Multi-Messenger Data Analysis - Part I

Markus Ahlers

Niels Bohr Institute, Copenhagen

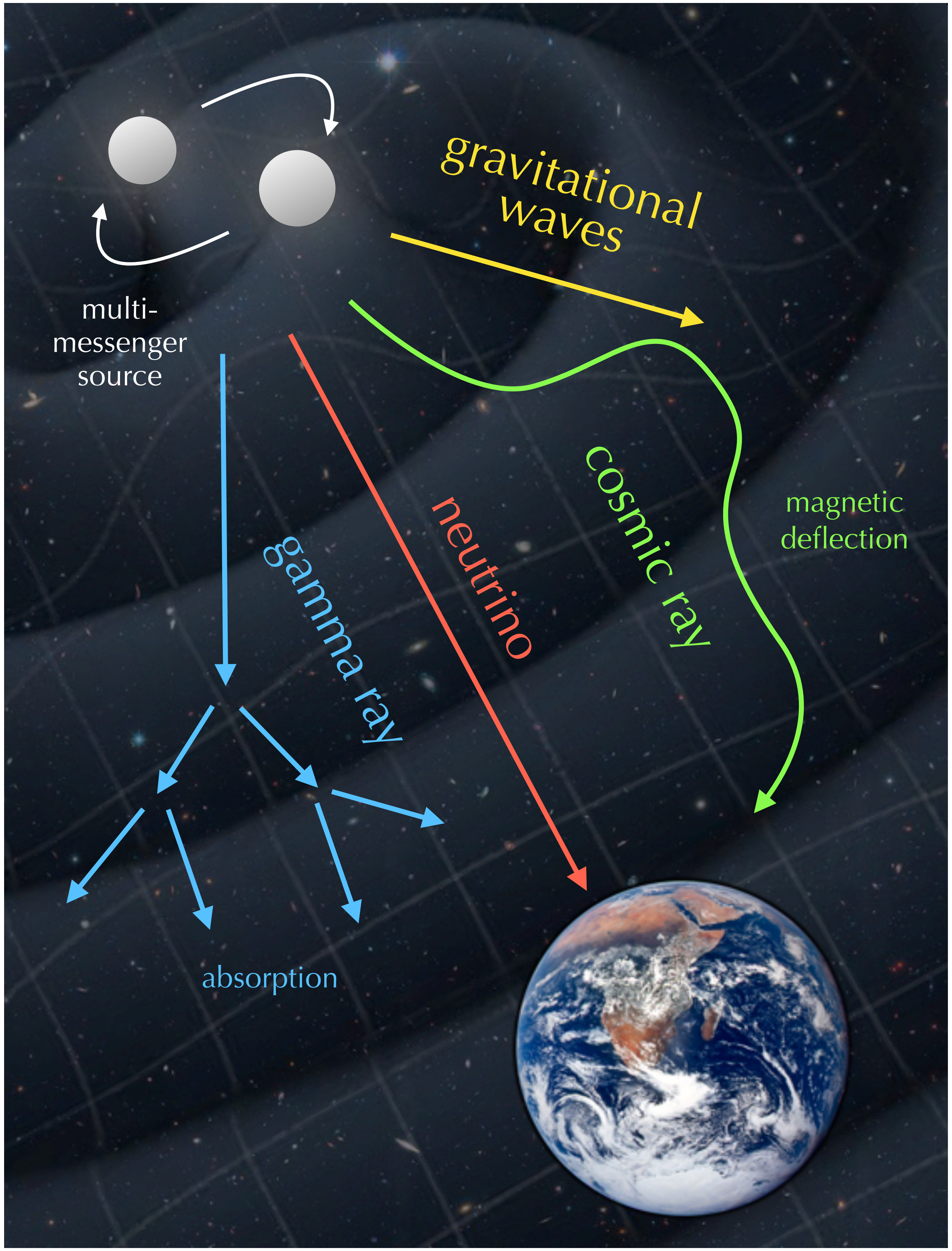
KSETA Topical Course

Karlsruhe, March 8, 2023

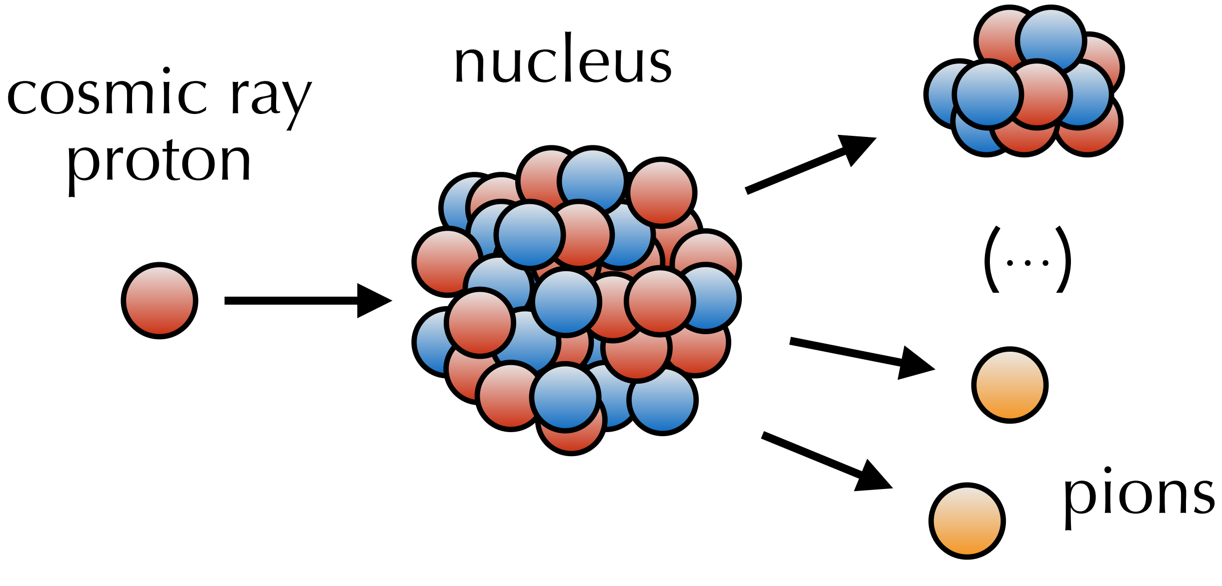
VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Multi-Messenger Paradigm



Acceleration of **cosmic rays** - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.

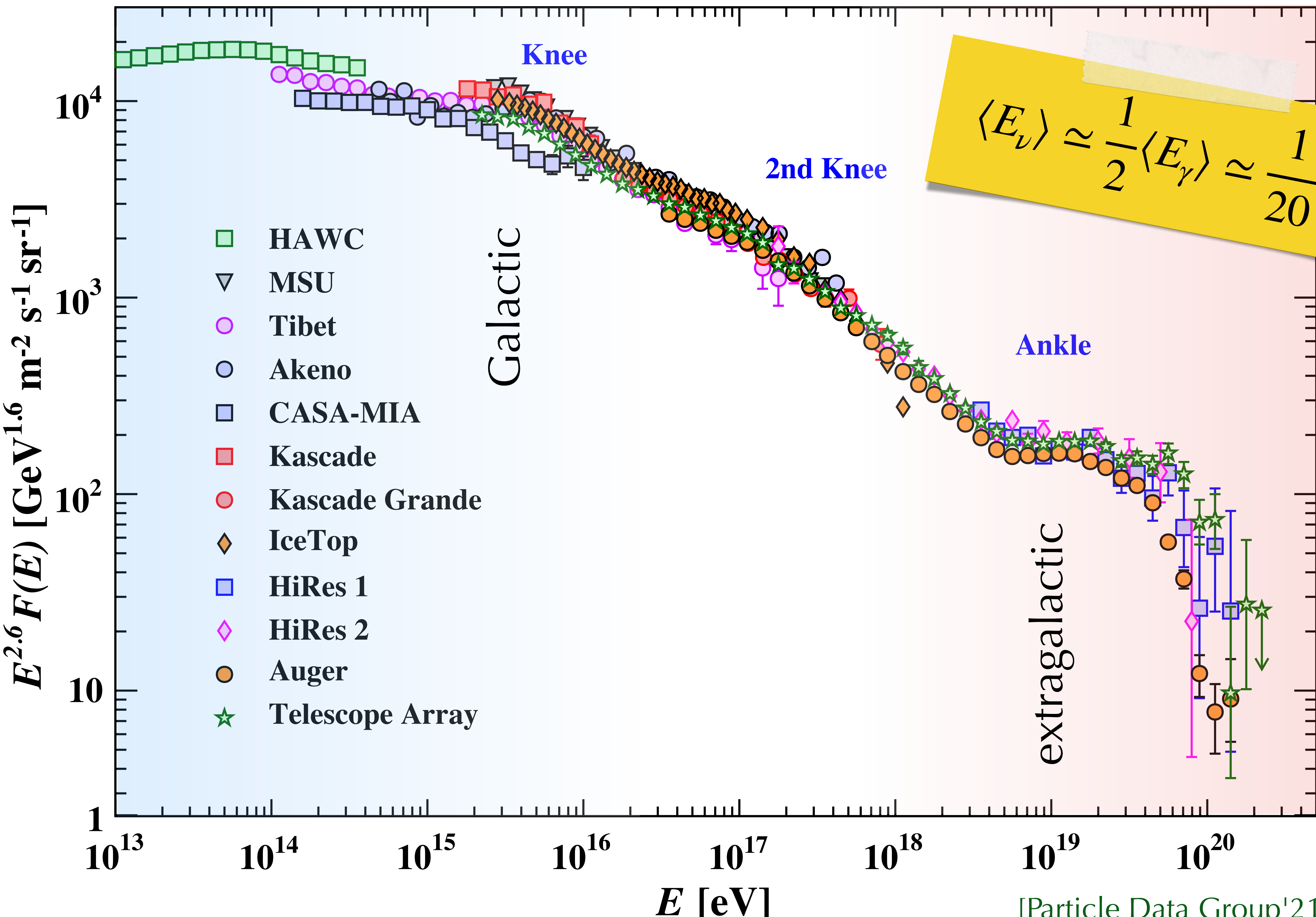


Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^0 \to \gamma + \gamma$$

$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

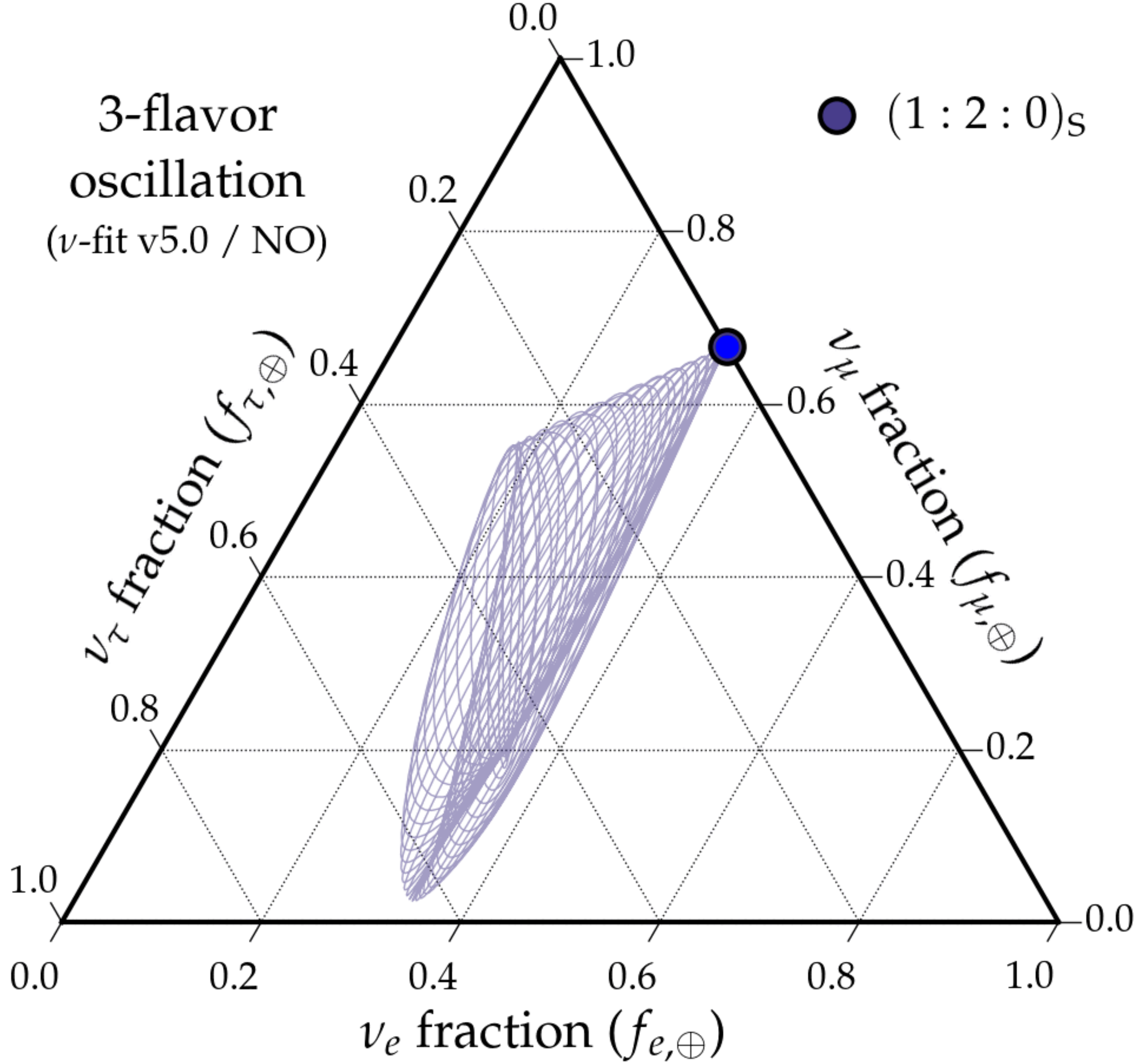
Very-High Energy Cosmic Rays



$$\langle E_\nu \rangle \simeq \frac{1}{2}\langle E_\gamma \rangle \simeq \frac{1}{20} E_{\rm N}$$

[Particle Data Group'21]

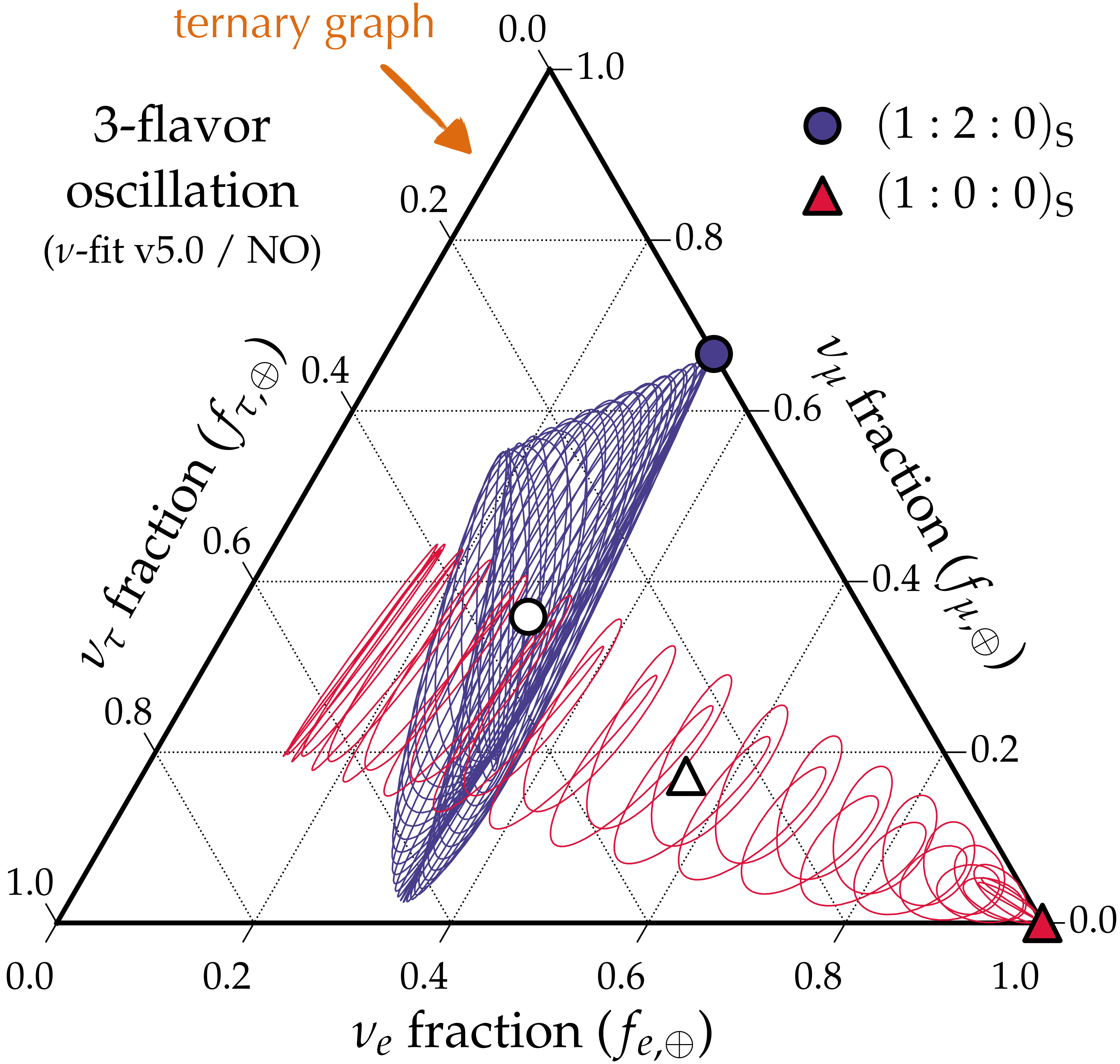
Astrophysical Flavours



Astrophysical Flavours

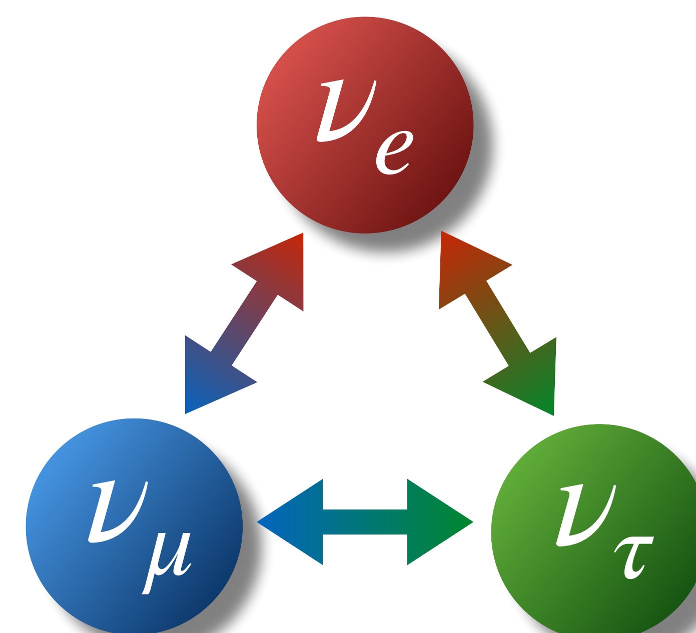
ternary graph

3-flavor oscillation
(ν-fit v5.0 / NO)

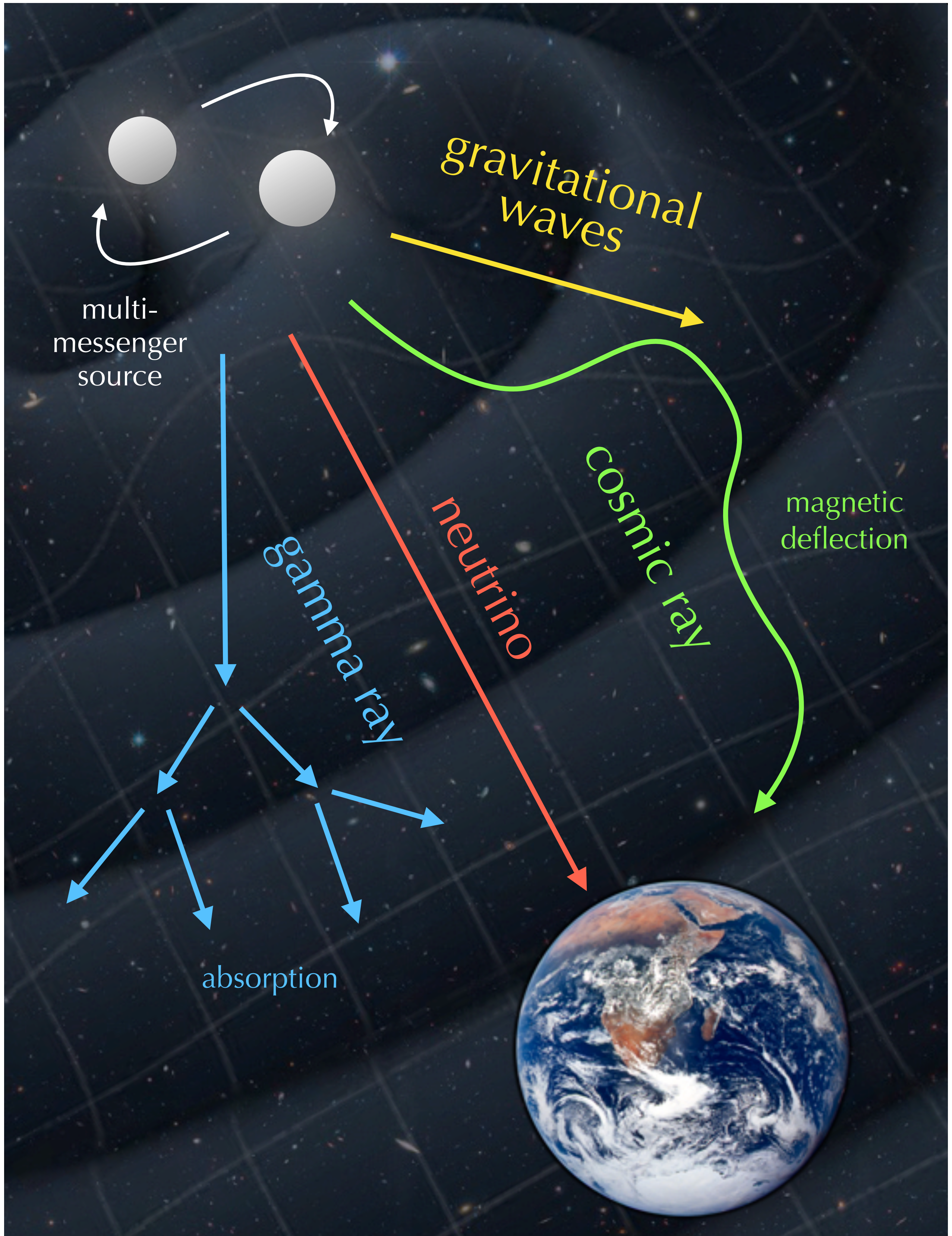


flavor ratios
on production

Superposition of
flavor and mass states
induce oscillations.



Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

Detector Requirements

Neutrino **charged and neutral current (CC & NC) interactions** are visible by Cherenkov emission of relativistic secondaries in transparent media.

back-of-the-envelope ($E_\nu \sim 1\mathrm{PeV} = 10^{15}$ eV):

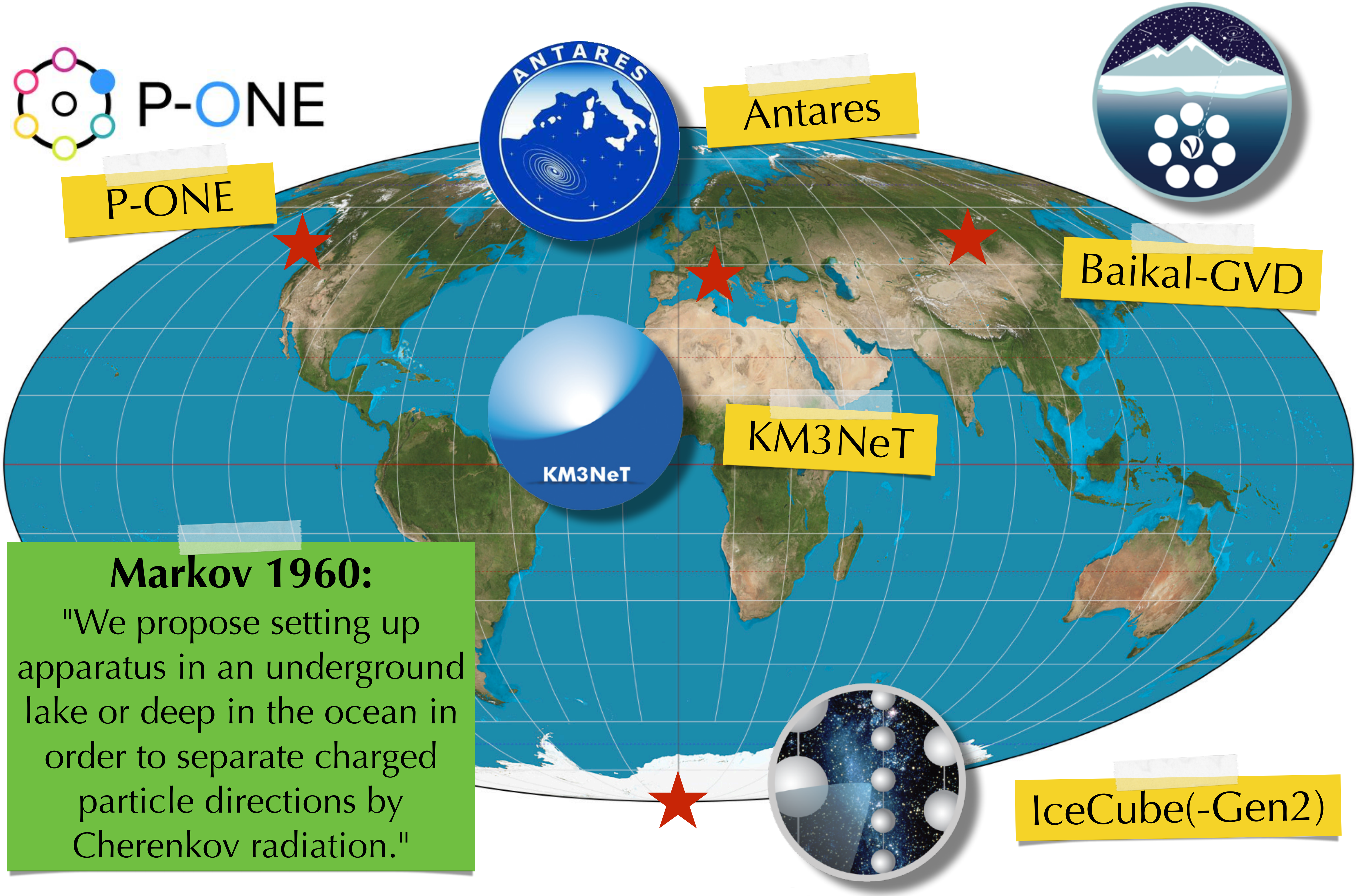
- **flux of neutrinos** : $$\frac{\mathrm{d}^2N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5\mathrm{yr}}$$
- **cross section** : $$\sigma_{\nu N} \sim 10^{-8}\sigma_{pp} \sim 10^{-33}\mathrm{cm}^2$$
- **targets**: $$N_N \sim N_A \times V/\mathrm{cm}^3$$

➜ **rate of events** :

$$\boxed{\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}}$$

minimum detector size: 1km³

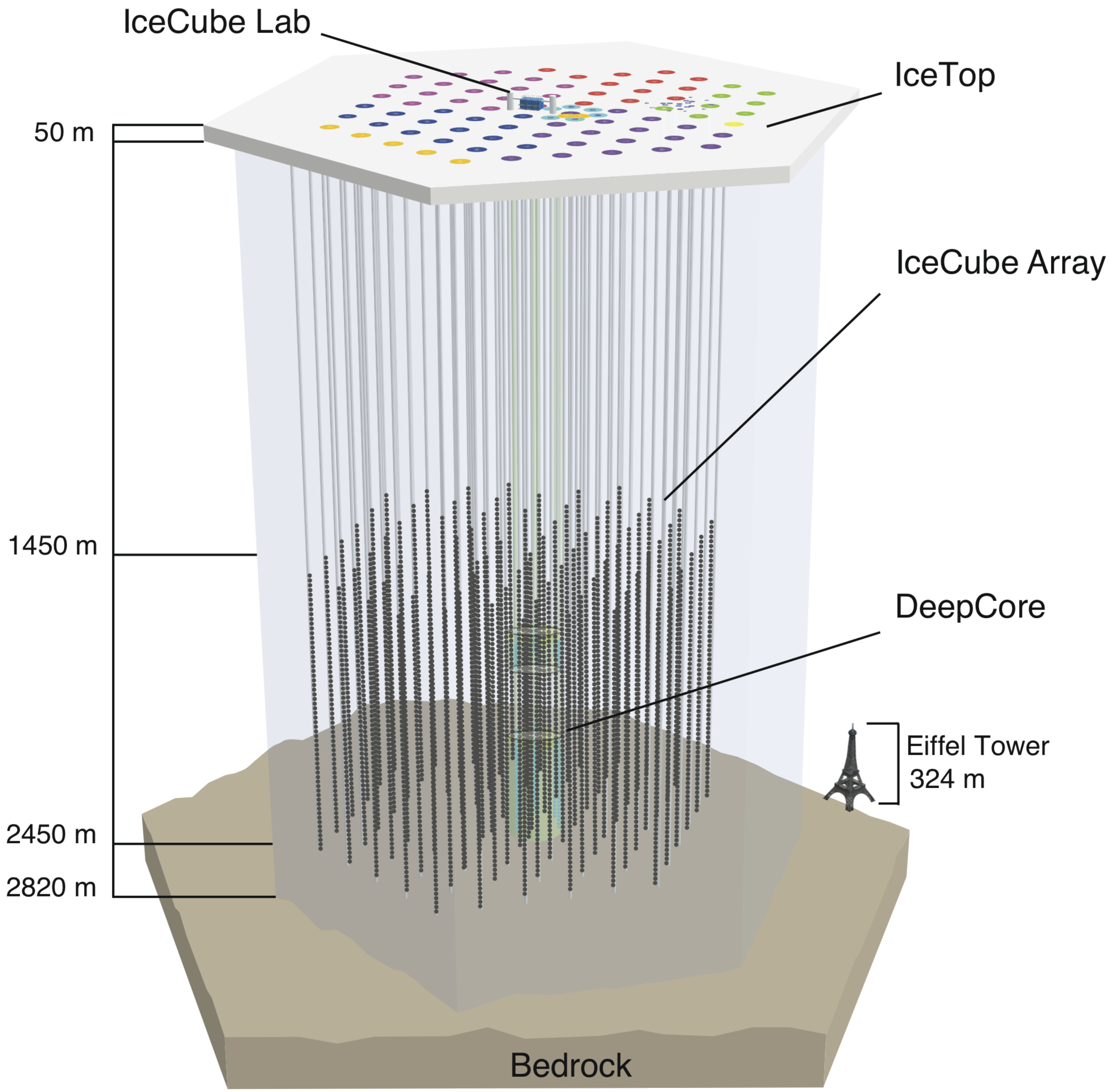
Optical Cherenkov Telescopes



Markov 1960:

"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation."

IceCube Observatory

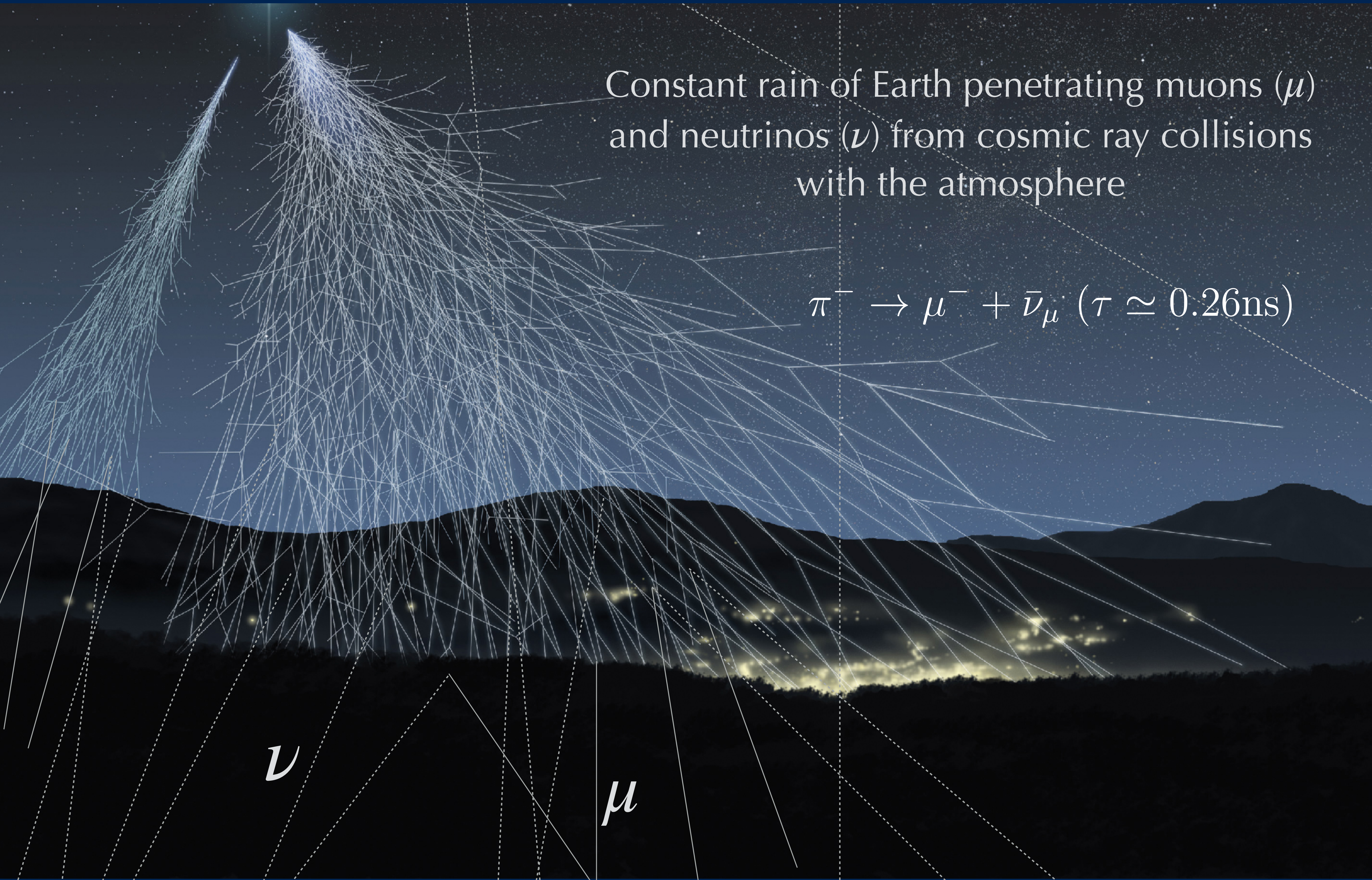


- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

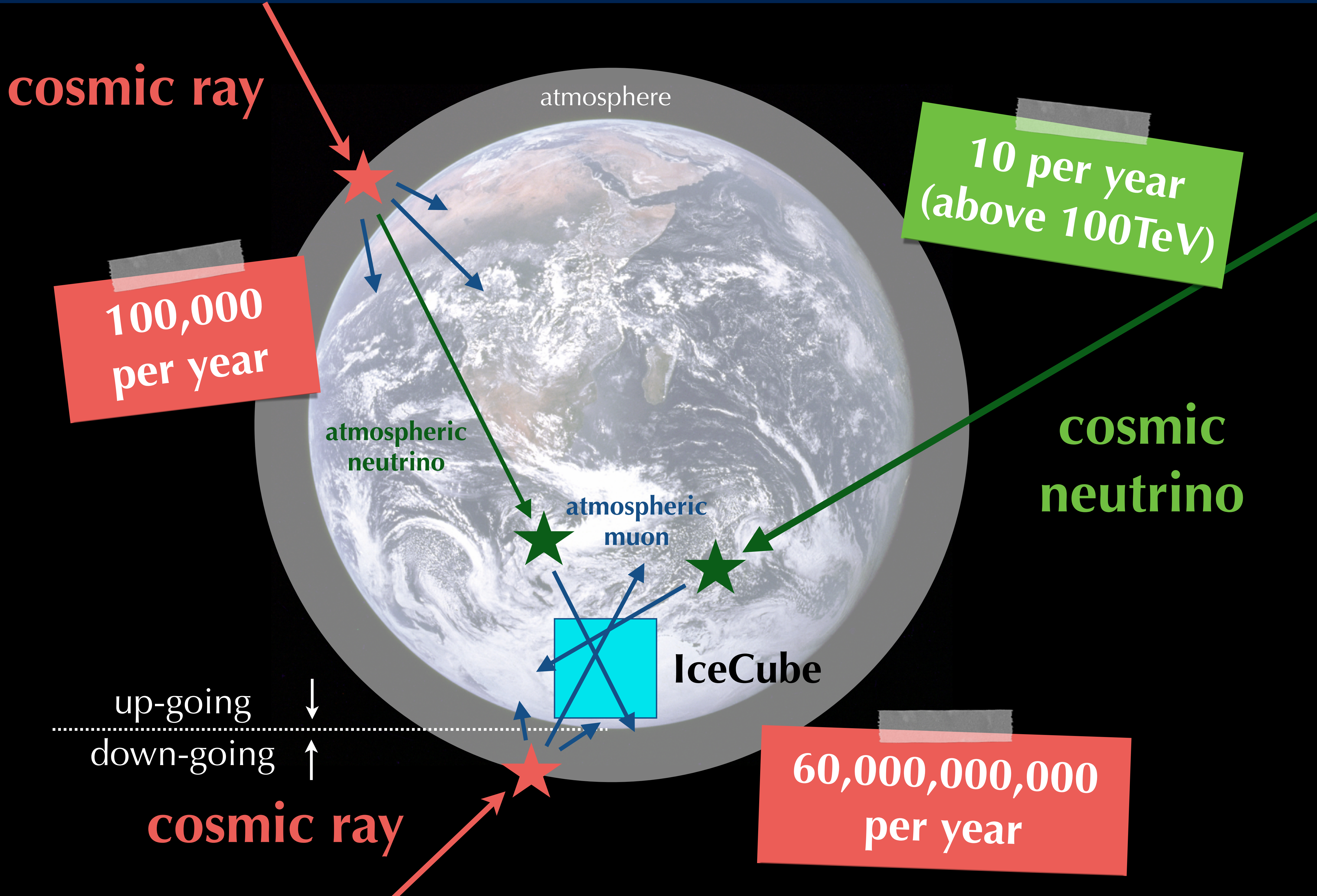
Atmospheric Background

Constant rain of Earth penetrating muons (μ) and neutrinos (ν) from cosmic ray collisions with the atmosphere

$$\pi^- \to \mu^- + \bar{\nu}_\mu \ (\tau \simeq 0.26\text{ns})$$

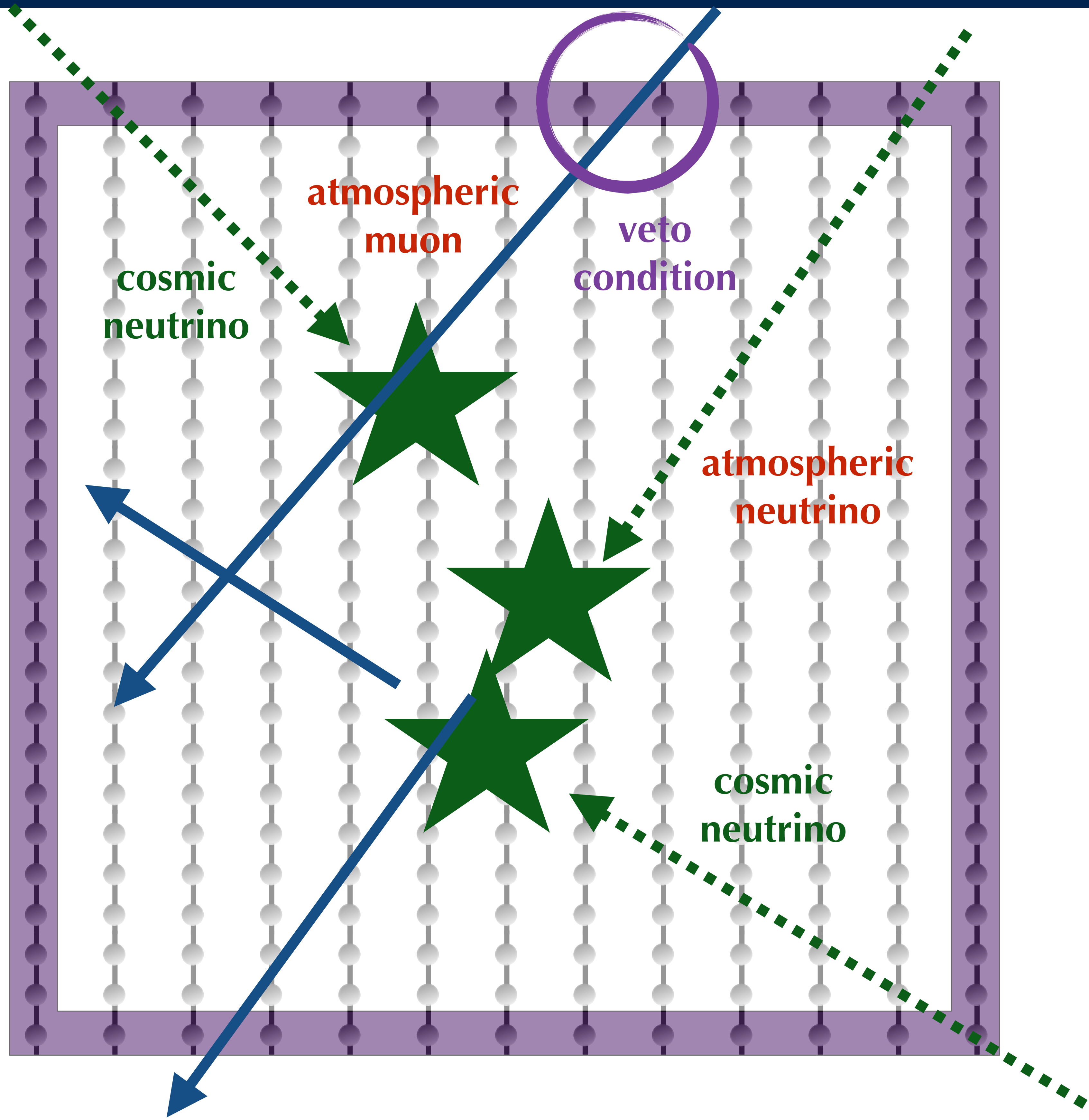


Neutrino Selection I



Neutrino Selection II

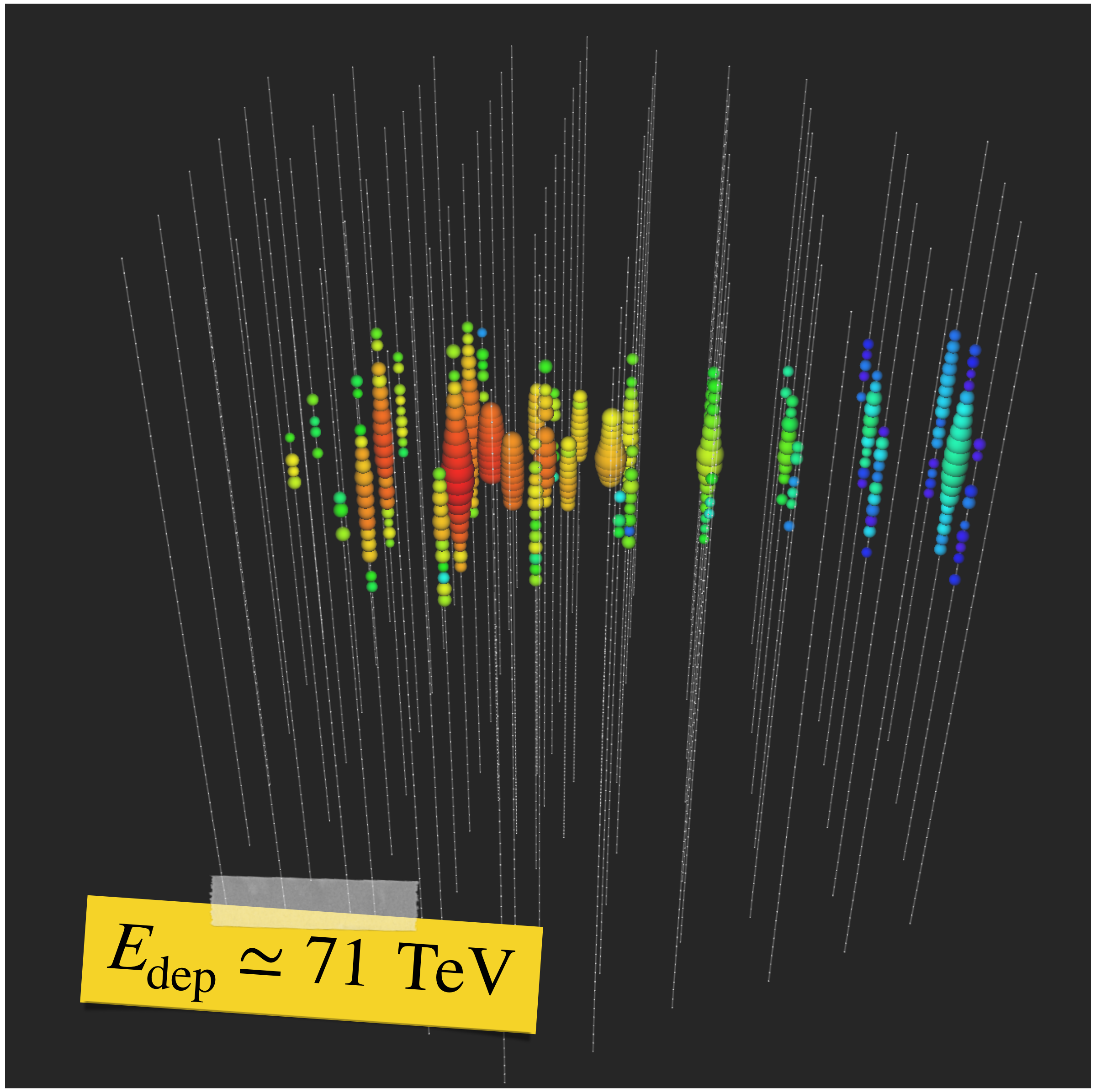
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis



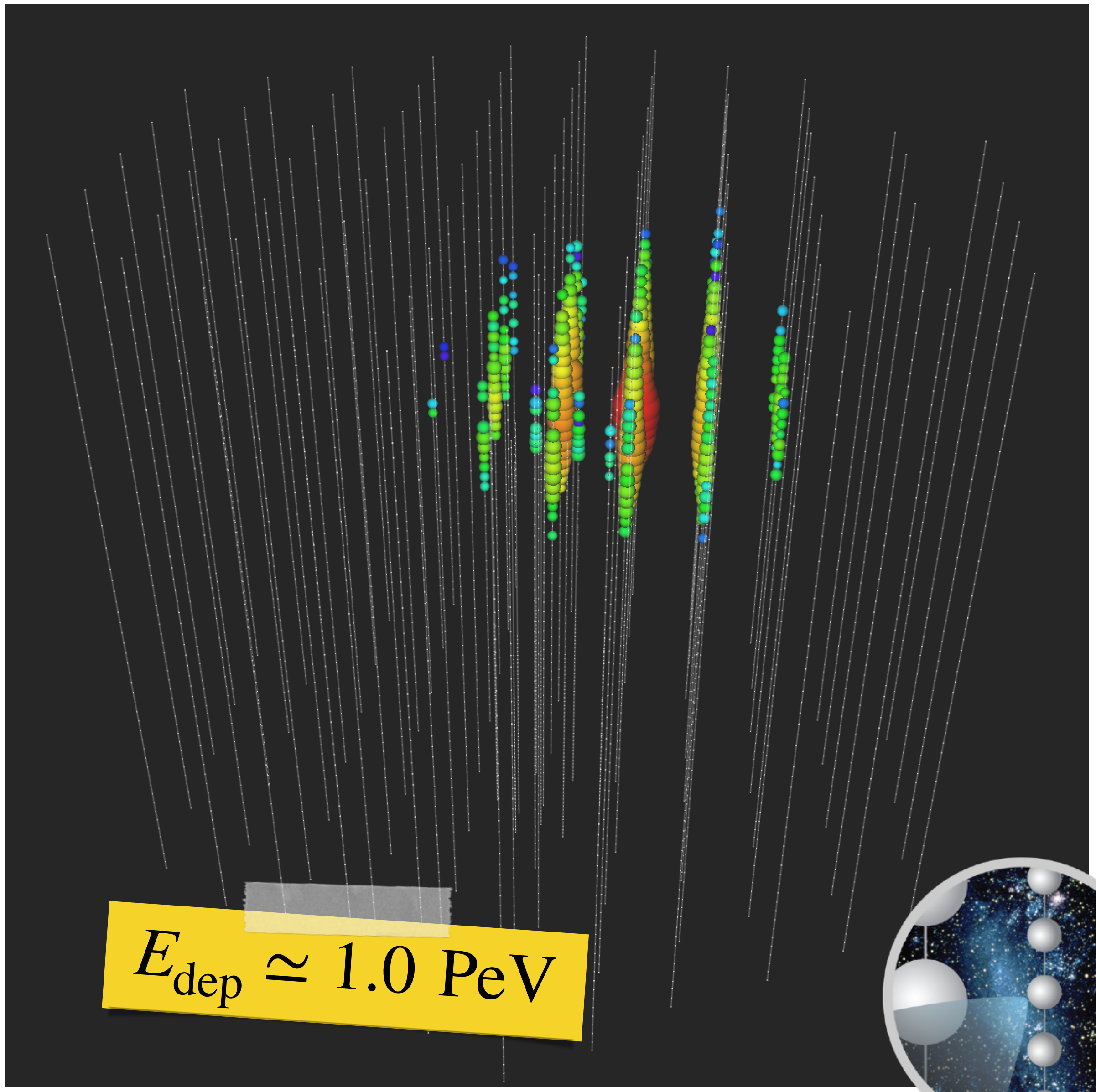
High-Energy Neutrinos

First observation of high-energy astrophysical neutrinos by IceCube in 2013.

"track event" (e.g. ν_μ CC interactions)

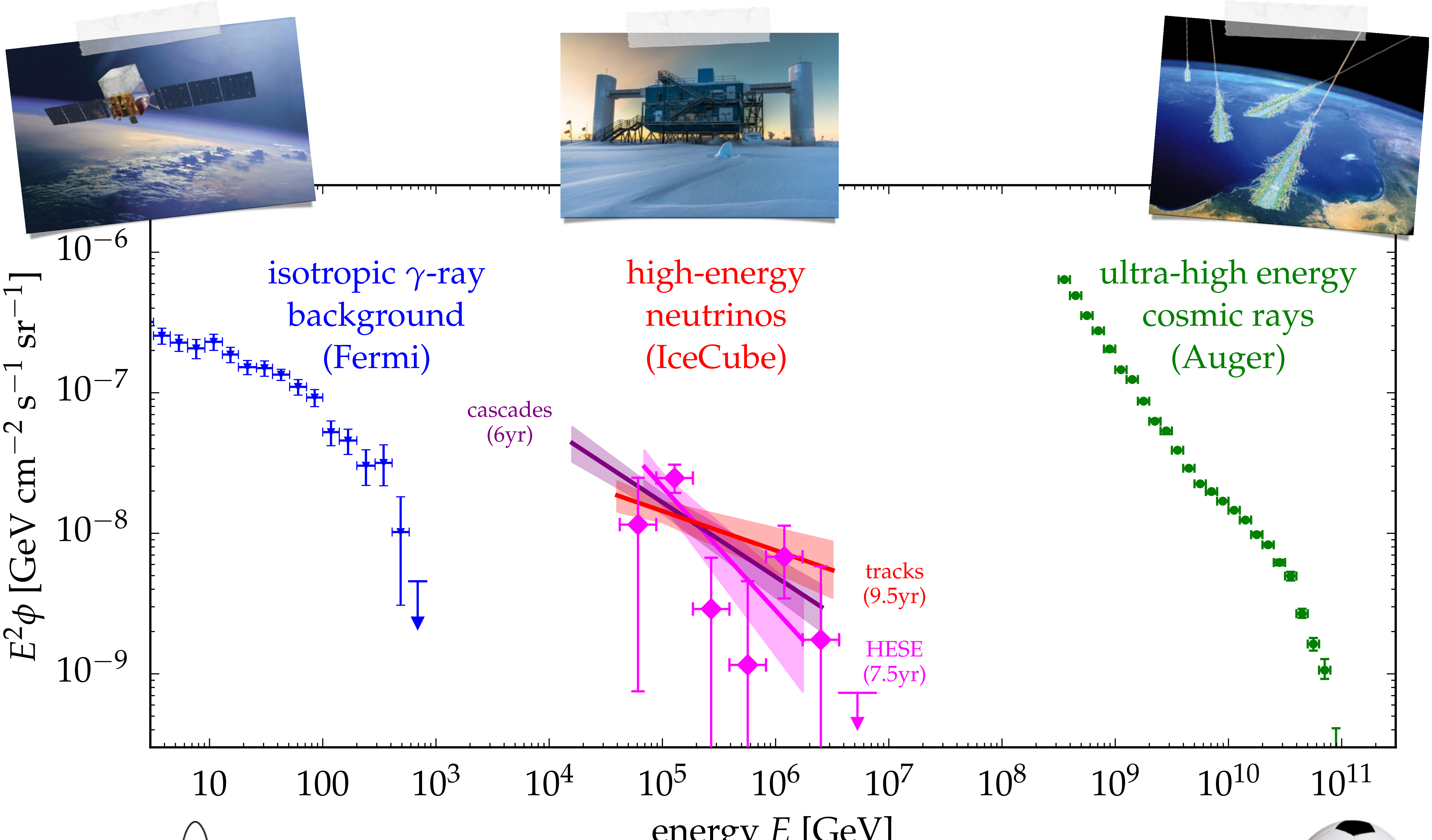


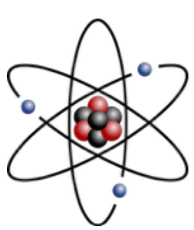
"cascade event" (e.g. NC interactions)



(colours indicate arrival time of Cherenkov photons from **early** to **late**)

Diffuse TeV-PeV Neutrinos

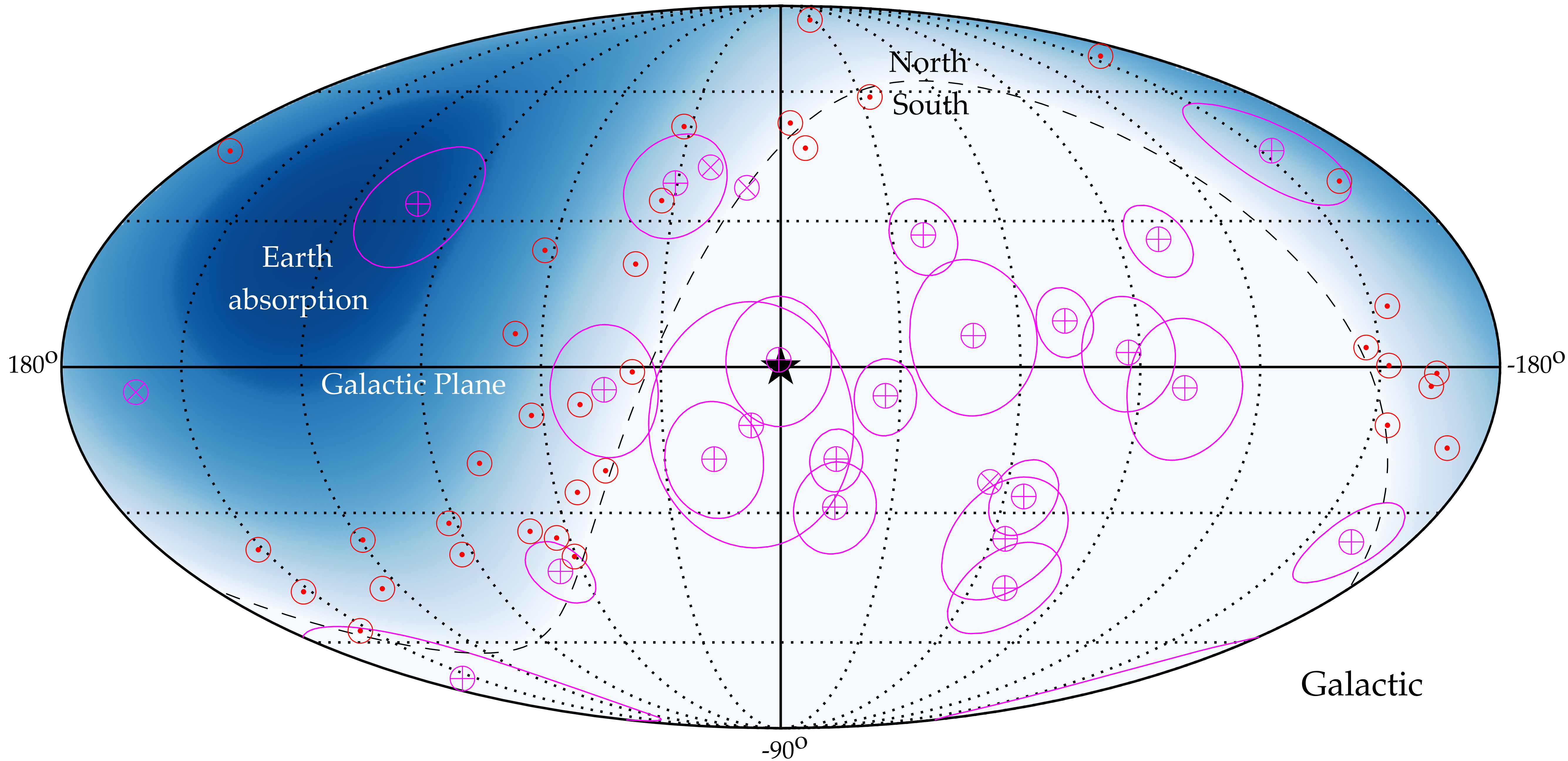




[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; arXiv:2011.03545]

Status of Neutrino Astronomy

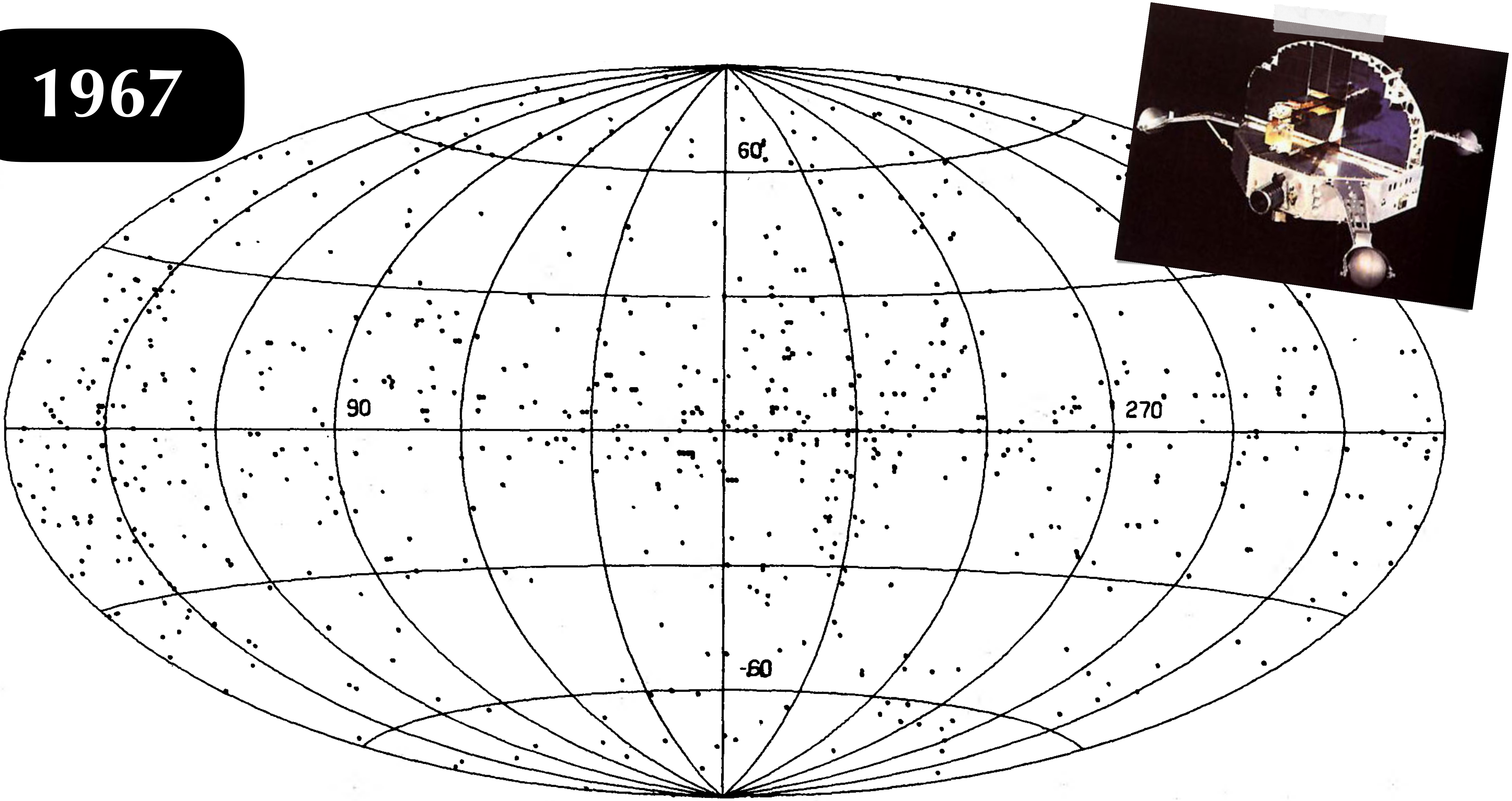
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Status of Neutrino Astronomy

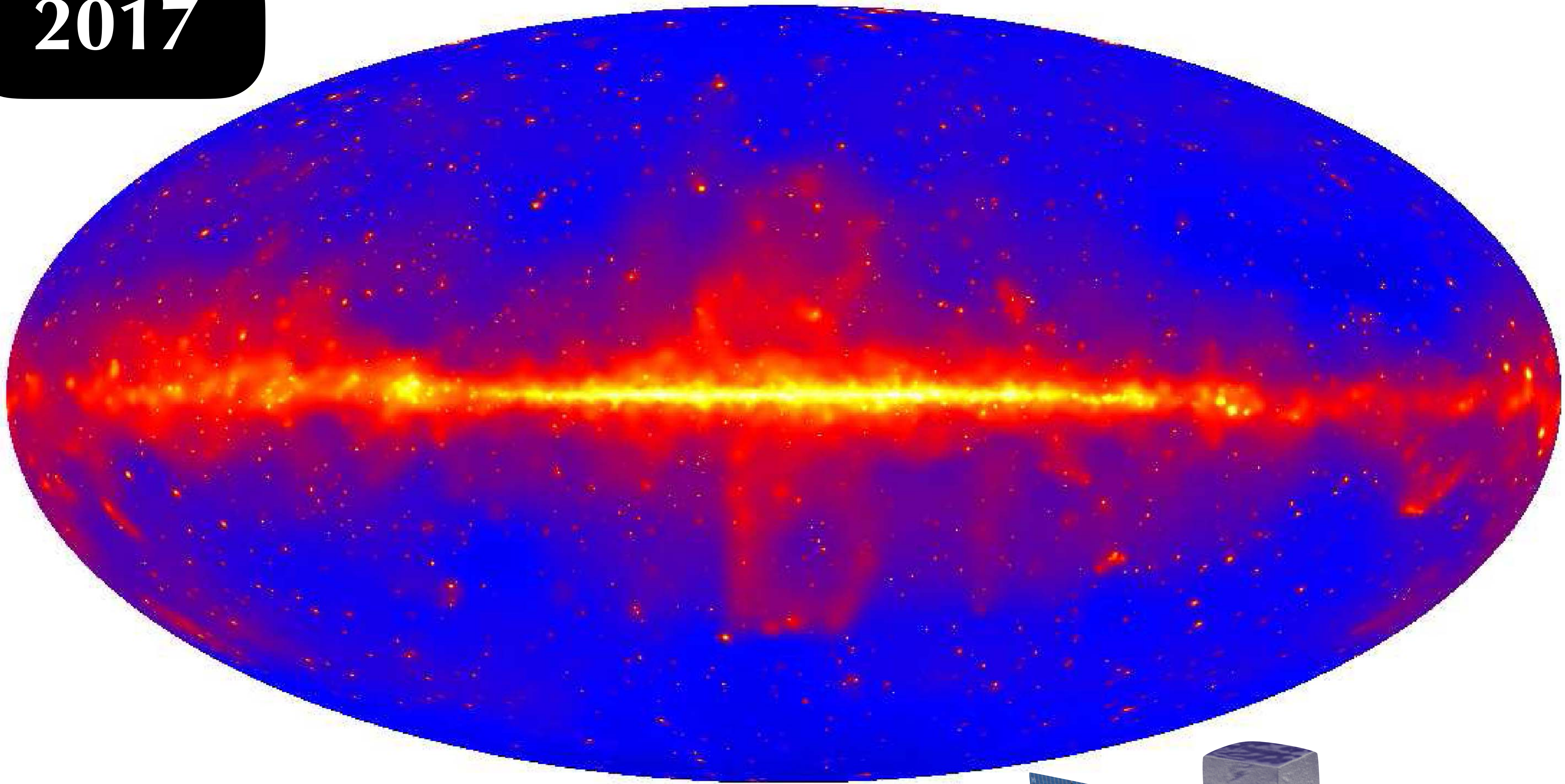
1967

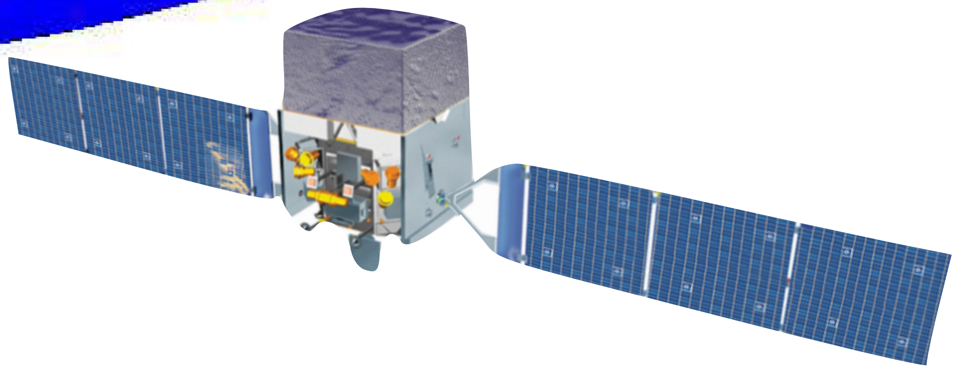


Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar'67)

Status of Neutrino Astronomy

2017





Fermi-LAT gamma-ray count map

Statistical Hypothesis Tests

Typical problem in physics and astronomy:

You have collected data with your experiment or observatory and want to test a theory (**signal hypothesis** H_1).

- *How can you judge if the hypothesis is correct or wrong?*
- *How does the alternative hypothesis* (**null hypothesis** H_0) *look like?*
- *How confident can you be that your conclusions are correct?*
- In most cases there is a chance that your decision is wrong:
  - You decided that H_1 is **correct**, but it is actually **wrong**. (type I error)
  - You decided that H_1 is **wrong,** but it is actually **correct.** (type II error)

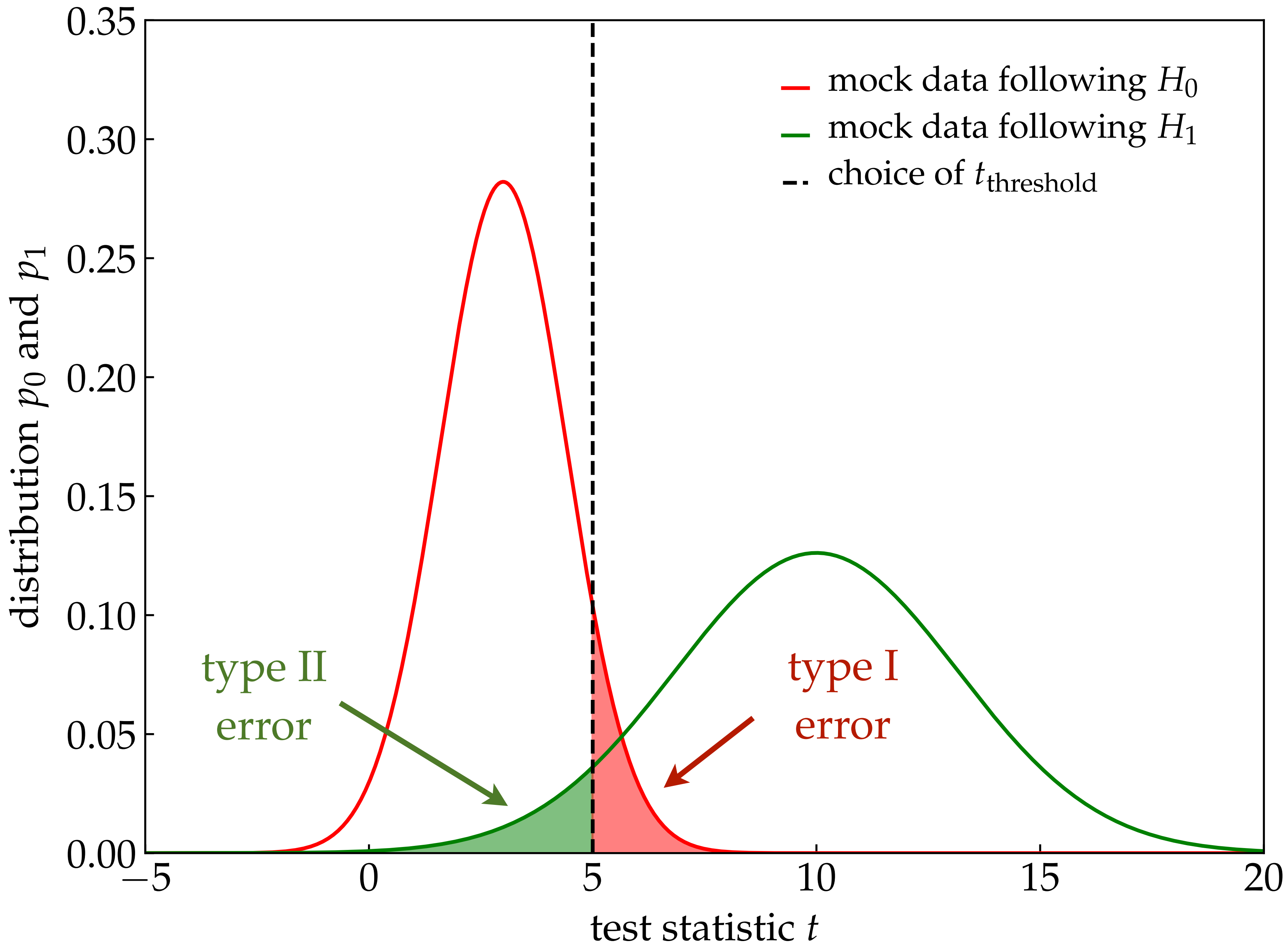
Statistical Hypothesis Tests

- A statistical hypothesis test is based on a quantity called **test statistic** that allows us to quantify the degree of confidence that your decision was right or wrong.

- A useful test statistic:
  - is **sensitive** to the signal hypothesis H_1 (that's a must!)
  - is **efficiently calculable** (*e.g.* fast calculation on your computer)
  - has a **well-known behaviour** for data following the null hypothesis H_0

- If we apply the statistical test to the observed data we can quantify the Type I ("false positive") and Type II ("false negative") errors by comparing to the expected test statistic distribution, p_0 and p_1, of data following background (H_0) and signal (H_1) hypothesis, respectively.

Statistical Hypothesis Tests



In a hypothesis test we have to choose a **threshold test statistic value** to either reject or accept the hypothesis.

Statistical Hypothesis Tests

- **significance** (α):

  probability that background creates outcome with $t_{\rm thr}$ or larger:

$$\alpha = \int_{t_{\rm thr}}^{\infty} \mathrm{d}t\, p_0(t) \qquad \text{(type I error)}$$

  - **Note:** It is a convention that t increases for a more "signal-like" outcome. If not, just define a new test statistic $t' \equiv -t$.

- **power of test** $(1-\beta)$:

  probability that signal creates outcome with $t_{\rm thr}$ or less:

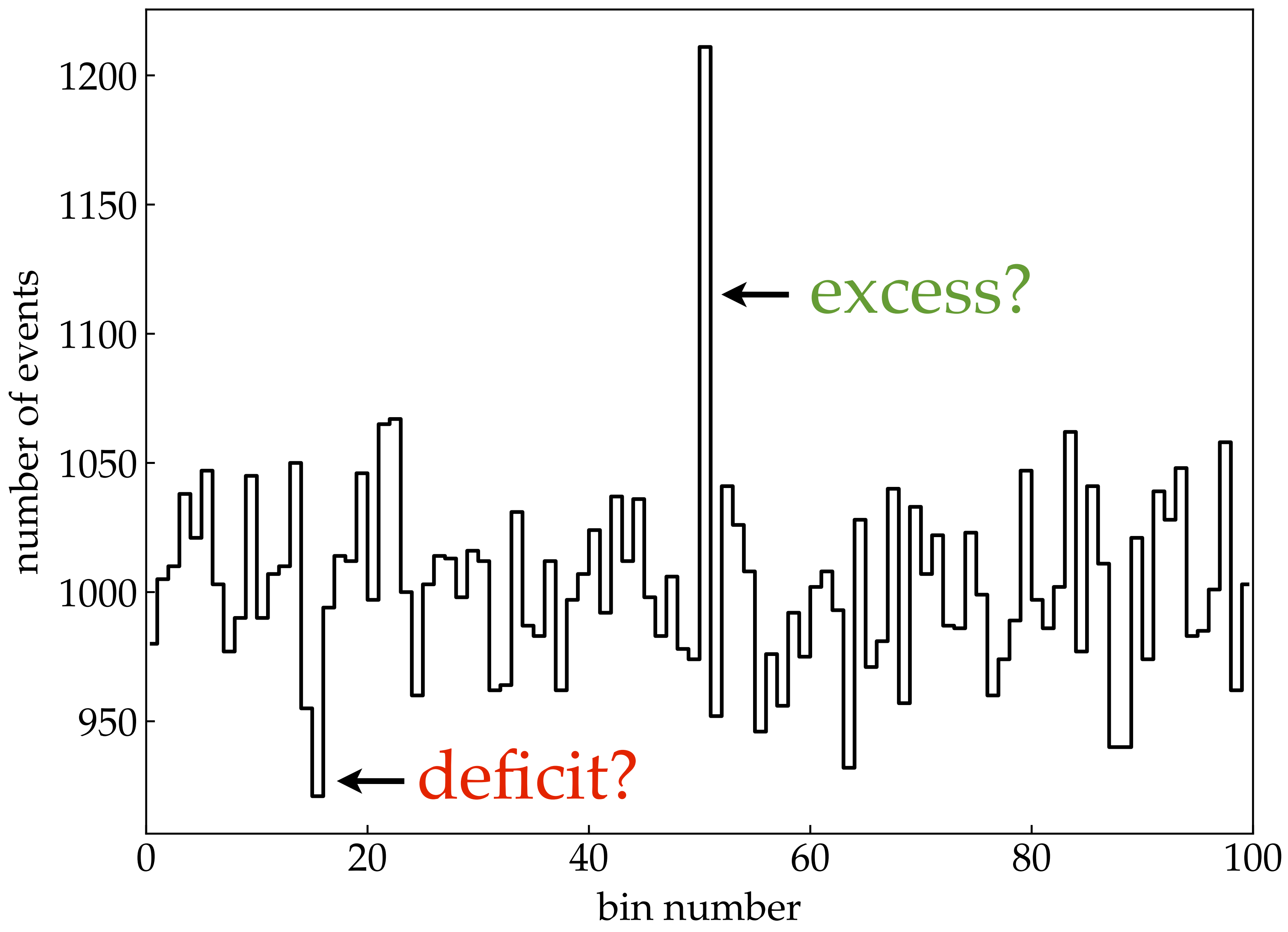
$$\beta = \int_{-\infty}^{t_{\rm thr}} \mathrm{d}t\, p_1(t) \qquad \text{(type II error)}$$

Statistical Hypothesis Tests

- A good statistical test will have good "separation" of p_0 and p_1 to allow to minimize type I/II errors. Separation from background allows to quantify significance of event excesses:
  - **discovery** (in particle physics): $\alpha = 5.7 \times 10^{-7} \quad (5\sigma)$
  - **evidence** (in particle physics): $\alpha = 2.7 \times 10^{-3} \quad (3\sigma)$
- Often, we want to estimate the performance of a statistical test prior to a measurement by simulations. We can determine this by tuning the signal strength, *e.g.* the IceCube experiment uses:
  - **discovery potential**: $\alpha = 5.7 \times 10^{-7} \qquad \beta = 0.5$
  - 90 % **sensitivity level**: $\alpha = 0.5 \qquad \beta = 0.1$

Statistical Hypothesis Tests

- Consider data (N_{tot} "events") distributed in N_{bins} bins.
- **Question:** Is there an excess or deficit in the data?



Likelihood Function

- **Likelihood function** $\mathscr{L}(\boldsymbol{\theta}\,|\,\mathbf{x})$ for data vector $\mathbf{x}$ and parameter vector $\boldsymbol{\theta}$.
- Assuming(!) Poisson statistics in our bins:

$$\mathscr{L}(\boldsymbol{\mu}\,|\,\mathbf{x}) = \prod_{i=1}^{N_{\rm bins}} \frac{1}{x_i!}\mu_i^{x_i}e^{-\mu_i}$$

- Null hypothesis ("no signal"):

$$\mu_i = \mu_{\rm bg} = {\rm const}$$

- Signal hypothesis ("signal (excess or deficit) in bin 1"):

$$\mu_i = \begin{cases} \mu_{\rm sig} + \mu^*_{\rm bg} & i = 1 \\ \mu^*_{\rm bg} & {\rm else} \end{cases}$$

- Note that, in general: $\mu_{\rm bg} \neq \mu^*_{\rm bg}$

Maximum-Likelihood

- For (mathematical) convenience $\mathscr{L} \rightarrow \ln \mathscr{L}$ ("log-likelihood"):

$$\ln \mathscr{L}(\boldsymbol{\mu} \,|\, \mathbf{x}) = \sum_{i=1}^{N_{\text{bins}}} (x_i \ln \mu_i - \mu_i) + \text{const}$$

- In general, maximum of $\mathscr{L}$ (or $\ln \mathscr{L}$) can only be determined numerically.
- *This example is easy enough to solve analytically.*
- maximum LH value of **background hypothesis** determined by:

$$\frac{\mathrm{d} \ln \mathscr{L}}{\mathrm{d}\mu_{\text{bg}}} = 0 = \sum_{i}^{N_{\text{bins}}} \left(\frac{x_i}{\mu_{\text{bg}}} - 1 \right)$$

- maximum $\hat{\mu}_{\text{bg}}$ is simply:

$$\hat{\mu}_{\text{bg}} = \frac{N_{\text{tot}}}{N_{\text{bins}}}$$

Maximum-Likelihood

- For the **signal hypothesis** we have to find the maximum w.r.t. signal and background strength:

$$\frac{\mathrm{d}\ln\mathscr{L}}{\mathrm{d}\mu_{\rm sig}} = 0 = \left(\frac{x_1}{\mu^*_{\rm bg} + \mu_{\rm sig}} - 1\right)$$

$$\frac{\mathrm{d}\ln\mathscr{L}}{\mathrm{d}\mu^*_{\rm bg}} = 0 = \left(\frac{x_1}{\mu^*_{\rm bg} + \mu_{\rm sig}} - 1\right) + \sum_{i=2}^{N_{\rm bins}}\left(\frac{x_i}{\mu^*_{\rm bg}} - 1\right)$$

- **Note**: signal term $\mu_{\rm sig}$ is (by construction) only present in bin 1.

- maximum $(\hat{\mu}^*_{\rm bg}, \hat{\mu}_{\rm sig})$ obeys:

$$\hat{\mu}^*_{\rm bg} = \frac{N_{\rm tot} - x_1}{N_{\rm bins} - 1} \qquad \hat{\mu}_{\rm sig} = x_1 - \hat{\mu}^*_{\rm bg}$$

Maximum-Log-Likelihood Ratio

- We now define the test statistic λ as the **maximum likelihood ratio**:

$$\lambda(x) \equiv -2\ln\frac{\mathcal{L}(\hat{\mu}_{\rm bg}, 0\,|\,\mathbf{x})}{\mathcal{L}(\hat{\mu}^*_{\rm bg}, \hat{\mu}_{\rm sig}\,|\,\mathbf{x})}$$

- After some algebra using the solutions for $\hat{\mu}^*_{\rm bg}$, $\hat{\mu}_{\rm bg}$ and $\hat{\mu}_{\rm sig}$:

$$\lambda(x) = 2x_1\ln\left(\frac{N_{\rm bins}}{N_{\rm tot}}x_1\right) + 2(N_{\rm tot} - x_1)\ln\left(\frac{N_{\rm bins}}{N_{\rm tot}}\frac{N_{\rm tot}-1}{N_{\rm bins}-1}\right)$$

- **Note:** The first (second) term in this equation vanishes in the special case $x_1 = 0$ ($N_{\rm tot} - x_1 = 0$).
- Let's explore the behaviour of this TS:

```
max_LH_example.ipynb
```

Maximum-Log-Likelihood Ratio

- Example python notebooks can be found here:

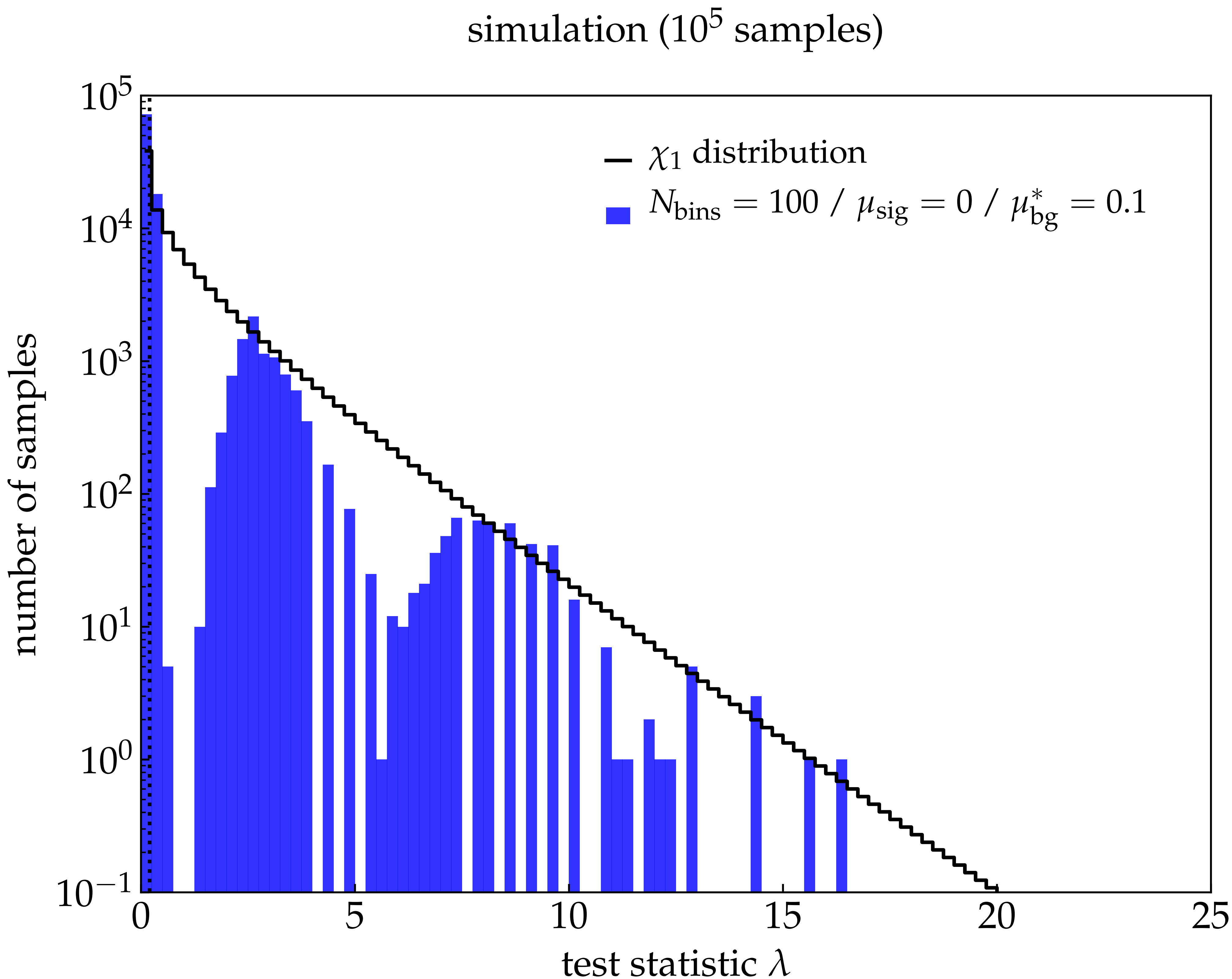
  `https://github.com/mahlers77/KSETA2023`

- You can use *Google Colaboratory* to execute the python notebook:

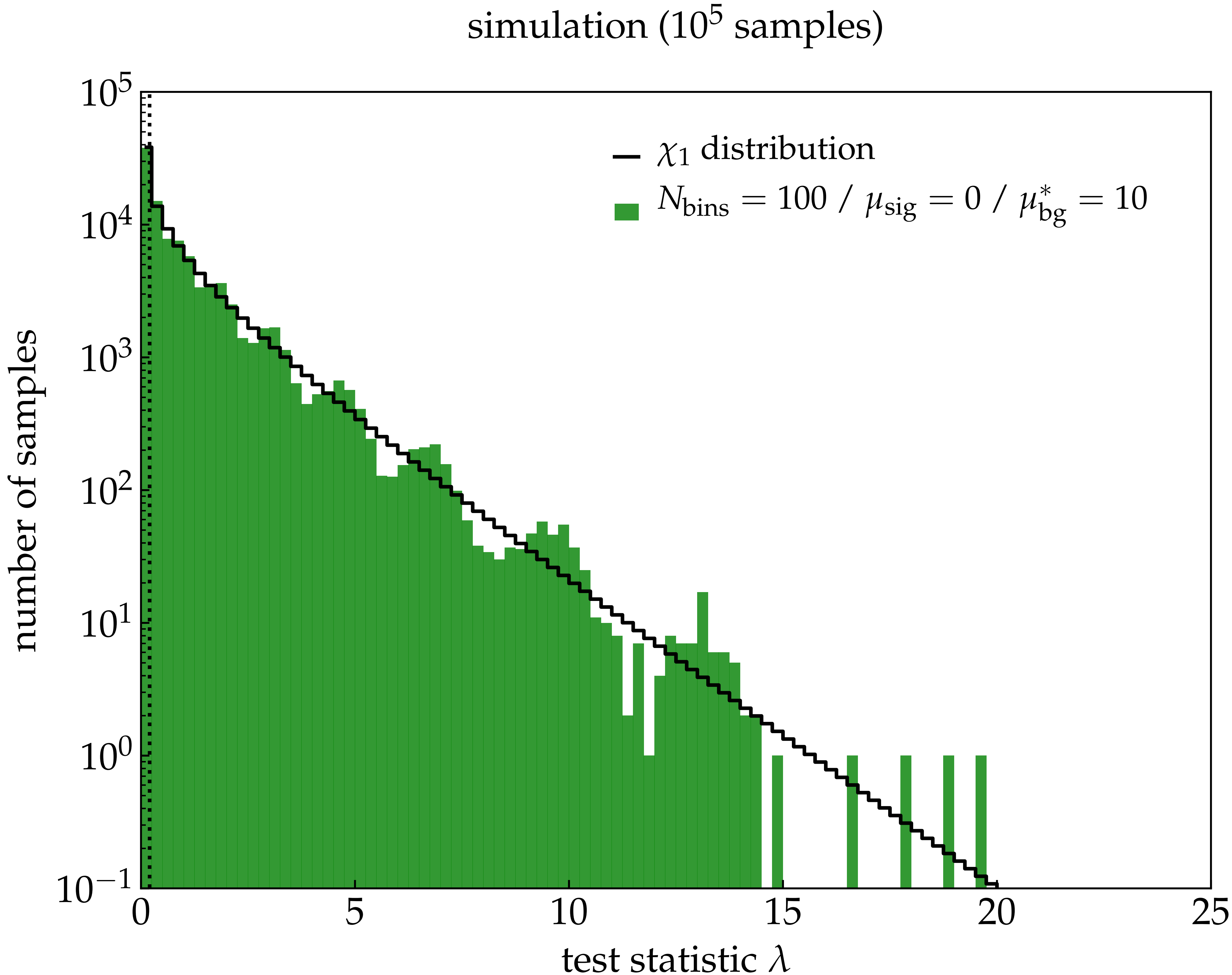
  `https://colab.research.google.com`

- Generate TS distributions from mock data for various cases:
  - small and large background expectations
  - small and large signal expectations
  - small and large number of bins

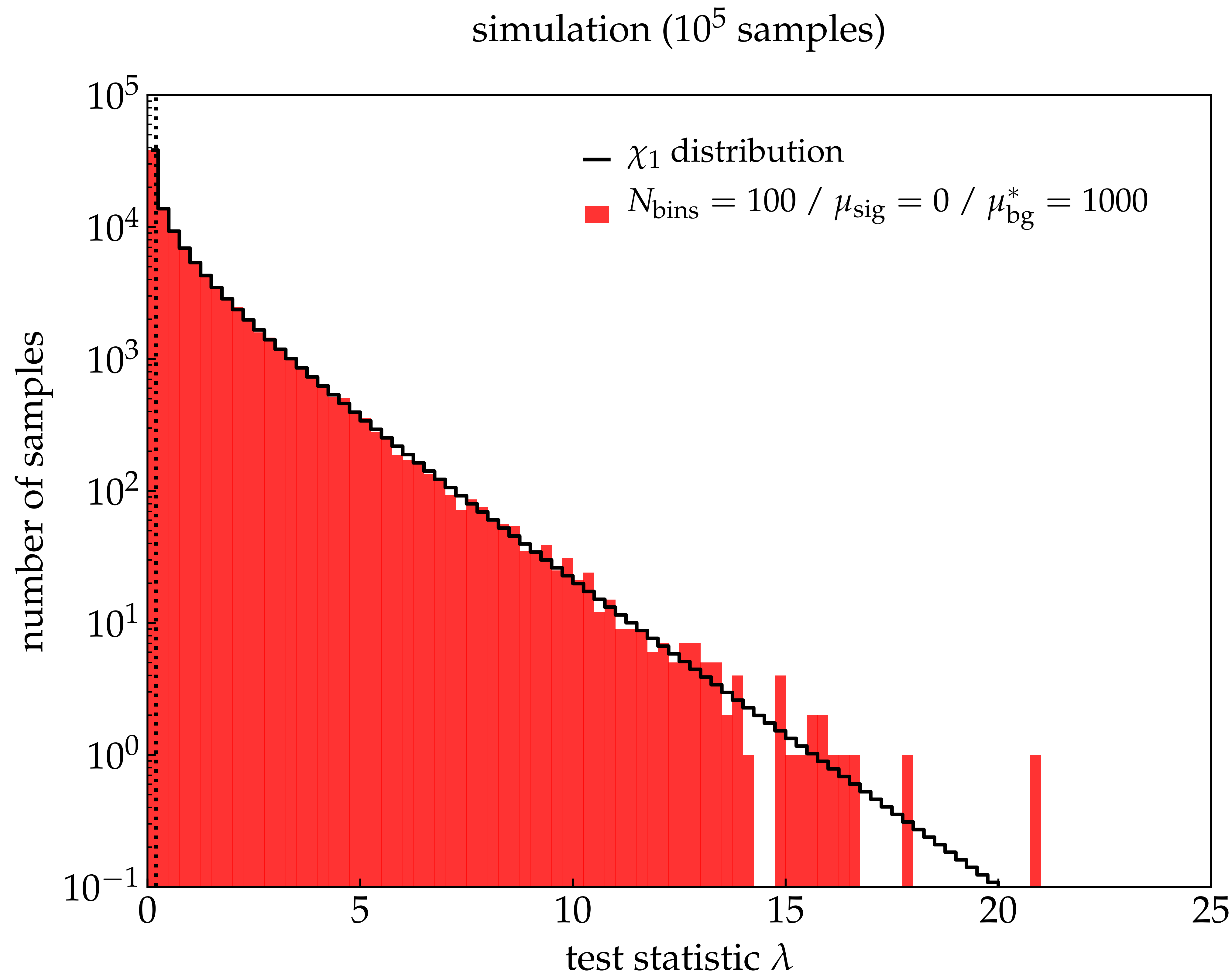
Maximum-Log-Likelihood Ratio



Maximum-Log-Likelihood Ratio



Maximum-Log-Likelihood Ratio



Wilks' Theorem

THE LARGE-SAMPLE DISTRIBUTION OF THE LIKELIHOOD RATIO FOR TESTING COMPOSITE HYPOTHESES[1]

BY S. S. WILKS

(. . .)

Theorem: If a population with a variate x is distributed according to the probability function $f(x, \theta_1, \theta_2 \cdots \theta_h)$, such that optimum estimates $\bar{\theta}_i$ of the θ_i exist which are distributed in large samples according to (3), then when the hypothesis H is true that $\theta_i = \theta_{0i}$, $i = m + 1, m + 2, \cdots h$, the distribution of $-2 \log \lambda$, where λ is given by (2) is, except for terms of order $1/\sqrt{n}$, distributed like χ^2 with $h - m$ degrees of freedom.

[Wilks, Annals Math.Statist. 9 (1938) 1]

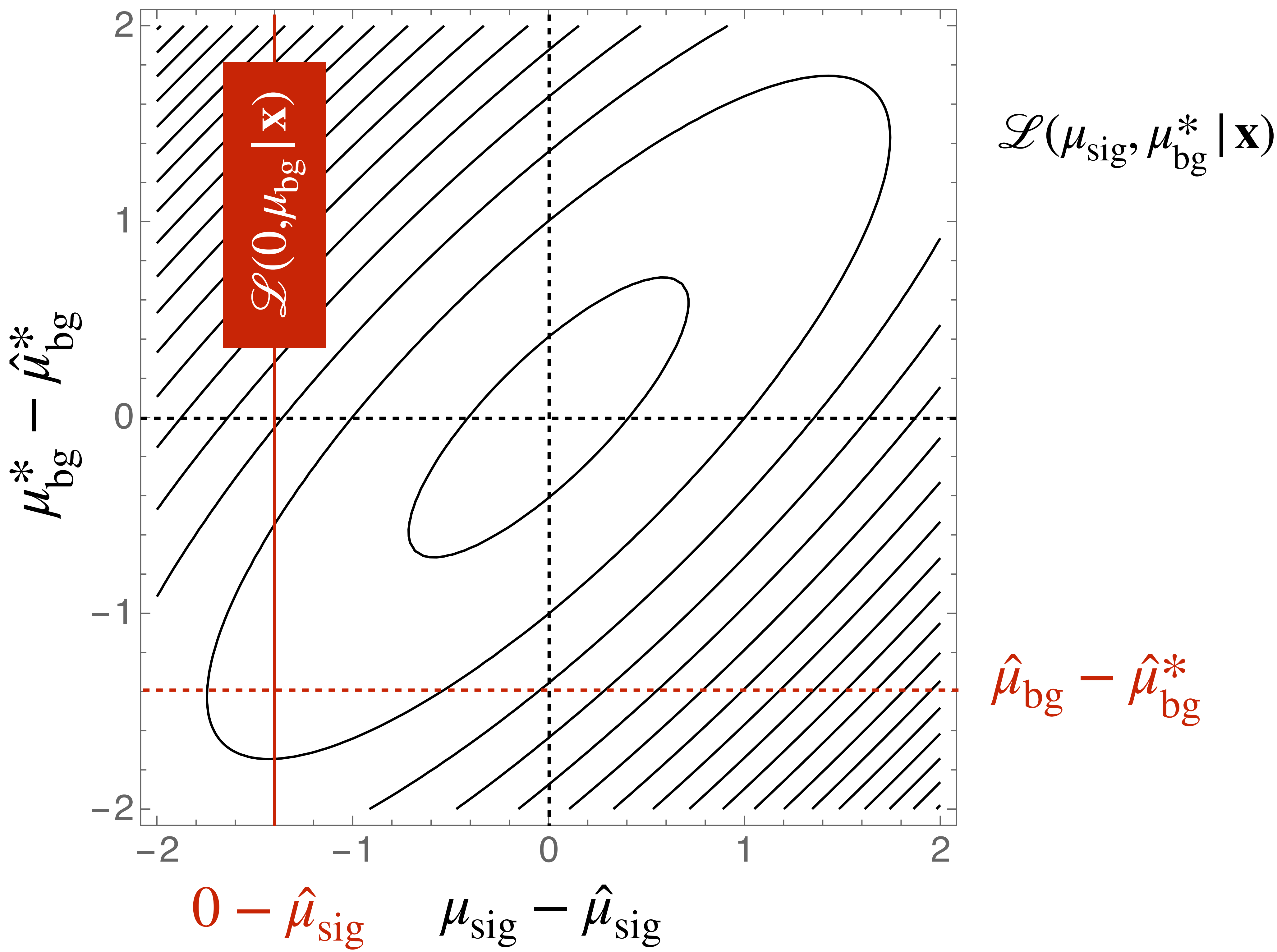
Wilks' Theorem

- *Prerequisites*:
  - Let $\mathbf{x}$ be data that follows a probability function $f(\mathbf{x}\,|\,\theta_1, \ldots, \theta_n)$.
  - **Unconstrained likelihood** $\mathscr{L}(\theta_1, \ldots, \theta_n\,|\,\mathbf{x})$ has maximum at $\hat{\theta}_1, \ldots, \hat{\theta}_n$.
  - True hypothesis is $\theta_1^{(0)}, \ldots, \theta_m^{(0)}$ with $m < n$.
  - **Constrained likelihood** $\mathscr{L}(\theta_1^{(0)}, \ldots, \theta_m^{(0)}, \theta_{m+1}, \ldots, \theta_n\,|\,\mathbf{x})$ has maximum at $\hat{\theta}'_{m+1}, \ldots, \hat{\theta}'_n$.
- For a large number of samples $\mathbf{x}$, the distribution of the test statistic:

$$\lambda(\mathbf{x}) \equiv -2\ln\frac{\mathscr{L}(\theta_1^{(0)}, \ldots, \theta_m^{(0)}, \hat{\theta}'_{m+1}, \ldots, \hat{\theta}'_n\,|\,\mathbf{x})}{\mathscr{L}(\hat{\theta}_1, \ldots, \hat{\theta}_n\,|\,\mathbf{x})}$$

approaches a χ^2_k **distribution** with $k = n - m$ in the limit of large N_{tot}.

Wilks' Theorem



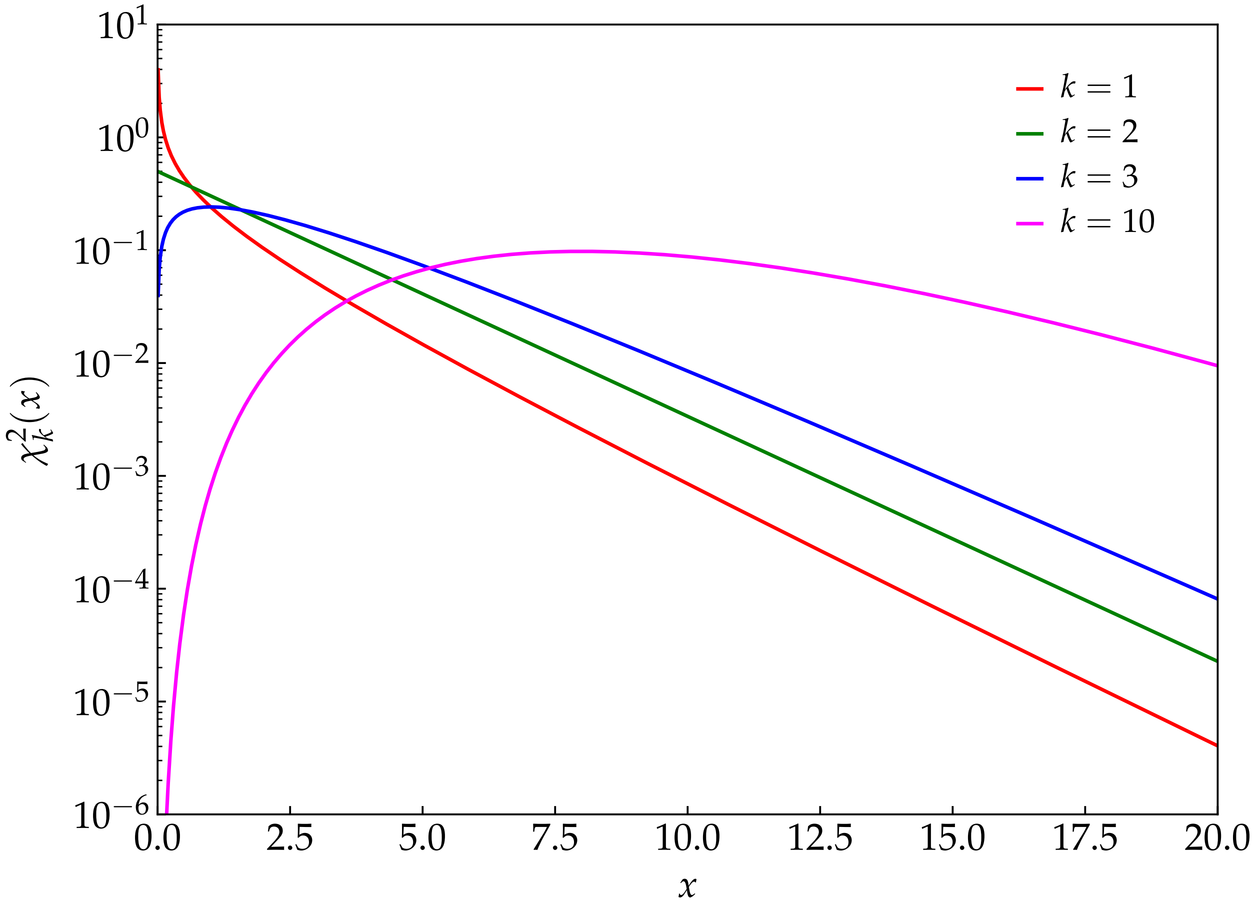
Chi-Square Distributions

- Definition of the χ^2_k **distribution:**

$$\chi^2_k = \frac{x^{k/2-1}e^{-x/2}}{2^{k/2}\Gamma(k/2)}$$

- **degrees of freedom** in our example:

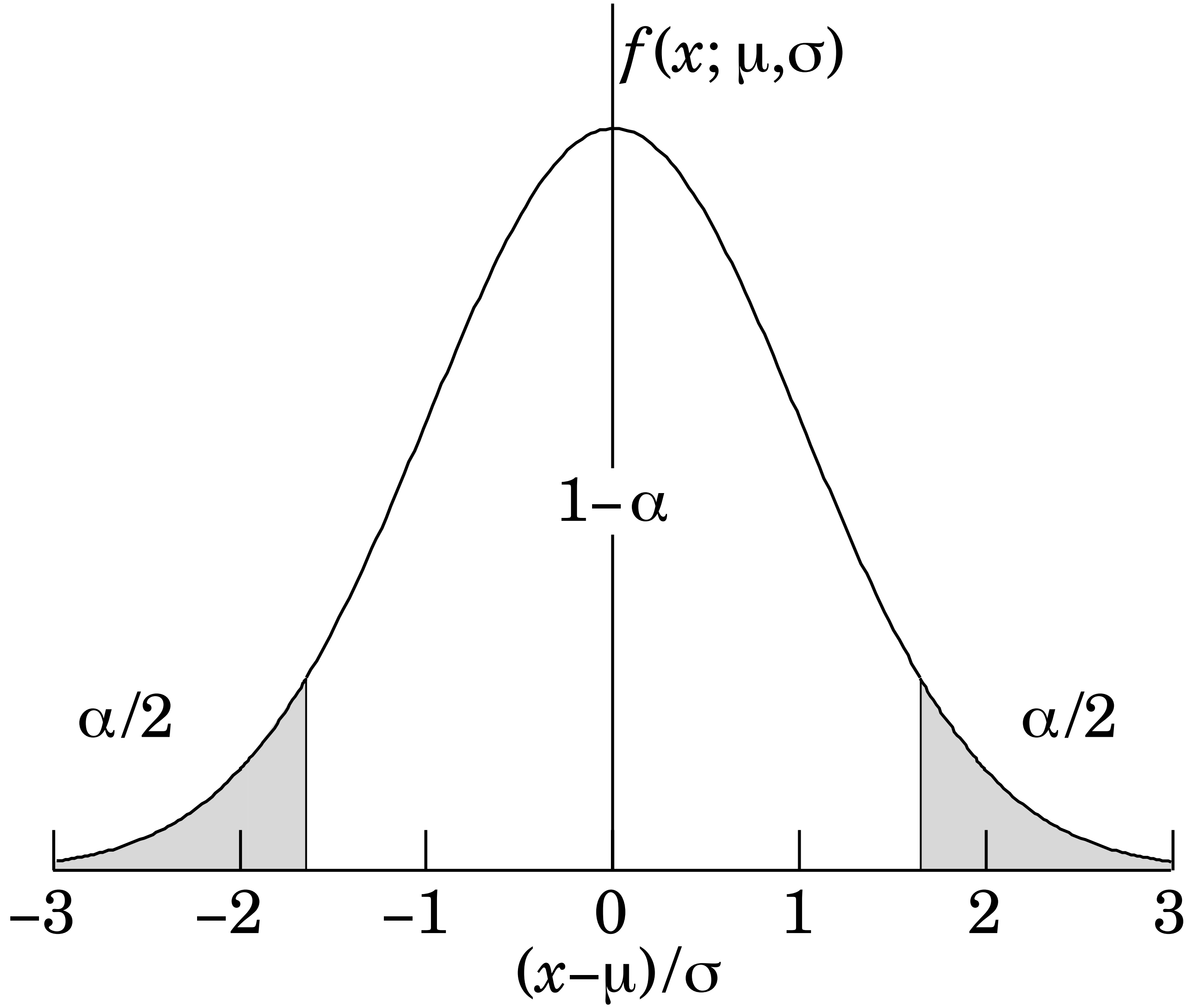
$$k = 2 - 1 = 1$$



- integral over χ^2_k distribution is related to the integrated probability of a k-variate normal distribution:

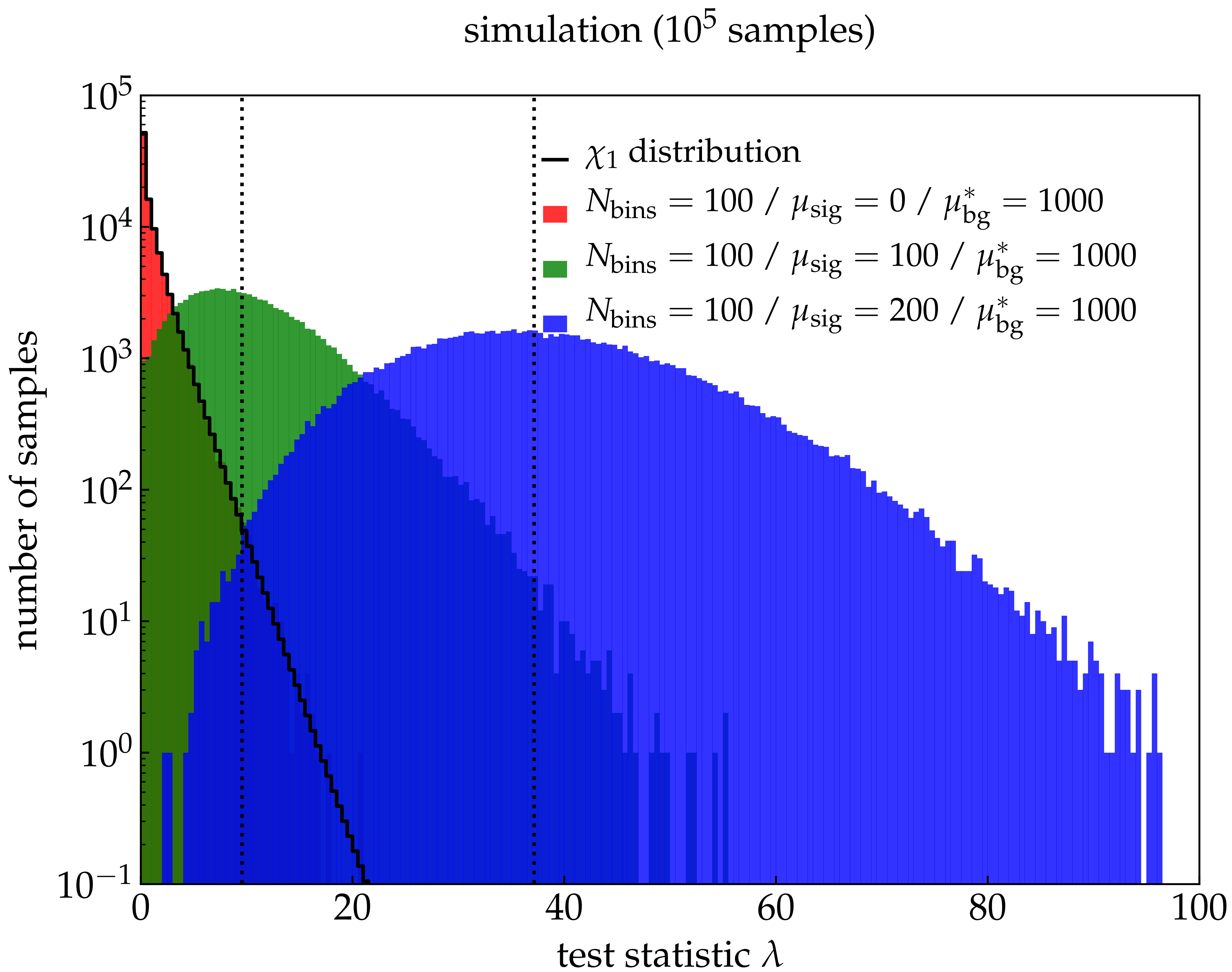
$$\int_{\lambda_{\rm obs}} {\rm d}\lambda\, \chi^2_k(\lambda) = \int_{\mathbf{r}^T\boldsymbol{\Sigma}^{-1}\mathbf{r}>\lambda_{\rm obs}} {\rm d}r_1\ldots{\rm d}r_k \frac{1}{\sqrt{(2\pi)^k\det\boldsymbol{\Sigma}}}\exp(-\mathbf{r}^T\boldsymbol{\Sigma}^{-1}\mathbf{r}/2)$$

Chi-Square Distributions



$$\alpha = \int_{\lambda_{\rm obs}} \mathrm{d}\lambda\, \chi^2_1(\lambda) = 1 - \mathrm{erf}\left(\sqrt{\lambda_{\rm obs}/2}\right)$$

Application of Wilks' Theorem



Application of Wilks' Theorem

- For large $N_{\rm tot}$ we can apply Wilks' theorem and calculate the **"p-value"** of an observed excess:

$$p = \int_{\lambda_{\rm obs}}^{\infty} {\rm d}\lambda\, \chi^2_k(\lambda) = 1 - {\rm erf}(\sqrt{\lambda_{\rm obs}/2})$$

- From signal simulations ($\mu_{\rm bg} = 1000$, $N_{\rm bins} = 100$), we can determine the median test statistic and corresponding **significance level,** *e.g.*:
  - $\mu_{\rm sig} = 100 \;\to\; \lambda_{\rm med} \simeq 9.8 \;\to$ Wilks' theorem: $p_{\rm med} \simeq 0.0017$
  - $\mu_{\rm sig} = 200 \;\to\; \lambda_{\rm med} \simeq 38.0 \;\to$ Wilks' theorem: $p_{\rm med} \simeq 7.1 \times 10^{-10}$
- The **5σ discovery threshold** corresponds to $\mu_{\rm sig} \simeq 162$ events.

Application of Wilks' Theorem

- **discovery potential:**

Level of $\mu_{\rm sig}$ such that $50\,\%$ of samples have a chance probability of less than 5.7×10^{-7} to be generated by background only.

- This is a challenge for brute-force background simulation – you need $N_{\rm samples} \gg 10^7$ for accuracy!

- **Wilks' theorem** allows to extrapolate the background distribution much simpler:

Level of $\mu_{\rm sig}$ such that $50\,\%$ of samples have $\lambda \geq \lambda_{\rm threshold} = 5^2 = 25$.

Li-Ma Formula

ANALYSIS METHODS FOR RESULTS IN GAMMA-RAY ASTRONOMY

TI-PEI LI AND YU-QIAN MA
High Energy Astrophysics Group, Institute of High Energy Physics,
Academia Sinica, Beijing, China

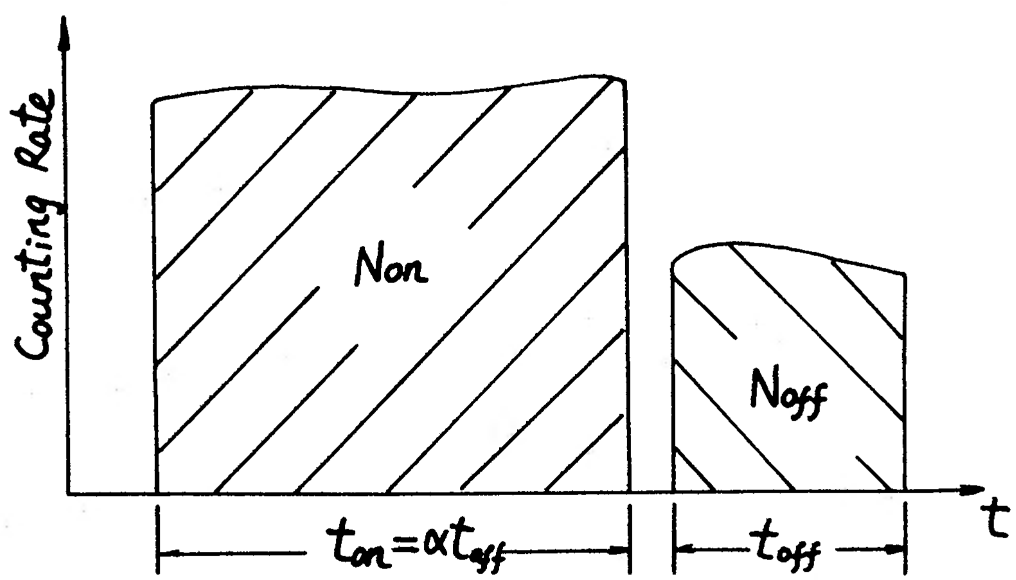
Received 1982 September 20; accepted 1983 February 7

ABSTRACT

The current procedures for analyzing results of γ-ray astronomy experiments are examined critically. We propose two formulae to estimate the significance of positive observations in searching γ-ray sources or lines. The correctness of the formulae are tested by Monte Carlo simulations.

[Li & Ma, ApJ 272 (1983) 317]

$$\boxed{S = \sqrt{-2\ln\lambda} = \sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2}}$$



$$N_{\rm on} \to x_1$$

$$N_{\rm off} \to N_{\rm tot} - x_1$$

$$\alpha^{-1} \to N_{\rm bins} - 1$$

Example: IceCube 10-yr Data

- We can devise a simplified version of this analysis by a binned maximum likelihood test with an energy threshold.

- Analysis of IceCube PS data from '08-'18 : `IceCube_allsky.ipynb`

- We can estimate the background expectation $\mu_{\rm bgr,i}$ via **RA scrambling**:

$$\mathrm{RA} \to \mathrm{RA} + \theta_{\rm rnd}$$

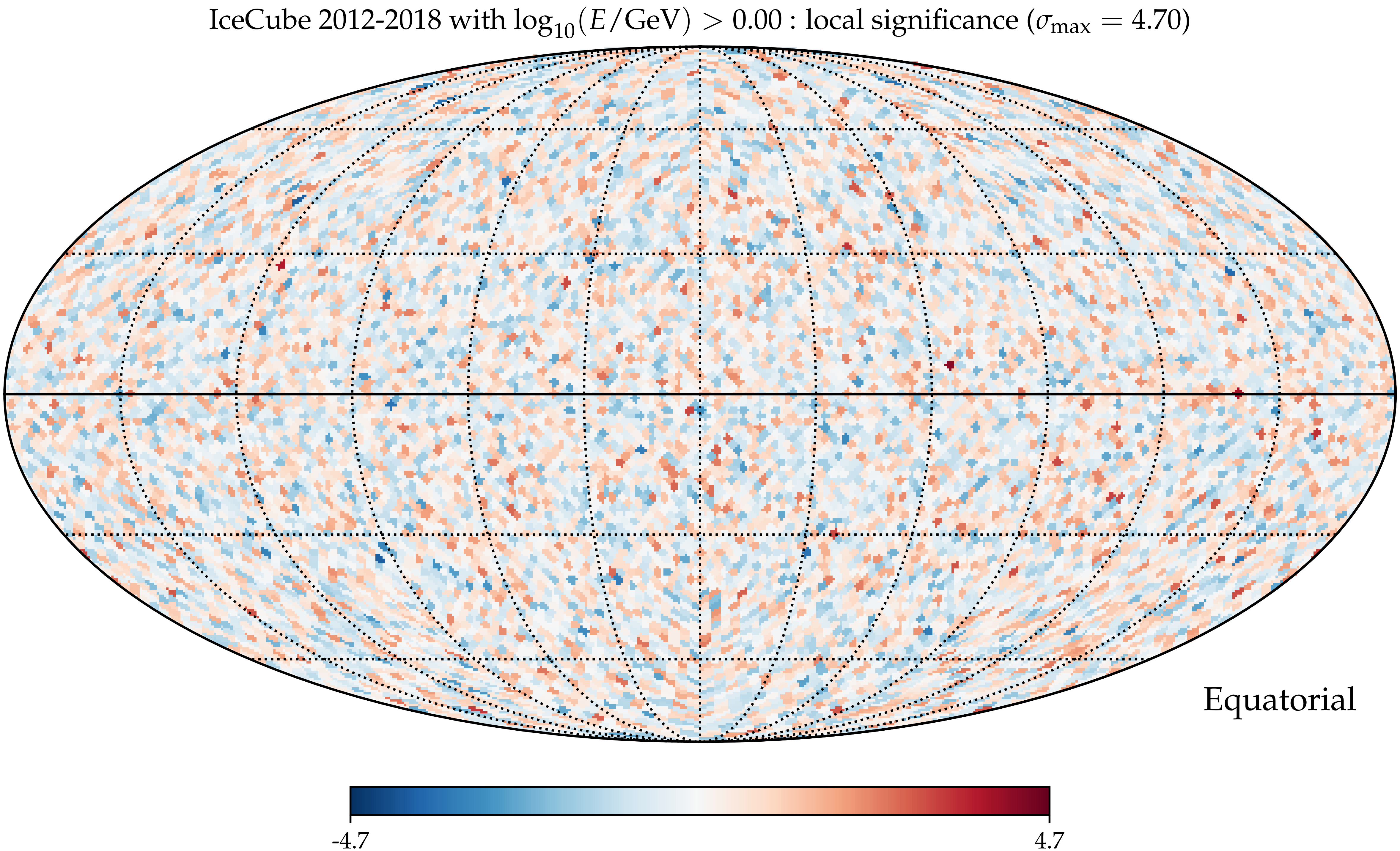
- The maximum log-likelihood ratio for a **point-source in each pixel *i*** can be approximated as:

$$\lambda_i = -2\ln\frac{\mathscr{L}_{0,i}}{\mathscr{L}_i} = 2x_i\left(\ln x_i - \ln\mu_{\rm bgr,i}\right) - 2\left(x_i - \mu_{\rm bgr,i}\right)$$

- Pre-trial p-value and significance S (units of σ) per bin:

$$p = 1 - \mathrm{erf}(\sqrt{\lambda_i/2}) \qquad S = \sqrt{\lambda_i}$$

Example: IceCube 10-yr Data



`IceCube_allsky.ipynb`

Unbinned Max-Likelihood

- The previous maximum-likelihood test required that we binned events.
- We can incorporate the uncertainty of the event reconstruction in an **unbinned maximum likelihood** test for n_s signal events:

$$\mathscr{L}(n_s, \boldsymbol{\theta} \,|\, \mathbf{x}) = \prod_{i=1}^{N_{\rm tot}} \left[\frac{n_s}{N_{\rm tot}} S_i(\boldsymbol{\theta}) + \left(1 - \frac{n_s}{N_{\rm tot}}\right) B_i\right]$$

- For instance, in a neutrino analysis with uncertainties of event location $\boldsymbol{\Omega}$ and energy E described by probability distributions w_i, the **signal** and **background** weights are:

$$S_i(\boldsymbol{\theta}) = \int \mathrm{d}\Omega \int \mathrm{d}E\, w_i(\Omega, E) T_{\rm sig}(\Omega, E, \boldsymbol{\theta})$$

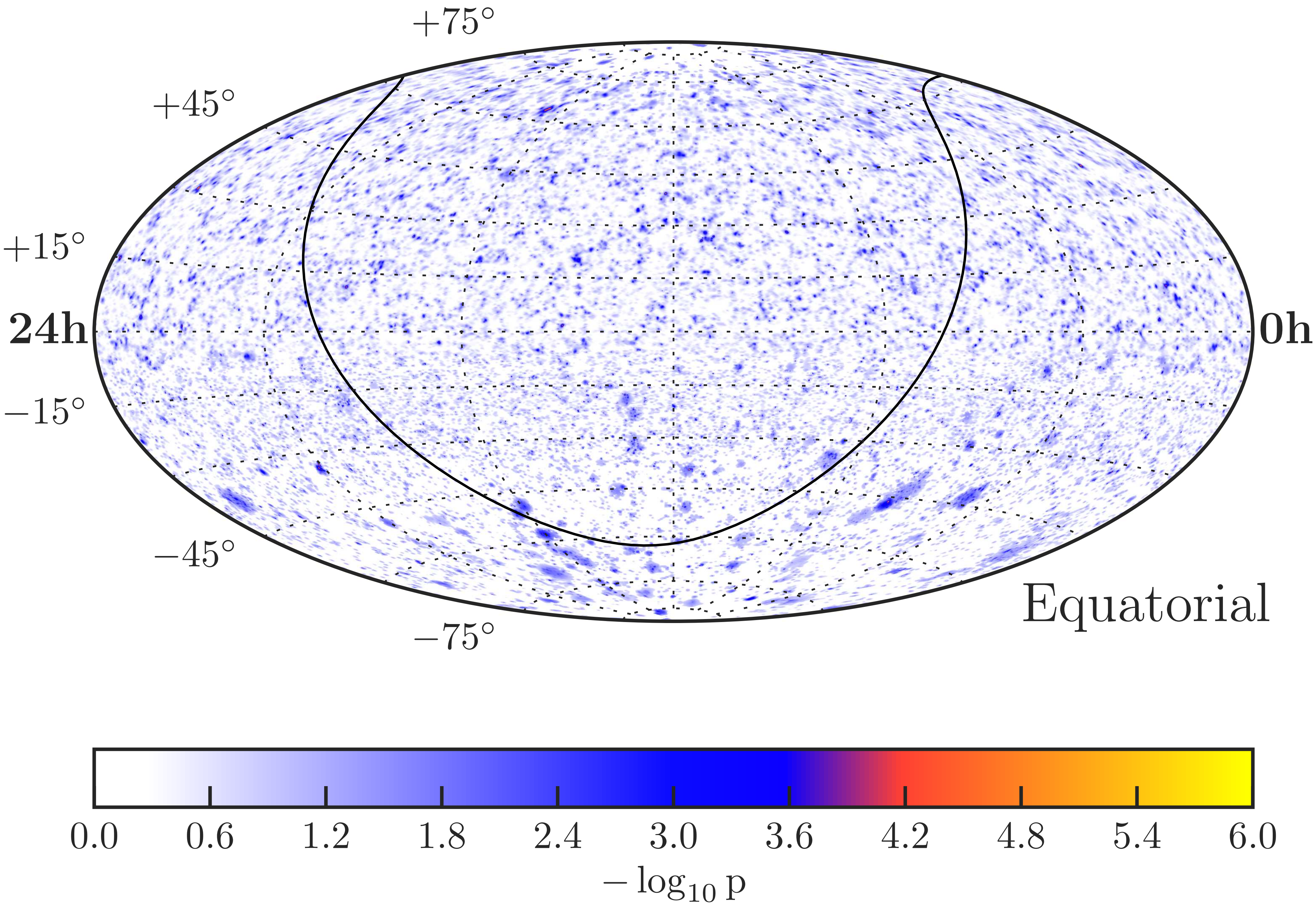
$$B_i(\boldsymbol{\theta}) = \int \mathrm{d}\Omega \int \mathrm{d}E\, w_i(\Omega, E) T_{\rm bgr}(\Omega, E)$$

Unbinned Max-Likelihood

- Normalized signal template $T_{\rm sig}(\Omega, E, \boldsymbol{\theta})$:
  - point-source analysis: $\boldsymbol{\theta} = \{\gamma_{\rm src}, \mathbf{n}_{\rm src}\}$
  - stacking of M (identical) PSs: $\boldsymbol{\theta} = \{\gamma_{\rm src}, \mathbf{n}_1, \ldots, \mathbf{n}_M, \mathbf{w}_1, \ldots, \mathbf{w}_M\}$
  - extended sources: $\boldsymbol{\theta} = \{\gamma_{\rm src}, \mathbf{n}_{\rm src}, \sigma_{\rm src}\}$

- Normalized background template $T_{\rm bgr}(\Omega, E)$:
  - background of **atmospheric muons and neutrinos** with spectrum $E^{-3.7}$ (conventional) and $E^{-2.7}$ (prompt) components; azimuthally symmetric
  - derived from **MC simulations** or from **background scrambling**, *i.e.* randomized arrival times (corresponding to right ascension scrambling at Southpole).

Example: IceCube 7-year



[IceCube ApJ 835 (2017) 2, 151]

IceCube "all-sky" point-like source search:
each location tested for an excess!

Trial Correction

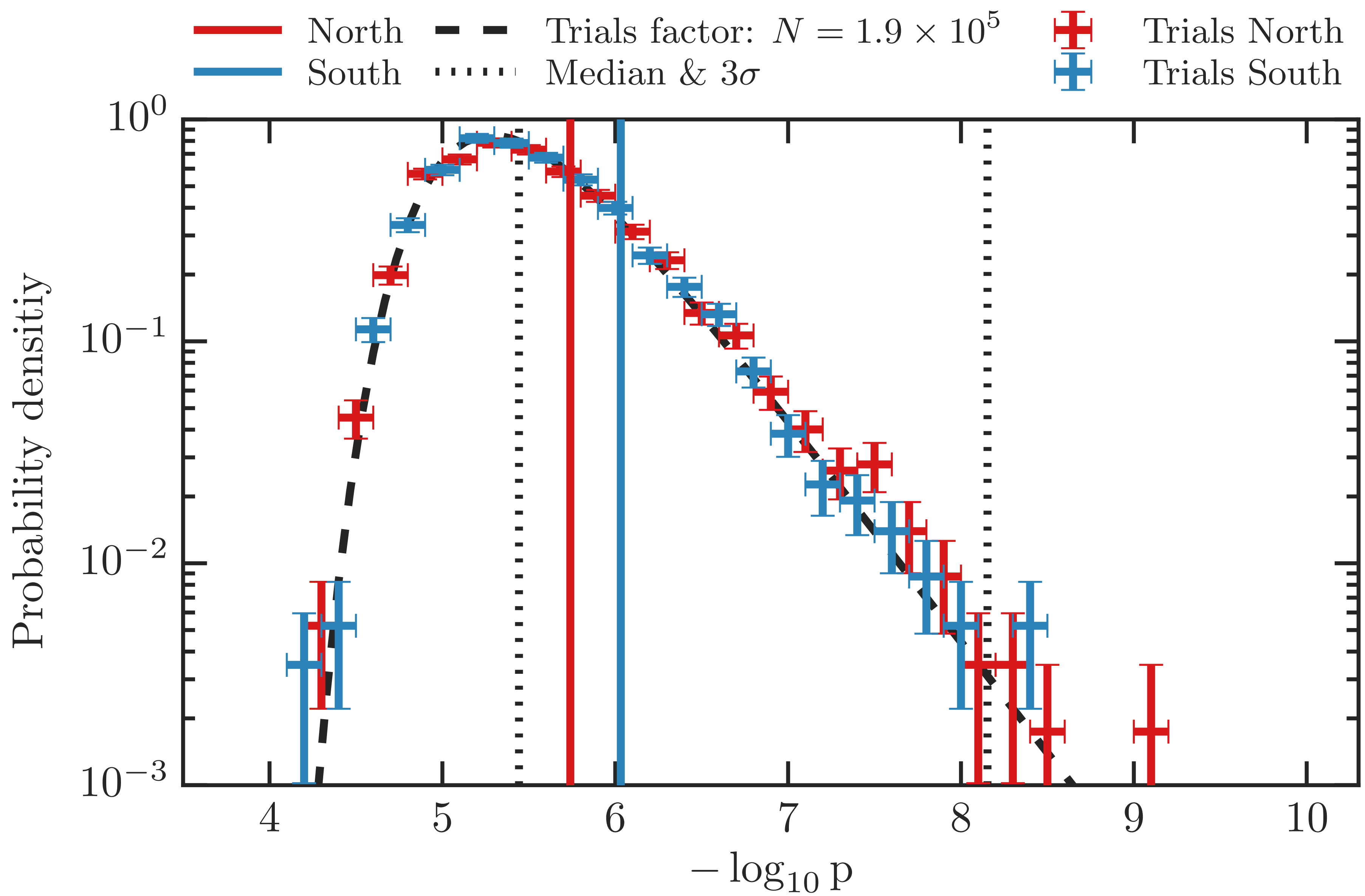
- What happens if we want to find a signal not just in the first bin but in any of the $N_{\rm bins}$ bins?
- We can simply repeat the test over all bins and identify the bin with minimal p-value $p_{\rm min}$.
- **Problem:** There are many bins ("hypothesis") and we have to account for the fact that there can be a chance fluctuation in the local p-values.
- If $N_{\rm bins}$ are independent of each other (as in our example) then we can define a post-trial p-value as:

$$p_{\rm post} = 1 - \underbrace{(1 - p_*)^{N_{\rm bins}}}_{\text{background probability}} \simeq N_{\rm bins} p_*$$

- Number of independent "trials" ($N_{\rm trials}$) is often difficult to estimate.

Example: IceCube 7-year

- Trial factor: $N_{\rm trials} \sim N_{\rm bins} \sim \mathcal{O}(10000)$
- IceCube procedure: choose maximal $p_{\rm local}$ in sky map as a new test statistic}and compare against maximal $p_{\rm local}$ of randomly generated maps.



[IceCube ApJ 835 (2017) 2, 151]

Binomial Test

- Consider a sorted list of p-values $p_i \leq p_j$ $(i < j)$. Trial-corrected p-value is:

$$p'_1 = 1 - (1 - p_1)^N$$

- We can ask, how likely it is that the background yields **at least two p-values** with $p \leq p_2$:

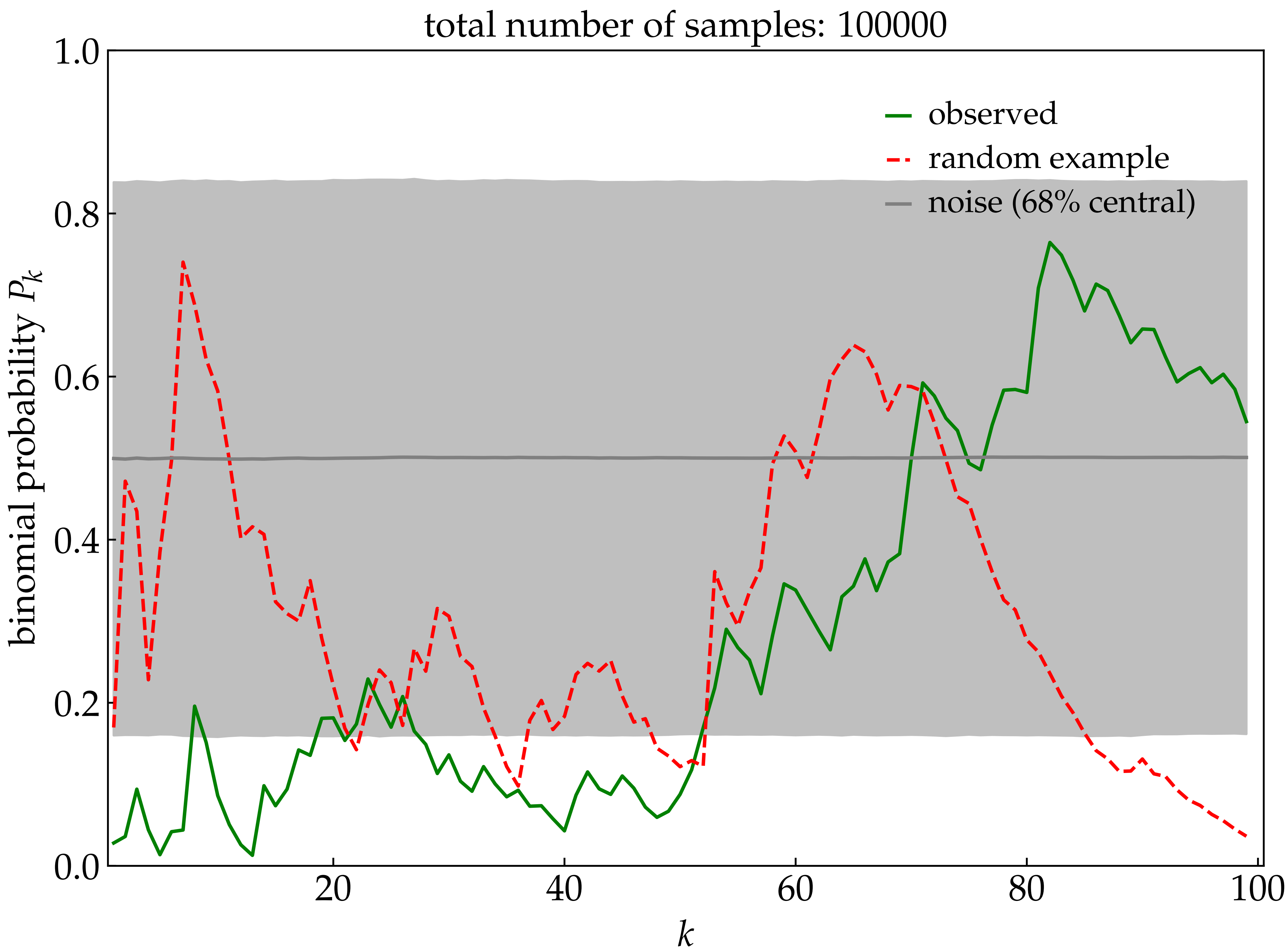
$$p'_2 = 1 - (1 - p_2)^N - Np_2(1 - p_2)^{N-1}$$

- In general, the background probability for **at least k p-values** with $p \leq p_k$:

$$p'_k = 1 - \sum_{n=0}^{k-1} \binom{N}{n} p_k^n (1 - p_k)^{N-n} \simeq 1 - \frac{\Gamma(k, Np_k)}{\Gamma(k)}$$

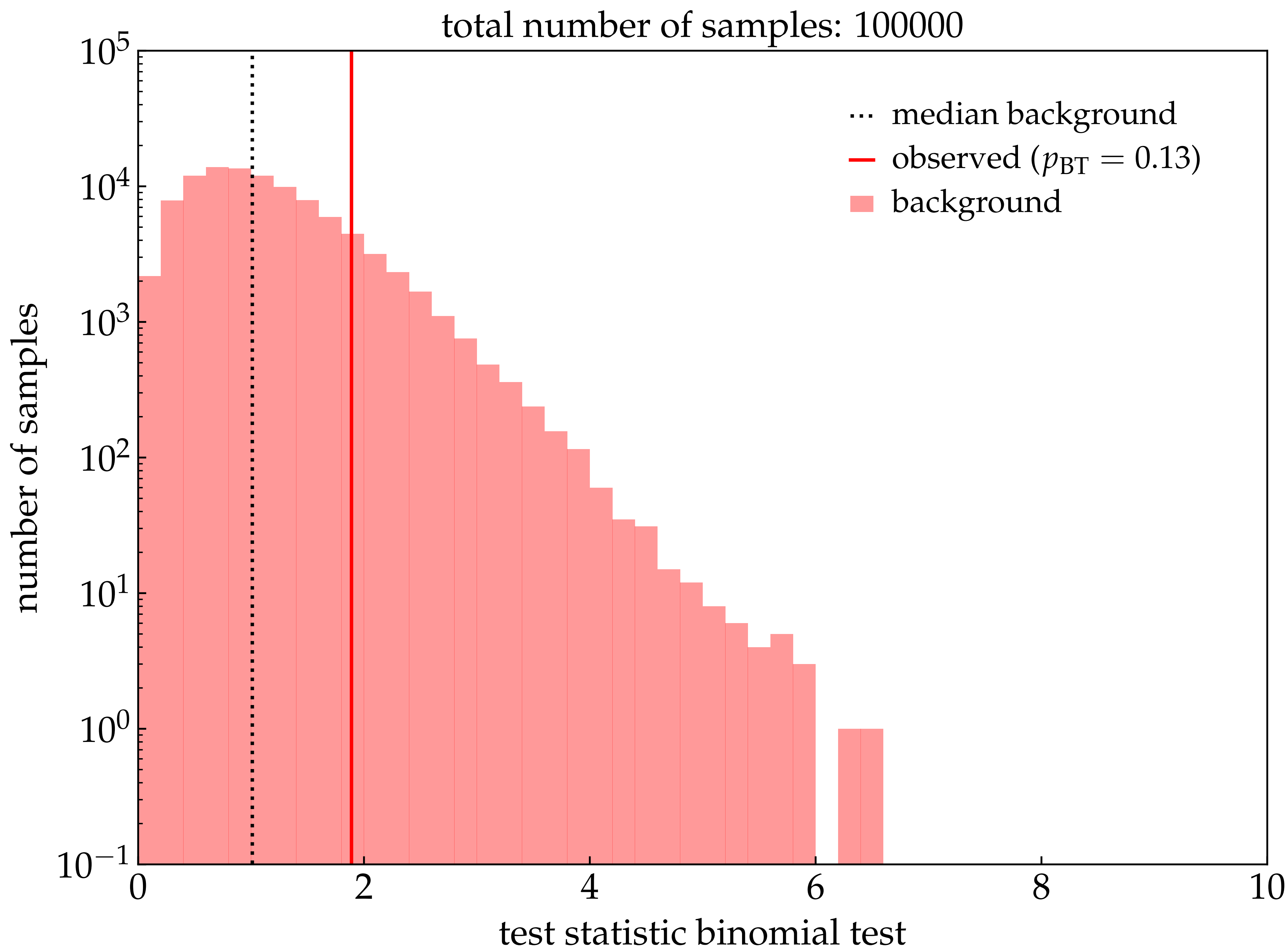
- We can define a **new test statistic** as : $t \equiv \min\{p'_k\}$ ("binomial test").

Example: IceCube



IceCube_allsky.ipynb

Example: IceCube



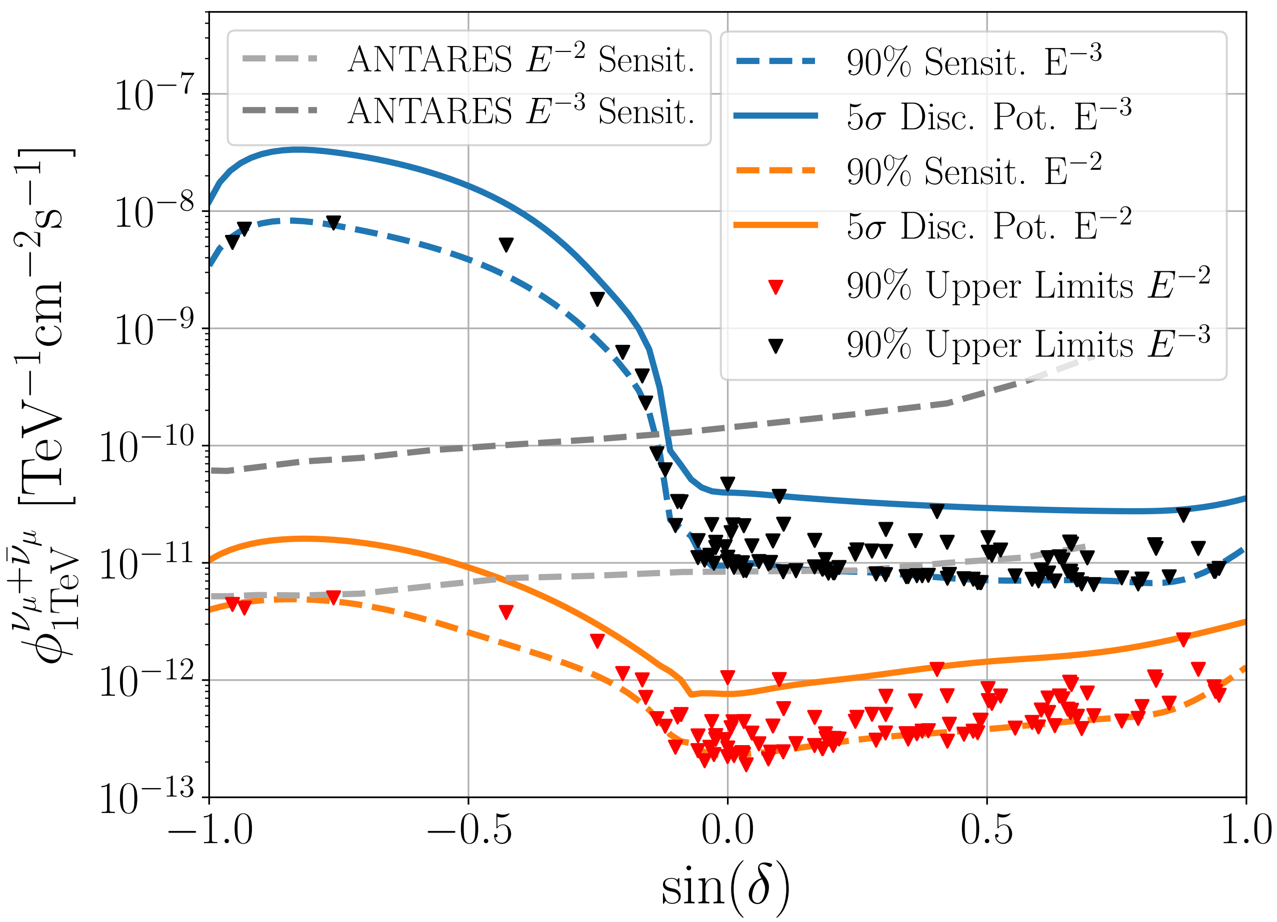
`IceCube_allsky.ipynb`

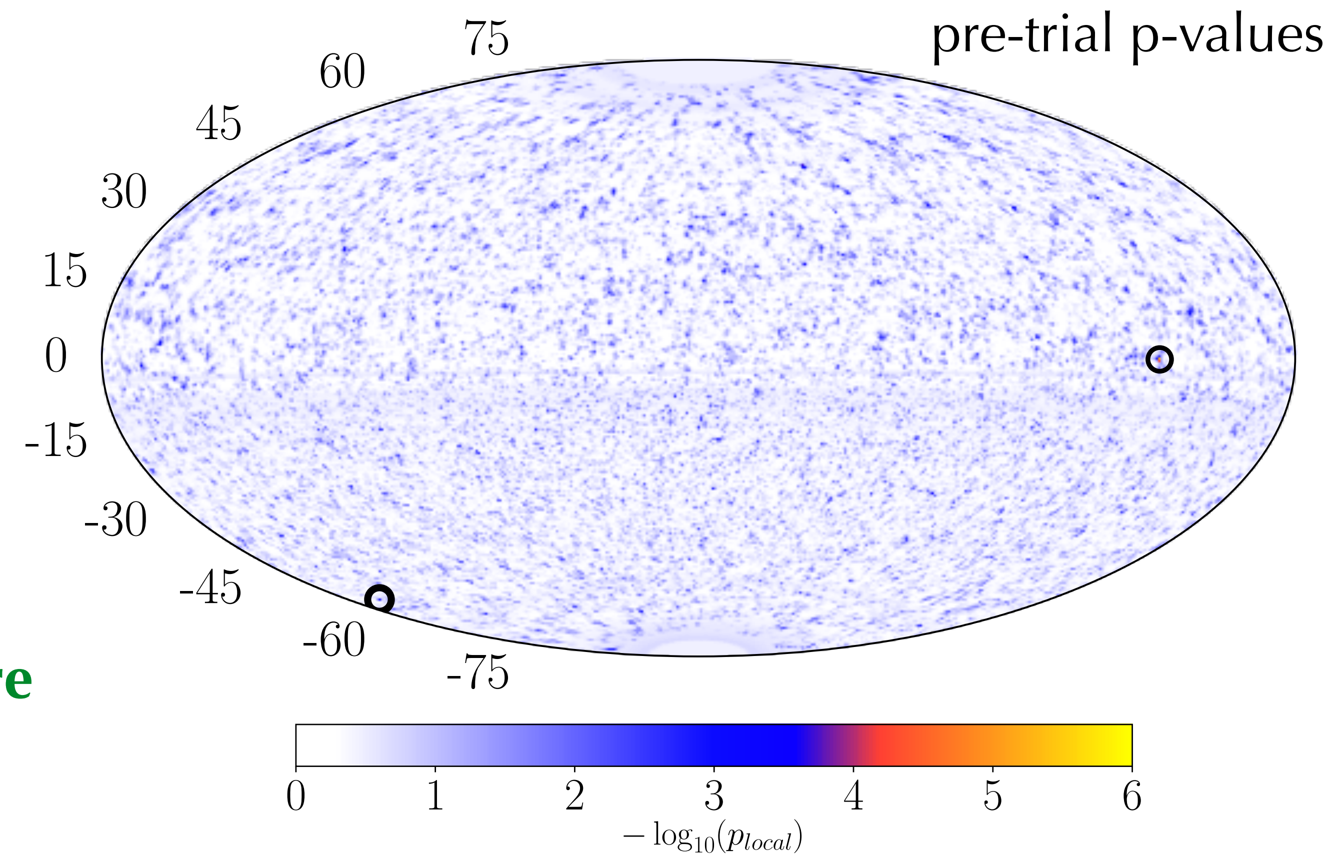
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

ICECUBE

Southern Hemisphere | Northern Hemisphere





[IceCube, PRL 124 (2020) 5]

- **No significant** time-integrated point sources emission in all-sky search.
- **No significant** time-integrated emission from known Galactic and extragalactic high-energy sources, but interesting candidates, e.g. NGC 1068.

Example : IceCube and NGC 1068

Evidence for neutrino emission from the nearby active galaxy NGC 1068

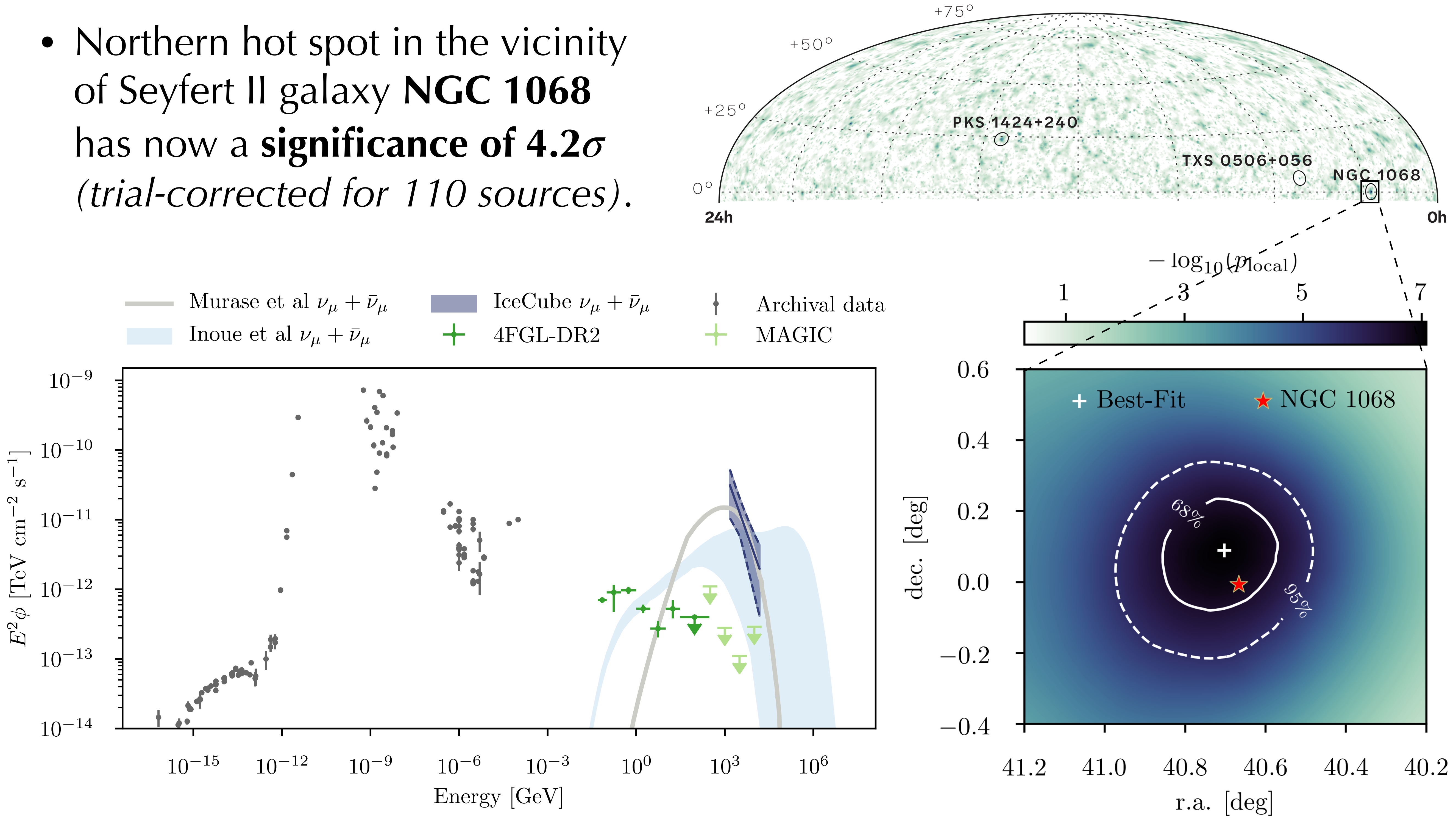
IceCube Collaboration*†

A supermassive black hole, obscured by cosmic dust, powers the nearby active galaxy NGC 1068. Neutrinos, which rarely interact with matter, could provide information on the galaxy's active core. We searched for neutrino emission from astrophysical objects using data recorded with the IceCube neutrino detector between 2011 and 2020. The positions of 110 known gamma-ray sources were individually searched for neutrino detections above atmospheric and cosmic backgrounds. We found that NGC 1068 has an excess of 79^{+22}_{-20} neutrinos at tera–electron volt energies, with a global significance of 4.2σ, which we interpret as associated with the active galaxy. The flux of high-energy neutrinos that we measured from NGC 1068 is more than an order of magnitude higher than the upper limit on emissions of tera–electron volt gamma rays from this source.

[IceCube, Science 378 (2022) 6619]

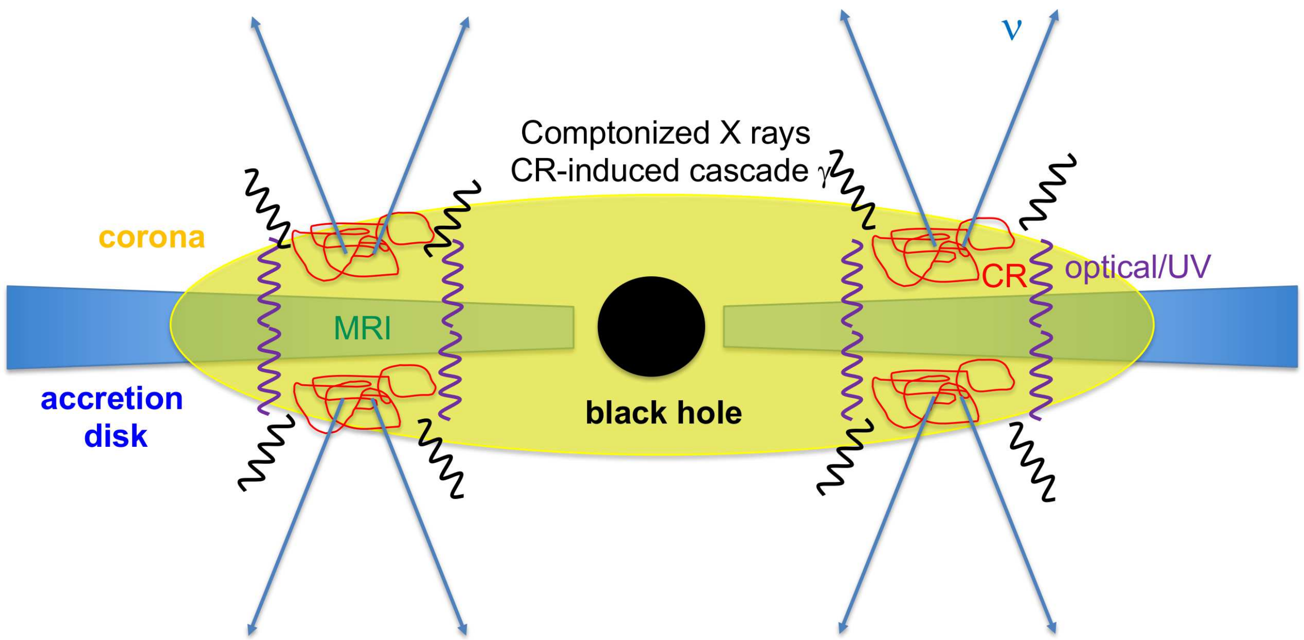
Excess of NGC 1068

- Northern hot spot in the vicinity of Seyfert II galaxy **NGC 1068** has now a **significance of 4.2σ** *(trial-corrected for 110 sources)*.

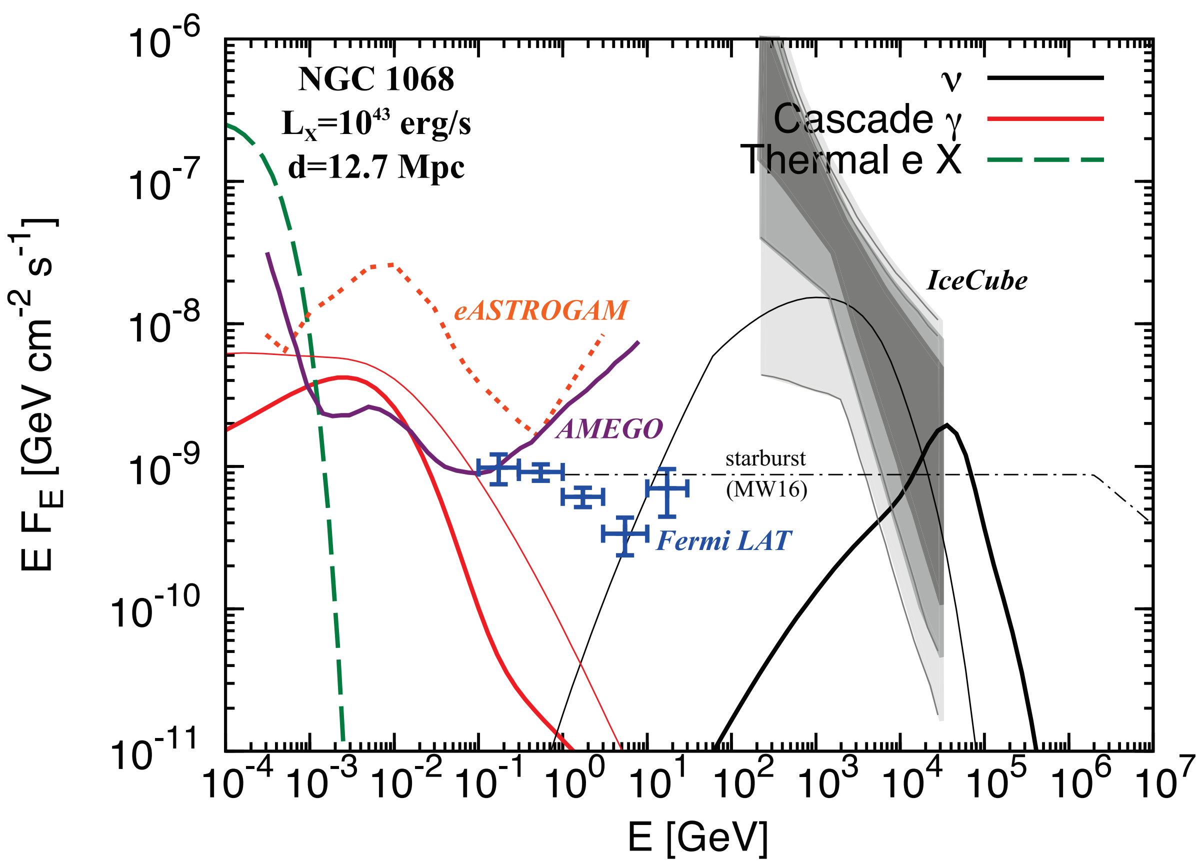


[IceCube, PRL 124 (2020) 5 **(2.9σ post-trial)**; Science 378 (2022) 6619 **(4.2σ post-trial)**]

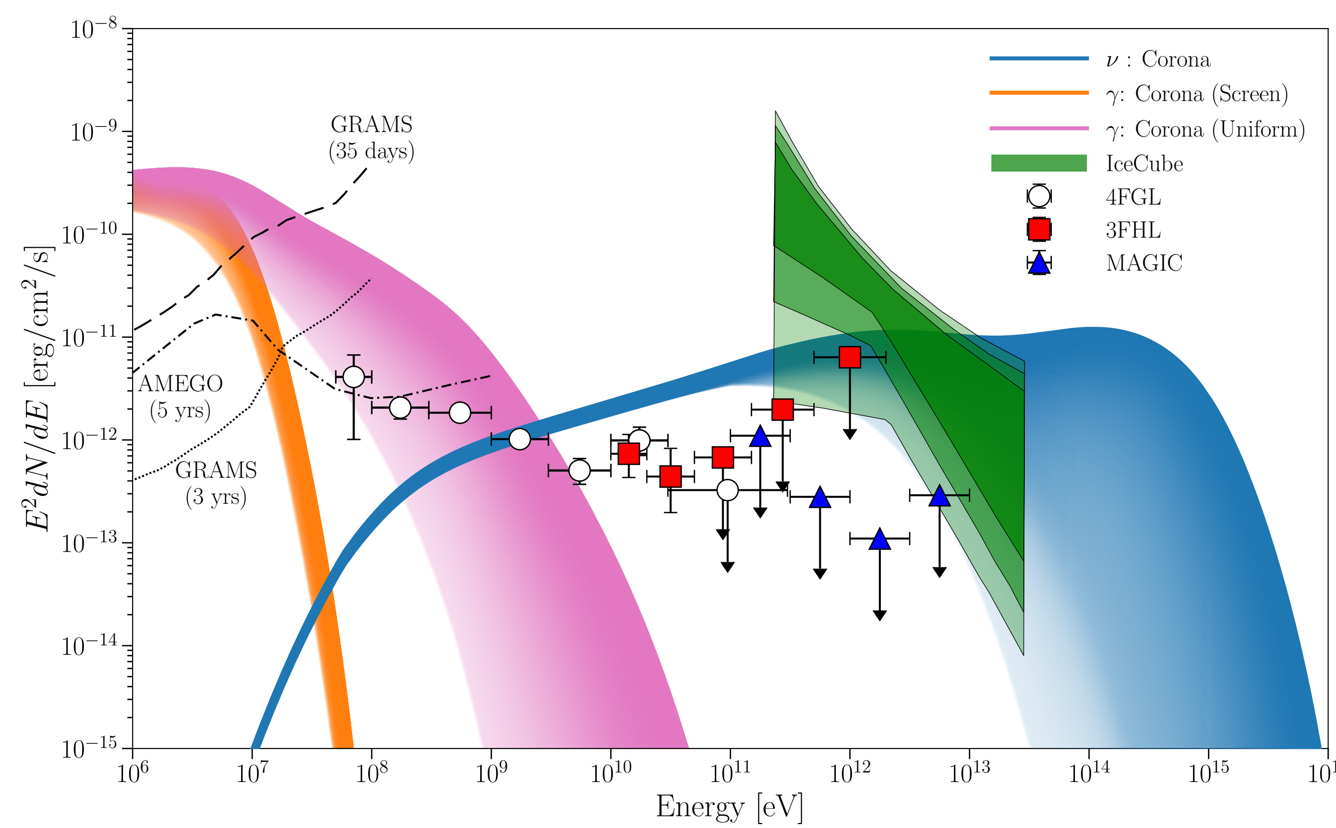
Excess of NGC 1068



- **Soft spectrum** ($\gamma = 3.2 \pm 0.2$) within 1.5-15 TeV indicates peak or cutoff in ν emission.
- Effective **absorption** of accompanying γ-rays in X-ray photons of **AGN corona.**



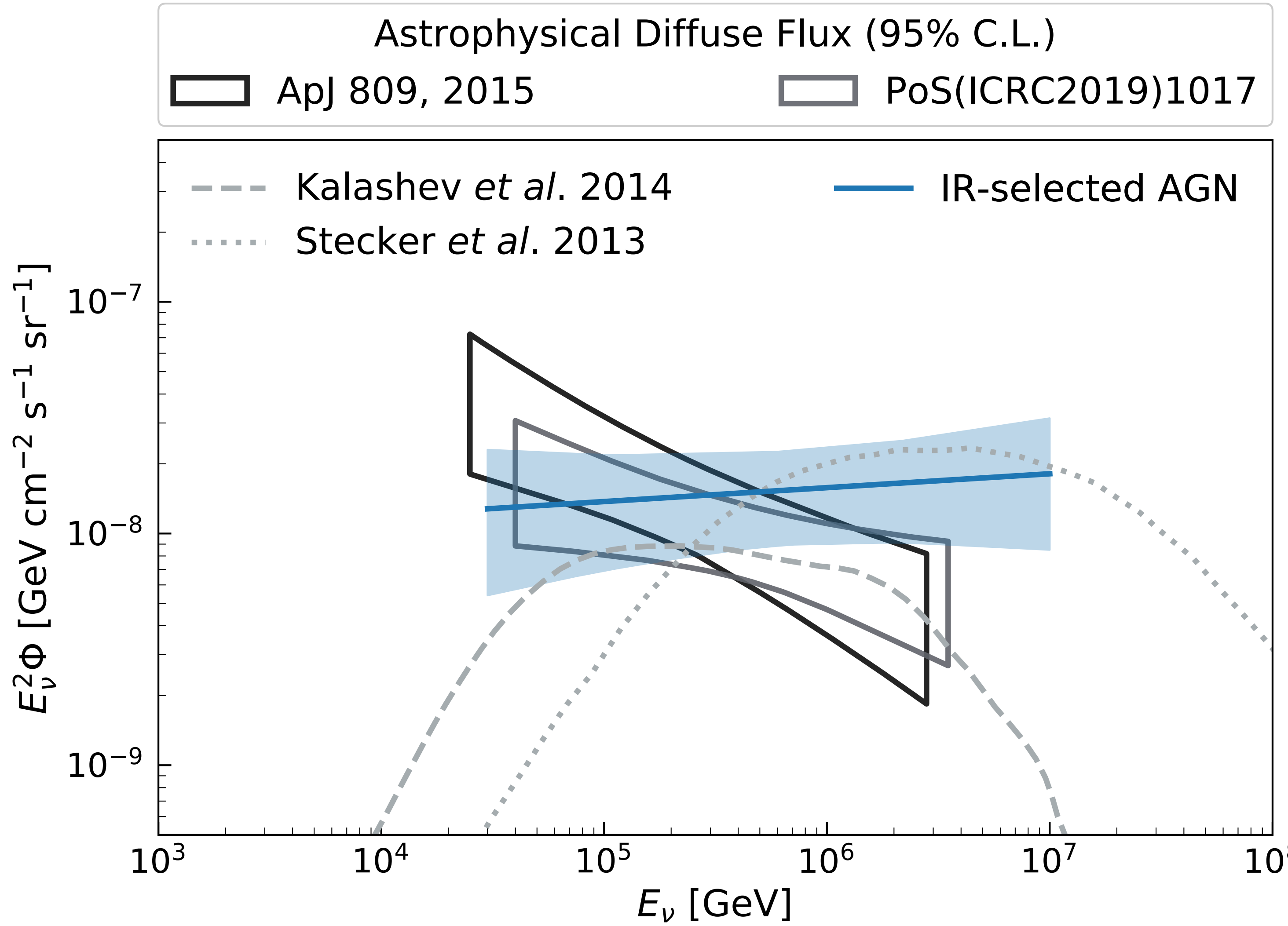
[Murase, Kimura & Meszaros '20]



[Inoue, Khangulyan & Doi '20]

Excess of NGC 1068

- Hadronic γ-rays in **cores of AGNs** are suppressed due to pair production in X-ray background.
- IceCube finds a **2.6σ excess** for 32,249 AGN selected by their IR emission.



[IceCube, PRD 106 (2022) 2]

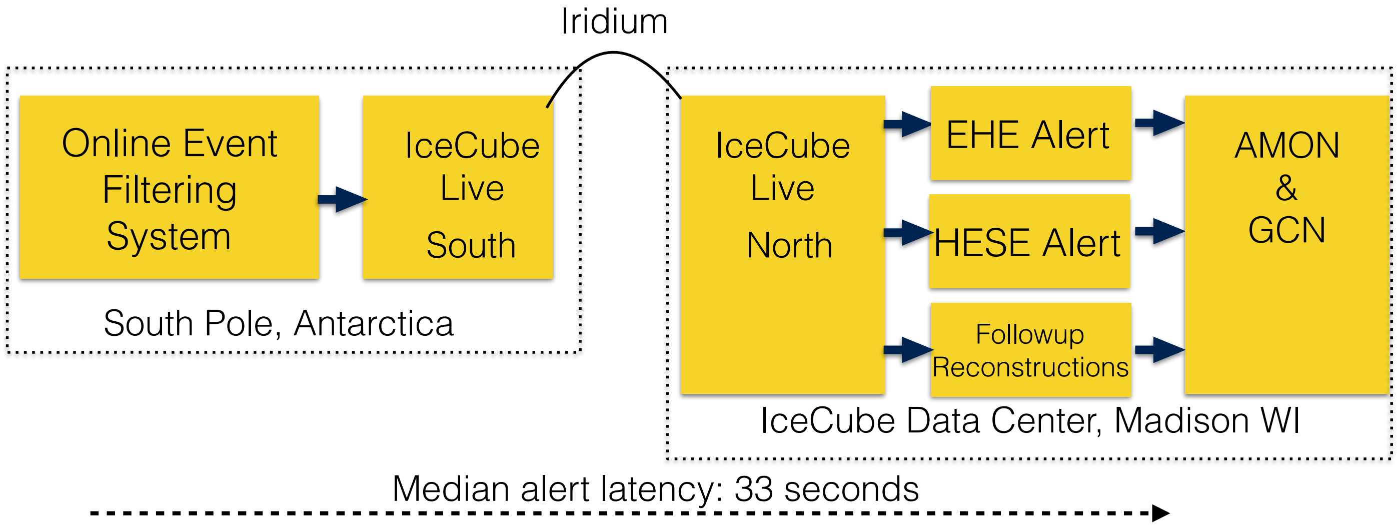
TABLE I. Properties of the AGN samples created for the analysis. The surveys used for the cross-match to derive each sample, the final number of selected sources, cumulative X-ray flux in the 0.5-2 keV energy range from the selected sources [44] and the completeness (fraction of total X-ray flux from all AGN in the Universe contained in the sample) are listed.

	Radio–selected AGN	IR–selected AGN	LLAGN
Matched catalogues	NVSS + 2RXS + XMMSL2	AllWISE + 2RXS + XMMSL2	AllWISE + 2RXS
Nr. of sources	9749	32249	15887
Cumulative X-ray flux [erg cm^{-2} s^{-1}]	7.71×10^{-9}	1.43×10^{-8}	7.26×10^{-9}
Completeness	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$

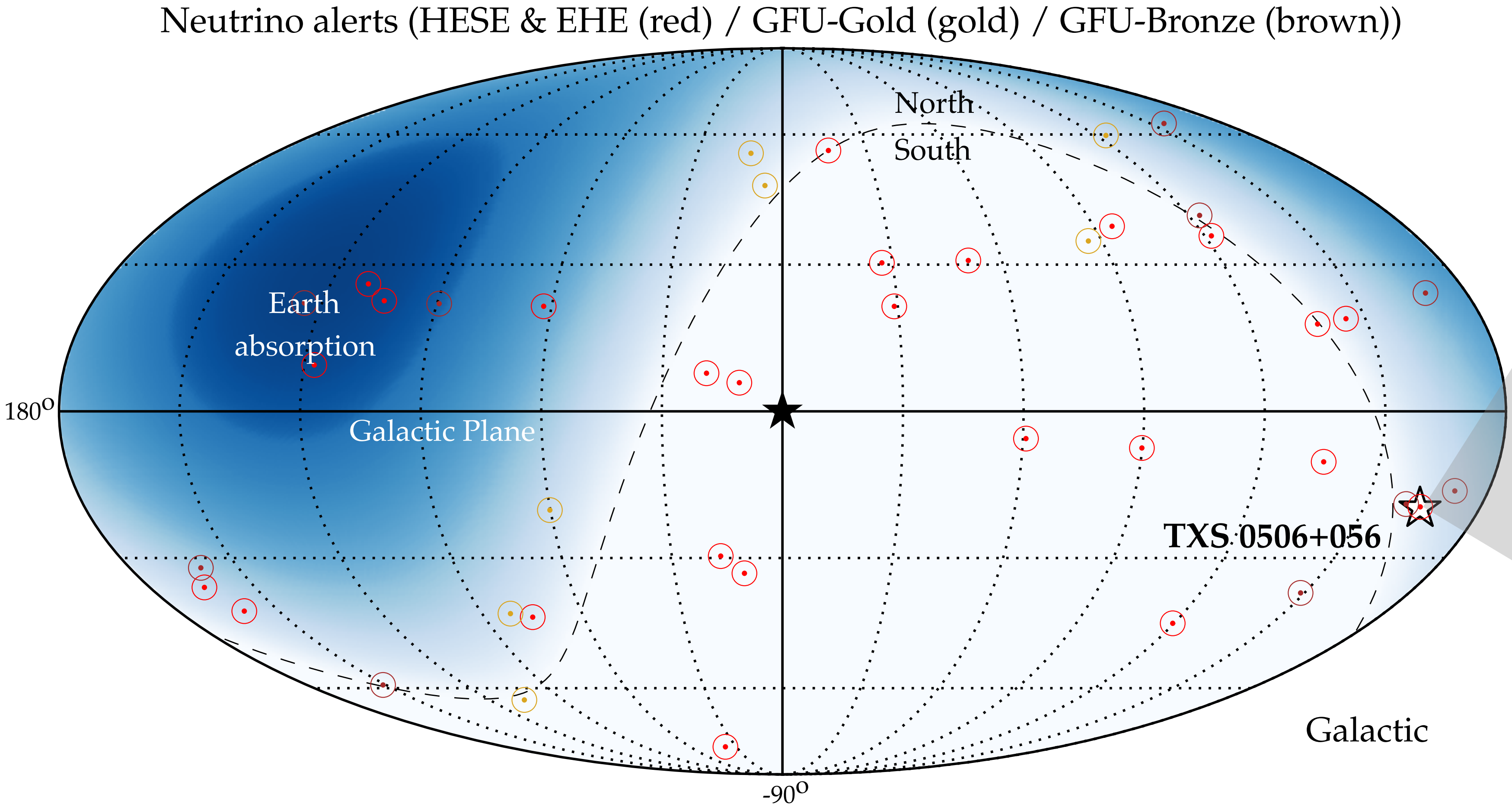
Realtime Neutrino Alerts

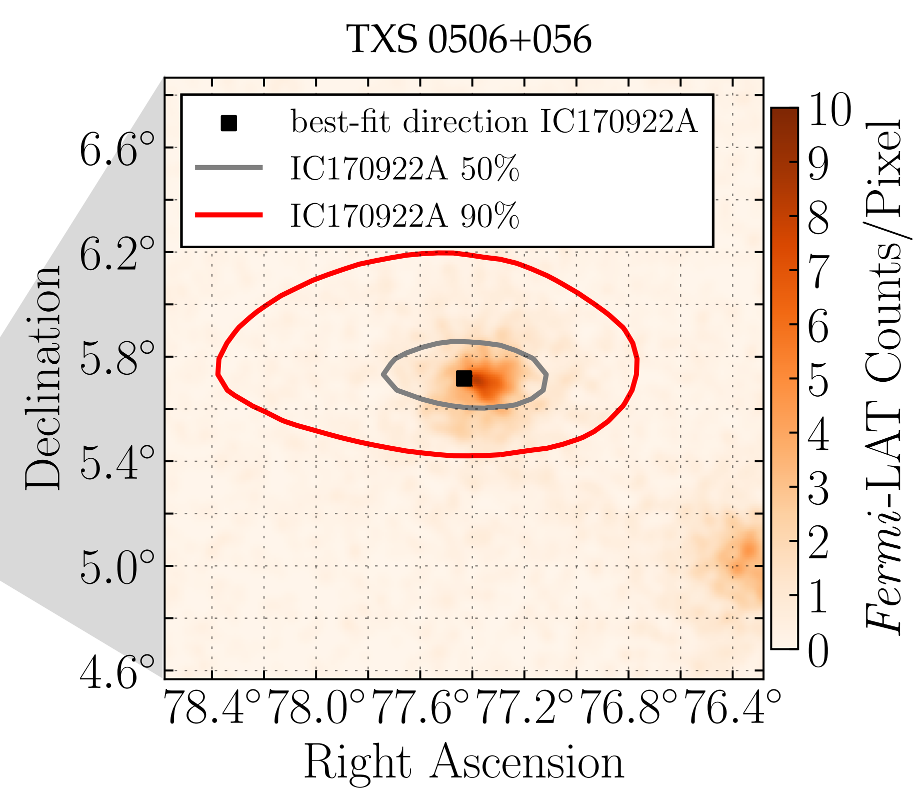
Low-latency (<1min) **public neutrino alert system** established in April 2016.

- **Gold alerts:** ~10 per year
  >50% signalness
- **Bronze alerts:** ~20 per year
  30-50% signalness



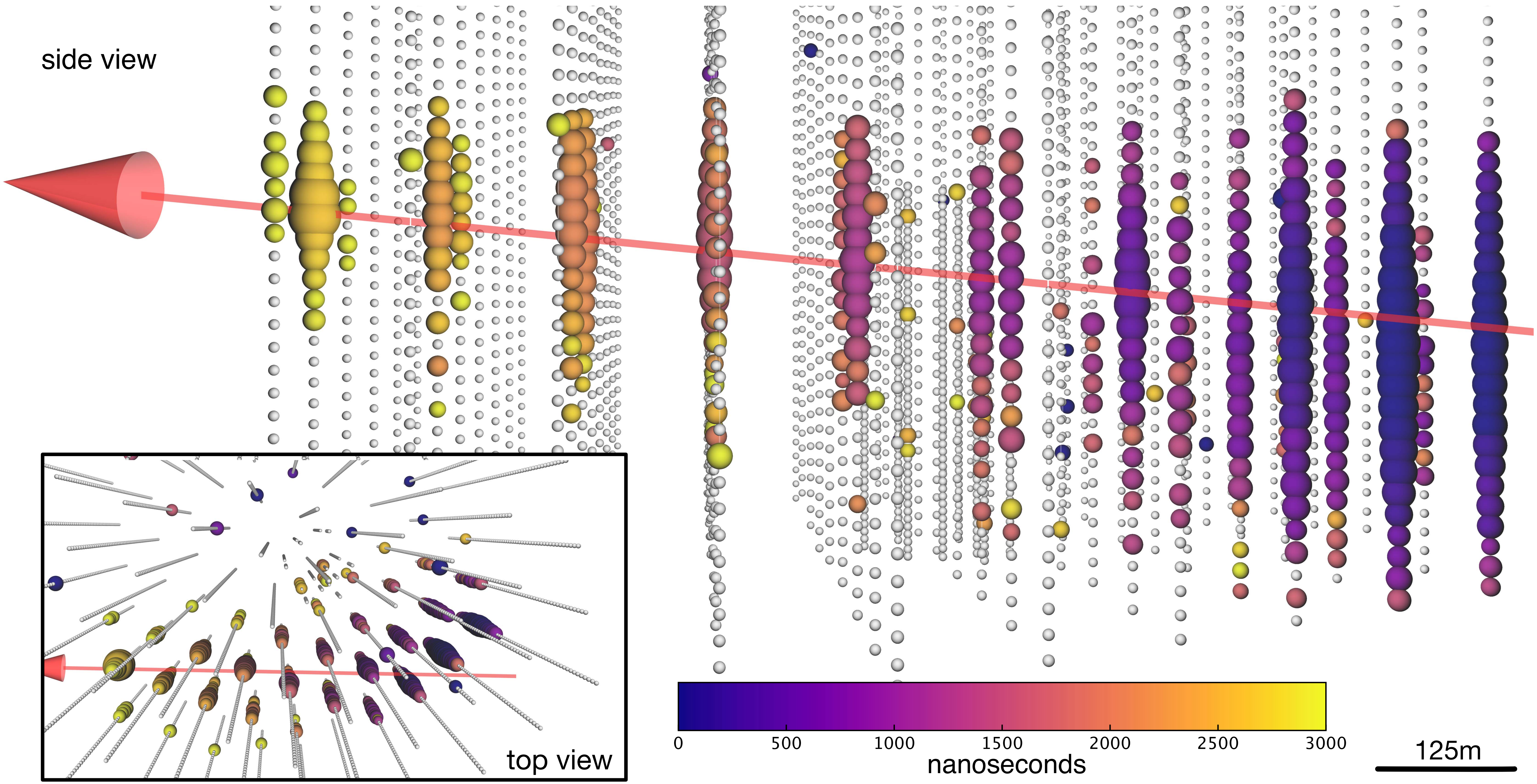
[IceCube, PoS (ICRC2019) 1021]





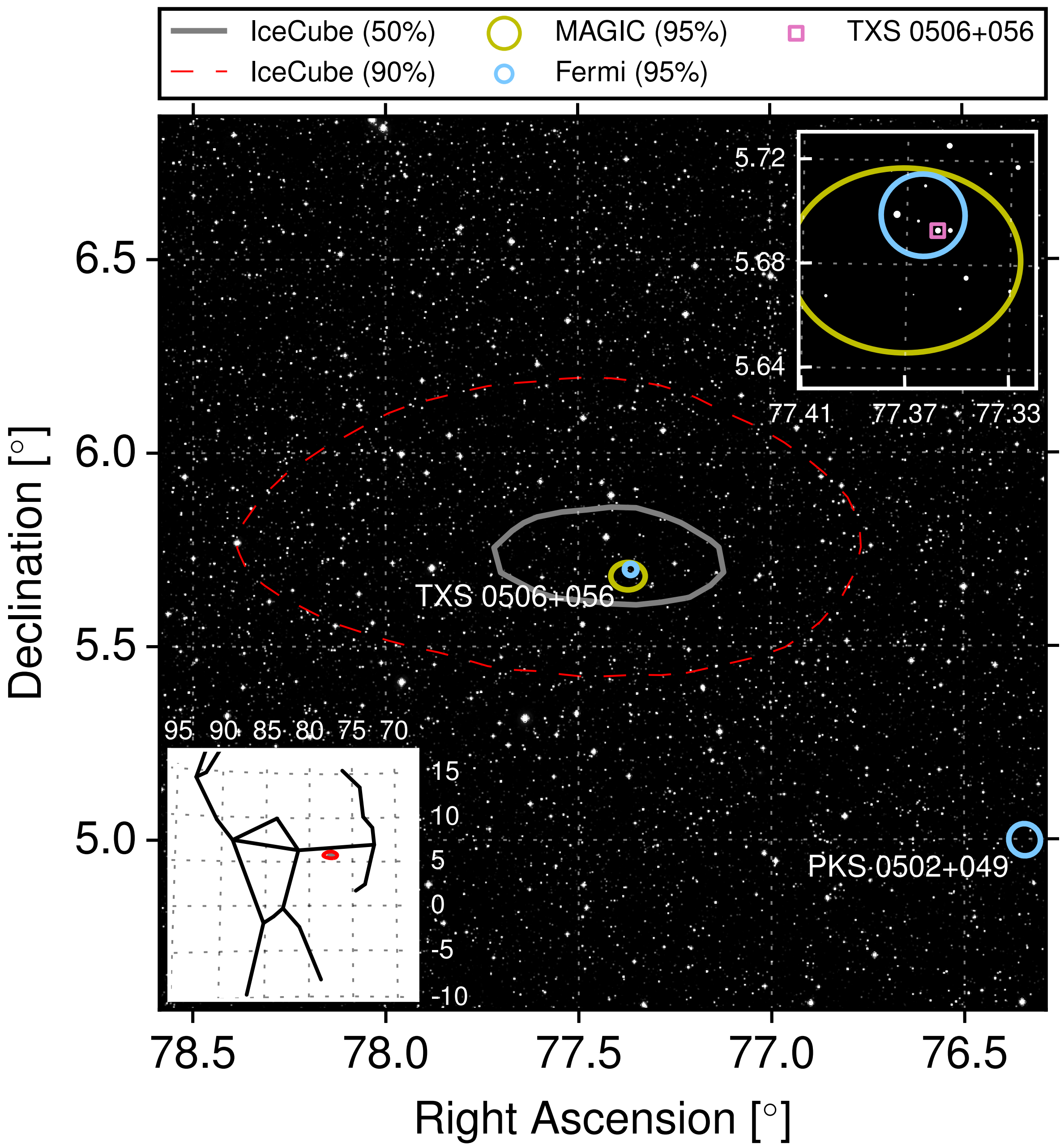
Realtime Neutrino Alerts

IC-170922A



up-going muon track (5.7° below horizon) observed September 22, 2017
best-fit neutrino energy is about 300 TeV

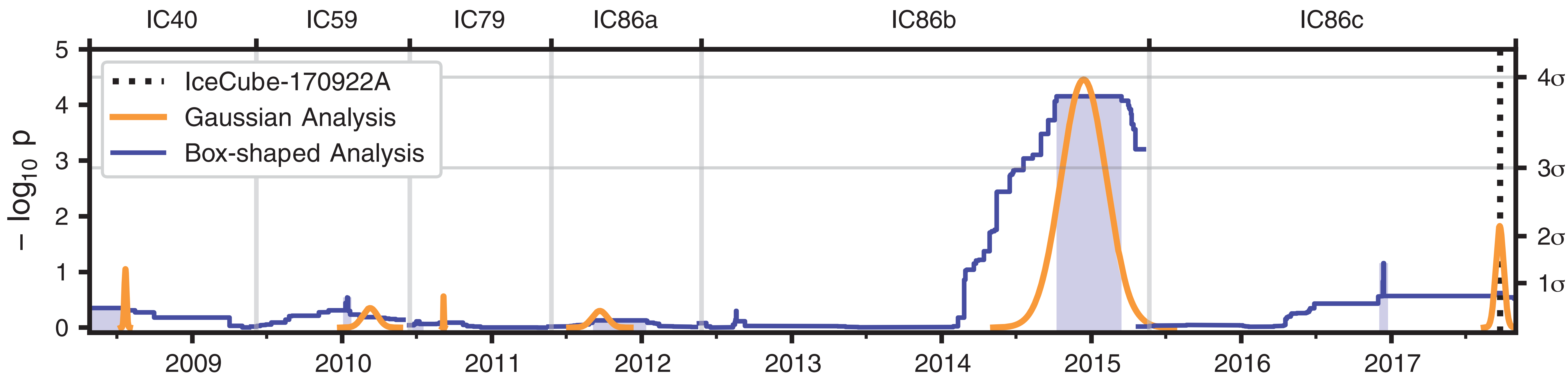
TXS 0506+056



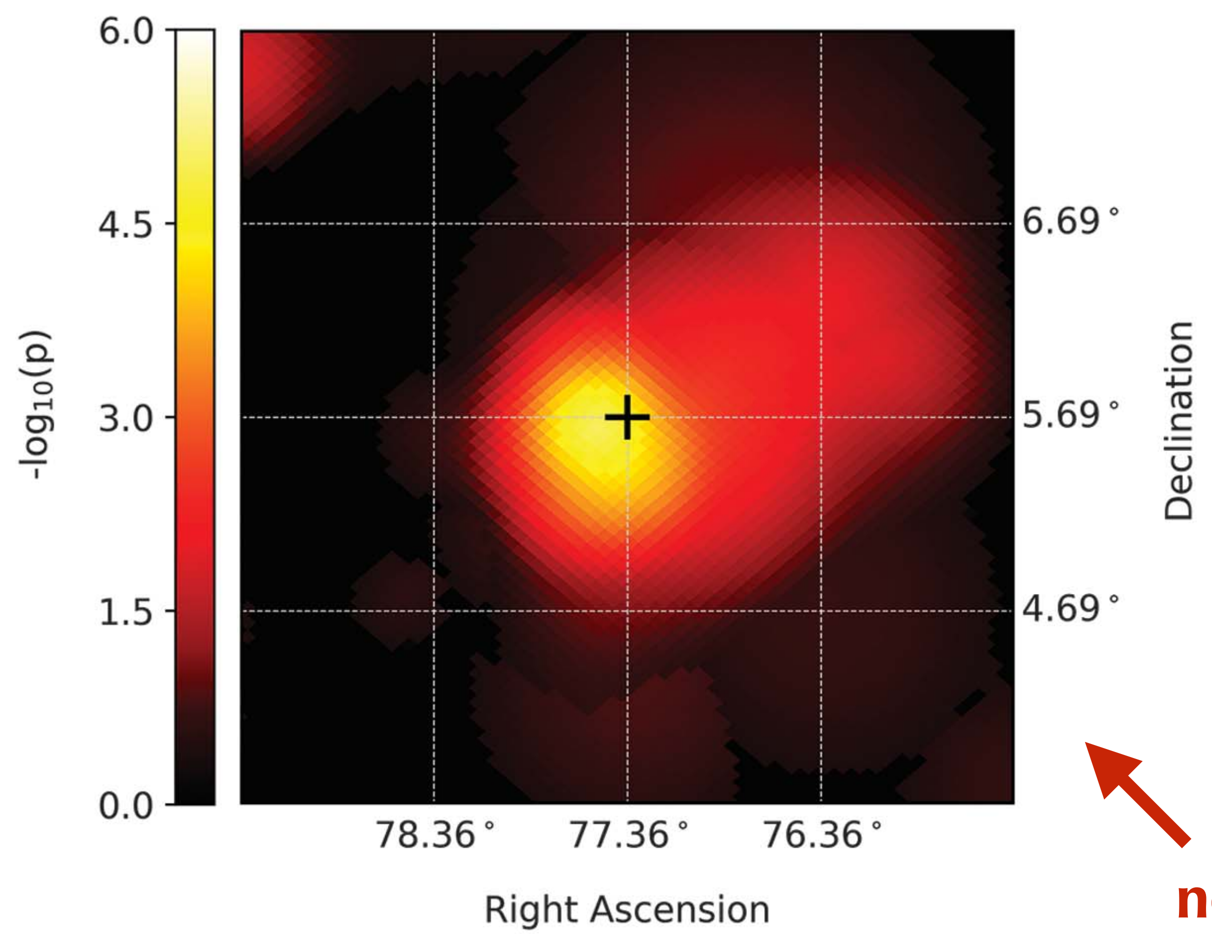
[IceCube++, Science 361 (2018) 6398]

- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

Neutrino Flare in 2014/15



[IceCube, Science 361 (2018) 6398]



neutrino "morphology" of 2014/15 flare

- Independent 3.5σ evidence for a **neutrino flare** (13±5 excess events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times that of Fermi-LAT γ-rays**.