IceCube Search for Neutrinos from Thousands of Fast Radio Bursts

Alicia Mand on behalf of the IceCube Collaboration

TeVPA 2026, Tendo

Fast Radio Bursts (FRBs)

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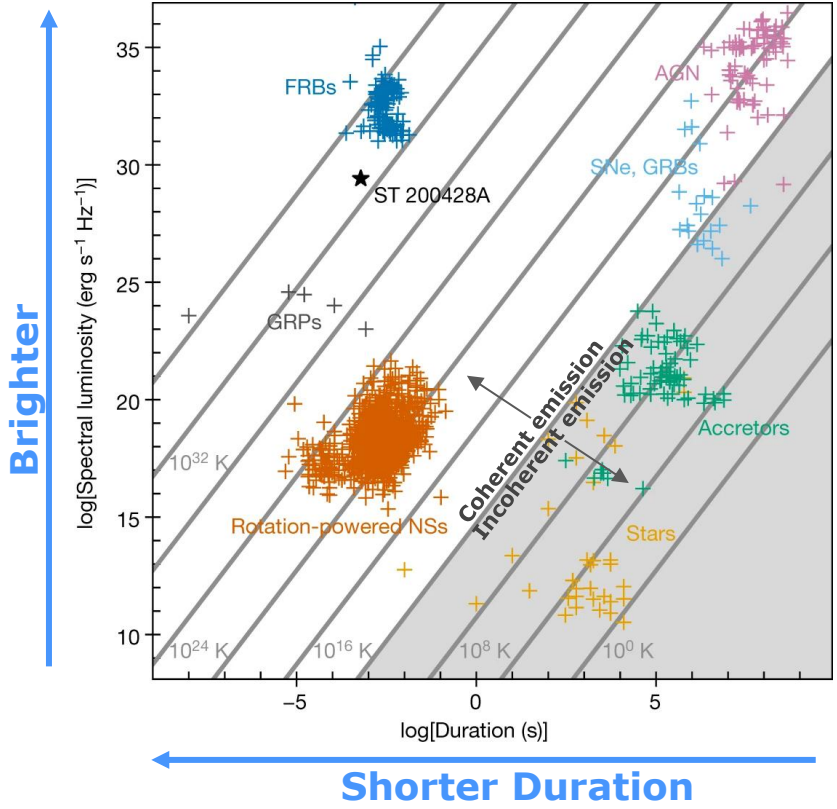
- Brief, intense, bursts of radio waves
  - Short (~millisecond) and bright (~jansky)



Bochenek, C.D., Ravi, V., Belov, K.V. *et al. Nature* **587**, 59–62 (2020). DOI:10.1038/s41586-020-2872-x

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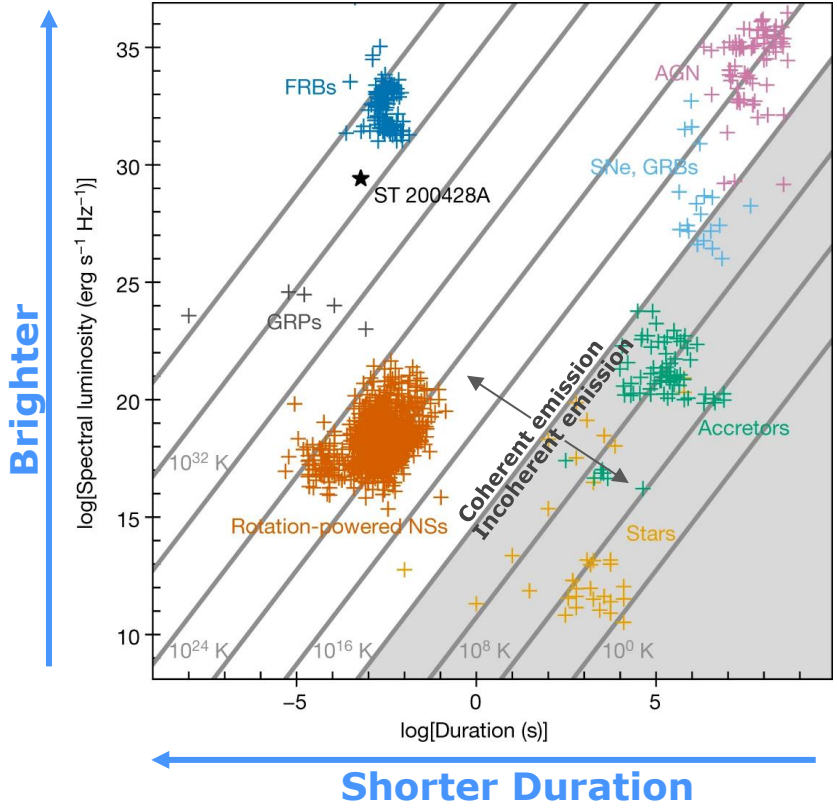

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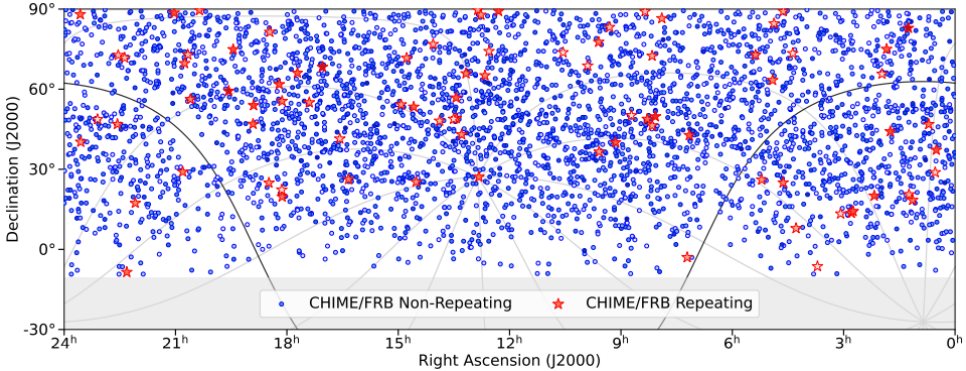
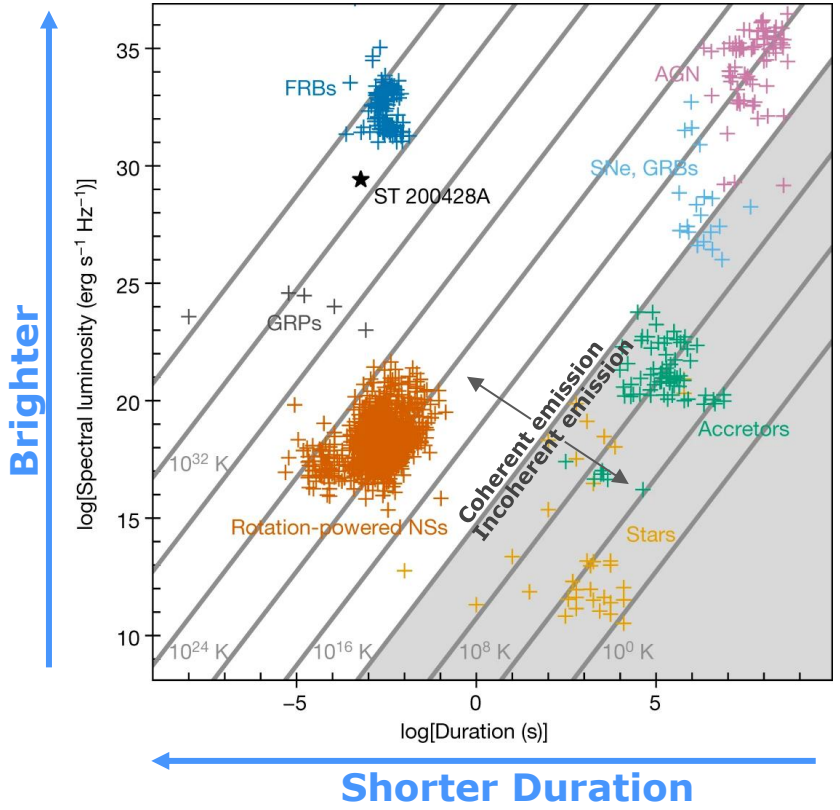


The CHIME/FRB Collaboration, *ApJS* **283**,34(2026).DOI:10.3847/1538-4365/ae3828



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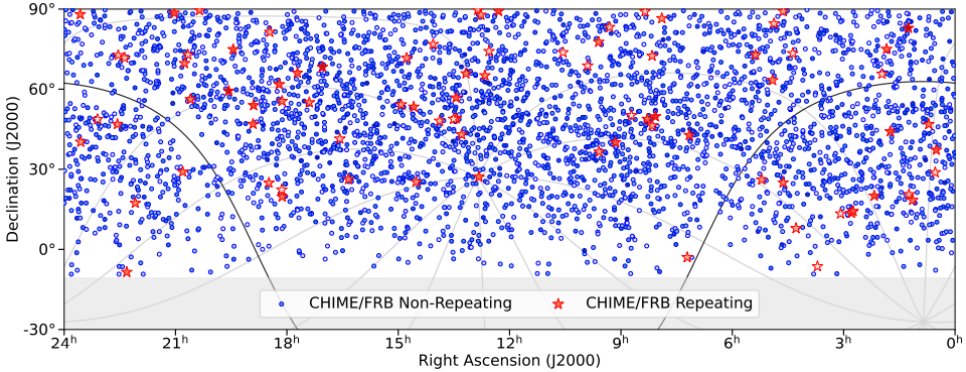
Fast Radio Bursts (FRBs)

* Some models predict neutrino emission

- Brief, intense, bursts of radio waves
  - Short (~millisecond) and bright (~jansky)
- (Mostly) extra-galactic
- Occur all over the sky
- Unknown production mechanisms*
  - Many models proposed (esp. magnetars)



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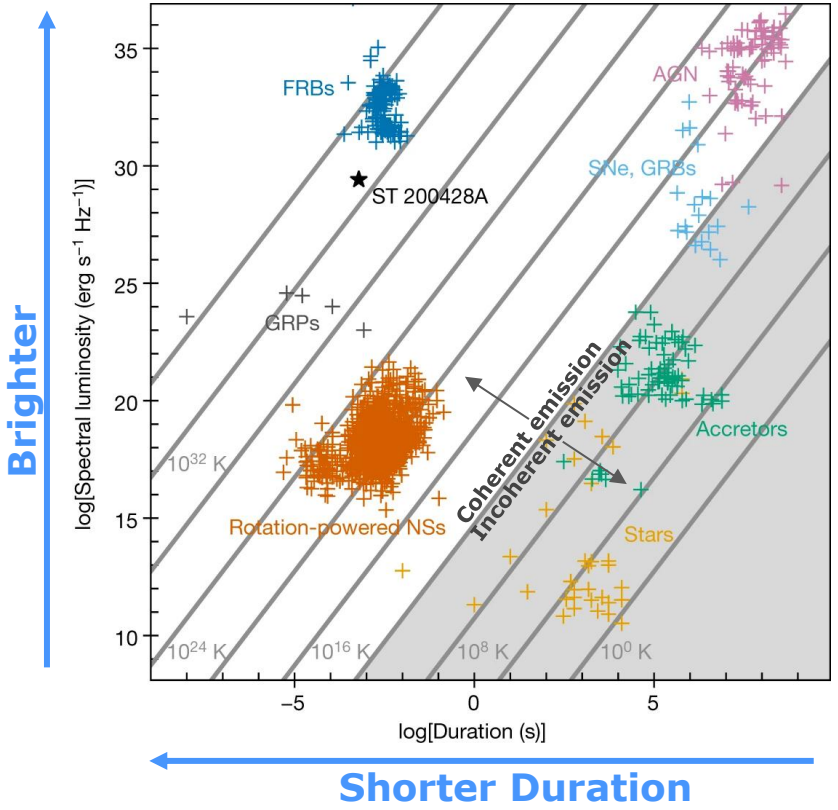

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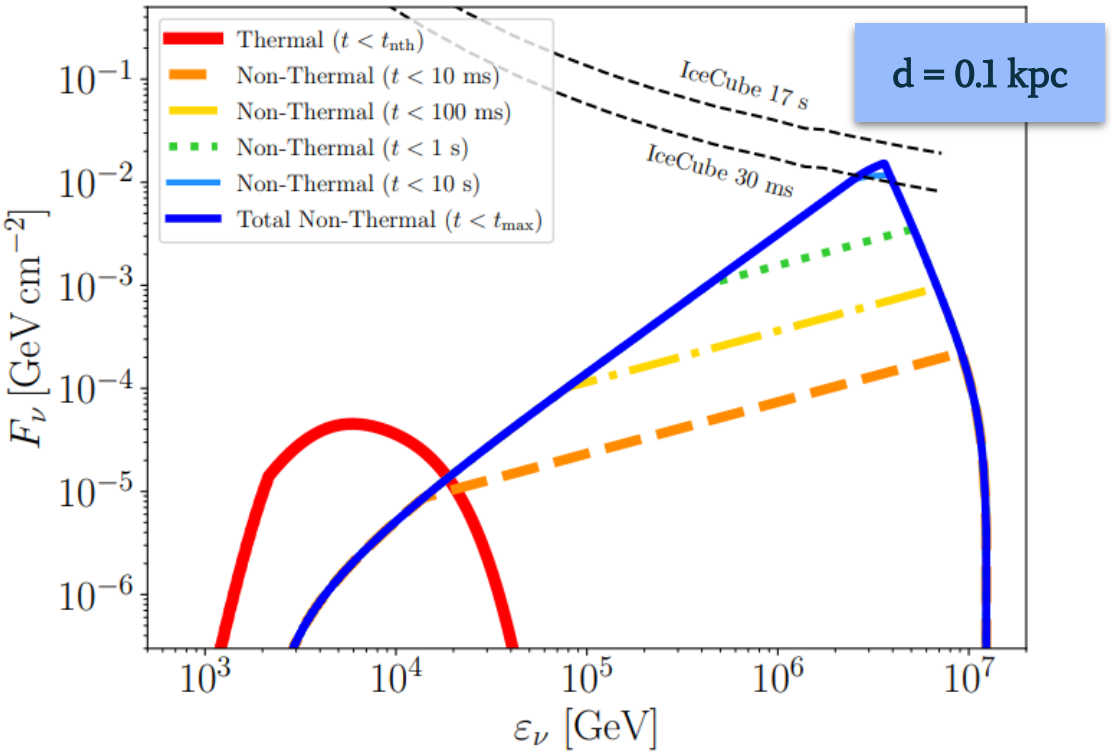
Neutrinos from Magnetar FRBs

- Ultra Relativistic shock propagating into external magnetized medium
- Photo-hadronic interactions of relativistic protons produce neutrinos



B. D. Metzger and K. Fang 2020 ApJL 902 L22

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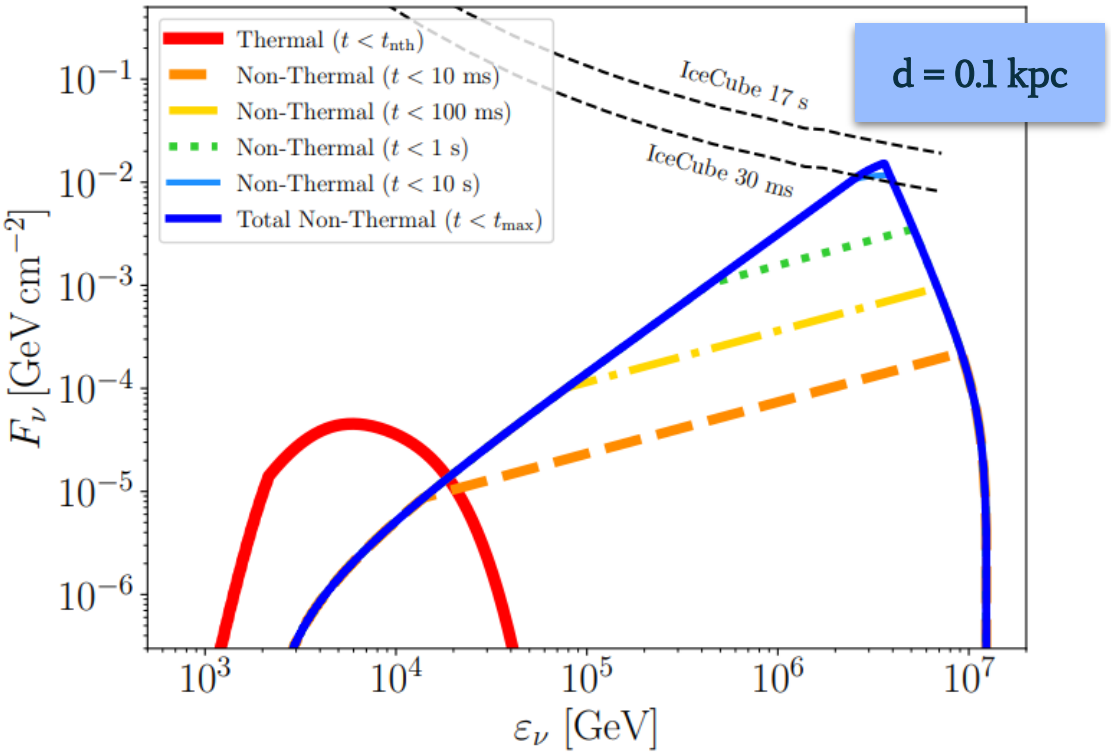
- Neutrinos observable by IceCube
- ~TeV - PeV gamma rays observable by HAWC



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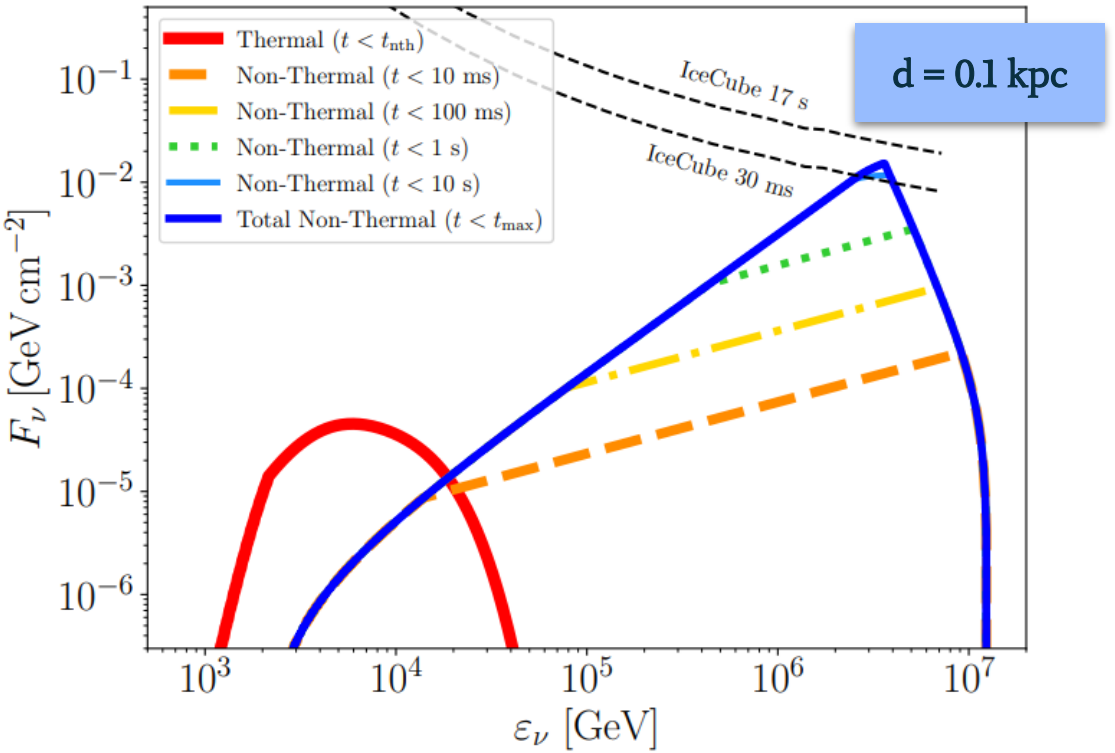
- Ultra Relativistic shock propagating into external magnetized medium
- Photo-hadronic interactions of relativistic protons produce neutrinos

- Neutrinos observable by IceCube
- ~TeV - PeV gamma rays observable by HAWC
- Analytical model with order-of-magnitude estimation
- Assumes E^{-2} proton spectrum



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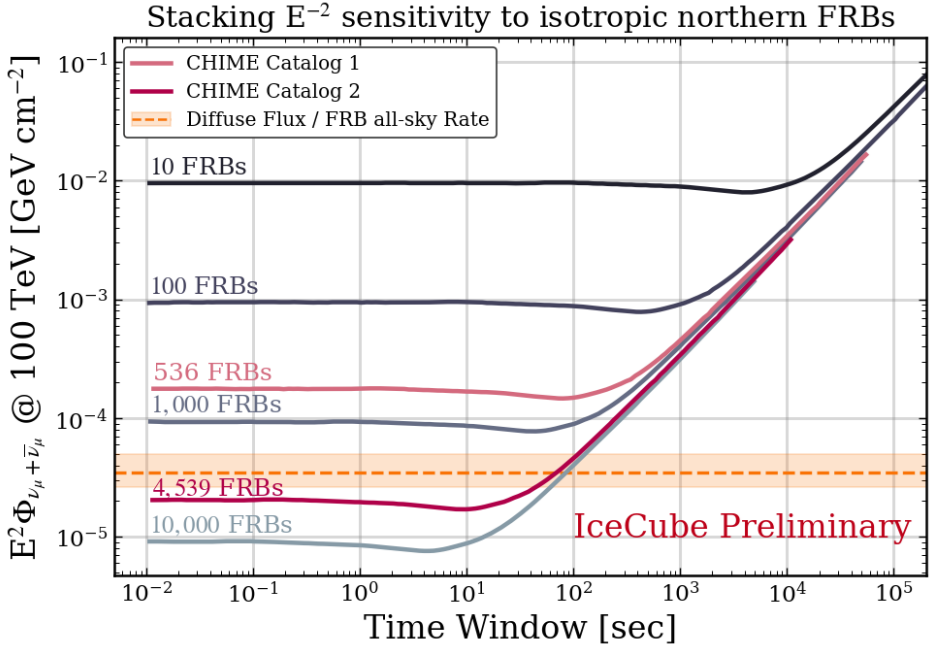
Previous IceCube Follow-ups of FRBs

- 5 Previous searches have been conducted using IceCube data
  - 3 In-collaboration, 2 using public datasets
- All non-detections
- Various time-windows
  - 10 ms - time-integrated
- All in-collaboration searches used fewer than 30 FRBs



More FRBs → Better Sensitivity
Shorter time window → Better Sensitivity

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  - 10 ms - time-integrated
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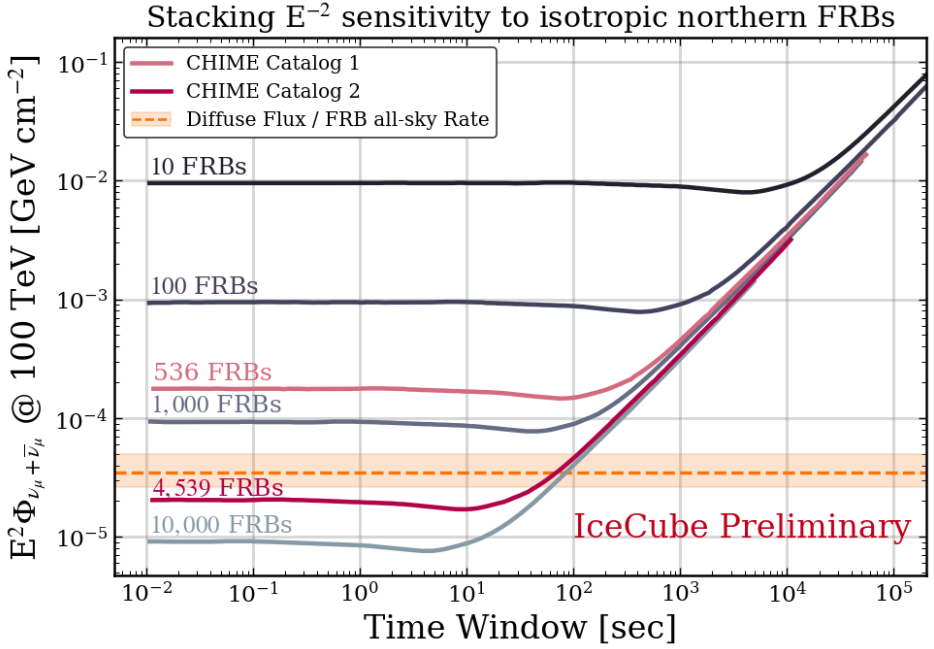
- **CHIME's new catalog (Catalog-2) has more than 4500 FRBs!**



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IceCube

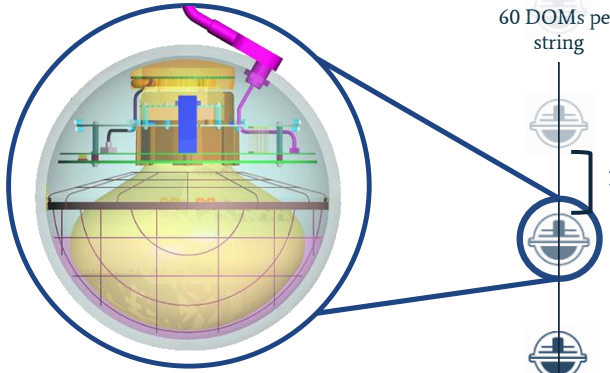
5,160 Digital Optical Modules

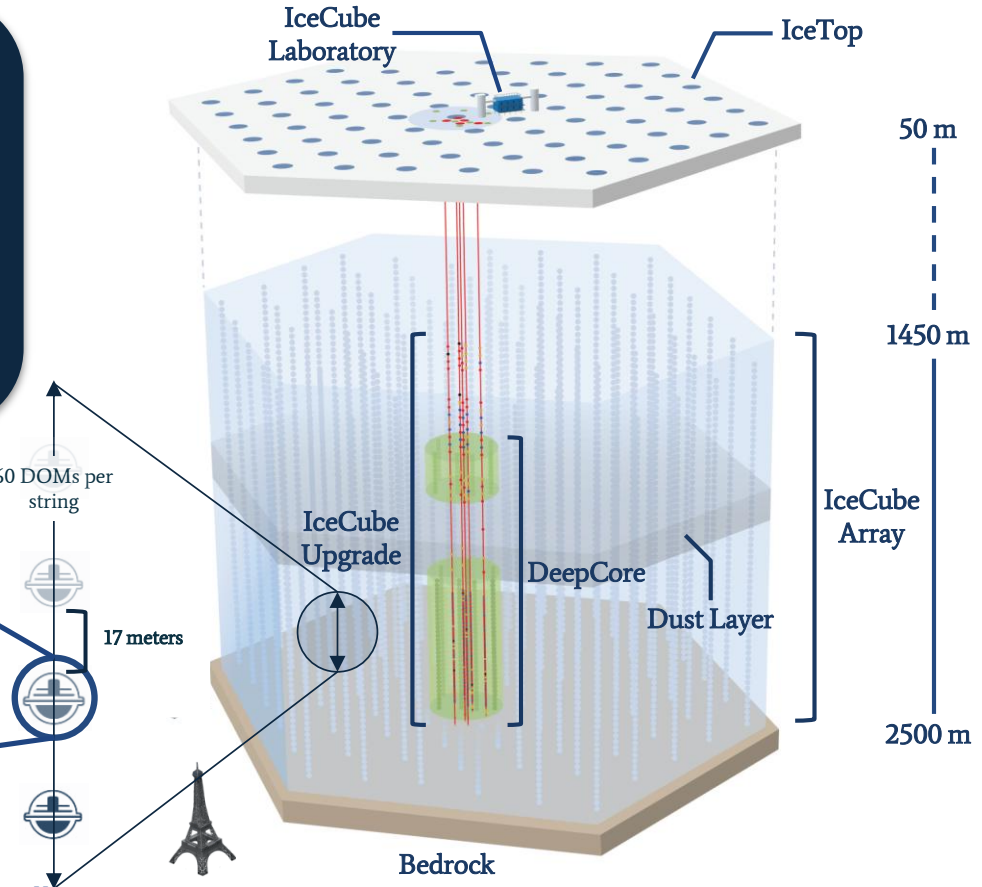
86 Strings with 60 DOMs each

Surface array for cosmic ray physics

Completed in 2010

Upgrade installed in 2026!





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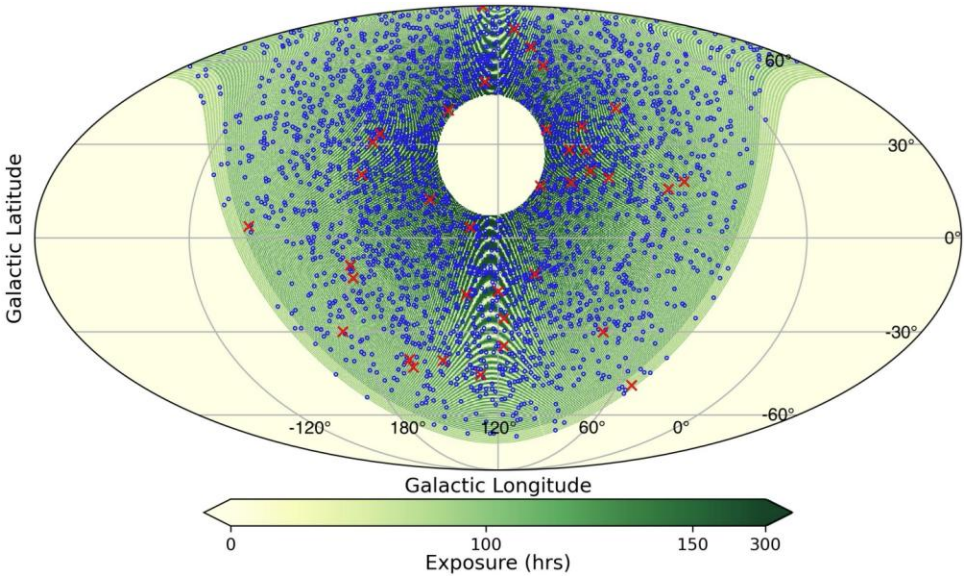
- Field of regard encompasses entire sky above -11° dec



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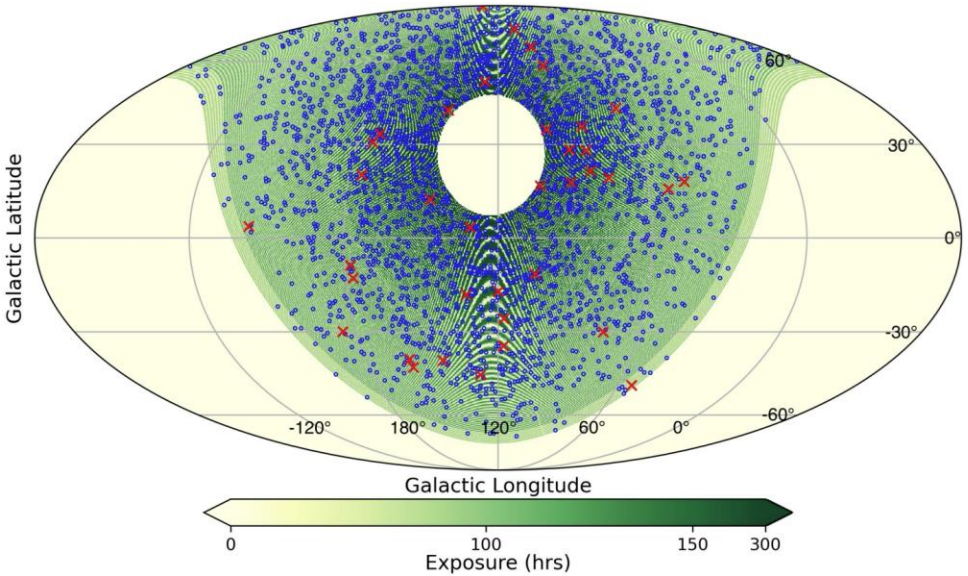
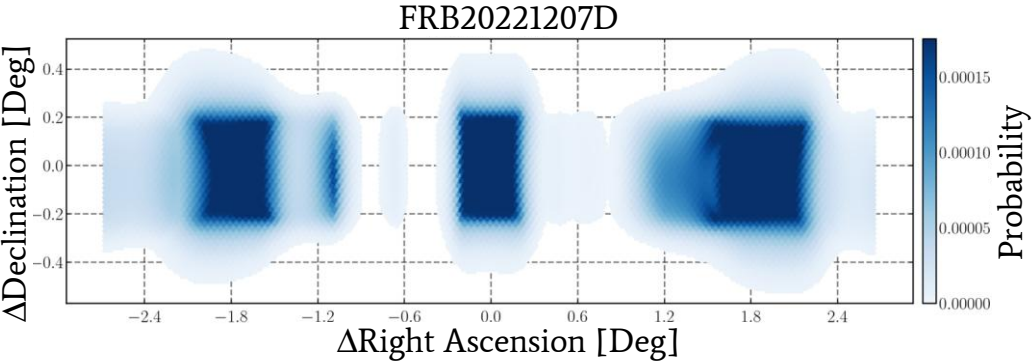
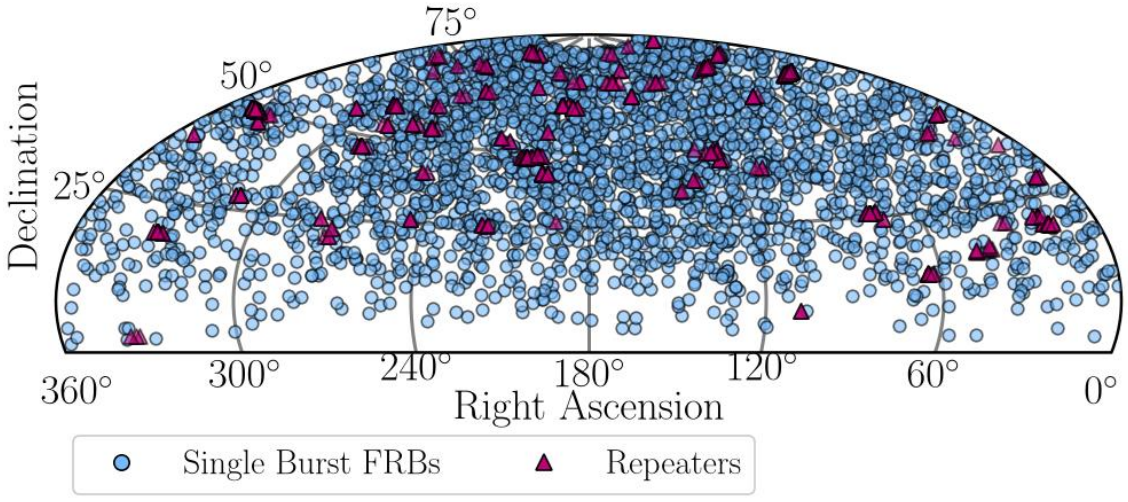
CHIME Is a Hydrogen Mapping Experiment that happens to be **really good** at detecting FRBs!

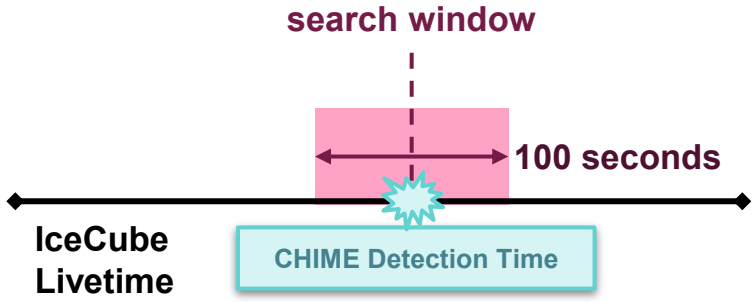


We are searching for **spatial** and **temporal** (± 50 seconds of burst detection) coincidence of neutrinos with fast radio bursts





- Incorporating CHIME's localization information as a spatial prior
- Apply unbinned likelihood method
- Maximize the test statistic across the entire spatial prior



Burst Name	(RA, Dec)	MJD	TS_{fit}	ns_{fit}	γ_{fit}	Pre-trial p_{val}	Post-trial p_{val}	Pre-Trial Significance	Post-trial Significance	RA_{fit}, Dec_{fit}	Class	Repeater Name
FRB20221207D	(20.88, 20.50)	59920.18	17.54	1.00	4.73	6.083e-05	4.831e-02	3.84	1.66	(22.85, 20.34)	Repeater	FRB20220529A
FRB20200614A	(29.11, 65.73)	59014.69	6.79	0.99	4.61	1.082e-03	-	3.07	-	(24.96, 65.6)	Repeater	FRB20180916B
FRB20210213A	(191.72, 83.28)	59258.47	5.87	0.98	2.74	2.781e-03	-	2.77	-	(206.64, 83.05)	Single Burst	-
FRB20230629G	(65.41, 77.54)	60124.74	5.78	0.98	4.85	2.777e-03	-	2.77	-	(60.98, 77.37)	Single Burst	-
FRB20220331A	(288.67, 82.53)	59669.10	5.62	0.98	3.10	2.669e-03	-	2.79	-	(302.68, 82.32)	Single Burst	-
FRB20201229A	(202.54, 44.24)	59212.62	5.52	0.98	3.25	1.129e-03	-	3.05	-	(200.19, 44.2)	Single Burst	-
FRB20191107A	(66.09, 73.60)	58794.89	4.55	0.96	2.41	2.373e-03	-	2.82	-	(59.92, 73.68)	Repeater	FRB20180814A
FRB20210429B	(355.62, 78.80)	59333.20	4.05	0.95	1.67	2.275e-03	-	2.84	-	(355.91, 78.93)	Single Burst	-
FRB20190609D	(115.92, 51.69)	58643.94	3.31	0.92	3.96	1.359e-03	-	3.00	-	(113.05, 51.64)	Single Burst	-

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Best-fit (RA, Dec) reported by CHIME

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IceCube unblinded test statistic

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Best-fit number of signal events over background

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Best-fit spectral index

Burst Name	(RA, Dec)	MJD	TS_{fit}	ns_{fit}	γ_{fit}	Pre-trial p_{val}	Post-trial p_{val}	Pre-Trial Significance	Post-trial Significance	RA_{fit}, Dec_{fit}	Class	Repeater Name
FRB20221207D	(20.88, 20.50)	59920.18	17.54	1.00	4.73	6.083e-05	4.831e-02	3.84	1.66	(22.85, 20.34)	Repeater	FRB20220529A
FRB20200614A	(29.11, 65.73)	59014.69	6.79	0.99	4.61	1.082e-03	-	3.07	-	(24.96, 65.6)	Repeater	FRB20180916B
FRB20210213A	(191.72, 83.28)	59258.47	5.87	0.98	2.74	2.781e-03	-	2.77	-	(206.64, 83.05)	Single Burst	-
FRB20230629G	(65.41, 77.54)	60124.74	5.78	0.98	4.85	2.777e-03	-	2.77	-	(60.98, 77.37)	Single Burst	-
FRB20220331A	(288.67, 82.53)	59669.10	5.62	0.98	3.10	2.669e-03	-	2.79	-	(302.68, 82.32)	Single Burst	-
FRB20201229A	(202.54, 44.24)	59212.62	5.52	0.98	3.25	1.129e-03	-	3.05	-	(200.19, 44.2)	Single Burst	-
FRB20191107A	(66.09, 73.60)	58794.89	4.55	0.96	2.41	2.373e-03	-	2.82	-	(59.92, 73.68)	Repeater	FRB20180814A
FRB20210429B	(355.62, 78.80)	59333.20	4.05	0.95	1.67	2.275e-03	-	2.84	-	(355.91, 78.93)	Single Burst	-
FRB20190609D	(115.92, 51.69)	58643.94	3.31	0.92	3.96	1.359e-03	-	3.00	-	(113.05, 51.64)	Single Burst	-

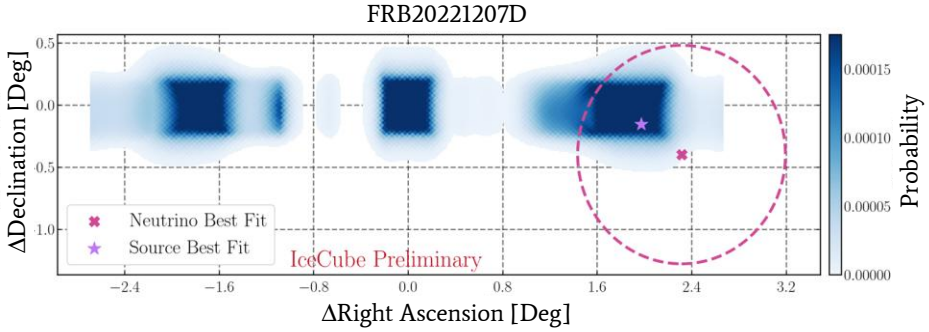
Trials factor = # Single (repeat) bursts considered

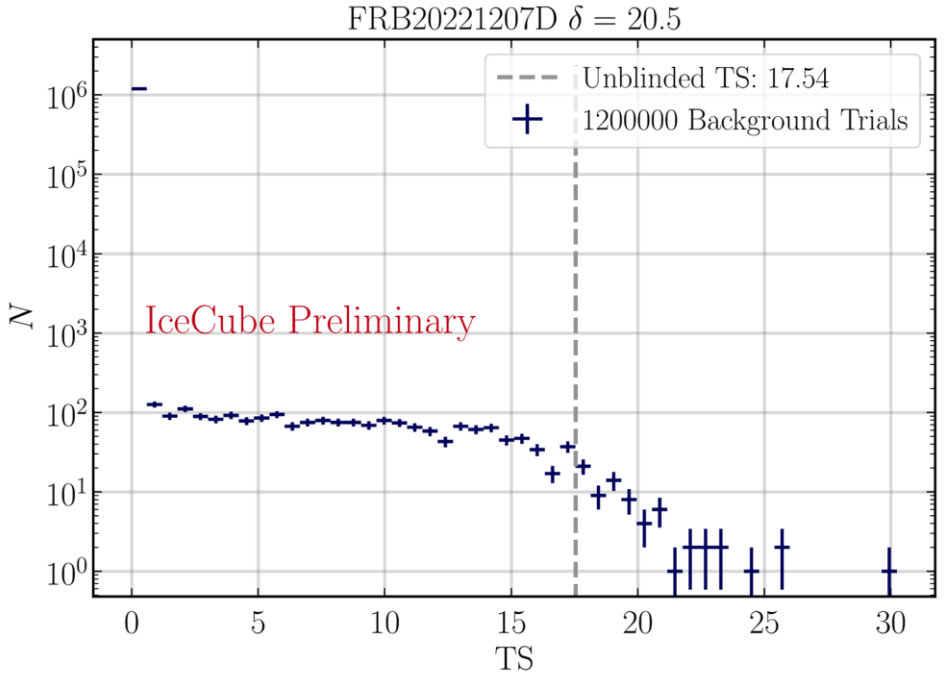
Burst Name	(RA, Dec)	MJD	TS_{fit}	ns_{fit}	γ_{fit}	Pre-trial p_{val}	Post-trial p_{val}	Pre-Trial Significance	Post-trial Significance	RA_{fit}, Dec_{fit}	Class	Repeater Name
FRB20221207D	(20.88, 20.50)	59920.18	17.54	1.00	4.73	6.083e-05	4.831e-02	3.84	1.66	(22.85, 20.34)	Repeater	FRB20220529A
FRB20200614A	(29.11, 65.73)	59014.69	6.79	0.99	4.61	1.082e-03	-	3.07	-	(24.96, 65.6)	Repeater	FRB20180916B
FRB20210213A	(191.72, 83.28)	59258.47	5.87	0.98	2.74	2.781e-03	-	2.77	-	(206.64, 83.05)	Single Burst	-
FRB20230629G	(65.41, 77.54)	60124.74	5.78	0.98	4.85	2.777e-03	-	2.77	-	(60.98, 77.37)	Single Burst	-
FRB20220331A	(288.67, 82.53)	59669.10	5.62	0.98	3.10	2.669e-03	-	2.79	-	(302.68, 82.32)	Single Burst	-
FRB20201229A	(202.54, 44.24)	59212.62	5.52	0.98	3.25	1.129e-03	-	3.05	-	(200.19, 44.2)	Single Burst	-
FRB20191107A	(66.09, 73.60)	58794.89	4.55	0.96	2.41	2.373e-03	-	2.82	-	(59.92, 73.68)	Repeater	FRB20180814A
FRB20210429B	(355.62, 78.80)	59333.20	4.05	0.95	1.67	2.275e-03	-	2.84	-	(355.91, 78.93)	Single Burst	-
FRB20190609D	(115.92, 51.69)	58643.94	3.31	0.92	3.96	1.359e-03	-	3.00	-	(113.05, 51.64)	Single Burst	-

IceCube best-fit source location within prior

Burst Name	(RA, Dec)	MJD	TS_{fit}	ns_{fit}	γ_{fit}	Pre-trial p_{val}	Post-trial p_{val}	Pre-Trial Significance	Post-trial Significance	RA_{fit}, Dec_{fit}	Class	Repeater Name
FRB20221207D	(20.88, 20.50)	59920.18	17.54	1.00	4.73	6.083e-05	4.831e-02	3.84	1.66	(22.85, 20.34)	Repeater	FRB20220529A
FRB20200614A	(29.11, 65.73)	59014.69	6.79	0.99	4.61	1.082e-03	-	3.07	-	(24.96, 65.6)	Repeater	FRB20180916B
FRB20210213A	(191.72, 83.28)	59258.47	5.87	0.98	2.74	2.781e-03	-	2.77	-	(206.64, 83.05)	Single Burst	-
FRB20230629G	(65.41, 77.54)	60124.74	5.78	0.98	4.85	2.777e-03	-	2.77	-	(60.98, 77.37)	Single Burst	-
FRB20220331A	(288.67, 82.53)	59669.10	5.62	0.98	3.10	2.669e-03	-	2.79	-	(302.68, 82.32)	Single Burst	-
FRB20201229A	(202.54, 44.24)	59212.62	5.52	0.98	3.25	1.129e-03	-	3.05	-	(200.19, 44.2)	Single Burst	-
FRB20191107A	(66.09, 73.60)	58794.89	4.55	0.96	2.41	2.373e-03	-	2.82	-	(59.92, 73.68)	Repeater	FRB20180814A
FRB20210429B	(355.62, 78.80)	59333.20	4.05	0.95	1.67	2.275e-03	-	2.84	-	(355.91, 78.93)	Single Burst	-
FRB20190609D	(115.92, 51.69)	58643.94	3.31	0.92	3.96	1.359e-03	-	3.00	-	(113.05, 51.64)	Single Burst	-

Highest pre-trials significance of 3.84σ:
FRB 20211207D (Repeater of FRB 20220529A)
DM of 246.26 [pc/cm^3]
SNR of 9.97
Repeater has 31 Bursts in CHIME Catalog 2

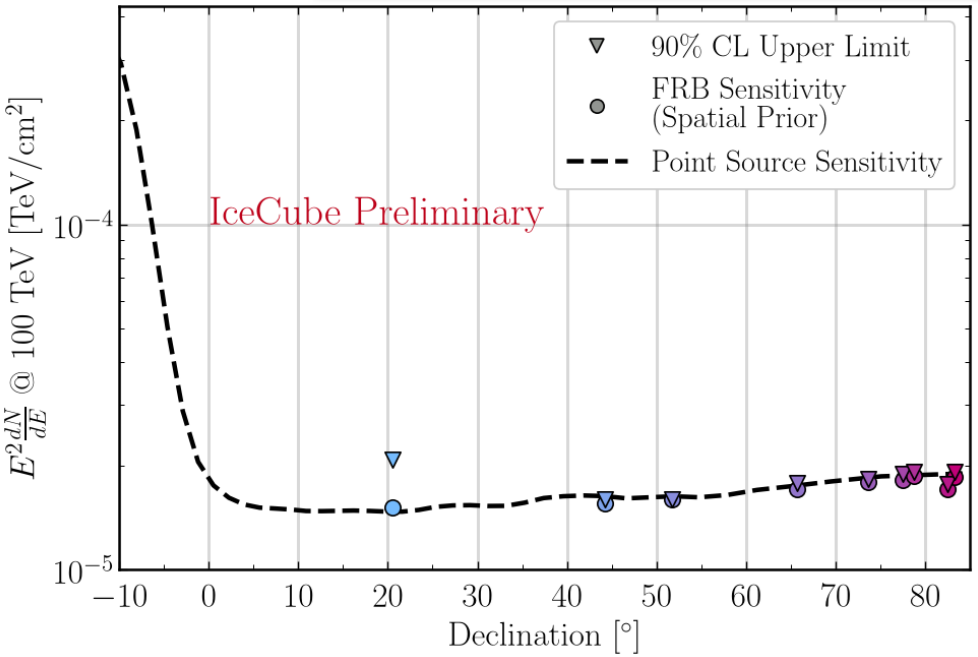




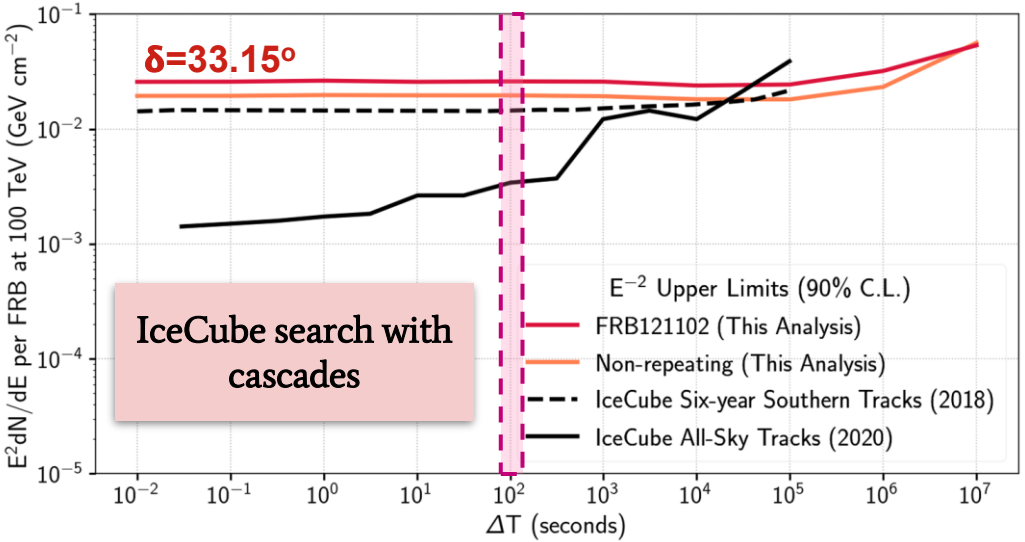
Upper limits

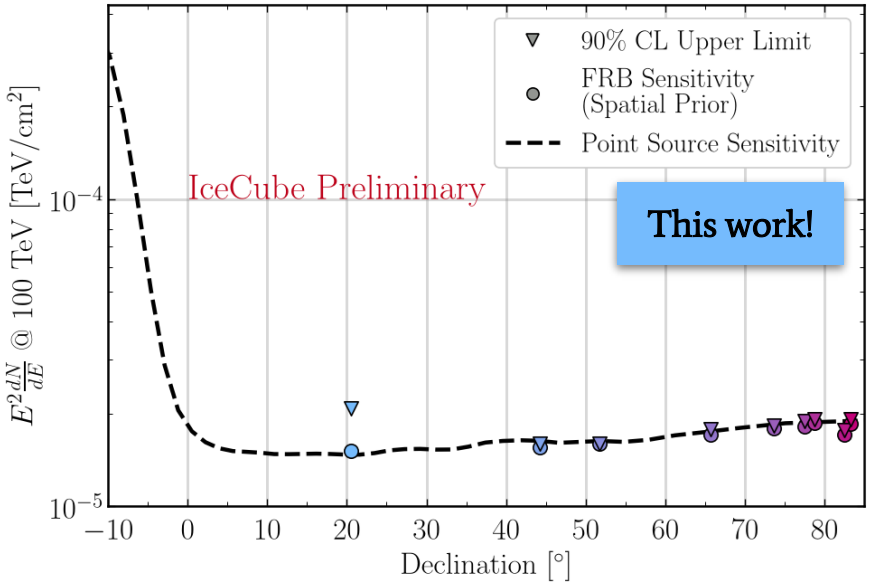
Point source sensitivity differs slightly from spatial prior sensitivity

FRB	Classification	Declination [°]	Upper Limit [TeV/cm^2]
FRB 20221207D	Repeater	20.5	2.08×10^{-5}
FRB 20201229A	Single	44.24	1.60×10^{-5}
FRB 20190609D	Single	51.69	1.60×10^{-5}
FRB 20200614A	Repeater	65.73	1.79×10^{-5}
FRB 20191107A	Repeater	73.6	1.84×10^{-5}
FRB 20230629G	Single	77.54	1.90×10^{-5}
FRB 20210429B	Single	78.8	1.92×10^{-5}
FRB 20220331A	Single	82.53	1.77×10^{-5}
FRB 20210213A	Single	83.28	1.92×10^{-5}



Comparing to Previous Limits

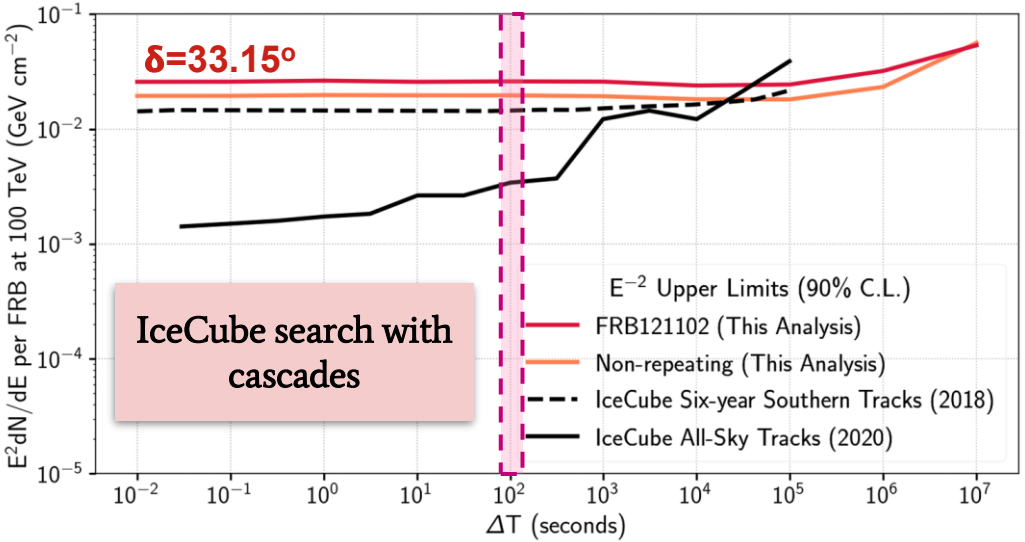




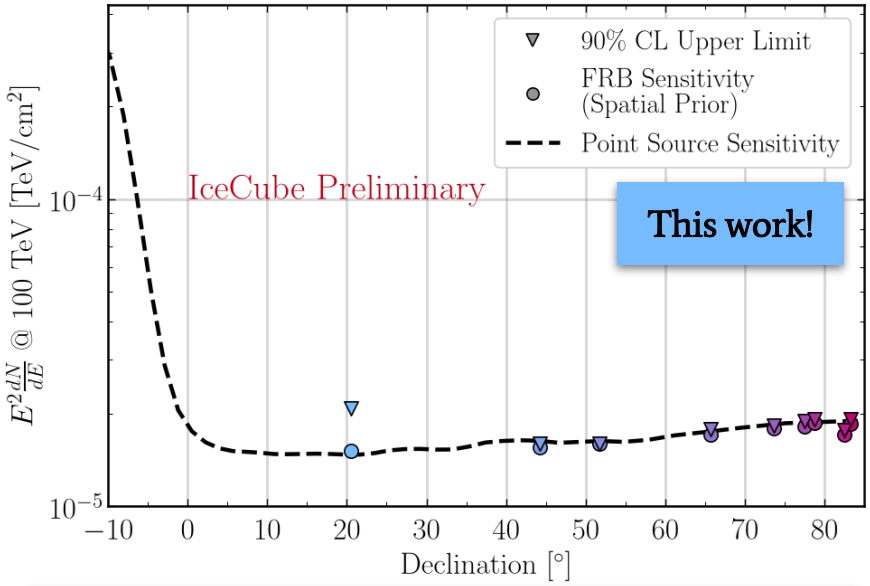
Orange and black lines are stacking limits

IceCube Collaboration, *ApJ* **946**,2(2023).DOI:10.3847/1538-4357/acbea0

Comparing to Previous Limits



Orange and black lines are stacking limits

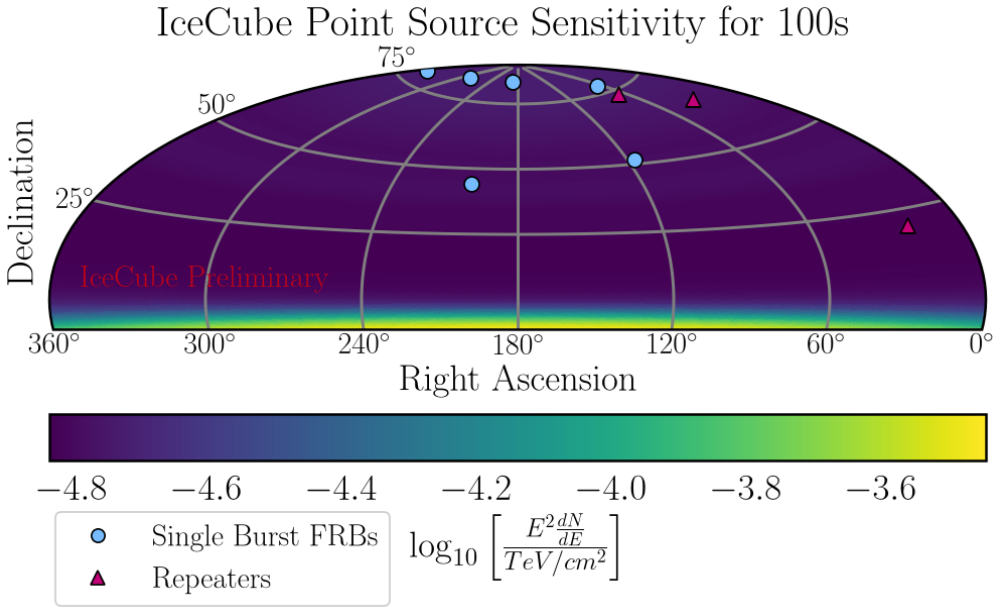


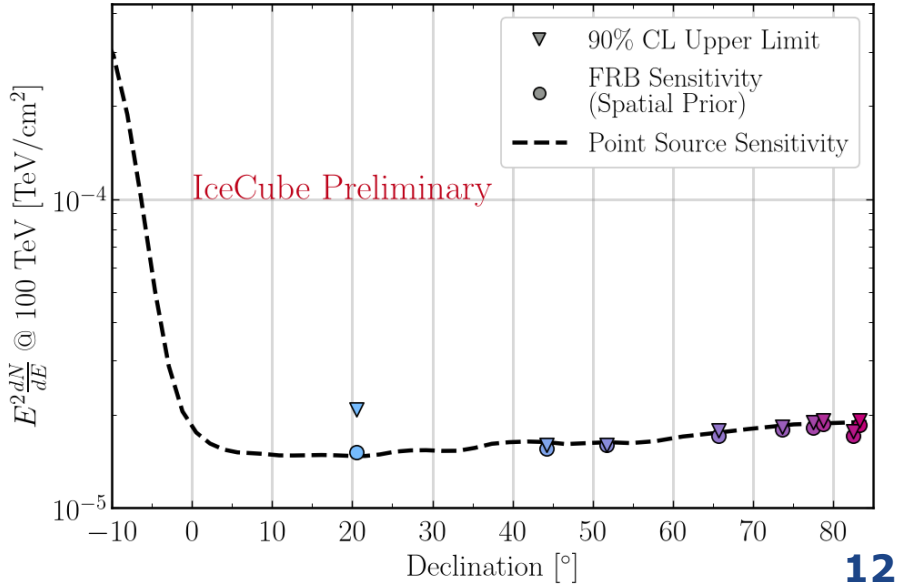
This analysis' limits are ~2 orders of magnitude stronger than previous analyses

IceCube Collaboration, *ApJ* **946**,2(2023).DOI:10.3847/1538-4357/acbea0

Conclusions

- We have conducted the largest search for neutrinos from FRBs
  - Results consistent with background expectation
- Our most significant (pre-trials correction) result is 3.84**σ** (post: 1.66)
- We set upper limits for our most significant FRBs





BACKUP

Maximum Likelihood Method

We apply an unbinned maximum likelihood method in order to search for sources:

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

Likelihood that there are n_s neutrinos from the source

Signal term: probability that the i^{th} event originates from this source

Background term: probability that the i^{th} event is a background event

Poisson term: extended likelihood term to account for fluctuations in the number of events observed (specific to transient analyses)

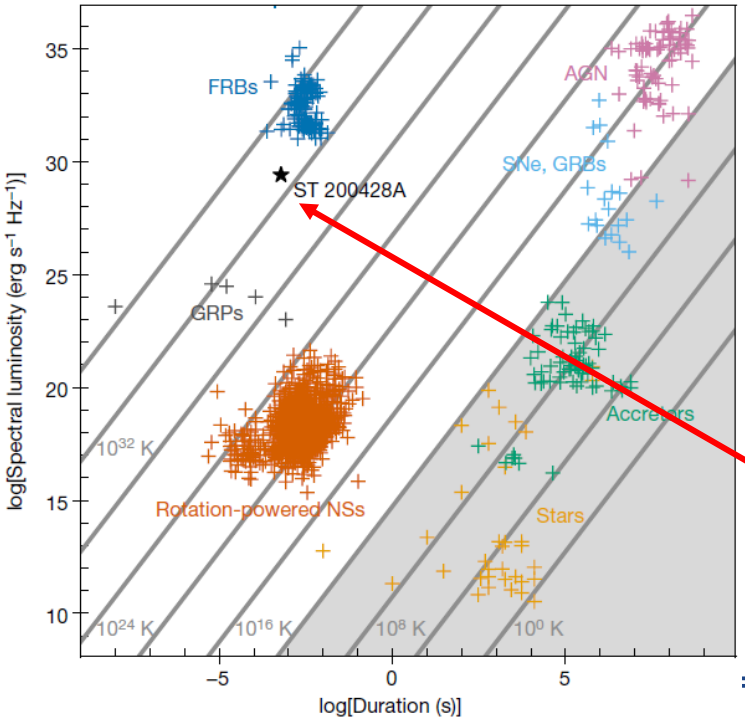
$$\mathrm{TS} = \max_{n_s, \gamma} \left[2 \ln \left(\frac{\mathcal{L}(n_s, \gamma)}{\mathcal{L}(n_s = 0)} \right) \right]$$

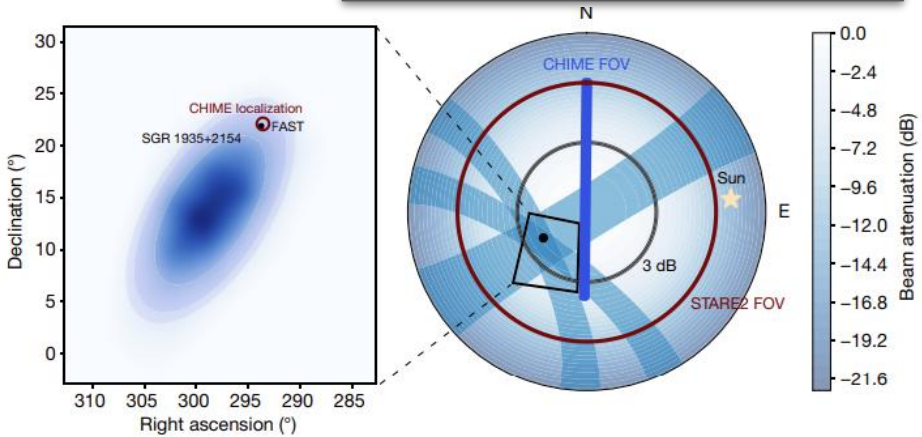
Test Statistic (TS): log-likelihood ratio between best fit parameters and null hypothesis ($n_s = 0$)

Association of Magnetar with FRB 200428

Typically referred to as FRB-like signal

- SGR 1935+2154 observed by FAST in X-rays at same time as CHIME and STARE2 FRB observation

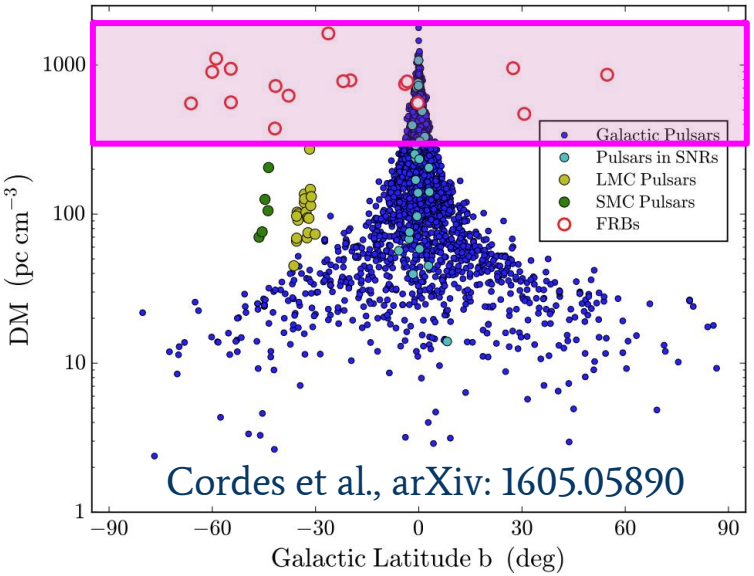




- First FRB-Like signal from known source class (magnetars)
- Low energy compared to weakest FRB signals (30x less energetic than weakest)
- Galactic origin (all other FRBs are extragalactic)
- Luminosity roughly consistent with FRB

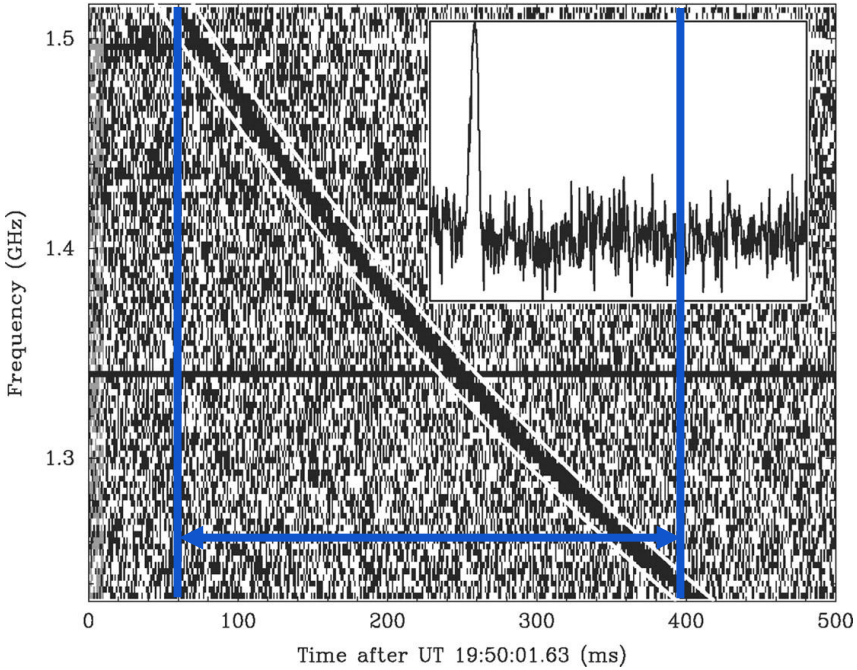
Bochenek, C.D., Ravi, V., Belov, K.V. *et al.* A fast radio burst associated with a Galactic magnetar. *Nature* 587, 59–62 (2020). https://doi.org/10.1038/s41586-020-2872-x

Localizing FRBs

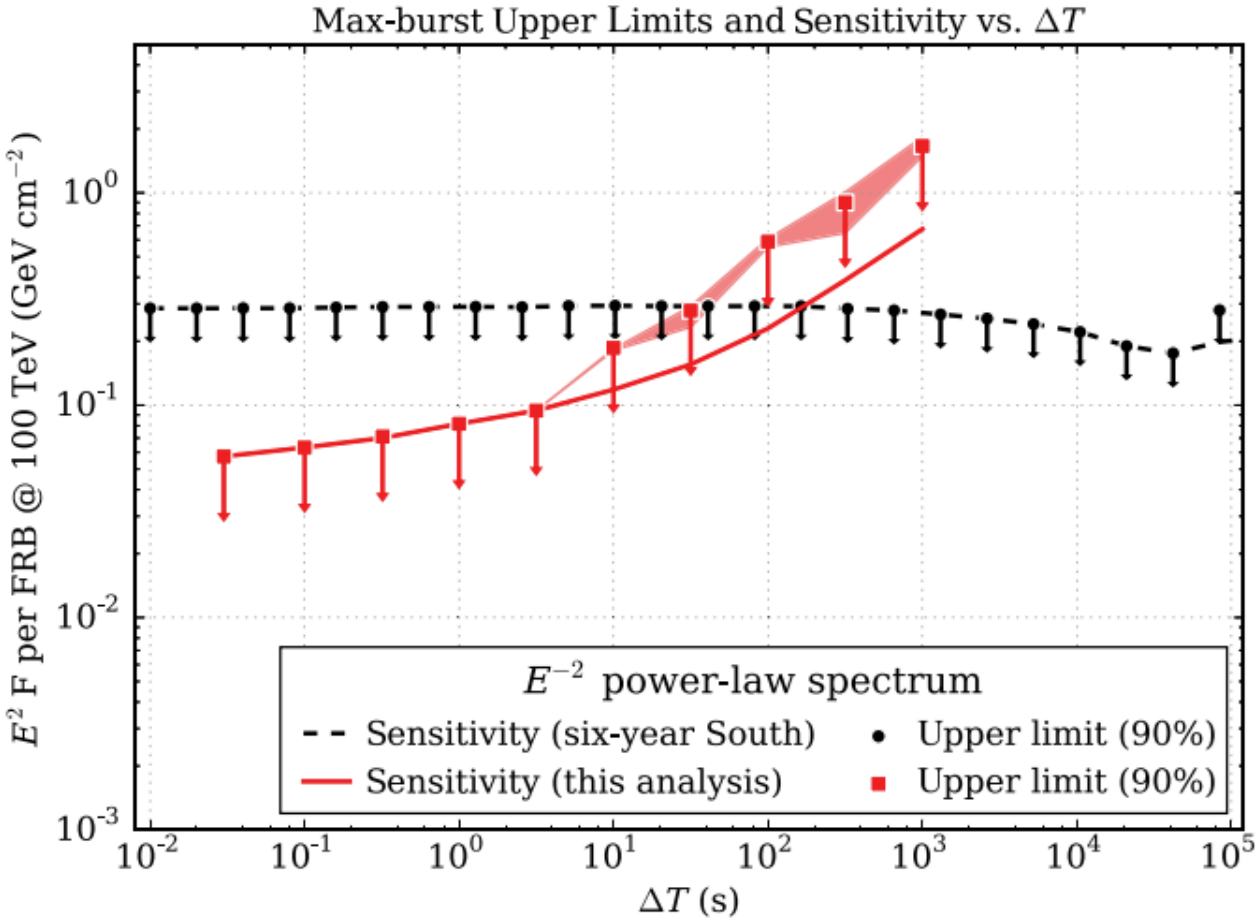


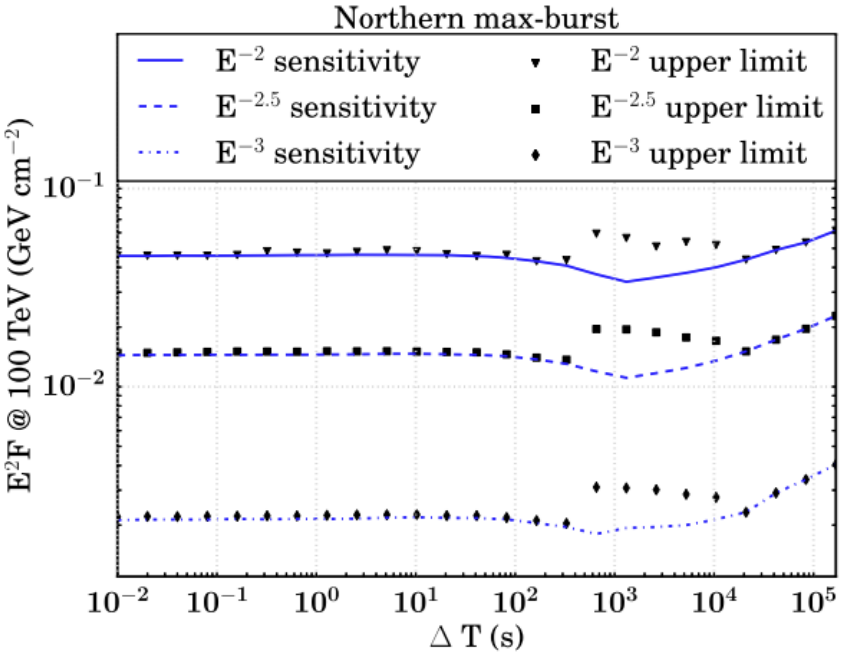
Dispersion Measure (DM): measure of integrated column density of free electrons measured along the line of sight

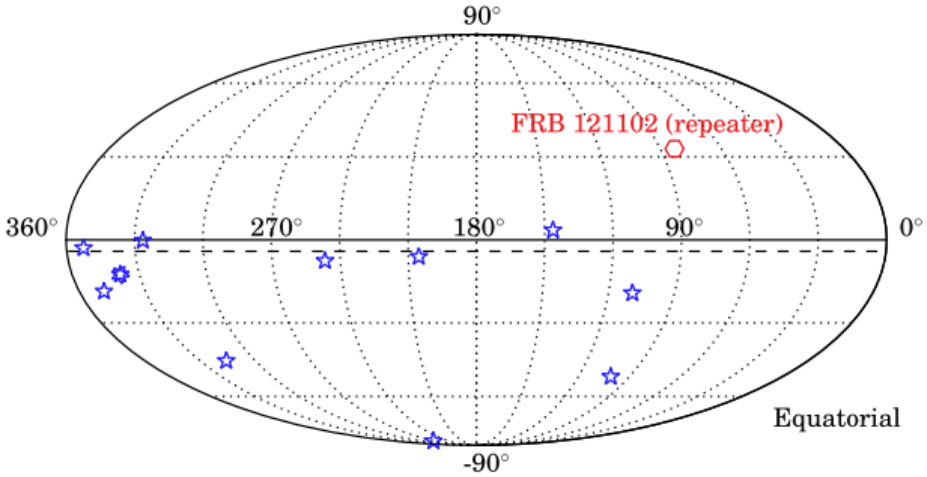
- DMs larger than what Milky Way alone can provide
- Consistent with **extragalactic origin**



$$\Delta t = \frac{e^2}{2\pi m_e c}(\nu_{\rm lo}^{-2} - \nu_{\rm hi}^{-2})\ {\rm DM} \approx 4.15\,(\nu_{\rm lo}^{-2} - \nu_{\rm hi}^{-2})\ {\rm DM\ ms}$$


Max-burst Upper Limits and Sensitivity vs. ΔT
E^2 F per FRB @ 100 TeV (GeV cm^{-2})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5
ΔT (s)
E^{-2} power-law spectrum
Sensitivity (six-year South)
Sensitivity (this analysis)
Upper limit (90%)
Upper limit (90%)


Northern max-burst
E^{-2} sensitivity
E$^{-2.5}$ sensitivity
E^{-3} sensitivity
E^{-2} upper limit
E$^{-2.5}$ upper limit
E^{-3} upper limit
E^{2}F @ 100 TeV (GeV cm^{-2})
10^{-1}
10^{-2}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
Δ T (s)


90°
FRB 121102 (repeater)
360°
270°
180°
90°
0°
Equatorial
-90°