Search for Neutrinos from Precursors and Afterglows of Gamma-Ray Bursts using the IceCube Neutrino Observatory

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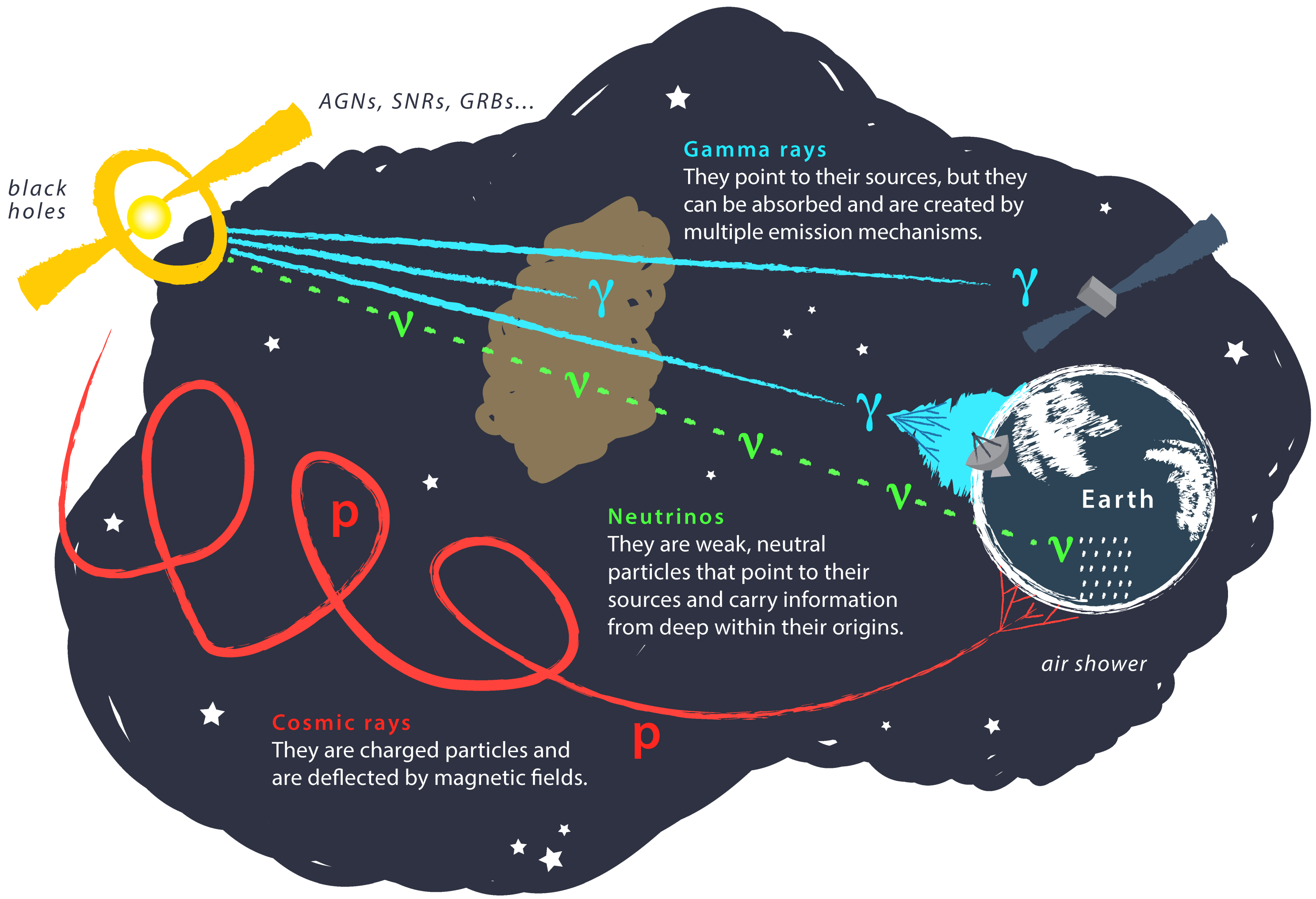
For the IceCube collaboration

Cosmic rays and neutrino connection

- High energy Cosmic rays (CR) sources are not well identified.
- Cosmic rays can lead to production of neutrinos.
- Neutrinos point back to their origins and can help identify the sources of CRs, and how they are produced.



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Gamma Ray Bursts as sources of high-energy neutrinos

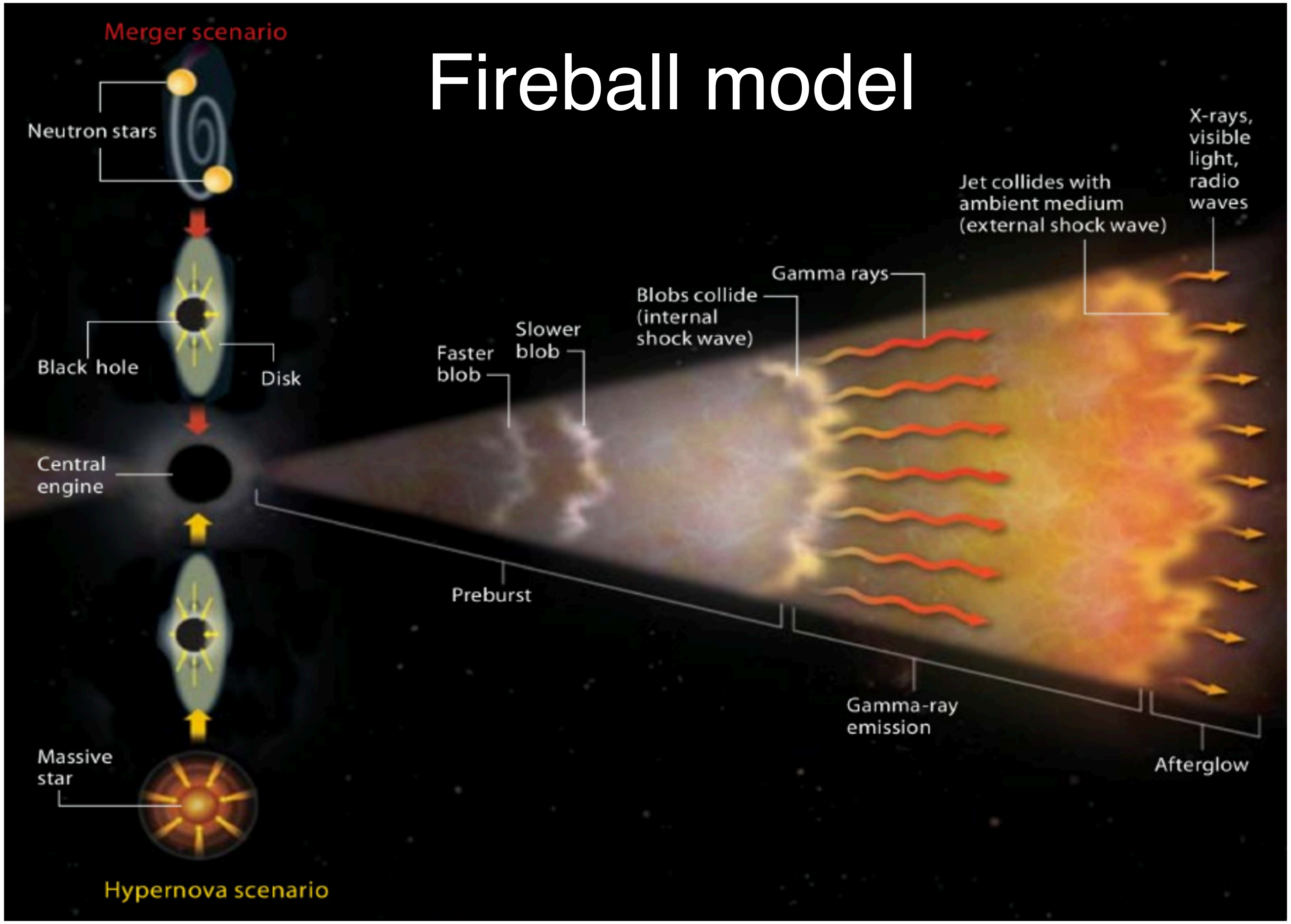
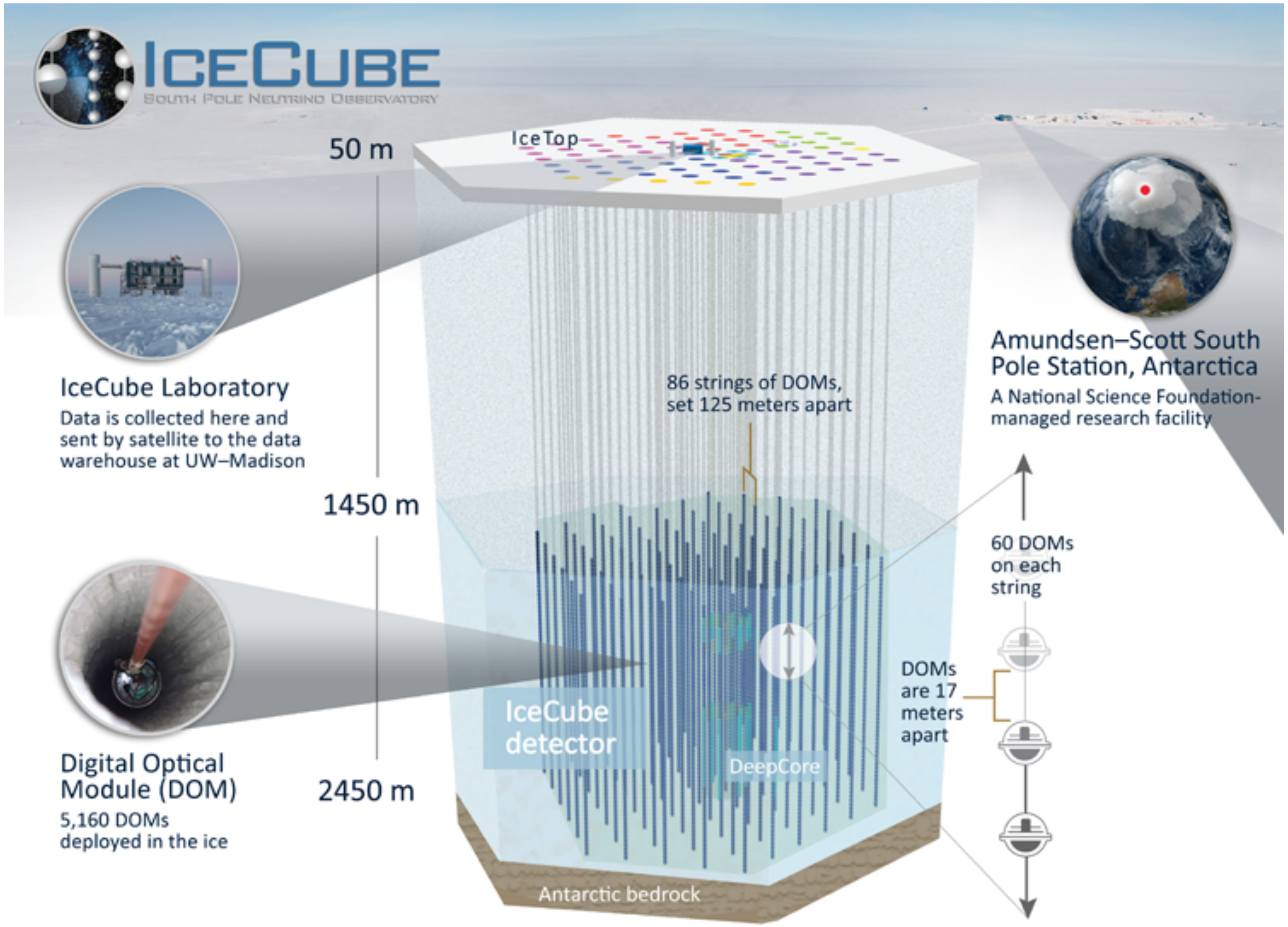


Image Credits: NASA

- GRBs have three main phases of emissions: precursor, prompt and afterglow.
- Shocks in jet are likely place for CR acceleration.
- These can also be sites for neutrino production.

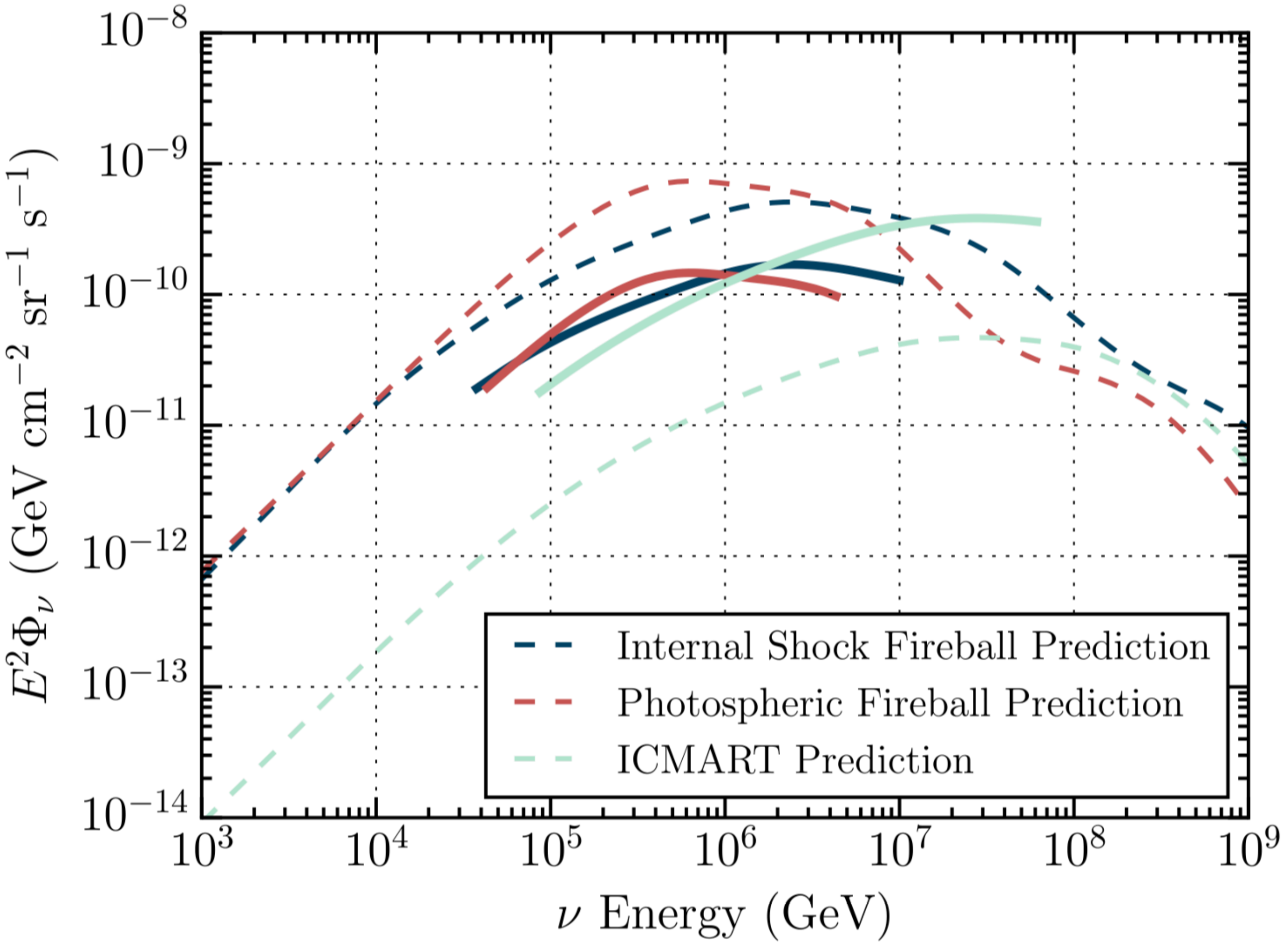
IceCube Neutrino Observatory



- A Cherenkov detector at the South Pole making use of Antarctic ice as the detection medium.
- Total instrumented volume: 1 km^3.
- Total 5160 Digital Optical Modules deployed over 86 strings.

Previous results

- Previous IceCube searches primarily focused on the prompt phase, typically <100s, and found no evidence of neutrino emission.
- Recent observations of gamma-rays by HESS long after prompt phase motivates us to look in a larger time window.
- What is new in our analysis:
    - More data used for the analysis
    - Search for neutrino correlations is not limited to the prompt phase of GRBs.



Upper limits (90% CL, solid lines) to the predicted per-flavor quasi- diffuse flux of numerical neutrino production models (dashed lines) for benchmark parameters f_p = 10 and Γ= 300 over the expected central 90% central energy containment interval of detected neutrinos for these models, combining the presented analysis with the previously published IceCube results.

Image source: M. G. Aartsen et al. ApJ 843 no. 2, (July, 2017) 112.

Going forward: 4 analyses

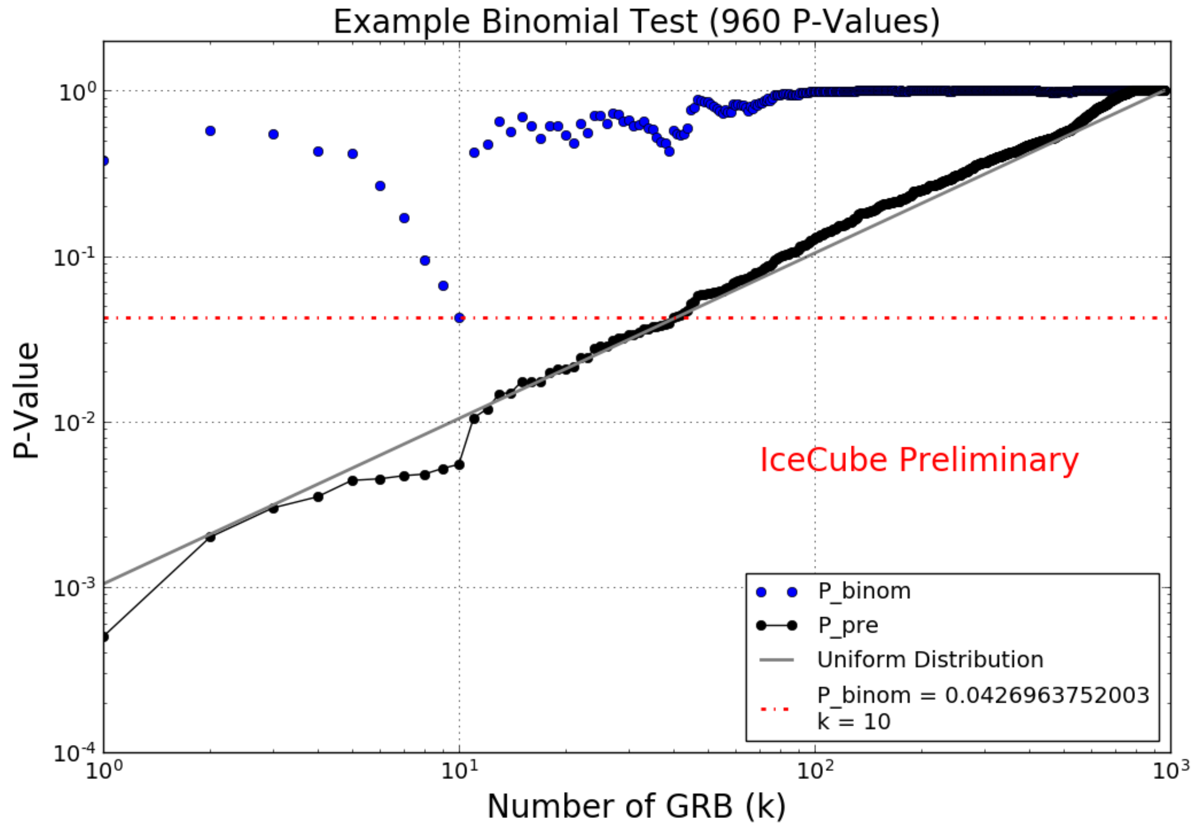
- Four independent analyses are designed to investigate neutrino correlations with GRBs
- The GRB data used for all the analyses is obtained from IceCube's publicly available online GRB catalog; GRBWeb: https://user-web.icecube.wisc.edu/~grbweb_public/ .
- All the analyses use the same sample of IceCube data which consists of well reconstructed muon neutrino events between the period of May 2011 and October 2018.
- The method of Maximum likelihood is used to determine the best fit parameters in each analysis.

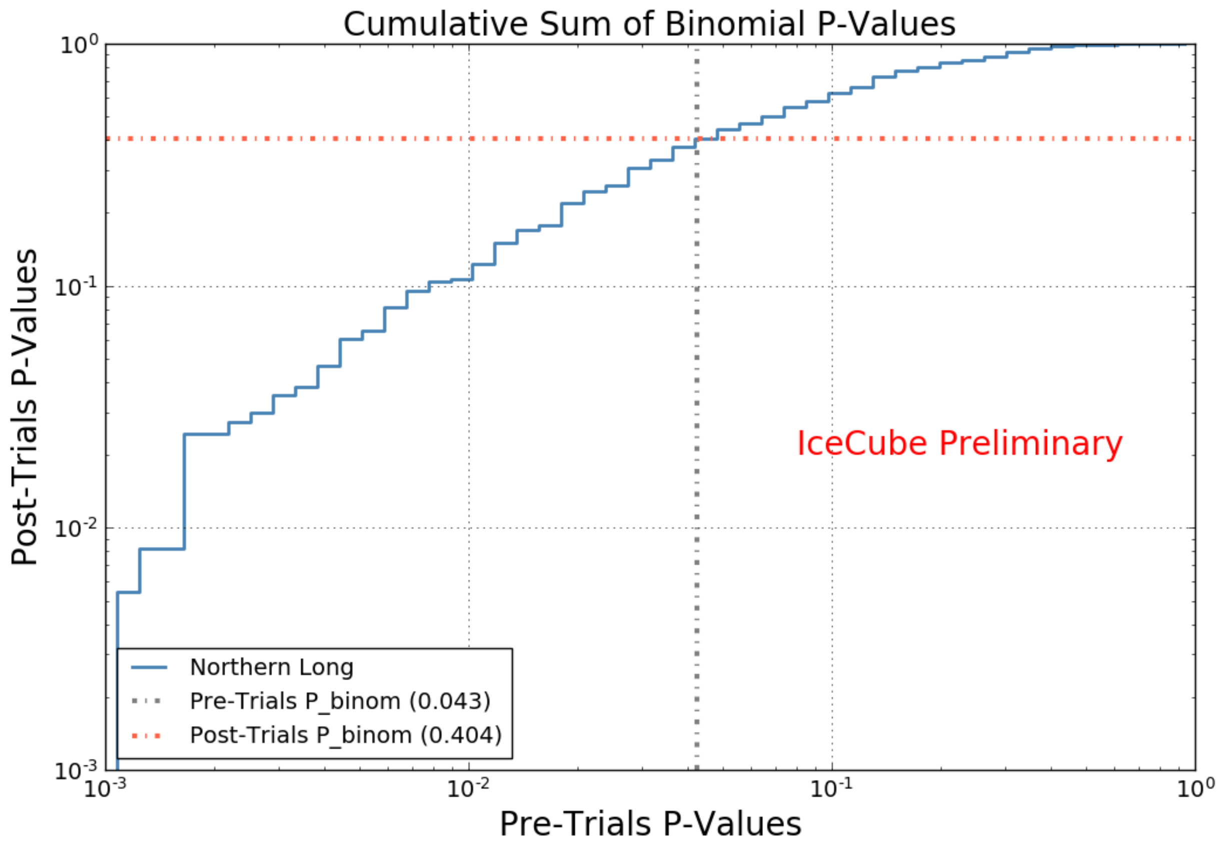
Analysis name	#GRBs selected	T_{100}	GRB localisation uncertainty	#GRBs only localised by GBM
Extended Time Window	2091	Required to be known	any	1236
Precursor/Afterglow	733	-	$< 0.2^{\circ}$	-
GBM Precursor	133	-	any	100
Stacked Precursor	872	-	$< 1.5^{\circ}$	-

Binomial testing

- For two of the four analyses we obtain lists of p-values, one for each GRB analysed. We use Binomial test to determine if there is a sub-population of result out of these lists which is statistically more significant.

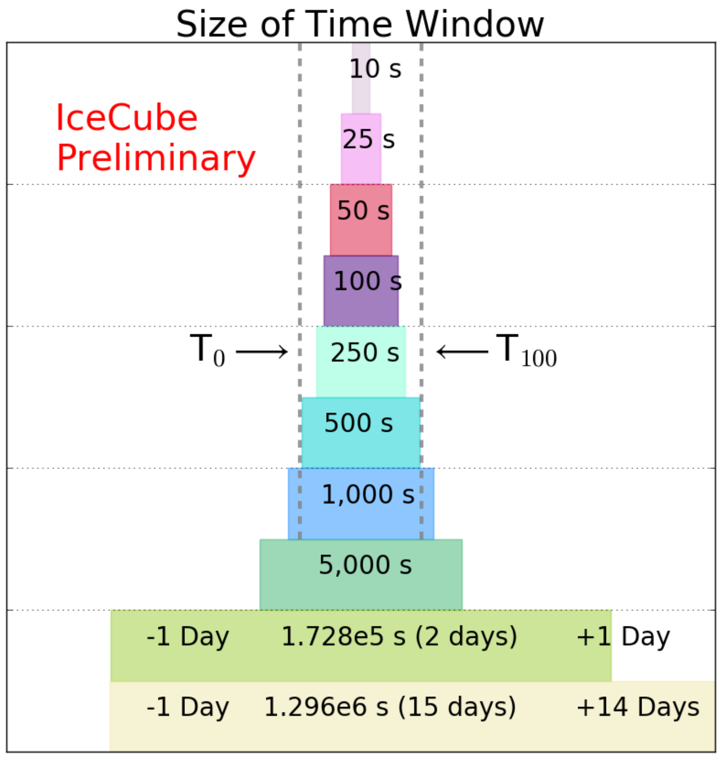
$$P(k) \equiv P(n \geq k|N, p_k) = \sum_{m=k}^{N} \frac{N!}{(N-m)!m!} p_k^m (1-p_k)^{N-m}$$





Extended Time Window

- Each GRB investigated in 10 time windows centred on prompt phase
- Most significant p-value chosen for GRB
- The 2,091 GRBs are split into four sub-samples by hemisphere and duration.
- P-values of all GRBs in each sub-sample are analysed with binomial test.

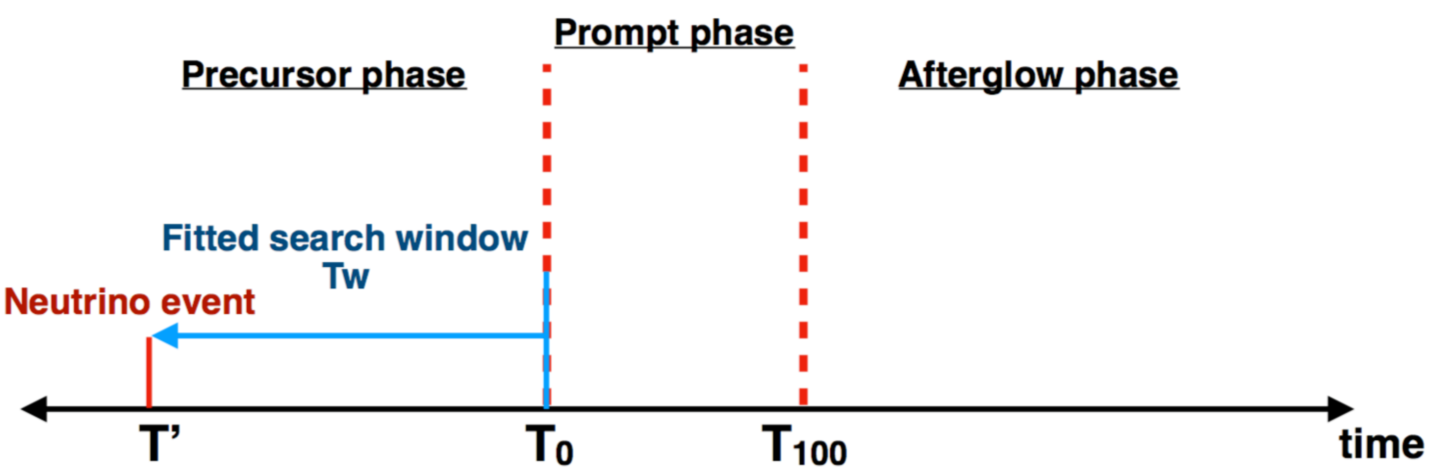


Results:

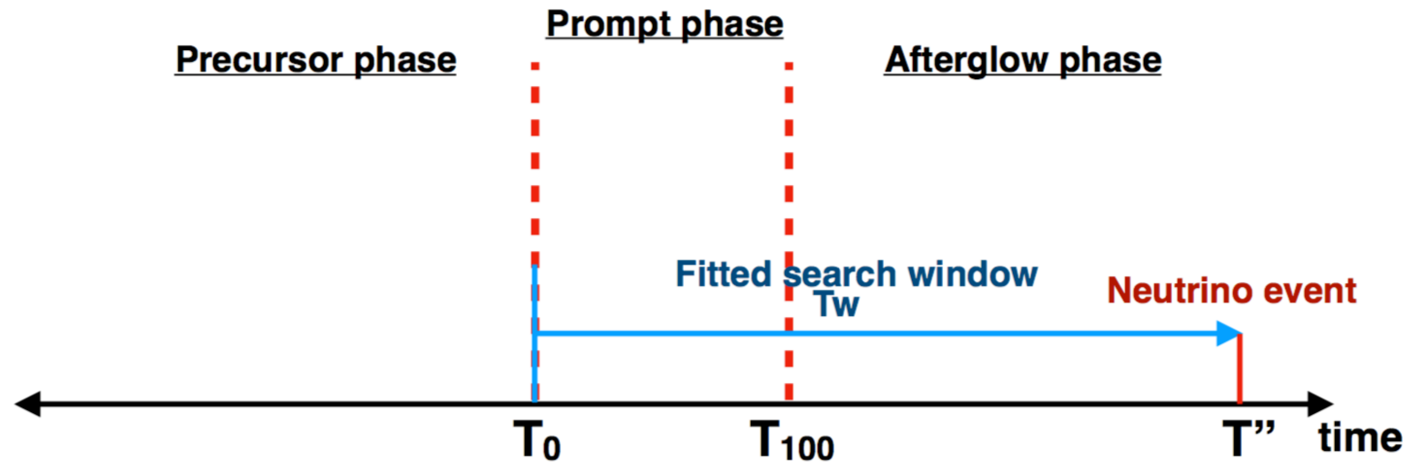
Sub-Population	Number of GRBs	Post-trial Binomial P-Value
Northern Long	960	0.038
Northern Short	183	0.799
Southern Long	814	0.898
Southern Short	134	0.849

Precursor/Afterglow

- Each GRB is analysed separately. Best fit time window, number of neutrino events, and p-value obtained for each GRB.
- Two searches for neutrino correlations performed, with different time window ranges:
  - **Precursor search**: **up to 14 days prior** to start of prompt phase.
  - **Prompt+afterglow search: up to 14 days after** the start of prompt phase.
- P-values of all 733 GRBs analyzed with binomial test, once for precursor and once for prompt+afterglow.



Precursor search

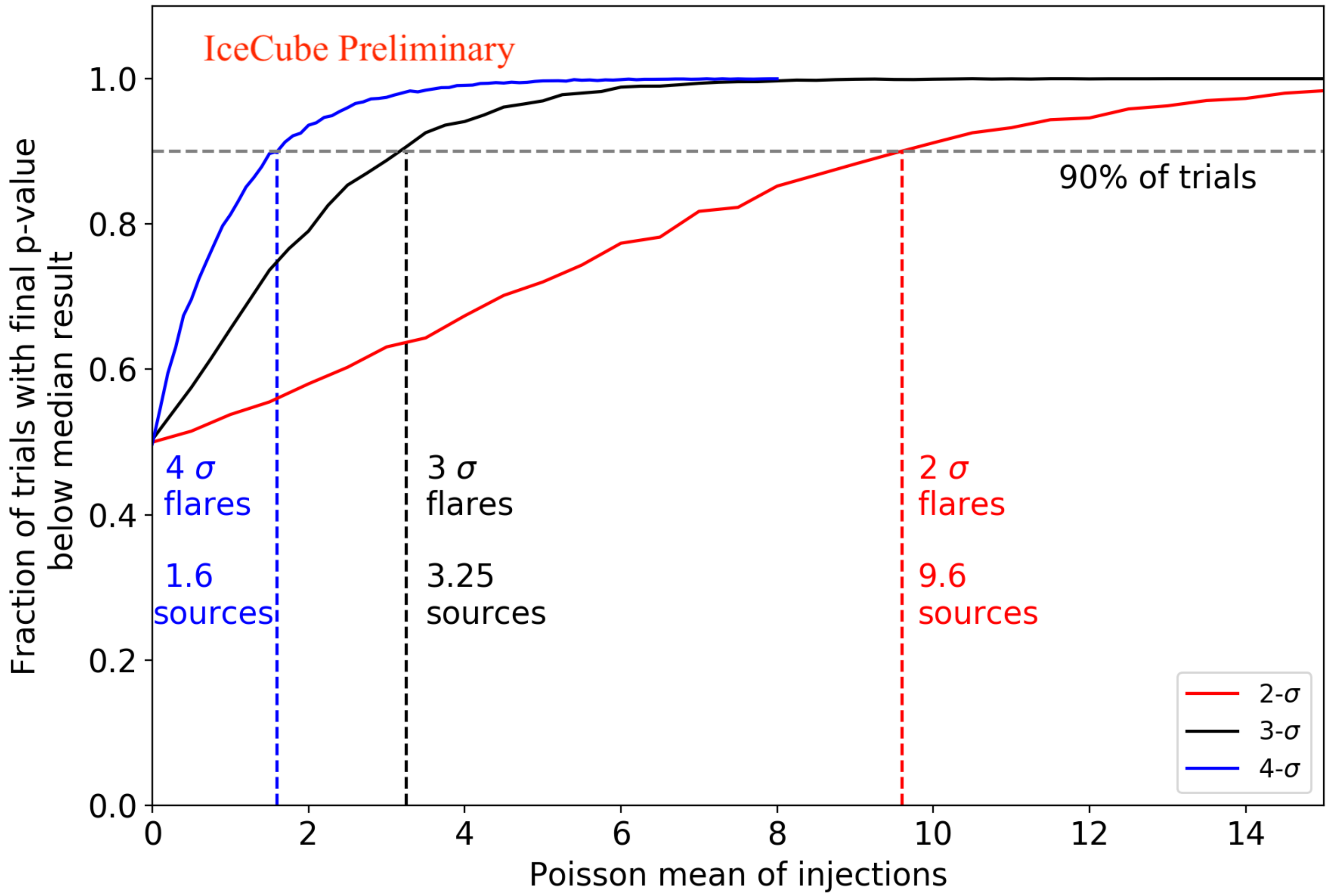


Prompt+afterglow search

Precursor/Afterglow

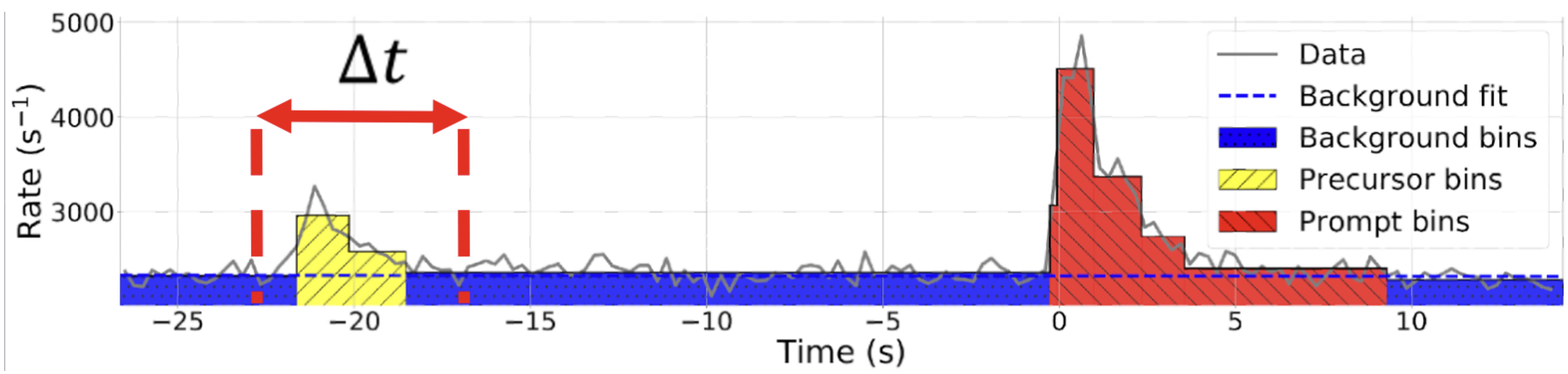
- Precursor search results: post-trial p-value = 0.495
- Prompt+afterglow search results: post trial p-value = 0.486

The results are comparable with a median background expectation (i.e. post-trial p-value of 0.5)



GBM Precursor

- Fermi-GBM analysis identified 217 GRB precursor gamma-ray flashes (https://doi.org/10.1103/PhysRevD.102.103014)
- 133 out of 217 overlap with IceCube data taking period.
- Examine precursor time windows of each of these 133 GRBs to search for neutrino excess
- Consider most significant p-value → Apply correction for choosing best of 133 p-values
- Results: No coincident neutrinos → p-value = 1



Stacked Precursor

- Fermi-GBM analysis showed precursors occur less than 250s before prompt emission

  → This analysis: search for neutrinos in 250 s before prompt emission
- Use all well localised bursts (872 GRBs)
- Stacking analysis: Fit combined signal excess of all GRBs → No trial correction needed.

- Results:
  - 5 low energy neutrinos found in spatial coincidence with GRBs and within 250s precursor time window.
  - fully consistent with background expectation

==> p-value = 1

GRB name	$\Delta\alpha$ ($^\circ$)	σ_α ($^\circ$)	E (GeV)	Δt (s)
GRB130131B	10.3	2.6	676	196.0
GRB141220A	2.0	2.2	47	2.7
GRB160314B	5.8	1.2	1023	91.6
GRB160705B	5.2	1.5	794	158.5
GRB160912A	6.1	2.3	525	143.6

Conclusion

- The four analyses presented here all report observations consistent with background expectations.
- The binomial tests did not report any significant sub-populations with statistically significant results for the GRBs considered in each analysis.
- The results are being used to compute upper limits on neutrino fluxes from GRBs.
- The results and the upper limits will be presented in a paper which is in progress.

Thank you!