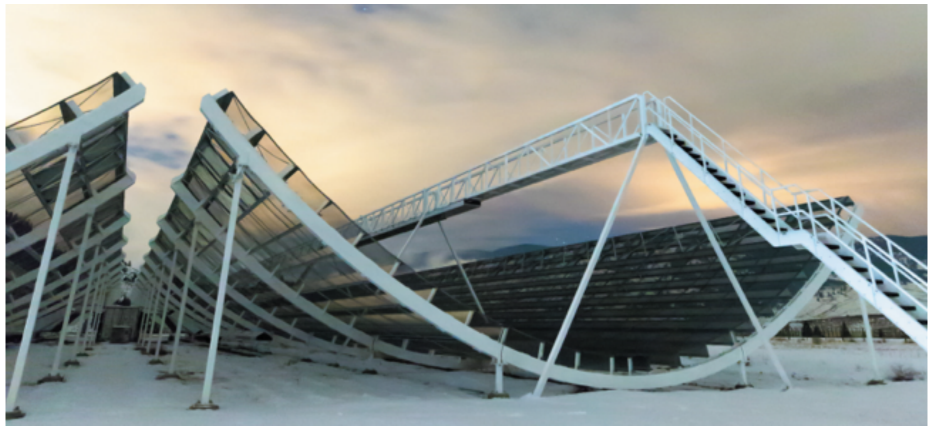
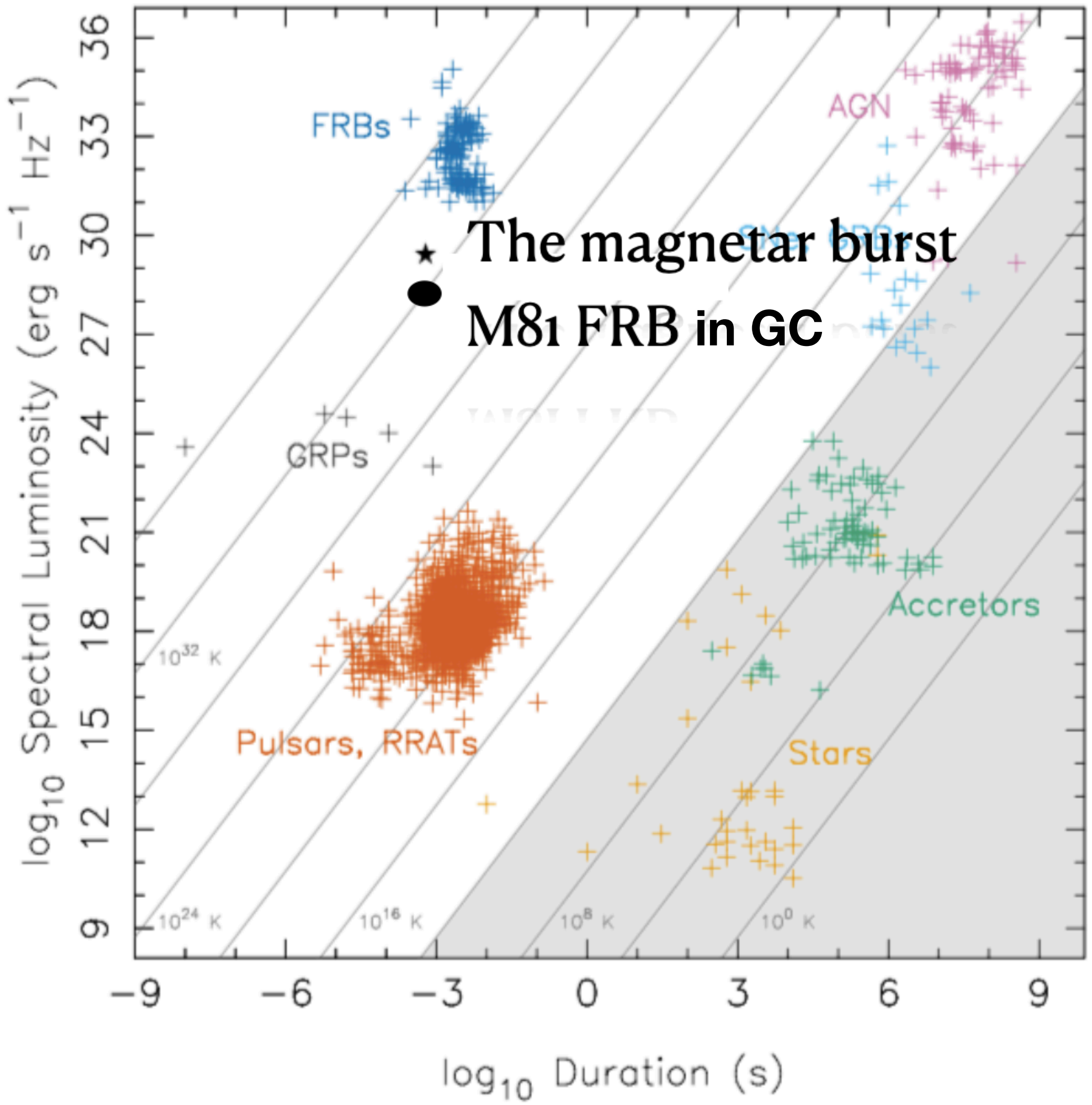


Mysteries of Fast Radio Bursts

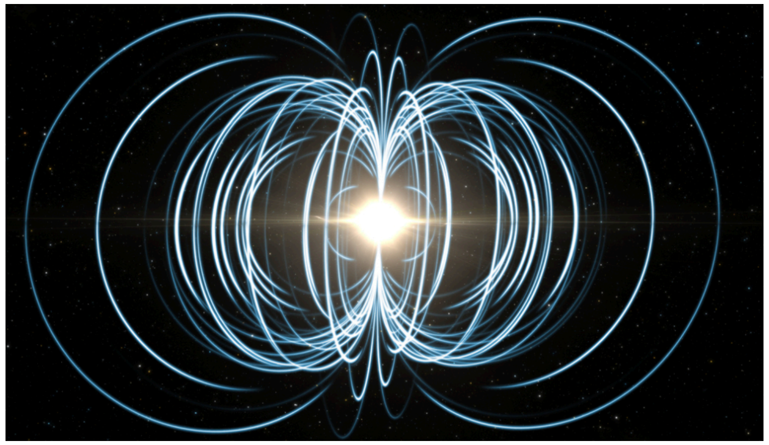
Dongzi Li
Princeton Spitzer Fellow

Mysteries about the source

- Direct evidence:
  - Some FRB repeats (Splitler+14,16) —> Some are non-catastrophic events
  - The FRB-like burst from a Galactic magnetar (CHIME/FRB collaboration20, Bochenek+20)—> An ordinary magnetar can emit FRBs
    - **Rate ok**: Interpolated volumetric rate can possibly explain all FRBs (with orders of magnitude uncertainties)
    - **Energy budget ok**: Magnetic energy 1e47 erg for 10^15 G surface field magnetar. It is possible to have instantaneous release



Bochenek+20



magnetar: neutron star with extremely high magnetic field

neutron star: the collapsed core of a massive giant

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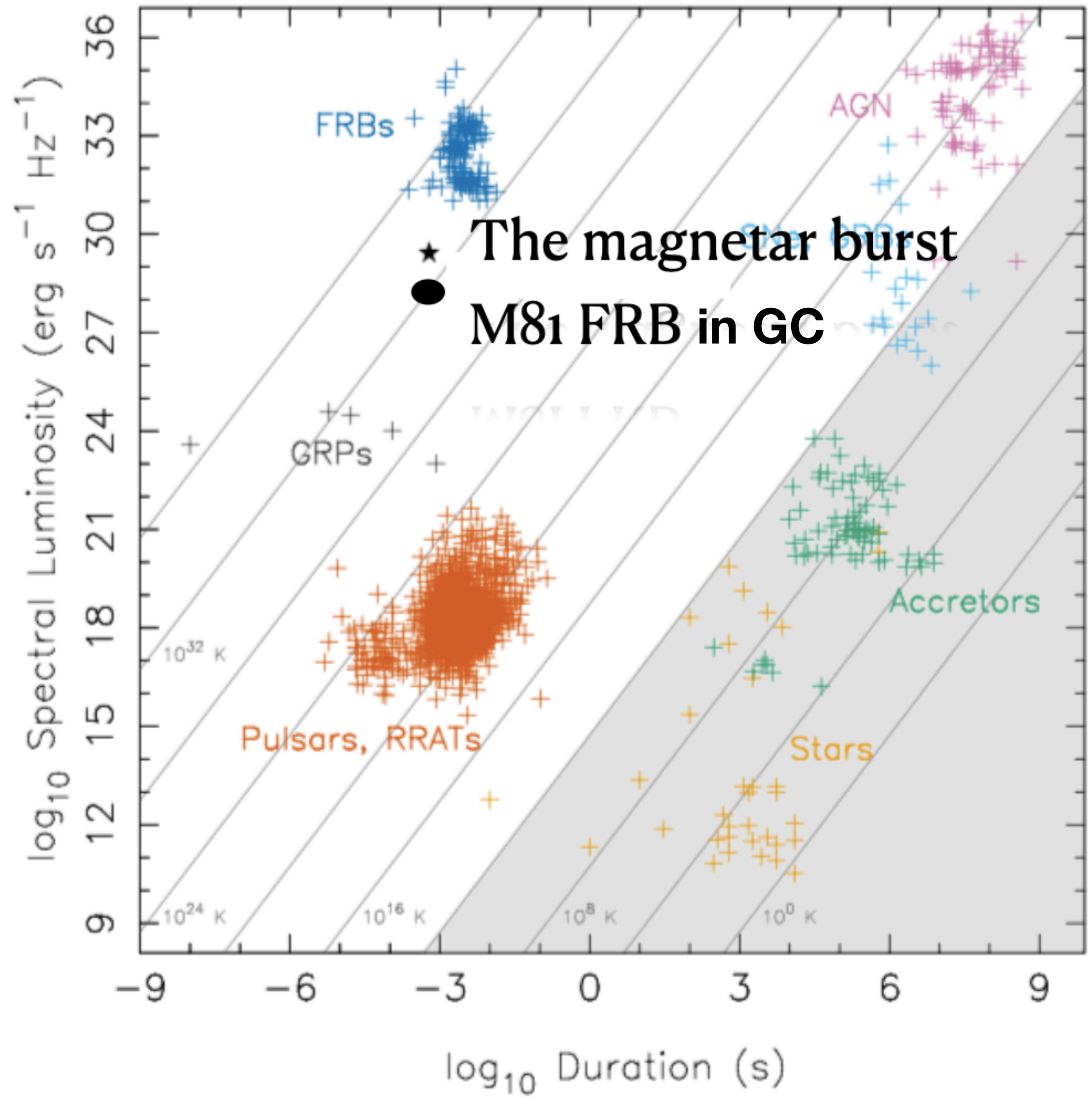
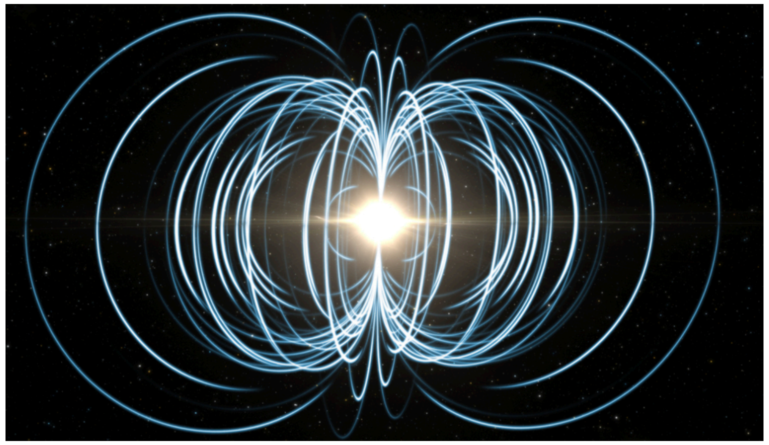
  - The FRB-like burst from a Galactic magnetar (CHIME/FRB collaboration20, Bochenek+20) —> An ordinary magnetar can emit FRBs
  - But there are lots of things we didn't expect with ordinary magnetars!
    - The long-term periodicity (20CHIME/FRB collaboration, Li as the corresponding author)
    - The location of lots of FRBs
    - The magneto-environment



Bochenek+20

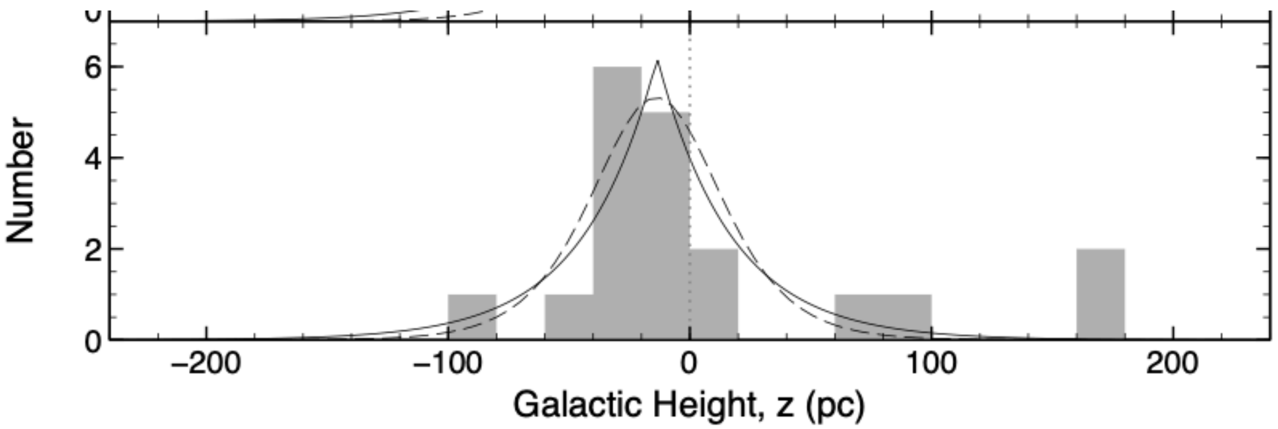


magnetar: neutron star with extremely high magnetic field

neutron star: the collapsed core of a massive giant

Puzzle: LOCATION

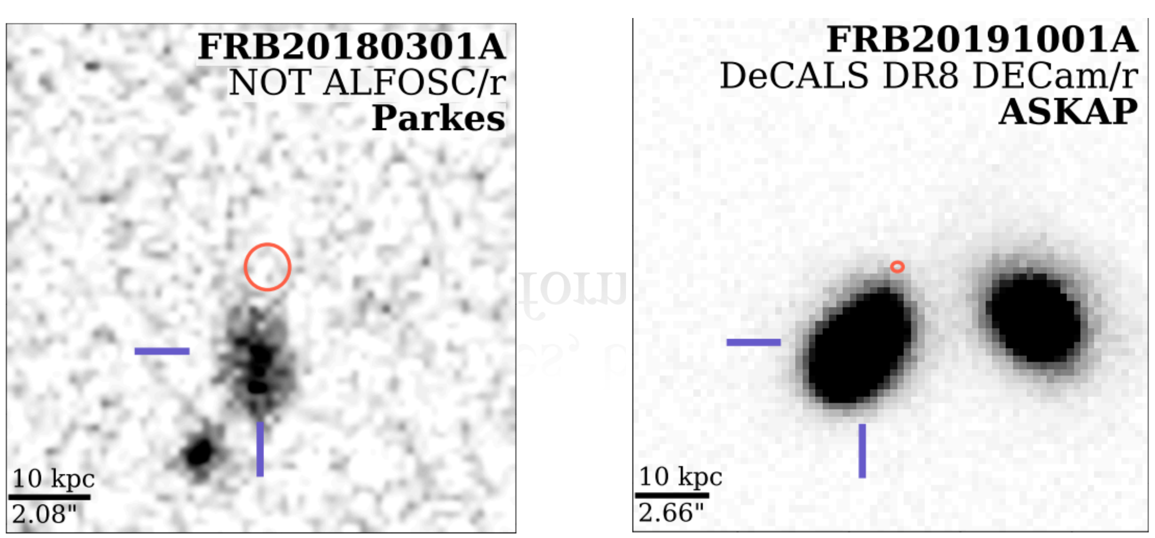
- Magnetars are young < 1e5yr, they trace star-formation



17+Kaspi

But for FRBs:

- A small fraction of them are localized to massive, red, low star forming host galaxies (Law+23, Sharma+23, Gordon+23)
- A large fraction of FRBs localized to star-forming galaxies, but they are away from the star-forming regions.



Gordon+23

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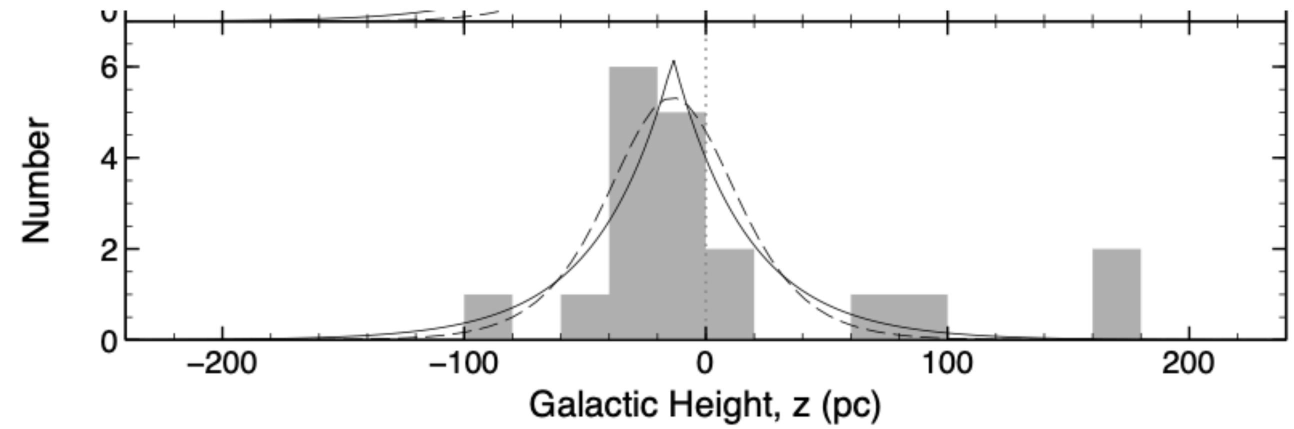


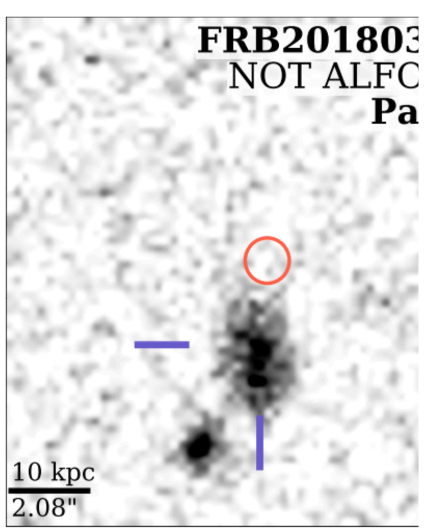
17+Kaspi

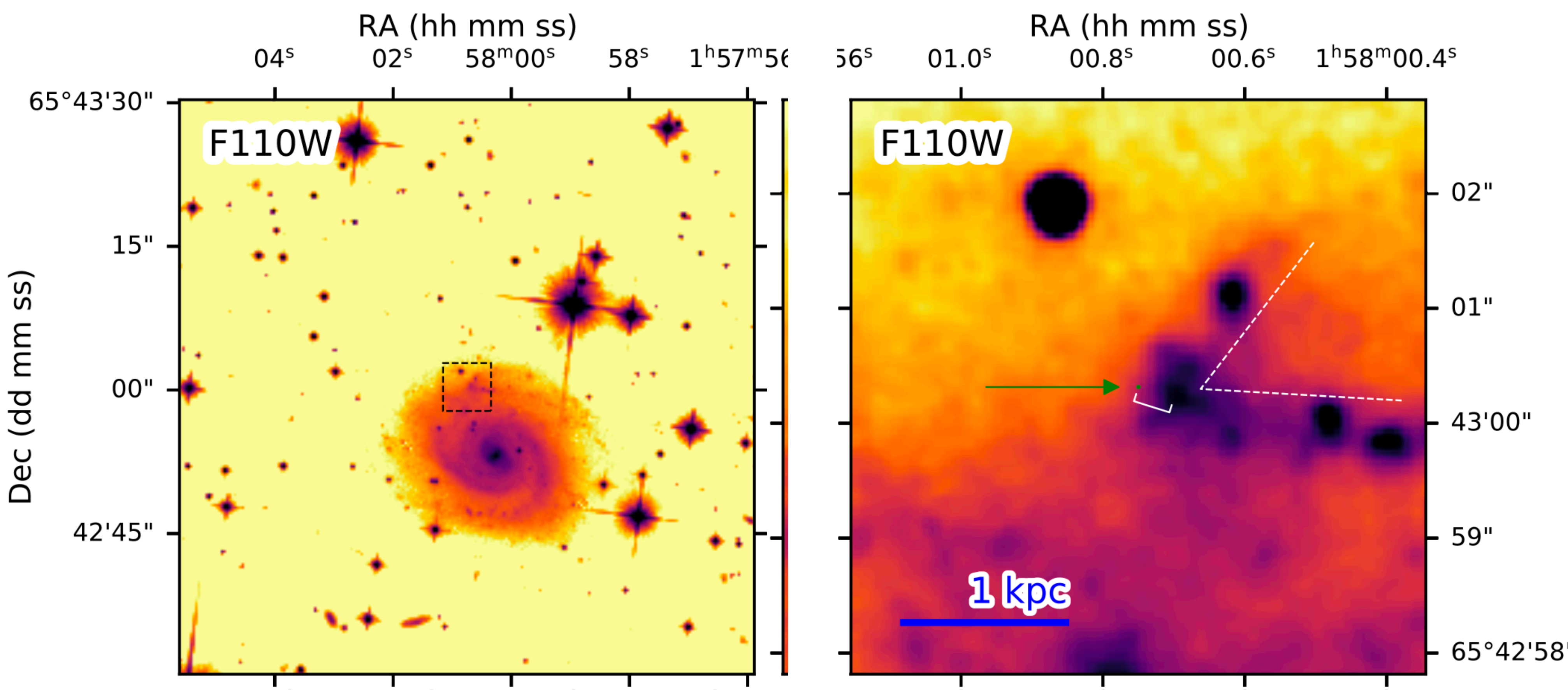
But for FRBs:

- A small fraction of them are localized to massive, red, low star forming host galaxies (Law+23, Sharma+23, Gordon+23)

- 250pc from the nearest star-forming region. But few kpc from the dominant SF region

- A large fraction
star-forming gal
away from the s





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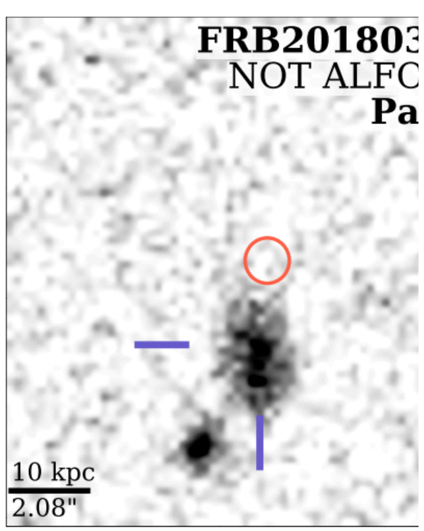
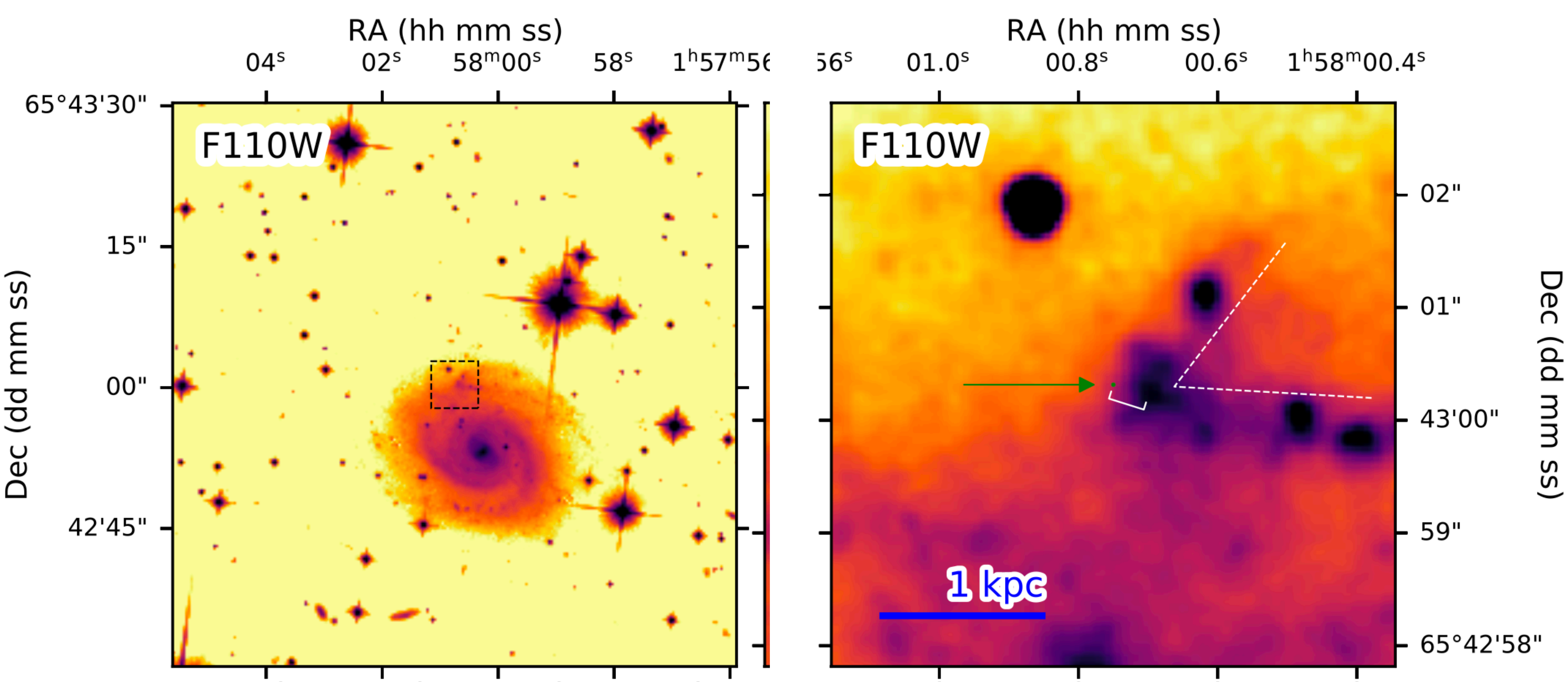


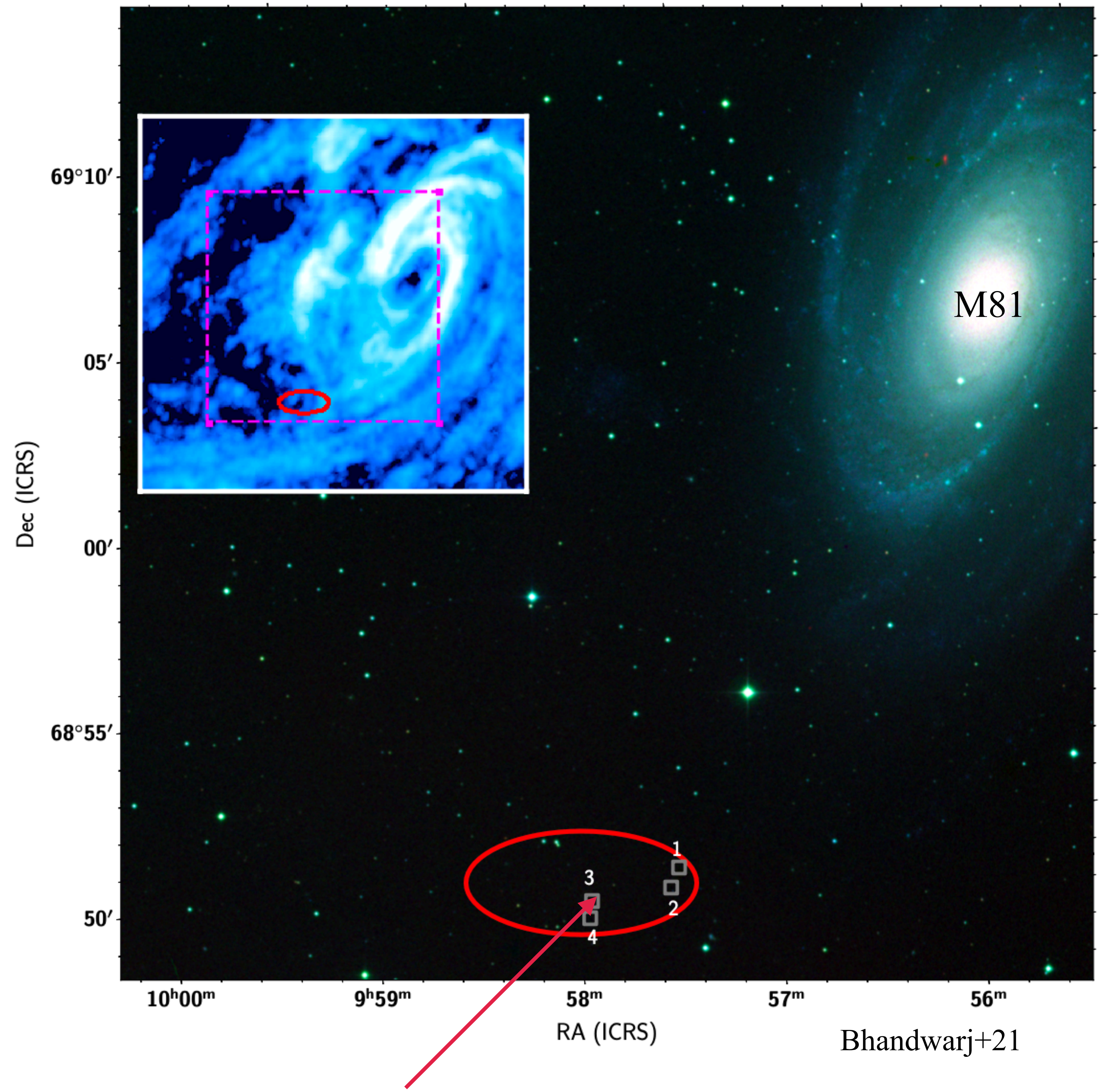


Gordon+23

- Are we missing orders of magnitude more in the star forming region due to observation biases ?
  - Separate the analysis for sources found at different frequency
- Or the source is ~sep/v>Myr old?

Puzzle: LOCALIZATION: 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
    - GCs hosts only ~0.001% stellar mass compared to galaxies. But GC has enhanced dynamic crossing.



Bhandwarj+21

GC[PR95] 30244 & FRB 20200120E

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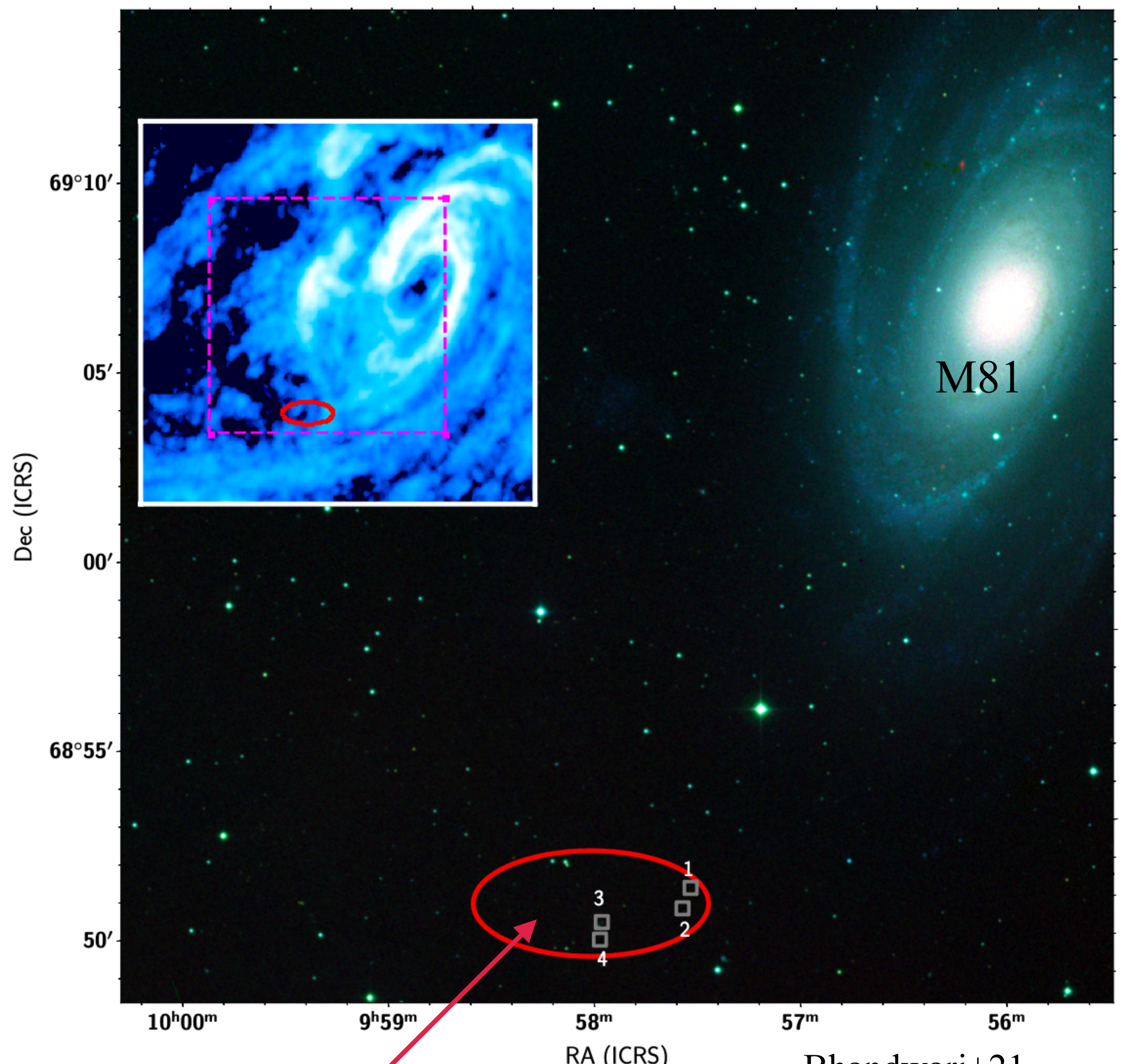

Bhandwarj+21

GC[PR95] 30244 & FRB 20200120E

There exist a dynamic formation channel for FRBs!

- Potentially compose a non-negligible fraction in local universe
- We should still see most FRBs in field galaxies from this channel, but not associated star-forming regions

Puzzle: LOCALIZATION: the globular cluster FRB

Enable us to probe a dynamic formation channel:

Constraints:
rate: should have an active one per 1000 GC
Spectral luminosity: need to be able release energy in ms

Dynamically formed magnetar? (Kremer,..Li+21,23)
rate requires: WD-WD merger (NS-NS merger, or per-merger model can't reach the rate)

Mildly magnetized millisecond pulsar? (Li, Pen23) $L_\nu = 10^{30}\mathrm{erg/s/Hz}\, B_{10}^2 P_{-3}^{-4} f_r \Delta\nu_9^{-1} N^{-1} \frac{4\pi}{\Omega}$
highly beamed to reach the spectral luminosity (As seen with a Crab giant pulse(Bij+21)

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Important for Cosmological application:

A population with less contamination from local environment.
- (DM 0.1pc/cm^3 at GC). Little circum-burst material

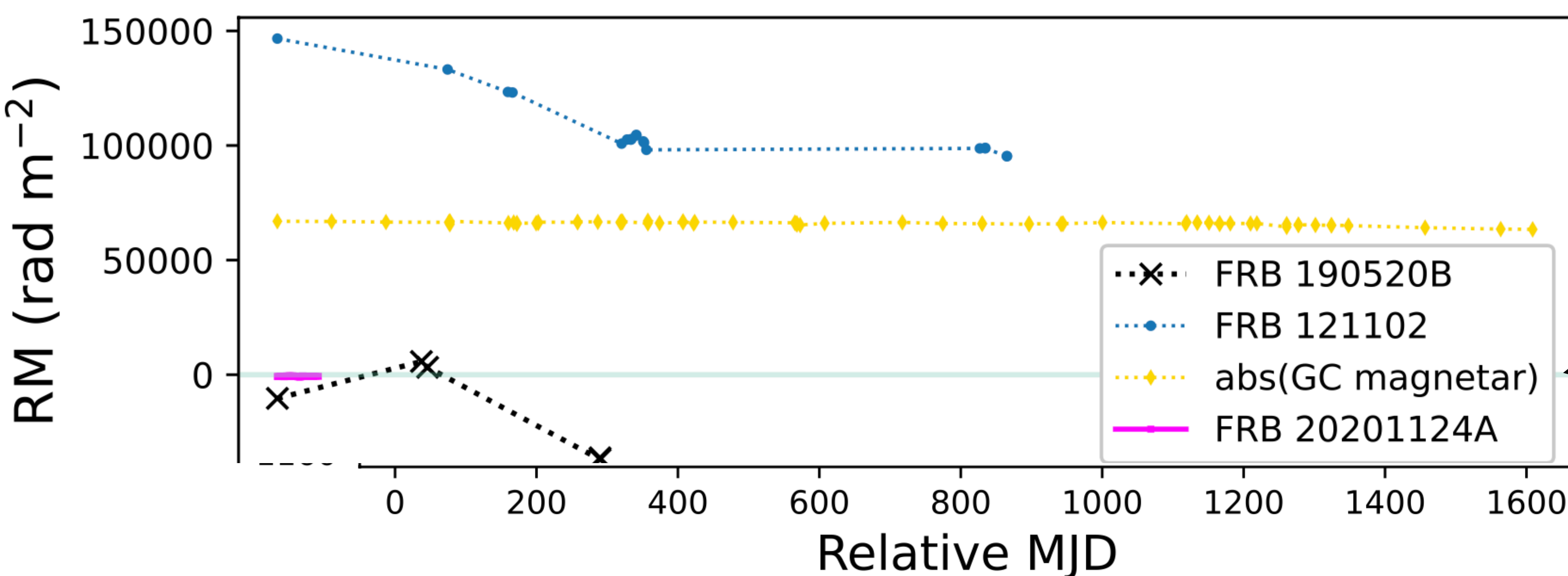
Should look for this population:

Staring at nearby massive elliptical galaxies.
Observe M87 (15000GCs) with FAST for 10h, expect 5 sources, but no detection yet.

Puzzle: unusually large, fast-varying RM

varies at month timescale

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

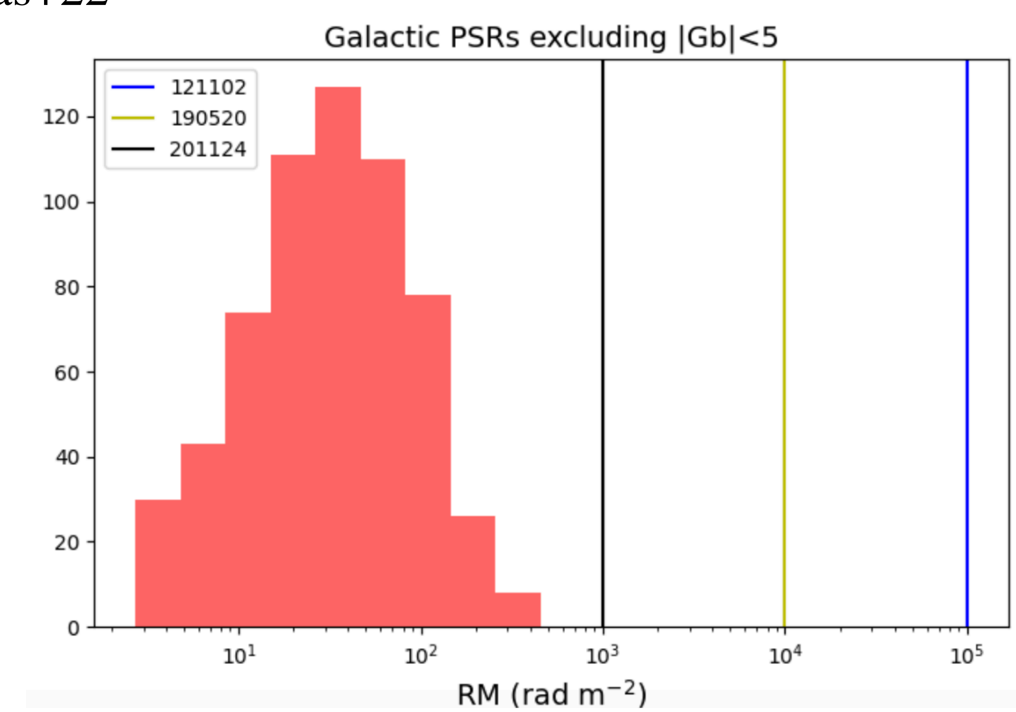


Only other object is the galactic centre magnetar

Anna-Thomas+22

Young supernovae remnant?
(e.g.Margalit+18, Piro+18)

Introduced by a companion?
(e.g. Wang+22)



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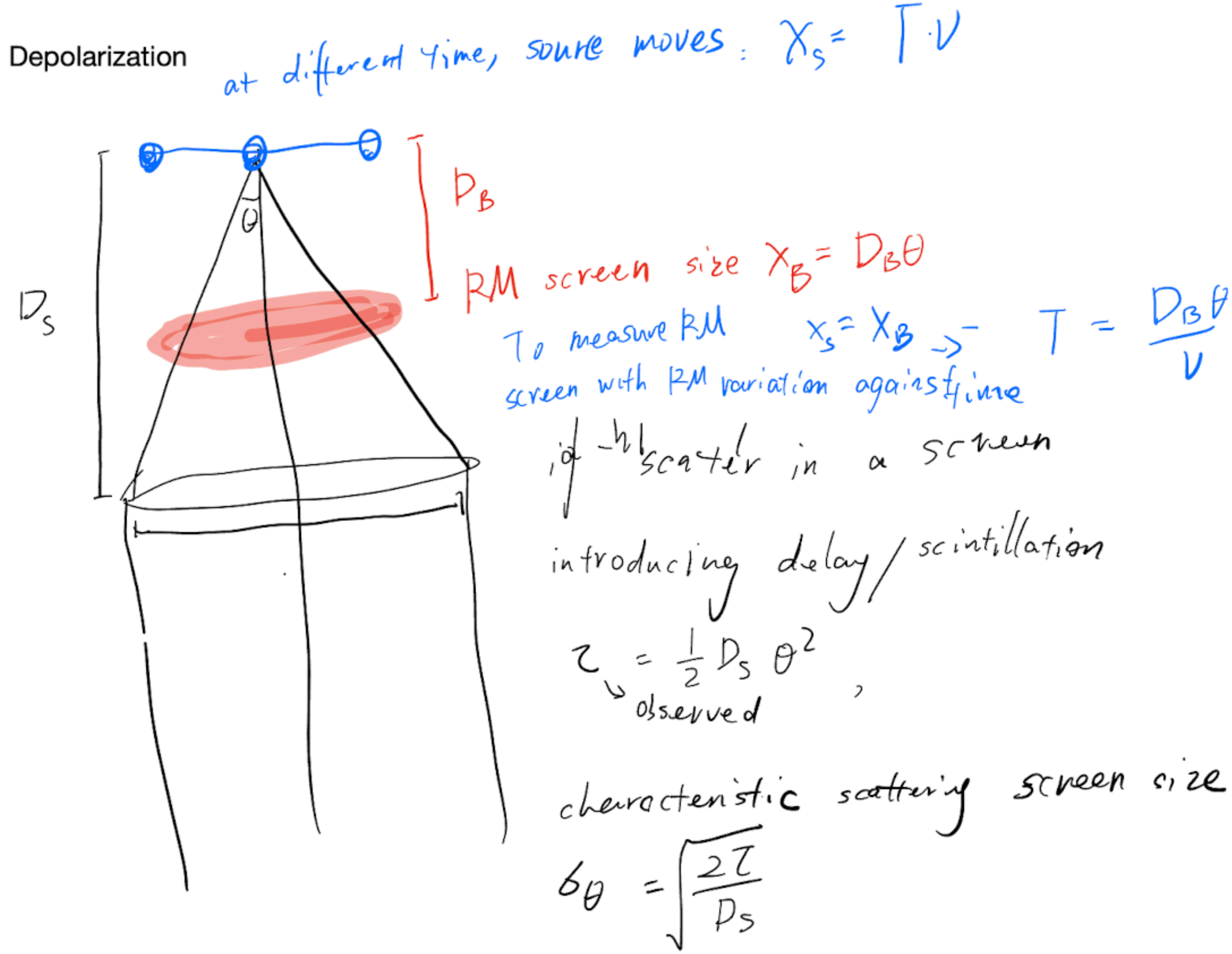
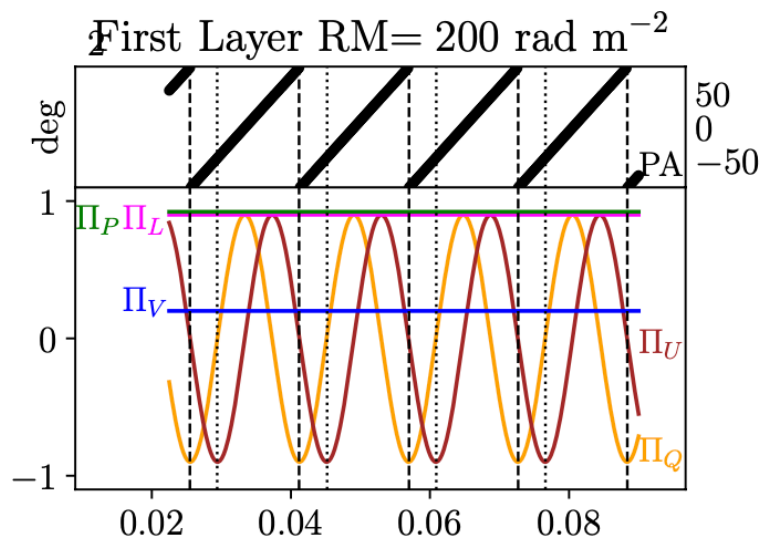
How to distinguish them?

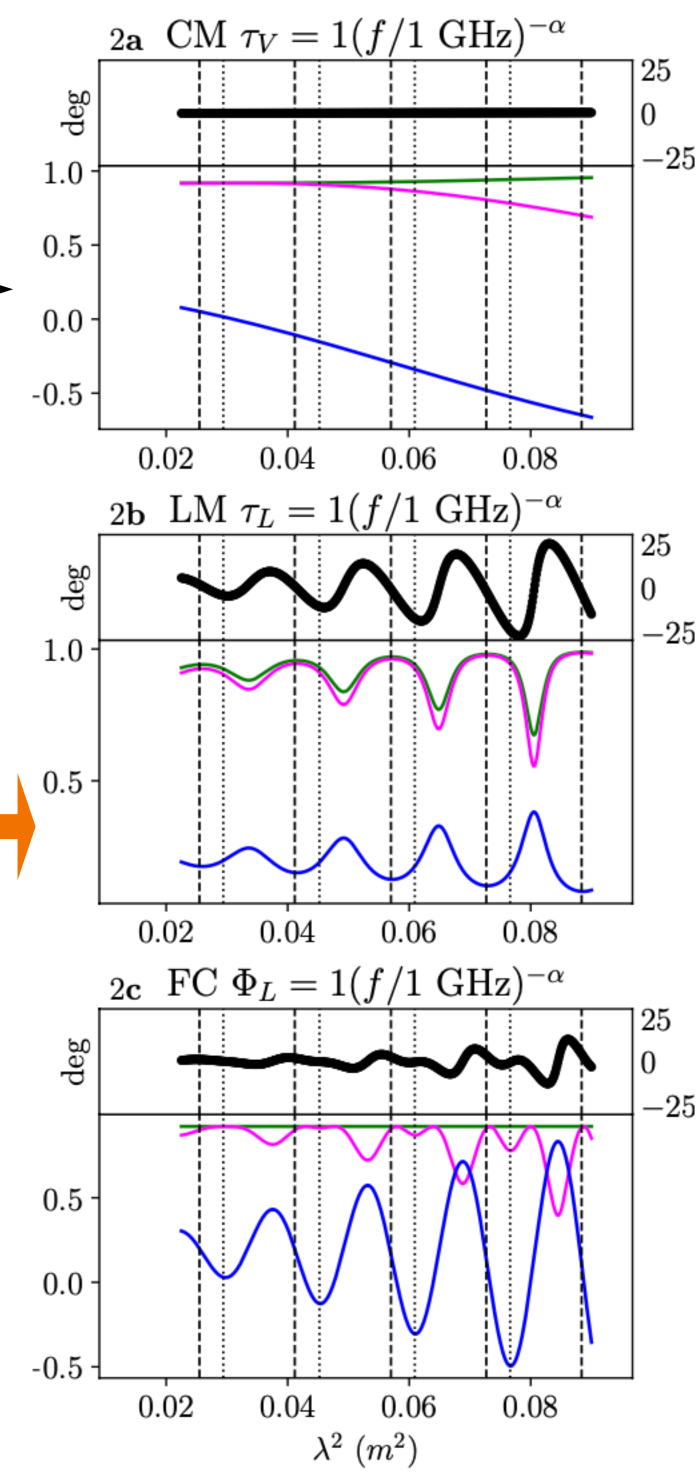
May be by modelling the depolarization



Puzzle: Magneto-environment: structures along LOS

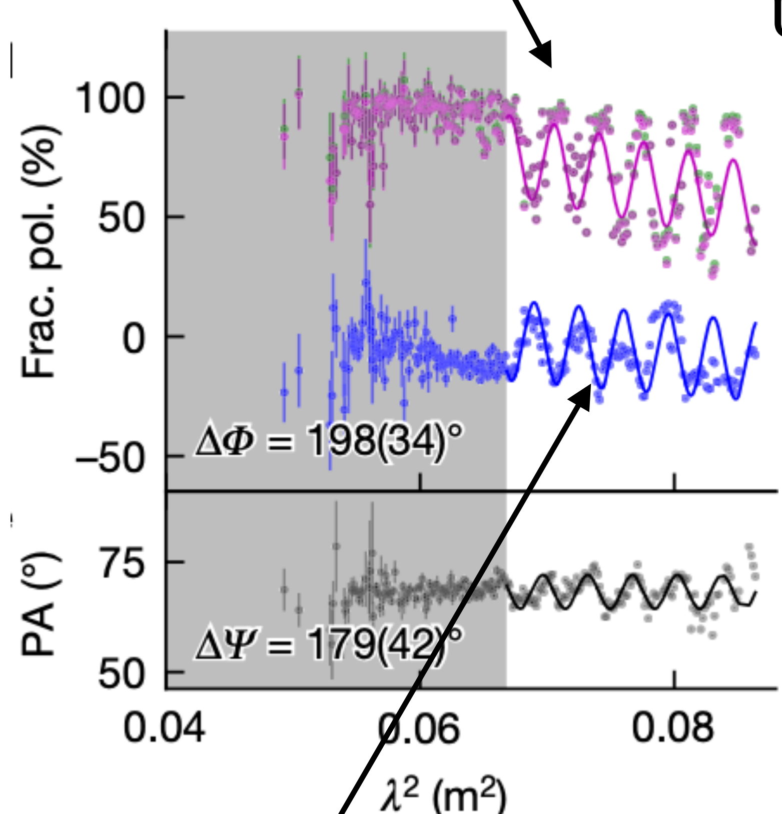


after different kinds of second layer



FRB 20201124A

Polarization/linear fraction



Circular fraction

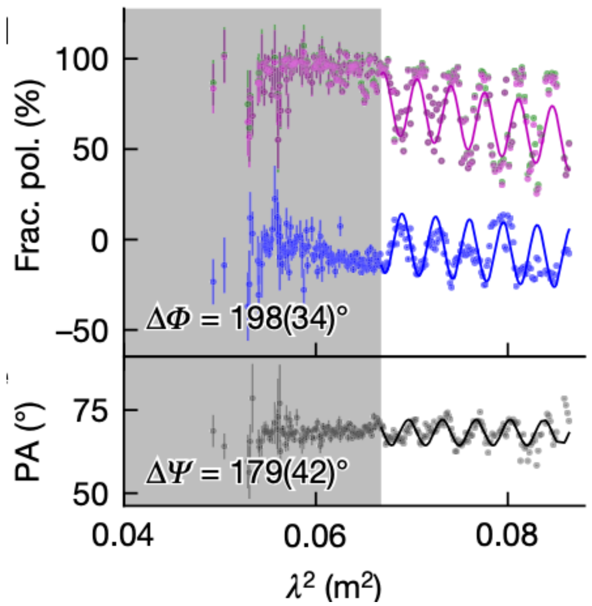
Unique signature of a middle layer with linear absorption

Xu+21

A dictionary for different “fossils”

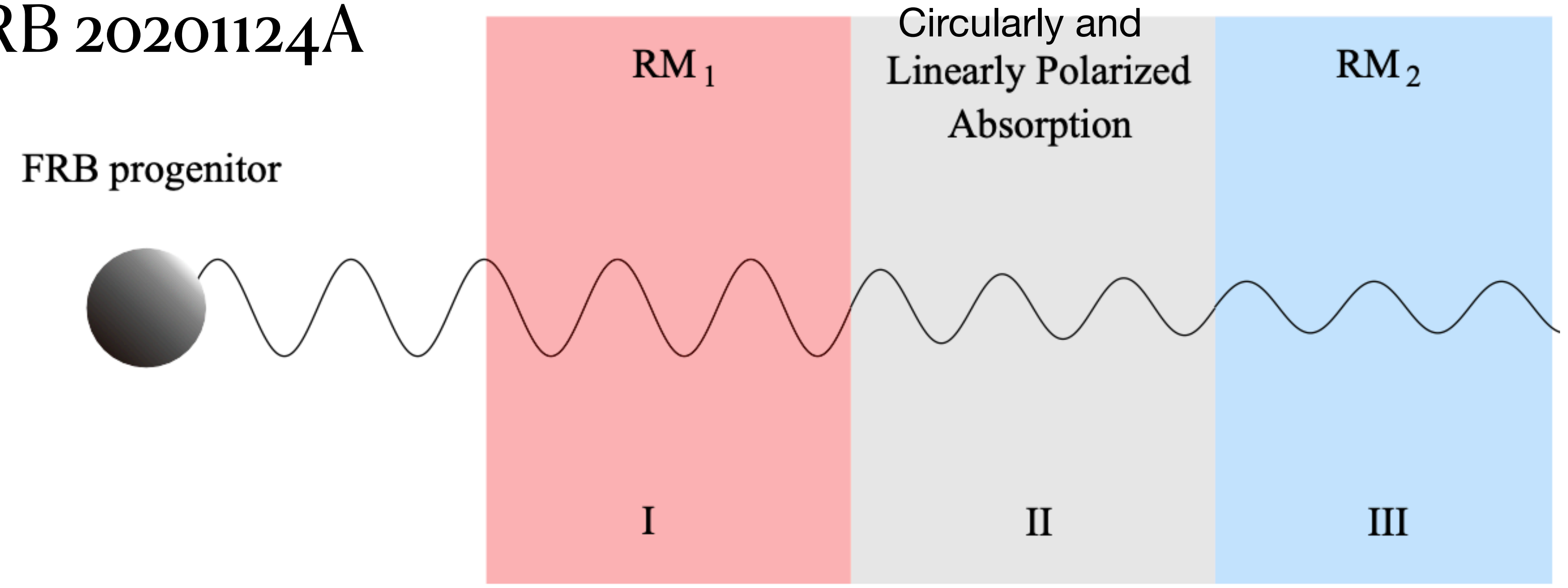
Li in prep

Puzzle: Magneto-environment: structures along LOS



consistent with Synchrontron-cyclotron absorption with B>G, gamma~1-10

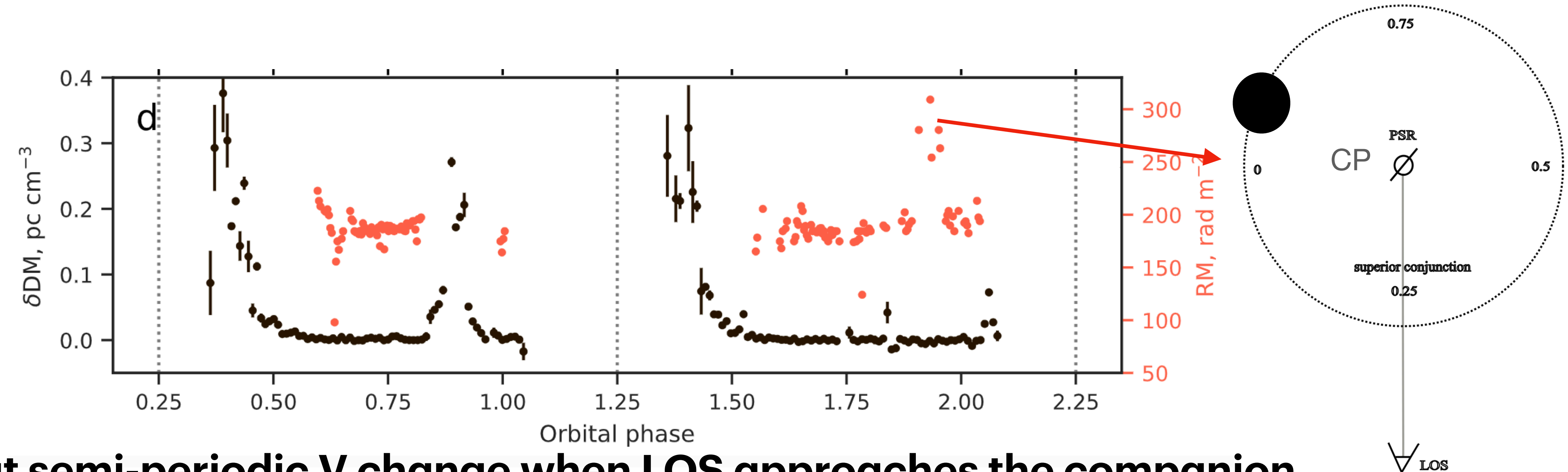
FRB 20201124A



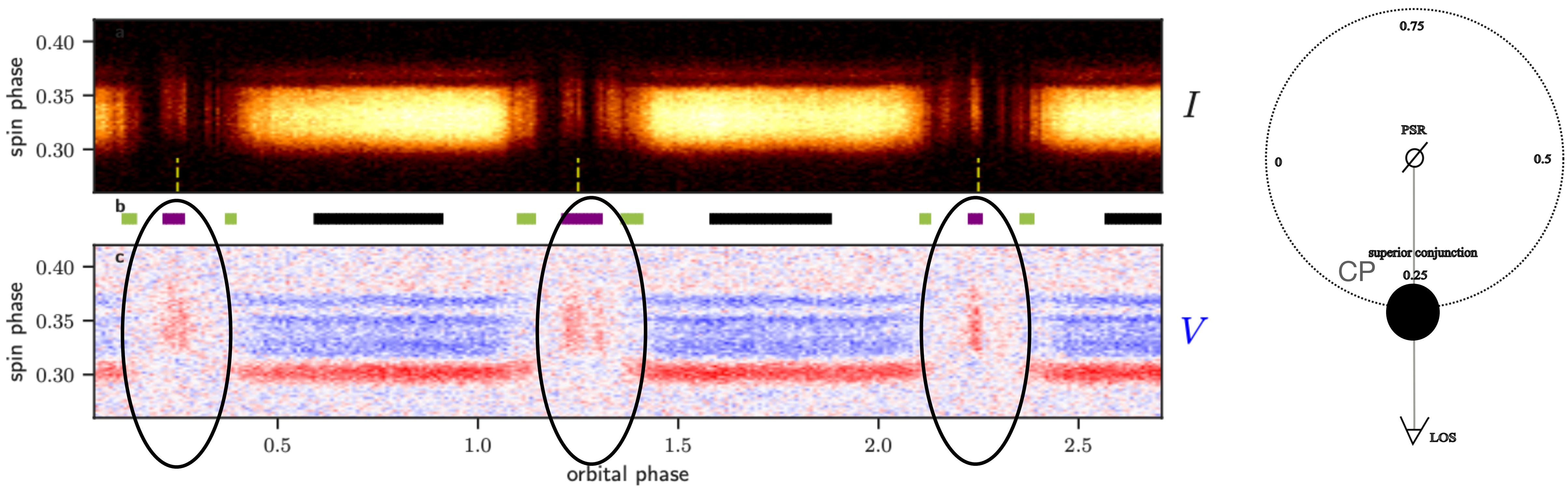
Seems more like the environment near a companion SNR ~mG

What do we see in the system with a neutron star and a companion?

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



But semi-periodic V change when LOS approaches the companion



Dongzi Li+23 Nature 618..484L

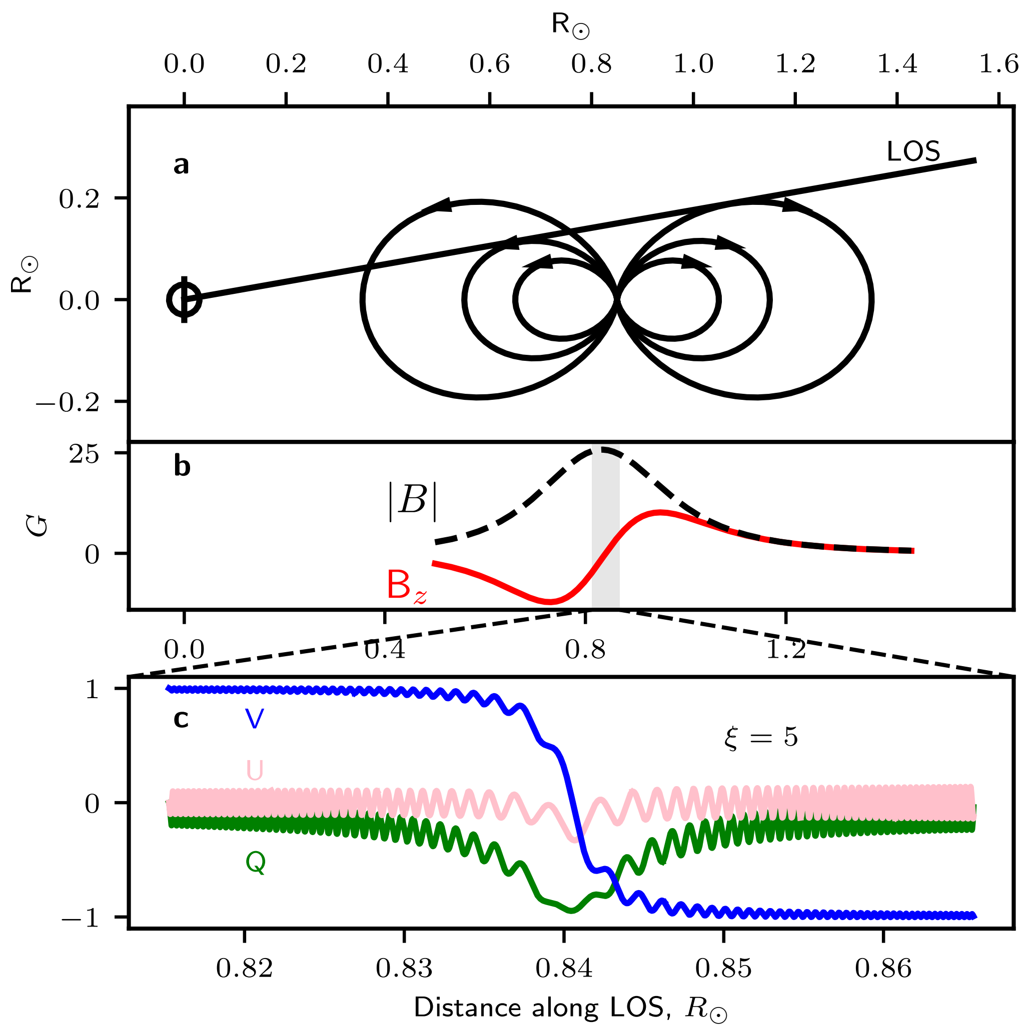
Model can reproduce the complex V profile

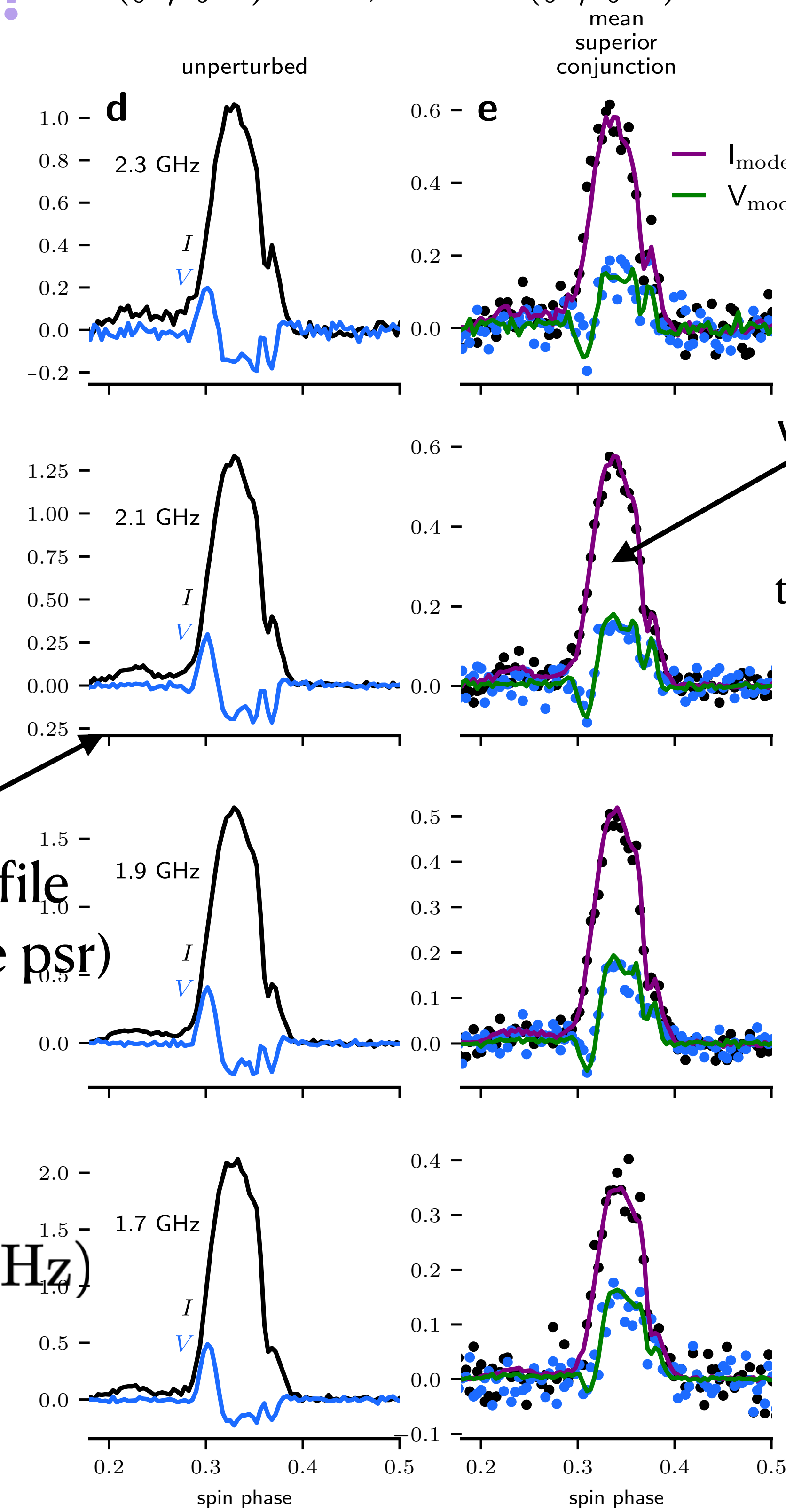
with mode tracking and circular absorption

(identical for all spin phases):

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

We can model it
and probe the companion magnetosphere!





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

Original profile
(cp behind the psr)

dots
observed data

The radio wave follows the B_z reversal

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

Dongzi Li+23 Nature 618..484L

Maybe some FRBs have a companion?

Ter5A	FRBs
• Large irregular RM variation	• A reasonable fraction of repeaters 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	○ Lots of repeaters (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)
• Indicated extreme RM	• FRB 20121102A, 20190520 (Michilli+18, Anna-Thomas+22)

Can explain other observation mysterious

The FRB detected in globular cluster, the FRBs with long-term periodicity

Summary

- **FRBs can be emitted from magnetars but there are still lots of puzzles.**

- **There are dynamically formed FRBs**
  - Could magnetar formed by WD-WD merger or mildly magnetized ms-pulsar
  - A great target for cosmological application

- **Lots of FRBs are seen with unusual magneto-environment**
  - Similar to the the case seen in pulsar binary system
  - Does FRB has companions?

- Dongzi Li

- In collaboration with Kyle Kremer, Tony Piro, Wenbin Lu, Anna Bilous, Scott Ransom, Robert Main, FAST FRB key project, KJ Lee, Bing Zhang, Yuanpei Yang, Nadja Aldarondo, Sterl Phinney

Puzzle: LOCALIZATION: the globular cluster FRB: a new population!

rate requirements: should have an active one per 1000 GC
—> pre-merging/merging model not working

Can millisecond pulsar work?
Has to justify both the rate and energetics

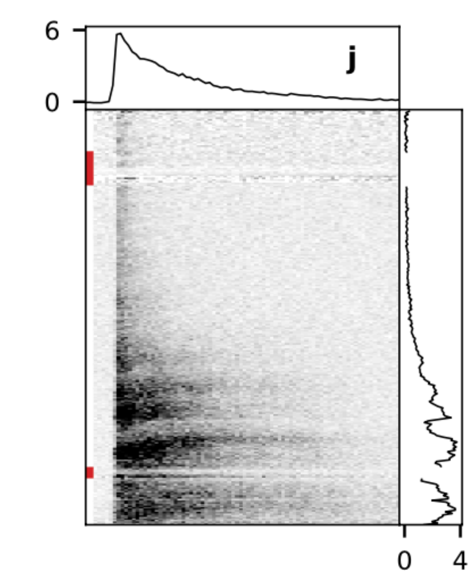
Total spin energy is high, but has to instantaneously emit is a problem

$$L_\nu = 10^{30}\mathrm{erg/s/Hz}\, B_{10}^2 P_{-3}^{-4} f_r \Delta\nu_9^{-1} N^{-1} \frac{4\pi}{\Omega}$$

magnetic dipole radiation is not enough to explain the bright FRBs: if ISOTROPIC EMISSION!

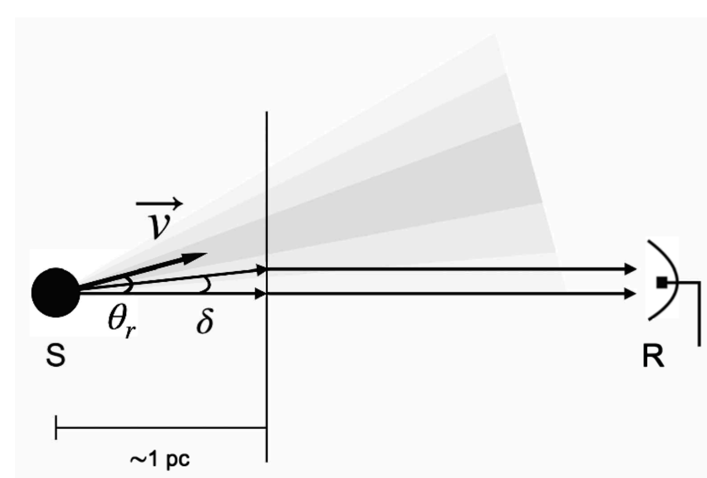
If omega = 1/gamma^2, with gamma=10^4
For M81 bursts, ok with B=10^8 G and for other FRBs, ok with B=10^10 G

Individual spectrum luminosity, total energy emitted, age all fine



The nebula lens has resolution of 0.6 arcs,
has to be resolved by the lens
in the scattering tail

The frequency drift in the scattering
tail indicates high beamed emission
with gamma=10^4 (Bij+21)



backup

Puzzle: unusually large, fast-varying RM

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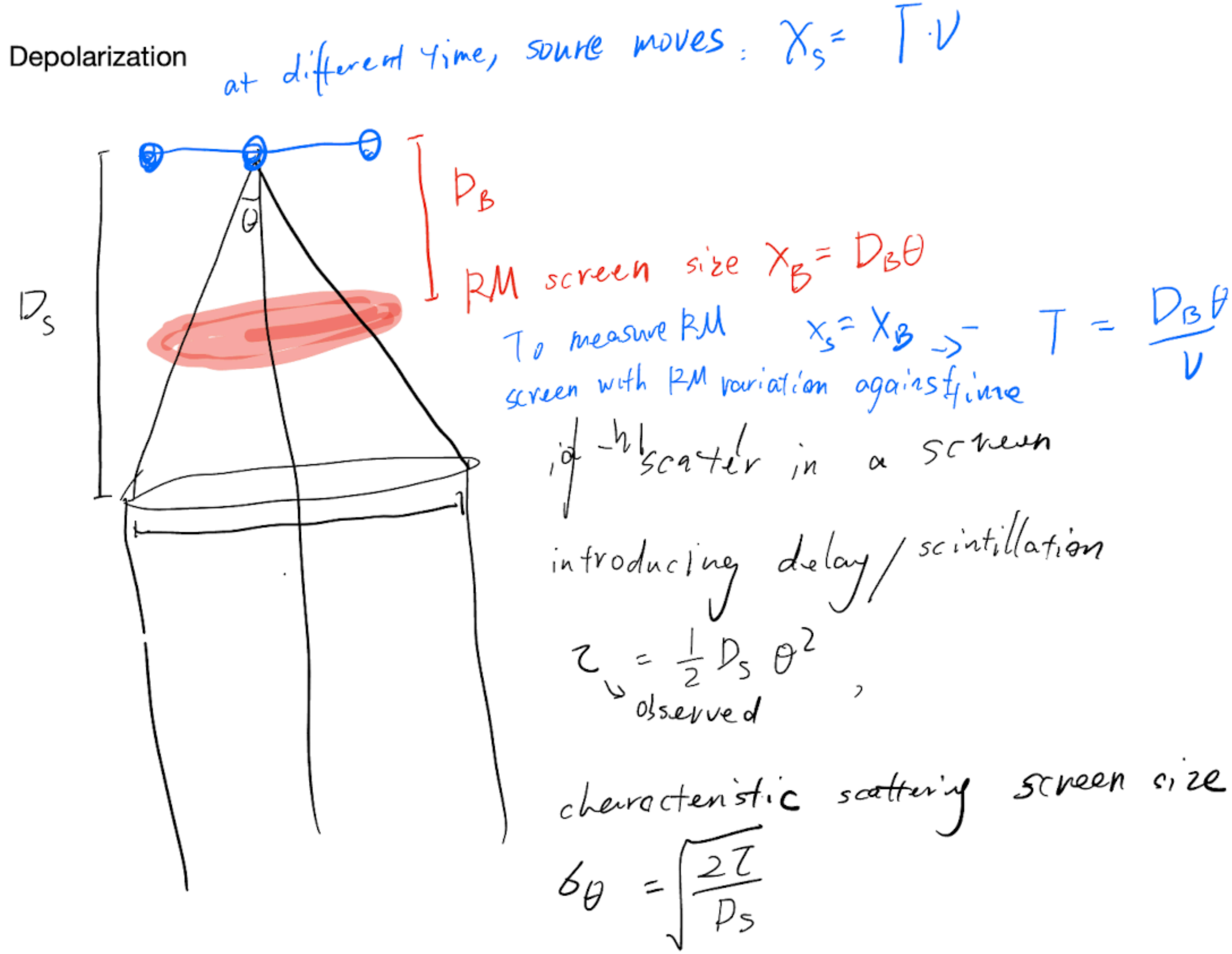
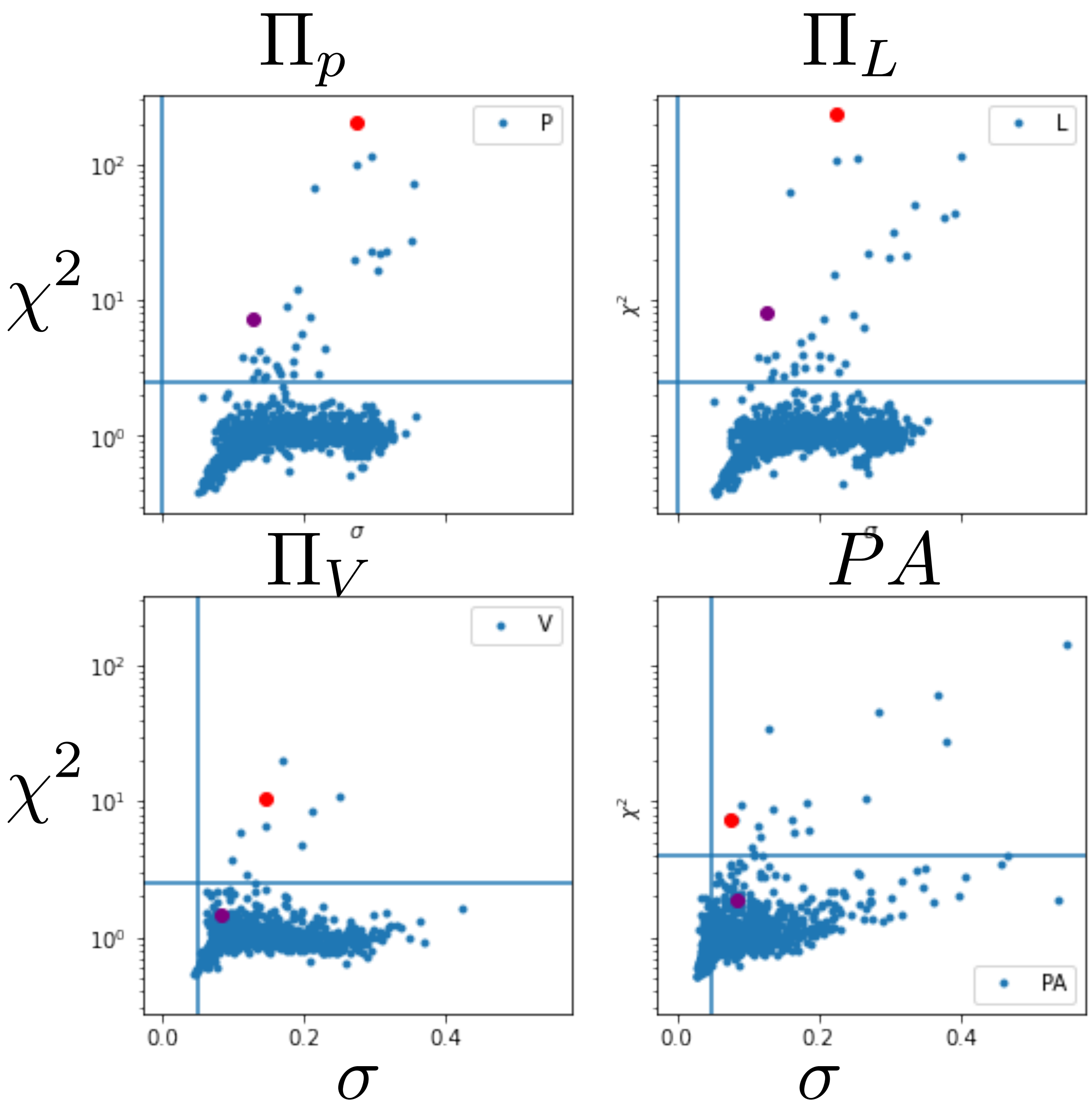
How to distinguish them?

May be by modelling the depolarization



How to find the polarized propagation effects?

Test with the 1600 bursts from FRB 20201124A (Xu+2022)



Nadja Aldarondo@upr

Data from FAST KEY PROJECT, shared by Heng Xu

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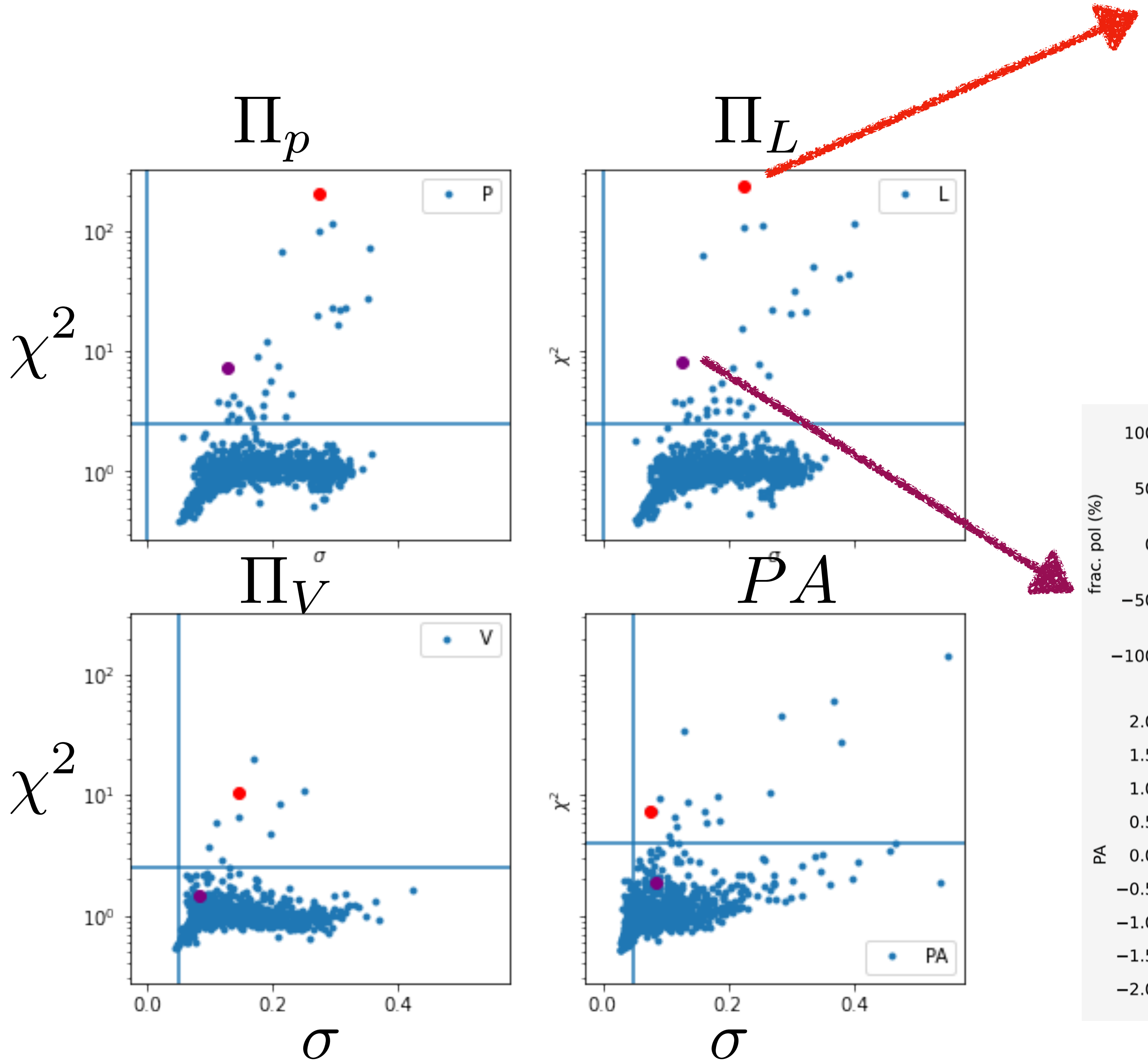
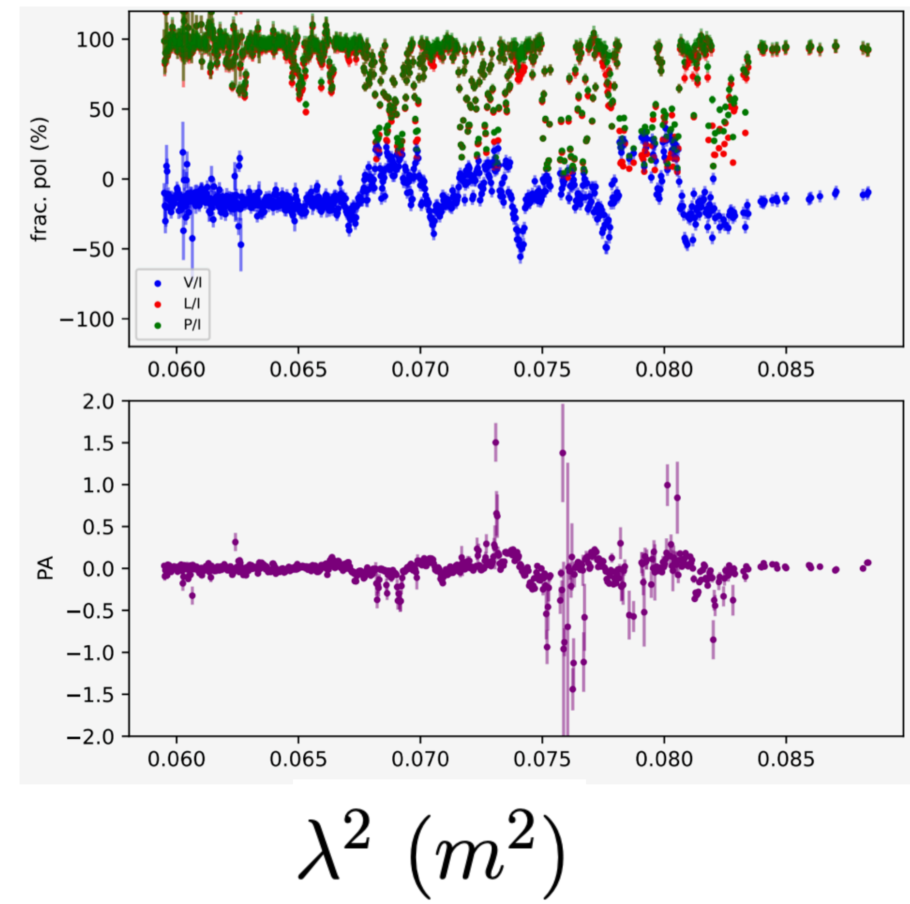
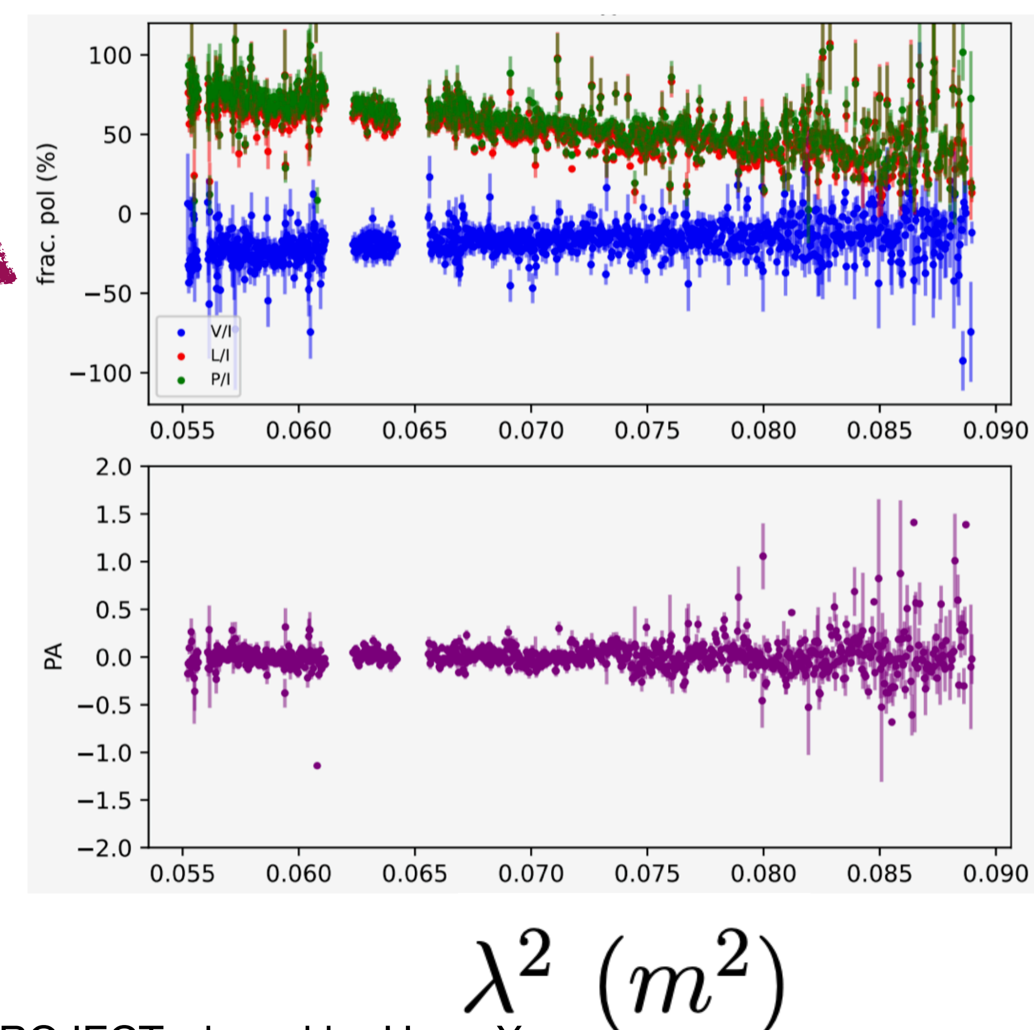




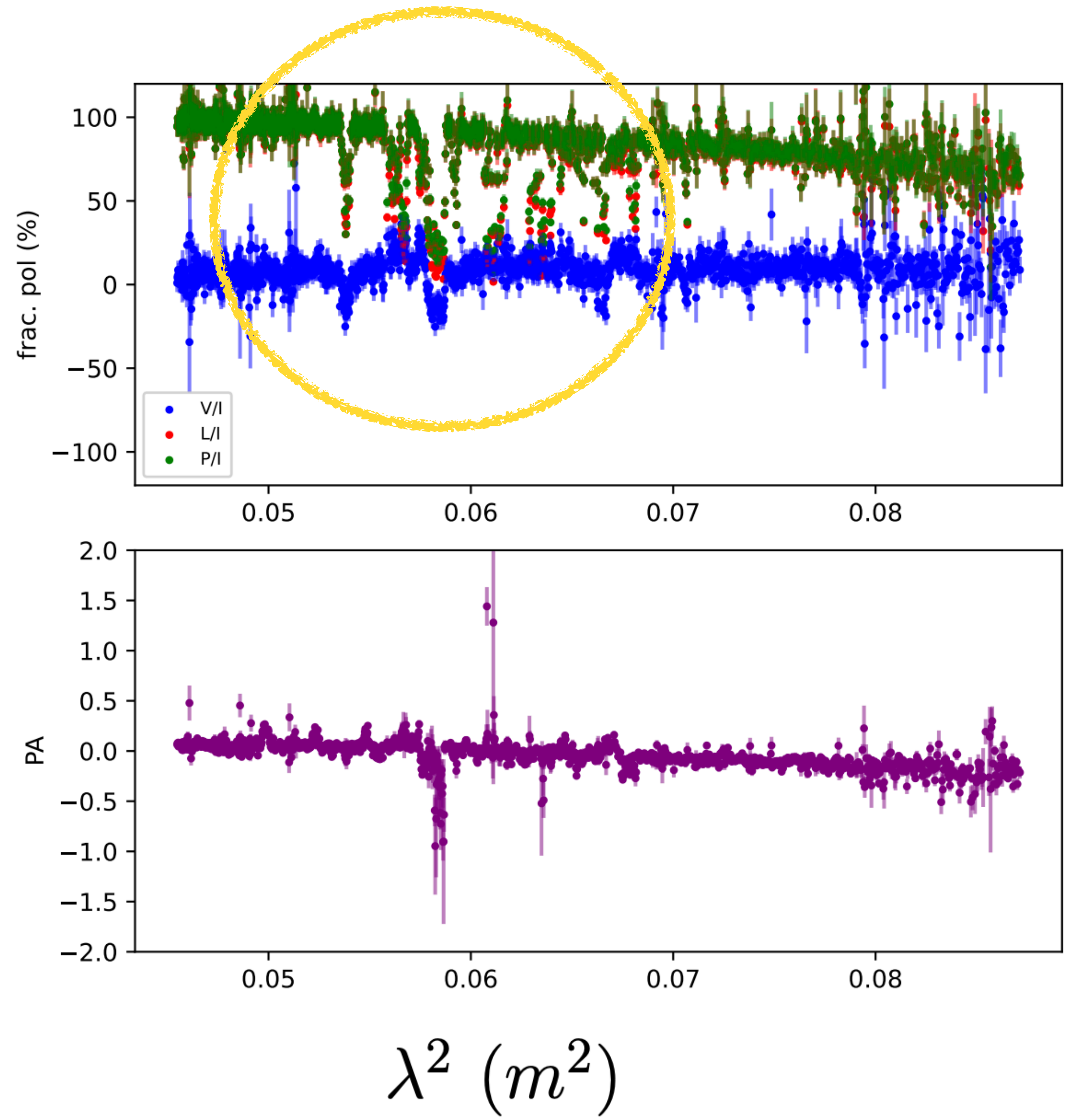


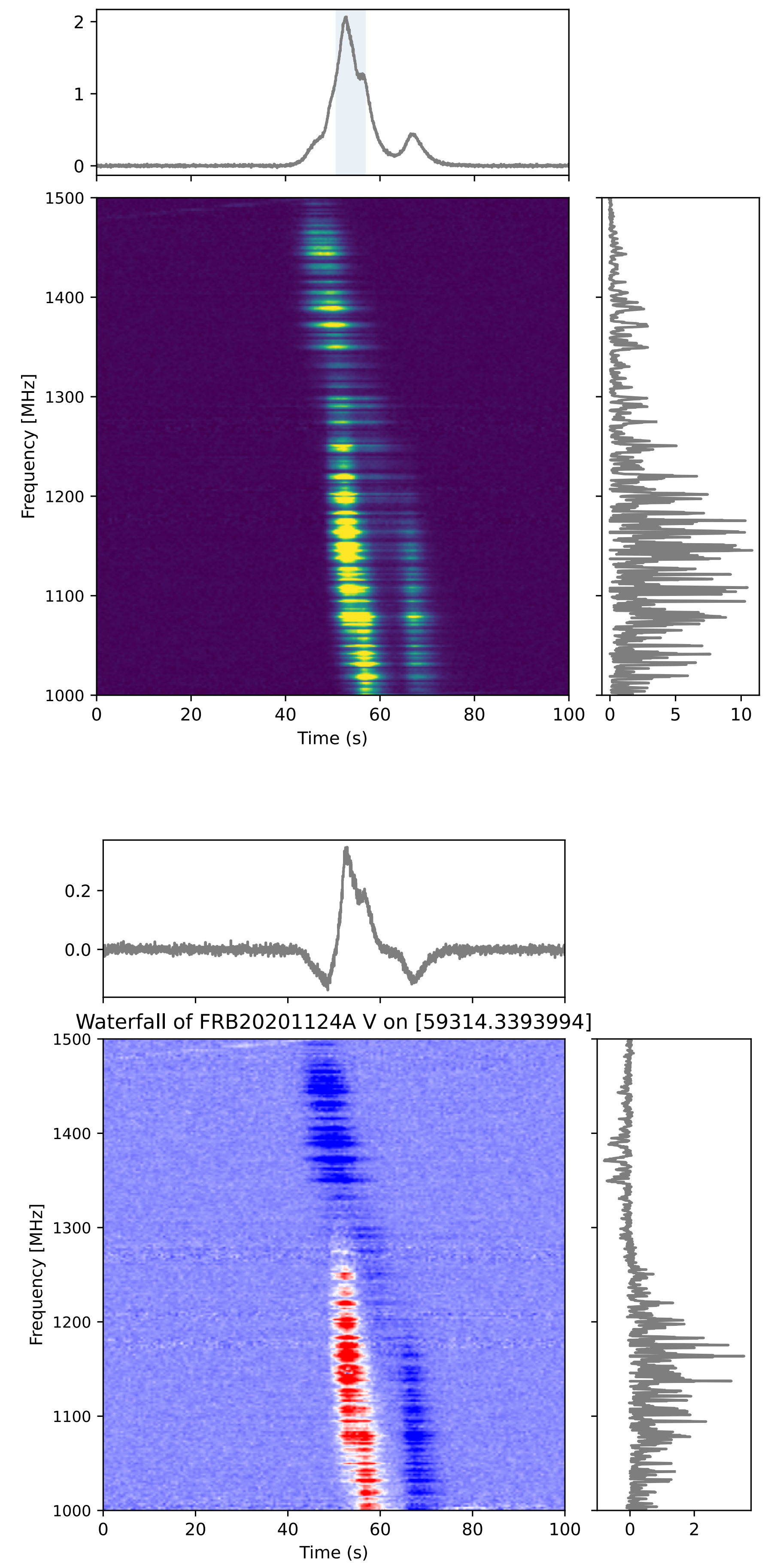
Credit to my summer student Nadja Aldarondo@upr

Data from FAST KEY PROJECT, shared by Heng Xu

Some unexpected

Happening in narrow frequency





Credit to Nadja Aldarondo@upr

Data from FAST KEY PROJECT, shared by Heng Xu

It is fun to search for Polarized propagation

- There are lots of polarized propagation effects beyond RM.
- They show us LOS with special magneto-environment
    - Can be used to probe the most magnetized region
    - Can provide evidence for binary systems
- Different polarized propagation effects are all distinguishable and can be searched with the simplest chi^2 test
- Waiting to find the regularity, decide the mechanism and constrain the environment

Maybe some FRBs are in binary

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• 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)
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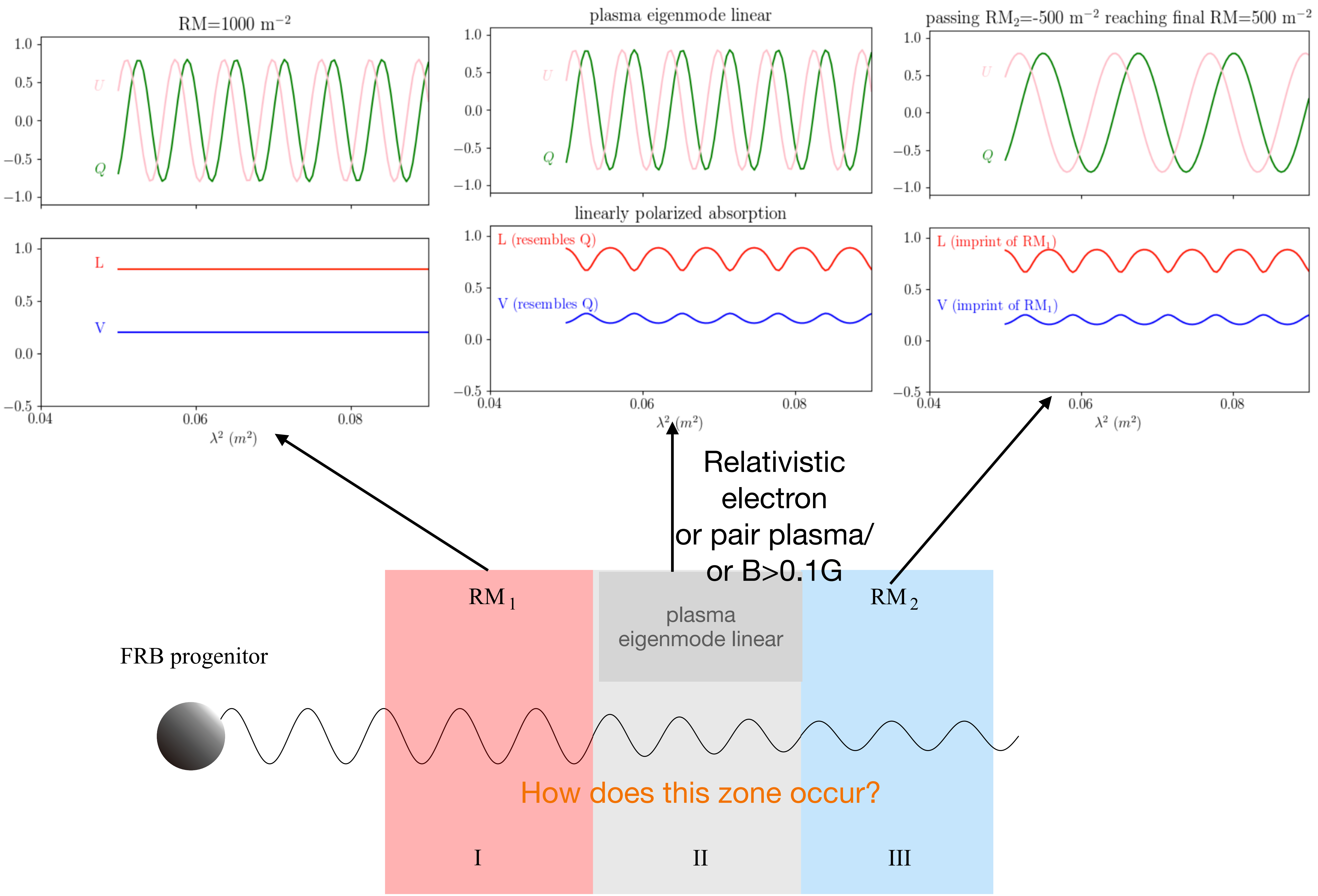
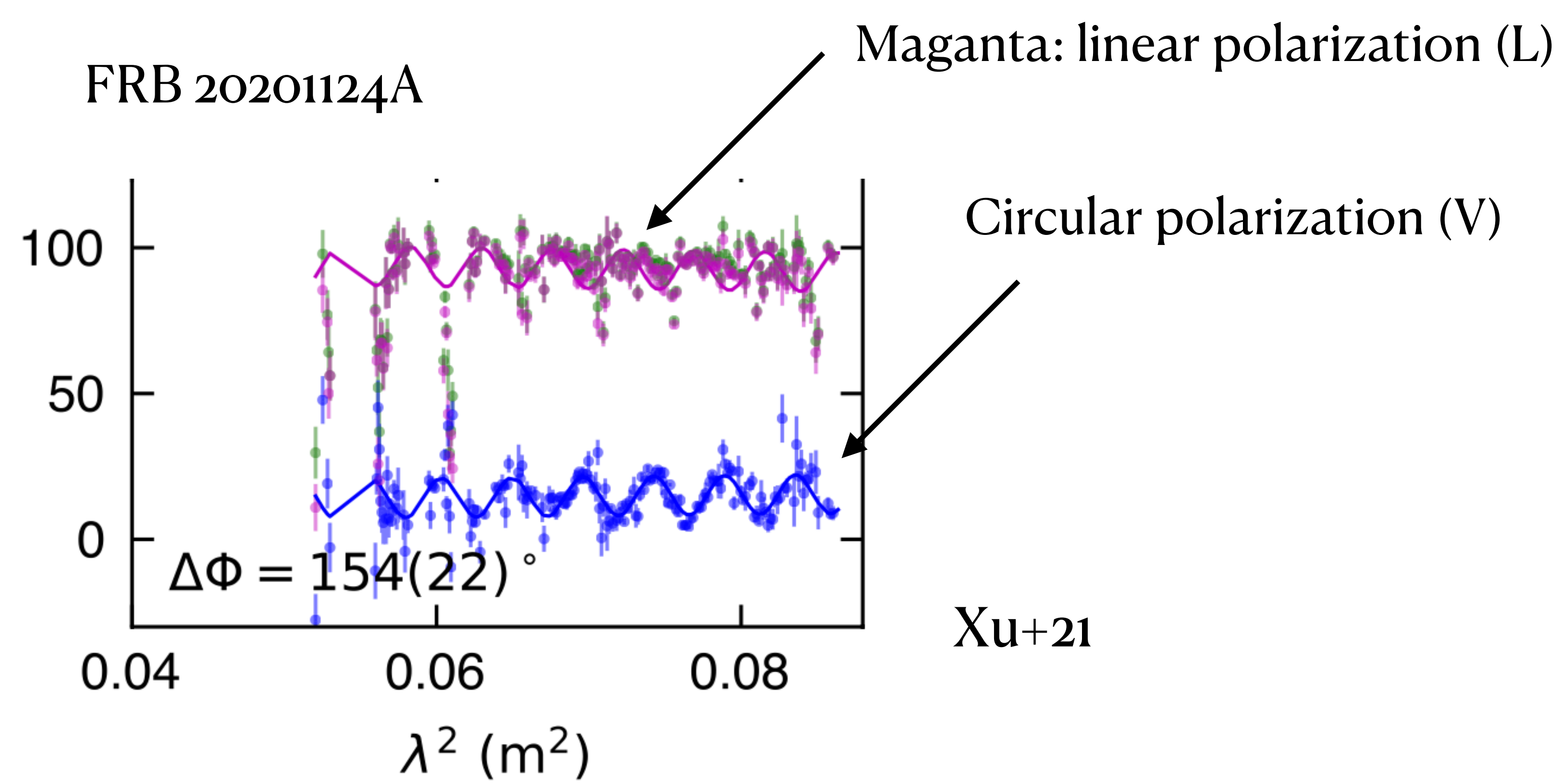
Can explain other observation mysterious

the FRBs offset from the star-forming region, the FRB detected in globular cluster, the FRBs with long-term periodicity

FRB20201124A (FRB wiggler): evidence of multi-layer medium

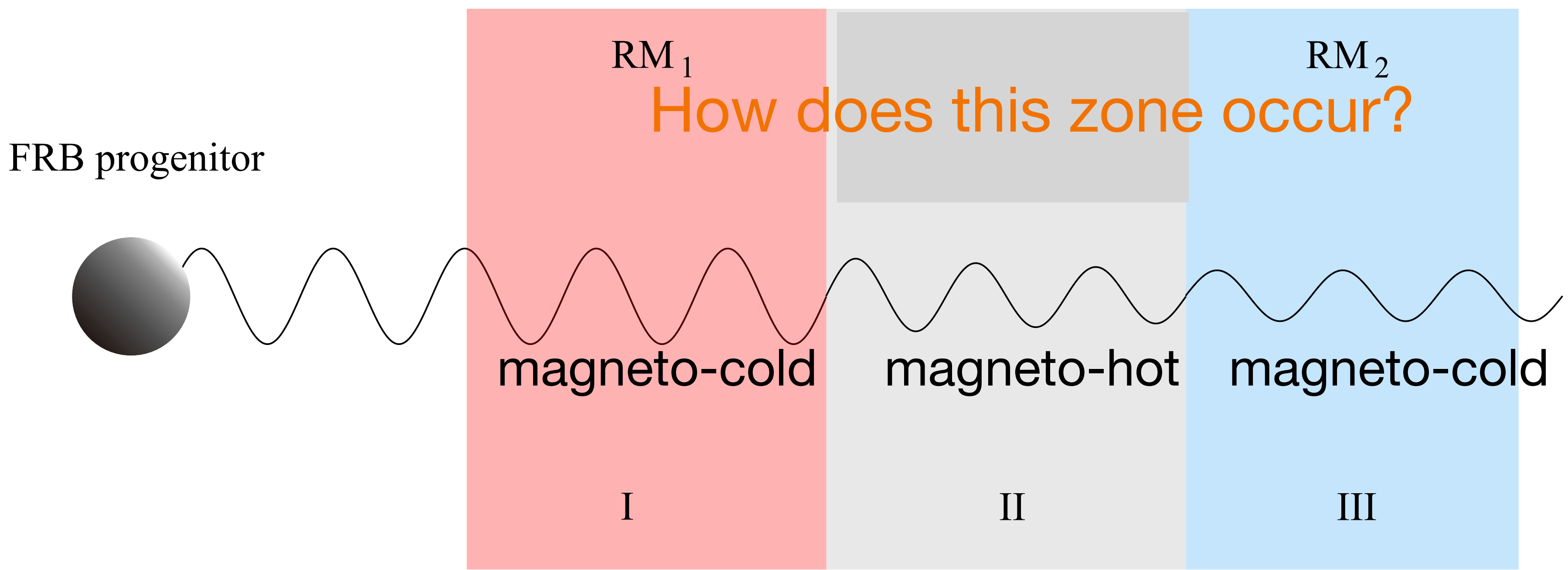


Unusual magneto-environment of FRBs: structure along LOS



RM like-Oscillation in L ,V —> but RM does not change LV

—> have passed a region with plasma eigenmode linear

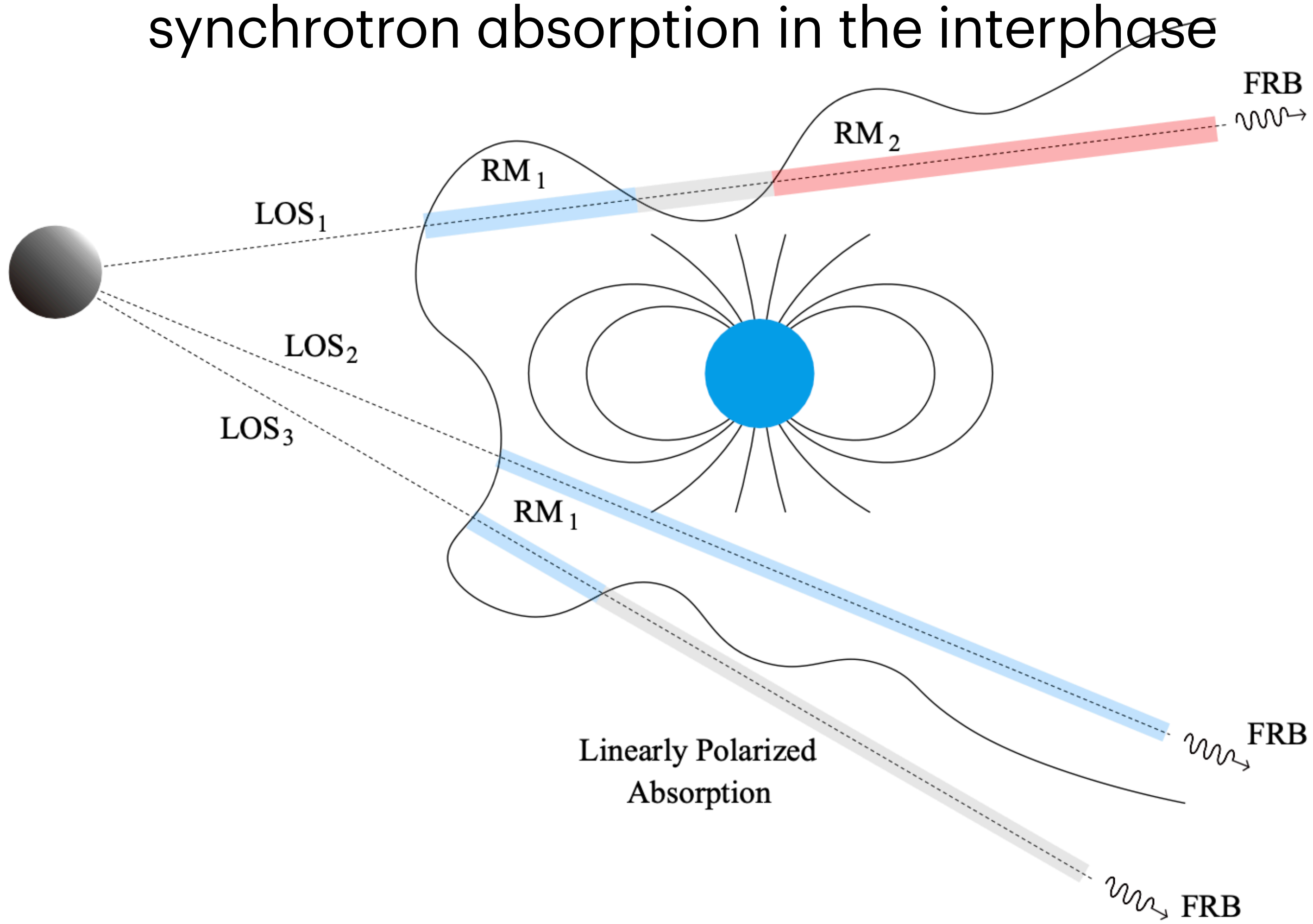


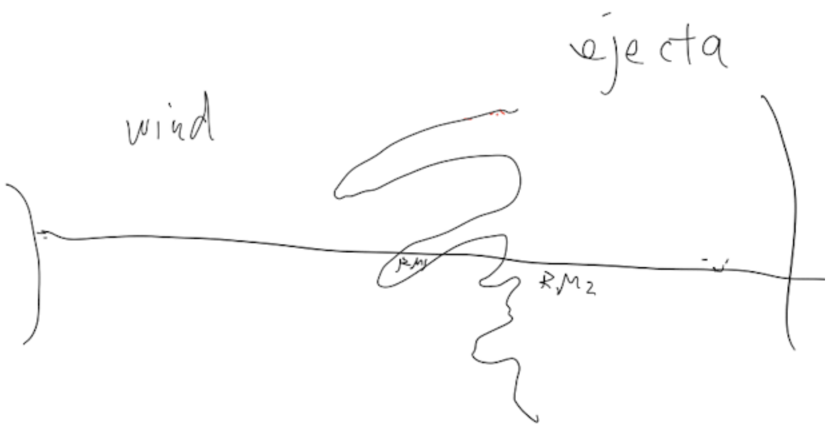
at least 30% RM variation

5% or 100% RM variation

FRB20201124A potential scenarios

RM from the companion wind,
synchrotron absorption in the interphase



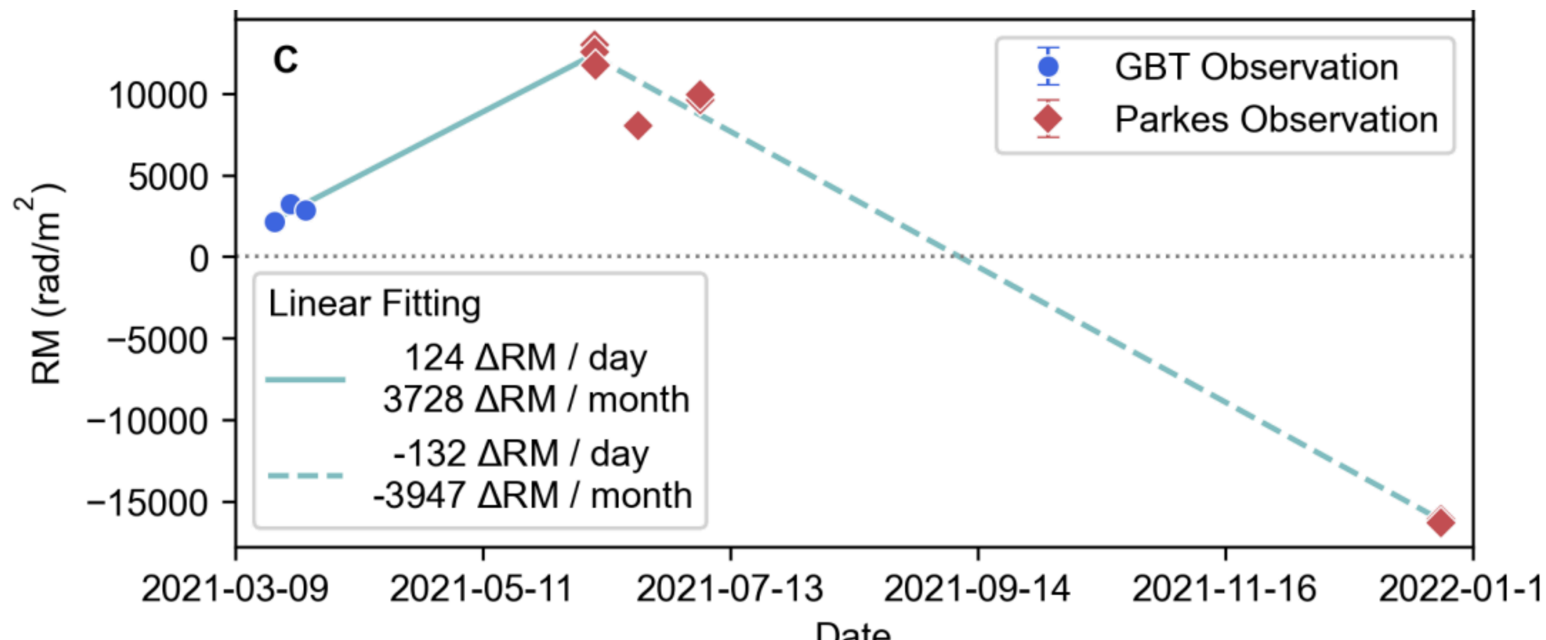


Puzzle 3: The magneto environment

- Order 1 irregular RM fluctuation of repeaters (2 out of 6 FRBs with multiple RM measurements: e.g. Xu+22, Dai+22)

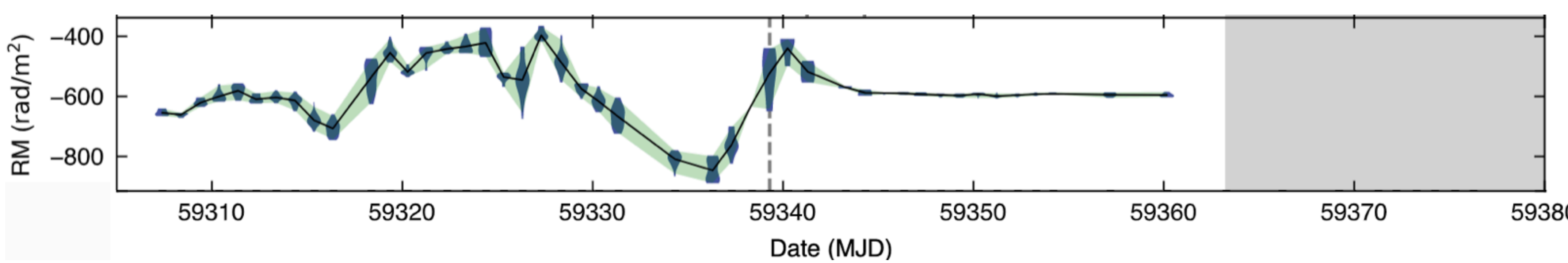
timescale: ~month
—>spatial scale: 1 month * 100km/s ~ AU
very small

FRB 20190520B



Dai+22

FRB 20201124A



Xu+21

A globular cluster pulsar binary in magneto-active environment

Remind us of FRBs

- Large irregular RM variation
- Polarized absorption and Faraday conversion (also observed in FRB 20201124A)
- Obvious increase of V (may be able to explain the large V observed in some FRB20201124A bursts)

- Require B>10G for the LOS close to companion, where dDM=0.02pc/cm^3 —> expect RM > 10^6 m^2 (close to FRB121102)

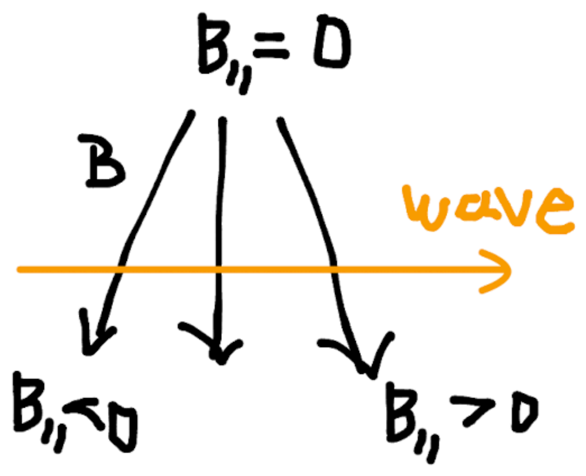
Look at high frequency to search for LOS eclipsed at lower frequency

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

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



Maybe some FRBs are in binary

Advantage:

- The magneto-environment: eg. introducing large, fast varying RMs, Faraday conversion and polarized absorption
- Diverse behavior, depending on the orbital inclination angle, separation, companion
- May explain the long-term periodicity
- Abundant in globular clusters, and can have longer age, so offset from the star-forming region. Does not trace star formation and stellar mass.

Challenge:

- Strong wave effect (Lu+20)? separation >AU —> require massive companion/accreting black hole —> again, why offset from the star forming region?

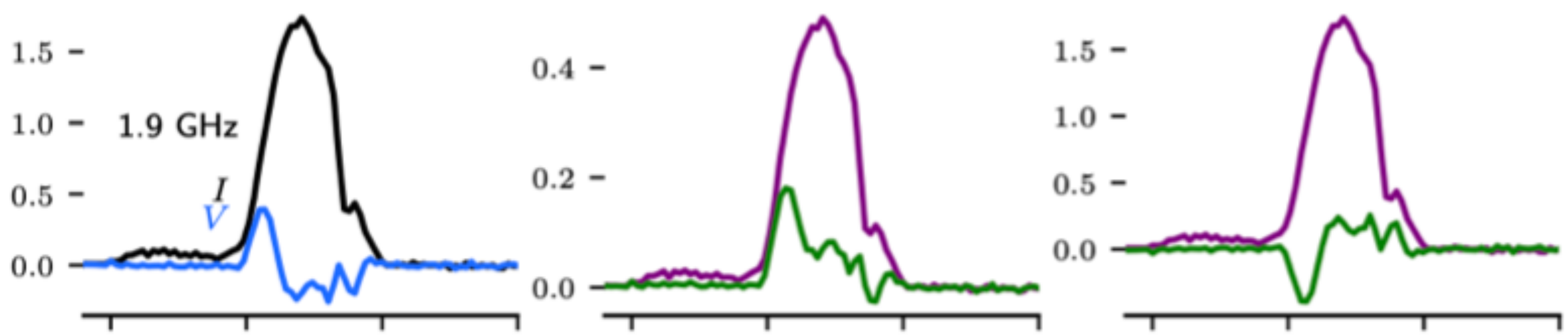
- Need more evidence!

Modelling V

The complicated V profile enable us to distinguish different propagation effects

All spin phase going through the same propagation effect

original profile (when cp behind the psr) | **after circular absorption** | **after Faraday conversion**



Companion behind VS companion in front —> isolated propagation effects

Modelling V Against FREQUENCY