# Searches for heavy dark matter decay with IceCube

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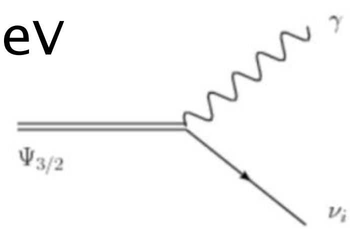
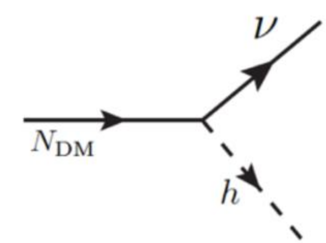
# Motivation

- Many models of physics Beyond-the-Standard-Model contain heavy (>TeV) dark matter expected to decay into SM particles, including high energy neutrinos
- The discovery of high energy cosmic neutrinos by IceCube and the lack of point sources has opened up many questions about their origin
- Despite a lot of theoretical papers on the subject, very few experimental lifetime limits exist above 100 TeV




High Theoretical Interest - Some recent publications on the topic:

Are IceCube neutrinos unveiling PeV-scale decaying dark matter?
Esmaili, Arman and Serpico, Pasquale Dario, JCAP 1311

Reconciling neutrino flux from heavy dark matter decay and recent events at IceCube
Atri Bhattacharya, Mary Hall Reno, Ina Sarcevic, JHEP 06

Superheavy dark matter and IceCube neutrino signals: Bounds on decaying dark matter
Rott, Kohri, Park Phys. Rev D92

Testing the Dark Matter Scenario for PeV Neutrinos Observed in IceCube
Murase, Laha, Ando, Ahlers, Phys. Rev. Lett. 115

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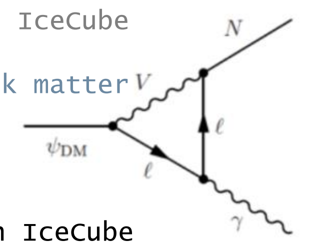
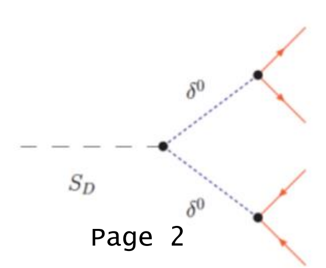


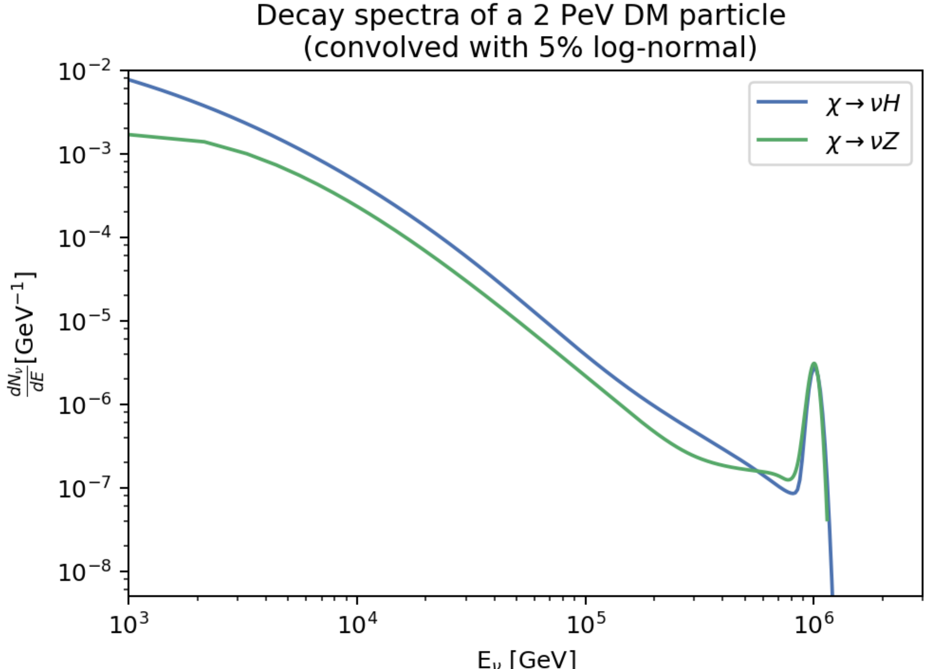
# Data samples

- Two similar independent analyses are performed on two non-overlapping data sets

| Cascade sample | Track sample |
|---|---|
| High energy (>TeV) events<br>Very high purity | |
| 2yr (6.2010-6.2012) | 6yr (6.2009-6.2015) |
| Full sky coverage | Up-going events θ > 85° |
| | ~30x higher $A_{eff}$ |
| Significantly better energy resolution | |
| 278 events | 340'000 events |

# Dark matter decay channel

- The chosen benchmark channels is:
  - $\chi \to H\nu / Z\nu$, flavour agnostic
    (resulting ν spectra are not distinguishable by IceCube)
- Due to the relatively poor energy resolution, the analysis is not too sensitive to the assumed decay channel
- Other channels will be analyzed in the future ($\nu\nu$, $ee\nu$, ZZ, WW, $\tau\tau$, $\mu\mu$, bb, …)



# Dark matter model

- The dark matter decay signal is composed of:
  - Extragalactic component
    - Isotropic, partially red shifted

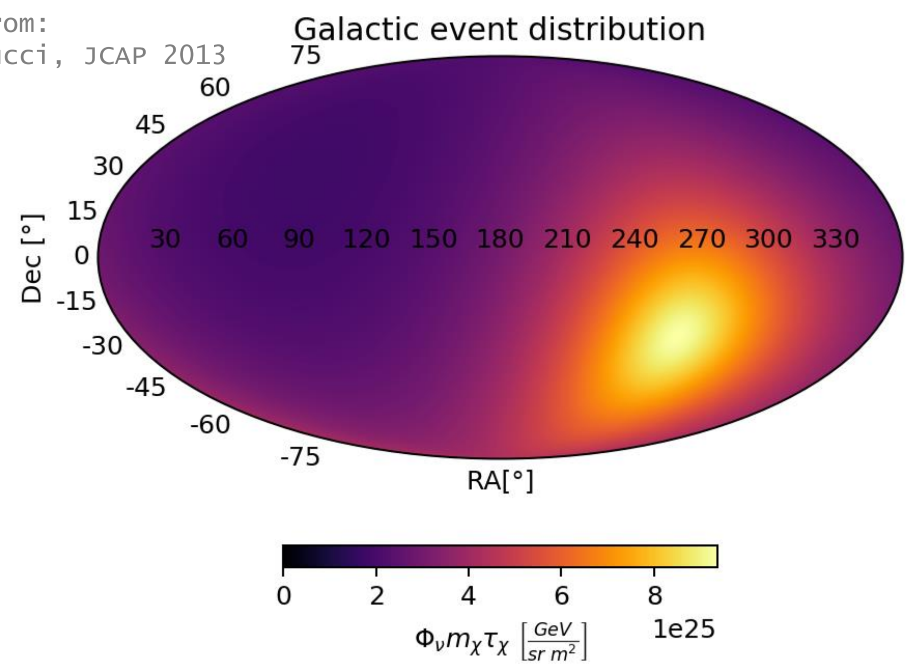
ΛCDM Parameters from: Planck Collaboration, A&A 594 (2016) A13]

$$\left(\frac{d\Phi}{dE}\right)_E = \frac{\rho_\chi}{4\pi m_\chi \tau_\chi}\int_0^\infty \frac{dz}{H(z)}\frac{dN}{dE}$$

  - Galactic component
    - Follows the Burkert halo profile
      - $R_s$ = 9.26 kpc
      - $\rho_\odot$ = 0.487 GeV cm$^{-3}$

$$\left(\frac{d\Phi}{dE}\right)_G = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN}{dE}\int_0^\infty \rho_\chi \, ds$$

Parameters from: Nesti & Scalucci, JCAP 2013




  - The two components contribute roughly equally to the neutrino flux at Earth and thus both have to be taken into account

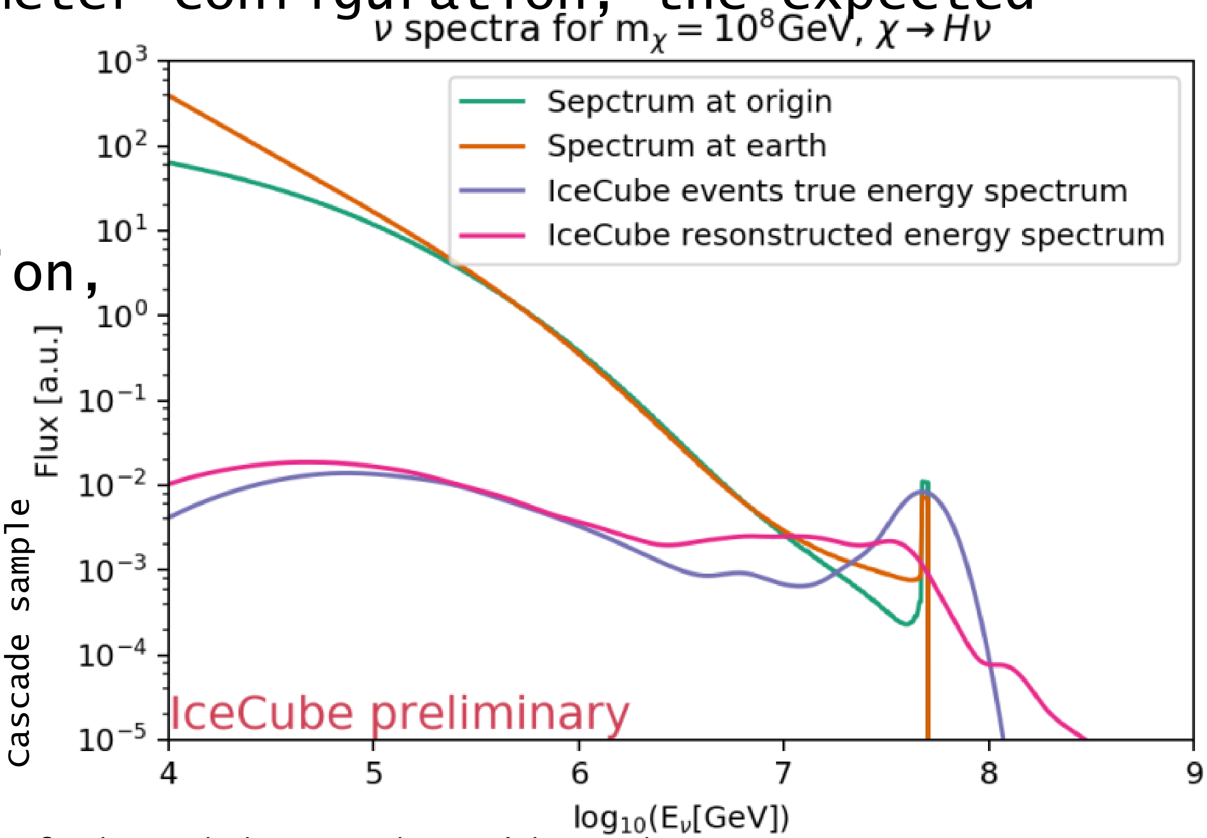
# Flux predictions

- The fluxes considered and their *parameterizations* are:
  - Signal:
    - Galactic DM decay flux
    - Extra-galactic DM decay flux

    (*mass, lifetime*)
  - Backgrounds:
    - Atmospheric background
    - Isotropic astrophysical power law (*normalization, index*)

# Flux predictions

- The observables used are log(E), right ascension, cos(zenith)
- For a given parameter configuration, the expected neutrino flux is calculated
- Using a full detector simulation, the distribution of reconstructed events is calculated



# Analysis methods

- Both analyses use the TS:

$$TS = \ln\left(\frac{L(\hat{\phi}_{astro}, \hat{\gamma}_{astro}, \hat{m}, \hat{\tau})}{L(\hat{\phi}_{astro}, \hat{\gamma}_{astro}, \tau = \infty)}\right)$$

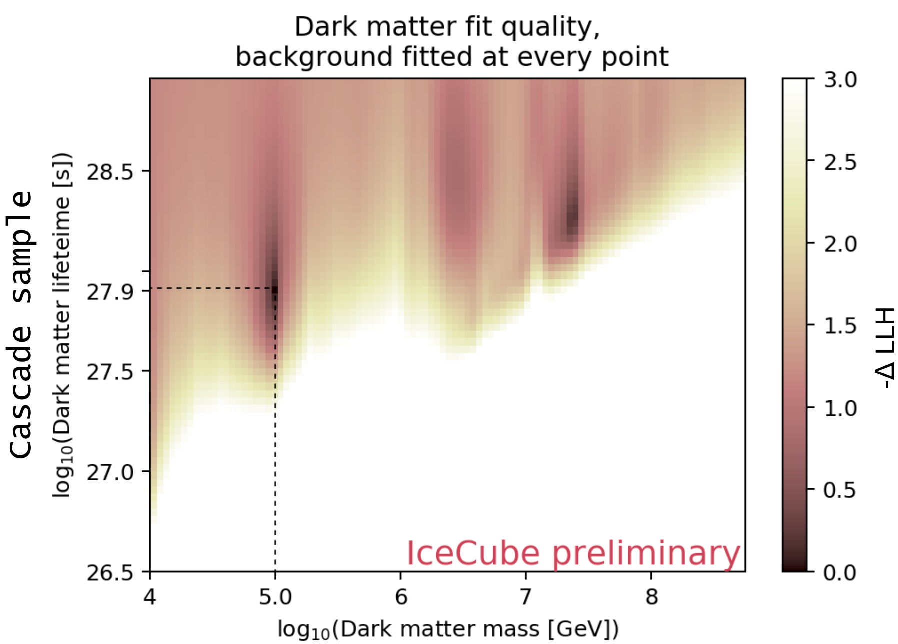
- Sets of pseudo-experiments are performed with background and background + injected signal and the resulting TS is compared to the data
- If the pseudo-experiments with a certain DM mass and lifetime are not compatible with the data, that model can be excluded

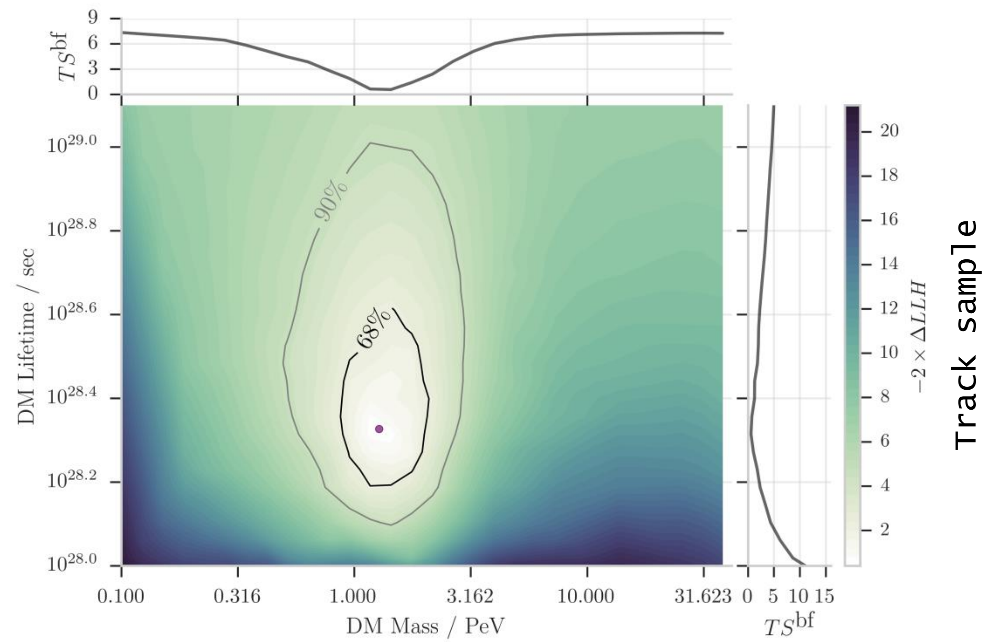
| Track analysis | Cascade analysis |
|---|---|
| Binned likelihood method 26-41-4 bins in E-RA-θ | Unbinned likelihood method |
| Neyman limit construction | 2D Feldman Cousins acceptance regions in $\hat{m}$ –TS |
| One sided 90% c.l. intervals | Two sided 90% c.l. intervals |

# Data fits

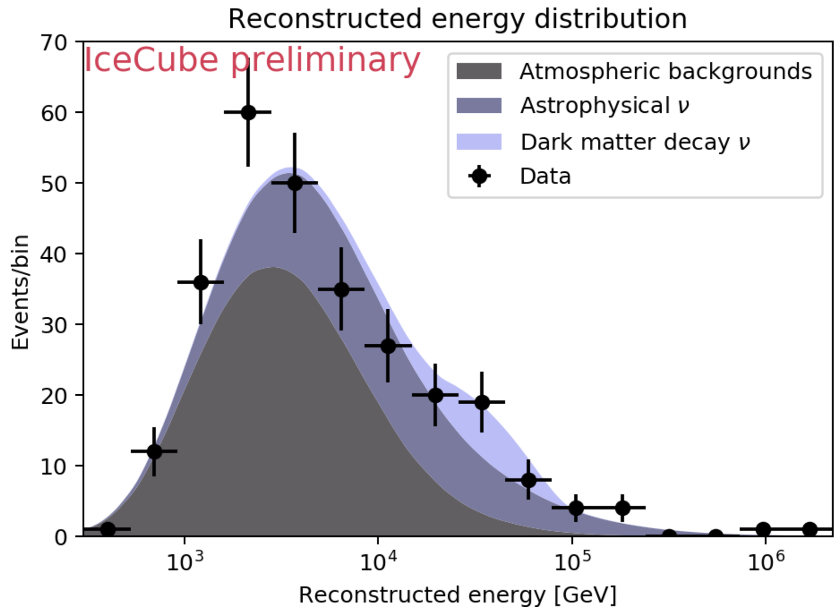
| Cascade sample Bg. | Cascade sample Bg.+S | | Track sample Bg.+S | Track sample Bg. |
|---|---|---|---|---|
| 2.17 | 1.62 | Astrophysical flux at 100 TeV [$GeV^{-1}cm^{-2}sr^{-1}s^{-1}$] | 0.16 | 0.97 |
| 2.72 | 2.78 | Astrophysical power index | 1.99 | 2.16 |
| | 0.1 | $m_{DM}$ [PeV] | 1.3 | |
| | 8.2 | $\tau_{DM}/10^{27}$s | 22 | |

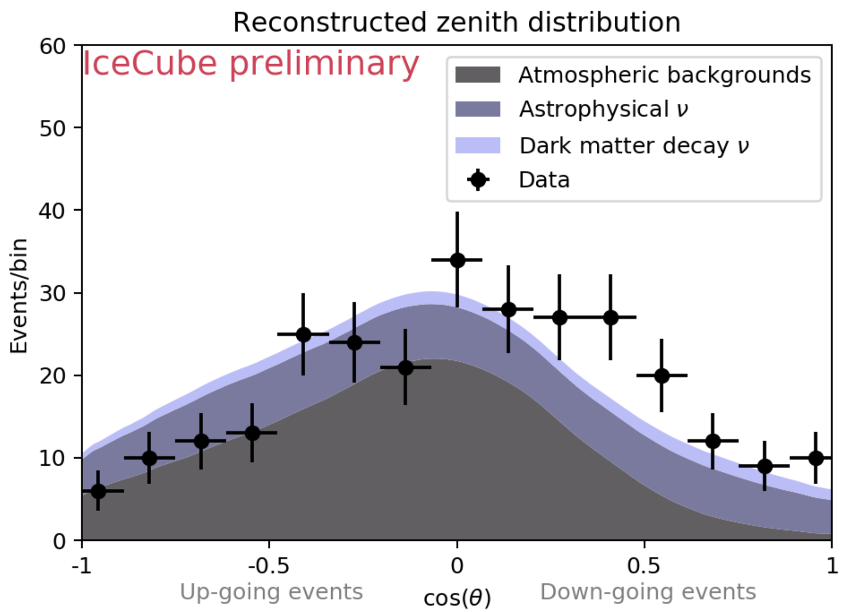
The way the analysis work, the fits always converge to finite lifetimes

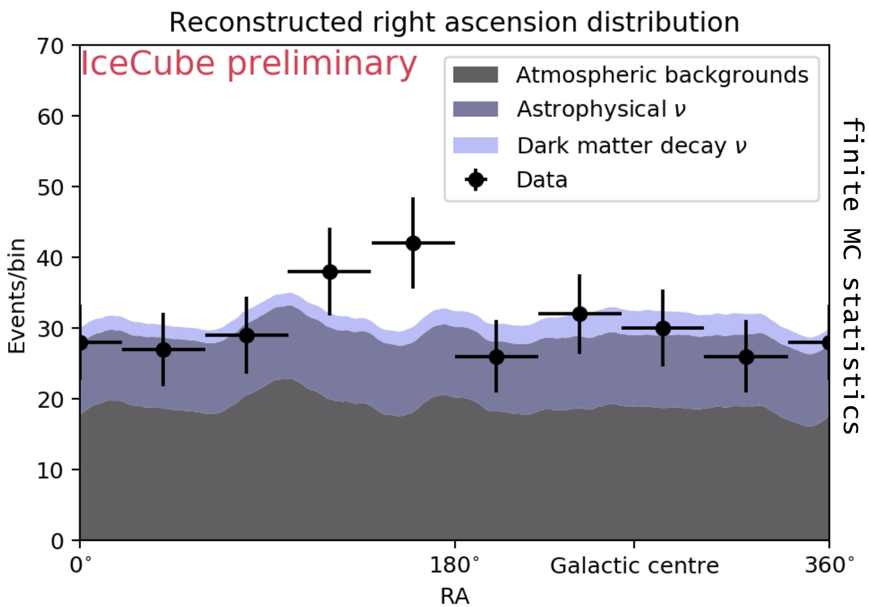


# Event distributions: Cascades

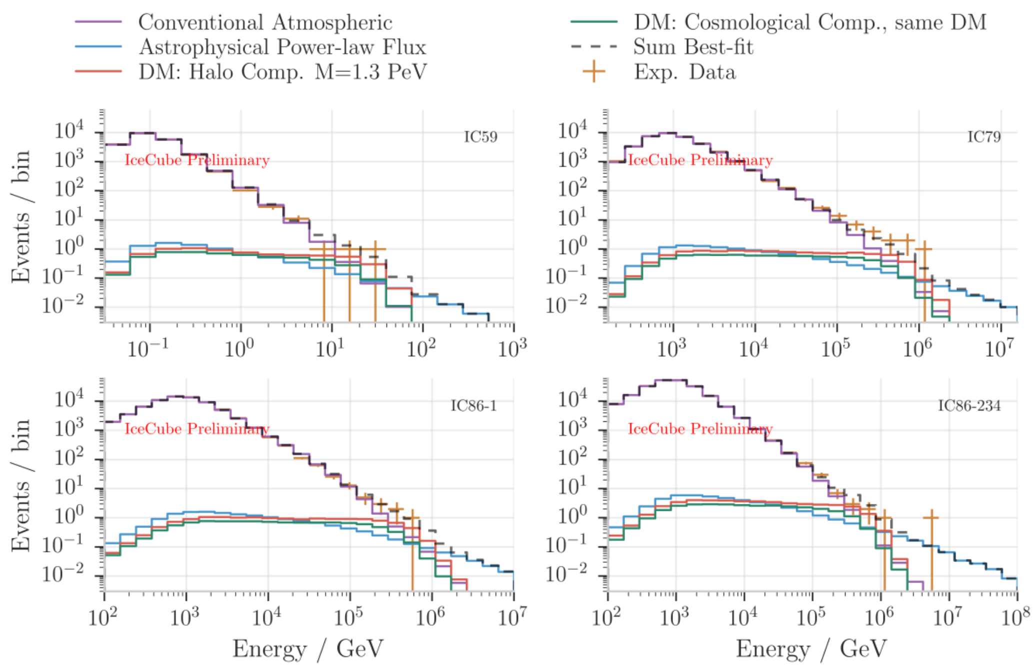


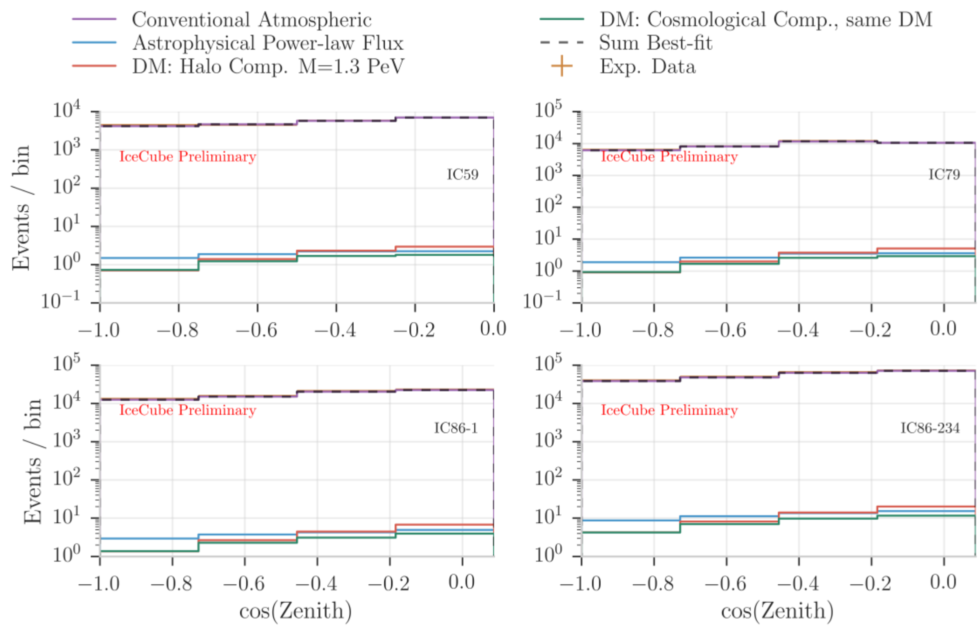



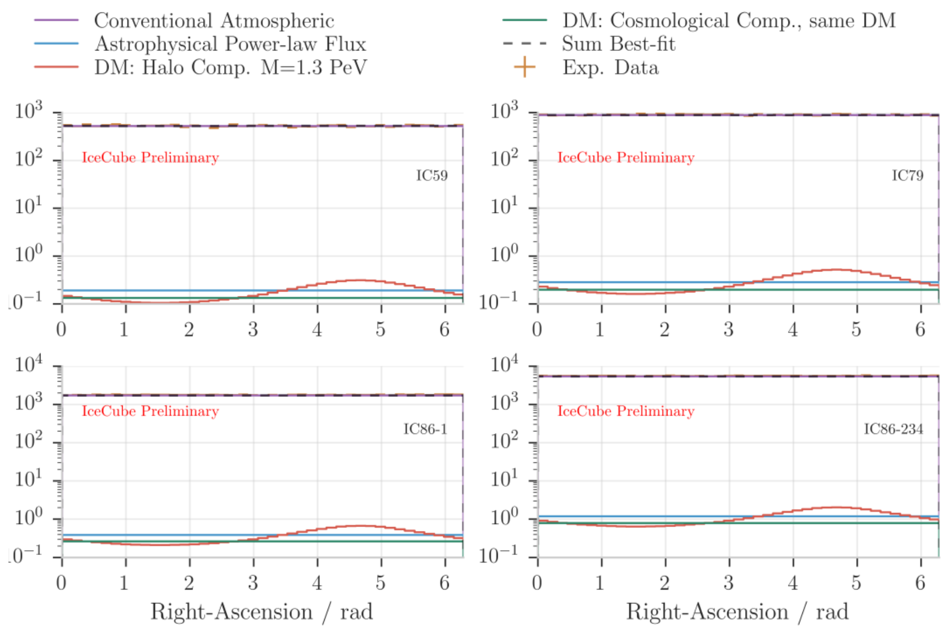




Fluctuations due to finite MC statistics

# Event distributions: Tracks

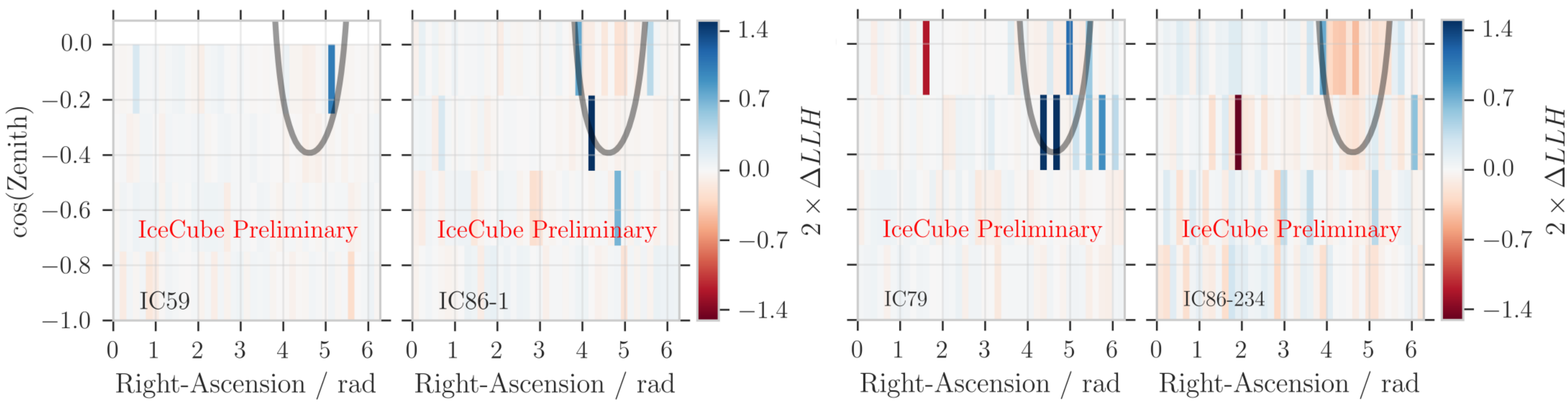


# Signal significance

- Comparing data to pseudo unblindings gives p values of 0.55 for cascades and 0.034 tracks
  - For the track analysis most of the significance is coming from the first three years of data
    - In order to be conservative the limit is thus derived using one sided 90% c.l. intervals

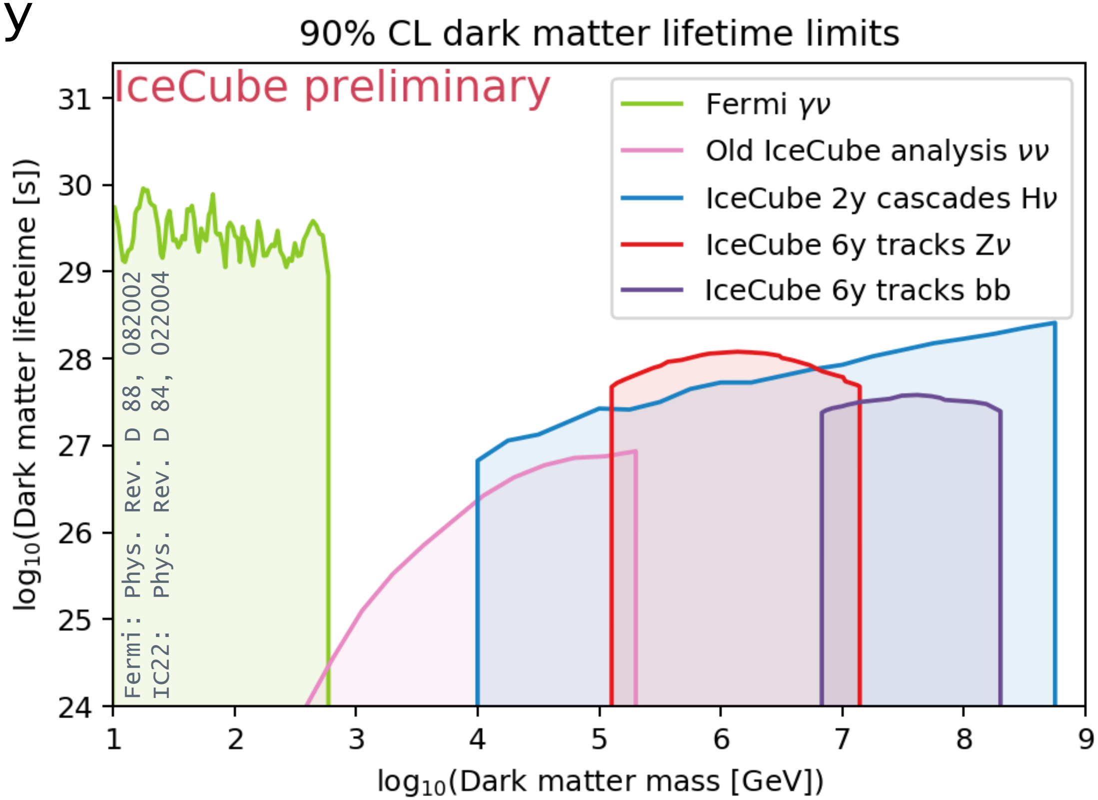


# Systematics

- Track analysis
  - Ice model systematics, DOM efficiencies and atmospheric flux uncertainties:
    - These are treated as nuisance parameters that are directly included into the original fit
    - They lead to a minor reduction in the limit
  - Halo model systematics are derived by changing halo profile parameters within their uncertainties and determining the effect on the derived limit
    - The overall effect of the halo profile uncertainties is ~10%
- Cascade analysis
  - Preliminary systematic study was done before unblinding
  - Full systematics study coming soon
  - The calculated systematics are:
    - Halo model, Atmospheric flux uncertainties, Prompt atmospheric flux, DOM efficiency, Simulation statistics

# Lifetime limit

- From the non-observation of a strong dark matter signal a lifetime limit can be derived
- The limit is currently the best experimental dark matter lifetime limit at high masses

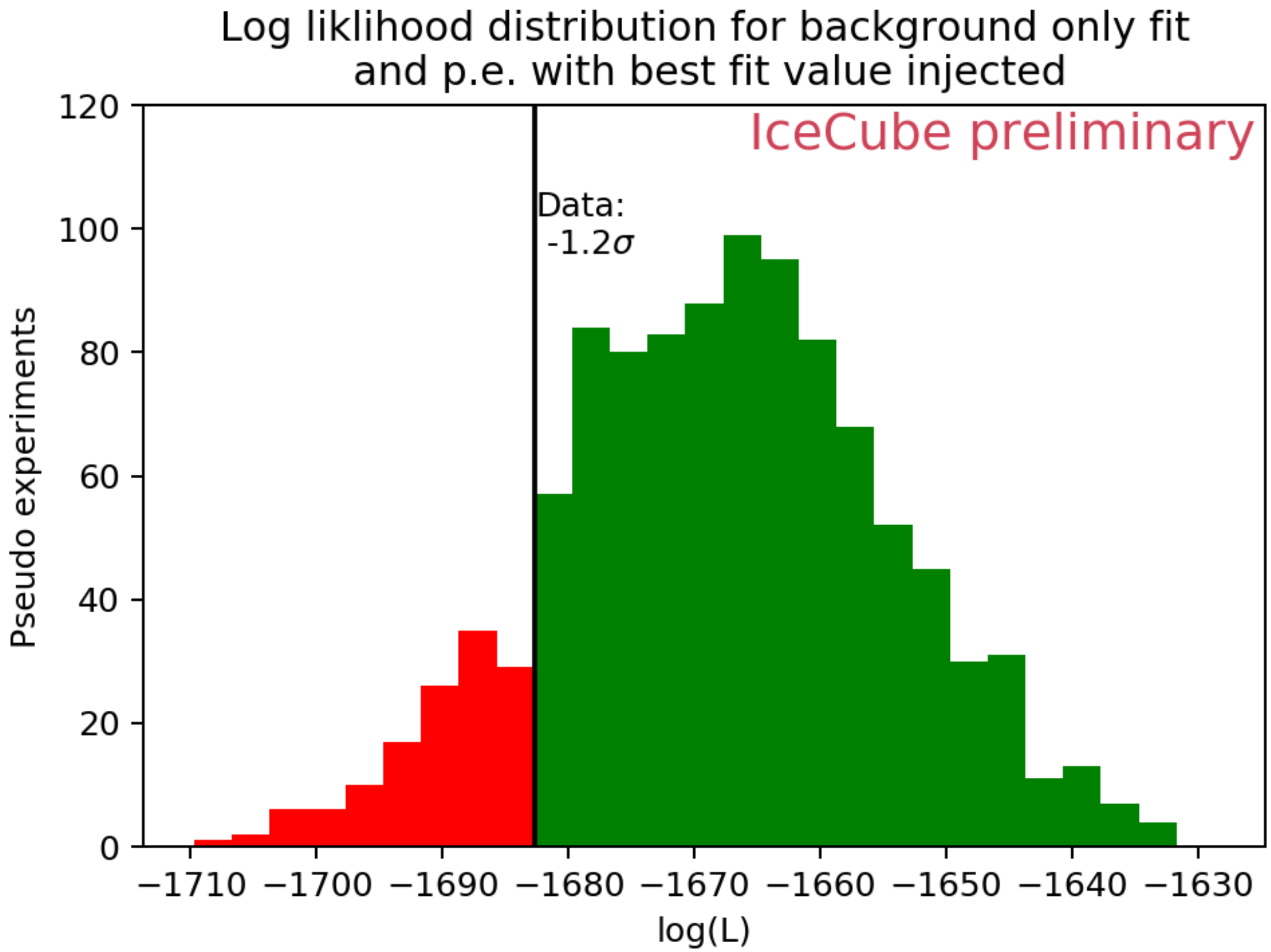


# Summary and outlook

- 2 independent analysis have been performed on two non-overlapping neutrino samples
- Dark matter decay signal has been fitted on top of an atmospheric background and an astrophysical power-law
- No significant dark matter signal has been detected
- Preliminary results yield a new upper lifetime limit for heavy dark matter particles
- What you can expect in the near future:
  - A full systematic study
  - Limits for other decay channels
  - A combined ICRC contribution and publication

# Backup

# Backup

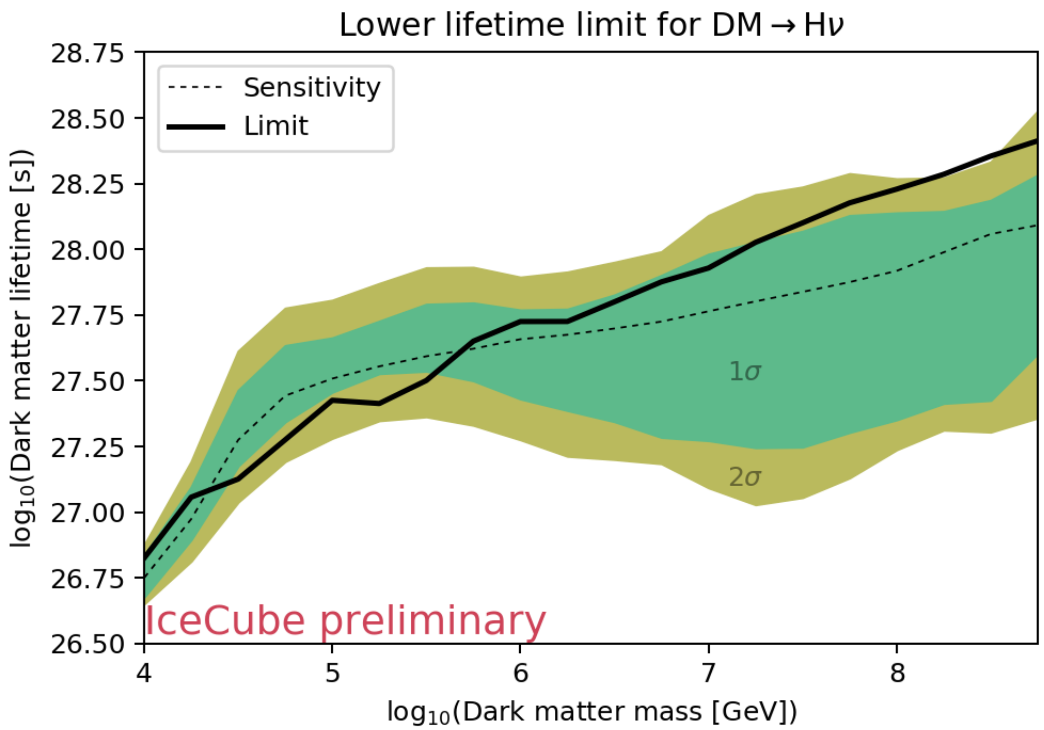

Log liklihood distribution for background only fit
and p.e. with best fit value injected
IceCube preliminary
Data:
-1.2σ
Pseudo experiments
0
20
40
60
80
100
120
−1710
−1700
−1690
−1680
−1670
−1660
−1650
−1640
−1630
log(L)

# Backup

Tracks fit parameters:

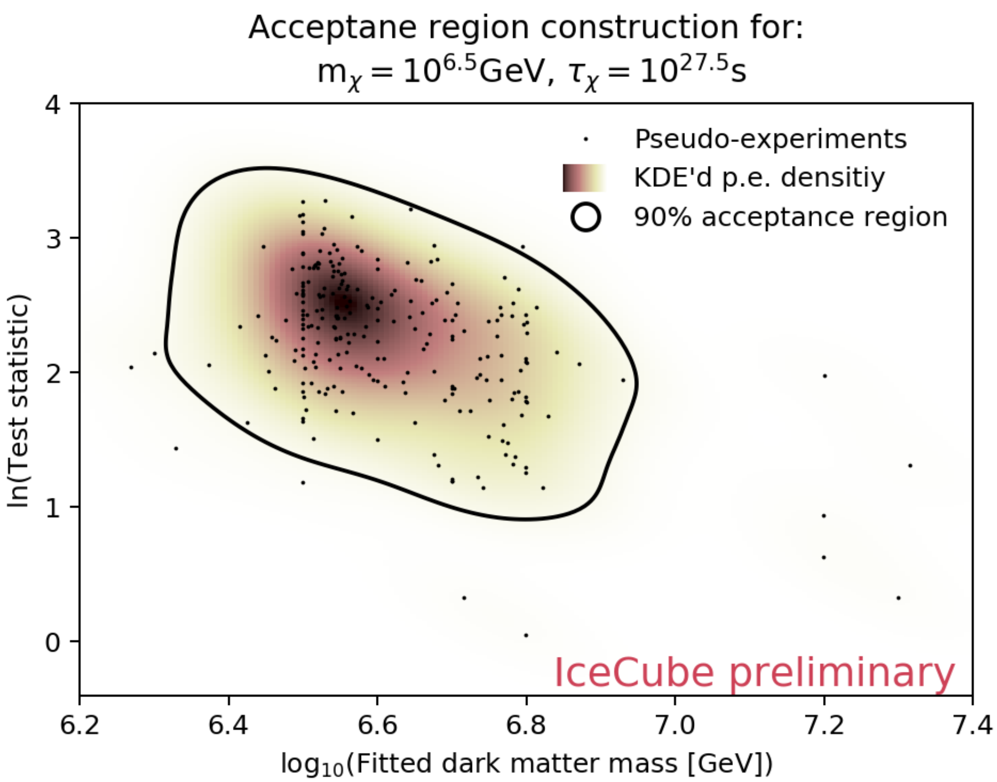
- Dark matter mass
- Dark matter lifetime
- Astrophysical flux normalization
- Astrophysical flux index
- Conventional atmospheric flux normalization
- Prompt atmospheric flux normalization
- Cosmic ray composition
- Cosmic ray kaon/pion ratio
- DOM efficiency
  Ice models
- Ice absorption
- Ice scattering

# Backup



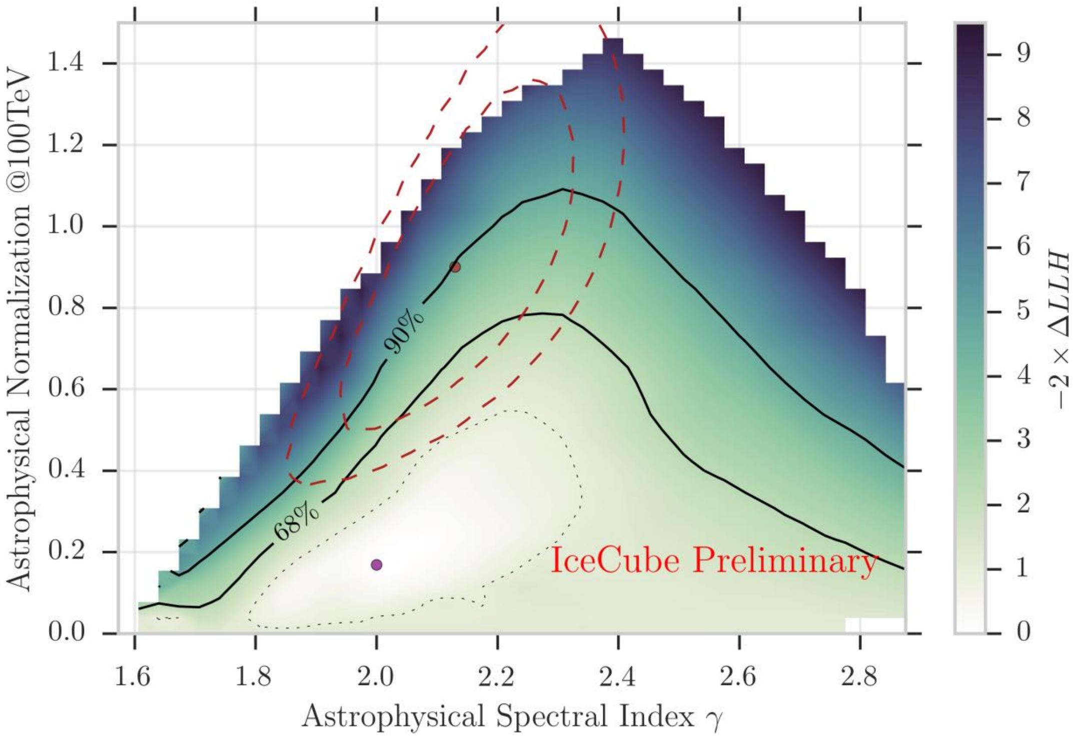
Lower lifetime limit for DM → Hν
Sensitivity
Limit
$\log_{10}$(Dark matter lifetime [s])
$\log_{10}$(Dark matter mass [GeV])
28.75
28.50
28.25
28.00
27.75
27.50
27.25
27.00
26.75
26.50
4
5
6
7
8
1σ
2σ
IceCube preliminary

# Backup



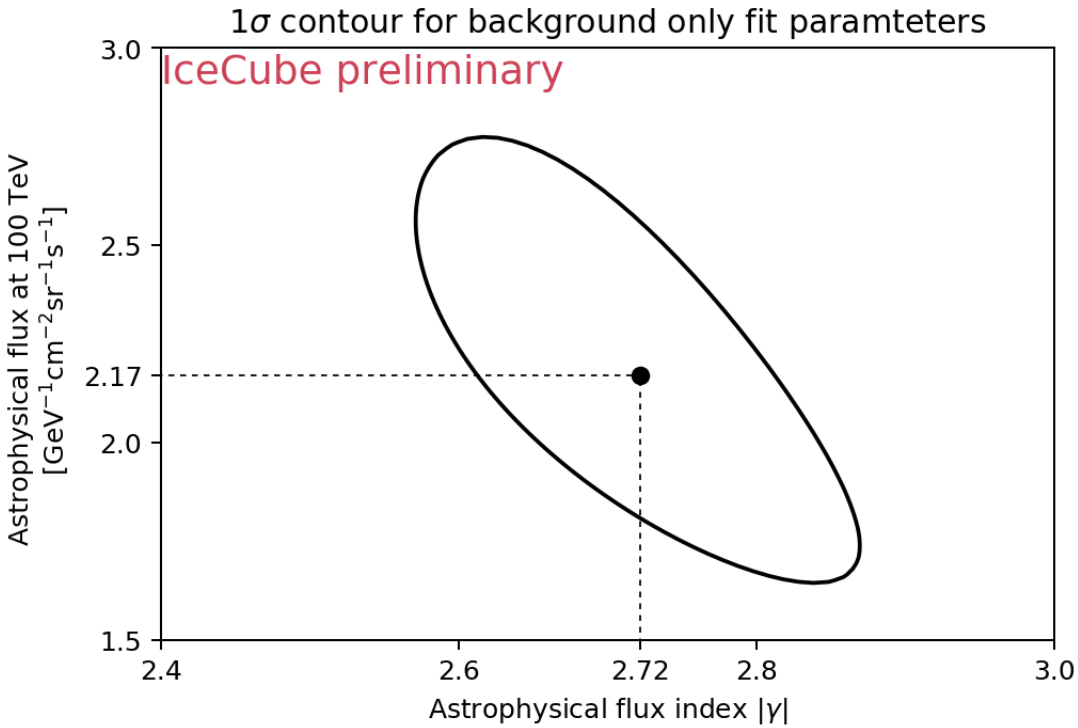
Acceptane region construction for:
$m_\chi = 10^{6.5}$GeV, $\tau_\chi = 10^{27.5}$s
Pseudo-experiments
KDE'd p.e. densitiy
90% acceptance region
IceCube preliminary
ln(Test statistic)
$\log_{10}$(Fitted dark matter mass [GeV])

# Backup



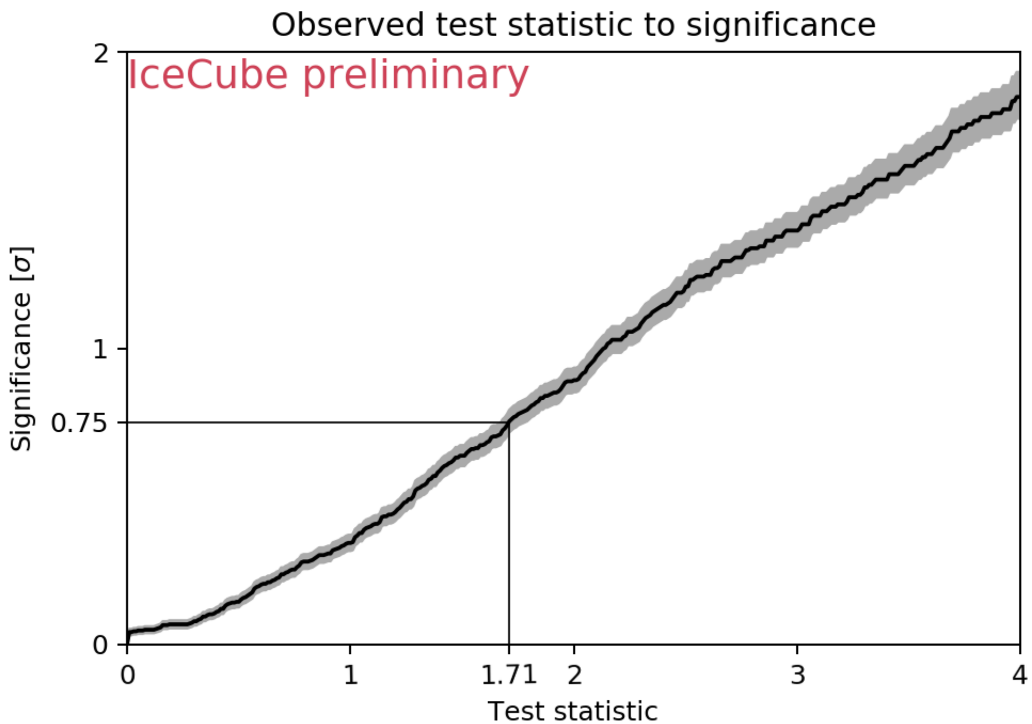
Astrophysical Normalization @100TeV
Astrophysical Spectral Index $\gamma$
$-2 \times \Delta LLH$
90%
68%
IceCube Preliminary

# Backup



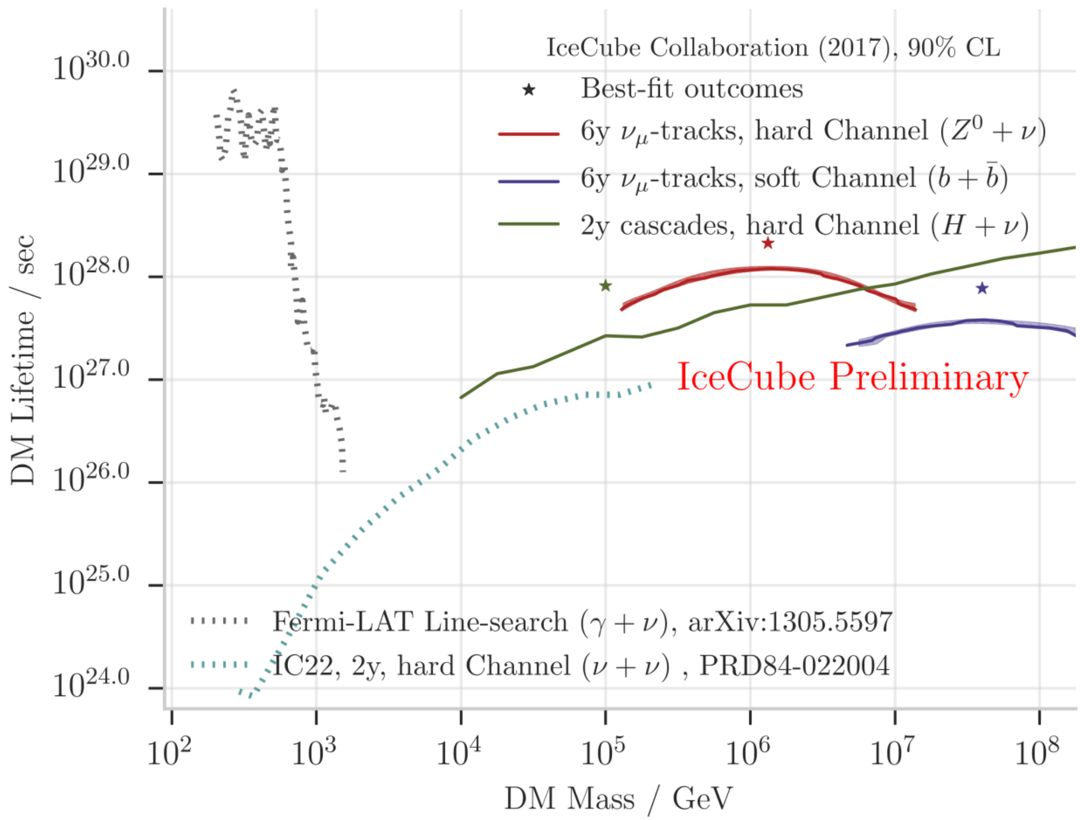
1σ contour for background only fit paramteters
IceCube preliminary
Astrophysical flux at 100 TeV
[GeV⁻¹cm⁻²sr⁻¹s⁻¹]
3.0
2.5
2.17
2.0
1.5
2.4
2.6
2.72
2.8
3.0
Astrophysical flux index |γ|

# Backup



Observed test statistic to significance
IceCube preliminary
Significance [σ]
Test statistic
0
0.75
1
2
0
1
1.71
2
3
4

# Backup



IceCube Collaboration (2017), 90% CL
Best-fit outcomes
6y $\nu_\mu$-tracks, hard Channel $(Z^0 + \nu)$
6y $\nu_\mu$-tracks, soft Channel $(b + \bar{b})$
2y cascades, hard Channel $(H + \nu)$
IceCube Preliminary
Fermi-LAT Line-search $(\gamma + \nu)$, arXiv:1305.5597
IC22, 2y, hard Channel $(\nu + \nu)$ , PRD84-022004
DM Lifetime / sec
DM Mass / GeV
$10^{30.0}$
$10^{29.0}$
$10^{28.0}$
$10^{27.0}$
$10^{26.0}$
$10^{25.0}$
$10^{24.0}$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$