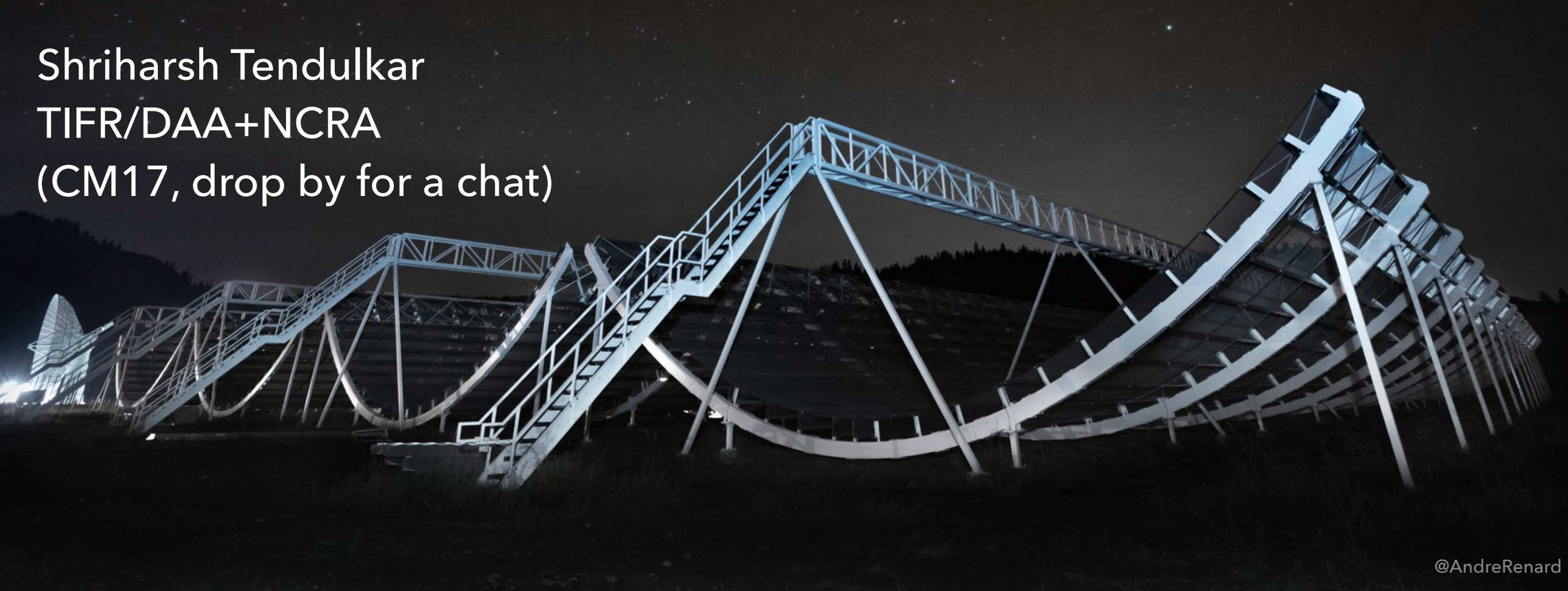
FAST RADIO BURSTS

UNDERSTANDING FRBS THROUGH MULTIWAVELENGTH STUDIES

Shriharsh Tendulkar
TIFR/DAA+NCRA
(CM17, drop by for a chat)



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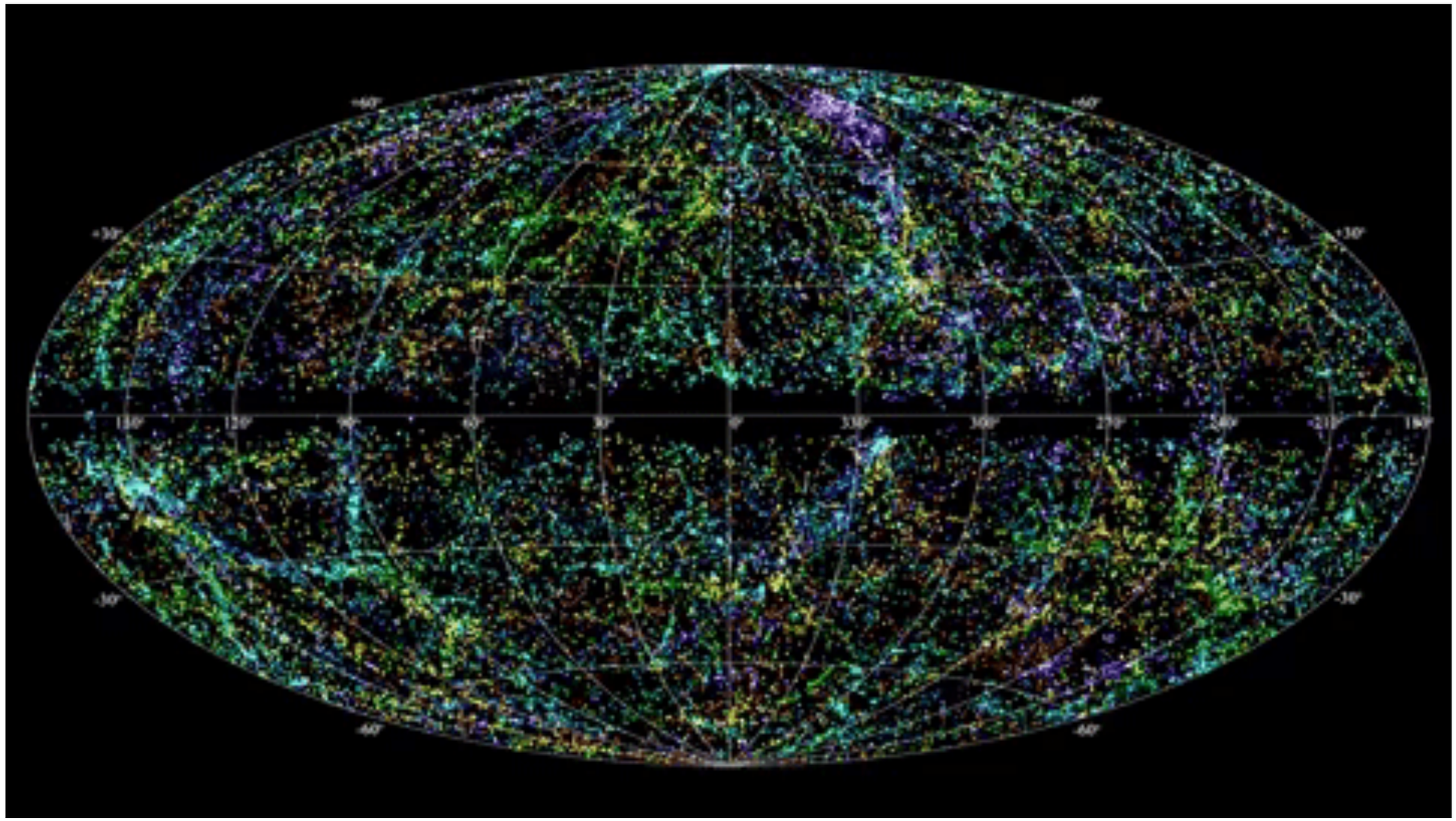
+ VLA/realfast: Casey Law, Geoff Bower ++
+ European VLBI Network: Jason Hessels, Benito Marcote, Cees Bassa ++

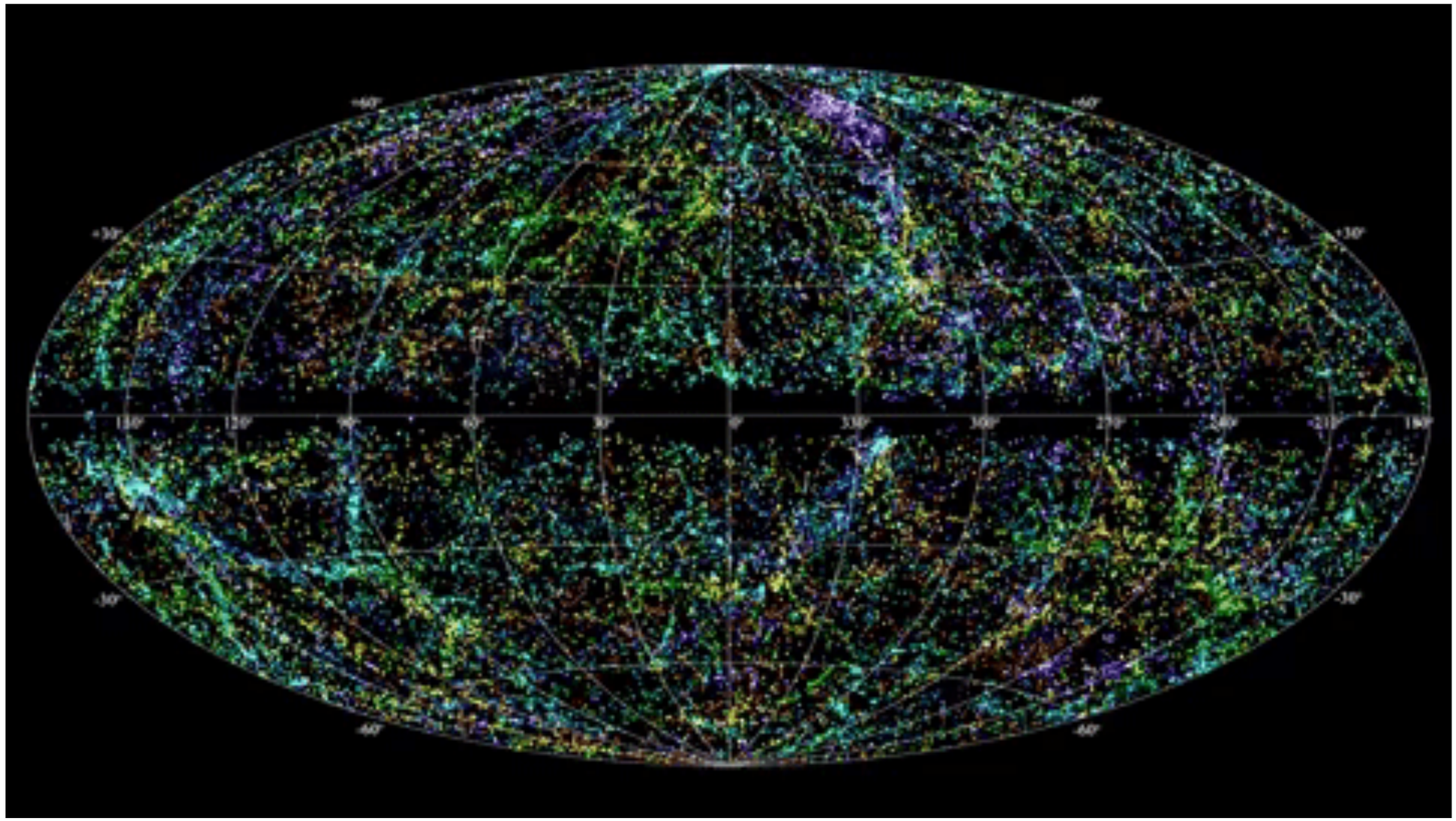
ASTROPHYSICAL MYSTERY!



Short + Bright Radio Emission (few repeat!)

10^3 per sky per day (Lawrence+2017)

ASTROPHYSICAL MYSTERY!



Short + Bright Radio Emission (few repeat!)

10^3 per sky per day (Lawrence+2017)

ASTROPHYSICAL MYSTERY!

- Dispersed: arrival time is freq dependent

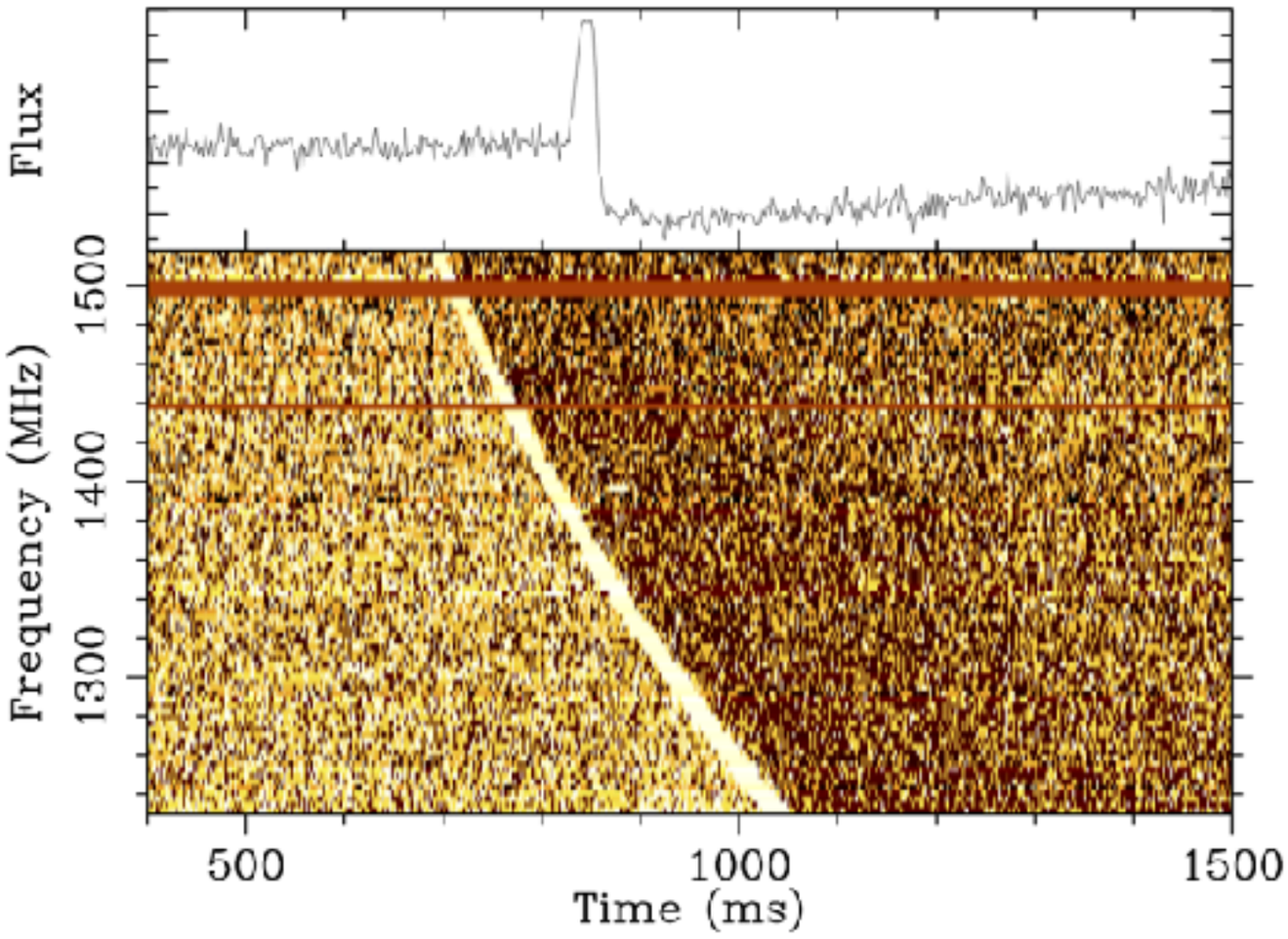
  $t_{arr} \propto DM\ \nu^{-2}$

- Dispersion measure

  $DM = \int n_e dl$

- DM not apriori known
  - Computationally expensive search
- Proxy for distance

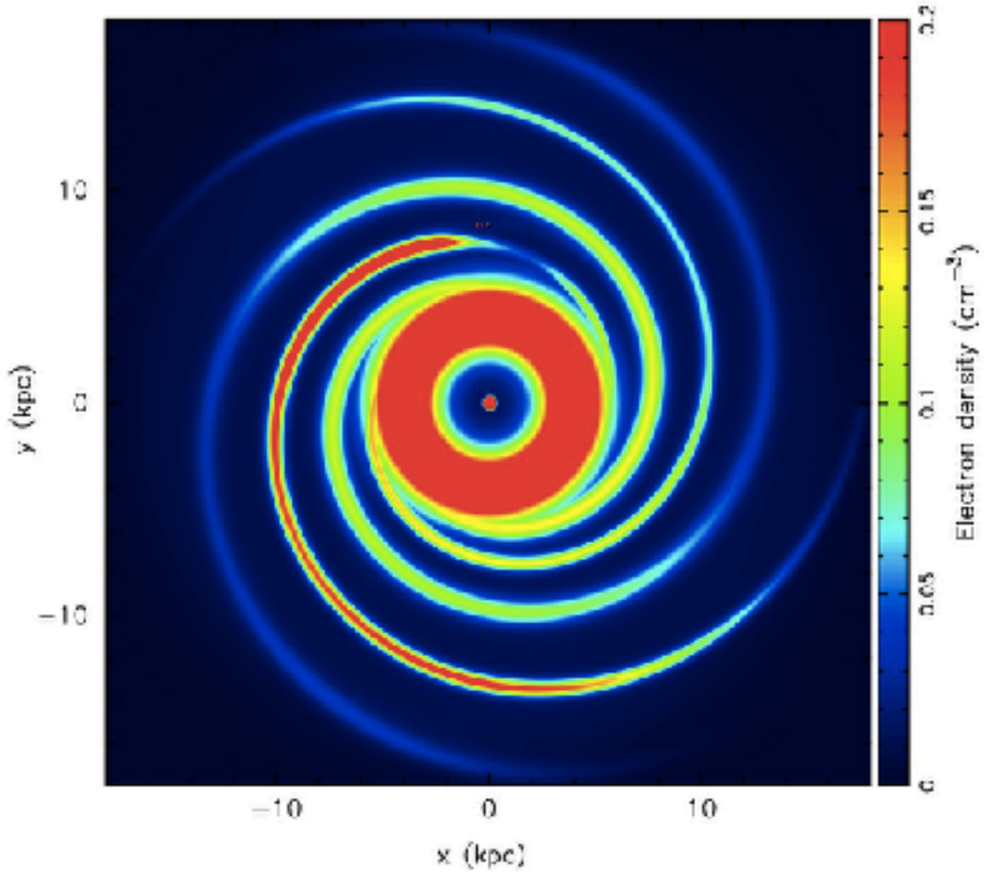
  (after subtracting MW DM)



Lorimer et. al. 2007
(Fig from Petroff et al 2019)

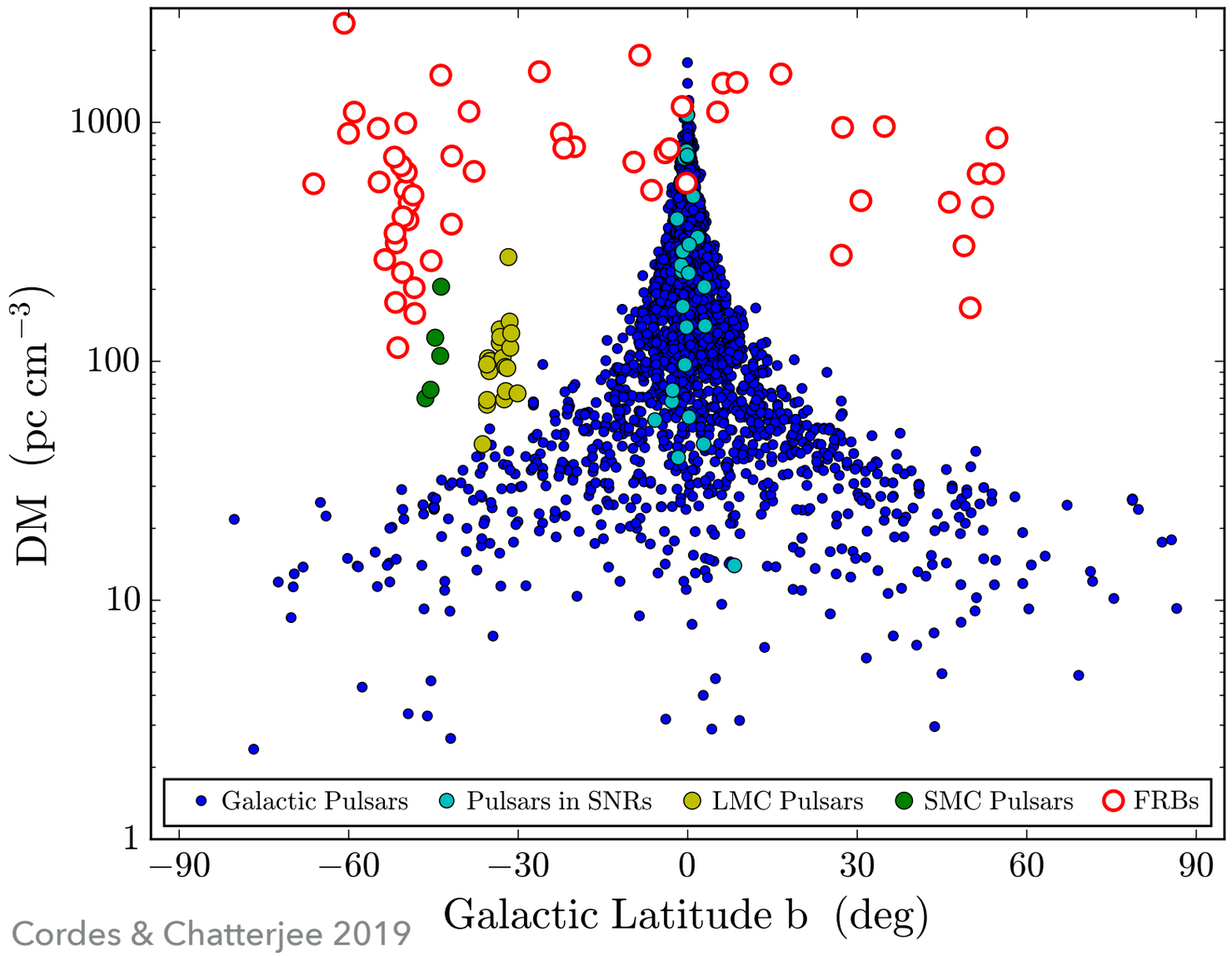
EXTRAGALACTIC LOCATIONS

Electron Distribution in the Milky Way



Yao et al 2017

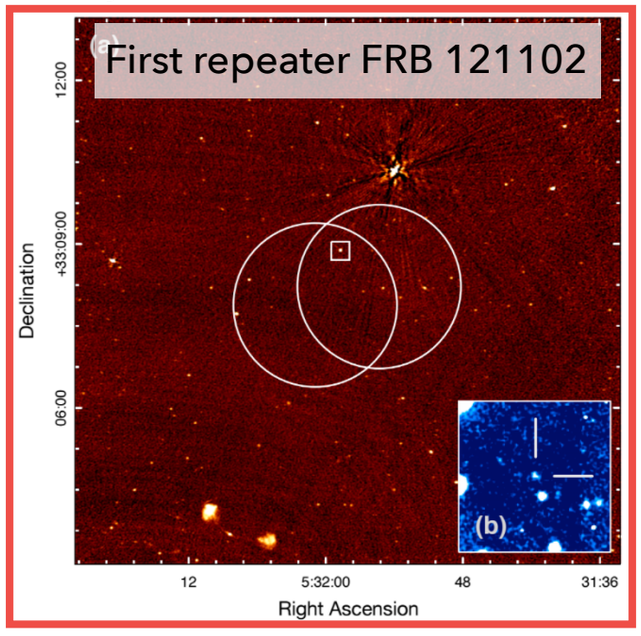
Halpha, continuum radio observations rule out local DM contributions

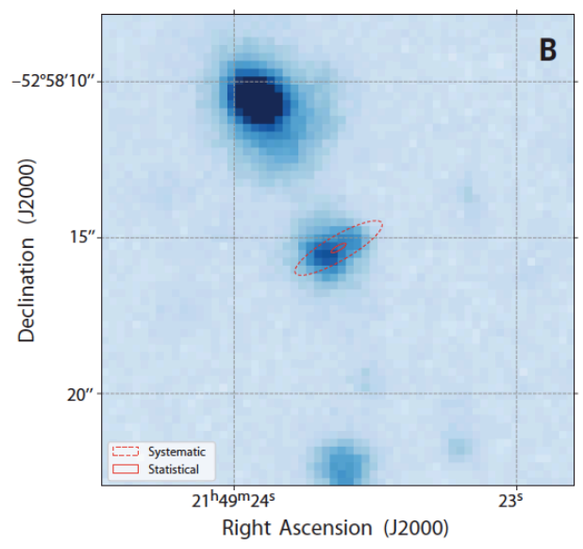


Cordes & Chatterjee 2019

EXTRAGALACTIC LOCATIONS

Chatterjee .. SPT et al 2017 z = 0.19732





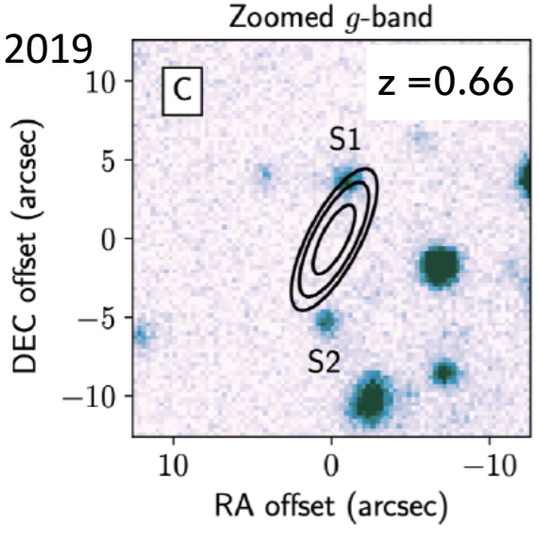
Prochaska et al. 2019

z =0.47

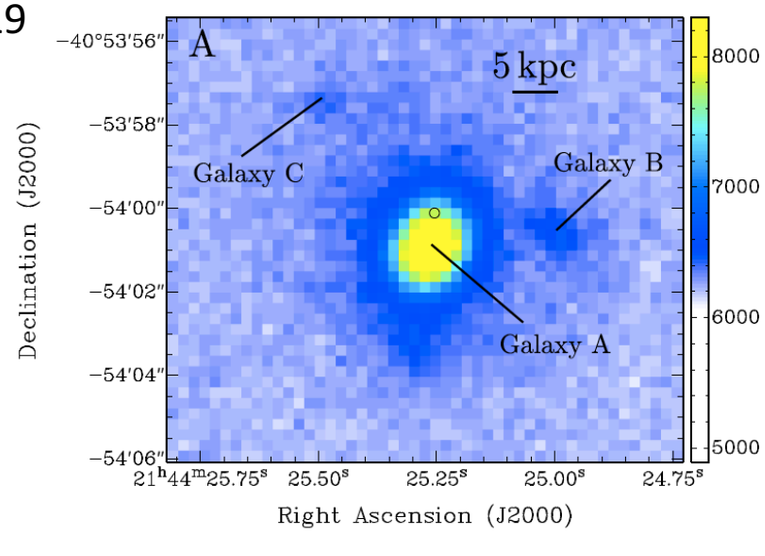
6 localizations:

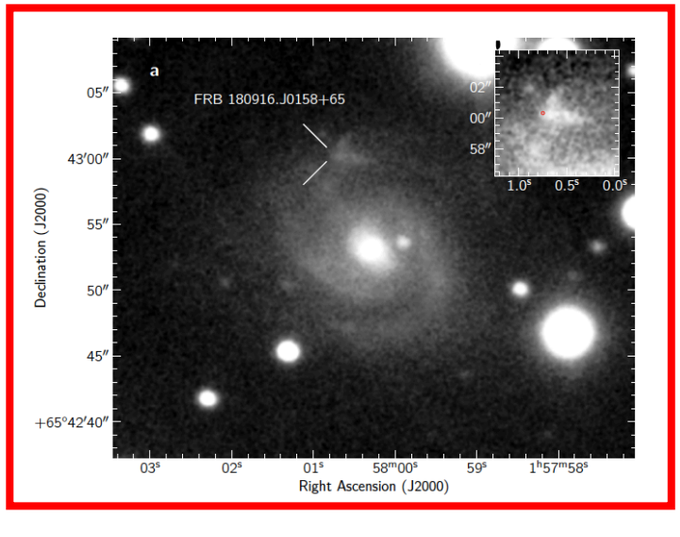
- 2 repeaters
  1 dwarf, 1 spiral
- 4 (thus far) non-repeaters
  3 elliptical-type
  1 spiral

Ravi et al. 2019



Bannister et al. 2019 z = 0.32





Marcote .. SPT et al 2020

z =0.03 (150 Mpc)

ENERGETICS

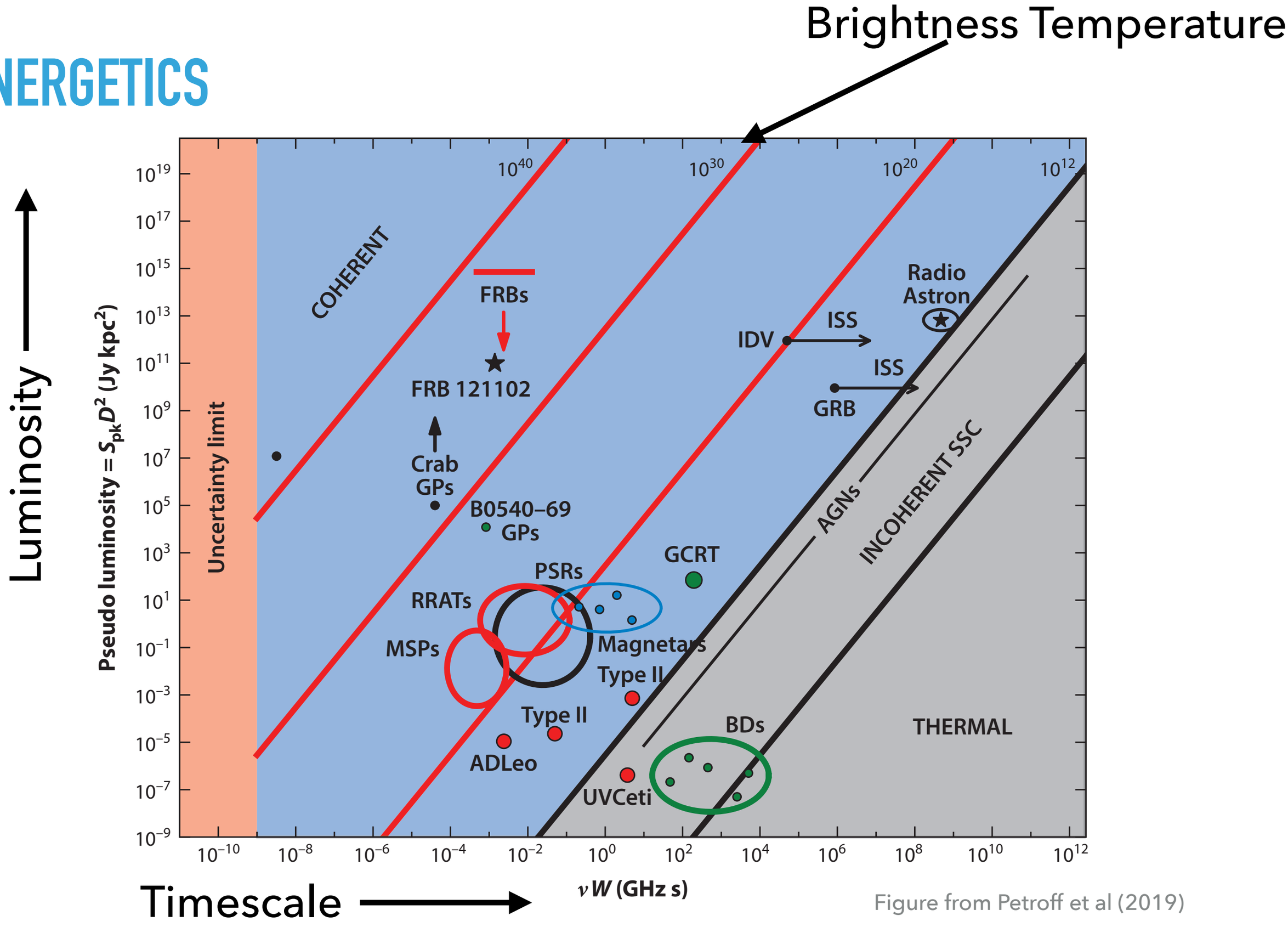
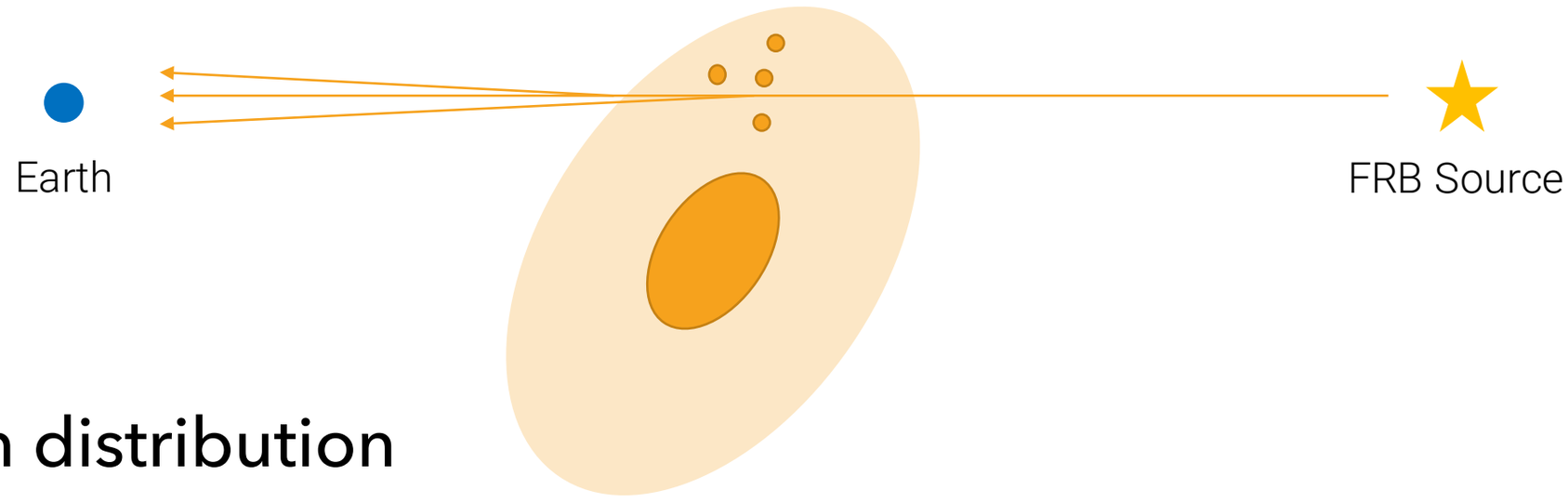


Figure from Petroff et al (2019)

COSMOLOGICAL PROBES

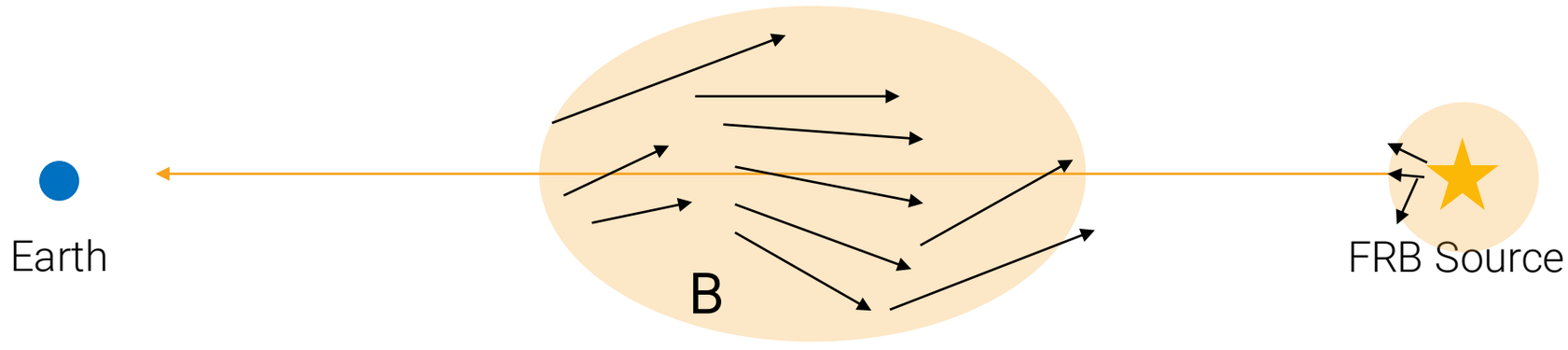
- Polarized radio waves
- Interacts with every electron and B-field



- Turbulence, baryon distribution
  - Hell reionization at z~3
- Magnetic field distributions
- Gravitational lensing

COSMOLOGICAL PROBES

- Polarized radio waves
- Interacts with every electron and B-field



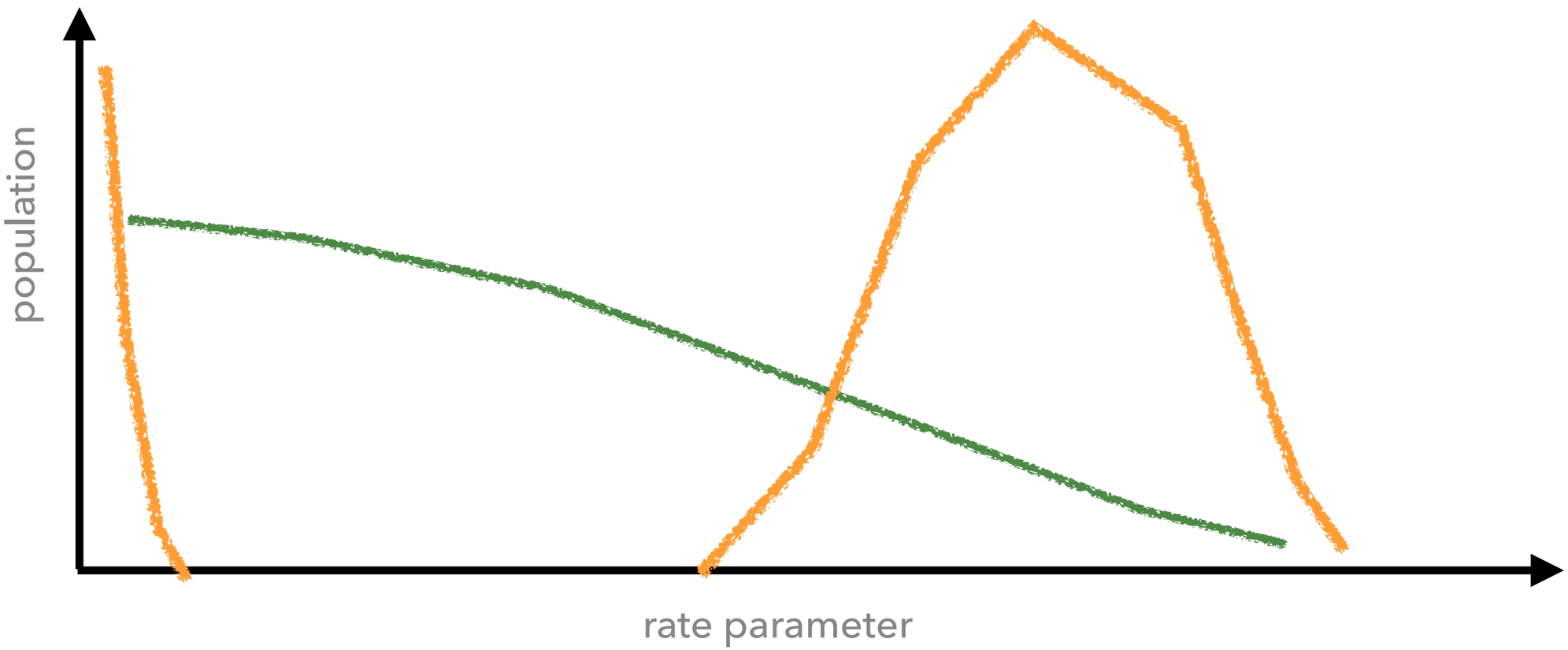
Also probe environments around the FRB (Michilli+ *Nature* 2018)

- Turbulence, baryon distribution
  - Hell reionization at z~3
- Magnetic field distributions
- Gravitational lensing

REPEATERS AND NON-REPEATERS

- Some FRBs repeat – same position, almost the same DM
  Most FRBs haven't been seen to repeat
  Despite ~10^1 – 10^3 hrs of obs

- Are they different populations? or different ends of the same population?



WHAT ARE THEY?

- ~10^{10-12} times brighter than Crab giant pulses

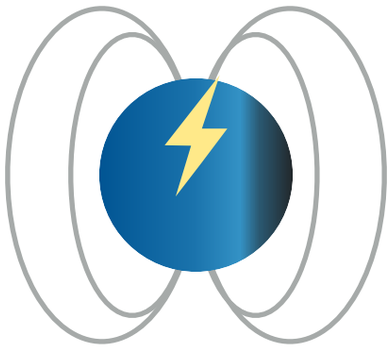
http://frbtheorycat.org Platts .. SPT et al 2019

Fuel	Engine	Transmission
(stores energy)	(sources energy)	(converts energy to EM)
Magnetic Field	Magnetic Reconnection	Synchrotron Radiation
Rotational Energy	Magnetic Acceleration	Curvature Radiation
Kinetic Energy	Shocks	
Gravitational Potential		

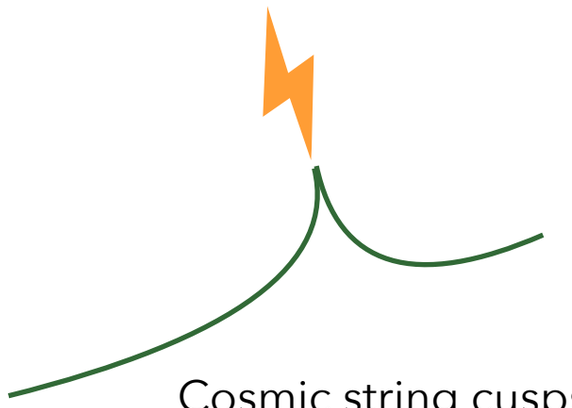
WHAT ARE THEY?

- ~10^{12} times brighter than Crab giant pulses
- Magnetar? NS Binary? More exotic?

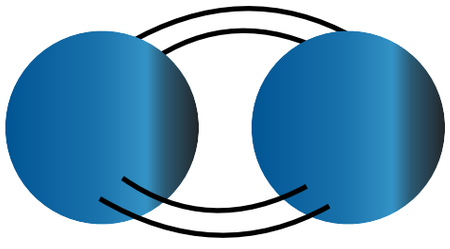
http://frbtheorycat.org Platts .. SPT et al 2019



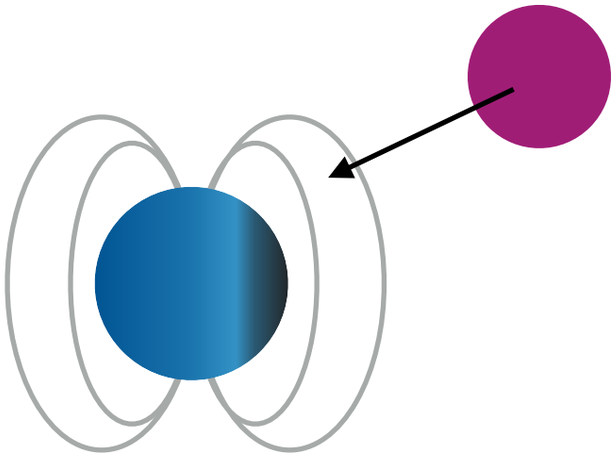
Magnetic field reconnection/ star quake



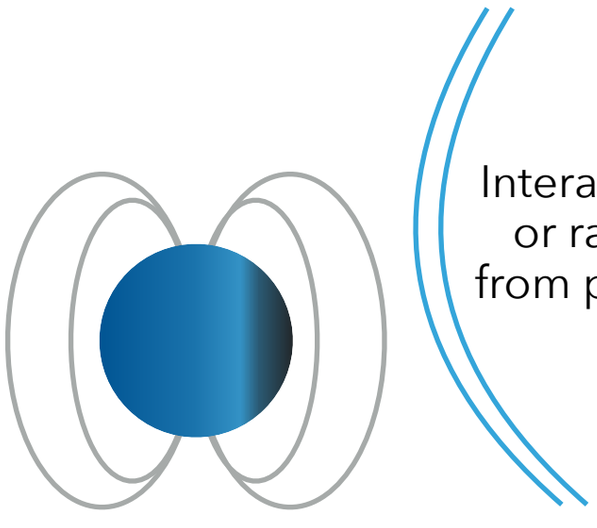
Cosmic string cusps



Merger/Coalescence



Interaction with asteroid/ axion nugget



Interaction with winds or radiative shocks from pulsars, OB stars, AGNe

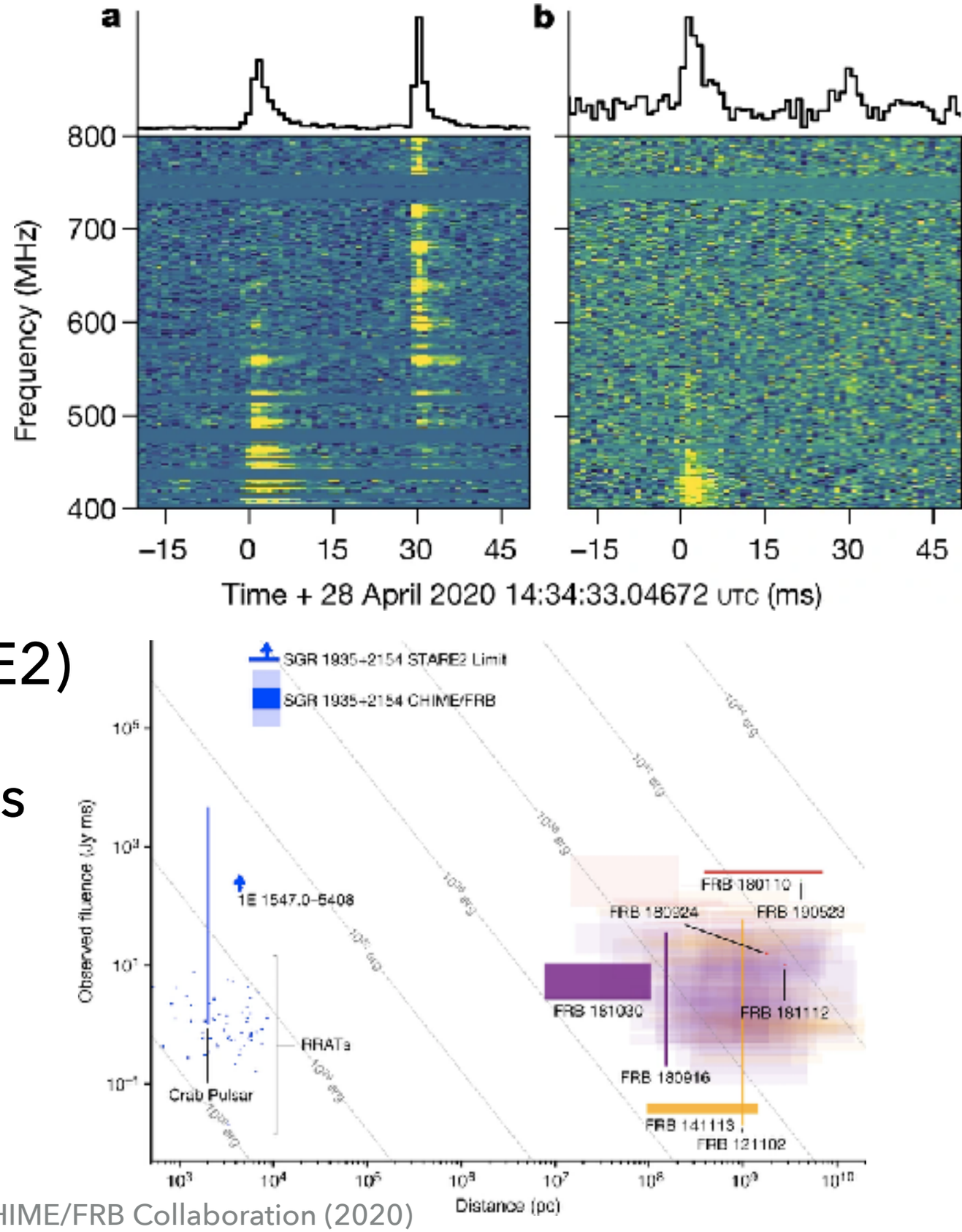
A GALACTIC "FRB"

- Since Nov 2019:
  SGR 1935+2154 active
  X-ray flares/bursts

- 28th April 2020: CHIME/FRB detected a very bright radio burst (also detected by STARE2)

  - Lower end of the energetics

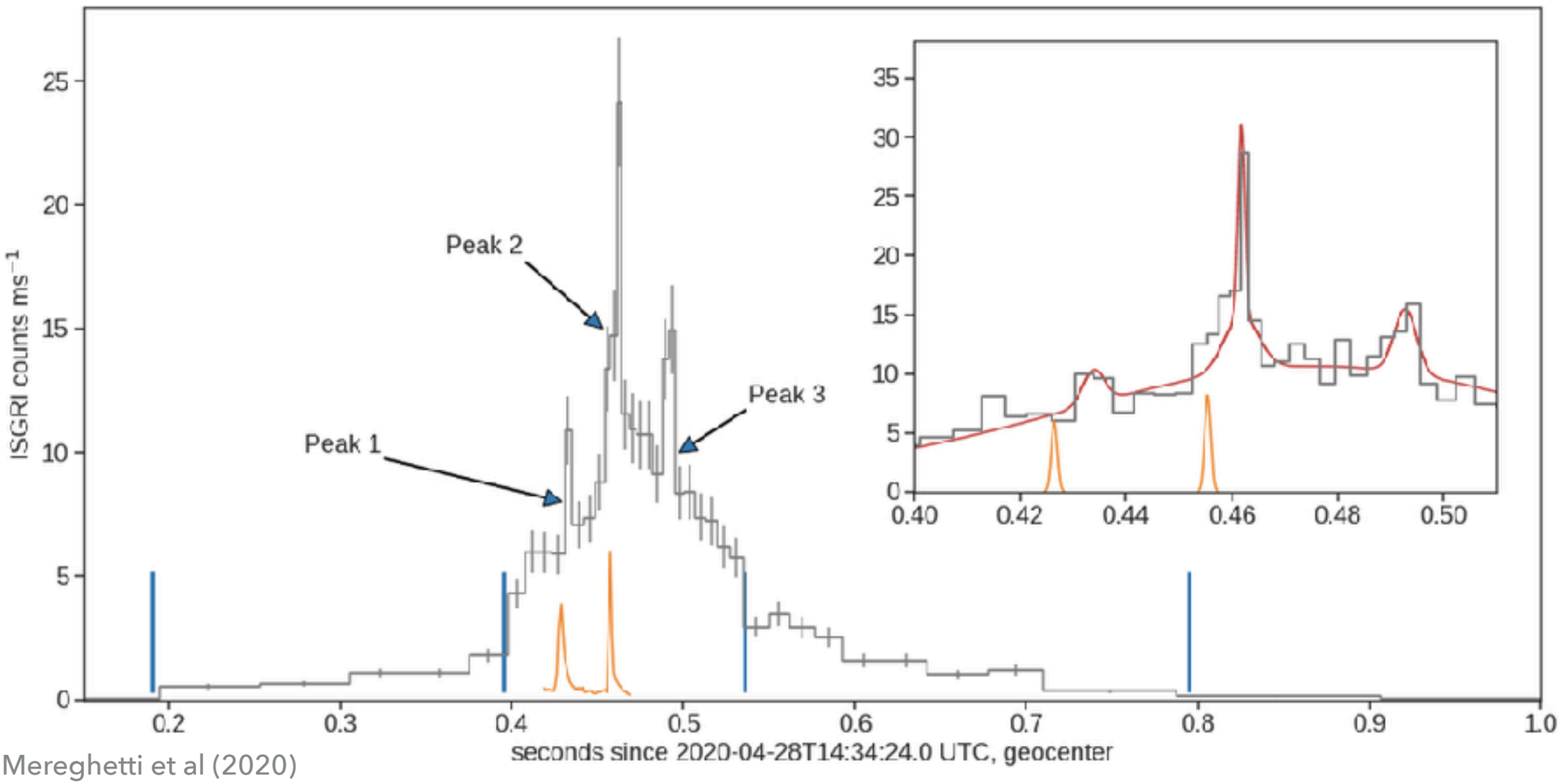
- First FRB from a canonical magnetar



CHIME/FRB Collaboration (2020)

A GALACTIC "FRB"

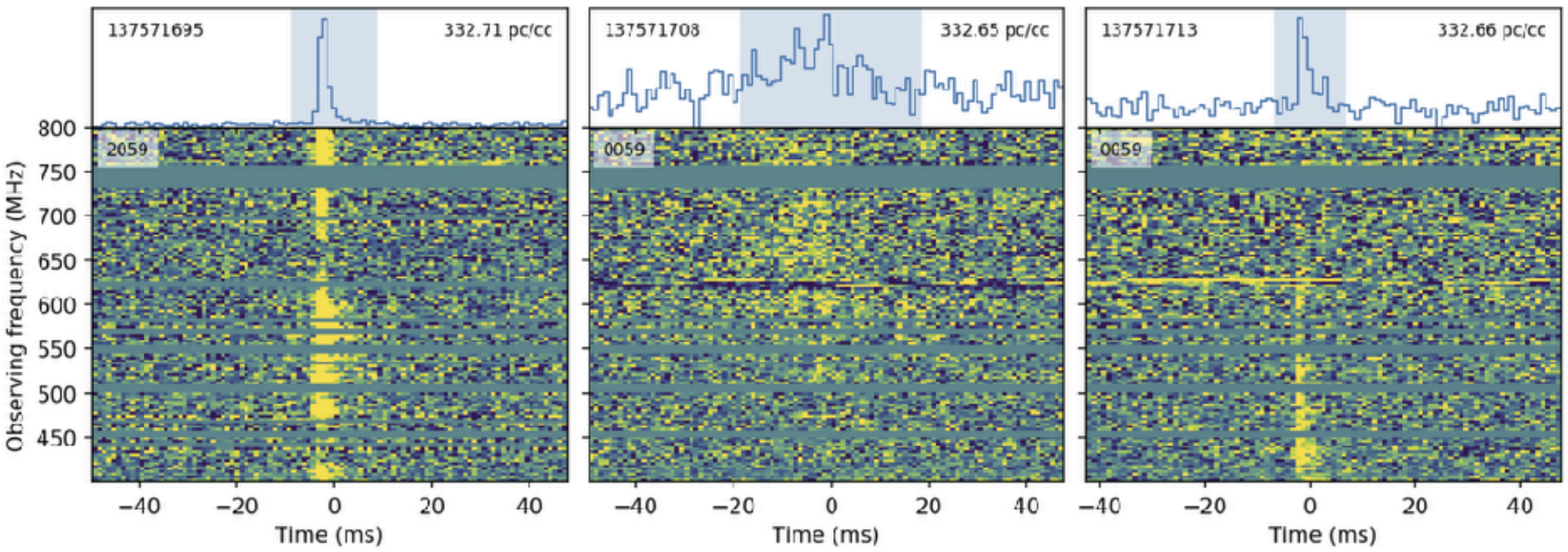
- Multi-peaked 'hard' X-ray burst just after radio



Mereghetti et al (2020)

A GALACTIC "FRB"

- Multi-peaked 'hard' X-ray burst just after radio
- BUT – many other X-ray bursts w/o radio (CHIME/FRB Coll 2020, Lin et al 2020)
- Many radio bursts w/o X-ray (CHIME/FRB Coll. 2020, Kirsten et al 2020)



SO DOES THAT SOLVE ALL OUR PROBLEMS?

- SGR 1935+2154-like magnetars likely don't explain all FRBs
- The occurrence rate may be consistent with the volumetric rate as a population
- But individual FRBs (repeaters and non-repeaters) have behavior/activity that SGR 1935+2154 (or other magnetars) have not replicated

MAGNETARS & "MAGNETARS"

- Canonical Galactic magnetar (Duncan & Thomson 2003)
- Extremely temperamental
  Show high energy transients
  - Flares, Giant flare
    Outbursts
- Complex magnetic field
  Dipolar field can be lower (10^{12} G)
- 10-20% of core-collapse rate
  (~24 in MW)

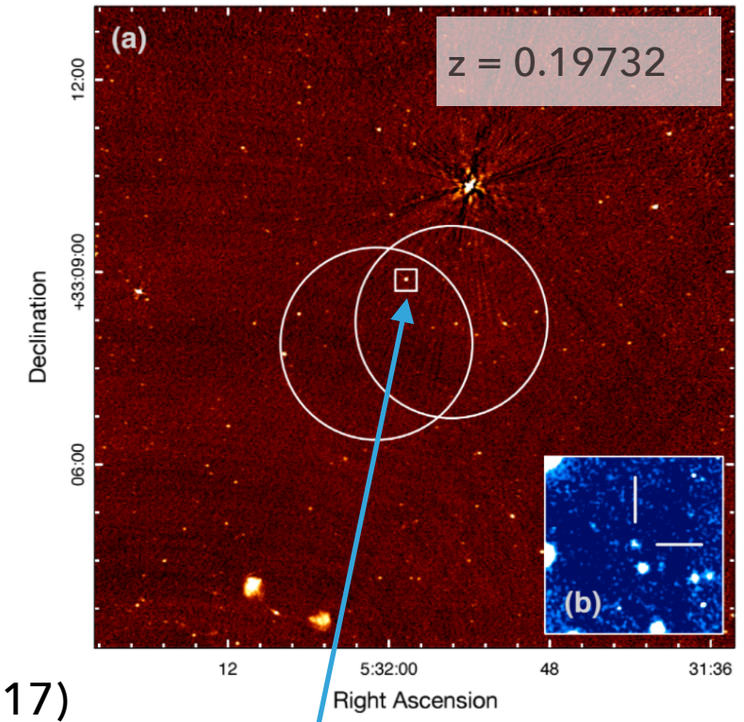
- Millisecond magnetars
  (Long GRBs, SLSNe-I)
- Need an extremely high dipolar field ($10^{15\text{-}16}$ G)
- No need for temperamental behaviour, complex fields
- RARE
  Birth rate ~ 10^{-4} of CCSN rate
- Prefer low metallicity environments

THE ENVIRONMENTS OF FRBS AND WHAT THEY CAN TELL US

FRB 121102 (2016–2017)

- Most FRBs were localized to ~few arcmin
- The first repeater (FRB 121102) detected by Arecibo (RIP) –> localized with the JVLA
- Low metallicity dwarf galaxy host (Tendulkar et al 2017)
- Why is it in a dwarf 10^4x less massive than MW?
- Low metallicity –> long GRBs and superluminous supernovae (SLSNe-I)

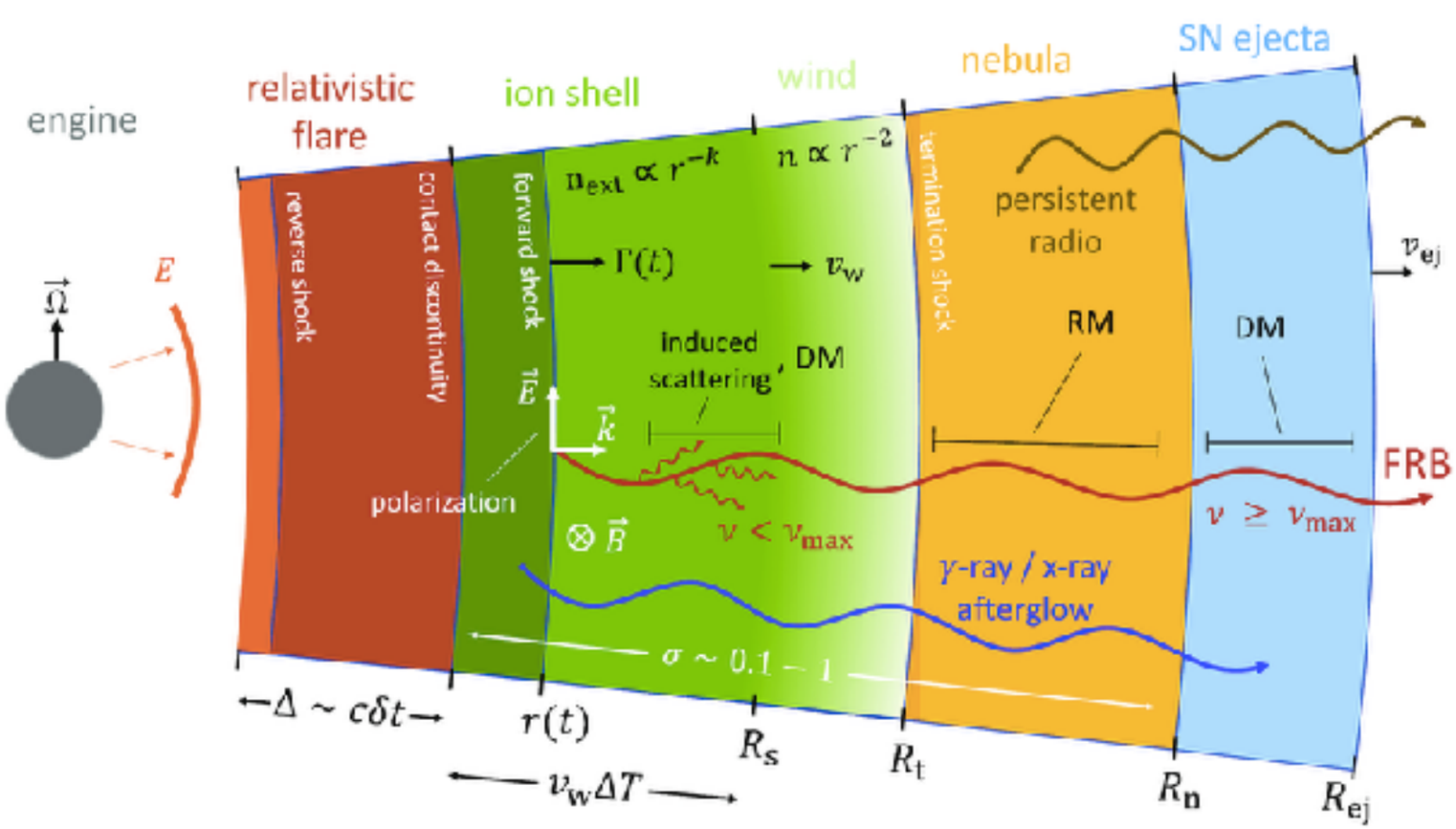
Chatterjee .. SPT et al 2017



Co-located with a very bright persistent radio source:
$\nu L\nu \sim 10^{38}\,\mathrm{erg\,s^{-1}}$

MILLISECOND MAGNETAR MODEL

- LGRBs/SLSNe-I are thought to have millisecond magnetar engines
- If these also have flares could produce FRBs
- Also explains persistent radio source (nebula)

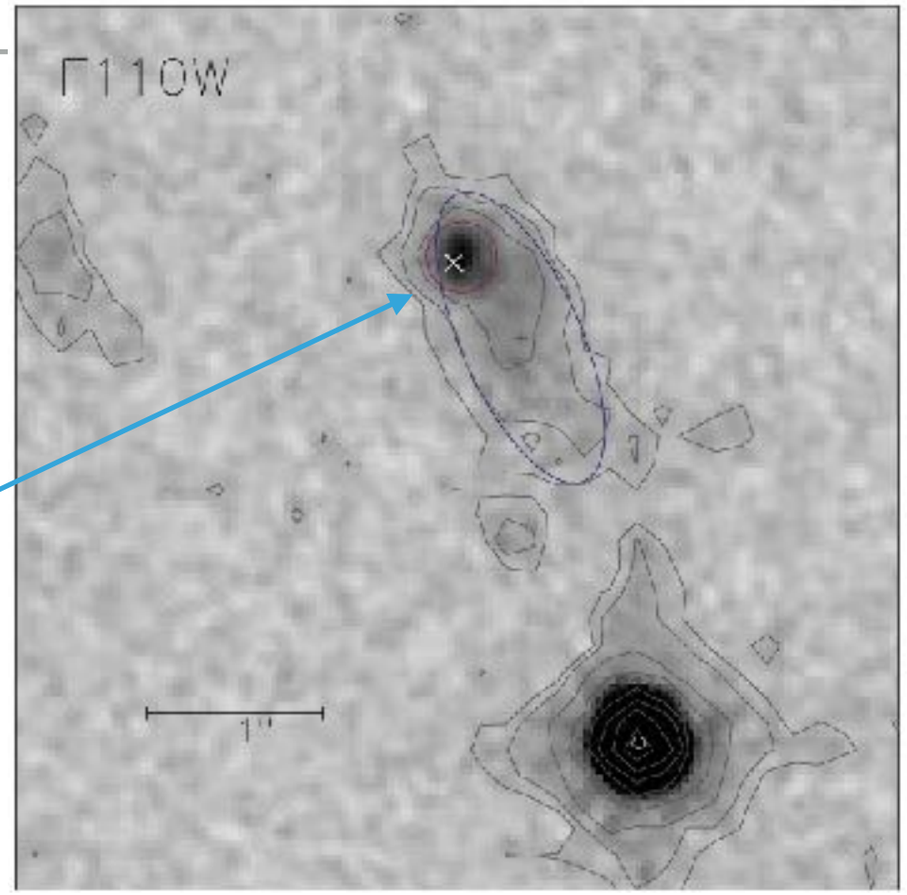


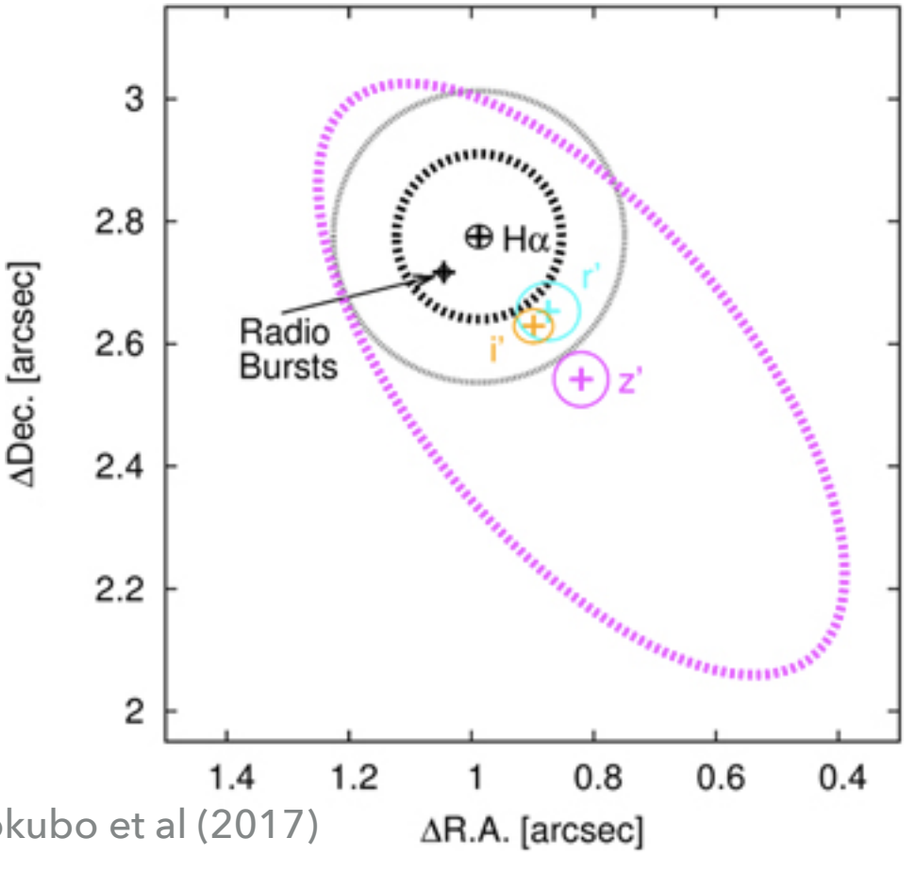
Metzger et al (2019), Margalit et al (2018)

POSITIONAL OFFSET

- VLBI position (5 mas; Marcote…SPT et al 2017)
- Near a star-forming knot in an irregular galaxy (Bassa, SPT et al 2017)
- AO imaging (Kokubo et al 2017)
- 260 pc offset between the peak star forming region

Bassa et al (2017)





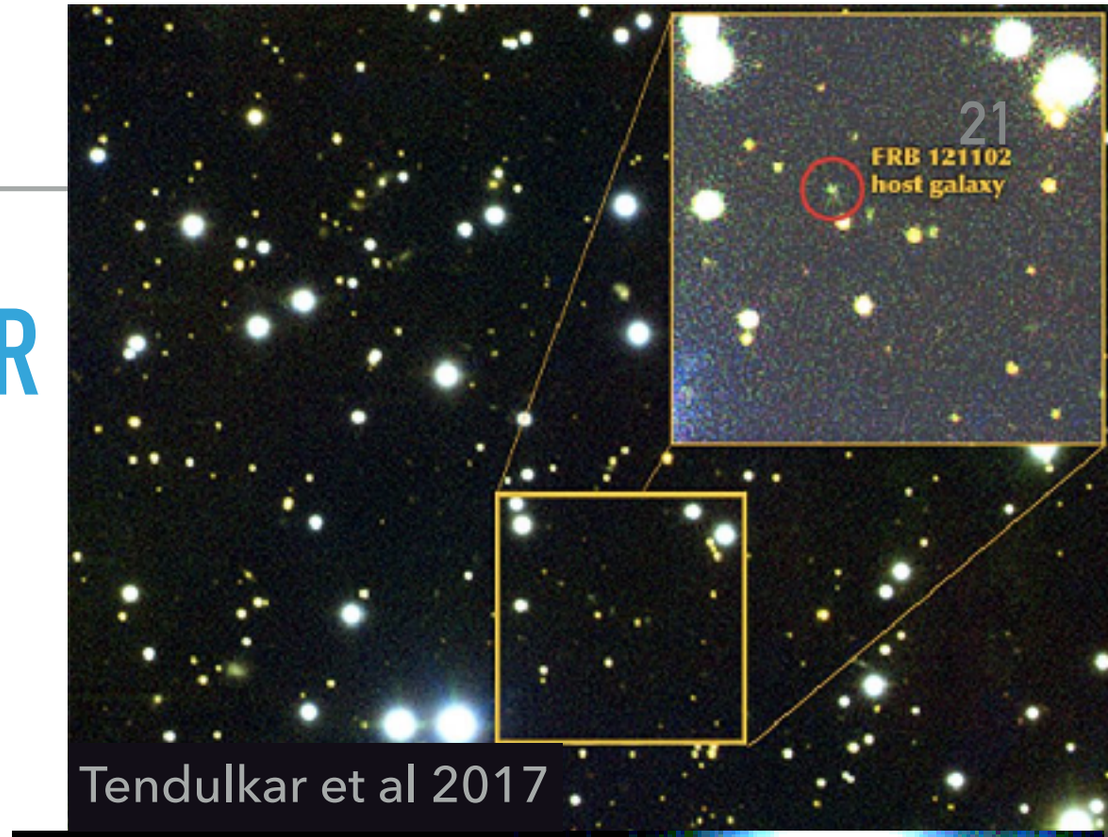
Kokubo et al (2017)

LOCALIZATION OF A NEARBY REPEATER

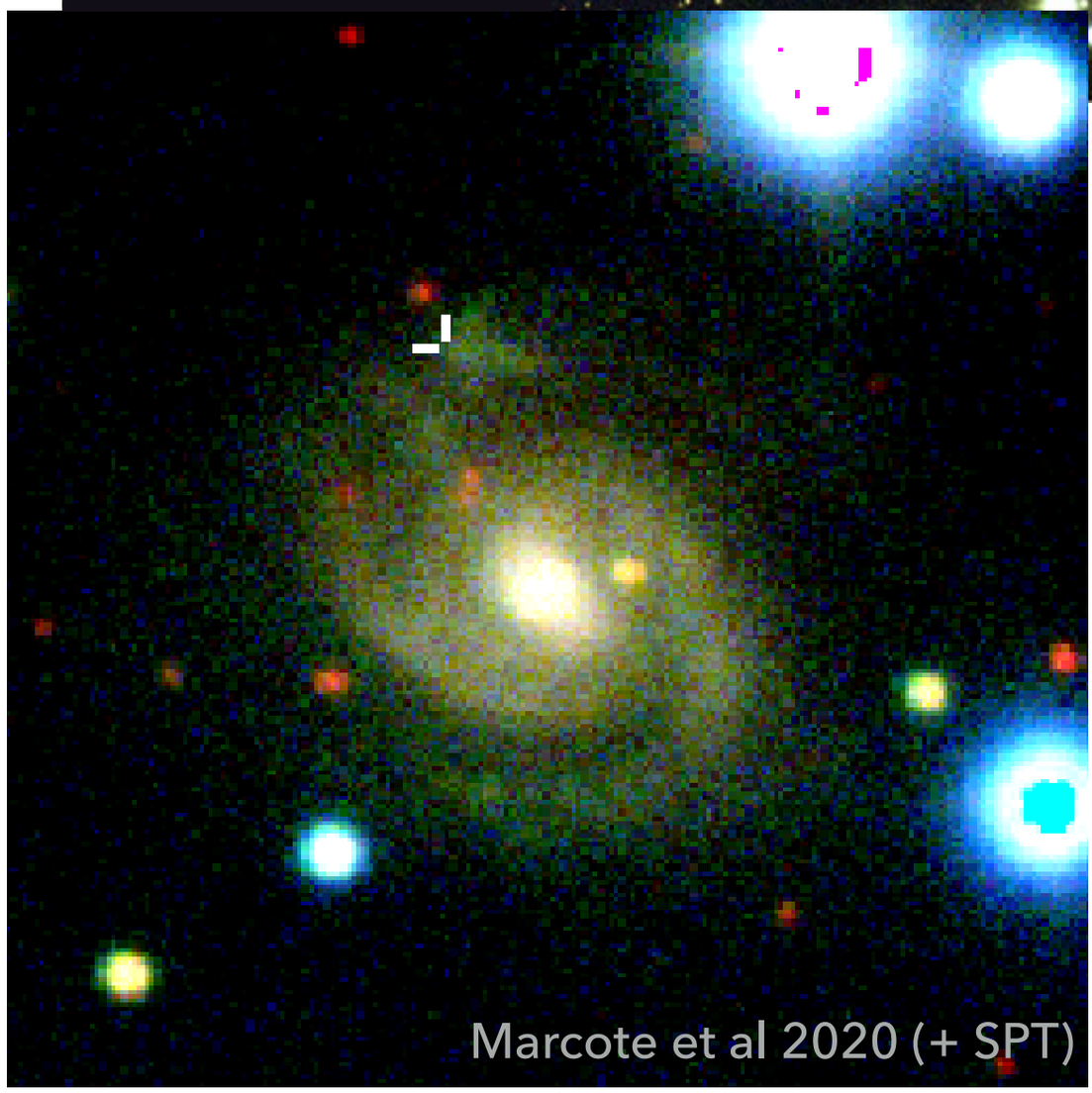
- FRB 180916 –> repeater detected by CHIME/FRB

- Using VLBI, localized R3 to a galaxy at 150 Mpc
  (Marcote et al 2020, 2 mas!)

- The nearest FRB yet.
  Very different galaxy from the first repeater

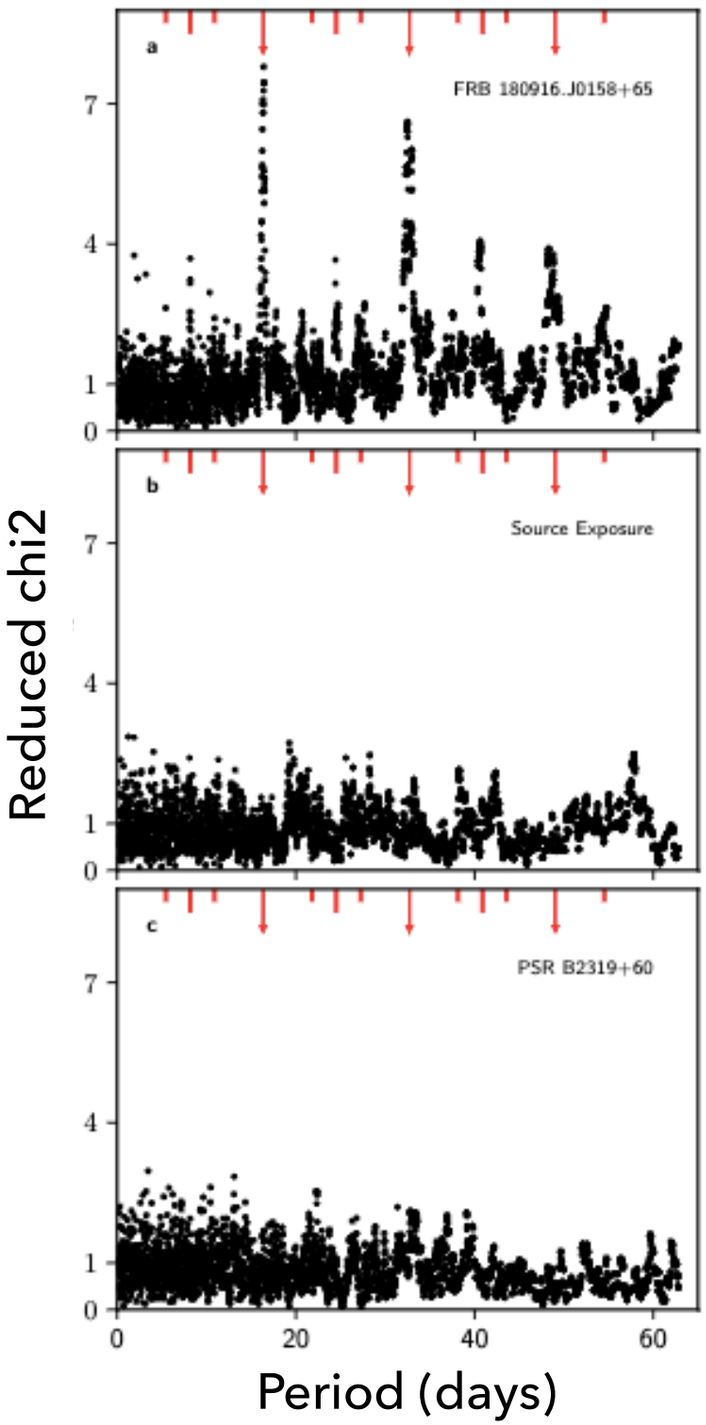


Tendulkar et al 2017



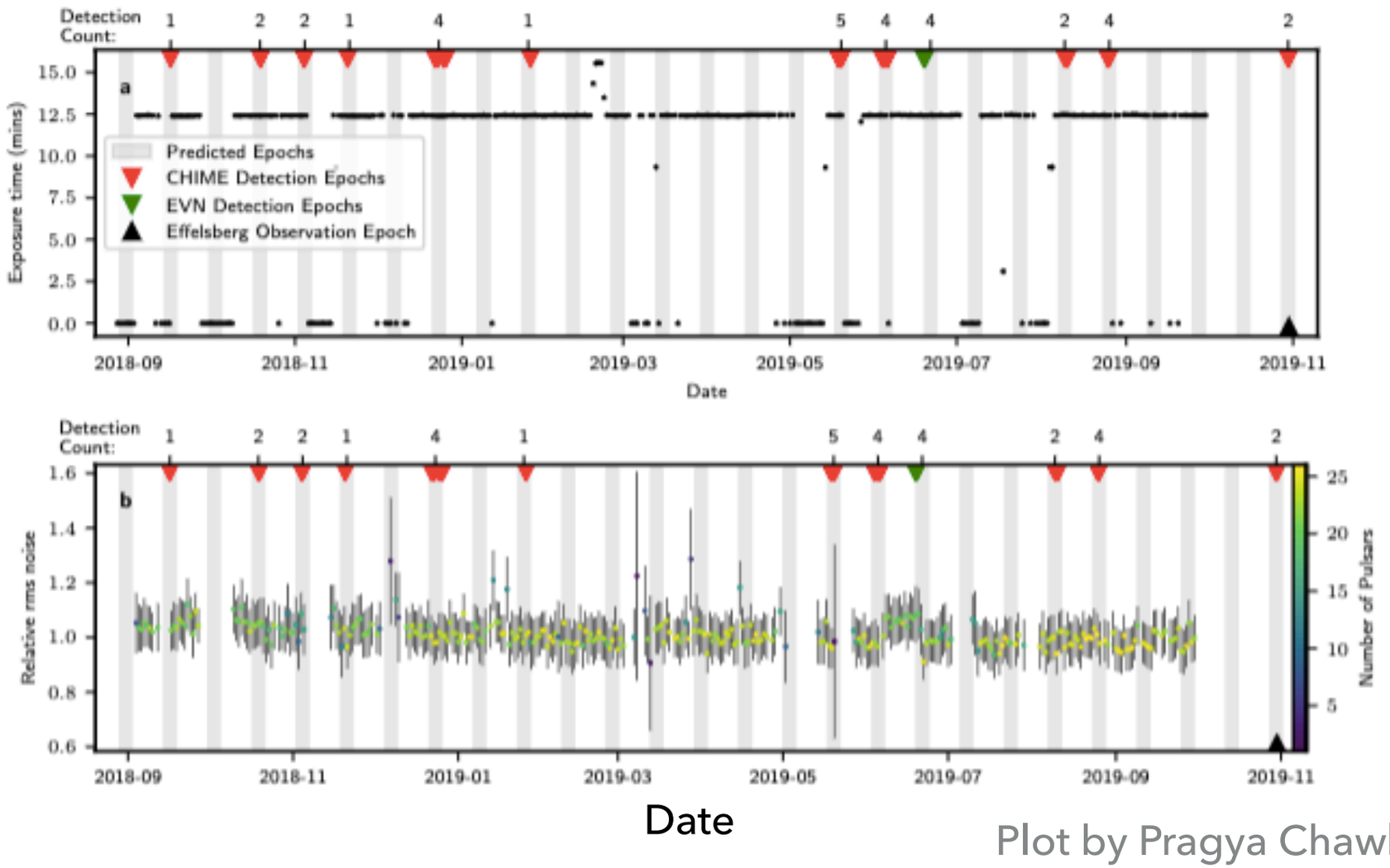
Marcote et al 2020 (+ SPT)

PERIODIC BURST ACTIVITY FROM FRB 180916 (R3)



Plot by Dongzi Li, Hsu-Hsien Lin

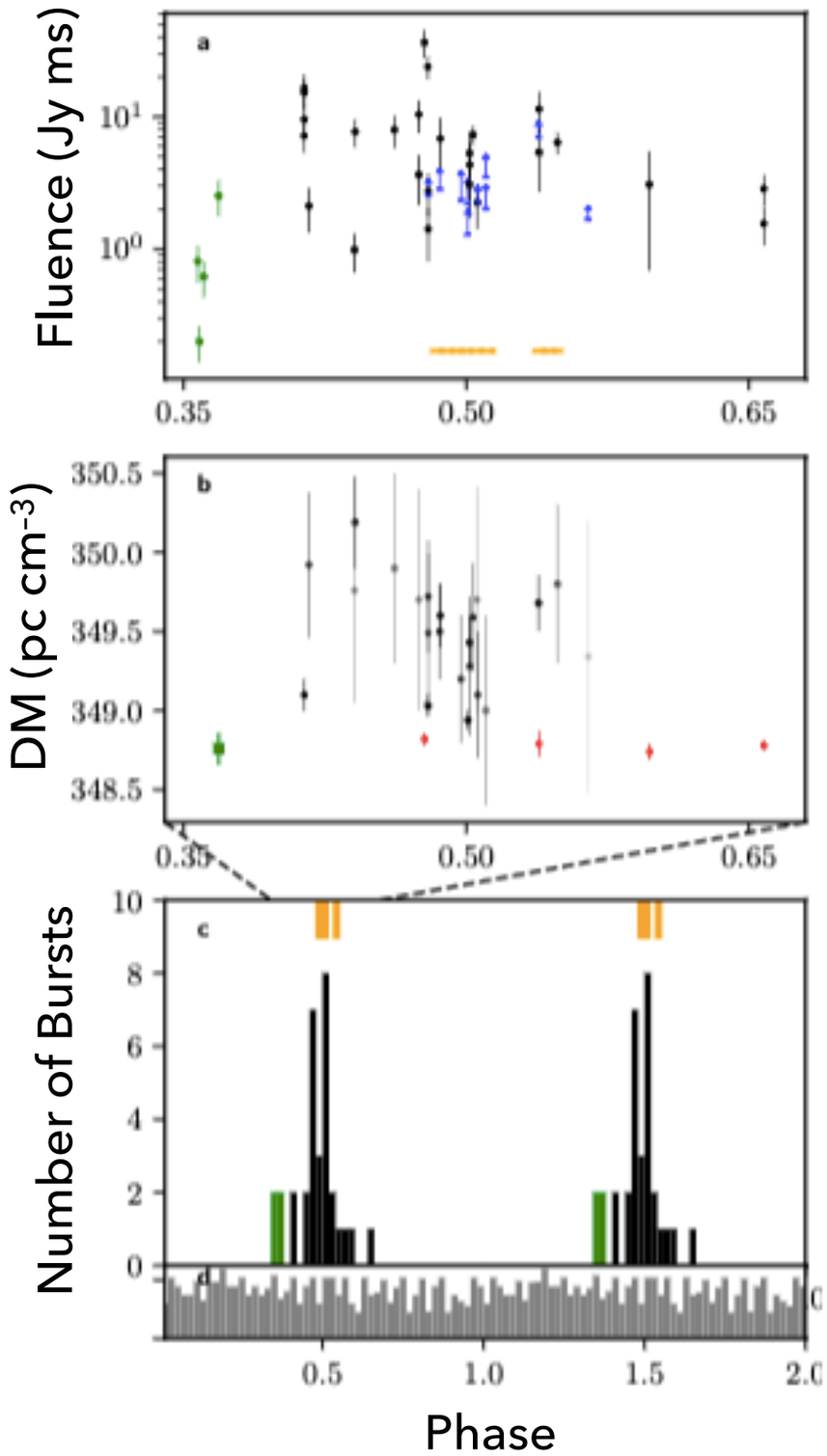
CHIME/FRB Collaboration (2020)



Plot by Pragya Chawla

PERIODIC BURST ACTIVITY

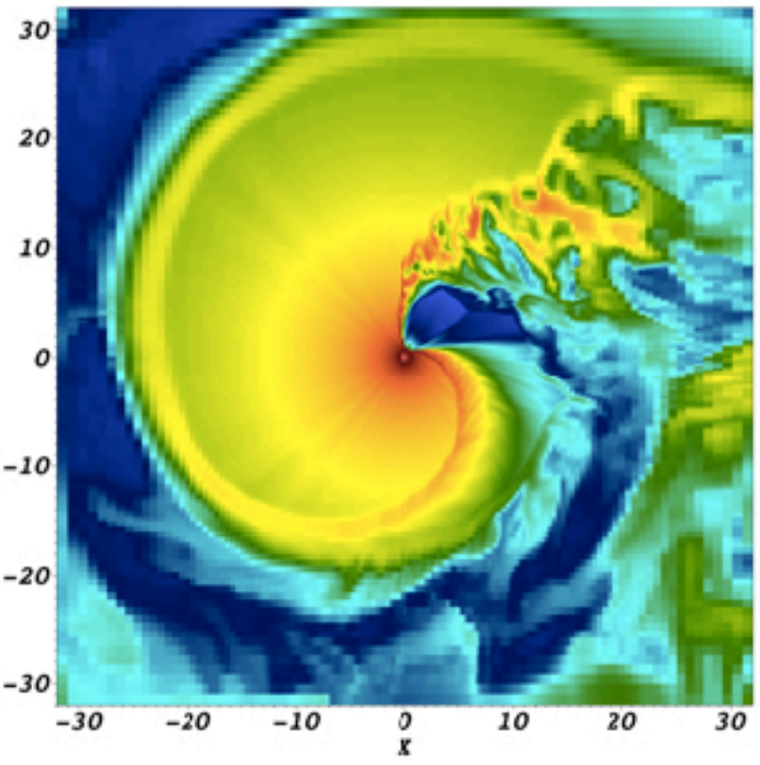
- Source shows activity at 16.35 day period
- Bursts arrive in a 4 day window (at 400-800 MHz)
- Duty cycle is not 100%
- Timescale – rotation? orbit? precession?
  - Is there another underlying periodicity?

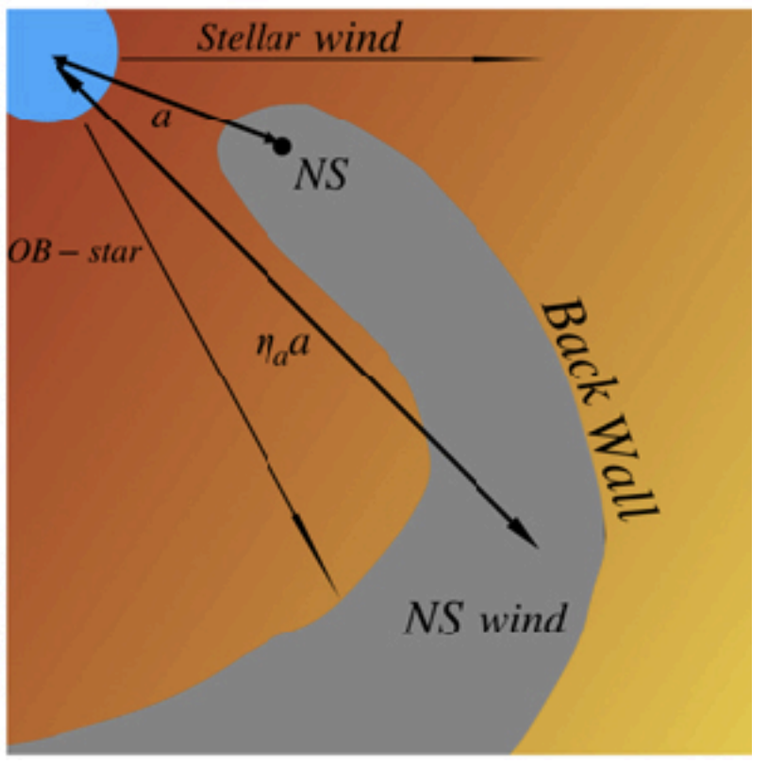


Plot by Bridget Anderson, Ziggy Pleunis, Dongzi Li

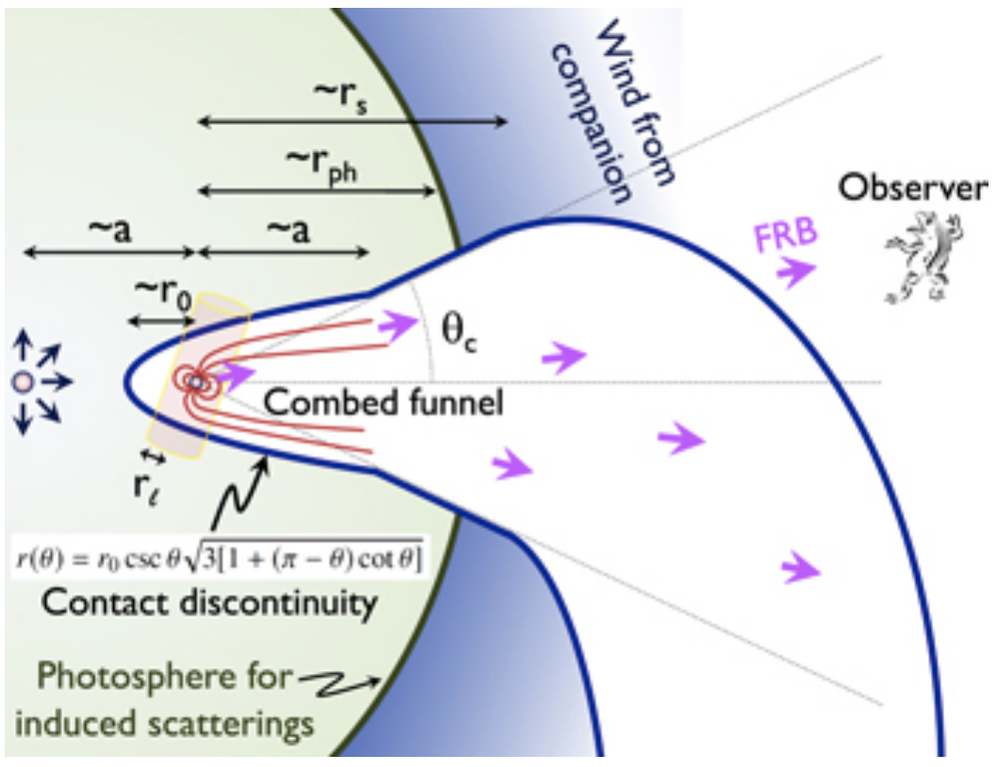
MODELS

Orbital Period





Pulsar in orbit around an OB star: Lyutikov et al (2020).
Simulations from Bosch-Ramon et al. (2015)

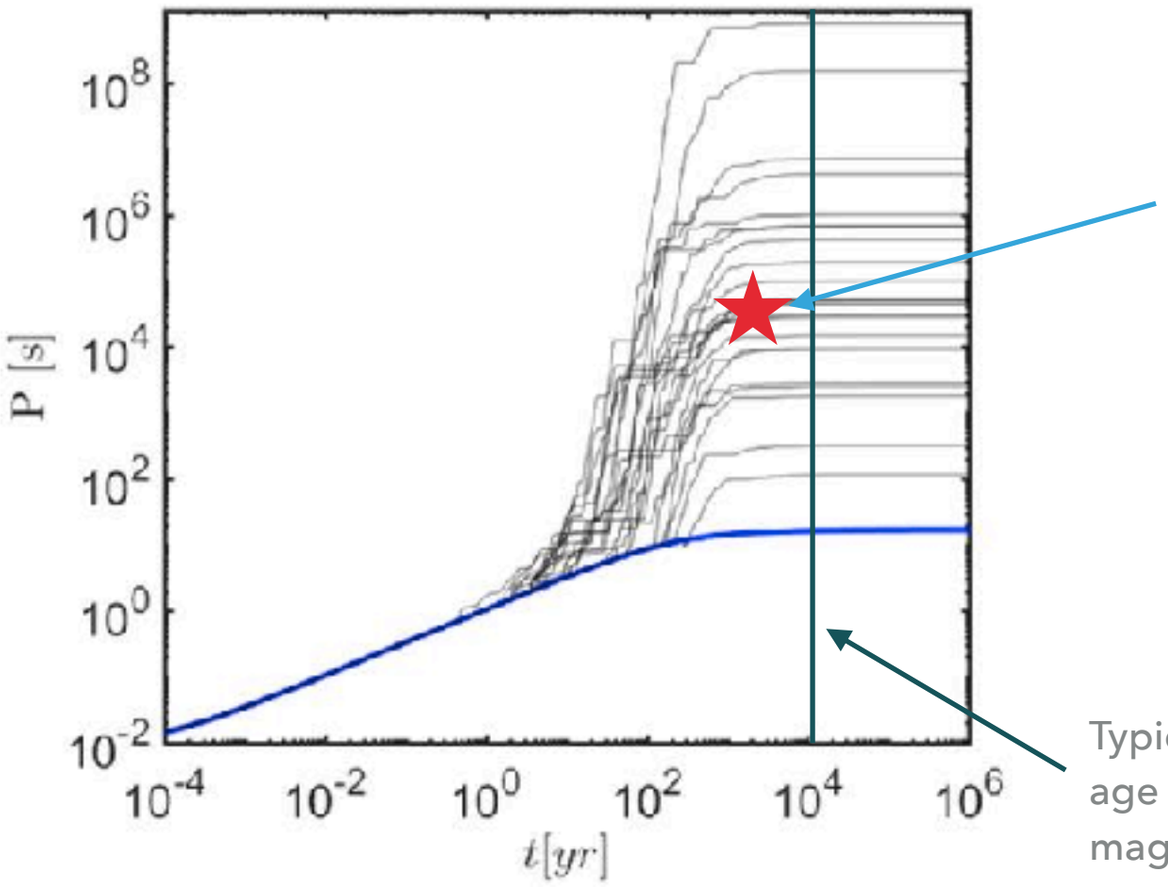


Similar model: Ioka & Zhang(2020).

Certainly possible, HMXBs, Gamma-ray binaries, have few day to 100-day periods

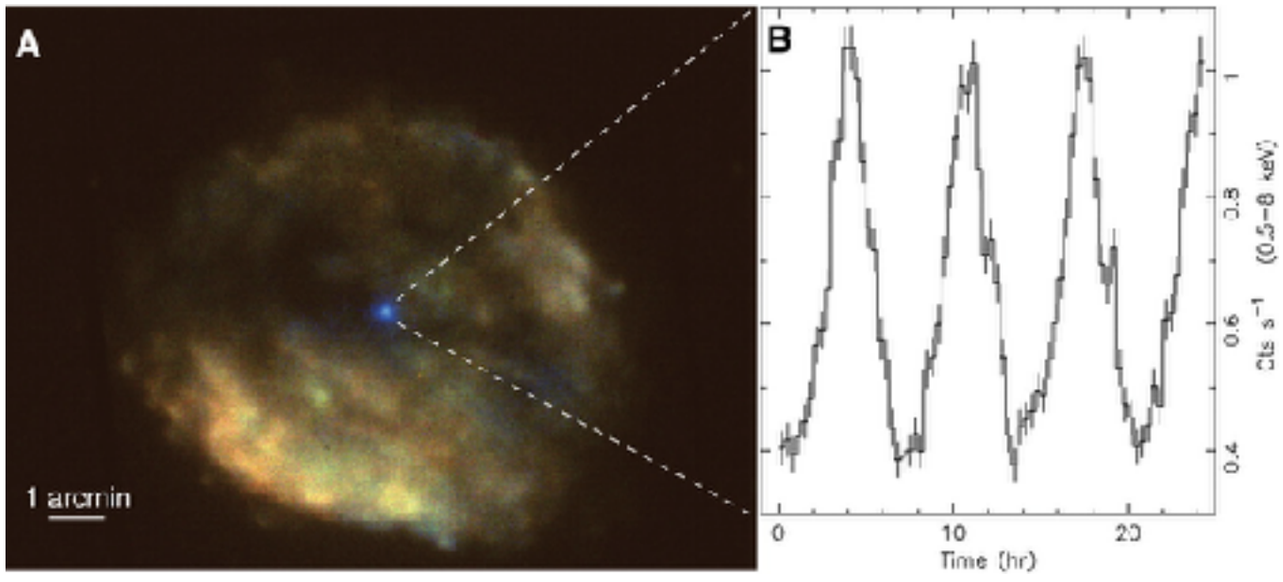
MODELS

Rotation Period of isolated magnetar



Ultra-long period magnetars (Beniamini et al 2020)

Typical active age for Galactic magnetars

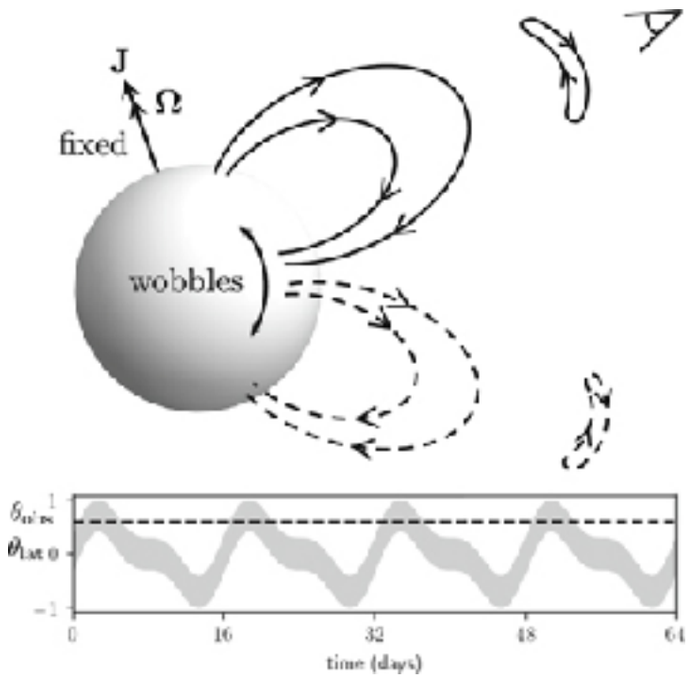


6.67 hr period from 1E161348–5055 (De Luca et al 2006)

Canonical magnetars could slow down soon after birth through a loaded wind

MODELS

Precession Period

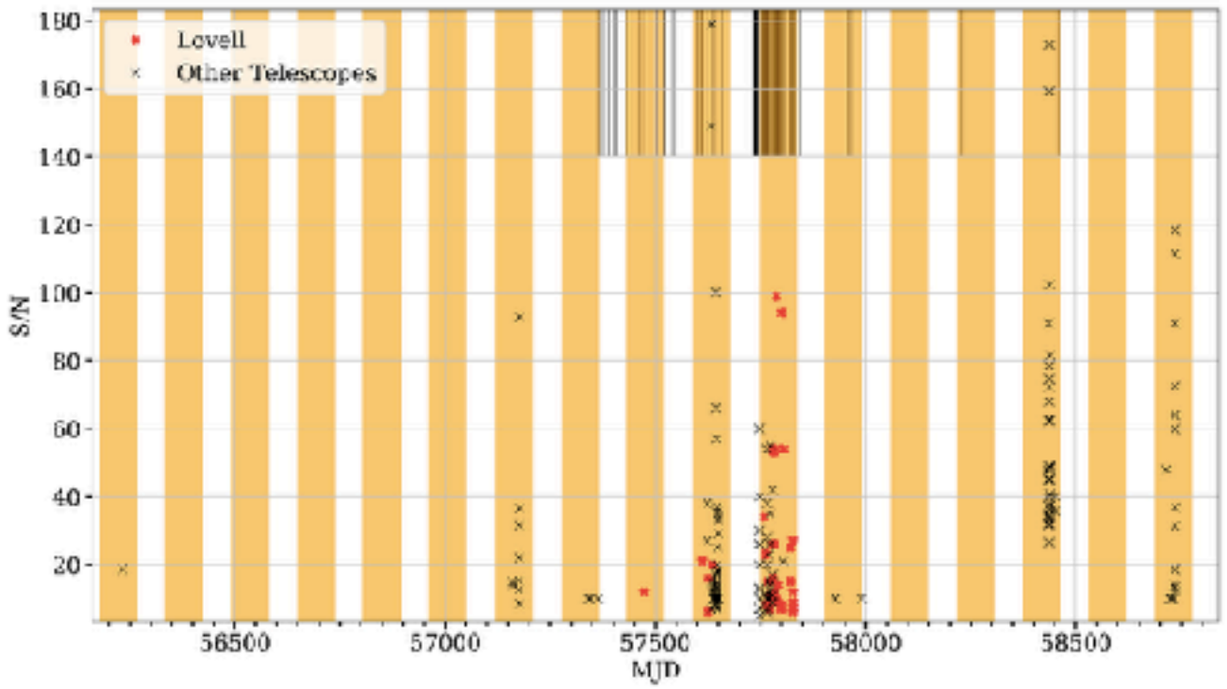


Hyperactive magnetar
with 10^{16} G field
Levin et al (2020)

A very strong magnetic field (10^{16} G) diffuses and causes warps and deformations.

–> Wobbling and precession

PERIODICITY IN FRB 121102 TOO



Rajwade et al 2020

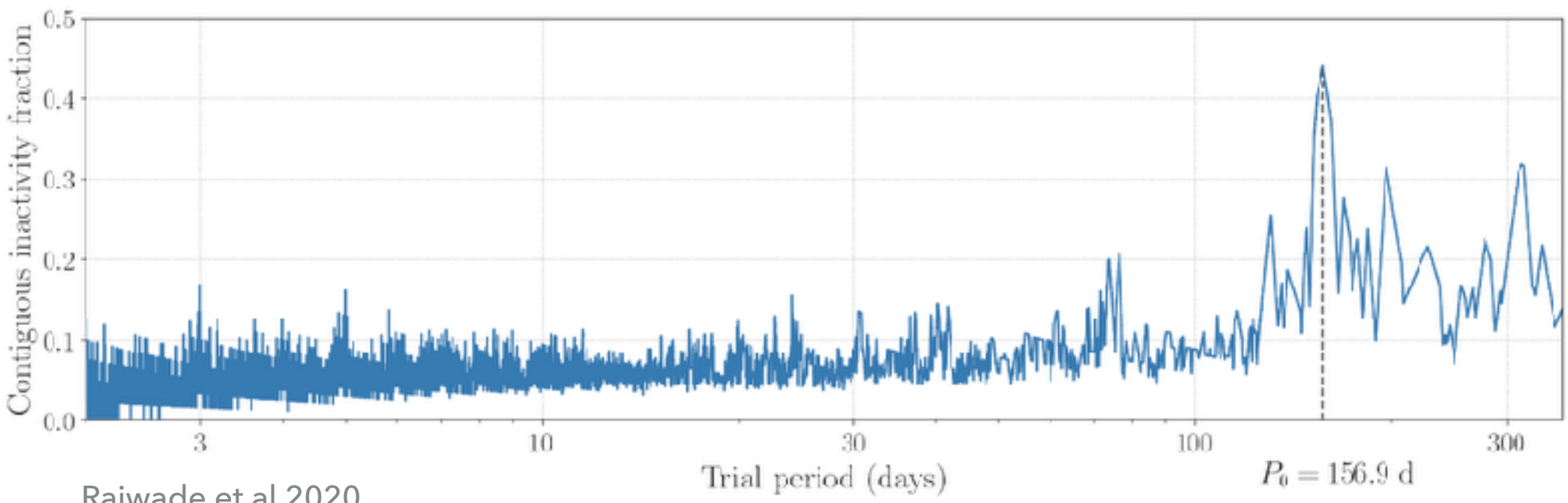
Apparent periodicity of 157 days

(Rajwade et al 2020)

Confirmed: 161+/- 5 days

(Cruces et al 2020)

Really long for rotation!



Rajwade et al 2020

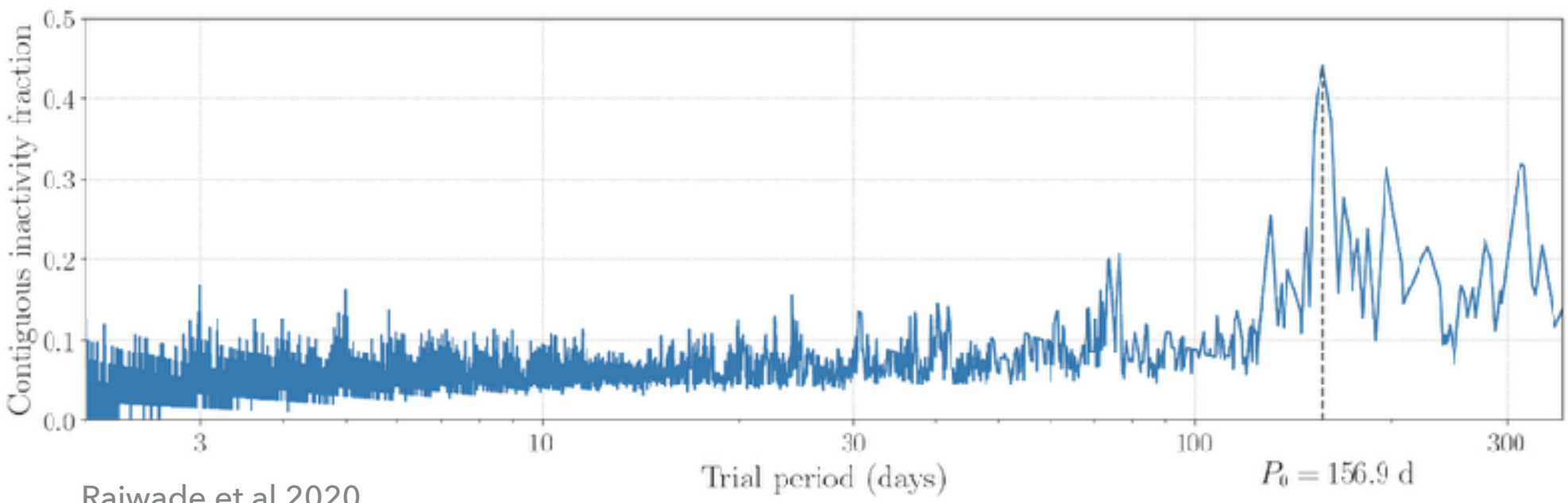
PERIODICITY IN FRB 121102 TOO

161 day period:

Hard to explain for rotation and precession — but achievable through tweaking B-field

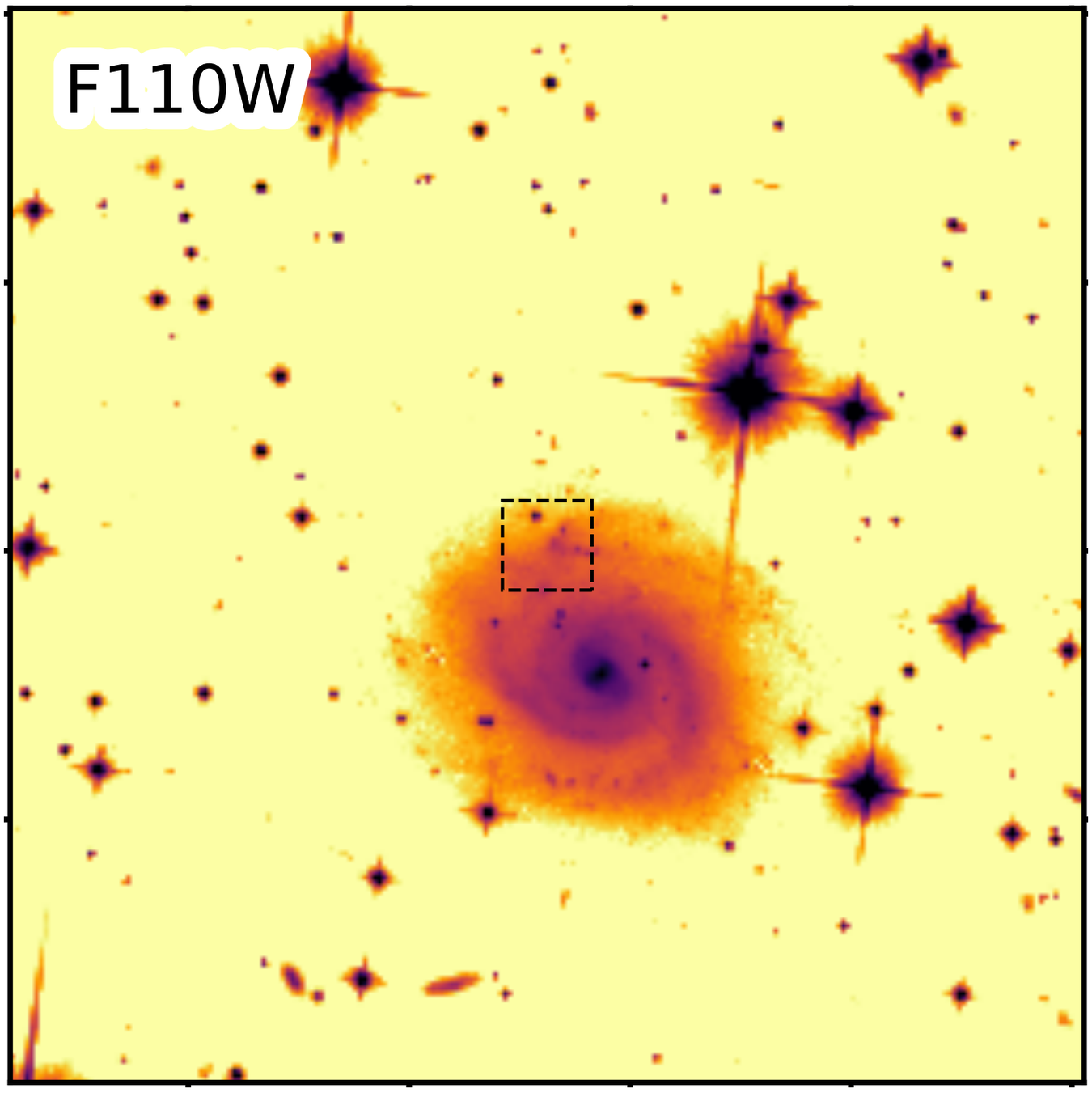
Natural for orbital periods

Rajwade et al 2020



Rajwade et al 2020

IS FRB 180916 A BINARY?



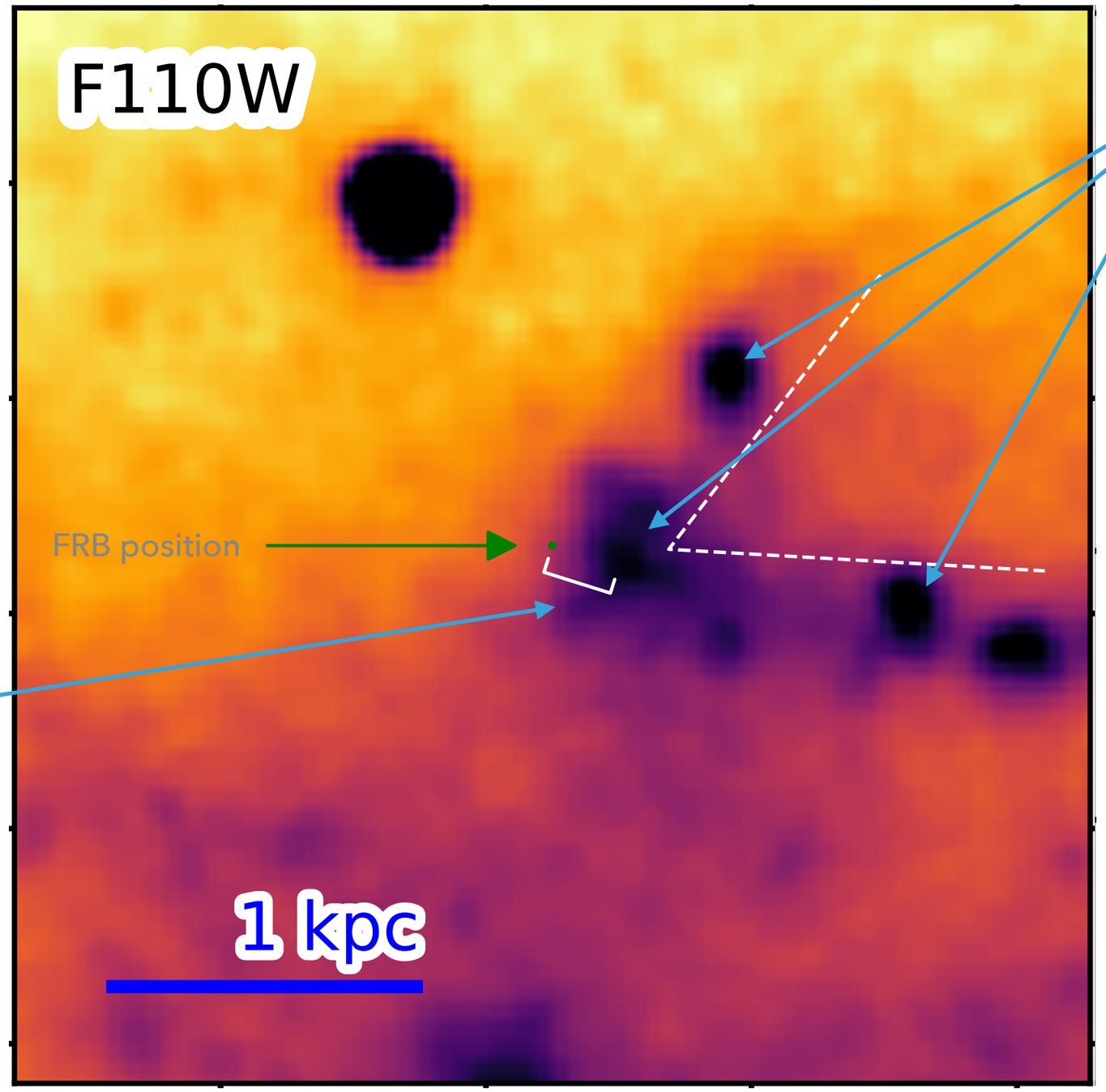
Tendulkar et al (2020), in review

IS FRB 180916 A BINARY?

Green circle is 36 mas radius
VLBI error + astrometric error

Little to no
star-formation
at FRB location

250 pc offset



Resolution of
< 60 pc!

Tendulkar et al (2020), in review

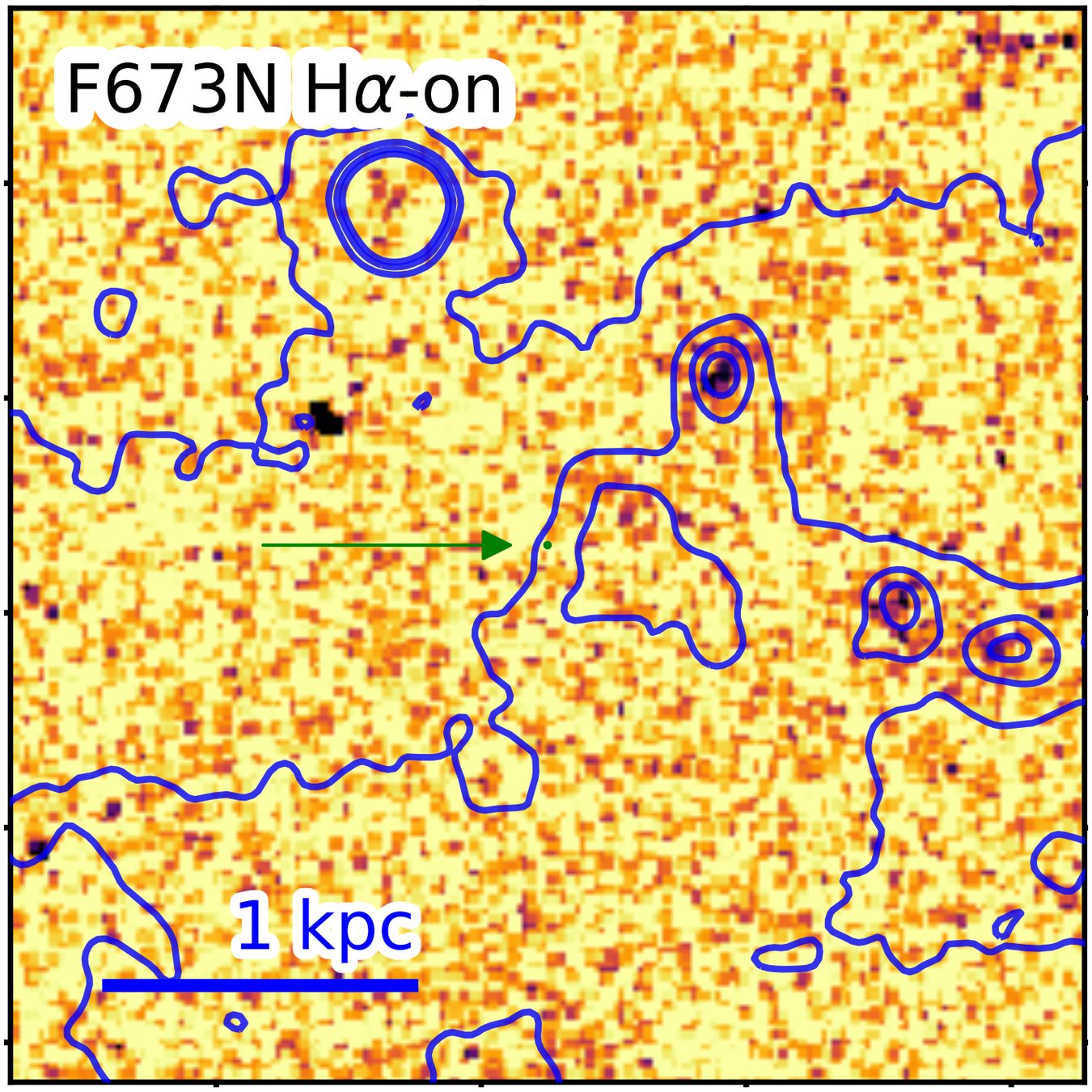
IS FRB 180916 A BINARY?

Halpha traces star-formation rate via young, massive, bright stars

Halpha at the FRB location constrained to 10^{37} erg/s

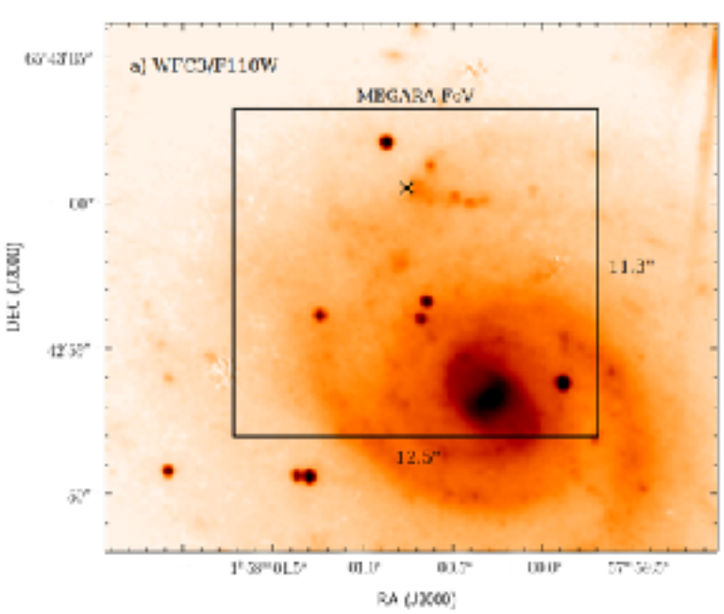
–> SFR < 10^{-4} Msun/year

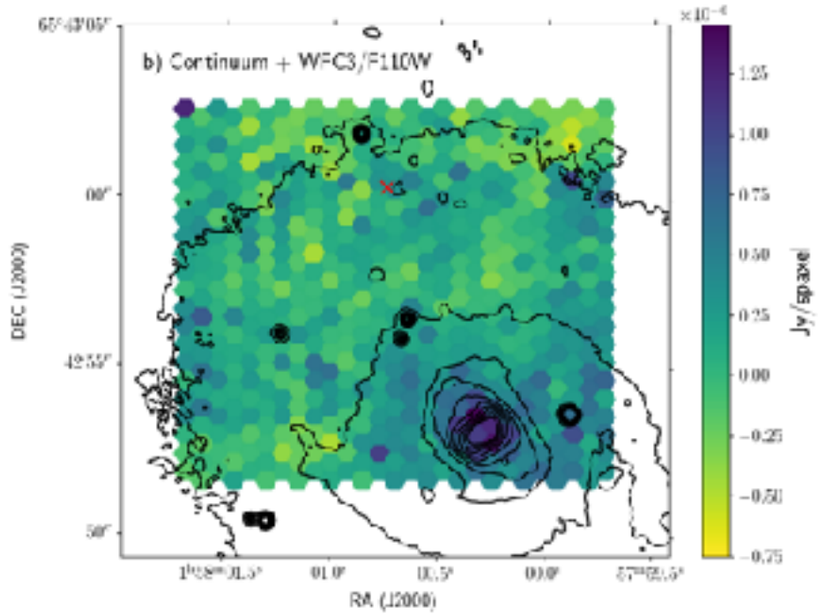
–> Any star > O6V

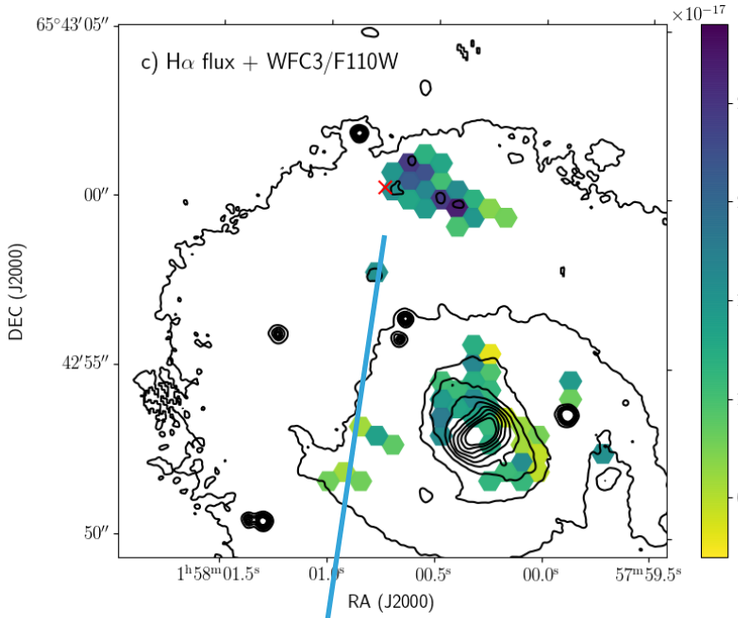


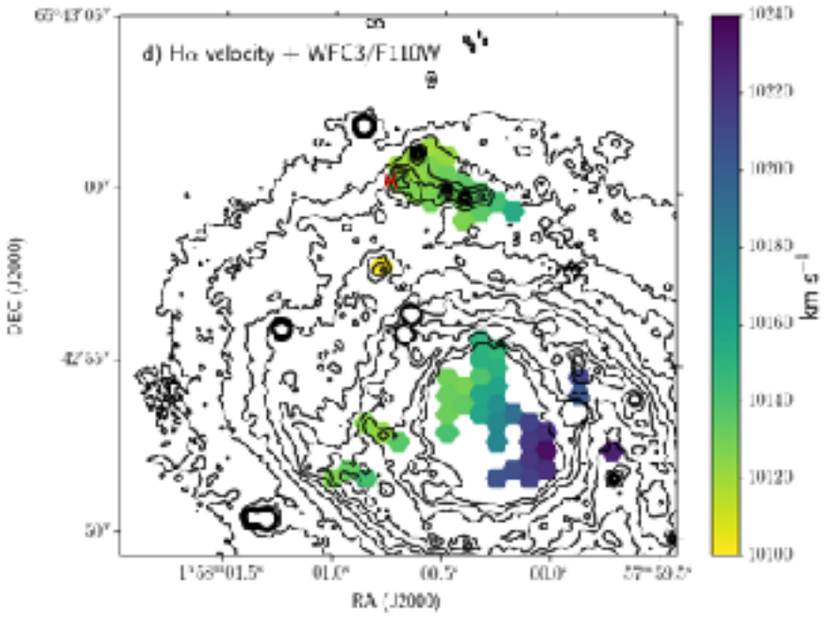
Tendulkar et al (2020), in review

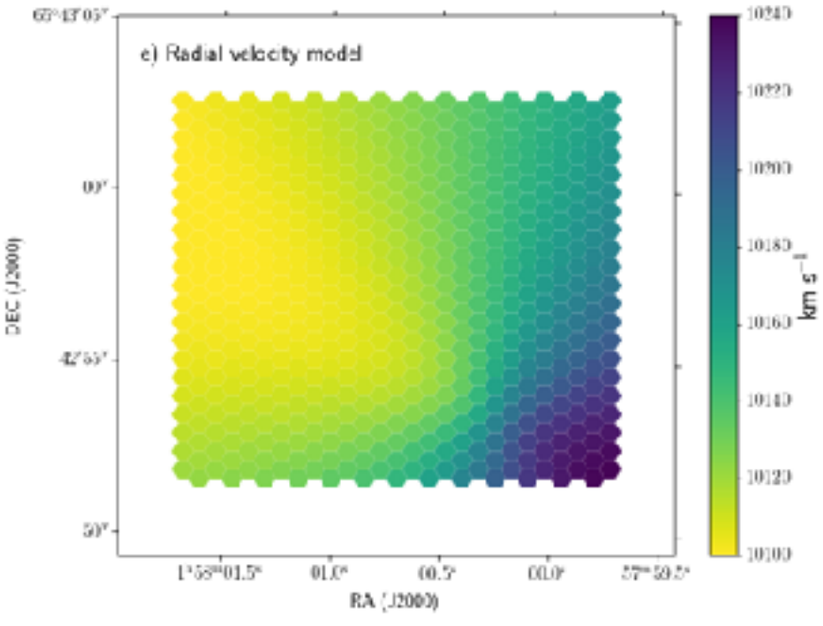
IFU SPECTROSCOPY











V-shaped structure is a part of the spiral arm, not separate satellite galaxy

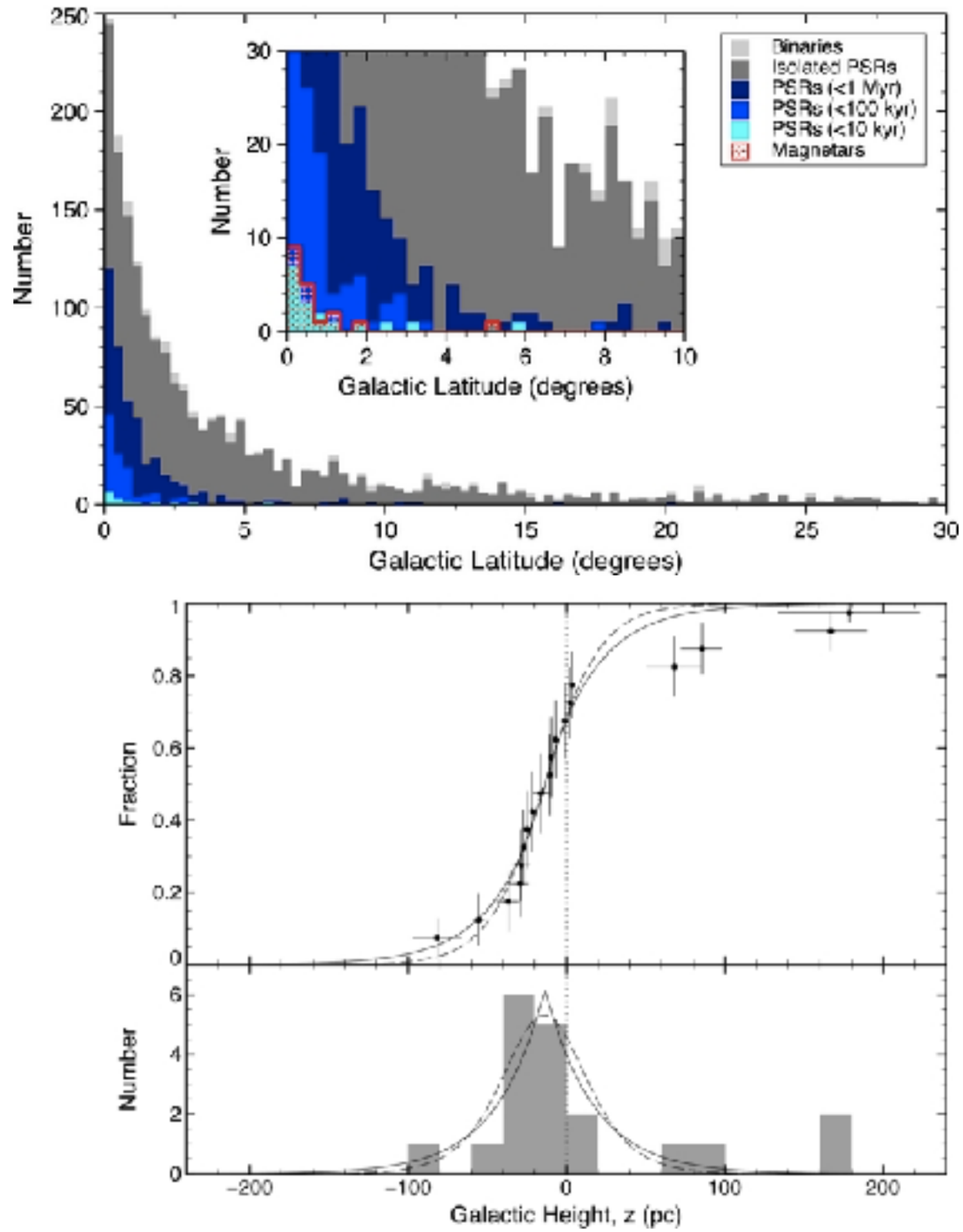
Little star formation at FRB location

WHERE DOES THE 250 PC OFFSET COME FROM?

A 250 pc offset from a star-forming region is significant

Magnetars are young (<10 kyr)
Found near SF regions

Magnetar scale height —>
20-30 pc (little dispersion)



Olausen & Kaspi (2014)

WHERE DOES THE 250 PC OFFSET COME FROM?

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Magnetar scale height –>
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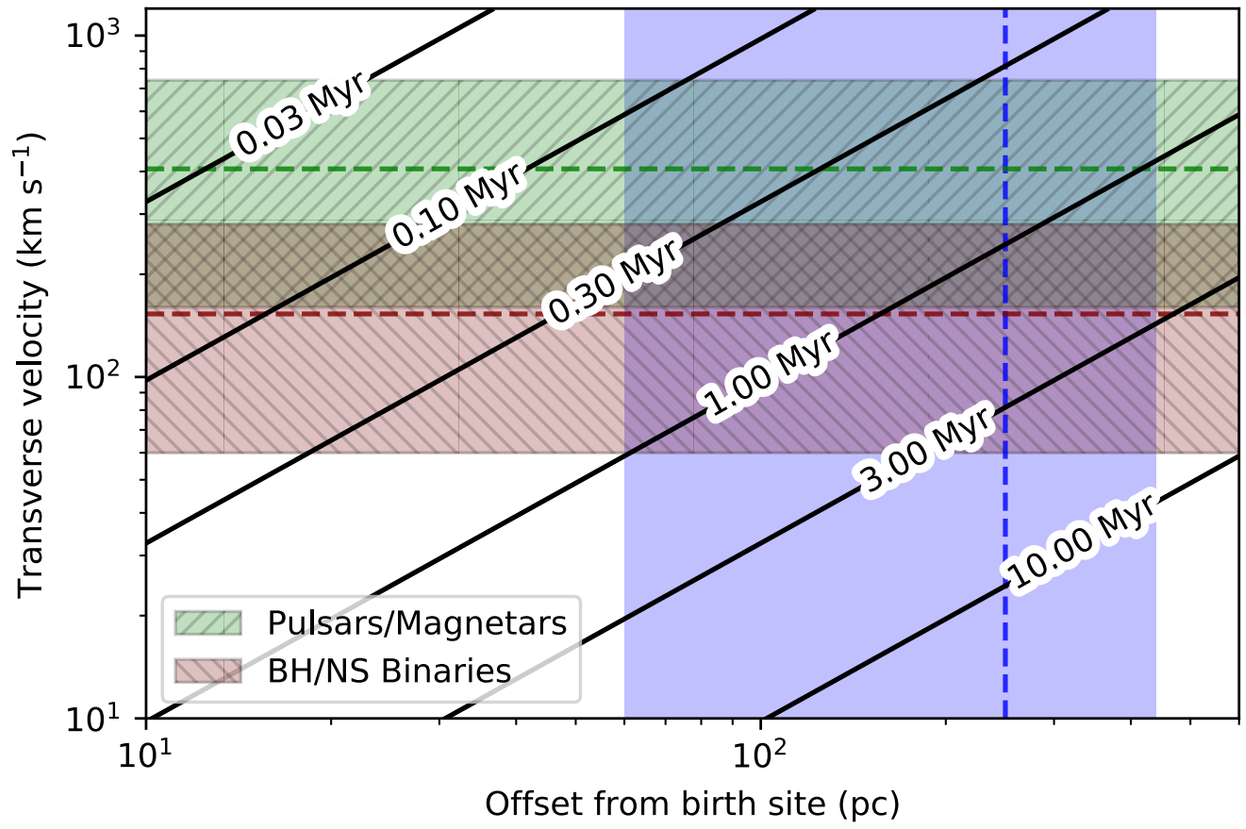
HMXBs show ~400 pc offsets from nearby SF regions (Bodaghee & Tomsick 2014)



Age is not an issue since activity is driven by the orbit not by the magnetar's flaring

SO WHAT CAN IT BE

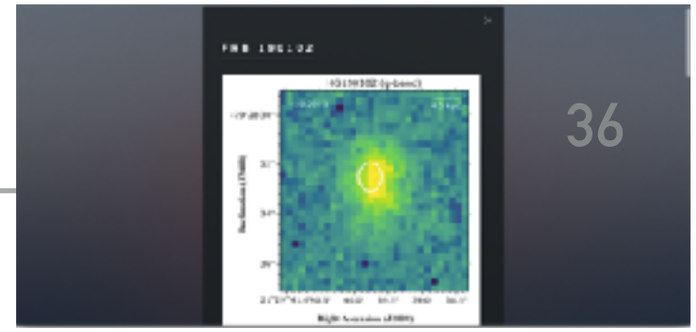
- Unlikely to be Galactic magnetar analog unless
  - magnetar formed from a runaway OB star?

    few % of OB stars are ejected at high velocities, live for few Myr, enough time to travel 250 pc
    much lower rate of formation
  - Magnetar formed from alternative mechanisms (AIC?)

    also much lower rate
- Periodicity, position all suggest OB star binary

  late O or early B star (fainter than O6V)

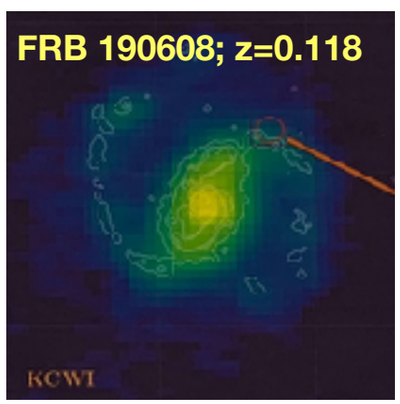
HOST CHARACTERISTICS

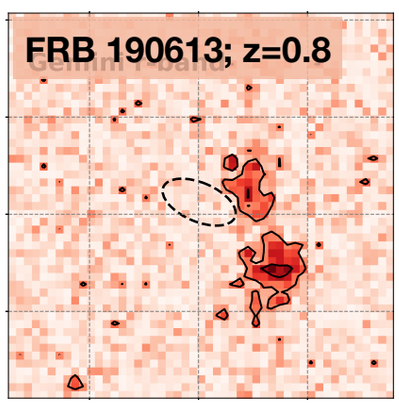


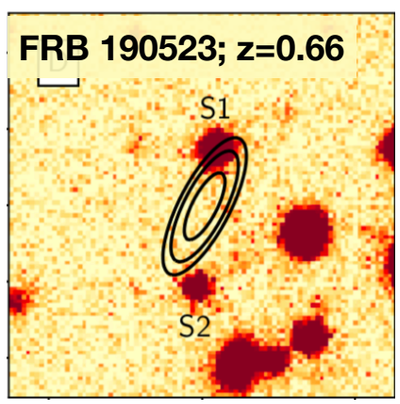
https://frbhosts.org

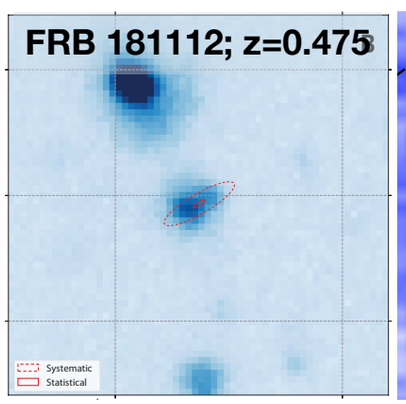
Active/Star-forming ⟵ ⟶ Quiescent

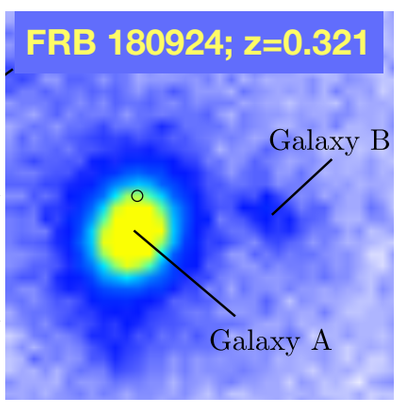
Non-repeaters



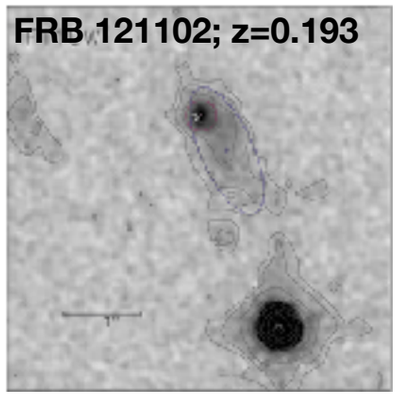


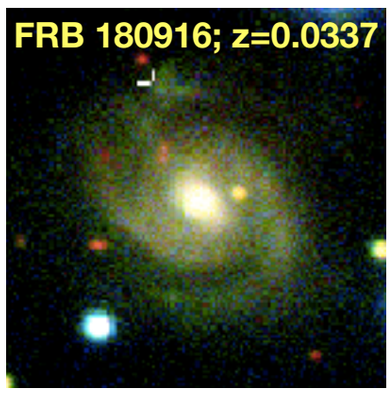






Repeaters



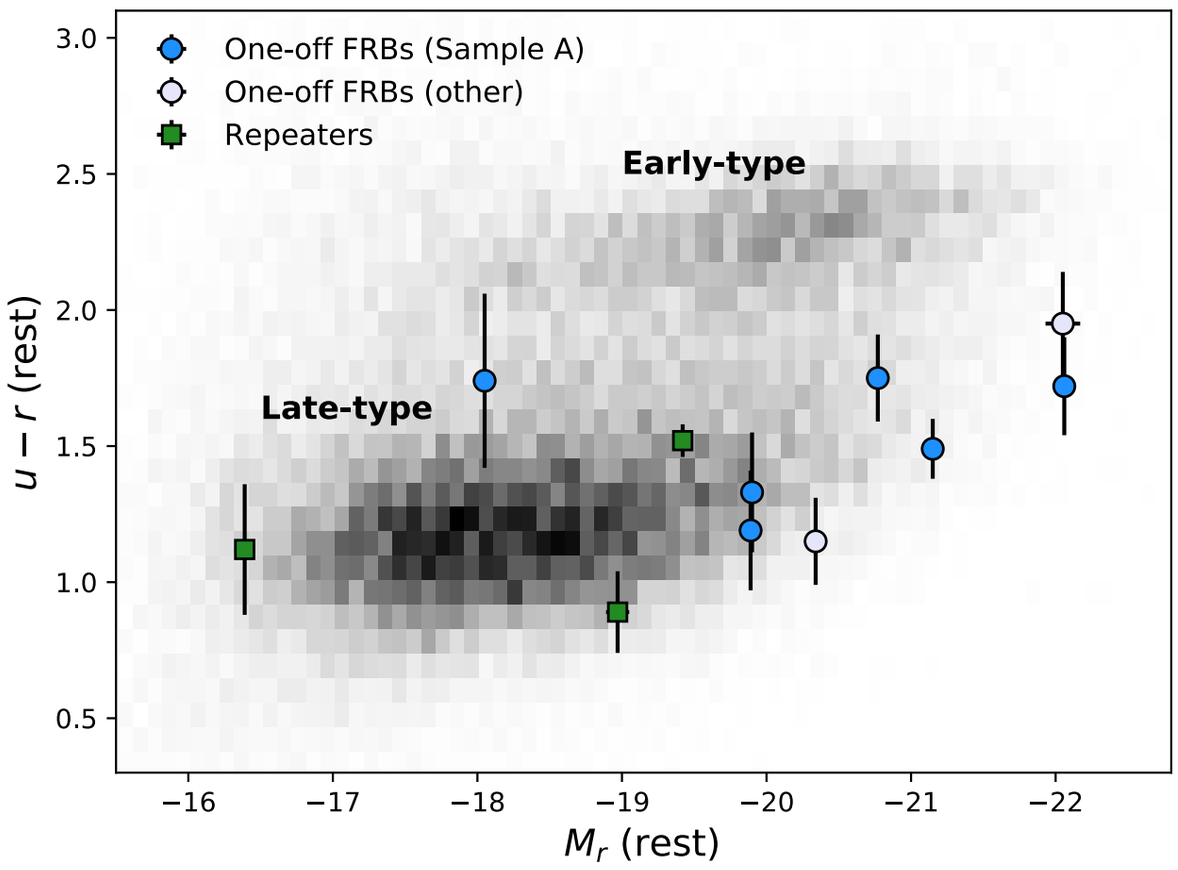


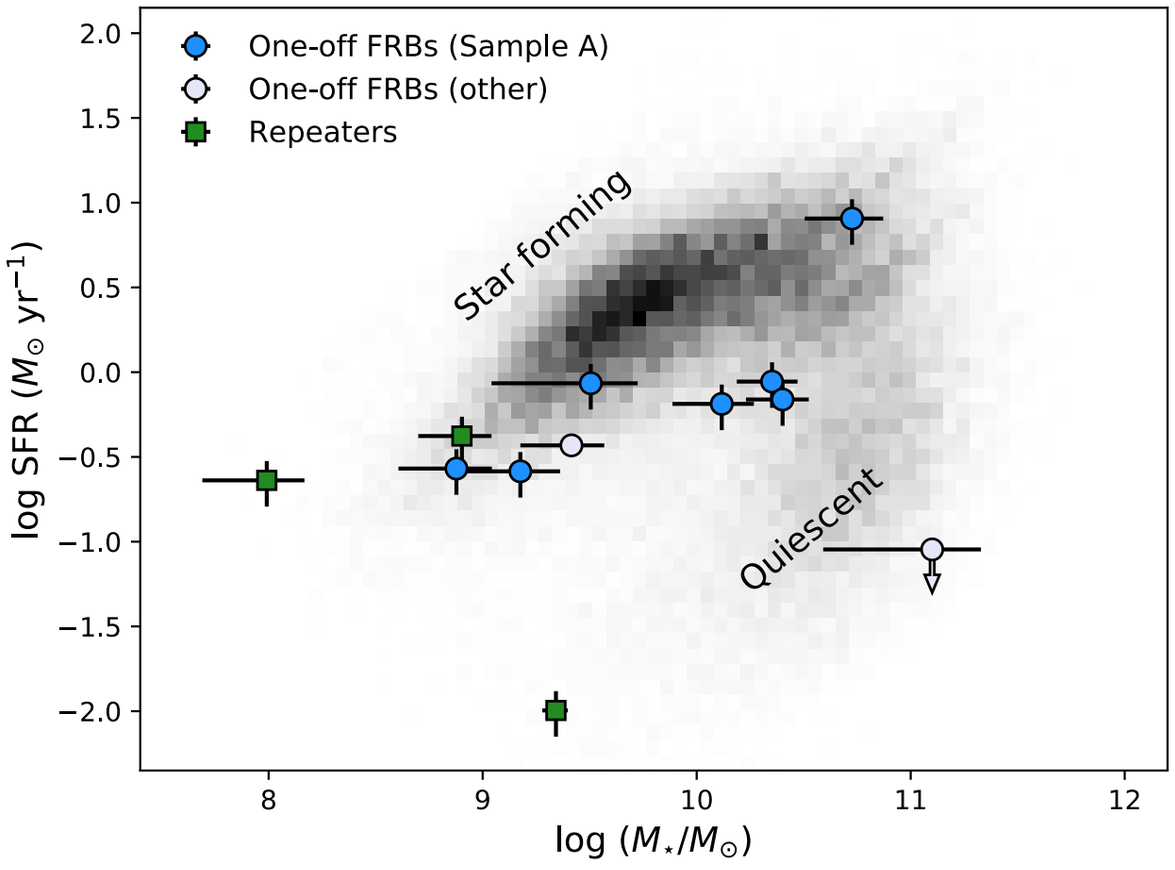
Probabilistic association
(R4 – NGC 3252, 20 Mpc)

References:
FRB 121102 — Chatterjee+ 2017
FRB 180916 — Marcote+ 2020
FRB 190608 — Chittidi+ 2020
FRB 190613 — Law+ 2020 (in review)
FRB 190523 — Ravi+ 2019
FRB 181112 — Prochaska+ 2019
FRB 180924 — Bannister+ 2019

HOST CHARACTERISTICS

Range of host properties, but
repeater hosts are typically lighter





Heintz et al (2020)

IMPORTANCE OF VLBI + HST

- Statistically, FRB host properties are consistent with all Galactic magnetars (Bochenek et al 2020)
- But so are HMXBs
  No difference unless you look very closely
- Similar relation to SFR, stellar mass, even offsets from galaxy centers etc
- Understanding the local environment of FRBs is crucial

FOCUS ON THE NEAREST FRBS

- Even with VLBI and HST, need a sample of the nearest FRBs
  - Also likely to be bright and have X-ray/optical counterparts
- An FRB at z=1 is not useful for understanding mechanisms but is useful for cosmology without needing VLBI
- An FRB at 20 Mpc is the inverse
- CHIME/FRB detecting more and more repeaters, localizing them with VLBI
  Can’t do this for non-repeaters! :(

VLBI FOR NON-REPEATERS

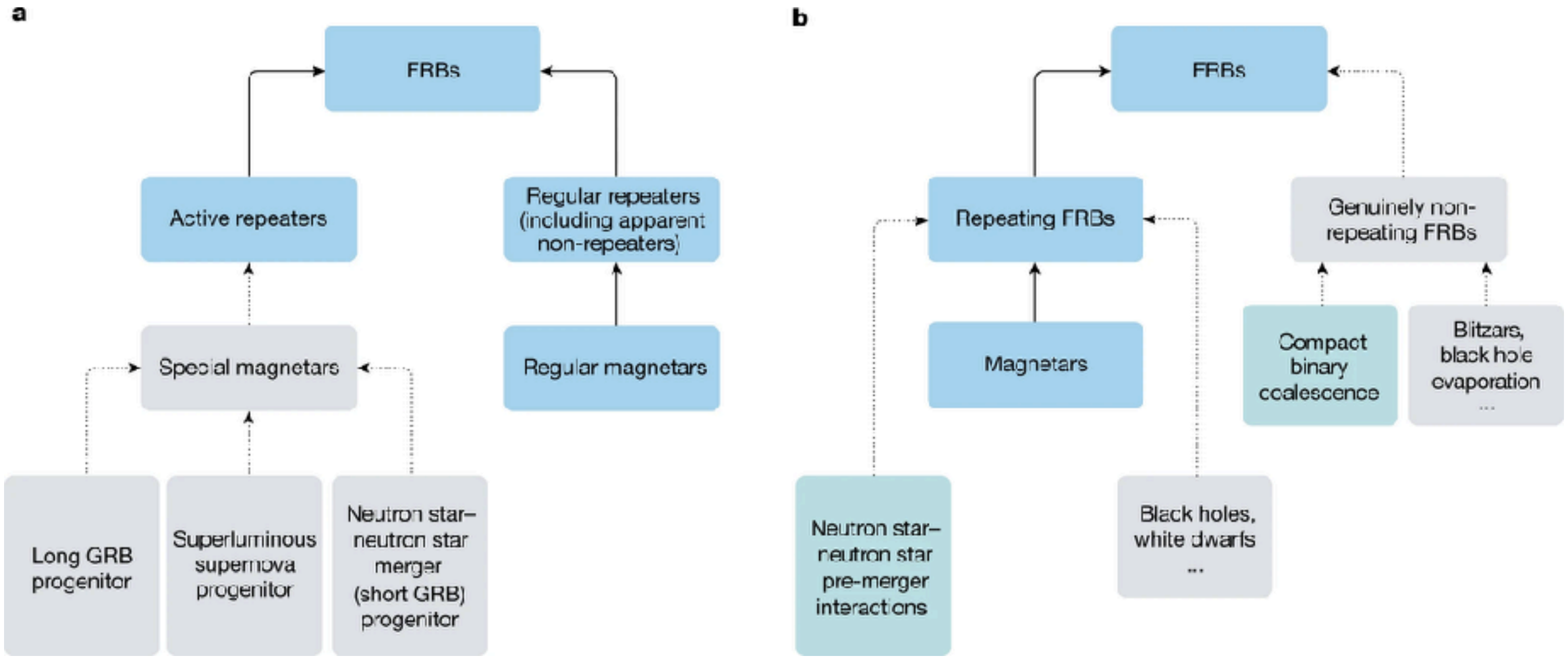
- VLBI telescopes are built for small field of view
  Cannot find non-repeating FRBs efficiently
- CHIME/FRB building outrigger telescopes
  Get 50 mas localization for every FRB (repeater and non-repeater)
- Aim to get ~1000 localized FRBs every year in 2 years!

CONCLUSIONS

It is not sufficient to know which galaxy an FRB is coming from

The local environment of FRBs is crucial to understand their astrophysical origins

We have to focus on detecting and localizing the *nearest* FRBs



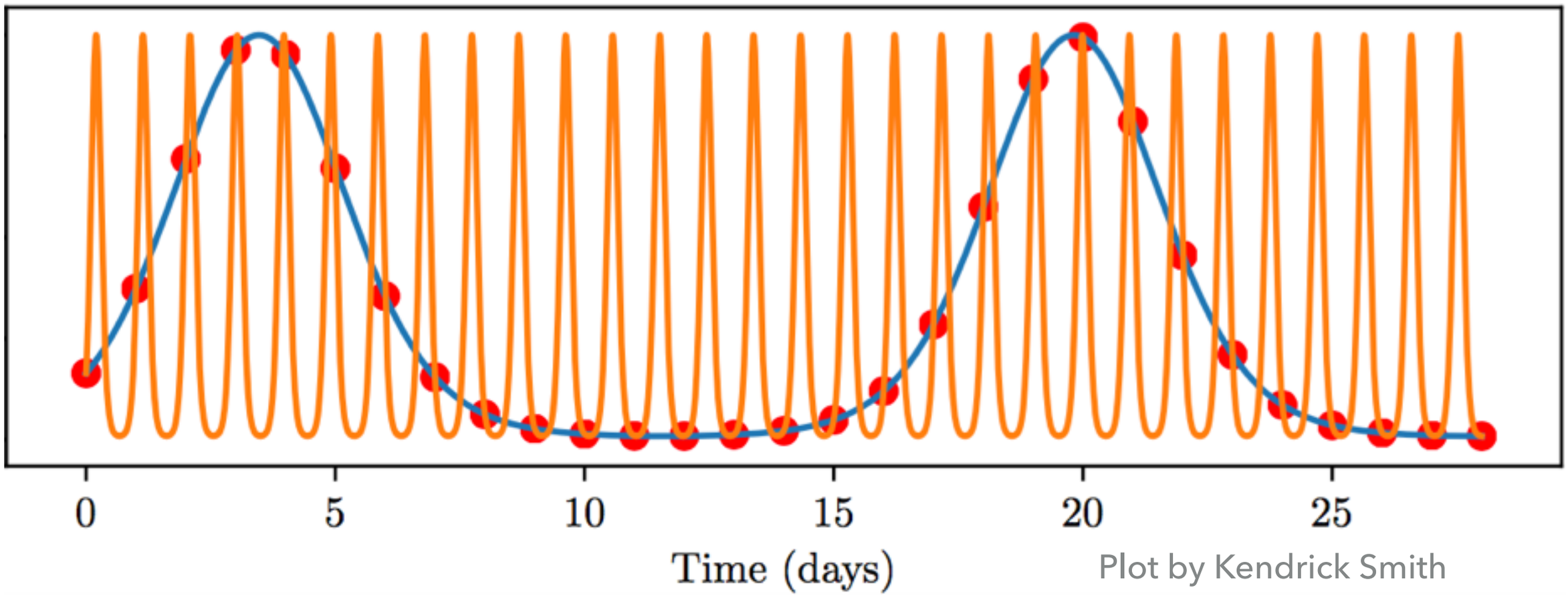
Zhang, B. (2020, Nature review article)

ALIASING

- CHIME observes R3 once a sidereal day (for 10 min)
- Periodic sampling causes aliasing

Unaliased: f = (1/16.35)
Aliased: f = (1/16.35) + 1

$$f_{\text{int}} = N f_{\text{sid}} +/- f_{\text{obs}}$$



Plot by Kendrick Smith