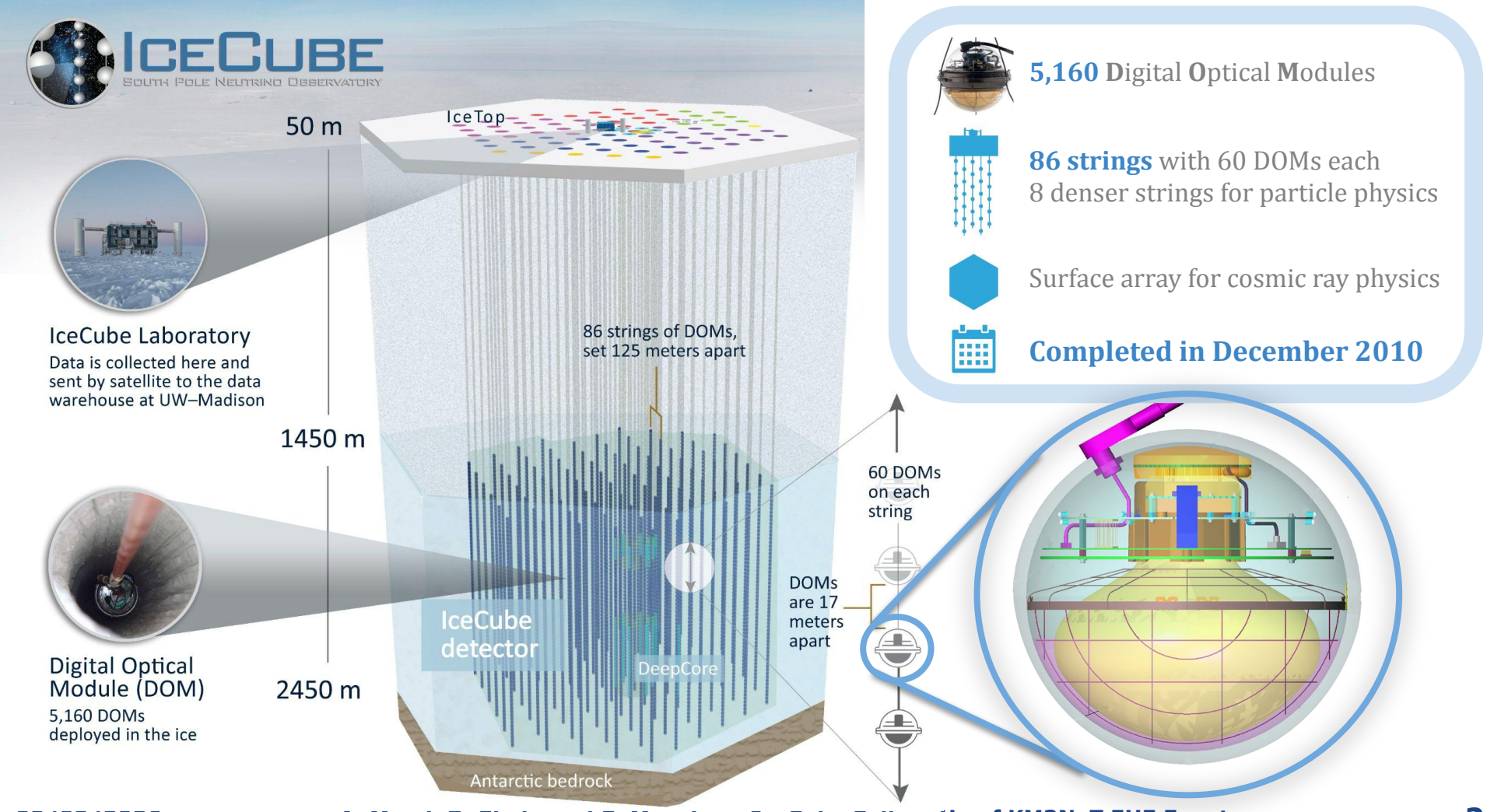
Results from the IceCube Follow-Up of the KM3-230213A Event

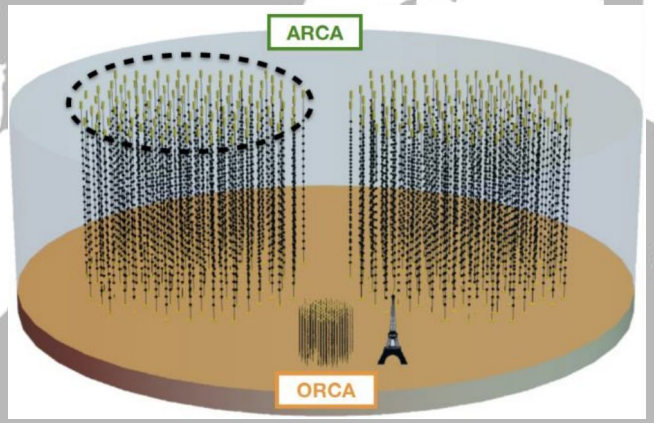
Alicia Mand, **Riya Shah**, and Sarah Mancina
for the IceCube Collaboration
TeVPA 2026, Tendo


IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock
60 DOMs on each string
DOMs are 17 meters apart
5,160 Digital Optical Modules
86 strings with 60 DOMs each
8 denser strings for particle physics
Surface array for cosmic ray physics
Completed in December 2010

Overview of KM3NeT

Two-detector configuration:

- Oscillation Research with Cosmics in the Abyss (ORCA)
- Astroparticle Research with Cosmics in the Abyss (ARCA)



ORCA
(ex ANTARES Site)

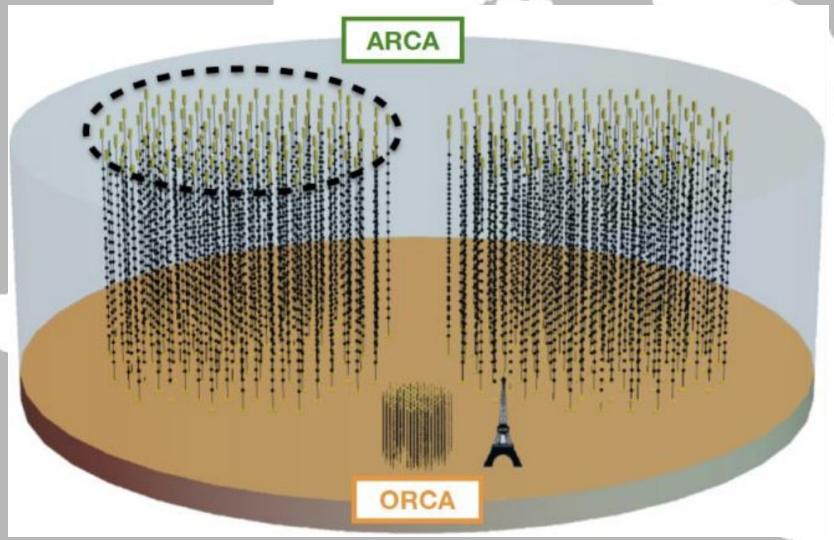
- **Dense spacing between detection lines**
- **Neutrino mass measurements and low energy neutrino astronomy (1-100 GeV)**

ARCA

- **More sparsely spaced detection lines**
- **High energy astrophysical neutrino studies (10^2-10^8 GeV)**

Overview of KM3NeT

- Digital Optical Modules (DOMs) suspended in the Mediterranean sea
- Data is transmitted to shore via optical fiber
- Deployed using buoys



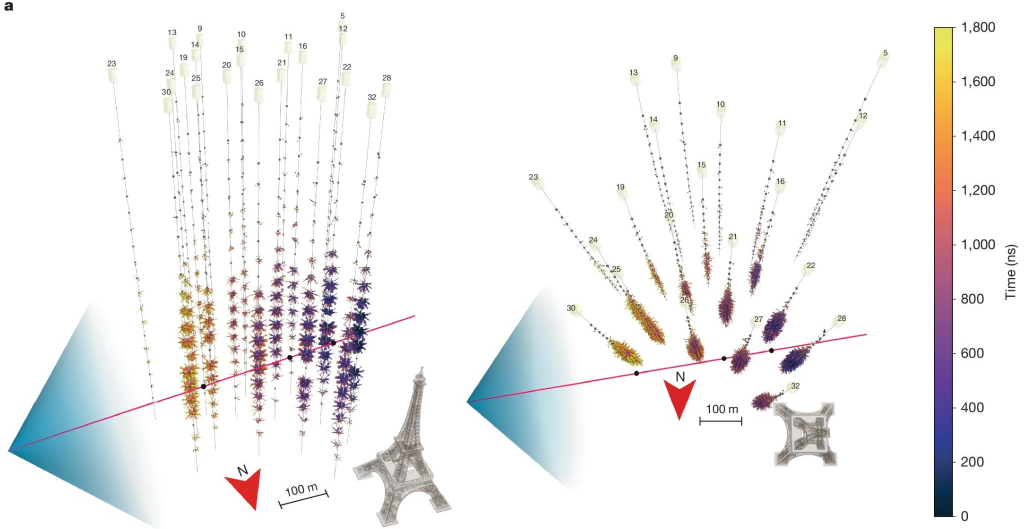
KM3-230213A

- Detected February 13th 2023 at 01:16:47 UTC in ARCA Detector
  - Only ~10% planned lines installed and operating at time of detection

- Best-fit location of (RA, dec) = (94.3º, -7.8º)

$$E_\nu = 220^{+570}_{-100}\ \mathrm{PeV}$$

Highest energy neutrino reported of all time!

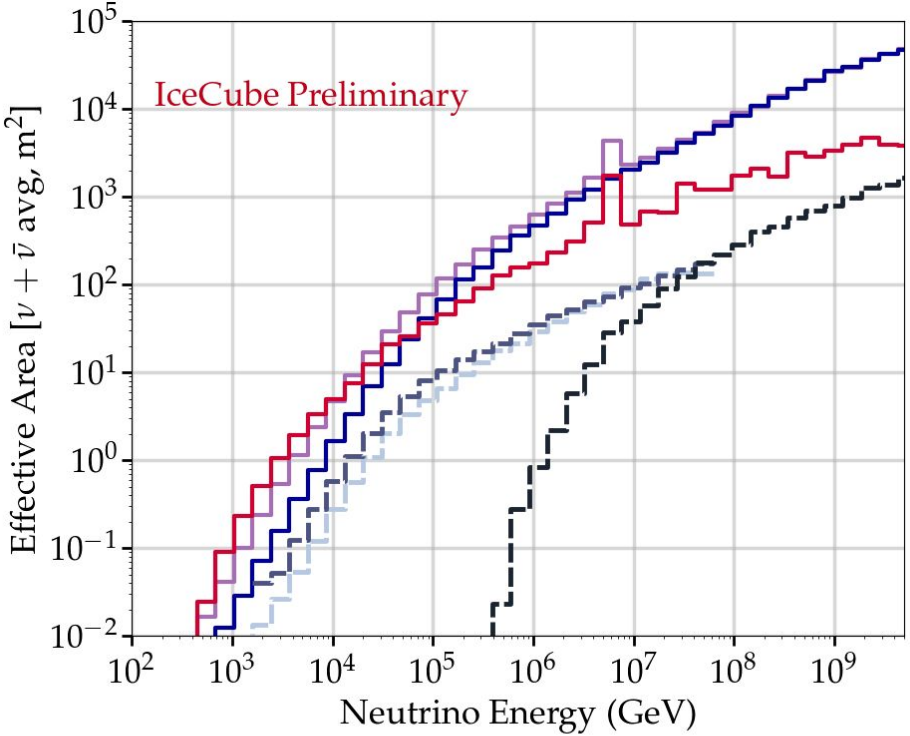


The KM3NeT Collaboration *Nature* **638**, 376–382

Comparing IceCube and KM3NeT

Comparing IceCube and KM3NeT

Definition
Effective Area - area that an ideal detector would have to be to be equivalent to our detector



IceCube GFU Tracks
All-flavor summed at $\delta = -7.8°$

IceCube Tracks $\nu_{\mu/\tau}^{CC}\bar{\nu}_{\mu/\tau}^{CC}$
summed at $\delta = -7.8°$

IceCube Cascades
All-flavor summed at $\delta = -7.8°$

KM3NeT-6 All-sky $\nu_{\mu}^{CC}\bar{\nu}_{\mu}^{CC}$
(VLVnT, 2021)

KM3NeT-21 All-sky $\nu_{\mu}^{CC}\bar{\nu}_{\mu}^{CC}$
(ICRC, 2023)

KM3NeT-21 All-flavor All-sky
Bright Tracks (Nature, 2025)

Detector	Livetime
KM3NeT ARCA Detector	355 days
IceCube	15 years

Much longer livetime and larger effective area than KM3NeT

Comparing IceCube and KM3NeT

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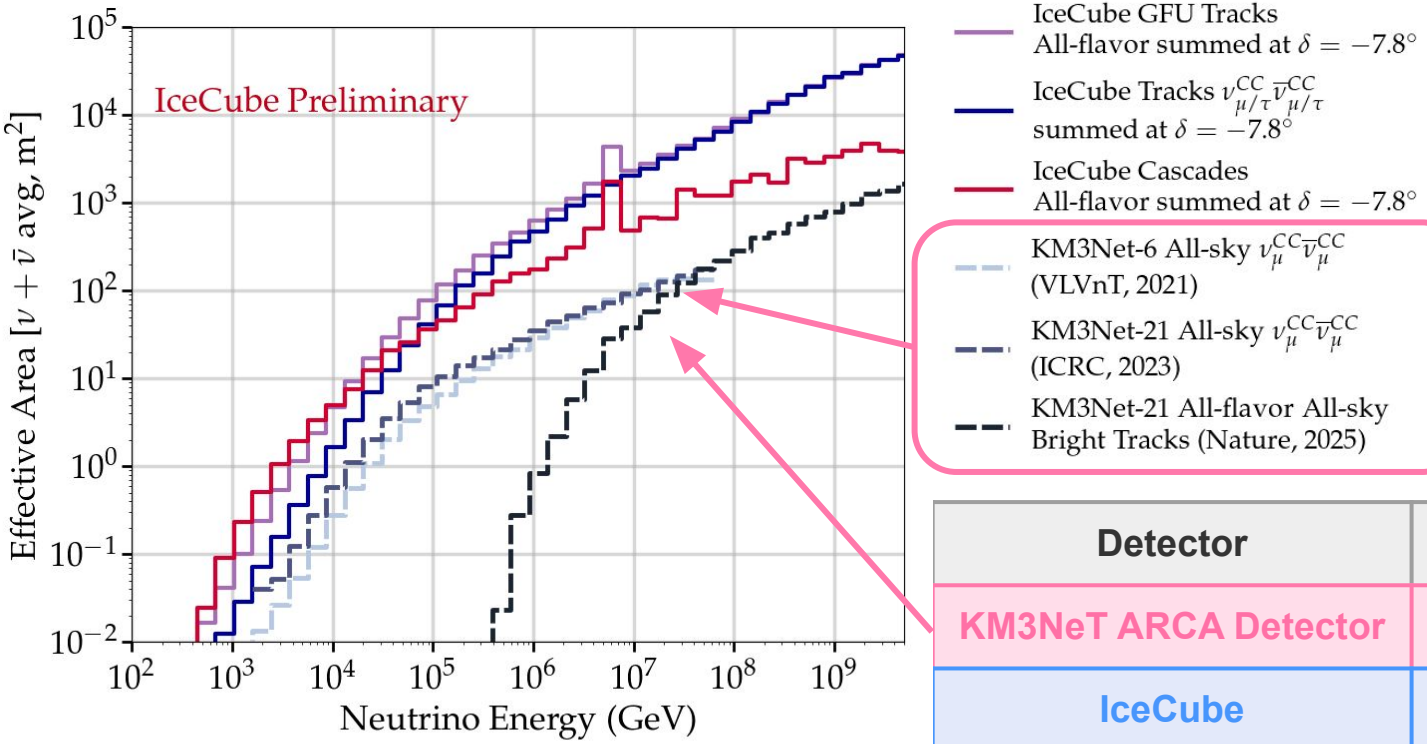

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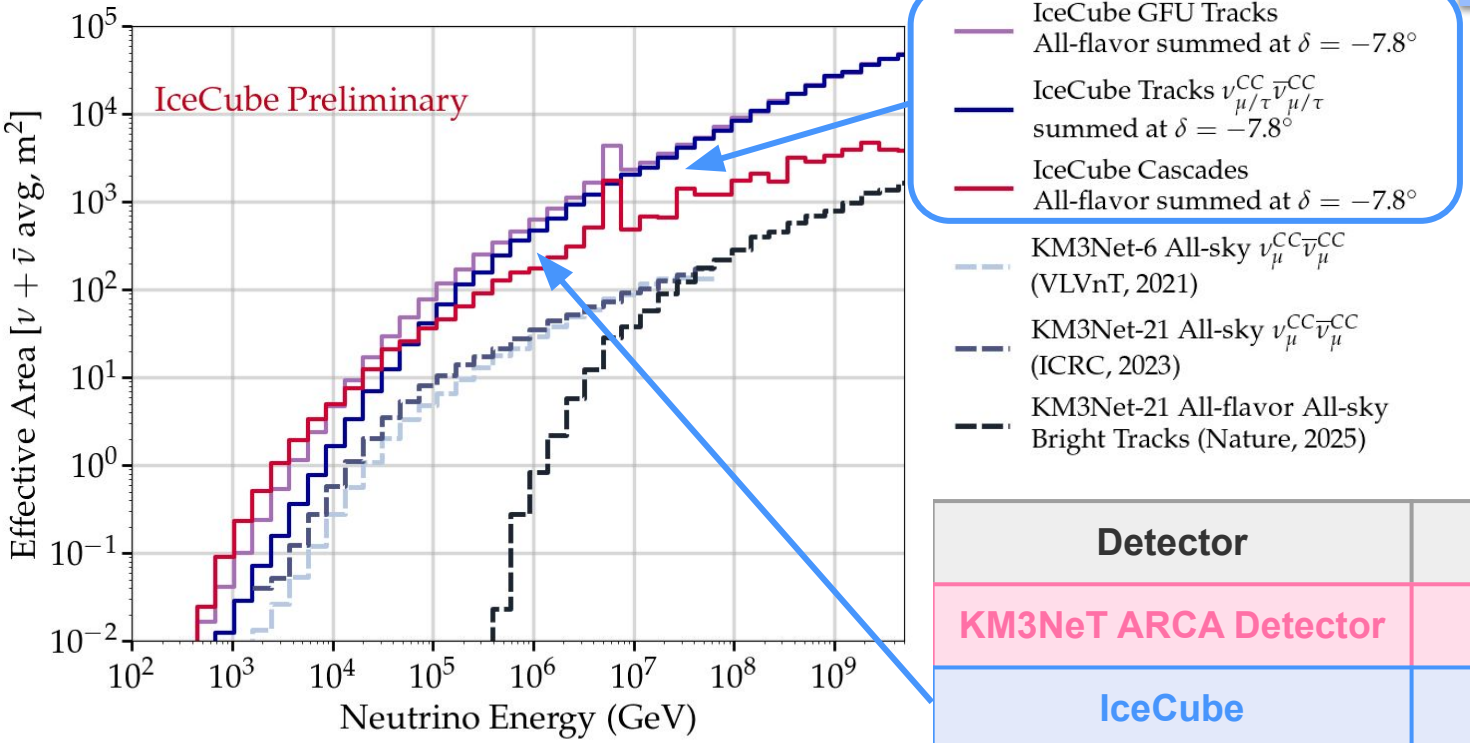

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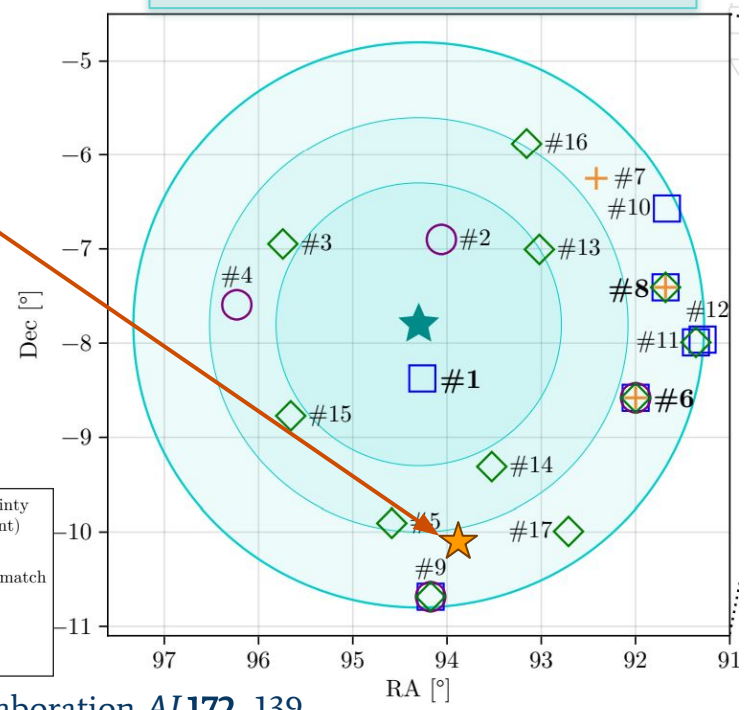
Origins and Investigations

- No clear origin
  - No GRBs, supernovae, or TDEs have been identified in 99% confidence region
  - 12 nearby blazars but no temporal association
- KM3NeT dedicated public IceCube follow-up
  - Reports slight excess
  - ***Consistent with background expectation (post-trial p-value of 0.07)***
- Many hypotheses have been suggested
  - Cosmogenic neutrino
  - Primordial Black Hole
  - Beyond the standard model
  - …and more!

KM3NeT Localization
with nearby source candidates



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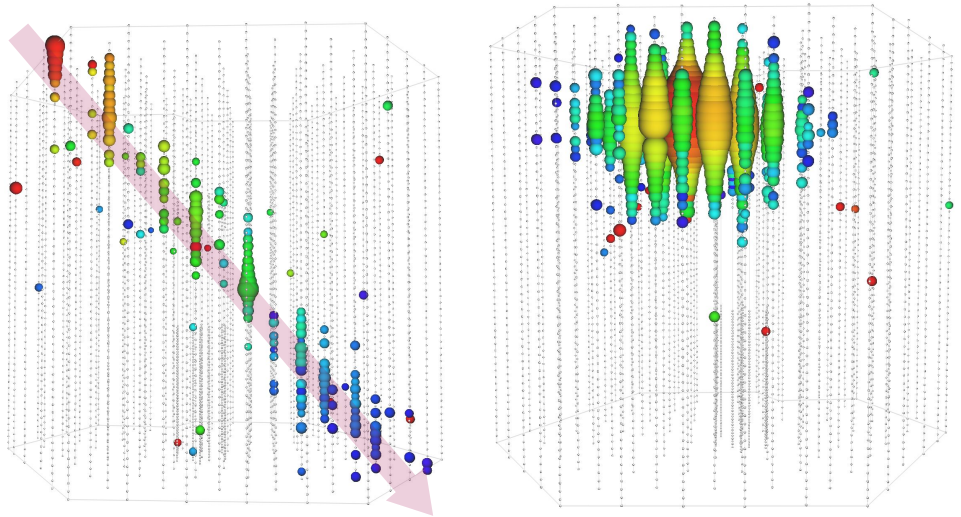
Three Follow-up Analyses Conducted

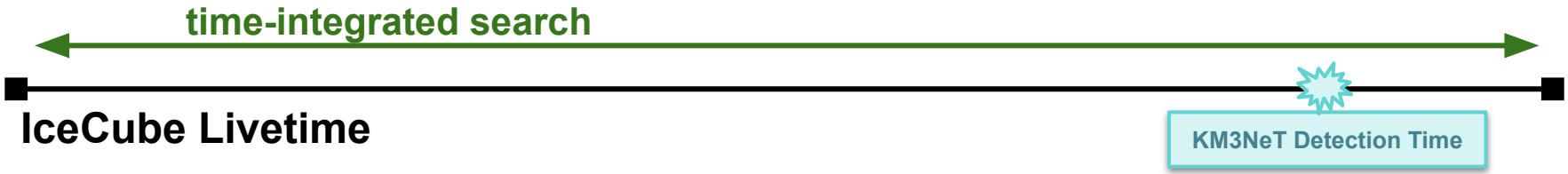
1. Time-integrated and time-dependent search for neutrinos
2. Flare search for neutrinos
3. Non-GFU (Gamma-ray follow-up) Detection of KM3-230213A

Using events from all-flavor NC and CC neutrino interactions!



Three Follow-up Analyses Conducted

1. Time-integrated and time-dependent search for neutrinos
   a. Time-integrated searches with different localizations
      i. Reproduced from KM3NeT Nature paper to match KM3NeT's independent follow-up analysis (flat prior)
      ii. Investigated using Gaussian prior as well
      iii. Both results consistent with background hypothesis (p-values of 0.93, 0.94 for flat and Gaussian priors)



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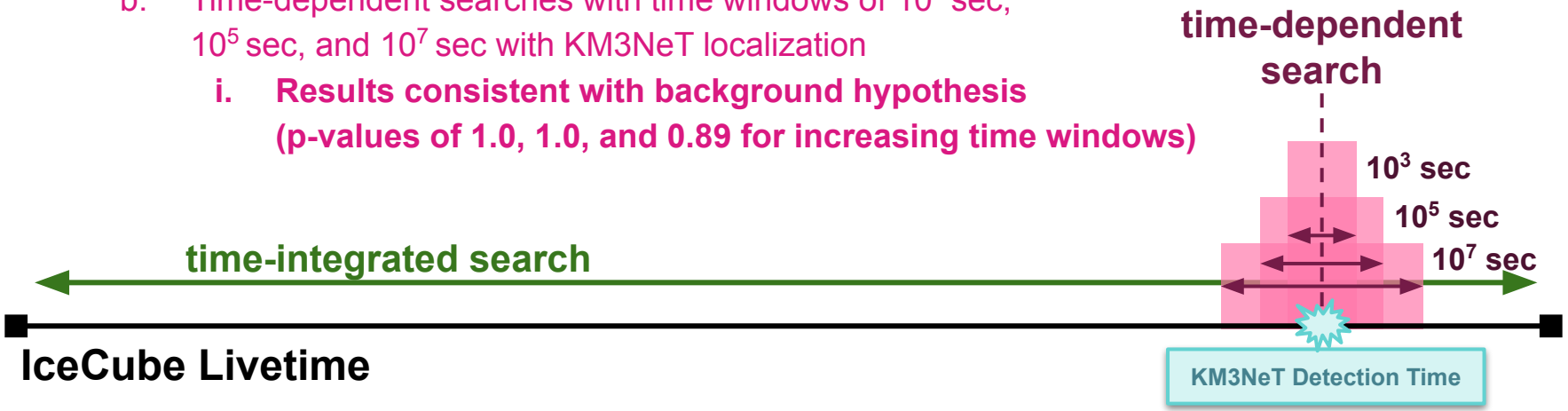
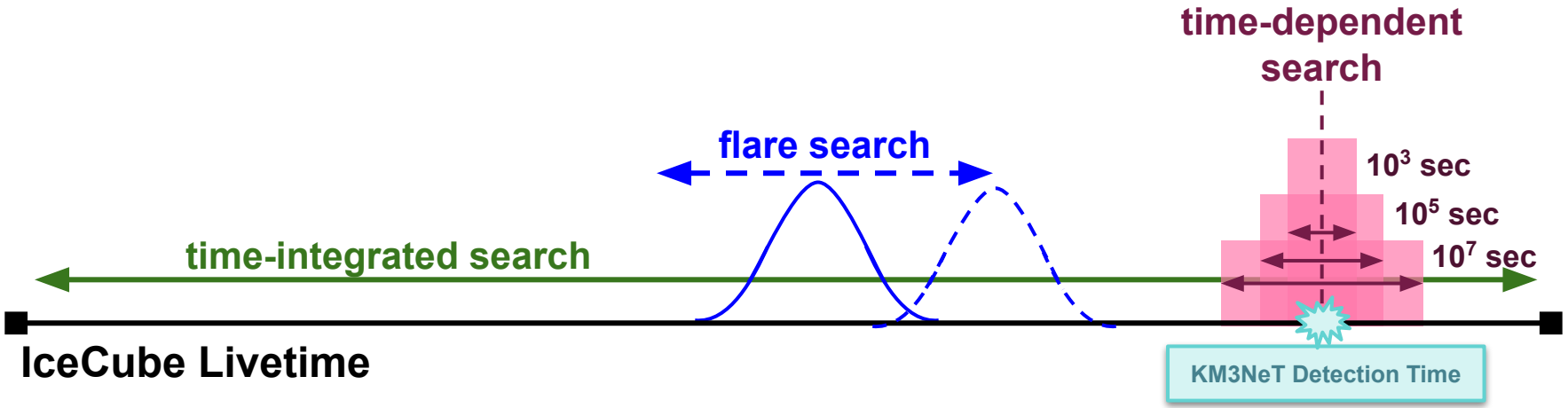
      ii. Investigated using Gaussian prior as well
      iii. Both results consistent with background hypothesis
   b. Time-dependent searches with time windows of 10^3 sec, 10^5 sec, and 10^7 sec with KM3NeT localization
      i. Results consistent with background hypothesis (p-values of 1.0, 1.0, and 0.89 for increasing time windows)



Three Follow-up Analyses Conducted

2. Flare search for neutrinos
   a. Grid search for neutrino flare near best-fit location of KM3-230213A
   b. Fitting for both flare duration and time of flare



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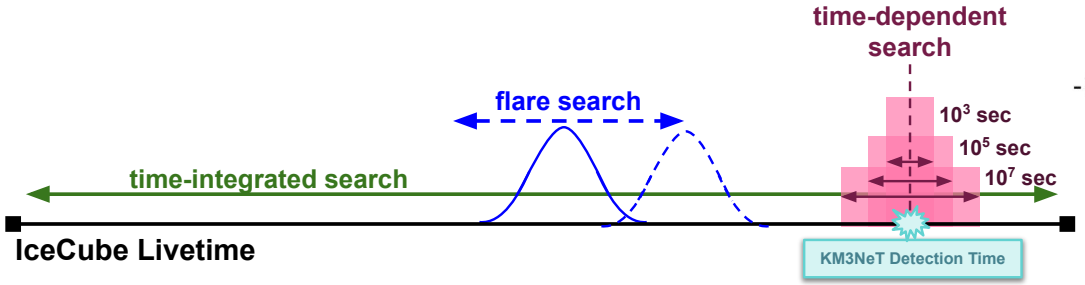
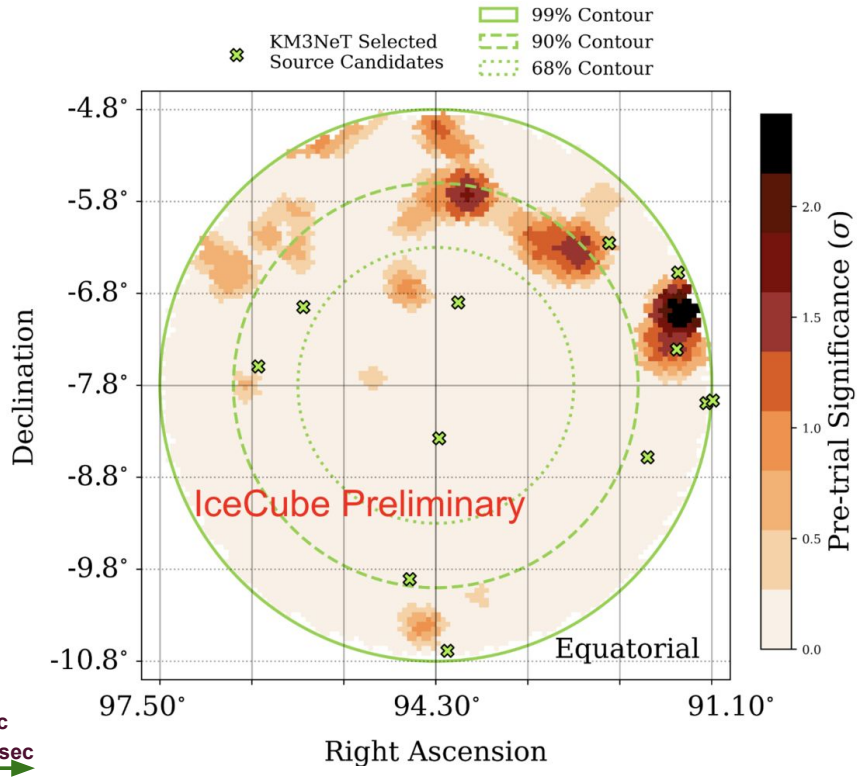
      i. **Post-trial corrected results consistent with background hypothesis (post-trial p-value of 1.0)**





Three Follow-up Analyses Conducted

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   a. Placing upper limits on KM3NeT event based on GFU-Cluster Non-detection
   b. Upper limits placed at KM3NeT location and nearby monitored source: **PKS 0605-085**
   c. Already known result, no additional analysis done

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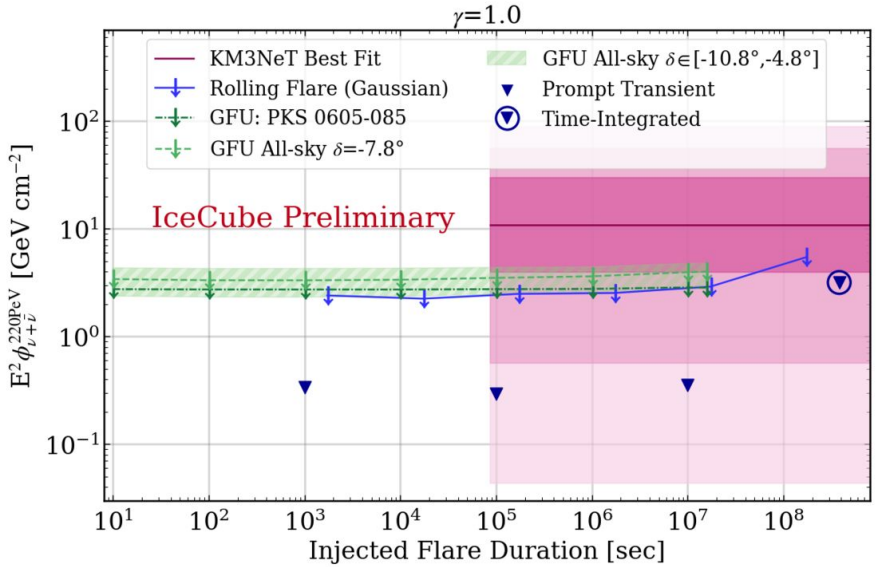

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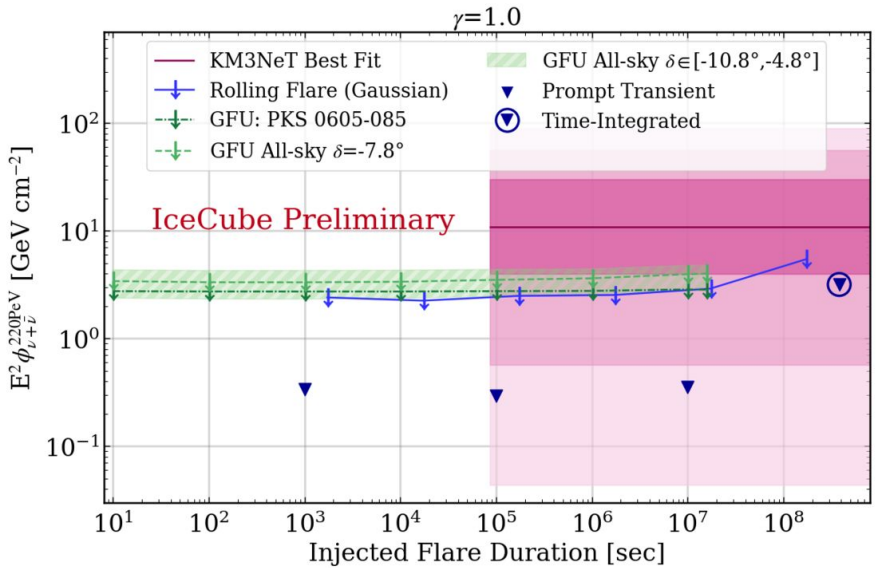
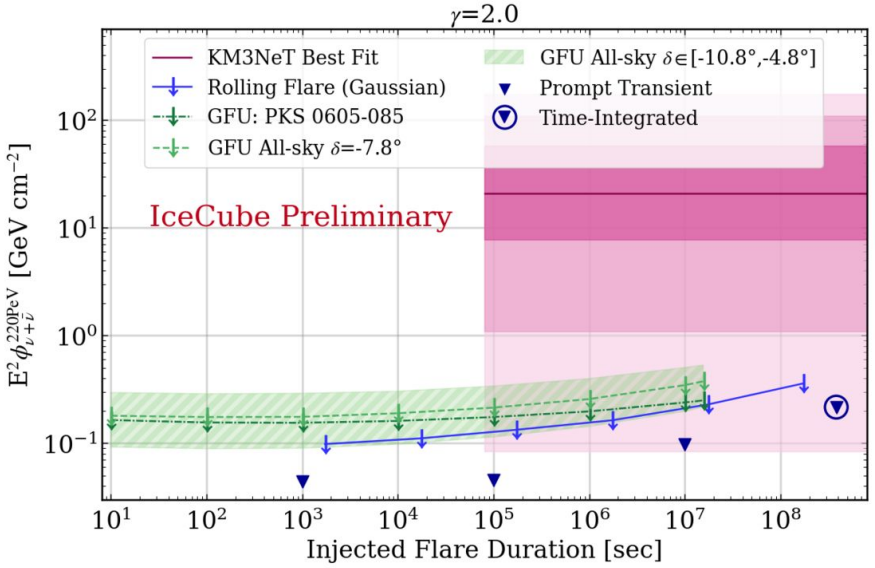
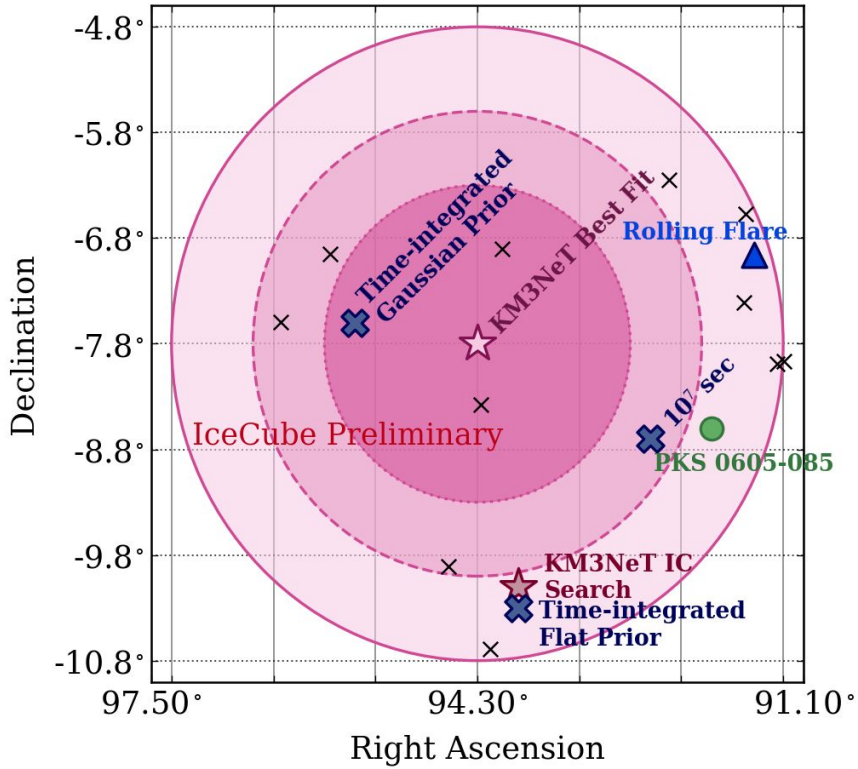




Conclusion

- Upper limits placed on all-sky GFU non-detection & on lack of temporarily coincident events from PKS 0605-085
- 3 types of follow-up analyses were conducted within KM3NeT's 99% containment region
  - Search for steady point-source with Gaussian and flat priors
  - Search for emission during specified boxed time-windows
  - Search for flaring neutrino point-source within IceCube's livetime
- All search results consistent with the background-only hypothesis



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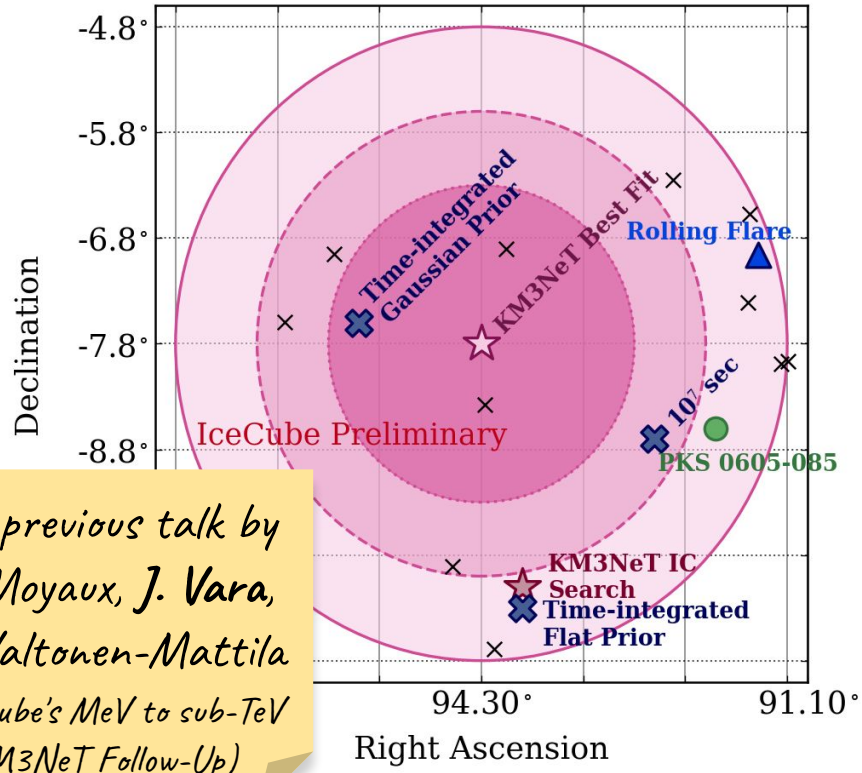


See previous talk by E. Moyaux, J. Vara, N. Valtonen-Mattila (IceCube's MeV to sub-TeV KM3NeT Follow-Up)

Supplementary Slides

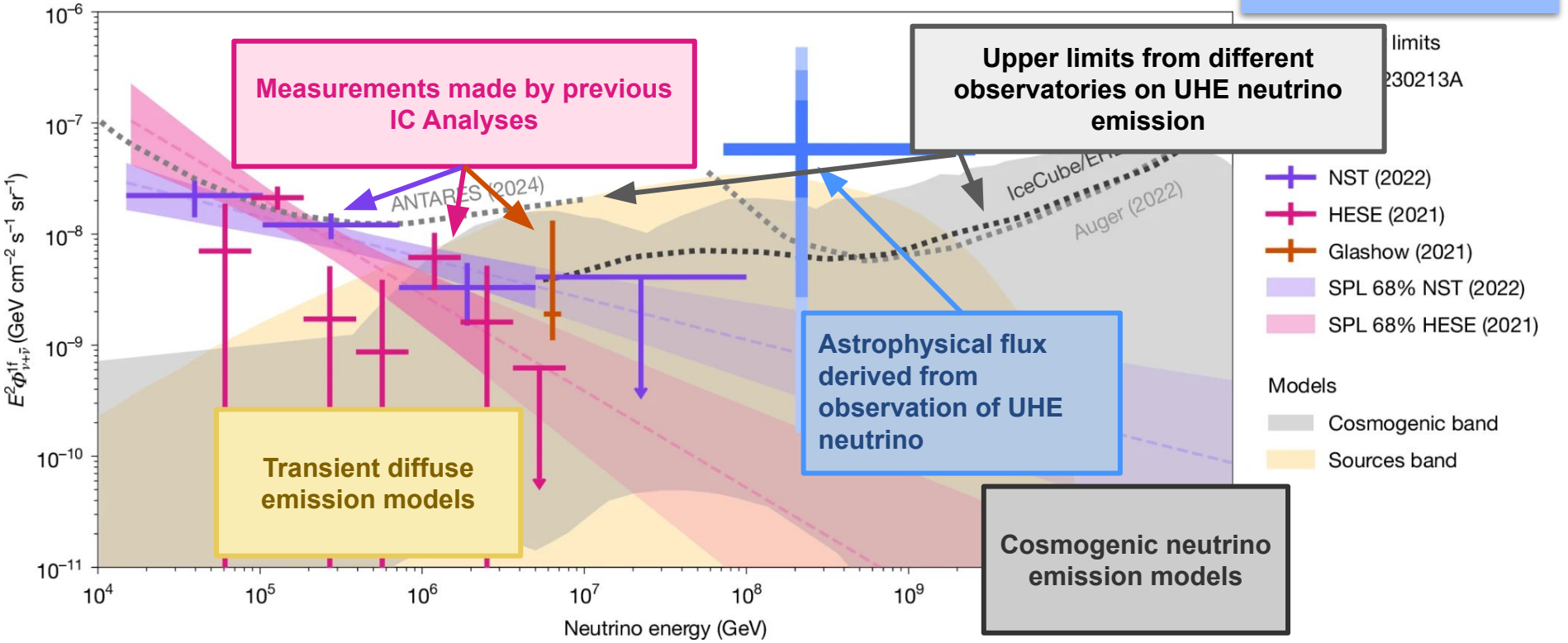
Summary of Results

Analysis	Prior	Best-Fit Location (RA, Dec)	n_s	γ_{fit}	Pre-trial (post-trial) p-value
KM3NeT Public IC Data	Flat	93.9°, -10.1°	15.1	N/A*	0.07 (post)
Time-Integrated	Flat	93.9°, -10.3°	13.04	2.1	0.93
Time-Integrated	Gaussian	95.5°, -7.6°	33.97	4.0	0.94
Time-dependent 10^3 sec	Gaussian	-	0.0	-	1.0
Time-dependent 10^5 sec	Gaussian	-	0.0	-	1.0
Time-dependent 10^7 sec	Gaussian	92.6°, -8.7°	3.56	2.30	0.89
Flare ~1 day (fit)	-	91.6°, -7.0°	6.78	4.0	1.0 (post)

* KM3NeT does not include energy weighting in their public data search

Comparison with Models and Measurements

Acronyms
UHE - Ultra-high energy



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IceCube-Related Analysis by KM3NeT

Dataset	n_{sig}	$-\log_{10}(p\text{-value})$	Flux Upper Limit $[\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}]$	(RA, Dec) [deg, deg]	Distance [deg]	P-value
ARCA6-21	0.4	0.044	1.8×10^{-8}	(94.3, −7.8)	0.0	-
	1.3	1.308	1.9×10^{-8}	(96.7, −6.8)	2.6	0.44
ORCA6-18	0	-	2.1×10^{-7}	-	-	-
ORCA18-23	0	-	2.3×10^{-6}	-	-	-
ORCA-combined	-	-	2.0×10^{-7}	-	-	-
ANTARES	0	-	1.1×10^{-8}	(94.3, −7.8)	0.0	-
	1.9	1.936	1.7×10^{-8}	(94.4, −5.3)	2.5	0.53
IceCube	1.4	0.327	1.2×10^{-9}	(94.3, −7.8)	0.0	-
	15.1	3.782	6.3×10^{-9}	(93.9, −10.1)	2.4	0.07

No significant excess of IceCube events from public data

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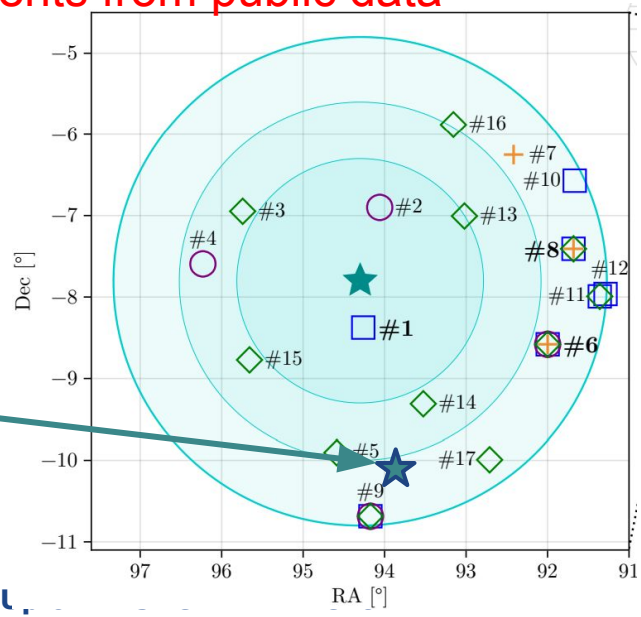
	15.1	3.782	6.3×10^{-9}	(93.9, −10.1)	2.4	0.07

No significant excess of IceCube events from public data

- Neglected energy weighting and assumed flat spatial prior of 3° in radius
- KM3NeT reported a *slight IceCube excess* at a distance of 2.4° from best-fit location at **(RA, Dec) = (93.9, -10.1)**
  - p-value: 0.07



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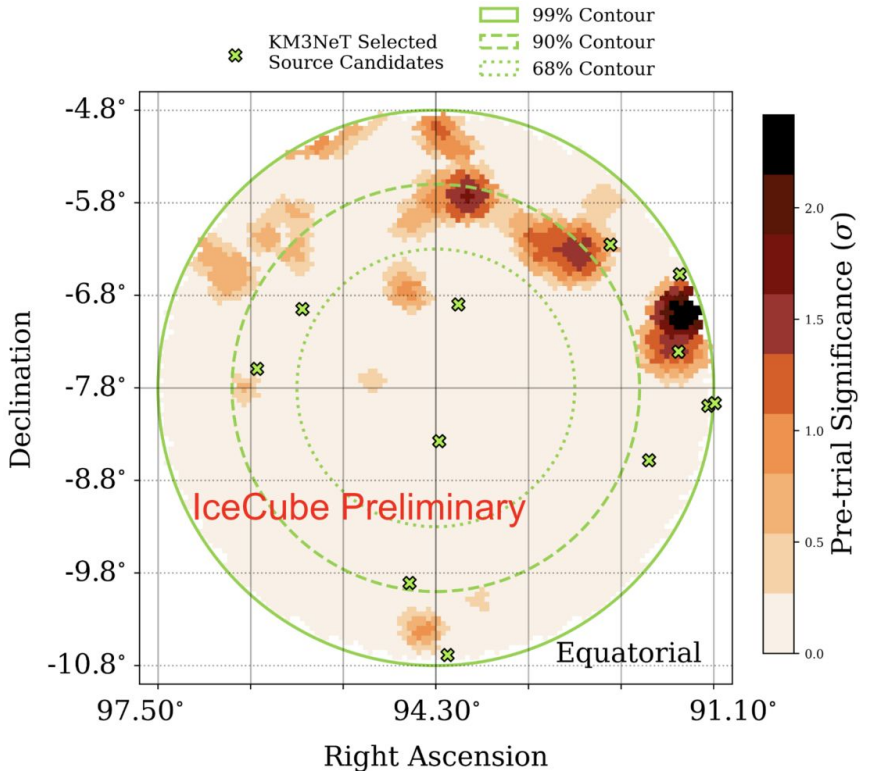
Flare Results

RA	Dec.	Pre-trial p-value	Pre-trial significance	Post-trial significance
91.58	-6.96	0.0078	2.42σ	0σ

ns	γ	σt (Days)	T0 (MJD)
6.78	4.0	0.95	59961.92

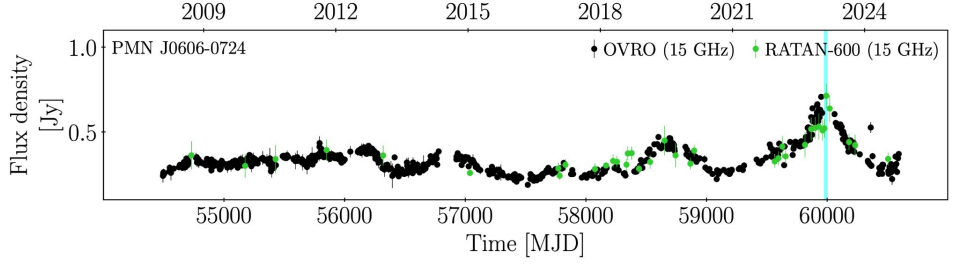
Jan. 17, 2023 @ 22:06:55 UTC

About 1 month before KM3NeT detection



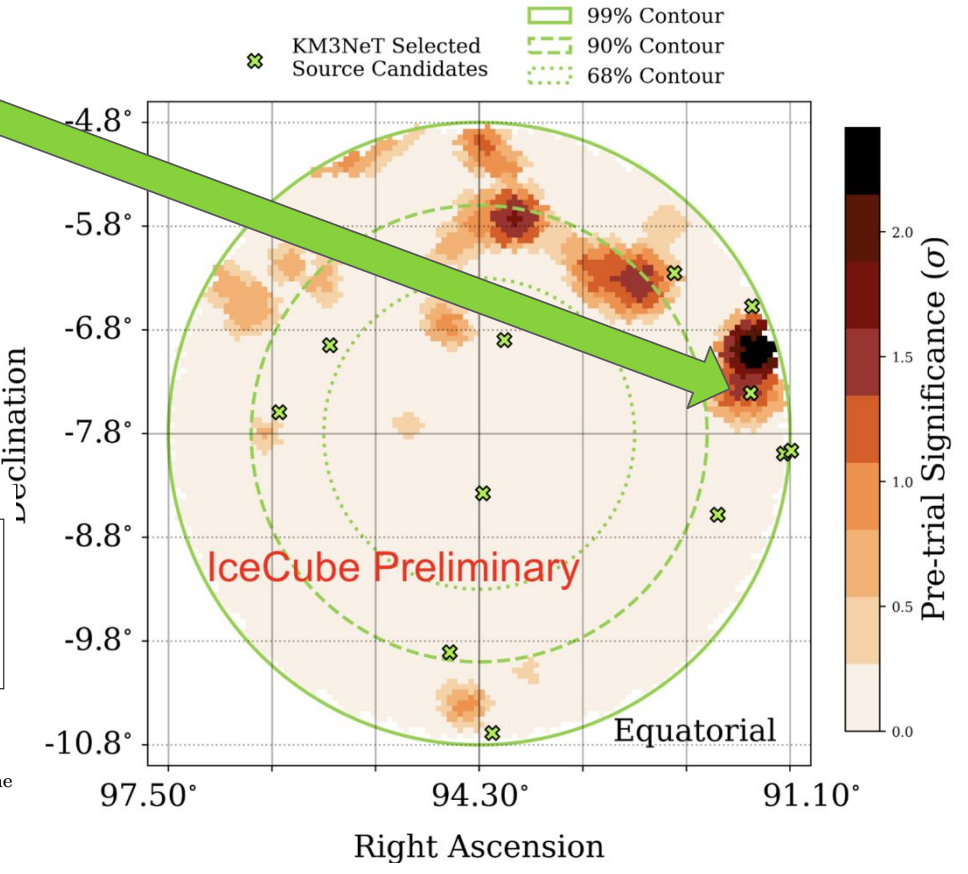
Flare Results

- Flaring blazar PMN J0606-0724
  - Gamma = 4.0
  - Dt ~ .0055 days
  - T0 ~ 57500 MJD (NOT FLARE TIME)
  - ~0.46deg away from hottest pixel center



(b) The radio light curve for PMN J0606-0724 that experiences a major flare in close coincidence to the neutrino arrival (Section 5.2).

KM3NeT Collaboration, et al. "Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A." *arXiv preprint arXiv:2502.08484* (2025).



Flare Results

- Non-flaring compact radio source NVSS J060639-063421
  - Gamma ~ 2.25
  - Dt ~ 200 days
  - T0 ~ 59600
  - ~0.39deg away from hottest pixel center

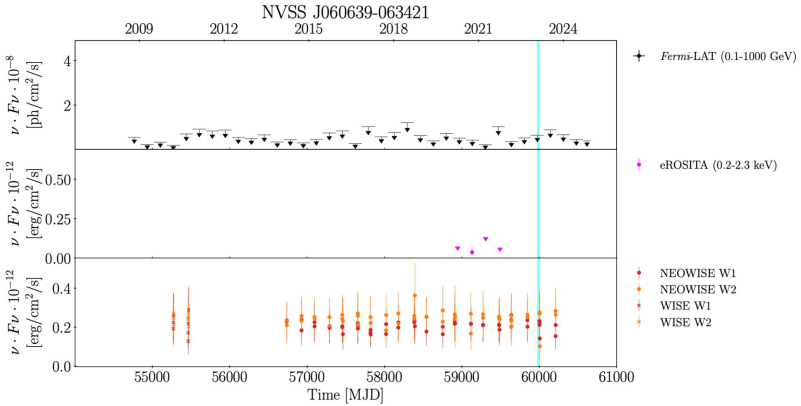


Figure A15. Multi-wavelength light curves of NVSS J060639-063421 (#10). The panels display from top to bottom: *Fermi*-LAT gamma-ray light curves integrated over 6-months; X-ray data from *eROSITA*; IR data from WISE/NEOWISE. The cyan stripe highlights the arrival time of KM3-230213A.

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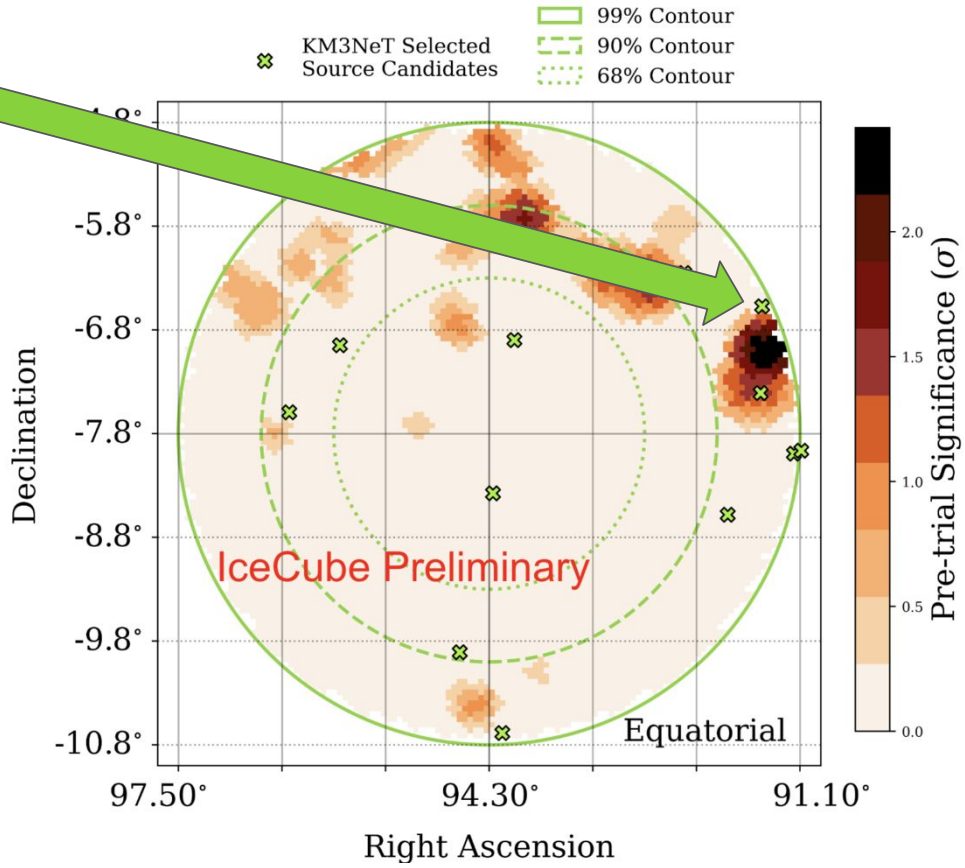
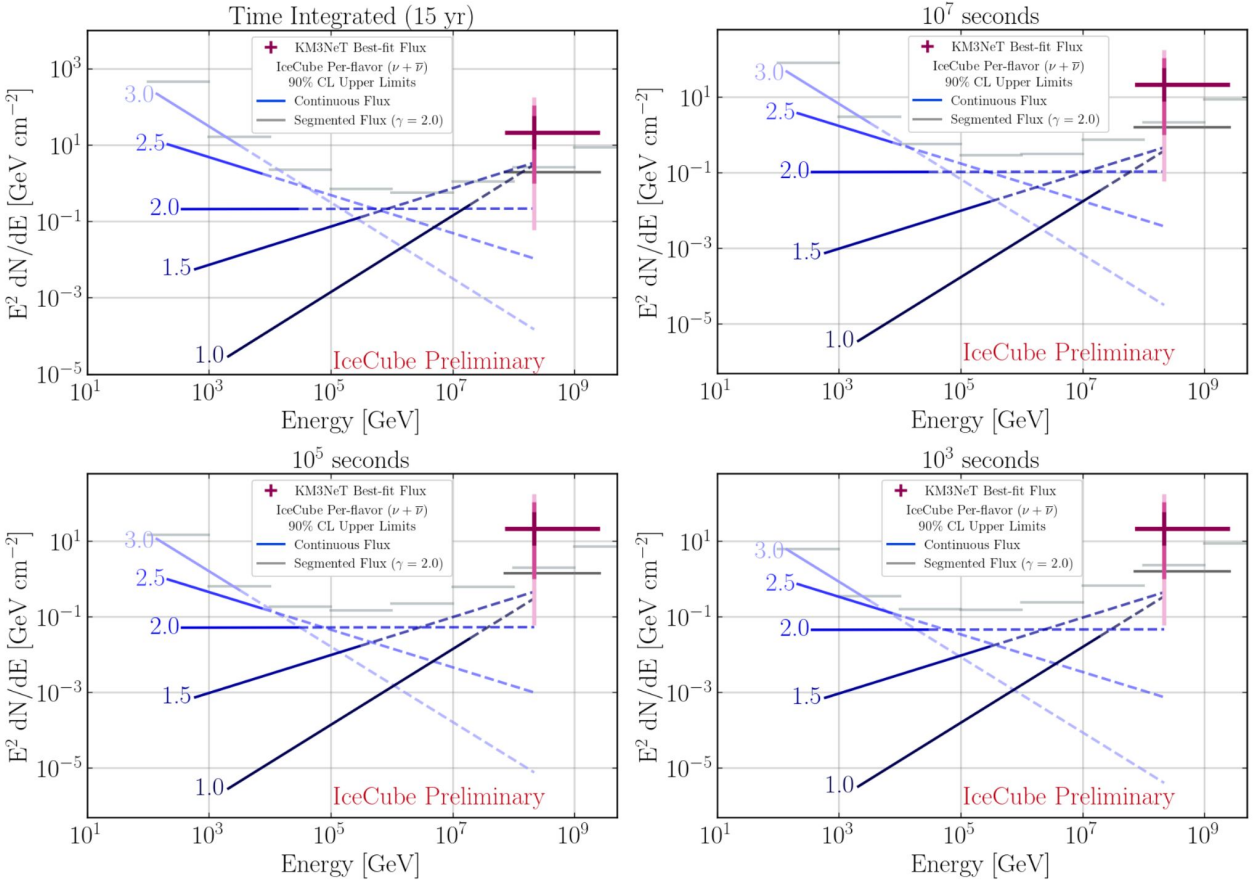


Time-Integrated & Time-Dependent Results



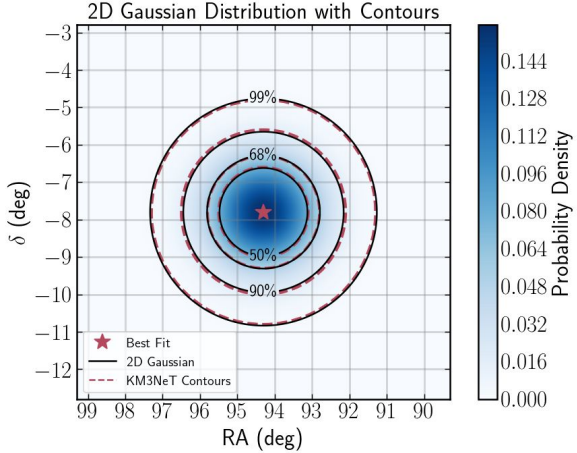
Spatial Priors in Likelihood Analyses

Incorporating a spatial prior adds a penalty term to our likelihood

$$\mathcal{L}(n_s, \gamma) = \frac{(n_s + n_b)^N}{N!} e^{-(n_s+n_b)} \times \prod_{i=1}^{N} \left(\frac{n_s}{n_s + n_b} \mathcal{S}(\mathbf{x_i} \mid \gamma) + \frac{n_b}{n_s + n_b} \mathcal{B}(\mathbf{x_i}) \right) \times P_K(x_s)$$

$$\mathrm{TS} = \max_{n_s, \gamma} \left[2 \ln \left(\frac{\mathcal{L}(n_s, \gamma)}{\mathcal{L}(n_s = 0)} \right) \right] + 2 \log \left[\frac{P_K(x_s)}{P_K(x_0)} \right]$$

Gaussian Prior



Each point is treated with equal probability within the circle

Flat Prior