Search for High-Energy Neutrino Emission from Fast Radio Bursts

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IPA 2017 – Neutrino Astronomy II parallel session
May 8th, 2017

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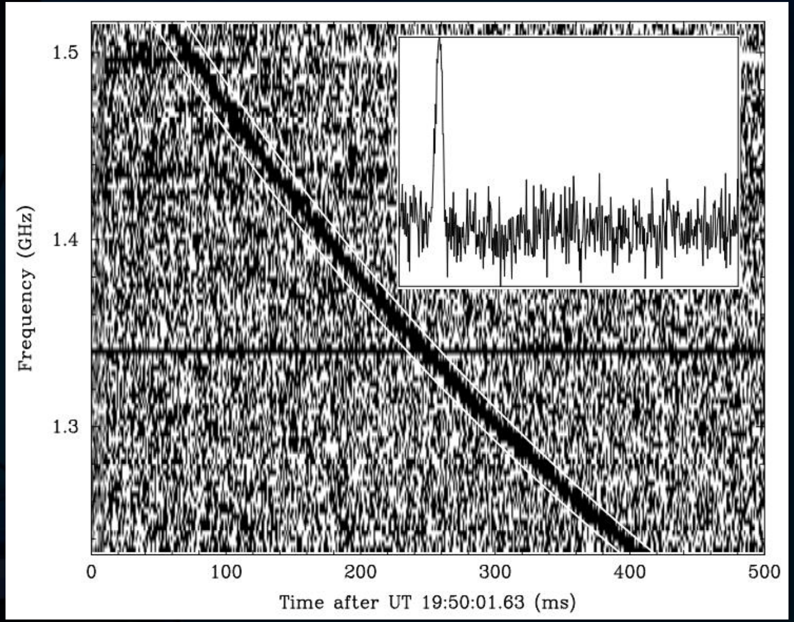
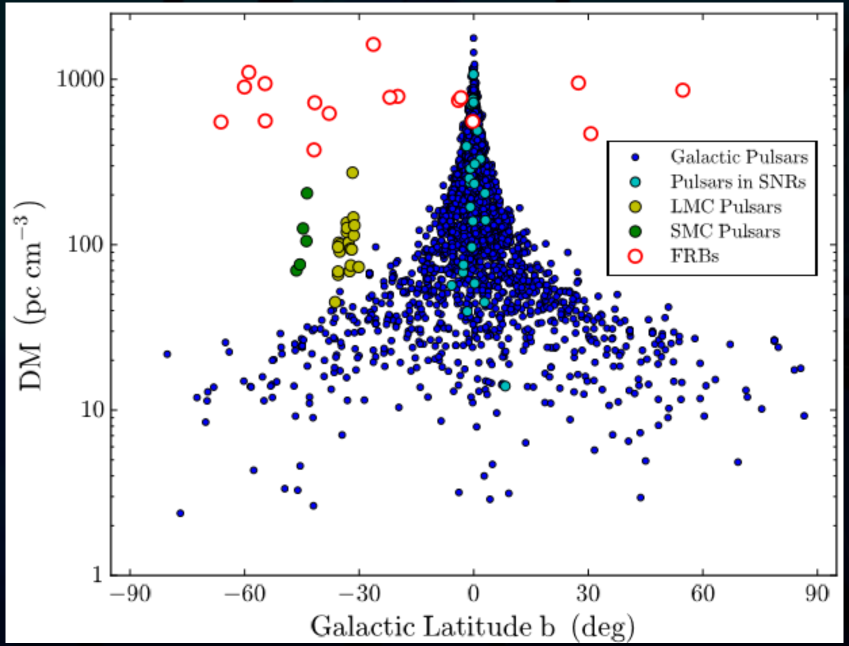
Fast Radio Bursts (FRBs)

- 21 FRB sources discovered; all-sky rate ~3,000 events/day
  - One source has repeated more than 100 times
- Bright radio emission for < 5 ms → compact source
- Time delay of low frequency components consistent with dispersion in interstellar plasma



Lorimer et al., **Science** 318 (5851): 777-780



Cordes et al., arXiv:1605.05890

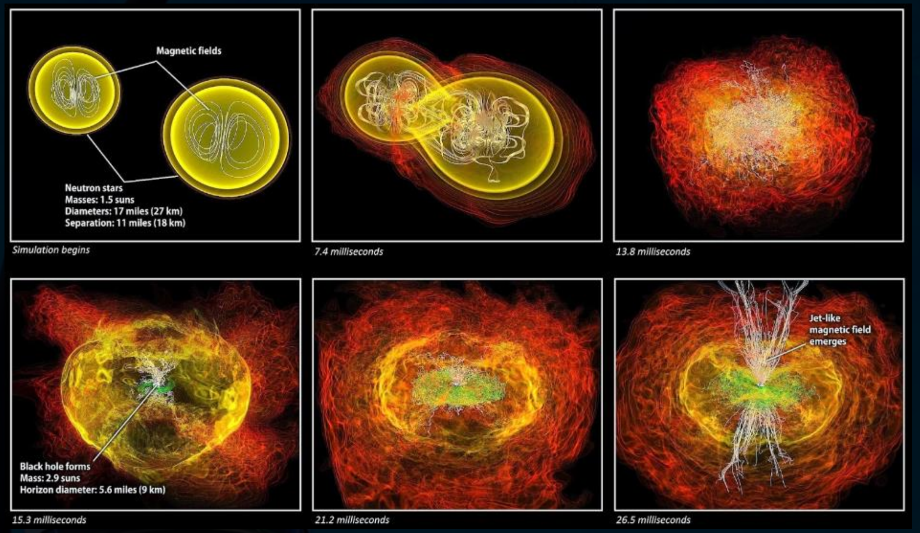
Dispersion Measure (DM): the integrated column density of free electrons measured along line of sight.

- DMs are larger than the Milky Way alone could provide
- Distribution consistent with that of a uniformly filled Euclidean space → likely extragalactic

Models for FRBs

- Blitzars
  [H. Falcke and L. Rezzolla, A&A 562, A137 (2014)]
- Binary neutron star mergers
  [T.Totani, Pub. Astron. Soc. Jpn. 65, L12 (2013)]
- Evaporating primordial black holes
  [Halzen *et al.*, PRD 1995]
  - "MeV neutrinos" → IceCube's Supernova stream

"Cataclysmic" Models

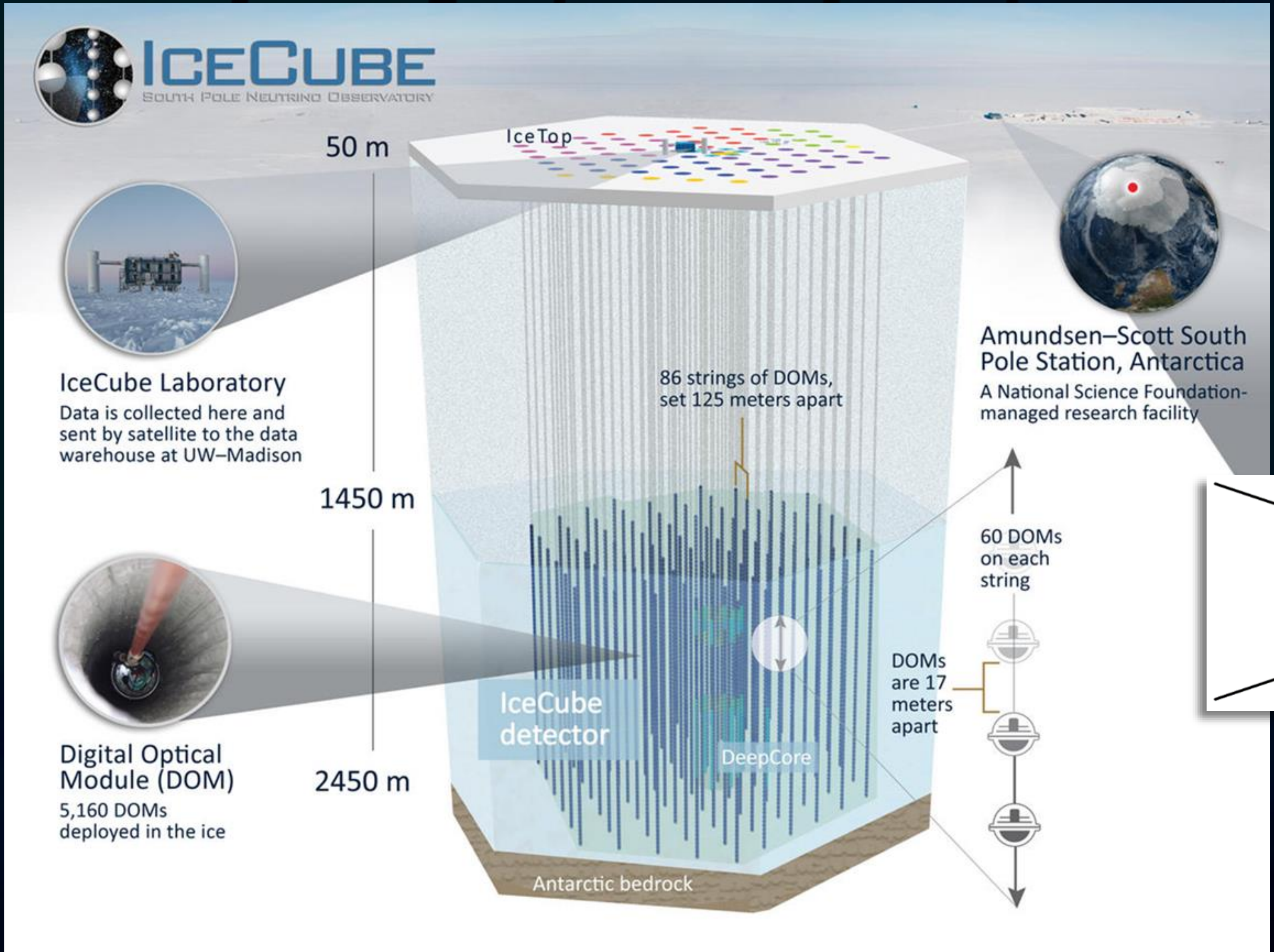


- Pulsars passing through asteroid belts
  [J. J. Geng and Y. F. Huang, ApJ 809, 24 (2015)]
- Magnetar/SGR hyperflares
  [S. B. Popov and K. A. Postnov, arXiv:1307.4924]
  [Halzen *et al.* (2005) asto-ph/0503348]
  - "TeV neutrinos"? → This analysis

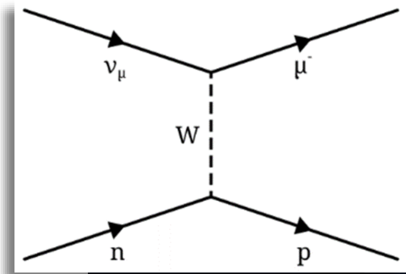
Allow Repeating

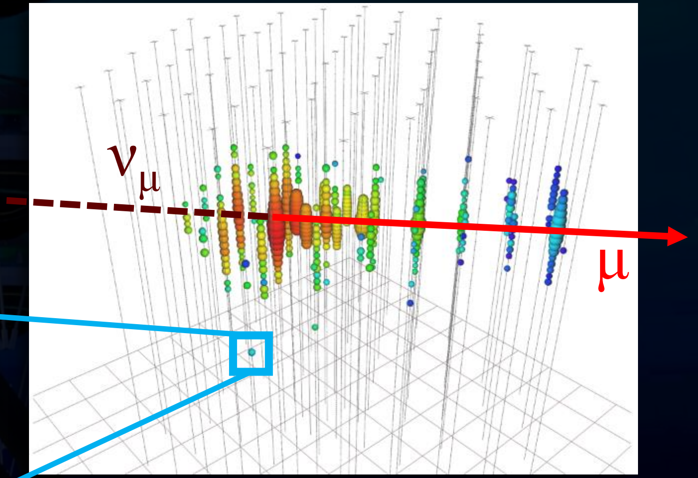
- No concrete neutrino production models yet

IceCube Neutrino Observatory



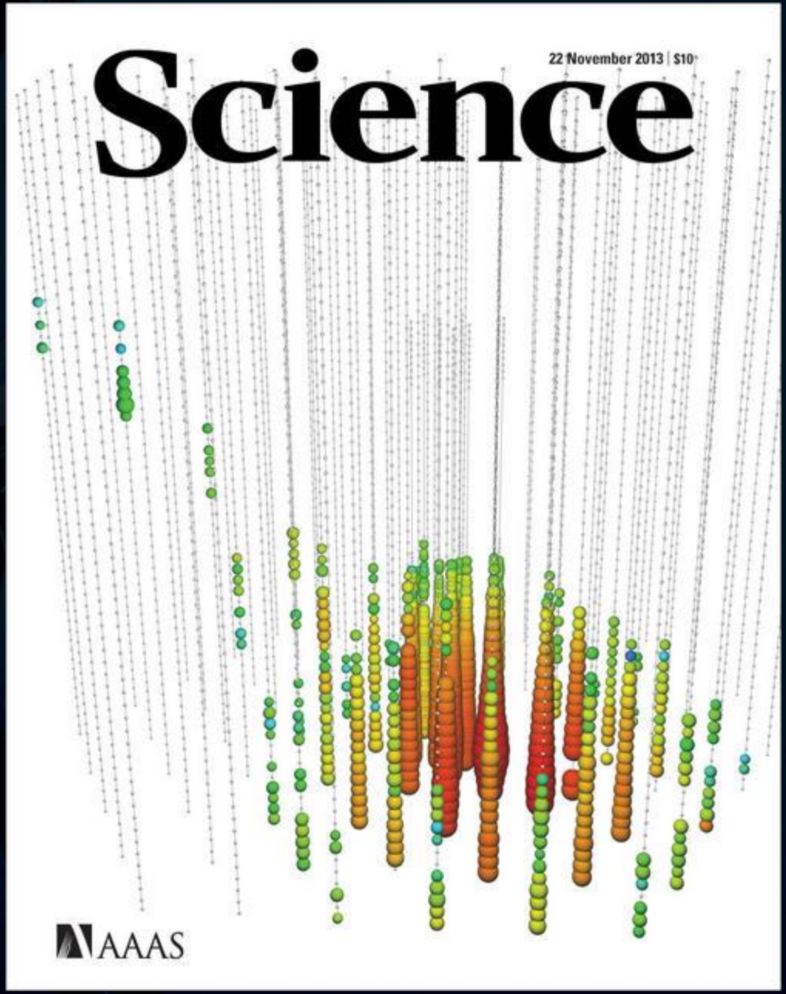
- km^3 detector observes neutrinos with energy above ~10 GeV
- PMT array detects Cherenkov radiation from secondary particles from in-ice interactions
- Muons create long tracks with angular resolution <1° at high energies





IceCube's Astrophysical Neutrino Flux

- IceCube observed an astrophysical ν_μ flux
  - Excluded purely atmospheric origin at 5.6σ significance
    [“Observation and Characterization of a Cosmic Muon Neutrino Flux from the Northern Hemisphere Using Six Years of IceCube Data” Aartsen *et al*. ApJ 833, 1 (2016)]
- No source of astrophysical neutrinos has yet been identified
  - Gamma-ray bursts show no significant correlation with high-energy neutrino events
  - Blazars and star-forming galaxies are also disfavored



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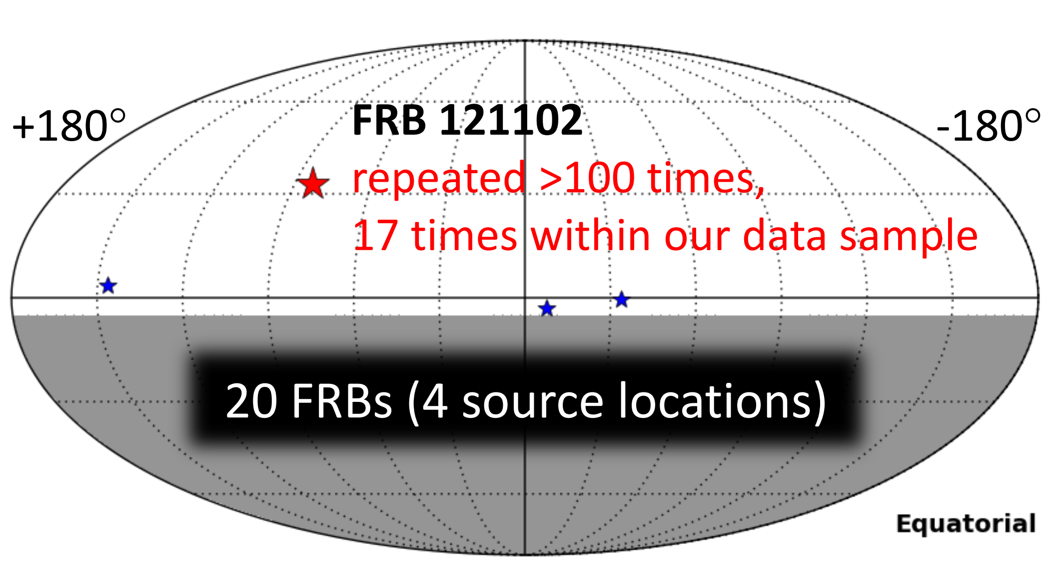
Event Samples & FRBs

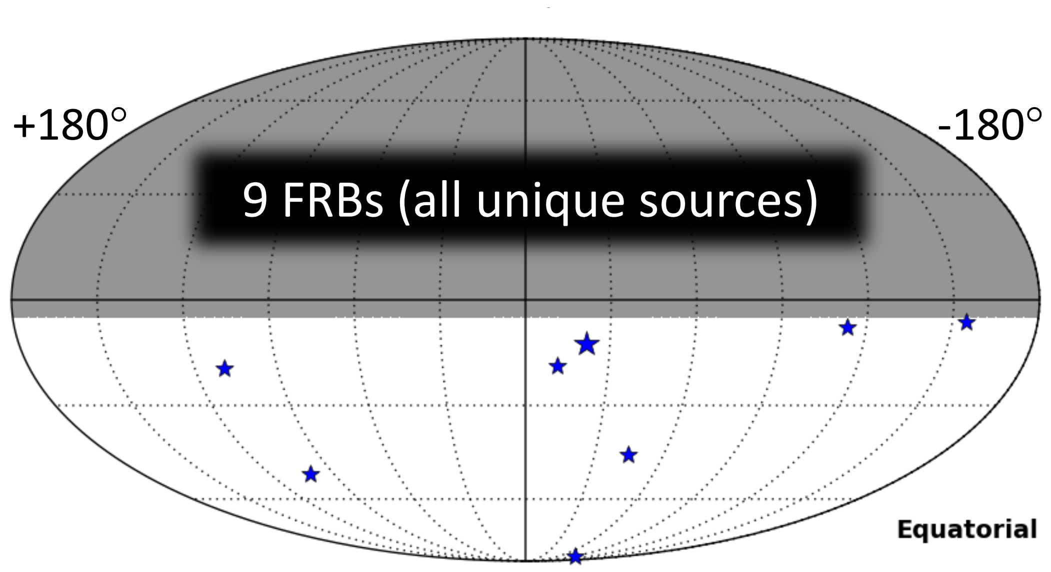
NORTH (δ>-5°)

- 842,597 events from 2011 – 2016
  - 6 mHz in hemisphere
- Dominated by atmospheric neutrinos



SOUTH (δ<-5°)

- 379,261 events from 2010 – 2015
  - 2.5 mHz in hemisphere
- Dominated by atmospheric muons



Total sample of 1.2 million events in 6 years

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Analysis Method: Unbinned Maximum Likelihood

- The likelihood of observing N events with properties $\{x_i\}$ for $(n_s + n_b)$ expected events is

$$\mathcal{L}(N, \{x_i\}; n_s + n_b) = P_{Poisson}(N; n_s + n_b) \prod_{i=1}^{N} P(x_i)$$

- The normalized probability of observing an event with properties x_i is $P(x_i)$:

$$P(x_i) = \frac{n_s S(x_i) + n_b B(x_i)}{n_s + n_b}$$

$$S_i = S_{\text{time}}(t_i) \cdot S_{\text{space}}(\vec{x}_i)$$
$$B_i = B_{\text{time}}(t_i) \cdot B_{\text{space}}(\vec{x}_i)$$

No energy dependence

$$T \coloneqq \ln \frac{\mathcal{L}(N, \{x_i\}; n_s + n_b)}{\mathcal{L}_0(N, \{x_i\}; n_b)}$$

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Search Strategies

Testing two hypotheses in parallel:

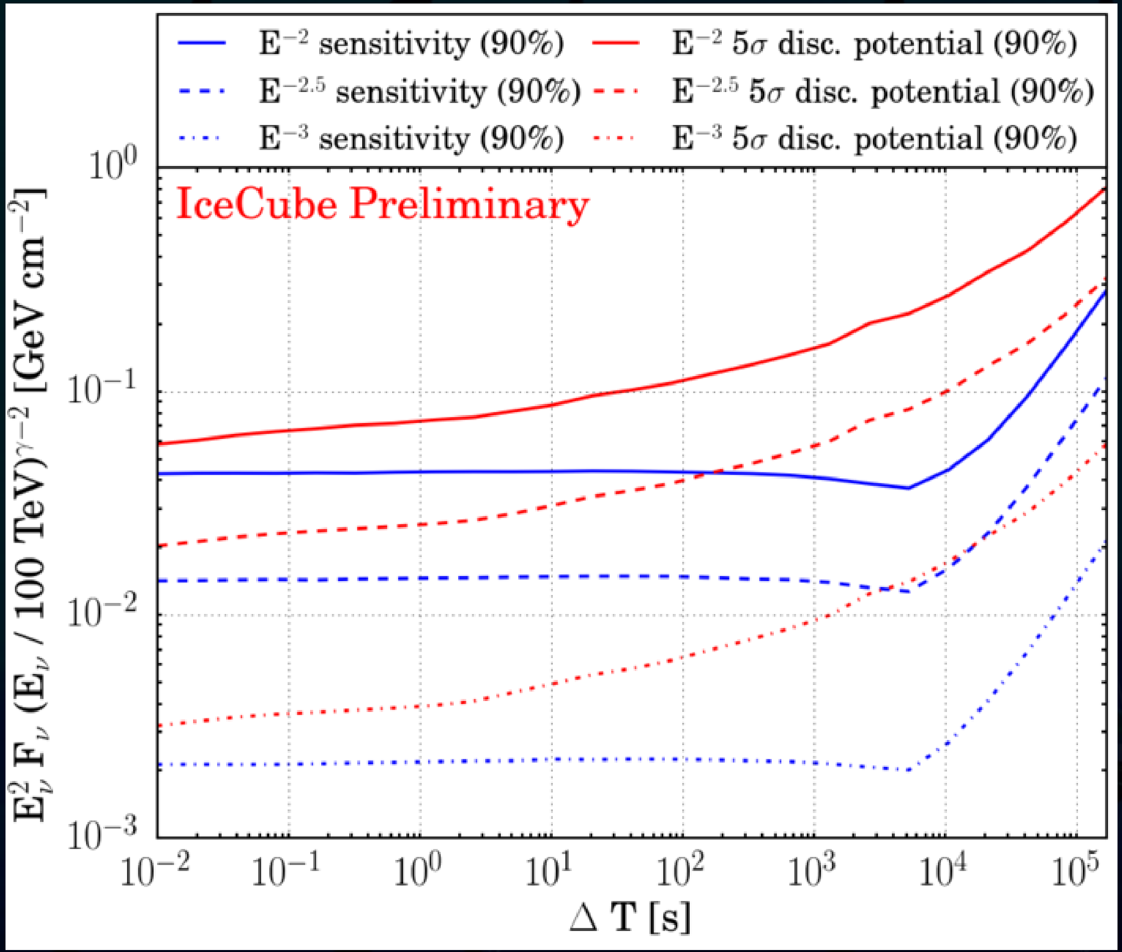
- **Stacking Search:** Does this source class emit neutrinos?
  - Method: Evaluate correlation of event sample with all FRBs in hemisphere
  - Detect sub-threshold emission from multiple sources
- **Max-Burst Search:** Does any of the sources emit neutrinos?
  - Method: Evaluate correlation of event sample with each FRB independently
  - Detect significant emission from strongest source

Expanding time windows:

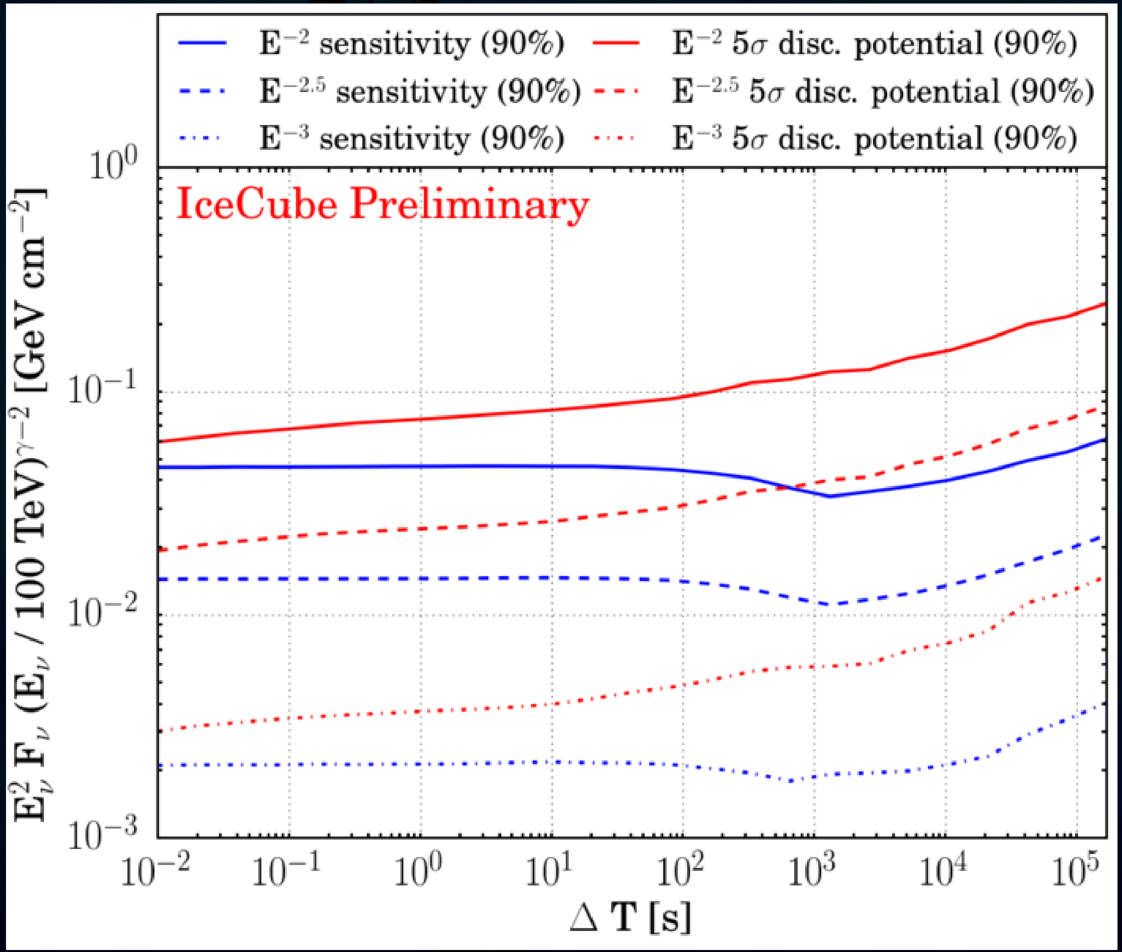
- Evaluate each test for events in a time window centered on each FRB
- 25 windows: $\pm$5 ms, $\pm$10 ms, $\pm$20 ms, … , $\pm$0.97 days

Sensitivity & Discovery Potential: North

Northern Stacking Sensitivities

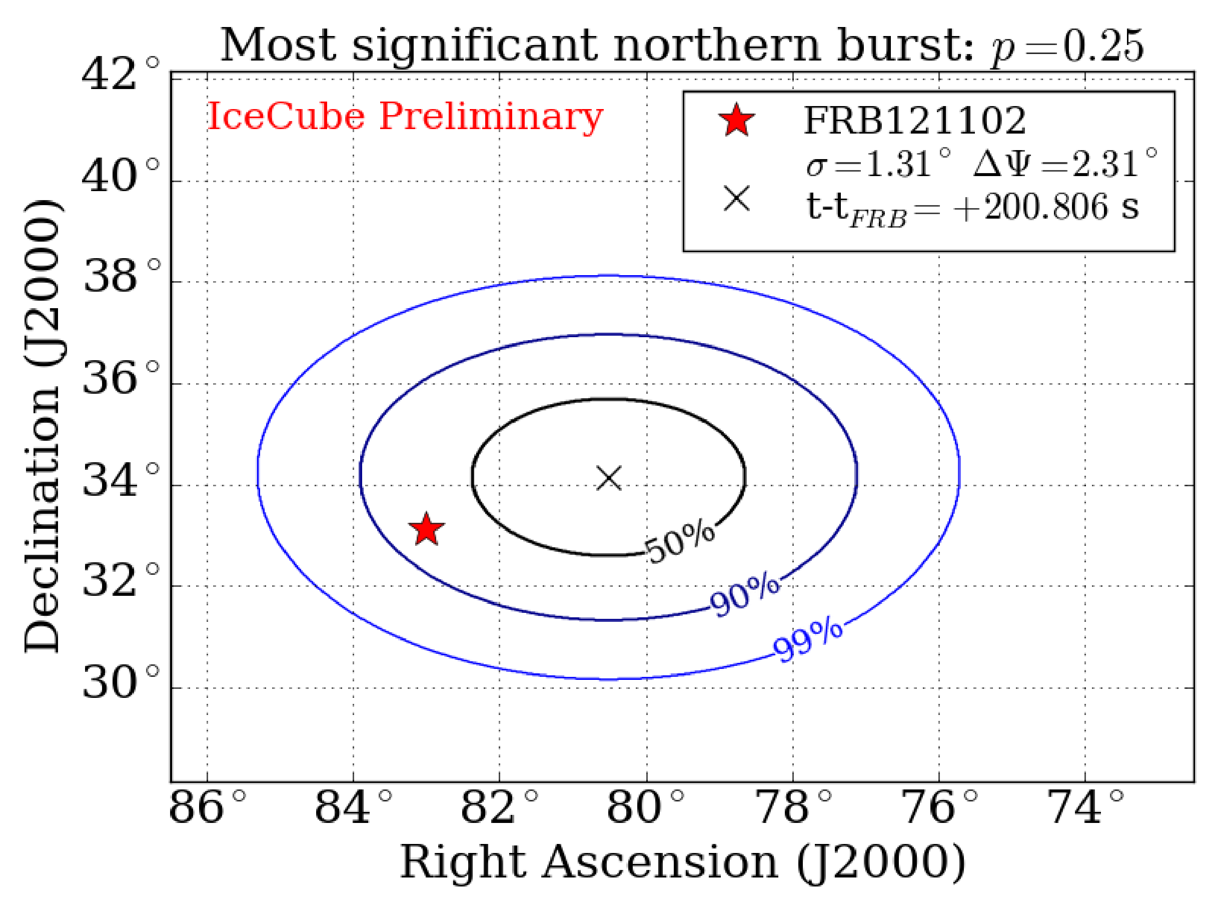


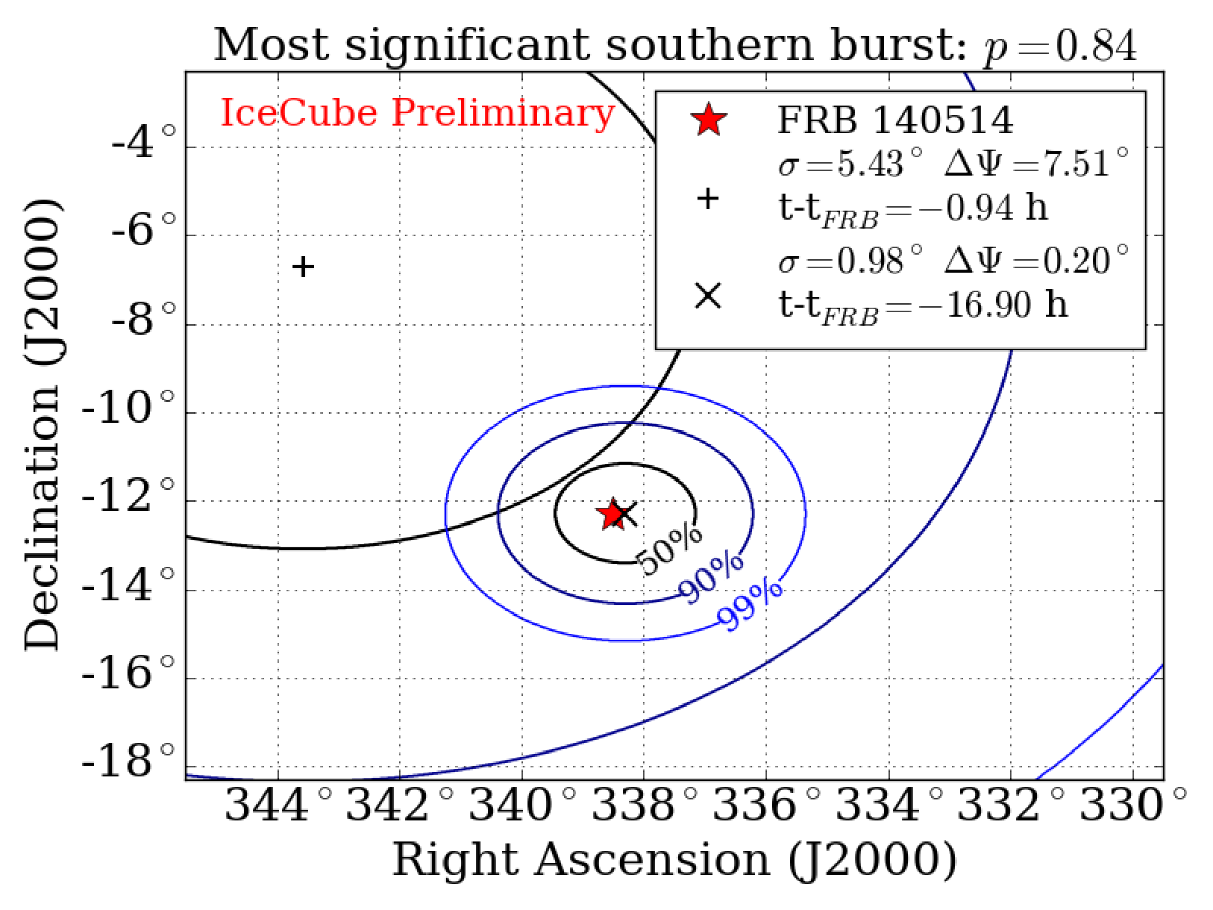
Northern Max-Burst Sensitivities



Results: Max-Burst Search

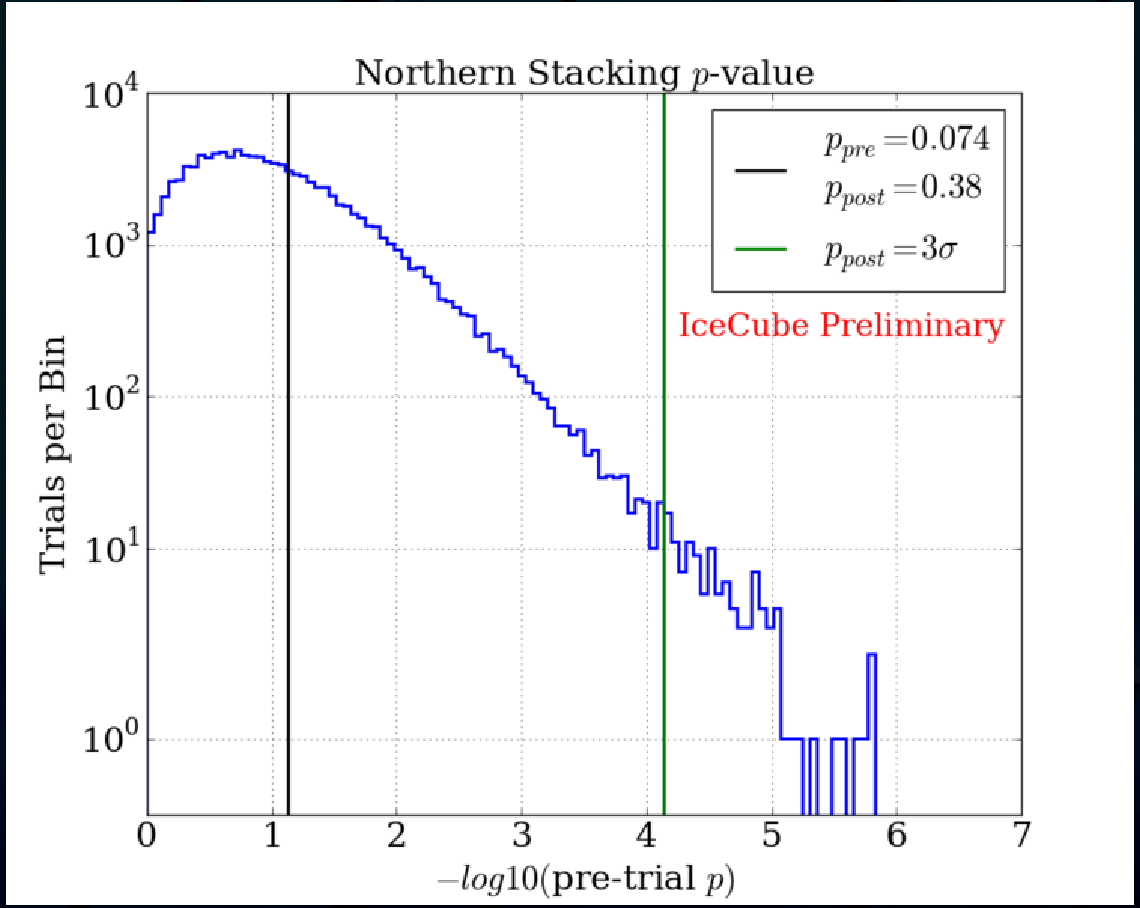
- Max-burst p-values are consistent with background:
  North: pre-trial p = 0.034; **p = 0.25** **South:** pre-trial p = 0.41; **p = 0.84**

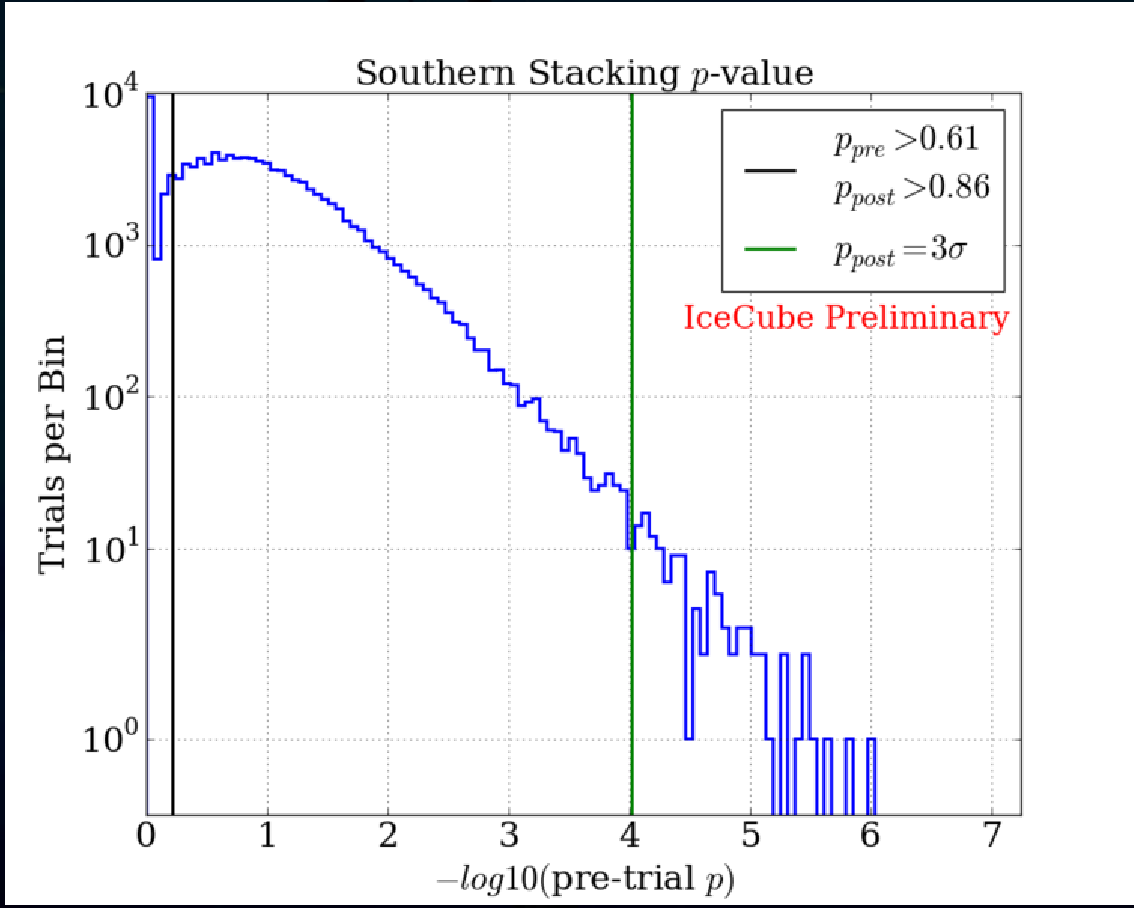




Results: Stacking Search

- Stacking p-values are consistent with background:
  North: pre-trial p = 0.074; **p = 0.38** **South:** pre-trial p > 0.61; **p > 0.86**





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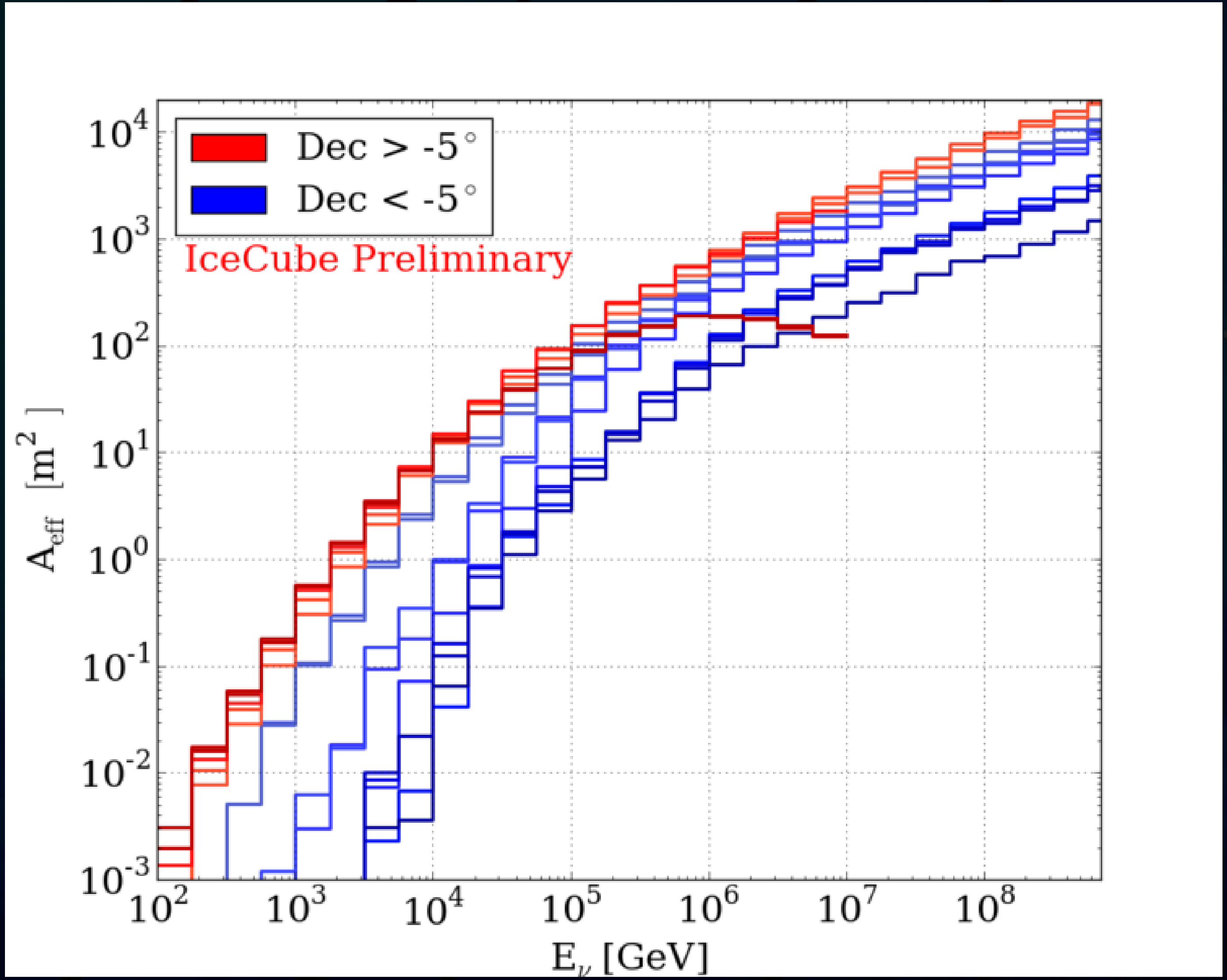
Conclusion and Outlook

- In a search for high-energy track events coincident with 29 FRBs from May 2010 to May 2016, no significant signal was observed.
- Future Upgrades:
  - Update analysis for FRBs observed since analysis began, and
  - Allow for quicker analysis of newly discovered FRBs
    - E.g., CHIME expects to observe >10 FRBs *per day* once online in 2017
  - Include cascade events: angular resolution O(10°), but still sensitive in small ΔT
- Low-energy search: We are searching for low-energy neutrino emission from FRBs via IceCube's Supernova stream, which detects rises in the overall PMT rate due to low-energy neutrino events
  - Temporal coincidence of PMT rate with FRB arrival times?

Backup

Effective Area at FRB Declinations



- Harder cuts in the southern hemisphere reduce muon contamination at the expense of effective area
- In the northern hemisphere, FRBs north of the equator lose effective area at high energies due to Earth absorption.

Northern Source List (page 1 of 2)

Bursts	Time[YYYY/MM/DD]	Duration [ms]	RA	DEC	Telescope	IceCube Seasons
FRB 110523	2011/05/23 15:06:19.738 UTC	1.73	-00°12'	21h45'	Green Bank RT	IC86-2011
FRB 110703	2011/07/03 18:59:40.591 UTC	<4.3	-02°52'	23h30'	Parkes HTRU	IC86-2011
FRB 130628	2013/06/28 03:58:00.02 UTC	<0.05	03°26'	09h03'	Parkes HTRU	IC86-2013
FRB 121102 **b0 **repeated****	2012/11/02 06:47:17.117 UTC	3.3	33°05'	05h32'	Arecibo RT	IC86-2012
FRB 121102 **b1**	2015/05/17 17:42:08.712 UTC	3.8	33°08'	05h32'	Arecibo RT	IC86-2014
FRB 121102 **b2**	2015/05/17 17:51:40.921 UTC	3.3	33°08'	05h32'	Arecibo RT	IC86-2014
FRB 121102 **b3**	2015/06/02 16:38:07.575 UTC	4.6	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b4**	2015/06/02 16:47:36.484 UTC	8.7	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b5**	2015/06/02 17:49:18.627 UTC	2.8	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b6**	2015/06/02 17:49:41.319 UTC	6.1	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b7**	2015/06/02 17:50:39.298 UTC	6.6	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b8**	2015/06/02 17:53:45.528 UTC	6.0	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b9**	2015/06/02 17:56:34.787 UTC	8.0	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b10**	2015/06/02 17:57:32.020 UTC	3.1	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b11**	2015-11-13 08:32:42.375 UTC	6.73	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b12**	2015-11-19 10:44:40.524 UTC	6.10	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b13**	2015-11-19 10:51:34.957 UTC	6.14	33°08'	05h32'	Arecibo RT	IC86-2015
FRB 121102 **b14**	2015-11-19 10:58:56.234 UTC	4.30	33°08'	05h32'	Arecibo RT	IC86-2015

Northern Source List (page 2 of 2)

FRB 121102 **b15**	2015-11-19 11:05:52.492 UTC	5.97	33°08'	05h32'	Arecibo RT	IC86-2015	
FRB 121102 **b16**	2015-12-08 04:54:40.262 UTC	2.50	33°08'	05h32'	Arecibo RT	IC86-2015	
FRB 121102 **b17**	2016-08-23 17:51:23.921 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b18**	2016-09-02 16:19:00.221 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b19**	2016-09-02 16:41:01.770 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b20**	2016-09-07 11:59:05.944 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b21**	2016-09-12 10:58:30.947 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b22**	2016-09-14 10:18:36.232 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b23**	2016-09-15 11:11:02.962 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b24**	2016-09-17 10:29:09.447 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
FRB 121102 **b25**	2016-09-18 10:50:31.802 UTC	<5	33°08'	05h32'	VLA	IC86-2016	Not in analysis
LOFAR North Pole burst	2011-12-24 04:33 UTC	660 s (long burst)	86°21'46.4"	22h53'47.1"	LOFAR	IC86-2011	Only in Max-burst test

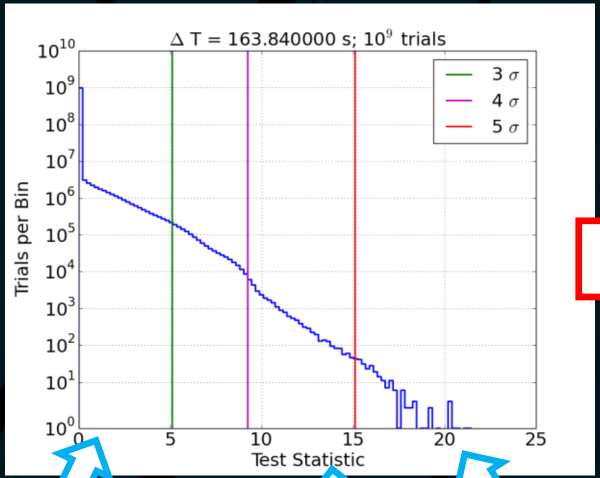
- Inclusion of the LOFAR radio burst (https://arxiv.org/pdf/1512.00014v1.pdf) in the source list was suggested and approved by the Transients working group. The LOFAR burst will not be included in the stacking test, as it is not a member of the FRB source class.

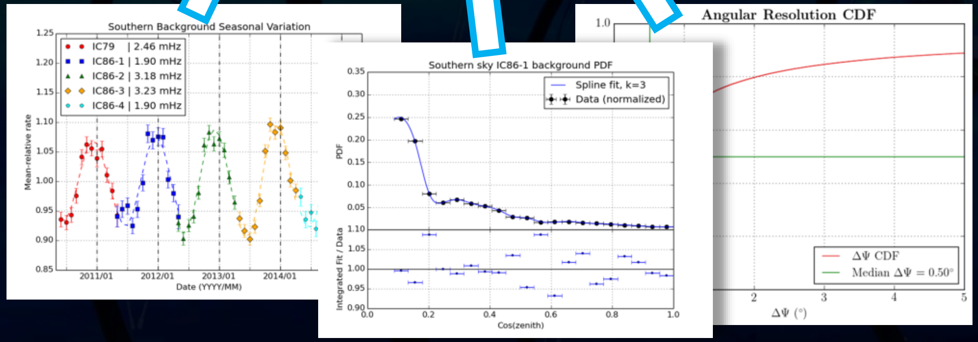
Southern Source List

Bursts	Time[YYYY/MM/DD]	Duration [ms]	RA	DEC	Telescope	IceCube Seasons
FRB 010621	2001/06/21 13:02:10.795 UTC	7.8	18h52′	-08°29′	Parkes	Before IceCube
FRB 010724	2001/07/24 19:50:01.63 UTC	4.6	01h18′	-75°12′	Parkes	Before IceCube
FRB 011025	2001/10/25 00:29:13.23 UTC	9.4	19h07′	-40°37′	Parkes	Before IceCube
FRB 090625	2009/06/25 21:53:52.85 UTC	<1.9	03h07′	-29°55′	Parkes	Not in analysis
FRB 110220	2011/02/20 01:55:48.957 UTC	5.6	22h34′	-12°24′	Parkes	IC79(-2010)
FRB 110627	2011/06/27 21:33:17.474 UTC	<1.4	21h03′	-44°44′	Parkes	IC86-2011
FRB 120127	2012/01/27 08:11:21.723 UTC	<1.1	23h15′	-18°25′	Parkes	IC86-2011
FRB 121002	2012/10/02 13:09:18.402 UTC	2.1; 3.7	18h14′	-85°11′	Parkes	IC86-2012
FRB 130626	2013/06/26 14:56:00.06 UTC	<0.12	16h27′	-07°27′	Parkes	IC86-2013
FRB 130729	2013/07/29 09:01:52.64 UTC	<4	13h41′	-05°59′	Parkes	IC86-2013
FRB 131104	2013/11/04 18:04:01.2 UTC	<0.64	06h44′	-51°17′	Parkes	IC86-2013
FRB 140514	2014/05/14 17:14:11.06 UTC	2.8	22h34′	-12°18′	Parkes	IC86-2014
FRB 150418	2015/04/18 04:29:05.370 UTC	0.8	07h16′	−19° 00′	Parkes	IC86-2014
FRB 150807	2015/08/07 17:53:55.78 UTC	0.35	22h40′	-55°16′	Parkes	Not in analysis

Finding a p-value from the TS

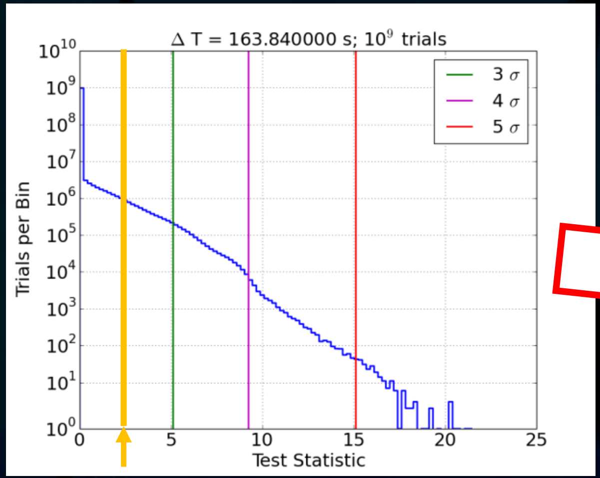
Construct a background TS distribution from Monte Carlo





Background PDFs used in Monte Carlo

Compare real observed TS to background for a pre-trial p-value

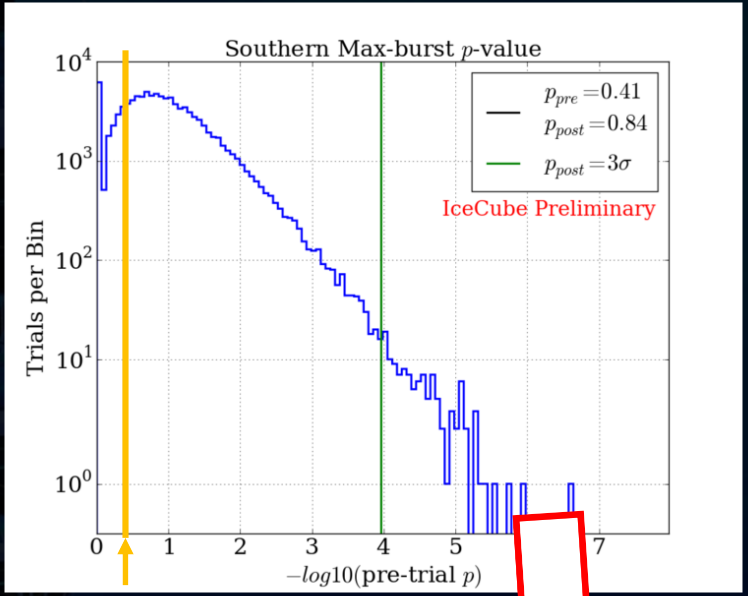


Observed TS

This is done separately in every time window

The lowest p-value is our observed pre-trial p-value

The p-value is compared to background trials to account for a time-windows induced trials factor



Observed p-value

Post-trials p-value