Multi-messenger observations with the KM3NeT telescope: search for high energy neutrinos coinciding with fast radio bursts

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Journées de Rencontre des Jeunes Chercheurs

October 28, 2023

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4: CNRS-IN2P3, France

Summary

❖ Neutrino astrophysics

❖ Fast Radio Bursts

❖ The KM3NeT experiment

❖ Analysis of 22 months of data

Neutrino astrophysics

❖ Multi Messenger astronomy:

<< Coordinated observation and interpretation of signals carried by disparate "messengers": electromagnetic radiation, gravitational waves, neutrinos, and cosmic rays >> [1]

❖ Multi messenger observations:

- **SuperNova 1987A**
- Binary neutron star merger: **GW170817**

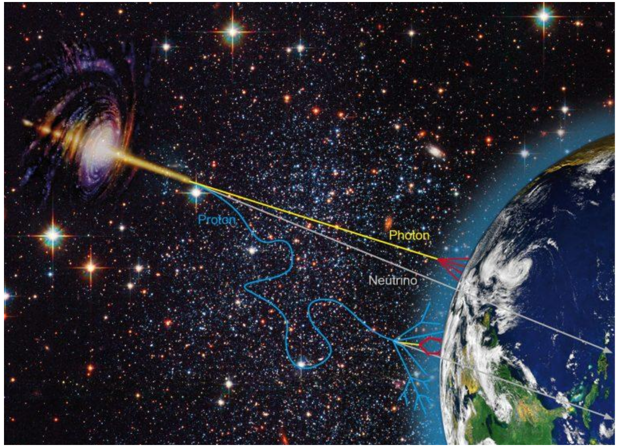
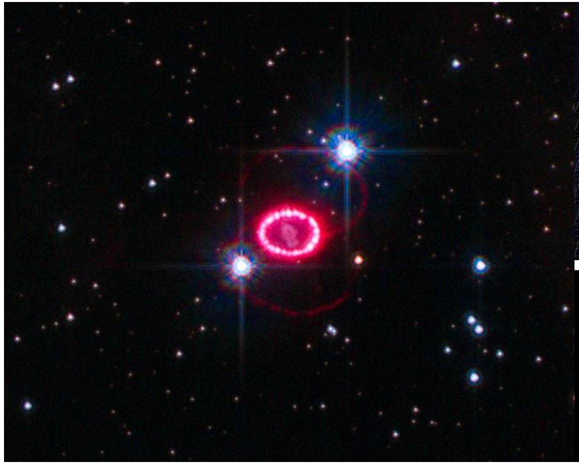
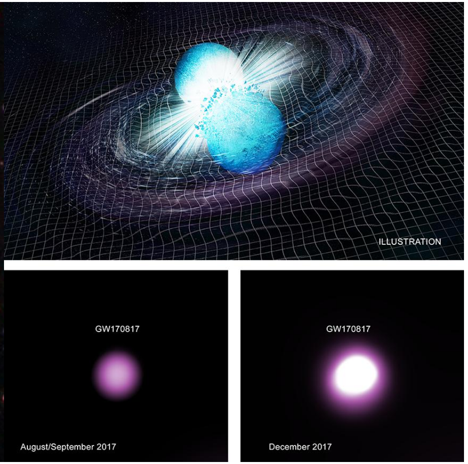


Illustration of the 4 messengers of the Universe: Gravitational waves, electromagnetic radiations, neutrinos and cosmic rays. Credit: From IRAP, Anna Franckowiak



SuperNova SN 1987A. Credit: Hubble Space Telescope



Binary neutron star merger GW170817. Credit: NASA/Chandra

1: https://en.wikipedia.org/wiki/Multi-messenger_astronomy

Neutrino astrophysics

❖ Multi Messenger astronomy:

<< Coordinated
carried by disp
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rays >> [1]

❖ Multi me

- **SuperN**
- Binary n

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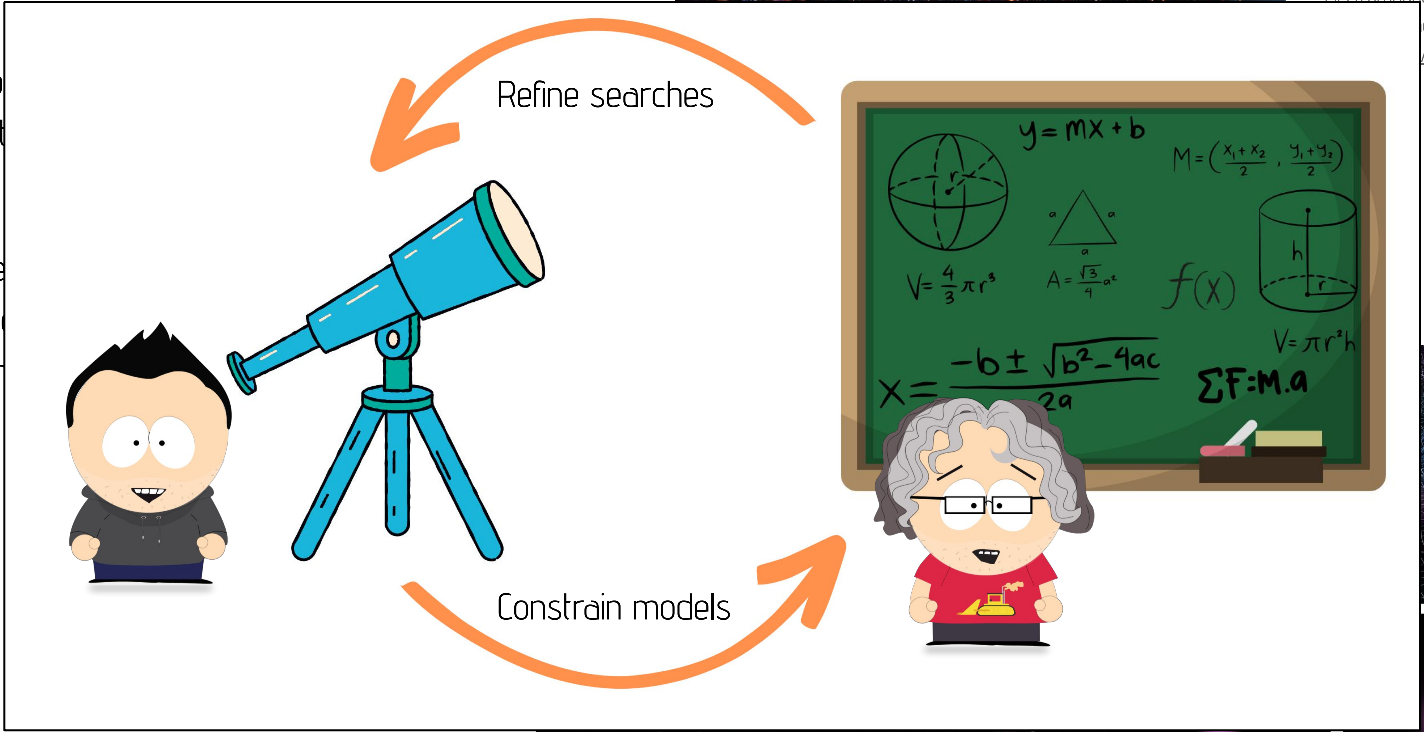

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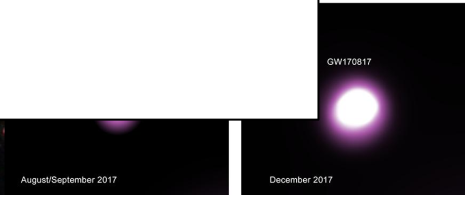
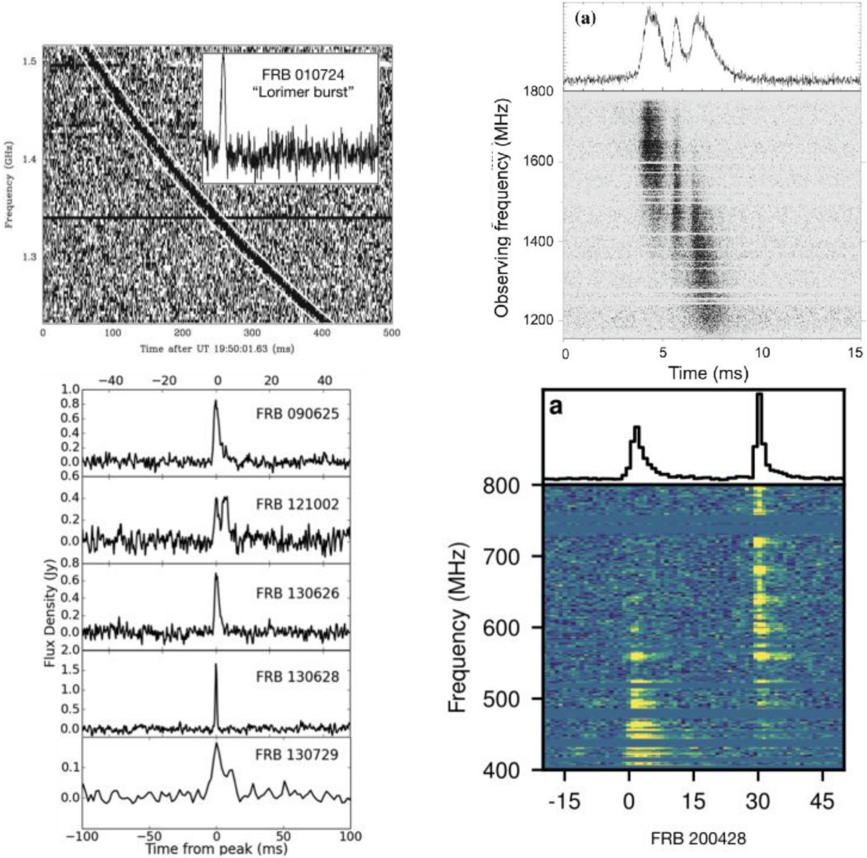


Binary neutron star merger GW170817. Credit: NASA/Chandra

1: https://en.wikipedia.org/wiki/Multi-messenger_astronomy

Fast Radio Bursts

- Bright millisecond radio flash
- First detection in 2007 by Parkes [1]
- “Perytons” signals, from magnetron shutdown (Parkes)
- First **Repeating** source in 2016 by Arecibo [2]
- FRBs **localized** in galaxies by interferometry [3]
- Association of a FRB with a **magnetar**, SGR 1935+2514 [4]



Several graphics showing FRBs. Top left: “Lorimer burst”, first FRB ever discovered by Parkes [1]. Top right: FRB 121102A, first repeater observed by ARECIBO [6]. Bottom left: five other bursts observed by Parkes [5]. Bottom right: FRB 200428A, first and only burst associated to an object, the magnetar SGR 1935+2154 [4].

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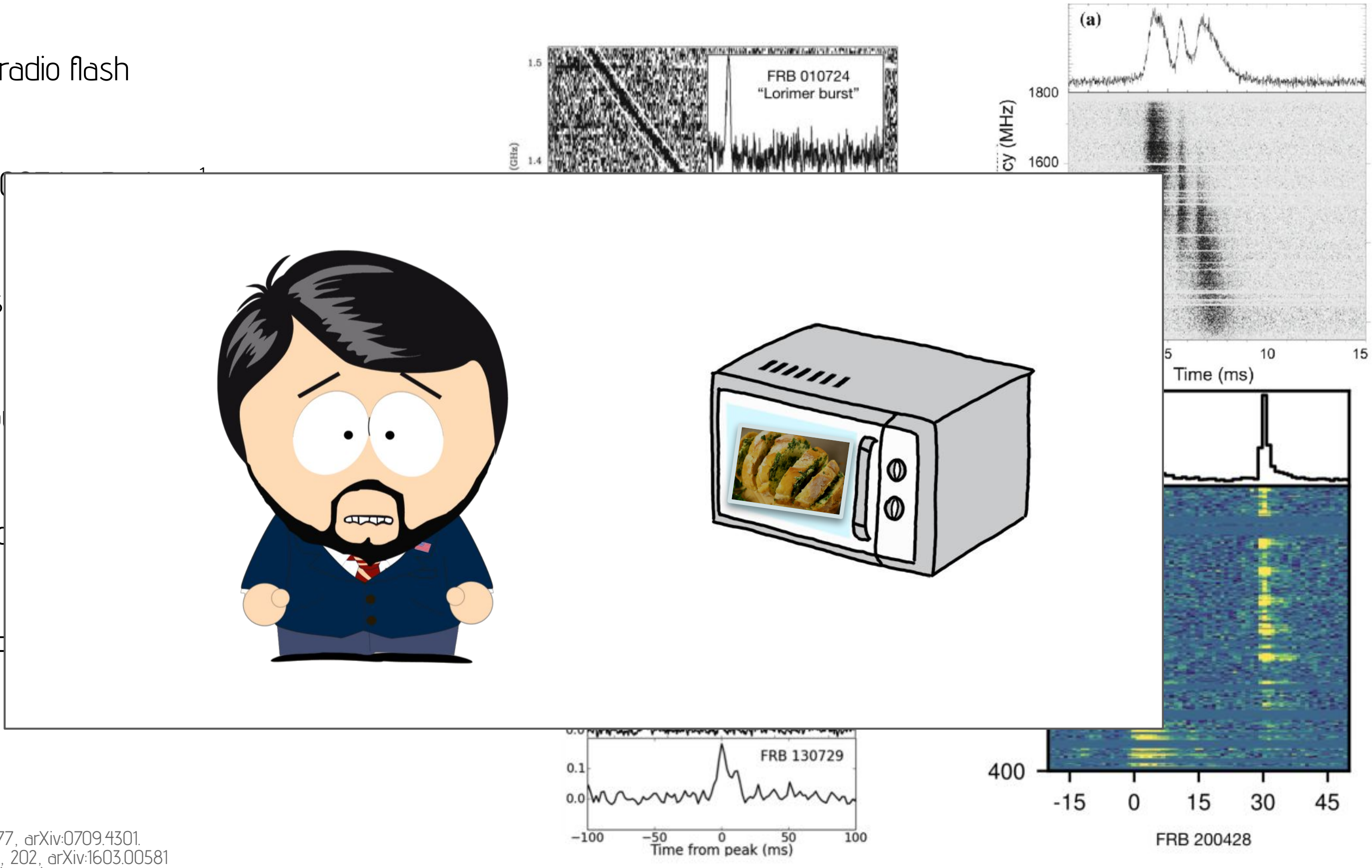
2: Spitler, L. et al. (2016), Nature (London) 531, 202, arXiv:1603.00581
3: Bannister, K. W., et al. (2019), Science 365 (6453), 565, arXiv:1906.11476
4: CHIME/FRB Collaboration,(2020), Nature (London) 587 (7832), 54, arXiv:2005.10324
5: Zhang, B. 2022, The Physics of Fast Radio Bursts. arXiv: 2212.03972
6: Petroff, Emily & Hessels, J. & Lorimer, D.. (2019). AAR, 27. 10.1007/s00159-019-0116-6.

- Bright millisecond radio flash
- First detection in 20
- "Perytons" signals
- First **Repeating** so
- FRBs **localized** in c
- Association of a FR

  SGR 1935+2514 [4]



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Name Fast Radio Burst (FRB)

Observables

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

Duration ~ Millisecond

Traits Large dispersion (DM)

Polarized signal (RM)

Large scattering

Repeating Sometimes

Inferred characteristics

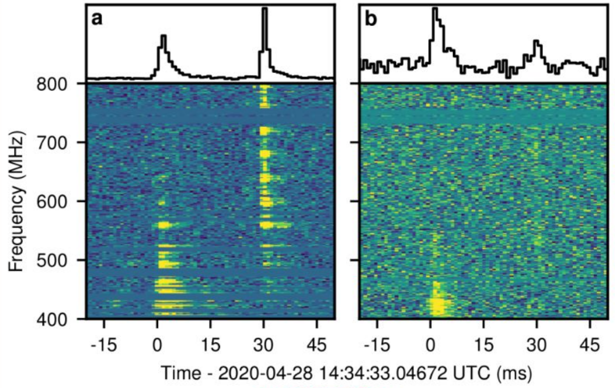
Source Extra-galactic sources

Magnetars (?)

Mechanism Coherent emission

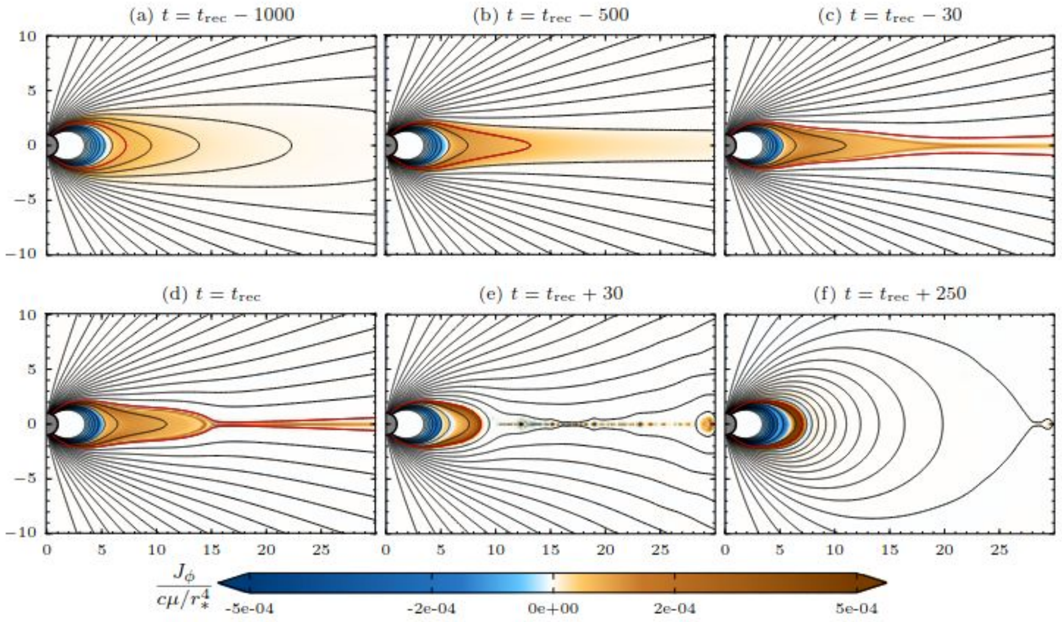
Environment Energetic, dense magnetized, perturbed plasma

Figure from: The CHIME/FRB Collaboration, 2020, arXiv: 2005.1032, https://doi.org/10.1038%2Fs41586-020-2863-y



Seal

- Neutrinos could be produced in magnetars [1,2]
- FRBs and neutrinos are produced by **two mechanisms**
- No **energy estimate** for neutrinos
- No **flux estimate** for neutrinos

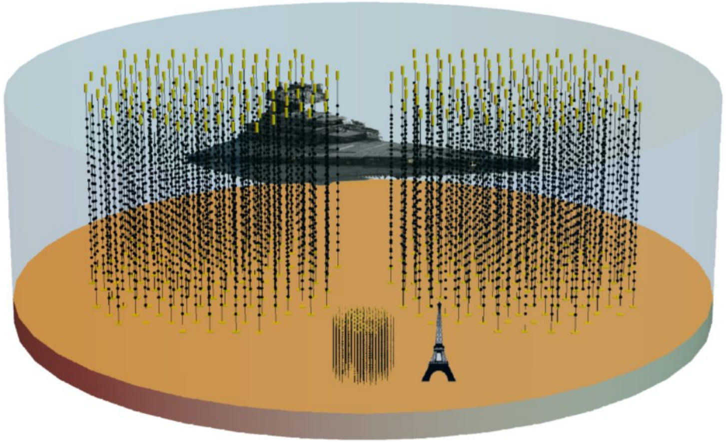


Description of the current sheet formation and magnetic reconnection. The black lines are the field lines, and the color show the toroidal current density. Reconnection begins at t_{rec}, figure (d). From [1]

1: Zhang, B., Dai, Z. G., Mészáros, P., Waxman, E., & Harding, A. K. 2003, ApJ, 595, 346
2: Adrian D. Metzger et al 2020 ApJL 902 L22

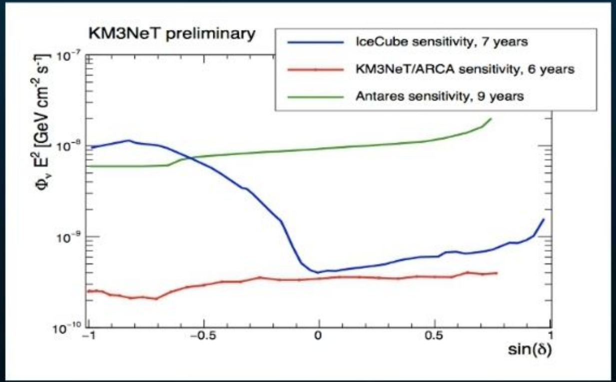
The KM3NeT experiment

- Two Detectors in the Mediterranean Sea: ORCA & ARCA



ARCA and ORCA relative sizes.
Eiffel tower: 330m high ; Star Destroyer from Star Wars: 1600m long

- Oscillation Research with Cosmic in the Abyss
- Astrophysics Research with Cosmic in the Abyss



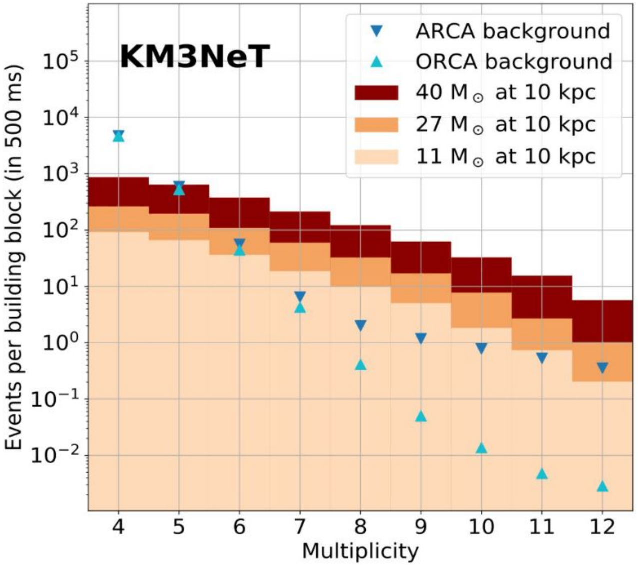
Sensitivity of the KM3NeT-ARCA detector for the discovery of cosmic neutrino sources as function of their declination in the sky

- Detects Čerenkov light from the neutrinos interaction products
- The construction started in 2015
- The largest neutrino detector in the Northern Hemisphere
- Successor of the ANTARES experiment

The KM3NeT expriment

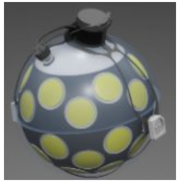
❖ Digital Optical Module (DOM)

- ➢ 31 PMTs ⟹ Redundancy enables:
  - ➢ Hardware failure
  - ➢ Background discrimination
  - ➢ High coverage
  - ➢ SuperNova detection
- ➢ Digitising board
- ➢ Compass, Piezo sensor, …



KM3NeT's DOM performances at the MeV energy:
Event rate for SuperNovae of different masses. A high enough multiplicity enable to observe an excess that can be attributed to a SuperNova. The background (mainly 40K) is dominating for multiplicities below 6 coincidences only. Credit: The KM3NeT Collaboration

- Both ORCA & ARCA are under construction

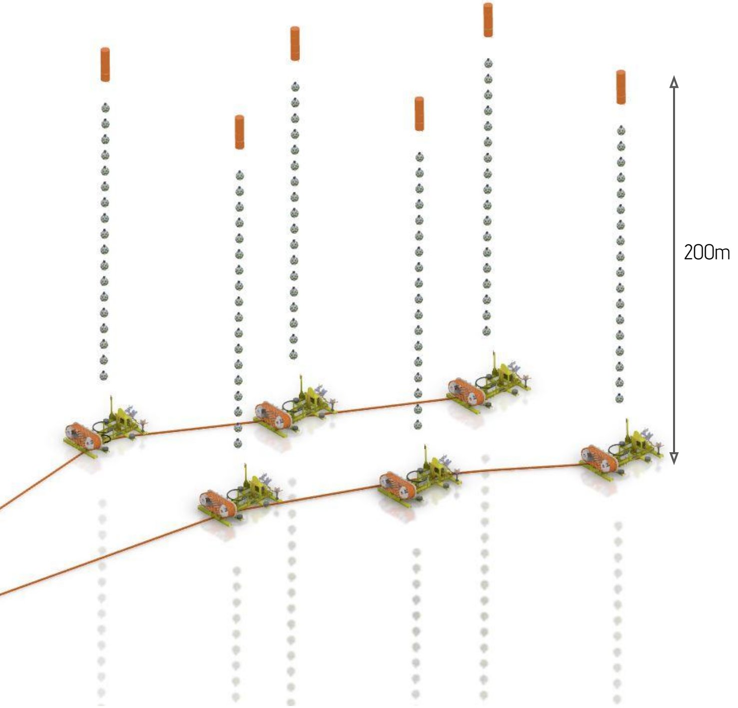


Digital Optical Module

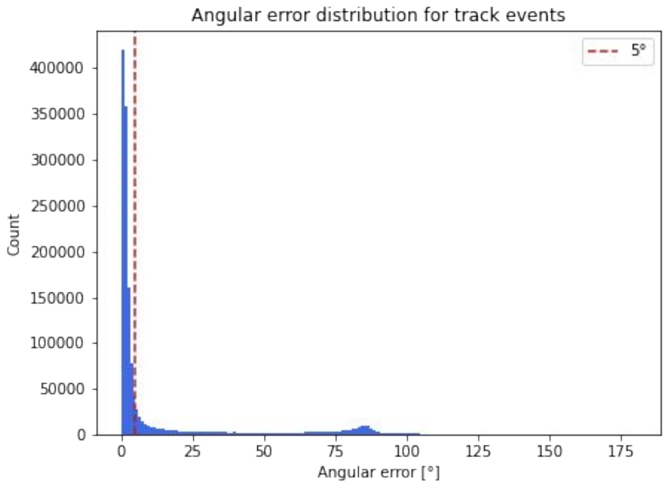
ORCA anchor

Scale
Strings spacing 1:5
Modules spacing 1:10

ORCA6 - 6 lines

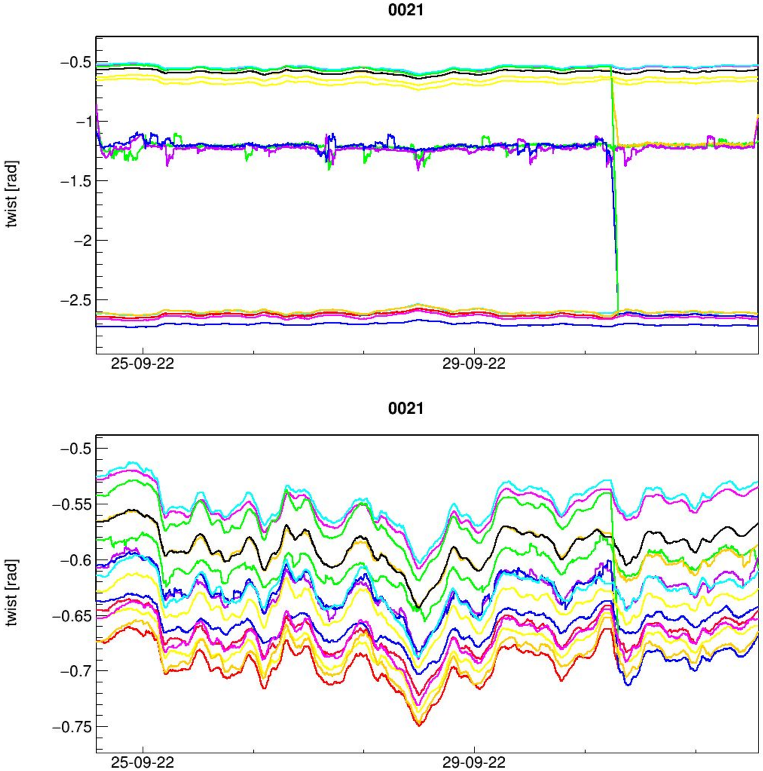


- Detectors have not reached their full potential
- Physics analyses are already possible
- Calibration is needed!



Orientation calibration

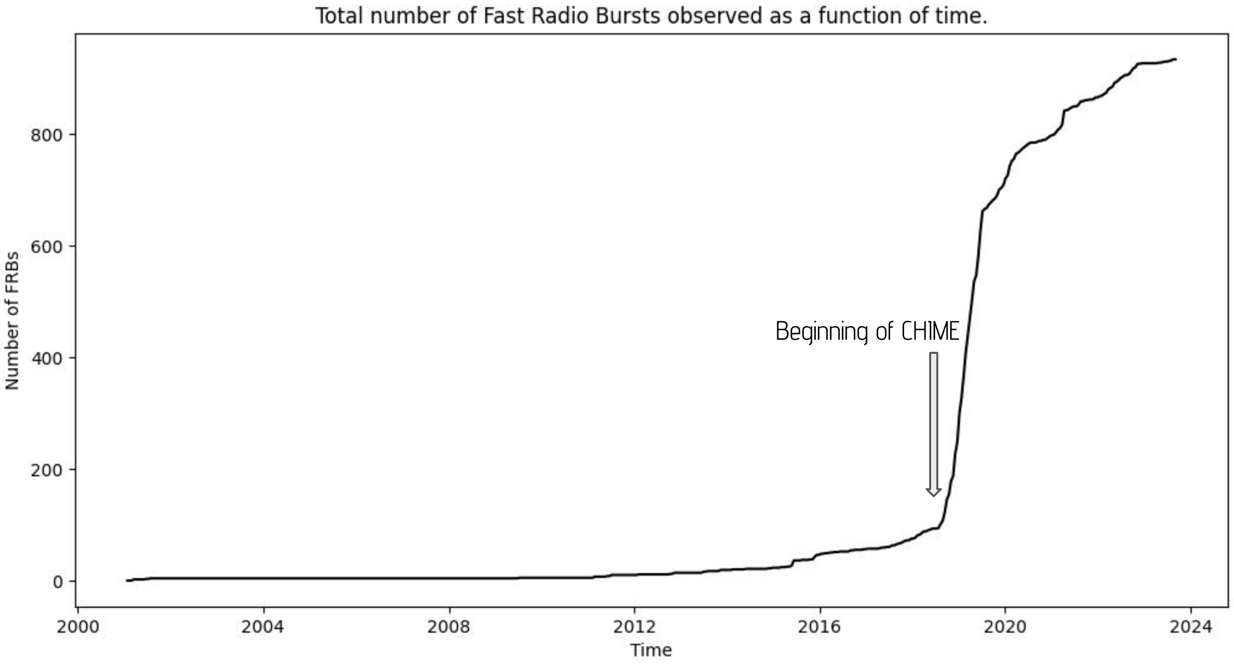
- Aiming 0.1° in angular resolution ⇒ 20cm accuracy in position
- Digital Optical Modules have their positions and orientations fluctuate with sea currents
  - Positioning is realized with acoustic triangulation
  - Orientation is realized with magnetic compasses



Twist evolution of 18 modules of the string n° 21 of ARCA

Fast Radio Bursts

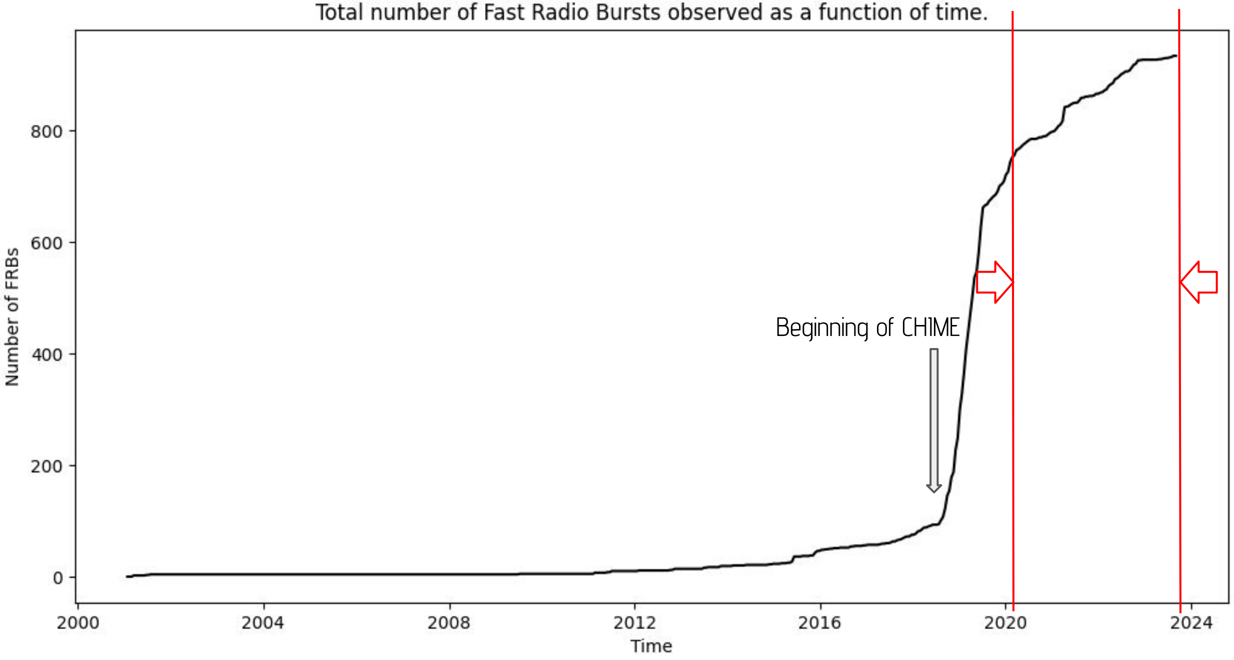
- 900+ bursts detected today



Fast Radio Bursts

- 900+ bursts detected today

Total number of Fast Radio Bursts observed as a function of time.



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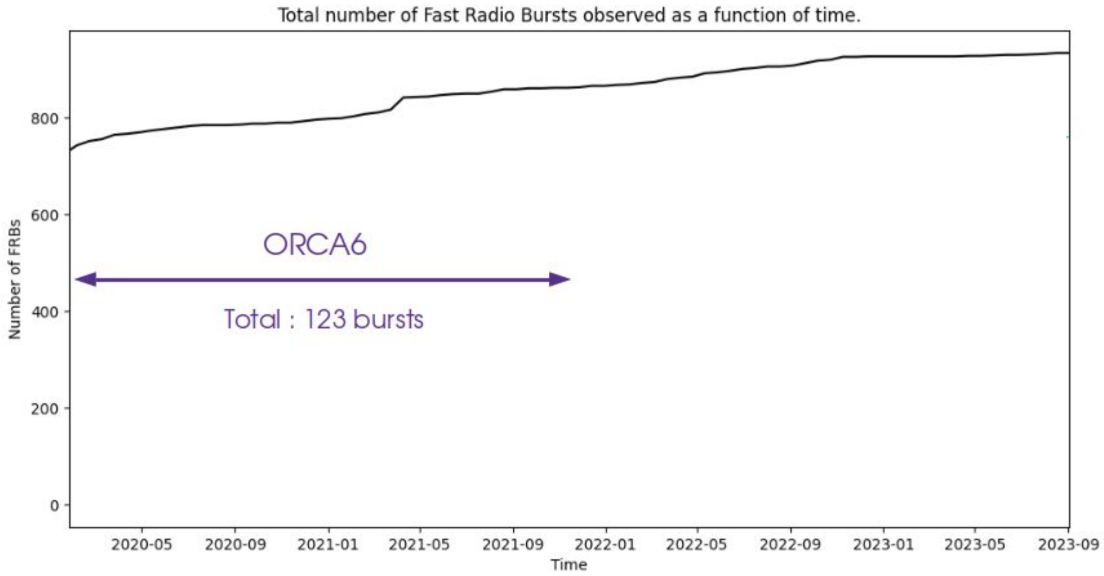

- The Transient Name Server keeps track of all published astrophysical transients
- Many FRBs are discovered by data mining in the radiotelescopes archives, i.e. are not available directly upon detection

Fast Radio Bursts

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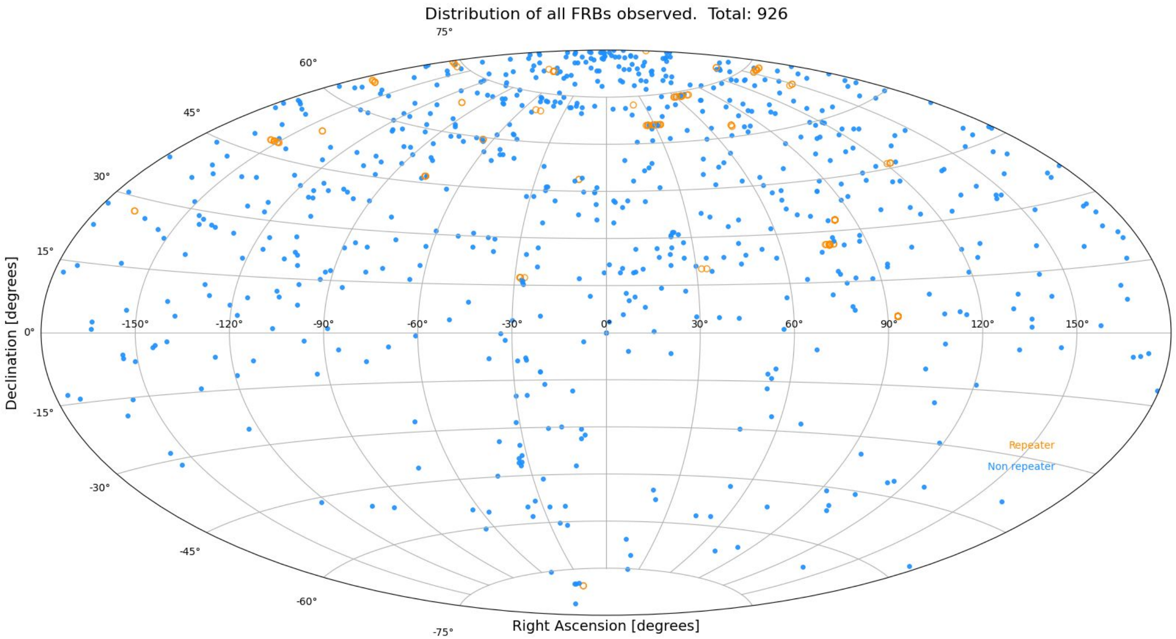
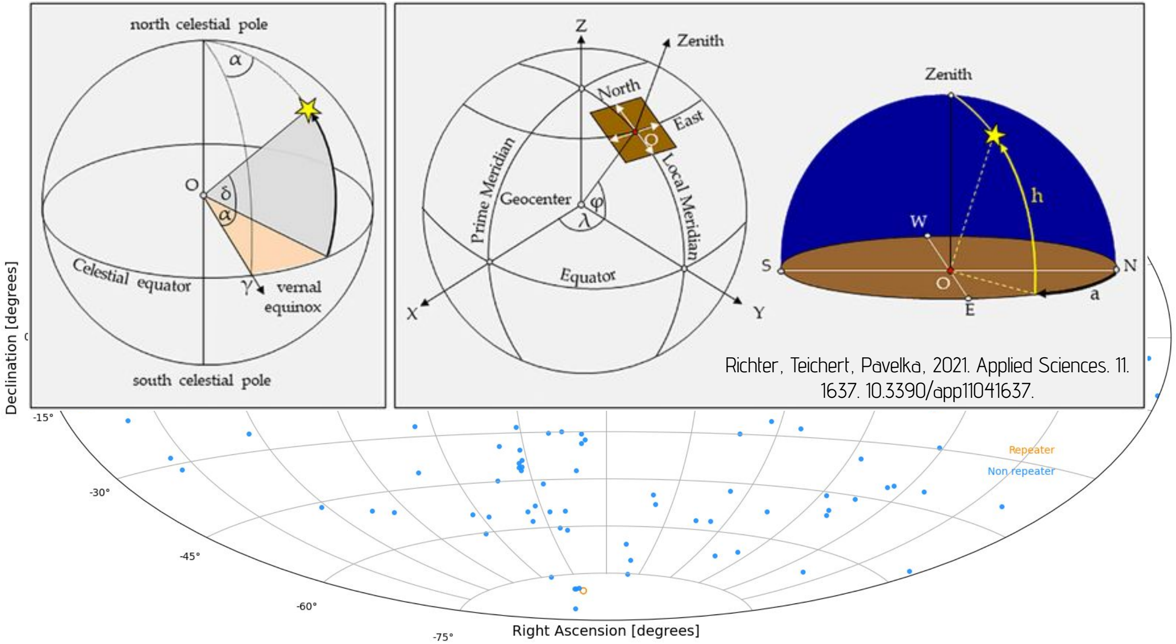


Fast Radio Bursts

- ❖ 900+ bursts detected today

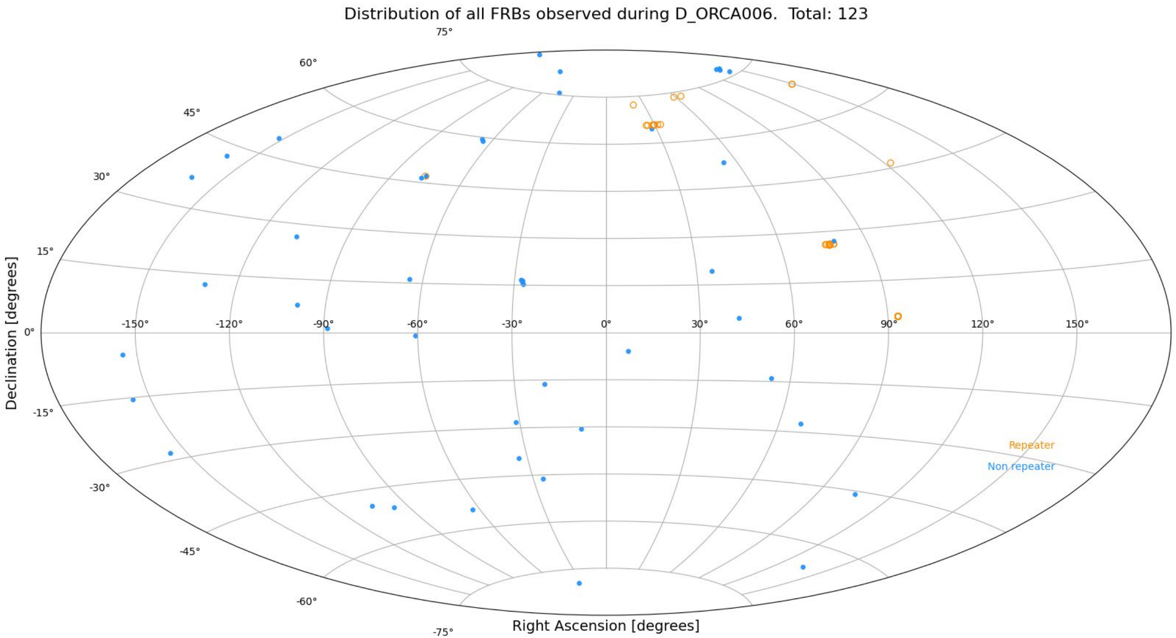
Equatorial — Local



Richter, Teichert, Pavelka, 2021. Applied Sciences. 11. 1637. 10.3390/app11041637.

ORCA6 analysis

- 900+ bursts detected today
- ORCA6 configuration lasts from January 27, 2020 to November 18, 2021
- 123 bursts are left in this 22 month period

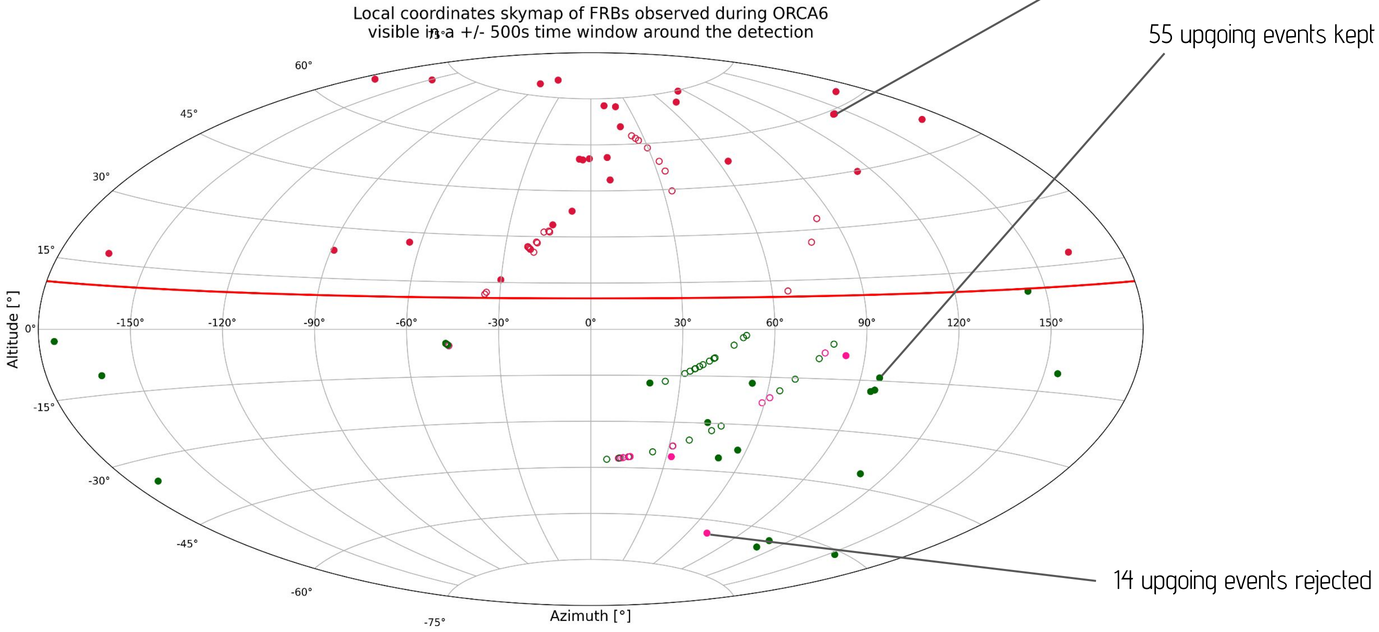


ORCA6 analysis

- 900+ bursts detected today
- ORCA6 configuration lasts from January 27, 2020 to November 18, 2021
- 123 bursts are left in this 22 month period
- 69 bursts are left visible from the ORCA site, for **upgoing events**
- **55 bursts are left** when we take into account the ORCA lifetime

Azimuth-Altitude representation

[-90°, **+10°**] Altitude acceptance



- 38 Bursts from 2 repeaters (FRB 20180301A & FRB 20201124A) and 17 unique bursts

FRB 20200702E	FRB 20210405F	FRB 20210402A	FRB 20210322A	FRB 20210202D	FRB 20201016B	FRB 20210408H
FRB 20200701I	FRB 20210405E	FRB 20210401C	FRB 20210321A	FRB 20210118D	FRB 20200906A	FRB 20210407E
FRB 20200627A	FRB 20210405D	FRB 20210328A	FRB 20210320C	FRB 20210117A	FRB 20210630A	FRB 20210407B
FRB 20200615E	FRB 20210405C	FRB 20210327C	FRB 20210303A	FRB 20201229E	FRB 20210530F	FRB 20210407A
FRB 20200607A	FRB 20210404C	FRB 20210327B	FRB 20210301A	FRB 20201210A	FRB 20210517C	FRB 20210405I
FRB 20200514B	FRB 20210404B	FRB 20210327A	FRB 20210220A	FRB 20201124B	FRB 20210517B	FRB 20210405H
FRB 20200508A	FRB 20210403B	FRB 20210326A	FRB 20210214G	FRB 20201124A	FRB 20210517A	FRB 20210405G
FRB 20200430A	FRB 20210403A	FRB 20210323A	FRB 20210212G	FRB 20201123A	FRB 20210410D	

Hypotheses for this analysis

Known characteristics of FRBs so far

- Dense environments favouring baryon emissions
- **Extra-galactic** signals from **compact** objects
- **Millisecond** duration
- Probably two categories: **repeating** sources and one-off bursts
- No energy or flux estimates

Hypotheses for the first KM3NeT analysis

- **Simultaneous** emission of FRB and neutrino(s) → short Time Window of ±500s
- No guess on **neutrino energy**: possible search in ORCA and ARCA
- All bursts are considered **unique**, even repeaters!

Start with a first analysis:
On/Off Binned Analysis on ORCA6

ORCA6 Analysis Strategy

- Strategy : **ON/OFF binned** analysis
  - The ON region has both the background and source signal
  - The OFF region is used to estimate the background
  - Optimize cuts performed on the event dataset with the Model Rejection Factor [1]
  - Compare the signal rate to the background rate
- Time Window of 1000 seconds : $t_{\nu} \in [\, t_{FRB} - 500\ s \,;\, t_{FRB} + 500\ s \,]$

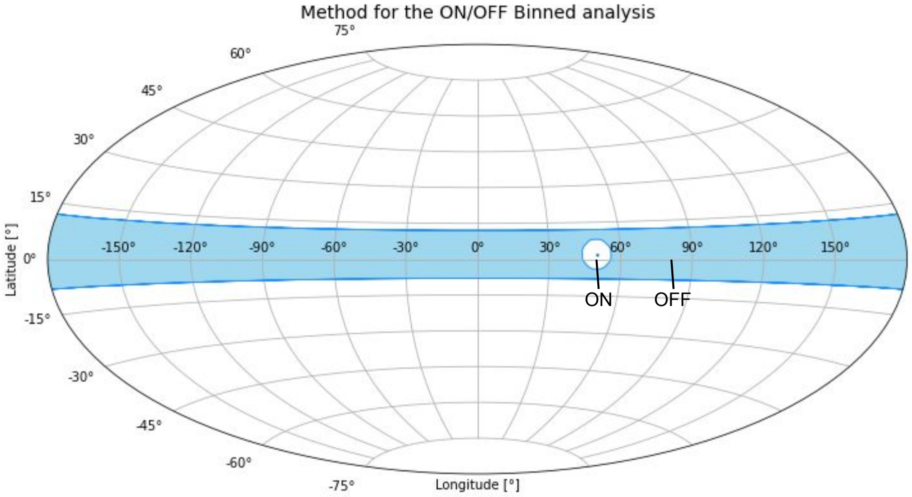
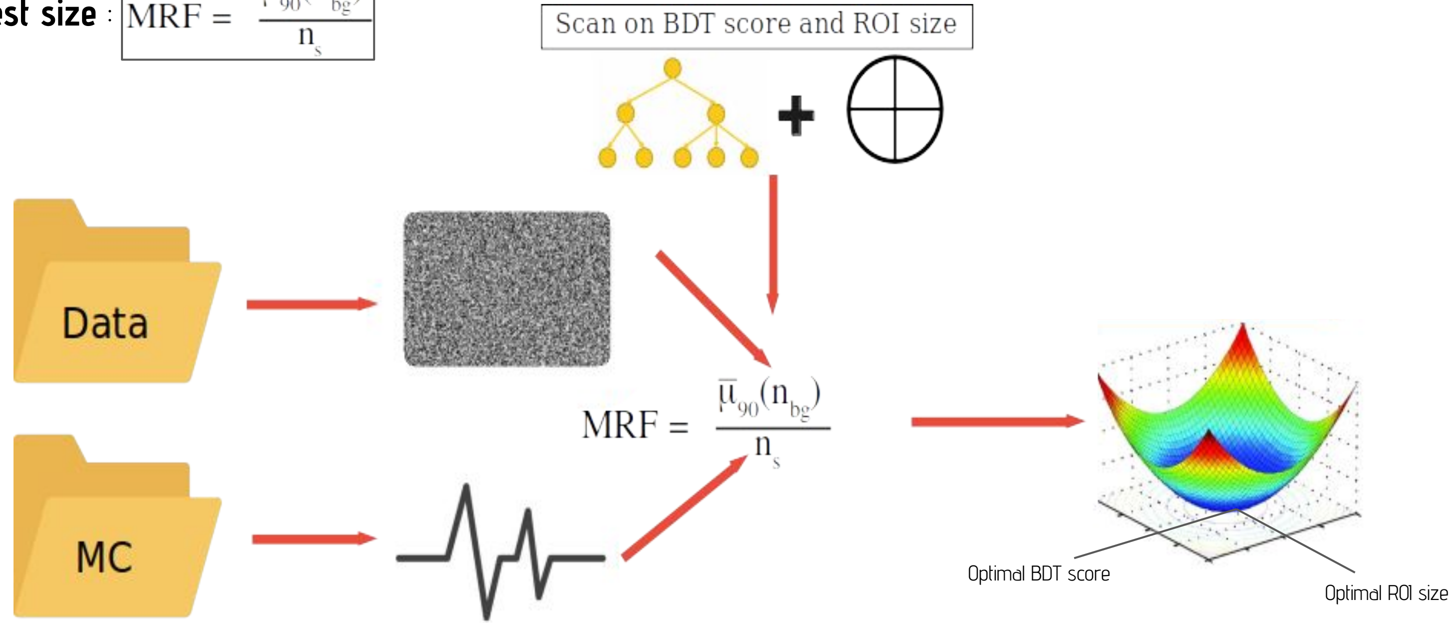


Illustration of the ON/OFF method

ORCA6 Analysis Strategy

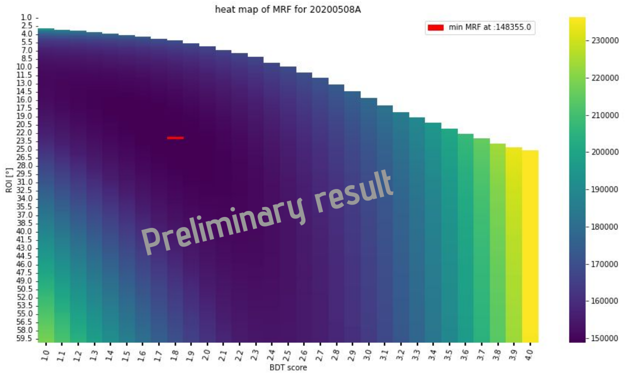
- Background in **elevation band**, from scrambled data of several runs
- Signal from Monte Carlo simulations
- Model Rejection Factor [1,2] used to optimize the two cuts **Boosted Decision Tree score** & **Region Of Interest size** : $\mathrm{MRF} = \frac{\bar{\mu}_{90}(n_{bg})}{n_s}$



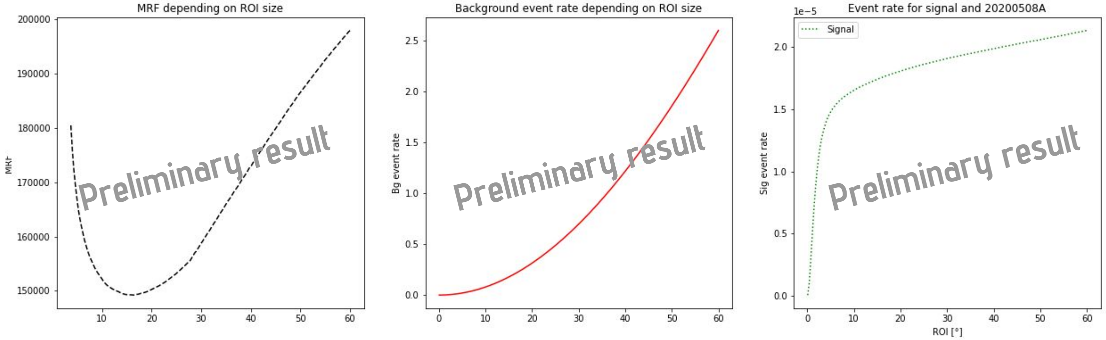
1: Hill, Rawlins, 2003, https://doi.org/10.1016/S0927-6505(02)00240-2
2: Feldman, Cousins, 1997, arXiv:9711021v2

ORCA6 Optimization Results

- Optimization selection: Example of FRB
  - ROI size:
  - BDT score:



Scan on the two parameter space: the BDT score (as 10^{-score}) and ROI size [°]. The color gradient shows the MRF potential. The minimum of the MRF is never reached even after 60° of ROI.

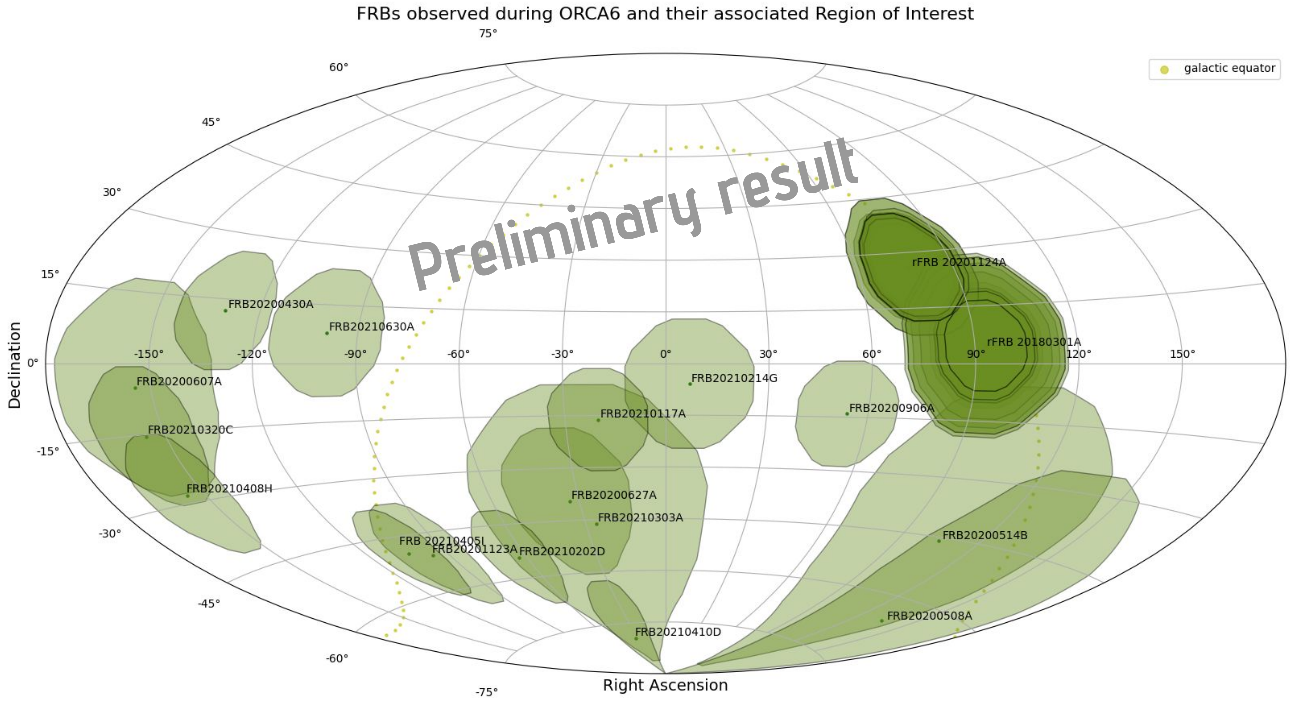


Model rejection potential, expected background and signal in the Region Of Interest. The MRF shows where selected events minimizes the ratio background/signal. The background increases as the square of the ROI but the signal has a less steep increase.

- 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°



Conclusion and Outlook

- A first analysis with 22 months of data is undergoing
  - 55 FRBs are studied in search for neutrino-FRB correlation

- A second analysis to study other periods, with more bursts
  - If we drop the correlation criterion, FRBs outside the period can be studied
  - **Stacked analysis** planned: search in a long period a faint excess of signal coming from all FRB directions. The FRB and neutrino emissions can be uncorrelated

- Refine the models to get more inputs for searches

Thank you for your attention!

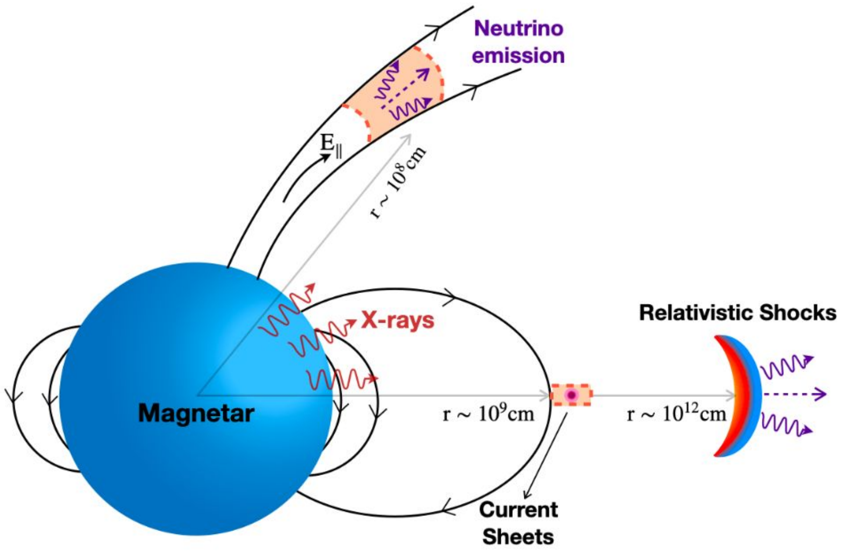


Figure 1. Schematic picture of neutrino production within the magnetosphere, current sheets and relativistic shocks of a flaring magnetar. The purple wiggles or dot (in the case of current sheets) denote the direction of neutrino emission.

Production of both neutrinos & FRB:

⇒ Possible ! ✓

Dense, magnetised, perturbed and energetic plasma

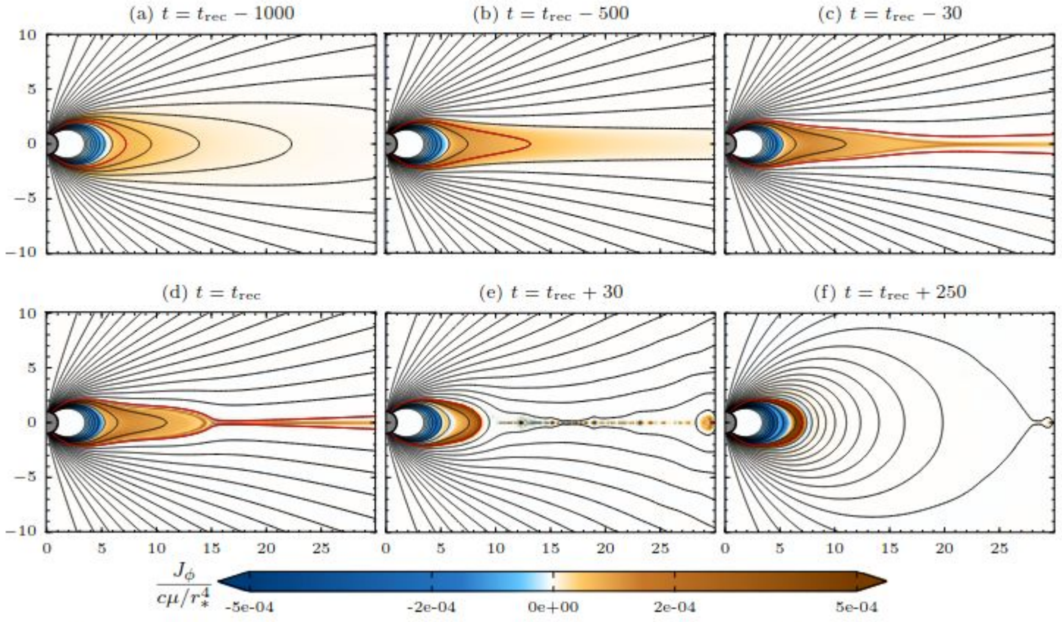
⇒ Decorrelated ! ?

2 different processes :

→ one implying a magnetized environment (FRB);

→ the other a hadron-dense medium (neutrinos)

- Thanks to FRB 200428A, we know one very probable source of FRBs: **magnetars**
- Neutrinos could be produced in magnetars [1,2]
- No **energy estimate** for neutrinos
- No **flux estimate** for neutrinos
- FRBs and neutrinos are produced by **two mechanisms**
- **Repeating sources** constrain models further



Description of the current sheet formation and magnetic reconnection. The black lines are the field lines, and the color show the toroidal current density. Reconnection begins at t_{rec}, figure (d). From [1]

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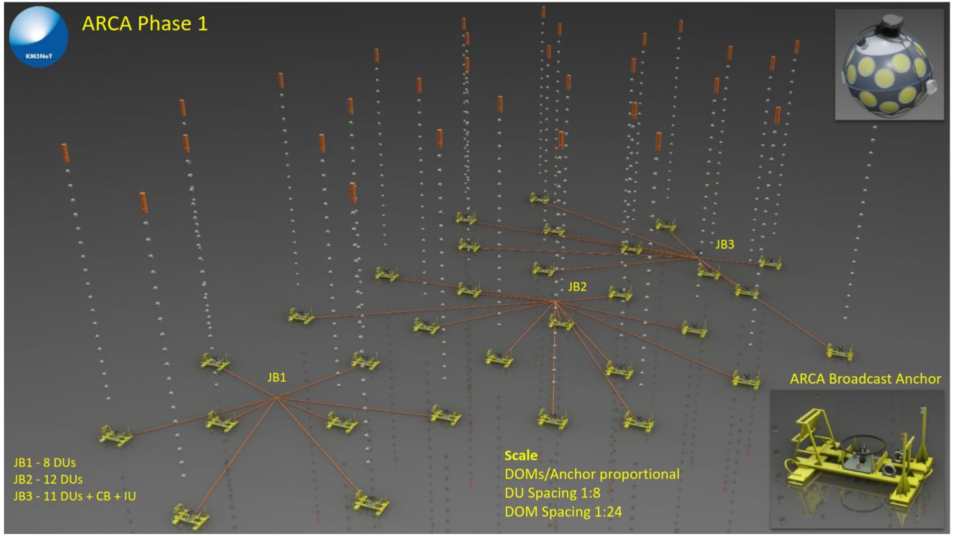

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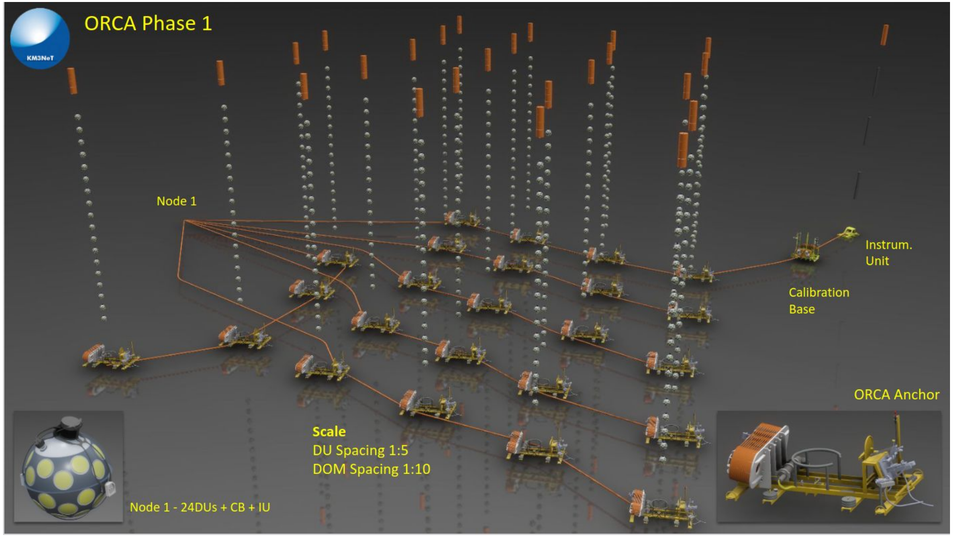
ARCA – 31 lines

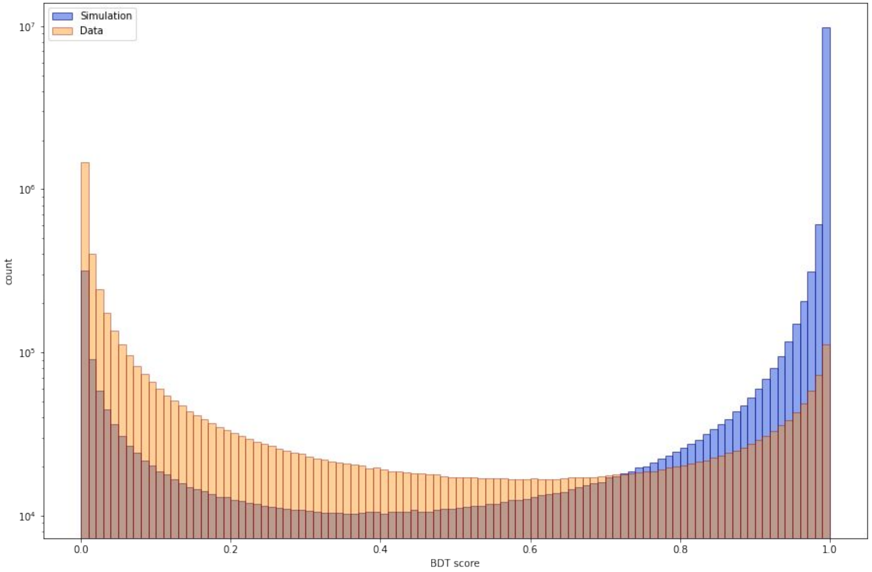
ORCA – 28 lines



BDT

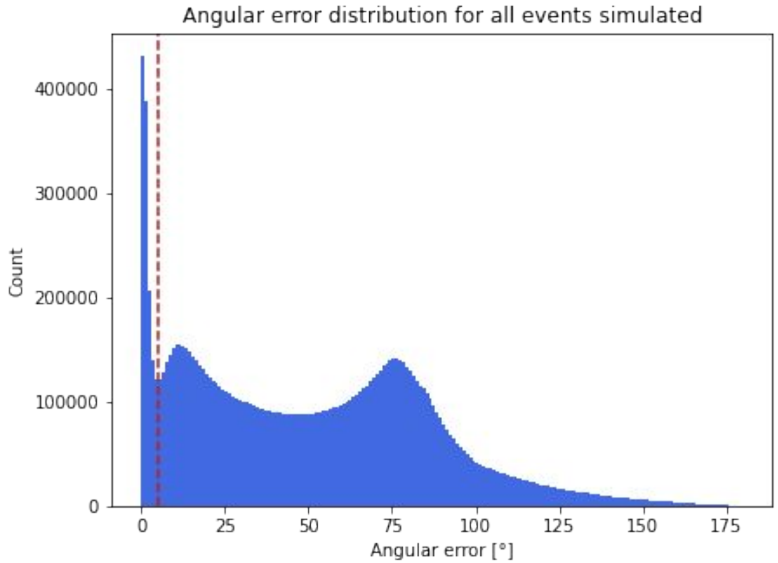
Boosted Decision Tree score

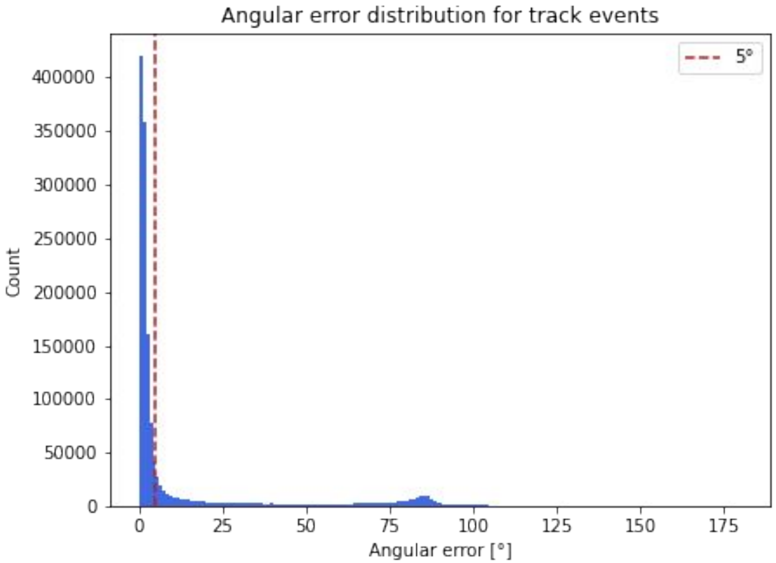
- Data is mainly background, both with shower and track events
- Simulations are neutrinos, all flavours are simulated



Angular error Simulation (ORCA6)

Difference between true neutrino direction and reconstructed neutrino direction





Model Rejection Factor

- Assume a signal flux $\Phi(E,\theta)$
- The average upper limit is the Poisson probability of occurrence:
  - The Feldman-Cousins upper limit is actually the upper limit of the FC confidence interval, that is a modified gaussian confidence interval optimized for low event rate experiments.

$$\bar{\mu}_{90}(n_b) = \sum_{n_{obs}=0}^{\infty} \mu_{90}(n_{obs}, n_b) \frac{(n_b)^{n_{obs}}}{(n_{obs})!} \exp(-n_b)$$

- The number of observed events n_{obs} is not known, so averaged out with sum. The aUL thus only depends on the background rate.
- The strongest constraint on the expected signal flux is the set of cuts that minimizes the ratio $\mu(n_{bg})/n_s$, the so-called MRF
- The final upper limit on the expected signal flux is then:

$$\Phi(E,\theta)_{90\%} = \Phi(E,\theta) \frac{\mu_{90}(n_{obs}, n_b)}{n_s}$$

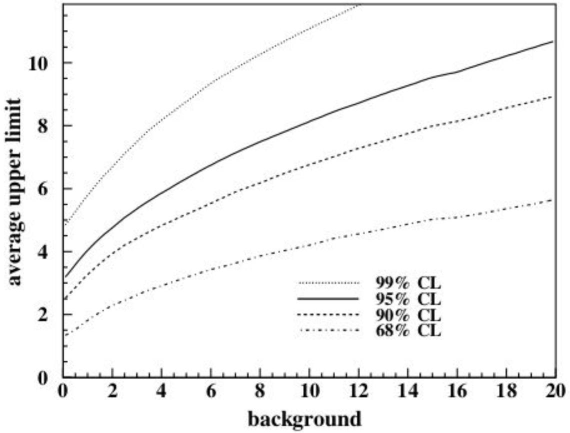


Fig. 1. Average 90% Feldman–Cousins upper limit that would be obtained by an ensemble of experiments with no true signal in the presence of expected background.