Low-energy Neutrinos as a signal for Solar WIMPs

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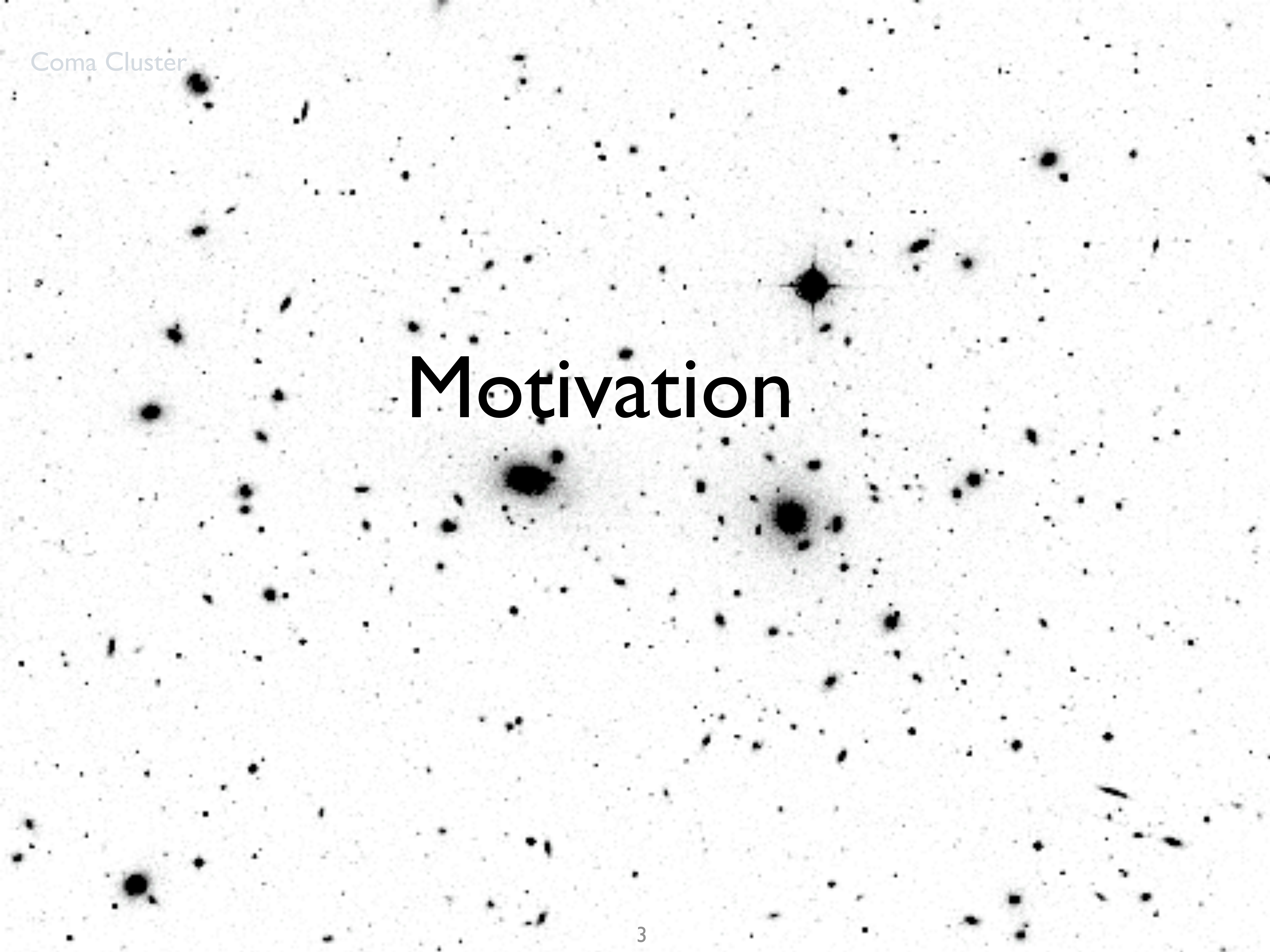
C.Rott, T.Tanaka, Y. Itow JCAP09(2011)029 (arXiv1107.3182)
C. Rott, J. Siegal-Gaskins, J.F.Beacom (arXiv1208.0827)

OKC colloquium Dec 14, 2012

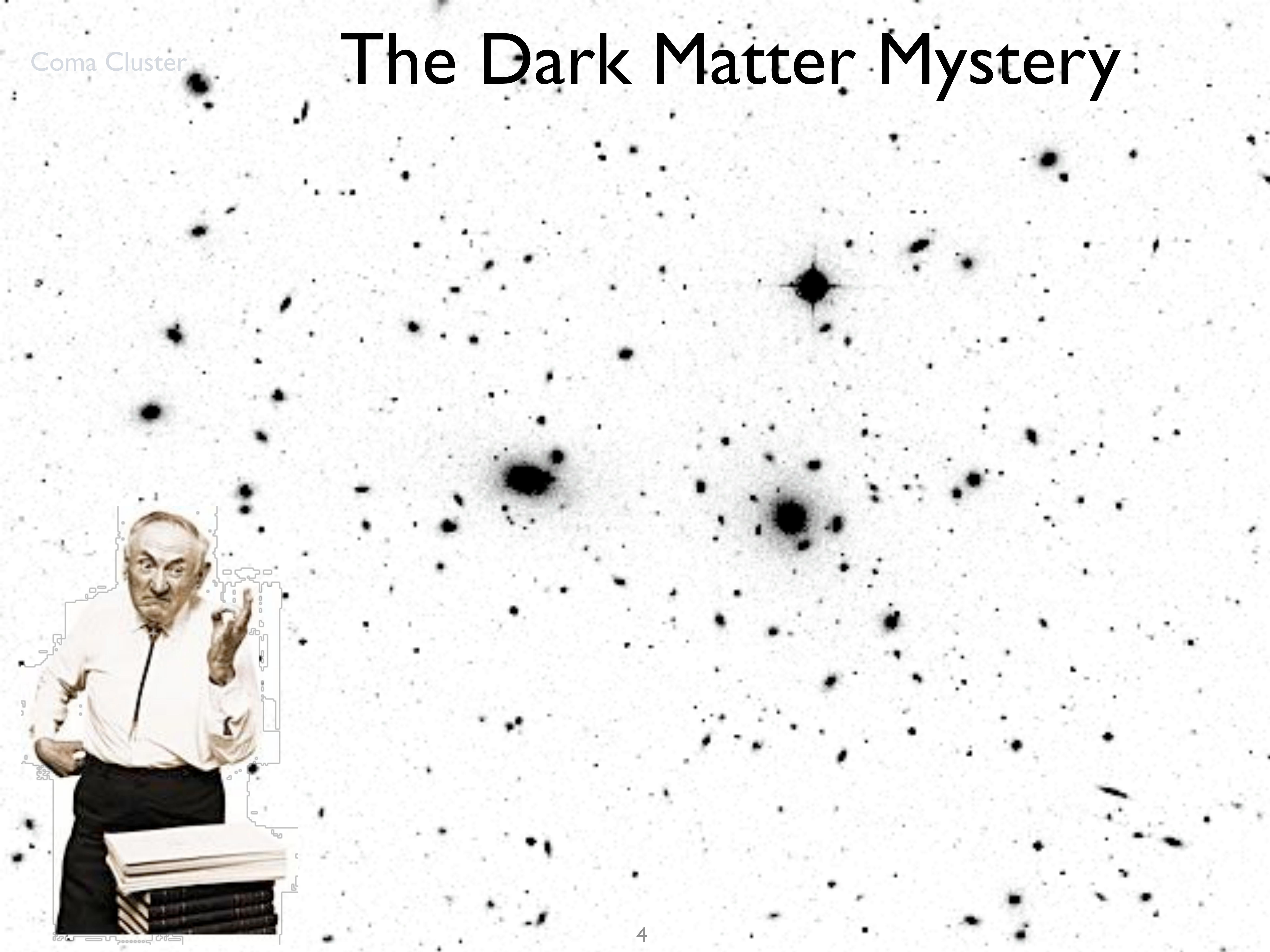
Coma Cluster

- Motivation
- Dark Matter Capture in the Sun
- Review of current results
- Future Prospect
- Conclusions



Motivation

The Dark Matter Mystery



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
  - ...

Coma Cluster

The Dark Matter Mystery

- Since Zwicky observed the Coma cluster evidence has hardened
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  - ...

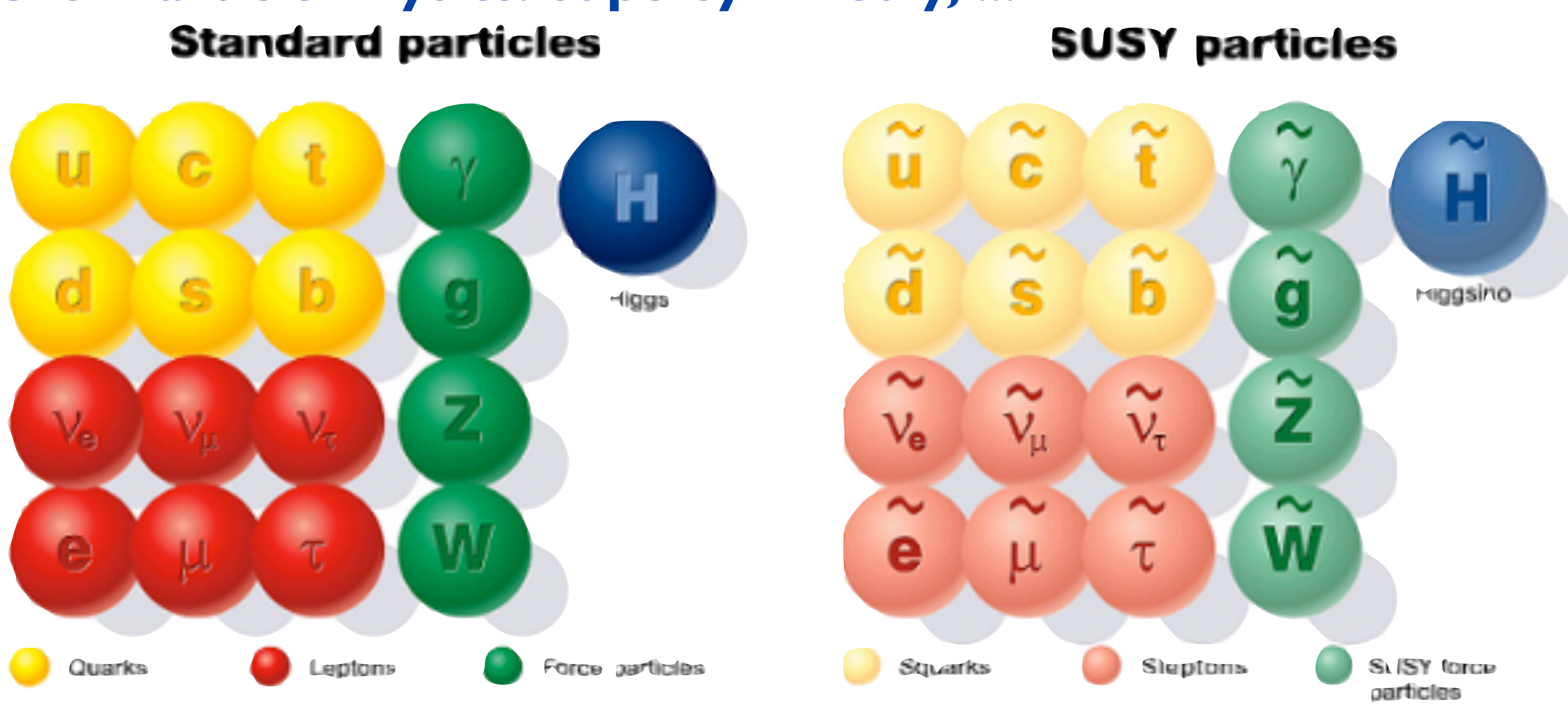
- Dark Matter already gravitationally “observed”, but ...
  - What is it ?
  - What are it’s properties ?

Weakly Interacting Massive Particle (χ)

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

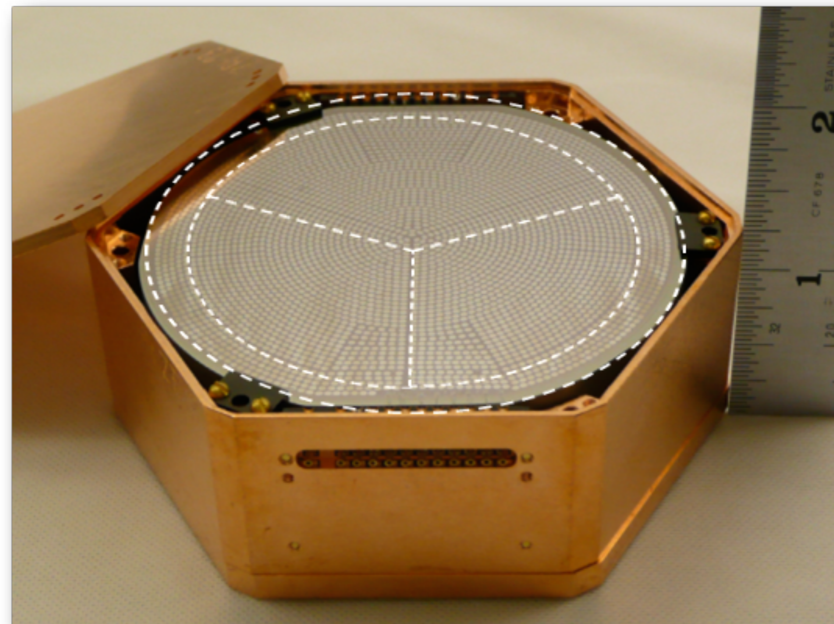
WIMP

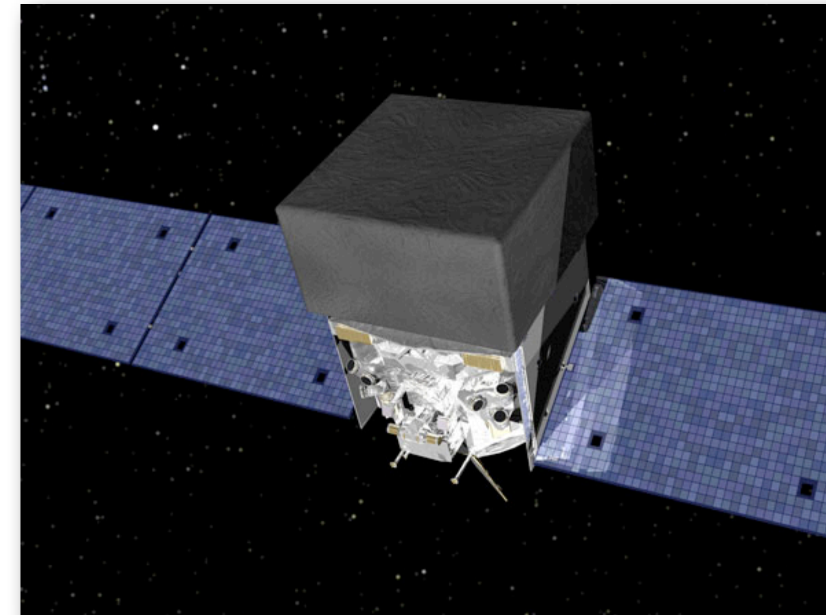
- **WIMPs often arise naturally in extensions to the Standard Model of Particle Physics: Supersymmetry, ...**



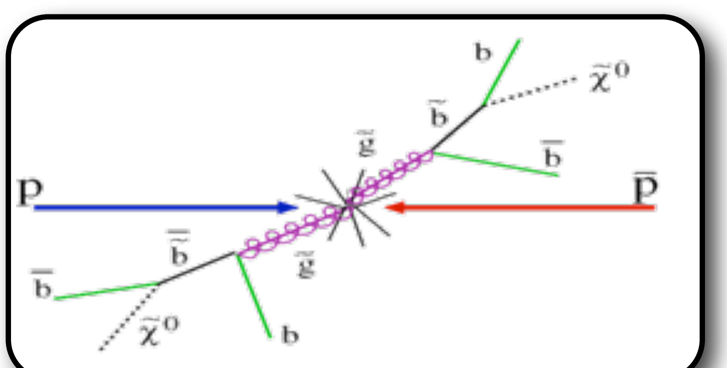
Searches for WIMPs

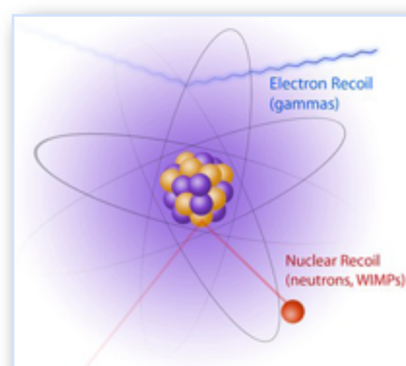
Colliders | Direct | Indirect

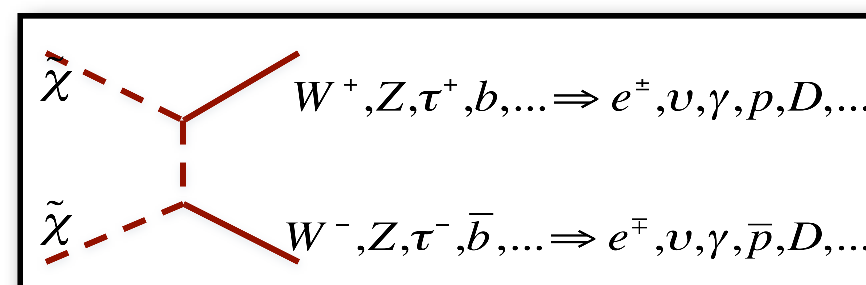




Production | Scattering | Annihilation







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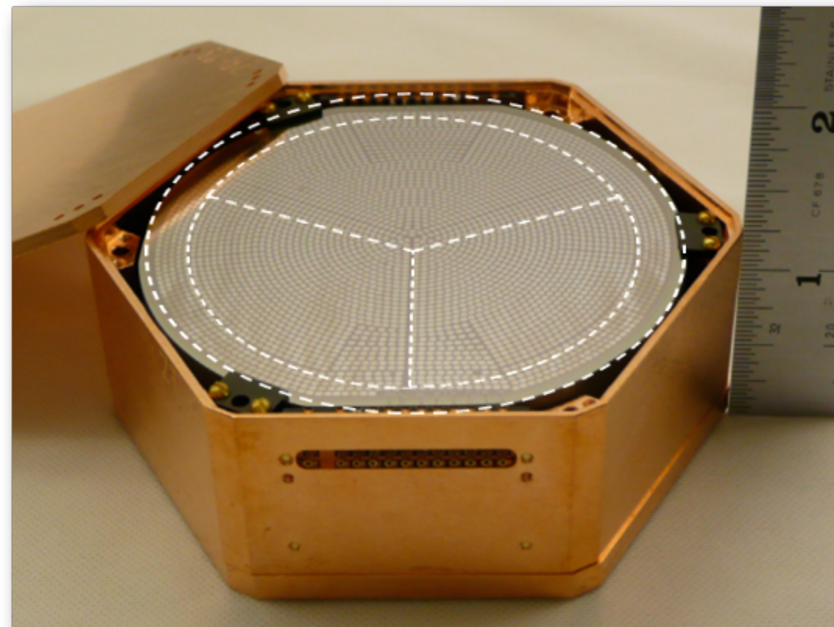

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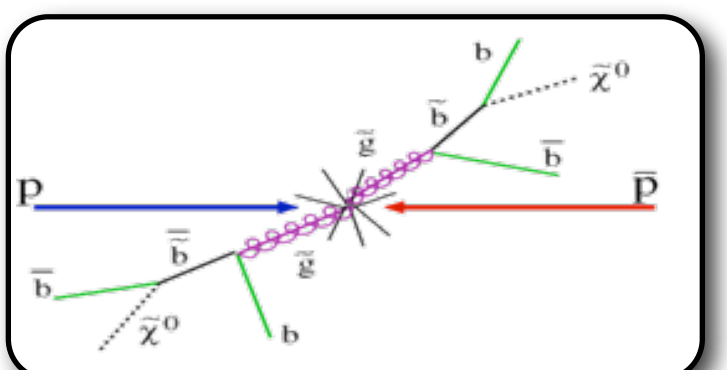

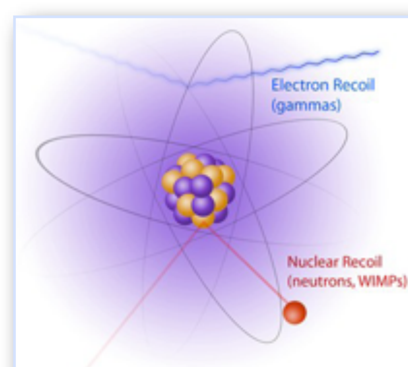

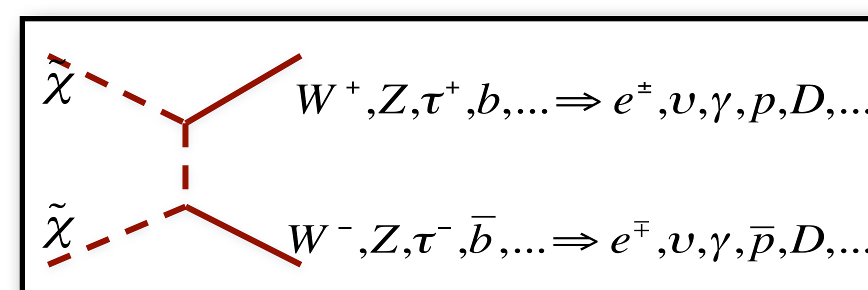

Searches for WIMPs

Colliders

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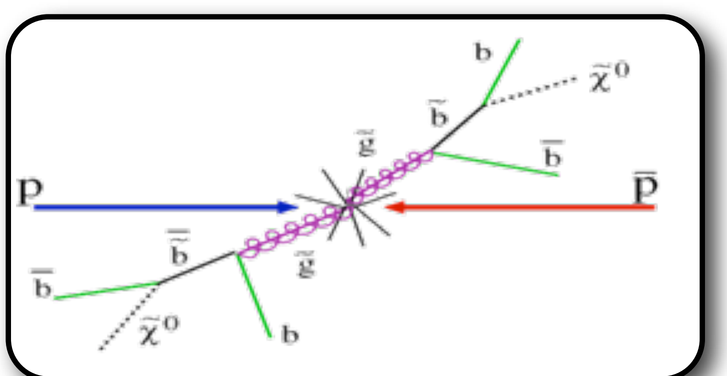

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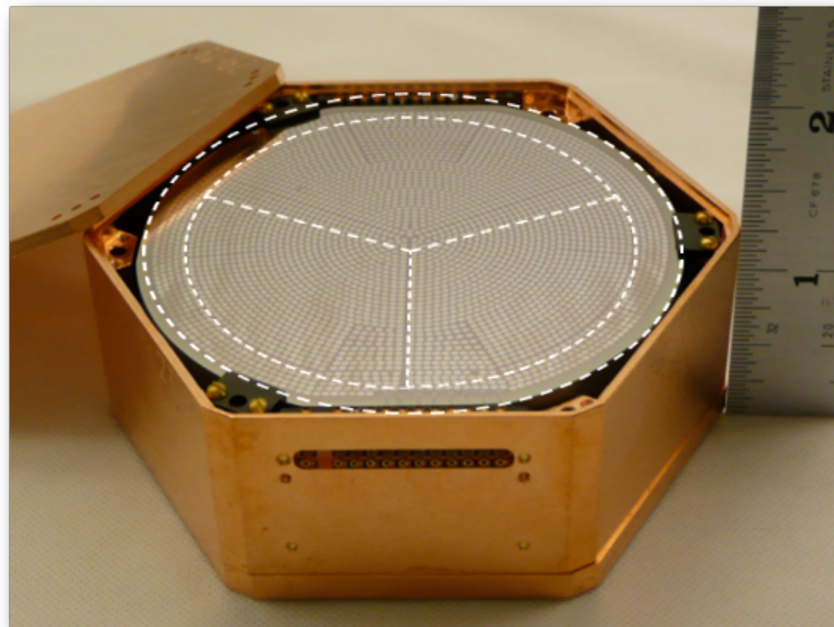
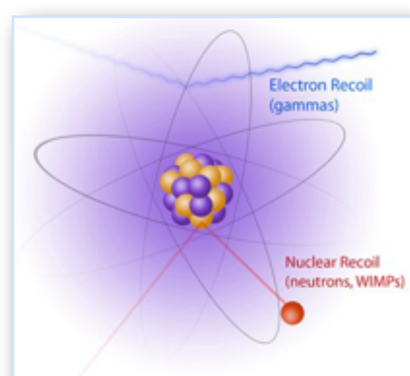
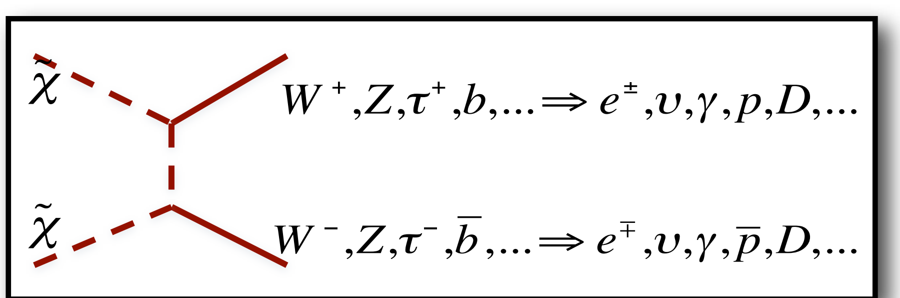


Scattering



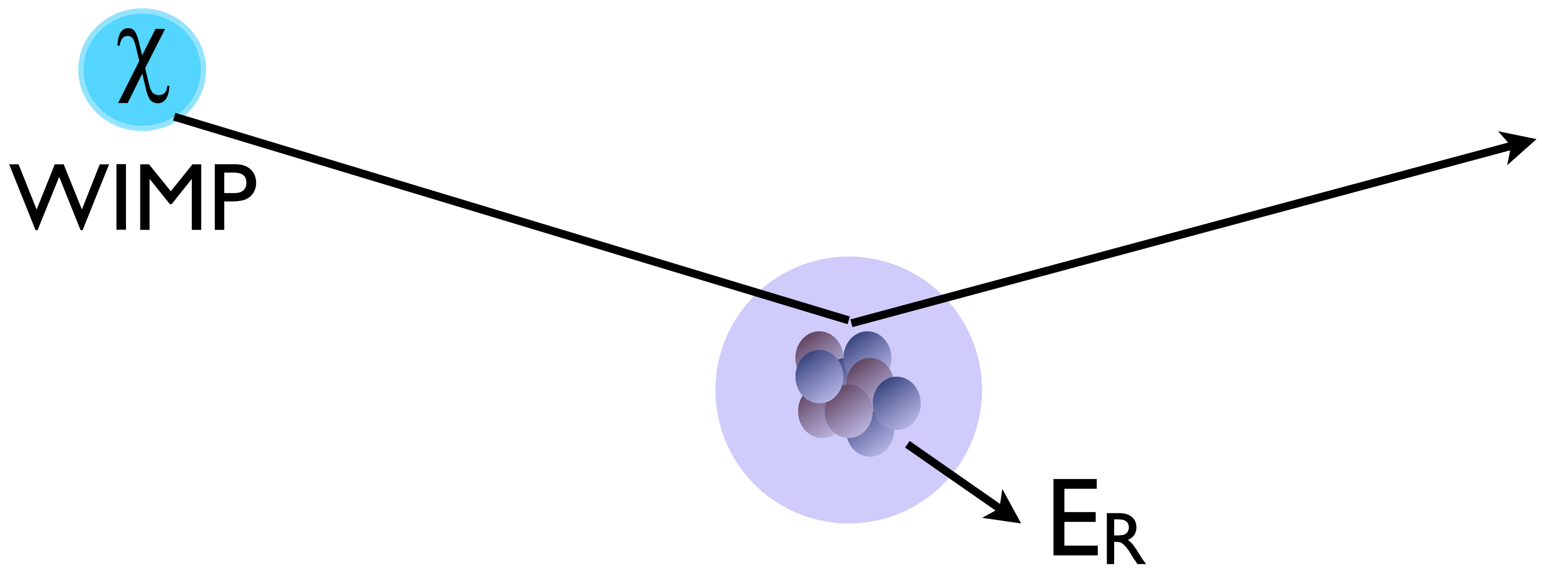
Indirect

Annihilation



- Solar WIMPs Searches are an odd ball -- use annihilations to test scattering

WIMP Direct Detection



- Expected event rate for a direct detection experiment

Astrophysics

$$R \sim N \frac{\rho_\chi}{\mathrm{m}_\chi} \sigma_{\chi \mathrm{N}} \langle v \rangle \qquad n_\chi = \frac{\rho_\chi}{\mathrm{m}_\chi}$$

Experiment

Particle Physics

N = Number of target nuclei in the detector
n_χ = local WIMP number density
m_χ = WIMP mass
<v> = mean velocity relative to the target
$\sigma_{\chi N}$ = WIMP-nucleus scattering cross section

Expected scattering cross section

- A general WIMP candidate: fermion (Dirac or Majorana), boson or scalar particle
- The most general, Lorentz invariant Lagrangian has 5 types of interactions
- In the extreme non-relativistic limit relevant for galactic WIMPs (10^{-3} c) the interactions leading to WIMP-nuclei scattering are classified as (Goodman and Witten, 1985):
  - **Spin Independent:** Scalar interactions (WIMPs couple to nuclear mass, from the scalar, vector, tensor part of L)

$$\sigma_{\mathrm{SI}} \sim \frac{\mu^2}{\mathrm{m}_\chi^2}[Z f_p + (A - Z) f_n]^2$$

coherent interaction on all nucleons
-> A^2 enhancement

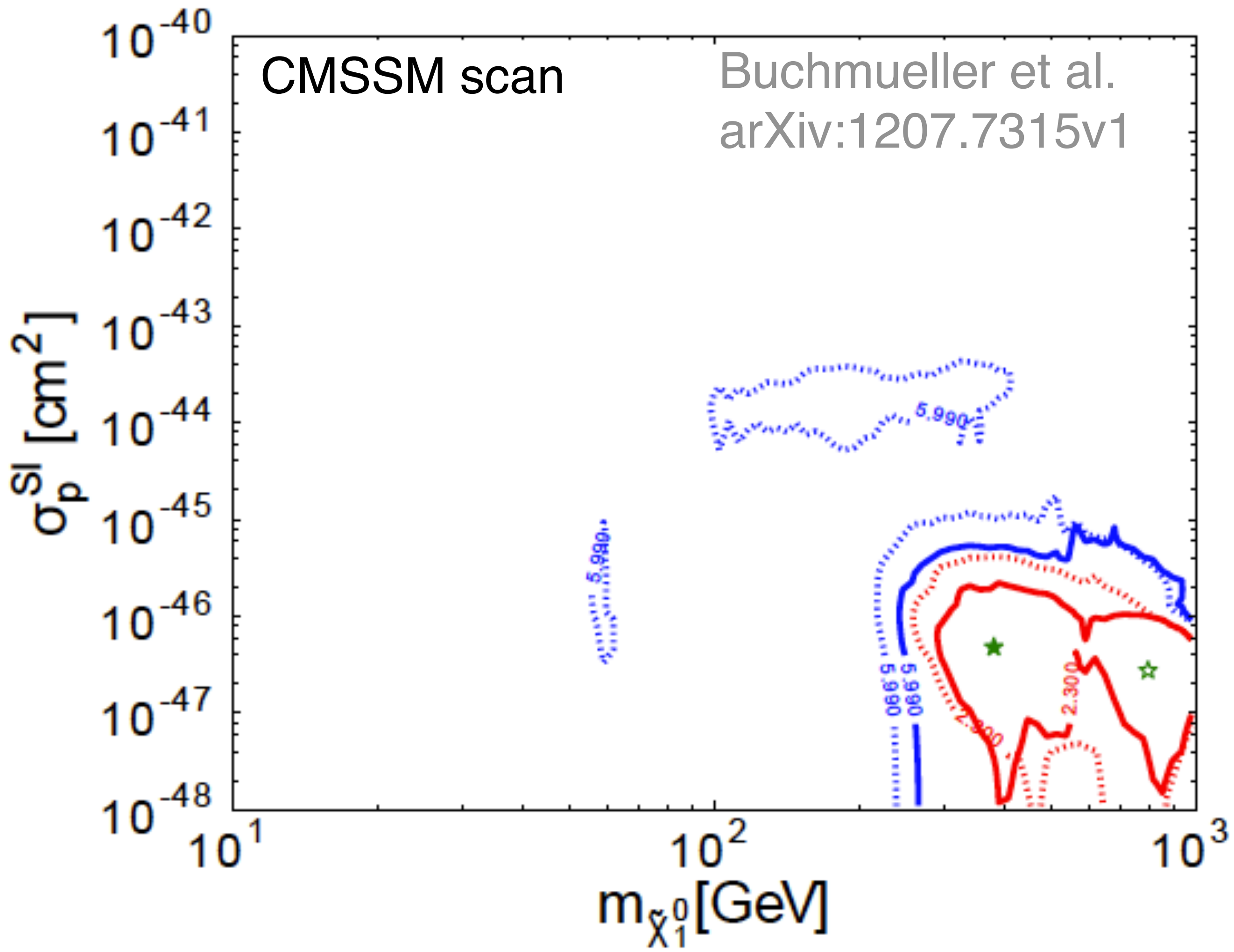
  - **Spin Dependent:** Spin-spin interactions (WIMPs couple to the nuclear spin, from the axial part of L)

$$\sigma_{\mathrm{SD}} \sim \mu^2 \frac{J_{\mathrm{N}} + 1}{J_{\mathrm{N}}}(a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

    - J - coupled angular momentum of the nucleus
    - $\{S_{n(N)}\}$ spin of neutron in nucleus
    - a_n, a_p - coupling constants

couple to the spin of the nucleus
-> unpaired n or p

Direct Detection Experiments



- Expected event rates are very small
- To increase event rates, use a large target mass

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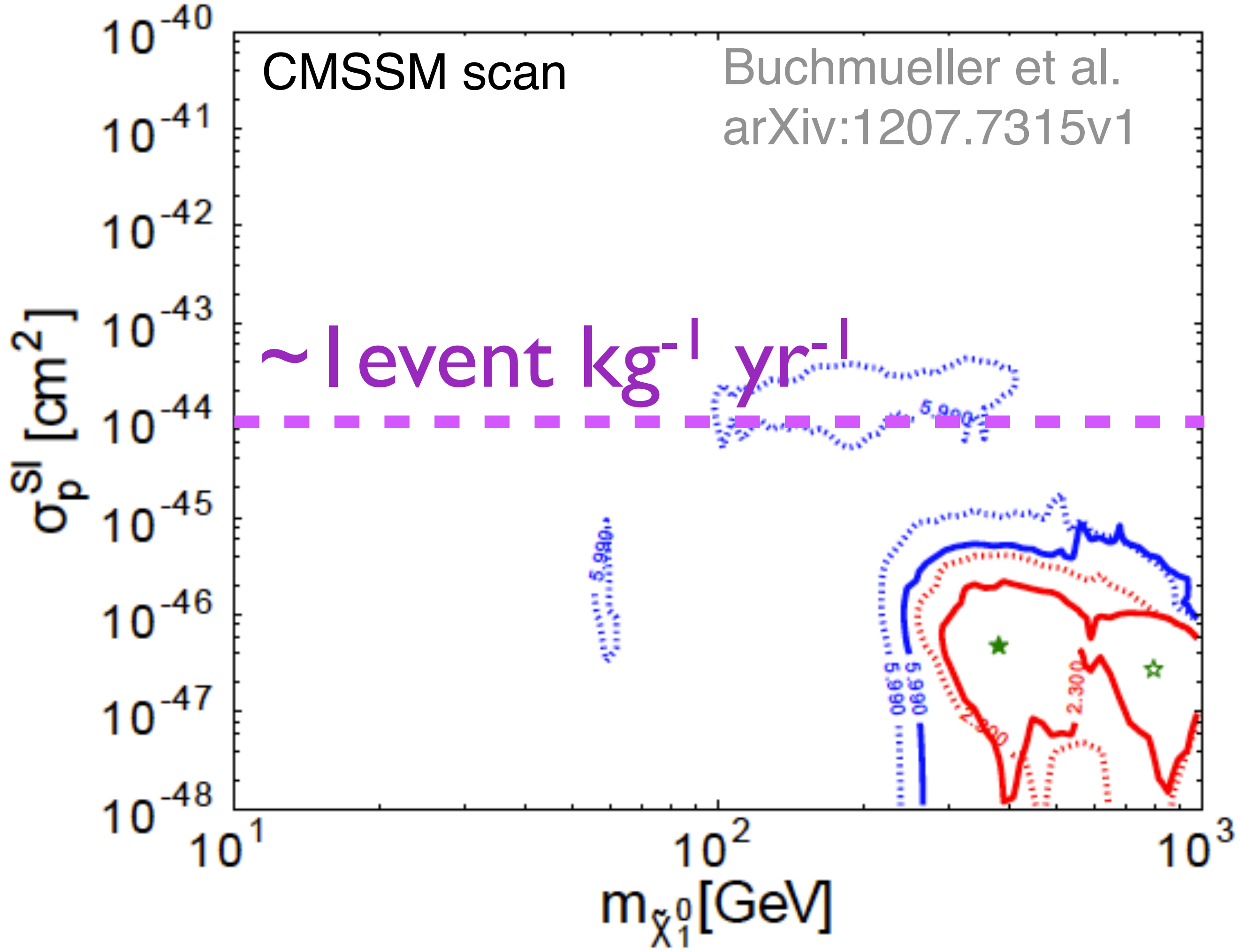

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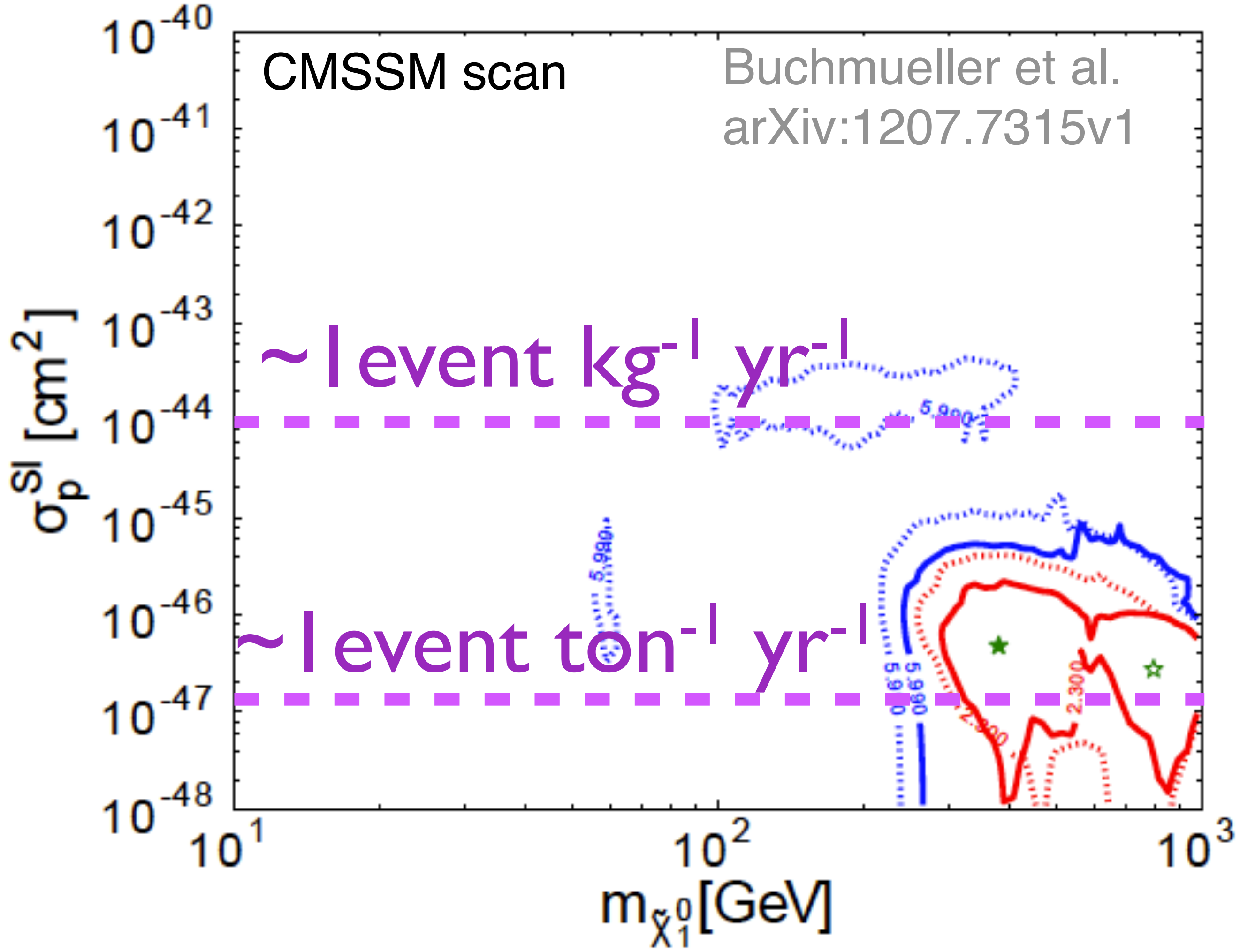

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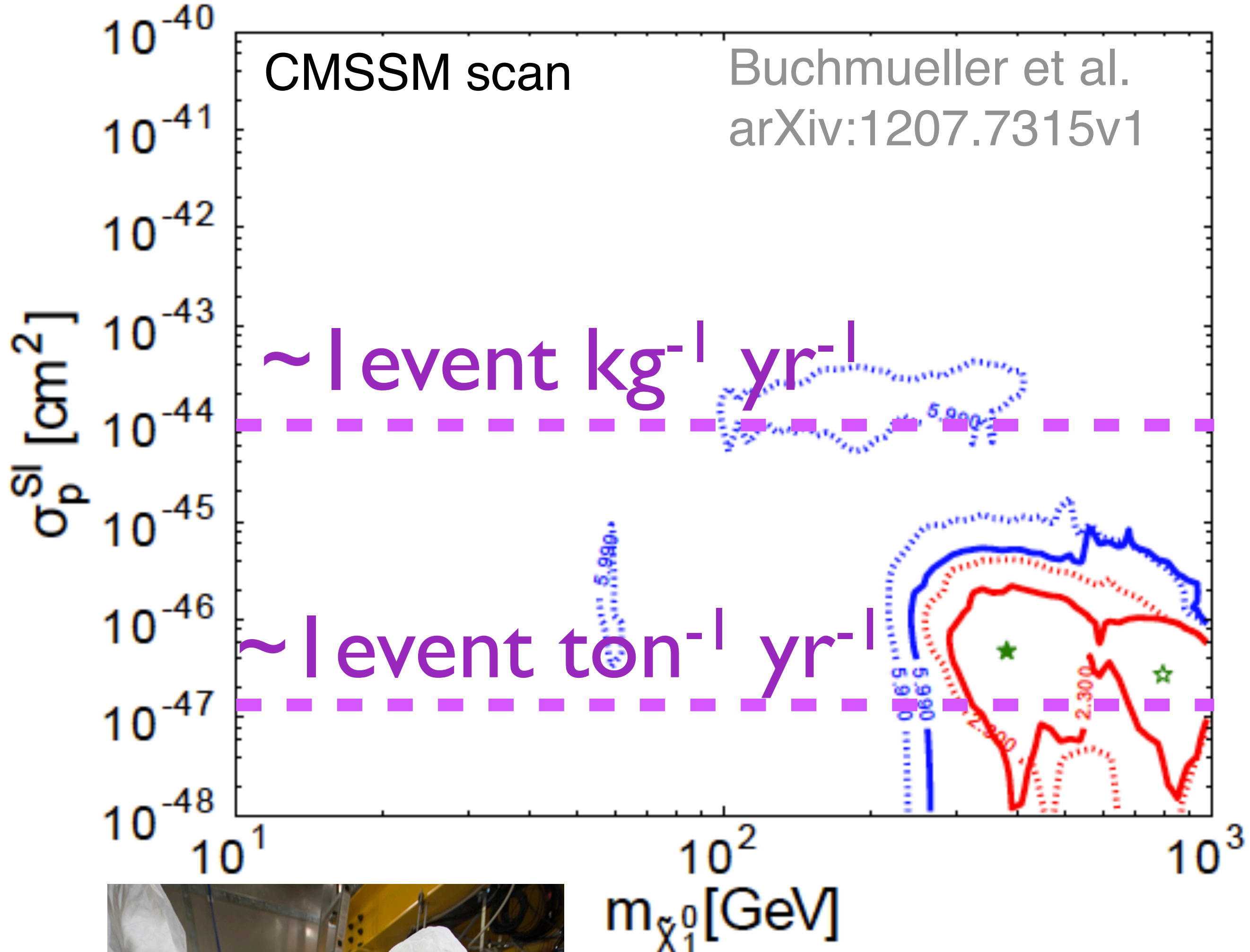

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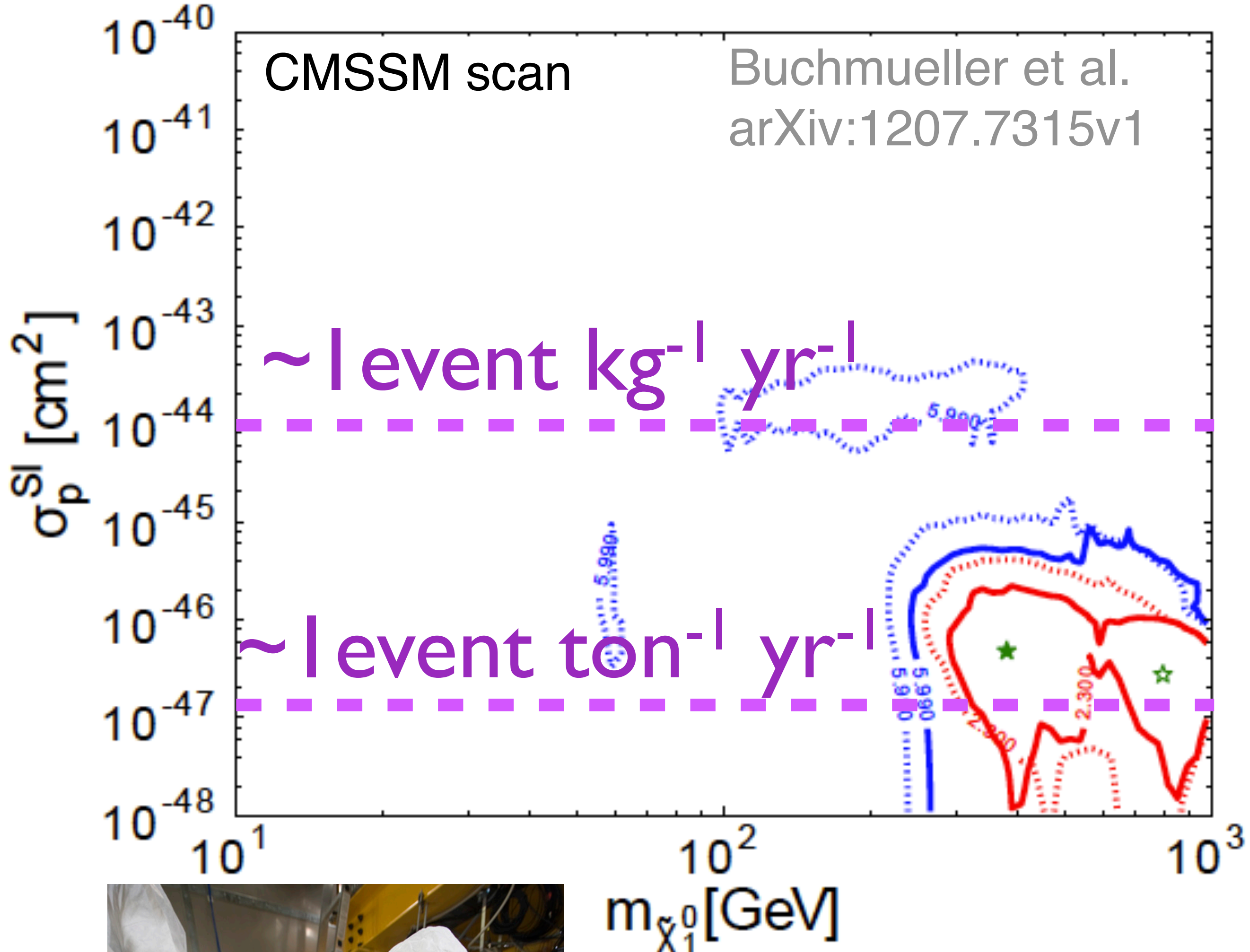

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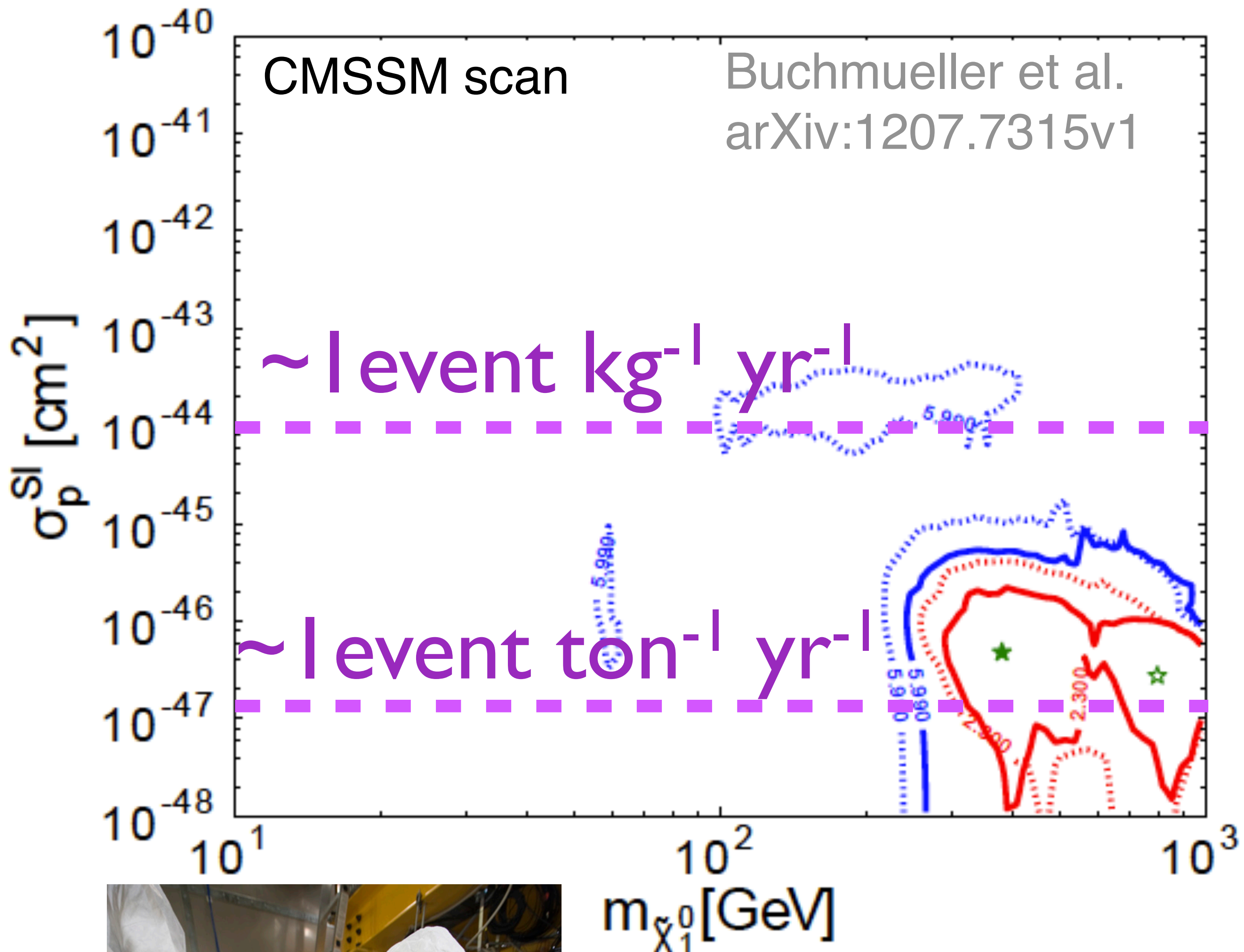

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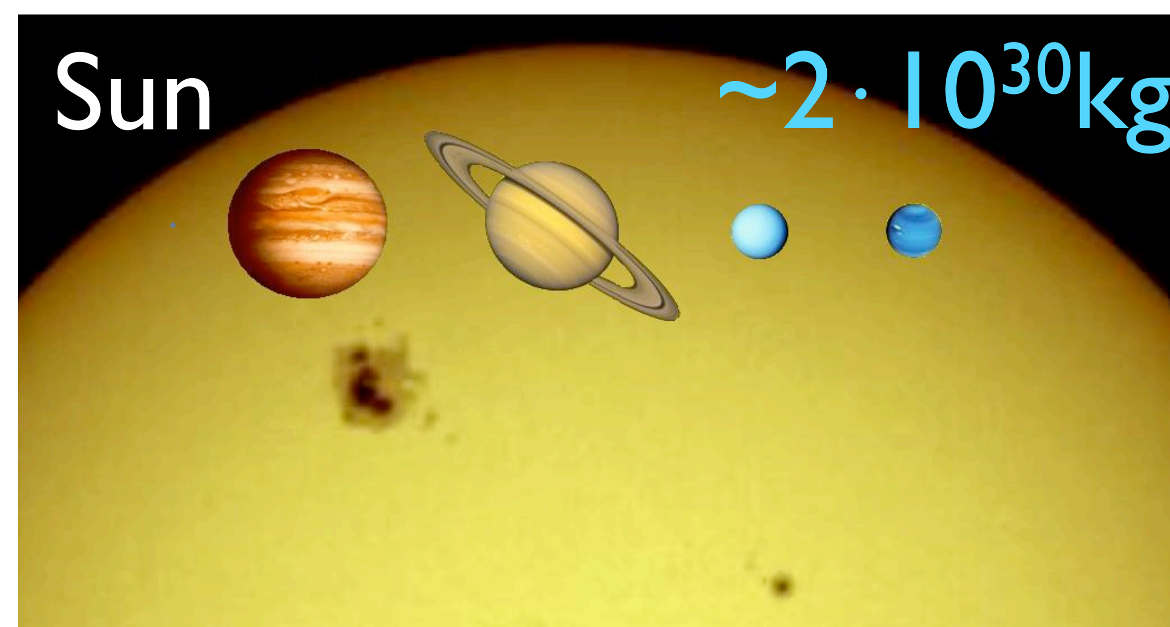
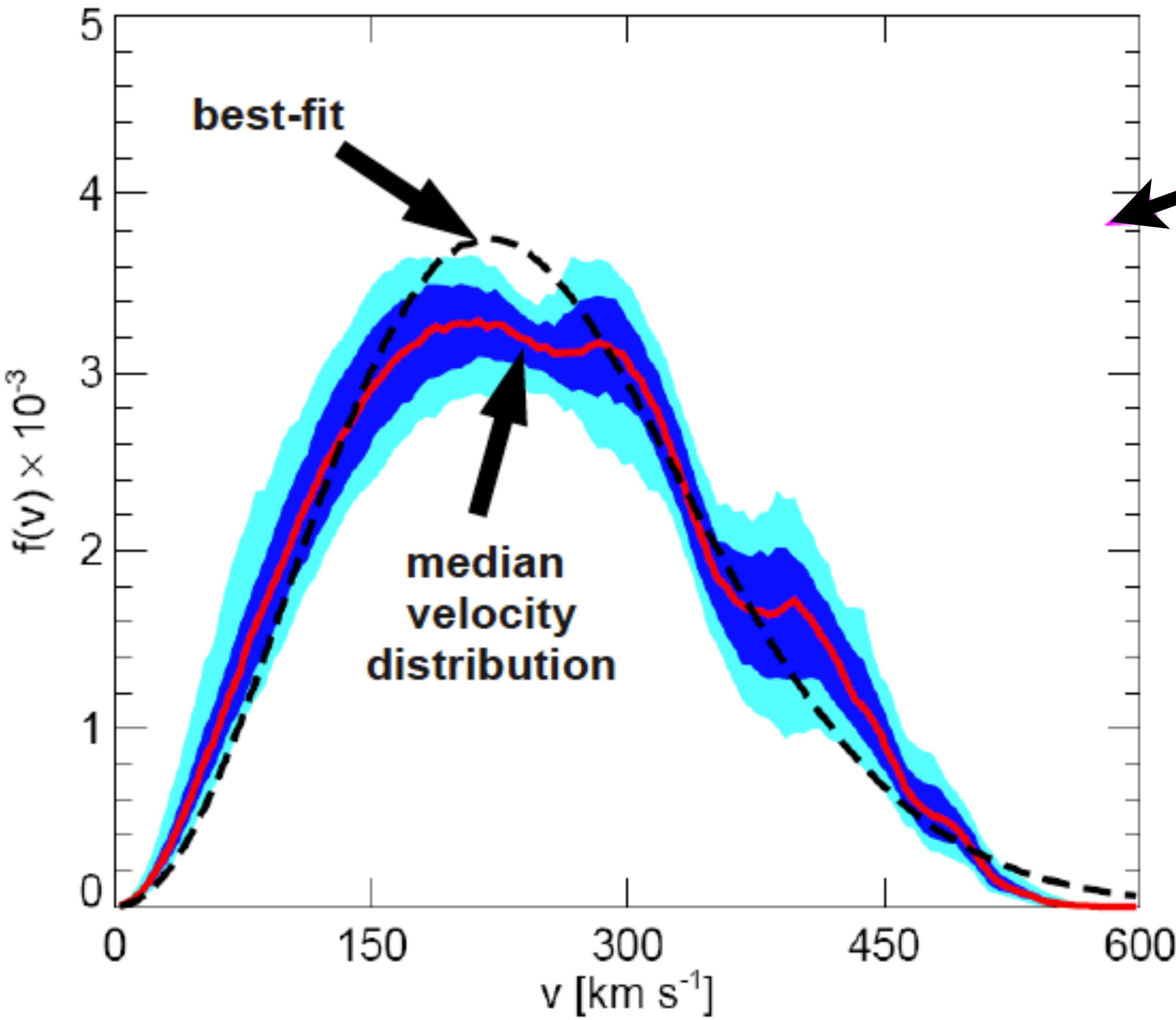
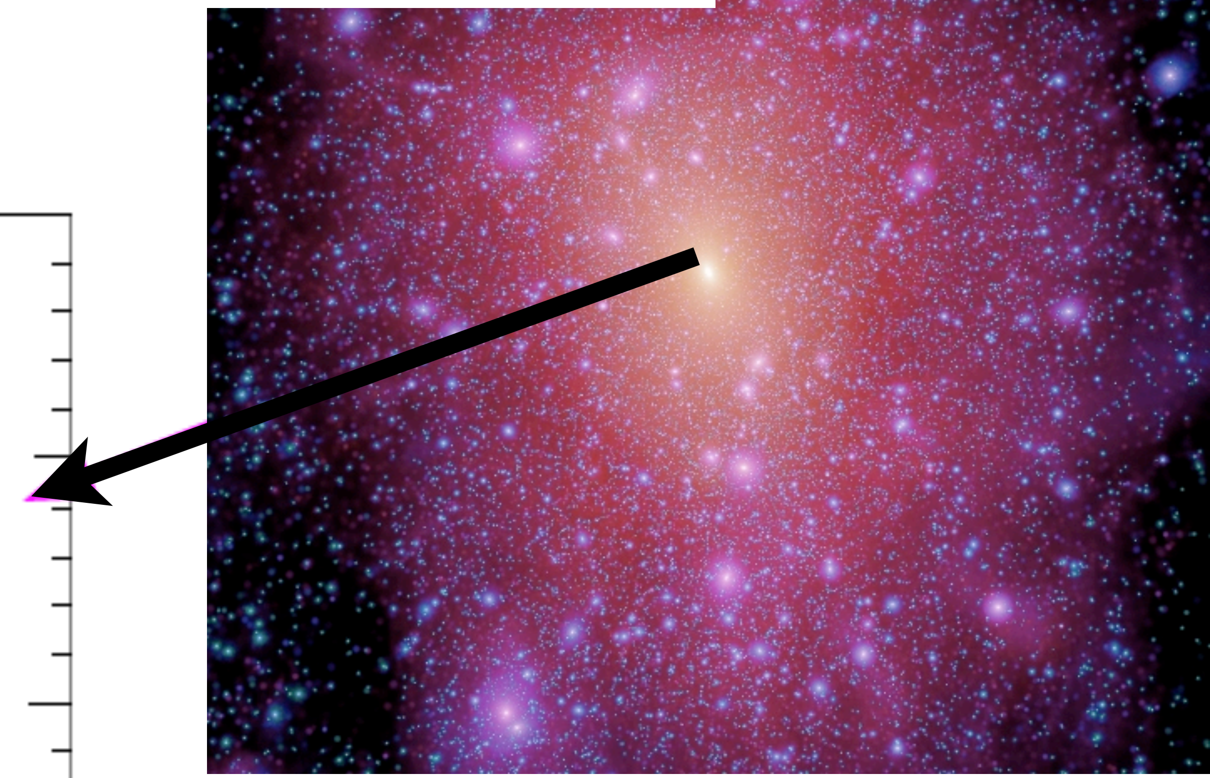


Local Dark Matter Density / Velocity



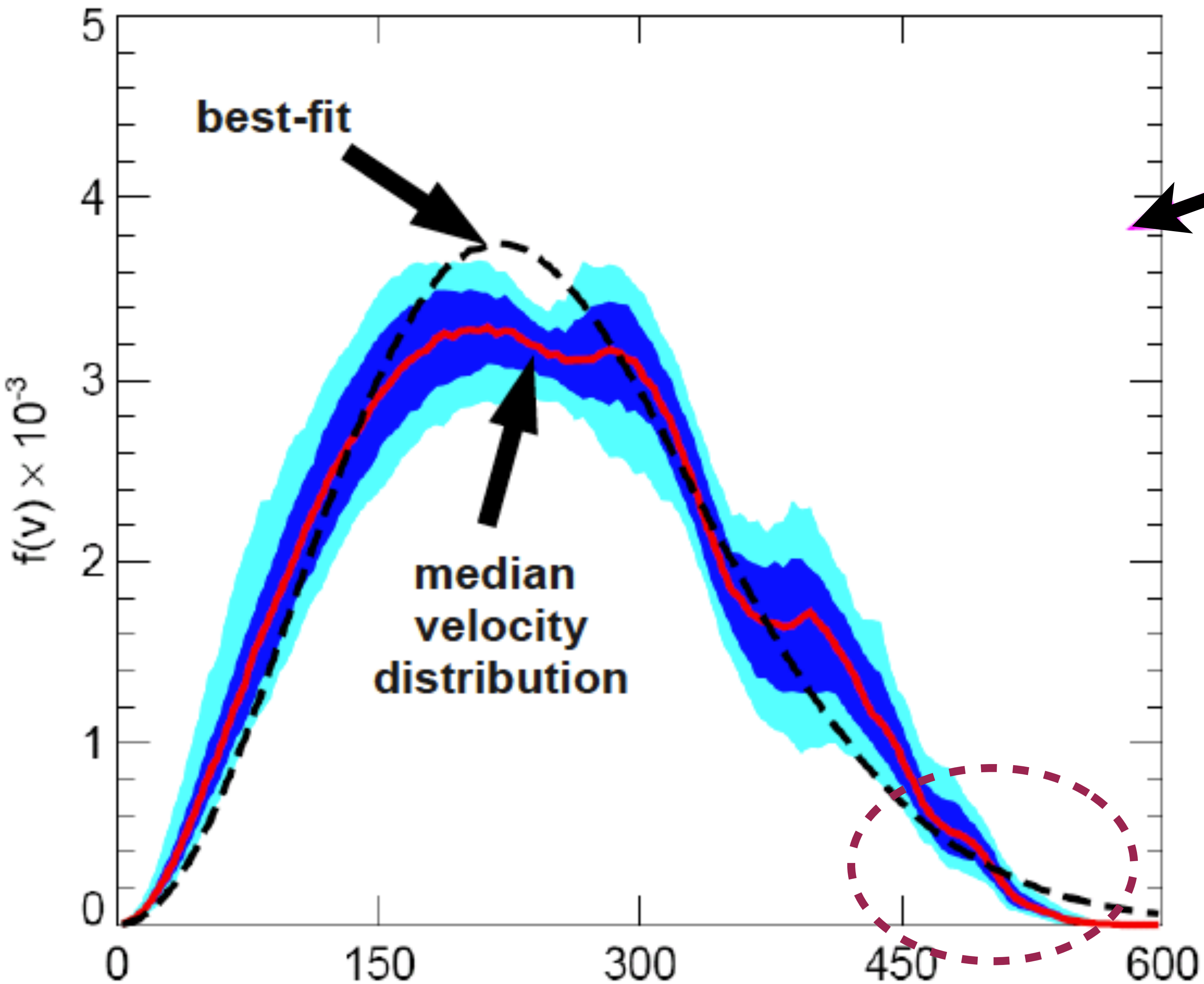


Velocity distribution still not very well understood

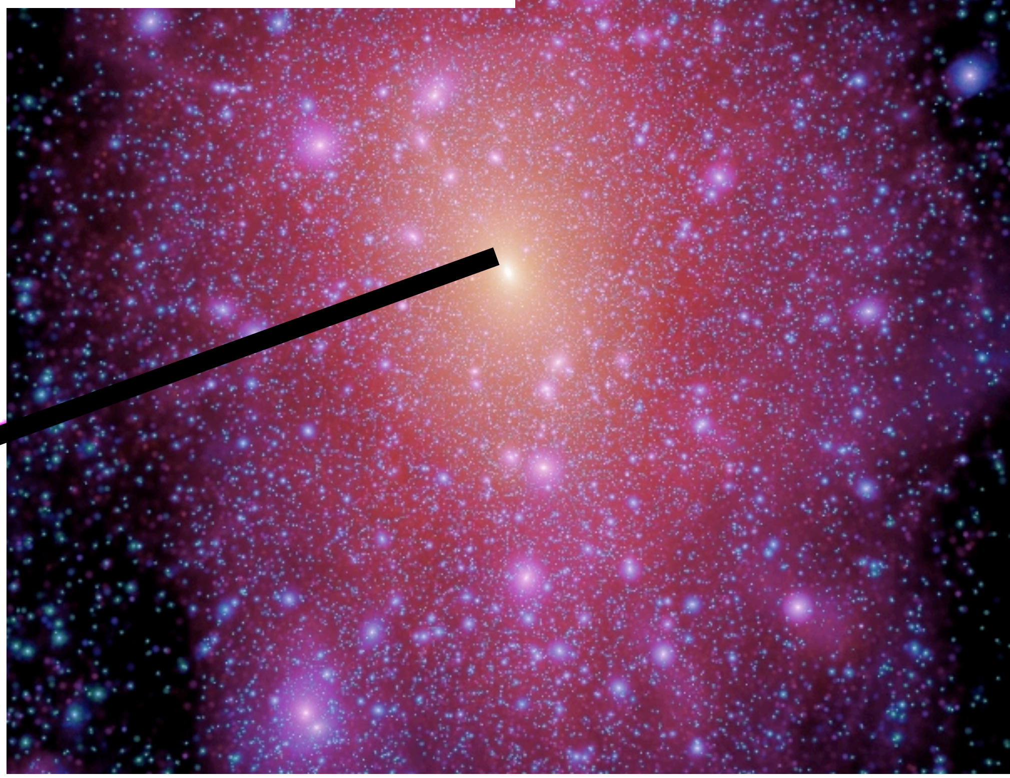
Maxwellian is reasonable

Local dark matter density ~0.3GeV/cm^3

Local Dark Matter Density / Velocity



large recoils
"best sensitivity" with
direct detection



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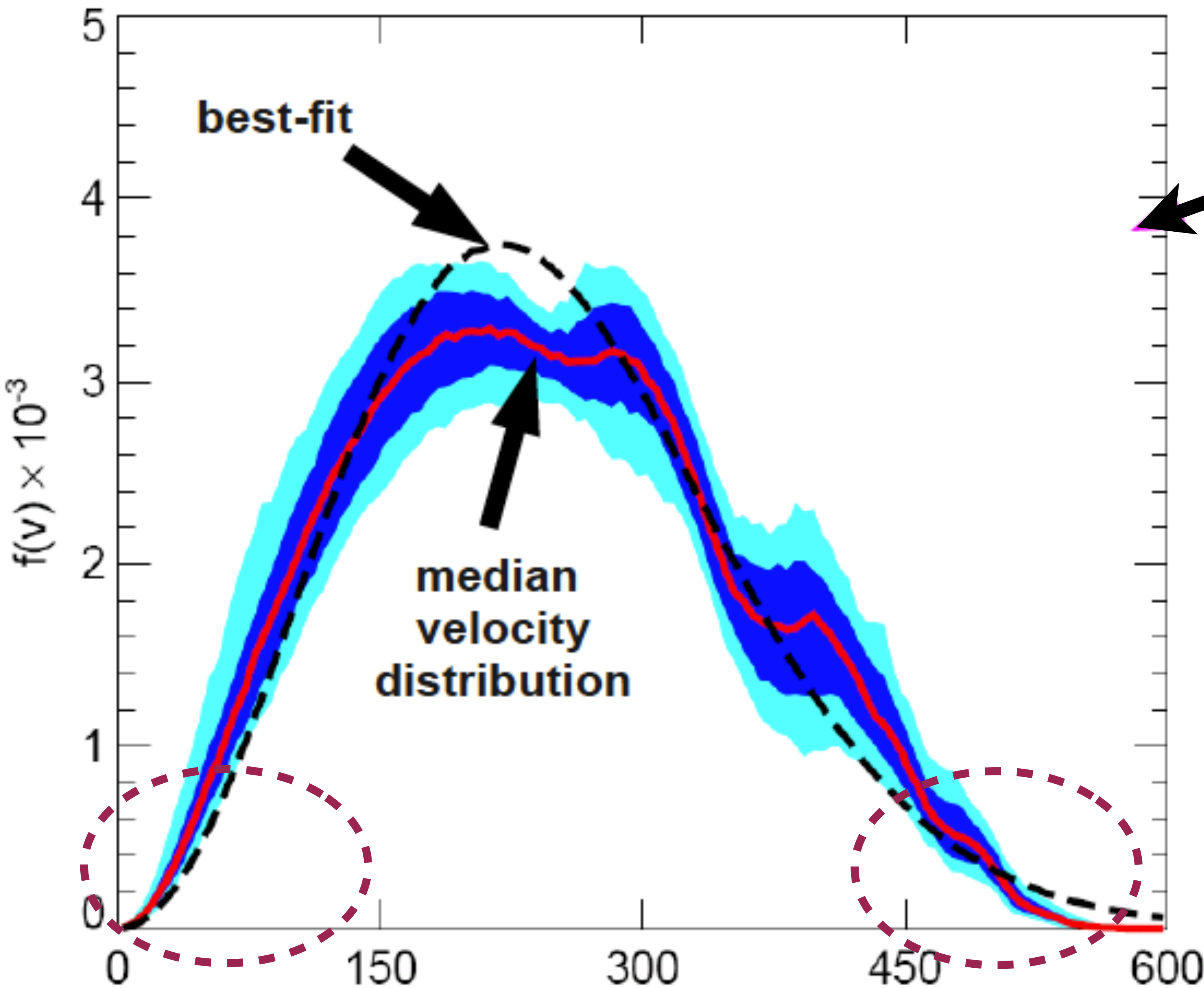
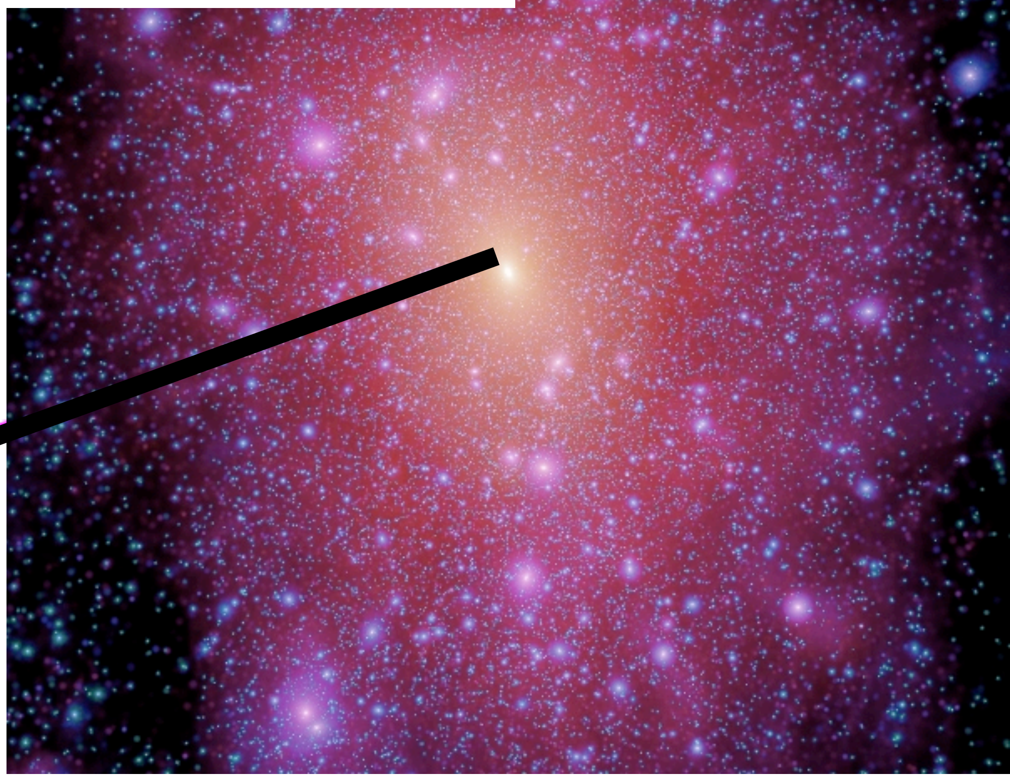
Local dark matter density $\sim 0.3 GeV/cm^3$

Local Dark Matter Density / Velocity



small recoils
"easiest" to be captured in the Sun/Earth - indirect searches

large recoils
"best sensitivity" with direct detection



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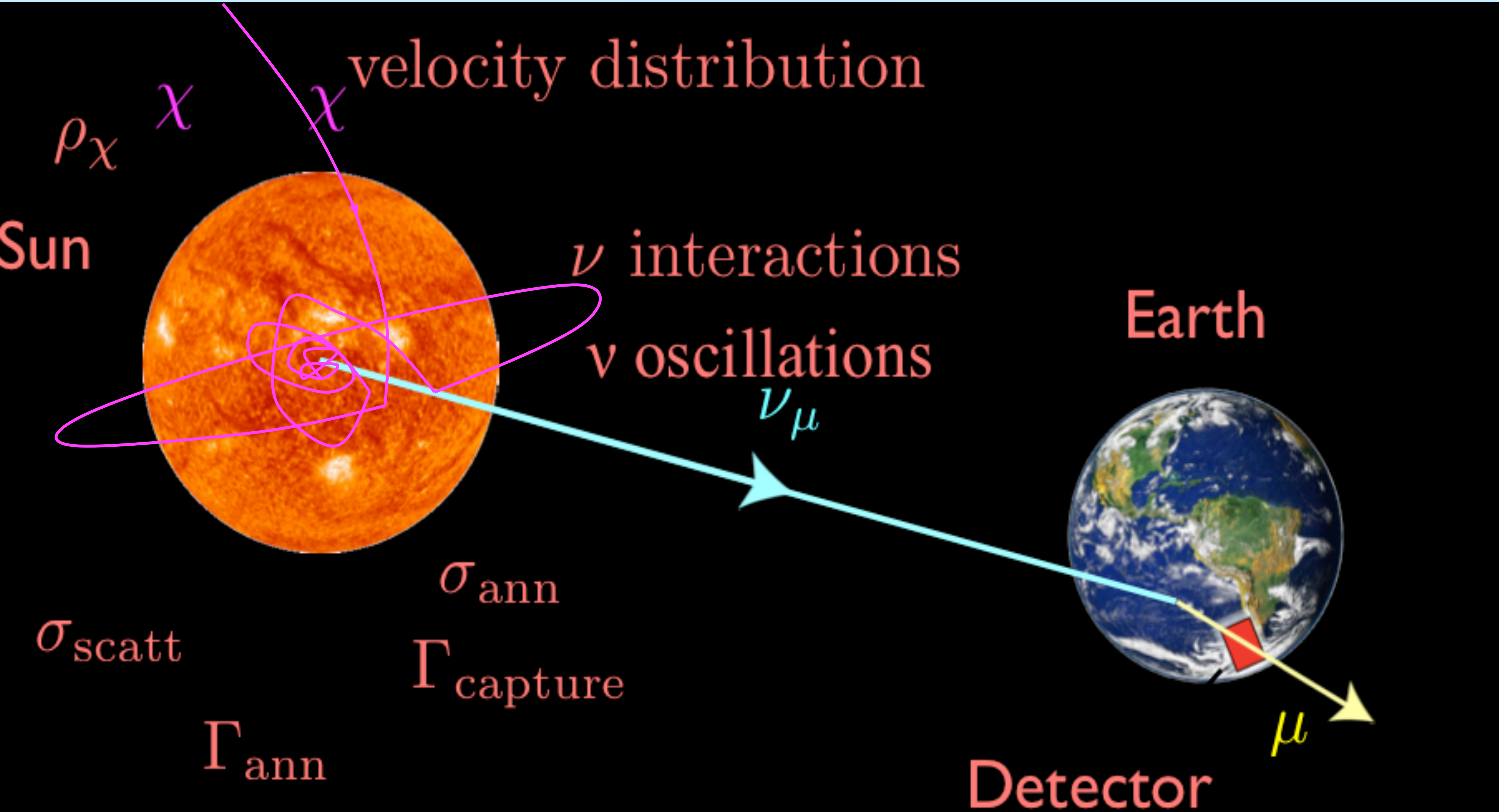
Solar WIMP Signal

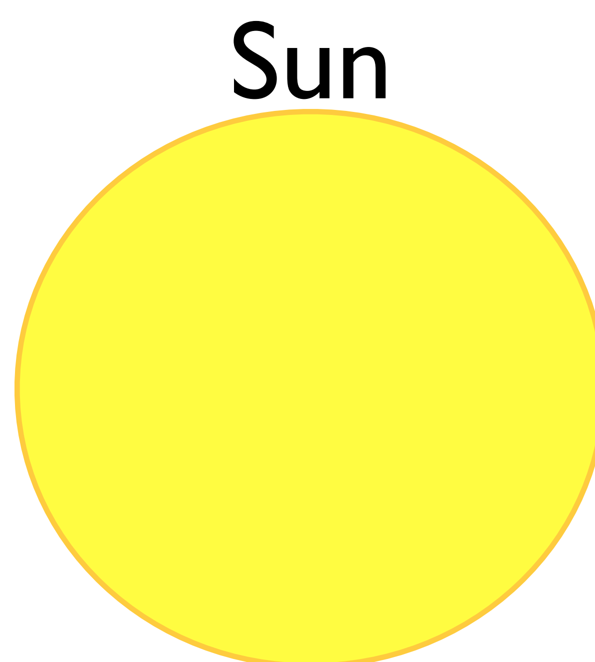


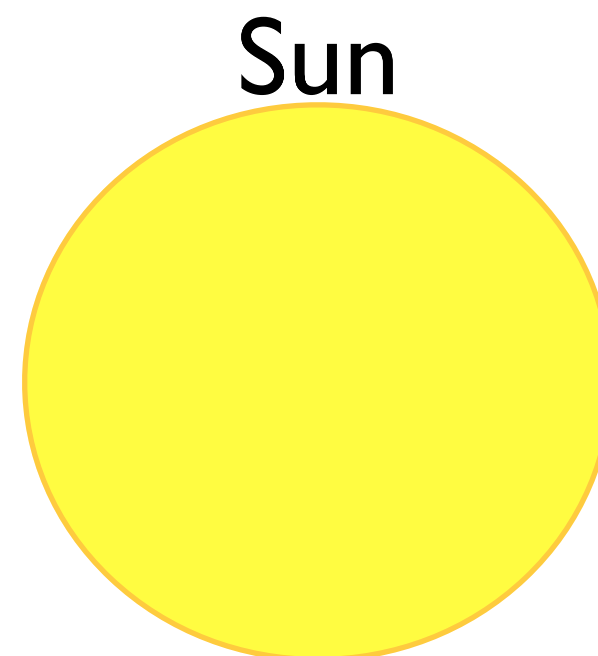
Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

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

Solar WIMP Equilibrium

- Dark Matter accumulates and starts annihilating → Neutrinos are the only particles that can make it out
- At equilibrium ($\Gamma_A = 1/2\,\Gamma_C$) the neutrino flux does not depend on the self annihilation cross section !



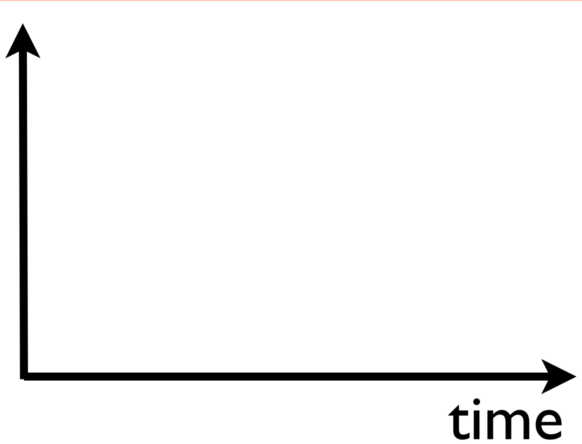


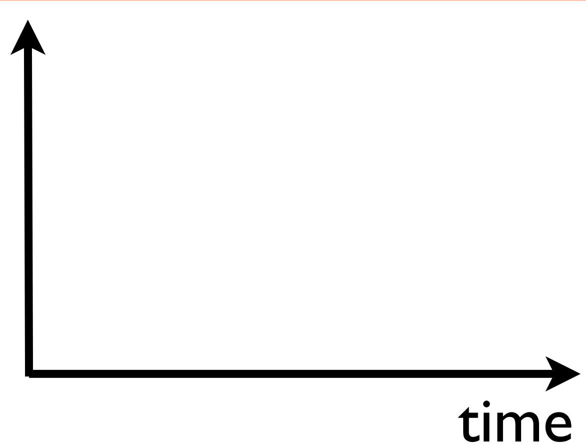
Self-annihilation cross section: **large** **small**

WIMP-Nucleon scattering: same in both (⇒assume capture rates are identical)

N = #WIMPs, Capture Rate (Γ_C), Annihilation Rate (Γ_A), Evaporation

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$





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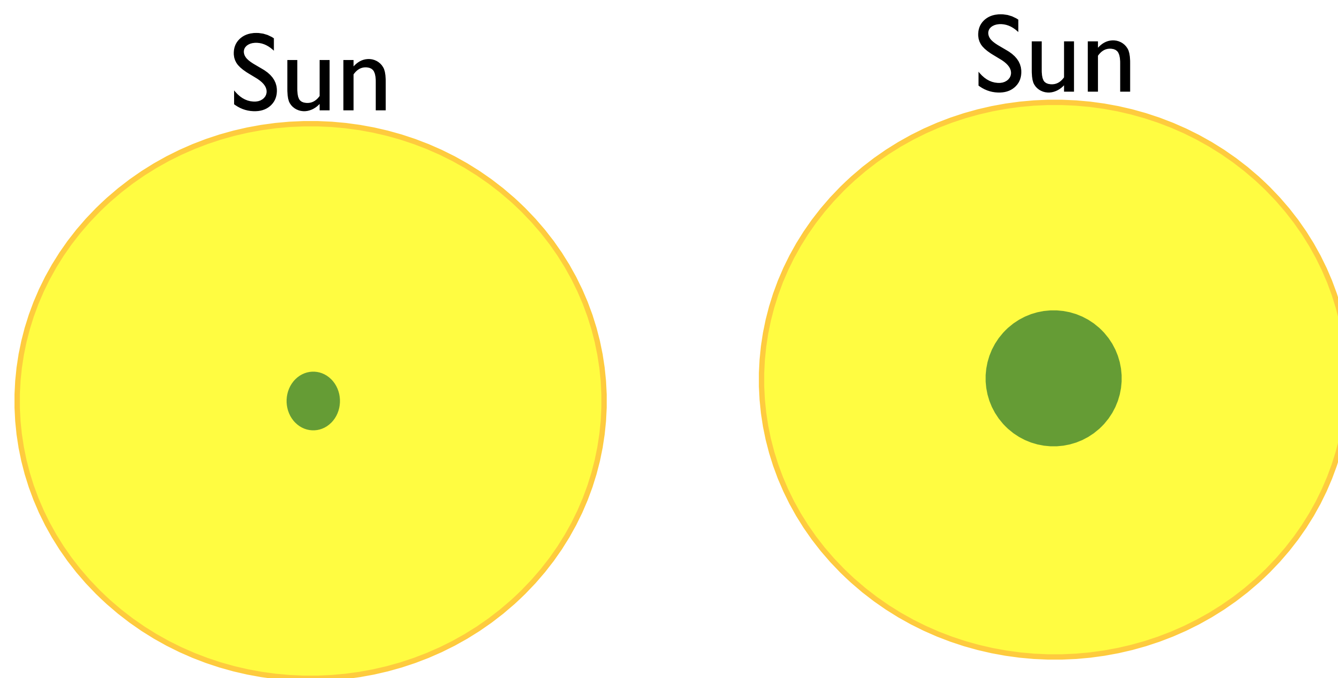

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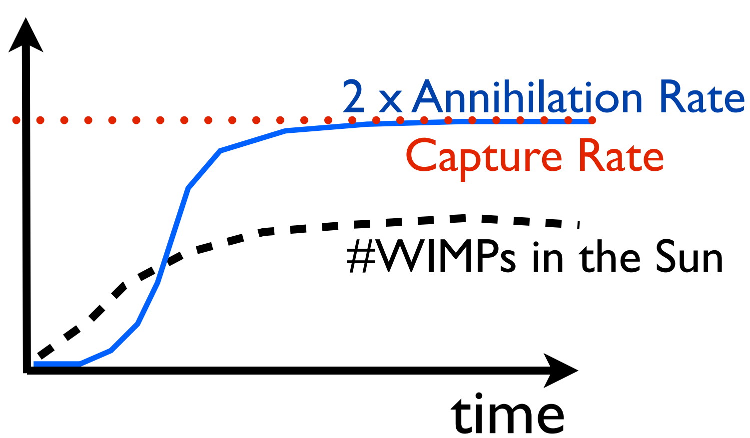
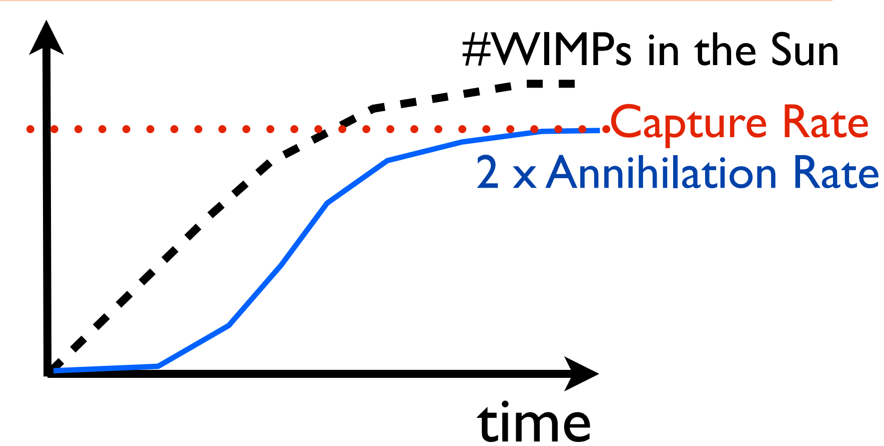
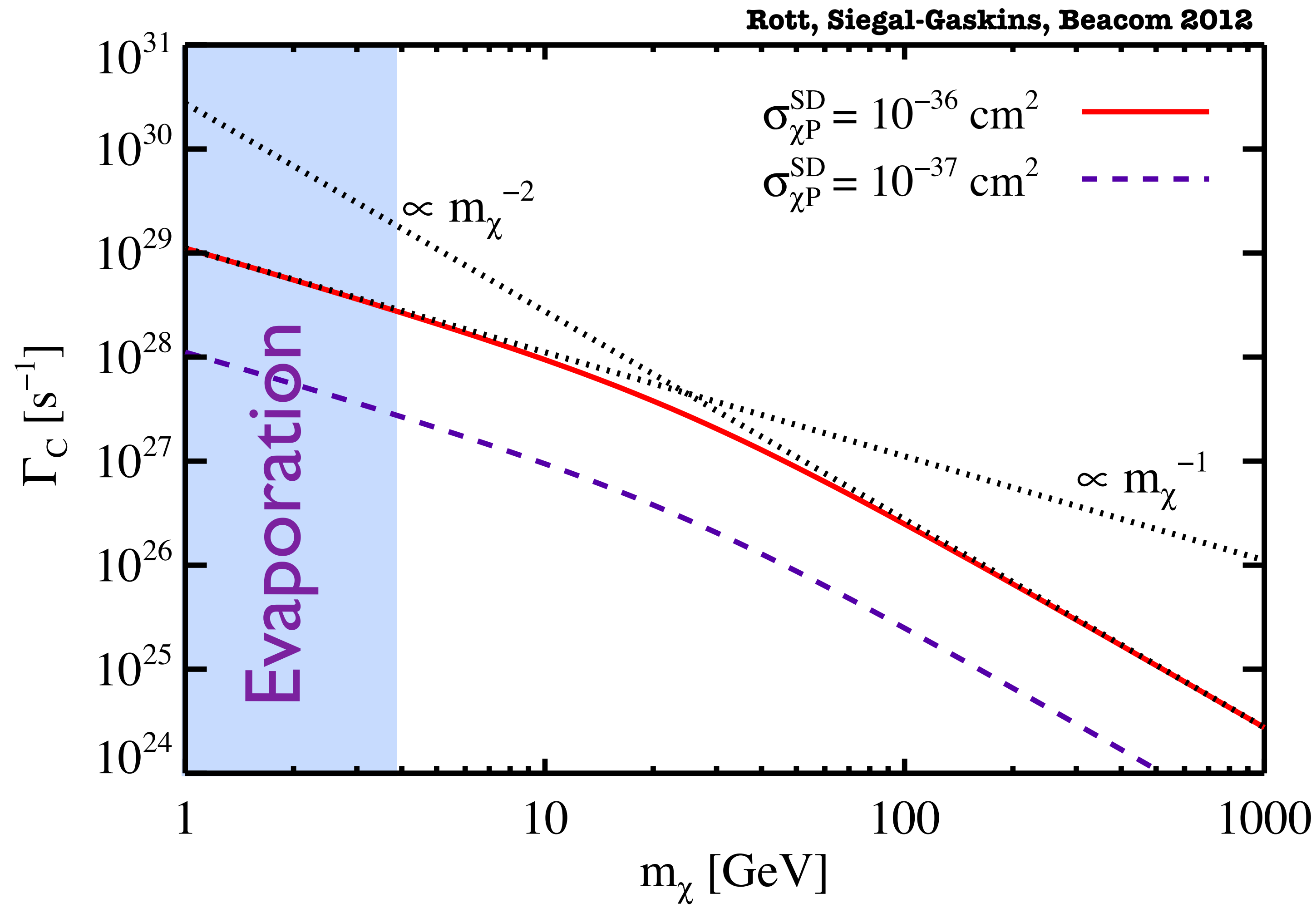




Solar WIMP Capture

- 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 (Γ_A=Γ_C/2)
  - The neutrino flux only depends on the WIMP-Nucleon scattering cross section



The capture rates scales as:

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

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

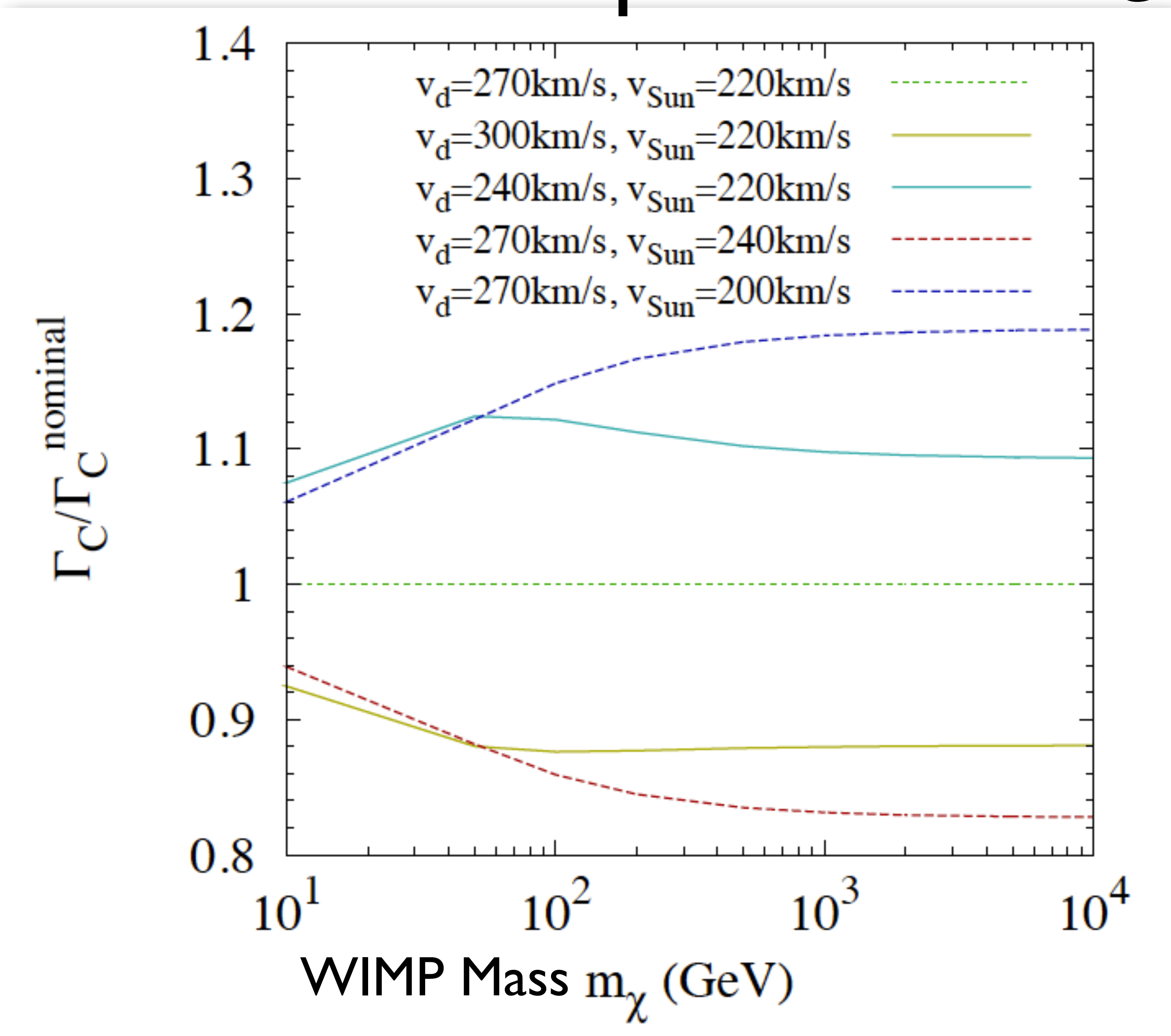
number density + kinematic suppression

m_A - is the target mass

Halo Uncertainties on the capture rate

C.Rott, T. Tanaka, Y. Itow, JCAP09(2011)029

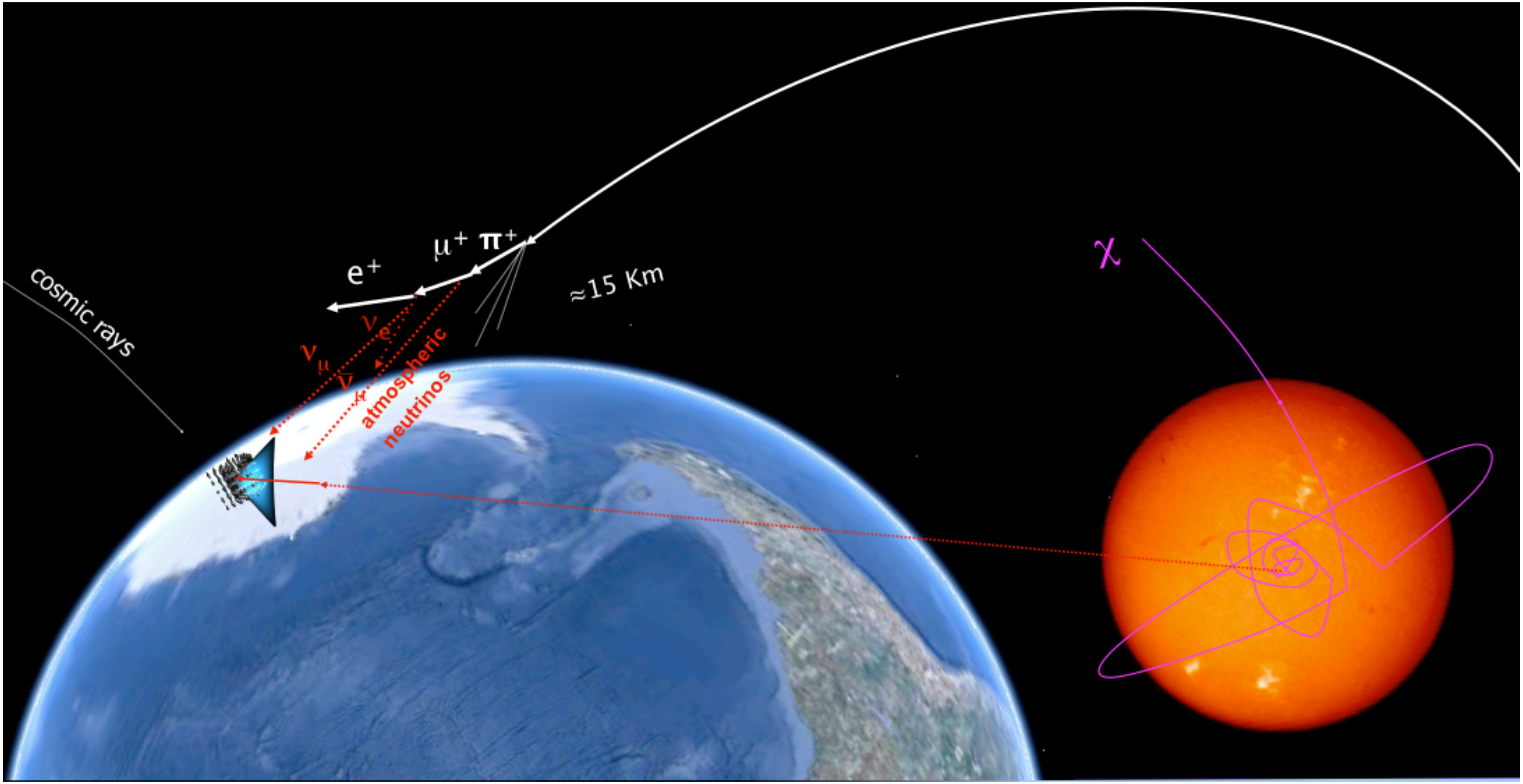
Effect on Capture Rate Γ_C



Assume a Maxwellian velocity distribution of the WIMPs outside the potential well of the Sun with a dispersion of v_d
Circular velocity of the Sun is assumed to be v_{SUN}=220km/s

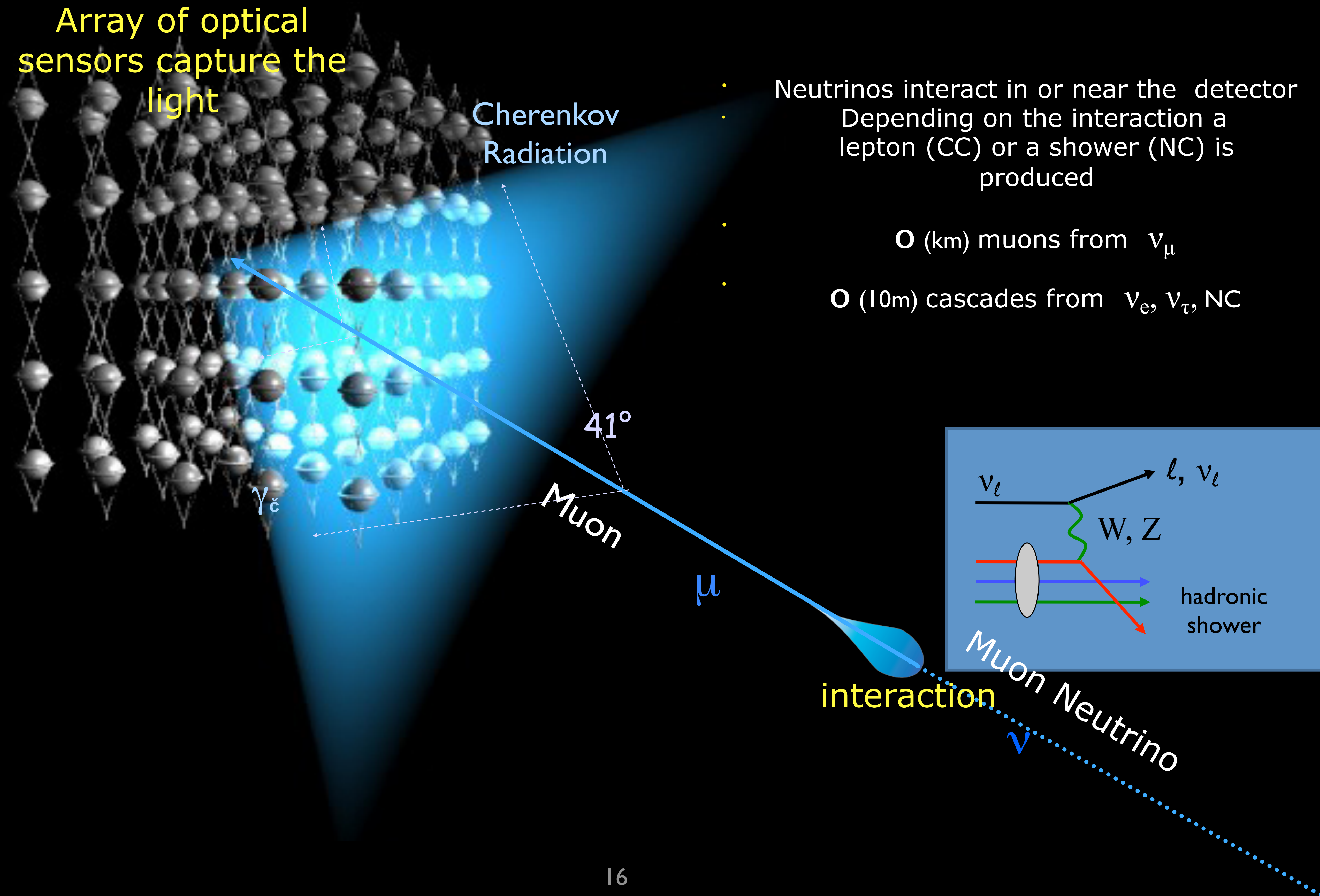
- While uncertainties in the dark matter distribution can result in significantly different annihilation rates in the Sun, results tend to be on the conservative side
- Direct detections have to deal with the same uncertainties, and interpretations of results is by no means simpler
- Sun irons out fluctuations in the local density or velocity distribution

Search for Solar WIMPs



Principle of an optical Neutrino

- Neutrinos interact in or near the detector
- Depending on the interaction a lepton (CC) or a shower (NC) is produced
- O (km) muons from ν_μ
- O (10m) cascades from ν_e, ν_τ, NC



The IceCube Neutrino Telescope

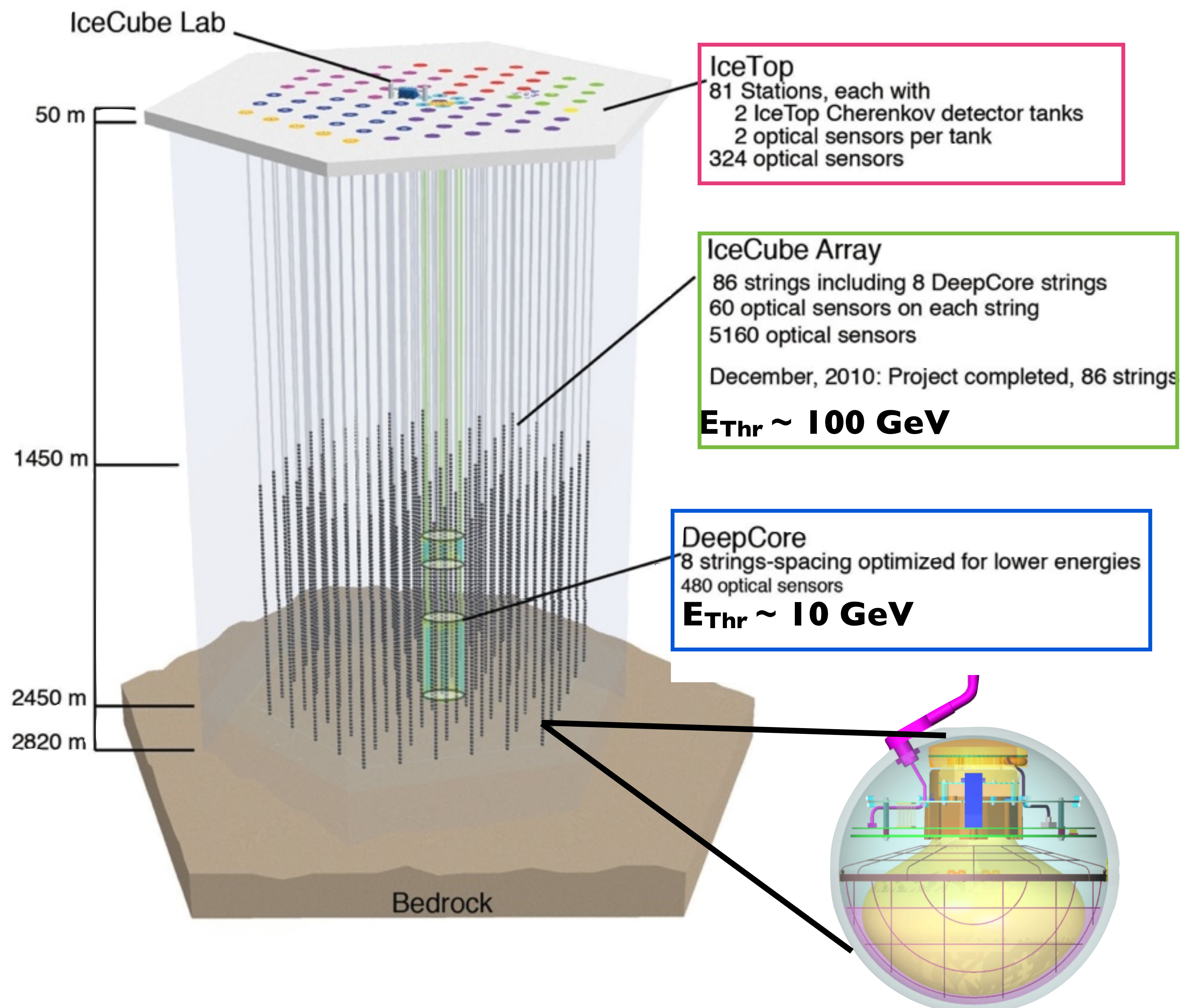
Gigaton Neutrino Detector at the Geographic South Pole

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



The IceCube Neutrino Telescope

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

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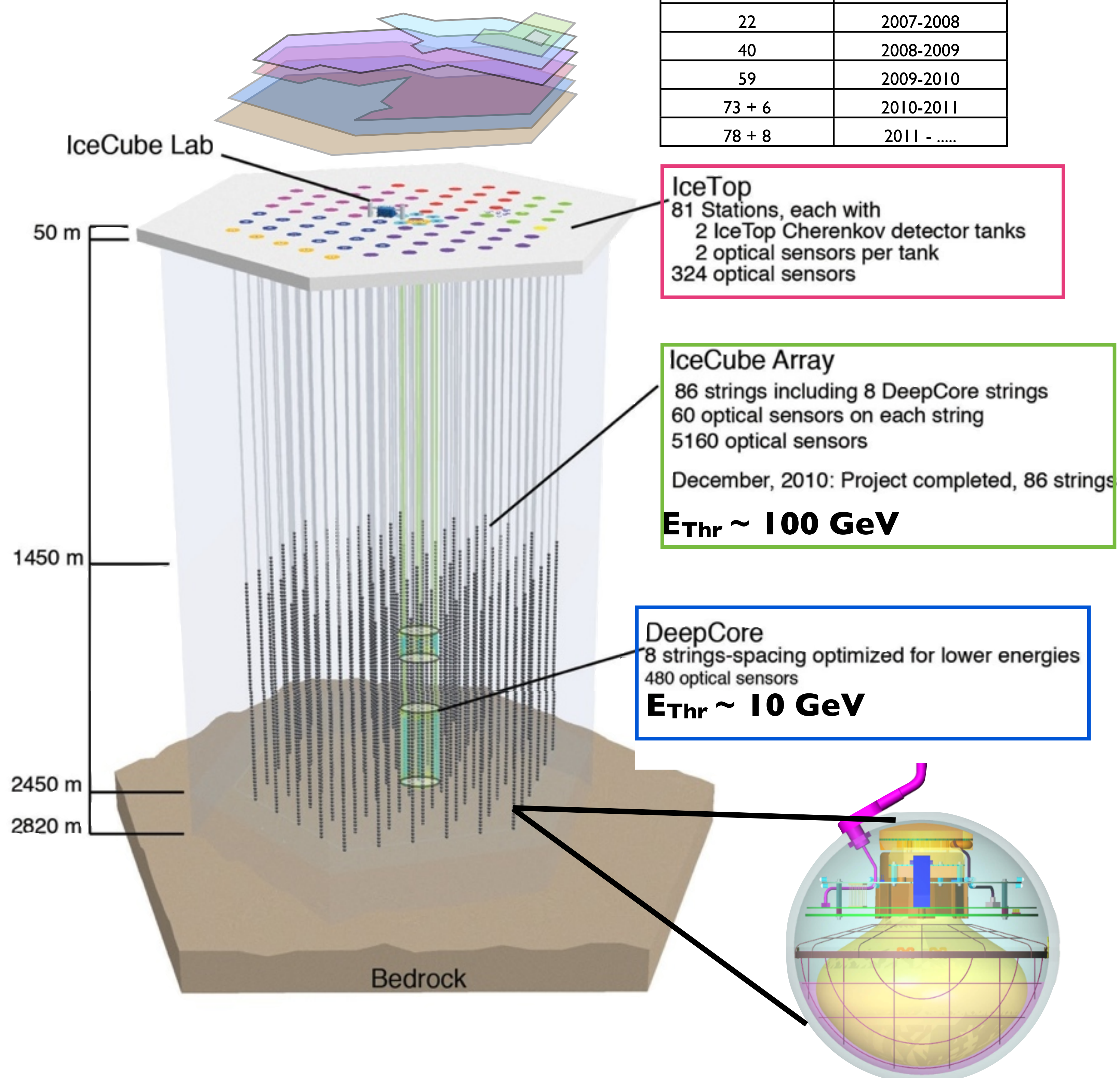

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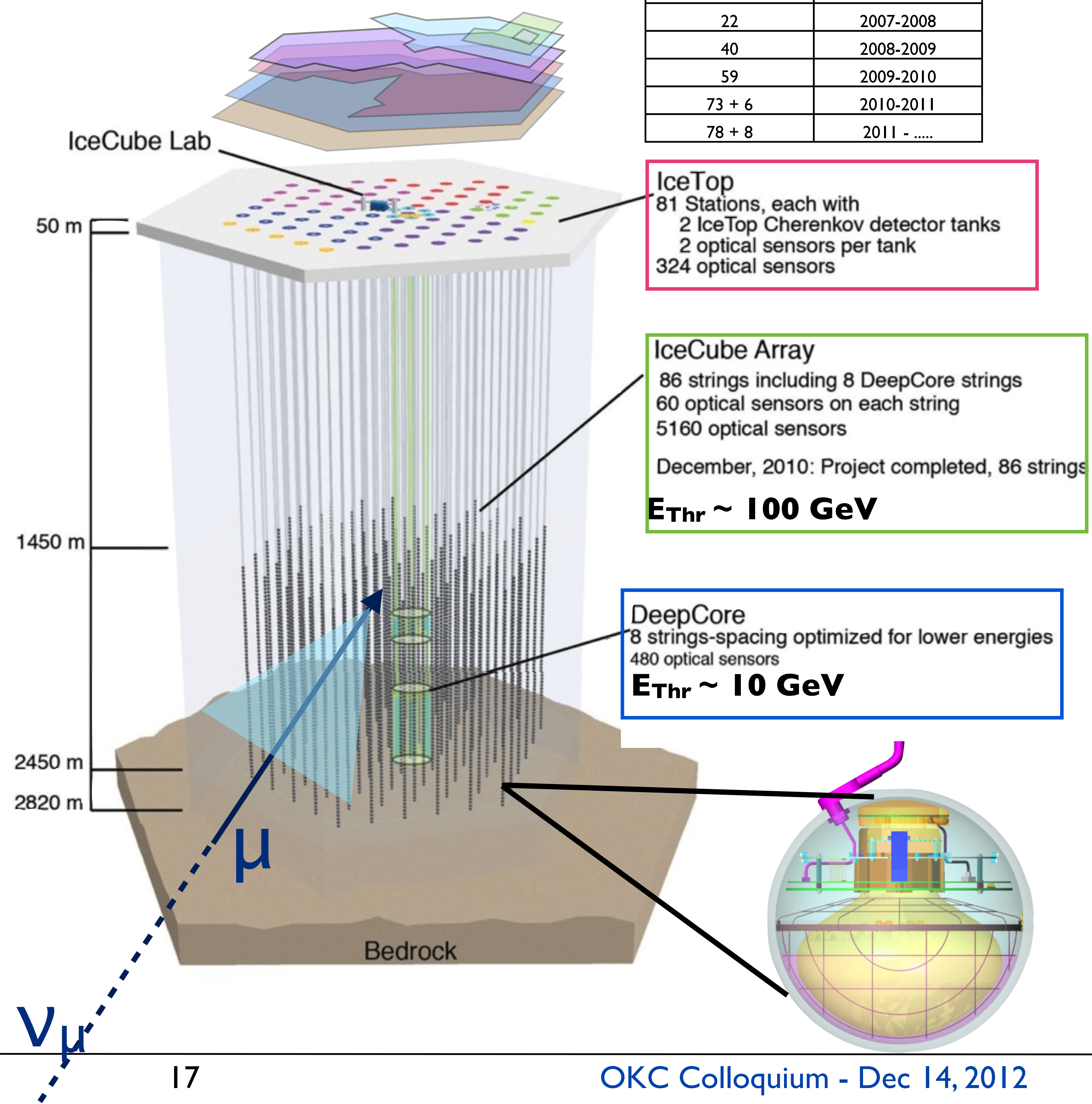
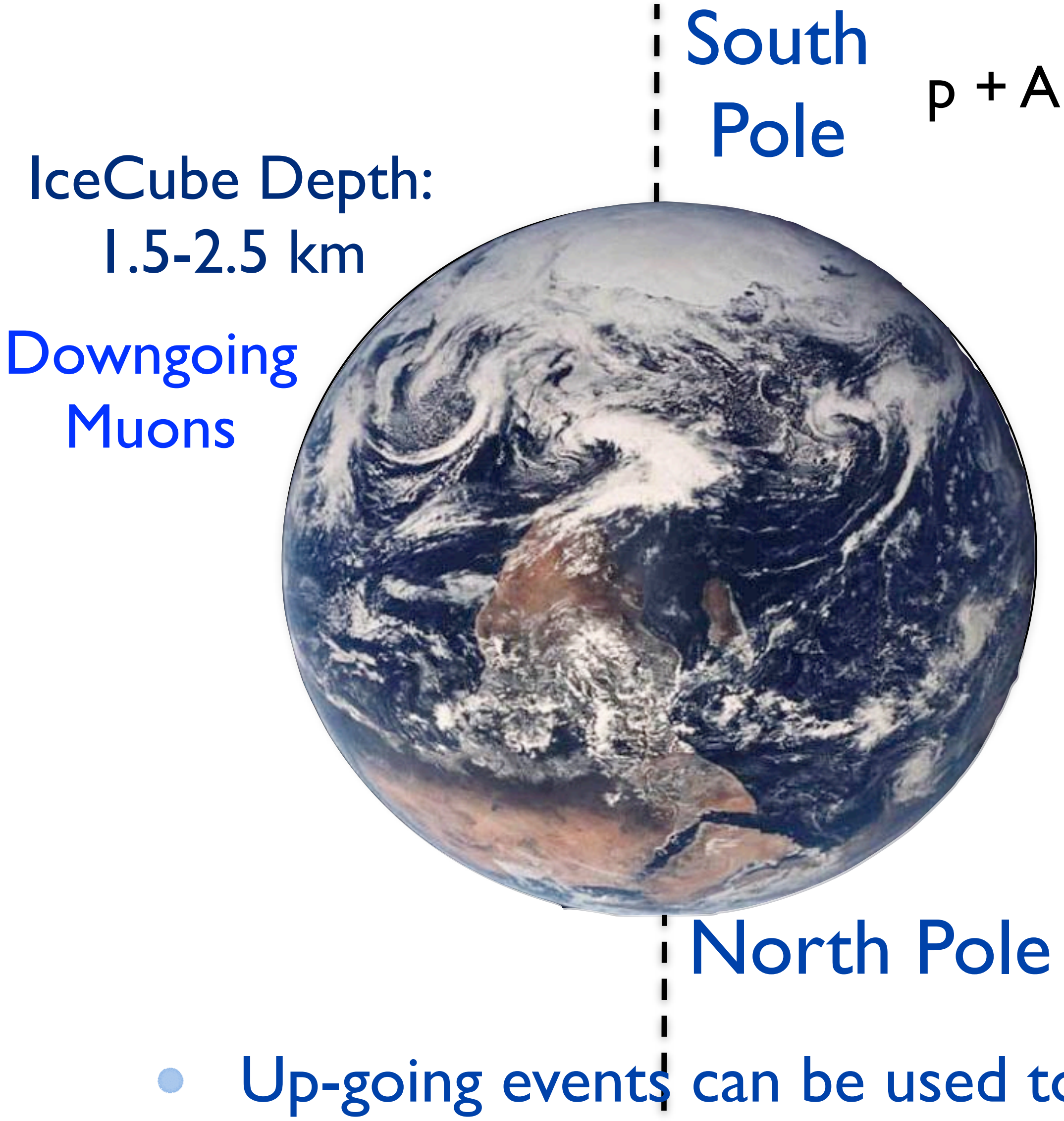
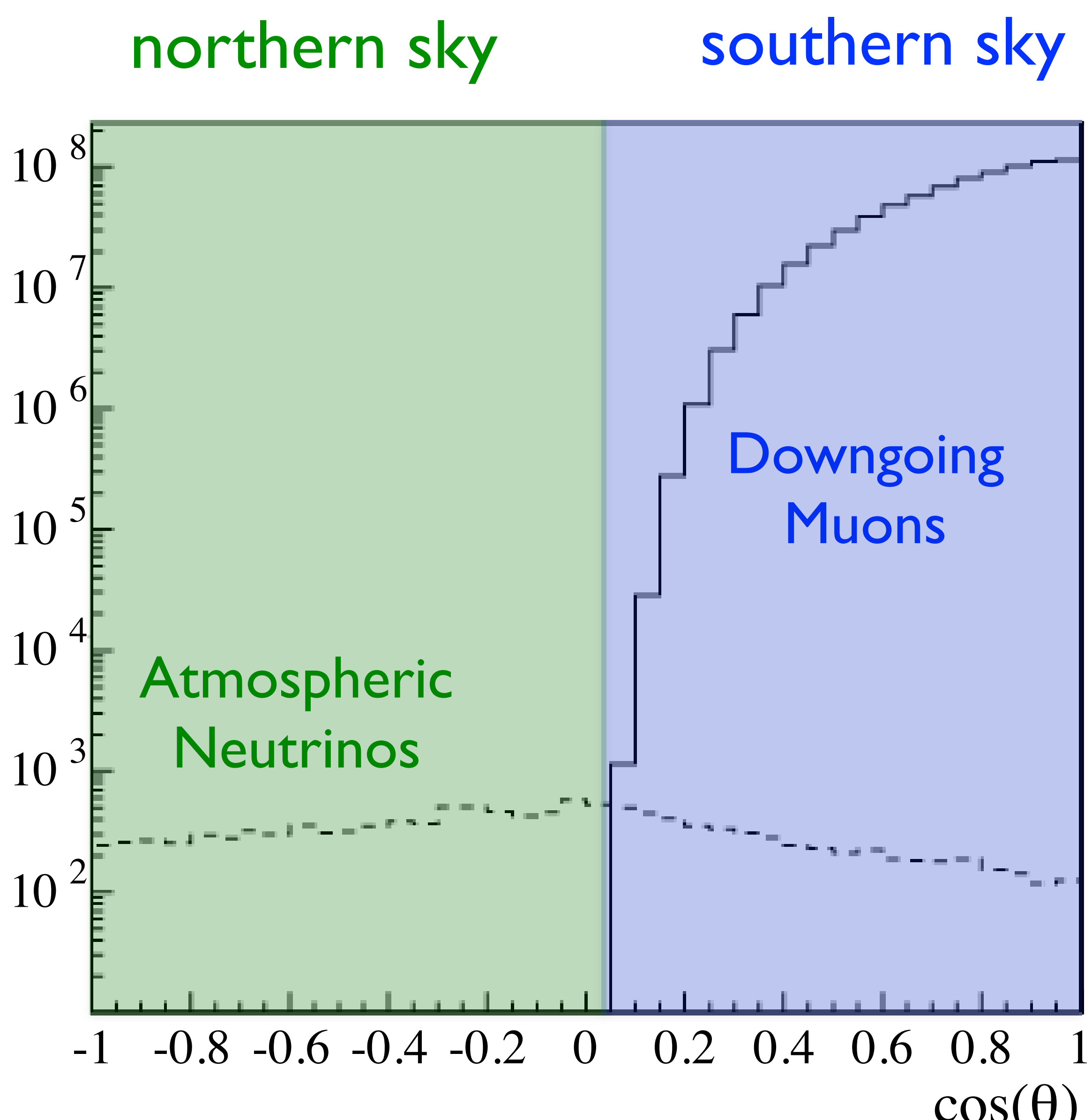


Signals in IceCube

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





Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube

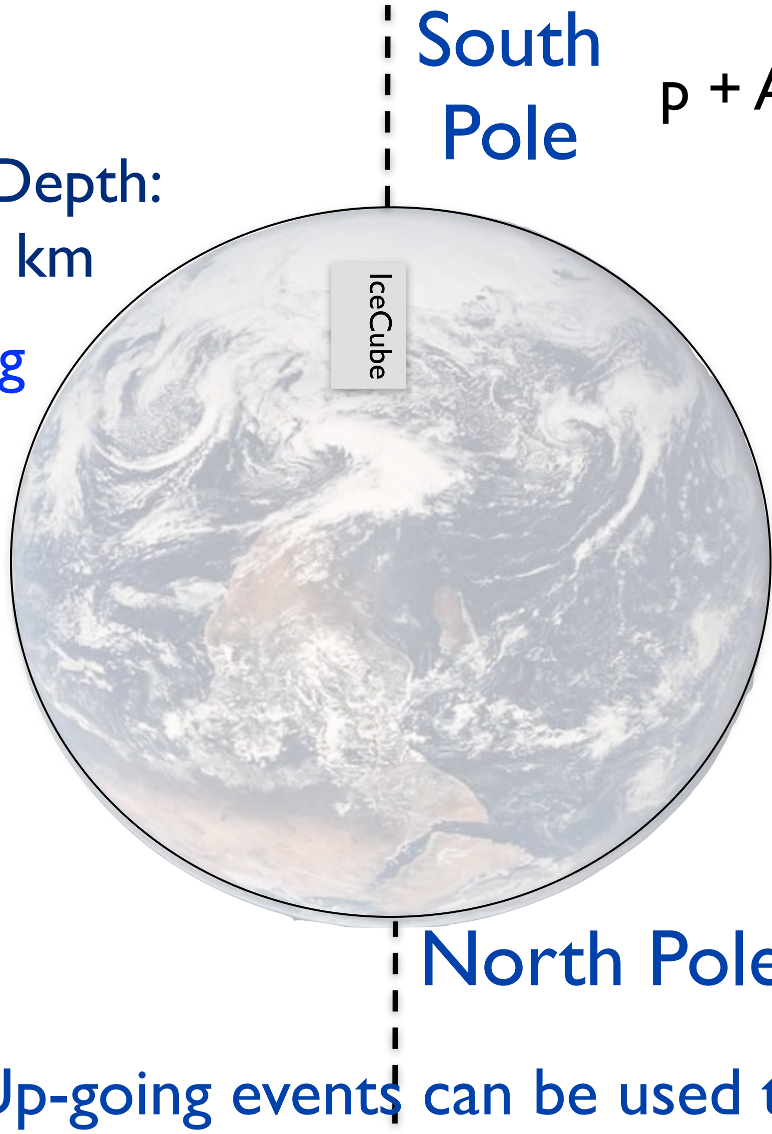
- Up-going events can be used to obtain "clean" neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

Signals in IceCube

South Pole

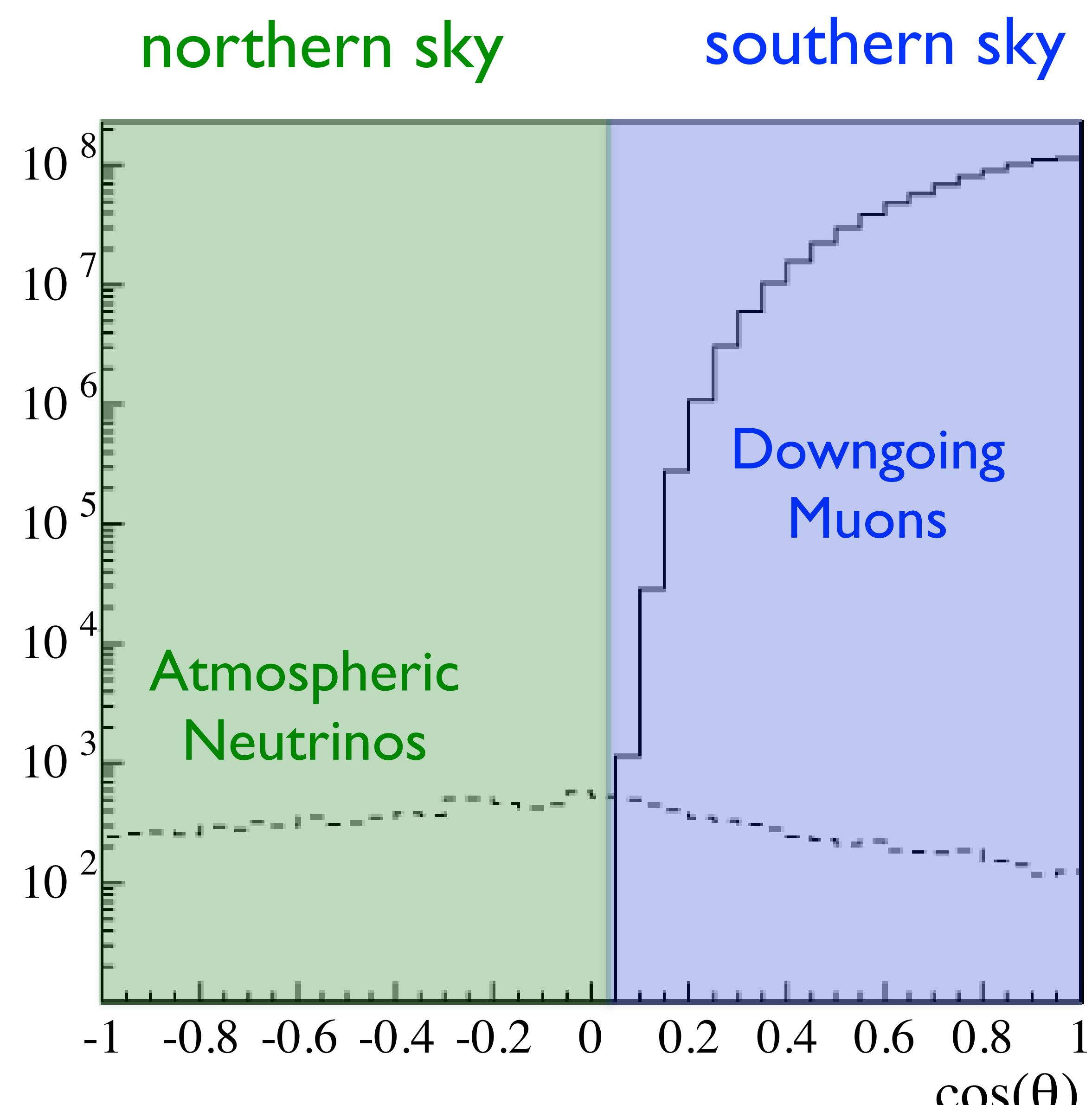
IceCube Depth: 1.5-2.5 km

Downgoing Muons



North Pole

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



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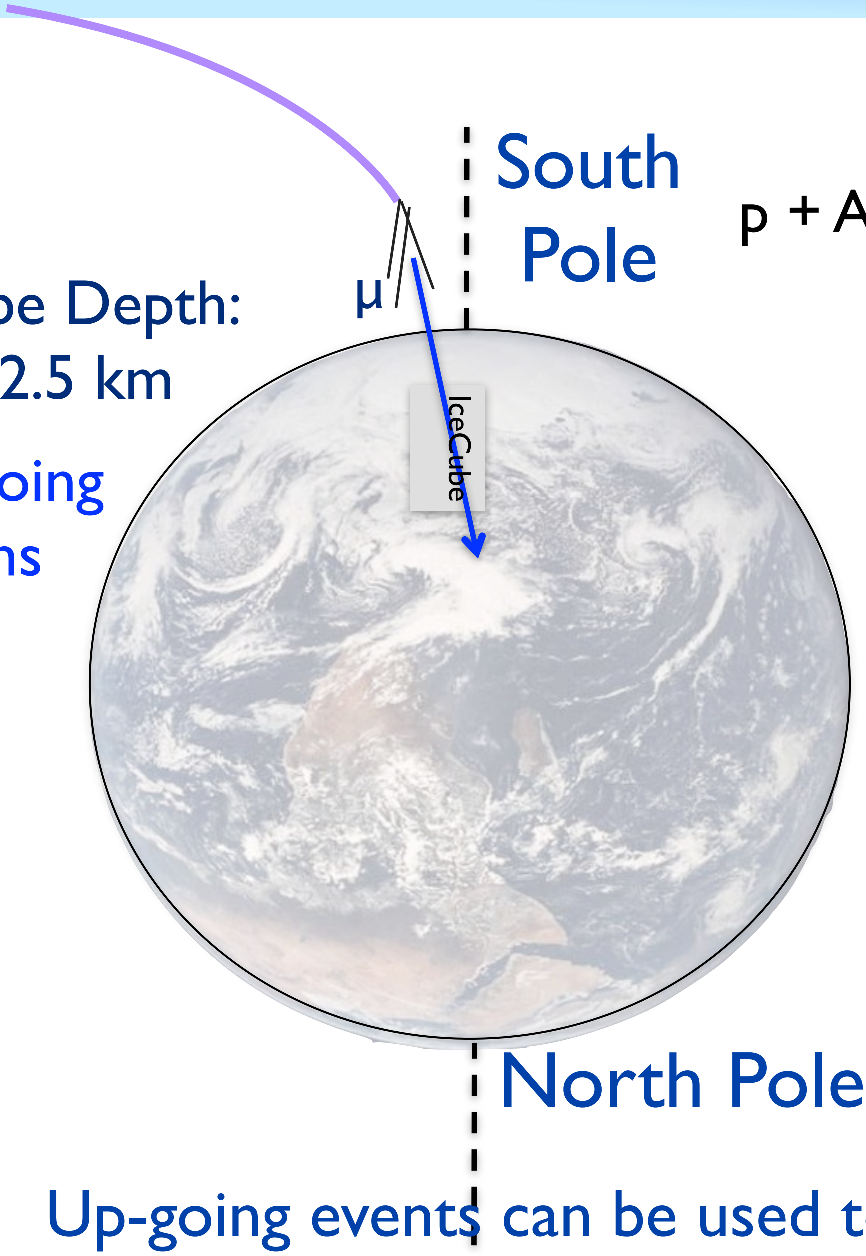
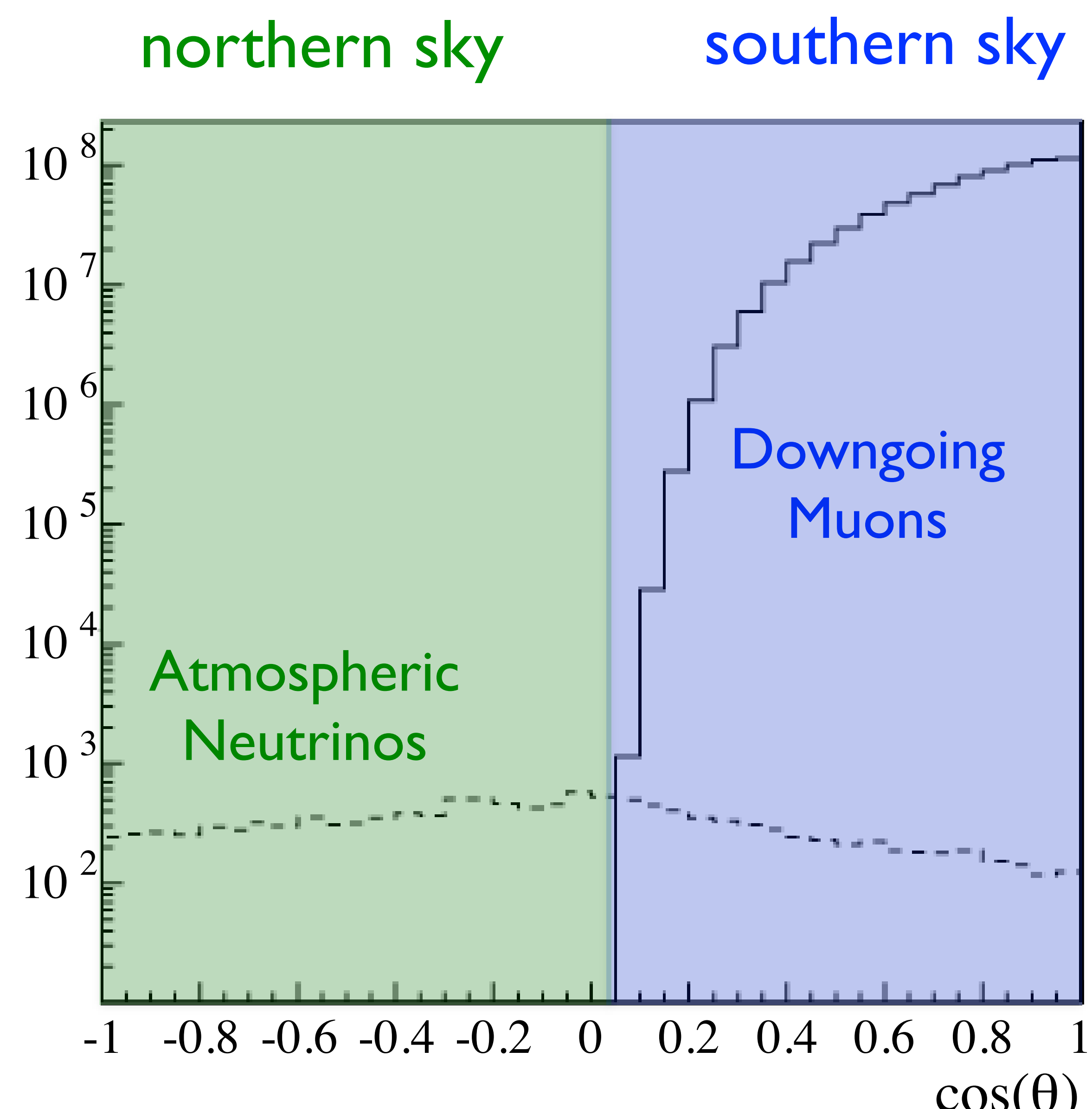
1.5-2.5 km



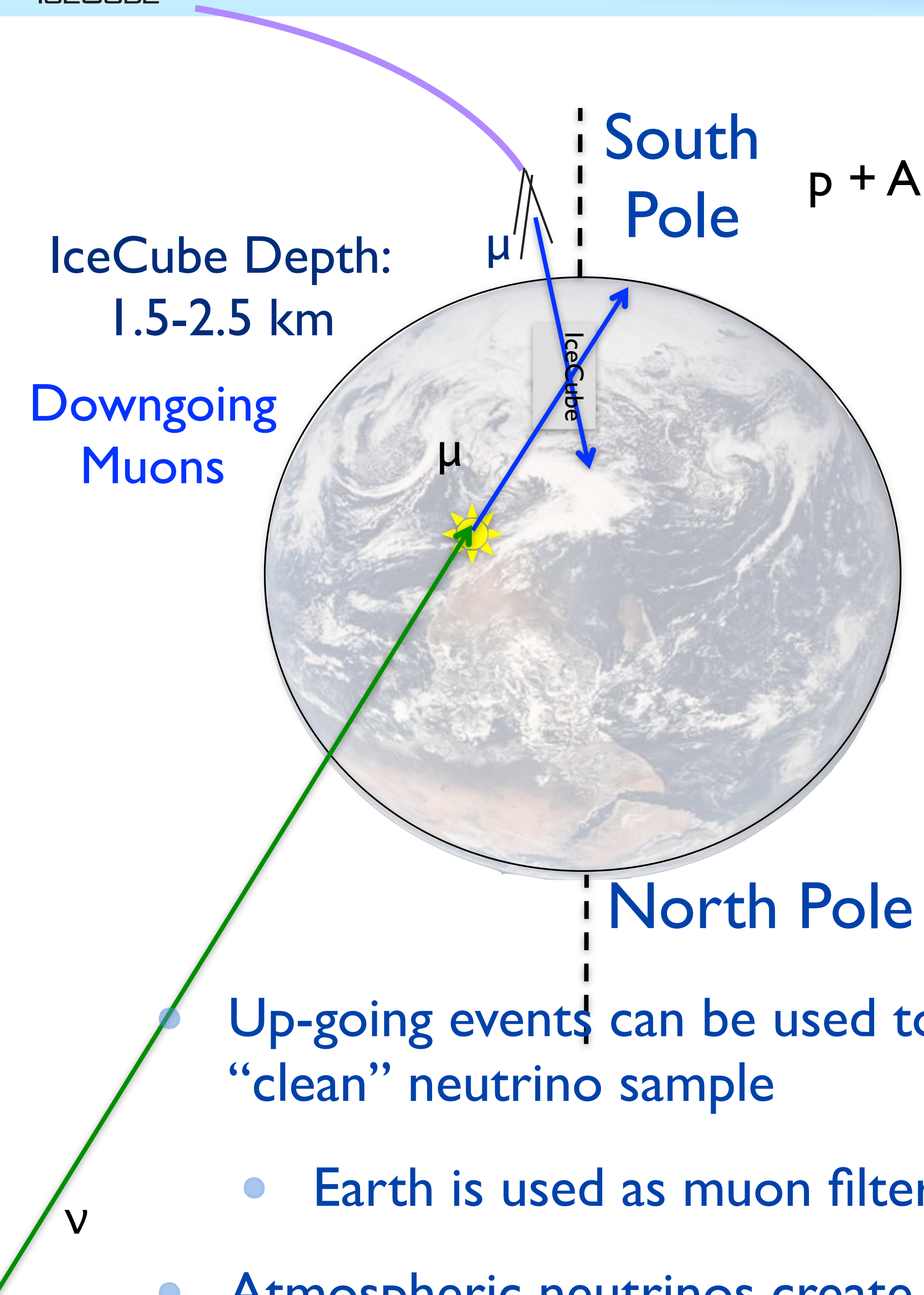


Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube

- 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

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



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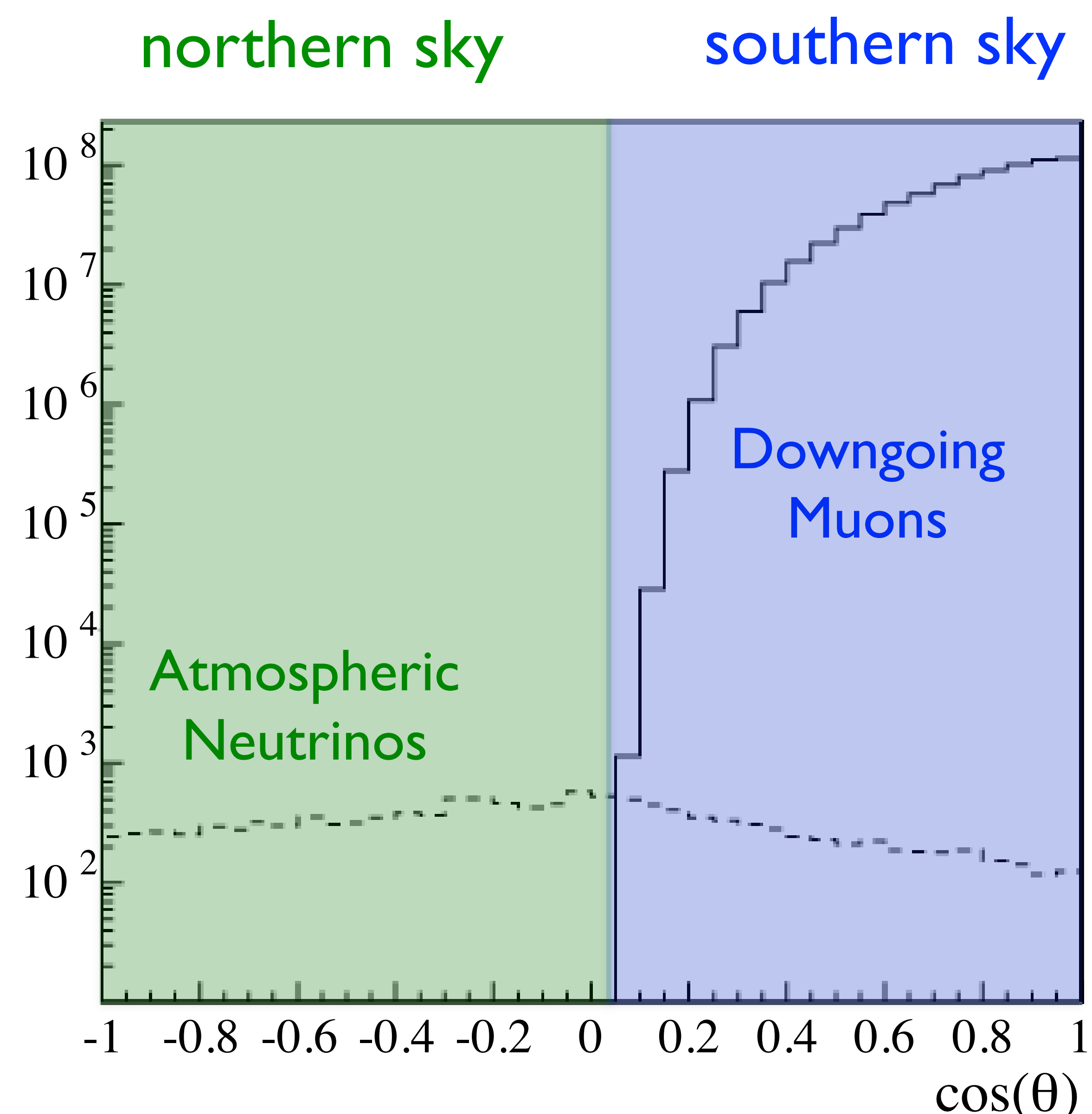

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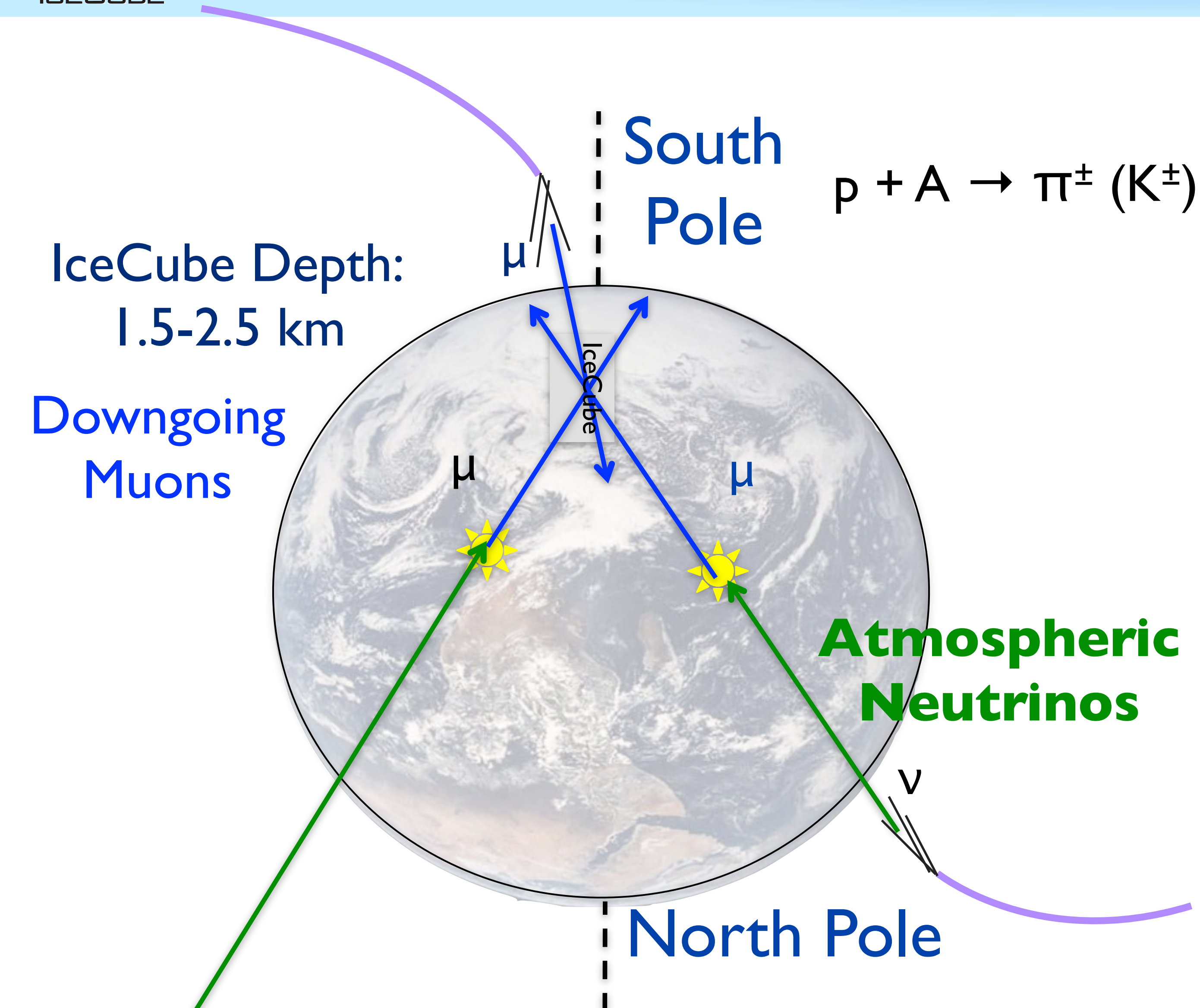

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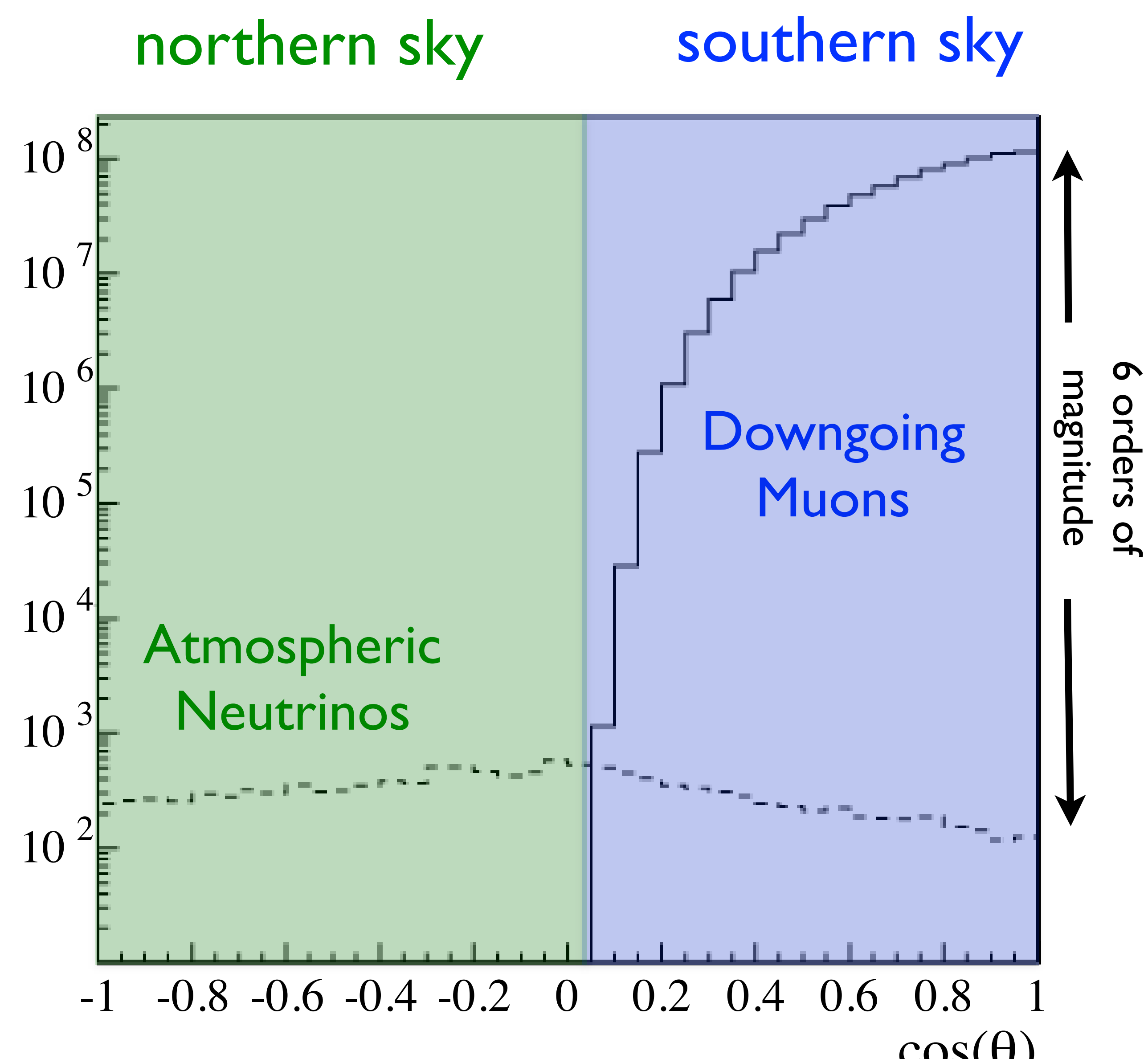

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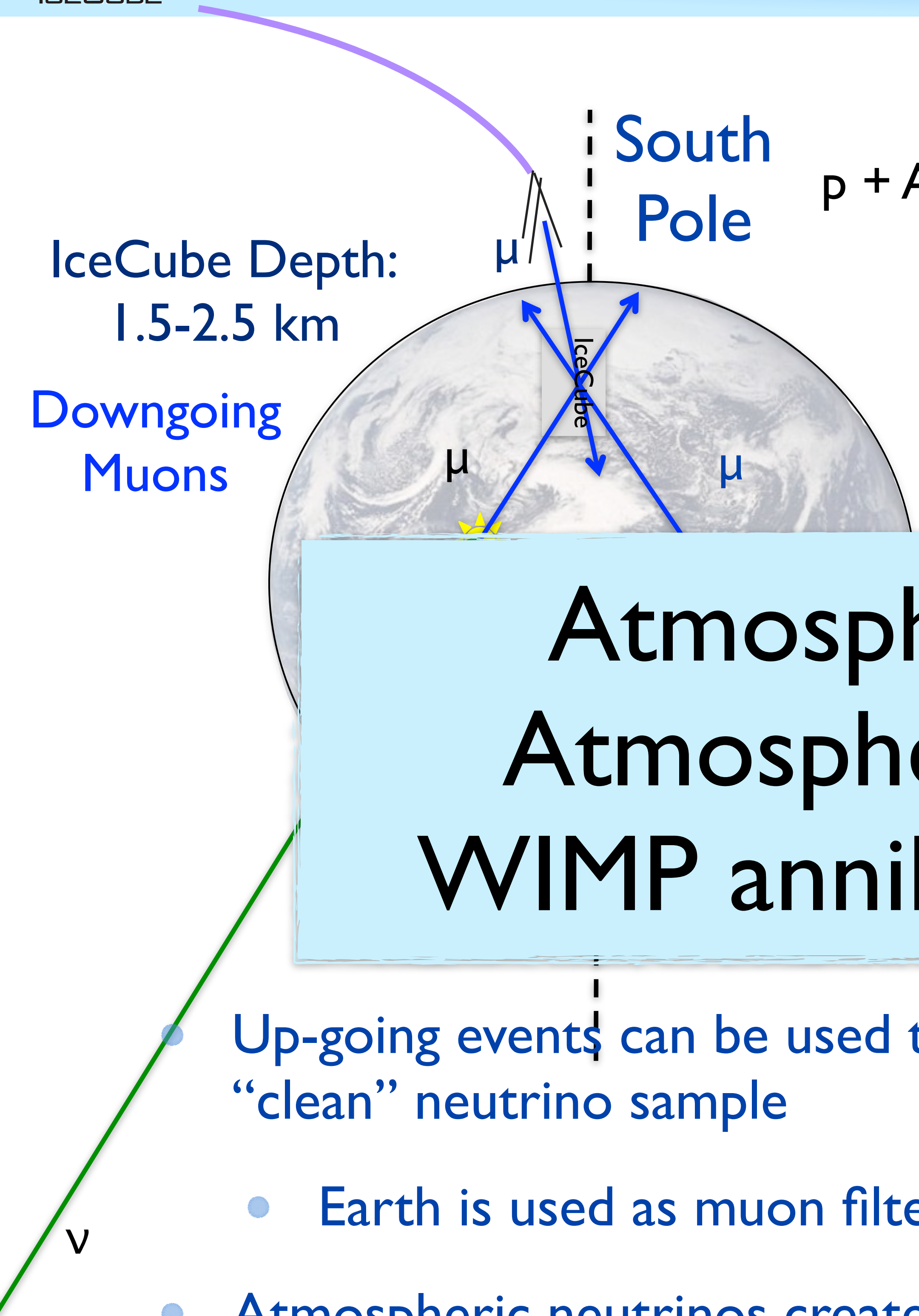
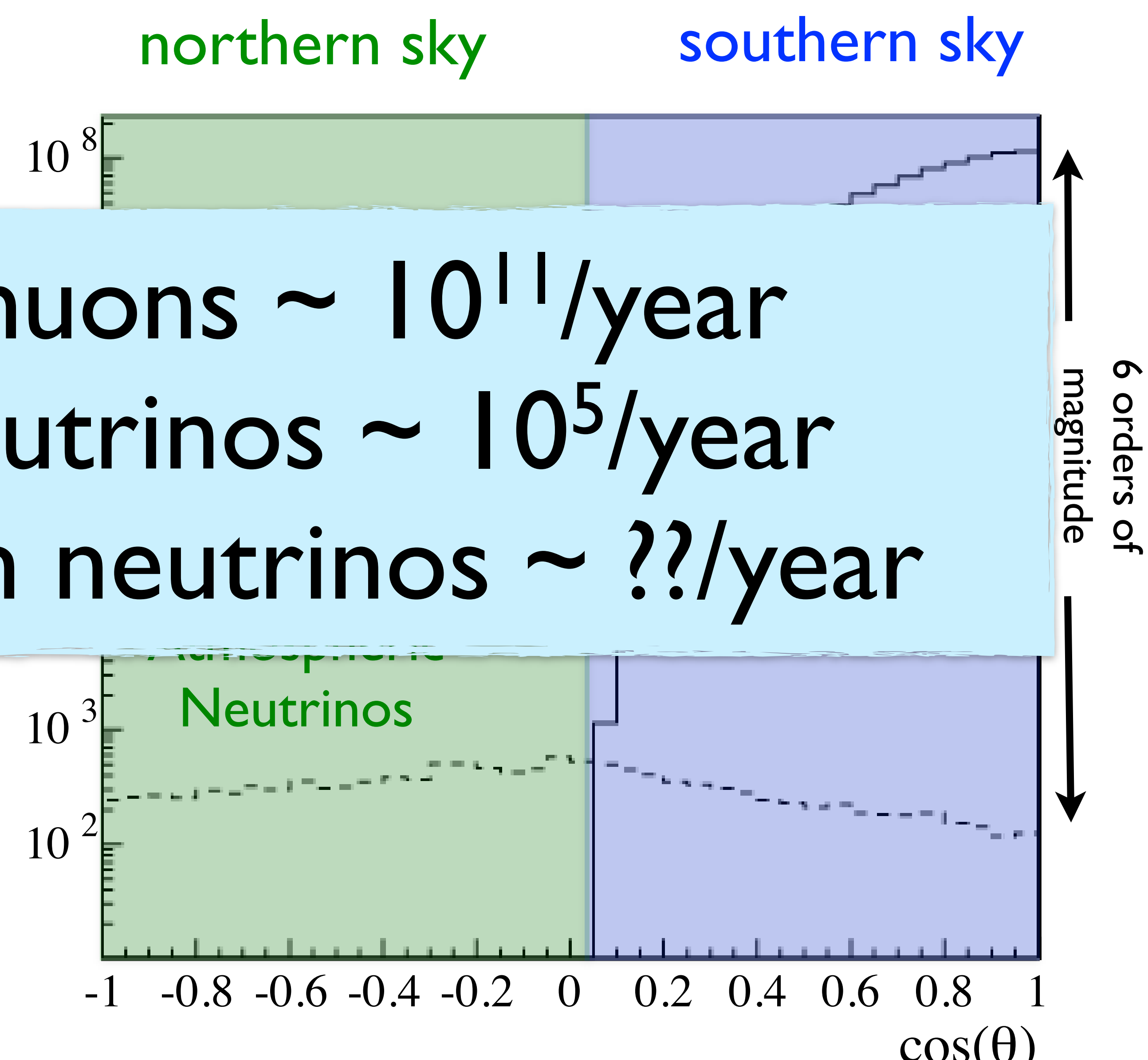




Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube

Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
WIMP annihilation neutrinos ~ ??/year

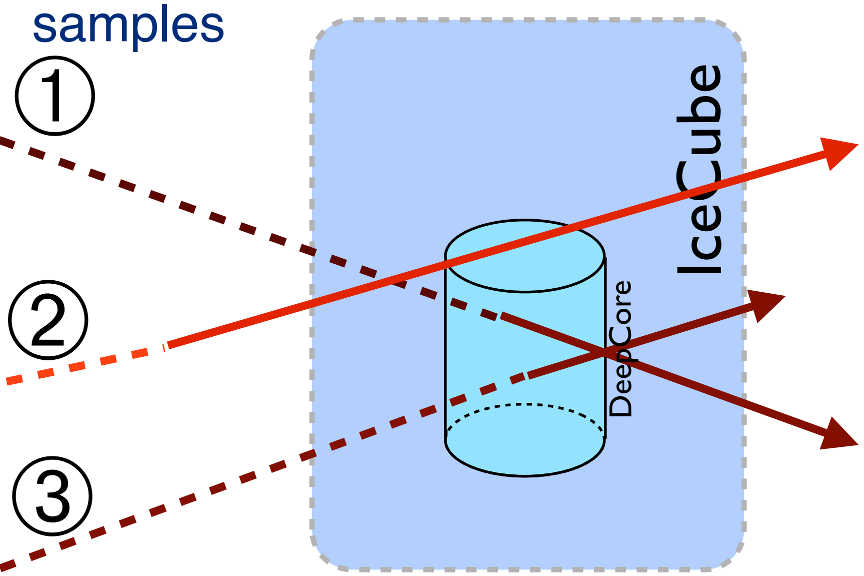
- Up-going events can be used to obtain "clean" neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

IceCube/DeepCore Solar WIMP Analysis

DeepCore Solar WIMP Sensitivity

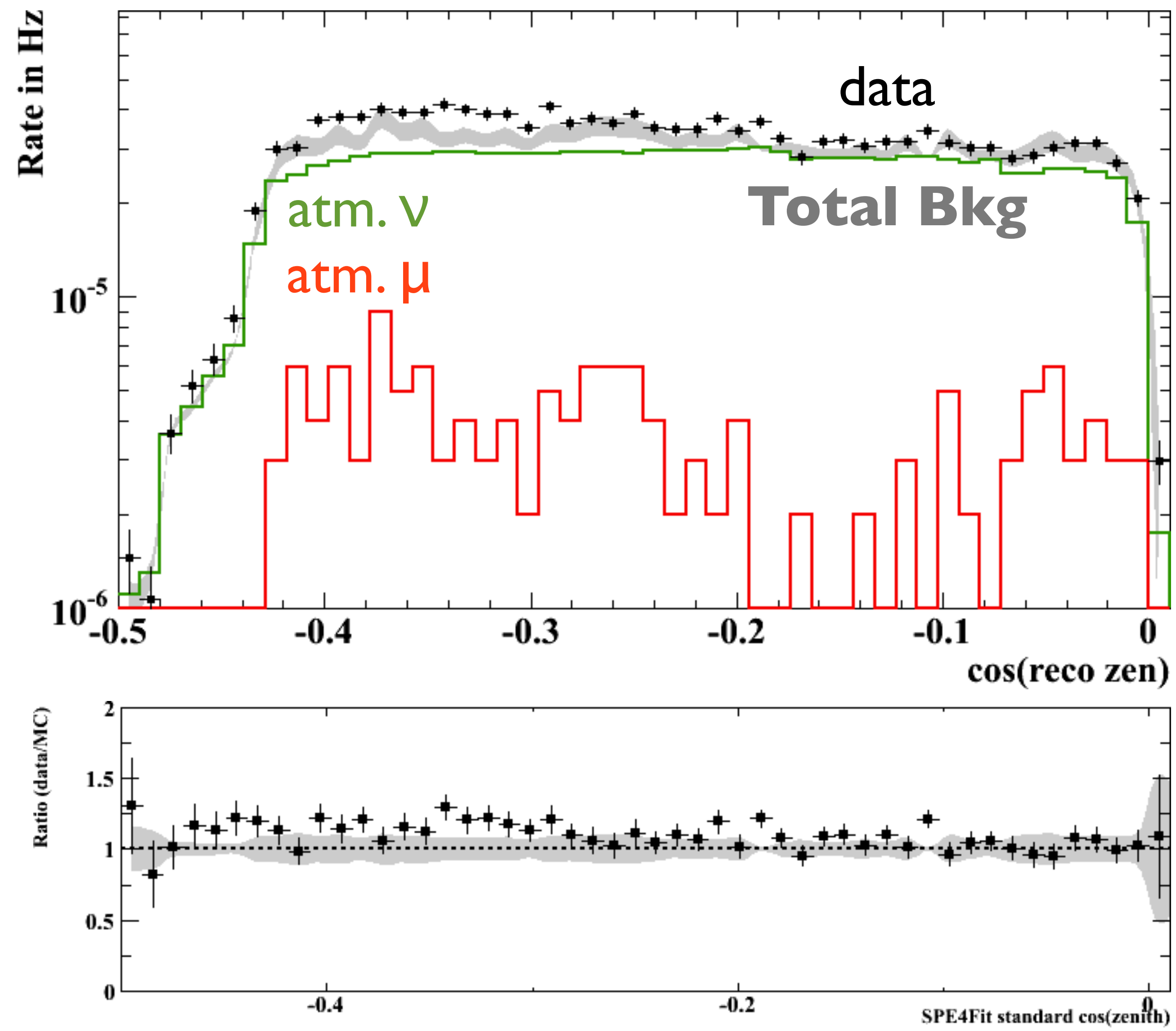
IceCube 79-string 318days (May 2010 - May 2011)

Analysis performed separately for austral summer (Sun above horizon) and austral winter (Sun below horizon) - 3 independent samples



Compare distribution of the final sample to these PDFs of background and signal to determine most likely signal content and combine likelihoods, weighted by relative livetime

② Event Selection (Winter, High energy, 151days)



- Event selection with separate BDT
- Training on off-source data + signal simulation
- Optimized final cut on BDT output- run llh-analysis for various selection criteria to determine best sensitivity

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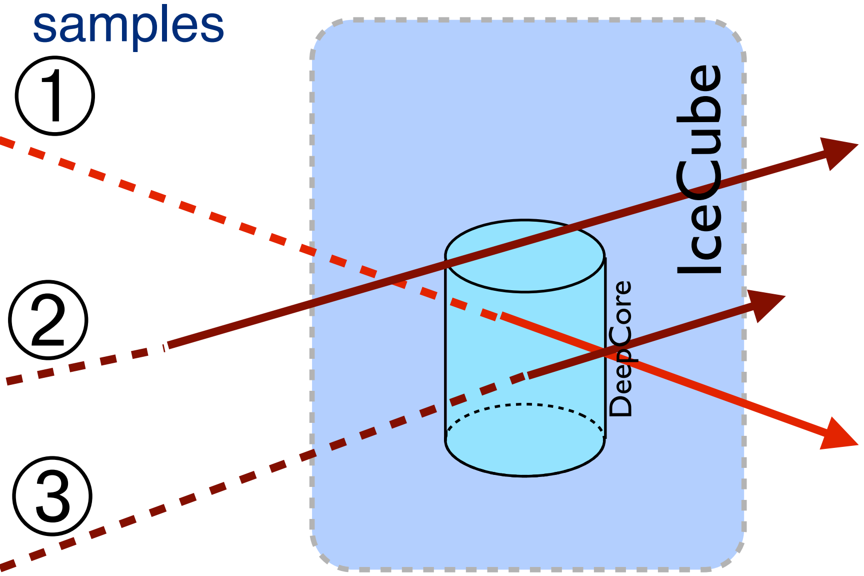
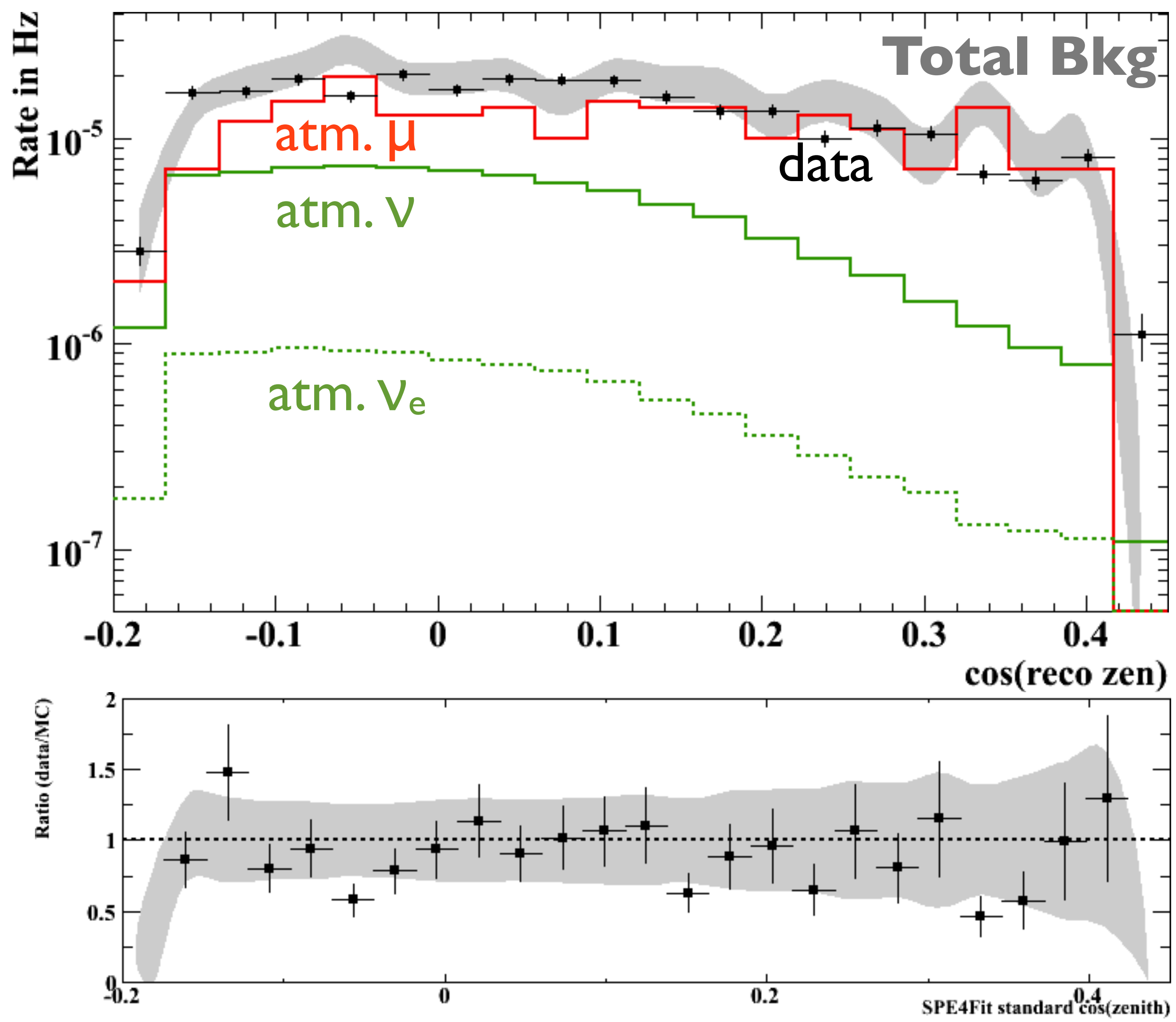


Compare distribution of the final sample to these PDFs of background and signal to determine most likely signal content and combine likelihoods, weighted by relative livetime

① Event Selection (Summer, Low energy, 166days)



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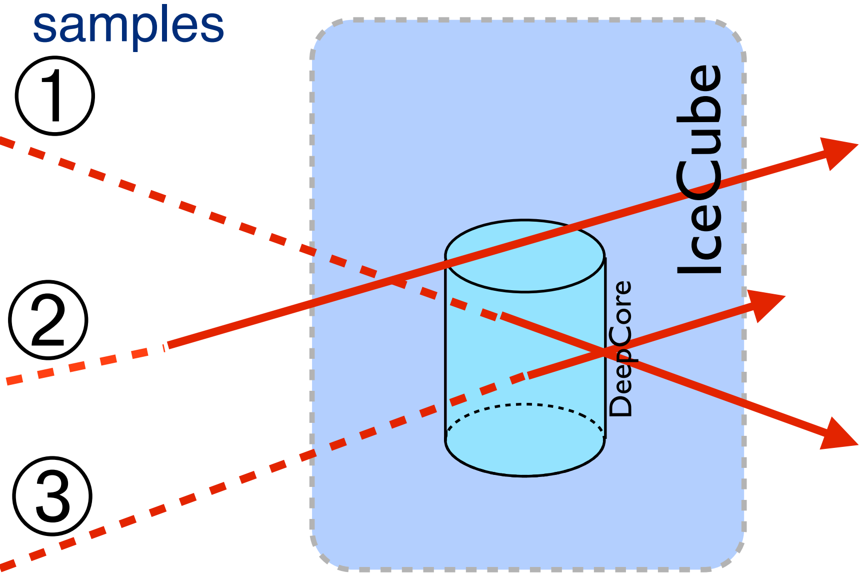

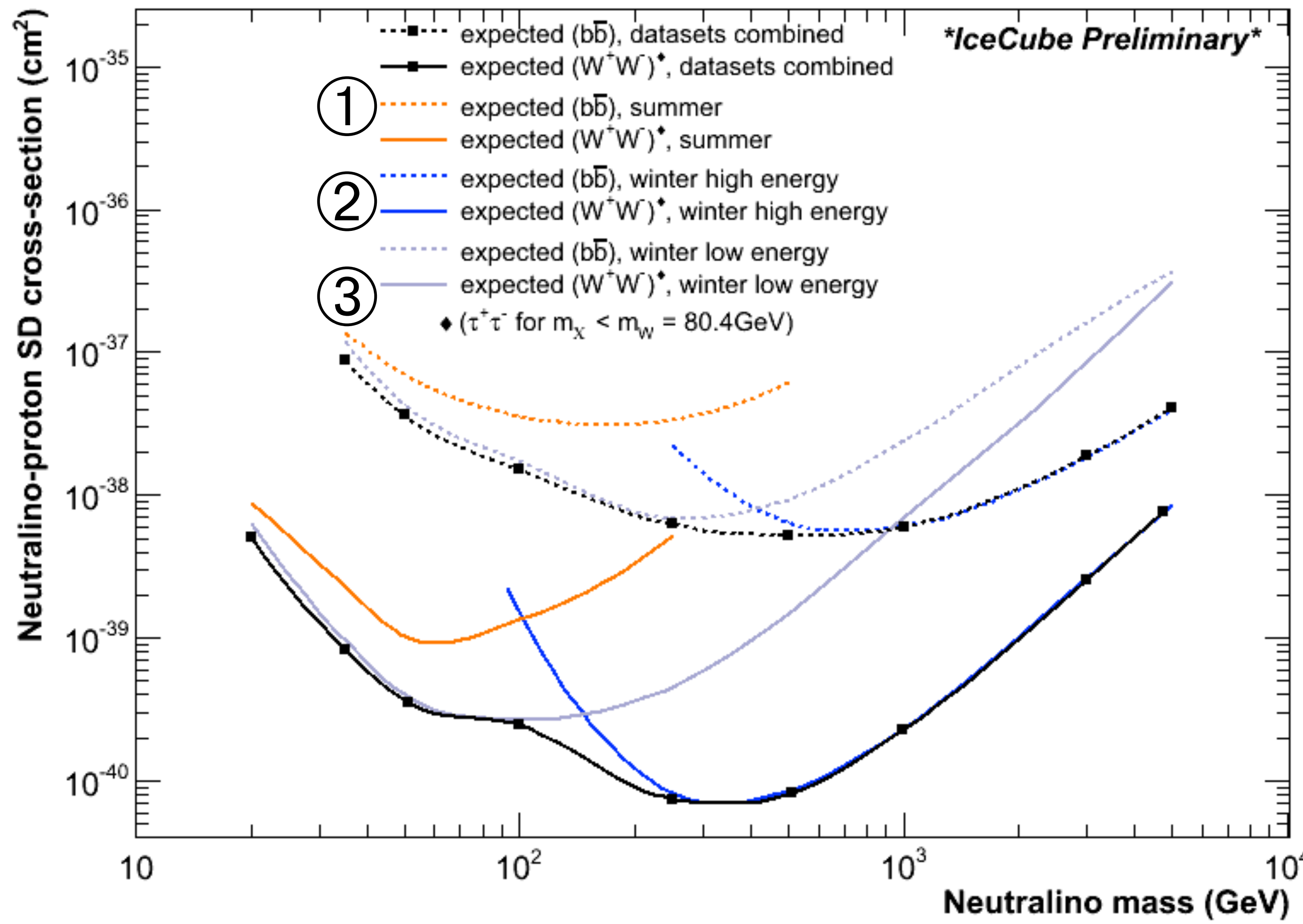

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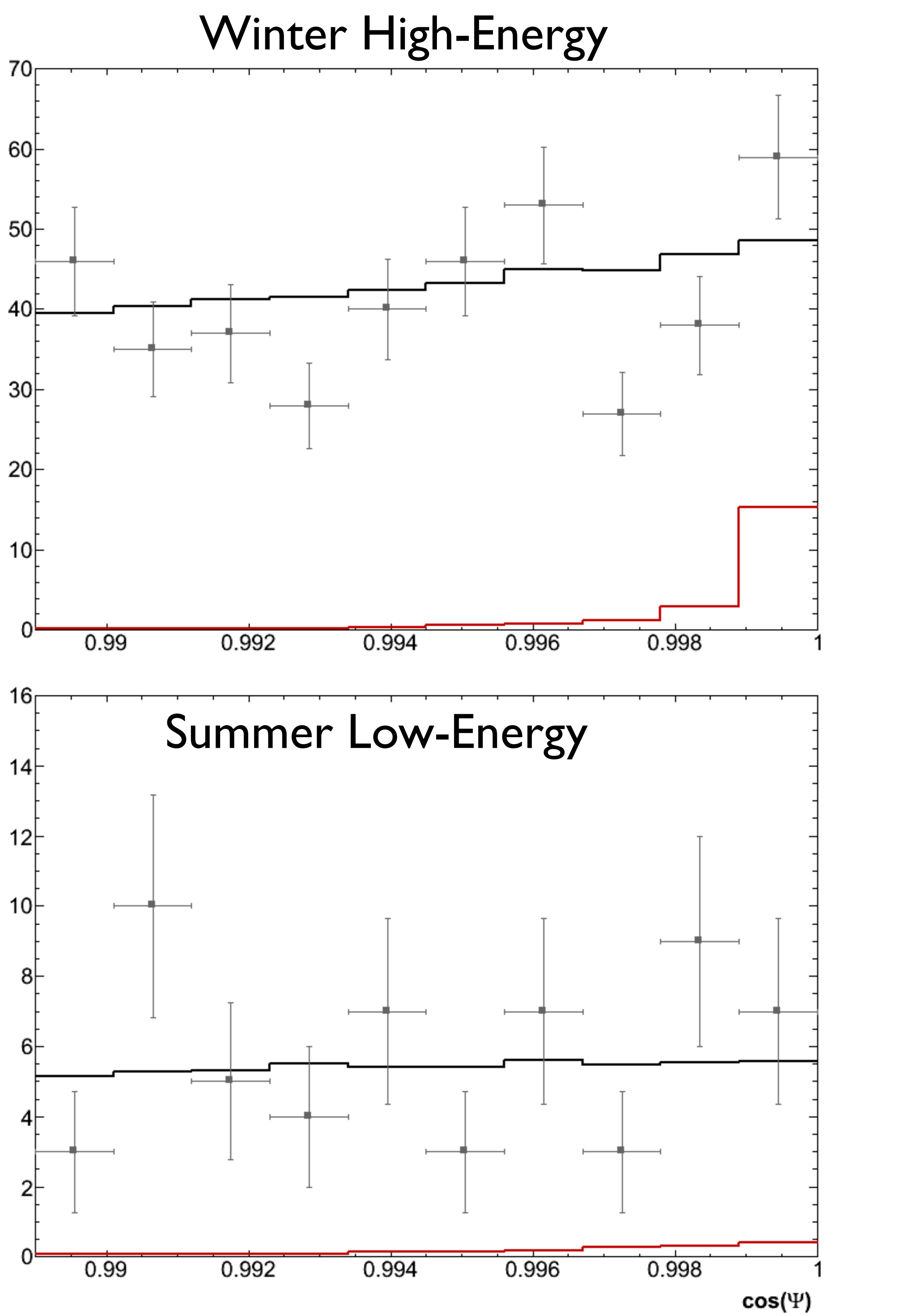
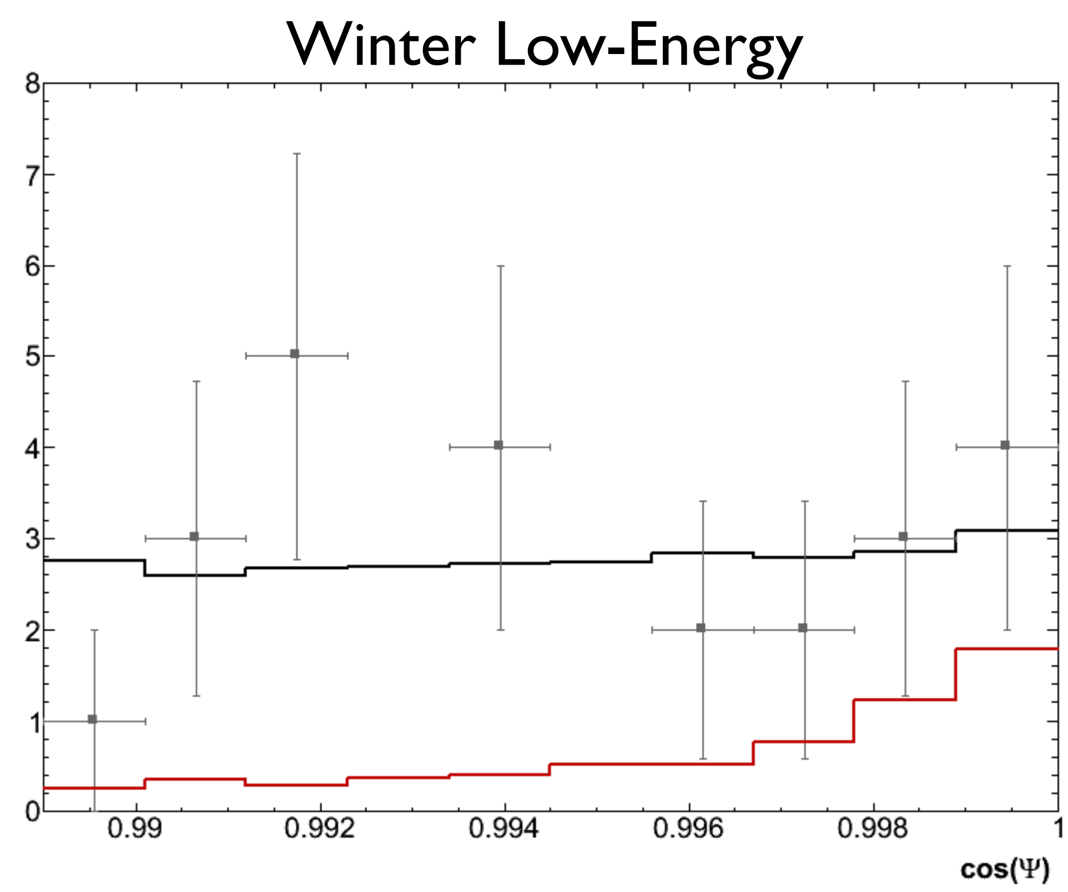
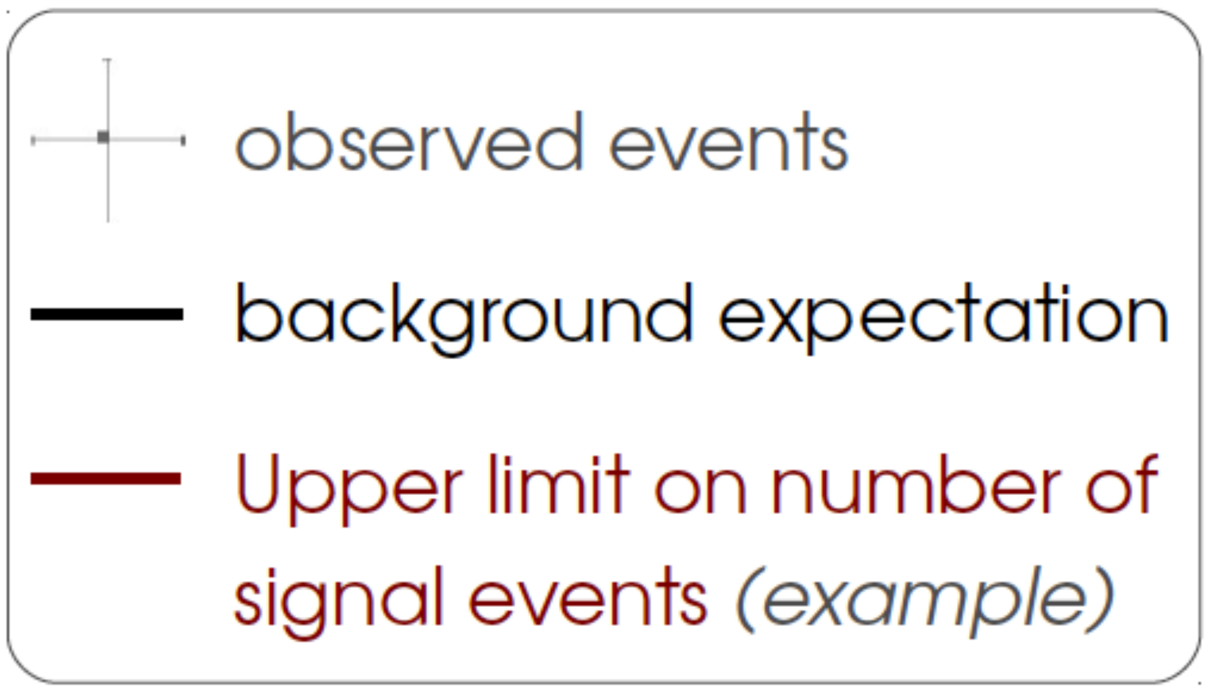
$$\mathcal{L}(\mu) = \prod_i^{n_{obs}} f(\Psi_i|\mu), \quad \text{where} \quad f(\Psi|\mu) = \frac{\mu}{n_{obs}} f_s(\Psi) + (1 - \frac{\mu}{n_{obs}}) f_{bg}(\Psi)$$

IC79 Solar WIMP Unblinding







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T. Tanaka et al. Astrophys. J. 742, 78 (2011)
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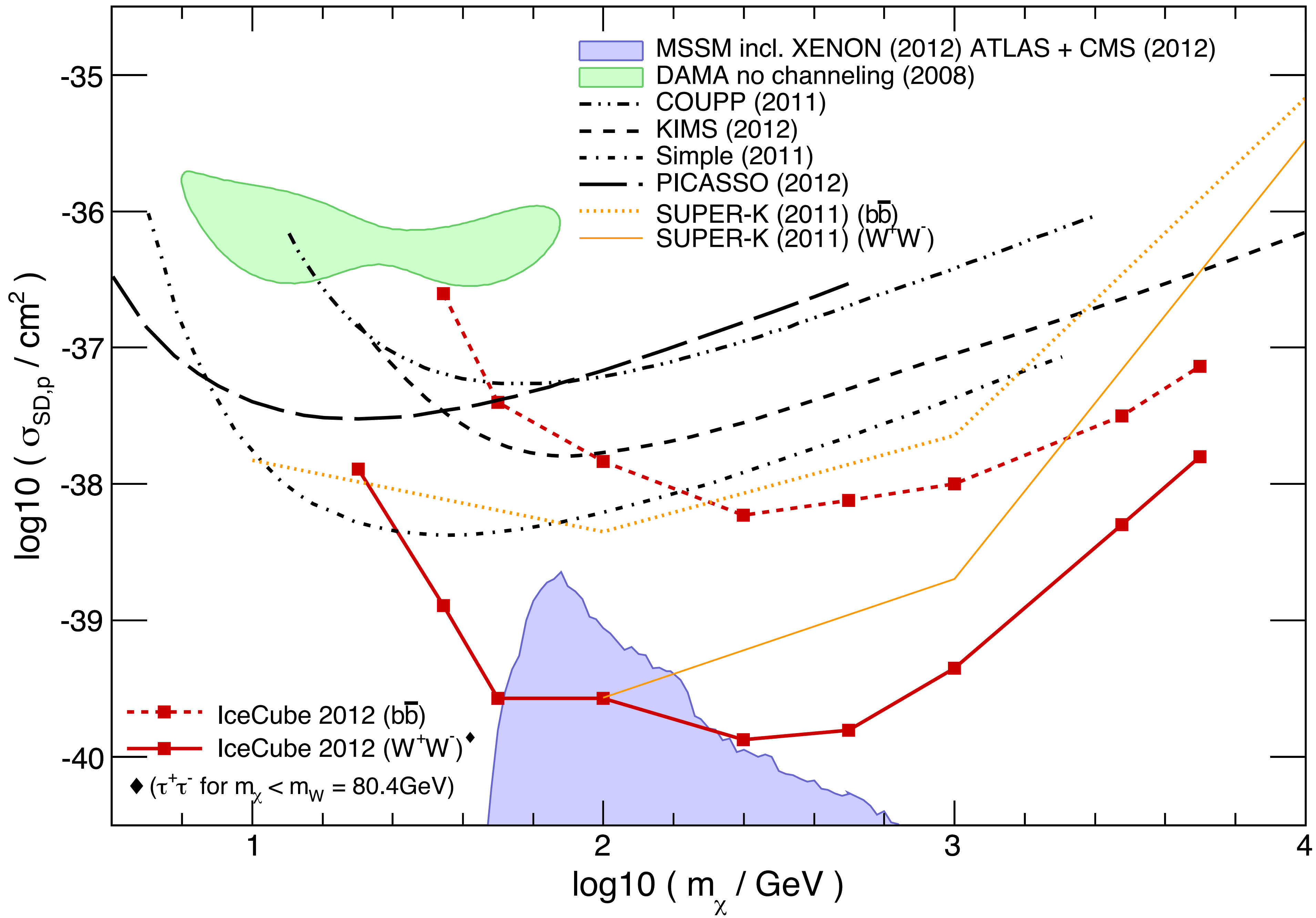
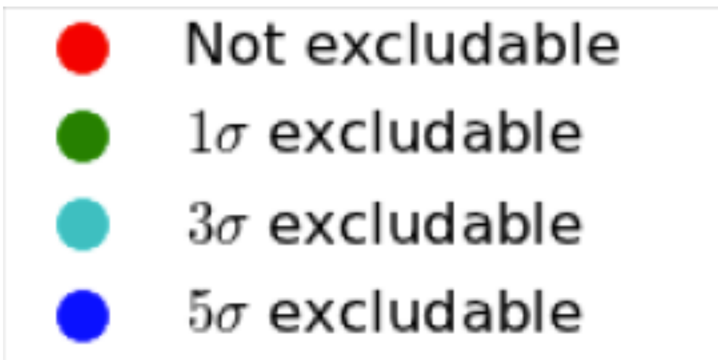


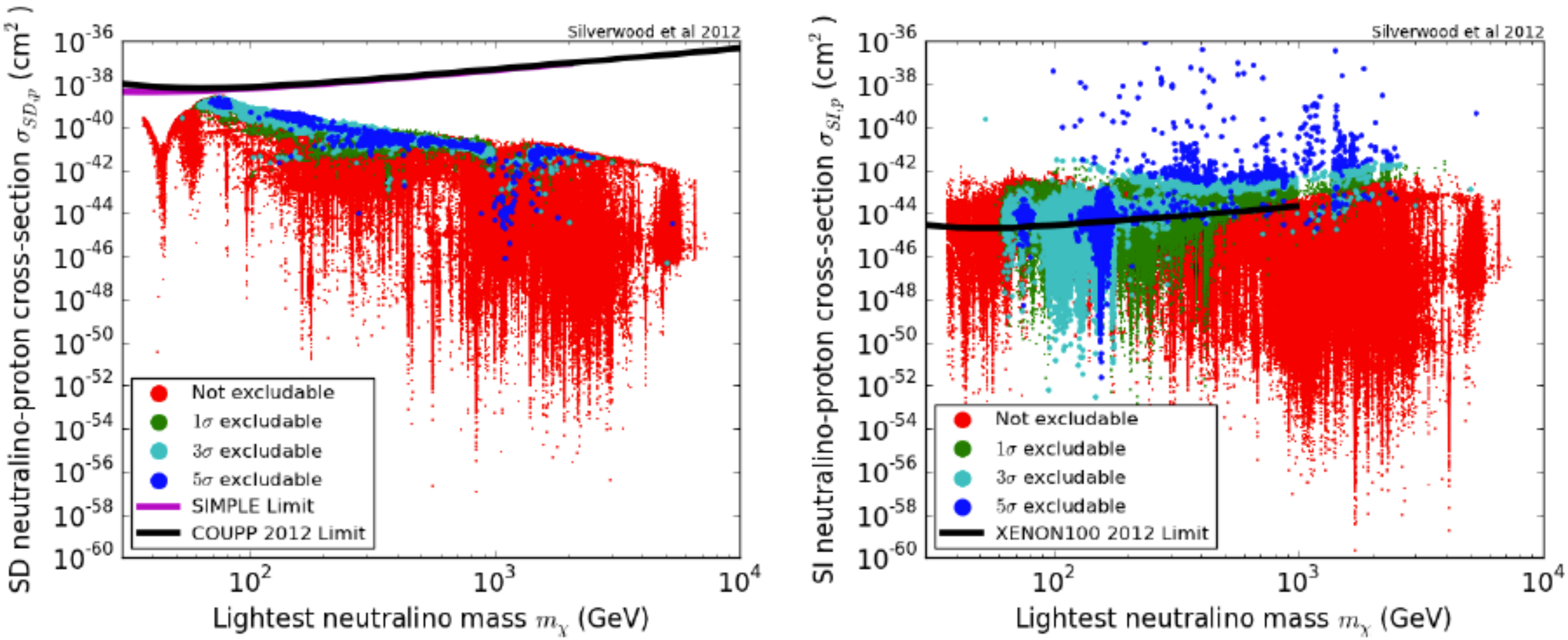
1yr of DeepCore data already significantly more sensitive than 8yrs of AMANDA+IceCube

MSSM models can be tested (see for example

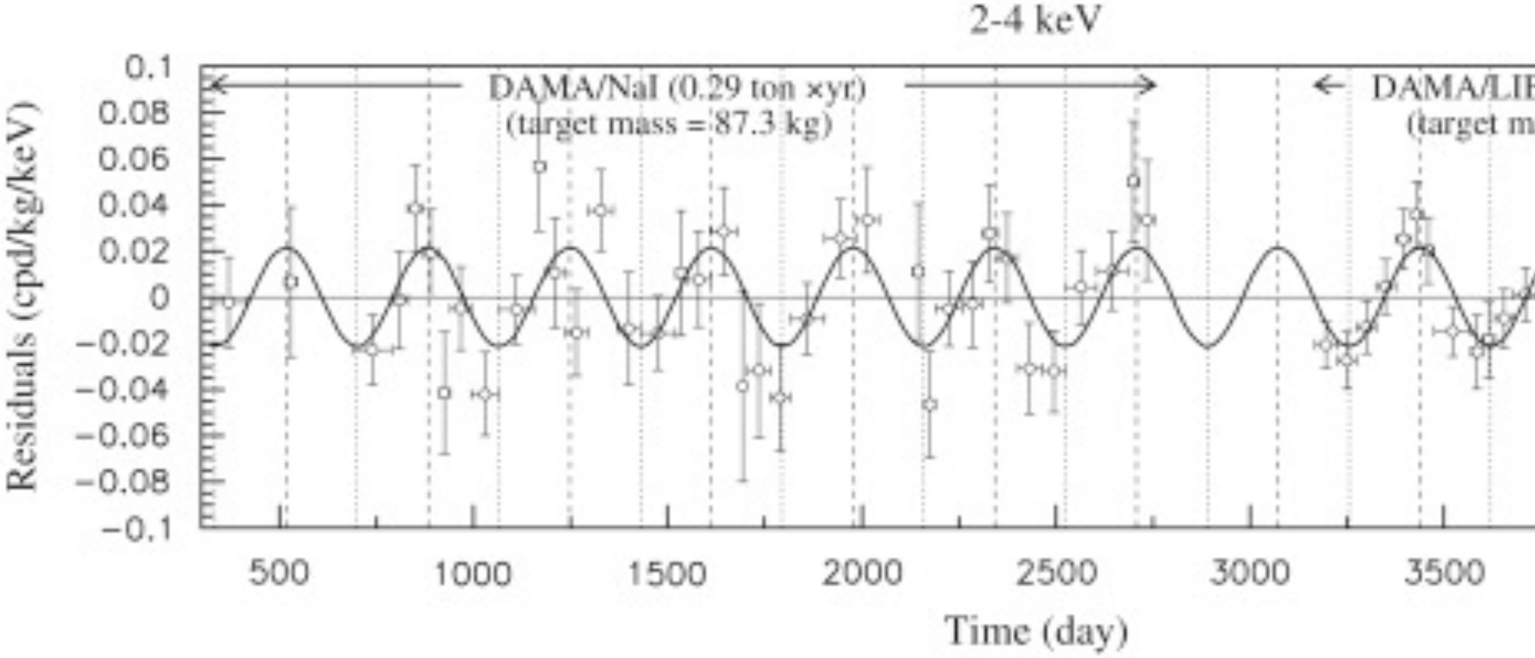
Relevance of results

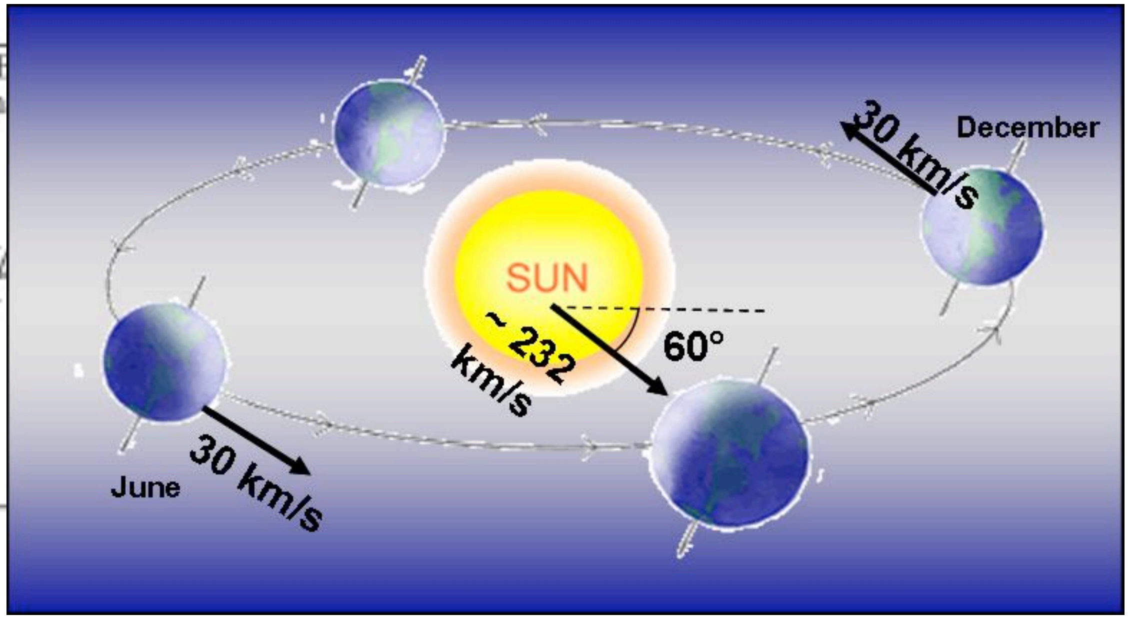


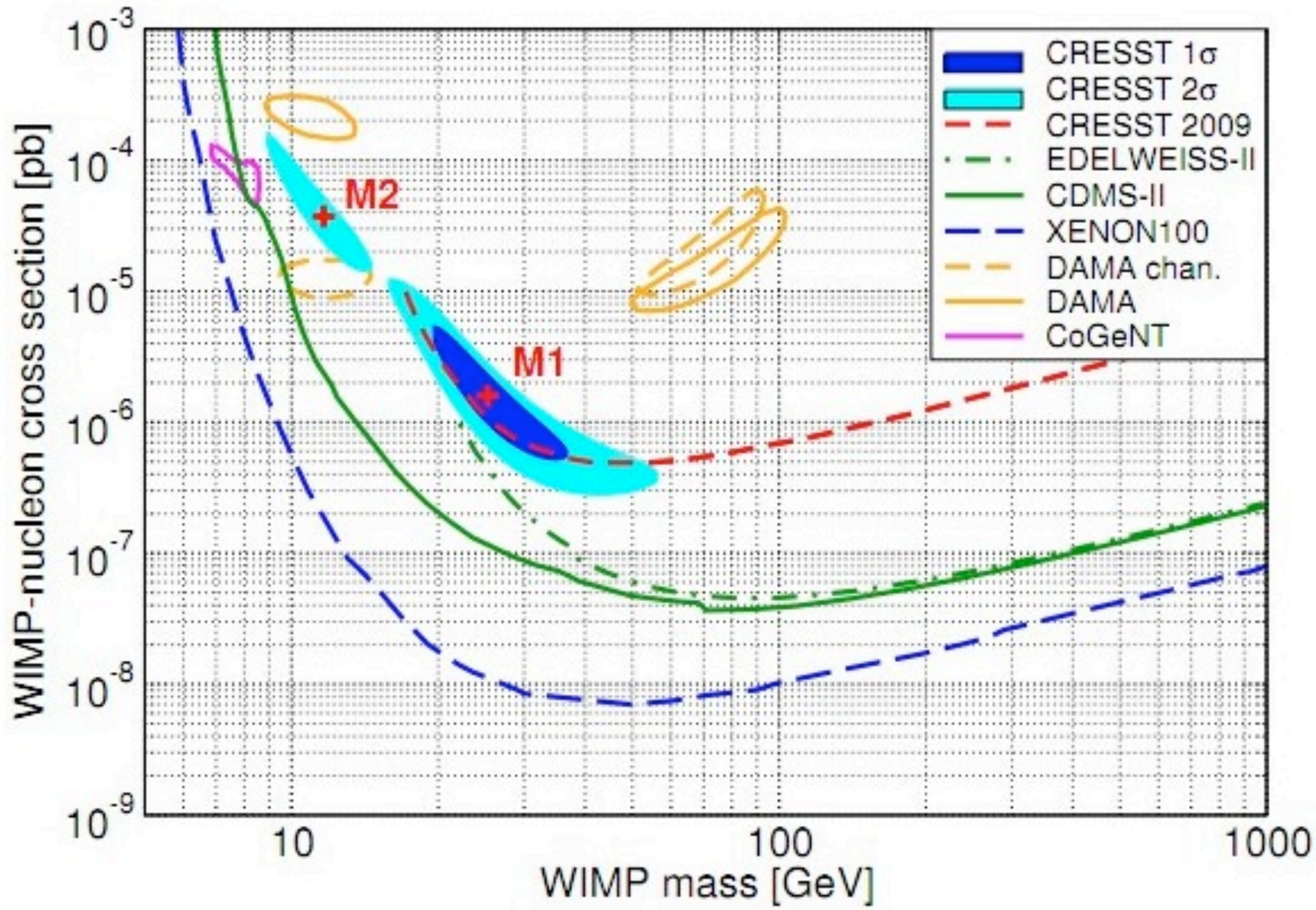
Current IceCube Searches can already exclude a significant region of the SUSY parameter space (MSSM-25)



Low-mass WIMPs ?

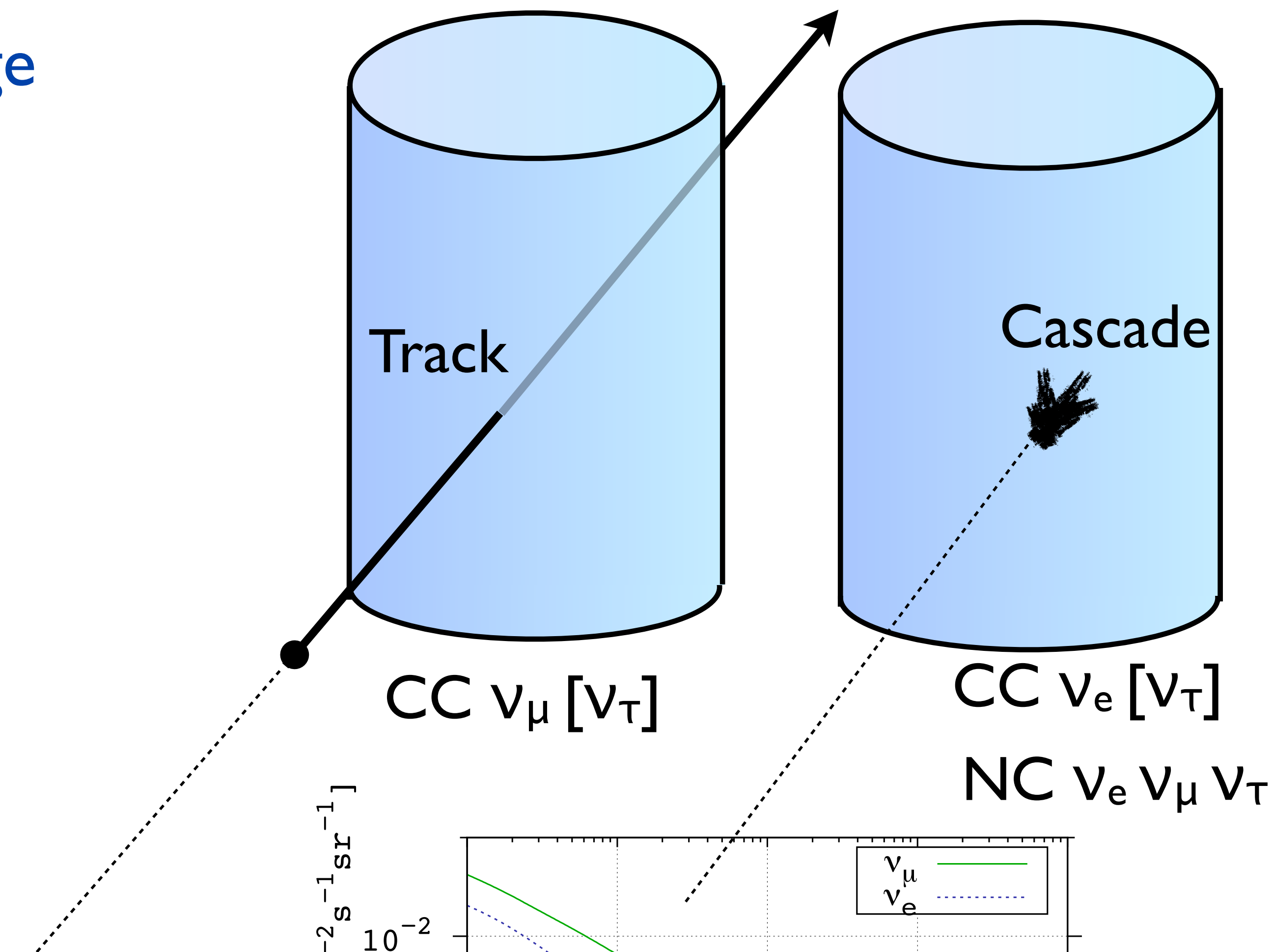


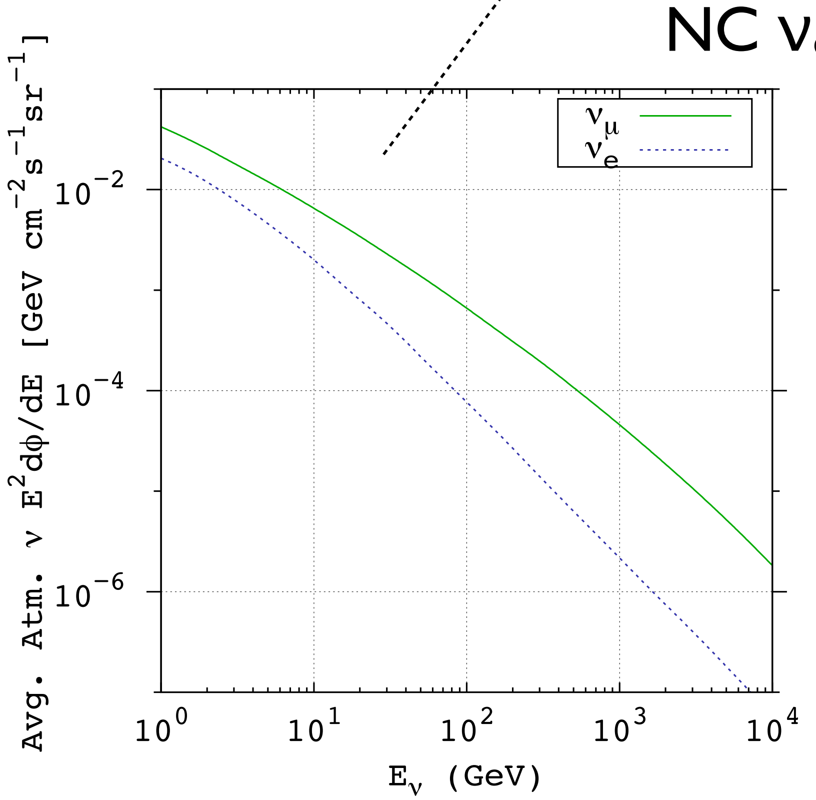




Comparison of tracks and cascades

- For neutrino energies where the average muon track length approaches the detector diameter:
  - ν_μ ν_e signal rates similar
  - but $R(\nu_\mu^{atm}) >> R(\nu_e^{atm})$
- ν_τ and NC events also contribute to signal cascade rates
- Fully contained events
  - Better energy resolution
  - Utilize all data (not just up-going)
  - Treat all flavors in a similar way
  - Less dependence on "muon propagation"





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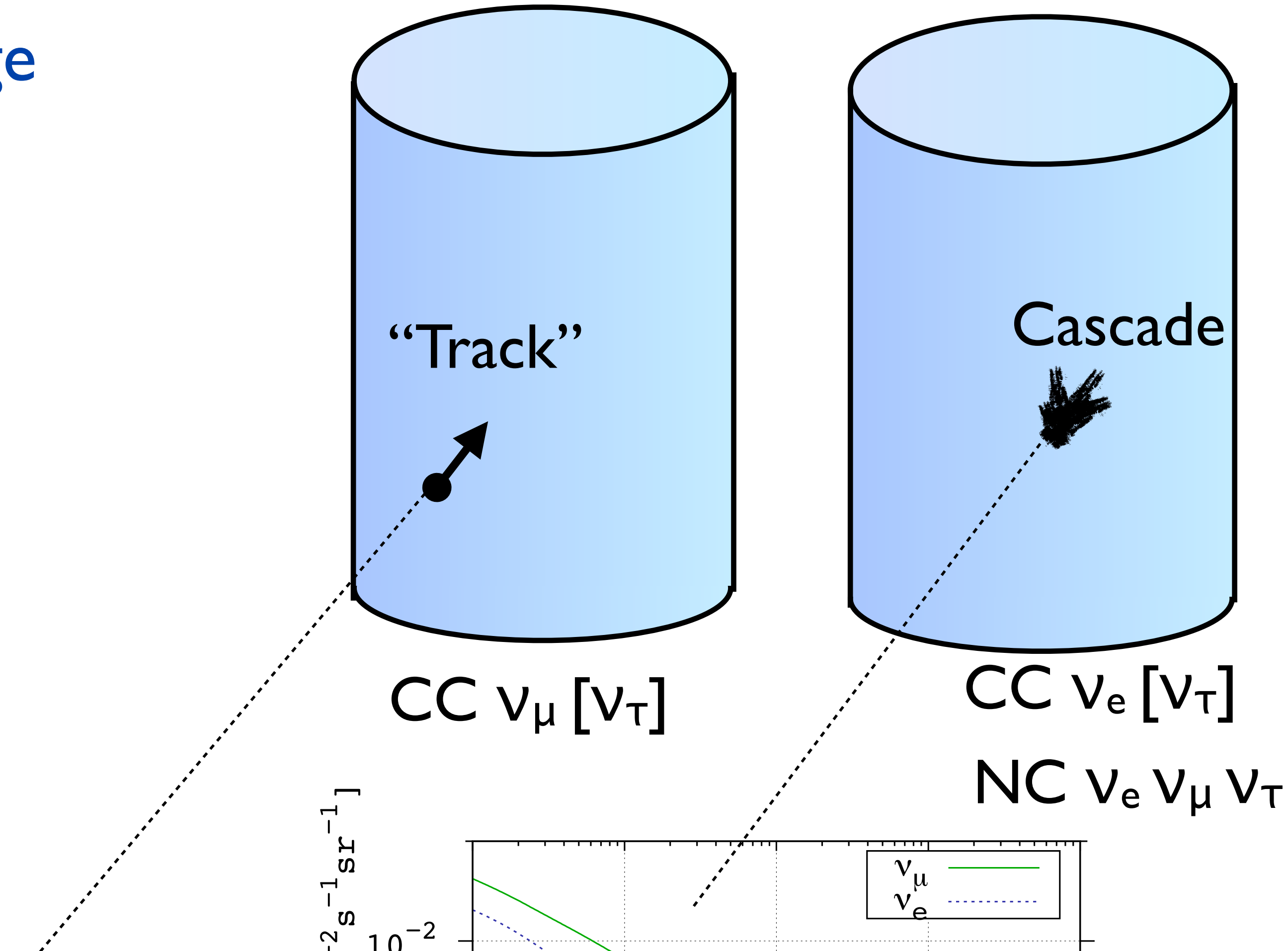
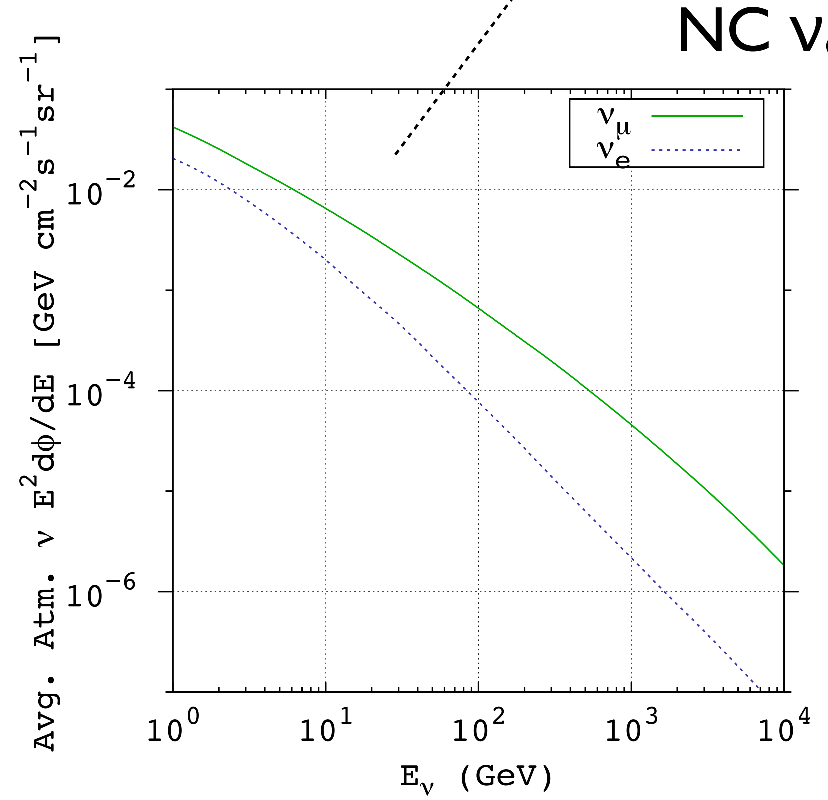
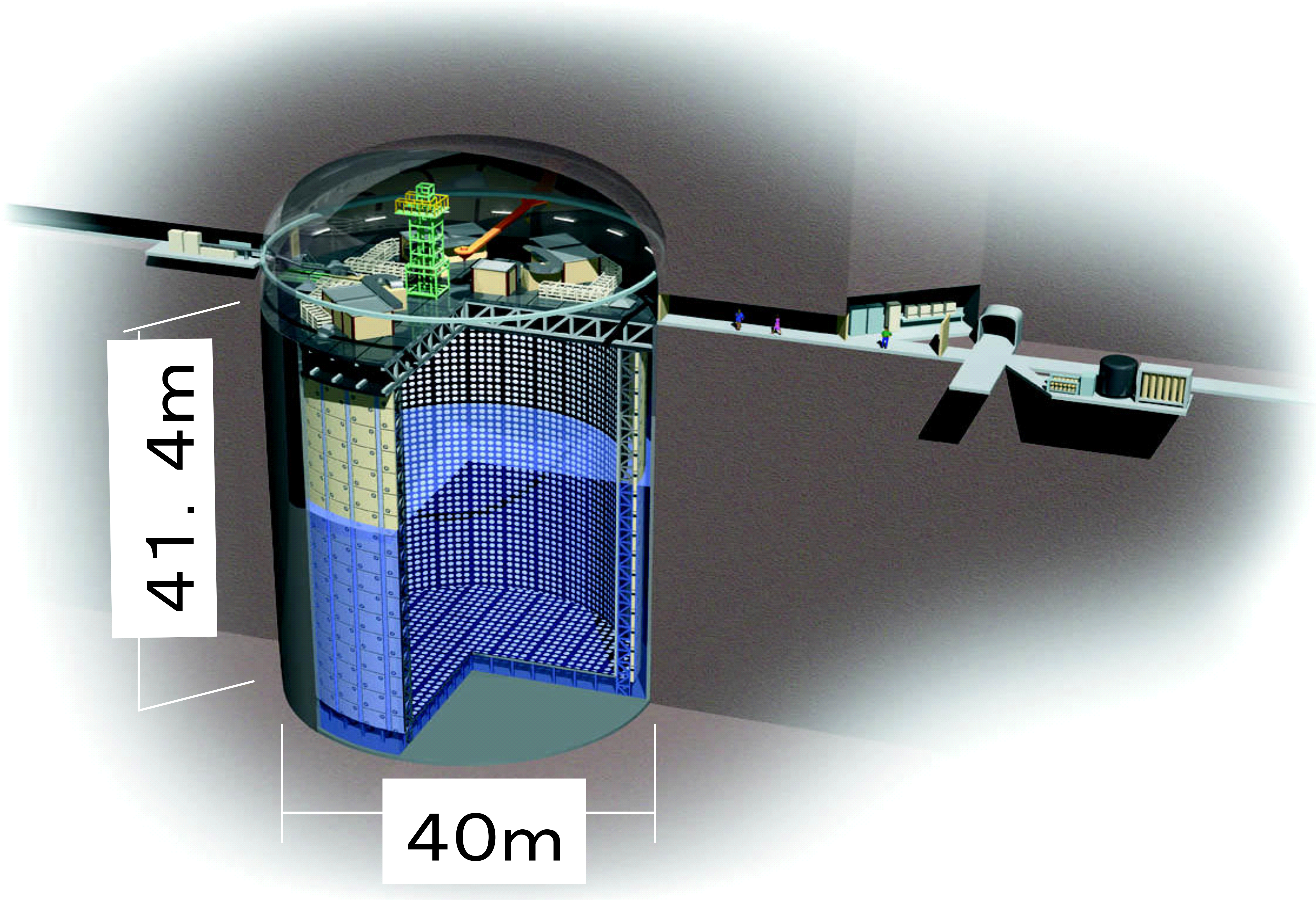




Super-Kamiokande

Super-Kamiokande



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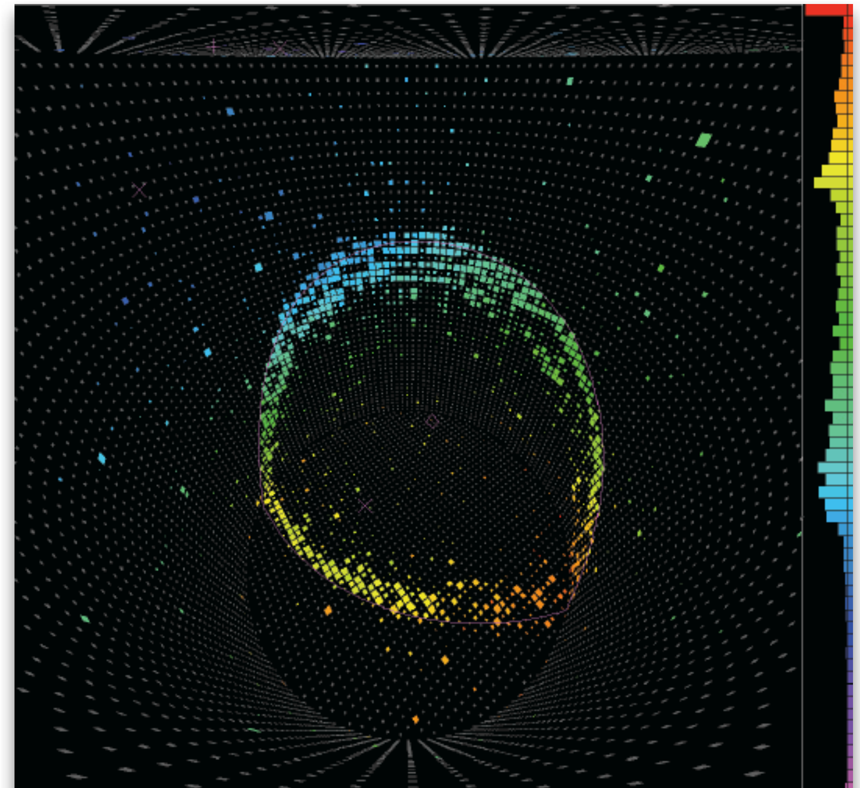
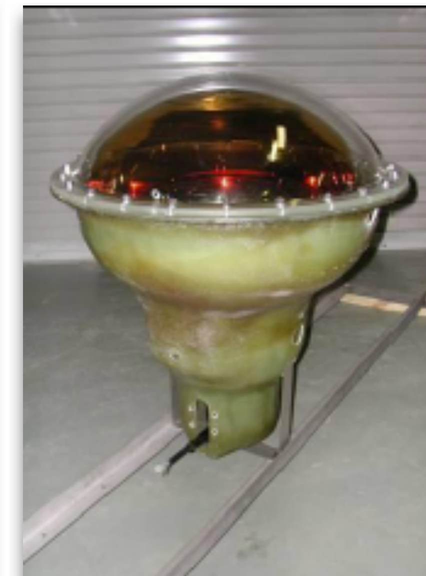
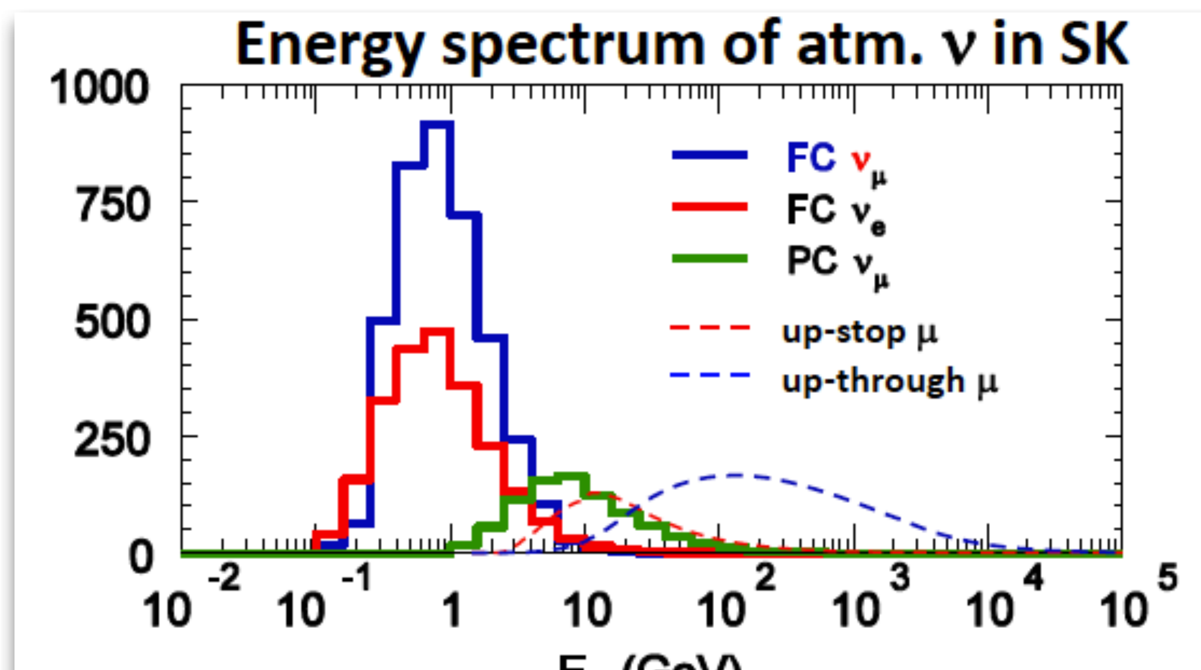




- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996
- ~11K 20” PMTs
- Photo coverage ~40%

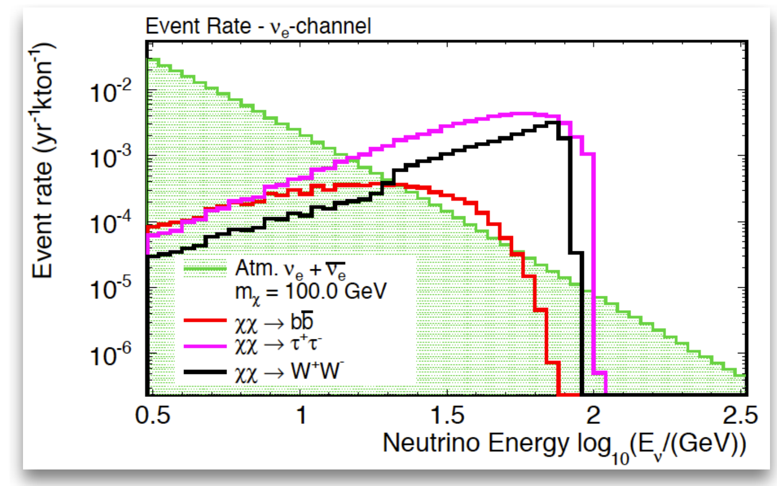


WIMP Signal comparison

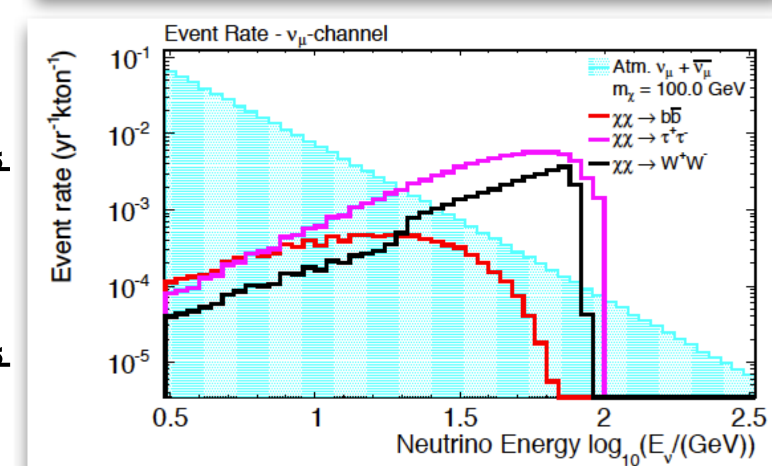
- Example: Assume m_χ=100GeV and annihilation rate of 1fb ($10^{-39}cm^2$)
  - ~2.45 x 10^{23} /s
- Event rates (of starting events) assume an opening angle around the Sun that is equivalent to the kinematic angle
- Assume angle average atmospheric neutrino flux (Honda) as background
- Event rates for neutrinos + antineutrinos of each flavor
- Regardless of annihilation channel the signal looks similar

Rott, Tanaka, Itow JCAP09(2011)029

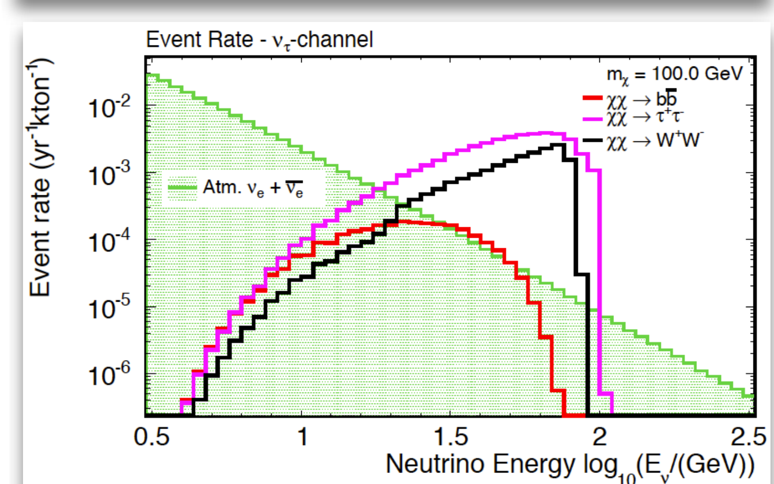
ν_e^{sig} vs. ν_e^{atm}



ν_μ^{sig} vs. ν_μ^{atm}

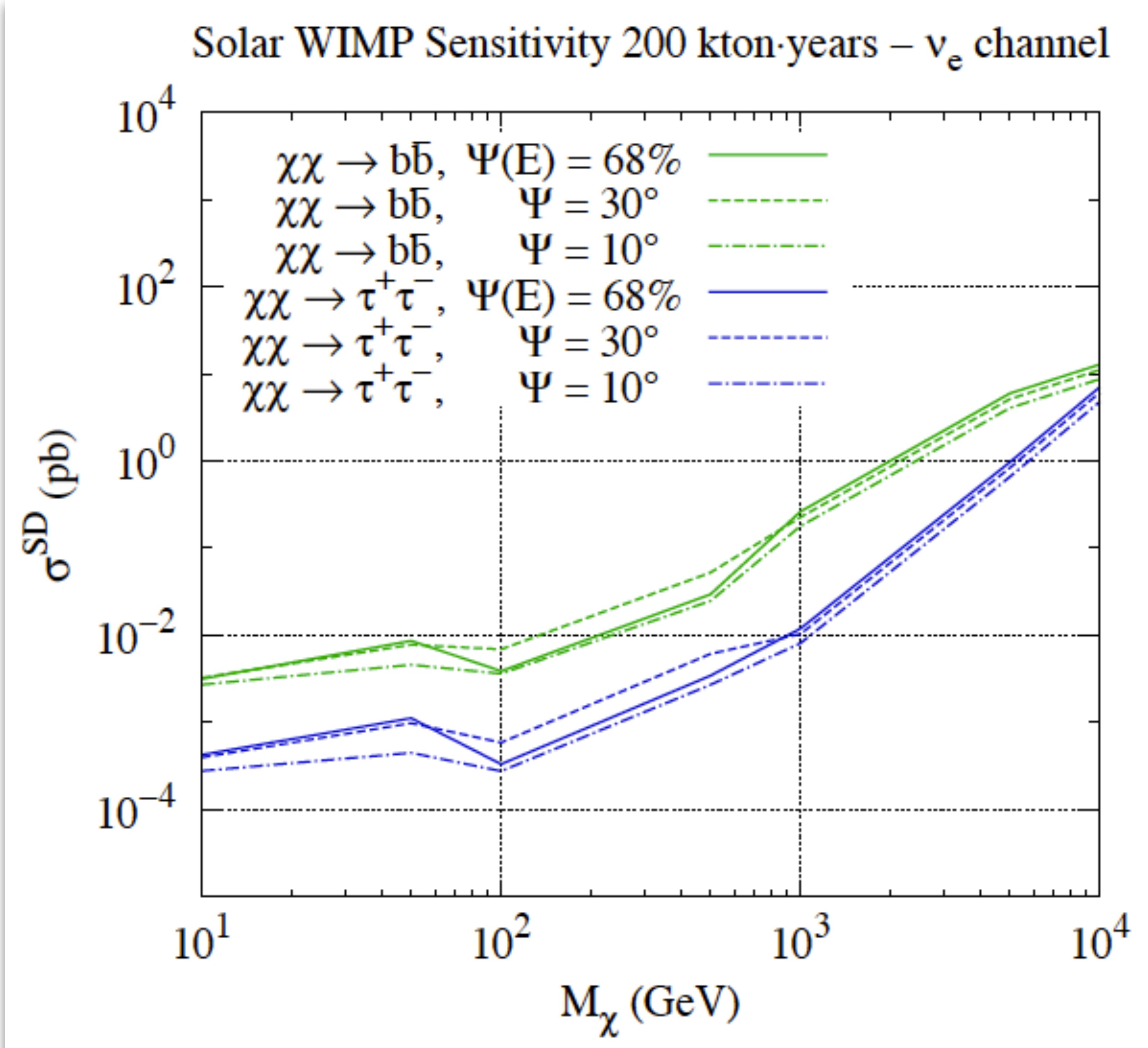


ν_τ^{sig} vs. ν_e^{atm}



Compute Sensitivity for a Generic Detector

- Assume a generic detector
    - Consider vertex contained events (starting events)
        - results can be scaled to any detector size
- Compare different opening angles around the Sun
    - ψ=30°
    - ψ=10°
    - ψ(E)=68%
- Assume 3 different energy cuts:
    - m_χ[10GeV,100GeV] E_{Thr}=1GeV
    - m_χ[100GeV,1TeV] E_{Thr}=10GeV
    - m_χ[1TeV,10TeV] E_{Thr}=100GeV



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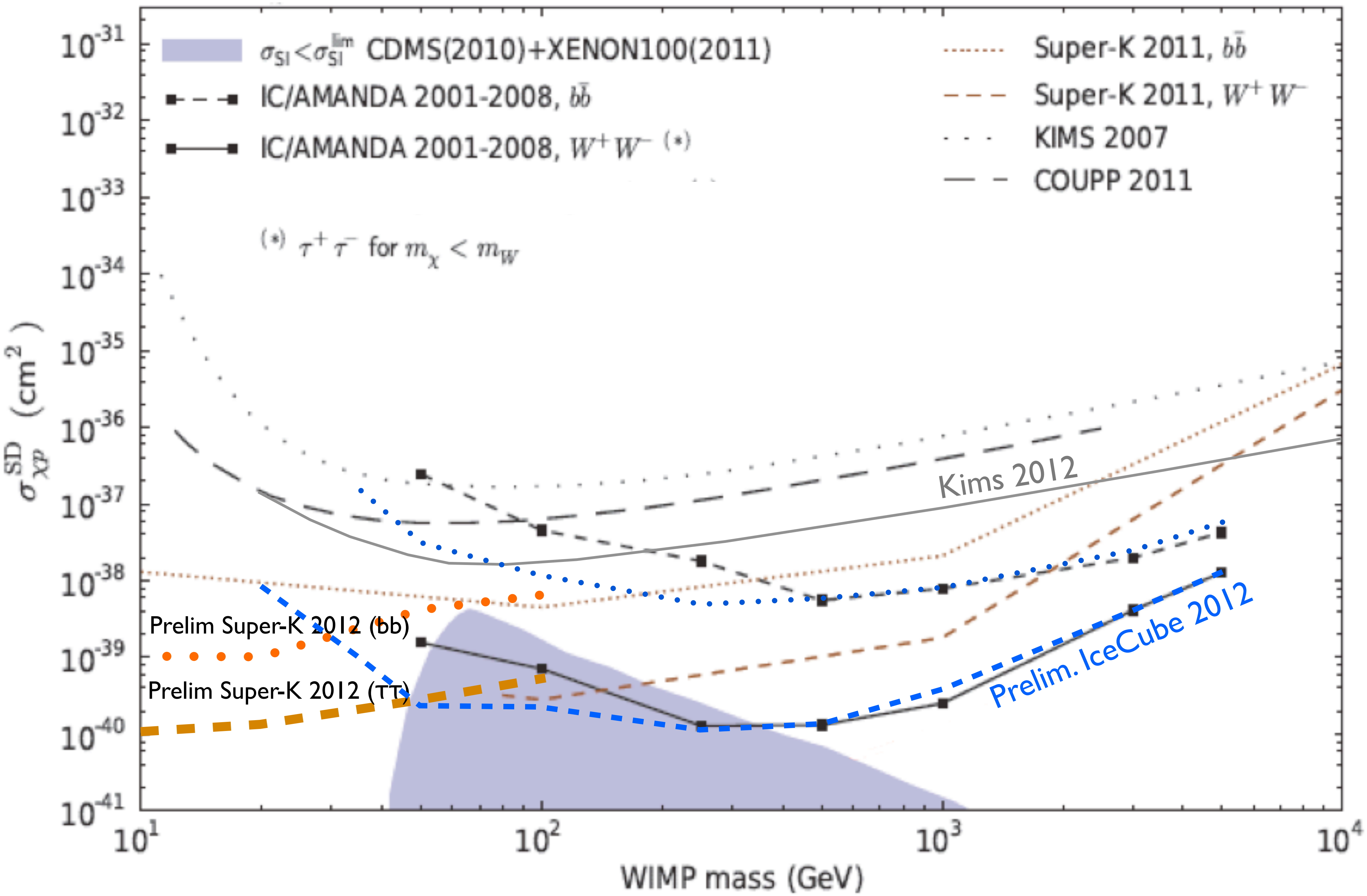
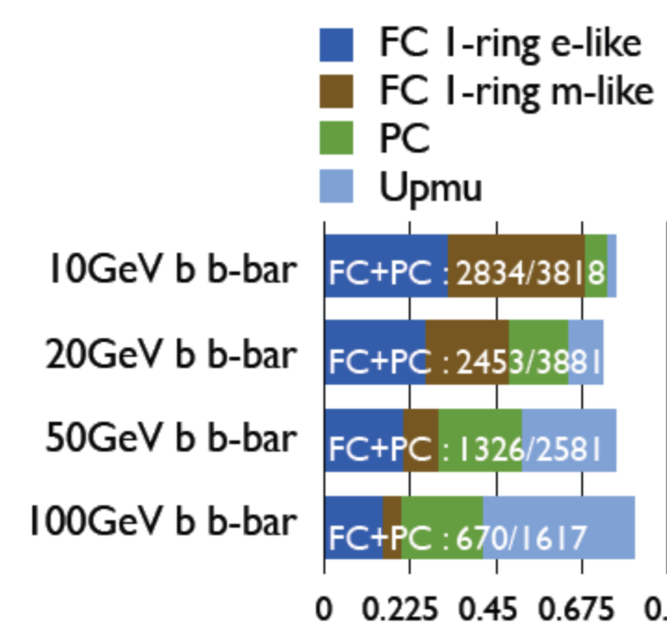


Data from Super-K I-III (2806days)

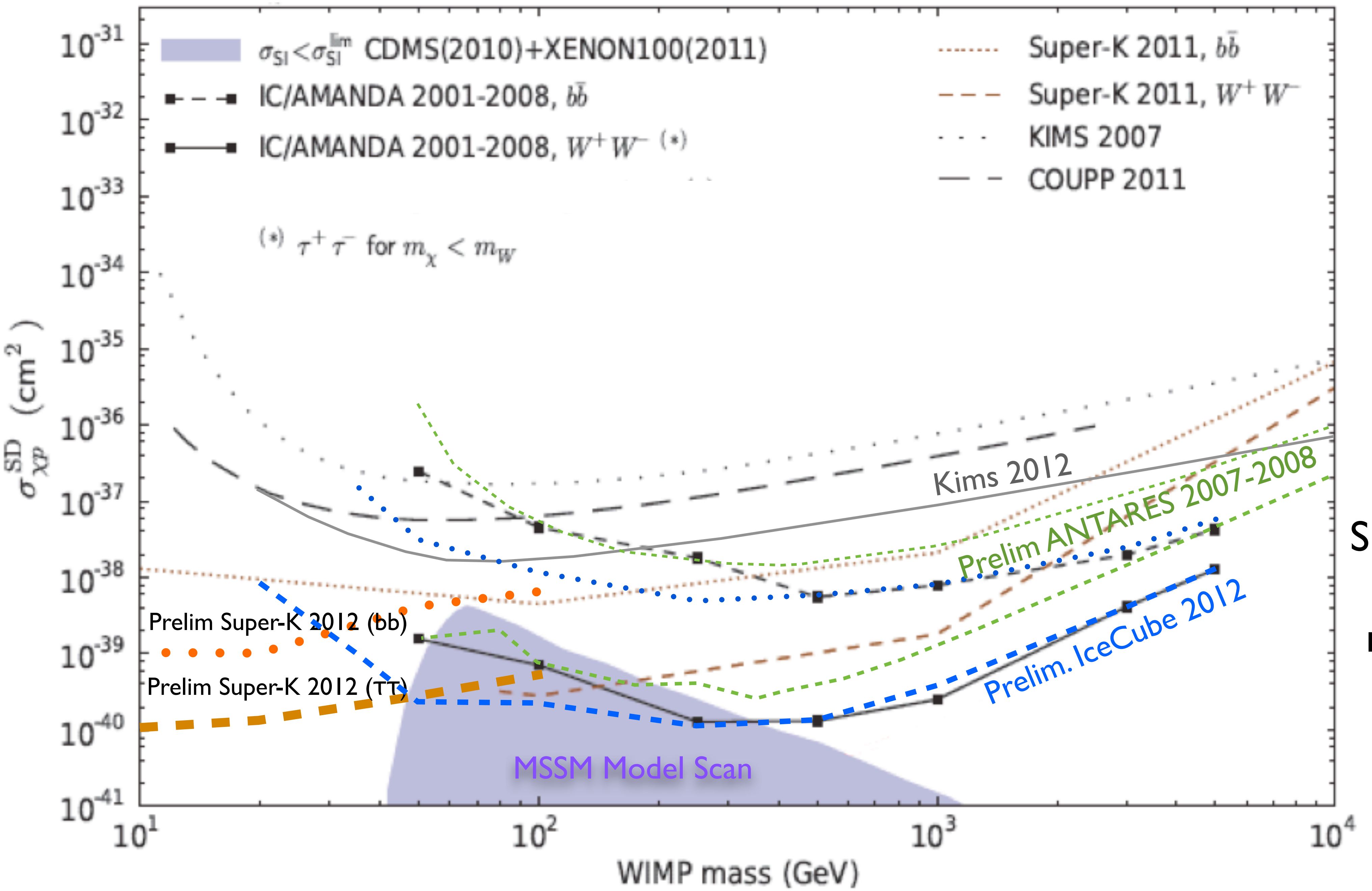


Energy / Angular Fit
Derive 90% Bayesian upper limit on allowed WIMP induced events

see:
Preliminary Super-K Limit Neutrino 2012
Preliminary IceCube/DeepCore Limit IDM 2012

Most recent Solar WIMP Limits

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)



Neutrino Detector data starts to constrain MSSM

1yr of DeepCore data already significantly more sensitive than 8yrs of AMANDA+IceCube

Super-K demonstrates what future low-threshold neutrino detectors will be able to do

see:
Preliminary Super-K Limit Neutrino 2012
Preliminary IceCube/DeepCore Limit IDM 2012
Preliminary ANTARES Limit Neutrino 2012

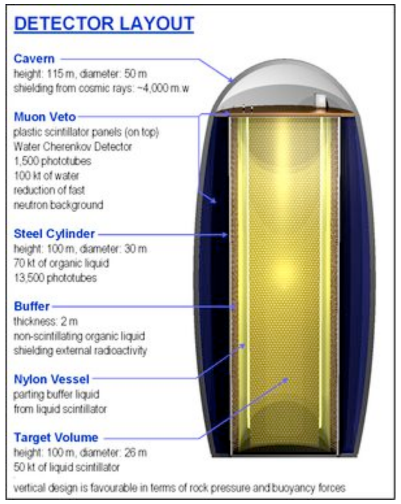
Future Prospects with “high-energy” neutrinos

Neutrino Detectors

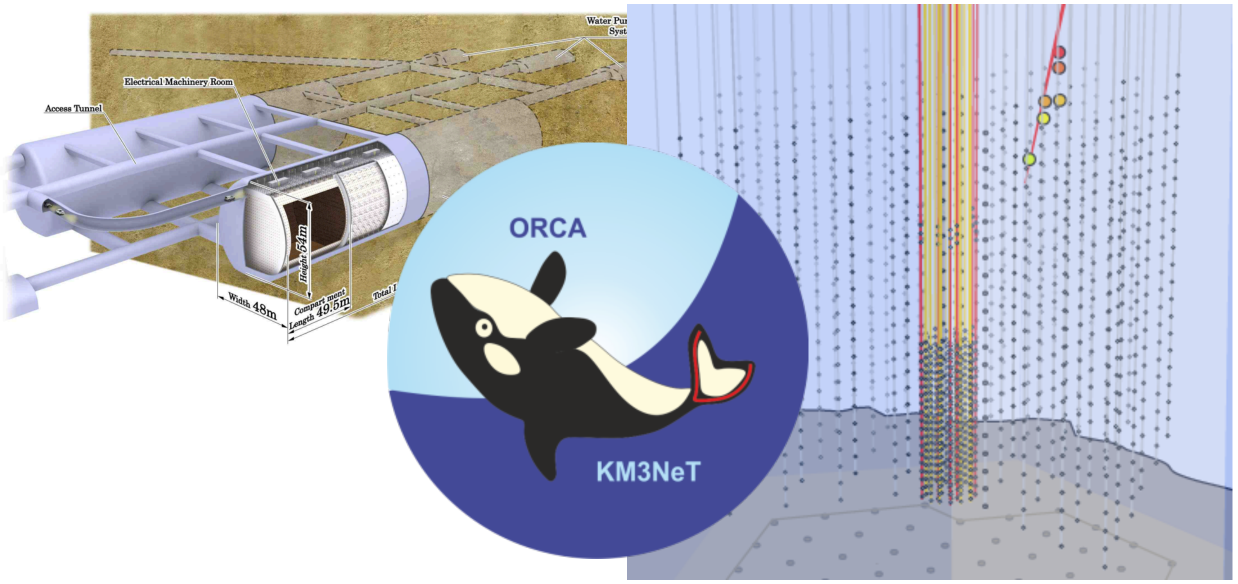
- Strong interest in the neutrino community to build one or more large neutrino detectors, based on proven or new technology
- All these detectors have tremendous potential for dark matter detection and should be one of the primary design drivers

LAr TPC

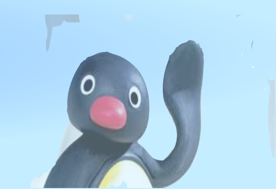
Scintillator



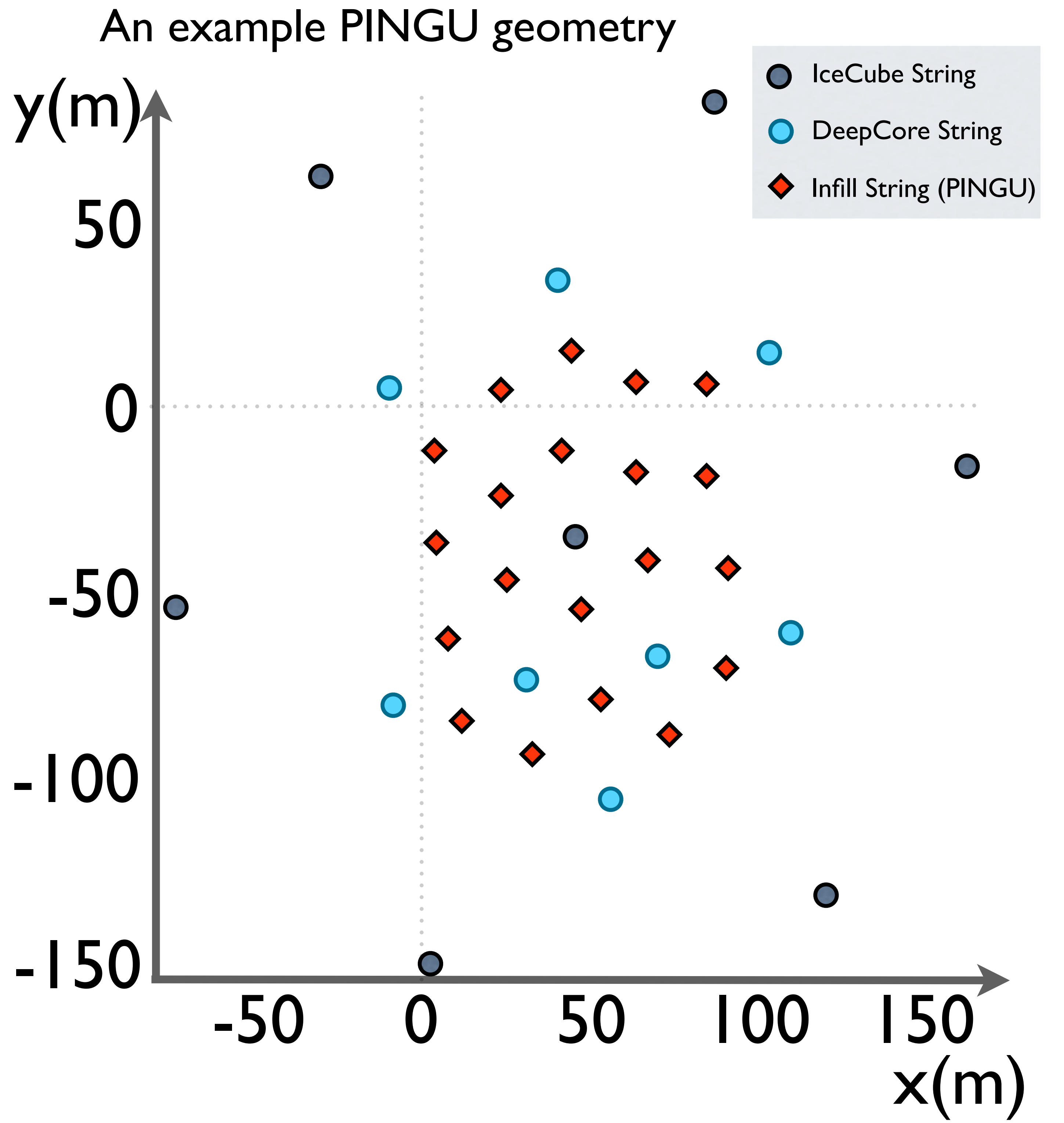
Water / Ice Cherenkov



PINGU - Precision IceCube Next Generation Upgrade



- Test low mass WIMPs and precision measurements of neutrino oscillations
  - Needs energy threshold of few GeV
- Developing a proposal to further in-fill DeepCore, called PINGU
  - Instrument a volume of about 10MT with ~20 strings each containing 50-60 optical module
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors



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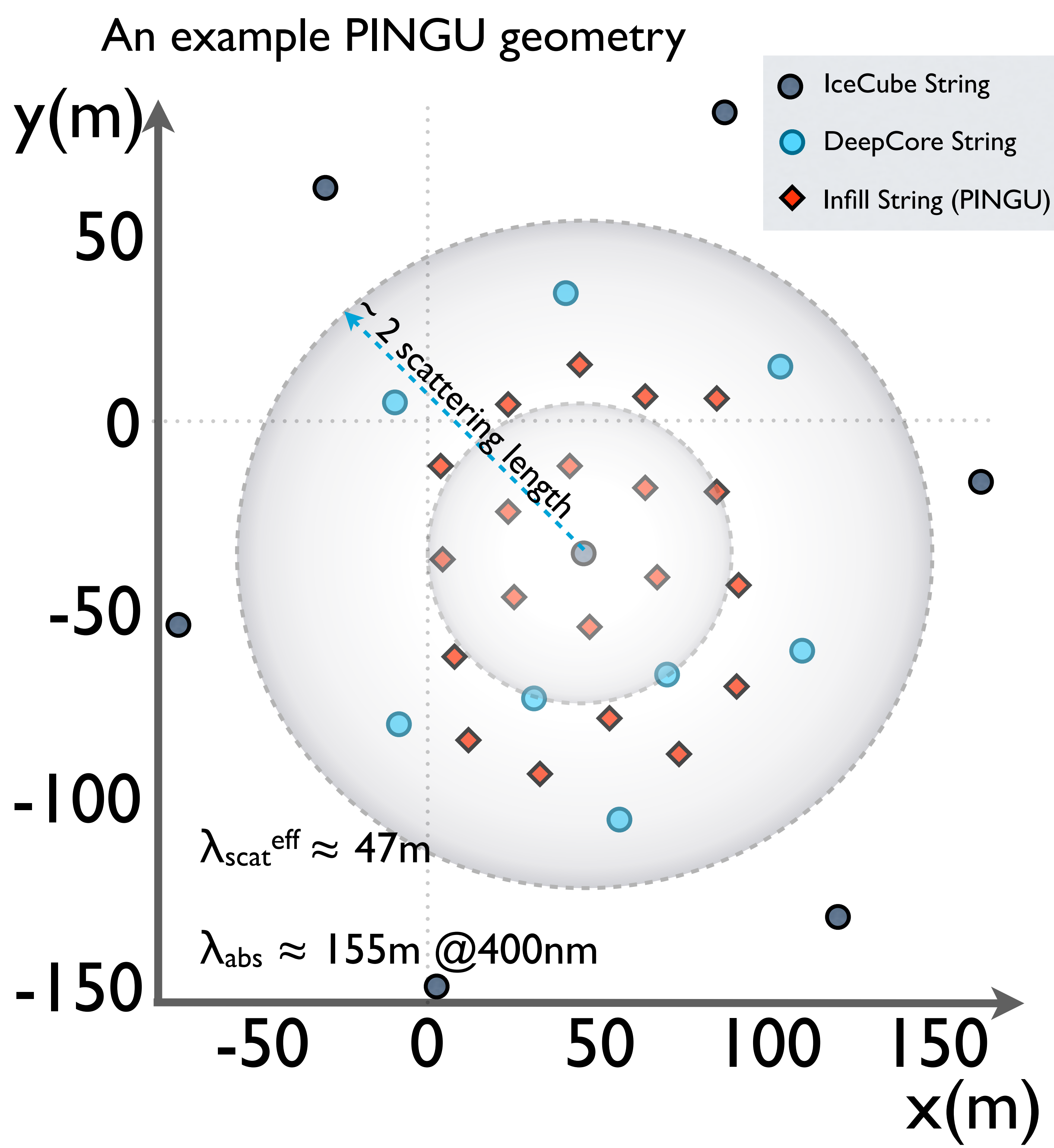
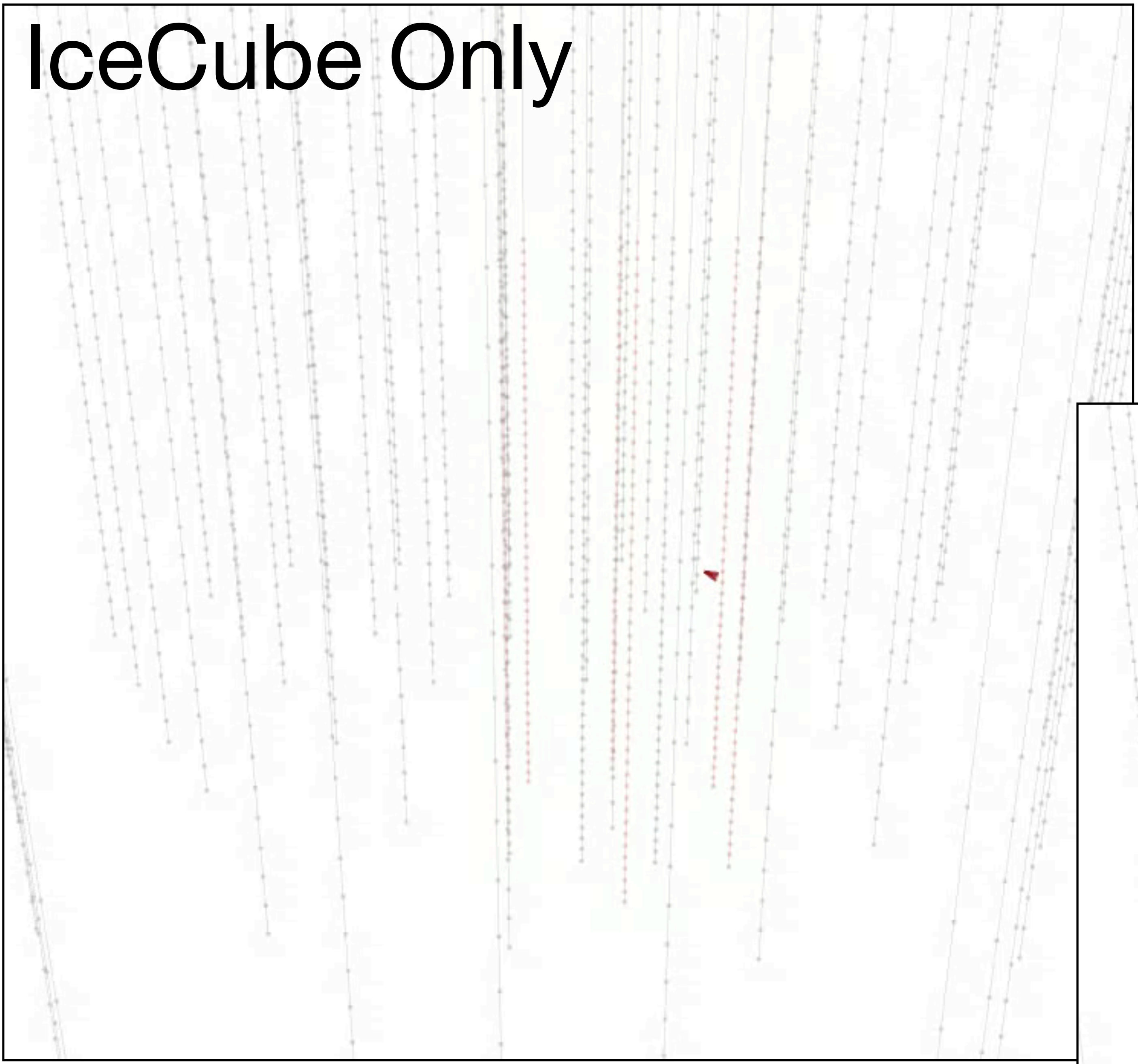
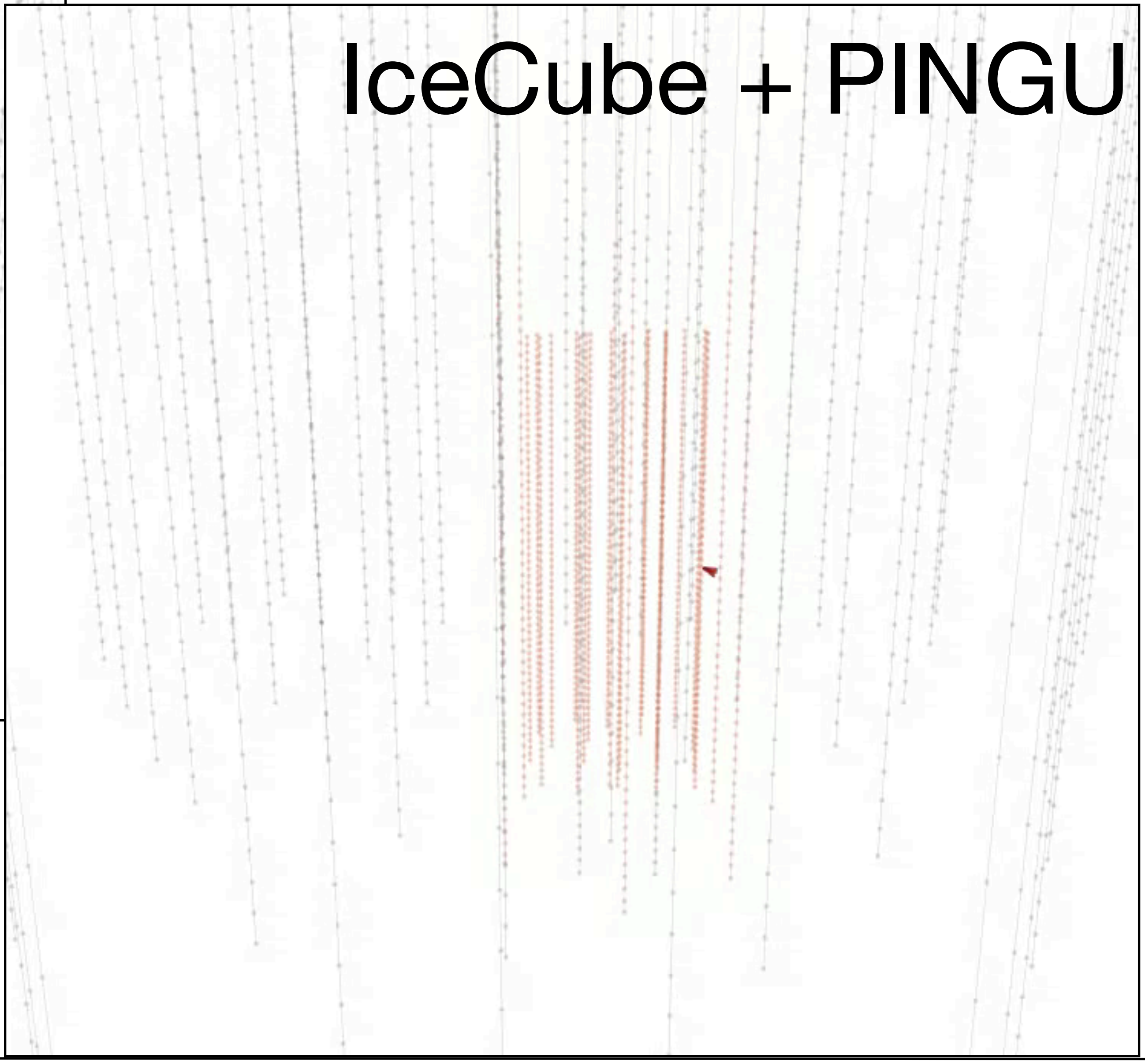


Example Event (simulation)



- 9 GeV muon neutrino (physics only hits)

[~4.9GeV muon / ~4.5GeV shower]



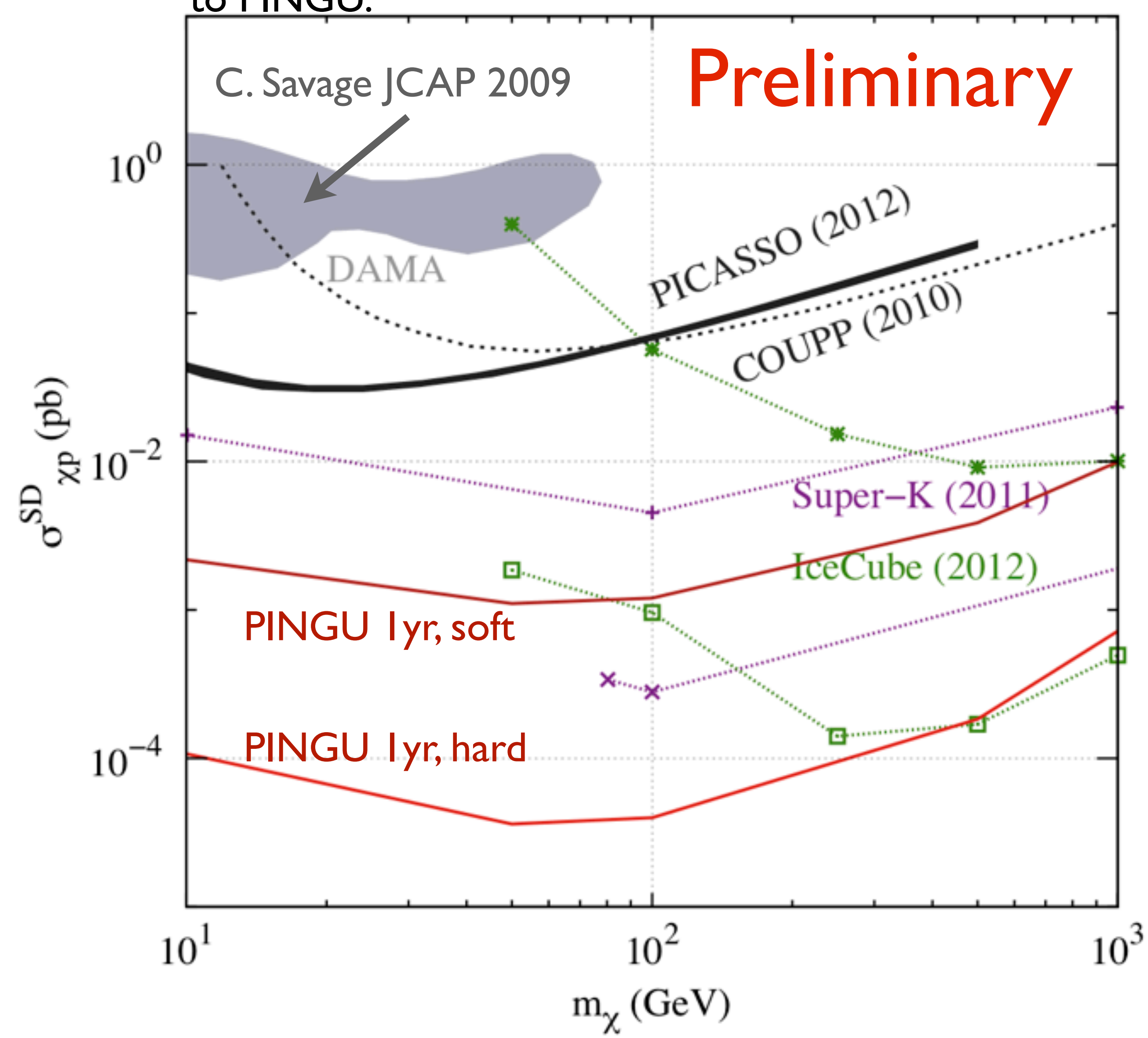
20 ⇒ 50 hit modules

PINGU and Solar WIMPs

- Preliminary solar WIMP sensitivity based PINGUs effective volume
- Assume that atmospheric muon backgrounds can be effectively rejected (not included in the sensitivity)

- Low-mass WIMP scenarios well testable
- Next steps:
  - Detailed study with full PINGU simulation
  - More sophisticated event reconstruction
  - Check atmospheric muon background

Adapted **Rott, Tanaka, Itow JCAP09(2011)029** to PINGU.



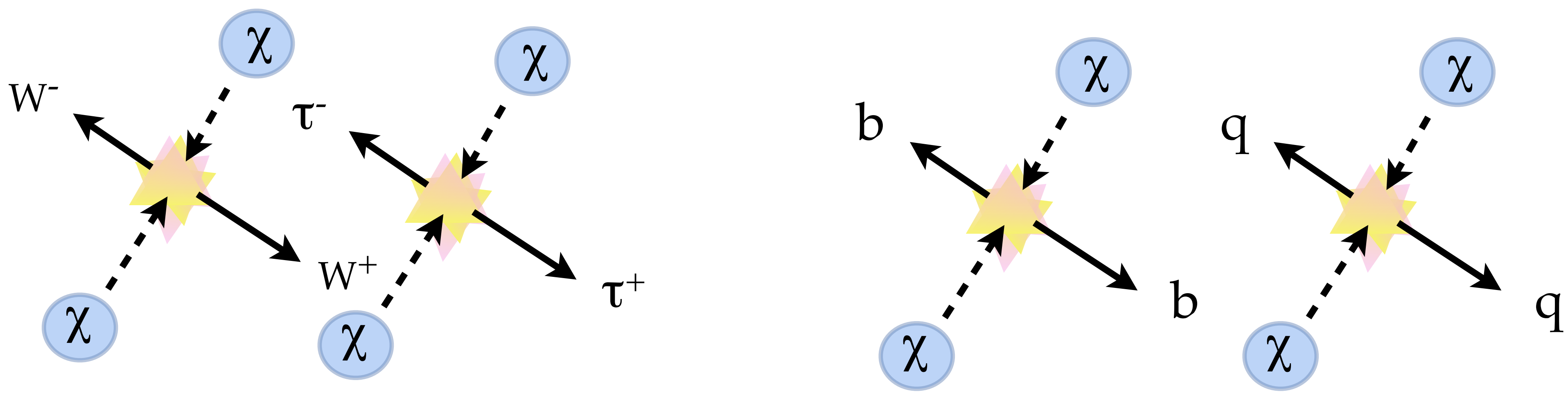
New Detection Channel

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

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

$\nu\nu$ $W^- W^+$ $\tau^- \tau^+$ $b\bar{b}$ $q\bar{q}$ e^+e^-

highest energy neutrinos

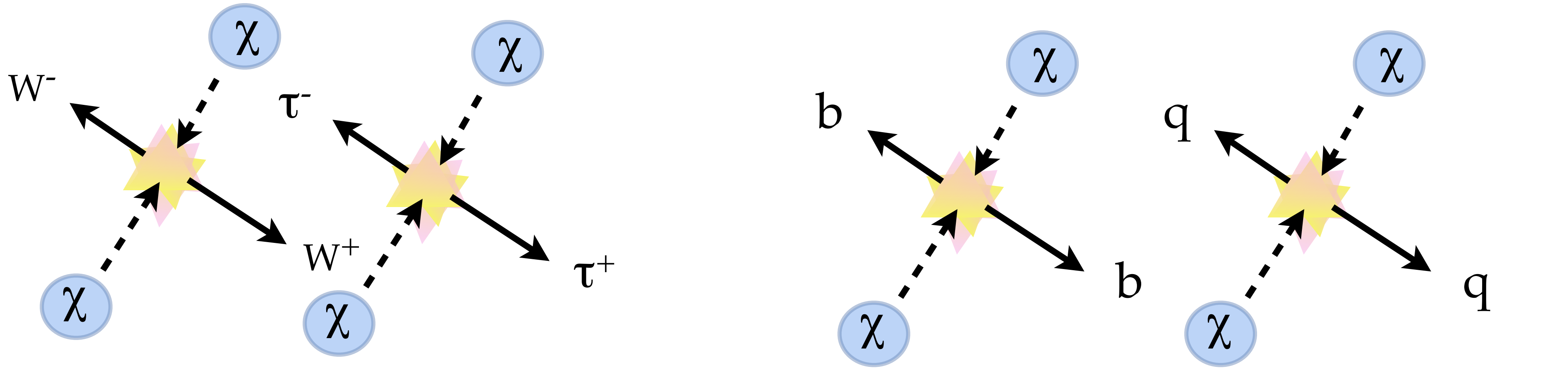
fewest neutrinos

Benchmarks
Br 100%

Hard channel

Soft channel

Dark Matter Annihilation in the Sun



high energy neutrinos from annihilation / decay products

νν W⁻ W⁺ τ⁻ τ⁺ bb qq e⁺e⁻

highest energy neutrinos

fewest neutrinos

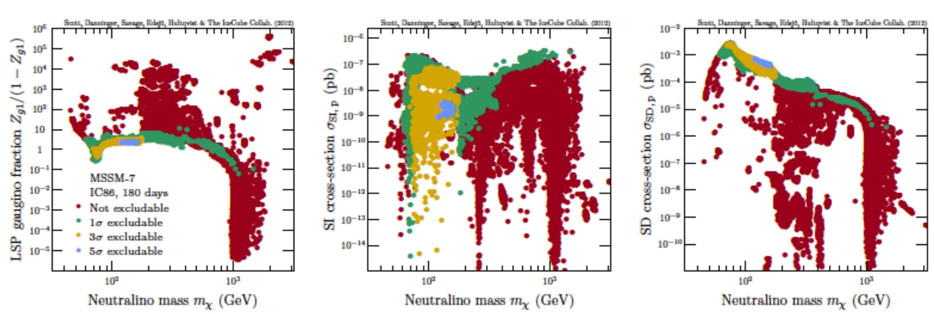
Benchmarks
Br 100%

Hard channel

Soft channel

Specific
Model

$$\mathcal{L}_{\text{total}}(n_{\text{tot}}, \Xi|\psi) = \mathcal{L}_{\text{num}}(n_{\text{tot}}|\psi) \prod^{n_{\text{tot}}} \mathcal{L}_{\text{ang},i}(\phi'_i|\psi)\, \mathcal{L}_{\text{spec},i}(N_i|\psi)$$



see: Scott, Savage, Edsjo and IceCube Collaboration "Use of event-level neutrino telescope data in global fits for theories of new physics" arXiv1207.0810

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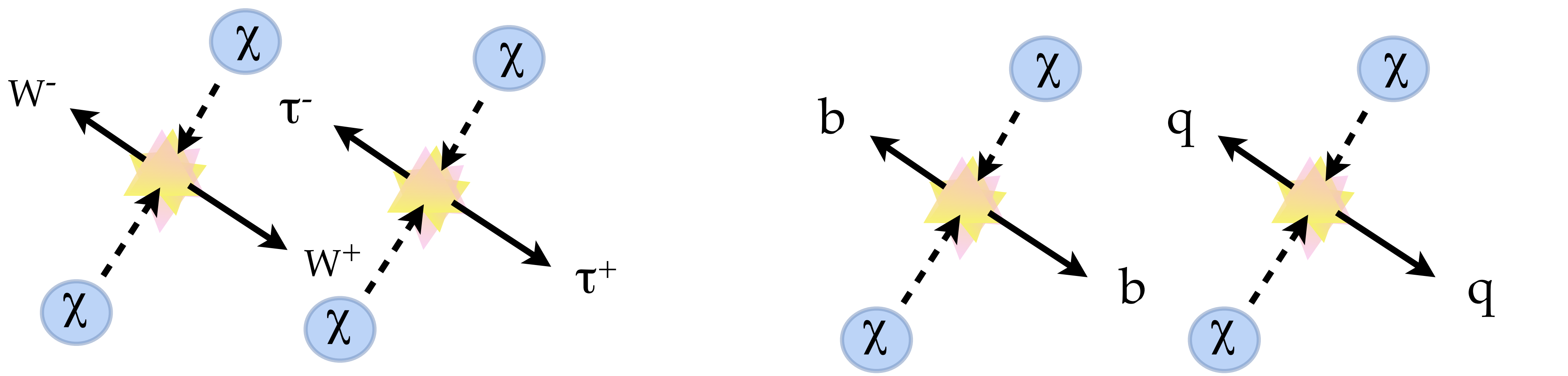


high energy neutrinos from annihilation / decay products

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

highest energy neutrinos

fewest neutrinos

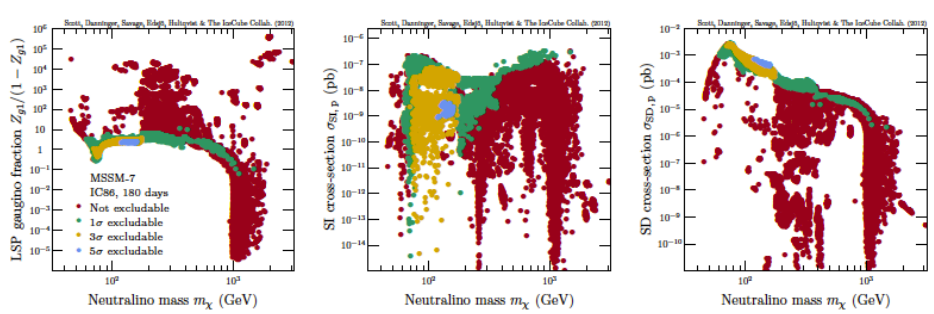
Benchmarks
Br 100%

Hard channel

Soft channel

Specific
Model

$$\mathcal{L}_{\rm total}(n_{\rm tot}, \Xi|\psi) = \mathcal{L}_{\rm num}(n_{\rm tot}|\psi) \prod^{n_{\rm tot}} \mathcal{L}_{{\rm ang},i}(\phi'_i|\psi)\, \mathcal{L}_{{\rm spec},i}(N_i|\psi)$$



see: Scott, Savage, Edsjo and IceCube Collaboration "Use of event-level neutrino telescope data in global fits for theories of new physics" arXiv1207.0810

low energy neutrinos from hadronic shower

see: Rott, Siegal-Gaskins, Beacom arXiv1208.0827

Low-Energy Neutrinos from the Sun Solar

Possible annihilation channels:

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

few neutrinos

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few neutrinos

some "high energy" neutrinos in decays

⇒ basis of present day searches

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

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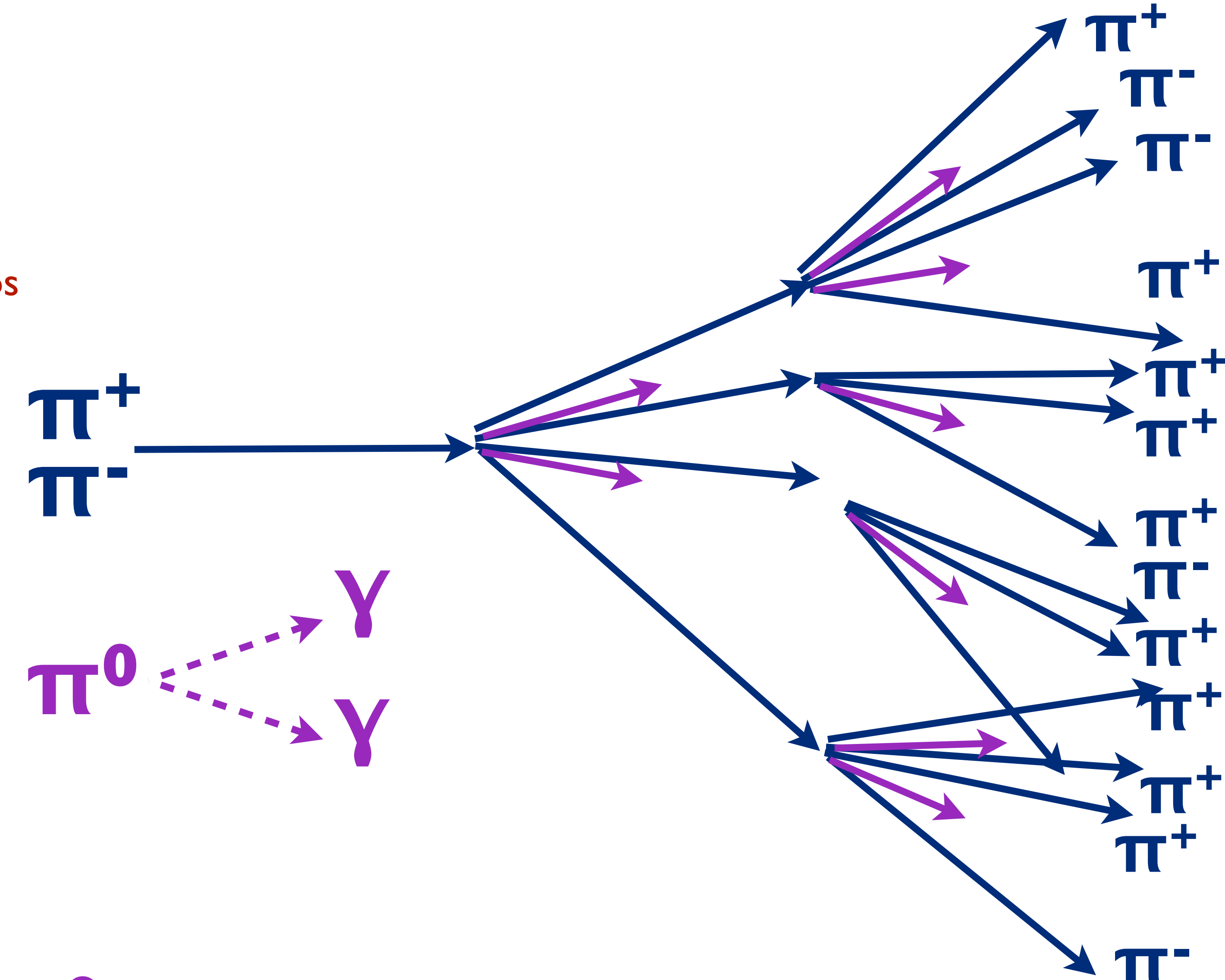

π^0
- Lifetime too short to interact

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

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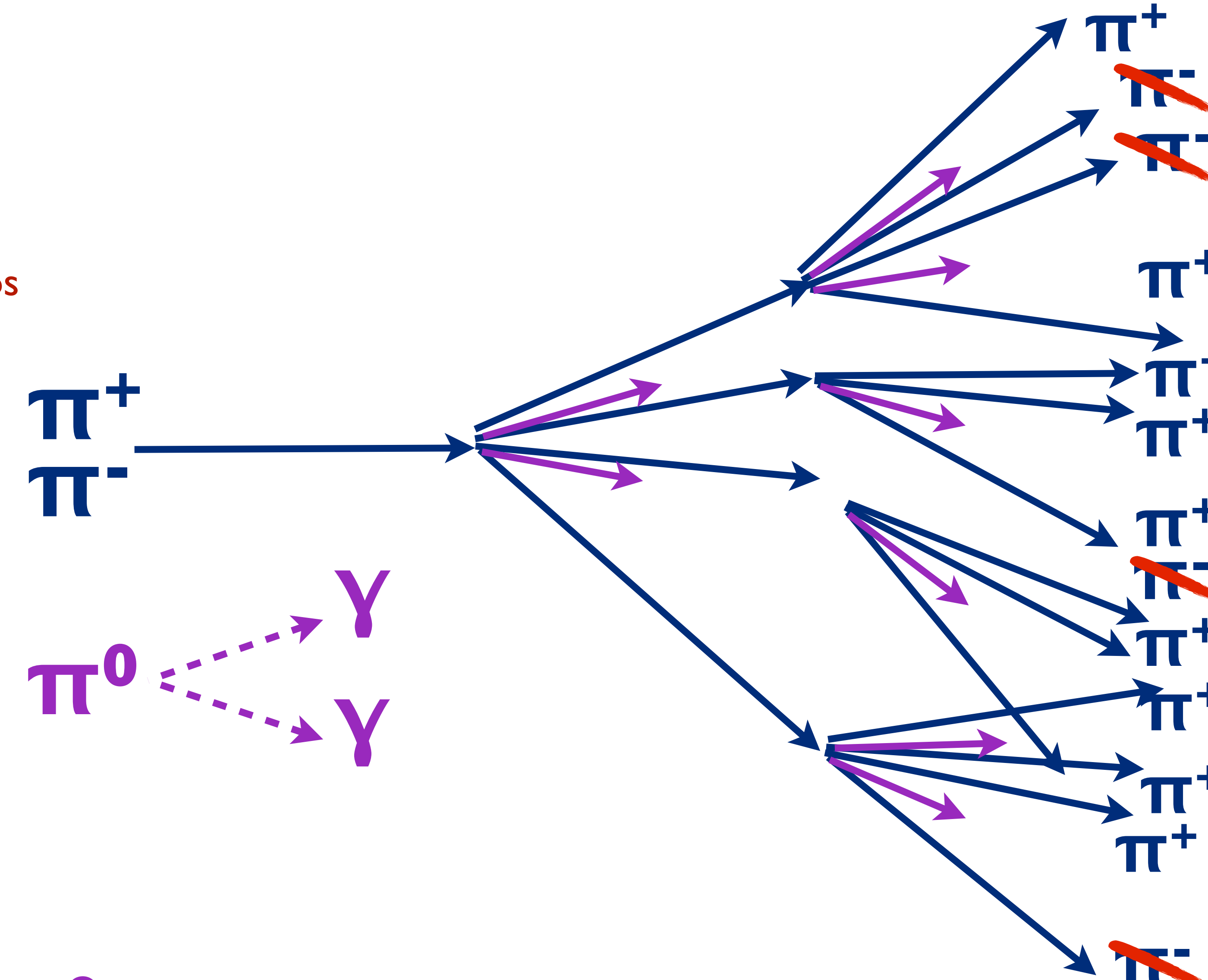

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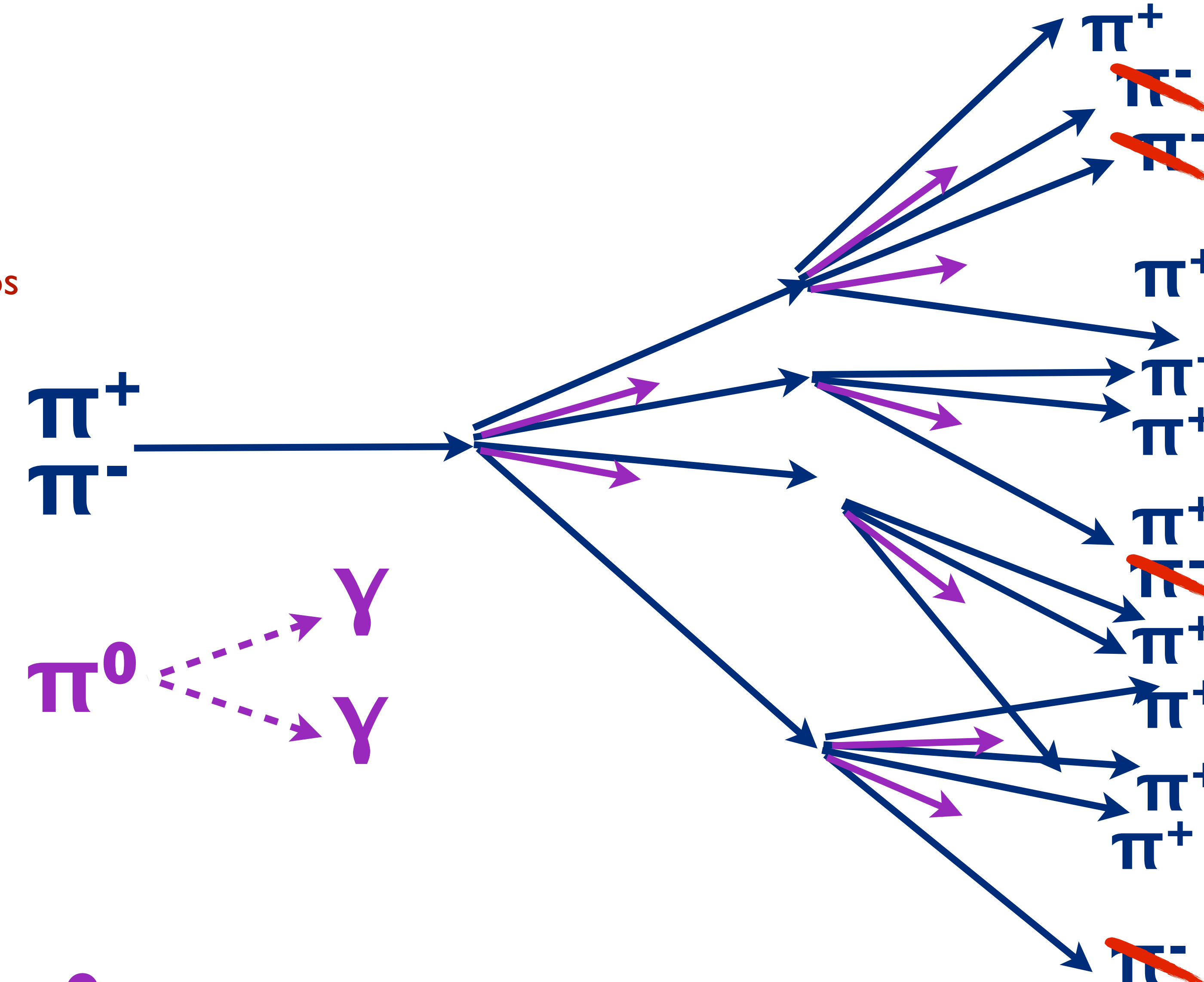

Charged pions decay at rest producing neutrinos up to E=52.8MeV

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

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

π^0

- Lifetime too short to interact

π^-

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- Produces secondary particles in collision with protons
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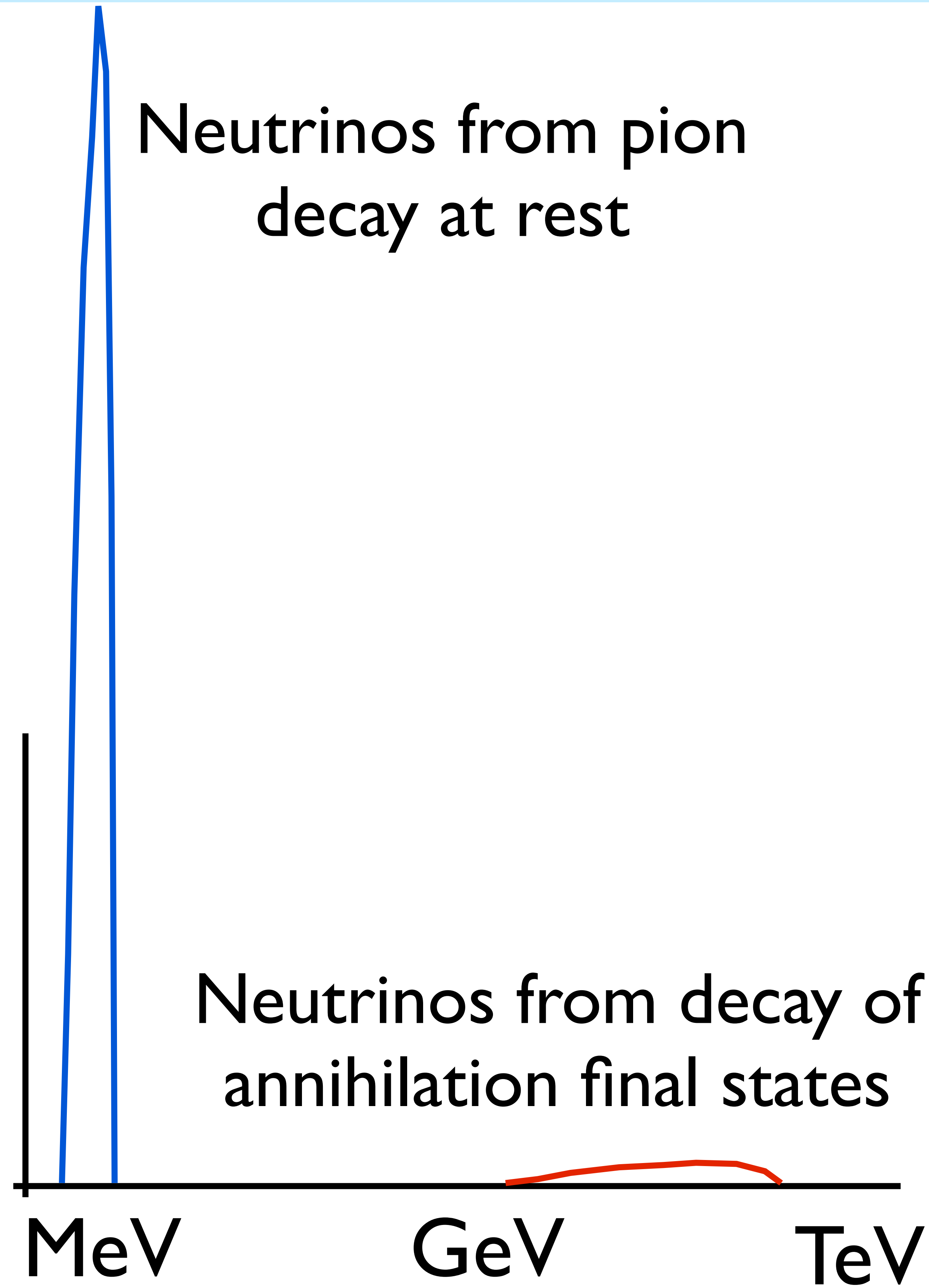
Neutrino signals - Example W-Boson

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

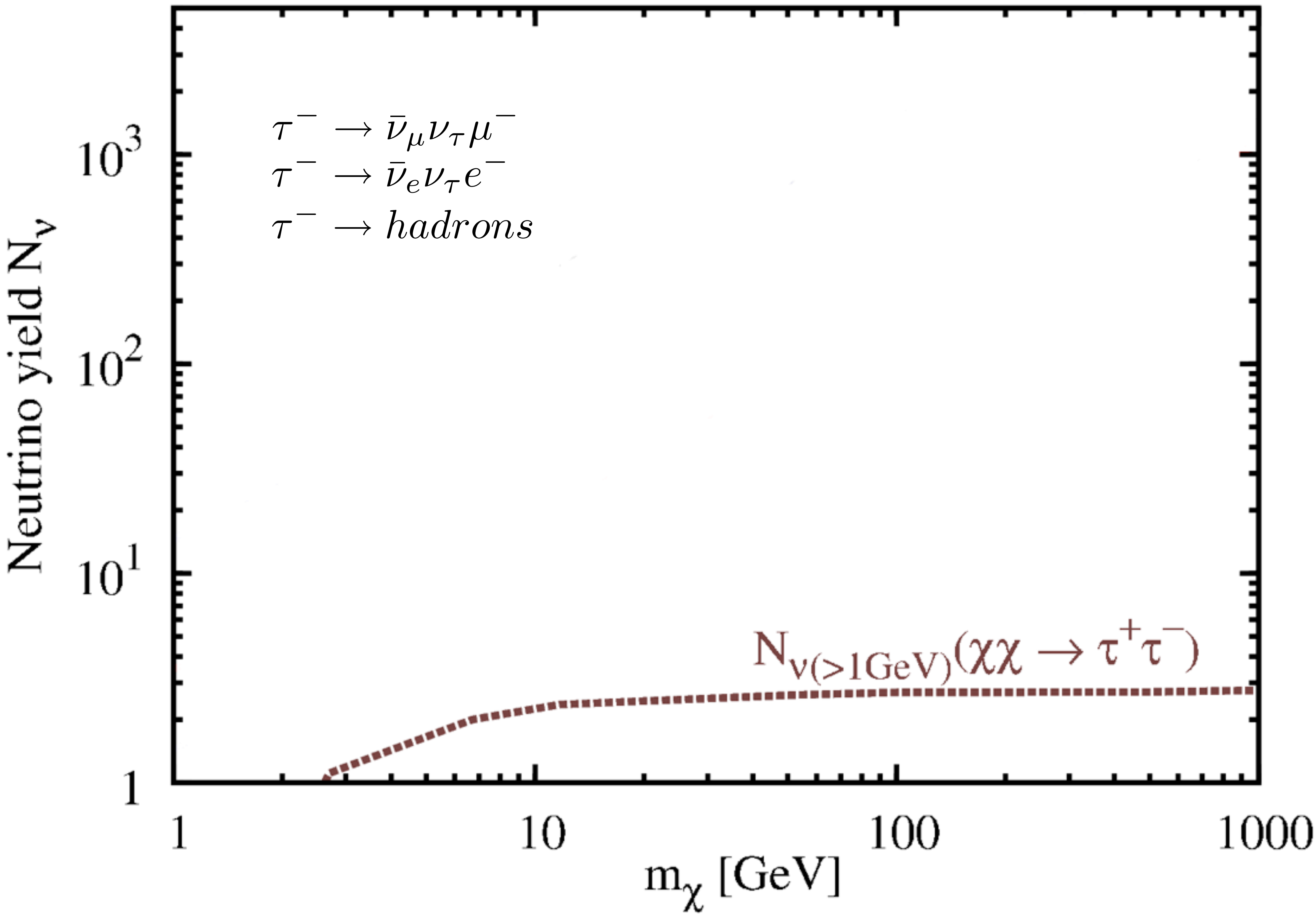
$\longrightarrow qq$ ~67%

Let's have a closer look at this:

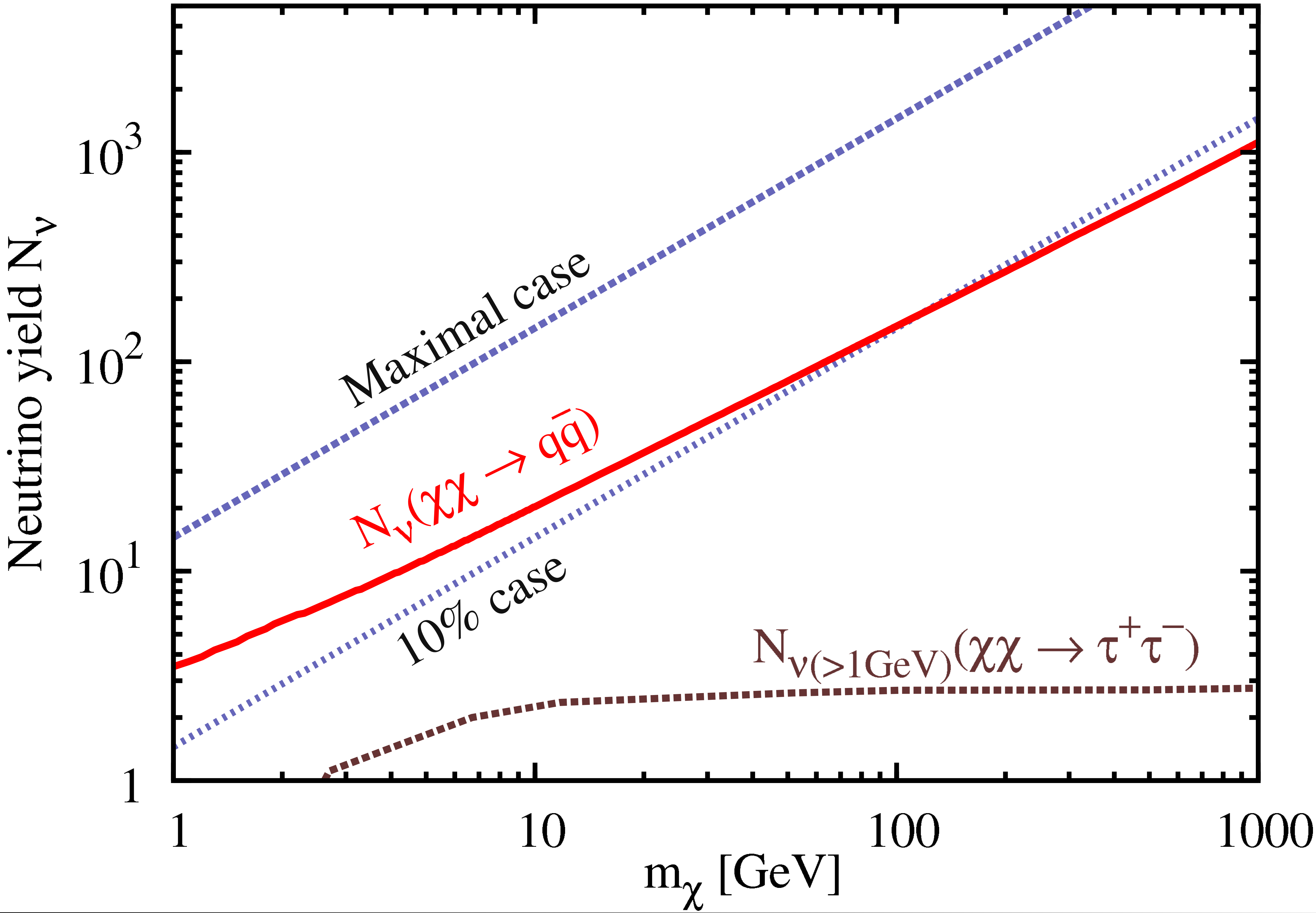
$e^+\nu_e$	1 high energy ν + em shower
$\mu^+\nu_\mu$	1 high energy ν + muon
$\tau^+\nu_\tau$	1 high energy ν + tau decay
qq	hadronic shower



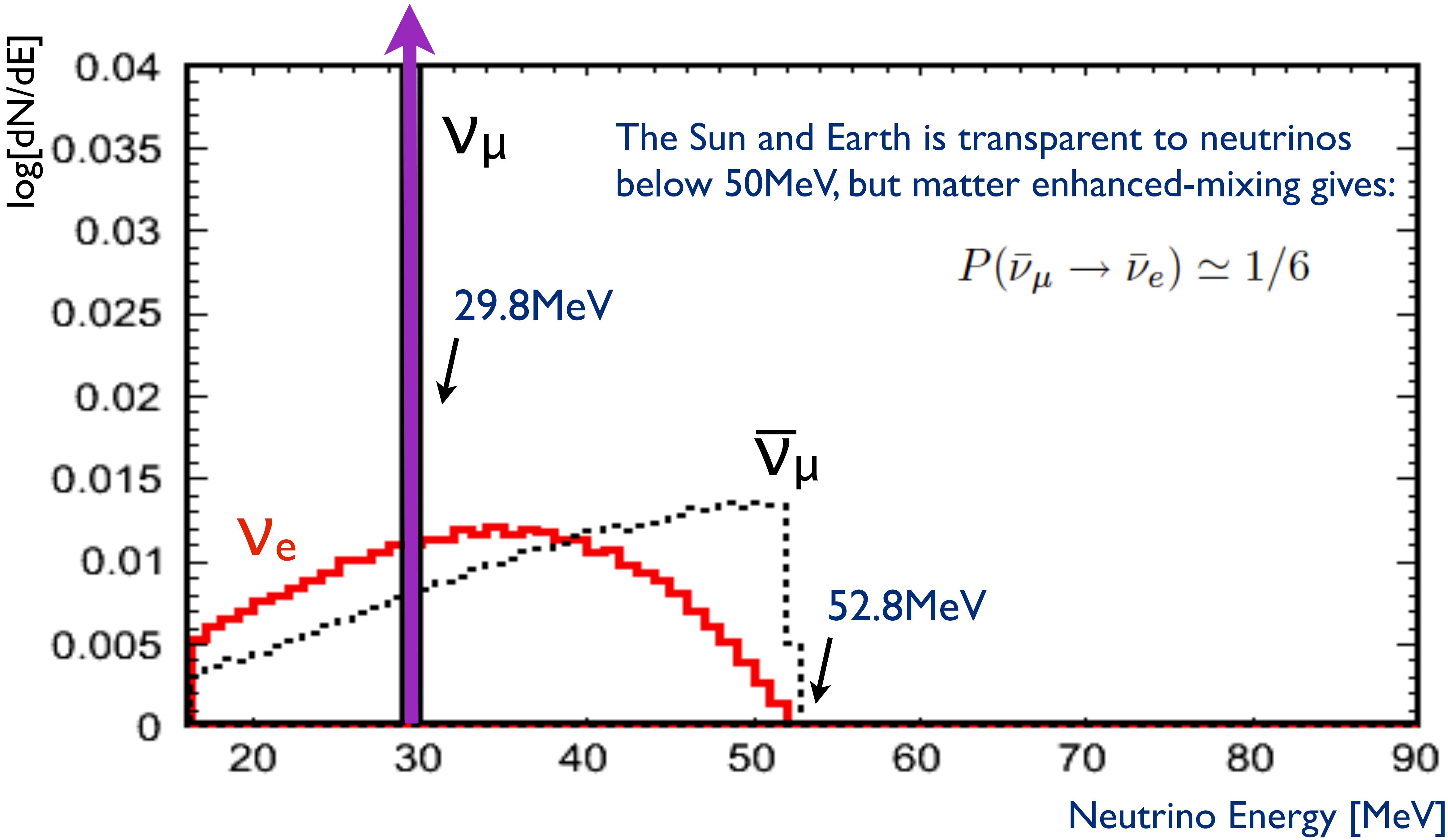
What's the Neutrino yield ?



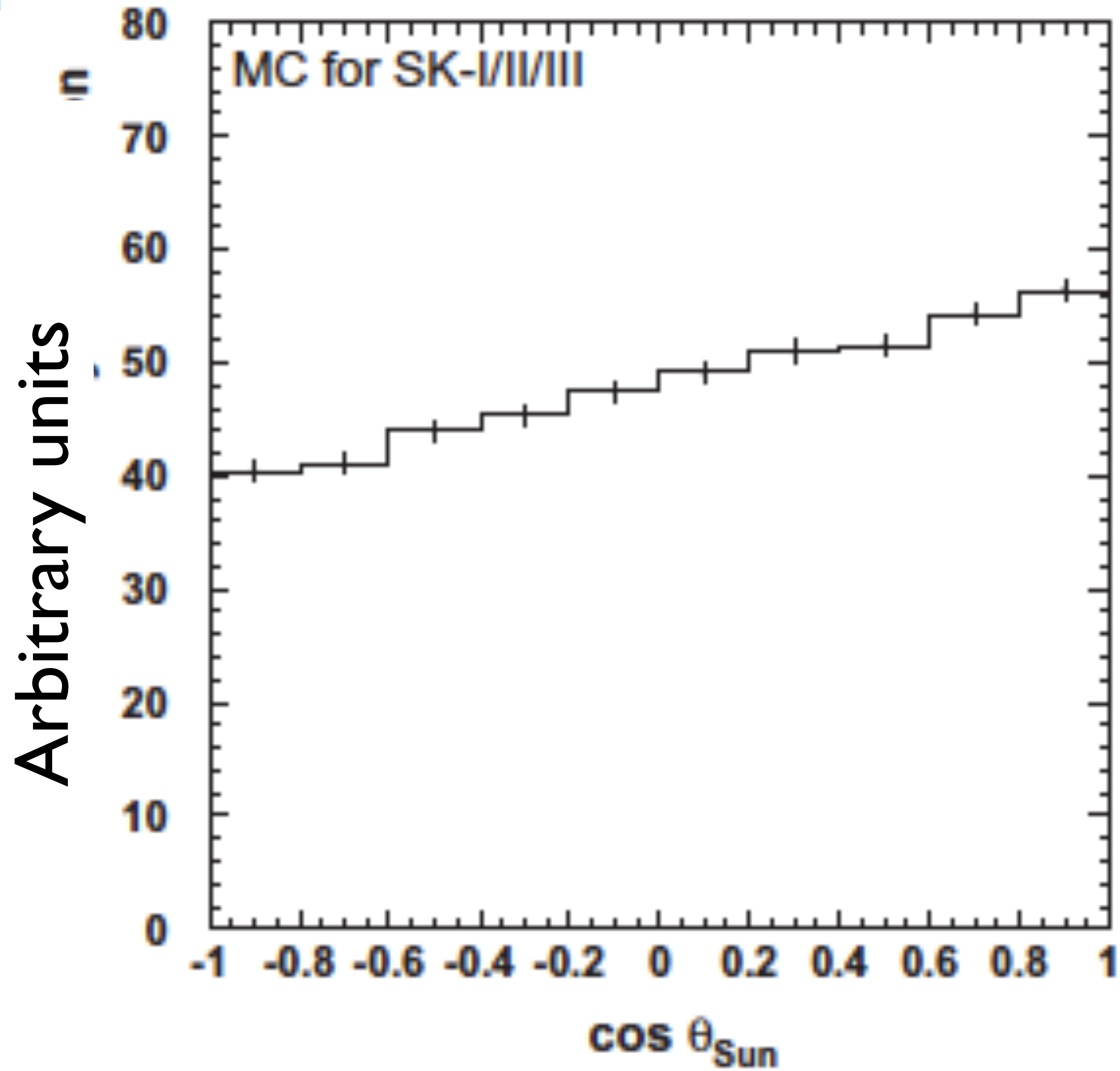
Neutrino yield



Neutrino Spectrum in the Sun (normalized to unity)

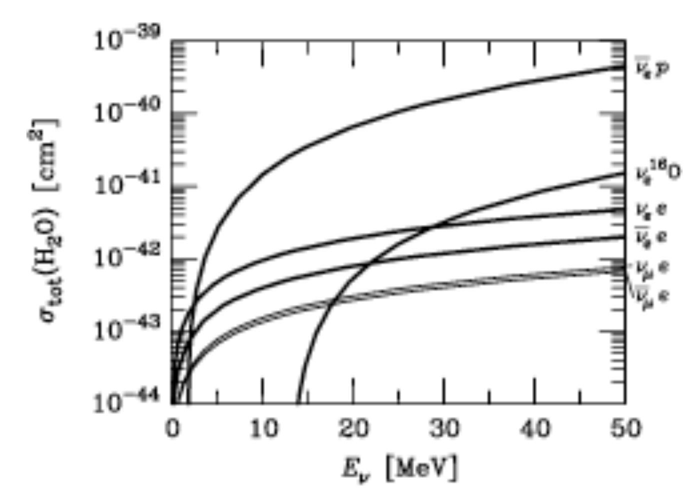


Inverse beta-decay



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

"large" cross section, but little directionality

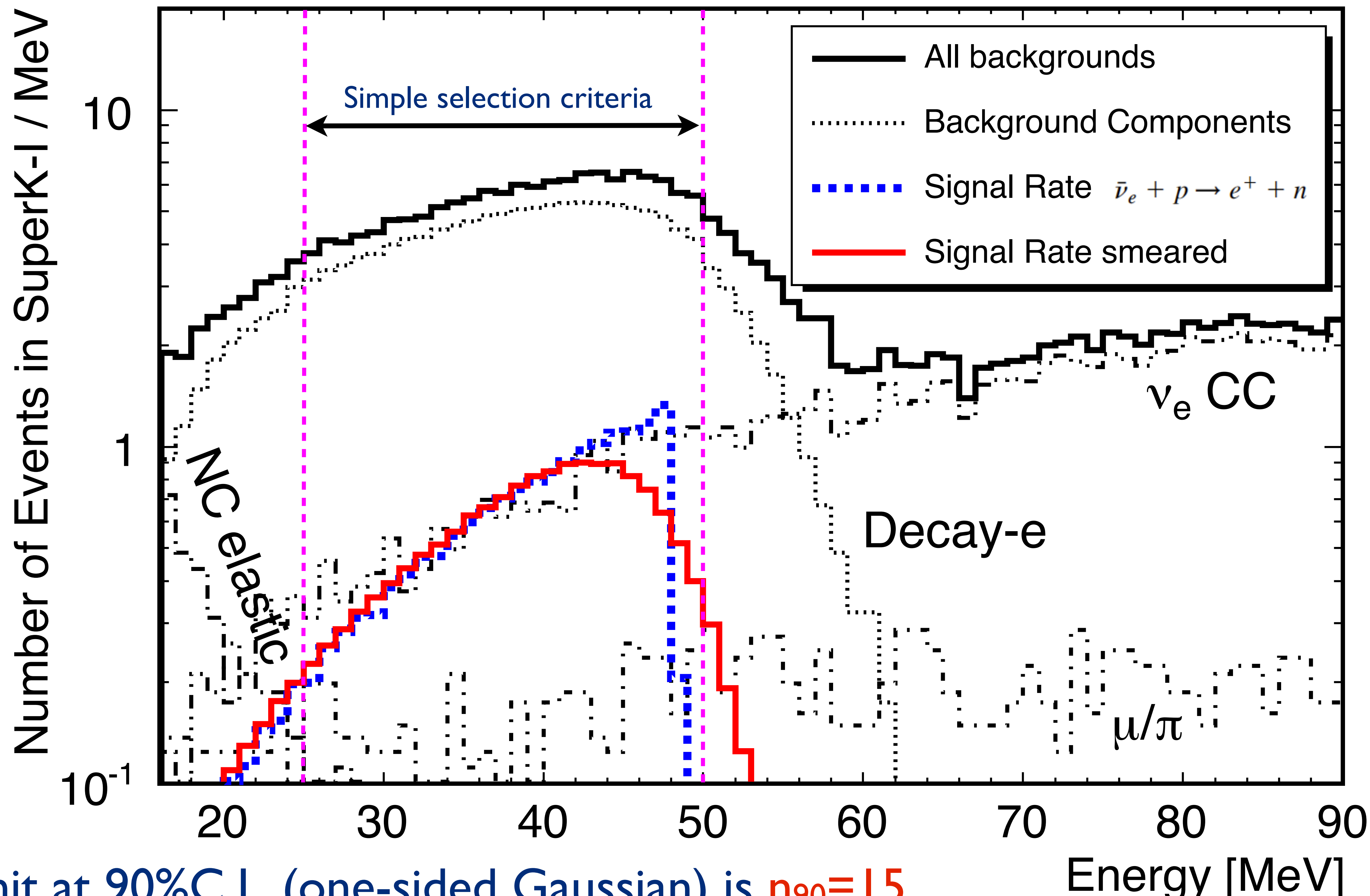


$$\sigma_{\nu p} \simeq \left[0.0952 \times 10^{-42}\,\mathrm{cm}^2\,((E_\nu/\,\mathrm{MeV}) - 1.3)^2\right](1 - 7E_\nu/m_p)$$

Sensitivity Calculation Super-K

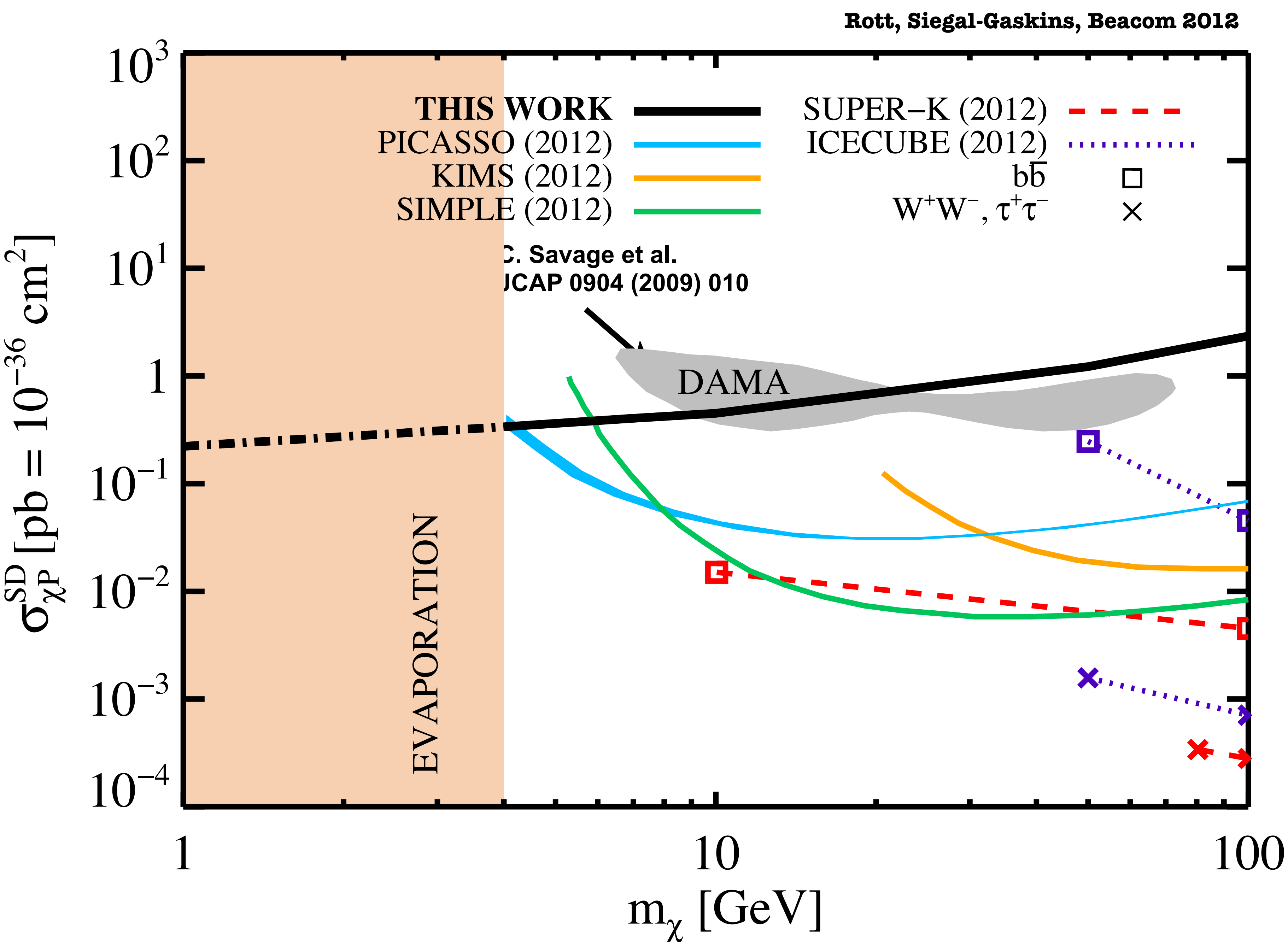
Positrons carry energy of $E_e \simeq [E_\nu - 1.3\ \mathrm{MeV}]\,(1 - E_\nu/m_p)$

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

Interesting signatures for future neutrino detectors (LENA, Hyper-K, ...), other nuclear final states could provide additional sensitivity

Gadolinium

- Decay electron events are the dominant background
- Identifying neutron 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

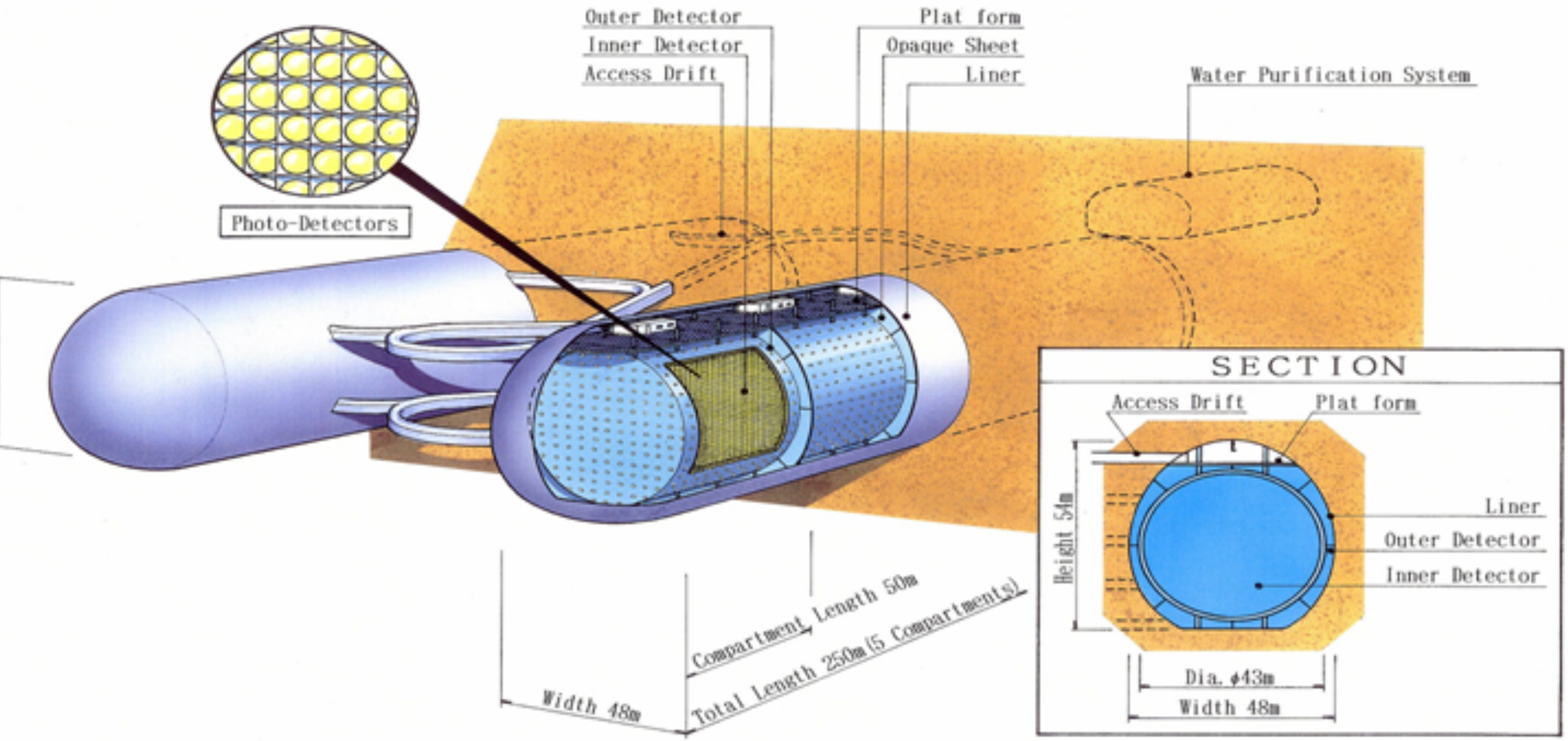
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

EGADS

November 2011

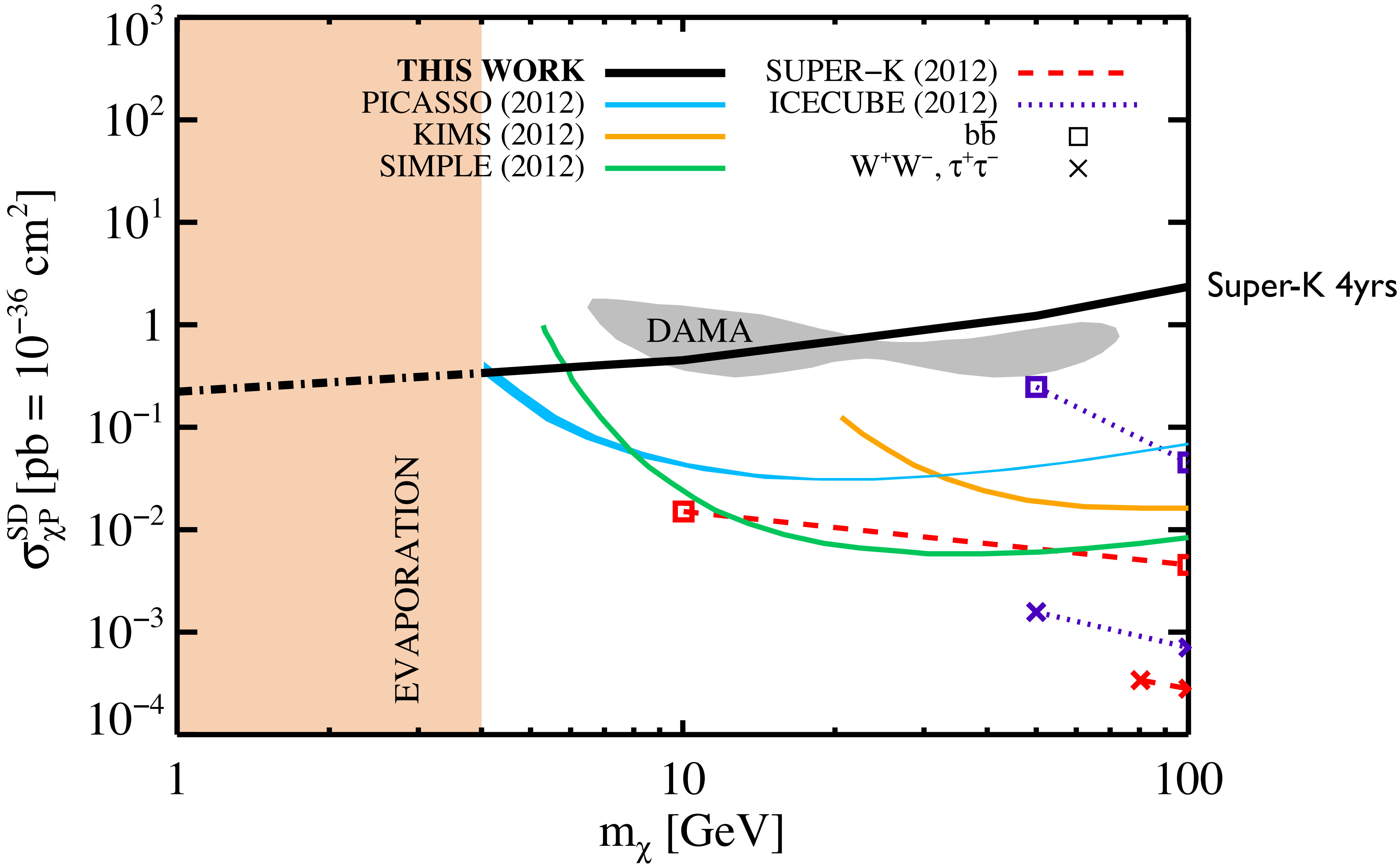
200tons
240 50-cm PMT's

Hyper-K



Outer Detector
Inner Detector
Access Drift
Plat form
Opaque Sheet
Liner
Water Purification System
Photo-Detectors
SECTION
Access Drift
Plat form
Liner
Outer Detector
Inner Detector
Height 54m
Dia. ϕ43m
Width 48m
Compartment Length 50m
Total Length 250m (5 Compartments)
Width 48m

Hyper-K Sensitivity 4yrs



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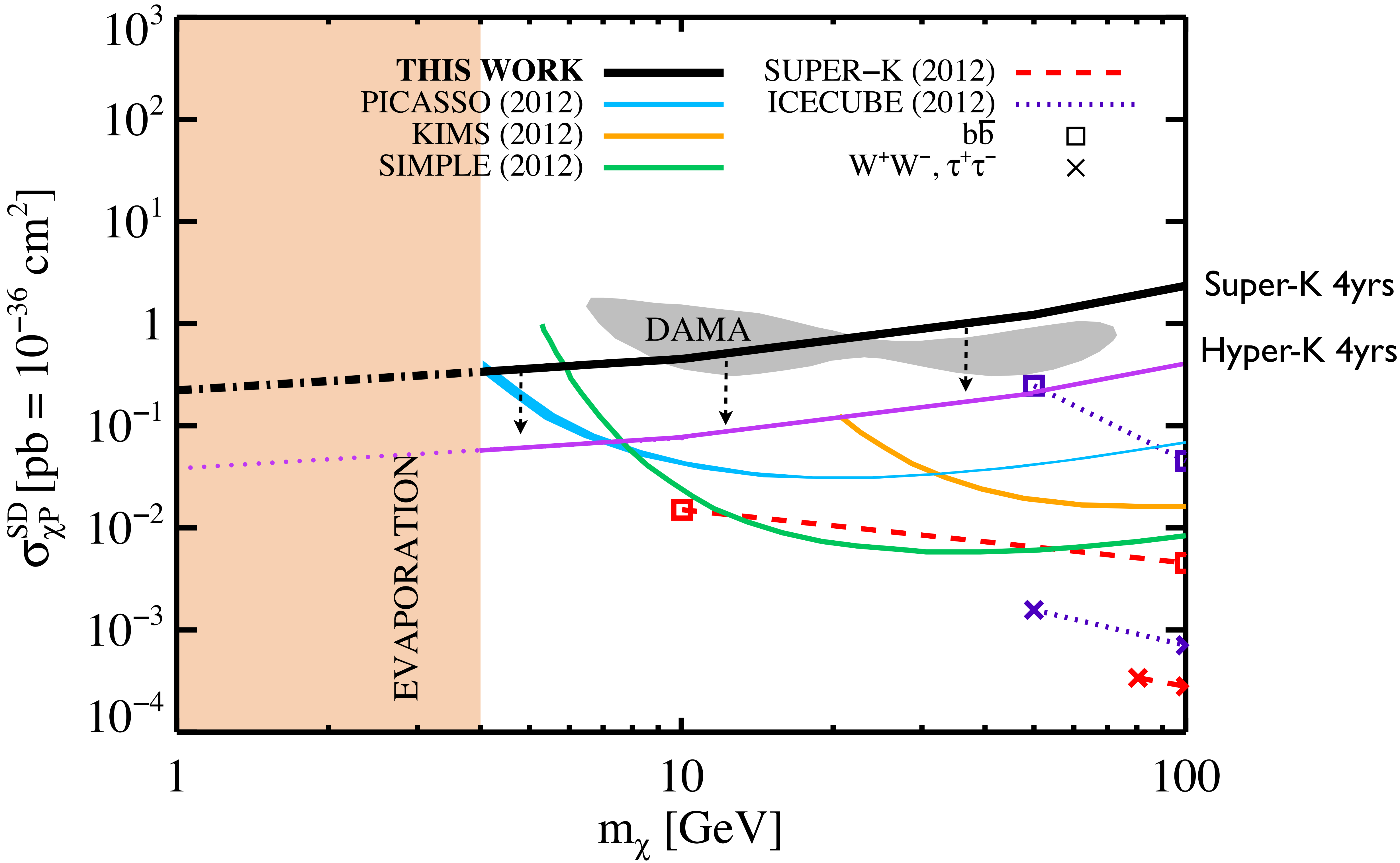

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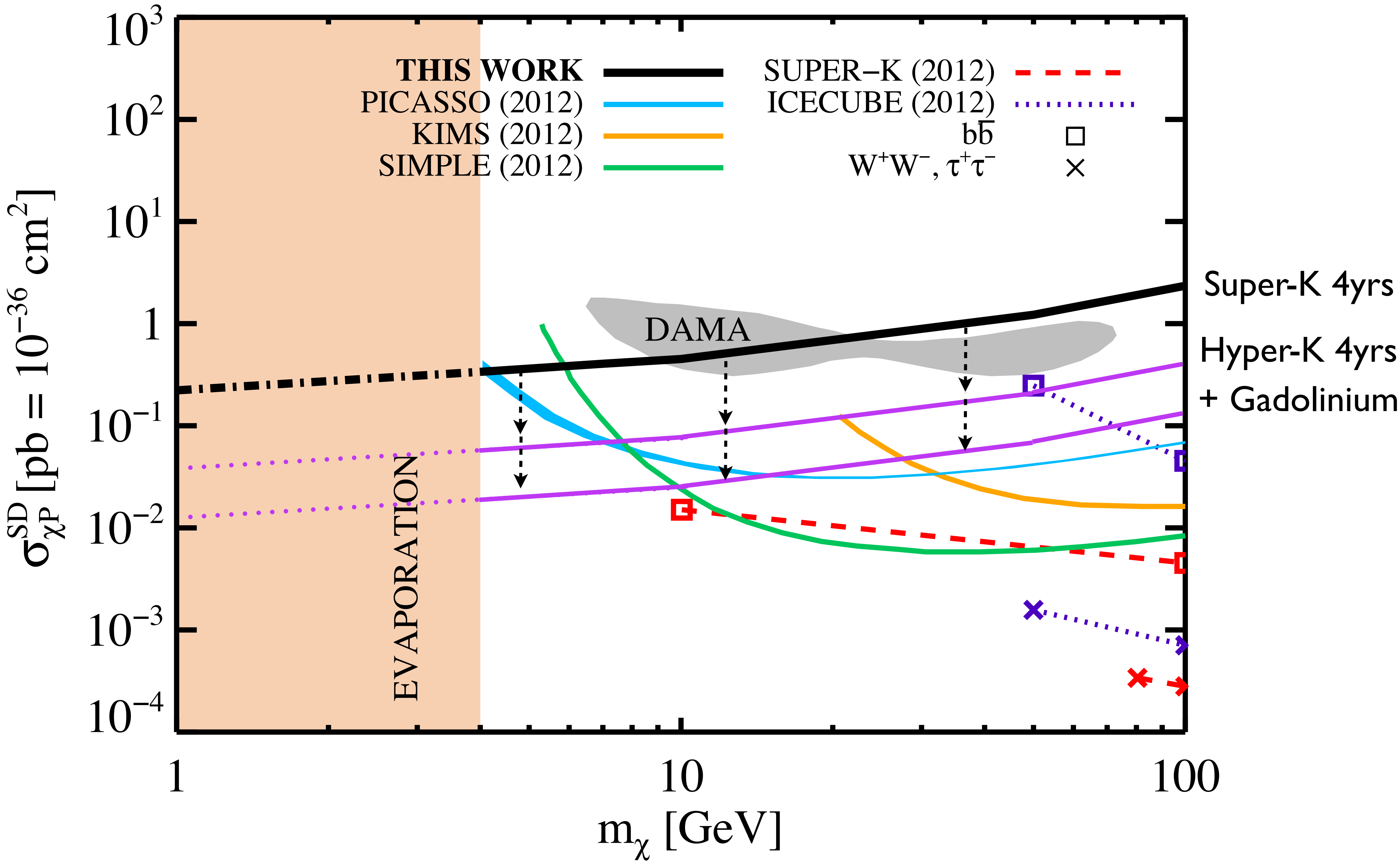

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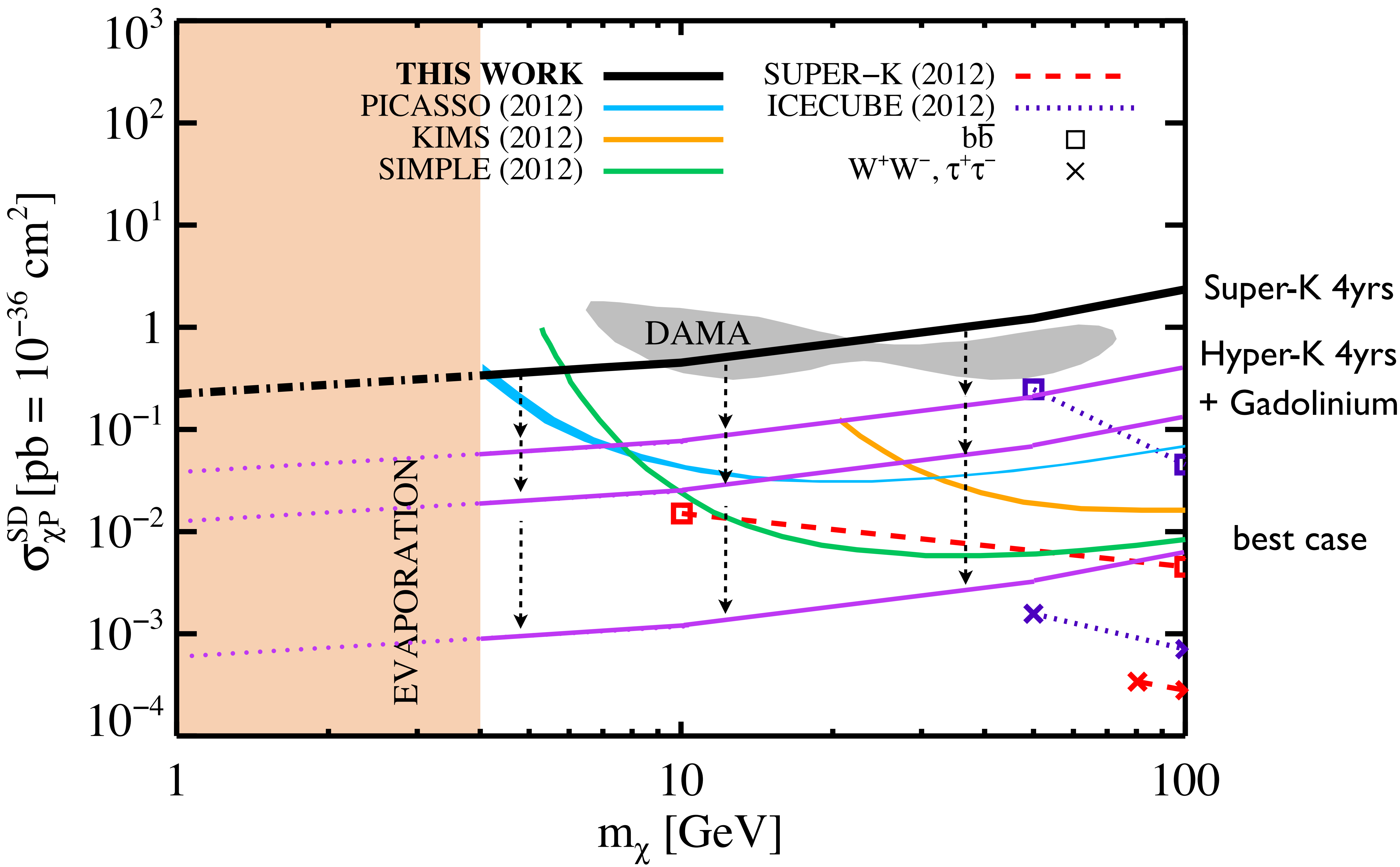


Why low-energy neutrinos

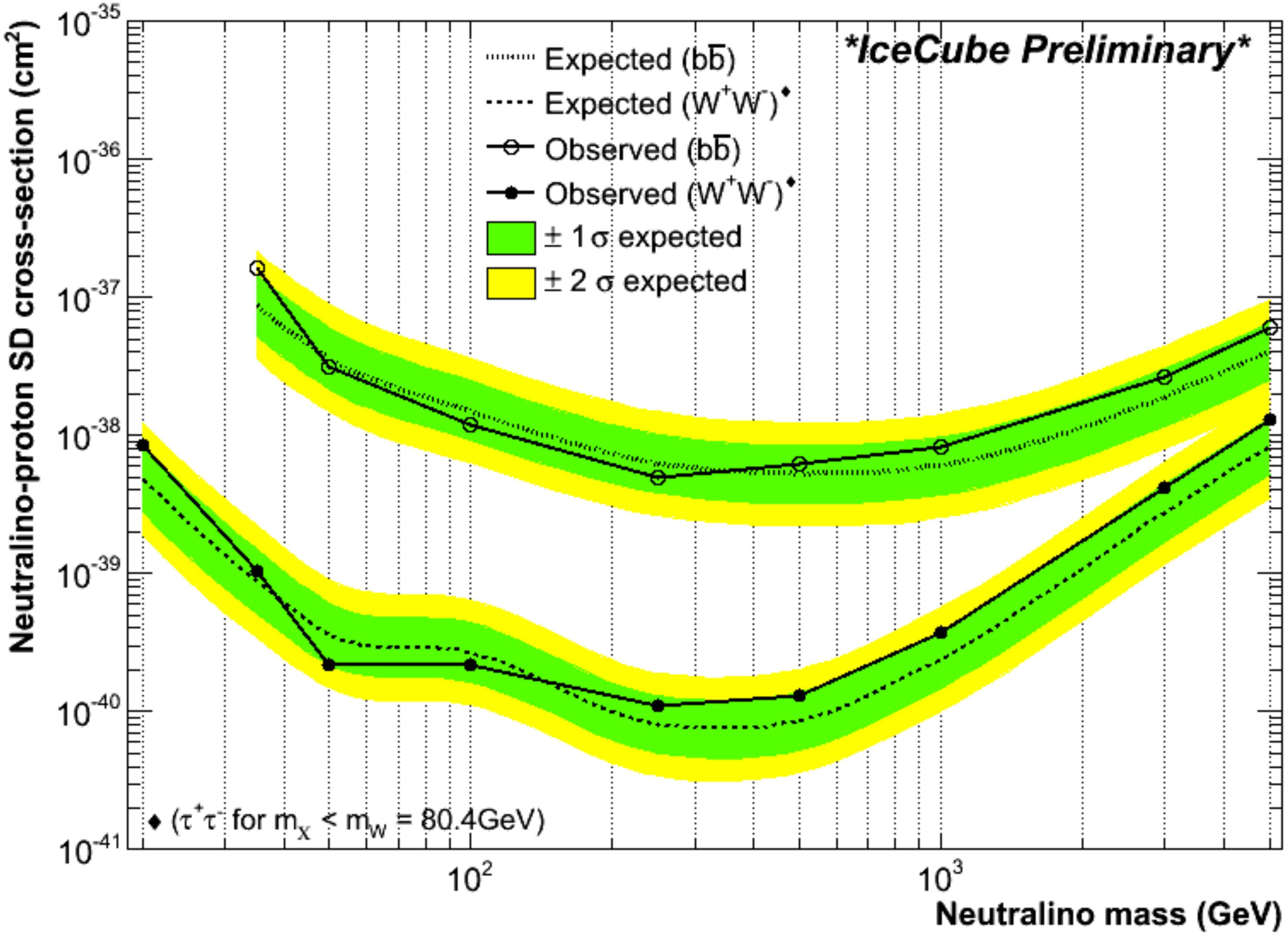
- Sensitivity is nearly flat as function of WIMP mass
  - Low-WIMP mass scenarios can be tested
- Low-energy neutrino flux is relatively independent of the mix of final states
- Sensitivity to scenarios in which no high energy neutrinos are produced
- Observation of a combination of low-energy and high-energy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

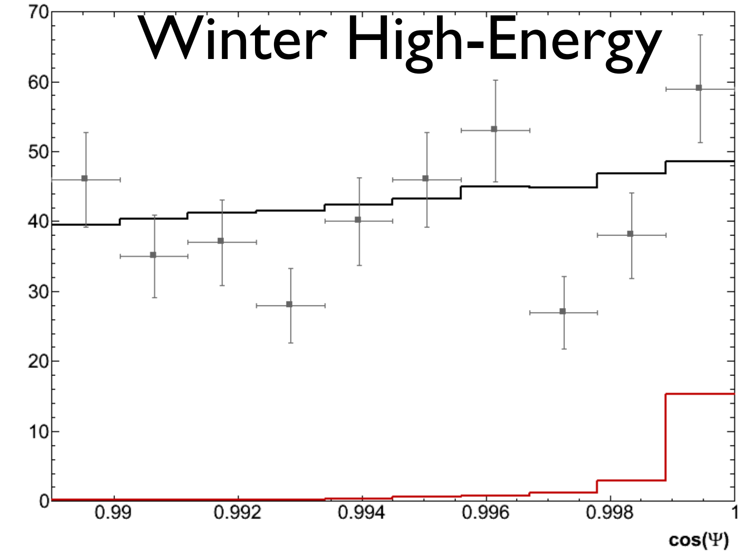
Conclusions

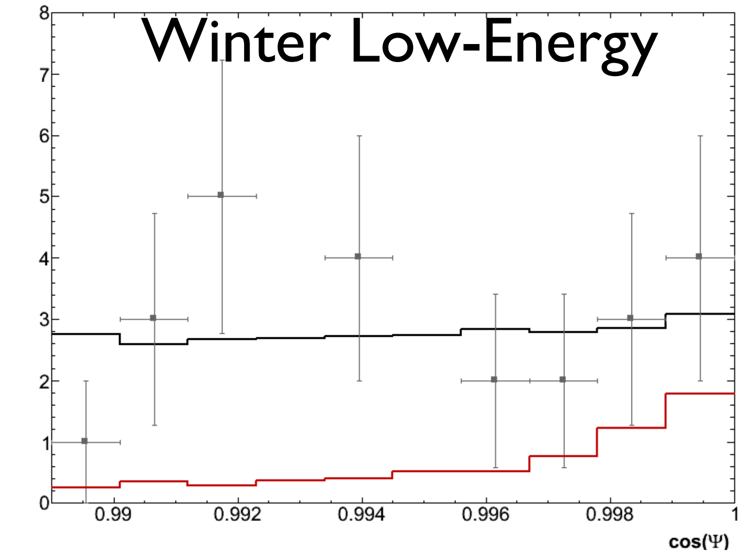
- Striking WIMP signatures provide high discovery potential for indirect searches
- Super-K and IceCube provide world best limits on the SD WIMP-Proton scattering cross section
- Neutrinos extremely sensitive to test low-mass WIMP scenarios at current and future detectors
- New detection channel with low-energy neutrinos offers additional discovery potential

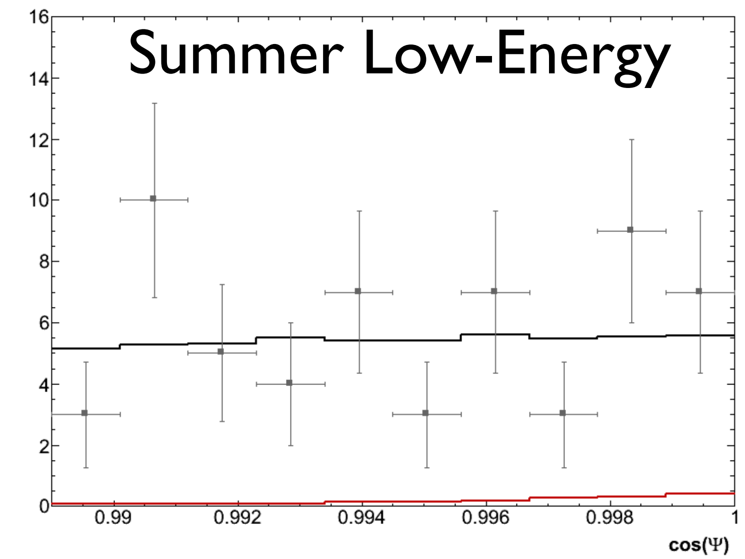
Backup

IceCube 79-strings result

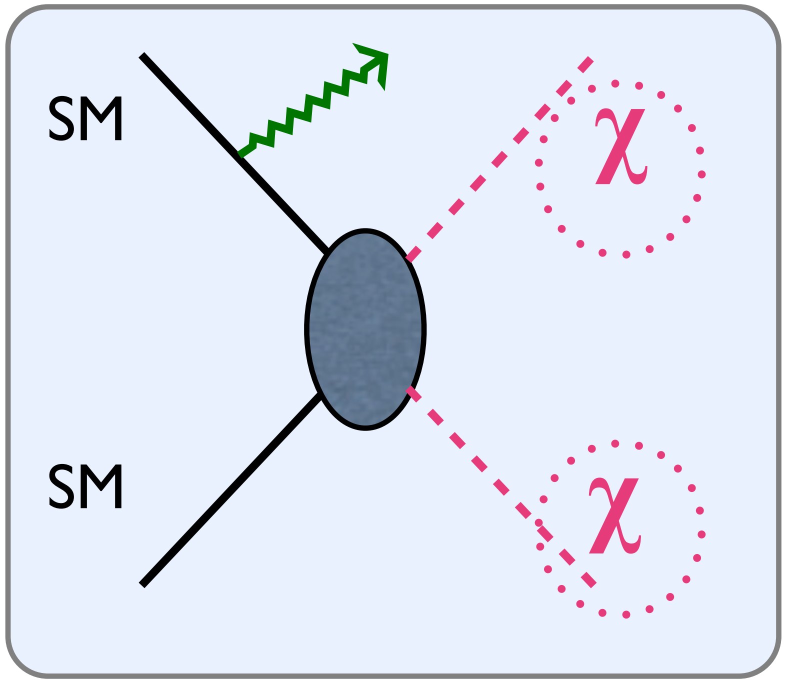






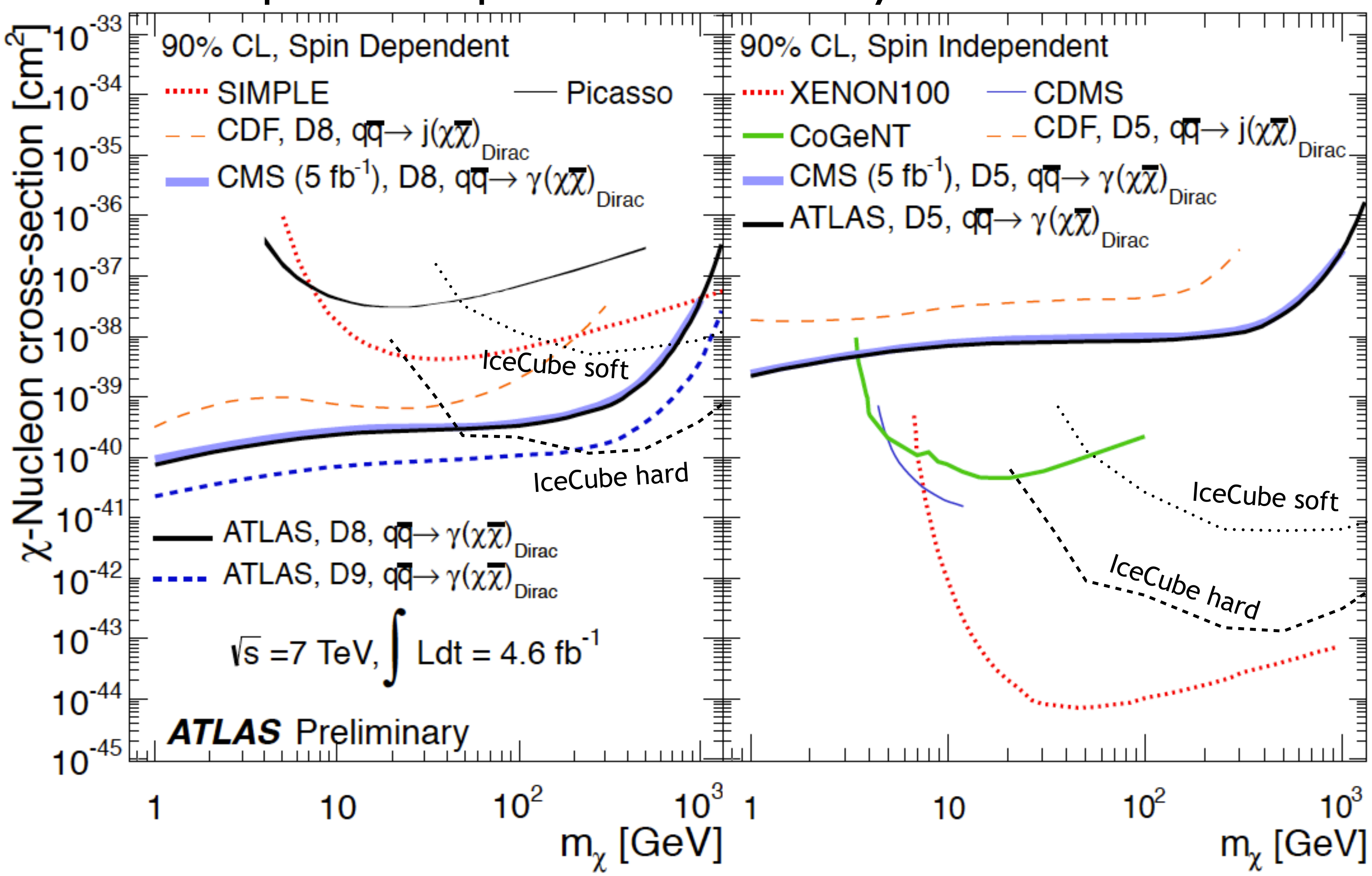


LHC - Indirect - Direct Connection



WIMPs at LHC:
WIMPs expected to interact with Standard Model (SM) particle via new interaction
Assume mediating particles too heavy to be produced directly
→ effective field theory (contact interaction)

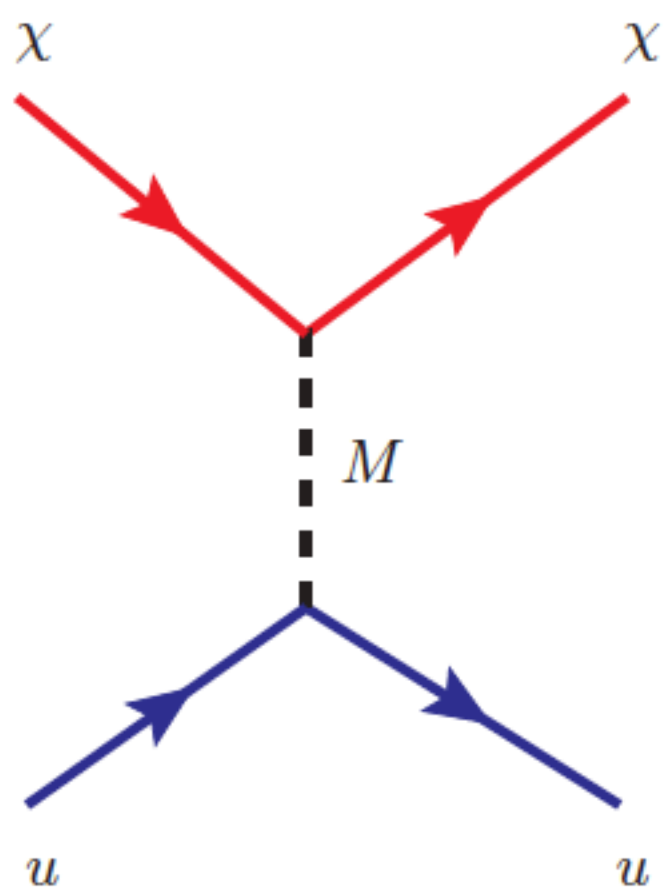
Example: mono-photon + E_T^{miss} analysis

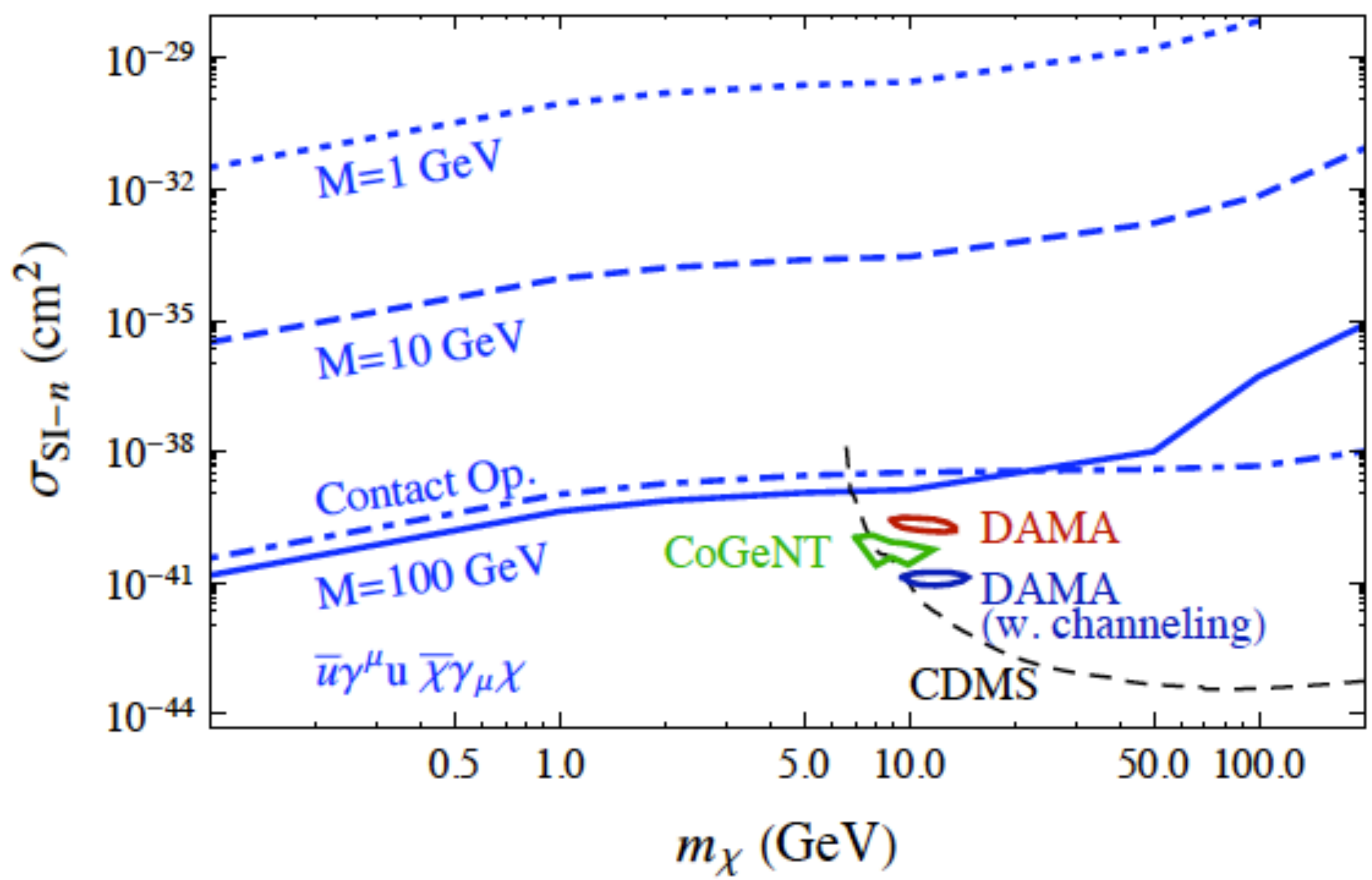


Observation of a indirect WIMP signal
→ combined with LHC search start probing underlying theory

Accelerator Bounds

Bai et.al. JHEP1012



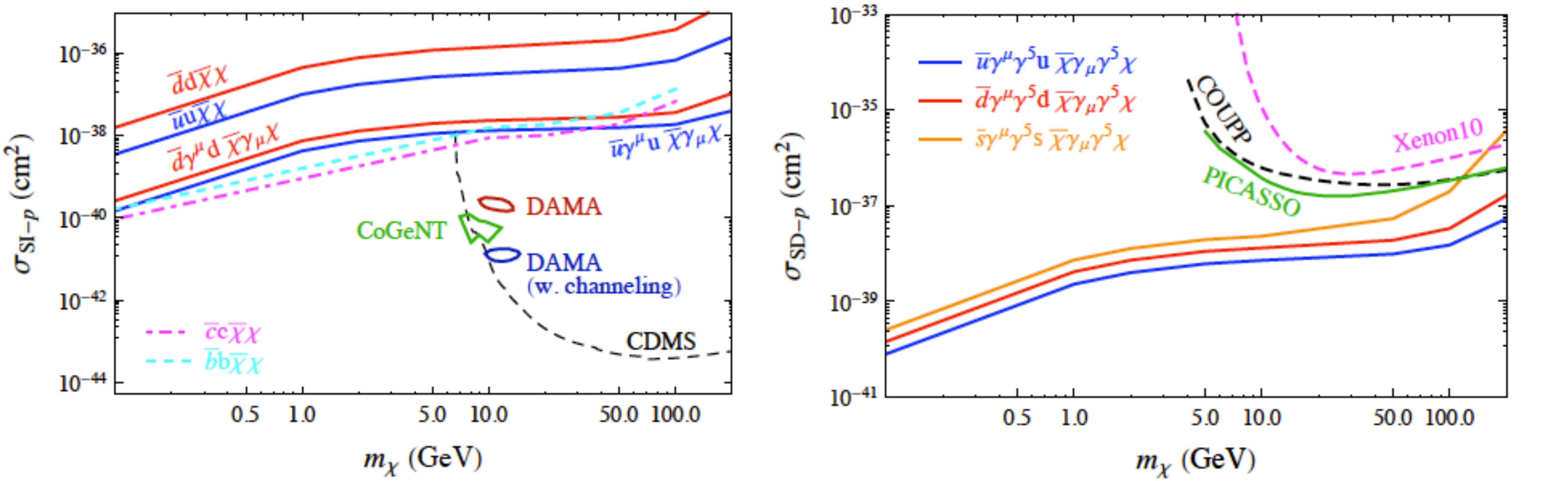


Direct detection enhanced over collider production if exchange has light mediator

M < p_T(1jet)

Accelerator Bounds - Monojets

Bai et.al. JHEP1012



Paper analyzed implications of CDF monojet search in "direct detection" plane