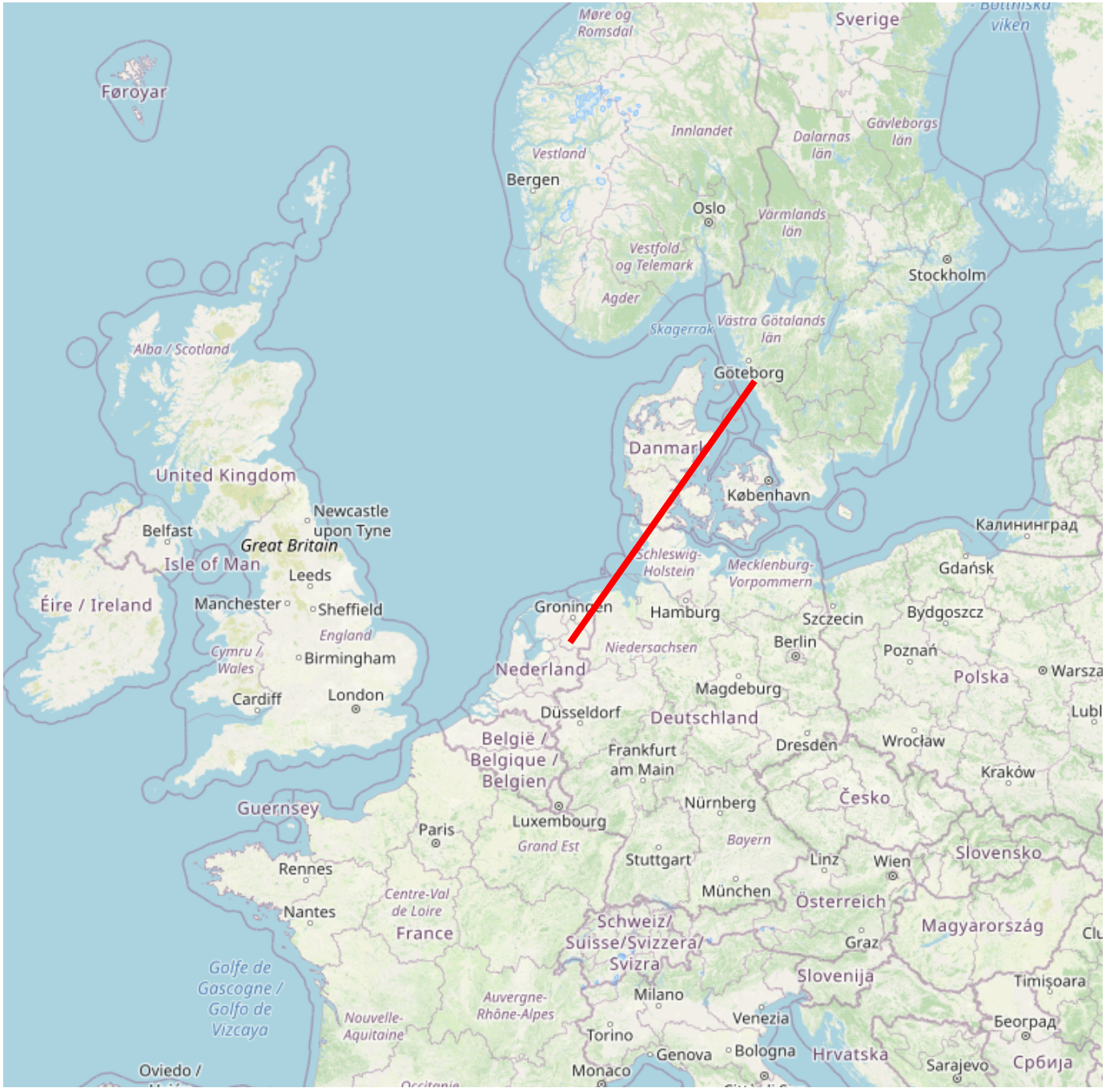
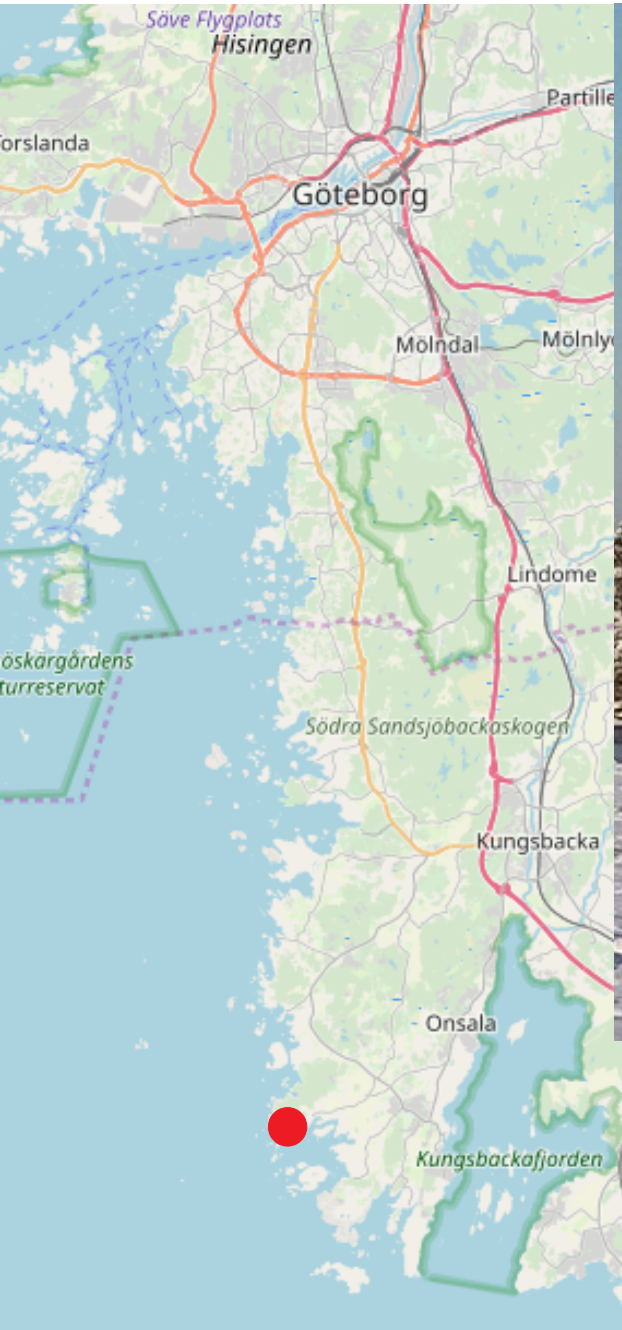
PRECISELy localising and timing FRBs – hunting cosmic flashes with VLBI

Franz Kirsten
On behalf of the PRECISE-team

ASTRON / Chalmers – OSO

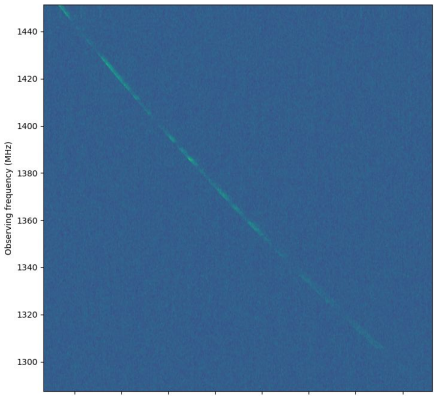


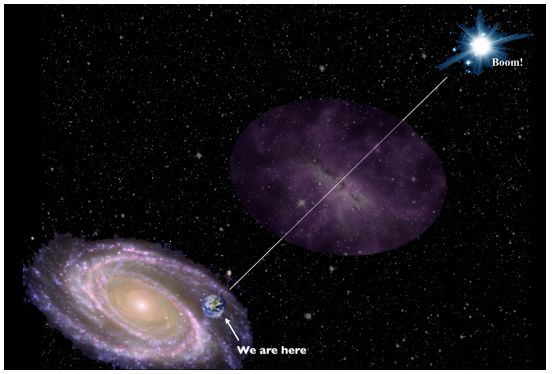
Onsala Space Observatory – OSO

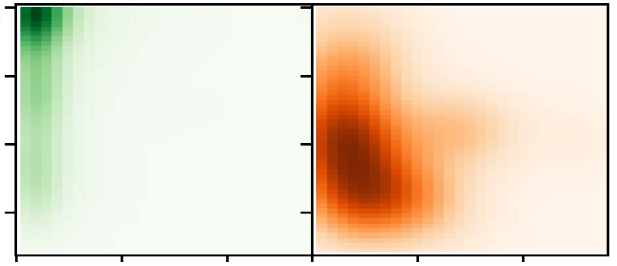


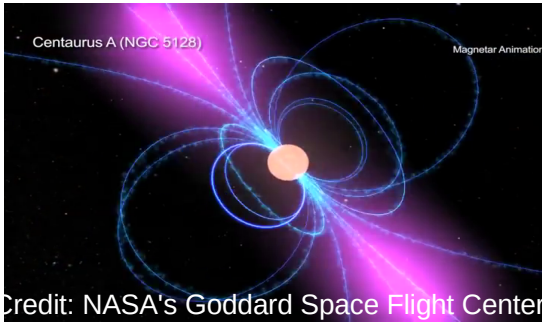
Fast Radio Bursts – FRBs in a nutshell

- Millisecond duration bursts that are highly dispersed
  - ➔ Only see in the radio band so far
- Very common phenomenon: 1000s per sky per day
- Large dispersion measure tells us they're extragalactic
- Inferred distances imply they're highly energetic
  - ➔ Emit as much energy per bust as the sun does in a day
  - ➔ Must be a coherent emission mechanism
- Vast majority of bursts only ever seen once (~650 published)
  - ➔ A small population of repeaters
- At this point we still do not know what generates the bursts
  - ➔ Magnetars for repeaters?
  - ➔ Cataclystic events for one-offs?
- Excellent cosmological probes!

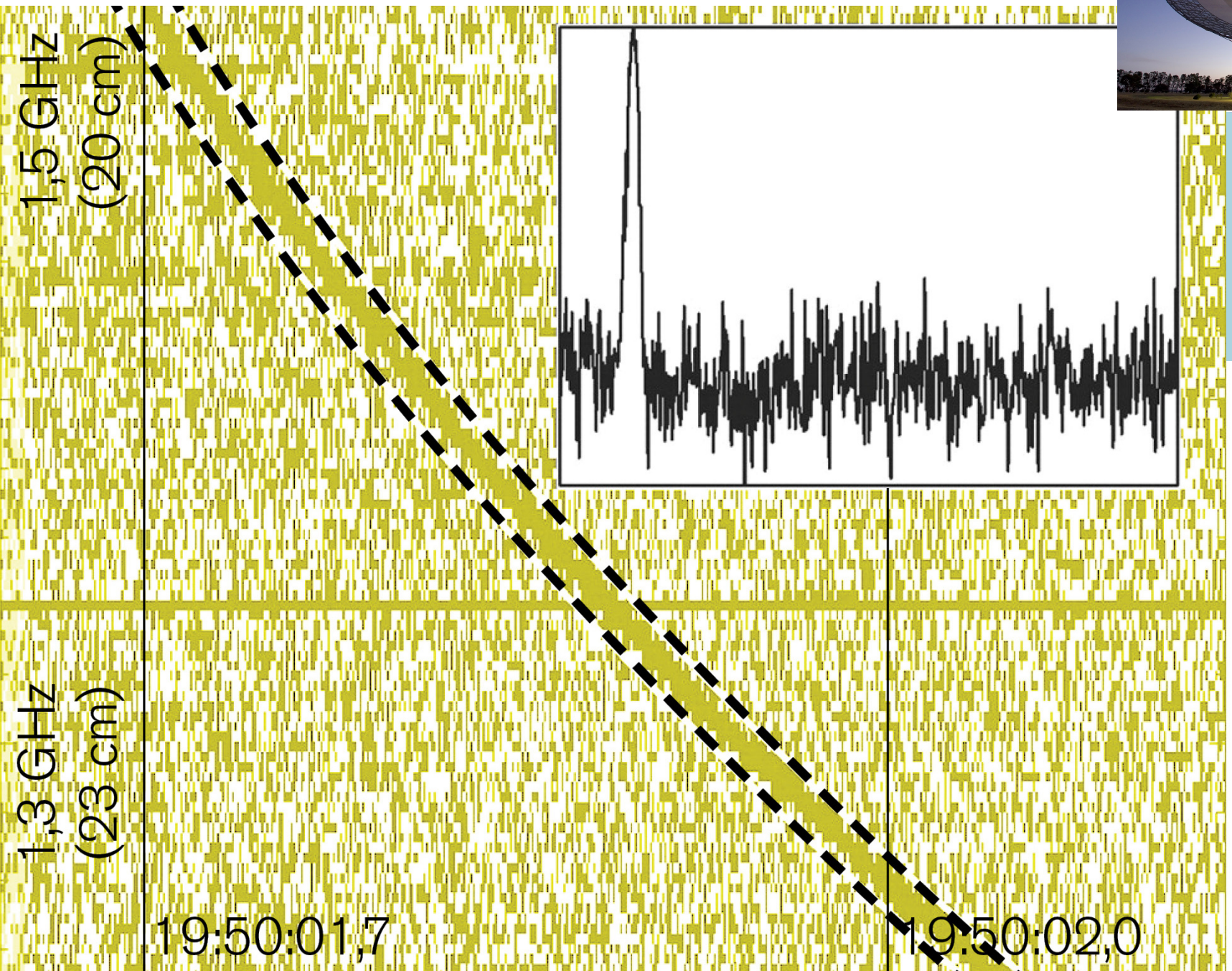




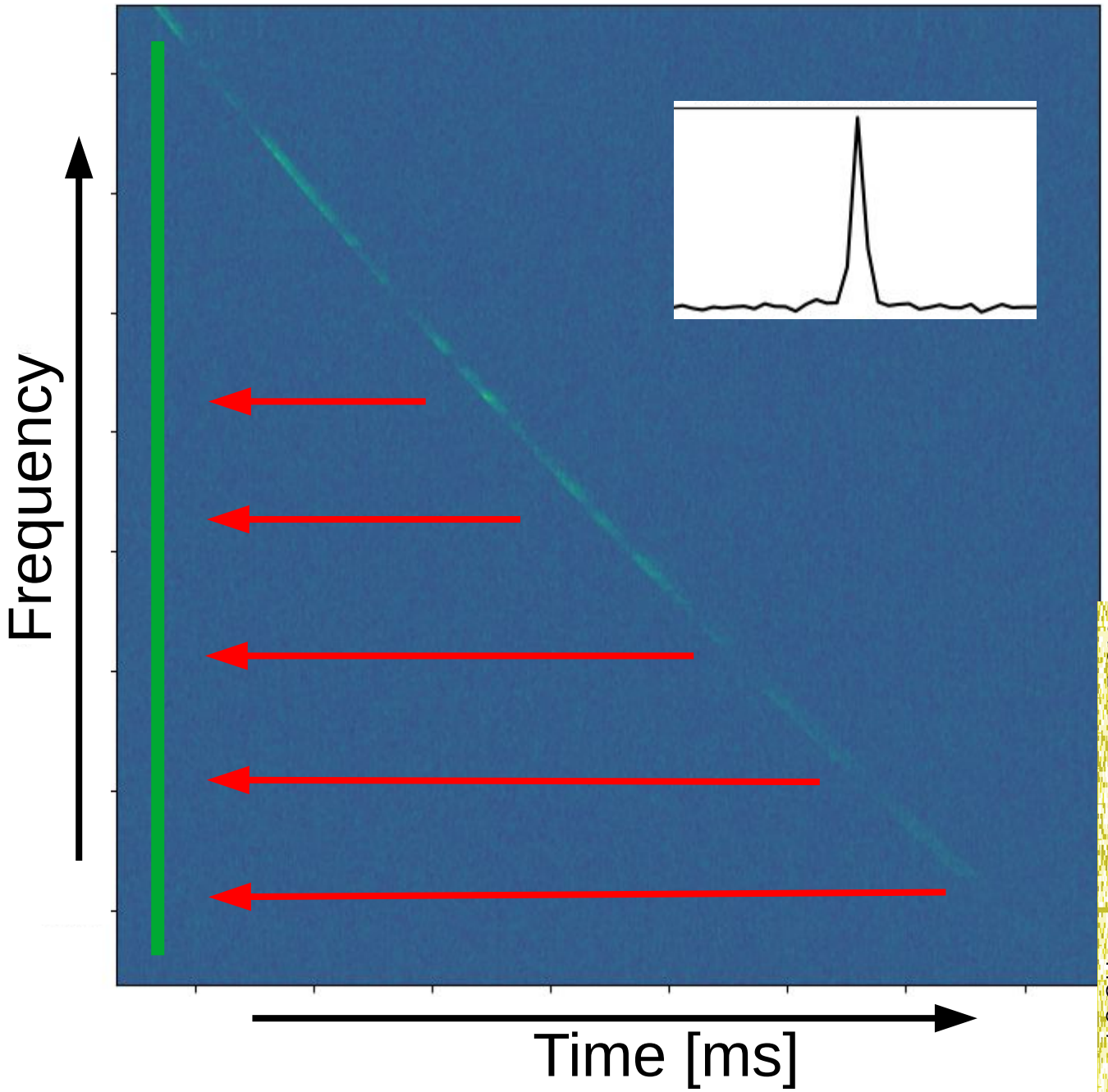




The Lorimer Burst, 2007



Fast Radio Bursts – FRBs

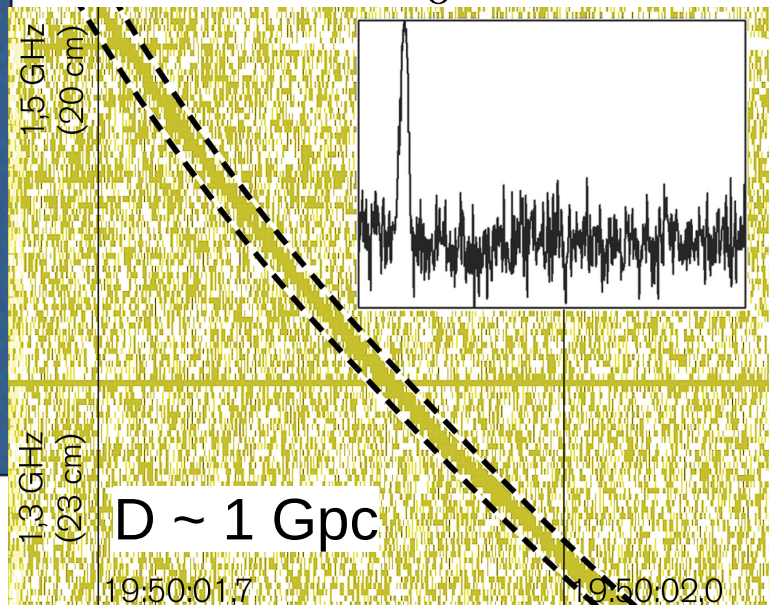


Pulses traverse ISM, i.e. encounter free electrons. Causes group delay because of frequency dependent refractive index of the cold plasma

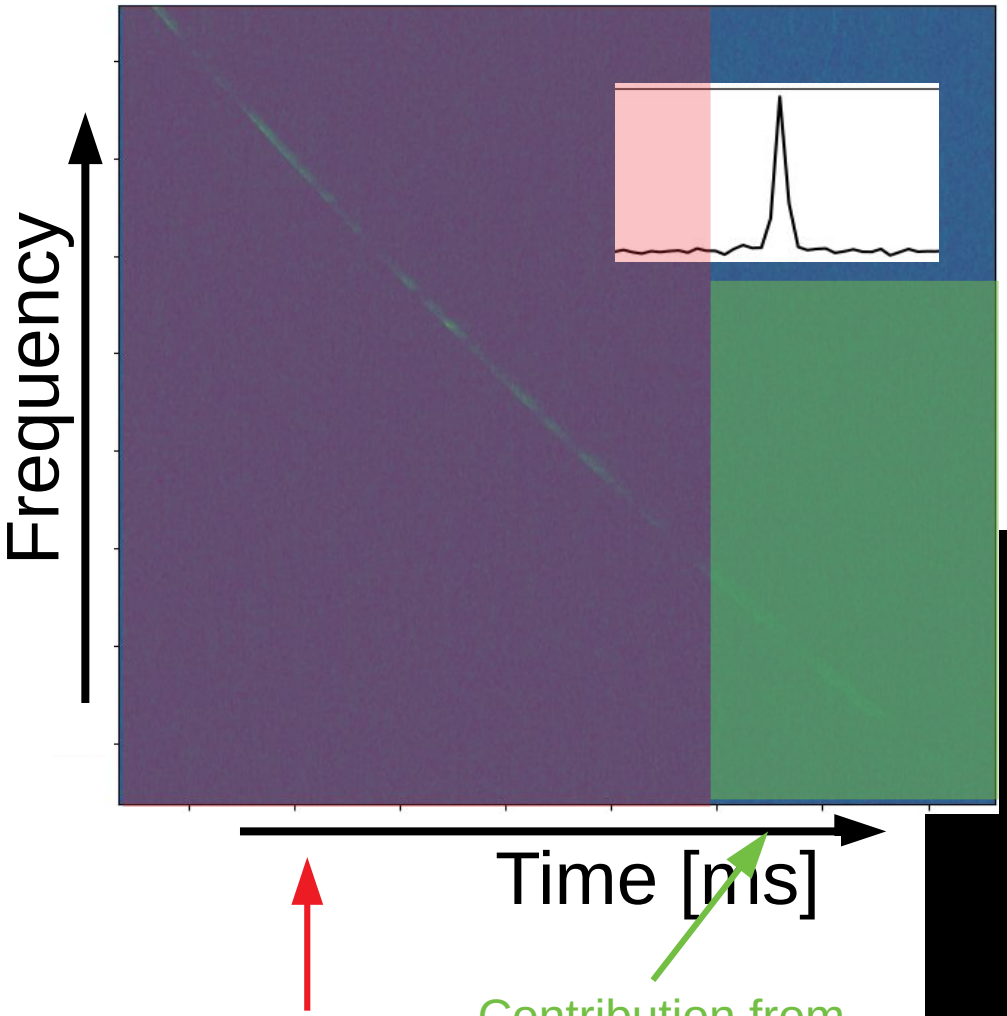
$$\mu = \sqrt{1 - A\frac{n_e}{f^2}}$$

Dispersion measure

$$DM = \int_0^D n_e \, dl$$



Fast Radio Bursts – FRBs

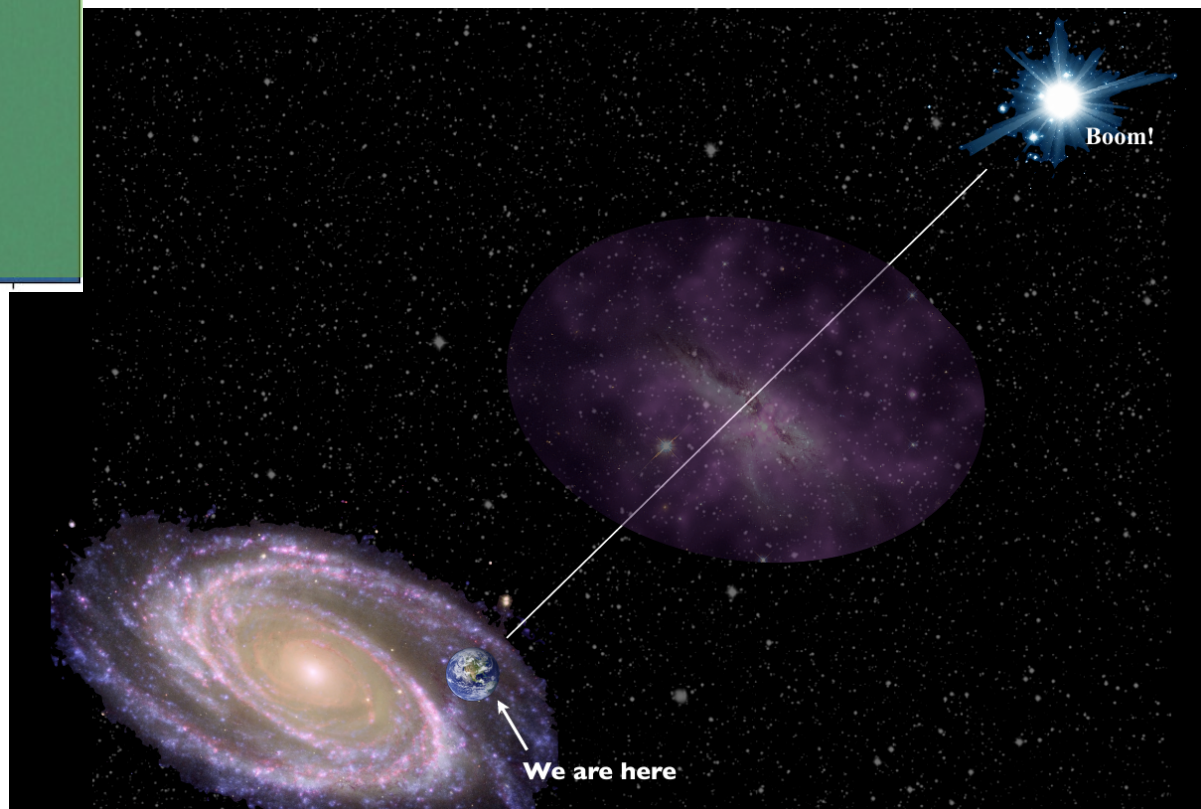


Contribution from intergalactic space!

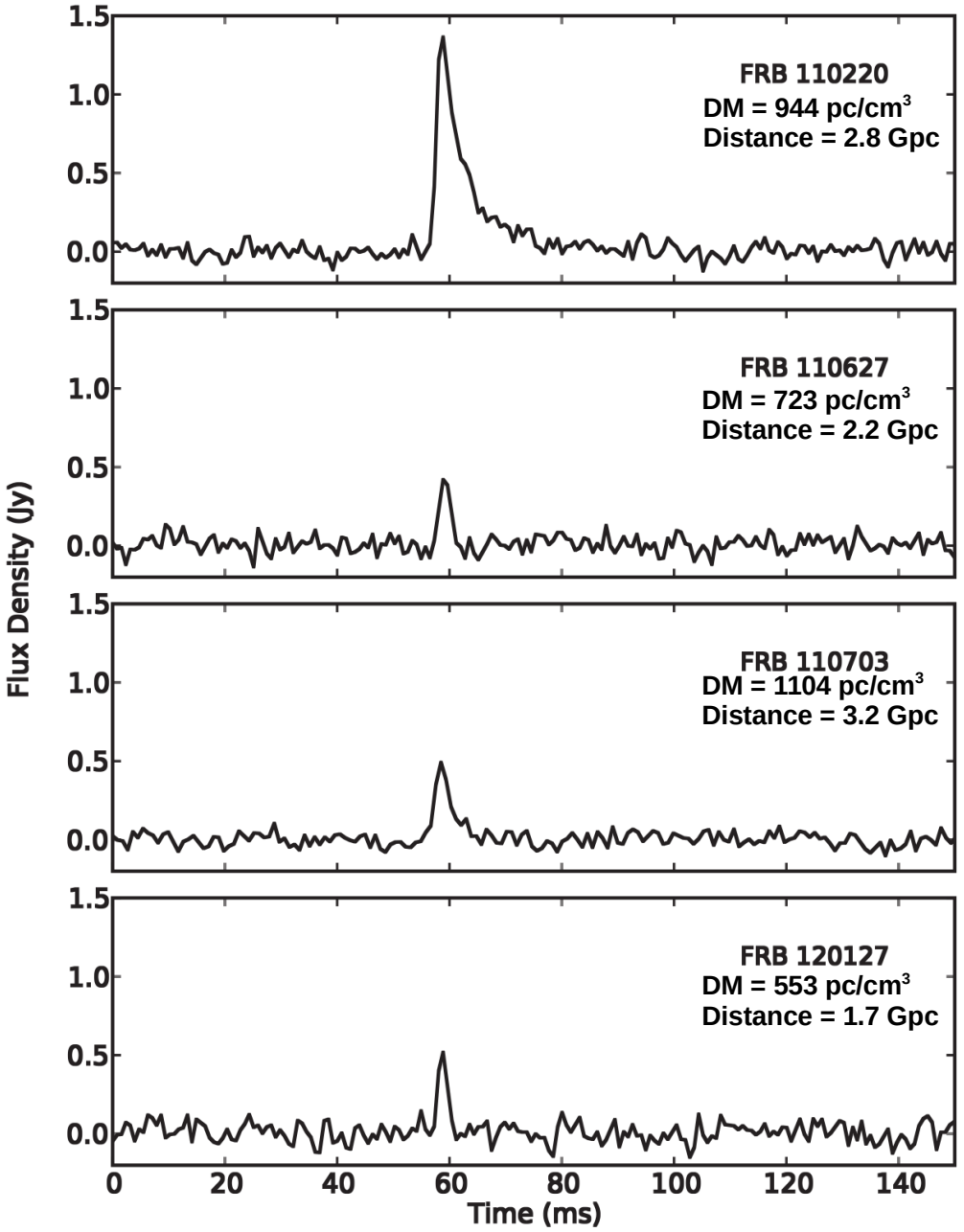
Contribution from our Galaxy

Dispersion measure
~100 < DM < ~3000
→ 0.03 < z < 0.66

Cosmologic origin

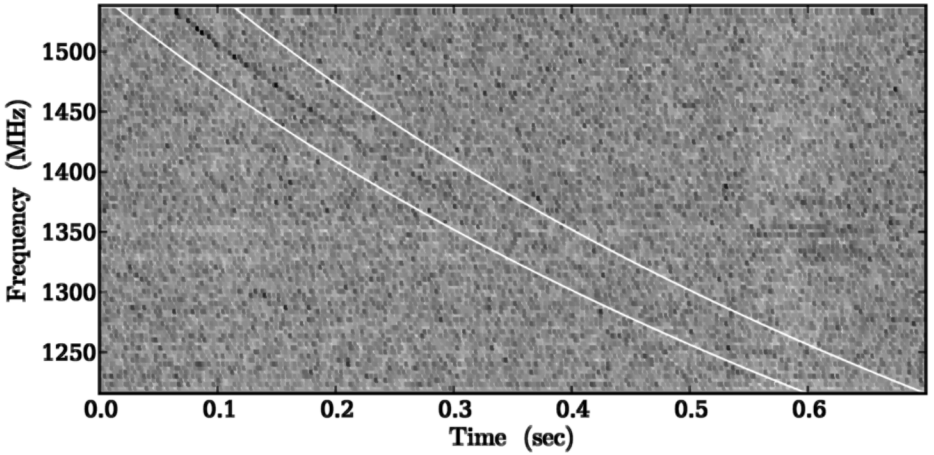


The next four FRBs, 2013



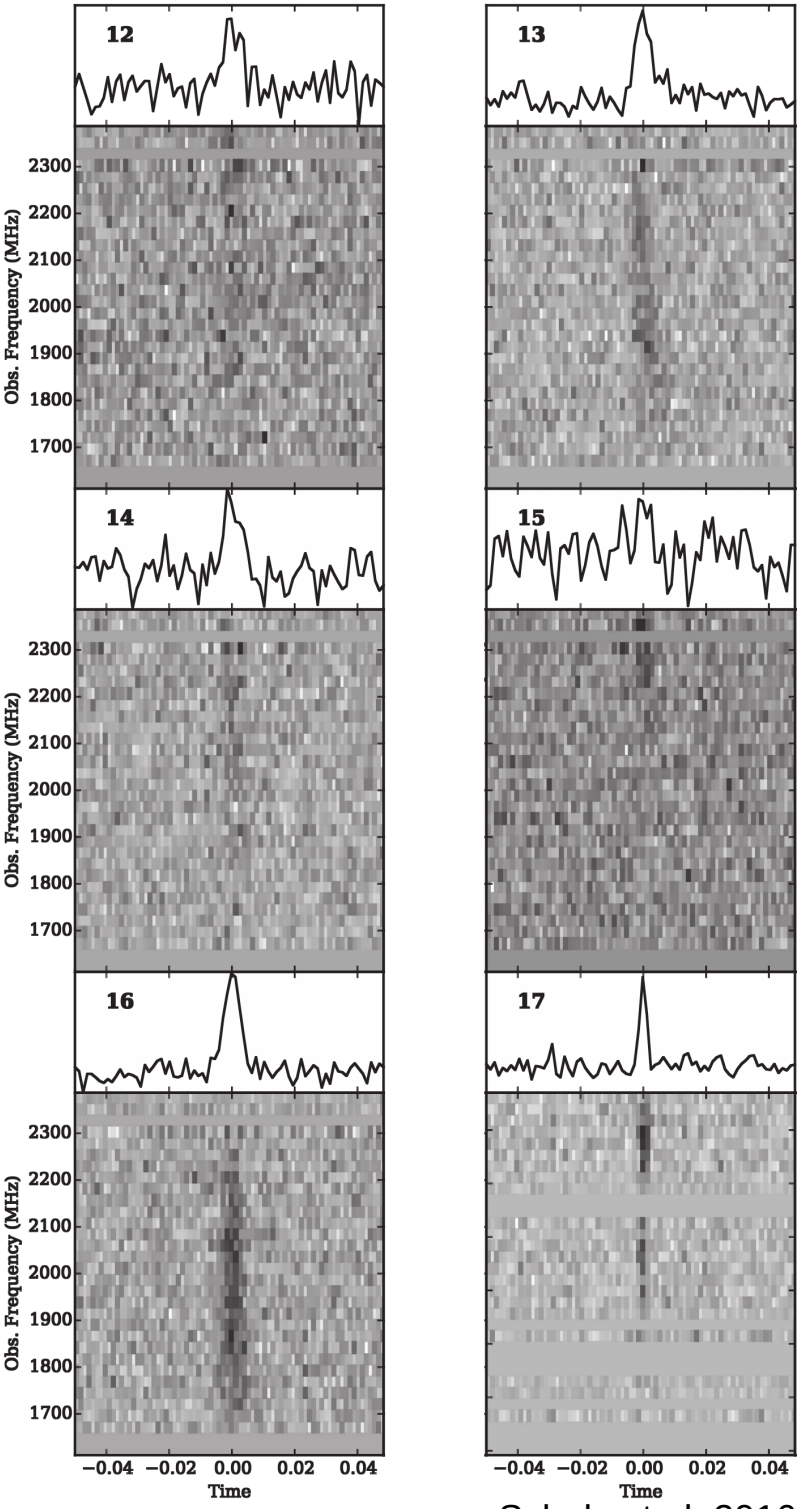
Thornton et al., 2013

FRB 20121102 – the first REPEATER!



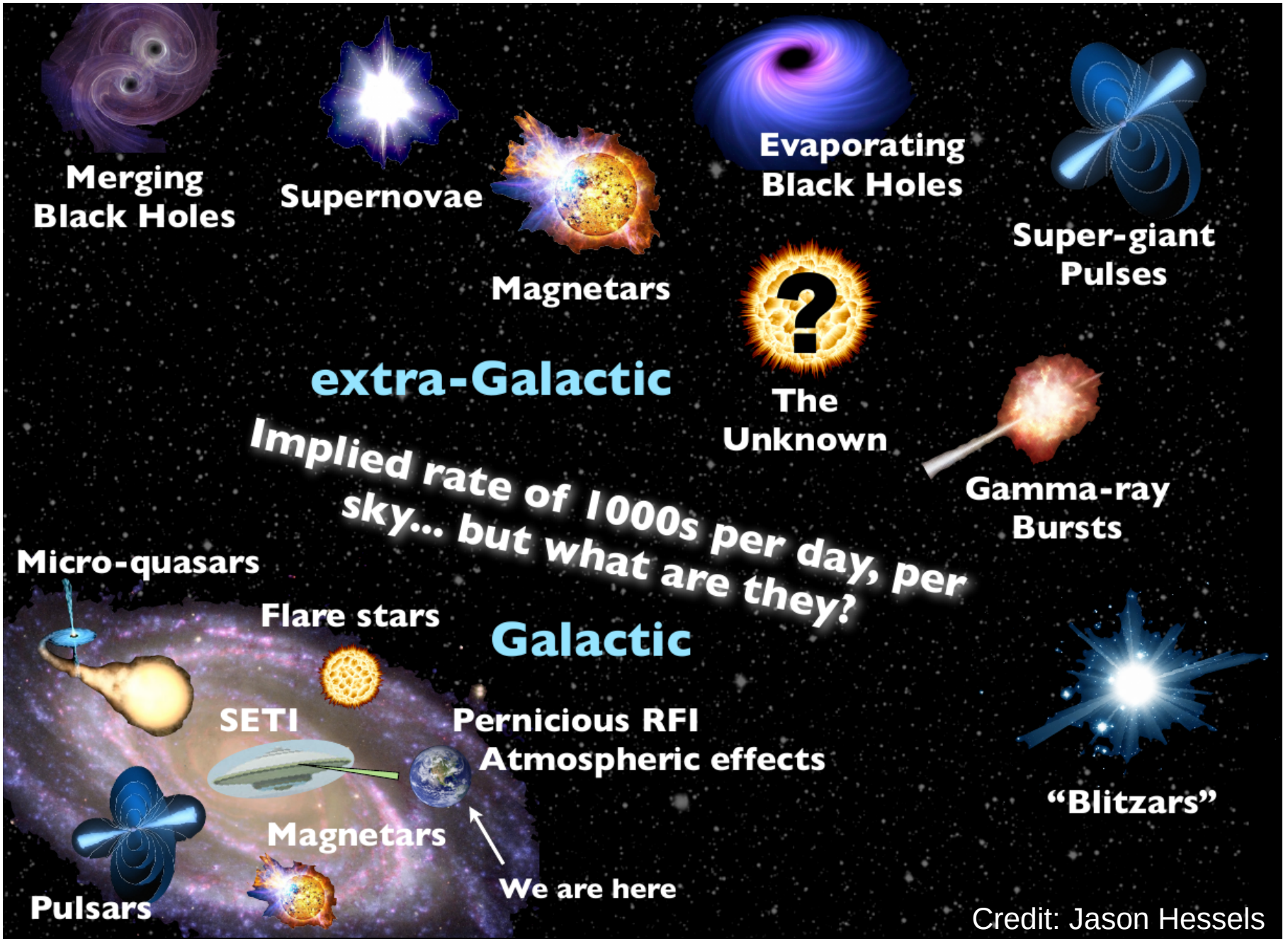
Spitler et al. 2014

DM = 557 pc/cm^3
Distance ~ 1.0 Gpc
Redshfit ~ 0.26



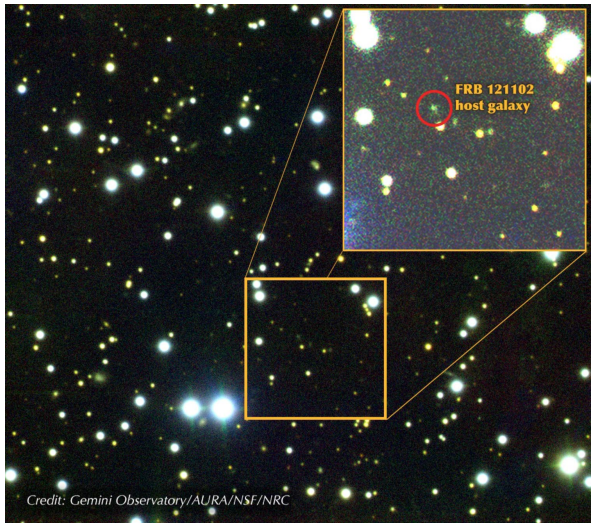
Scholz et al. 2016

So, but what are they?

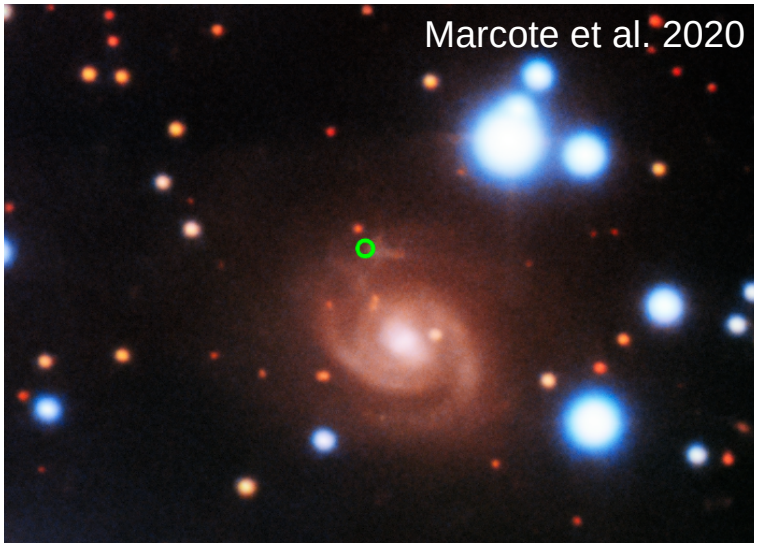


Key ingredients to help understand FRBs

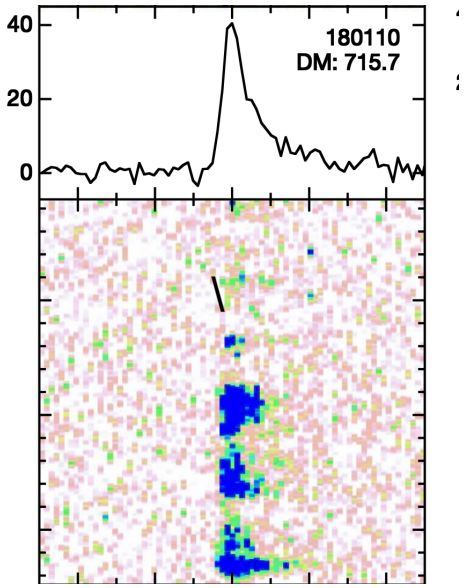
Host galaxies



Local Environment

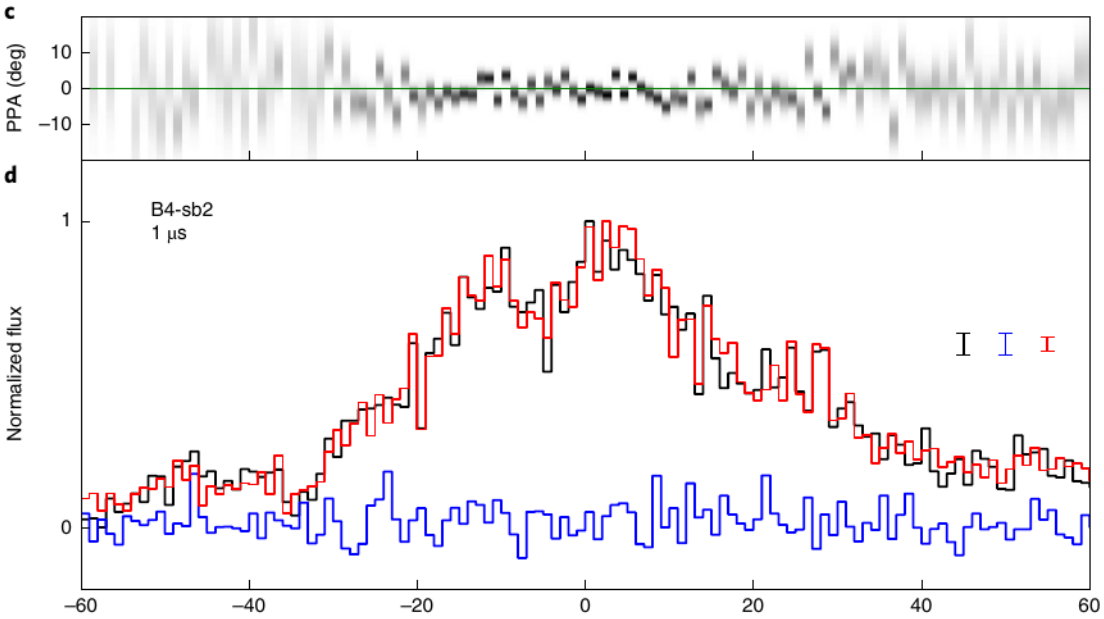


Spectral coverage, aka SED



Shannon et al., (2018)

Spectro-temporal polarimetry



Nimmo et al. 2021

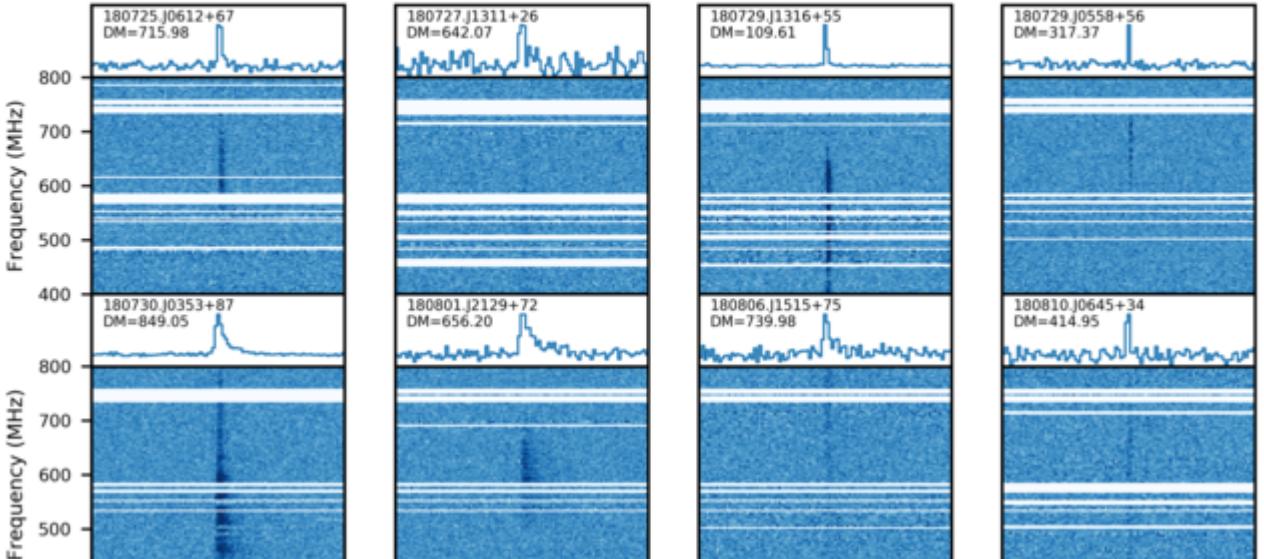
FRB hunting machines

CHIME/FRB – FRB hunting

CHIME/FRB Collaboration, 2019

FOV ~ 200 deg^2
→ typical localisation good to 10's arcmin
→ can go down to 10's arcsec with baseband recordings

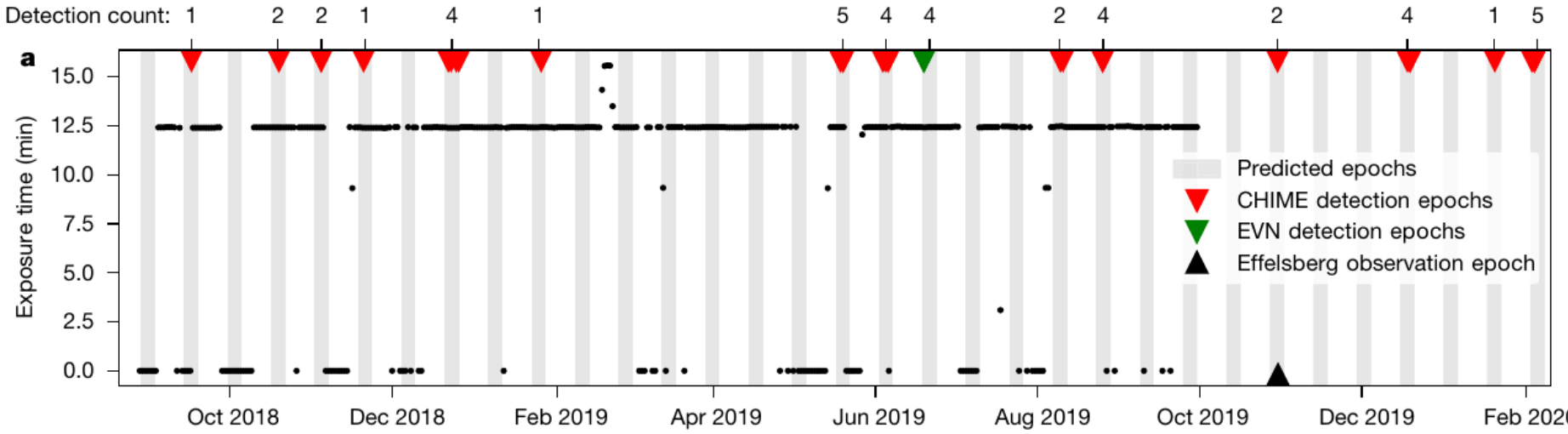
Not good enough for host assignment, let alone pinpointing environment



~650 FRBs published
20 repeaters

FRB periodic activity

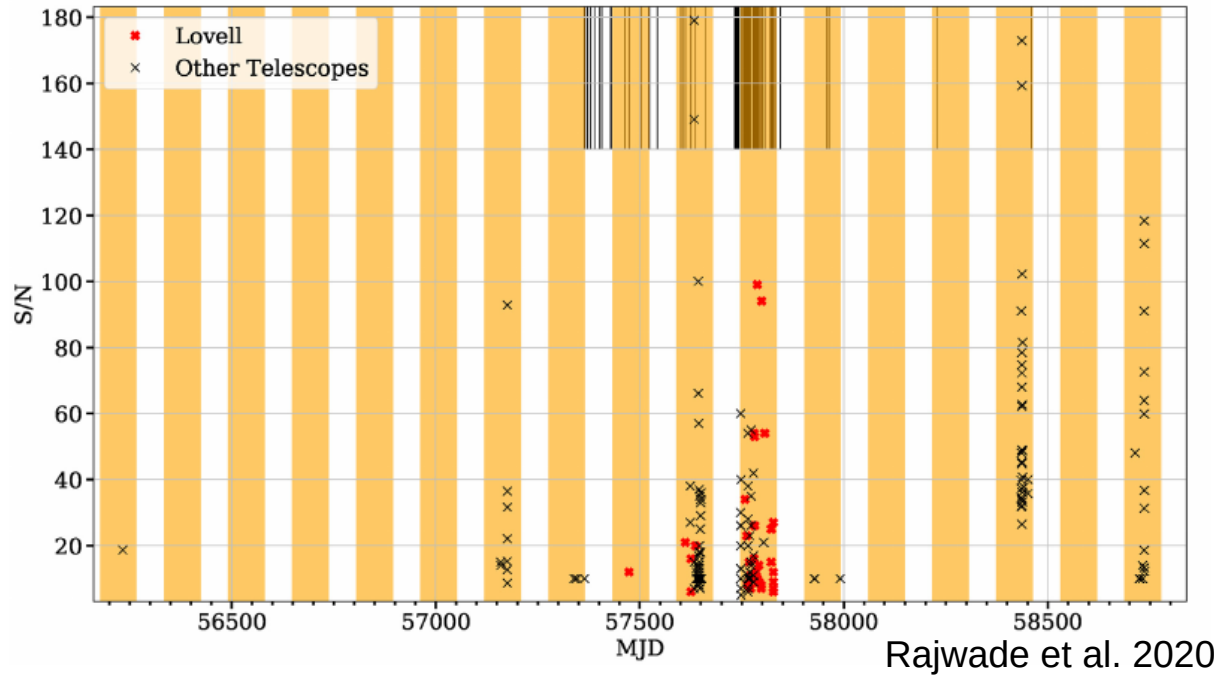
CHIME/FRB collaboration 2020



Certain periodic activity window for FRB 20180916B: **16.35 days**

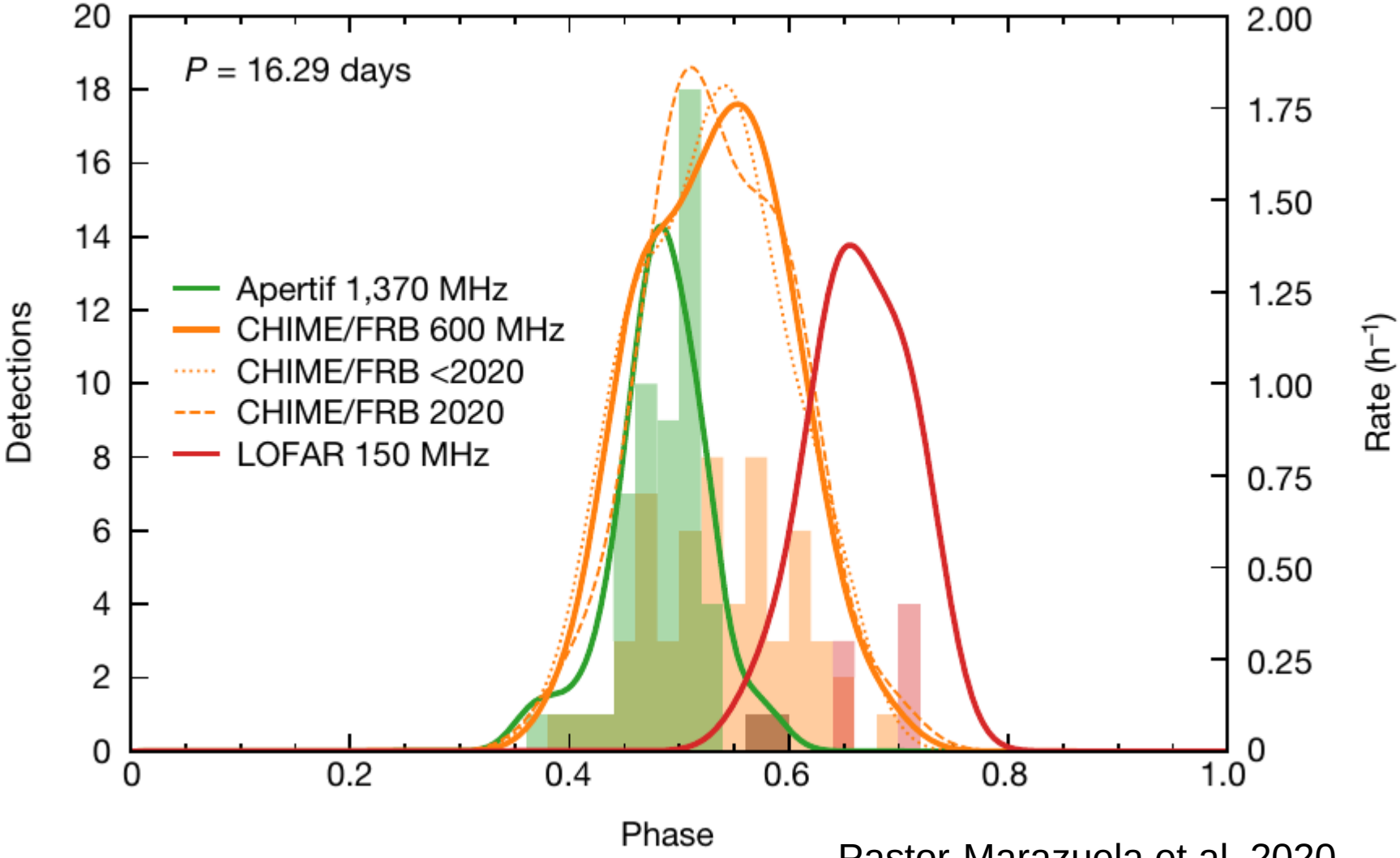
Possible periodic activity for FRB 20121102: **157 days**

→ Binary systems?
→ Precession?



Rajwade et al. 2020

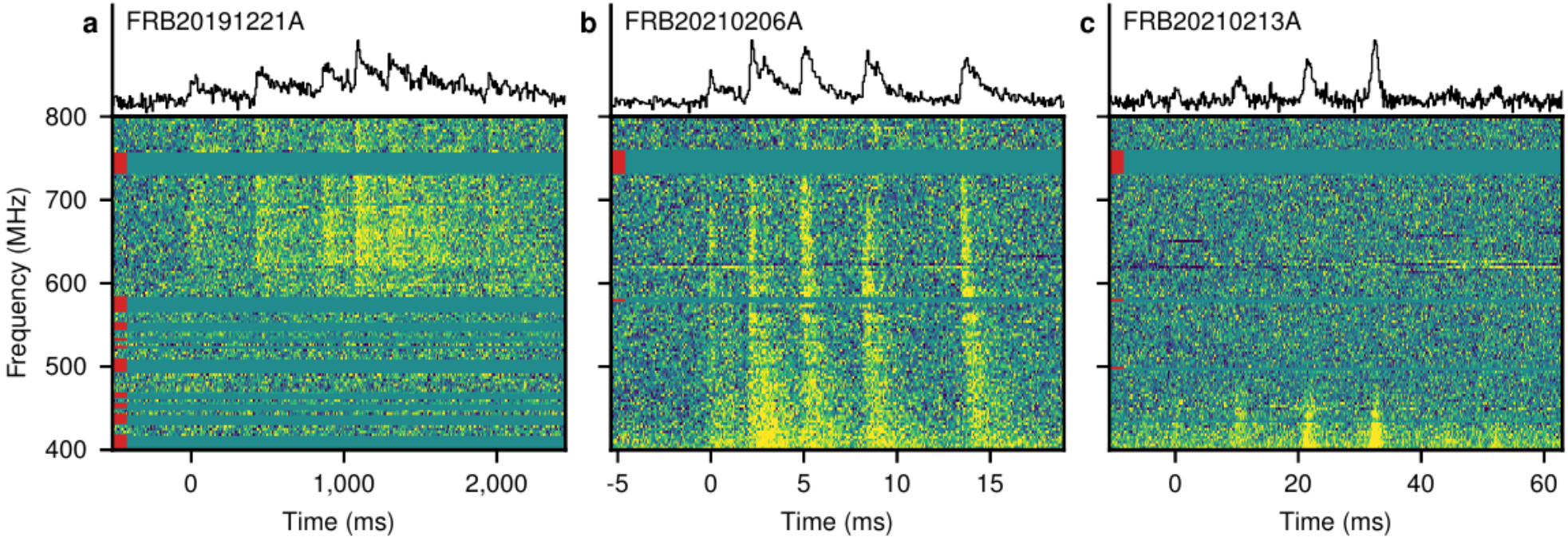
FRB chromatic periodic activity



Pastor-Marazuela et al. 2020

FRB quasi-periodic components

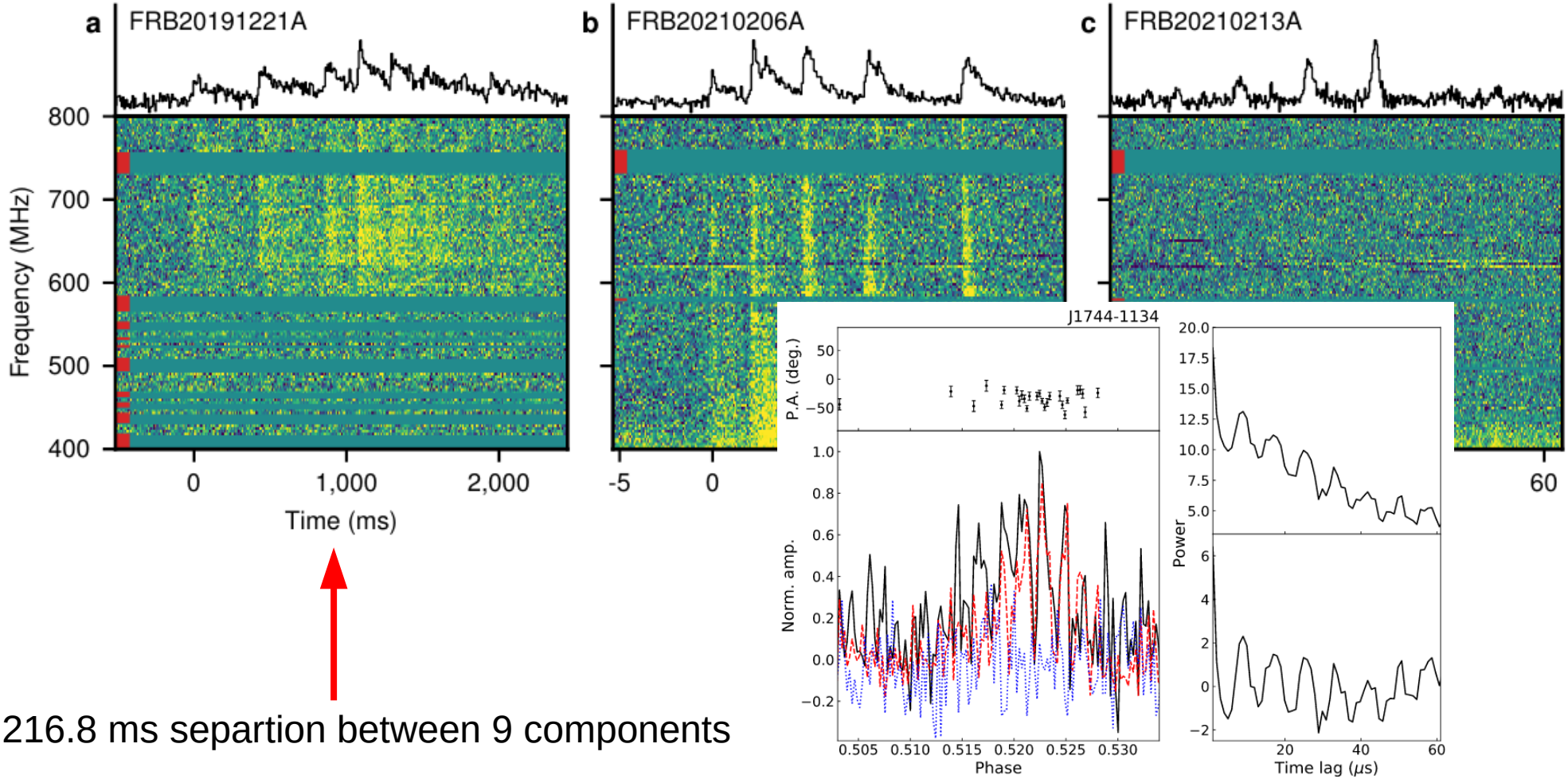
CHIME/FRB Collaboration 2021



216.8 ms separtion between 9 components

FRB quasi-periodic components

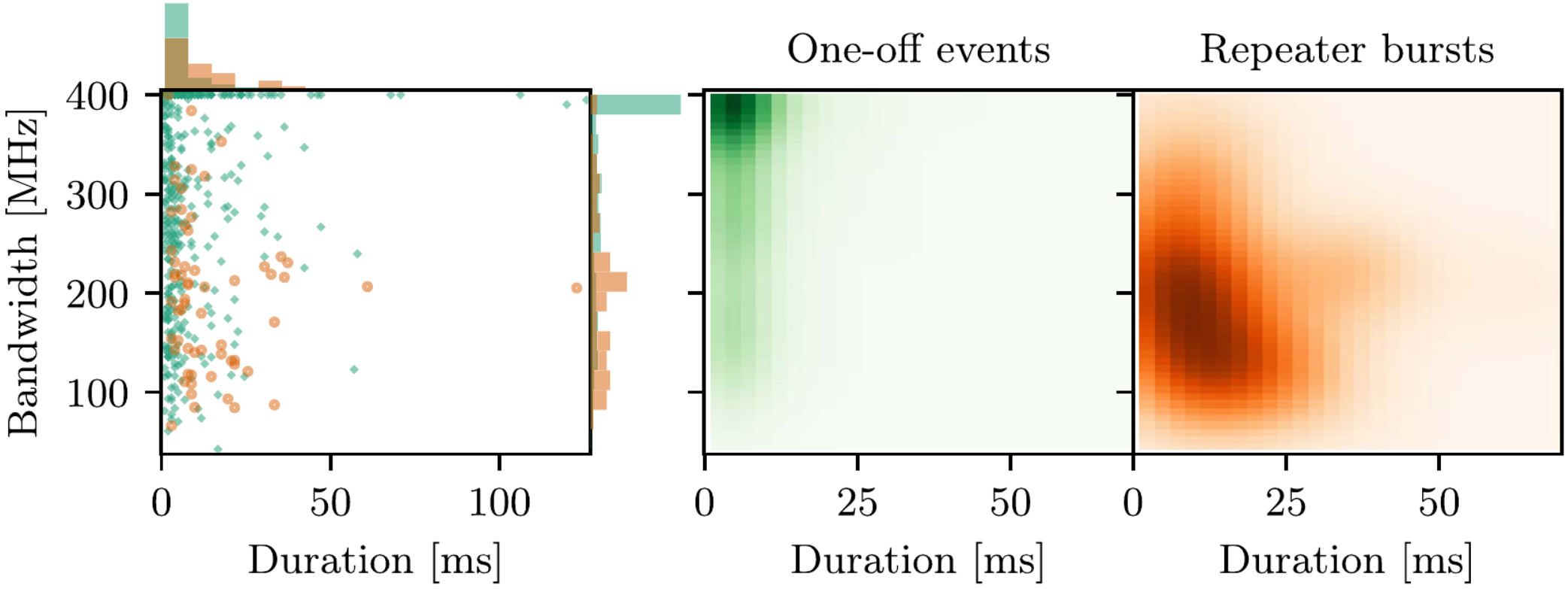
CHIME/FRB Collaboration 2021



216.8 ms separtion between 9 components

Liu et al. 2022

Morphologically, repeaters seem **statistically different** from one-offs

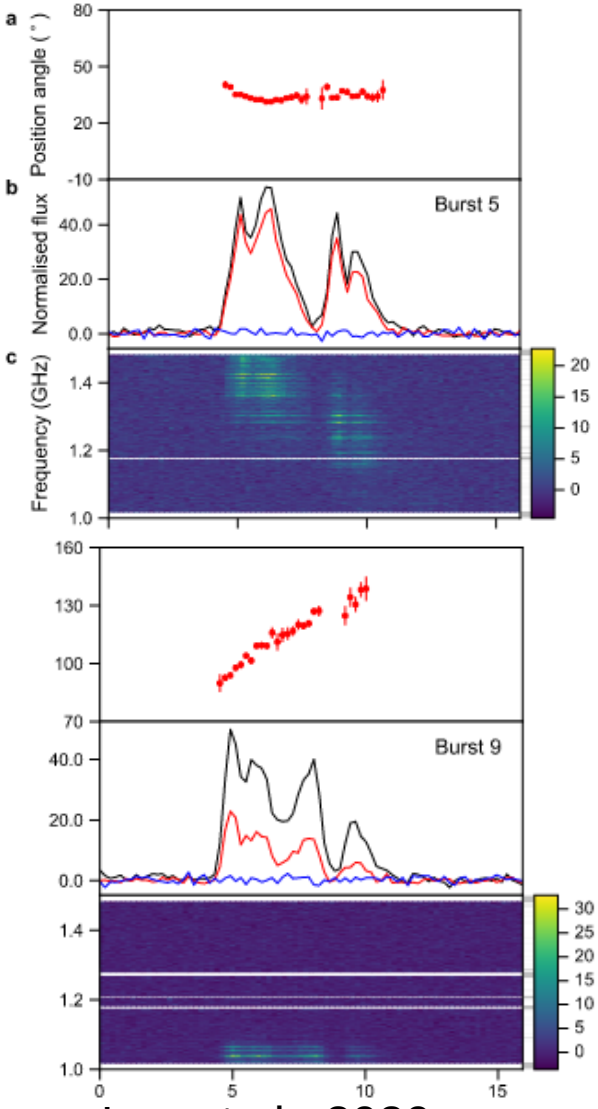


On average, **repeaters**
have **longer duration** and
are **narrower in bandwidth**

Beaming? Propagation? Intrinsic?

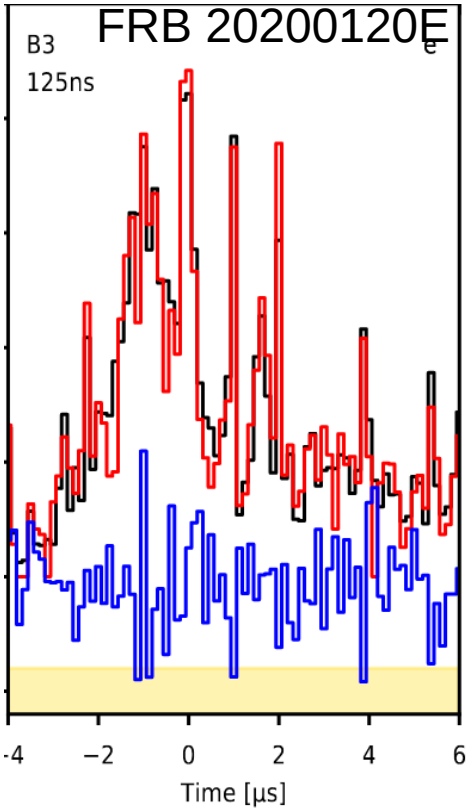
FRB polarimetry

FRB 20180301

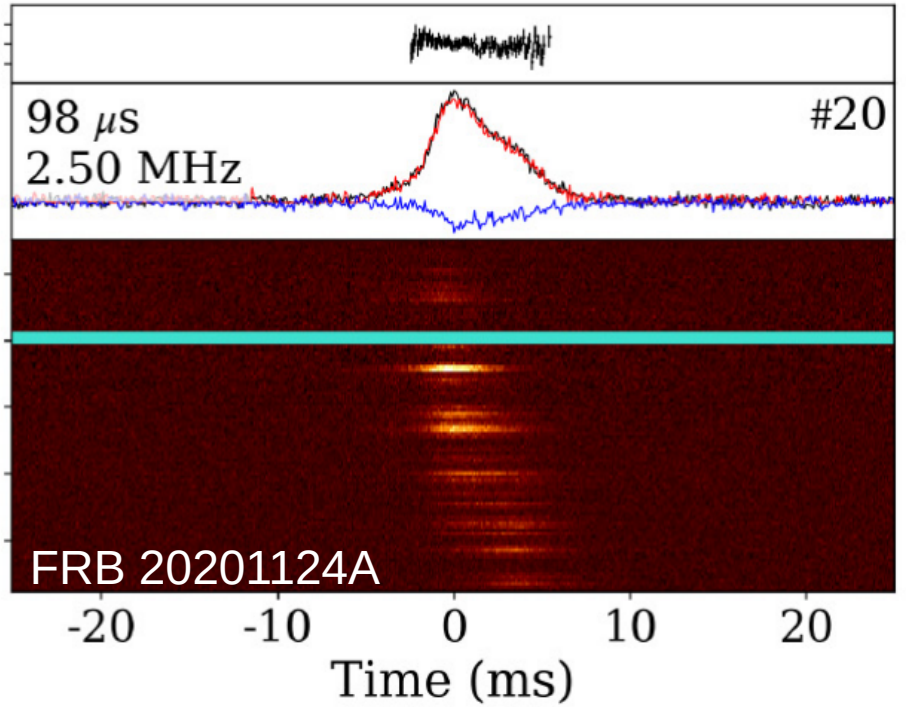


Luo et al., 2020

- Variable PPA
- Microstructure
- Hints of circular polarisation

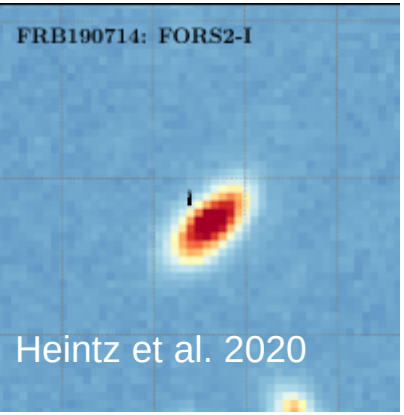


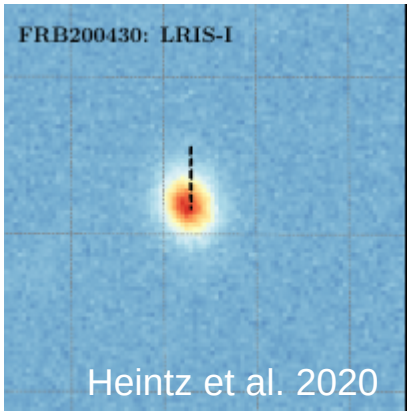
Nimmo et al., 2021

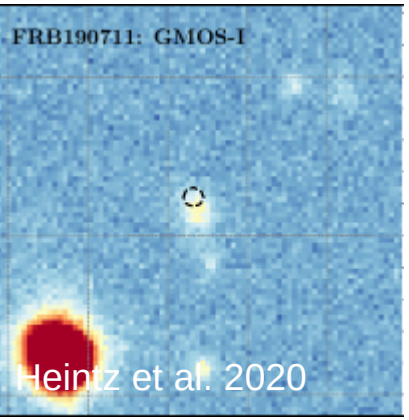


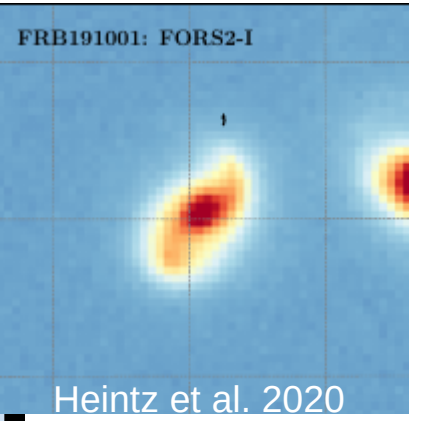
Hilmarsson et al., 2021

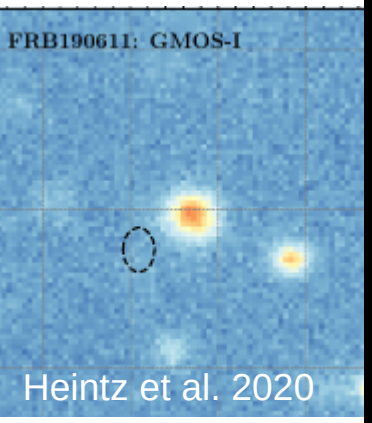
ASKAP – FRB hunting+localisation

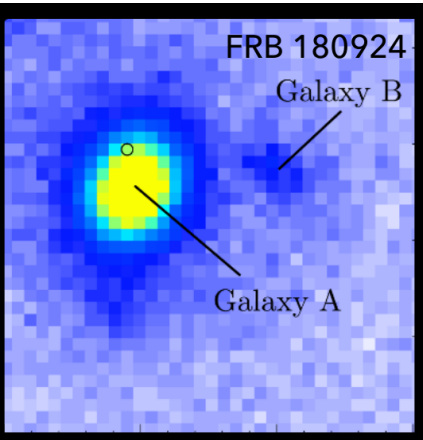




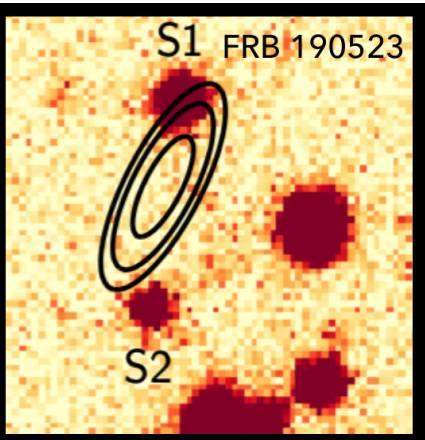




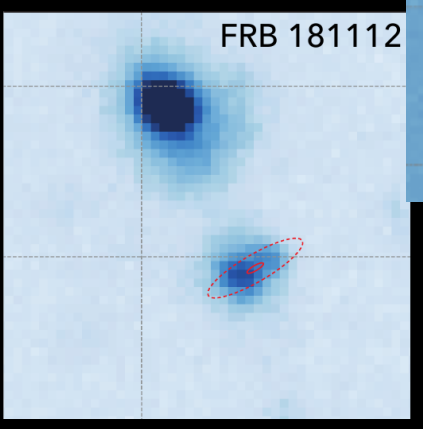




Bannister et al. 2019

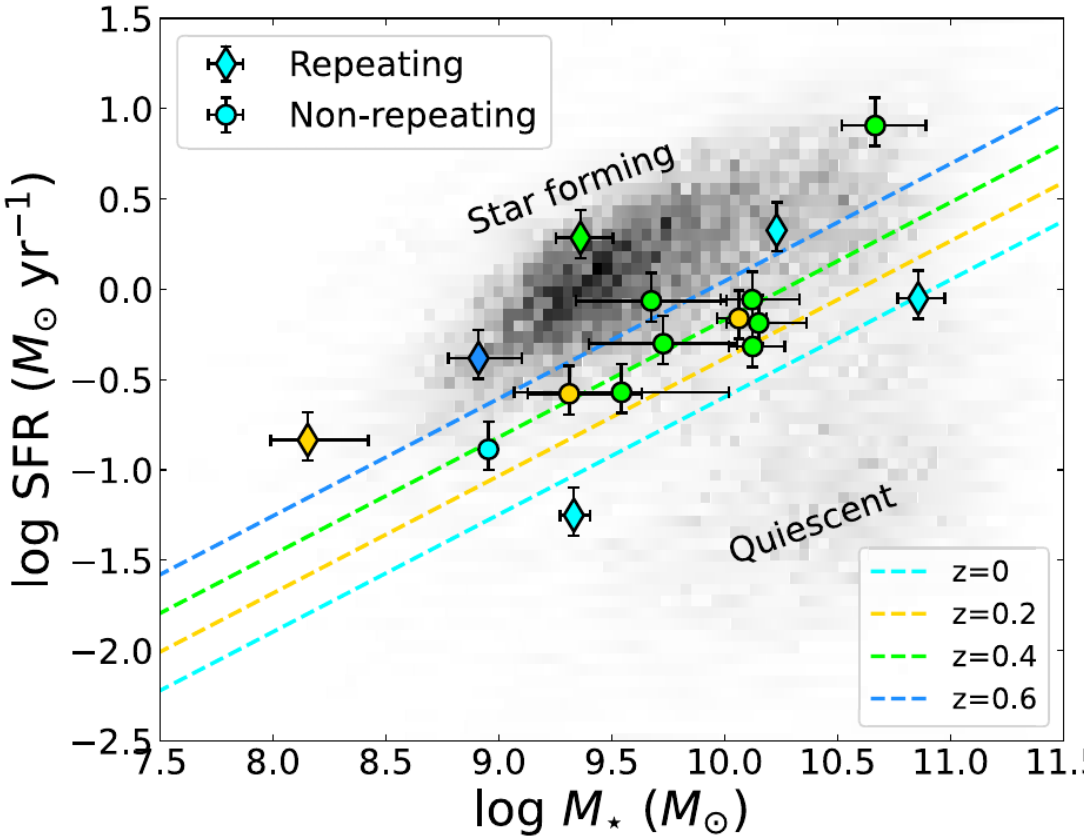


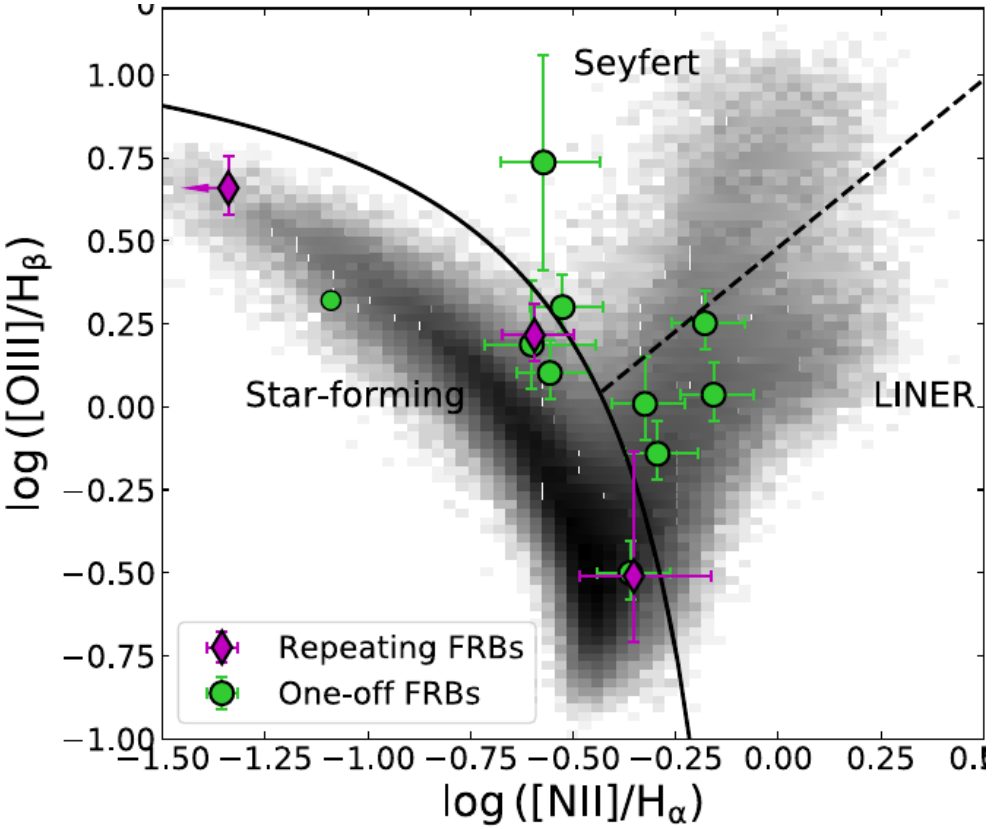
Ravi et al. 2019



Prochaska et al. 2019

FRB hosts





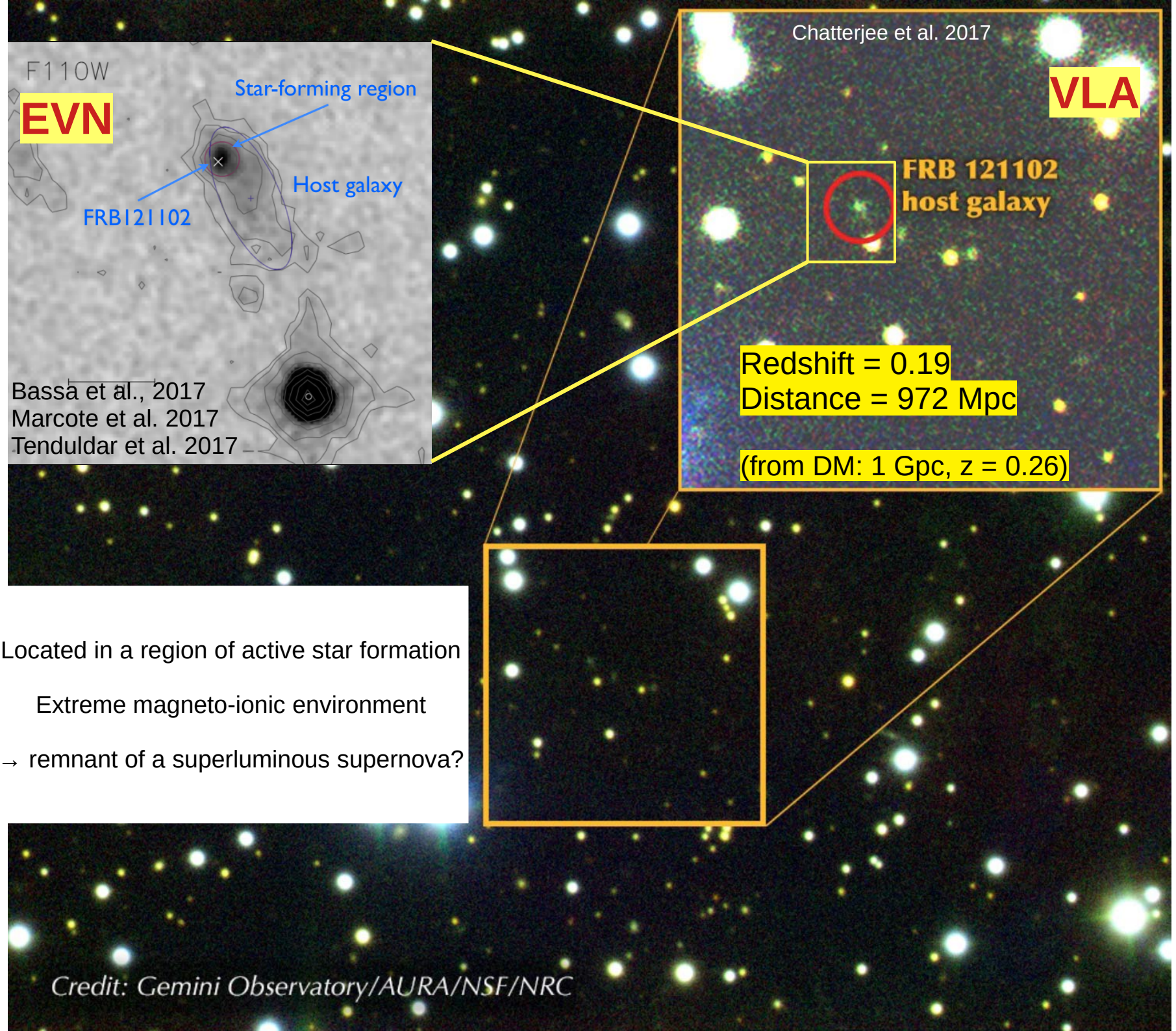
Bhandari et al. 2022

Are FRBs associated with Star formation?

Local environment – targeted searches with interferometric arrays

European VLBI Network

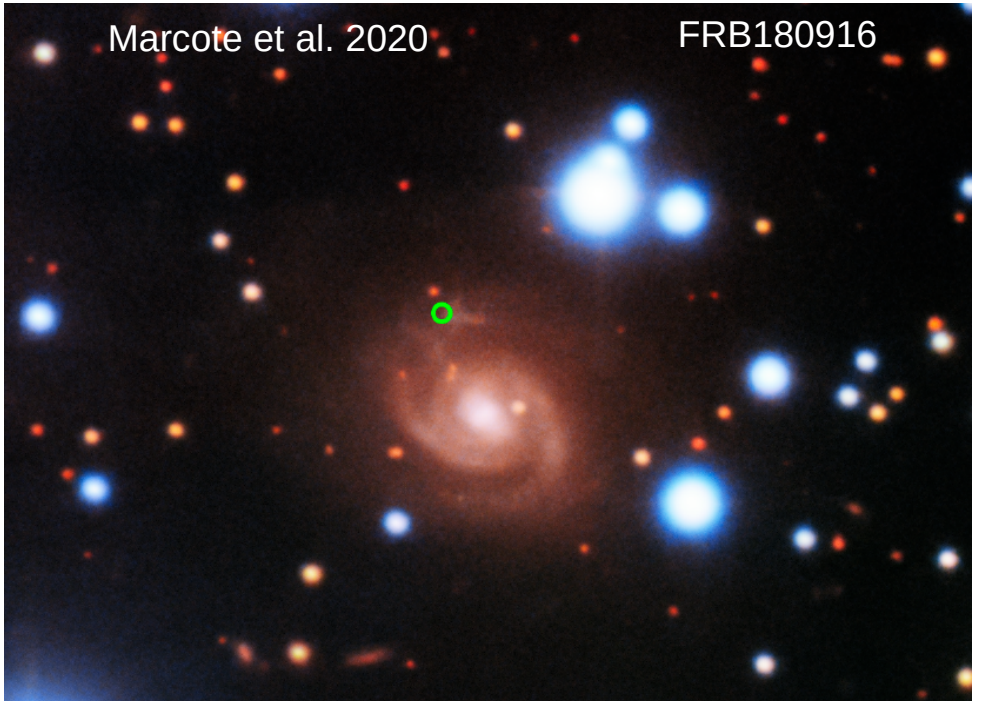
Jansky Very Large Array

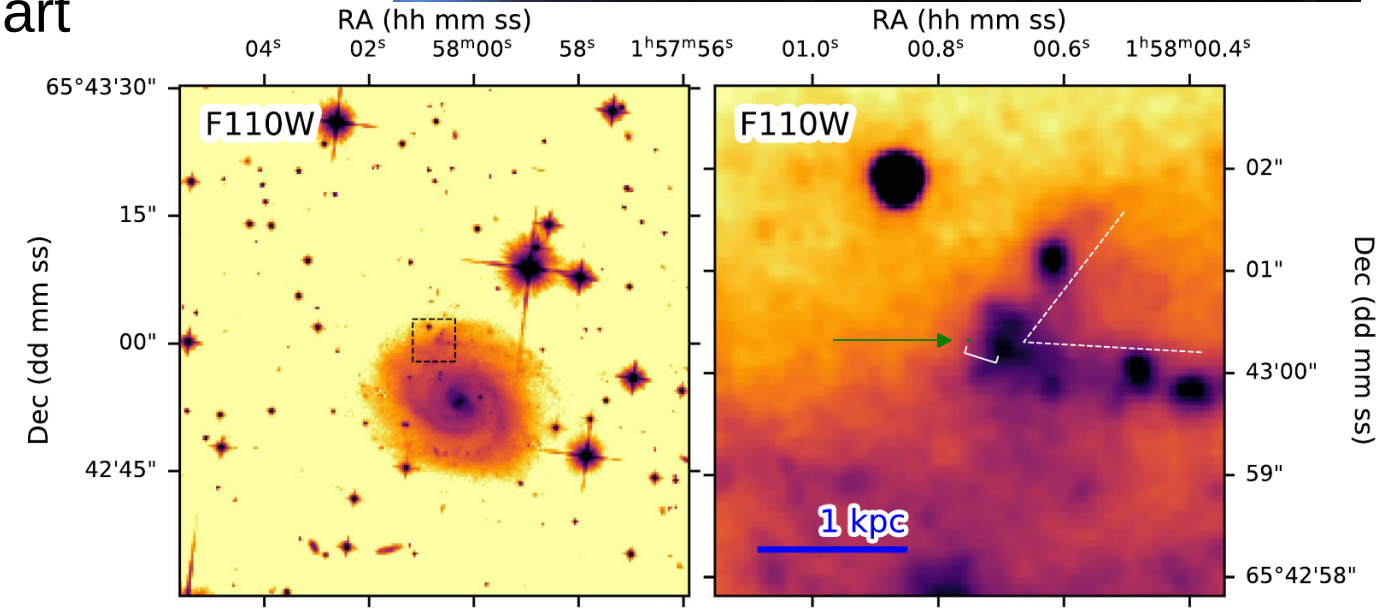

F110W
EVN
Star-forming region
Host galaxy
FRB121102
Bassa et al., 2017
Marcote et al. 2017
Tenduldar et al. 2017
Chatterjee et al. 2017
VLA
FRB 121102
host galaxy
Redshift = 0.19
Distance = 972 Mpc
(from DM: 1 Gpc, z = 0.26)
Located in a region of active star formation
Extreme magneto-ionic environment
→ remnant of a superluminous supernova?
Credit: Gemini Observatory/AURA/NSF/NRC

FRB 20180916B

Close to but offset from a knot of Active star formation

- Assuming a young magnetar origin, too far even for highest known kick velocity
- No persistent counterpart

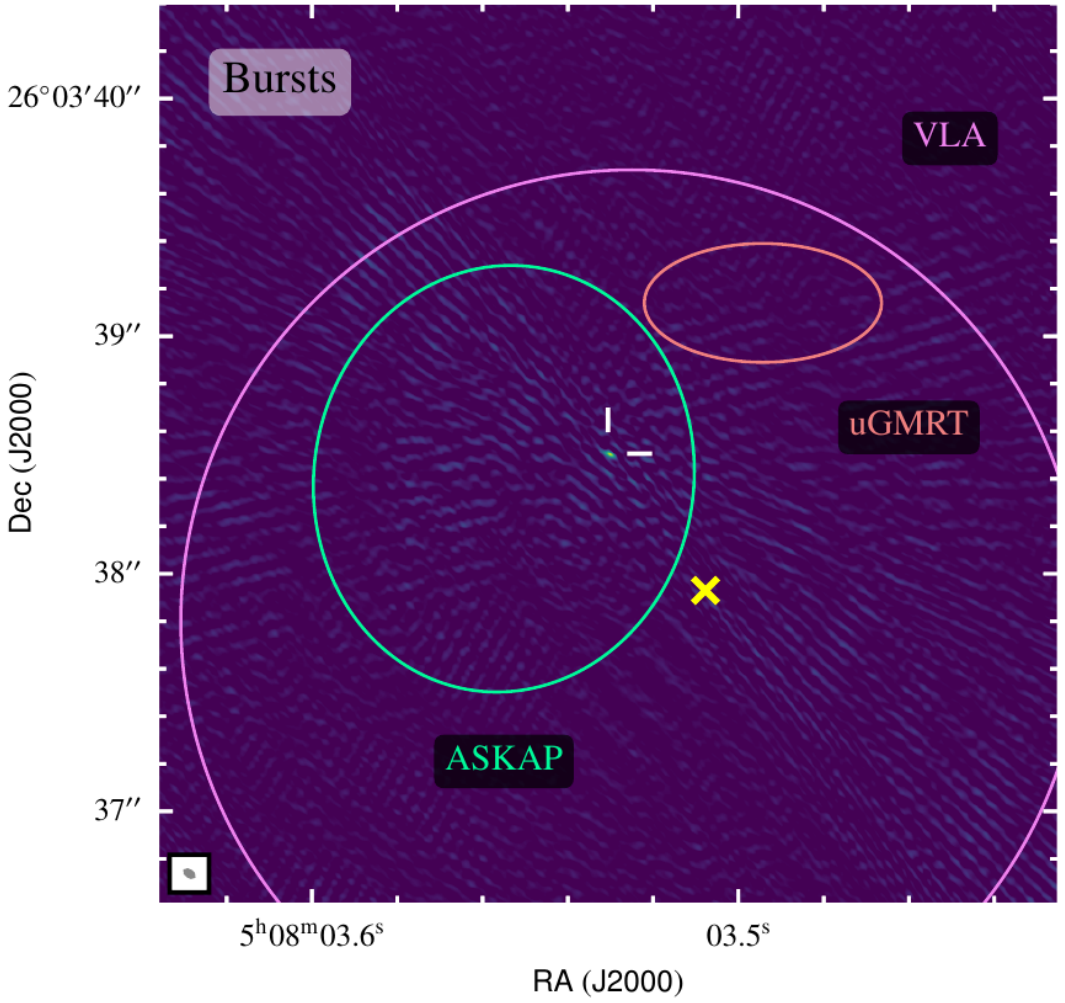


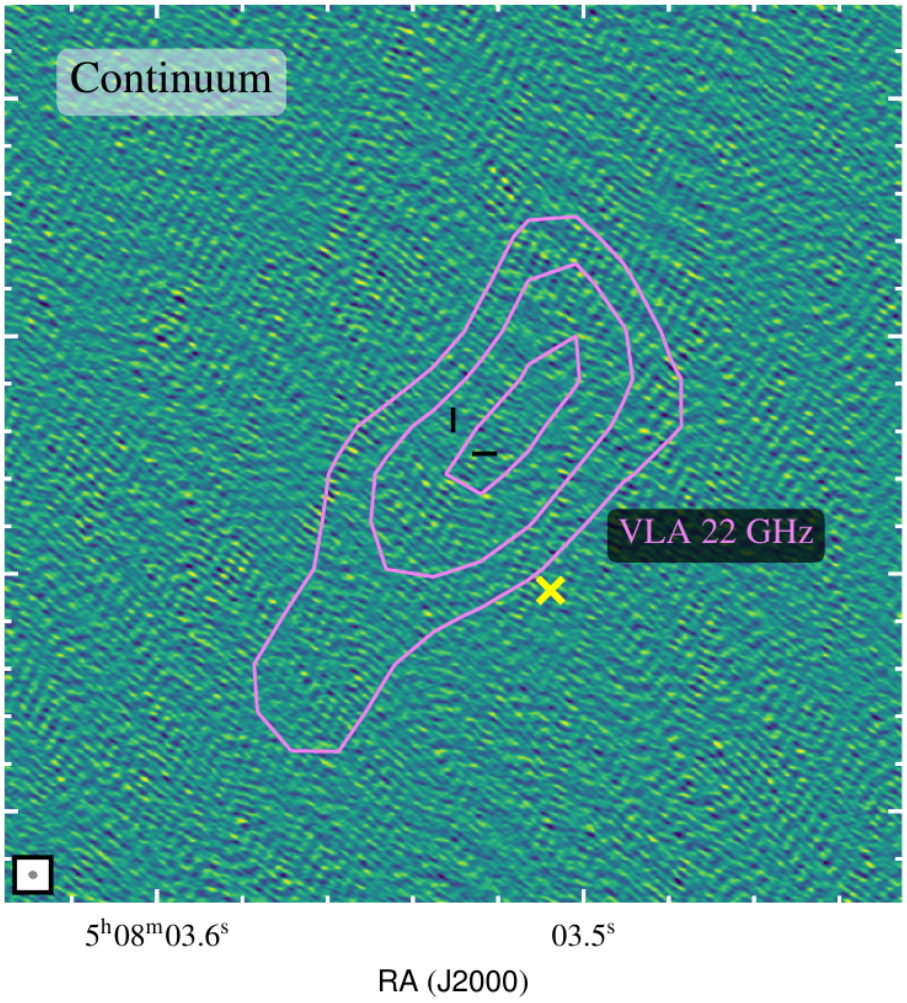


Tendulkar et al. 2021

FRB 20201124A – an FRB in a **star-forming region**

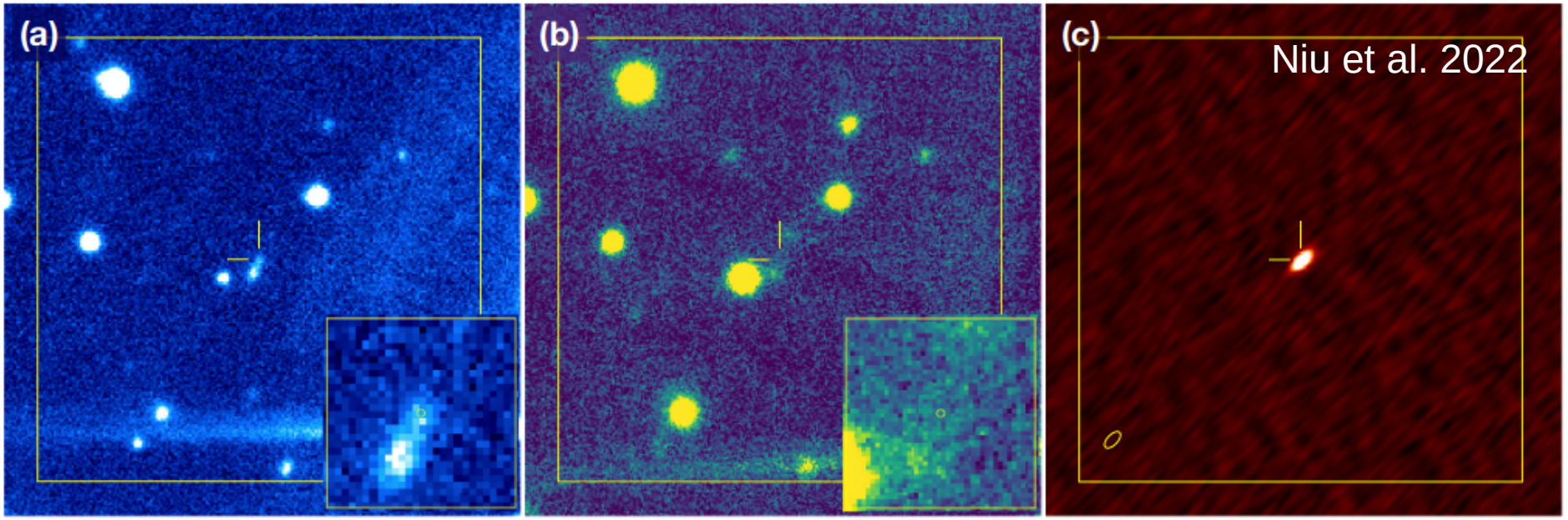
Nimmo et al., 2022, ApJL





No compact persistent counterpart on scales < 160 mas → extended emission is SFR slightly offset from core of star formation → great case for **young magnetar origin**

FRB 20190520B – the R1 twin



- Second FRB with apparently compact (~arcsec) persistent counterpart
- Extremely high host contribution to DM
- Also very active
- Hence referred to as the “R1 twin”

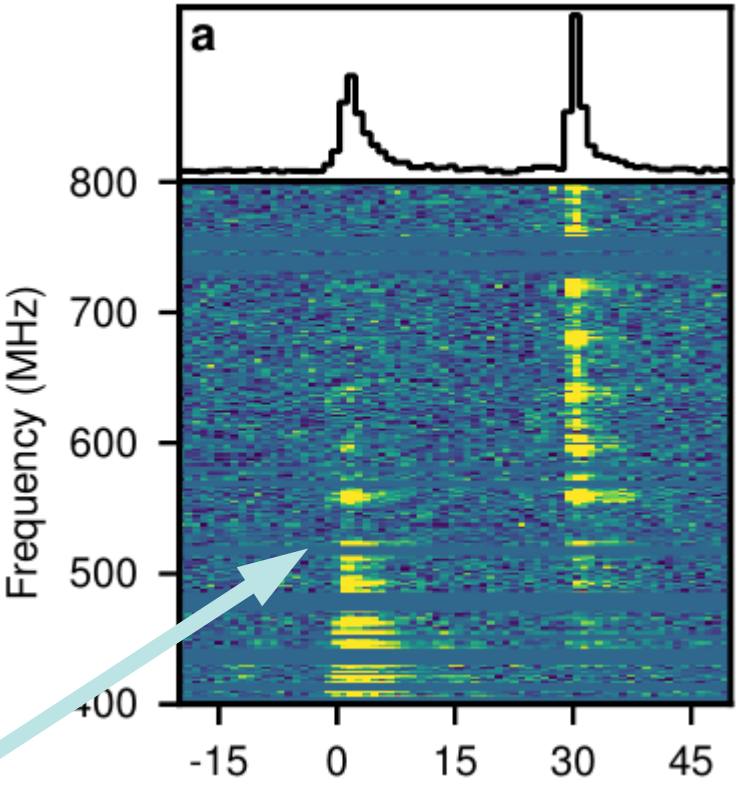
Bursts from a GALACTIC magnetar

SGR 1935+2154

1.5 MJy ms

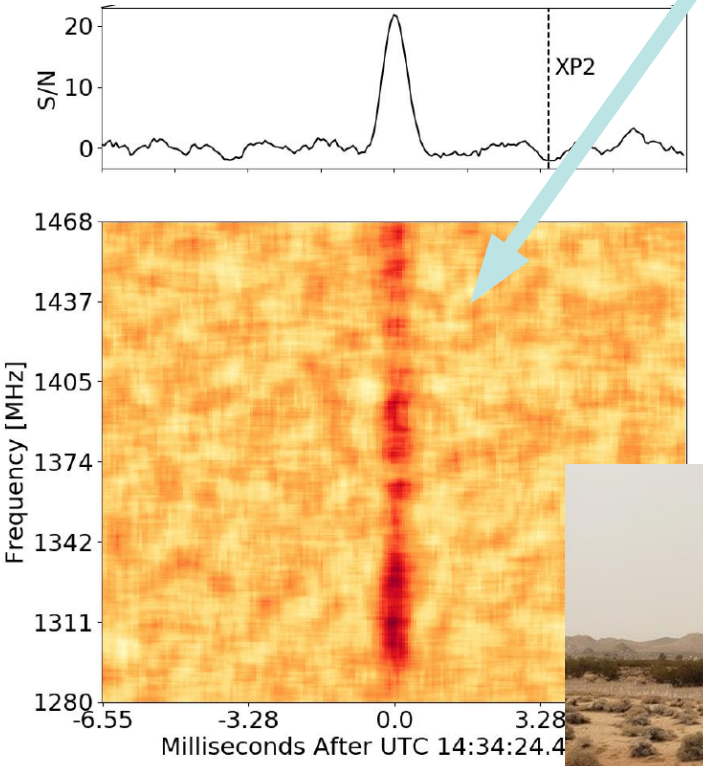
CHIME

600 MHz



CHIME/FRB collaboration et al. 2020

1350 MHz



Bochenek et al. 2020

STARE2

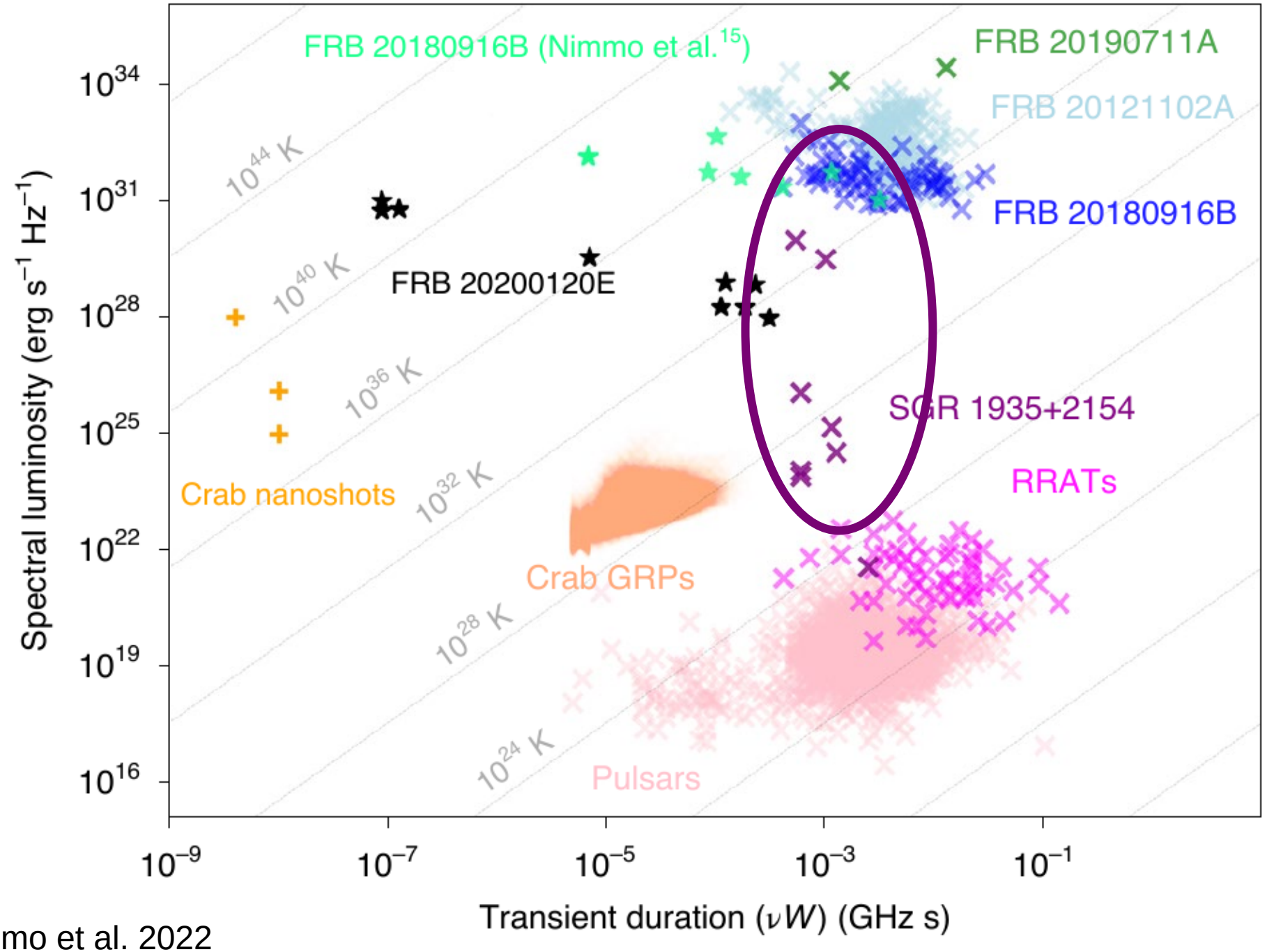
Credit: NASA/JPL-Caltech

700 kJy ms

ATel #13681, 28 April

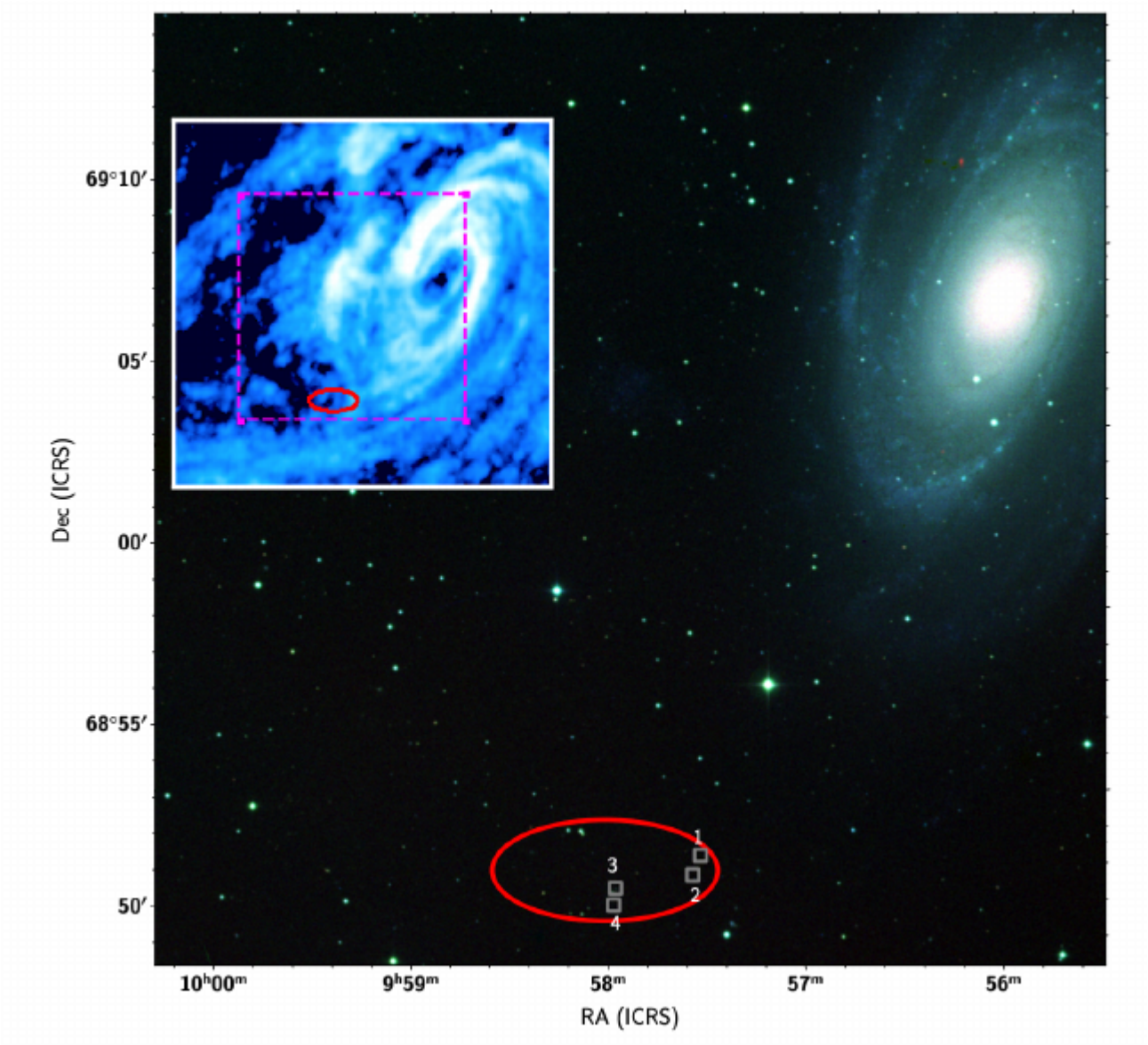
ATel #13684, 29 April

Transient Phase Space – linking FRBs and Pulsars



Nimmo et al. 2022

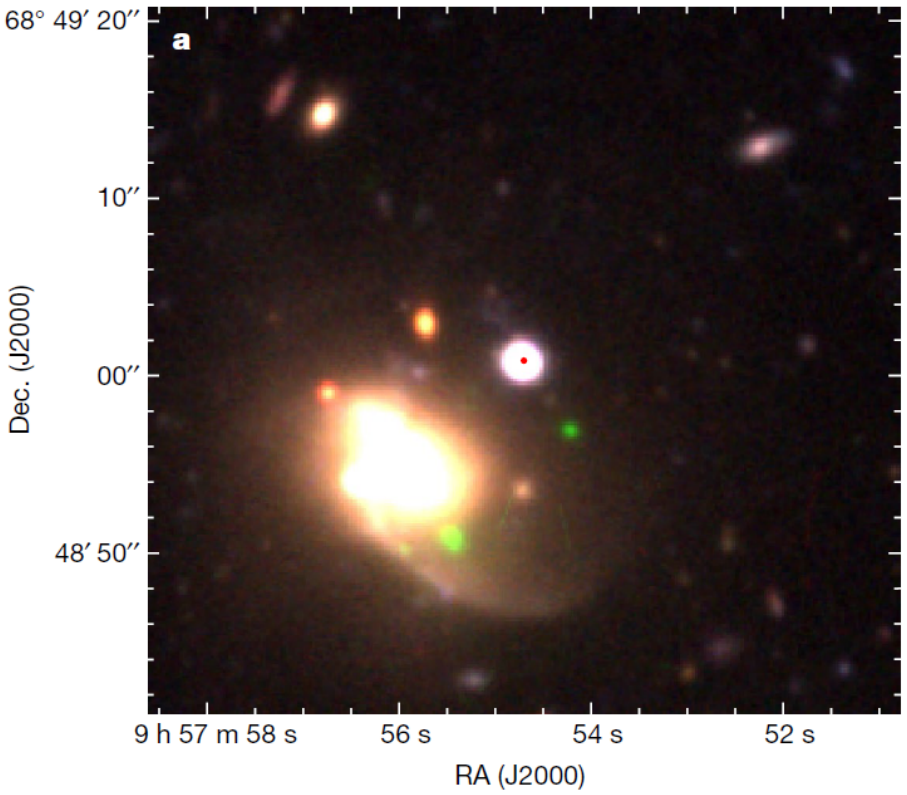
And there is FRB 20200120E close to M81

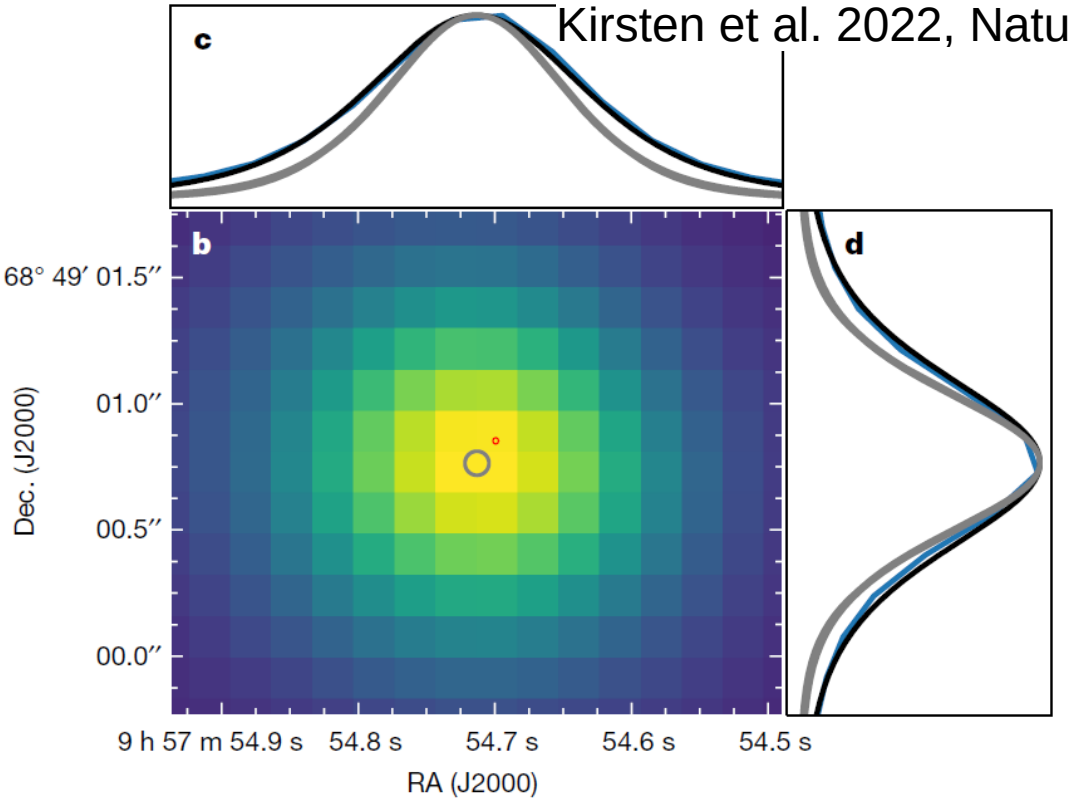


Bhardwaj et al. 2021

1. M81 HII region
2. X-ray source
3. M81 Globular cluster
4. Radio source

FRB 20200120E – and FRB in a **globular cluster** right in our **backyard**





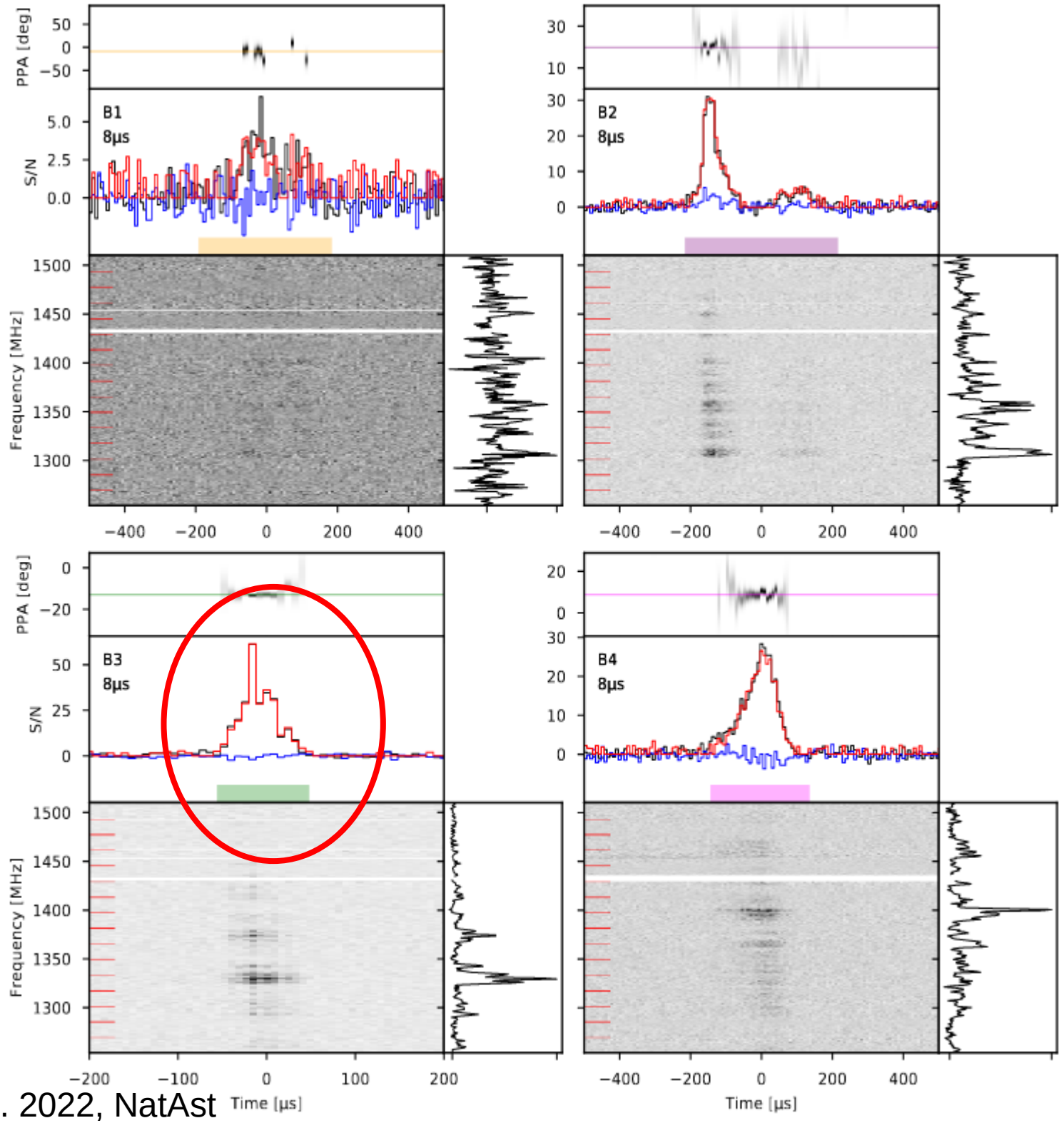
Kirsten et al. 2022, Nature

In a GC that is part of the grand design spiral galaxy **M81 at 3.6 Mpc**

Significantly offset (~116 mas = 2 pc) from optical center of GC – Hubble follow-up to come

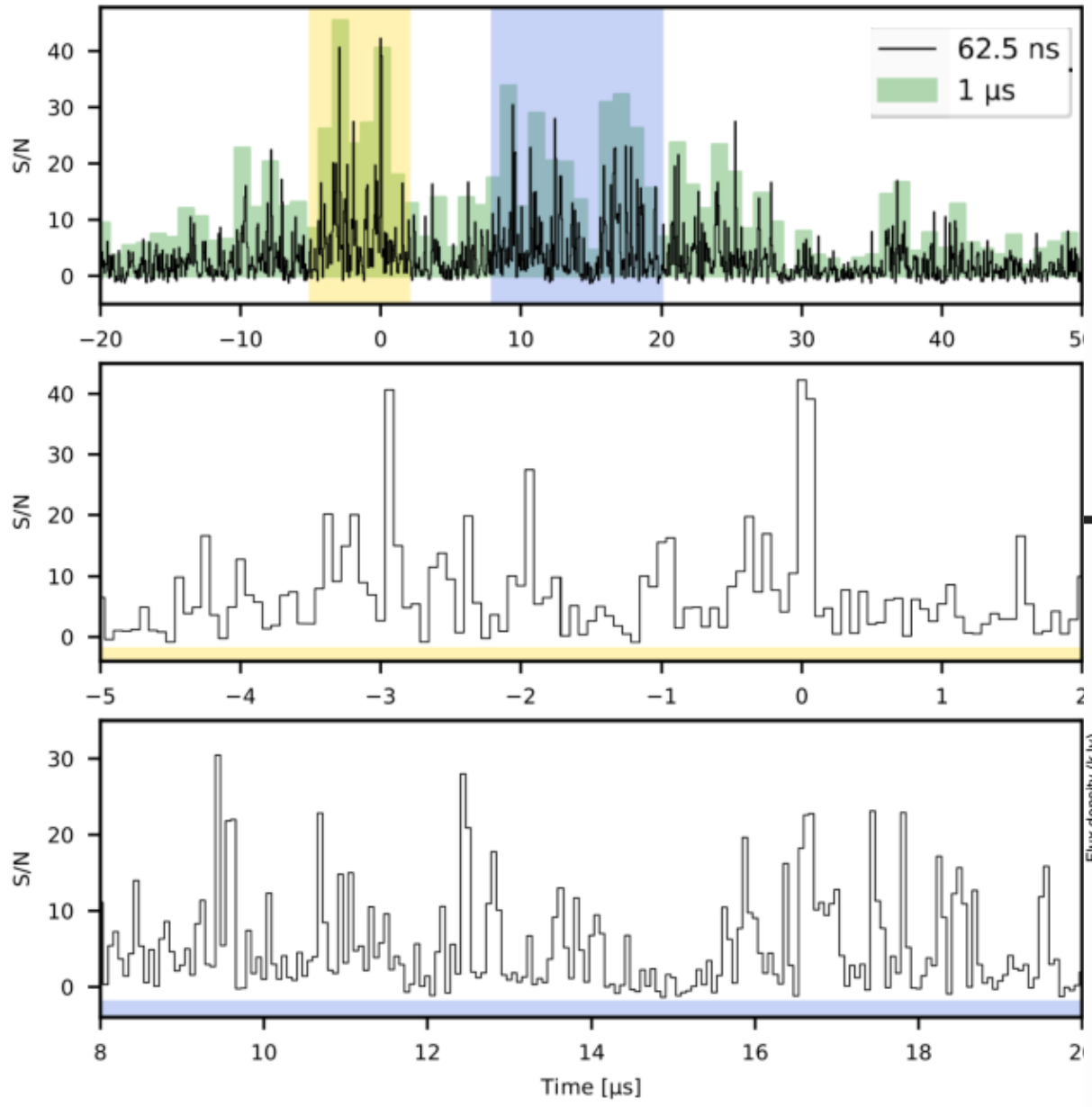
GC origin questions the FRB engine to be a magnetar formed via core-collapse SN

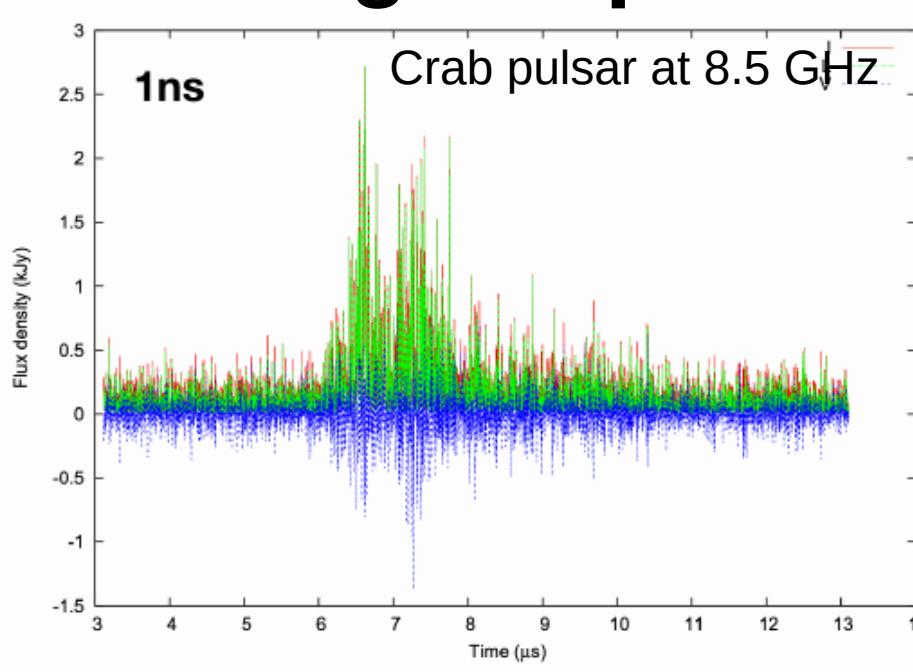
Either a completely different beast or a magnetar formed via accreation-induced collapse of a white dwarf

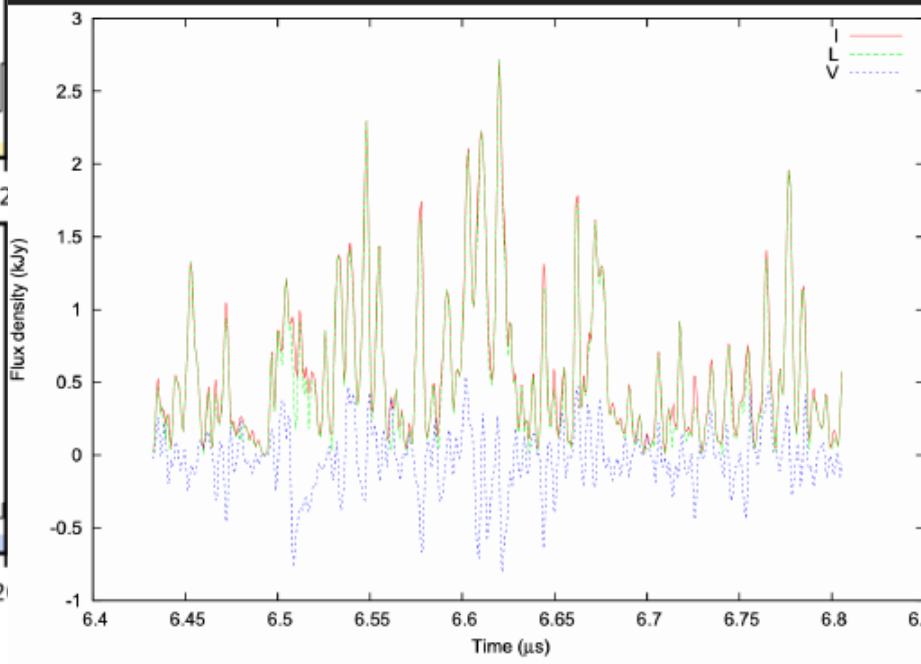


Nimmo et al. 2022, NatAst

Linking FRB 20200120E and Crab giant pulses



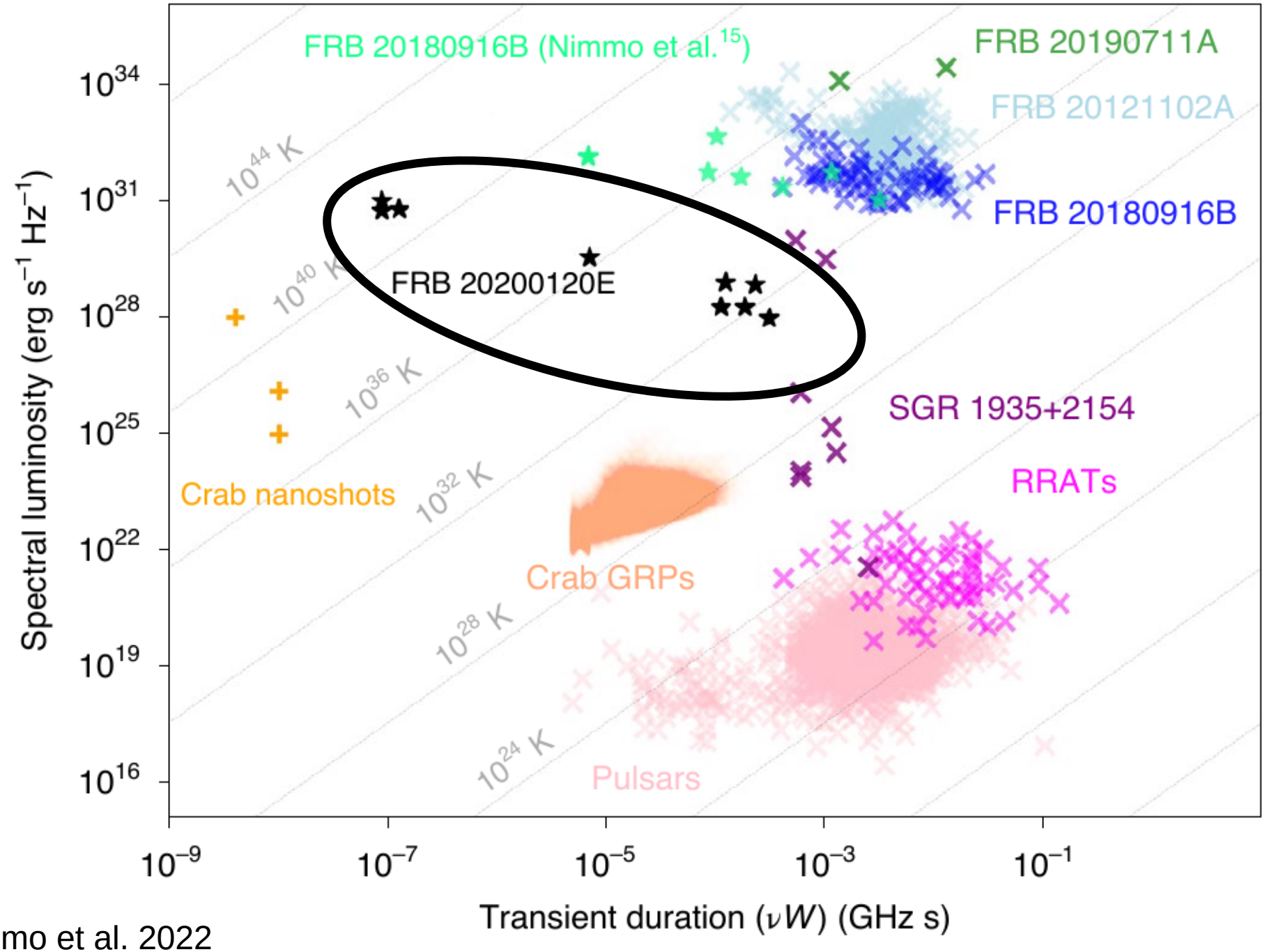




Nimmo et al. 2022, NatAst

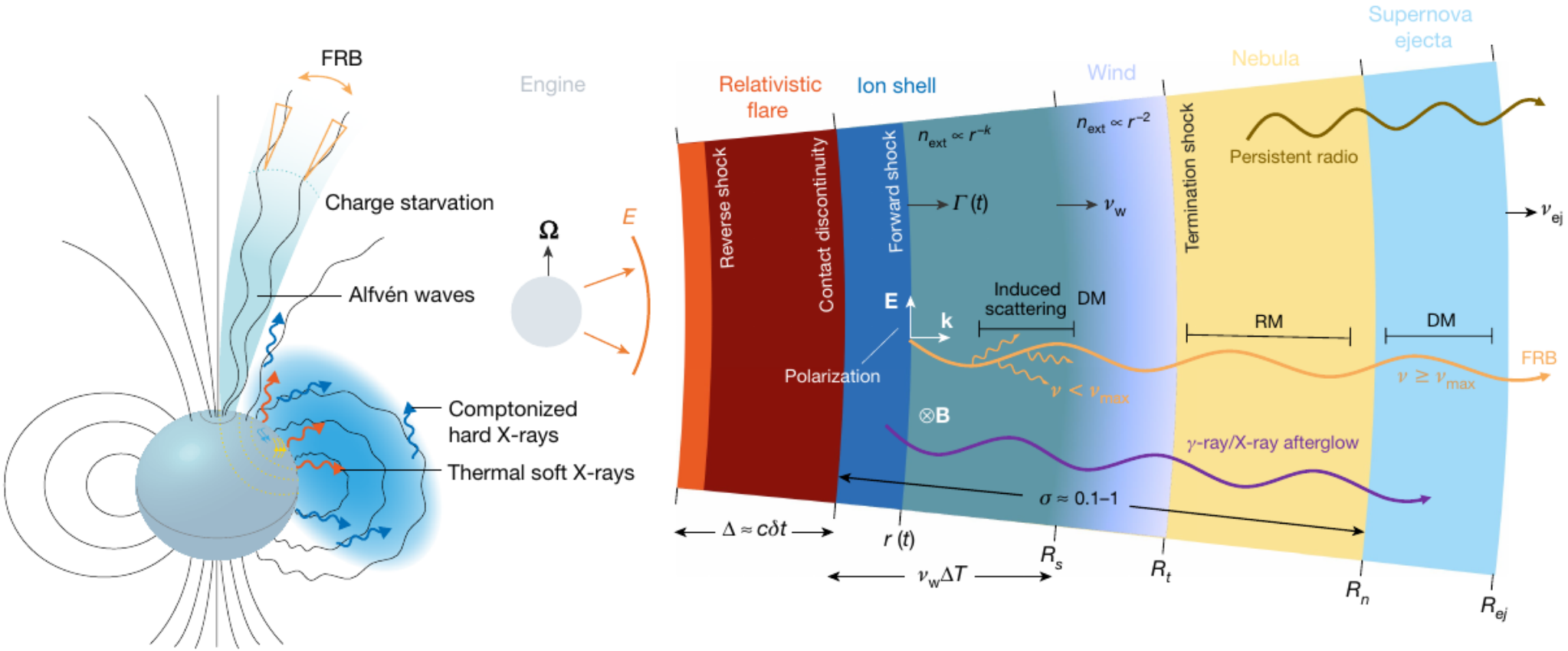
Jessner et al. 2010

Transient Phase Space – linking FRBs and Pulsars



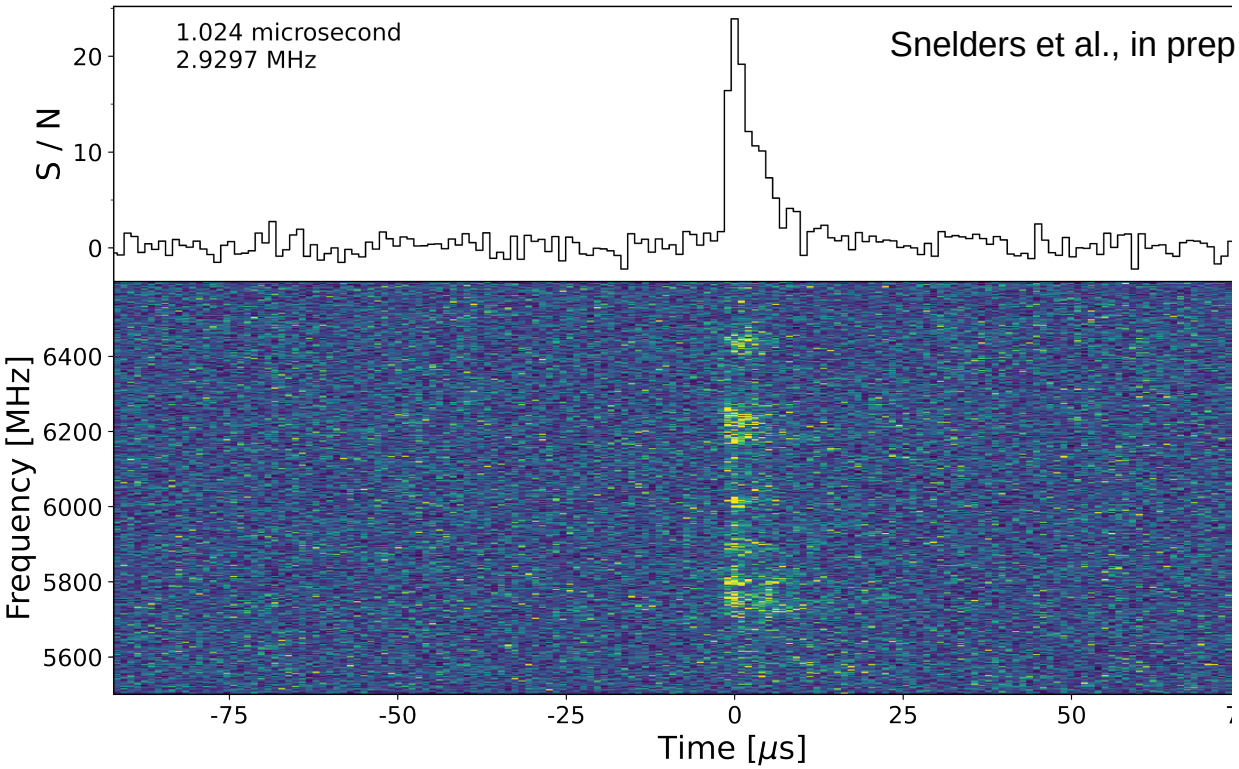
Nimmo et al. 2022

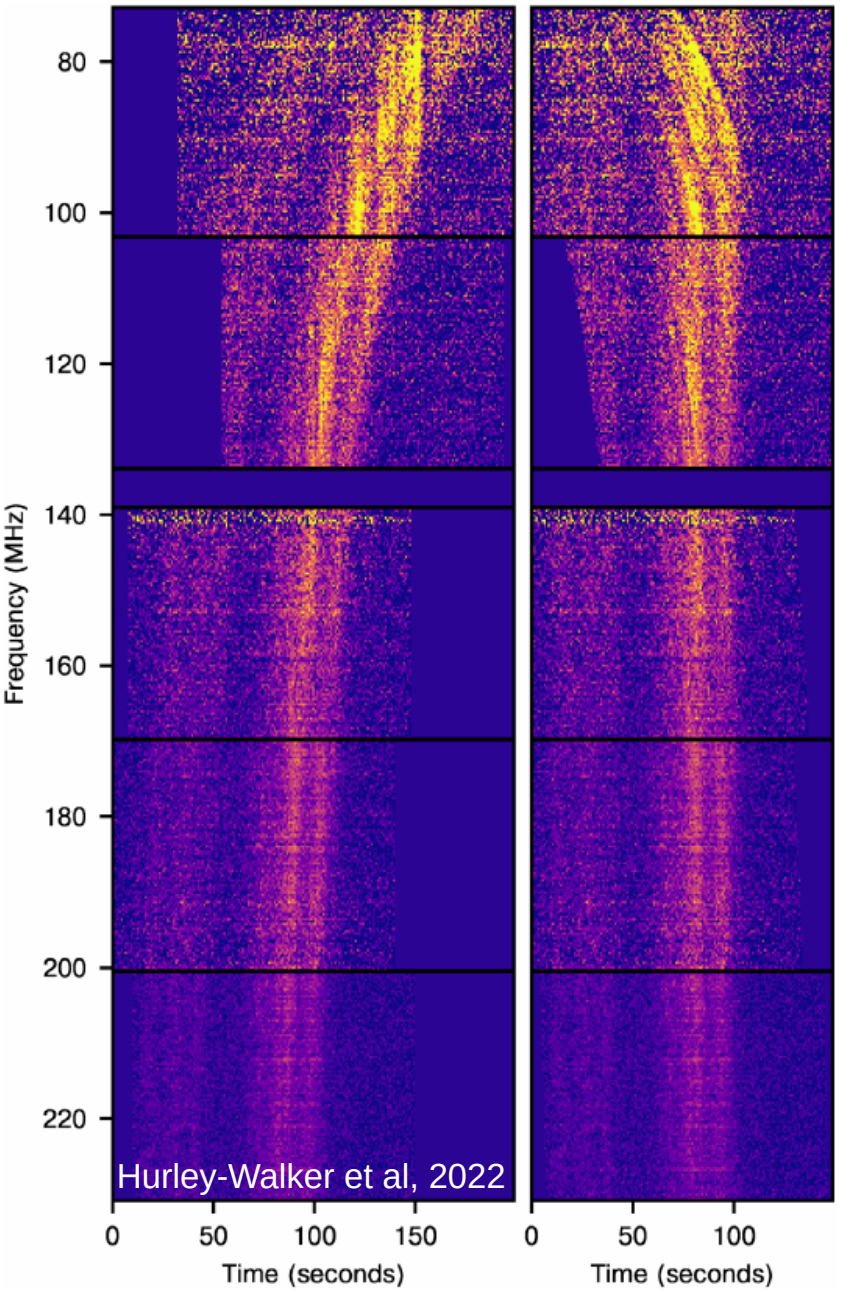
Emission mechanism models involving magnetars



Zhang, 2020, Nature

Unexplored parameter space





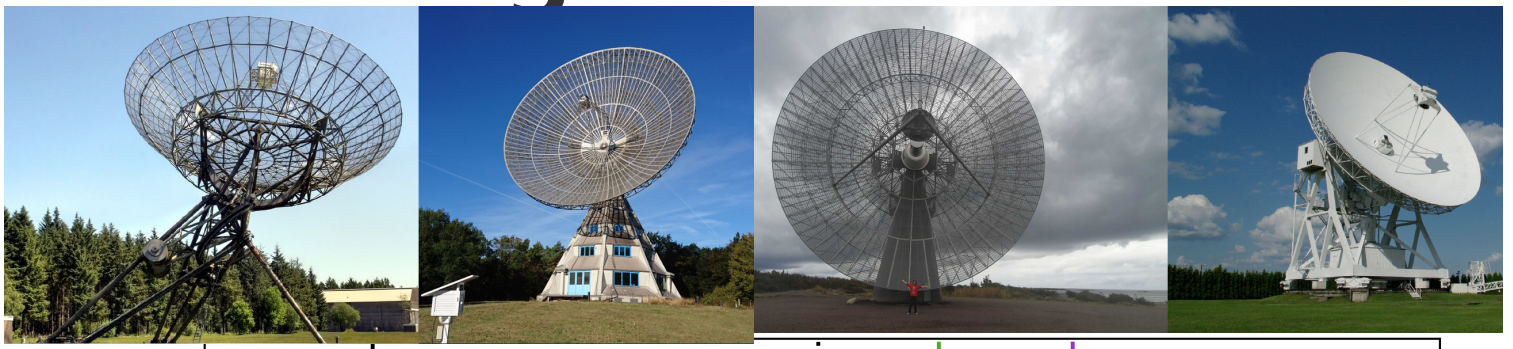
We're mostly searching for millisecond-bursts

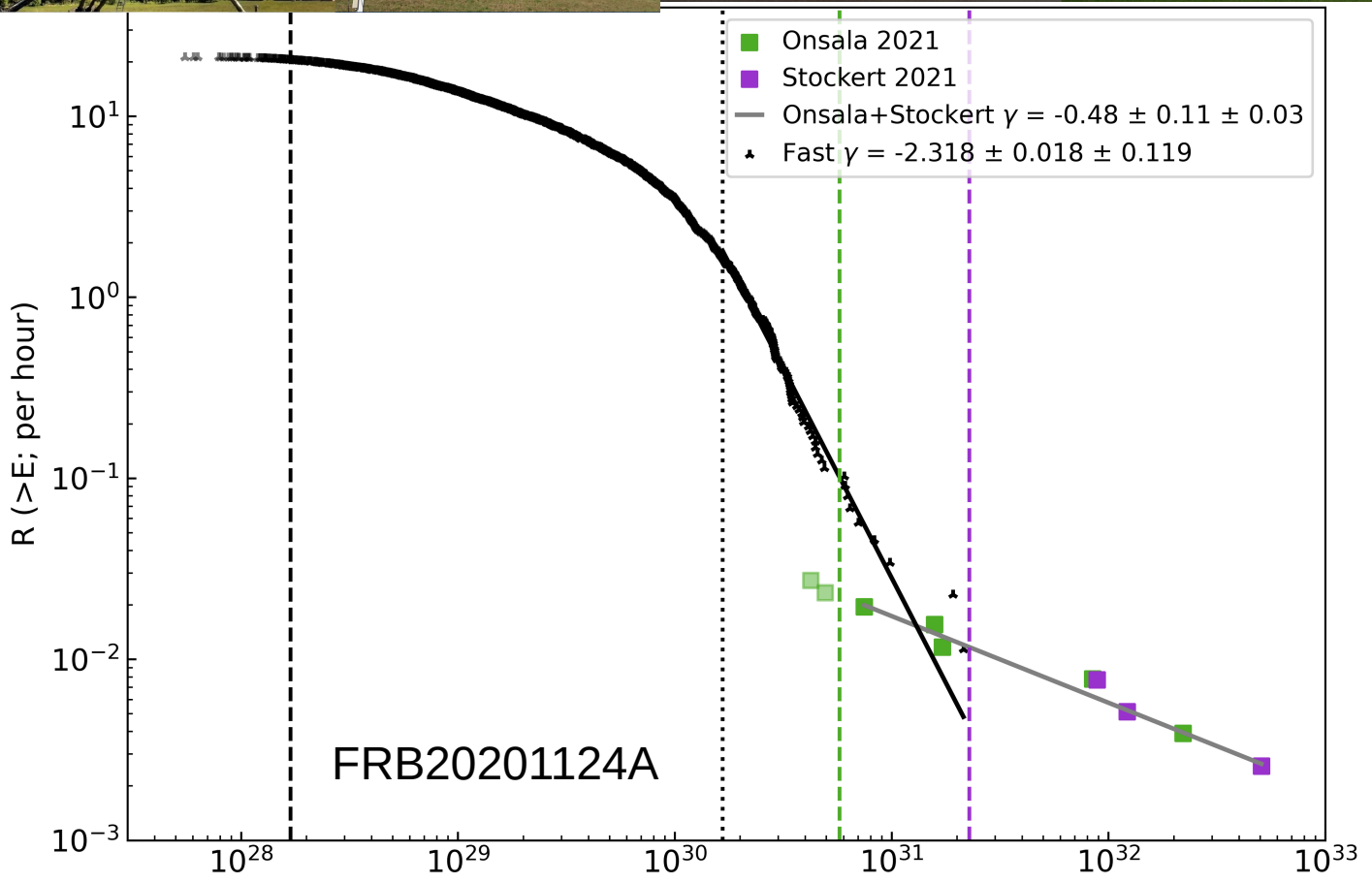
- ➔ what about microsecond, second, minute timescales?

Mostly explored two bands: 400-800 MHz (CHIME/FRB) & ~1500 MHz

- ➔ What about > 5 GHz?

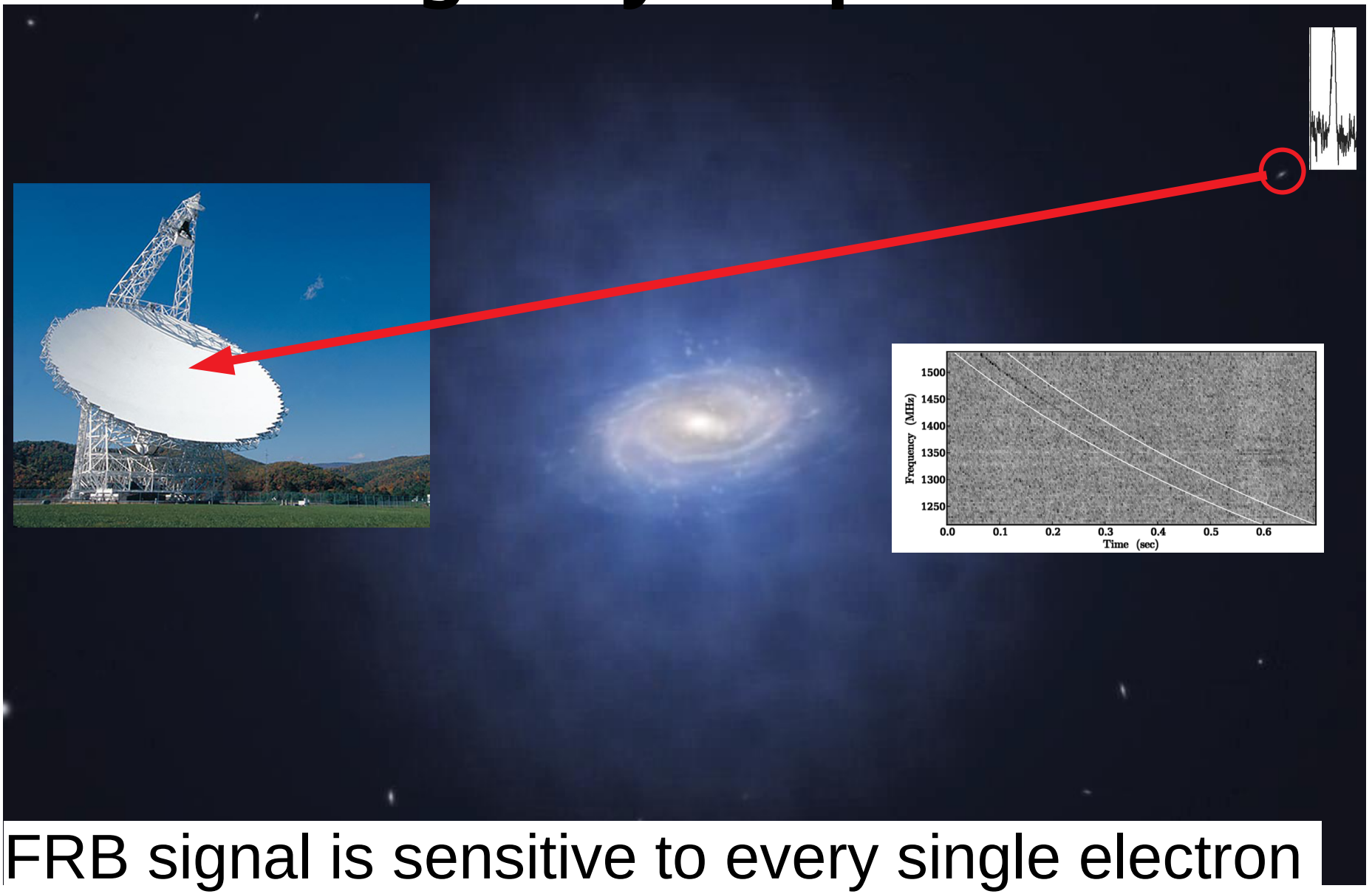
Unexplored parameter space – how bright can we get?





Kirsten et al., in prep

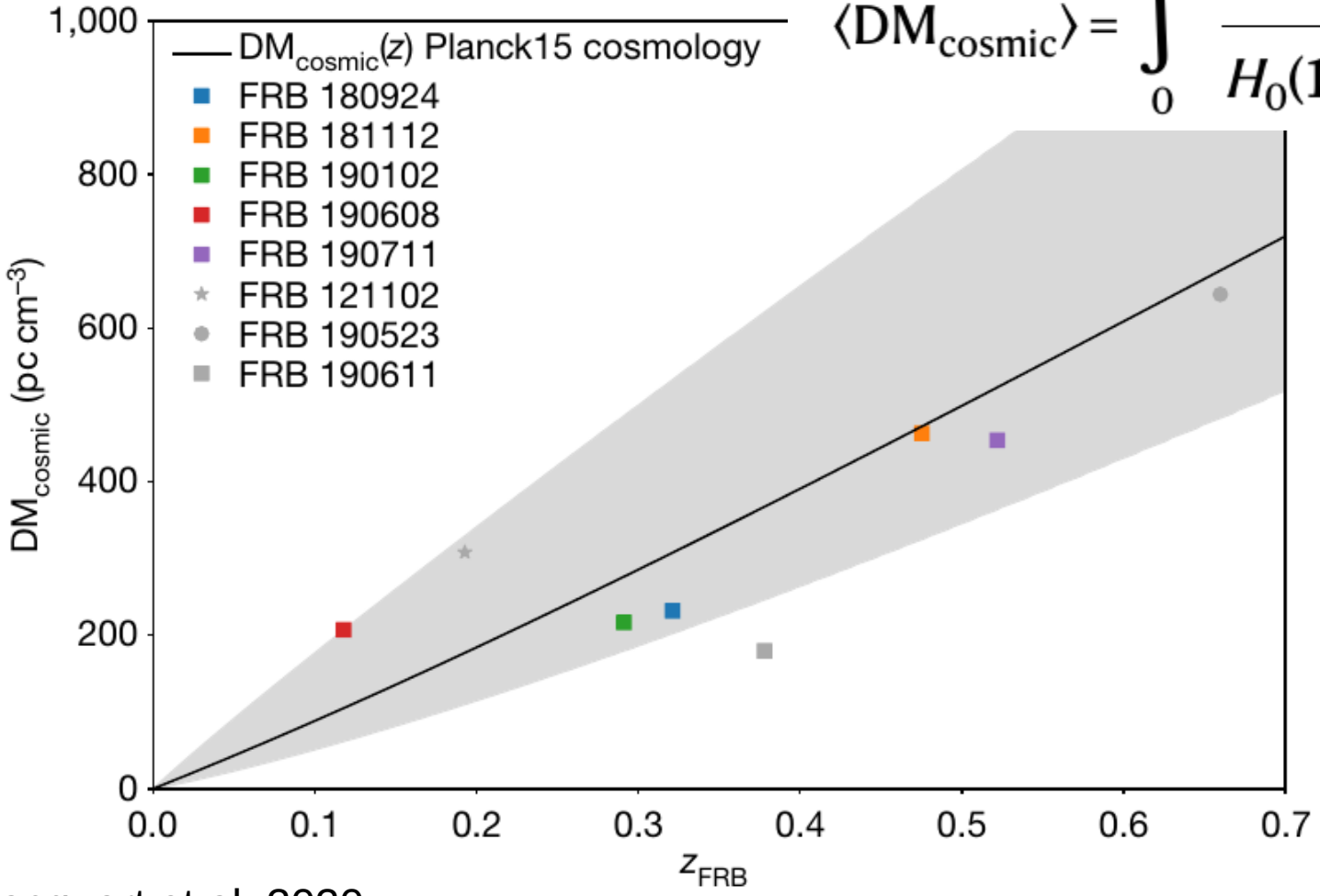
FRBs as cosmological probes – the missing baryons problem



FRB signal is sensitive to every single electron along the way via the dispersion measure!

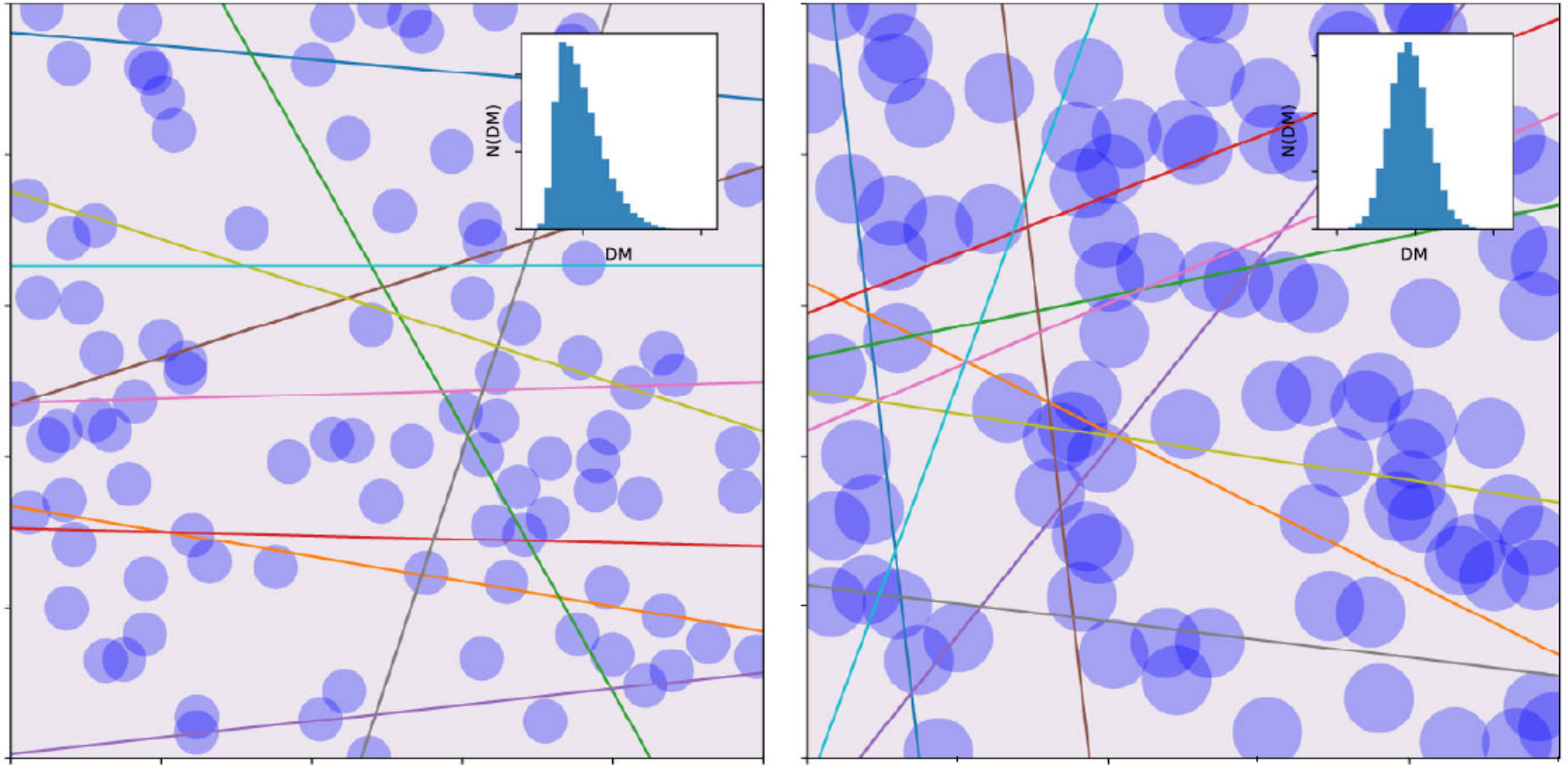
FRBs as cosmological probes – the Macquart relation (c.f. the missing Baryon problem)

$$\langle \mathrm{DM_{cosmic}} \rangle = \int_0^{z_{\mathrm{FRB}}} \frac{c\bar{n}_{\mathrm{e}}(z)\mathrm{d}z}{H_0(1+z)^2\sqrt{\Omega_{\mathrm{m}}(1+z)^3+\Omega_{\Lambda}}}$$



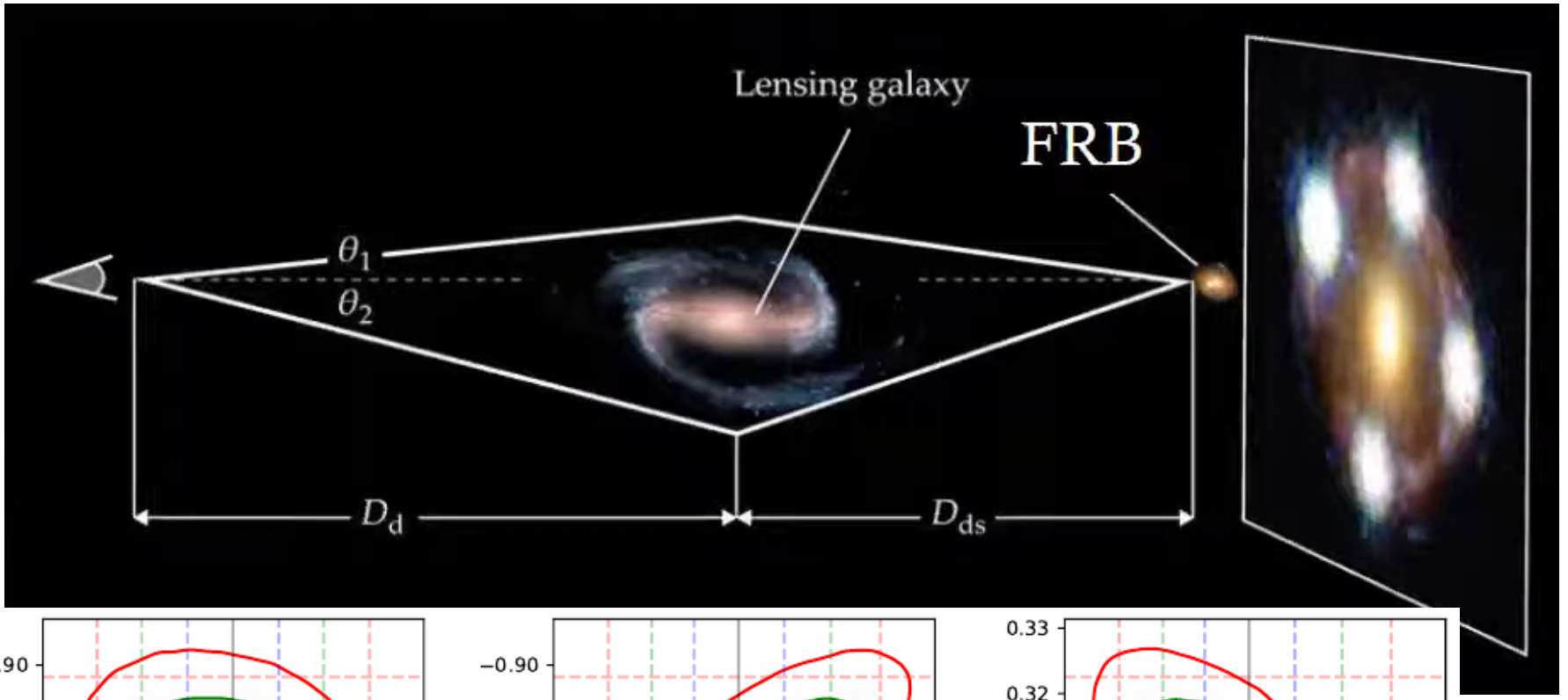
Macquart et al. 2020

FRBs as cosmological probes – the Re-ionisation history

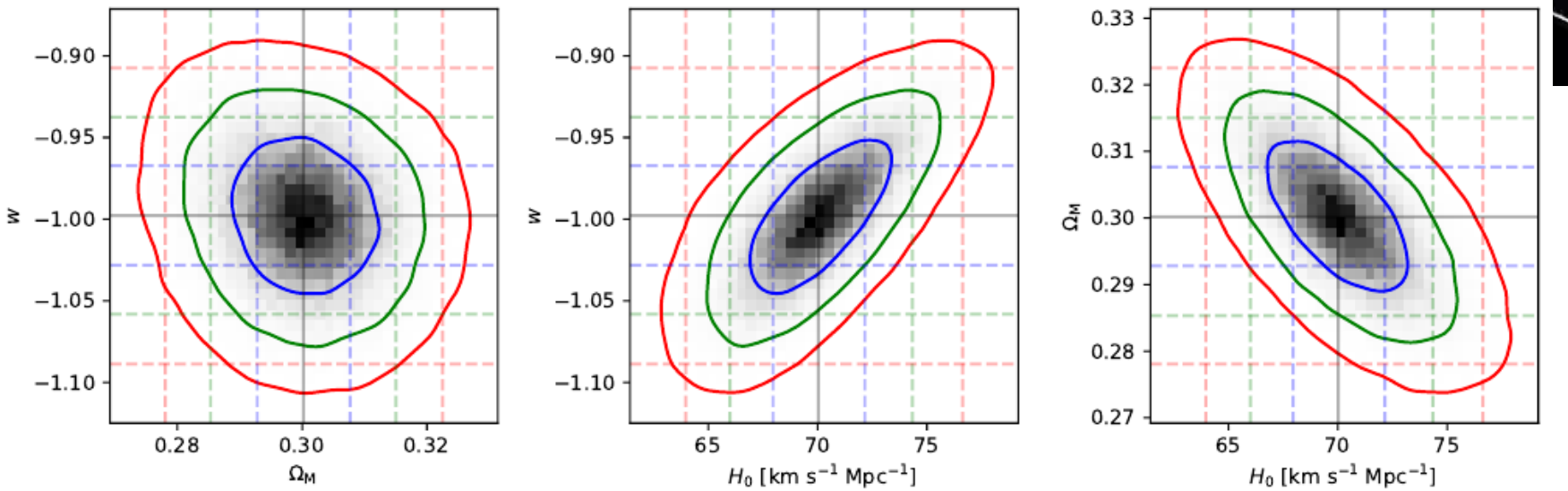


Petroff et al. 2022, from Bhandary & Flynn 2021

FRBs as cosmological probes – the Hubble tension

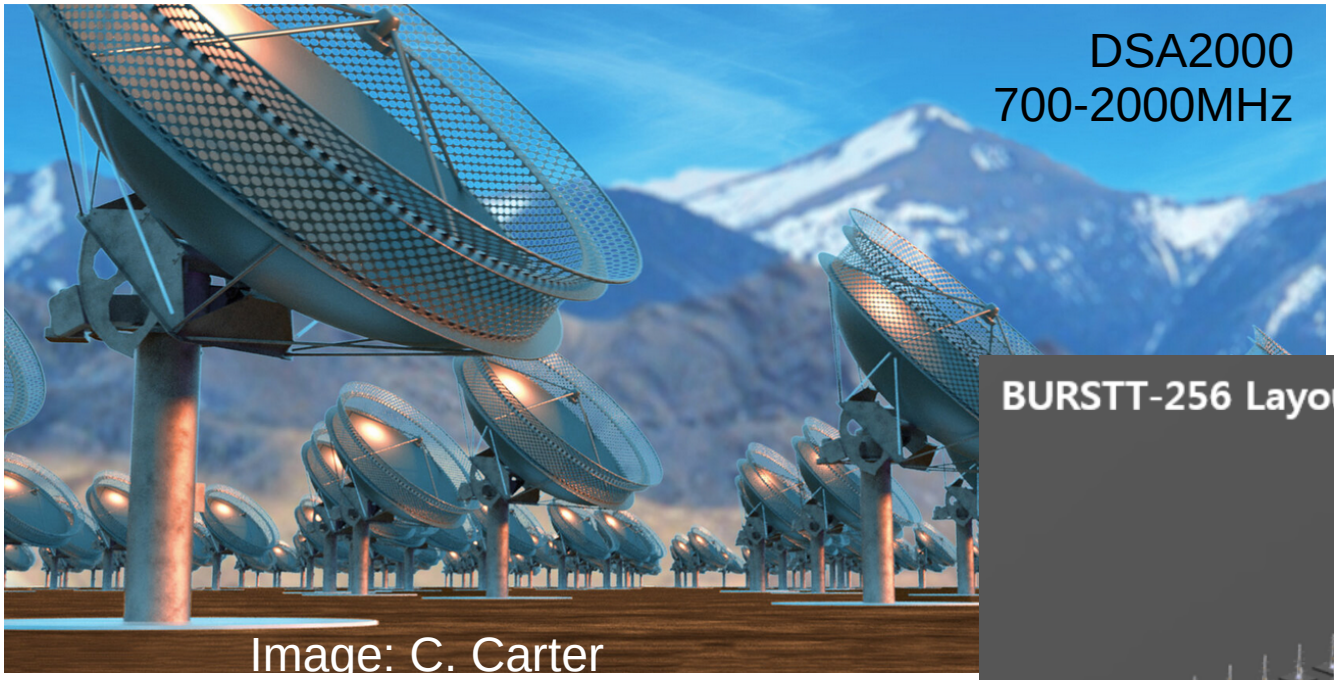


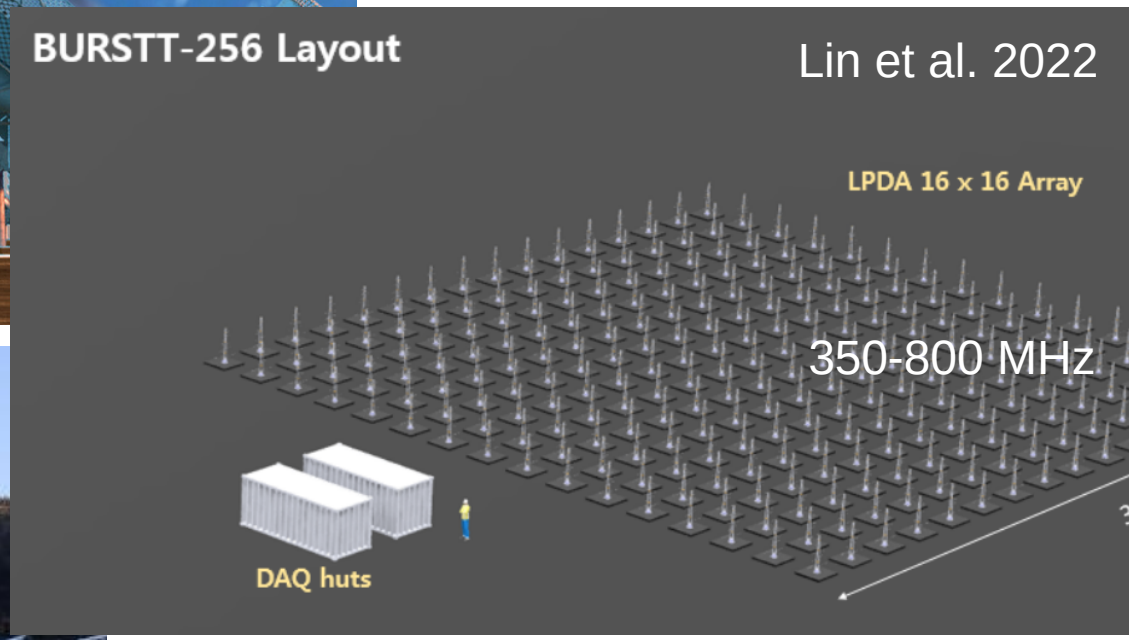
Freddie Pagani



Wucknitz et al. 2020

The future is bright for FRB science





Fast Radio Bursts – FRBs in a nutshell

- Millisecond duration bursts that are highly dispersed
  - ➔ Only see in the radio band so far
- Very common phenomenon: 1000s per sky per day
- Large dispersion measure tells us they're extragalactic
- Inferred distances imply they're highly energetic
  - ➔ Emit as much energy per bust as the sun does in a day
  - ➔ Must be a coherent emission mechanism
- Vast majority of bursts only ever seen once (~650 published)
  - ➔ A small population of repeaters
- At this point we still do not know what generates the bursts
  - ➔ Magnetars for repeaters?
  - ➔ Cataclystic events for one-offs?
- Excellent cosmological probes!