CHARTS: Canadian-Chilean array for radio transient studies

Project presentation and system developments

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Outline

Presenting on behalf of students and co-I's
CHARTS collaboration

Millisecond transient radio sky

- Understand fast radio bursts (**FRBs**)
- All-sky FRB rate $\mathcal{R} \sim 10^3\,\mathrm{d}^{-1}$
- Observational properties:
  - Duration of $t_\mathrm{w} \sim$ µs–ms
  - Broadband spectrum $\nu = \sim$0.2–6 GHz
  - Brightness temperature $T_\mathrm{b} \sim 10^{40}$ K
  - Extreme energetics $E \sim 10^{35}$–10^{45} erg
  - Some FRBs repeat ∼4–10 %

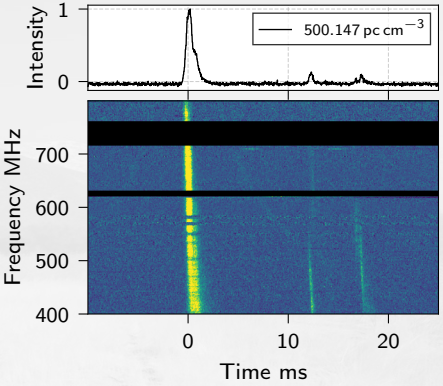

Figure: Fast radio burst (one-off) detected by the CHIME/FRB Collaboration, June 2021 (Cassanelli et al. 2022).

FRB detection: a $\mathcal{R}$ and cost optimization

- FRB radio detection needs:
  - Large collector $A_e \rightarrow$ increased sensitivity Γ K Jy^{-1}
  - Huge field-of-view $\Omega \rightarrow$ increased chance of detection
  - Angular resolution $\theta_{res} \rightarrow$ localization
- Solution: multi-beam radio interferometer with many beams!

$$\Gamma \propto A_e \propto 1/\theta_{res} \quad (1)$$

- FRB detection rate $\mathcal{R}$ (CHIME/FRB Collaboration et al. 2021; Chawla et al. 2017)

$$\mathcal{R} \propto \Delta\nu^{0.75} n_a^{1.5} t_s^{-0.7} \quad (2)$$

- Bandwidth $\Delta\nu$: not heavily penalized
- Sampling time t_s is limited by the pulse width t_w

Figure: Canadian Hydrogen Intensity Mapping Experiment (CHIME) and its FRB backend (CHIME/FRB). Credits: Andre Renard.

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Most FRBs have been found at high Dec

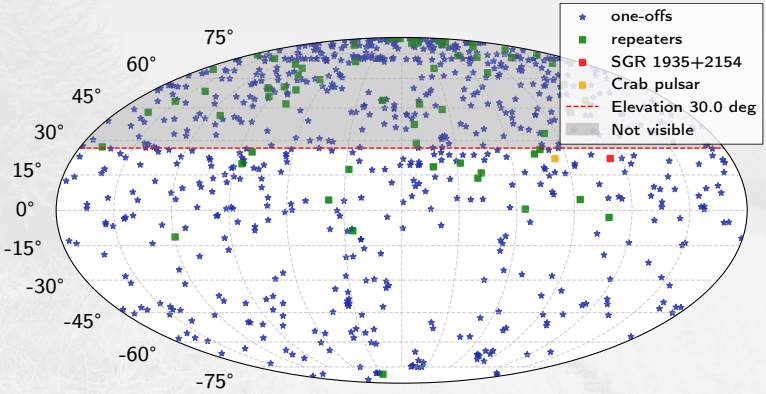

Figure: FRBs sky distribution in RA and Dec.

- Most FRBs have been detected above $\delta > 0°$
- There are no long wavelength experiments in the Southern Hemisphere
- Less than $\sim$20 % $\delta < 0°$

A new radio interferometer: CHARTS

- Location: South America
- Exploit nearly empty sky at low latitudes
- A transient specific radio array
- Most experiments designed for multi-purpose besides transients
  - Limited FoV
  - Reduced monitoring capabilities
- The Galactic center has the potential of another **magnetar bright radio burst**
- Atacama region full with multiwavelength capabilities to follow-up

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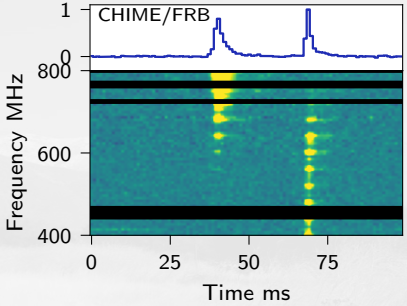

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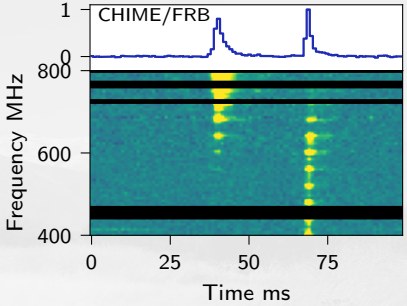

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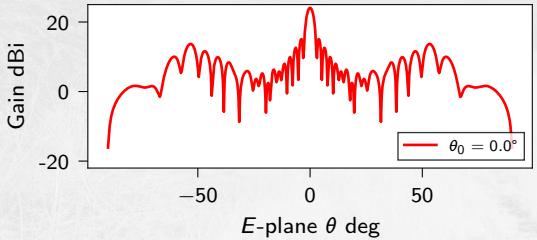
- Multiplexed and differential RF architecture
- New generation digitizers (Xilinx RFSoC)
- Prioritized number of antennas: $\mathcal{R} \propto \Delta\nu^{0.75} n_a^{1.5}$
- $A_e \propto n_p n_a \lambda^2$; $n_a = 256$ single-pol
- HPBW $\approx 100^\circ$
- FoV: $\Omega = \Omega_a = 8 \times 10^3\,\mathrm{deg}^2$
- 300–500 MHz passband



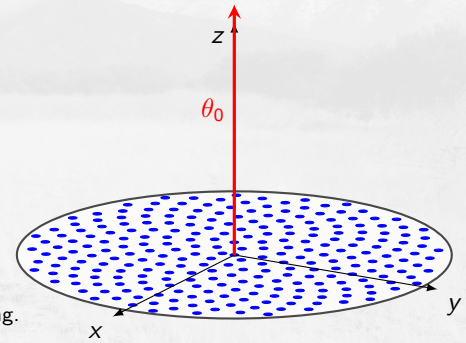


Figure: CHARTS configuration and beamforming.

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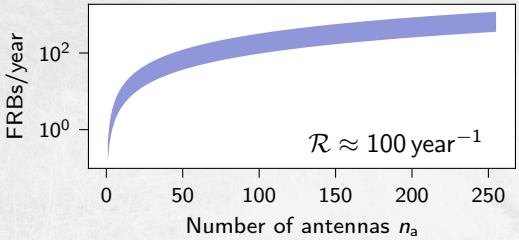

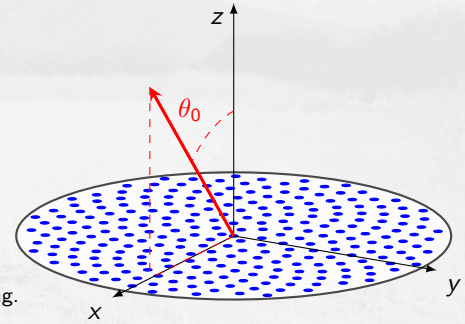

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CHARTS' scientific objectives

1. **Emission mechanisms**
   - Astrophysical process that produces FRBs
2. **FRB progenitors**
   - Identify sources and type of galaxy where they occur
3. **Magnetar bursts and bright pulsar giant pulses**
   - Monitor local (Milky Way) phenomena that may be related to FRBs
4. **New repeating FRBs**
   - Some FRBs repeat but less than 5 % repeaters found in the South

- Optimized for bright FRBs
- FRBs slightly brighter near 400 MHz

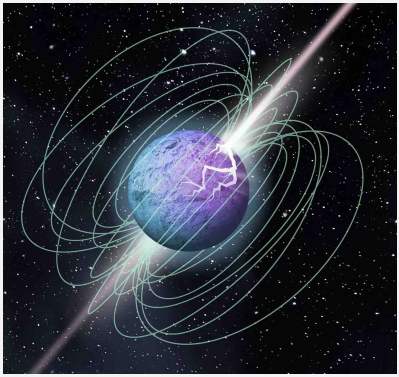
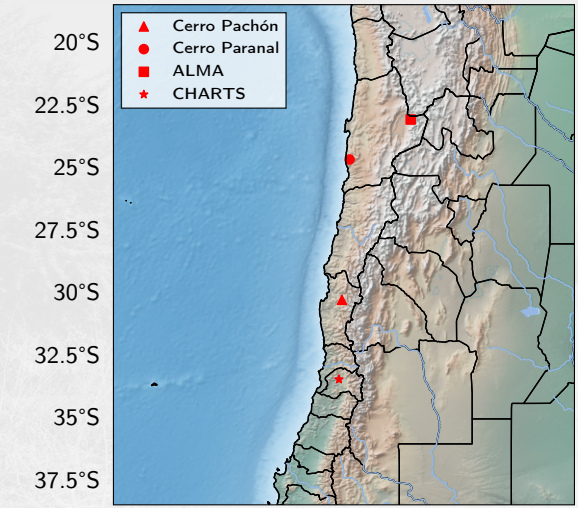
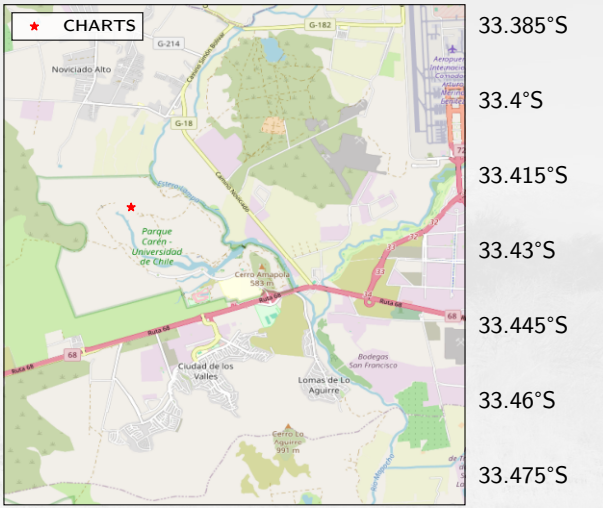


Figure: An artist's impression shows an outburst from a magnetar (McGill University Illustration).

CHARTS Earth locaton lat -33°





Site: Laguna Carén

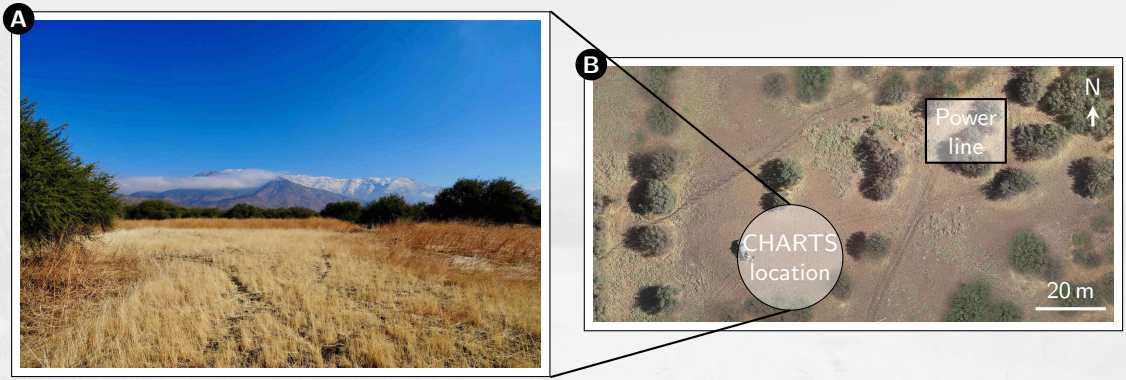


Figure: **A**: Laguna Carén site. **B**: View from the site. Array will cover $\sim$20 m $\times$ 20 m. Location is deep within the park with restricted access to the public.

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CHARTS field-of-view Ω

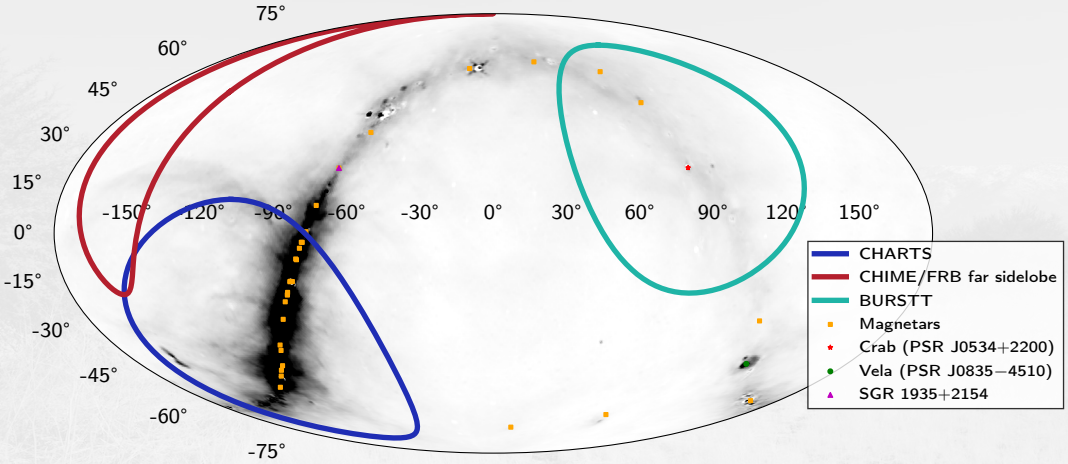

Figure: CHIME/FRB far sidelobe (Lin et al. 2024), BURSTT (Ling et al. 2023), and CHARTS FoV. Magnetars (Olausen & Kaspi 2014) and Galactic synchrotron background (300 MHz; BeyondPlanck Collaboration et al. 2023).

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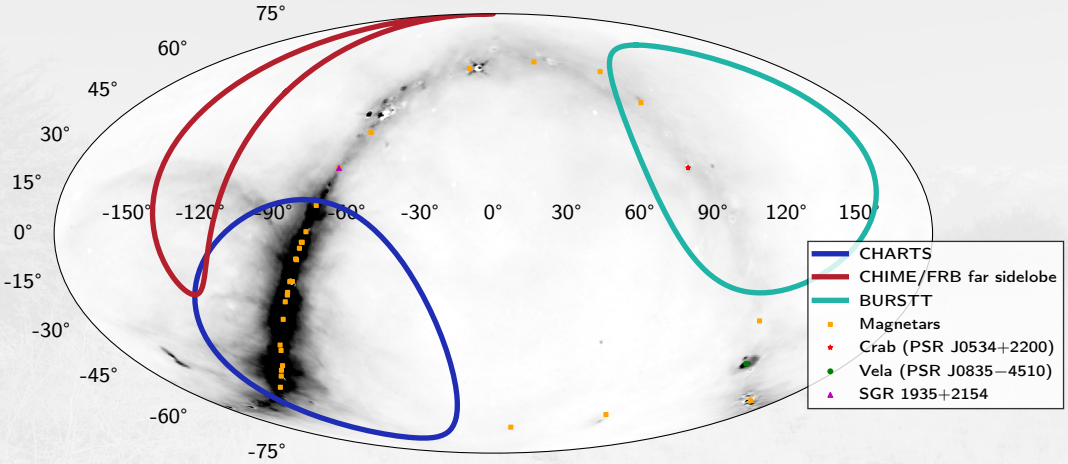

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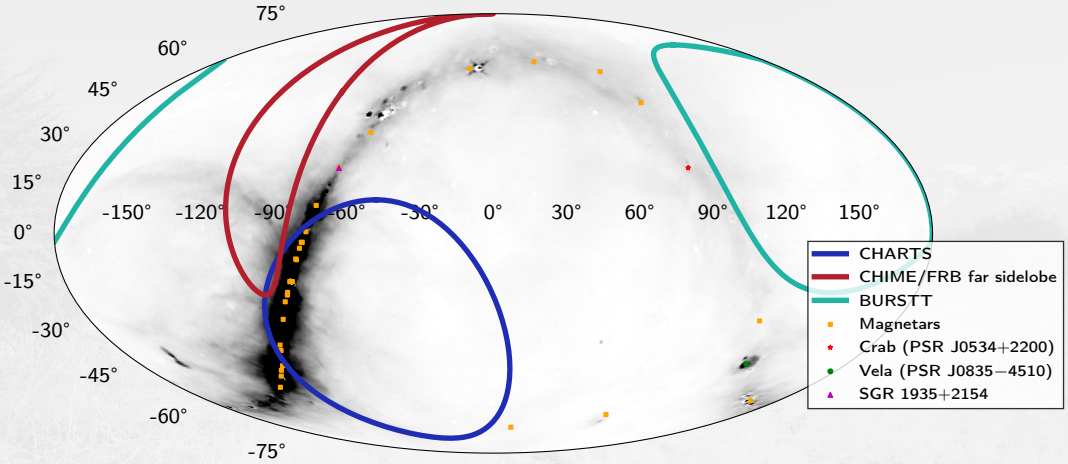

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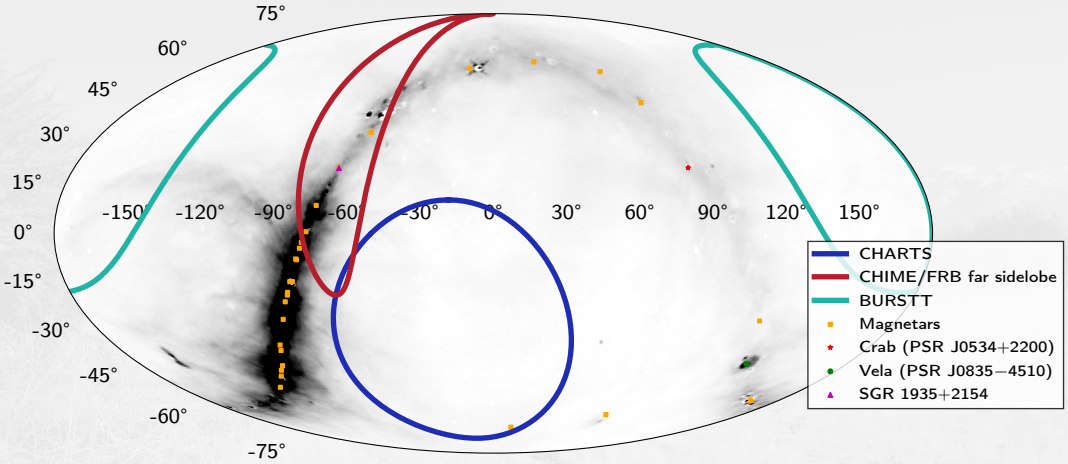

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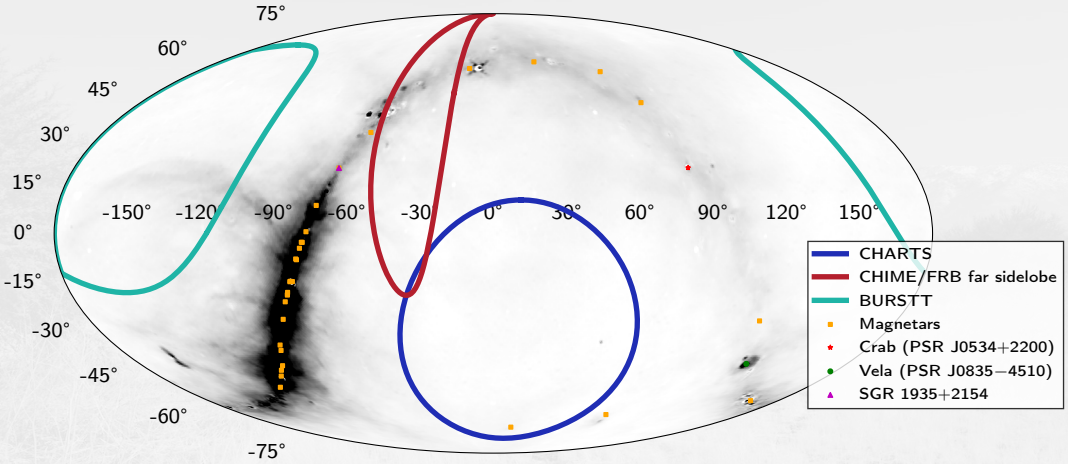

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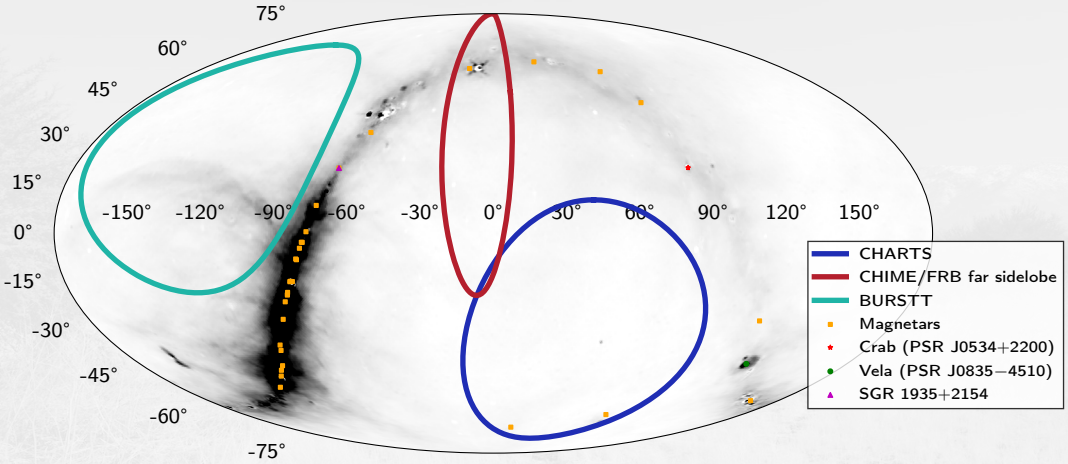

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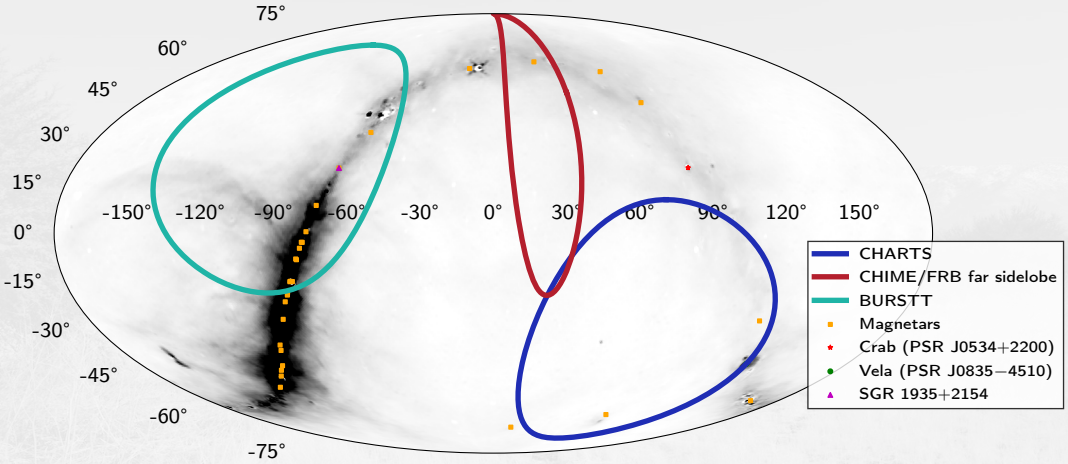

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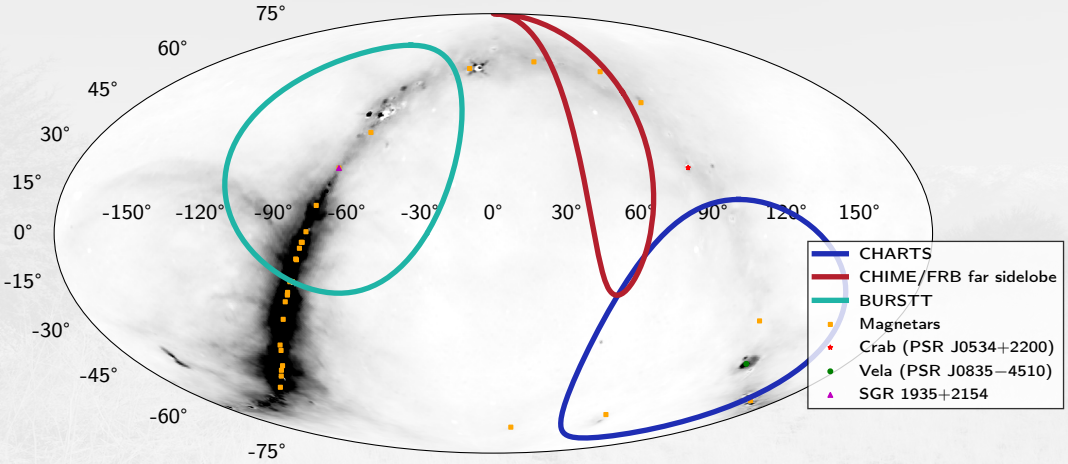

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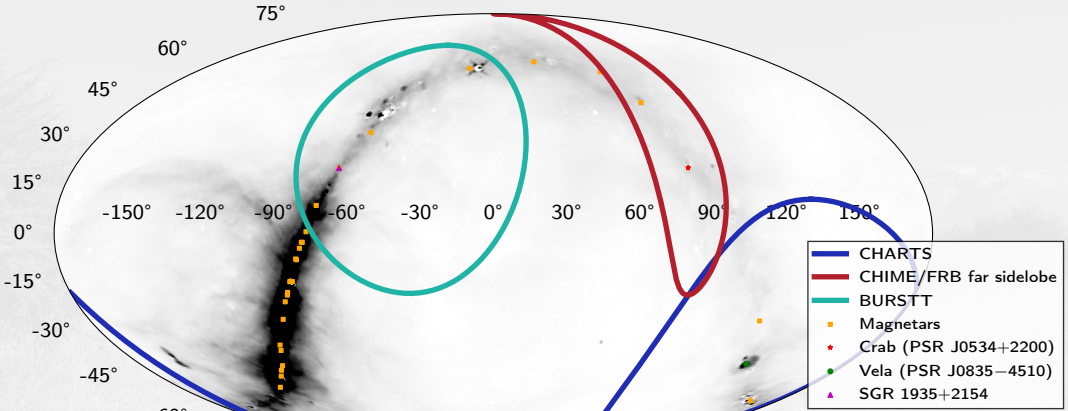

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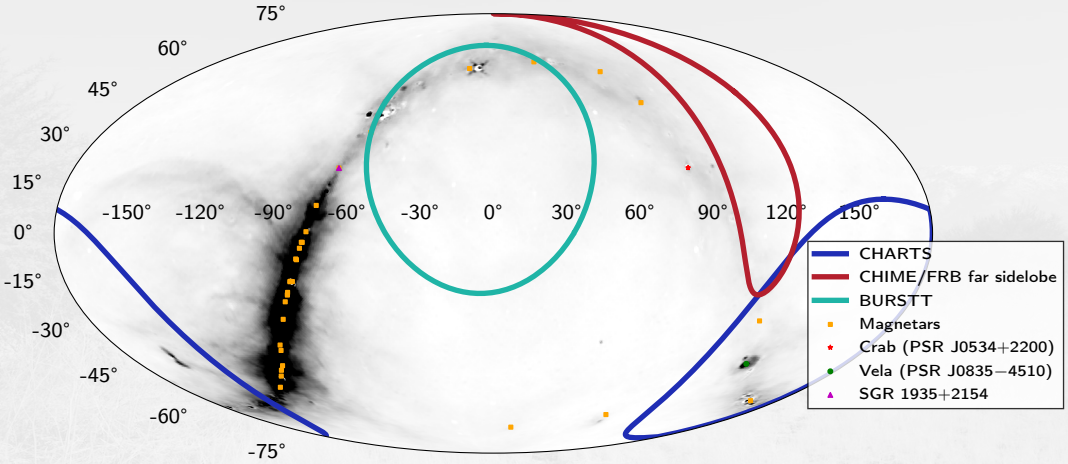

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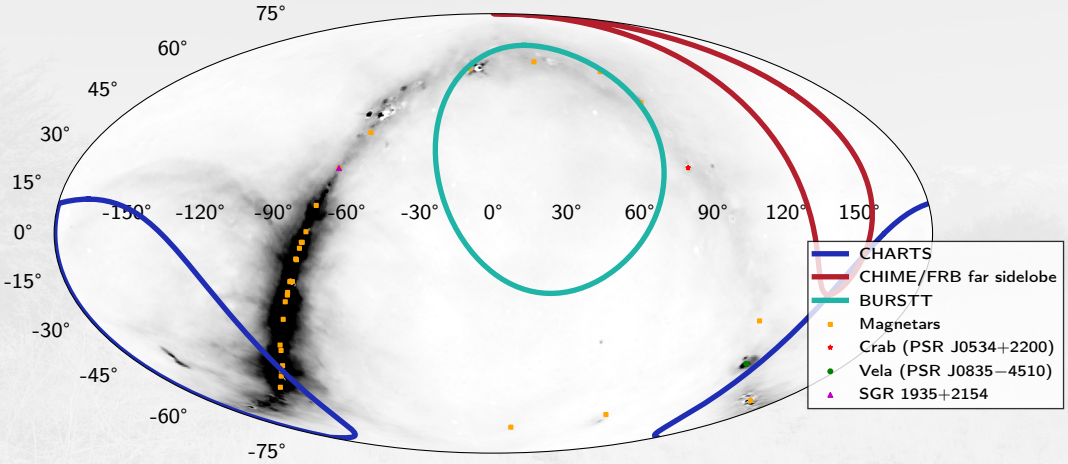

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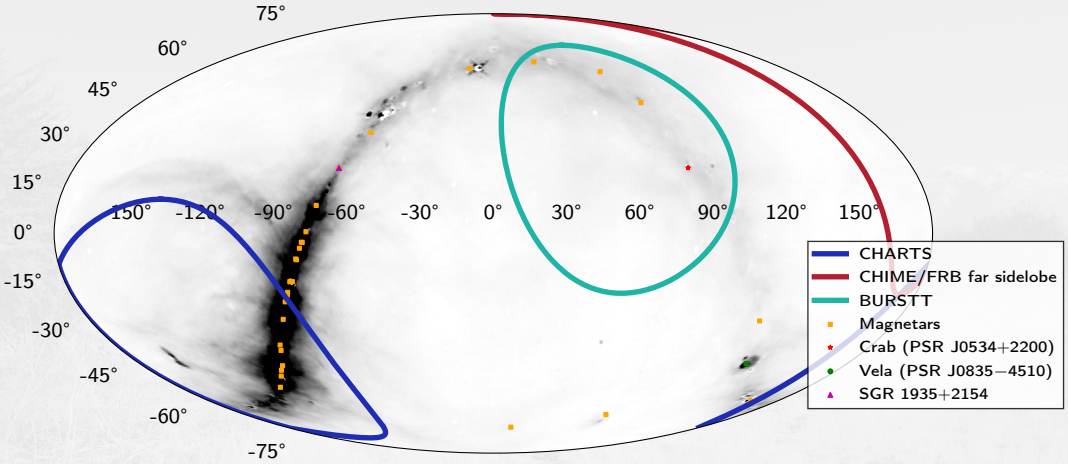

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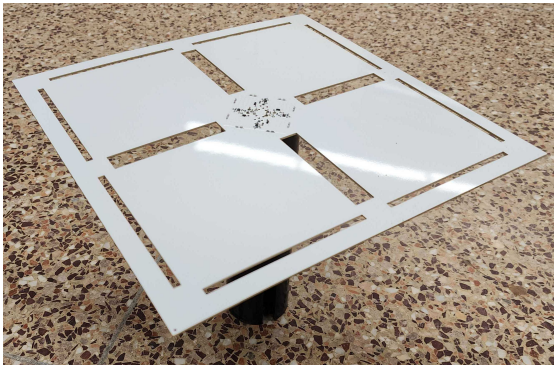
Antenna developments HPBW $\approx 90\,\mathrm{deg}$

- A planar printed antenna
- Differential $Z_\mathrm{a} = 100\text{–}130\,\Omega$
- Led by: Dr. Albert Wai Kit Lau
- HPBW $\approx 90\,\mathrm{deg}$
- $\sim$7 dBi
- Aperture array Ω is the antenna FoV Ω_a
- $T_\mathrm{sys} < 50\,\mathrm{K}$

28 cm $\times$ 28 cm



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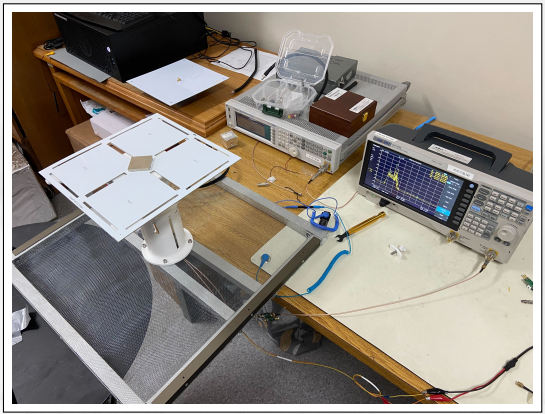

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Radio frequency chain

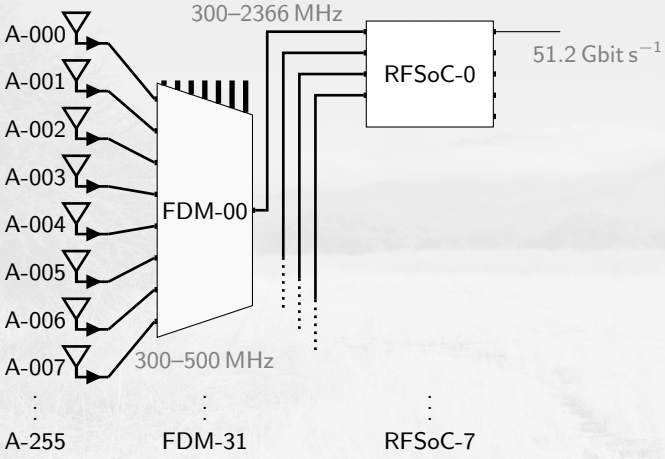

Figure: Radio frequency chain for 256 antennas.

- Passband 300–500 MHz
- $\Delta\nu = 200$ MHz
- Frequency division mutiplexer (FDM)
- Xilinx RFSoC ditigizer
- 32 antennas per digitizer
- 1 FDM every 8 antennas
- CHARTS analog components:
  - 256 antennas
  - 32 Multiplexers
  - 8 RFSoC
- Differential implementation: $Z \neq 50\,\Omega$
- Effective bandwidth 2.45 GHz
- Entire system: 410 Gbit s^{-1}

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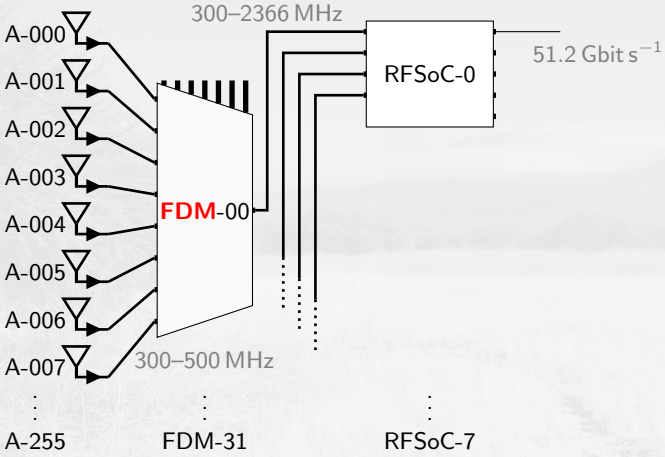

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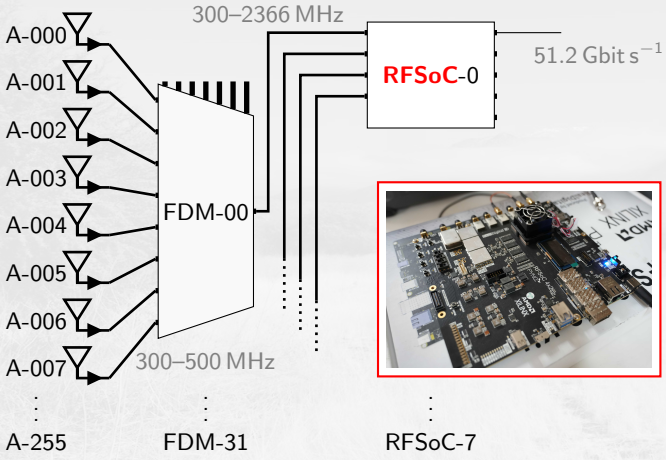

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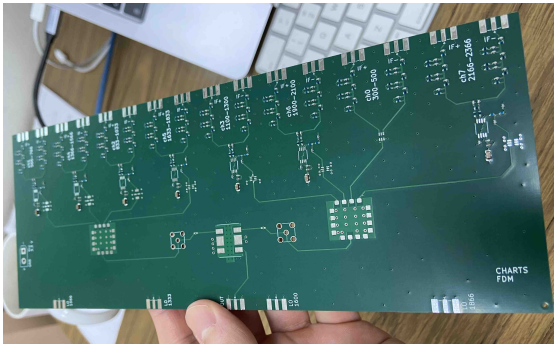
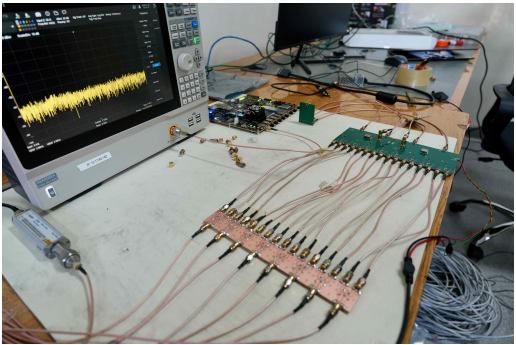
- Full band: 300–2400 MHz
- Differential impedance
- Electrical length, coupling, isolation, impedance matching, bias-tee, baluns, not a simple project!





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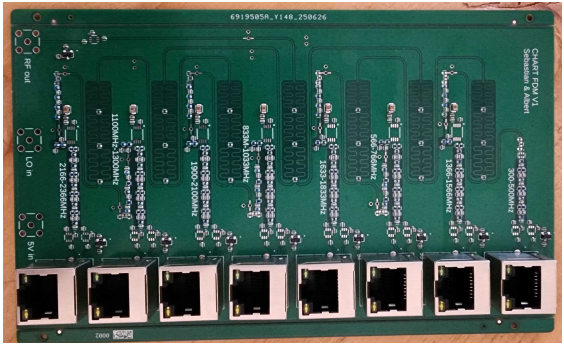
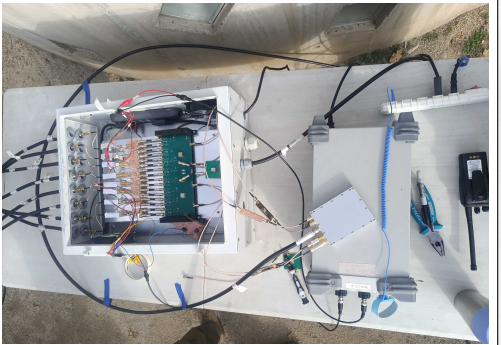
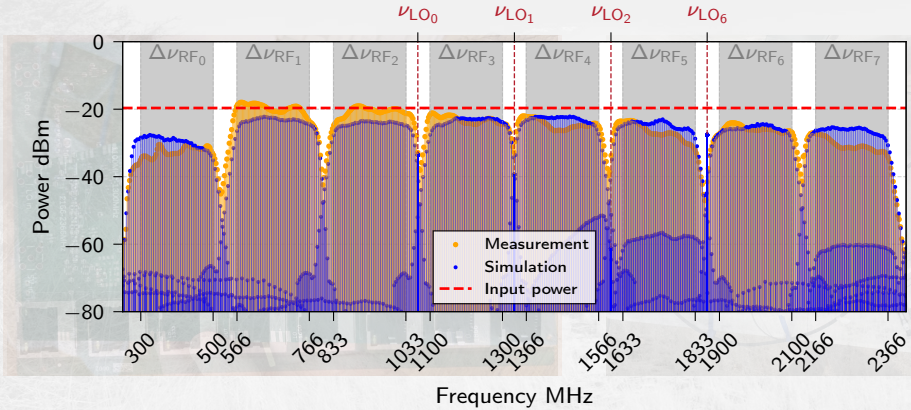




Frequency division multiplexer (FDM) development

- Lead by MSc. **Sebastián Manosalva**
- Full band: 300–2400 MHz
- Differential impedance
- Electrical length, coupling, isolation, impedance matching, bias-tee, baluns, not a simple project!



F-engine: RFSoC demux implementation

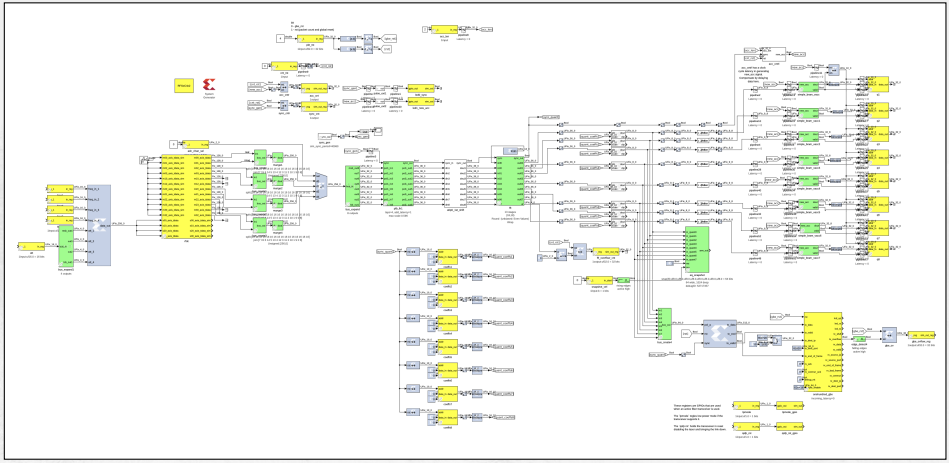


Figure: CASPER-based (Hickish et al. 2016) spectrometer in RFSoC 4x2. Led by Bruno Pollarolo.

F-engine: RFSoC demux implementation

$4 + 4$ bit
Fourier Transform
demux
LO tones
Linked to 100 GbitE

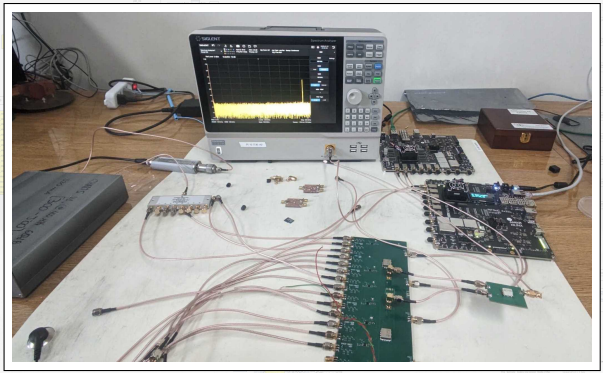
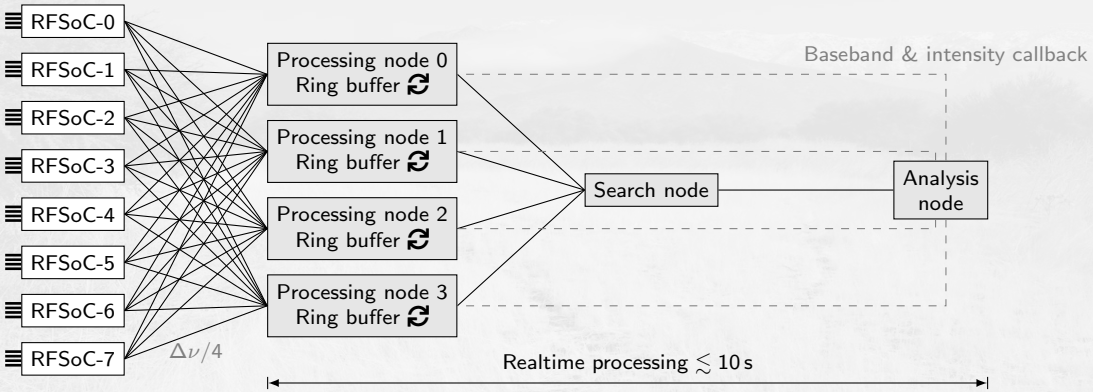


Figure: CASPER-based (Hickish et al. 2016) spectrometer in RFSoC 4x2. Led by **Bruno Pollarolo**.

FX-engine architecture



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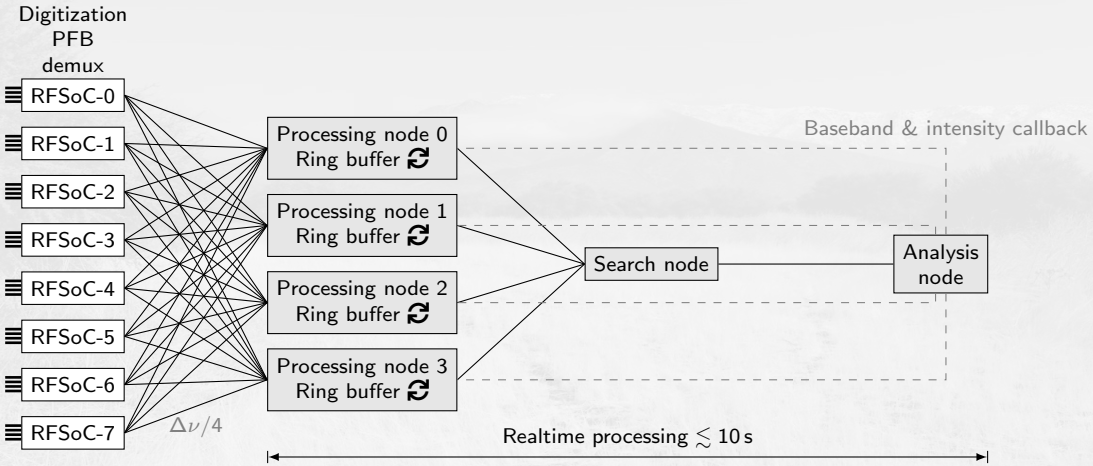

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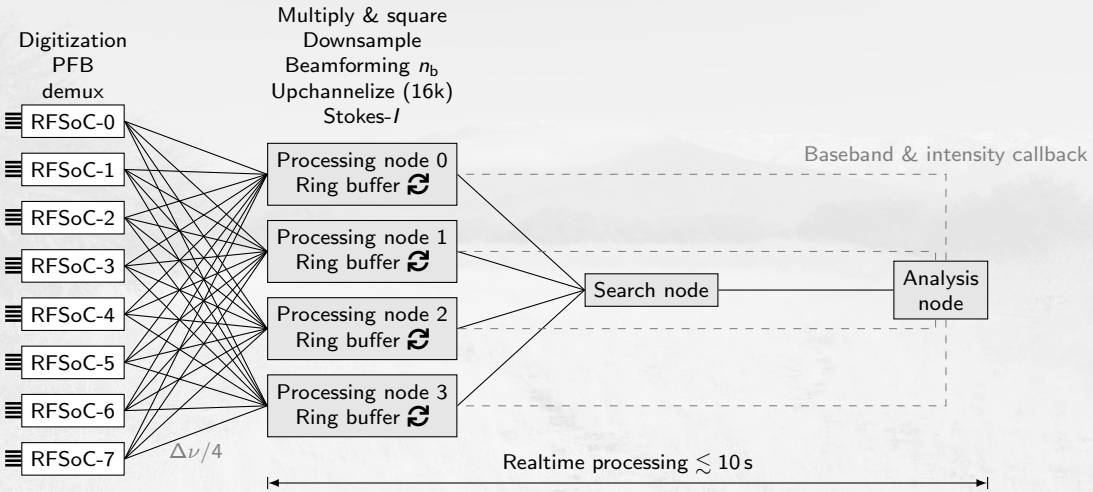

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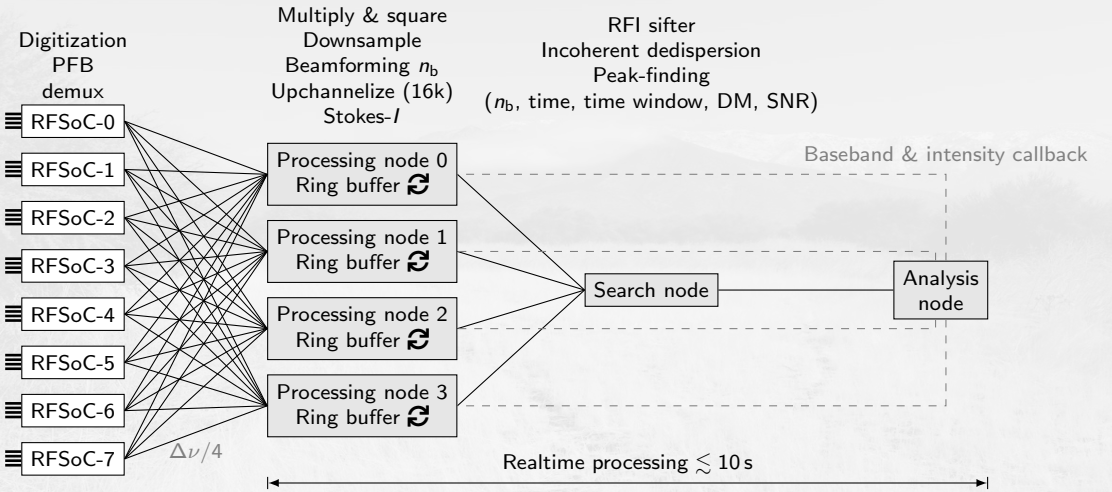

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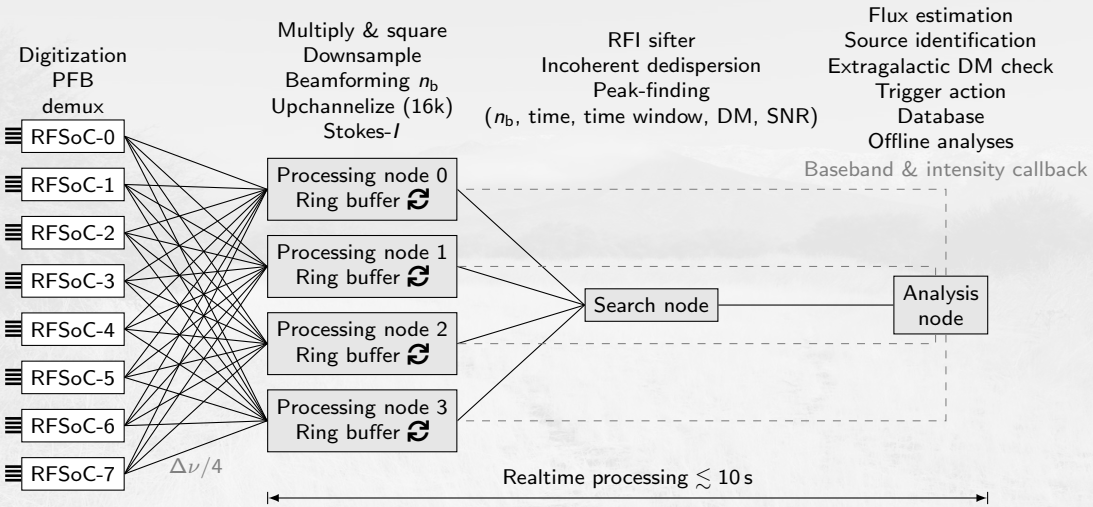

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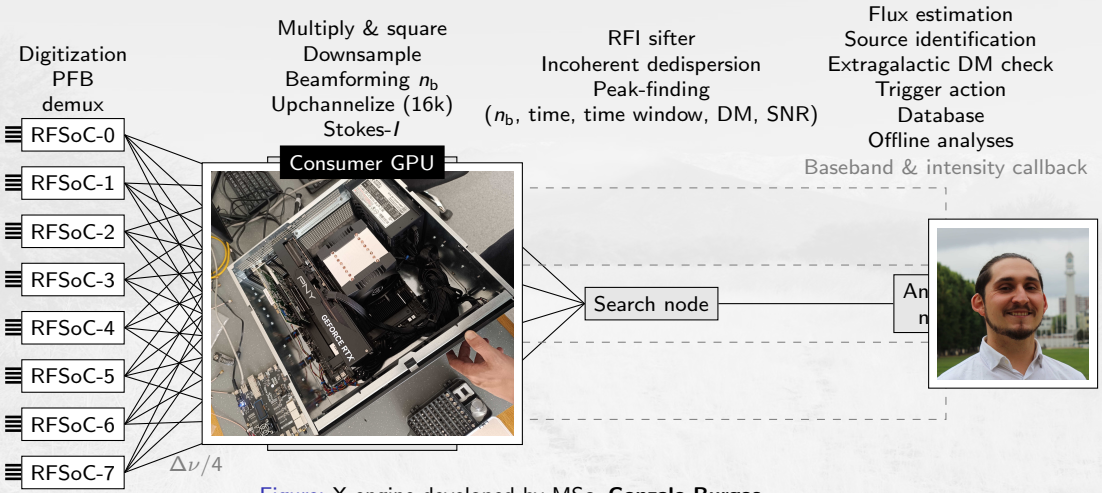
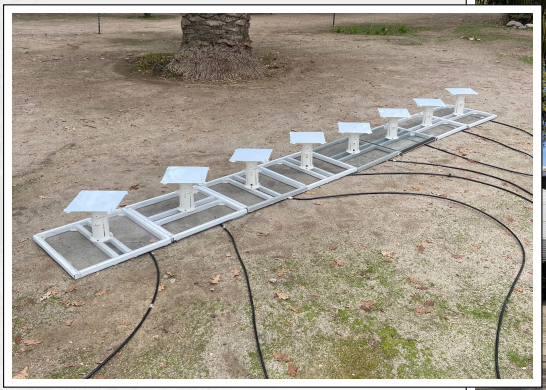


Figure: X-engine developed by MSc. **Gonzalo Burgos**.

CHARTS-8 prototype and preliminar performance



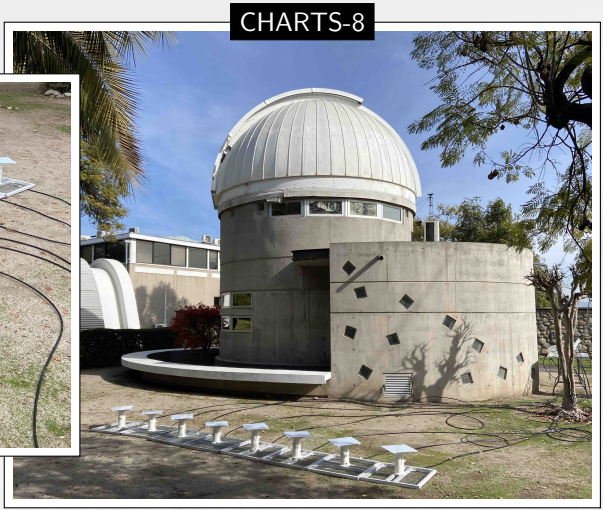
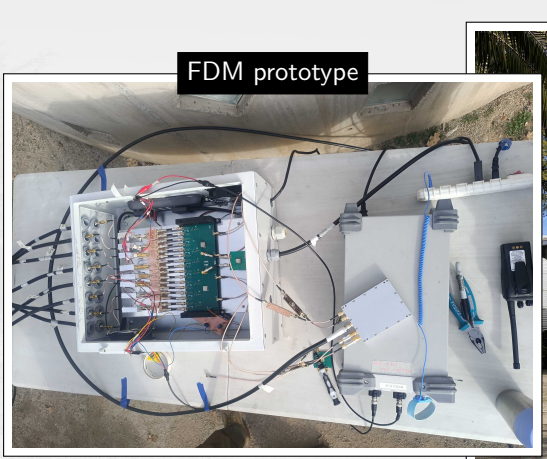


Figure: CHARTS-8 prototype at Universidad de Chile.

CHARTS-8 prototype and preliminar performance



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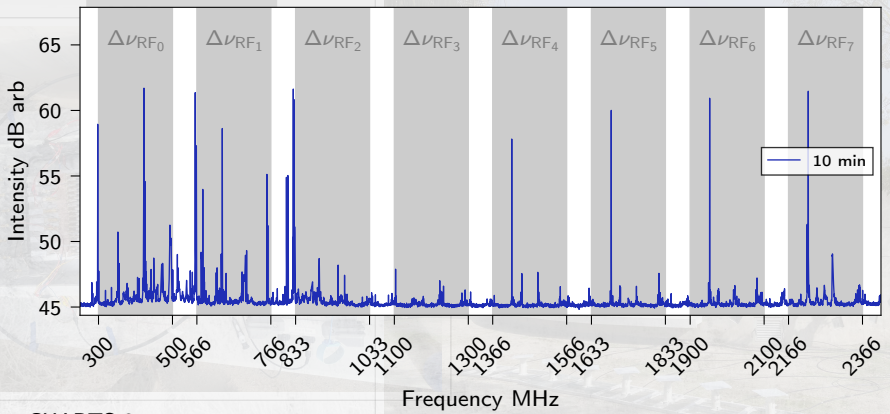

Figure: CHARTS-8 prototype at Universidad de Chile.

Summary and takeaways

Table: CHARTS parameter summary.

Parameter	Value
Antenna beam (HPBW)	90 deg
Antenna polarization number n_p	1
Bandwidth $\Delta\nu$	200 MHz
Channel bandwidth	300 kHz
Field-of-view (FoV)	$\sim 8 \times 10^3$ deg^2
Frequency channels	$\sim$600
Number of antennas n_a	256
Number of beams n_b	10^3
Passband	300–500 MHz
Search sample time (t_s)	1 ms
Sample time (t_s)	3 µs
System temperature T_{sys}	50 K

- CHARTS: a modest instrument a great impact
- To be built entirely at university level
- Optimized for $\mathcal{R}$ and cost
- We prioritize n_a rather than $\Delta\nu$
- Cost impact:
  - Custom optimized antenna
  - FDM → less digitizers
  - Differential RF
  - Consumer GPUs
- **CHARTS-32 January 2026**

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- **CHARTS-32 January 2026**

CHARTS and beyond

- Pathfinder CHARTS-8
- **CHARTS** will start operating mid-2026 24/7 operations
- CHARTS will find $\mathcal{R}_{\rm CHARTS} \approx 100\,{\rm year}^{-1}$
- CHARTS will localize bright and nearby low-DM FRBs
- Collaboration at multiwavelength followups
- **CHARTS white paper in prep.!**

¡Gracias! Thanks!

- ANID BASAL FB210003
- ANID / Fondo 2023 QUIMAL/ QUIMAL230001
- Dunlap Seed Fund
- MITACS Globalink

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Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO

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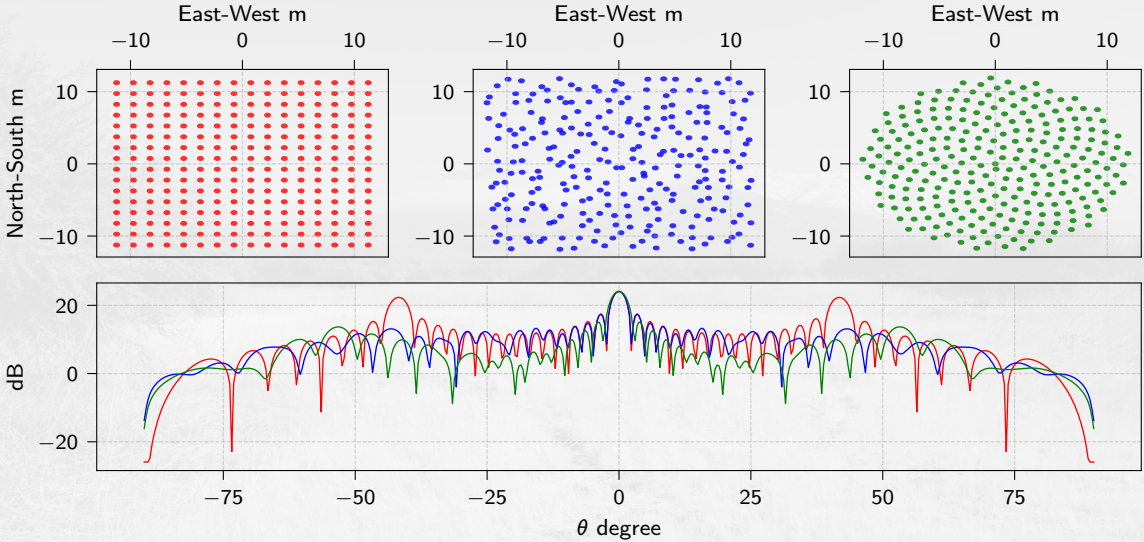
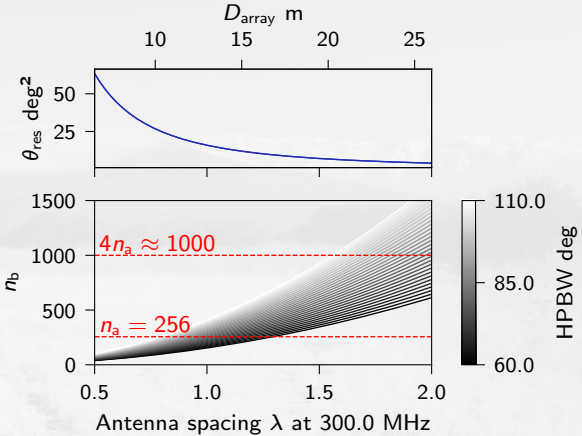
Array configuration ($d = 1.5\lambda$, $\theta_{\text{res}} = 2.3^\circ$, $n_{\text{b}} = 1226$)



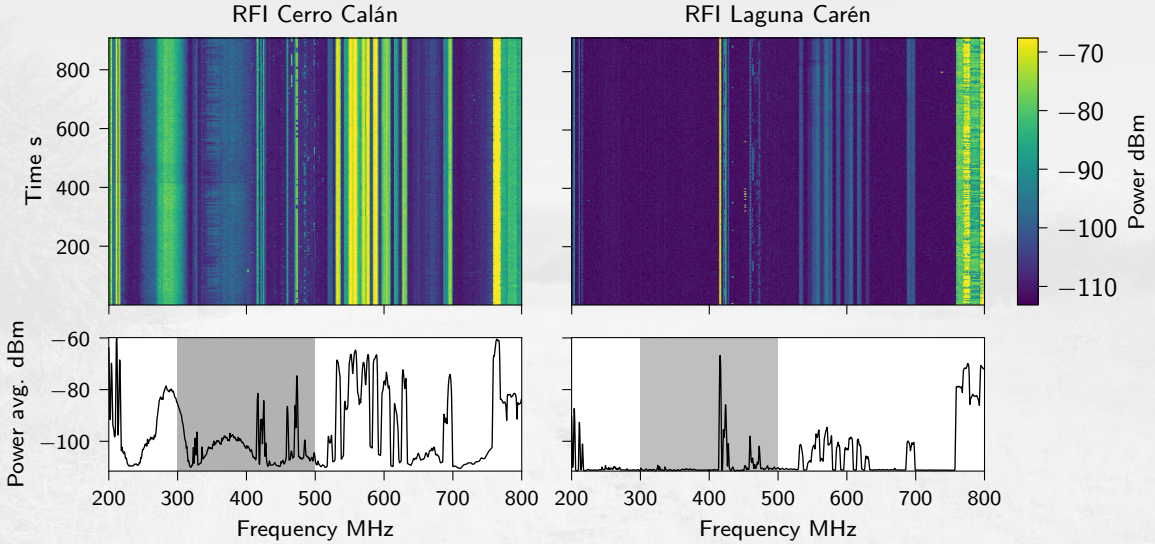
CHARTS field-of-view Ω, beams n_b, and angular resolution θ_{res}

- Angular resolution vs. computation resources
- Complexity $\propto n_a \times n_b$
- CHARTS will cover the full Galactic center $\sim 5\,\mathrm{h\,d^{-1}}$
- $\Omega \approx 8 \times 10^3\,\mathrm{deg}^2 \rightarrow n_b = 10^3$ (honeycomb lattice)
- Triggered baseband capabilities $\theta_{res} \approx \mathrm{SNR}^{-1}$

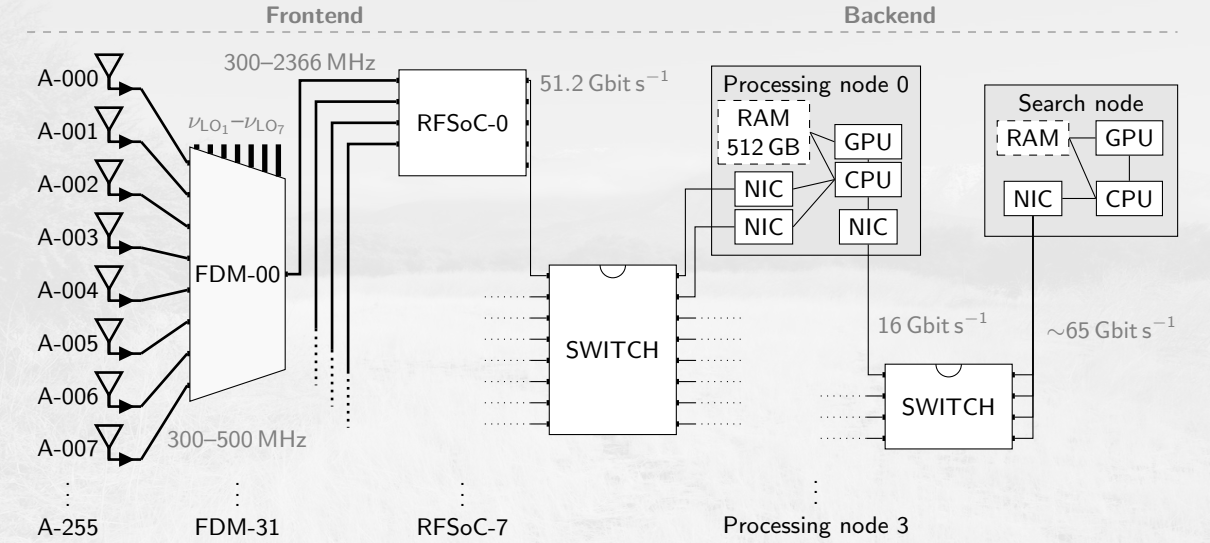


Figure

Radio frequency interference



CHARTS overview



Pulsars frequency spectra J0837+0610

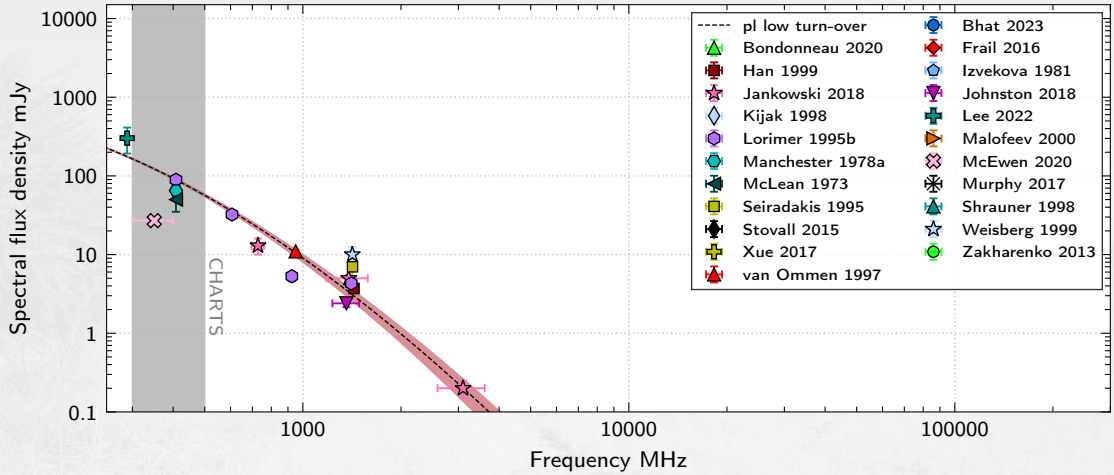


Figure: Frequency spectra for pulsar J0837+0610 (Swainston et al. 2022). Maximum S_ν near 100 MHz, though there are many reason why **not** to observe at those frequencies.

Pulsars frequency spectra Vela

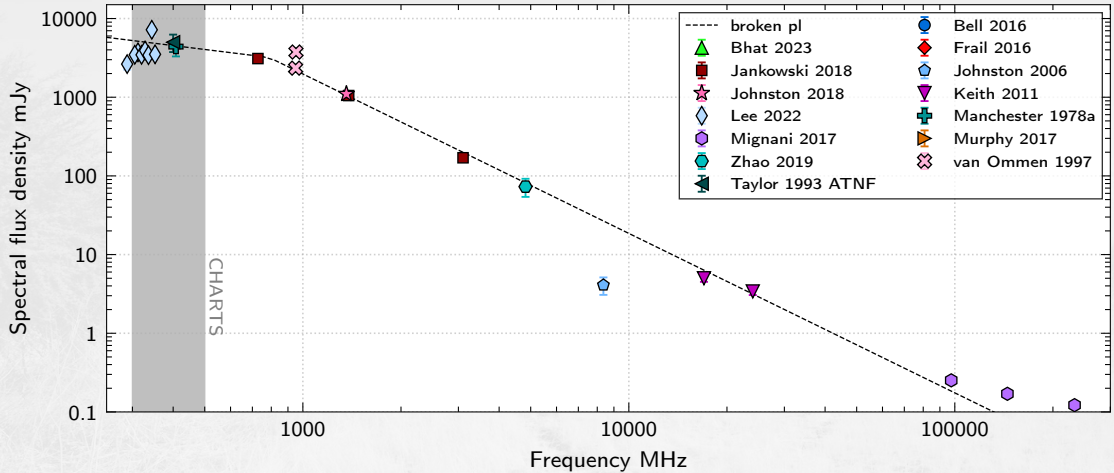


Figure: Frequency spectra for pulsar J0835-4510 (Vela) (Swainston et al. 2022). Maximum S_ν near 100 MHz, though there are many reason why **not** to observe at those frequencies.

Pulsars frequency spectra J2018+2839

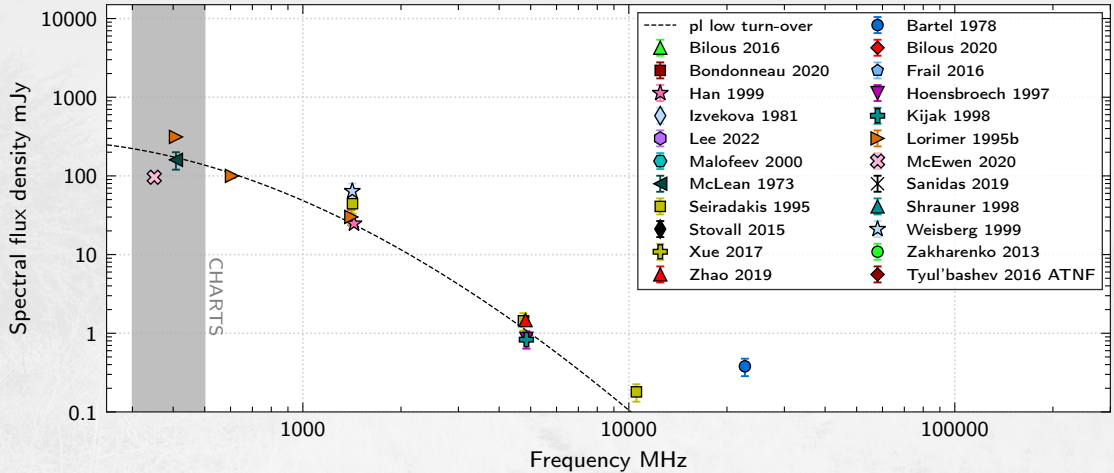


Figure: Frequency spectra for pulsar J2018+2839 (Swainston et al. 2022). Maximum S_ν near 100 MHz, though there are many reason why **not** to observe at those frequencies.

Radio radiation foreground (or frequency spectrum) → an optimum?

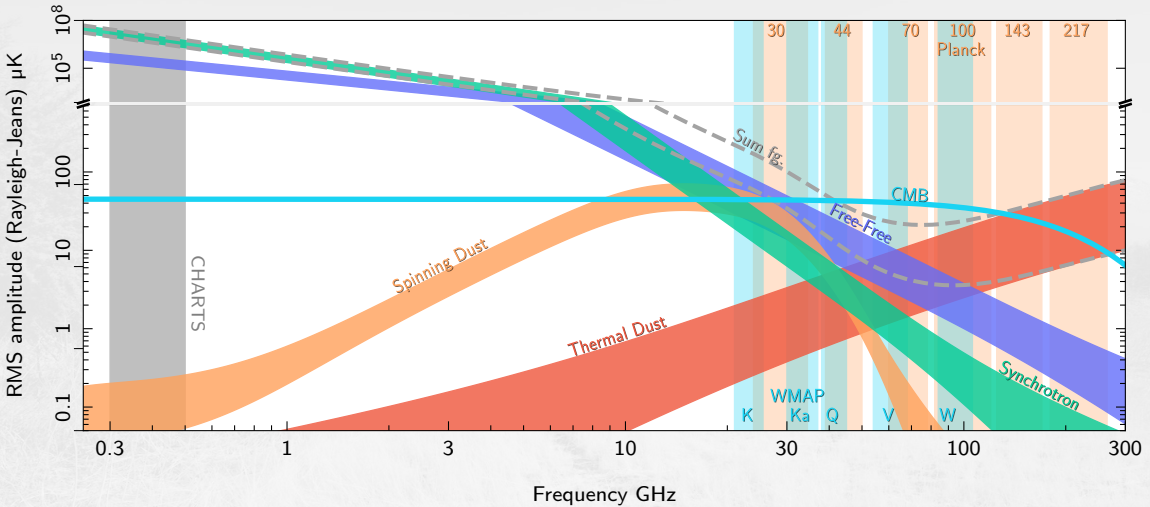
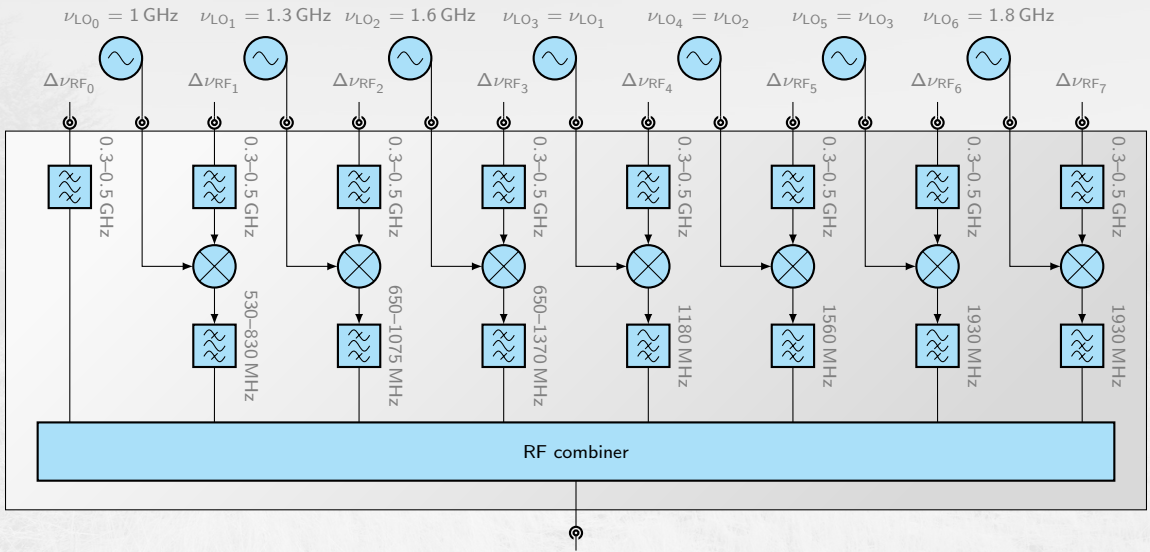


Figure: Adapted from BeyondPlanck Collaboration et al. (2023).

Frequency division multiplexer (FDM)



CHARTS' scientific objectives

1. **Emission mechanisms**
   - Magnetospheric emission
   - Coherent curvature radiation
2. **FRB progenitors**
   - Spiral and dwarf galaxies, globular clusters, etc.
3. **Magnetar bursts and bright pulsar giant pulses**
   - Galactic bright radio bursts
   - Super giant pulses
4. **New repeating FRBs**
   - There are only 4 repeating FRBs below $\delta < 0^\circ$

- Optimized for nearby and bright FRBs (low-DM)
- FRBs slightly brighter near 400 MHz

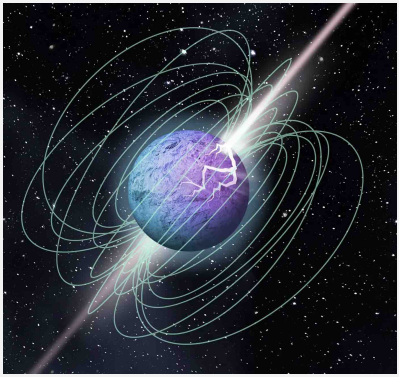


Figure: An artist's impression shows an outburst from a magnetar (McGill University Illustration).

Antenna developments: scaled model

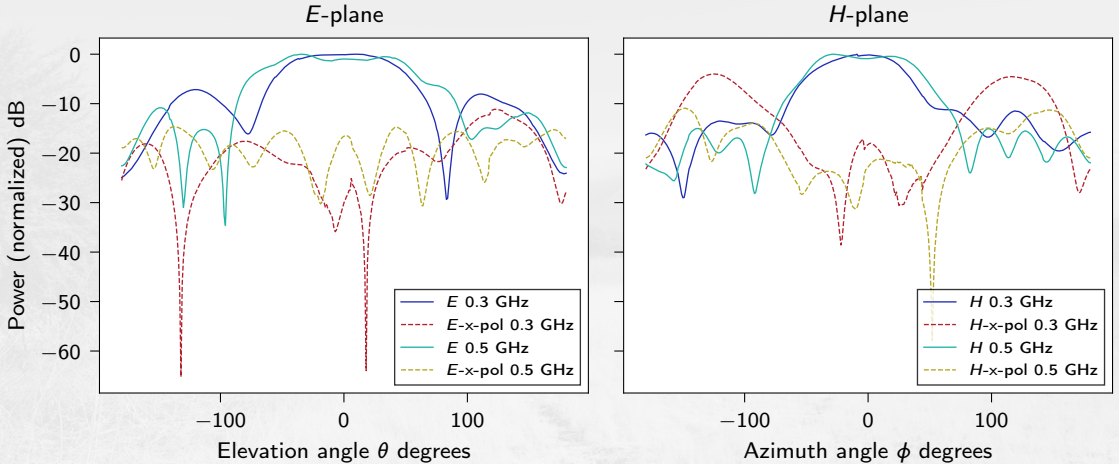
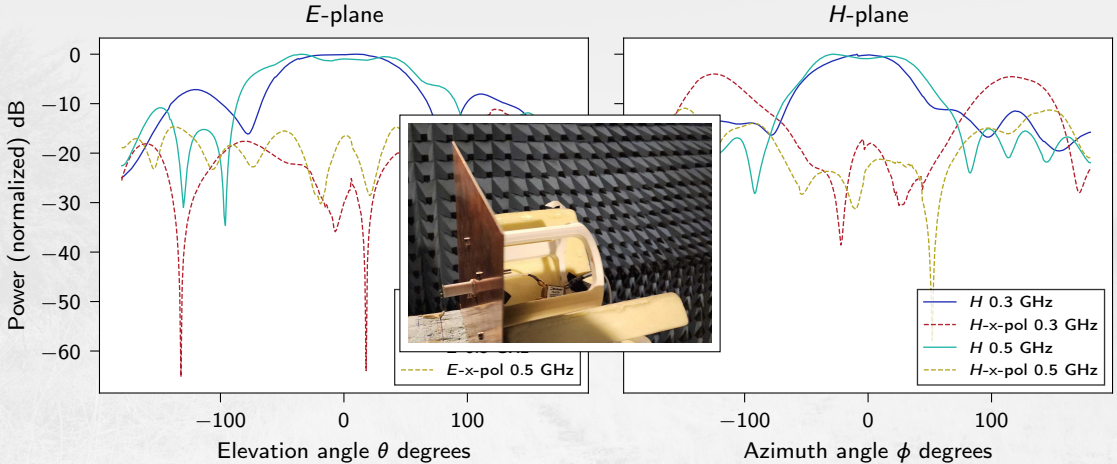


Figure: Antenna power pattern measurements using a 1:5.5 scaled model.

Antenna developments: scaled model



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Summary

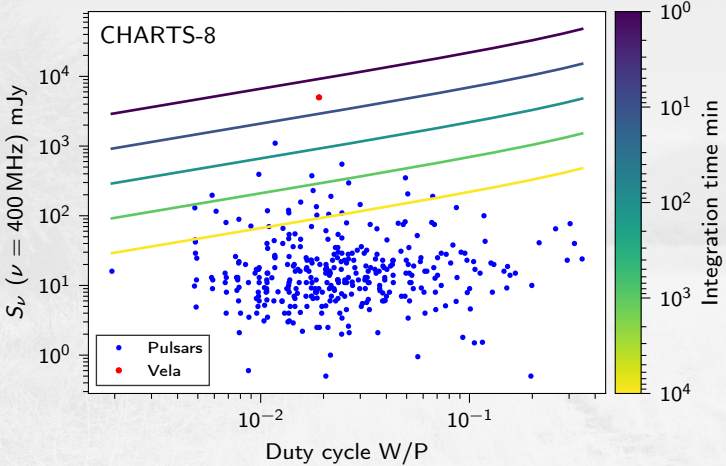

Figure: Pulsar detection CHARTS-8 Southern Hemisphere.

CHARTS team: astronomers, engineers, and physisists

Canada University of Toronto

- Prof. S. Hum (EE)
- Dr. A.W.K. Lau
- Prof. J. Mena-Parra (A&A)
- A. Renard
- Prof. K. Vanderlinde (A&A)

USA Harvard University

- Prof. L. Connor (A&A)

Chile Universidad de Chile

- EE. student O. Arias
- MSc. G. Burgos
- Prof. T. Cassanelli (EE)
- Prof. R. Finger (A&A)
- EE. MSc. student S. Manosalva
- EE. student F. Muñoz
- EE. student B. Pollarolo