Dark Matter Searches with Neutrinos

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APEC Seminar (Astronomy - Particle Physics - Experimental Physics - Cosmology)
Seminar
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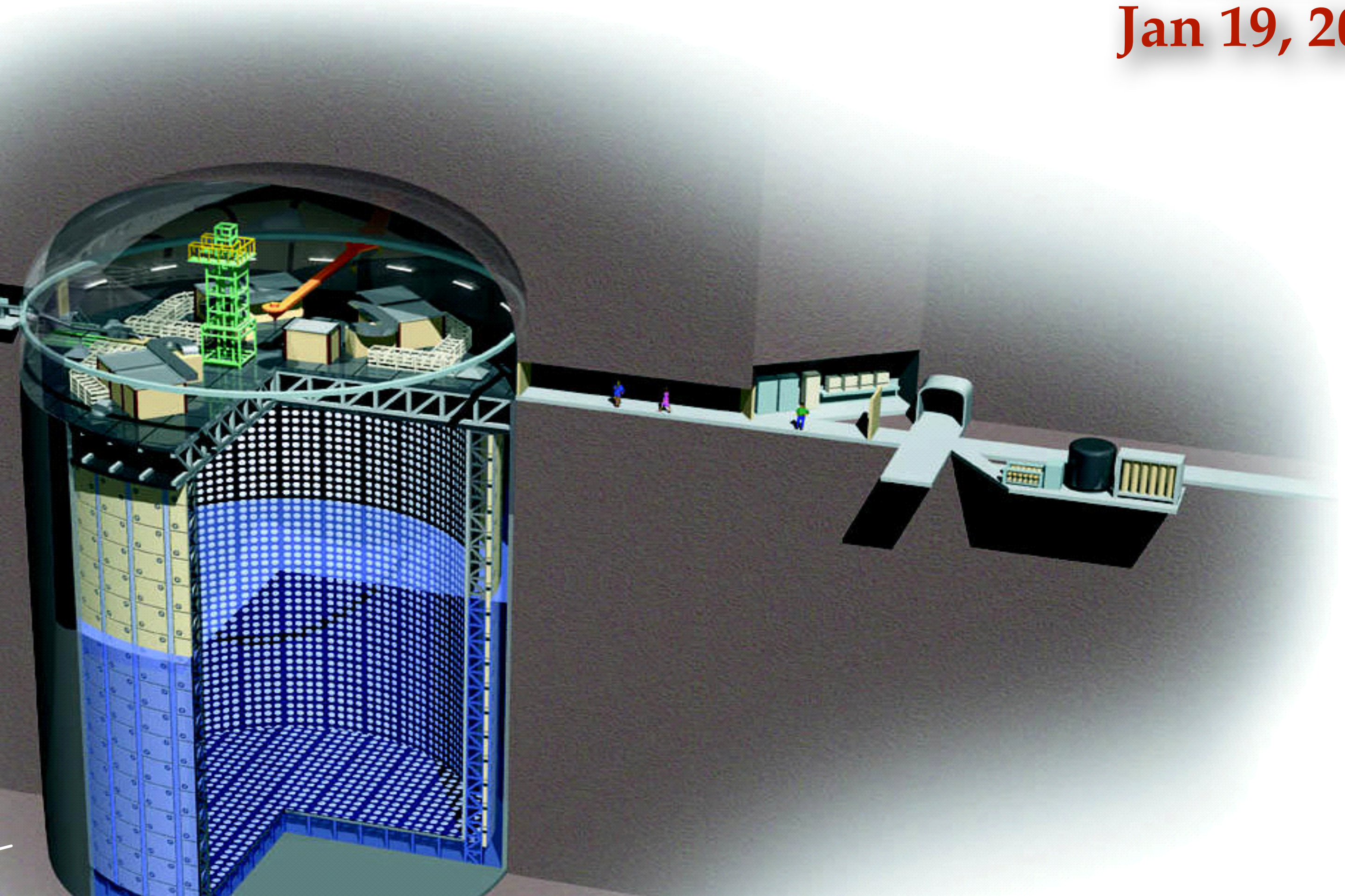
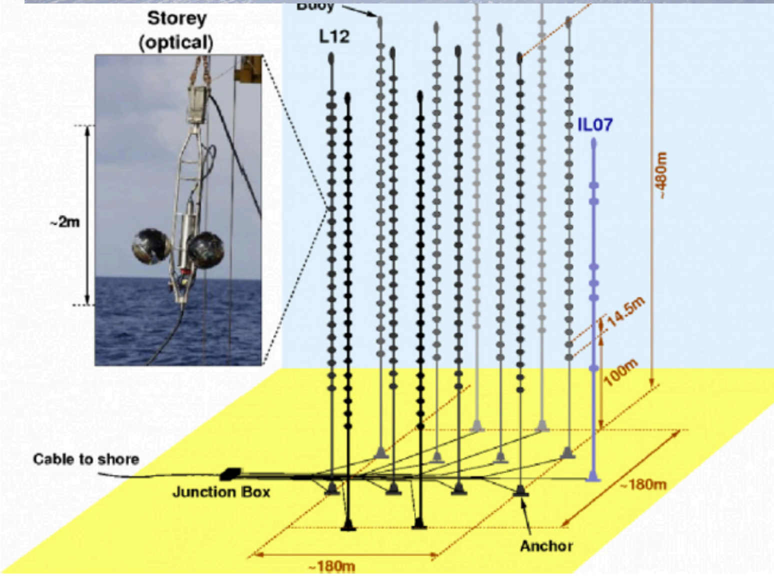
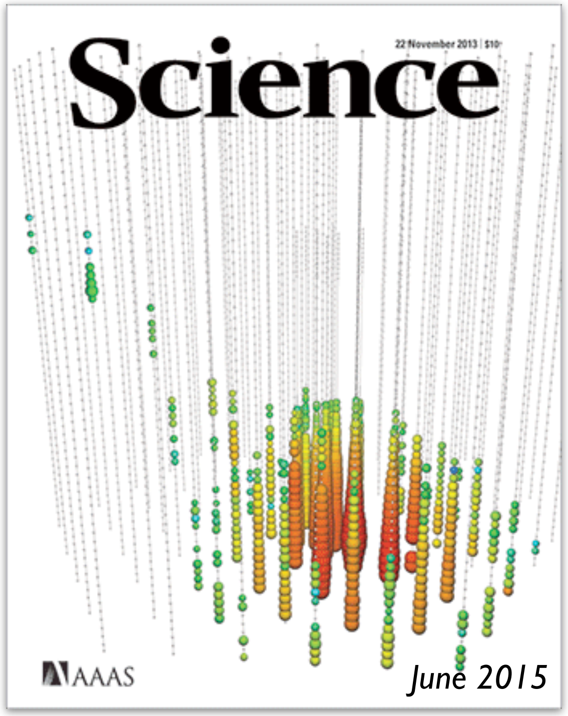


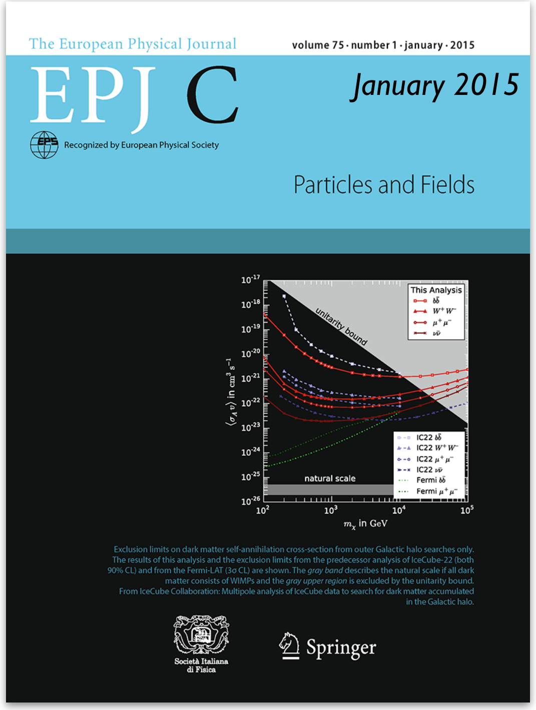


Outline

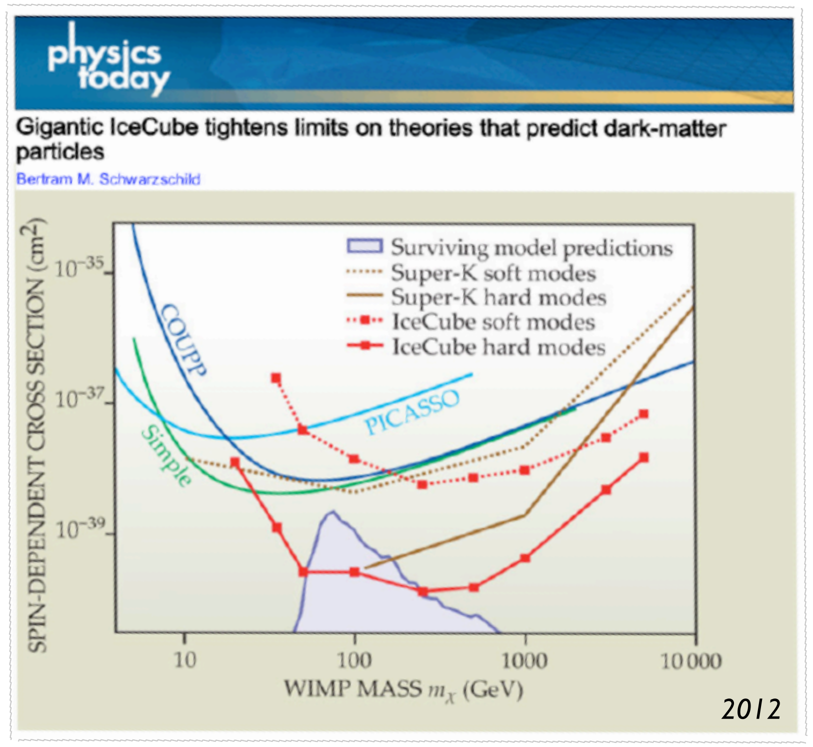


Neutrino Detectors and IceCube

Heavy Dark Matter Decays



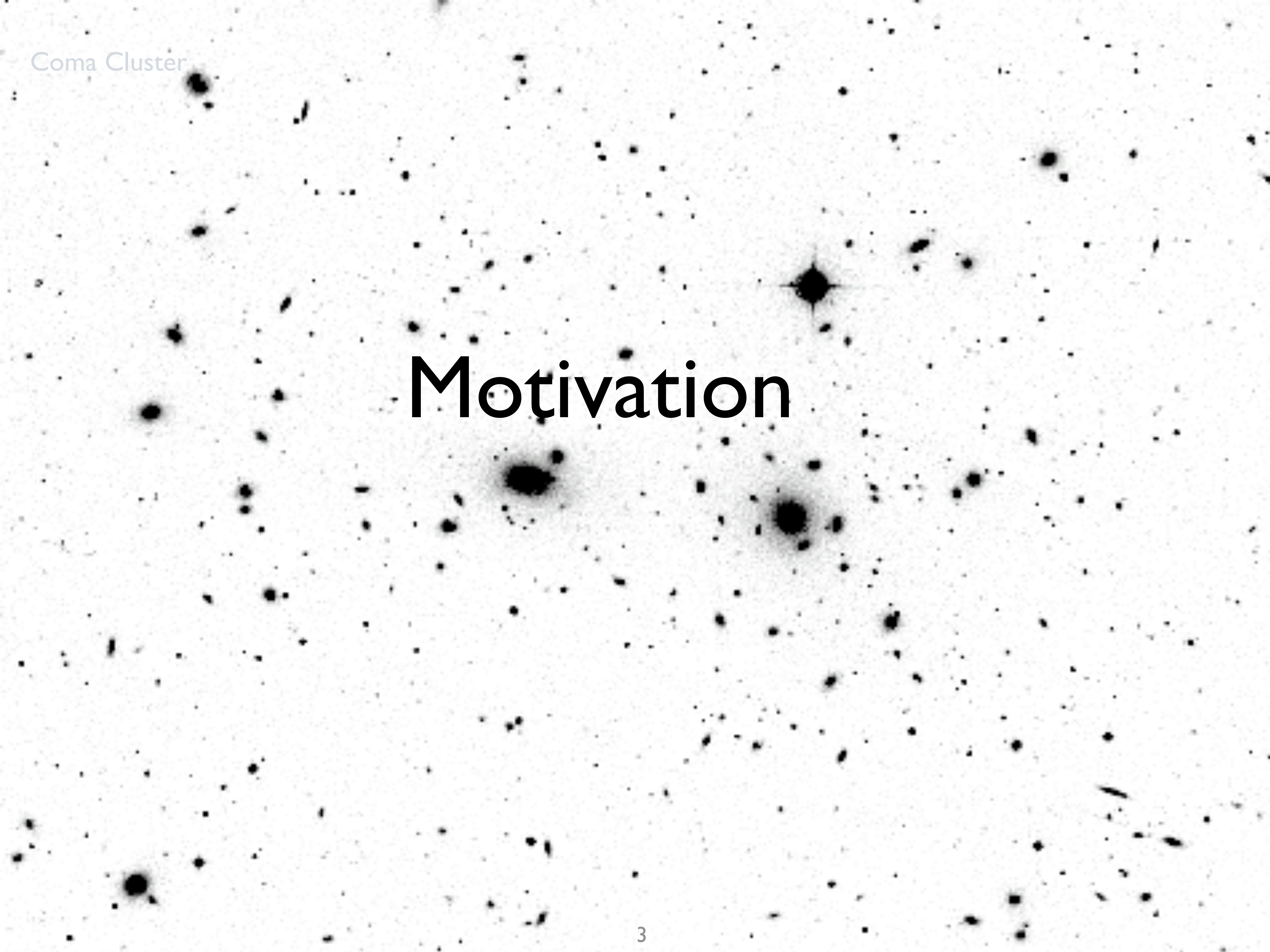
Galactic Dark Matter Annihilation



Gigantic IceCube tightens limits on theories that predict dark-matter particles

Bertram M. Schwarzschild

Dark Matter Annihilations in the Sun



Motivation

The Dark Matter Mystery

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

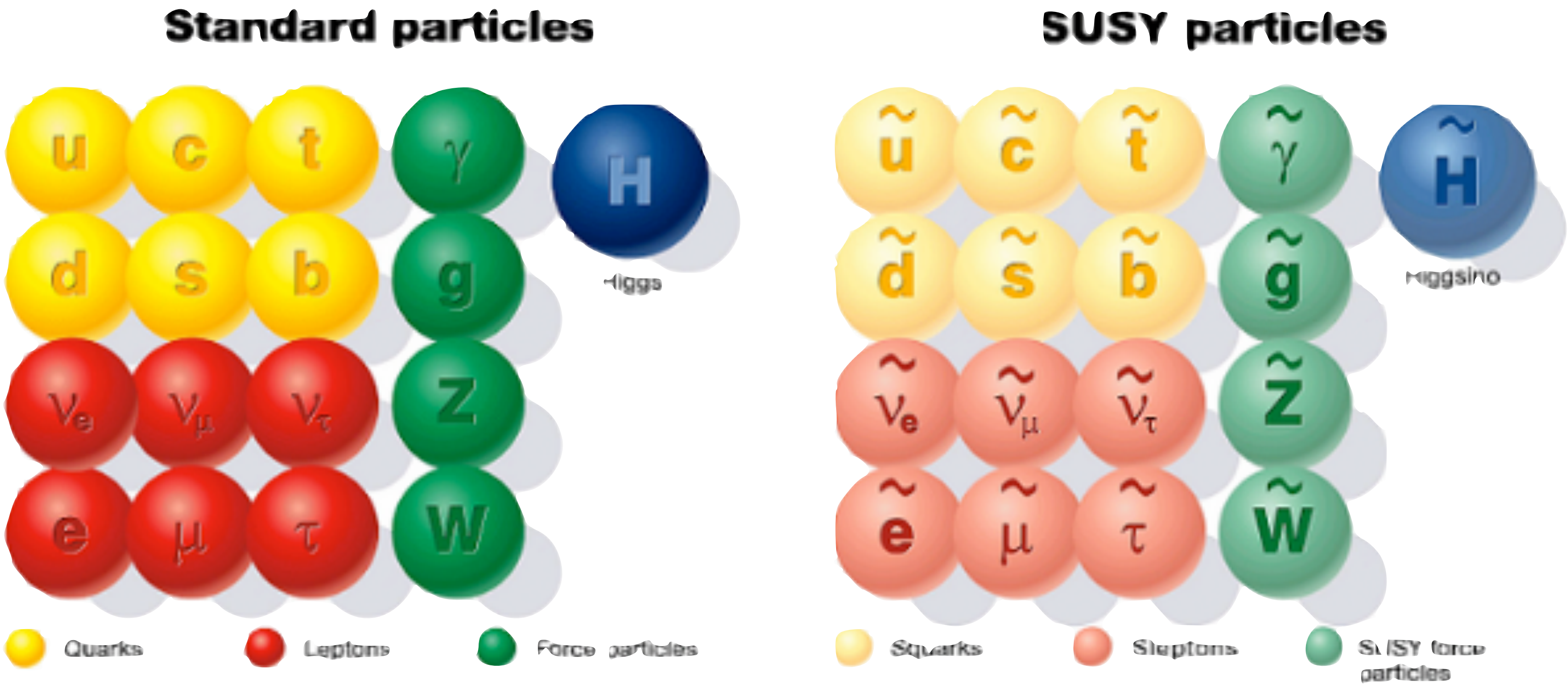
- Dark Matter already gravitationally “observed”, but ...
  - What is it ?
  - What are it’s properties ?

Weakly Interacting Massive Particle (χ)

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

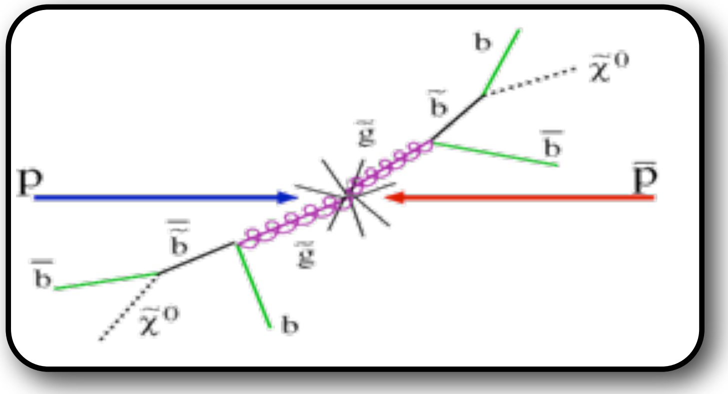
WIMP

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



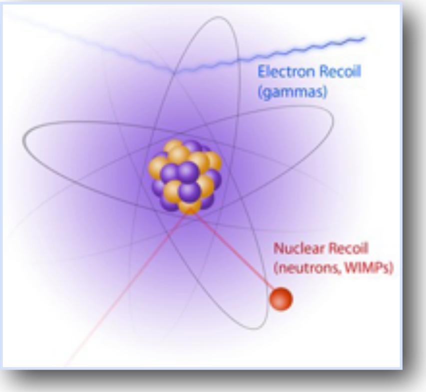
Searches for WIMPs

Production

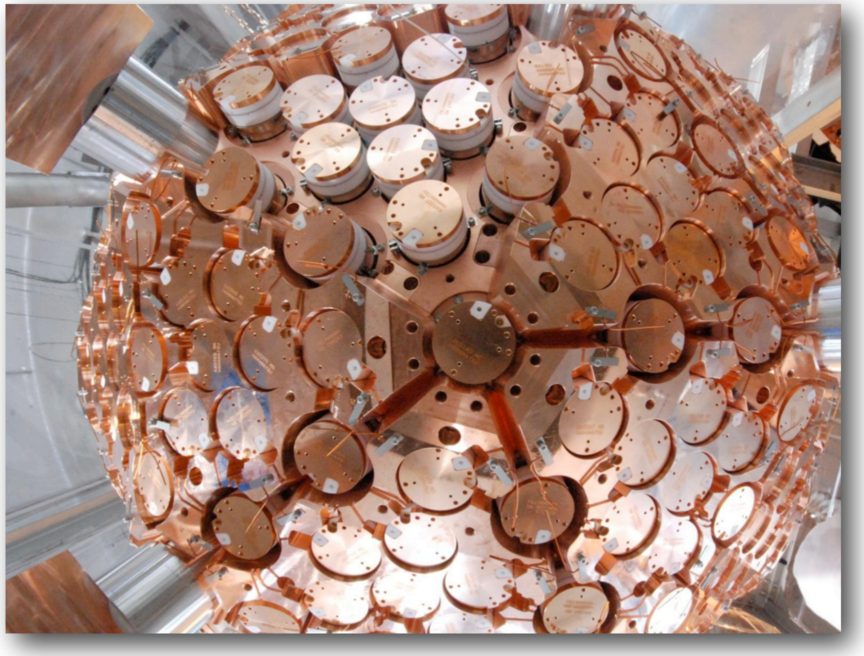


Colliders

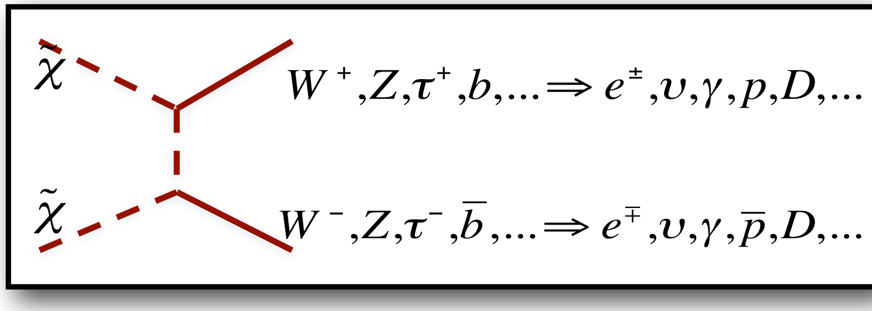
Scattering



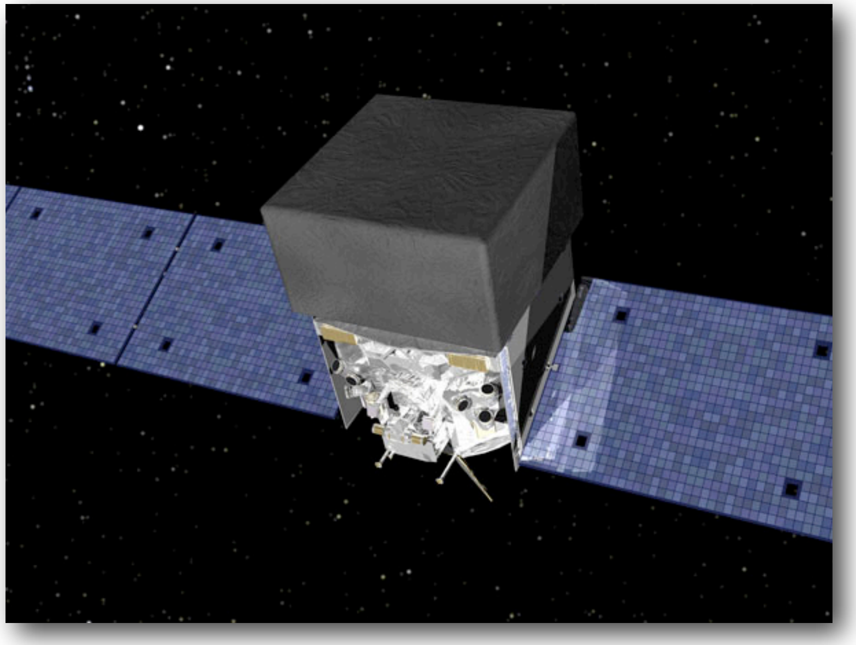
Direct



Annihilation

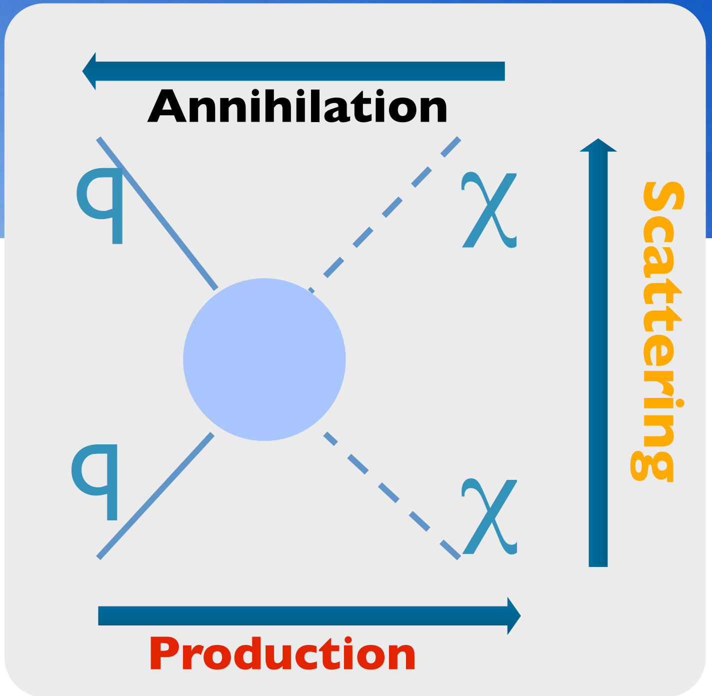


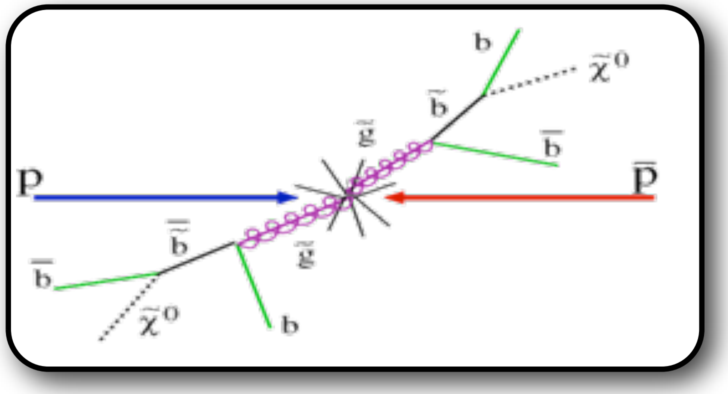
Indirect



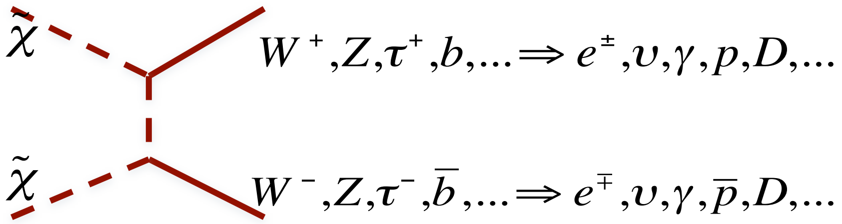
Role of Neutrinos

WIMP - Weakly Interacting Massive Particle



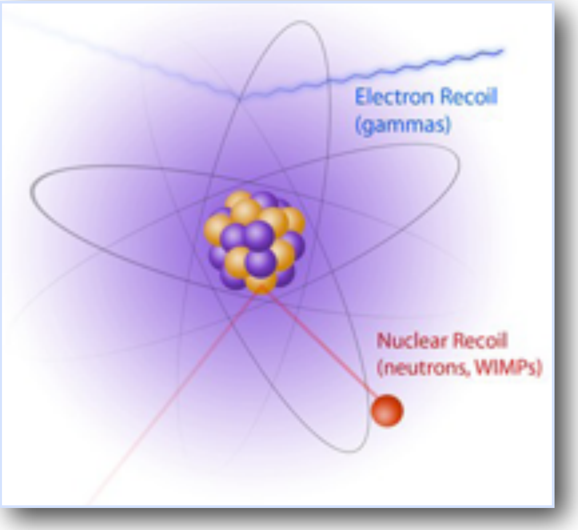


- **Production**
  - Colliders
- **Indirect Searches**
  - Annihilation of Dark Matter in Galactic Halo, ...
    - Gamma-rays, electrons, neutrinos, anti-matter, ...
  - Annihilation signals from WIMPs captured in the Sun (or Earth)
    - Neutrinos
- **Direct Searches**
  - WIMP scattering of nucleons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



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

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



WIMP Self-annihilation cross section

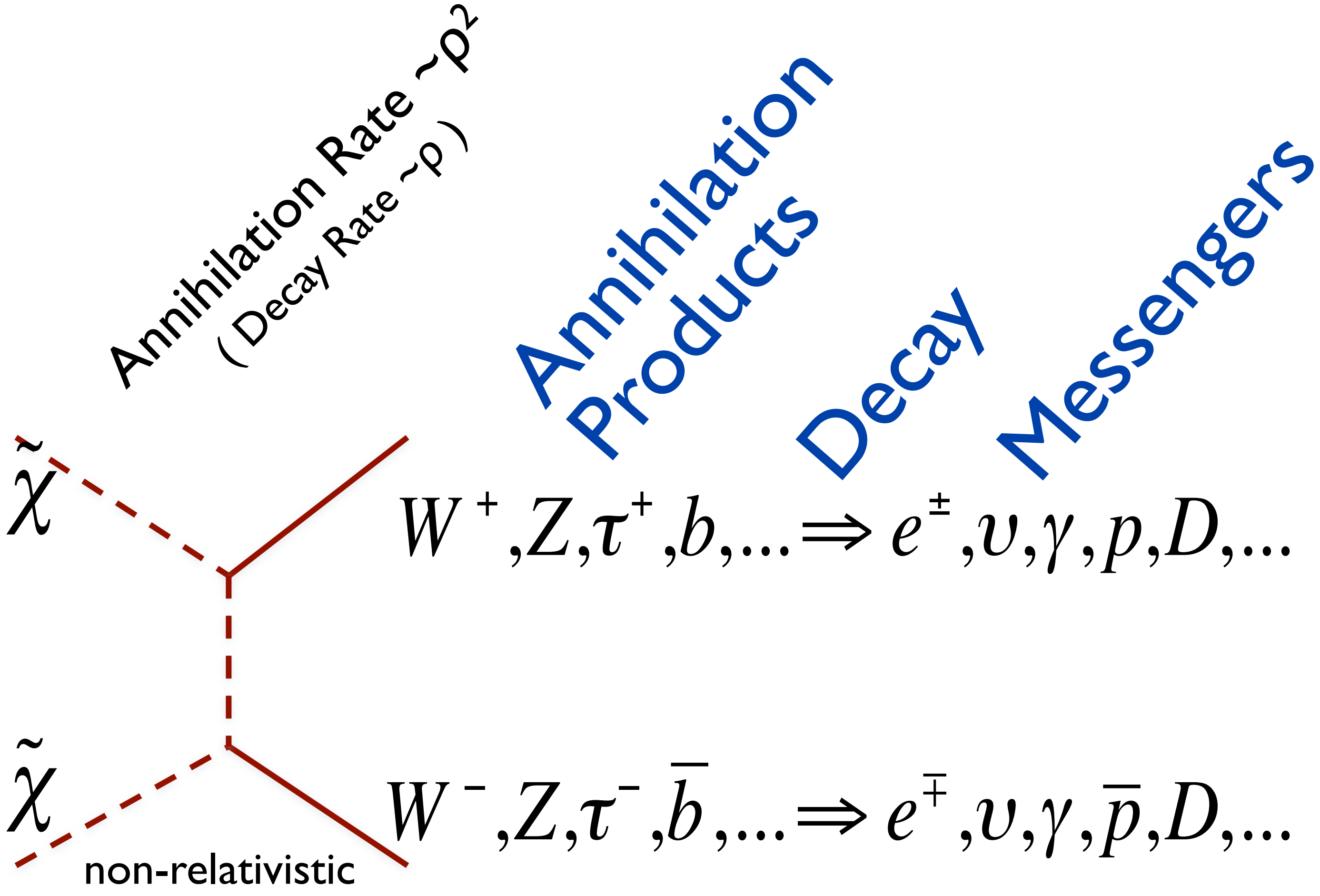
WIMP-Nucleon Scattering cross section

Dark Matter Annihilation Signals

- Identify overdense regions of dark matter

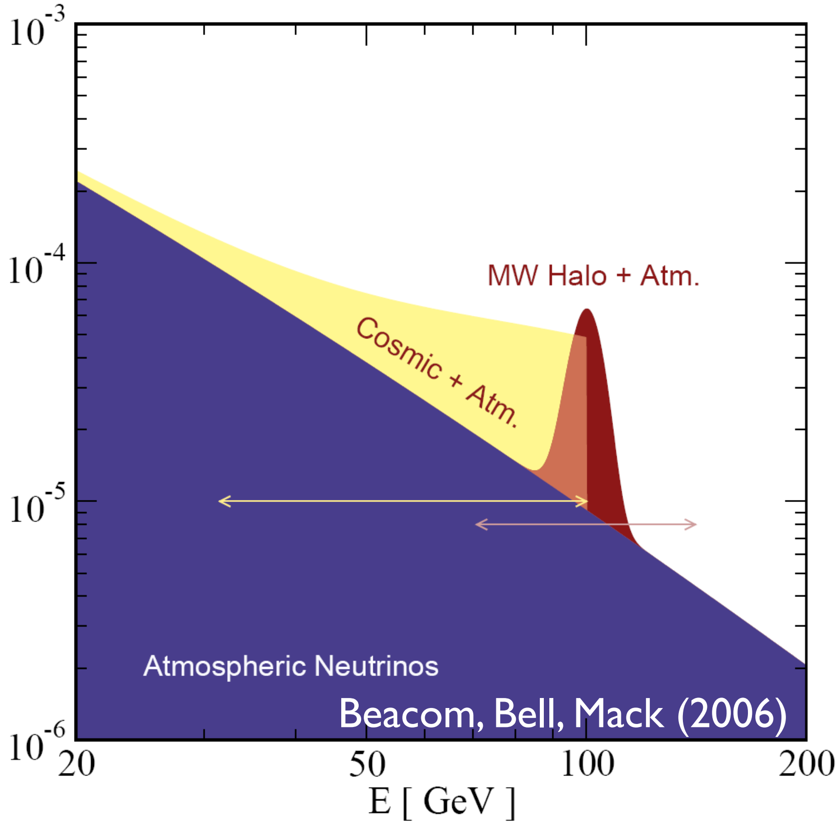
  ⇒self-annihilation can occur at significant rates

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

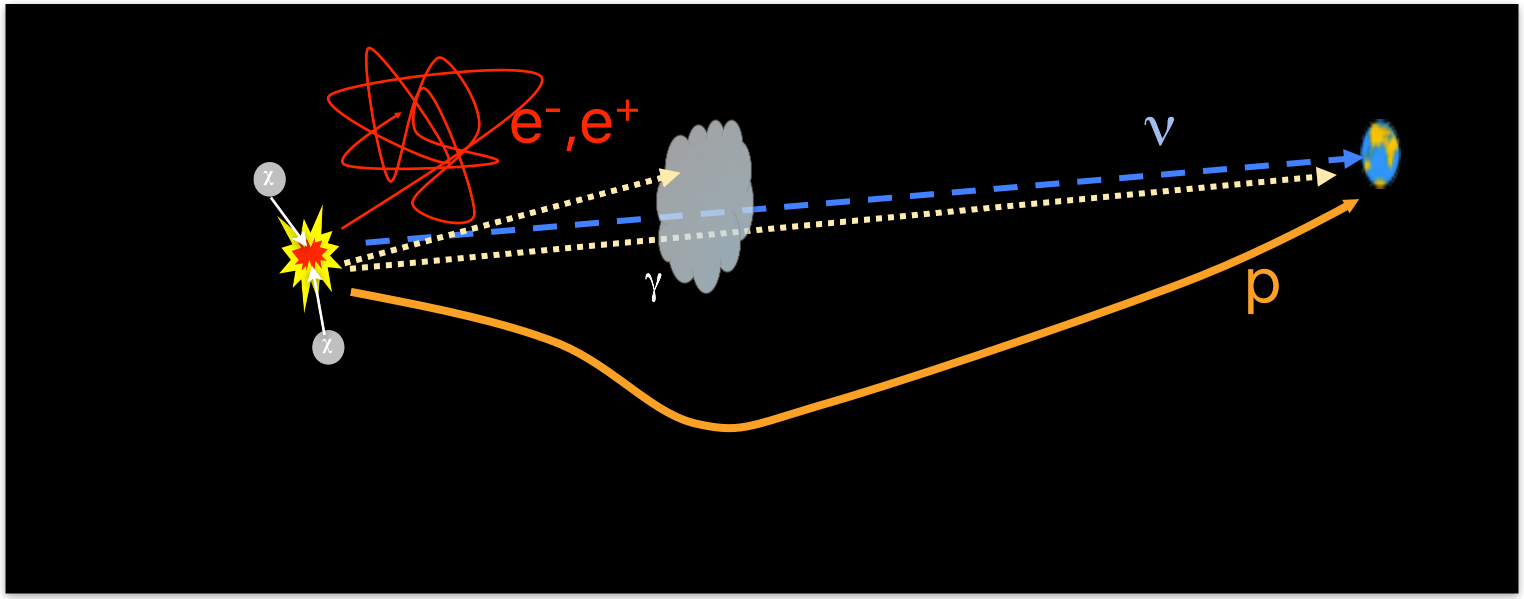


$$W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \upsilon, \gamma, p, D, \ldots$$

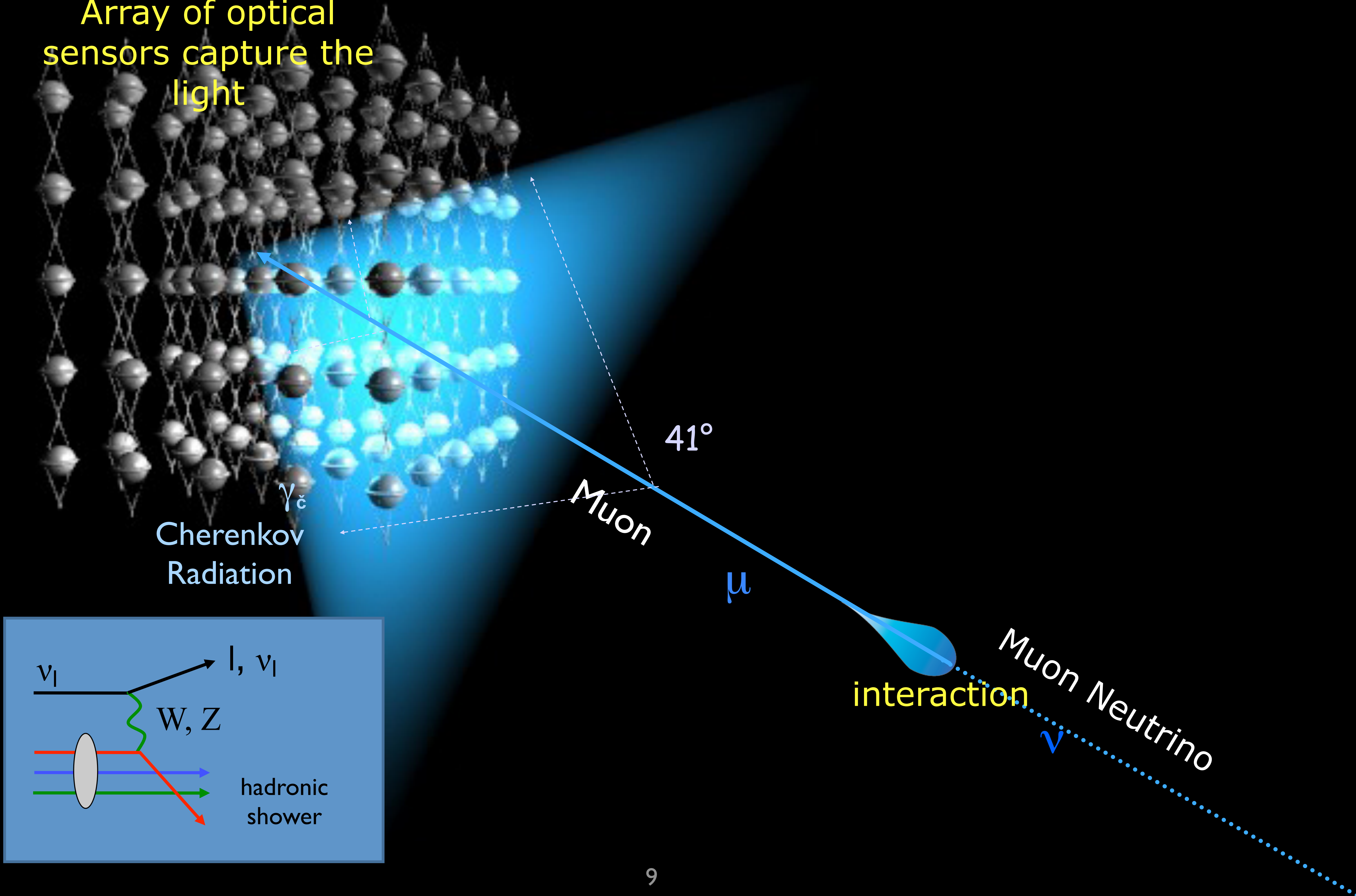
$$W^-, Z, \tau^-, \bar{b}, \ldots \Rightarrow e^\mp, \upsilon, \gamma, \bar{p}, D, \ldots$$



Beacom, Bell, Mack (2006)



Principle of an optical Neutrino Telescope



Array of optical sensors capture the light

Cherenkov Radiation

interaction

Muon

Muon Neutrino

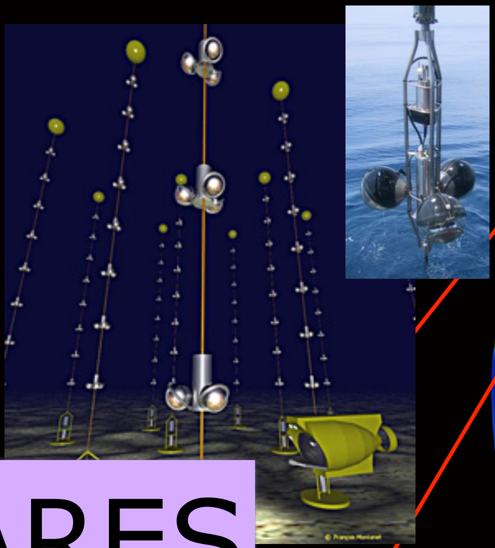
Neutrino Telescopes

Neutrino Telescopes / Detectors

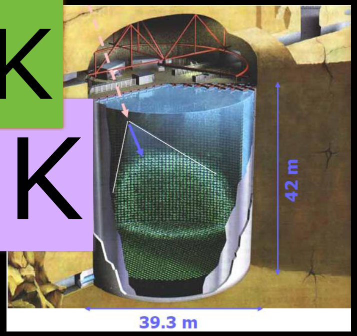
Baksan

...Dumand

Nemo



ANTARES

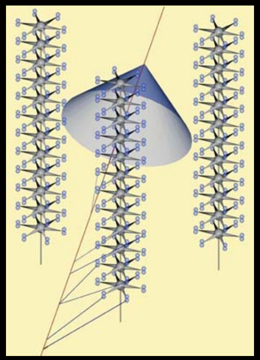


Hyper-K

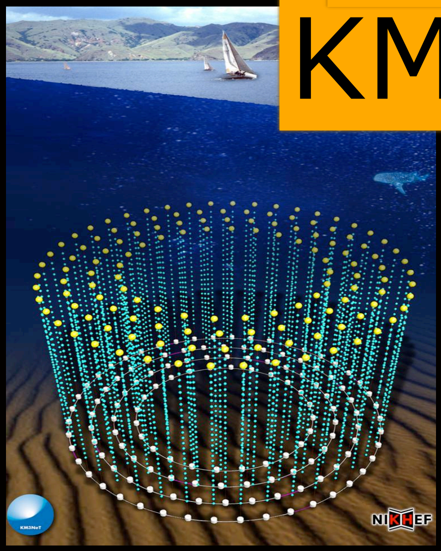
Super-K

Lake Baikal

GVD



Nestor



ORCA

KM3Net

IceCube

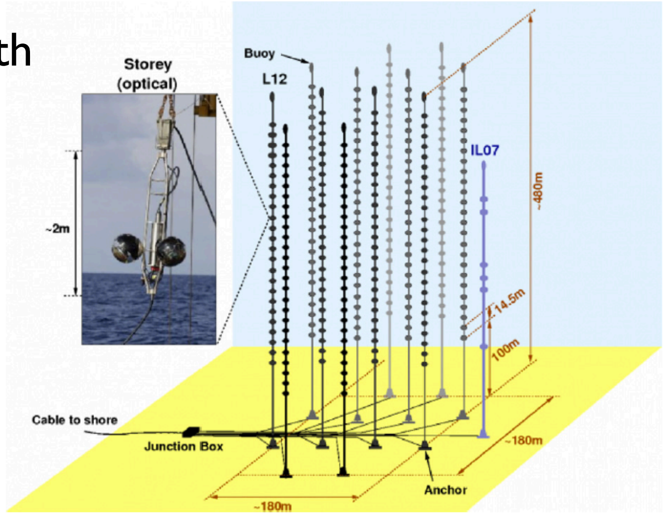
AMANDA

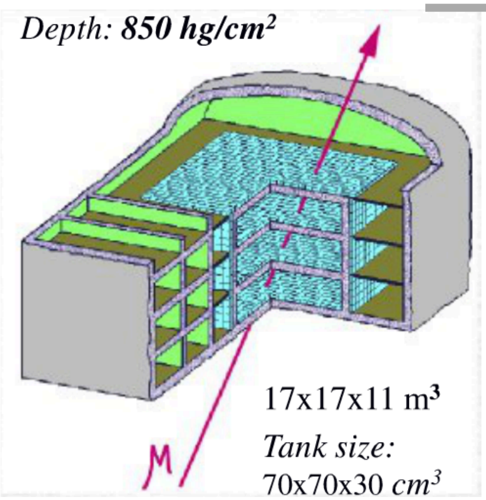
PINGU/Gen2

- Active
- Retired
- Prototype
- Construction
- Planned

Neutrino Telescopes / Detectors

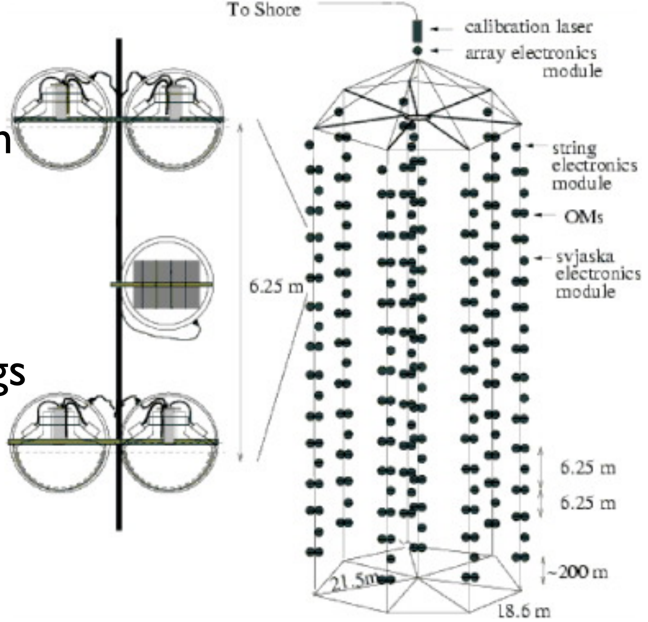
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10”PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



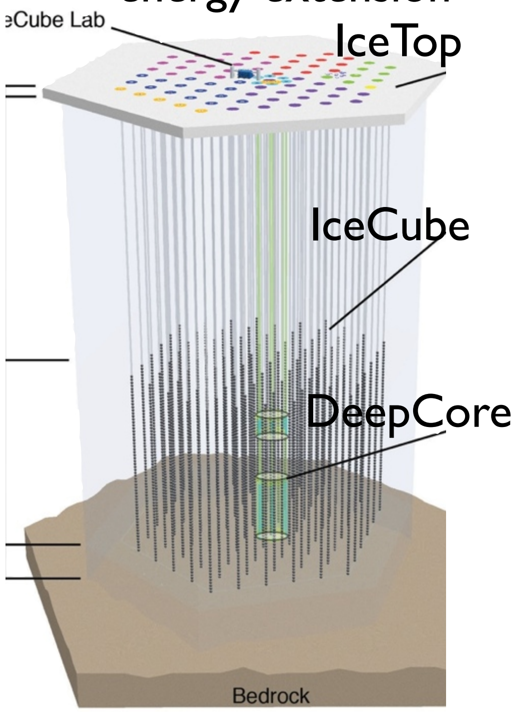


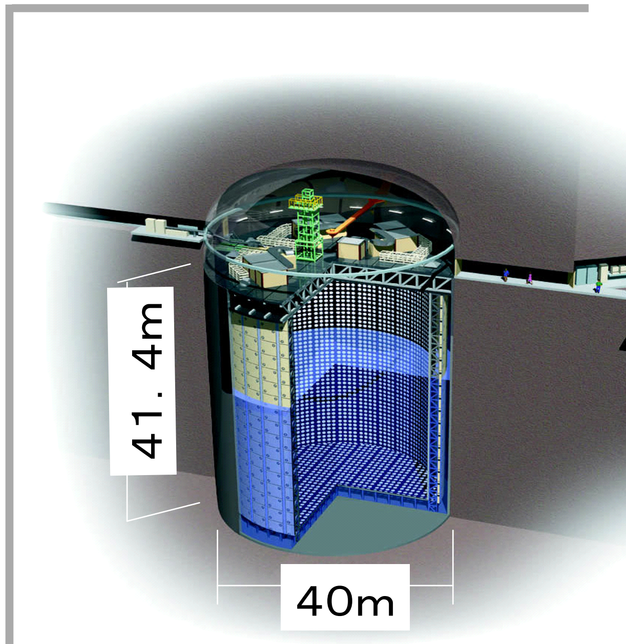
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- 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 ~1km^3
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension





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

The IceCube Neutrino Telescope

Gigaton Neutrino Detector at the Geographic South Pole

5160 Digital optical modules distributed over 86 strings

Completed in December 2010, start of data taking with full detector May 2011

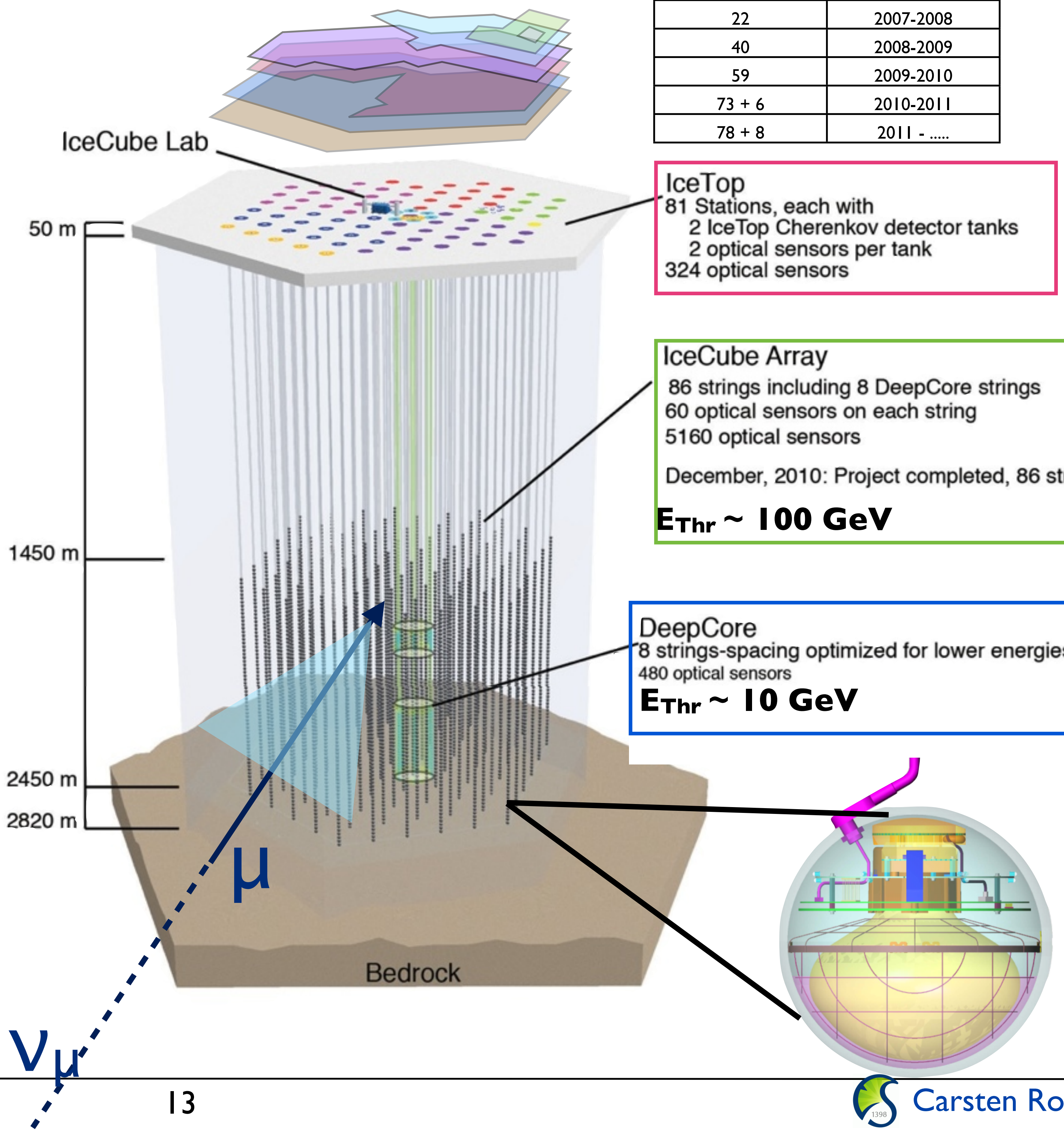
Data acquired during the construction phase has been analyzed

Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

Dark Matter Searches

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

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



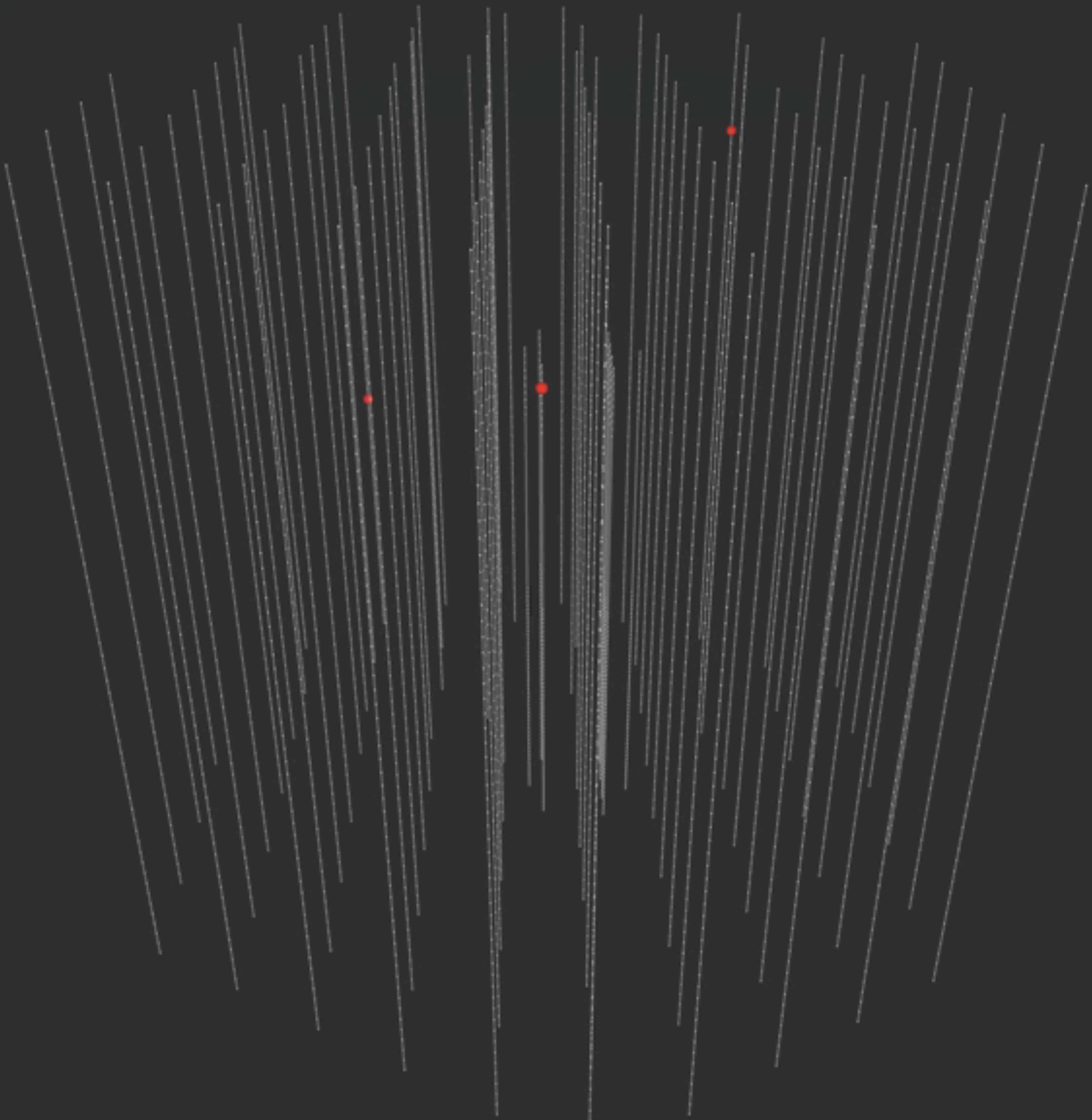
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

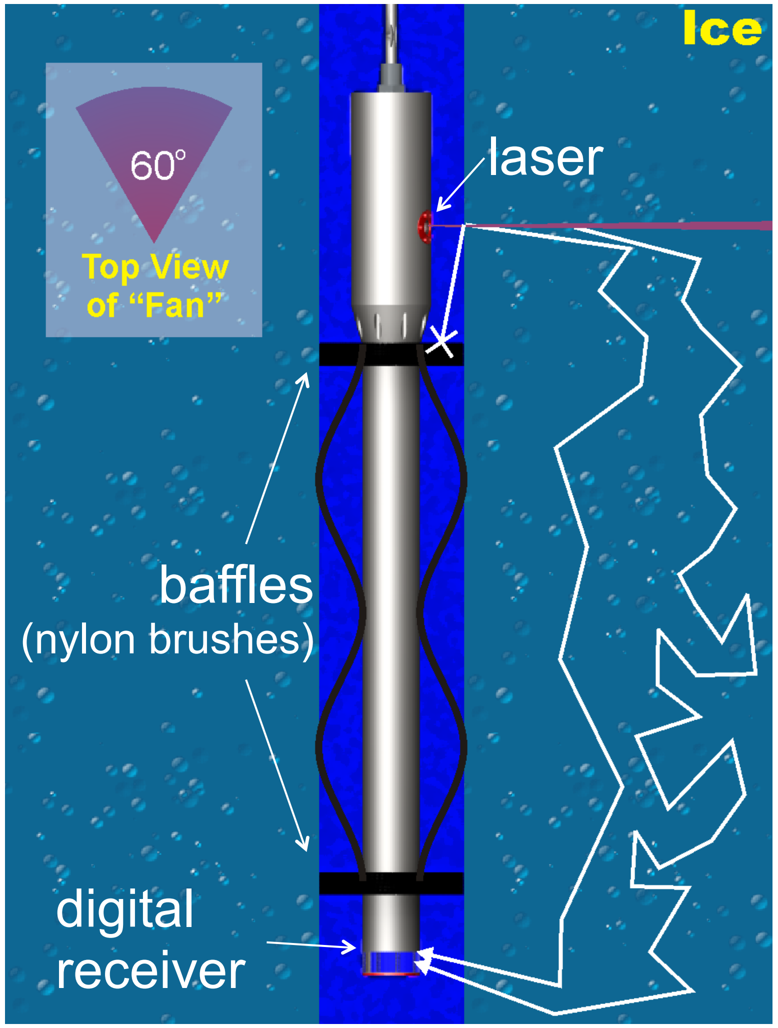
December, 2010: Project completed, 86 strings

E_{Thr} ~ 100 GeV

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
E_{Thr} ~ 10 GeV



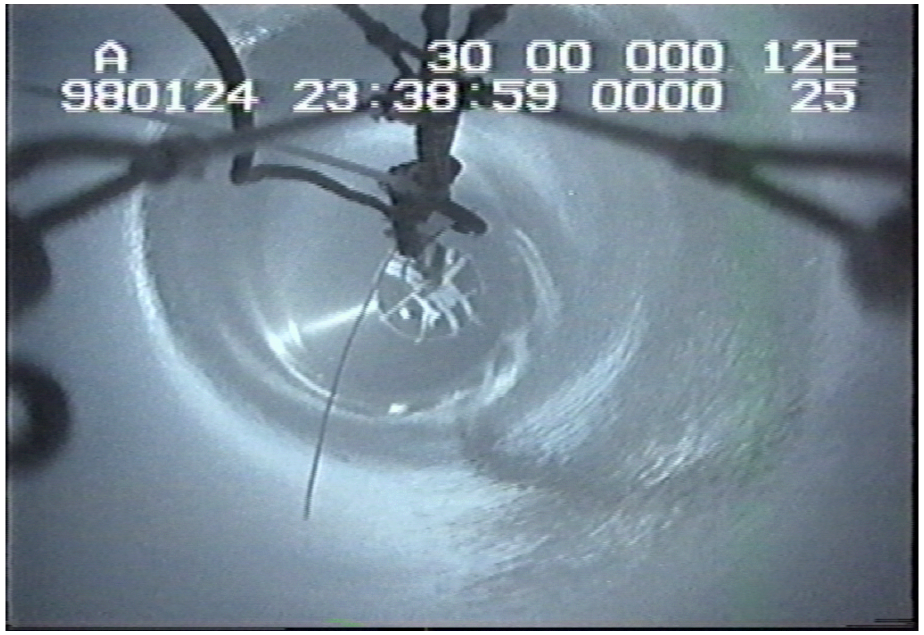
The Ice

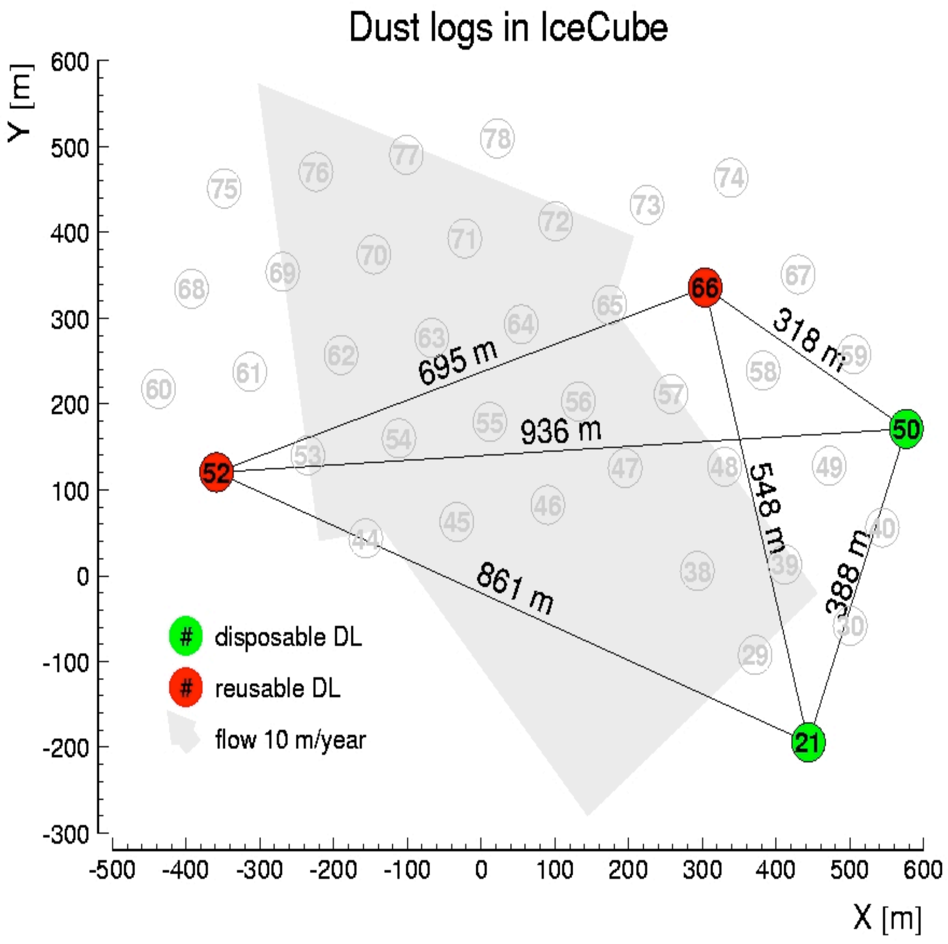


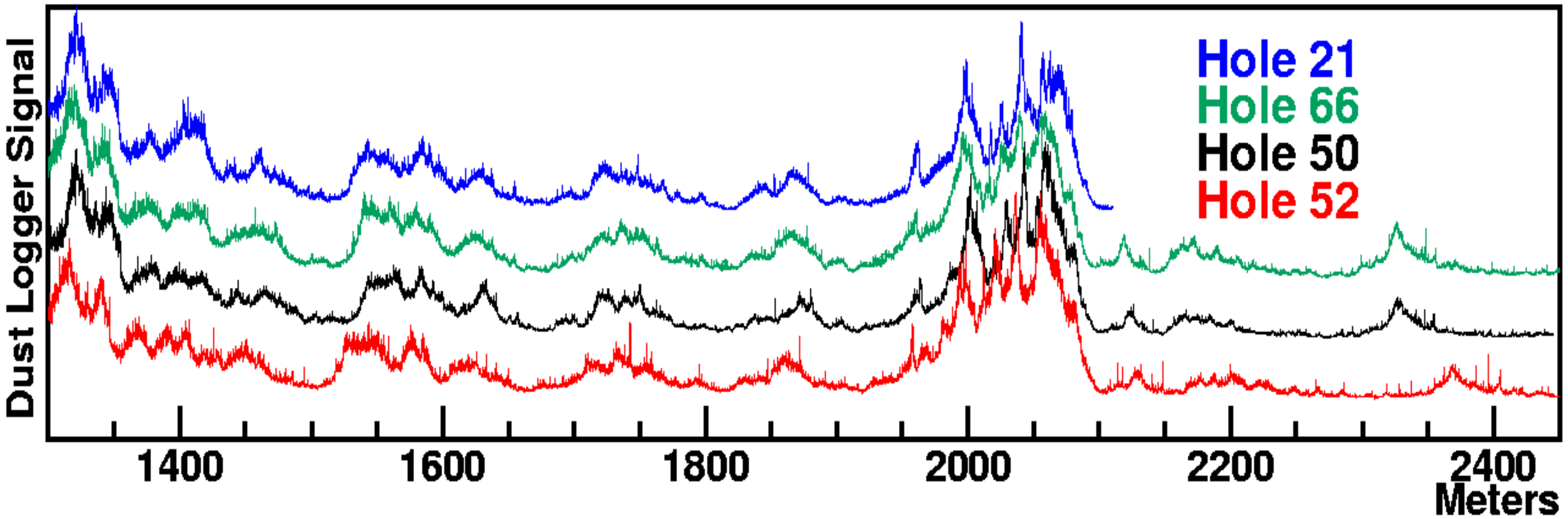
Major calibration efforts resulted in a very precise understanding of the ice surrounding the IceCube detector

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - One pair of Camera DOMs

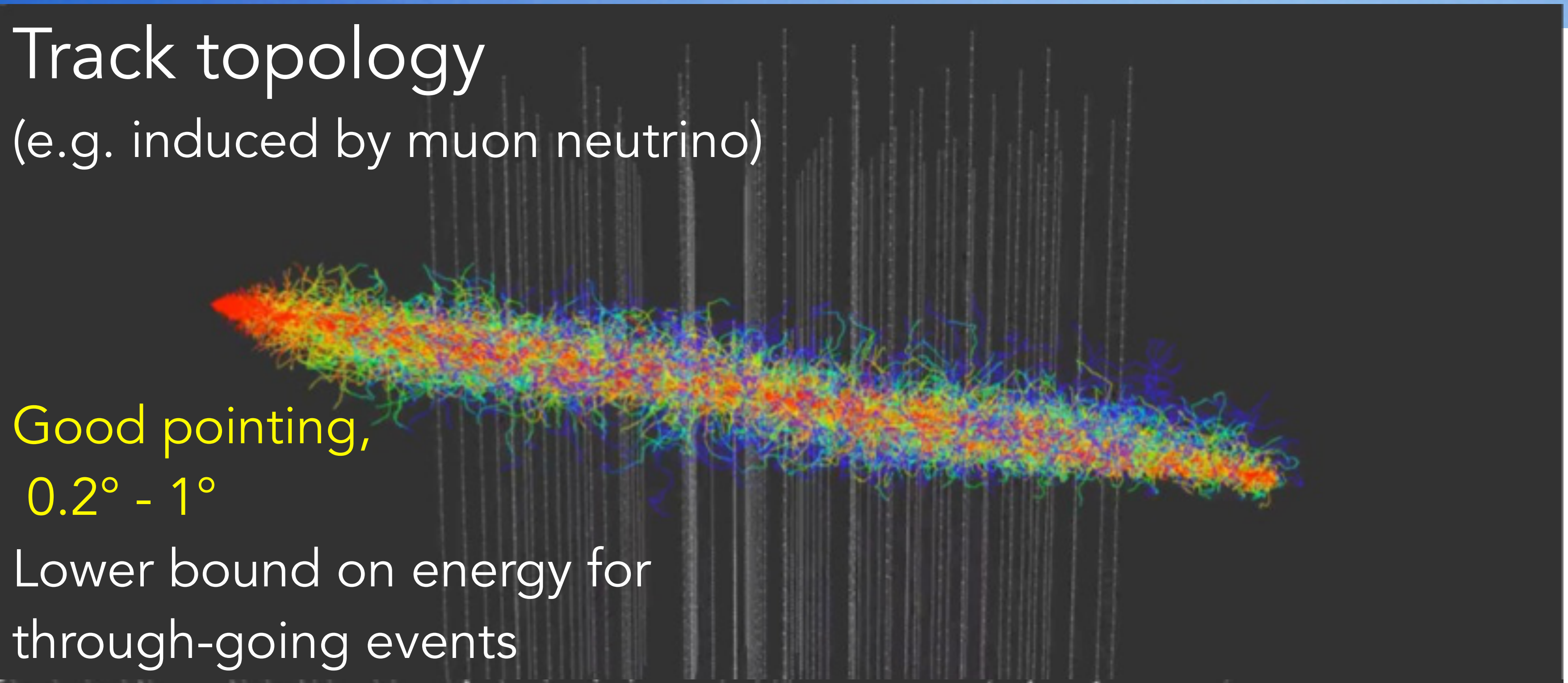
absorption length ~ 210m
scattering length ~20-40m







Event Topologies in IceCube

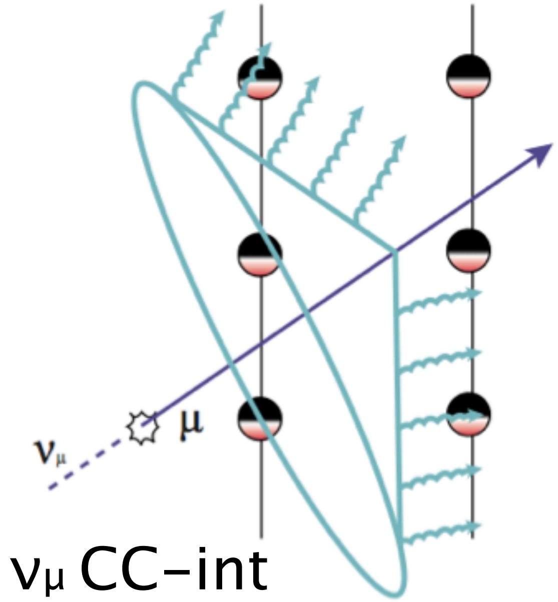


Track topology

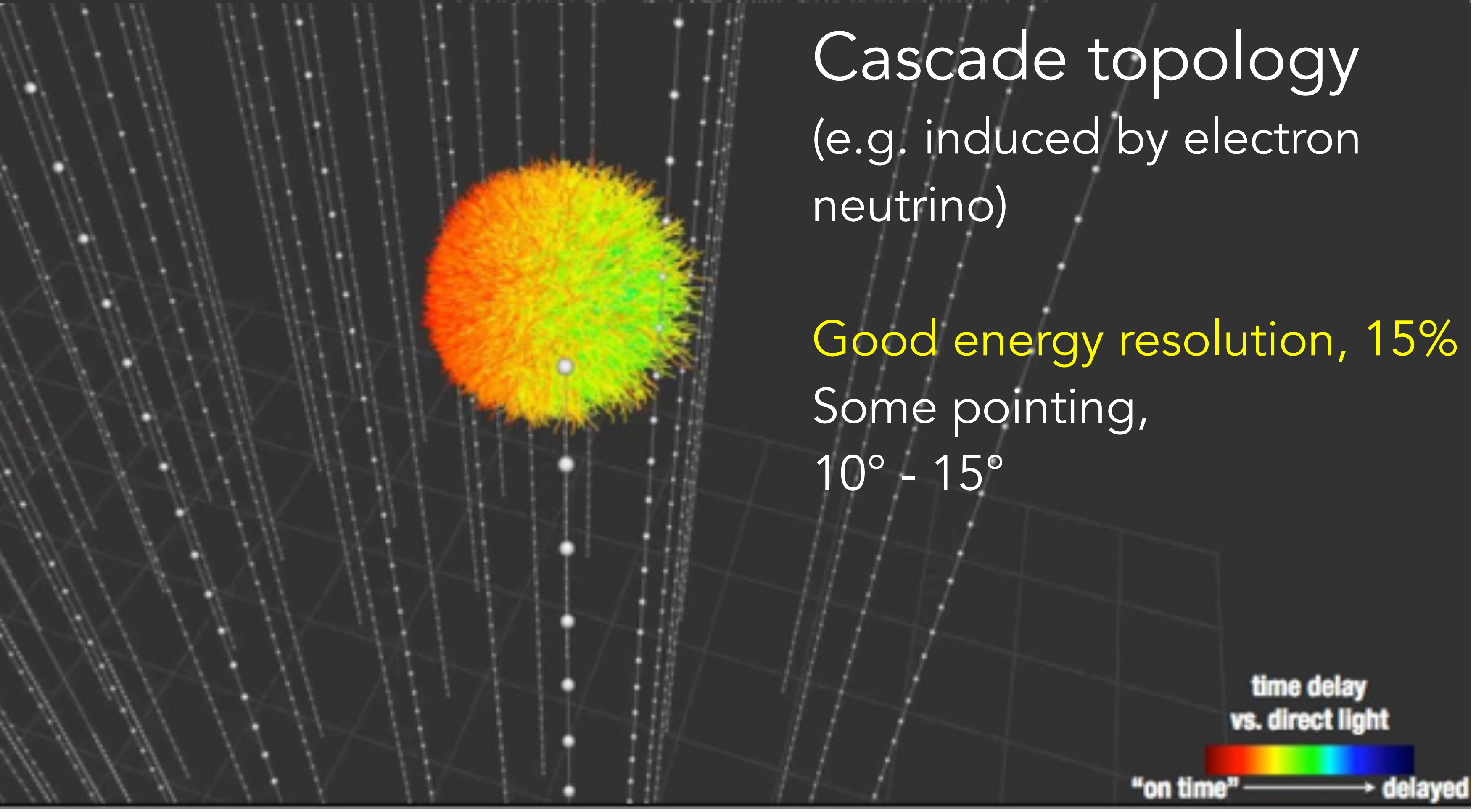
(e.g. induced by muon neutrino)

Good pointing,
0.2° - 1°

Lower bound on energy for through-going events



ν_μ CC–int

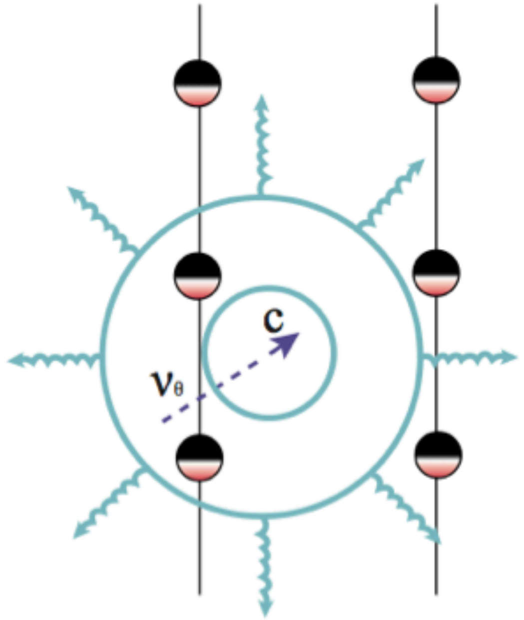


Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

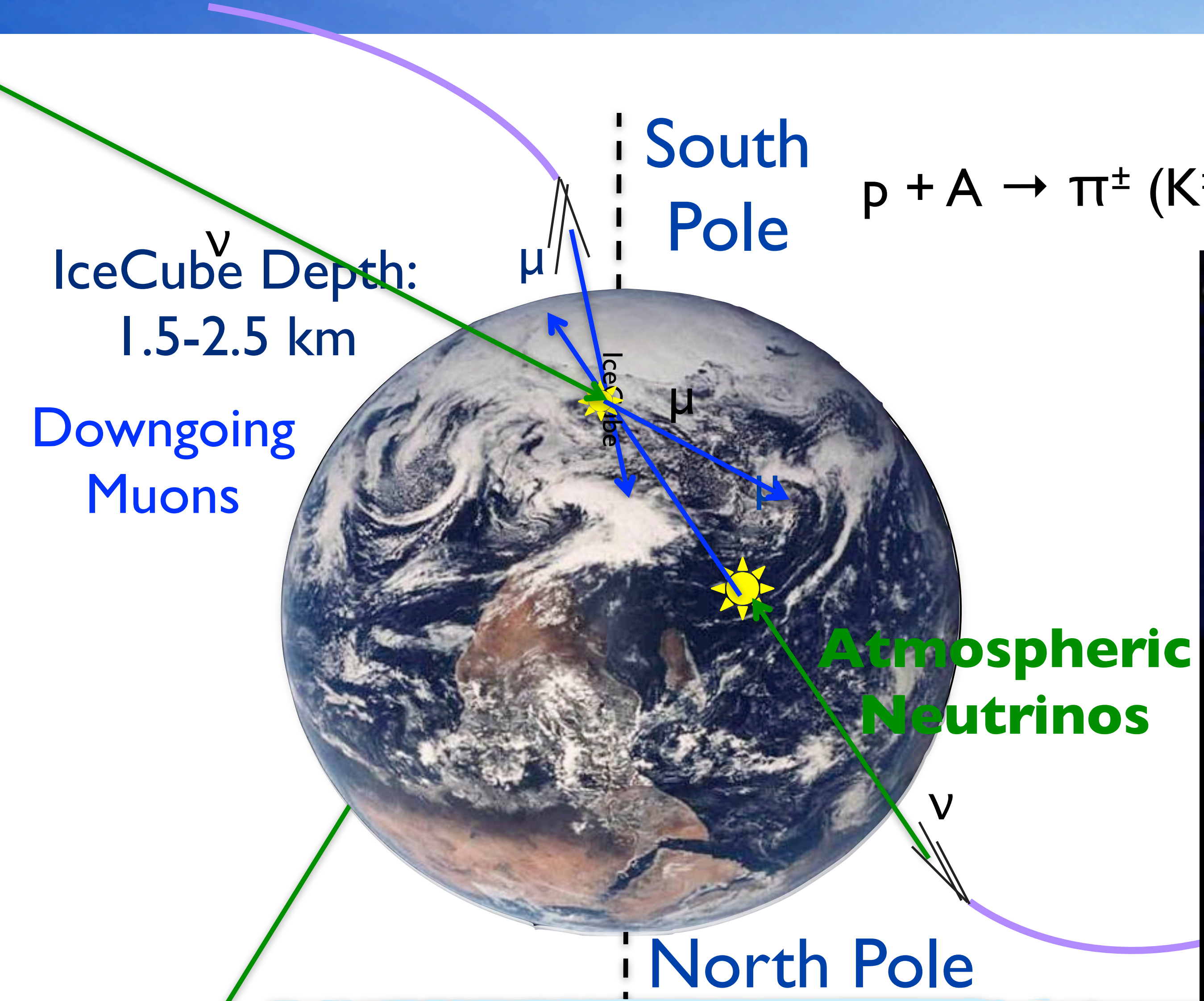
Some pointing,
10° - 15°

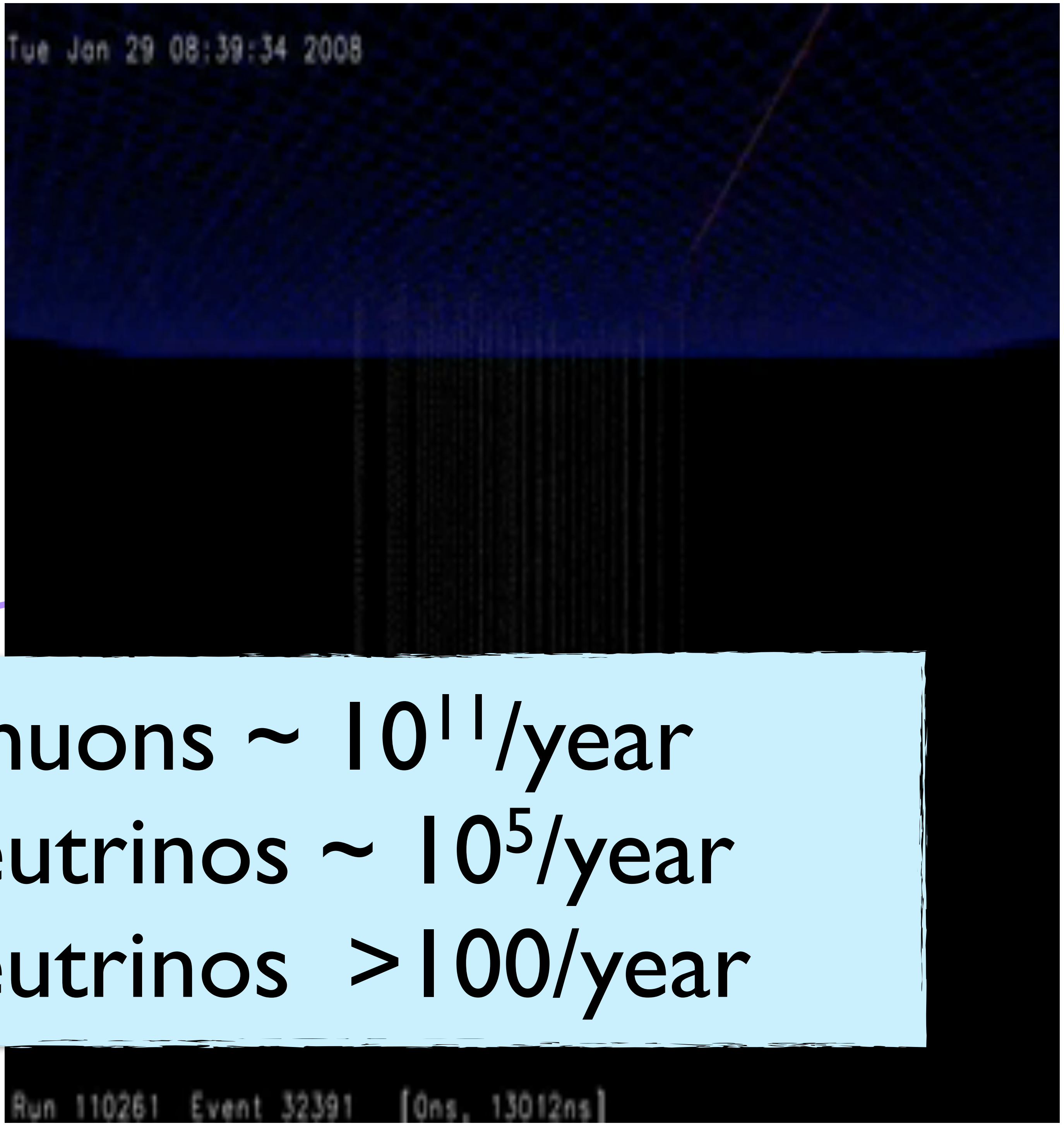


ν_e ν_τ CC–int & ν_i NC–int

Signals in IceCube

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





Atmospheric muons ~ 10^{11}/year

Atmospheric neutrinos ~ 10^{5}/year

Astrophysical neutrinos >100/year

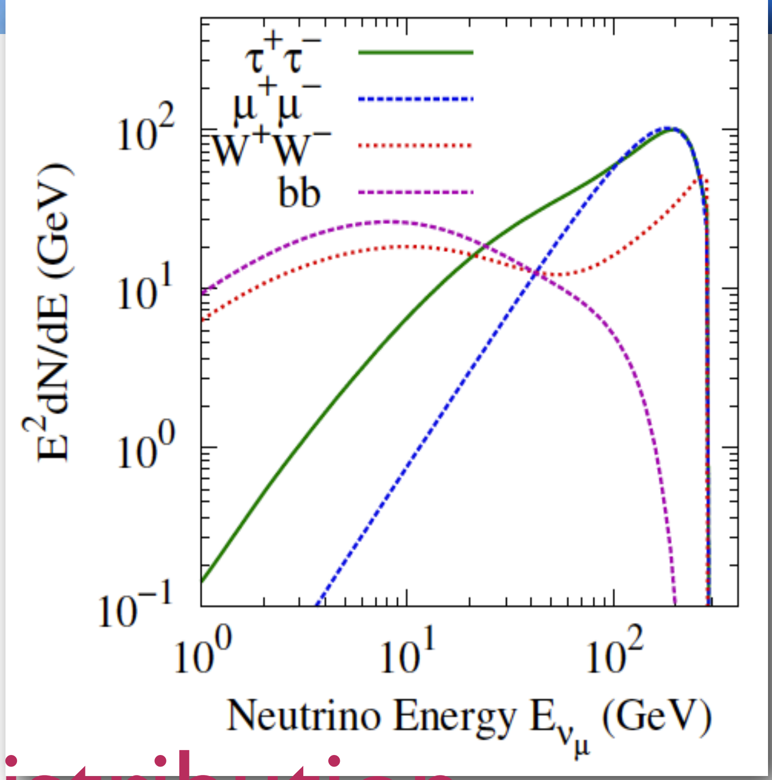
irreducible neutrino background to extra terrestrial neutrino fluxes

Dark Matter Self-annihilations

$<\sigma_A v>$

Dark Matter in the Milky Way

Dark Matter Annihilation



Measure Flux **Particle Physics**

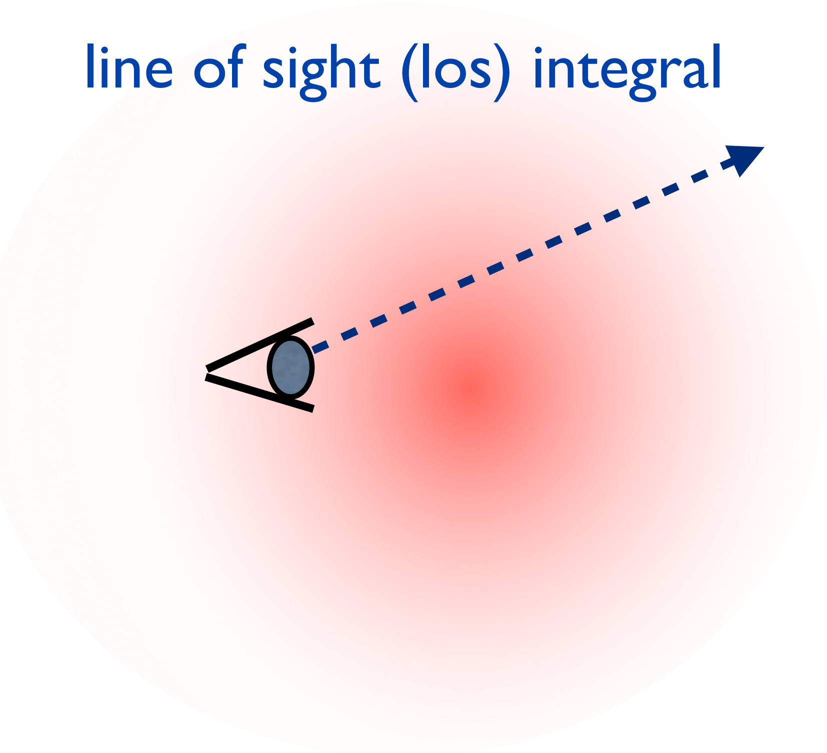
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f$$

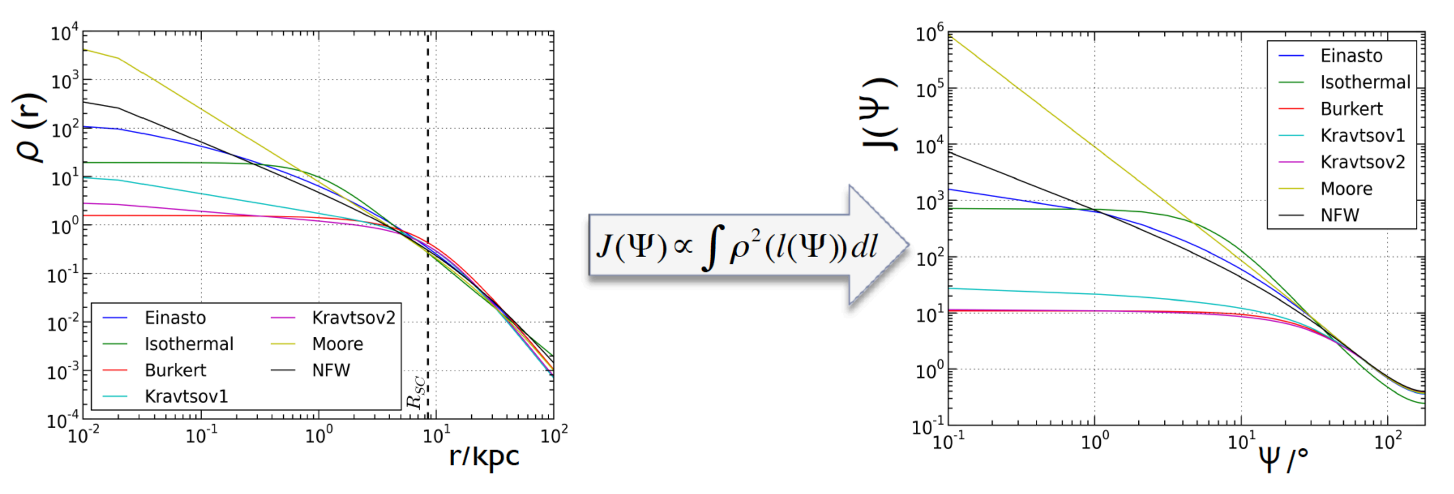
x

Dark Matter Distribution

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

line of sight (los) integral



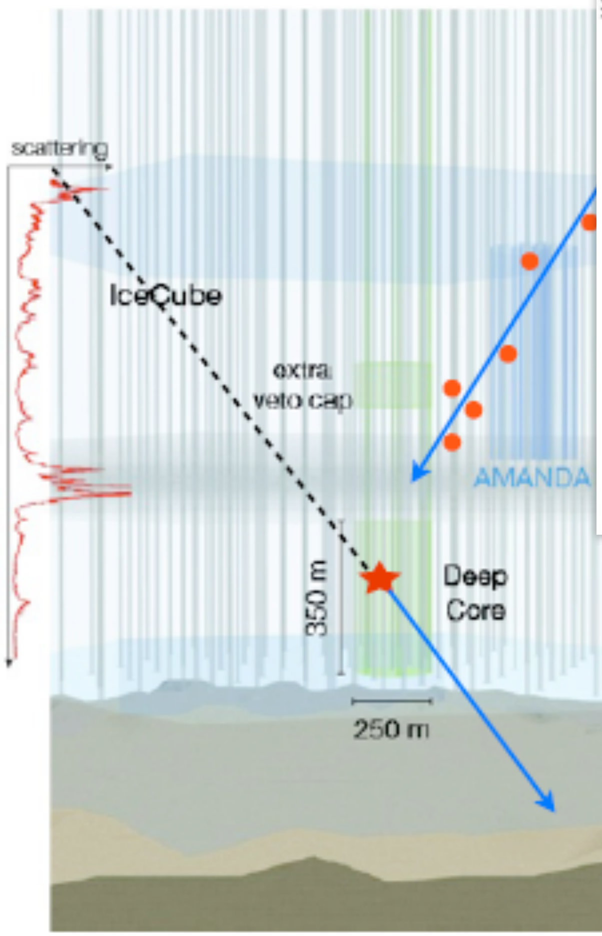


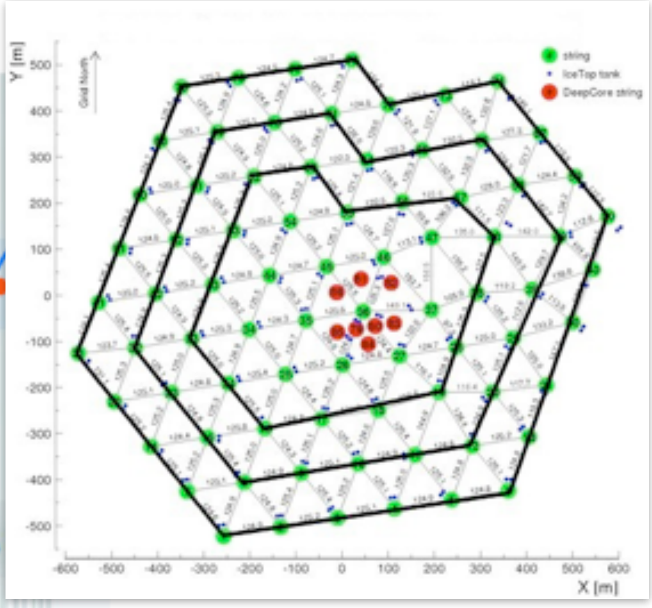
$J(\Psi) \propto \int \rho^2(l(\Psi))dl$

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



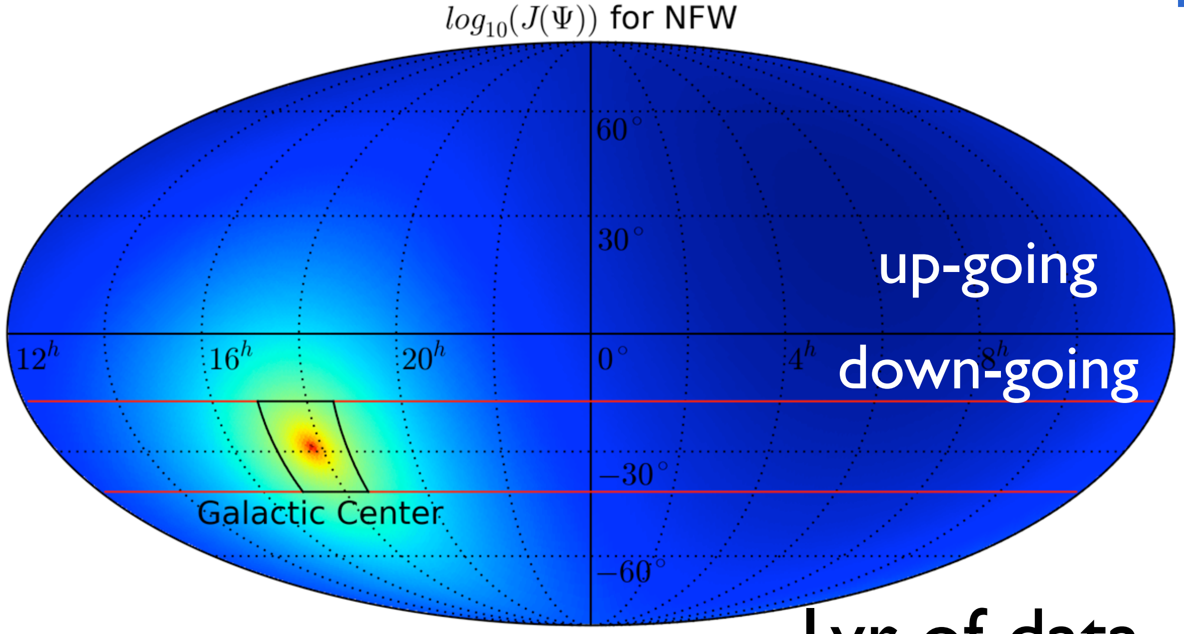


Two analyses, combined based on best sensitivity (dotted).

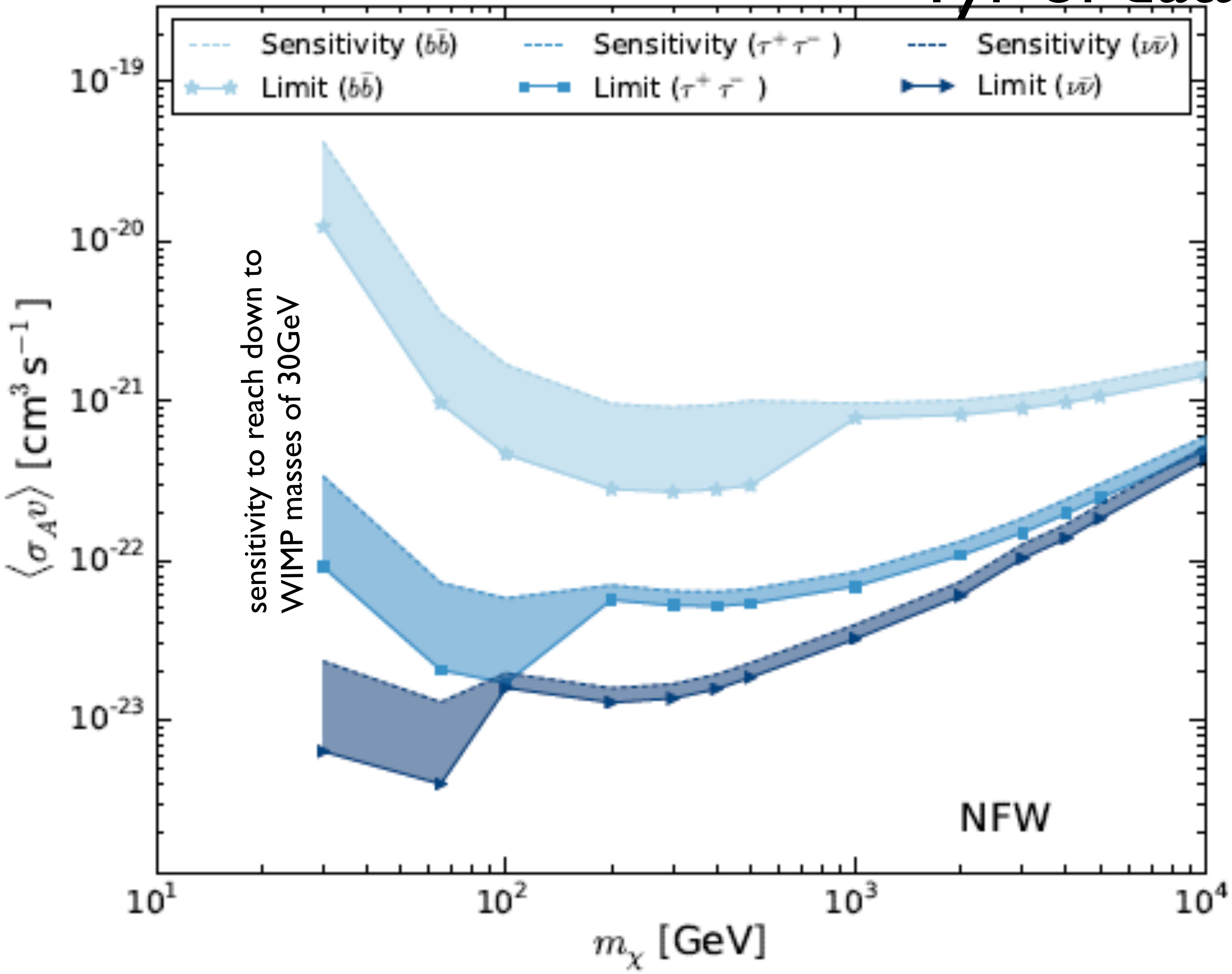
Both analyses observed underfluctuations

"High energy" analysis: 0.5 σ

"Low energy" analysis: 2σ

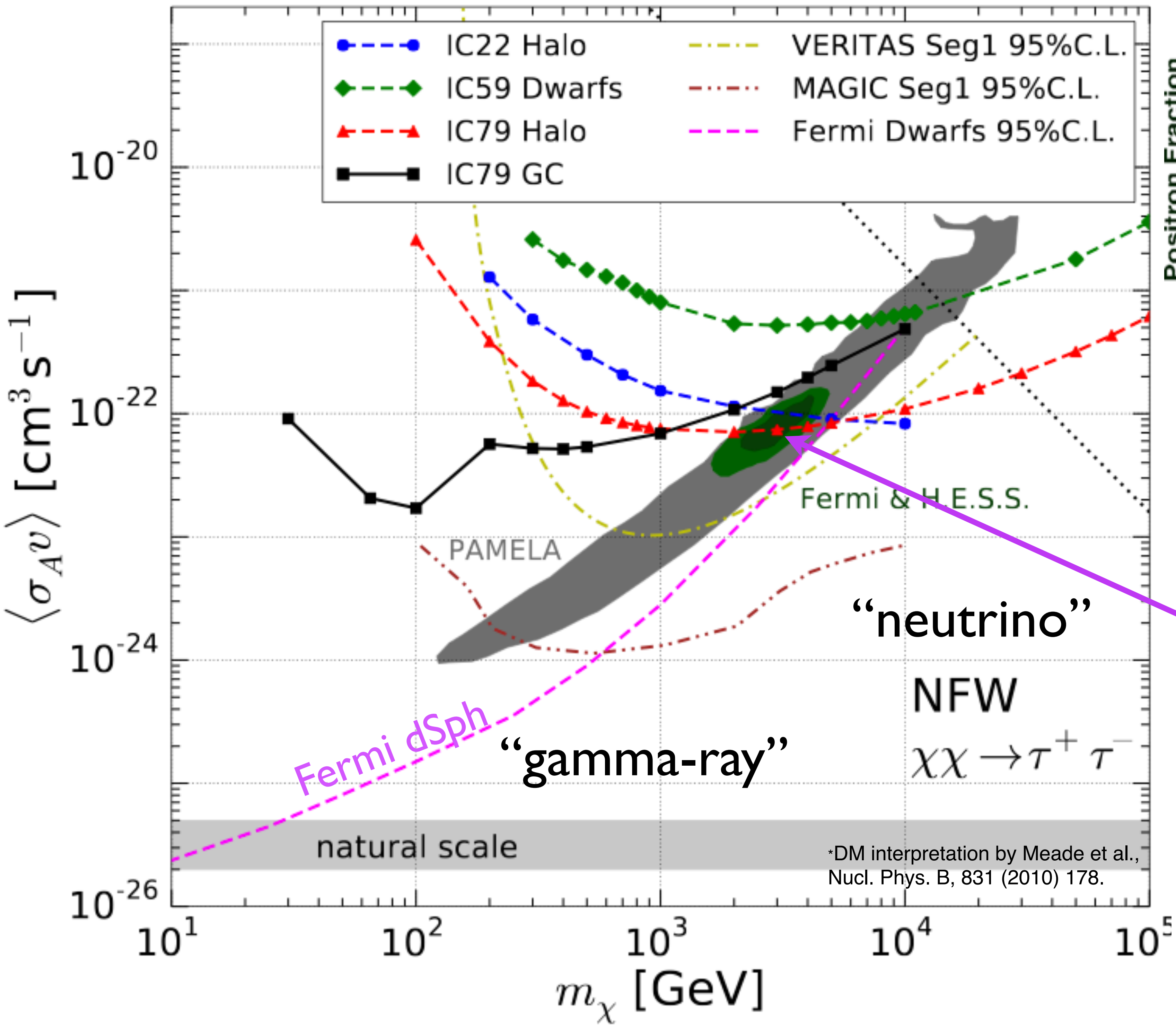


1yr of data

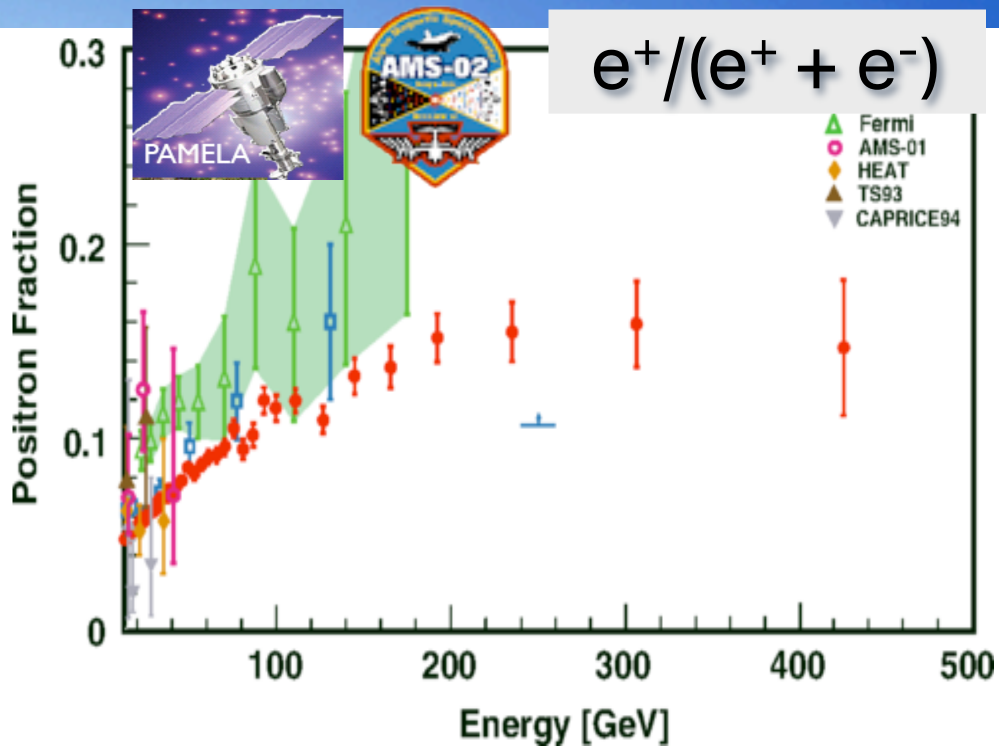


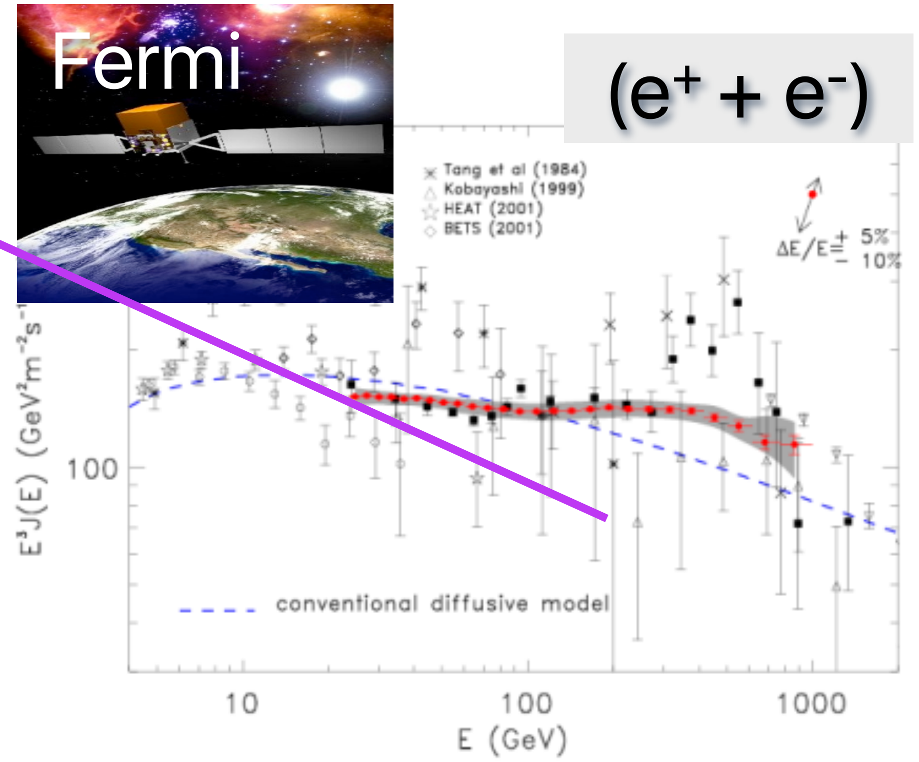
Separate Low energy and High energy optimizations:
GC is above the horizon
→ Fiducial volume in central strings
→ refined muon veto from surrounding layers
Use scrambled data for background estimation

Neutrinos test lepton anomalies



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



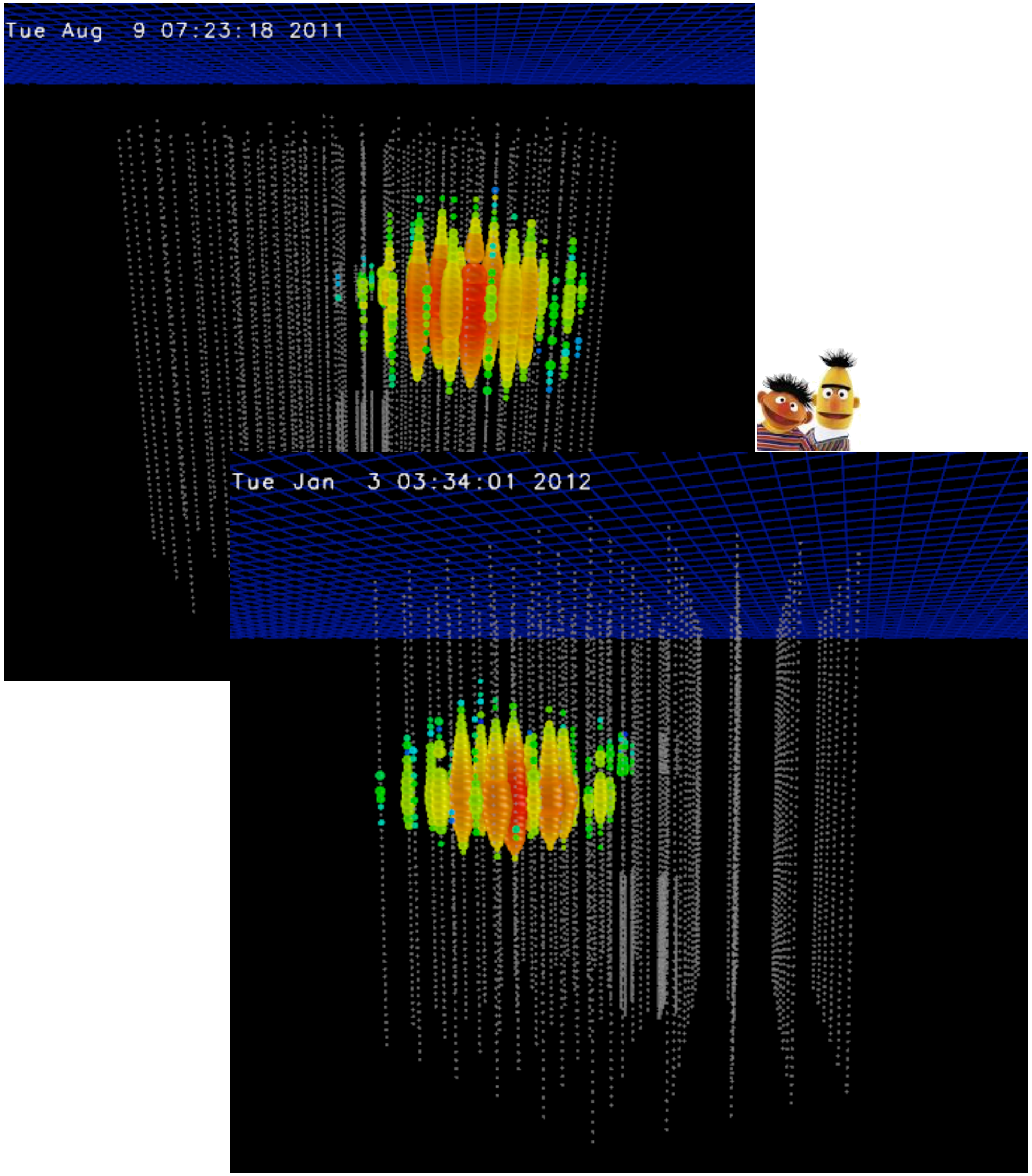


IceCube can probe models motivated by the observed lepton anomalies

Dark Matter Decay - High Mass Dark Matter

Search for highest energy neutrinos

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



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

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

Ernie & Bert are not GZK, but ...

Heavy Dark Matter

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

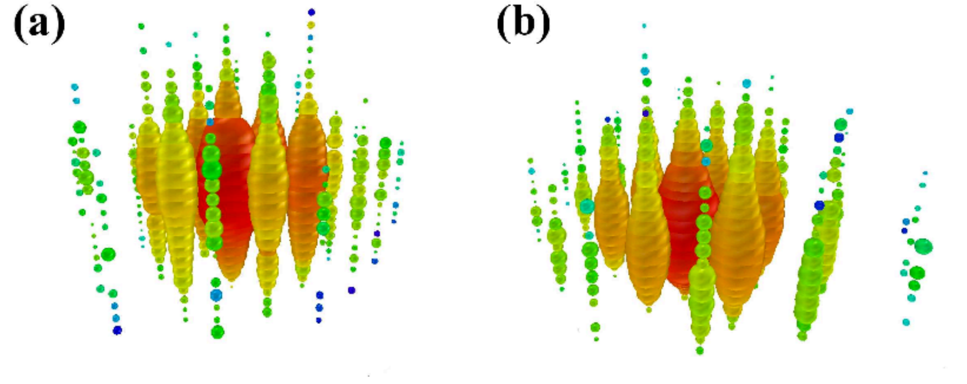


FIG. 4. The two observed events from (a) August 2011 and (b) January 2012. Each sphere represents a DOM. Colors represent the arrival times of the photons where red indicates early and blue late times. The size of the spheres is a measure for the recorded number of photo-electrons.

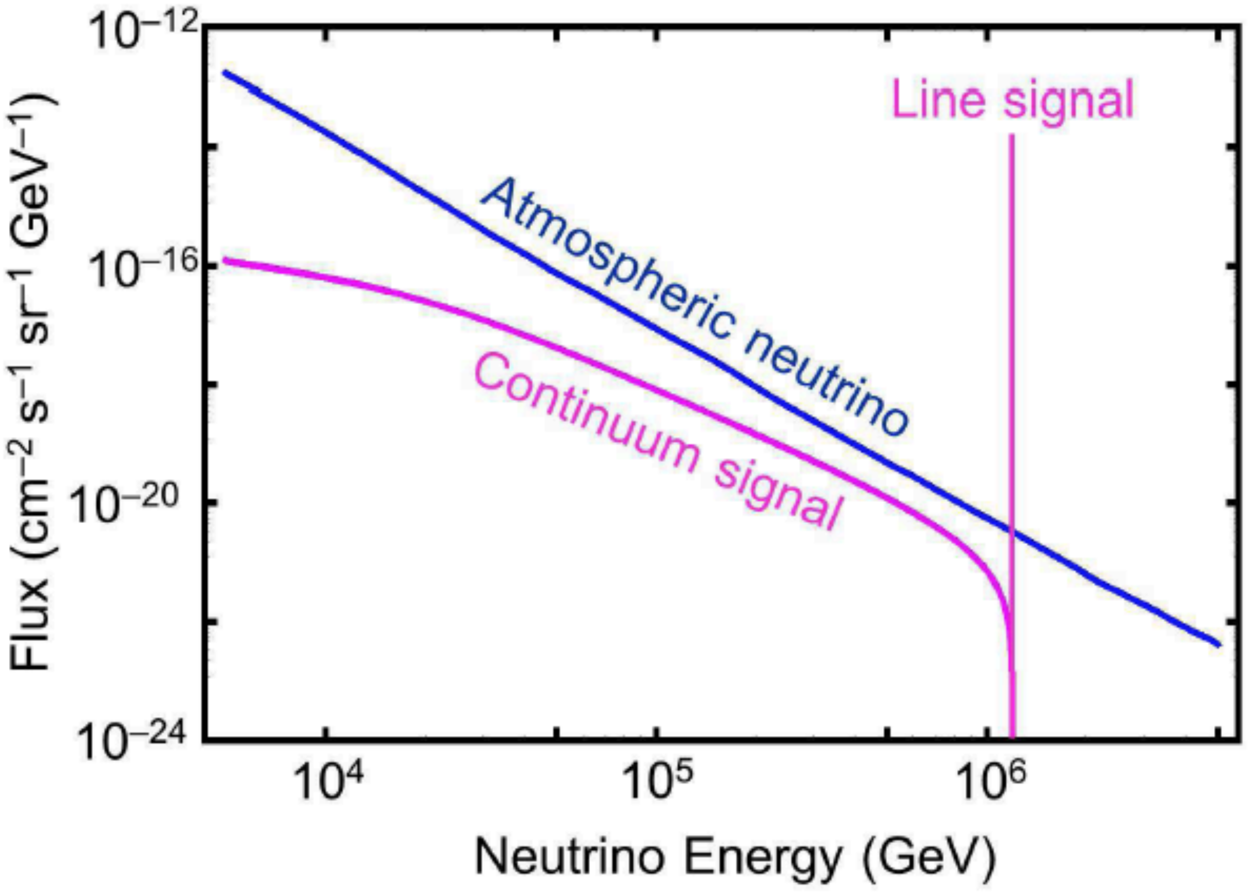
Could this be dark matter ?

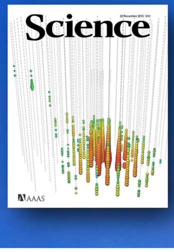
example: B. Feldstein, A. Kusenko, S. Matsumoto, and T. Yanagida arXiv:1303.7320v1 / Phys.Rev. D88 (2013) 1, 015004

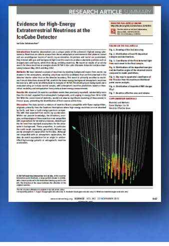
Evidence:
- 2.4PeV Dark Matter Particle mass
- Flux can be related to the lifetime $\tau_{\rm DM}$

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

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



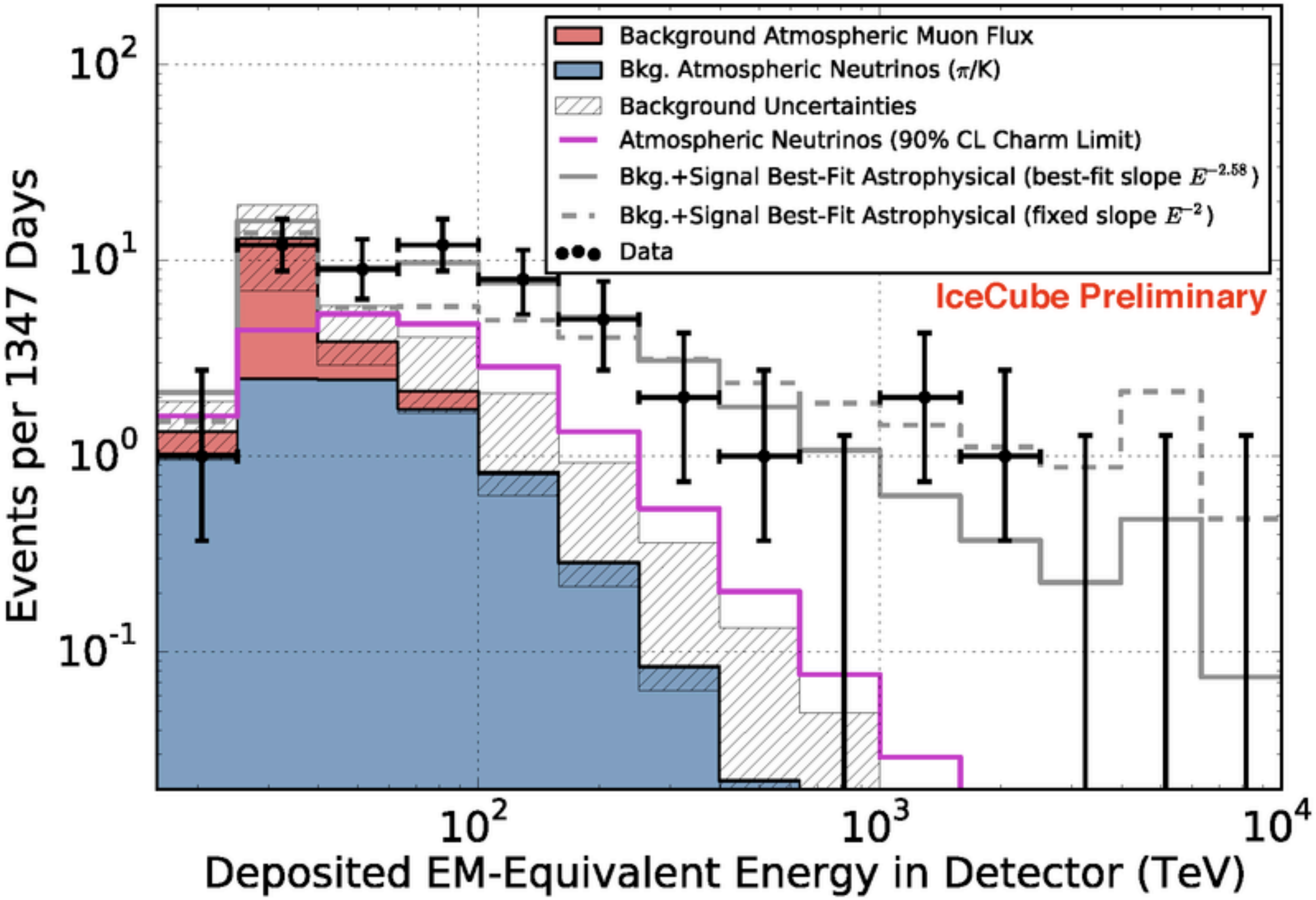




High-energy neutrino search 4yrs

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

Expectation from conventional atm.
muons and neutrinos ~21.6



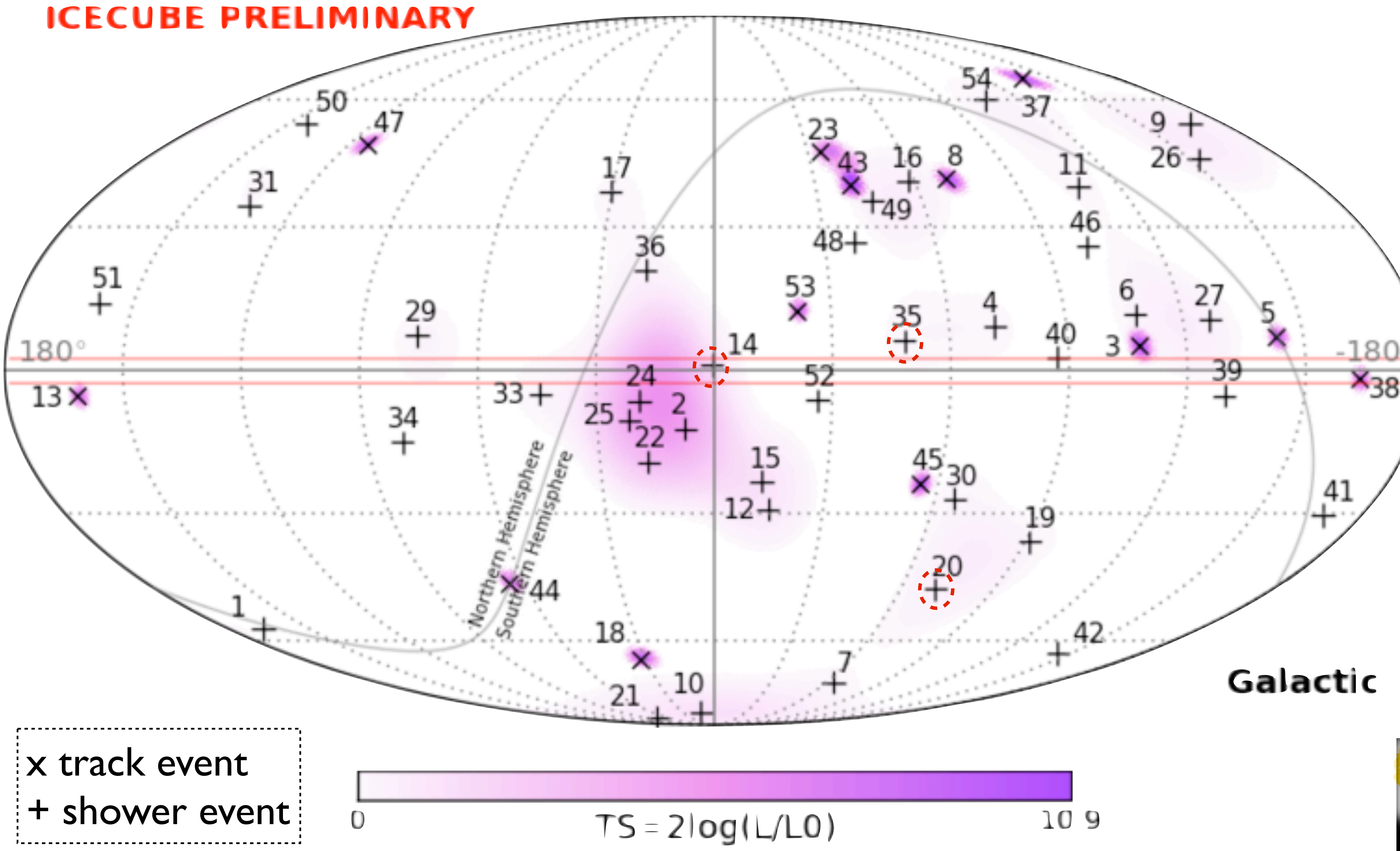
- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including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

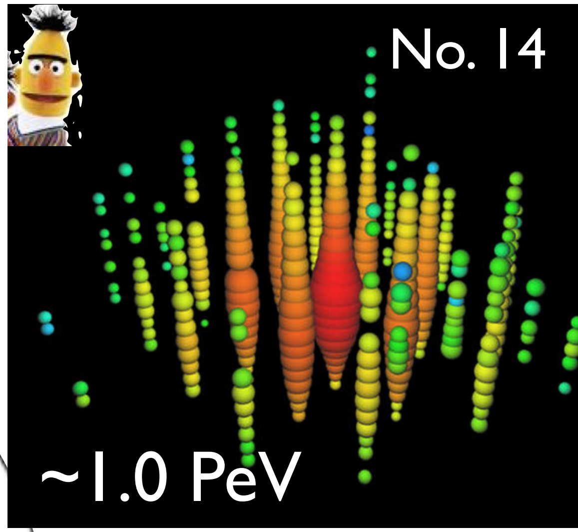
~7 sigma rejection of atmospheric-only hypothesis

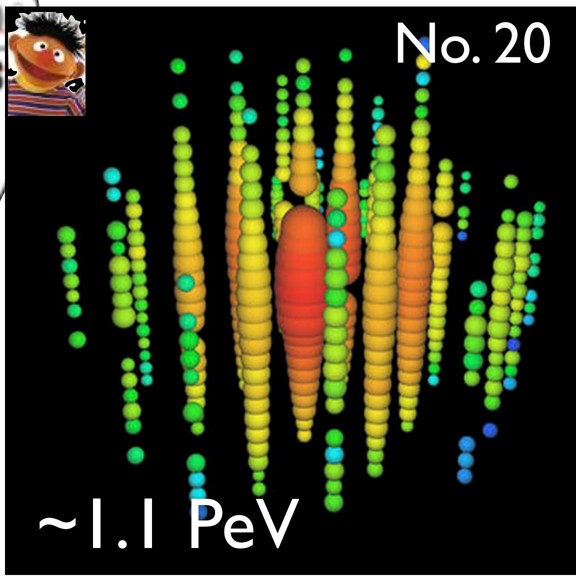
ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

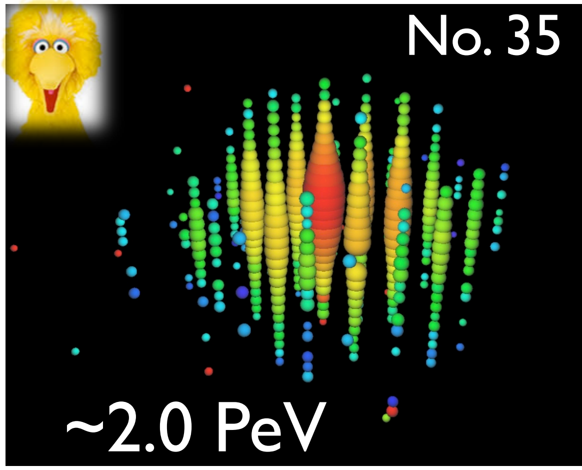
Skymap HESE-4yrs

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







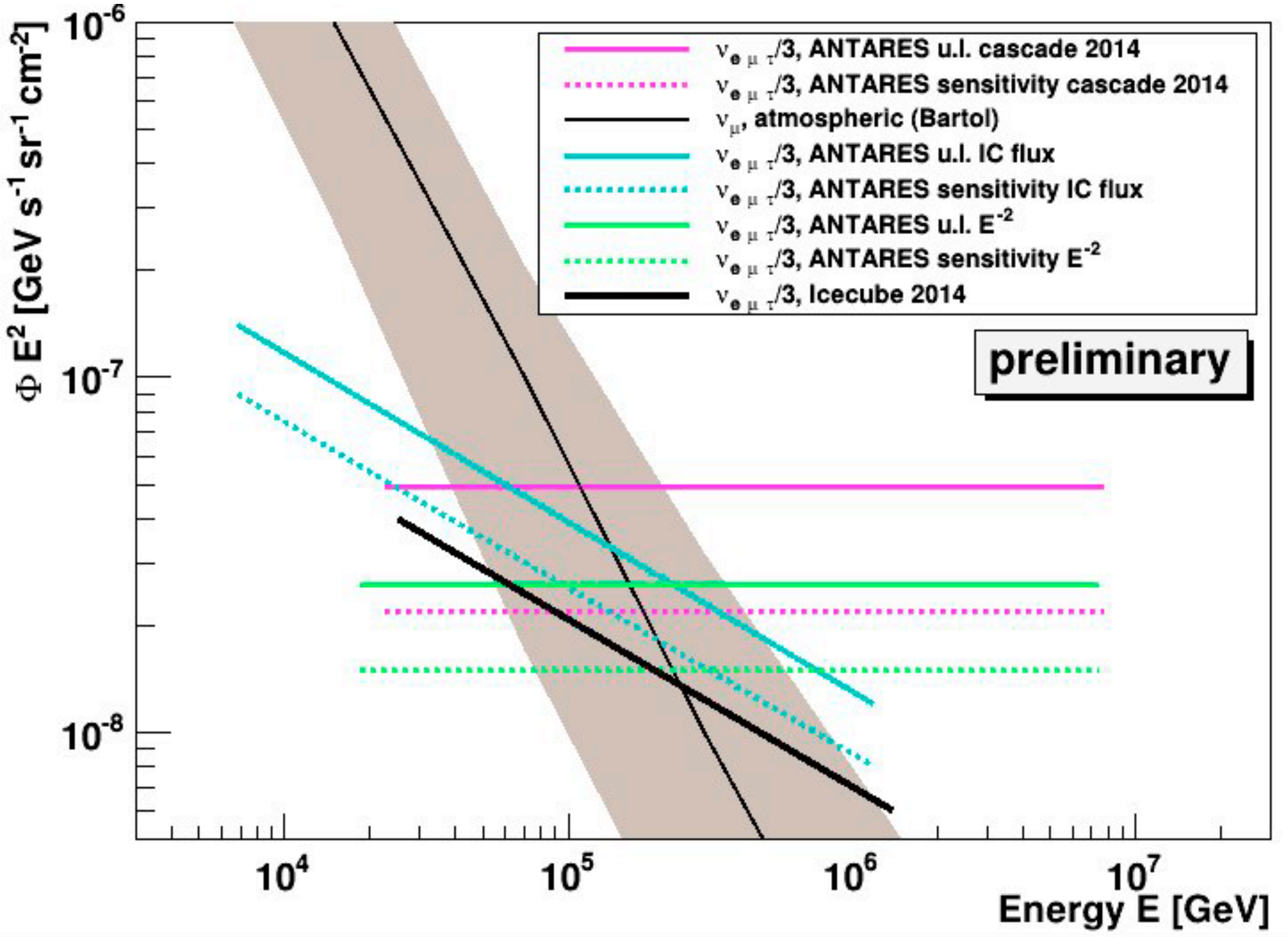


no significant correlations -- spacial or temporal

p-value for cascade events “clustering” 18%

Independent confirmation ?

ANTARES ICRC 2015



Expected events:

- Background: 9.5 ± 2.5
- Astrophysical 5.0 ± 1.1

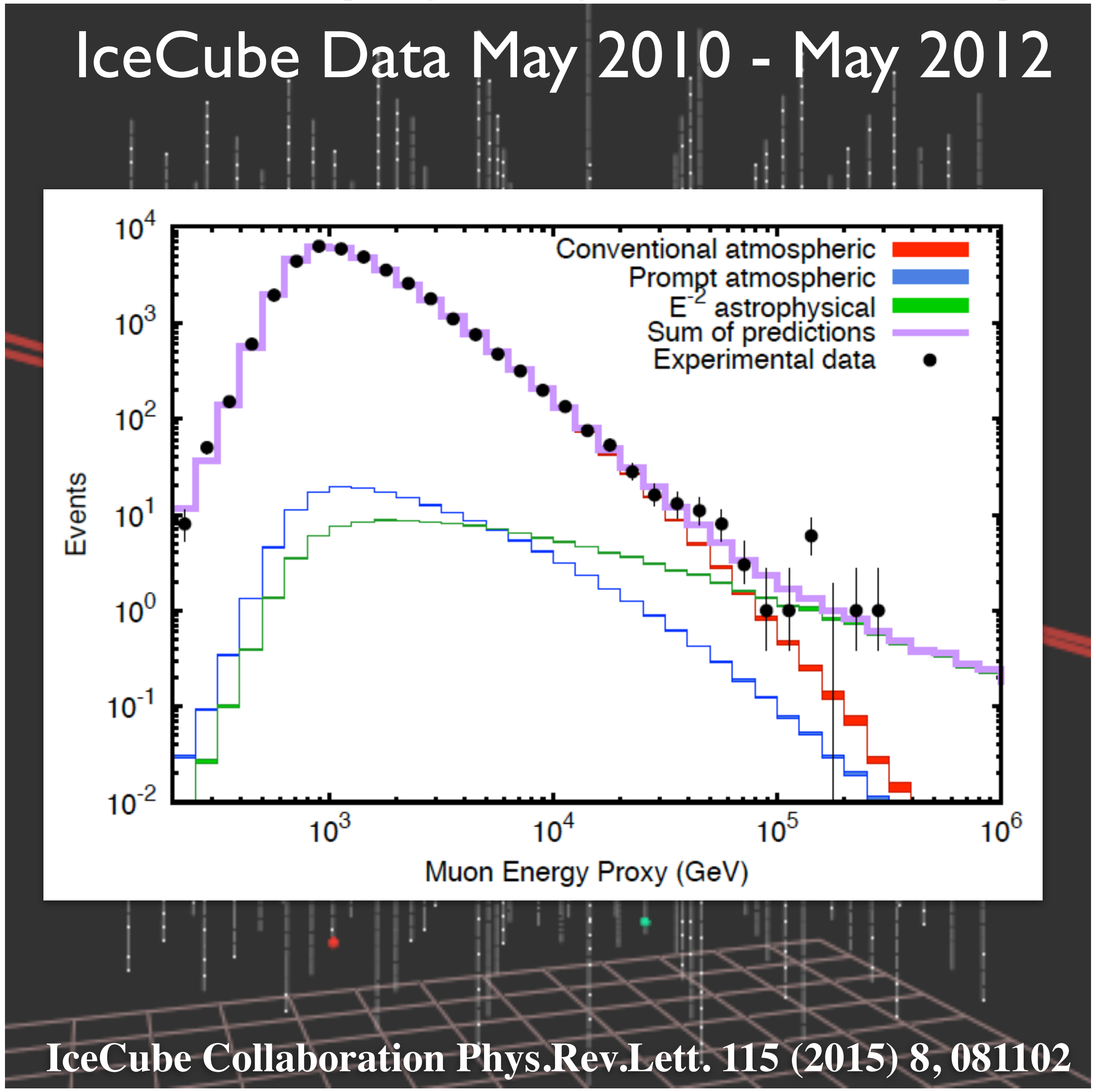
Observed

12 events

Results:

- Consistent with background
- Consistent with IceCube

IceCube up-going muon analysis


IceCube Data May 2010 - May 2012

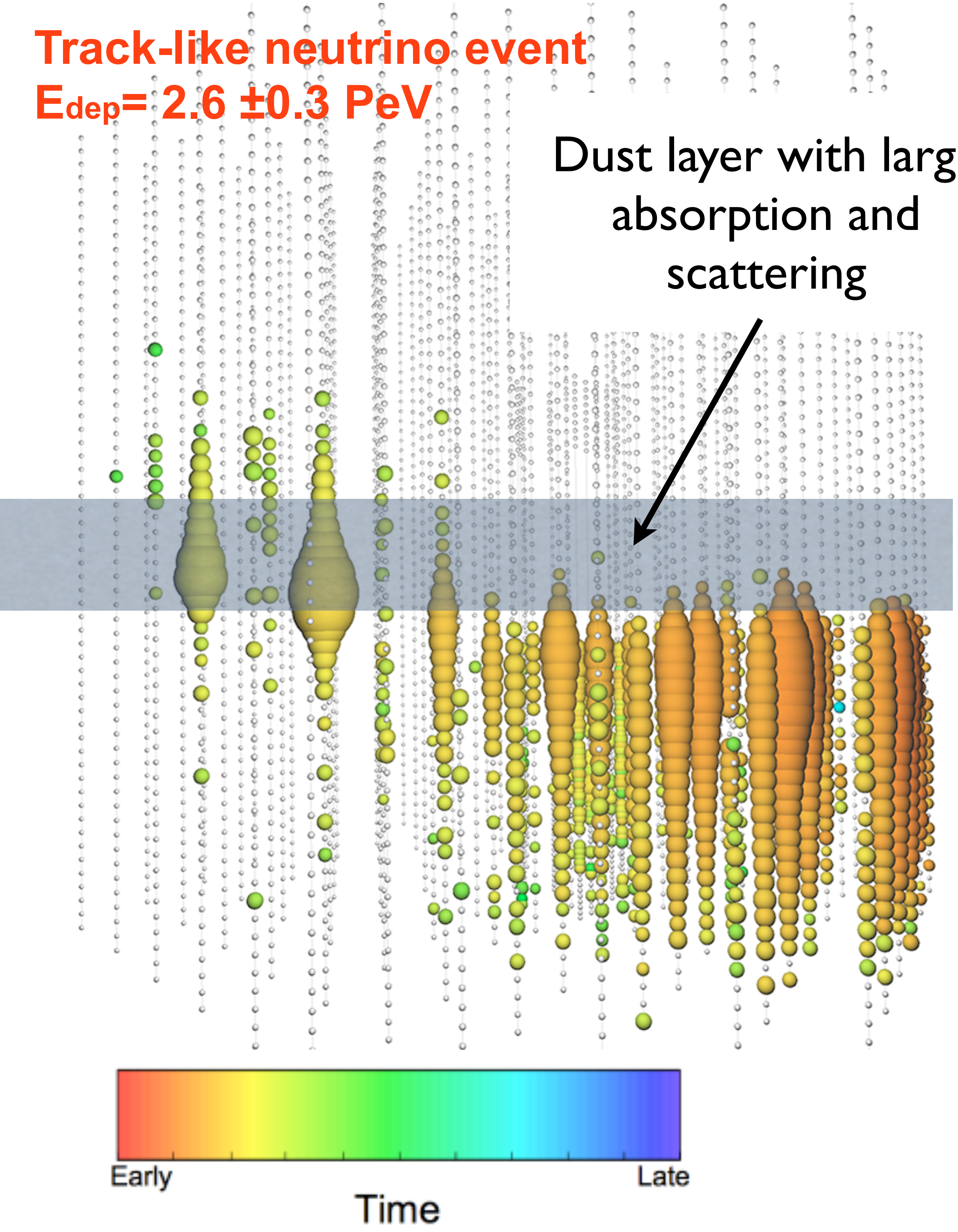
IceCube Collaboration Phys.Rev.Lett. 115 (2015) 8, 081102

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

Best fit astrophysical flux consistent with High-Energy Starting Events

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

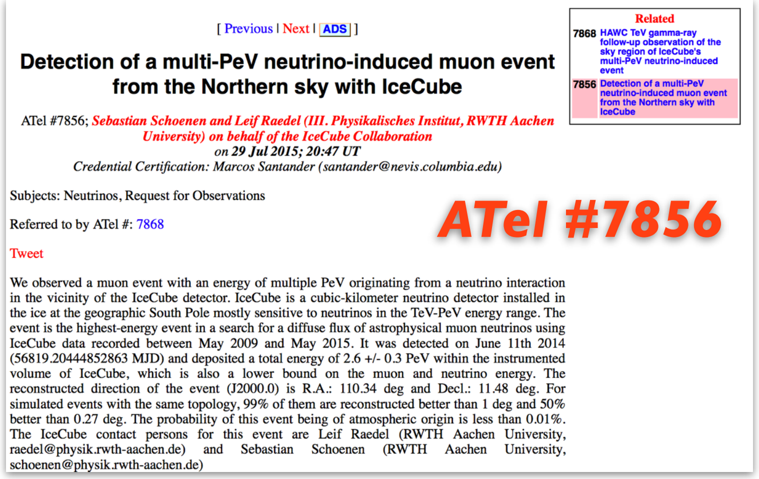
Multi-PeV Track Event



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

Dust layer with large absorption and scattering

- Up-going (i.e. not a CR muon)
- Deposited energy: 2.6±0.3 PeV
  - Lower bound on the neutrino energy
  - Neutrino energy significantly higher
- Date: June 11, 2014
- Direction: 11.48° dec / 110.34° RA
- Angular resolution <1°



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

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

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

Subjects: Neutrinos, Request for Observations

Referred to by ATel #: 7868

Tweet

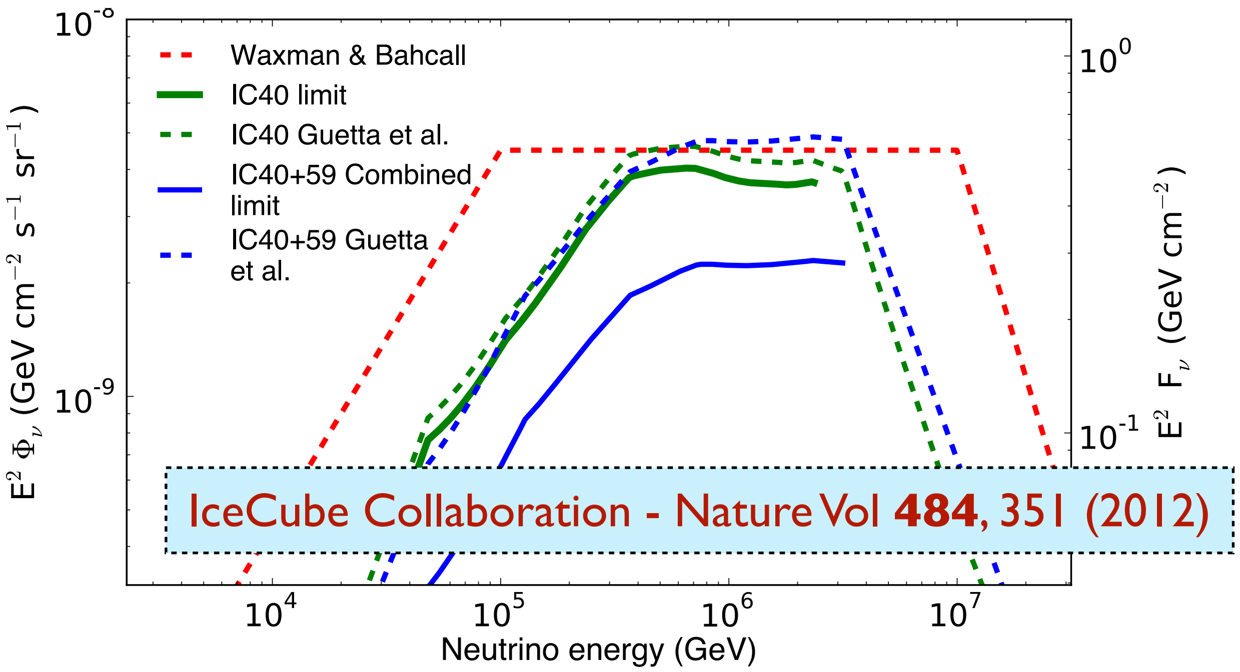
We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event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

ATel #7856

Origin of the high-energy neutrinos ?

Extra Galactic

Gamma Ray Burst



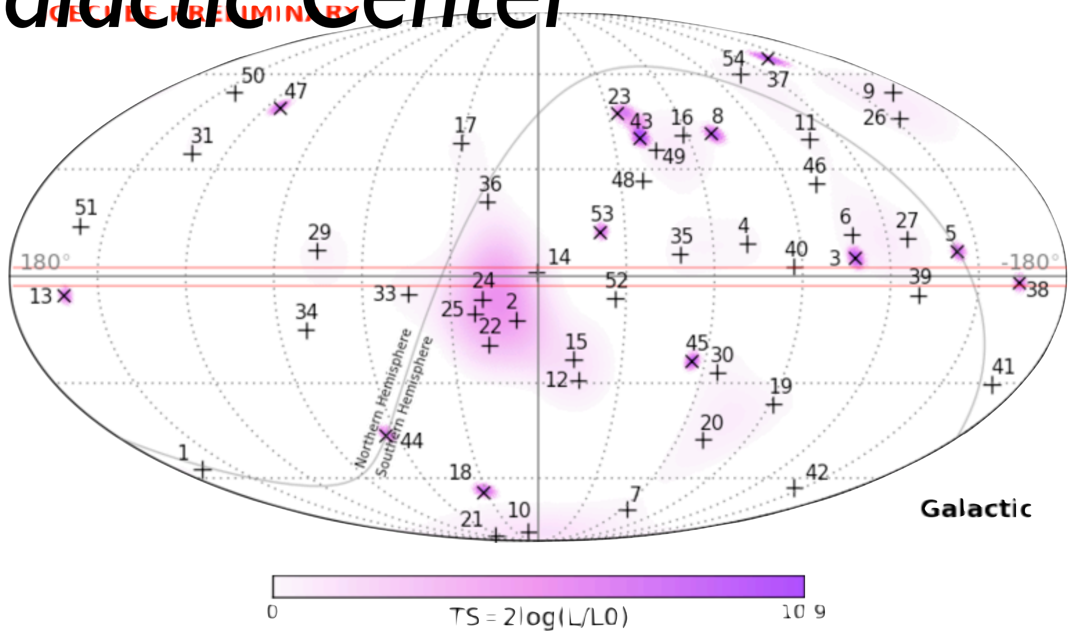
IceCube Collaboration - Nature Vol **484**, 351 (2012)

Active Galactic Nuclei / Starburst Galaxies

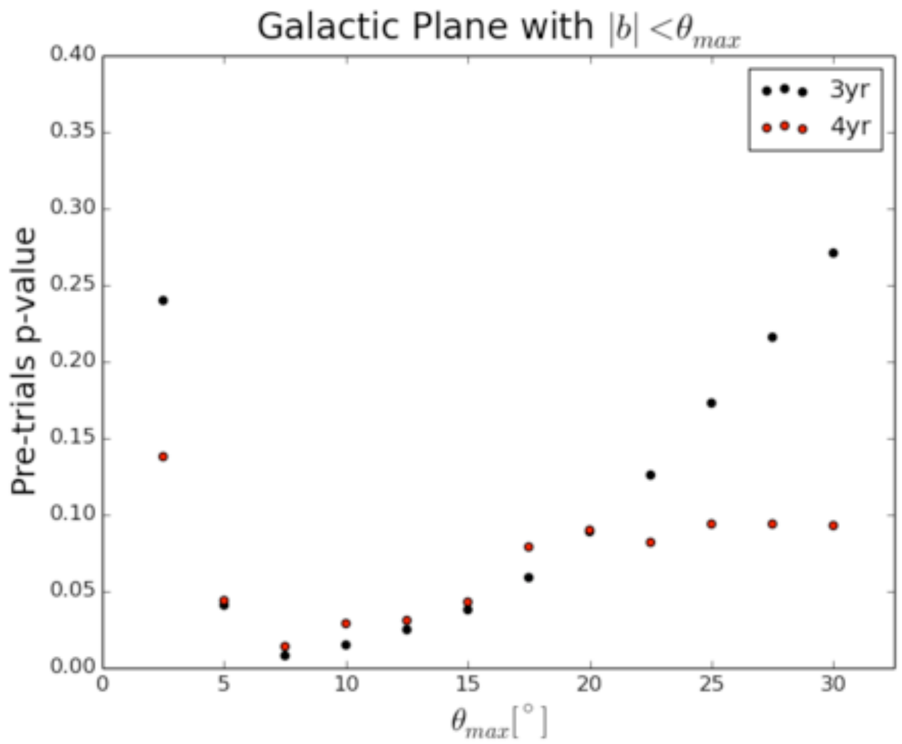
Starburst	M82	148.97	69.68	0.07	0.15
Radio Galaxies	NGC 1275	49.95	41.51	0.0	–
	Cyg A	299.87	40.73	0.9	0.03
	3C 123.0	69.27	29.67	0.0	–
	M87	187.71	12.39	0.0	–
	Cen A	201.37	-43.02	0.03	0.49

Galactic

Galactic Center



Galactic Plane

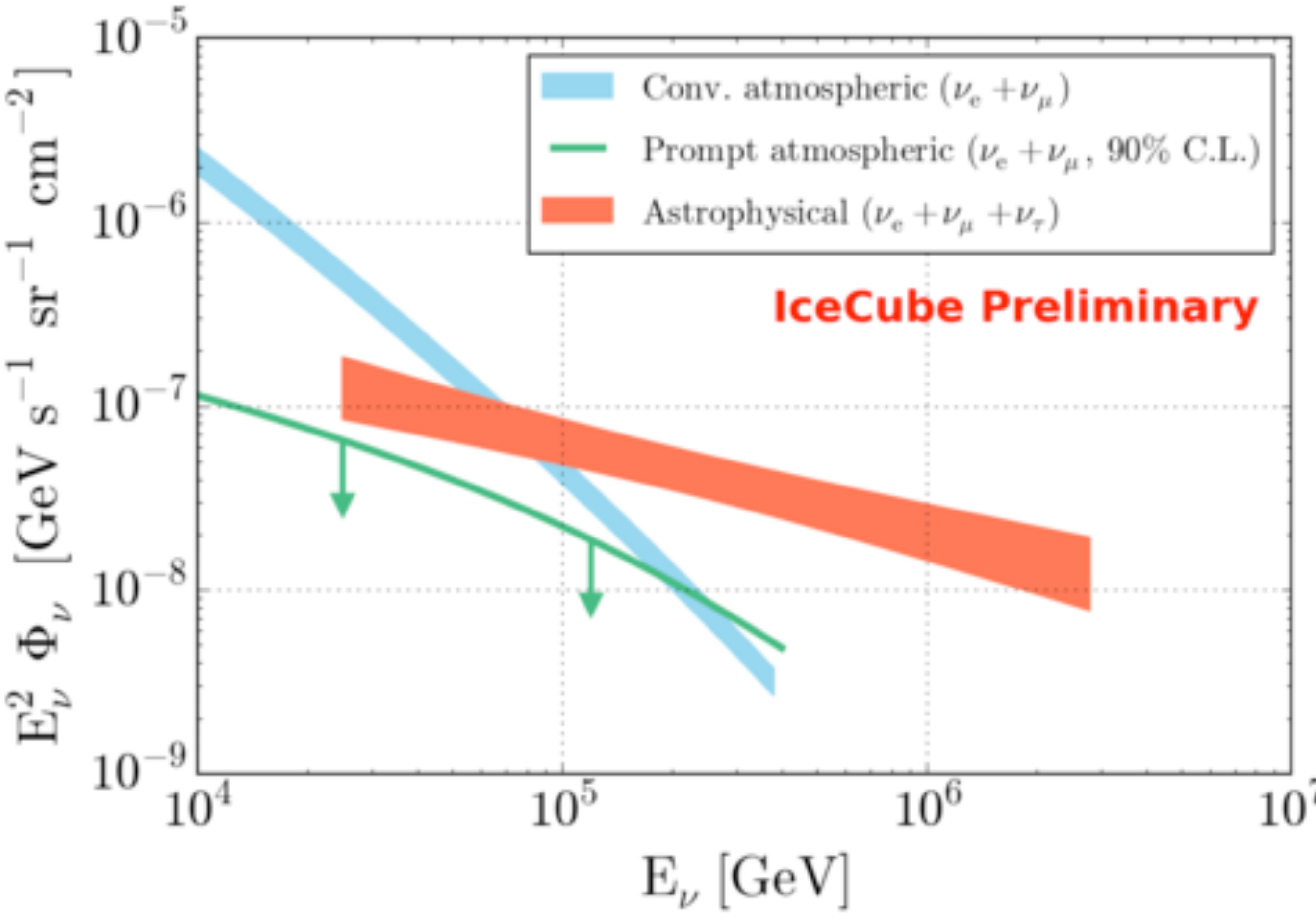


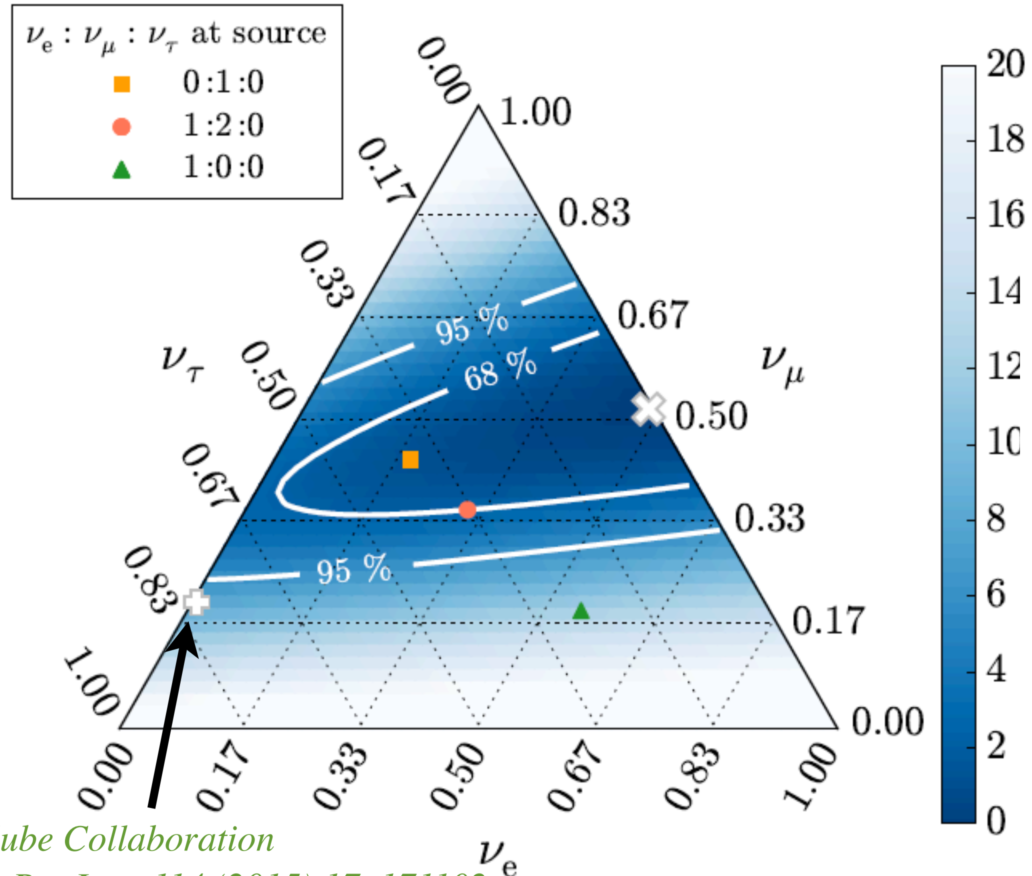
IceCube Collaboration Astrophys.J. 809 (2015) 1, 98

Global fit

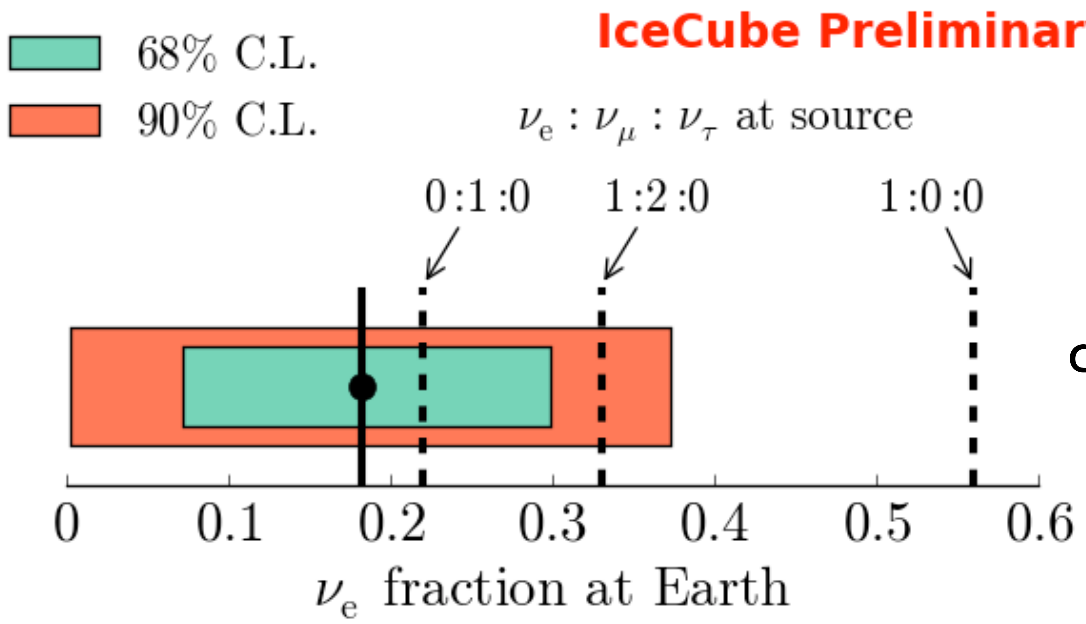
- Global fit of several IceCube analyses
  - Variety of selection criteria for both shower-like and track-like events
  - Data are fit to three observables
    - Energy, zenith angle, event topology

1:2:0 pion-decay
0:1:0 muon-damped
1:0:0 neutron-beam





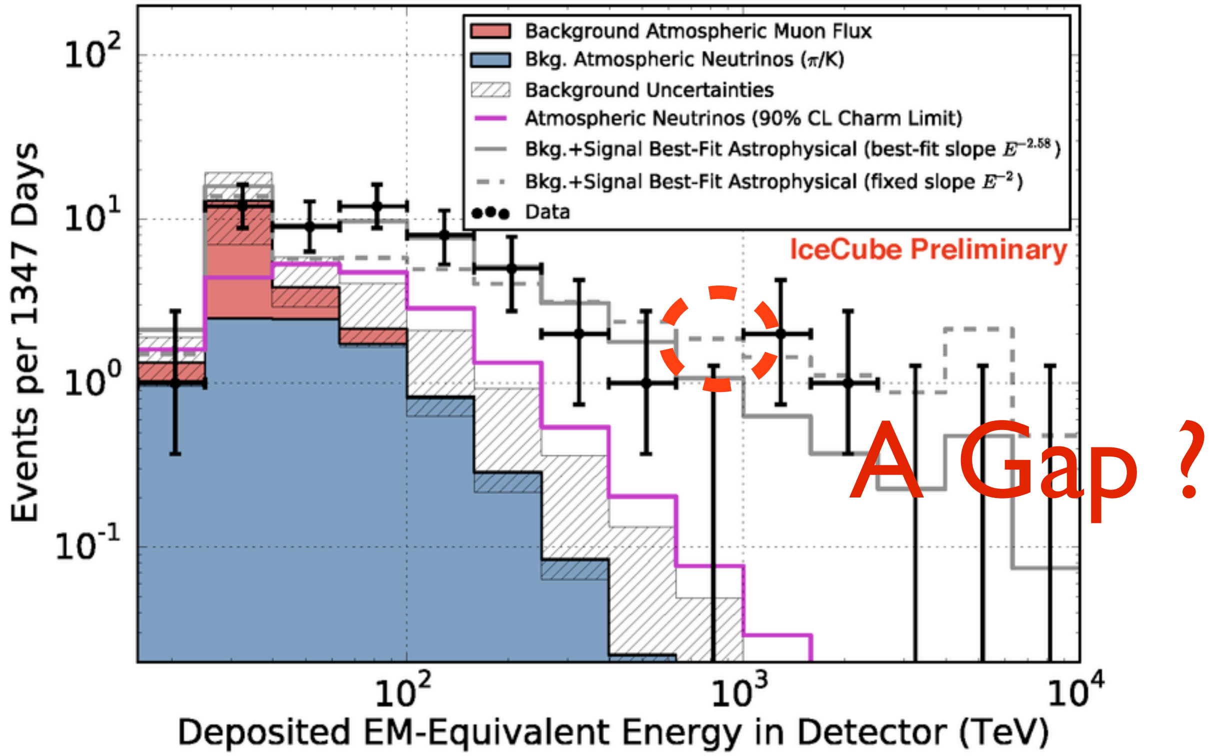
IceCube Collaboration Phys.Rev.Lett. 114 (2015) 17, 171102



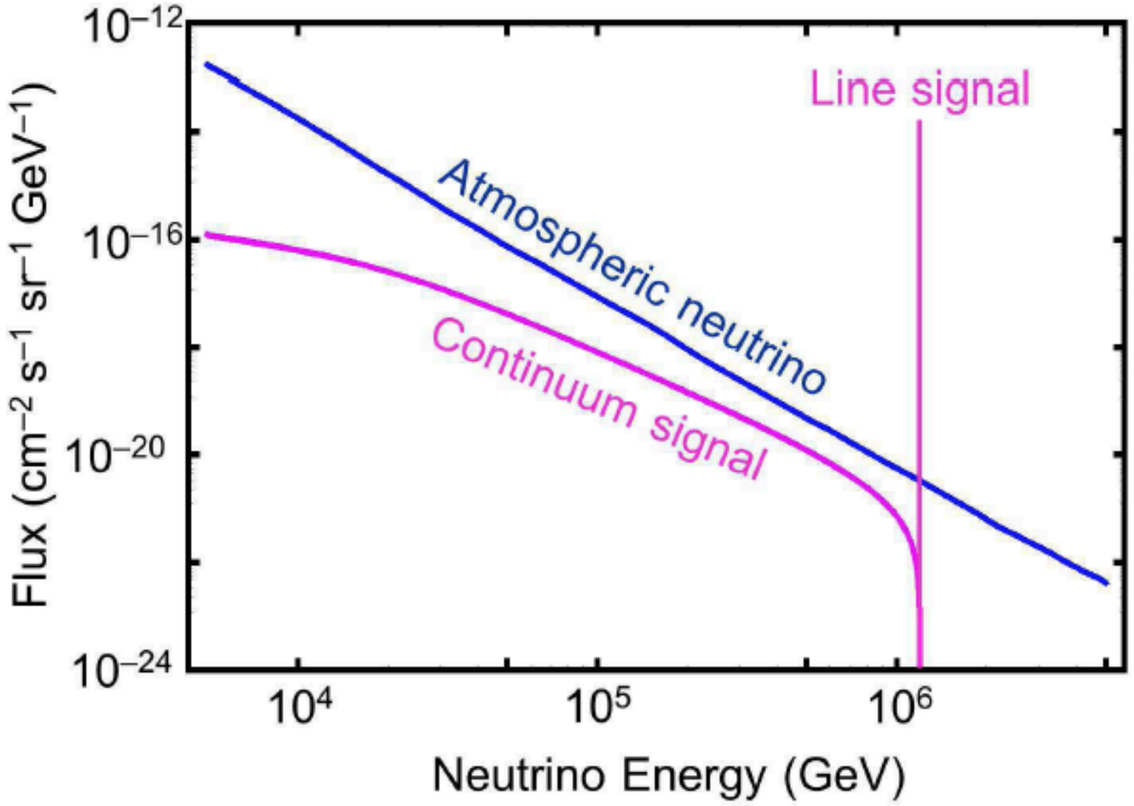
neutron-decay dominated source rejected at 3.6σ

Heavy Dark Matter Decay

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

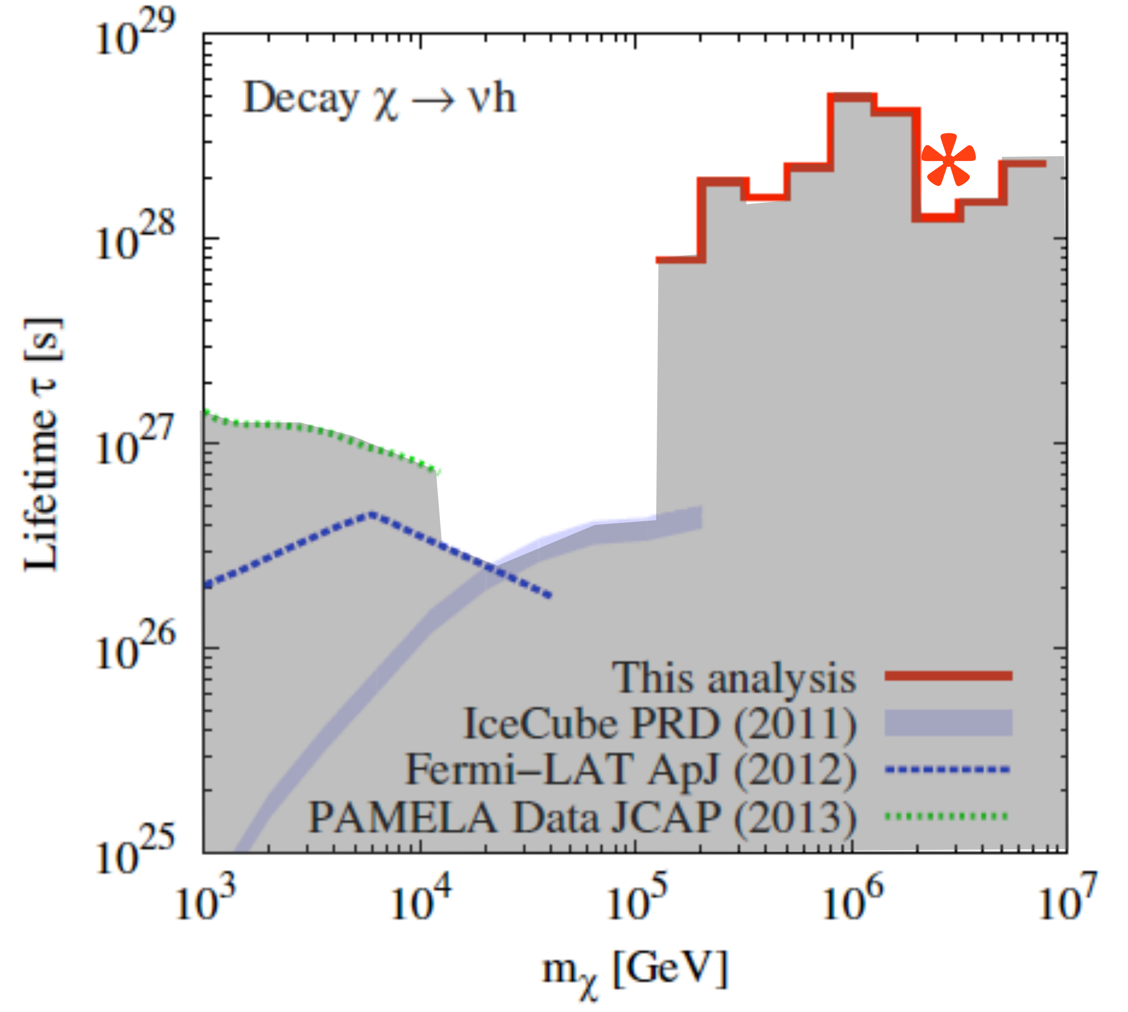


A Gap ?



Bound on lifetime $\sim 10^{28}$s

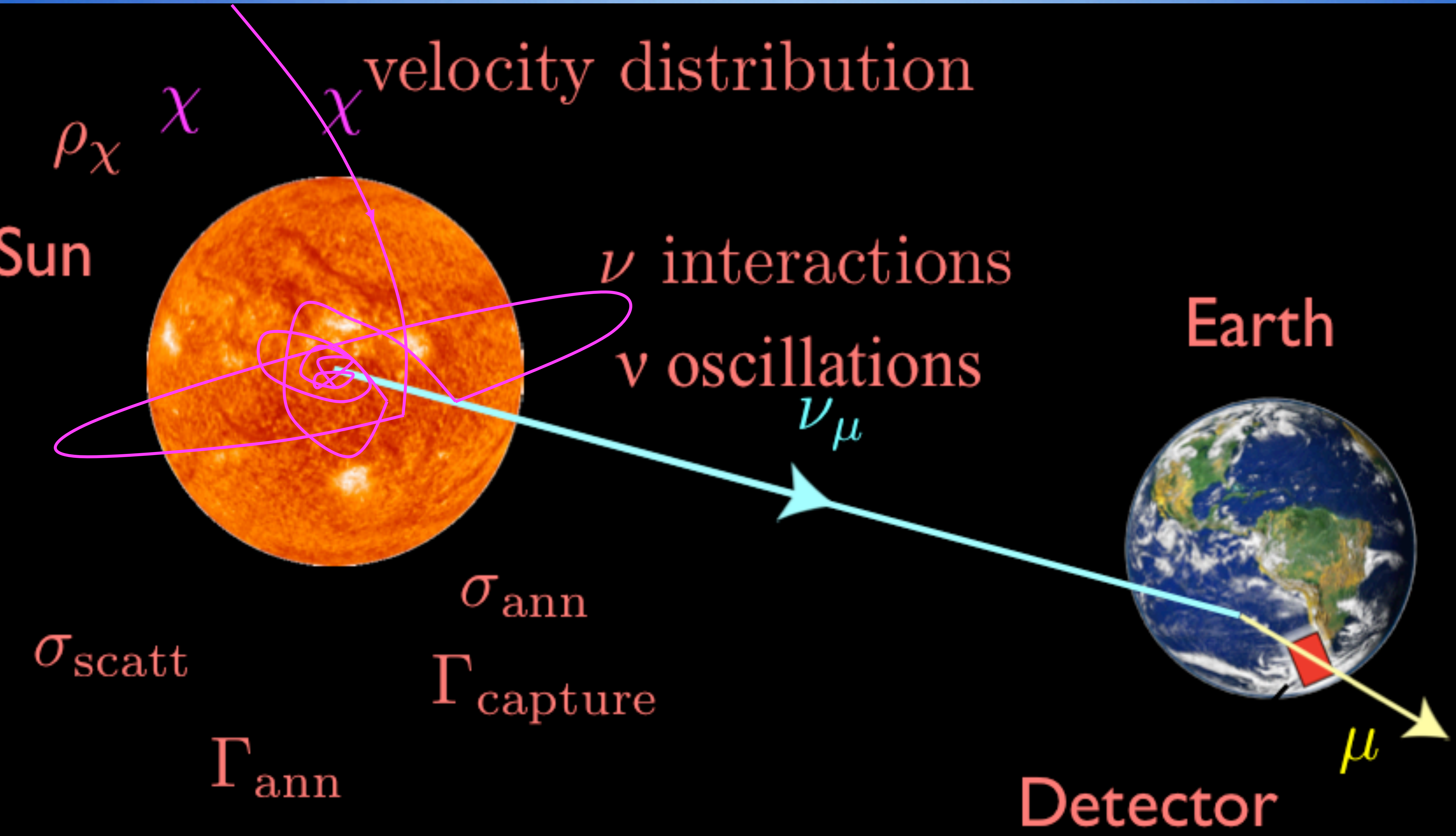
Rott, Kohri, Park PHYS. REV. D 92, 023529 (2015)



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

Solar WIMP Searches
WIMP-Nucleon Scattering

Solar WIMPs



χ χ velocity distribution

ρ_χ

Sun

ν interactions

ν oscillations

Earth

ν_μ

$\sigma_{\rm ann}$

$\sigma_{\rm scatt}$

$\Gamma_{\rm capture}$

$\Gamma_{\rm ann}$

μ

Detector

Freese '86

Krauss, Srednicki & Wilczek '86

Gaisser, Steigman & Tilav '86

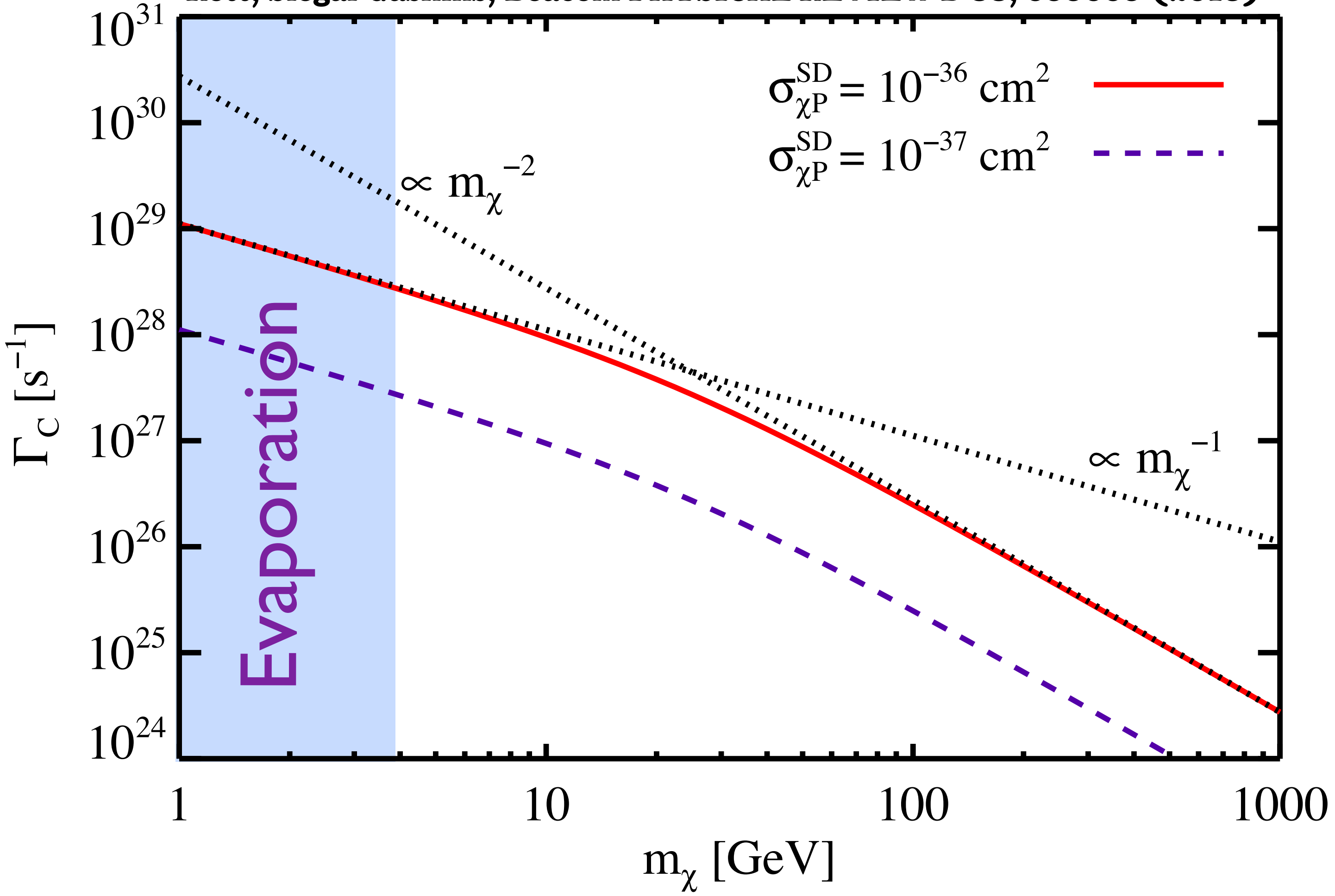
Silk, Olive and Srednicki '85

Gaisser, Steigman & Tilav '86

Solar WIMP 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

Rott, Siegal-Gaskins, Beacom PHYSICAL REVIEW D 88, 055005 (2013)



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

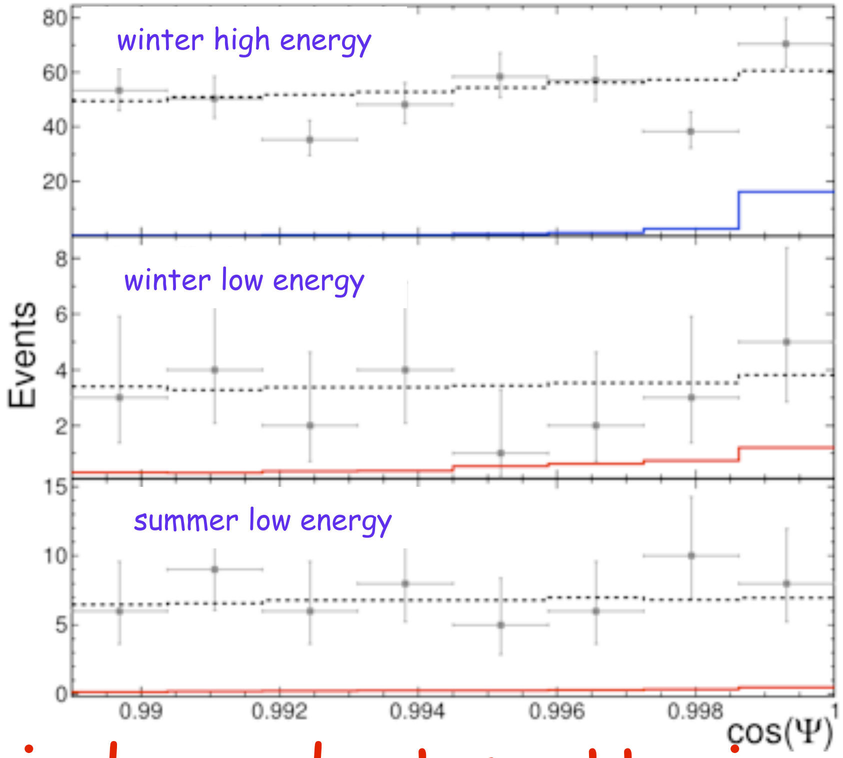
m_A - is the target mass

IceCube Solar WIMP Limits

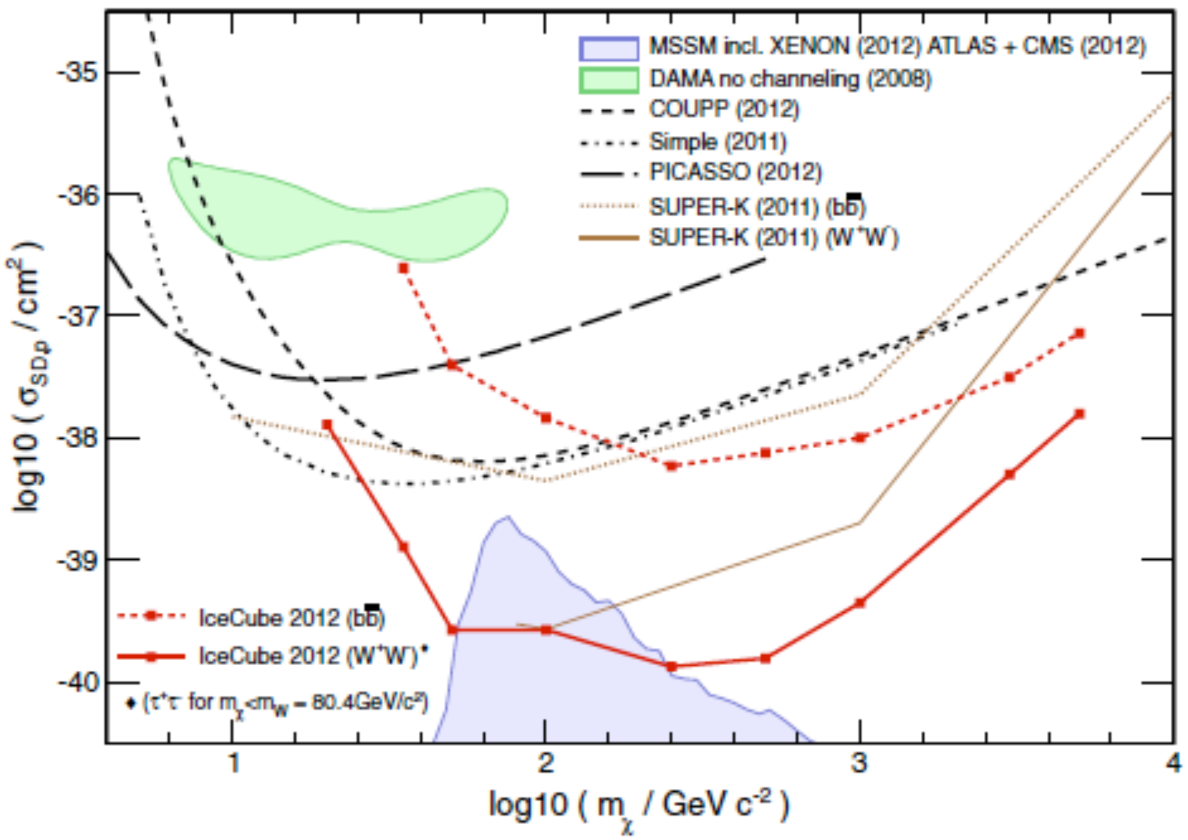
PRL 110, 131302 (2013)

- IceCube 79-strings configuration (partially completed DeepCore)
  - 318 days (May 2010 - May 2011)
- Search for an excess of events from the direction of the Sun
  - use track events for better pointing
- Separate summer and winter analysis
  - use outer detector to veto down-going muons for summer analysis

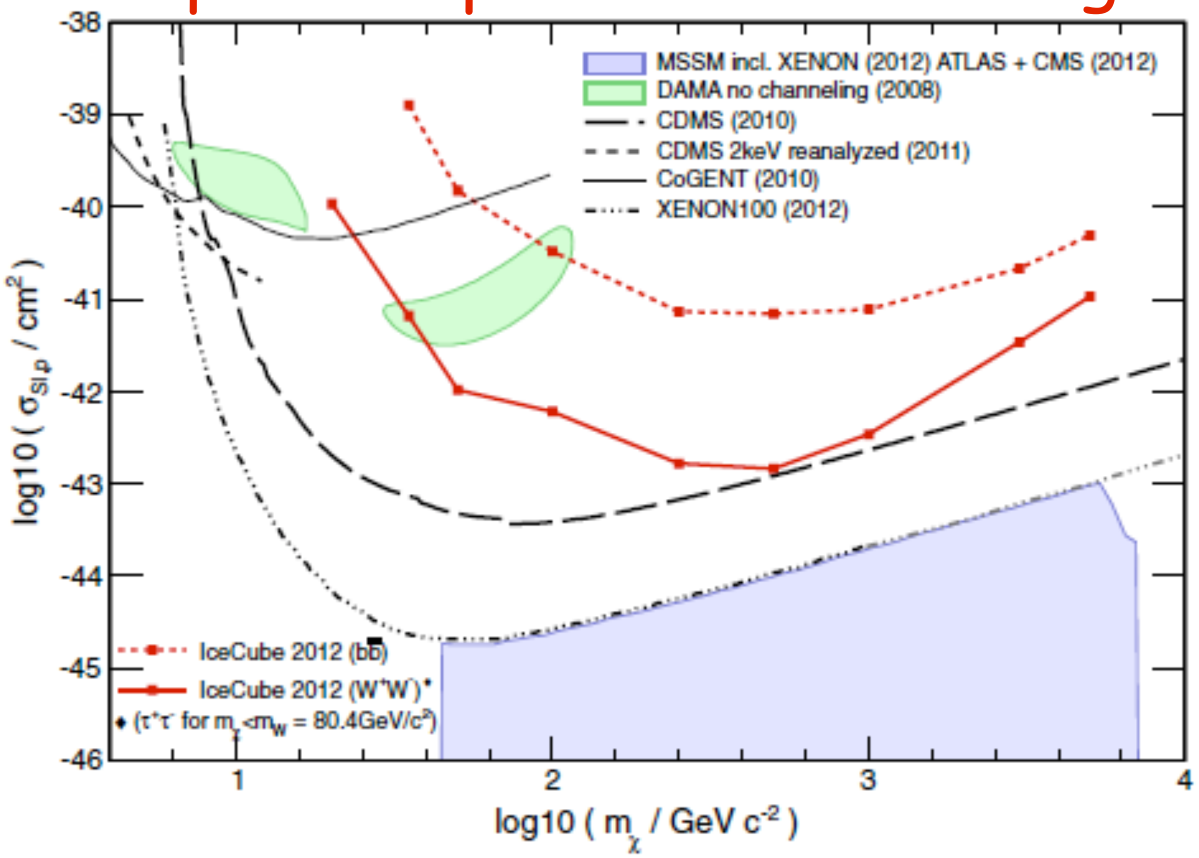
Observed events



Spin-dependent scattering

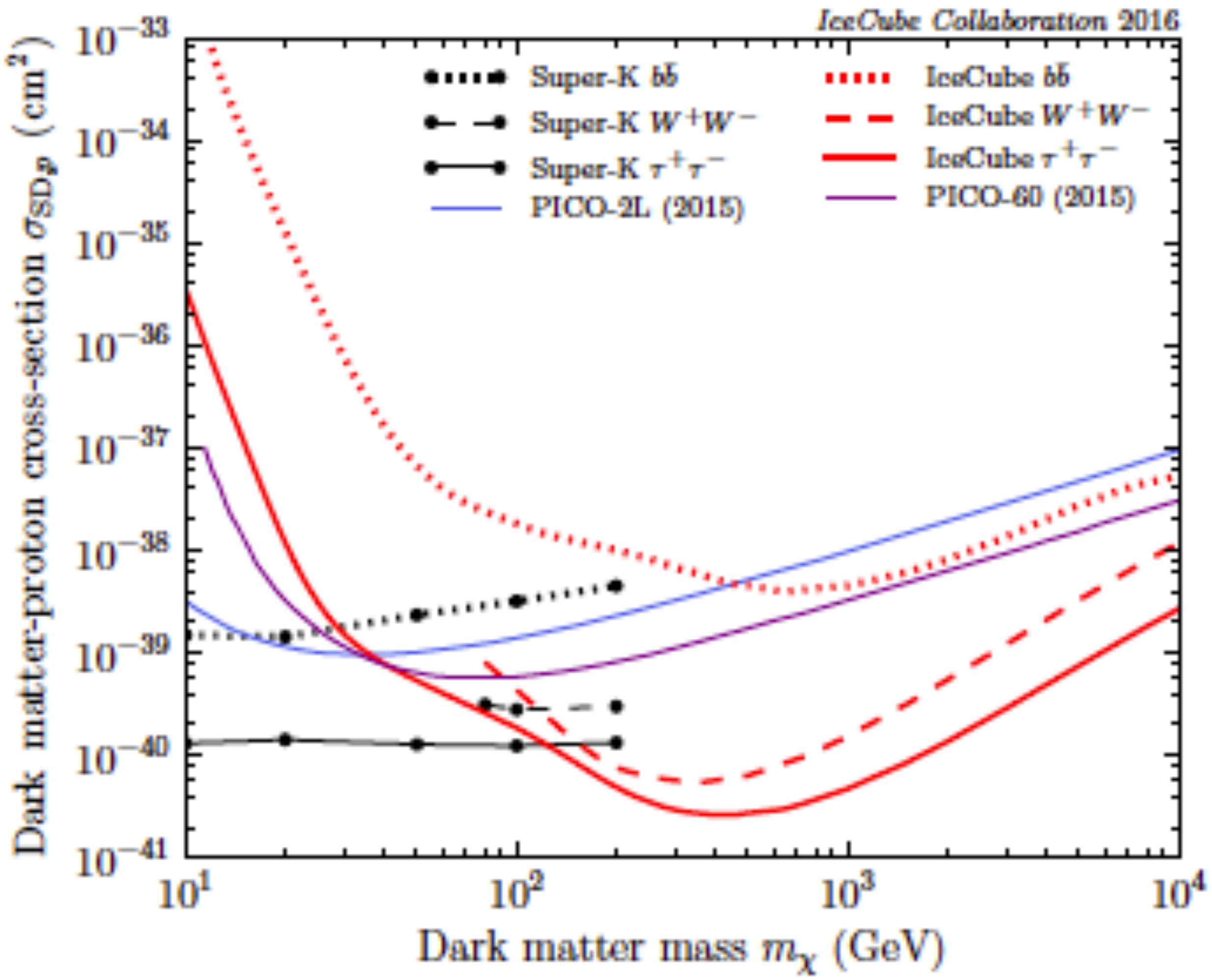


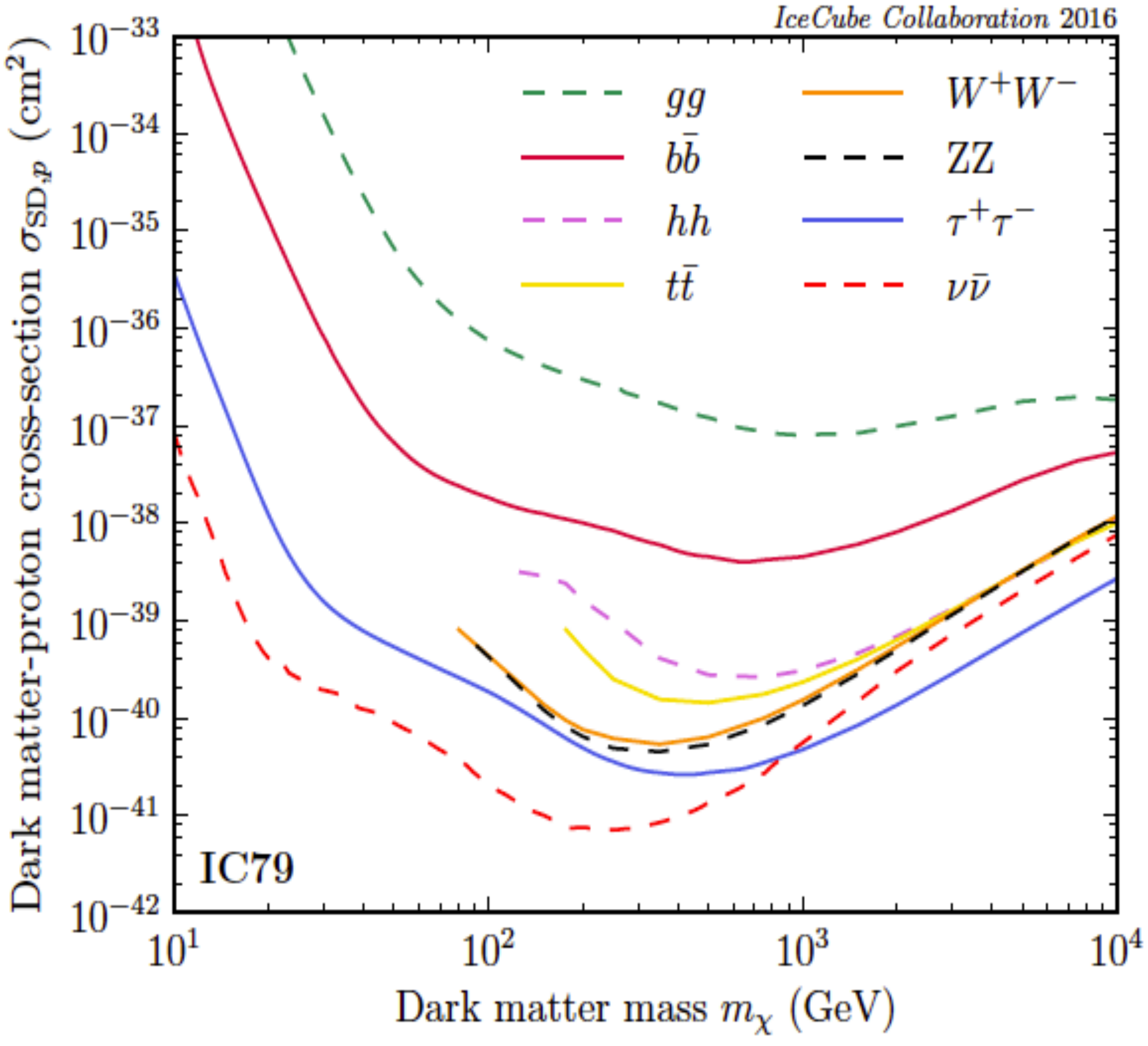
Spin-independent scattering

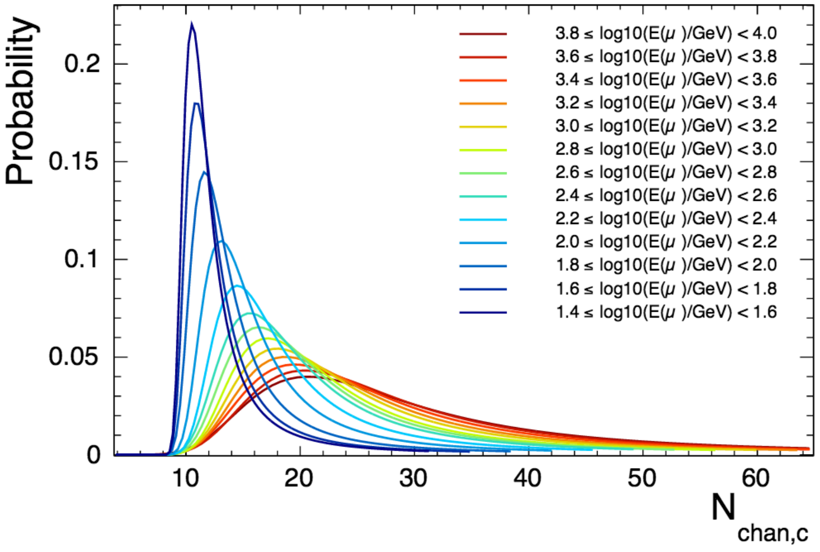


Improved Solar WIMP Bounds

http://arxiv.org/pdf/1601.00653.pdf





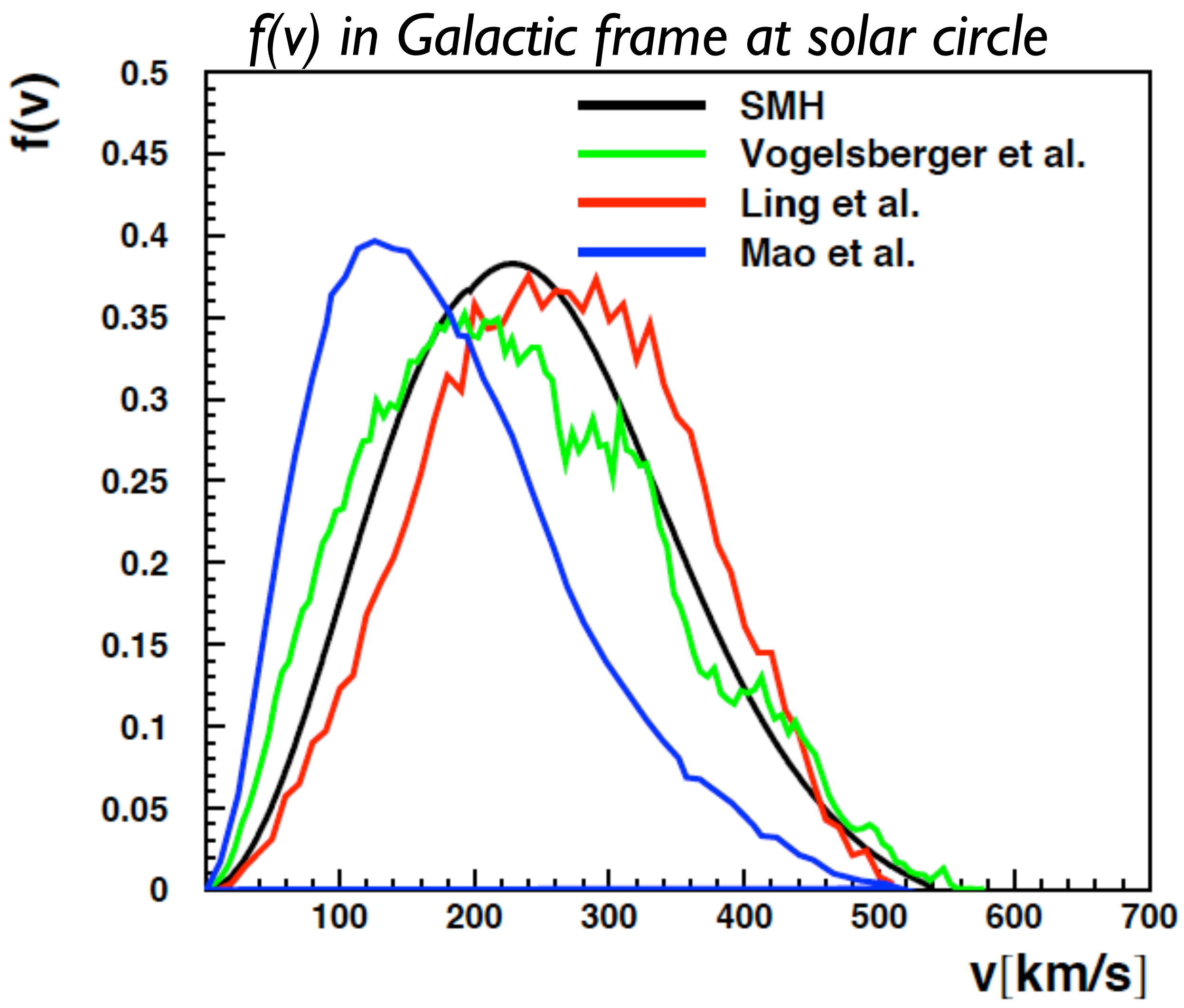


- Including energy in the likelihood

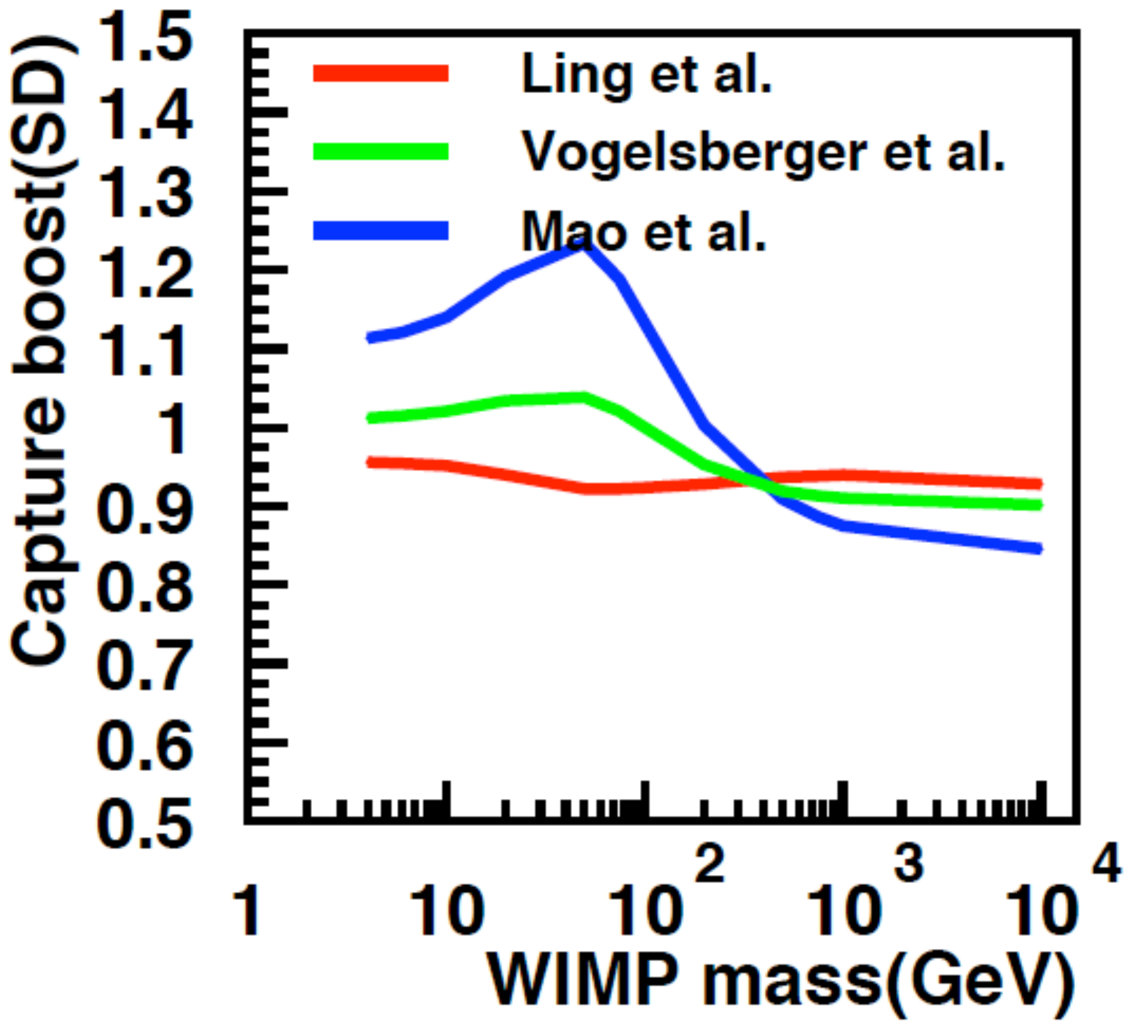
Impact of velocity distribution

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

Choi, Rott, Itow JCAP 1405 (2014) 049



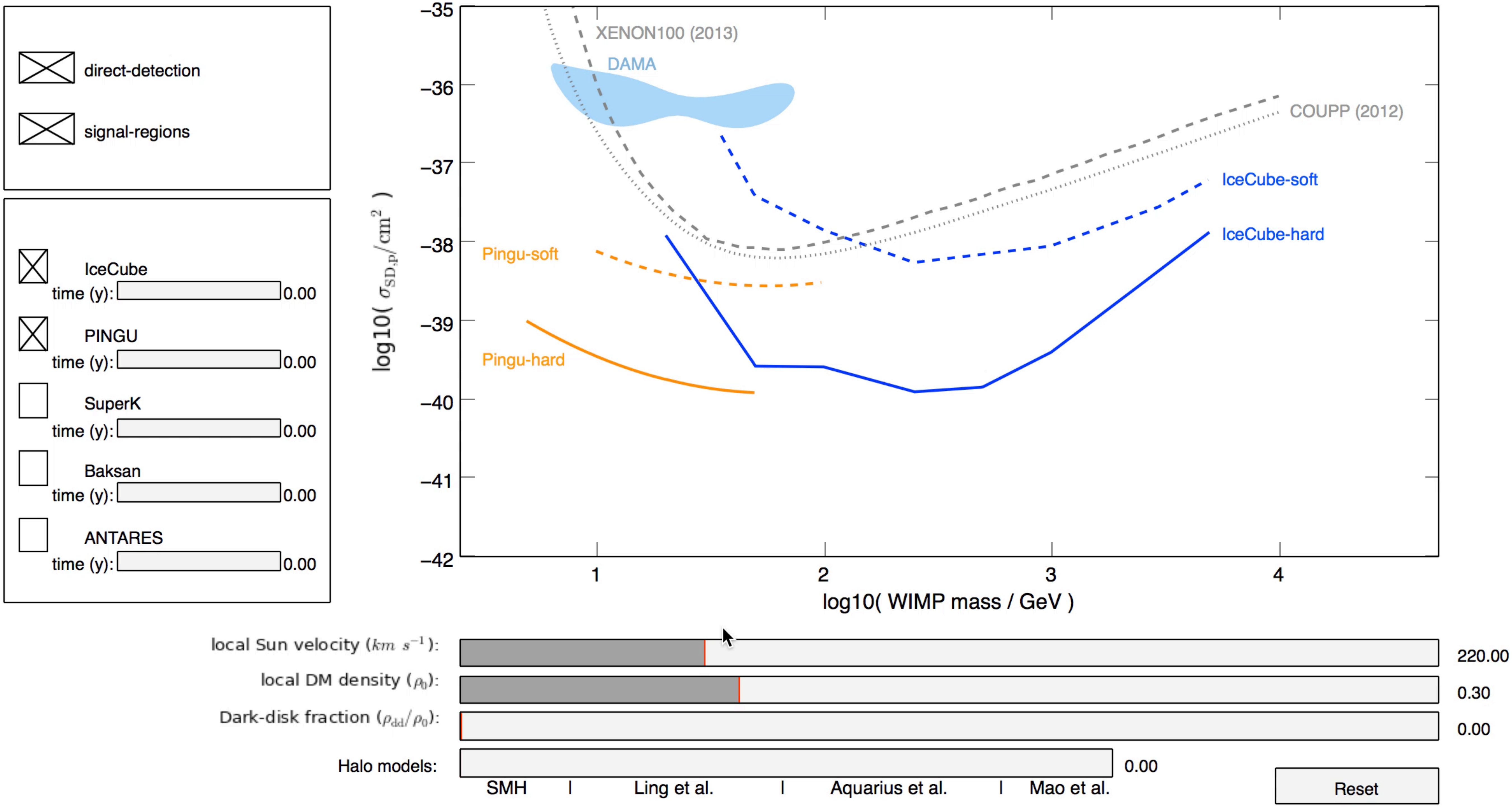
f(v) in Galactic frame at solar circle



- 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

interactive tool to study impact of astrophysical parameters



☒ direct-detection

☒ signal-regions

☒ IceCube
time (y): 0.00

☒ PINGU
time (y): 0.00

☐ SuperK
time (y): 0.00

☐ Baksan
time (y): 0.00

☐ ANTARES
time (y): 0.00

local Sun velocity ($km\ s^{-1}$): 220.00

local DM density (ρ_0): 0.30

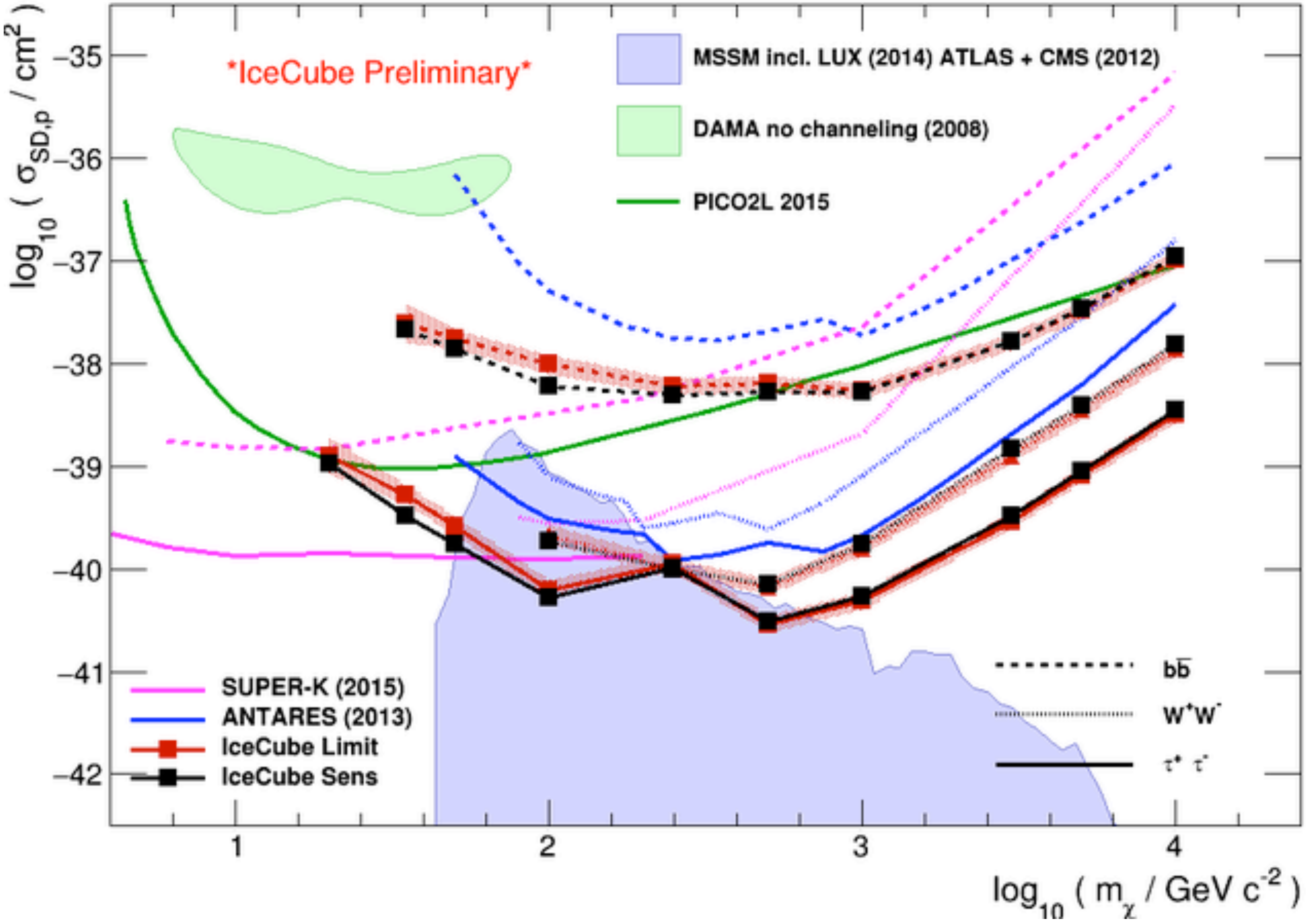
Dark-disk fraction (ρ_{dd}/ρ_0): 0.00

Halo models: 0.00
SMH | Ling et al. | Aquarius et al. | Mao et al.

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

Solar WIMPs

IceCubeColl., PoS(ICRC2015) 1099



Neutrino bounds extremely competitive with Dark Matter direct detection

&

Can test models beyond the reach of LHC

Low Energy Neutrinos from the Sun

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

Low-Energy Neutrinos from the Sun

Possible annihilation channels:

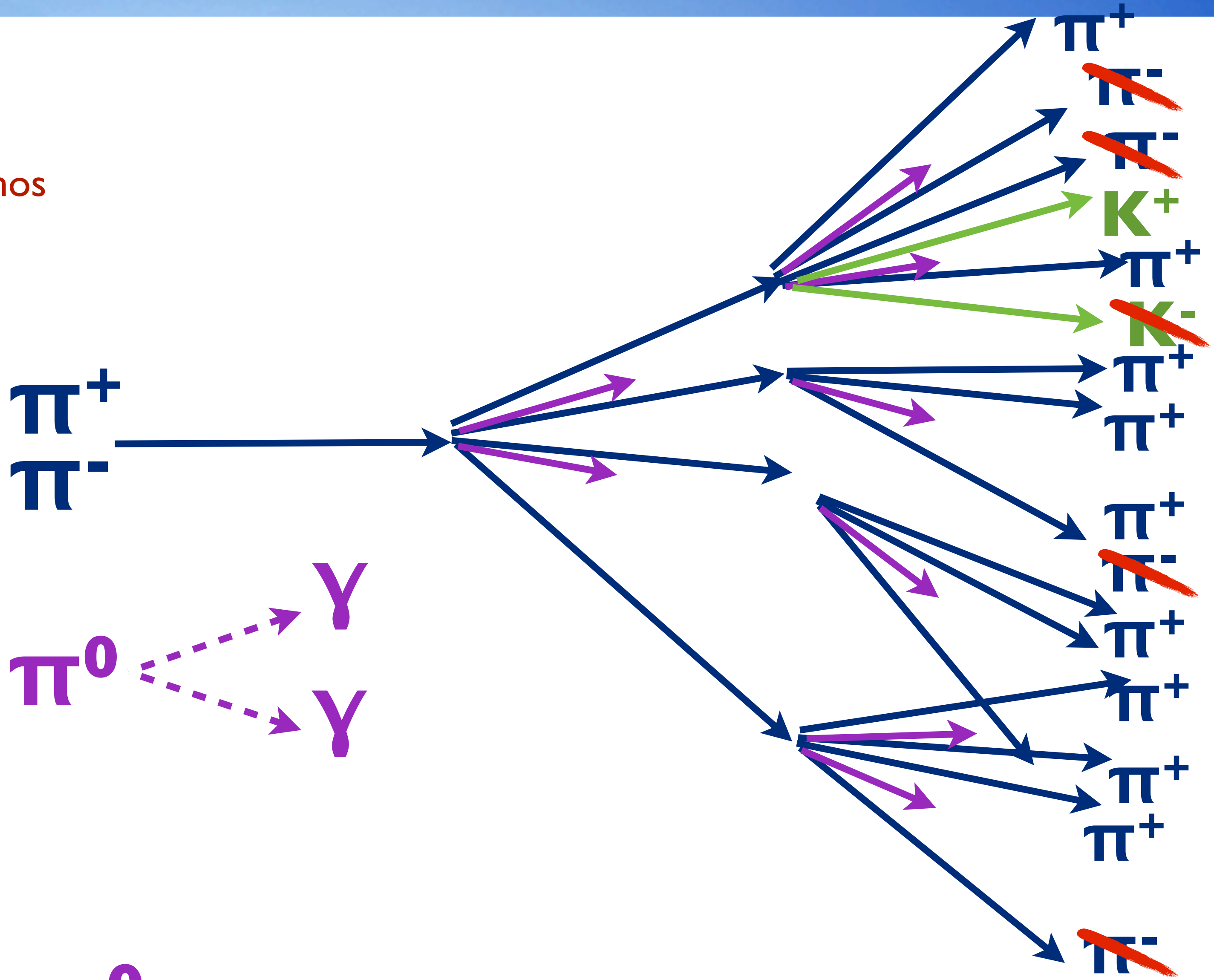
qq,gg,cc,ss,bb,tt,W^+W^-, ZZ, $\tau^+\tau^-$, $\mu^+\mu^-$, $\nu\nu$, e^+e^-,$\gamma\gamma$

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

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

π^0

- Lifetime too short to interact

π^-

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

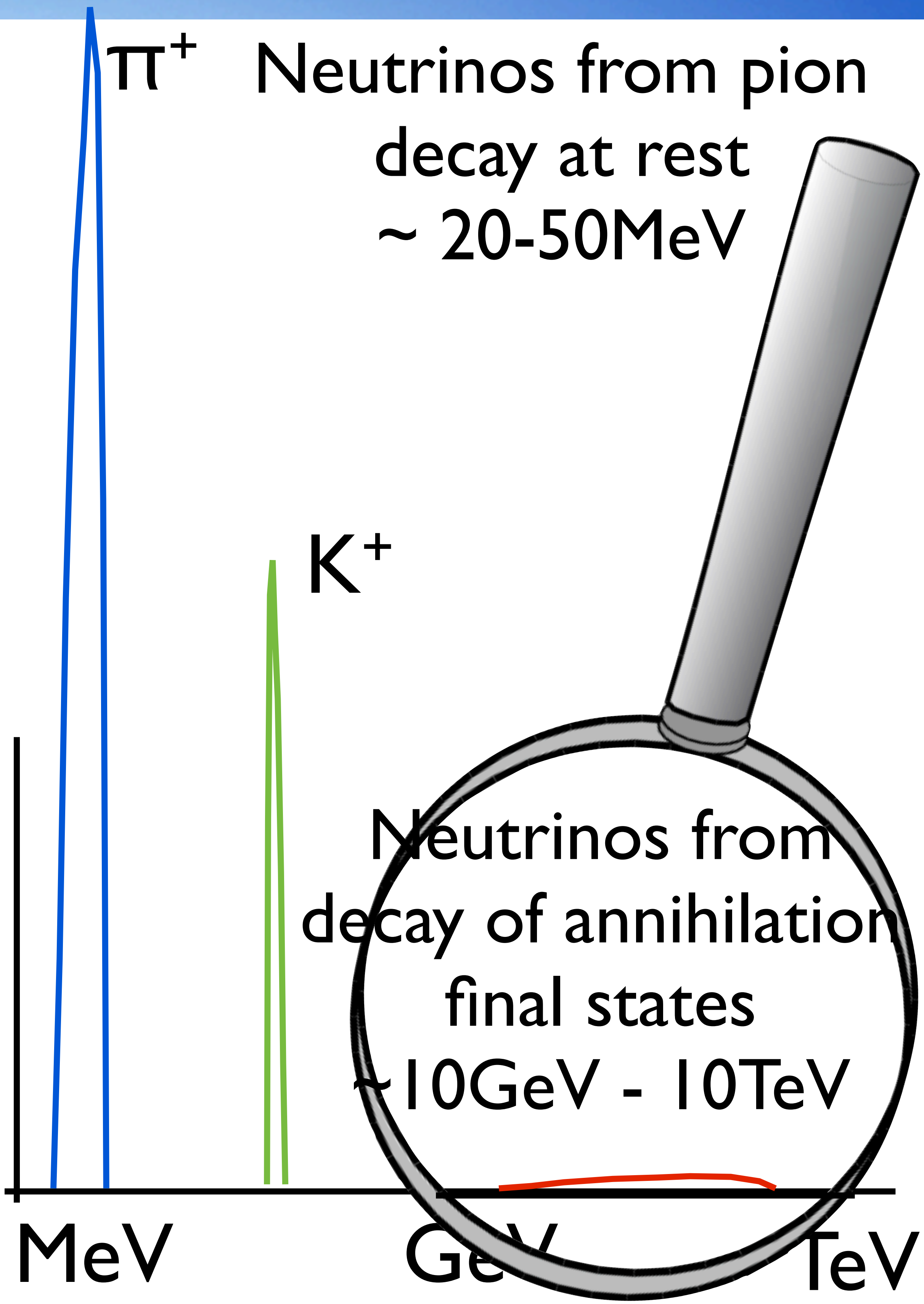
Neutrino signals - Example W-Boson

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

$\longrightarrow qq$ ~67%

Let’s have a closer look at this:

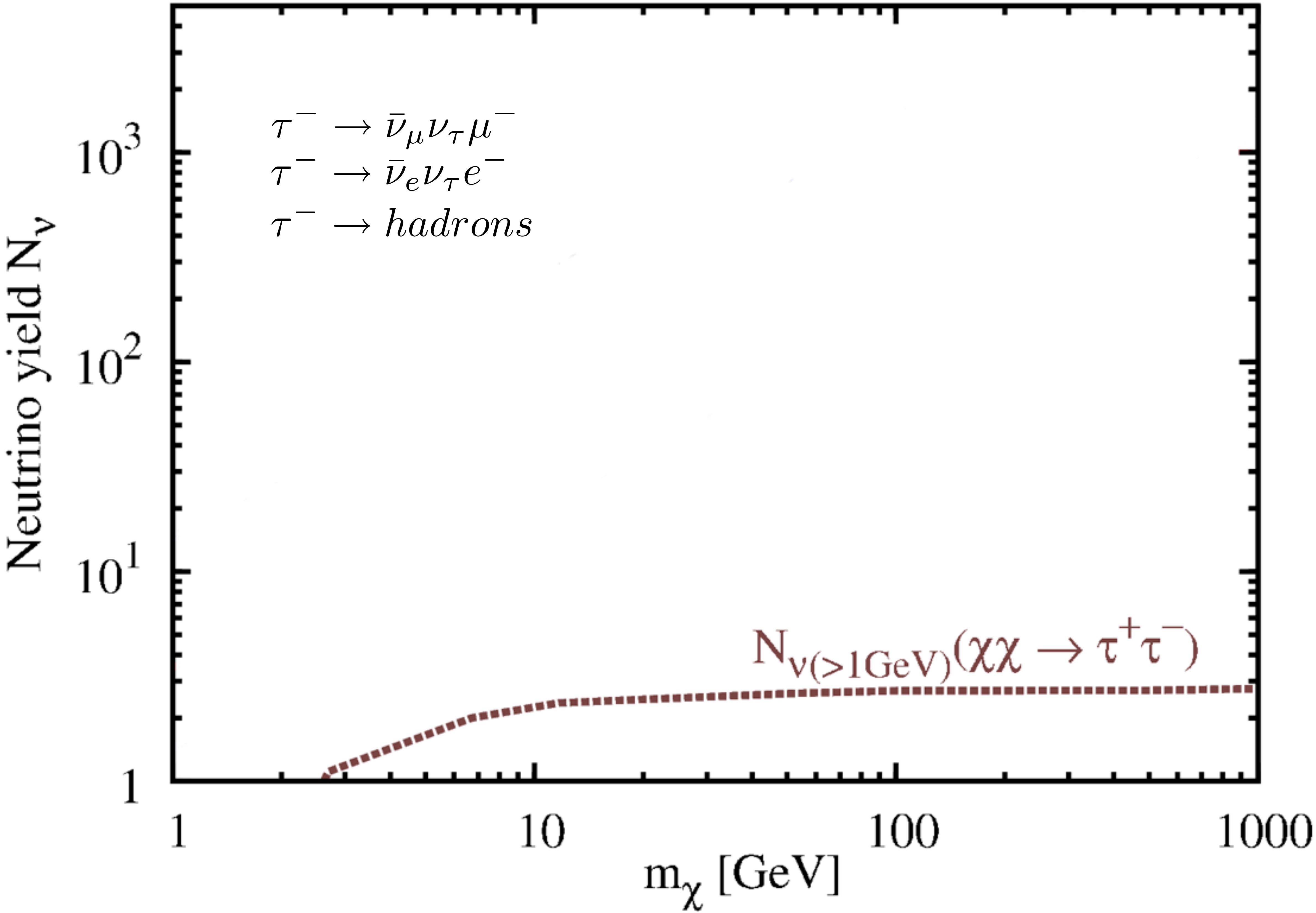
$e^+\nu_e$	1 high energy ν + em shower
$\mu^+\nu_\mu$	1 high energy ν + muon
$\tau^+\nu_\tau$	1 high energy ν + tau decay
qq	hadronic shower



Neutrinos from pion decay at rest ~ 20-50MeV

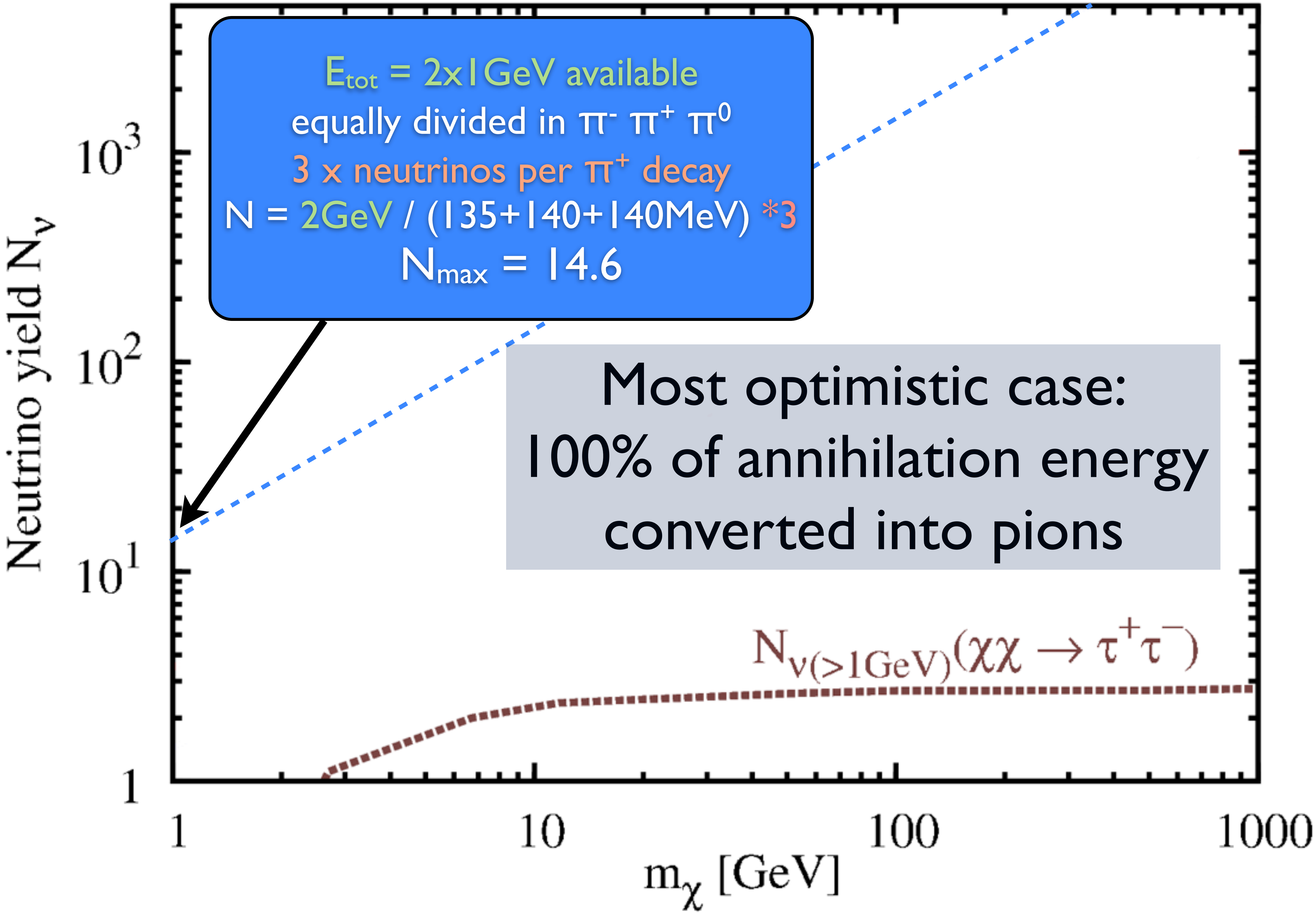
Neutrinos from decay of annihilation final states ~10GeV - 10TeV

What is the Neutrino yield ?



$$\tau^- \rightarrow \bar{\nu}_\mu \nu_\tau \mu^-$$
$$\tau^- \rightarrow \bar{\nu}_e \nu_\tau e^-$$
$$\tau^- \rightarrow hadrons$$

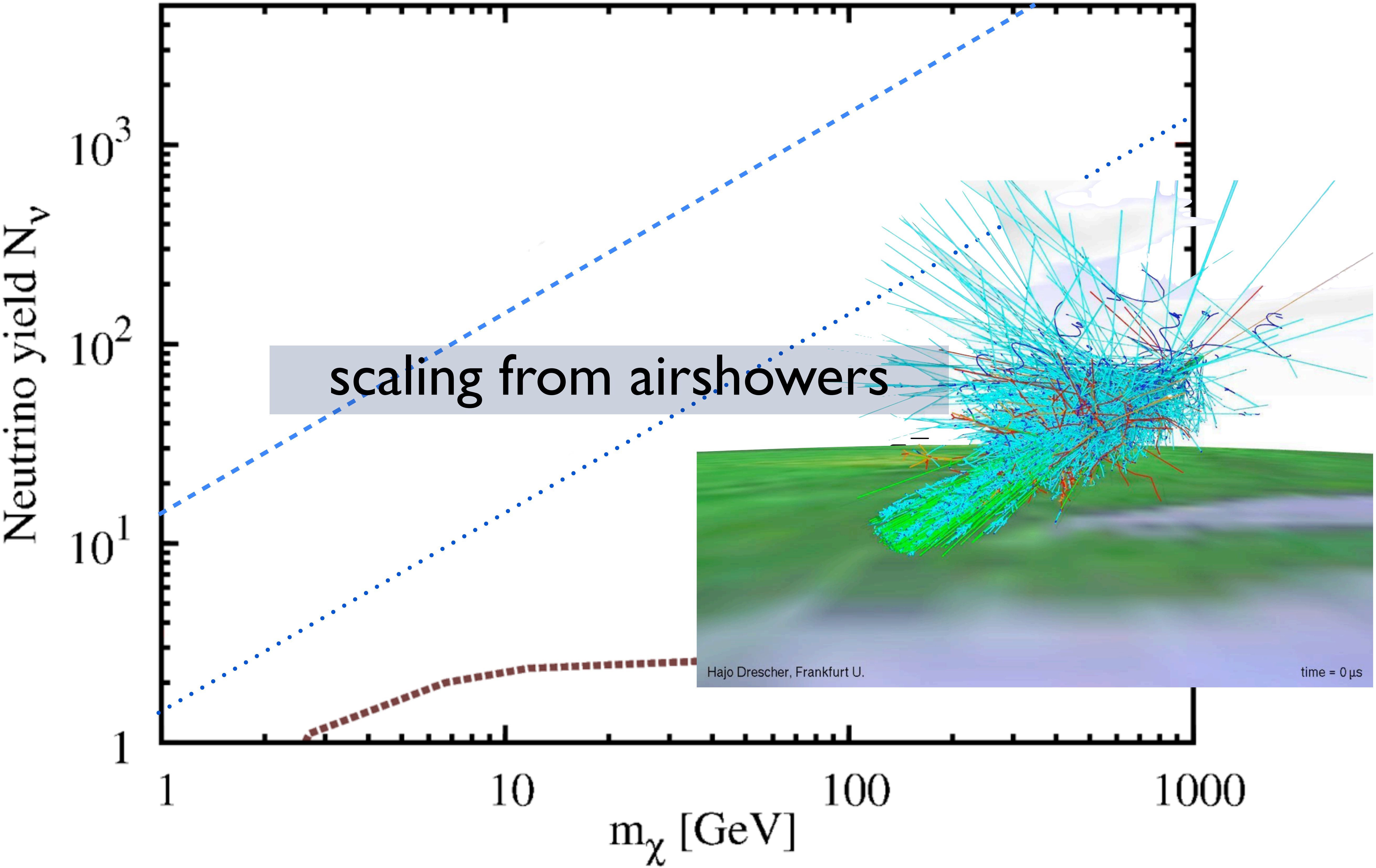
What’s the Neutrino yield ?



E_{tot} = 2x1GeV available
equally divided in $\pi^- \pi^+ \pi^0$
3 x neutrinos per π^+ decay
N = 2GeV / (135+140+140MeV) *3
N_{max} = 14.6

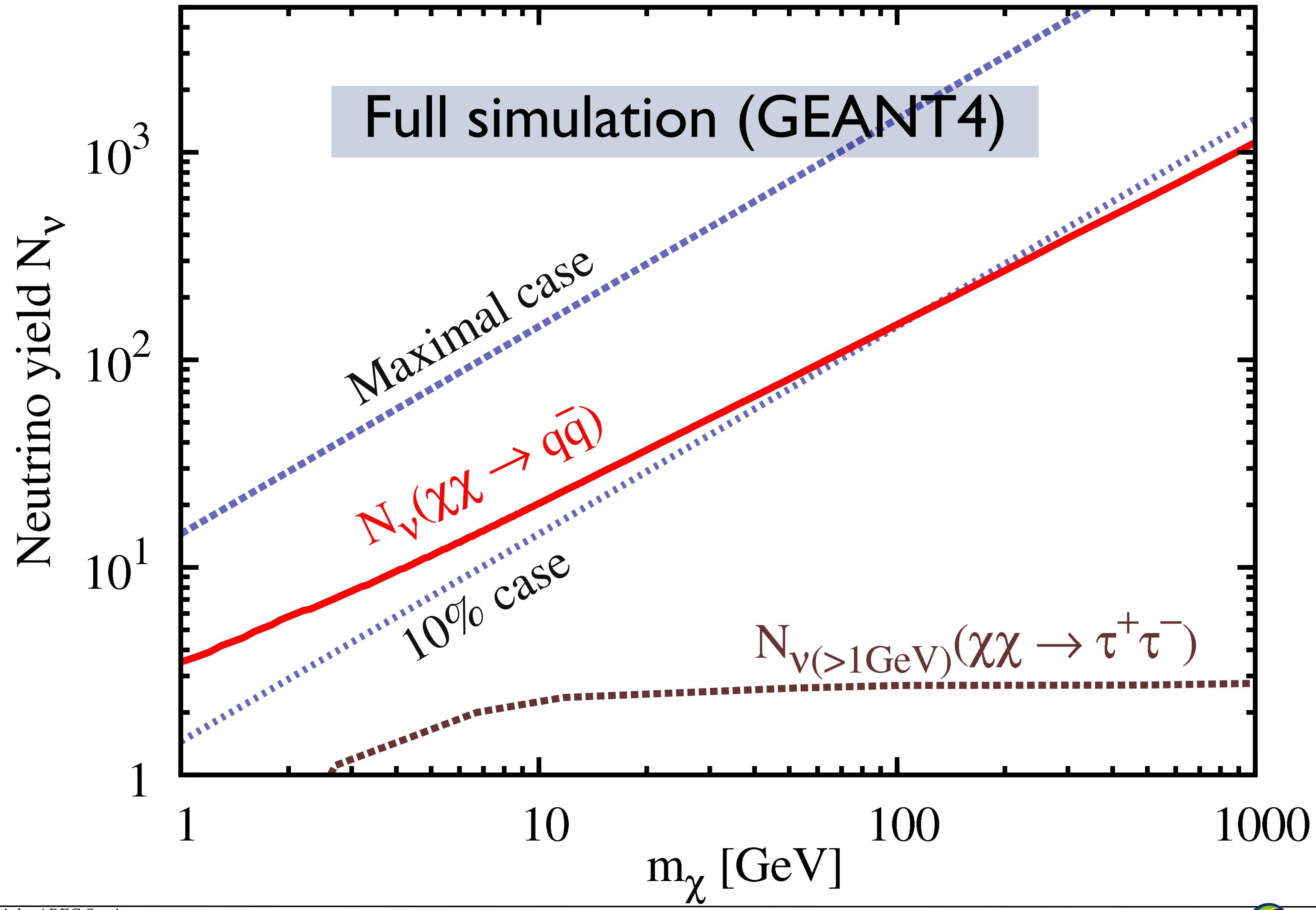
Most optimistic case:
100% of annihilation energy converted into pions

What’s the Neutrino yield ?

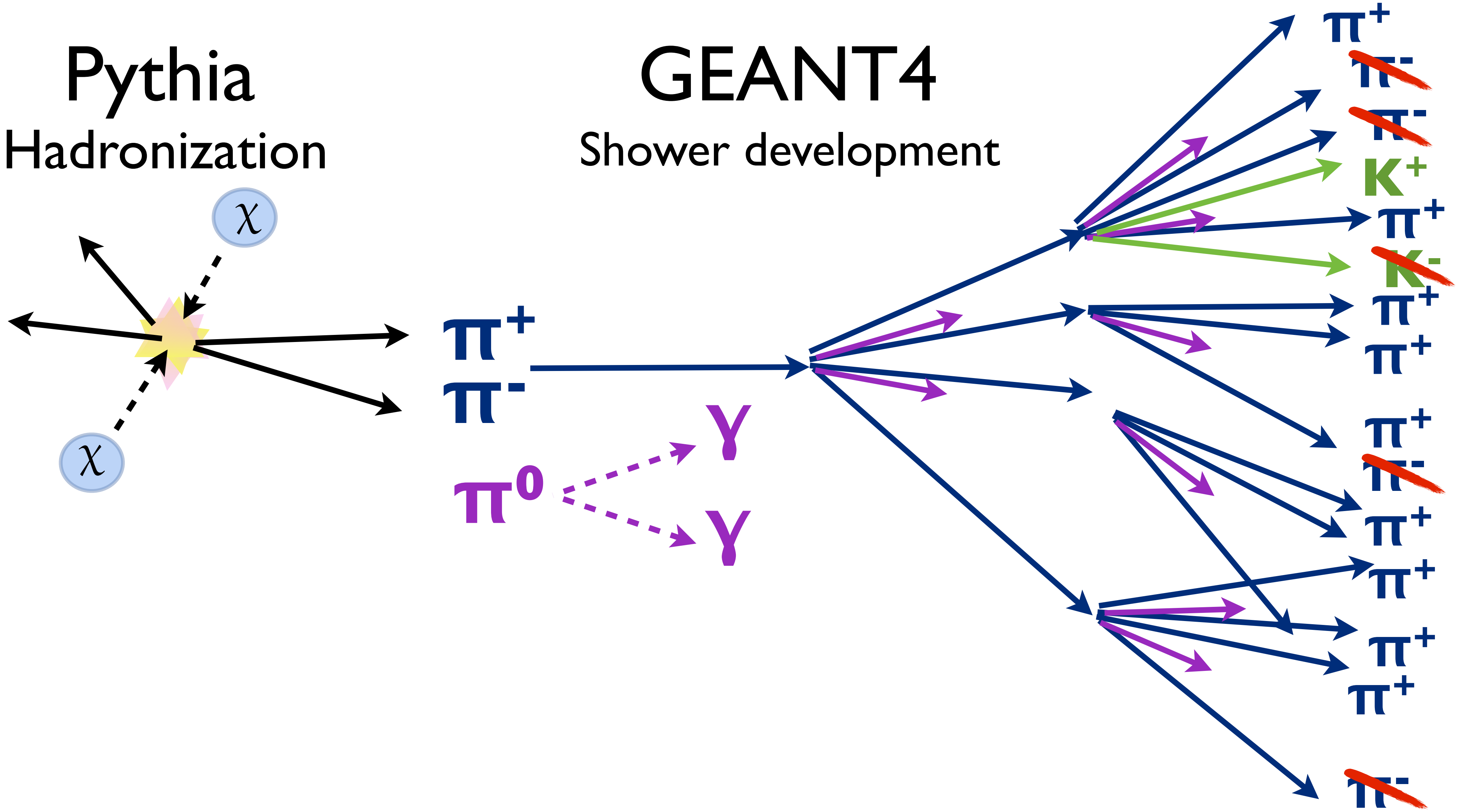


scaling from airshowers

Neutrino yield



Pion and kaon yield



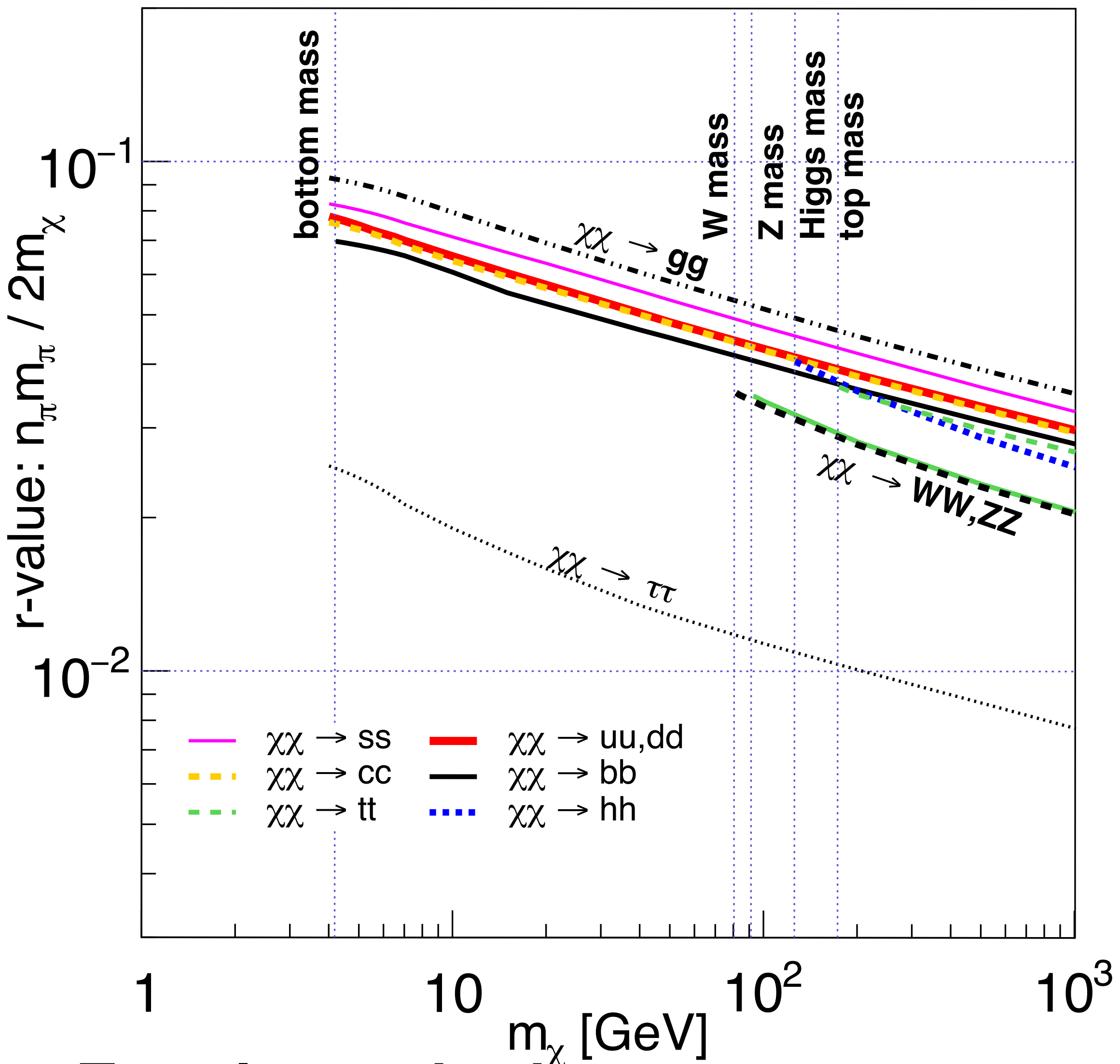
Pythia
Hadronization

GEANT4
Shower development

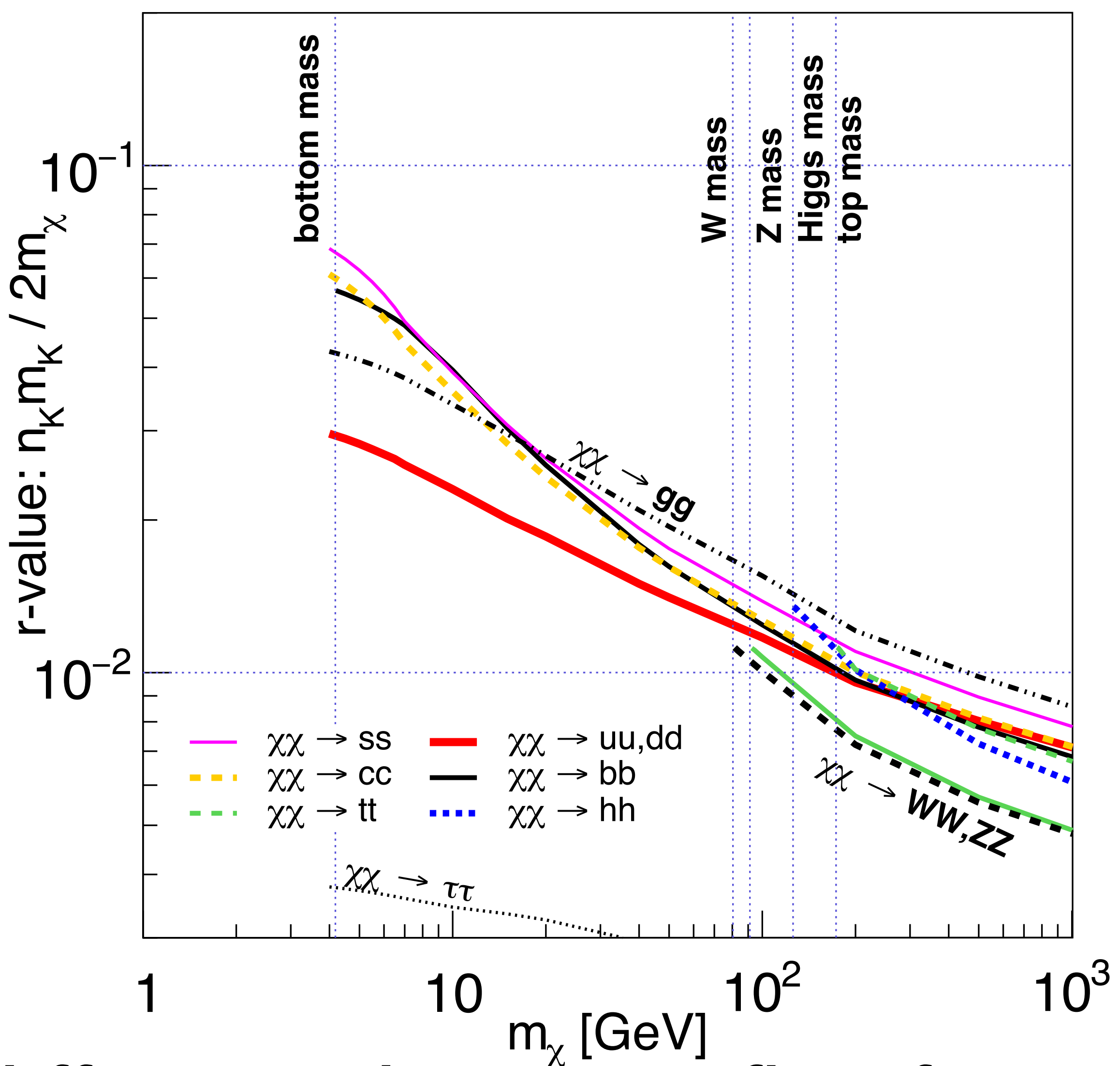
- Simulation to determine pion and kaon yields per channel
- Define r-value as the fraction of center-of-mass energy that goes into pions (π^+) or kaons(K^+) decaying at rest.

Pion and Kaon yields

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



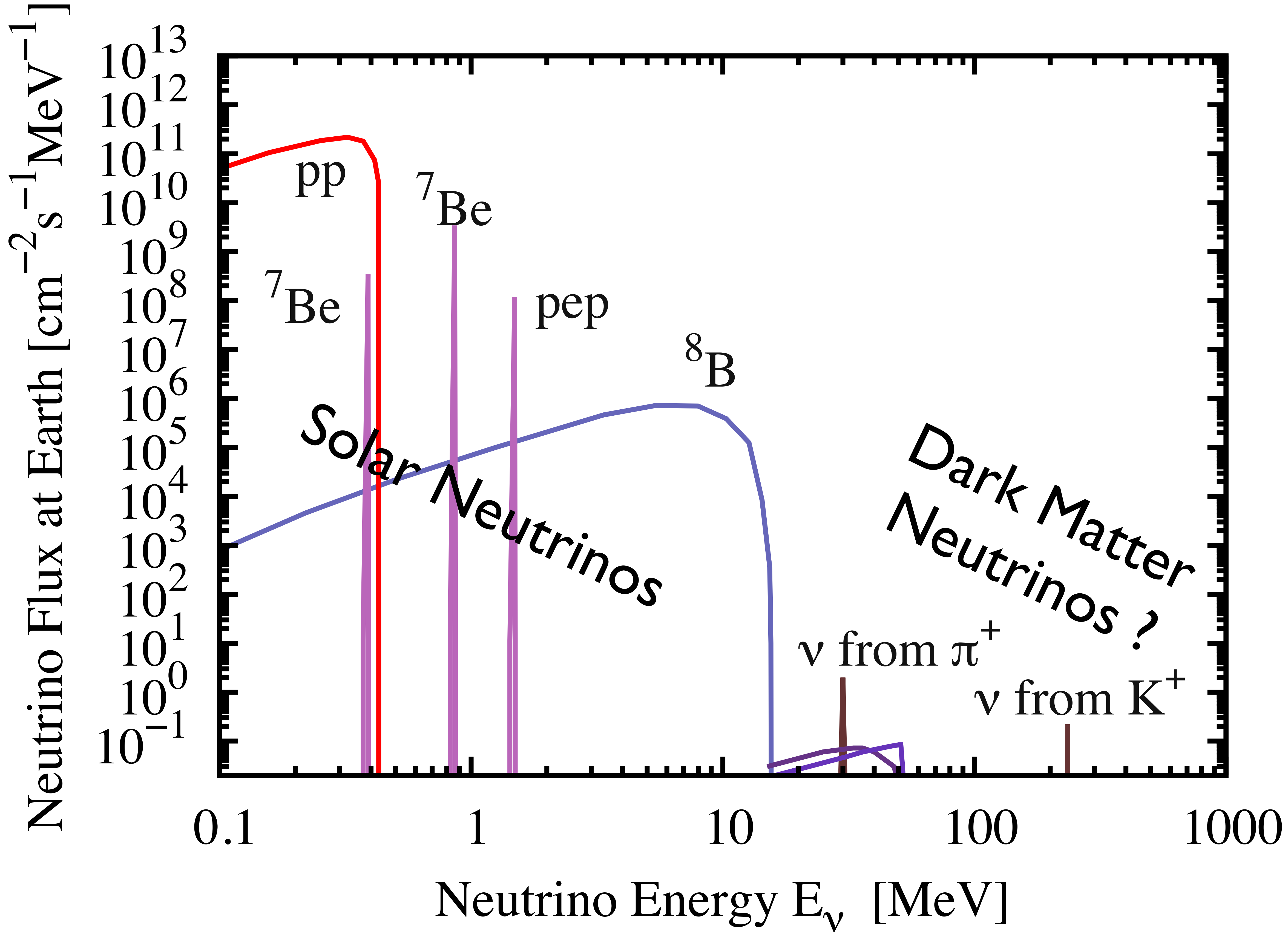
K^+ r-value - fraction of center-of-mass energy which goes into K^+



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

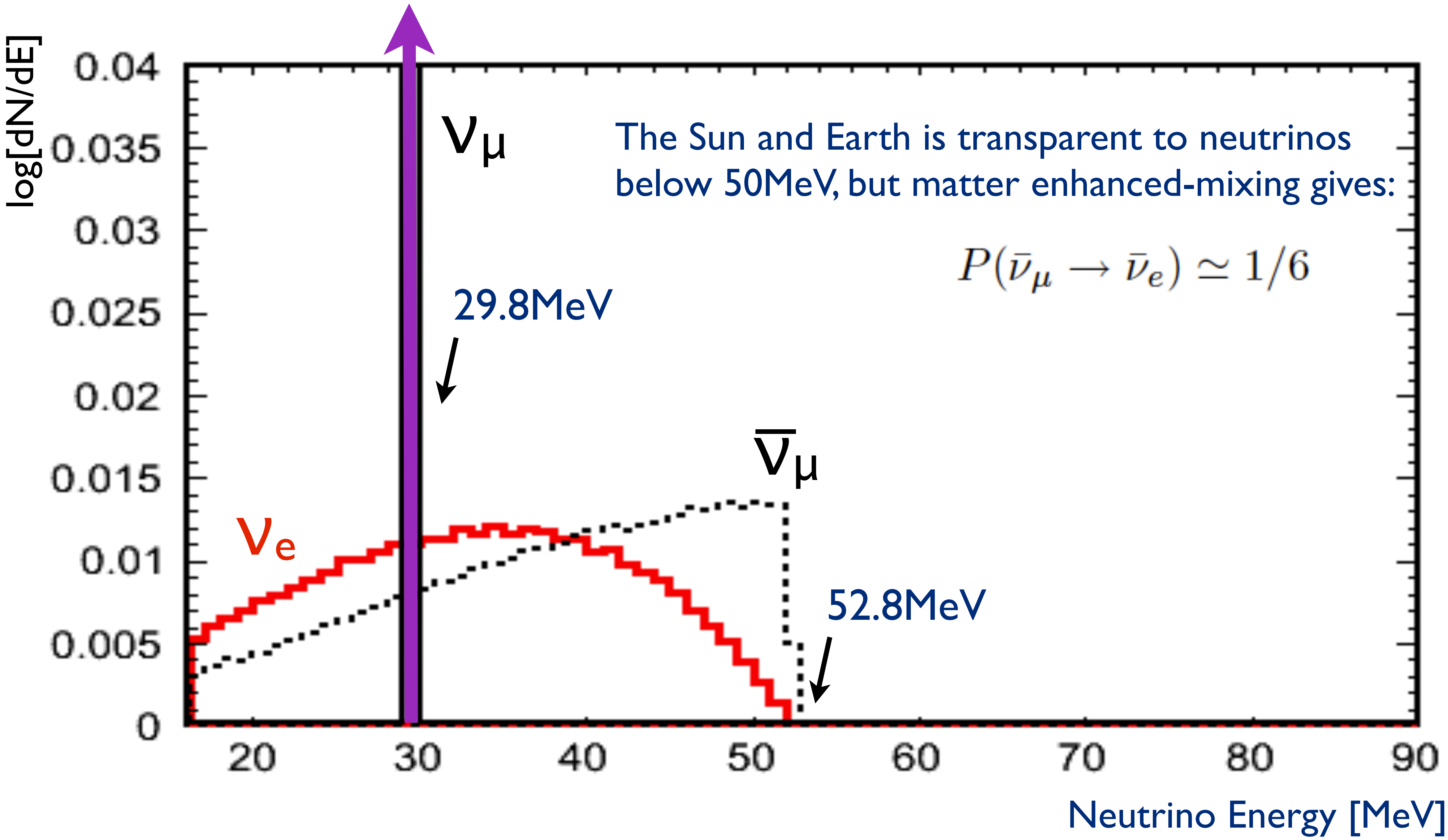
Sensitivity for decay at rest in the Sun

Low Energy Solar WIMP signal



Expected low-energy Neutrino Signal

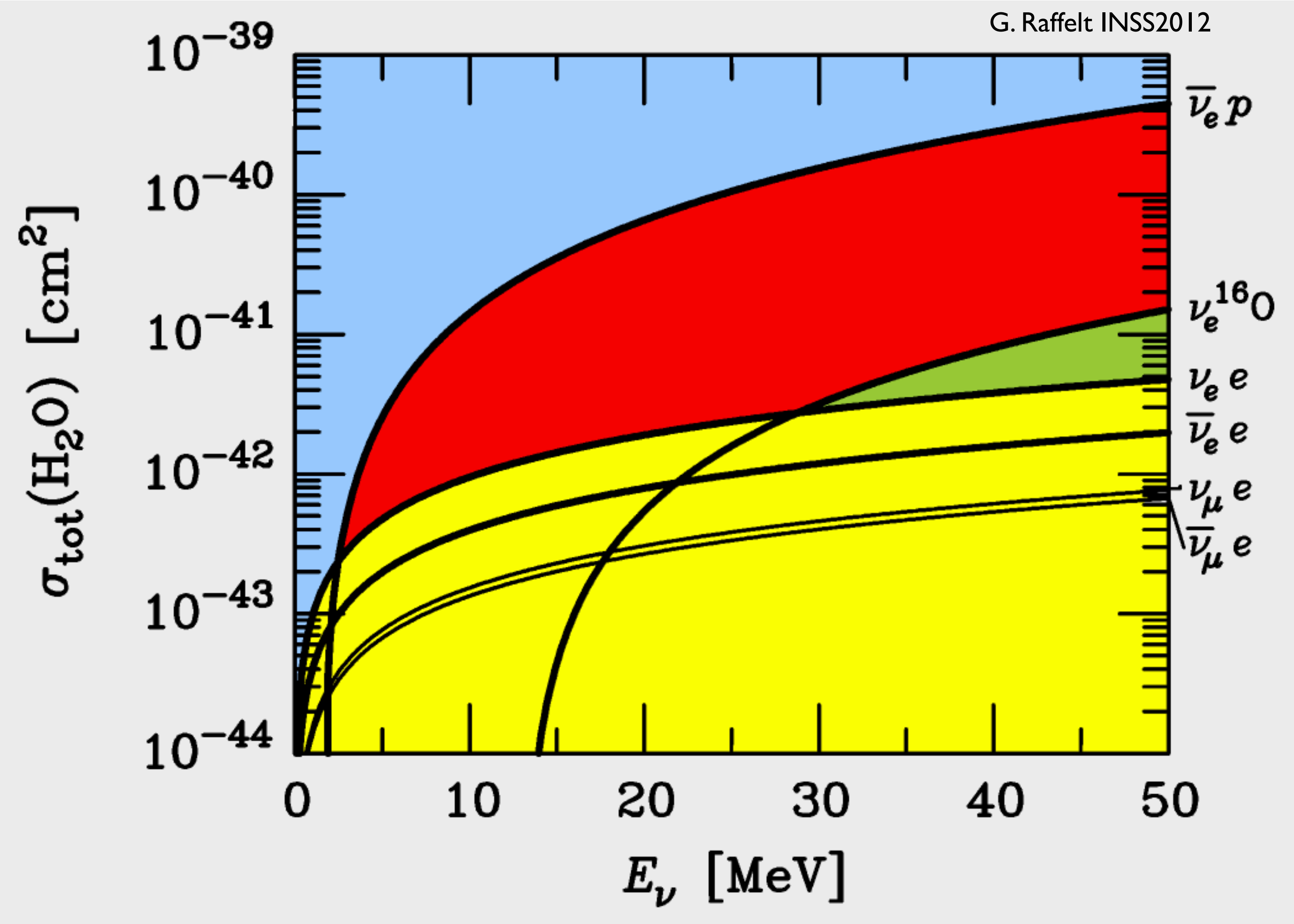
Neutrino Spectrum from pion decay at rest (normalized to unity)



The Sun and Earth is transparent to neutrinos below 50MeV, but matter enhanced-mixing gives:

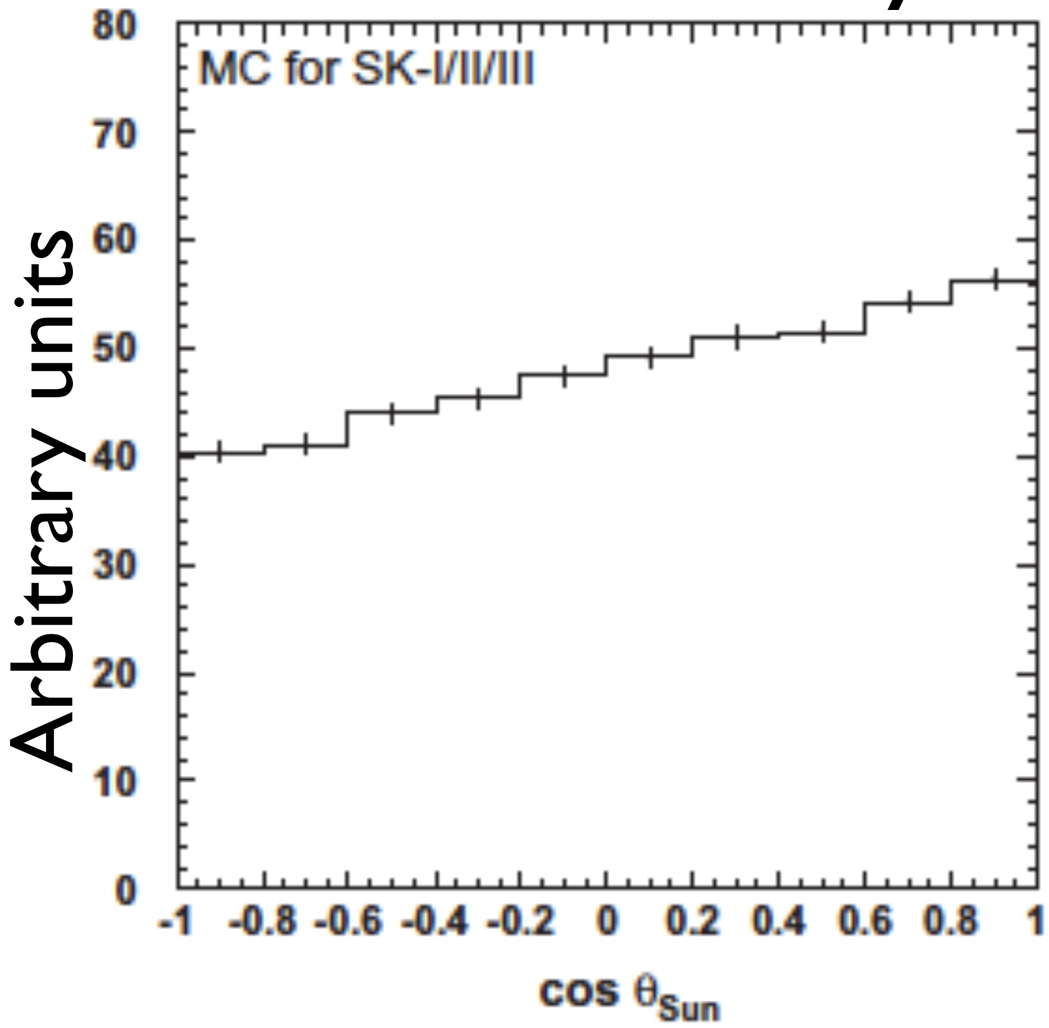
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq 1/6$$

Inverse beta-decay



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

"large" cross section, but little directionality



Backgrounds

K. Bays {Super-K Collaboration}
Phys.Rev. D85 (2012) 052007

The background events mainly caused by the atmospheric neutrinos, solar neutrinos and muon-induced spallation products.

NC Elastic

“atmospheric”

Decay electron

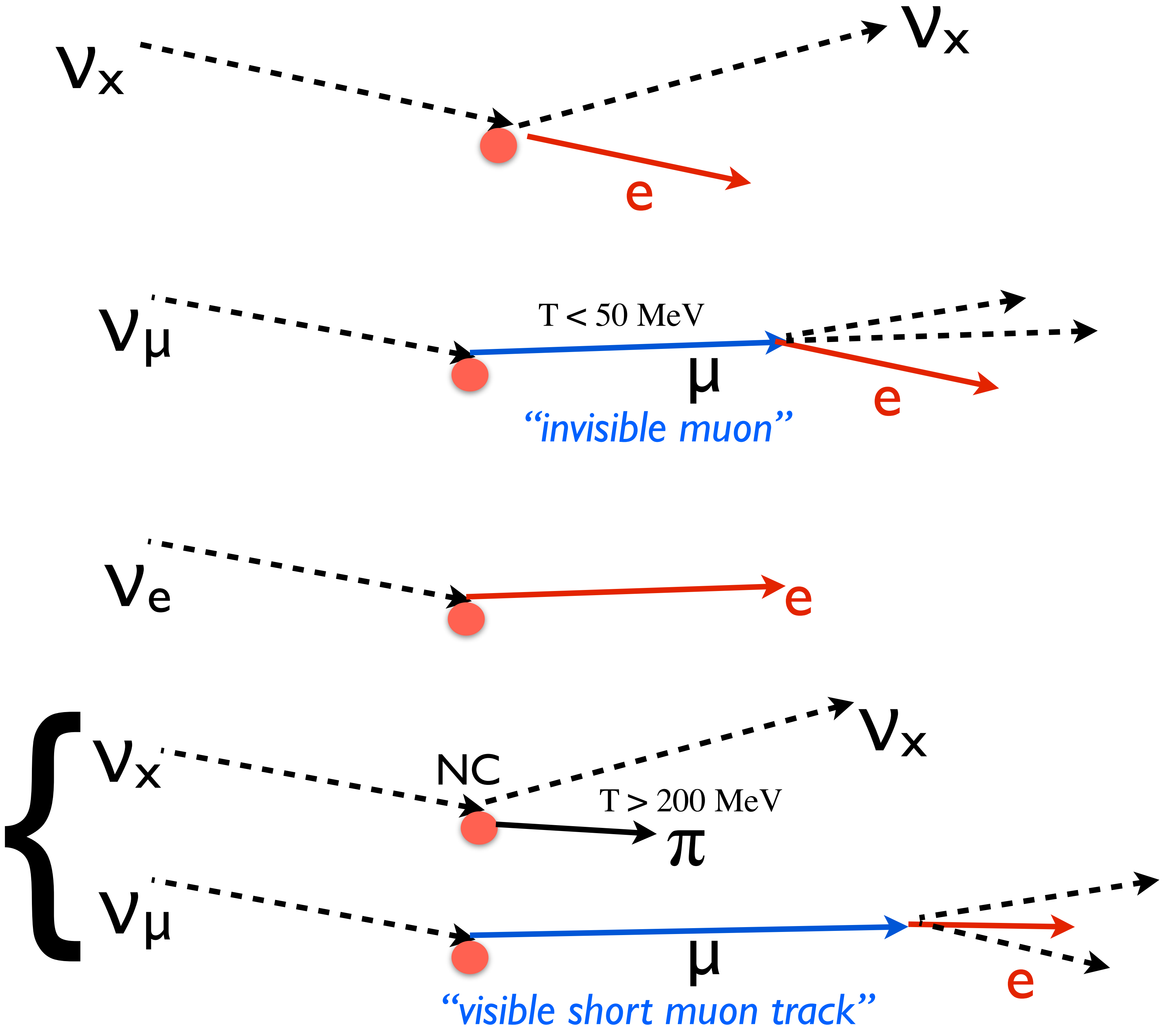
“atm. muon neutrinos”

ν_e CC

“atm. electron neutrinos”

μ/π

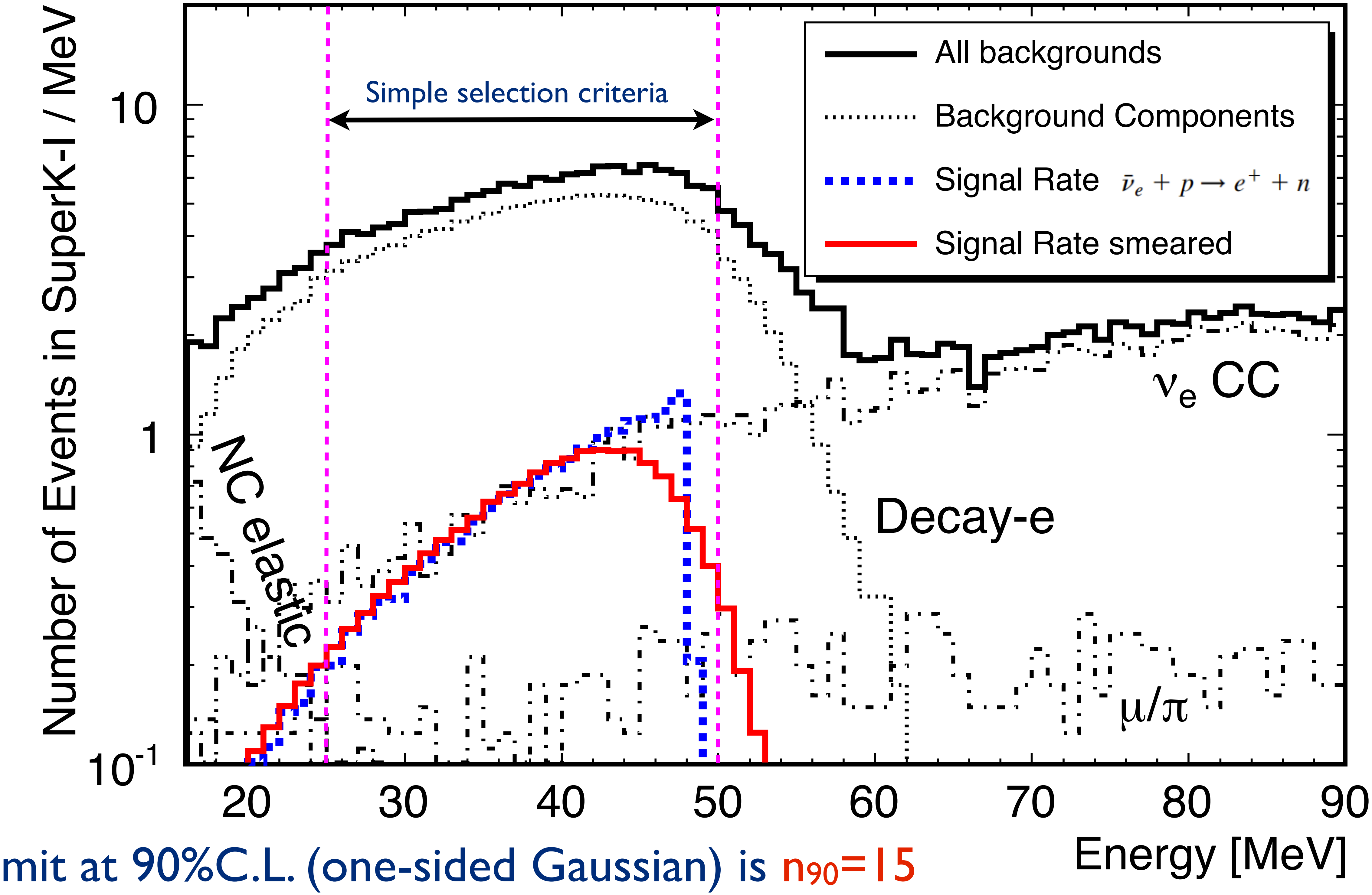
“μ/π production from atm. neutrinos”



Sensitivity Calculation Super-K

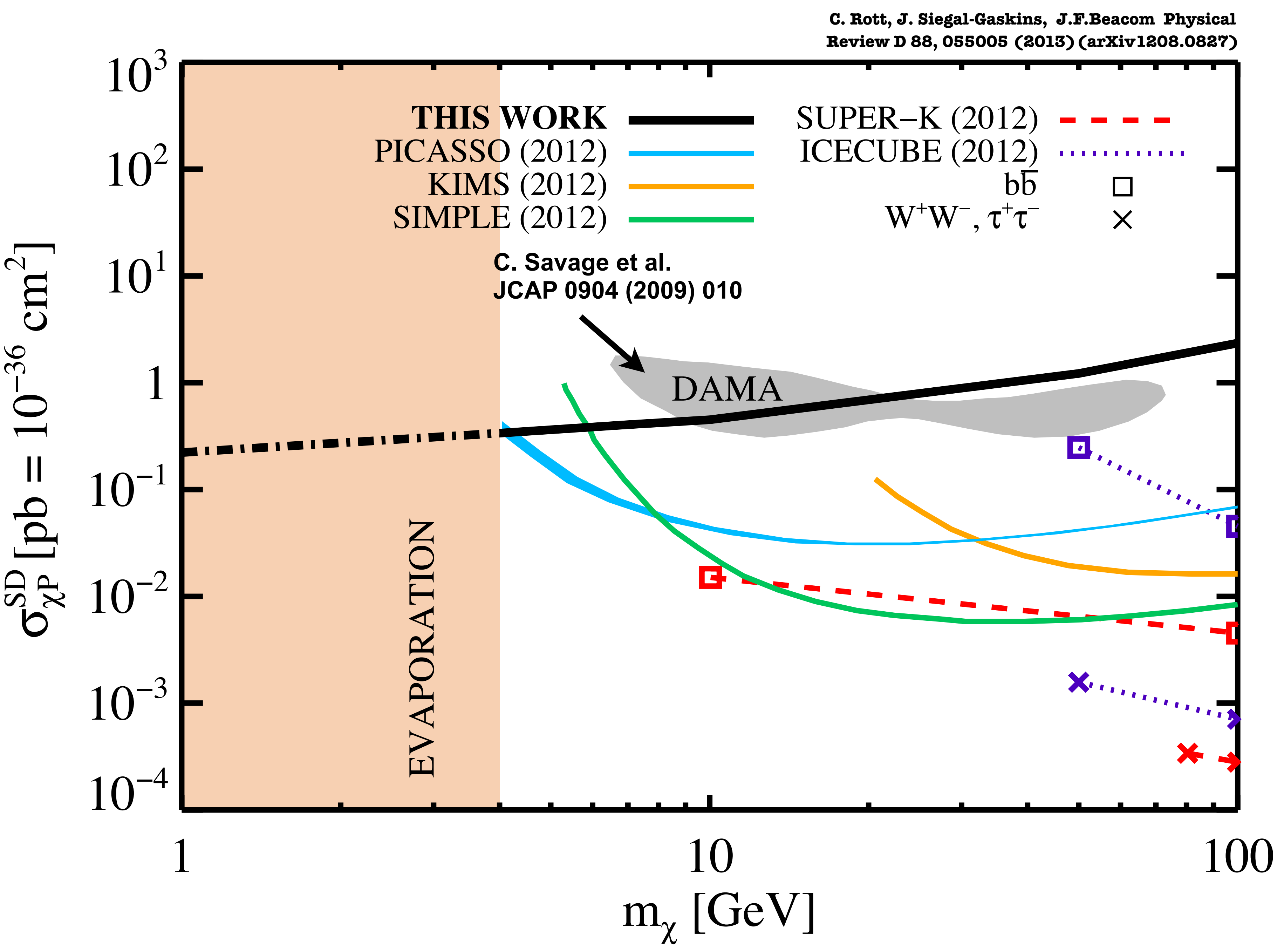
Positrons carry energy of $E_e \simeq [E_\nu - 1.3\,\text{MeV}](1 - E_\nu/m_p)$

To visualize the signal has been scaled to be "detectable"



Limit at 90%C.L. (one-sided Gaussian) is $n_{90}=15$

WIMP Sensitivity Super-K



Previous searches relied on high energy neutrinos directly from the decays of annihilation products

Model the full hadronic shower in the Sun

WIMP sensitivity continues to improve for low masses

Minimal dependence on annihilation channels

New key detection channel to compliment other searches

Super-K data can already be used to test DAMA/Libra

Gadolinium

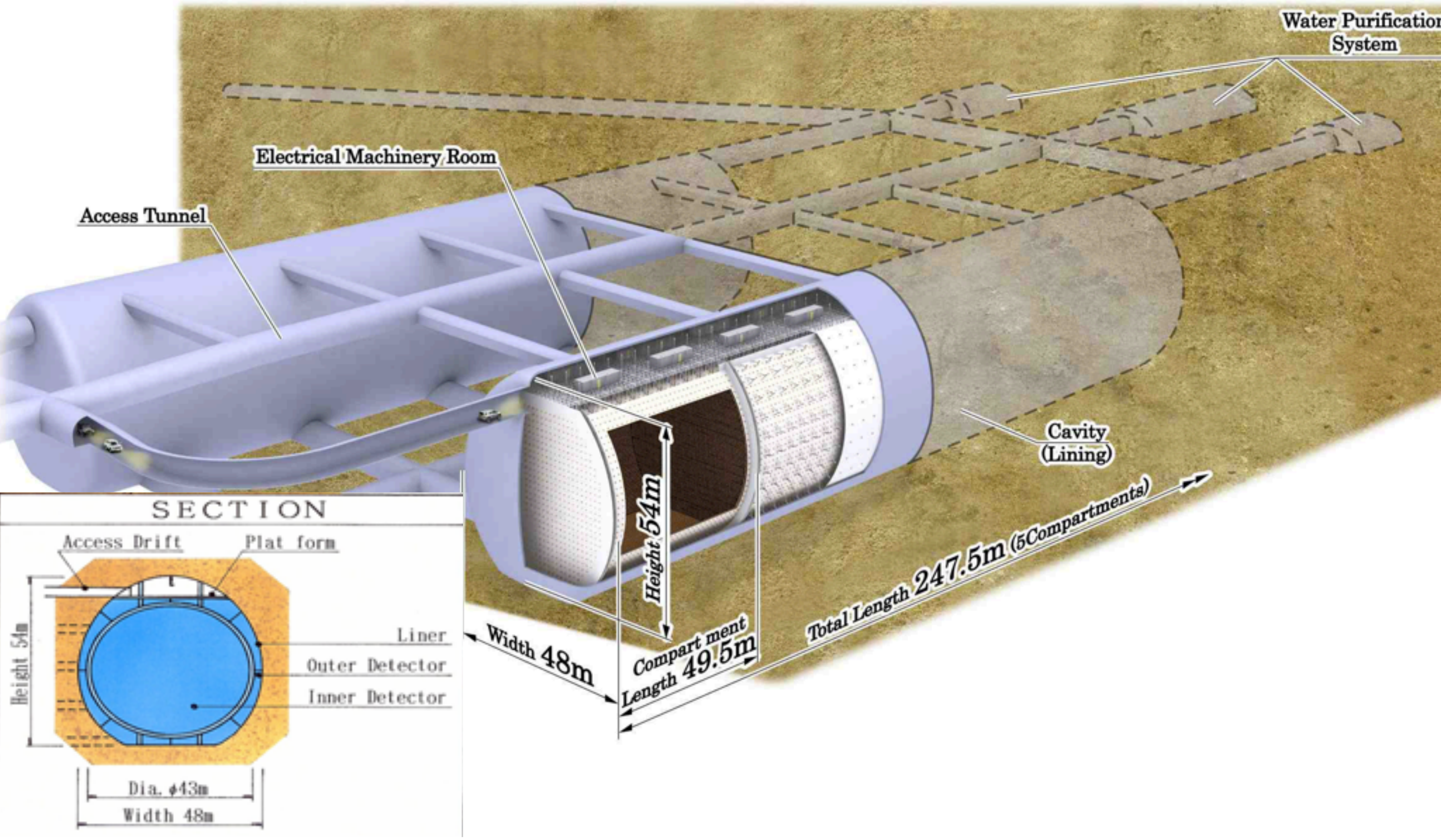

EGADS

- Decay electron events are the dominant background
- Identifying neutrons of the inverse beta decay reaction can provide a way to discriminate against this background
- *Proposal*: Add Gd to Super-K [Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004]
  - Neutron capture on Gd emits a 8.0 MeV γ cascade after a characteristic time ~ 30μs
  - $GdCl_3$ and $Gd_2(SO_4)_3$, unlike metallic Gd, are highly water soluble
  - 100 tons (0.2% by mass in SK) would yield >90% neutron captures on Gd

$$\begin{array}{l} \bar{\nu}_e + p \rightarrow e^+ + n \\ \qquad\qquad\qquad\;\downarrow \\ \qquad\qquad\qquad n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma \end{array}$$

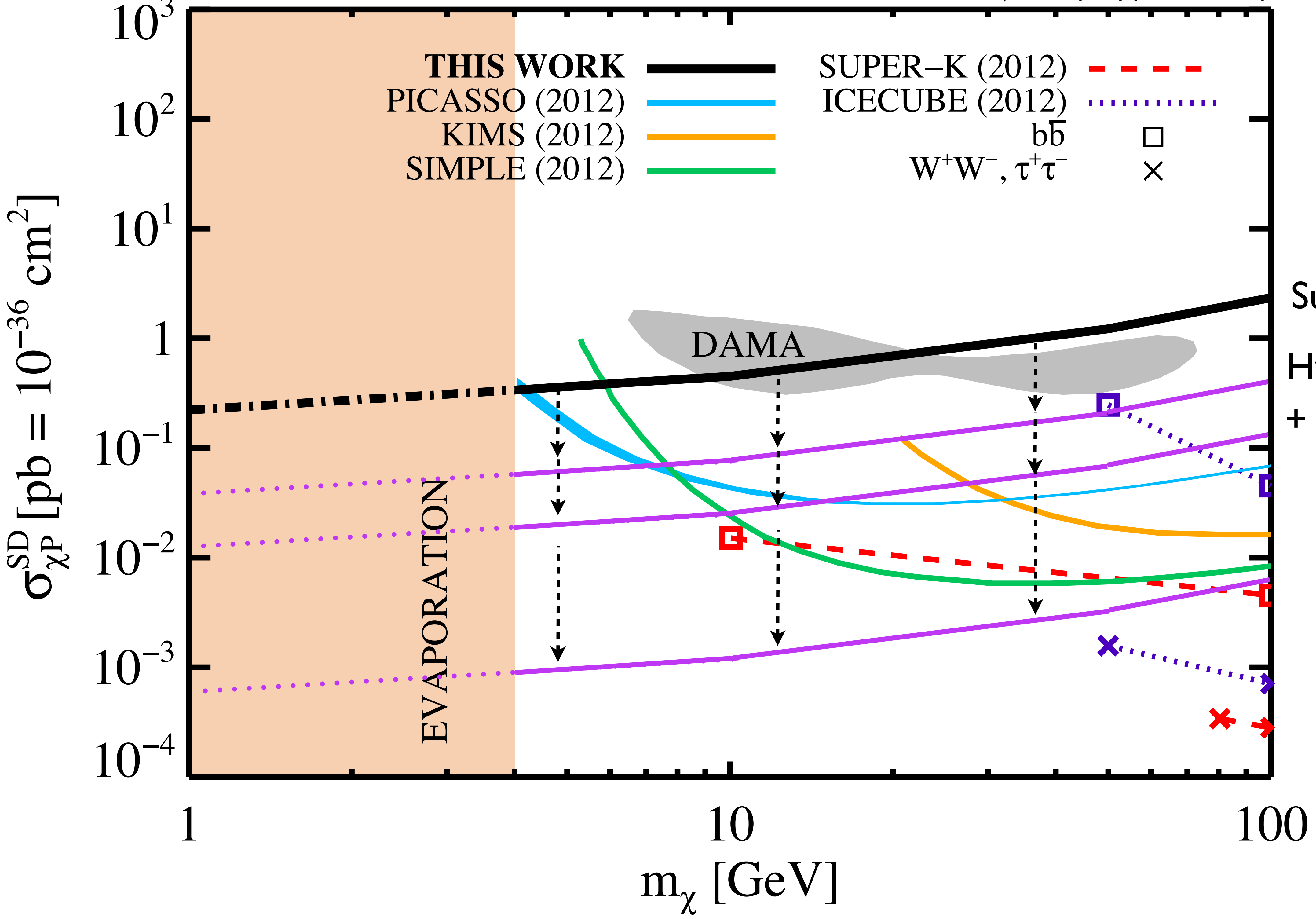
Looking forward to the addition of Gd in 201X

Hyper-K


Water Purification
System
Electrical Machinery Room
Access Tunnel
Cavity
(Lining)
Height 54m
Width 48m
Compart ment
Length 49.5m
Total Length 247.5m (5Compartments)
SECTION
Access Drift
Plat form
Liner
Outer Detector
Inner Detector
Height 54m
Dia. ϕ43m
Width 48m

Hyper-K Sensitivity 4yrs

C. Rott, J. Siegal-Gaskins, J.F.Beacom Physical Review D 88, 055005 (2013) (arXiv1208.0827)

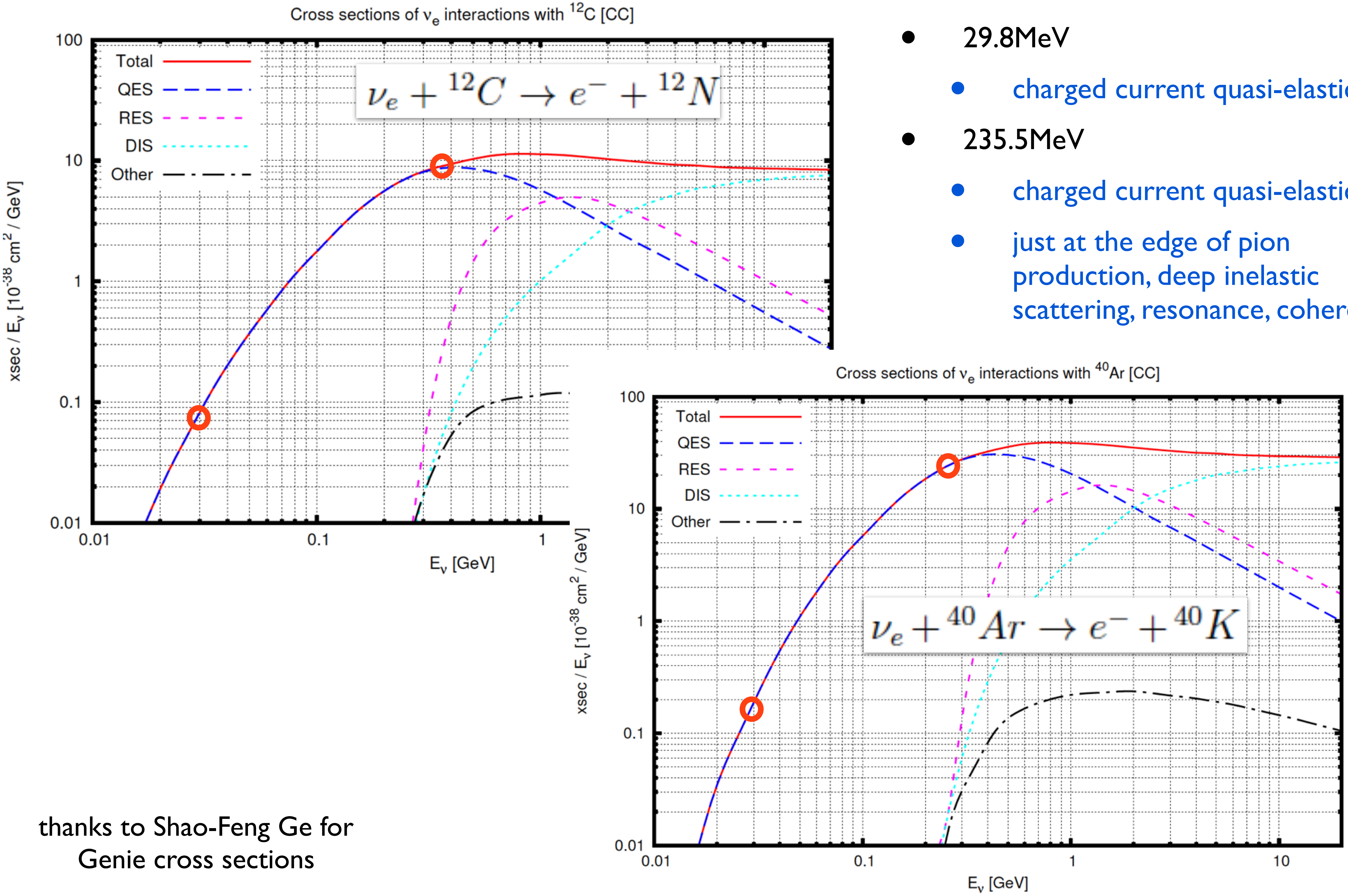


Super-K 4yrs

Hyper-K 4yrs
+ Gadolinium

best case

Neutrino cross section



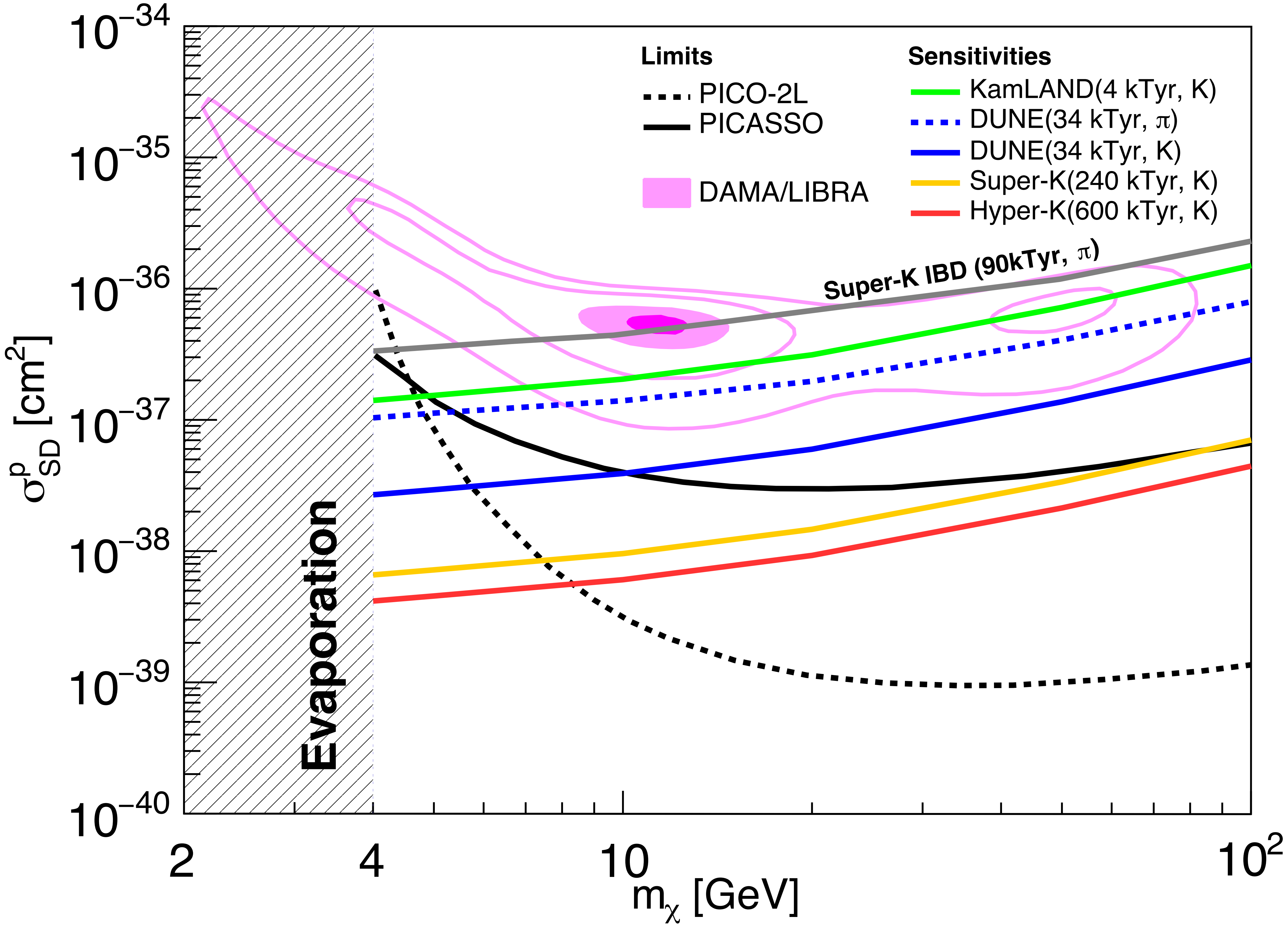
$$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$$

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$$

- 29.8MeV
  - charged current quasi-elastic
- 235.5MeV
  - charged current quasi-elastic,
  - just at the edge of pion production, deep inelastic scattering, resonance, coherent

thanks to Shao-Feng Ge for Genie cross sections

Sensitivity



Future directions

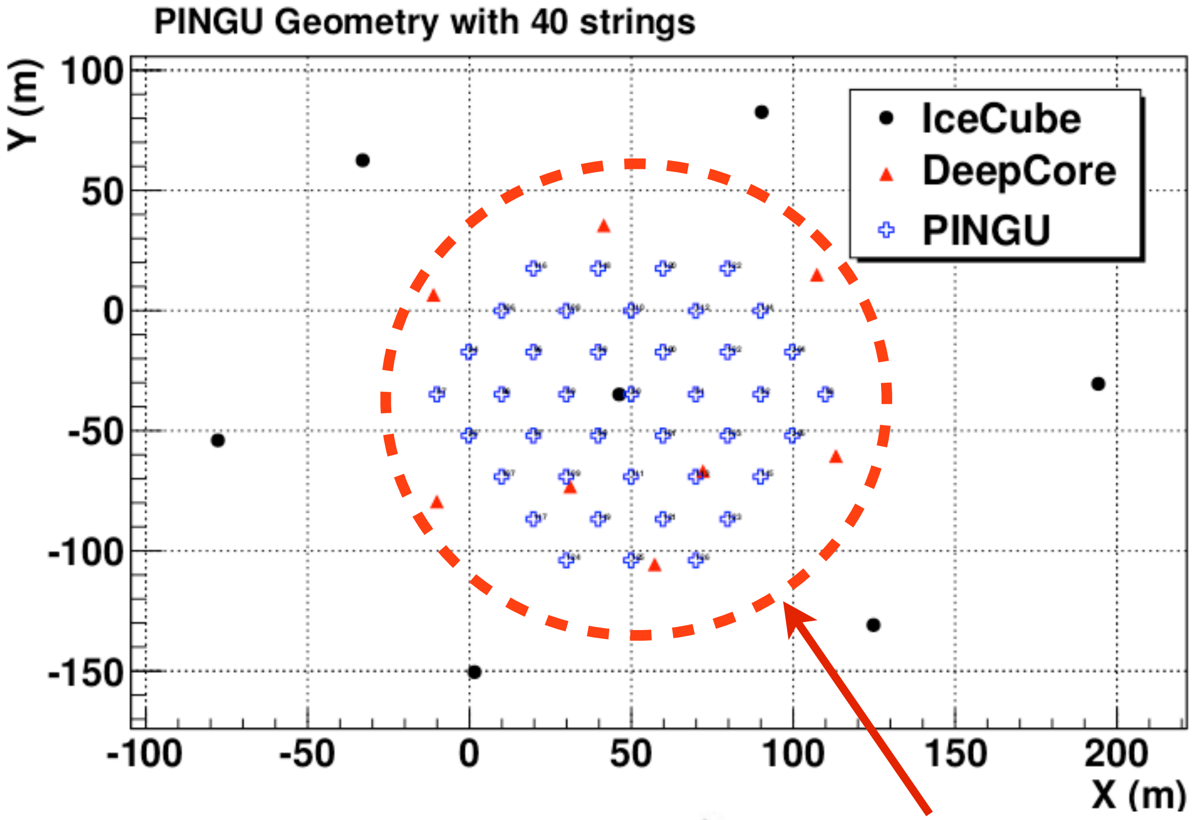
Future of IceCube

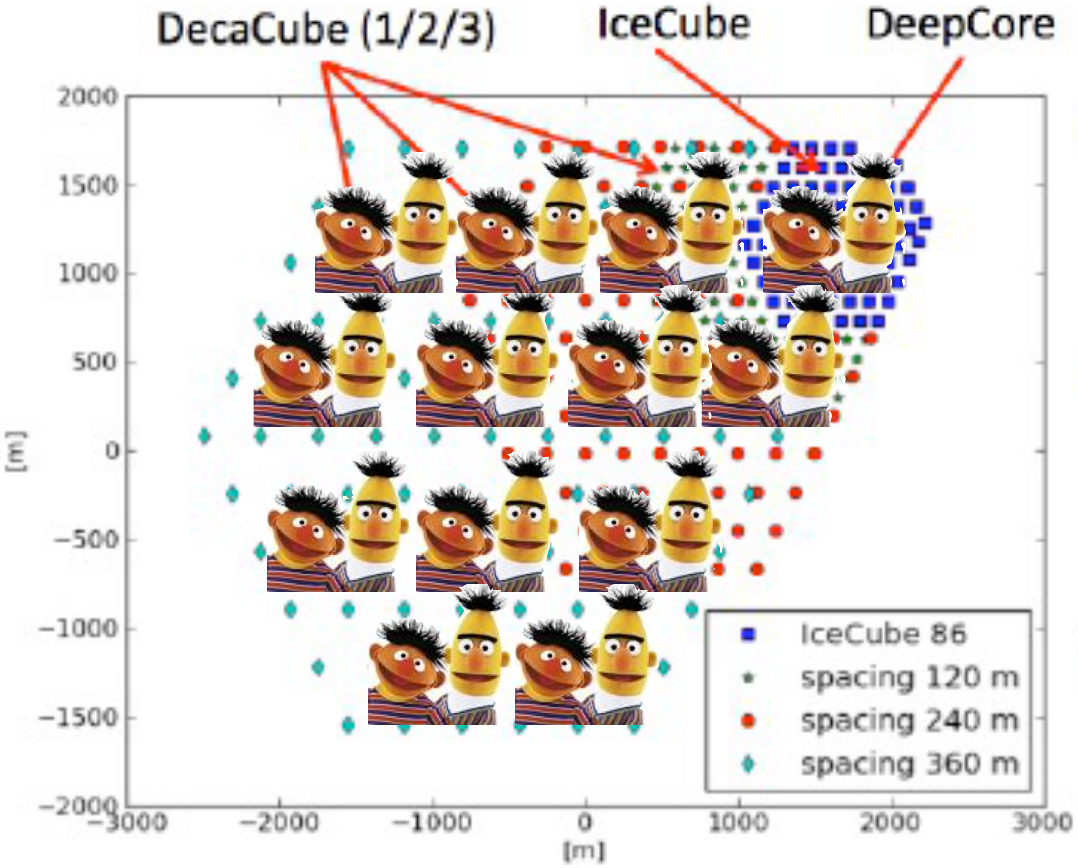
- Make it more precise
  - GeV threshold

PINGU - LOI:
arXiv:1401.2046

- Make it bigger

Gen2 - LOI:
arXiv:1510.05228

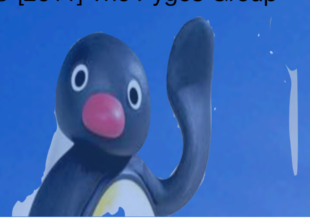




Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3



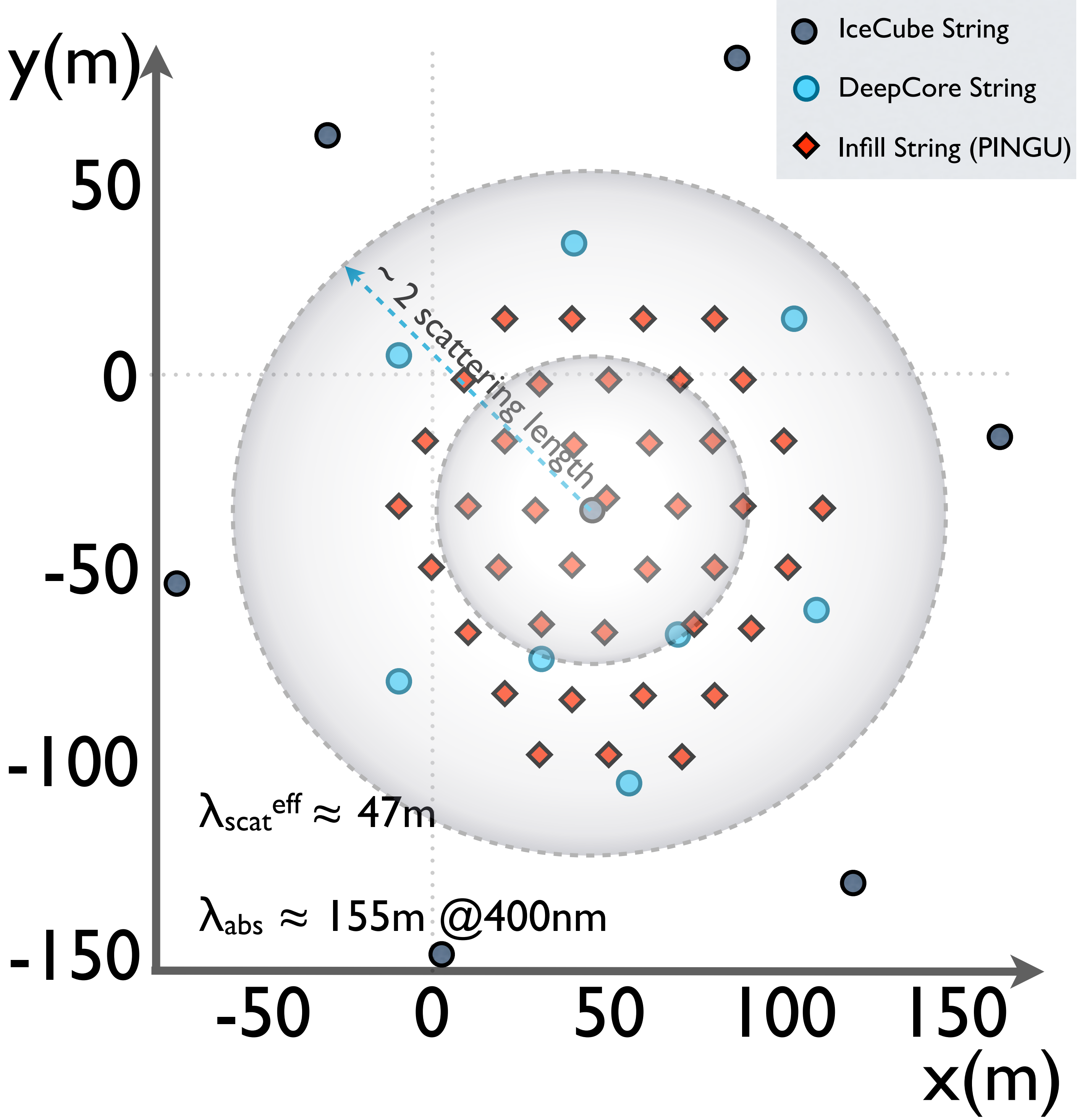
PINGU - Precision IceCube Next Generation Upgrade

Precision **I**ceCube **N**ext **G**eneration **U**pgrade

- PINGU upgrade plan
  - Instrument a volume of about 5MT with ~40 strings each containing 60-100 optical modules
  - 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

An example PINGU geometry (40 strings)

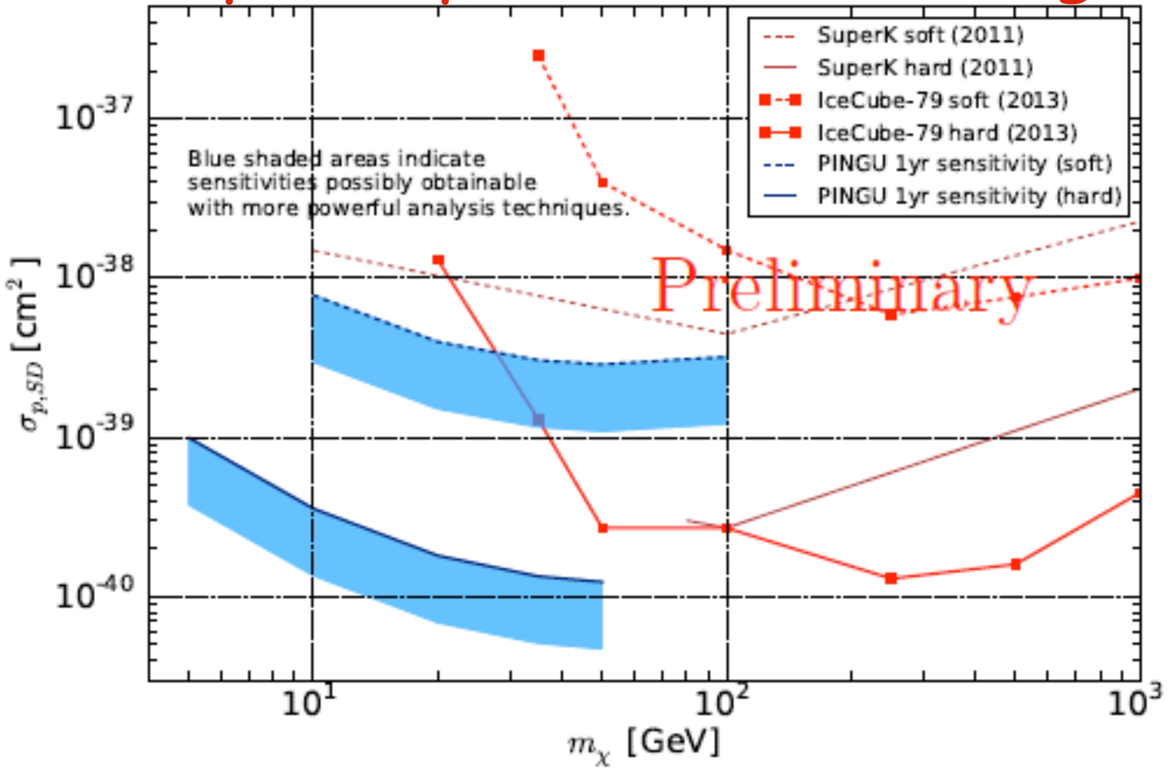
Note: PINGU geometry is still being optimized



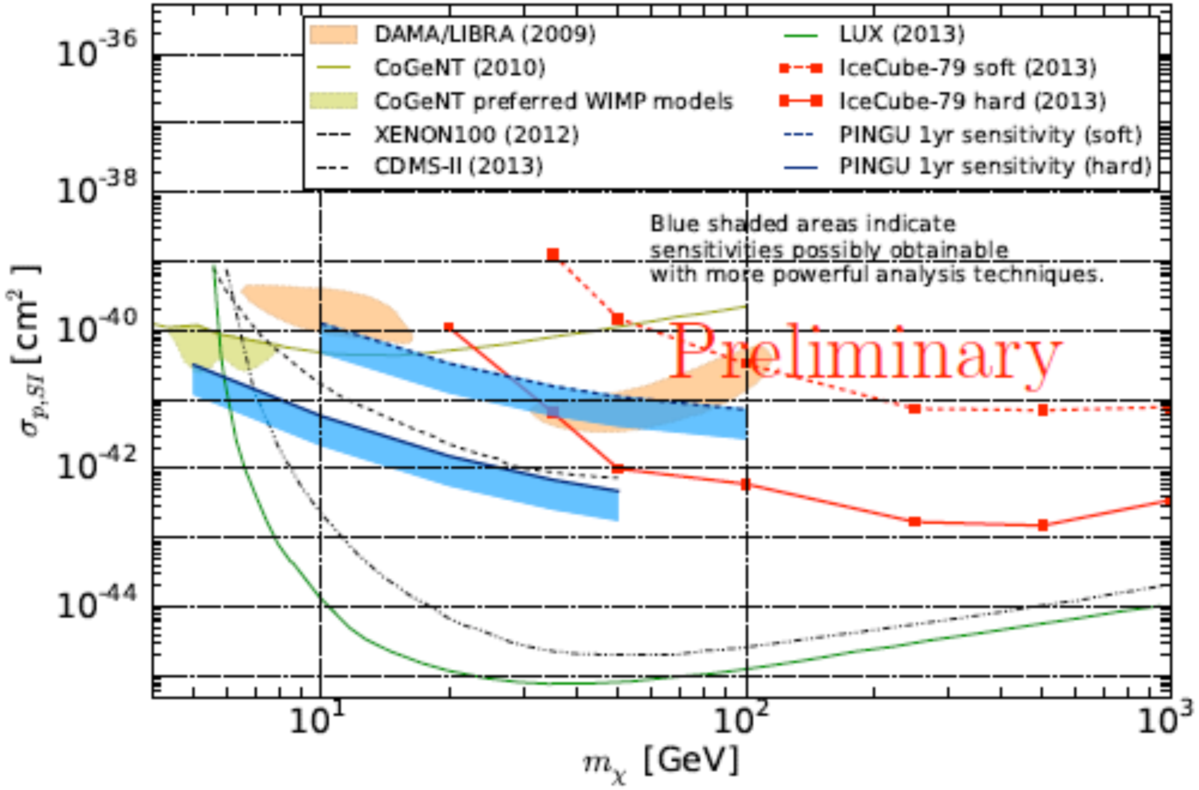
PINGU Dark Matter Sensitivity

- Solar WIMP dark matter
  - Sensitivity reaches to WIMP masses of ~5 GeV
  - World-leading limits for SD WIMPs with one year of data
- Low mass WIMP region testable
  - Test DAMA/LIBRA with indirect search also in the SI-scattering

Spin-dependent scattering

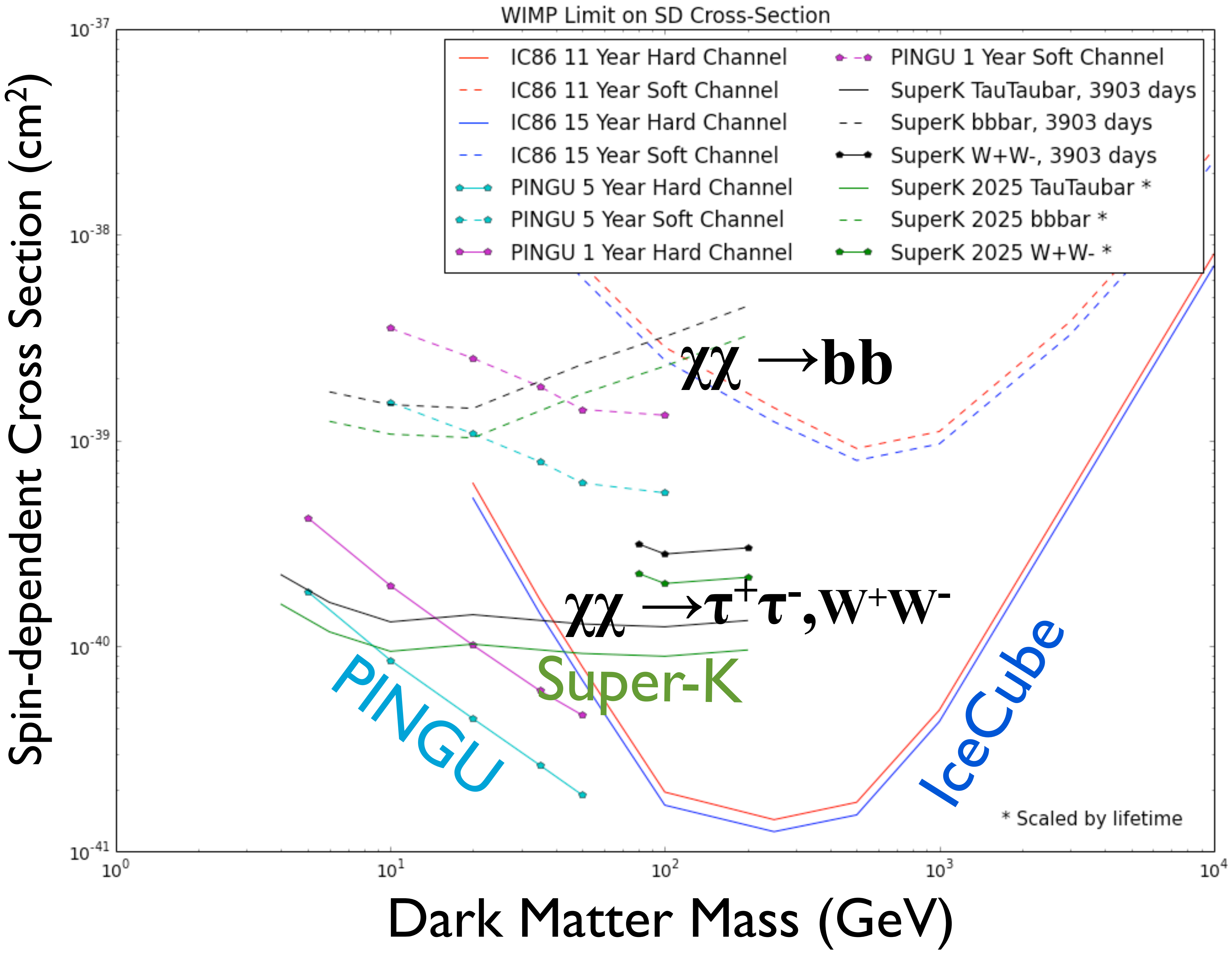


Spin-independent scattering



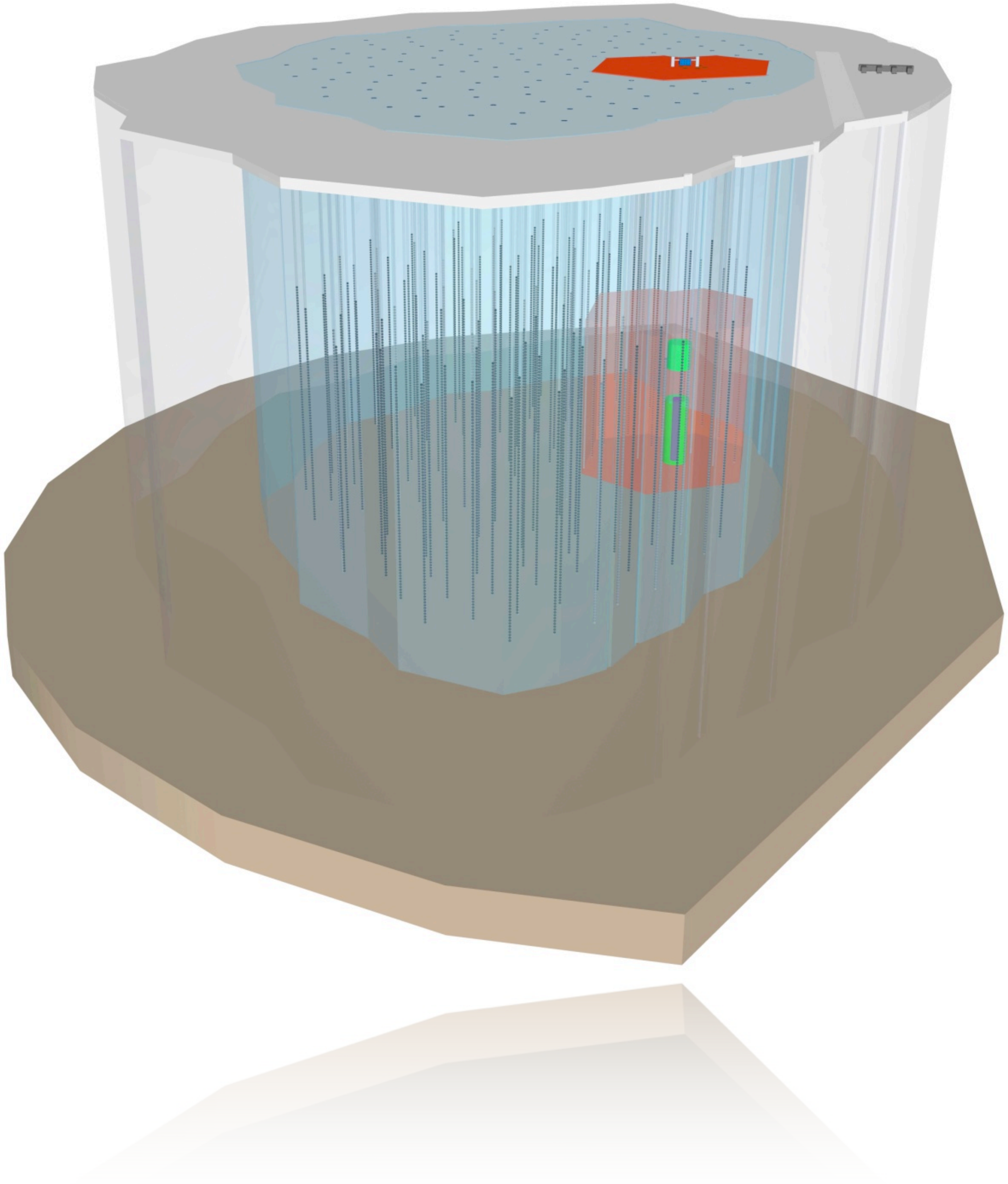
PINGU LOI *arXiv:1401.2046*

PINGU Dark Matter Sensitivity



Conclusions

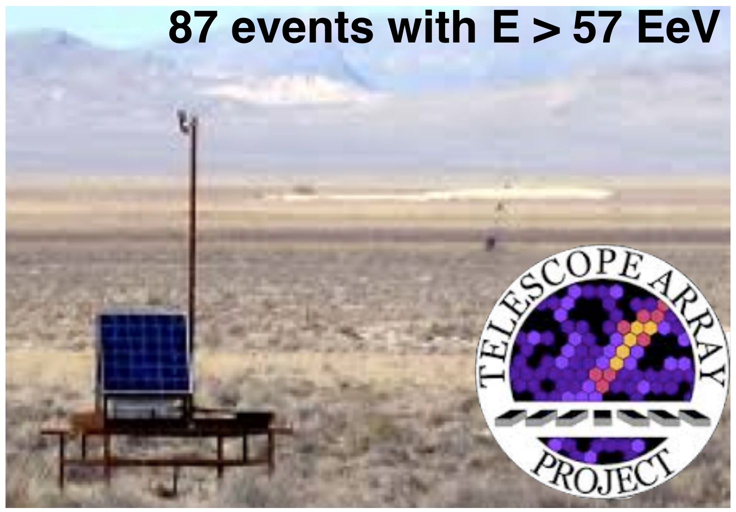
- Striking WIMP signatures provide high discovery potential for indirect searches
- Models motivated by positron excess and gamma-ray observations can and have been tested by IceCube
- Neutrino Telescopes provide world best limits on SD WIMP-Proton scattering cross section
- Neutrinos extremely sensitive to test low-mass WIMP scenarios at current and future detectors
- New detection channel with low-energy neutrinos offers additional discovery potential
- Lifetimes of heavy decaying dark matter can be constrained to 10^{28}s using neutrino signals



Thanks !

UHE Cosmic-Ray correlations with HE neutrinos

87 events with E > 57 EeV



700 km² surface array of 507 plastic scintillation detectors
+ 3 fluorescence detector stations

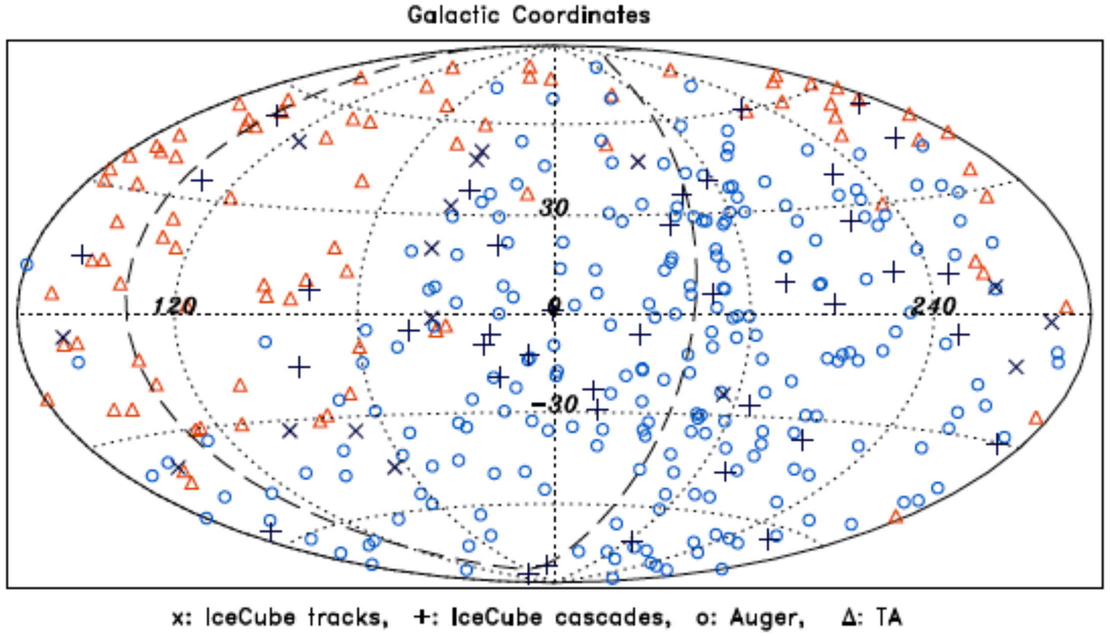
△ Dataset: May 2008 - May 2014

231 events with E >52 EeV

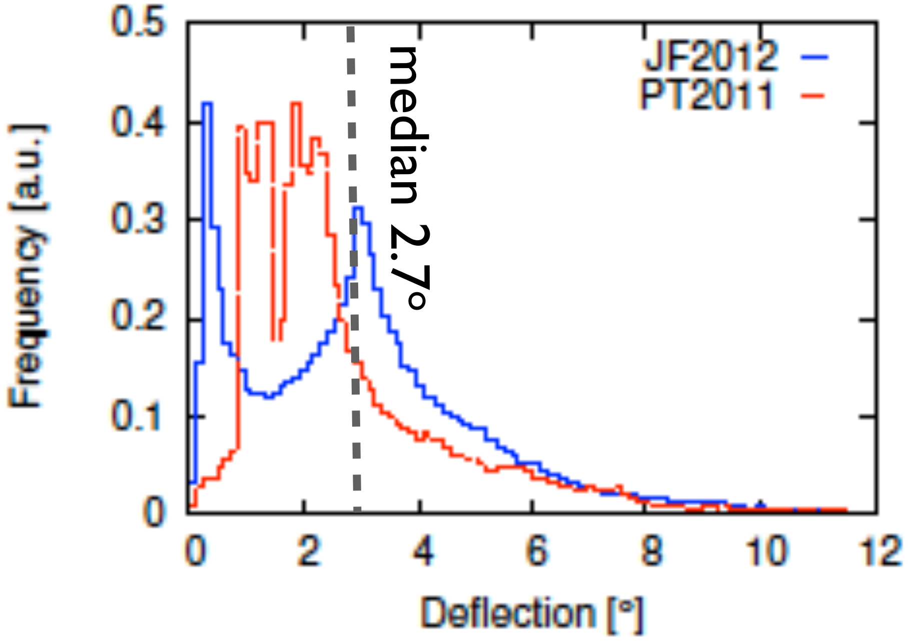
3000 km² surface array with 1660 water-Cherenkov detectors
+ 4 fluorescence detector stations

○ Dataset: Jan 2004 - March 2014

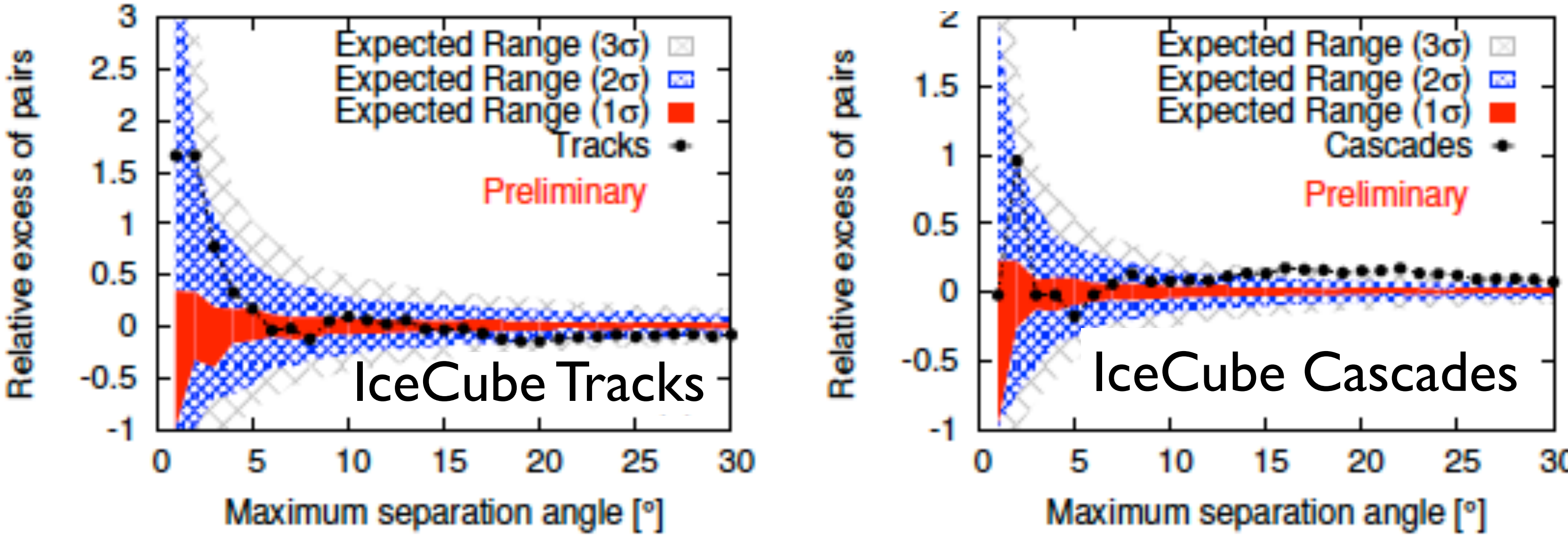
ICRC2015 IceCube + Auger + TA Collaborations [arxiv1511.02109](https://arxiv.org/abs/1511.02109)



Distribution of UHECR deflections in Galactic magnetic fields for rigidity E/Z>100EeV



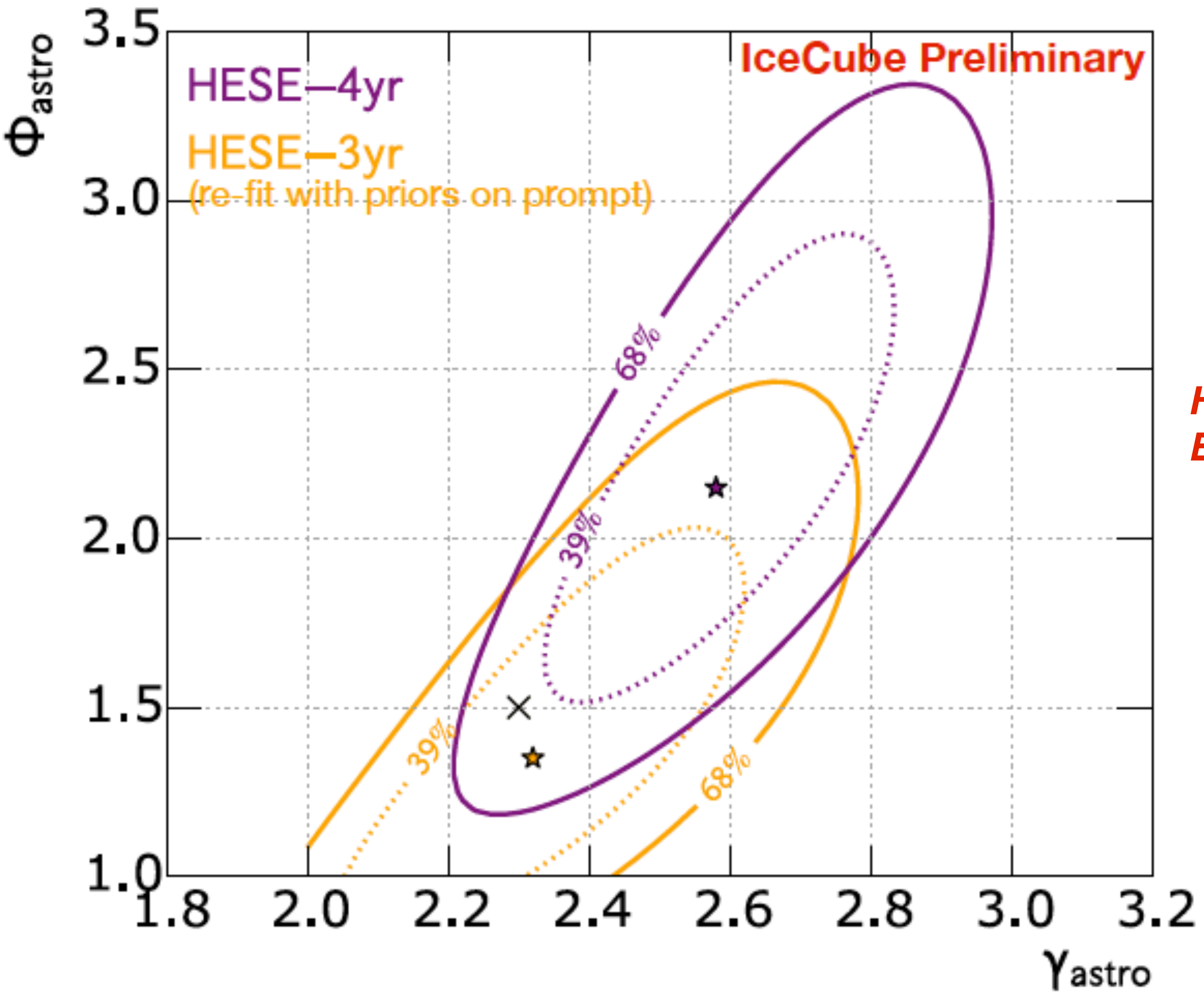
[PT2011] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg, K. J. Newton-McGee, Astrophys. J. 738 (2011) 192.
[JF2012] R. Jansson & G. R. Farrar, Astrophys. J. 757 (2012) 14.



Relative excess of pairs, $[n_p(\alpha)/\langle n_p^{\mathrm{iso}}(\alpha)\rangle] - 1$

- More statistics needed. All results below 3.3σ

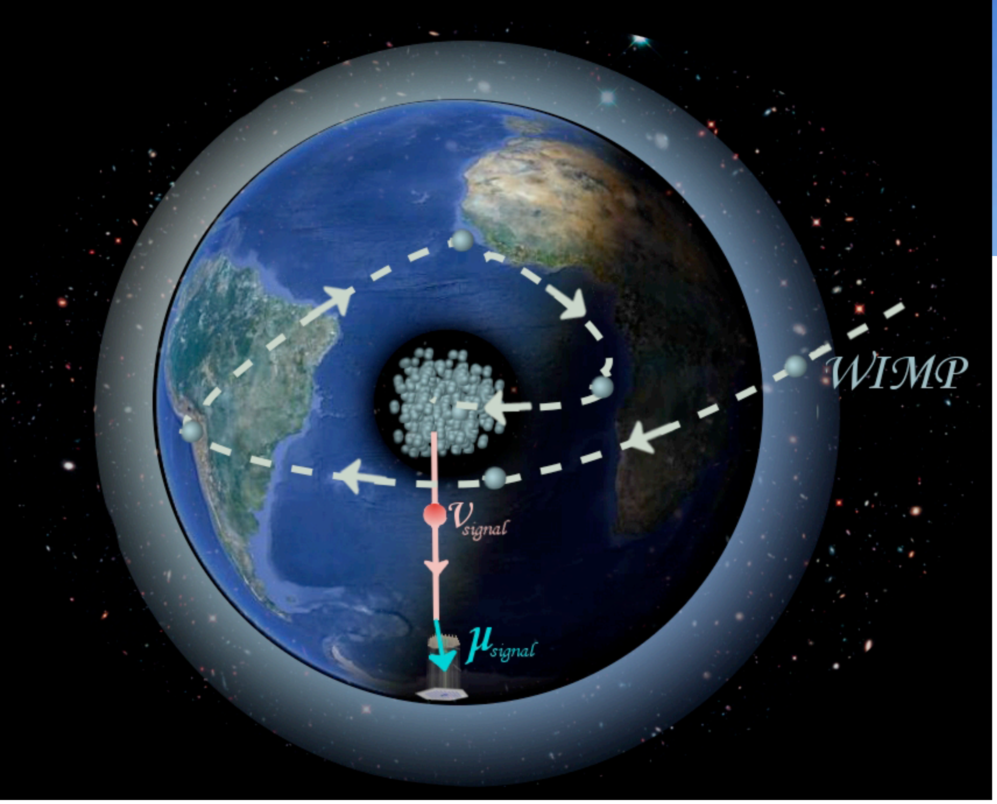
Spectral index and flux



Contour plot in spectral index vs. normalization at 100TeV

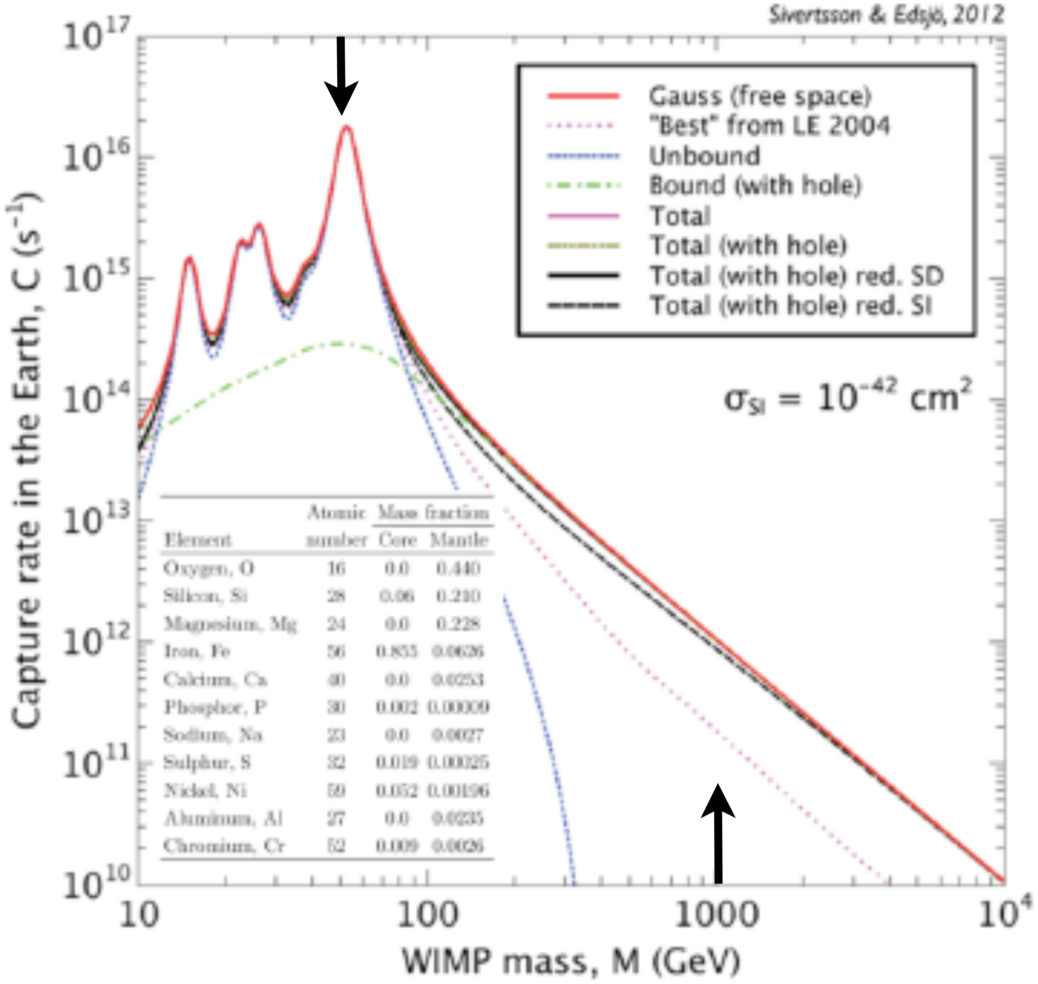
HESE-4yrs best fit flux:
$E^2\Phi$ = ~2.2 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

Spectral index has steepened
(no new PeV events but relatively large number in TeV)

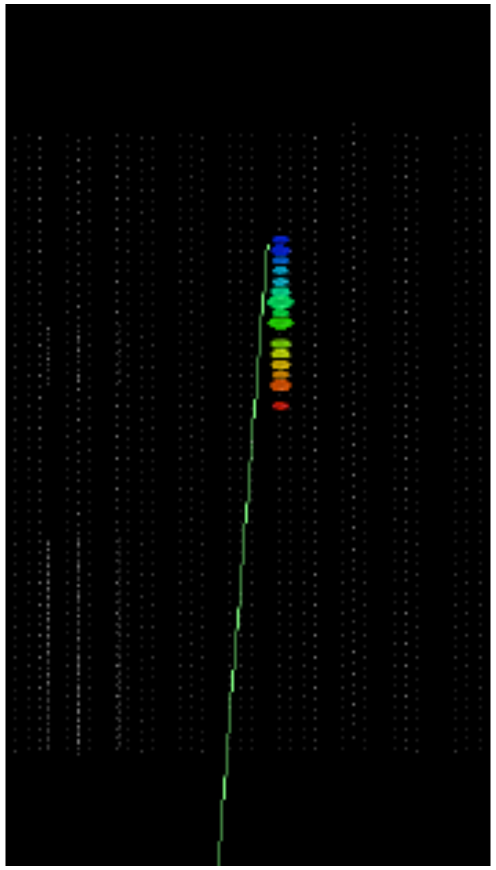


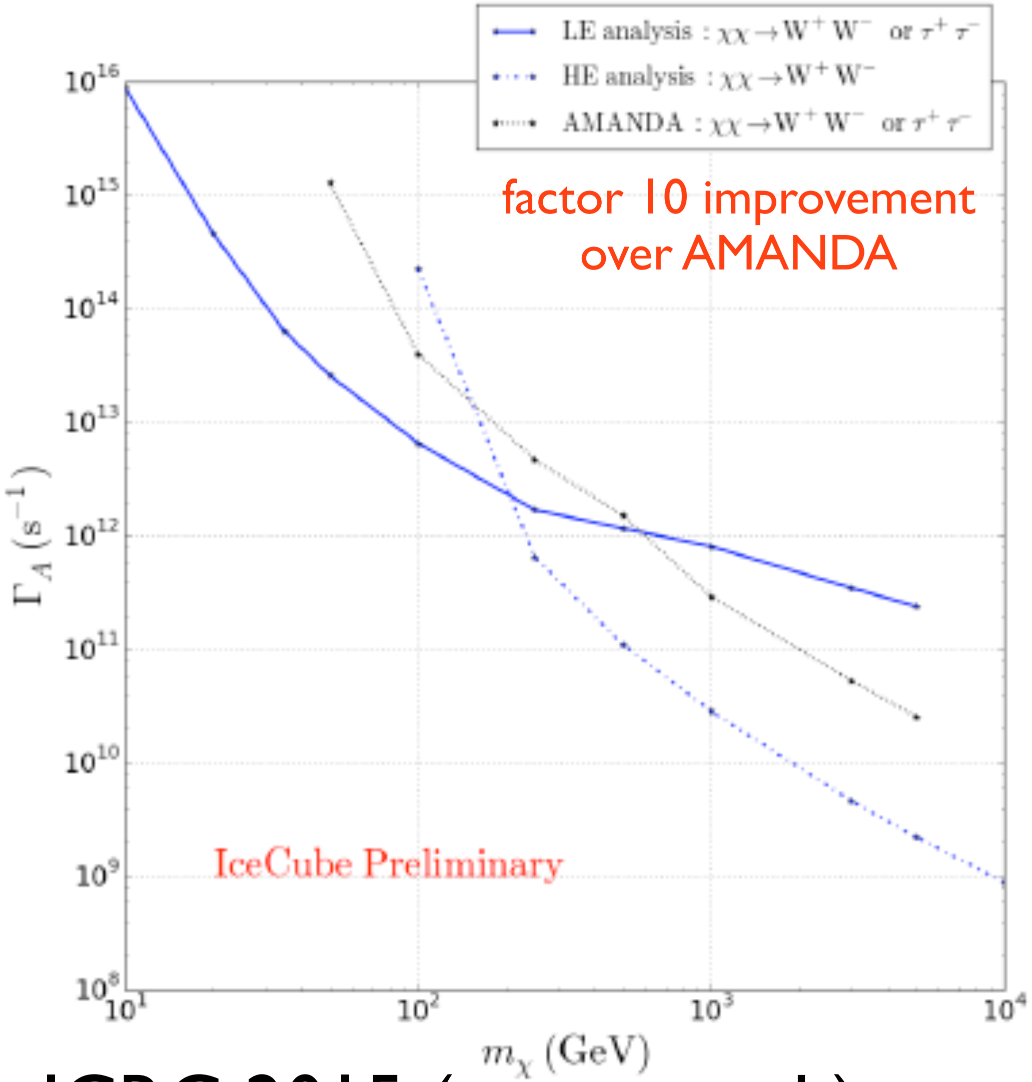
Earth WIMPs

- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux
- IC86-1 dataset: 2 statistically independent analyses
  - Low energy & High energy



Element	Atomic number	Mass fraction Core	Mantle
Oxygen, O	16	0.0	0.440
Silicon, Si	28	0.06	0.210
Magnesium, Mg	24	0.0	0.228
Iron, Fe	56	0.855	0.0626
Calcium, Ca	40	0.0	0.0253
Phosphor, P	30	0.002	0.00009
Sodium, Na	23	0.0	0.0027
Sulphur, S	32	0.019	0.00025
Nickel, Ni	59	0.052	0.00196
Aluminum, Al	27	0.0	0.0235
Chromium, Cr	52	0.009	0.0026

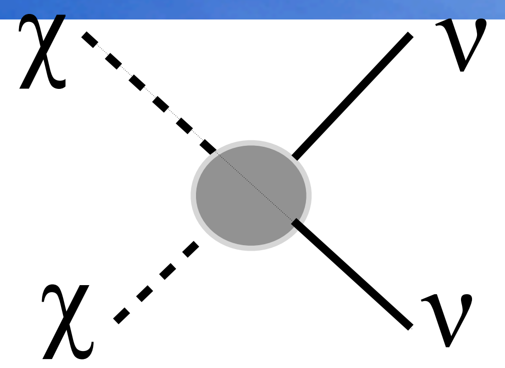




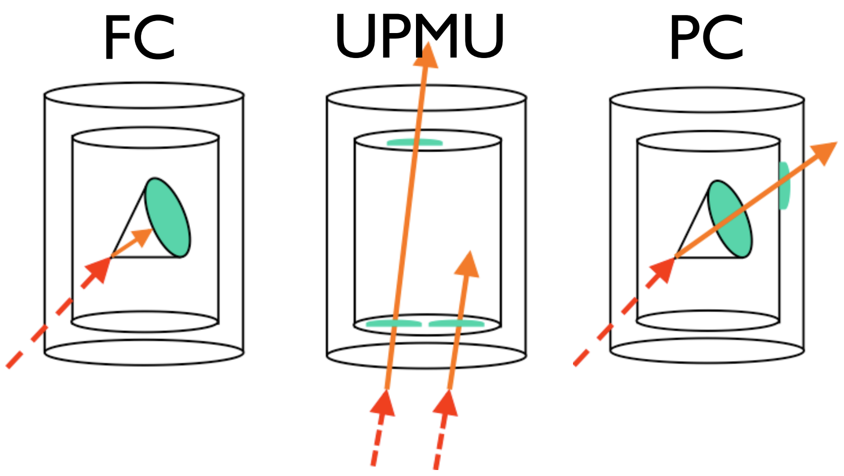
factor 10 improvement over AMANDA

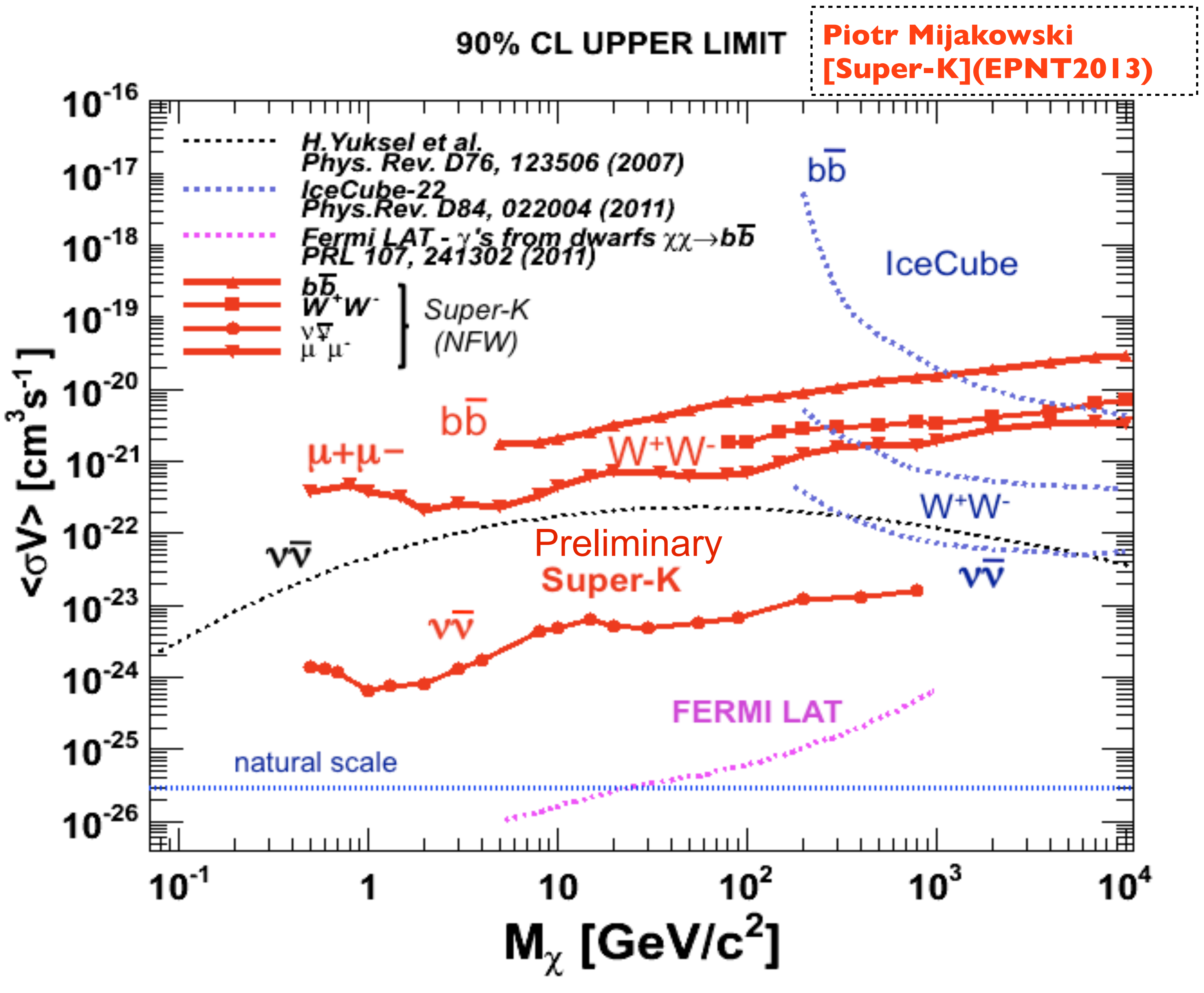
- First result of Earth WIMP analysis expected at ICRC 2015 (next month)

Super-K - Galactic Search



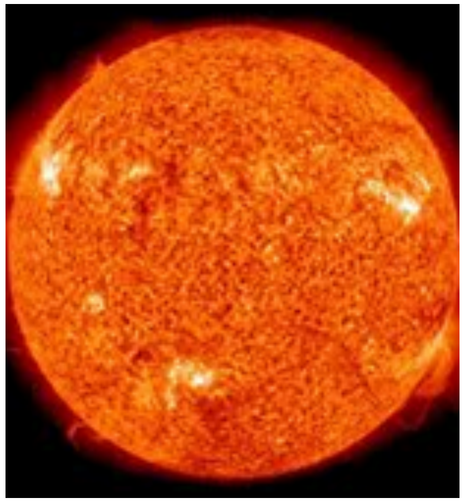
- Search for a diffuse signal from Milky Way halo
  - Assume annihilation into νν, bb, or WW
- Use all samples e-like + mu-like FC + PC (2806 days)+UPMU (3109 days)
- Use all neutrino flavors and topologies




Piotr Mijakowski [Super-K](EPNT2013)

What other improvements are possible ?

- What determines the signal rate ?
  - $S \sim (\Gamma_A/4\pi d^2)\ P_{\nu\rightarrow\nu}\ \sigma_{\nu N}(E_\nu)\ f_{channel}\ V\ T_{Life}$



1/6

1/6-1/2

IBD

O

C

Ar

HE

π^+

K^+

Super-K

Hyper-K

KamLAND

RENO50

JUNO

Dune

MICA

... and keep backgrounds low

Neutrino Oscillations

Normal mass hierarchy

R. Lehnert and T. J.Weiler, Phys. Rev. D 77, 125004 (2008) [arXiv:0708.1035 [hep-ph]].

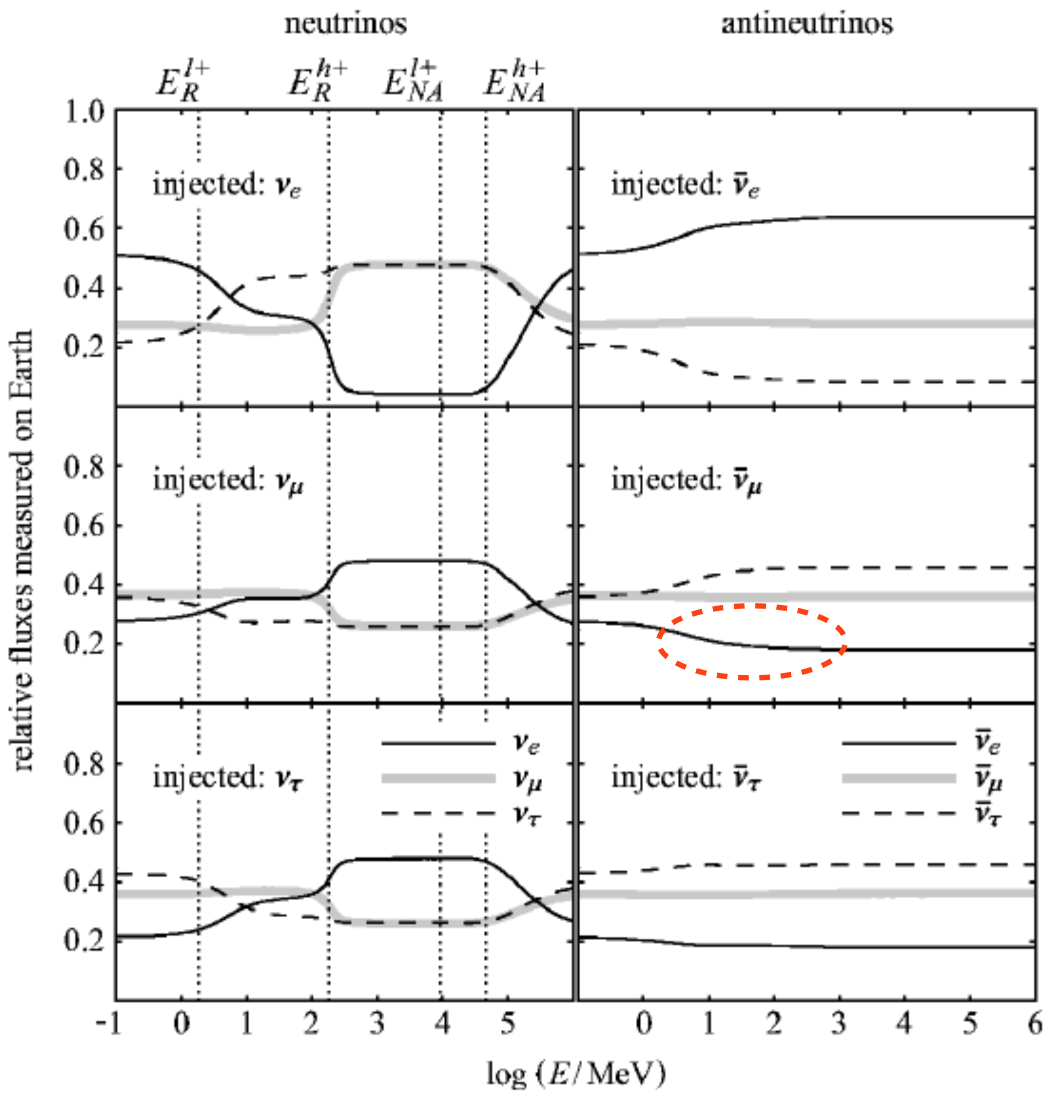


FIG. 3: Solar neutrino and antineutrino flavor probabilities at Earth versus energy, for a single injection flavor and fo normal mass hierarchy. Here, we have taken $\theta_{13} = 12°$, $\delta = 0$. All other neutrino parameters are as in Fig. 2. The ν_μ ai spectra and $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ spectra are interchanged if $\delta = \pi$ is chosen. Vertical dotted lines mark the characteristic scales fc lower-energy resonance given by Eqs. (50) and (52) and the higher-energy resonance given by Eqs. (53) and (54).

Inverted mass hierarchy

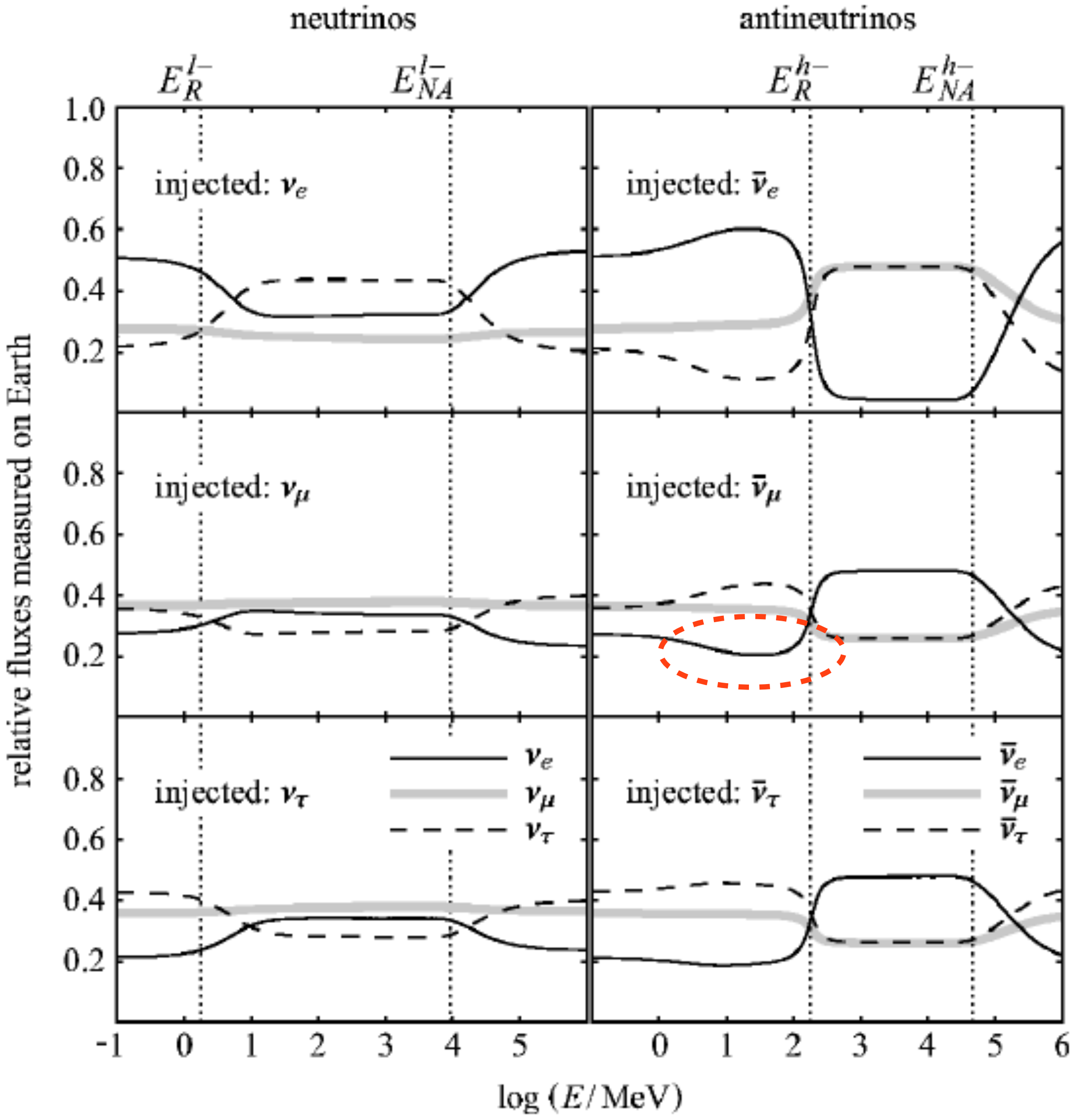
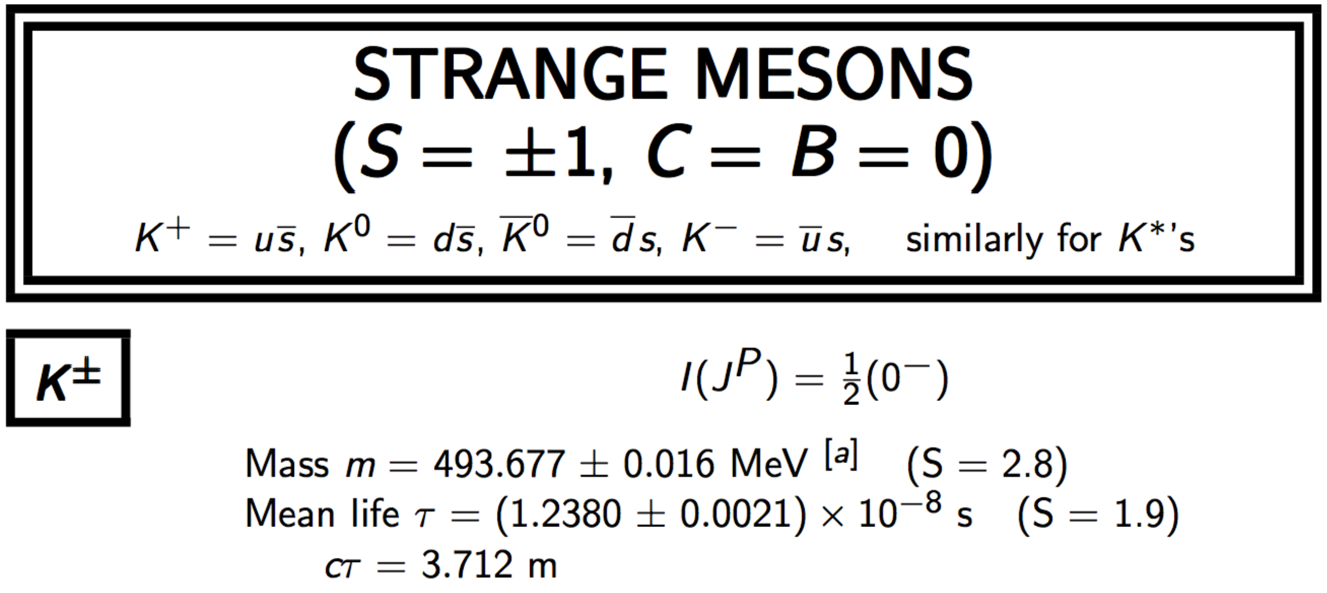


FIG. 4: Neutrino and antineutrino flavor probabilities on Earth versus energy, for the inverted hierarchy. Here, we have taken $\delta m^2_{32} = -3.0 \times 10^{-3}\,\mathrm{eV}^2$. All other neutrino parameters are as in Fig. 3 (including $\theta_{13} = 12°$ and $\delta = 0$). The ν_μ and ν_τ spectra and $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ spectra are interchanged if $\delta = \pi$ is chosen.

Kaons

K^+, K^-, K^0 and $\bar{K}^0$

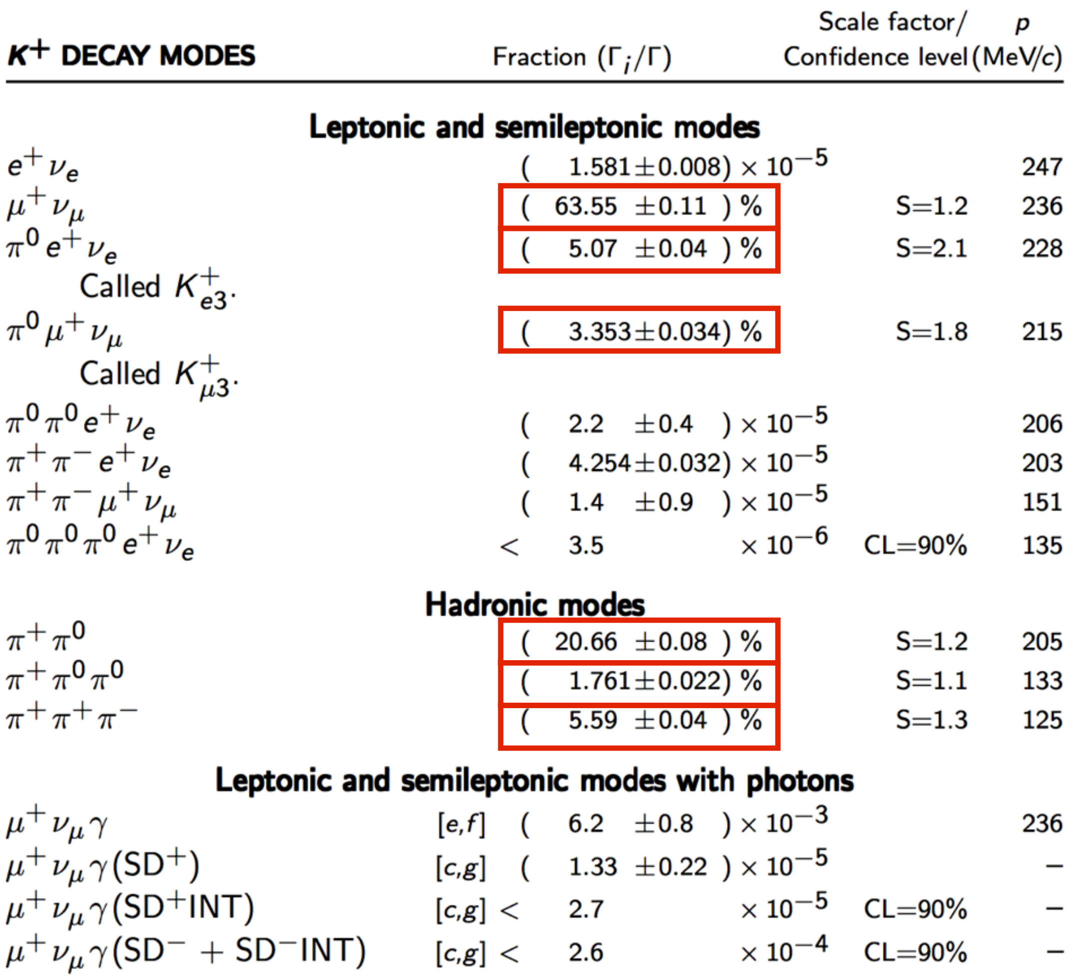


STRANGE MESONS
($S = \pm1$, $C = B = 0$)

$K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\overline{K}^0 = \overline{d}\,s$, $K^- = \overline{u}\,s$, similarly for K^*'s

$K^\pm$ $I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [a] (S = 2.8)
Mean life $\tau = (1.2380 \pm 0.0021) \times 10^{-8}$ s (S = 1.9)
$c\tau = 3.712$ m



K^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Leptonic and semileptonic modes				
$e^+\nu_e$		$(1.581 \pm 0.008) \times 10^{-5}$		247
$\mu^+\nu_\mu$		(63.55 ± 0.11) %	S=1.2	236
$\pi^0 e^+\nu_e$		(5.07 ± 0.04) %	S=2.1	228
Called K^+_{e3}.				
$\pi^0\mu^+\nu_\mu$		(3.353 ± 0.034) %	S=1.8	215
Called $K^+_{\mu3}$.				
$\pi^0\pi^0 e^+\nu_e$		$(2.2 \pm 0.4) \times 10^{-5}$		206
$\pi^+\pi^- e^+\nu_e$		$(4.254 \pm 0.032) \times 10^{-5}$		203
$\pi^+\pi^-\mu^+\nu_\mu$		$(1.4 \pm 0.9) \times 10^{-5}$		151
$\pi^0\pi^0\pi^0 e^+\nu_e$		$< 3.5 \times 10^{-6}$	CL=90%	135
Hadronic modes				
$\pi^+\pi^0$		(20.66 ± 0.08) %	S=1.2	205
$\pi^+\pi^0\pi^0$		(1.761 ± 0.022) %	S=1.1	133
$\pi^+\pi^+\pi^-$		(5.59 ± 0.04) %	S=1.3	125
Leptonic and semileptonic modes with photons				
$\mu^+\nu_\mu\gamma$	[e,f]	$(6.2 \pm 0.8) \times 10^{-3}$		236
$\mu^+\nu_\mu\gamma(\mathrm{SD}^+)$	[c,g]	$(1.33 \pm 0.22) \times 10^{-5}$		–
$\mu^+\nu_\mu\gamma(\mathrm{SD}^+\mathrm{INT})$	[c,g]	$< 2.7 \times 10^{-5}$	CL=90%	–
$\mu^+\nu_\mu\gamma(\mathrm{SD}^- + \mathrm{SD}^-\mathrm{INT})$	[c,g]	$< 2.6 \times 10^{-4}$	CL=90%	–

$K^+ \longrightarrow \mu^+\nu_\mu$ 63.5% (235.5MeV line)

$\pi^0 e^+\nu_e$
$\pi^0\mu^+\nu_\mu$ 8.4%

$\pi^+\pi^0$
$\pi^+\pi^0\pi^0$ 28.0% (pions)
$\pi^+\pi^+\pi^-$