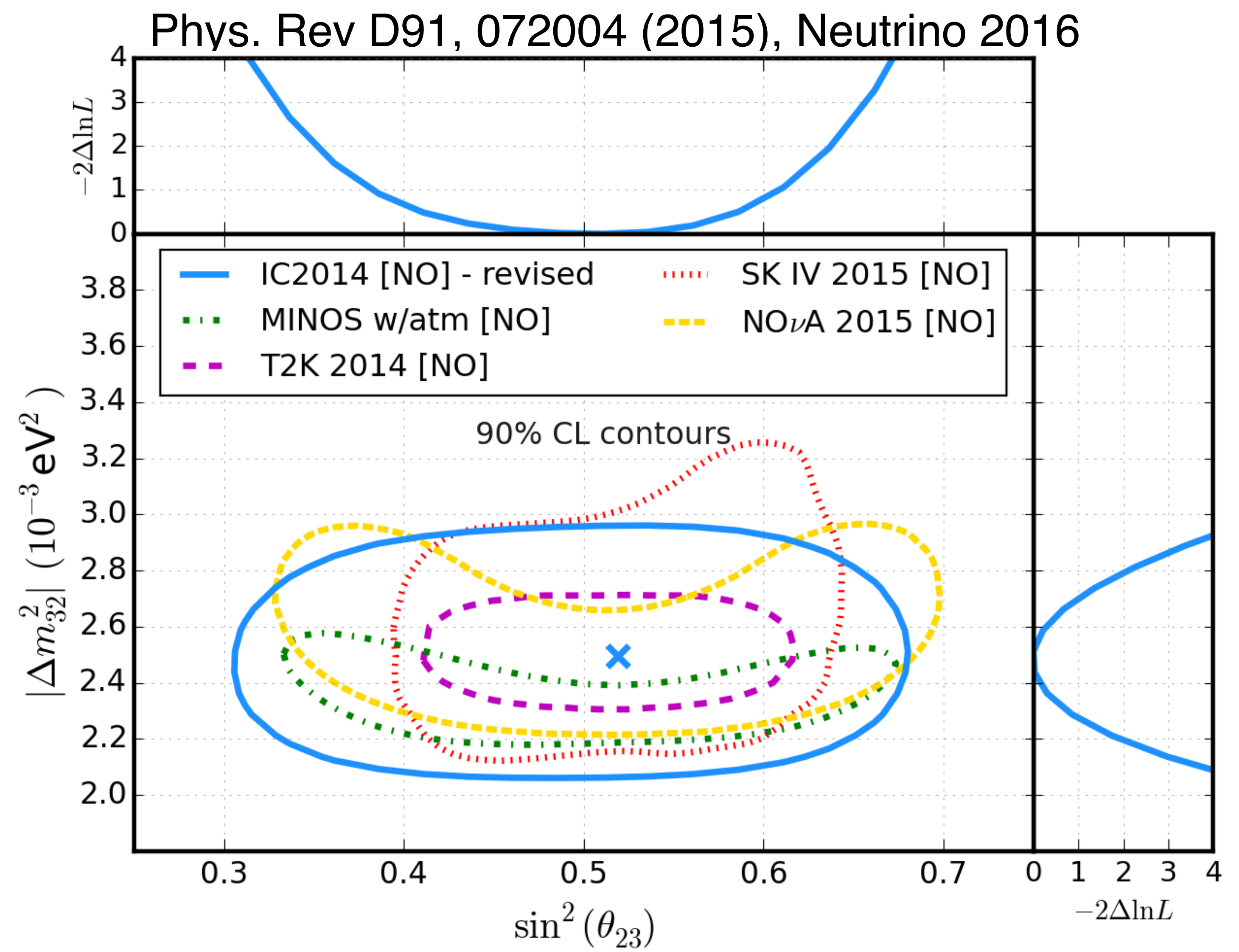
Short version https://arxiv.org/pdf/1607.02671.pdf

New PINGU Geometry



Compared to 40 string geometry
1. One less drilling/deployment season
2. Fewer holes drilled (saves fuel)
3. Fewer holes and one less season means we can refurbish drill rather than build a new one.

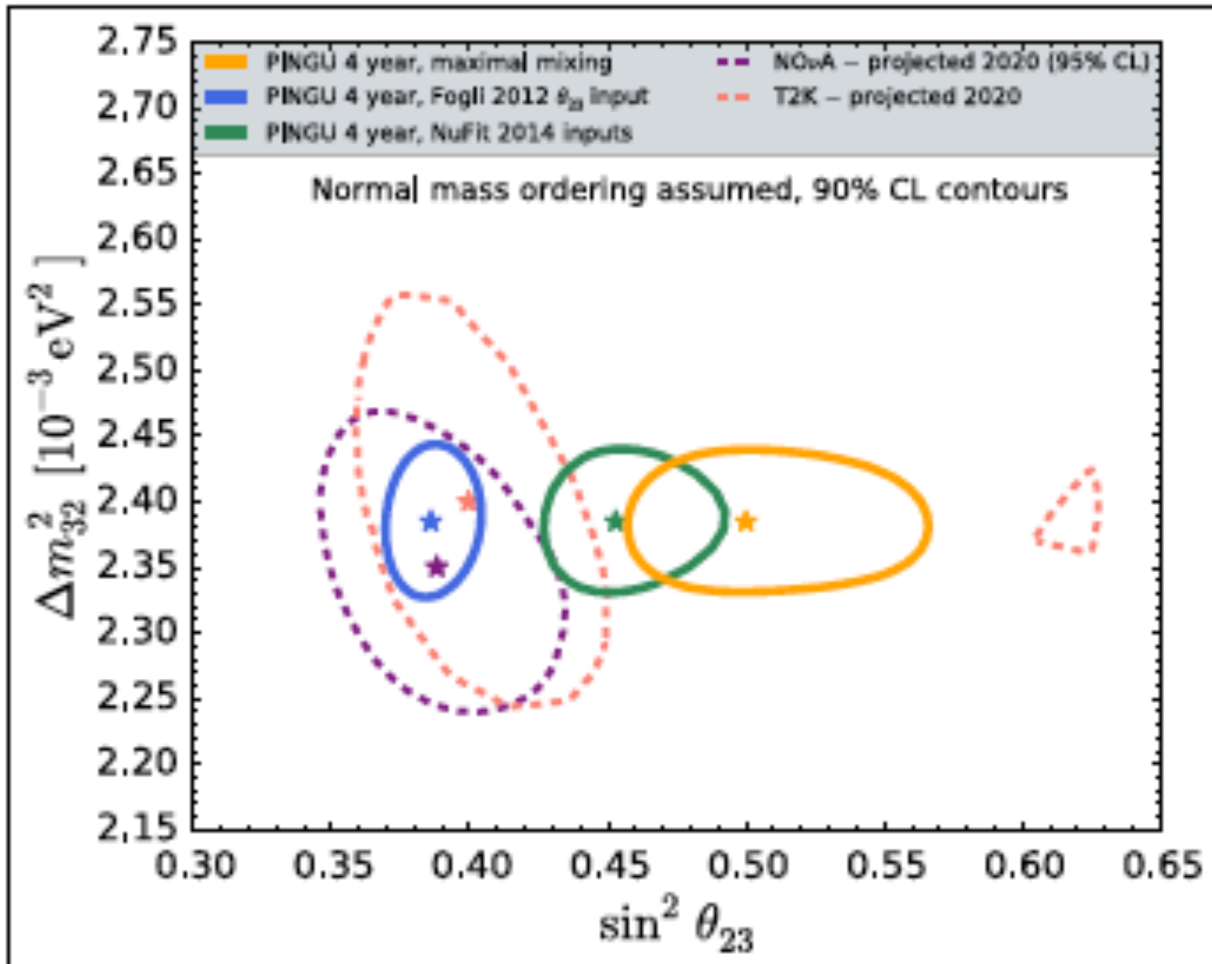




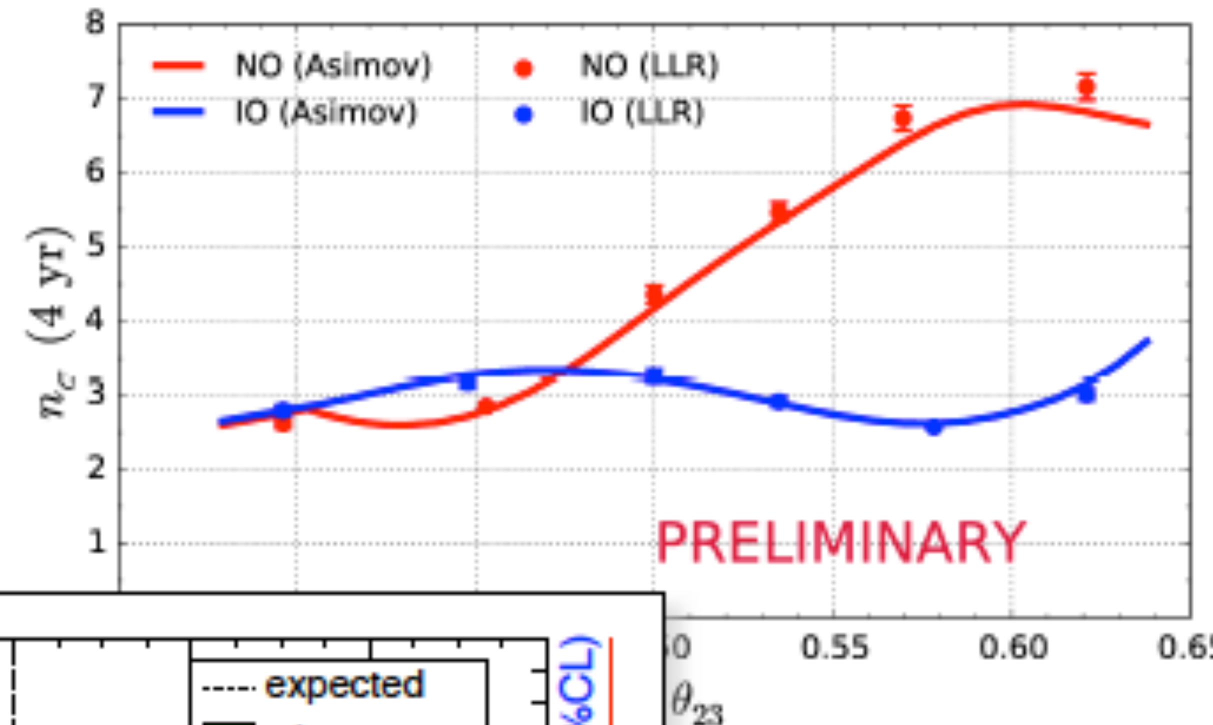
3 years of DeepCore data

- 5174 events observed 6830 expected for no oscillation
- perform 2D fit in *E* and *cos(θ)*

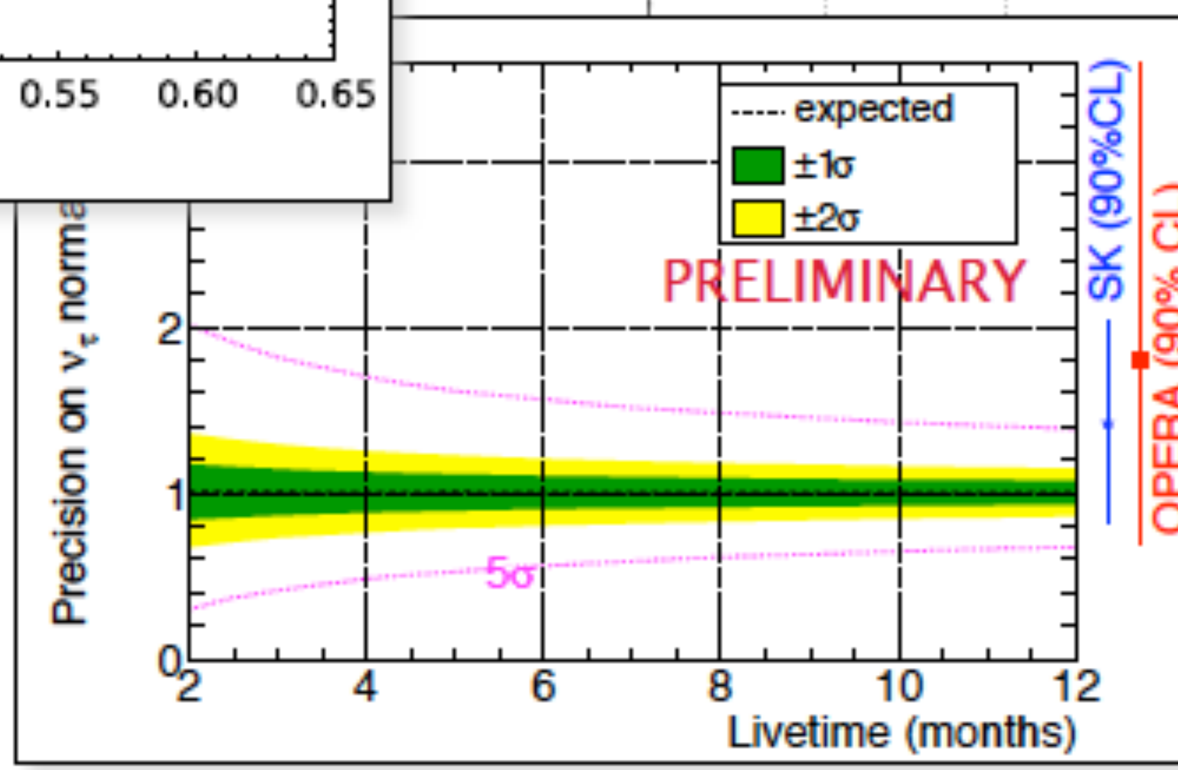
Neutrino Physics with PINGU



Determination of the neutrino mass ordering

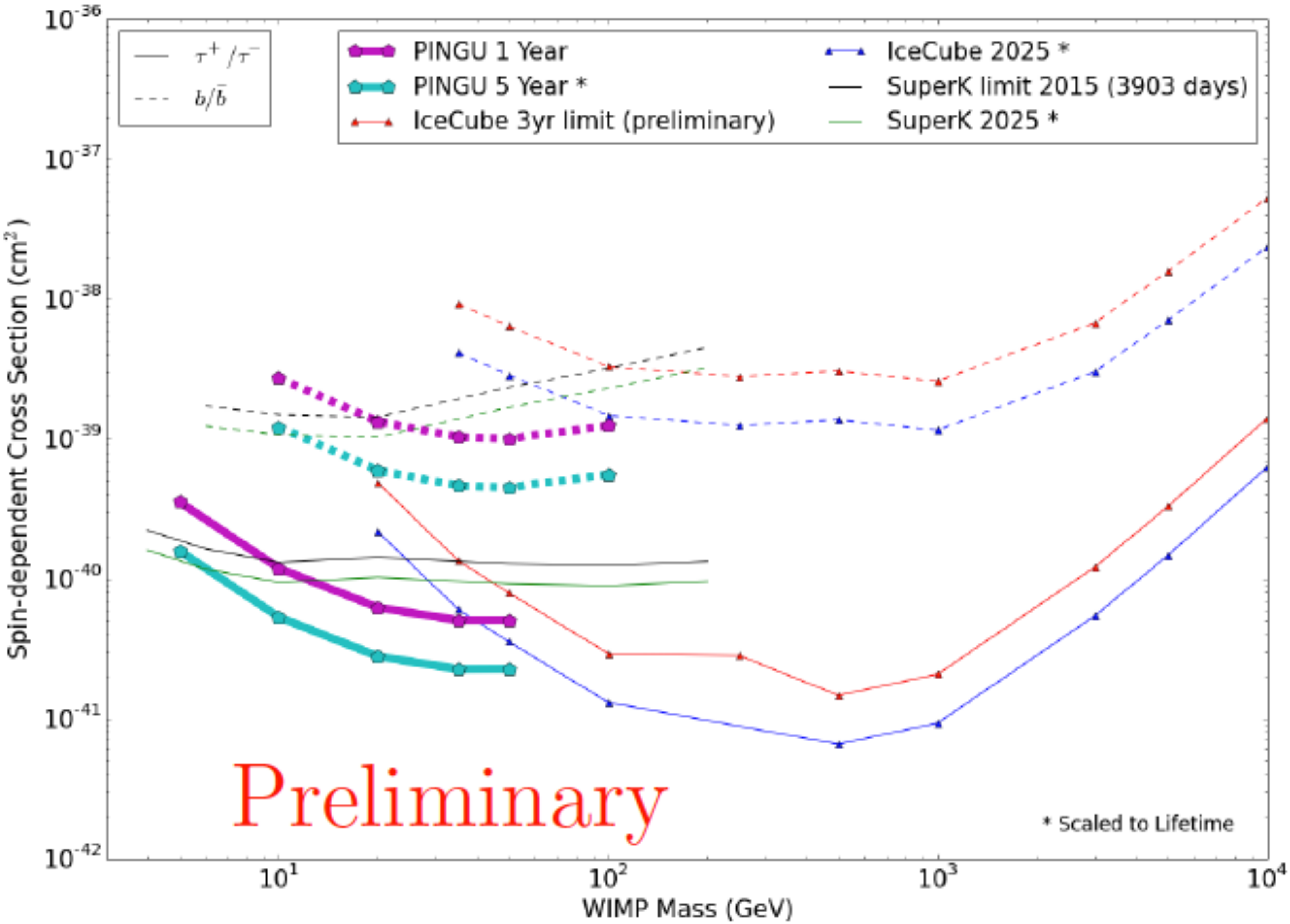


Measurement of mixing parameters with different method/energy range – Excellent sensitivity to octant of θ_{23}

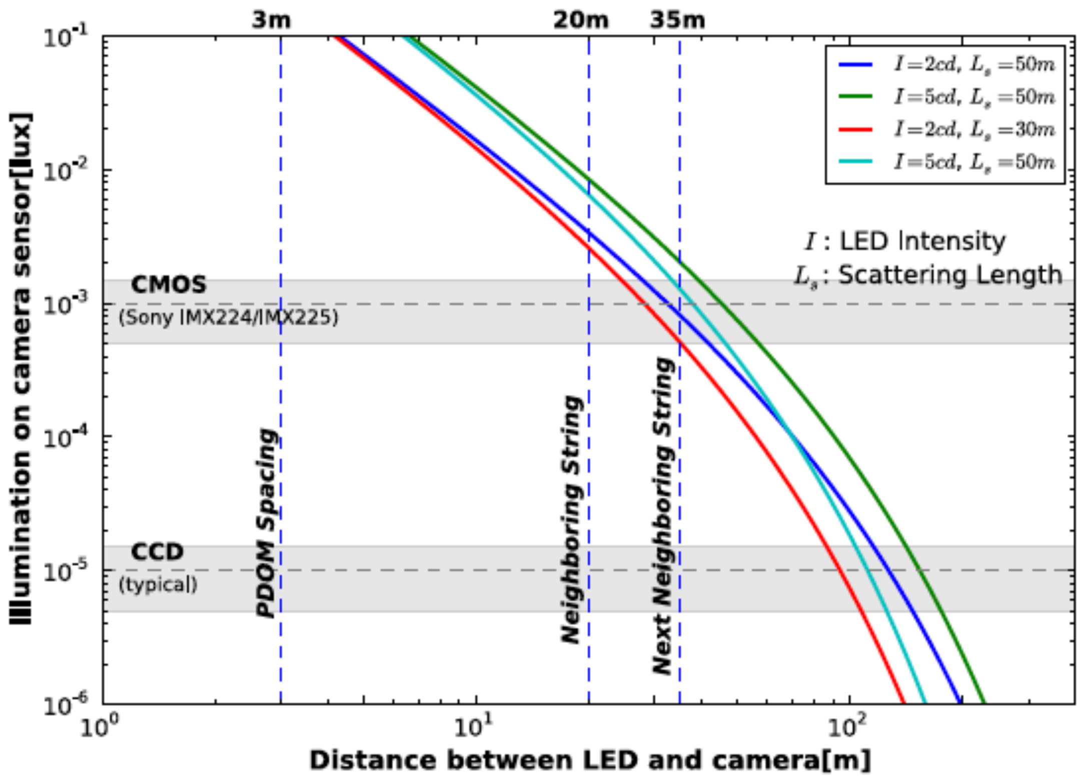


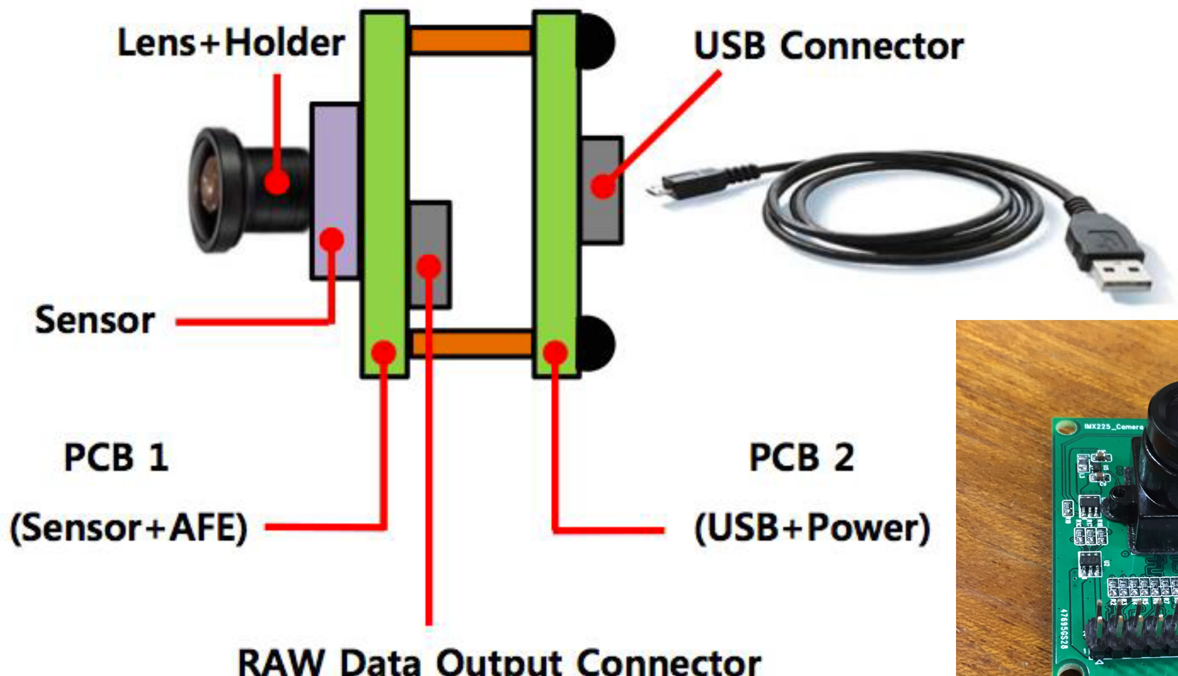
Precision measurement of ν_τ appearance – probe unitarity of PMNS matrix

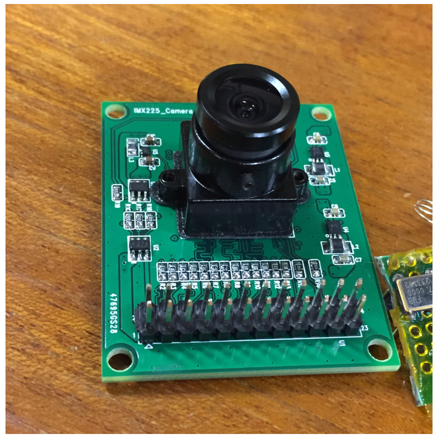
PINGU DM Sensitivity



Ice Camera System





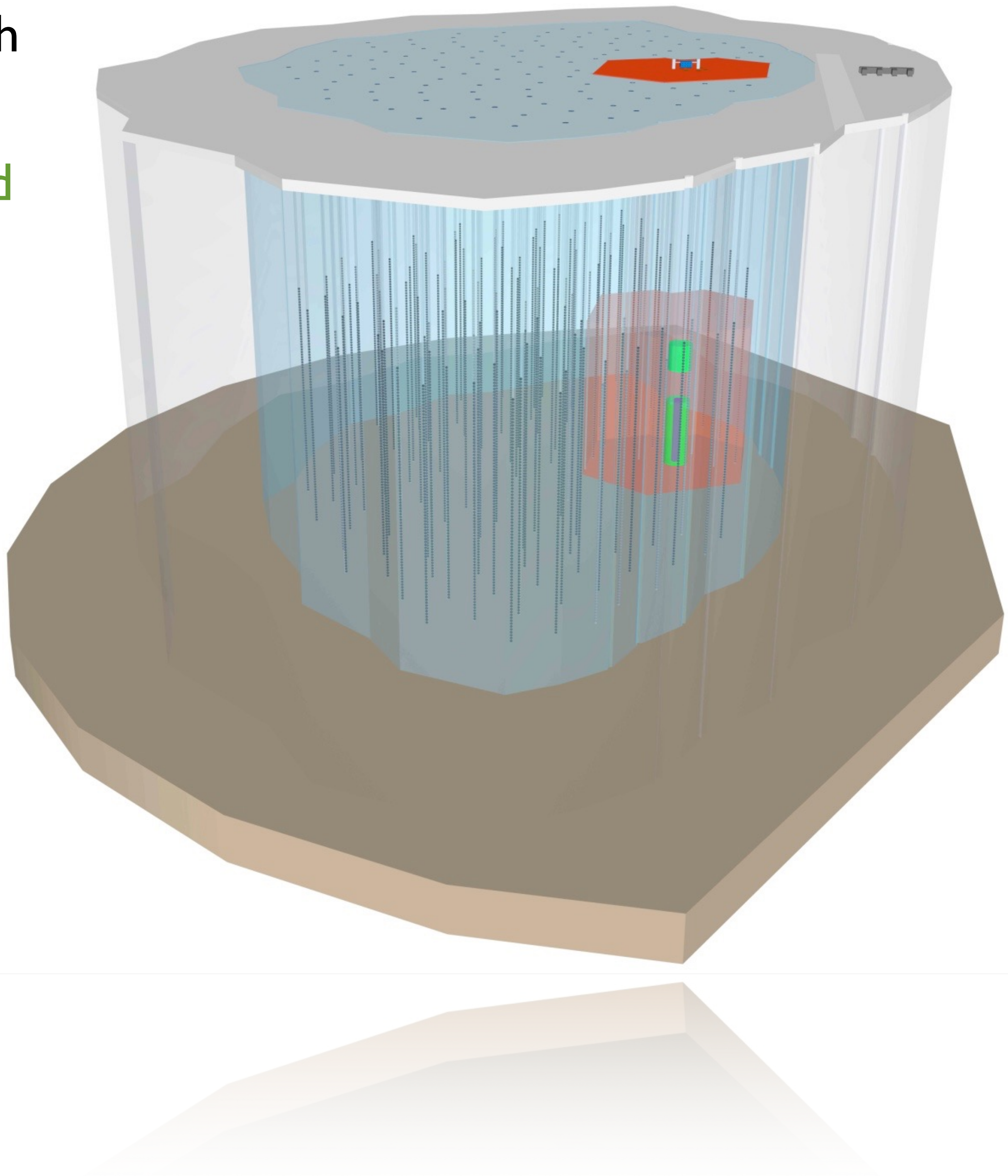


- Ice properties dominant source of sys. uncertainties for most analyses
- Low cost camera system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability

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

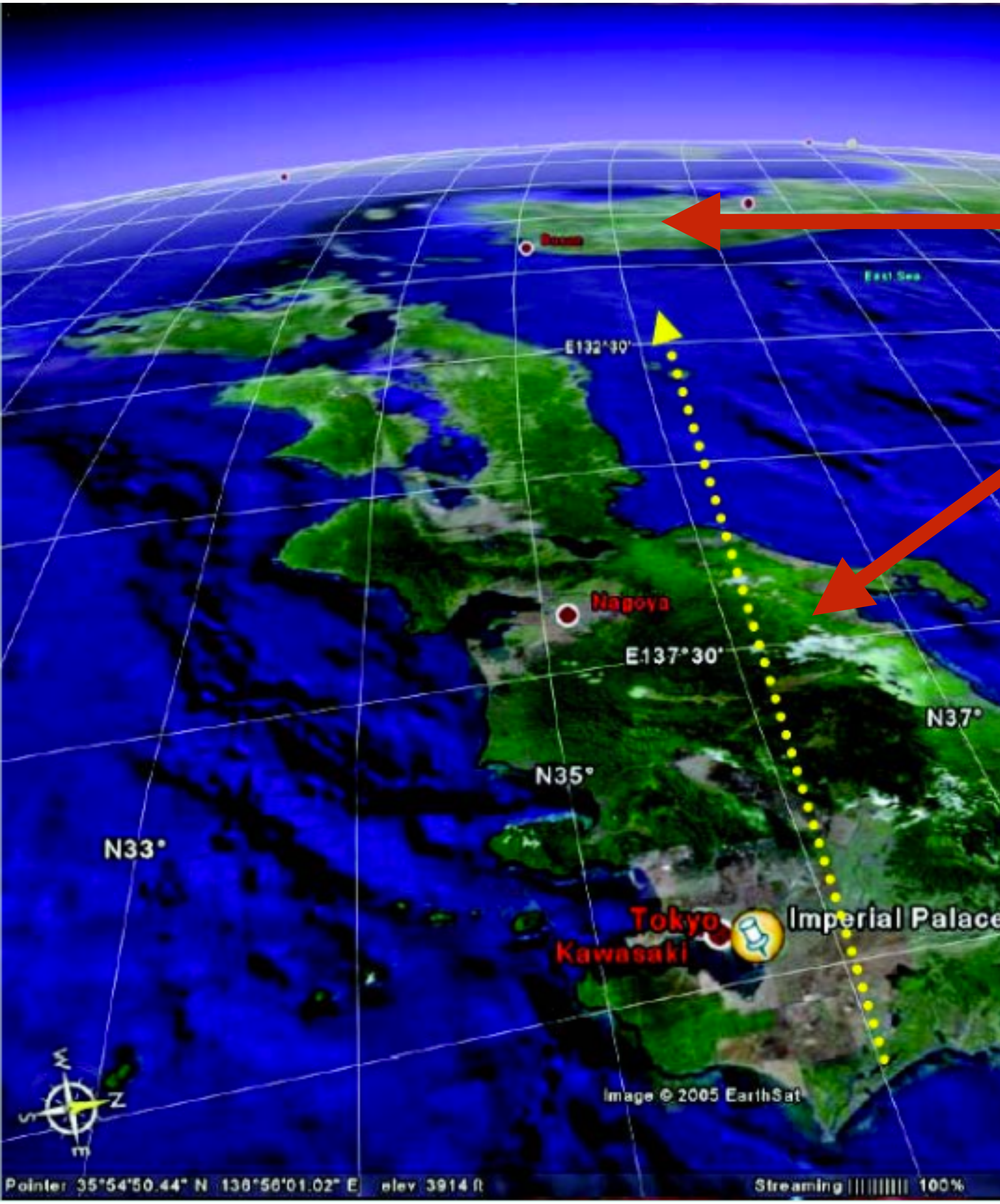
Conclusions

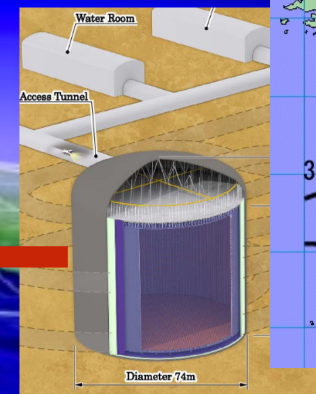
- Striking DM signatures might provide high discovery potential for indirect searches
- Models motivated by positron excess and gamma-ray observations can and have been tested with neutrino telescopes
- Lifetimes of heavy decaying dark matter can be constrained to 10^28s using neutrino signals
- Neutrino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

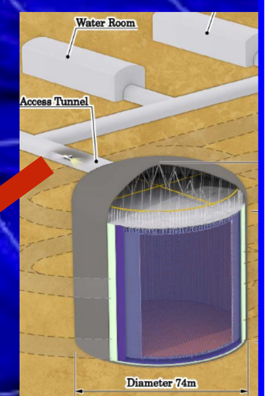


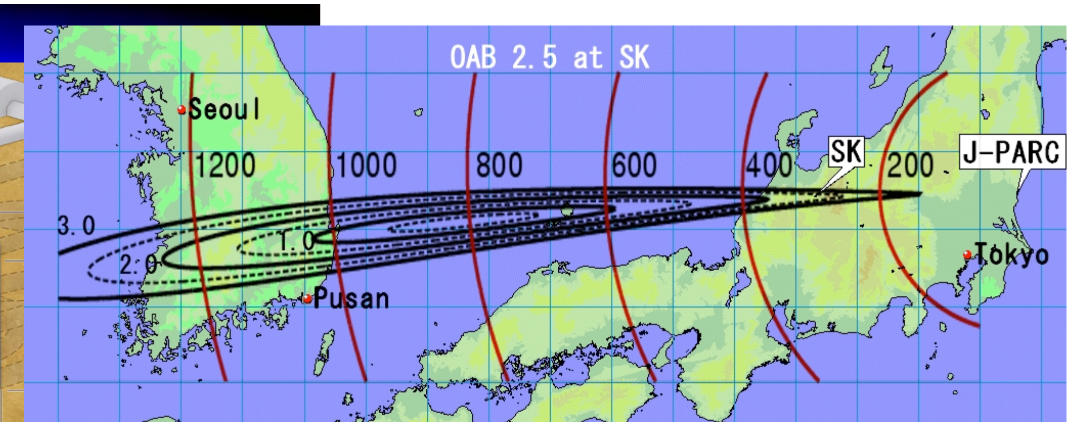
Thanks !

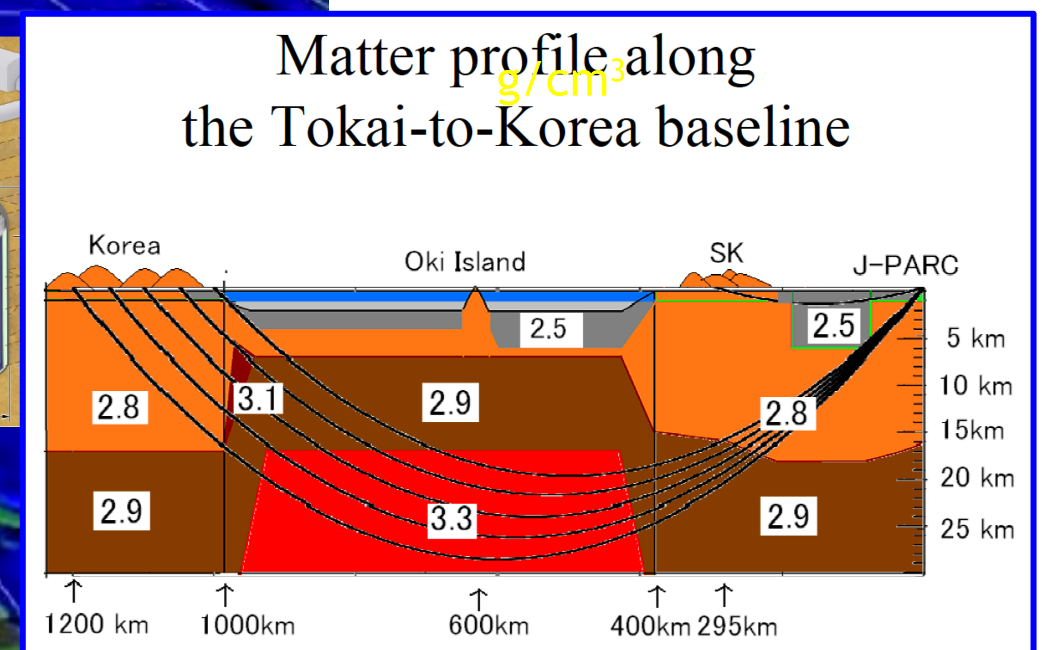
Tokai-to-Hyper-K & Korea (T2HKK)











Physics Potentials with the Second Hyper-Kamiokande Detector in Korea

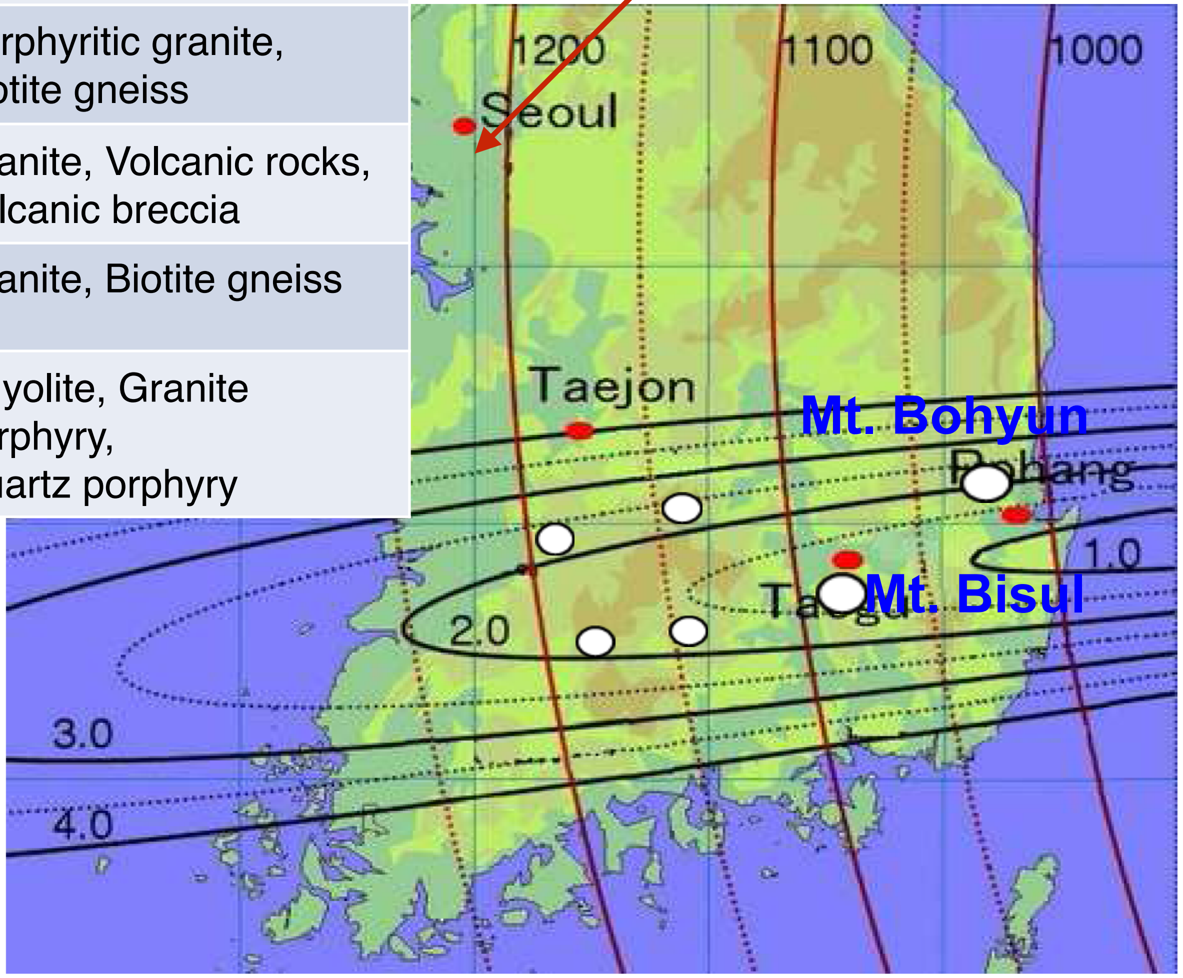
(Hyper-Kamiokande Proto-Collaboration)

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

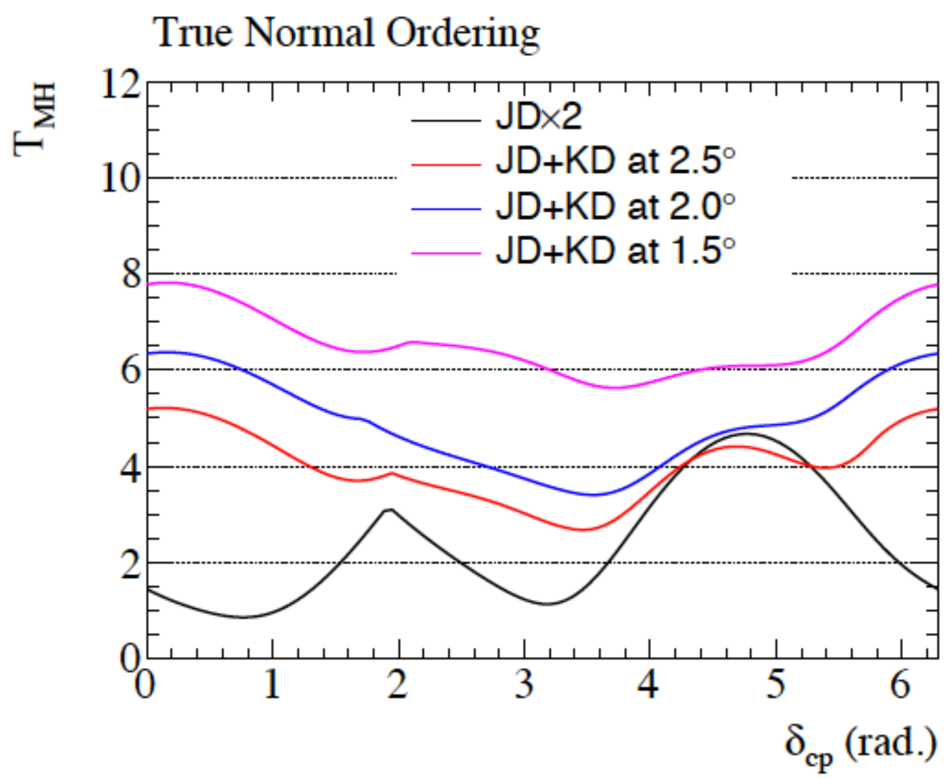
Site	OAB	Baseline	Height	Rock
Mt. Bisul	~1.3°	1088 km	1084 m	Granite porphyry, Andesitic breccia
Mt. Hwangmae	~1.8°	1140 km	1113 m	Flake granite, Porphyritic gneiss
Mt. Sambong	~1.9°	1180 km	1186 m	Porphyritic granite, Biotite gneiss
Mt. Bohyun	~2.2°	1040 km	1126 m	Granite, Volcanic rocks, Volcanic breccia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



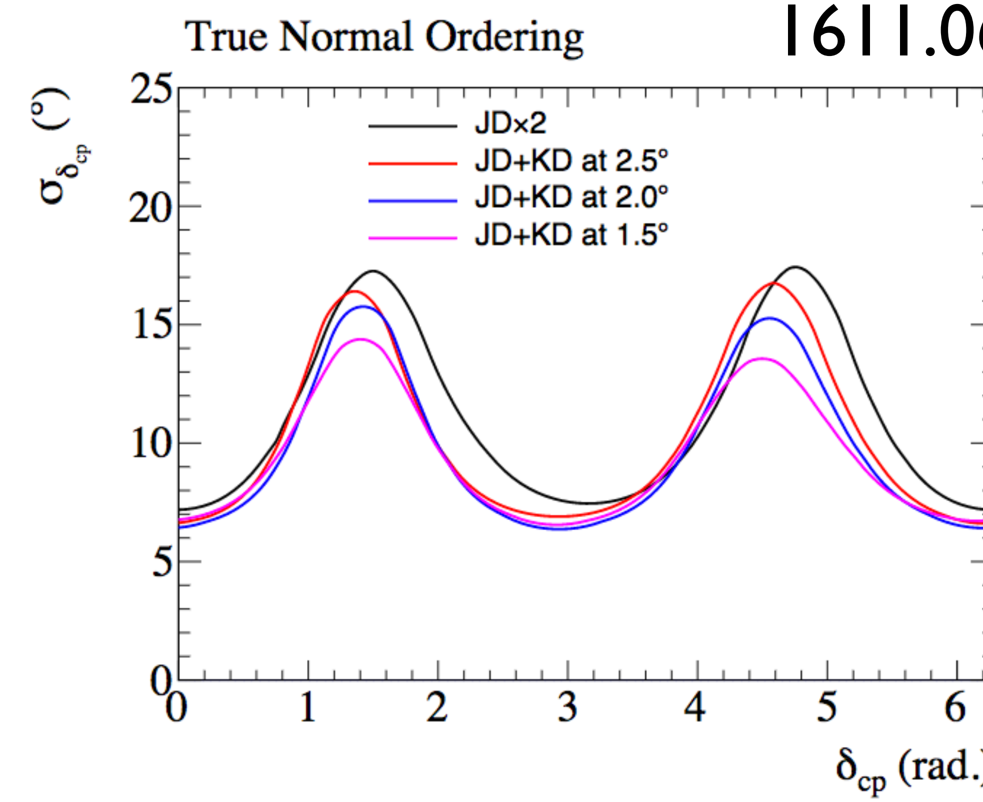
arXiv:1611.06118

- 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

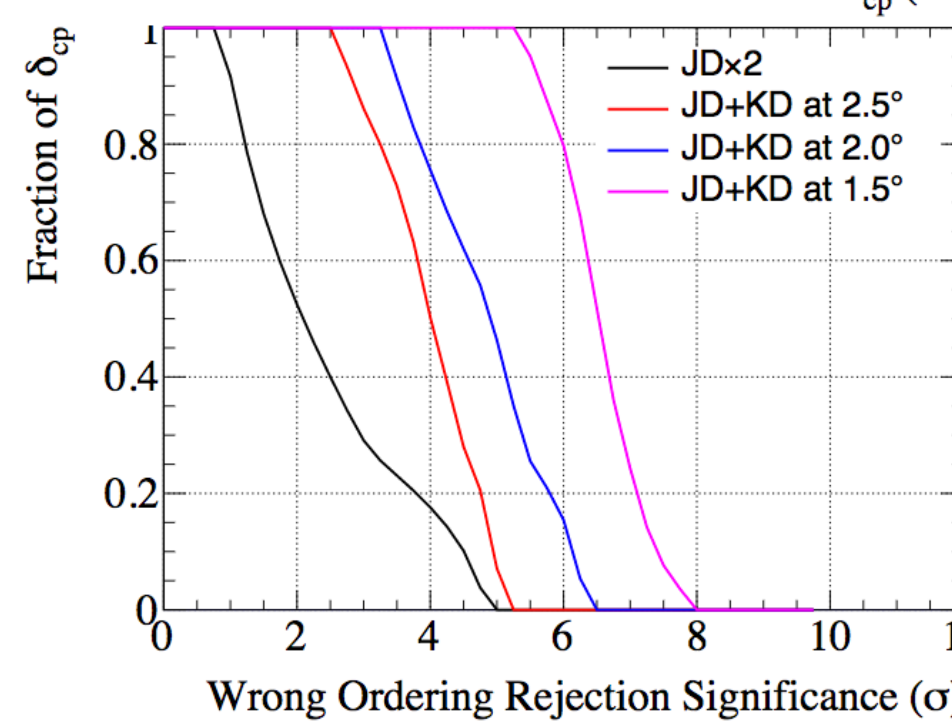


FIG. 19: The fraction of δ_{cp} values (averaging over the true mass ordering) for which the wrong hierarchy can be rejected with a given significance or greater.