The CHIME/FRB VOEvent Service

Real-time Alerts of CHIME Fast Radio Bursts

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Outline

- Overview
- Subscriptions and event handling
- Real-time alerts
- Thresholds, data quality, and performance
- Post real-time alerts
- Conclusion

UNDERLINED WORDS ARE CLICKABLE LINKS!

Overview

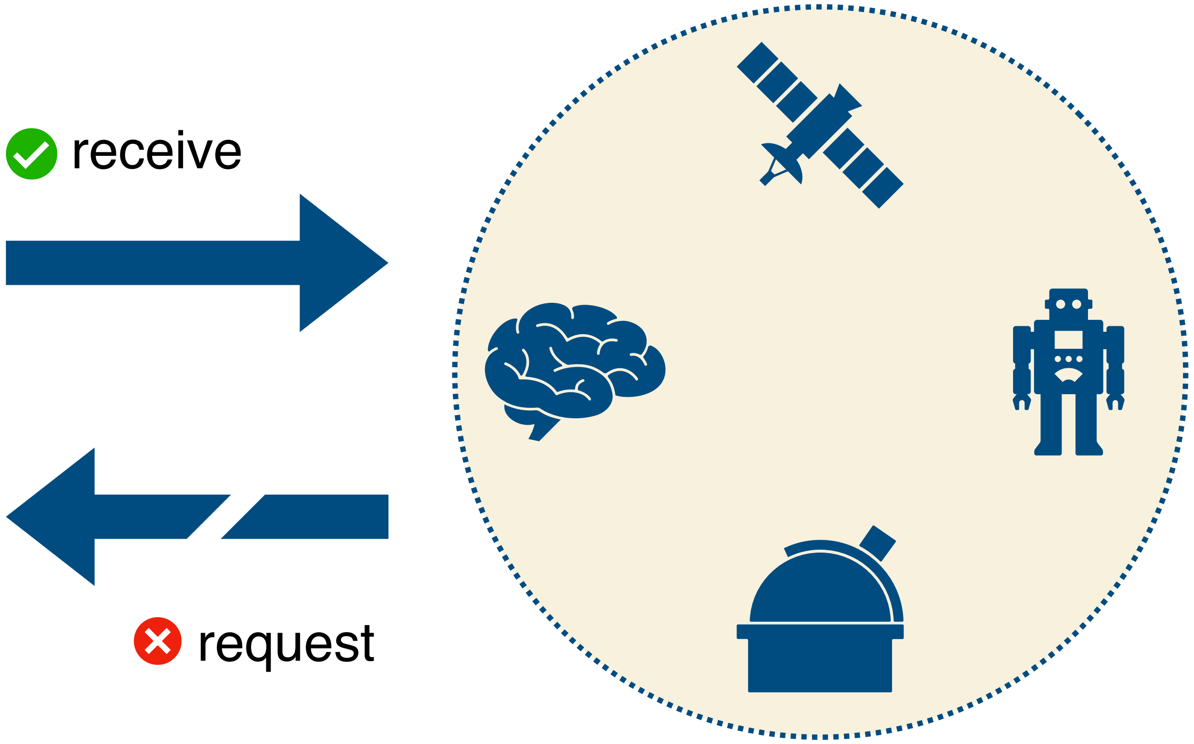
A Push Service

The Service is **push-based**: alerts are delivered to subscribers only once.

Contrast with **pull-based**: alerts cannot be requested from the Service.

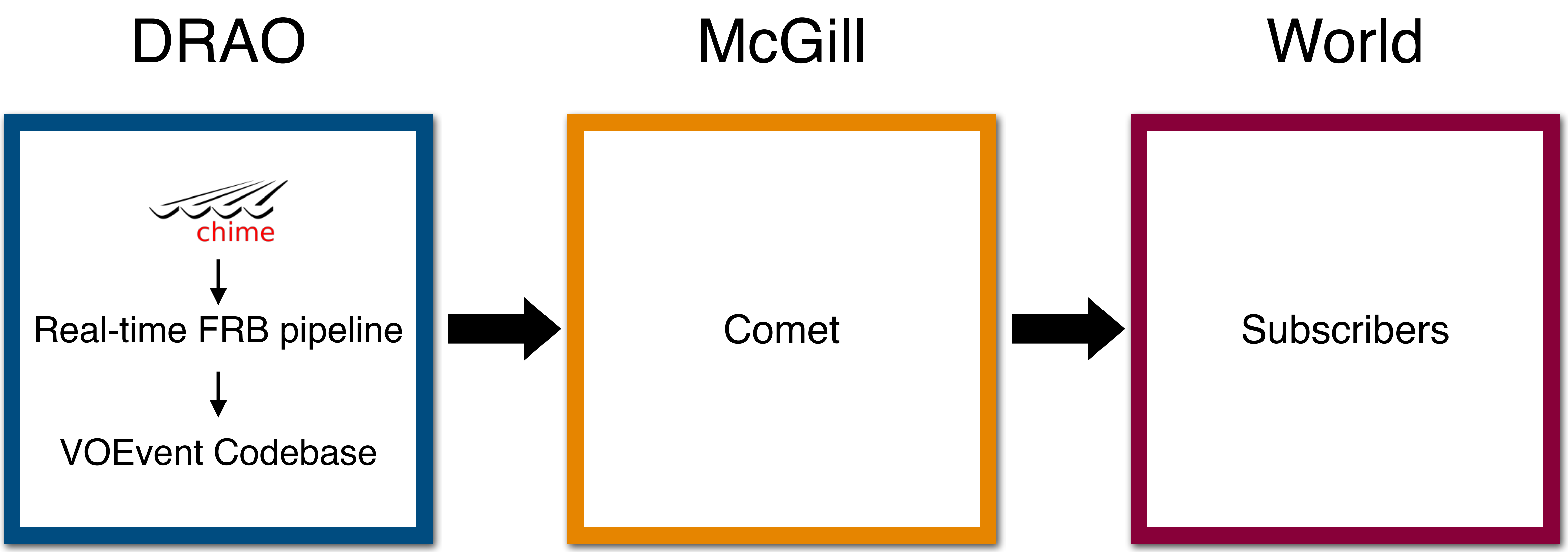
Subscribers must plan their follow-up campaigns to be able to **take action at any given moment** while the Service is live.

Photo credit: CHIME Collaboration



The CHIME/FRB VOEvent Service

The CHIME/FRB VOEvent Service



Subscriptions and Alert Handling

How to Subscribe to the Service

The Service is operated on a subscription basis and all new subscribers must submit basic information to facilitate delivery of VOEvents.

CHIME/FRB will collect user information and store it in a password-protected database located at the CHIME telescope site.

No passwords will be required or collected from the subscriber.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made on the CHIME/FRB public webpage here.

1. Email address

- Email formatted VOEvents may be sent here.
- Changes, interruptions, or other important communications about the service will be sent here.
- Be sure to **check junk/spam folders** frequently to avoid missing important communications from the Service.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made on the CHIME/FRB public webpage here.

2. Name

- Subscriber’s name.
- This individual will be addressed in all email communications about the Service.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made on the CHIME/FRB public webpage here.

3. Institution or affiliation

- The name of the scientific collaboration to which the subscriber belongs; or,
- The name of the academic institution with which the subscriber is associated; or,
- Another recognized collaboration, experimental group, or research body.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made on the CHIME/FRB public webpage here.

4. IP address of a VOEvent broker

- The **public** IP address where the subscriber's VOEvent broker will run.
- Only required if subscriber elects to receive XMLs.
- Use a **static** IP address wherever possible.
- Public IP addresses can be obtained with search engines and at the command line.

```
$ dig +short myip.opendns.com @resolver1.opendns.com

$ dig TXT +short o-o.myaddr.l.google.com @ns1.google.com
```

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made on the CHIME/FRB public webpage here.

5. Flag to receive XML version

- In the subscription process, select “**XMLs**” (or “**both**”) to opt-in for the VOEvent XML.
- The XML It will be delivered to the VOEvent broker with the IP address as specified previously.
- Otherwise, selecting **“emails”** will prevent the subscriber from receiving the XML version of the VOEvent.

How to Subscribe to the Service

Items that will be Stored by CHIME/FRB

Subscription requests can be made on the CHIME/FRB public webpage here.

6. Flag to receive email version

- In the subscription process, select **“emails”** (or **“both”**) to opt-in to the email VOEvent.
- The email VOEvent will be delivered to the email address that was provided previously.
- Otherwise, selecting **“XMLs”** will prevent the subscriber from receiving email VOEvents.

How to Receive CHIME/FRB VOEvents

Getting the machine-readable VOEvent XML

Step 1

Subscription requests can be made on the CHIME/FRB public webpage here.

Step 2

Install a VOEvent broker. **The remaining material assumes use of comet.**

Step 3

Assuming the IP address of the broker has been added to the allow-list, run the broker with the following command:

```
$ twistd -n comet --remote=chimefrb.physics.mcgill.ca
--local-ivo=ivo://test_user/test -print-event
```

Note: take care if copy-pasting the above command! Double dashes “-“ may not render properly in your command prompt.

How to Receive CHIME/FRB VOEvents

Getting the email version of the VOEvent

Step 1

Subscription requests can be made on the CHIME/FRB public webpage here.

Step 2

Emails are sent to the address provided during the subscription process.

Notes

(1) **Monitor spam and junk** folders for messages from chimefrb-voevent-service@googlegroups.com, the dedicated CHIME/FRB VOEvent email agent.

(2) **Do not reply** to emails from chimefrb-voevent-service@googlegroups.com.

(3) Other **news about the Service** may also be sent to your provided email.

How to Parse CHIME/FRB VOEvents

Parsing the machine-readable VOEvent XML

Step 1

Become familiar with comet event handlers (documented here).

Step 2

Use an XML convenience library for extracting VOEvent meta data (voevent-parse).

Step 3

Obtain core CHIME/FRB meta data using a convenience function e.g.

voeventparse.get_grouped_params()

Step 4

Select meta data of interest from the above e.g. DM, SNR, sky location.

How to Parse CHIME/FRB VOEvents

In need of further instruction?

Follow our Jupyter notebook tutorial!

Step 1

Go to the CHIME/FRB Open Data GitHub IO page.

Step 2

Review the Jupyter notebook tutorial.

Step 3

If desired, one can download the Jupyter notebook and associated XML files.

Real-time Alerts

Virtual Observatory Events (VOEvents)

The VOEvent XML Standard is described by the IVOA here.

Key Features

- Machine readable representation of meta data, especially objects.
- Relies on XML, an existing object representation medium for web services.
- Standardizes reports of observations for virtually any domain.

Use Cases

- Gamma-ray Coordinates Network or Transient Alert Network (GCN/TAN) brings together instruments across the electromagnetic spectrum as they coordinate multi-wavelength observations of gamma-ray or X-ray targets with VOEvents.

FRB VOEvents

The FRB VOEvent standard was first defined in Petroff et al. 2017.

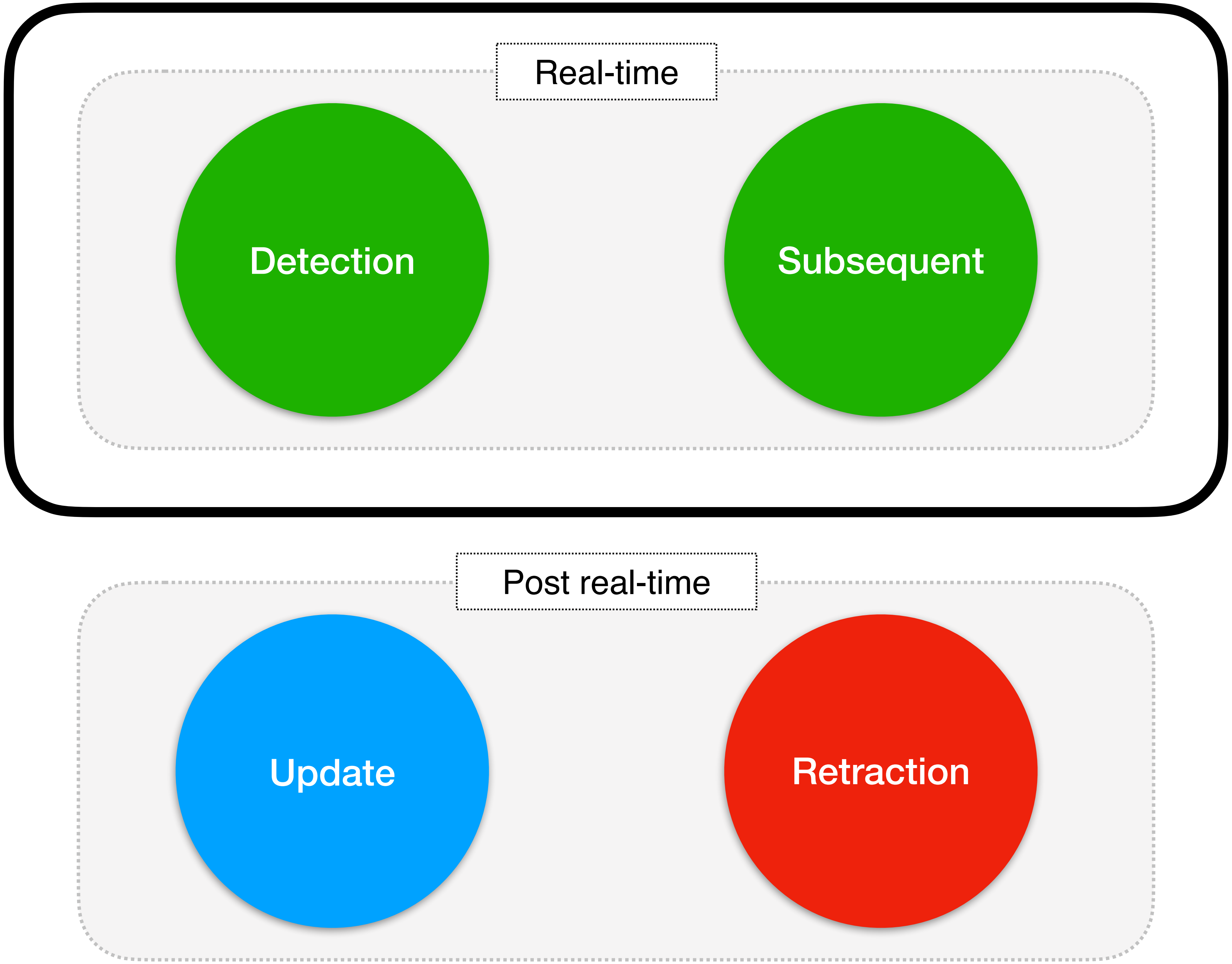
Key Features

- A new medium for reporting FRB observations in a machine-readable format.
- Prescribes four types of VOEvents for FRB observations.

Use Cases

- CHIME/FRB implements all four types, with some modifications and extensions.

CHIME/FRB VOEvents



CHIME/FRB Detection and Alert Criteria

A complete description of the real-time FRB detection pipeline is here [1].

All radio signals reaching the L2-L3 stage are assigned an **event number** and are referred to as Events.

If an Event satisfies the alert criteria it will be published as a VOEvent of one type:

- **Detection**, for a new FRB
- **Subsequent**, for an FRB associated with a known source

The **alert criteria** are:

- SNR >= 10; and
- Not associated with a known Galactic source; and
- Intensity and/or baseband callback data were requested.

Published VOEvents represent a **subset** of all FRB events that are detected and further processed by CHIME/FRB.

VOEvent XML Documents

The VOEvents are text documents styled in XML with a defined structure.

Click the **links** to go to the relevant slides.

Link →
Link →
Link →
Link →
Link →
Link →
Link →

```
<VOEvent […]>
   <Who>[…]</Who>
   <What>[…]</What>
   <WhereWhen>[…]</WhereWhen>
   <How>[…]</How>
   <Why>[…]</Why>
   <Citations>[…]</Citations>
</VOEvent>
```


Jupyter notebook tutorial.

The `<VOEvent>` Section

IVORN

- **I**nternational **V**irtual **O**bservatory **R**esource **N**ame, similar format to a URL/URI, a unique identifying string for every VOEvent that uses ivo:// prefix.
- Example:

`ivo://ca.chimenet.frb/FRB-DETECTION-#2021-08-19-21:50:28.900992UTC+0000_7f17d982b325`

role

- `“observation”` for detections of new or known FRBs.
- `“utility”` for measurement updates or retractions (post real-time).
- `“test”` for fake VOEvents that are meant to test that the Service is working.

Jupyter notebook tutorial.

The <Who> Section

AuthorIVORN

- Shortened IVORN identifying CHIME/FRB as the author of the VOEvent.

Author → contactEmail

- Reach out here for questions about CHIME/FRB VOEvents.

Author → contactName

- Any communications via email can address this CHIME/FRB member.

Date

- Date and time when the VOEvent XML was created.

Jupyter notebook [tutorial].

The <What> Section

Overview

All relevant meta data for the observation is reported here as named parameters.

Values originate from the real-time FRB detection pipeline.

Observatory Parameters
- backend
- bandwidth
- bits_per_sample
- centre_frequency
- npol
- sampling_time
- tsys

Event Parameters
- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

advanced parameters
- dm_gal_ne_2001_max
- dm_gal_ymw_2016_max
- timestamp_utc_inf_freq
- timestamp_utc_inf_freq_error

Jupyter notebook tutorial.

The `<What>` Section

Observatory Parameters

- backend
- bandwidth
- bits_per_sample
- centre_frequency
- npol
- sampling_time
- tsys

backend

- Real-time FRB search backend produced these meta data.

bandwidth

- Nominal CHIME receiving bandwidth is 400 MHz (400 - 800 MHz).

bits_per_sample

- The raw intensity data consists of 16384 frequency channels at 0.983 ms cadence as 8-bit integers.

Jupyter notebook tutorial.

The <What> Section

Observatory Parameters

- backend
- bandwidth
- bits_per_sample
- centre_frequency
- npol
- sampling_time
- tsys

centre_frequency

- Centre observing frequency of the CHIME band, 400 MHz.

npol

- CHIME antennas have 2 polarizations (dual).

sampling_time

- Real-time FRB search resolution is 0.983 ms.

tsys

- CHIME receiver noise temperature is 50 K.

Jupyter notebook tutorial.

The <What> Section

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

dm

- Real-time (`bonsai` [1]) dispersion measure in cm^{-3} pc of the burst.

dm_error

- Real-time (`bonsai` [1]) dispersion measure uncertainty with one of five values: [0.404, 0.404, 0.809, 1.62 , 3.24] cm^{-3} pc.

event_no

- CHIME/FRB internal event number.
- Assigned at L2-L3 in the event registration process.
- Use this in all communications with CHIME/FRB regarding individual VOEvents.

Jupyter notebook tutorial.

The <What> Section

Event Parameters

- dm
- dm_error
- event_no
- event_type
- known_source_name
- pipeline_name
- pos_error_semimajor_deg_95
- pos_error_semiminor_deg_95
- snr
- timestamp_utc
- timestamp_utc_error

event_type

- Real-time event classification based on comparison of DM with Galactic DM estimates.
- EXTRAGALACTIC or AMBIGUOUS.

Extragalactic: $DM - M > 5\sigma$
Ambiguous: $5\sigma \geq DM - M > 2\sigma$
Galactic: $2\sigma \geq DM - M$

where σ is the uncertainty in the DM measurement and M is given by

$$M = \max\{DM_{NE2001}, DM_{YMW2016}\}$$ [1]

Jupyter notebook tutorial.

The <What> Section

Event Parameters

dm
dm_error
event_no
event_type
known_source_name
pipeline_name
pos_error_semimajor_deg_95
pos_error_semiminor_deg_95
snr
timestamp_utc
timestamp_utc_error

known_source_name

- **Subsequent** alerts are published for detections of sources known both internally and publicly.
- The strength of association with the named source is measured by a probability.
- The probability of association with this source is reported in the <Why> section as the <Inference probability="…"> value in [0, 1].
- Some subsequent alerts may be associated with more than one known source; a probability is calculated for each, and only the most probable one is reported in the VOEvent.
- The known source name is either a TNS name, with format FRBYYYYMMDDx, or an internal CHIME/FRB **event number**.

Jupyter notebook tutorial.

The <What> Section

Event Parameters

dm
dm_error
event_no
event_type
known_source_name
pipeline_name
pos_error_semimajor_deg_95
pos_error_semiminor_deg_95
snr
timestamp_utc
timestamp_utc_error

Important!

The error ellipse is not guaranteed to be axis-aligned with the local right ascension and declination directions.

pipeline_name

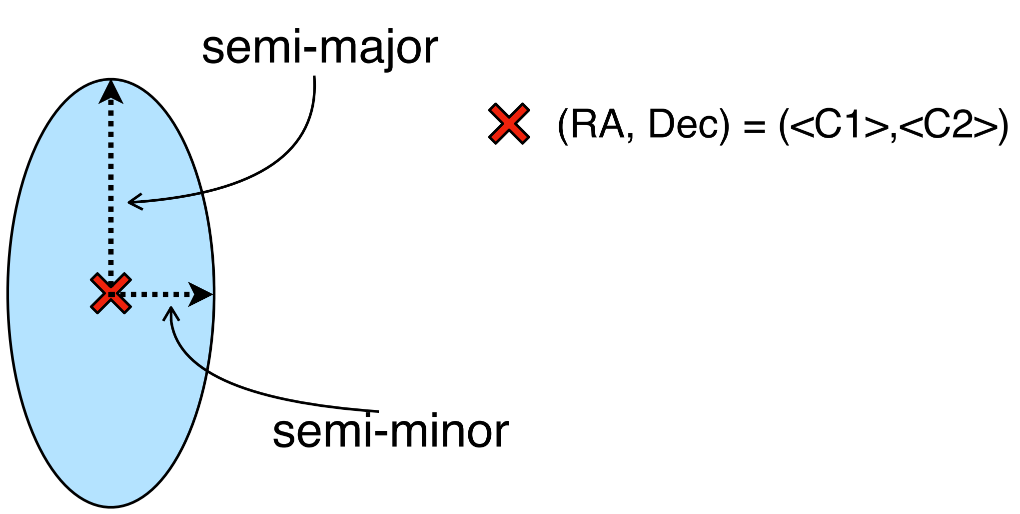
- Name of the pipeline that produced the results published in the VOEvent.

pos_error_semimajor_deg_95

- Error ellipse semi-major axis to 95% confidence in degrees.

pos_error_semiminor_deg_95

- Error ellipse semi-minor axis to 95% confidence in degrees.



Jupyter notebook tutorial.

The <What> Section

Event Parameters

dm
dm_error
event_no
event_type
known_source_name
pipeline_name
pos_error_semimajor_deg_95
pos_error_semiminor_deg_95
snr
timestamp_utc
timestamp_utc_error

snr

- Signal to noise ratio (SNR) of the detection beam.
- In the case of a multi-beam detection, the maximum SNR is reported.

timestamp_utc

- Detection time in UTC at 400 MHz after correction for dispersion, using the DM reported in the event.
- String formatted Pythonic `datetime` object with timezone info e.g. 2021-09-07 12:34:56.789000+00:00

timestamp_utc_error

- Uncertainty in the detection time, propagated from the uncertainty in the DM.
- Float number of seconds.

Jupyter notebook tutorial.

The <What> Section

Advanced Parameters

- dm_gal_ne_2001_max
- dm_gal_ymw_2016_max
- timestamp_utc_inf_freq
- timestamp_utc_inf_freq_error

dm_gal_ne_2001_max

- Maximum Galactic DM along line of sight referenced from the NE 2001 model.

dm_gal_ymw_2016_max

- Maximum Galactic DM along line of sight referenced from the YMW 2016 model.

Jupyter notebook tutorial.

The `<What>` Section

advanced parameters

- dm_gal_ne_2001_max
- dm_gal_ymw_2016_max
- timestamp_utc_inf_freq
- timestamp_utc_inf_freq_error

timestamp_utc_inf_freq

- Detection time in UTC at infinite frequency after correction for dispersion, using the timestamp at 400 MHz, the DM, and

$$k_{DM} = \frac{1.0}{2.41 \times 10^{-4}} \ \mathrm{cm}^3 \cdot \mathrm{s}^{-1} \cdot \mathrm{pc}^{-1} \ [2]$$

- String formatted Pythonic `datetime` object.

timestamp_utc_inf_freq_error

- Uncertainty in the detection time, propagated from the uncertainty in the timestamp at 400 MHz and the uncertainty in the DM.
- Float number of seconds.

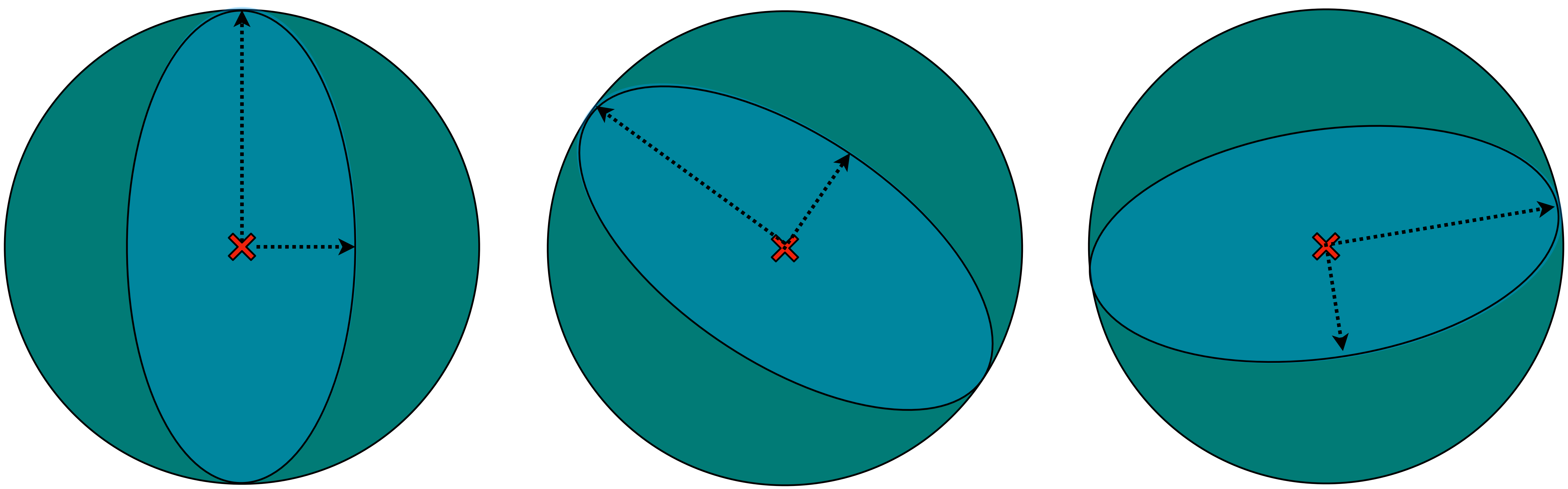
Jupyter notebook tutorial.

The `<WhereWhen>` Section

Spatial (localization and coordinate system) and **temporal** (arrival time) information.

The real-time localization is reported as **a circle in equatorial coordinates**.

An elliptical localization is also available in the <What> section, representing a subset of the circular region (see possible scenarios below).



(RA, Dec) = (<C1>,<C2>) [see Jupyter notebook tutorial]

Jupyter notebook tutorial.

The <How> Section

Currently contains a link to the CHIME/FRB public webpage: chime-frb.ca

As the public webpage evolves and expands, we may publish links to downloadable post real-time data products from the public webpage in the VOEvent.

Jupyter notebook tutorial.

The `<Why>` Section

The VOEvent Standard requires authors to publish an **importance** factor, a number from 0 to 1.

For observations of transient events, the number reflects the confidence in an astrophysical origin: 0 is lowest confidence, 1 is highest confidence.

The CHIME/FRB VOEvent Standard uses a real-time machine learning score from 0 to 1 to indicate this confidence, with an **internal threshold of 0.9.**

Additionally, a **probability** is reported *for subsequent alerts only* to indicate the likelihood of association with a known source.

Only the most likely association is reported, and the known source may be internal to CHIME/FRB or catalogued publicly.

- Integers of (e.g. 60792403, 183253678) are **CHIME/FRB event numbers.**
- Names formatted “FRB YYYYMMDDx” are **TNS names**.

Jupyter notebook [tutorial].

The `<Citations>` Section

All VOEvents are citable in a basic way by their VOEvent IVORN.

Citations contain the VOEvent IVORN for a previous publication.

Subsequent VOEvent
- A **follow-up** observation that cites a previous detection.

Retraction VOEvent
- Offline **retraction** of a previous FRB, either detection or subsequent.

Update VOEvent
- Offline analysis results that **supersede** a previous detection or subsequent.

Jupyter notebook tutorial.

Thresholds, Data Quality, and Performance

Selecting Your Own Thresholds

Parameter	Data Type	Example Scenarios
dm	float	Low-DM targets →
event_type	str	Study AMBIGUOUS events only →
known_source_name	str	Trigger on specific repeating FRBs →
pos_error_semimajor_deg_95	float	Estimate chance coincidence probability for FoV →
pos_error_semiminor_deg_95	float	
snr	float	High-SNR low-DM targets for potentially nearby FRBs →
timestamp_utc	str	Trigger to search for temporal coincidences or afterglows →
timestamp_utc_inf_freq	str	
Right Ascension	float	Trigger on coordinates in observatory FoV →
Declination	float	

Table 1: Example thresholding scenarios for individual CHIME/FRB VOEvent meta data. Note that a general follow-up campaign will likely combine several scenarios into one. (Arrows link to a slide with more details on the parameter.)

Recommended SNR Thresholds

		Alert Type	Tier 1	Tier 2	Tier 3
Rate [day^-1]	FRB Candidates	Detection	0.88	0.94	1.04
		Subsequent	0.16	0.18	0.19
	Non-FRB Candidates	Detection	0.14	0.29	0.34
		Subsequent	0.00	0.00	0.00
			$SNR \geq 12$	$SNR \geq 11$	$SNR \geq 10$

Table 2: Average daily rate of VOEvents published between 17 June 2021 and 2 September 2021 (77 days). The rates are split by those events that were verified as FRBs (true positives) or non-FRBs (false positives) by humans **after** the VOEvent was published.

Alert Latency by Type

A basic latency measurement is defined as the difference in time between detection at 400 MHz and publication to the VOEvent Network.

Additional delays due to Internet traffic and routing between broadcaster and subscriber are **not accounted for**.

	Counts	Average Latency [s]	Standard Deviation [s]
Detection	149	12.42	3.92
Subsequent	19	12.99	3.07

Table 3: VOEvent latency by alert type between 17 Jun 2021 to 2 Sep 2021, reported as average and standard deviation over the 77 day period.

Alert Latency by Verified Class

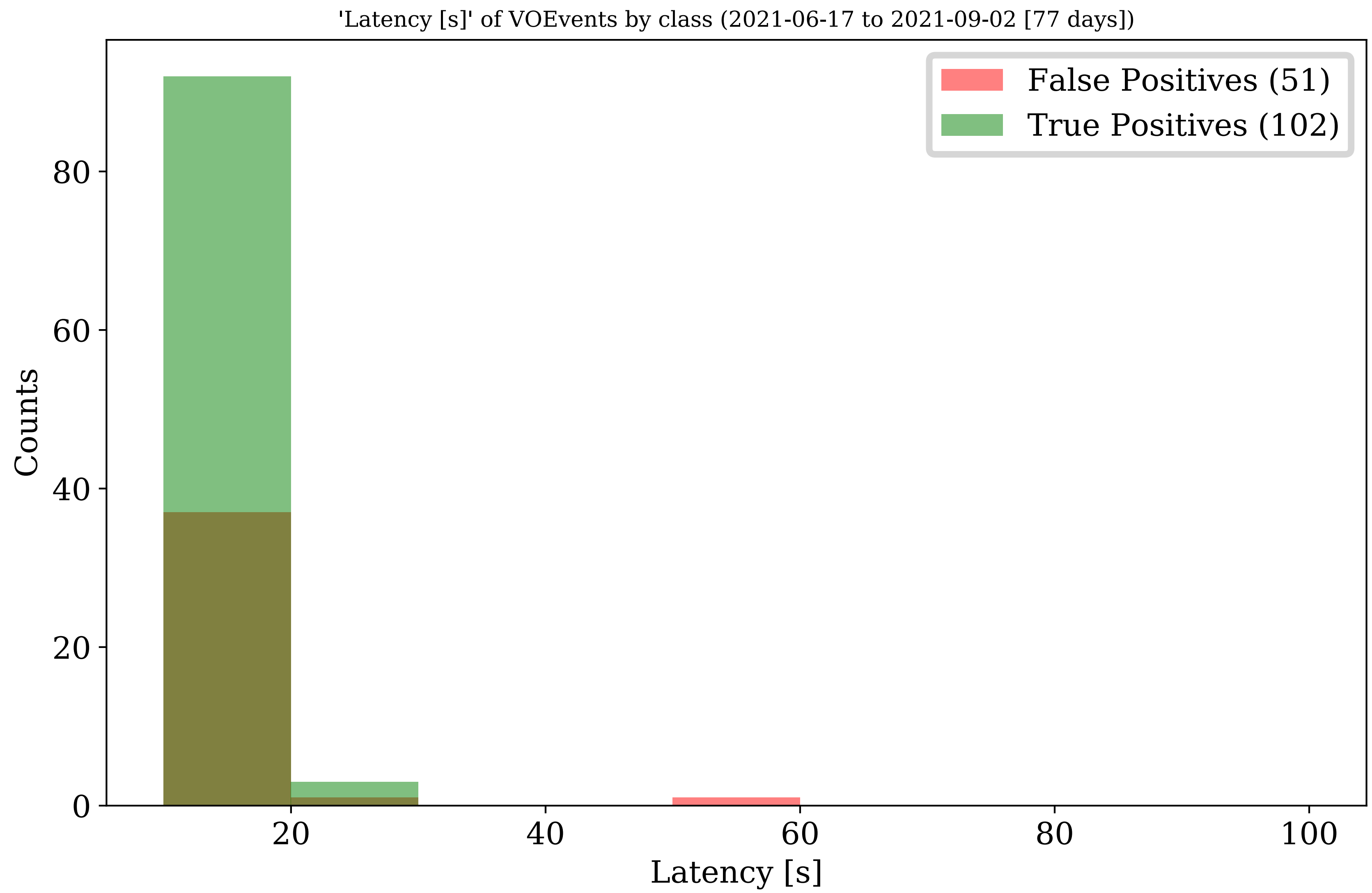


Figure 1: Latency of VOEvents published from 17 Jun 2021 to 2 Sep 2021. Post real-time human verification status is indicated by green for FRB Candidates and red for non-FRB Candidates. Most VOEvents are published with a latency of 10 to 20 seconds with respect to the detection at 400 MHz.

Data Quality

The **importance** value of CHIME/FRB VOEvents is the best available real-time indication of data quality.

The value reflects a score in [0, 1.0] of the real-time machine learning classifier that attempts to distinguish two classes: Astrophysical, and RFI.

Internally a cut of 0.9 is applied before publishing a VOEvent, but subscribers are encouraged to **consider a higher cut of 0.98** to achieve a lower false positive rate.

Data Quality Factors

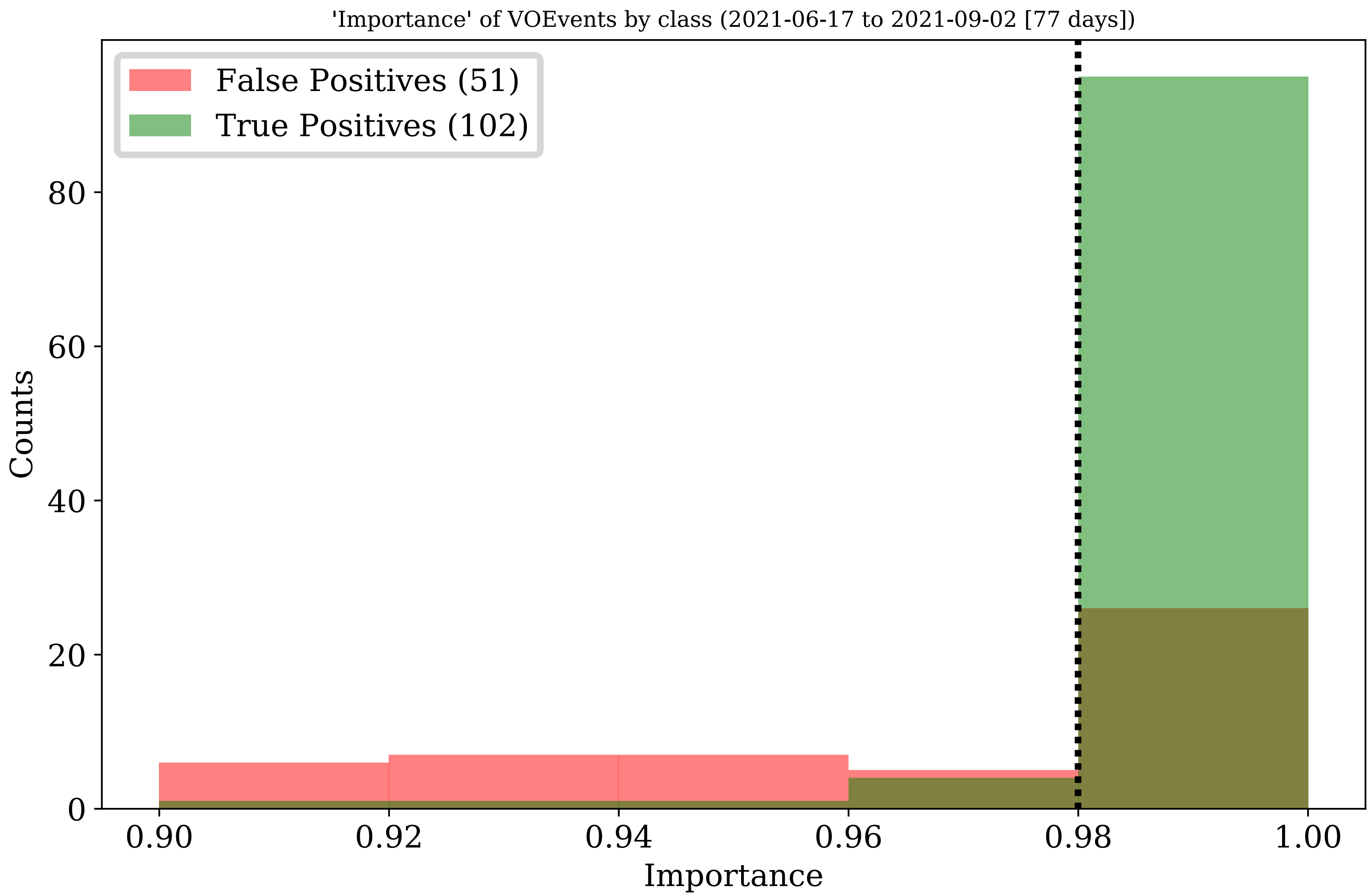


Figure 2: Importance value of VOEvents published from 17 Jun 2021 to 2 Sep 2021. Post real-time human verification status is indicated by green for FRB Candidates and red for non-FRB Candidates.

Misclassifications and False Associations

(1) RFI Contamination

- The real-time machine learning classifier has a non-zero false positive rate.

(2) Galactic Source Contamination

- Uncertainty of Galactic electron density maps (NE2001, YMW 2016).

(3) Incorrect Association with a Known FRB

- An event is detected and associated by chance with a known FRB.
- Tends to be more common for events detected in the $\delta \gtrsim 70°$ regime, related to the fact that CHIME has twice daily sky exposure in this range [2].

Real-time Localization Challenges

Single beam events are published with the sky coordinates of the beam centre.

(1) Side-lobe detection
- Off-meridian sensitivity of formed beams to **very bright events** results in a **side-lobe event**.

(2) SNR clipping
- Very bright multi-beam events lead to **clipping** of the max SNR.
- Clipping confuses the real-time localization algorithm, resulting in potentially bad central coordinates and error region.

Real-time Localization Challenges

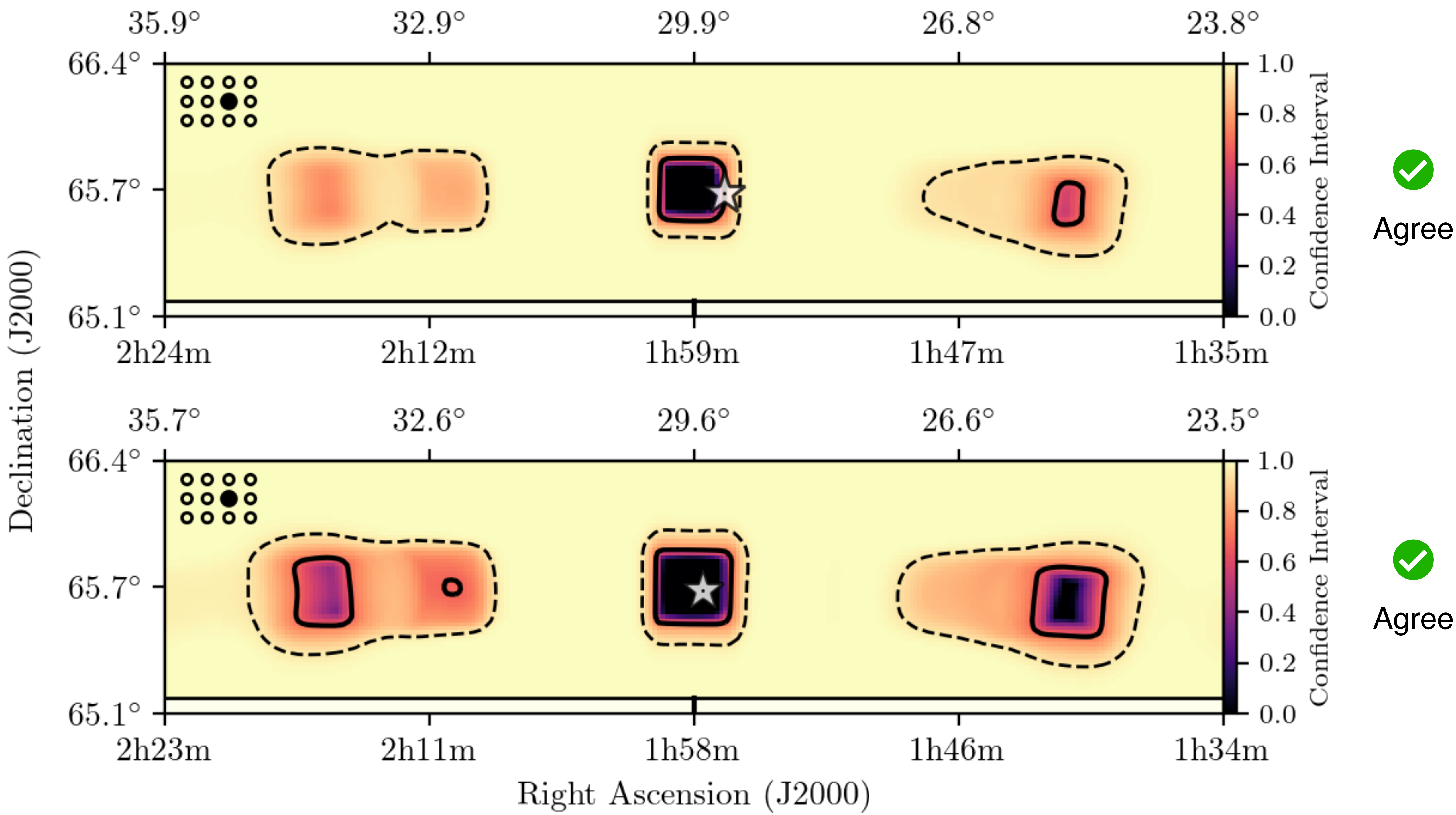


Figure 4: The true location of FRB 20180916B (star) is shown against the detection beam and its first side lobes, for two different events from the source. The method of pulsar analogues was used (see [3]) to produce the χ^2 surface and the 68% (solid) and 95% (dashed) confidence contours. The beam detection pattern is shown in the top left of each subplot. The beam centre is indicated by the black tick along the horizontal axis. The star and the black tick agree, indicating an accurate real-time localization. Figure courtesy of A. Josephy.

Real-time Localization Challenges

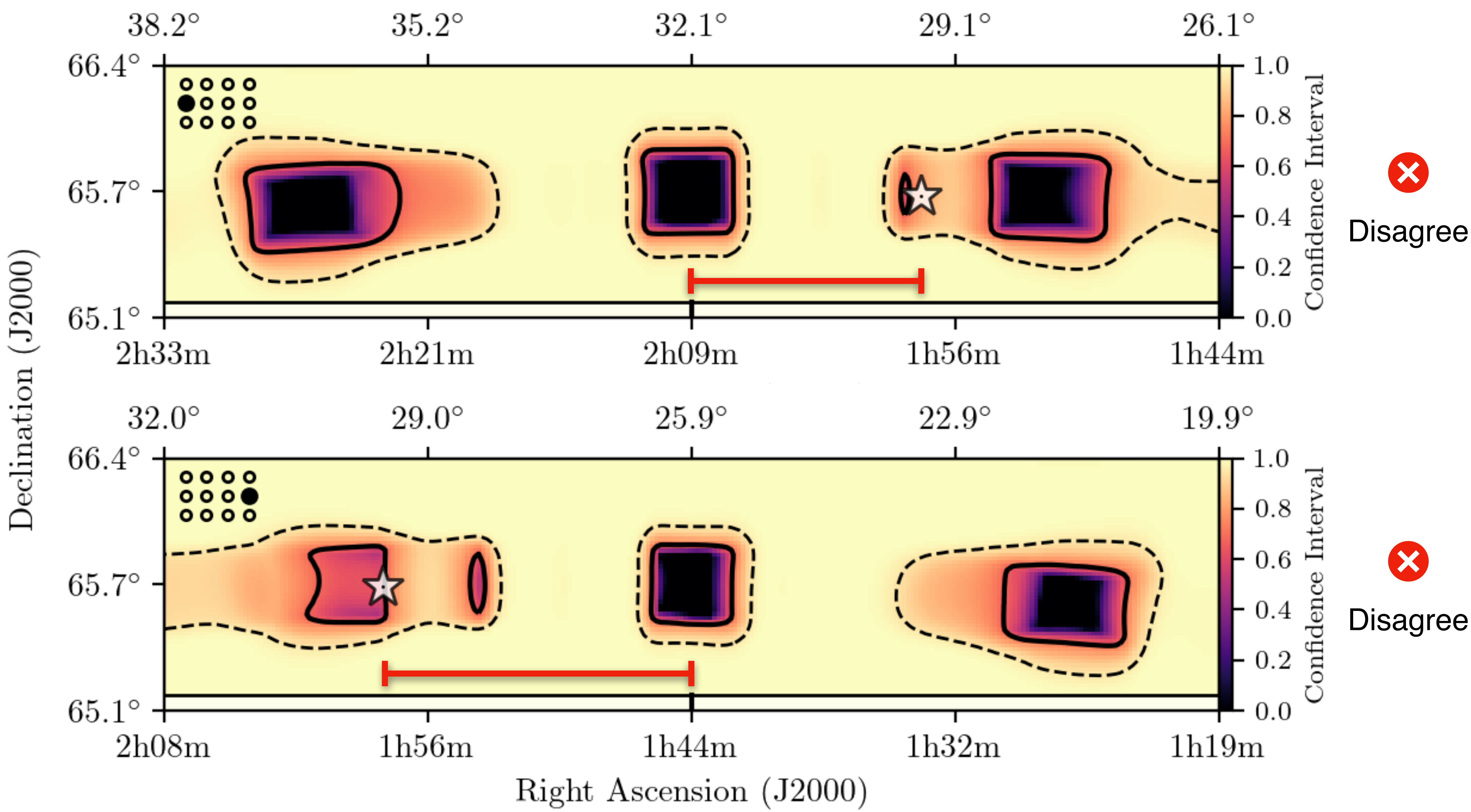


Figure 5: The true location of FRB 20180916B (star) is shown against the detection beam and its first side lobes, for two different events from the source, with contours colour scale, and all markings as in **Figure 4**. The disagreement between the star and black tick point to a side lobe detection. Figure courtesy of A. Josephy; see [3] for more details.

Service Outages and Downtime

Interruptions to the VOEvent Service should be expected and all follow-up observers should **design campaigns** with this consideration in mind.

Notifications of prolonged outages will be provided on a **best-effort basis via email** to the address provided during the subscription process.

Be sure to monitor **junk/spam** for important notices.

Upstream

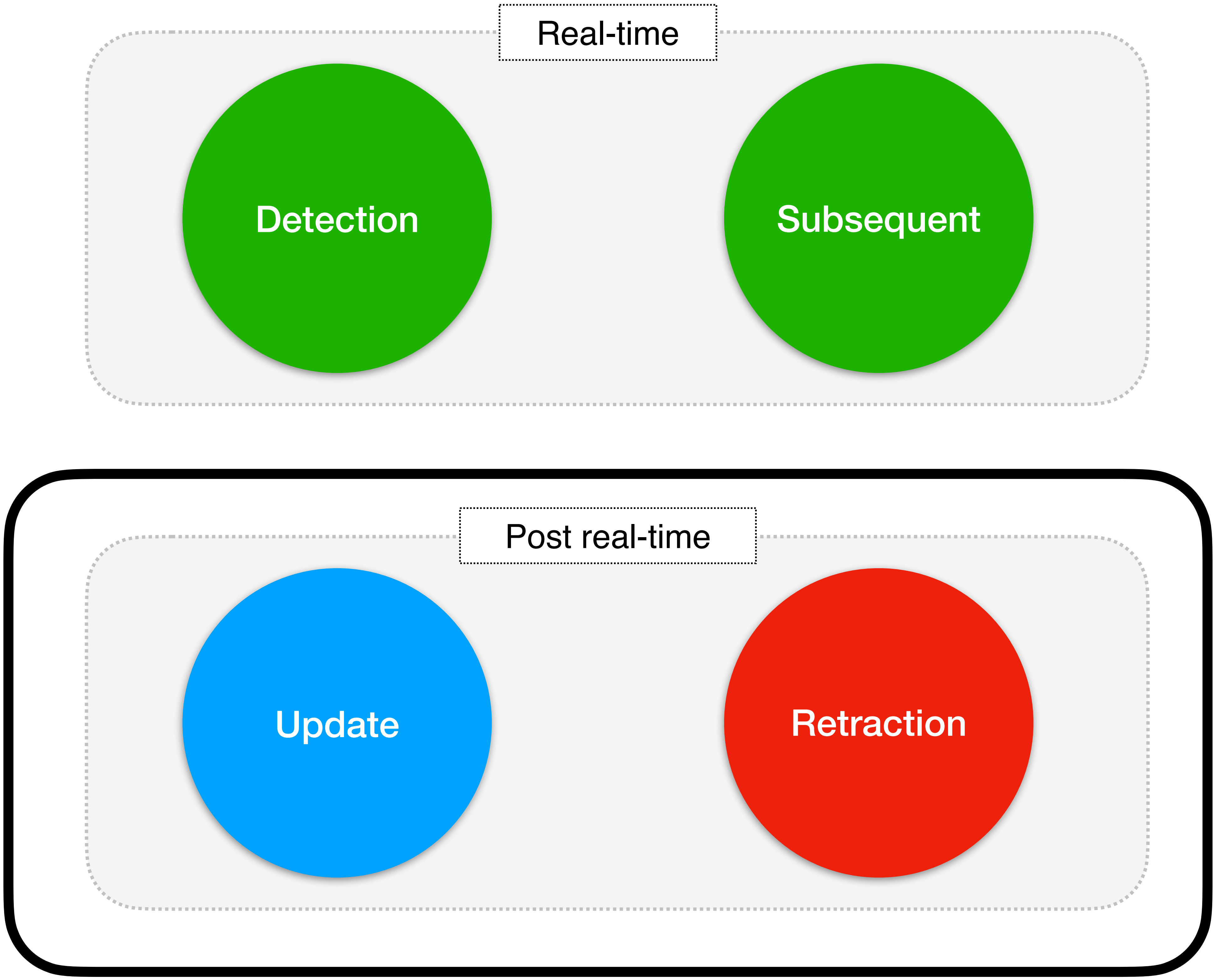
- CHIME telescope up-time fluctuations:
  - Unplanned power or network loss
  - Planned upgrade cycles

Downstream

- McGill Comet broker up-time fluctuations:
  - Unplanned power or network loss
  - Planned upgrade cycles

Post Real-time Alerts

CHIME/FRB VOEvents



Real-time Alerts may be Retracted

Detection and subsequent VOEvents are subject to **retraction**, issued once per day.

Refer to the Jupyter notebook tutorial for further details.

The subscriber should **forego** planned follow-up of retracted alerts.

Retraction Scenarios

1. False positive due to RFI contamination
   - RFI mitigation is not perfect and is under iterated improvement.
2. Mis-association with known source (Galactic, or FRB)
   - Side lobe detections of bright pulsars e.g. the Crab Nebula pulsar.
   - Higher chance coincidence probability in certain sky regions ($\delta \gtrsim 70^\circ$ [2]).

Real-time Alerts may be Updated

The following represent **future enhancements** to the VOEvent Service.

Latency is hard to estimate but could be hours to days.

Update VOEvent #1: Transient Name Server (TNS) object name
- Published after successful submission to the TNS.

Update VOEvent #2: Miscellaneous post-processing analysis
- Maximum redshift from Macquart relation.
- Chance coincidence probability.

Update VOEvent #3: Intensity analysis
- Data products from analysis of the dynamic spectrum and intensity localization.

Update VOEvent #4: Baseband analysis
- Data products from analysis of the raw voltages and baseband localization.

Conclusion

Summary

Questions that have been addressed in this presentation include:

1. What is the CHIME/FRB VOEvent Service?
2. How can I connect to the Service?
3. Where can I access additional help resources?
4. What is a VOEvent? What is an FRB VOEvent? How is CHIME/FRB using them?
5. What information is contained in a CHIME/FRB VOEvent?
6. I received a VOEvent from CHIME/FRB; how do I extract information from it?
7. How can I place thresholds on VOEvents that are meaningful for my follow-up campaign?
8. What thresholds does CHIME/FRB recommend for data quality?
9. How long will it take for me to receive a VOEvent after an FRB is detected?
10. I received a VOEvent from CHIME/FRB; how do I know if its a real FRB or not?
11. How accurate and precise are the localizations published in real-time VOEvents?
12. I have not received a VOEvent in a while; is there a problem with the Service?
13. What is next for the Service?

Stay Tuned for More!

Photo credit: CHIME Collaboration

McGill · University of Toronto · UBC The University of British Columbia · NRC · CNRC DRAO · PI Perimeter Institute · MIT · NRAO · West Virginia University

References

[1] CHIME/FRB Collaboration, M. Amiri, K. Bandura, P. Berger, M. Bhard- waj, M. M. Boyce, P. J. Boyle, C. Brar, M. Burhanpurkar, P. Chawla, J. Chowdhury, J. F. Cliche, M. D. Cranmer, D. Cubranic, M. Deng, N. Denman, M. Dobbs, M. Fandino, E. Fonseca, B. M. Gaensler, U. Giri, A. J. Gilbert, D. C. Good, S. Guliani, M. Halpern, G. Hinshaw, C. Ho¨fer, A. Josephy, V. M. Kaspi, T. L. Landecker, D. Lang, H. Liao, K. W. Ma- sui, J. Mena-Parra, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. L. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei Ravandi, S. M. Ran- som, A. Renard, P. Scholz, K. Sigurdson, S. R. Siegel, K. M. Smith, I. H. Stairs, S. P. Tendulkar, K. Vand erlinde, and D. V. Wiebe. The CHIME Fast Radio Burst Project: System Overview. The Astrophysical Journal, 863(1):48, August 2018.

[2] Manchester and Taylor, 1975.

[3] CHIME/FRB Collaboration, B. C. Andersen, K. Bandura, M. Bhard- waj, P. Boubel, M. M. Boyce, P. J. Boyle, C. Brar, T. Cassanelli, P. Chawla, D. Cubranic, M. Deng, M. Dobbs, M. Fandino, E. Fonseca, B. M. Gaensler, A. J. Gilbert, U. Giri, D. C. Good, M. Halpern, A. S. Hill, G. Hinshaw, C. H¨ofer, A. Josephy, V. M. Kaspi, R. Kothes, T. L. Landecker, D. A. Lang, D. Z. Li, H. H. Lin, K. W. Masui, J. Mena- Parra, M. Merryfield, R. Mckinven, D. Michilli, N. Milutinovic, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei-Ravandi, M. Rahman, S. M. Ransom, A. Renard, P. Scholz, S. R. Siegel, S. Singh, K. M. Smith, I. H. Stairs, S. P. Tendulkar, I. Tretyakov, K. Vanderlinde, P. Yadav, and A. V. Zwaniga. CHIME/FRB Discovery of Eight New Repeating Fast Radio Burst Sources. The Astrophysical Journal Letters, 885(1):L24, November 2019.