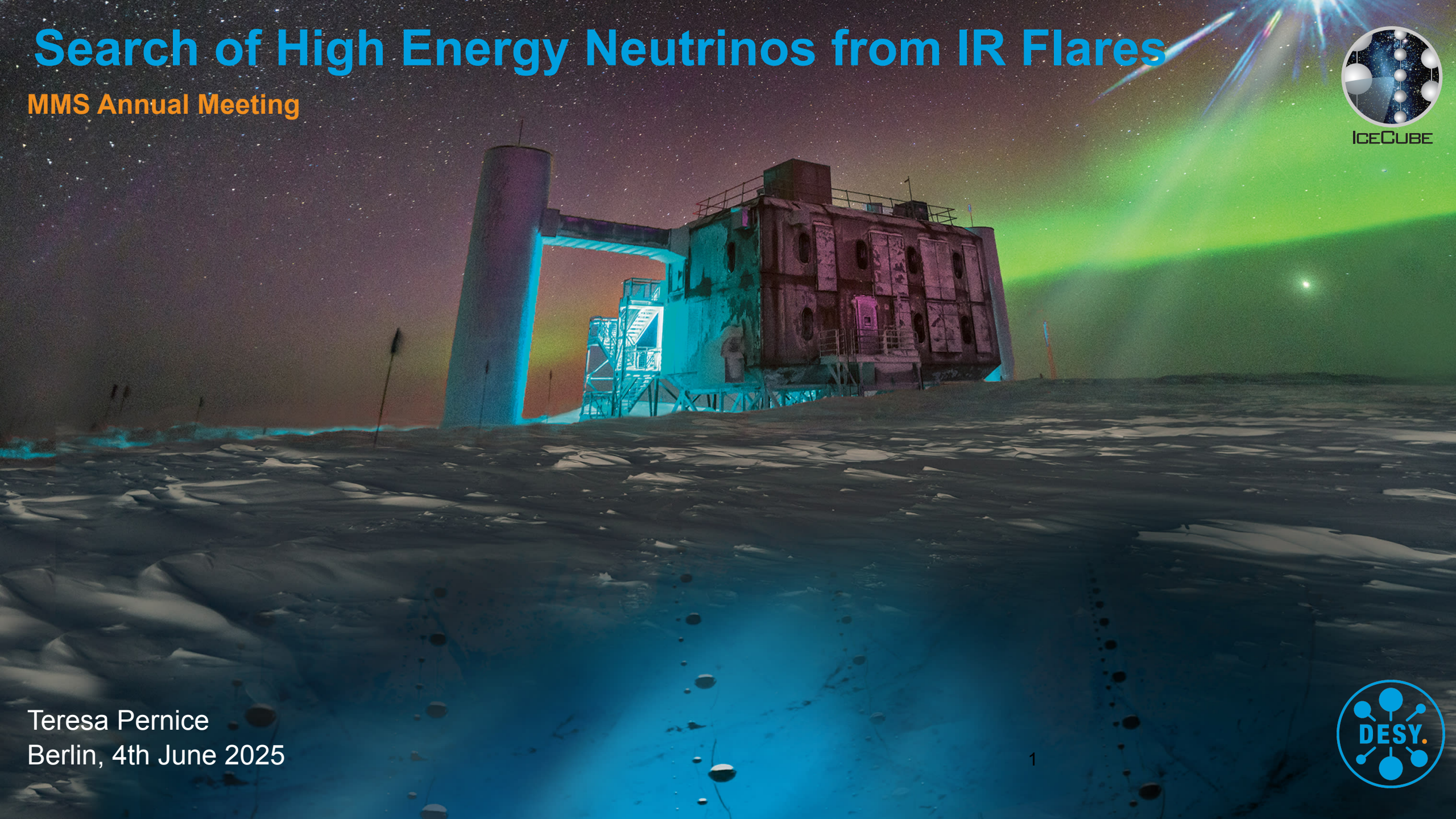
Search of High Energy Neutrinos from IR Flares

MMS Annual Meeting

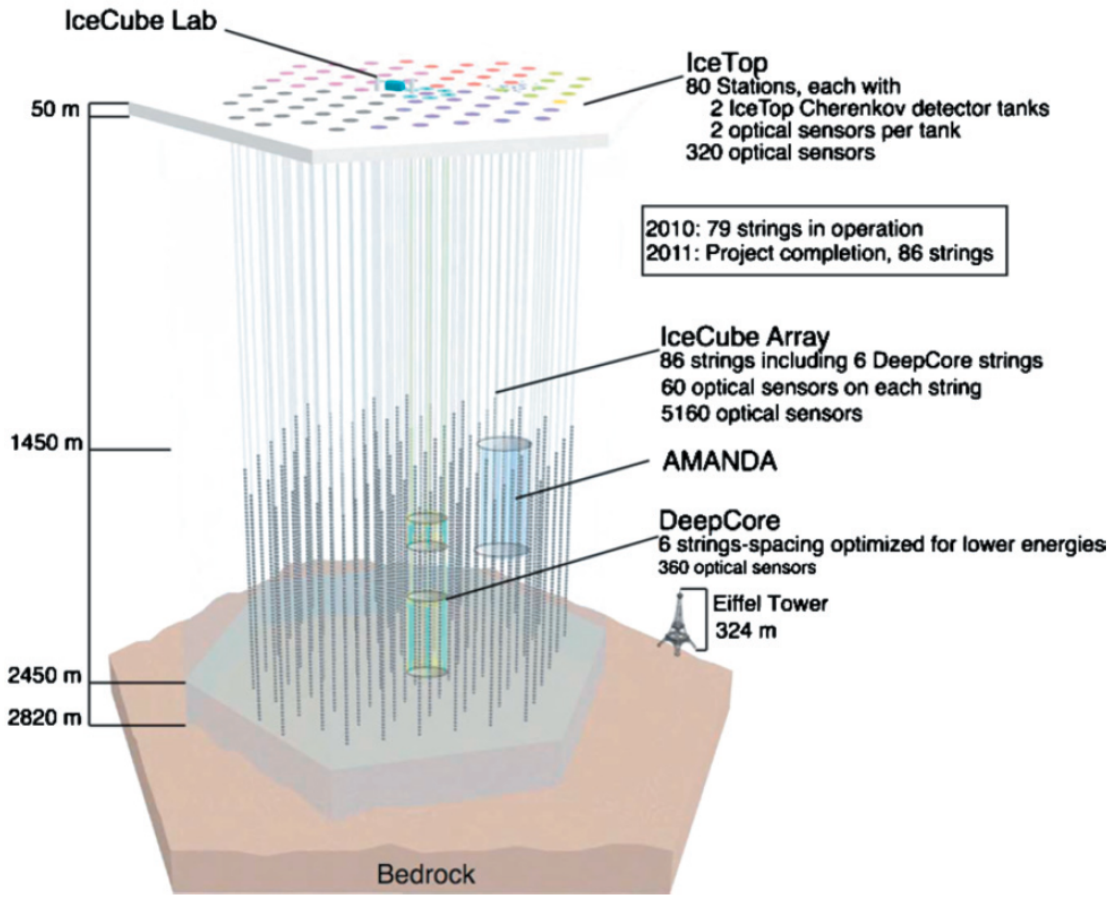


Teresa Pernice
Berlin, 4th June 2025

Outline

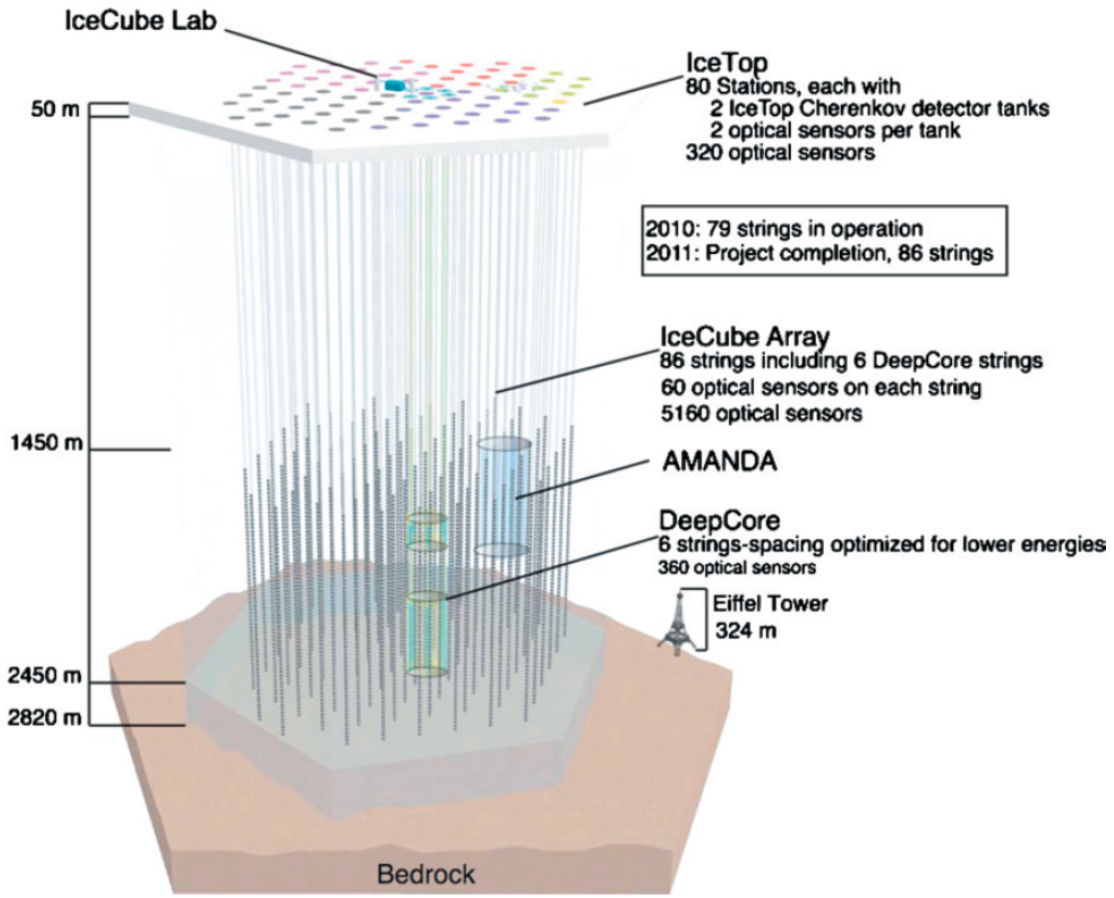
- **IceCube**
- **TDEs** as sources of high-energy neutrinos
- **IR flares** and dust echoes
- Analysis Overview
- Sensitivity Results

The IceCube Neutrino Observatory

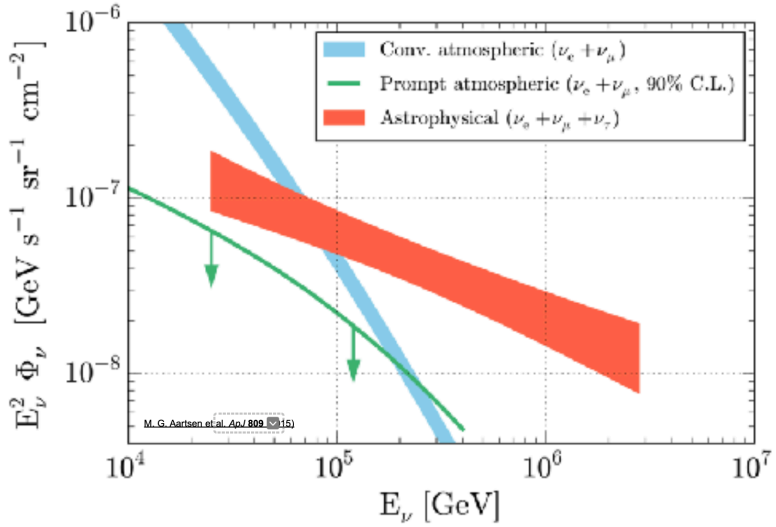


- 1 km^3 of instrumented ice at the South Pole
- Detection of **Cherenkov light** produced by electrically charged secondary particles

The IceCube Neutrino Observatory

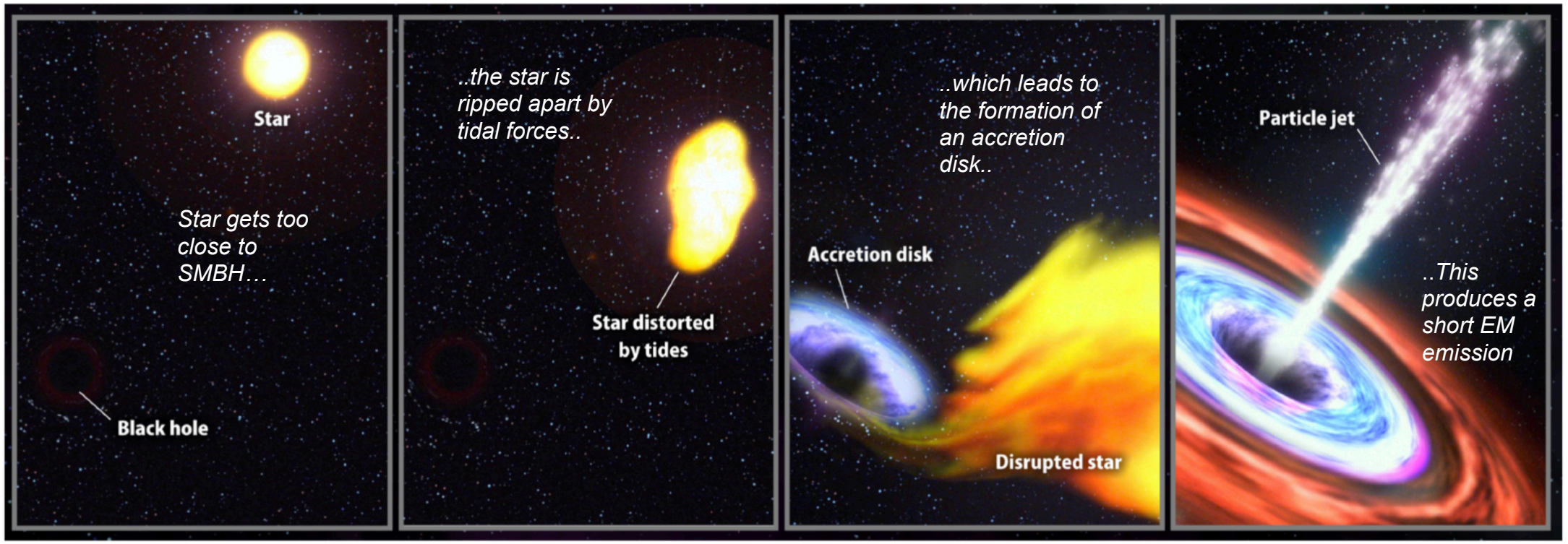


- 1 km^3 of instrumented ice at the South Pole
- Detection of **Cherenkov light** produced by electrically charged secondary particles
- Isotropic **astrophysical flux** of neutrino was measured



What are the **sources** of these neutrinos?

Tidal Disruption Events (TDEs)



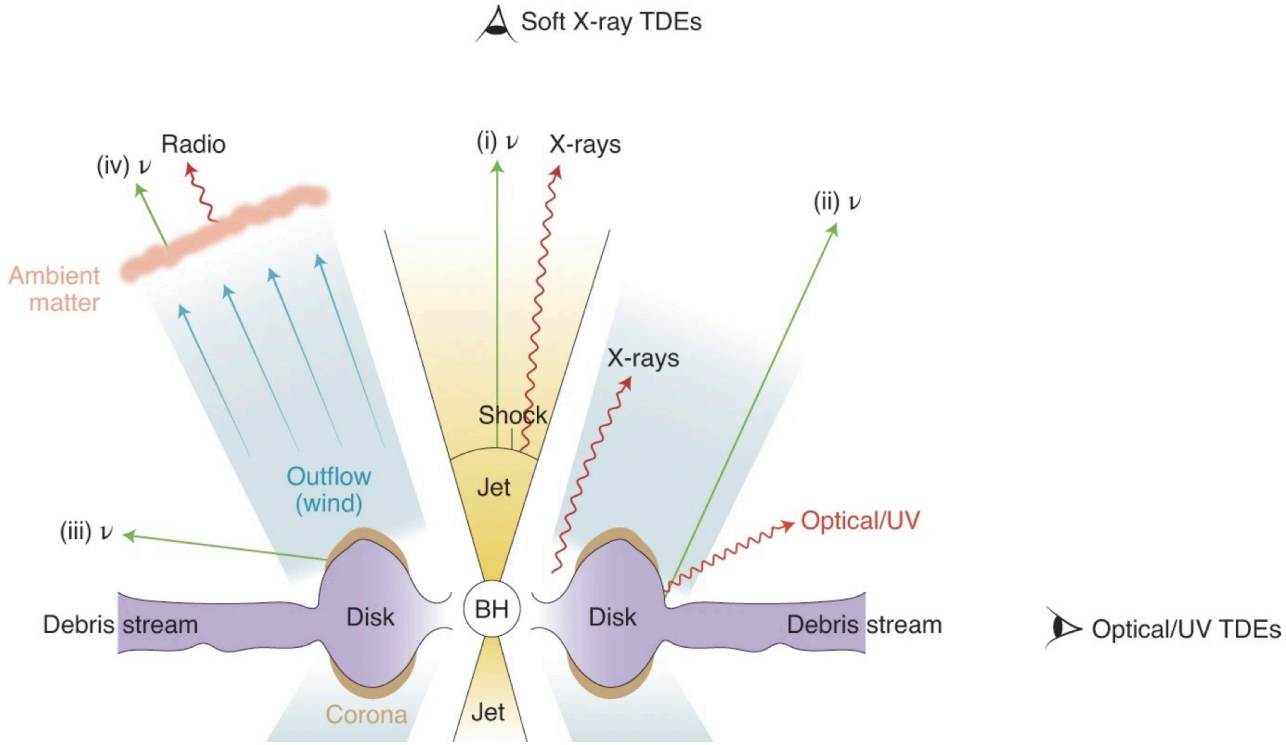
Credit: NASA

1 2 3 4

TDE unification model

Multi-wavelength observations

- Based on the viewing angle with respect to the black hole orientation, TDEs exhibit different kinds of emission
- **X-rays** produced by the **inner accretion disk**
- **Optical/UV emission**, observed thanks to large optical time domain survey like **ZTF,** from **reprocessed X-ray emission**
- **Radio emission** because of relativistic jets



TDE unification model

TDEs in coincidence with HE neutrinos

*Stein et al. 2021 , Reusch et al. 2022

Do TDEs produce neutrinos?

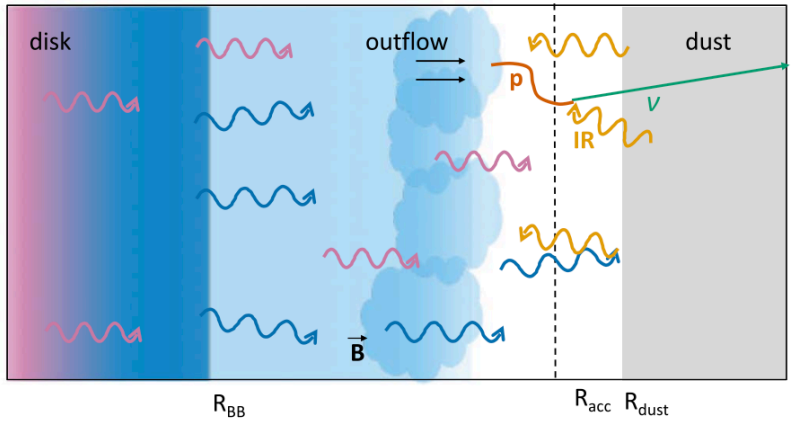
- Through optical **ZTF** follow-up observations, two high energy neutrinos were associated with TDE/AGN flaring activity (**AT2019dsg** and **AT2019fdr**)*
- A third candidate was identified as HE neutrino counterpart (**AT2019aalc**)

⇒ All candidates present high OUV luminosities accompanied by a **delayed IR emission** (**dust echoes**)

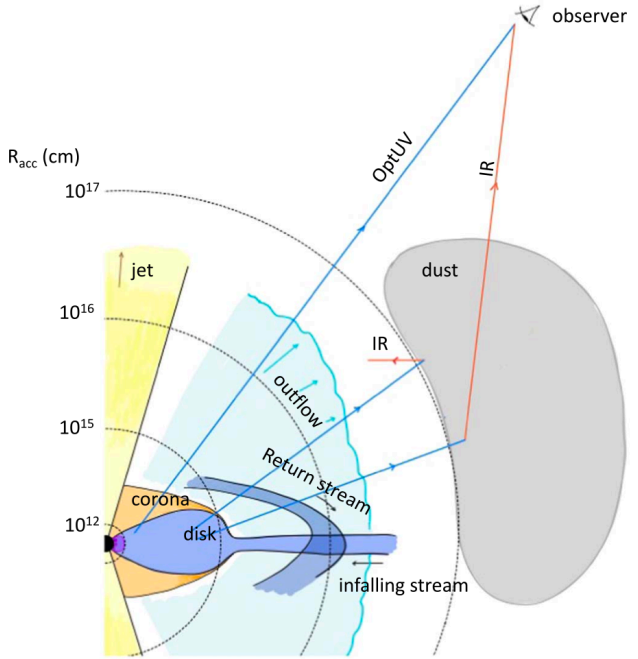
The dust echo model

IR model

- **Dust echoes** are reverberation of the flare radiation
- Flare's emission (optical to X-ray) is absorbed and reprocessed by surrounding hot dust into IR
- Neutrinos are produced in the interaction between **very high energy protons** and the IR photons from dust echoes
- Observed as delayed IR flares, dust echoes help to identify **obscured TDEs**



[2] Walter Winter and Cecilia Lunardini 2023 ApJ 948 42



Flaires

A Comprehensive Catalog of Infrared Flares

- Follow-up analysis on a sample of 63 accretion flares did not show any excess of high-energy neutrino signal over background
- A more comprehensive catalog of IR flares is needed!! ⇒ Flaires by (Necker et al. 2024):
    1. 823 significant dust-echo-like flares
    2. Full sky sample that spans full IceCube data-taking period
- The sources in the catalog are *consistent* with **dust echo** from accretion flares (luminosity, extension and temperature)
- Excluded sources that are flagged as **quasar**, **blazars, AGNs** (to exclude non-thermal processes for IR emission)

We end up with a total of **528** sources

FlaireStack: Stacking analysis of IR Flares

Search for high-energy neutrinos from IR flares

Unbinned likelihood method: Probability of observing data given the hypothesis

- Probability Density Functions (PDFs) to model event distributions:

    1. Signal PDF ($\mathcal{S}$) → Describes how likely an event is to come from an astrophysical source
    2. Background PDF ($\mathcal{B}$) → Models random atmospheric neutrino events or detector noise

$$\mathscr{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}(\nu_i, \gamma) + \left(1 - \frac{n_s}{N} \right) \mathcal{B}(\nu_i) \right) .$$

N: total number of observed events
n_s: signal strength
γ: Assumed neutrino spectrum index

Goal: Maximise the likelihood to have n_s and γ that best fit the data

FlaireStack: Stacking analysis of IR Flares

Search for high-energy neutrinos from IR flares

Stacking: *What is the contribution of a population of sources to the overall diffuse neutrino flux?*

Advantages of stacking:

- Increases **statistical power** by combining multiple sources
- Helps detect weaker sources that would be below detection thresholds
- Reduces the effect of random background fluctuations

$$\mathcal{S} = \sum_{j=1}^{M} w_j \mathcal{S}_j(\nu_i, \gamma)$$

w_j: **weight** assigned to each source based on the contribution to the combined signal

Fixed weights likelihood:

Not all sources contribute equally, so we apply weights based on their expected contribution.

1. Each source is **pre-assigned** a **weight** based on physical properties (Bolometric fluence, distance, etc)

FlaireStack: Stacking analysis of IR Flares

Search for high-energy neutrinos from IR flares

Likelihood ratio test

We compare the likelihood of two competing hypotheses:

1. **Background only** hypothesis $H_0 \rightarrow$ Assumes that all events originate from background sources.
2. **Signal + Background** hypothesis $H_1 \rightarrow$ Assumes that events originate from both background and signal

To evaluate if there is evidence for a signal, we estimate the **Test statistics** (**TS**):

$$TS = -2 \log \frac{\mathscr{L}(H_0)}{\mathscr{L}(H_1)}$$

- Large TS values, implies that the data is more likely to contain a signal!

FlaireStack: Stacking analysis of IR Flares

Search for high-energy neutrinos from IR flares

→ We generate several background trials to understand how fluctuations can mimic signal
→ This helps to set thresholds for **sensitivity** and **discovery potential**

Sensitivity and Discovery Potential (DP)

Sensitivity:

- Minimum flux needed to have 90% of the signal trials with TS > median TS_bkg

Discovery Potential:

- Flux needed to get a signal TS above the 5sigma threshold in 50% of the cases

Flarestack

Software and weighting method

- *Flarestack* to test for correlation with Flaires catalogue
- *Stacking* by **weighting** each source by their **Bolometric Fluence**

flarestack

docs passing | CI failing | pypi package 2.4.5 | coverage 75% | launch binder | DOI 10.5281/zenodo.6966491

Code for unbinned likelihood analysis of astroparticle physics data, created by @robertdstein.

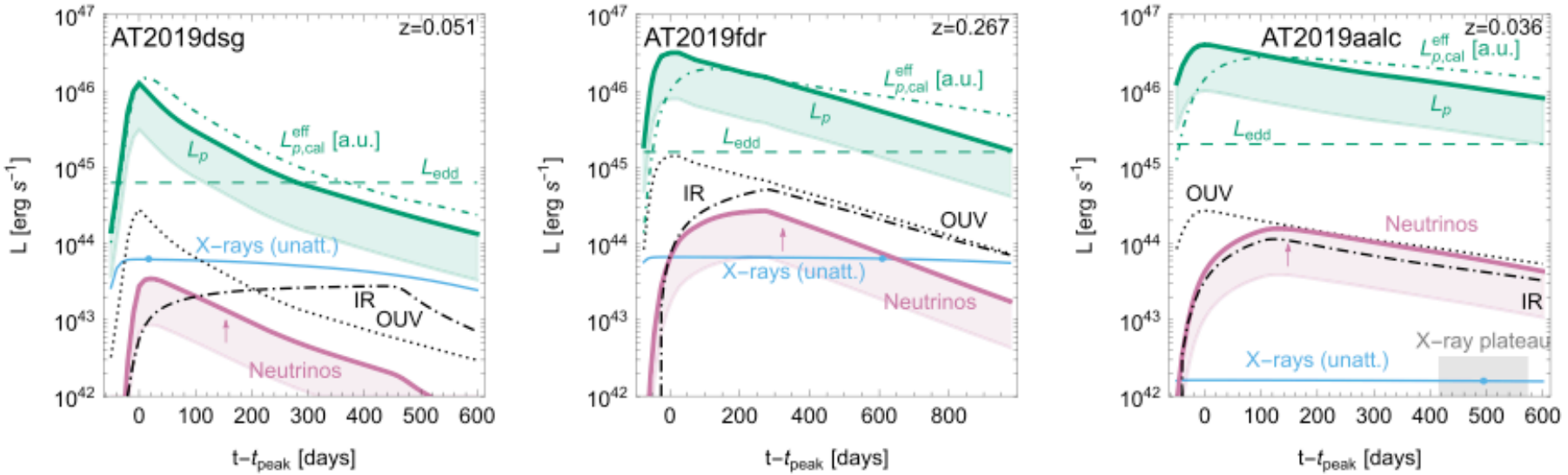
Both time-dependent and time-independent analyses can be performed, as well as a "flare-search" algorithm to find event clustering in time as well as space.

Performs single point source analyses, as well as the stacking of sources according to predefined weighting. Also performs stacking analyses where the signal strength of each source is fit individually.

→ Higher **bolometric fluence** implies higher neutrino luminosity

- **Time-dependent** analysis: 1 year box model

→ Search for neutrinos from the peak of the dust echo to one year before

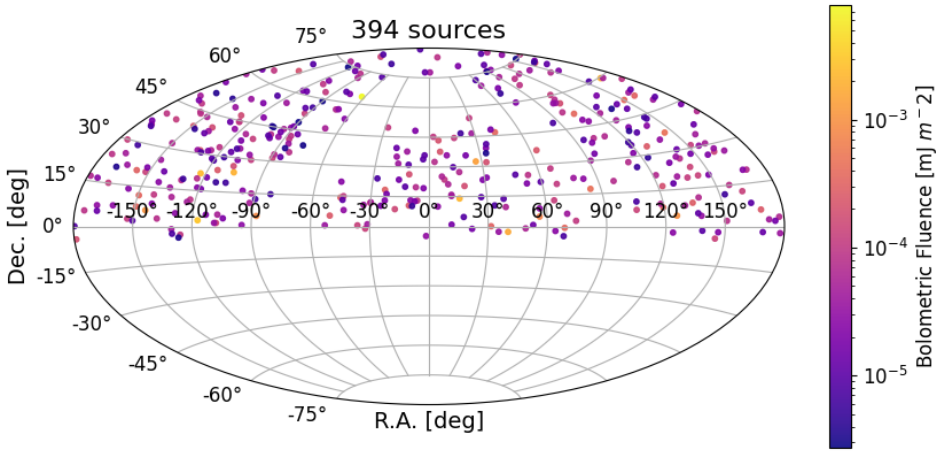


[2] Walter Winter and Cecilia Lunardini 2023 ApJ 948 42

Analysis Overview:

Stacking analysis using a comprehensive catalog of Dust-Echo-like IR Flares

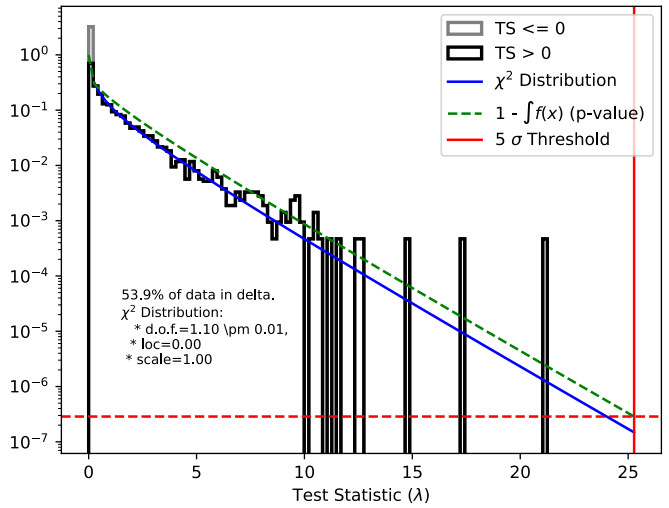
- We keep **394** sources in the Northern Sky
- Correlation with 10-yr through going muon **tracks**
- Energy PDF $E^{-\gamma}$,
- Gamma tested: $\gamma = 1, 2, 2.5$
- **Time dependent analysis**: 1 year box model (from the dust echo peak to one year before)
- Weighting: **Bolometric fluence**

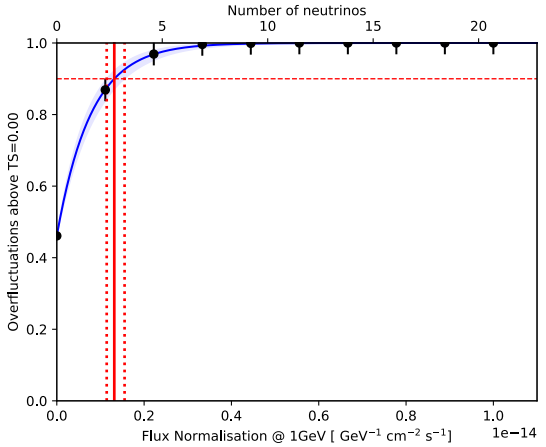


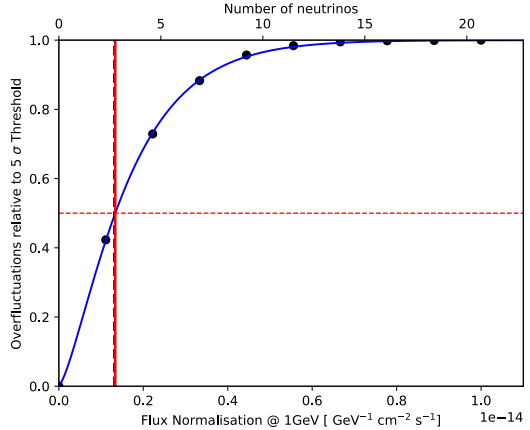
Northern Sky: Sensitivities

nt_v005_p01

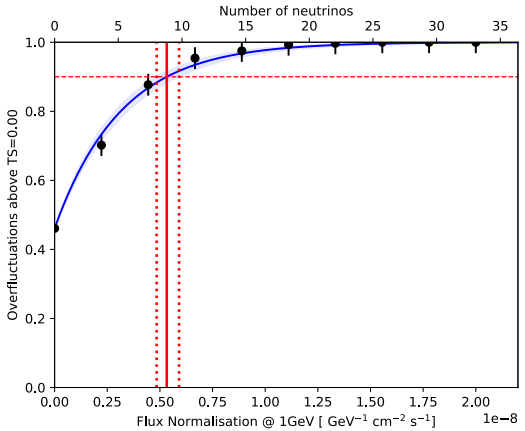
$\gamma = 1$

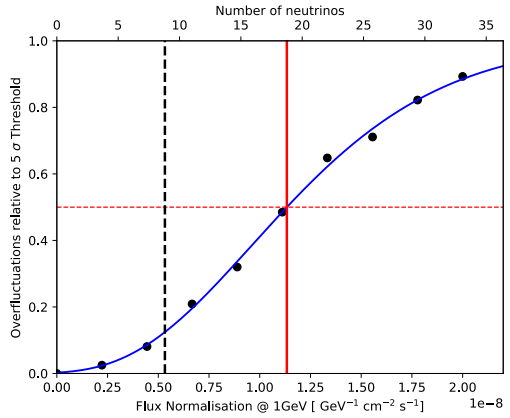




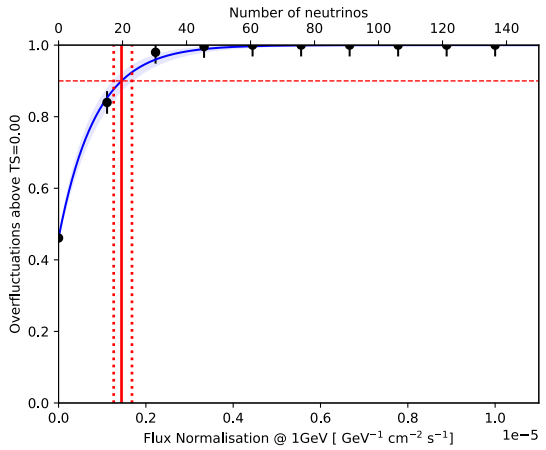


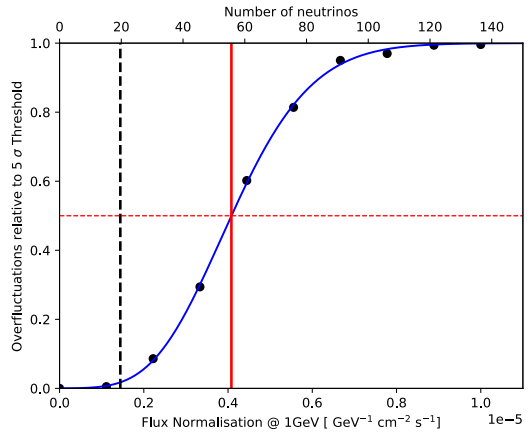
$\gamma = 2$



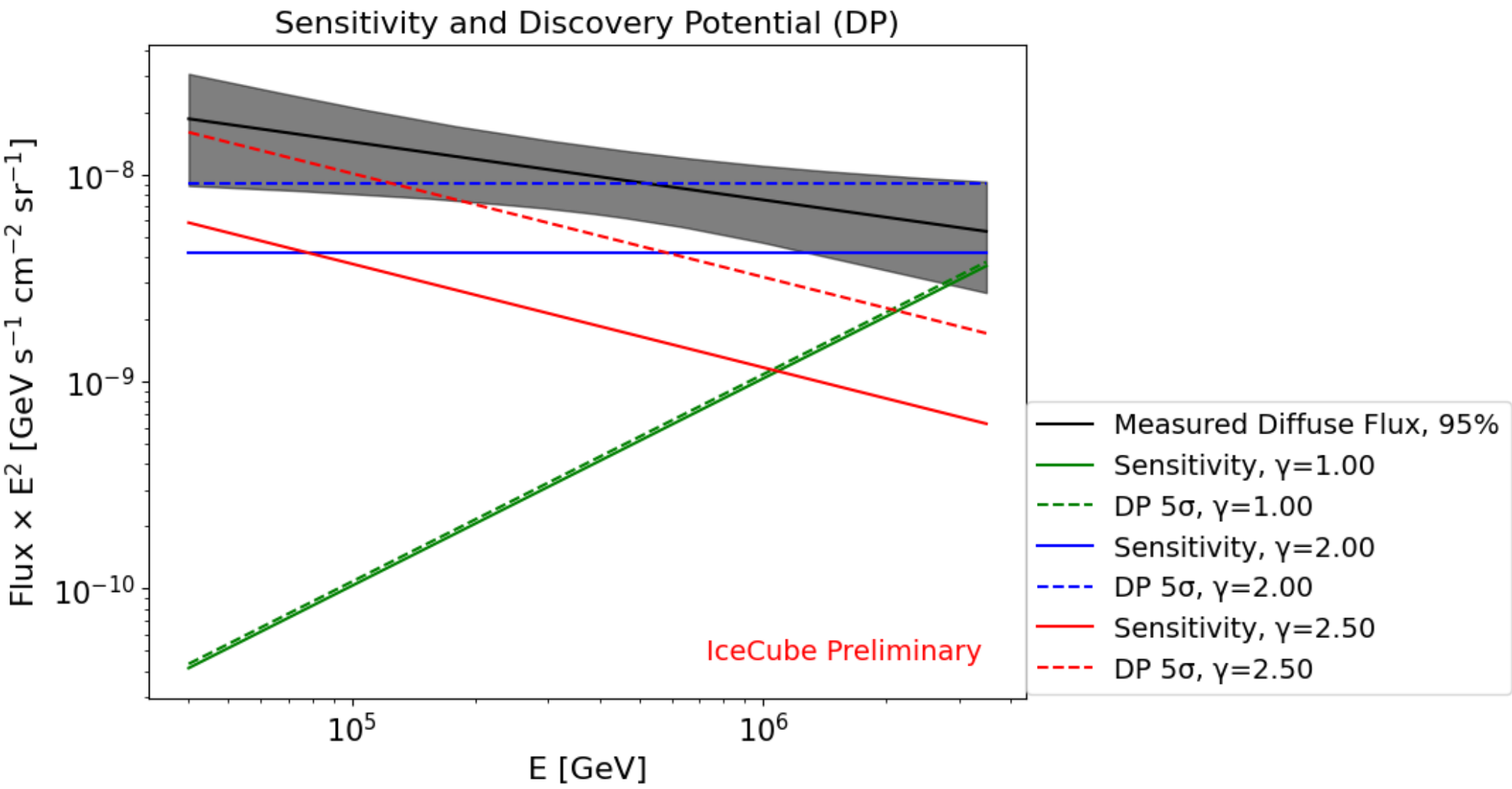


$\gamma = 2.5$





Sensitivities and Discovery Potential in flux space

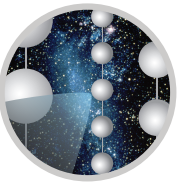


What’s next?

Unblinding Plan!

- Hypothesis: Test IR flares as neutrino emitters. A power law model will be tested, motivated by the dust echo model
- P-value: What is the excess of signal over background?
- Further calculations: Cosmological integration of the full population treating the sources in the catalog as standard candles

Thank you!



Contact

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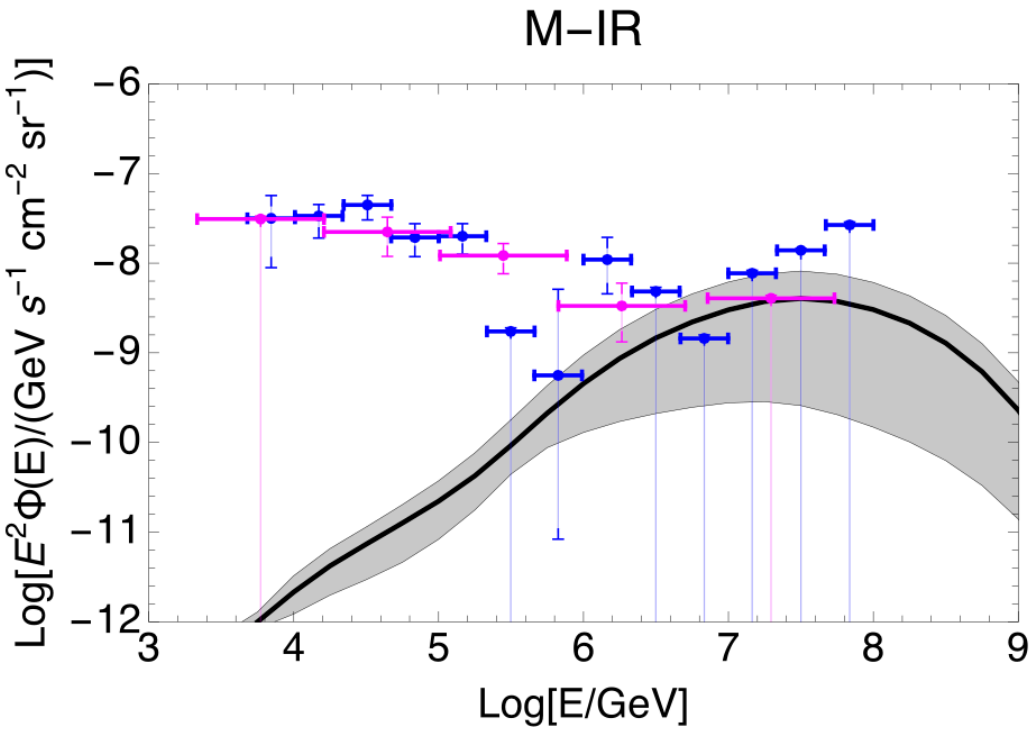
Backup Slides

New value of gamma to test

- Expected diffuse flux of neutrinos have been predicted for TDEs in [1]
- Data points represent IceCube measurements from cascade (blue) and tracks (magenta)
- The IR model may contribute at the **highest energies**
- The computed spectrum from the IR photon interaction seems to follow a power law with **gamma = 1**



[1] Walter Winter and Cecilia Lunardini 2023 ApJ 948 42

Northern Sky: Bias plots

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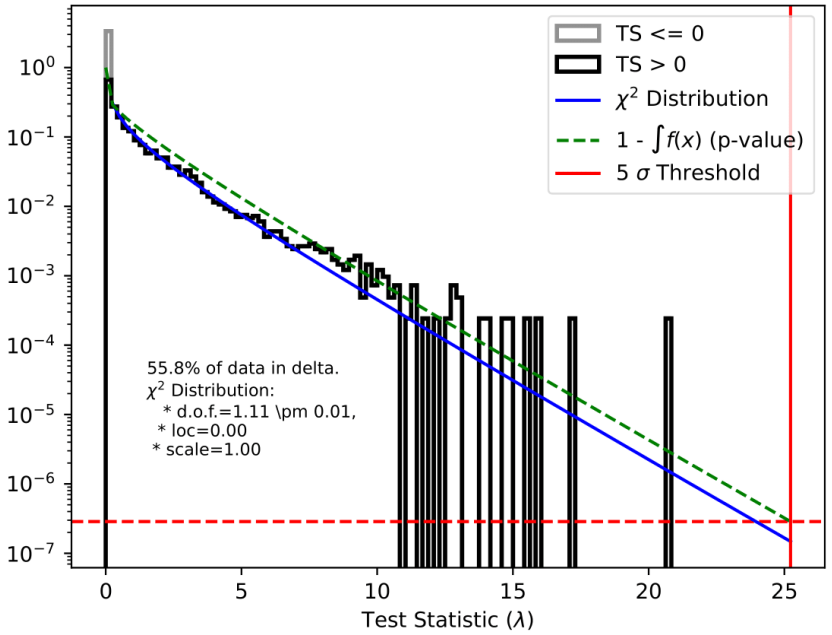

- Bias plots check whether the likelihood reconstruction is accurate
- They compare injected vs. estimated parameter values