New twists in the story of fast radio bursts

Image credit: Danielle Futselaar

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ASTRON - Netherlands Institute for Radio Astronomy

Universiteit van Amsterdam

European Research Council
Established by the European Commission

NWO
Netherlands Organisation for Scientific Research

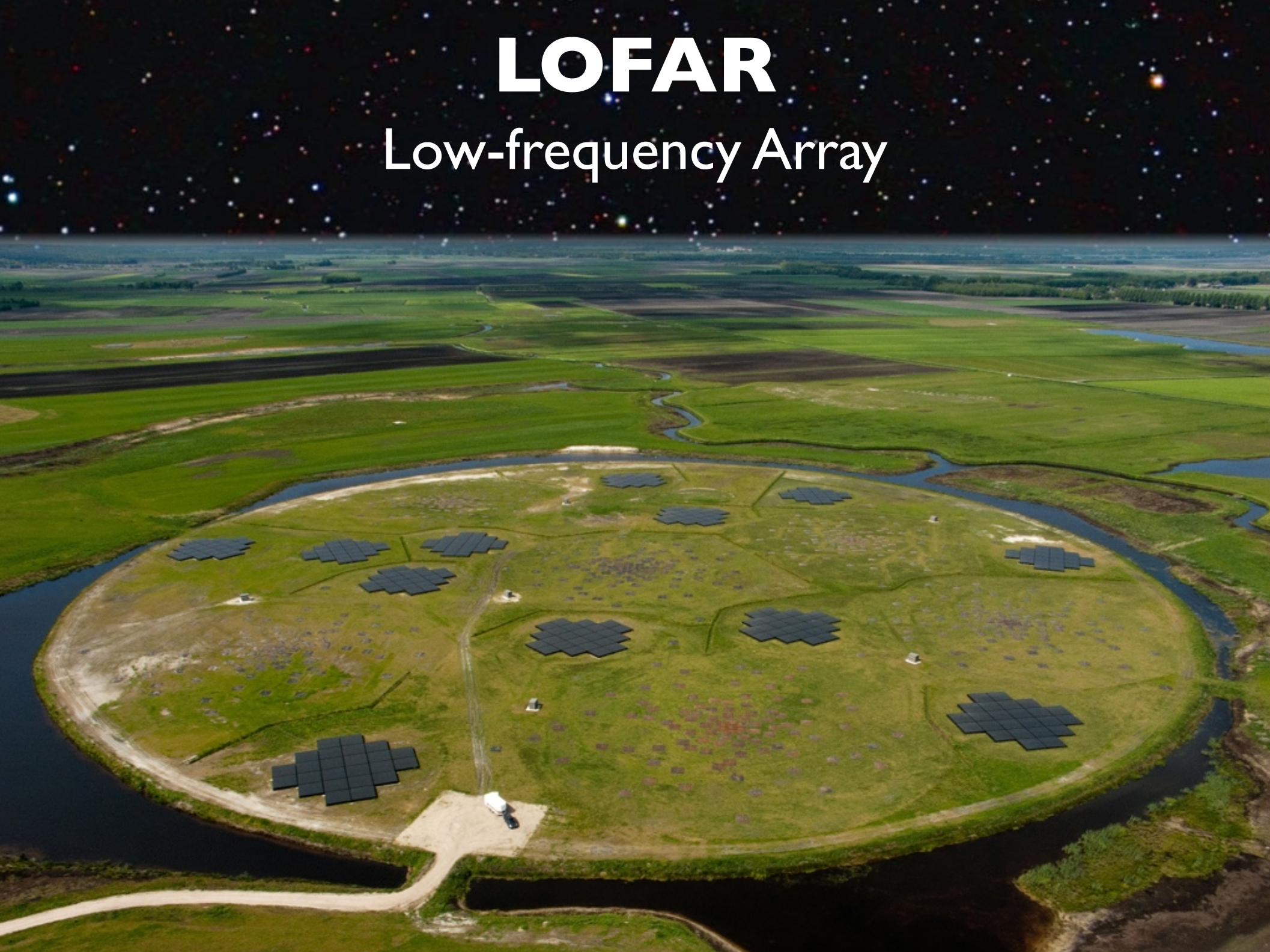
ASTRON
Netherlands Institute for Radio Astronomy

My universe...

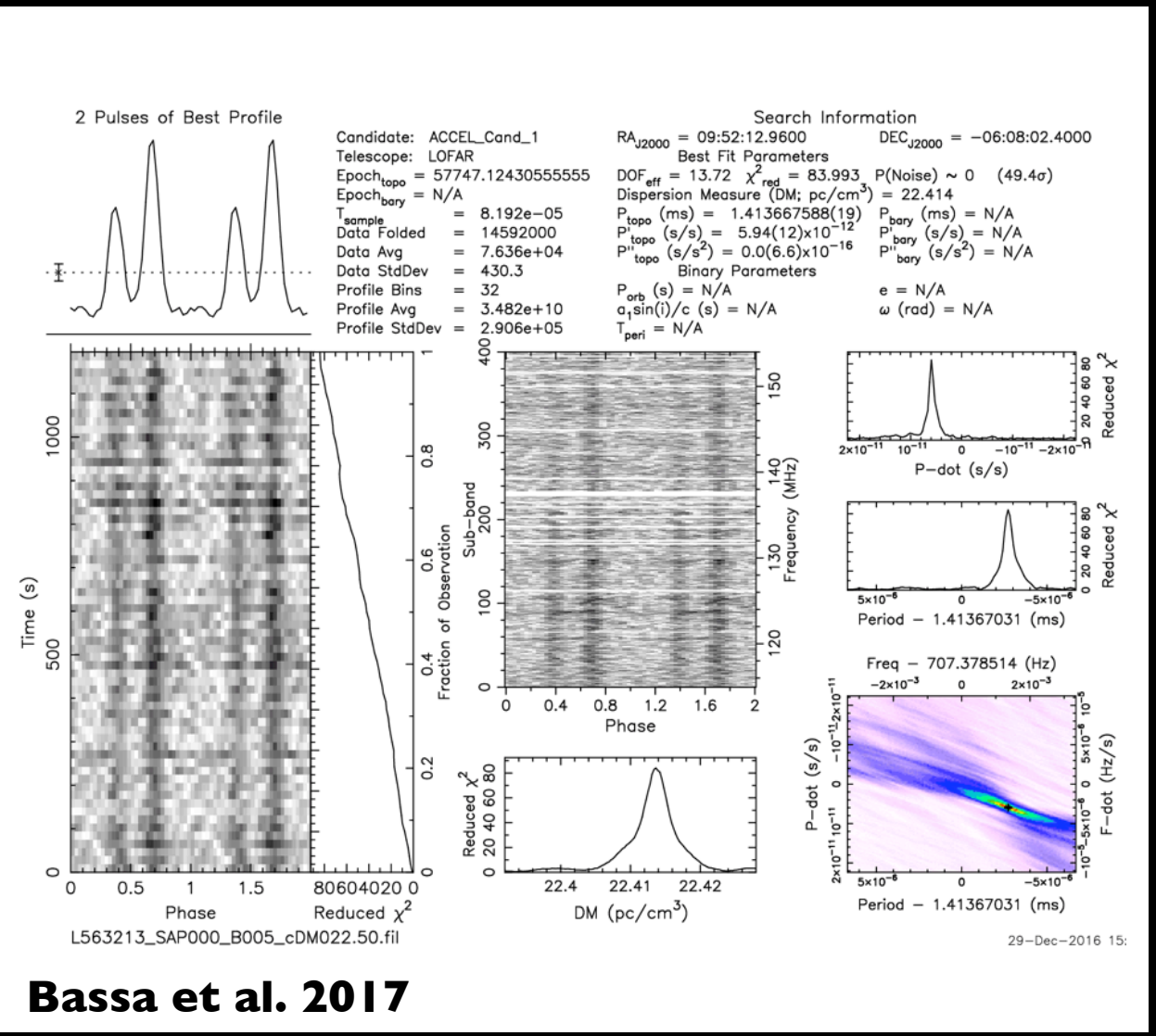

LOFAR
ASTRON
Westerbork
Anton Pannekoek Institute (UvA)
Nes
Oost-Vlieland
Den Helder
Schagen
Heerhugowaard
Alkmaar
Hoorn
Purmerend
IJmuiden
Zaanstad
Haarlem
Amsterdam
Amstelveen
Katwijk aan Zee
Hoofddorp
Leiden
Zoetermeer
Haag
Delft
Gouda
Utrecht
Nieuwegein
Rotterdam
Vlaardingen
Ridderkerk
Tiel
Groningen
Roden
Hoogezand
Assen
Stadskanaal
Steenwijk
Emmeloord
Meppel
Emmen
Hoogeveen
Coevorden
Hardenberg
Kampen
Zwolle
Lelystad
Almelo
Oldenzaal
Rijssen
Borne
Enschede
Losser
Glanerbrug
Haaksbergen
Lochem
Vreden
Ahaus
Winterswijk
Stadtlohn
Aalten
Emmerich
Bocholt
Borken

LOFAR

Low-frequency Array



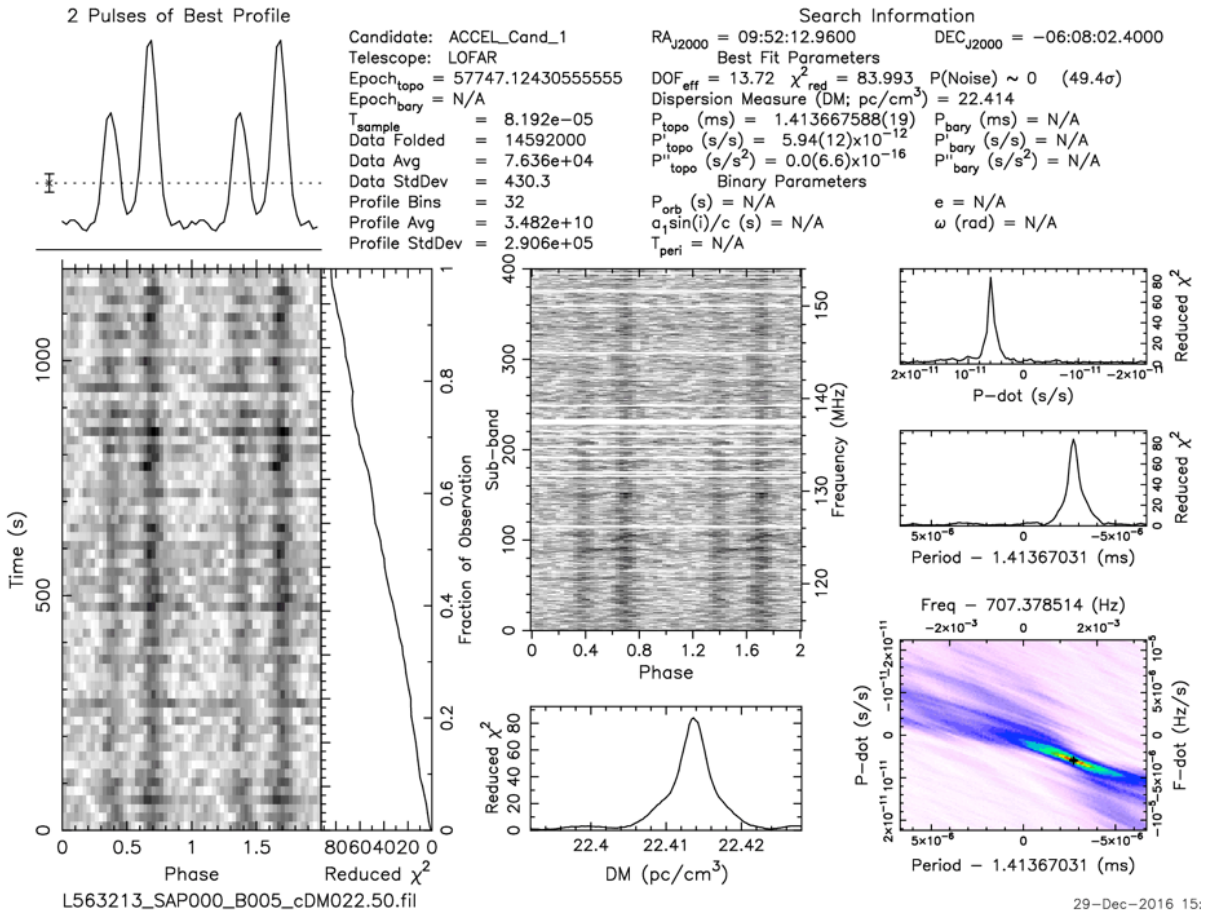
LOFAR Discovery



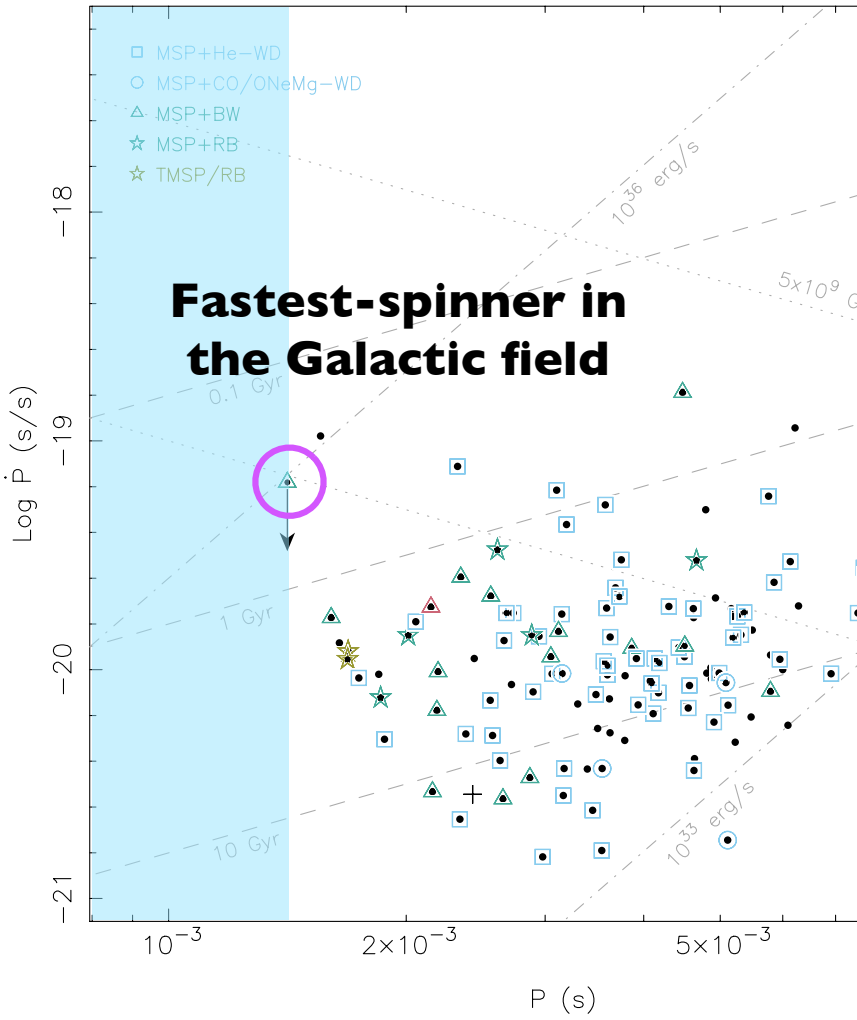
Bassa et al. 2017

1.4 ms / 707 Hz radio pulsar

LOFAR ms-Pulsar Discovery

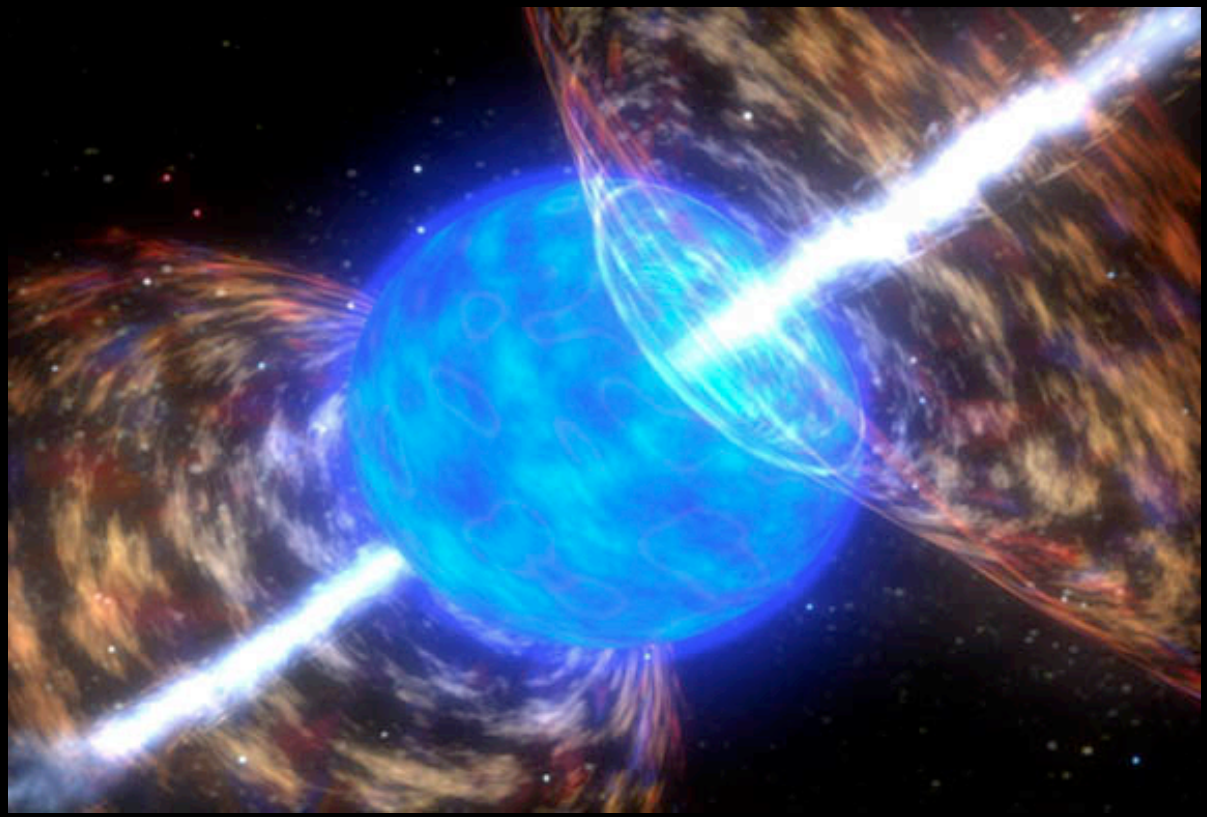


Bassa et al. 2017



1.4 ms / 707 Hz radio pulsar

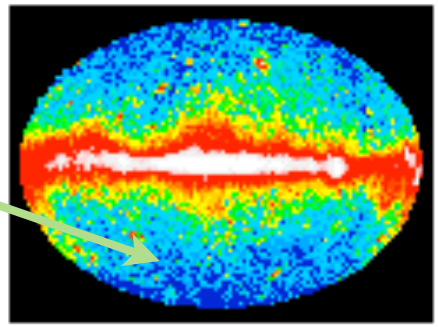
Gamma-ray Bursts



Are there also similar signals in the radio?

Gamma-ray Bursts

Typical FoV of a radio telescope is << 1 sq. deg.



Are there also similar signals in the radio?

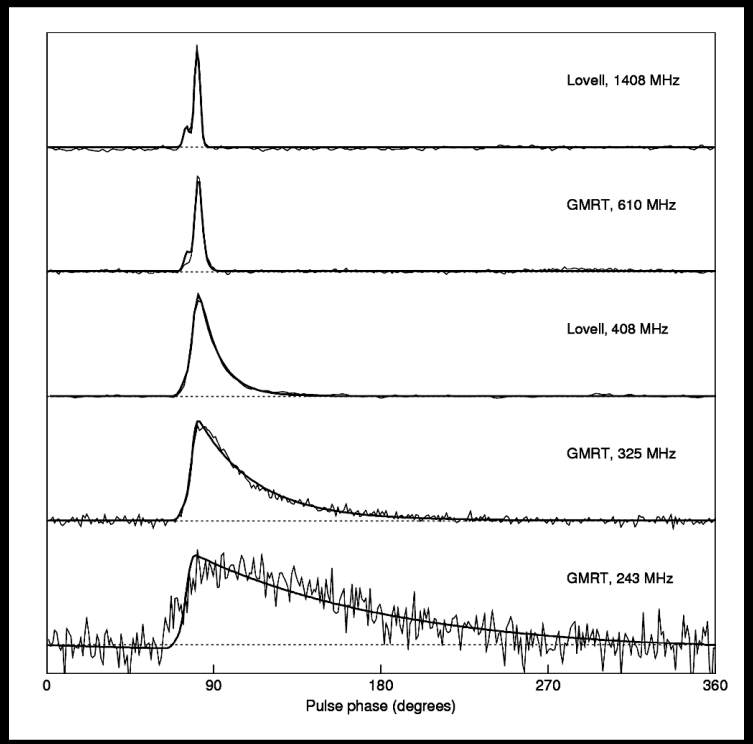
Propagation Effects

Observed signal →

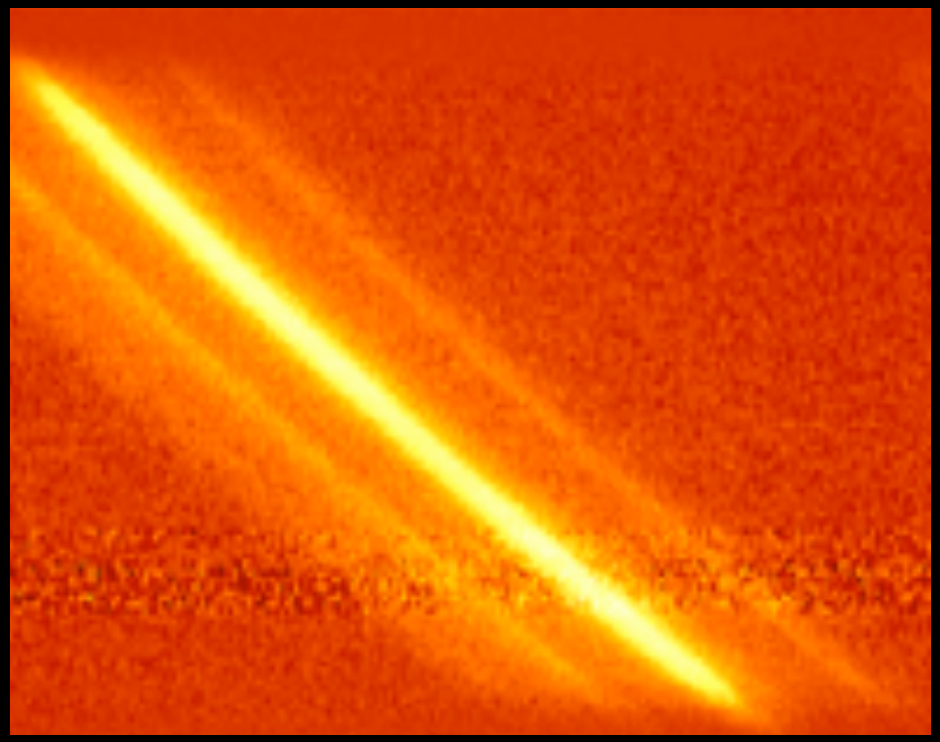
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

↑ Emitted signal

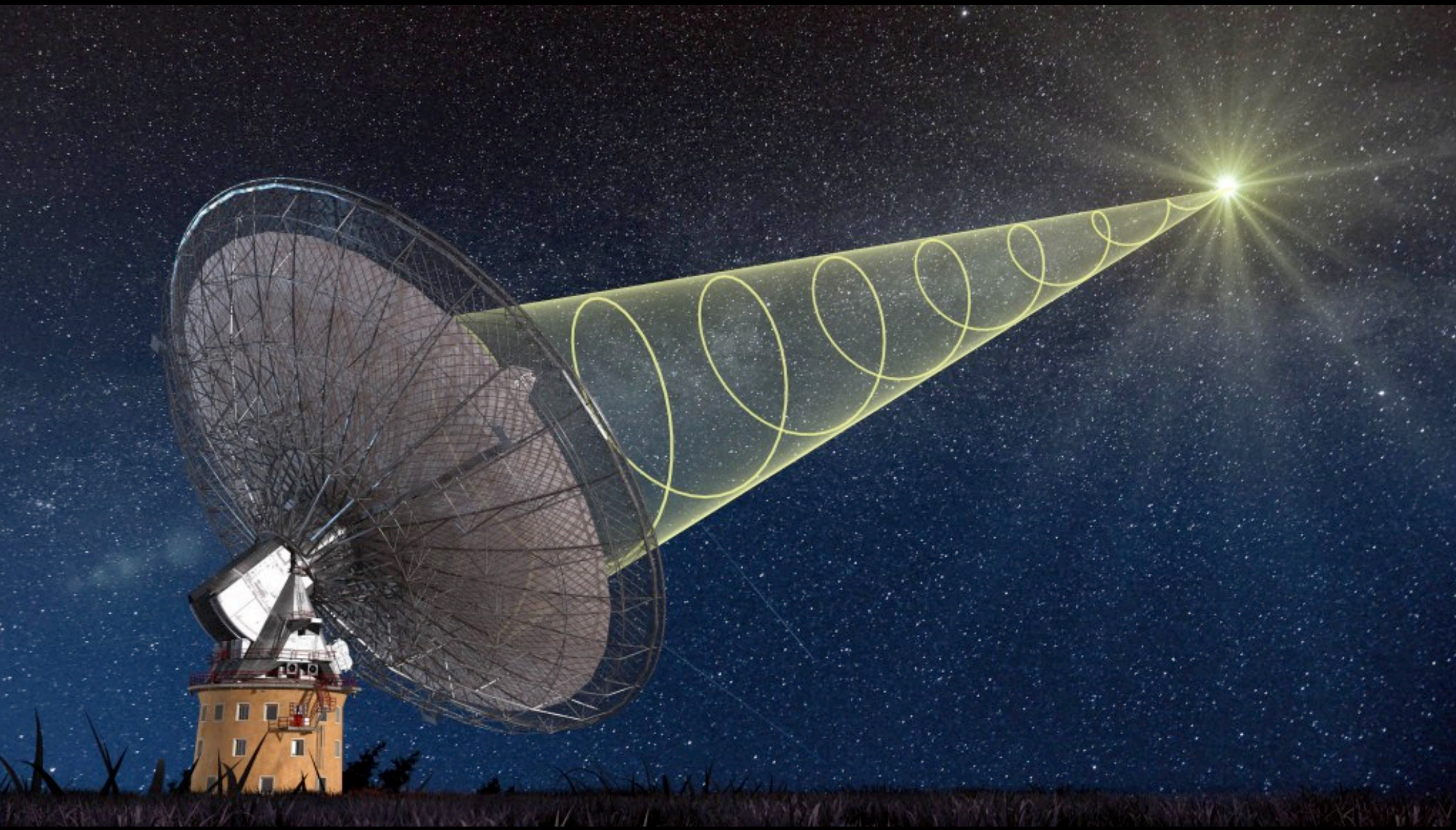
Scattering



Dispersion

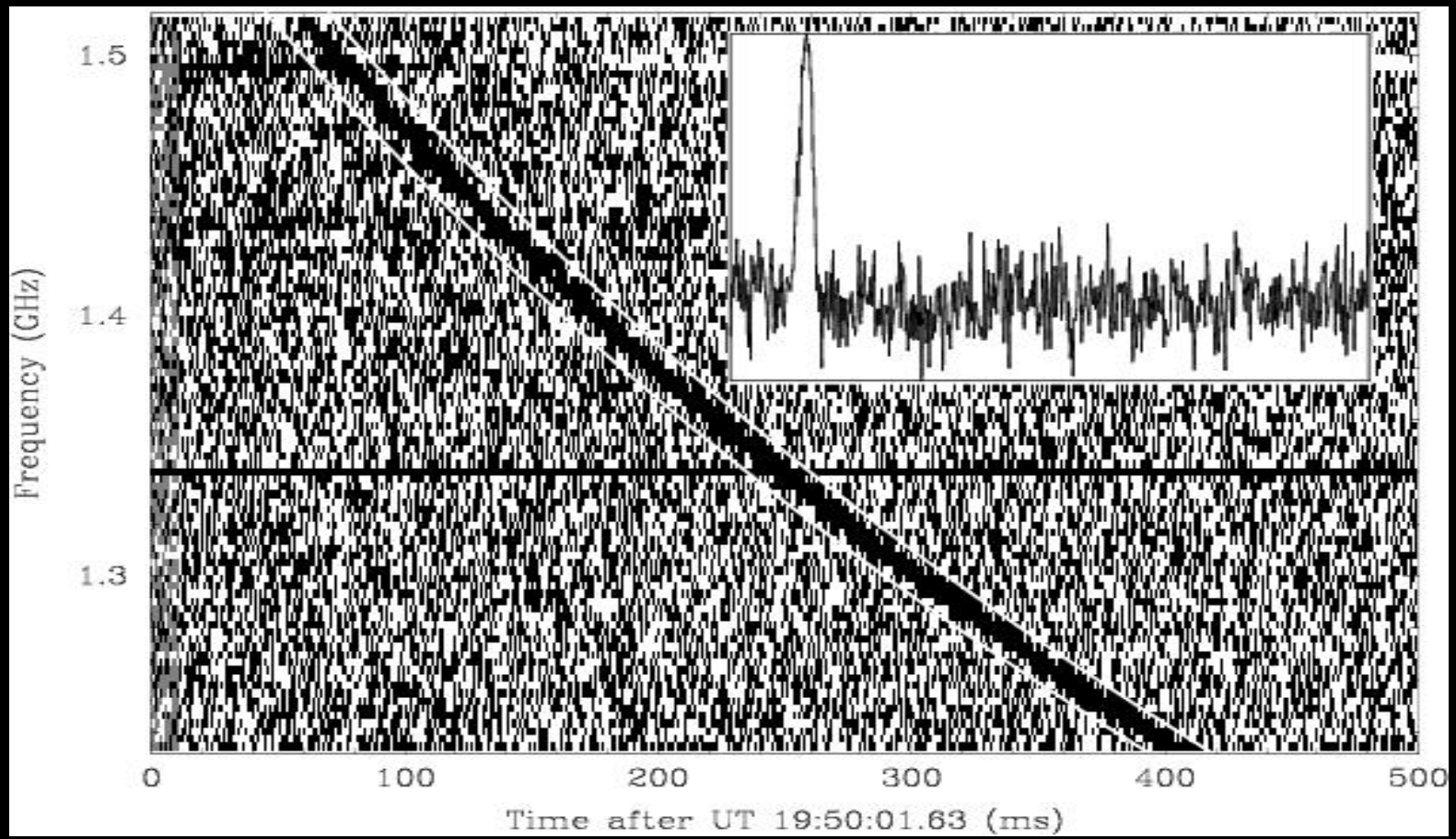


Fast Radio Bursts



Lorimer et al. 2007
Thornton et al. 2013

2007: The Lorimer Burst



Frequency

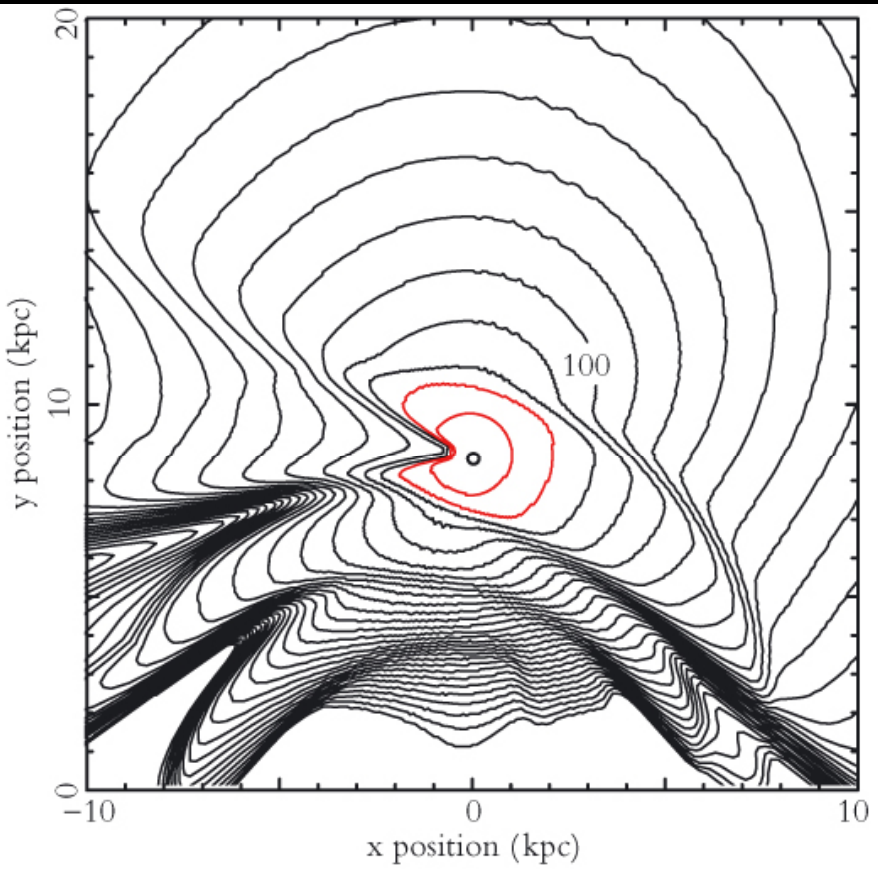
Time

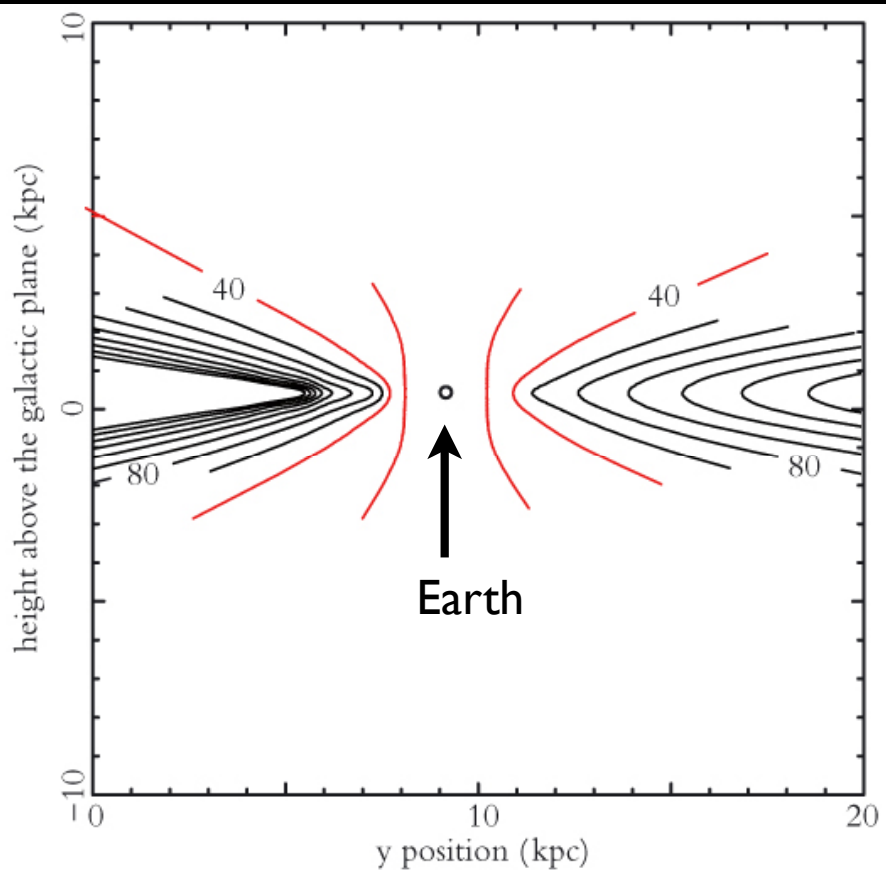
Lorimer et al. 2007

Galactic Dispersion

Galaxy top-down

Along Galactic plane

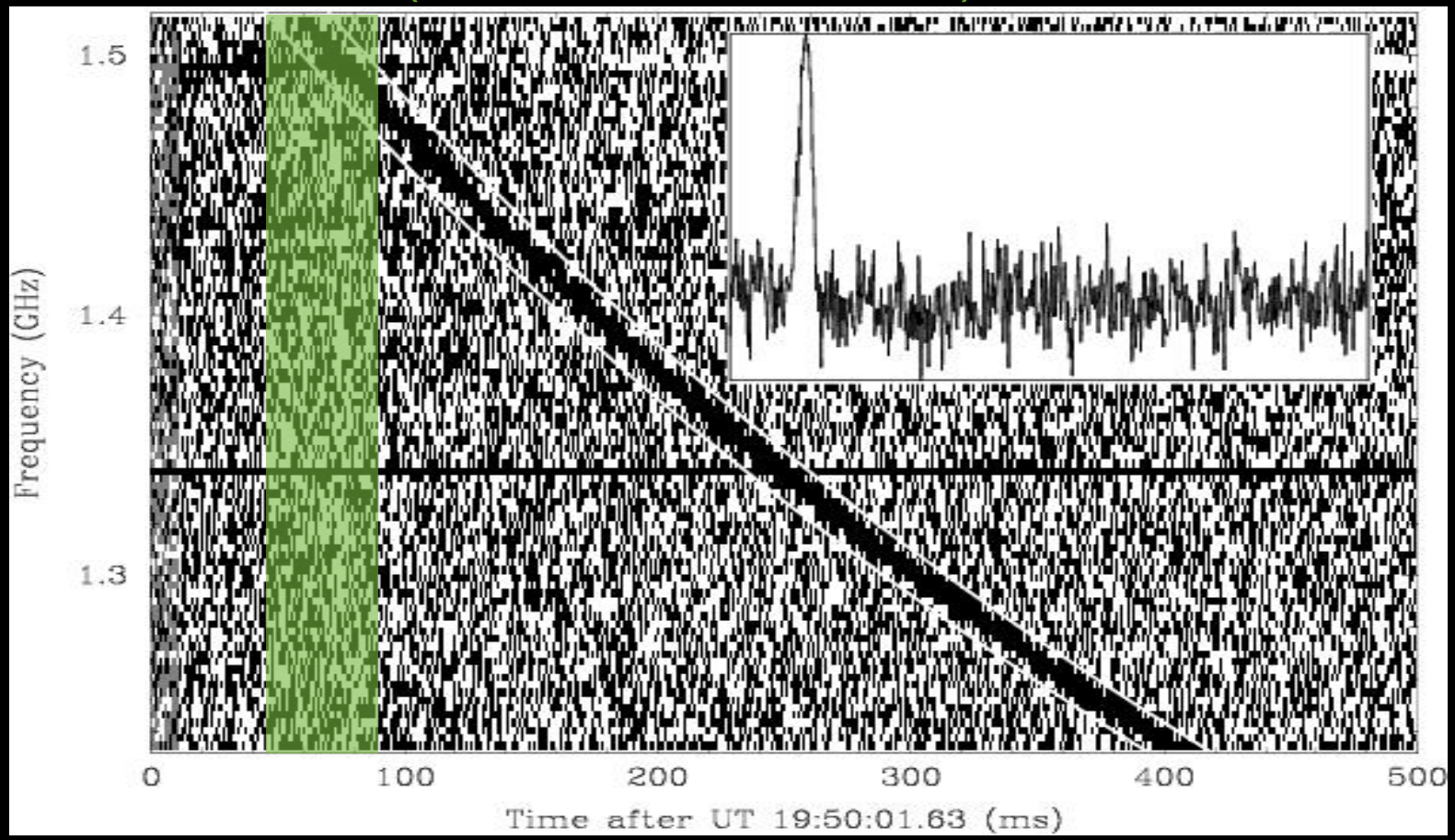




Contours of constant dispersion measure (NE2001 model; Cordes & Lazio)

2007: The Lorimer Burst

ISM (interstellar medium)



Frequency ↑

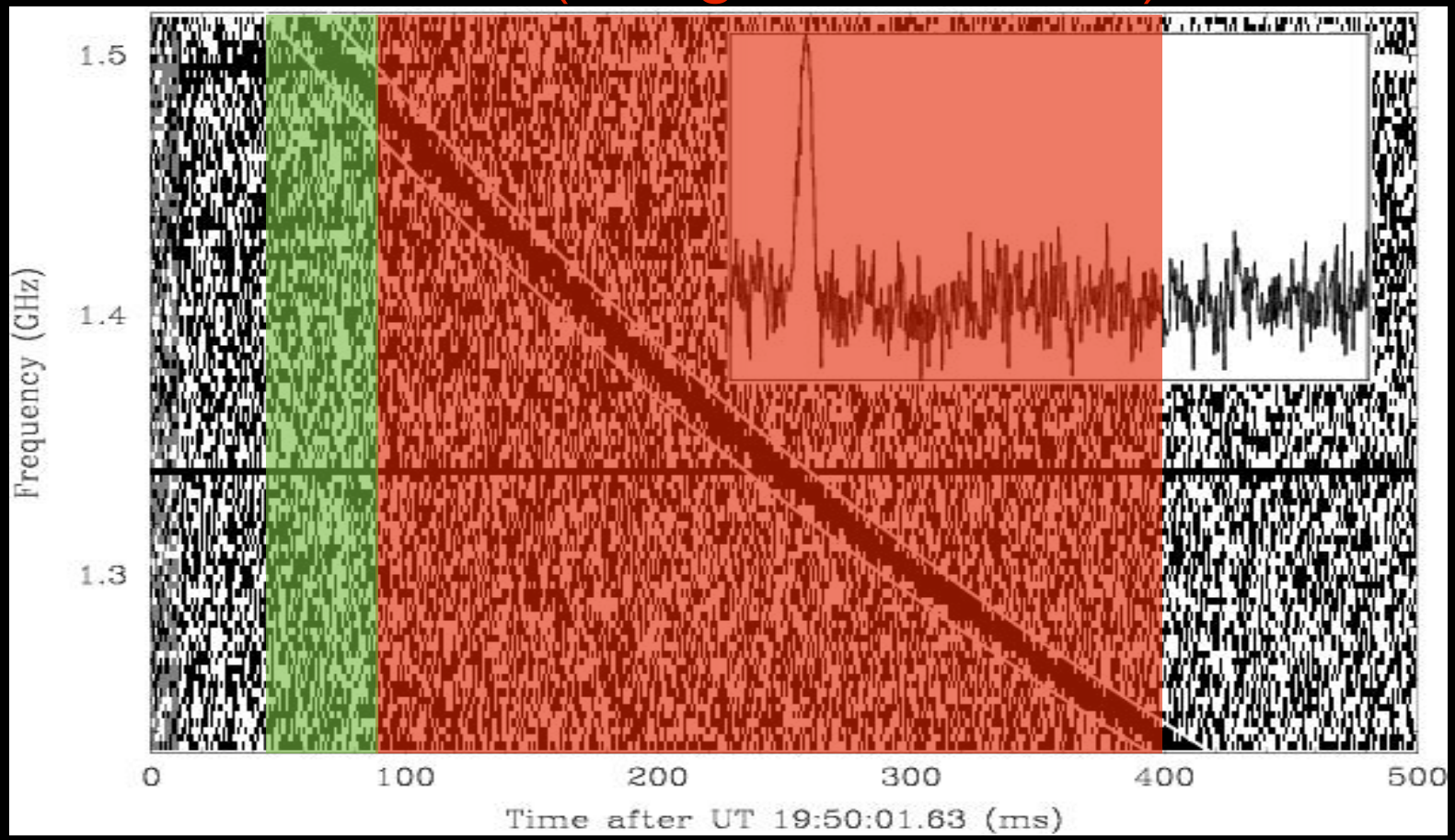
Time →

Delay too large to come from just the galaxy

Lorimer et al. 2007

2007: The Lorimer Burst

ISM IGM (intergalactic medium) + Host?



Frequency ↑

Time →

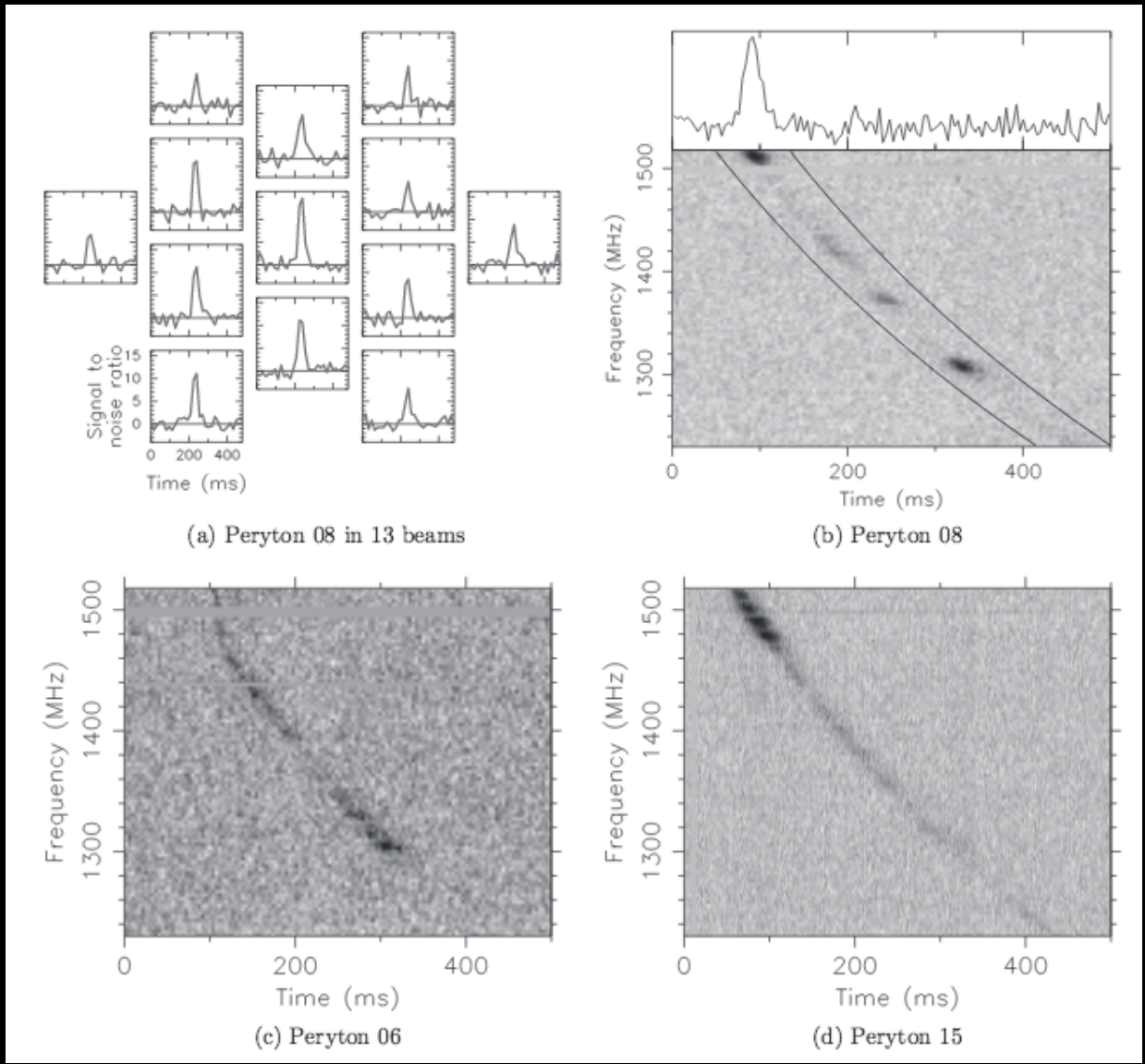
Delay too large to come from just the galaxy

Lorimer et al. 2007

...time passes, people are getting frustrated that they can't find more such bursts.

The Infamous Perytons

Human-made signals add confusion



Burke-Spolaor

The Infamous Perytons

Casts the shadow of a man, but is something quite different

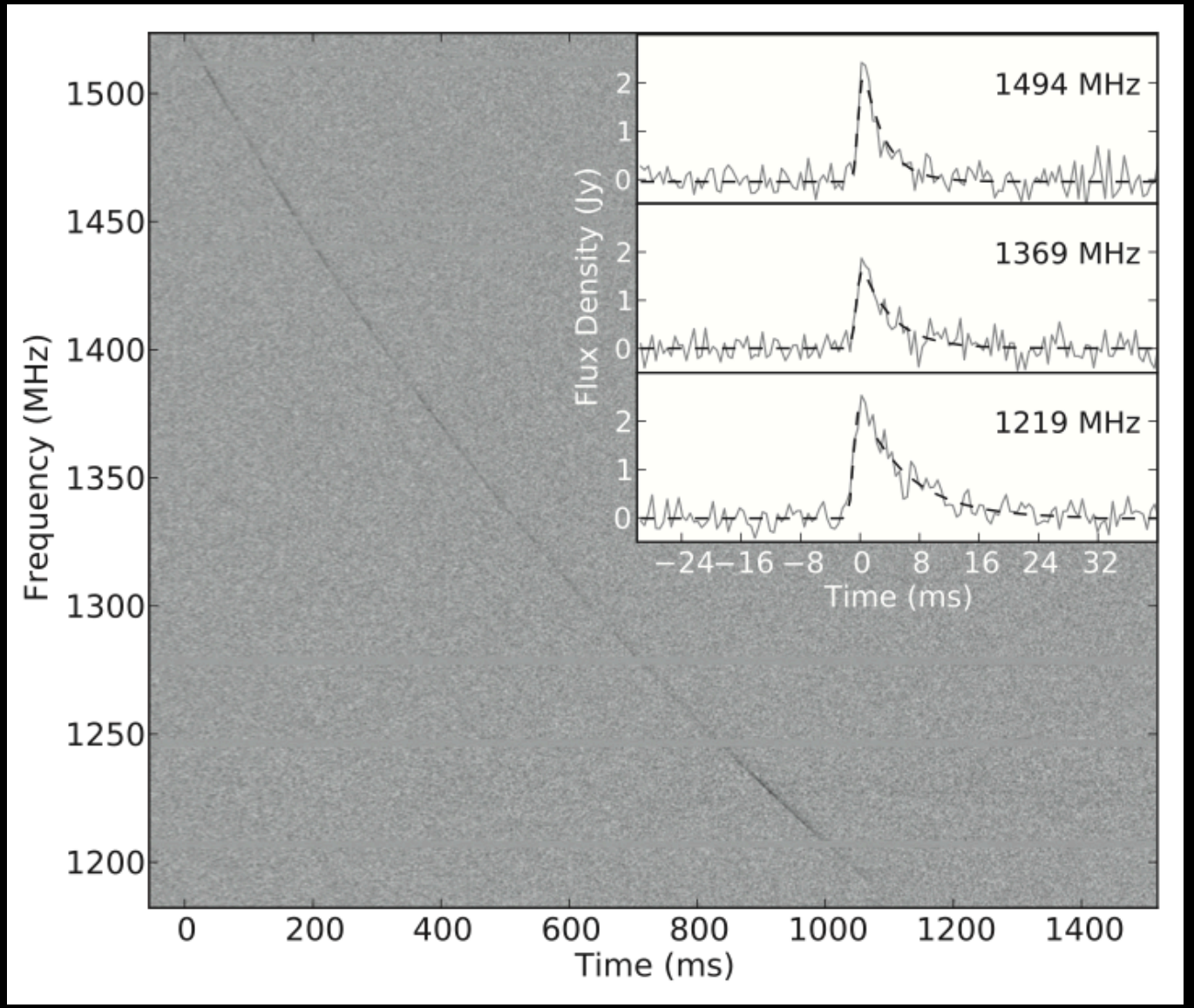
Kind of looks like an astronomical signal, but it is not

The Infamous Perytons

Turned out to be a microwave at the observatory

Radio frequency interference is an important foreground

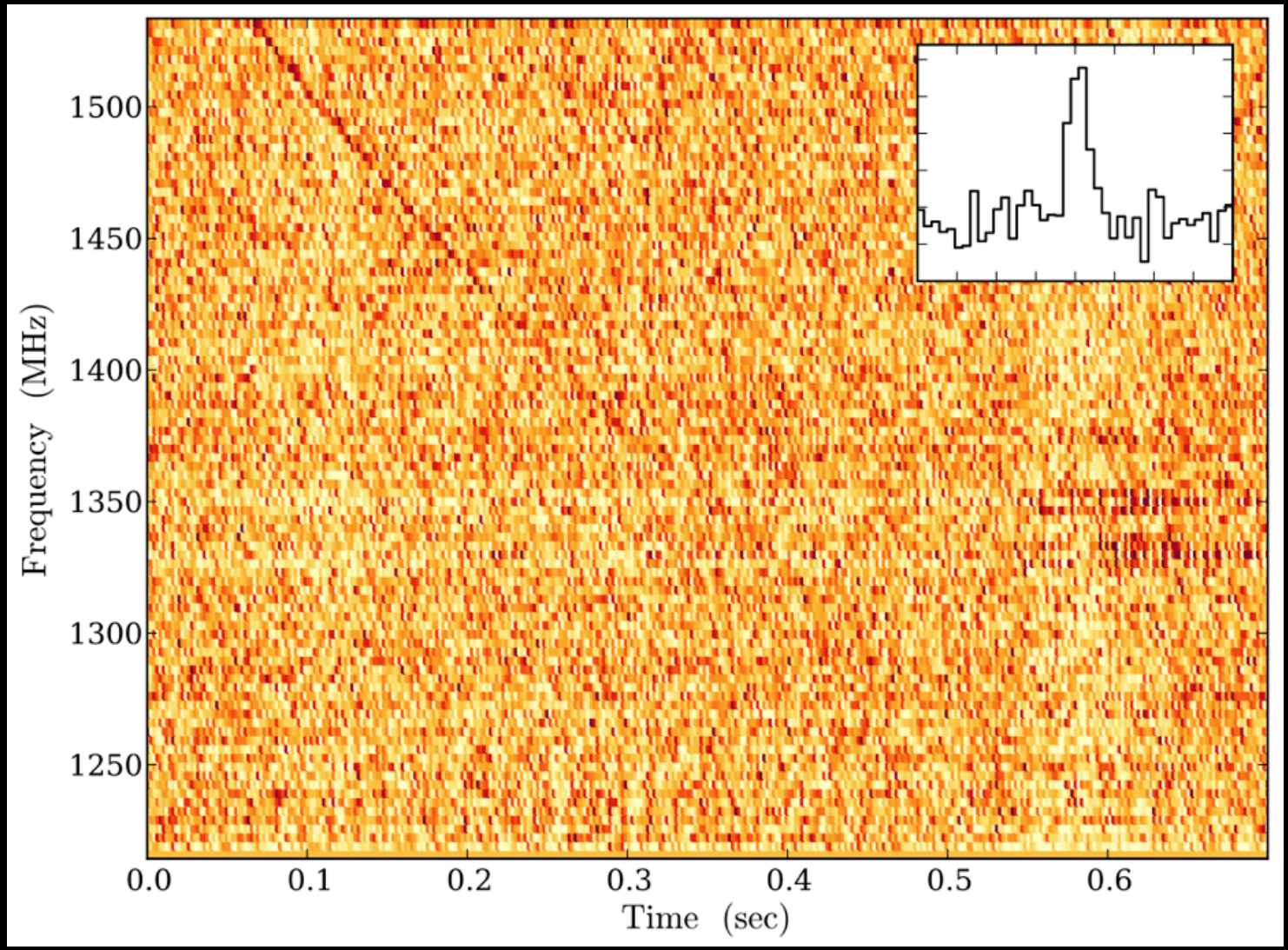
2013: The Thornton Bursts



There is a population of FRBs

Thornton et al. 2013

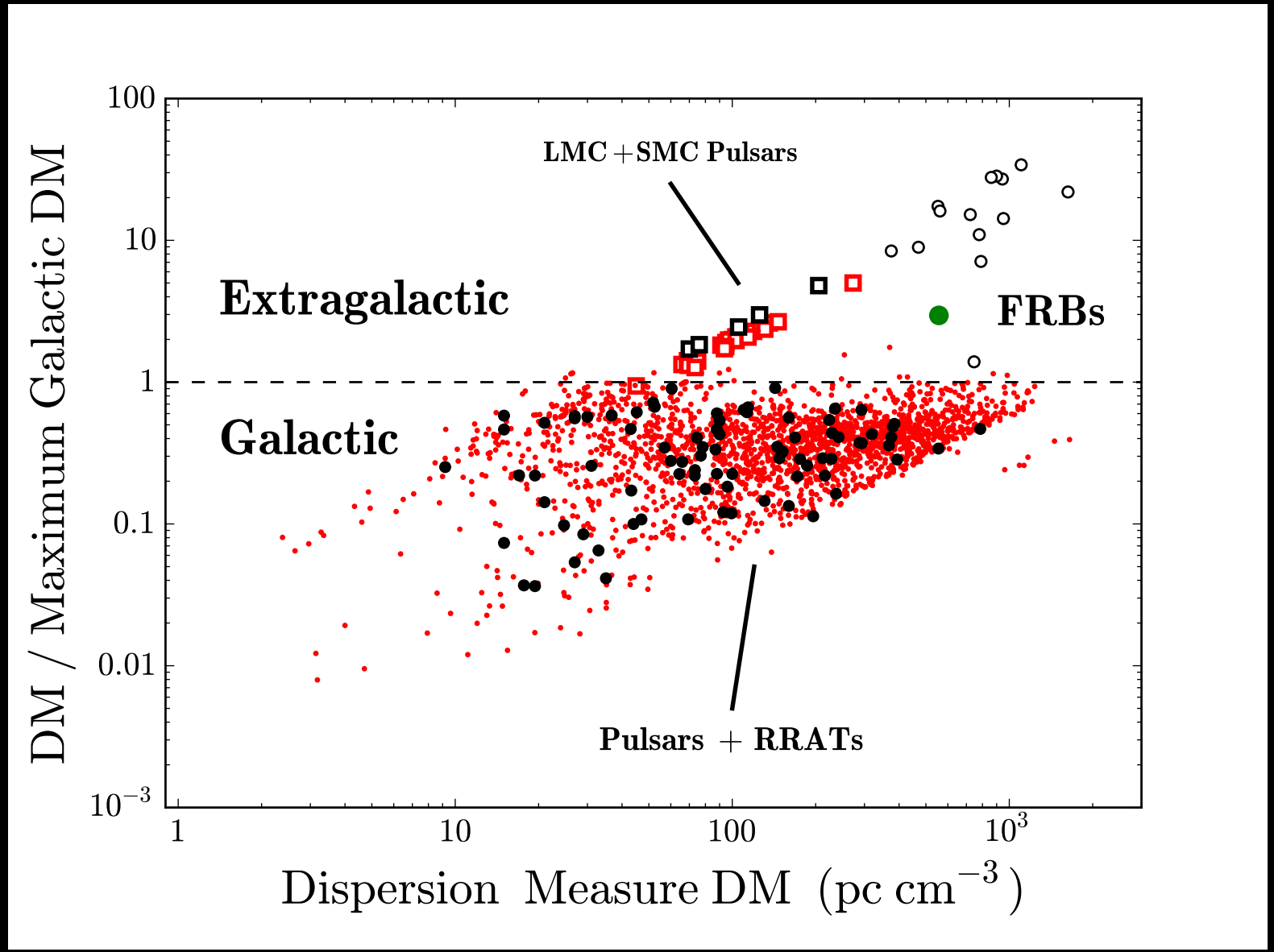
The Arecibo Burst



First non-Parkes FRB

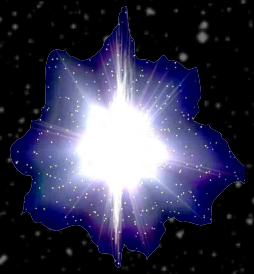
Spitler, Cordes, Hessels et al. 2014

Of Mice & Pulsars/RRATs/FRBs

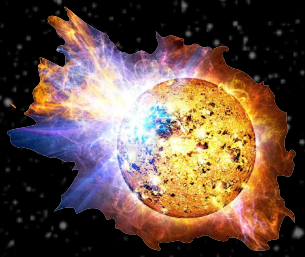


Cordes

Merging Black Holes

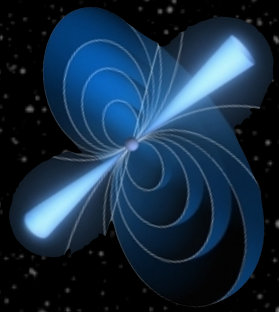


Supernovae



Magnetars

Evaporating Black Holes



Super-giant Pulses

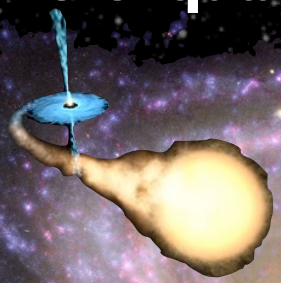
The Unknown

Gamma-ray Bursts

extra-Galactic

Implied rate of 1000s per day, per sky... but what are they?

Micro-quasars



Flare stars

Galactic

SETI

Pernicious RFI
Atmospheric effects

Magnetars

We are here

Pulsars

“Blitzars”

Why important?

- Sites of extreme energy density. Important probes of extreme (astro)physics?
- New type of astrophysical object?
- Probes of intervening material.

FRB121102 Discovery & Repeats

Spitler, Cordes, Hessels et al. 2014
Spitler, Scholz, Hessels et al. 2016
Scholz, Spitler, Hessels et al. 2016

Image credit: Danielle Futselaar


Arecibo

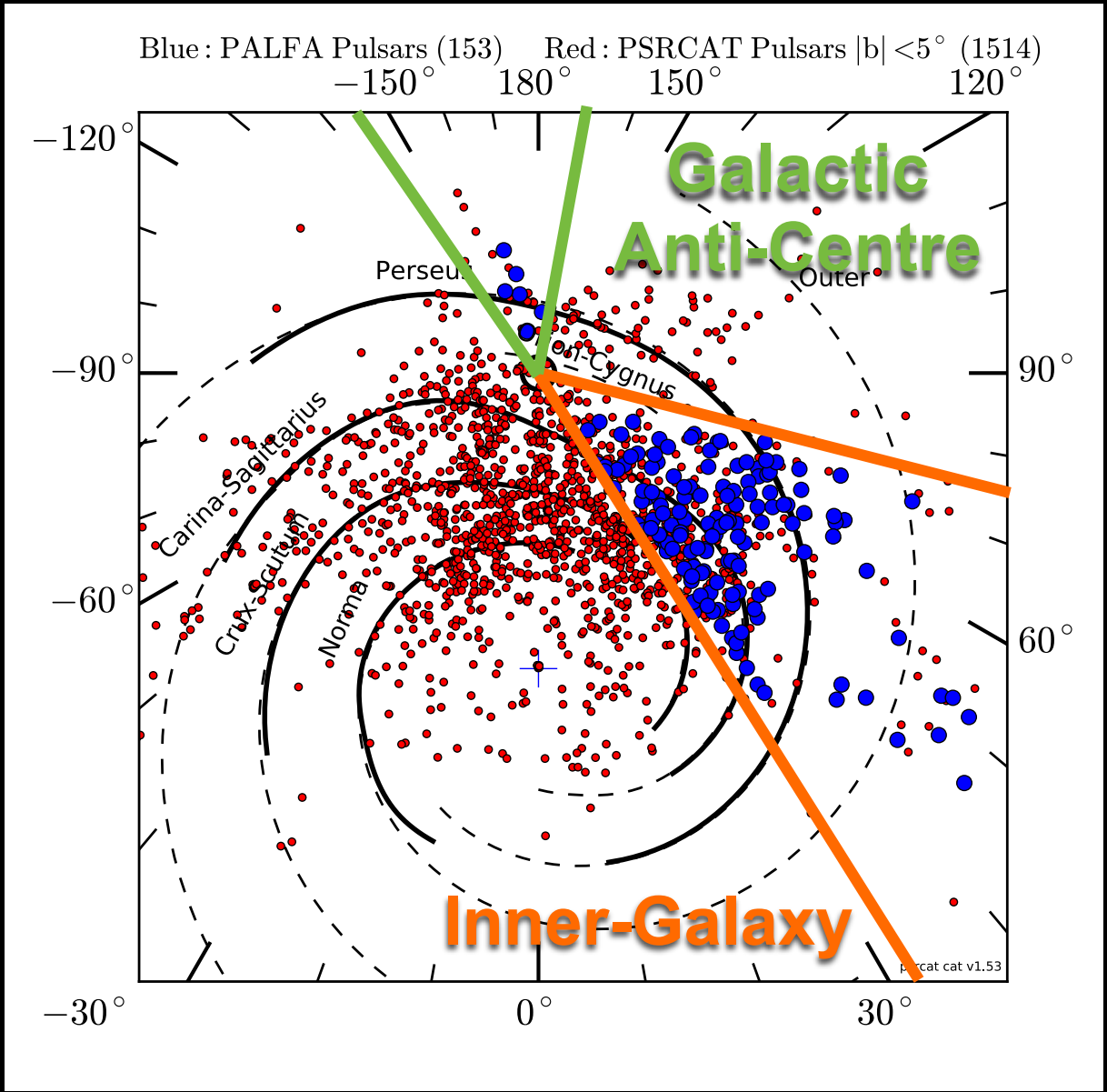
PALFA Survey

Bogdanov

- Survey for pulsars and fast transients with Arecibo
- Use 7-beam ALFA receiver
- Go deep in the Galactic plane
- 181 pulsar discoveries
- Deepest pulsar survey before the SKA

PALFA Survey Regions

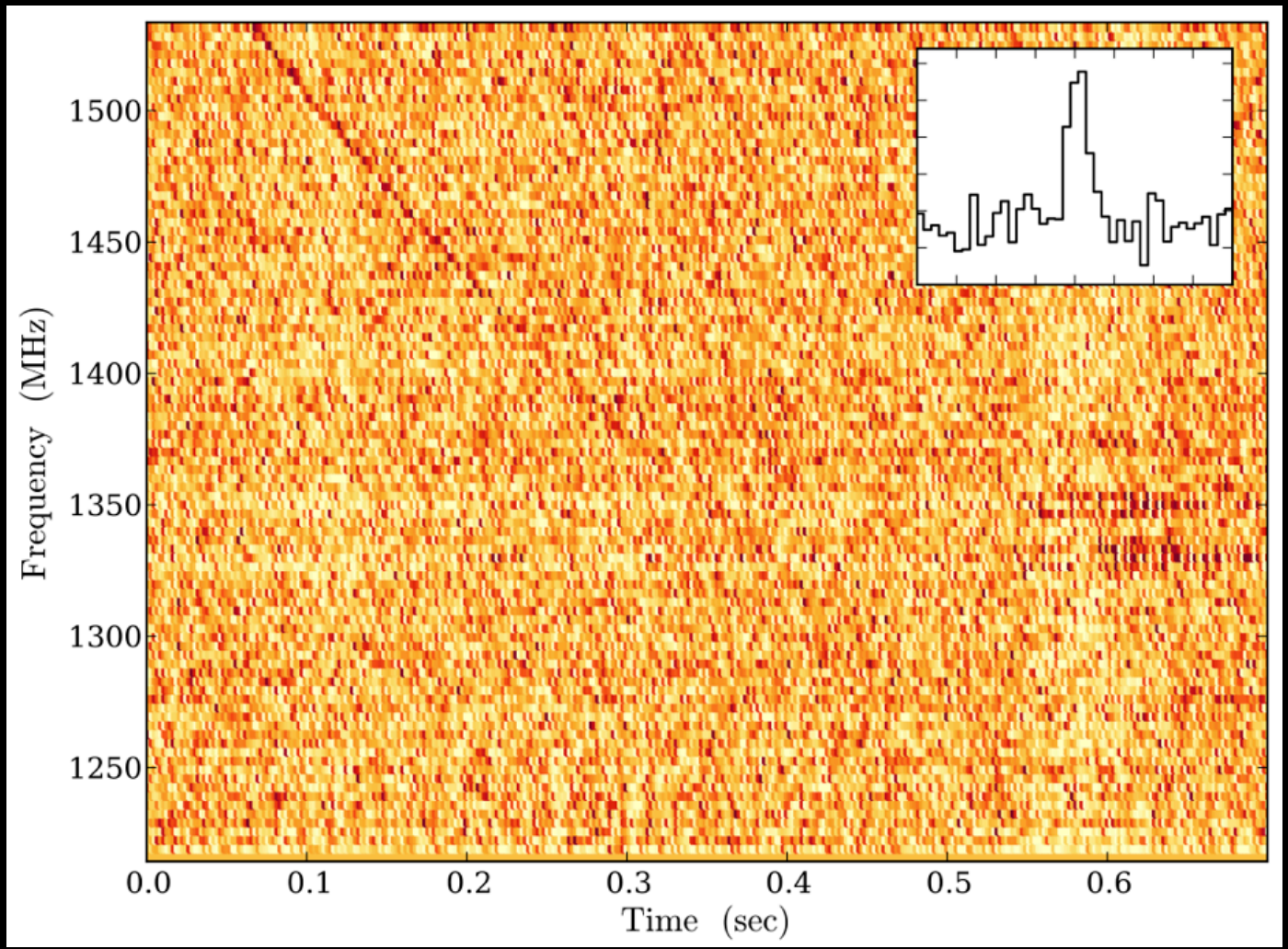
- Known pulsar
- New pulsar



Cordes

The Arecibo Burst

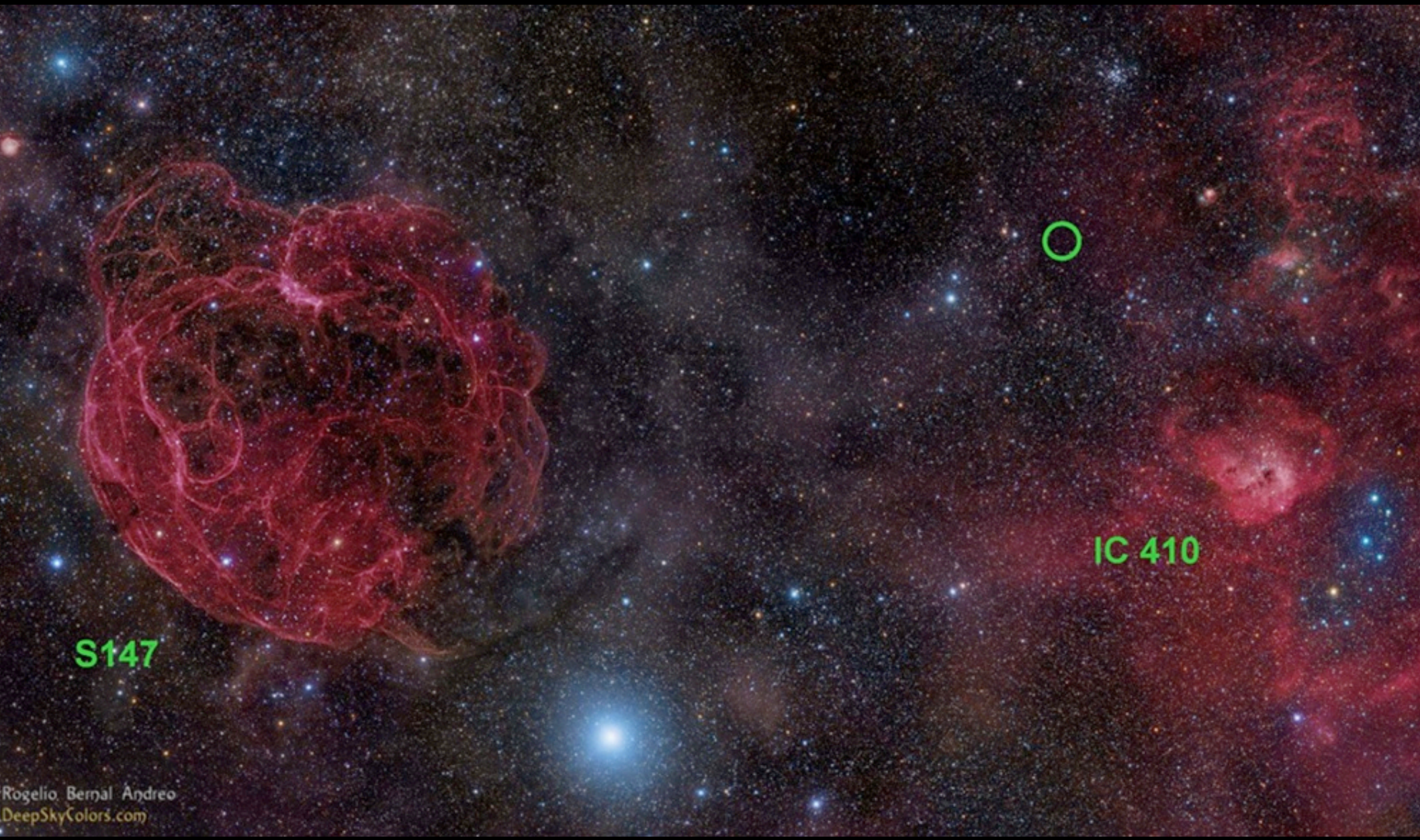
$DM_{FRB} = 3x\ DM_{Max\ Gal.}$



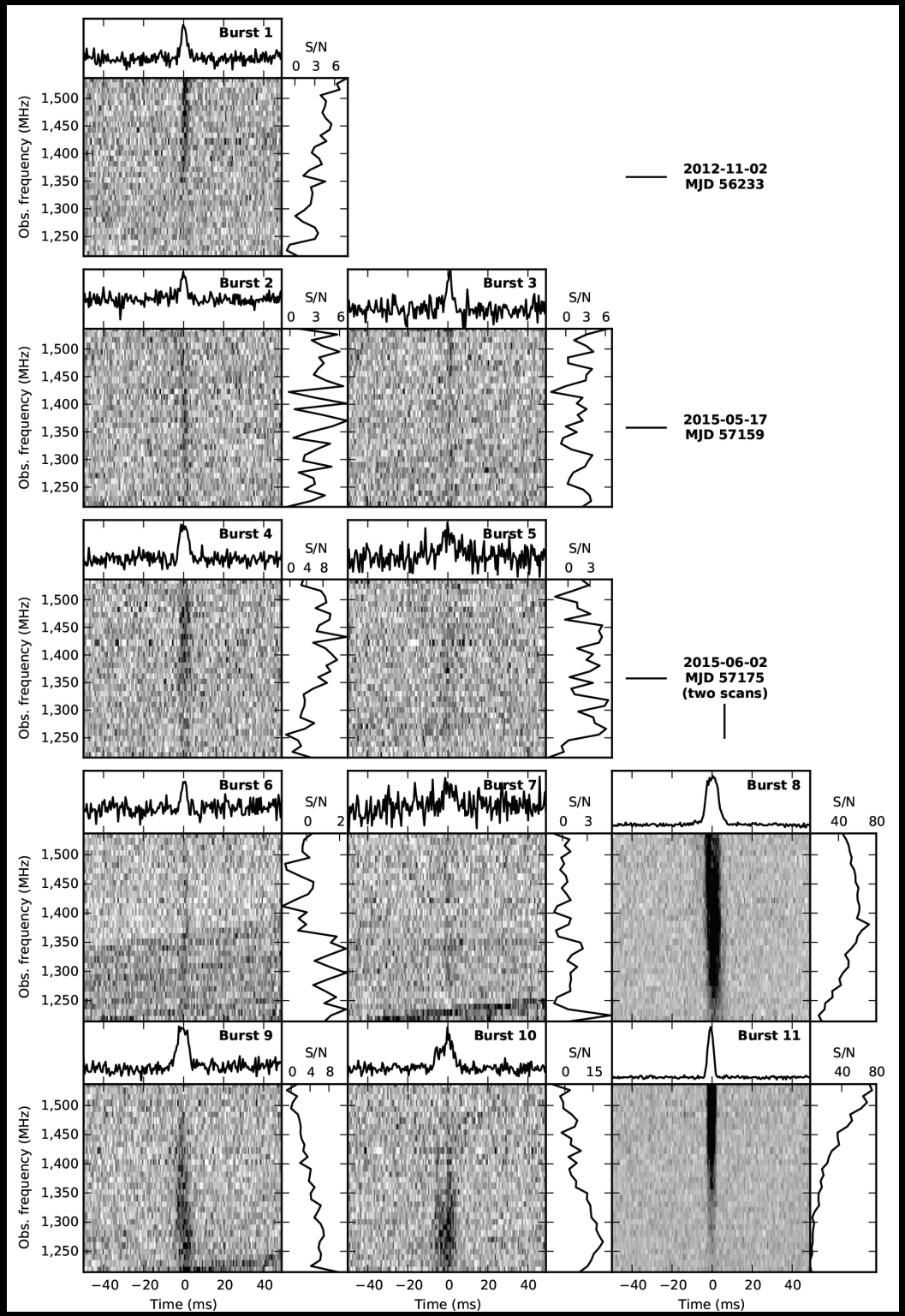
First non-Parkes FRB

Spitler, Cordes, Hessels et al. 2014

Where was the Arecibo Burst?



In Galactic plane, but not obviously Galactic

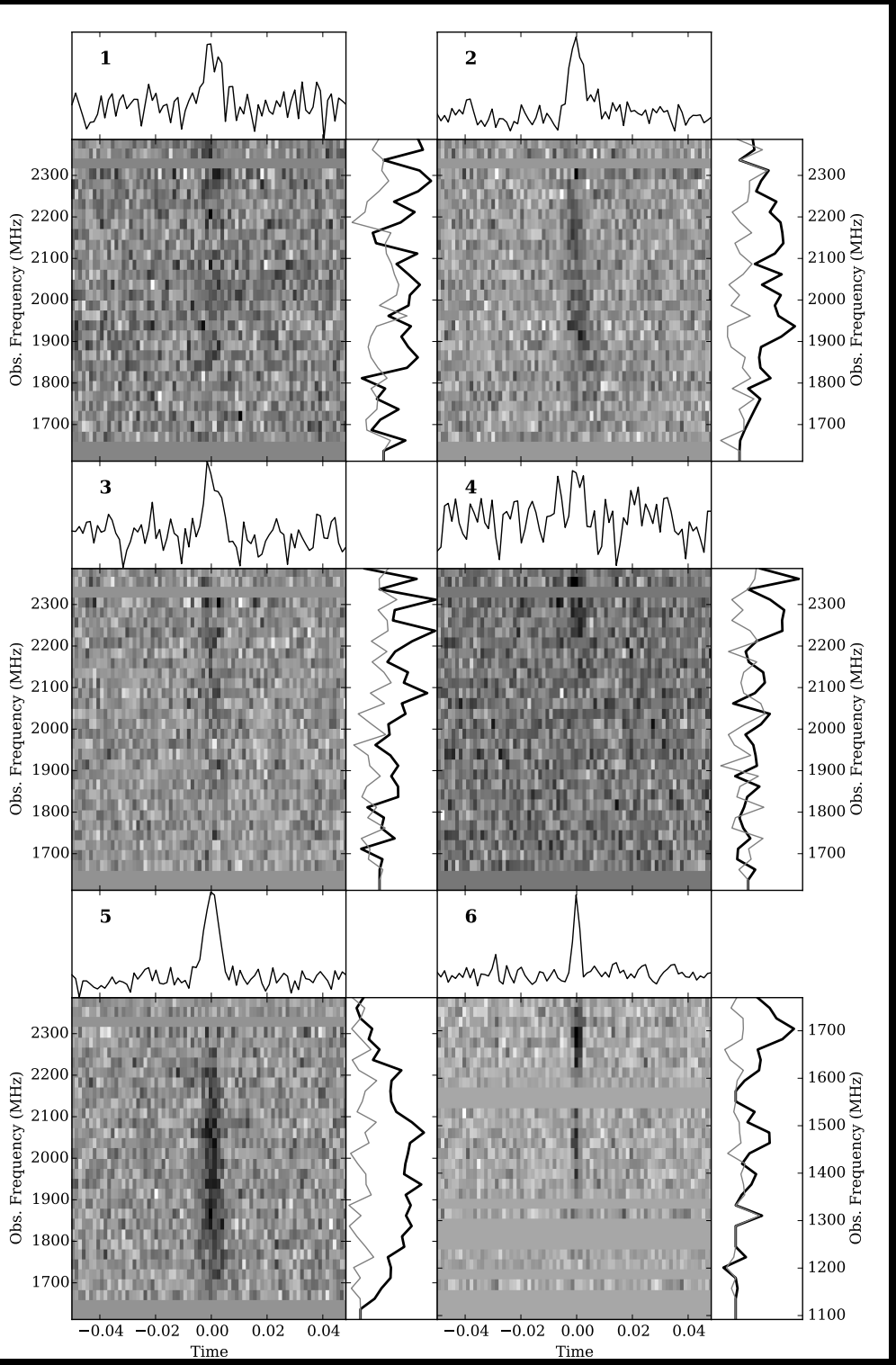


10 New AO Bursts!

First repeating Fast Radio Burst!

Spitler, Scholz, Hessels et al. 2016

Scholz



GBT Detections

MWL study supports extragalactic origin

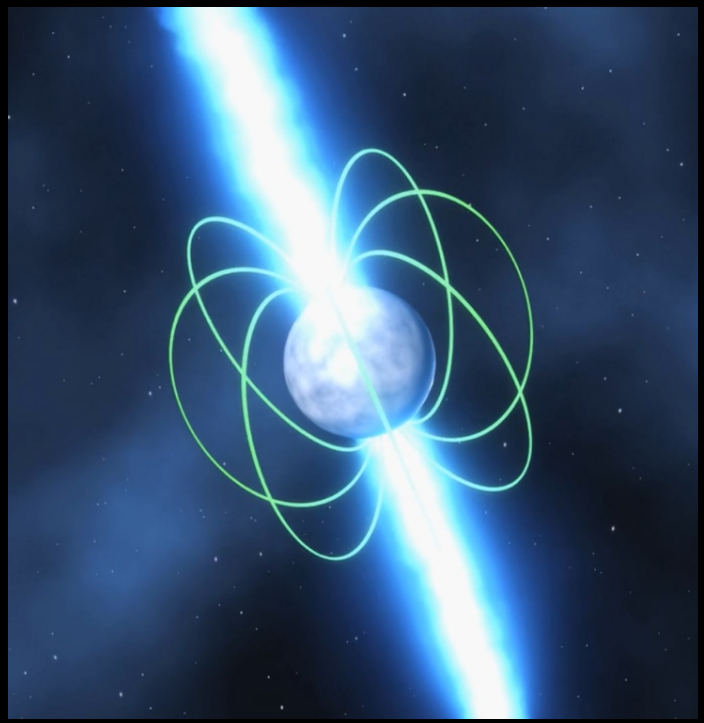
Also an Arecibo single-pixel detection

Scholz, Spitler, Hessels et al. 2016

Why important?

Rules out a cataclysmic source (at least for this FRB)

vs.



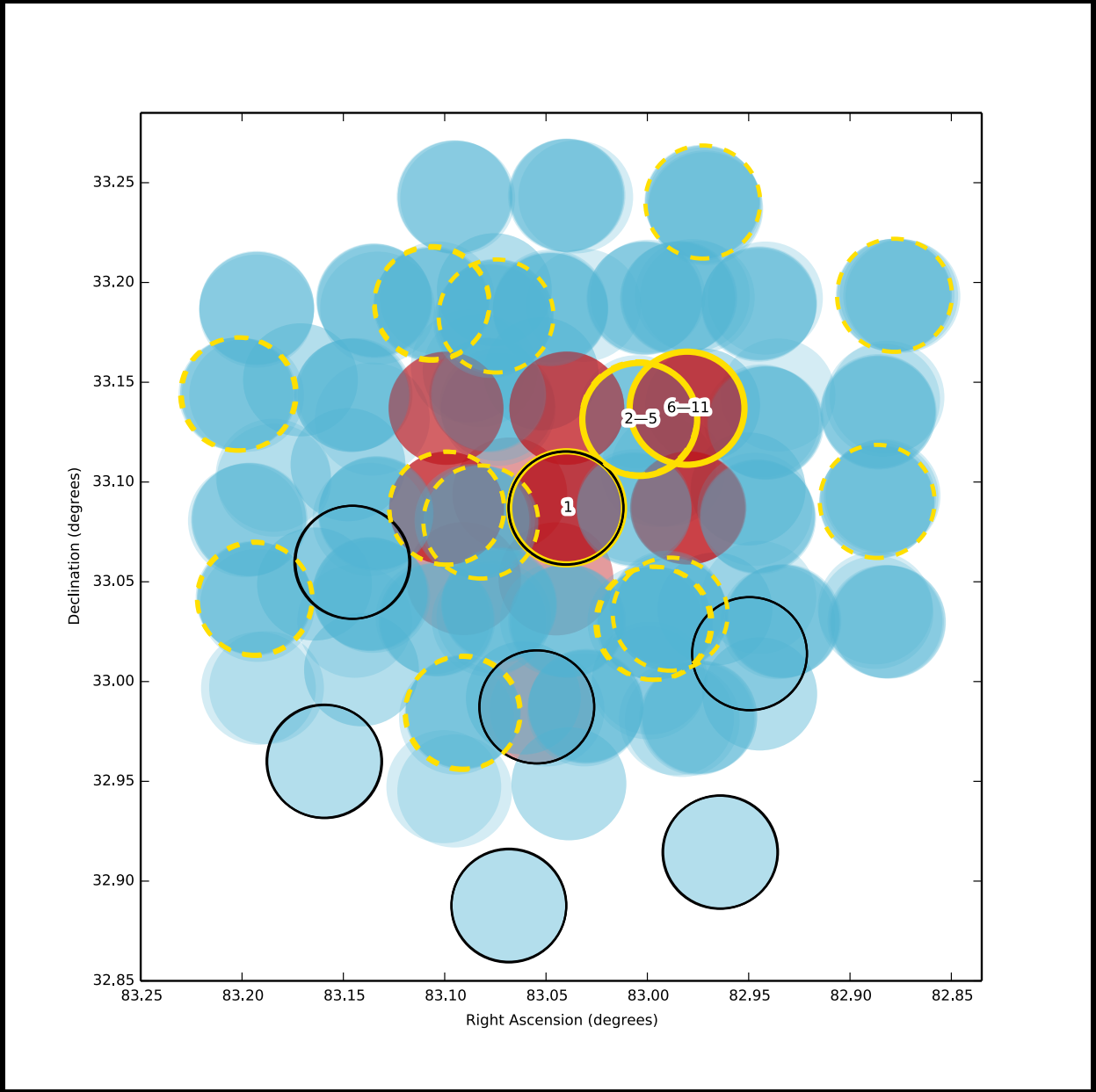
One-time-only explosion

Pulsar on steroids

Arecibo L-Band Feed Array

7-pixel receiver

Follow-up Observations



Hessels

Spitler, Scholz, Hessels et al. 2016

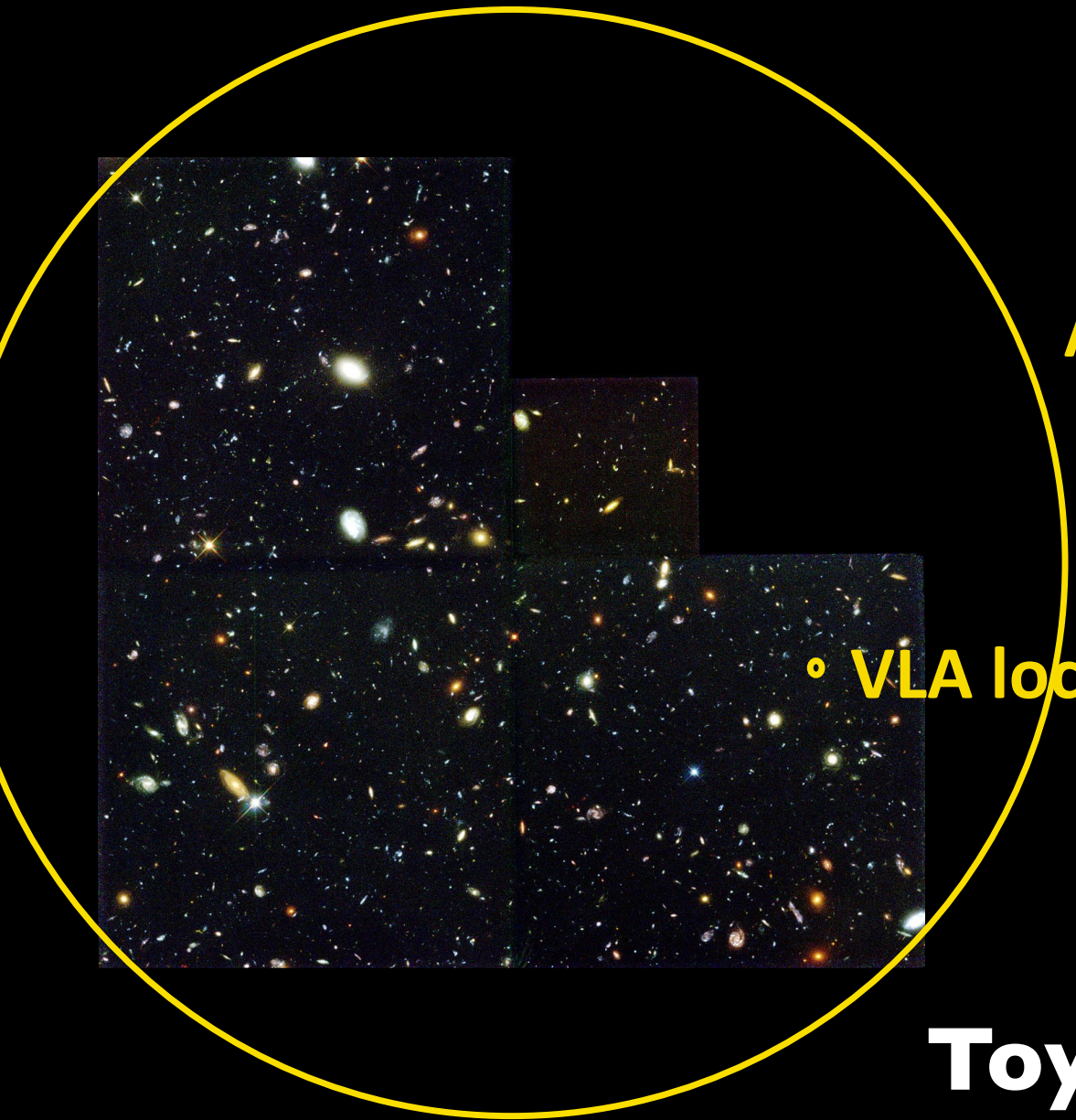
3 papers in January 2017

Image credits: Danielle Futselaar

VLA Localization

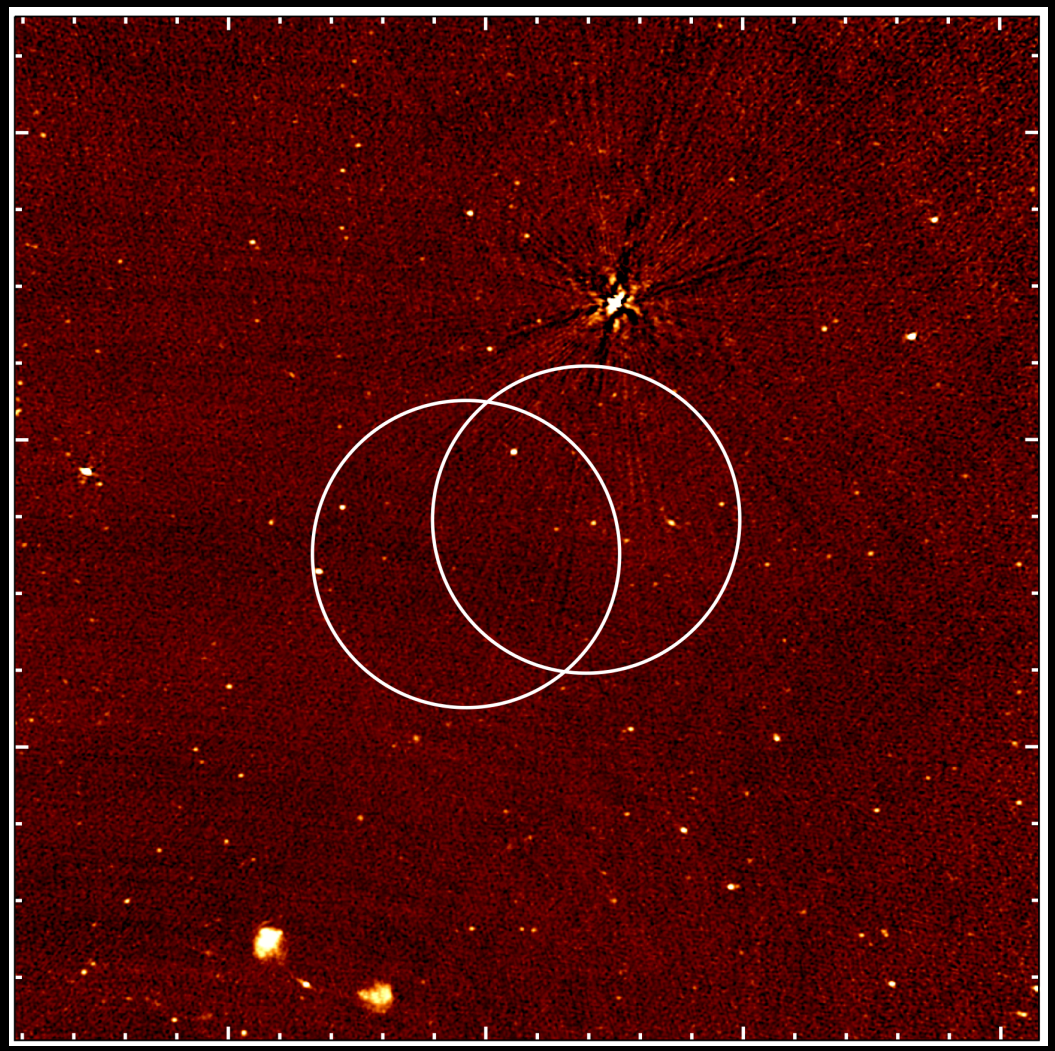
Chatterjee, Law, Wharton et al. 2017, Nature

The Need for Localization



Toy comparison with Hubble Deep Field

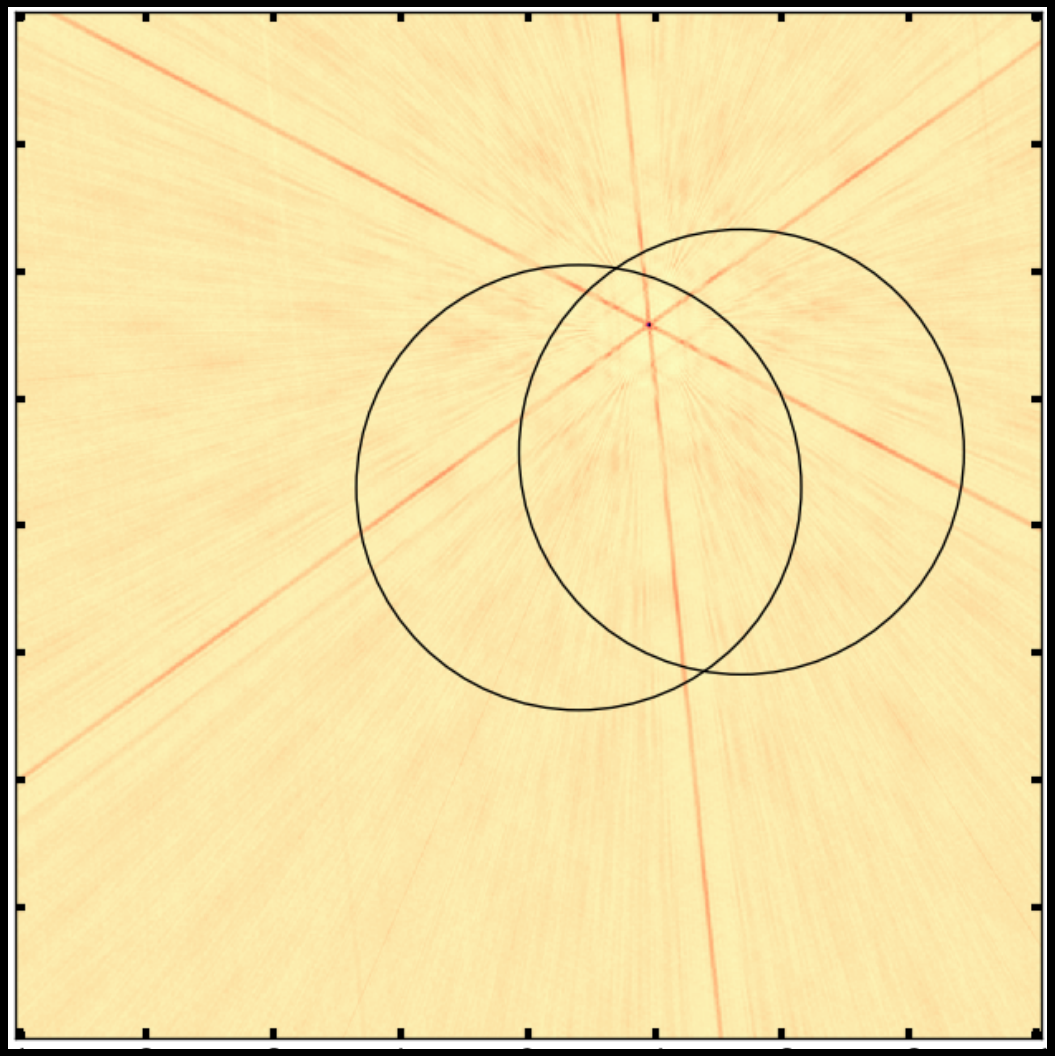
VLA Localization



10s of radio sources in an ultra-deep (10s of hrs) VLA image

Chatterjee et al. 2017

VLA Localization

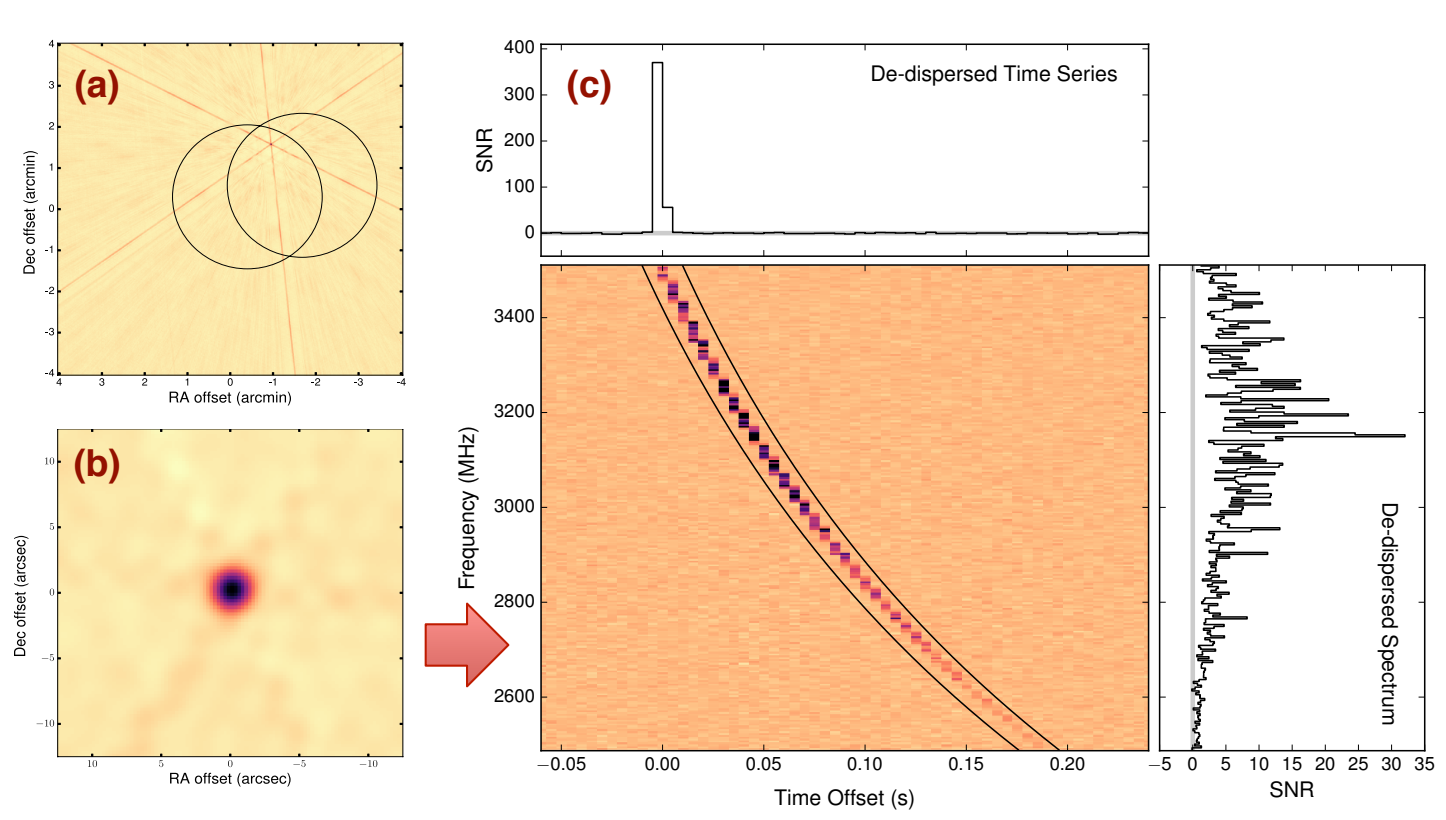


...and suddenly a burst (this is a 5-ms snapshot)

Chatterjee et al. 2017

VLA Localization

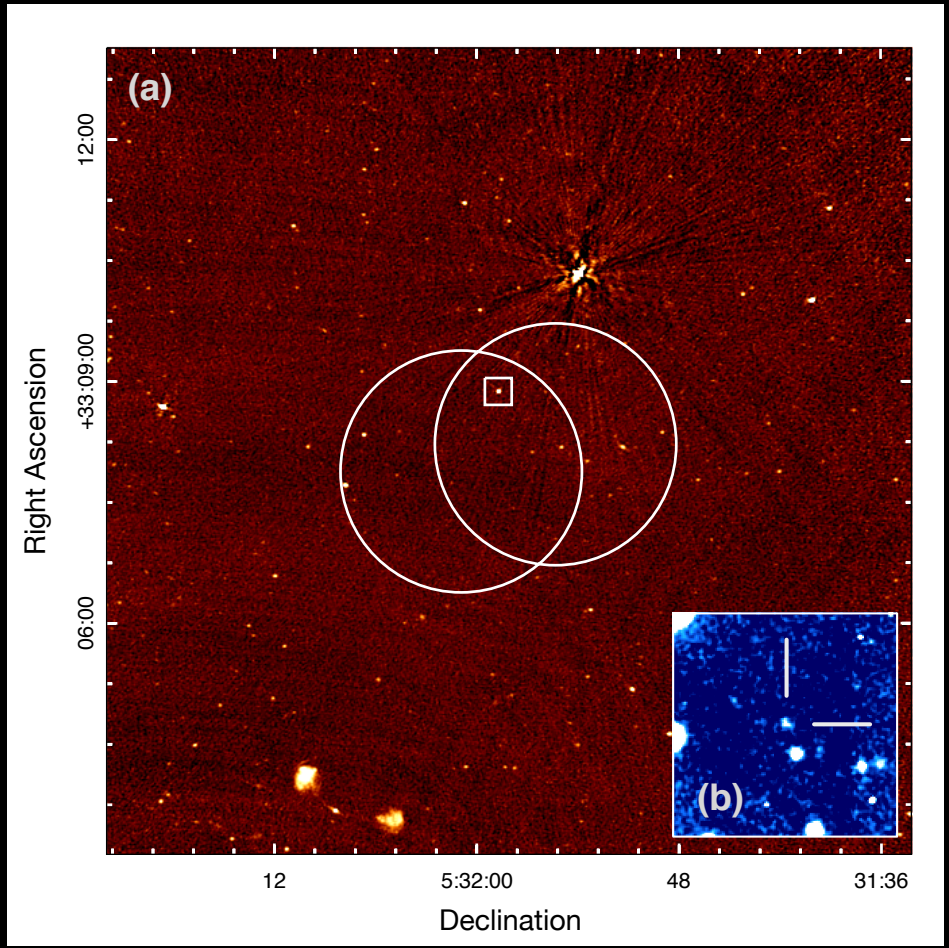
Localization to ~100mas



After tens of hours of observing and 1 year of trying

Chatterjee et al. 2017

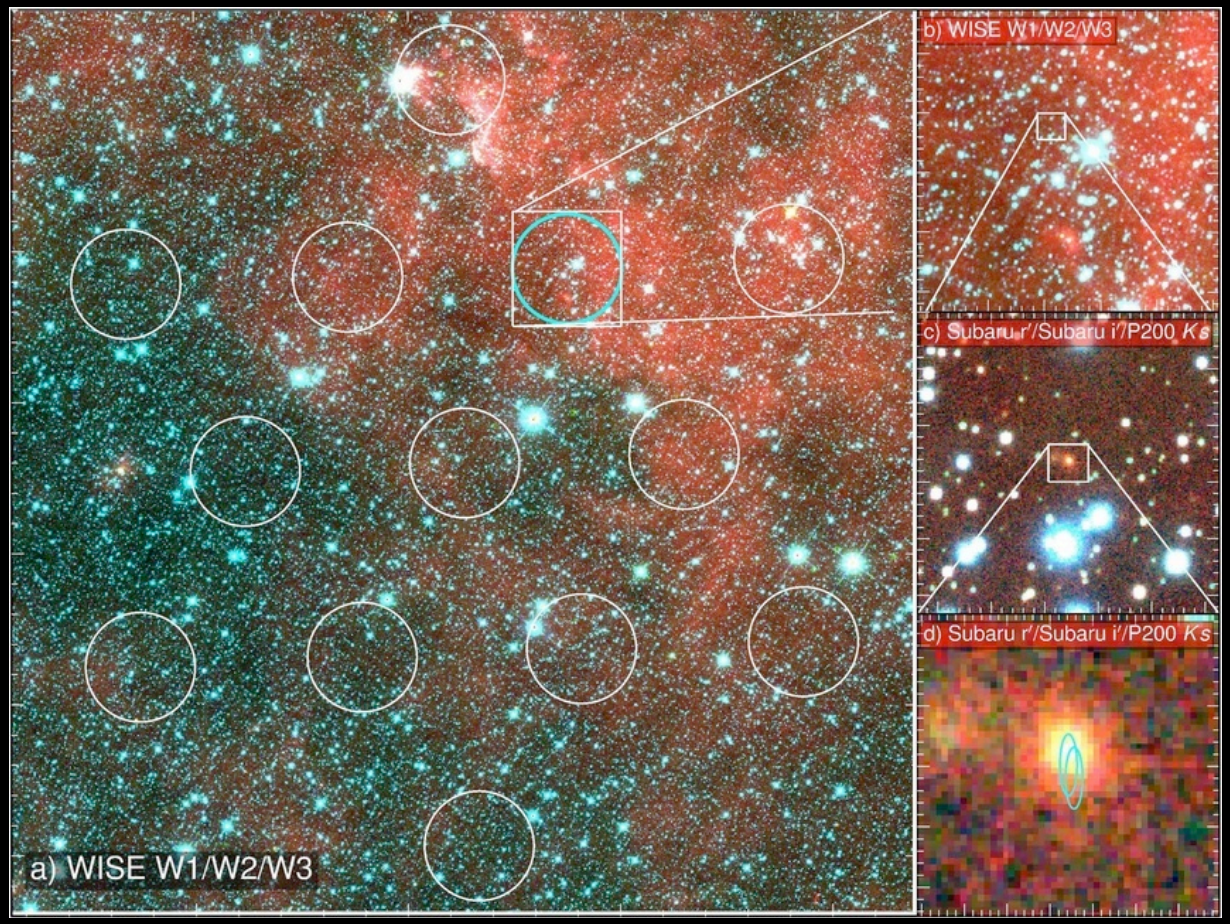
VLA Localization



Association with persistent radio and optical sources

Chatterjee et al. 2017

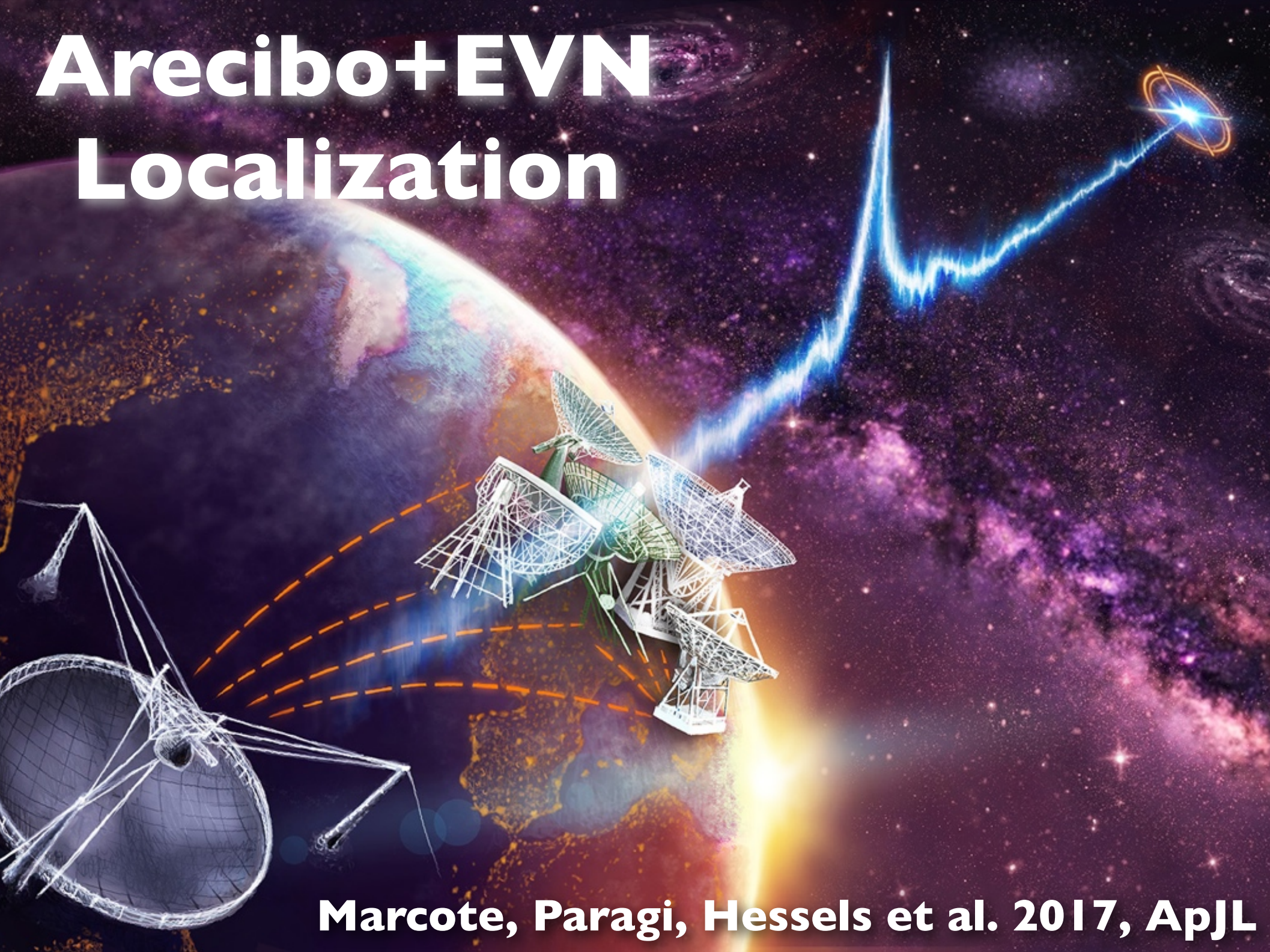
This is a direct localization, not an afterglow



Keane et al. 2016

Avoids the ambiguity in localizing a burst based on time coincidence with a multi-wavelength event

Arecibo+EVN Localization



Marcote, Paragi, Hessels et al. 2017, ApJL

Why Zoom-in Even Further?

- Do the bursts come from *exactly* the position of the persistent radio source?
- What is their physical relation?
- Are the bursts coming from the center or the outskirts of the host galaxy?

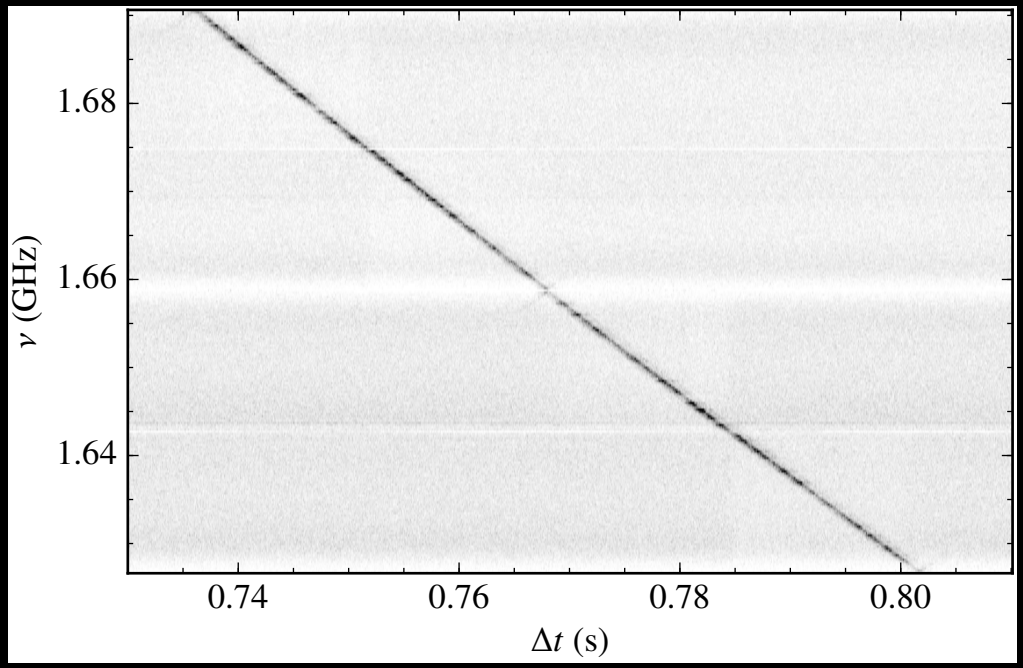
The European VLBI Network

- Global network of radio telescopes connected together via high-speed fiber.
- Signals processed in Dwingeloo, The Netherlands.

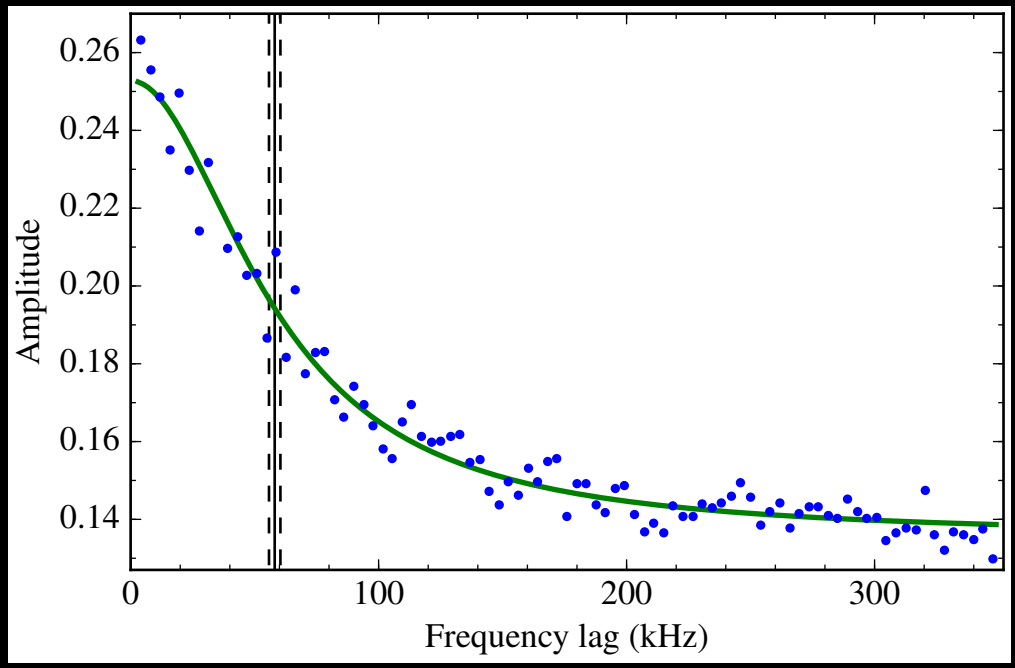
Joint Arecibo+EVN Observations

- Connecting Arecibo to European telescopes gives much higher resolving power.
- Arecibo provides the raw collecting area.
- Angular sizes similar to viewing a tennis ball from across the Atlantic.

Arecibo+EVN Detects a burst!



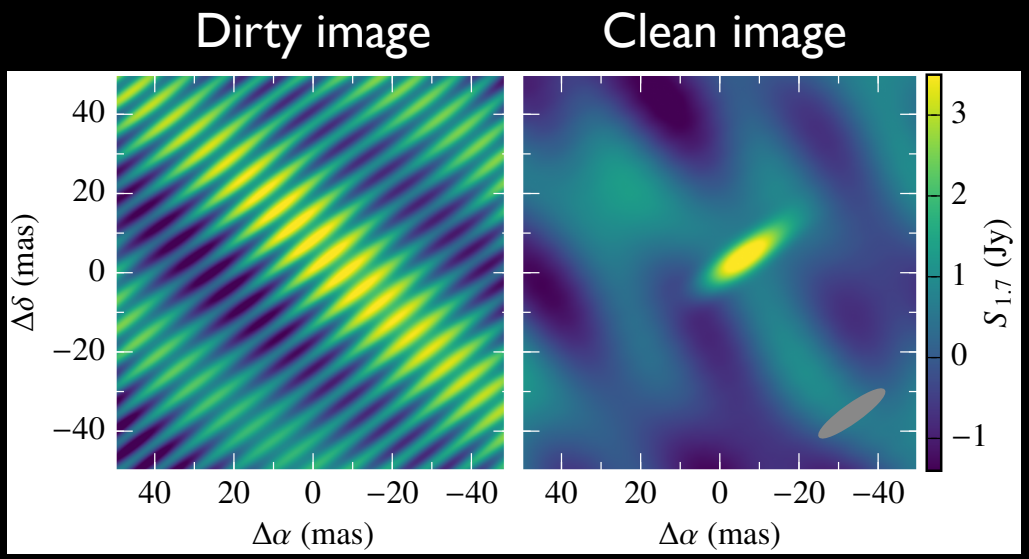
Dynamic spectrum from Arecibo auto-correlations



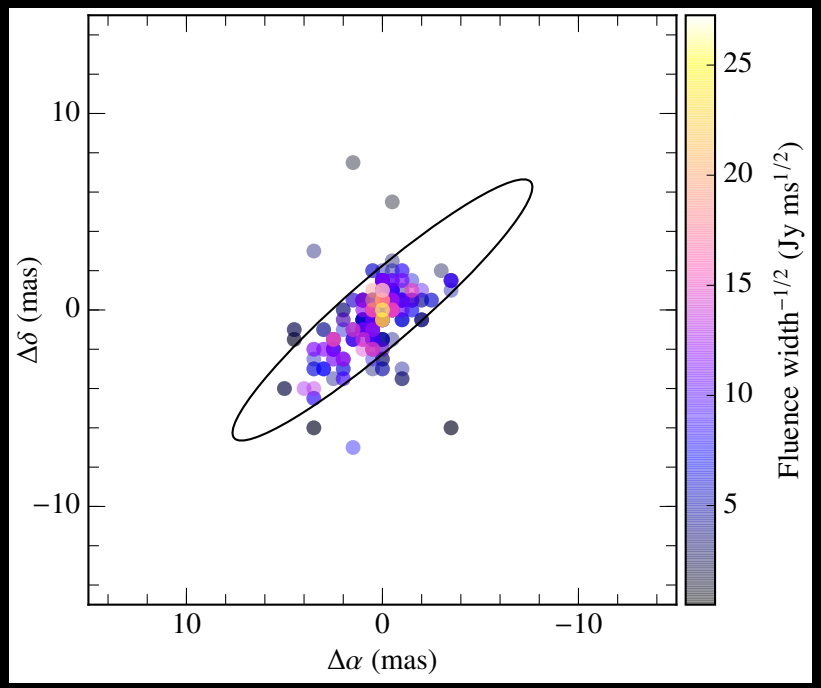
ACF in the frequency direction. Shows Galactic diffractive scintillation?

One bright & 3 weak bursts detected in a 2-hr campaign

Arecibo+EVN Localization



Brightest FRB121102 burst seen by Arecibo+EVN



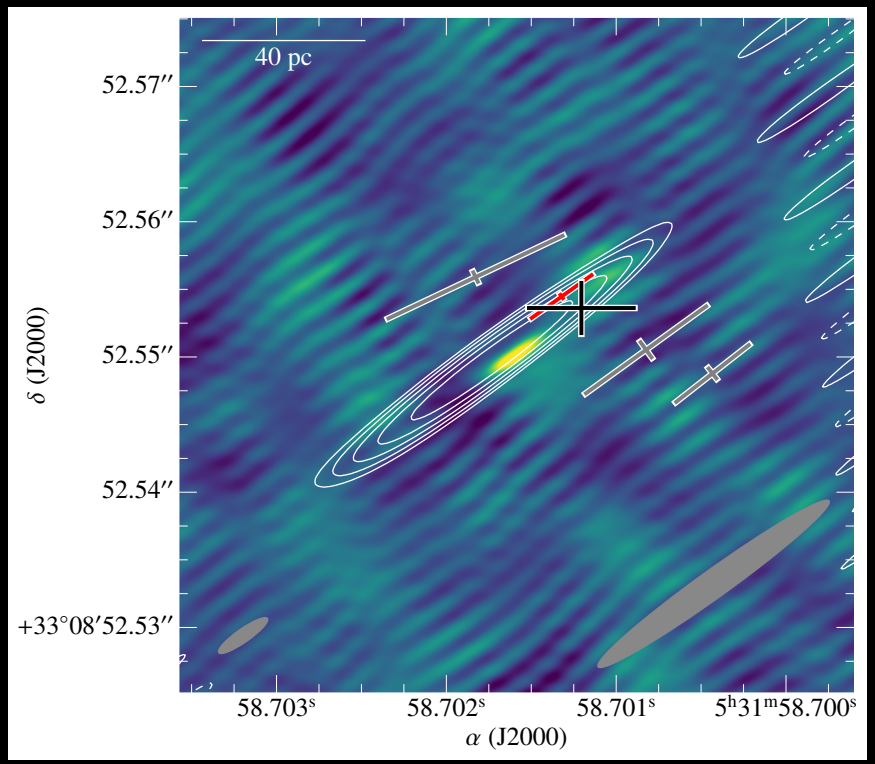
Localizations of pulses from test pulsar B0525+21

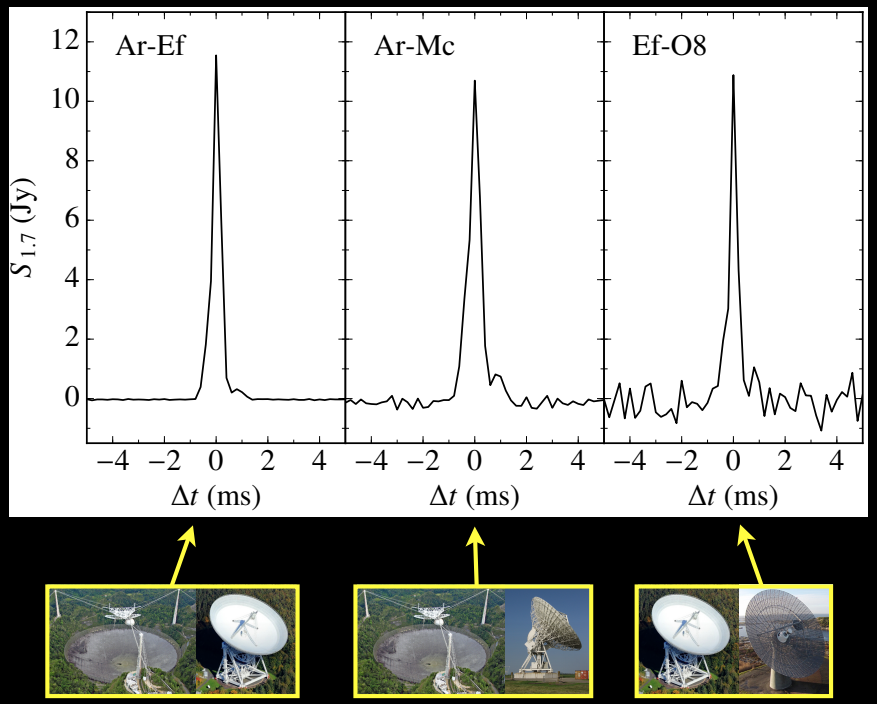
Quantifying systematic errors on the position

Marcote et al. 2017

Arecibo+EVN Localization

Localization to ~10mas





Bursts and persistent radio source are physically related

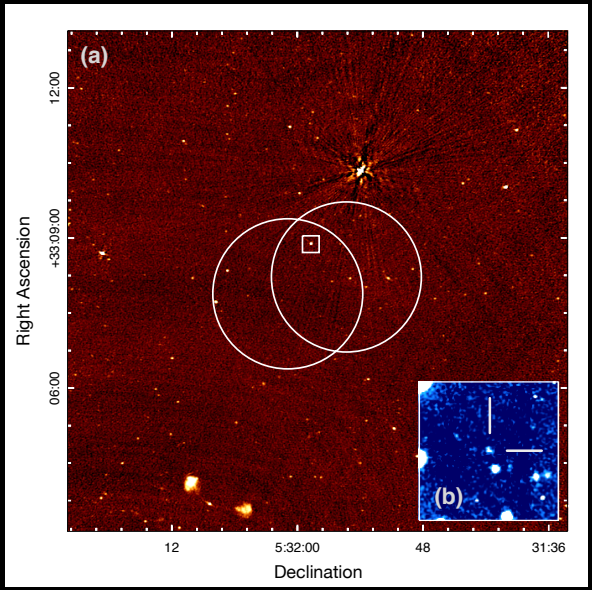
(coincident to within < 40 pc at 1Gpc)

Marcote et al. 2017

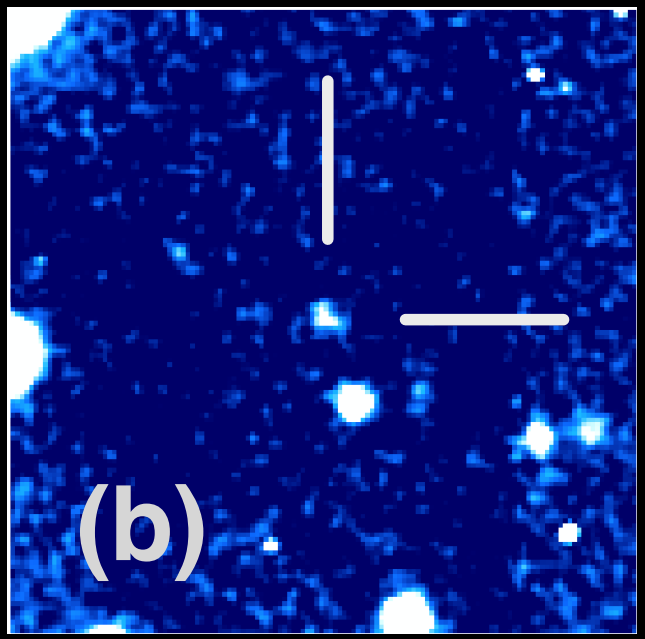
Gemini redshift

Tendulkar, Bassa, Cordes et al. 2017, ApJL

What is the optical source?

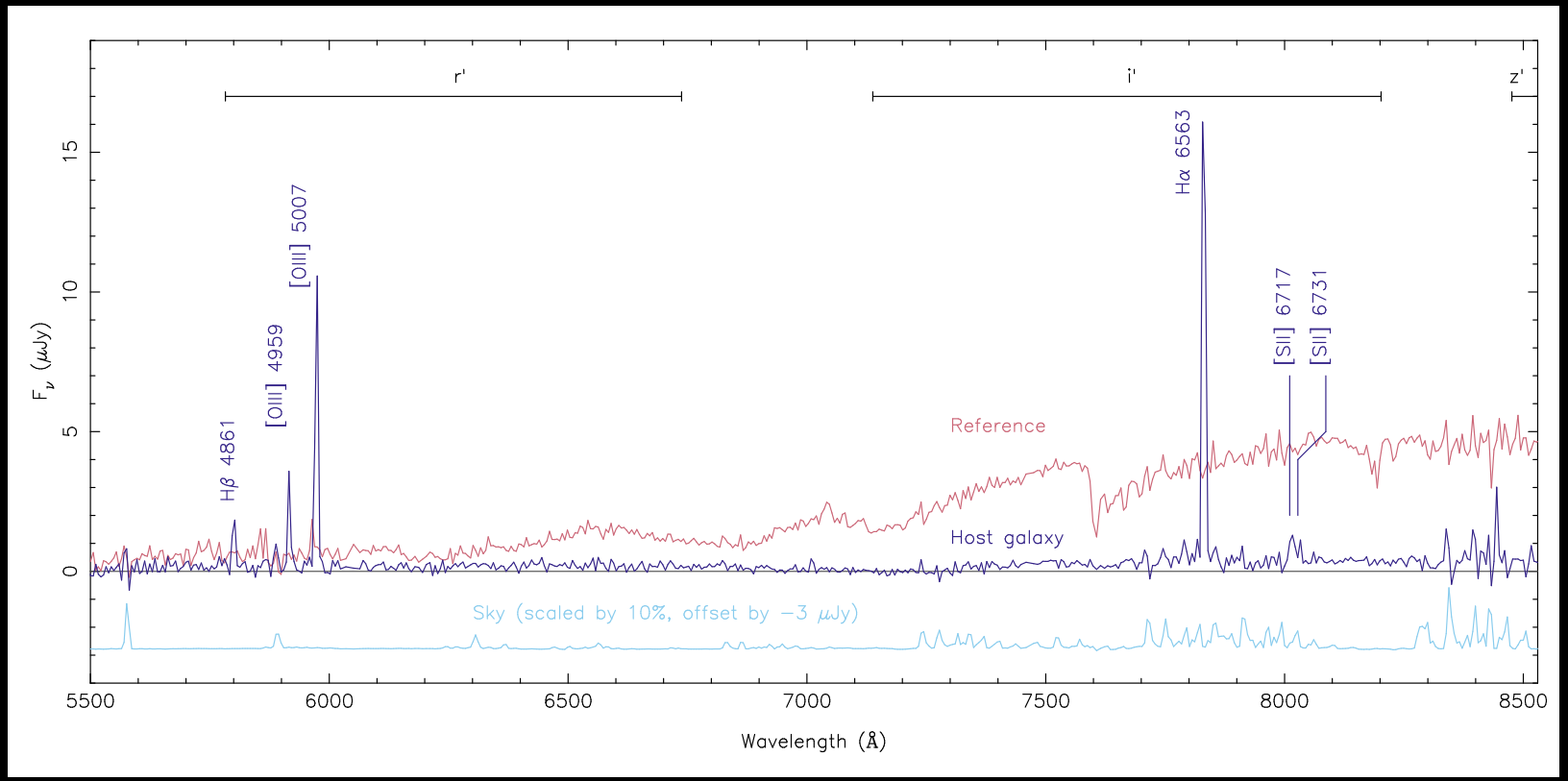


- 25th mag., roughly 100 million times fainter than the naked eye limit.
- Is this a star, or a (small) galaxy?



Gemini Redshift

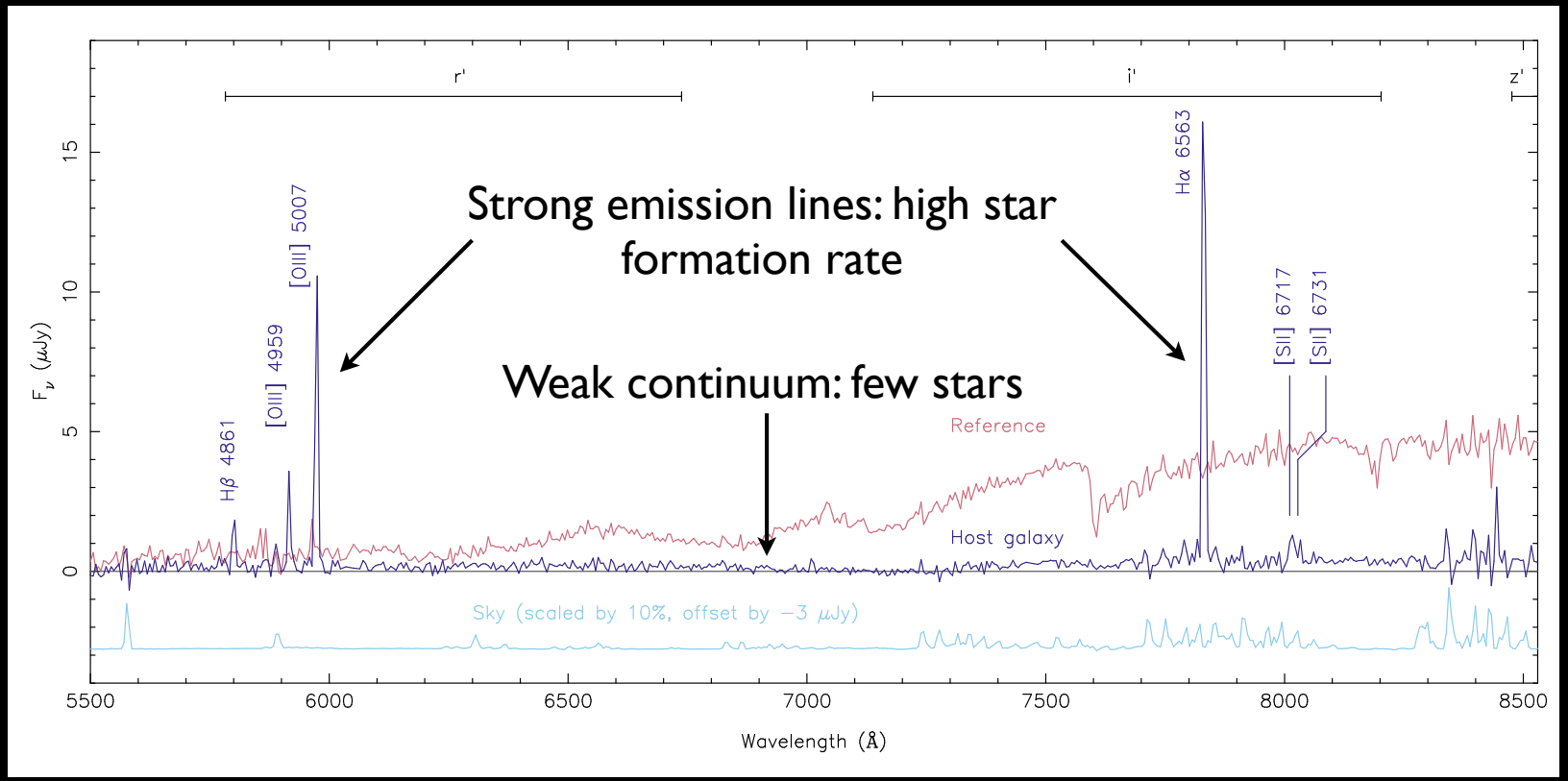
5.5 hours with the 8-m Gemini North



Tendulkar et al. 2017

Gemini Redshift

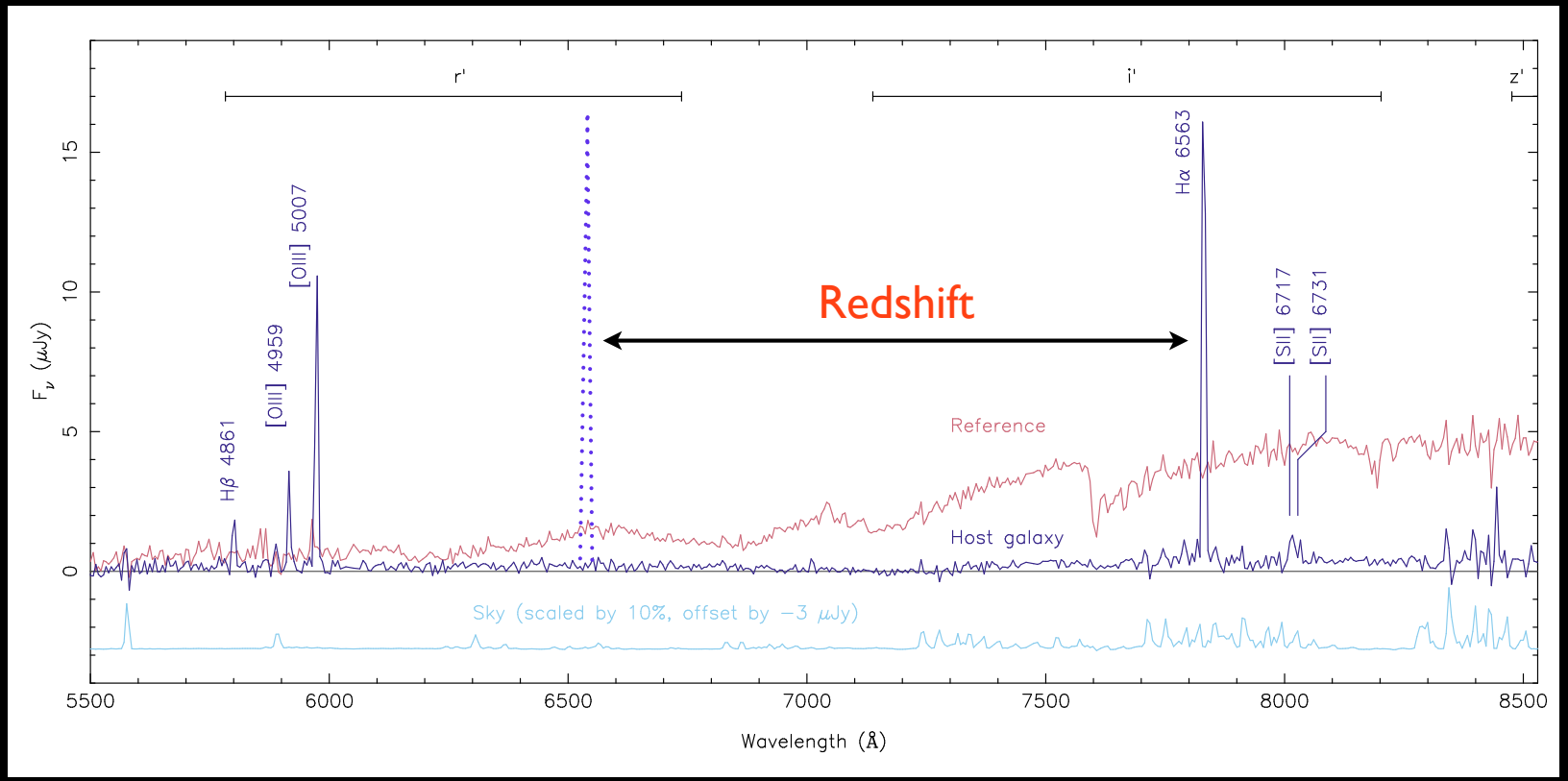
5.5 hours with the 8-m Gemini North



Tendulkar et al. 2017

Gemini Redshift

5.5 hours with the 8-m Gemini North

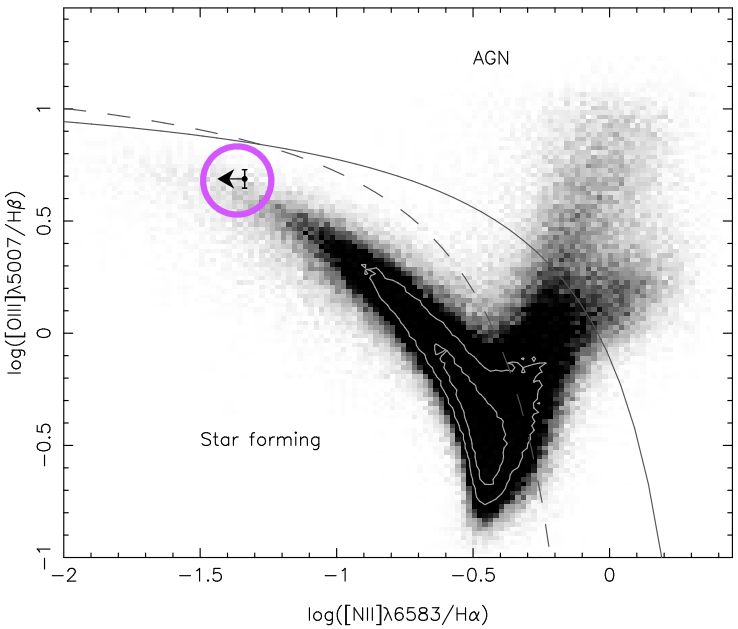


Host is a dwarf galaxy at z = 0.19 (~1Gpc)

(sets energy scale of bursts, ~10^{40} erg/s)

Tendulkar et al. 2017

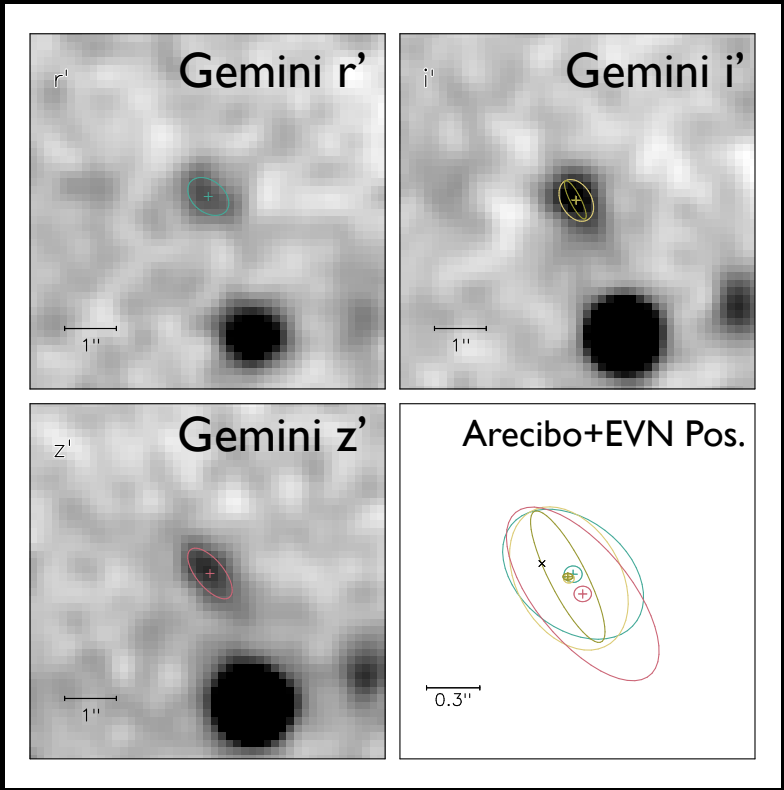
BPT Diagram

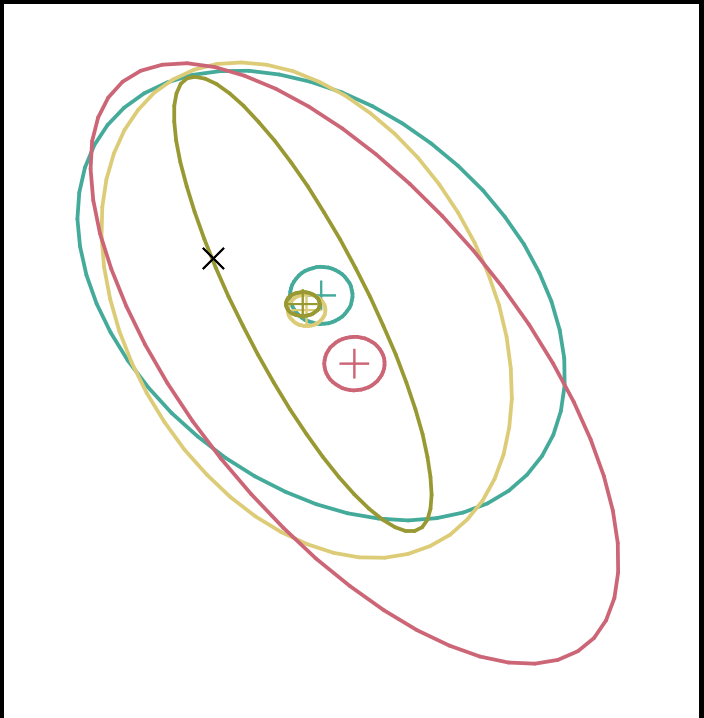


Optical emission is likely from star formation rather than AGN activity

Tendulkar et al. 2017

Compare with Arecibo+EVN Localization



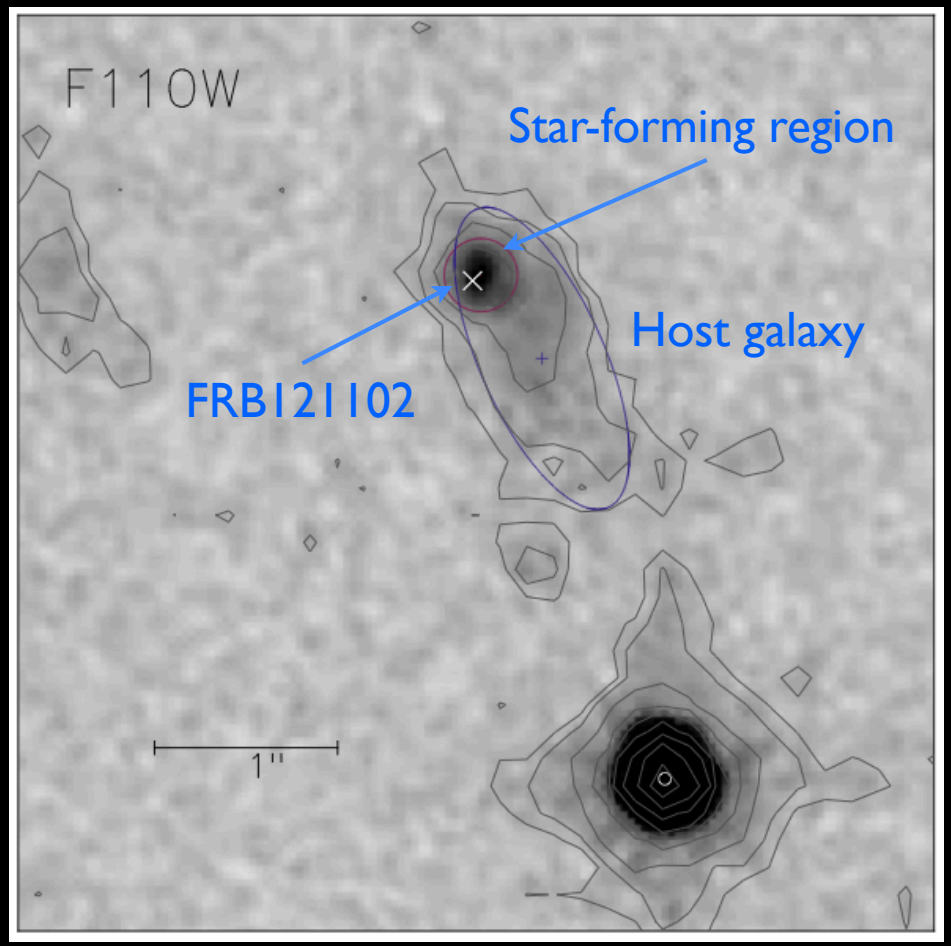


Bursts and optical centroid of galaxy are separated by ~0.2”

(0.5-1kpc, a quarter to half the radial extent of the host galaxy)

Tendulkar et al. 2017

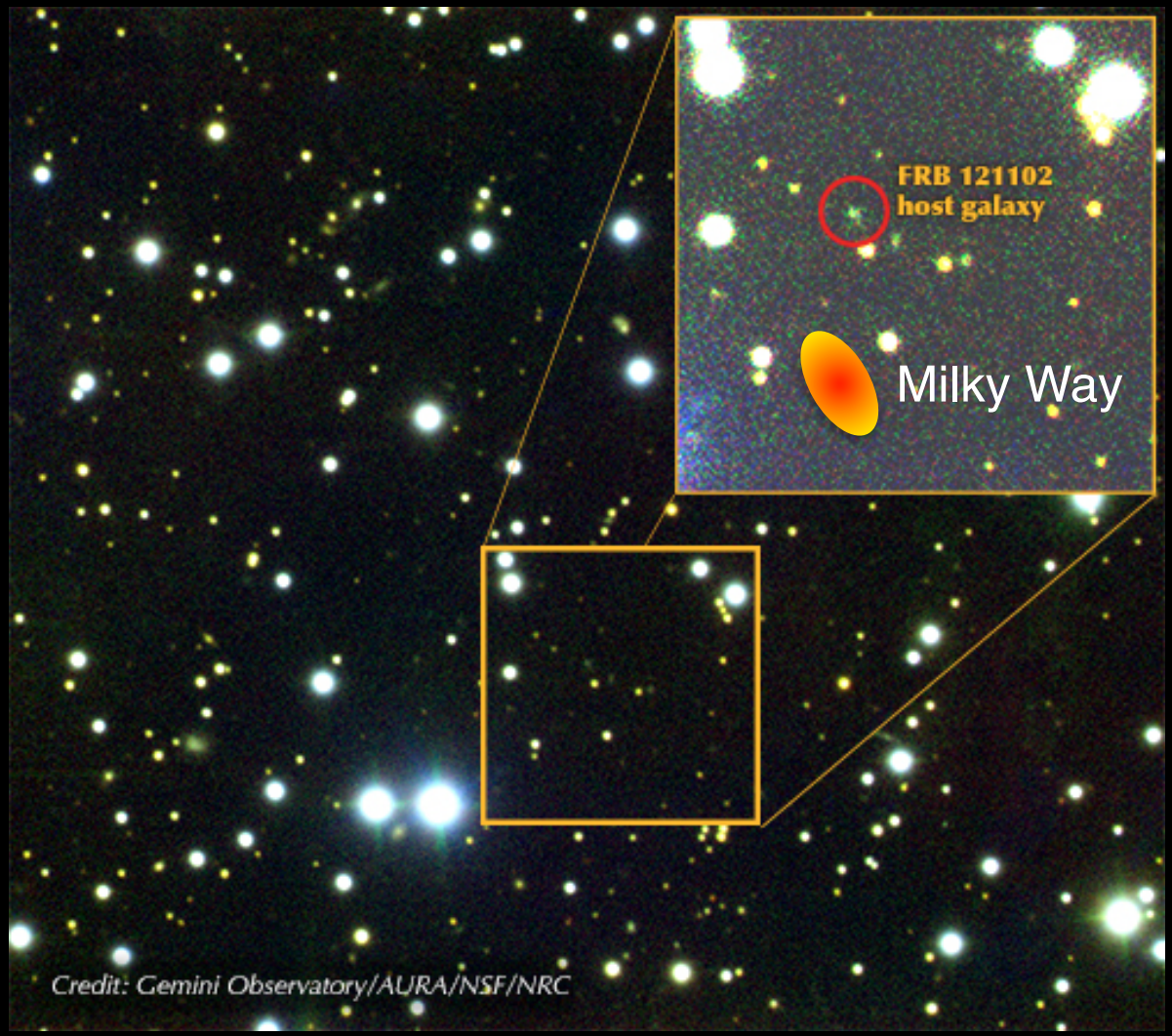
FRB121102 with HST



Clearly associated with a star-forming region in the host

Bassa et al. 2017

The Host Galaxy

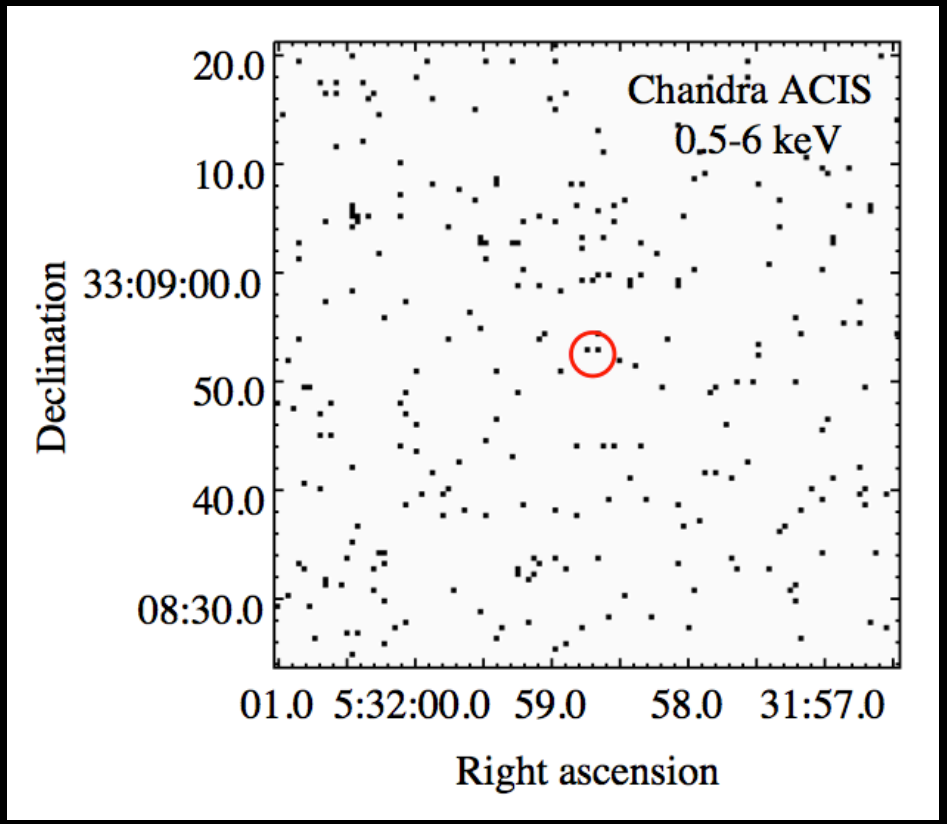


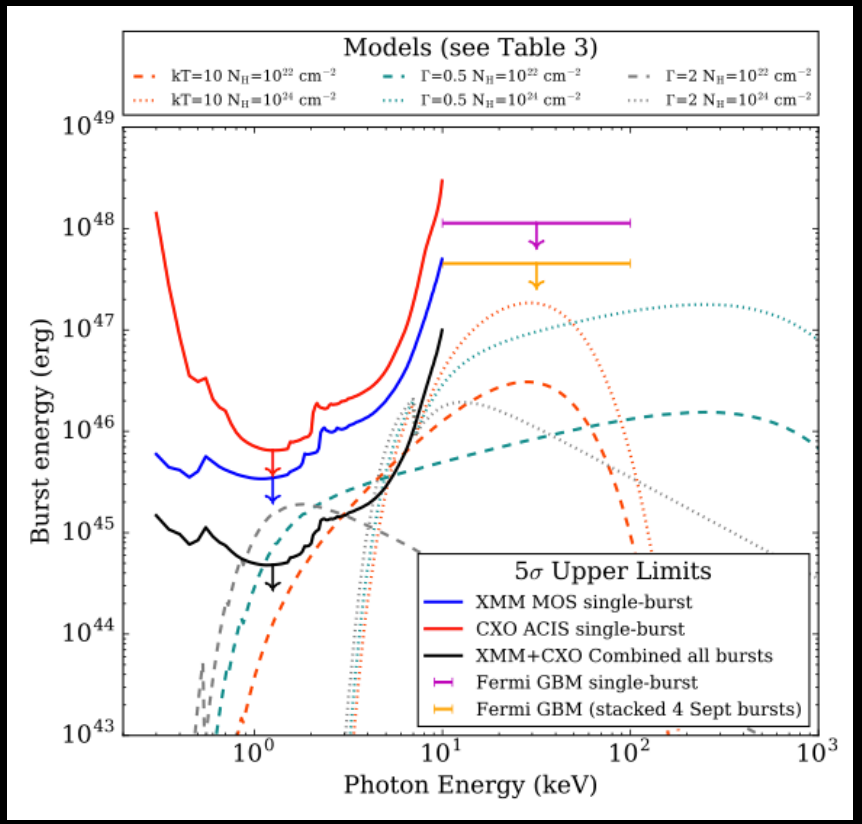
- 25th mag., roughly 100 million times fainter than the naked eye limit.
- Each burst (briefly) outshines all other stars in the galaxy!!
- 1000x less massive than the Milky Way.

Relation to long GRBs and superluminous SNe?

More recent insights...

FRB121102 with XMM & Chandra





No persistent X-ray source

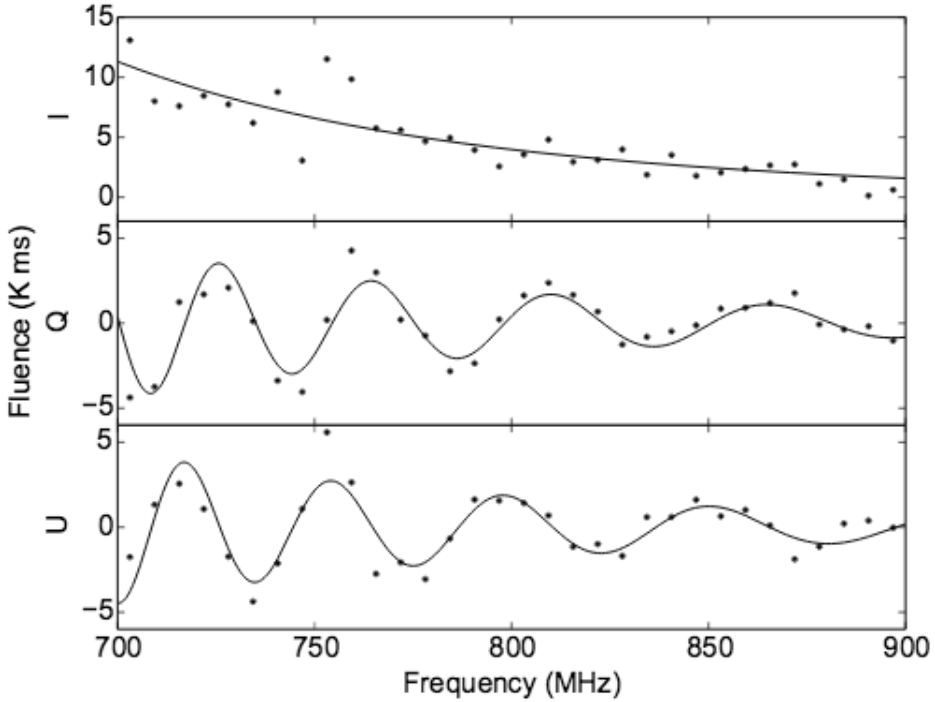
Only lightly constrains magnetar models

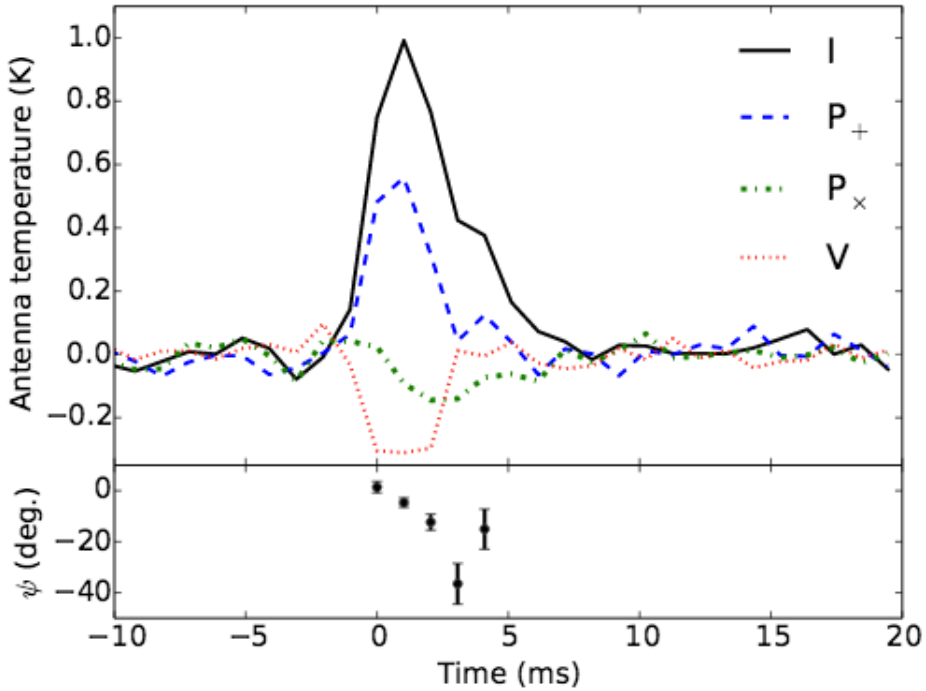
Scholz et al. 2017

In the absence of prompt multi-wavelength counterparts, we need to focus more on the properties of the radio bursts themselves, e.g.:

- **Polarimetric properties.**
- **Time-frequency structure in the burst shapes.**

Green Bank Telescope FRB



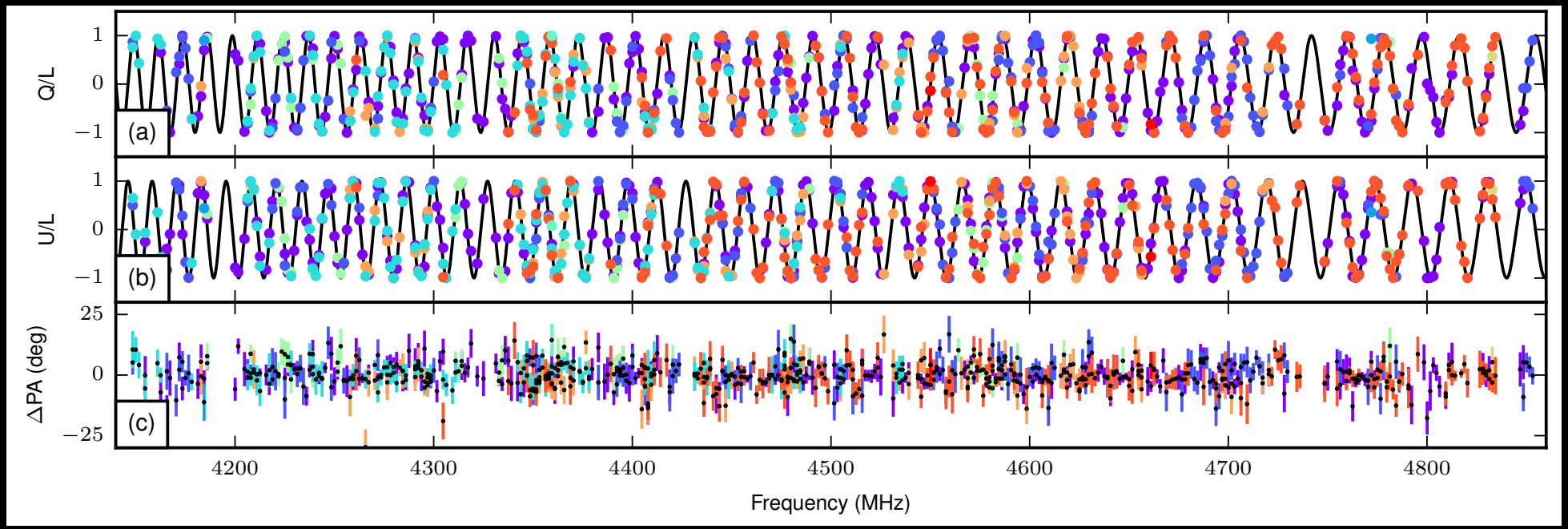


Masui et al. 2015

Rotation measure = -186rad/m2!

Local magnetization & scattering

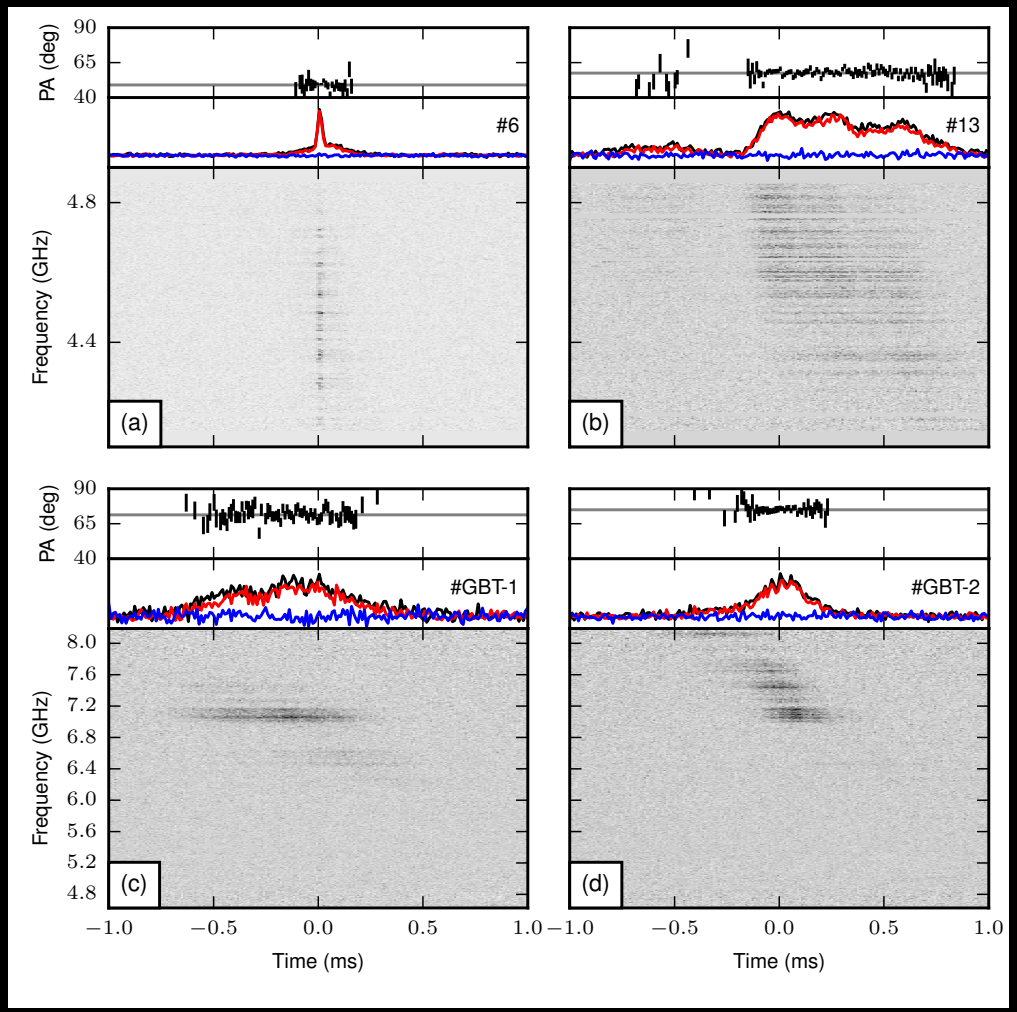
Rotation measure of the Repeater

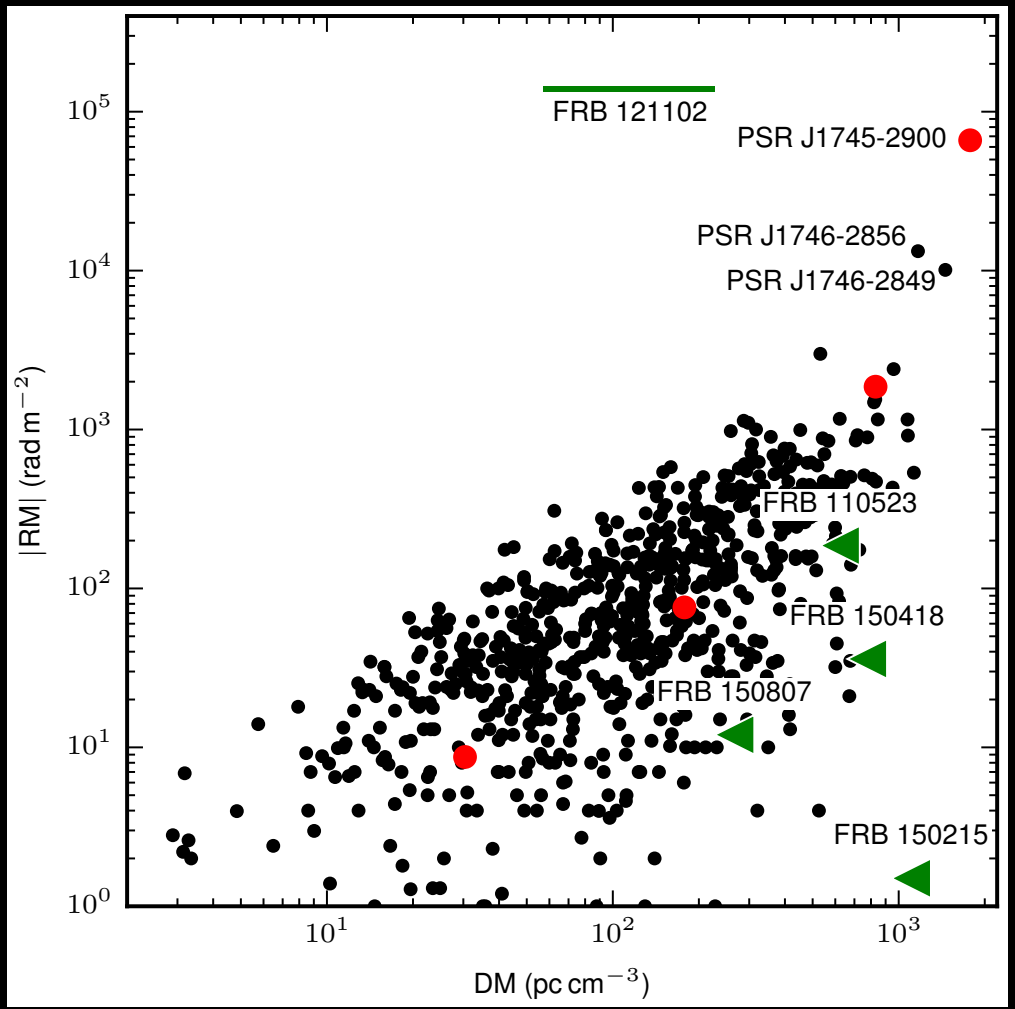


Michilli, Seymour, Hessels et al. 2018

Rotation measure ~ 140,000 rad m^{-2}
in the source reference frame:
$(1+Z)^2$, here Z = 0.193

Rotation measure of the Repeater



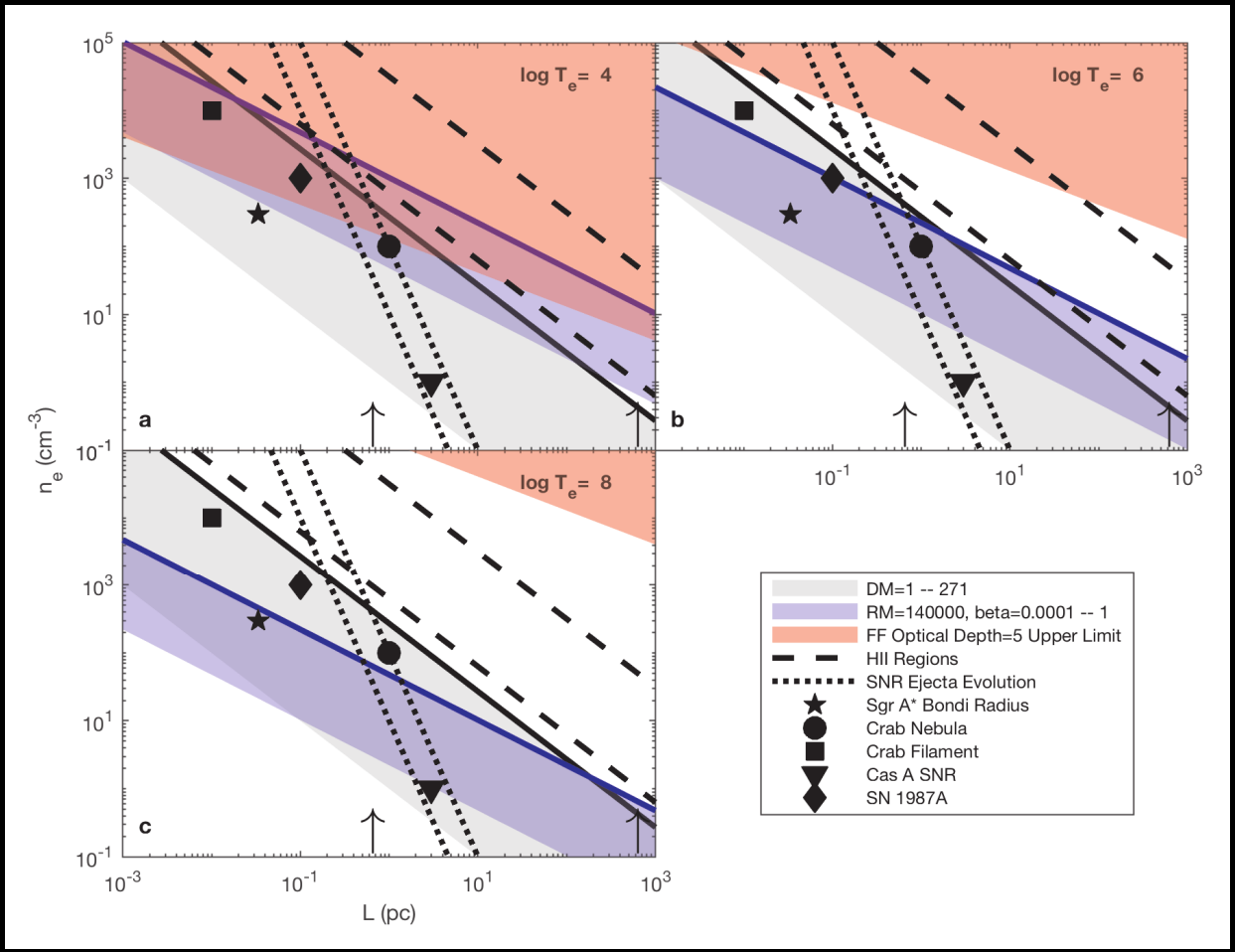


Michilli, Seymour, Hessels et al. 2018

Bursts ~100% linearly polarized and can be ~30 microsec wide!

Rotation measure of the Repeater

Equipartition constraints

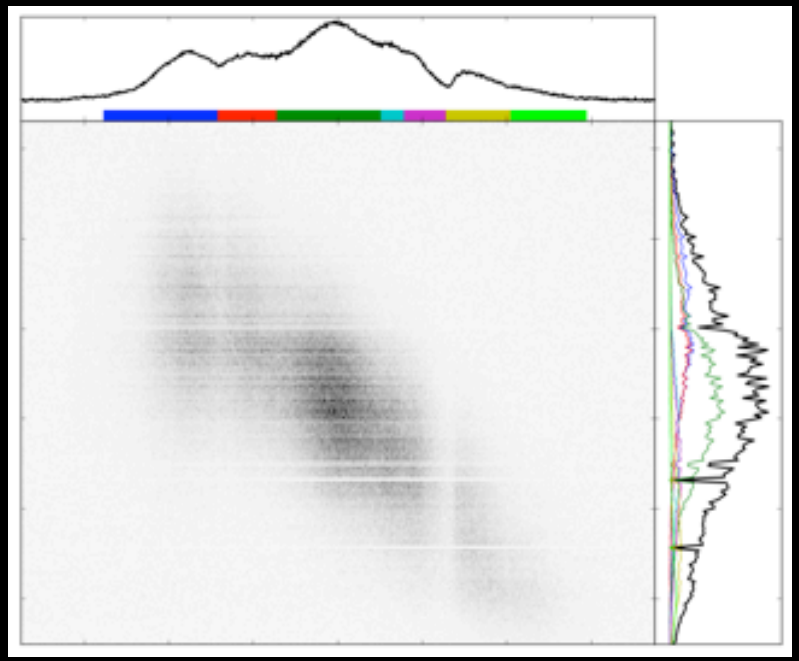


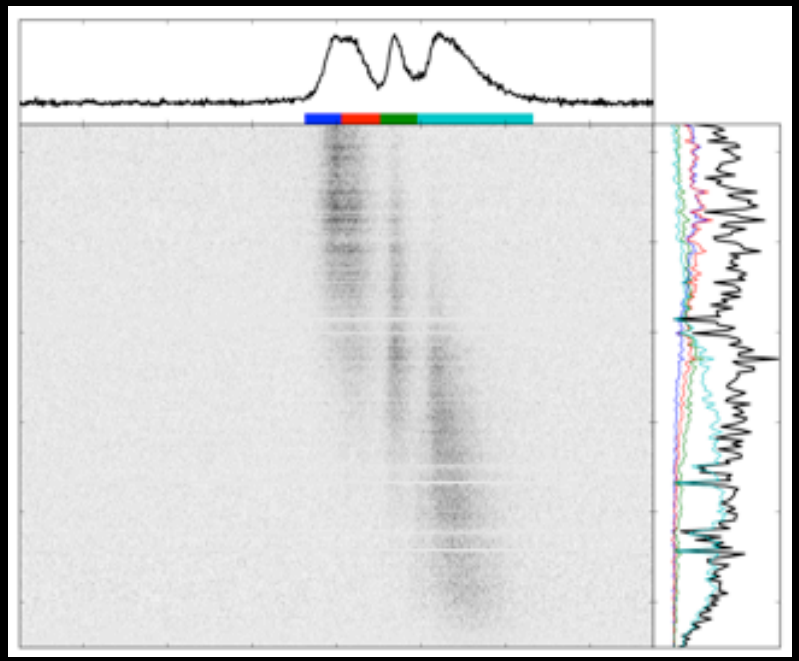
Michilli, Seymour, Hessels et al. 2018

> mG local magnetic field

Near a massive black hole or within a powerful nebula?

Bizarre Bursts

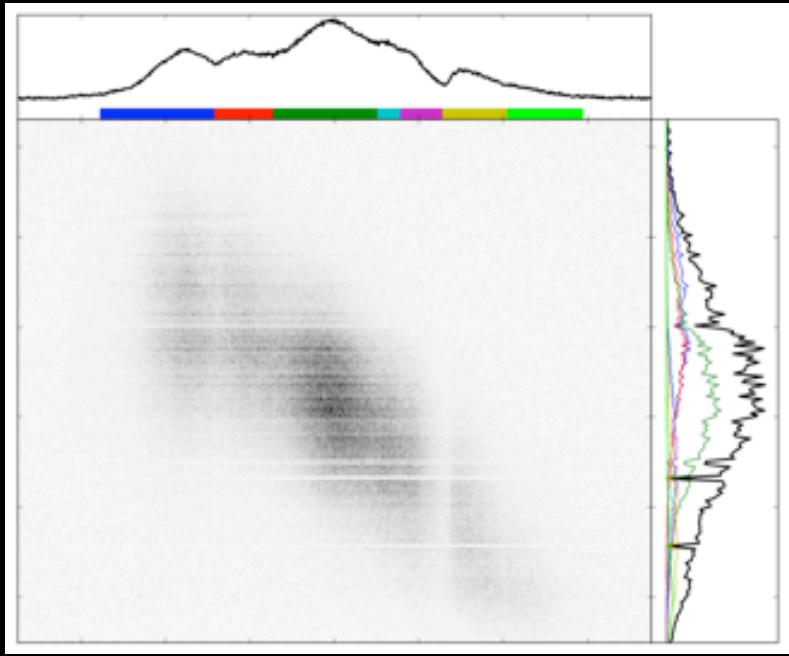


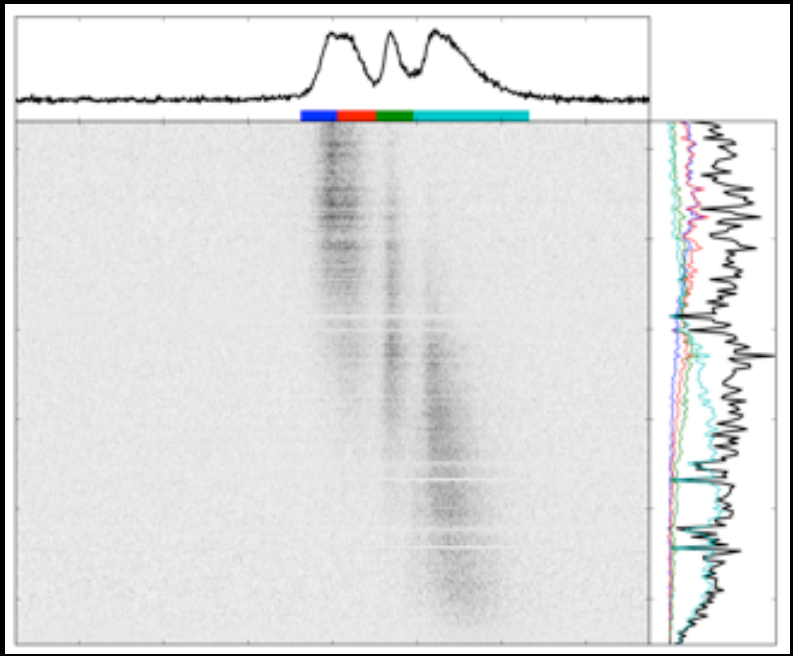


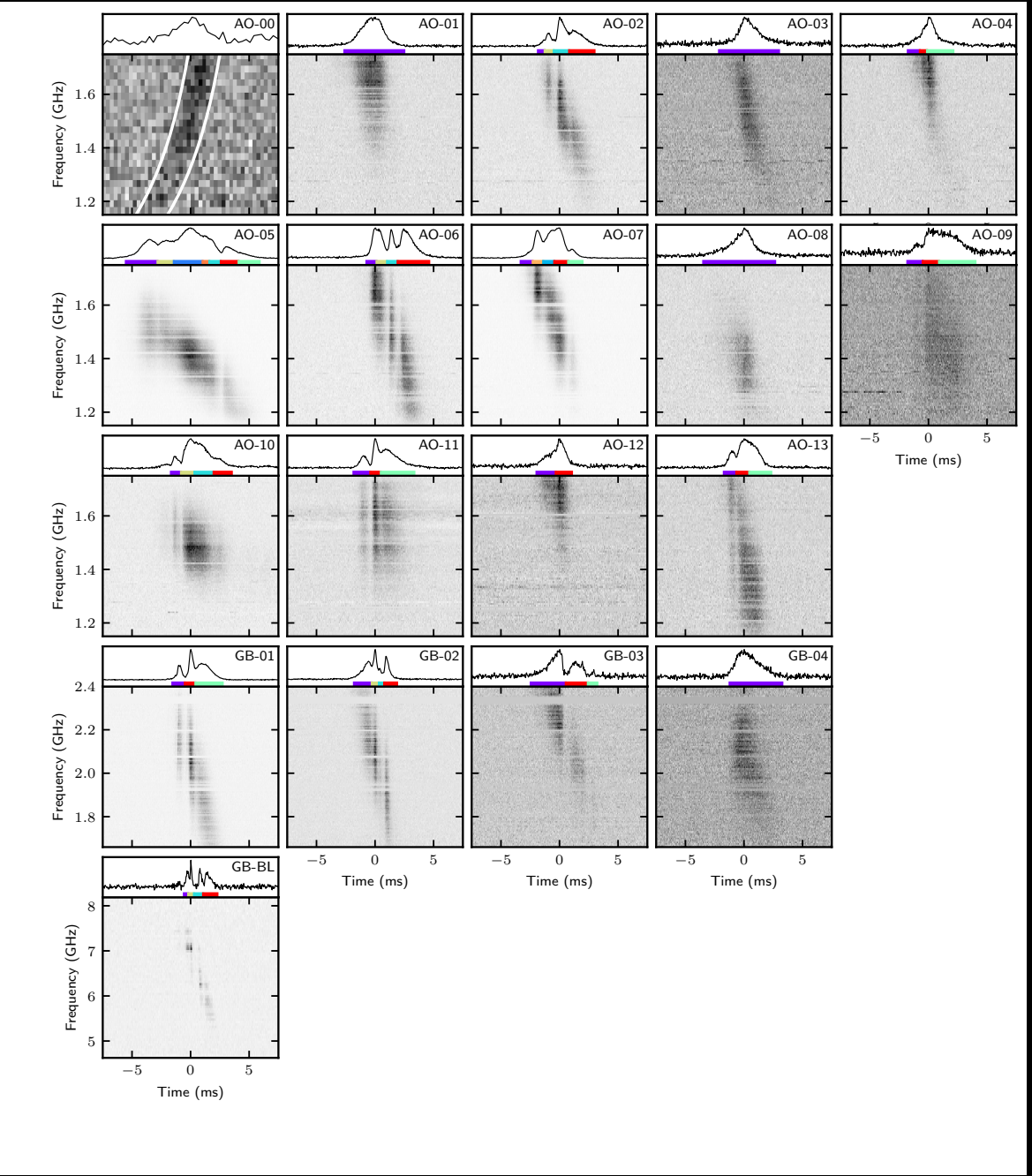
Hessels et al. 2018 (in prep)

Using Arecibo to understand the bursts' spectrotemporal behavior and search (again) for periodicity

Bizarre Bursts

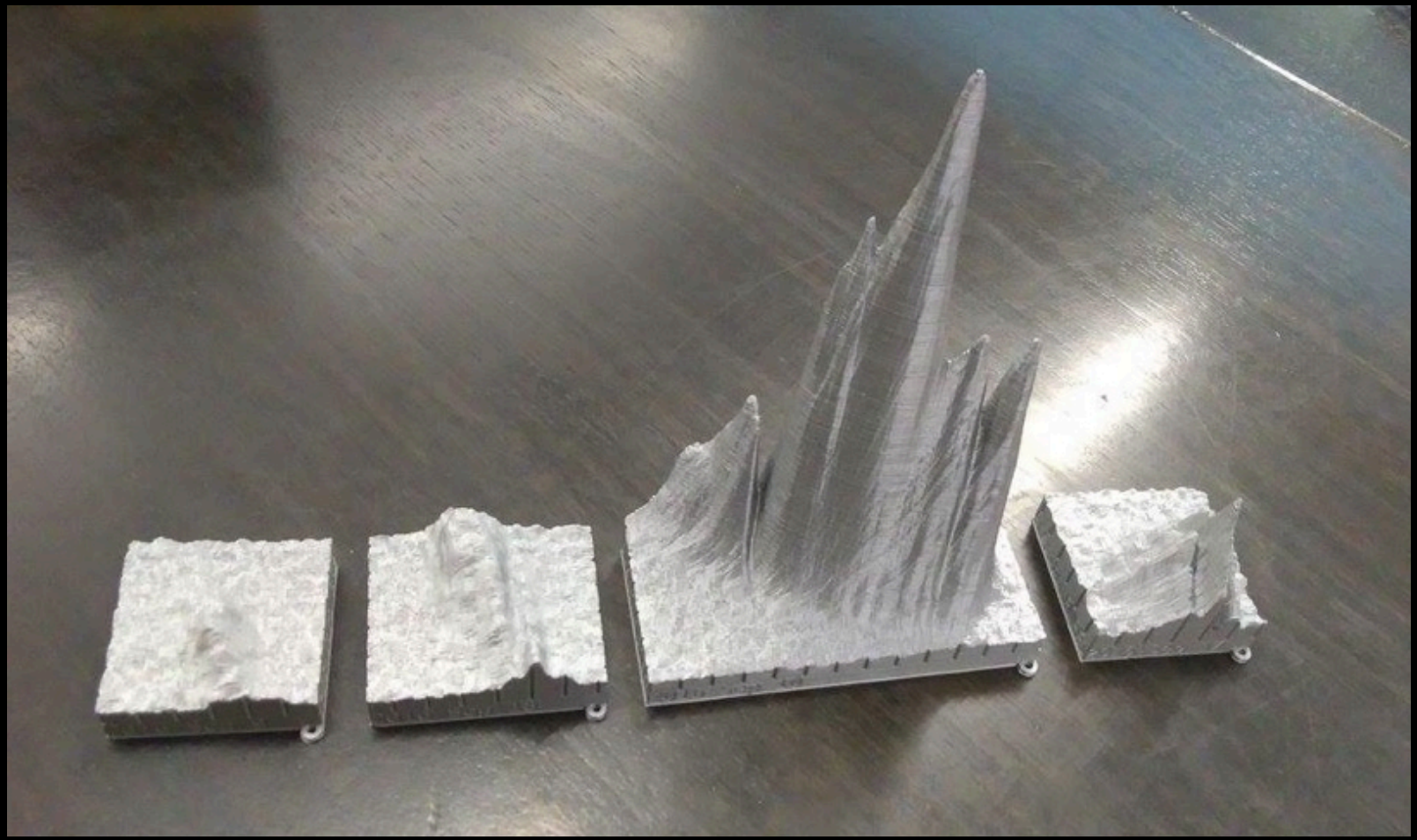






Hessels et al. 2018 (in prep)

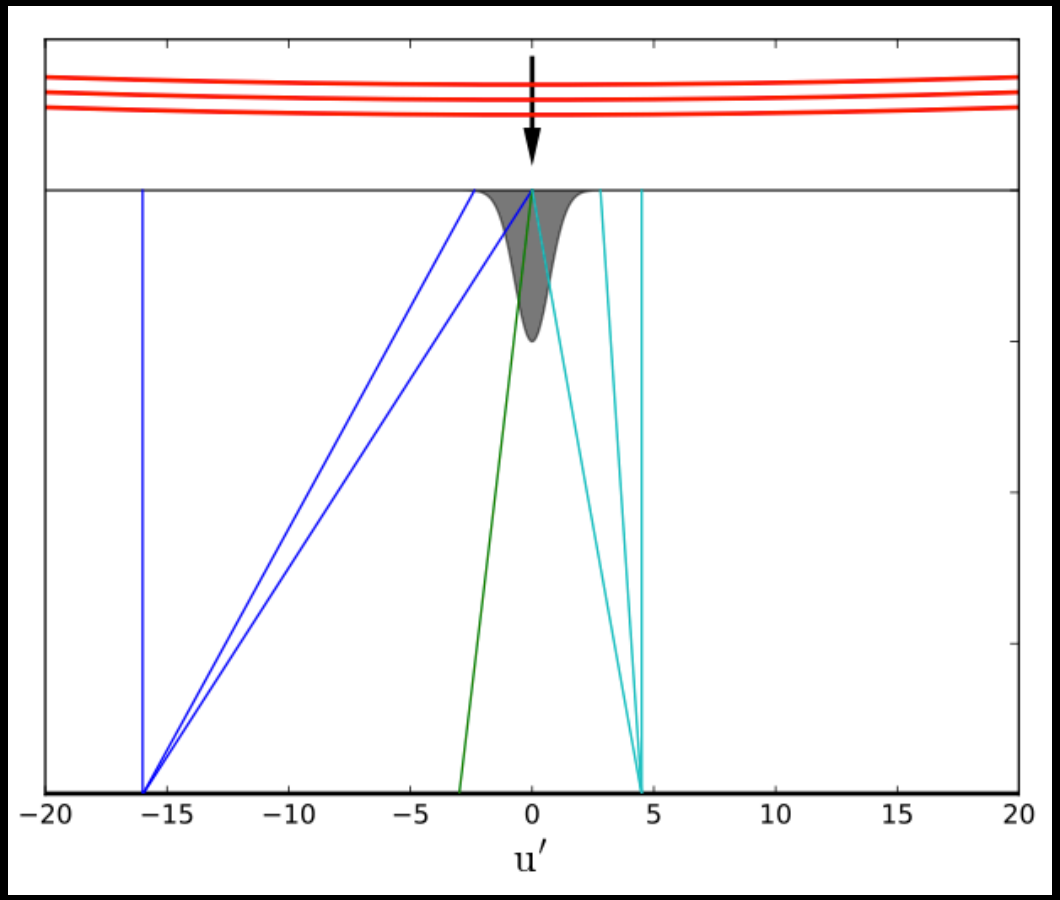
Bizarre Bursts



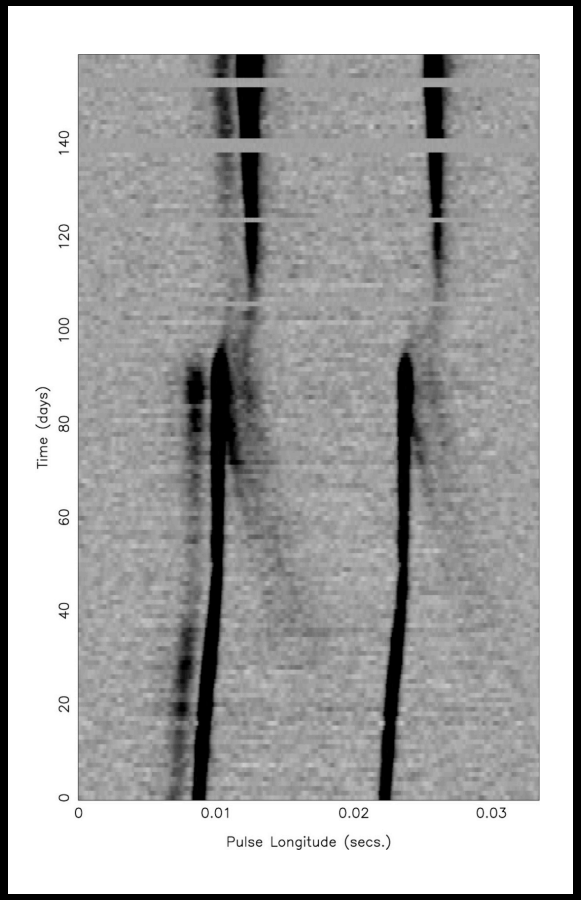
Anne Archibald

World's worst keychain

Bizarre Bursts



Toy lensing model



Observed Crab echoes

Graham-Smith & Lyne

Intrinsic and/or propagation effects?

Cordes et al. 2017

Summary

- **FRB121102 requires a source that can survive creating the bursts themselves.**

- **It is located at 1Gpc in a star-forming region of a dwarf galaxy.**

- **It is coincident with a persistent radio source (nebula, AGN-like?).**

- **Energy scale of bursts (~10^{40} erg/s) is still possible with an extreme neutron star.**

- **It inhabits an extremely magnetized environment.**

- **Spectrotemporal behavior of bursts appears to be very diagnostic.**