Title: Mysteries of fast radio bursts

Speakers: Dongzi Li

Series: Strong Gravity

Date: March 23, 2023 - 1:00 PM

URL: https://pirsa.org/23030115

Abstract: Fast Radio Bursts (FRBs) are extremely energetic, millisecond-duration radio bursts coming outside our galaxy. The burst arrival time at different frequencies implies the number of electrons it has encountered in the foreground. Therefore, FRB is considered a promising new cosmology probe. The uncertainty of the circum-burst environment is one of the biggest concerns regarding its potential as a probe. In this talk, I will review the current understanding of the FRB progenitor and the recent study of the circum-burst environment. I will also discuss the many remaining mysteries, including the seemingly diverse nature of the sources, the magneto-environment, and the 16-day periodicity I found with one source. With the current and upcoming instruments, there will be more FRBs with orders of magnitude better spatial resolution detected in the next few years. The result will be an explosion of opportunity for understanding the burst origin and probing cosmic matter distribution at various spatial scales.

Zoom link: https://pitp.zoom.us/j/92030175800?pwd=dWlGVjV0Qnh5bGhLMk1pd01yRmNKQT09

Mysteries of Fast Radio Bursts

Dongzi Li
Caltech Sherman Fairchild Fellow

FAST FRB
Key Science Project

Mysteries of Fast Radio Bursts
(cm/m) telescopes

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Caltech Sherman Fairchild Fellow

FAST FRB
Key Science Project

The largest radio telescope in 1960s

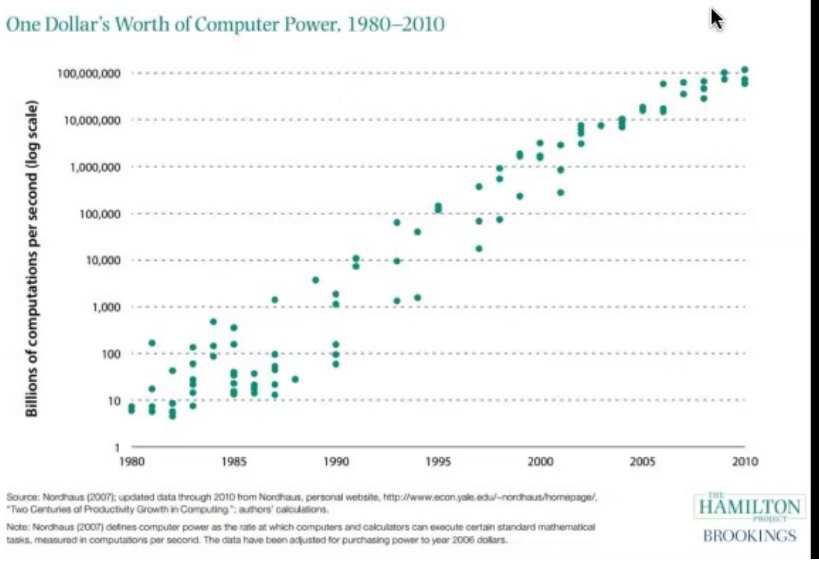
305m Arecibo telescope, completed in1963

Difficult to increase the size/sensitivity

But hey,
there are cheap computing power and memory!

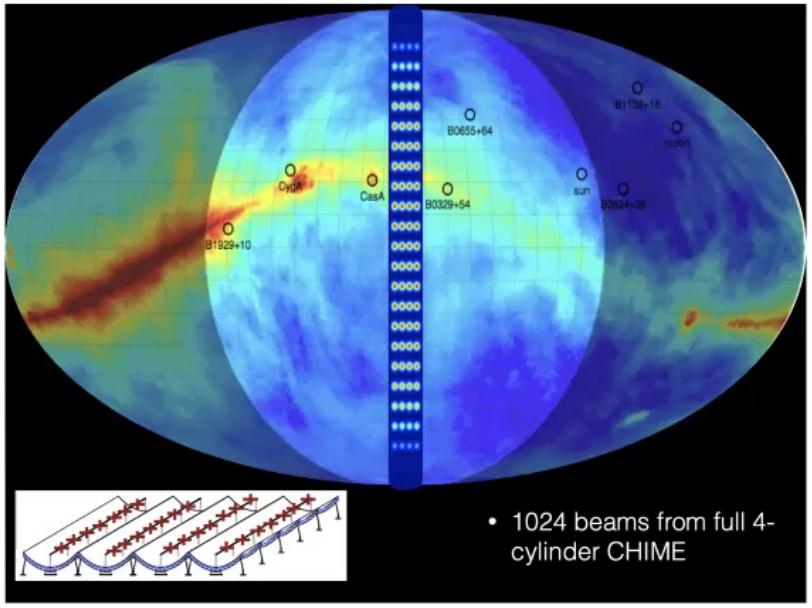
The largest radio telescope now

500m FAST telescope, completed in 2016



Modern survey interferometer

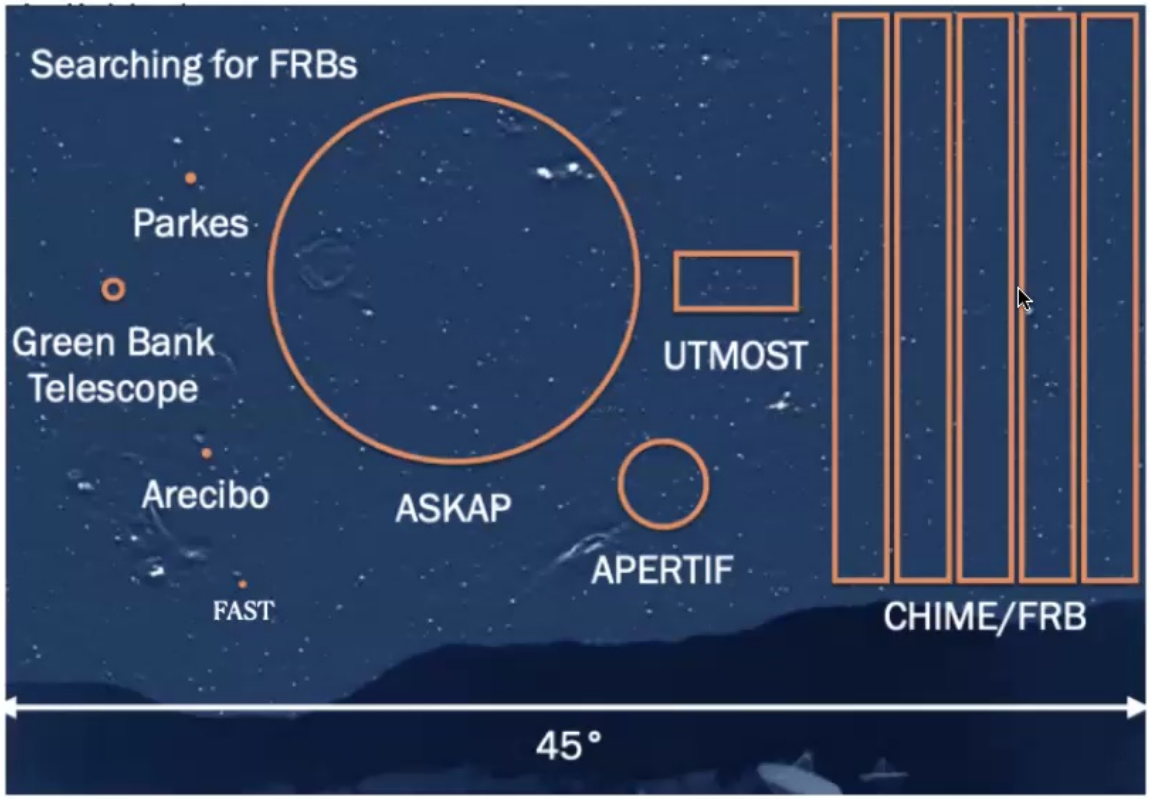
CHIME
1024 receivers, 1024 digital beams
scanning the sky 24/7 as Earth rotates
first-light 2017



Raw data rate: 17Tb/s
Realtime search with128 compute nodes with over 2500 CPU cores and 32,000 GB of RAM

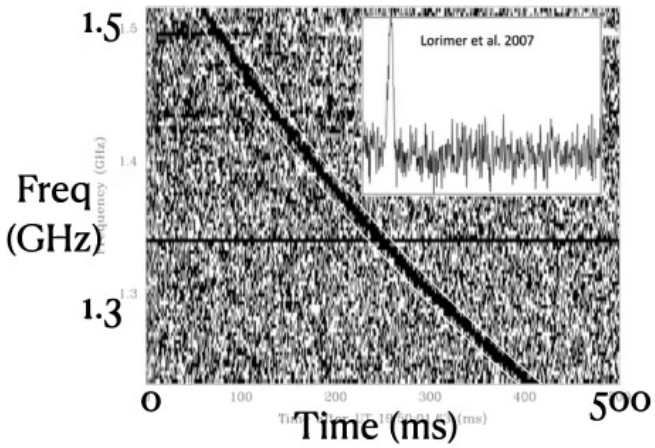
Large field of view

CHIME:
Canadian Hydrogen Intensity Mapping Experiment
survey 3/4 of the sky every day
at redshift 0.8-2.5



Fast radio bursts (FRBs)

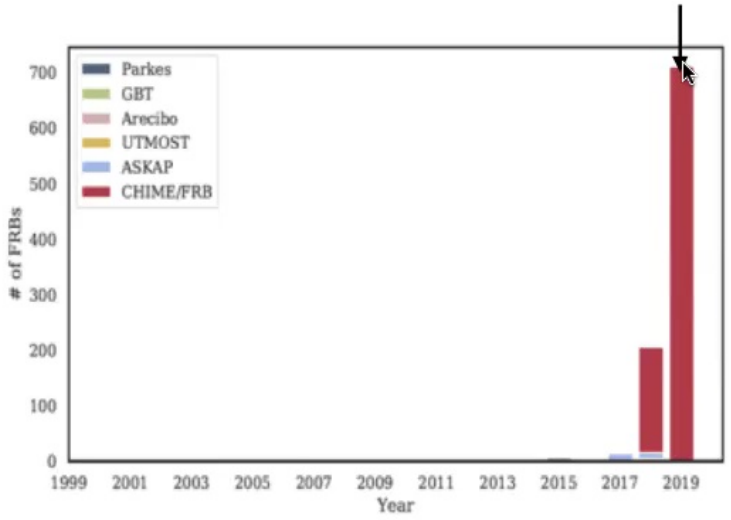
- Bright ~milisecond bursts in radio
  - First discovered in 2007 (Lorimer+07)
    - Searches of FRBs date back to 1979 (Phinney+79)
    - FRB-like detection in 1980 towards M87 (Linscott+80)

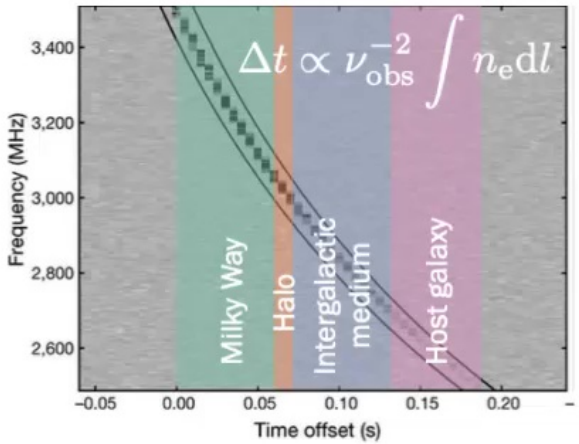


delay between frequency —> DM —> electron column

New cosmology probe!

CHIME catalogue paper 2021

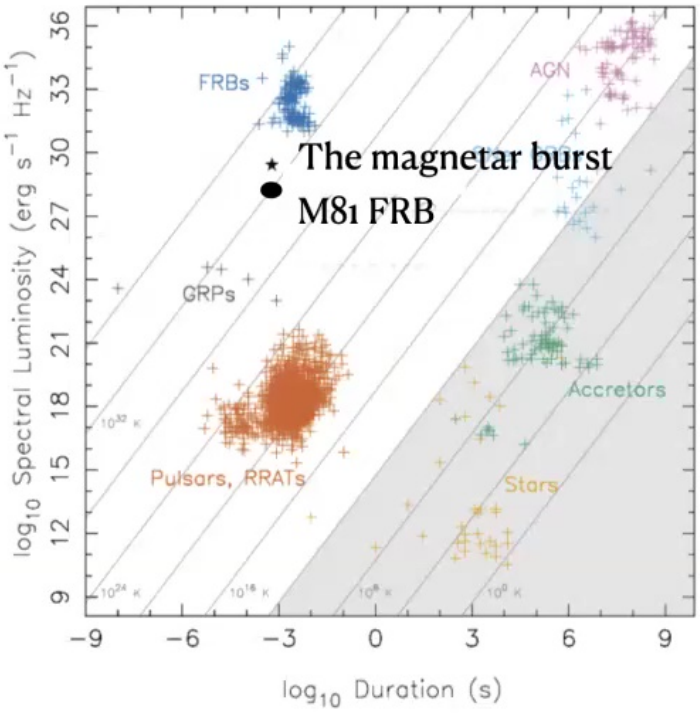




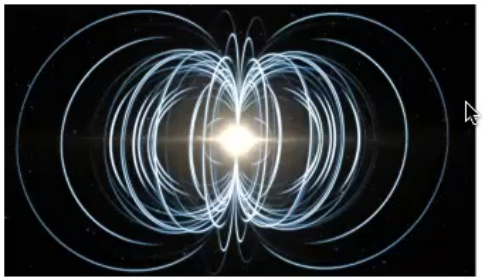
FRB progenitor

- Energy up to 1e35 erg/s/Hz
- Sky rate: ~1e3 /sky/day for fluence>1Jy-ms at 1.4GHz (Lawrence+17)

- Direct evidence:
  - The discovery of first repeater (Splitler+14,16) —> at least part of the FRBs, if not all, are non-catastrophic events
  - The detection of FRB-like burst from a Galactic magnetar (CHIME/FRB collaboration20, Bochenek+20)—> magnetar can be a progenitor



Bochenek+20



magnetar: neutron star with extremely high magnetic field

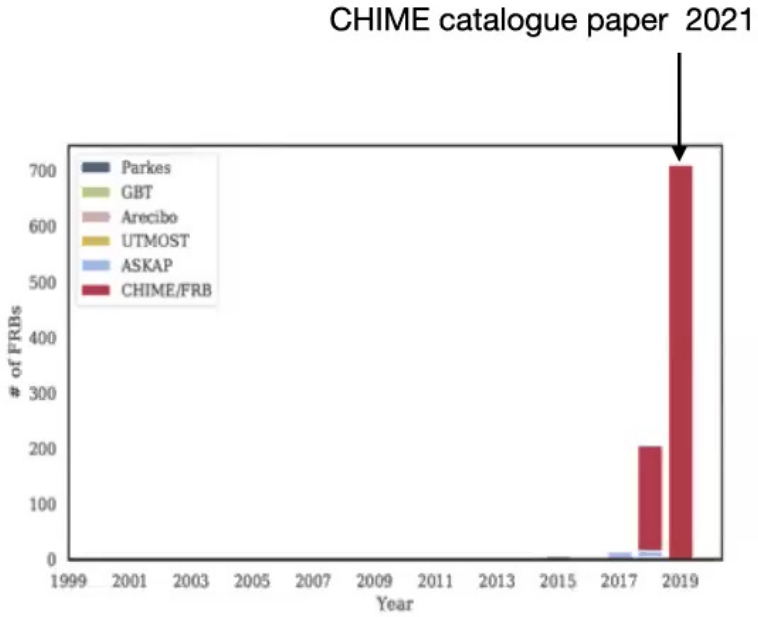
neutron star: the collapsed core of a massive giant

Now >600 published FRBs

- Improved understanding of the progenitor
- Moving forward, what are the observation that will help?

Start from the puzzles from recent study:

- The long-term periodicity
- Localization
- The active magneto-environment



Puzzle 1: the long-term periodicity of FRBs

Until 2020, the repeating of FRBs are observed to be sporadic

- Lots of attempts on FRB121102 (eg. Spitler+16, Scholz+16, Zhang+18, Grourdji+19, Rajwade+20→ ~150 day)
  - Uneven exposure

- CHIME/FRB
  - A lot more repeaters
  - Regular daily exposure → search periodicity of days

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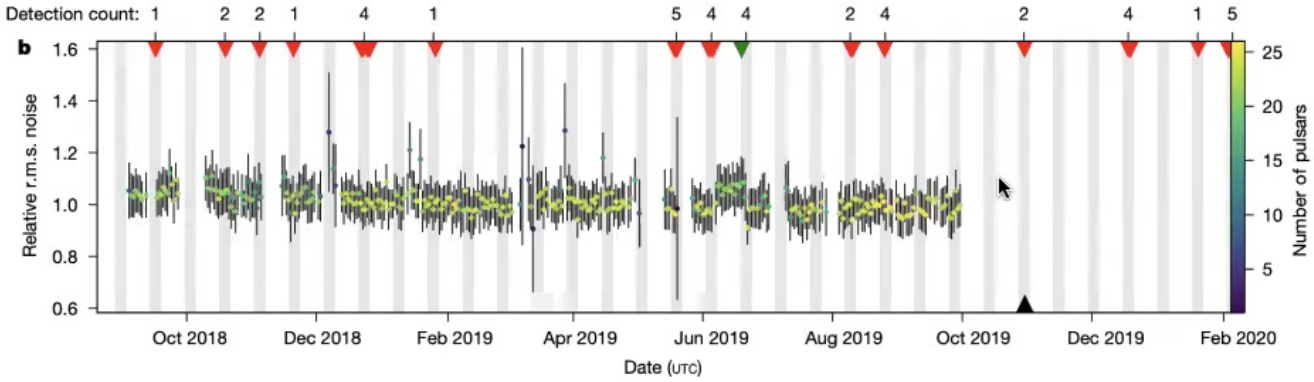
- Detection of a 16-day periodicity from FRB 180916



Nature **volume 582,** pages351–355(2020)

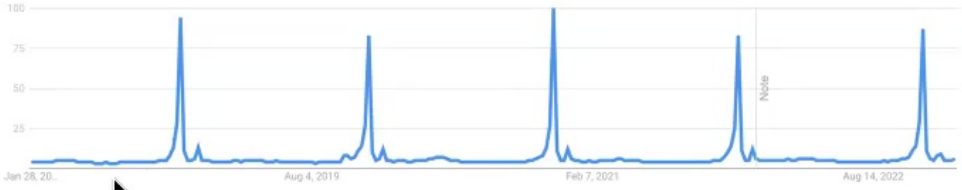
CHIME/FRB collaboration
D.Z. Li as corresponding author

Puzzle 1: the long-term periodicity of FRBs

Until 2020, the repeating of FRBs are observed to be sporadic

Justify significance given non-Poisson statistics
beat from the sidereal day

what's periodicity? eg. the time when US people search "turkey"



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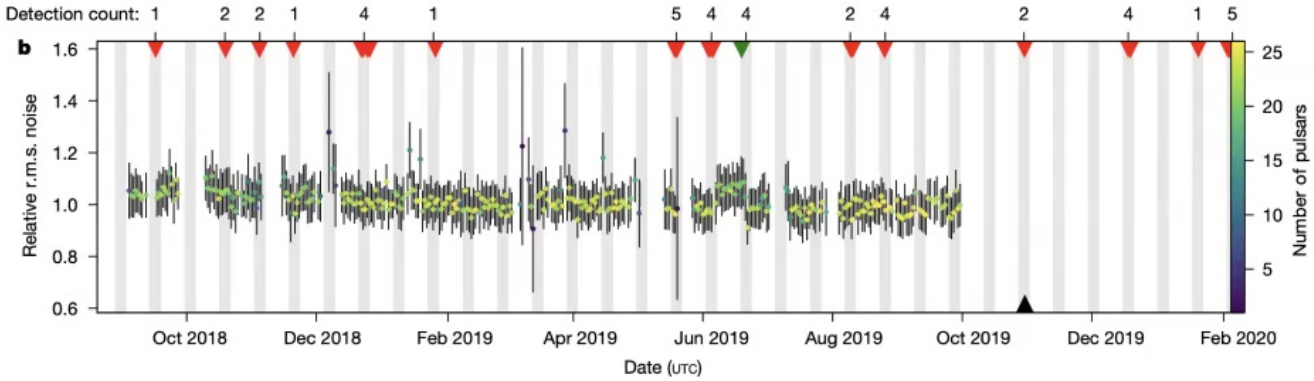

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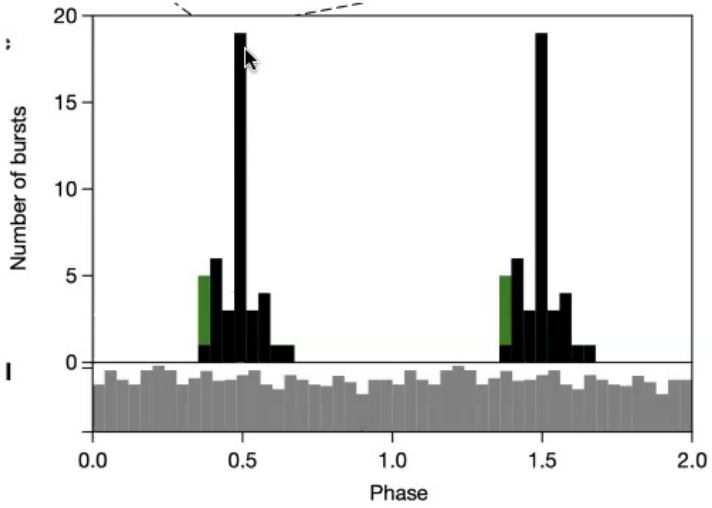

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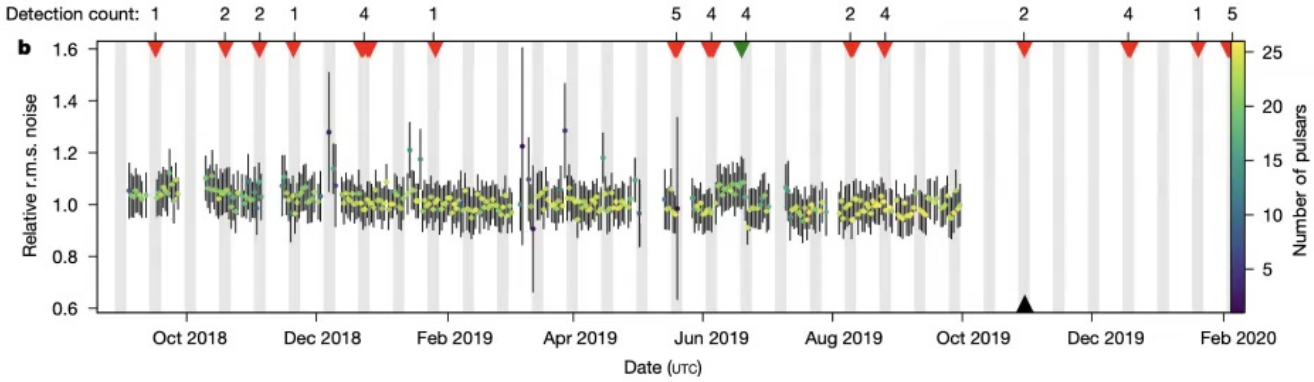

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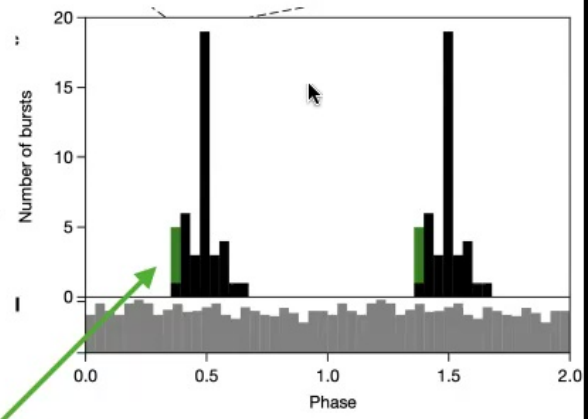
Puzzle 1: the long-term periodicity of FRBs

- Detection of a 16-day periodicity from FRB 180916
  - Observationally: high efficiency follow-ups!

multi-wavelength follow-ups from: Scholz+20, Chawla+20, Pearlman+20, Tavani+20, Andreoni+20, Pilia+20, Aggarwal+20….

  - Follow-up highlights:
    - Detection from 0.1GHz to 6GHz Pastor-Marazuela+20, Pleunis+21)



detection at higher frequency

Nature **volume 582,**
pages351–355(2020)

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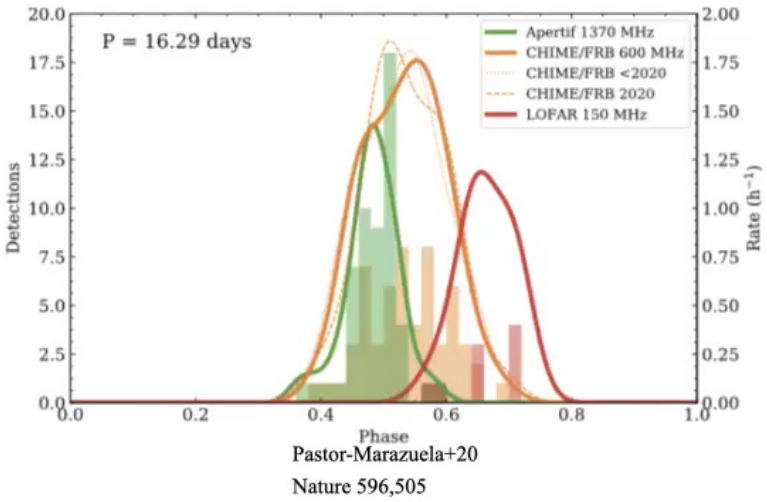
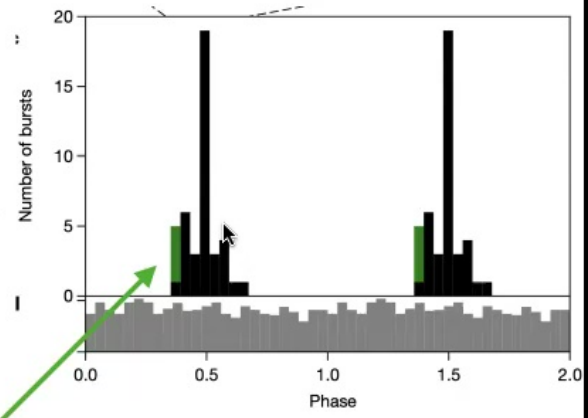


Pastor-Marazuela+20
Nature 596,505



detection at higher frequency

Active window keeps drifting to 6GHz (Bethapudi+22)

Puzzle 1: the long-term periodicity of FRBs

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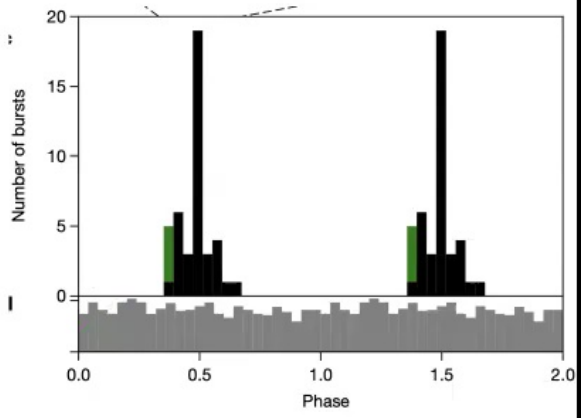


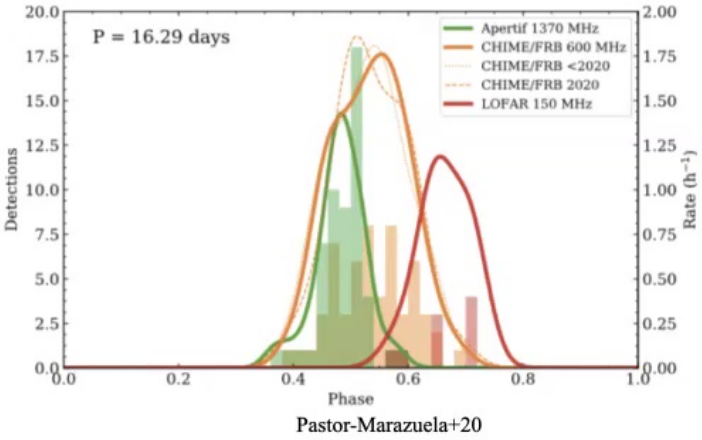
- Theoretically: Binary orbit? Precession? Spin
—> important to our understanding of FRB progenitors

Eg. Sridha+22,
Zhang20,Tong+20,Gu+20,Mottez+20,Zanazzi+20,Chernoff+20,
Ioka+20, Yuan+20,Lyutikov+20, Dai+20, Levin+20,
Chen20,Beniamini+20, Popov20

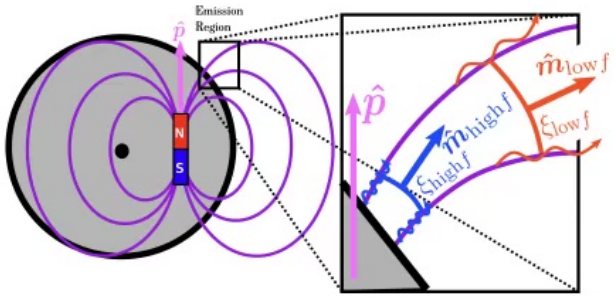
If companion-induced precession:
tight binary orbit (~minutes) (Huang+20)

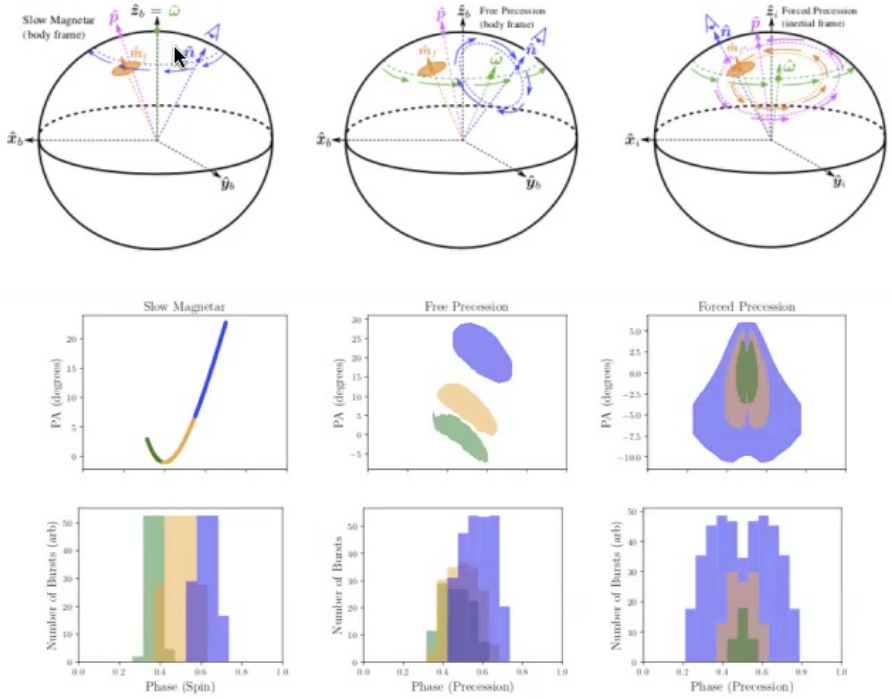
—> potential LISA source

- Chromatic active window could be due to altitude-dependent emission beam sweeping across LOS at different rotation phase.
- Can be tested with polarization angle (P.A)



Pastor-Marazuela+20





Li&Zanazzi 21
APJL 909, L25

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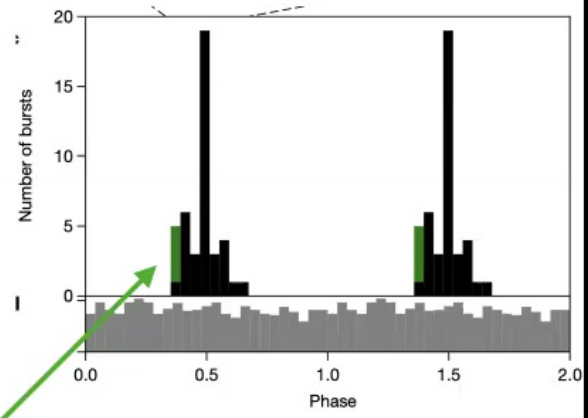


detection at higher frequency

- Find more samples
  - regular search of period at CHIME with Dr. Aaron Pearlman
- Keep monitoring the source, measuring PA
  - CHIME, GMRT, grad student Suryarao Bethapudi

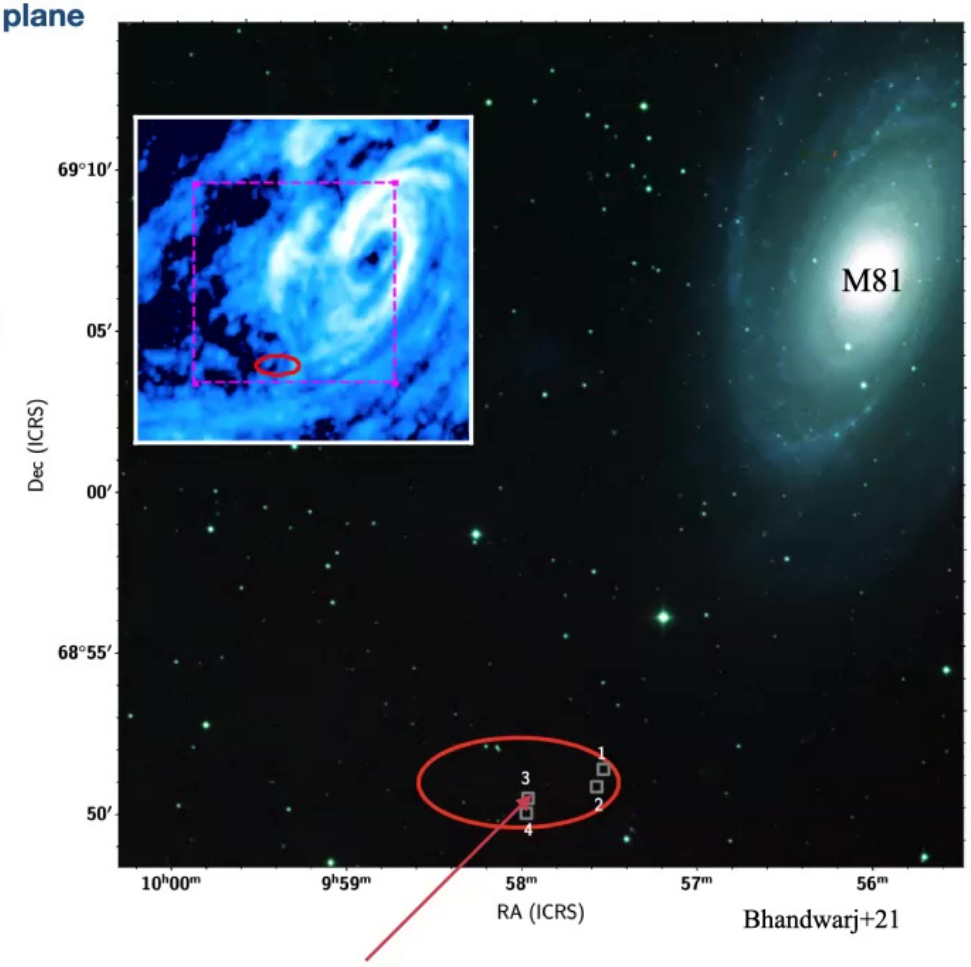
Nature **volume 582,** pages351–355(2020)

CHIME/FRB collaboration
D.Z. Li as corresponding author

Puzzle 2: the globular cluster FRB

All magnetars are found close to the galactic plane consistent with age<~10^5 yr

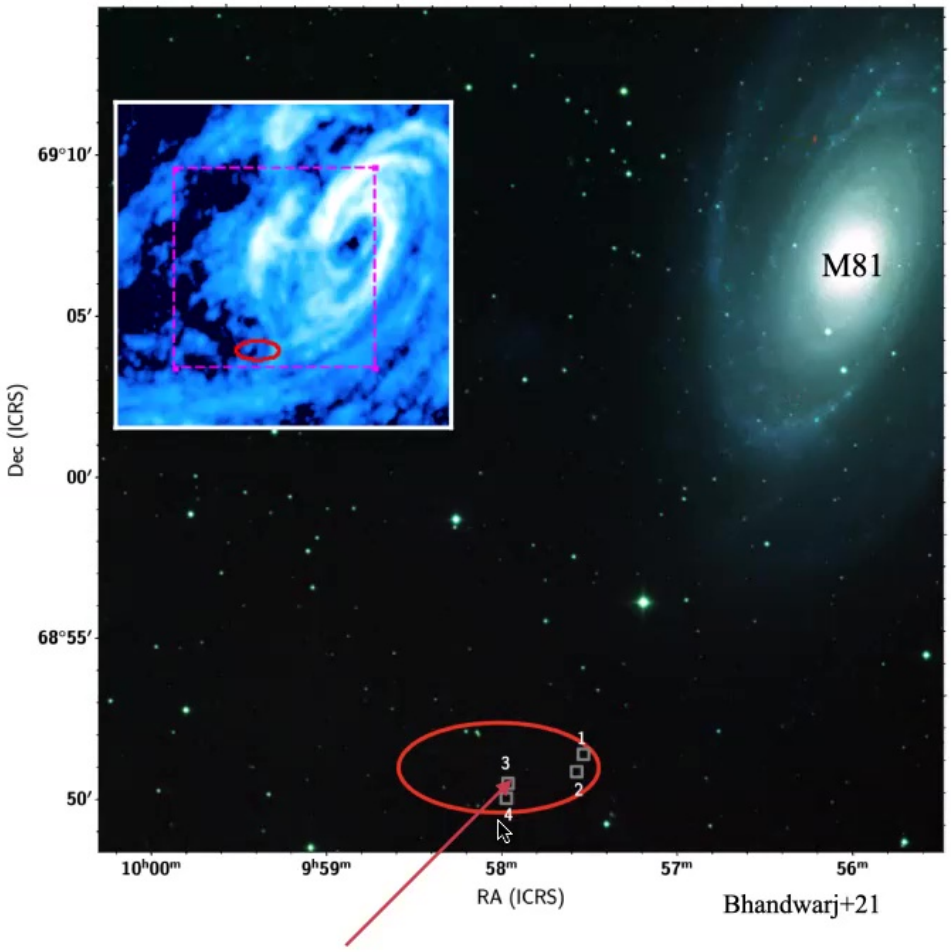
- A population of massive, red, low star forming host galaxies (Law in prep, Sharma+23, Gordon+23)
- Progenitor offset from star-forming region eg. age >100Myr?
- The most nearby FRB localized to a globular cluster (GC) 3.6 Mpc away Bhandwarj+21, Kirsten+21



GC[PR95] 30244 & FRB 20200120E

Puzzle 2: the globular cluster FRB

- The most nearby FRB localized to a globular cluster (GC) 3.6 Mpc away Bhandwarj+21, Kirsten+21
  - Known magnetars usually <<10^5 yr, tracks star formation
  - GC hosts old population
  - only ~0.001% stellar mass in GC compared to galaxy



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  - Known magnetars usually <<10^5 yr, tracks star formation
  - GC hosts old population
  - only ~0.001% stellar mass in GC compared to galaxy

- Even hypothetical dynamically formed magnetar in GC: ~1% compared to normal magnetar

Consider the dynamic channel

Formation Rates for Several Proposed FRB Progenitors in GCs

Event Type	Rate per CC GC (yr^{-1})	Volumetric Rate ($Gpc^{-3}yr^{-1}$)	Active Lifetime Required (τ) ($\times(f_v\zeta)^{-1}$)
Super-Chandrasekhar WD+WD mergers	6×10^{-9}	4	10^6 yr
(estimate including tidal capture)	7×10^{-8}	45	10^5 yr
WD+NS mergers	10^{-9}	0.8	6×10^6 yr
(estimate including tidal capture)	10^{-8}	6	8×10^5 yr
NS+NS mergers	10^{-10}	0.08	6×10^7 yr

Kremer, Tony, Li 21

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- The most nearby FRB localized to a globular cluster (GC) 3.6 Mpc away Bhandwarj+21, Kirsten+21

- **The fraction in the whole population?**

Need more samples!

Consider the dynamic channel

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Need more samples!

chance of coincidence: $P = A\rho_{\rm GC}$

increase with distance^2
with best resolution on Earth: mas
know in GC < redshift 0.1

Consider the dynamic channel

Formation Rates for Several Proposed FRB Progenitors in GCs

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Kremer, Tony, Li 21

Search for GC FRBs

- Known:
  - one source found in M81 (3.6 Mpc)
  - In total ~1300 GCs up to the distance (Harris+13).
- Best Target:
  - Virgo A (16Mpc): 15000 GCs —> **~10 sources**

500m FAST telescope,

- Expected rate for FAST: R~4 * 0.07/h * [(0.02Jy ms/5 Jy ms) * (3.6Mpc/ 16Mpc)^2]^{-1.4}

R~ 5/h

Useful discussion with Ue-Li Pen, Kyle Kremer

Search for GC FRBs

500m FAST telescope,

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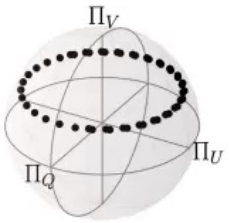
  R~ 5/h
- Observation (with FAST FRB key project)
  - 2021Jun, 2021July, 2021Aug, 2022Sep, 2023Jan (2h each time)
  - Effective ~3h, search DM: 50-20000pc/cm^3 —> non-detection

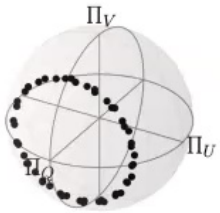
Observed with the help from Bing Zhang, WeiWei Zhu, Jiarui Niu, Dejiang Zhou

The magneto-environment: some basics

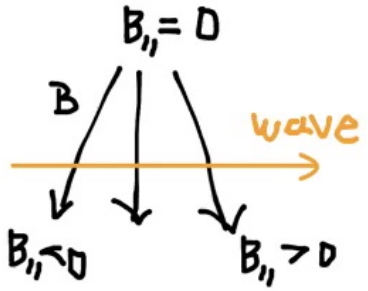
- Stokes parameter:
  - I (total intensity), Q, U (components of linear polarization), V (circular polarization)
  - Linear polarization L=(Q^2+U^2)^0.5



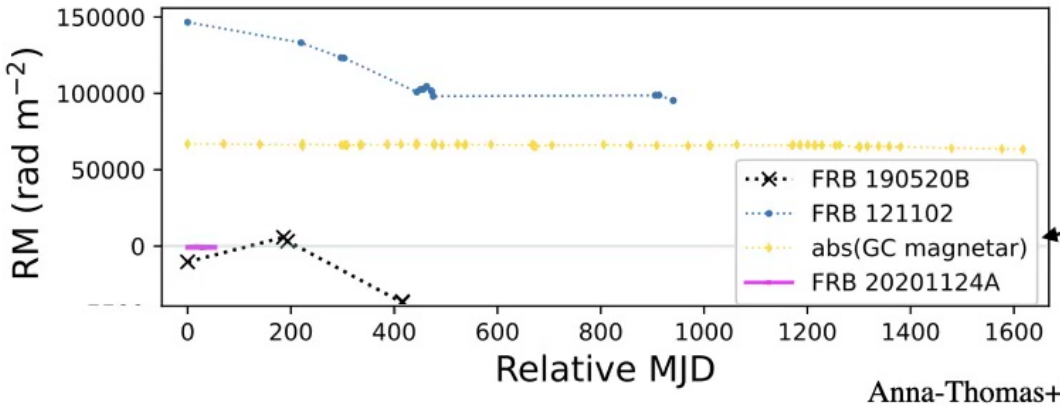
- Plasma eigenmode circular (typical ISM (micro G), IGM (nG)): Faraday rotation
  - Q, U rotate with wavelength^2, conserve L, V $\quad \mathrm{RM} \propto \int n_e B_{\parallel} ds$



- Plasma eigenmode linear: Faraday conversion
  - mix L and V
  - Relativistic electrons, pair plasma
  - Large magnetic field B>~500G f/GHz
  - B_// reversal $\quad B \gtrsim 3\,G\,(\Delta \mathrm{DM}/1\,\mathrm{pc\,cm^{-3}})^{-1/3}(f/\,\mathrm{GHz})^{-4/3}$



3. Unusual magneto-environment of FRBs: large varying RM



Only other object is the galactic centre magnetar

Anna-Thomas+22

A significant fraction of FRB have:

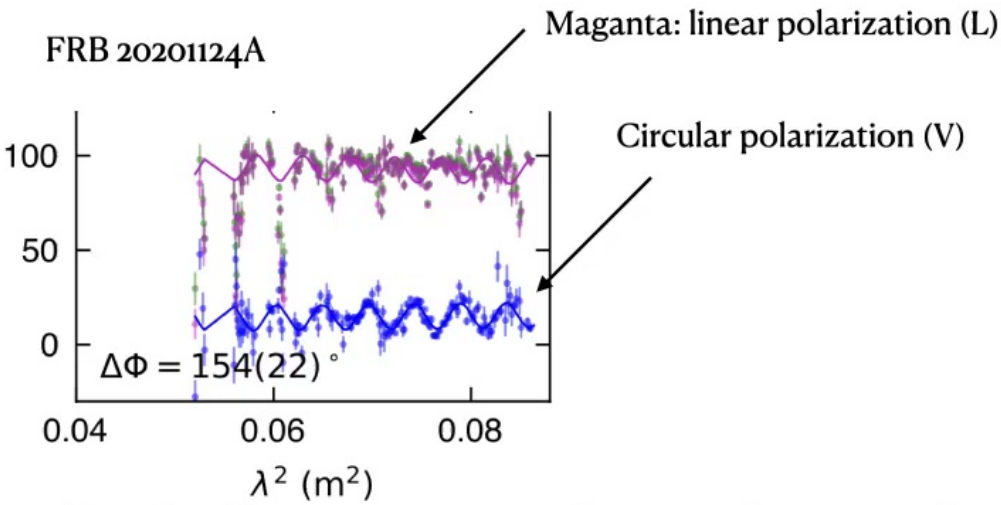
- Large RMs
- Large irregular RM fluctuation (3 out of 6 FRBs with multiple RM measurements: e.g. Xu+22, Dai+22)

—> highly variable magnetized medium around it

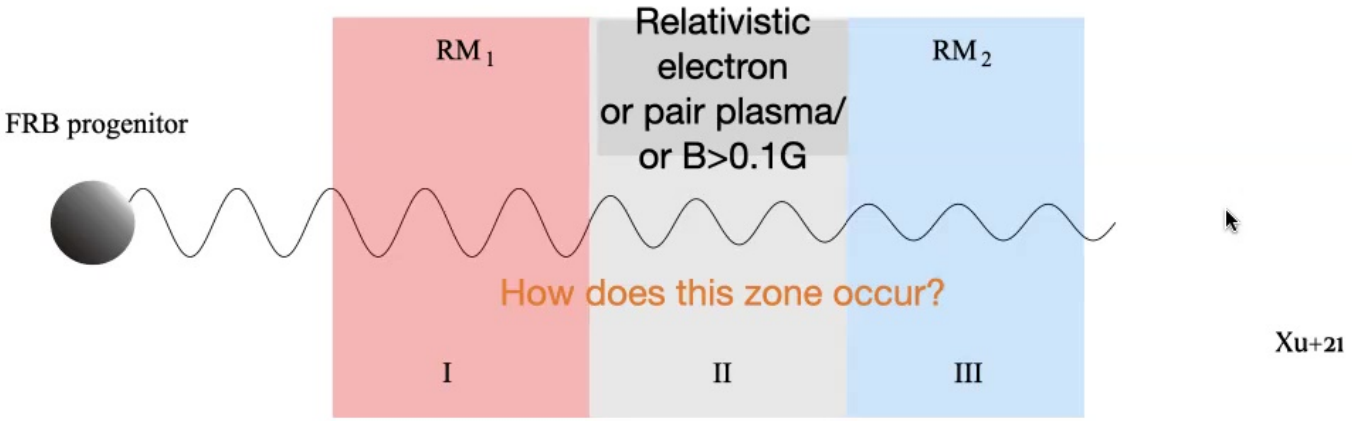
$$\mathrm{DM} = \int n_e ds$$

$$\mathrm{RM} \propto \int n_e B_{||} ds$$

Unusual magneto-environment of FRBs: structure along LOS



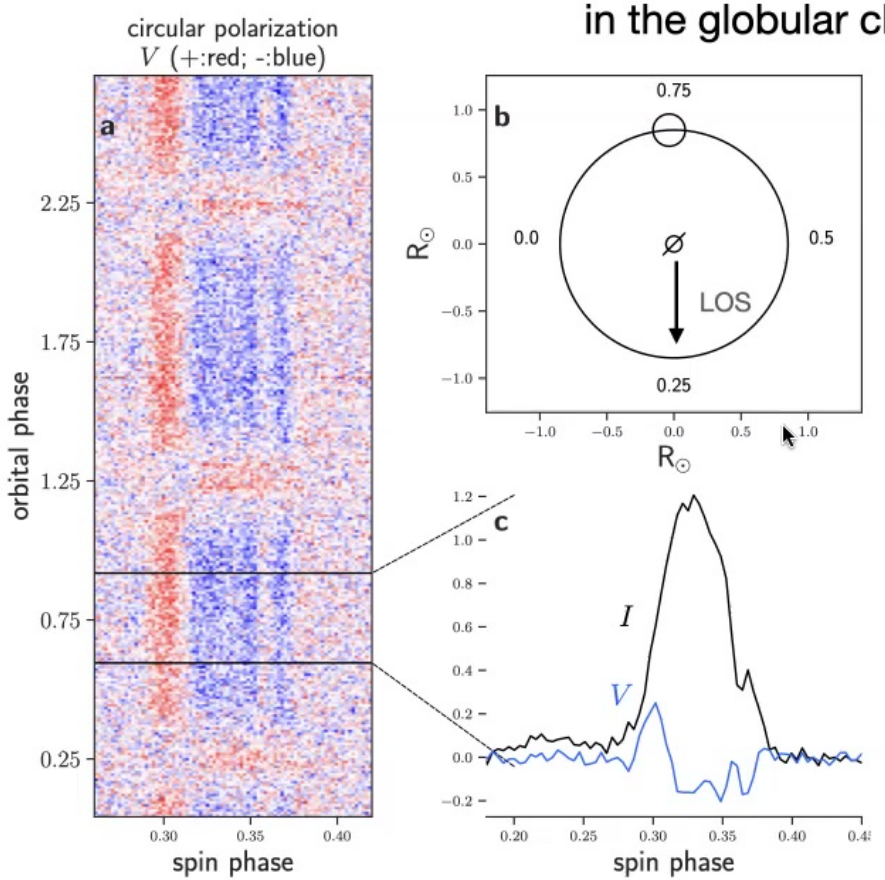
RM like-Oscillation in L ,V —> but RM does not change LV
—> have passed a region with plasma eigenmode linear



Xu+21

In a globular cluster pulsar

Ter5A: PSR 1744-24A
Pulsar with a ~0.08 Msun companion
in the globular cluster Terzan 5

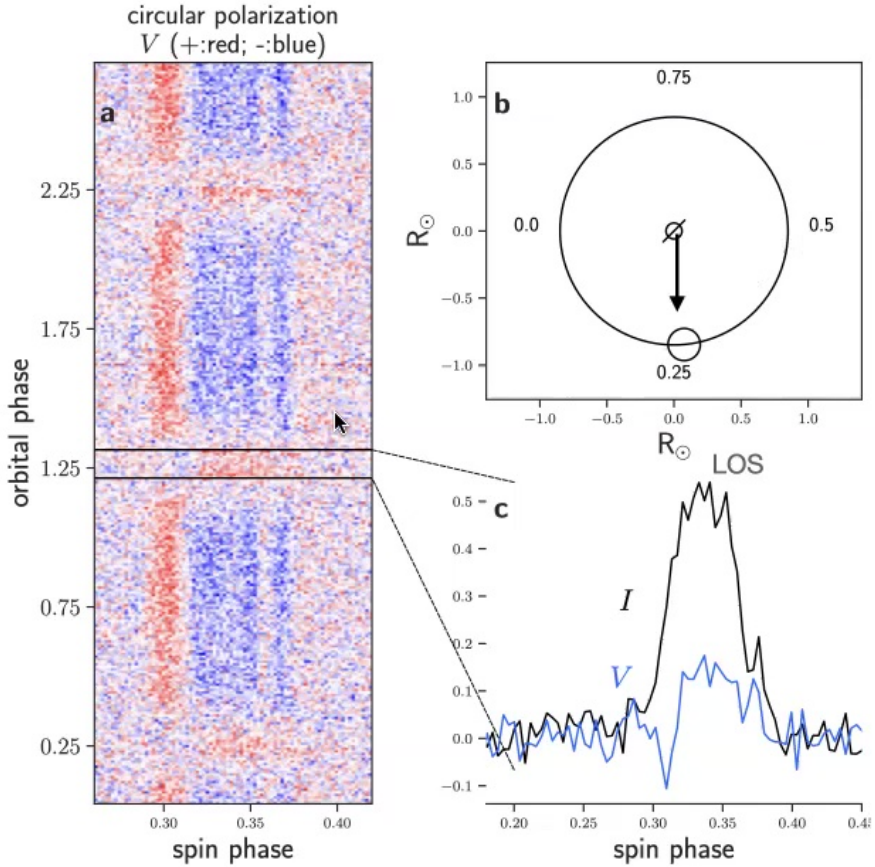


Companion behind VS companion in front —> isolated propagation effects

In collaboration with Anna Bilous, Scott Ransom, Robert Main, Yuan-pei Yang

Dongzi Li+ arXiv: 2205.07917 (accepted by Nature)

Change in circular polarization



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Modelling V

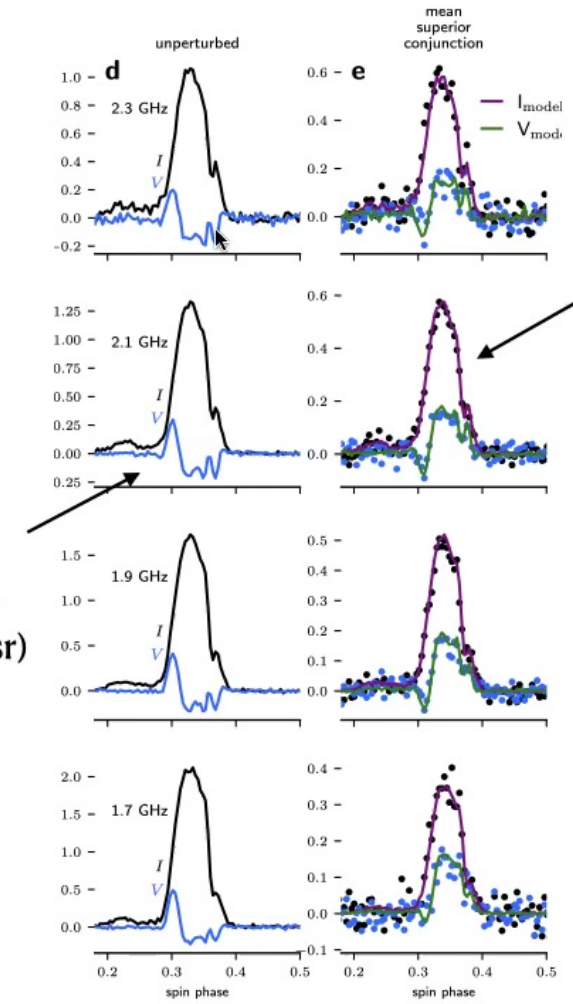
We can model the V profile

with 5 parameters (identical for all spin phases):

$$\tau = (f/f_I)^{-\alpha_I}, \tau_v = (f/f_v)^{-\alpha_v}$$

+ V flip sign (mode tracking)

Model can reproduce the complex V profile



Solid lines: model produced with profile in left panel going through mode tracking + circular absorption

Original profile (cp behind the psr)

Dongzi Li+ arXiv: 2205.07917 (accepted by Nature)

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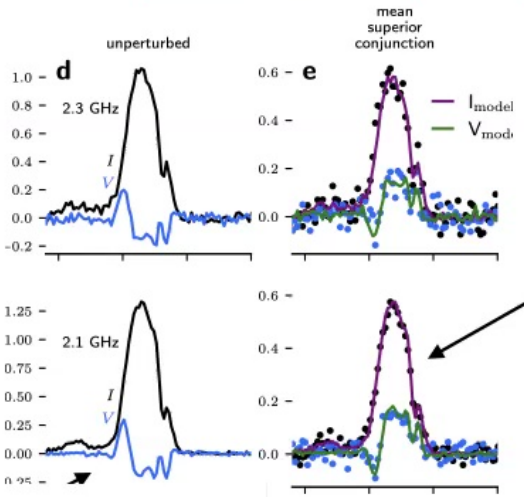

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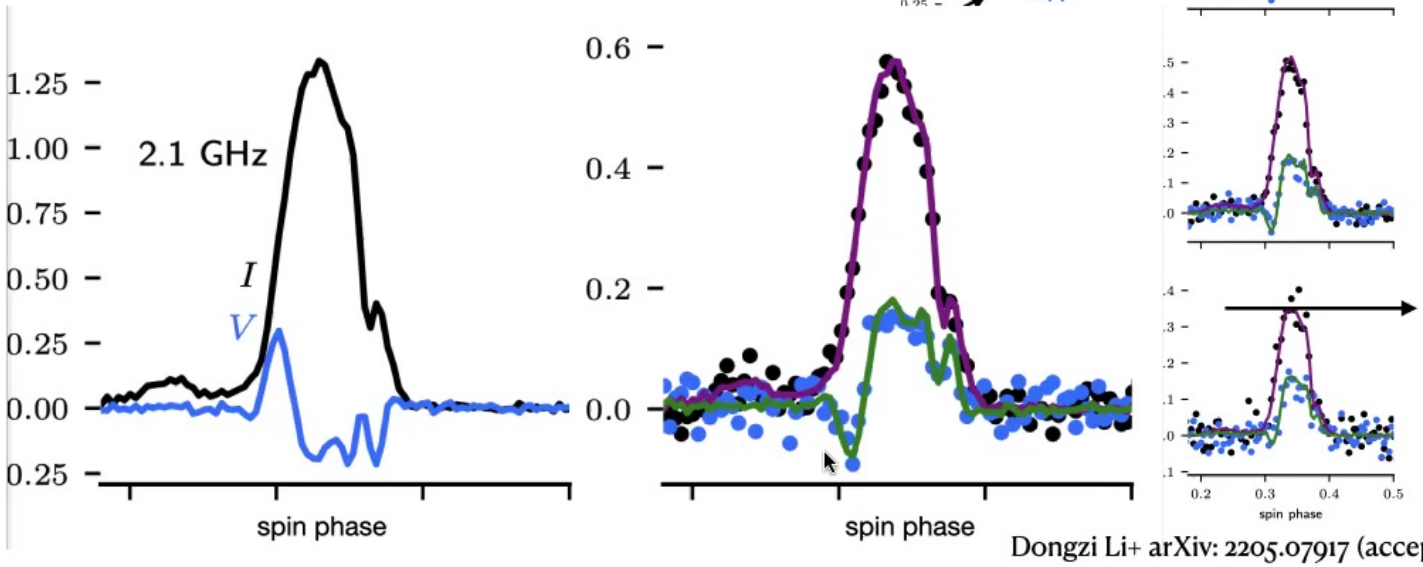

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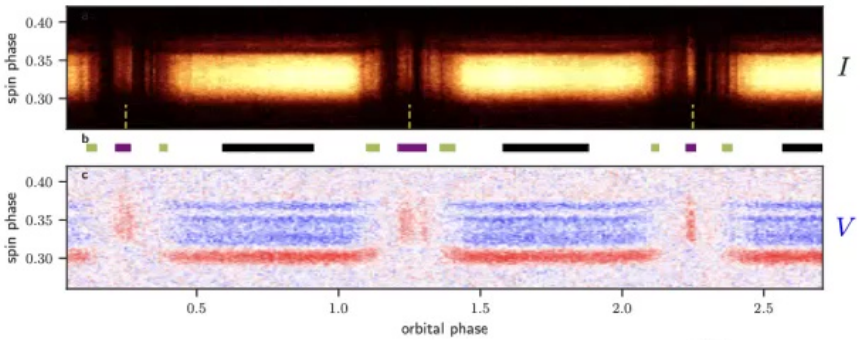
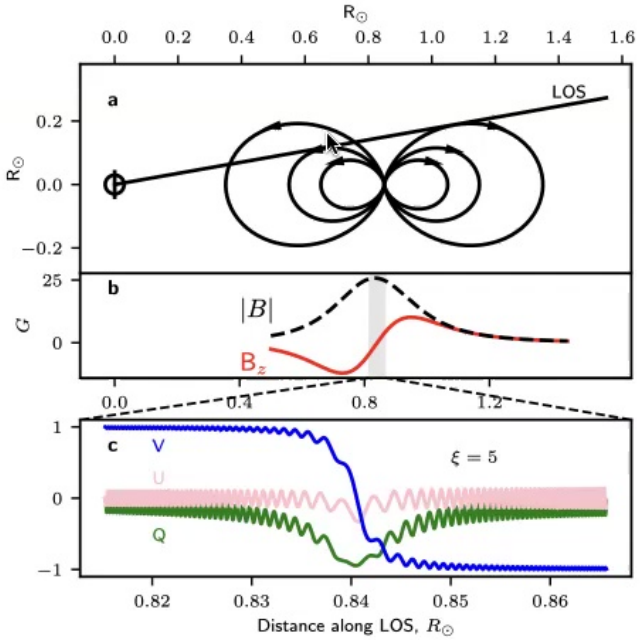
The circular polarization change (Faraday conversion/mode tracking)

Sign flipping best explained with
the pulsar light passing the companion poloidal field





(Thompson+94, Melrose+95, Gruzinov, Levin 19)

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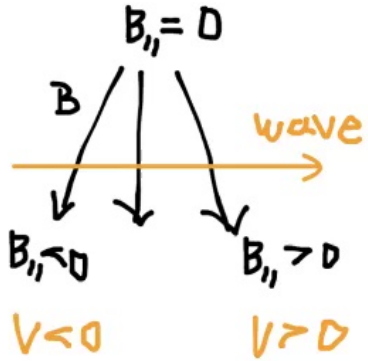

The radio wave follows the B_z reversal

require: B>$10\,G\,(\Delta \mathrm{DM}/0.1\,\mathrm{pc\,cm^{-3}})^{-1/3}(f/2\,\mathrm{GHz})^{-4/3}$

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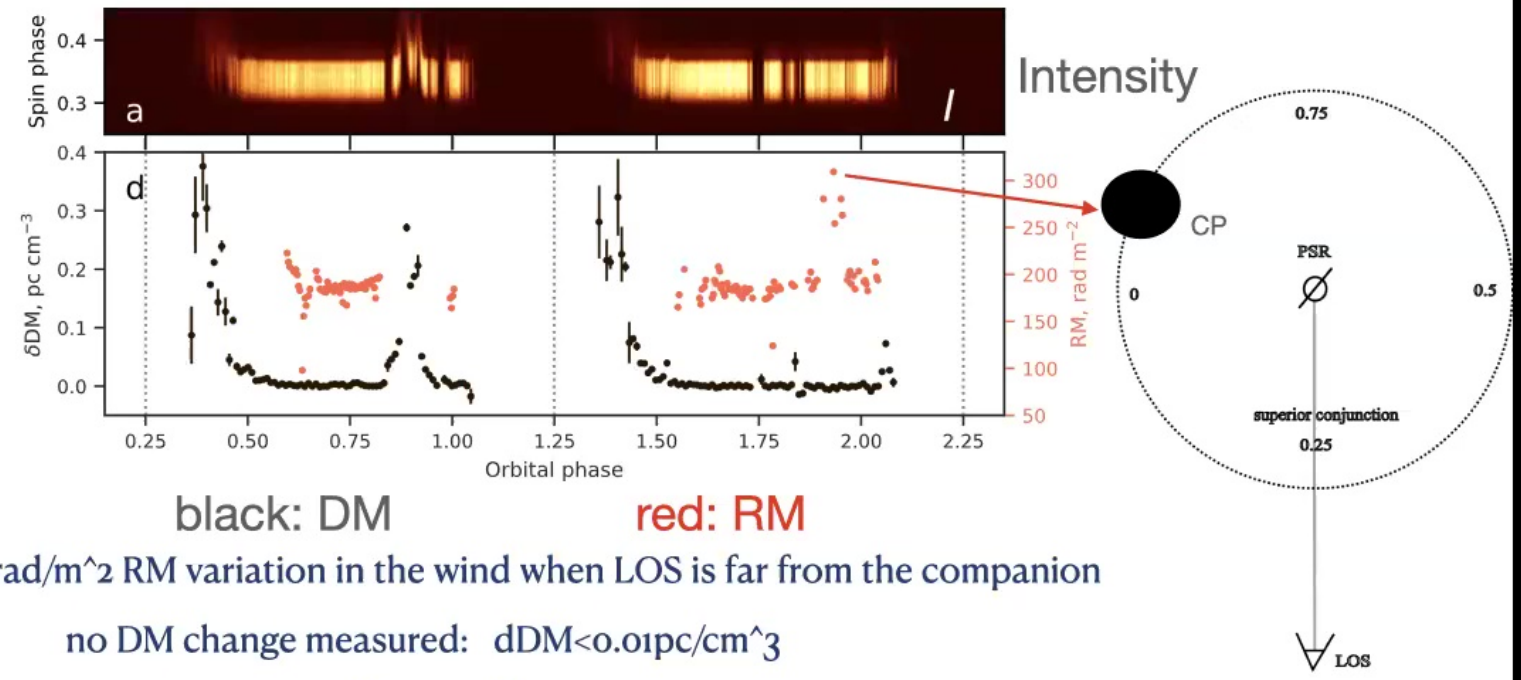
Large RM variation in the wind

Mini eclipses/RM/DM variations at random phases



black: DM red: RM

~100 rad/m^2 RM variation in the wind when LOS is far from the companion

no DM change measured: dDM<0.01pc/cm^3

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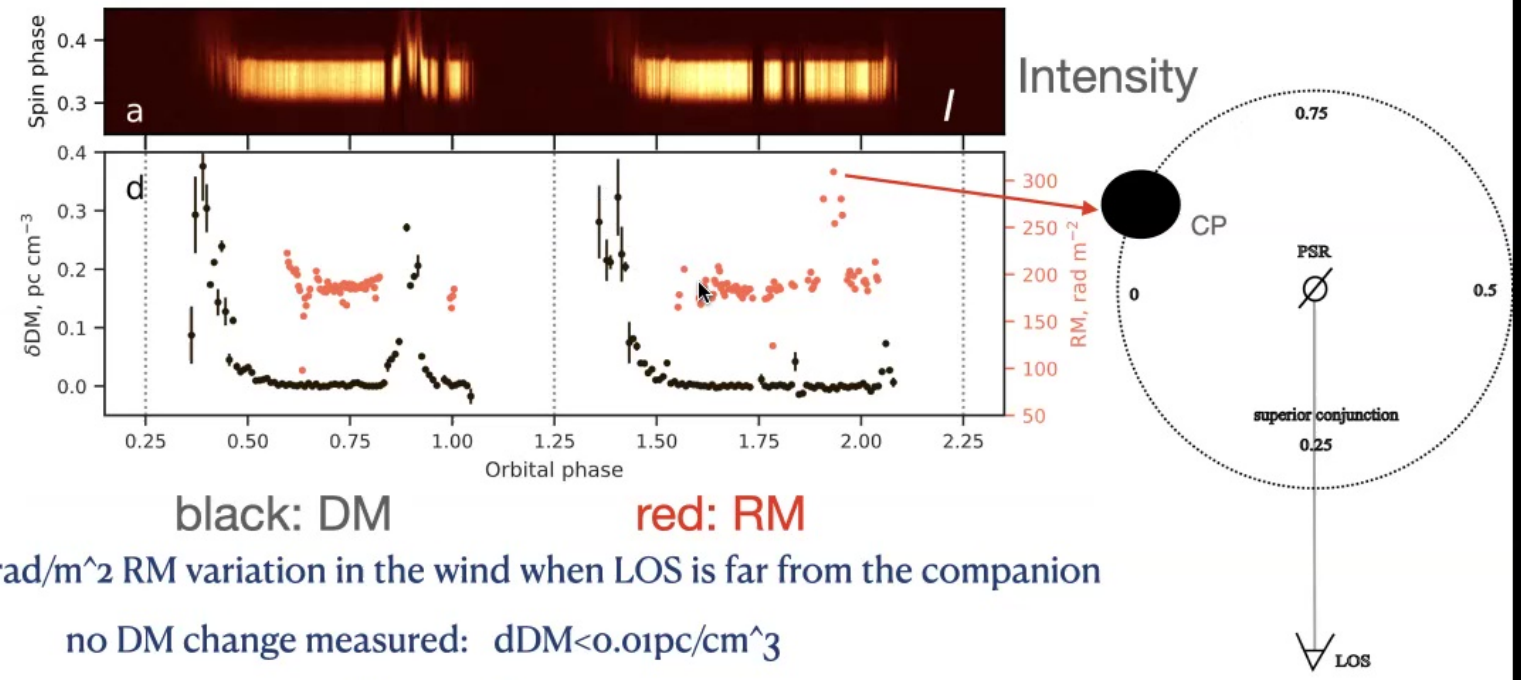

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FRB: The magneto environment

Ter5A	FRBs
• Large irregular RM variation	• 5/6 repeaters with more than one RM measurements show RM variations (eg. Michilli+18; Pleunis+21; Xu+21; Luo+20, Dai+22,Anna-Thomas+22,Mckinven+22)
• Depolarization due to fast RM variation	○ Possibly FRB 20121102A, FRB 20190520B (Feng+22)
• Polarized absorption and Faraday conversion	○ Possibly FRB 20201124A, FRB 20181112 (Xu+22, Kumar+22,Cho+20)
• Propagation increased V	○ Possibly FRB 20201124A (Xu+22)

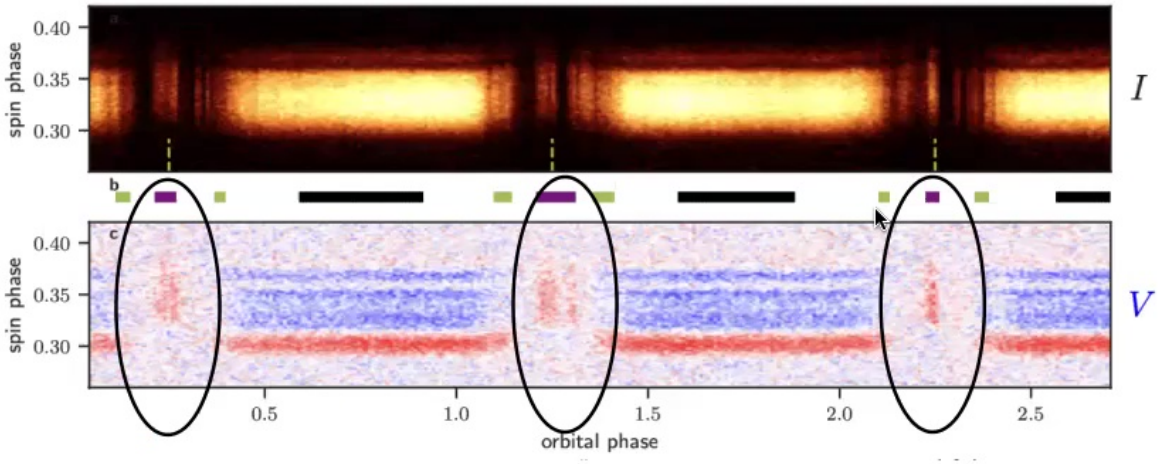
Maybe FRBs in binary?

(also suggested by the 16-day period and the globular cluster localization)

We can model/understand Ter5A well,
Our methods and understandings may help the study of FRBs

Moving forward: Polarization as a way to search for binary

- We see semi-periodic modulation of V
- A potential way to infer binary:
  - search for period in V
  - look at higher frequency for extreme LOS



- Currently only <10% FRBs has polarization study
- Plan to search for exotic polarization behavior in thousands of FRBs detected CHIME

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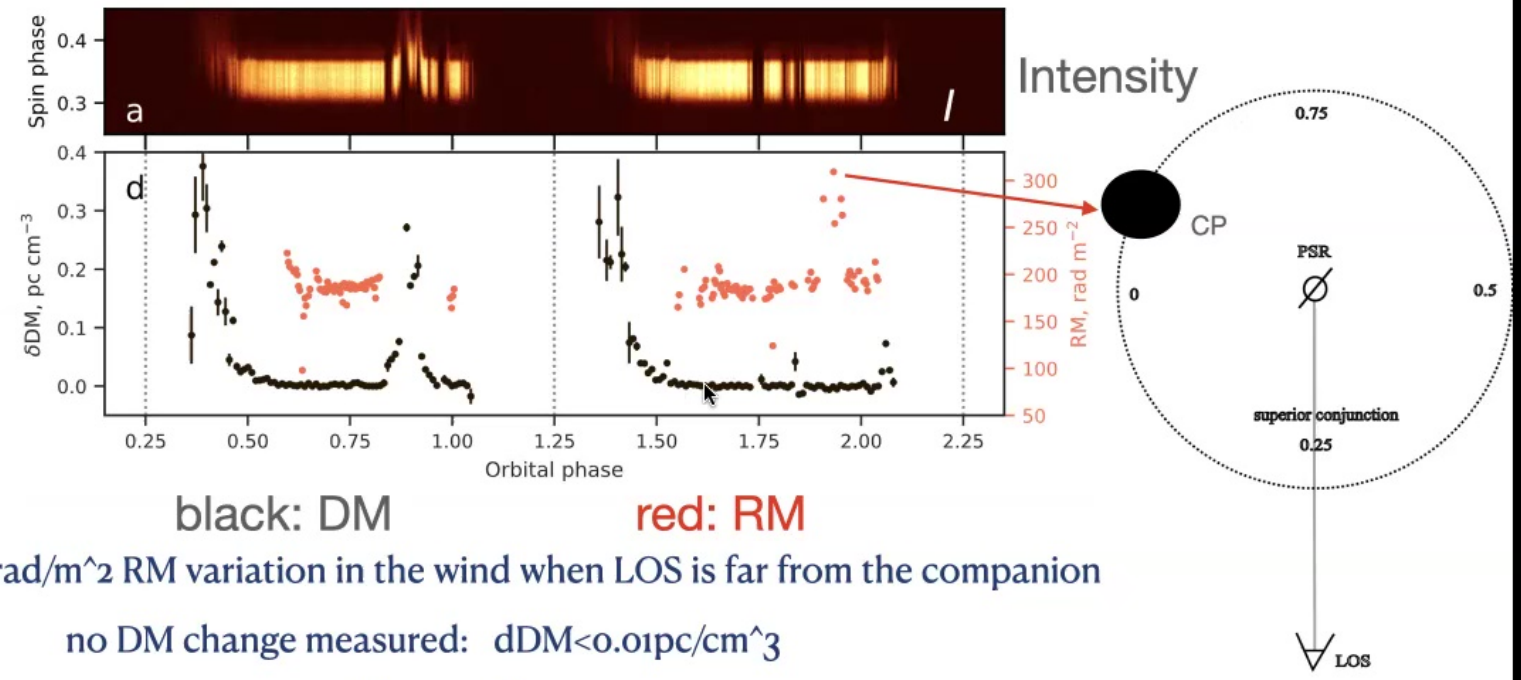

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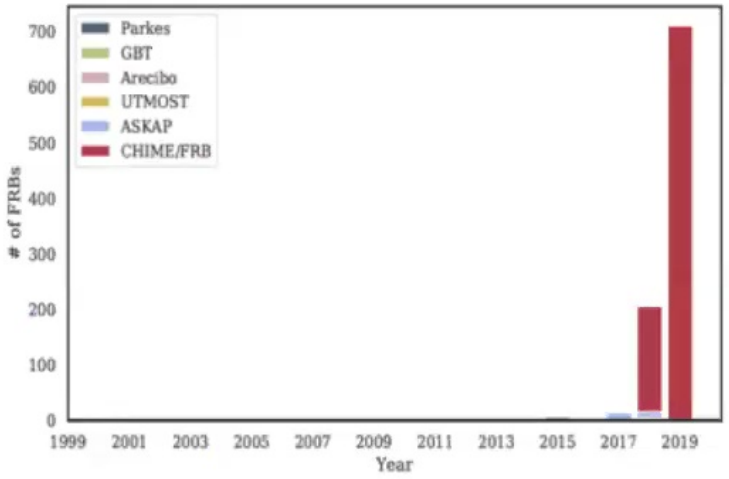
The mysteries of FRB

FRB are micros-ms duration radio bursts from cosmological distance:

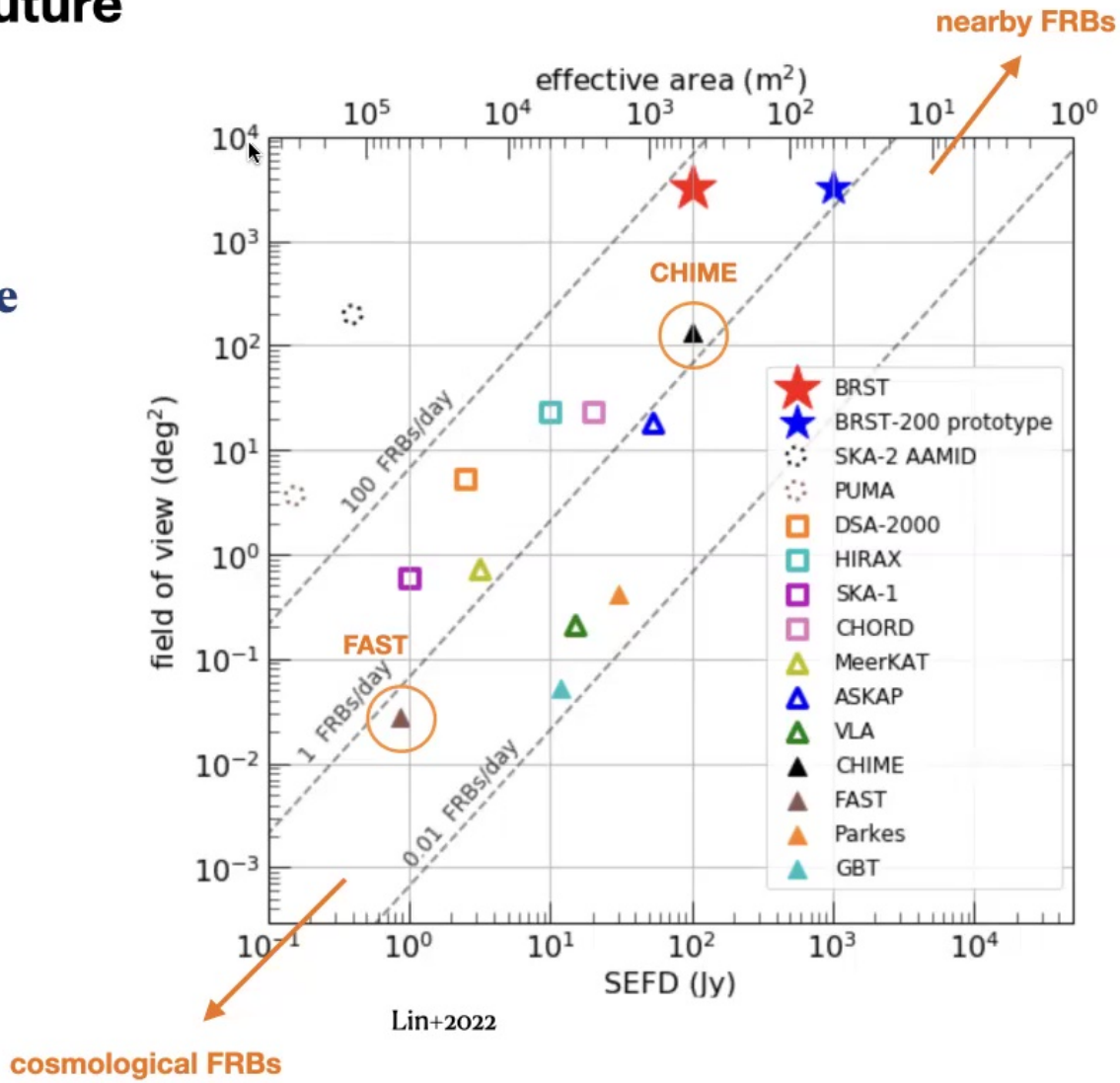
- Some of them, if not all, are non-catastrophic events
- Magnetars can produce FRBs

- Puzzles
  - The origin of the long-term periodicity
  - The existence of GC FRB
  - The extremely variant magneto-environment
- Ongoing effort to answer this question



Roadmap to the future

Orders of magnitude more bursts

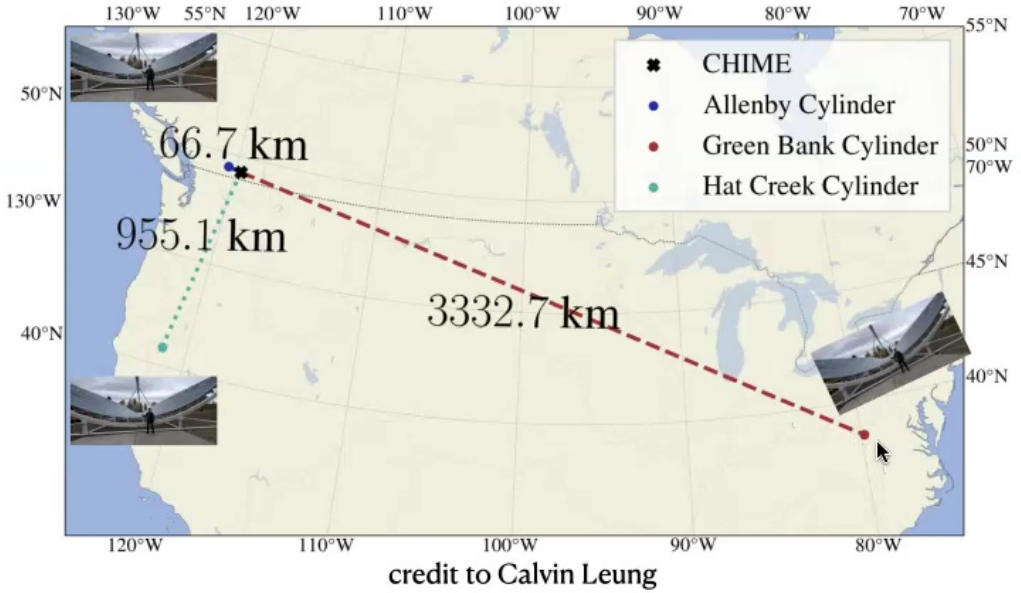


Roadmap to the future

Currently CHIME:
~1000/yr FRBs localized to ~15arcmin, baseband localized to ~sub-arcminute

DSA-2000:
~10^4/year FRBs localized to < 3-arcsecond
(300X better than CHIME intensity, 10X better than CHIME baseband)

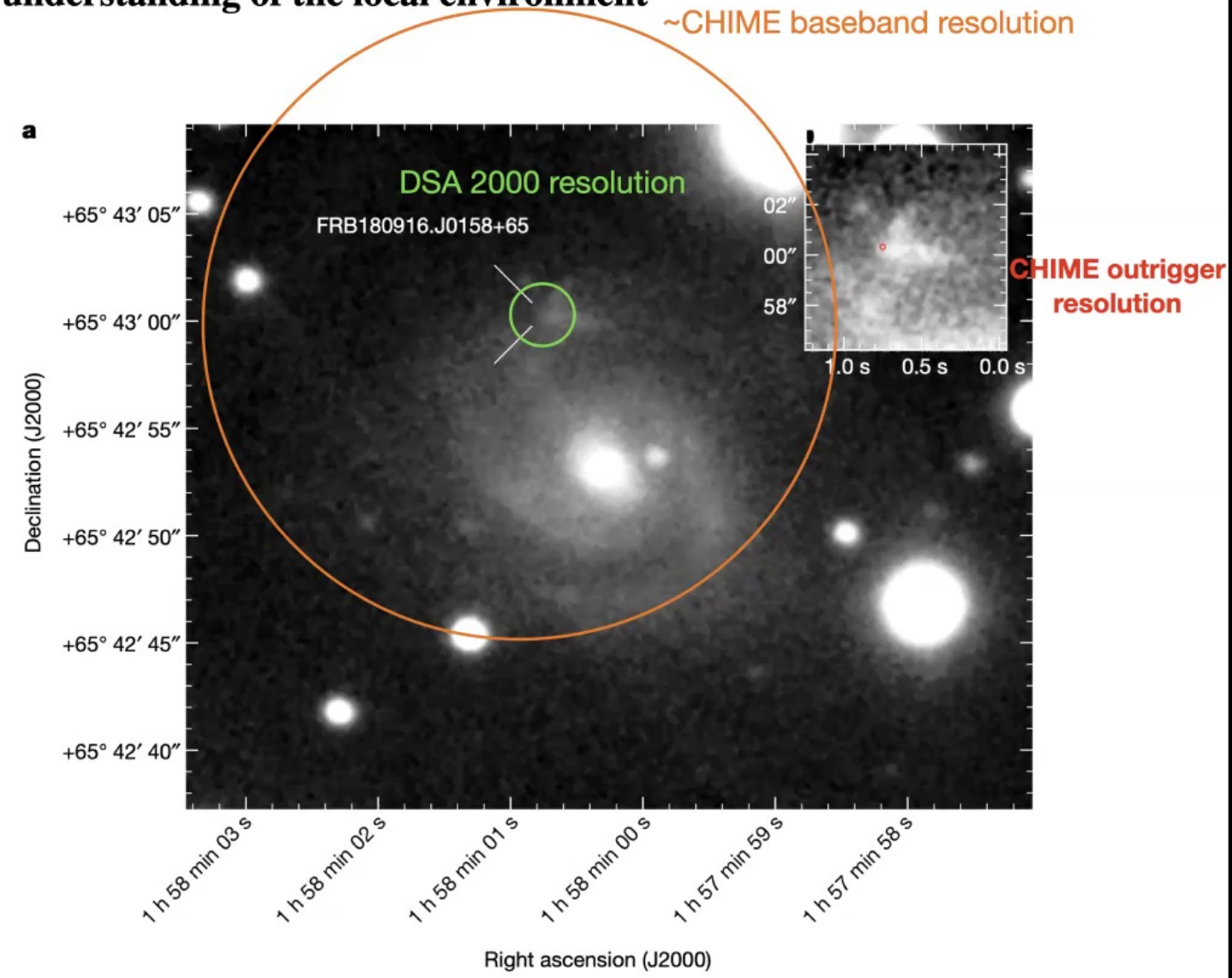
Orders of magnitude better resolution



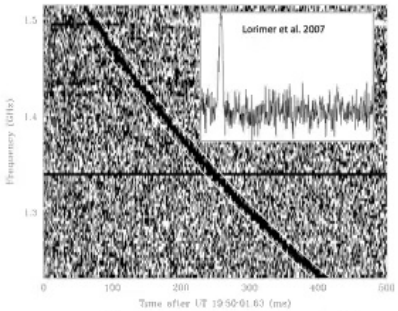
credit to Calvin Leung

CHIME outrigger: localize >1000 FRBs to <50 mas in two years
(10^4X better than CHIME intensity, 600X better than CHIME baseband

Improving understanding of the local environment

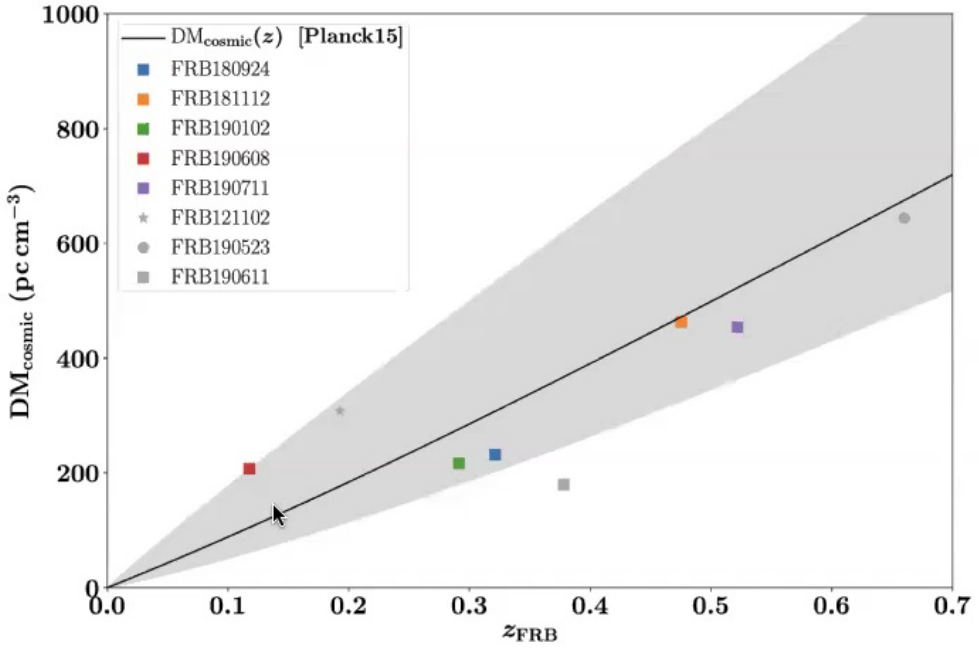


FRBs as probes



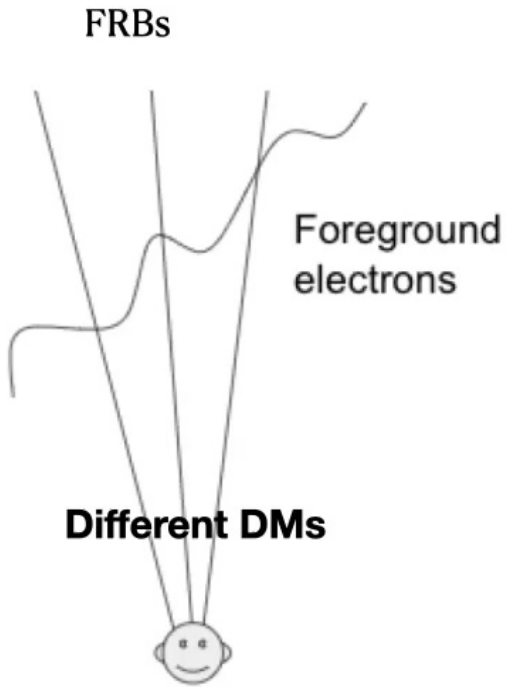
Total baryon content

delay between frequency —> DM
—> electron column

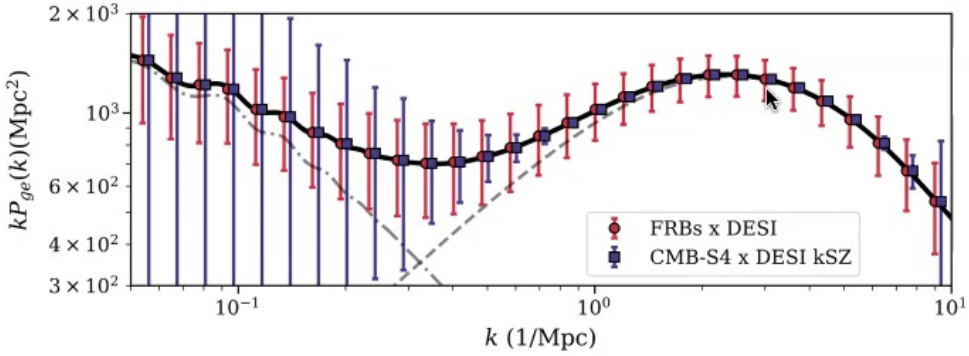


Macquart + 20

FRBs as probes



Sensitive to all spatial scales:
probe circum-galactic medium,
intra-cluster medium,
large scale structure

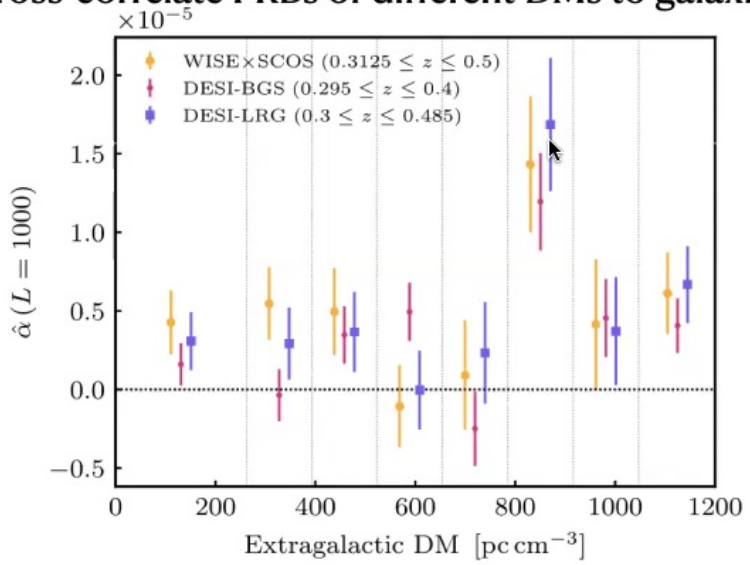


Madhavacheril + 19

FRBs as probes

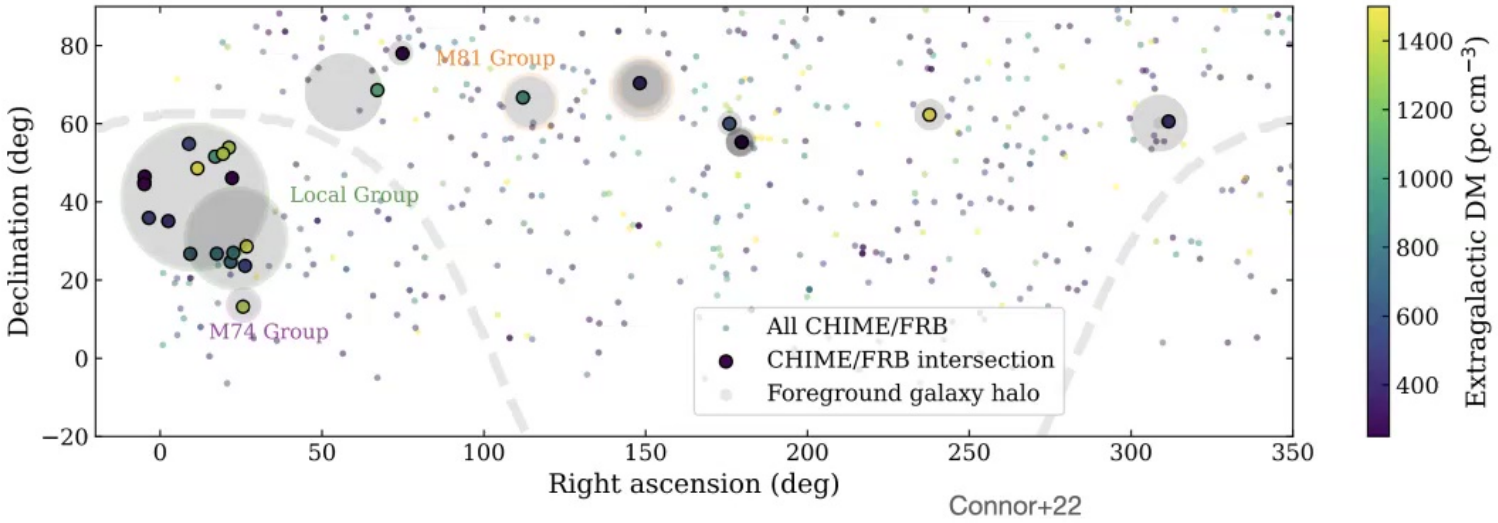
Probe circum-galactic medium: unknown level of galaxy-feedbacks

cross-correlate FRBs of different DMs to galaxies



Rafiei-Ravandi +21

comparing DMs of FRBs with various impact parameter to nearby galaxies



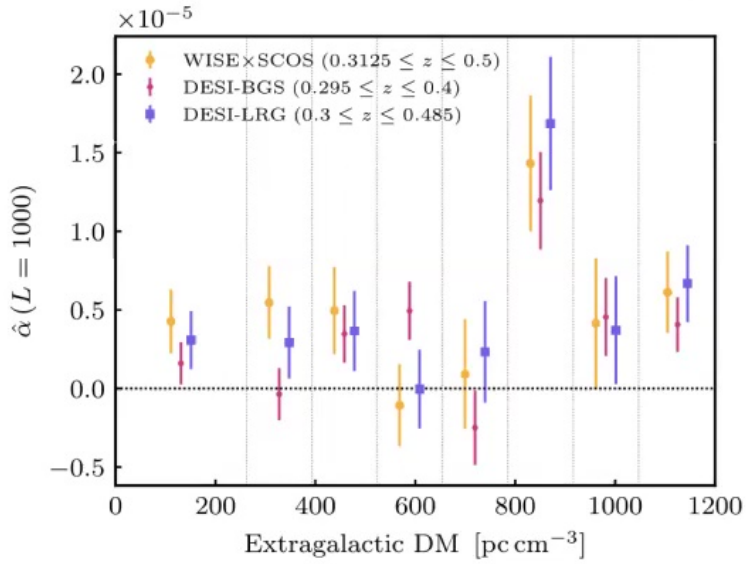
Connor+22

FRBs as probes

Probe circum-galactic medium:
unknown level of galaxy-feedbacks

Similar method:
Matter distribution in galaxy clusters, intergalactic medium

cross-correlate FRBs of different DMs to galaxies



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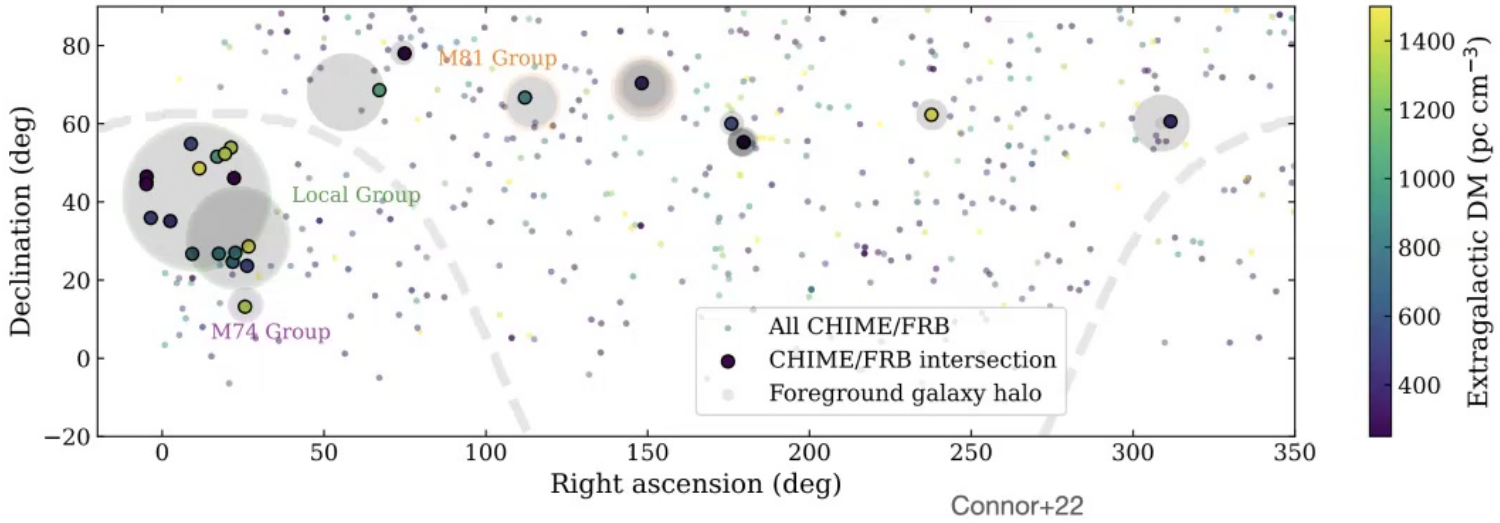


Connor+22

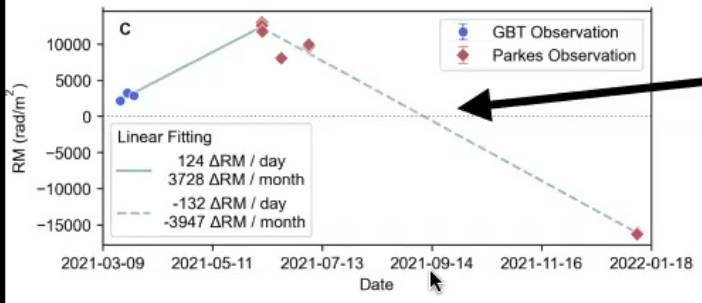
Warning: variant host environments

$$\mathrm{DM} = \mathrm{DM_{MW}} + \mathrm{DM_{halo}} + \mathrm{DM_{IGM}} + \frac{\mathrm{DM_{host}} + \mathrm{DM_{src}}}{1+z}$$

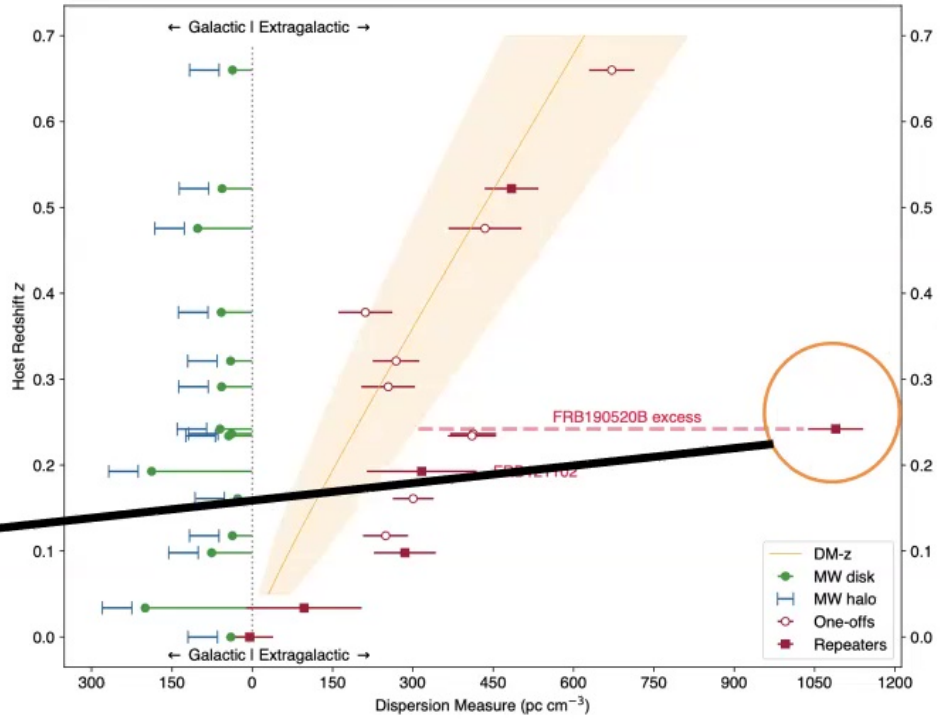
- Influence: Cosmological probe rely on good measurement of

$\mathrm{DM_{IGM}} - z$ relation

eg: missing baryons, IGM inhomogeneity, circumgalactic medium, Reionization history



Dai+22

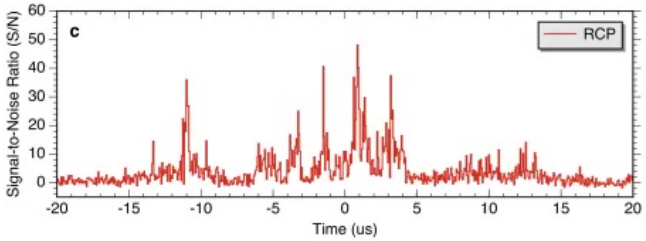


Niu+2021

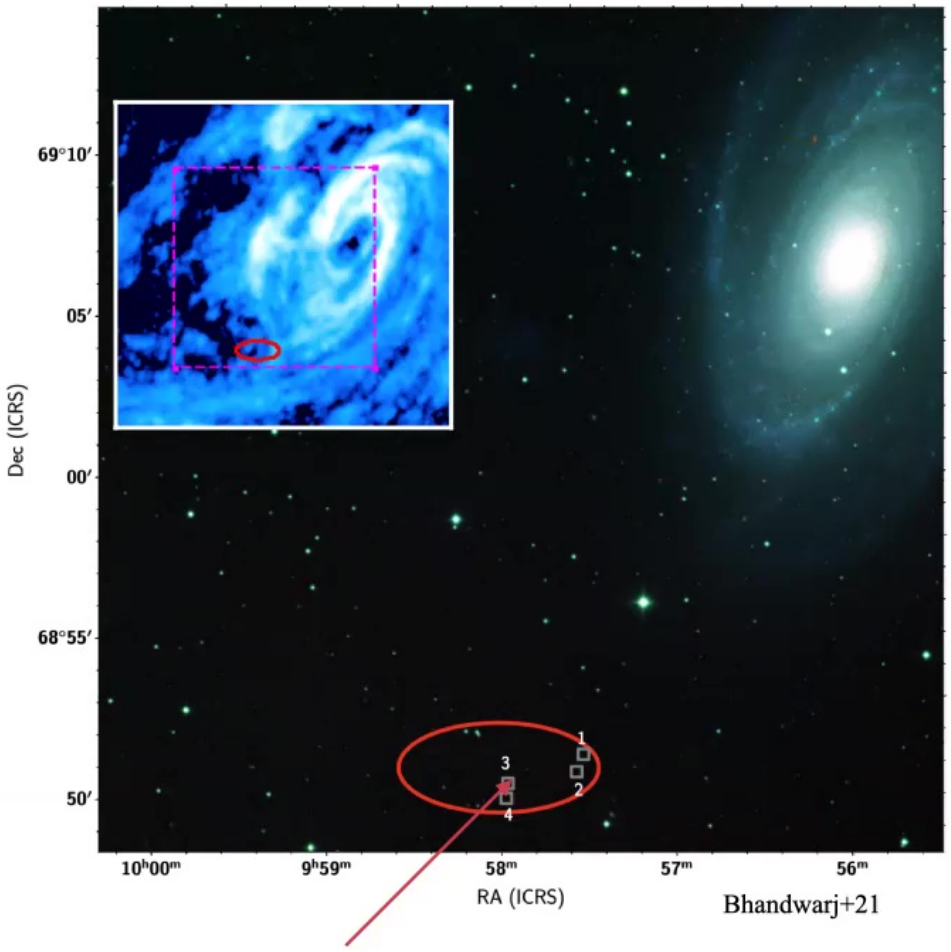
Find clean sub-samples

- GC FRBs: clean circumburst/ host environment: (DM 0.1pc/cm^3 at GC)

Possibly distinguishable feature



special sub-micro second shots feature



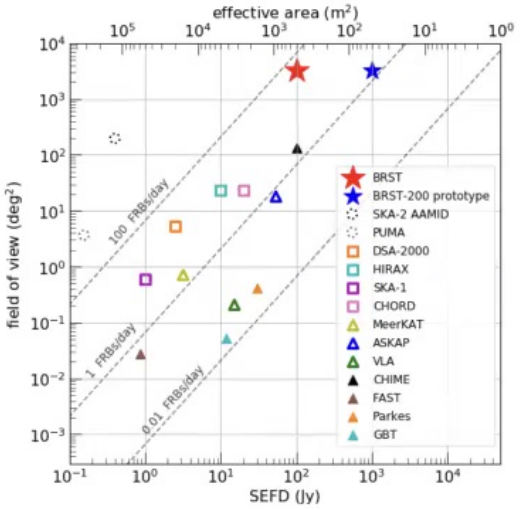
GC[PR95] 30244 & FRB 20200120E

FRBs as probes

Sensitive to all spatial scales:
probe circum-galactic medium,
intra-cluster medium,
large scale structure

Require large number of FRBs for statistics
Require good localization
eg. to resolve a halo at redshift 0.1, need localization <200mas
eg. to know the redshift

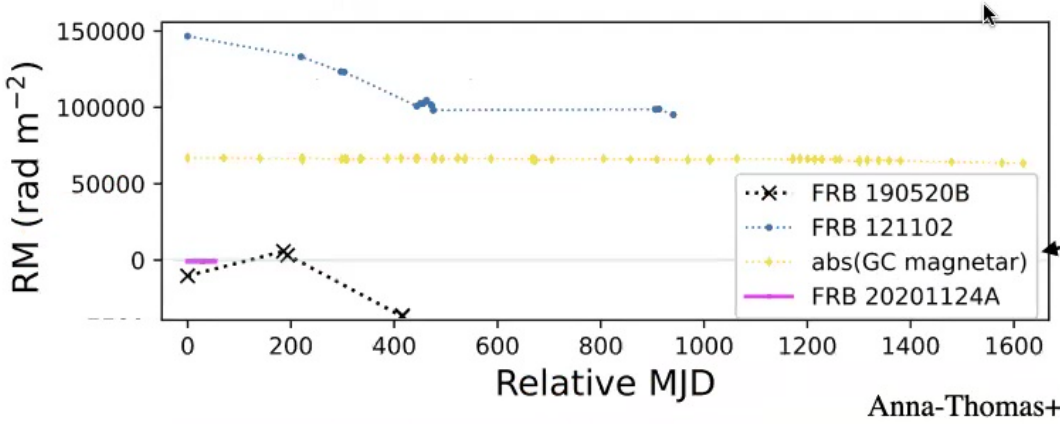
There will be significant progress in the next ten years!



- **Monitor nearby FRBs**
  - follow-up localized nearby FRBs with FAST,
  - monitoring galaxies with 10^4 globular cluster
- **Study magneto-environment for orders of more FRBs**
- **Multi-wavelength follow-ups**

- There is opportunities for a greater community
  - —>Dynamic formation channel of FRBs potentially related to populations observable with LISA
  - —>Probing matter distribution: halo mass distribution, constrain galaxy feedbacks, intracluster medium)
  - Statistical technique needed

3. Unusual magneto-environment of FRBs: large varying RM



Only other object is the galactic centre magnetar

Anna-Thomas+22

A significant fraction of FRB have:

- Large RMs
- Large irregular RM fluctuation (3 out of 6 FRBs with multiple RM measurements: e.g. Xu+22, Dai+22)

—> highly variable magnetized medium around it

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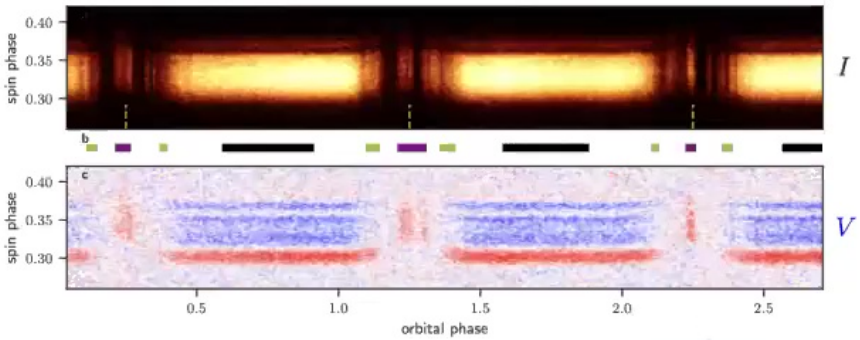

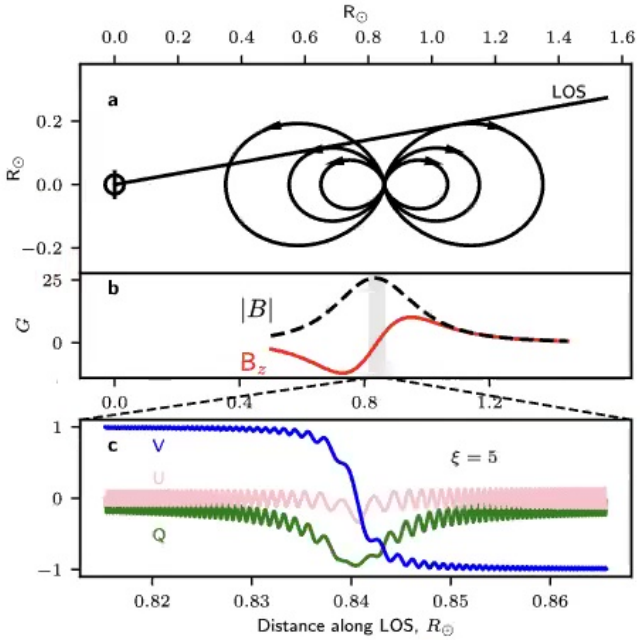

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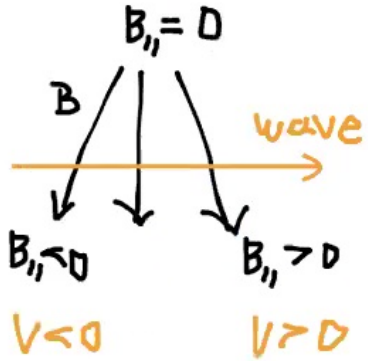

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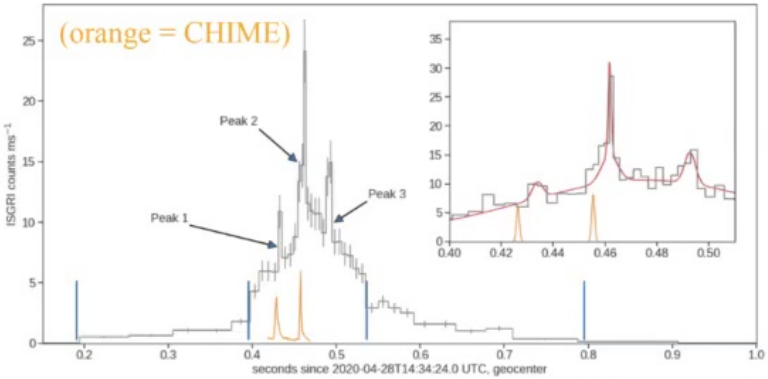
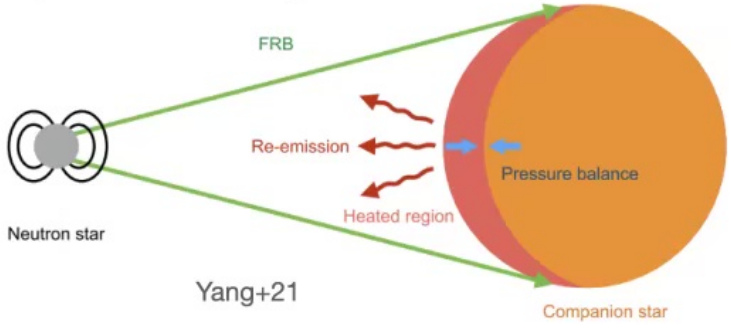
More nearby sources: opportunities for multi-wavelength follow-ups

X-ray: the galactic magnetar FRB-like bursts,
often accompany with the X-ray bursts with 1e3-1e5 X more energy



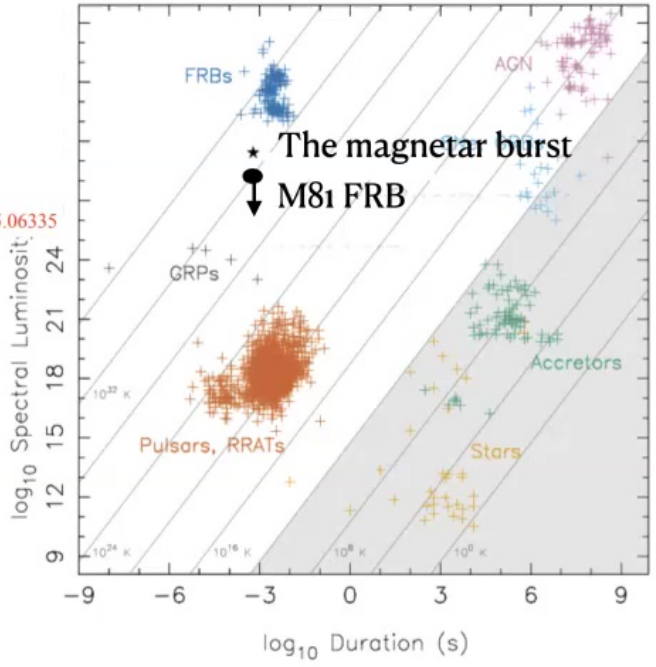
INTEGRAL collaboration (Mereghetti et al), 2005.06335

Optical: study the host.
In the binary scenario, potential optical flare caused by re-radiation from the companion shot by the FRB



Yang+21

Radio: Looking for low energy FRBs with FAST



Bochenek+20

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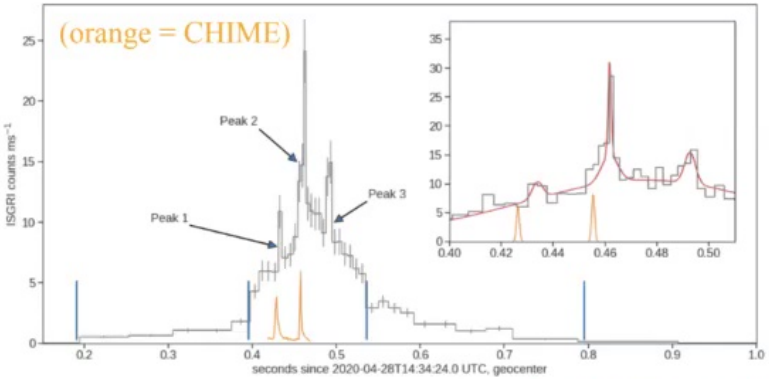

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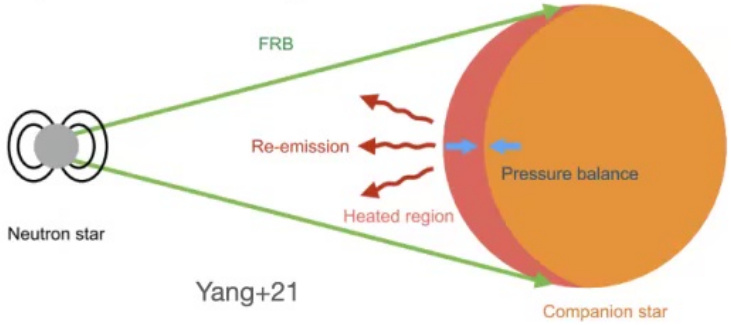

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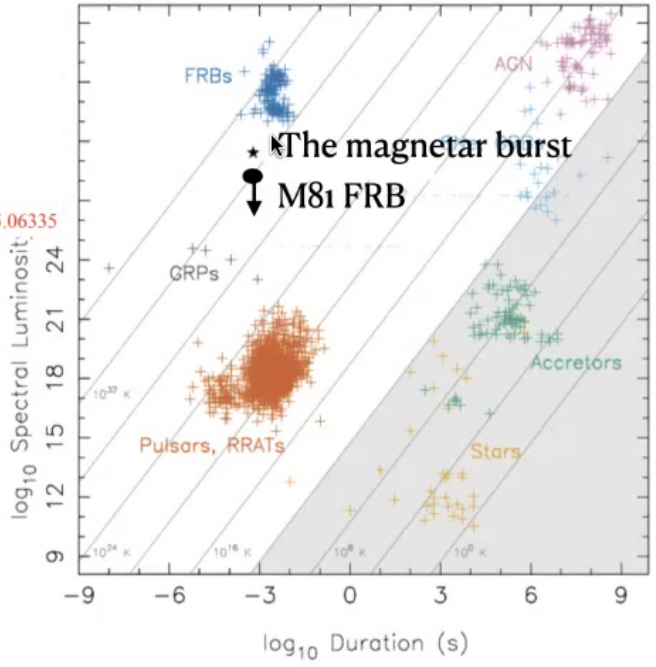

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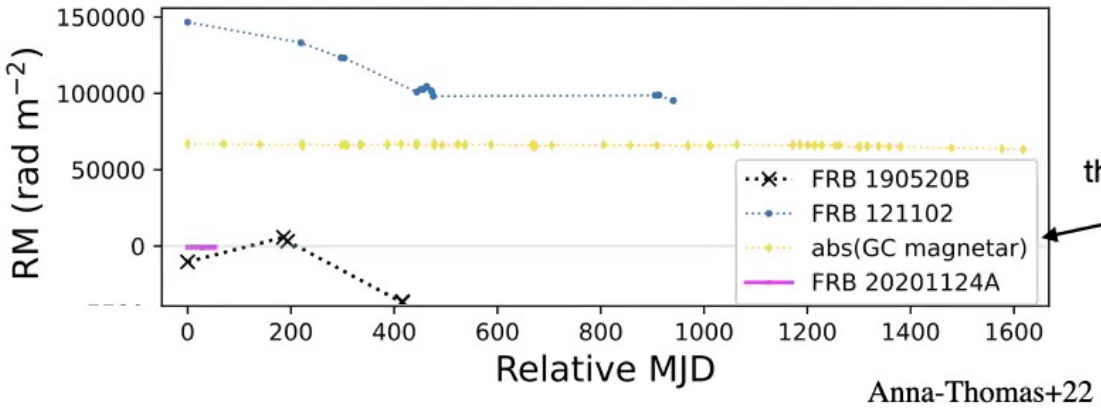

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