Solar WIMP Searches with MeV Neutrinos

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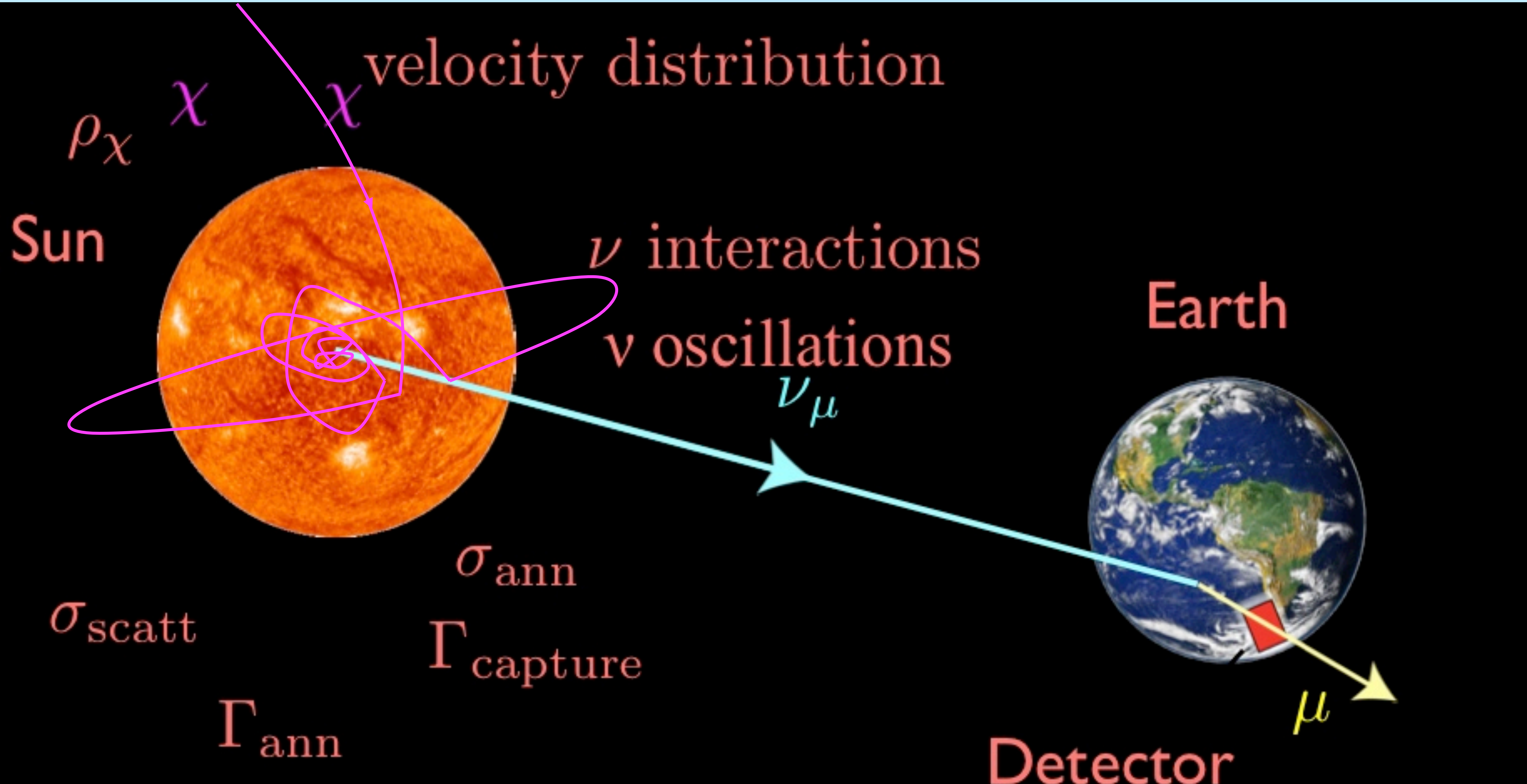
Overview

- Motivation
- Current Indirect bounds
- A new detection channel
- Sensitivity at current and next generation detectors
- Conclusions and Outlook

Solar WIMPs



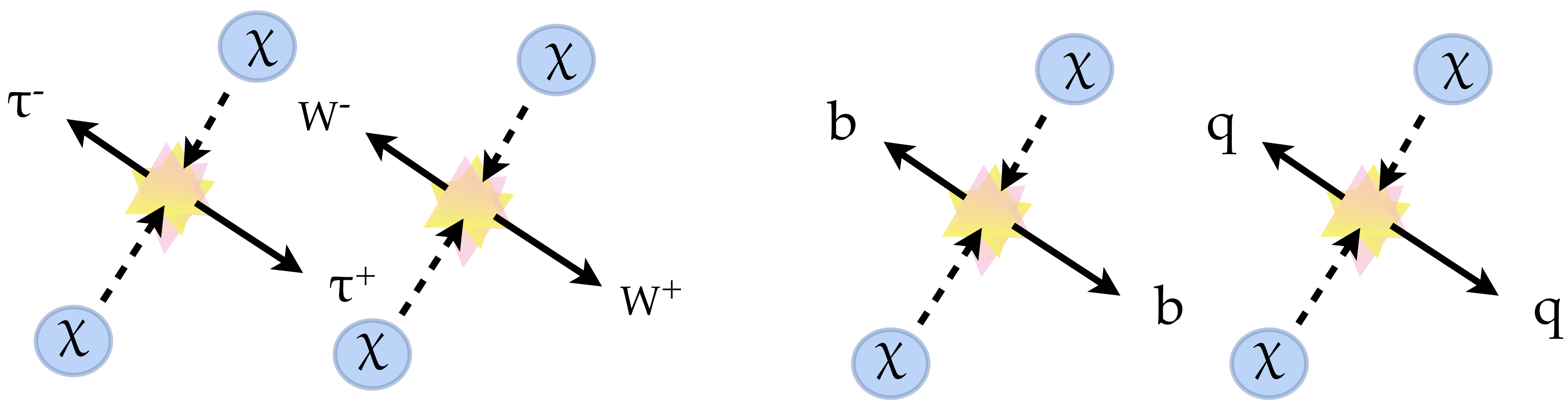
Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

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

Motivation

- Neutrino Telescope provide some of the best constraints on WIMP-Nucleon scattering through Solar WIMP searches
- How can we improve the sensitivity of present day and next generation instruments including those for low-mass WIMPs ?
- Can we find alternatives to present searches ?

Dark Matter Annihilation in the Sun



high energy neutrinos from annihilation / decay products

$\nu\nu$ $\tau^-\ \tau^+$ $W^-\ W^+$ bb qq e^+e^-

most high energy neutrinos

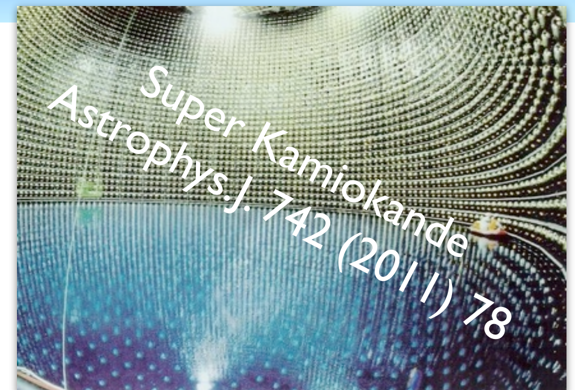
fewest high-energy neutrinos

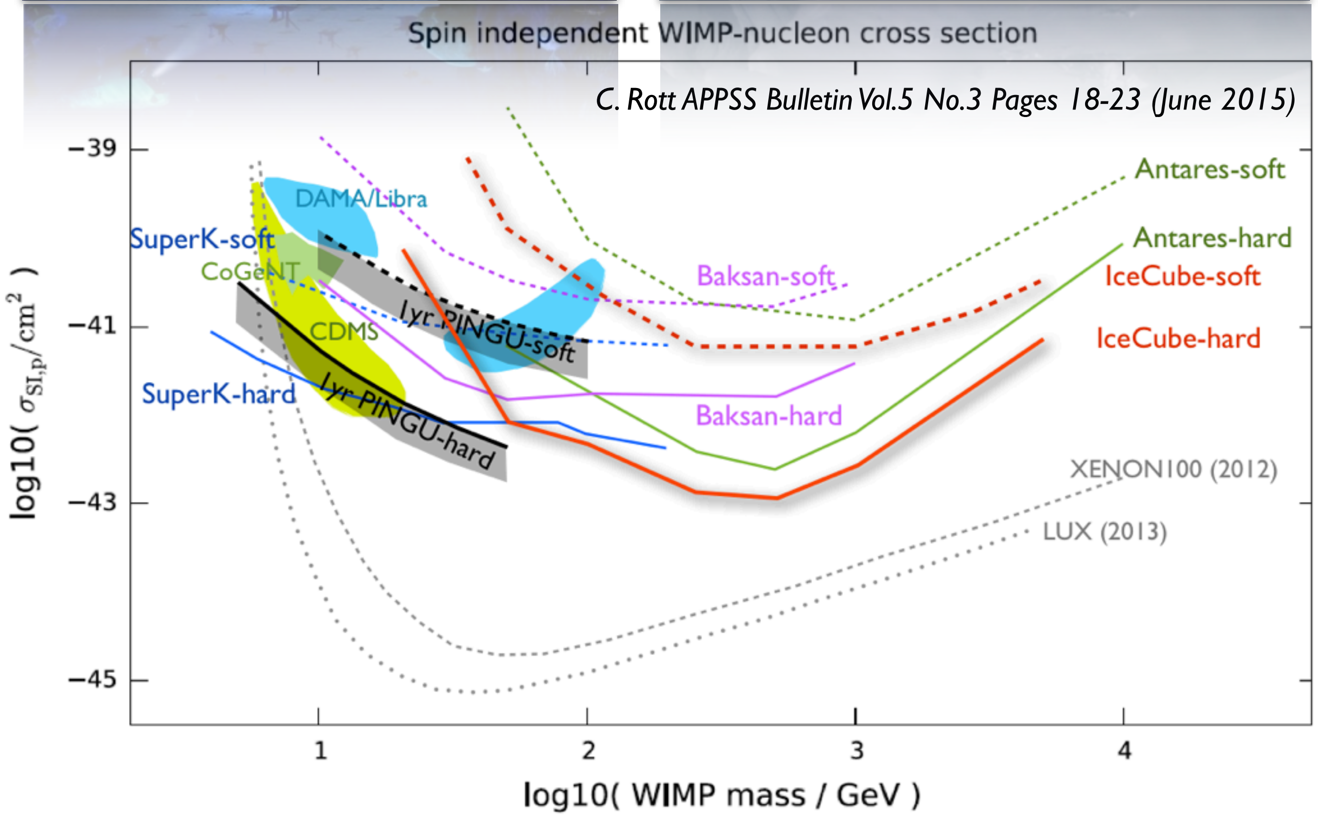
Define Benchmarks Scenarios with Br 100%

Hard channel

Soft channel

Current indirect bounds





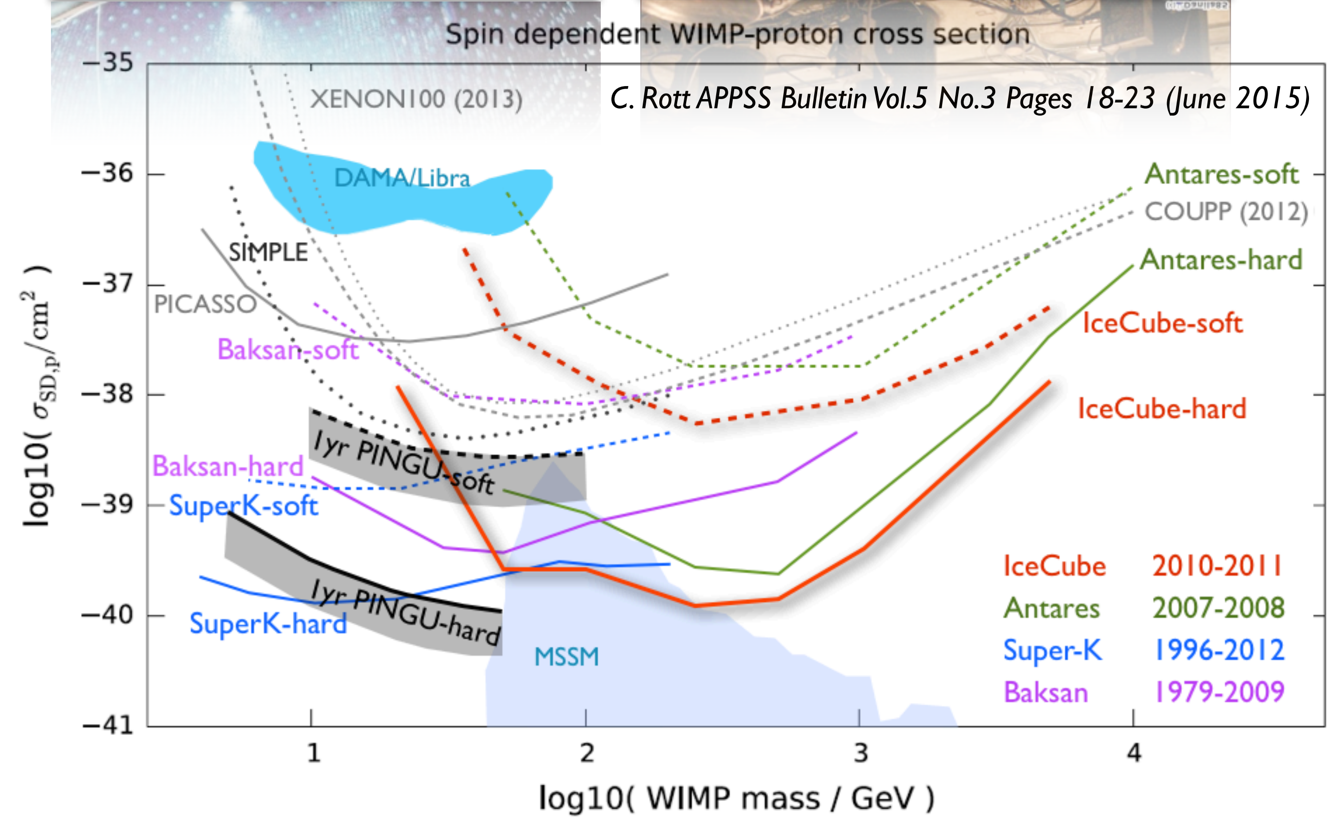


Table 1: Rough comparison of neutrino telescope characteristics relevant for current Solar DM searches. The median angular resolution ($\overline{\Theta}$) is quoted for different representative neutrino energies (E_ν), where applicable. More details in Refs. [35, 34] (IceCube), [39, 50] (ANTARES), [38, 51] (SK), and [40] (Baksan).

	Datasets with completed analyses	Livetime (days)	E_ν-range (GeV)	Instrumented volume (ton)	$\overline{\Theta}$ (°) at E_ν 25 / 100 / 1000 GeV
IceCube	2010-2011	317	$\gtrsim 10$	~1 Gton	13 / 3.2 / 1.3
ANTARES†	2007-2008	295	$\gtrsim 10$	~20 Mton	6 / 3.5 / 1.6
SK	1996-2012	3903	$\gtrsim 0.1$	~50 kton	1-1.4‡
Baksan	1979-2009	8803	$\gtrsim 1$‡	~3 kton	1.5‡ (tracks > 7 m)

† Preliminary 2007-2012 results correspond to 1321 days livetime

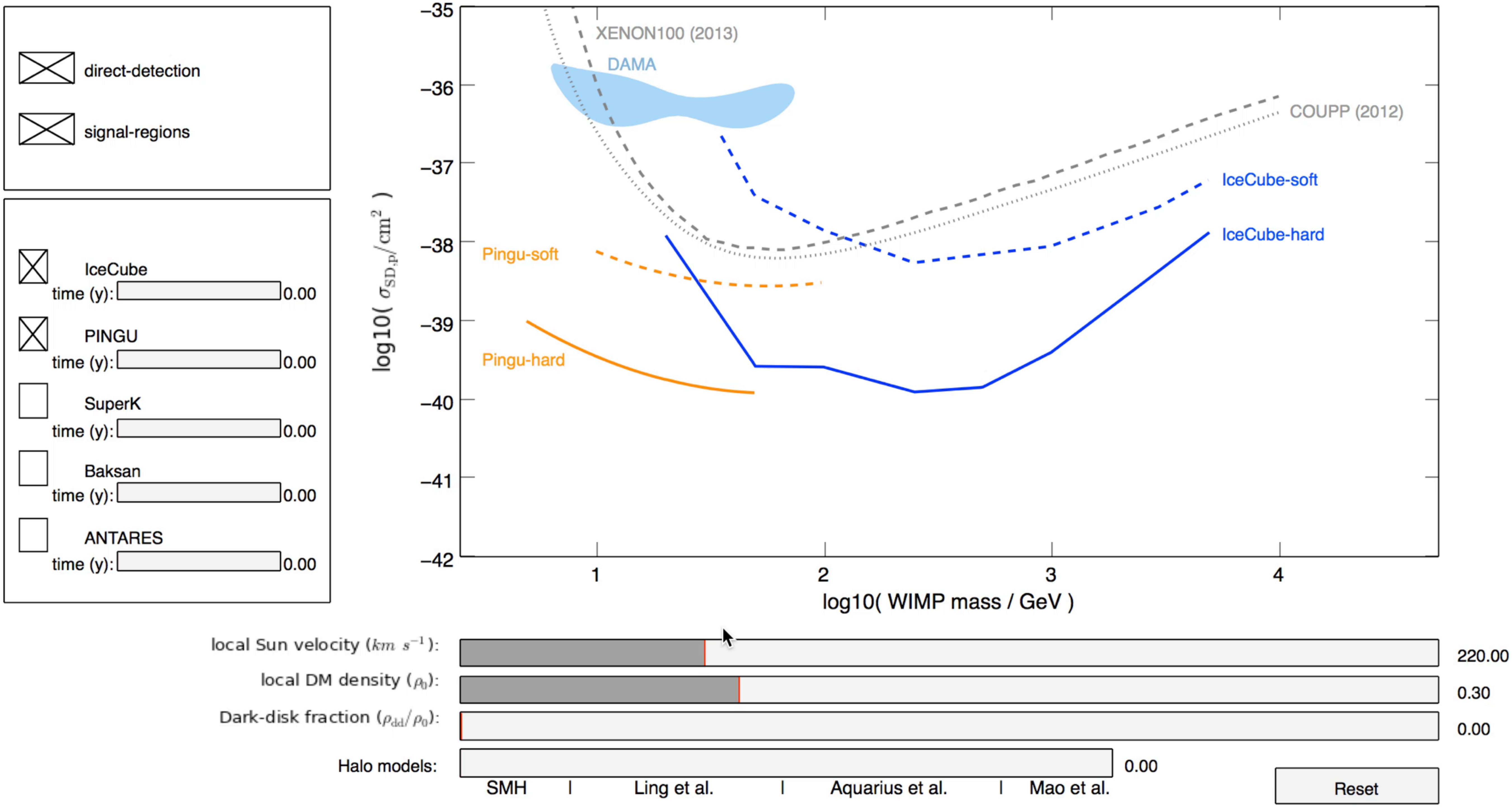
‡ Values are given at muon level (E_μ); $\overline{\Theta}$ dominated by kinematic scattering angle.

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

Impact of astrophysical uncertainties

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

interactive tool to study impact of astrophysical parameters

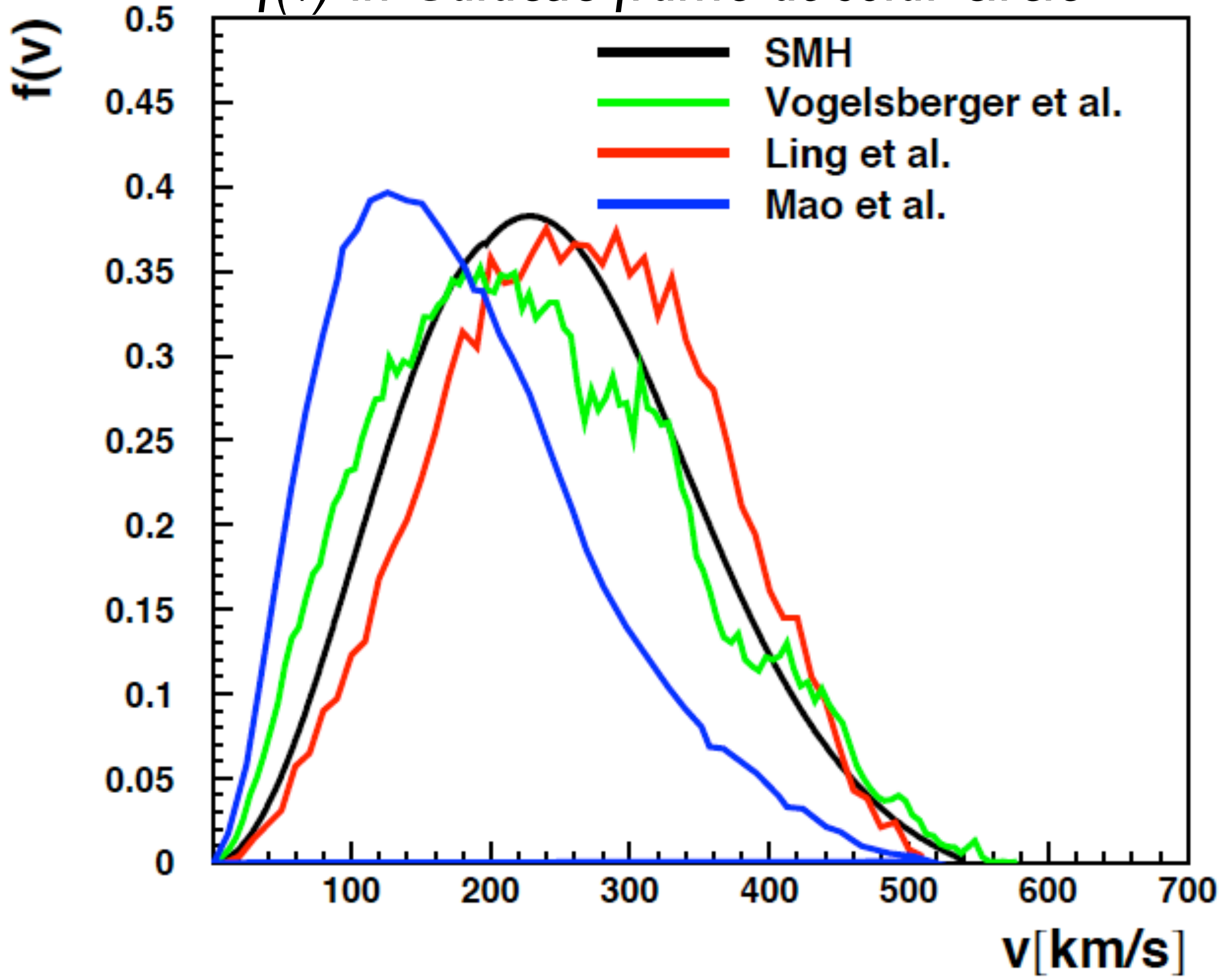


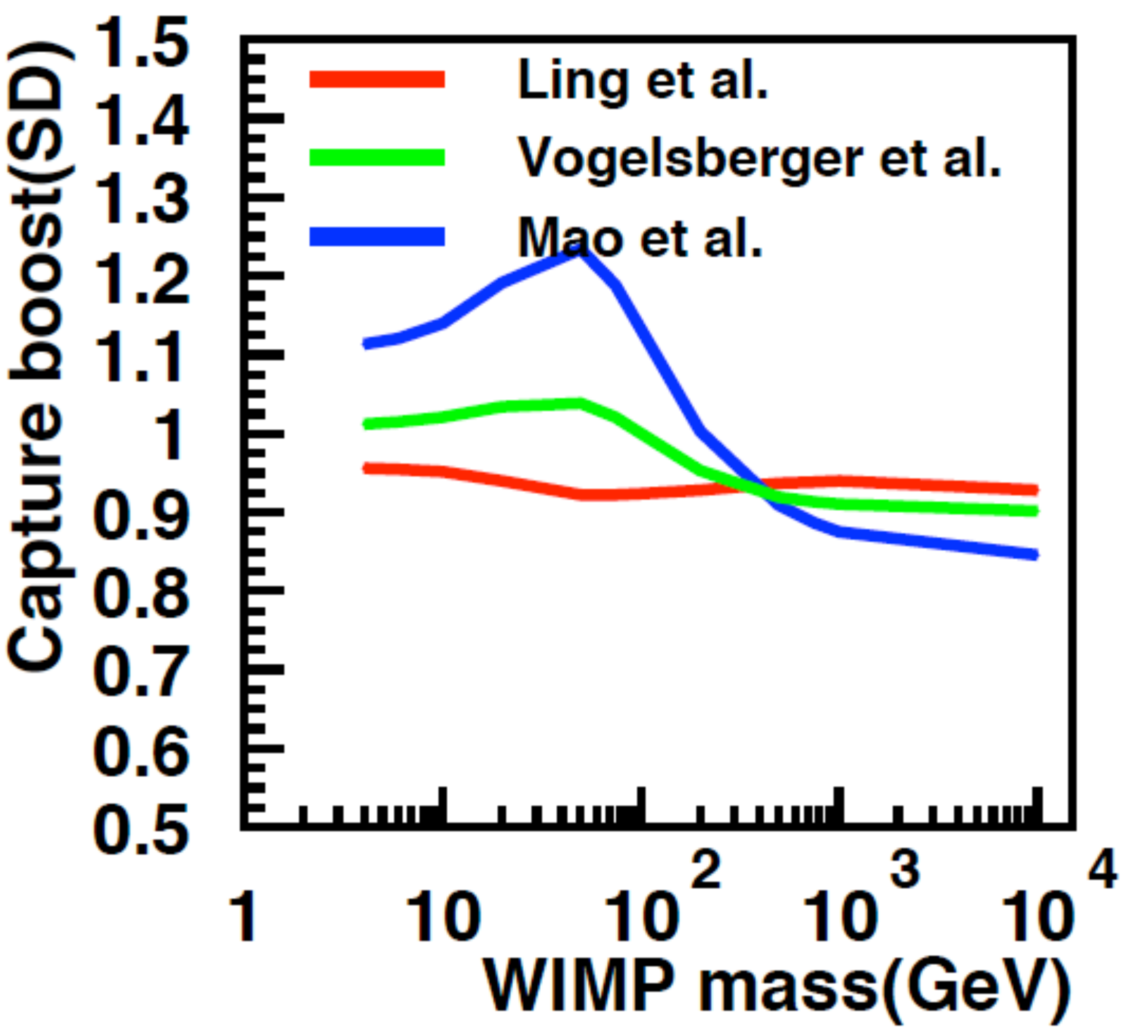
Impact of velocity distribution

- 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%

Low Energy Neutrinos from the Sun

Low-Energy Neutrinos from the Sun

Possible annihilation channels:

qq,gg

don

the absorption of stopped negative pions. They are captured into atomic orbits and emit x rays until they reach a sufficiently small radius (because of their large rest mass) to interact with the nuclear medium. At this point they disappear as pions and their rest mass appears as various reaction fragments. Because the available energy is small, the dominance of the delta resonance in this process is no longer assured but, because of the internal momenta of the nucleons, neither can contributions from the delta be ruled out entirely.

Ch

deca

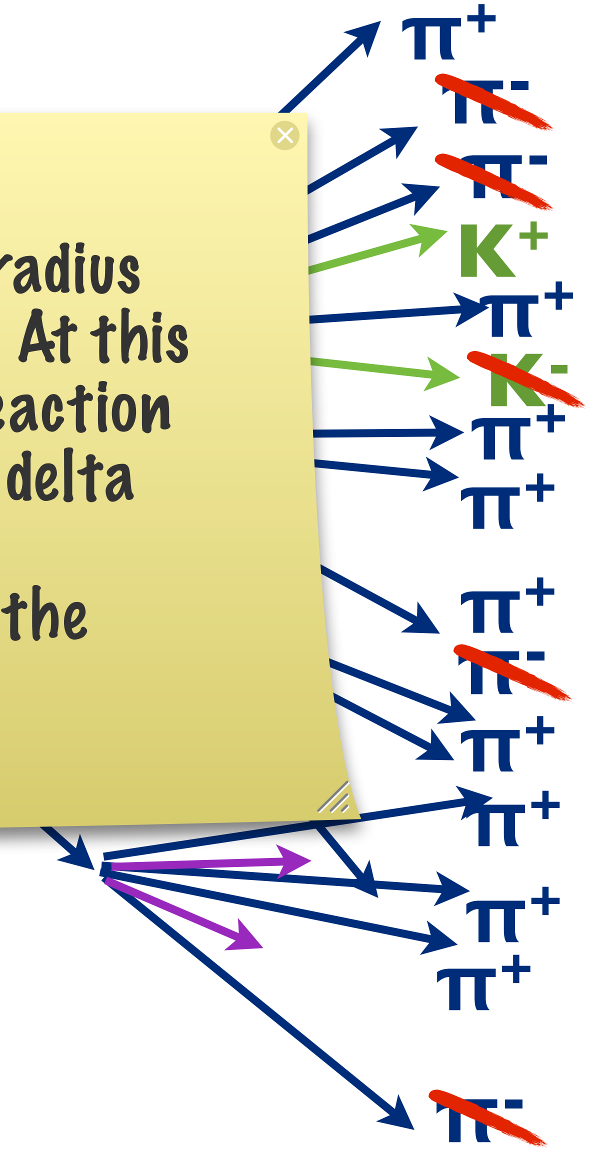
mon

π^+

K^+

For high-energy charged pions, the hadronic interaction length in the Sun is short compared to the decay and continuous energy-loss lengths, so the number of pions increases in each generation of the hadronic shower until loss processes dominate at low energies energies.

$\mu \rightarrow e \, \nu_e \nu_\mu$



ifetime too short to interact

nteraction length short compared to losses

- Produces secondary particles in collision with protons
- Dominant energy loss term is π^0 production

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

STRANGE MESONS
($S = \pm 1$, $C = B = 0$)

$K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\overline{K}^0 = \overline{d}\,s$, $K^- = \overline{u}\,s$, 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 $K^+_{\mu 3}$.				
$\pi^0\pi^0 e^+\nu_e$		$(2.2 \pm 0.4) \times 10^{-5}$		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)
$\pi^+\pi^+\pi^-$

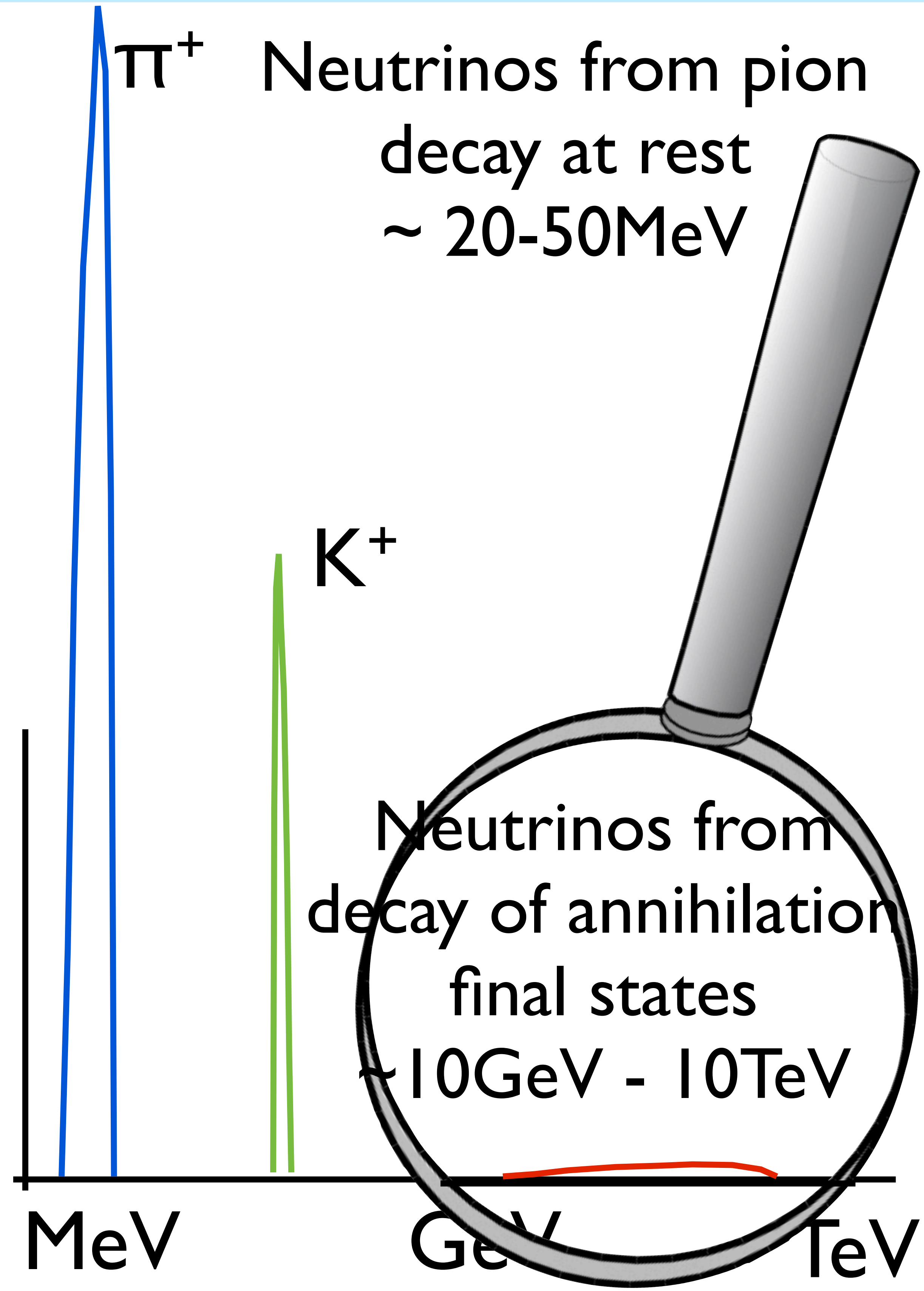
Neutrino signals - Example W-Boson

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

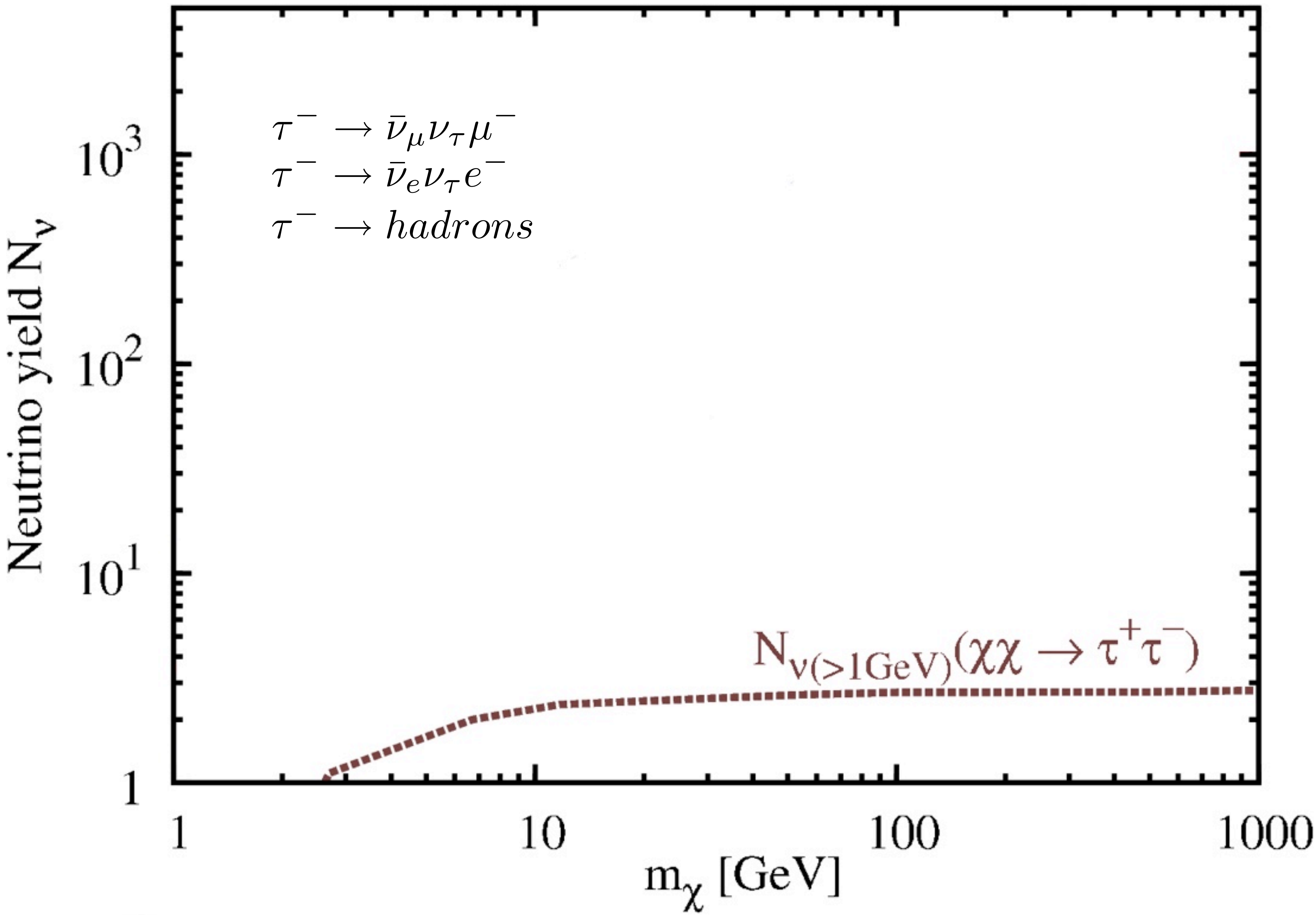
$\longrightarrow qq$ ~67%

Let's have a closer look at this:

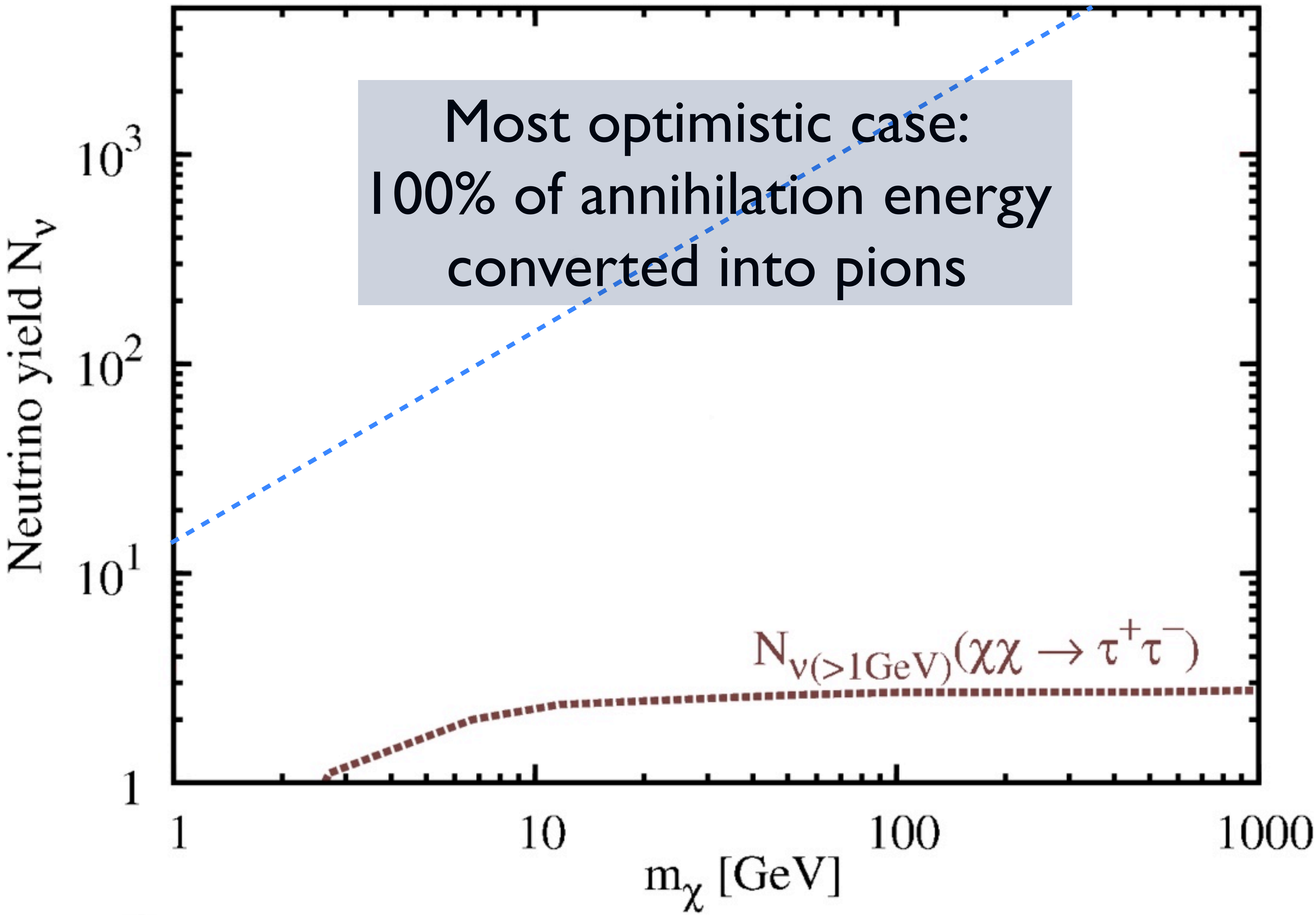
$e^+\nu_e$	1 high energy ν + em shower
$\mu^+\nu_\mu$	1 high energy ν + muon
$\tau^+\nu_\tau$	1 high energy ν + tau decay
qq	hadronic shower



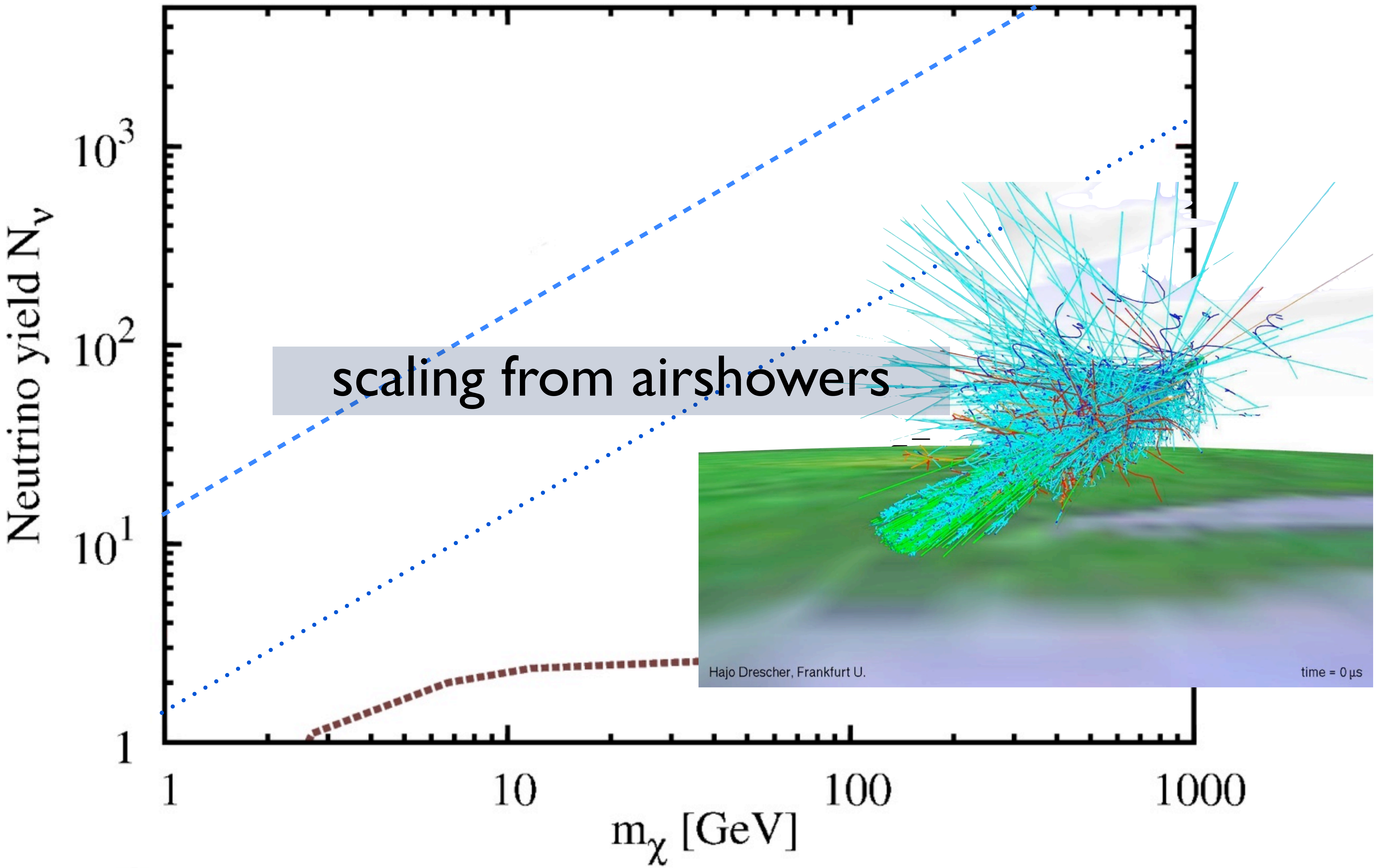
What is the Neutrino yield ?



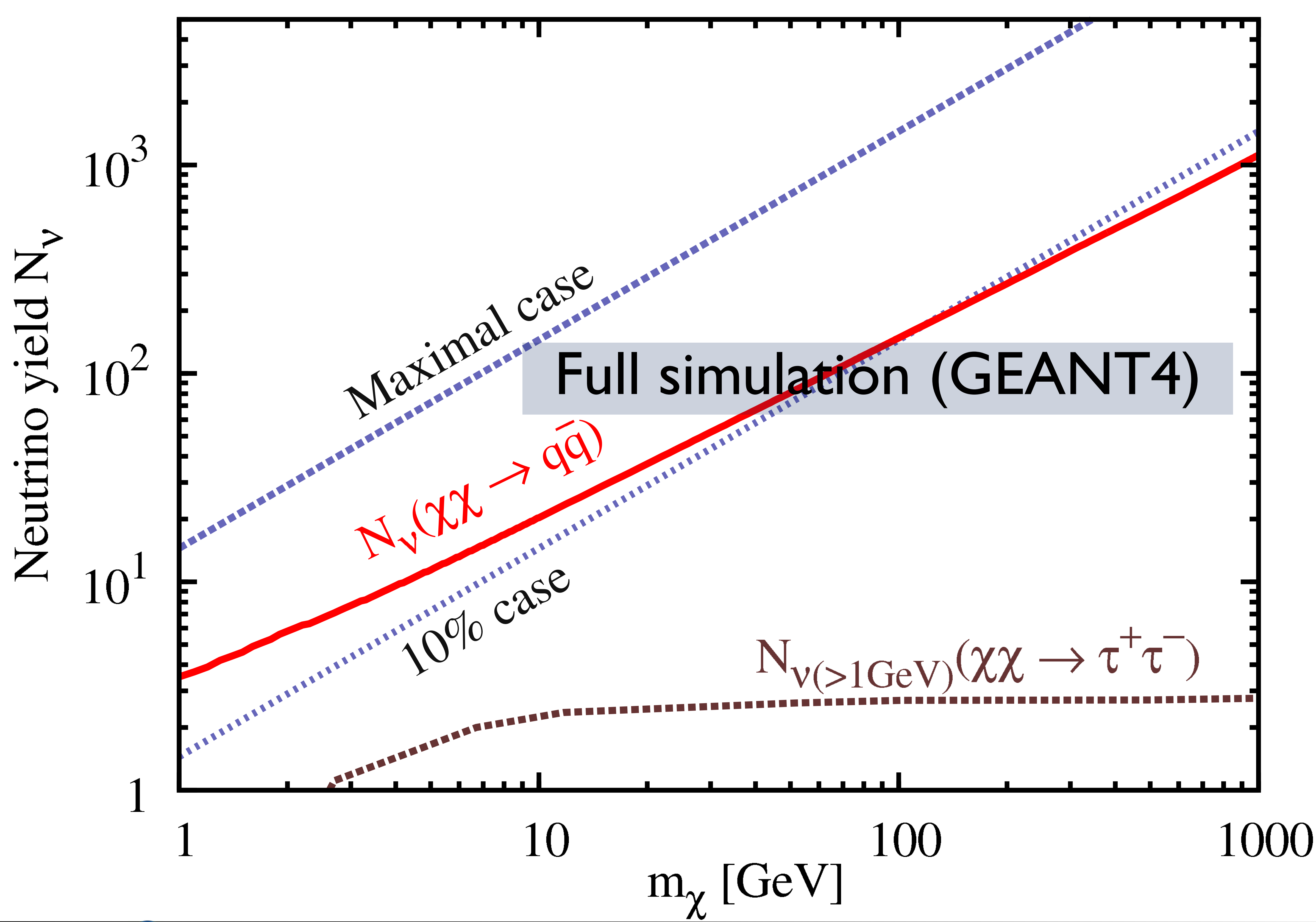
What's the Neutrino yield ?



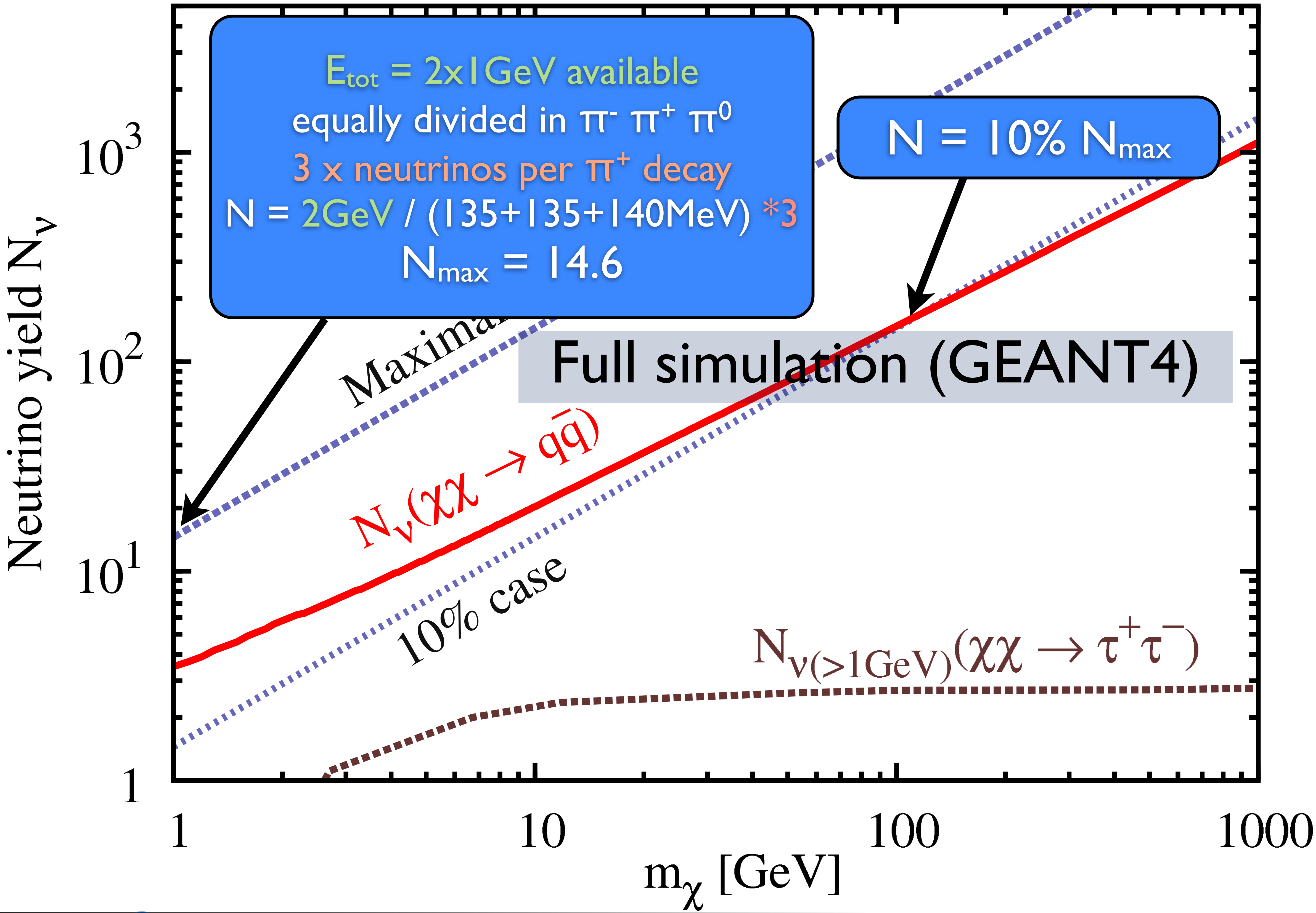
What's the Neutrino yield ?



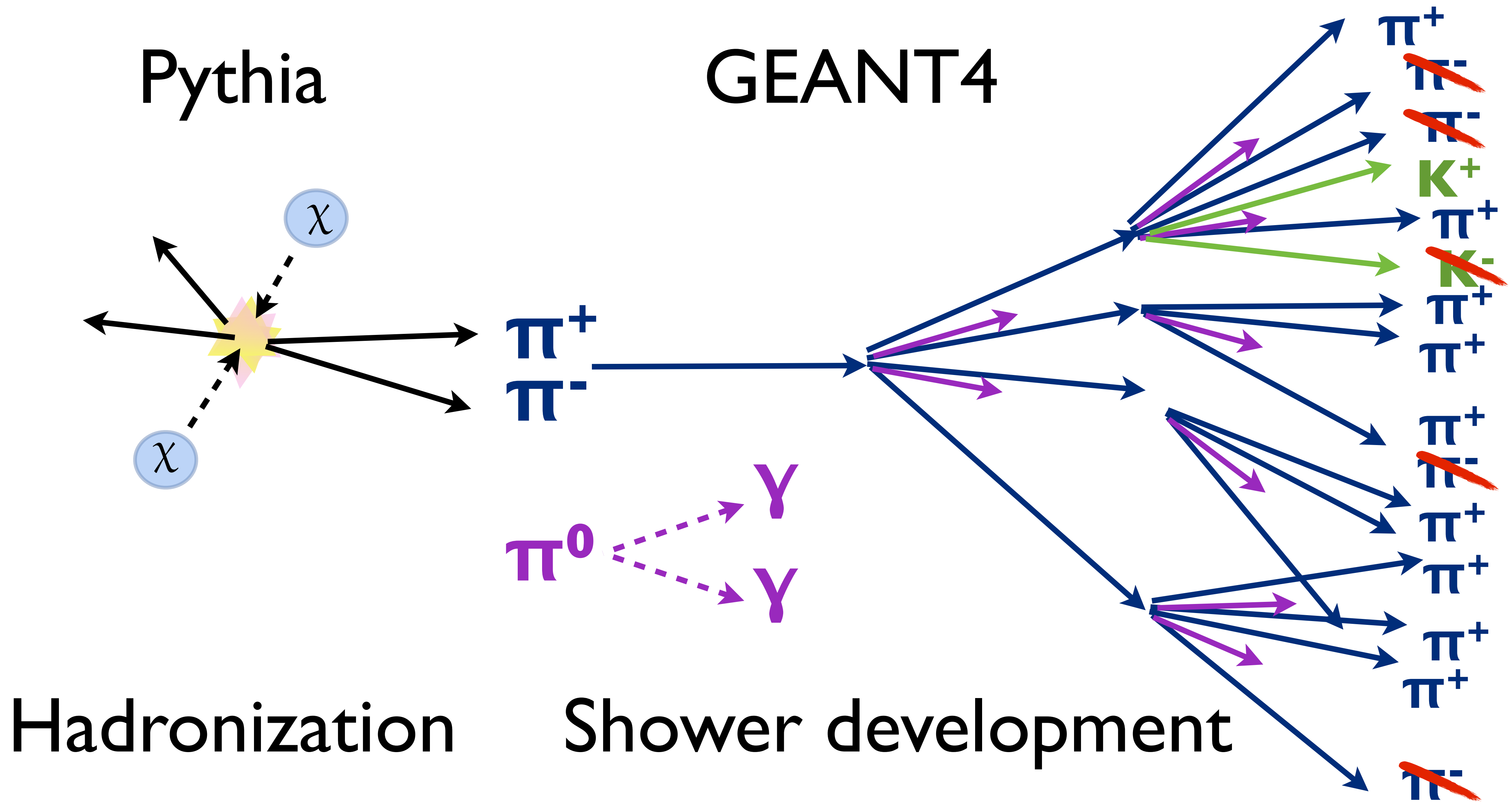
Neutrino yield



Neutrino yield



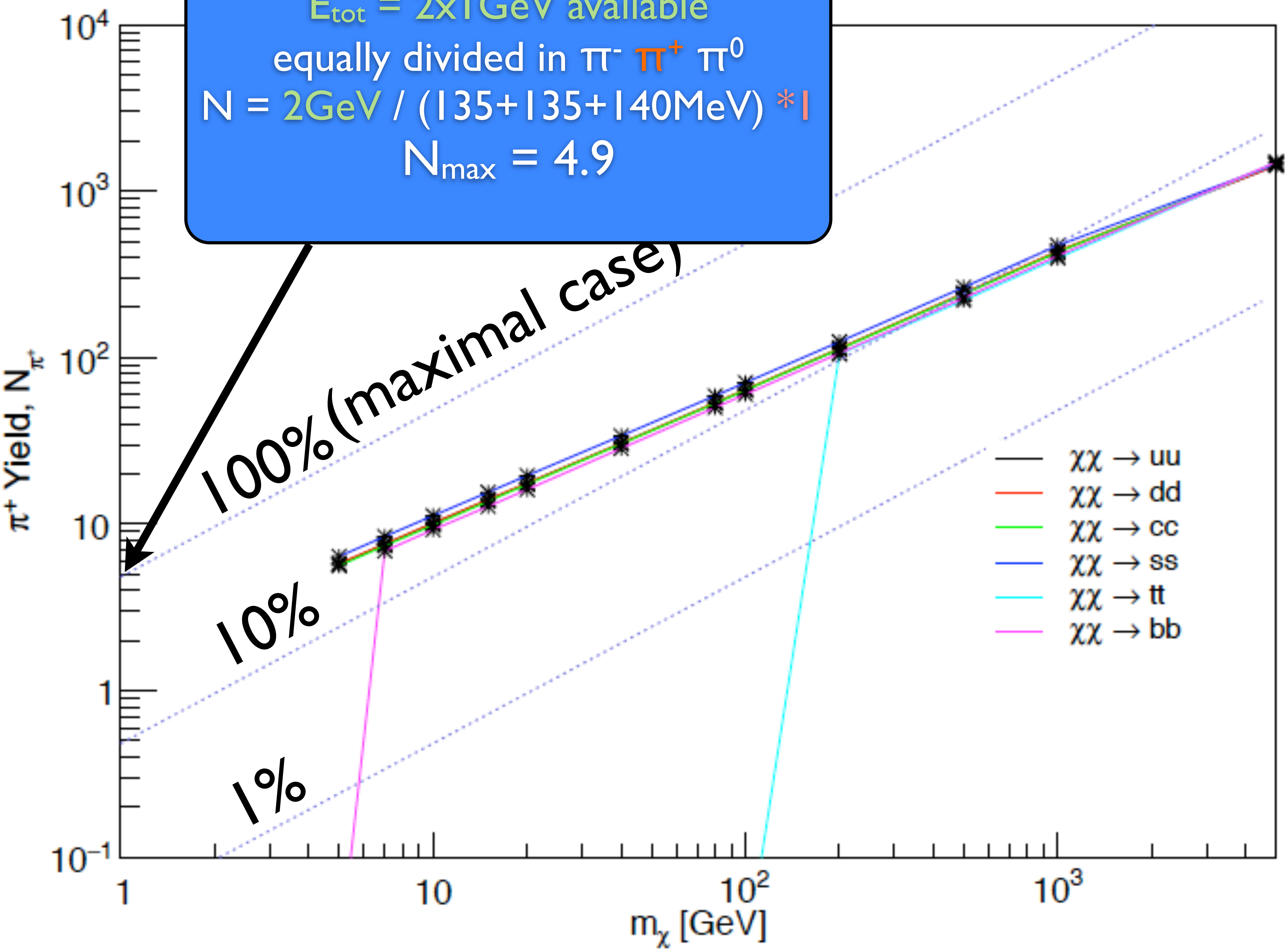
Pion and kaon yield



- 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.

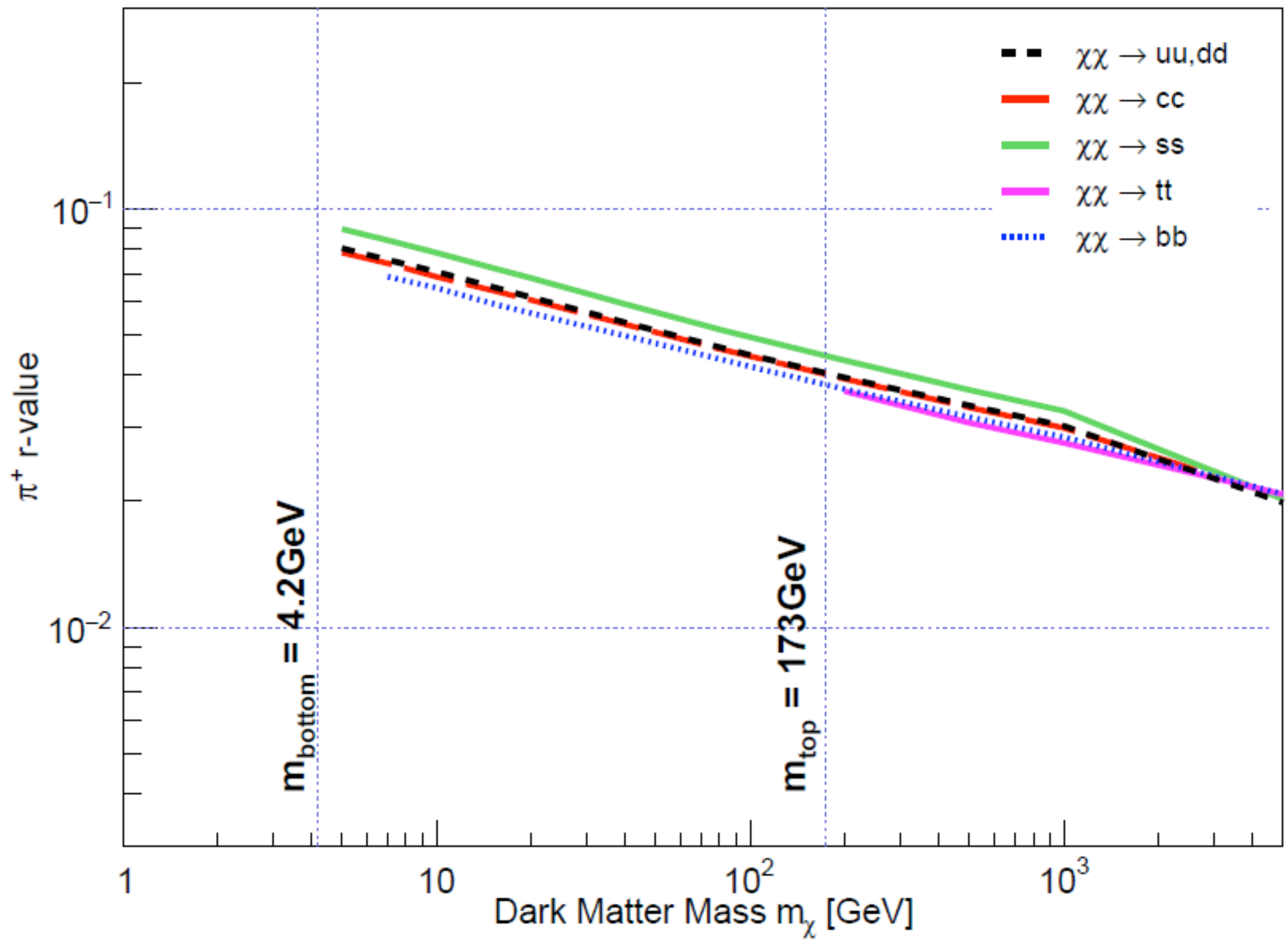
pi+ yield

E_{tot} = 2x1GeV available
equally divided in $\pi^- \pi^+ \pi^0$
N = 2GeV / (135+135+140MeV) *1
N_{max} = 4.9



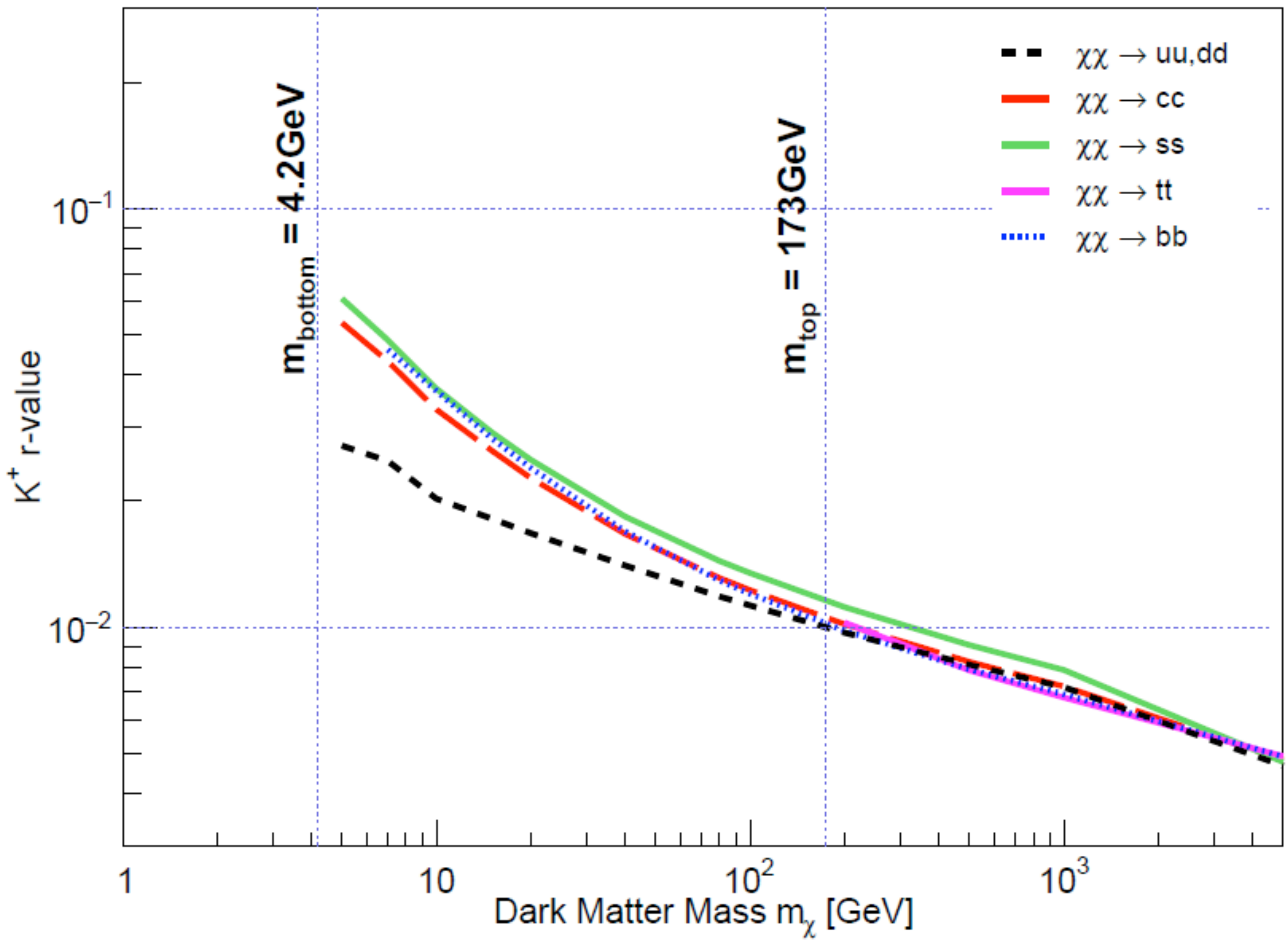
r-value pion

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



r-value kaon

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



Signal in Water Cherenkov

C. Rott, J. Siegal-Gaskins, J.F.Beacom (arXiv1208.0827)

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

Normal mass hierarchy

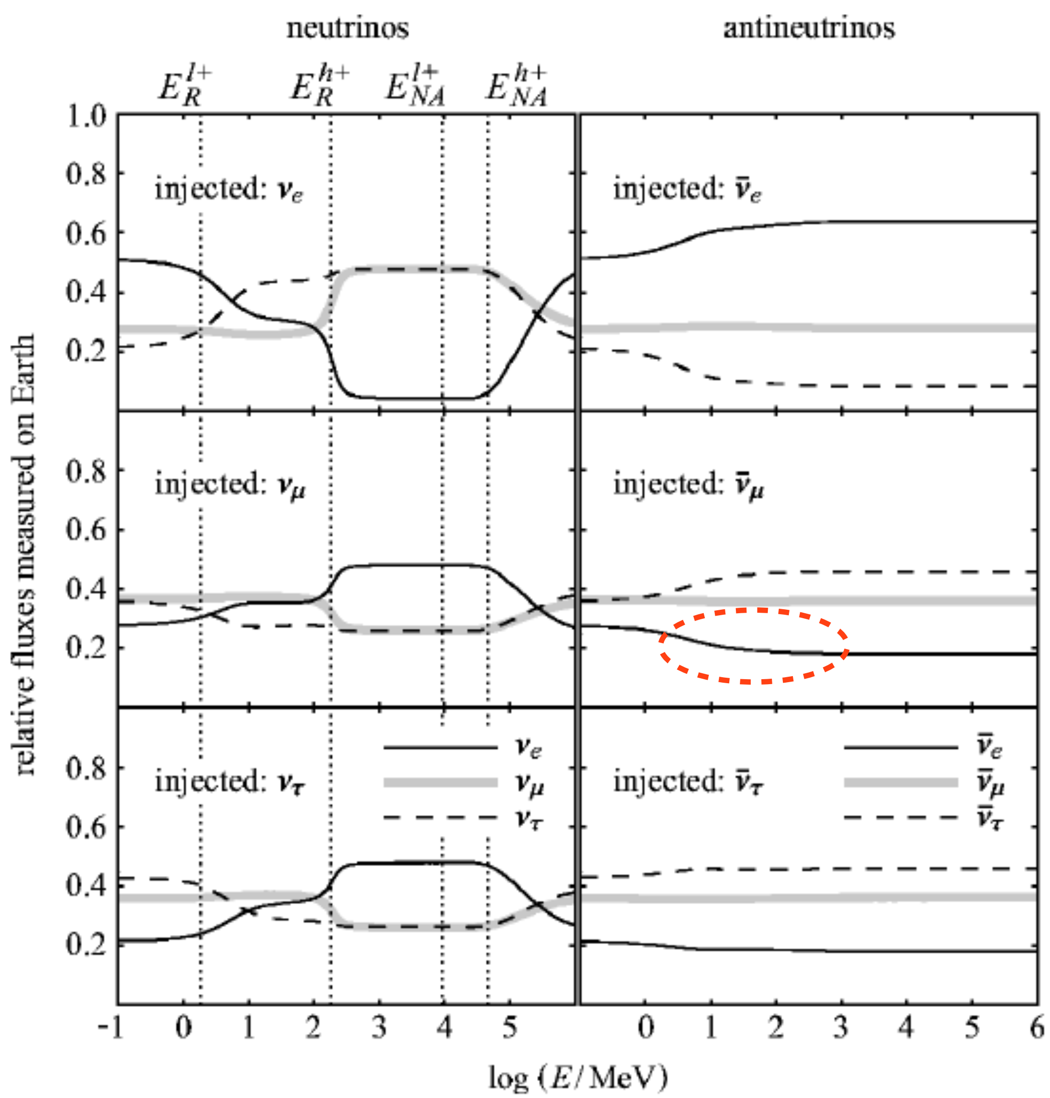


FIG. 3: Solar neutrino and antineutrino flavor probabilities at Earth versus energy, for a single injection flavor and fo normal mass hierarchy. Here, we have taken $\theta_{13} = 12°$, $\delta = 0$. All other neutrino parameters are as in Fig. 2. The ν_μ ai spectra and $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ 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

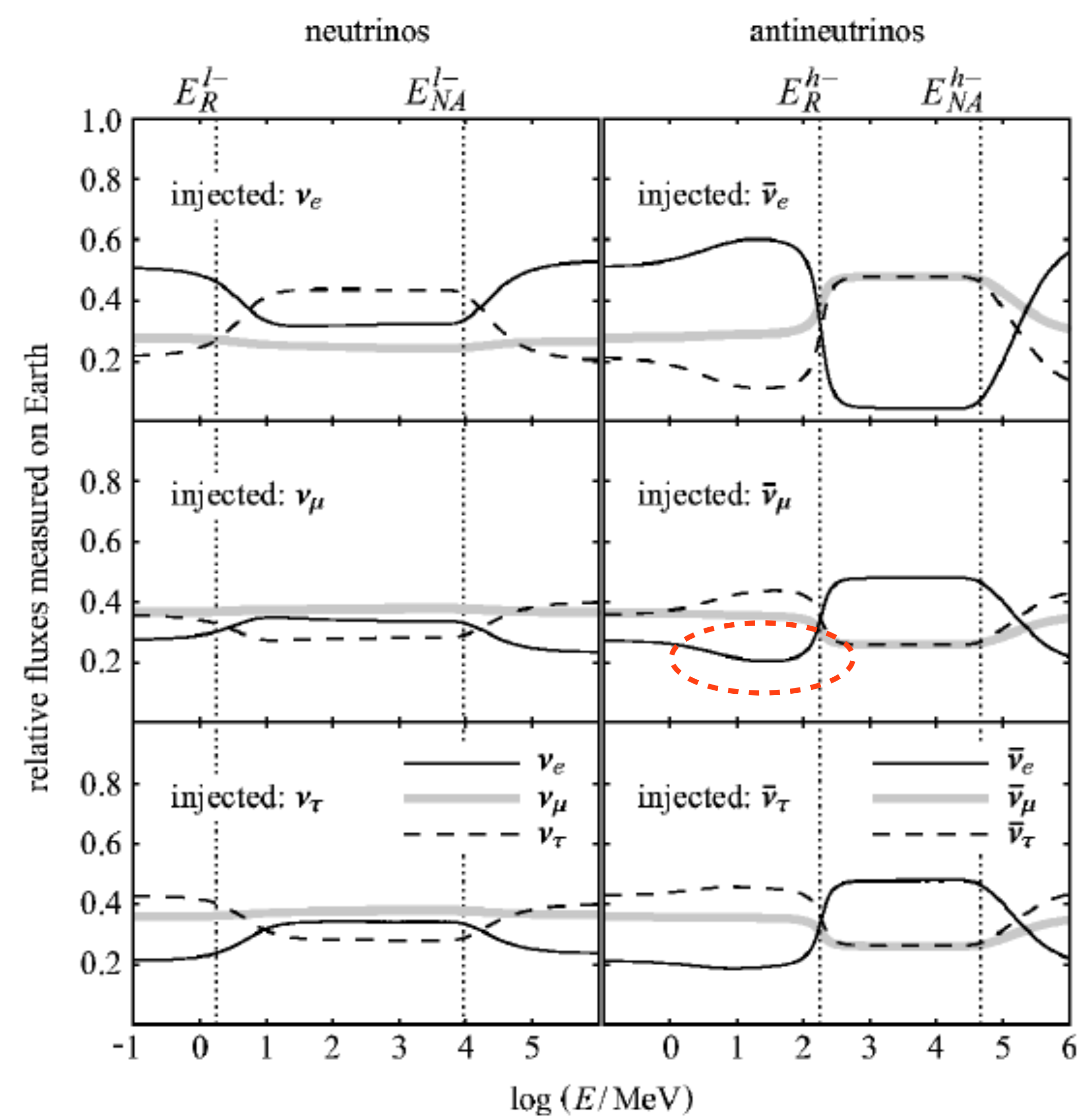
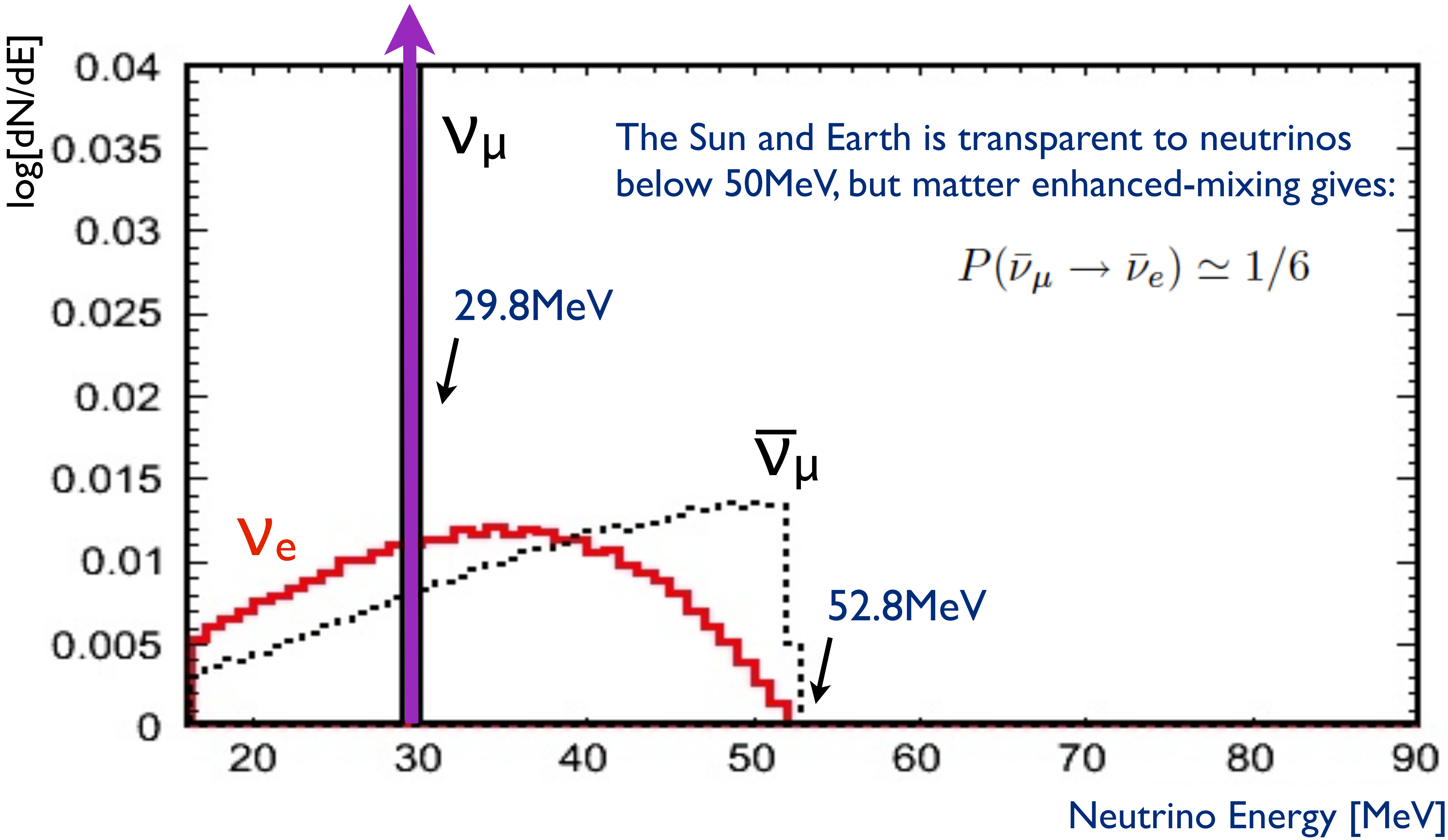
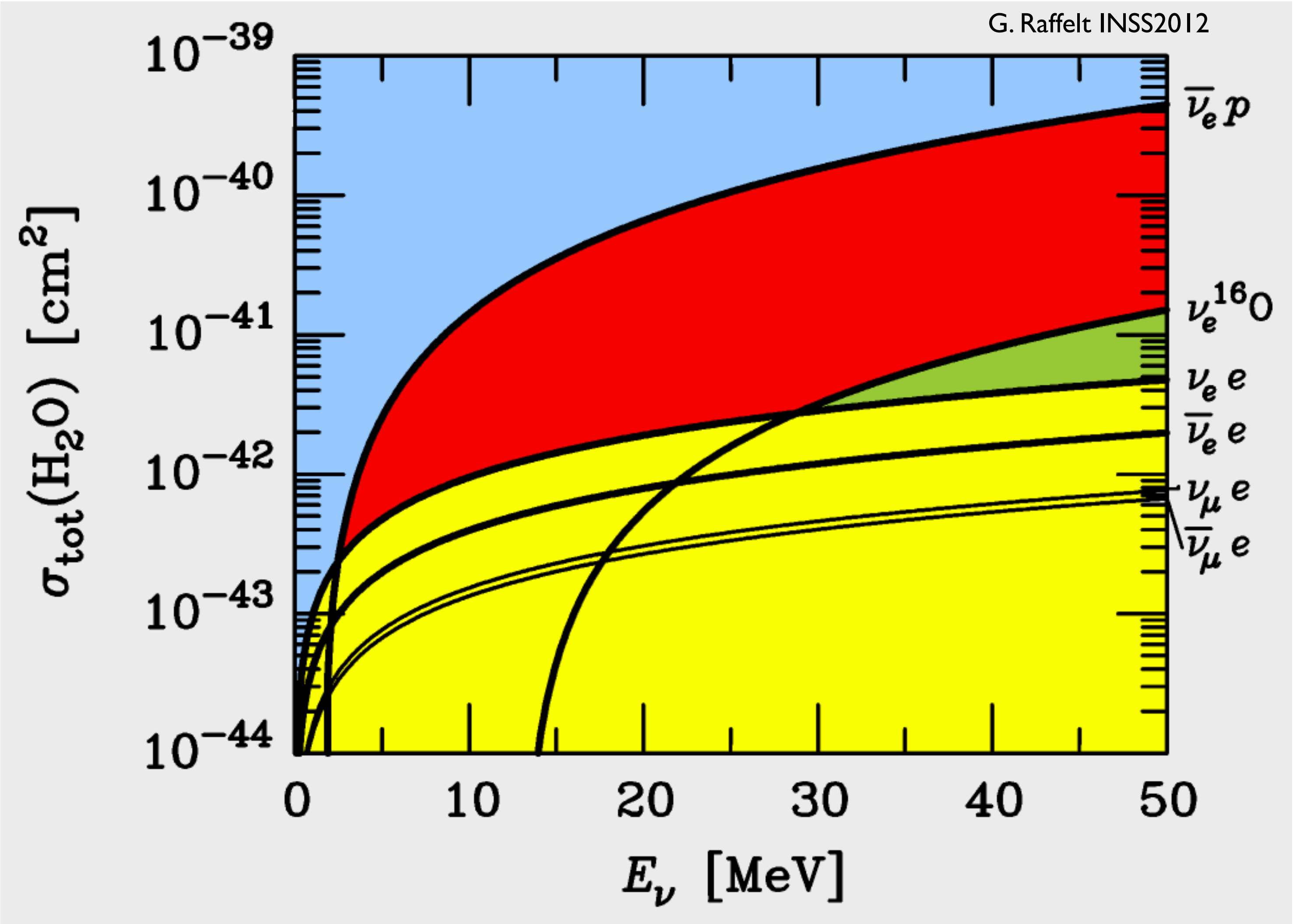


FIG. 4: Neutrino and antineutrino flavor probabilities on Earth versus energy, for the inverted hierarchy. Here, we have taken $\delta m^2_{32} = -3.0 \times 10^{-3}\,\mathrm{eV}^2$. All other neutrino parameters are as in Fig. 3 (including $\theta_{13} = 12°$ and $\delta = 0$). The ν_μ and ν_τ spectra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

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

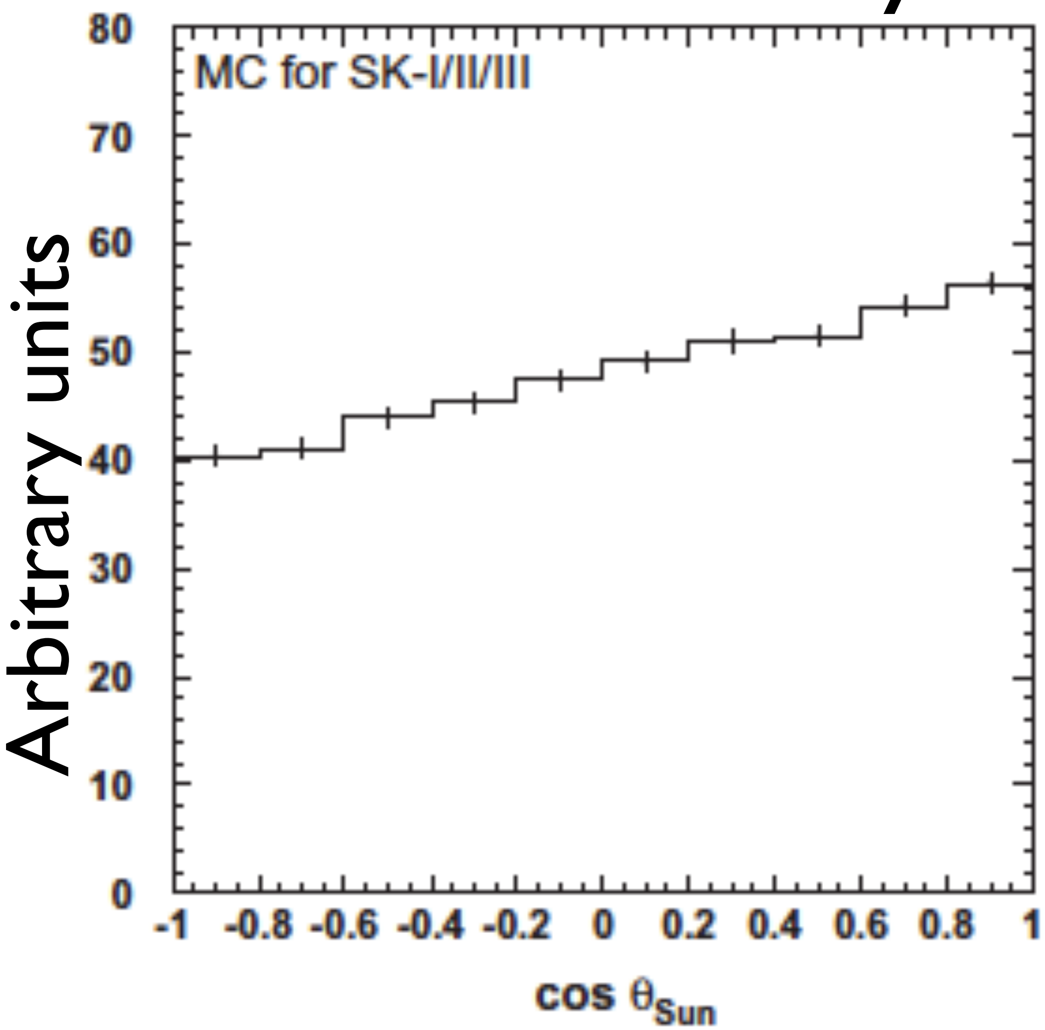


Inverse beta-decay



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

“large” cross section, but little directionality



Backgrounds

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

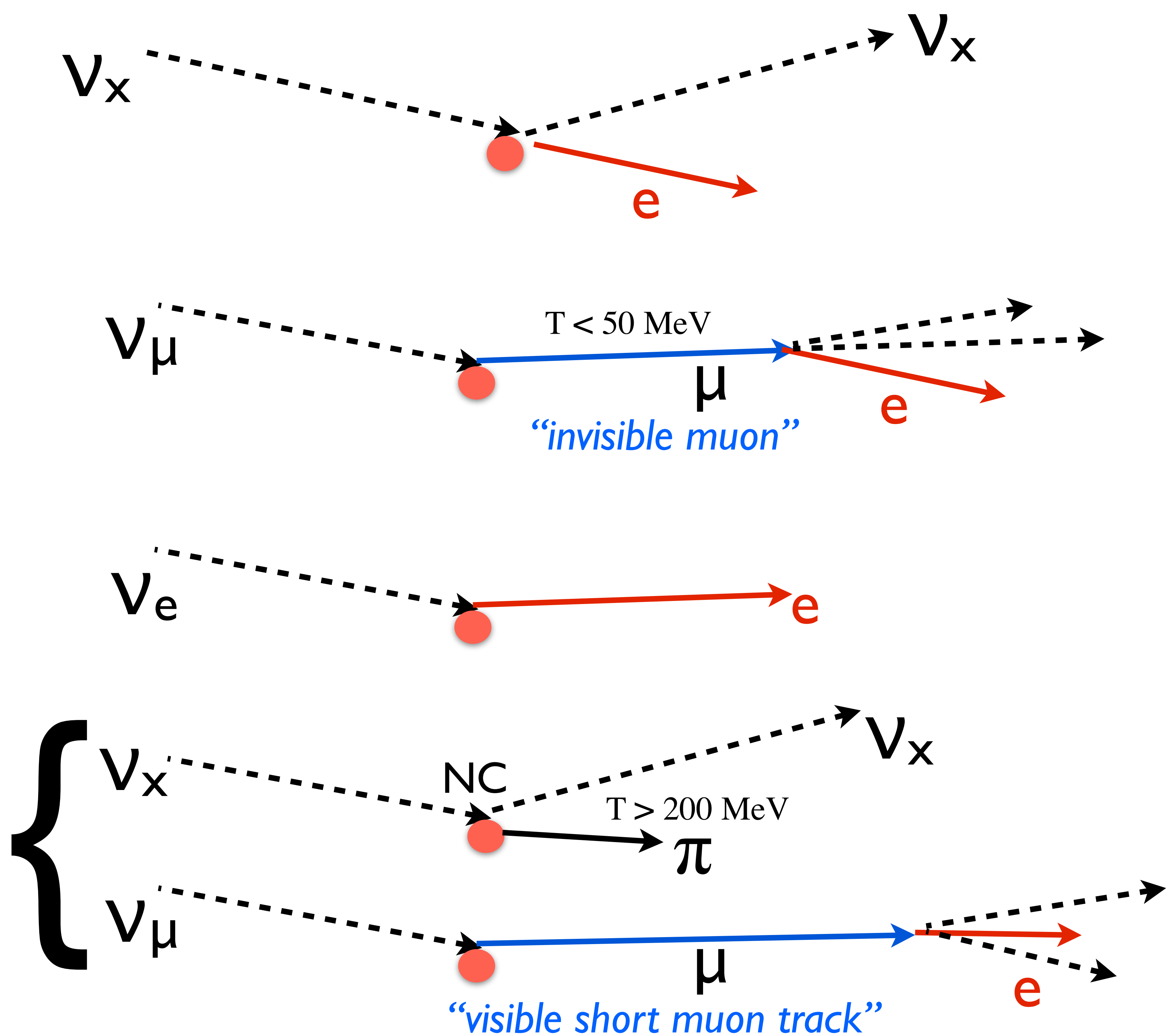
The background events mainly caused by the atmospheric neutrinos, solar neutrinos and muon-induced spallation products.

NC Elastic
"atmospheric"

Decay electron
"atm. muon neutrinos"

ν_e CC
"atm. electron neutrinos"

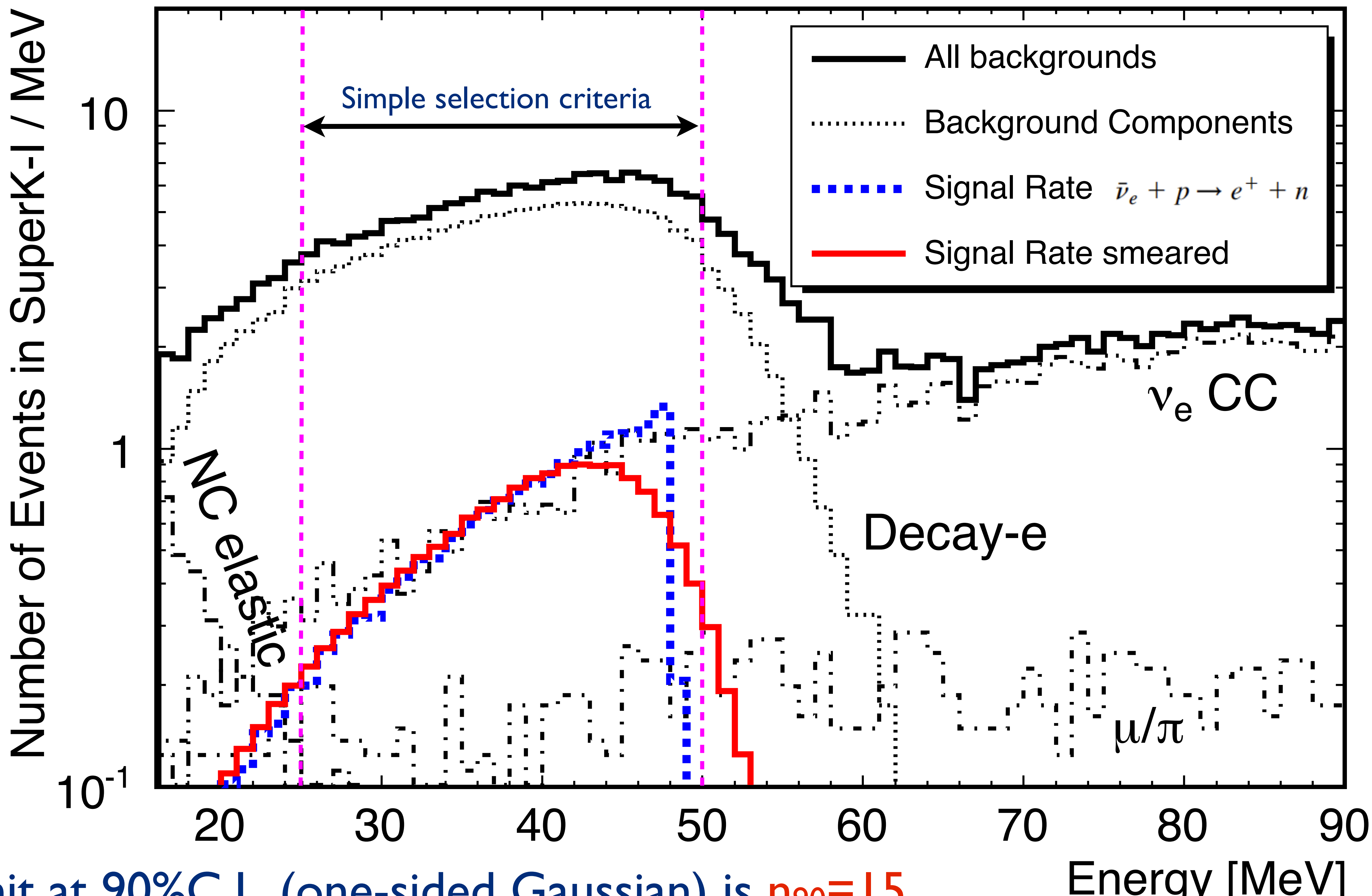
μ/π
"μ/π production from atm. neutrinos"



Sensitivity Calculation Super-K

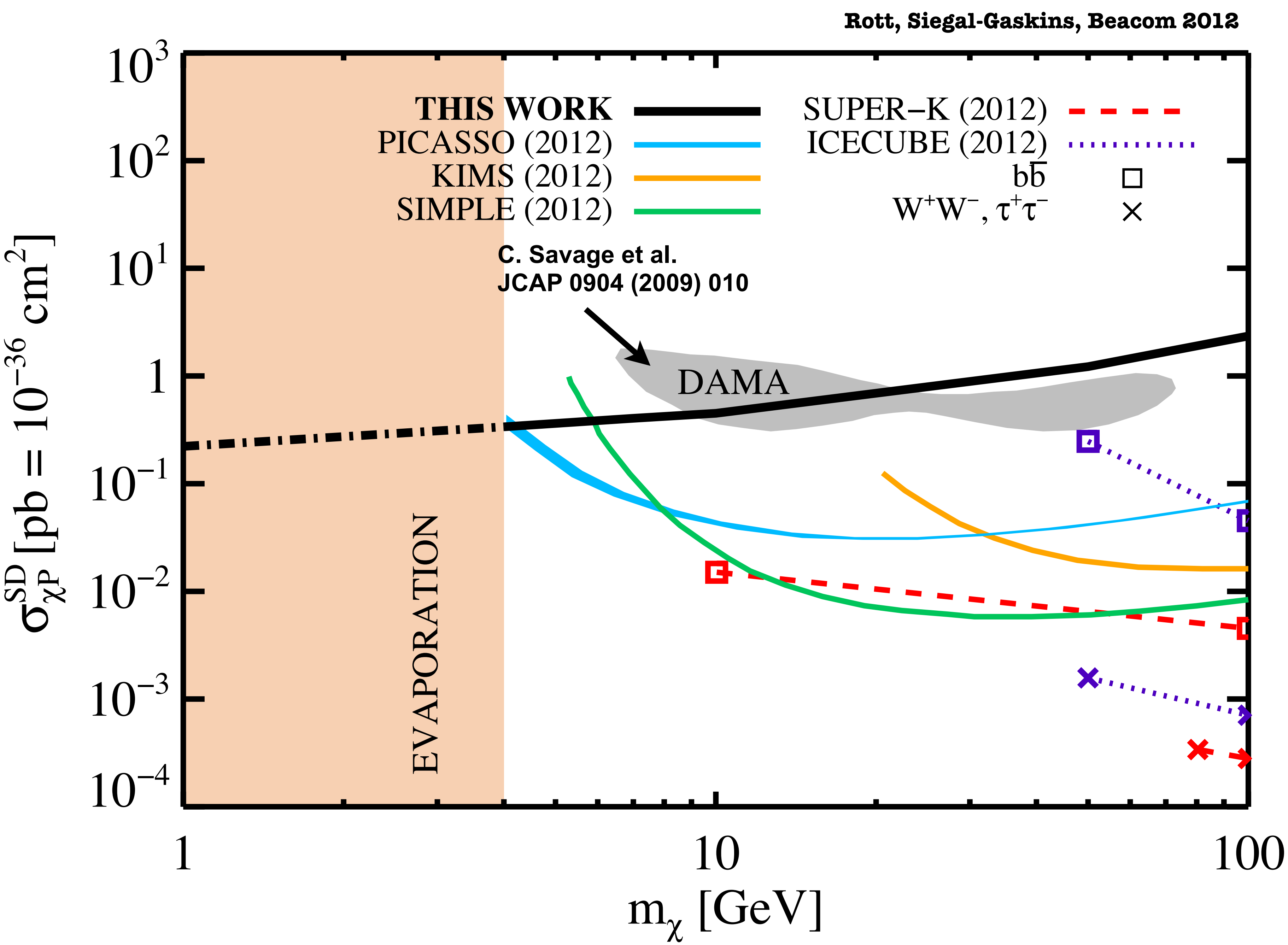
Positrons carry energy of $E_e \simeq [E_\nu - 1.3\ \mathrm{MeV}](1 - E_\nu/m_p)$

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

- 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

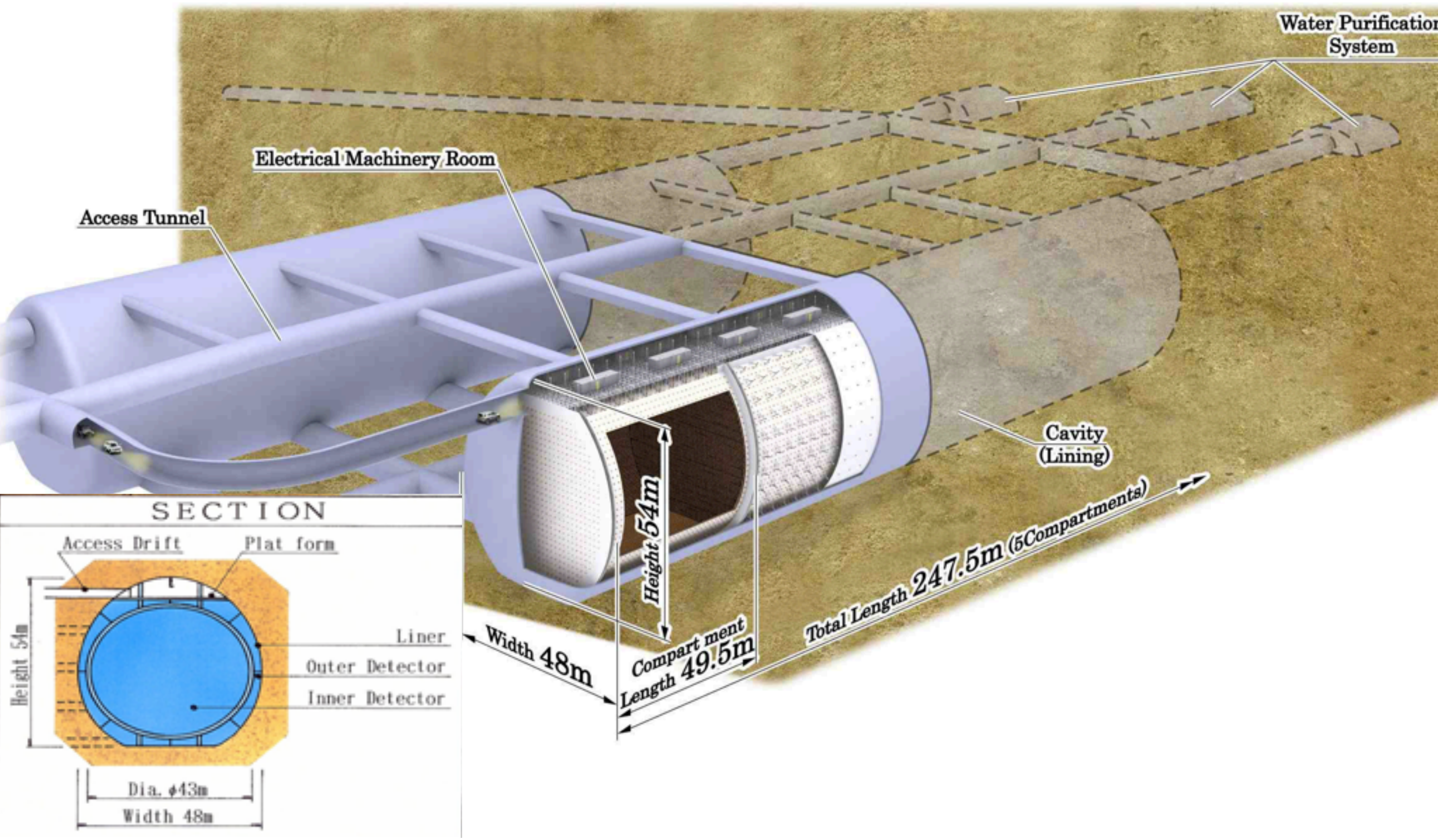
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\downarrow$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

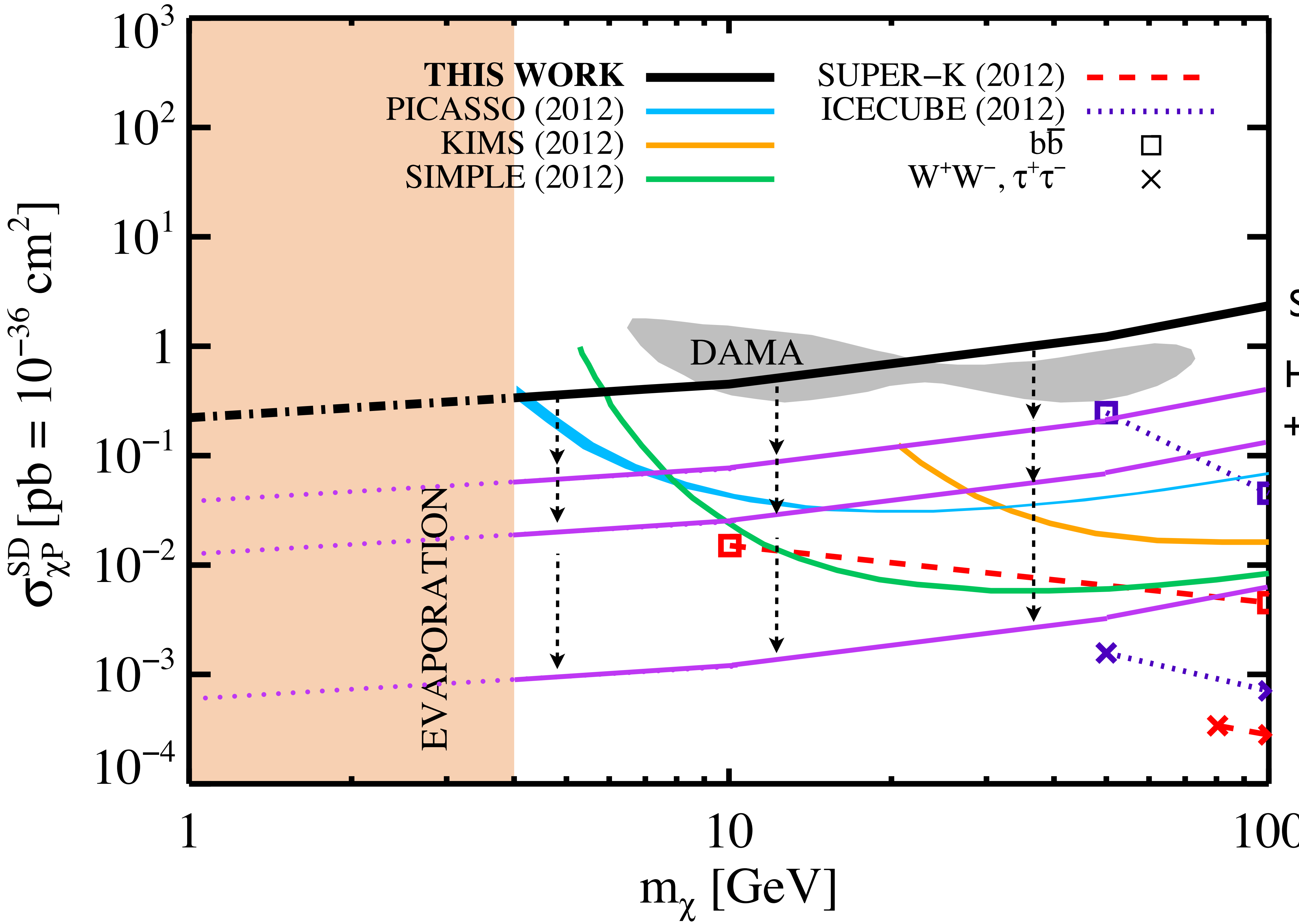

200tons
240 50-cm PMT's
EGADS
November 2011

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

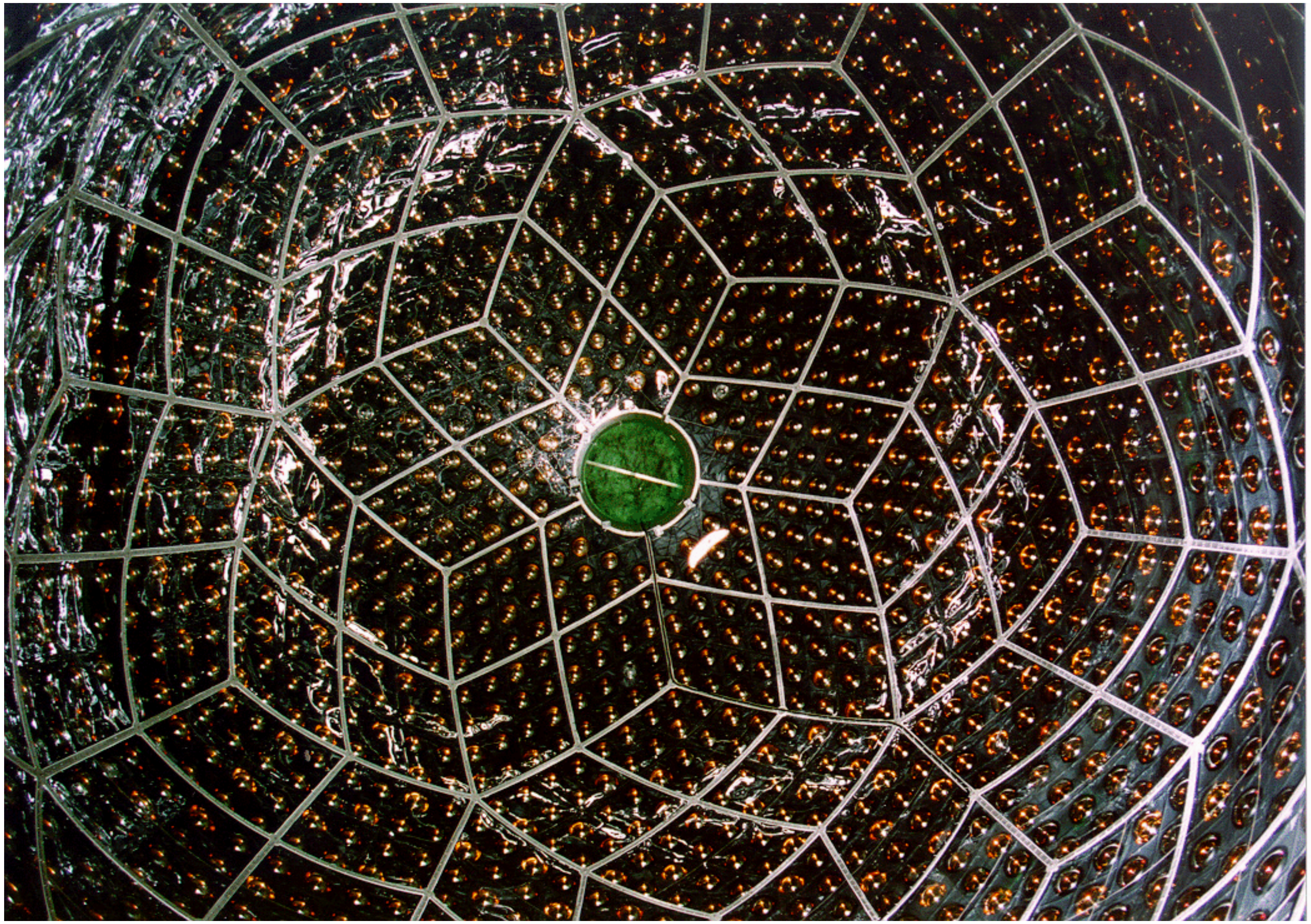
Hyper-K Sensitivity 4yrs



Liquid scintillator

KamLAND

- 1879 PMTs
- 18m diameter
- 1kton liquid scintillator (mineral oil)
  - FD ~ 0.5kton
- Exposure 3600days

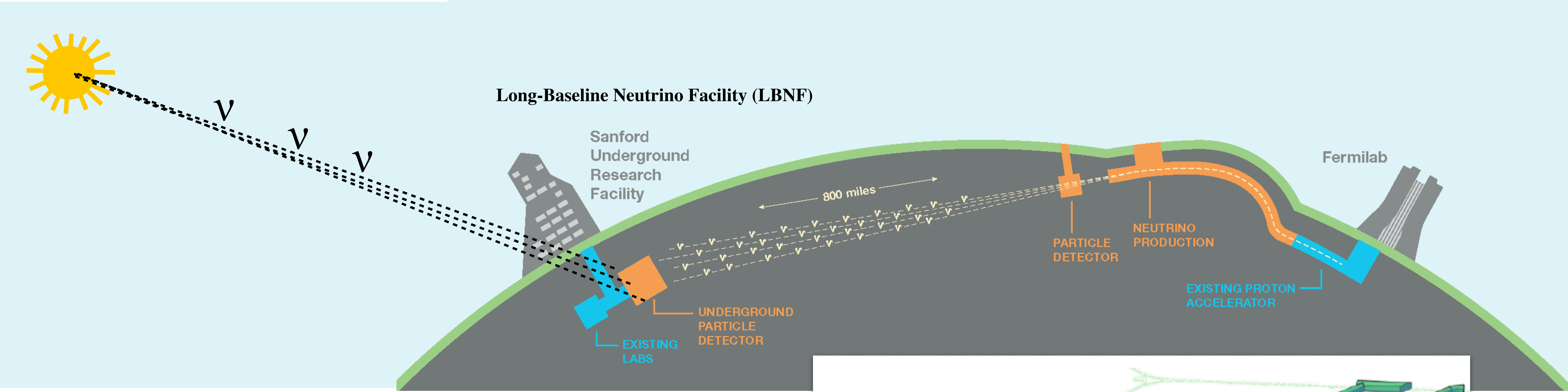


energy resolution is $6.4\,\%/\sqrt{E(\mathrm{MeV})}$.

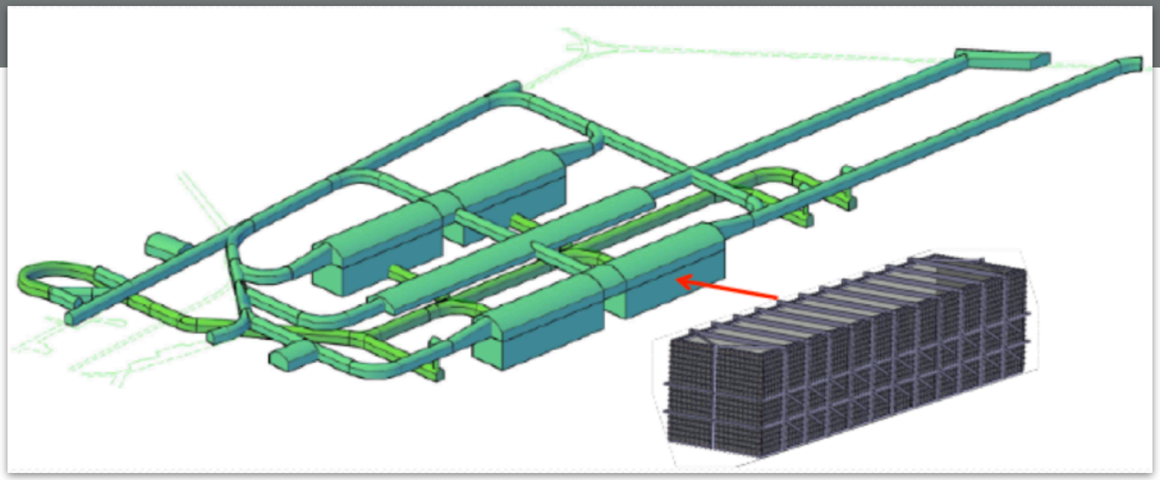
DUNE

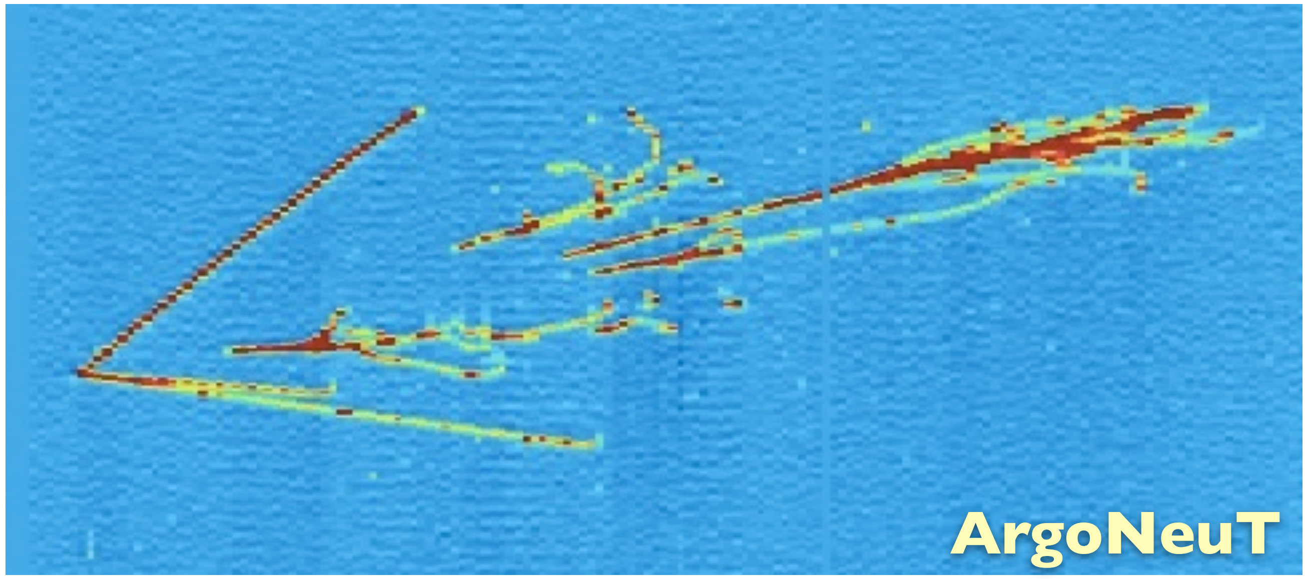
Deep Underground Neutrino Experiment

http://www.dunescience.org/

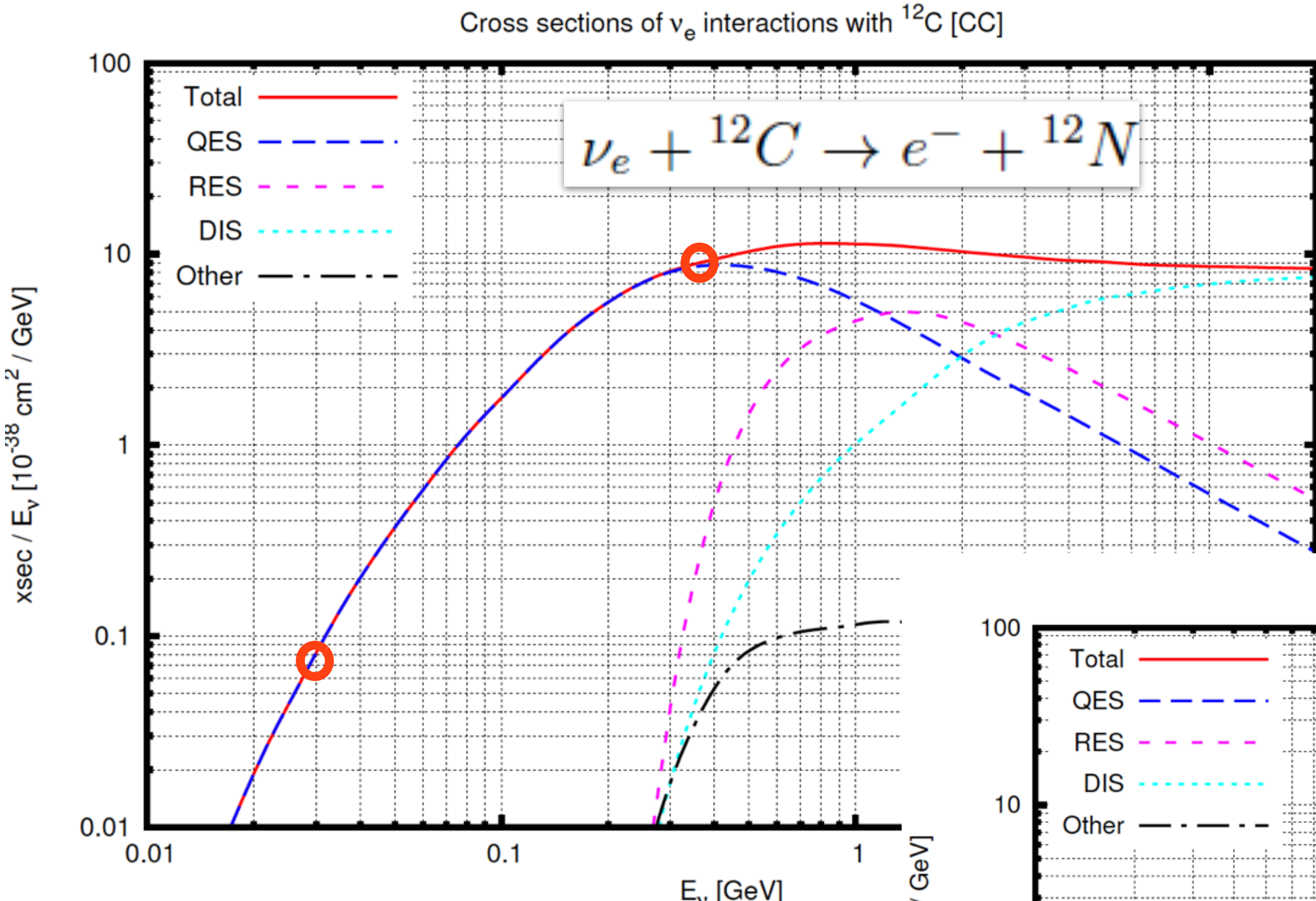


- 40kton cryogenic liquid argon detector
- Schedule (pending on funding profile)
  - Cavern excavation 2016–2017.
  - First 10 kton FD module in 2021 with 1.2 MW beam.
  - 4x10 kton modules by 2024 with upgraded 2.4 MW beam

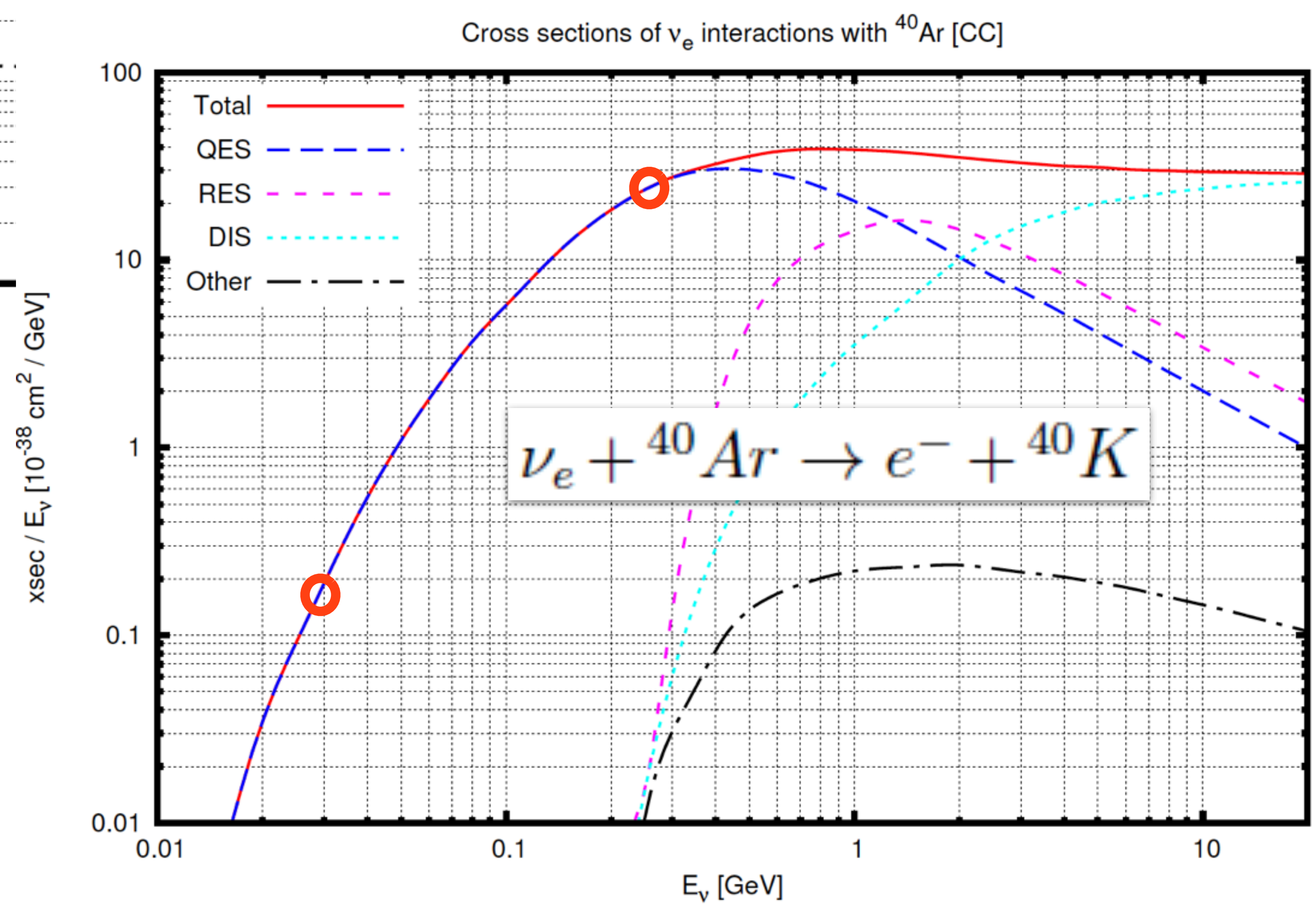




Neutrino cross section

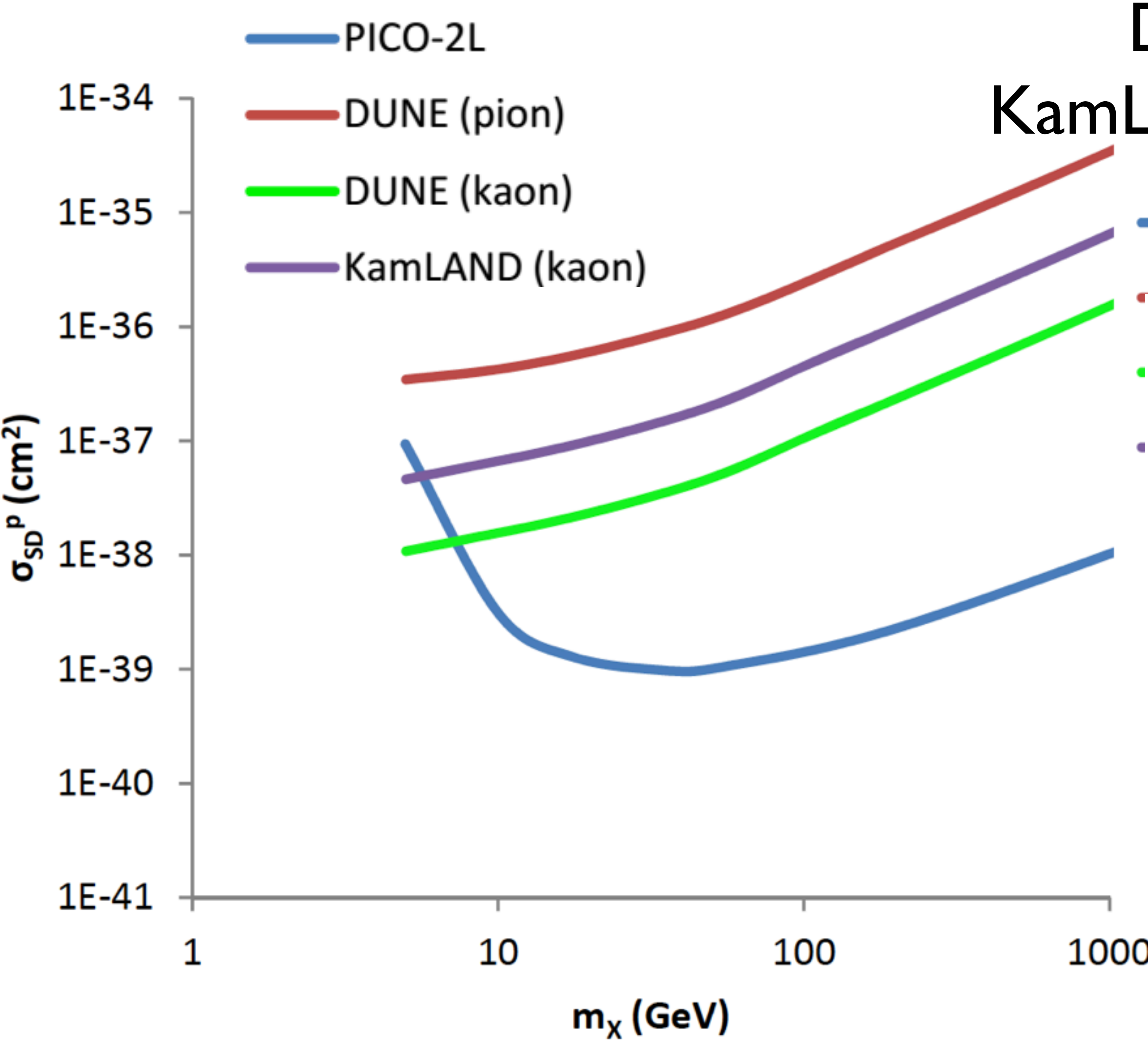


- 29.8MeV
  - charged current quasi-elastic
- 235.5MeV
  - charged current quasi-elastic,
  - just at the edge of pion production, deep inelastic scattering, resonance, coherent



thanks to Shao-Feng Ge for Genie cross sections

Sensitivity

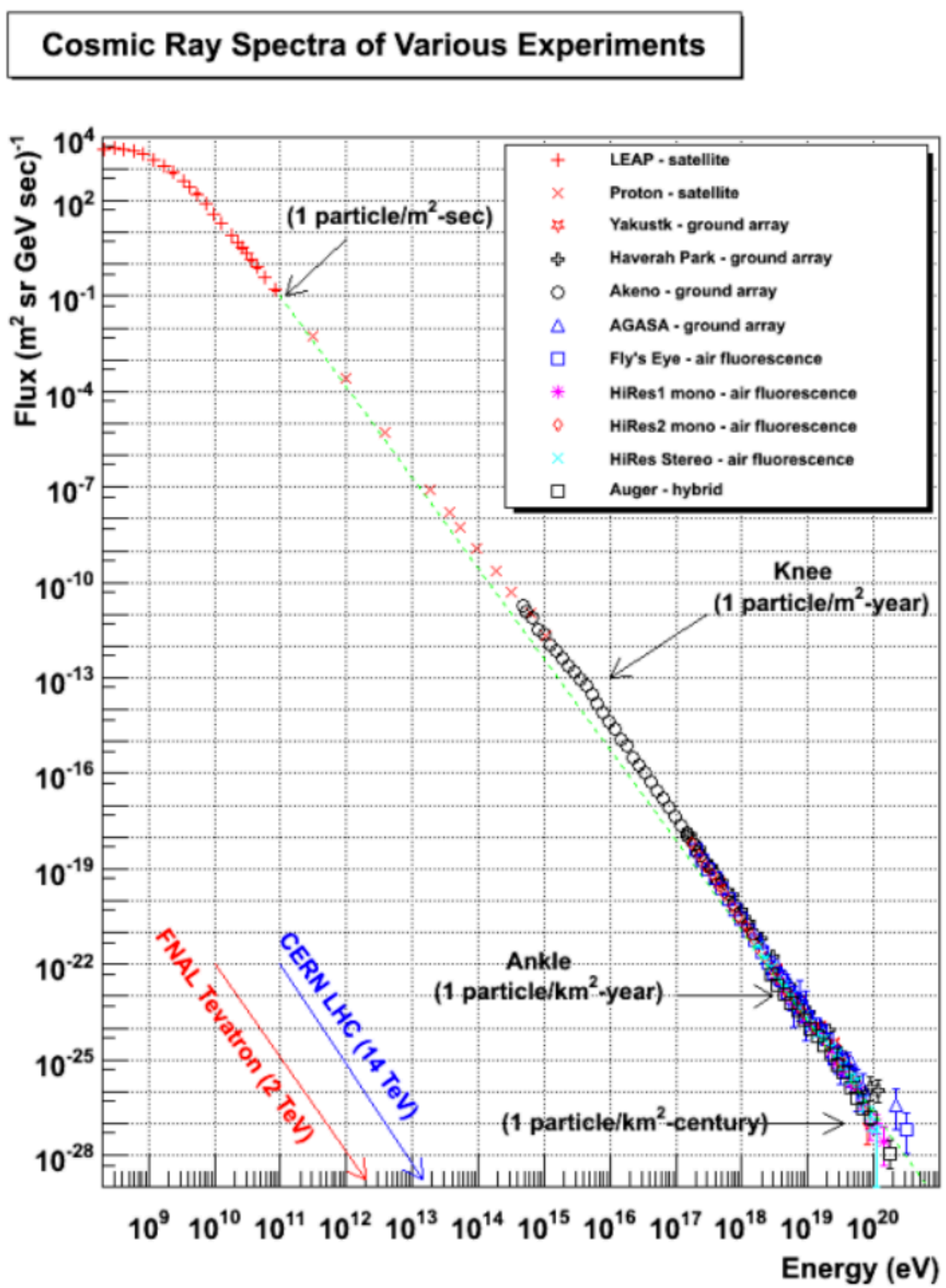


Dune 34kton*years
KamLAND 5kton*years

assumes NMH

- at low energy, take $\varepsilon \sim 1\,\%$ for LS
- KamLAND is signal limited
  - viable models produce < 1 event in KamLANDs exposure
  - problem → $\sigma_{\nu A}$ small at low E_ν
- DUNE could do much better (34 kT LAr TPC, 1 year)
  - still negligible background (1 yr)
  - competitive with direct detection at ~ 5 GeV (90% CL, $\varepsilon \sim 10\,\%$)
- other neutrino searches not sensitive (focused on high-energy neutrinos)

Pions from CR airshowers

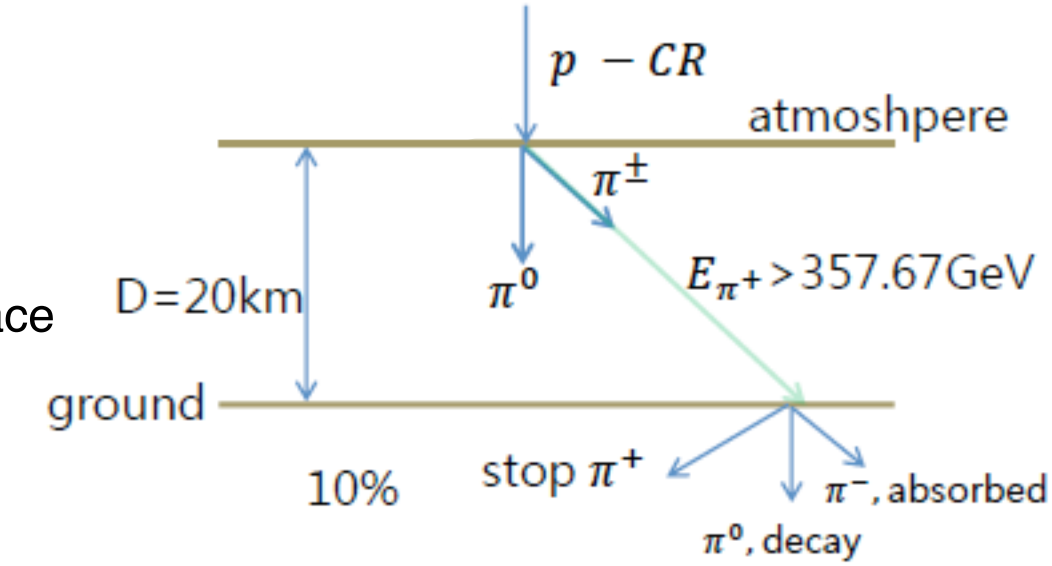


π^+ - reaching surface

$c\tau$=7.8045 m

d=20,000m

$m_{\pi^+}c^2$=139.57 MeV



$$E^2 = m^2c^4 + \frac{d^2}{c^2\tau^2}m^2c^4 \rightarrow E = mc^2\sqrt{1+\left(\frac{d}{c\tau}\right)^2}$$

- Estimate background from stopped pions from CR's hitting the Earth surface... very conservative estimate (no interaction in the atmosphere assumed)
- Pion at rest decay rate:

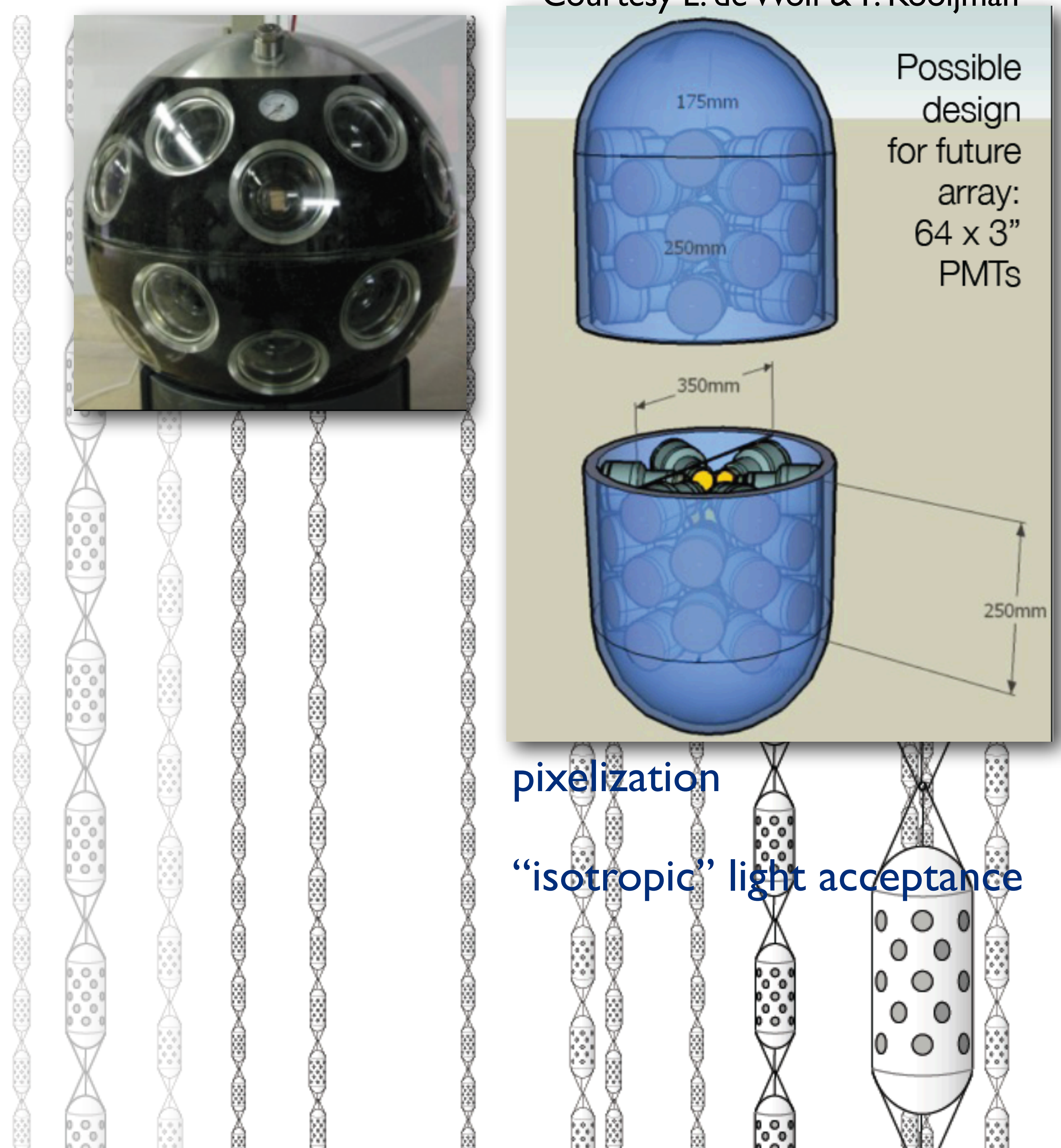
$$1.6 \times 10^{16}\,[pions][s]^{-1}$$

- The corresponding neutrino rate is that of a 100GeV WIMP at 3x10^{-39}cm^2

MICA -Megaton Ice Cherenkov Array

- In-fill of a few hundred strings
  - String spacings ~5 m, sensors spaced by ~1 m on a string
  - The Medium is the support structure
- An ambitious vision worth working towards:
  - Fiducial volume > 1MTon
  - Photo coverage ~10%
  - O(10 MeV) threshold for bursts
  - O(100 MeV) for single events
- IceCube and DeepCore provide active veto
  - No excavation is necessary, drilling/ deployment has been refined to an industrial process – deployment costs would be well below 10% of total
- Physics extraction from Cherenkov ring imaging in the ice

Courtesy E. de Wolf & P. Kooijman



pixelization

“isotropic” light acceptance

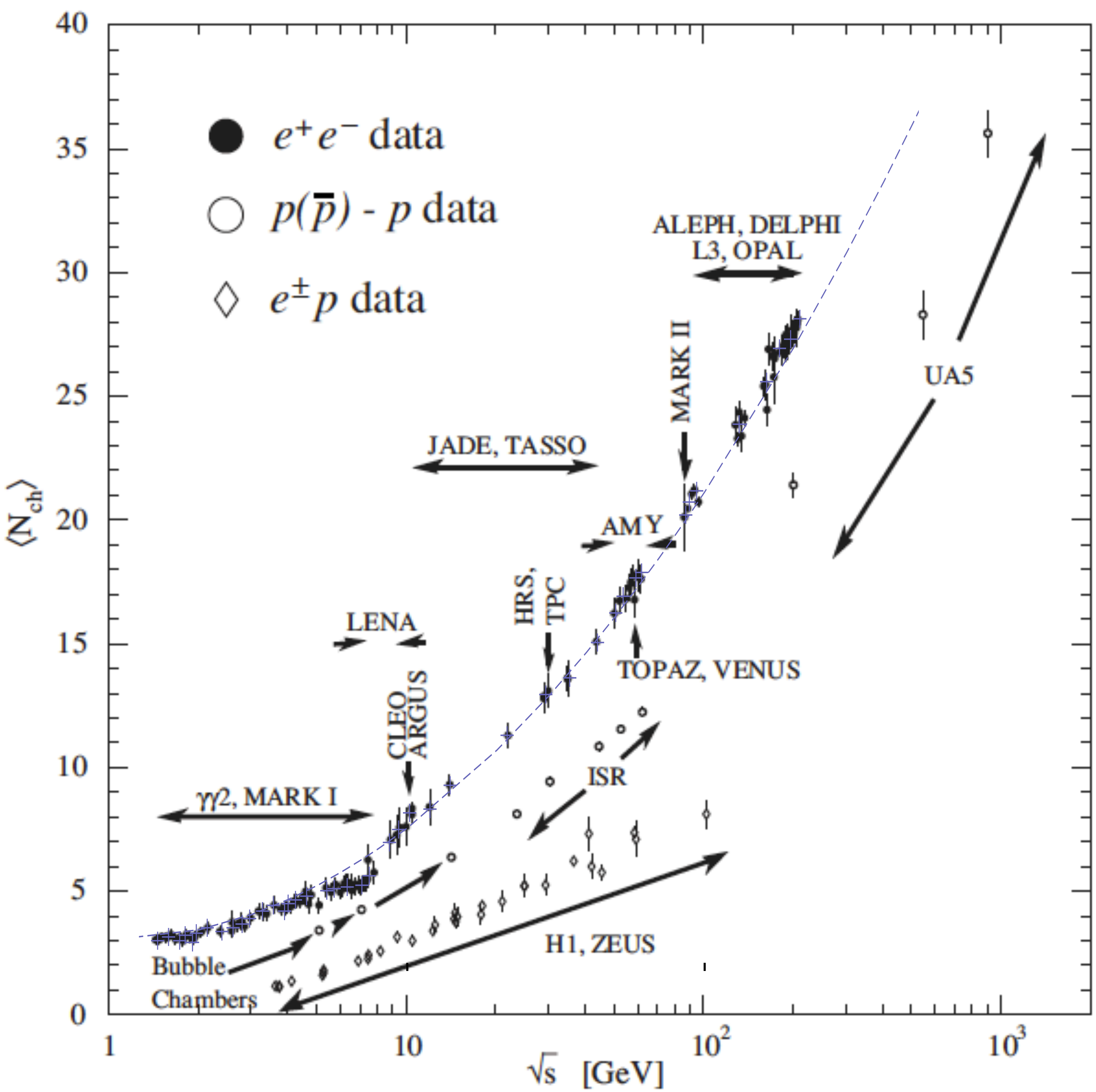
Why low-energy neutrinos

- Sensitivity is nearly flat as function of WIMP mass
  - Low-WIMP mass scenarios can be tested
- Low-energy neutrino flux is relatively independent of the mix of final states
- Sensitivity to scenarios in which no high energy neutrinos are produced
- Observation of a combination of low-energy and high-energy neutrinos could potentially disentangle the mix of WIMP annihilation final states

Conclusions

- Solar WIMPs provide very distinctive dark matter signal
- New detection channel with low-energy neutrinos offers additional discovery potential and give access to previously hidden scenarios
- Extremely sensitive to test low-mass WIMPs
- Searches at LS detectors are signal limited, sensitivity improves (~linear) with volume and exposure ... a case for large detectors

Thanks



- Model the final state multiplicity of WIMP-WIMP annihilations with e^+e^- collisions at same center of mass energy
- By using experimental data itself we reduce the dependency on simulations
- We fir the experimental data with an analytical function that fits extremely well:

$$N_\pi^{\mathrm{initial}} \simeq 3 + 4.5 \log_{10}^2(\sqrt{s}/\mathrm{GeV})$$

- We assume the energy is distributed equally among the final states

PICO-2L

- PICO-2L: 2 liter C_3F_8 bubble chamber in the SNOLAB underground laboratory, with a total exposure of 211.5 kg days

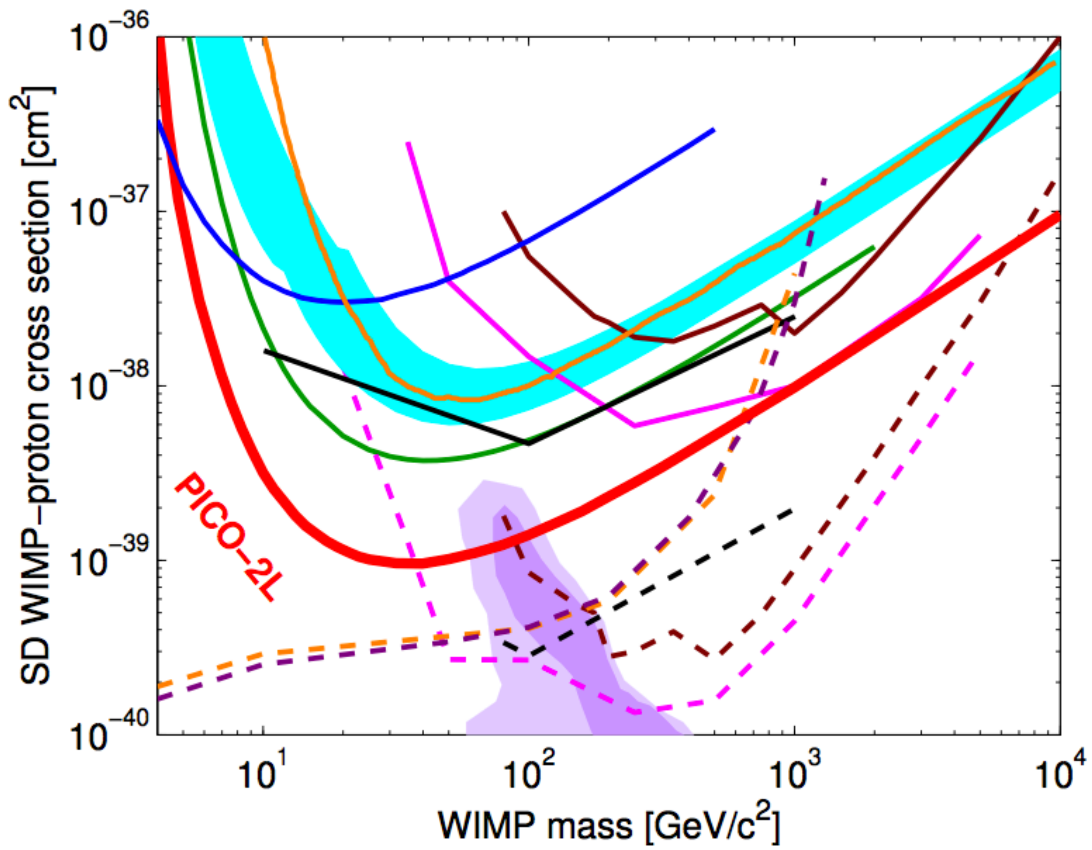


FIG. 5: (Color online) The 90% C.L. limit on the SD WIMP-proton cross section from PICO-2L is plotted in red, along with limits from COUPP (light blue region), PICASSO (dark blue), SIMPLE (green), XENON100 (orange), IceCube (dashed and solid pink), ANTARES (dashed and solid brown), SuperK (dashed and solid black), CMS (dashed orange), and ATLAS (dashed purple) [7, 9, 10, 25–30]. For the IceCube, ANTARES, and SuperK results, the dashed lines assume annihilation to W-pairs while the solid lines assume annihilation to b-quarks. The CMS and ATLAS limits assume an effective field theory, valid for a heavy mediator. The purple region represents parameter space of the CMSSM model of [24].

mu- decay in orbit vs weak capture

- Muon capture in hydrogen:
  - Capture Rate (4.5 $10^2 s^{-1}$) is factor 1000 smaller compared to decay (4.55 $10^5 s^{-1}$)
- Muon capture in helium:
  - Capture Rate (3.6 $10^2 s^{-1}$) is factor 1000 smaller compared to decay (4.55 $10^5 s^{-1}$)
- Muon capture in oxygen:
  - Capture Rate (1.0 $10^5 s^{-1}$) is factor ~1:5 to decay (5.6 $10^5 s^{-1}$)
- The Huff factor is a small correction on the muon lifetime. It takes into account the fact that the normal muon decay rate is reduced for a bound muon- as the binding energy reduces the energy available

D.F. Measday / Physics Reports 354 (2001) 243–409 295

Table 4.2
Some illustrative total capture rates for μ^- in nuclei. Also given is the mean lifetime. For the hydrogen isotopes, molecular formation complicates the situation. For other light elements (He, Li, Be, ^{10}B) the capture rate is the statistical average of the hyperfine states except for those marked (lhfs), i.e., lower hyperfine state. For $Z > 15$ the rate is always for the lower hyperfine state

Z (Z_{eff})	Element	Mean-life (ns)	Capture rate $\times 10^3 (s^{-1})$	Huff factor	Ref.
	μ^+	2197.03 (4)	455.16		[14]
1 (1.00)	^{1}H	$\boxed{2194.90\ (7)}$	$\boxed{0.450\ (20)}$	1.00	[23]
	^{2}H	2194.53 (11)	0.470 (29)		[211]
2 (1.98)	^{3}He	2186.70 (10)	2.15 (2)	1.00	
	^{4}He	$\boxed{2195.31\ (5)}$	$\boxed{0.356\ (26)}$		
3 (2.94)	^{6}Li	2175.3 (4)	4.68 (12)	1.00	[250]
	^{7}Li	2186.8 (4)	2.26 (12)		[250]
4 (3.89)	^{9}Be	2168 (3)	6.1 (6)	1.00	[183]
5 (4.81)	^{10}B	2072 (3)	27.5 (7)	1.00	[183]
	^{11}B (lhfs)	2089 (3)	23.5 (7)	1.00	[183]
6 (5.72)	^{12}C	2028 (2)	37.9 (5)	1.00	[183]
	^{13}C	2037 (8)	35.0 (20)		[183]
7 (6.61)	^{14}N	1919 (15)	66 (4)	1.00	[183]
8 (7.49)	^{16}O	$\boxed{1796\ (3)}$	$\boxed{102.5\ (10)}$	0.998	[183]
	^{18}O	1844 (5)	88.0 (14)		[183]
9 (8.32)	^{19}F (lhfs)	1463 (5)	229 (1)	0.998	[183]
13 (11.48)	^{27}Al (lhfs)	864 (2)	705 (3)	0.993	[183]
14 (12.22)	^{28}Si	758 (2)	868 (3)	0.992	[183]
20 (16.15)	Ca	334 (2)	2546 (20)	0.985	[183]
40 (25.61)	Zr	110.4 (10)	8630 (80)	0.940	[183]
82 (34.18)	Pb	74.8 (4)	12985 (70)	0.844	[183]
83 (34.00)	Bi	73.4 (4)	13240 (70)	0.840	[183]
90 (34.73)	Th	77.3 (3)	12560 (50)	0.824	[251]
92 (34.94)	U	77.0 (4)	12610 (70)	0.820	[252]

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

$\boxed{K^0_S}$

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

Mean life $\tau = (0.8954 \pm 0.0004) \times 10^{-10}$ s (S = 1.1) Assuming CPT

Mean life $\tau = (0.89564 \pm 0.00033) \times 10^{-10}$ s Not assuming CPT

$c\tau = 2.6844$ cm Assuming CPT

K^0_S DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes			
$\pi^0\pi^0$	(30.69 ± 0.05) %		209
$\pi^+\pi^-$	(69.20 ± 0.05) %		206

K^0_L DECAY MODES			Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic modes					
$\pi^\pm e^\mp \nu_e$ Called K^0_{e3}.		[o]	(40.55 ± 0.11) %	S=1.7	229
$\pi^\pm \mu^\mp \nu_\mu$ Called $K^0_{\mu3}$.		[o]	(27.04 ± 0.07) %	S=1.1	216
$(\pi\mu\text{atom})\nu$			$(1.05 \pm 0.11) \times 10^{-7}$		188
$\pi^0\pi^\pm e^\mp \nu$		[o]	$(5.20 \pm 0.11) \times 10^{-5}$		207
$\pi^\pm e^\mp \nu e^+ e^-$		[o]	$(1.26 \pm 0.04) \times 10^{-5}$		229
Hadronic modes, including Charge conjugation×Parity Violating (CPV) modes					
$3\pi^0$			(19.52 ± 0.12) %	S=1.6	139
$\pi^+\pi^-\pi^0$			(12.54 ± 0.05) %		133
$\pi^+\pi^-$	CPV	[q]	$(1.967 \pm 0.010) \times 10^{-3}$	S=1.5	206
$\pi^0\pi^0$	CPV		$(8.64 \pm 0.06) \times 10^{-4}$	S=1.8	209

$K_S \longrightarrow \pi^0\pi^0$ 30.7%

$\pi^+\pi^-$ 69.2% (pions)

$K_L \longrightarrow \pi^\pm\mu^\mp\nu_\mu$ 40.6%

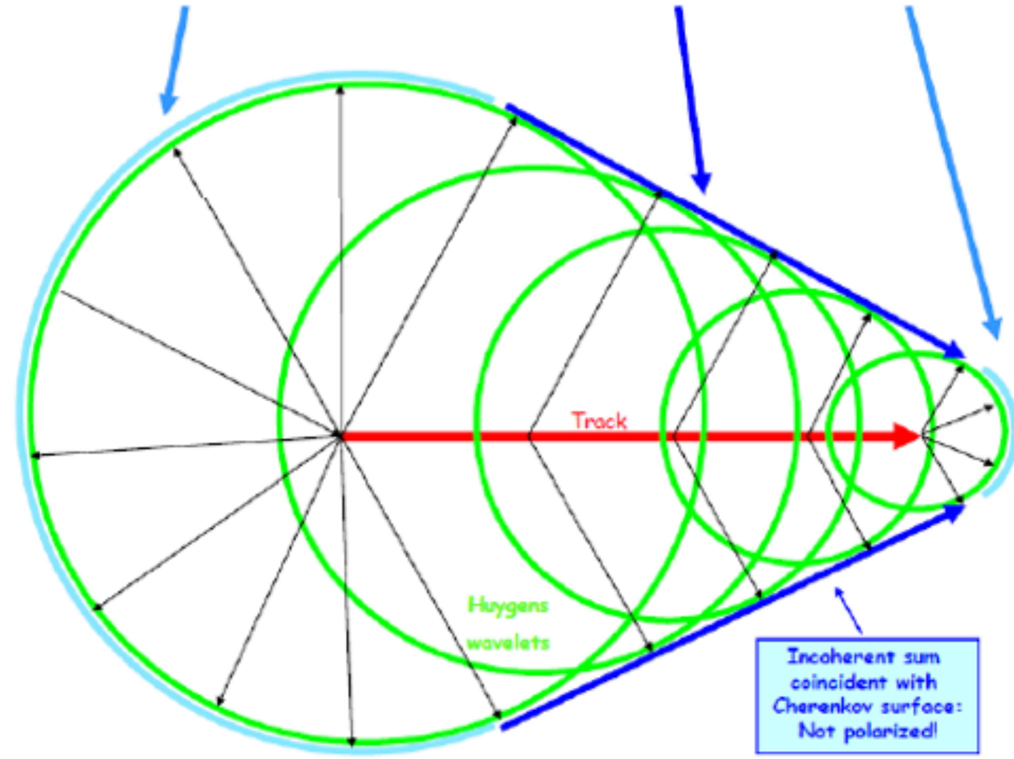
$\pi^\pm e^\mp \nu_e$ 27.0%

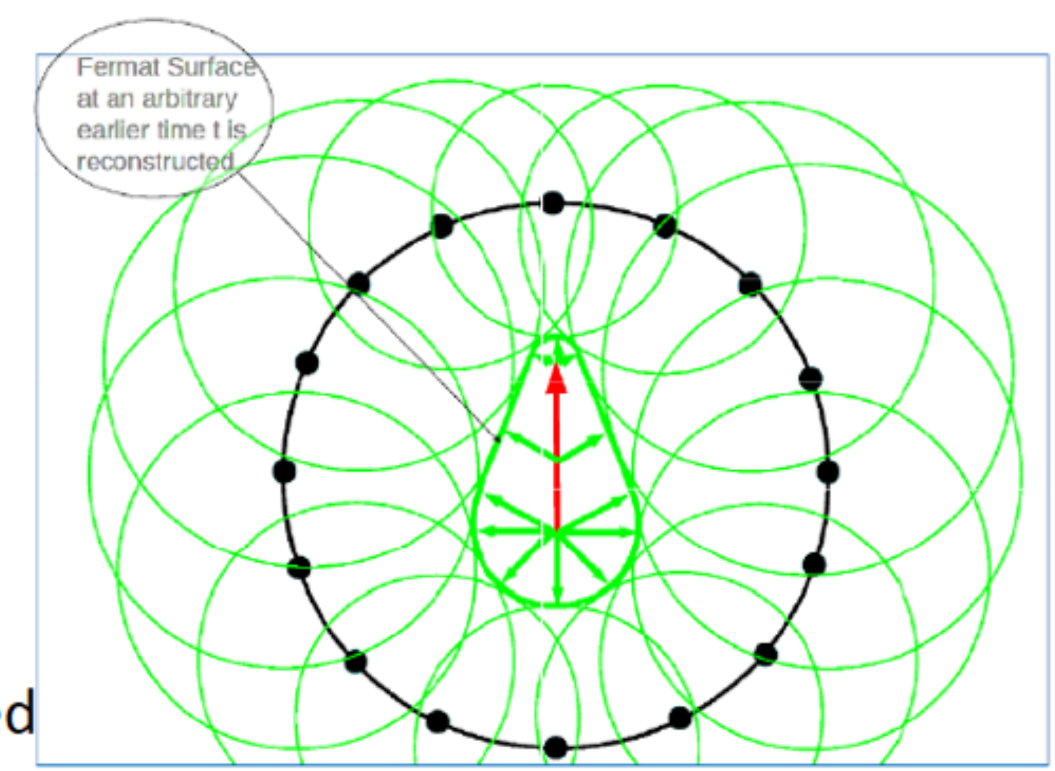
$3\pi^0$ 19.5%

$\pi^+\pi^-\pi^0$ 12.5% (pions)

Reconstruction in LS

- scintillator produces a spherical burst of light
- essentially a calorimeter
  - easy to get total energy
  - harder to get direction from a spherical burst of light
- but timing of when PMTs are illuminated can be used to reconstruct charged lepton track
  - essentially, Huygen's principle
- analysis of KamLAND data is on the way....
- we'll treat it as our benchmark detector ....





figures courtesy of John Learned