IceCube searches for neutrinos from dark matter annihilations in the Sun and Cosmic Accelerators

UNIVERSITÉ DE GENÈVE

ICECUBE

The Niels Bohr International Academy

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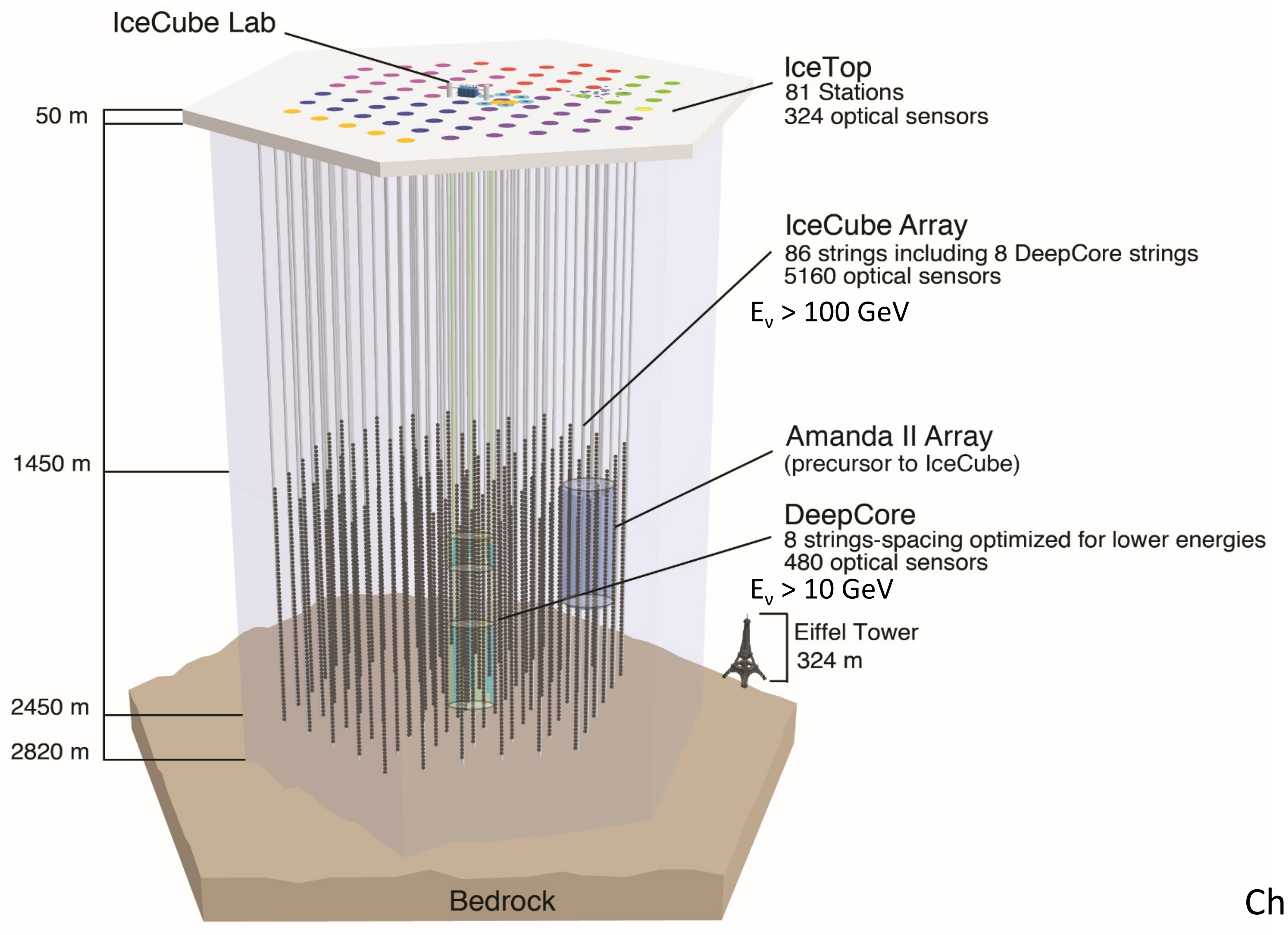
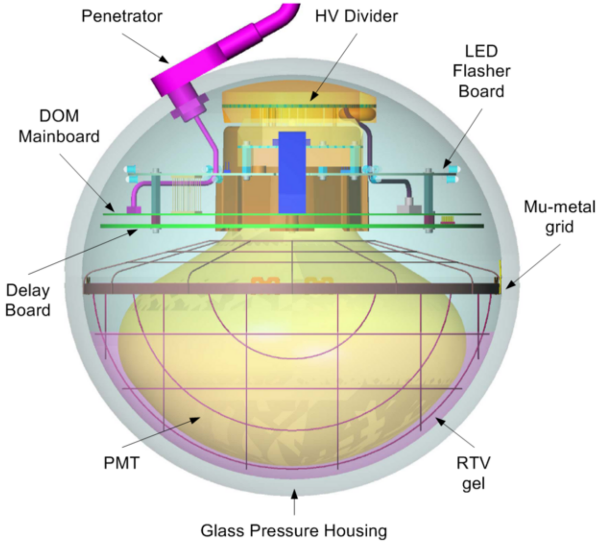
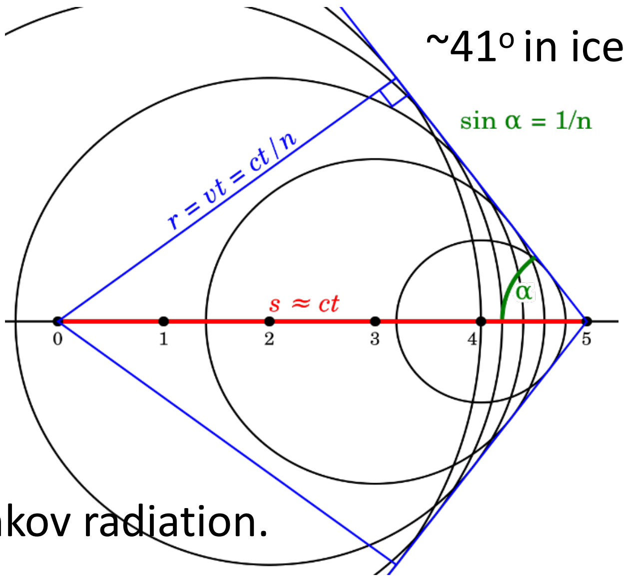
Swiss Physical Society Meeting 2016

23rd August 2016

The IceCube Neutrino Observatory



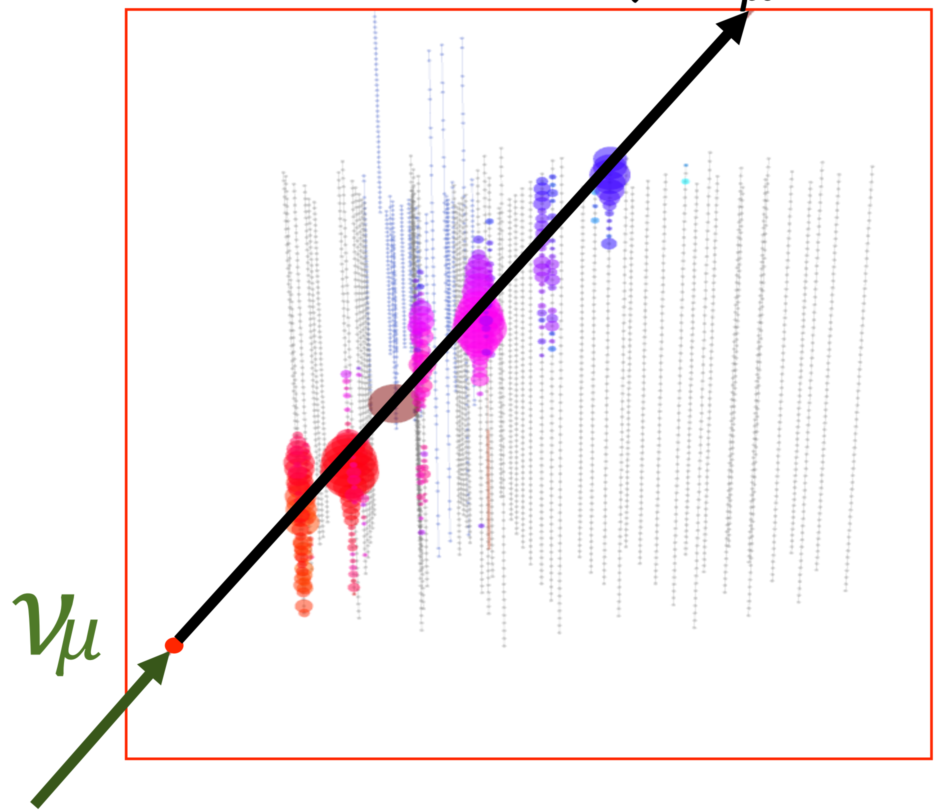




Cherenkov radiation.

In-ice Signatures

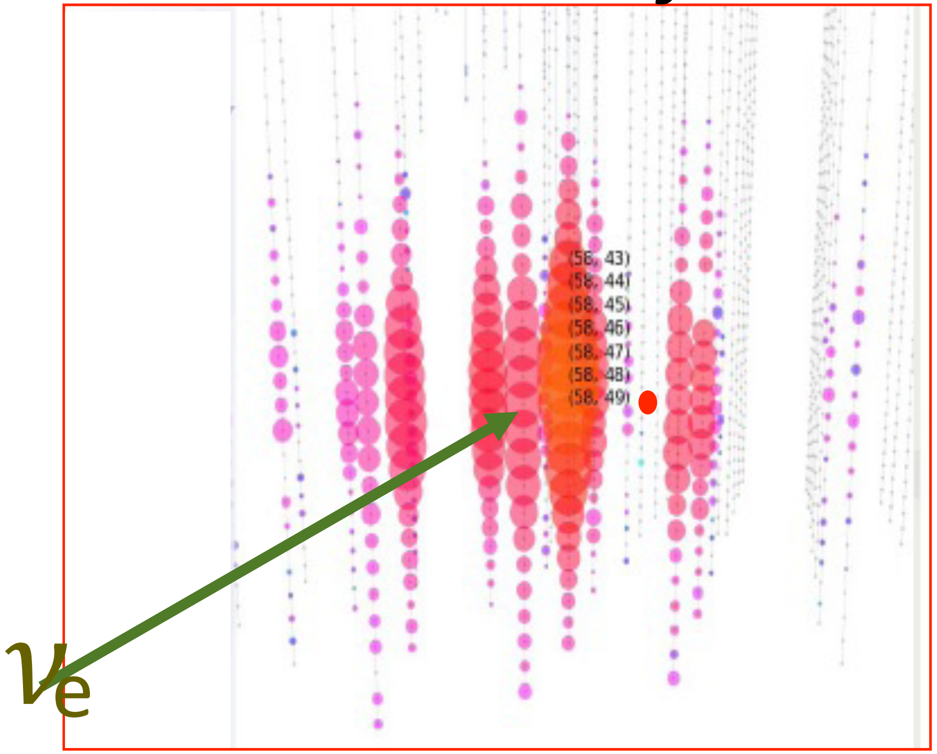
Muon tracks→ ν_μ CC



Good angular resolution: **Neutrino Astronomy**

- **(~0.6º at 10 TeV)**
- Vertex can be outside the detector: **Increased effective volume!**

cascades → all flavors



ν_e, ν_τ and all-flavor neutral current

Fully active calorimeter: **High energy resolution**

Angular reconstruction above ~50 TeV

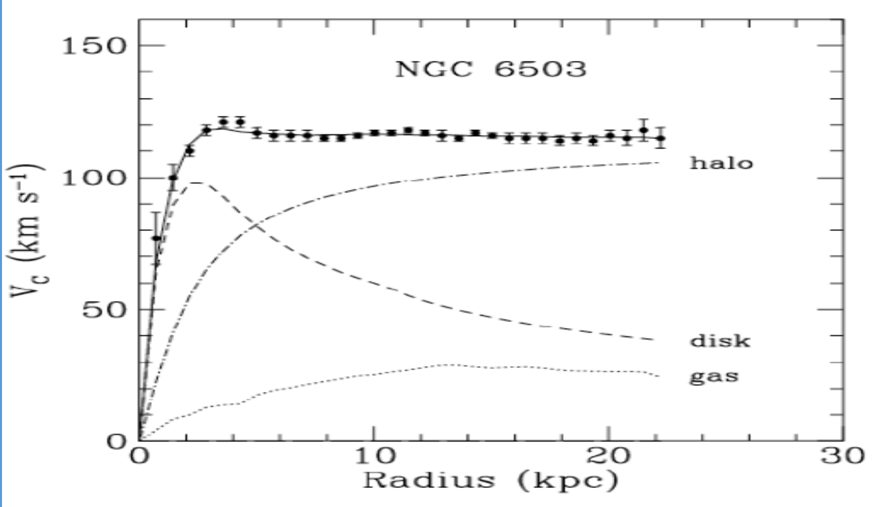
In both cases, ν and $\bar{\nu}$ are indistinguishable

Dark Matter

We know DM exists from:

- **Galactic Rotation Curves :**

$$\Omega_{dm} \geq 0.1$$

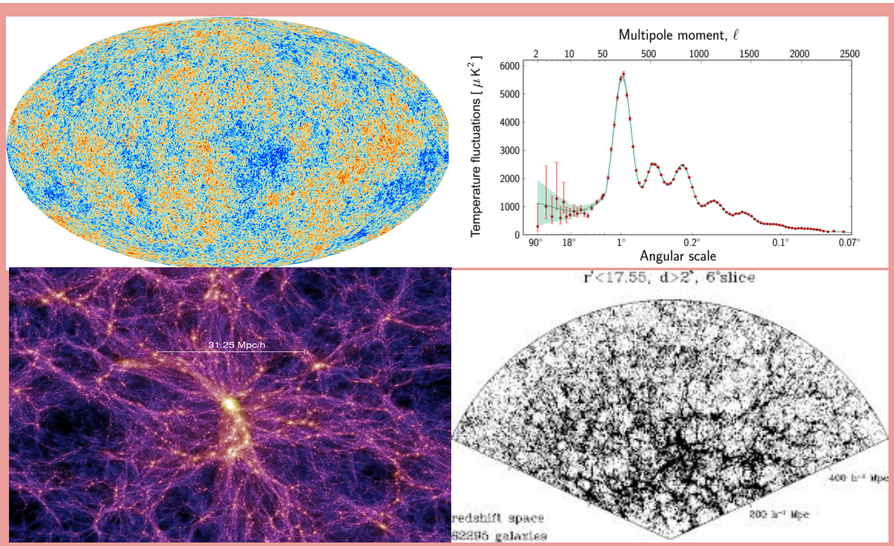


- **Gravitational Lensing** due to galaxy Clusters: Bullet Cluster : astro-ph/0608247

$$\Omega_{dm} \sim 0.2 - 0.4$$

- **Precision Cosmology**
  - Planck CMB Measurements
  - CDM simulations such as Millenium reproduce observed LSS

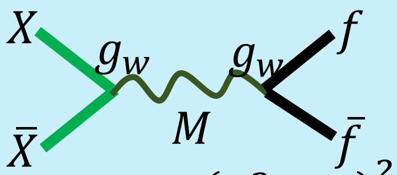
$$\Omega_{dm} = 0.268 \pm 0.02$$



Weakly Interacting Massive Particles

Dark Matter as a thermal relic of the Early universe.

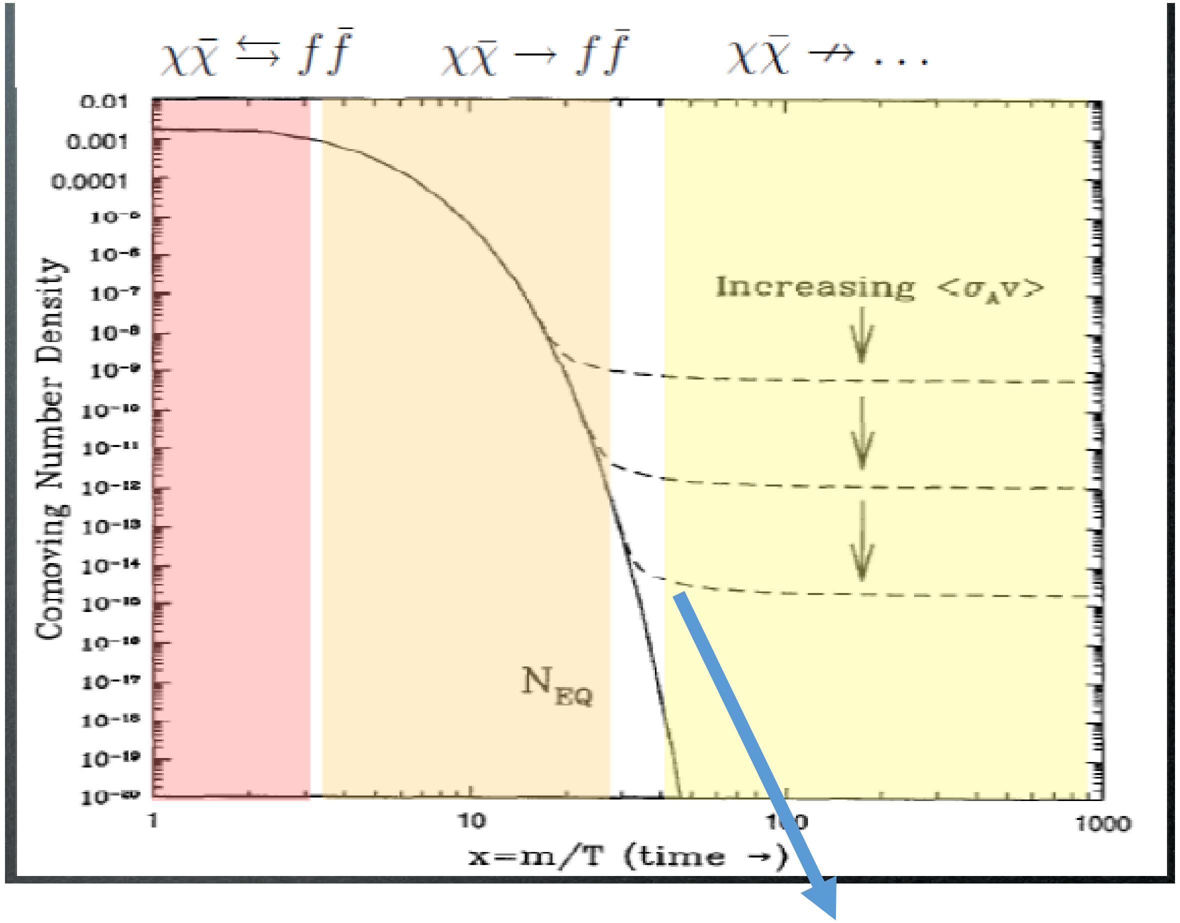
- Boltzmann equation of the early universe
  - $\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{ann} v \rangle [n_X^2 - n_{eq\,X}^2]$
- Relic $\Omega_{DM} \sim 0.27$
  For $\langle \sigma_{ann} v \rangle = 3\,.\,10^{-26}\ cm^3/s$



$$\langle \sigma_{ann} v \rangle \approx \frac{(g_w^2/4\pi)^2}{M^2} \approx 3\,.\,10^{-26}\ cm^3/s$$

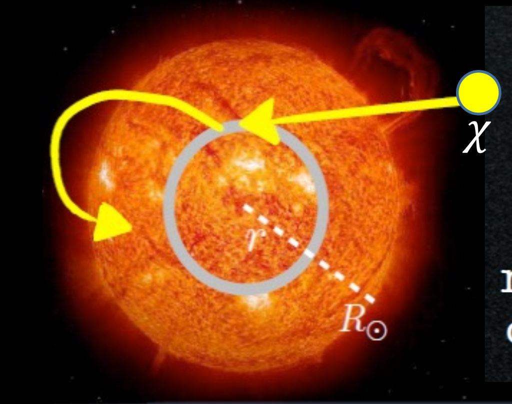
WIMP Miracle

- Stable WIMPS present in various theories
  - Neutralino in SUSY theories
  - Kaluza Klein particles.



Freeze out

WIMP Capture and Annihilation in the Sun



$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot \rm esc}^2}{v} \wp_i(v, v_{\odot \rm esc})$$

- ρ_{DM}: DM number density
- σ_i: Scattering Cross Section: $\sigma_{SD} \propto J(J+1)$, $\sigma_{SI} \propto A^2$
- $n_i(r)$: Number density of element i -> Solar Model
- $f_\odot(v)$: velocity distribution (in solar frame, without Sun's gravity)
- $\frac{v^2 + v_{\odot esc}^2}{v}$: effect of solar gravity

Spin Dependent scattering

- Only the hydrogen in the Sun contributes significantly.
- Lower event rates in direct detection experiments
- More interesting for IceCube

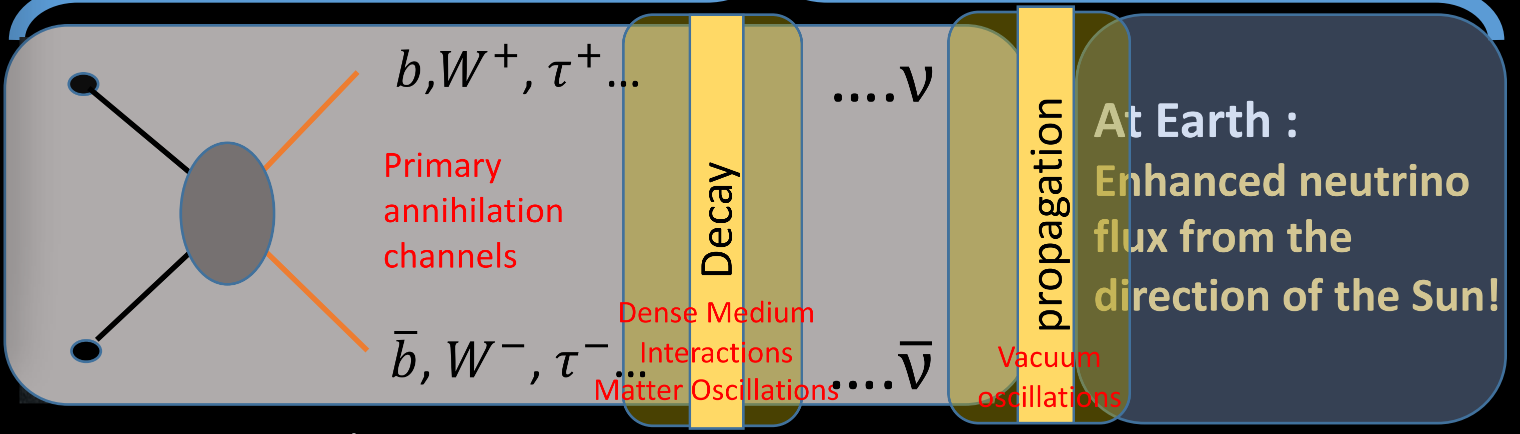
Spin Independent scattering

- Heavier nuclei contribute more due to $\propto A^2$ enhancement.
- Better sensitivity using direct detection experiments such as LUX, XENON etc

Capture

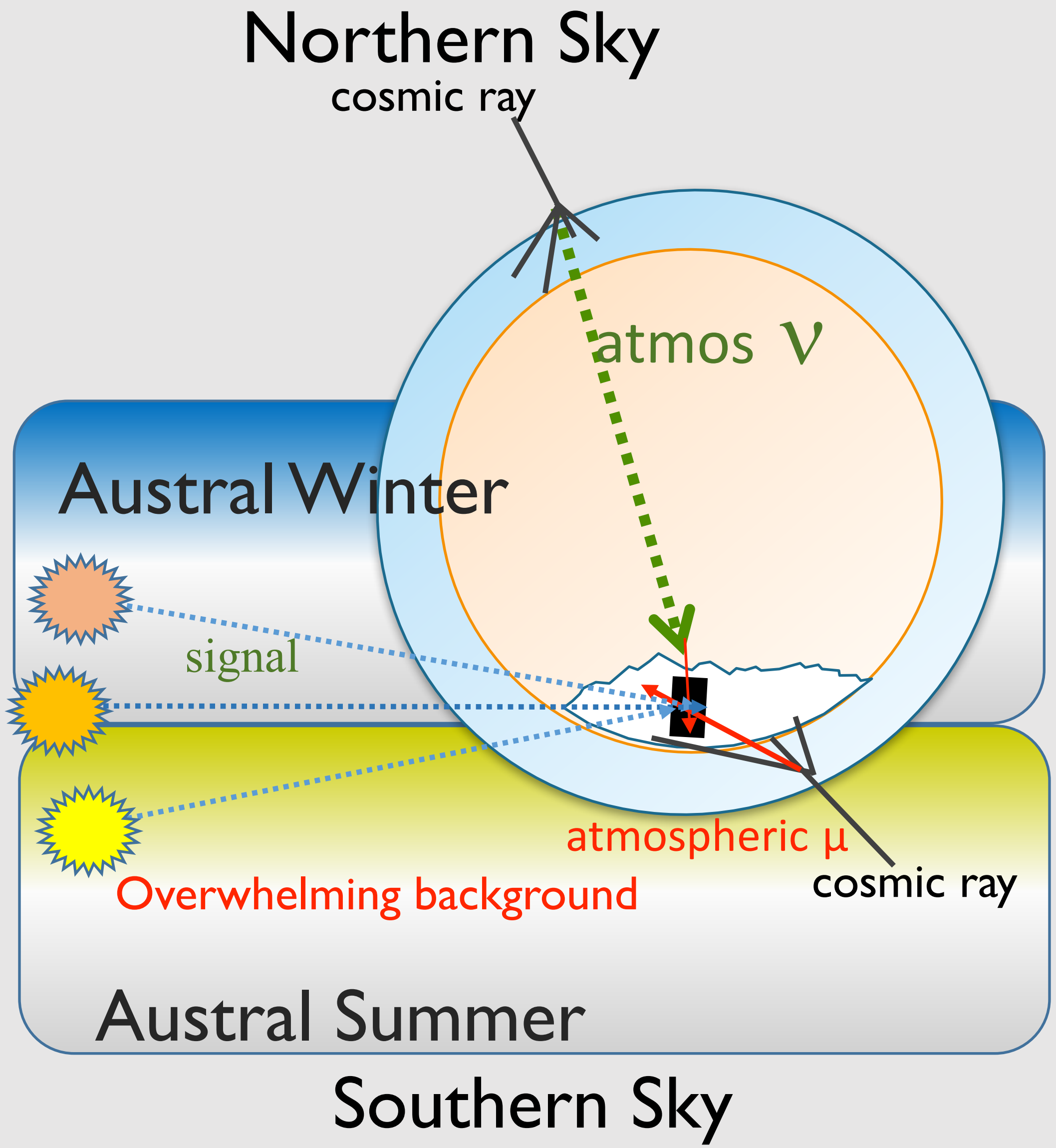
Equilibrium → $\Gamma_A^{equi} = \frac{1}{2} C_c$

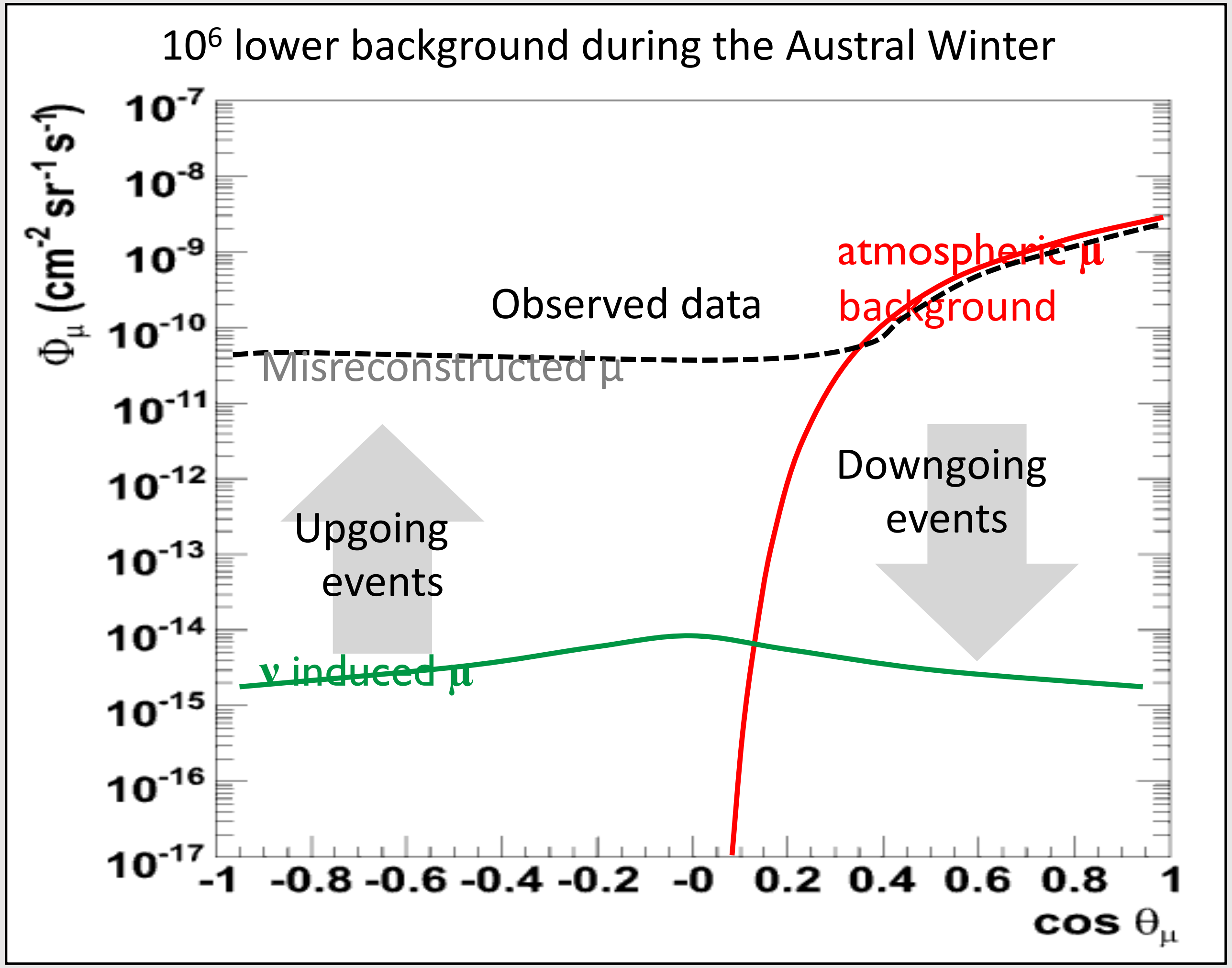
Annihilation



All calculations performed with DarkSusy/WimpSim

Events in IceCube



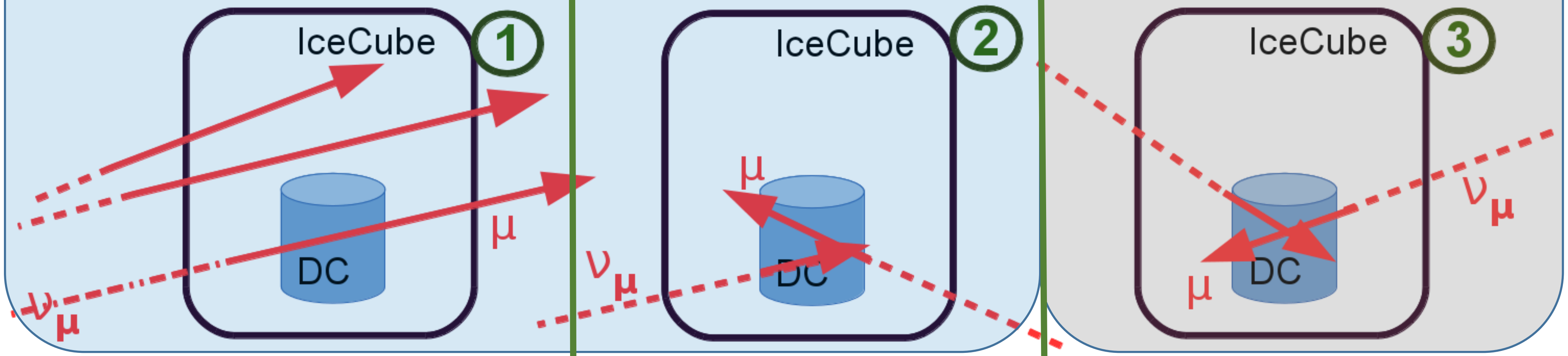


Event Selection Strategy

- *Up-going*
- *IceCube Dominated*
- *No Containment*

- *Up-going*
- *DeepCore Dominated*
- *Strong Containment*

- *Down-going*
- *DeepCore Dominated*
- *Strong Containment*



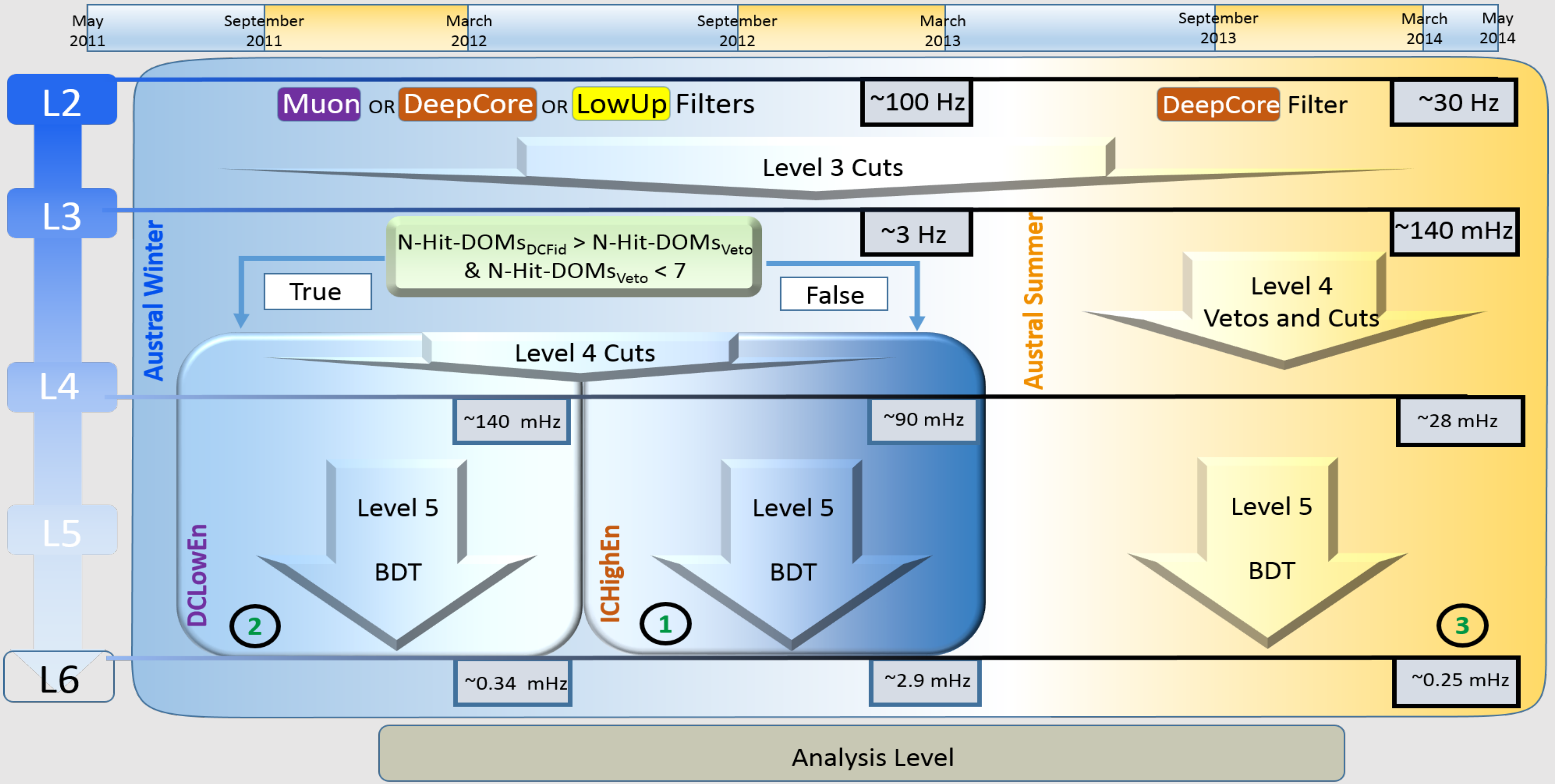
- *High Effective volume (IceCube)*
- *Good angular resolution*
  (< 2^O at 1 TeV)
- *Bad Energy resolution*
  (Only a lower limit)
- *> 100 GeV*

- *Smaller Effective volume (DeepCore)*
- *Worse angular resolution*
  (8^O at 50 GeV)
- *Good Energy resolution*
  ~20% below 100 GeV
- *< 100 GeV*

- *Smaller Effective volume (DeepCore)*
- *Worse angular resolution*
- *(14^O at 30 GeV)*
- *Good Energy resolution*
  ~20% below 60 GeV
- *< 100 GeV*

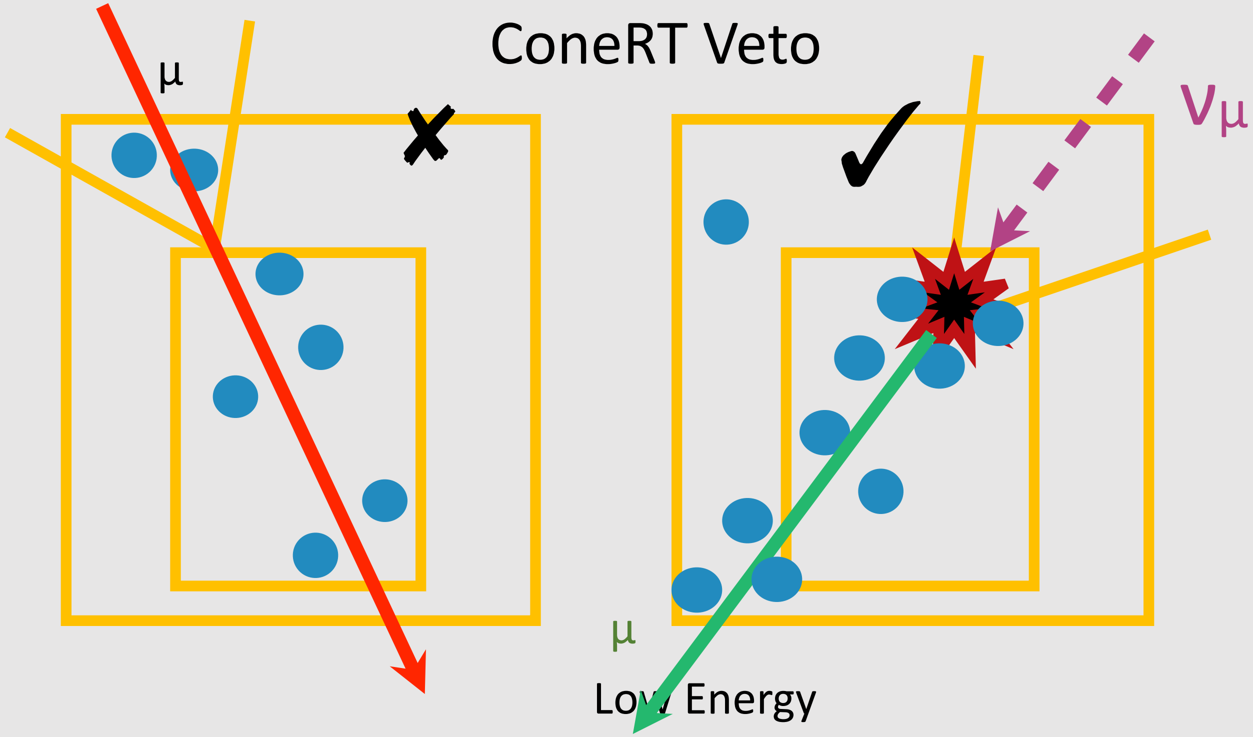
Attempts to isolate a down going IceCube dominated sample were not successful due to μ background.

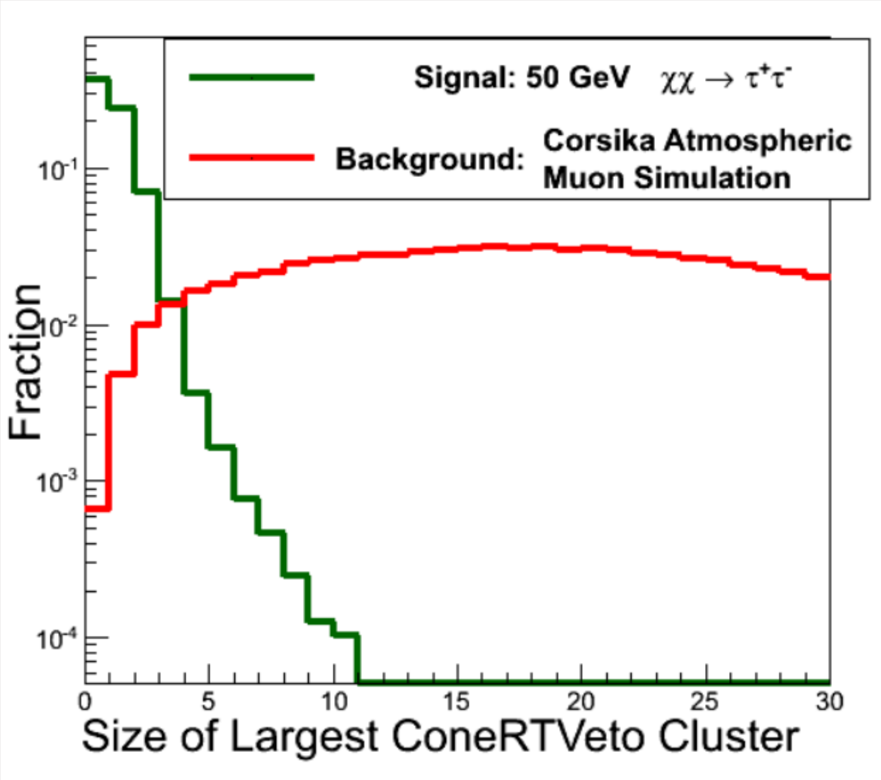
Samples


May 2011
September 2011
March 2012
September 2012
March 2013
September 2013
March 2014
May 2014
L2
L3
L4
L5
L6
Muon OR DeepCore OR LowUp Filters
~100 Hz
DeepCore Filter
~30 Hz
Level 3 Cuts
~3 Hz
~140 mHz
Austral Winter
Austral Summer
N-Hit-DOMs$_{DCFid}$ > N-Hit-DOMs$_{Veto}$ & N-Hit-DOMs$_{Veto}$ < 7
True
False
Level 4 Vetos and Cuts
Level 4 Cuts
~140 mHz
~90 mHz
~28 mHz
Level 5 BDT
Level 5 BDT
Level 5 BDT
DCLowEn
ICHighEn
2
1
3
~0.34 mHz
~2.9 mHz
~0.25 mHz
Analysis Level

Level 4 - Veto

3





Muons sneak past cuts on starting vertex.

(Falsely reconstructed starting vertex)

Look for hits within a 40 degree cone.

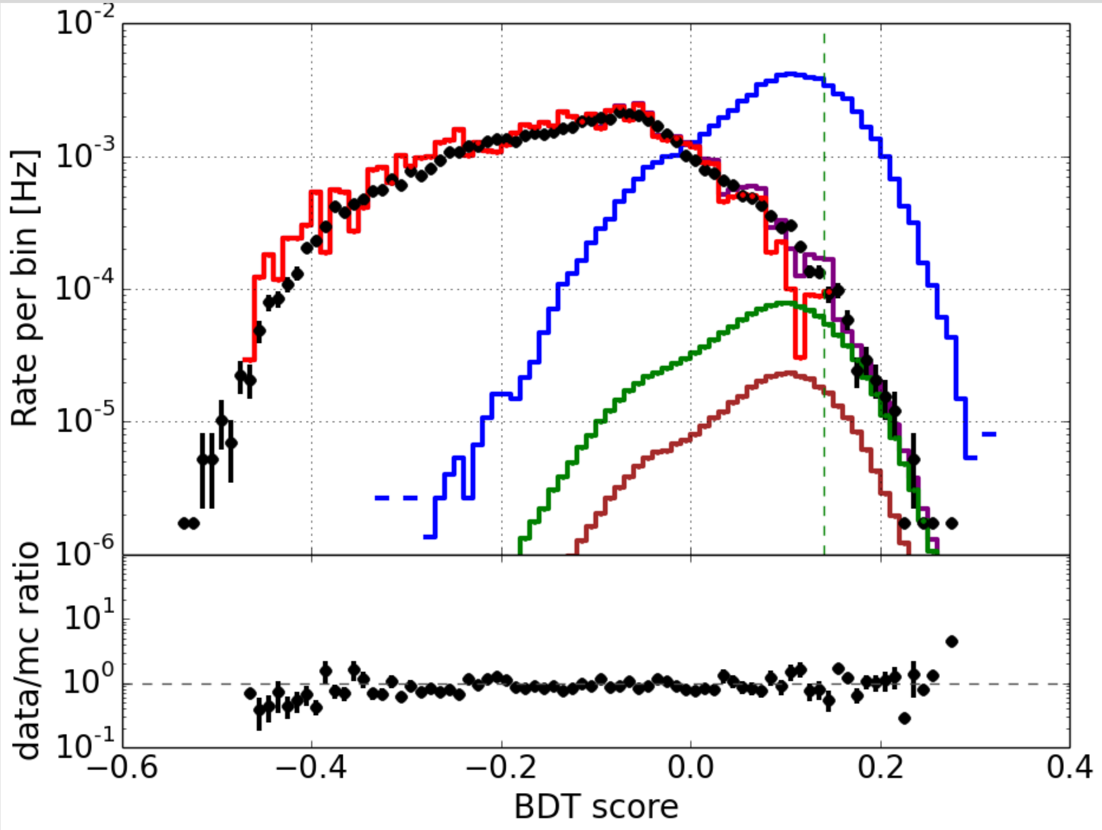
Sort them into clusters: within 250 metres and 1μs of each other

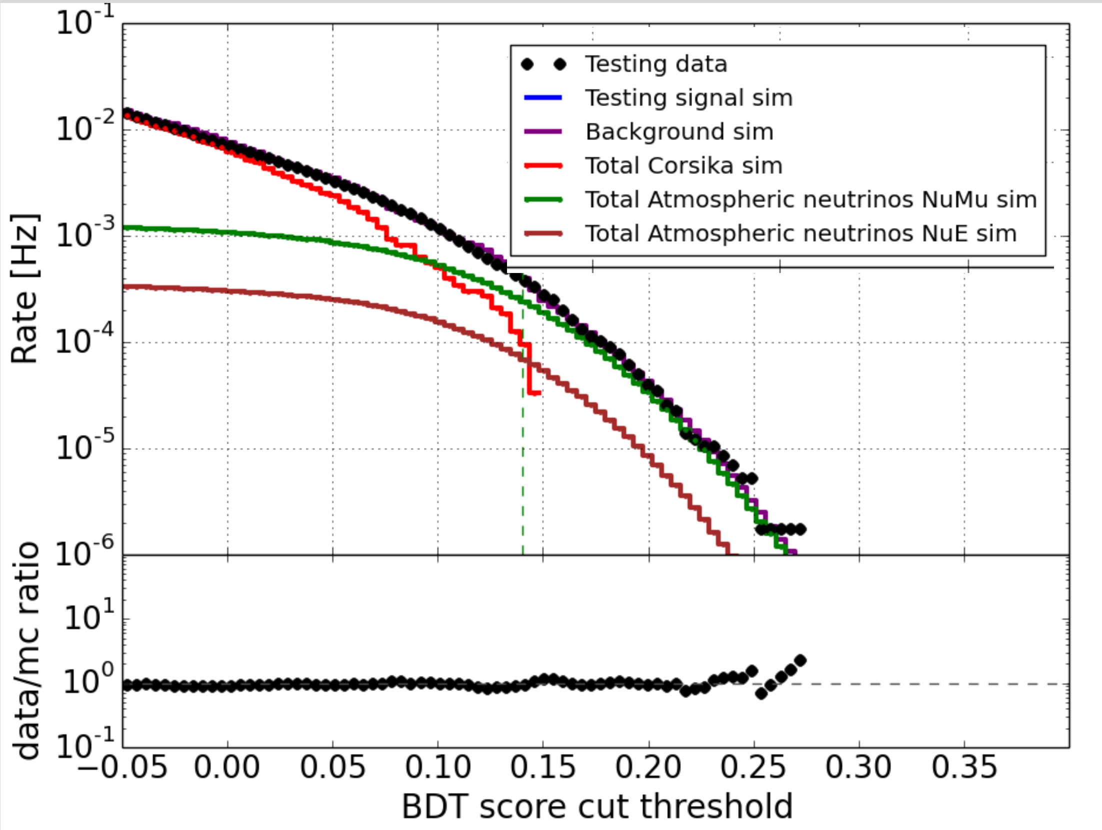
Count the size of the largest cluster

Cut at 3 rejects >80% of Bkg, keeps 90% of Signal.

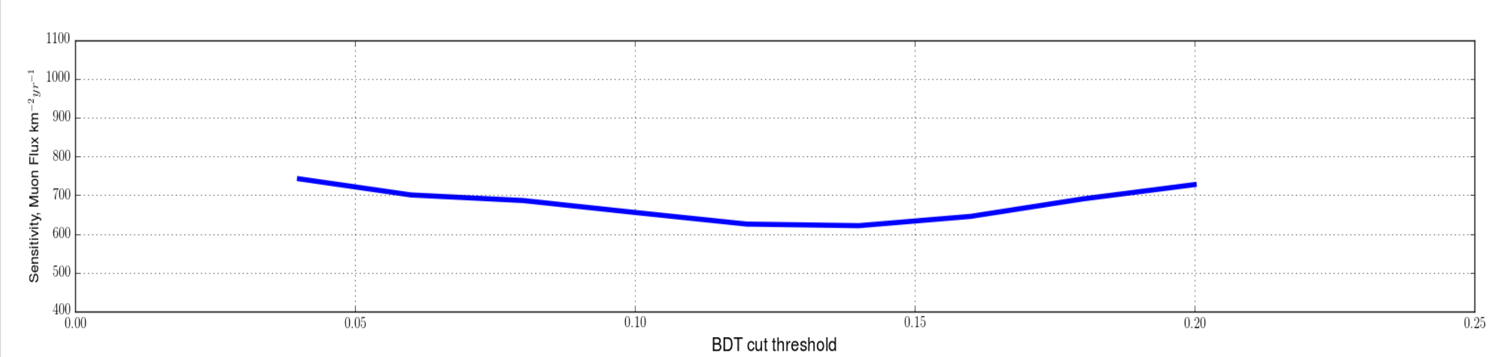
Level 5 – Boosted Decision Tree (contd)

2





Best BDT cut threshold for sensitivity chosen - the Model Rejection Factor method.

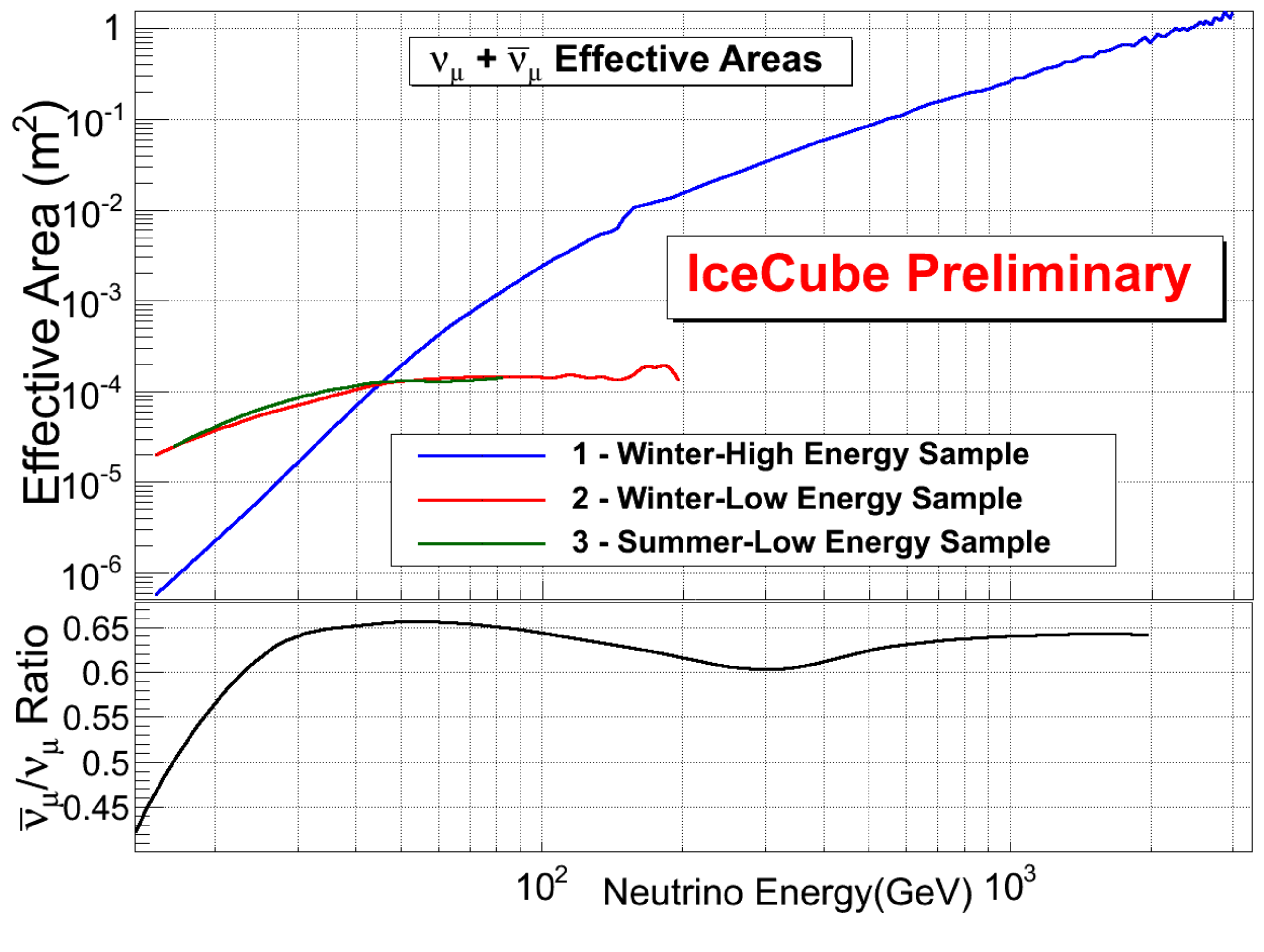


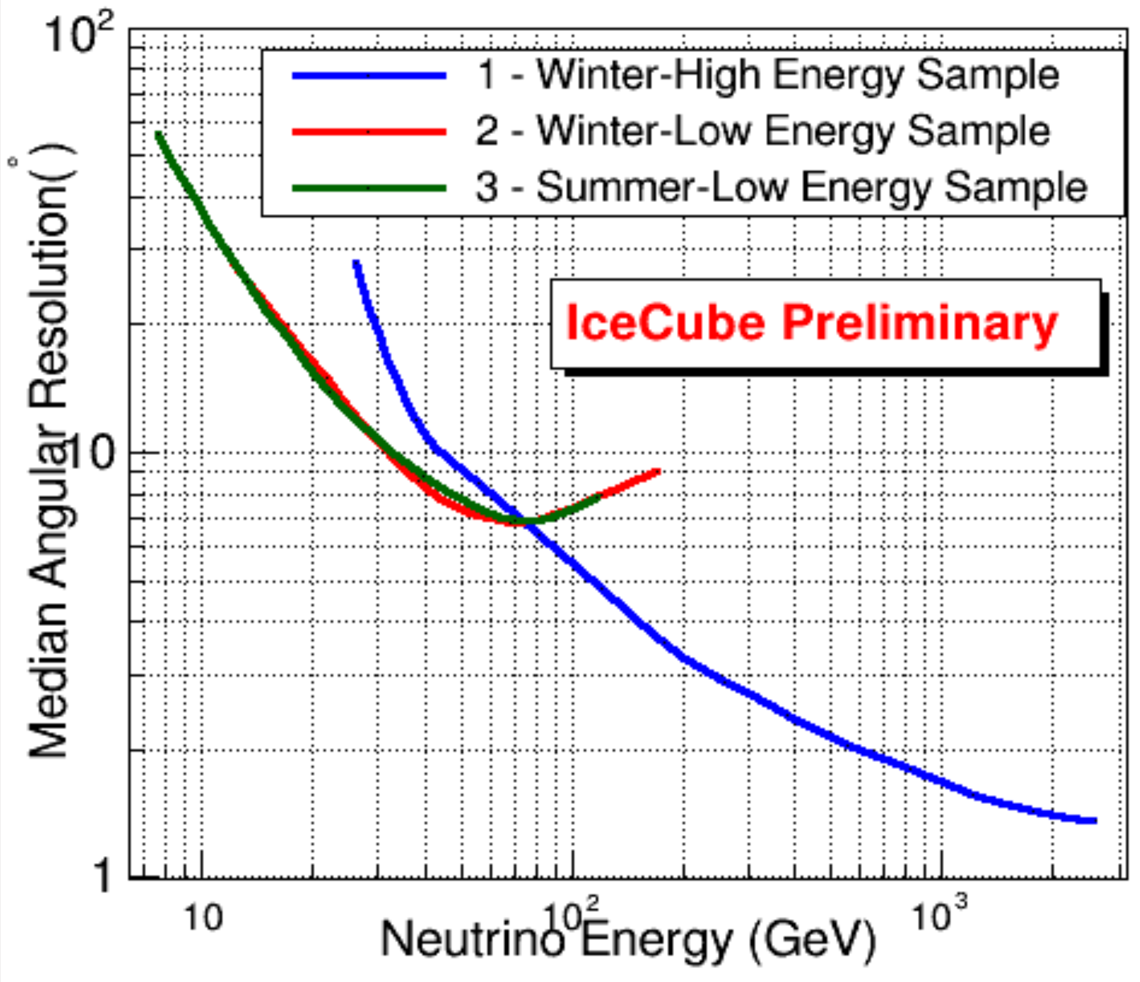
Final Samples Summary

	Sample	Rate (mHz)	Total MC (mHz)	Atmos $\nu_\mu + \overline{\nu}_\mu$ (mHz)	Atmos $\nu_e + \overline{\nu}_e$ (mHz)	Atmos μ (mHz)	Energy range (GeV)	Typical signal efficiency
1	Winter High Energy	2.9	3.0	2.1	0.1	0.8	100 -2000	24% (5 TeV χχ to W^+W^-)
2	Winter Low Energy	0.34	0.36	0.26	0.08	0.02	10-100	6% (50 GeV χχ to $\tau^+\tau^-$)
3	Summer	0.25	0.28	0.21	0.05	0.03	10-50	4% (20 GeV χχ to $\tau^+\tau^-$)

- Livetimes : Winter 528.28 days, Summer 490.77 days. Total 1019.05 days of data.
- Non overlapping, no events in common
- True event directions not examined. Analysis is blind.

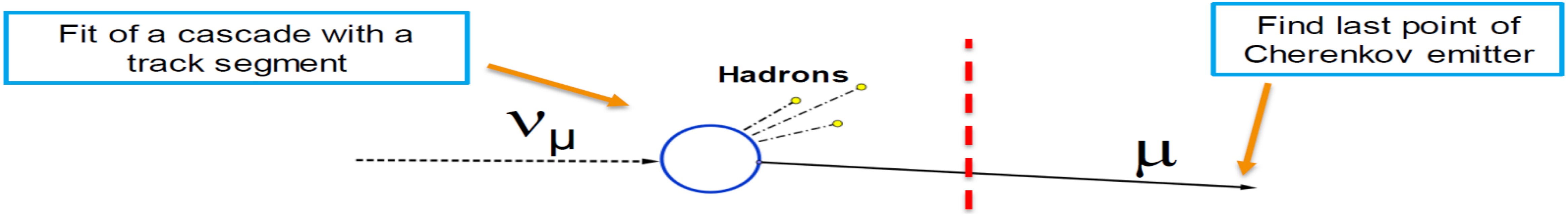
Event Selection Performance





Energy Reconstruction

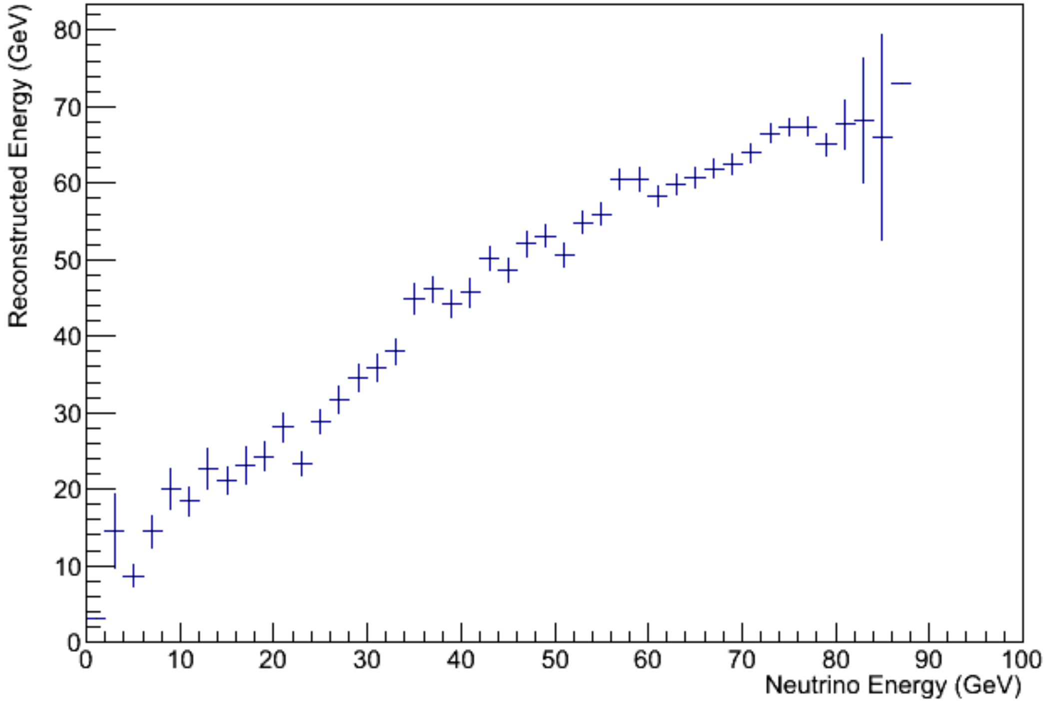
$$E_{\text{reco}} = E_\mu(R_\mu) + E_{\text{vertex}}(E_{\text{had}}, \vec{x}_{\text{vertex}})$$



A full neutrino energy estimator for contained tracks

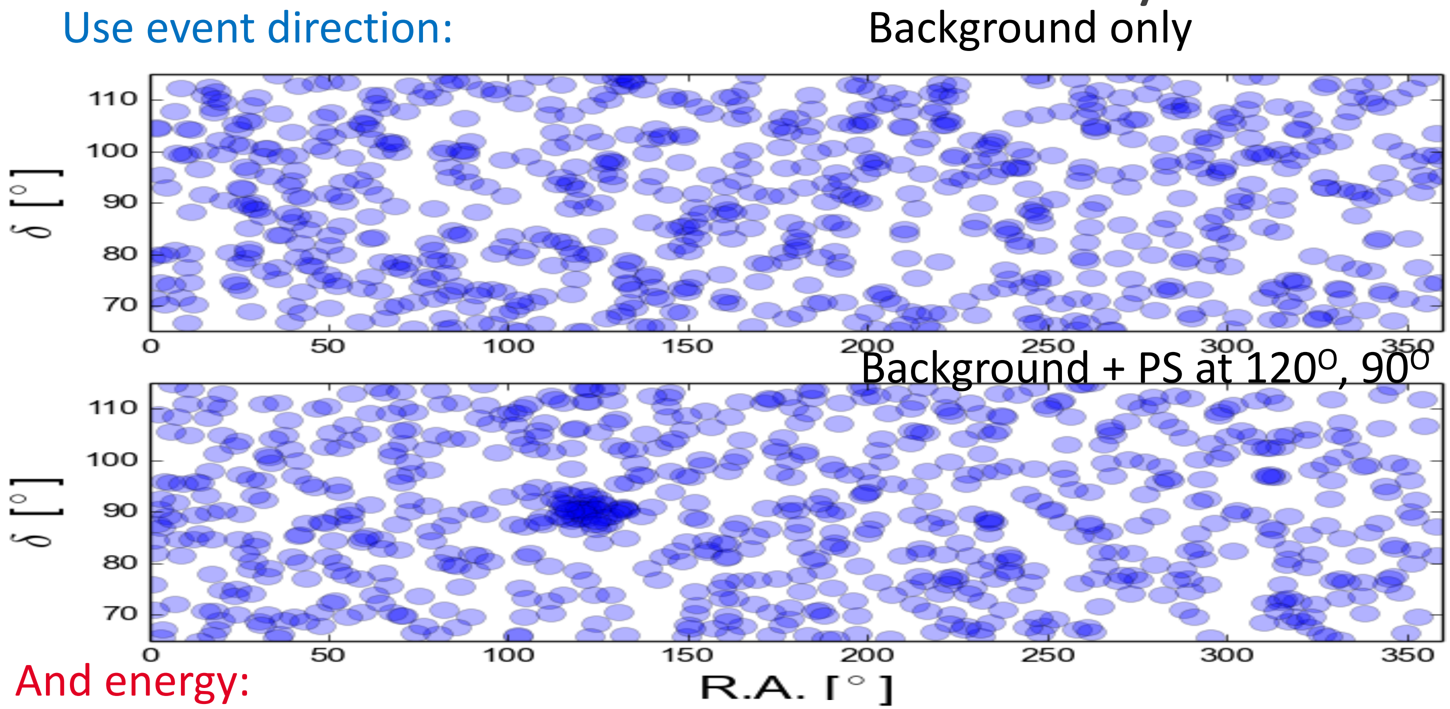
Enhances signal to background discrimination, and sensitivity for the DeepCore dominated samples (2) and (3)

Event energy information used for a Solar WIMP analysis for the first time in IceCube.



Analysis Method

Use event direction:



Background (atmospheric ν and μ) :

- Uniform within declination band

$$B(\delta_i)$$

Signal (Astrophysical ν from source) :

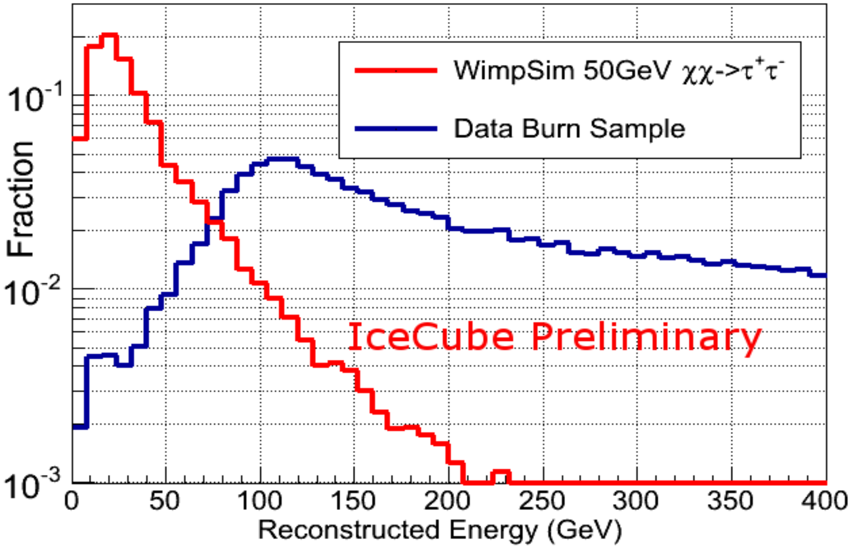
- Clustered around source

$$\mathrm{K}_{\mathrm{i}}^{j} = \frac{\kappa_i e^{\kappa_i \cos\left(\theta\left|\vec{r}_i - \vec{r}_j(t_i)\right|\right)}}{2\pi(e^{\kappa_i} - e^{-\kappa_i})}$$

Fisher Bingham distribution,
(Gaussian in directional statistics)

Event by event angular resolution

And energy:



$$\mathrm{S_i}(m_\chi, ch) = P(E_i|m_\chi, ch) * \mathrm{K}_{\mathrm{i}}^{j}$$

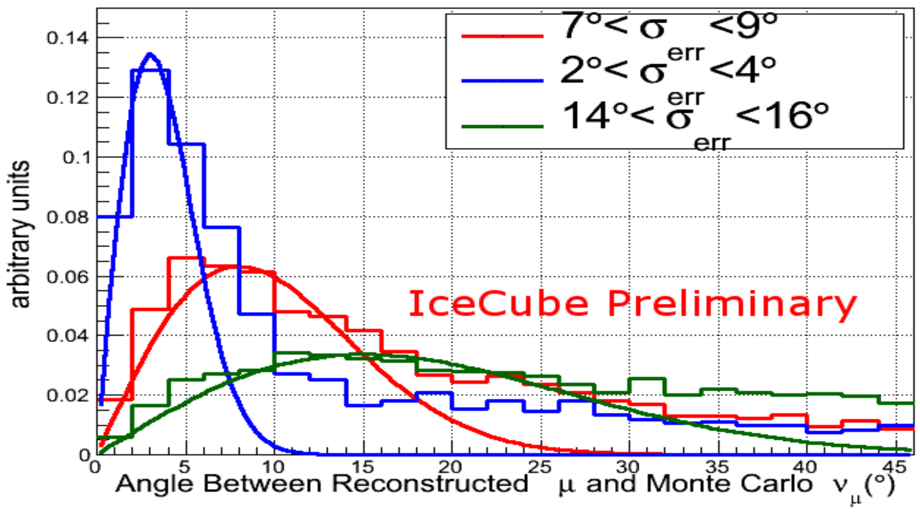
$$B_i = P(E_i|\phi_{atm}) * B(\delta_i)$$

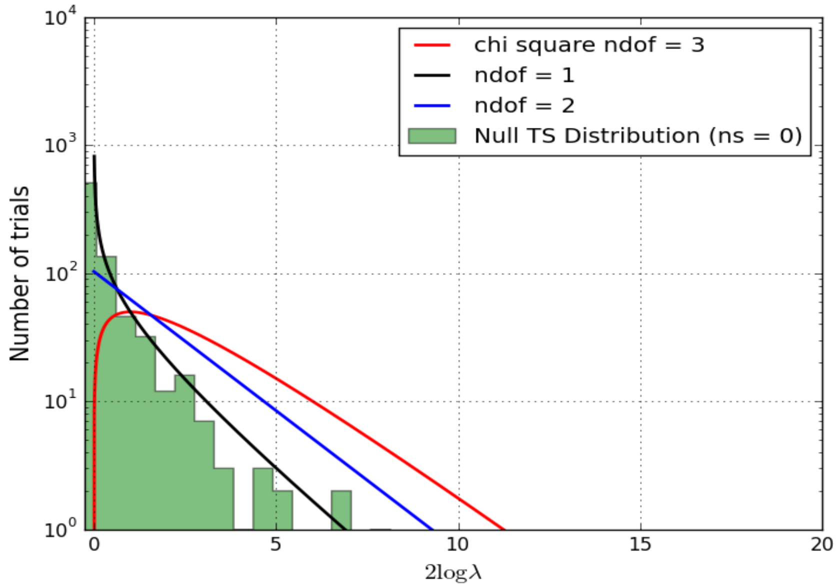
Likelihood:

$$\mathcal{L}(n_s) = \prod_{i=1}^{N}\left(\frac{n_s}{N}\mathrm{S_i}(m_\chi, ch) + (1 - \frac{n_s}{N})B_i\right)$$

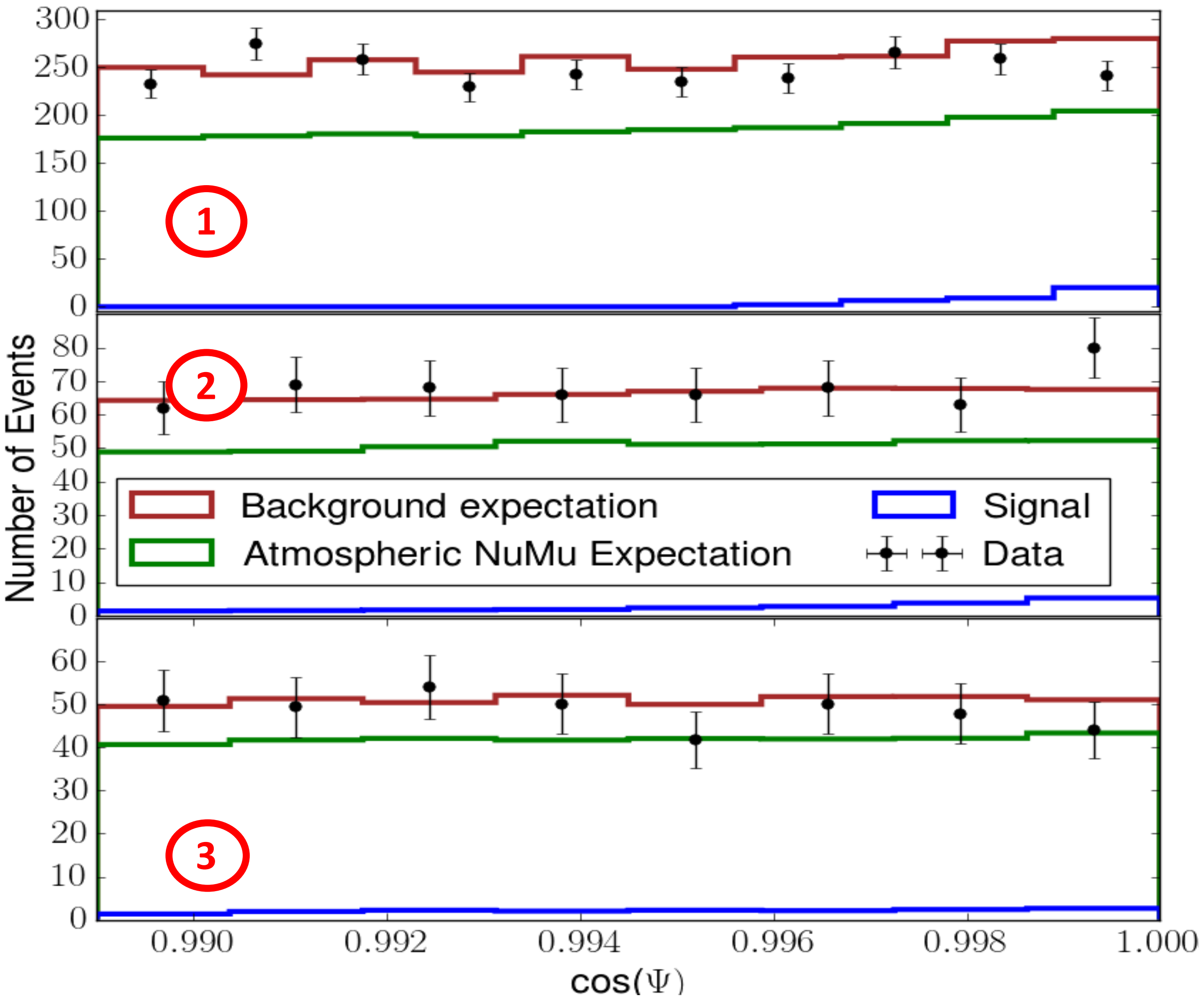
Analysis Method (contd)

- $B(\delta_i)$ and $P(E_i|\phi_{atm})$ are estimated from data.
  - Robust against false discovery
- $P(E_i|m_\chi, ch)$ is estimated from Monte Carlo
- K_i^j is analytic.
- Log likelihood can be maximized to find the best fit $\hat{n}_s$
- $-2\log\left(\frac{\mathcal{L}(n_s=0)}{\mathcal{L}(\hat{n}_s)}\right)$ is the test statistics and is distributed as $\chi^2(1\ \mathrm{dof})$ – (Wilke's theorem)
- Significance from many datasets scrambled in R.A.
- Confidence intervals on n_s - Feldman and Cousins.





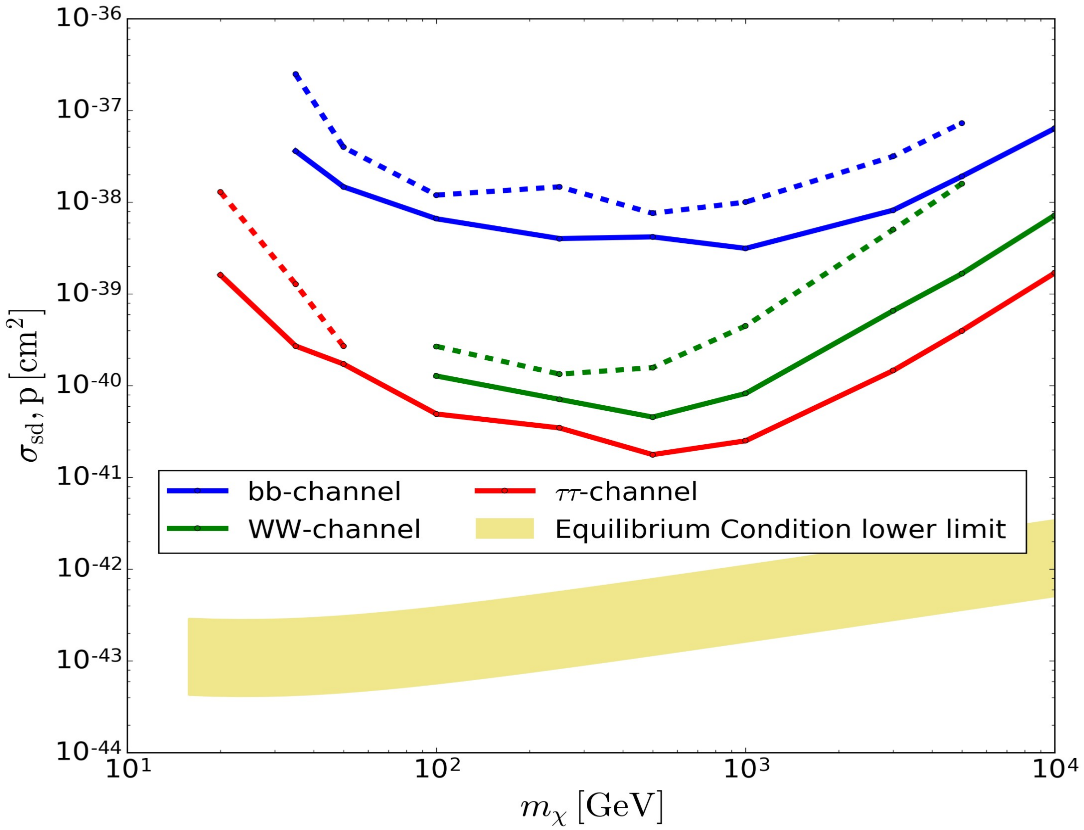
Results



- No statistically significant excess
- Best p – value ~16%

  500 GeV $\chi\chi \rightarrow b\bar{b}$

  $\hat{n}_s = 24.4$

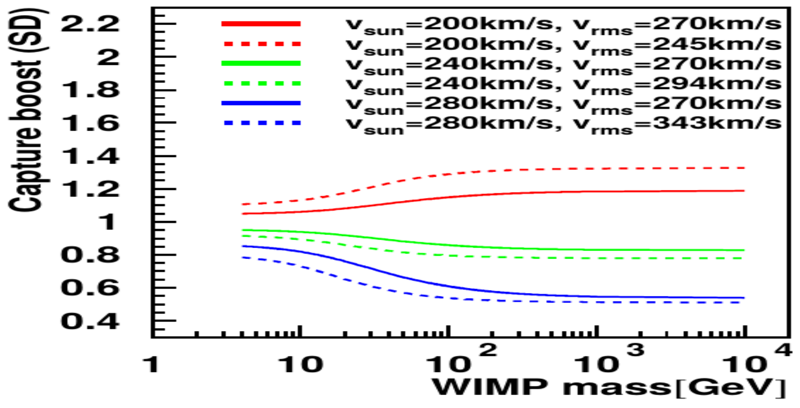


More livetime + better event selection + better analysis methods + bugfix -> Results better by ~1 order of magnitude w.r.t IC79

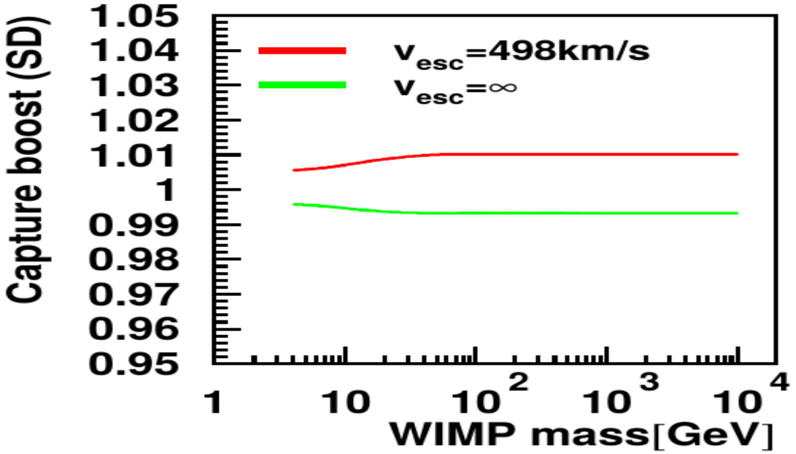
Astrophysical Uncertainties

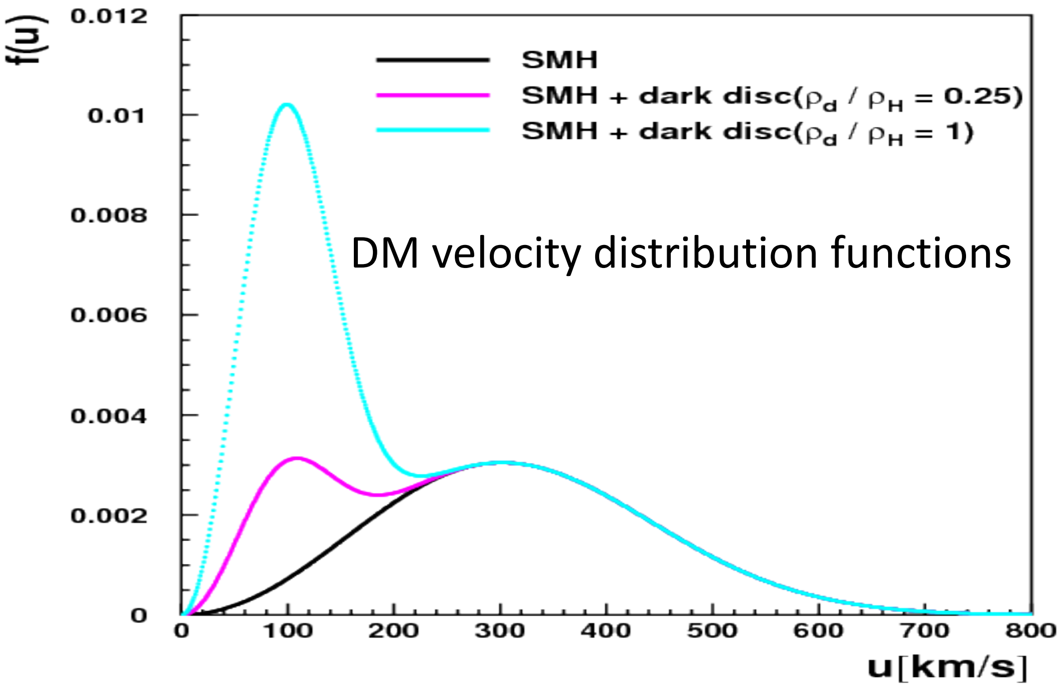
There are uncertainties on:

- The velocity of the Sun w.r.t the halo



- The fraction of DM in a co-rotating dark disk
- The galactic escape velocity



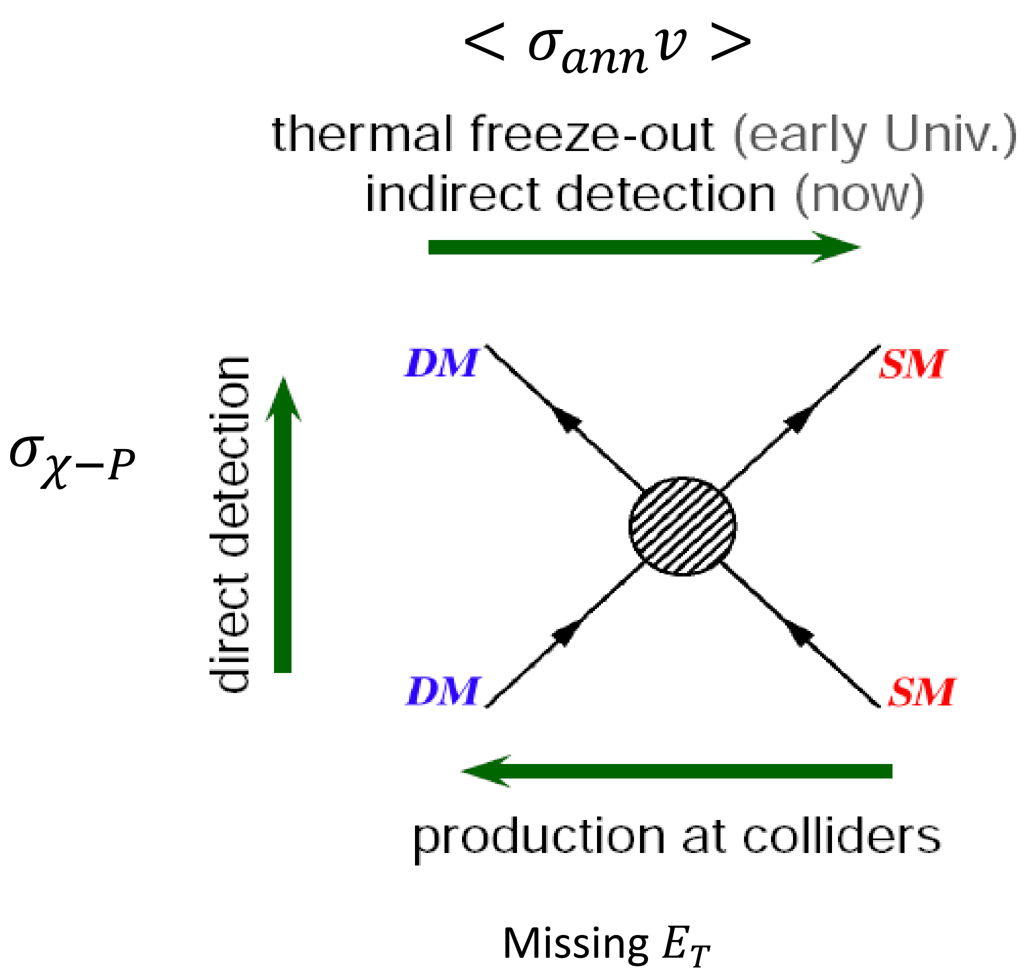


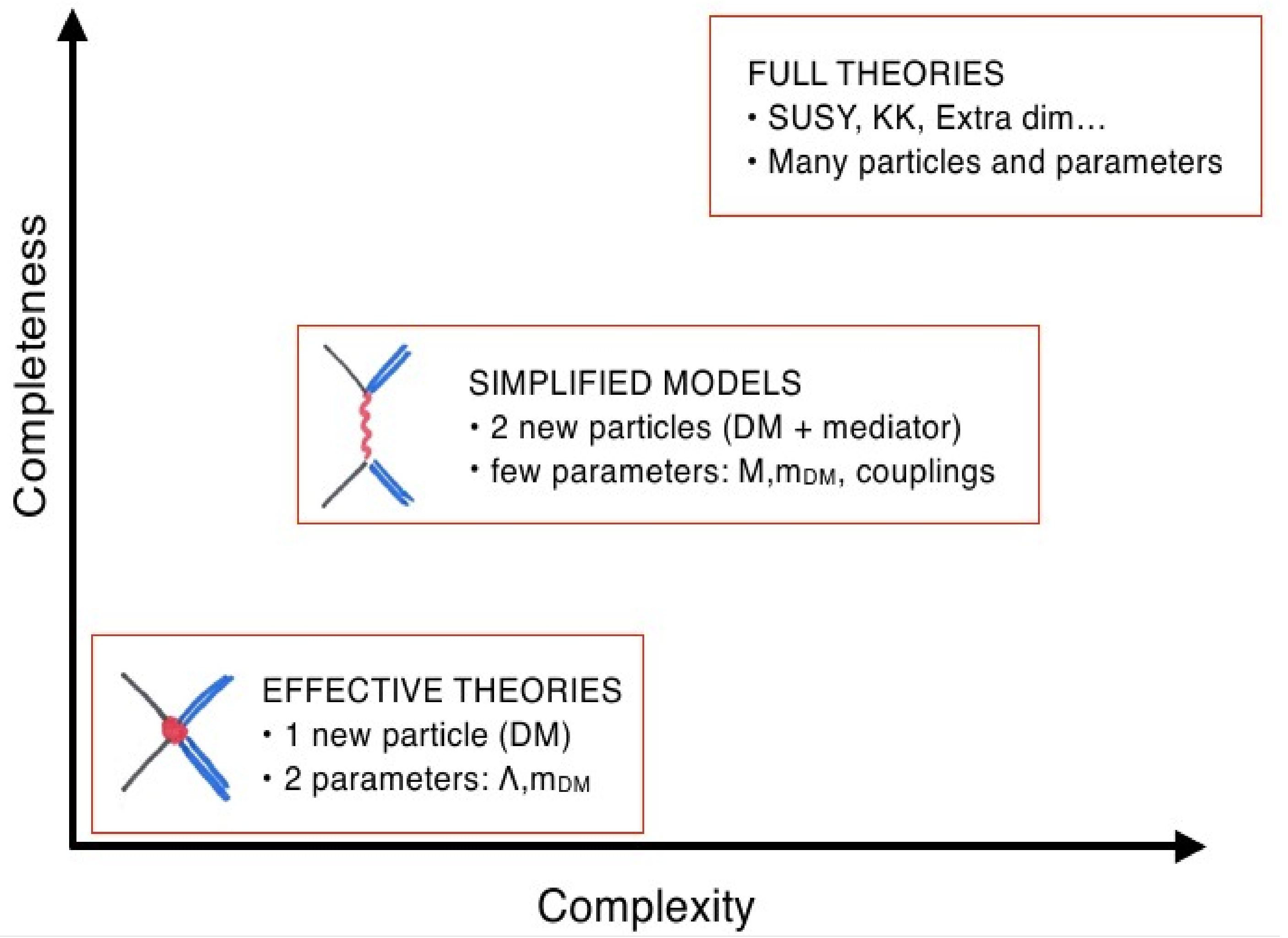
C. Rott et al. JCAP05 (2014) 049

The uncertainties are **20% (50%) at low (high) WIMP masses.**

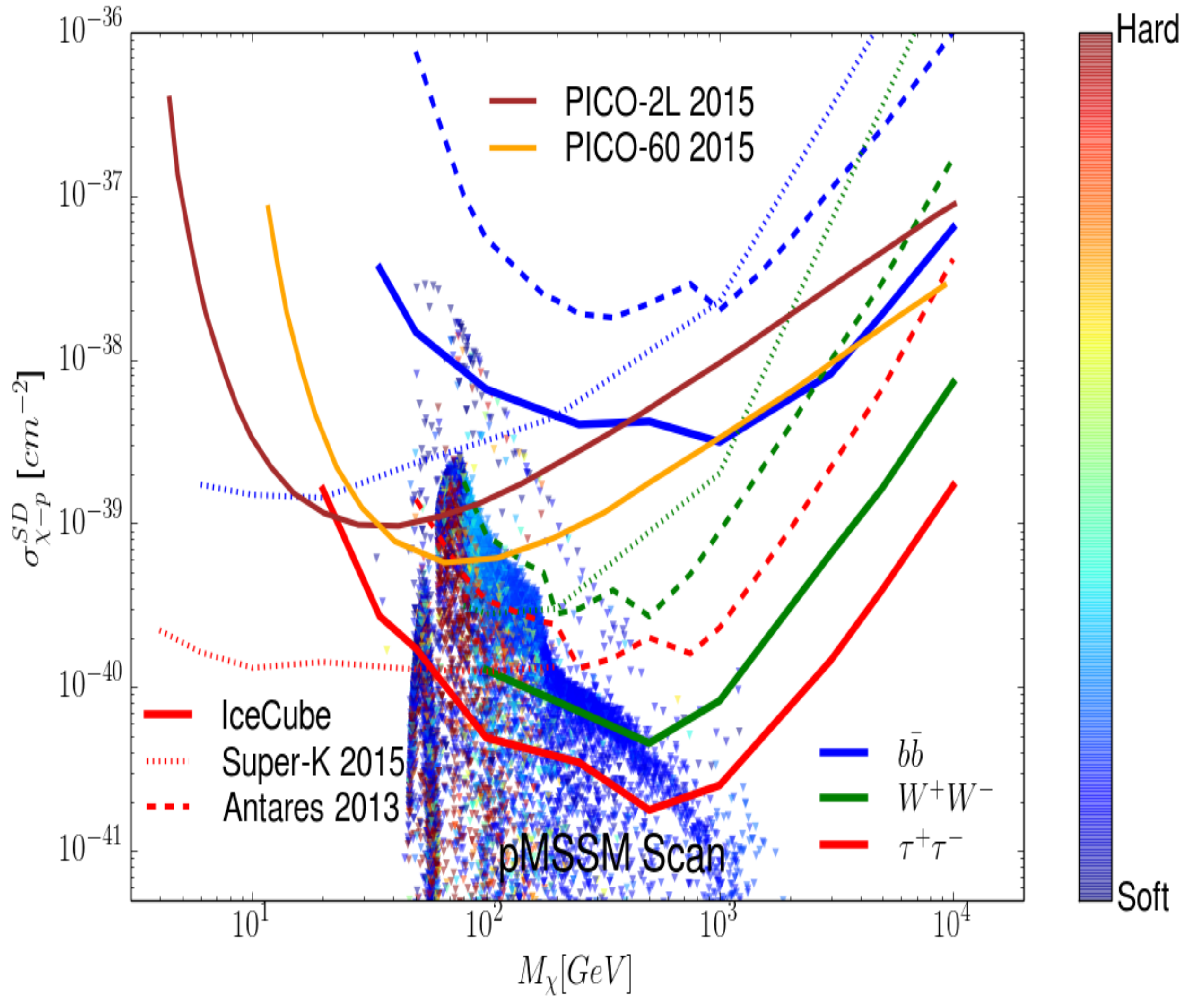
Conservative w.r.t. the dark disk fraction.

Complementarity and DM Models





Complementarity in the pMSSM



Only pMSSM models not excluded by LHC Run 1 are shown

Correct Higgs Mass and Relic density

SI $\sigma_{\chi\text{-}N}$ not greater than LUX bounds

Model colourcoded by hardness or softness of annihilation channels

"PMSSM benchmark models for Snowmass 2013" arXiv:1305.2419,

148.3 GeV Bino-Higgsino WIMP can be excluded at >90% C.L

Complementarity of DM Searches in a Consistent Simplified Model: the Case of Z'

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Mohamed Rameez,[d] **and Antonio Riotto**[c]

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[c] *Département de Physique Théorique and Center for Astroparticle Physics (CAP), Université de Genève, 24 quai Ansermet, CH-1211 Genève 4, Switzerland*

[d] *Département de Physique Nucléaire et Corpusculaire, Université de Genève, 24 quai Ansermet, CH-1211 Genève 4, Switzerland*

arXiv:1505.06513

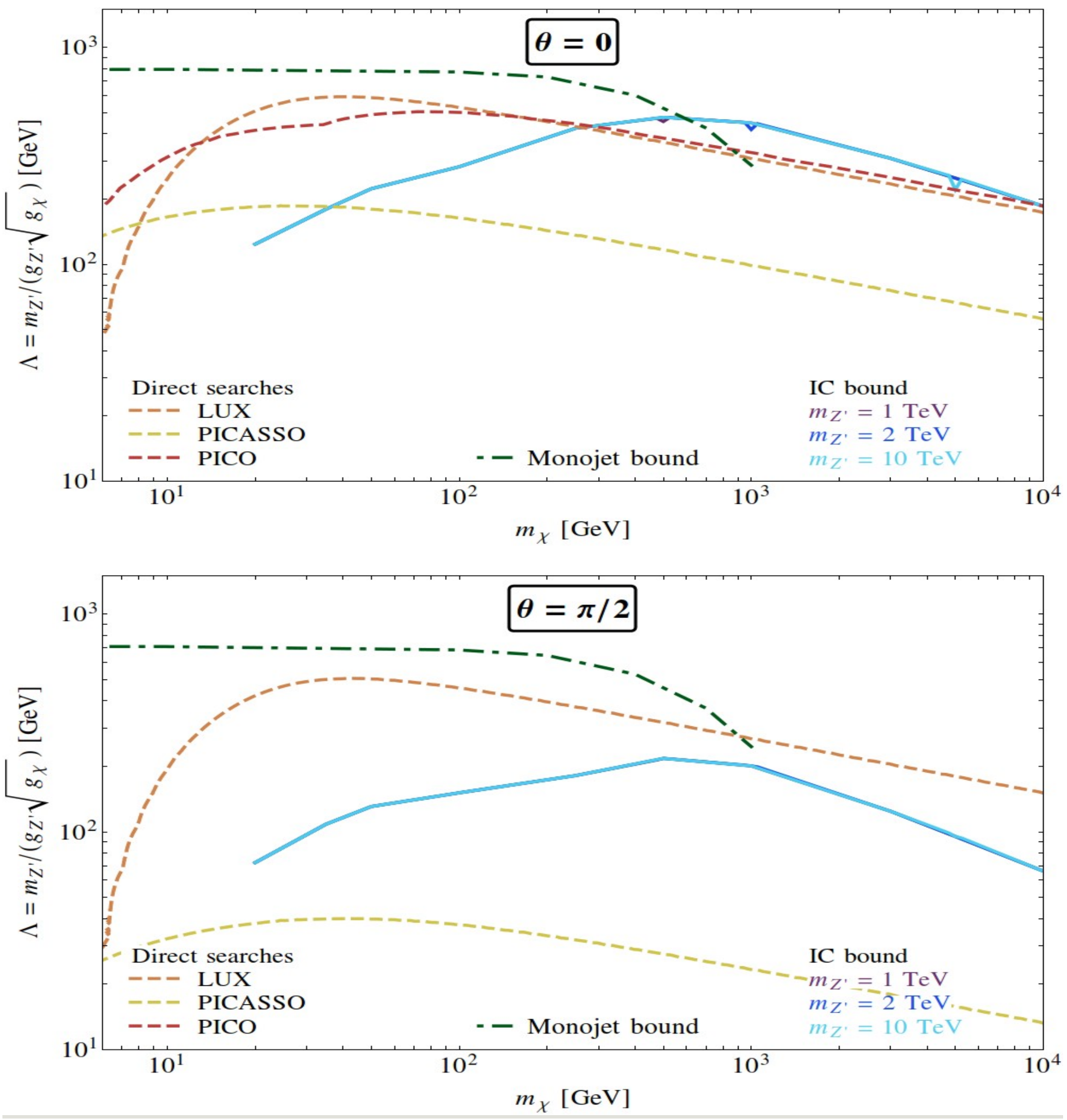
Complementarity of DM Searches in a Consistent Simplified Model: the Case of Z'
T. Jacques et. al. arXiv:1605.06513

U(1)' extension of the standard model :

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

One new gauge boson Z'

(mass $m_{Z'}$ given by SSB in a hidden sector)
Majorana DM, stable under Z_2 symmetry
U(1)' charges for cancellation of **SM X SM X U(1)'** gauge anomaly. Higgs is charged
Full lagrangian in backup slides
SD WIMP-Nucleon scattering in the non relativistic limit – Direct Detection constraints
Z-Z' mixing
LHC constraints from Z' → l^+l^- and monojet constraints on DM
Strongest constraints are from LHC below 400 GeV WIMP mass, and IC above 400 GeV, except for θ = π/2



The Emerging 750 GeV diphoton excess – portal to the dark sector?
E. Morgante et. al., JHEP 1607 (2016) 141

A pseudoscalar, P of mass 750 GeV:

- Scattering is SD at the NR limit

750 GeV > Ewk Scale

- Lagrangian is $SU(2)_L$ invariant, P couples to B.
- Guarantees annihilation to ZZ and Zγ

P also couples to gluons and/or quarks

- Run 1 constraints

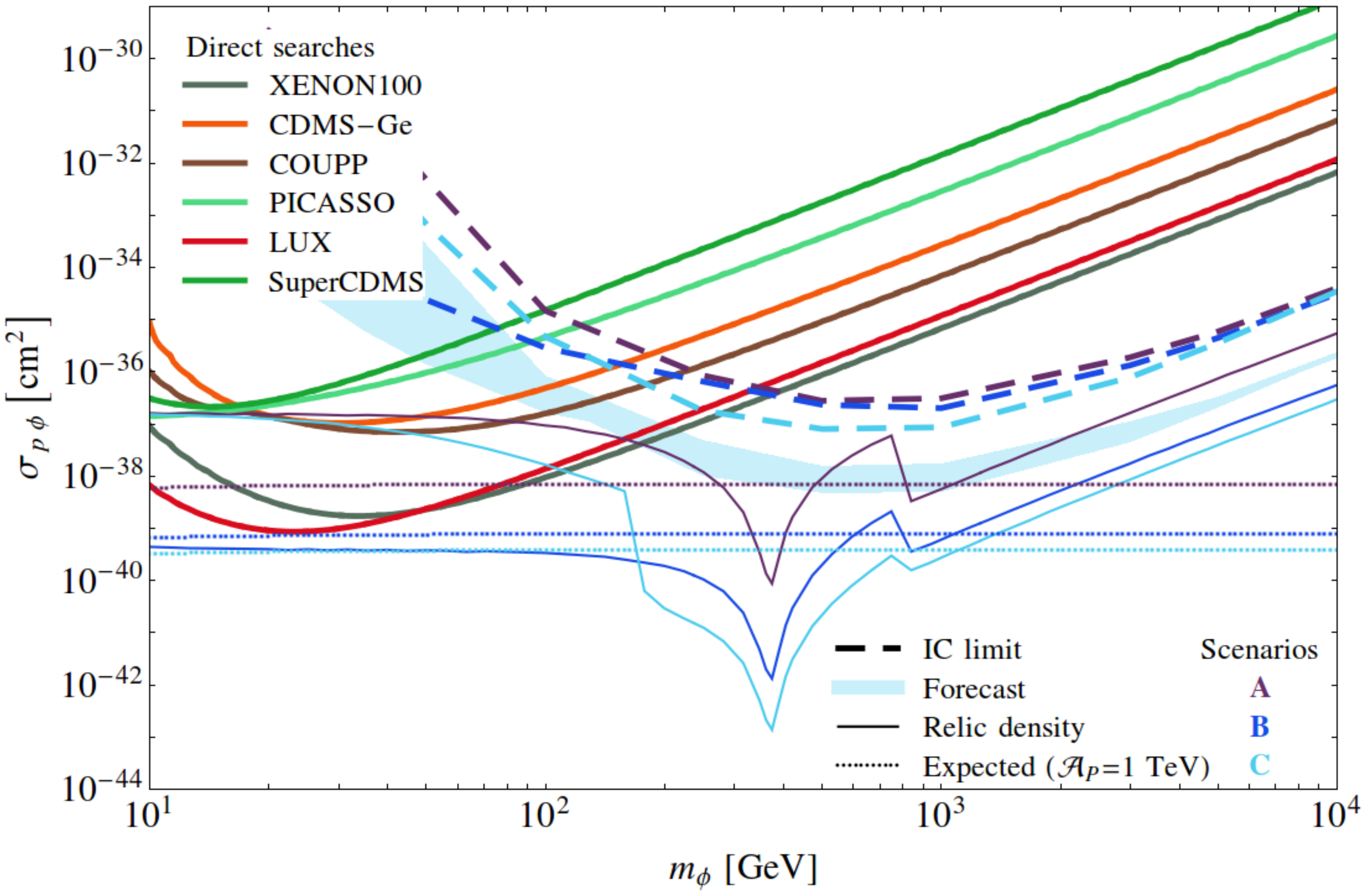
DM χ (fermion) or ϕ (scalar) stable under Z_2 symmetry.
3 scenarios.
P couples to :

- B, g, u, χ
- B, g, u, χ, b
- B, g, u, χ, t

WIMP-proton scattering in the NR limit

$i(\hat{S}_N.\frac{\hat{q}}{m_N})$ for scalar DM and

$(\hat{S}_\chi.\frac{\hat{q}}{m_N})\ (\hat{S}_N.\frac{\hat{q}}{m_N})$ for fermionic DM



(IC limits calculated using capture rates evaluated in R. Catena et al, JCAP 1504 (2015) 04, 042) and analytical simplification of IC sensitivity.

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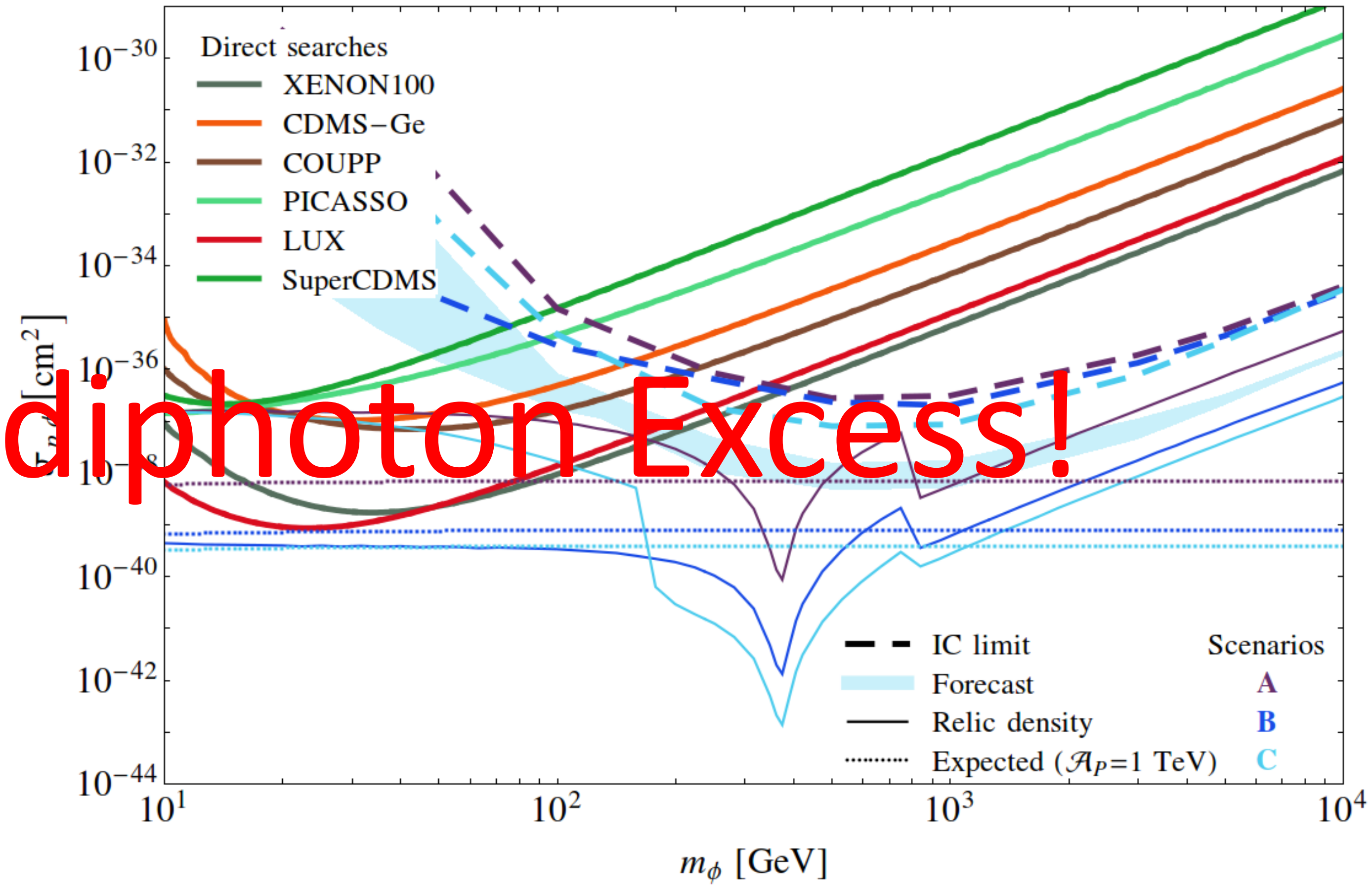
No 750 GeV diphoton Excess!



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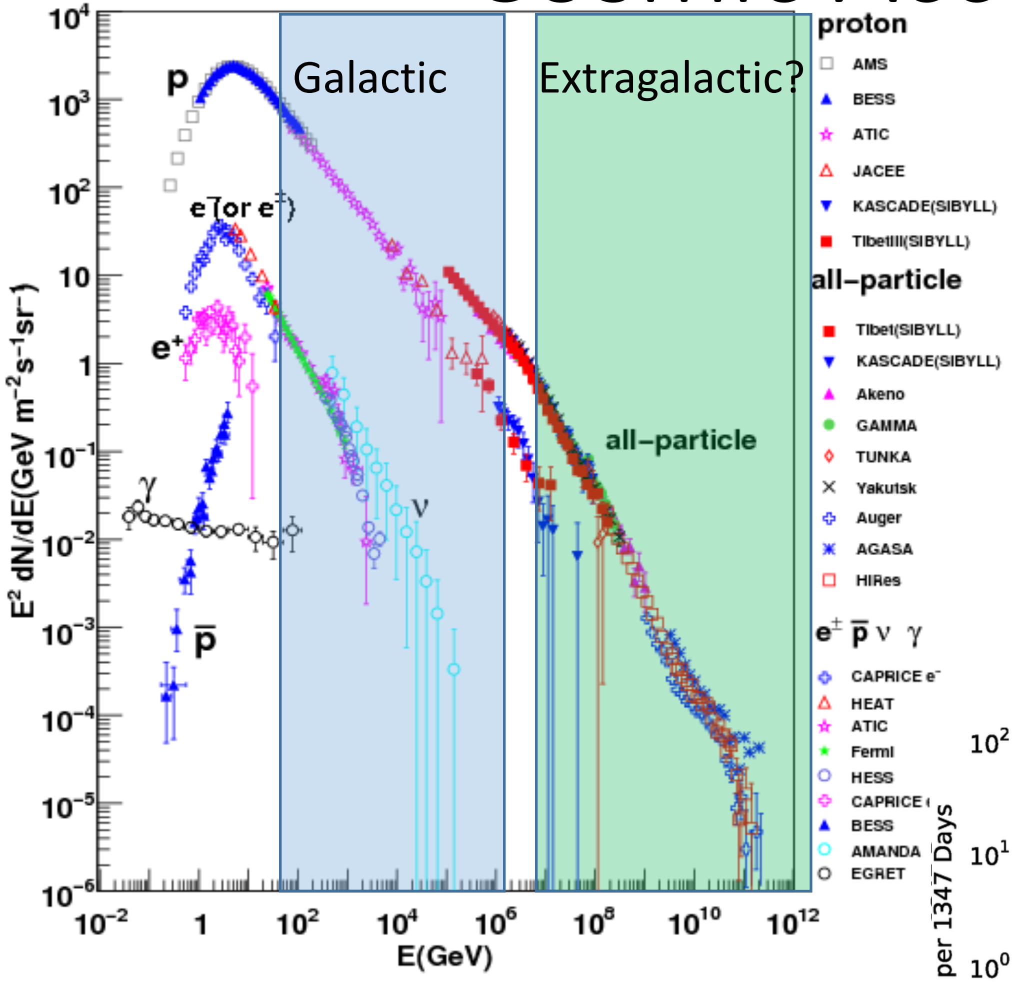
Searches for neutrinos from Cosmic Accelerators

Cosmic Accelerators and IceCube



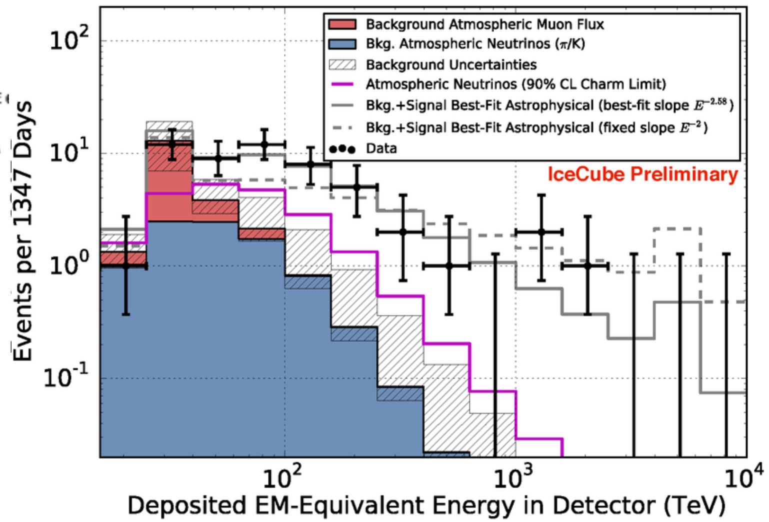
CRs, where do they come from? What accelerates them?

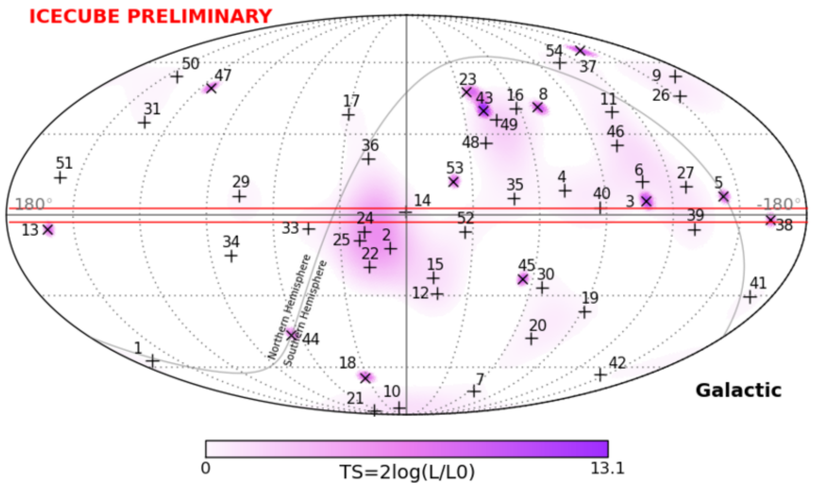
- Galactic: SNRs, microquasars?
- Extragalactic : AGNs, galaxy clusters, starburst galaxies, GRBs?

How are they accelerated? First order fermi acceleration – predicts parent proton spectrum of power law E^{-2} for an ideal shock.

- Neutrinos produced at source with same power law spectrum through p-p and p-γ interactions – pion decay – muon decay.
- 1:2:0 at source → 1:1:1 at Earth.

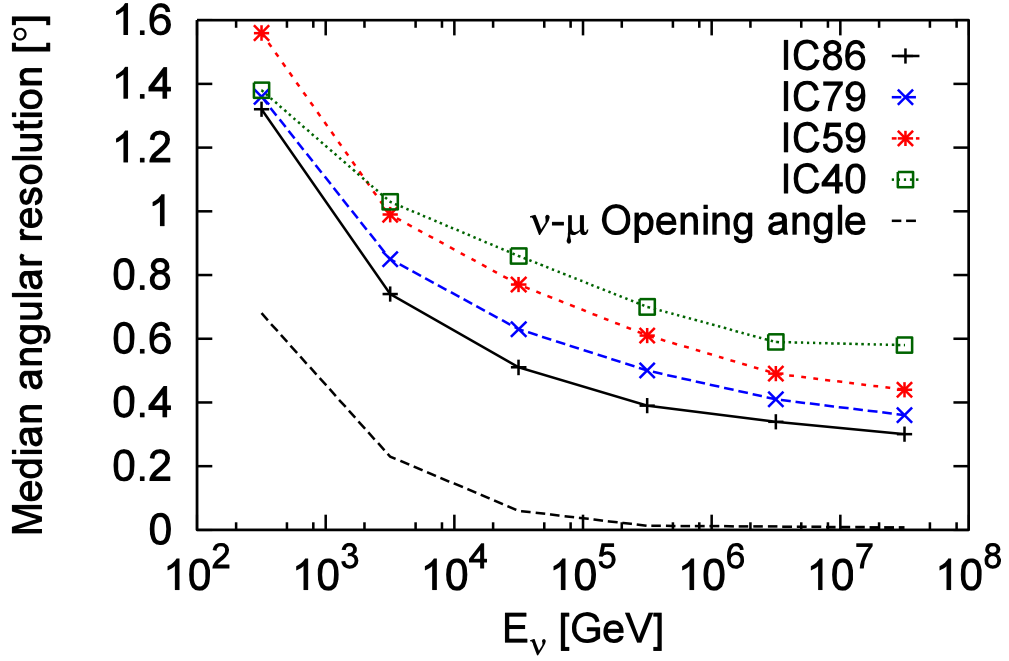
54 events seen on an expected background of $12.6 \pm 5.1\ \mu$ and $9.0^{+8.0}_{-2.2}\ \nu$. Atmospheric only origin rejected 6σ

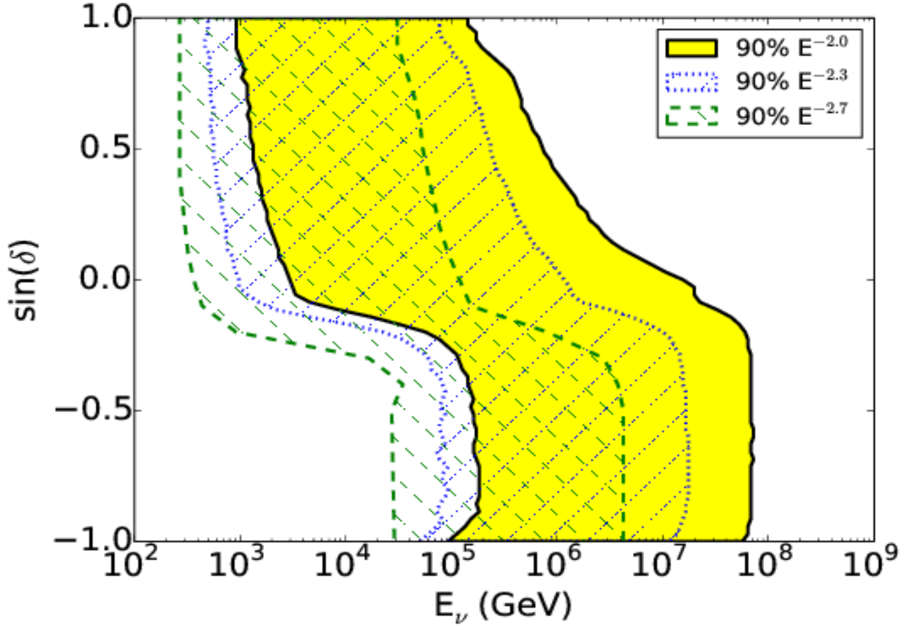


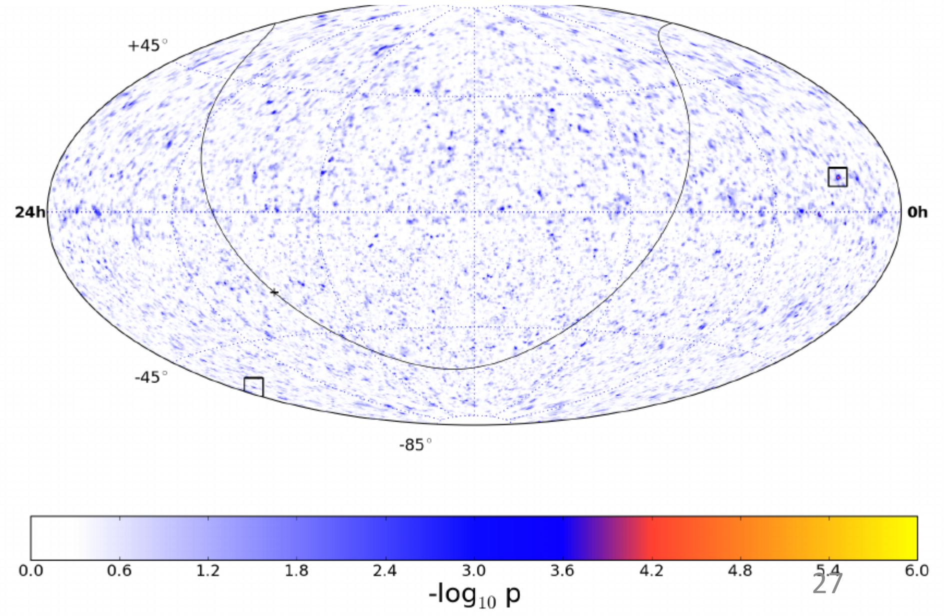


No statistically significant clustering

The IceCube samples of events dedicated to PS searches







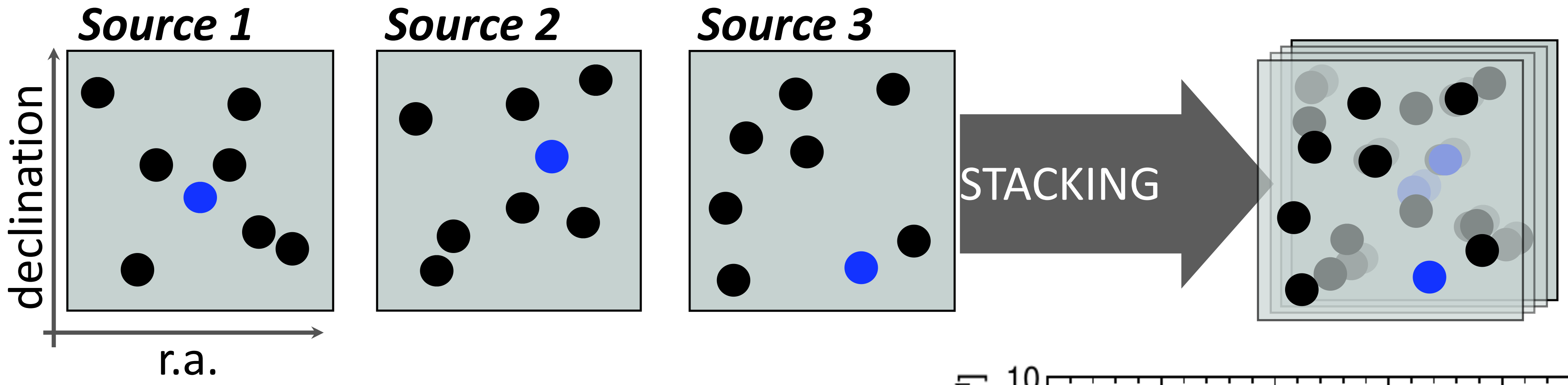
~400000 tracks, from IC40, 59, 79 and 86 (4 years of IceCube)

Northern sky: μ from $\nu_\mu + \bar{\nu}_\mu$ CC interactions

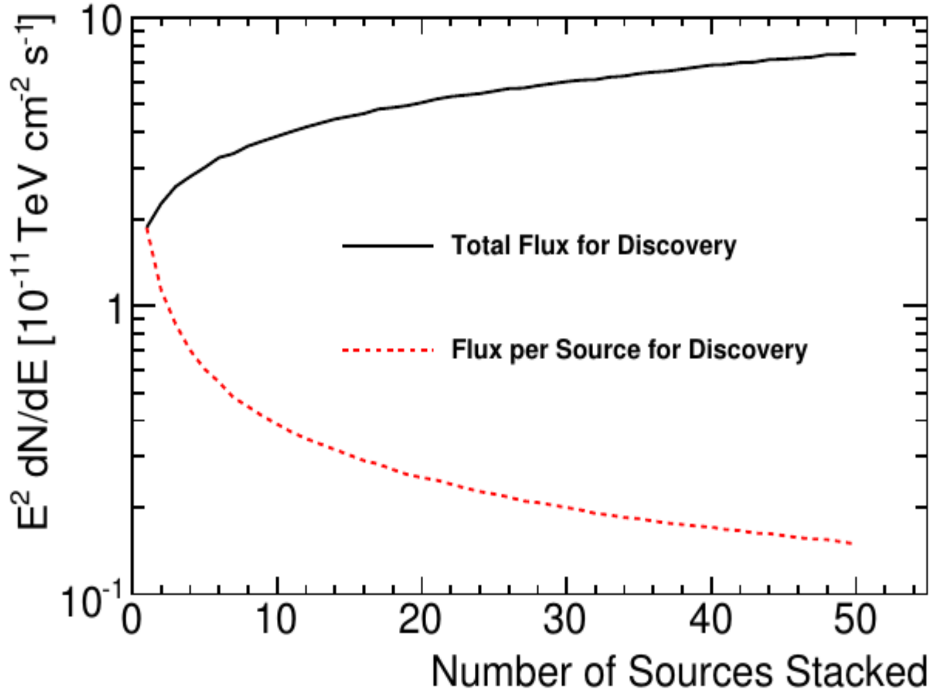
Southern sky: Atmospheric μ

All sky point source searches : no statistically significant excess – correcting for trials

The Stacking Method



$$S_i^{tot} = \frac{\sum_{j=1}^{N_S} W_j R_{IC}(\delta_j,\gamma) S_i^j}{\sum_{j=1}^{N_S} W_j R_{IC}(\delta_j,\gamma)}$$



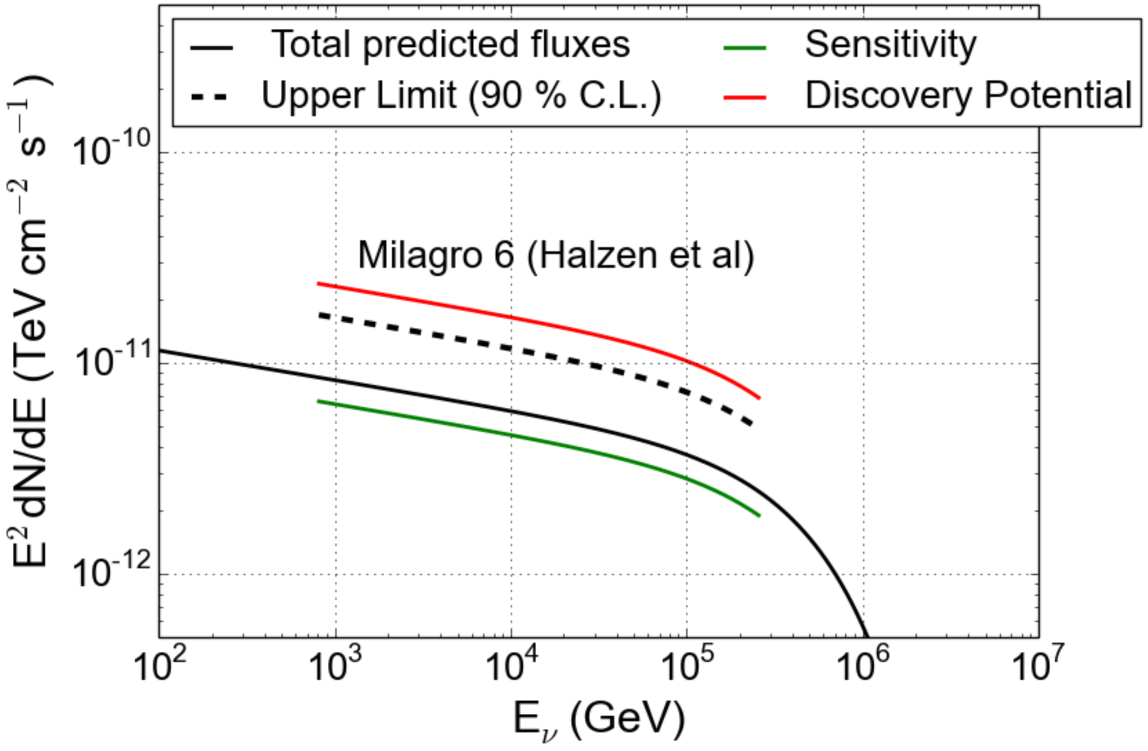
Theoretical weight W_j, detector acceptance $R_{IC}(\delta_j, \gamma)$

Sources that are individually too weak can still be detected as a catalog

Stacking Search Example : Milagro Hotspots

6 TeV associations with supernova remnants based on **Milagro observations**. Models from Halzen et al.

P value = 1.99% in IC86+79+59



F. Halzen, A. Kappes and A. O'Murchadha (Phys. Rev. D78:063004, 2008)

Compatible with the background only hypothesis.

Similar excess (2%) observed in IC40 a posteriori, hence excluded.

More data required.

Update : With more data, the significance has reduced again. 25% p value
(See Talk by Tessa Carver: TASK III session 1745 hrs)

Probably a background fluctuation

Summary/Conclusions

A search was carried out for ν from WIMP annihilations in the Sun:

- 3 years of IceCube data, Innovative background rejection, improved reconstructions
- Unbinned maximum likelihood method using energy estimators

We obtained:

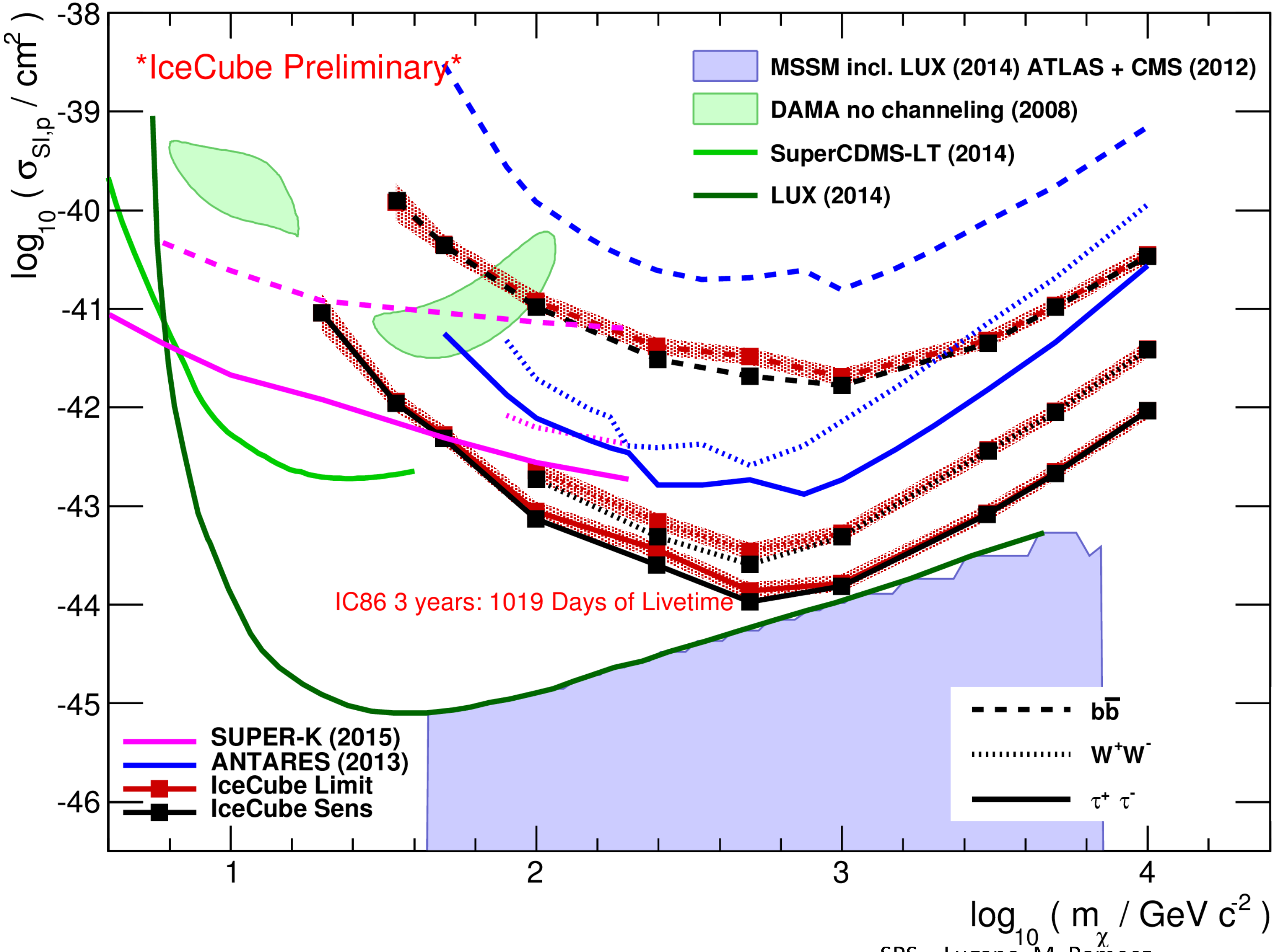
- No statistically significant excess
- The most stringent bounds on μ flux from the direction of the Sun above 80 GeV
- The most stringent constraint on the Spin Dependent WIMP-Nucleon scattering cross section.
- Can constrain theories of symmetric dark matter with candidate in 10GeV-10TeV range

Similar method was used to search for neutrinos from candidate sites for CR acceleration, such as SNRs

No statistically significant excess was found in any searches

Backup Slides

Results (contd)



Direct detection better for SI scattering

$$\sigma_{\chi-Nucleus} \;\; \alpha \;\; A^2$$

Constraints can be derived also on a host of other SD and SI velocity and momentum suppressed operators.

(R. Catena et al, JCAP 1504 (2015) 04, 042)

Systematic Uncertainties

Mass (GeV)	Channel	uncertainty in % (+ / -)
Absolute DOM efficiency		
20	$\tau^+\tau^-$	-11 / +29
50	$\tau^+\tau^-$	-8 / +23
100	W^+W^-	-9 / +19
500	$b\bar{b}$	-7 / +11
1000	W^+W^-	-6 / +9
Photon propagation in ice : Absorption and Scattering		
20	$\tau^+\tau^-$	-13 / +18
50	$\tau^+\tau^-$	-9 / +13
100	W^+W^-	-9 / + 11
500	$b\bar{b}$	-8 / + 7
1000	W^+W^-	-6 / + 4

Multi messenger Astronomy

Photons

>1 cm ~1 mm ~10 µm ~1 nm <0.1 nm

10^{-6} eV 10^{-4} eV 10^{-1} eV ~1 KeV > 100 KeV

Pulsars, quasars, radio galaxies The Big Bang (CMB) Non thermal processes

Cosmic Rays

Electrons, protons, heavy nuclei : 10^{8} - 10^{20} eV – Origins unknown.

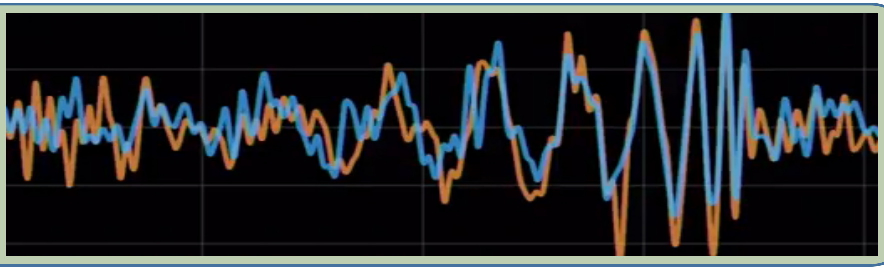
Gravitational Waves

Predicted by General relativity – Observed first in 2015

BH-BH merger ~410 MPc away.

Phys. Rev. Lett. 116 (6): 061102

New



Neutrinos

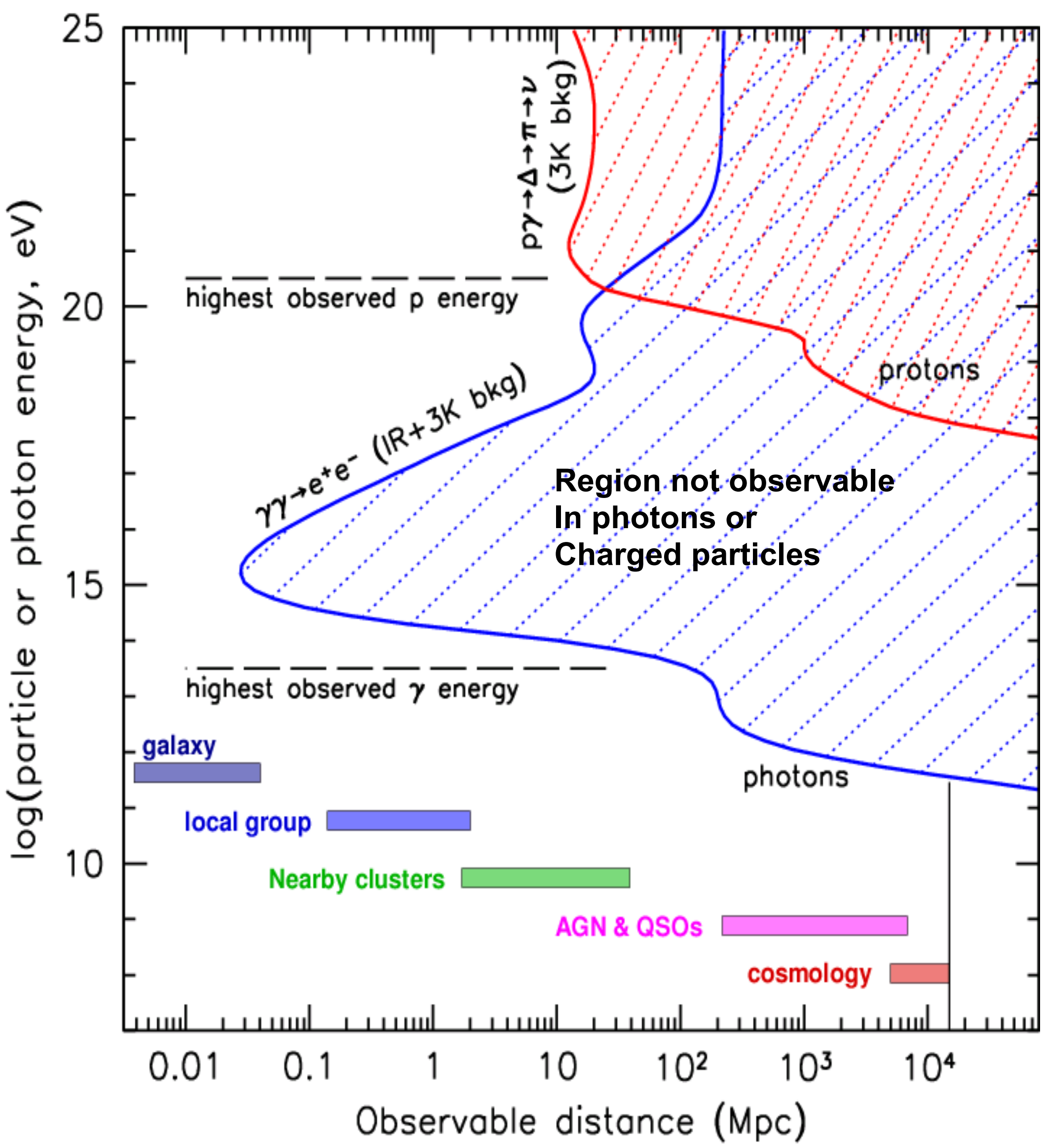
Proposed by Pauli in 1930, detected by Reines and Cowans in 1959, neutral, weakly interacting.

The Sun, SN1987 A – 10 MeV

Diffuse astrophysical flux >50 TeV

This Talk

The messenger horizon



γ-rays do not travel too far

- 1 TeV : Closest AGNs

CRs cannot point back

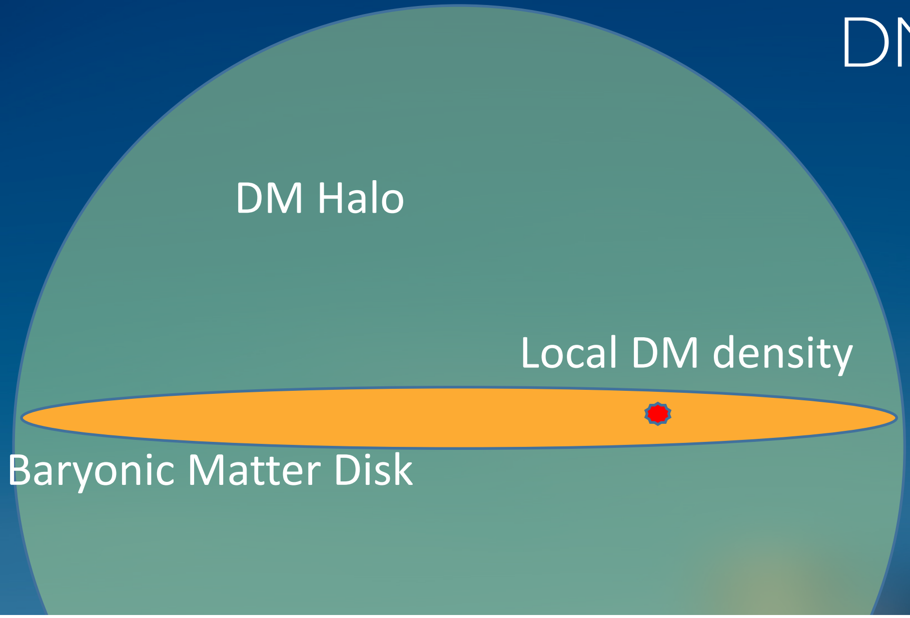
- Deflection : few degrees at ~50 EeV
- Horizon ~100 MPc – interactions with CMB

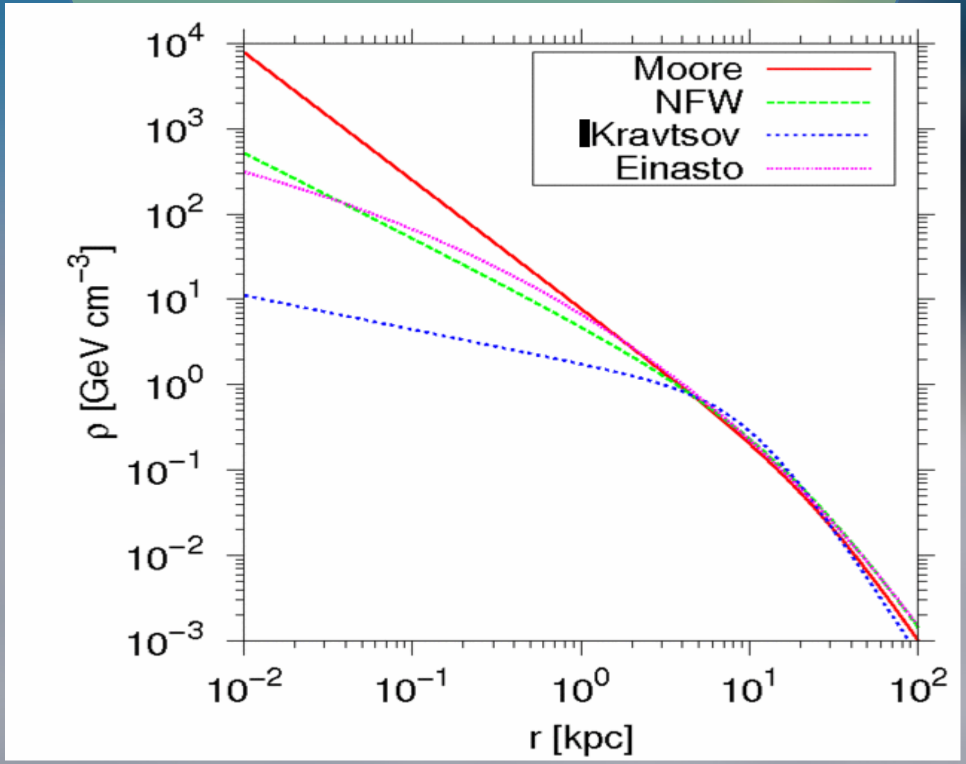
The neutrino - ideal messenger for the non thermal universe

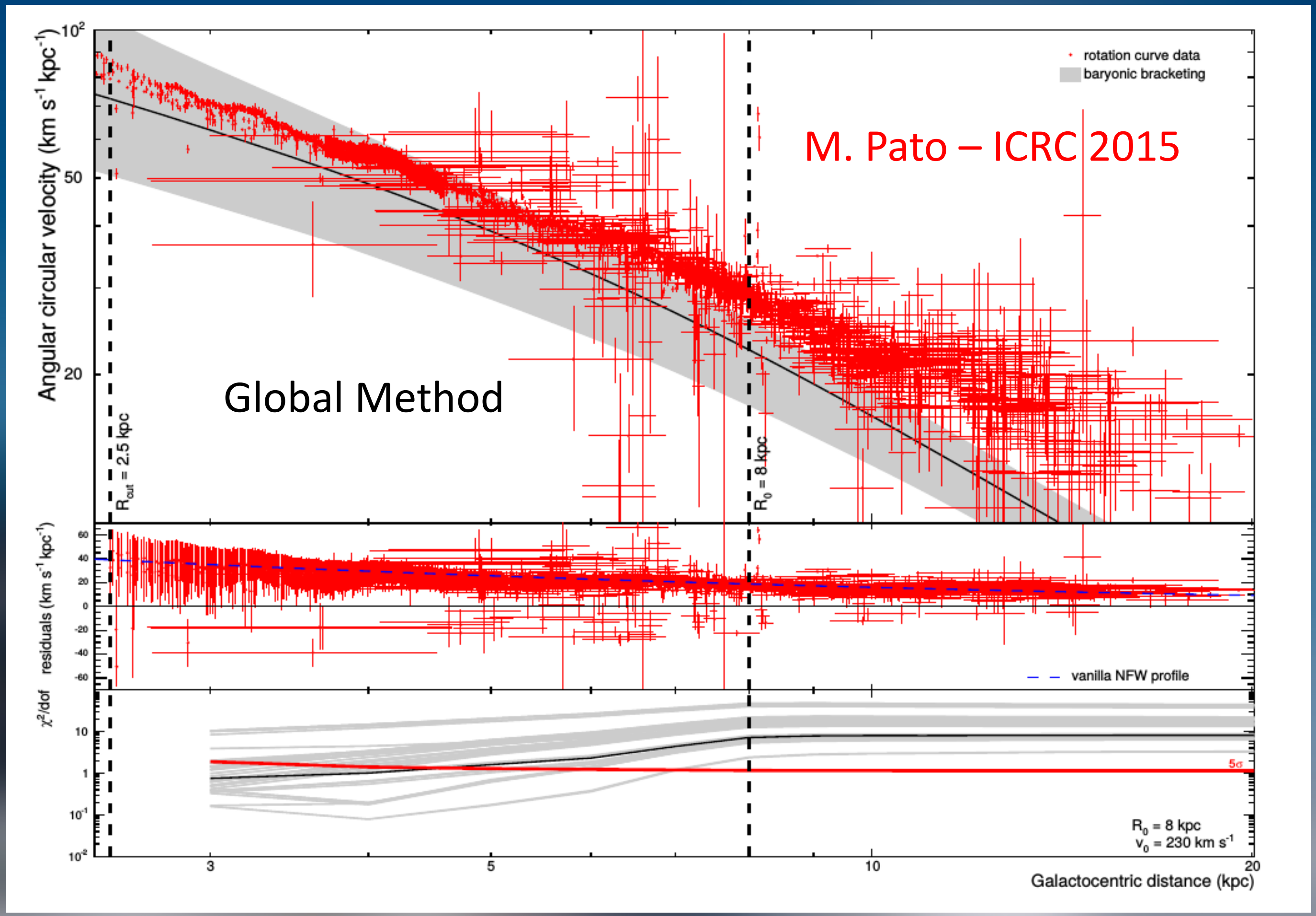
- Neutral, undeflected
  - – can point back
- Interacts only weakly
  - – can travel Gpc distances
  - – hard to detect
- We hope to see
  - The sites of CR acceleration
  - Dark Matter annihilation

IceCube was built to look for astrophysical neutrinos.

DM within our own Galaxy







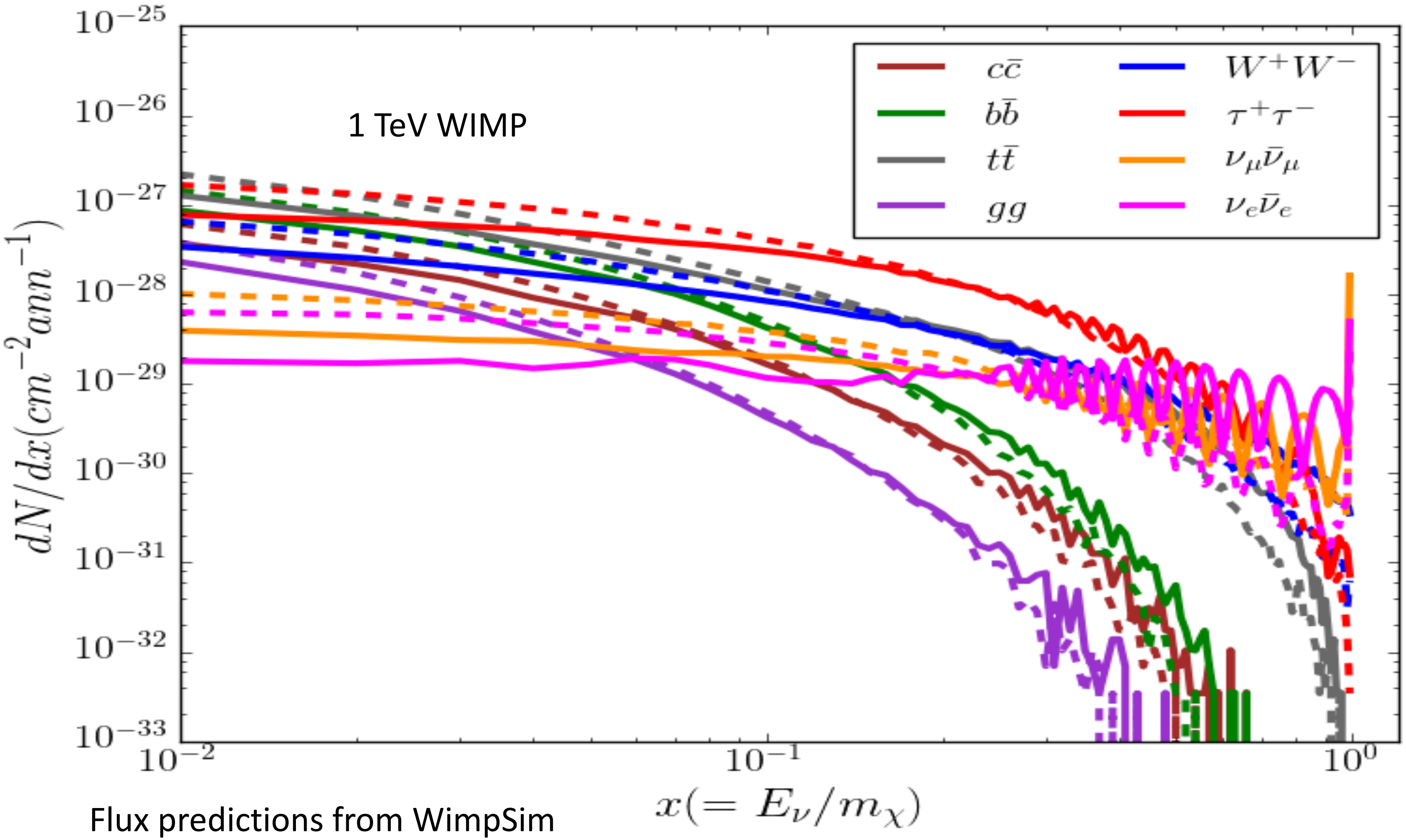
Global Method : Average ρ_{DM} at radius of orbit of Sun

$\sim 0.4 \pm 0.1\ GeV/cm^3$

Local Method : ρ_{DM} at the position of the Sun

'Local' and 'Global' methods now starting to agree on the local DM density See H.Silverwood et al, ICRC 2015.

ν from WIMP annihilations in the Sun



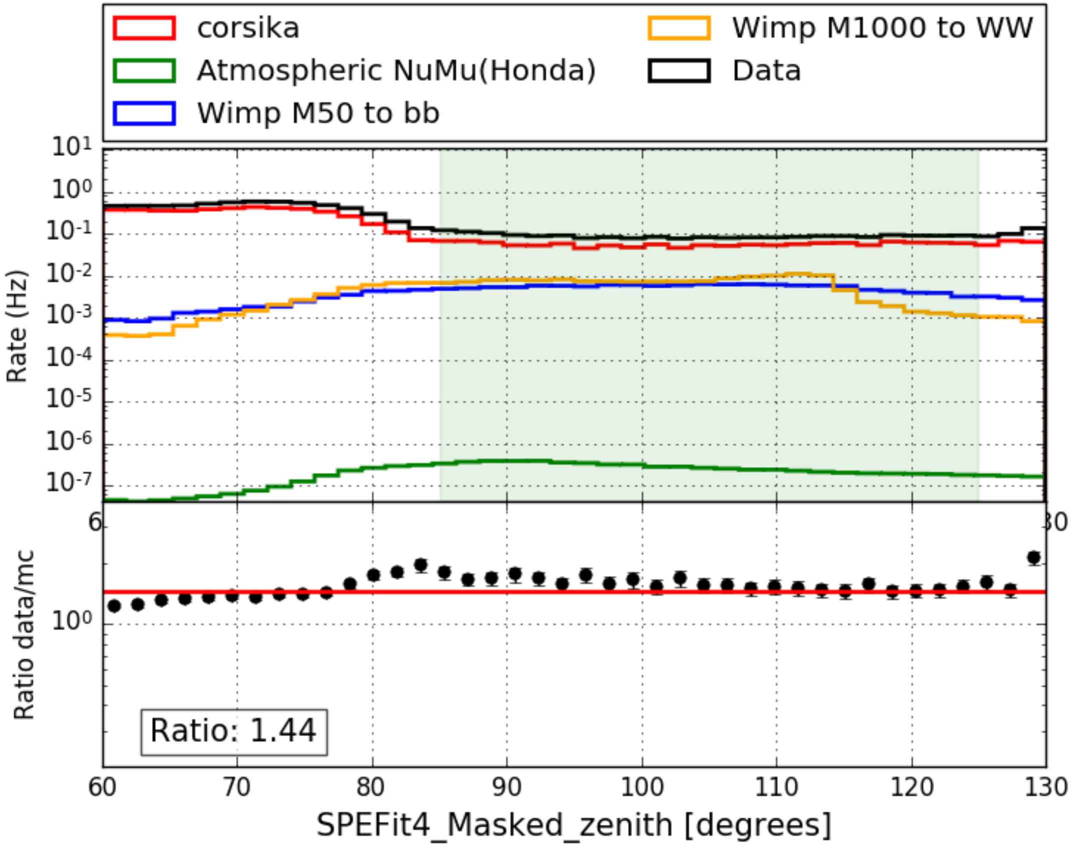
Flux predictions from WimpSim

Select:
W^+W^-, $\tau^+\tau^-$ (hard channels)
$b\bar{b}$ (soft channel)

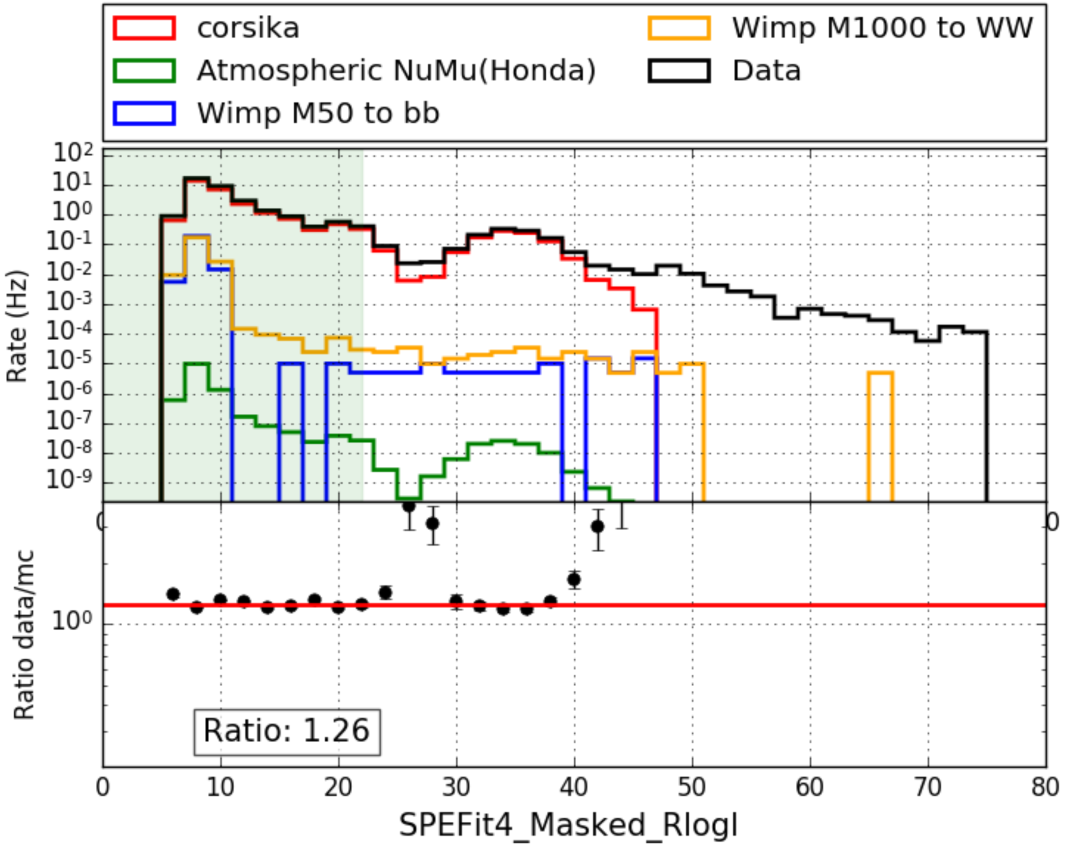
gg (even softer) and direct neutrino (even harder) are not theoretically favoured

1

Level 3 Cut examples

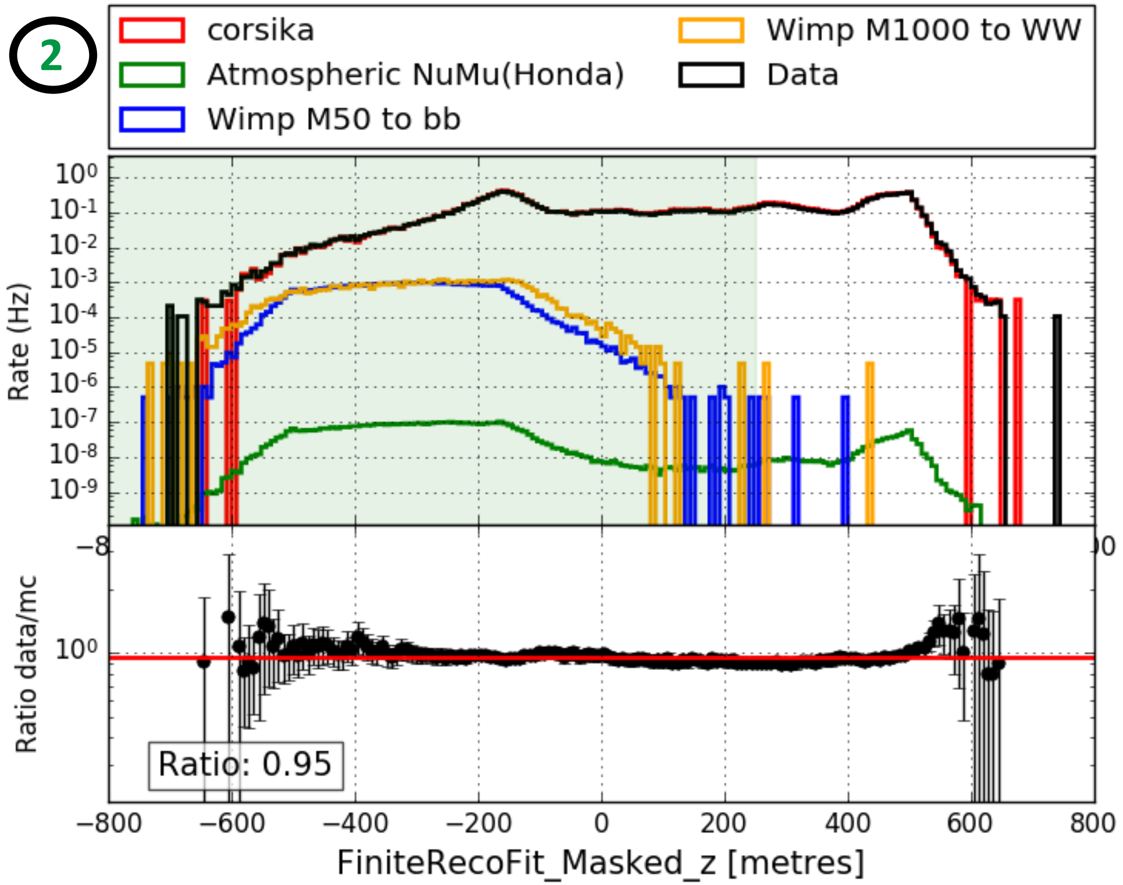


Explicit cut on reconstructed direction to select only horizontal tracks.

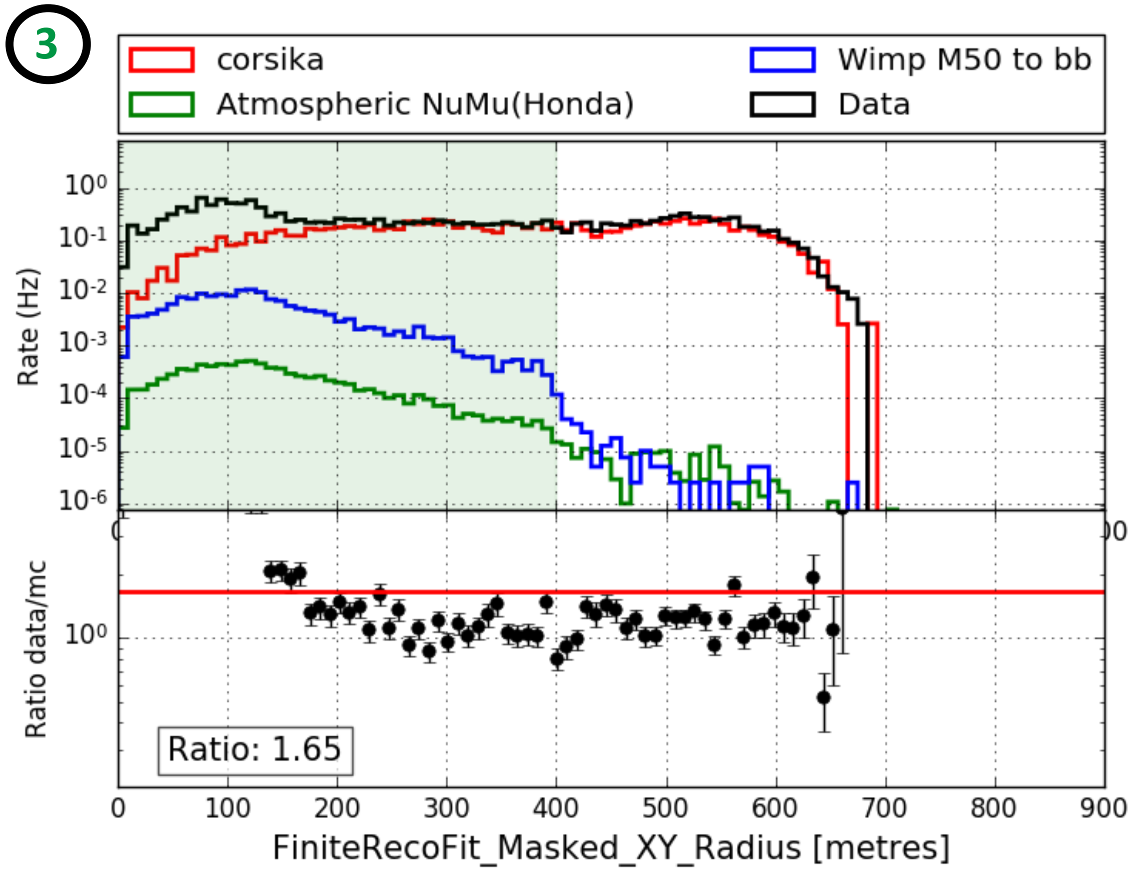


Reduced log likelihood.
Cut on quality, rejects badly reconstructed events.

Level 3 Cut Examples (continued)



Z coordinate of reconstructed starting vertex. Select events starting lower in the detector.



Distance along XY plane to starting vertex. Select events starting near center of the detector.

Level 5 – Boosted Decision Tree

Multivariate classification algorithm:

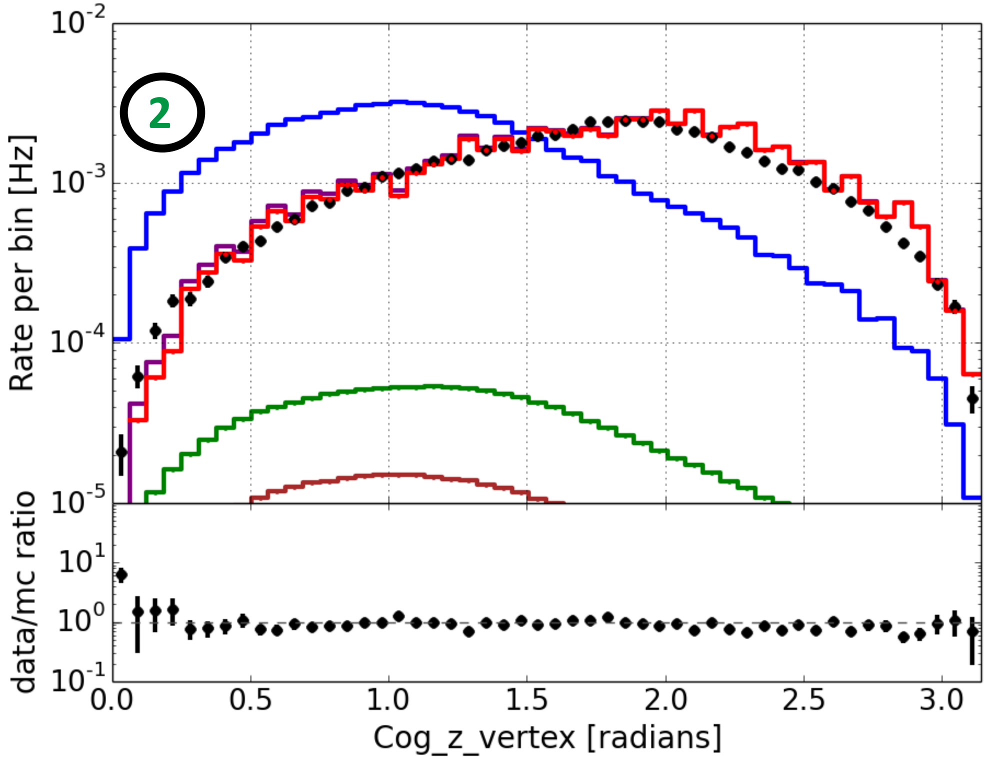
- Gives each event a score between -1.0 (background) and +1.0 (signal)
- Trained on a sample of signal like and background like events using selected variables.

Variables have to offer:

- Good Signal to background separation
- Good Data/MC agreement (avoid simulation artifacts)

Example BDT variable

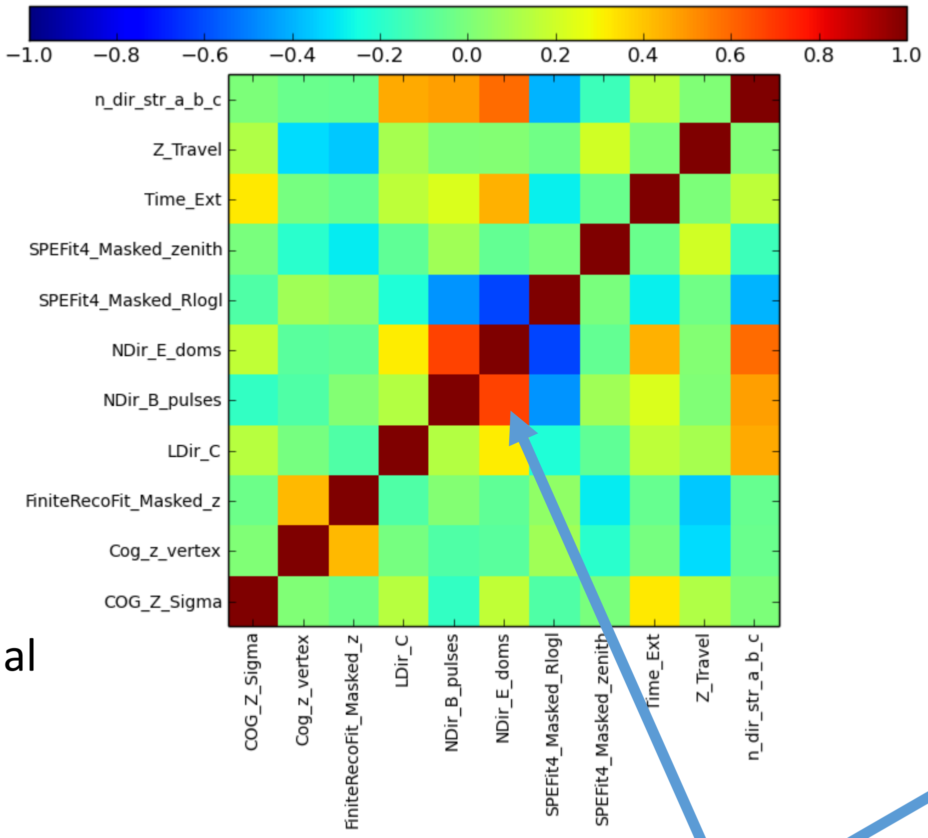
Zenith of vector between COG and Vertex



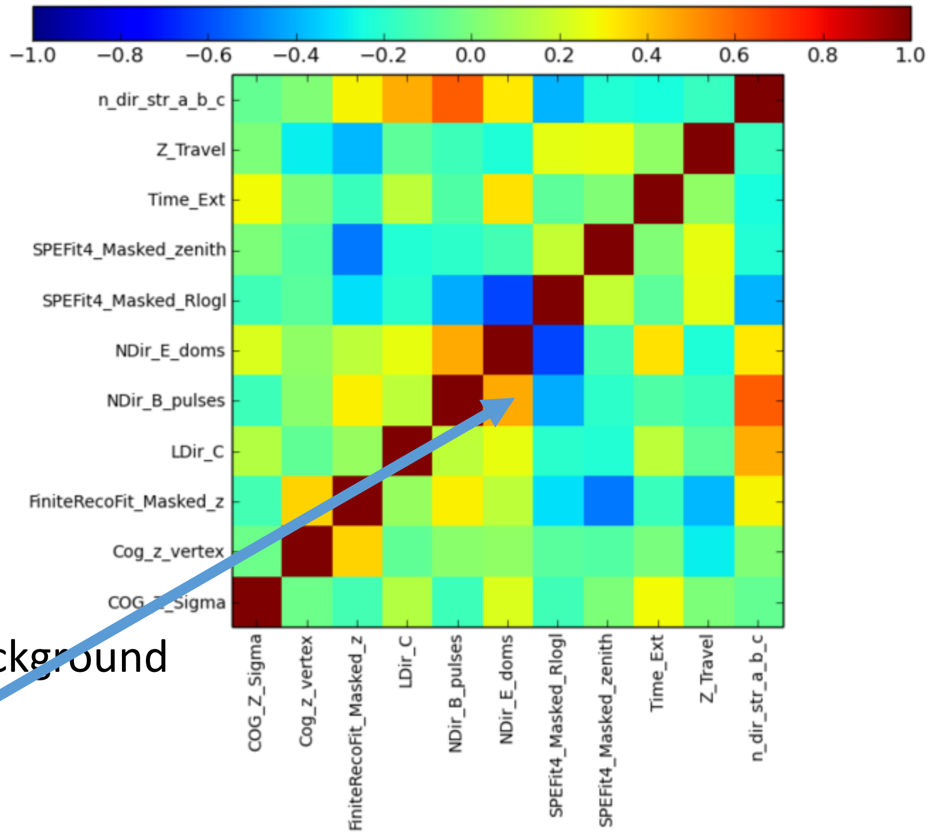
Level 5 – Boosted Decision Tree (contd)

Prefer variables that are not very correlated with each other.

2



Signal

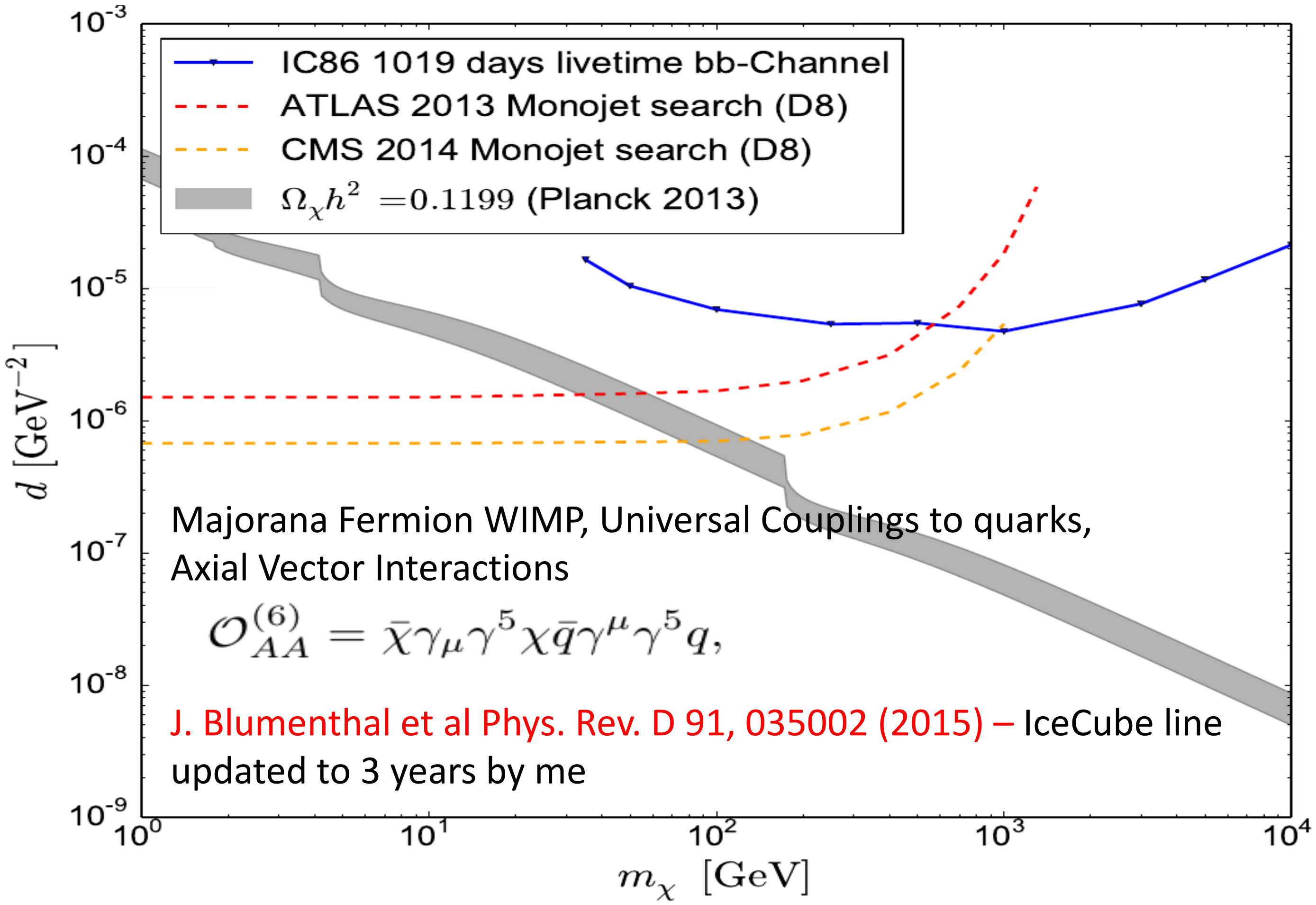


Background

Or different correlations for signal and background.

Complementarity and EFTs

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A



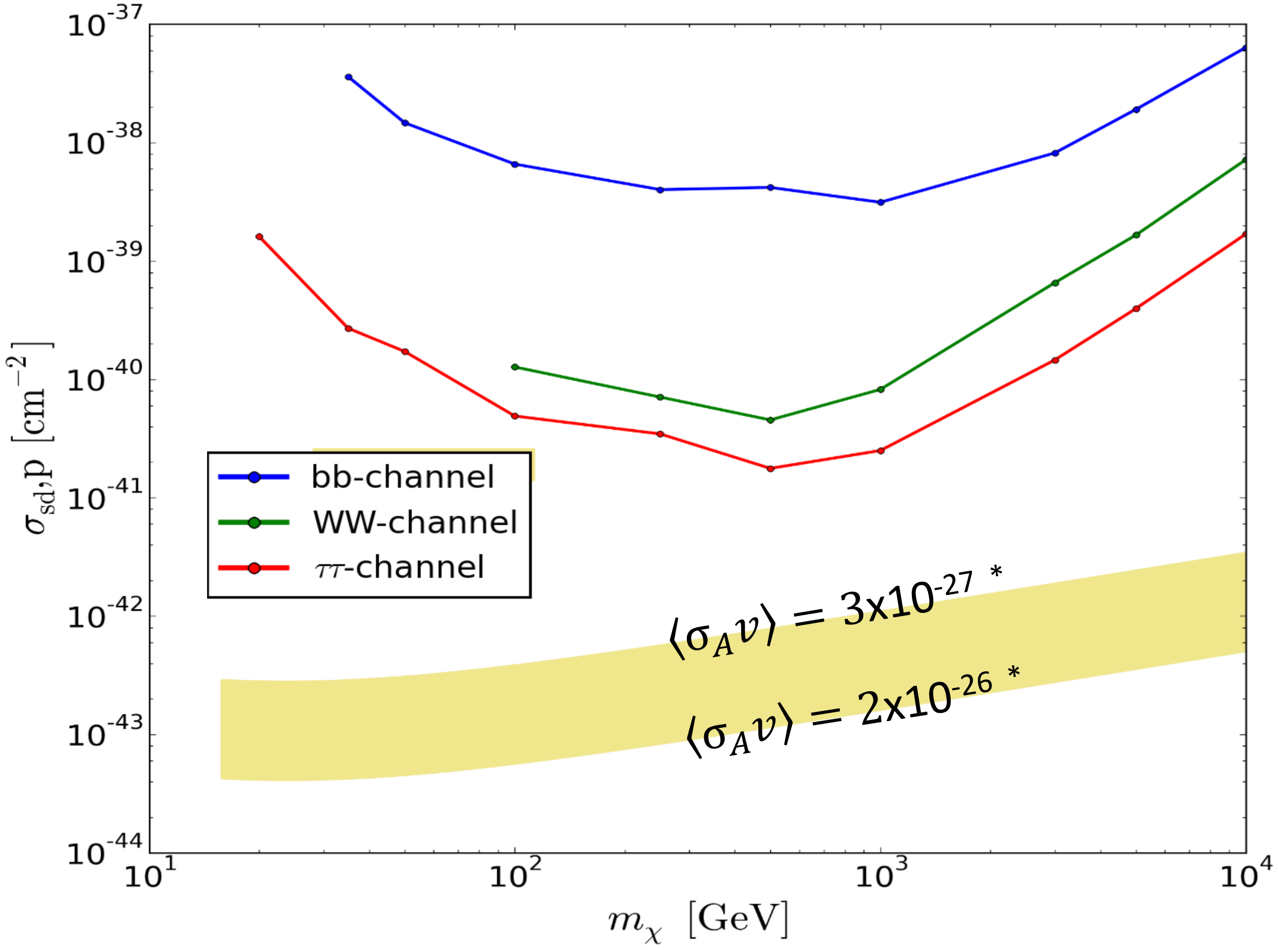
Majorana Fermion WIMP, Universal Couplings to quarks, Axial Vector Interactions

$$\mathcal{O}^{(6)}_{AA} = \bar{\chi}\gamma_\mu\gamma^5\chi\bar{q}\gamma^\mu\gamma^5 q,$$

J. Blumenthal et al Phys. Rev. D 91, 035002 (2015) – IceCube line updated to 3 years by me

EFT $$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{n>4}\frac{f^{(n)}}{\Lambda^{n-4}}\mathcal{O}^{(n)}.$$

Equilibrium revisited



There's a threshold σ_{SD} below which the equilibrium condition is not a valid assumption

$$\frac{t_\odot}{\tau_\odot} = 330\left(\frac{C_\odot}{s^{-1}}\right)^{1/2}\left(\frac{\langle\sigma_A v\rangle}{cm^3\ s^{-1}}\right)^{1/2}\left(\frac{m_\chi}{10\ GeV}\right)^{3/4},$$

Jungman and Kamionkowsky (1996)

Upcoming experiments like CTA have sensitivity towards DM $\langle\sigma_A v\rangle$ below the natural scale even at high WIMP masses

Our limits will remain above this threshold for a long time to come
Assuming $\langle\sigma_A v\rangle\sim$ natural scale.

Other Stacking Searches (No significant excess)

SNRs younger than 10000 years (Sedov Taylor Phase)

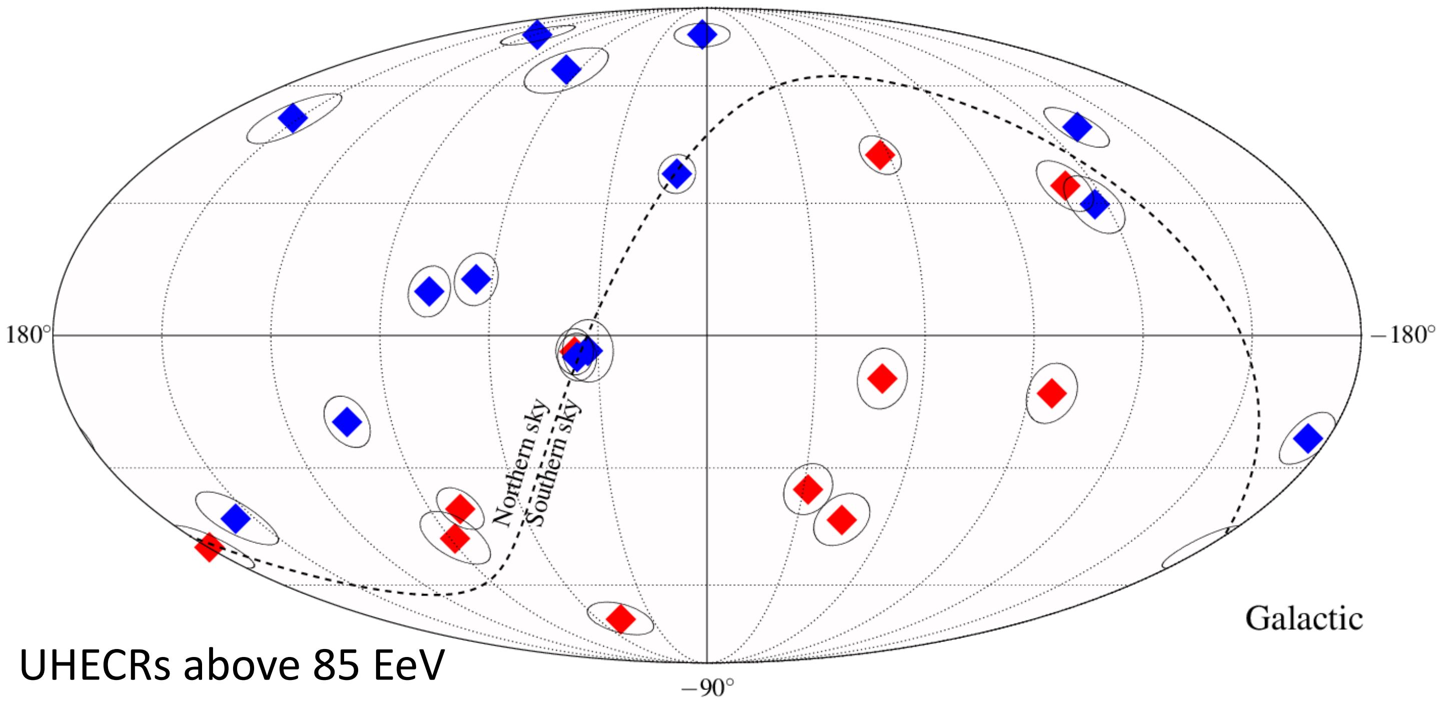
Starburst galaxies in the nearby universe : Contribute <1% of the diffuse astrophysical flux

Supermassive blackholes within the GZK horizon, from the 2MASS catalog : Contribute < 2% of the diffuse flux

Nearby Galaxy Clusters : Theoretical predictions are below current sensitivity.

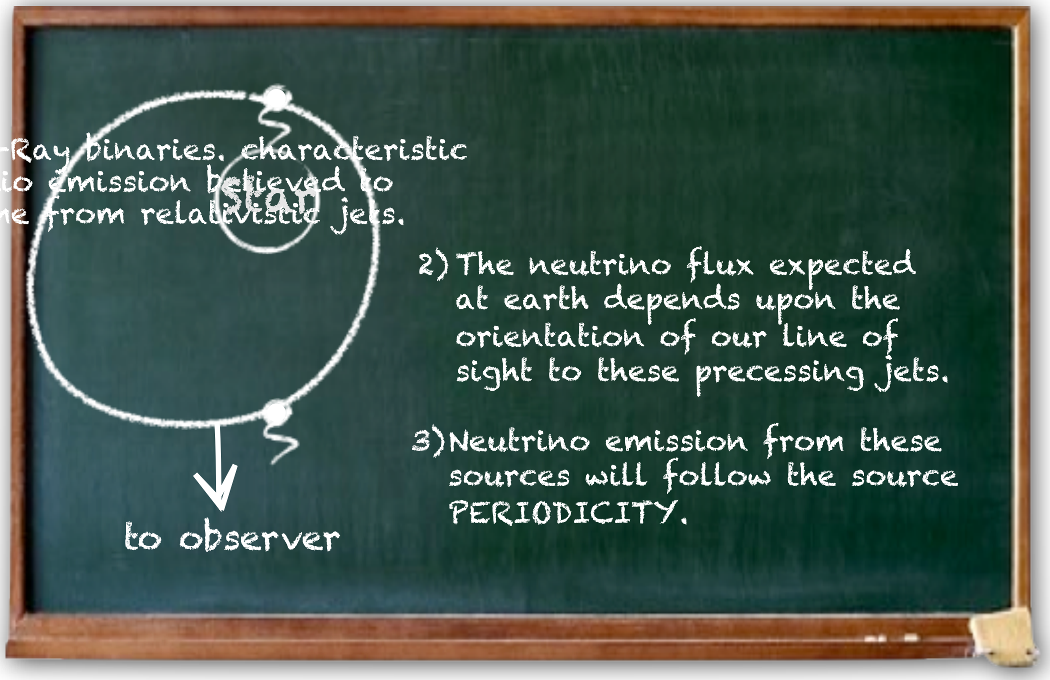
Arrival directions of Auger and TA UHECRs above 85 EeV

Limits better than Antares analysis by a factor of 25



UHECRs above 85 EeV

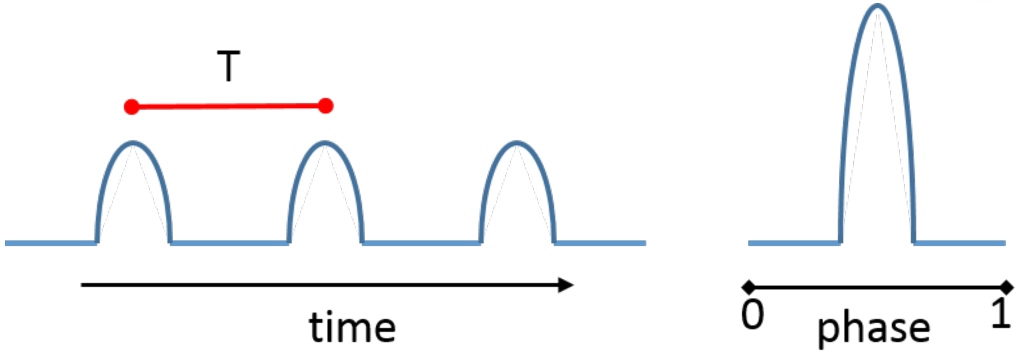
Periodic search – Gamma Ray binaries

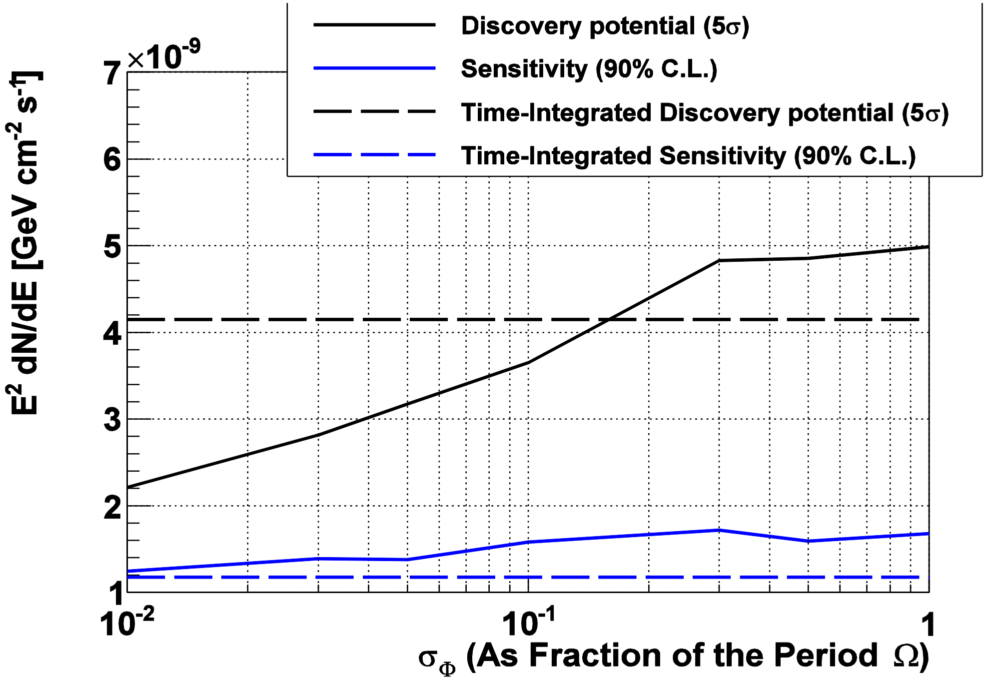


The Hypothesis: A neutrino signal will have the same periodicity as the optical and X-ray observations.
(not necessarily in phase with gamma)

Trial factor reduction: 10 micro quasars selected

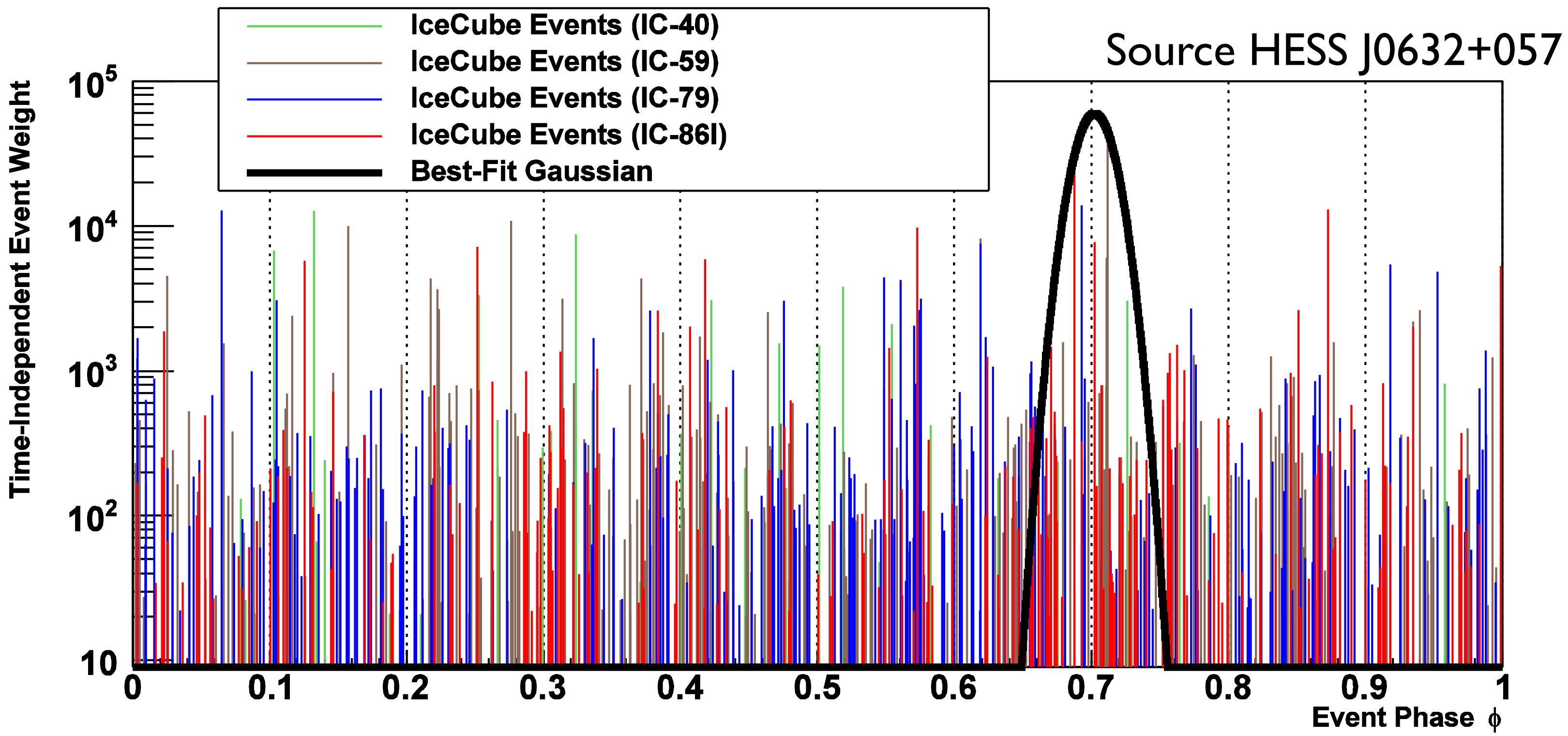
- Northern sky: detected in GeV or higher
- Southern sky: detected in TeV





Method : Look for a directional excess of events also clustered in phase.

Periodic Search (Results)



Post trial p value 44.3%

Background only hypothesis.

Pre trial p value : 8.67%, No significant excess