Multi-wavelength follow up of fast radio bursts

CHARLIE KILPATRICK
NORTHWESTERN UNIVERSITY

FAST & FORTUNATE
FRB FOLLOW-UP

https://sites.google.com/ucolick.org/f-4

with X. Prochaska, J. Burchett, Y. Dong, T. Eftekhari, A. Gordon, D. Jones, A. Mannings, C. Núñez, N. Tejos

CIERA

WHY MULTI-WAVELENGTH?

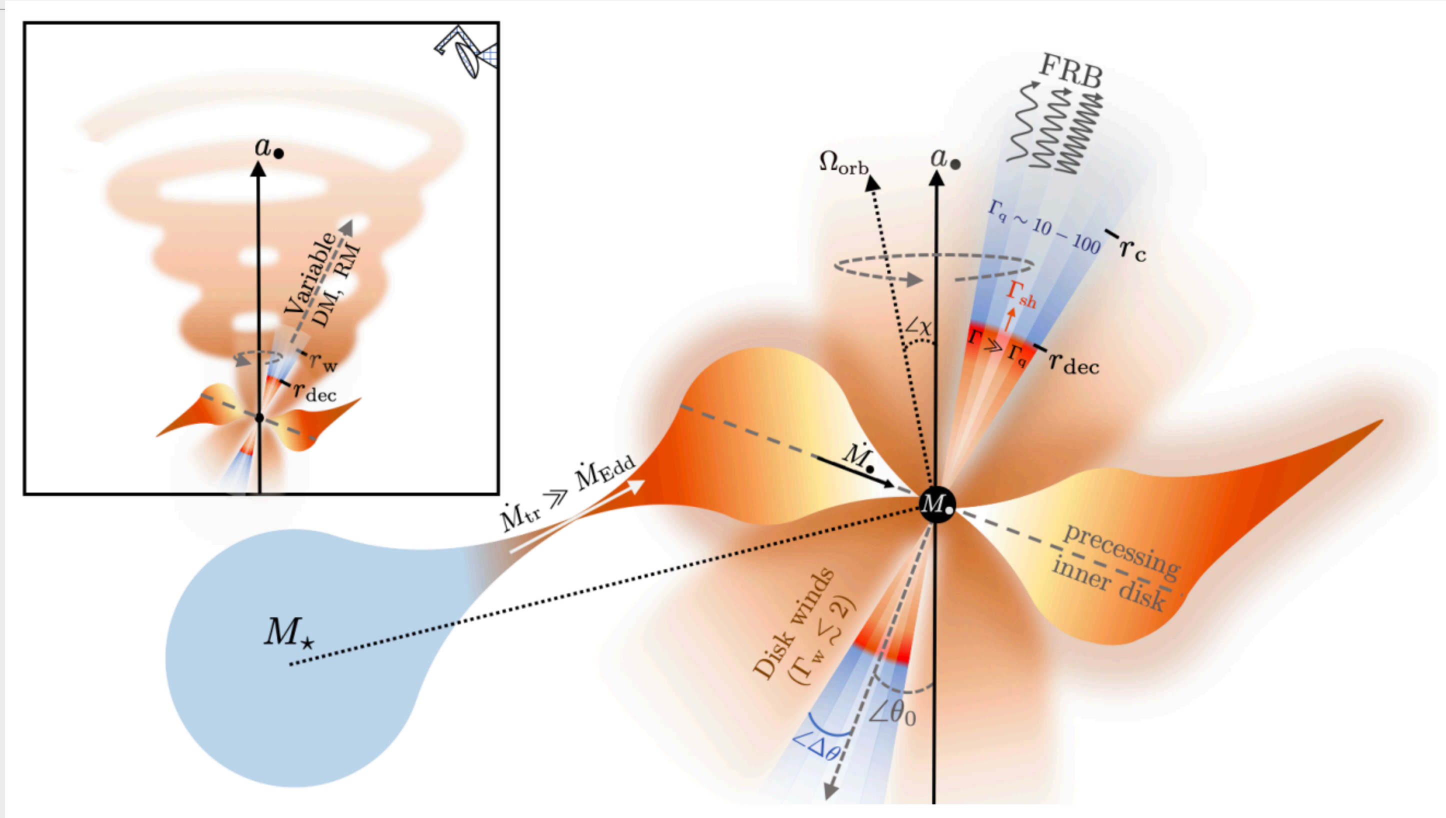
Many physical systems can emit radio bursts - a rich body of literature predicts dozens of counterpart models at shorter wavelengths

Name	Category	Progenitor	Type	Energy Mechanism	Emission Mechanism	LF Radio Counterpart	HF Radio Counterpart	Microwave Counterpart	THz Counterpart	OIR Counterpart	X ray Counterpart	Gamma ray Counterpart	GW Counterpart	Neutrino Counterpart	References	Comments
NS-WD Accretion	Accretion	NS-WD	Repeat	Mag. reconnection	Curv.	Yes	--	--	--	--	--	Yes, but unlikely detectable	--	--	URL	None
AGN-KBH	AGN	AGN-KBH Interaction	Repeat	Maser	Synch.	Yes	--	--	--	Supernova	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH.
AGN-SS	AGN	AGN-Strange Star Interaction	Repeat	Electron oscillation	--	Yes	--	--	--	Thermal	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH. GW from collapse and persistent GWs from SS.
Jet-Caviton	AGN	Jet-Caviton Interaction	Both	Electron scattering	Bremsst.	Yes	Yes	--	--	--	--	Possible GRB	Yes	--	URL • URL	Persistent scintillating radio emission.
Wandering Beam	AGN	Wandering Beam	Repeat	--	Synch.	Yes	--	--	--	--	Yes	--	--	--	URL	None
NS to BH (DM-Induced)	Collapse	NS to BH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes	--	URL	None
NS to KNBH	Collapse	NS to KNBH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	Possible afterglow	Possible GRB	Yes	--	URL • URL • URL	Possible X-ray afterglow and a short/long GRB created in NS birth prior to the FRB.
NS to Quark Star	Collapse	NS to Quark Star	Single	β-decay	Synch.	Yes	--	--	--	--	Yes	Yes	Yes	--	URL	The burst is predicted to be several seconds, explainable if the de-dispersion process that stacks f
SS Crust	Collapse	Strange Star Crust	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes	--	URL	None
Axion Cloud and BH	Collision / Interaction	Superradiant Axion Cloud and BH	Repeat	Laser	Synch.	Yes	--	--	--	--	--	--	Yes	--	URL	Observational counterparts could be associated with electron-positron annihilation and/or positroniu
Axion Minicluster and NS	Collision / Interaction	Axion Minicluster and NS	Single	Maser	Synch.	Yes	--	--	--	--	--	--	--	--	URL	None
Axion Quark Nugget and NS	Collision / Interaction	Axion Quark Nugget and NS	Repeat	Mag. reconnection	Curv.	Yes	Possible	Possible	--	--	--	--	--	--	URL	None
Axion Star and BH	Collision / Interaction	Axion Star and BH	Repeat	Electron oscillation	--	Yes	--	--	--	--	--	--	--	--	URL	None
Axion Star and NS	Collision / Interaction	Axion Star and NS	Single	Electron oscillation	Coherent dipole radiations	Yes	--	--	--	--	--	--	--	--	URL • URL • URL • URL • URL	None
NS and Primordial BH	Collision / Interaction	NS and Primordial BH	Both	Mag. reconnection	--	Yes	--	--	--	--	--	--	Yes	--	URL	None
Small Body and Pulsar	Collision / Interaction	Small Body and Pulsar	Single	Maser	Synch.	Yes	--	--	--	--	--	--	--	--	URL	None
NS and Asteroid Belt	Collision/ Interaction	NS and Asteroid Belt	Repeat	Electron stripping	Curv.	Yes	--	--	--	--	--	Yes	--	--	URL • URL	None
NS and Asteroids/Comets	Collision/ Interaction	NS and Asteroids/ Comets	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	Yes (probably too faint to detect)	Yes (probably too faint to detect)	--	--	URL	None

and so on...

Credit: FRB theory wiki, Tendulkar, Platts, Weltman+

WHY MULTI-WAVELENGTH?

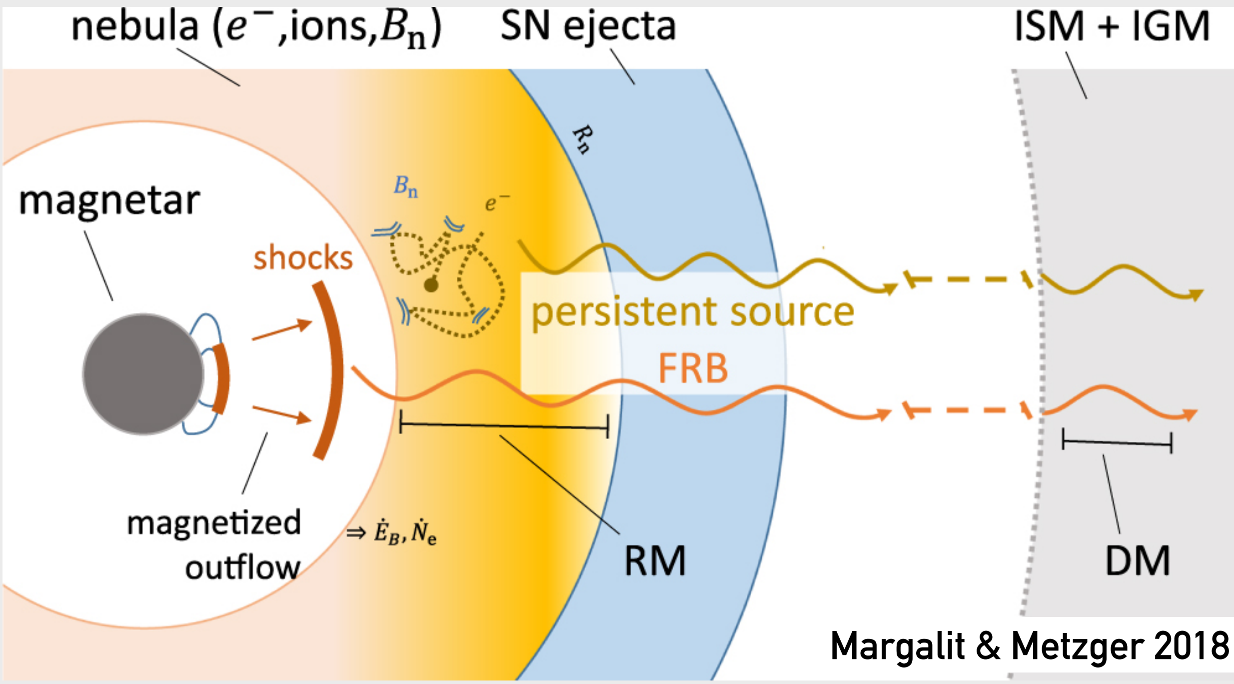


Sridhar+2021

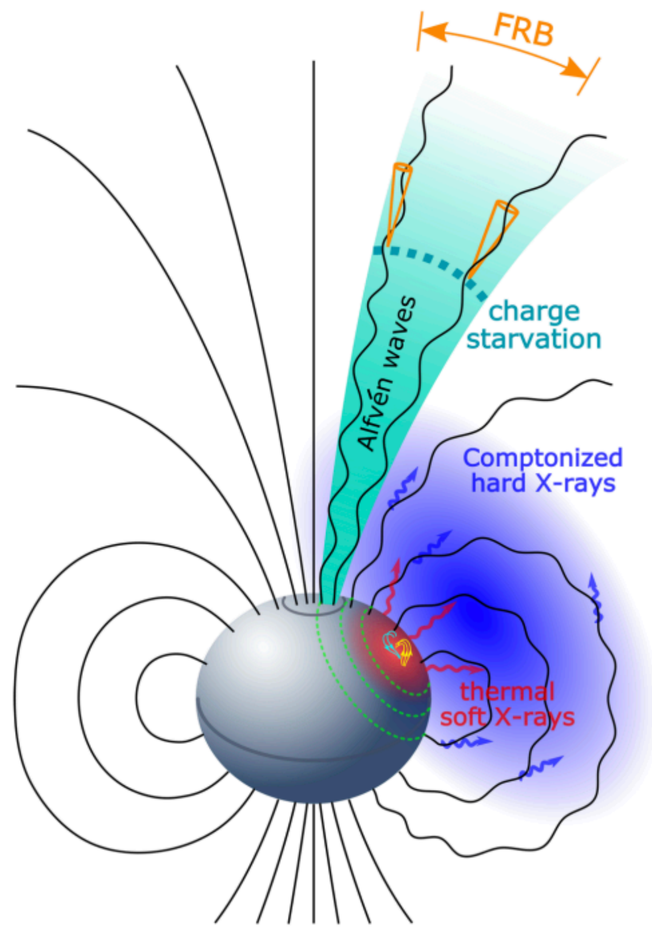
Accretion powered counterparts to FRBs with X-ray/optical/IR counterparts (ultra-luminous X-ray source, luminous red novae,

WHY MULTI-WAVELENGTH?

Eruption from a magnetar, requiring interaction with ejecta from prior eruptions (synchrotron maser) versus curvature emission in the magnetosphere



Margalit & Metzger 2018



Yang 2021

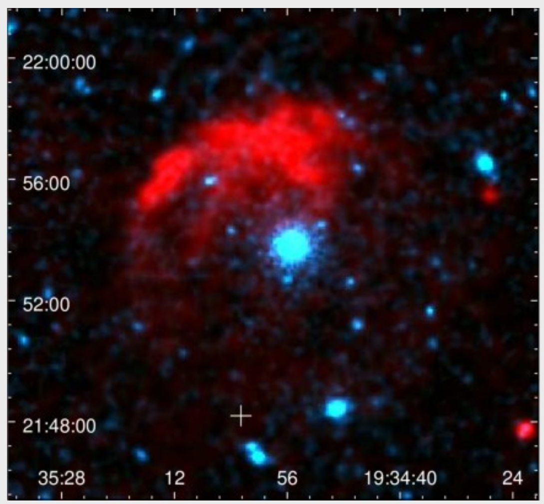
WHY MULTI-WAVELENGTH?

Prompt observations constrain emission mechanism, basic energetics, immediate environment

An associated transient in the optical or X-ray could reveal formation scenarios

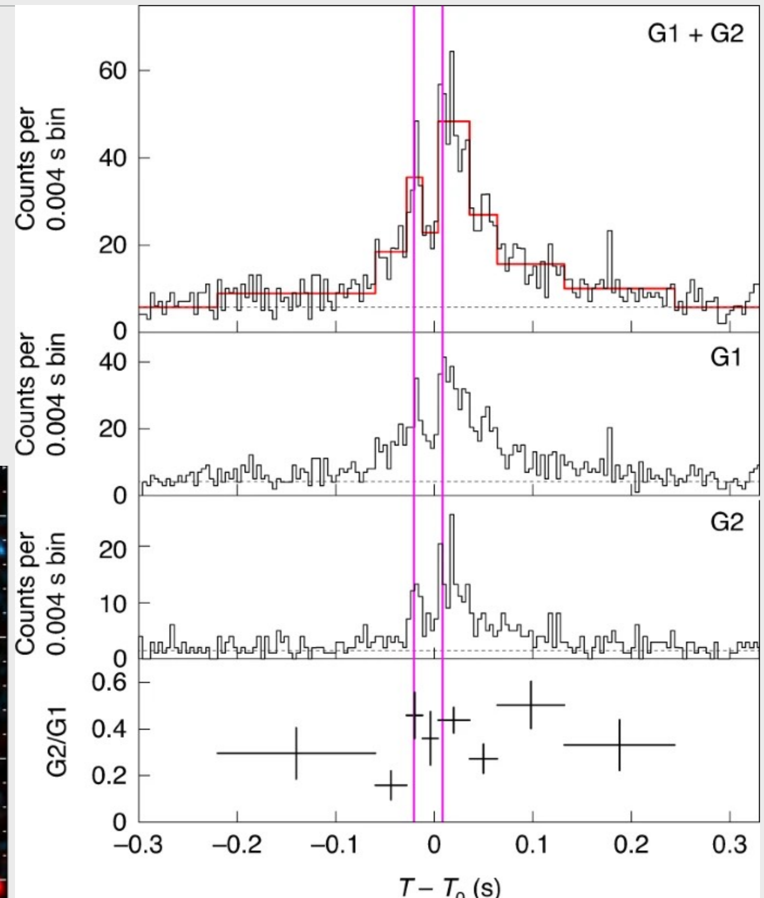
SGR 1935+2154 embedded in SN remnant G57.2+0.8

(6.6 kpc, 10-20,000 yr)



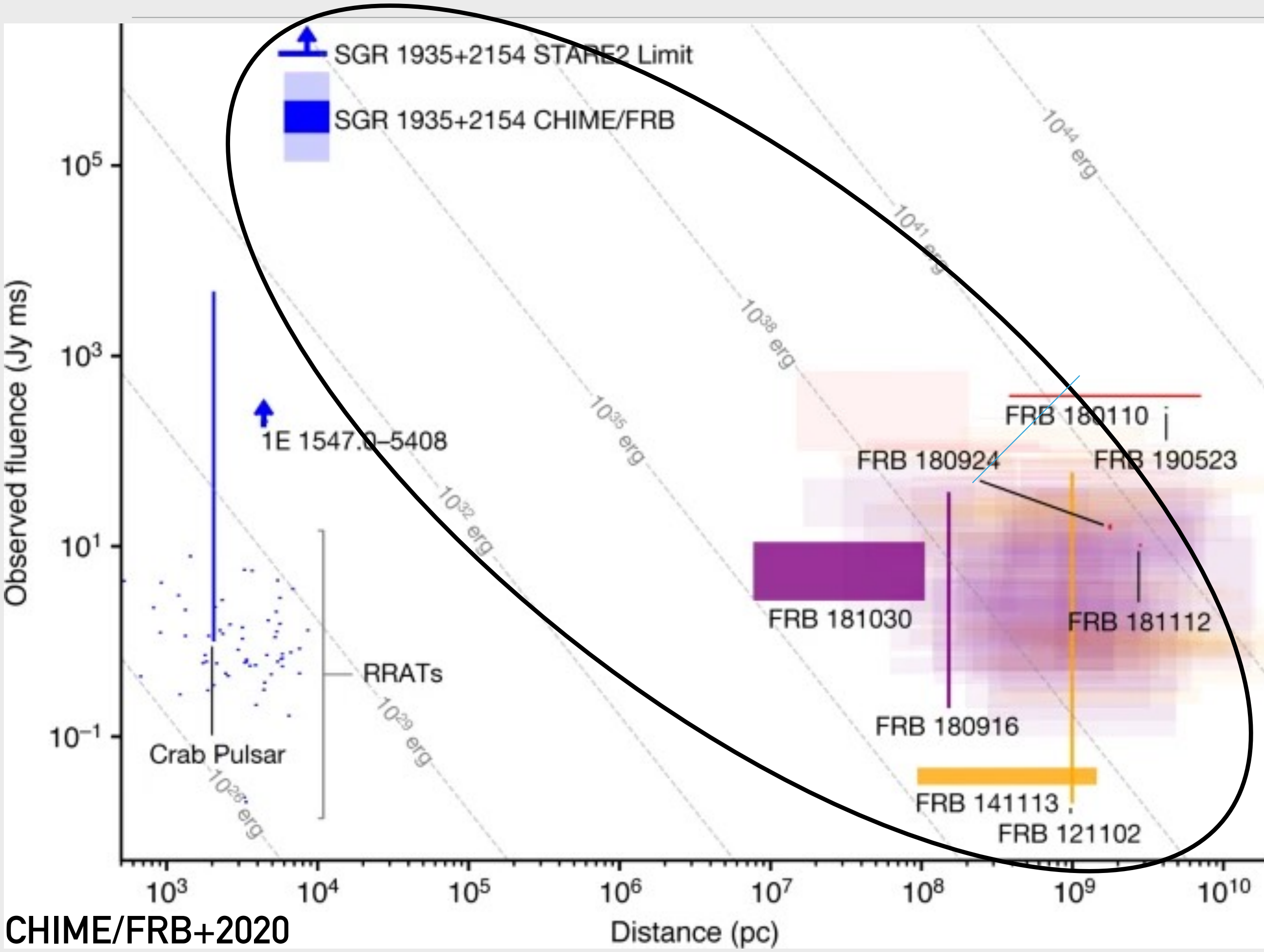
X-ray+radio: Zhou+2020

SGR 1935+2154



Ridnaia+2021, also Mereghetti+2020

WHY MULTI-WAVELENGTH?



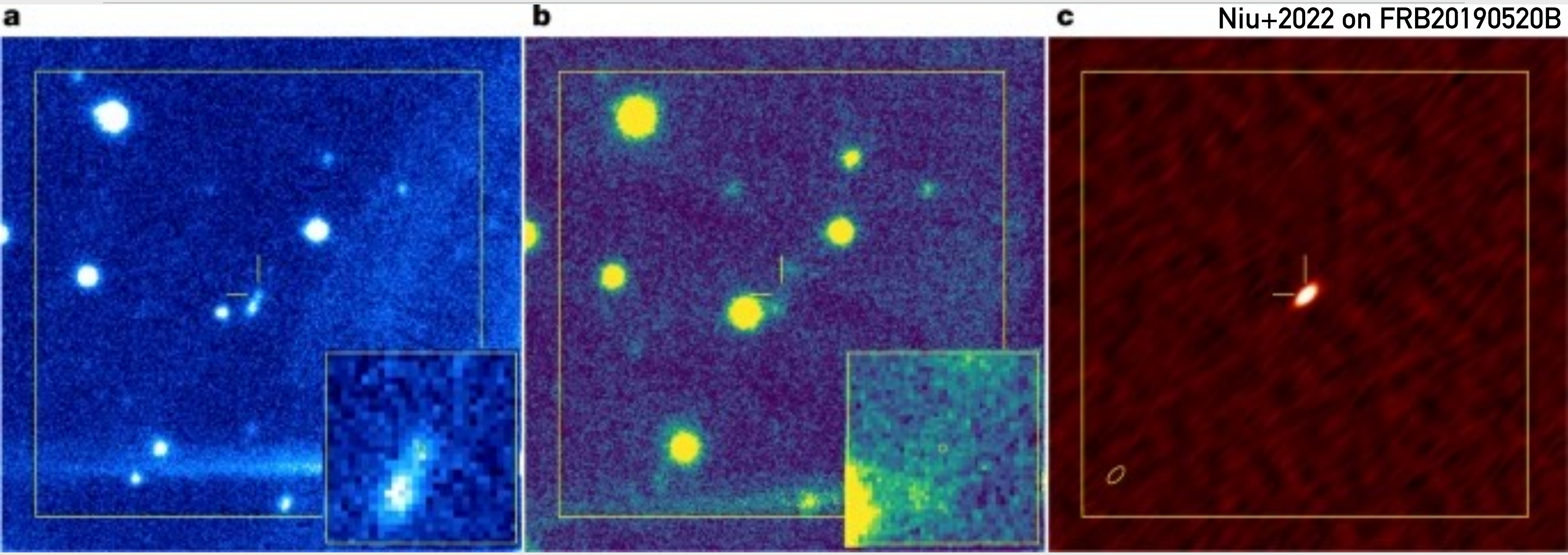
CHIME/FRB+2020

Is this all one population spanning ~6 decades in energy or are there multiple progenitor pathways?

Need additional constraints on their origin and source of FRB emission

PERSISTENT RADIO SOURCES

Niu+2022 on FRB20190520B

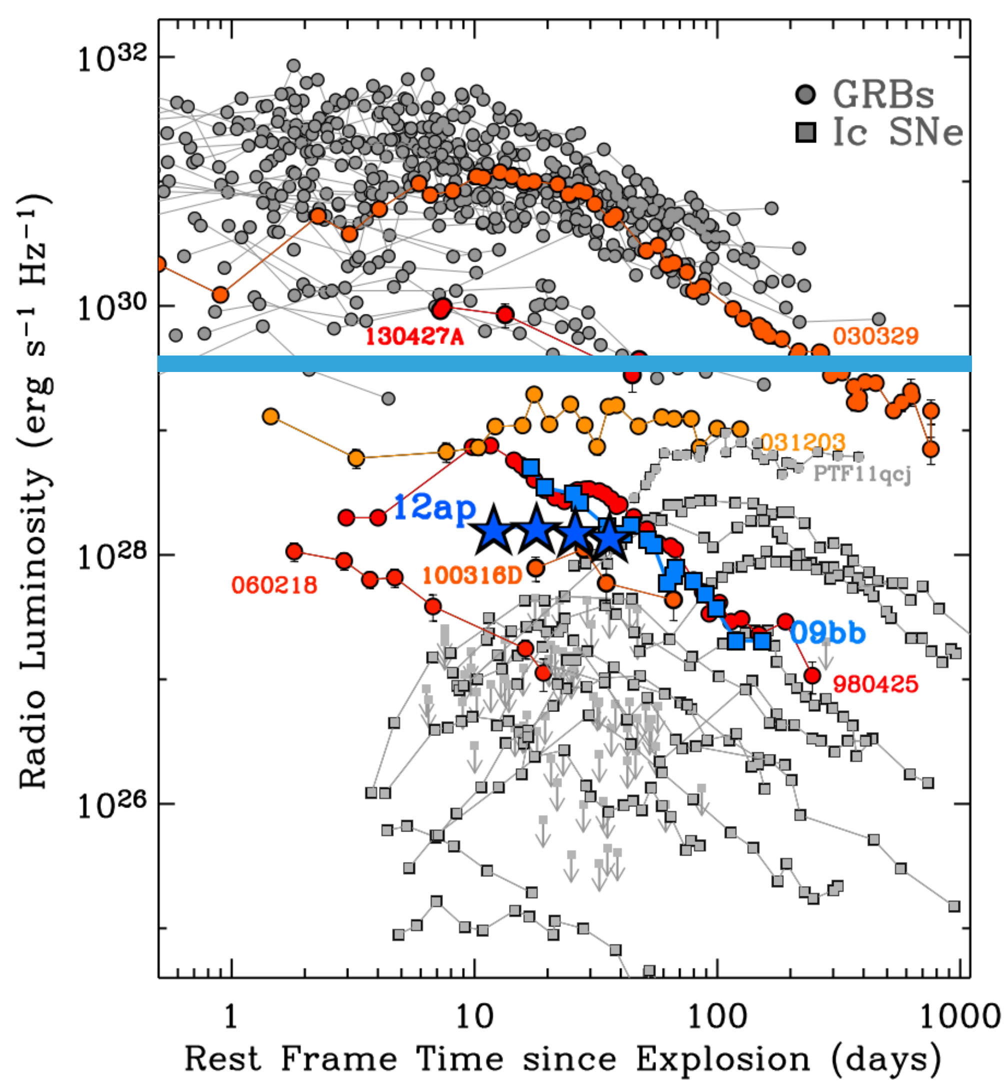


Non-nuclear, persistent radio sources are associated with fast radio bursts, likely associated with star formation (Mannings+2021, Law+2022) but with extreme luminosities $\sim 3 \times 10^{29}$ erg s^{-1} Hz^{-1}

PERSISTENT RADIO SOURCES

These extreme luminosities are higher than nearly all radio transients at peak light (let alone supernova remnants)

Requires either an extremely energetic source, implied star-formation rates ($\sim 1 - 10$ M$_\odot$ yr^{-1}) are far higher than implied in optical



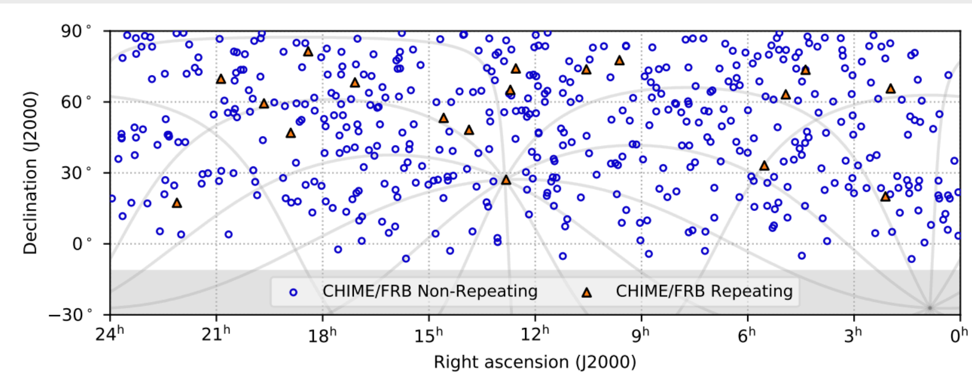
THREE MULTI-WAVELENGTH SEARCH STRATEGIES

Coincident imaging: search for counterparts in survey and archival imaging (±days to years of FRB)

Reactive follow up: triggering follow up after FRB occurs (+minutes to days of FRB)

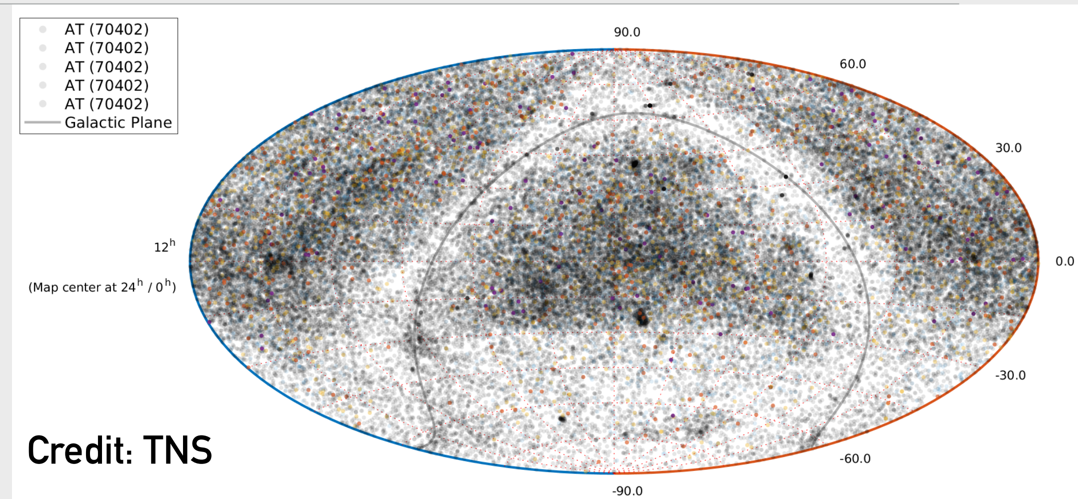
Pointing at repeaters: monitoring of known repeaters (±milliseconds to hours of FRB)

COINCIDENT SOURCES (±DAYS TO YEARS)



CHIME/FRB+2021

Crossmatching 492 unique CHIME sources (+well-localized sources in Heintz+2020)

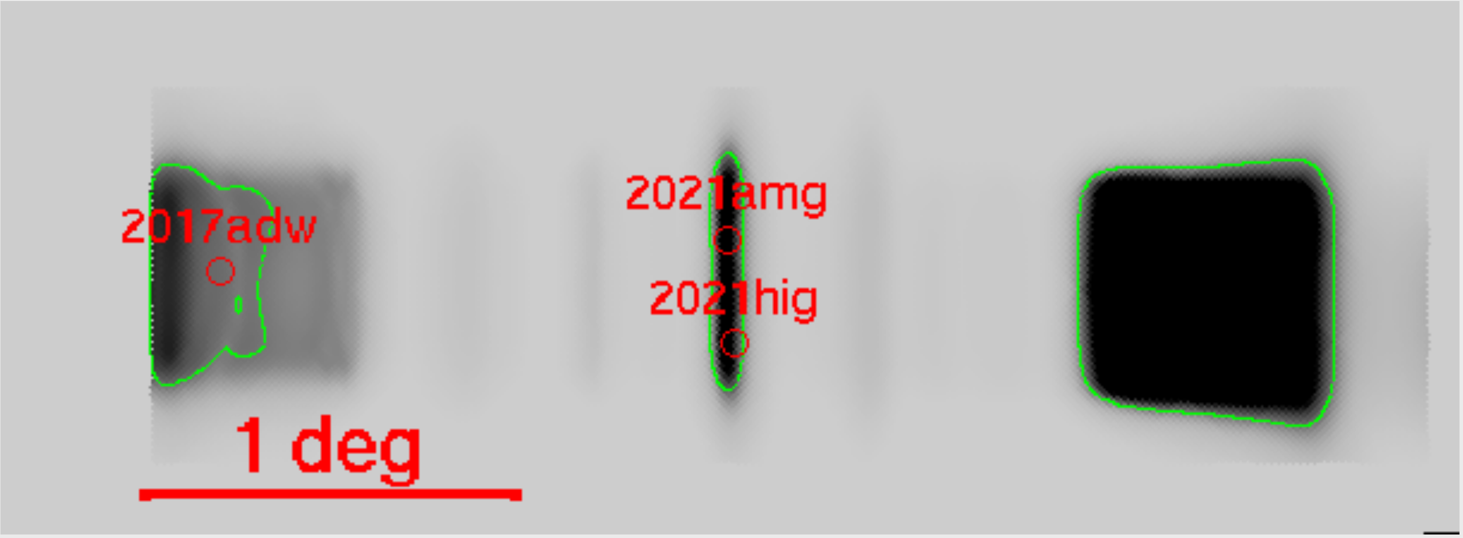


~80,000 known optical transients from Transient Name Server

How many optical transients are consistent with being in the likely volume of FRBs?

COINCIDENT SOURCES (±DAYS TO YEARS)

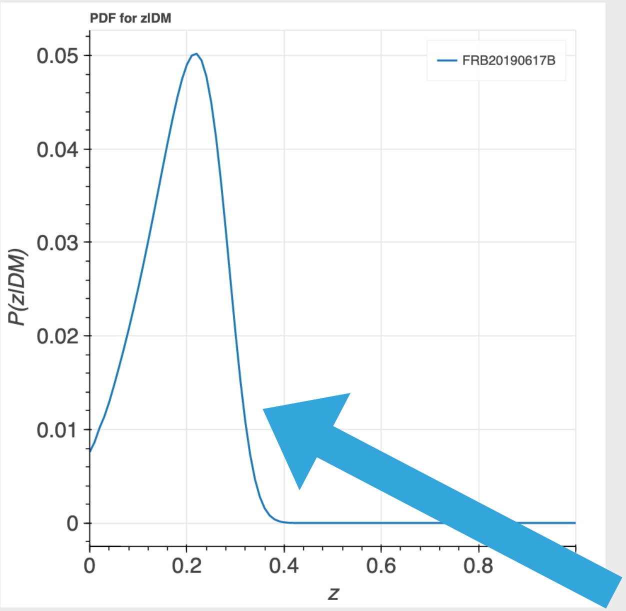
CHIME: FRB20190617B

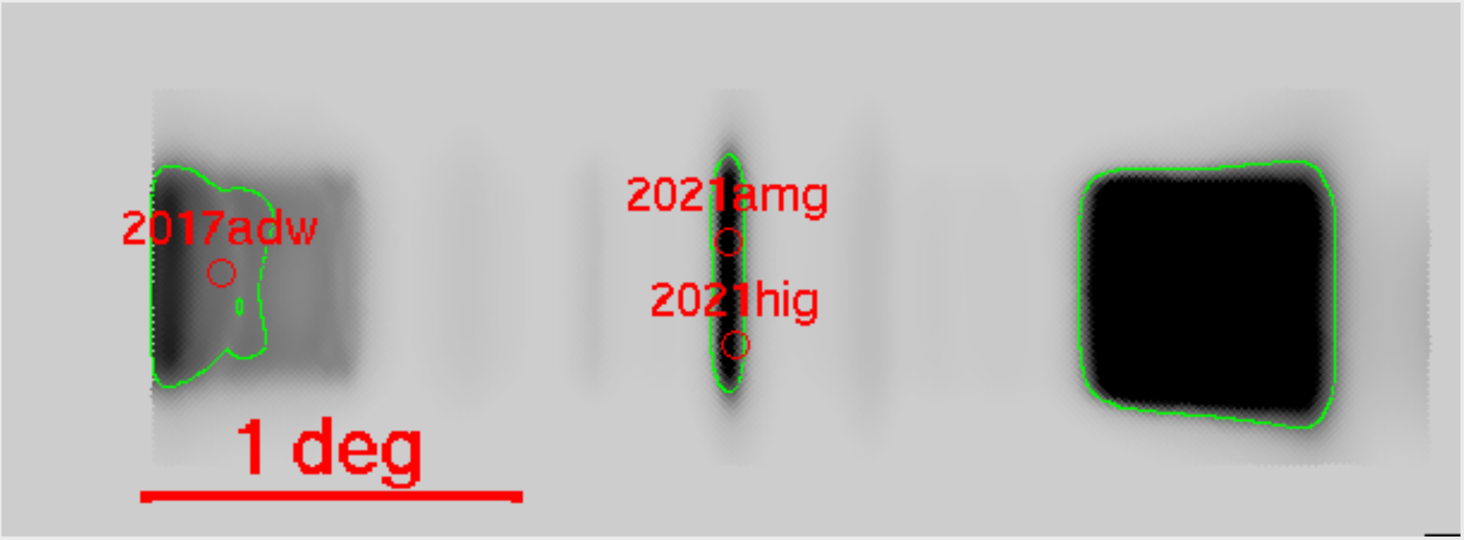


How many optical transients are consistent with being in the likely volume of FRBs?

COINCIDENT SOURCES (±DAYS TO YEARS)

CHIME: FRB20190617B





3σ most likely volume is z<0.36

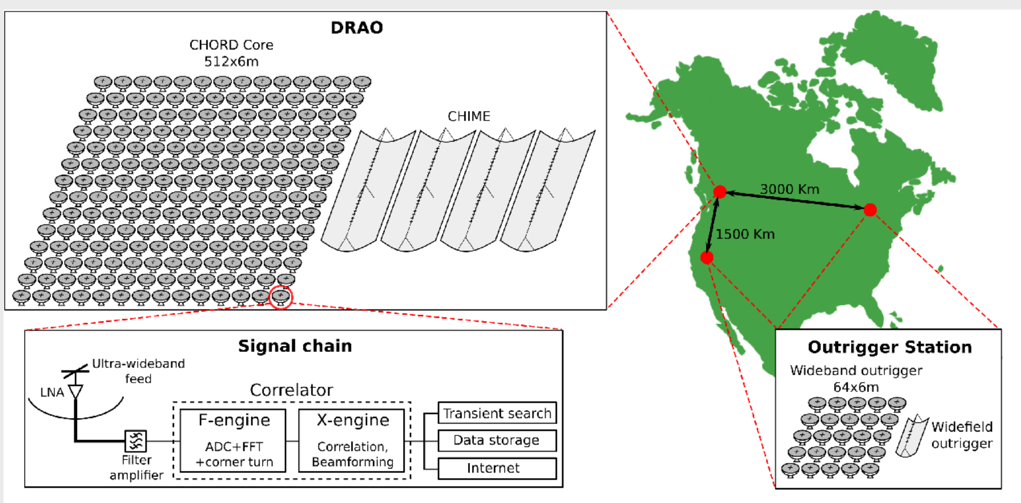
How many optical transients are consistent with being in the likely volume of FRBs?

COINCIDENT SOURCES (±DAYS TO YEARS)

Supernovae are major interlopers at these redshifts

55 SNe yr-1 deg-2 (z<0.36)

Localizations < 0.1 deg-2 will be exponentially more likely to positively identify optical counterparts with fewer chance coincidences



CHIME outriggers will consistently provide ~arcsecond-subarcsecond localization

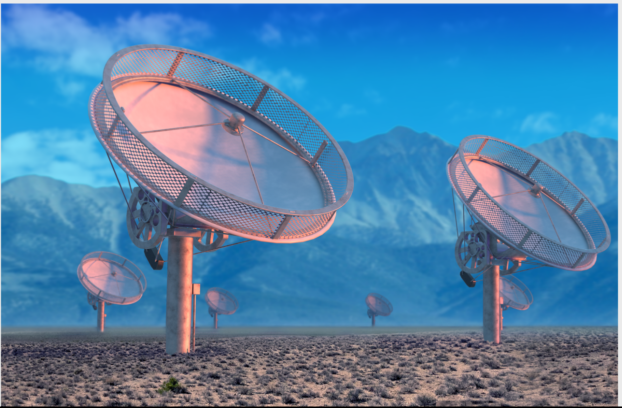
COINCIDENT SOURCES (±DAYS TO YEARS)

Supernovae are major interlopers at these redshifts

55 SNe yr-1 deg-2 (z<0.36)

Localizations < 0.1 deg-2 will be exponentially more likely to positively identify optical counterparts with fewer chance coincidences

DSA-2000



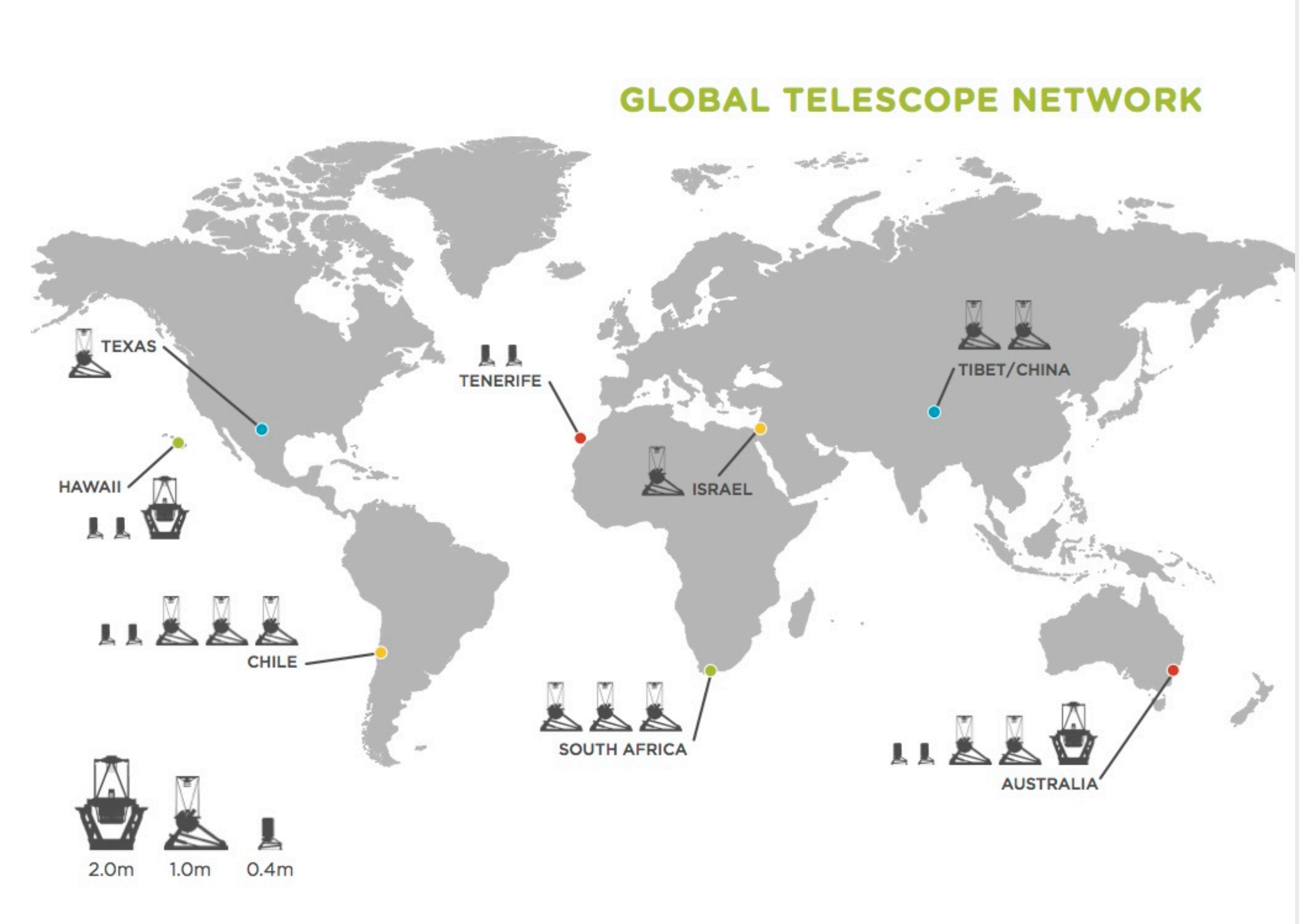
Rubin

SKA

RAPID FOLLOW UP (+MINUTES-YEARS)

F4 and collaborators are using rapid follow up to obtain imaging on timescales of ~minutes after a burst

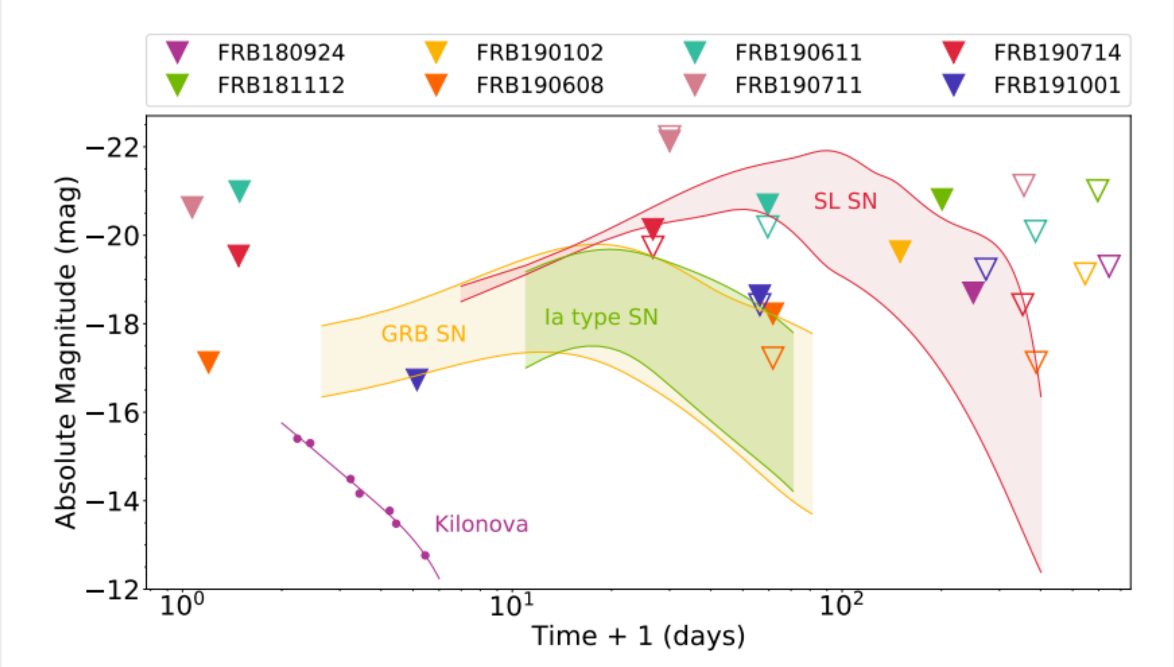
Rapid reaction can rule out slowly declining counterparts such as afterglows



RAPID FOLLOW UP (+MINUTES-YEARS)

Rapid, targeted follow-up imaging can rule out optical transients with short timescales:

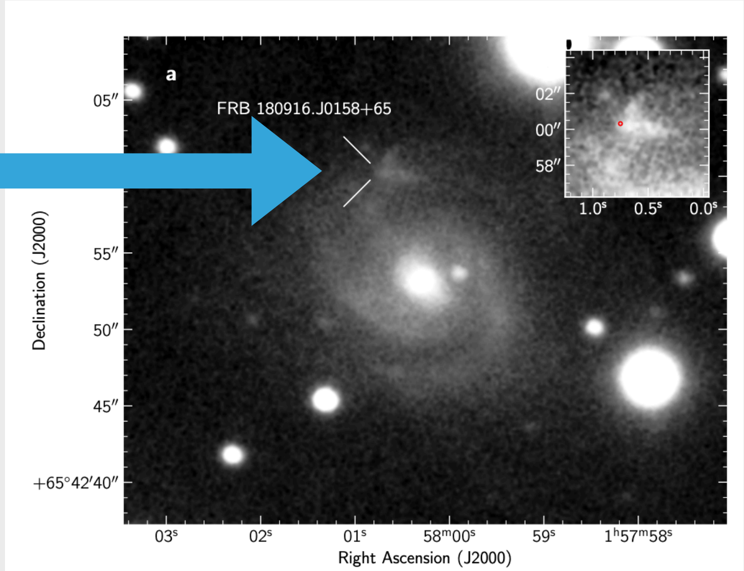
Those associated with NS (fast blue optical transients, kilonovae, luminous red novae, synchrotron afterglows)



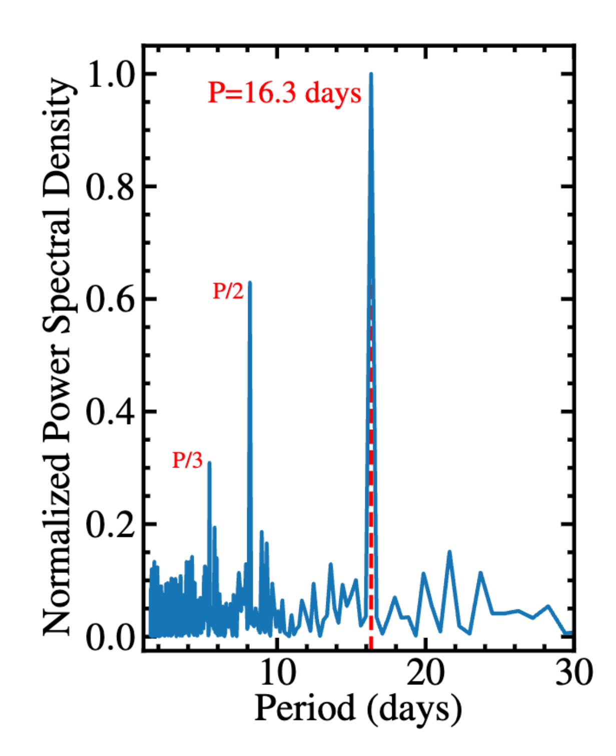
Núñez+2021

POINTING AT REPEATERS (±MILLISECONDS TO HOURS)

Localized with EVN after multiple bursts were detected



Marcote+2020



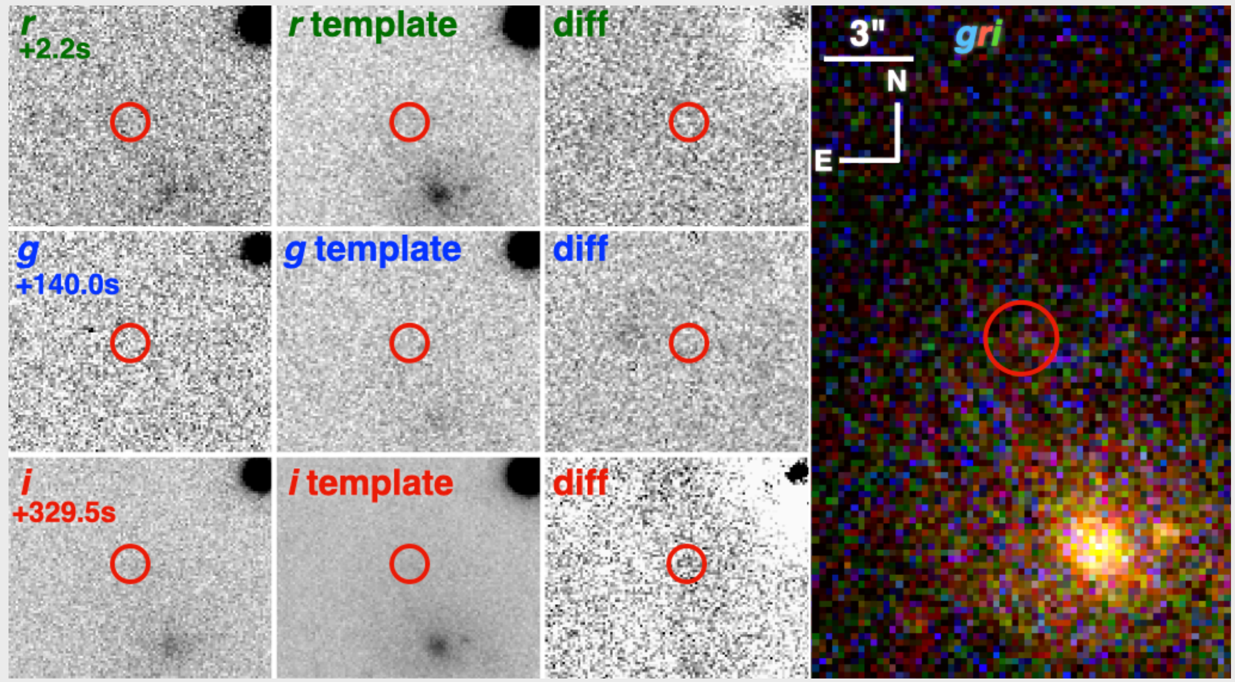
Periodic repeating FRB180916B (R3) was localized to the arm of a spiral galaxy at ~150 Mpc

Even with high foreground extinction and much larger distance, deep optical imaging provides comparable fluence constraints to those of Galactic magnetar

POINTING AT REPEATERS (±MILLISECONDS TO HOURS)

Most multi-wavelength follow up focuses on "lucky" observations of repeating FRBs (e.g., FRB121102, Scholz+2016, Scholz+2017)

Measured periodicity in FRB180916 has enabled a follow up bonanza (Pearlman+2020, Pilia+2020)

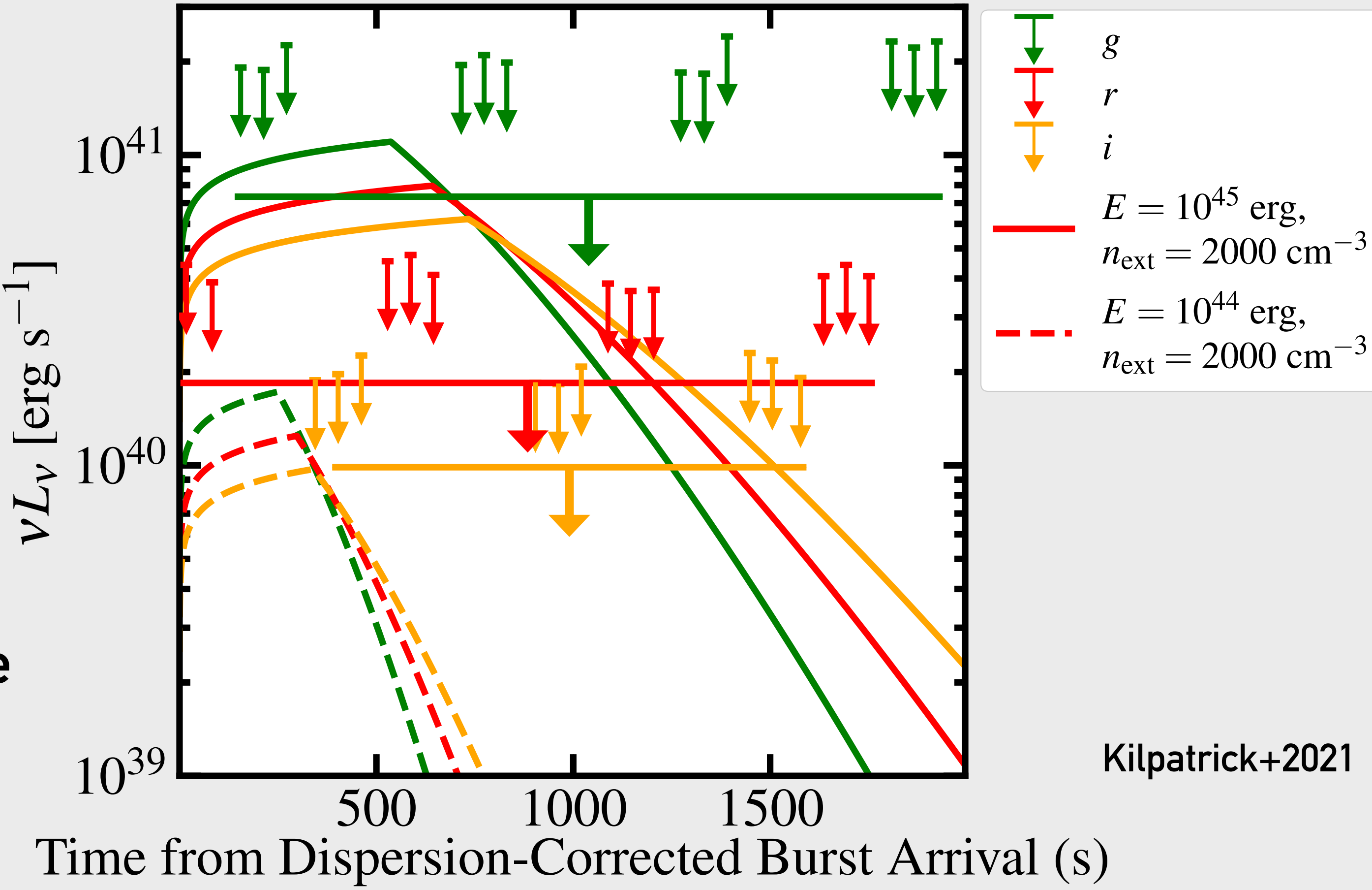


Kilpatrick+2021

POINTING AT REPEATERS (±MILLISECONDS TO HOURS)

Direct comparison to magnetar/synchrotron maser models (Metzger+2019) limits FRB parameter space

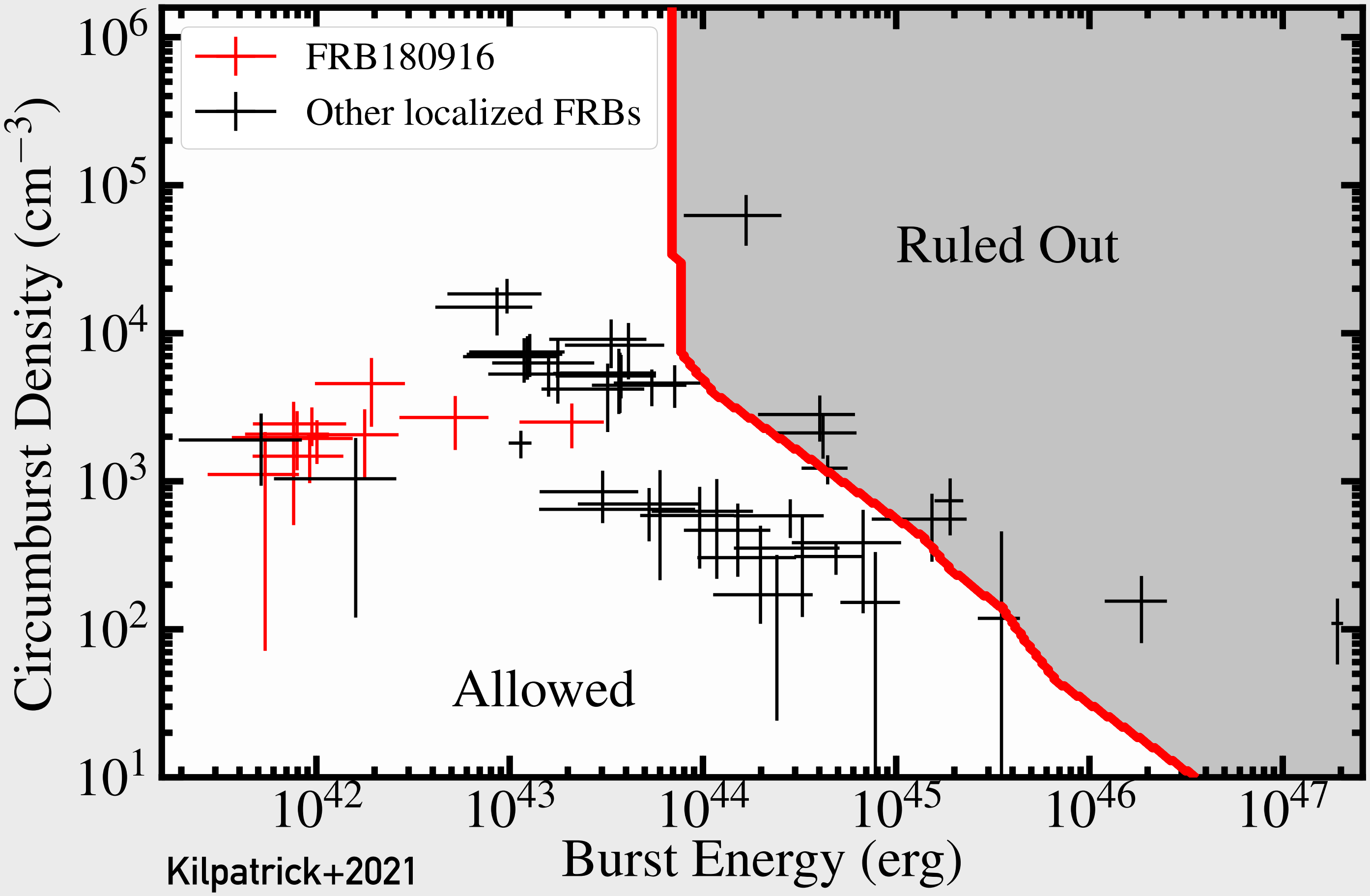
Limits approach to +2.2 seconds from dispersion-corrected burst timing (see next talk for ~millisecond constraints!)



Kilpatrick+2021

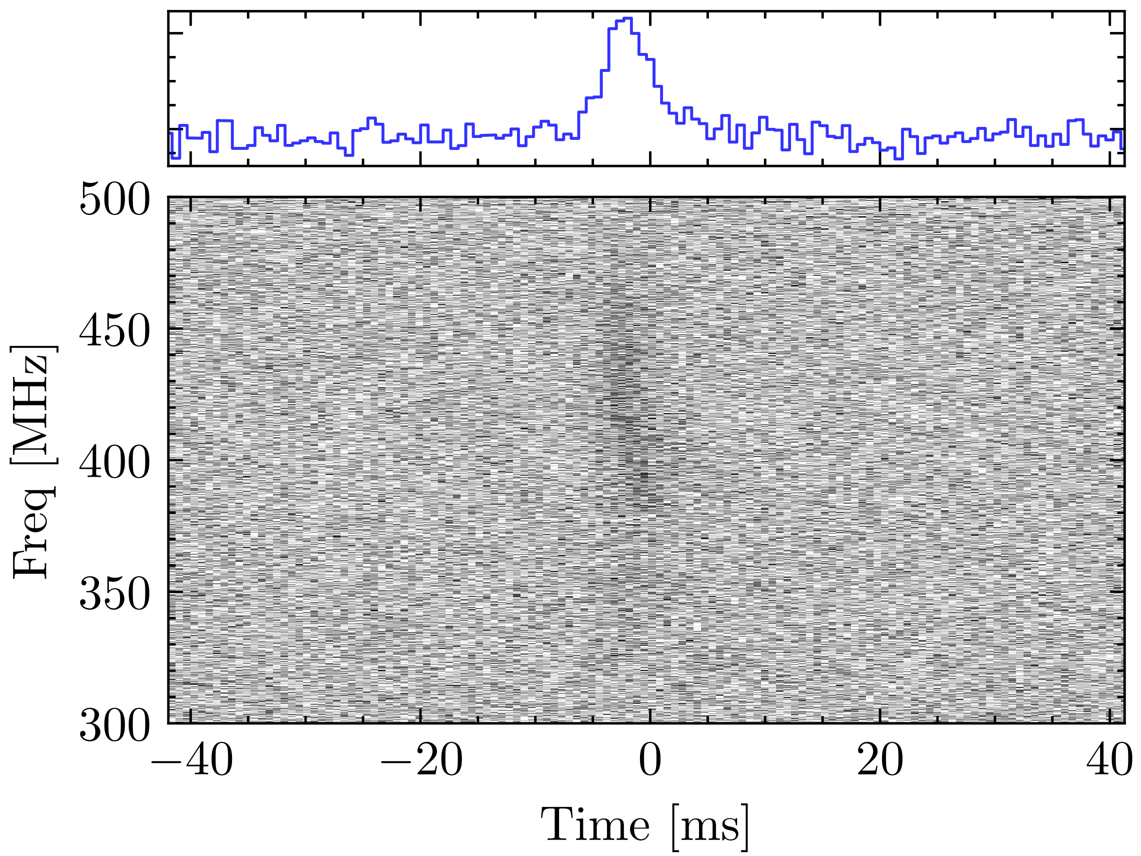
POINTING AT REPEATERS (±MILLISECONDS TO HOURS)

Direct comparison to magnetar/synchrotron maser models (Metzger+2019) limits FRB parameter space

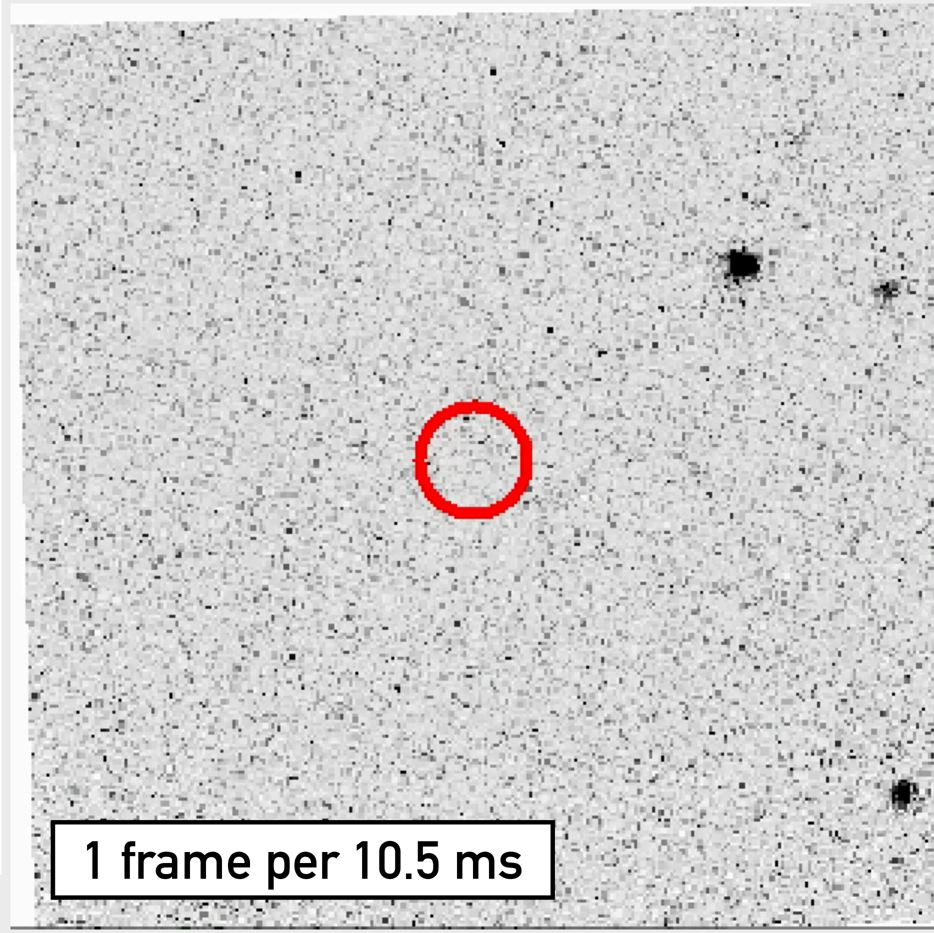


Kilpatrick+2021

POINTING AT REPEATERS (±MILLISECONDS TO HOURS)

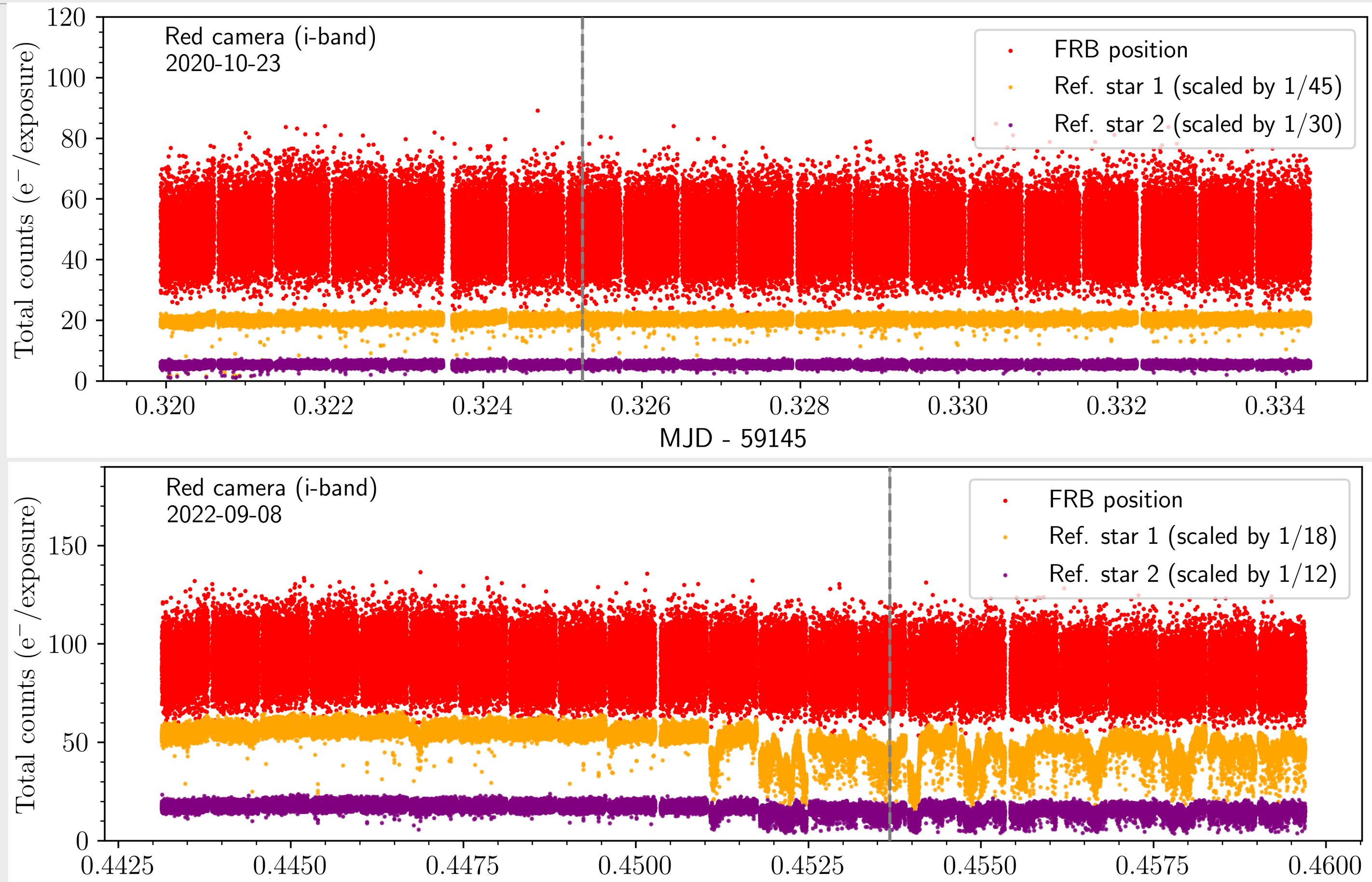


Kilpatrick+2023, in prep.



POINTING AT REPEATERS (±MILLISECONDS TO HOURS)

Deepest ~millisecond timescale constraints on the presence of an optical counterpart to a fast radio burst

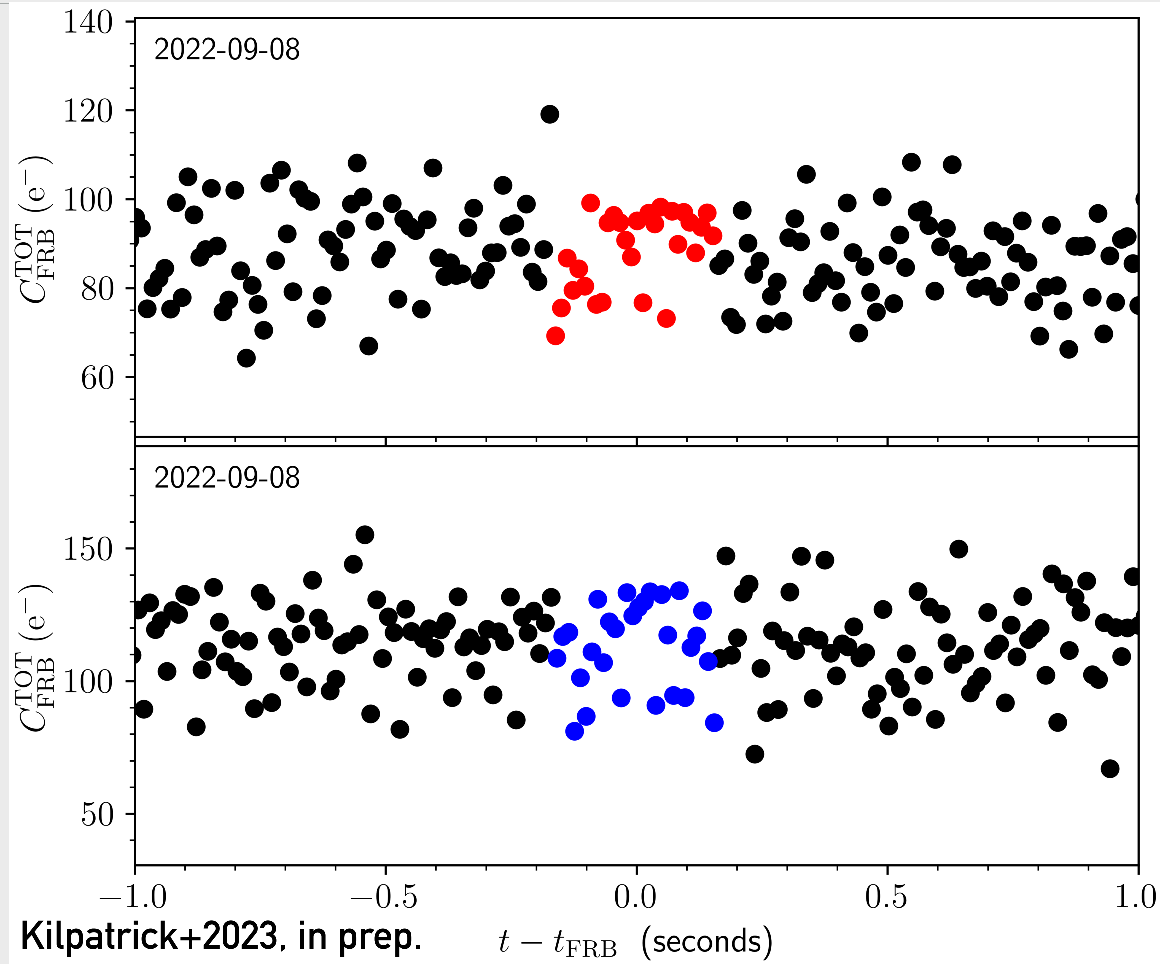


Kilpatrick+2023, in prep.

POINTING AT REPEATERS (±MILLISECONDS TO HOURS)

3-sigma for FRB emission fluence limit = 3 μJy s

Rules out optical/radio fluence of $> 2 - 7 \times 10^{-3}$



Kilpatrick+2023, in prep.

CONCLUSIONS

- Using existing FRB data, it is possible to rapidly crossmatch to all known optical transients in real time - future high-resolution discovery surveys and brokers will enable improved constraints from the flood of radio-optical transient discoveries
- Rapid follow up currently being done can detect fast-evolving optical counterparts (those from NS ejecta, luminous red novae)
- Coordinated, targeted observations remain one of the most promising ways to detect multi-wavelength counterparts for known repeaters