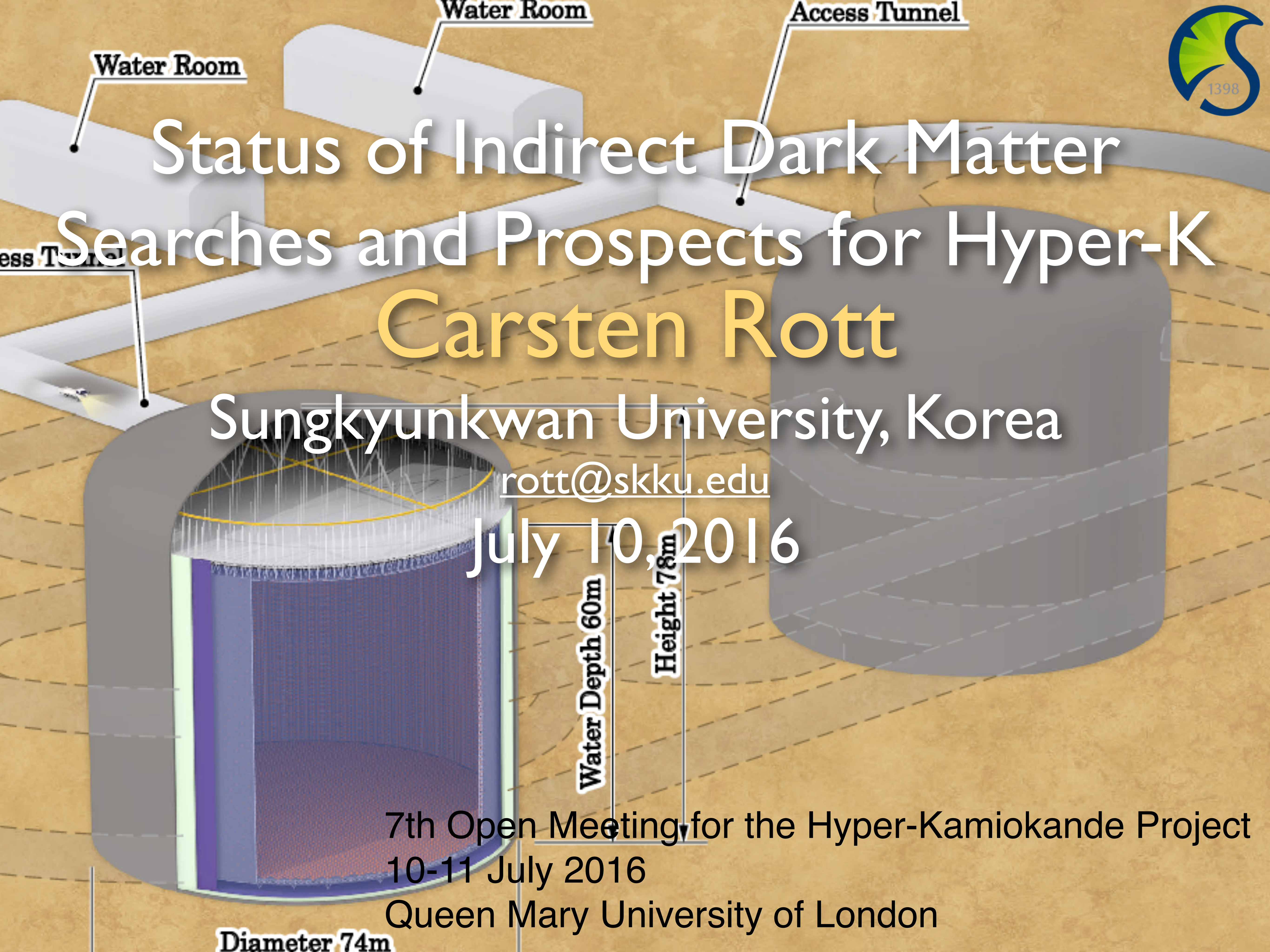

Status of Indirect Dark Matter Searches and Prospects for Hyper-K

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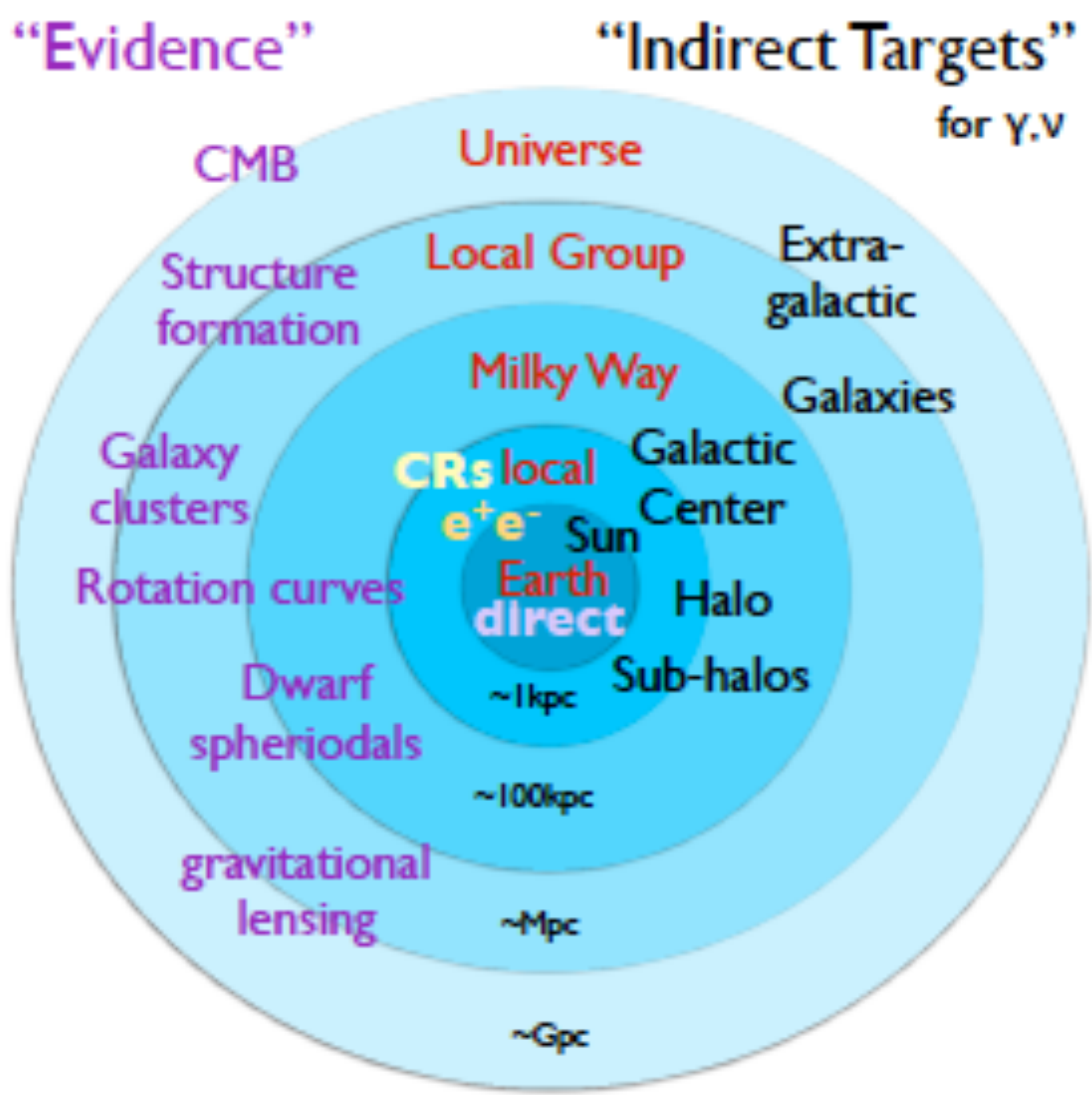
July 10, 2016

7th Open Meeting for the Hyper-Kamiokande Project
10-11 July 2016
Queen Mary University of London

Overview

- Motivation
- Dark Matter Search with Neutrinos
- Current Results and Sensitivities
  - Galactic Halo
  - Earth WIMPs
  - Solar WIMPs
- Conclusions

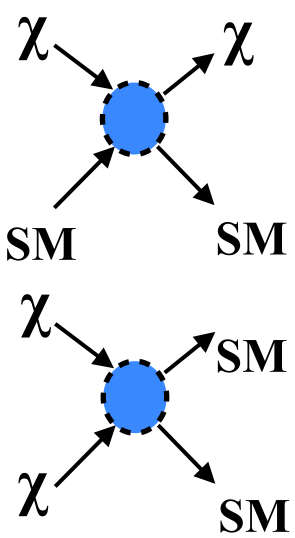
Motivation



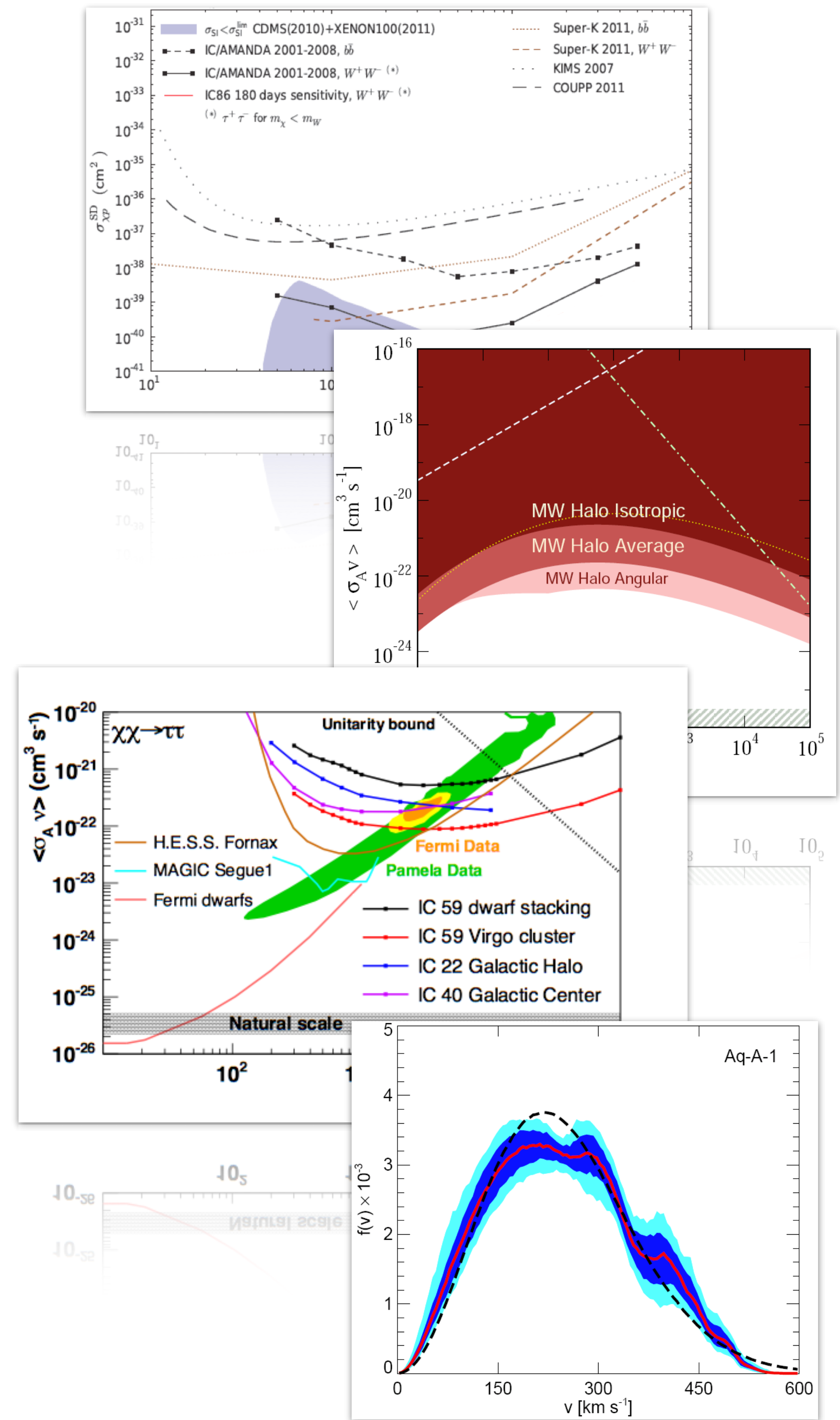
- Strong Evidence for Dark Matter
  - Structure formations - Cosmological simulations
  - Gravitational lensing
  - Rotation curves
  - Cosmic microwave background
  - ...

- Dark Matter already gravitationally "observed", but ...
  - What is it ?
  - What are it's properties ?

Motivation

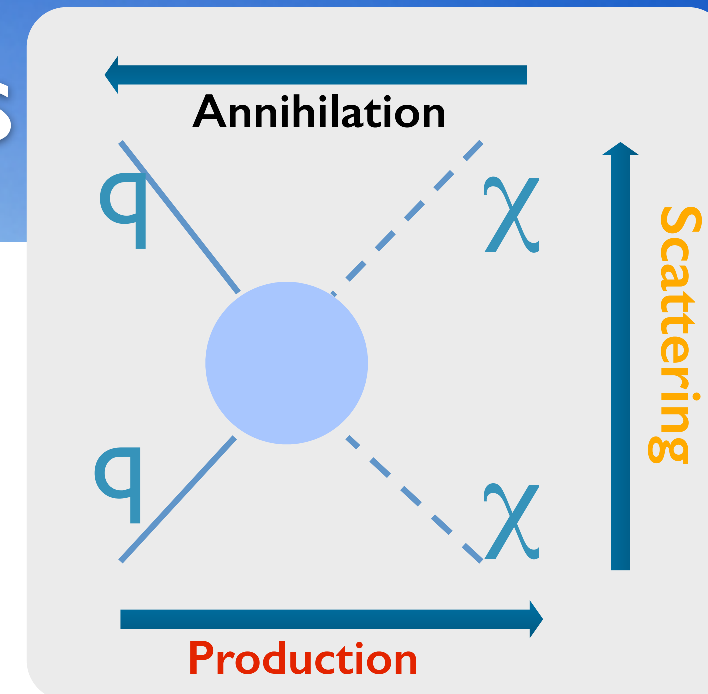


- Neutrino detectors are extremely competitive for probing WIMP Nucleon scattering cross section
- Neutrino signals can be used to set a conservative limit on the total dark matter self-annihilation cross section
- Neutrino signals have been able to test "claims" from other indirect channels or direct detection
  - Positron fraction (PAMELA, AMS-02, Fermi, ...)
  - DAMA/Libra
- Complementary to direct detection, different dependence on astrophysical uncertainties

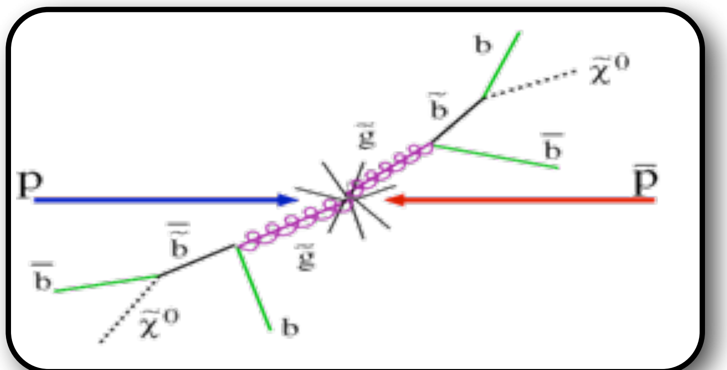


Dark Matter Searches with Neutrinos

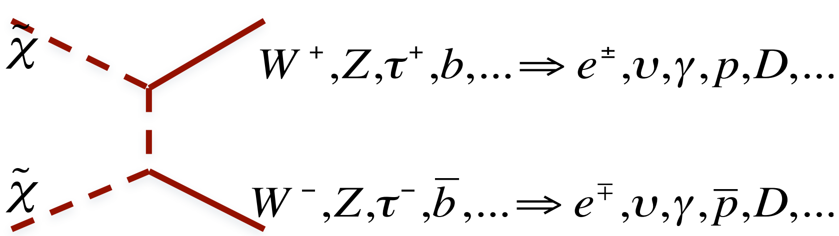
Role of Neutrinos

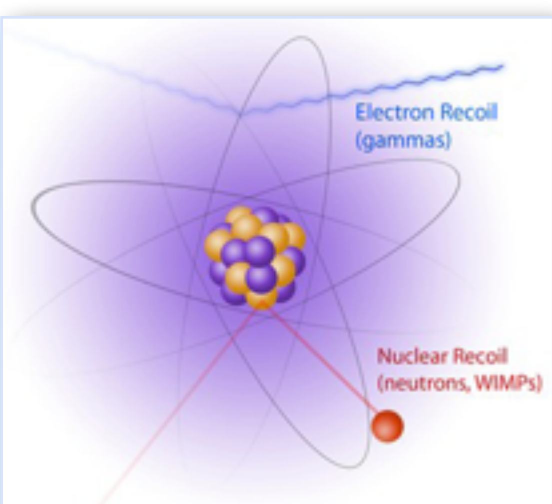


WIMP - Weakly Interacting Massive Particle



- **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





WIMP Self-annihilation cross section

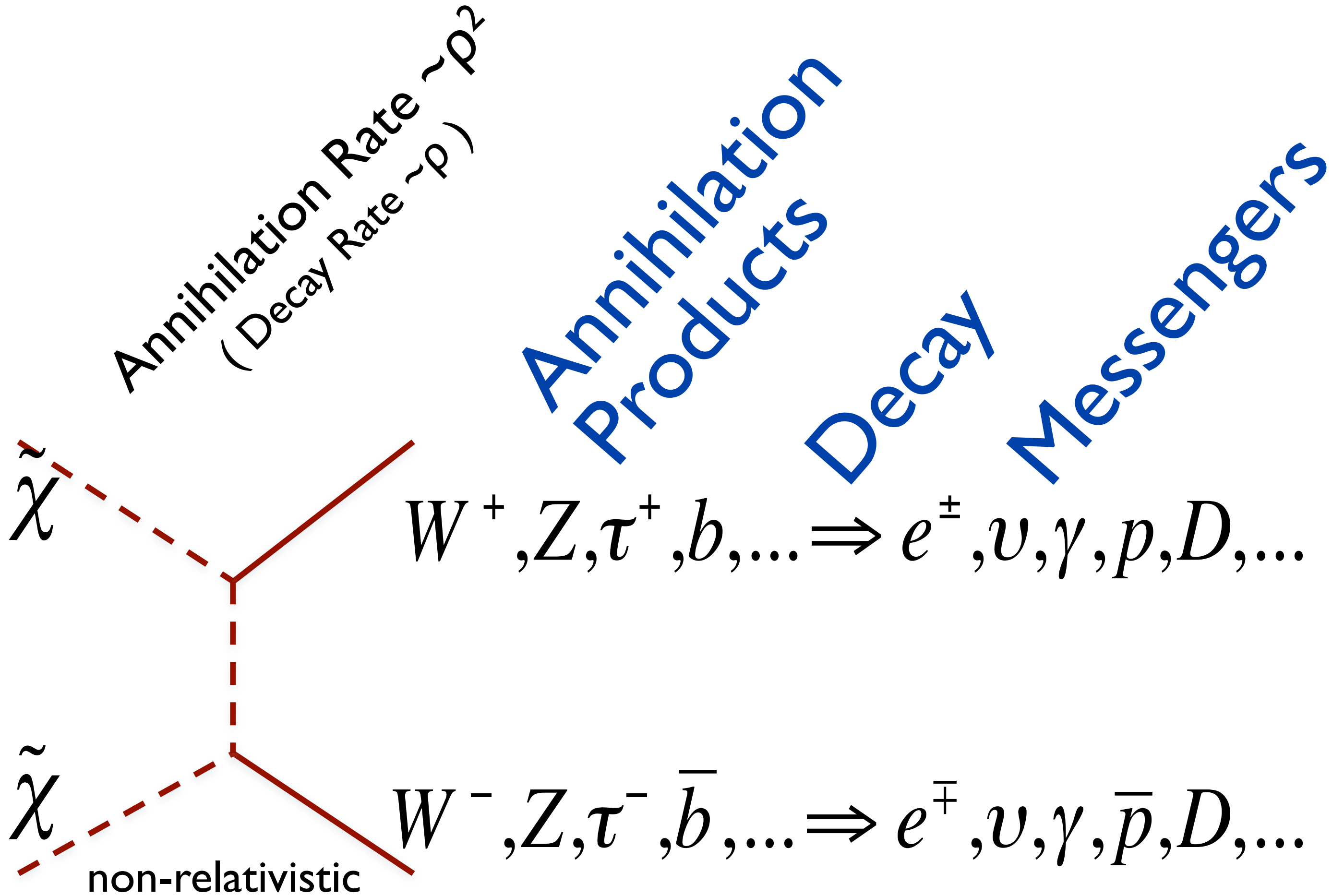
WIMP-Nucleon Scattering cross section

Dark Matter Annihilation Signals

- Identify overdense regions of dark matter

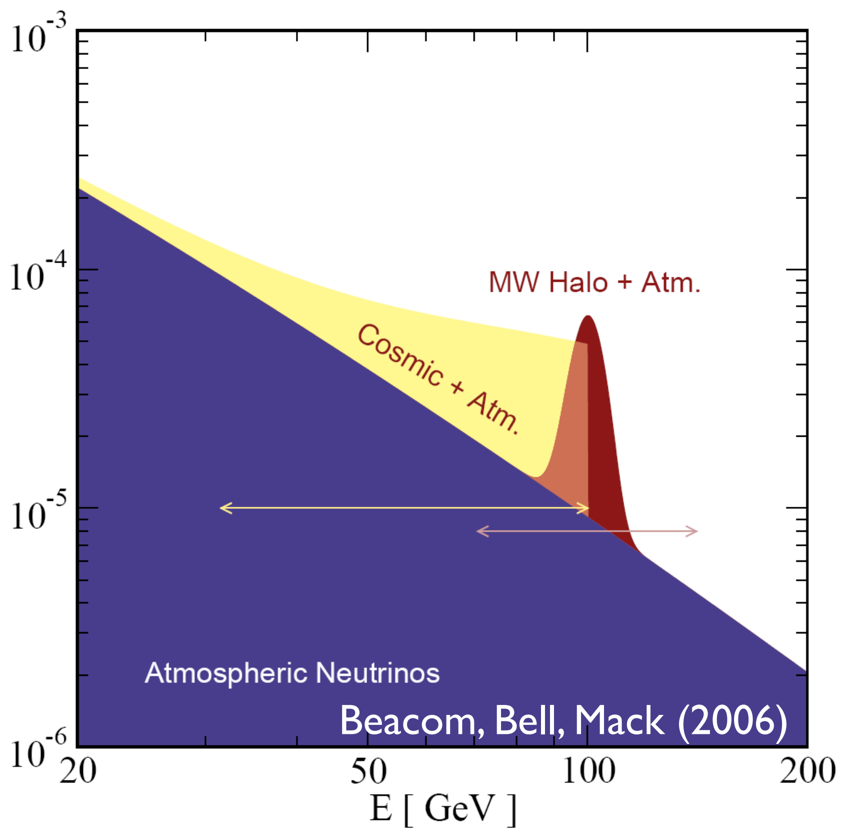
  ⇒self-annihilation can occur at significant rates

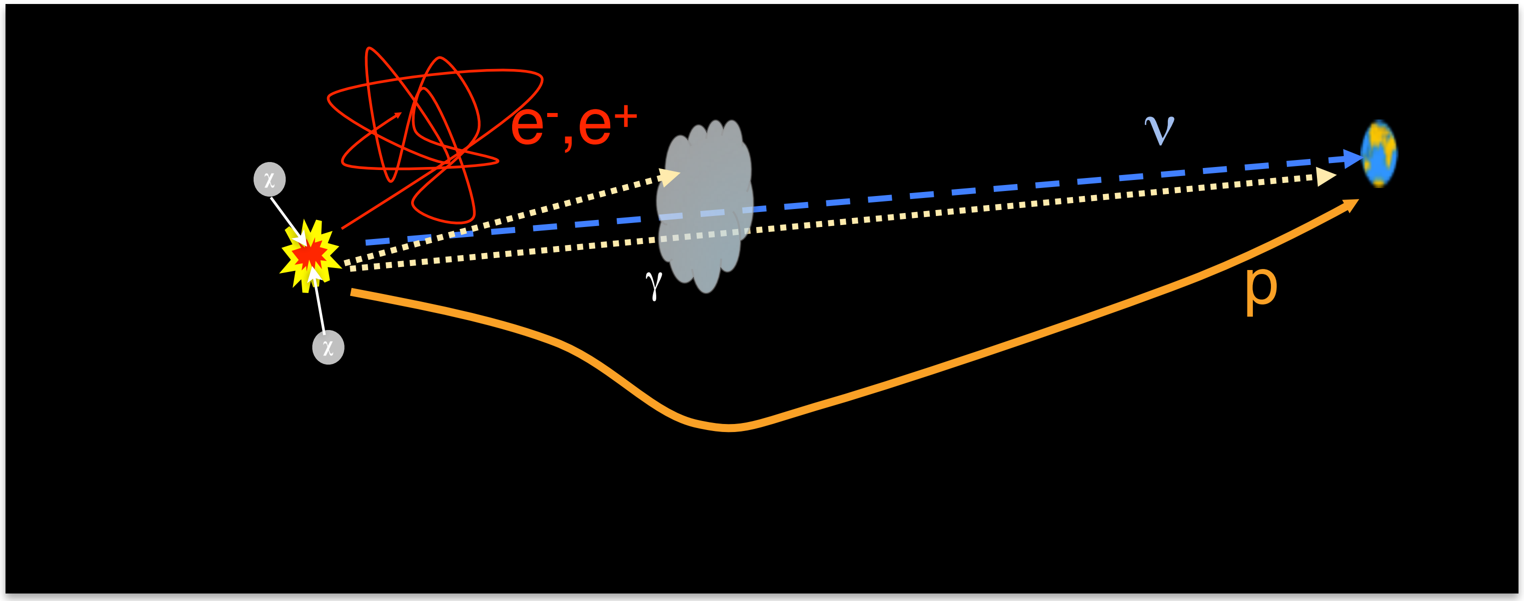
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds



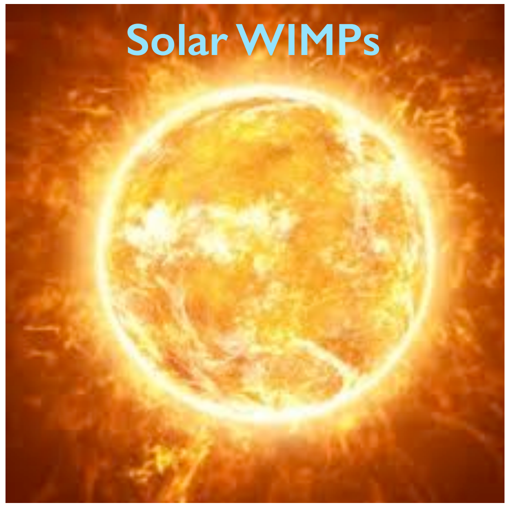
$\tilde{\chi}$ $W^{+}, Z, \tau^{+}, b, \ldots \Rightarrow e^{\pm}, \upsilon, \gamma, p, D, \ldots$

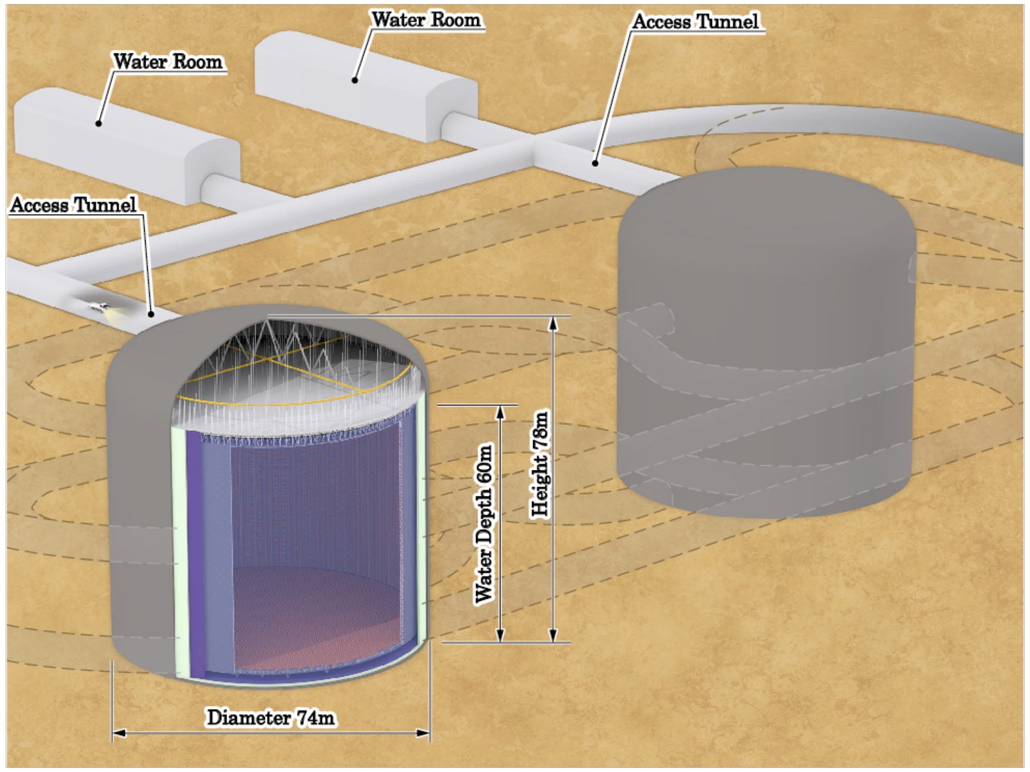
$\tilde{\chi}$ $W^{-}, Z, \tau^{-}, \bar{b}, \ldots \Rightarrow e^{\mp}, \upsilon, \gamma, \bar{p}, D, \ldots$

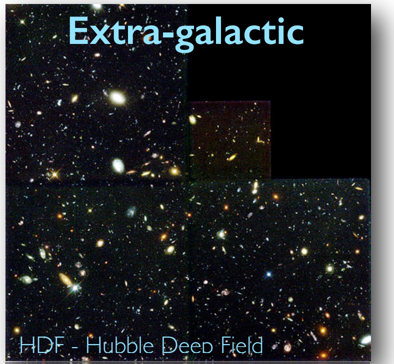


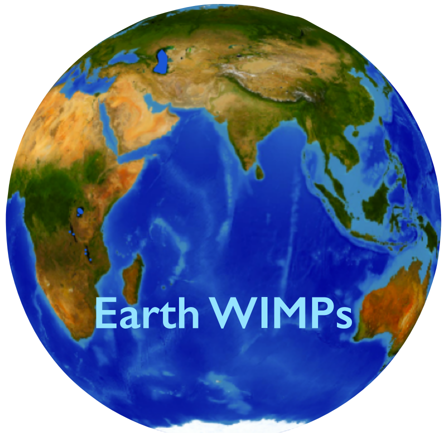


Dark Matter Signals at Hyper-K

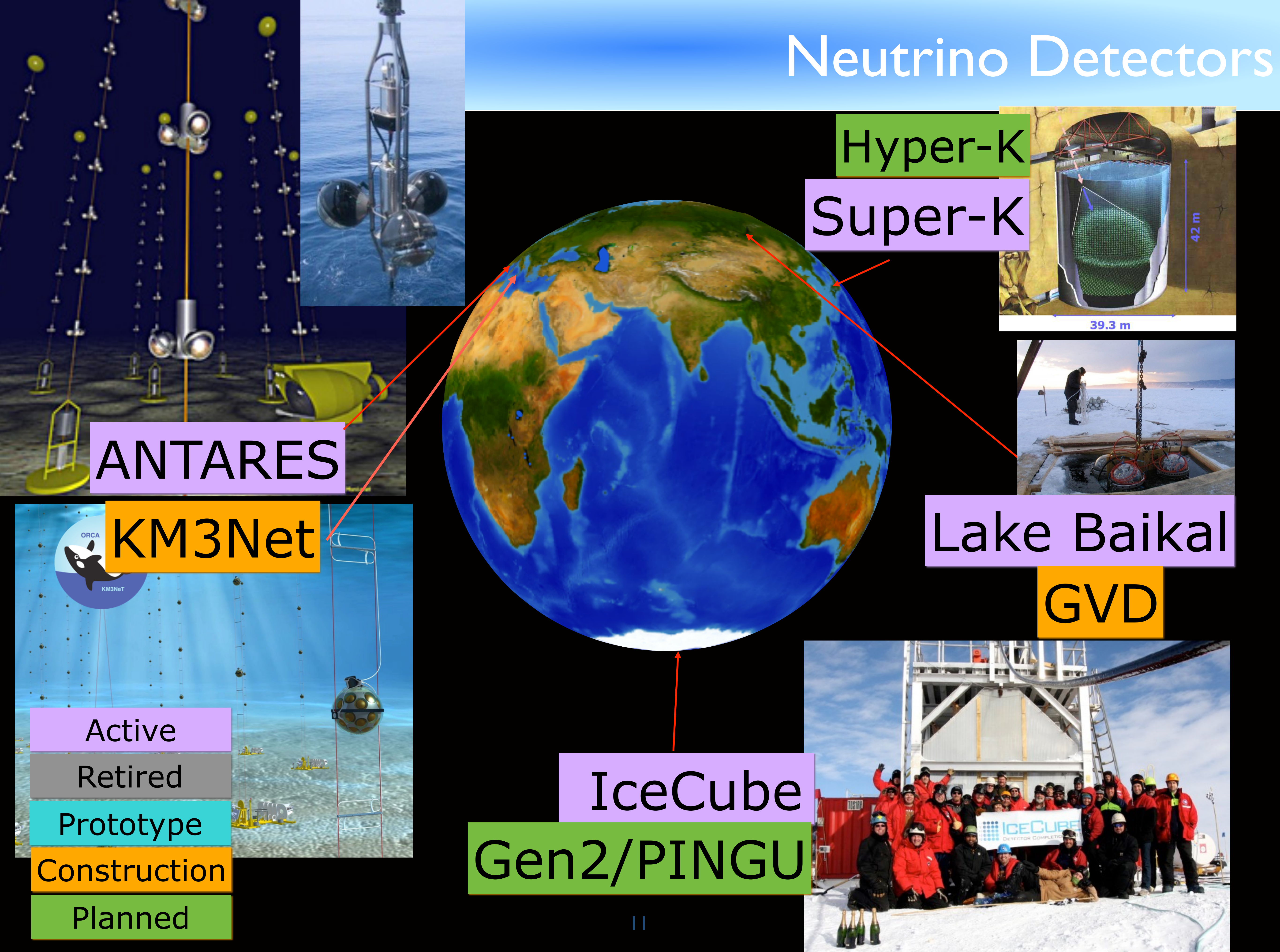






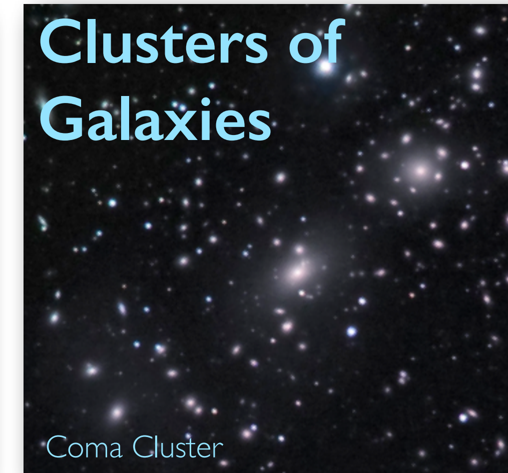


Current Results and Sensitivity Estimates


Neutrino Detectors
Hyper-K
Super-K
42 m
39.3 m
ANTARES
KM3Net
ORCA
KM3NeT
Lake Baikal
GVD
IceCube
Gen2/PINGU
ICECUBE
Active
Retired
Prototype
Construction
Planned

Galactic Halo / Galactic Centre

Sources



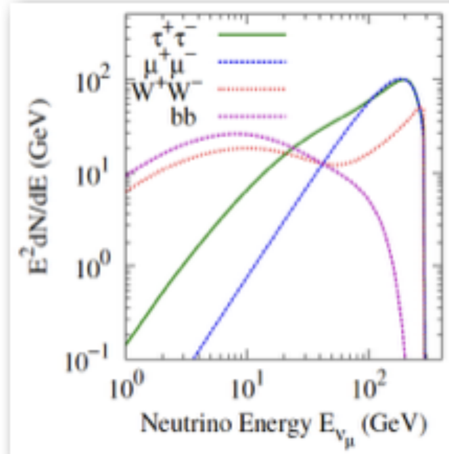
Extra-galactic	Milky Way Halo	Galactic Center	Dwarf Spheroidal	Clusters of Galaxies
small halo model dependence, boost factors	Large DM content, nearby source, O(10) larger flux than extra-galactic	Very dense DM accumulation, nearby source	no astrophysical backgrounds	large DM content, high boost factors from sub structure
Diffuse flux, spectral feature	Anisotropy	Extended Source	Point source	Extended source
signal weak compared to Galactic signal	relatively independent from DM halo profile	very strong dependence on DM density profile	cored profiles favored, less flux	understanding of boost factors

Dark Matter Halo Analyses

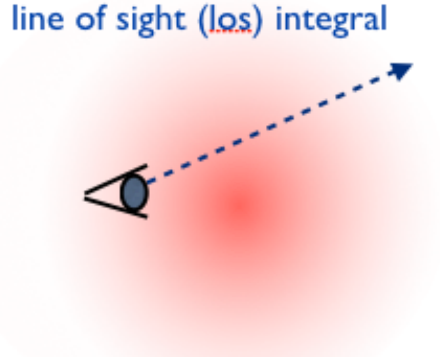
IceCube Collaboration arXiv:1606.00209v1

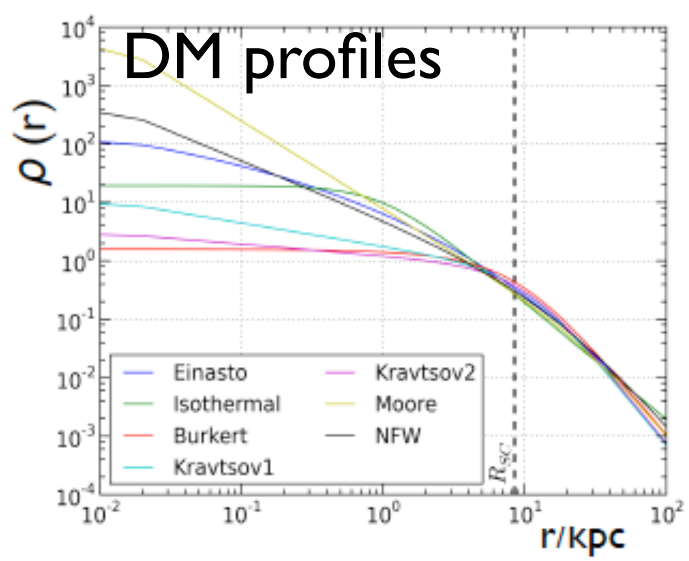
Measure Flux = Particle Physics × Dark Matter Distribution

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



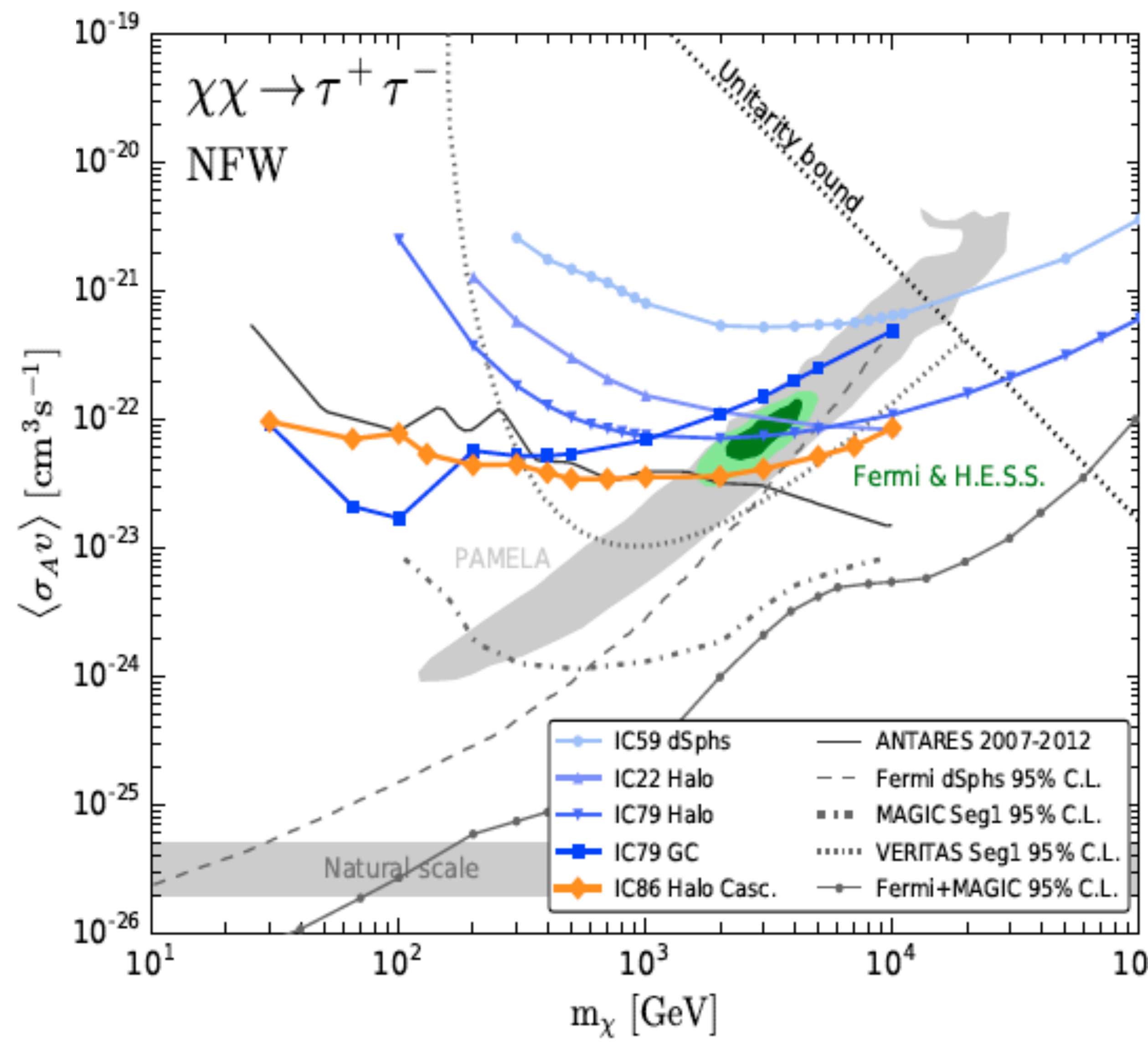
line of sight (los) integral





Models motivated by increase in positron fraction can be tested

- IceCube: GC above horizon
- ANTARES: ~60% of time below horizon
- Super-K extending to 1GeV in m_χ



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Measure Flux

Particle Physics

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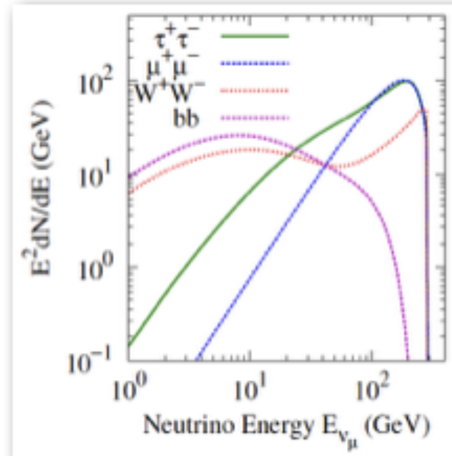
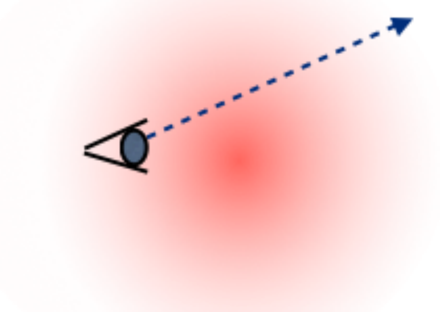


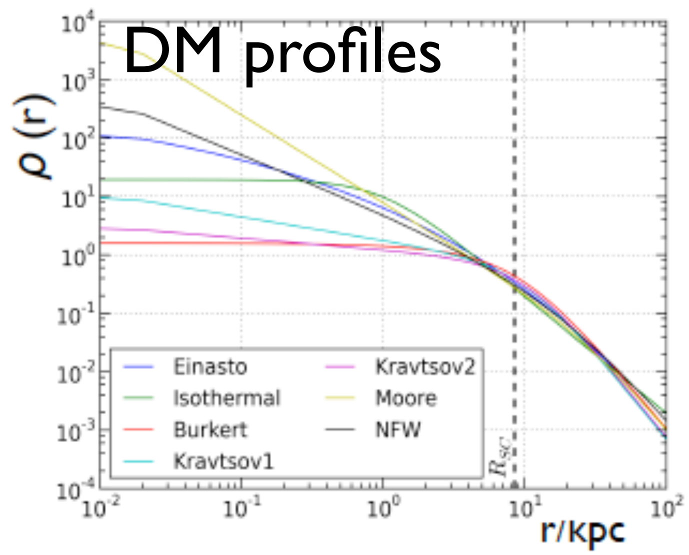
x

Dark Matter Distribution

line of sight (los) integral



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



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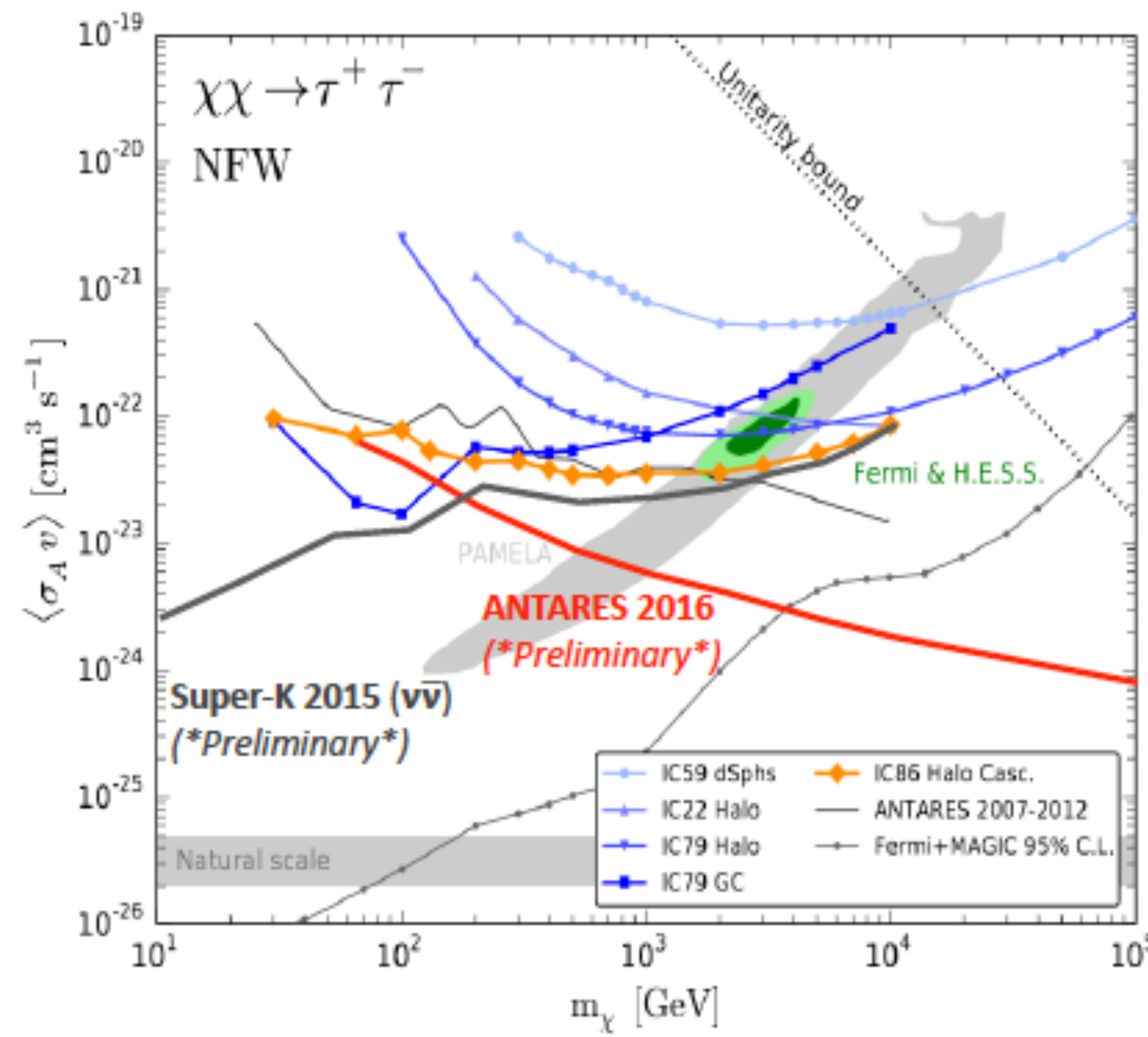

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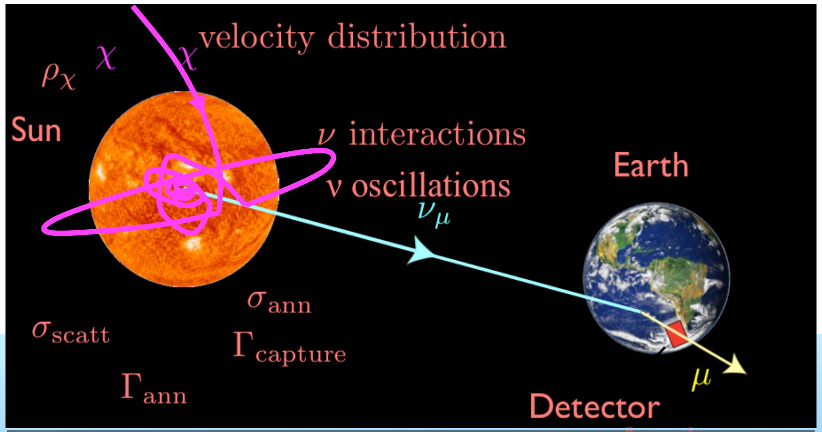
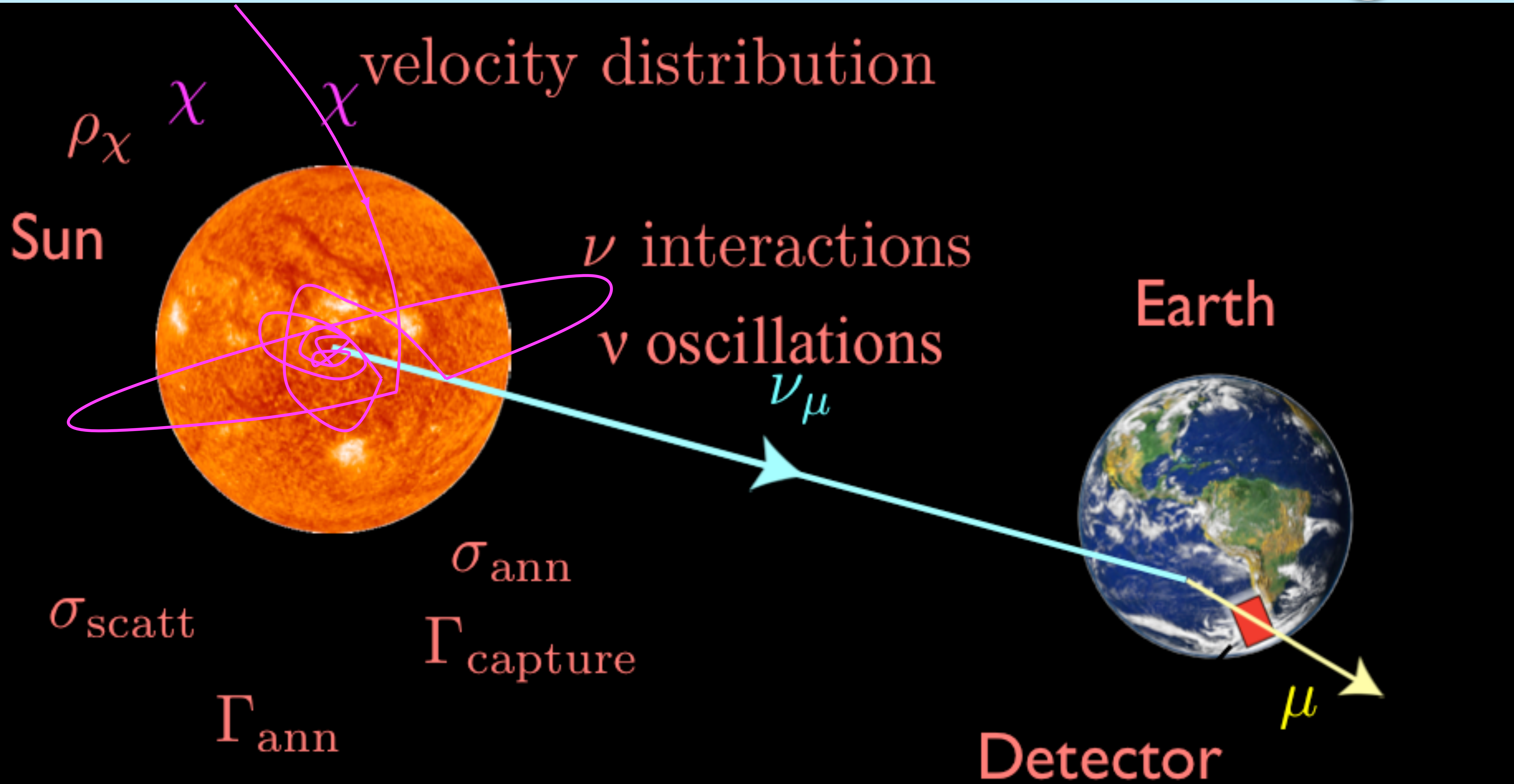

velocity distribution
ρ_χ
χ
χ
Sun
ν interactions
ν oscillations
Earth
ν_μ
$\sigma_{\rm ann}$
$\sigma_{\rm scatt}$
$\Gamma_{\rm capture}$
$\Gamma_{\rm ann}$
μ
Detector

Solar WIMPs

Solar WIMP Signal



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

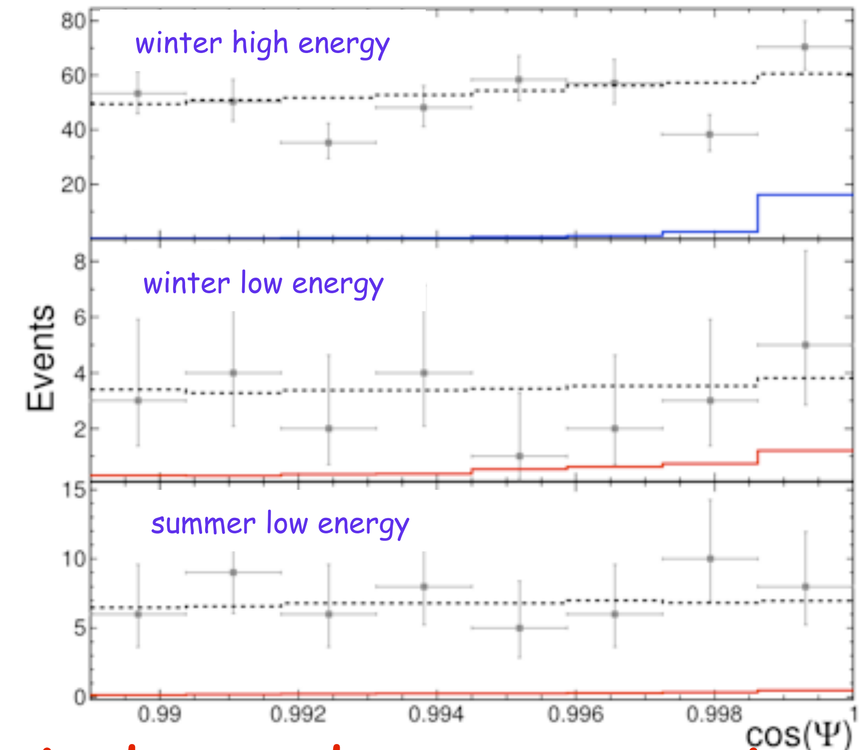
Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

IceCube Solar WIMP Limits

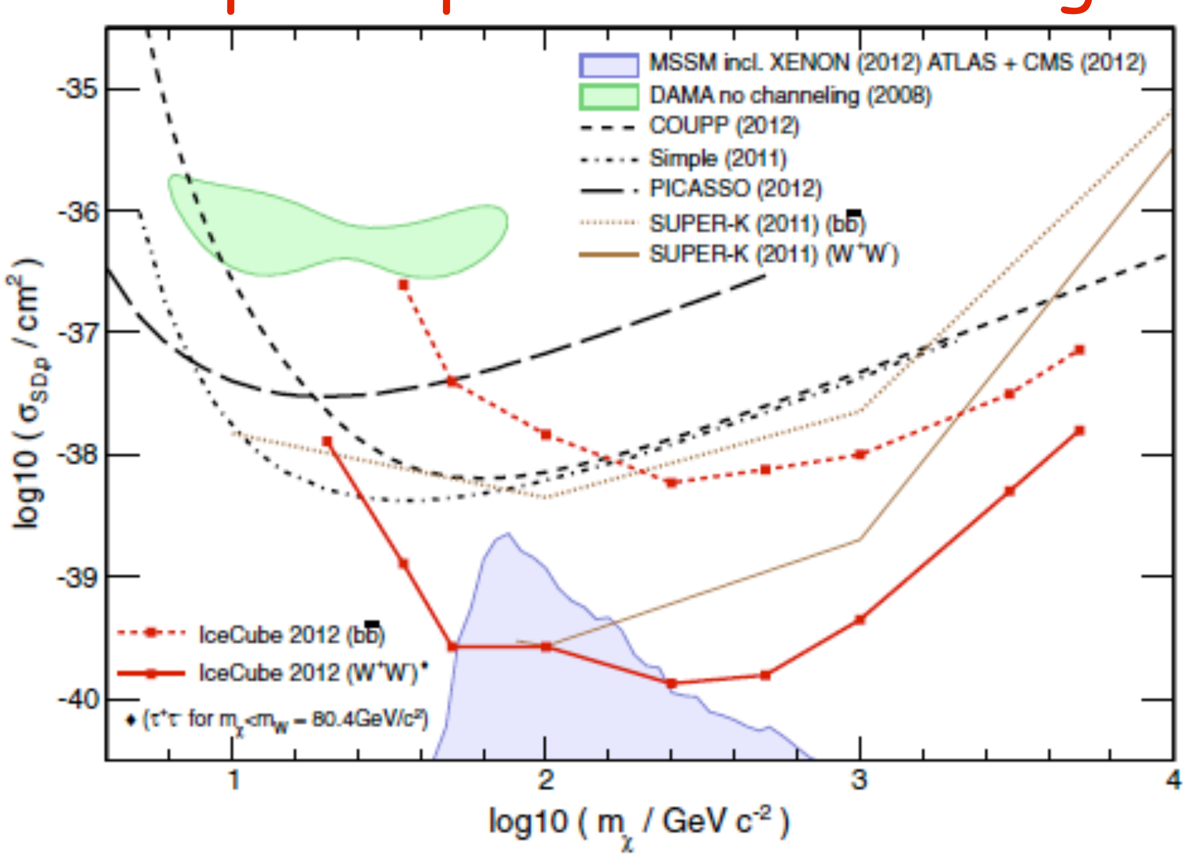
PRL 110, 131302 (2013)

- 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

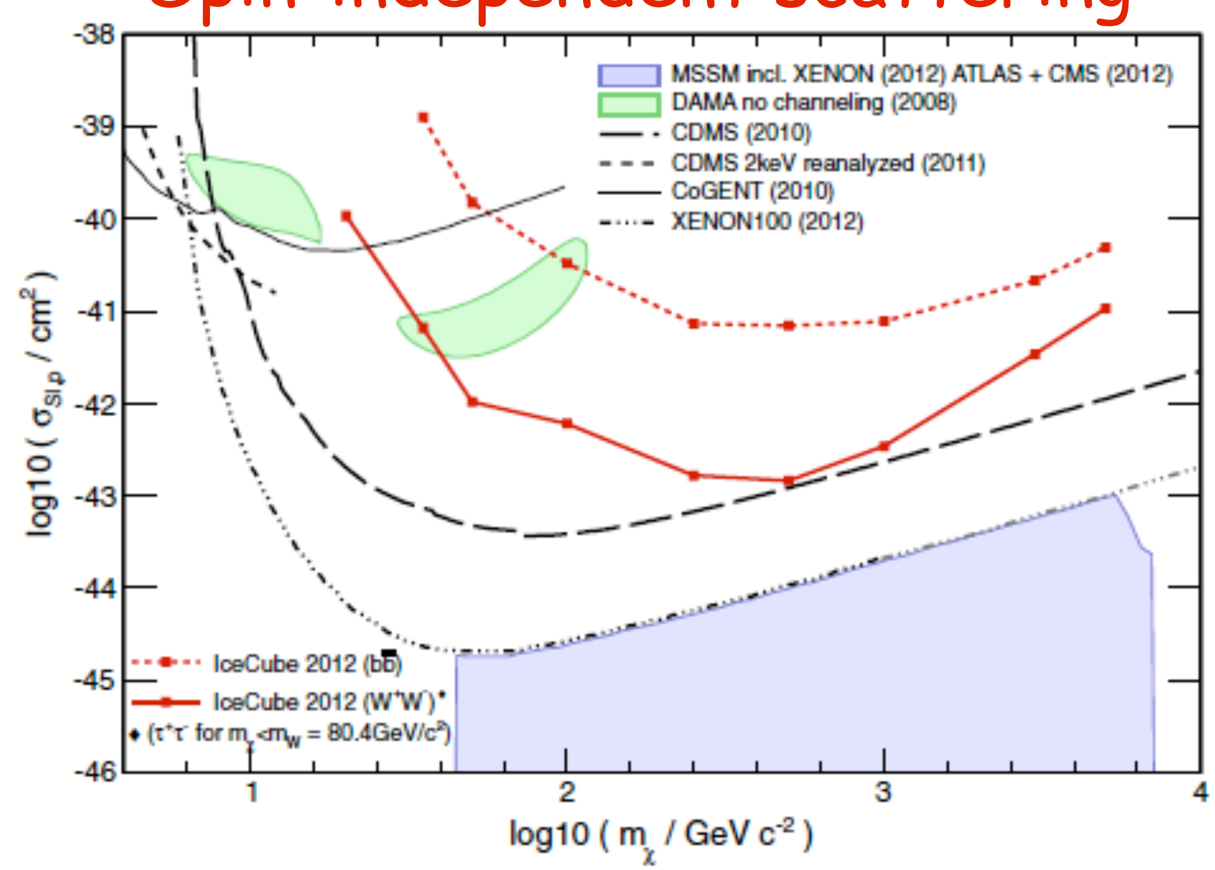
Observed events



Spin-dependent scattering



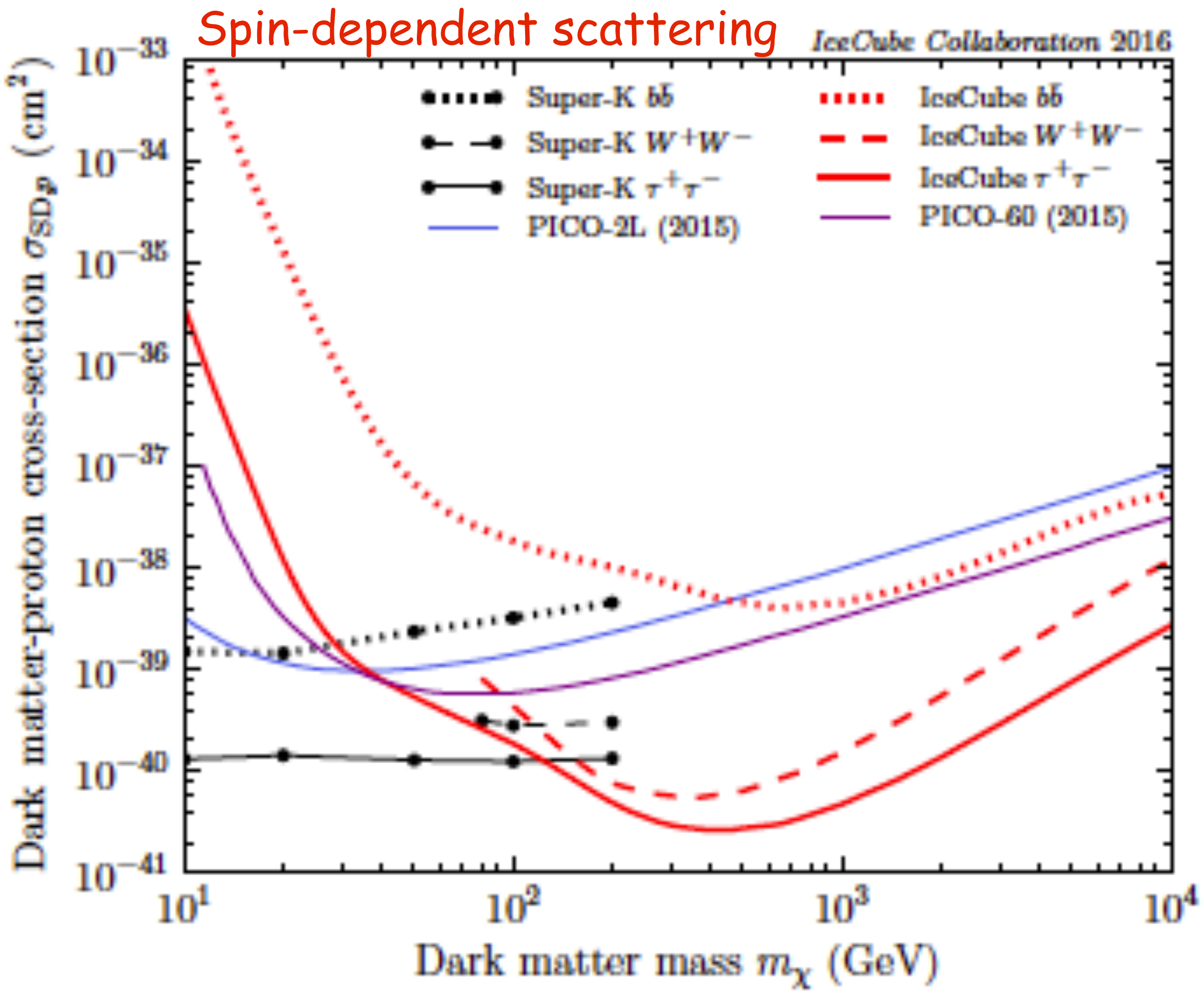
Spin-independent scattering

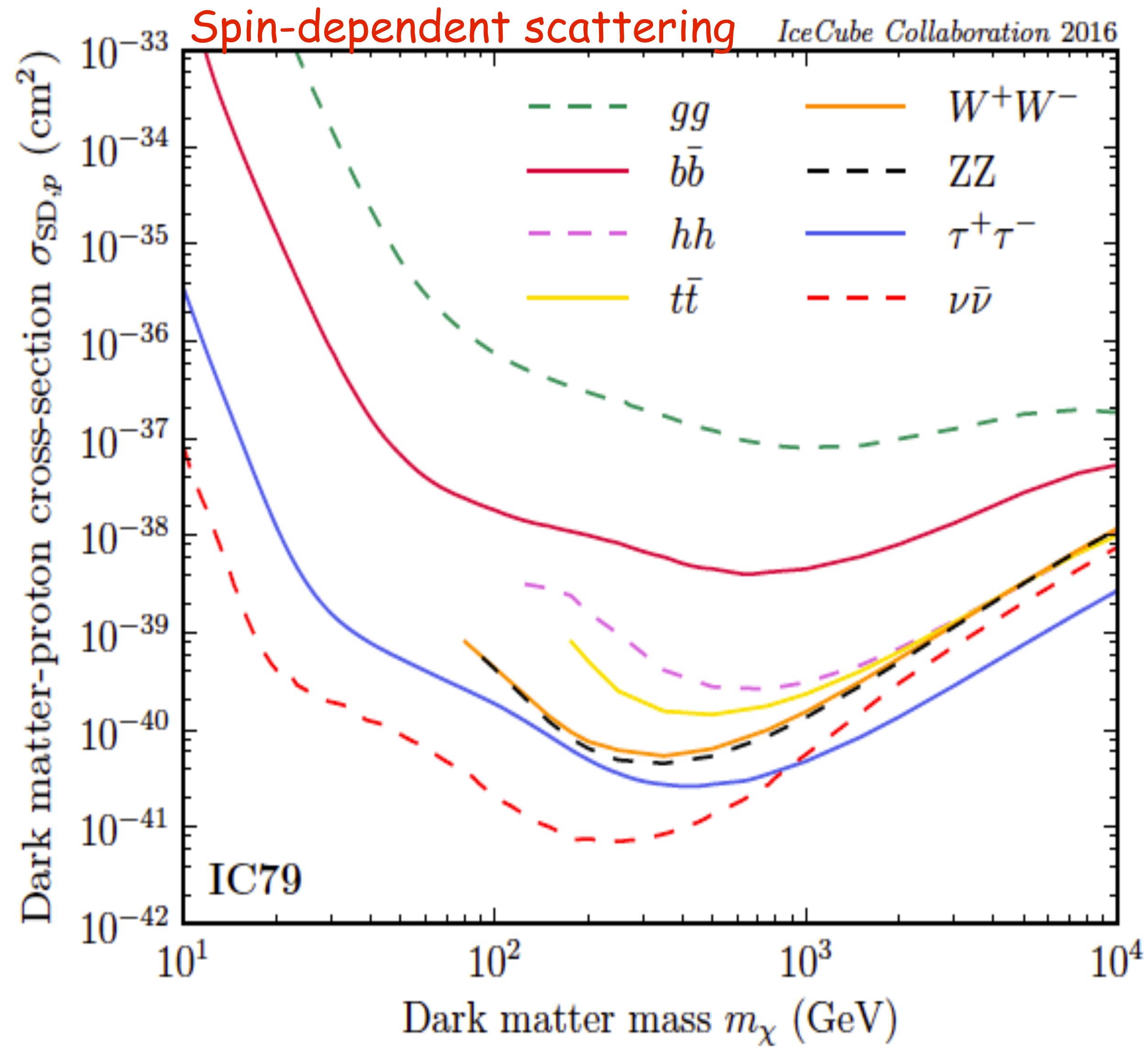


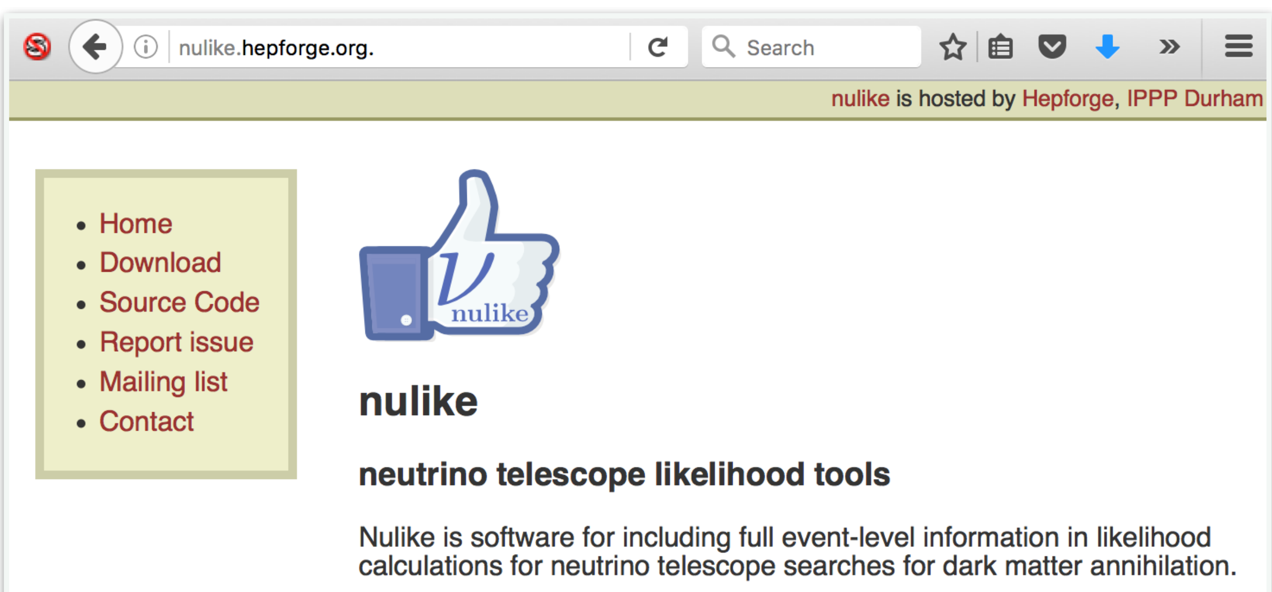
Improved Solar WIMP Bounds

http://nulike.hepforge.org./

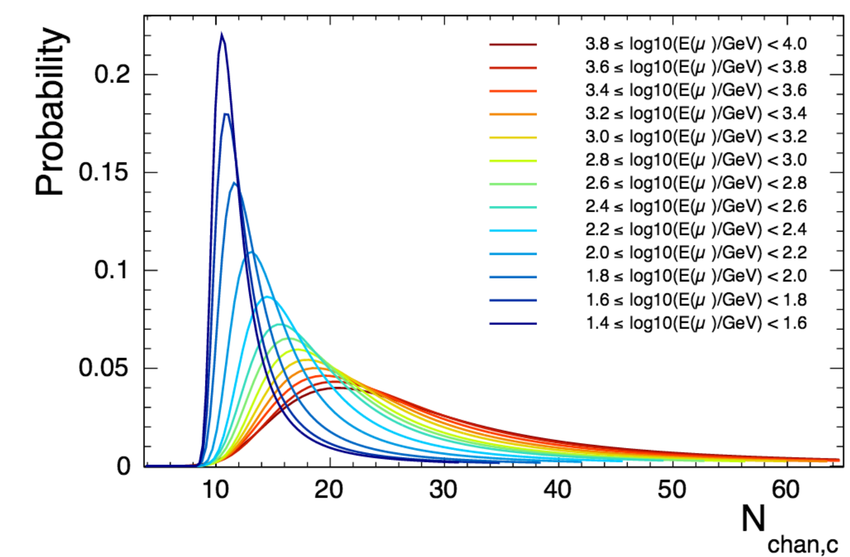
JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf



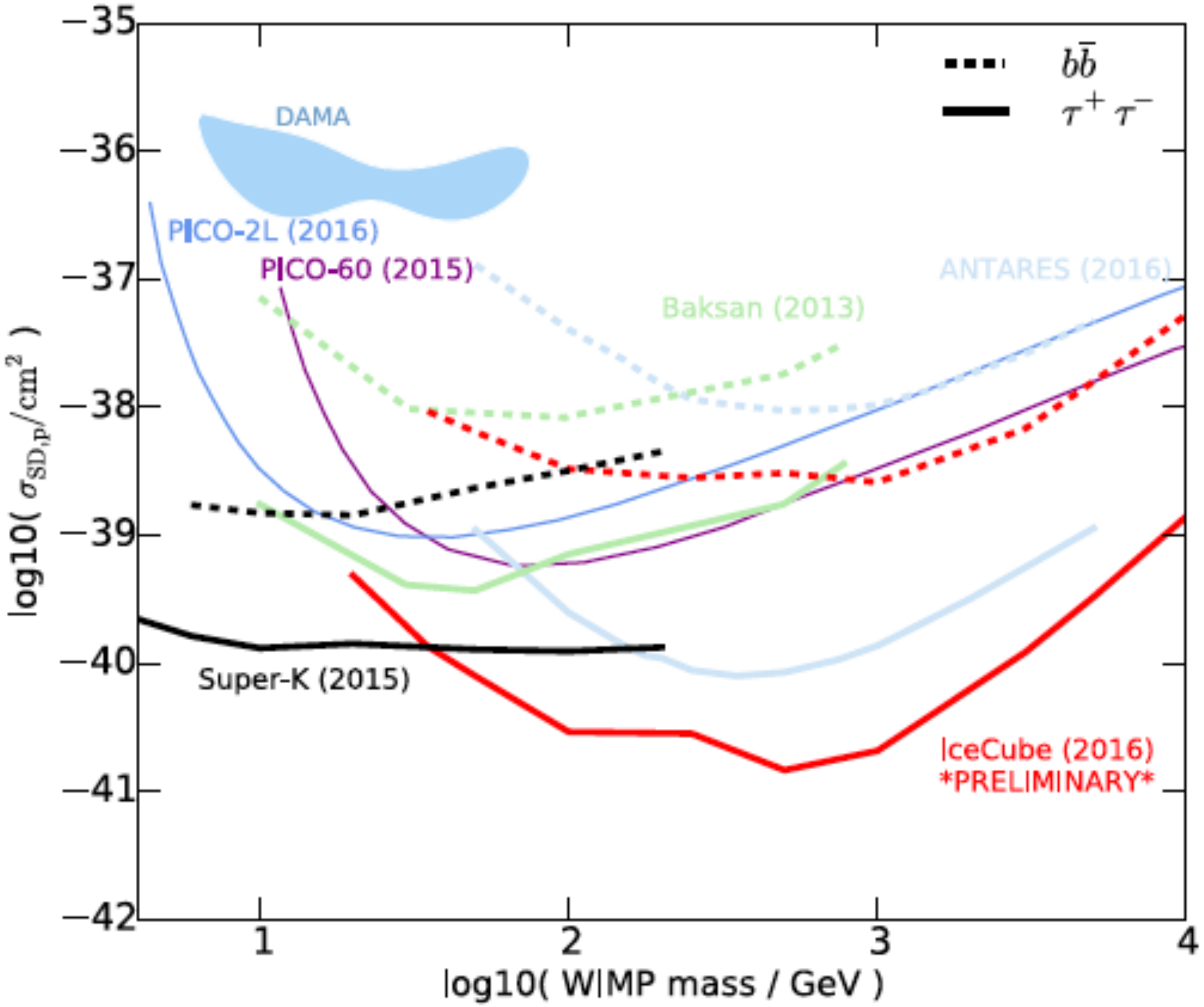




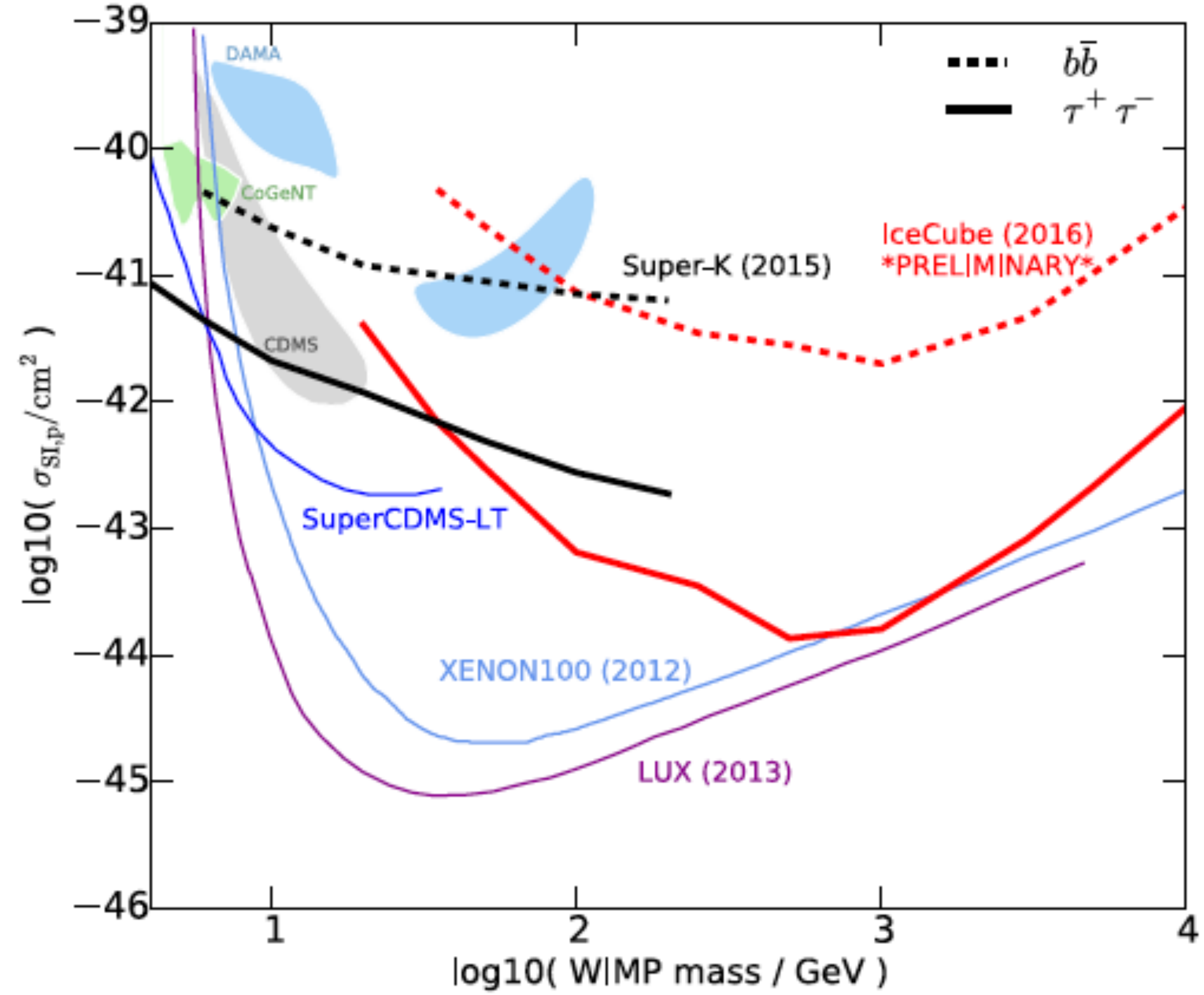
- Likelihood includes:
  - energy and directional information



Spin-dependent scattering

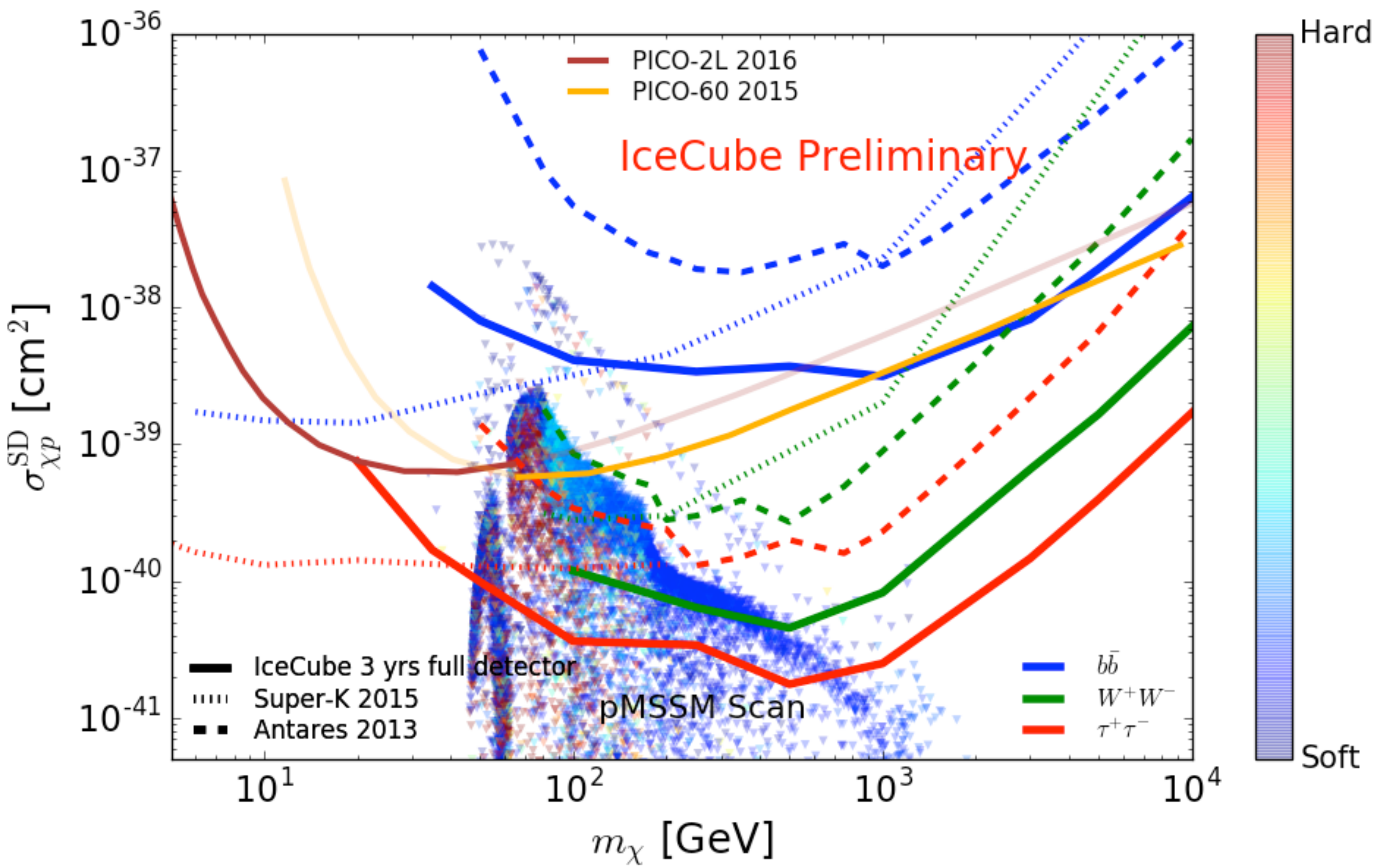


Spin-independent scattering



Solar WIMPs (Spin-dependent)

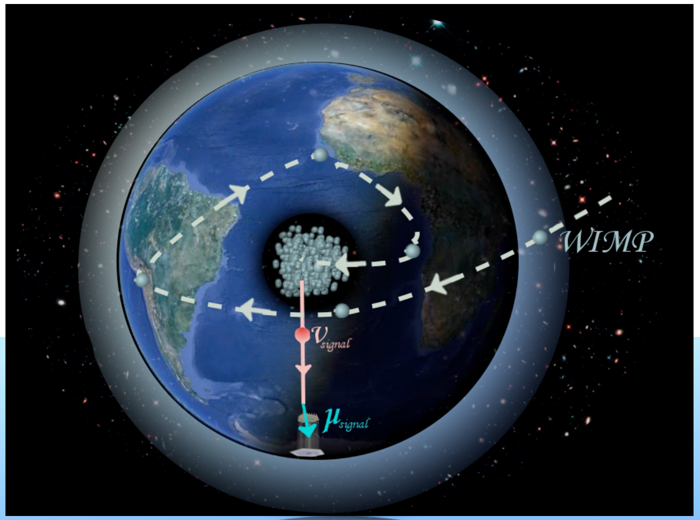
update from IceCubeColl., PoS(ICRC2015) 1099



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

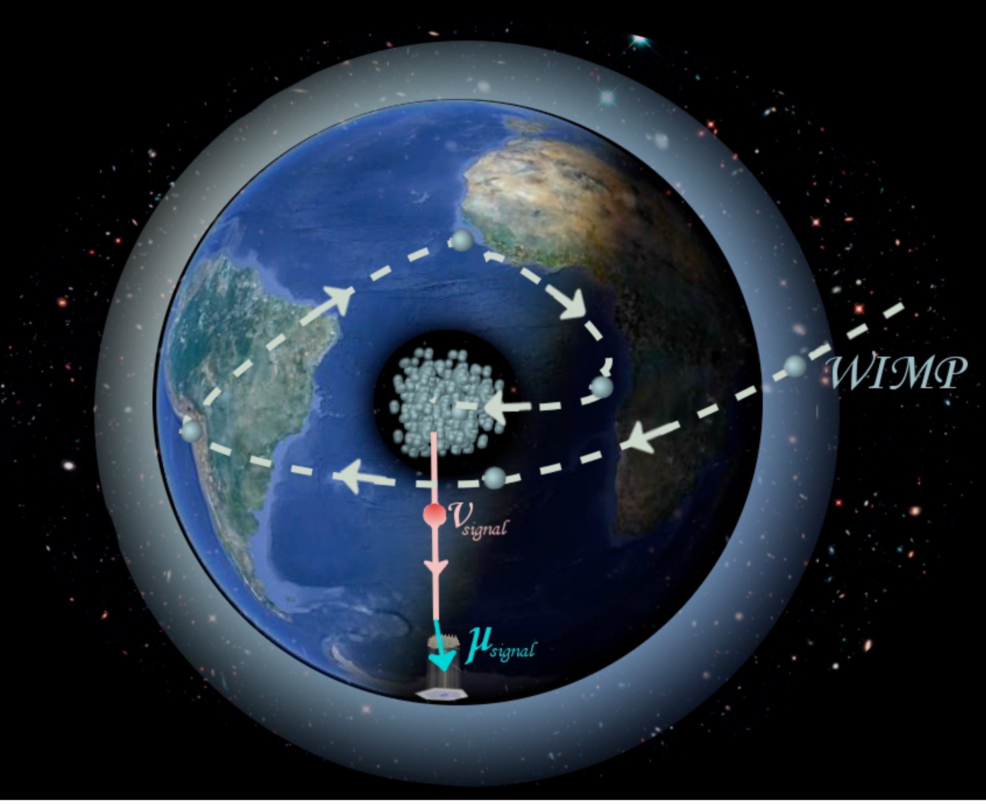
No evidence for dark matter

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

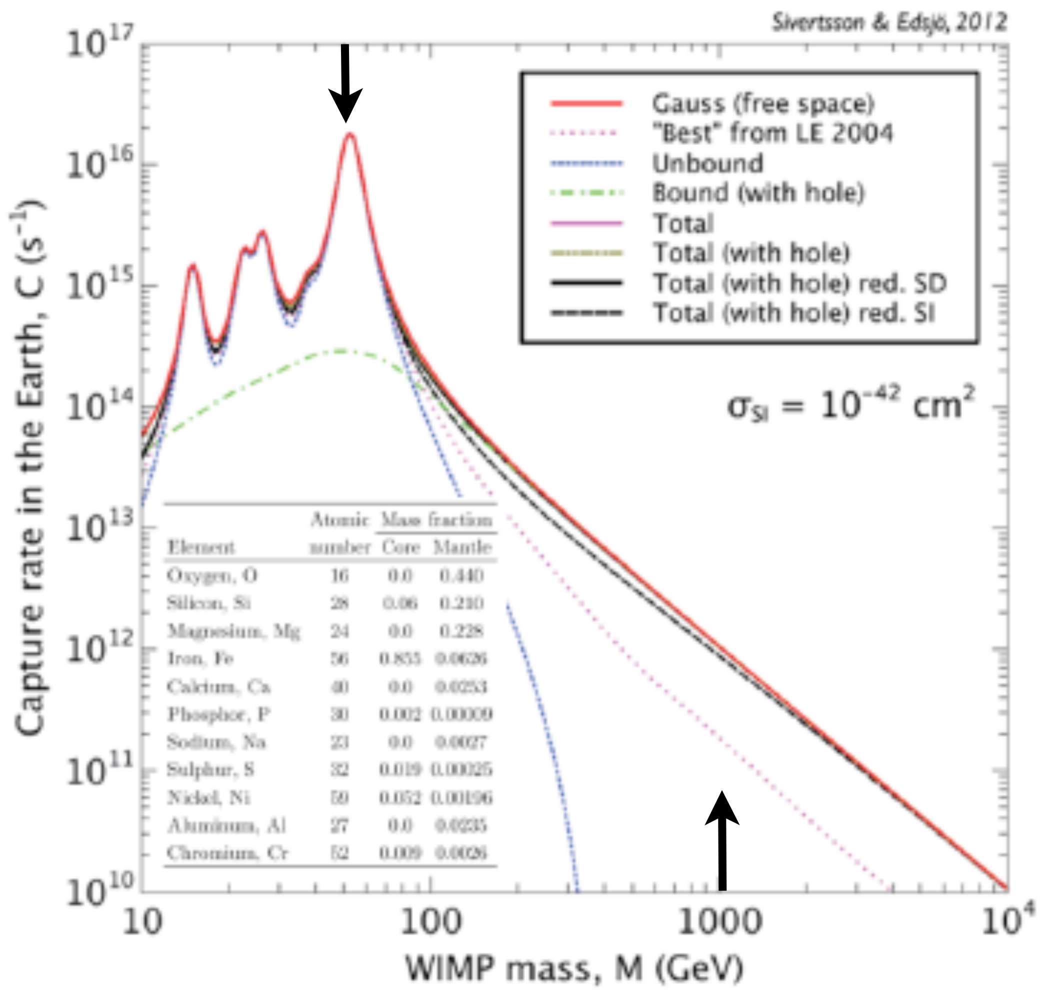


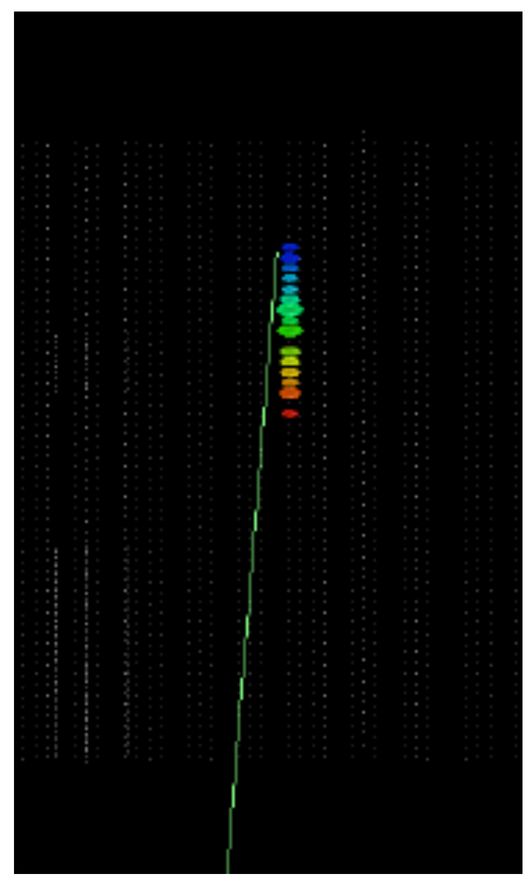
Earth WIMPs

Earth WIMPs



- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux
- IceCube: Two statistically independent analyses
  - Low energy & High energy
  - IC86-I (327 days of livetime during 2011/12)





Shape analysis

$$f(\Psi|\mu) = \frac{\mu}{n_{\mathrm{obs}}} f_s(\Psi) + \left(1 - \frac{\mu}{n_{\mathrm{obs}}}\right) f_{bg}(\Psi)$$

$$\mathcal{L} = \prod_i^{n_{\mathrm{obs}}} f(\Psi_i|\mu)$$

$$\mathcal{R}(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}$$

$\hat{\mu}$ is the best fit of μ to the observation

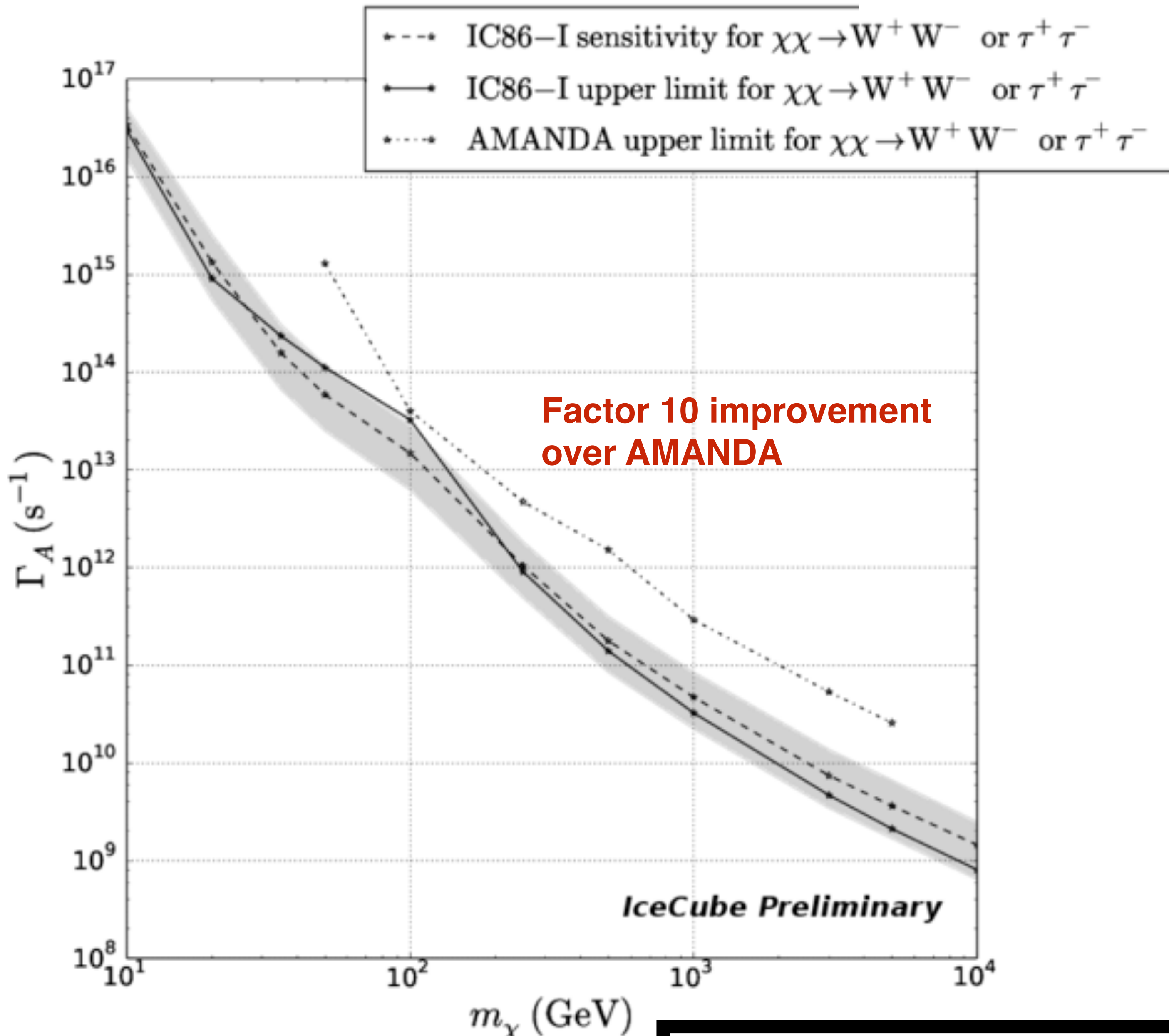
Earth WIMPs

- Combine High-energy and low-energy analysis, based on the best sensitivity

$$\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t}{\tau}\right), \quad \tau = (CC_A)^{-1/2}$$

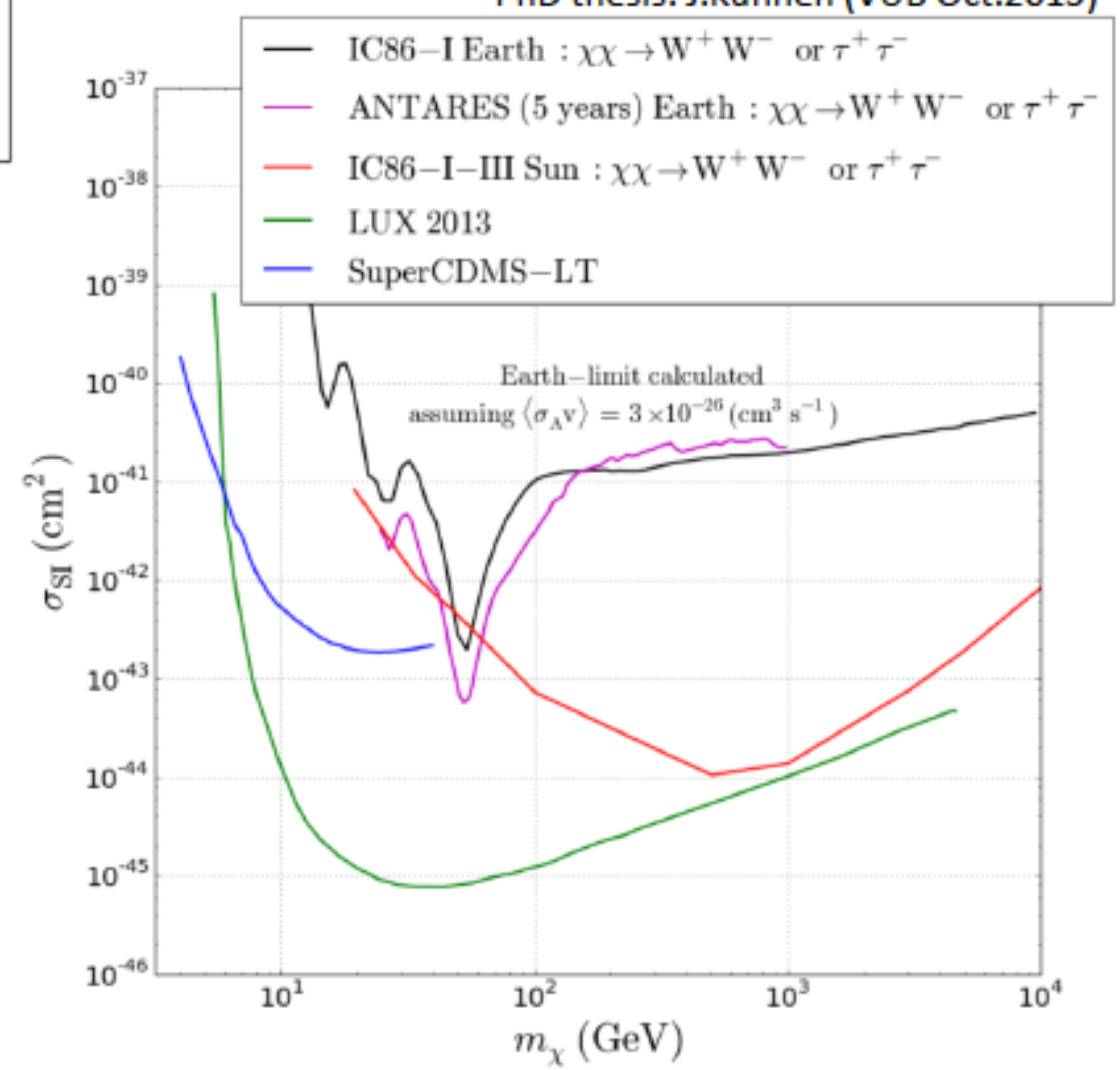
4.5 10^9years

Earth typically not in equilibrium

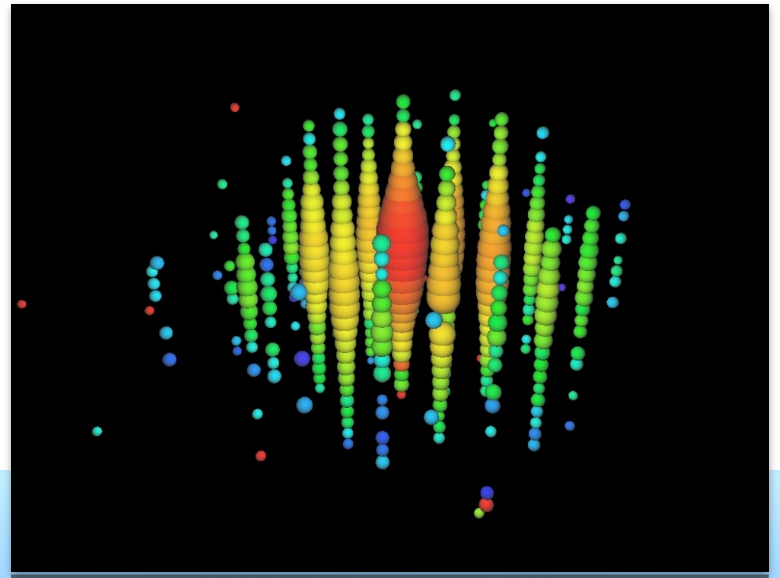


Factor 10 improvement over AMANDA

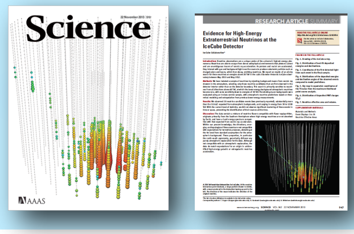
PhD thesis: J.Kunnen (VUB Oct.2015)



No evidence for dark matter



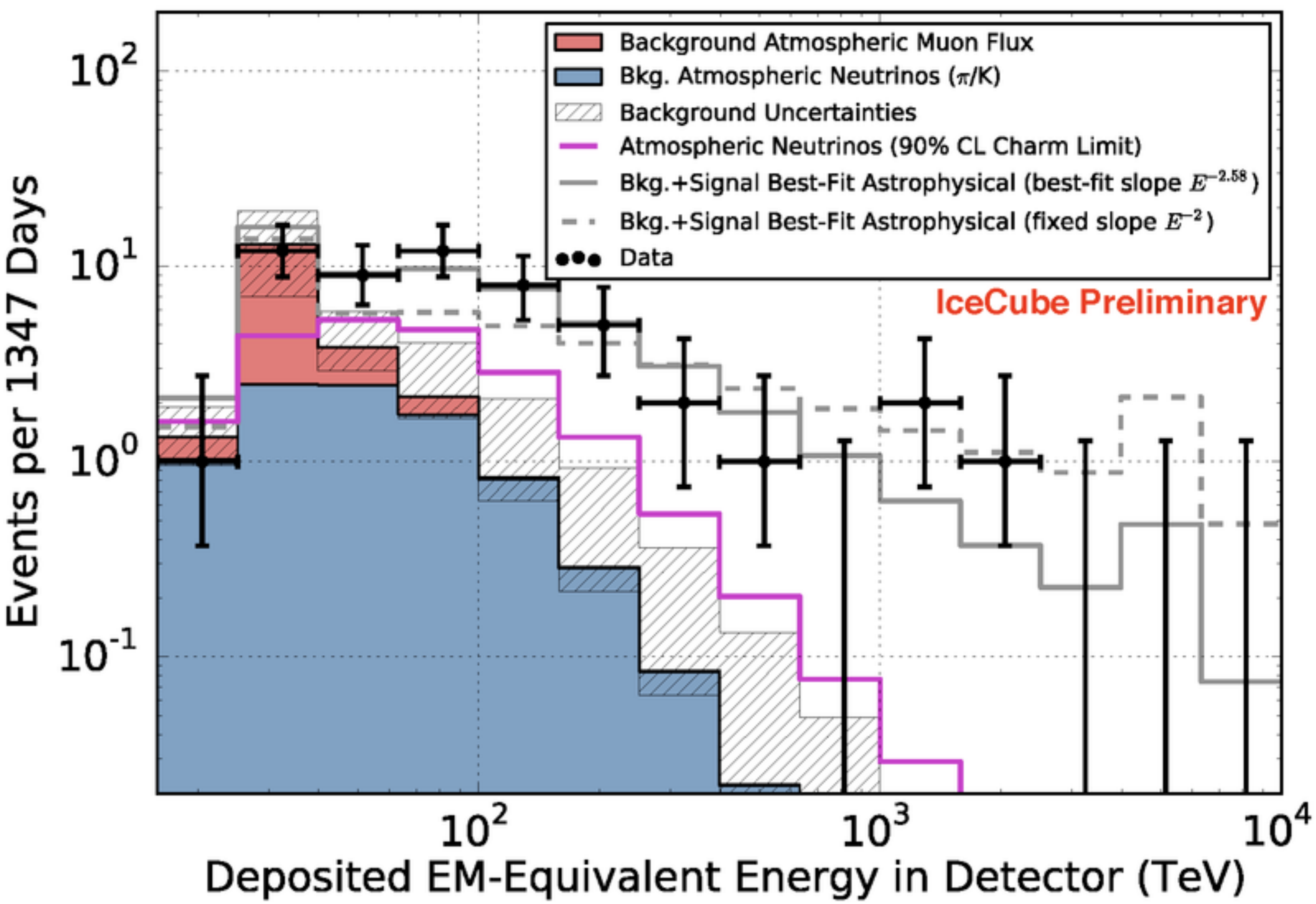
Astro-physical Neutrinos / Heavy Dark Matter ?



High-energy neutrino search 4yrs

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

Expectation from conventional atm. muons and neutrinos ~21.6



ICRC 2015 proceedings

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

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

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

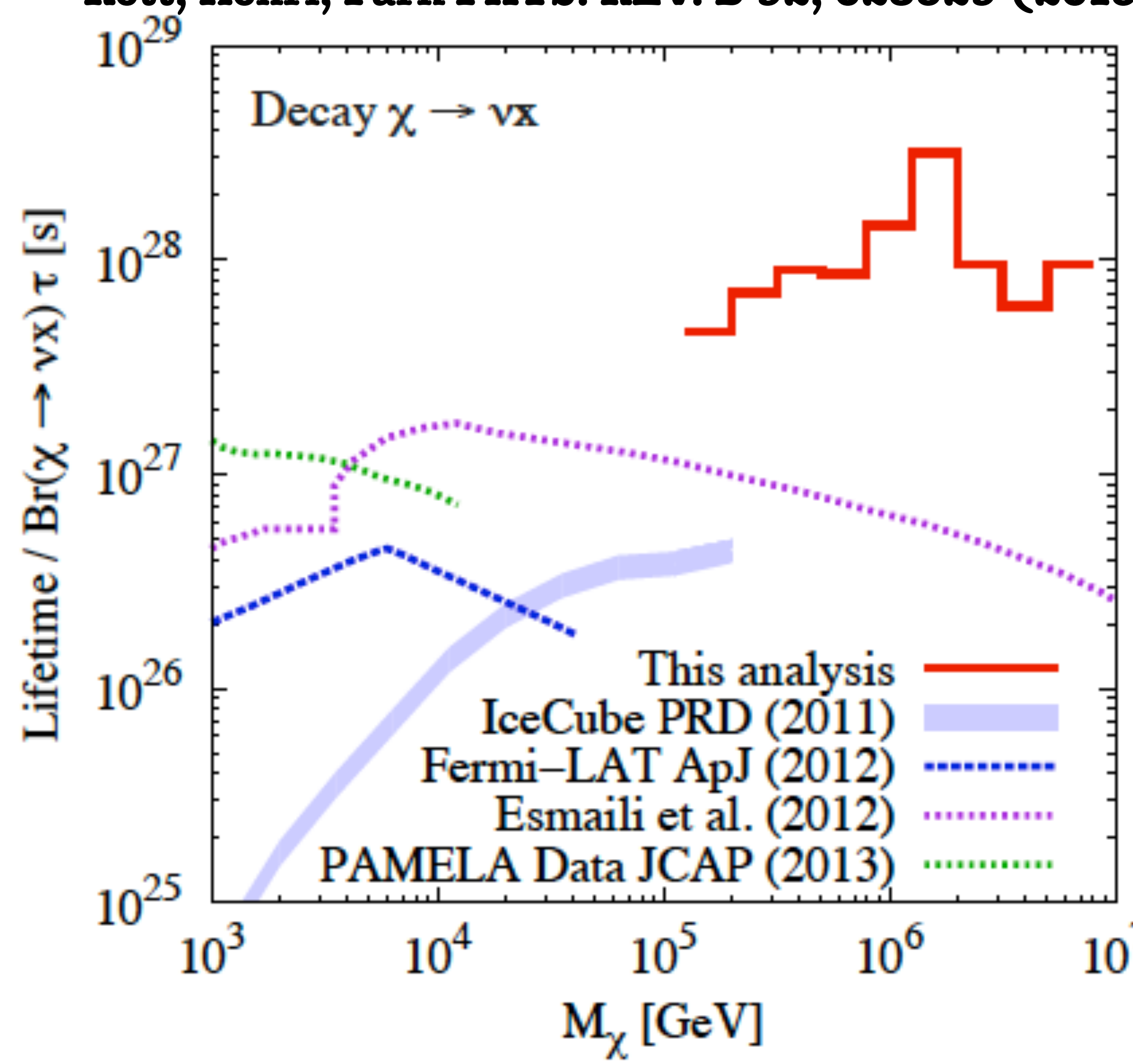
~7 sigma rejection of atmospheric-only hypothesis

Heavy Dark Matter Decay

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

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

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



<u>Heavy DM bounds with neutrinos, see also</u>
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

Heavy Dark Matter Decay

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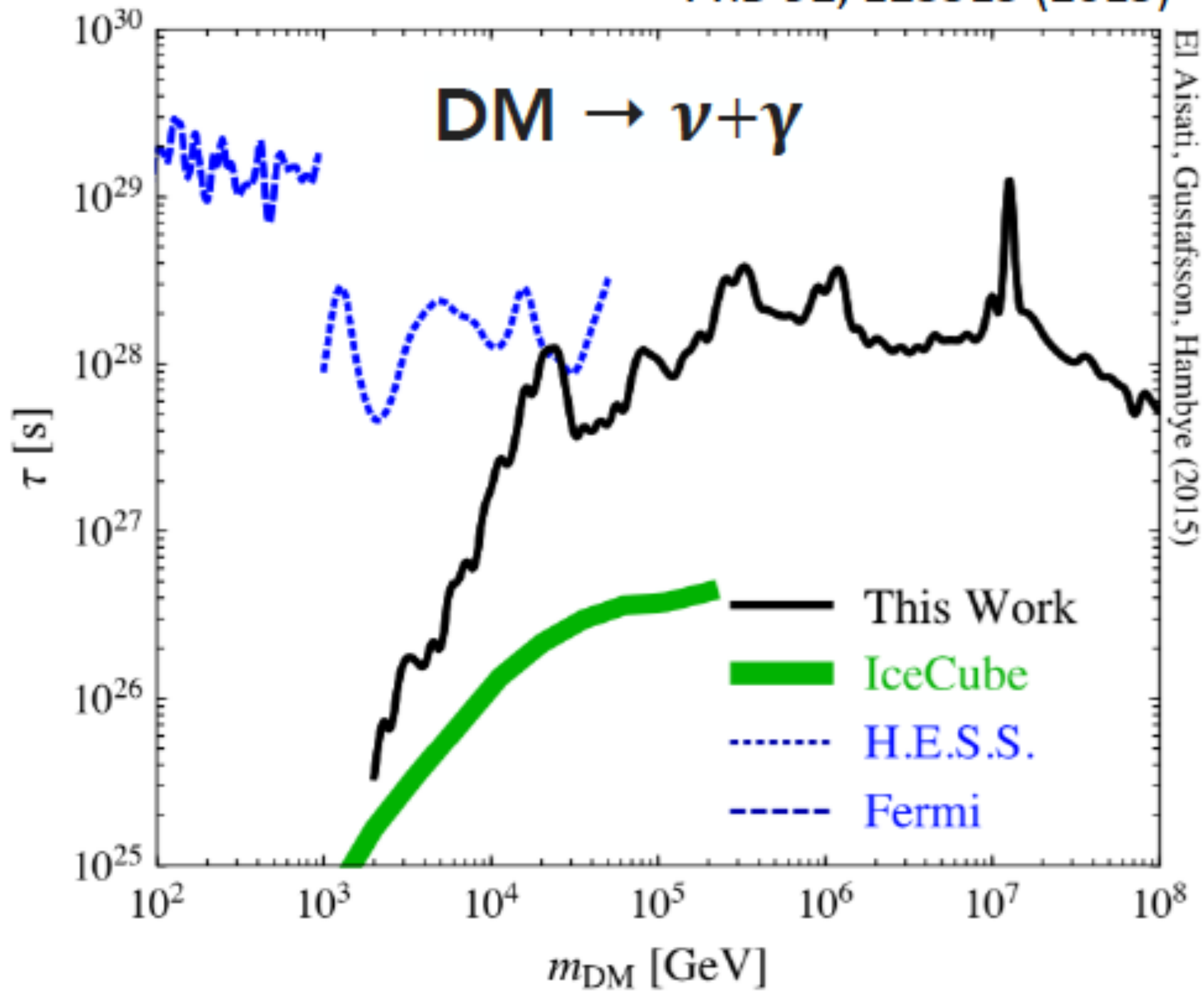
PRD 92, 123515 (2015)

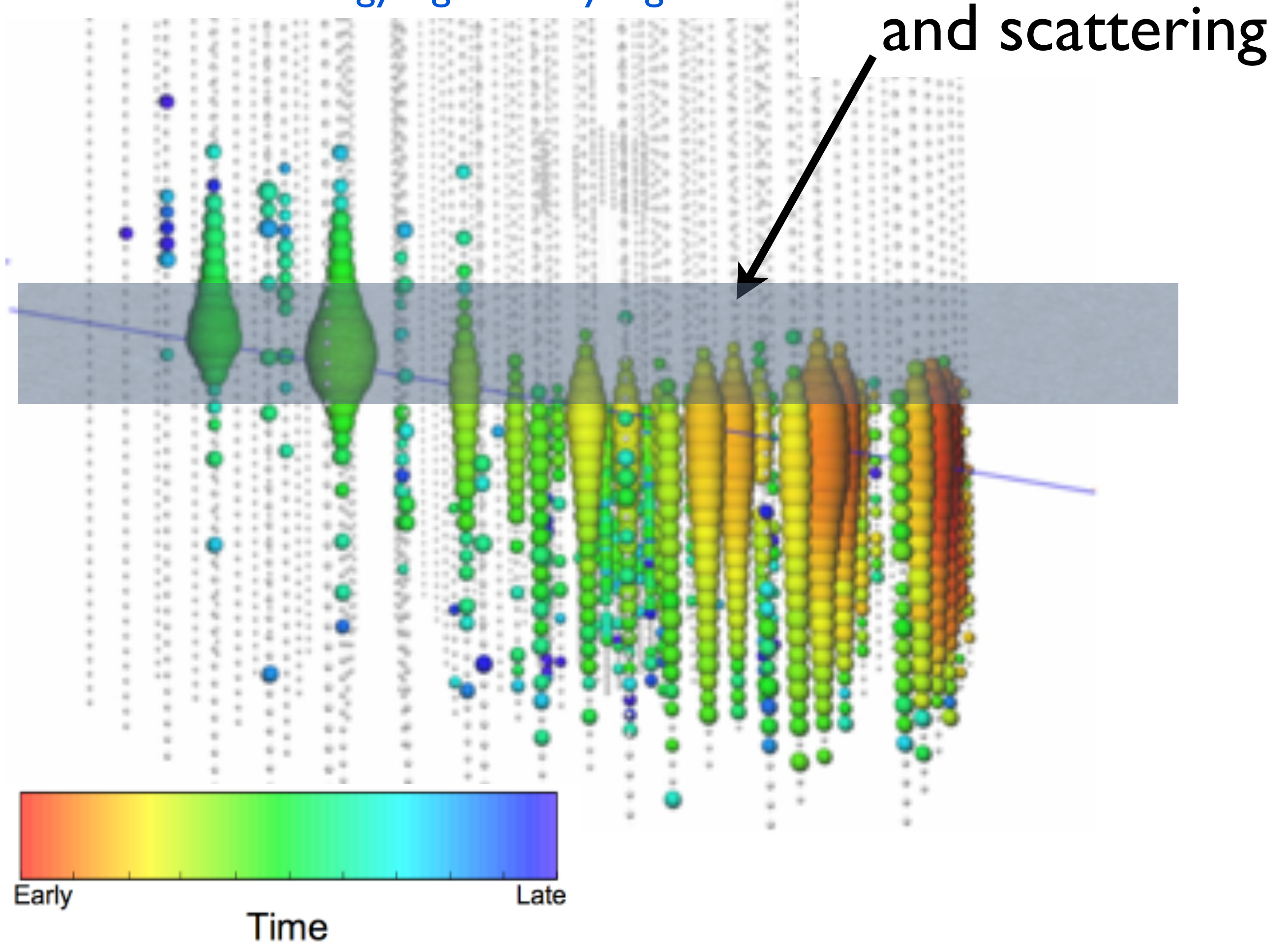


Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

Through-going muon tracks

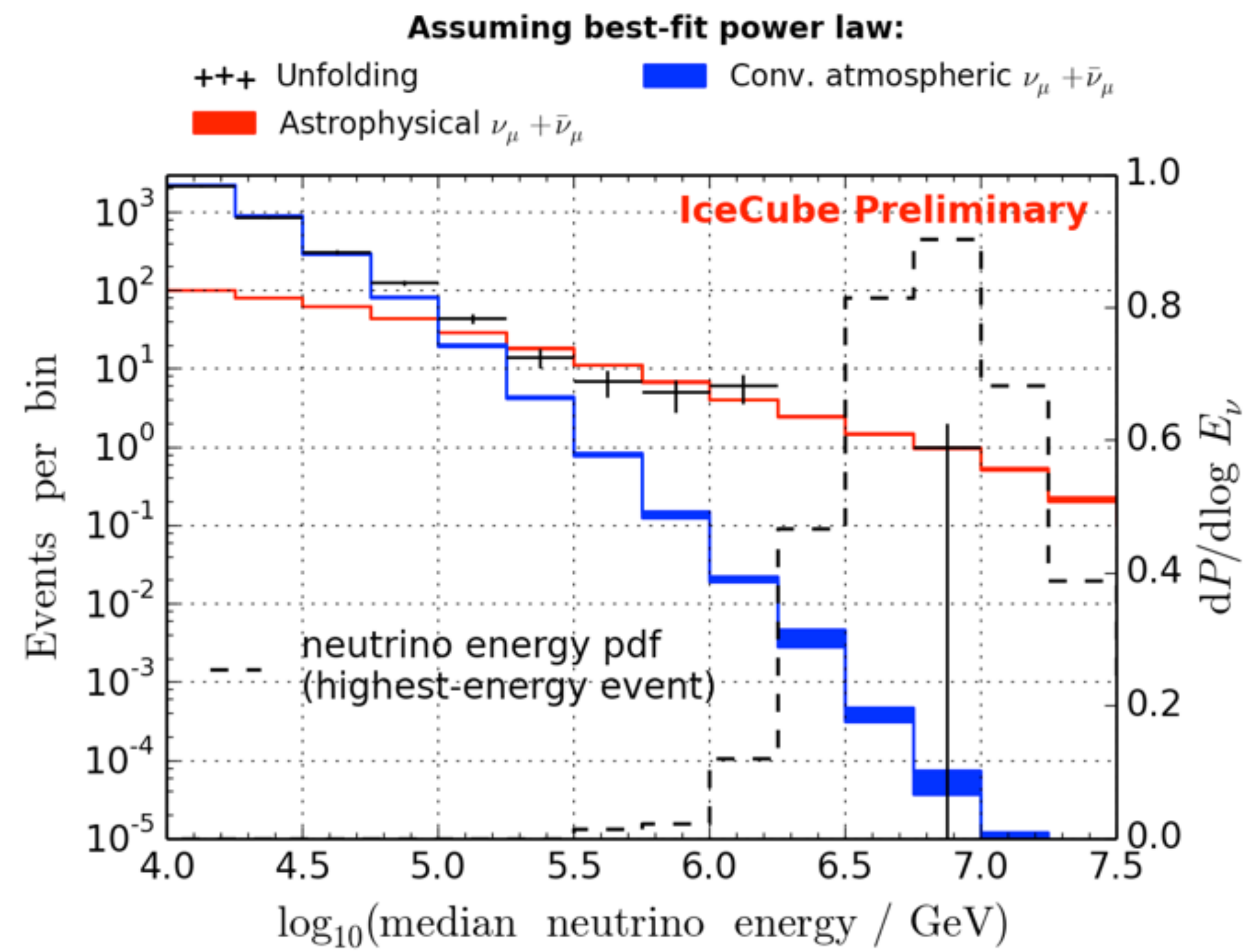
Up-going Track-like neutrino event
E_{dep}= 2.6 ±0.3 PeV

- Direction: 11.48° dec / 110.34° RA
  - Angular resolution <1°
- Deposited energy: 2.6±0.3 PeV
  - Lower bound on the neutrino energy
  - Neutrino energy significantly higher



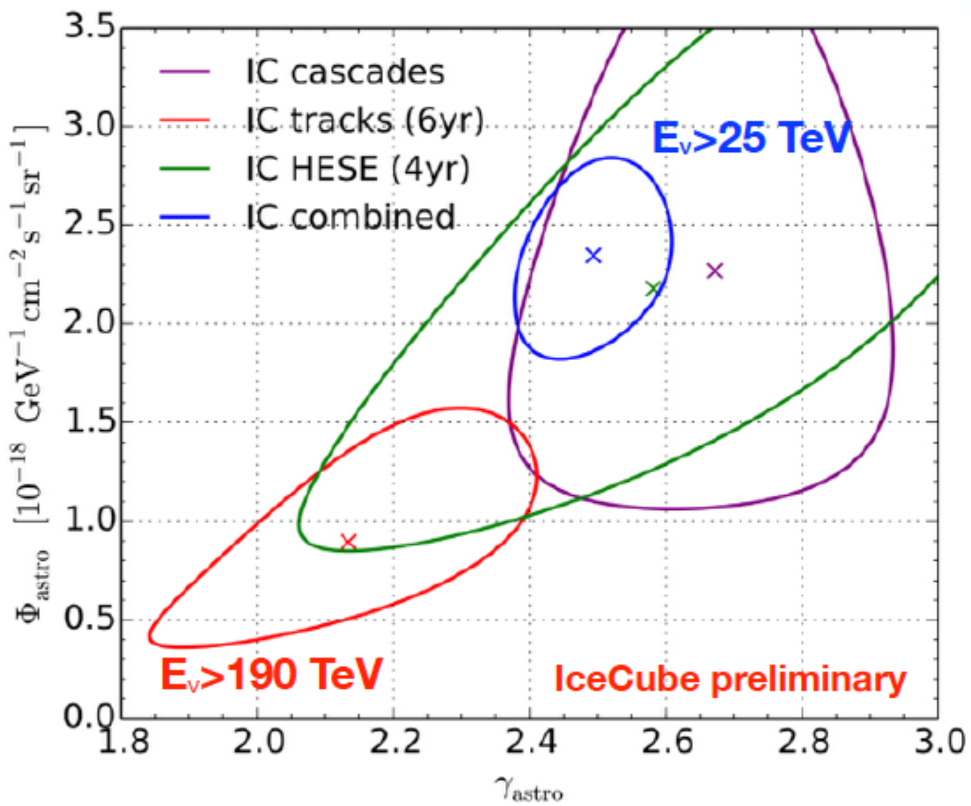
The event above was detected in IceCube on June 11, 2014. Image: IceCube Collaboration.

unfolded data assuming unbroken best-fit power law

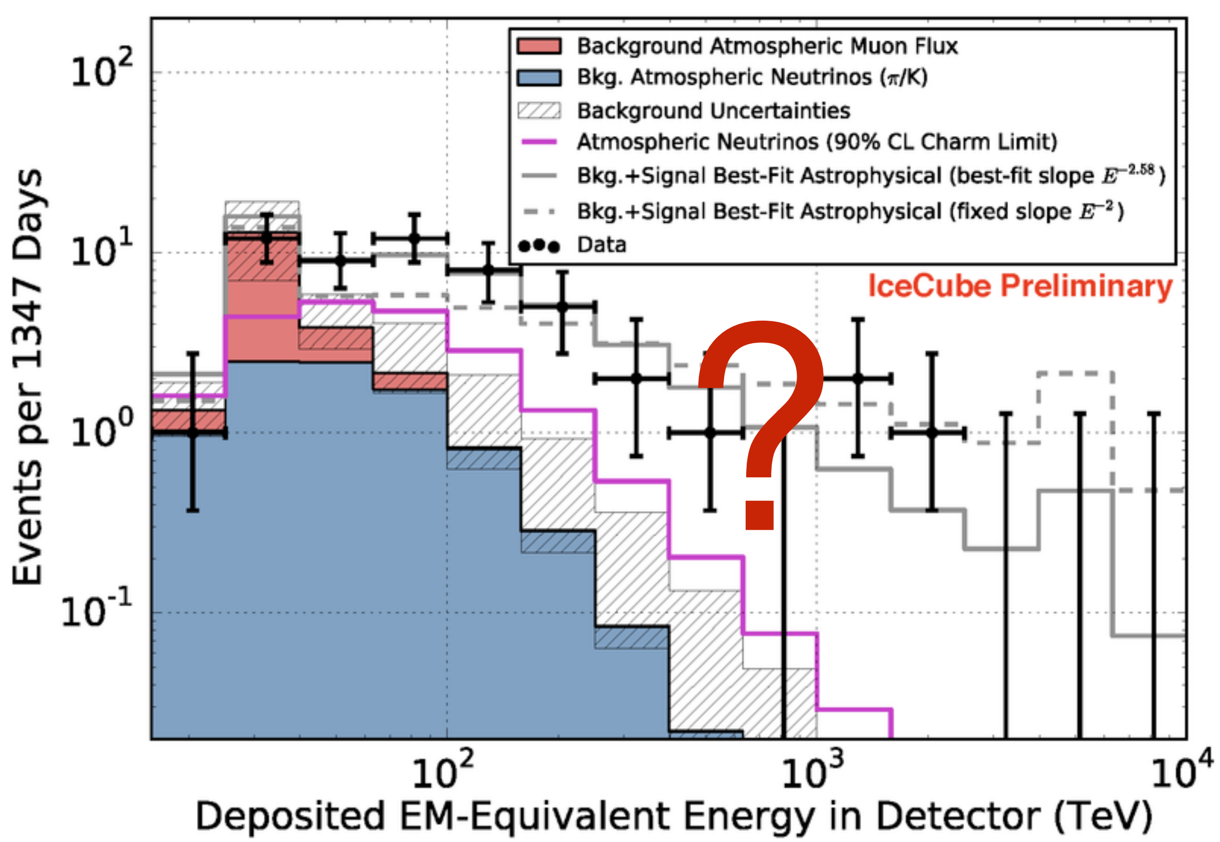


5.6 sigma detection of astrophysical neutrinos with through-going muons analysis

Beyond Standard Model Physics at the PeV scale



- Intense interest in high-energy neutrino region
  - Observations defy any simple explanation from a single generic source class
    - Multiple sources classes ?
    - Hints of new physics ?

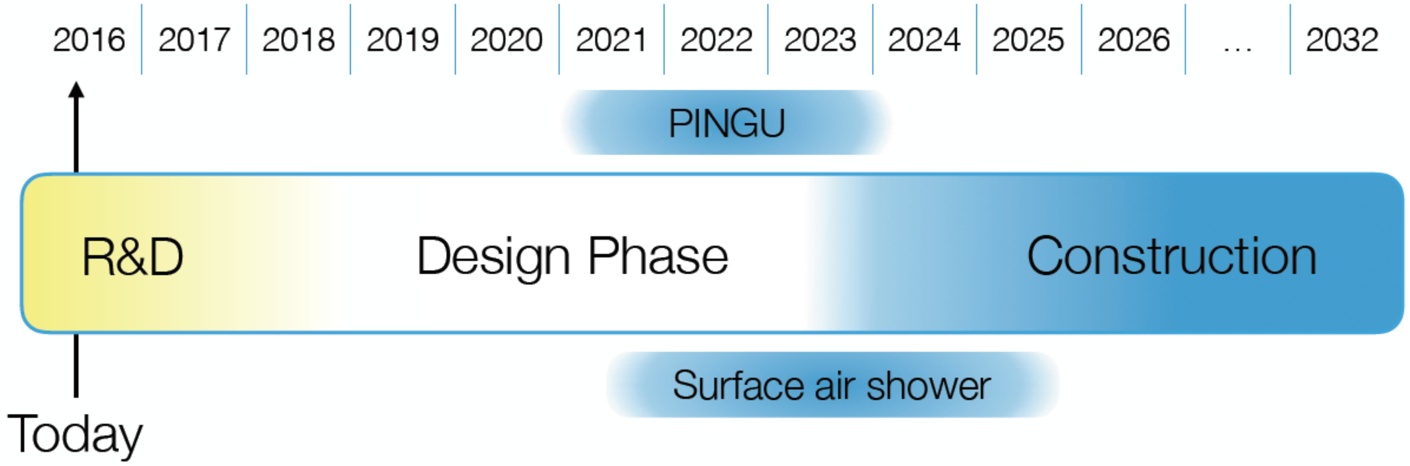


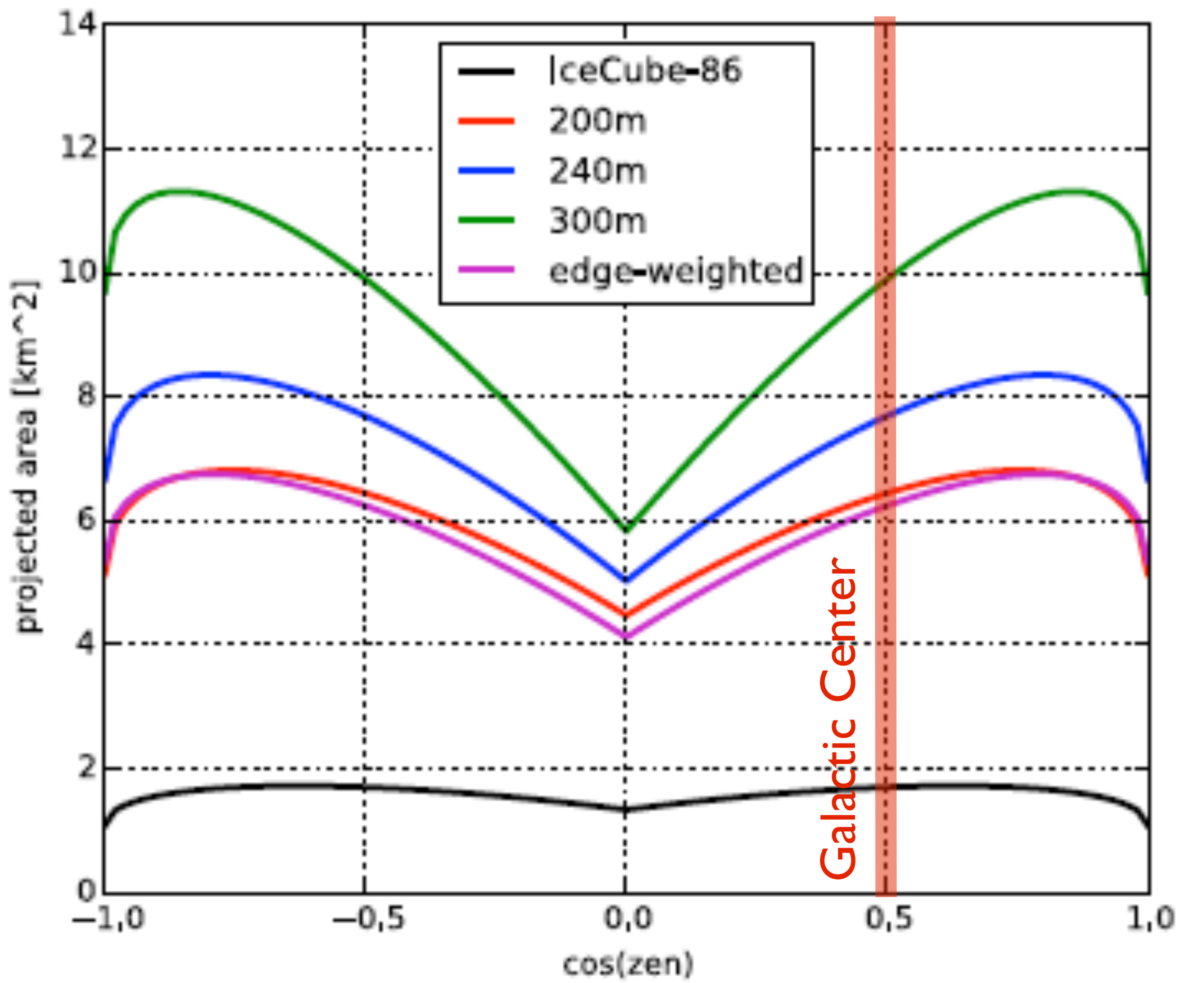
- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy right-handed neutrino dark matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and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

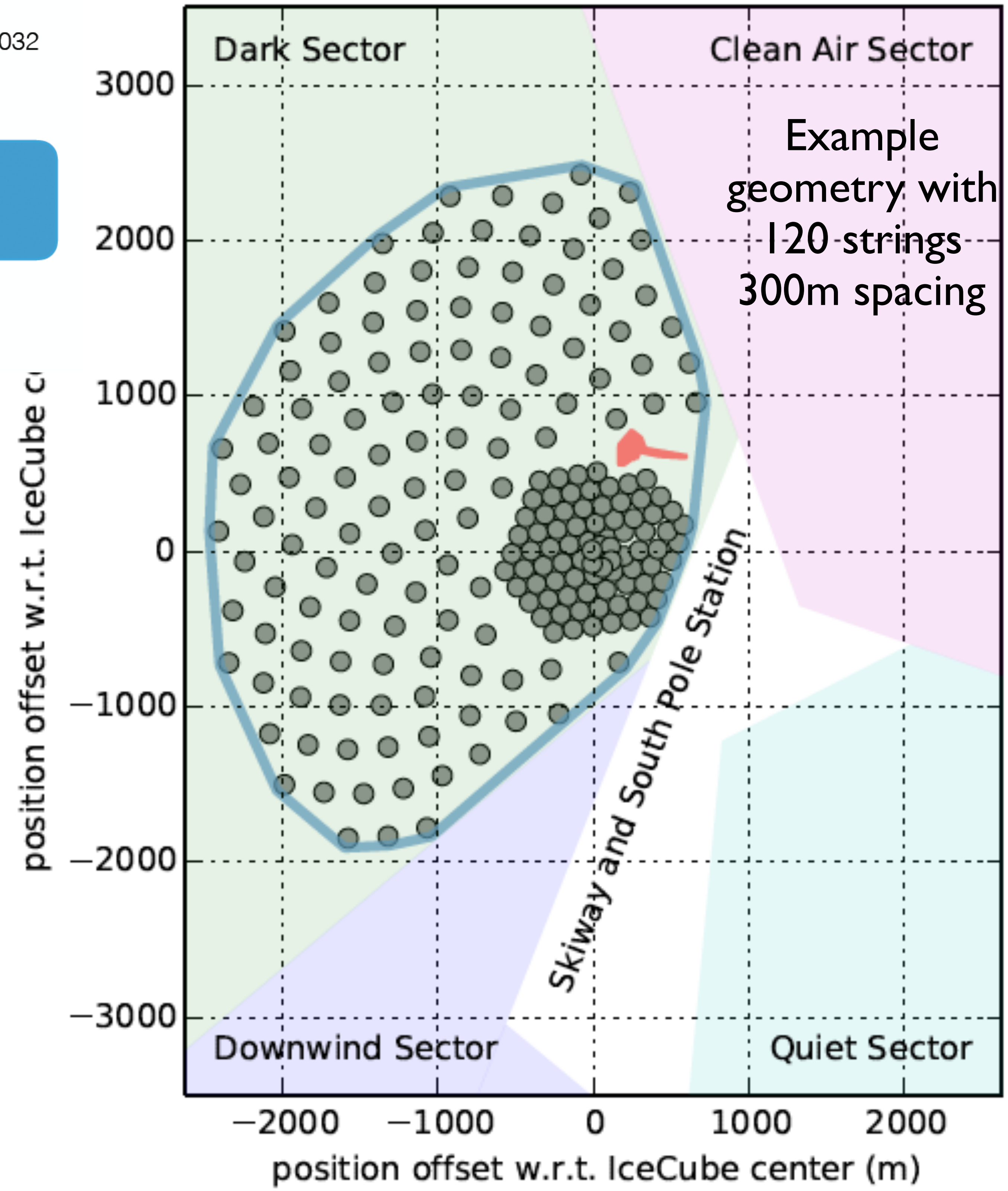
Future Plans

IceCube Gen 2

IceCube Coll. Gen2 LOI [arXiv:1412.5106]





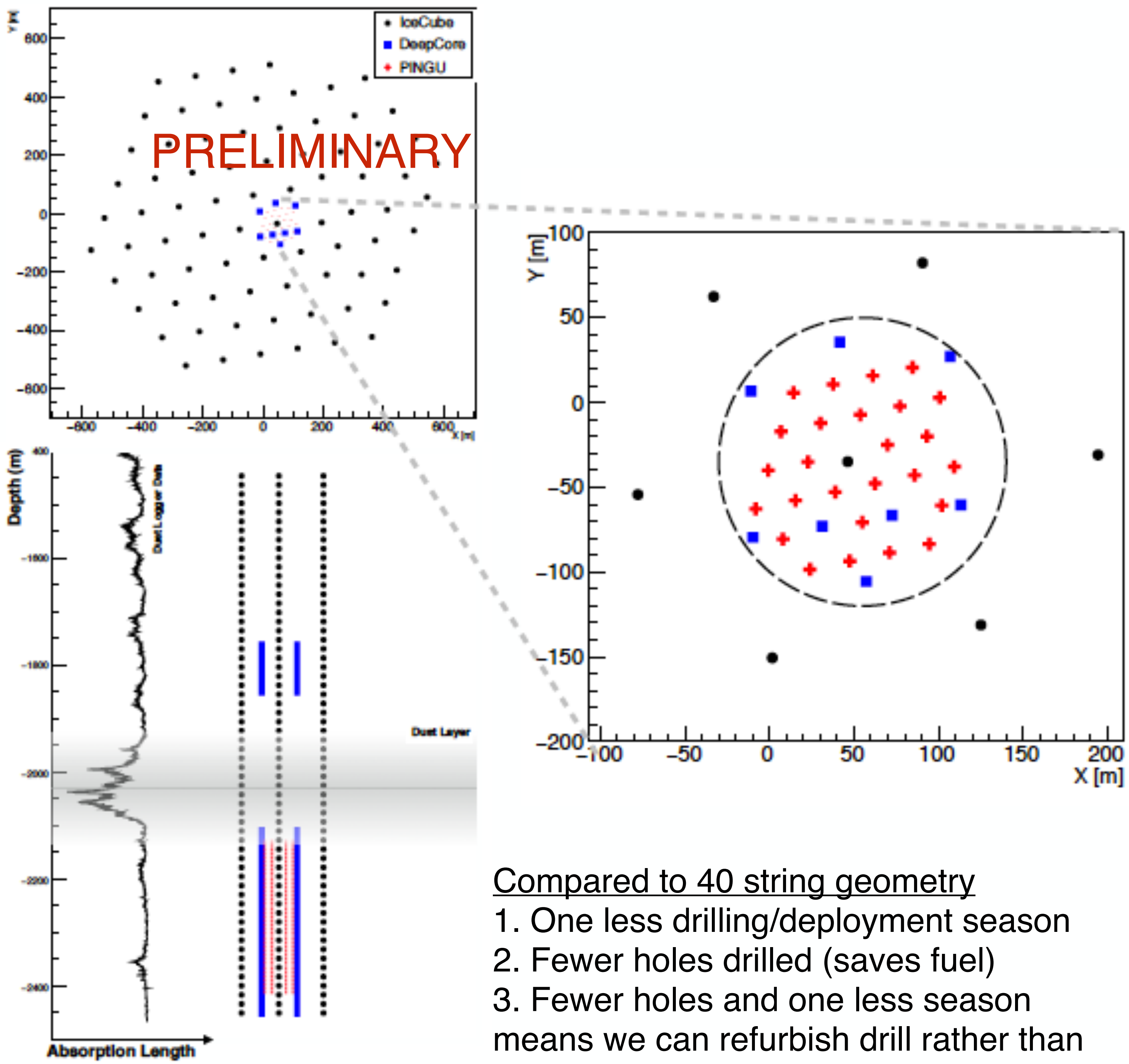


PINGU - Precision IceCube Next Generation Upgrade

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

PINGU LOI to be updated this summer

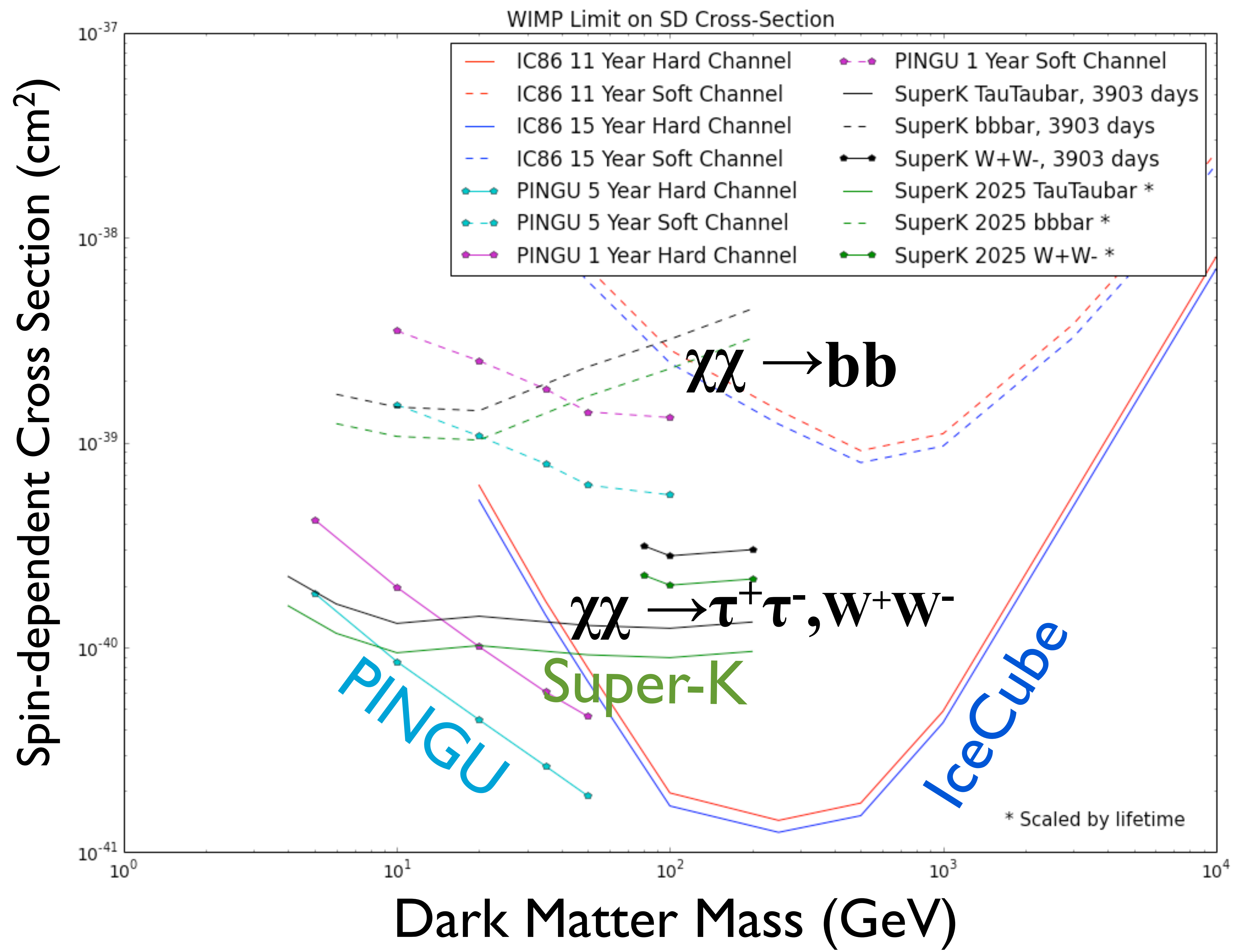
New PINGU Geometry



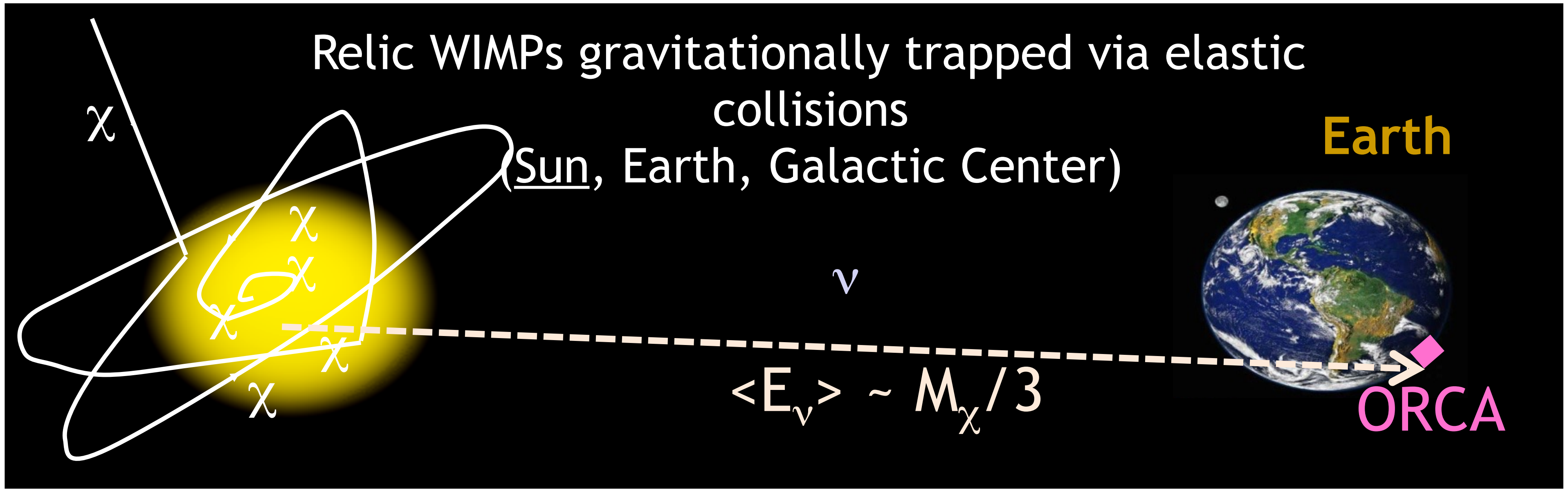
Compared to 40 string geometry

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

PINGU Dark Matter Sensitivity



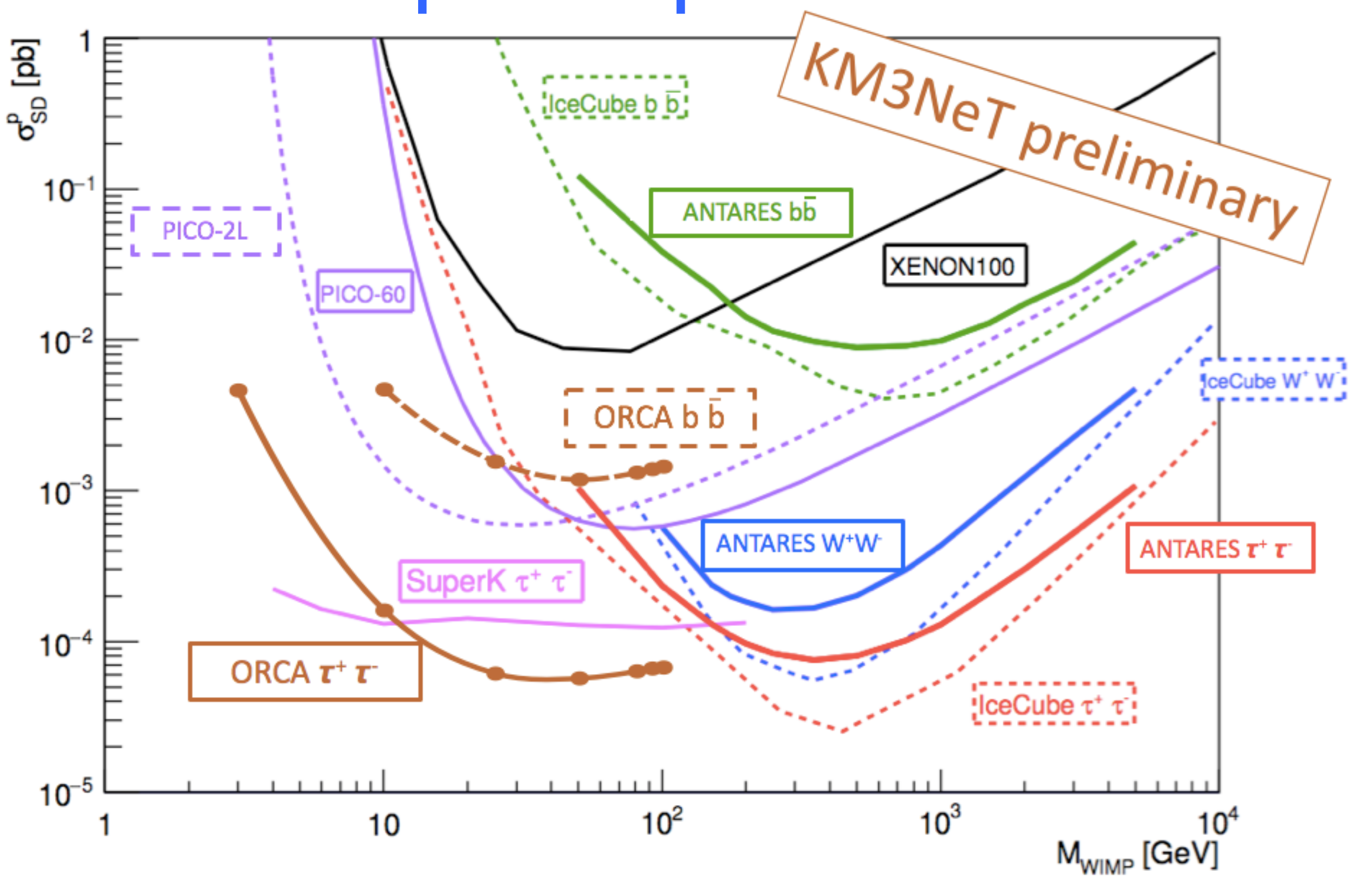
Indirect Detection of Dark Matter



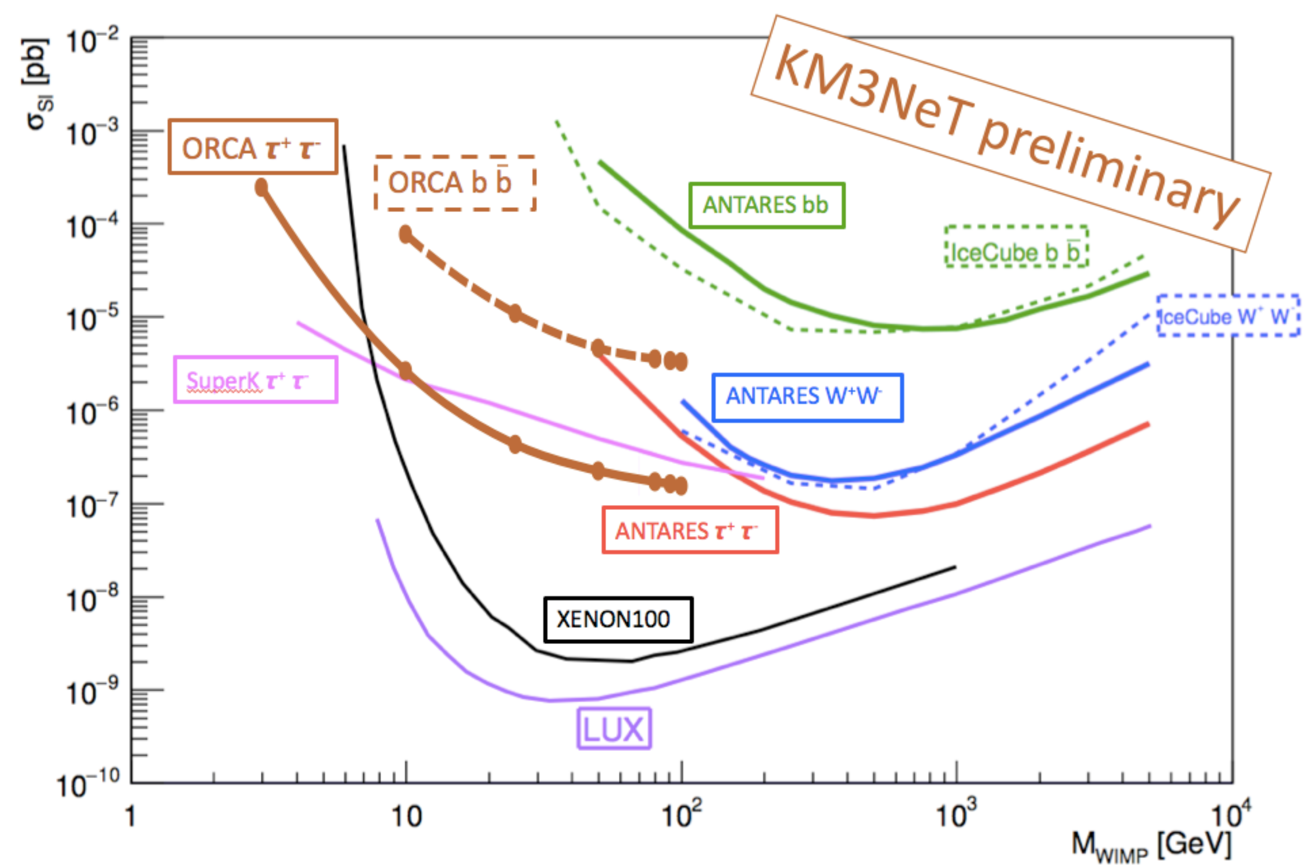
ORCA Schedule

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

Spin Dependent



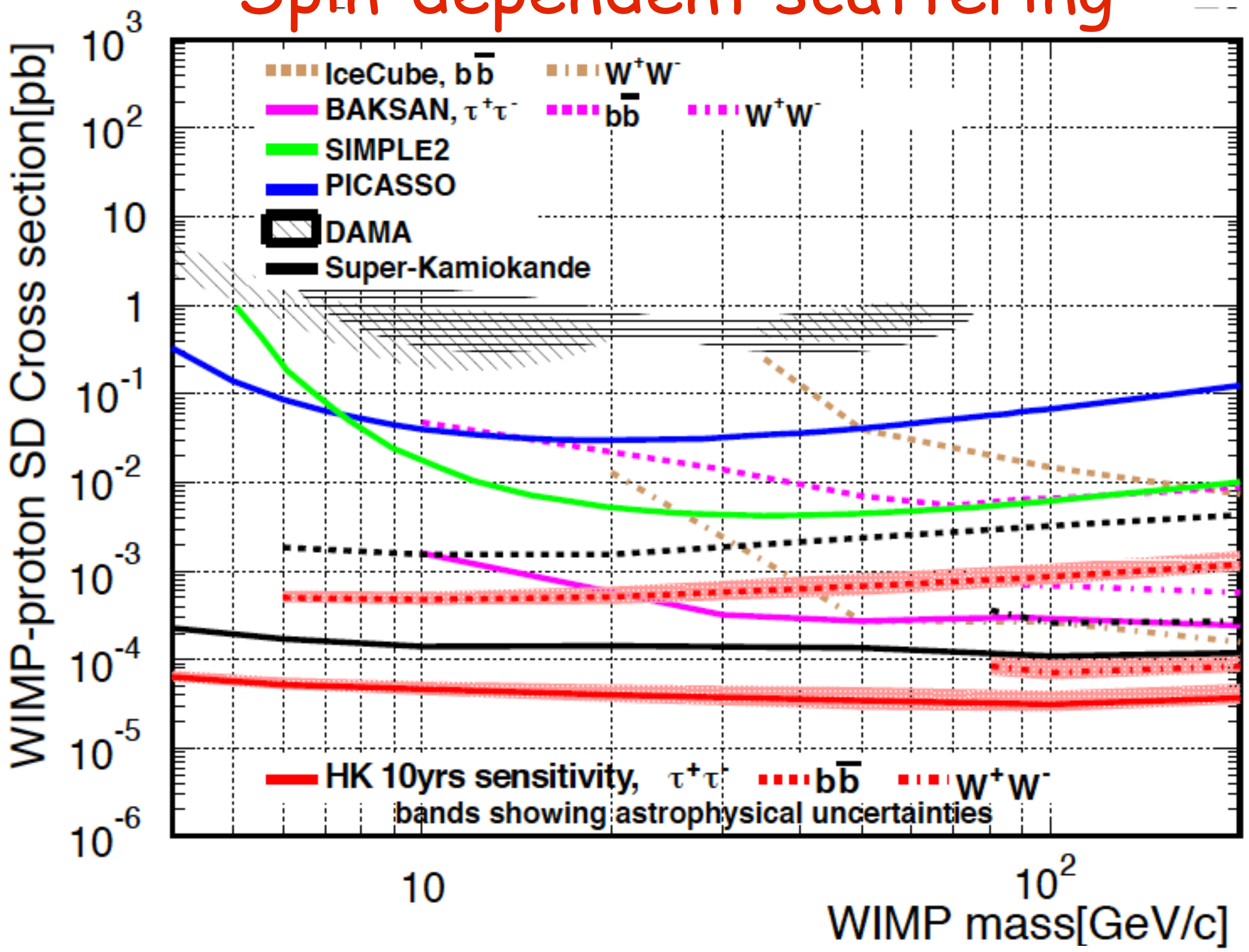
Spin Independent



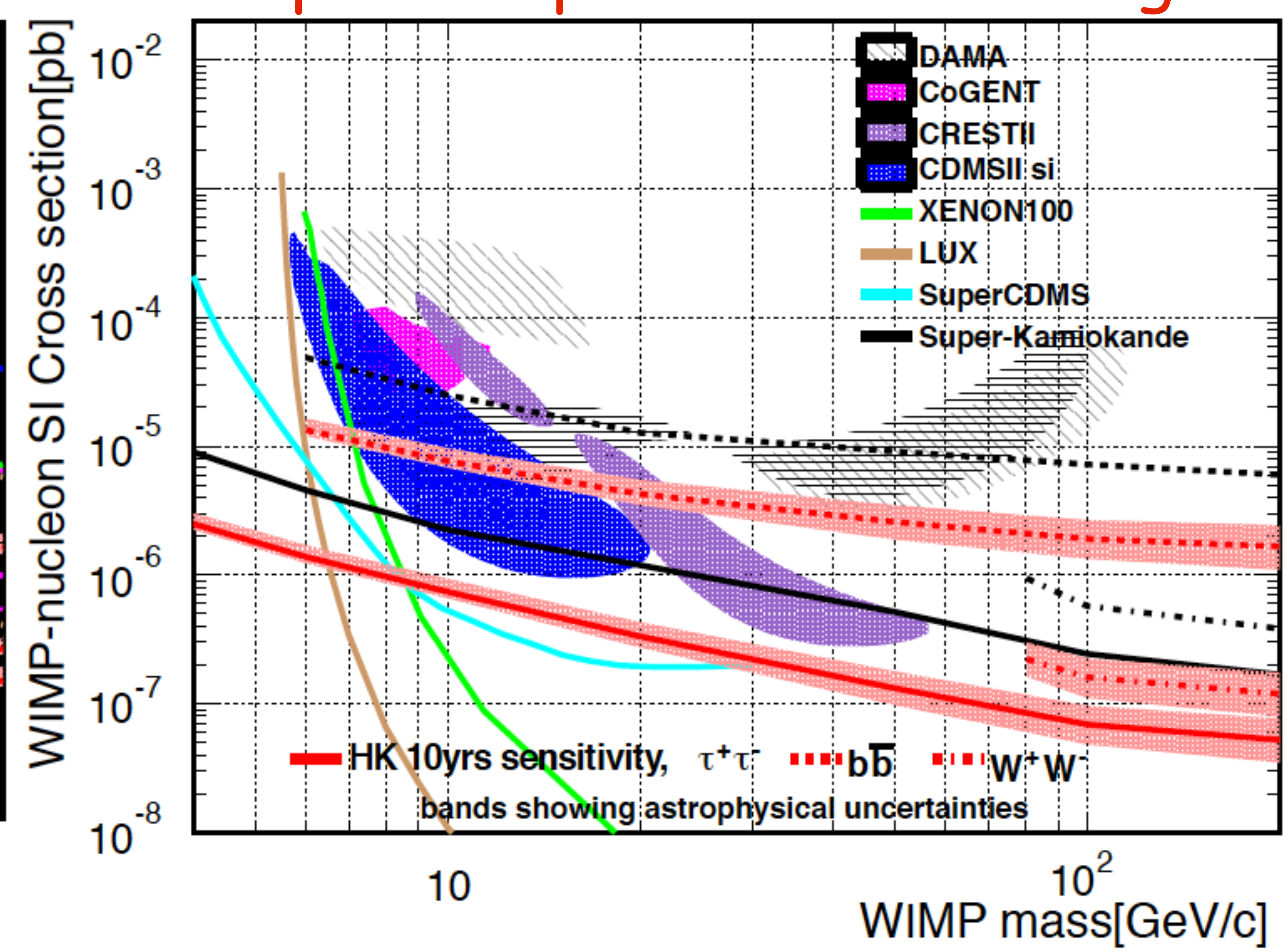
ORCA 3 years - tracks+showers

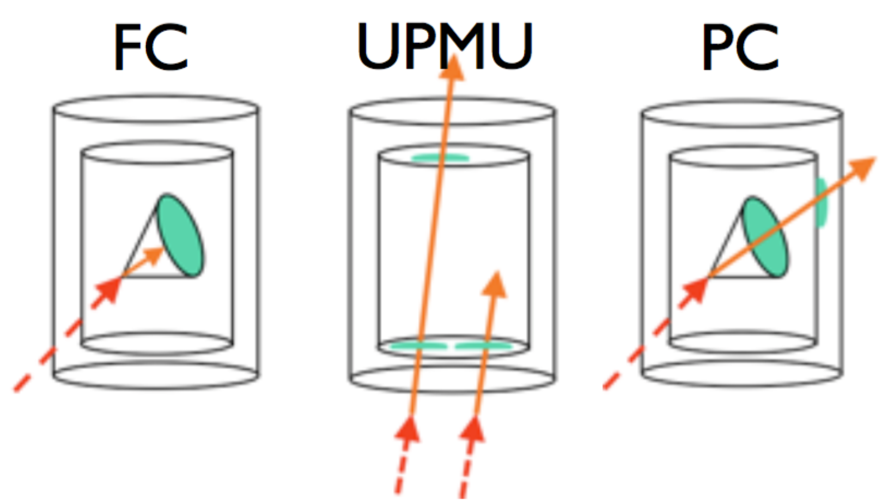
Solar WIMPs Hyper-K

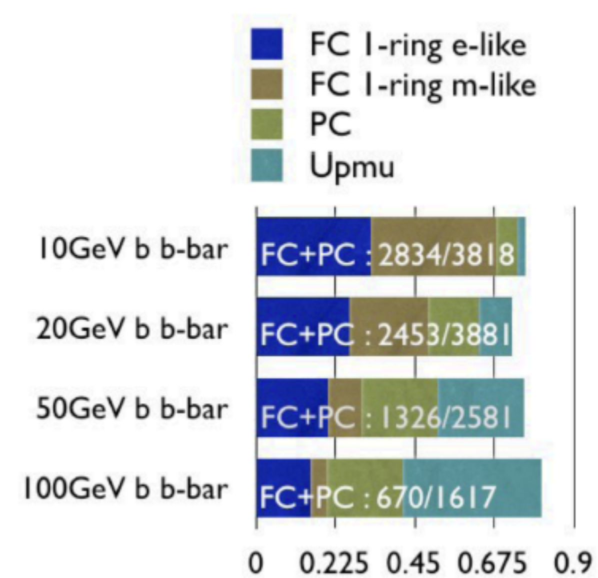
Spin-dependent scattering



Spin-independent scattering

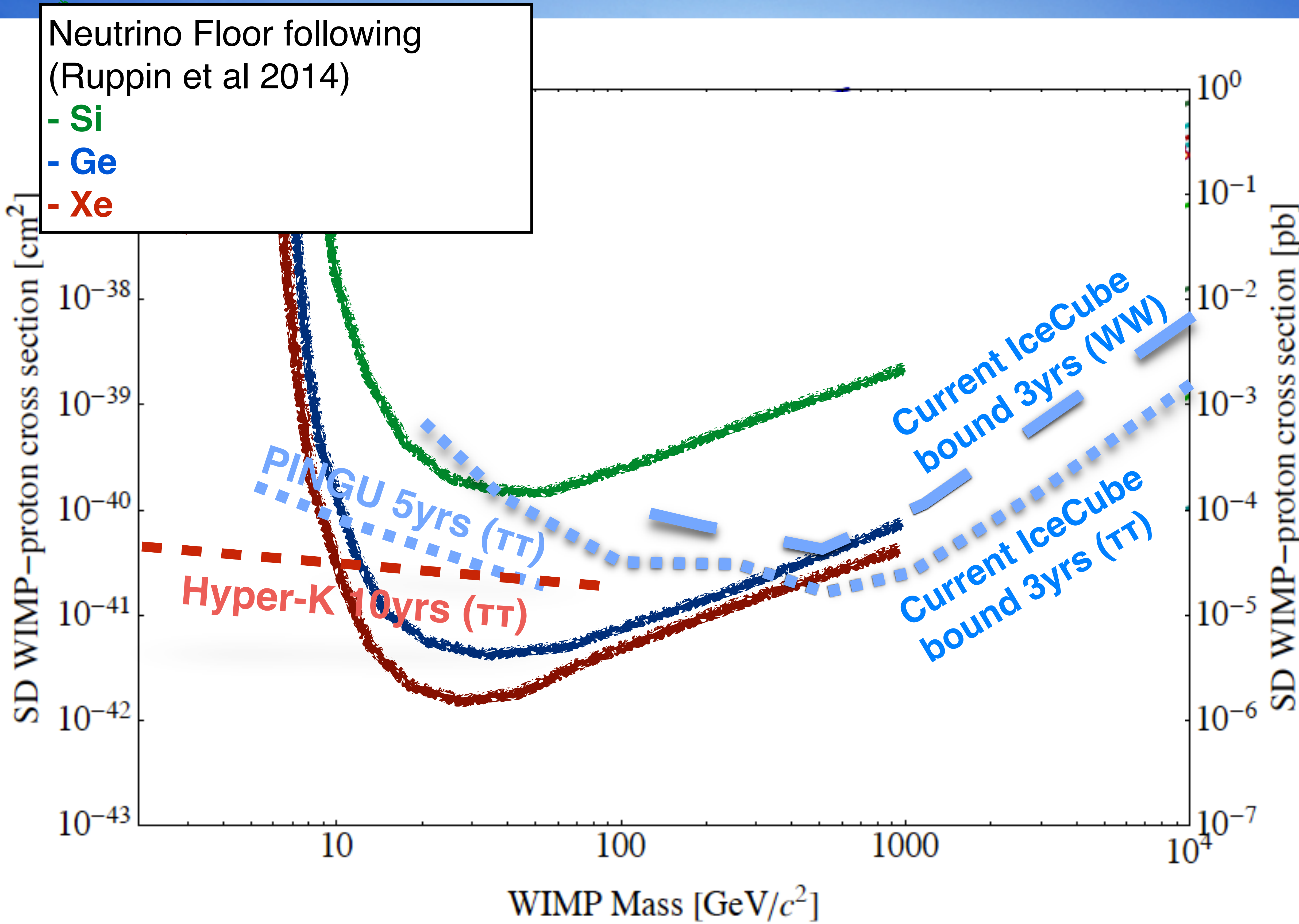






Sensitivity based on Koun et al. (Super-K Coll.) (2014)

Direct Detection Neutrino Floor



Neutrinos from stopped meson decay in the Sun

Low-Energy Neutrinos from the Sun

Possible annihilation channels:

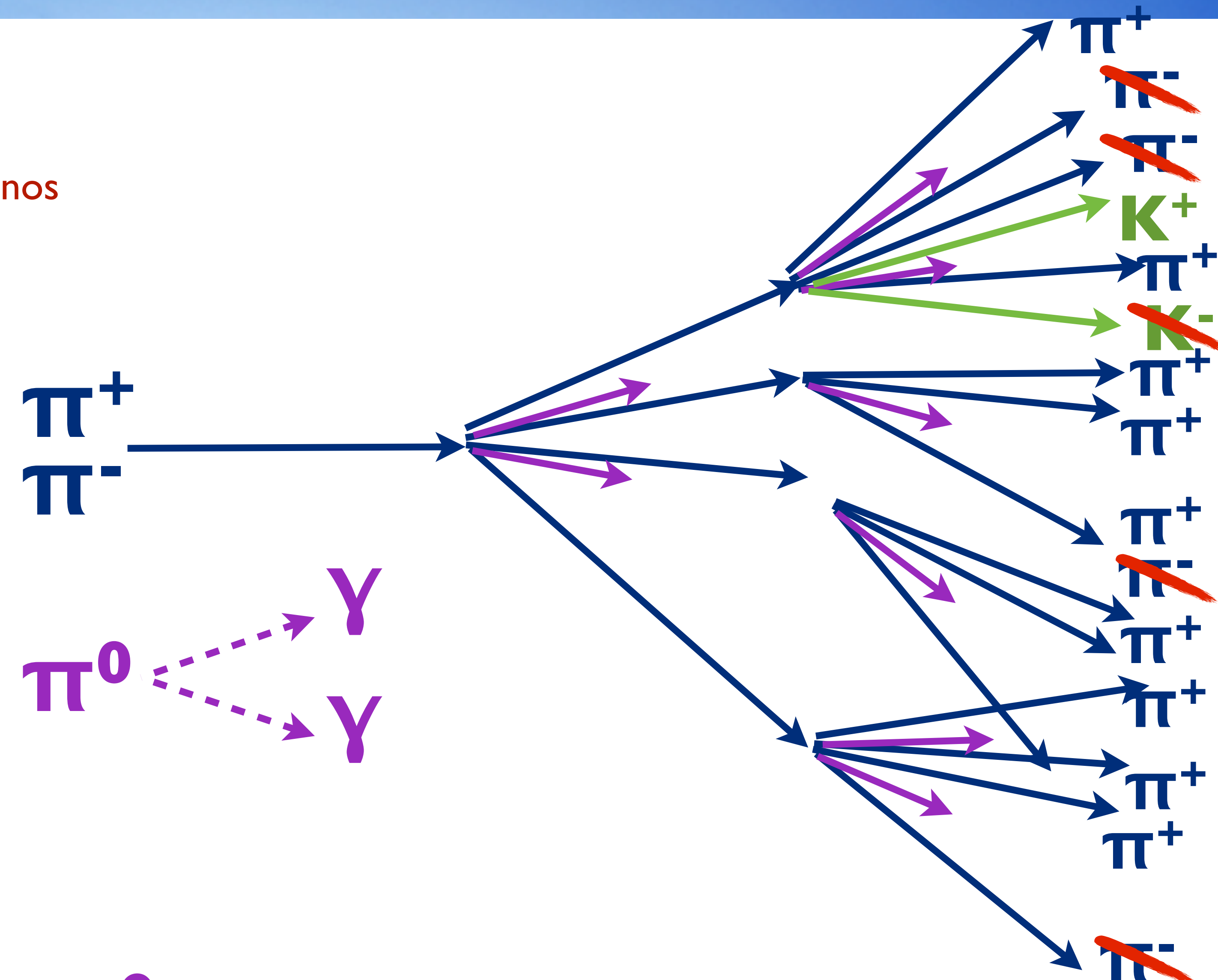
$q\bar{q}, gg, c\bar{c}, s\bar{s}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}, e^+e^-, \gamma\gamma$

few neutrinos

some "high energy" neutrinos in decays

$\Rightarrow$ basis of present day searches

dominant decay into hadrons



Charged pions and kaons decay at rest producing mono-energetic neutrinos

$\pi^+ \rightarrow \mu^+ \nu_\mu$ $E_\nu = 29.8\,\text{MeV}$

$K^+ \rightarrow \nu_\mu \mu^+$ $E_\nu = 235.5\,\text{MeV}$

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

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

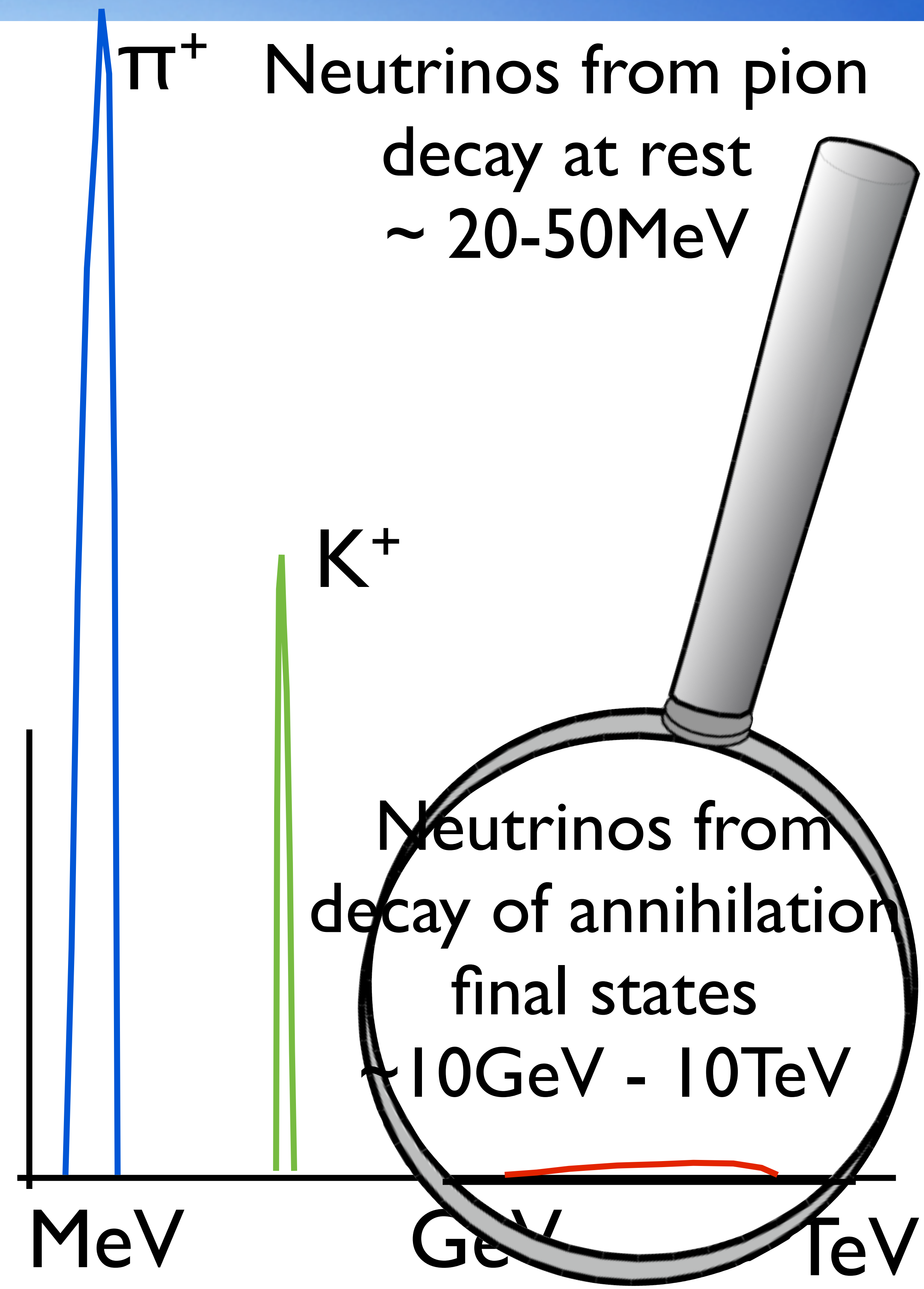
Neutrino signals - Example W-Boson

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

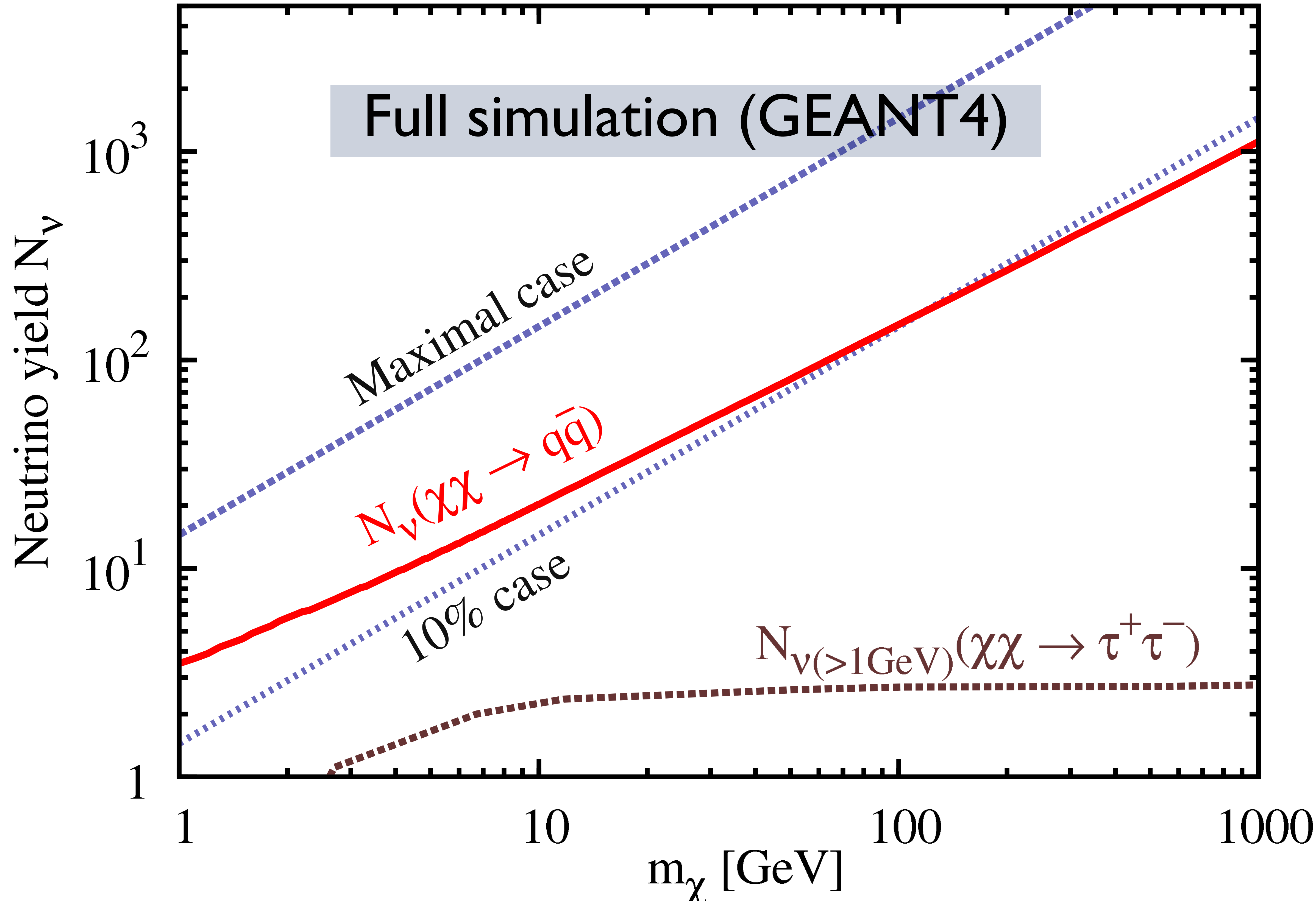
$\longrightarrow qq$ ~67%

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

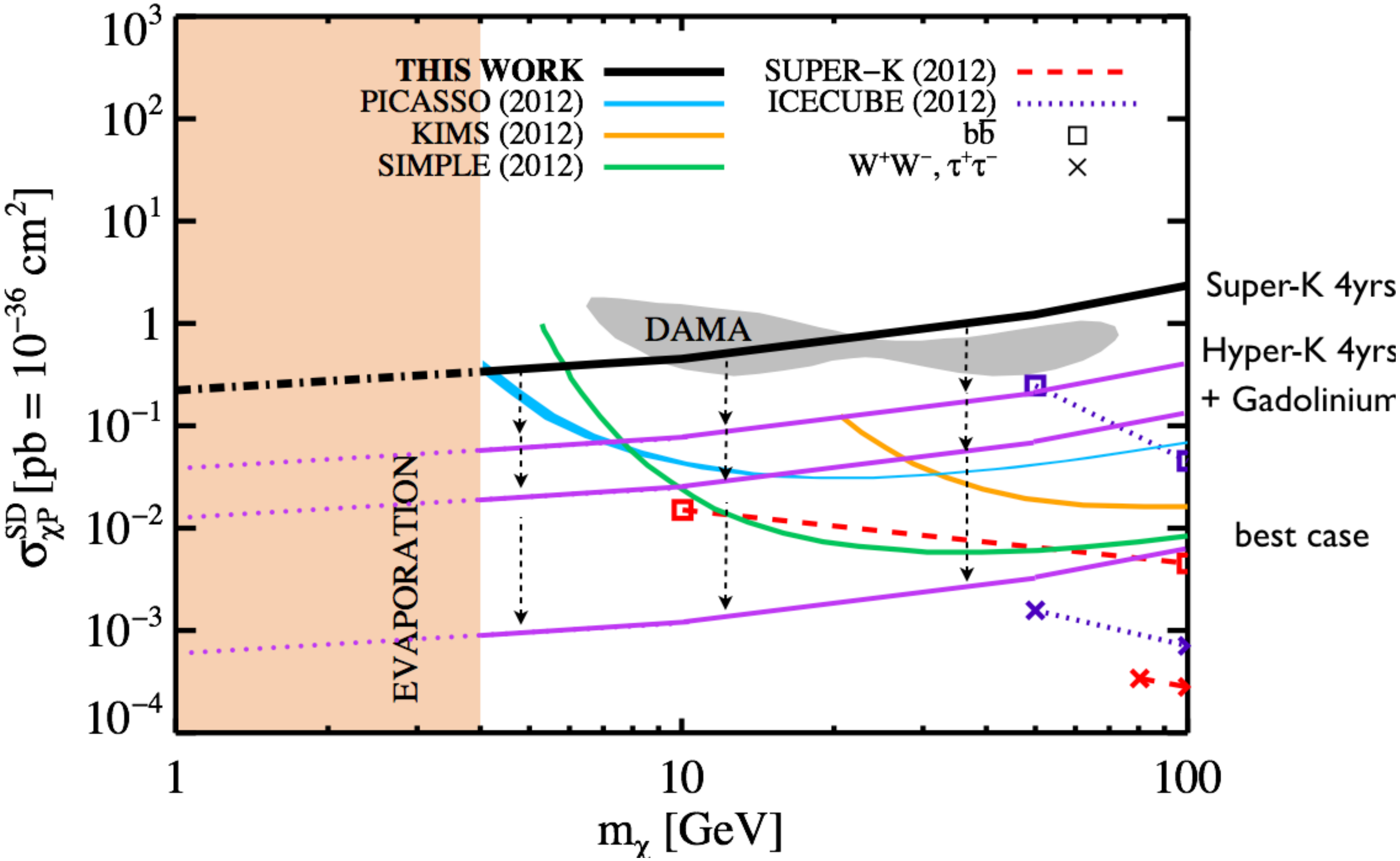


Neutrino yield



WIMP Sensitivity Super-K/Hyper-K

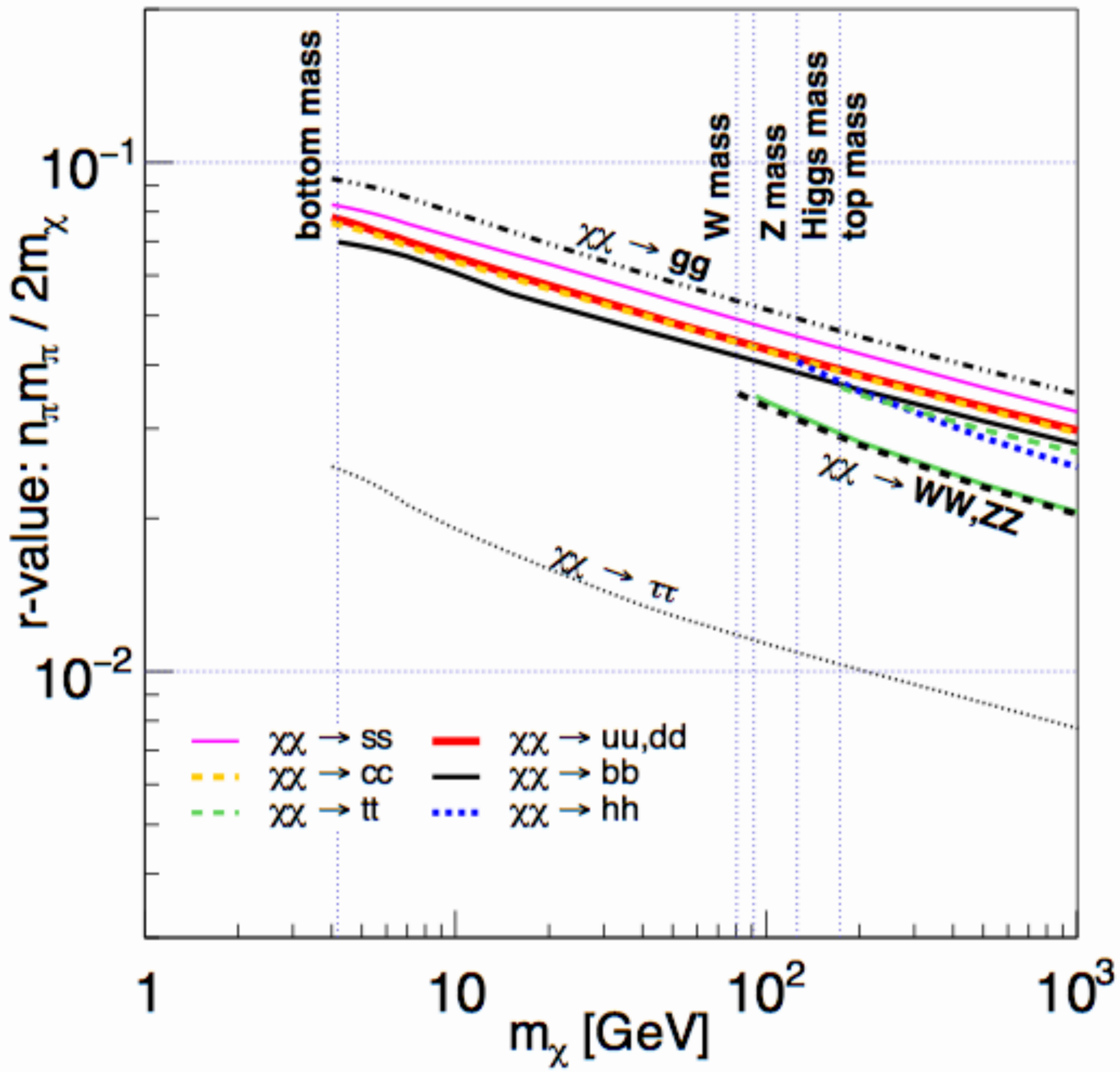
C. Rott, J. Siegal-Gaskins, J.F.Beacom Physical Review D 88, 055005 (2013) (arXiv1208.0827)



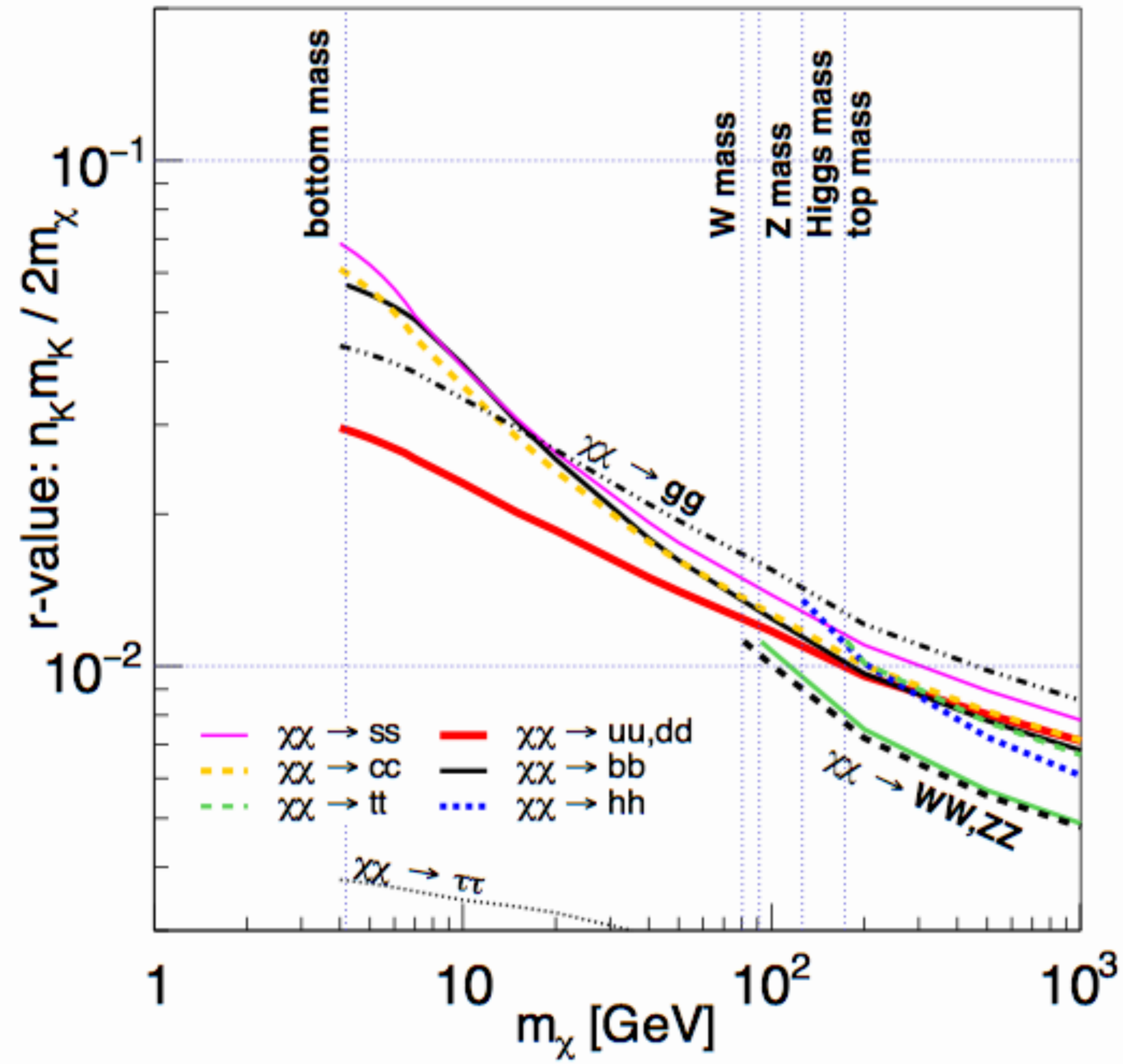
- Previous searches relied on high energy neutrinos directly from the decays of annihilation products
- Model the full hadronic shower in the Sun
- WIMP sensitivity continues to improve for low masses
- Minimal dependence on annihilation channels
- New key detection channel to compliment other searches
- Super-K data can already be used to test DAMA/Libra

Pion and Kaon yields

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



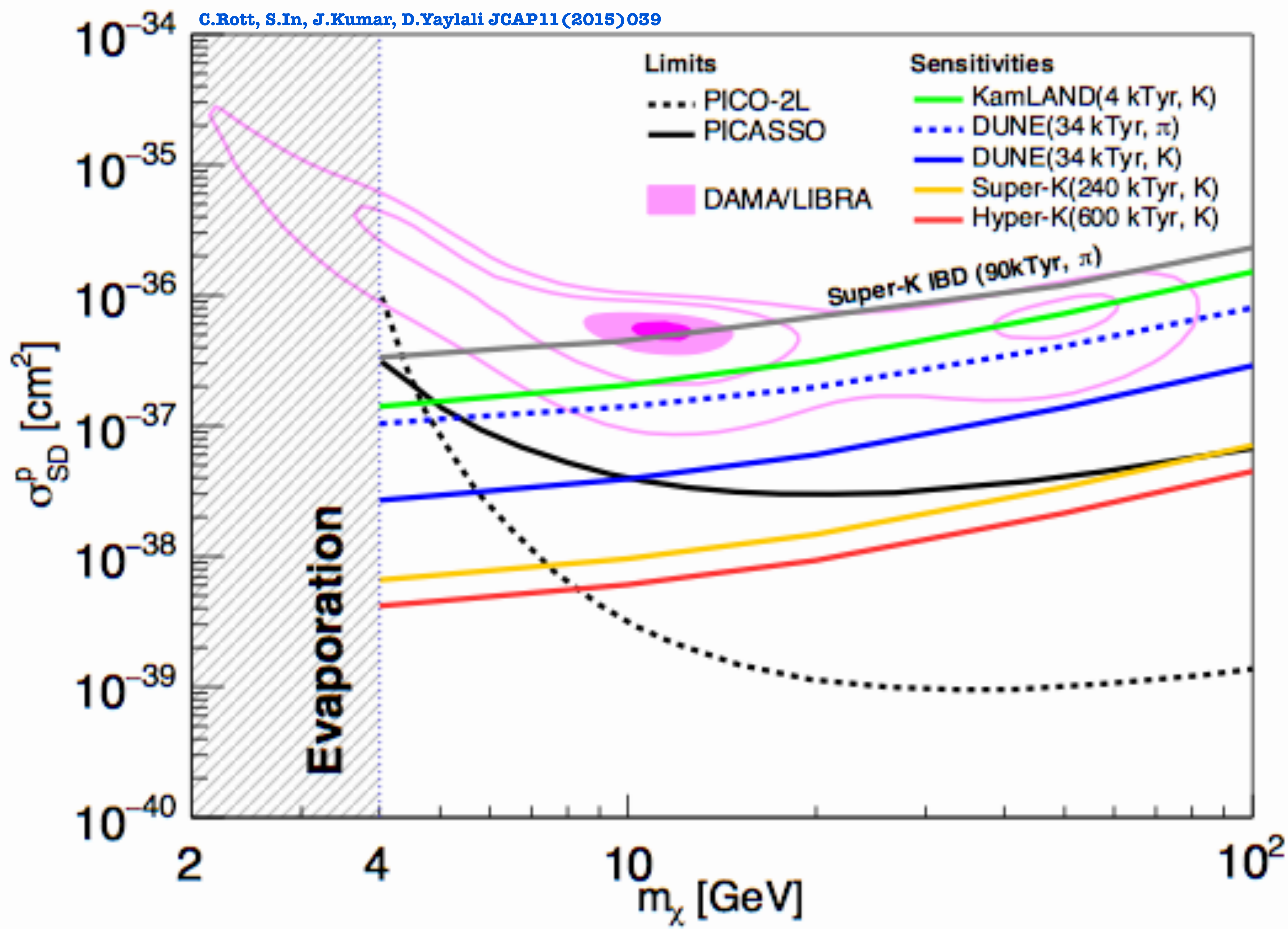
K^+ r-value - fraction of center-of-mass energy which goes into K^+



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

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



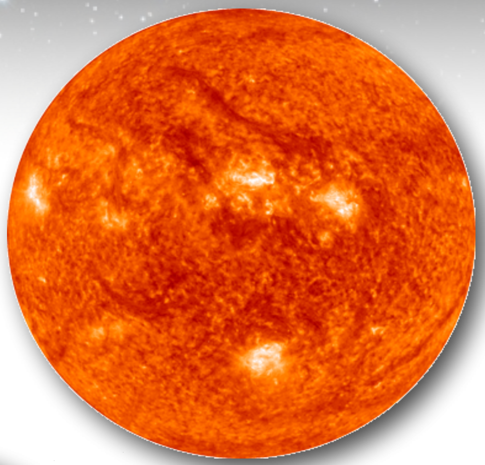
Conclusions

- Indirect Searches for Dark Matter with Neutrinos provide some unique discovery potential
- Hyper-K will be most competitive for dark matter (in particular SD WIMP-nucleon scattering) captured in the **Sun** for masses (4-25GeV)
  - Beat "direct detection neutrino" floor
  - Lines from stopped meson decay enhance signals and give sensitivity to branching fractions
- **Earth** WIMPs (for SI WIMP-nucleon scattering) of interest due to different dependence on dark matter velocity distributions
- Expect best sensitivity for dark matter annihilation in the Milky Way halo for low WIMP masses

Thanks !

Importance of Neutrinos

- **Galactic halo, Galactic center, Dwarf spheriodals, Cluster of Galaxies, ...**
  - Gamma-rays extremely competitive for low WIMP masses, but any detection would likely require an independent confirmation of neutrino signals
  - high masses(>1TeV) - large neutrino telescopes are most competitive
- **Dark Matter in the Sun**
  - Discovery channel for neutrinos
  - Due to significant neutrino absorption at high energies, Solar WIMP signals are detected in the energy range below 100GeV
- **Dark Matter in the Earth**
  - Capture mechanism highly favors low-mass (<60GeV) WIMPs
  - Very large uncertainties for any flux prediction as annihilation and capture rate are not expected to be in equilibrium



GC Sensitivity Hyper-K