Binned neutrino search in coincidence with FRB emissions

An example of an FRB / Neutrino analysis on KM3NeT

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FRB - Neutrino workshop, Institut d'Astrophysique de Paris
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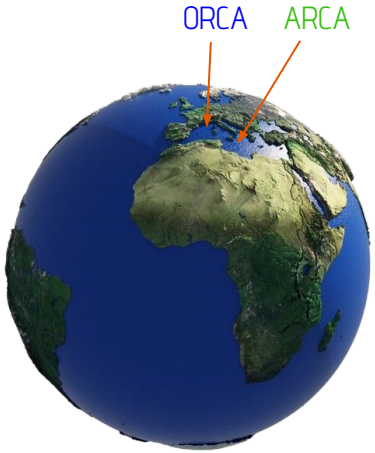
Introduction

- An example of a possible analysis in neutrino astrophysics
- Using KM3NeT data, we hope to find a **spatial and temporal correlation** of neutrino events with FRBs
- I will discuss:
  - Hypotheses made to build the analysis strategy
  - KM3NeT data selection and characterization
  - Analysis method and optimization results
  - Future prospects
- This symbol:  marks a question that could be discussed this afternoon, or to which I do not know the answer. In blue  s been answered
- One proceedings has been published recently, from the Journées de la SF2A 2023, in Strasbourg:

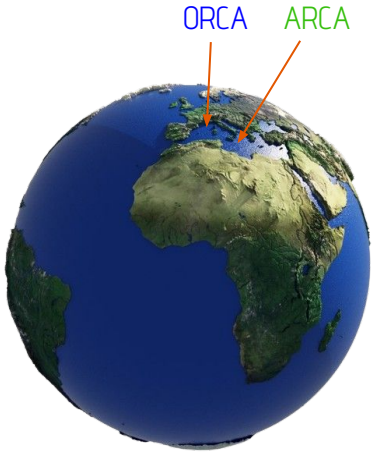
  https://drive.google.com/file/d/1mc-N-gz4-_OImr1HNb4yTA8CbWV_Ldez/view?usp=sharing



❖ Being built now in the Mediterranean Sea (Start: 2016, End: 2028?)

KM3NeT lines (ORCA + ARCA):	1+1	6+6	10+9	15+21	17+28	…	…	50+115?	…	115+230?
	2016	2020	2021	2022	2023	2024	2025	2026	2027	2028 …
FRB discovered:	52	797	863	863	932	??	??	??	??	??

Do we know the estimation of the future FRB rate discovery ?
→ Cherry: a few per day by CHIME ⇒ ~10^3 yr^{-1}



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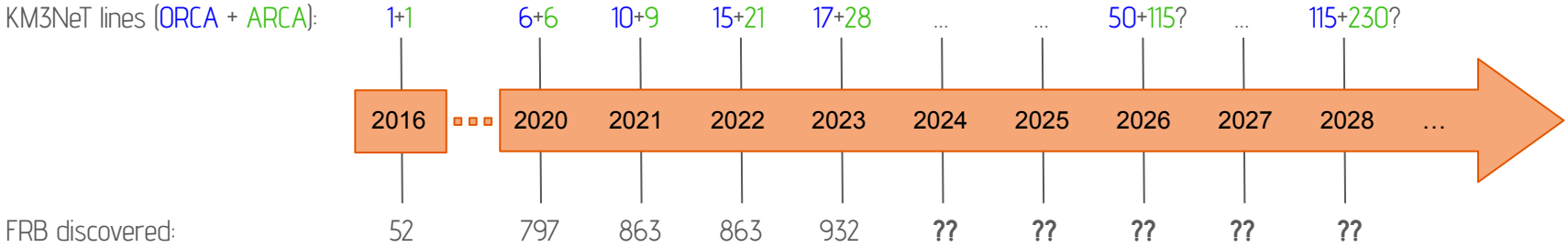
  - All detector configurations can be used, recent show better performance
  - The data preparation (processing, data quality, simulations) takes time to process
  - A long and stable period is preferred



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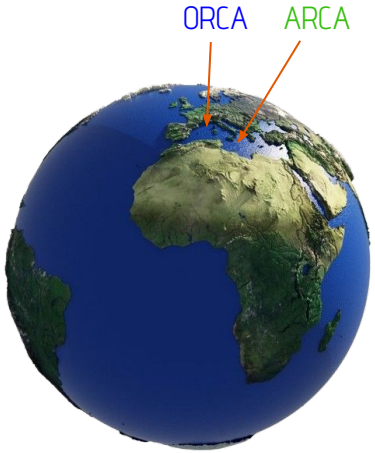

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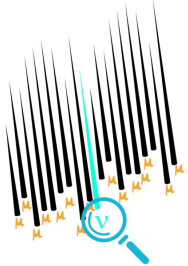
- KM3NeT is not at its full potential
  - Background discrimination
  - Shower event reconstruction



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Observables

Energy (isotropic) 10^{35}-10^{46} erg

Duration ~ Millisecond

Traits Large dispersion (DM)
Polarized signal (RM)
Large scattering

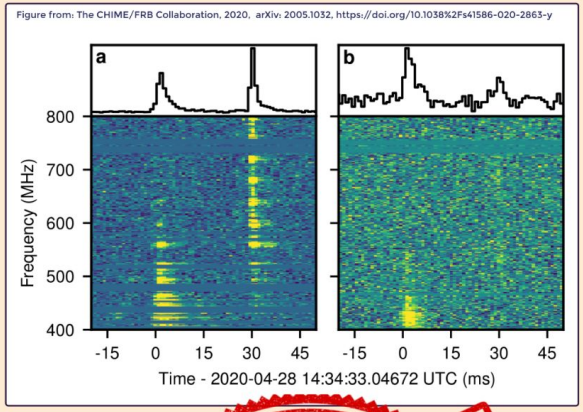
Repeating Sometimes

Inferred characteristics

Source Extra-galactic sources
Magnetars (?)

Mechanism Coherent emission

Environment Energetic, dense magnetized, perturbed plasma



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⇒ To be as **model-independent** as possible

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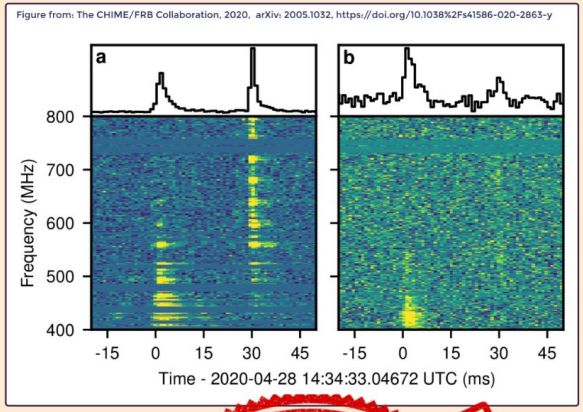

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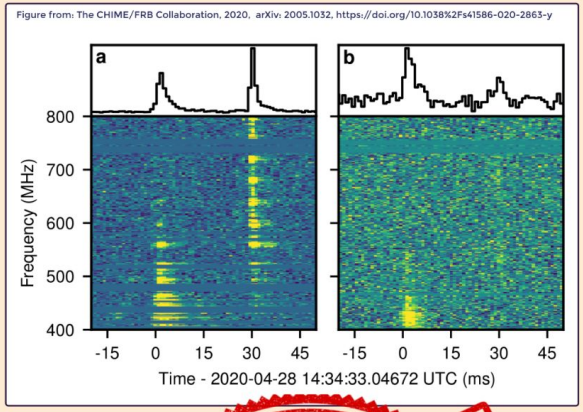

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Are magnetar models leading the FRB search ?

⇒ Guillaume: yes and no

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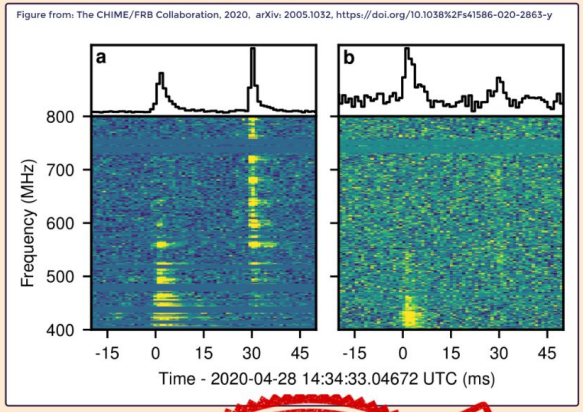


Seal

Hypotheses for this analysis

Hypotheses for the first KM3NeT analysis

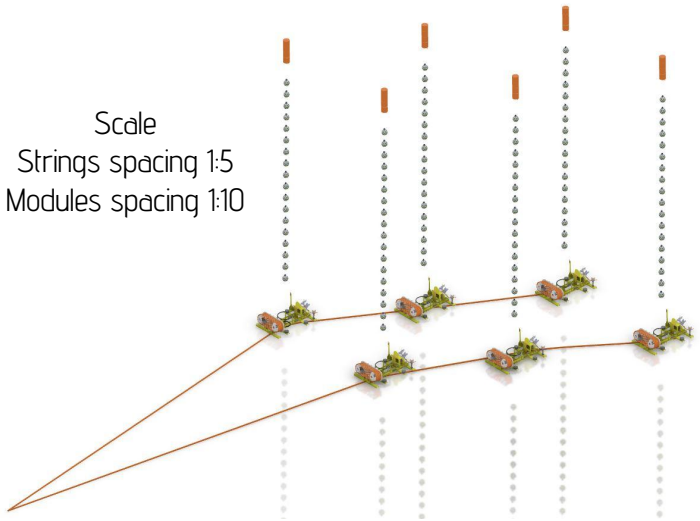
- **Simultaneous emission** of FRB and neutrino(s) ⇒ short time window of ±500s (compact objects)
- No guess on **neutrino energy**: possible search in ORCA and ARCA ⇒ Claire: ν @ TeV
- All bursts are considered **unique**, even repeaters!

Start with a first analysis:

- **ON/OFF Binned analysis with ORCA6**
- Research of a **spatial** and **temporal** correlation of neutrino events and FRB

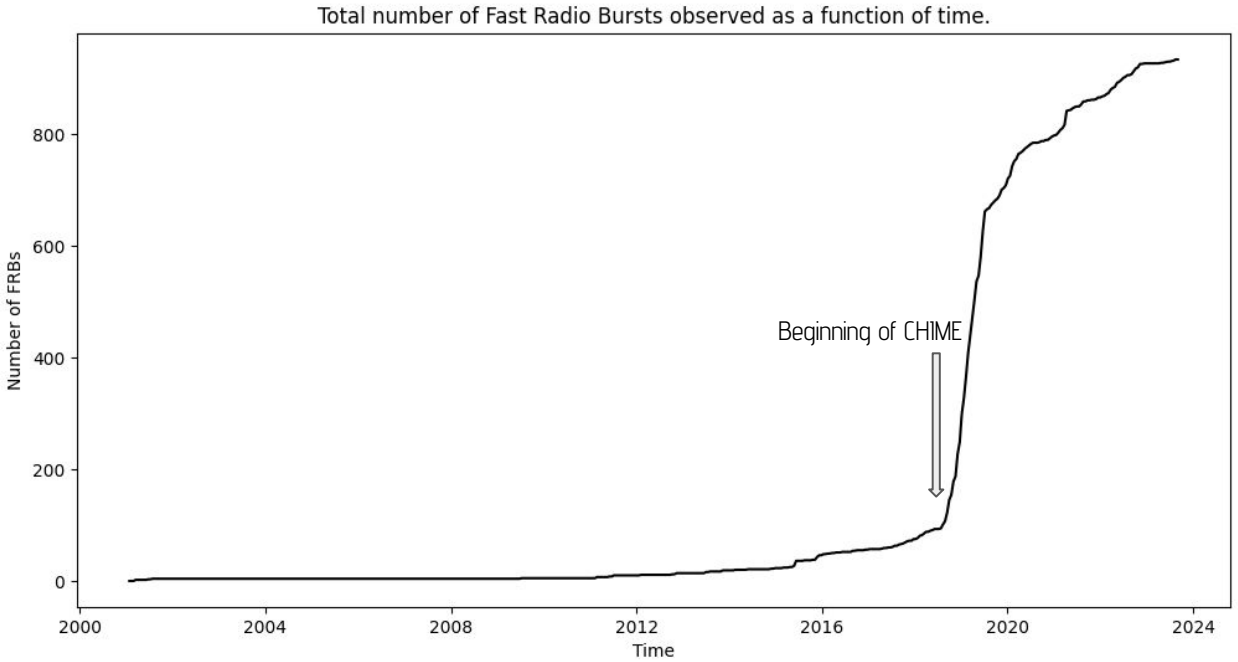
ORCA with 6 lines

Scale
Strings spacing 1:5
Modules spacing 1:10



Fast Radio Bursts Selection

- 900+ bursts detected today
- Mainly from the Northern Hemisphere by CHIME



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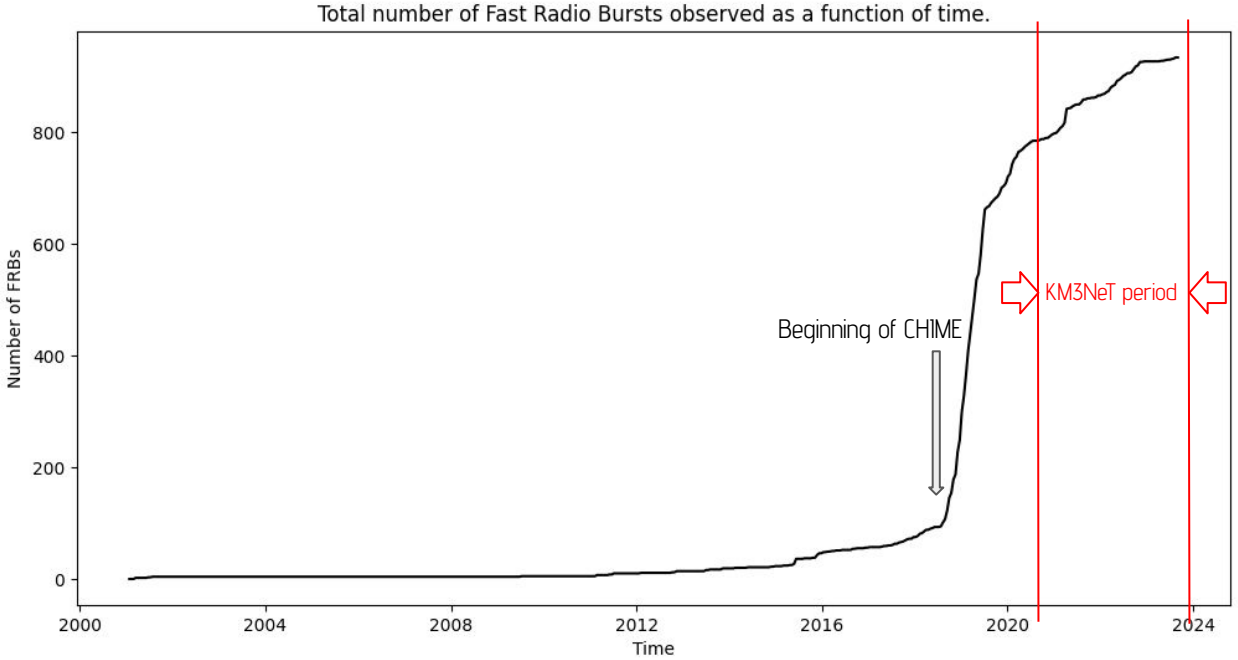
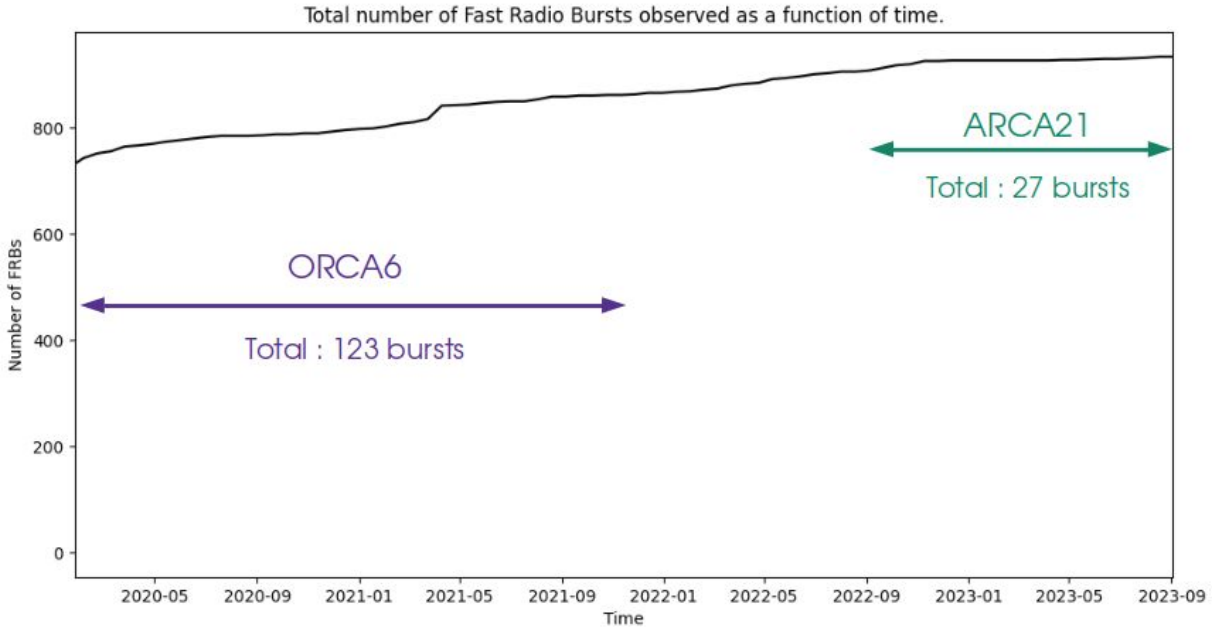


Fast Radio Bursts Selection

- 900+ bursts detected today
- Mainly from the Northern Hemisphere by CHIME
- KM3NeT is effectively in operation since January 2020
- Many FRBs are discovered by data mining in the radiotelescopes archives, i.e. are not available directly upon detection



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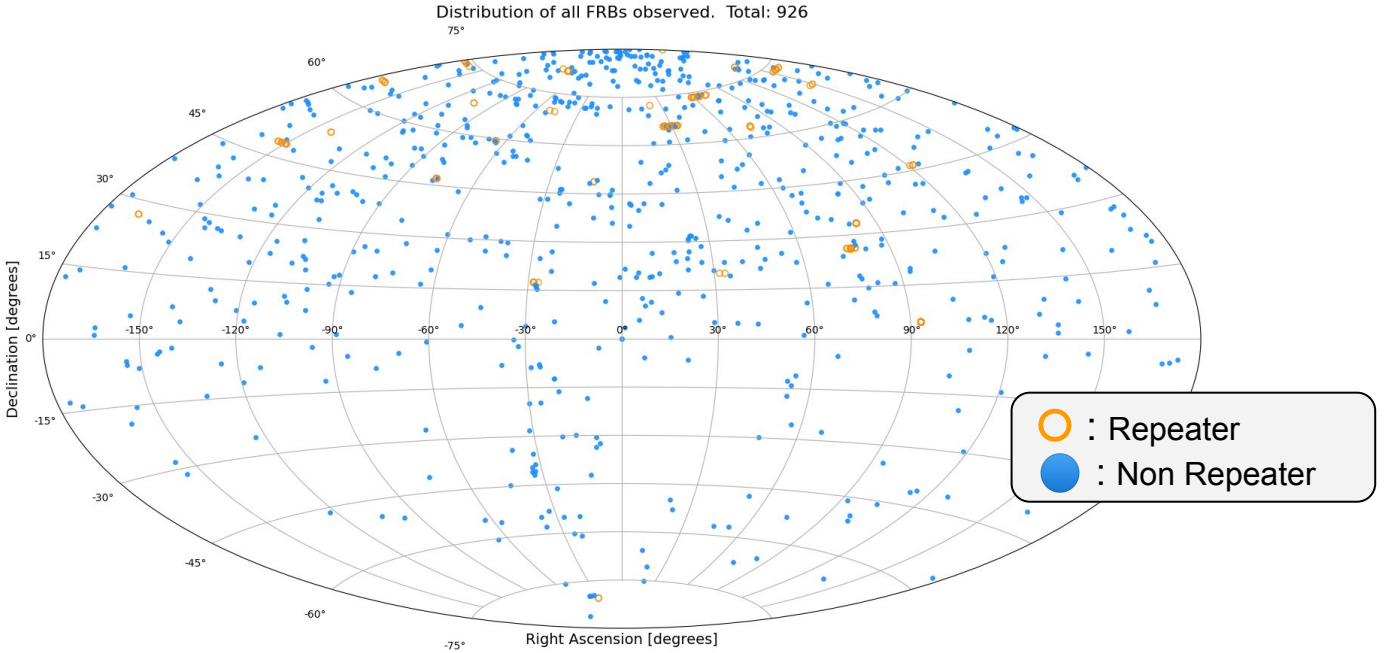
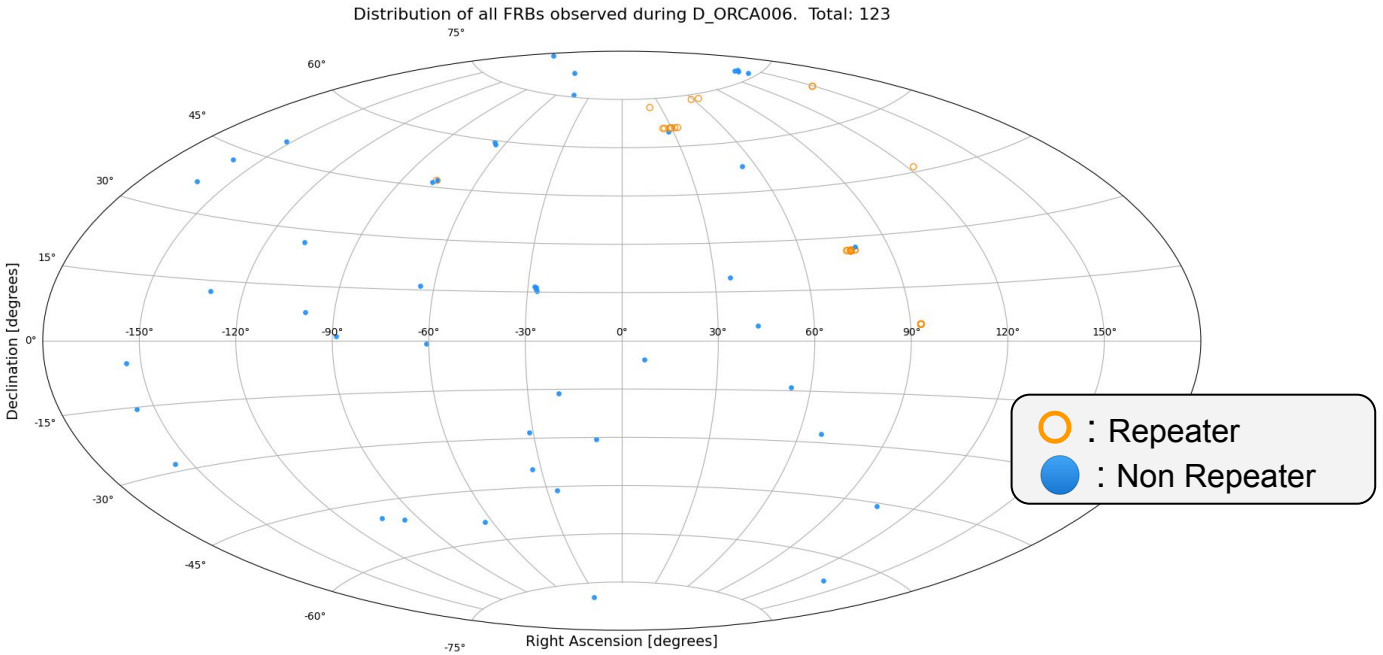


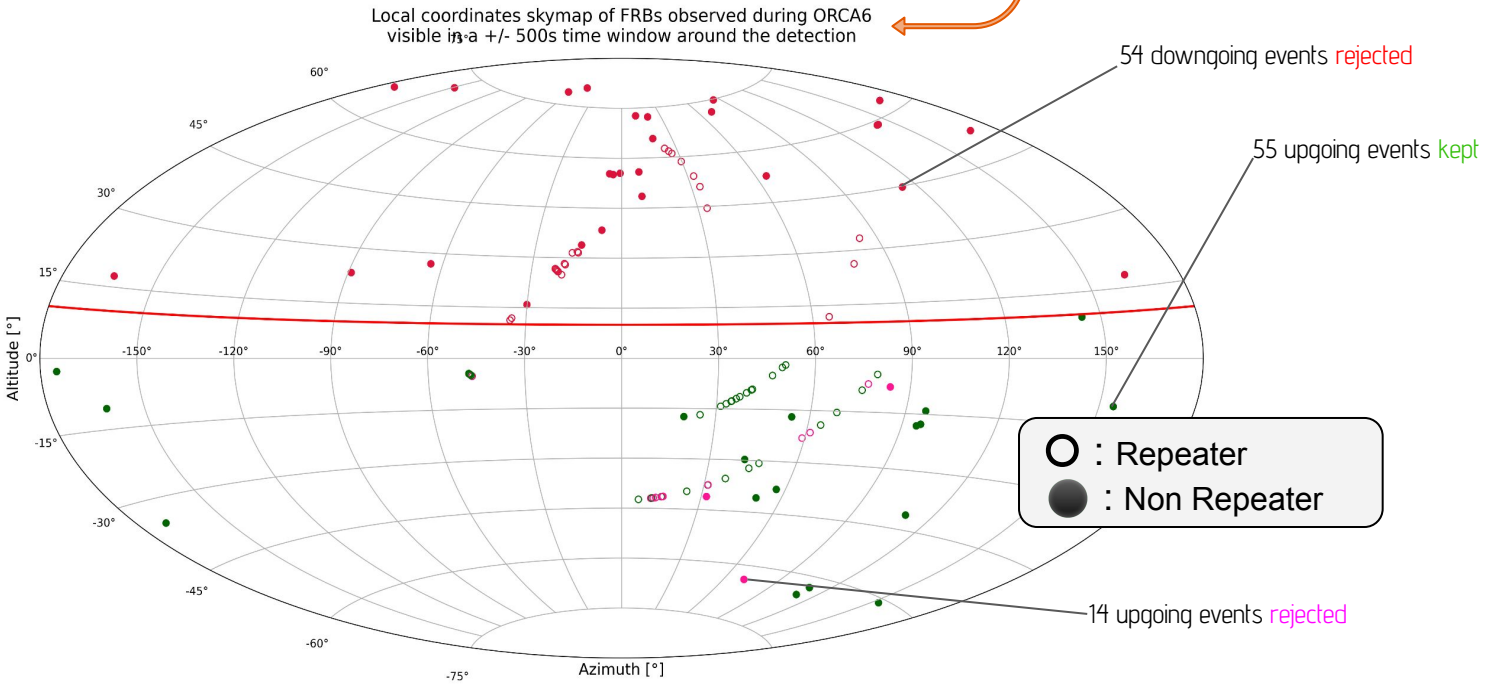
D_ORCA006 analysis

- D_ORCA006 configuration lasts from January 27, 2020 to November 18, 2021 ⟶ 22 months
- 123 bursts are left in this period



D_ORCA006 analysis

- D_ORCA006 configuration lasts from January 27, 2020 to November 18, 2021 ⟶ 22 months
- 123 bursts are left in this period ⟶ 69 bursts are located in the local up-going region ⟶ **55** are usable (taking into account the ORCA lifetime)



Azimuth-Altitude representation

[-90°, **+10°**] Altitude acceptance

Data selection: Fast Radio Bursts

N°	Name	RA [hourangle]	DEC [°]	Discovery Date (UT)	DM	Repeater	Reporting Group/s	Frequency	Redshift
1	FRB 20200430A	15:18:41.000	+12:20:23.00	2020-04-30 15:49:48.907	380.1		CRAFT	864.5	0.3797
2	FRB 20200508A	09:01:32.390	-65:35:42.70	2020-05-08 07:42:09.500	629		FRBCAT	835	0.4048
3	FRB 20200514B	07:01:00.550	-45:54:24.96	2020-05-14 05:40:45.700	349.4		UTMOST	835.2	0.147
4	FRB 20200607A	13:41:30.650	-05:08:24.10	2020-06-07 10:37:21.700	466.9		FRBCAT	835	0.4613
5	FRB 20200615E	06:12:54.960	+04:38:43.60	2020-06-15 02:51:30.241	518.6	**20180301A**	CRAFT	-	-
6	FRB 20200627A	21:47:00.000	-39:28:60.00	2020-06-27 19:23:41.644	294		CRAFT	920.5	0.2954
7	FRB 20200906A	03:35:00.000	-14:04:00.00	2020-09-06 21:40:50.923	577.8		CRAFT	864.5	0.5516
8	FRB 20201123A	17:34:40.560	-50:46:02.00	2020-11-23 10:11:59.482	433.9		MeerTRAP	1284	0.2998
9	FRB 20201124A	05:07:57.600	+26:11:24.00	2020-11-24 08:50:41.885	410.83	**20201124A**	CHIMEFRB	600	0.2443
10	FRB 20210117A	22:39:36.000	-16:11:25.20	2021-01-17 07:51:21.277	730		CRAFT	1271.5	0.7016

Data selection: Fast Radio Bursts

N°	Name	RA [hourangle]	DEC [°]	Discovery Date (UT)	DM	Repeater	Reporting Group/s	Frequency	Redshift
11	FRB 20210202D	19:46:48.740	-54:13:38.80	2021-02-02 12:38:25.339	609.16		MeerTRAP	-	-
12	FRB 20210214G	00:27:43.000	-05:49:56.00	2021-02-14 05:12:39.696	398.3		CRAFT	1271.5	0.4015
13	FRB 20210303A	22:15:52.300	-46:05:32.00	2021-03-03 01:28:46.900	366.9		UTMOST	835	0.3684
14	FRB 20210320C	13:37:16.800	-15:24:37.30	2021-03-20 18:38:08.508	384.8		CRAFT	864.5	0.3805
15	FRB 20210405I	17:01:21.500	-49:32:42.80	2021-04-05 04:14:40.470	566.43		MeerTRAP	-	-
16	FRB 20210407E	05:14:46.300	+27:04:12.30	2021-04-07 05:14:36.202	1785.3		CRAFT	1271.5	1.5002
17	FRB 20210408H	13:37:18.250	-28:17:02.90	2021-04-08 21:20:11.813	1195.95		MeerTRAP	-	-
18	FRB 20210410D	21:44:20.700	-79:19:05.50	2021-04-10 11:13:02.432	578.78		MeerTRAP	-	-
19	FRB 20210630A	17:23:07.409	+07:51:41.85	2021-06-30 12:48:11.200	943.7		UTMOST	835.55	0.8631

- 26 bursts from rFRB 20201124A and 12 from rFRB 20180301A (detail in backup)

Data Selection: KM3NeT runs

- Data Quality in KM3NeT: all runs are equal, but some runs are more equal than others!
  - Bioluminescence → "Bad run"
  - Detector stability → Event rate monitoring
  - Sea operations, calibration, DAQ issues can reduce the detector duty cycle

A **run**: 3 or 4 hours long

An **event**: collection of light in DOMs passing thresholds
Minimum of n DOMs triggered
Minimum of n lines triggered
Track and energy reconstruction with quality factor

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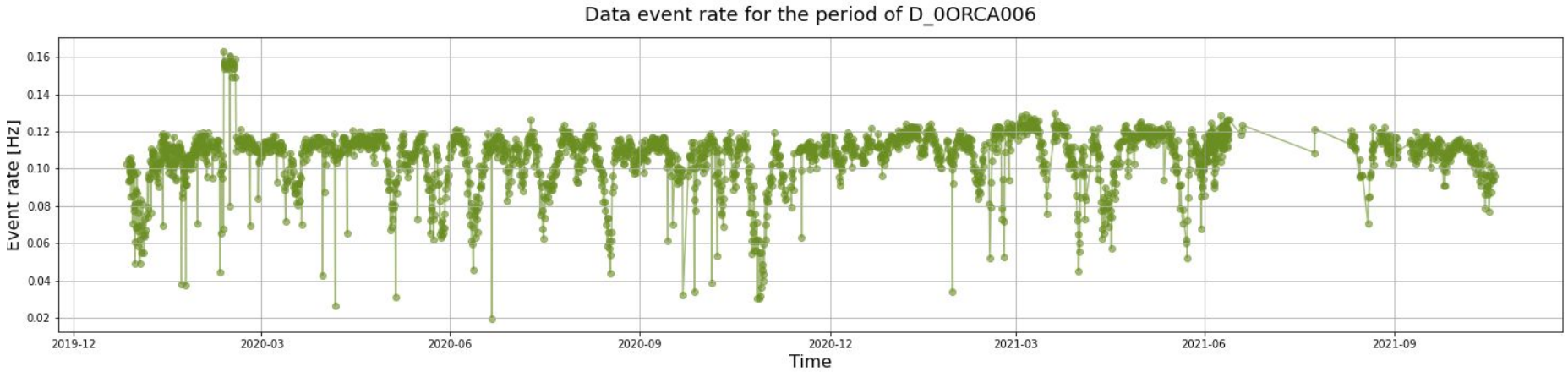

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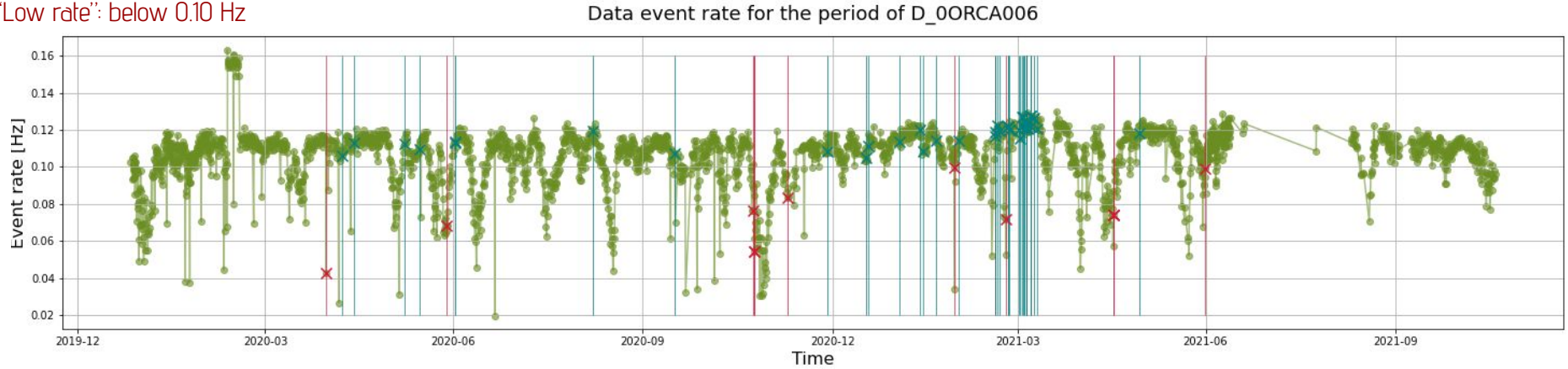
"Normal rate": within [0.10, 0.13] Hz
"Low rate": below 0.10 Hz



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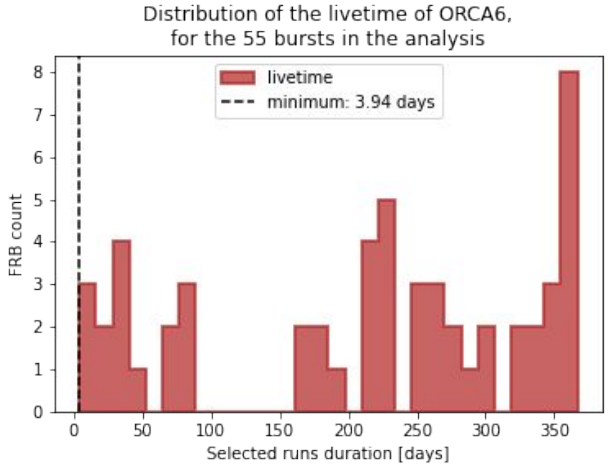
- Event rate during ORCA6 period
  - The variations are not due to signal, but are from the detector itself!
- Each run of interest has *similar runs* based on event rate comparison
  - Between 4 days and 367 days can be used for each FRB



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- The data is highly dominated by the background of **atmospheric muons** and **atmospheric neutrinos**
  - The muons are discriminated mainly through a **zenithal cut** (up-going events only)
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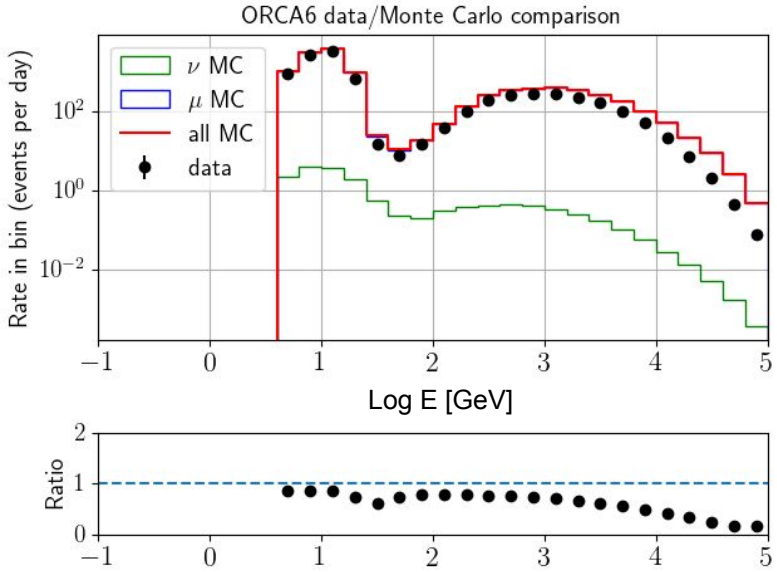
  - Need to understand the remaining discrepancies
  - After applying BDT cuts, neutrino should dominate

No cuts



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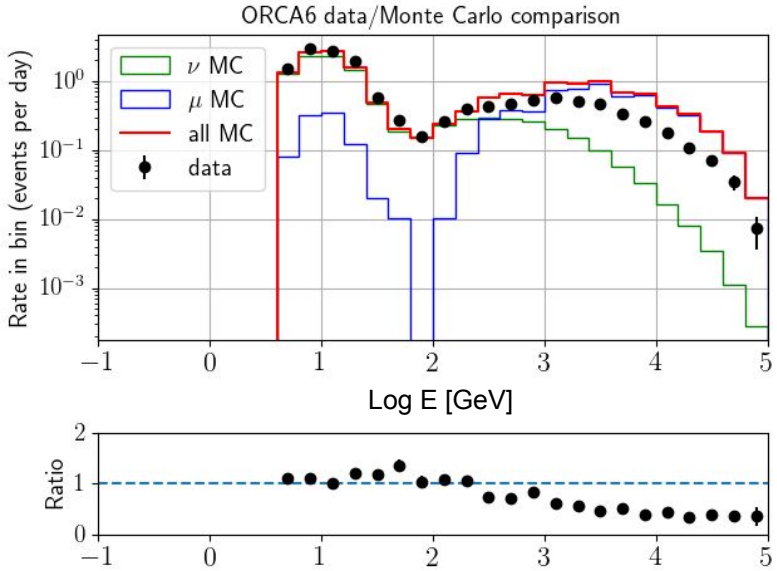
An example of some BDT cut



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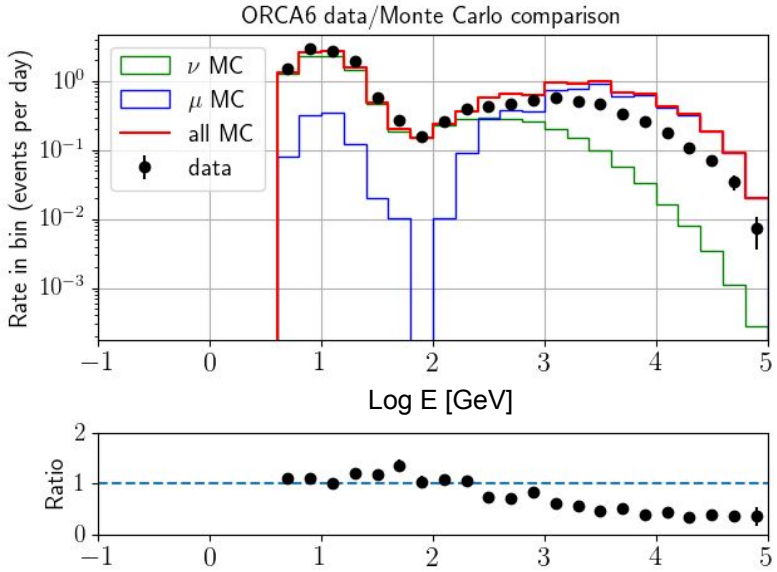
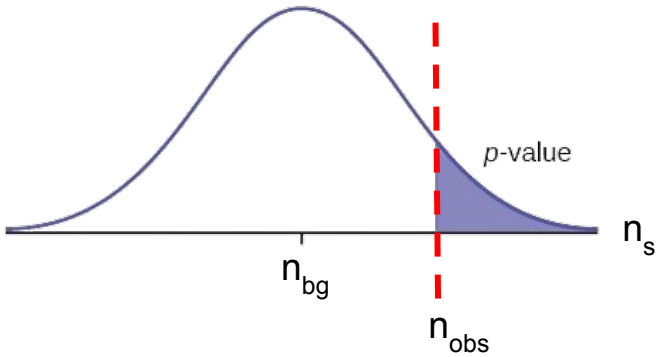
- Some additional cuts could also be made:
  - Reconstructed track length
  - Reconstructed energy
  - Number of triggered modules (high quality events)



- ON/OFF Analysis in a nutshell:
  1. Optimize the cuts on the event selection
  2. Estimate the background from scrambled data, without looking at the signal
  3. Look at the real events and conclude on some visible excess or not



Selection cuts optimization

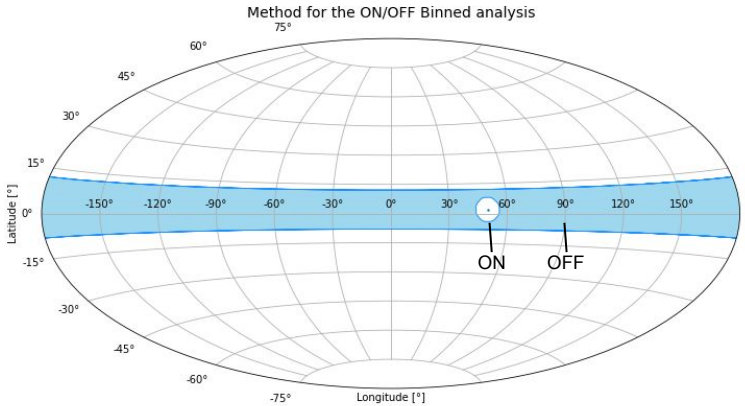
- Time Window of **1000 seconds** : $t_\nu \in [\, t_{FRB} - 500\ s\ ;\ t_{FRB} + 500\ s\,]$
- Model Rejection Factor used to **optimize the two cuts, BDT** score & **ROI** size :

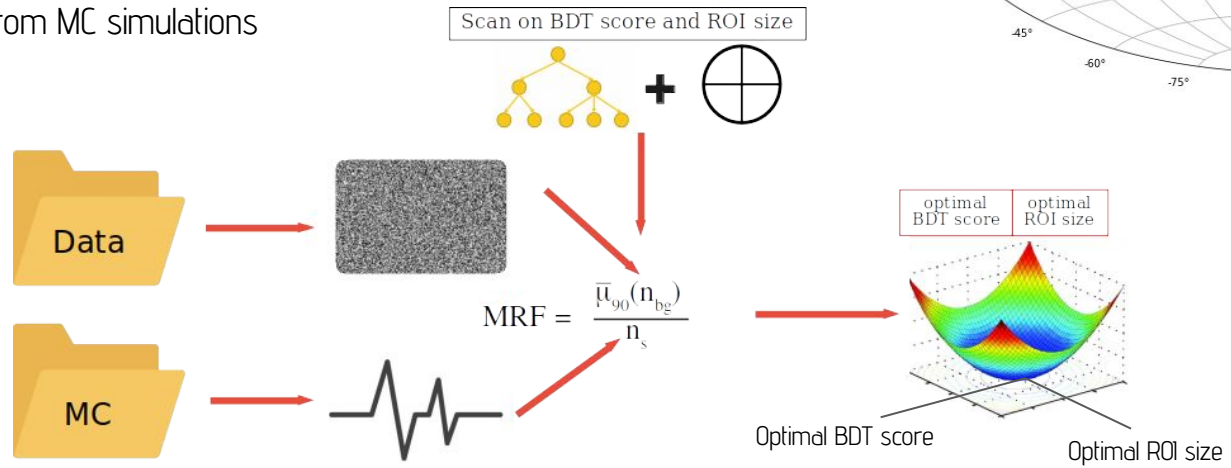
$$MRF = \frac{\bar{\mu}_{90}(n_{bg})}{n_s}$$

Feldman Cousins average upper limit at 90% confidence level [1,2]

Number of expected signal

- Background from real data
- Signal from MC simulations

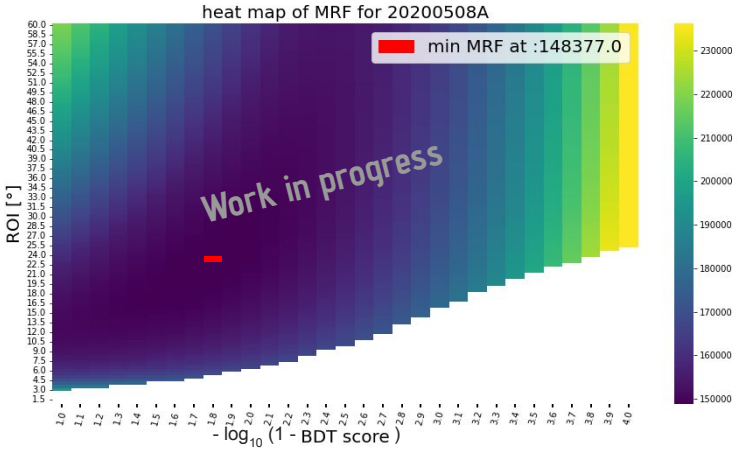




1: Hill, Rawlins, 2003, https://doi.org/10.1016/S0927-6505(02)00240-2
2: Feldman, Cousins, 1997, arXiv:9711021v2

ORCA6 Optimization Results

- Optimization selection: Example of FRB 20200508A
  - ROI size: 23°
  - BDT score: $1-10^{-1.8} = 0.984$



Scan on the two parameter space: the BDT score (as $1-10^{-\text{BDT score}}$) and ROI size [°]. The color gradient shows the MRF potential. The red mark shows the minimum for a factor around 10^6

ORCA6 Optimization Results

- Optimization selection: Example of FRB 20200508A
  - ROI size: 23°
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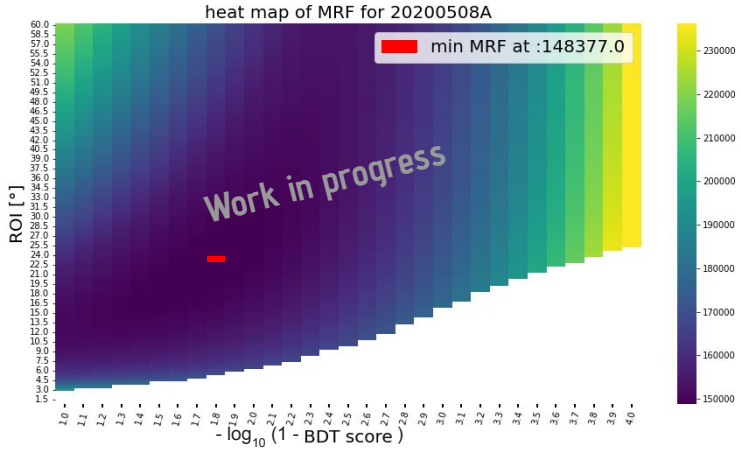

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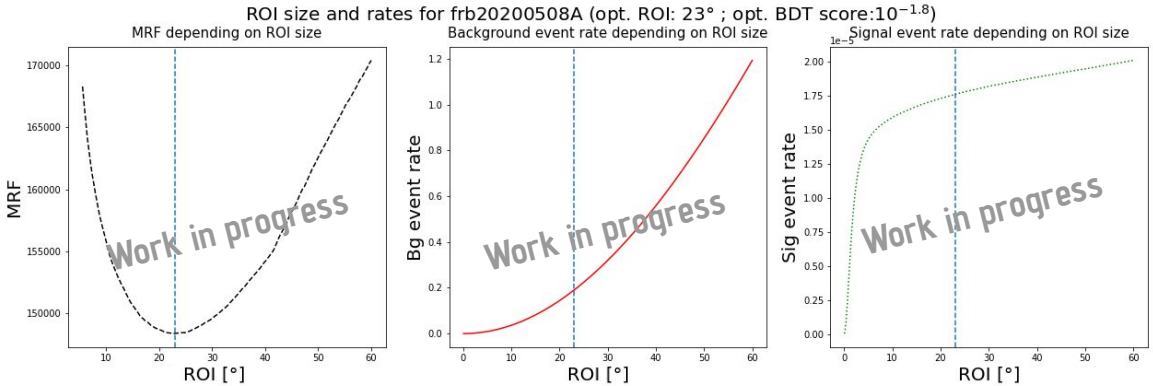
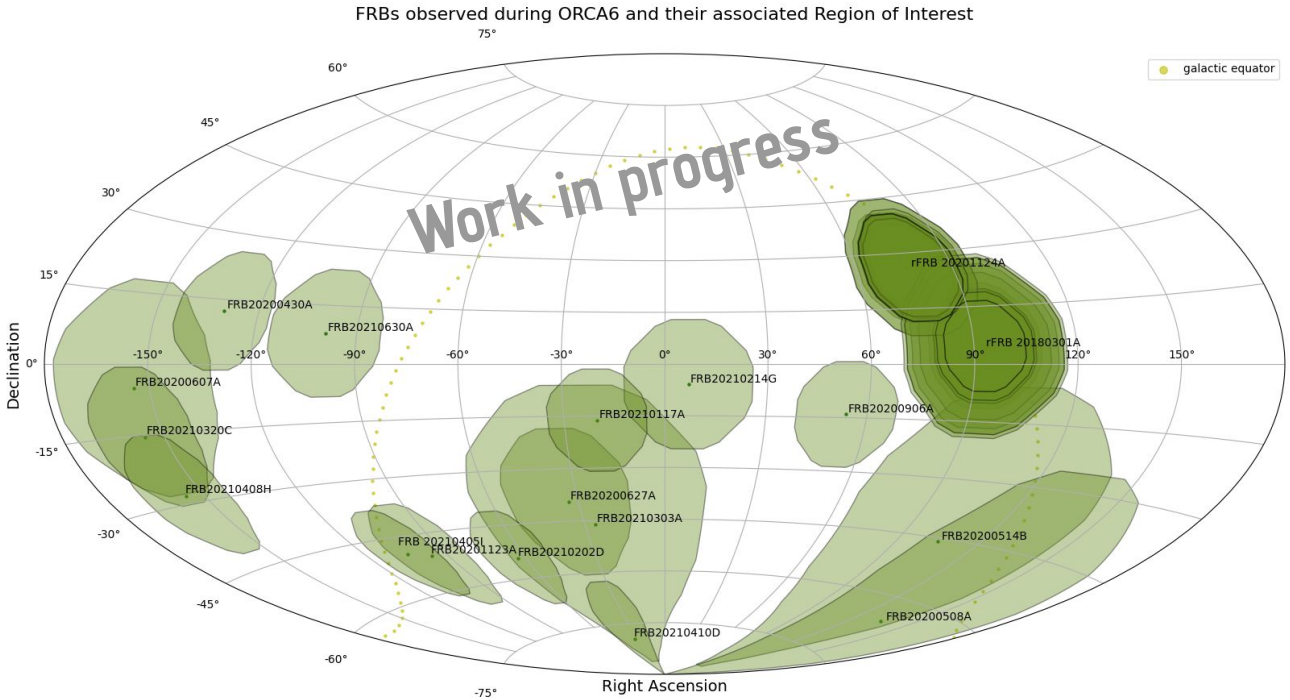


Model rejection potential, expected background and expected signal in the ROI. The MRF shows where selected events minimizes the ratio background/signal. The background increases as the square of the ROI but the signal has a slower growth.

- The expected background is much higher than the signal: one event only would have a very high significance
- After unblinding, proceed to the statistical analysis of the real data

ORCA6 Optimization Results

- Some Bursts need further investigation
- Average radii around 15-20° ⇒ it's huge, what does this imply ?



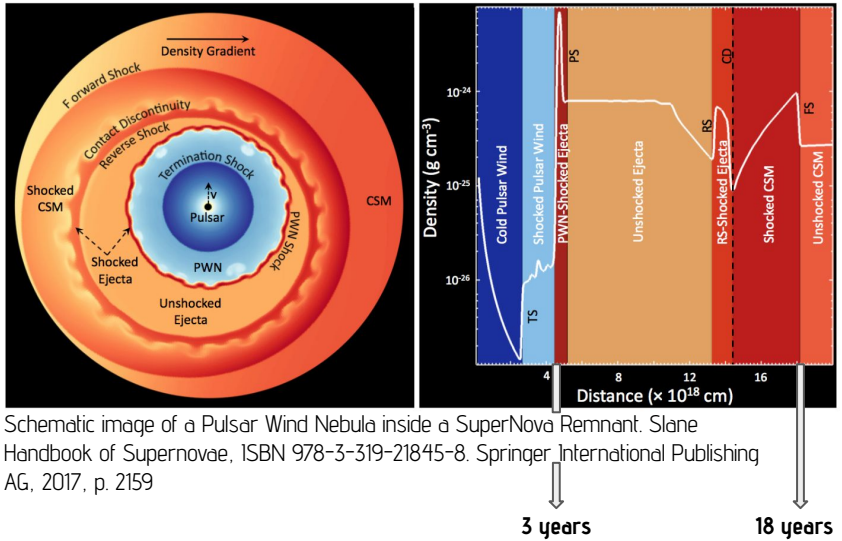
Further steps and Conclusion

- The optimisation with elevation dependent background is almost ready
- Thorough verification of the cuts optimization
- Solve anomalies for some of the bursts
- Un-blinding and analysis of the real data for each burst

- Think about the next analysis!

Next analysis strategy

- Candidate: Pulsar Wind Nebula from SNR
- Shocked regions can be a source of neutrinos
  - What if FRB and neutrinos are not correlated ?
    - Claire & Julien: no hint



Schematic image of a Pulsar Wind Nebula inside a SuperNova Remnant. Slane Handbook of Supernovae, ISBN 978-3-319-21845-8. Springer International Publishing AG, 2017, p. 2159

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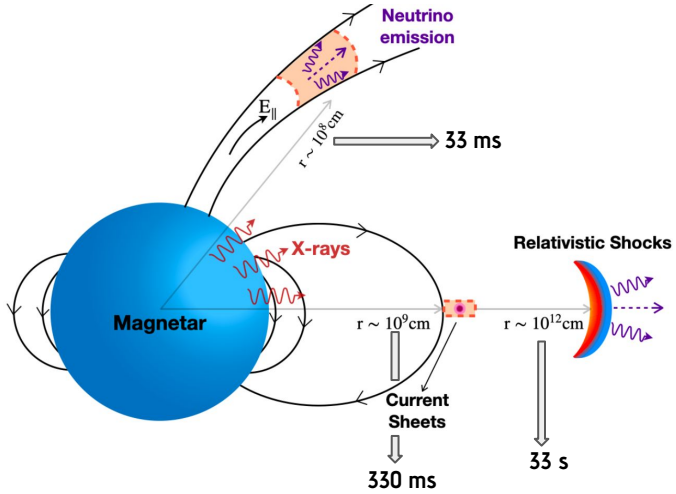

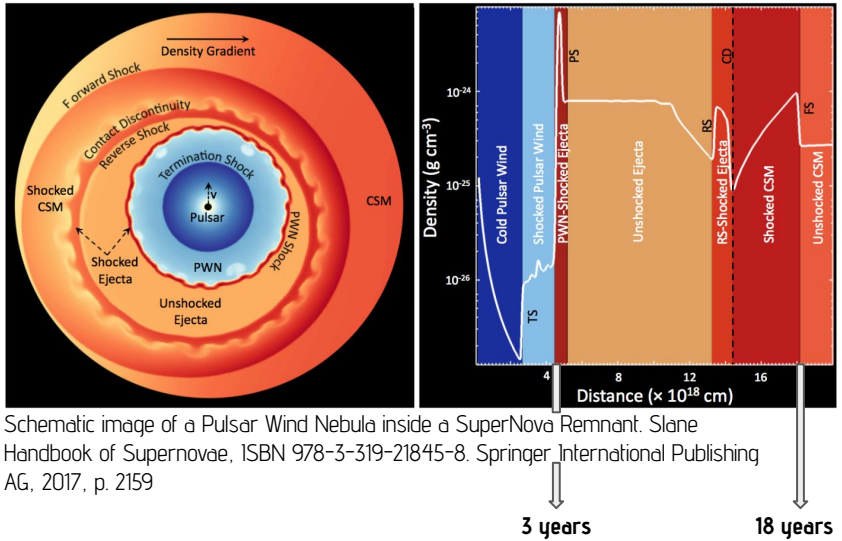

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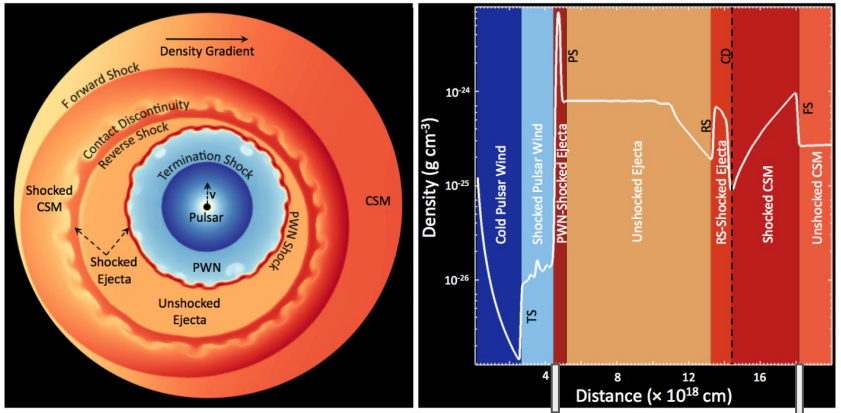

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- Stacked analysis ?
  - The whole FRB population could be studied
  - Should some cuts be applied on the selection of FRBs ? ⇒ Julien: trial factor problem

- Repeaters (and unknown repeaters) could be emitting neutrinos anytime

⇒ Next analysis would be a **Stacked likelihood analysis on ARCA21:** Research of a spatial correlation of neutrino events with all available FRBs

- Resolution ✔
- Neutrino statistics ✔
- FRB statistics ✔
- Search area ✔

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- Additional questions:
  - What do you think is this worth? What would be the best analysis?
  - For a stacked analysis, should we use all FRBs? What physical cuts on FRB selection?

Backup

Full FRB list 1/5

N°	Name	RA	DEC	Discovery Date (UT)	DM	Repeater	Reporting Group/s	Frequency	Redshift
1	FRB 20200430A	15:18:41.000	+12:20:23.00	2020-04-30 15:49:48.907	380.1		CRAFT	864.5	0.3797
2	FRB 20200508A	09:01:32.390	-65:35:42.70	2020-05-08 07:42:09.500	629		FRBCAT	835	0.4048
3	FRB 20200514B	07:01:00.550	-45:54:24.96	2020-05-14 05:40:45.700	349.4		UTMOST	835.2	0.147
4	FRB 20200607A	13:41:30.650	-05:08:24.10	2020-06-07 10:37:21.700	466.9		FRBCAT	835	0.4613
5	FRB 20200615E	06:12:54.960	+04:38:43.60	2020-06-15 02:51:30.241	518.6	20180301A	CRAFT	-	-
6	FRB 20200627A	21:47:00.000	-39:28:60.00	2020-06-27 19:23:41.644	294		CRAFT	920.5	0.2954
7	FRB 20200701I	06:12:54.960	+04:38:43.60	2020-07-01 23:52:50.618	517.3	20180301A	CRAFT	-	-
8	FRB 20200702E	06:12:54.960	+04:38:43.60	2020-07-02 01:05:33.417	516.5	20180301A	CRAFT	-	-
9	FRB 20200906A	03:35:00.000	-14:04:00.00	2020-09-06 21:40:50.923	577.8		CRAFT	864.5	0.5516
10	FRB 20201016B	06:12:54.960	+04:38:43.60	2020-10-16 16:26:21.187	515.6	20180301A	CRAFT	-	-

Full FRB list 2/5

N°	Name	RA	DEC	Discovery Date (UT)	DM	Repeater	Reporting Group/s	Frequency	Redshift
11	FRB 20201123A	17:34:40.560	-50:46:02.00	2020-11-23 10:11:59.482	433.9		MeerTRAP	1284	0.2998
12	FRB 20201124A	05:07:57.600	+26:11:24.00	2020-11-24 08:50:41.885	410.83	20201124A	CHIMEFRB	600	0.2443
13	FRB 20201124B	05:08:26.400	+26:11:24.00	2020-11-24 08:54:45.868	404.36	20201124A	CHIMEFRB	600	0.2368
14	FRB 20201210A	05:13:57.600	+26:12:00.00	2020-12-10 07:54:42.971	414.89	20201124A	CHIMEFRB	600	0.2327
15	FRB 20201229E	06:12:54.960	+04:38:43.60	2020-12-29 13:41:11.701	518.9	20180301A	CRAFT	-	-
16	FRB 20210117A	22:39:36.000	-16:11:25.20	2021-01-17 07:51:21.277	730		CRAFT	1271.5	0.7016
17	FRB 20210118D	06:12:54.960	+04:38:43.60	2021-01-18 11:35:08.060	518.3	20180301A	CRAFT	-	-
18	FRB 20210202D	19:46:48.740	-54:13:38.80	2021-02-02 12:38:25.339	609.16		MeerTRAP	-	-
19	FRB 20210212G	06:12:54.960	+04:38:43.60	2021-02-12 09:33:04.483	518.2	20180301A	CRAFT	-	-
20	FRB 20210214G	00:27:43.000	-05:49:56.00	2021-02-14 05:12:39.696	398.3		CRAFT	1271.5	0.4015

Full FRB list 3/5

N°	Name	RA	DEC	Discovery Date (UT)	DM	Repeater	Reporting Group/s	Frequency	Redshift	
21	FRB 20210220A	05:07:48.000	+26:11:24.00	2021-02-20 03:06:22.953	418.93	20201124A	CHIMEFRB	600		0.2522
22	FRB 20210301A	05:01:55.200	+26:10:48.00	2021-03-01 02:28:45.287	417.3	20201124A	CHIMEFRB	600		0.2644
23	FRB 20210303A	22:15:52.300	-46:05:32.00	2021-03-03 01:28:46.900	366.9		UTMOST	835		0.3684
24	FRB 20210320C	13:37:16.800	-15:24:37.30	2021-03-20 18:38:08.508	384.8		CRAFT	864.5		0.3805
25	FRB 20210321A	05:07:50.400	+26:11:24.00	2021-03-21 01:12:22.524	412.46	20201124A	CHIMEFRB	600		0.2462
26	FRB 20210322A	05:08:21.600	+26:11:24.00	2021-03-22 01:10:44.315	410.04	20201124A	CHIMEFRB	600		0.2425
27	FRB 20210323A	05:13:16.800	+26:12:00.00	2021-03-23 01:08:04.102	414.89	20201124A	CHIMEFRB	600		0.2348
28	FRB 20210326A	05:07:09.600	+26:11:24.00	2021-03-26 00:53:51.088	412.46	20201124A	CHIMEFRB	600		0.2477
29	FRB 20210327A	05:03:38.400	+26:11:24.00	2021-03-27 00:46:22.270	416.51	20201124A	CHIMEFRB	600		0.2596
30	FRB 20210327B	05:08:33.600	+26:11:24.00	2021-03-27 00:53:10.546	411.25	20201124A	CHIMEFRB	600		0.2433
31	FRB 20210327C	05:08:33.600	+26:11:24.00	2021-03-27 00:53:10.696	422.17	20201124A	CHIMEFRB	600		0.2536
32	FRB 20210328A	05:08:28.800	+26:11:24.00	2021-03-28 00:49:08.222	415.7	20201124A	CHIMEFRB	600		0.2477

Full FRB list 4/5

N°	Name	RA	DEC	Discovery Date (UT)	DM	Repeater	Reporting Group/s	Frequency	Redshift
33	FRB 20210401C	06:12:54.960	+04:38:43.60	2021-04-01 09:04:12.457	518.5	20180301A	CRAFT	-	-
34	FRB 20210402A	05:07:55.000	+26:01:60.00	2021-04-02 05:48:59.114	414	20201124A	CRAFT	1271.5	0.2482
35	FRB 20210403A	05:08:03.000	+26:03:39.00	2021-04-03 06:37:16.068	423	20201124A	CRAFT	1104	0.2562
36	FRB 20210403B	05:08:03.000	+26:03:39.00	2021-04-03 07:33:49.802	417	20201124A	CRAFT	1104	0.2505
37	FRB 20210404B	05:08:09.000	+26:08:44.00	2021-04-04 07:46:46.027	414	20201124A	CRAFT	1271.5	0.2478
38	FRB 20210404C	05:08:03.000	+26:03:39.00	2021-04-04 06:56:06.814	420	20201124A	CRAFT	1104	0.2534
39	FRB 20210405C	05:08:03.000	+26:03:39.00	2021-04-05 07:48:16.553	414	20201124A	CRAFT	1104	0.2478
40	FRB 20210405D	05:08:03.000	+26:03:39.00	2021-04-05 06:06:36.441	418	20201124A	CRAFT	895.75	0.2515
41	FRB 20210405E	05:08:03.000	+26:03:39.00	2021-04-05 06:14:36.096	414	20201124A	CRAFT	959.75	0.2478
42	FRB 20210405F	05:08:03.000	+26:03:39.00	2021-04-05 06:34:39.271	415	20201124A	CRAFT	895.75	0.2487
43	FRB 20210405G	05:08:03.000	+26:03:39.00	2021-04-05 06:44:57.149	411	20201124A	CRAFT	991.75	0.2449
44	FRB 20210405H	05:08:03.000	+26:03:39.00	2021-04-05 06:53:56.577	418	20201124A	CRAFT	959.75	0.2515

Full FRB list 5/6

N°	Name	RA	DEC	Discovery Date (UT)	DM	Repeater	Reporting Group/s	Frequency	Redshift	
45	FRB 20210405I	17:01:21.500	-49:32:42.80	2021-04-05 04:14:40.470	566.43		MeerTRAP	-	-	
46	FRB 20210407A	05:08:03.000	+26:03:39.00	2021-04-07 06:14:00.084	424	20201124A	CRAFT	1104		0.2572
47	FRB 20210407B	05:08:03.000	+26:03:39.00	2021-04-07 06:14:56.340	413	20201124A	CRAFT	1104		0.2469
48	FRB 20210407E	05:14:46.300	+27:04:12.30	2021-04-07 05:14:36.202	1785.3		CRAFT	1271.5		1.5002
49	FRB 20210408H	13:37:18.250	-28:17:02.90	2021-04-08 21:20:11.813	1195.95		MeerTRAP	-	-	
50	FRB 20210410D	21:44:20.700	-79:19:05.50	2021-04-10 11:13:02.432	578.78		MeerTRAP	-	-	
51	FRB 20210517A	06:12:54.960	+04:38:43.60	2021-05-17 06:25:18.841	522.4	20180301A	CRAFT	-	-	
52	FRB 20210517B	06:12:54.960	+04:38:43.60	2021-05-17 07:02:11.264	519.8	20180301A	CRAFT	-	-	
53	FRB 20210517C	06:12:54.960	+04:38:43.60	2021-05-17 07:26:54.640	532.4	20180301A	CRAFT	-	-	
54	FRB 20210530F	06:12:54.960	+04:38:43.60	2021-05-30 01:52:45.763	522.6	20180301A	CRAFT	-	-	
55	FRB 20210630A	17:23:07.409	+07:51:41.85	2021-06-30 12:48:11.200	943.7		UTMOST	835.55		0.8631

Angular error Simulation (ORCA6)

Difference between true neutrino direction and reconstructed neutrino direction