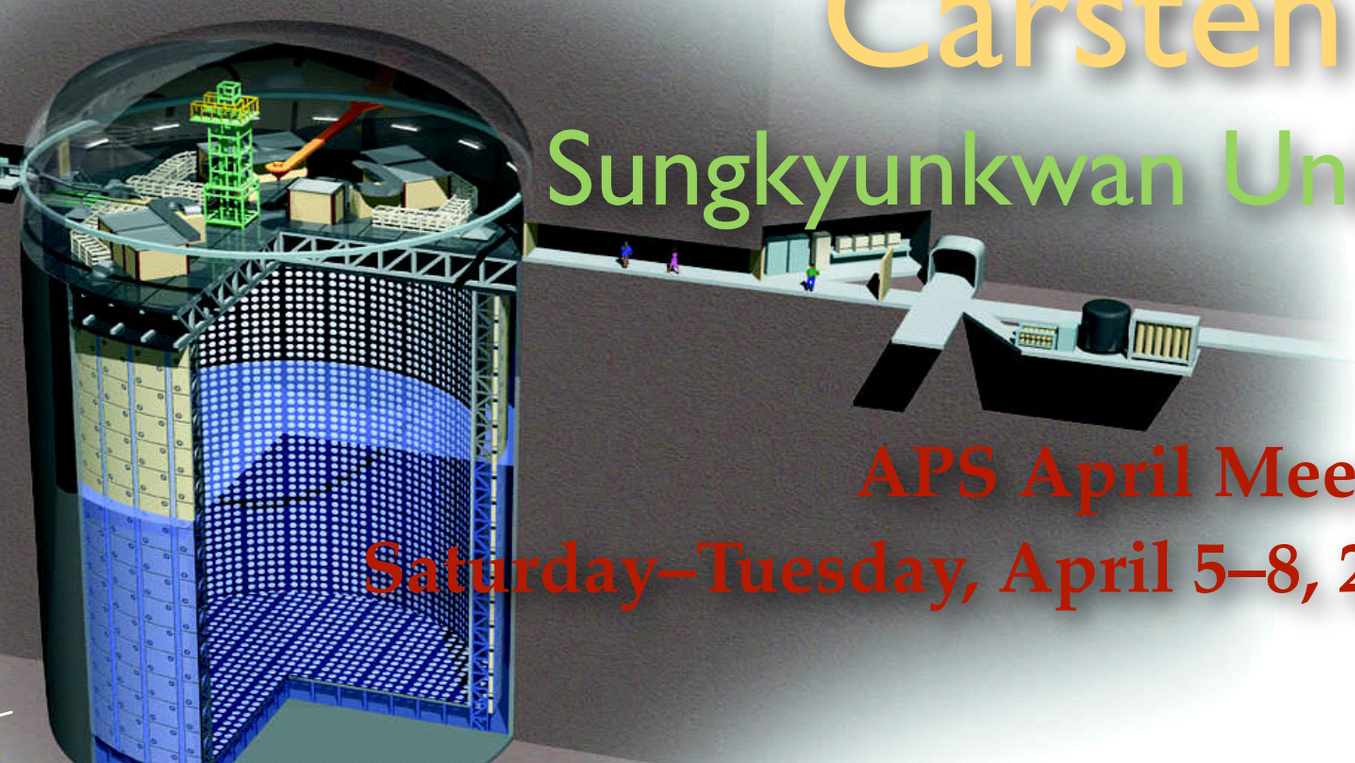
APS physics

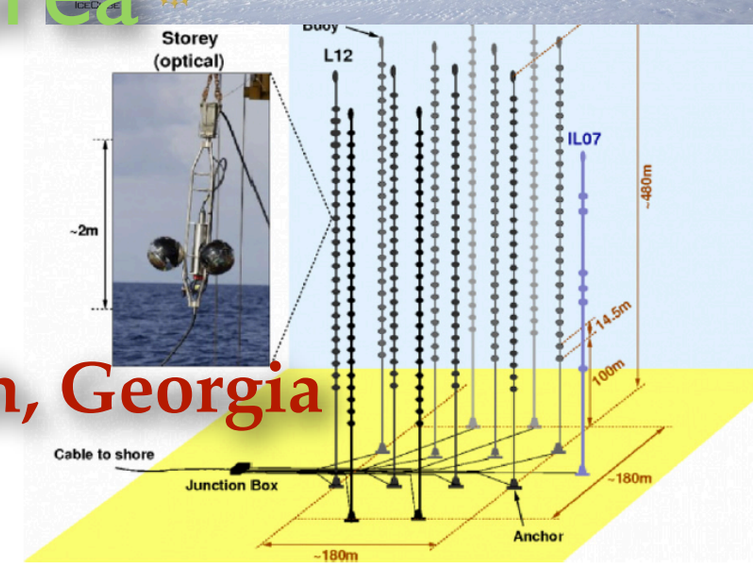
APRIL MEETING2014

Overview of Indirect Dark Matter Searches with Neutrinos

Carsten Rott

Sungkyunkwan University, Korea





APS April Meeting 2014

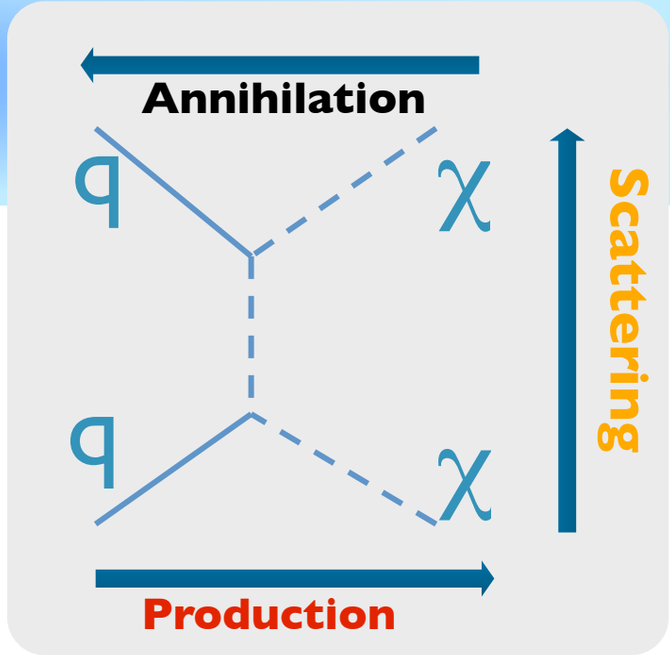
Saturday–Tuesday, April 5–8, 2014; Savannah, Georgia

Overview

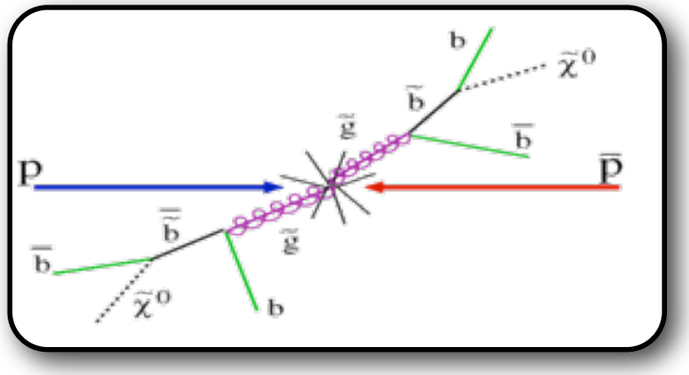
- Motivation
- Neutrino Signals from Dark Matter
- Neutrino Telescopes and Detectors
- Overview of latest results
  - Dark Matter Self-annihilation cross section
  - WIMP Nucleon scattering cross section
- Future Prospects
- Conclusions

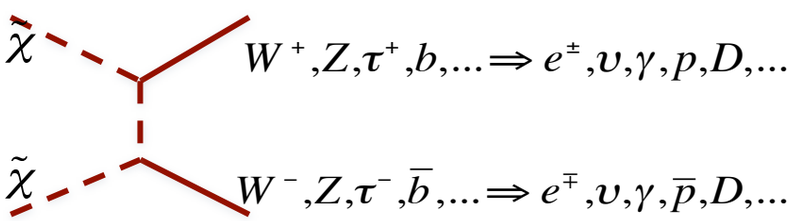
Motivation

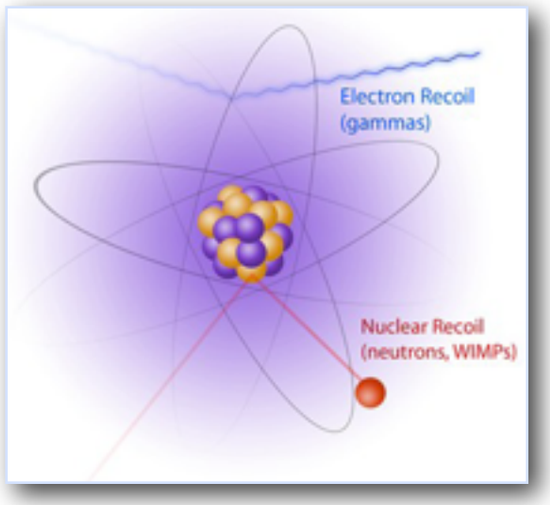
Role of Neutrinos



WIMP - Weakly Interacting Massive Particle





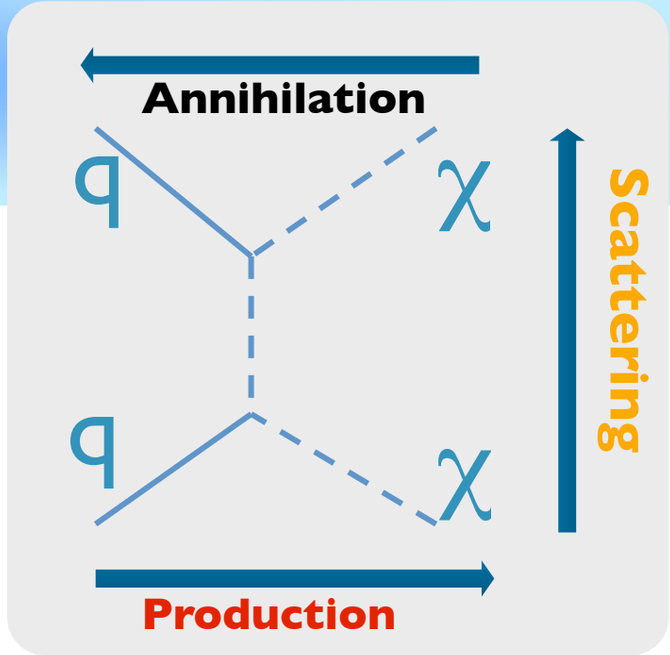


- **Production**
  - Colliders
- **Indirect Searches**
  - Annihilation of Dark Matter in Galactic Halo, ...
    - Gamma-rays, electrons, neutrinos, anti-matter, ...
  - Annihilation signals from WIMPs captured in the Sun (or Earth)
    - Neutrinos
- **Direct Searches**
  - WIMP scattering of nucleons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

WIMP Self-annihilation cross section

WIMP-Nucleon Scattering cross section

Role of Neutrinos



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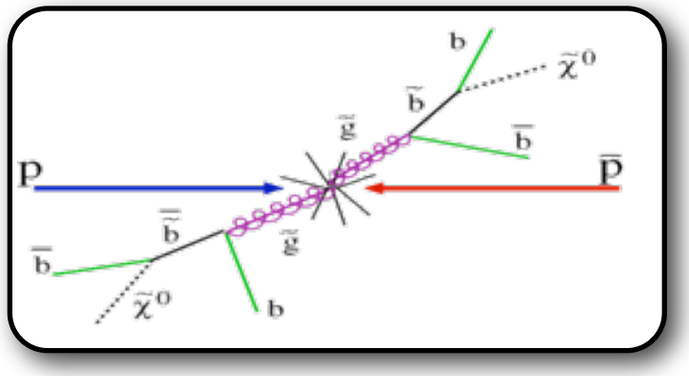

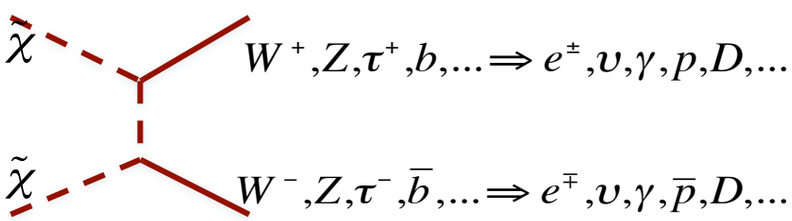

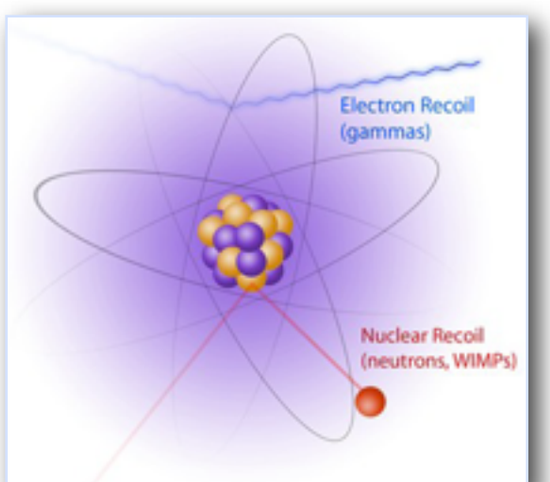

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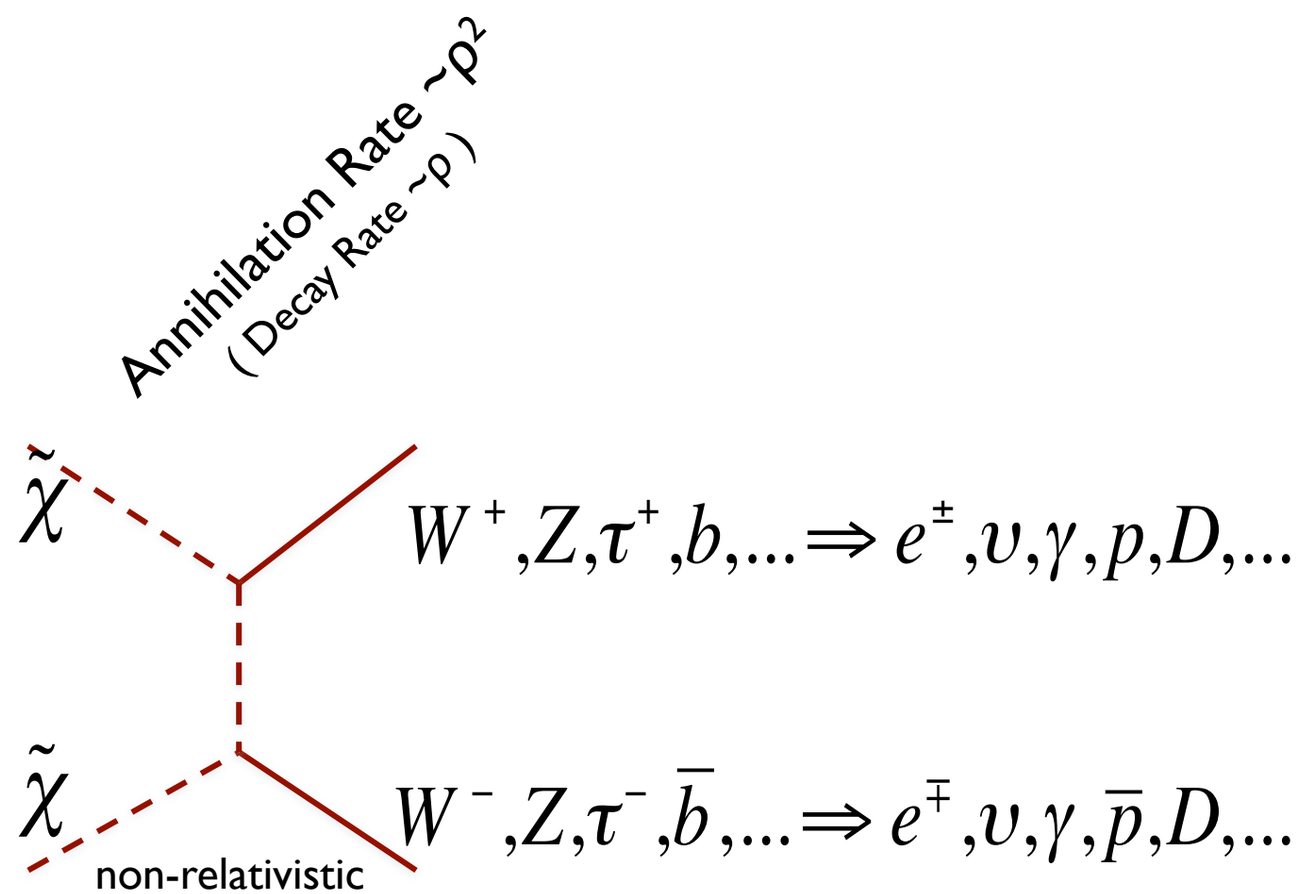
WIMP Self-annihilation cross section

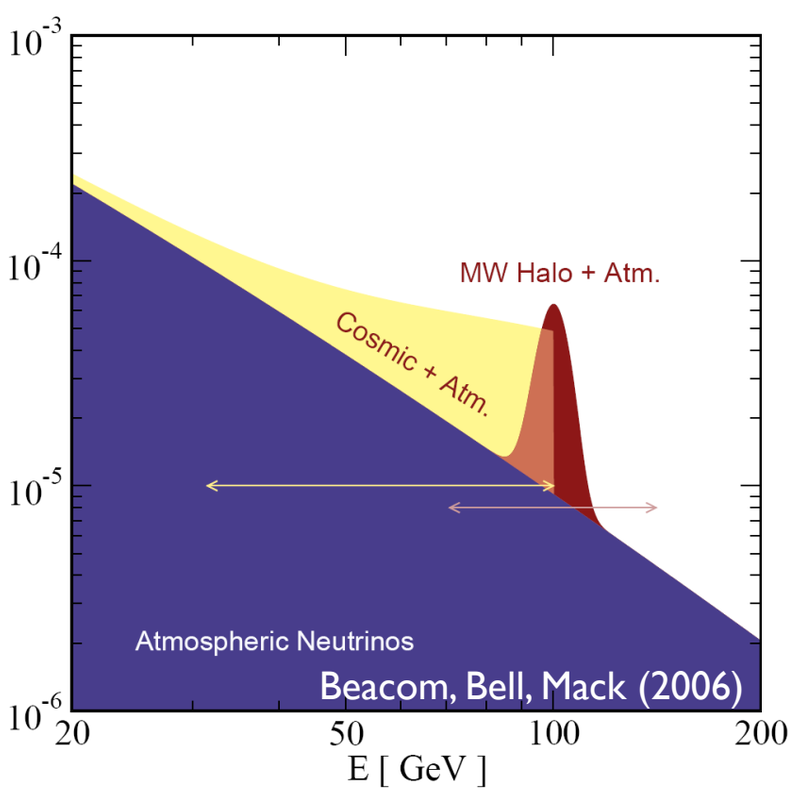
WIMP-Nucleon Scattering cross section

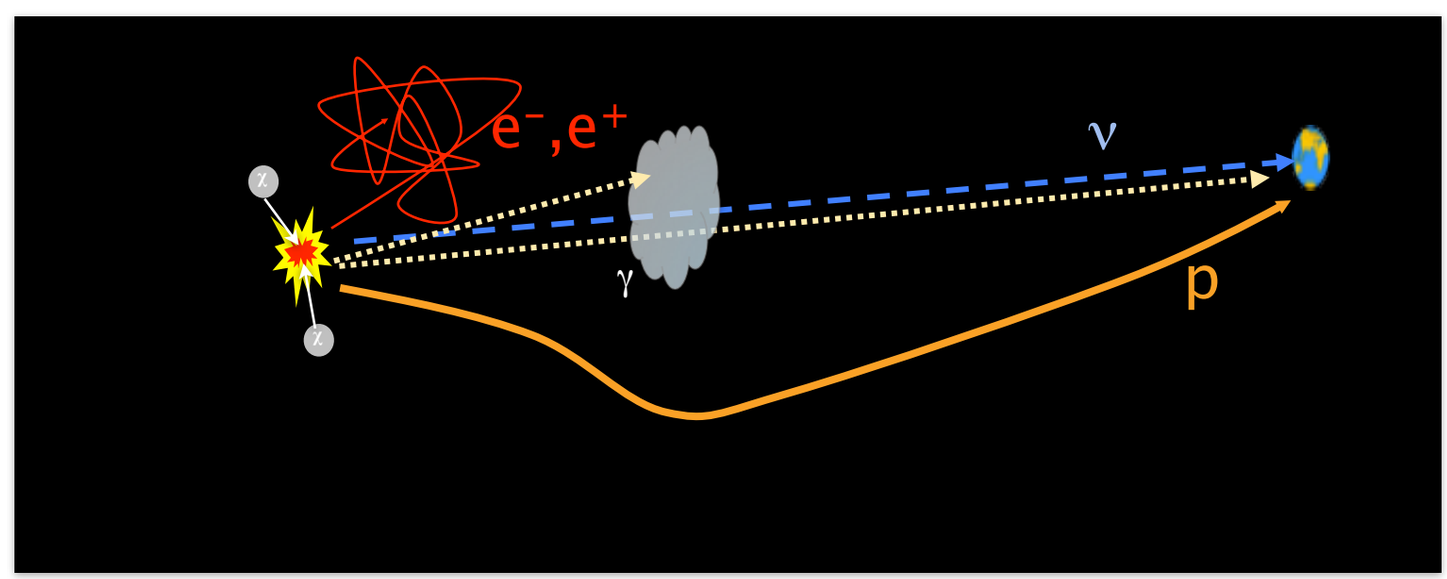
Dark Matter Annihilation Signals

- Identify overdense regions of matter

  ⇒self-annihilation can occur at significant rates
- Pick prominent Dark Matter target
- Understand backgrounds
- Features in the signal can be used to better distinguish backgrounds
  - Line / End-point







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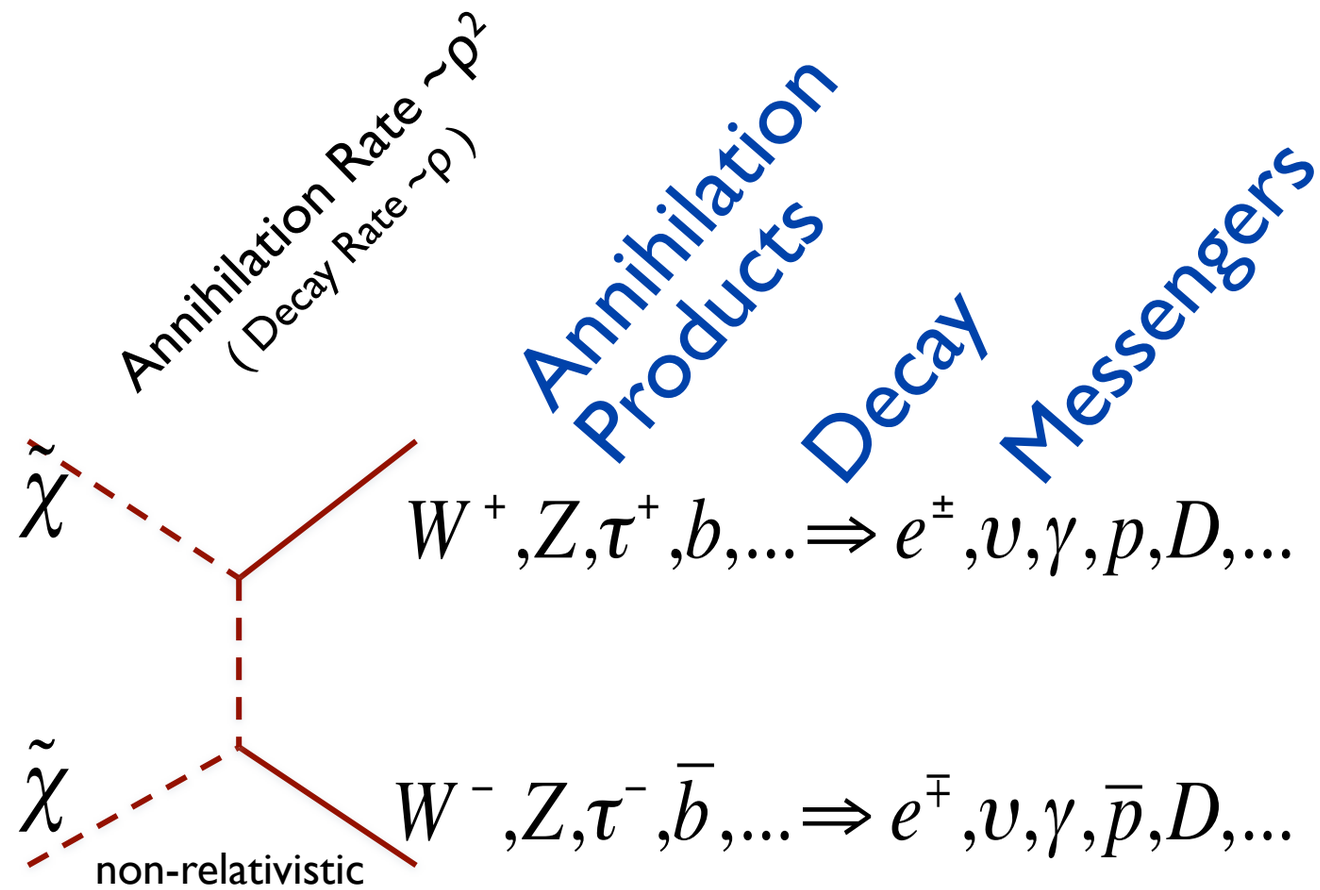
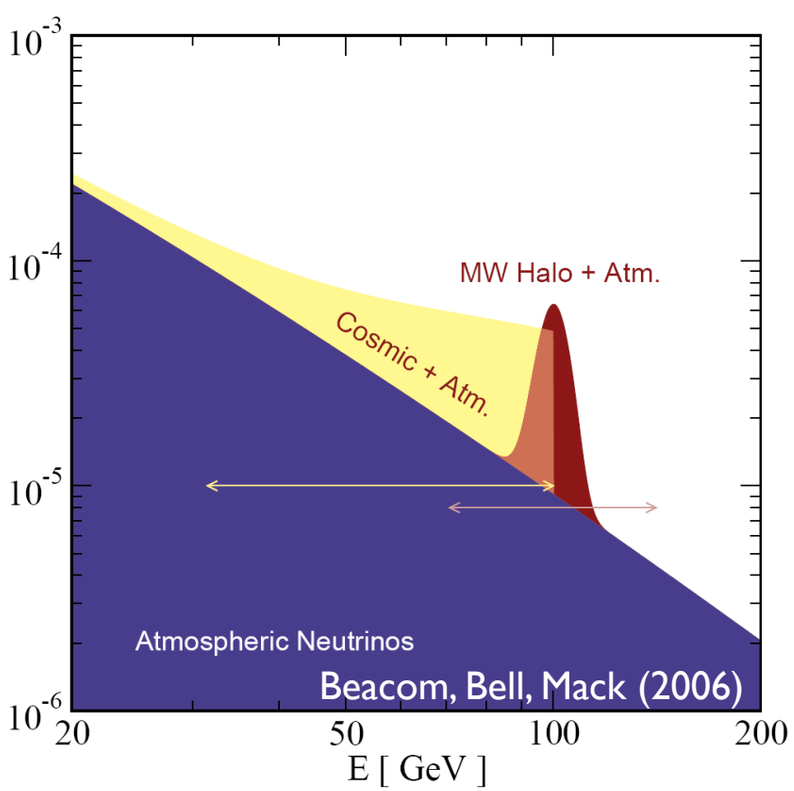
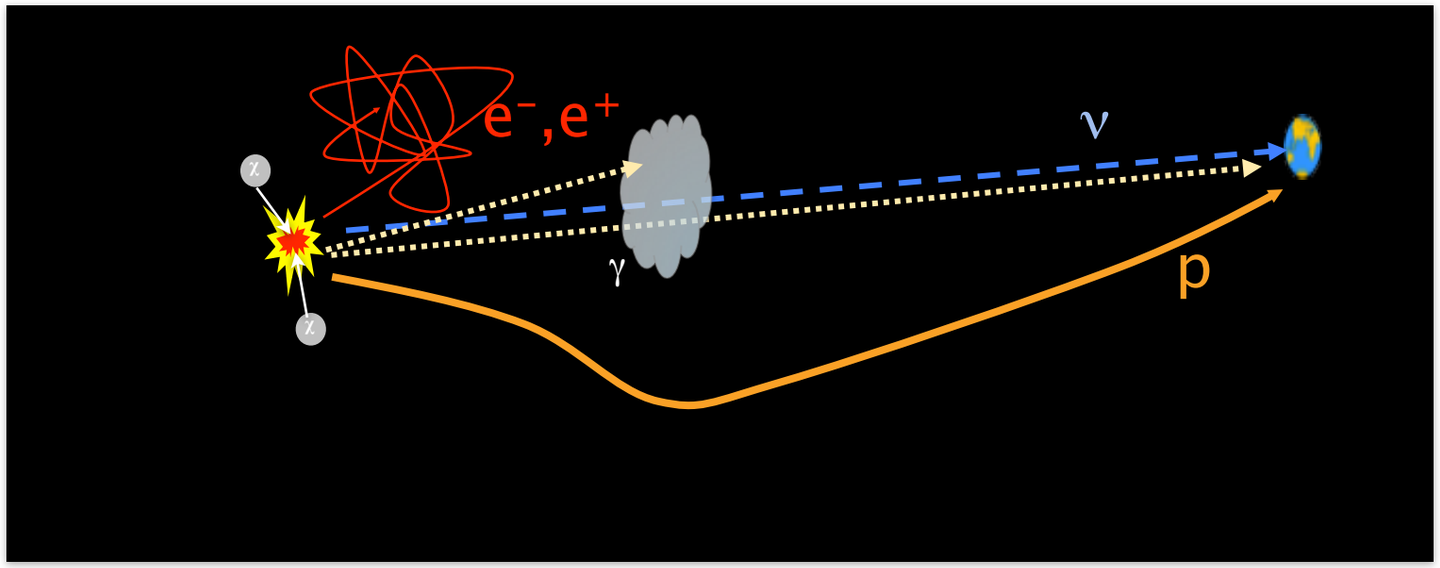
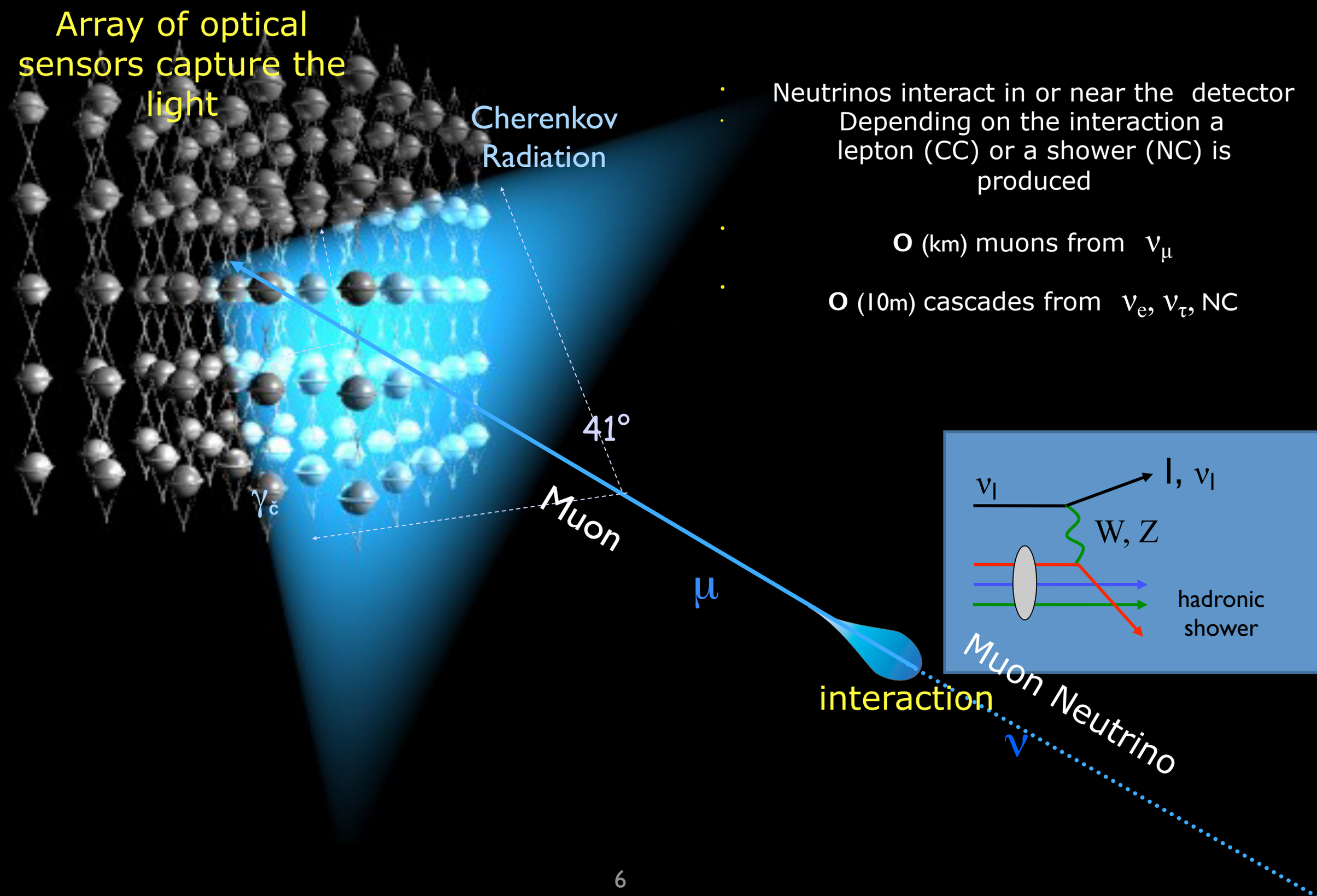






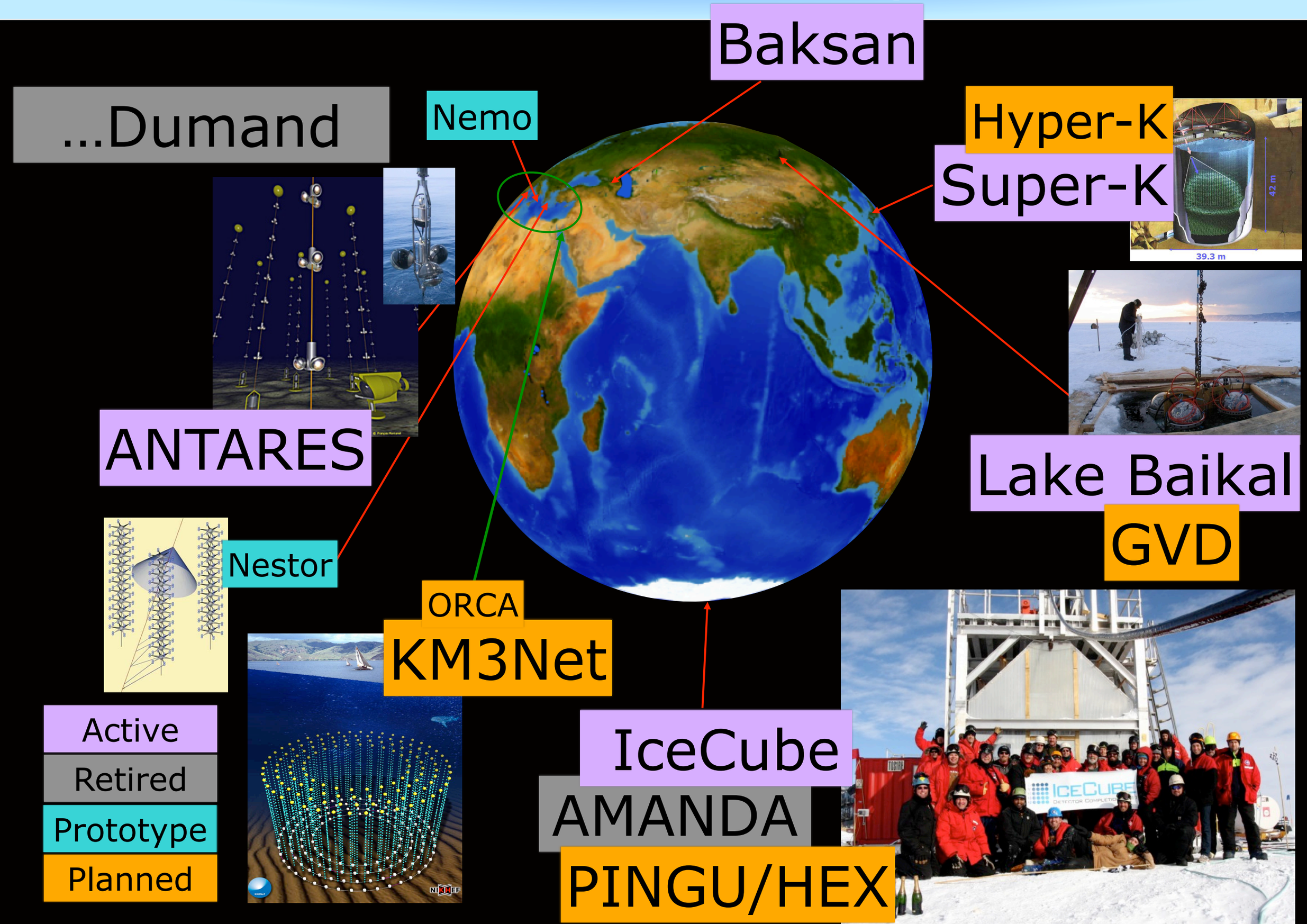
Principle of an optical Neutrino Detector



- 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

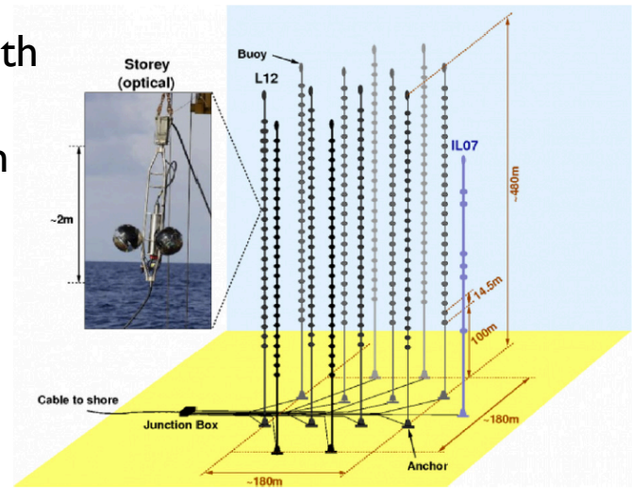
Neutrinos Telescopes

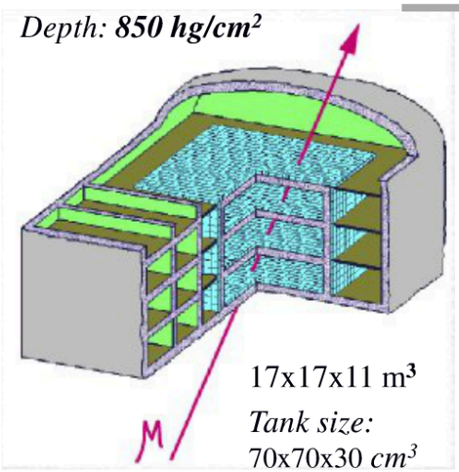
Neutrino Telescopes / Detectors



Neutrino Telescopes / Detectors

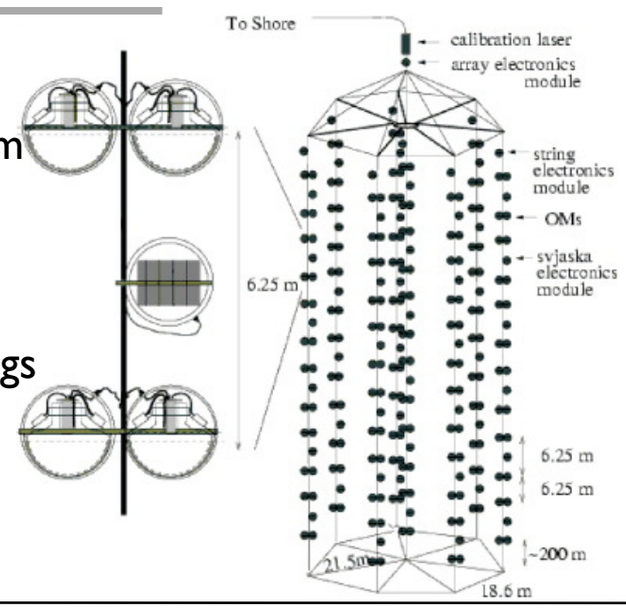
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



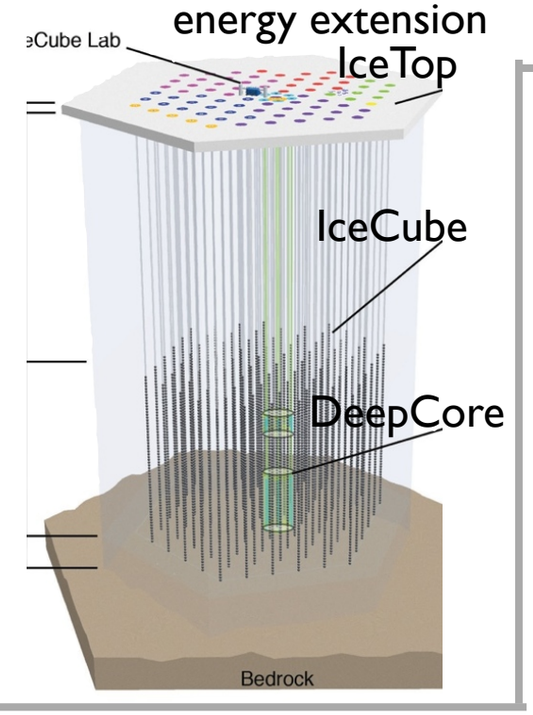


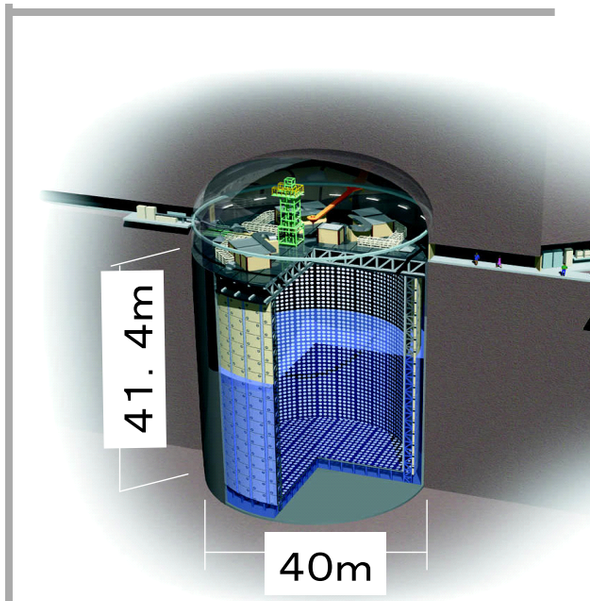
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- Lake **Baikal**, Siberia, at a depth 1.1 km NT36 in 1993
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length



- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km^3
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension





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

Signals in IceCube

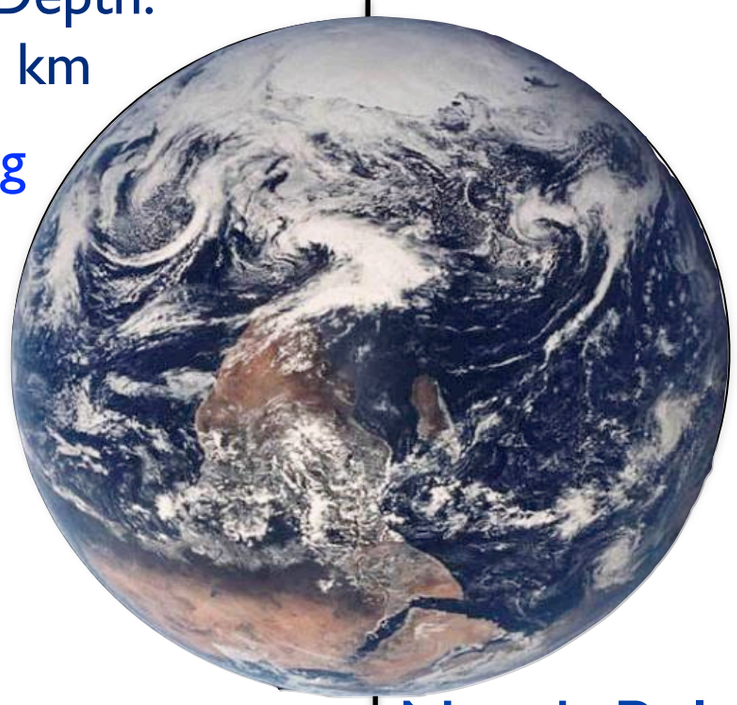
South Pole

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

$\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \rightarrow e^{+} \nu_{e} \nu_{\mu} \nu_{\mu}$

IceCube Depth:
1.5-2.5 km

Downgoing Muons



North Pole

- 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

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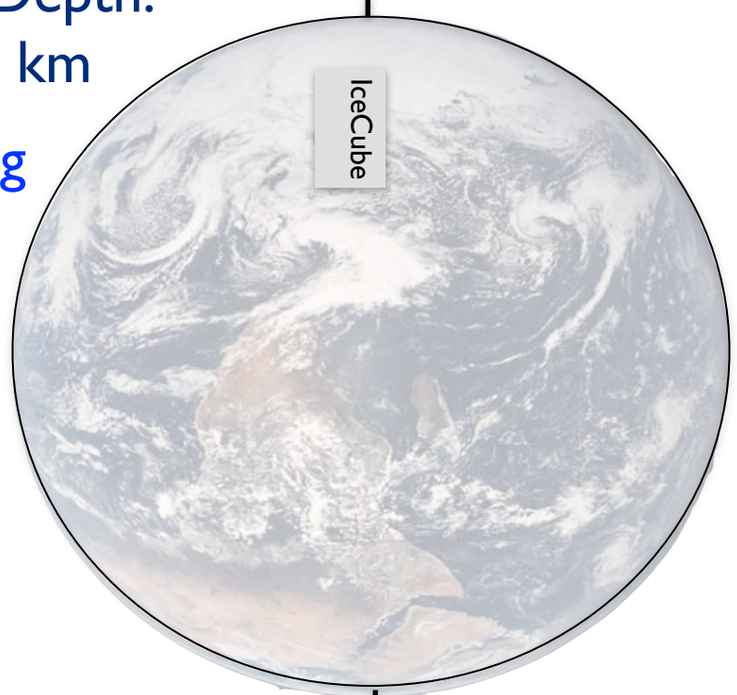

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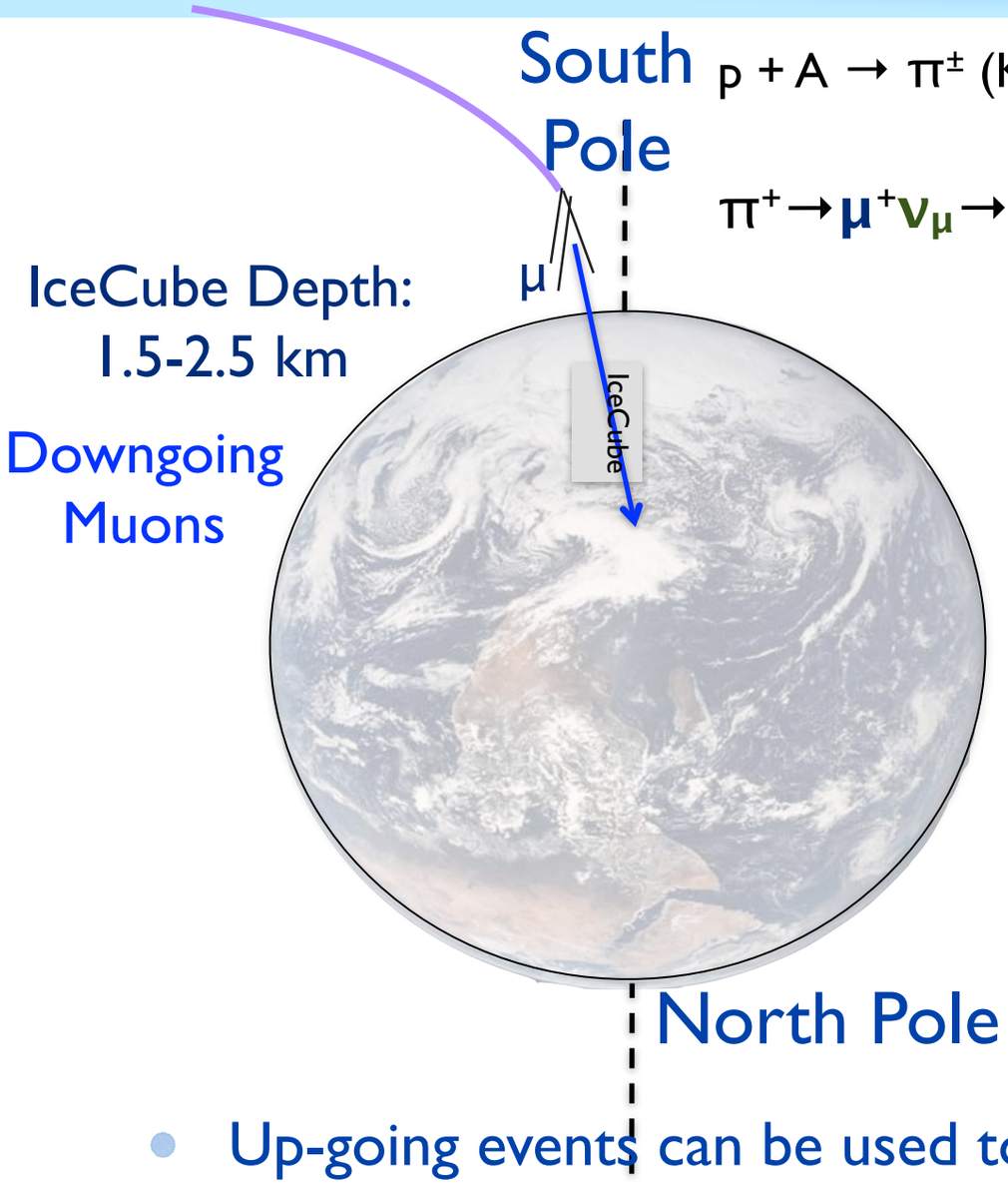

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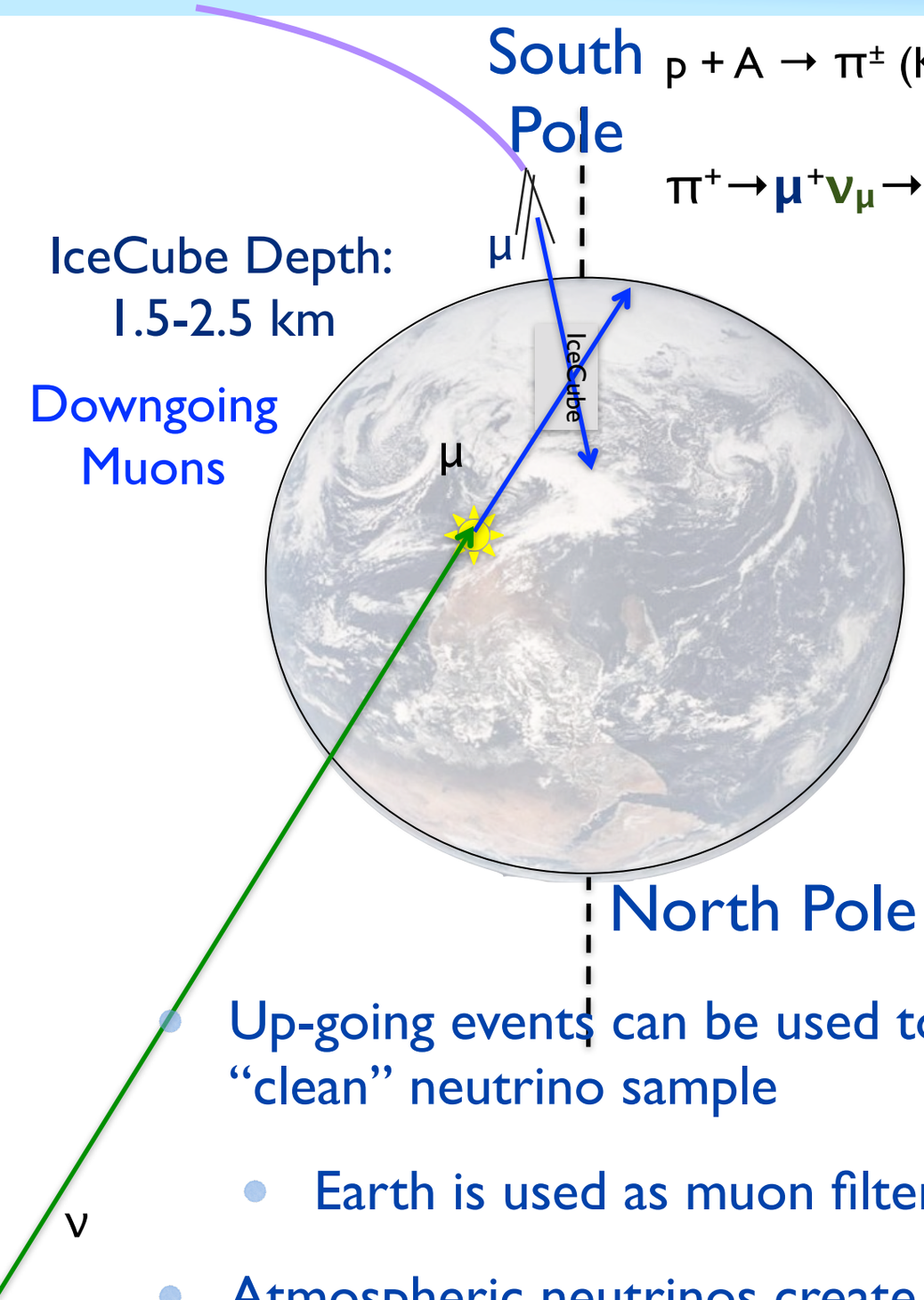

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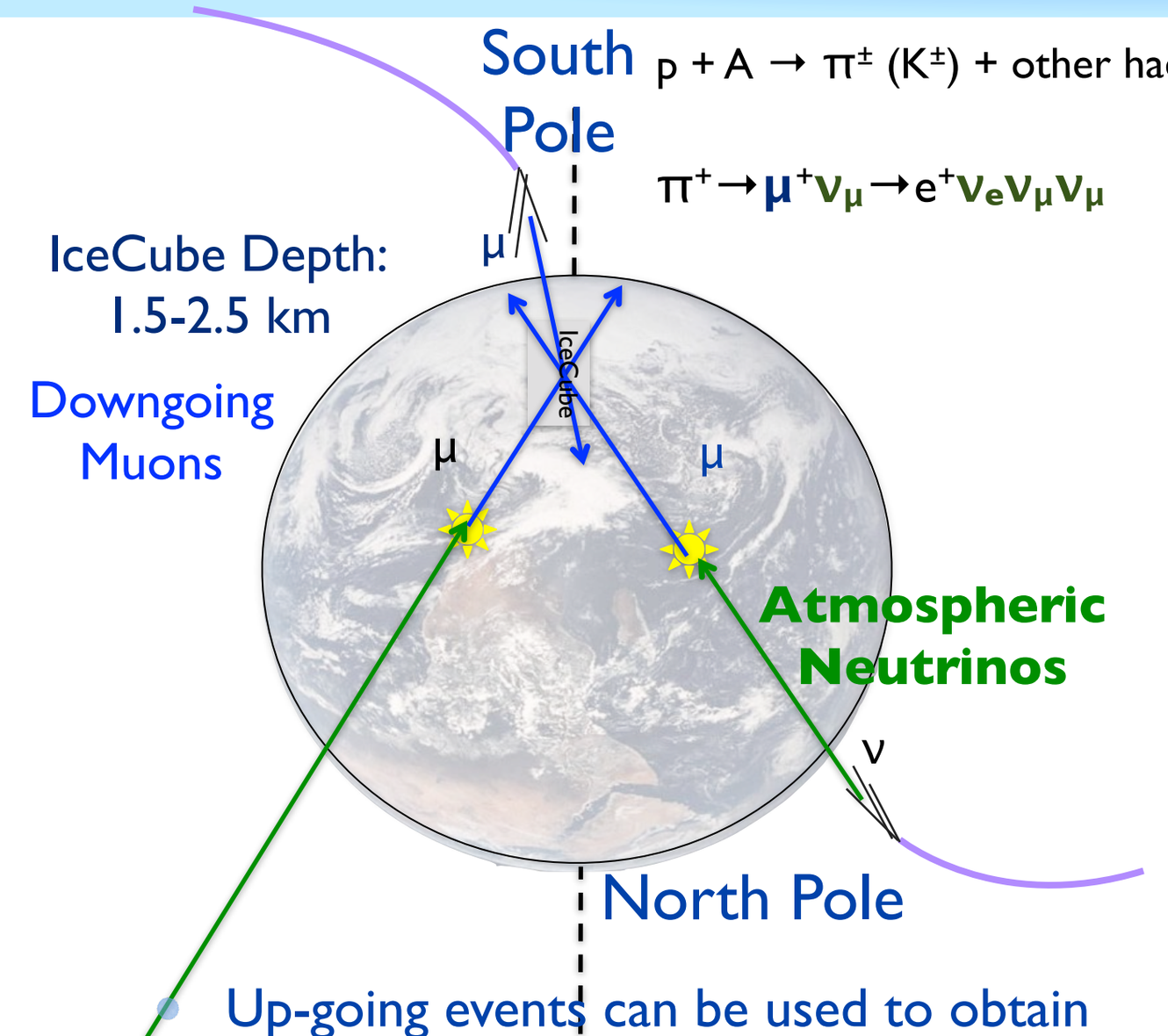

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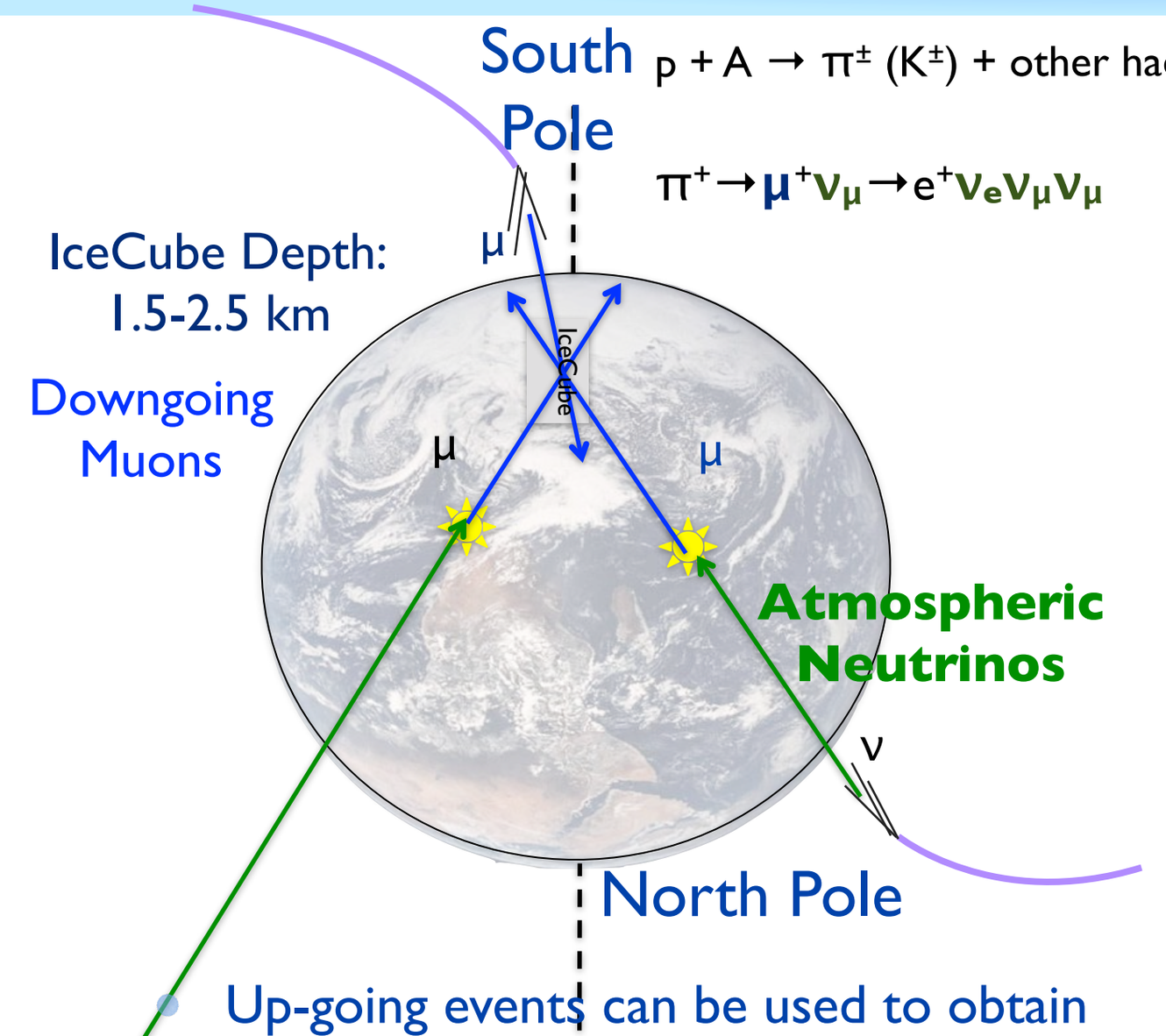

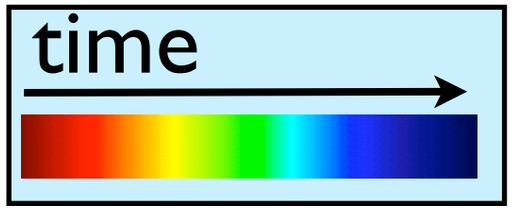

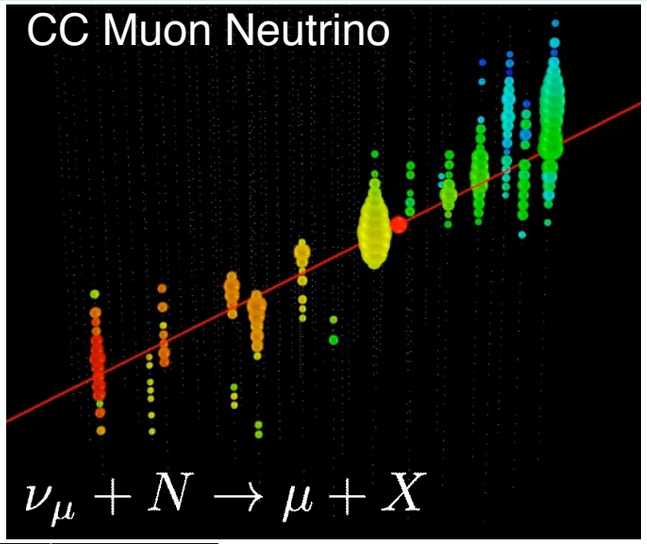

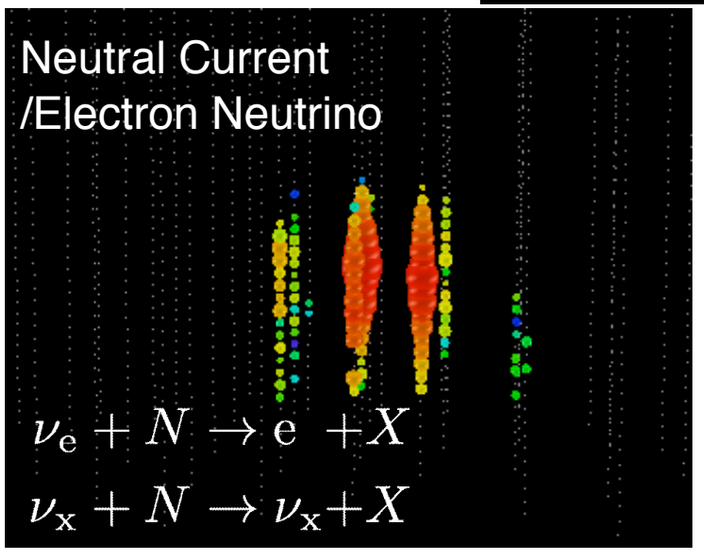

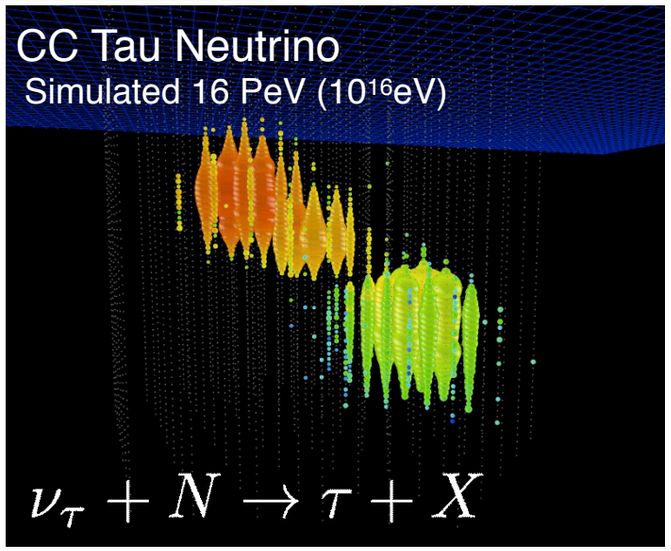

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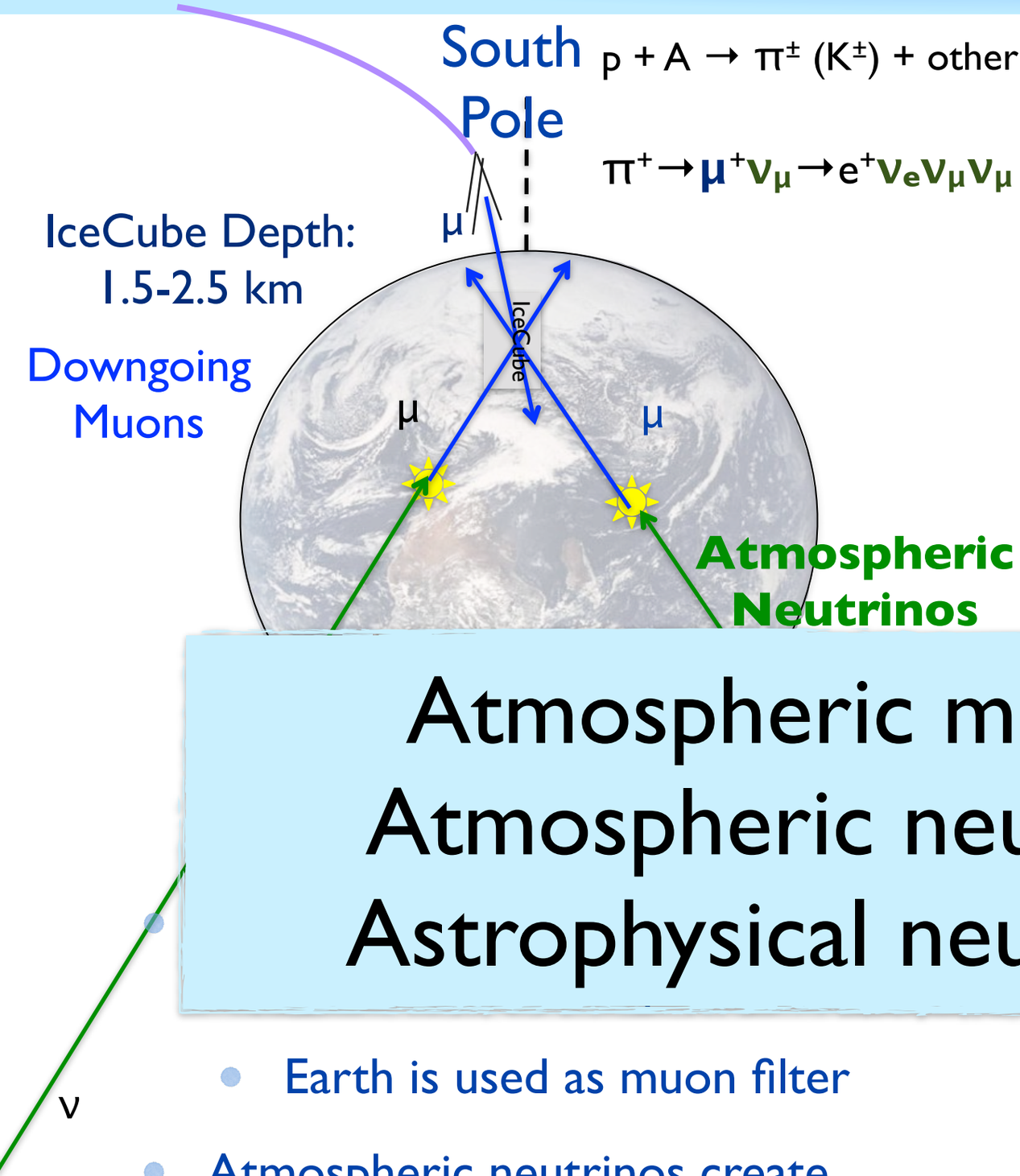
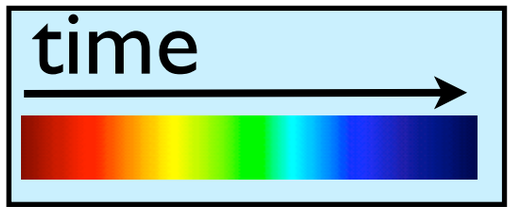
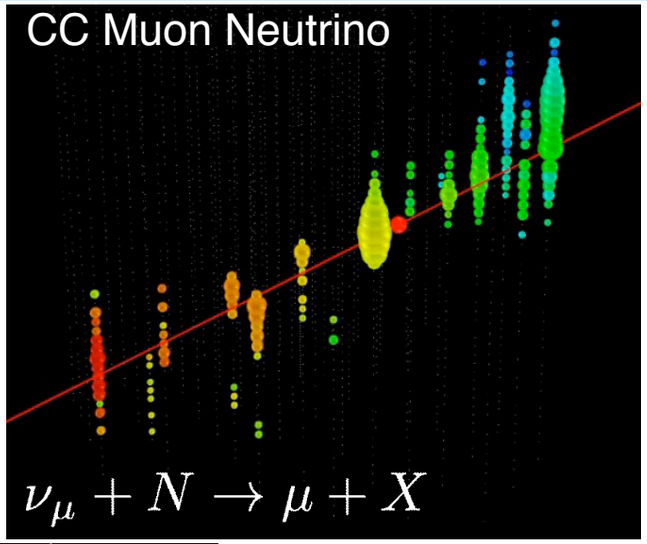
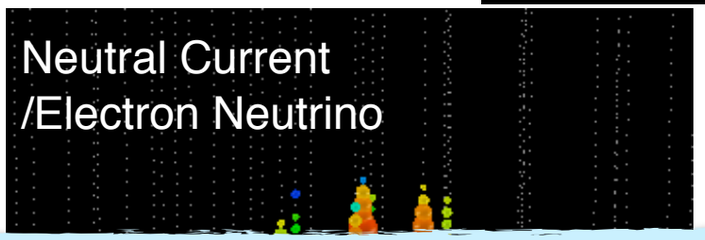
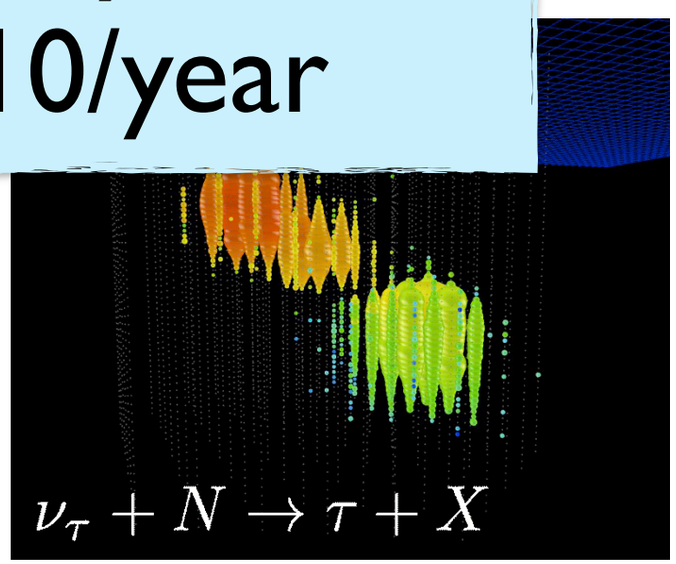








Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
Astrophysical neutrinos ~ >10/year



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Dark Matter Self-annihilations

$\langle \sigma_A v \rangle$

Dark Matter in the Milky Way

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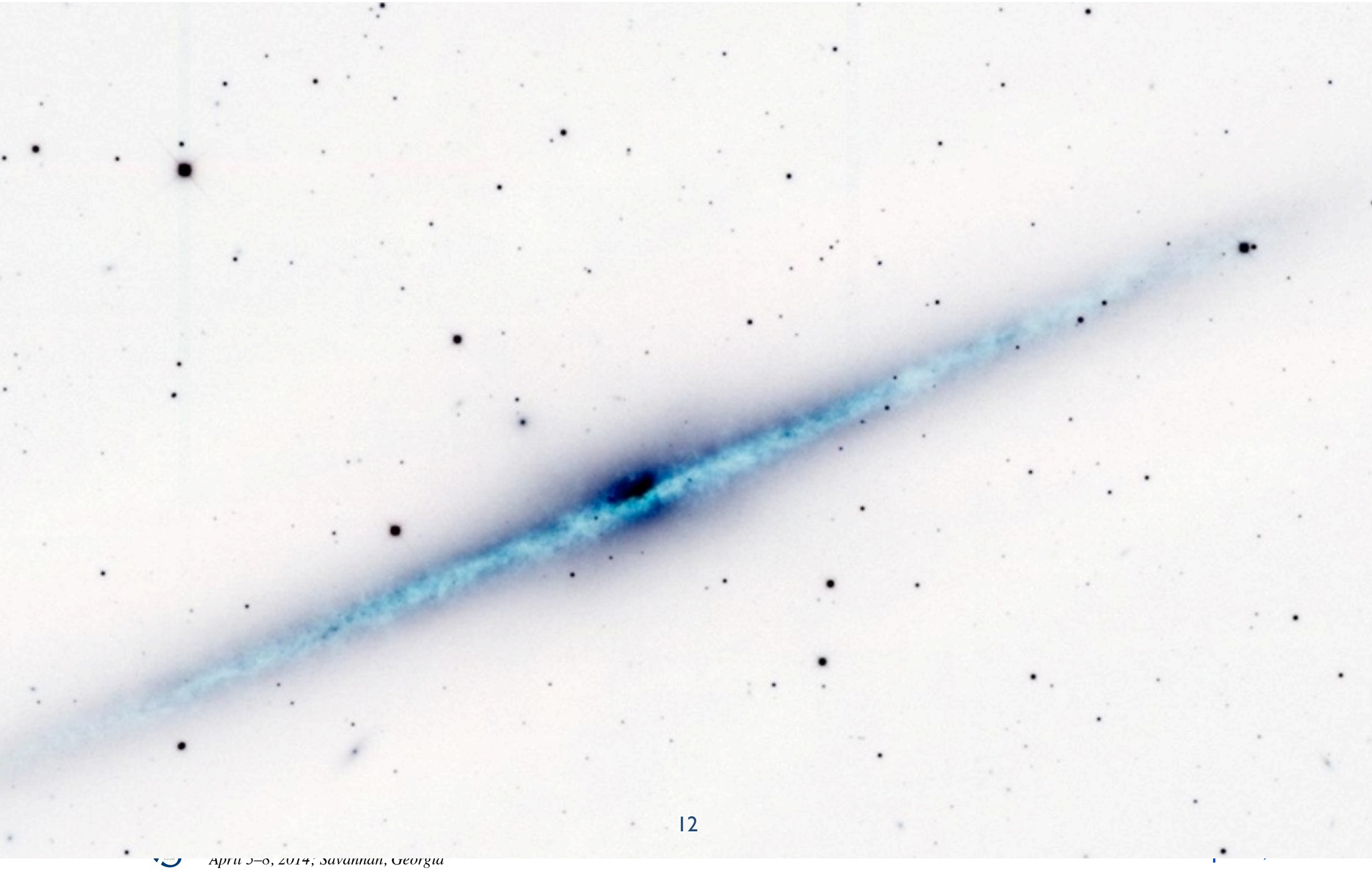

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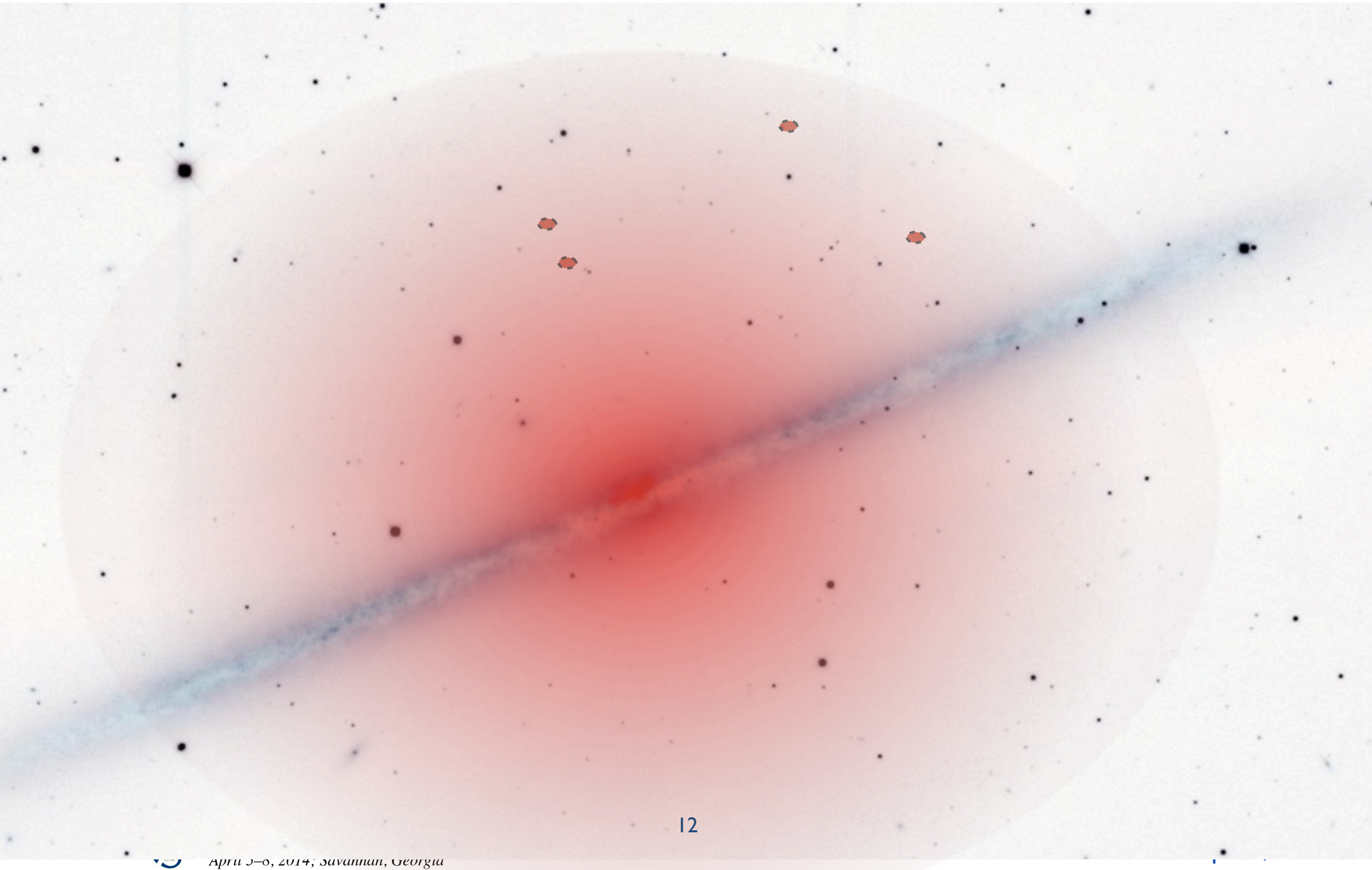

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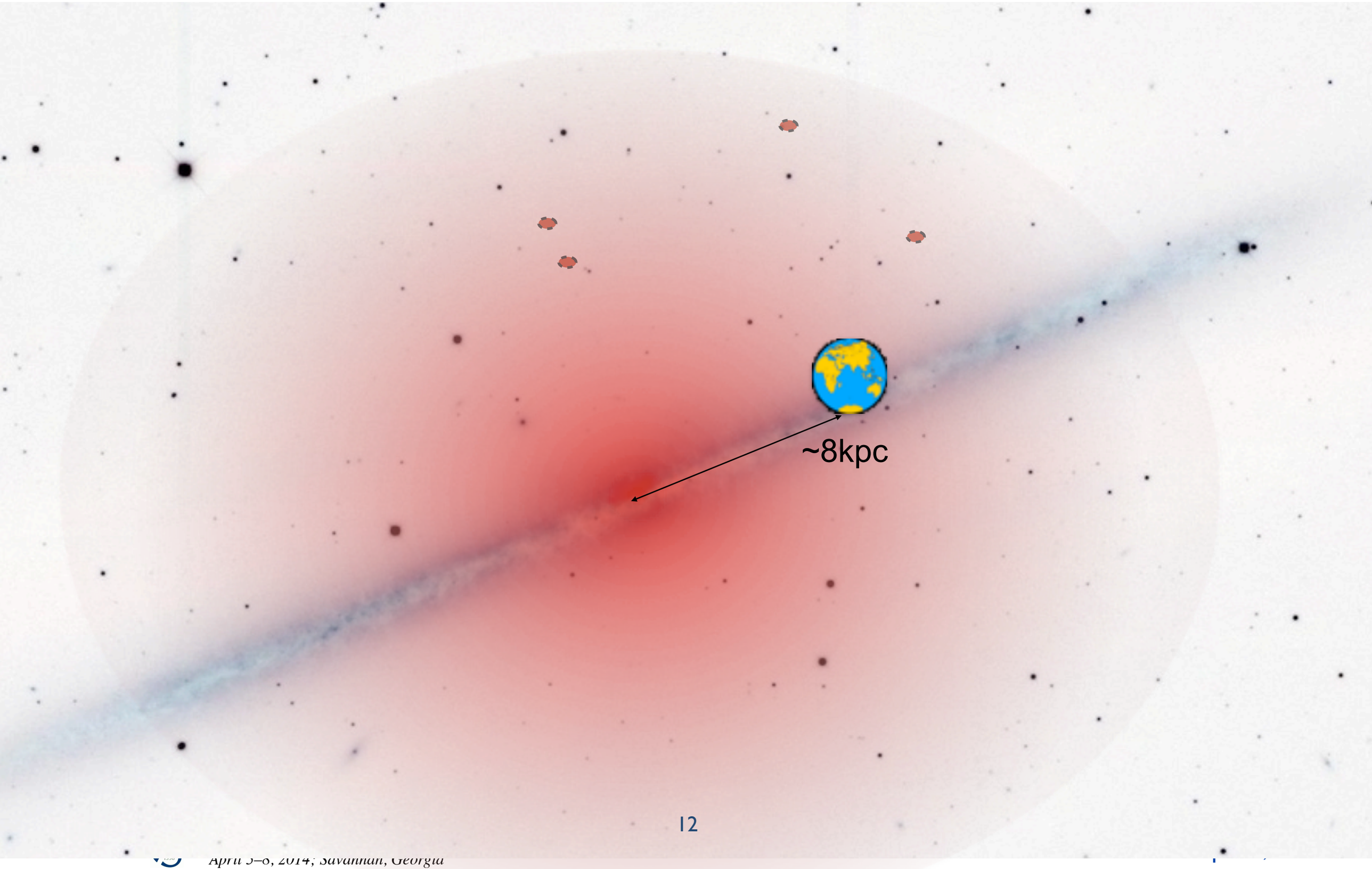

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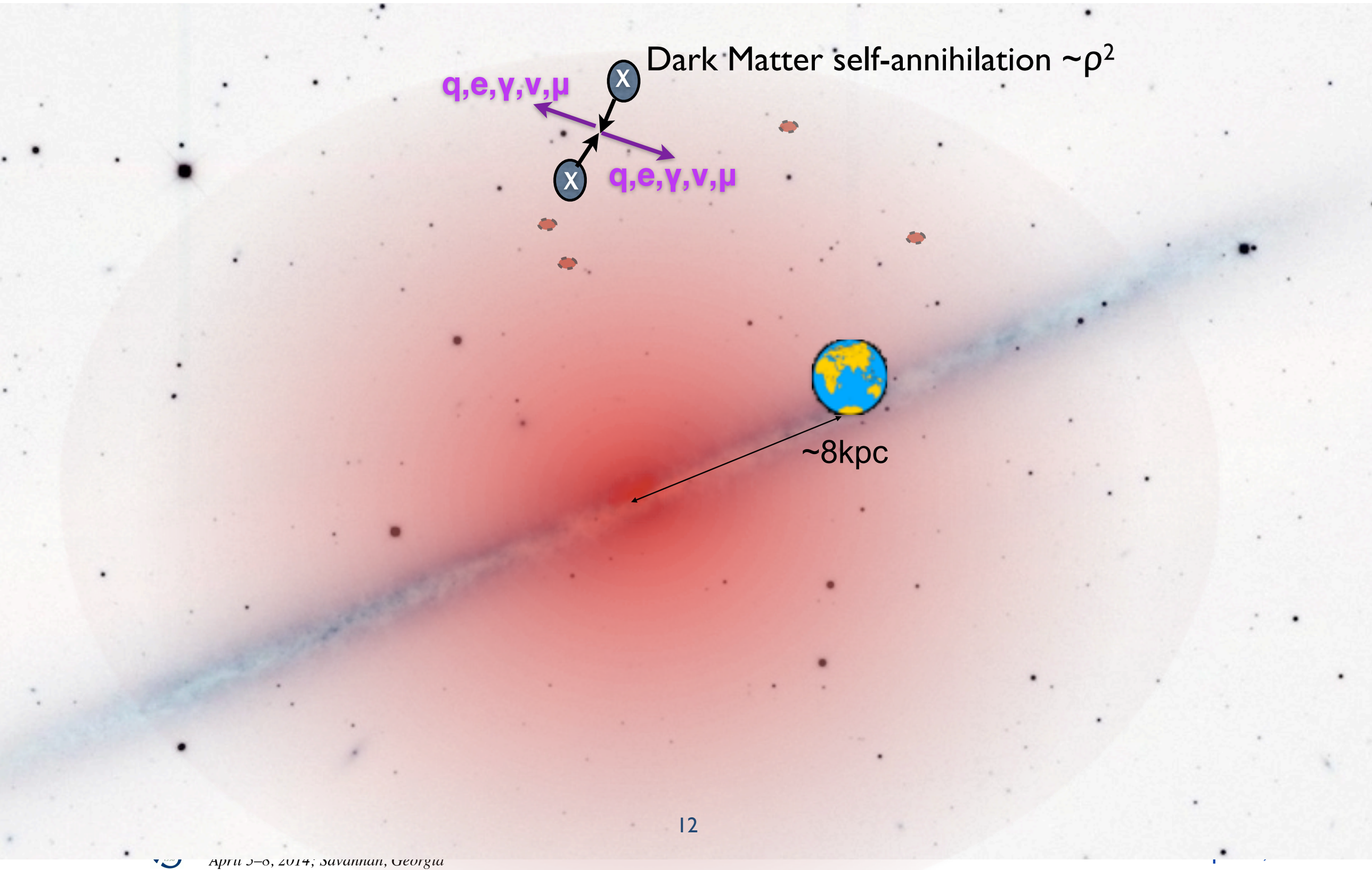

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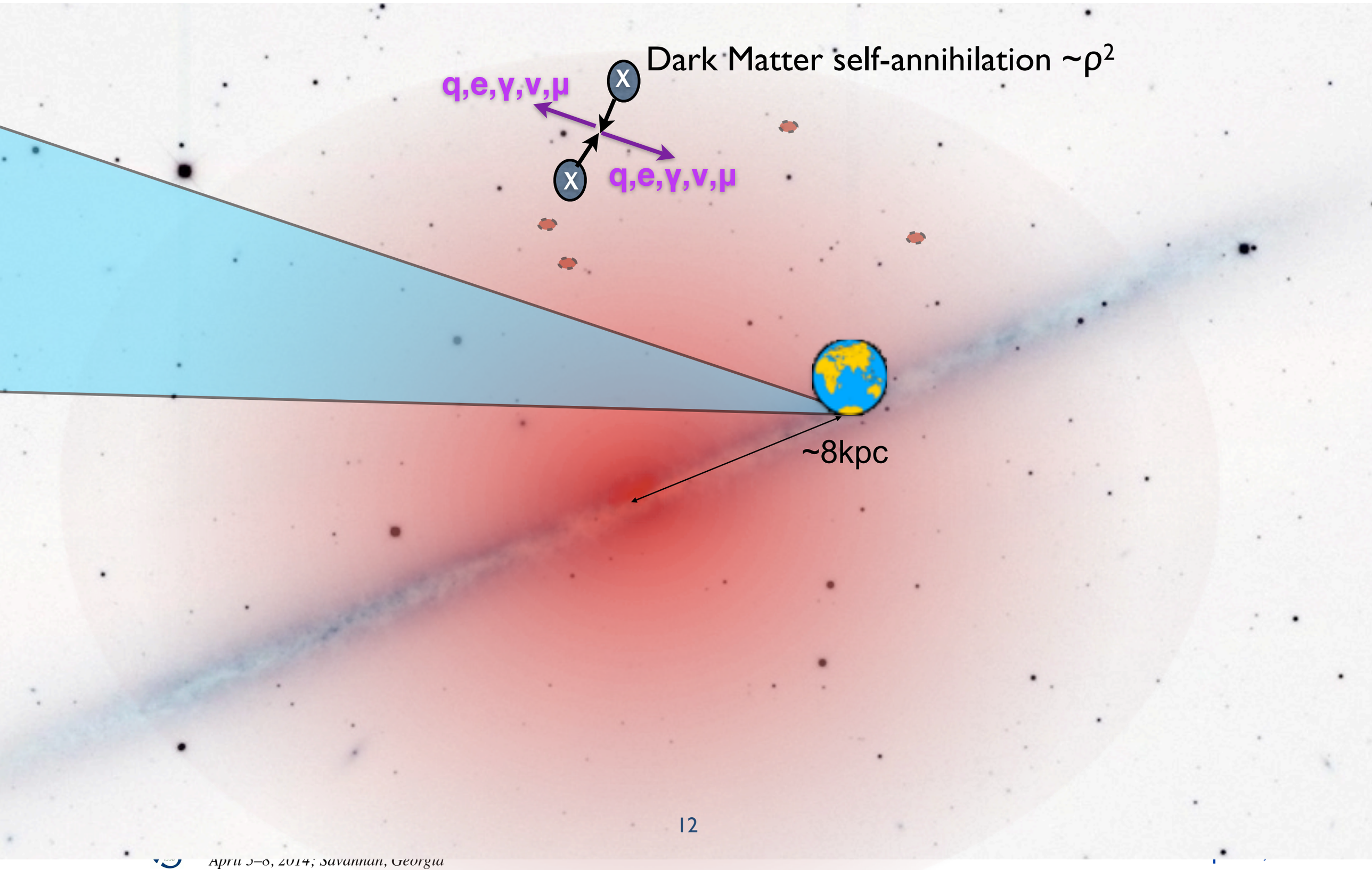

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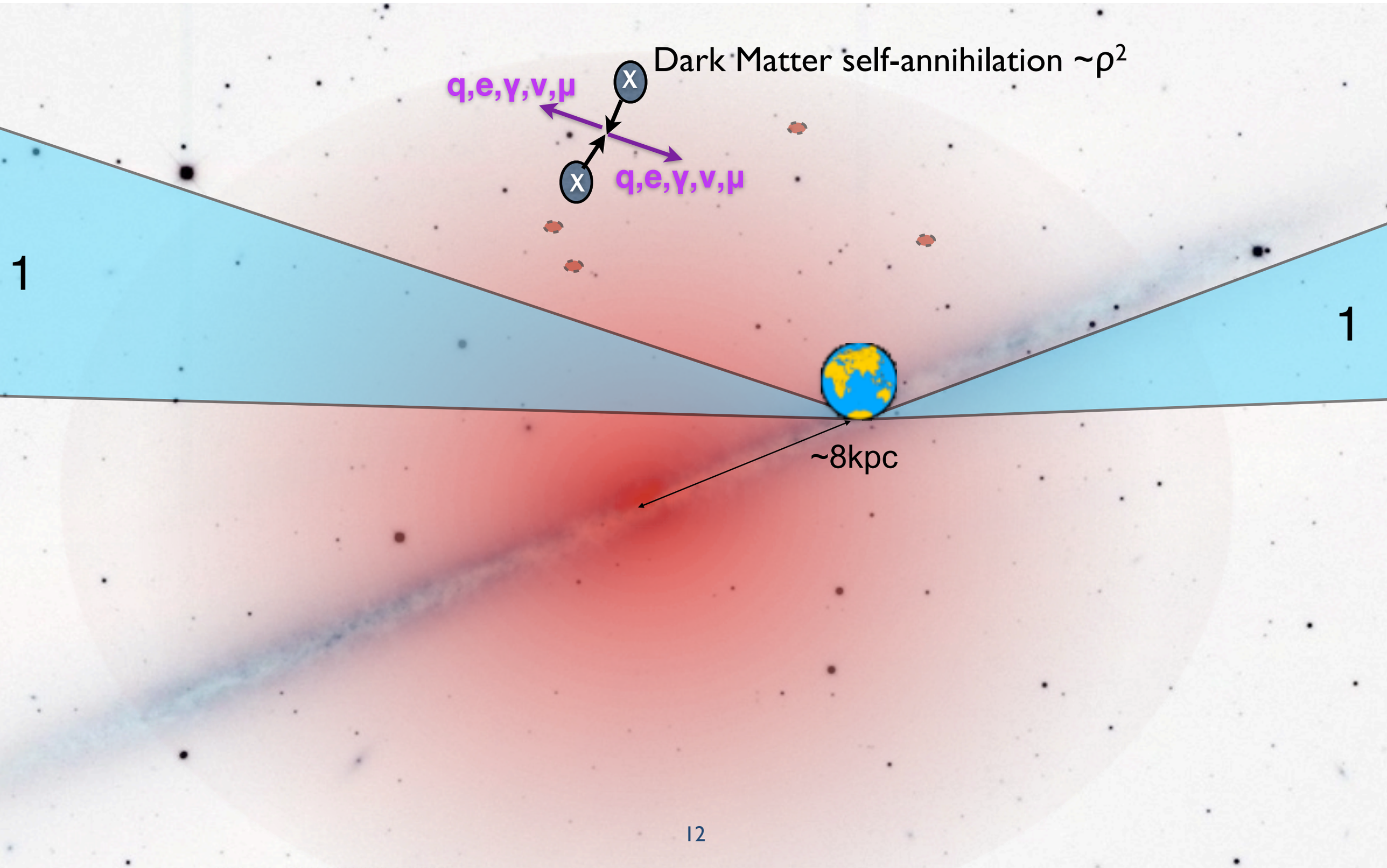

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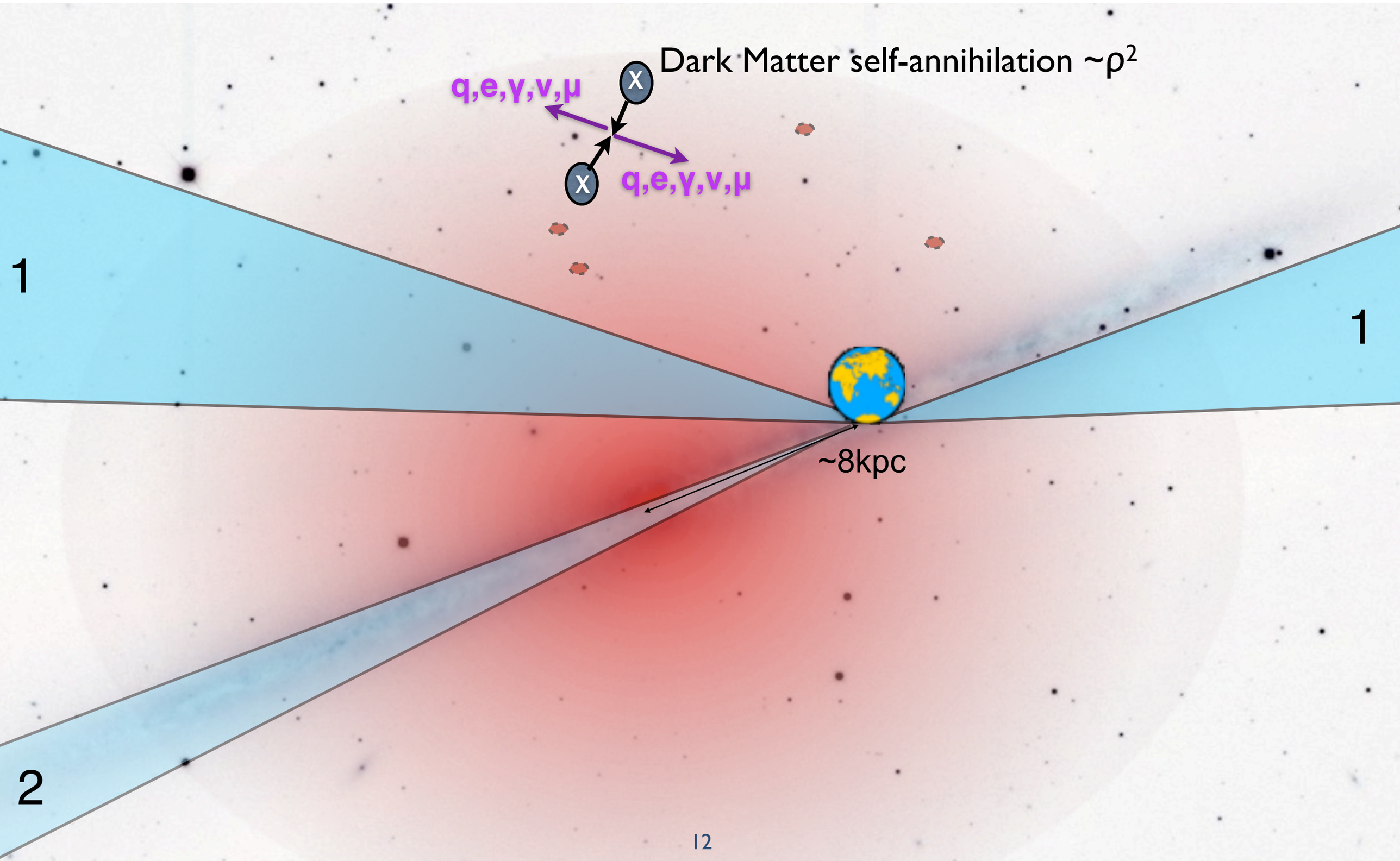

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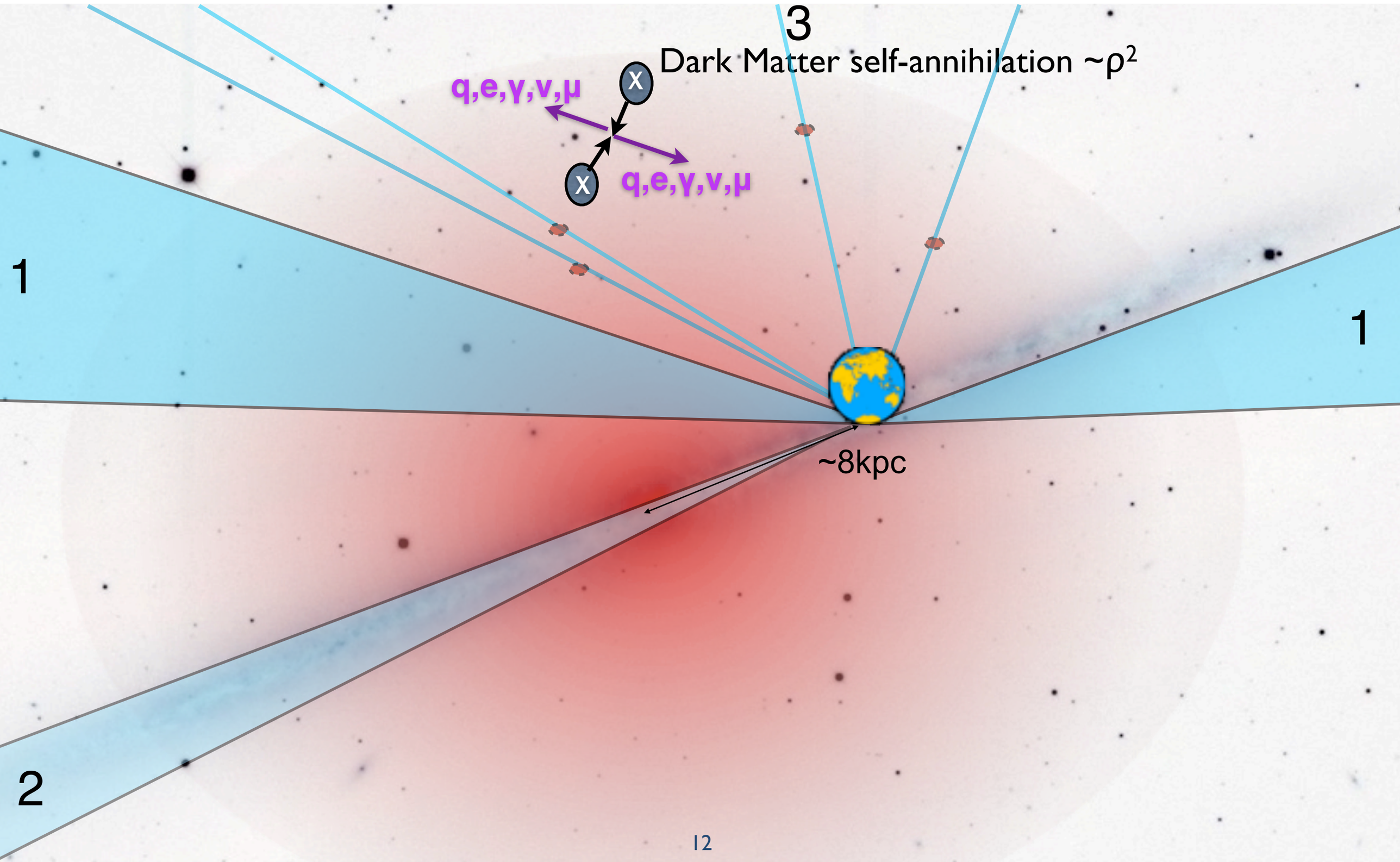

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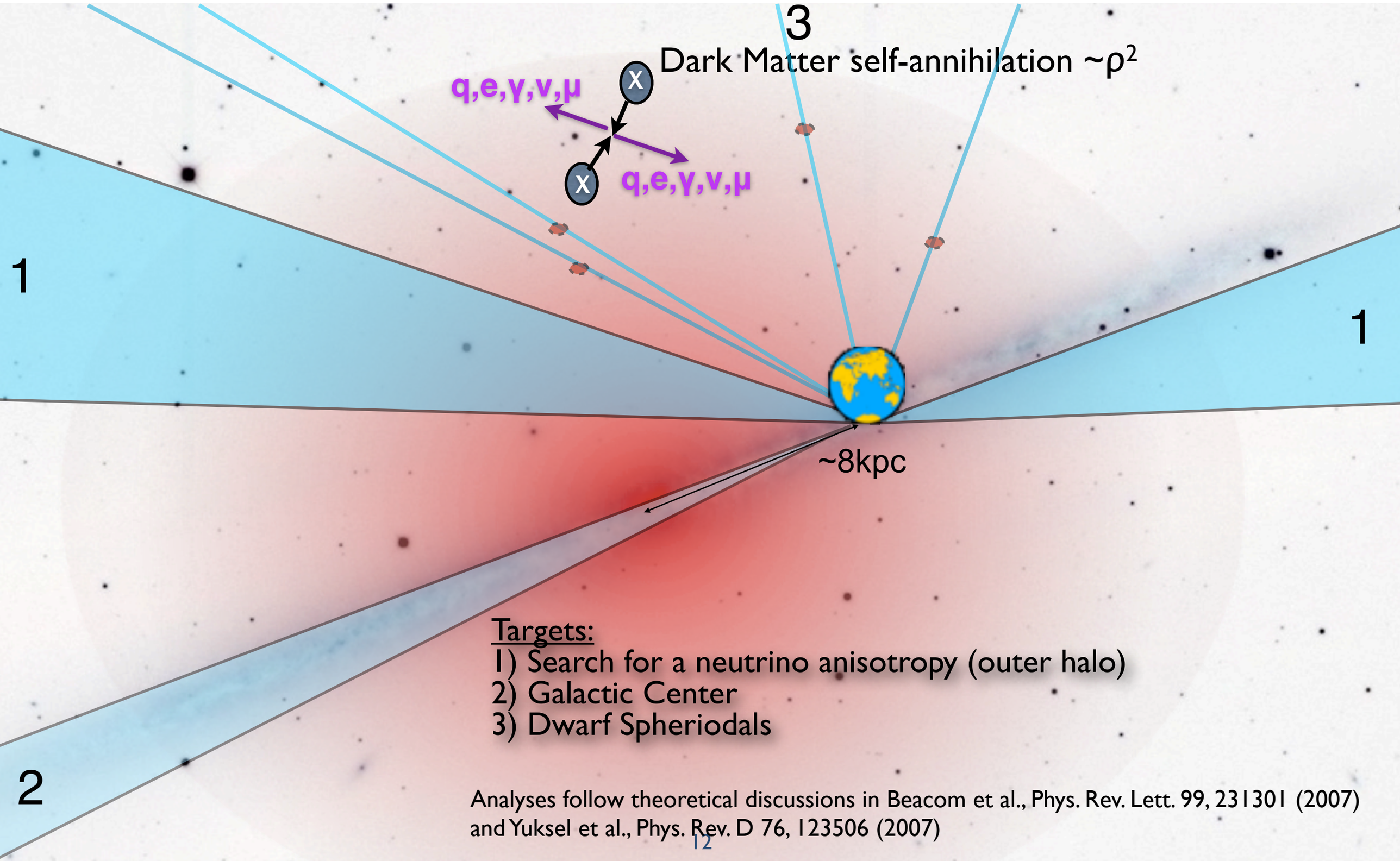


Targets:
1) Search for a neutrino anisotropy (outer halo)
2) Galactic Center
3) Dwarf Spheriodals

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

Dark Matter Annihilation

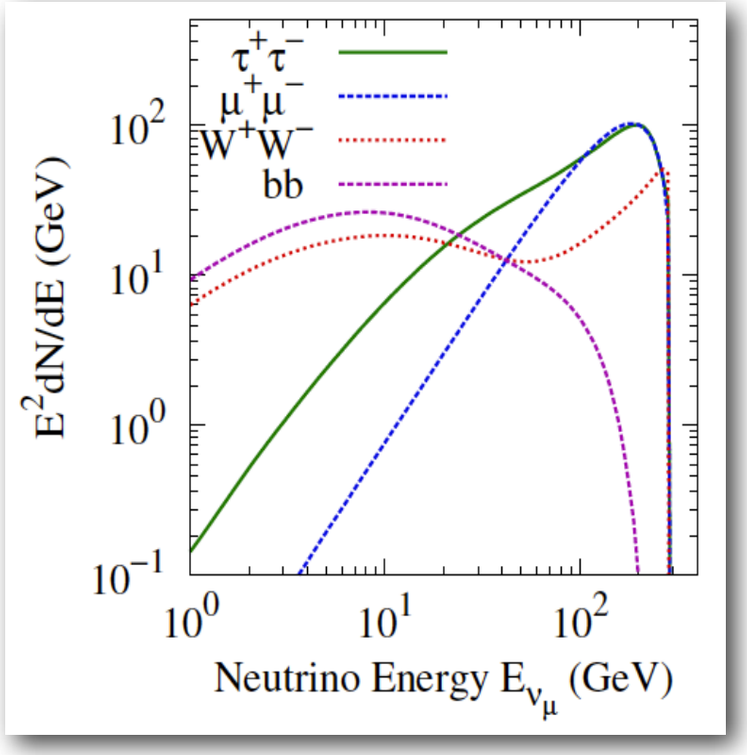
Measure Flux

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

=

Particle Physics

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

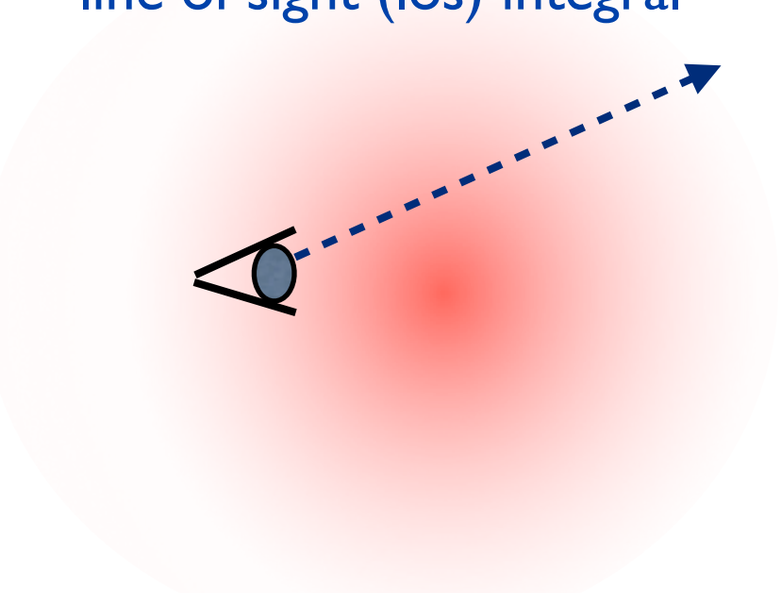


x

Dark Matter Distribution

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

line of sight (los) integral



Dark Matter Annihilation

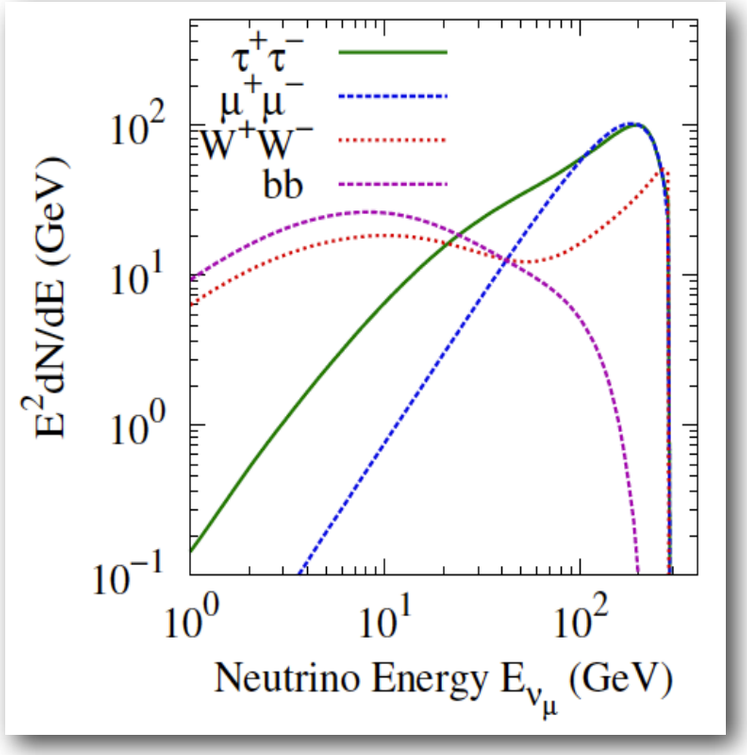
Measure Flux

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

=

Particle Physics

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

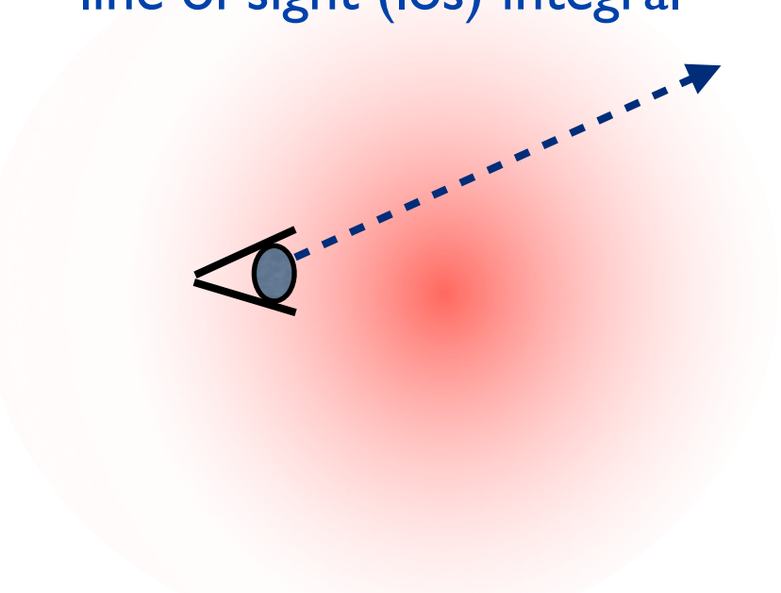


x

Dark Matter Distribution

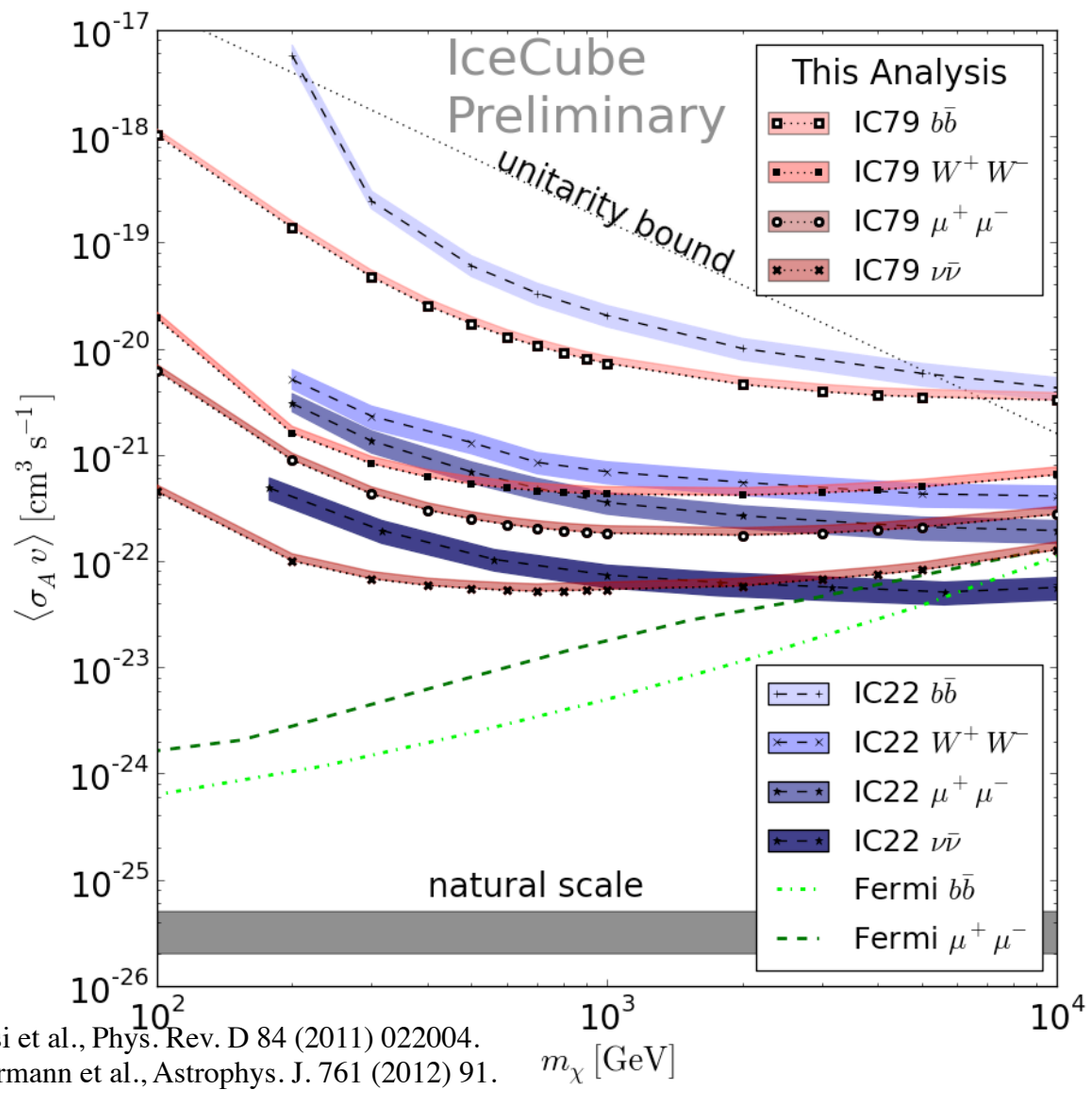
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\rm los} \rho^2(r(l,\phi'))dl(r,\phi')$$

line of sight (los) integral



IceCube Anisotropies in the Galactic Halo

- Galactic Center (GC) on the southern hemisphere
  - large backgrounds from down-going muons
- Search for anisotropy on Northern hemisphere
  - high-purity neutrino sample (up-going muon events)
- Assume annihilation into νν, bb, μμ, ττ, WW

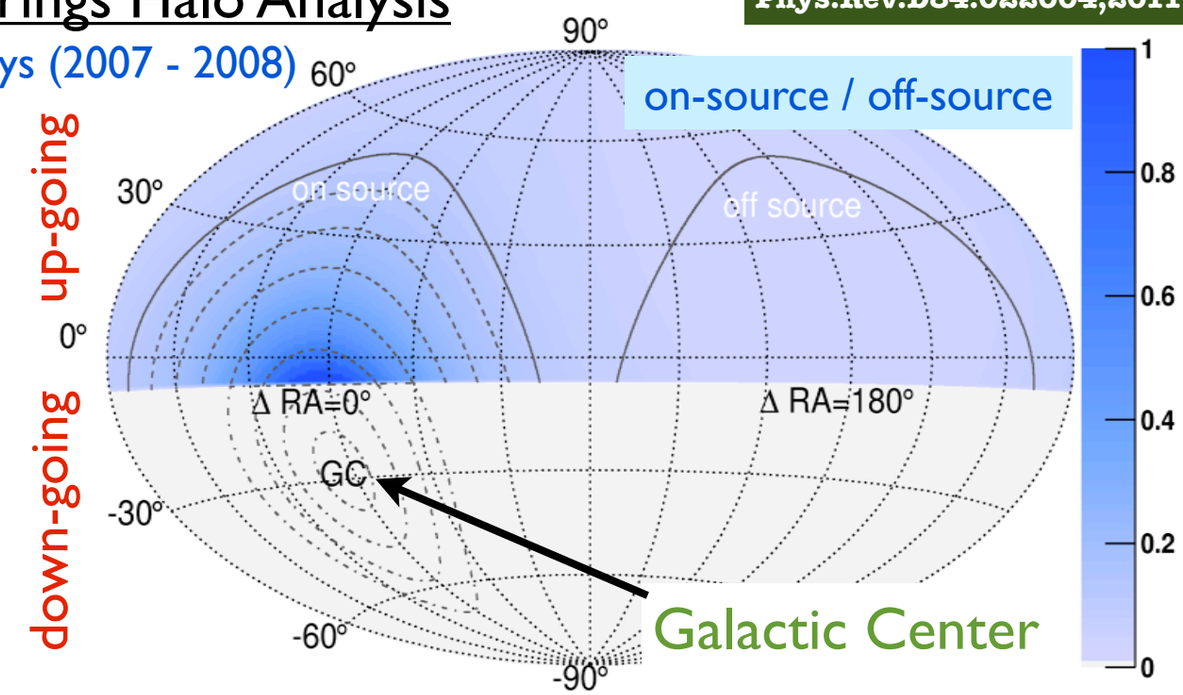


R. Abbasi et al., Phys. Rev. D 84 (2011) 022004.
M. Ackermann et al., Astrophys. J. 761 (2012) 91.

22-strings Halo Analysis

Phys.Rev.D84:022004,2011

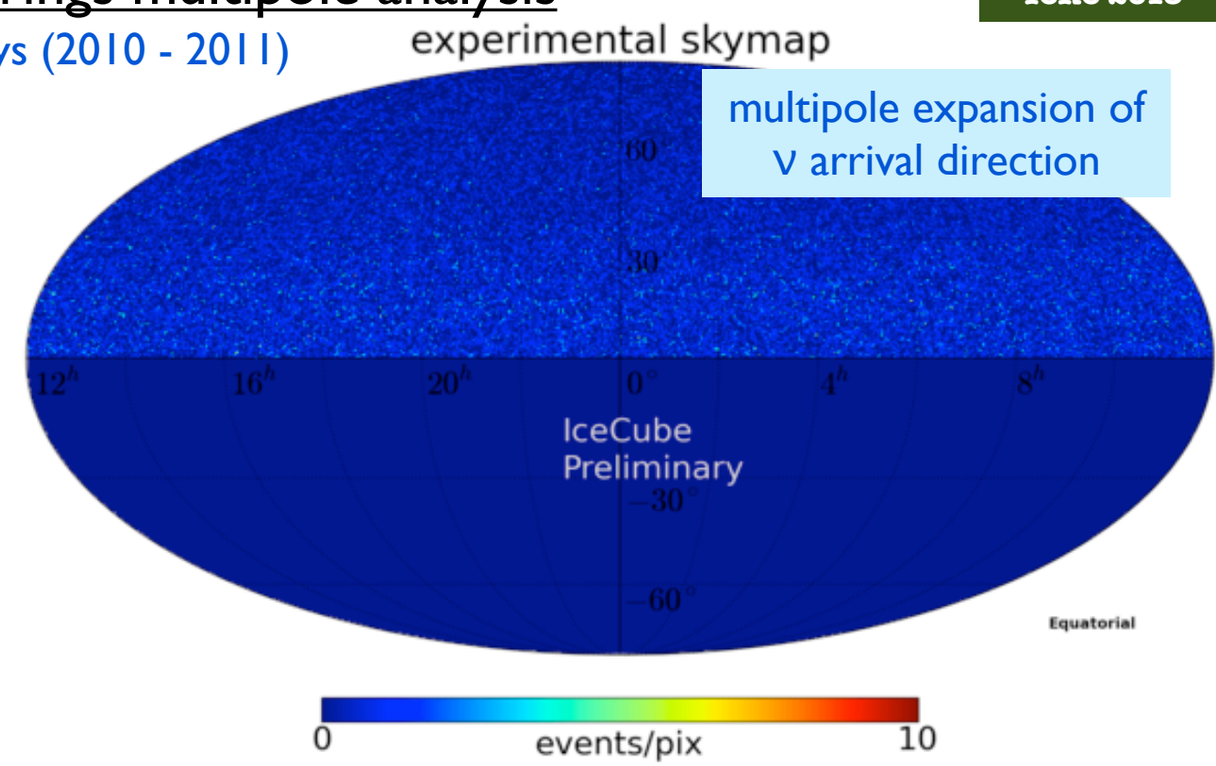
276 days (2007 - 2008)



79-strings multipole analysis

ICRC 2013

316 days (2010 - 2011)



IceCube Dwarf Spheriodal / Galaxy Clusters

- Dwarf spheriodal galaxies, clusters of galaxies, and large galaxies represent well defined sources of Dark Matter
  - Dark Matter distribution critical for optimization, assume conservative density profile

$$\frac{d\Phi_j(\Delta\Omega, E_j)}{dE_j} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_j}{dE_j}J(\Delta\Omega)$$

Analysis performed with 340days of IceCube 59 string data

Event selection via Boosted Decision Tree

For robustness the search windows and cut values were **optimized for 5 TeV WIMPs** and used for all WIMP-masses.

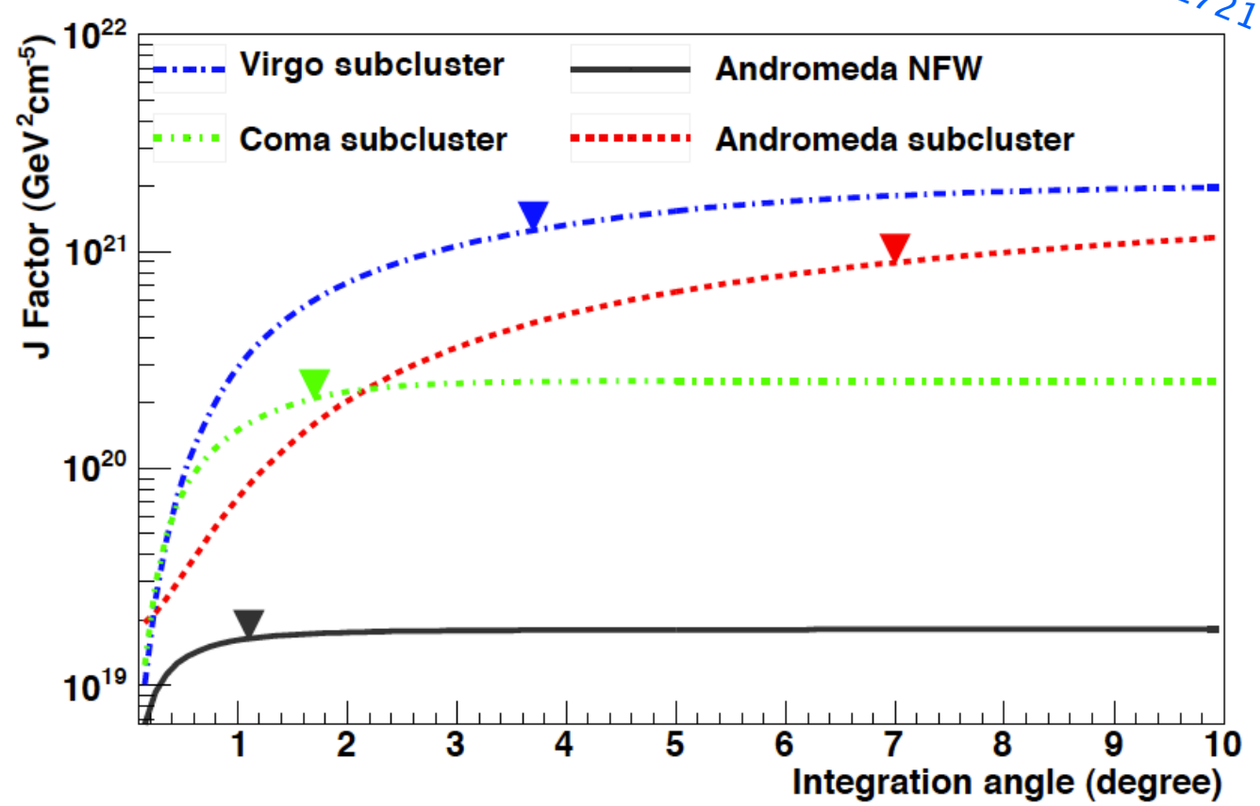
Source	declination	distance [kpc]	mass [$M_\odot$]	$\log_{10}J$ [GeV^2cm^{-5}]
Segue 1	+16°04'55"	23	1.58×10^7	19.6 ± 0.53
Ursa Major II	+63°07'48"	30	1.09×10^7	19.6 ± 0.40
Coma Berenices	+23°55'09"	44	0.72×10^7	19.0 ± 0.37
Draco	+57°54'55"	80	1.87×10^7	18.8 ± 0.13
M31	+41°16'09"	778	6.9×10^{11}	19.2 *
Virgo	+12°20'13"	22300	6.9×10^{14}	18.2 *
Coma	+27°56'20"	95000	1.3×10^{15}	17.1 *

J-factor source

Phys. Rev. Lett. 107, 241302 (2011)

Temple et al. 0707.4374

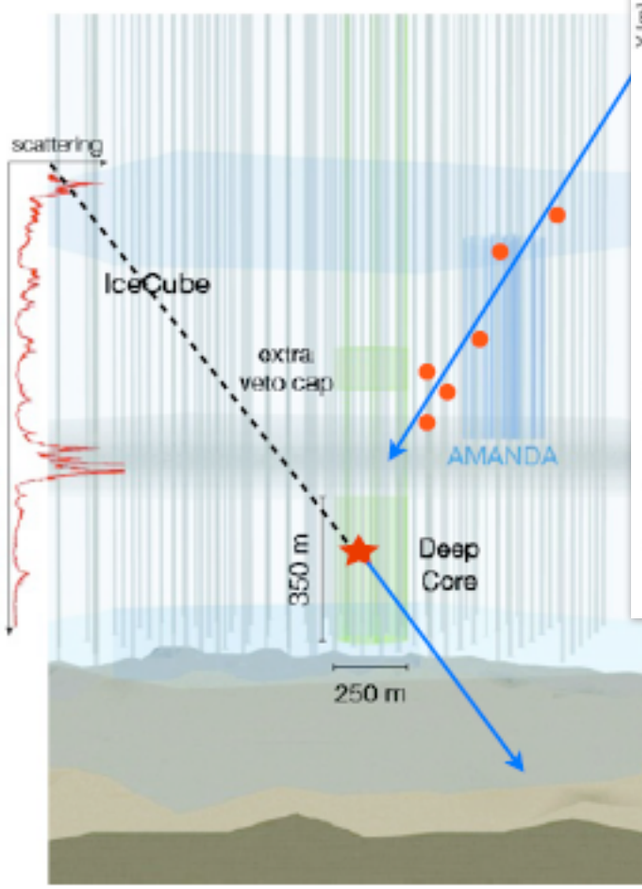
Gao et al. Mon.Not.Roy.Astron.Soc. 419 (2012) 1721

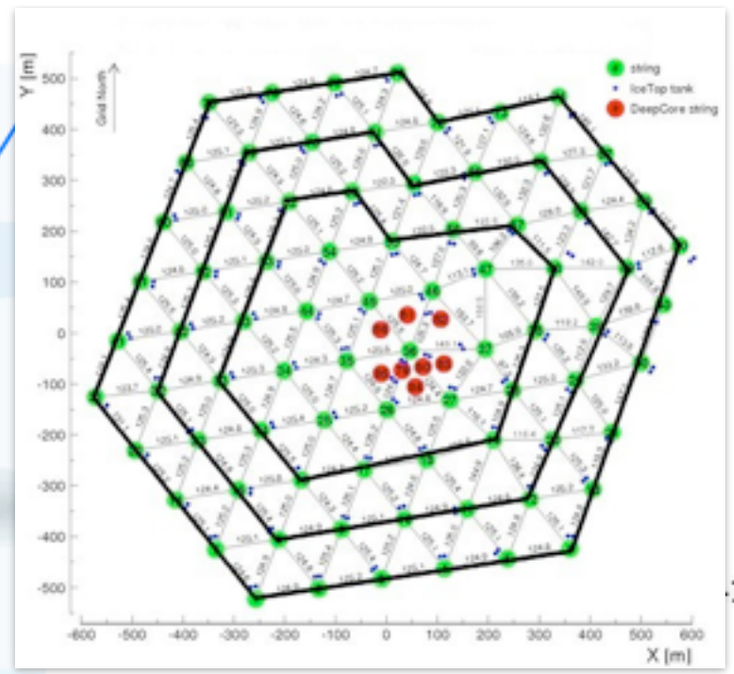


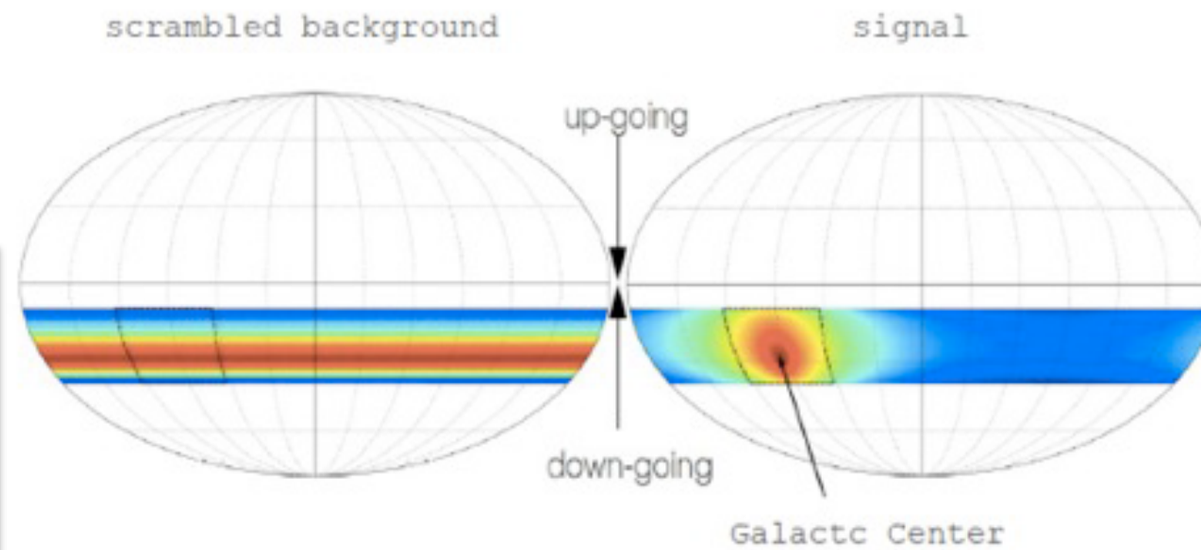
Phys.Rev. D88 (2013) 122001
arXiv:1111.2738 [astro-ph.HE]

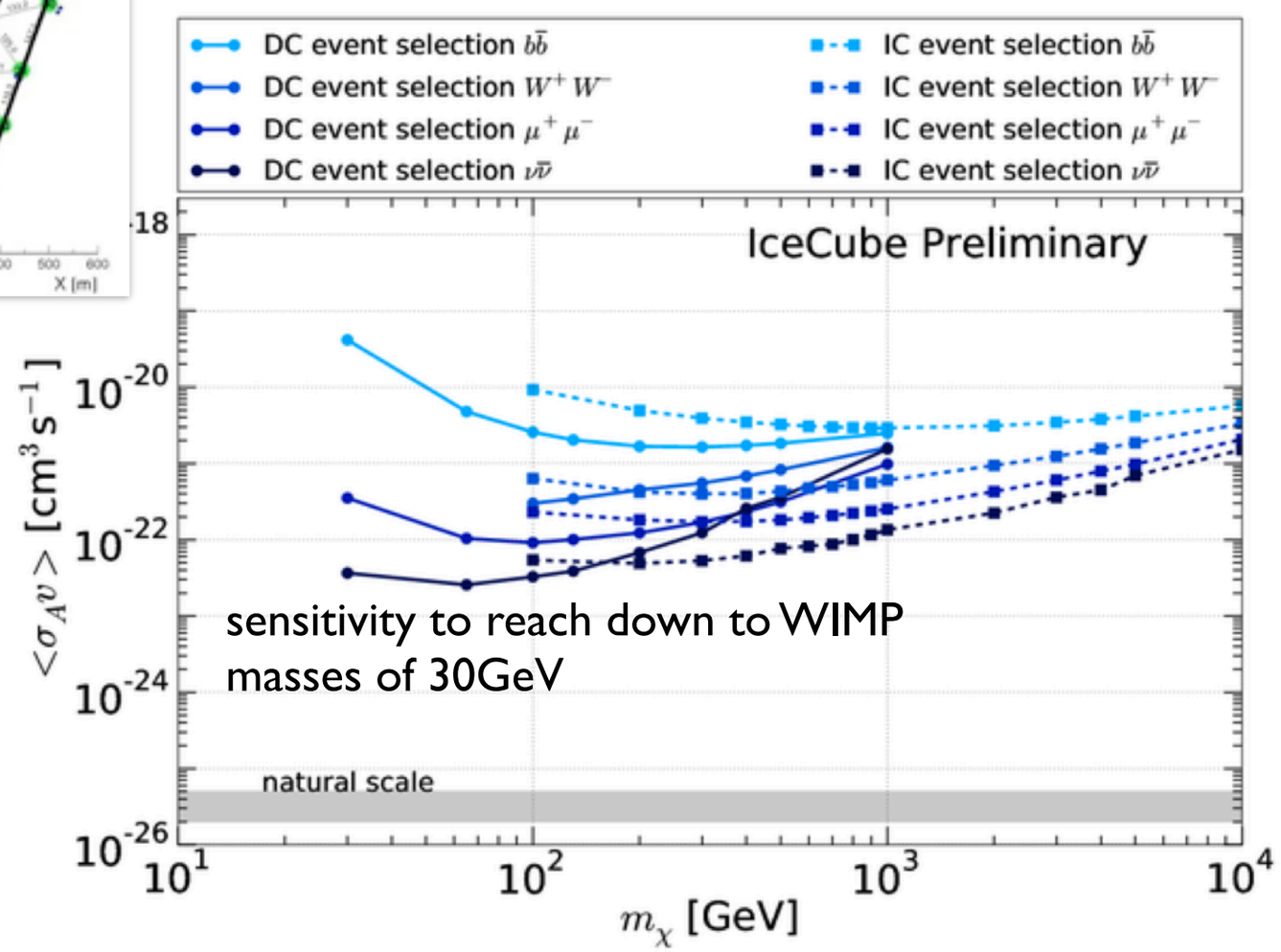
Galactic Center Search

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





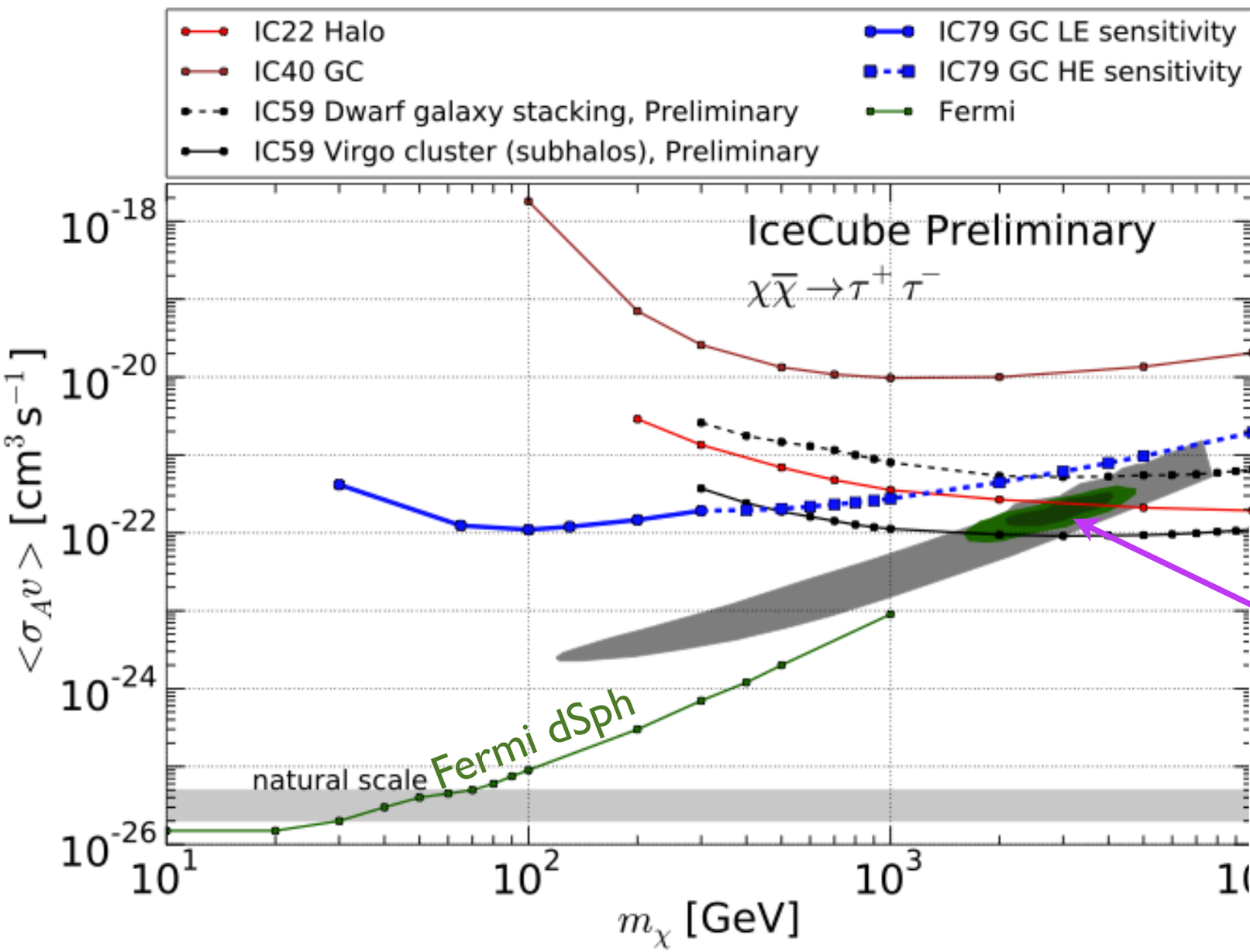


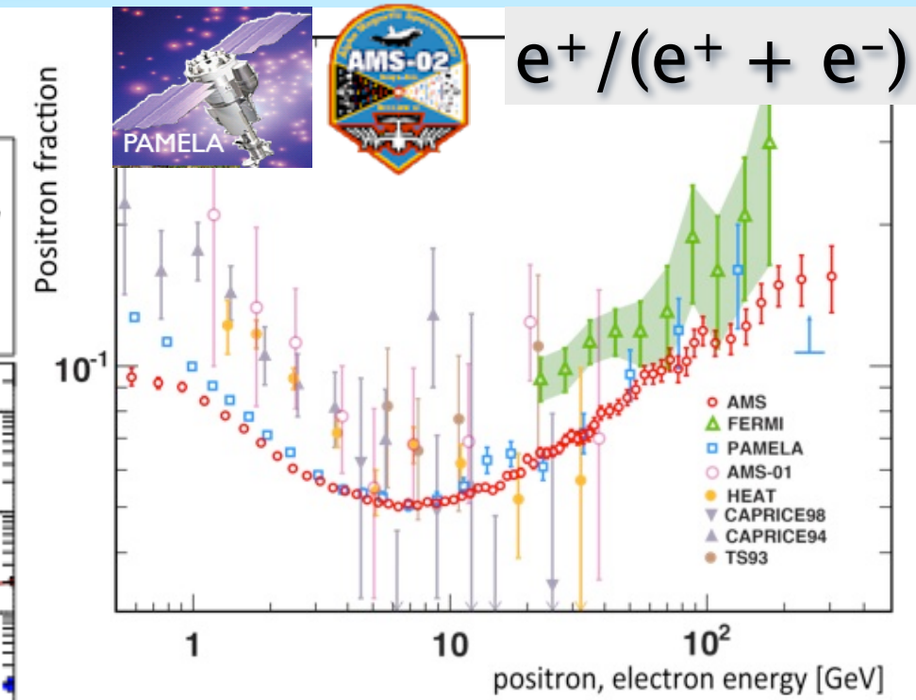


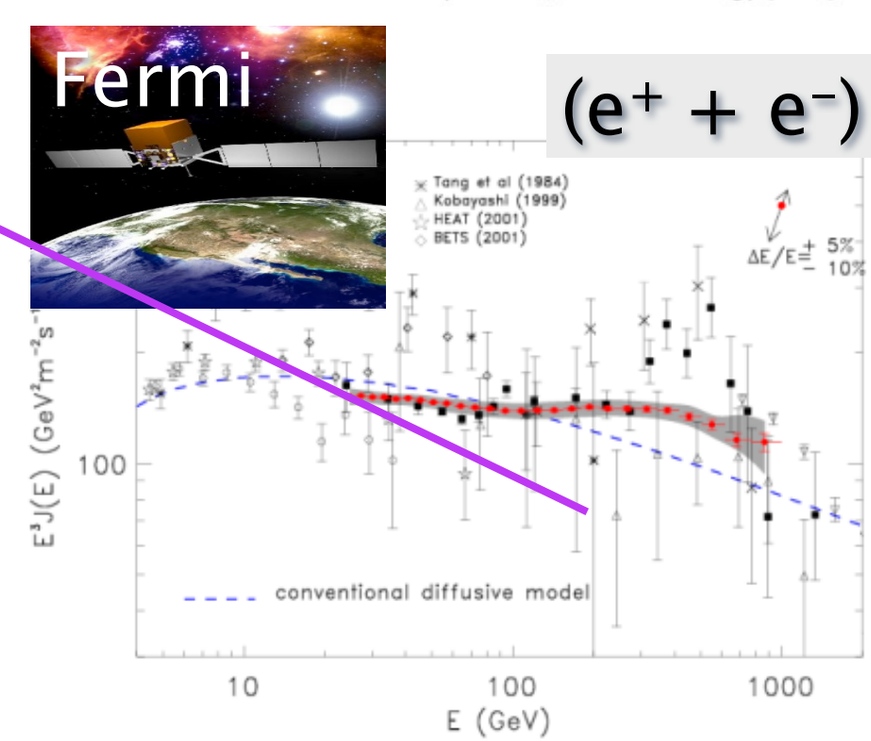
sensitivity to reach down to WIMP masses of 30GeV

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

Neutrinos test lepton anomalies

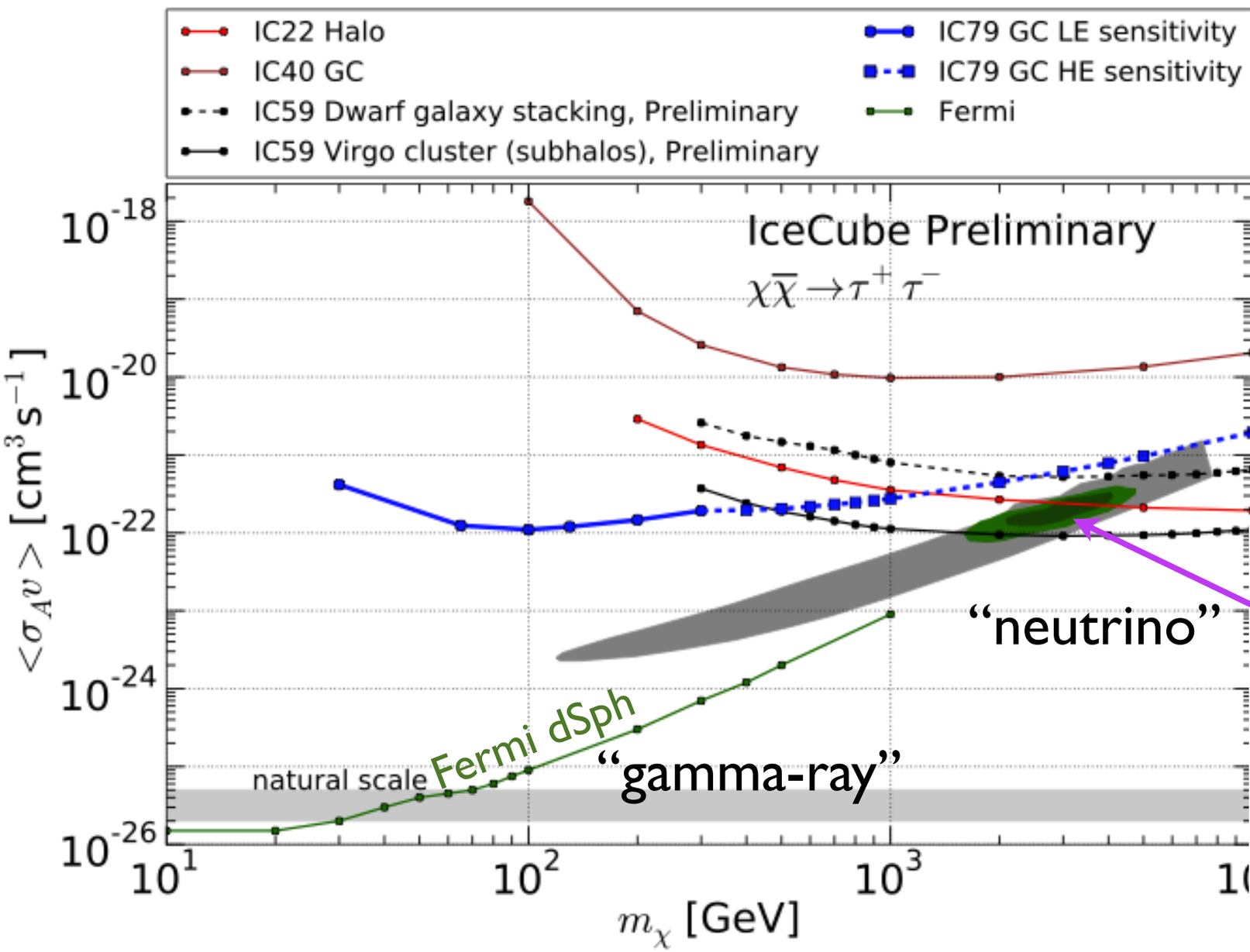


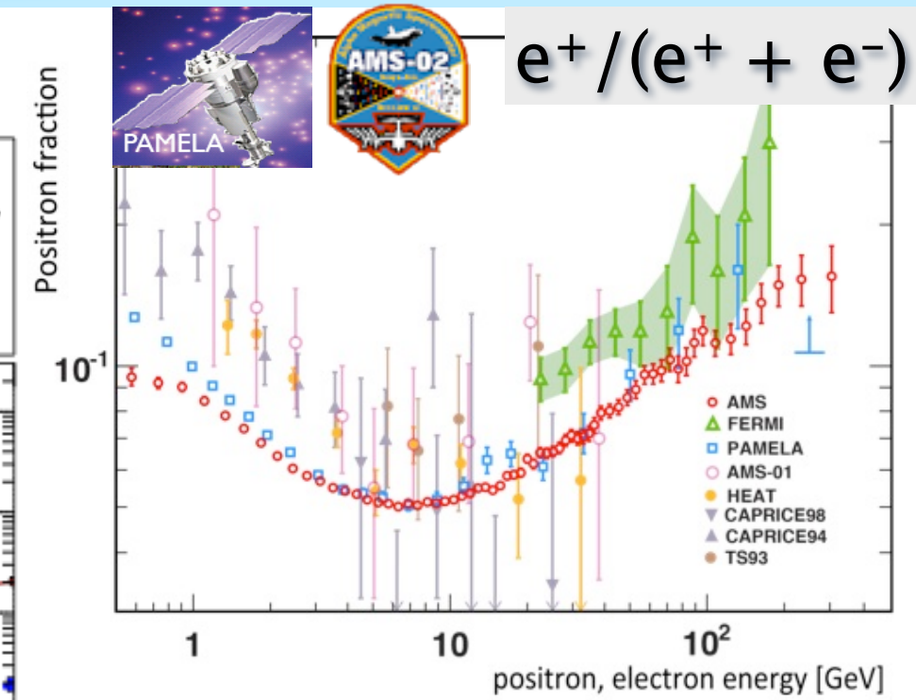


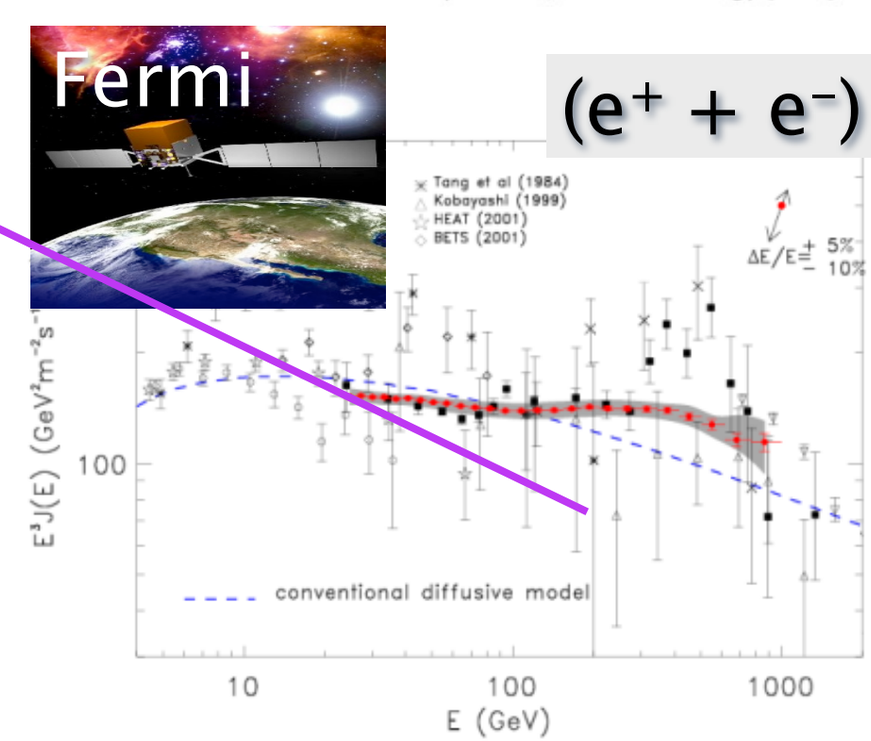


IceCube can probe models motivated by the observed lepton anomalies

Neutrinos test lepton anomalies

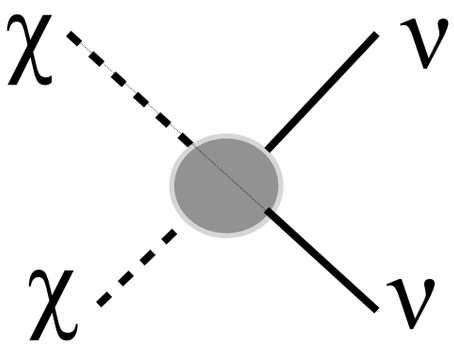




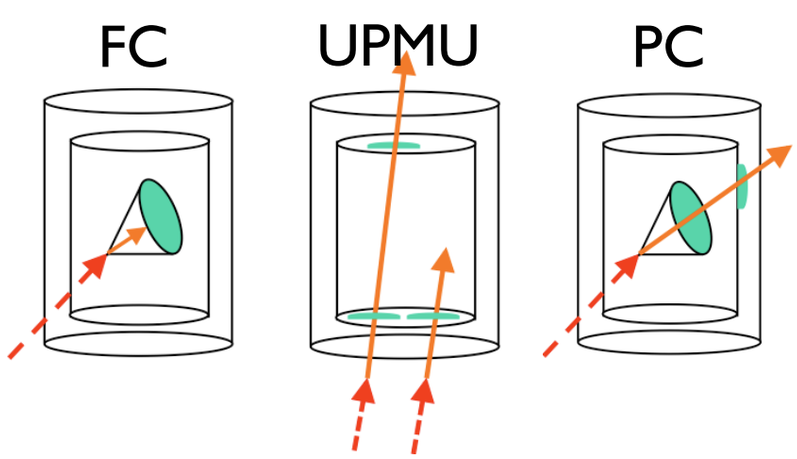


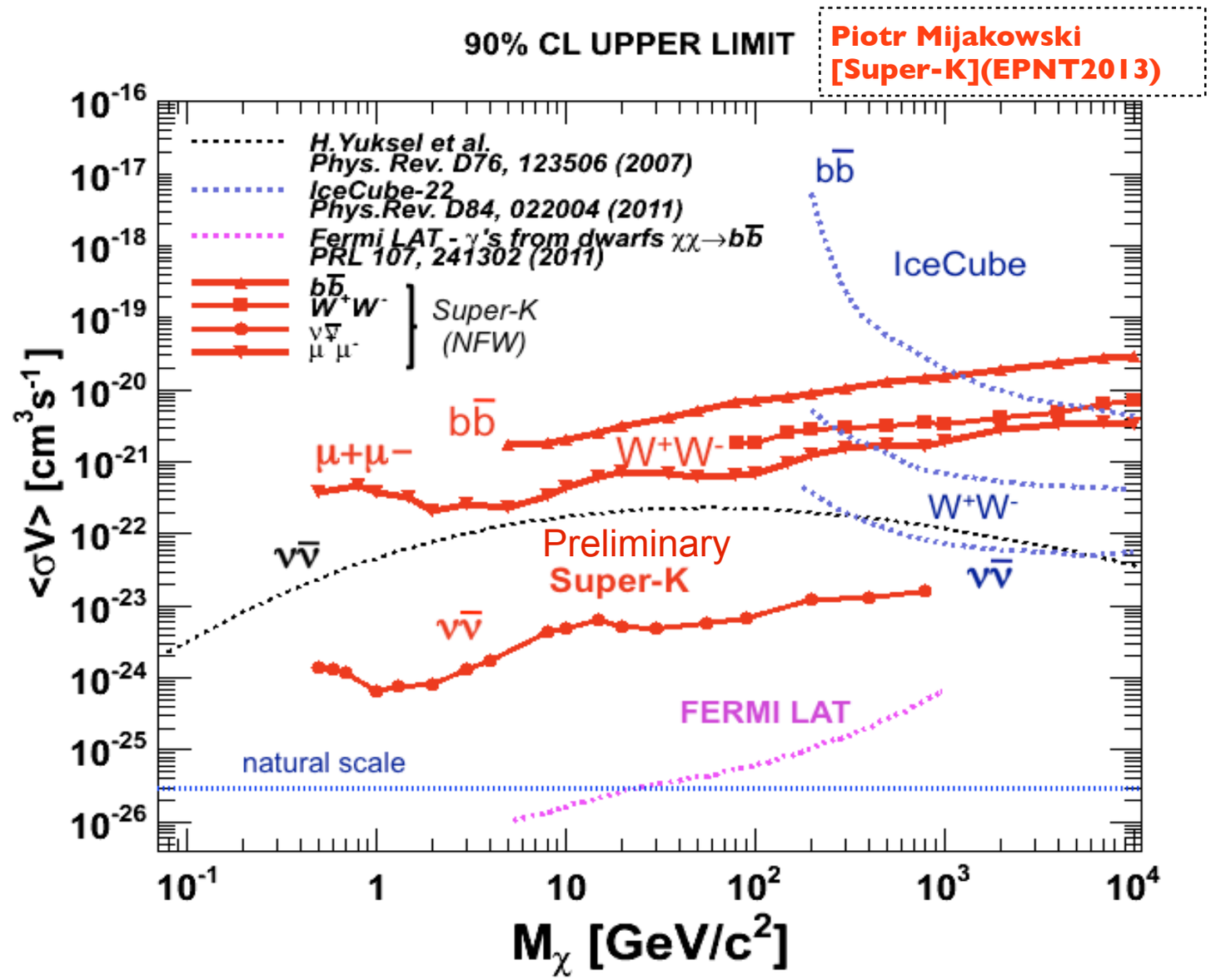
IceCube can probe models motivated by the observed lepton anomalies

Super-K - Galactic Search



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



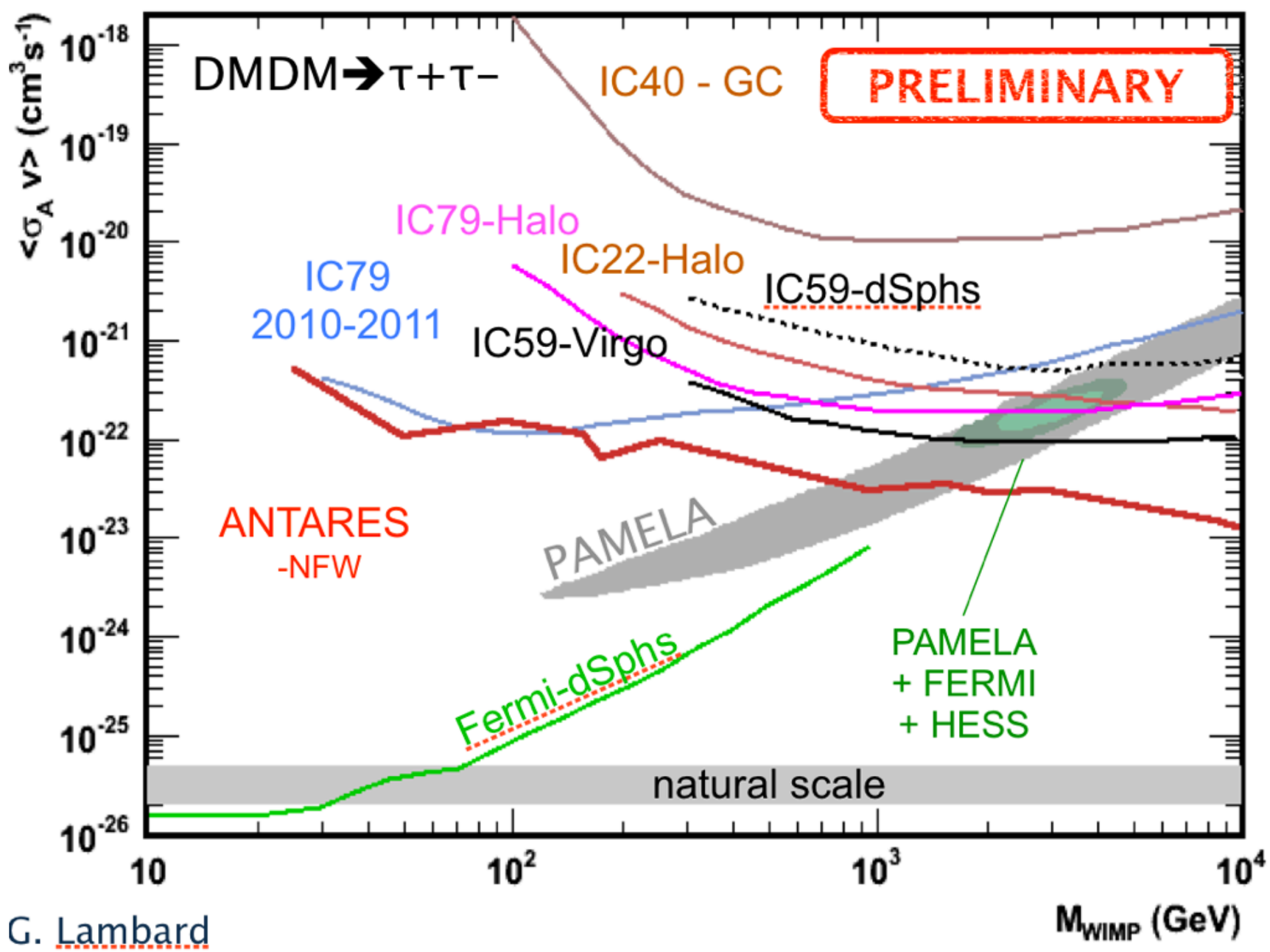


ANTARES Preliminary result shown at Moriond 2014

ANTARES - Galactic Center

- Dataset: 1321days from 2007-2012
- Neutrino spectra from Cirelli et al. 2010 (arxiv:1012.415)

ANTARES is on the Northern Hemisphere, benefit from low backgrounds in up-going neutrino sample



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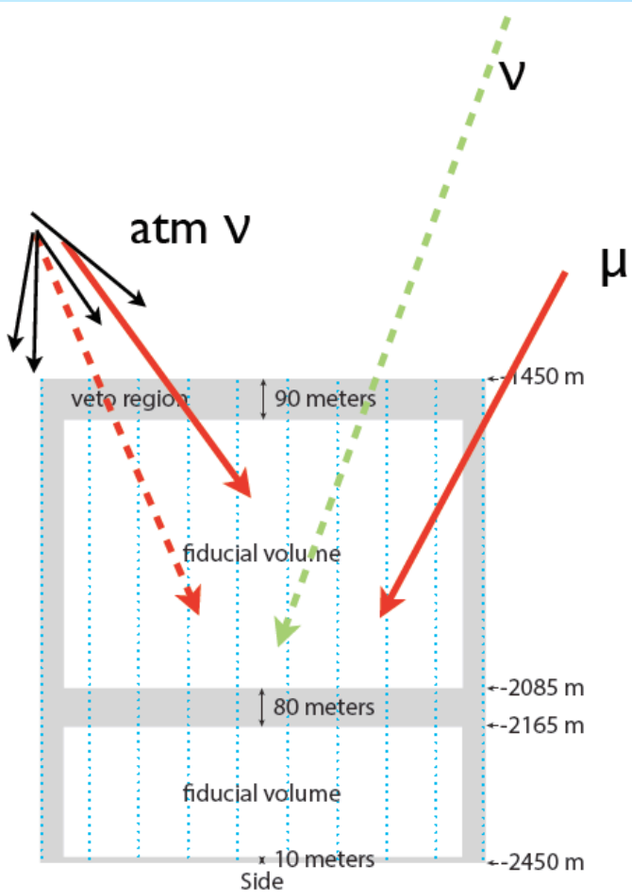
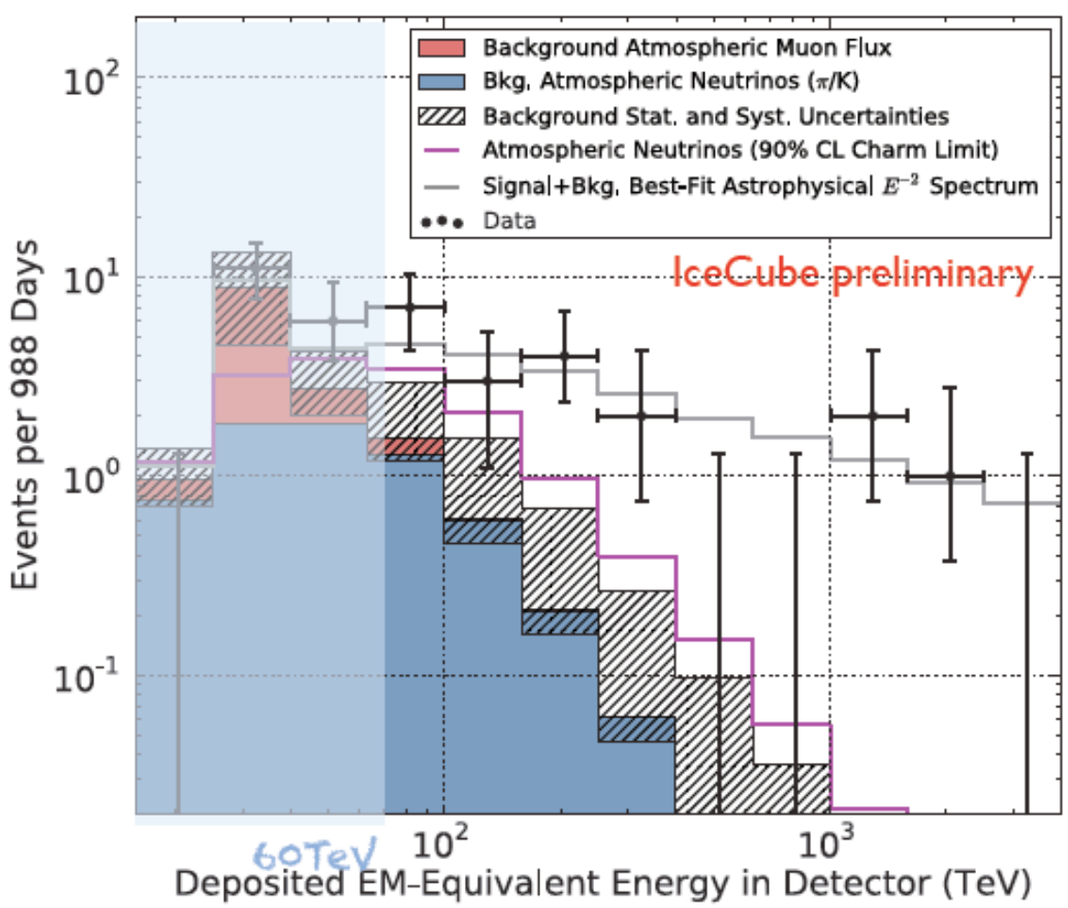
Dark Matter Decay - High Mass Dark Matter

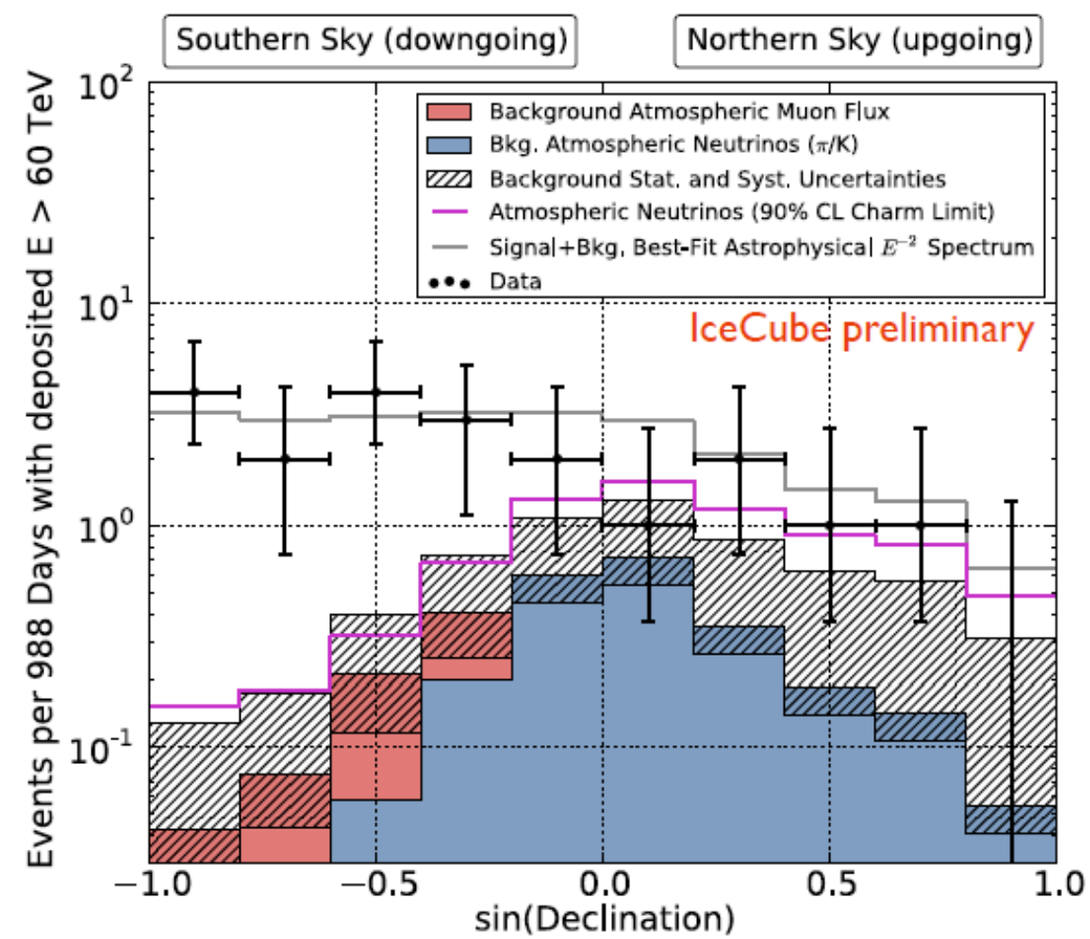
IceCube: High-energy neutrino events

See talk by Naoko Kurahashi Neilson

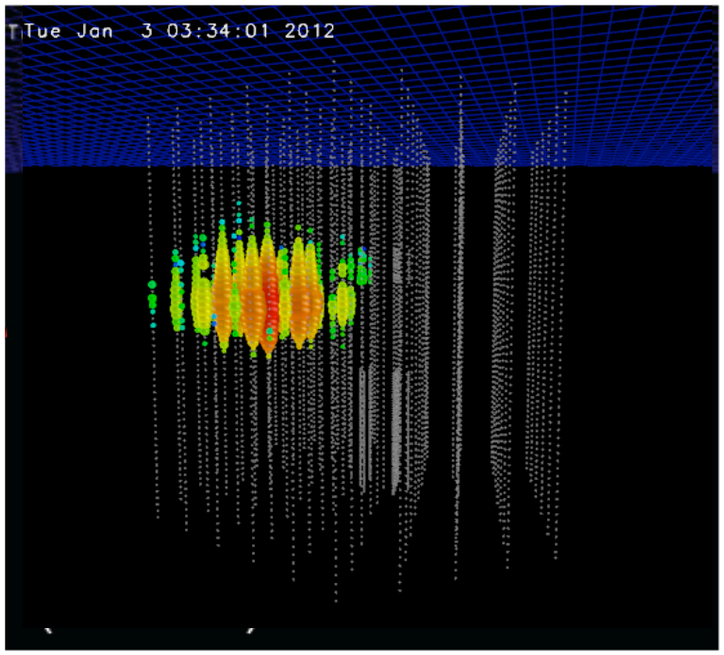


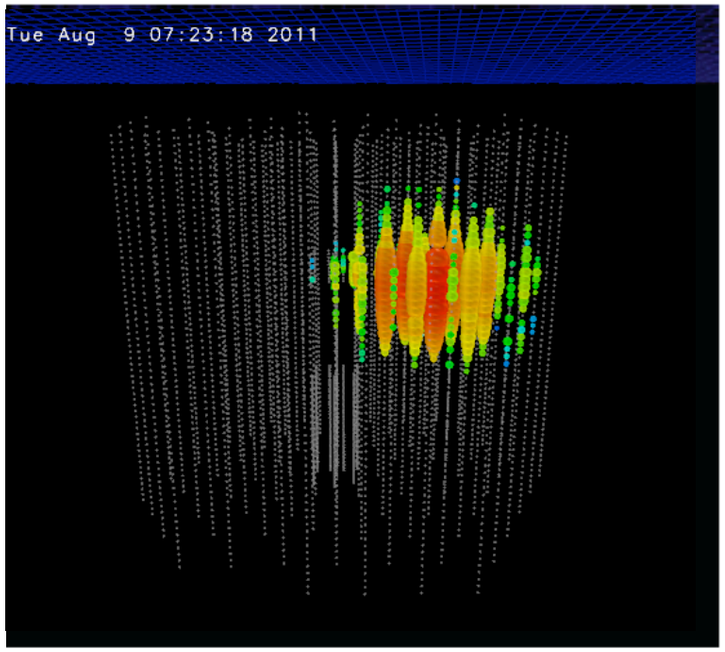
- 37 events observed (2010-2013)
  - 2 years analysis found 28 events Science 342, 1242856 (2013)
- energy spectrum >60TeV harder than background
- atmospheric origin rejected at 5.7σ

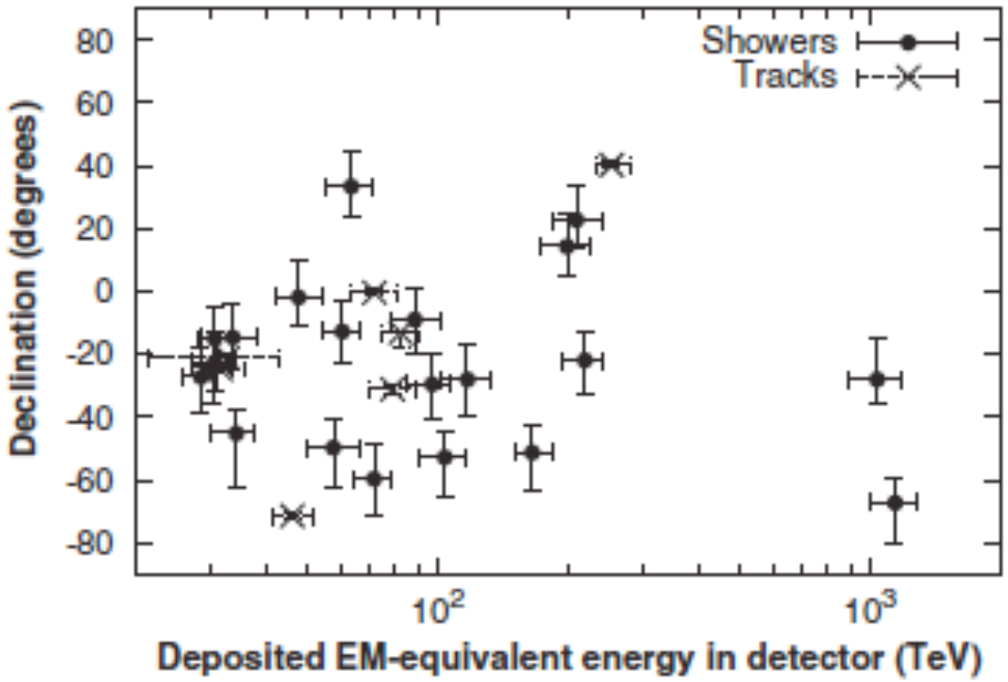




Origin of the PeV events







IceCube arXiv:1304.5356

- What do the two IceCube events tell us ? and the additional 26 events ?

Number of papers based on the 2 IceCube Events [Phys.Rev.Lett. 111 (2013) 021103)] are growing fast ....

Comprehensive discussion (example):
R.Laha et al. Phys. Rev. D 88, 043009

GZK neutrinos	a few events at ~ 100 TeV - 1 PeV implies many more events at higher energies	***Impossible***
Conventional atm. neutrinos	Very low flux predictions. Flavor ratio favors strongly favors muon neutrinos	***Implausible***
Prompt	Coincidence in down-going events. Possible only if proton composition; upward statistical fluctuation needed	***Unlikely***
Astrophysical	Most natural. Events are isotropic. Cannot be continuum spectrum. power law with break at ~ 2 PeV ?	***Plausible***
Dark Matter	2 events overlap in energy	**Intriguing**

Heavy Dark Matter

- IceCube's 2 high-energy cascade events of the 2 year sample of the 79 + 89-string detector
  - consistent with electron neutrino interactions at about 1PeV
    - reported events are intriguingly close in energy

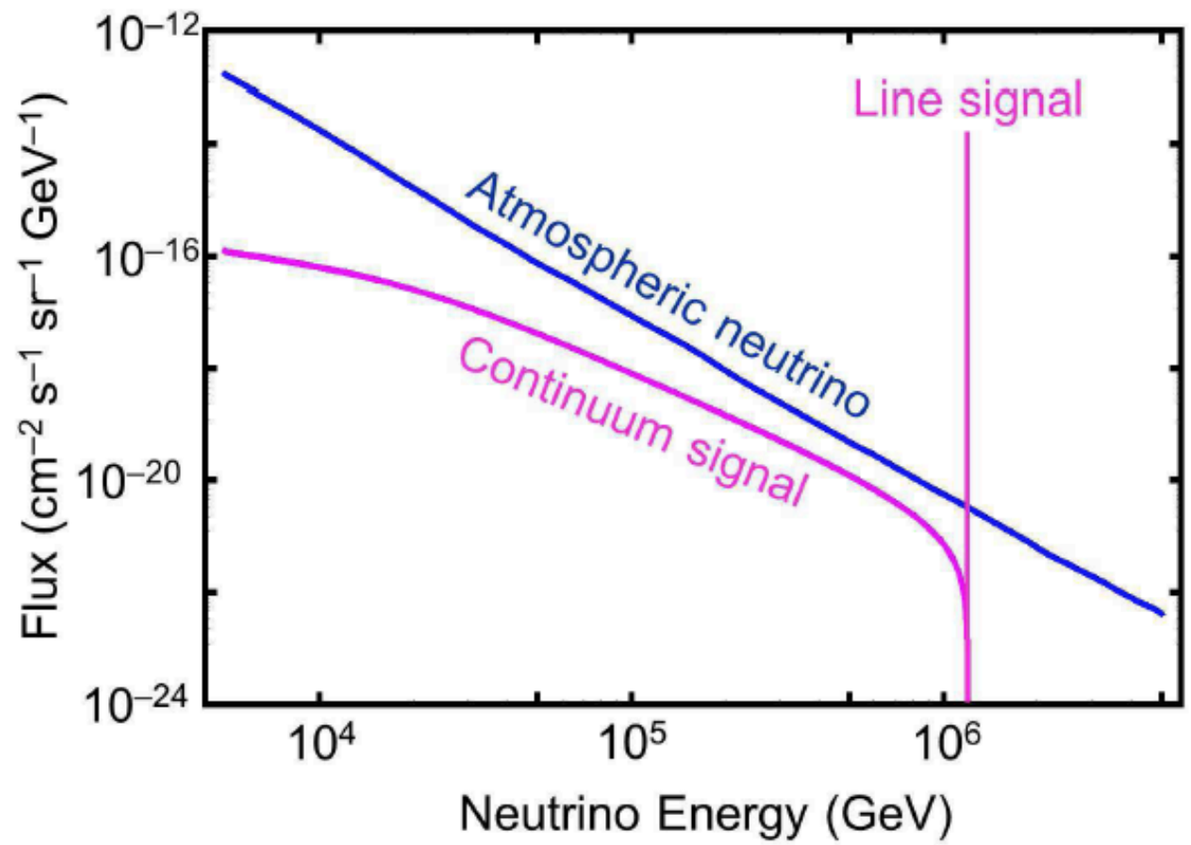
Could this be dark matter ?

example: B. Feldstein, A. Kusenko, S. Matsumoto, and T. Yanagida arXiv: 1303.7320v1 [hep-ph]

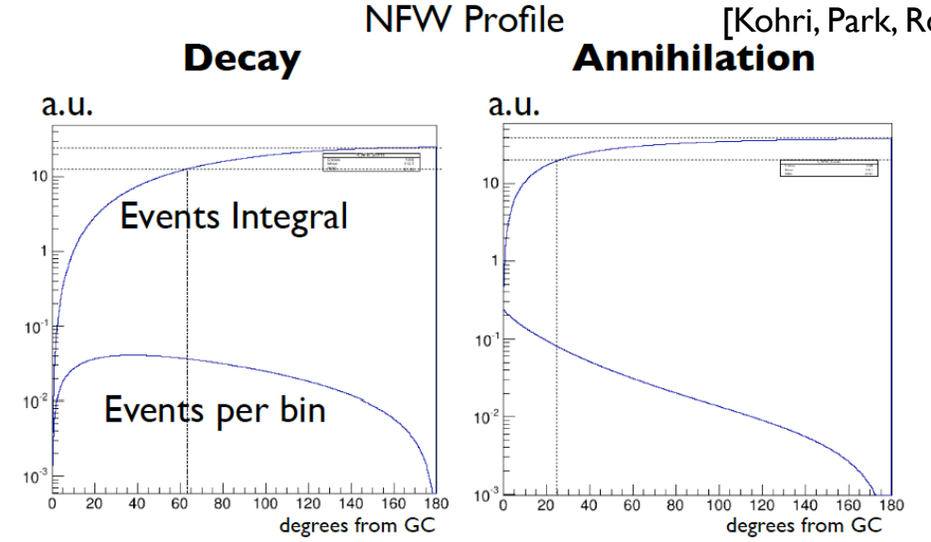
Evidence:
- 2.4PeV Dark Matter Particle mass
- Flux can be related to the lifetime $\tau_{\rm DM}$

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

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



NFW Profile [Kohri, Park, Rott (in prep.)]



50% of events within 65°

50% of events within 25°

Heavy Dark Matter

- IceCube's 2 high-energy cascade events of the 2 year sample of the 79 + 89-string detect
  - consistent with el interactions at ab
    - reported ever intriguingly clo

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example: B. Fel Matsumoto, and 1303.7320v1 [he

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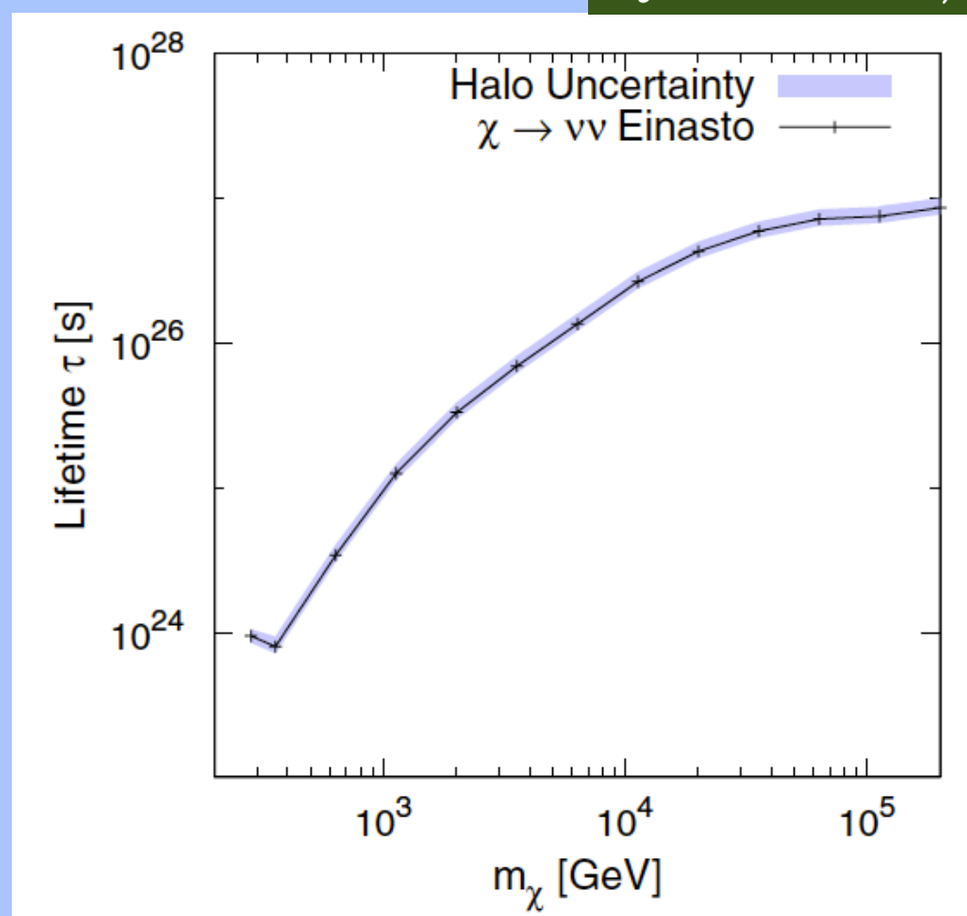
- Flux can be related to t

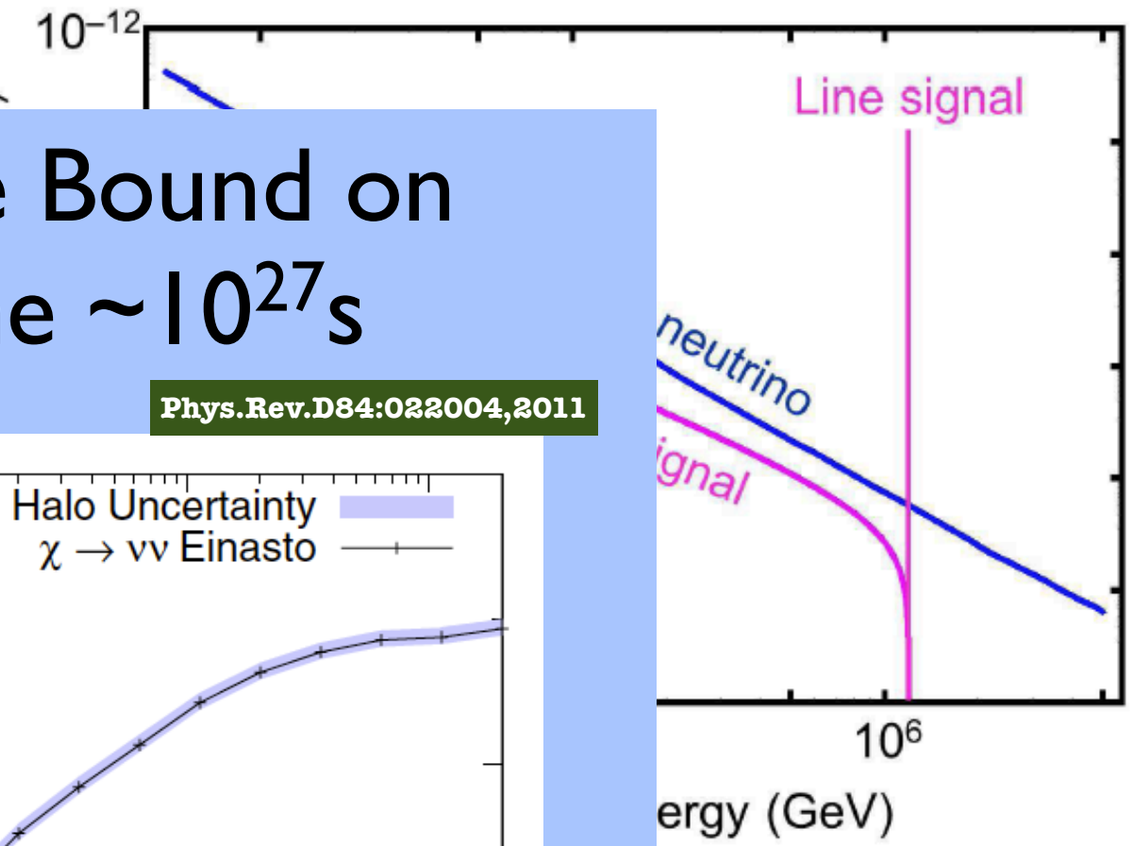
$$\tau_{\rm DM} \simeq 1.9 N_\nu$$

- Models
  - Singlet fermion in an
  - Hidden Sector Gaug
  - Gravitino Dark Matt Violation

IceCube Bound on lifetime ~10^{27}s

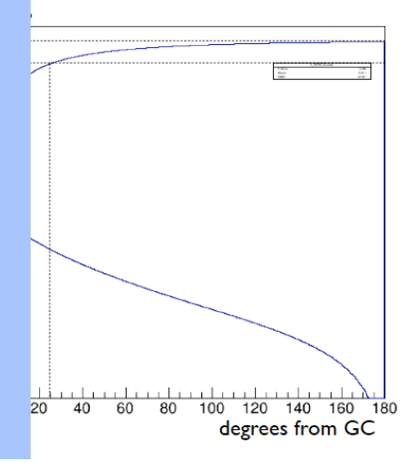
Phys.Rev.D84:022004,2011





le [Kohri, Park, Rott (in prep.)]

Annihilation



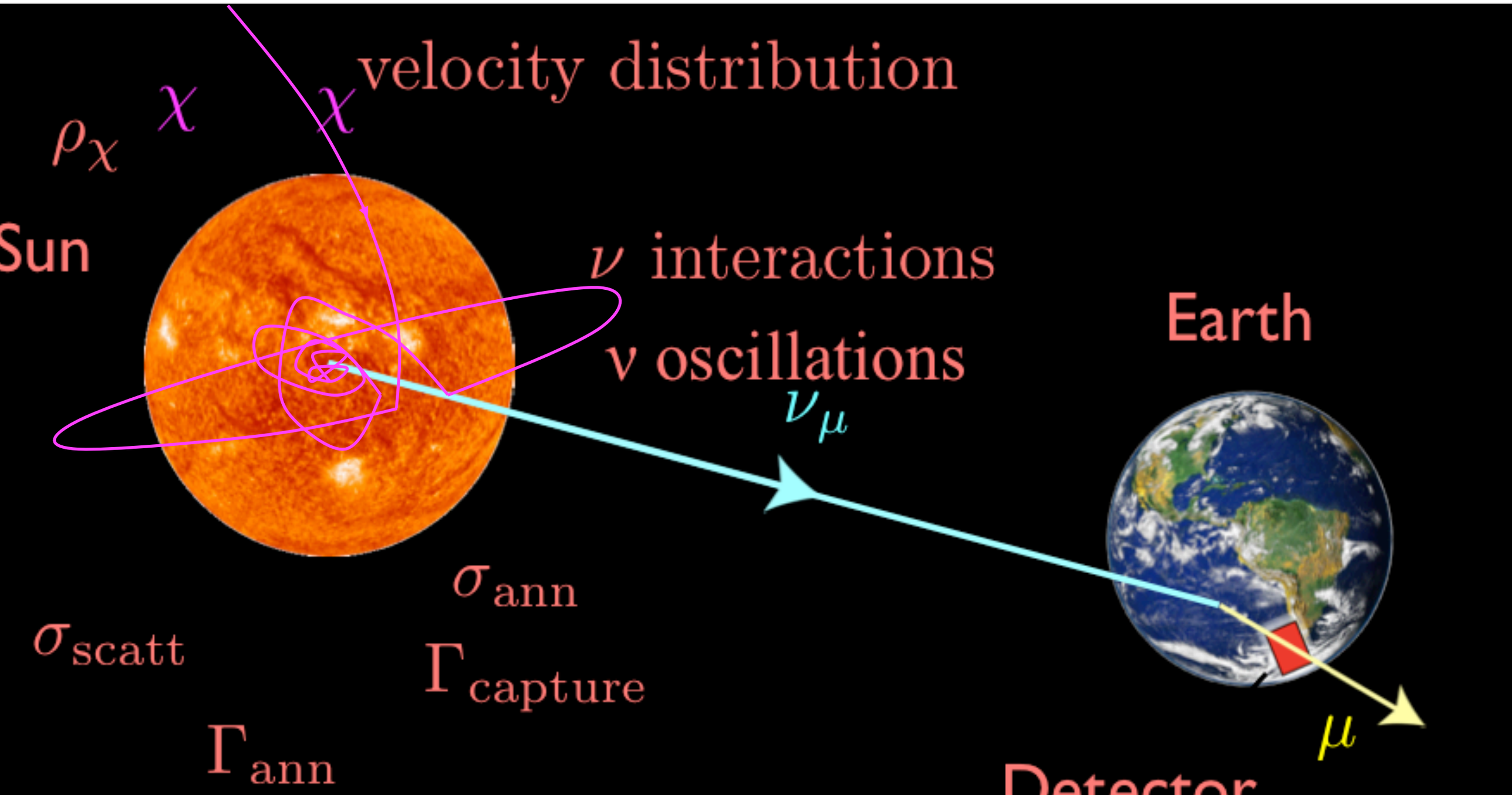
50% of events within 65°

50% of events within 25°

Solar WIMPs

σ_{scatt}

Solar WIMPs

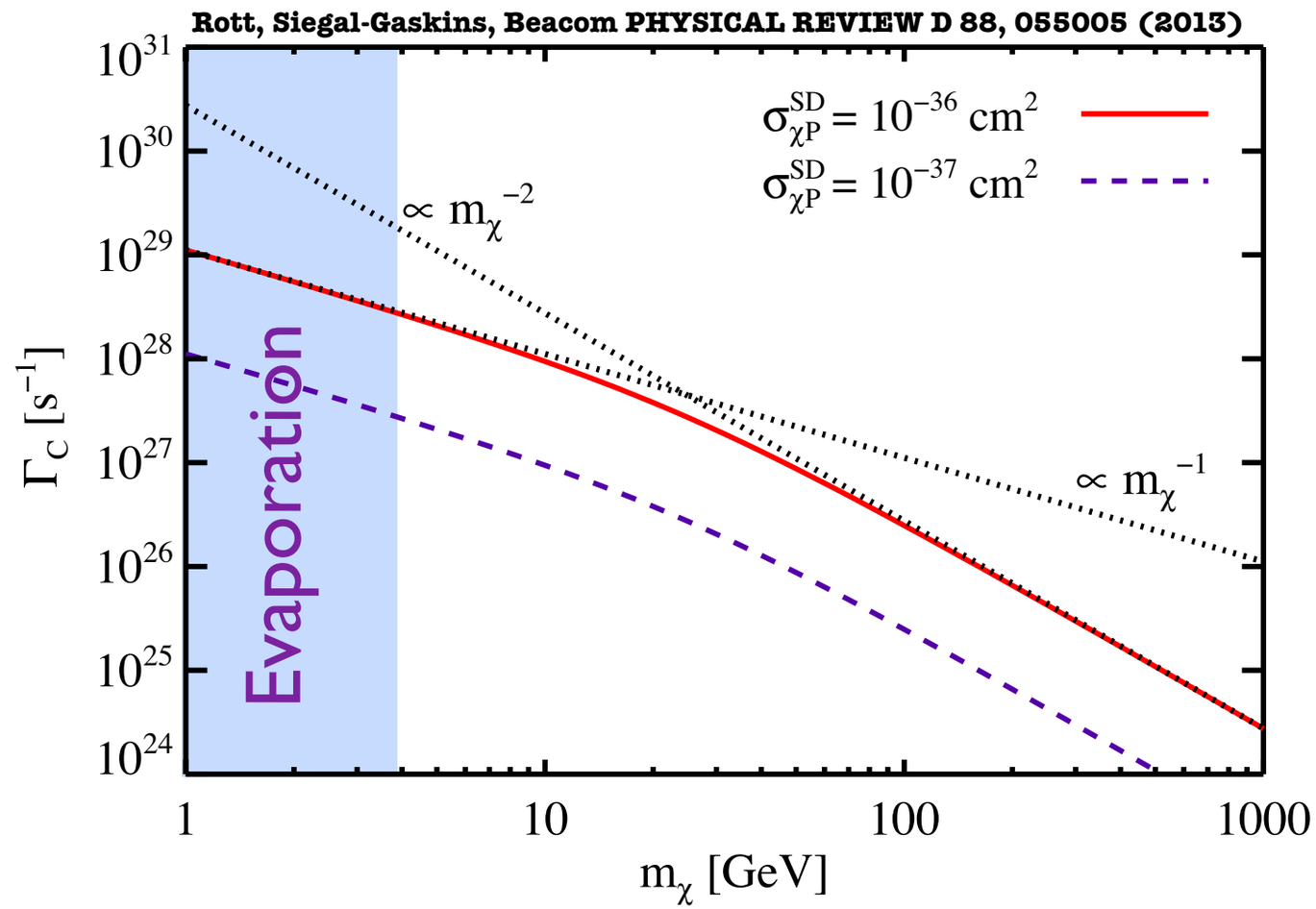


Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

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

Solar WIMP Capture

- WIMPs can get gravitationally captured by the Sun
  - Capture rate, Γ_C ,depends on WIMP-nucleon scattering cross section
- Dark Matter accumulates and starts annihilating
  - → Only neutrinos can make it out
- Equilibrium: The capture rate regulates the annihilation rate ($\Gamma_A=\Gamma_C/2$)
  - The neutrino flux only depends on the WIMP-Nucleon scattering cross section



The capture rates scales as:

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

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

number density + kinematic suppression

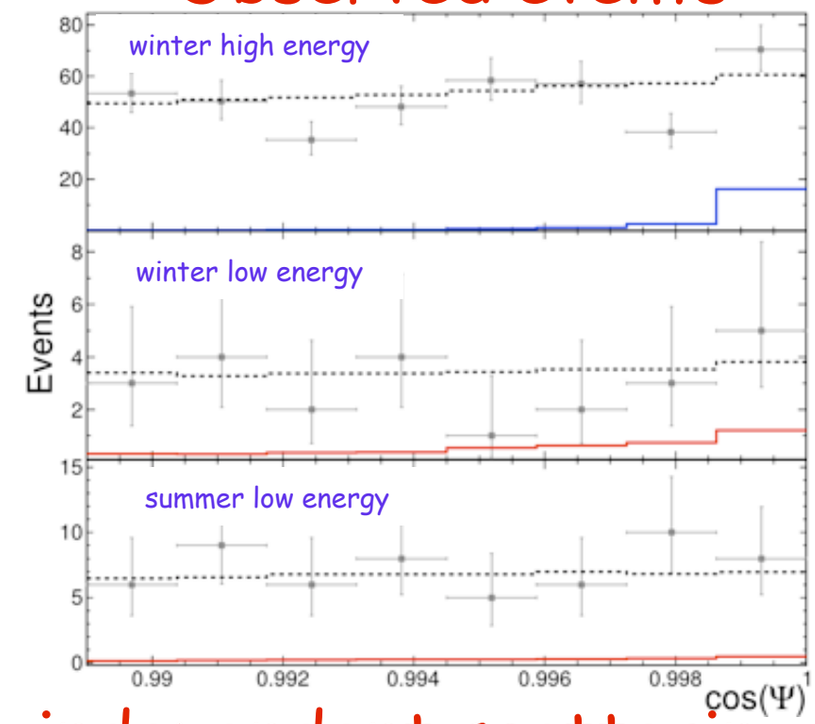
m_A - is the target mass

IceCube Solar WIMP Limits

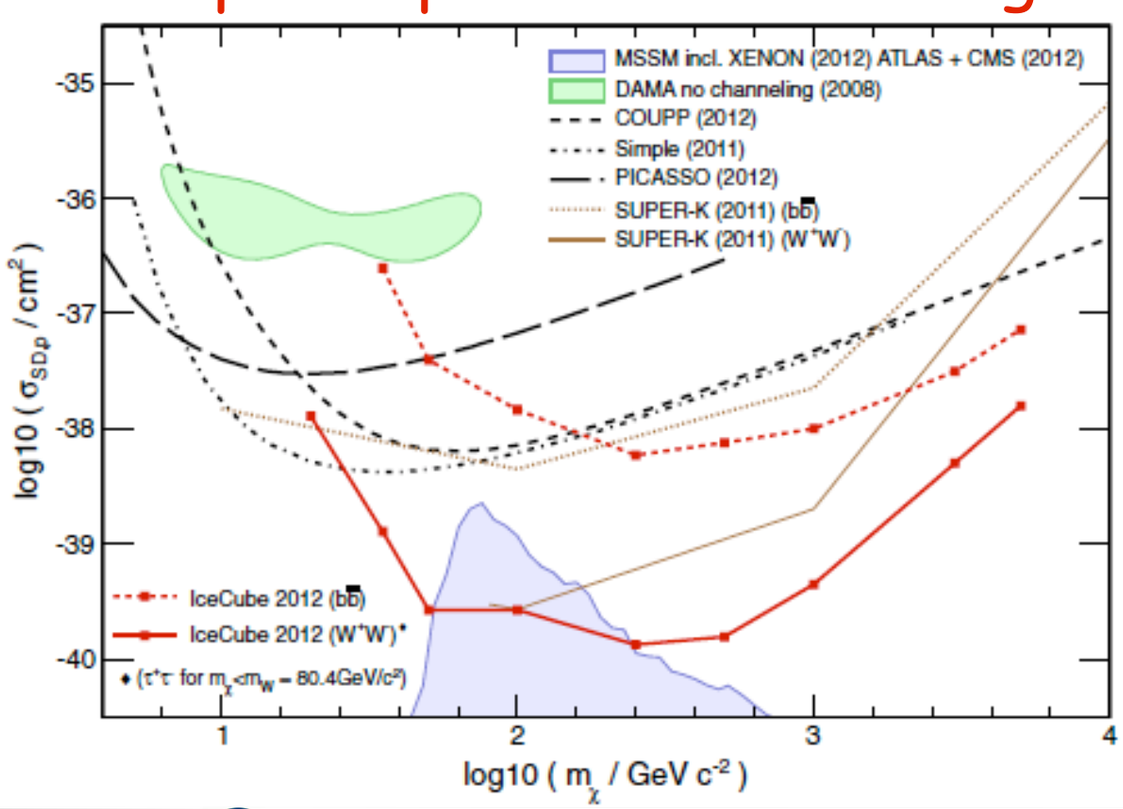
PRL 110, 131302 (2013)

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

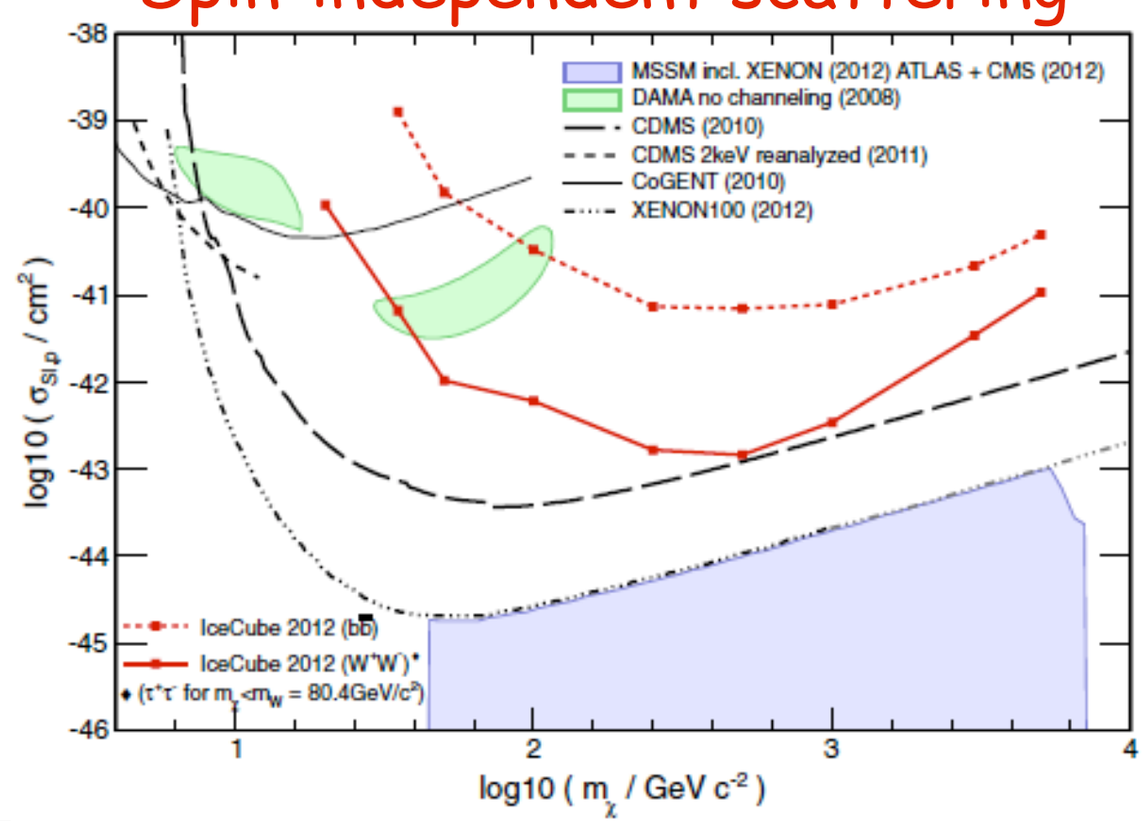
Observed events



Spin-dependent scattering

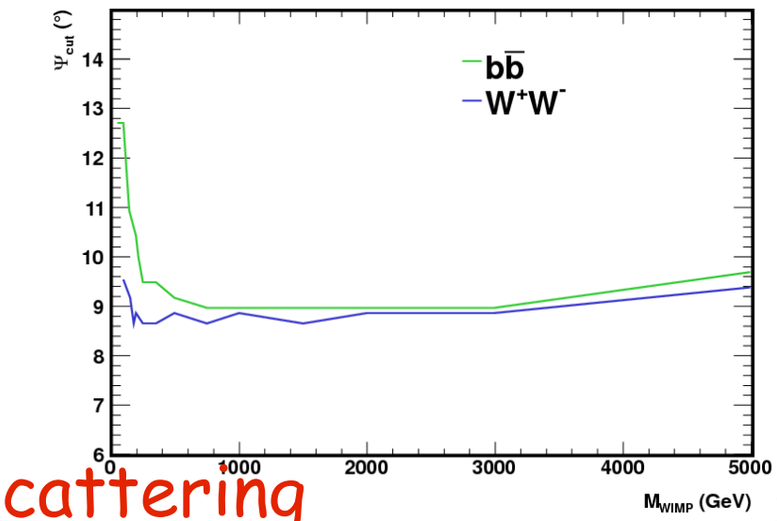


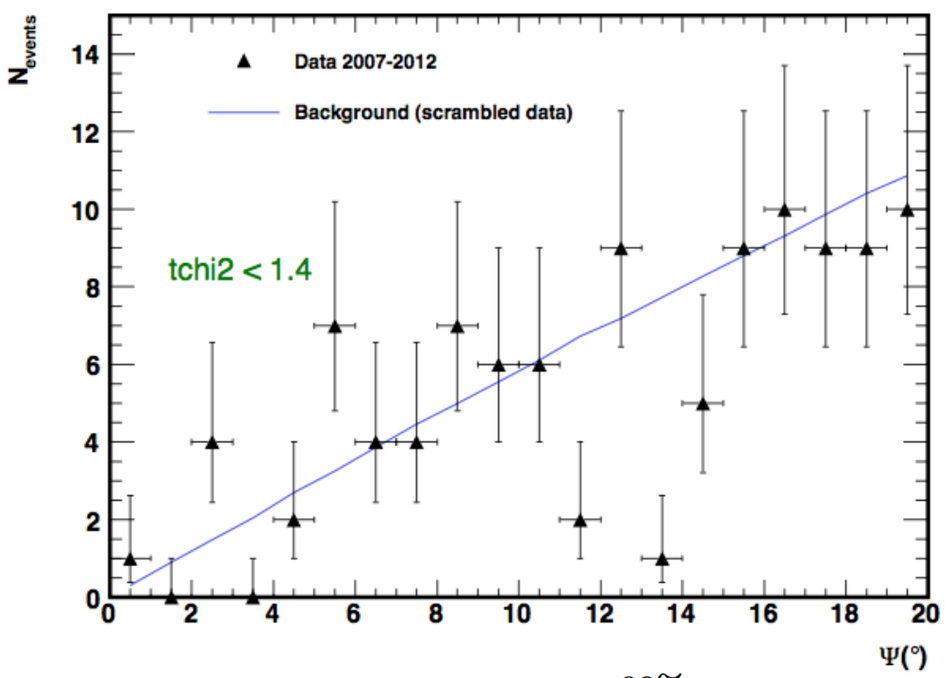
Spin-independent scattering



ANTARES - Solar WIMPs

- Dataset: 1321days from 2007-2012
- Data in the Sun direction time scrambled →Background
- Selection Cuts on the angular window size and on the track quality cut are chosen to optimize the flux sensitivity

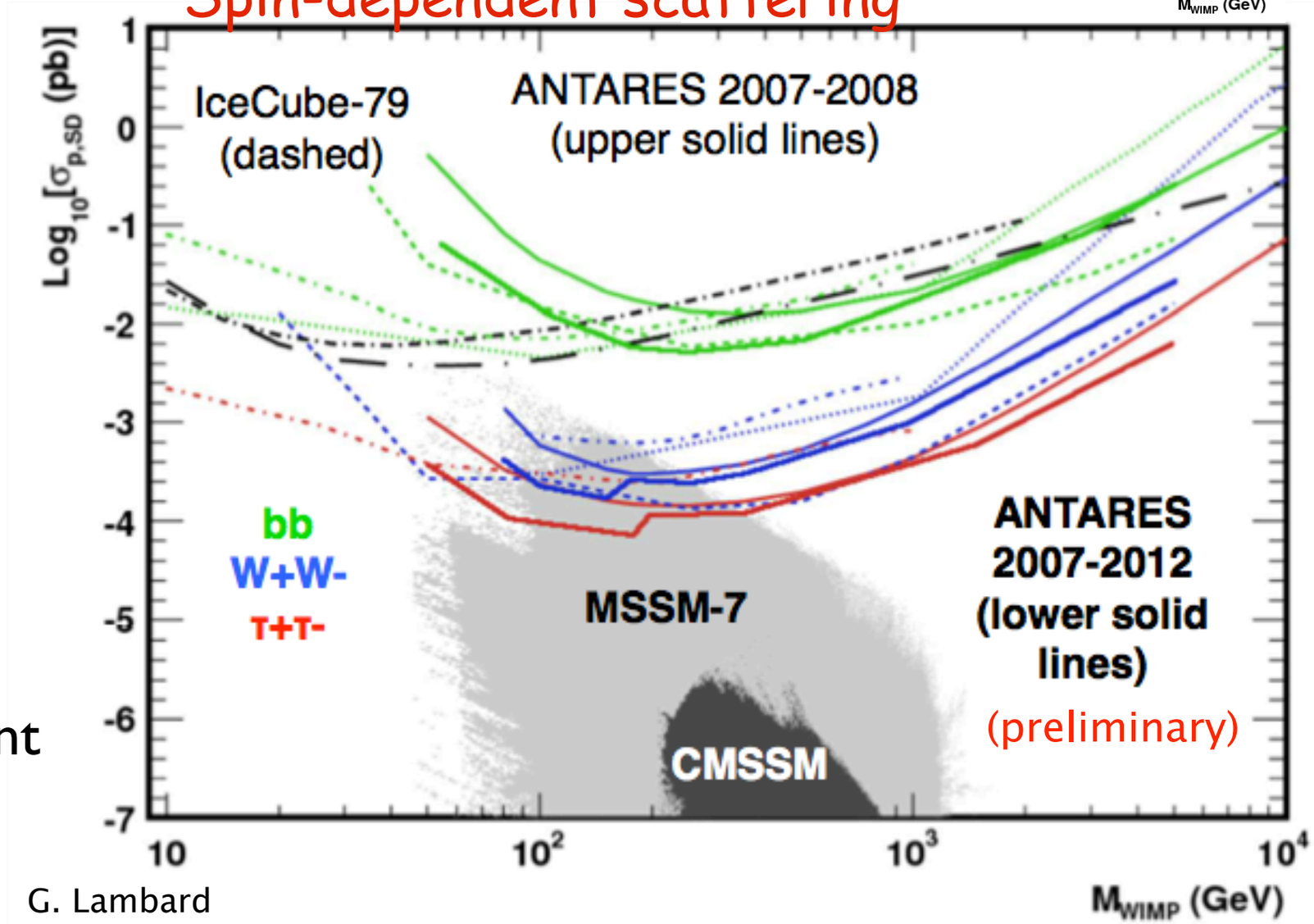




$$\bar{\Phi}_{\nu_\mu+\bar{\nu}_\mu} = \frac{\bar{\mu}^{90\%}}{\sum_i \bar{A}^i_{eff}(M_{WIMP}) \times T^i_{eff}}$$

- Observed events consistent with background expectations

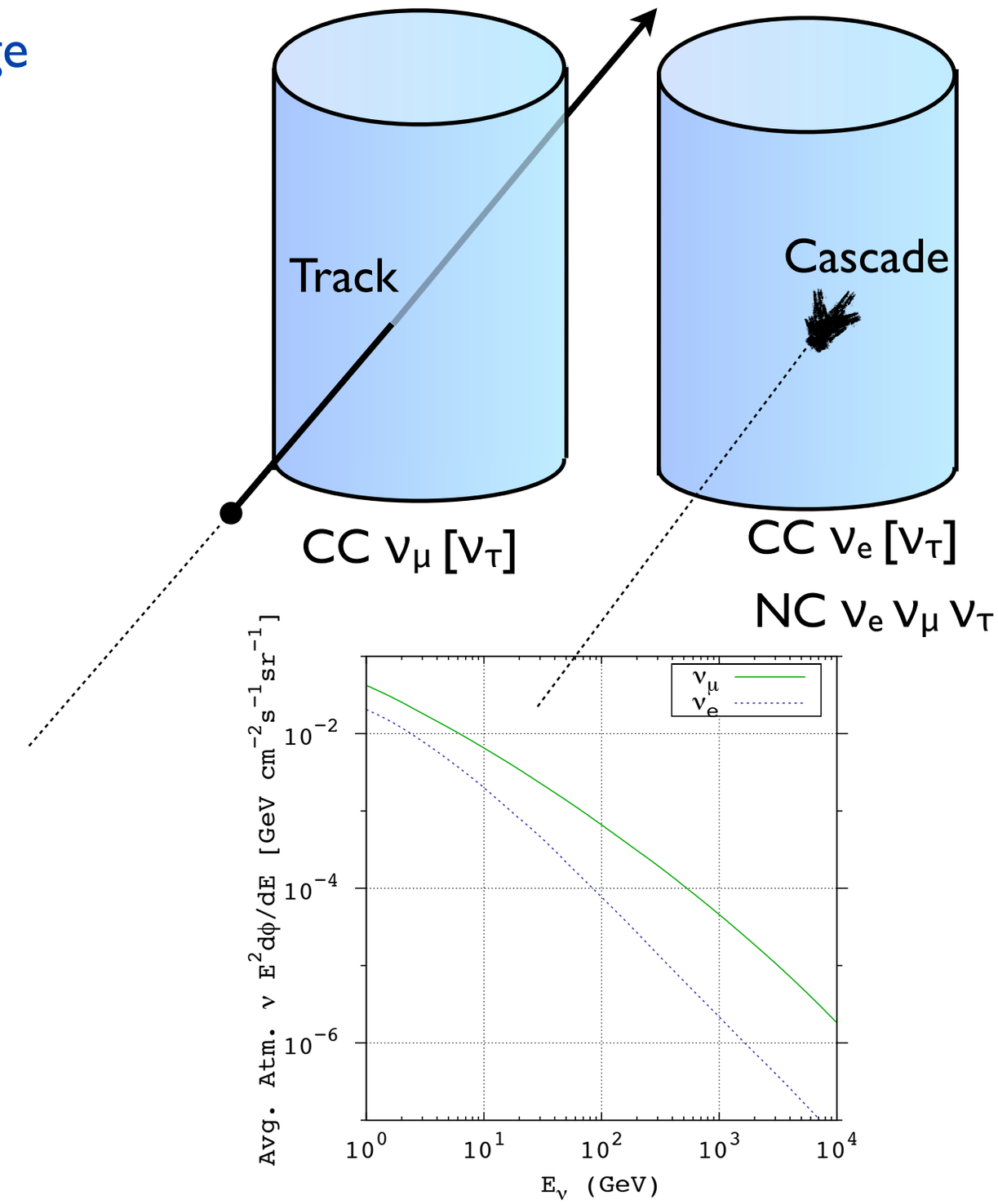
Spin-dependent scattering



G. Lambard

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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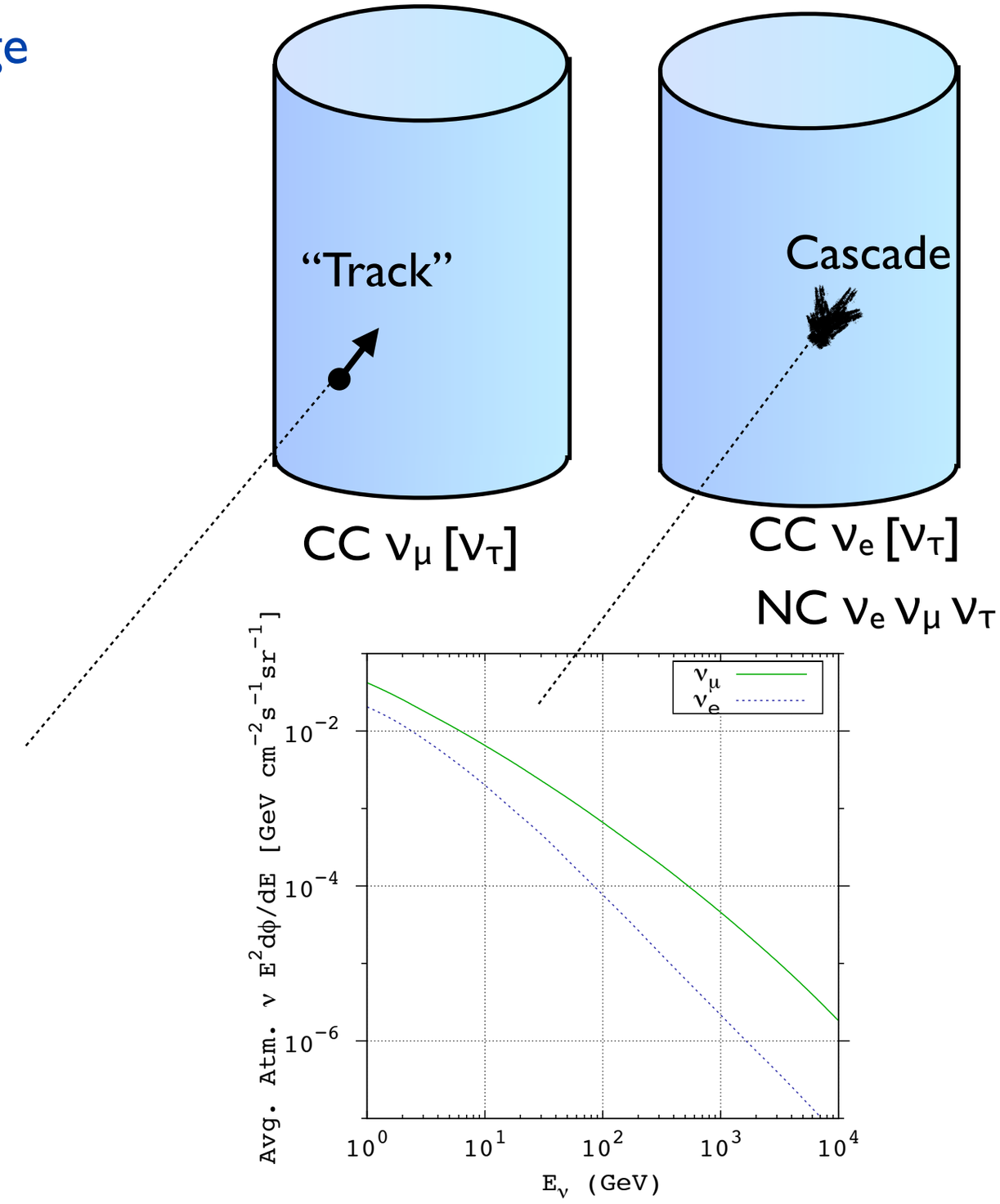
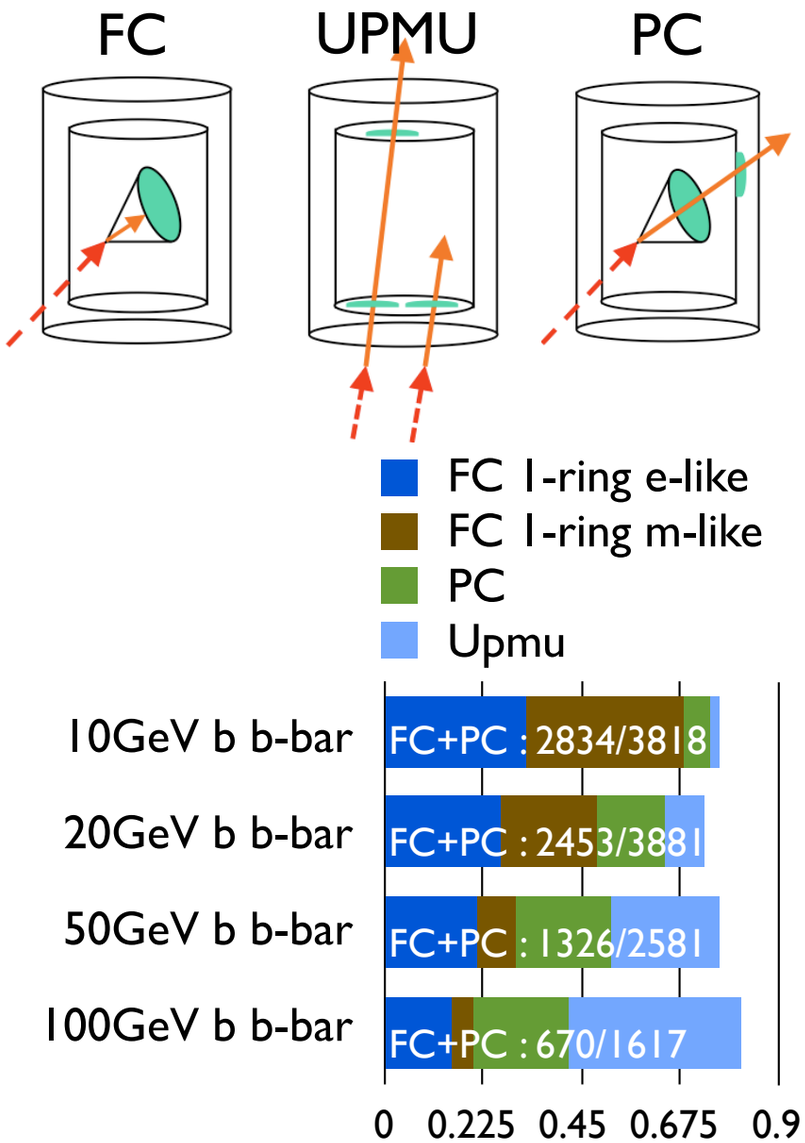
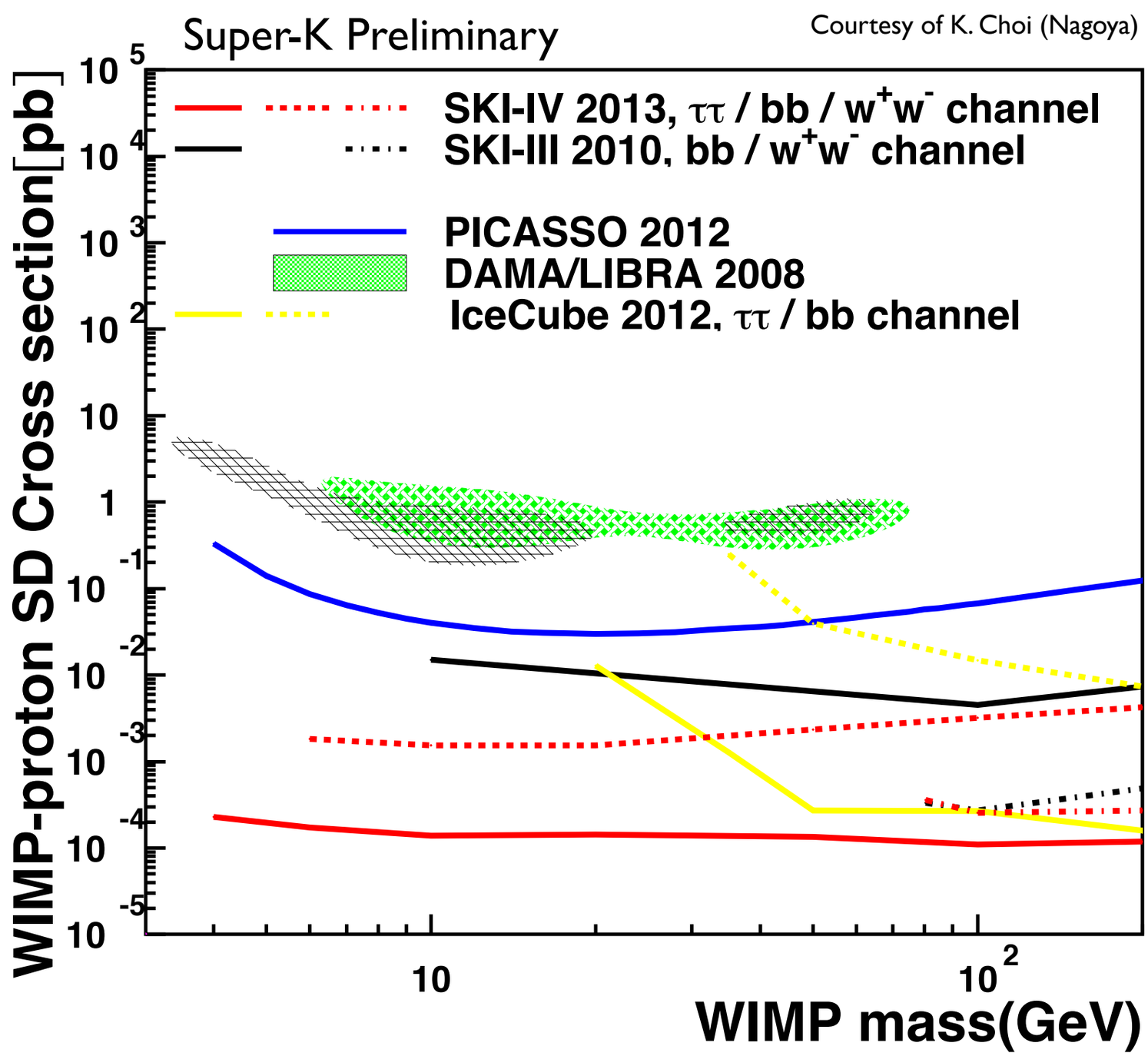


Super-Kamiokande Solar WIMPs



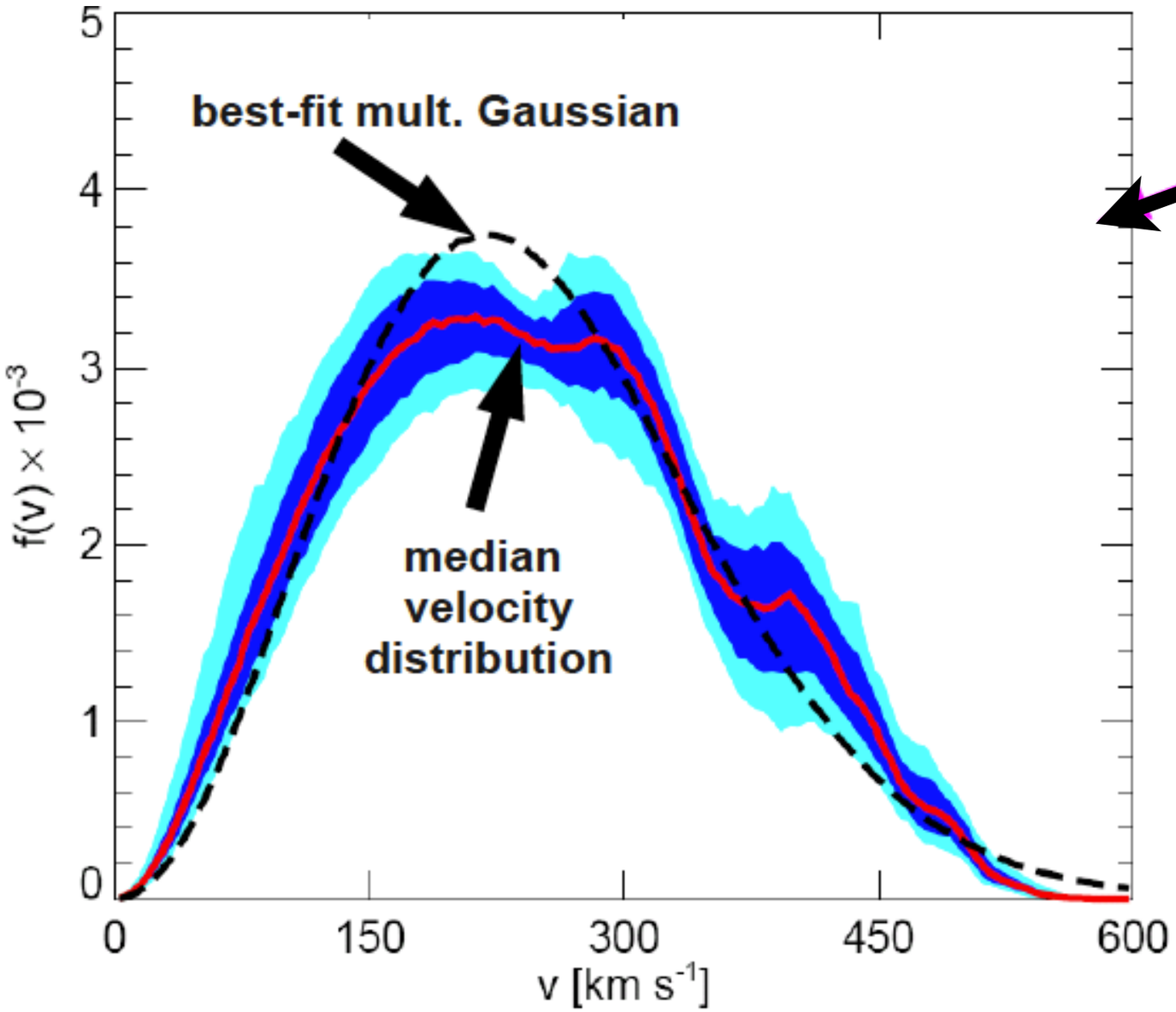


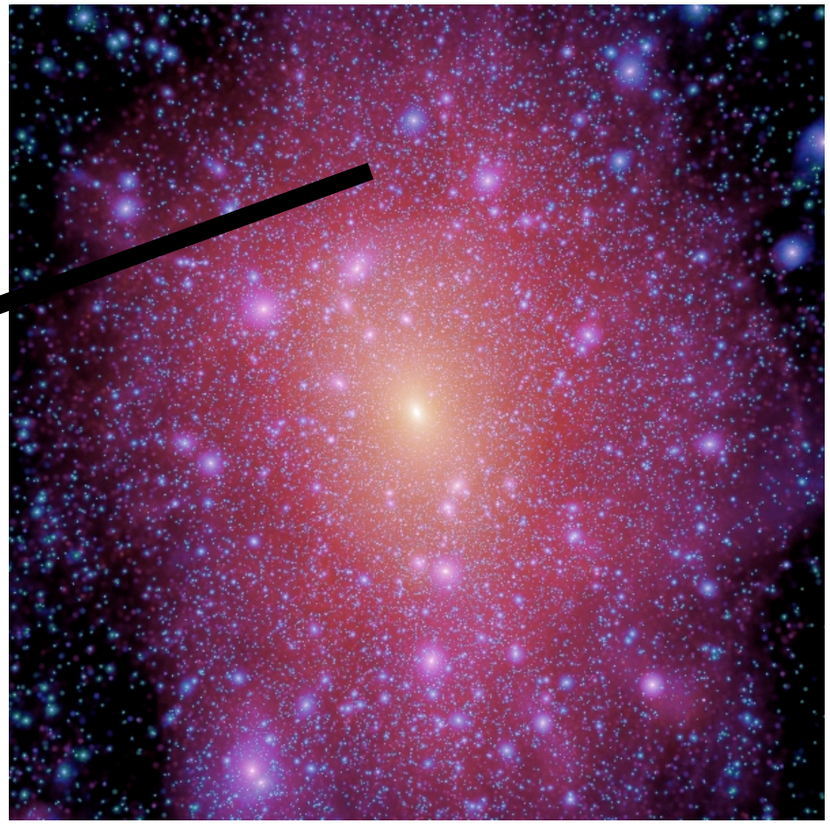
- Global fit of simulated dark matter signal + backgrounds to all DATA samples

low-mass WIMP region can be more effectively covered

Evidence for deviation of Maxwellian velocity distribution

Local Dark Matter Density / Velocity





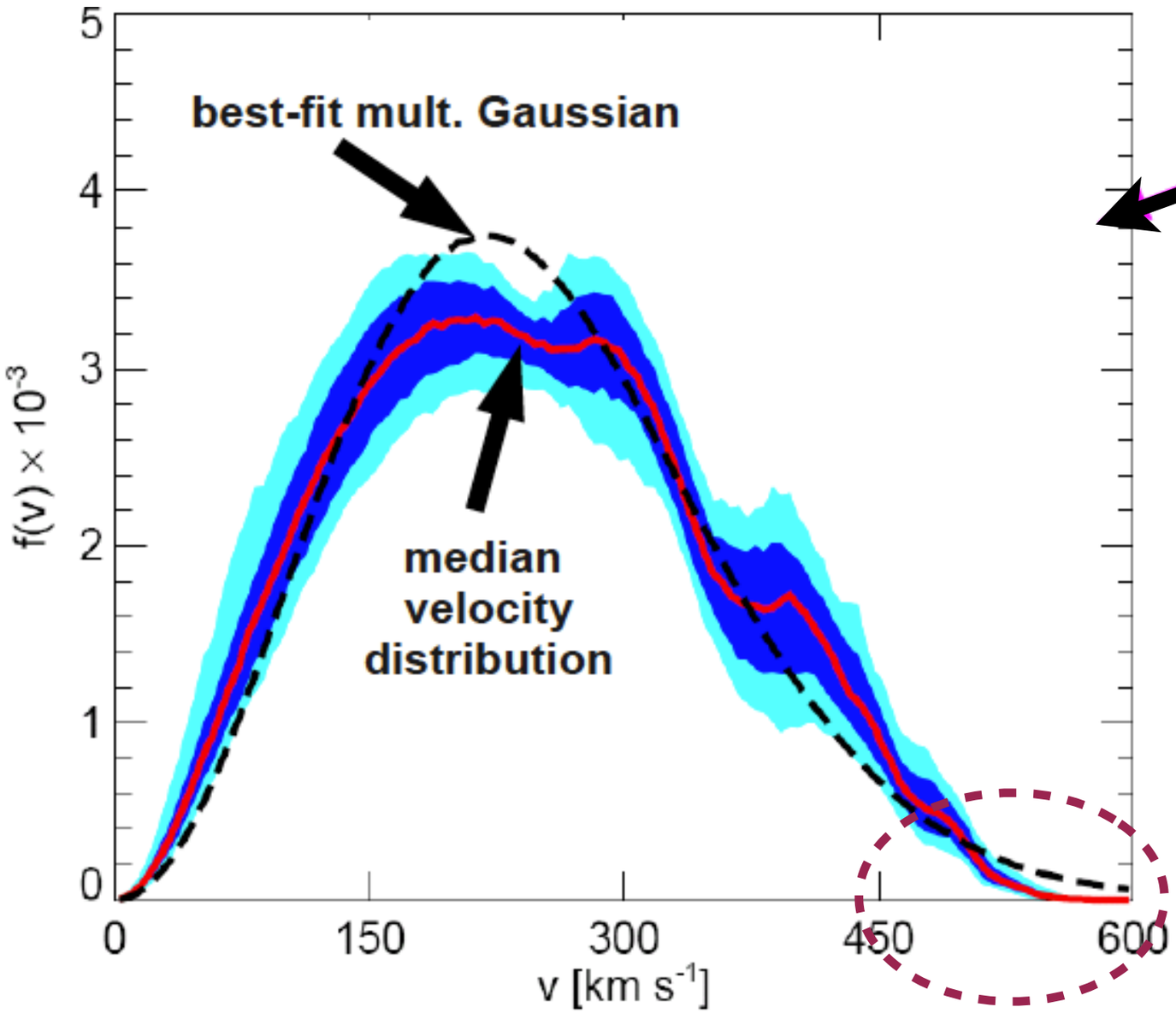
Velocity distribution still not very well understood

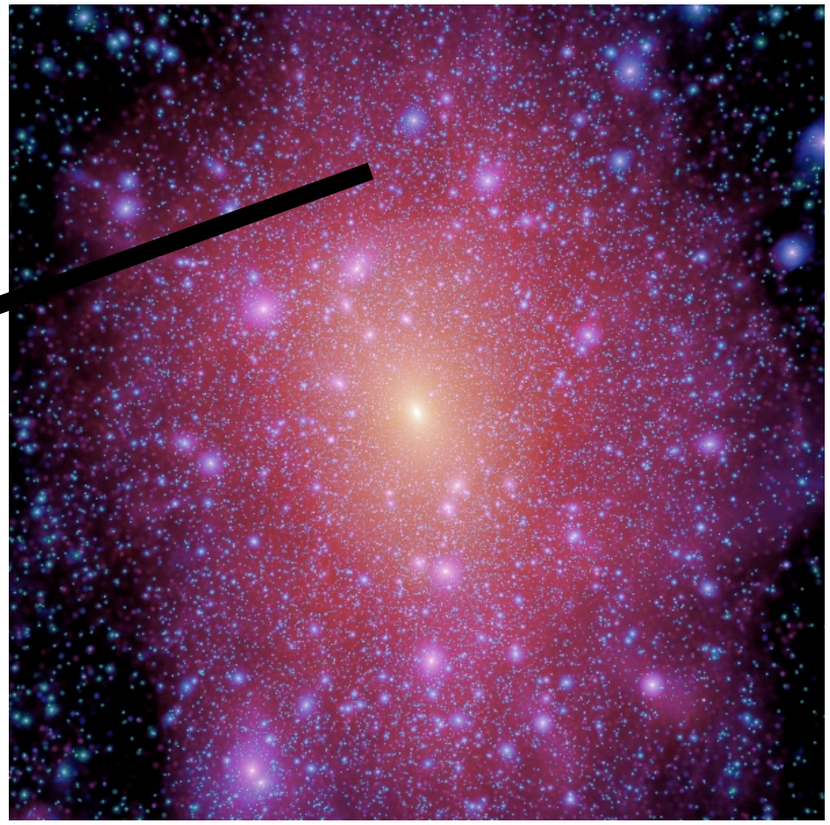
Maxwellian is reasonable

Local dark matter density ~0.3GeV/cm^3

Evidence for deviation of Maxwellian velocity distribution

Local Dark Matter Density / Velocity





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large recoils "best sensitivity" with direct detection

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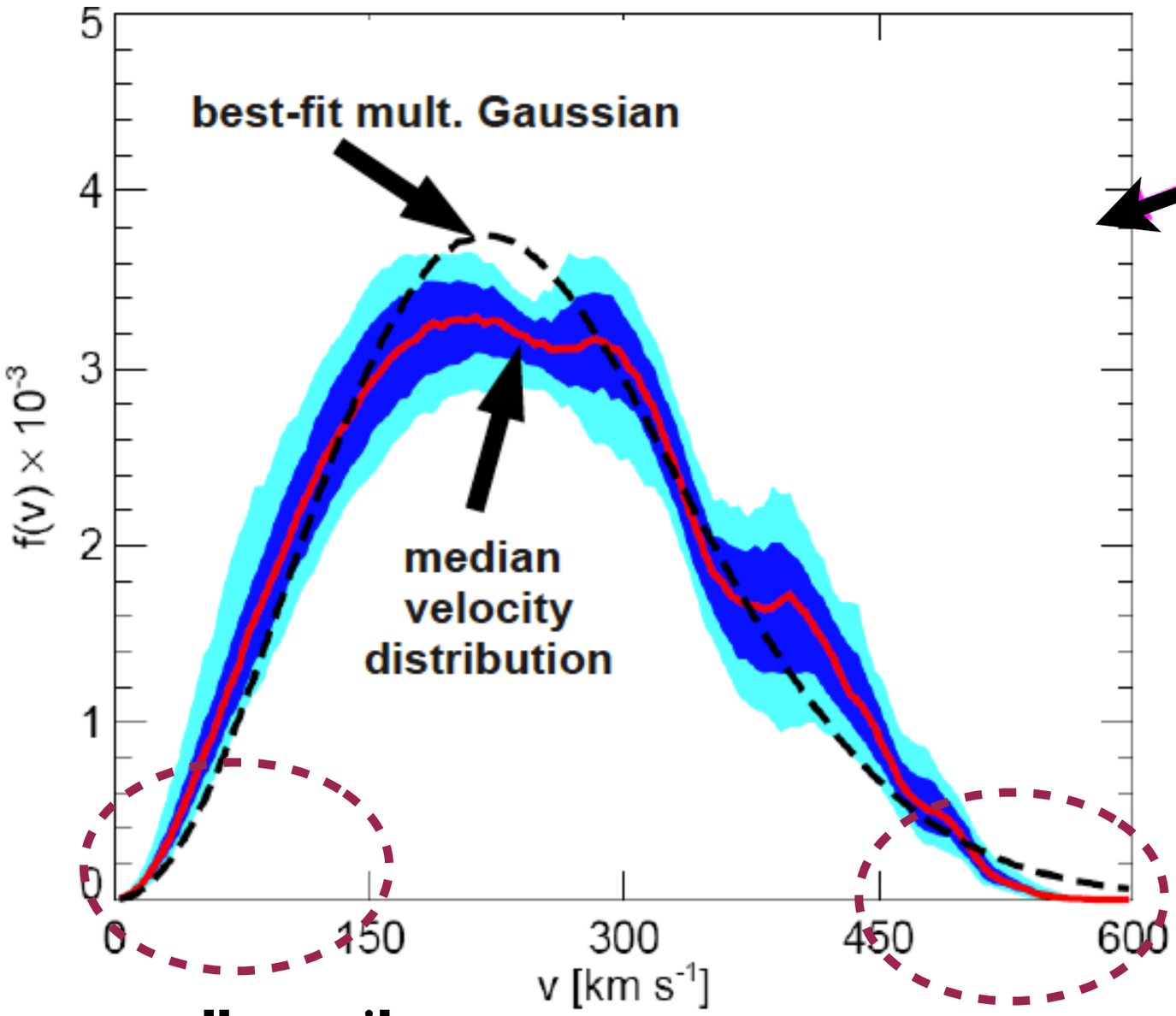
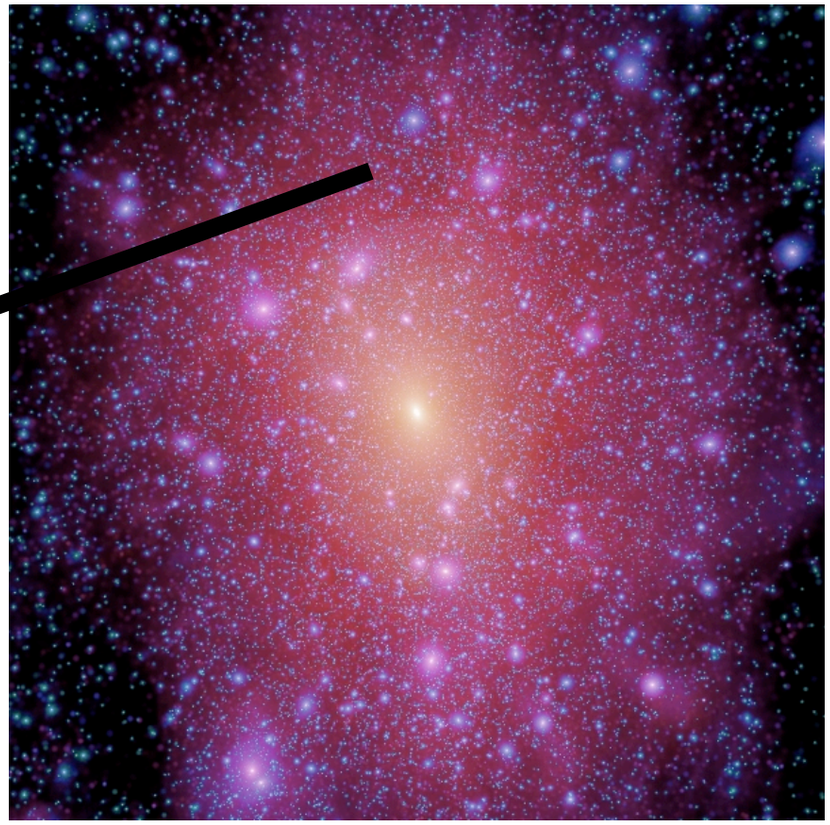
Evidence for deviation of Maxwellian velocity distribution

Local Dark Matter Density / Velocity





Velocity distribution still not very well understood

Maxwellian is reasonable

Local dark matter density ~0.3GeV/cm^3

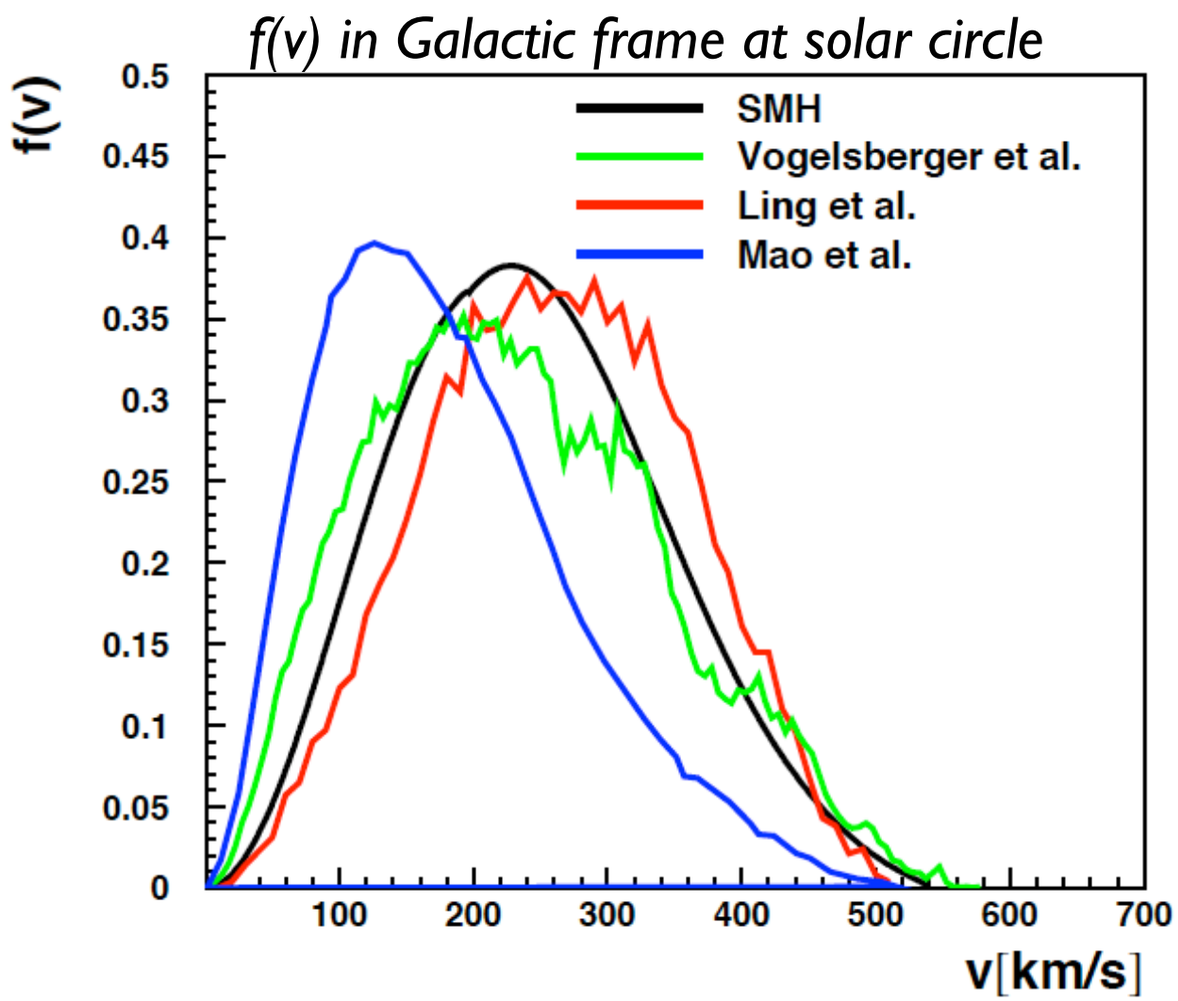
small recoils "easiest" to be captured in the Sun/Earth - indirect searches

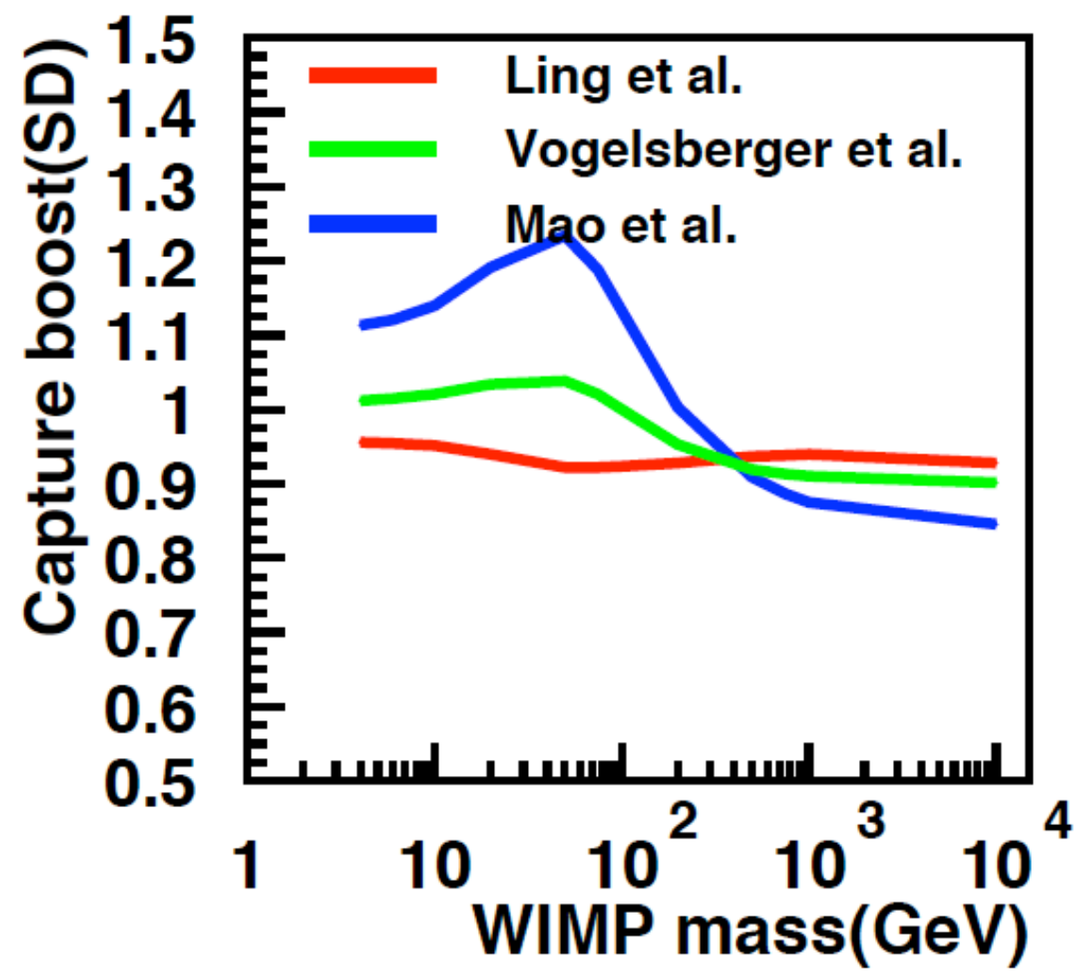
large recoils "best sensitivity" with direct detection

Impact of velocity distribution

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

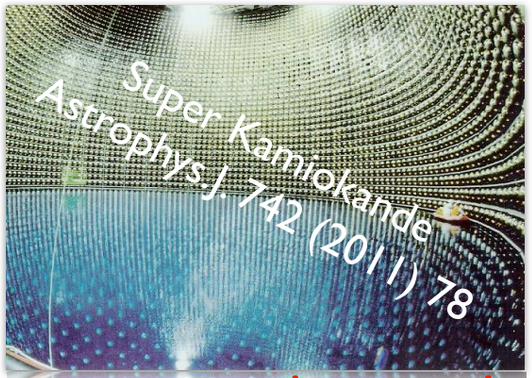
Choi, Rott, Itow arXiv:1312.0273

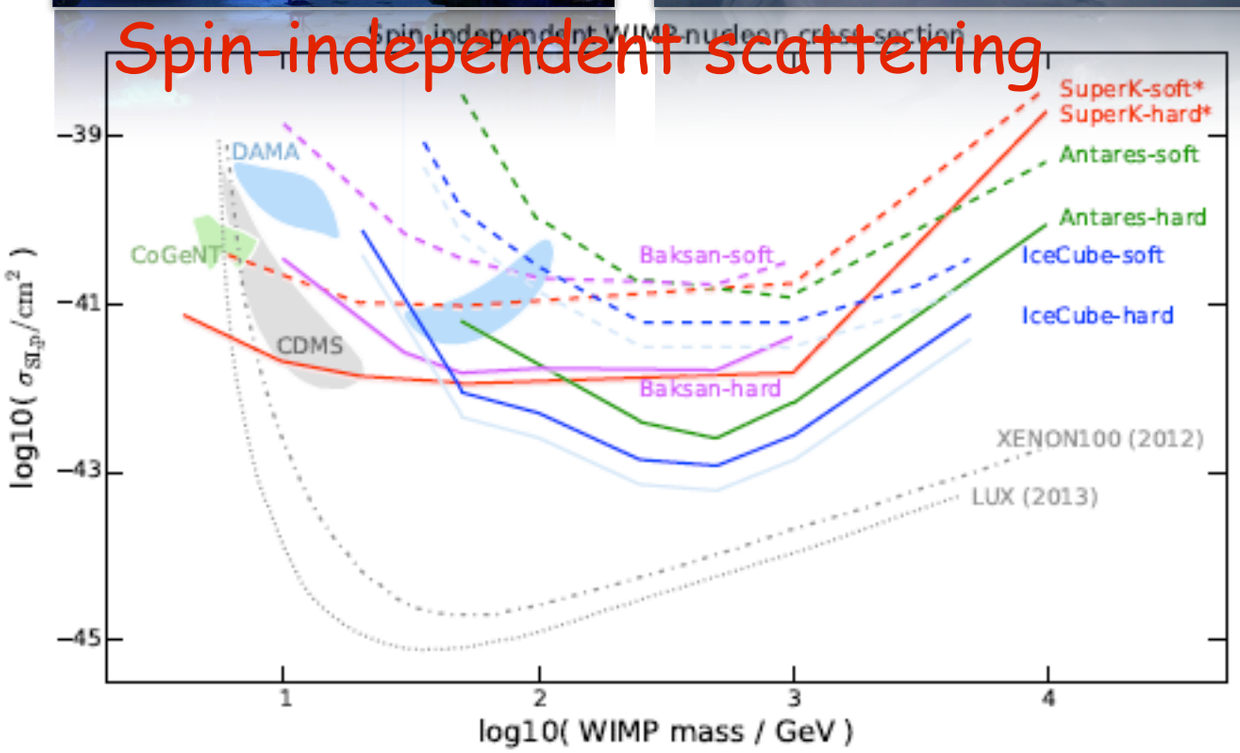


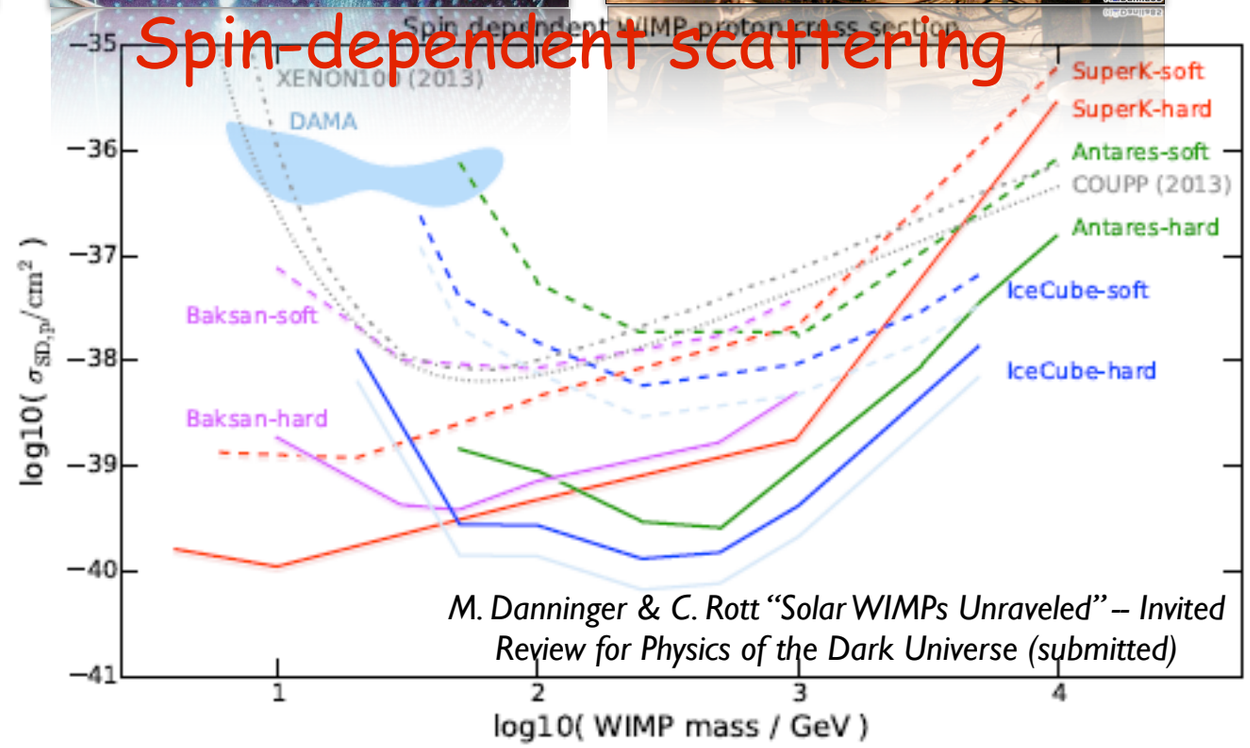


- A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%

Overview of limits







M. Danninger & C. Rott "Solar WIMPs Unraveled" – Invited Review for Physics of the Dark Universe (submitted)

Table 1: Rough comparison of neutrino telescope characteristics relevant for current Solar DM searches. The median angular resolution (Θ) 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

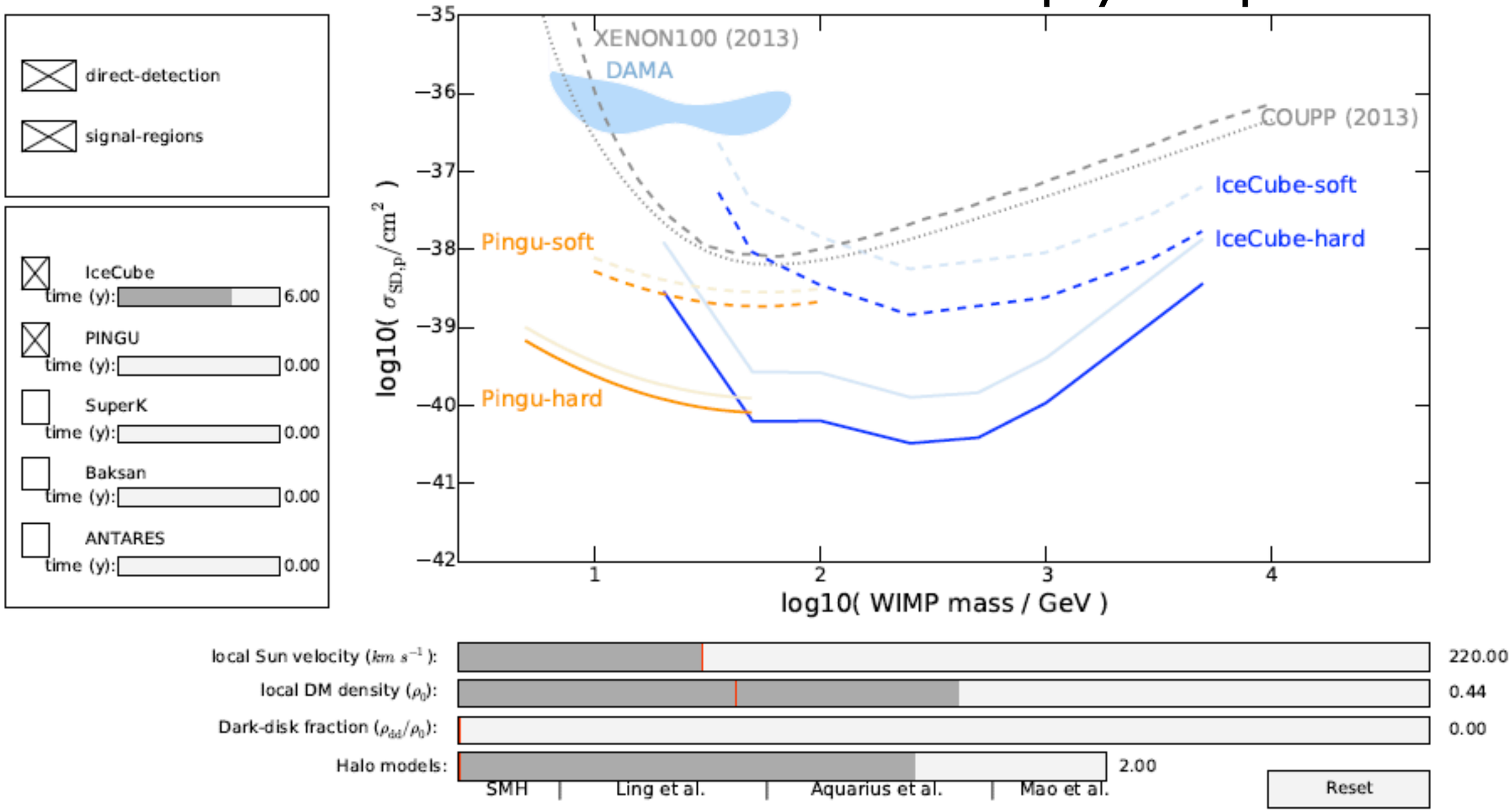
‡ Values are given at muon level (E_μ); $\overline{\Theta}$ dominated by kinematic scattering angle.

Neutrino Telescopes provide world best limits on SD WIMP proton scattering

Impact of astrophysical uncertainties

M. Danninger & C. Rott "Solar WIMPs Unraveled" – Invited Review for Physics of the Dark Universe (submitted)

interactive tool to study impact of astrophysical parameters



so far only for indirect searches implemented ... direct detection next

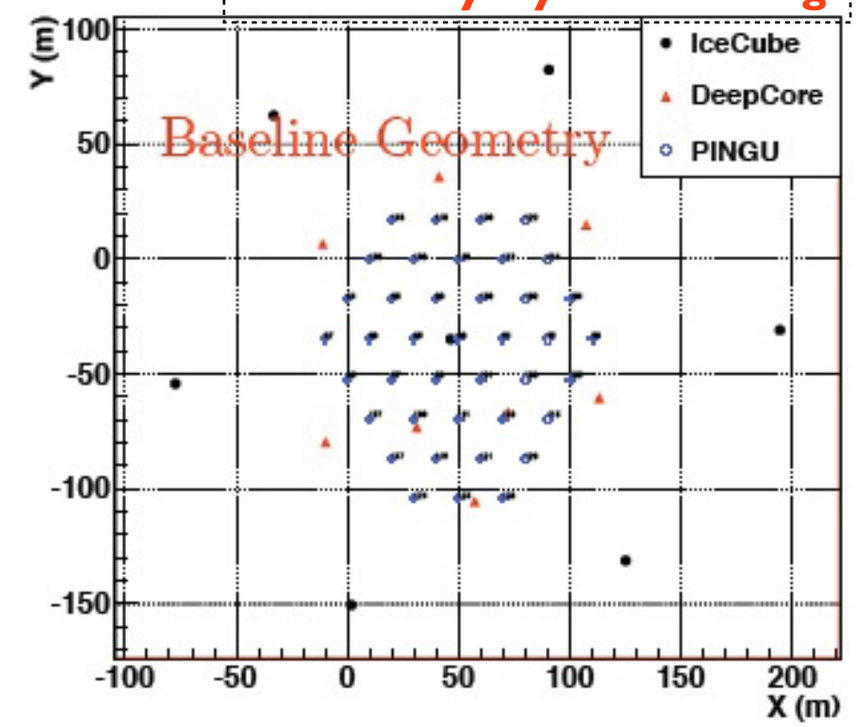
Future Prospects

PINGU Dark Matter Sensitivity

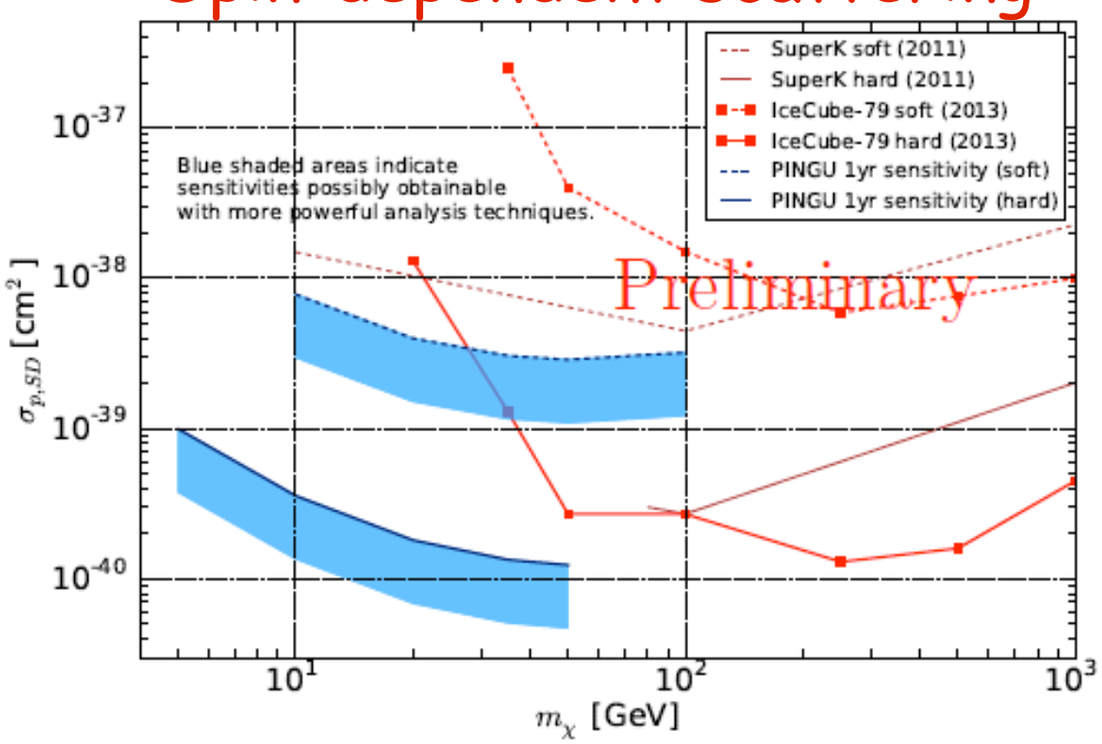
Precision **I**ceCube **N**ext **G**eneration **U**pgrade

- High density instrumentation:
  - baseline geometry: 40 strings (60 DOMs each)
  - Threshold ~ 1GeV
- Test low mass WIMP region -- capable to comfortably test DAMA/Libra

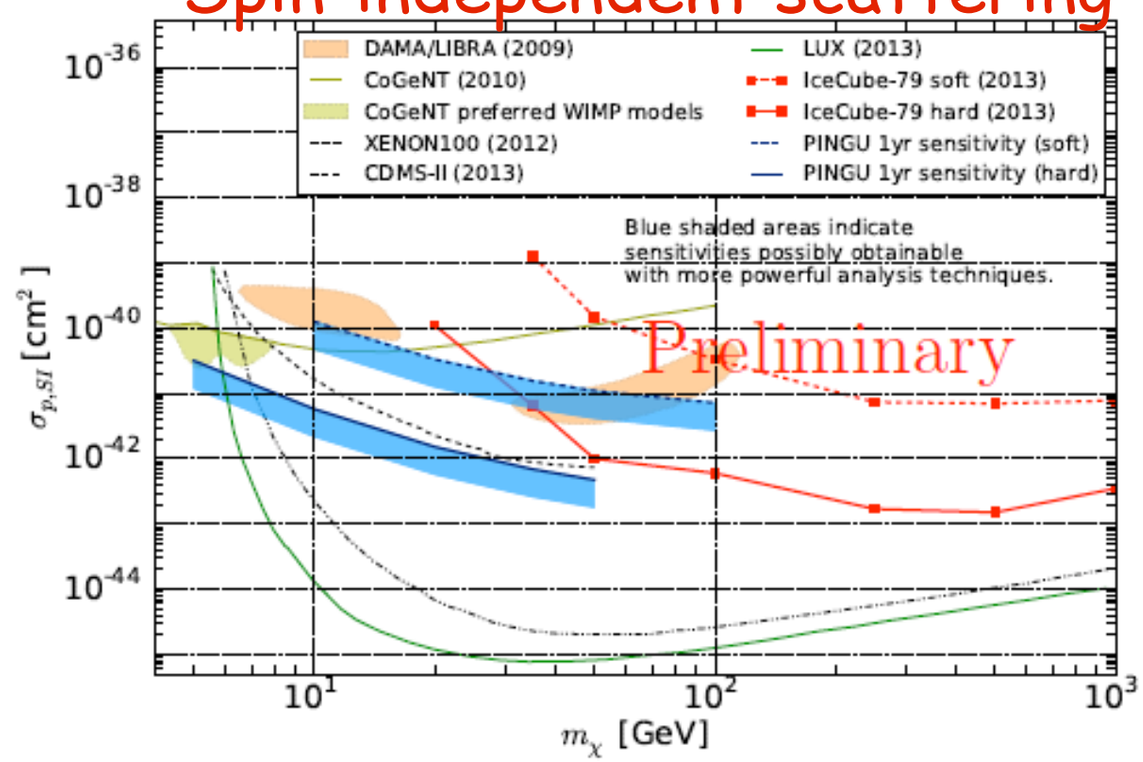
see talk by Tyce DeYoung



Spin-dependent scattering

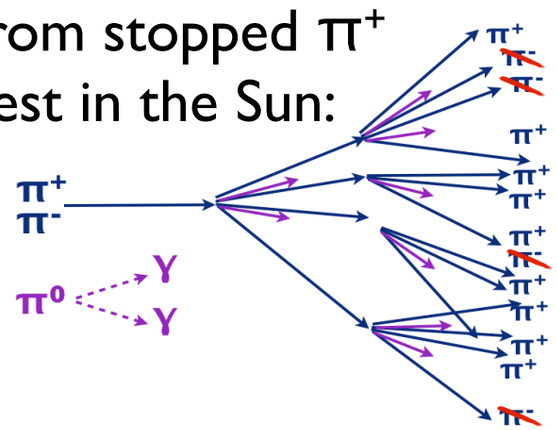


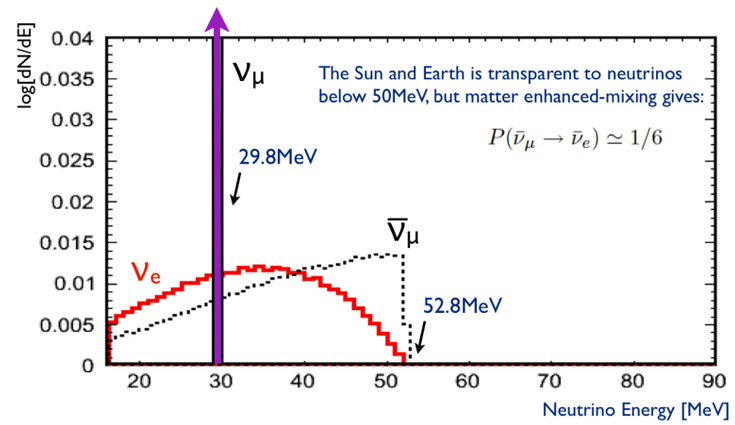
Spin-independent scattering



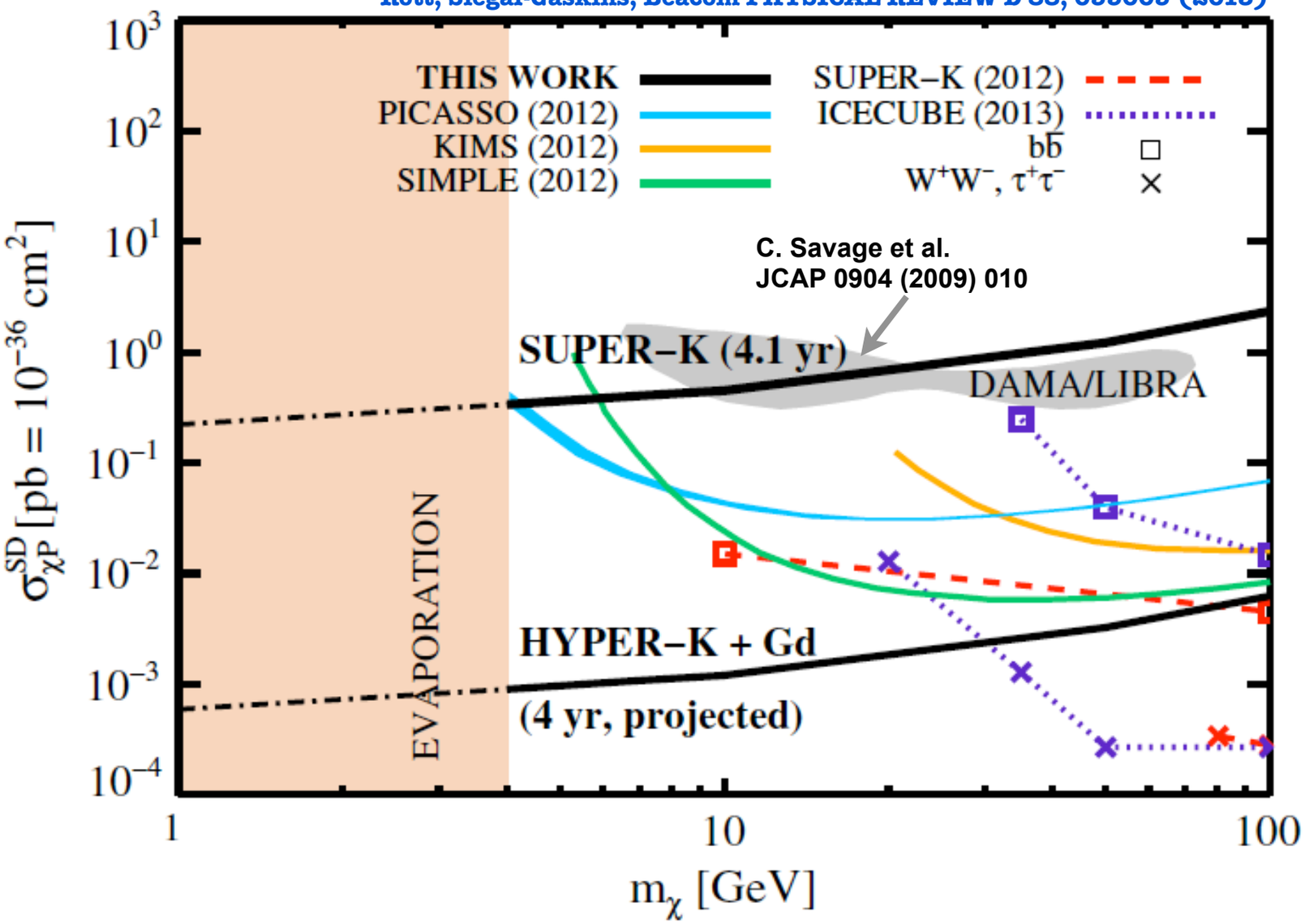
WIMP Sensitivity Super-K / Hyper-K

Neutrinos from stopped π^+ decay at rest in the Sun:





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



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 mix annihilation channels

New key detection channel to compliment other searches

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

Great Prospect for future detectors (Hyper-K, MICA, ...)

Conclusions

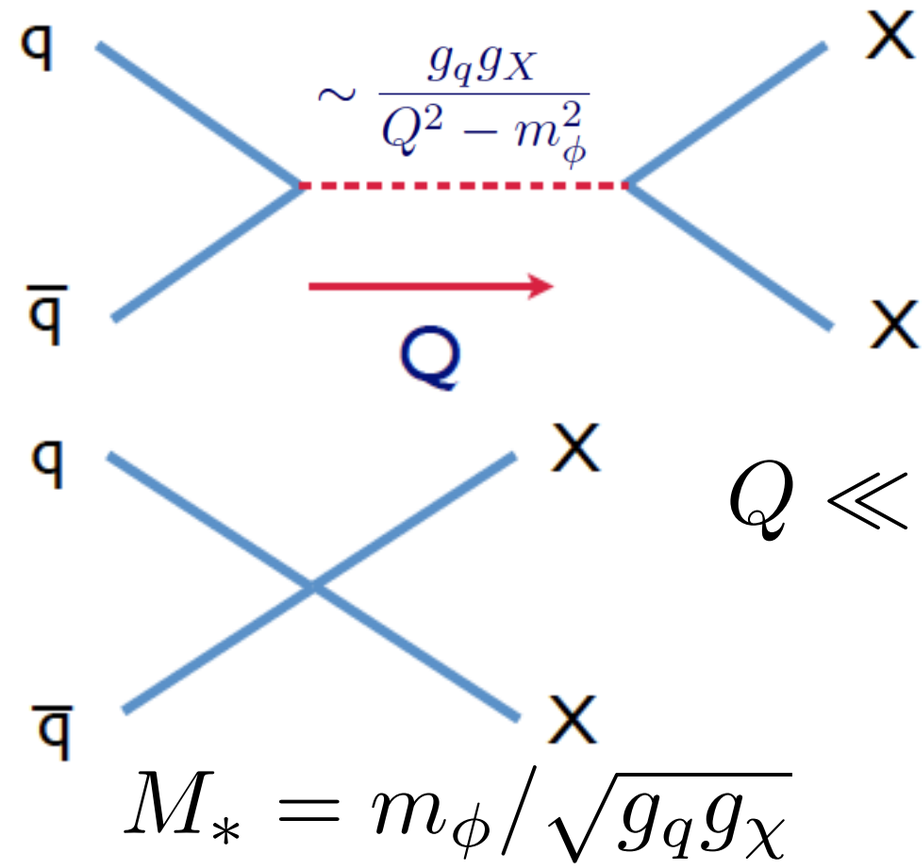
- Striking WIMP signatures provide high discovery potential for indirect searches
- Models motivated by positron excess and gamma-ray observations can and have been tested with neutrinos
- Neutrino Telescopes provide world best limits on SD WIMP-Proton scattering cross section
- Neutrinos extremely sensitive to test low-mass WIMP scenarios at current and future detectors
- New detection channel with low-energy neutrinos offers additional discovery potential

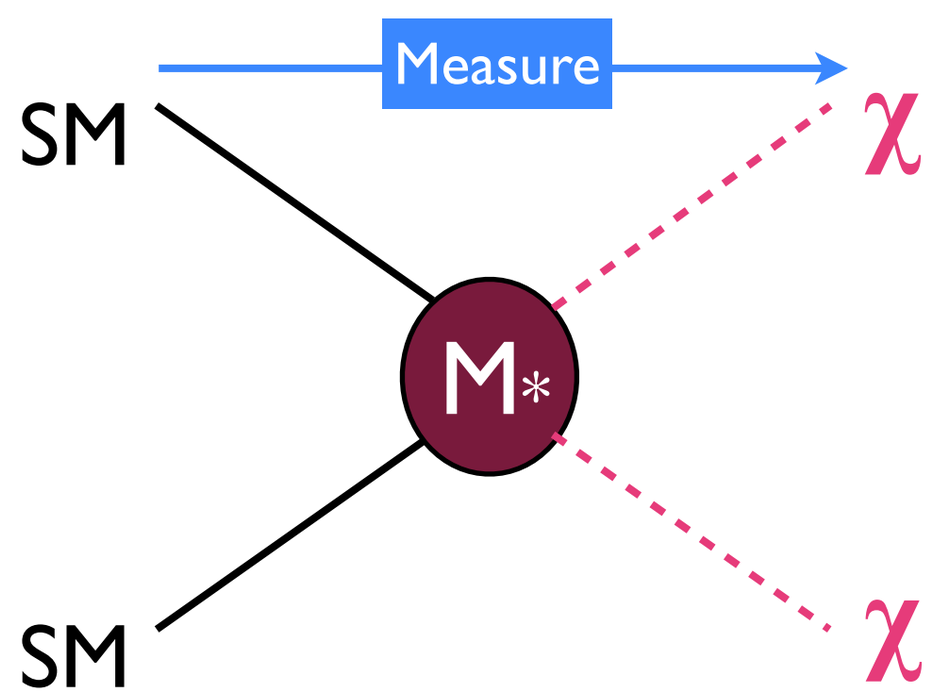
Thanks !

An Effective Theory of Dark Matter

Example for Dirac; similar for Majorana, Real, Complex

Name	Operator		Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	scalar	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$		im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$		im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$		m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	vector	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$		$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$		$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	axial-vector	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	tensor	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$		i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	scalar	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$		$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$		$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$		$\alpha_s/4M_*^3$





Invariant under Lorentz symmetry and $U(1)_{em}$

An Effective Theory of Dark Matter

Example for Dirac; similar for Majorana, Real, Complex

Name	Operator		Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	scalar	m_q/M_*^3
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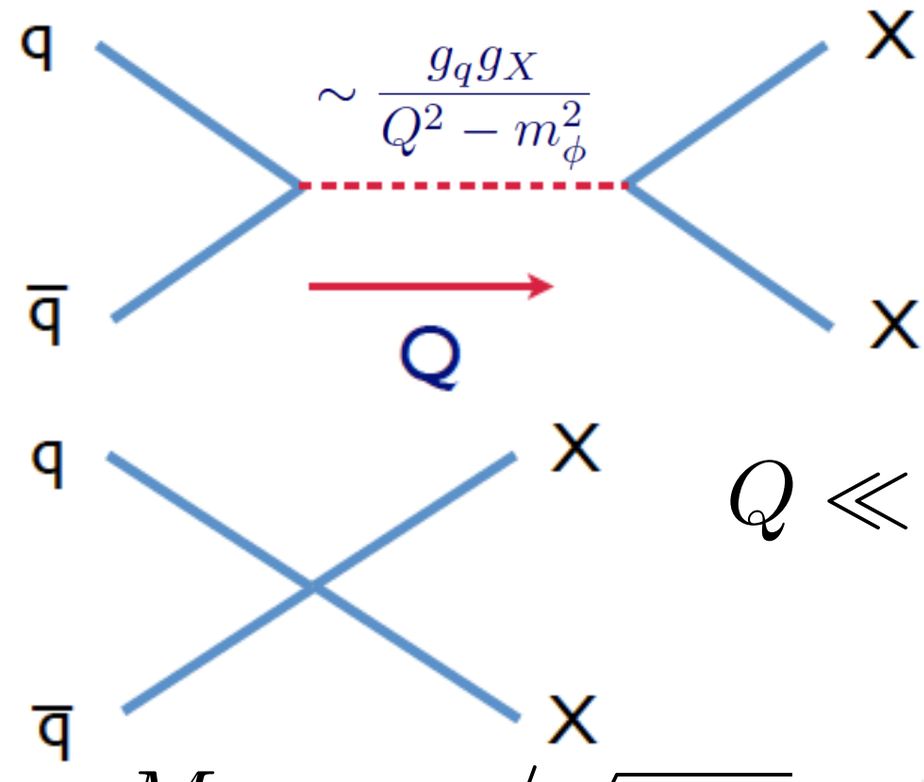
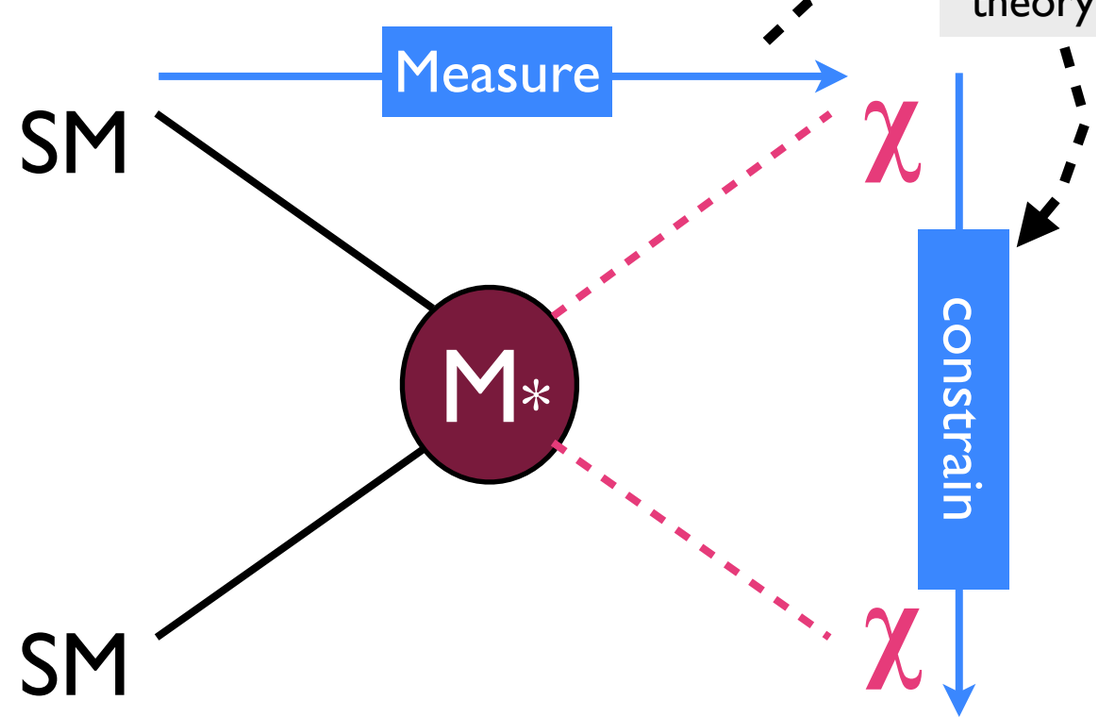
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$		m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	vector	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$		$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$		$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	axial-vector	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	tensor	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$		i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	scalar	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$		$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$		$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$		$\alpha_s/4M_*^3$



$Q \ll m_\phi$

$M_* = m_\phi / \sqrt{g_q g_\chi}$



Invariant under Lorentz symmetry and $U(1)_{em}$

Low-Energy Neutrinos - Solar WIMPs

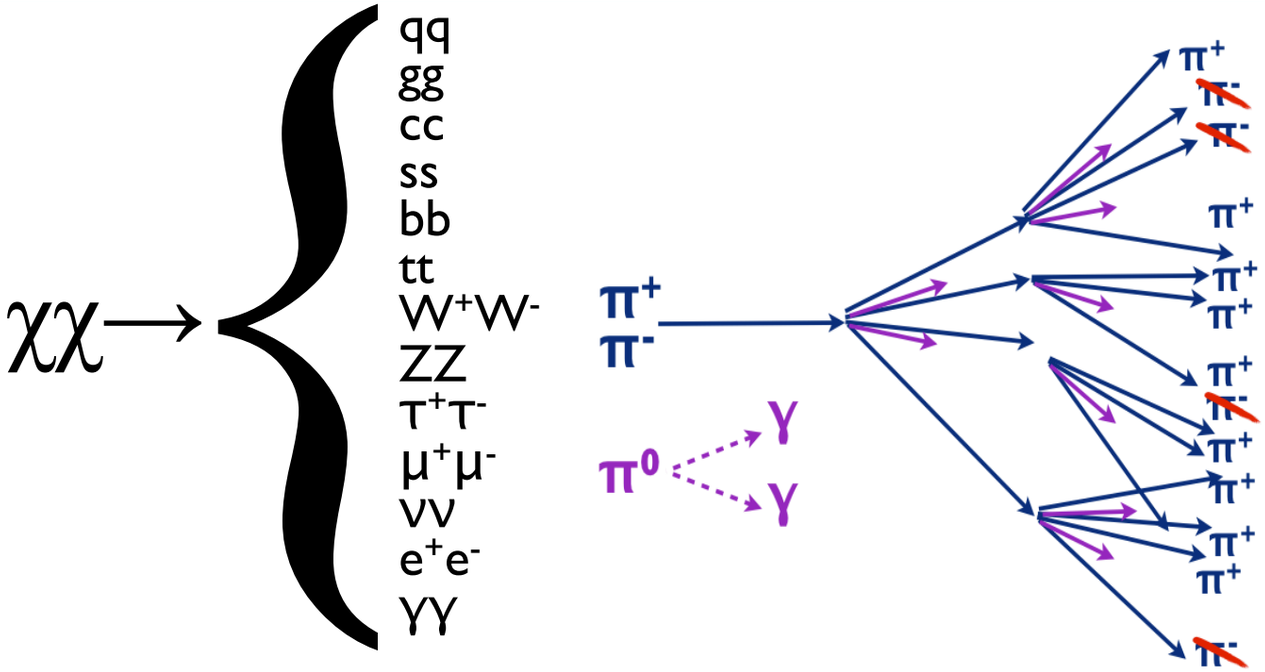
Rott, Siegal-Gaskins, Beacom 2012

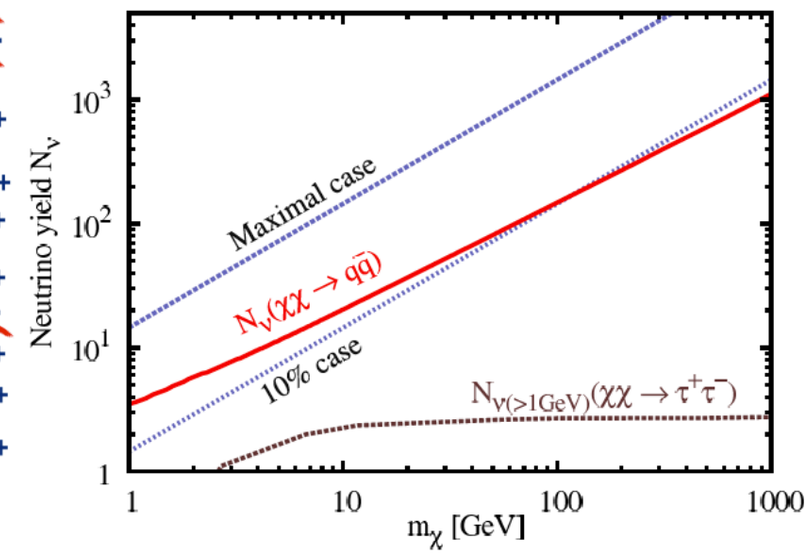
Previous searches relied on high energy neutrinos directly from the decays of annihilation products

Model the full hadronic shower in the Sun

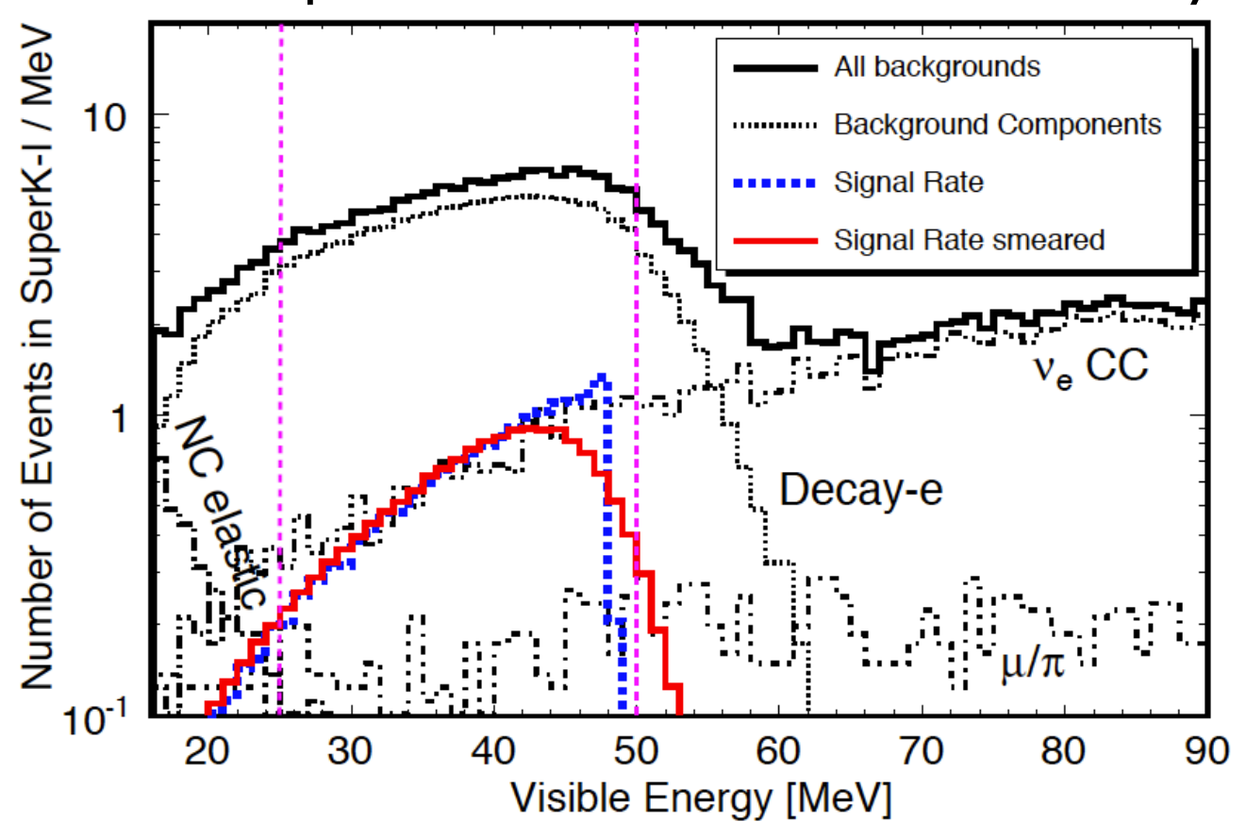
New key detection channel to compliment other searches; Super-K data can already be used to test DAMA

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



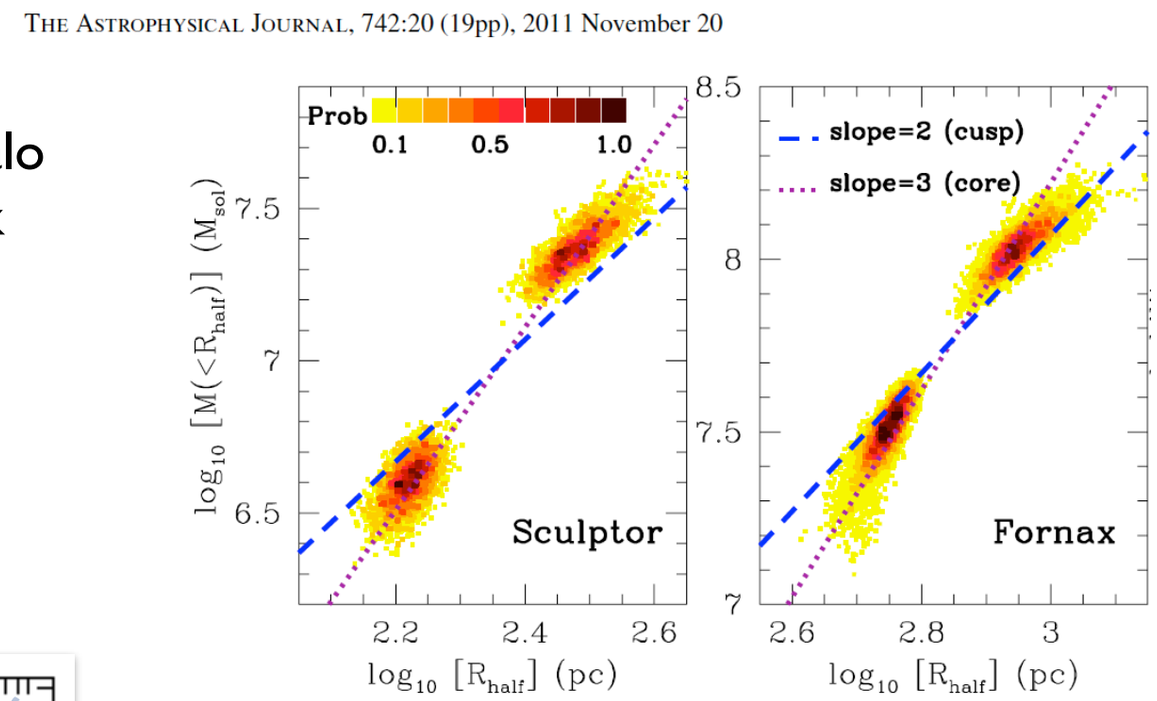


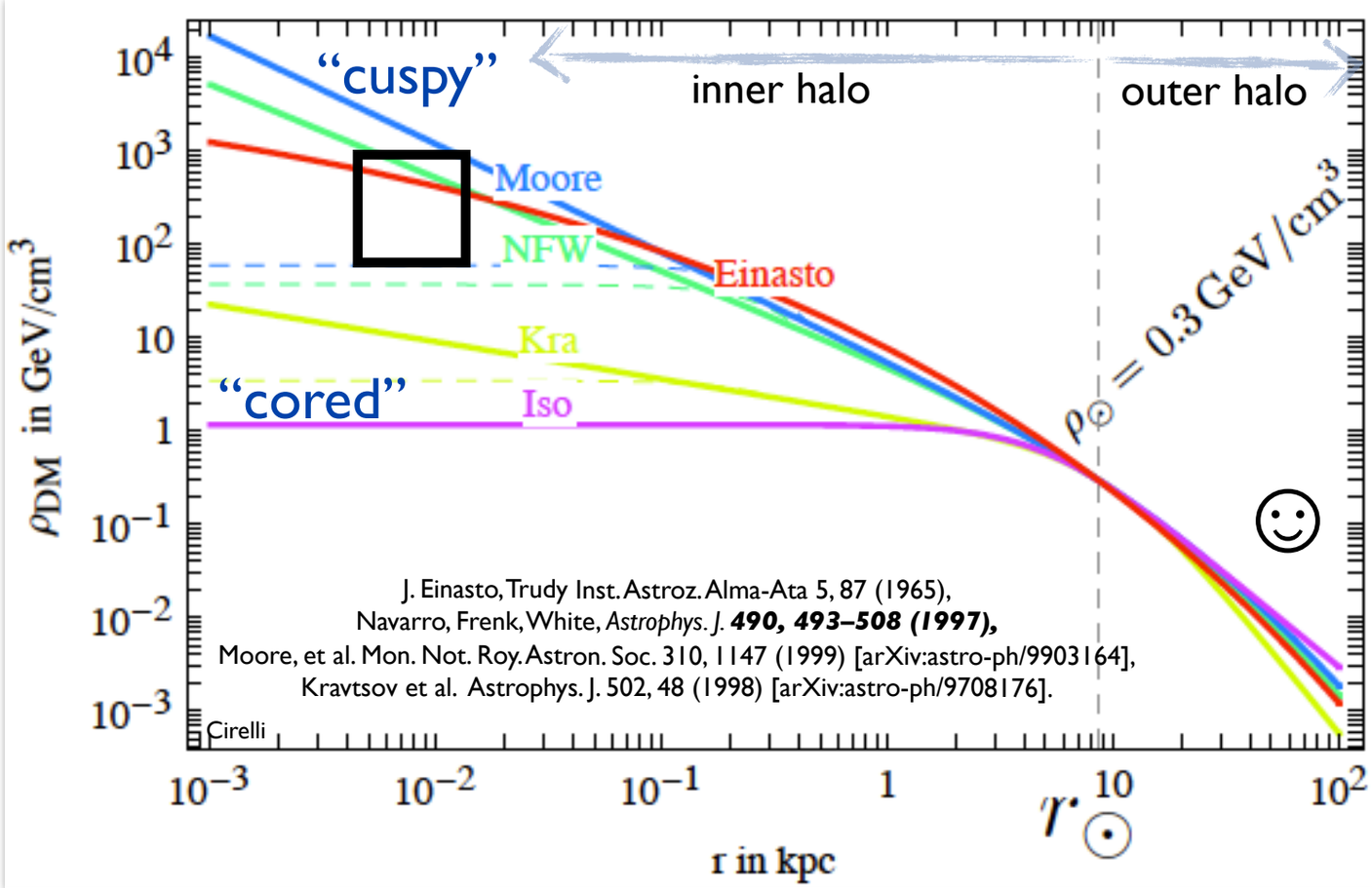
Example detection with inverse beta-decay



How Dark Matter is distributed

- N-body simulations of Milky Way like galaxies yield halo profiles ρ(r). Halo profiles described the average dark matter density (smooth)
- <u>Two major difficulties</u>
  - Inner halo shape (cuspy or cored ?)
  - Sub-structure in outer halo





Sources

small halo model dependence, boost factors

Diffuse flux, spectral feature

Large DM content, nearby source, O(10) larger flux than extra-galactic

Anisotropy

Very dense DM accumulation, nearby source

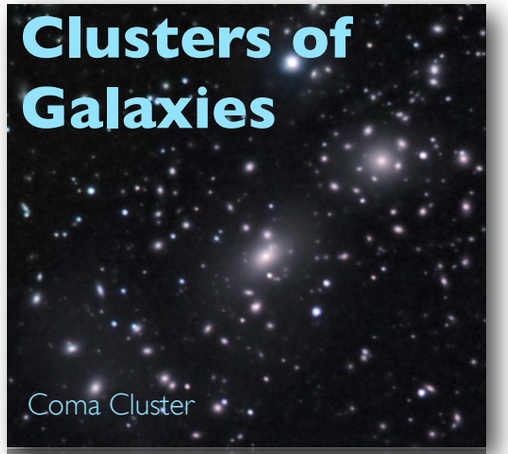
Extended Source

very strong dependence on DM density profile

no astrophysical backgrounds

Point source

cored profiles favored, less flux

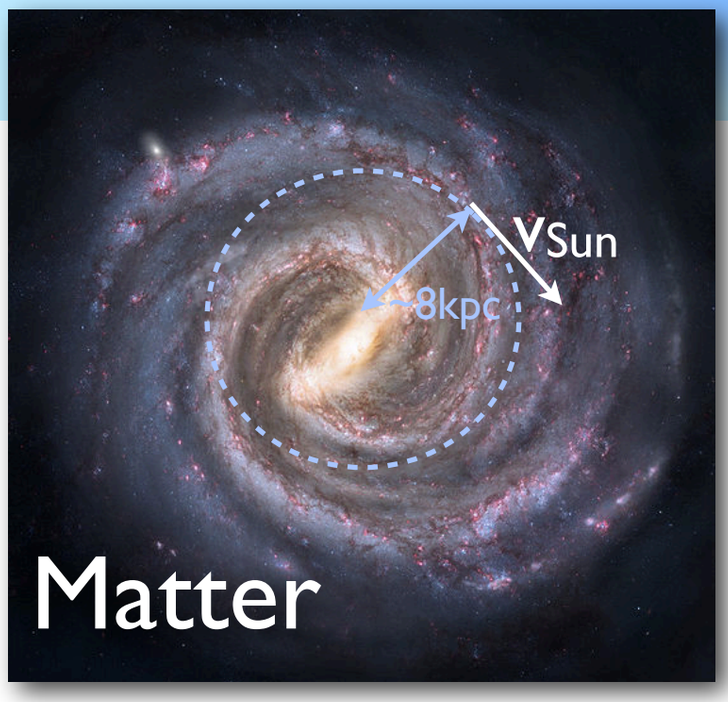


large DM content, high boost factors from sub structure

Extended source

understanding of boost factors

Solar WIMP Capture



+

Standard assumption

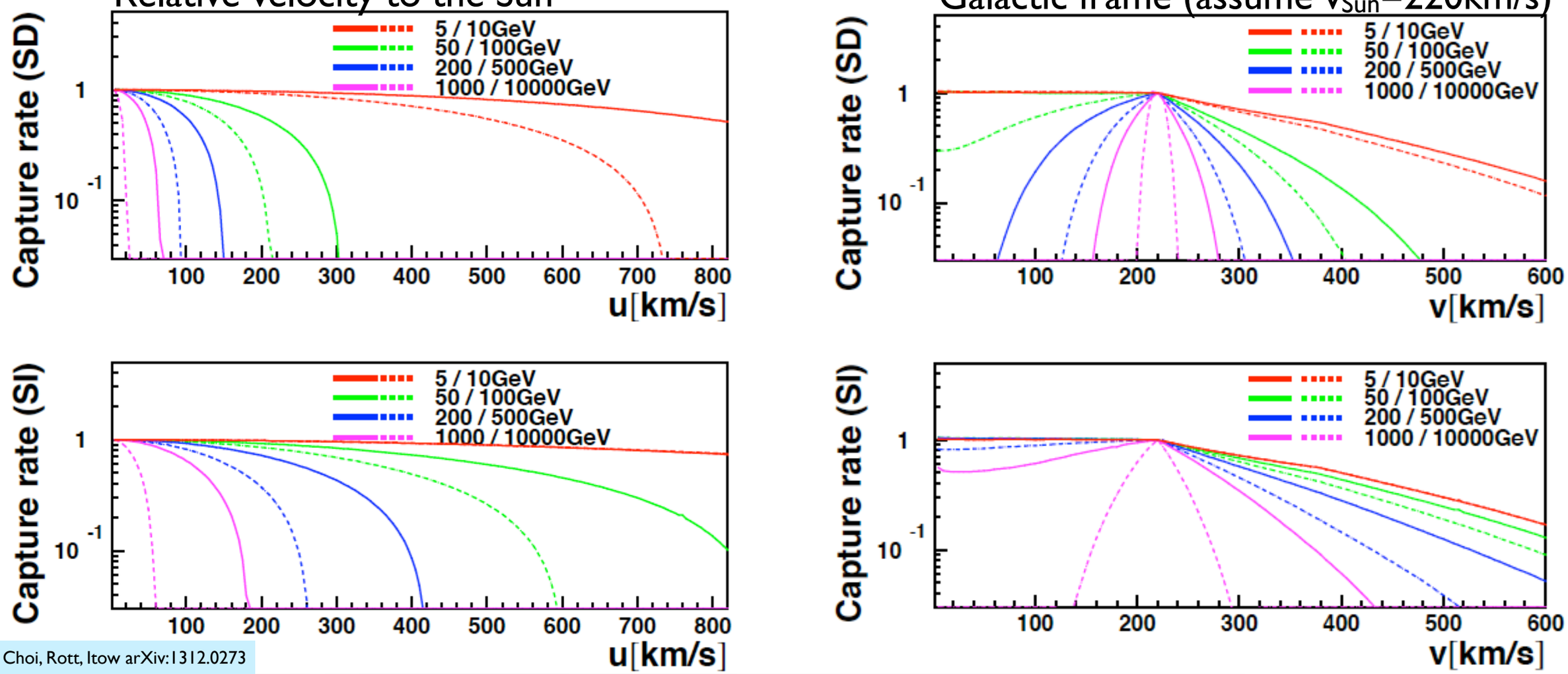
DM isotropic with Maxwellian velocity distribution

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

$$f(v)dv = \frac{4}{\sqrt{\pi}}\left(\frac{3}{2}\right)^{\frac{3}{2}} \frac{v^2}{{v_{rms}}^3} exp\left(-\frac{3}{2}\frac{v^2}{{v_{rms}}^2}\right)\Theta(v - v_{esc})dv$$

Relative velocity to the Sun

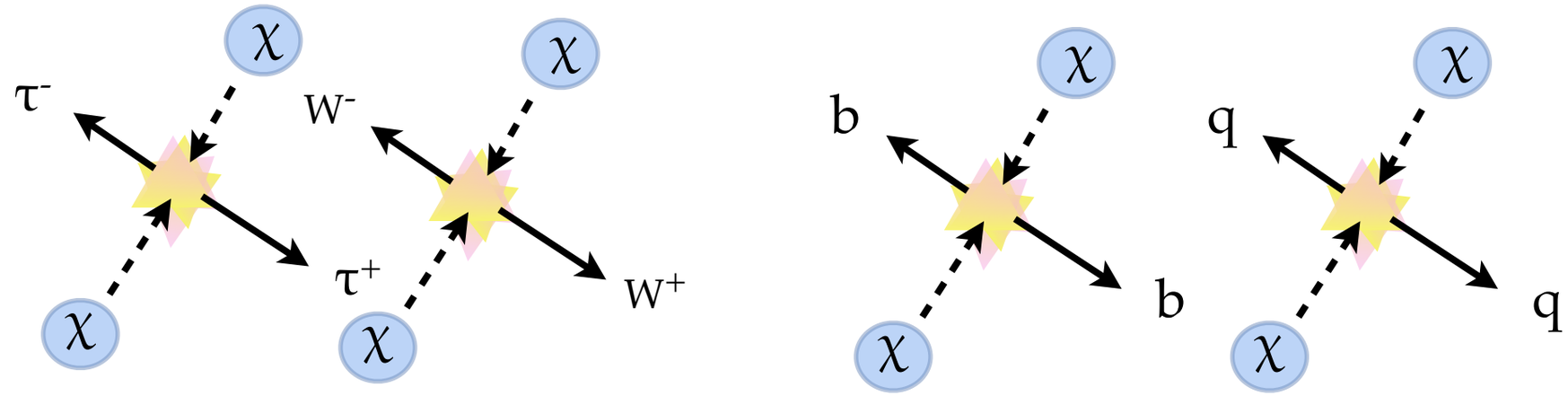
Galactic frame (assume v_{Sun}=220km/s)



Choi, Rott, Itow arXiv:1312.0273

Dark Matter Annihilation in the Sun

Model i: $Br(\tau\tau)_i$ + $Br(WW)_i$ + $Br(bb)_i$ + $Br(qq)_i$ + ... = 1



high energy neutrinos from annihilation / decay products

νν	$\tau^- \tau^+$	$W^- W^+$	bb	qq	e^+e^-
highest energy neutrinos					fewest neutrinos

Benchmarks
Br 100%

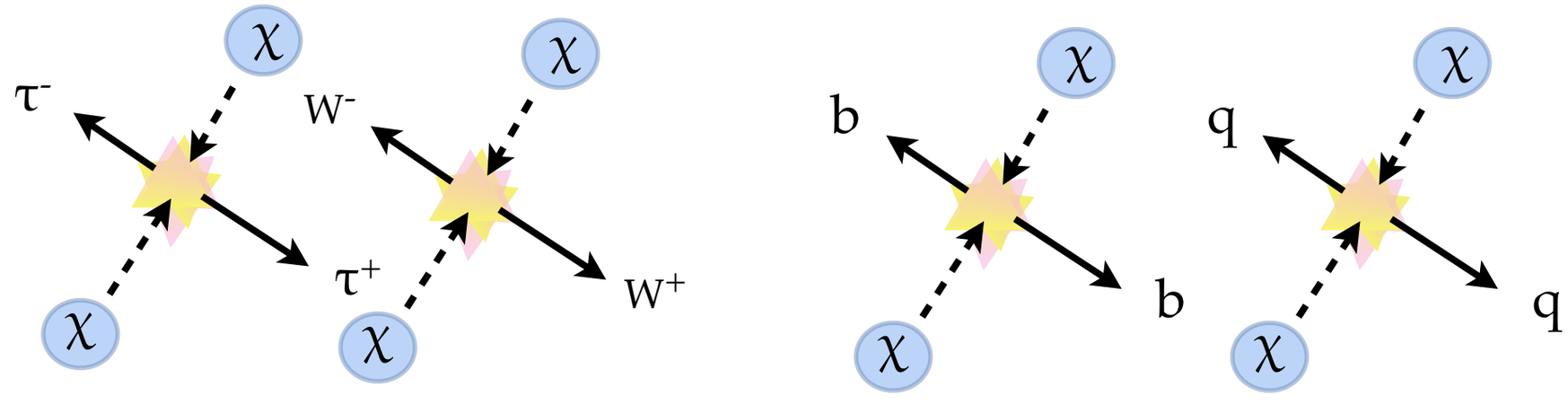
Hard channel

Soft channel

hard: WW, (ττ for $m_\chi < m_W$)
soft: bb

Dark Matter Annihilation in the Sun

Model i: $Br(\tau\tau)_i$ + $Br(WW)_i$ + $Br(bb)_i$ + $Br(qq)_i$ + ... = 1



high energy neutrinos from annihilation / decay products

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

highest energy neutrinos fewest neutrinos

Benchmarks
Br 100%

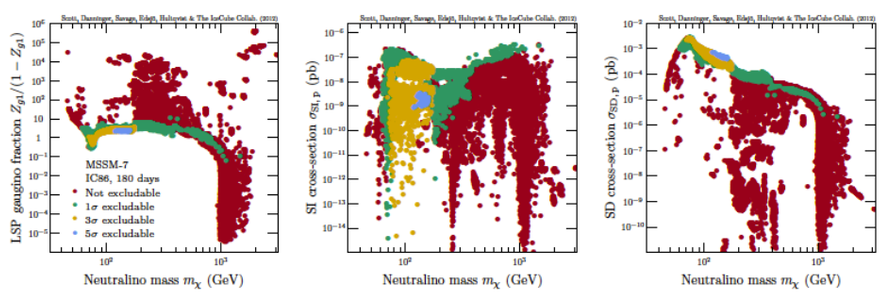
Hard channel

Soft channel

hard: WW, (ττ for $m_\chi < m_W$)
soft: bb

Specific Model

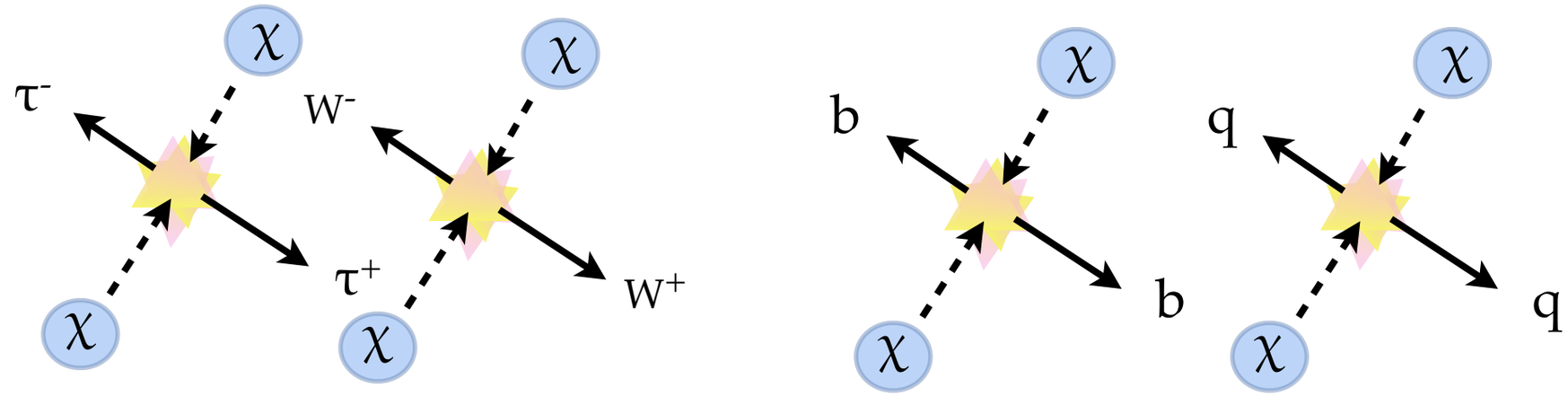
$$\mathcal{L}_{\text{total}}(n_{\text{tot}}, \Xi|\psi) = \mathcal{L}_{\text{num}}(n_{\text{tot}}|\psi) \prod^{n_{\text{tot}}} \mathcal{L}_{\text{ang},i}(\phi'_i|\psi)\, \mathcal{L}_{\text{spec},i}(N_i|\psi)$$



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

Dark Matter Annihilation in the Sun

Model i: $Br(\tau\tau)_i + Br(WW)_i + Br(bb)_i + Br(qq)_i + ... = 1$



high energy neutrinos from annihilation / decay products

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

highest energy neutrinos

fewest neutrinos

Benchmarks Br 100%

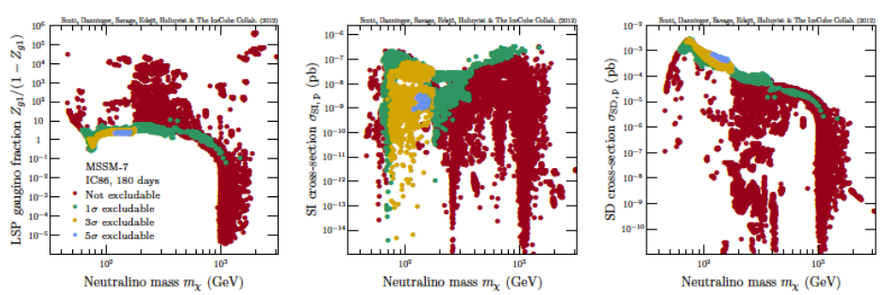
Hard channel

Soft channel

hard: WW, ($\tau\tau$ for $m_\chi < m_W$)
soft: bb

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

Relatively model independent

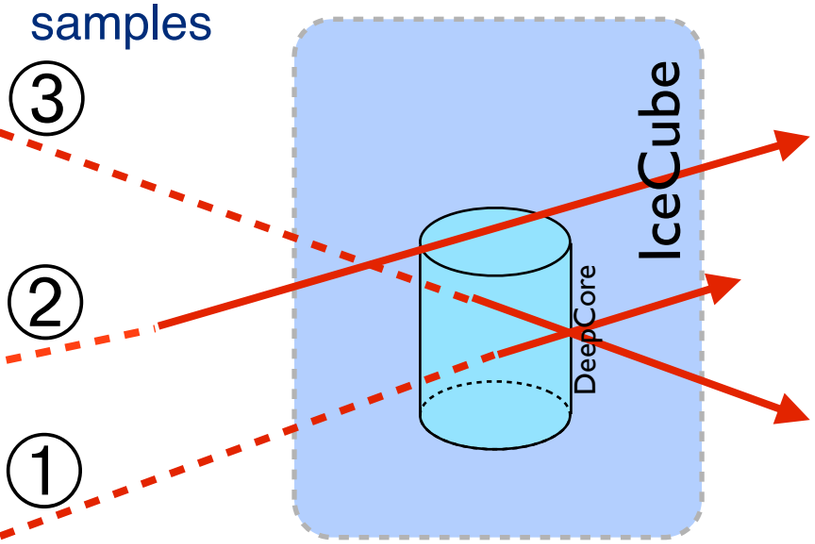
low energy neutrinos from hadronic shower

C. Rott, J. Siegal-Gaskins, and J. F. Beacom, Phys.Rev. D88 (2013) 055005, [arXiv:1208.0827].
N. Bernal, J. Martn-Albo, and S. Palomares-Ruiz, JCAP 1308 (2013) 011, [arXiv:1208.0834].

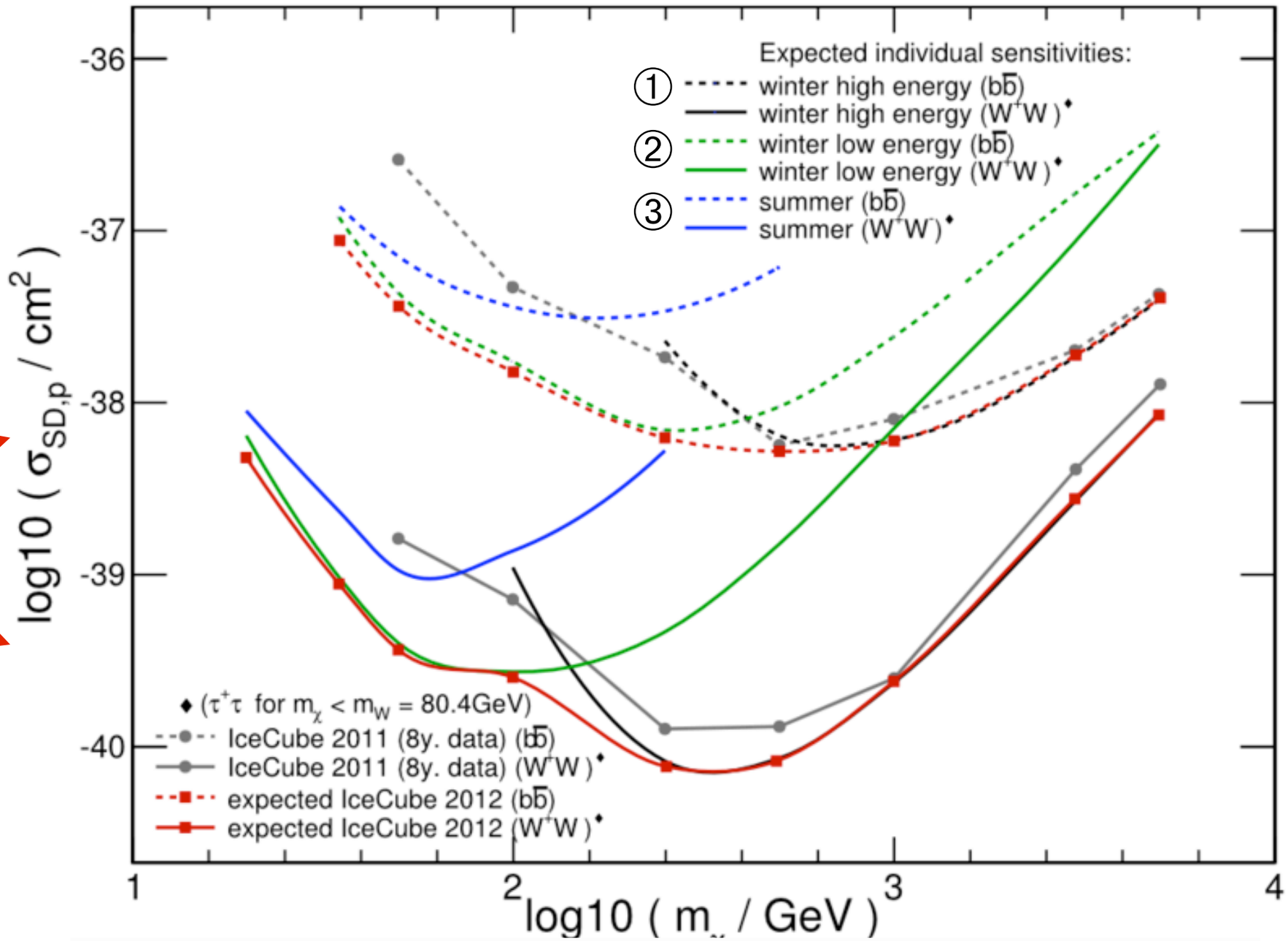
DeepCore Solar WIMP Sensitivity

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



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

Signals in IceCube

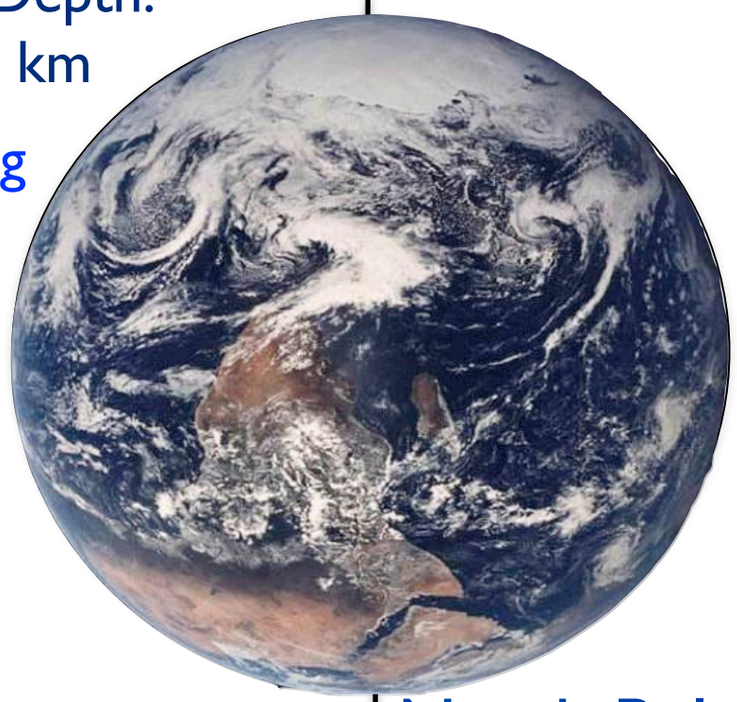
South Pole

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

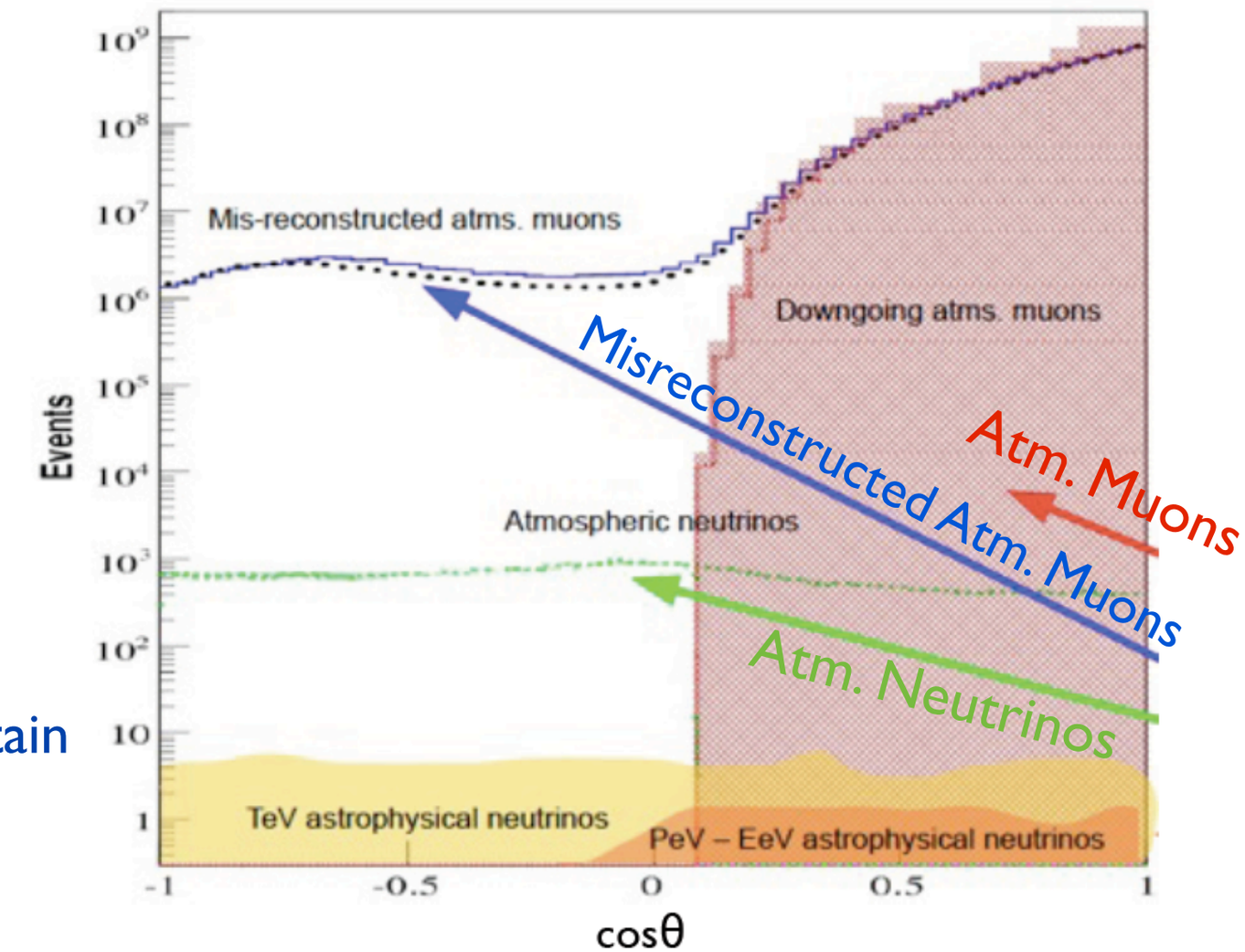
$\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \rightarrow e^{+} \nu_{e} \nu_{\mu} \nu_{\mu}$

IceCube Depth: 1.5-2.5 km

Downgoing Muons



North Pole



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  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

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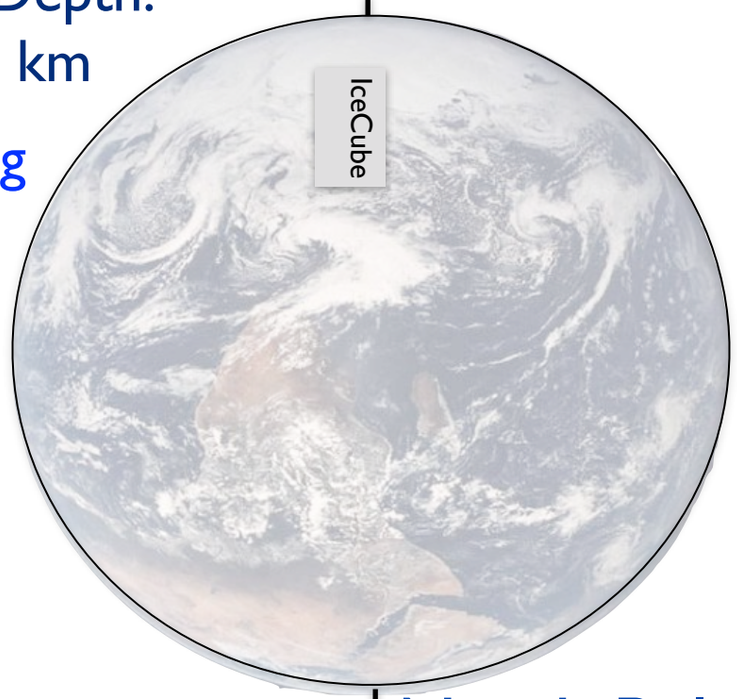

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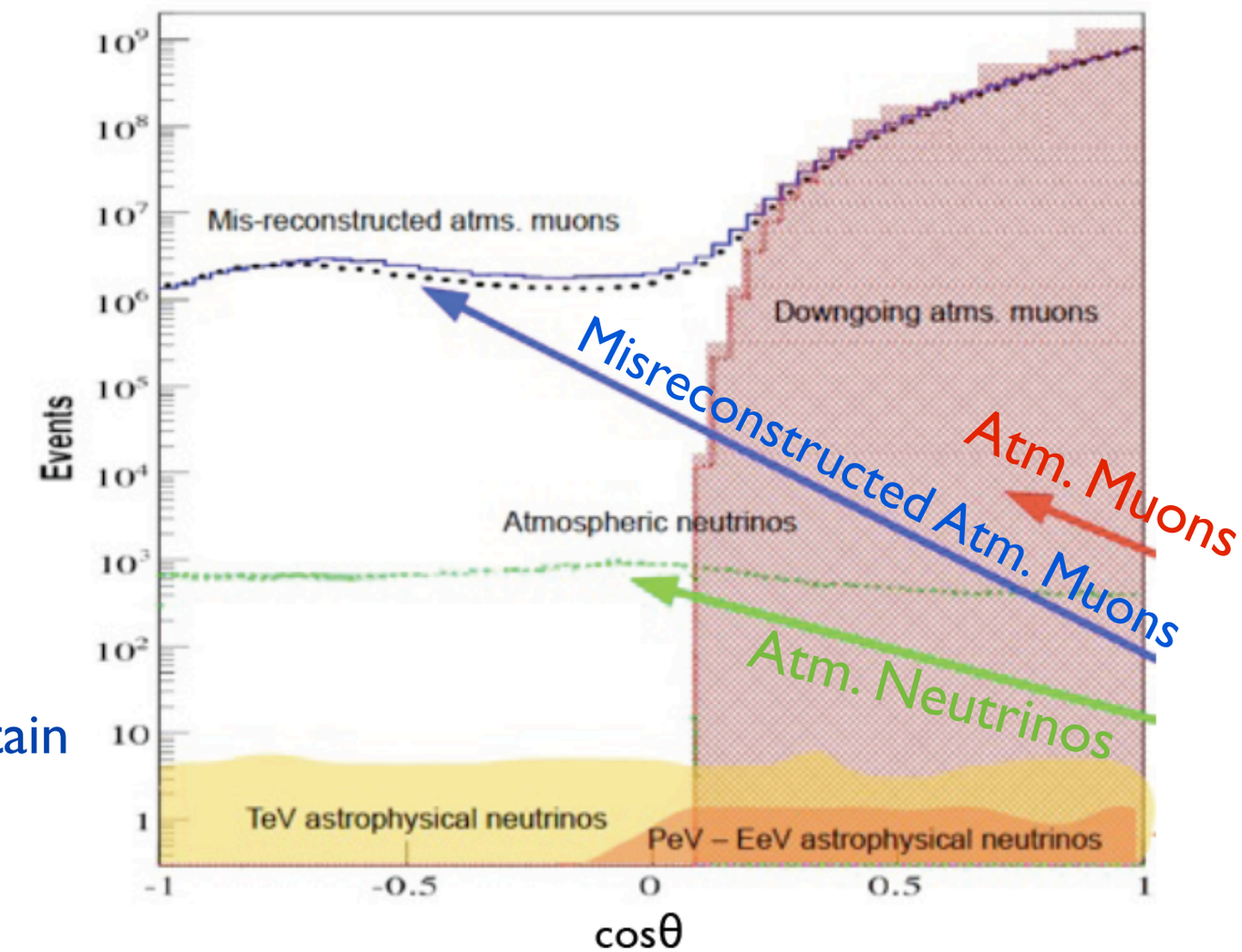

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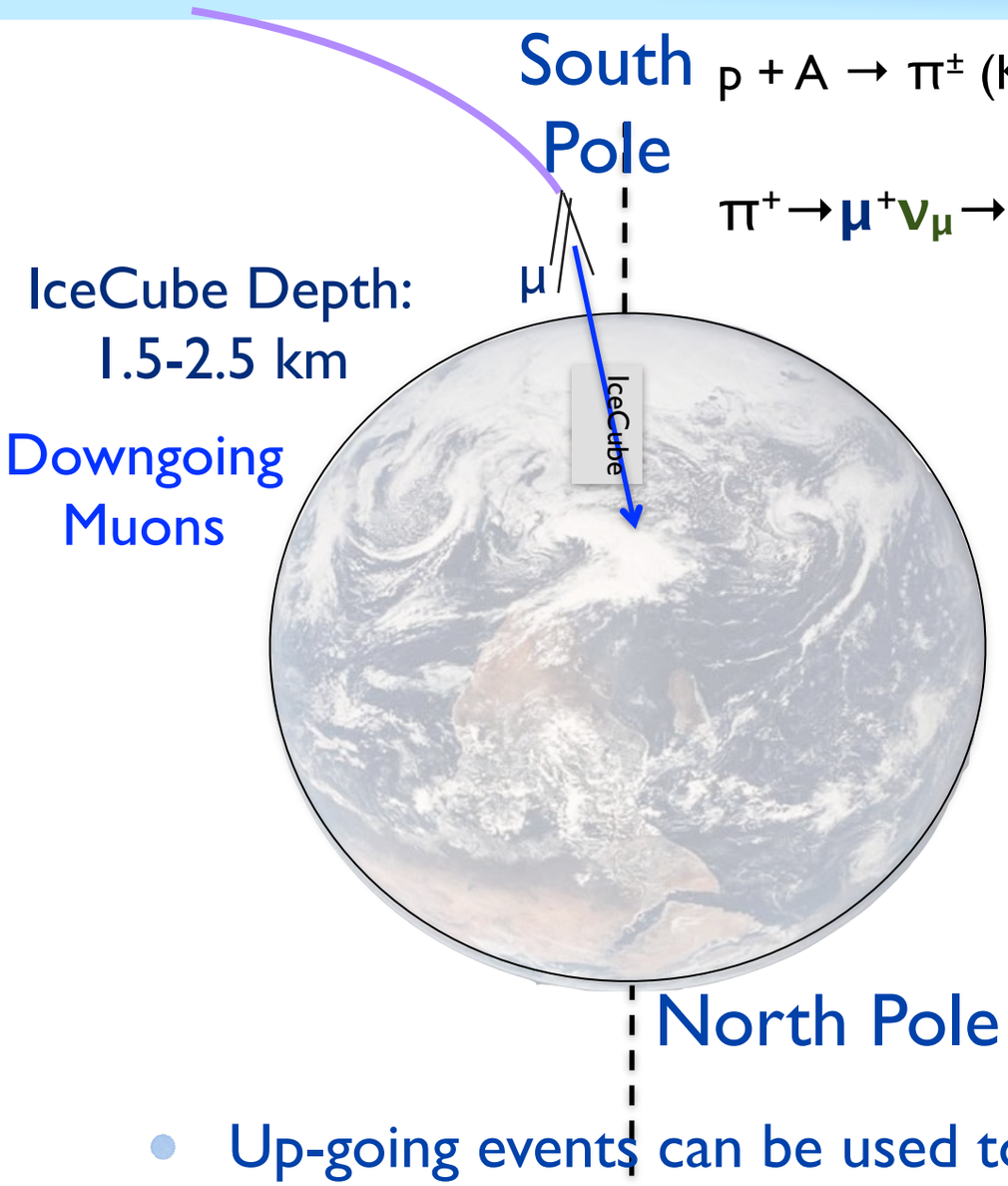

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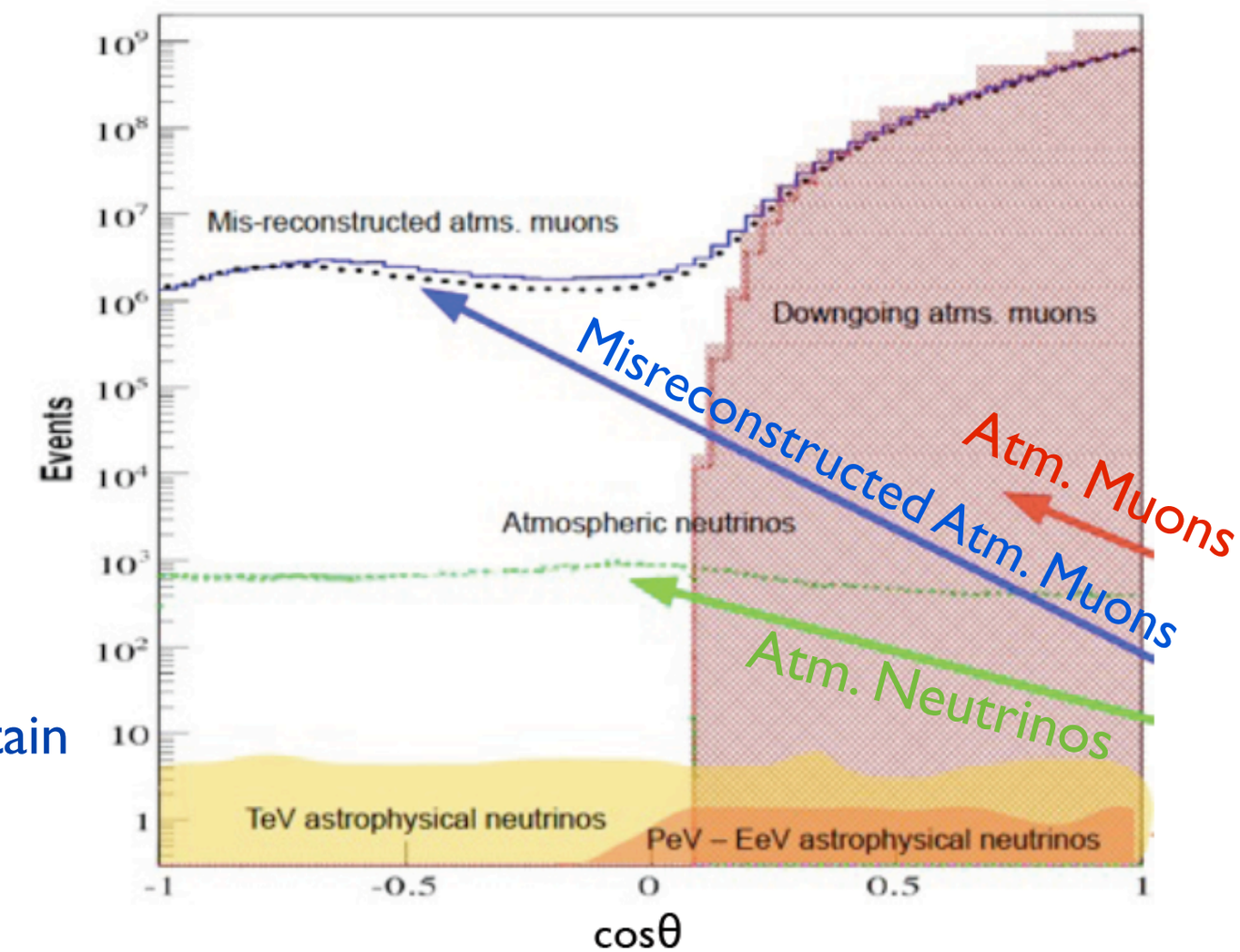

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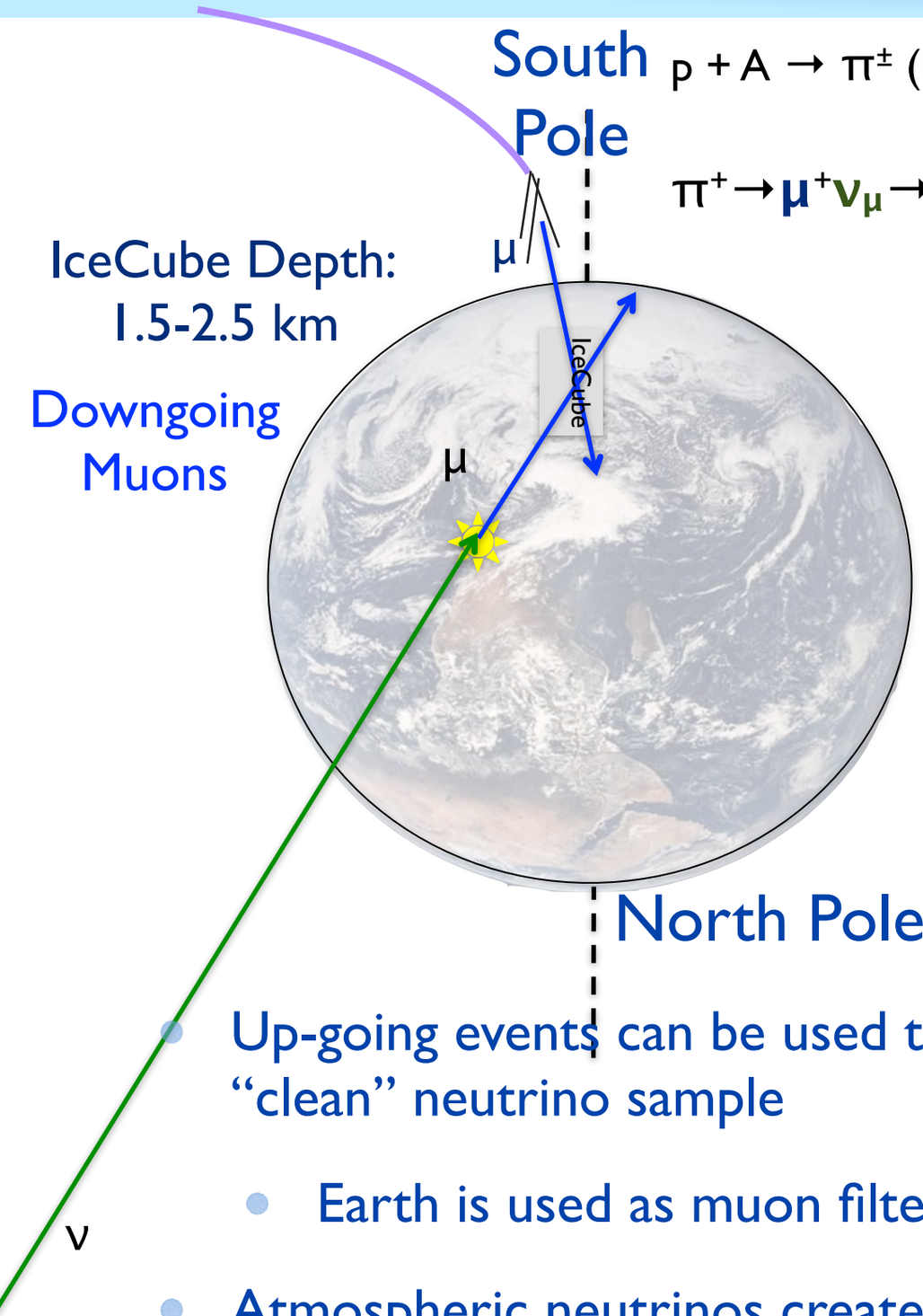

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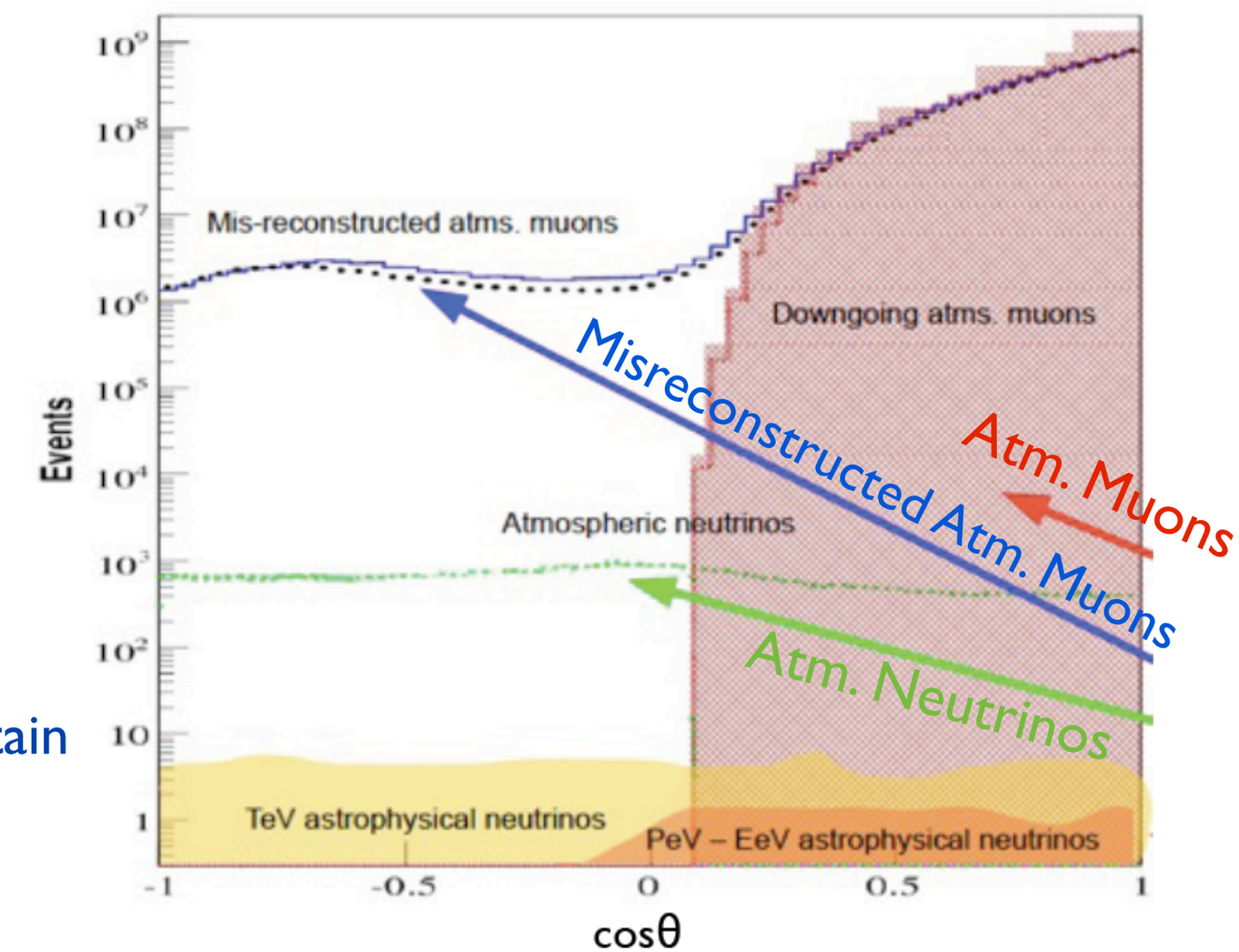

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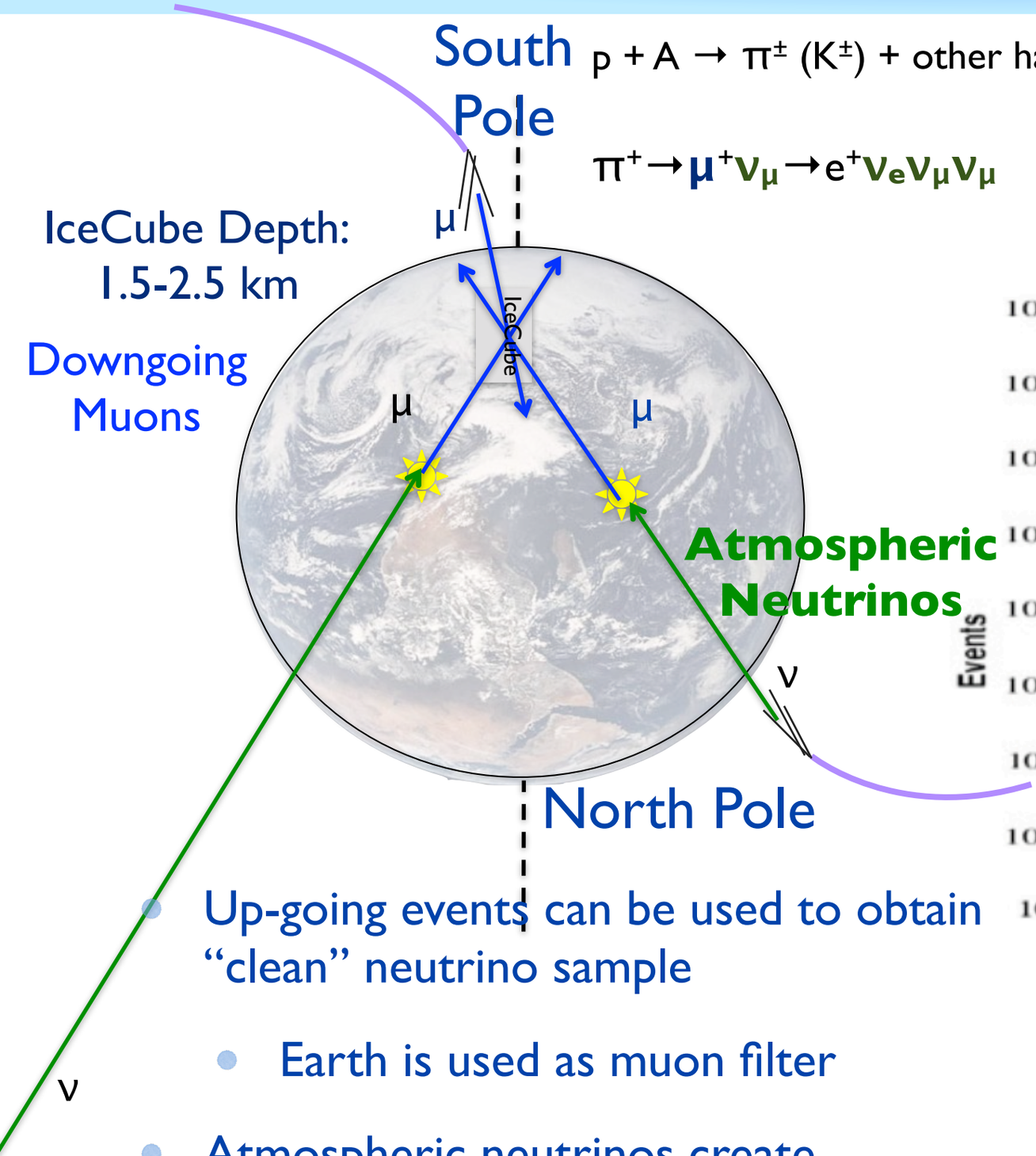

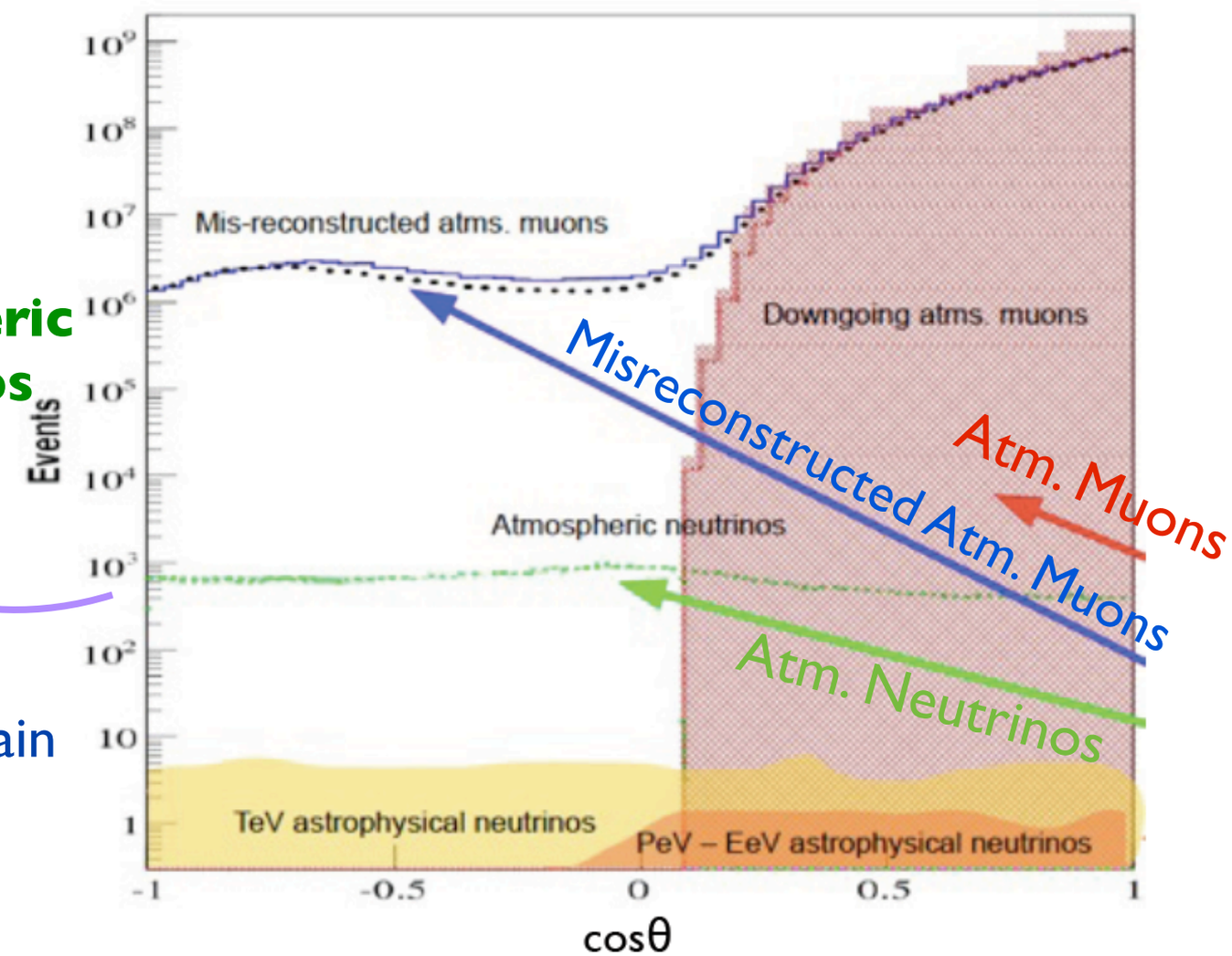

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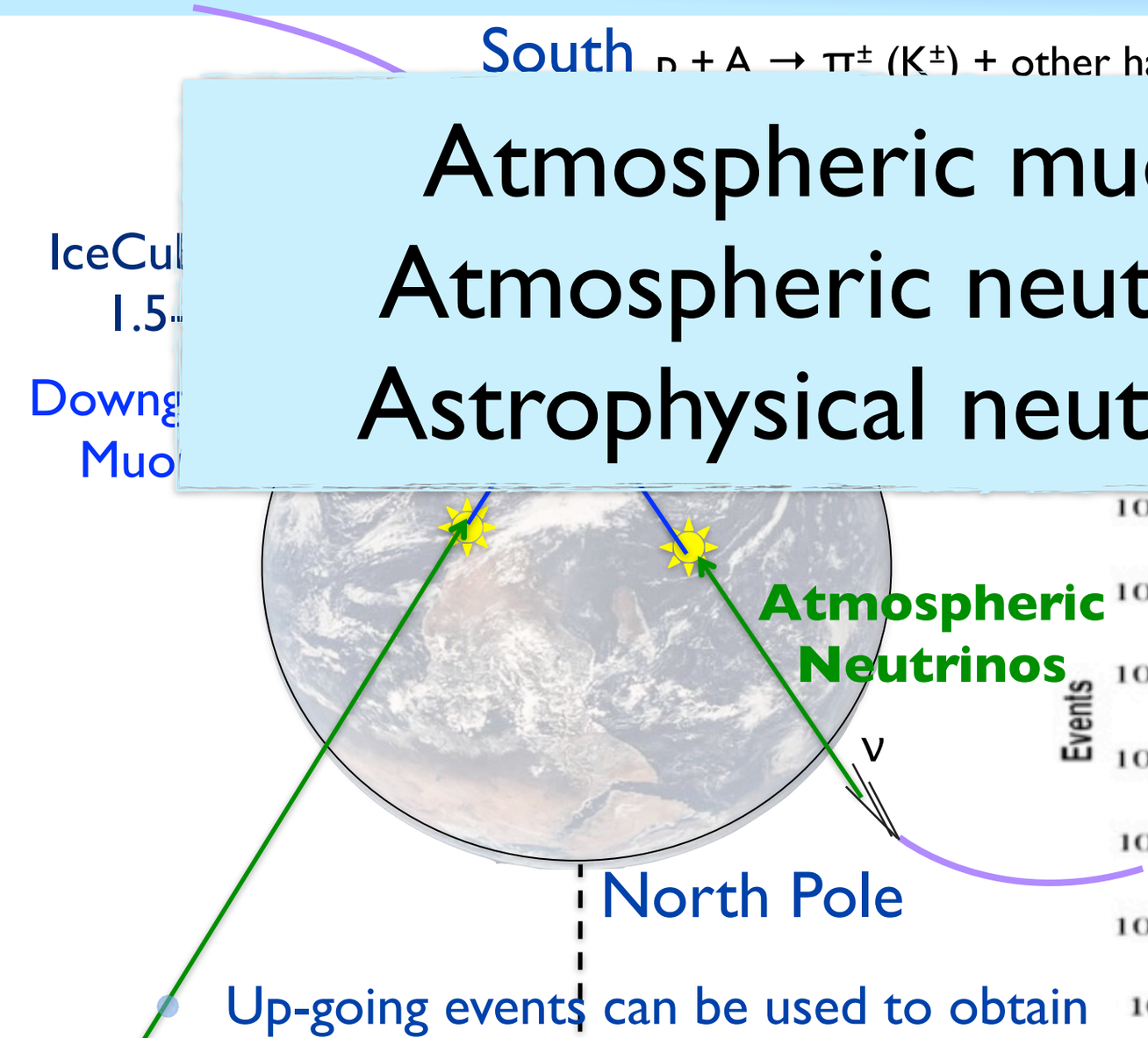
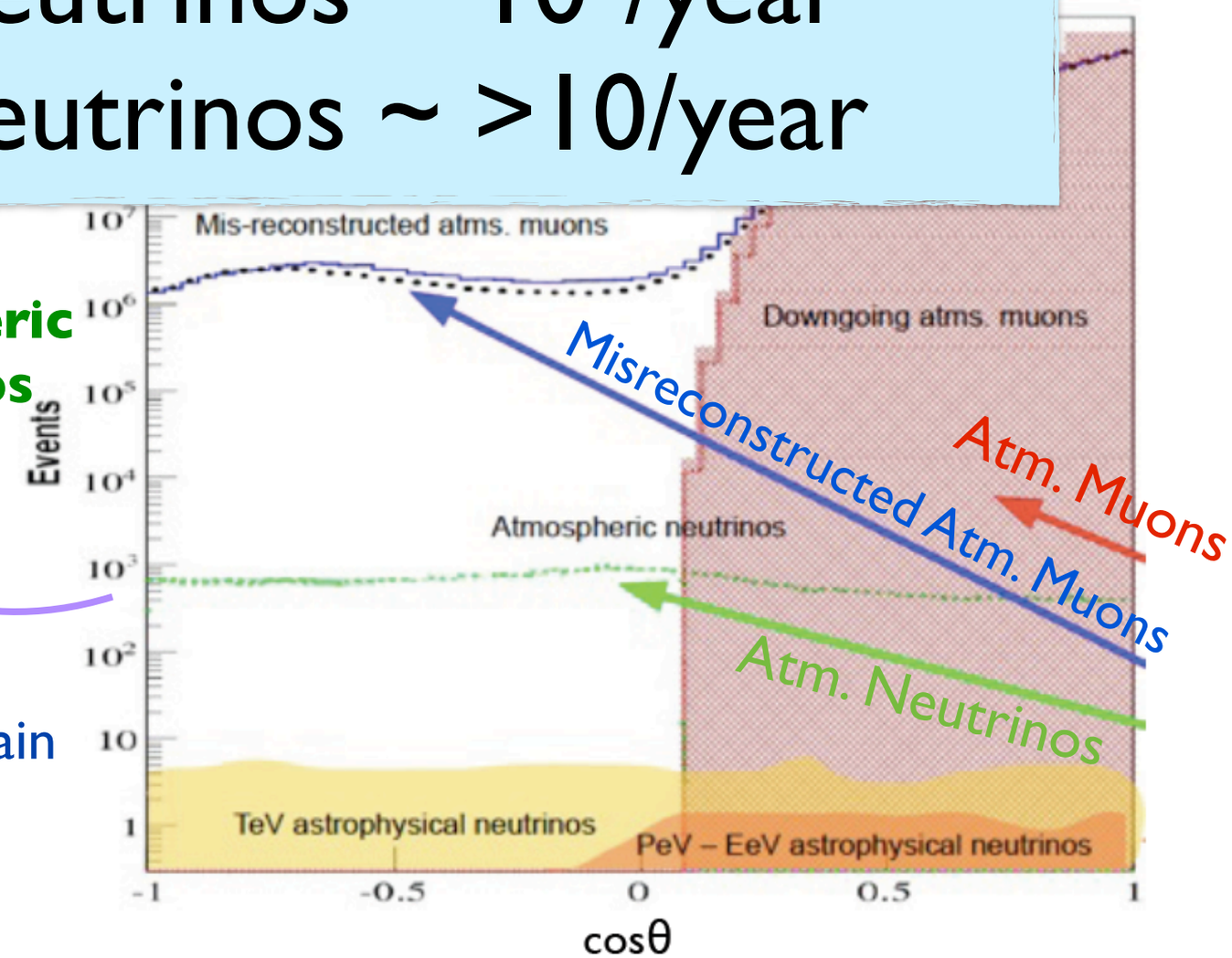
Signals in IceCube

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





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Neutrino from WIMP annihilations

Dark Matter self-annihilation or decay

Annihilation **K_{ann}** **$J(\psi)_{ann}$**

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

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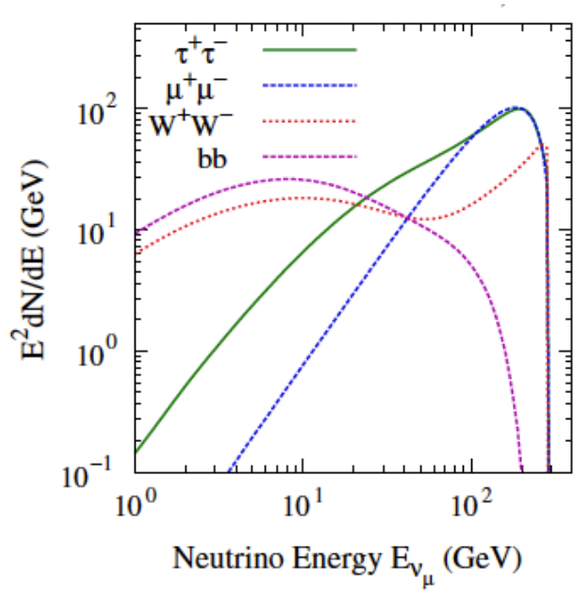
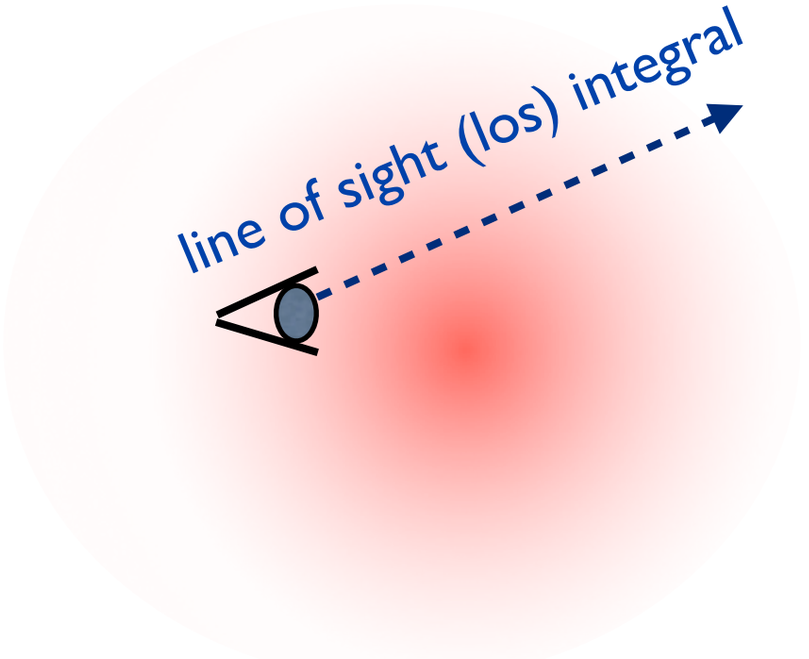
expected prompt signal for particles propagating directly to the observer (gamma-rays, neutrinos)





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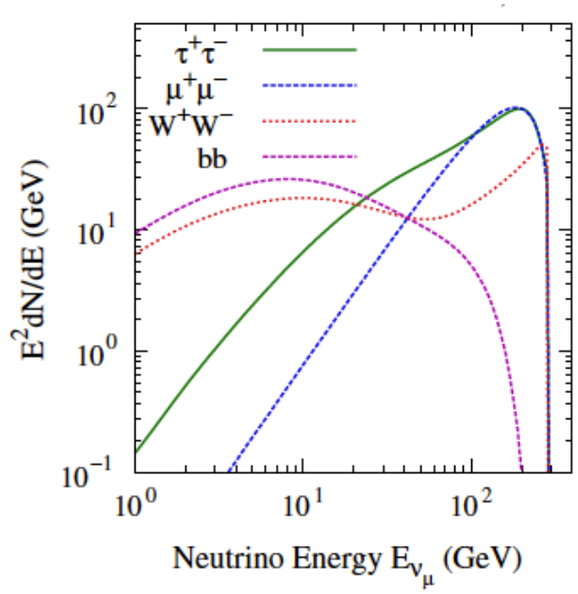

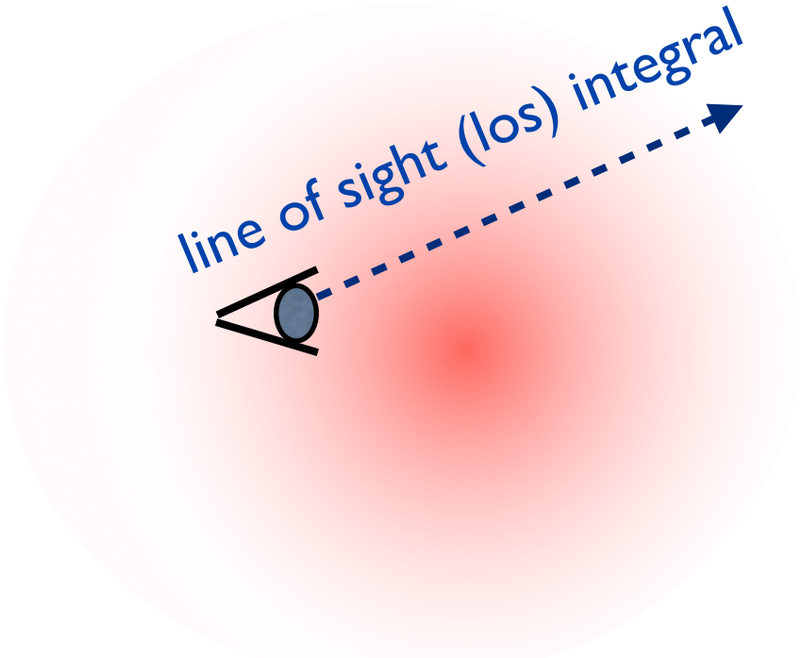

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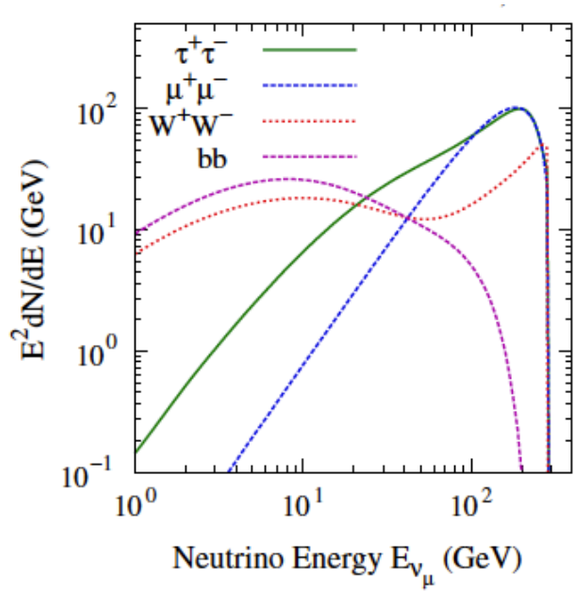

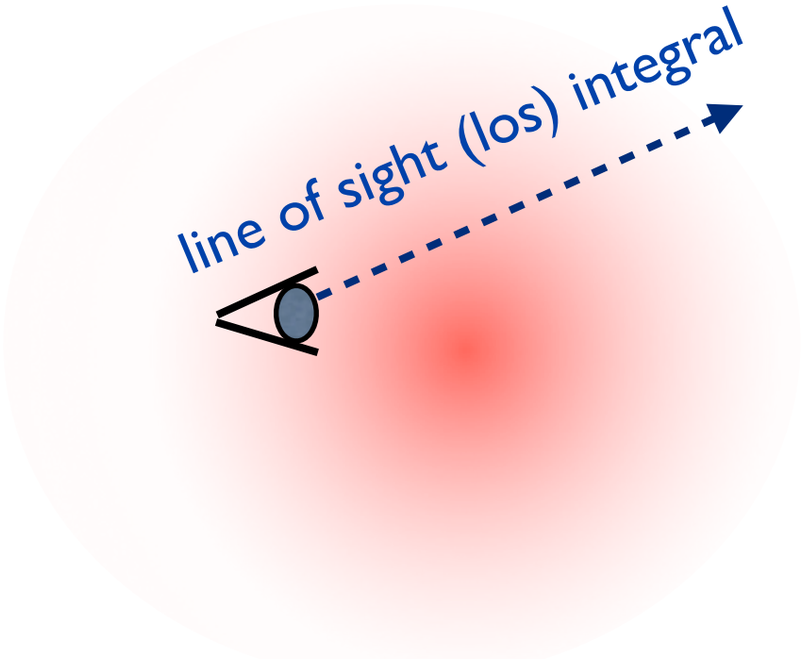

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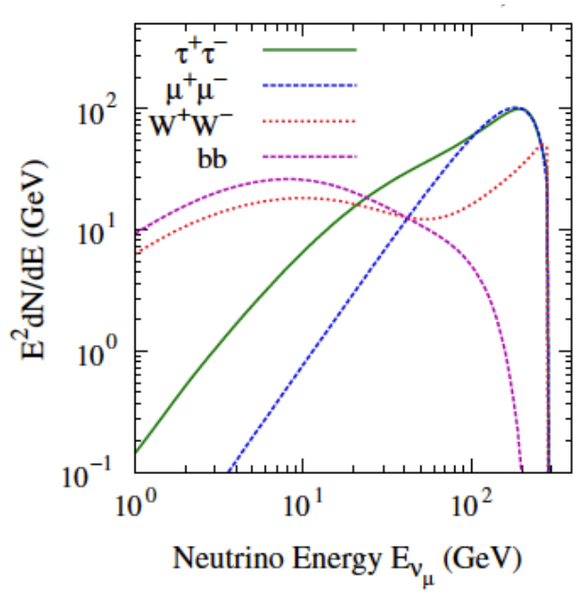

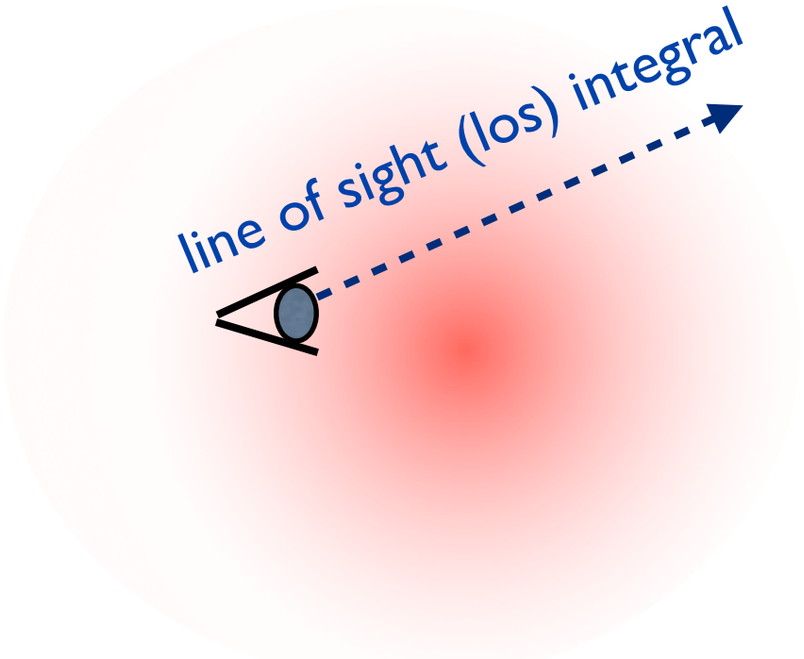

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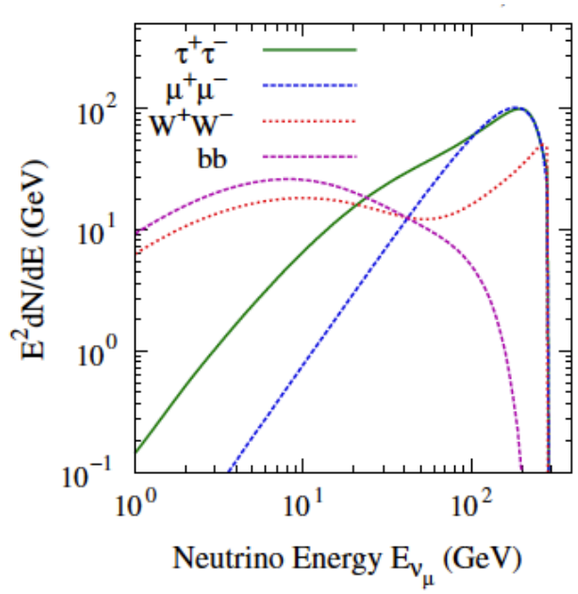

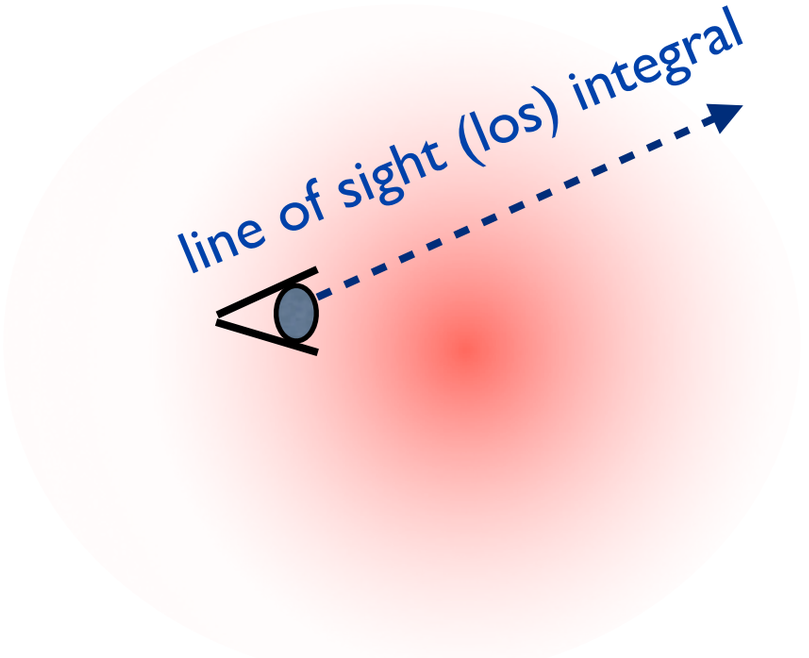

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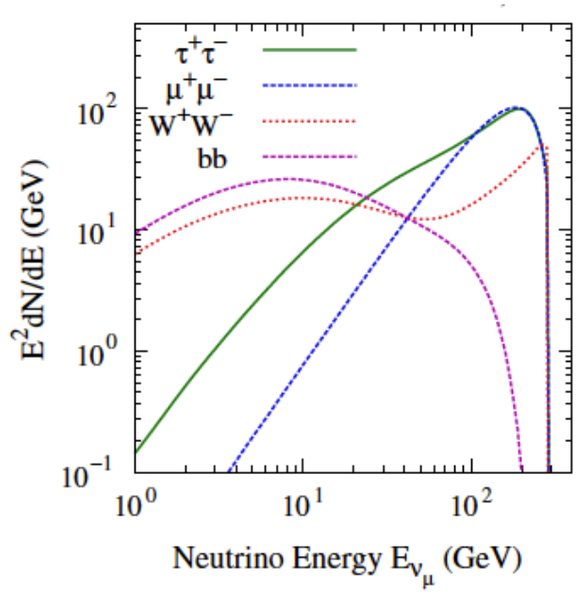

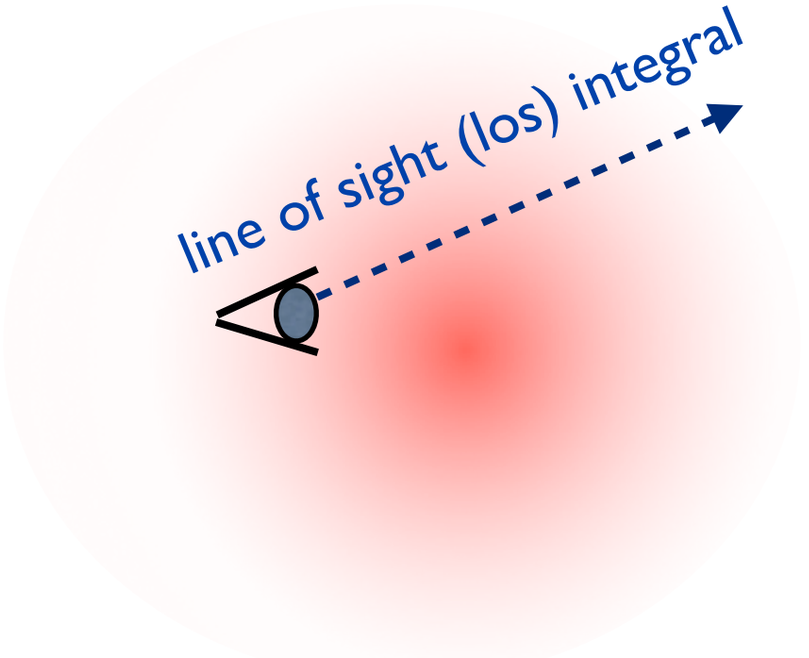

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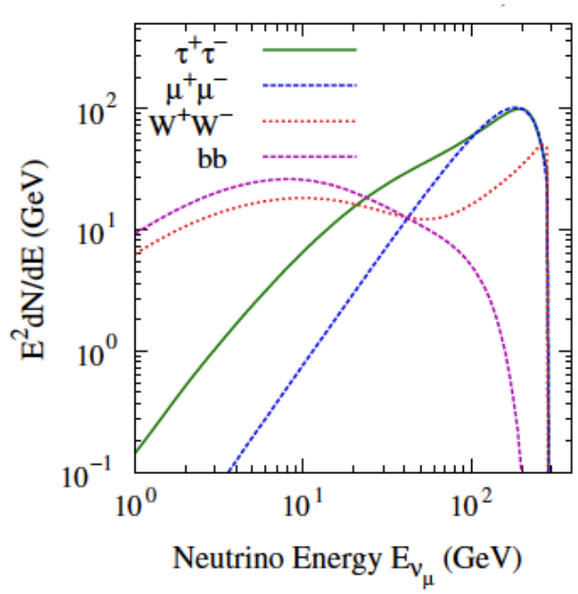
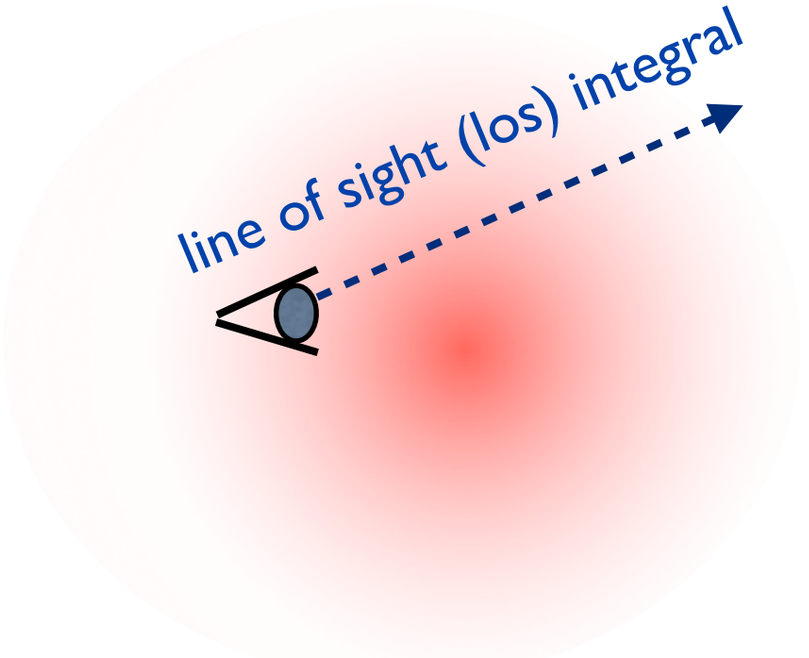
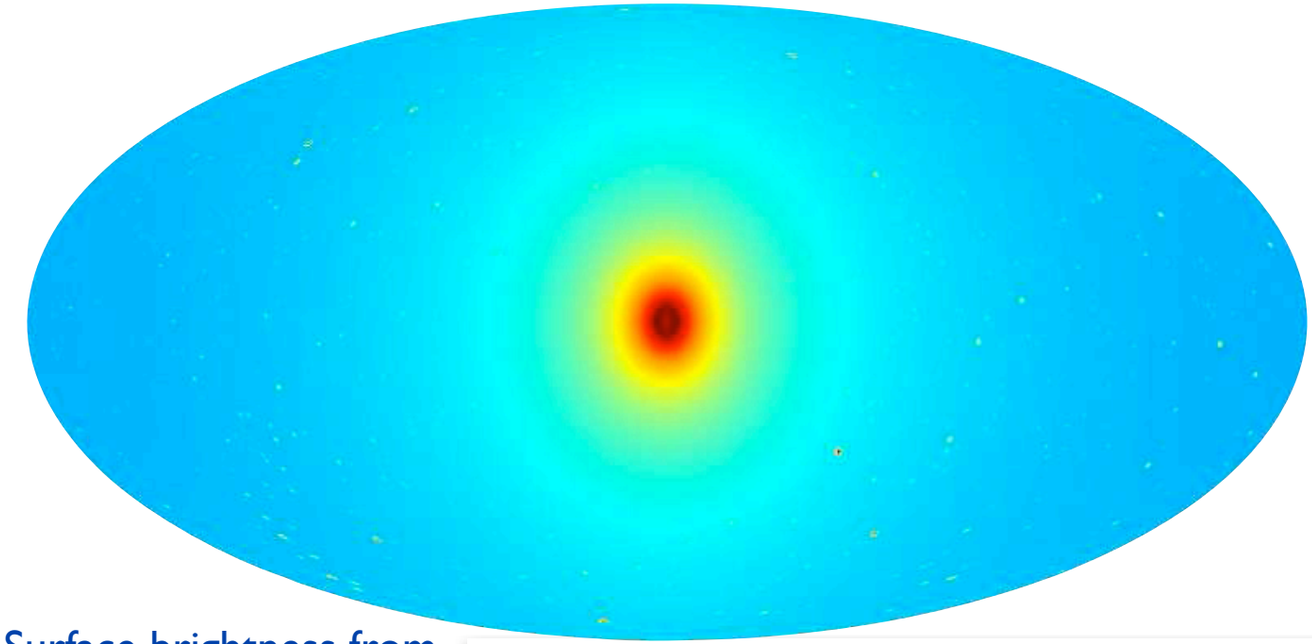




Boost factor

Astro-physical boost factor

- Local clumps in the DM halo enhance the density and boost the flux from annihilations:
  - Boost $B = \frac{\phi^{actual}(\vec{r})}{\phi^{smooth}(\vec{r})}$
- Typical boost factors are B~ 1-20 (simulations)
- Boost factor ~ 1 (for central halo region <10kpc) tidal stripping



Surface brightness from dark matter annihilation at the position of the Sun, calculated directly from the Aq-A-1 simulation.

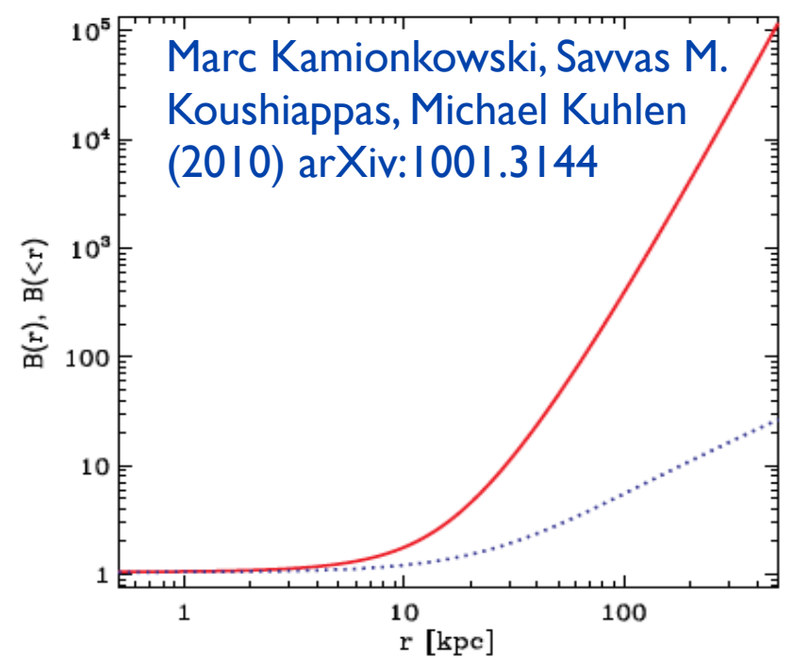
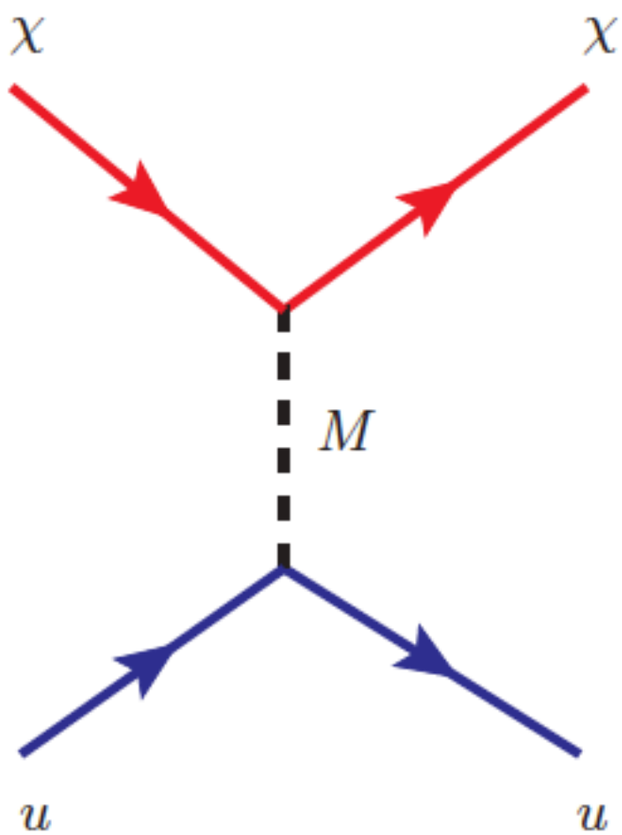


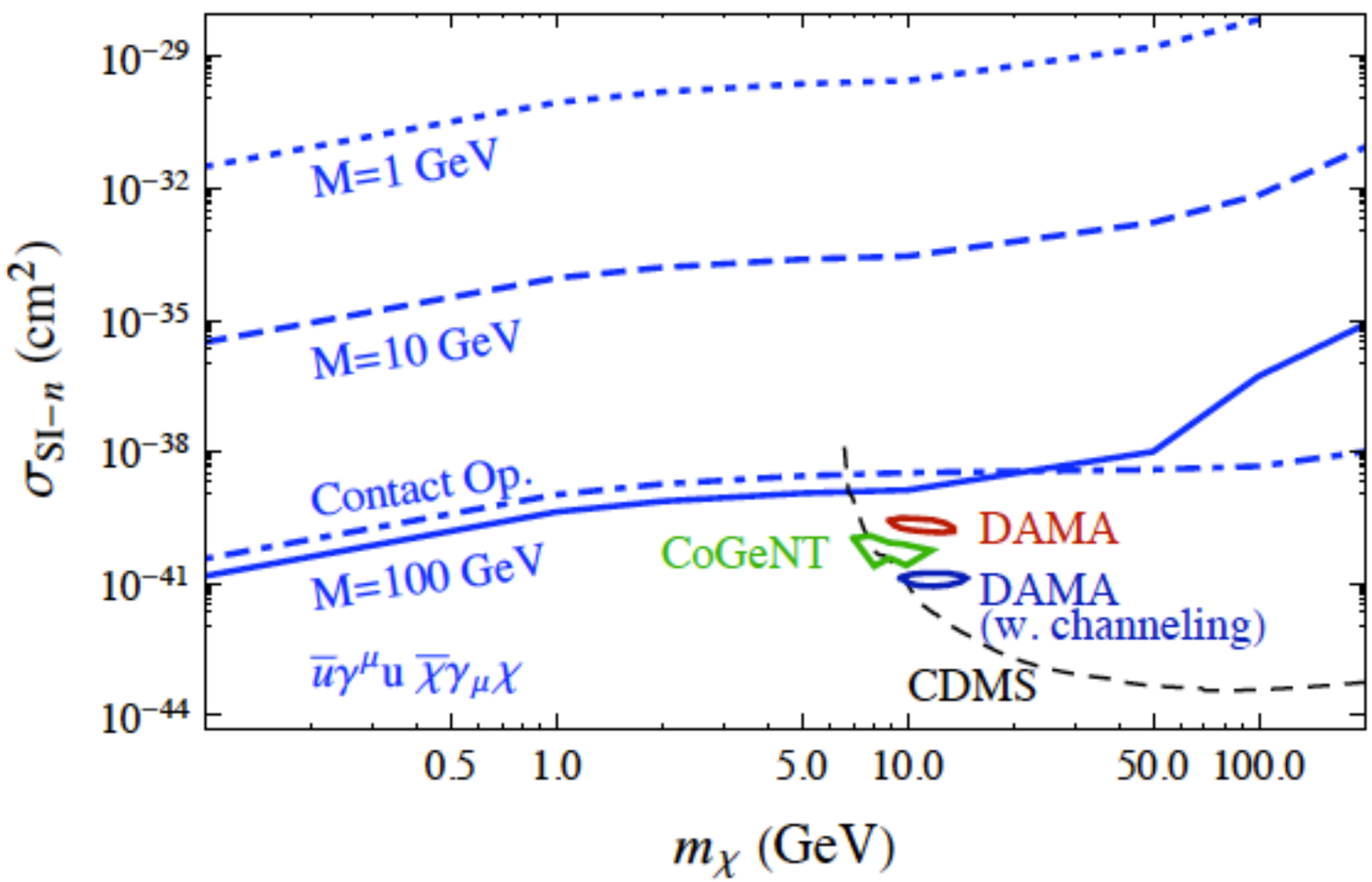
FIG. 4. The local substructure boost $B(r)$ (*solid*) and the cumulative luminosity boost $B(<r)$ (*dotted*), as a function of radius.

- Boost factor important for:
  - Galaxy clusters, Diffuse extra galactic, ...
- Not important for:
  - Galactic Center, Solar circle, ...

Accelerator Bounds



Bai et.al. JHEP1012

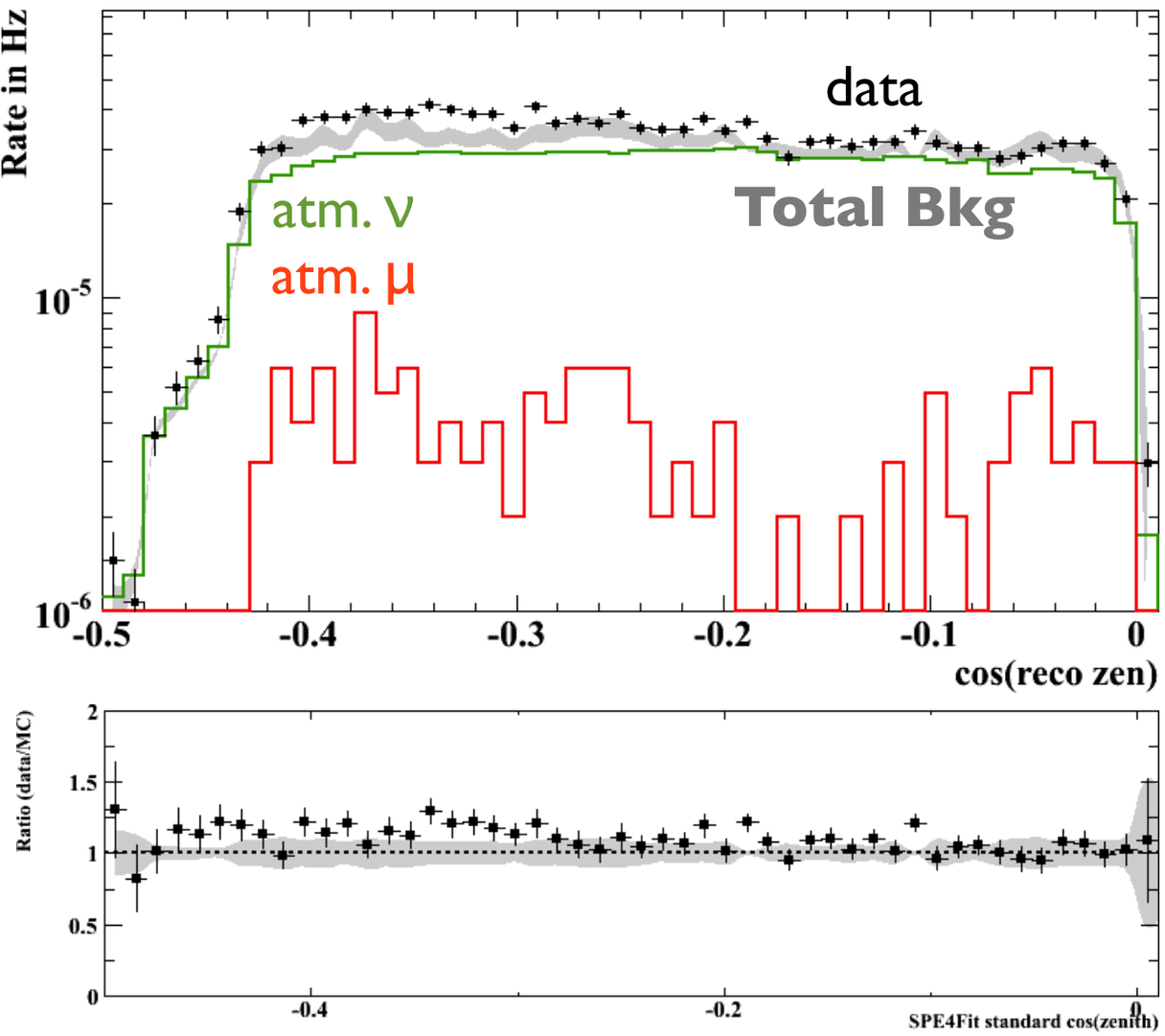


Direct detection enhanced over collider production if exchange has light mediator

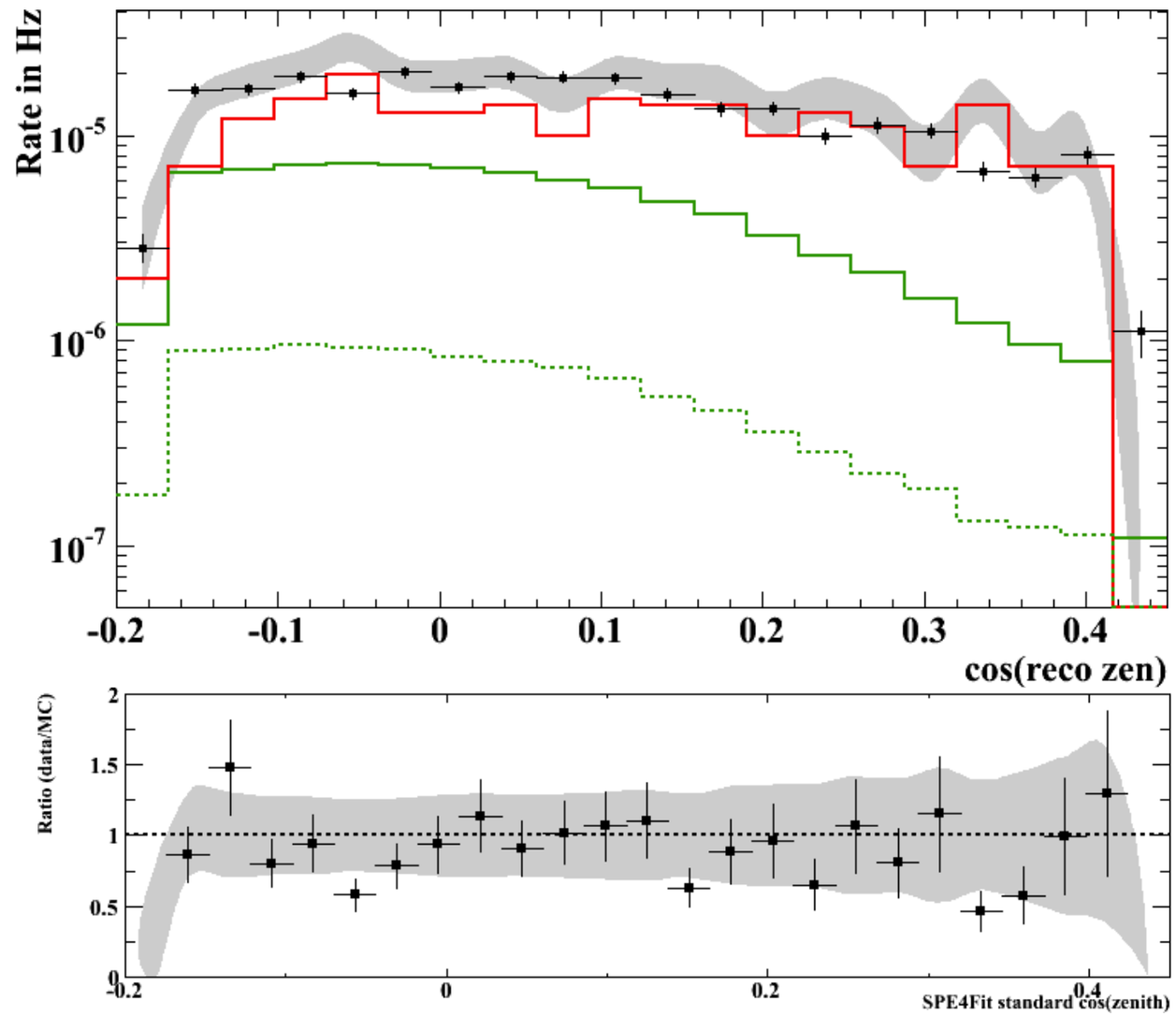
$M < p_T(1\text{jet})$

IC79 Solar WIMP

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



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



- 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

Sommerfeld Enhancement

- DM annihilation cross section in the low velocity regime can be enhanced through the "Sommerfeld effect"
  - when non-relativistic particles interact through some kind of force, their wave function is distorted by the presence of a potential
    - In QFT this corresponds to contributions of "ladder" Feynman diagrams
      - gives rise to (non-perturbative) corrections to cross section

$$\sigma v = S\,\underline{(\sigma v)_0}$$

"Sommerfeld boost"

tree level cross section times velocity

http://arxiv.org/pdf/0812.0360

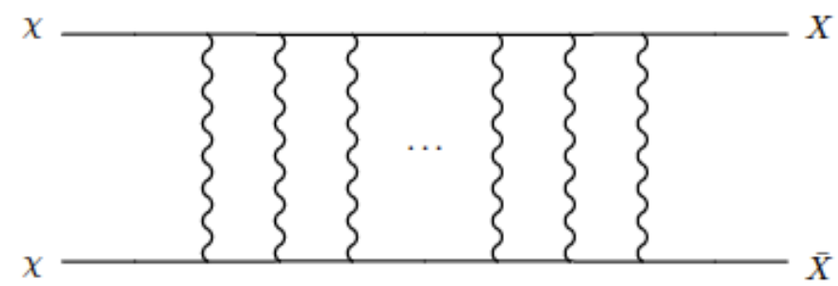


FIG. 1: Ladder diagram giving rise to the Sommerfeld enhancement for $\chi\chi \to X\overline{X}$ annihilation, via the exchange of gauge bosons.

- Simple case: a particle interacting through Yukawa potential:

Schroedinger Equation

$$\frac{1}{m}\frac{d^2\psi(r)}{dr^2} - V(r)\psi(r) = -m\beta^2\psi(r)$$

Ψ(r) is reduced two-body wave function for s-wave annihilation

$V(r) = -\frac{\alpha}{r}e^{-m_V r}$ attractive Yukawa potential mediated by a boson of mass m_V

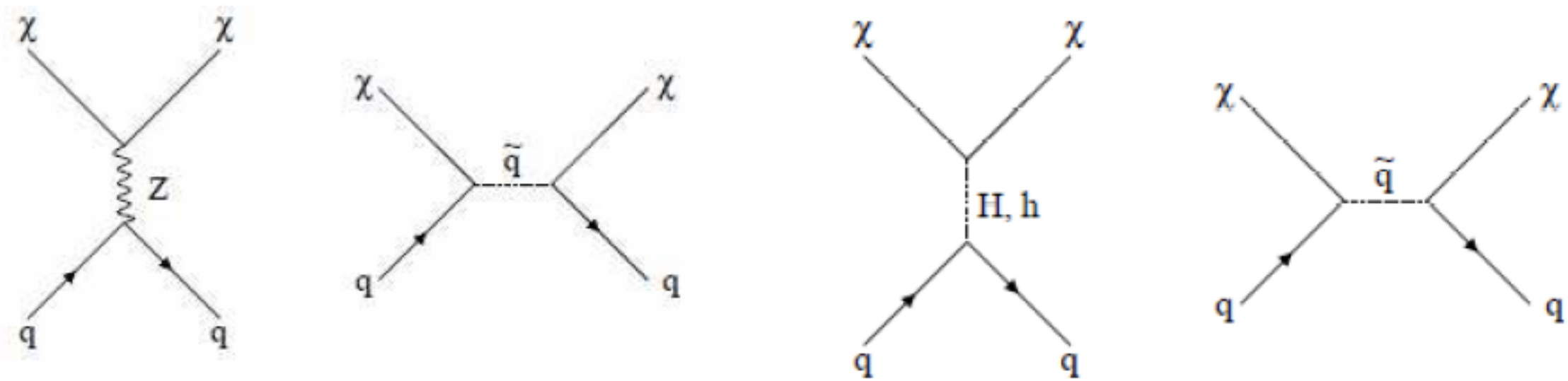
for m_V small the potential becomes Coulomb-like and Schrödinger equation can be solved analytically

$$S = \frac{\pi\alpha}{\beta}(1 - e^{-\pi\alpha/\beta})^{-1}$$

~1/v

WIMP Nucleon Interaction

- The nucleon coupling of a slow-moving Majorana neutralino (or of any WIMP in the extreme non-relativistic limit) is characterized by two terms: spin-dependent (axial vector) and spin-independent (scalar).



$$\sigma_{SD} = 32\frac{G_F^2\mu^2}{\pi}(a_p\{S_{p(N)}\} + a_n\{S_{n(N)}\})^2\frac{J+1}{J}$$

$$\mu = M_\chi M_N \ / \ M_\chi + M_N$$

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

$$\sigma_{SI} = \frac{4\mu^2}{\pi}(Zf_p + (A-Z)f_n)^2F^2(q)$$

- f_p , f_n - coupling constants to proton and neutron
- F(q) form factor