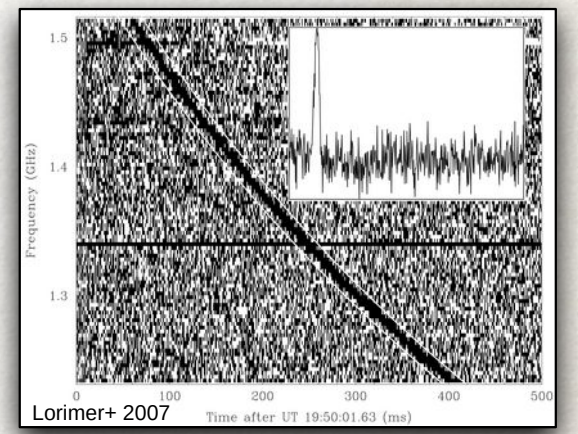
Fast Radio Burst Science with the MeerKAT Telescope Leading into the SKA Era



Fabian Jankowski

Researcher

LPC2E, CNRS, Université d'Orléans

Contact

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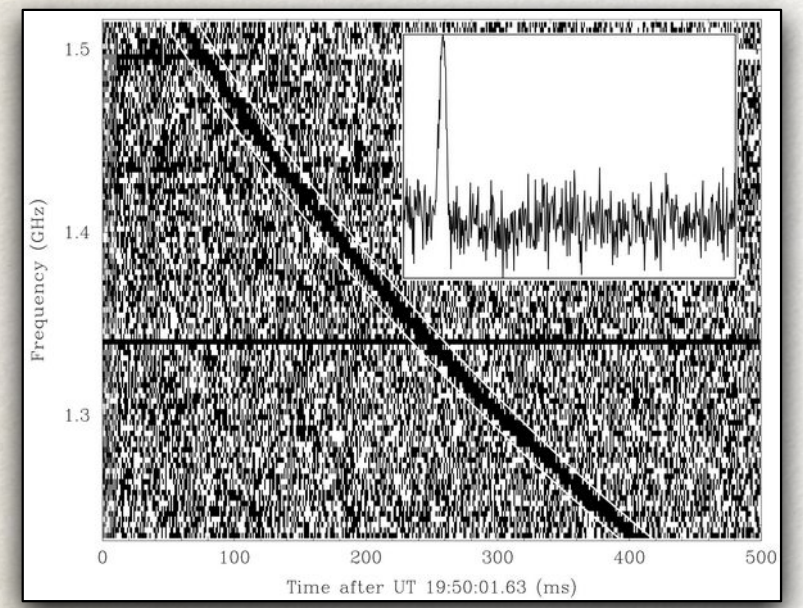
https://fabian.jankowskis.org

Talk Outline

1. Motivation
2. FRB Discovery & Localisation with MeerTRAP
3. Do FRBs Exhibit X-ray Emission?
4. Preparation for SKA
5. Conclusions

1. Motivation

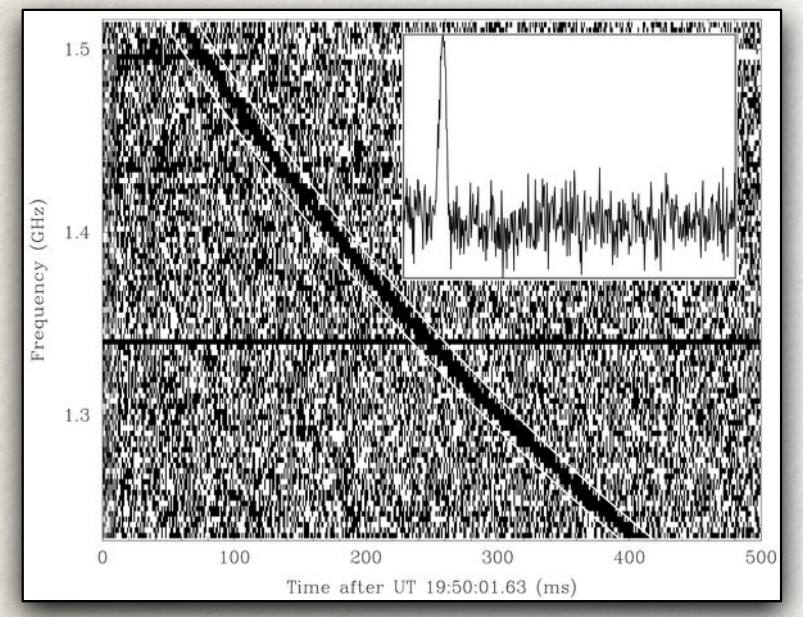
FRB Progenitor Mystery. What Creates FRBs?



Lorimer+ 2007

- What are their progenitors?
- Are there multiple classes of FRBs?
- Are the repeating and non-repeating FRBs from different objects?
- What is the physical mechanism that generates the bursts (high brightness temperature)?
- What other applications are there for FRBs?

FRB Progenitor Mystery. What Creates FRBs?



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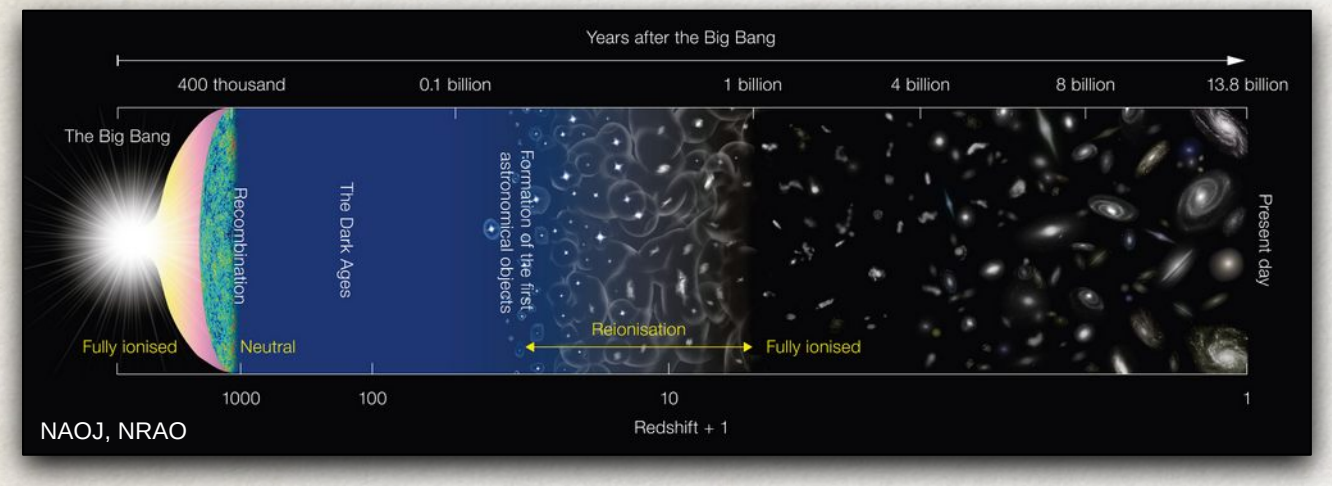
Shaw Prize in Astronomy 2023!
“Nobel of the East”

Shaw Prize

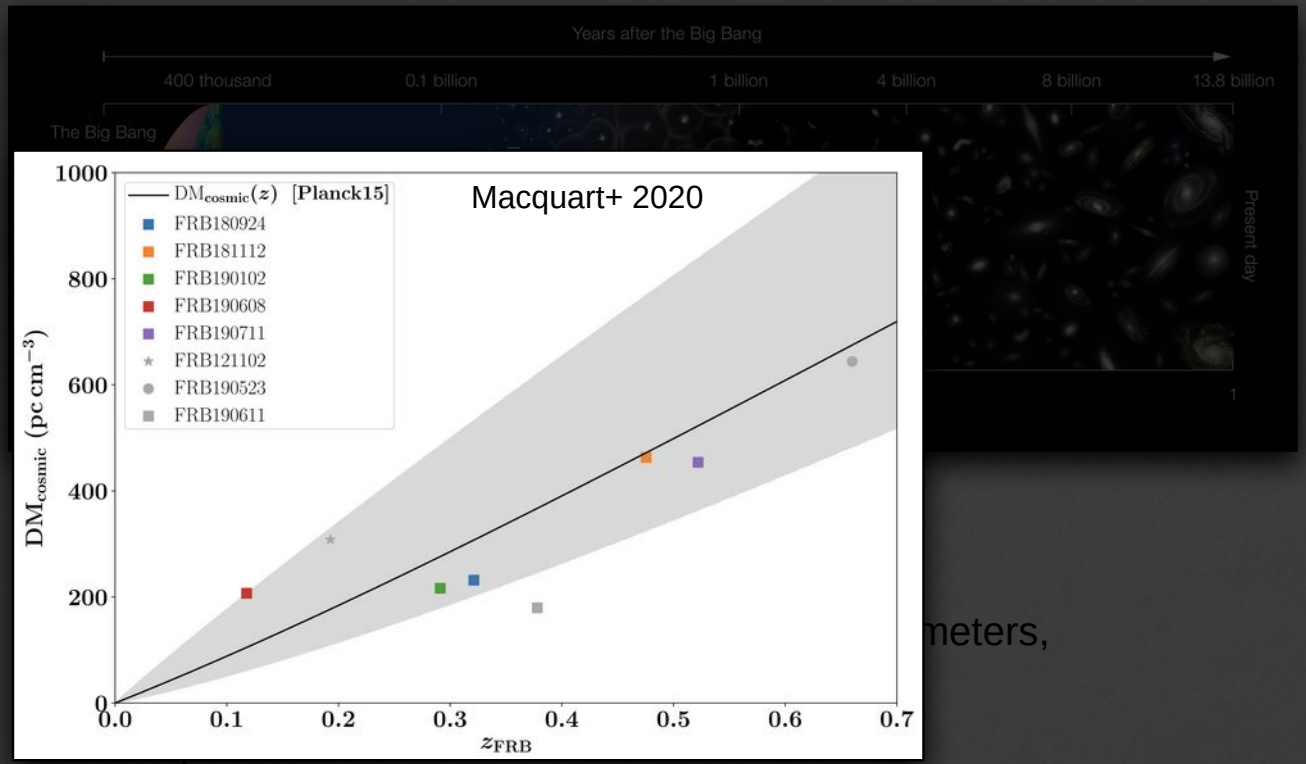
FRBs are Ideal Cosmological Probes



- Study the missing baryons
- Independent measurement of cosmological parameters, e.g. matter density and Hubble constant H_0.
  - Independent “vote” on Hubble tension
- Determine the re-ionisation history of the Universe
- Plasma lensing & gravitational lensing

FRBs are Ideal Cosmological Probes

Extragalactic DM (radio)



meters,

Host galaxy redshift (optical)

- Determine the ionization history of the Universe
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FRBs are Ideal Cosmological Probes

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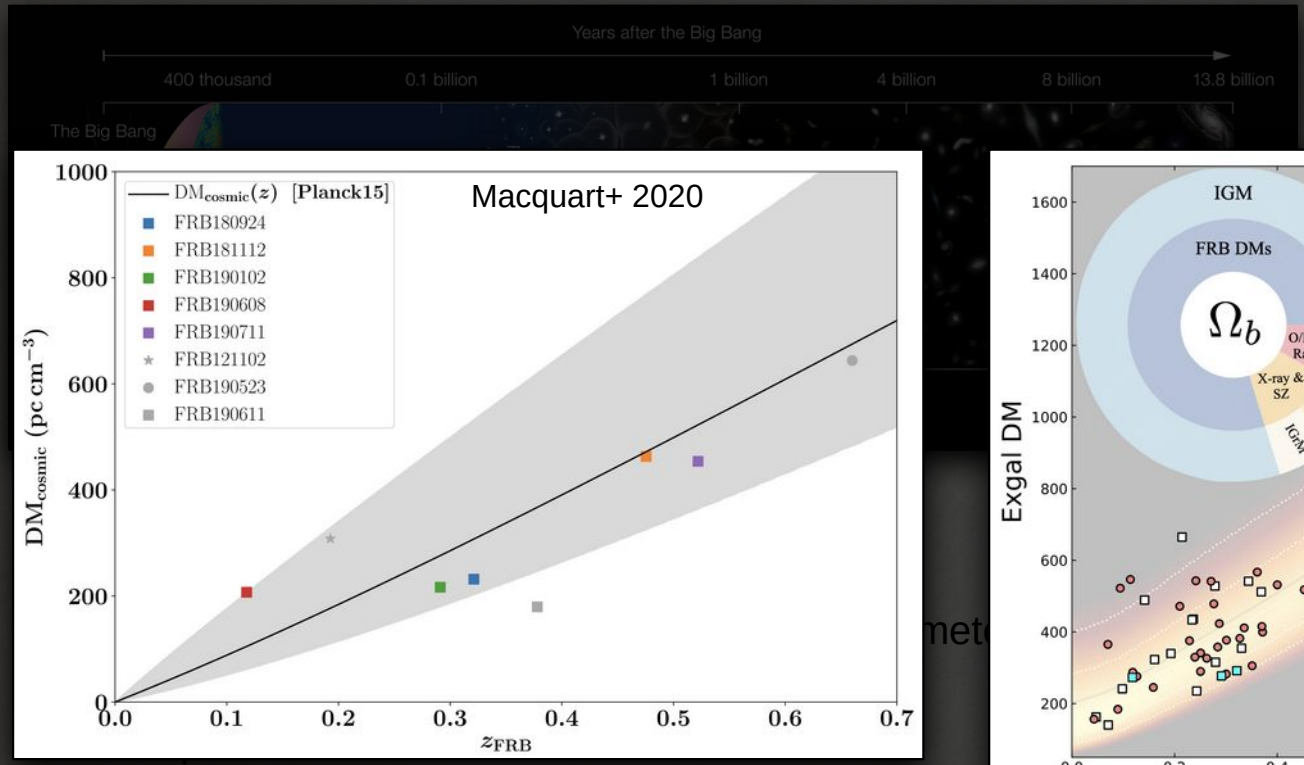
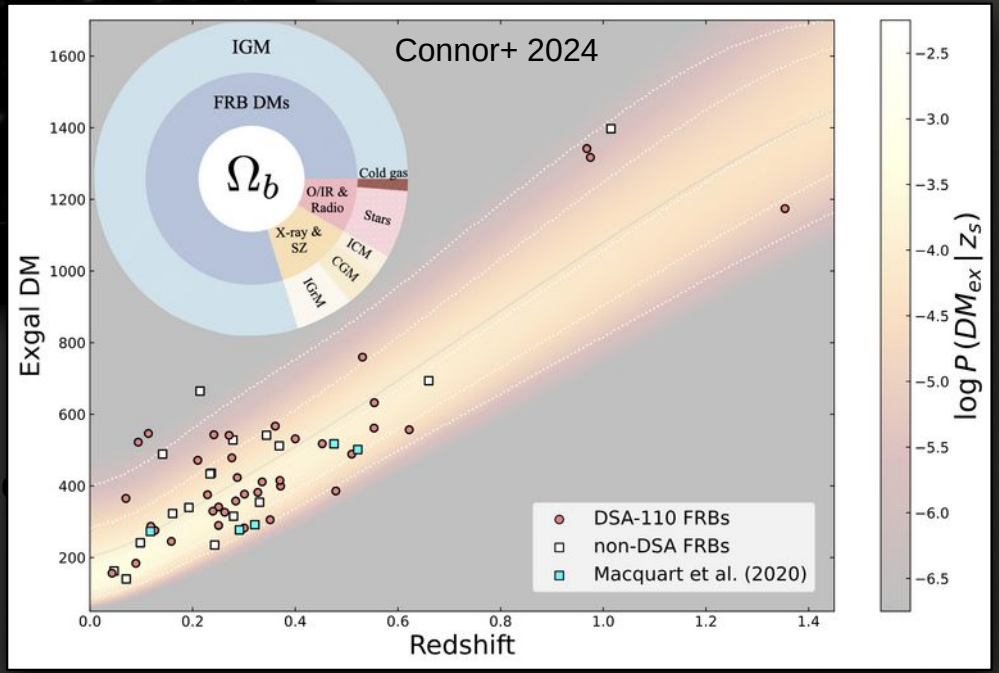




- Determine the ionization history of the Universe
- Plasma lensing & gravitational lensing

Host galaxy redshift (optical)

2. FRB Discovery & Localisation with MeerTRAP

On behalf of the MeerTRAP team

Fabian Jankowski

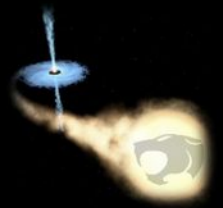
MeerTRAP and Friends

MEERTRAP

- Ben Stappers
- Tiaan Bezuidenhout
- Manisha Caleb
- Laura Driessen
- Fabian Jankowski
- Mateusz Malenta*
- Vincent Morello*
- Inés Pastor-Marazuela
- Kaustubh Rajwade
- Sotiris Sanidas*
- Mayuresh Surnis
- Jun Tian

MAX-PLANCK-GESELLSCHAFT

- Ewan Barr
- Marina Berezina
- Weiwei Chen
- Michael Kramer
- Jason Wu



FAST & FORTUNATE FRB FOLLOW-UP

UNIVERSITY OF OXFORD

- Aris Karastergiou
- Chris Williams

OXFORD e-Research CENTRE

- Karel Adamek
- Wes Armour
- Cees Carels
- Jan Novotny

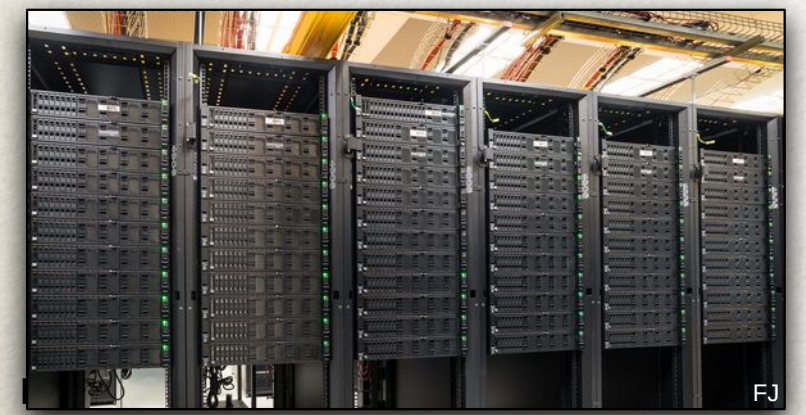
NRF National Research Foundation | SARAO South African Radio Astronomy Observatory

- Thomas Abbott
- Sarah Buchner
- Fernando Camilo
- David Horn
- Anton Joubert
- Jason Manley
- Simon Ratcliffe
- Maciej Serylak
- Lance Williams

Credit: Ben Stappers

Finding and Localising FRBs with the MeerKAT Telescope

Commissioned the MeerTRAP Instrument at MeerKAT



- Primary aims
  - Understanding what creates FRBs
  - Localising FRBs to their host galaxies

MEERTRAP

erc
European Research Council

MANCHESTER 1824
The University of Manchester

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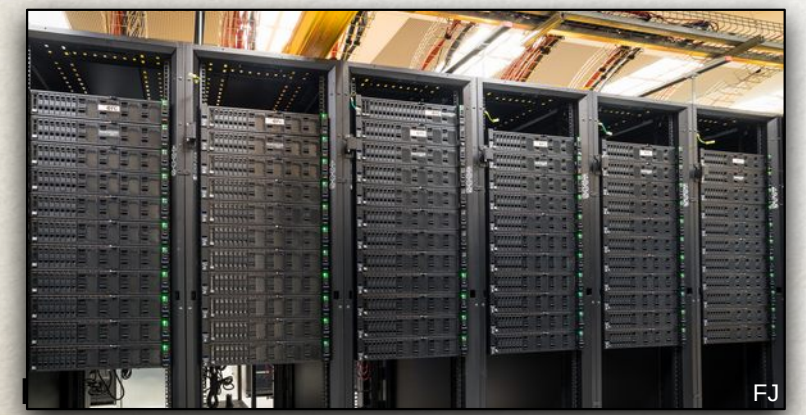

- Primary aims
  - Understanding what creates FRBs
  - Localising FRBs to their host galaxies
- Several million EUR project with various partner institutes (Bonn, Oxford, SARAO)
- Installed high performance servers at telescope site (user-supplied equipment)
- Designed, implemented, and commissioned observing & search software
- Scientific exploitation

MEERTRAP

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European Research Council

MANCHESTER 1824
The University of Manchester

The MeerTRAP Project

- Fully-commensal project
  - Piggybacks almost all projects
  - Huge amount of time on sky and sky coverage (~20,000 h over 5 yr)
- Real-time transient detection
- Excellent sensitivity (T_{sys} ~ 23 K, A_e/T_{sys} ~ 6.5 m^2/K at L-band)

FJ

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- Two surveys at the same time
  - Incoherent beam, ~1 deg^2 FoV, Parkes sensitivity
  - ~800 coherent beams, ~0.2 deg^2 FoV, GBT sensitivity
- Operating since late 2020

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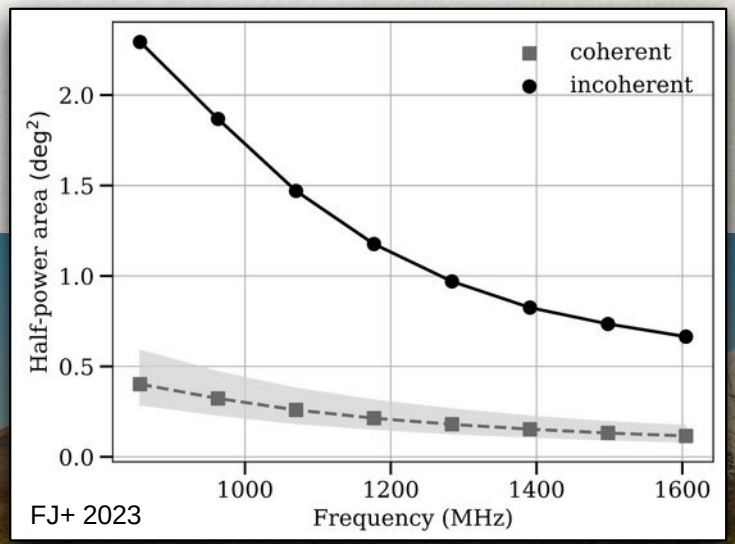
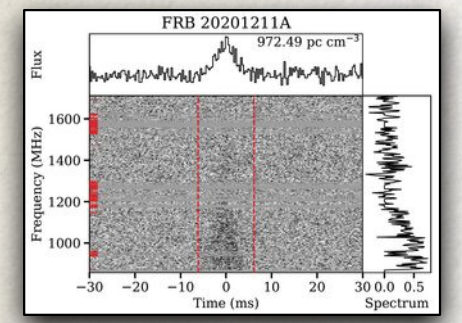
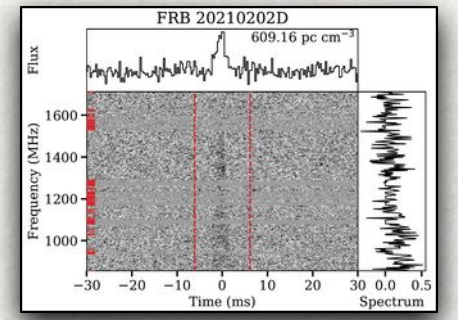
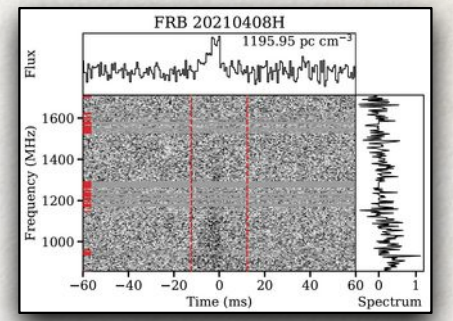
- 

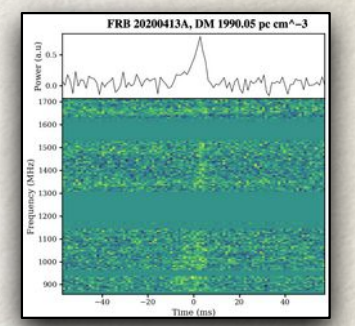
FJ+ 2023

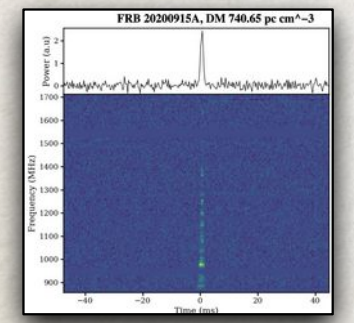
The First FRB Sample Discovered

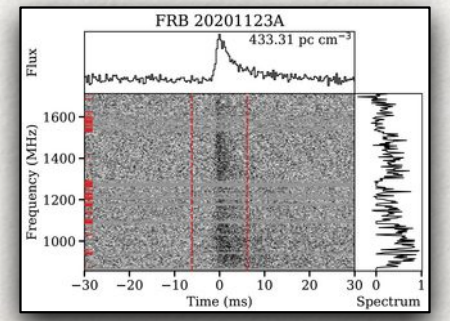


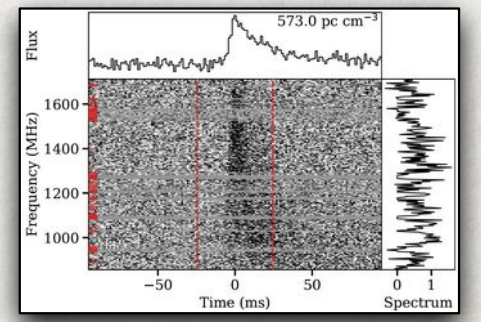


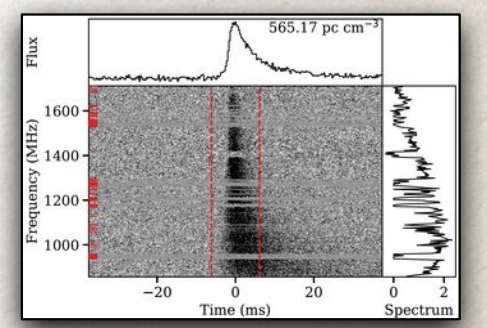


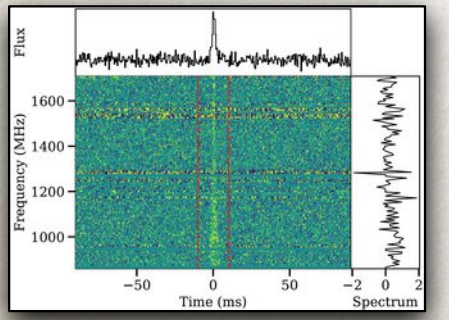


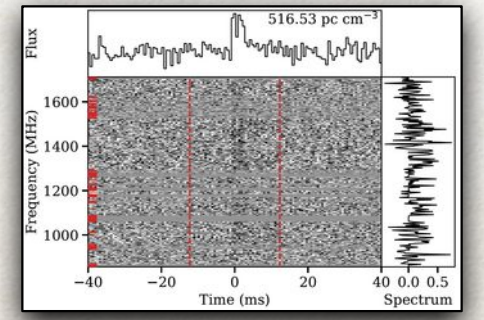


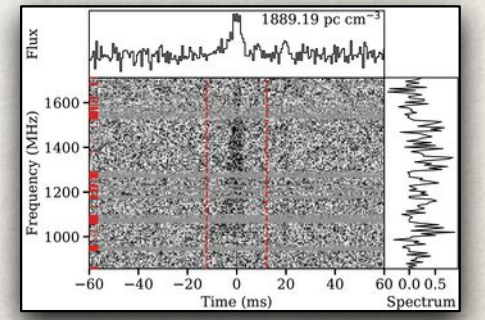










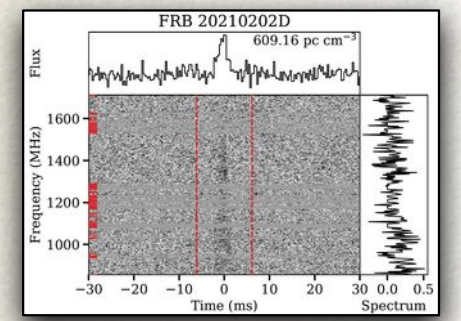


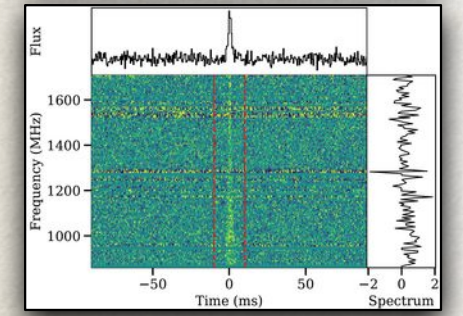
FJ+ 2023; Rajwade+ 2022; Driessen+ 2024; Caleb+ 2023

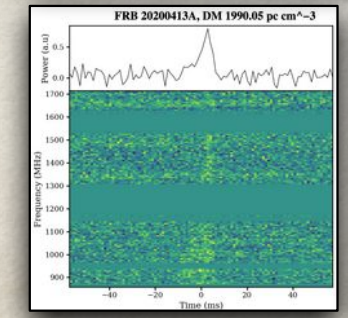
arXiv: 2302.10107; 2302.09787; 2302.09754

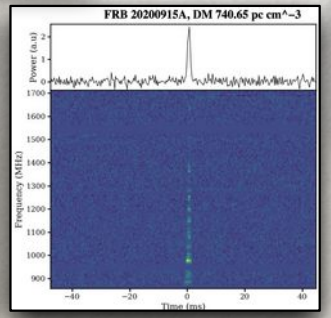
Fast Radio Burst Types

Unresolved

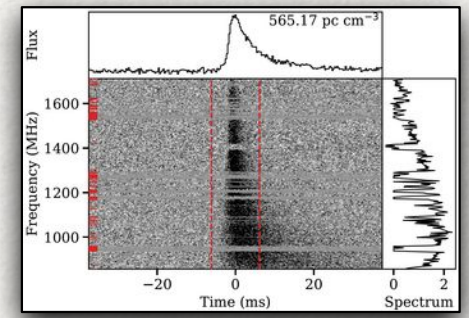


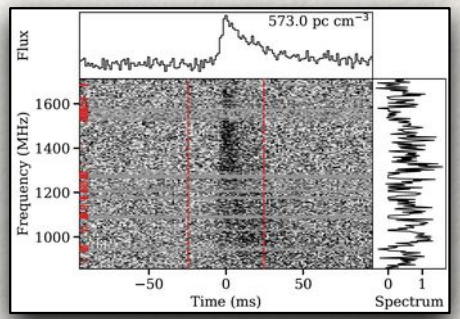


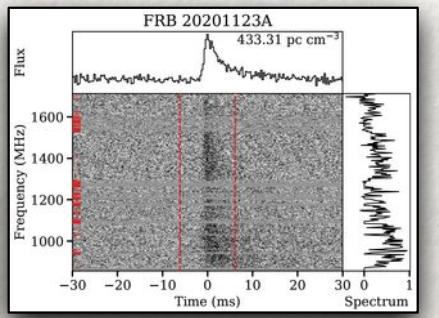


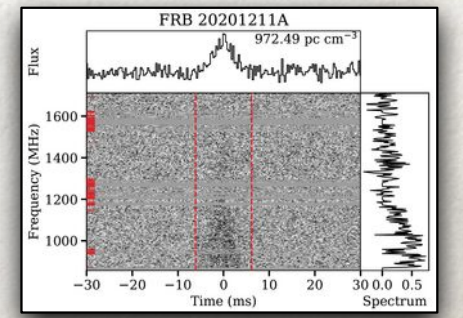


Scattered

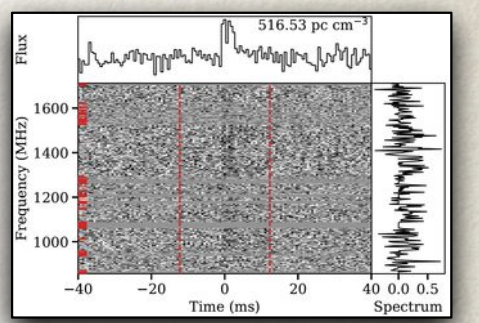


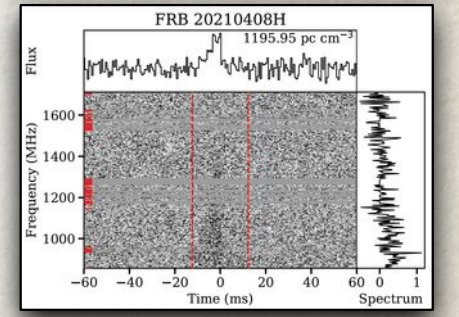


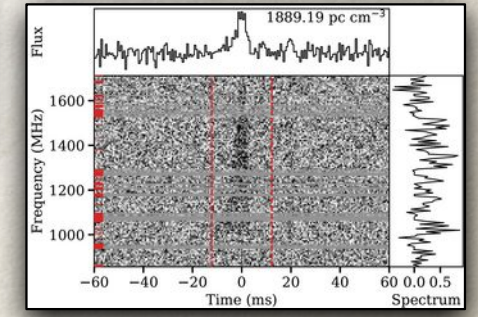




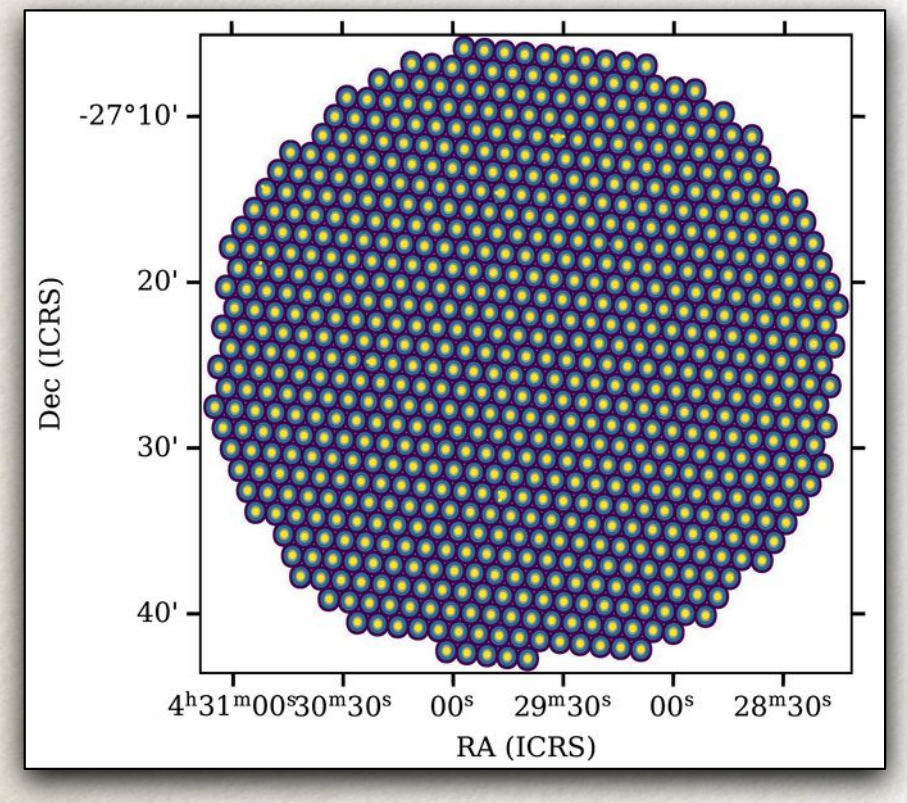
Complex







FRB Localisation is Crucial



- 1) Multi-beam triangulation
  - *SeeKAT* software
  - Based on (non) detection in neighbouring beams
- 2) Synthesis imaging & voltage buffer

Fabian Jankowski

Bezuidenhout+ 2023

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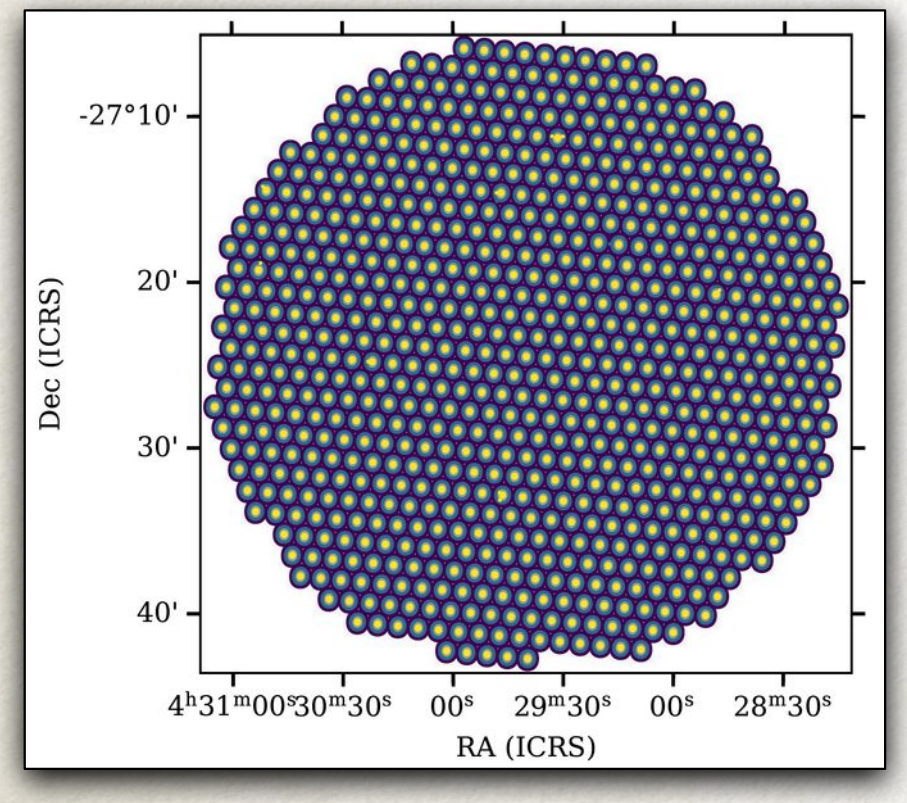
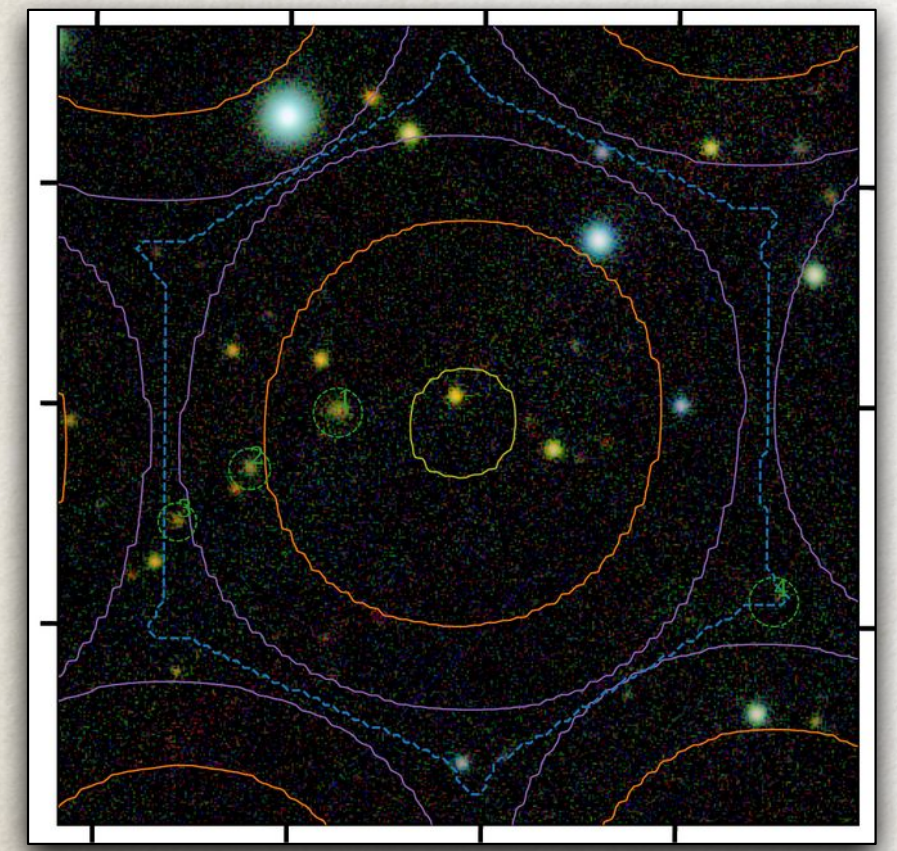


- 1) Multi-beam triangulation
  - *SeeKAT* software
  - Based on (non) detection in neighbouring beams
- 2) Synthesis imaging & voltage buffer
- Precision
  - Single-beam: ~0.9 arcmin^2
  - Multi-beam: O(100) arcsec^2
  - Synthesis image or voltage buffer: O(1) arcsec^2

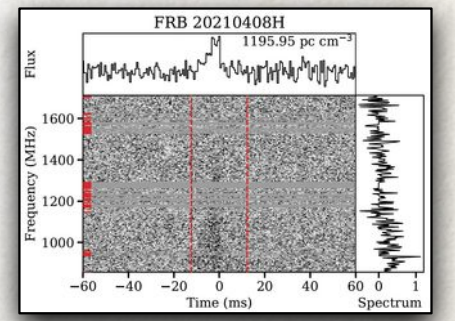
Fabian Jankowski

Bezuidenhout+ 2023

FRB - Host Galaxy Association

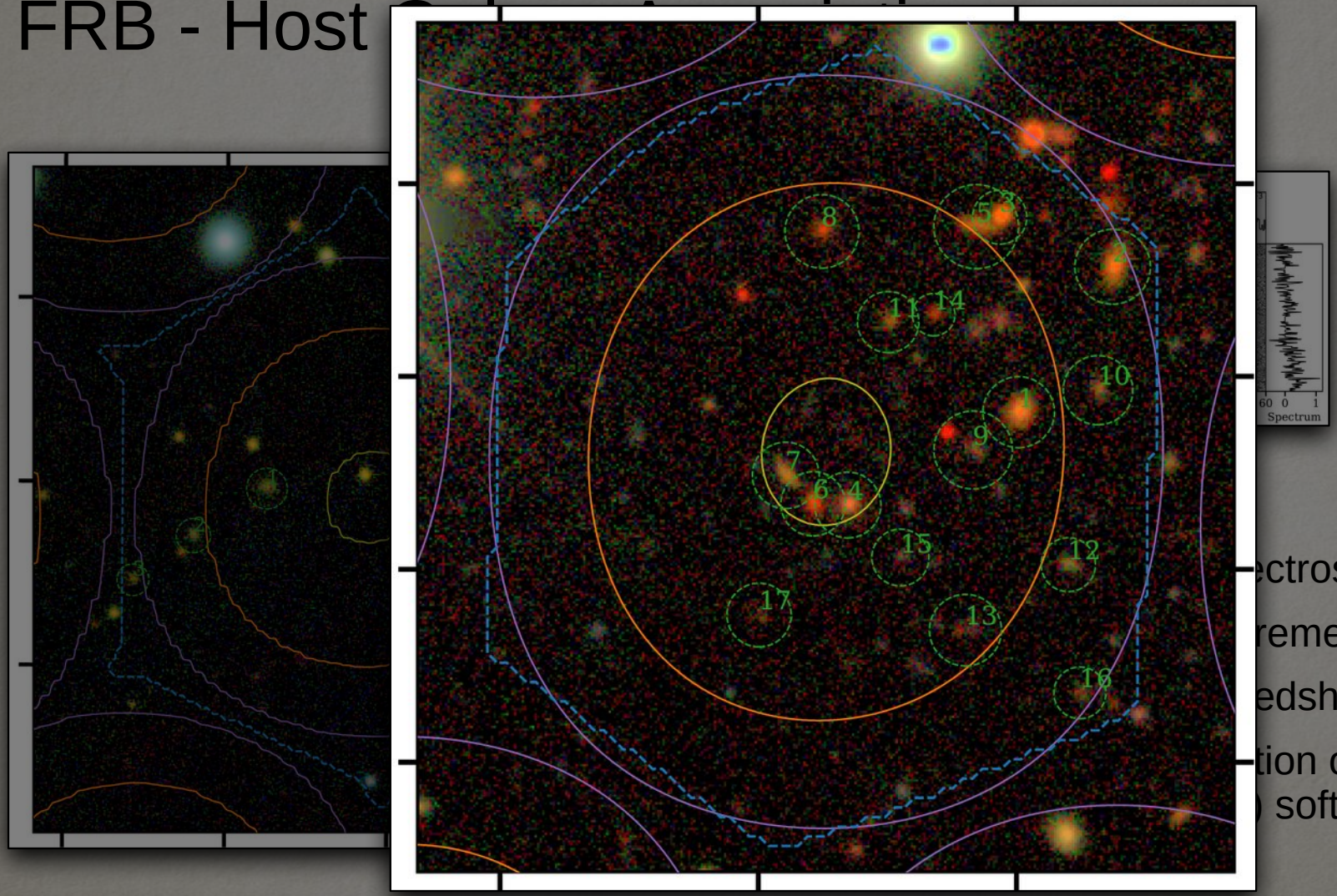


FJ+ 2023



- Aim: Host galaxy spectroscopic redshift
- Two distance measurements
- Calibrate DM_{cosmic} – redshift relation
- Probabilistic Association of Transients to their Hosts (PATH) software

FRB - Host



ectroscopic redshift

rements

edshift relation

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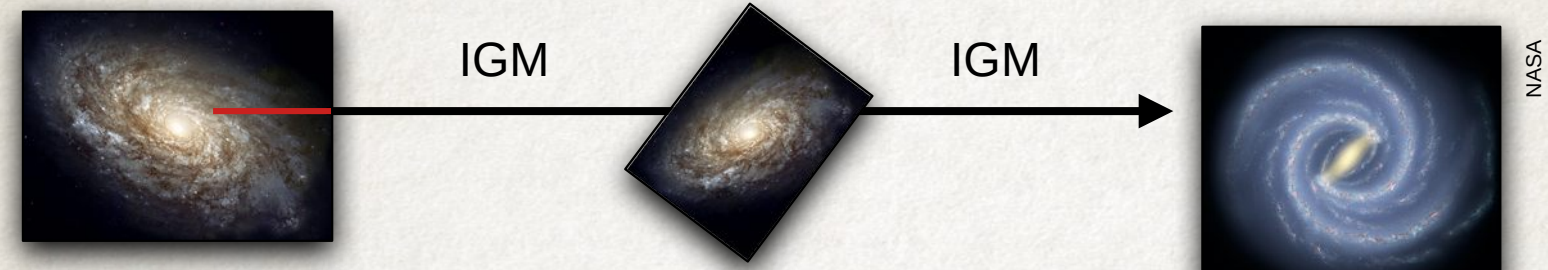
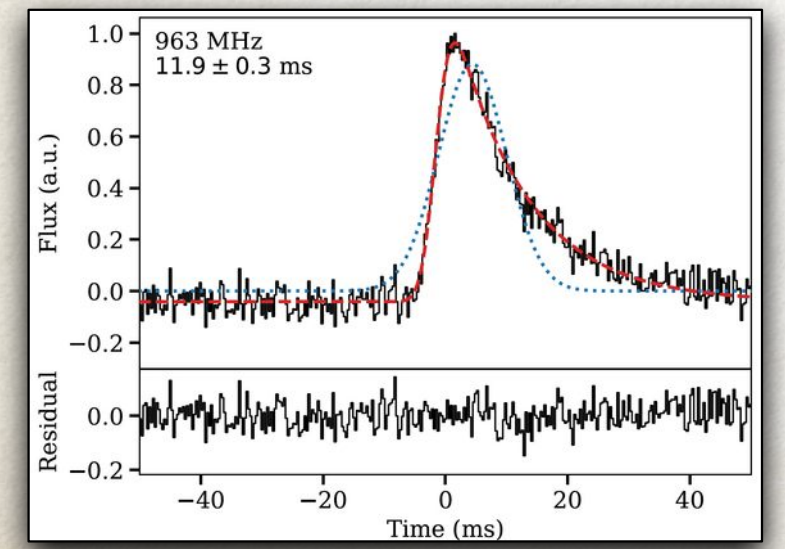
Scattering

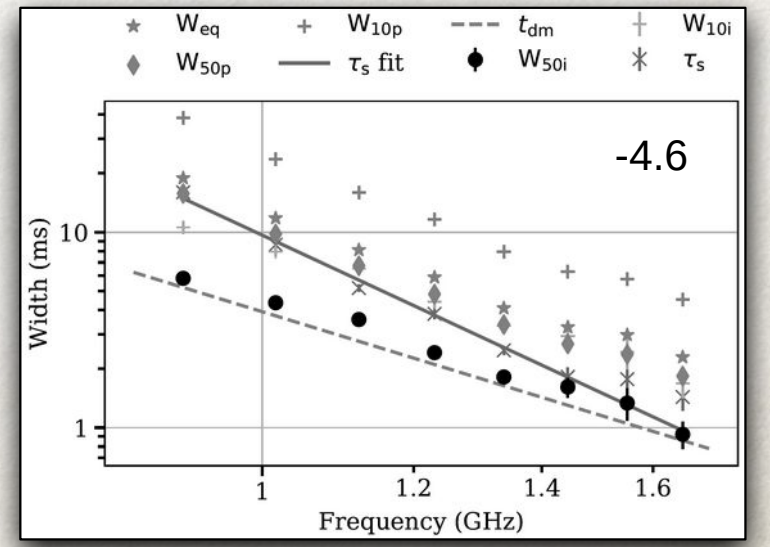


Host galaxy

Intervening galaxy & halo

MW halo & ISM





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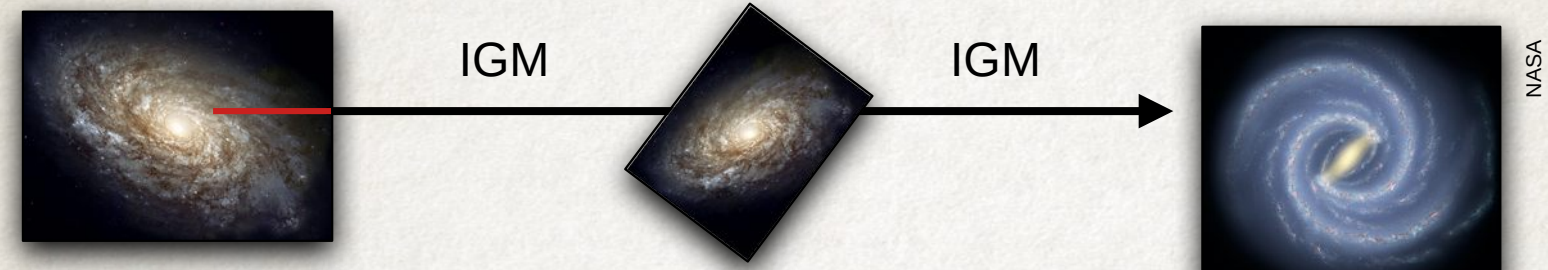

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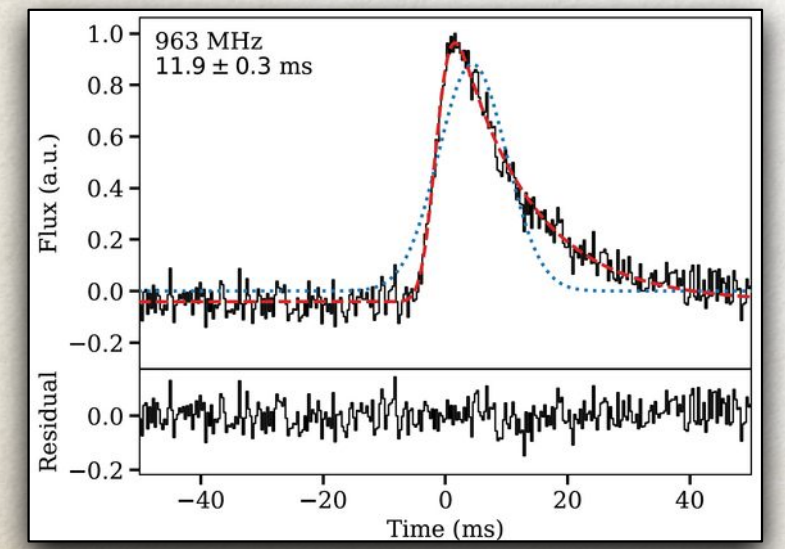
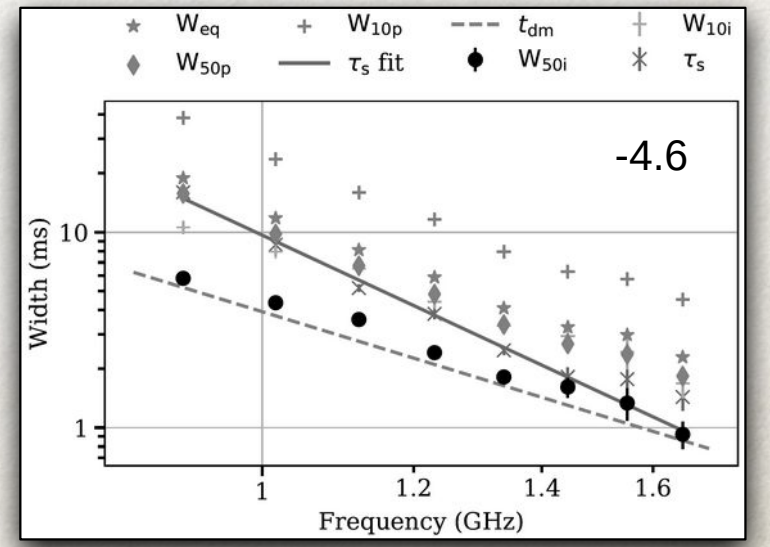
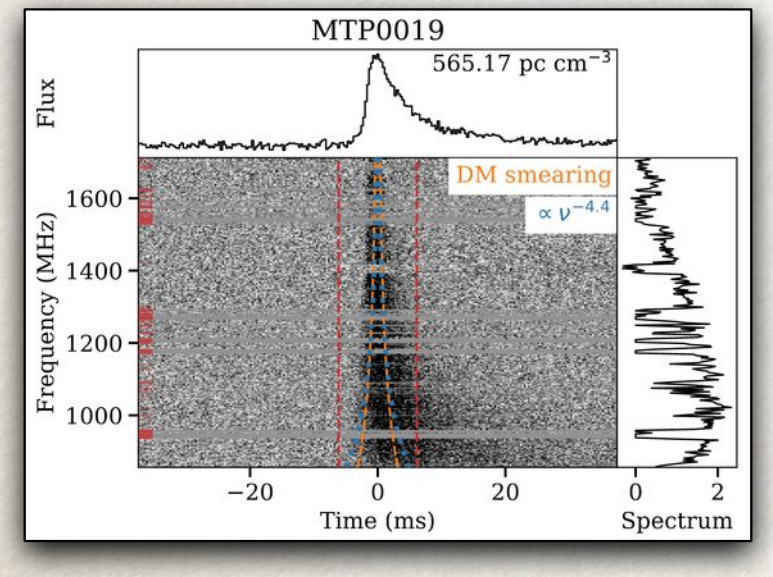




- 3 FRBs show significant scattering
- 1 shows hint
- Several limited by DM smearing
- Close to Kolmogorov

Scatfit Scattering Fit and Simulation Software

- Developed for low-S/N FRB data (S/N ≤ 30)
  - Reads data at native time & freq. resolution
  - Includes treatment of instrumental effects



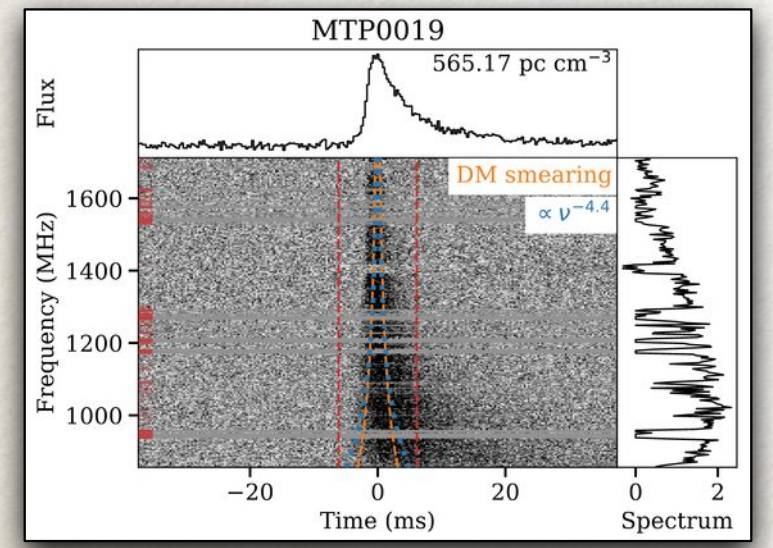
Driessen+ 2024

https://github.com/fjankowsk/scatfit

Jankowski+ 2023
ASCL: 2208.003

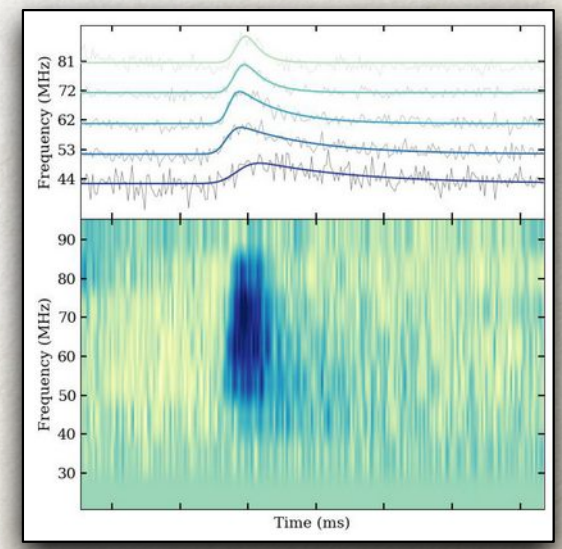
Scatfit Scattering Fit and Simulation Software

- Developed for low-S/N FRB data (S/N ≤ 30)
  - Reads data at native time & freq. resolution
  - Includes treatment of instrumental effects
- Recently adapted for pulsar data
- Supports standard FRB & pulsar data formats (SIGPROC, PSRFITS, Timer)
  - Verified on data from MeerKAT, NenuFAR, LOFAR, GMRT, NRT



Driessen+ 2024

PSR B0355+54 with NenuFAR



https://github.com/fjankowsk/scatfit

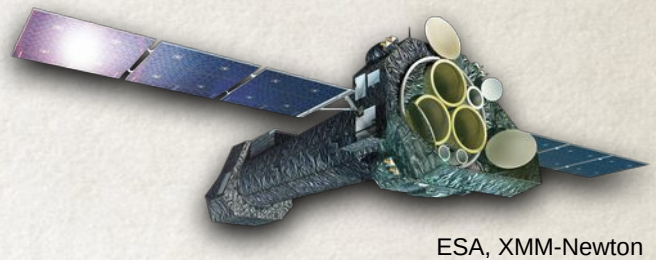
Jankowski+ 2023
ASCL: 2208.003

4. Do FRBs Exhibit X-ray Emission?

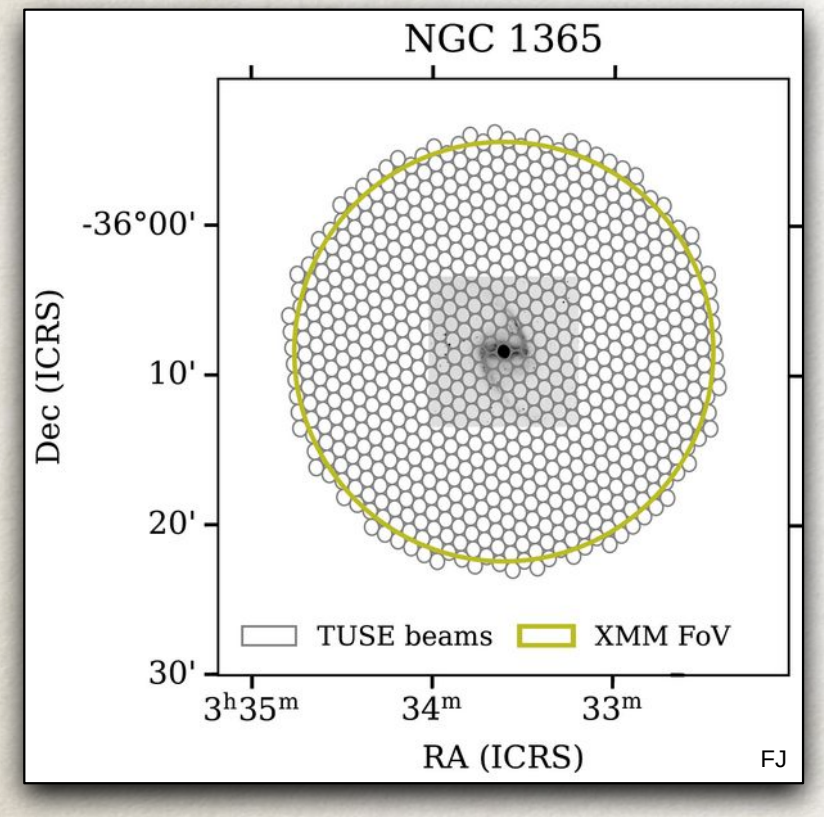
On behalf of Eppel, Kadler, Krumpe & team

Fabian Jankowski

XMM-Newton – MeerKAT FRB Search Project



ESA, XMM-Newton

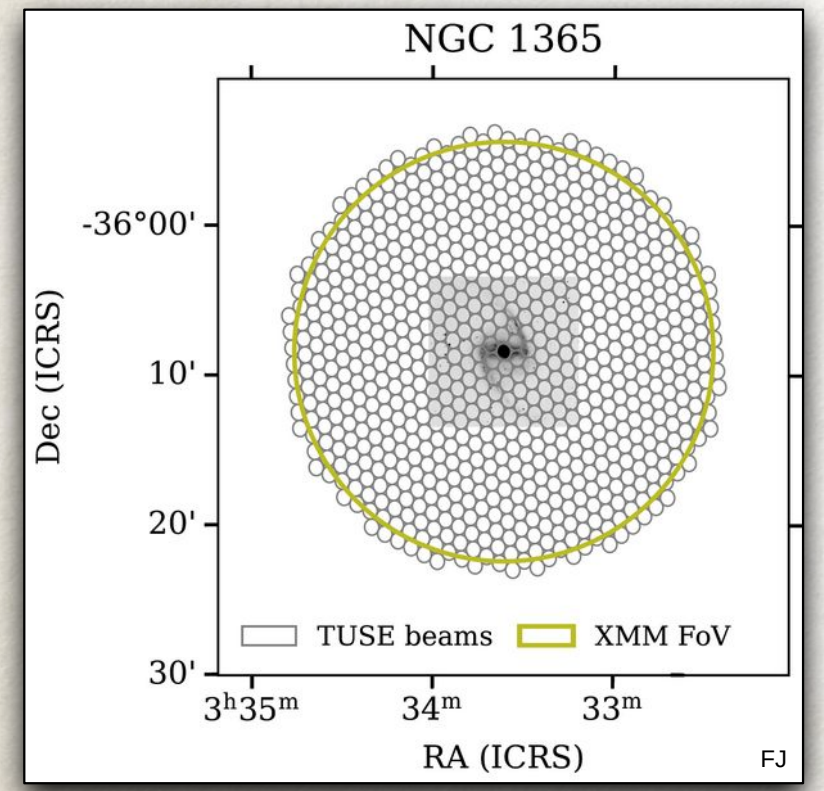


- Aims
  - Shadow *XMM-Newton* pointings on nearby (redshift < 0.2) galaxies with MeerKAT
  - Detect bright magnetar flares

Fabian Jankowski

XMM-Newton – MeerKAT FRB Search Project

ESA, XMM-Newton

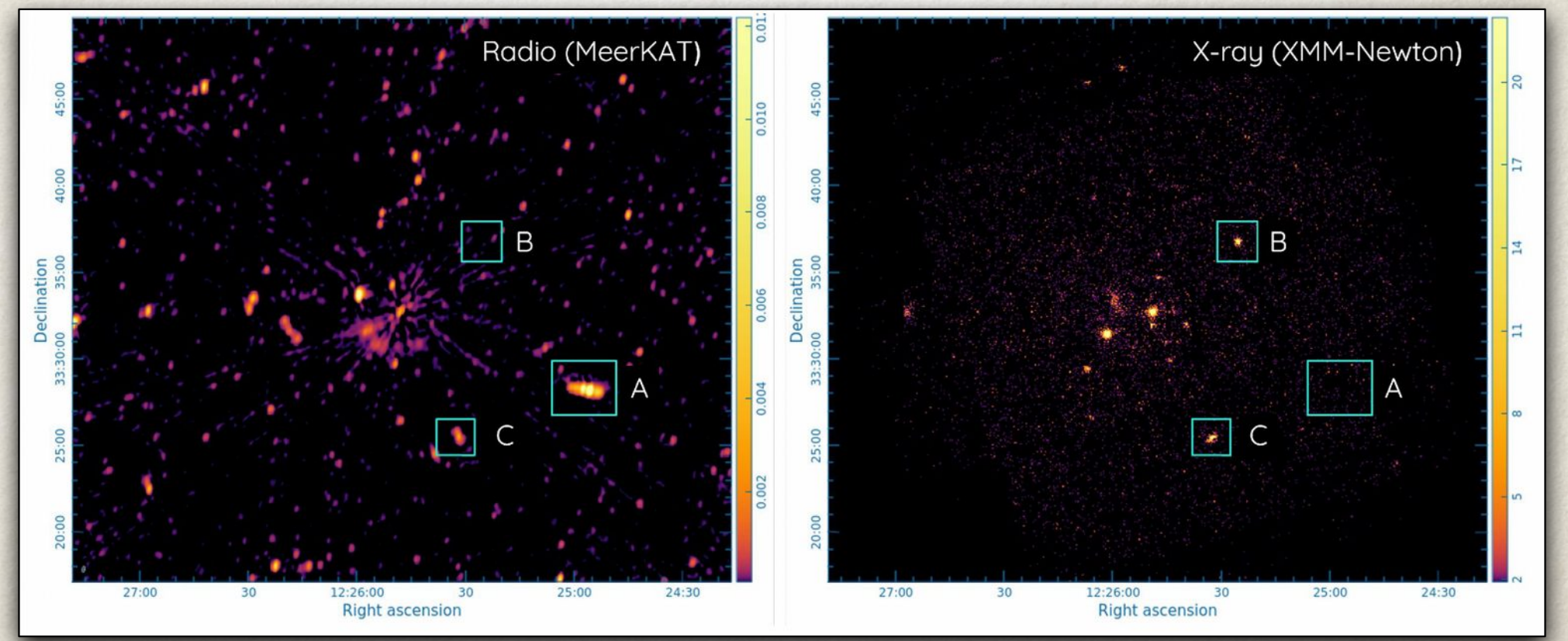


- Aims
  - Shadow *XMM-Newton* pointings on nearby (redshift < 0.2) galaxies with MeerKAT
  - Detect bright magnetar flares
- Motivated by Galactic “FRB” – X-ray burst connection (SGR 1935+2154)
- Team: PI Eppel, Uni Würzburg, D-MeerKAT, X-ray experts, FJ Technical Lead
- 20 hours of MeerKAT time granted in 2023/24
- Running since December 2023
  - No detection so far

Fabian Jankowski

Secondary Radio – X-ray Science

Credit: Florian Eppel



Fabian Jankowski

Build up simultaneous X-ray & radio coverage

5. Preparation for SKA

Fabian Jankowski

Preparation for the SKA Era

- MeerKAT is a SKA-mid precursor
  - Will be integrated into SKA-mid
- Test for SKA
  - Commensal science (transient searches)
  - Real-time data processing
- SKA will allow:
  - More FRBs (logN-logS & sub-arrays)
  - Detailed FRB repeater follow-up

FJ

Preparation for the SKA Era

- MeerKAT is a SKA-mid precursor
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- Test for SKA
  - Commensal science (transient searches)
  - Real-time data processing
- SKA will allow:
  - More FRBs (logN-logS & sub-arrays)
  - Detailed FRB repeater follow-up

- Software development that directly leads into SKA SDP
  - Single-pulse search pipeline (AstroAccelerate)
  - Control and monitoring system
- Interfaced well with South African SARAO team

FJ

6. Conclusions

Conclusions and Other Work

- Dozens of FRBs
- Robust FRB – host galaxy associations

Driessen+ 2024,
Caleb+ 2023,
Rajwade+ 2022, 2024

- Propagation effects (scattering, scintillation)
- Cosmology
- Multi-wavelength observations are important

Other work not mentioned

- Discovered first MeerKAT FRB repeater!

Jun+ 2024

- Discovered many Galactic transients
  - Slow 76-s pulsar

Caleb+ 2022,
NatAstro

  - Highly intermittent pulsar or magnetar

Surnis+ 2023

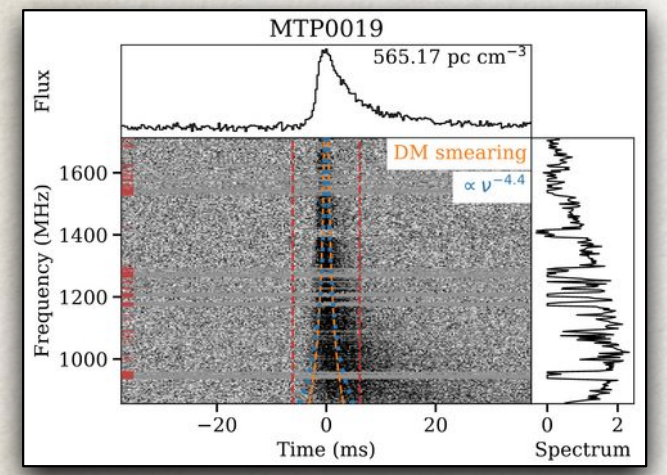
  - Pulsars & RRATs

Bezuidenhout+ 2023,
Turner+ submitted

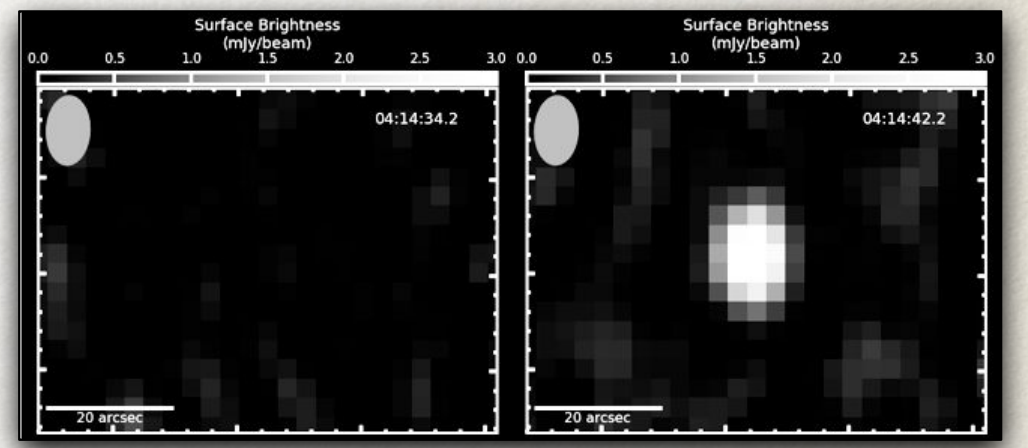
Fabian Jankowski

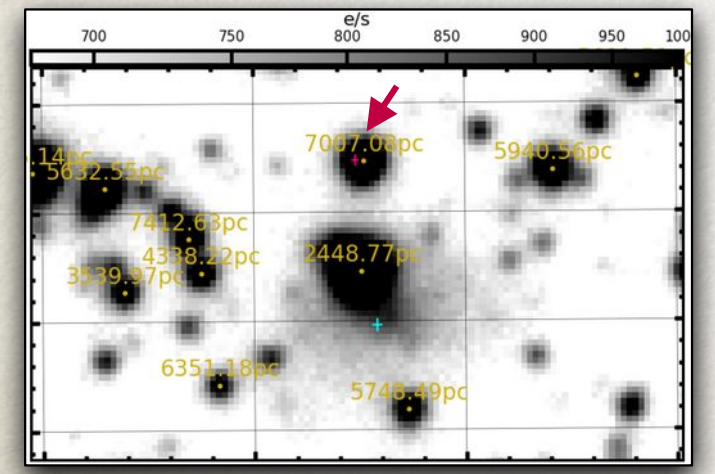
Extra Slides

Host Galaxies – MTP0019



Driessen+ 2024



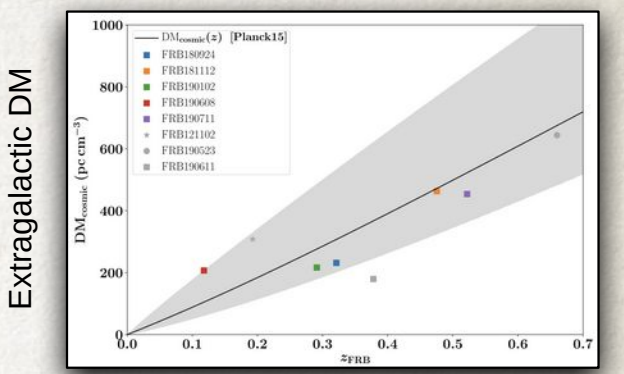


- Sub-arcsec localisation
- Galactic vs extragalactic?
- Faint optical source and persistent radio source,7.4” offset
- Galaxy obscured by foreground star. Star-forming spiral
- z_{spec} = 0.066
- Host DM ~30 units

arXiv: 2302.09787

Cosmology with FRBs

Macquart+ 2020



Host galaxy redshift

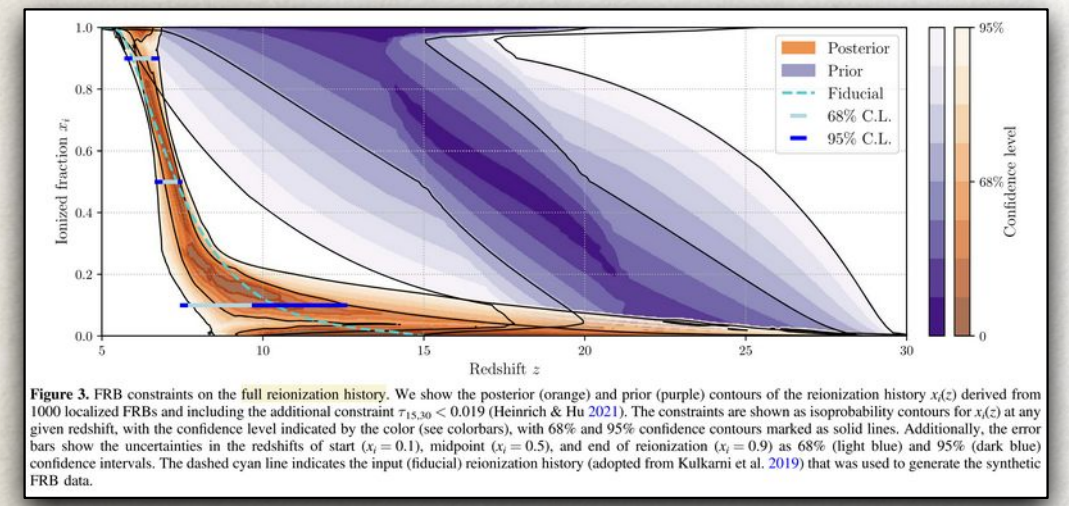
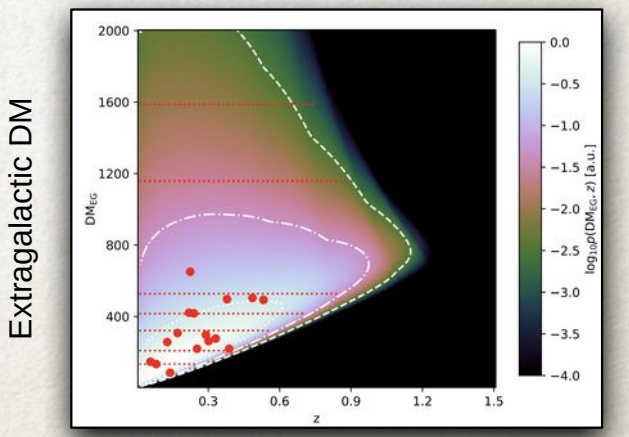


Figure 3. FRB constraints on the full reionization history. We show the posterior (orange) and prior (purple) contours of the reionization history $x_i(z)$ derived from 1000 localized FRBs and including the additional constraint $\tau_{15,30} < 0.019$ (Heinrich & Hu 2021). The constraints are shown as isoprobability contours for $x_i(z)$ at any given redshift, with the confidence level indicated by the color (see colorbars), with 68% and 95% confidence contours marked as solid lines. Additionally, the error bars show the uncertainties in the redshifts of start ($x_i = 0.1$), midpoint ($x_i = 0.5$), and end of reionization ($x_i = 0.9$) as 68% (light blue) and 95% (dark blue) confidence intervals. The dashed cyan line indicates the input (fiducial) reionization history (adopted from Kulkarni et al. 2019) that was used to generate the synthetic FRB data.

Heimersheim+ 2022



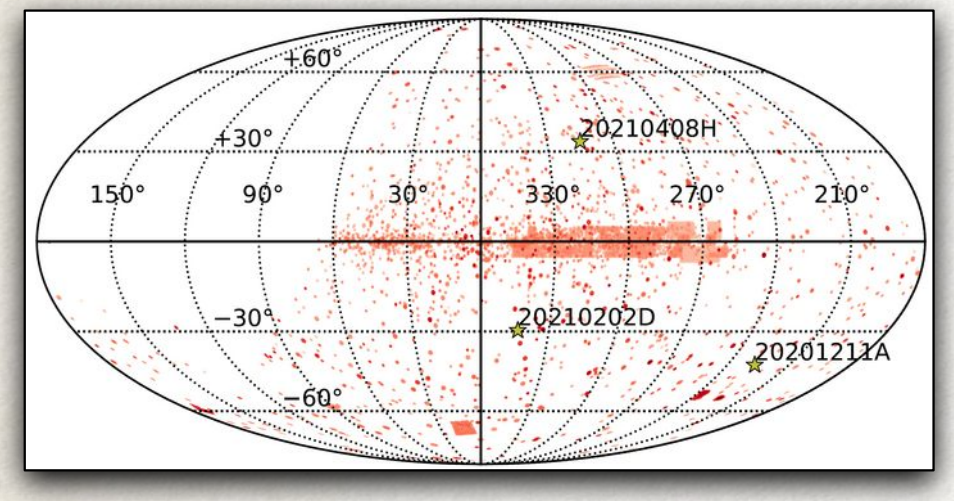
James+ 2022

Host galaxy redshift

Fabian Jankowski

Understanding the MeerTRAP Surveys & FRB All-sky Rates

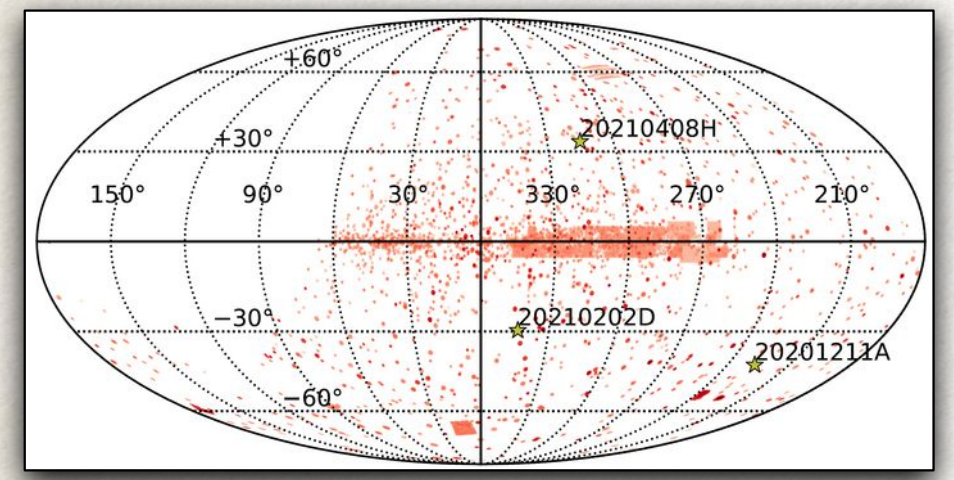
Understanding the MeerTRAP Surveys & FRB All-sky Rates



317.5 days on-sky time!

FJ+ 2023

Understanding the MeerTRAP Surveys & FRB All-sky Rates



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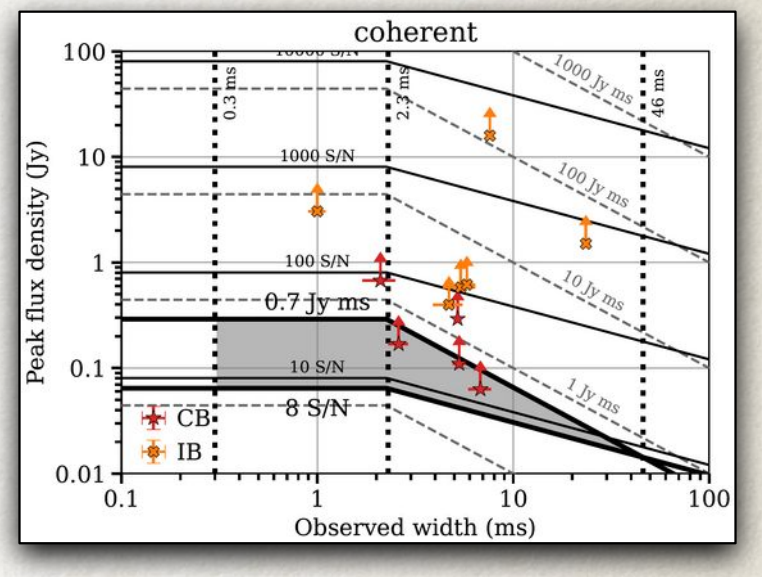
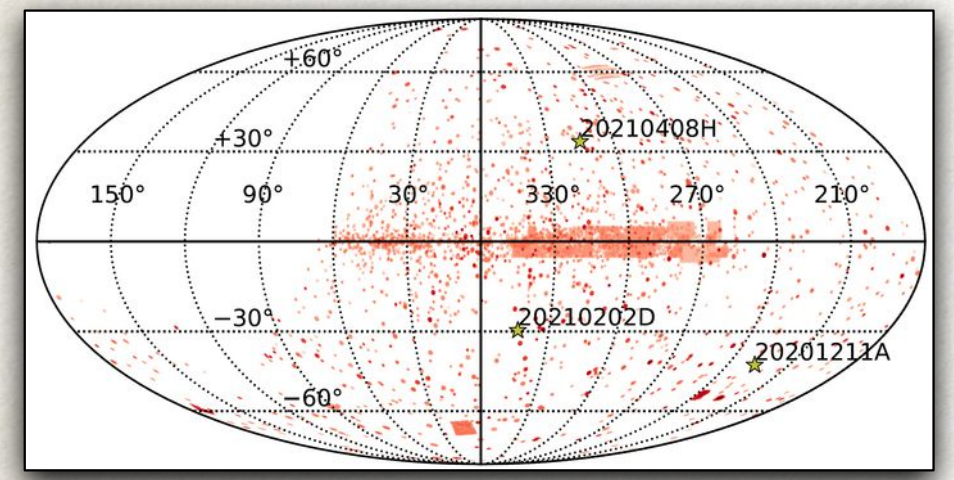
FJ+ 2023



F_c: 0.7 & 3.4 Jy ms

Understanding the MeerTRAP Surveys & FRB All-sky Rates



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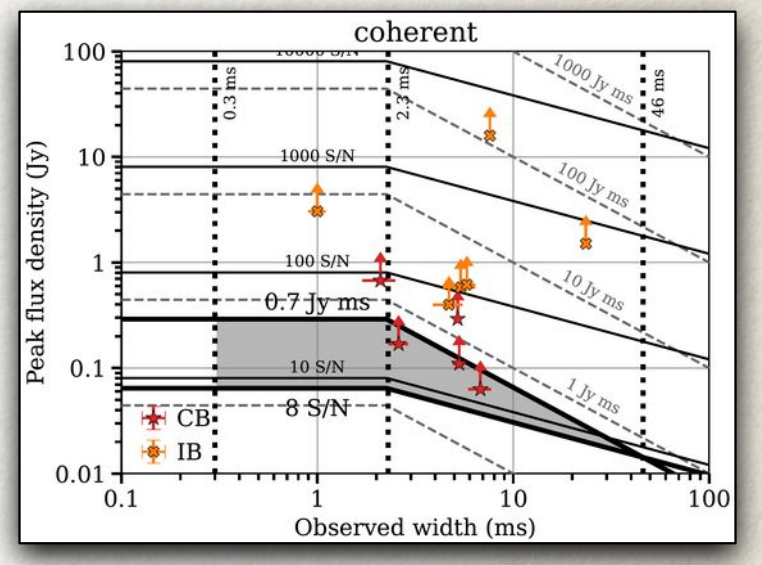
FJ+ 2023

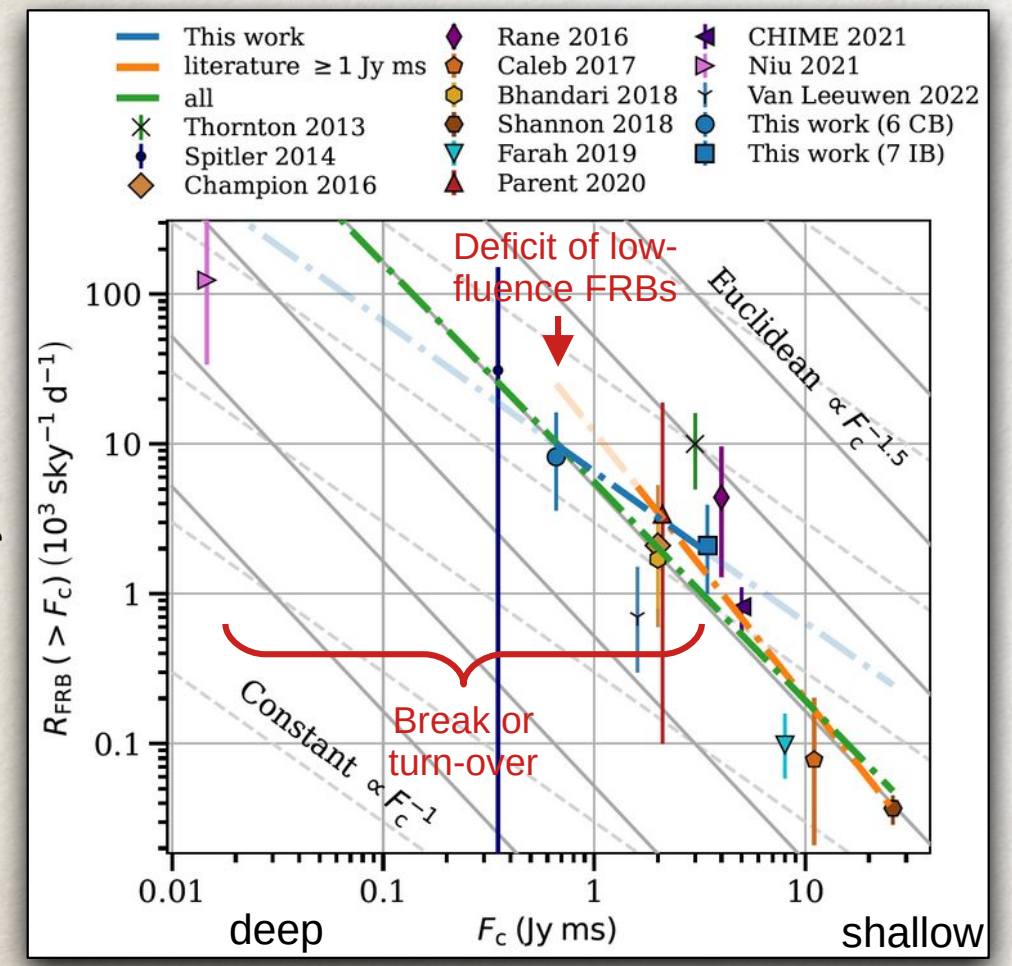


F_c: 0.7 & 3.4 Jy ms

Survey	t_{obs} (d)	$\langle A_{0.5} \rangle$ (deg^2)	c_s (deg^2 h)	Limiting fluence F_c (Jy ms)	N_{FRB} ($> F_c$)	All-sky rate R_{FRB} ($> F_c$) (10^3 sky^{-1} d^{-1})
Coherent	317.5	0.19	1448	0.66	6	$8.2^{+8.0}_{-4.6}$
Incoherent (total)	317.5	0.97	6662	3.44	7	$2.1^{+1.8}_{-1.1}$
Incoherent (subtracted)	317.5	0.78	5944	3.44	5	$1.7^{+1.8}_{-1.0}$

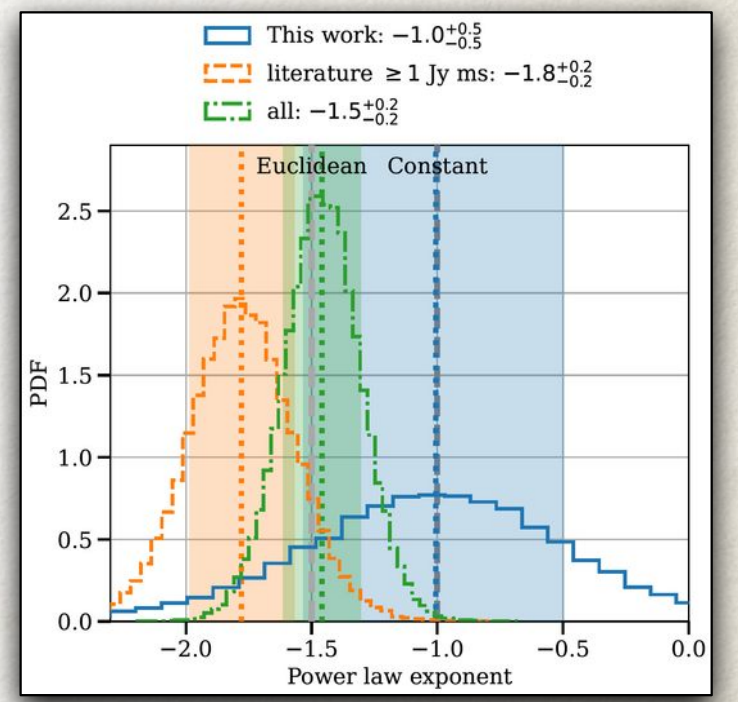
~2100 and 8200 FRBs per sky per day!

FRB All-sky Rates → Cosmology



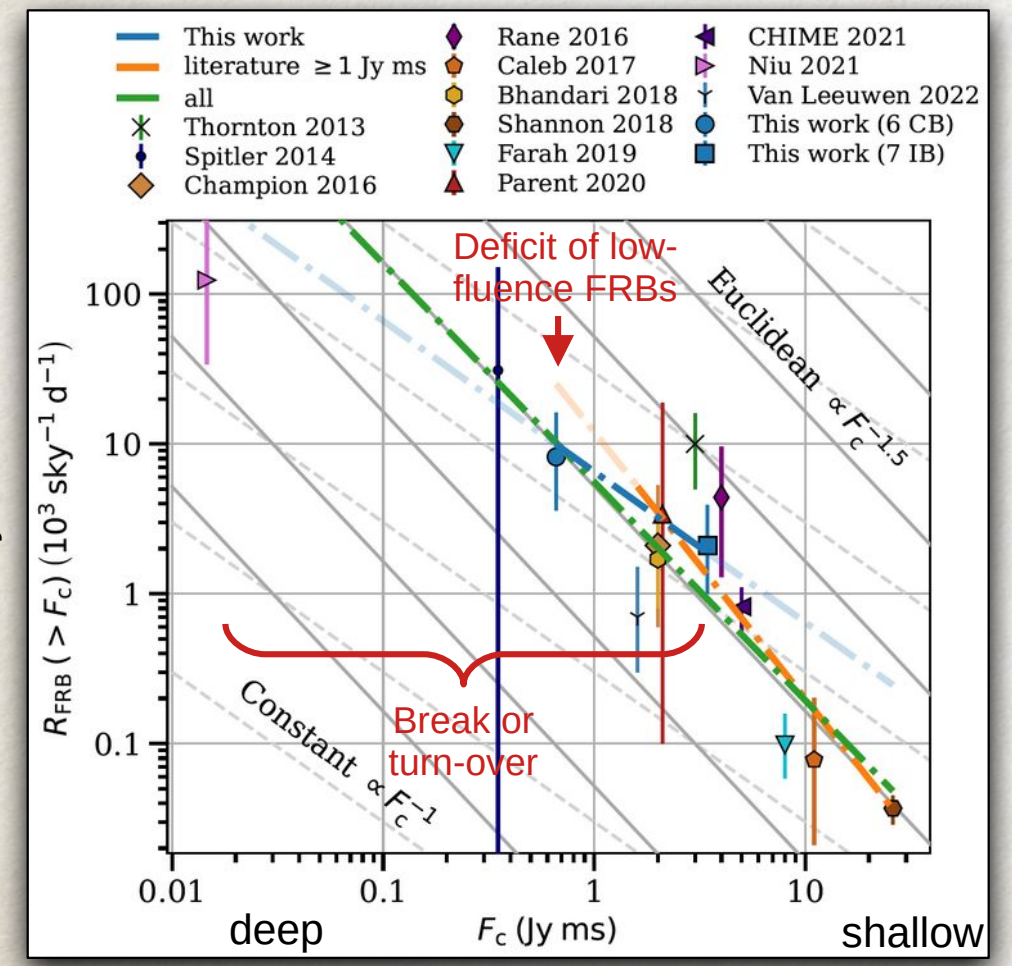
All-sky rate

Survey sensitivity



FJ+ 2023

FRB All-sky Rates → Cosmology



All-sky rate

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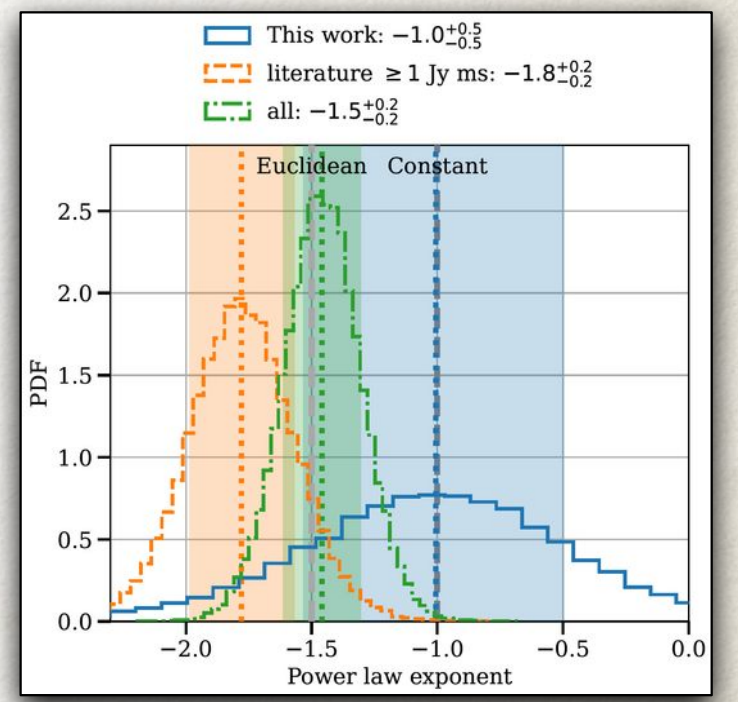

FJ+ 2023

- Deficit of low-fluence FRBs
- Due to cosmological effects or progenitor evolution