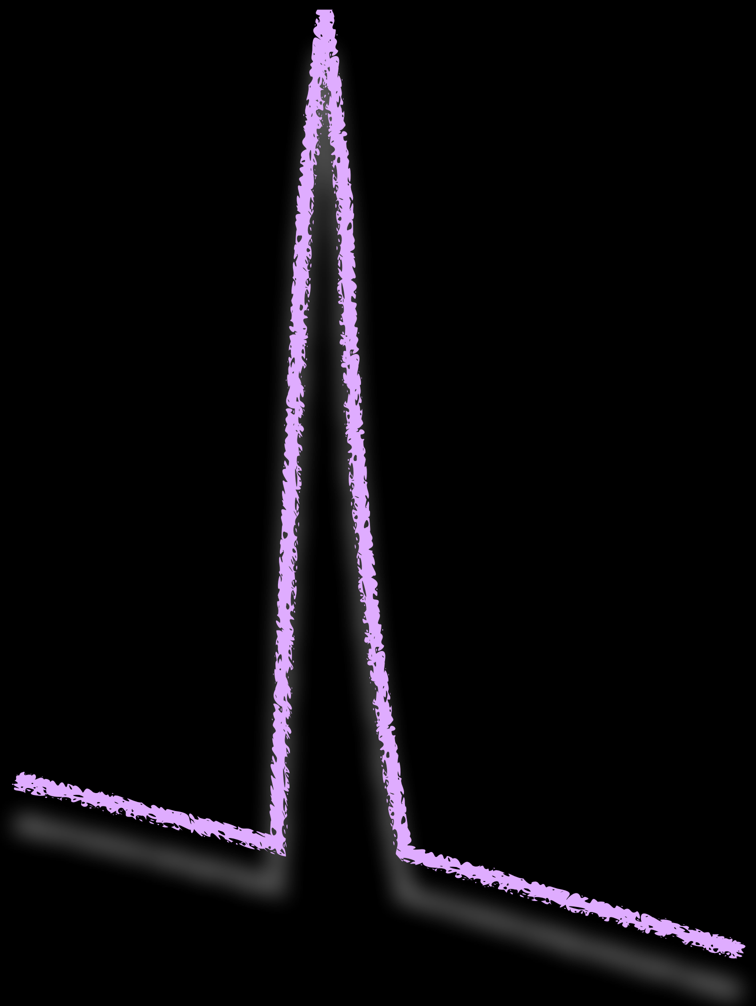
The Origins of the Universe's Fastest Transients



Wen-fai Fong

Northwestern University

@FongGroup

FAST & FORTUNATE FRB FOLLOW-UP

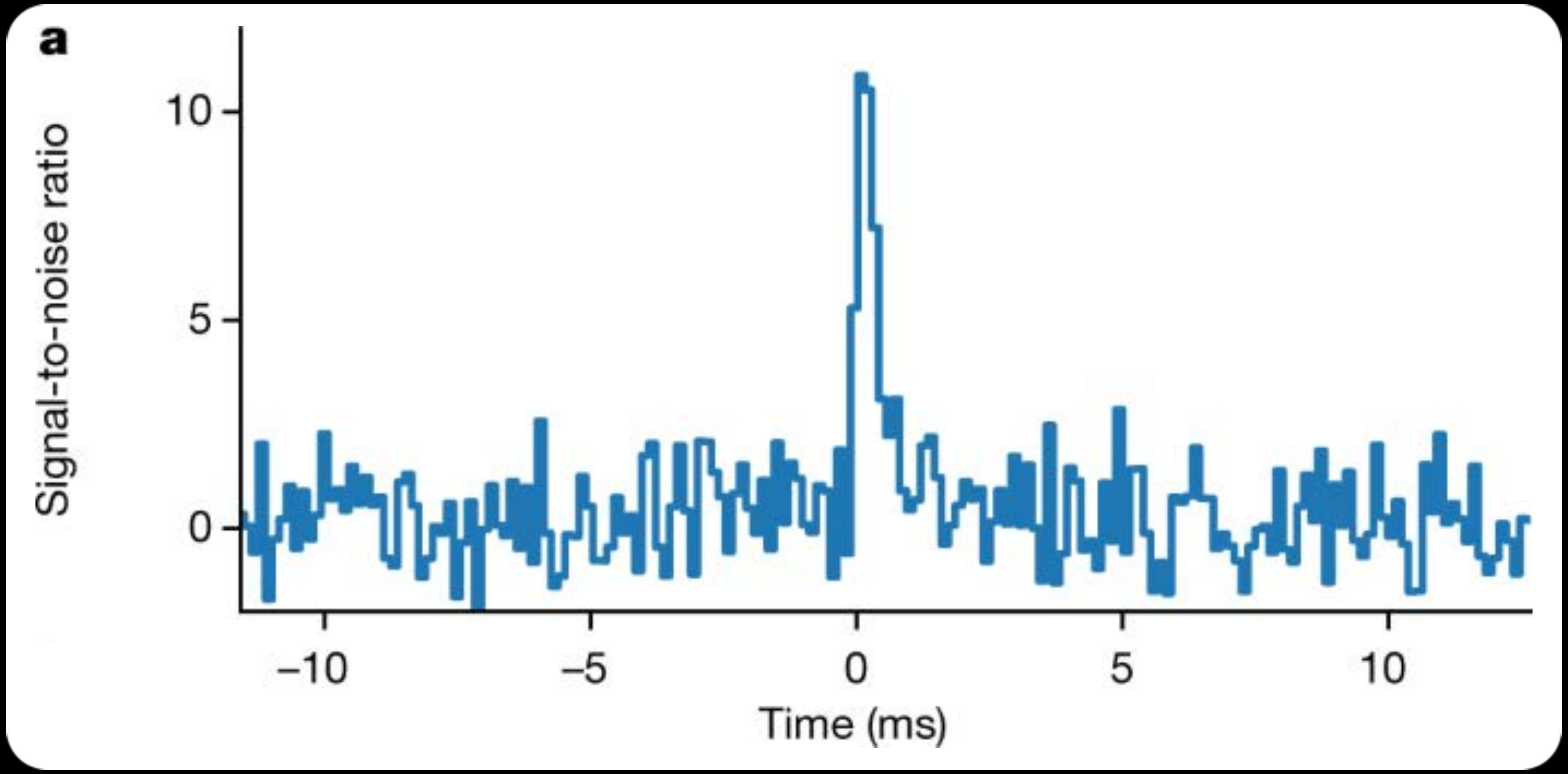
CRAFT

Thanks to:

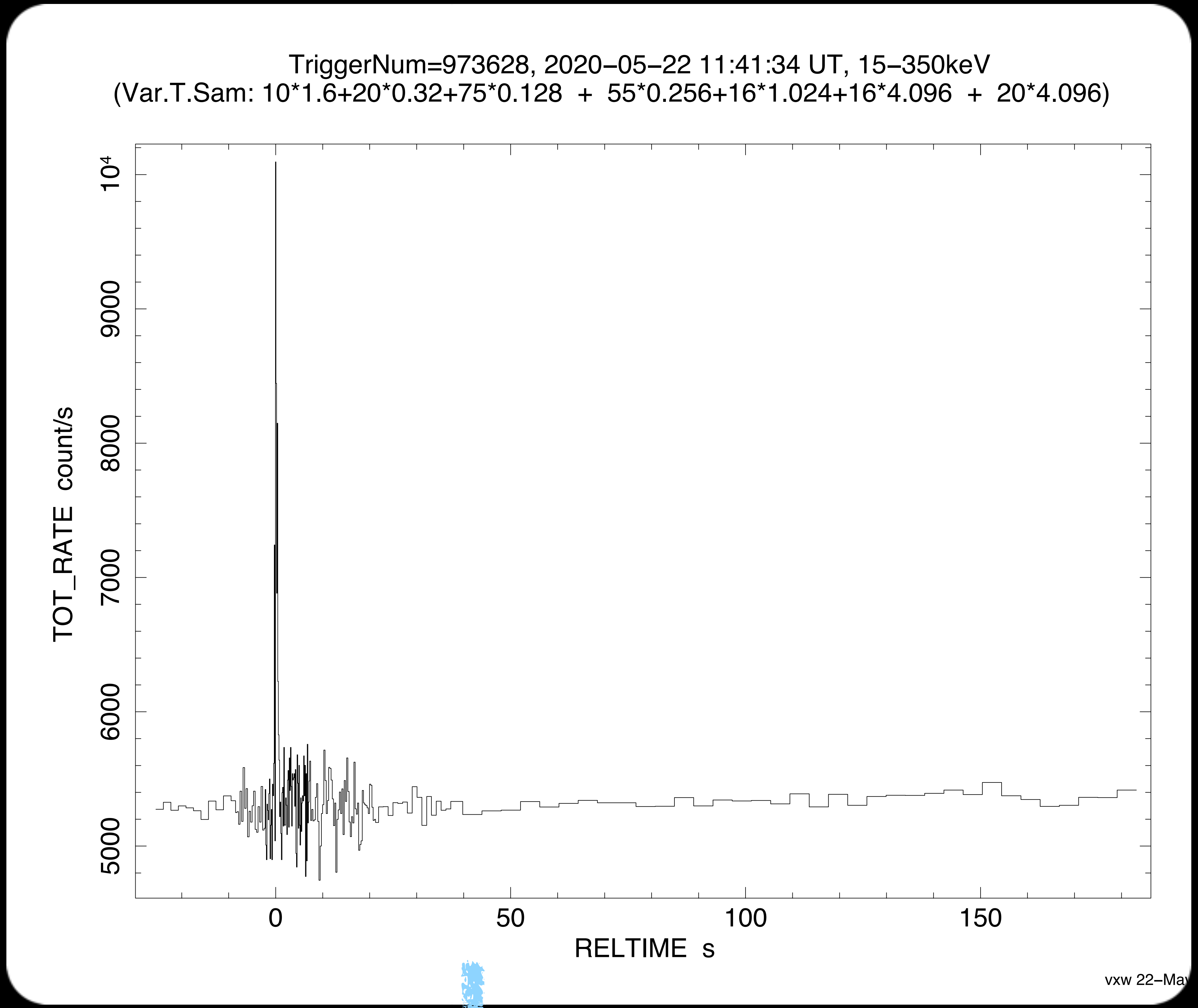
the David & Lucile Packard FOUNDATION

NSF

01.19.2022 IPMU APEC seminar (virtual, Tokyo)

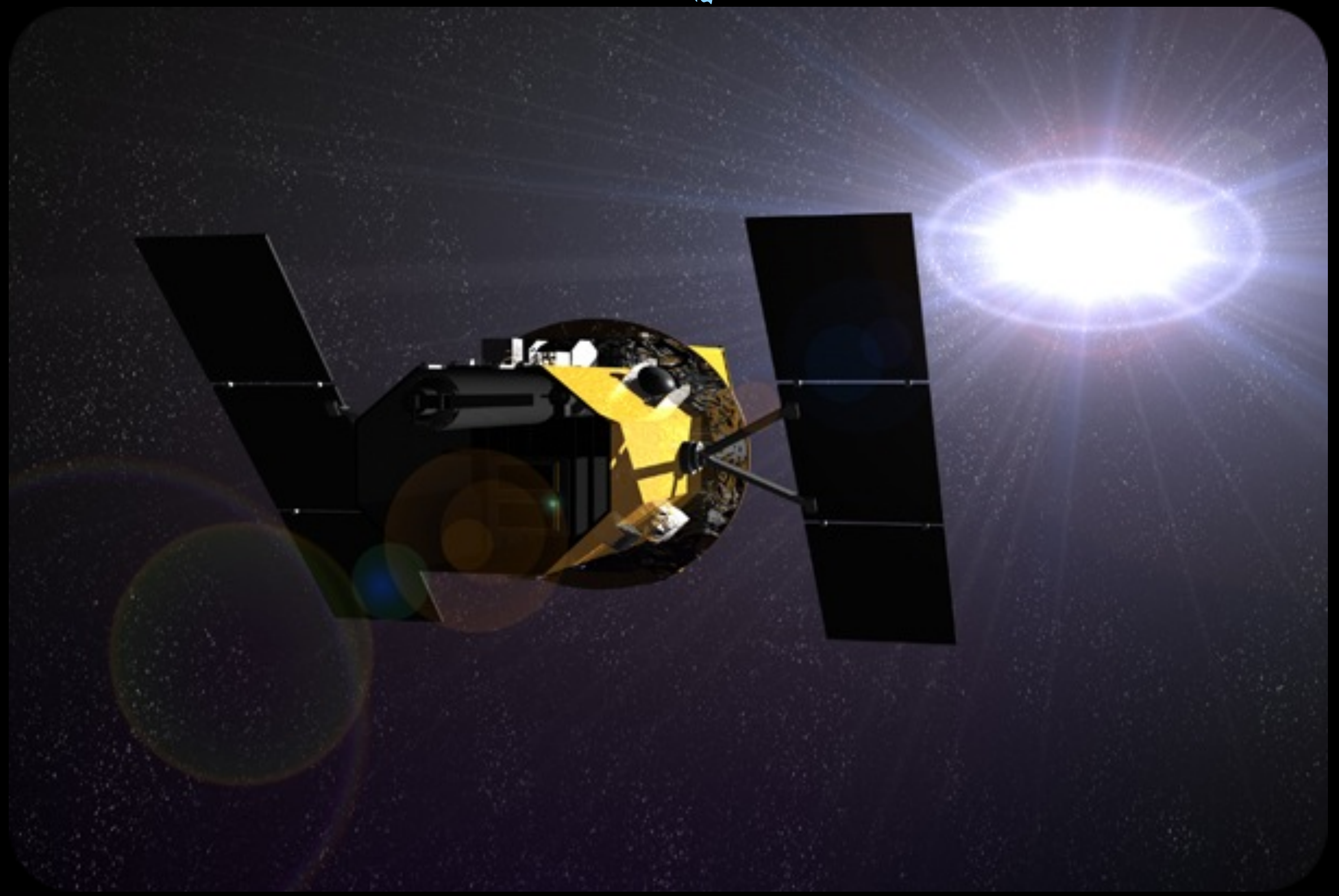


Ravi et al. 2019

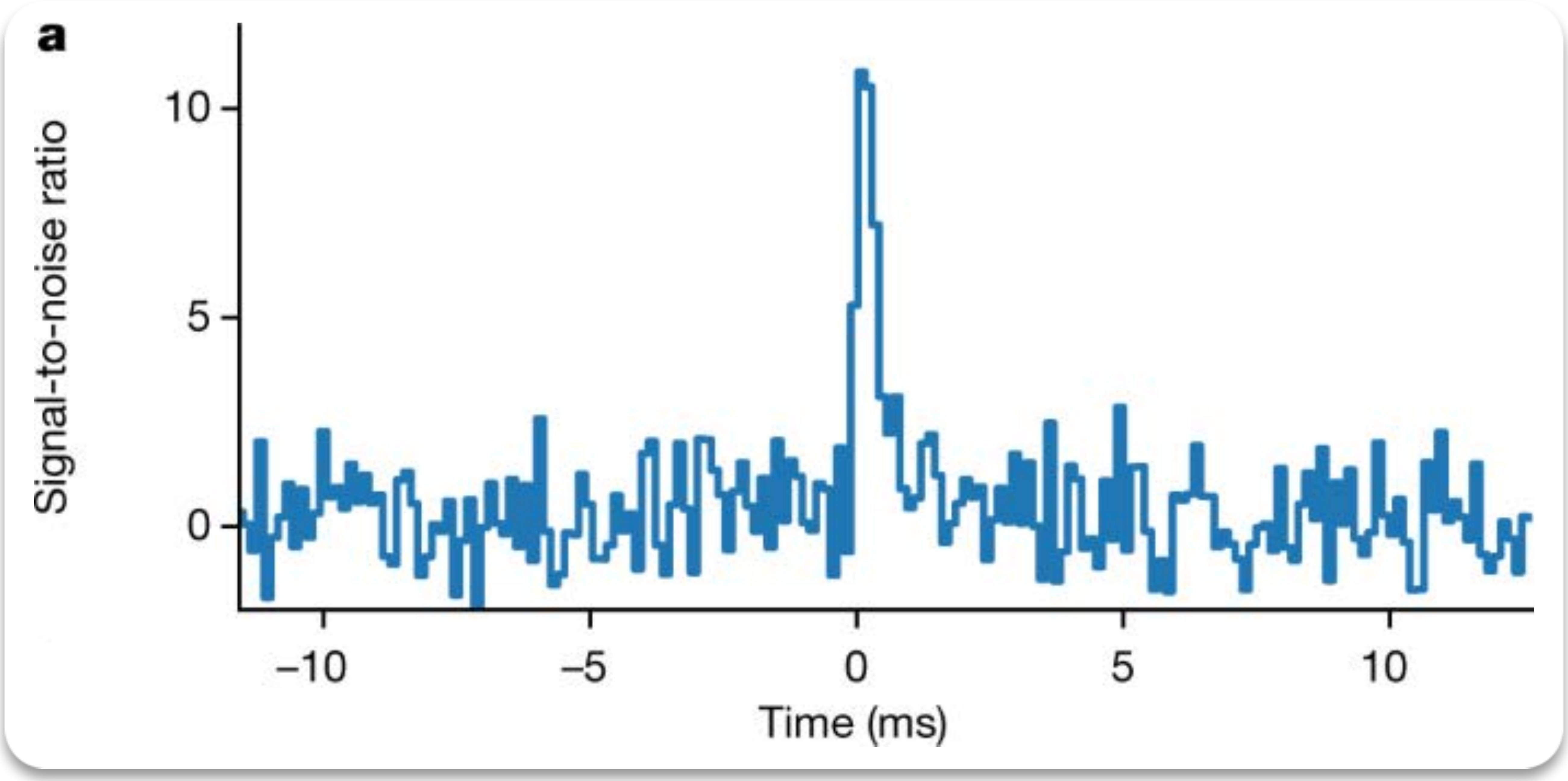


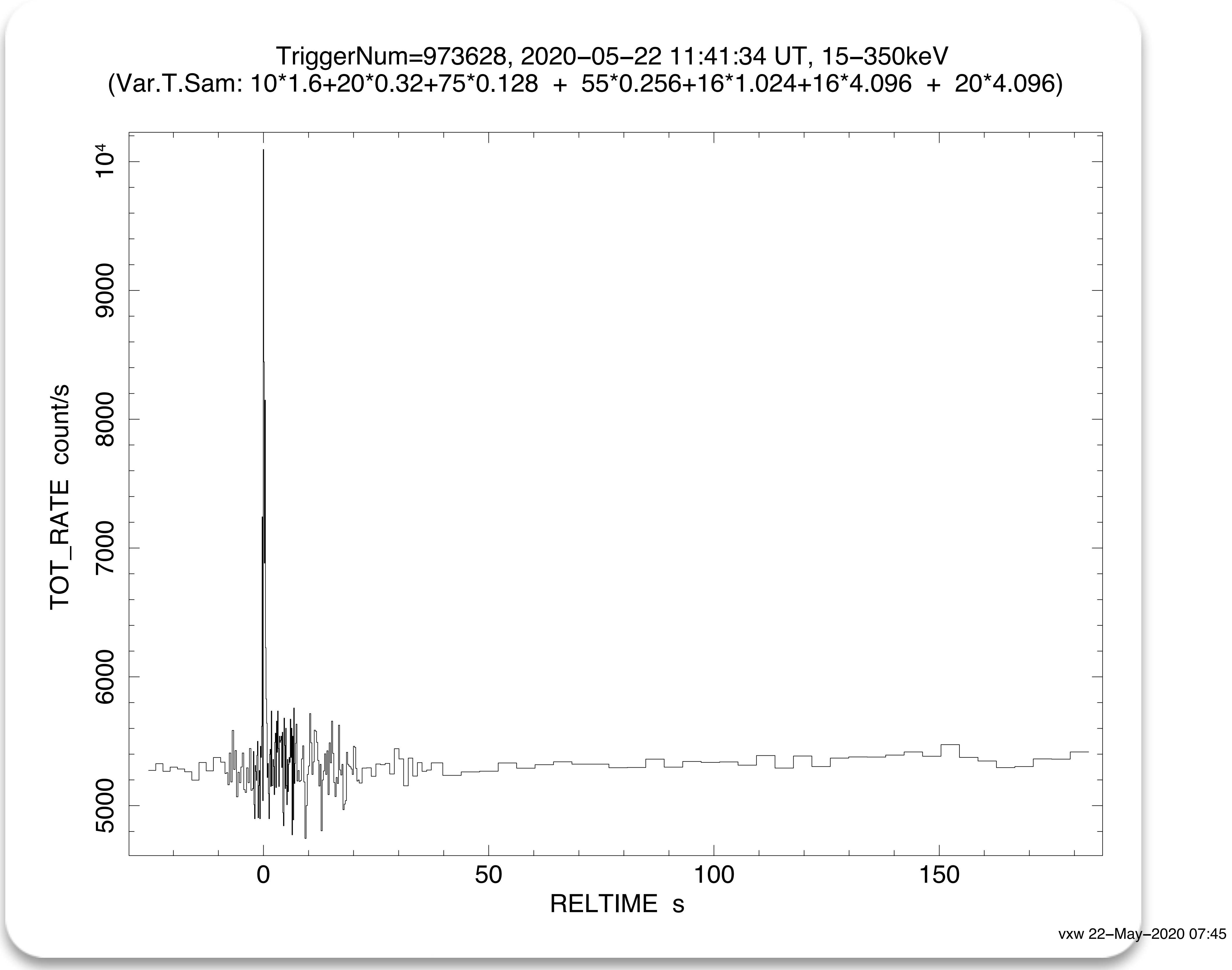
Credit: NASA

Australian Square Kilometer Array Pathfinder (ASKAP); Credit: CSIRO



NASA's Neil Gehrels *Swift* Observatory

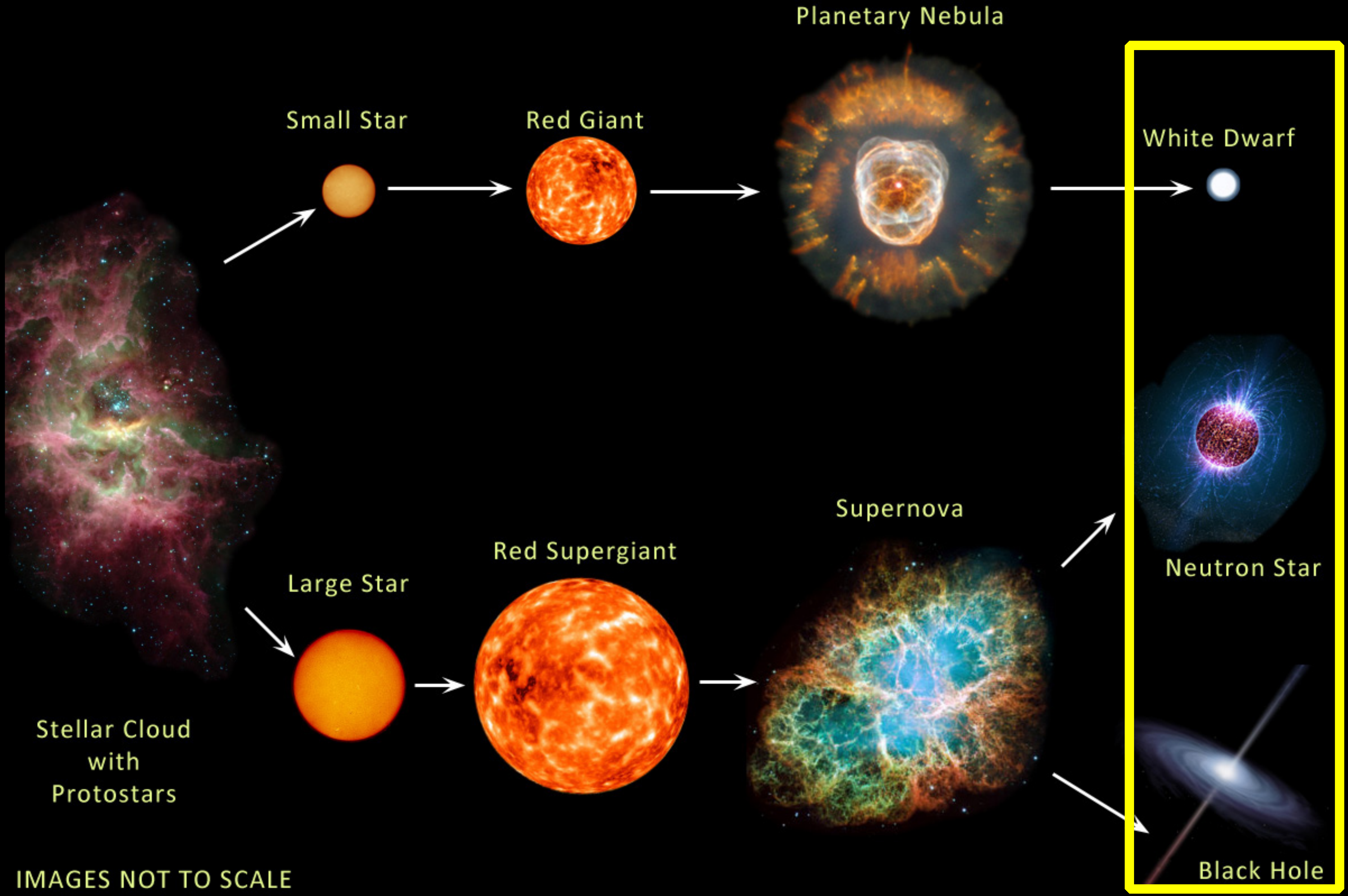




Fast Radio Burst (**FRB**)

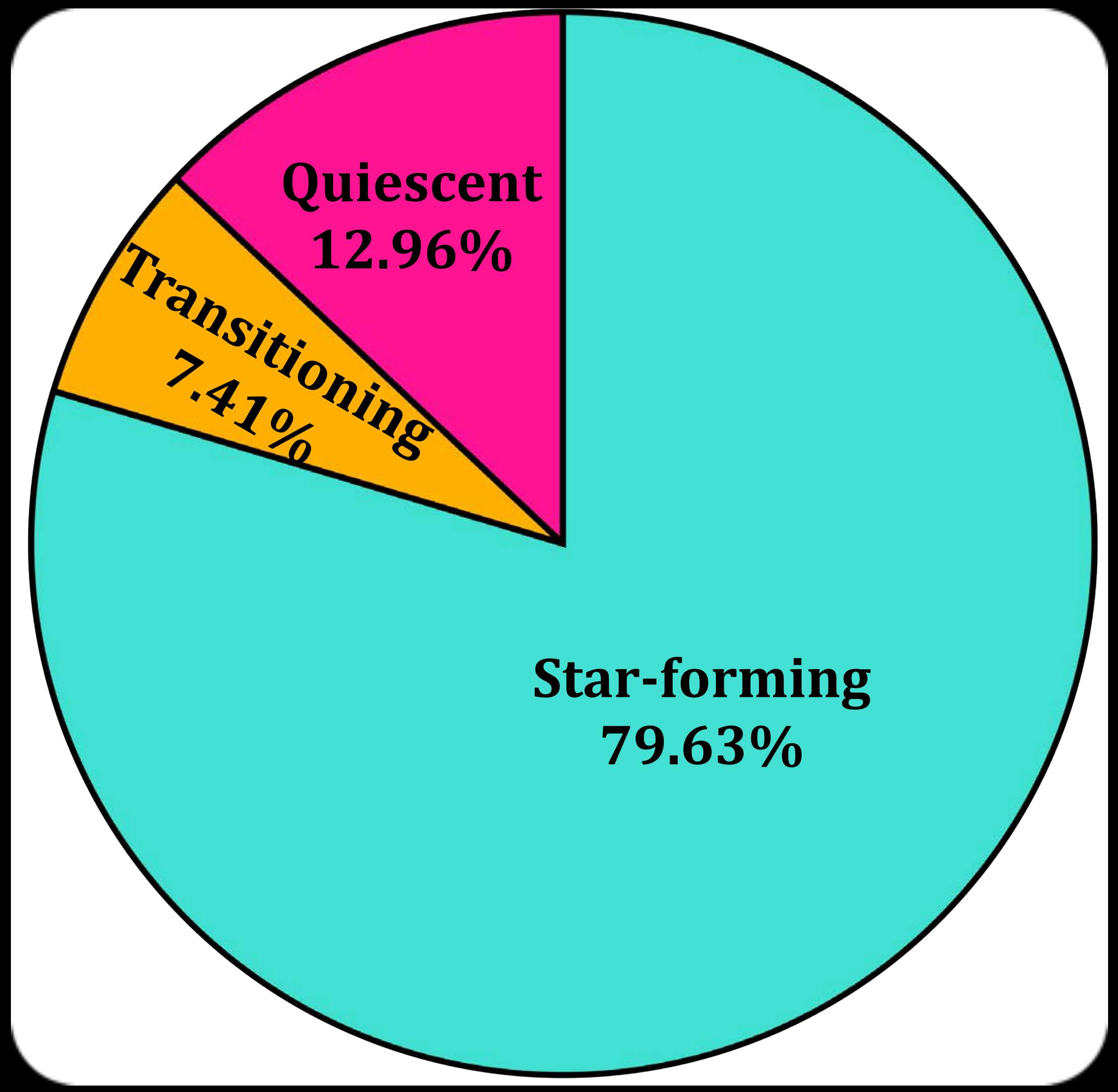
Gamma-ray Burst (**GRB**)

EVOLUTION OF STARS

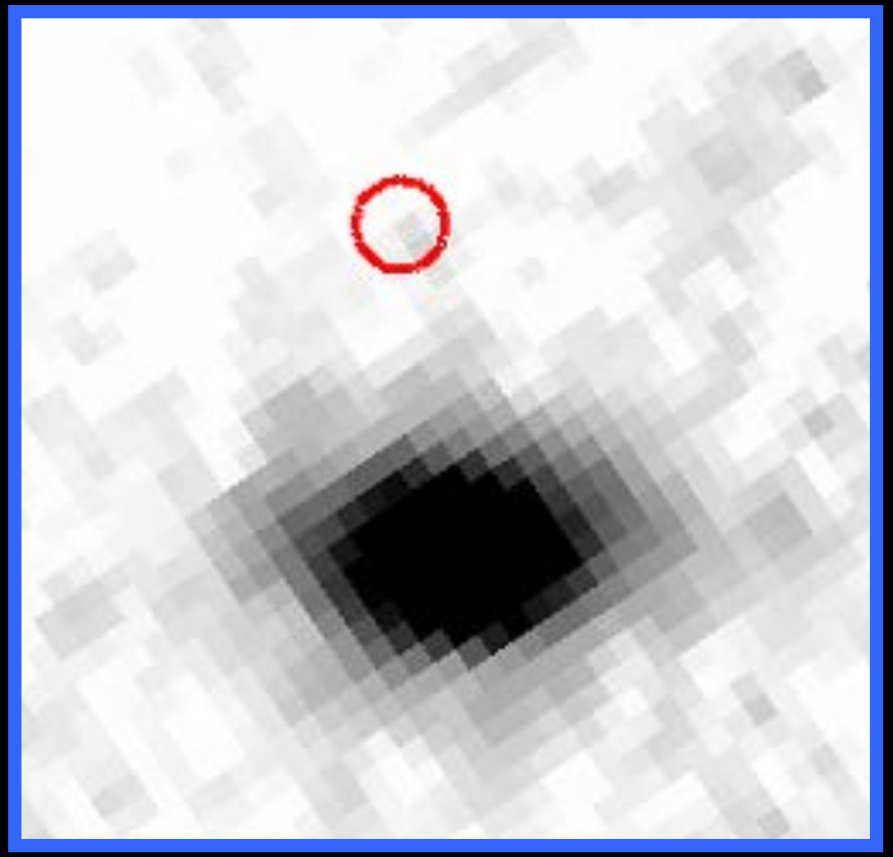


compact objects

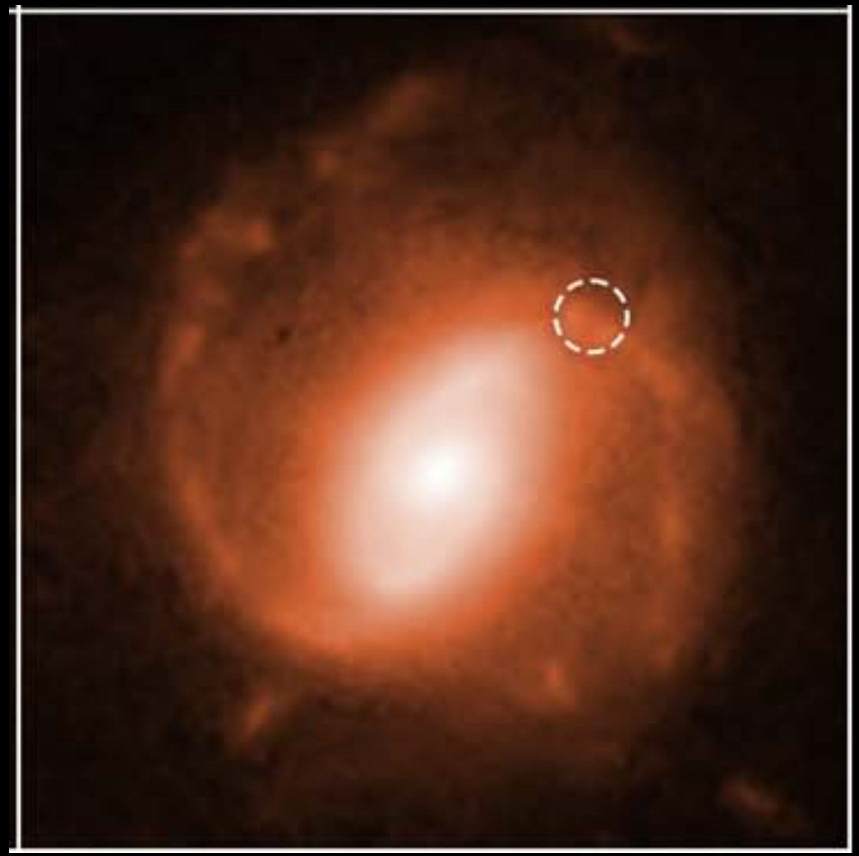
The Power of Host Galaxy Environments



SGRB host



FRB host



How do their environments connect to their origins?

What is the nature of their host galaxies?

Where are they located?

What types of environments give rise to these events?

How do they trace local properties such as galaxy star formation or stellar mass?

Motivating Questions for SGRBs & FRBs

What is the nature of their host galaxies?

Demographics, stellar population properties

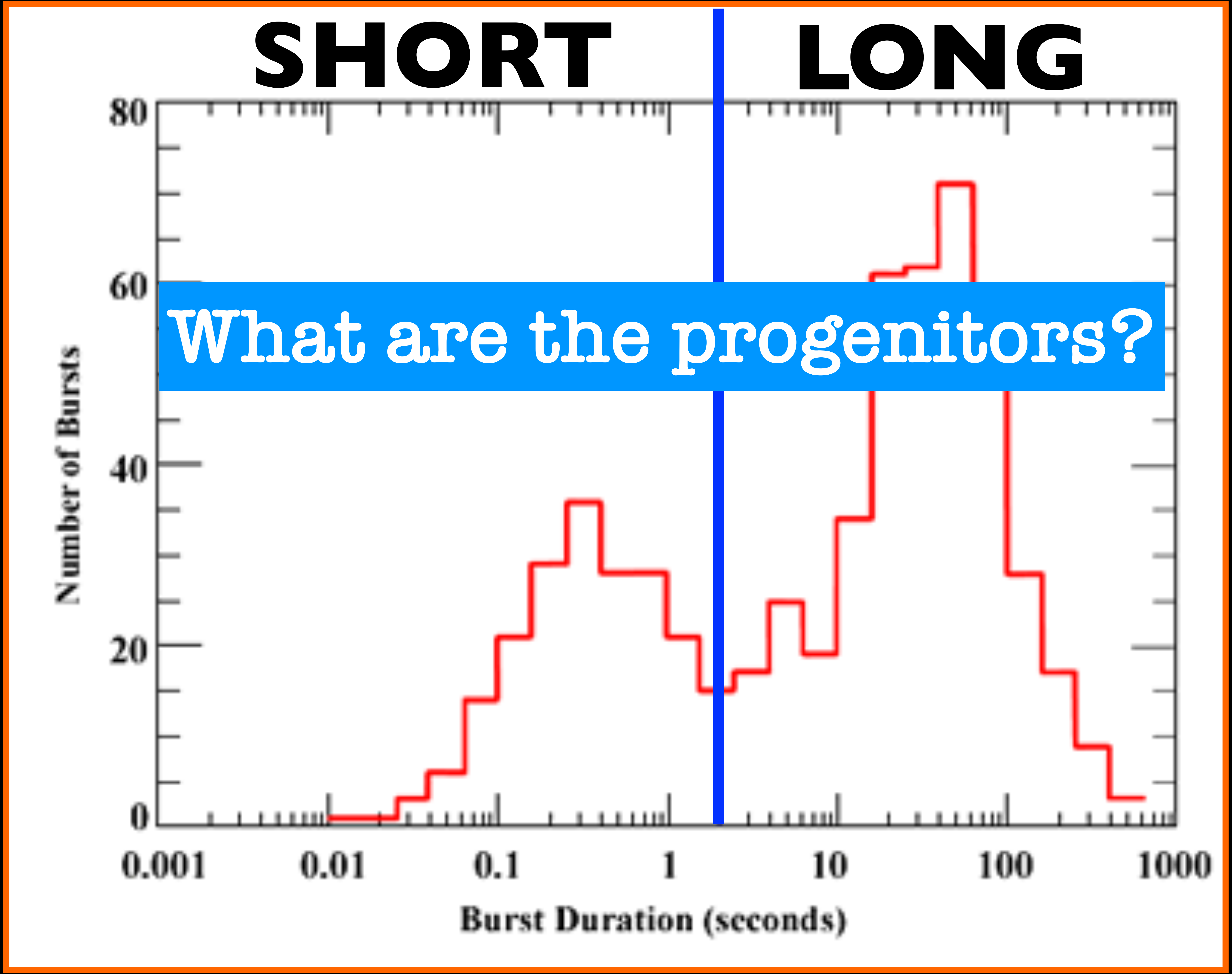
Where are they located?

Offsets, how they trace sub-structure

How do their environments connect to their origins?

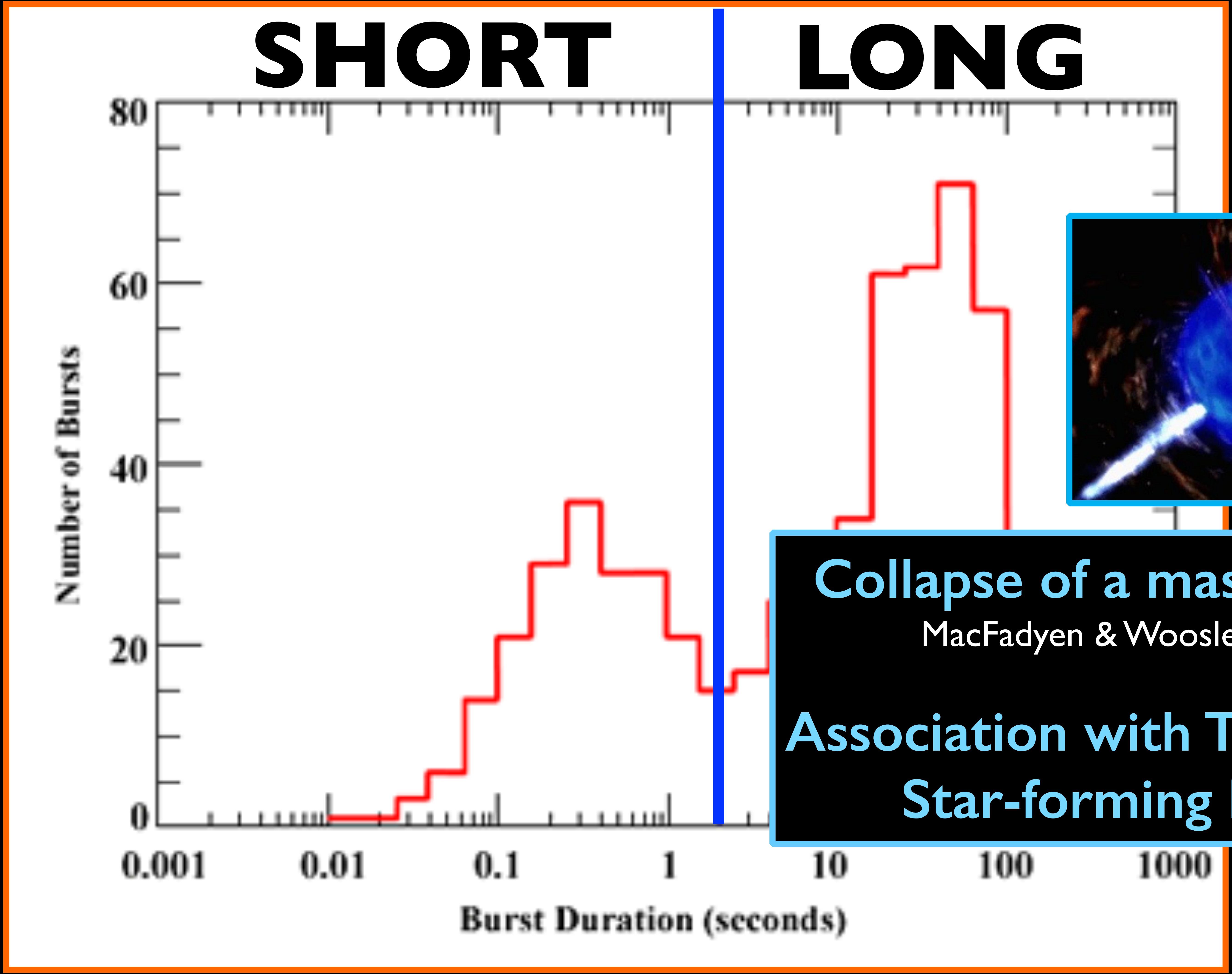
Short Gamma-ray Bursts

Prompt emission: Two populations



Kouveliotou et al. 1993, Nakar 2007

Prompt emission: Two populations

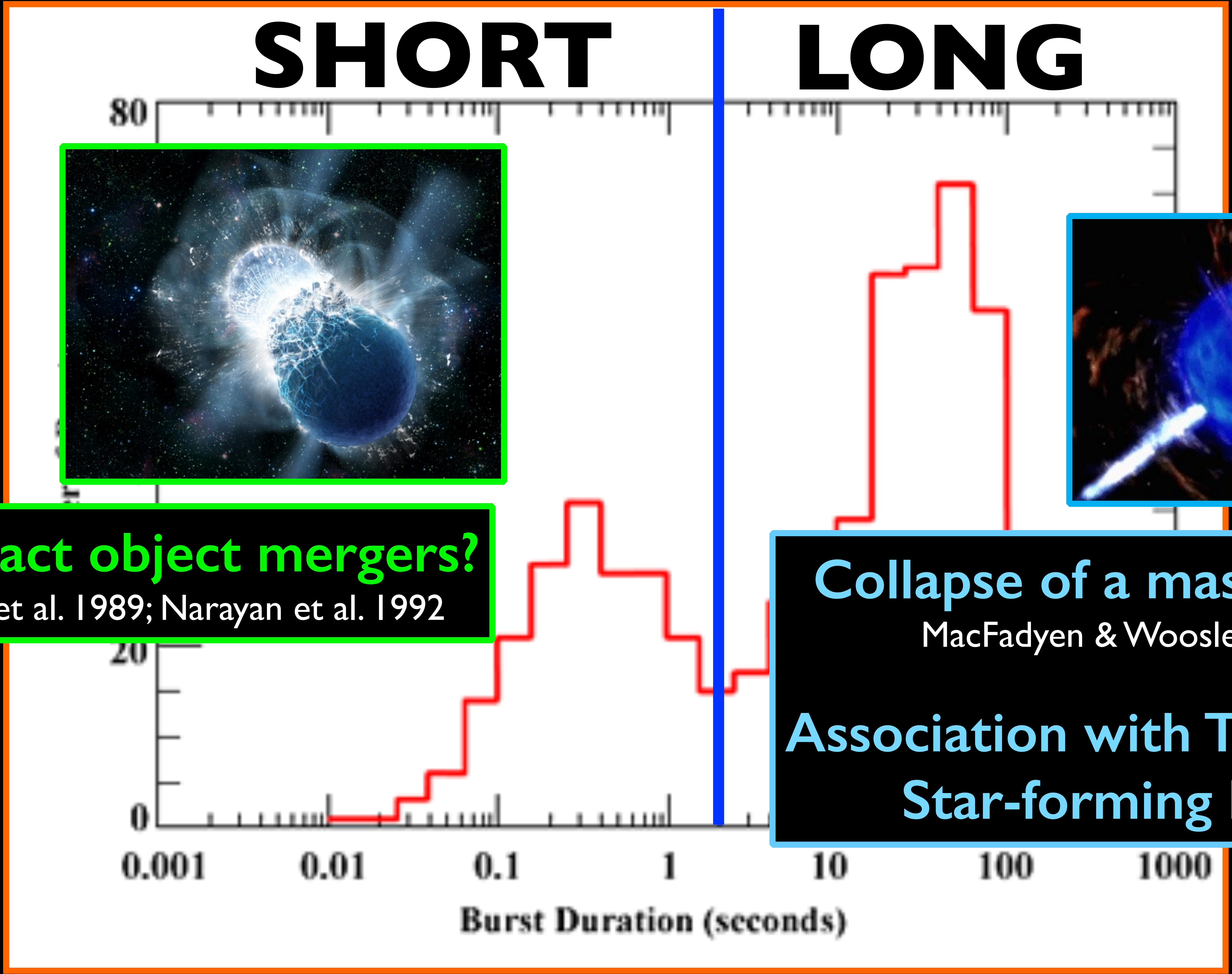


Collapse of a massive star
MacFadyen & Woosley 1999

Association with Type Ic SN
Star-forming hosts

Kouveliotou et al. 1993, Nakar 2007

Prompt emission: Two populations



Compact object mergers?

Eichler et al. 1989; Narayan et al. 1992

Collapse of a massive star

MacFadyen & Woosley 1999

Association with Type Ic SN

Star-forming hosts

Kouveliotou et al. 1993, Nakar 2007

merger

short-duration gamma-ray burst

compact object binary (NS-NS/NS-BH)

The great triumph of the multi-messenger discovery GW170817 and GRB170817A!

Illustrated by: Dr. Jessie Berta-Thompson

An observational golden era for mergers

OFF-AXIS
(Local mergers)

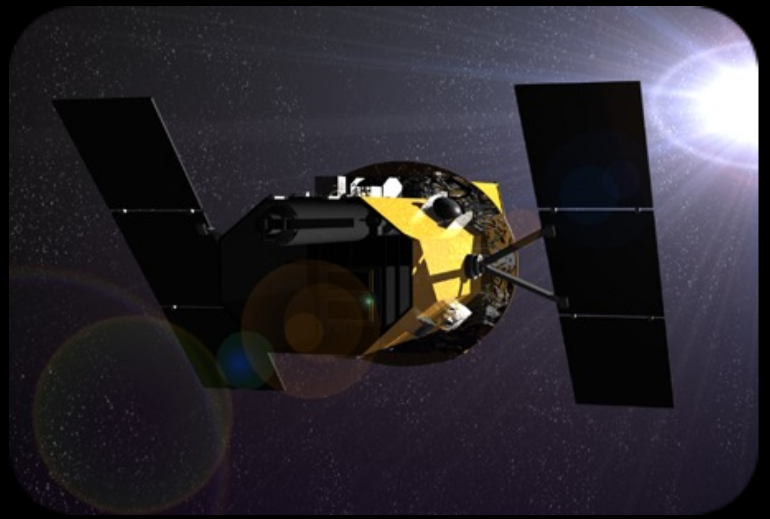
LIGO

Image Credits: NASA/SAO/Swift/Cruz deWilde

Complementary discovery streams

At present, short GRBs represent a major route to making progress in NS mergers.

ON-AXIS
(Cosmological Short GRBs)



Neil Gehrels Swift Observatory

Fermi

2004: Launch of *Swift*

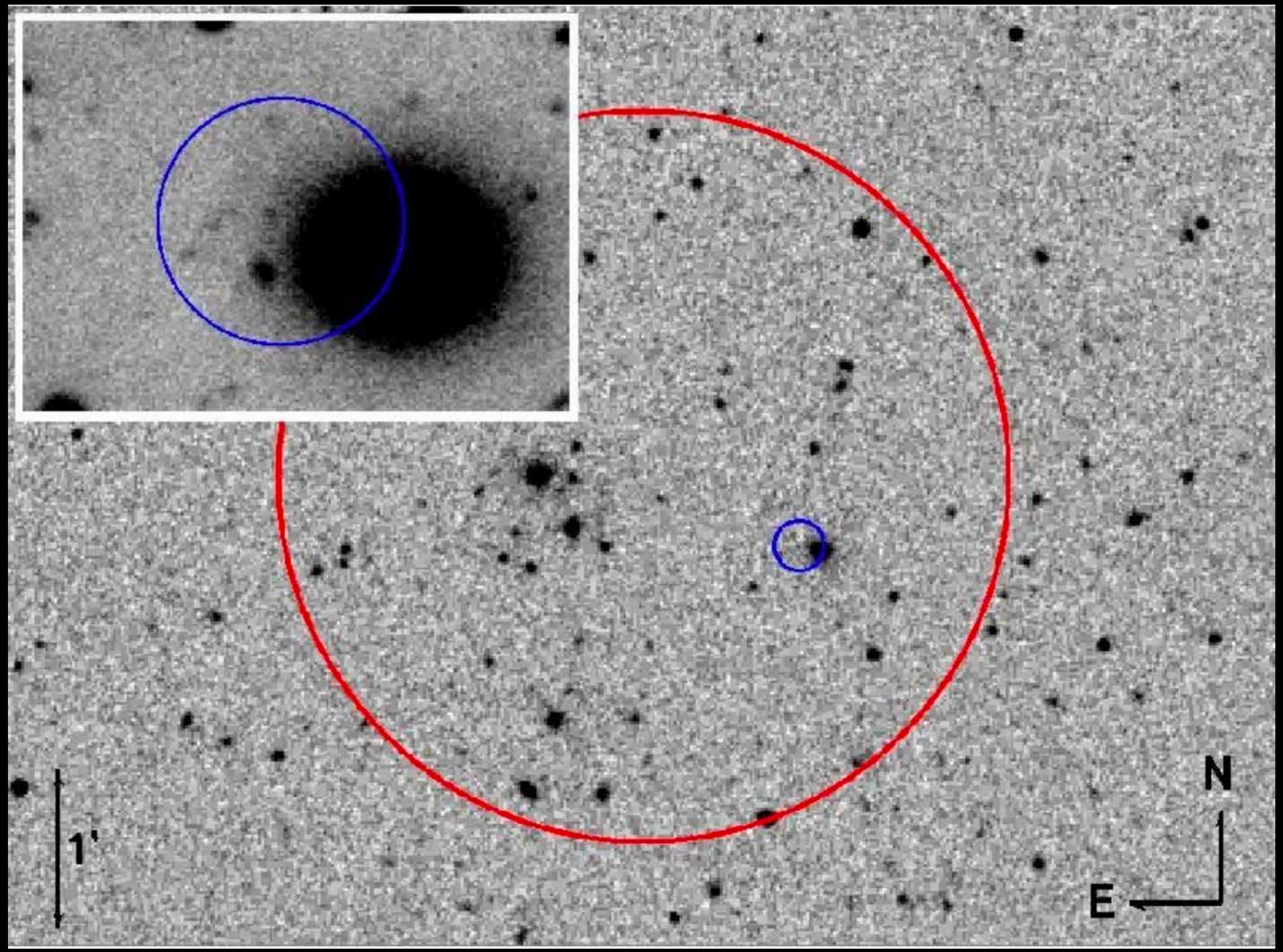
2005: The first detection of a **short GRB afterglow**!

A short γ-ray burst apparently associated with an elliptical galaxy at redshift z = 0.225

N. Gehrels, C. L. Sarazin, P. T. O'Brien, B. Zhang, L. Barbier, S. D. Barthelmy, A. Blustin, D. N. Burrows, J. Cannizzo, J. R. Cummings, M. Goad, S. T. Holland, C. P. Hurkett, J. A. Kennea, A. Levan, C. B. Markwardt, K. O. Mason, P. Meszaros, M. Page, D. M. Palmer, E. Rol, T. Sakamoto, R. Willingale, L. Angelini, A. Beardmore, P. T. Boyd, A. Breeveld, S. Campana, M. M. Chester, G. Chincarini, L. R. Cominsky, G. Cusumano, M. de Pasquale, E. E. Fenimore, P. Giommi, C. Gronwall, D. Grupe, J. E. Hill, D. Hinshaw, J. Hjorth, D. Hullinger, K. C. Hurley, S. Klose, S. Kobayashi, C. Kouveliotou, H. A. Krimm, V. Mangano, F. E. Marshall, K. McGowan, A. Moretti, R. F. Mushotzky, K. Nakazawa, J. P. Norris, J. A. Nousek, J. P. Osborne, K. Page, A. M. Parsons, S. Patel, M. Perri, T. Poole, P. Romano, P. W. A. Roming, S. Rosen, G. Sato, P. Schady, A. P. Smale, J. Sollerman, R. Starling, M. Still, M. Suzuki, G. Tagliaferri, T. Takahashi, M. Tashiro, J. Tueller, A. A. Wells, N. E. White & R. A. M. J. Wijers

Gehrels et al. 2005 (see also Bloom et al. 2006)

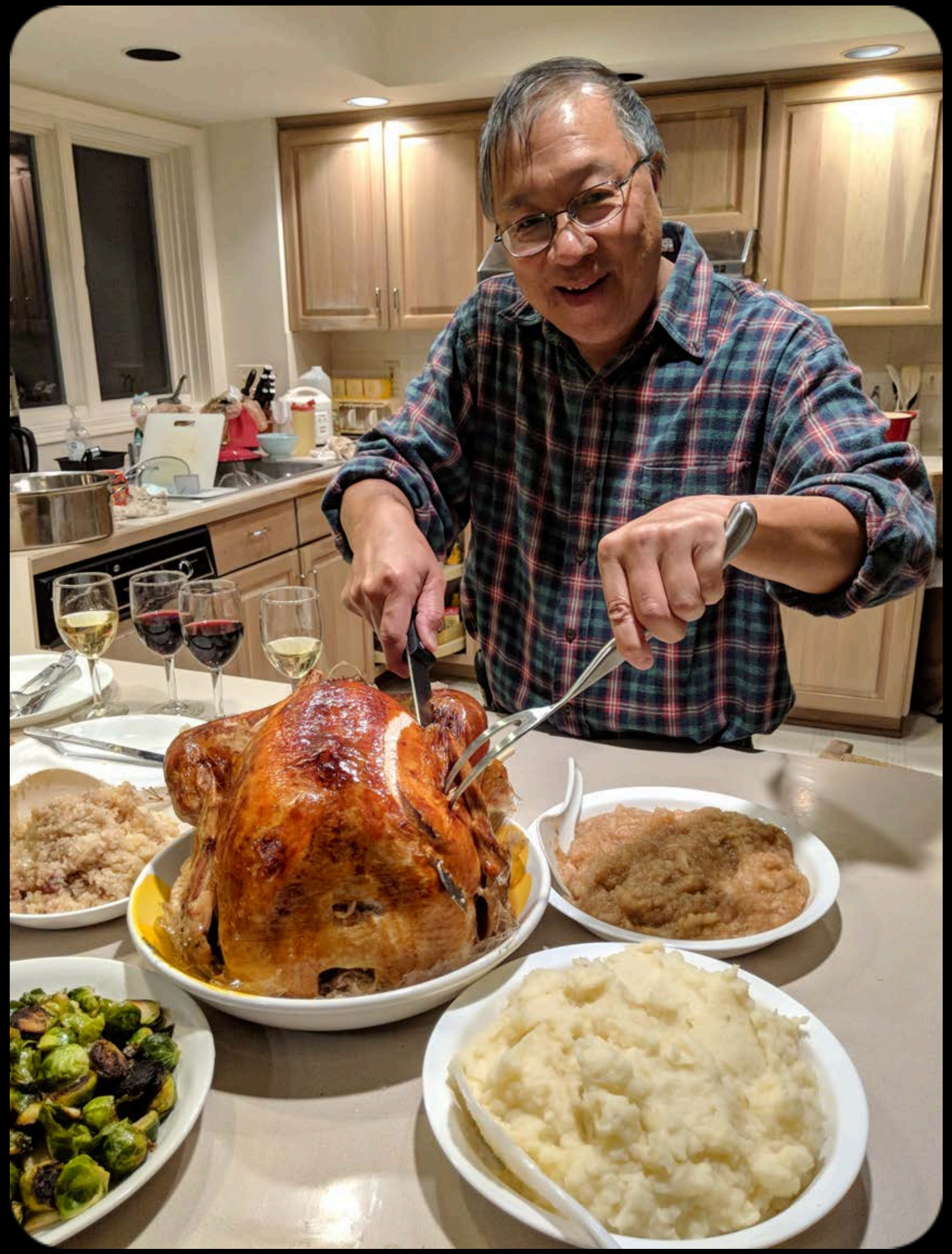
nature
International journal of science



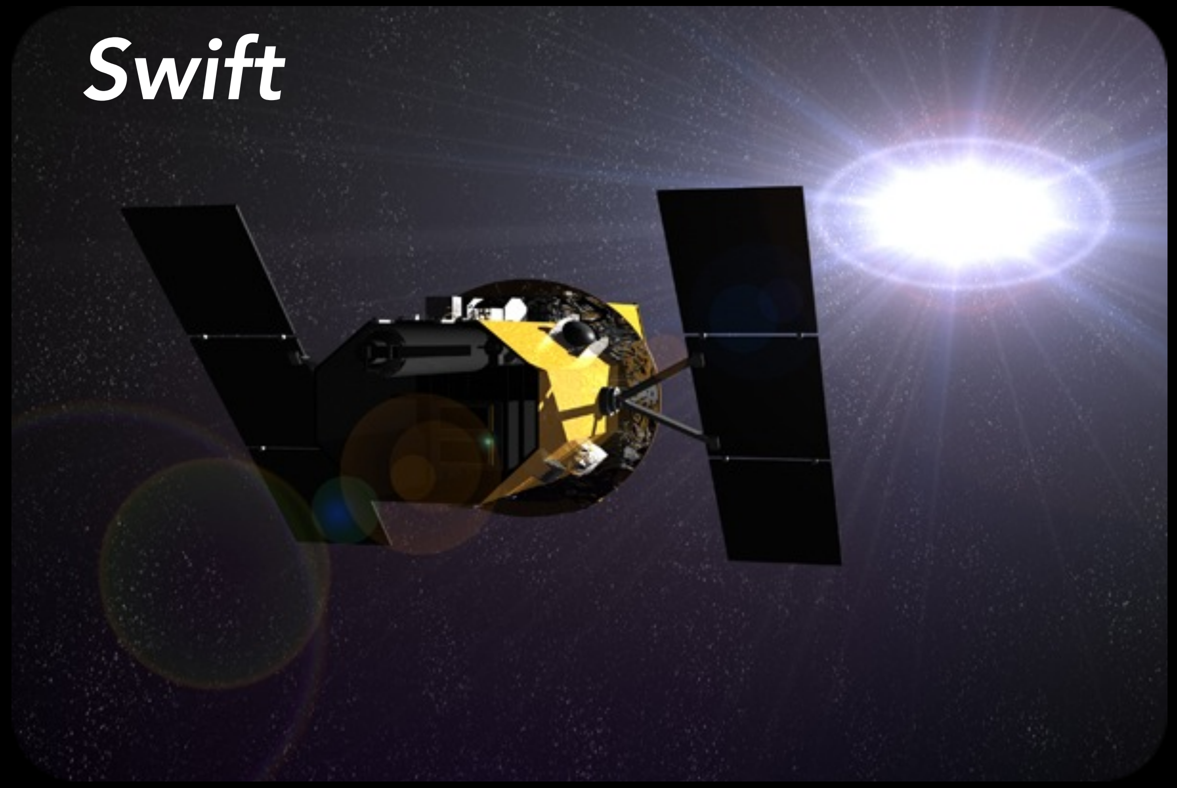
First X-ray afterglow in a short GRB and in an elliptical (old) galaxy!

*Afterglow is key to **localization** and **placement** within a host galaxy*

Chasing GRB afterglows in practice

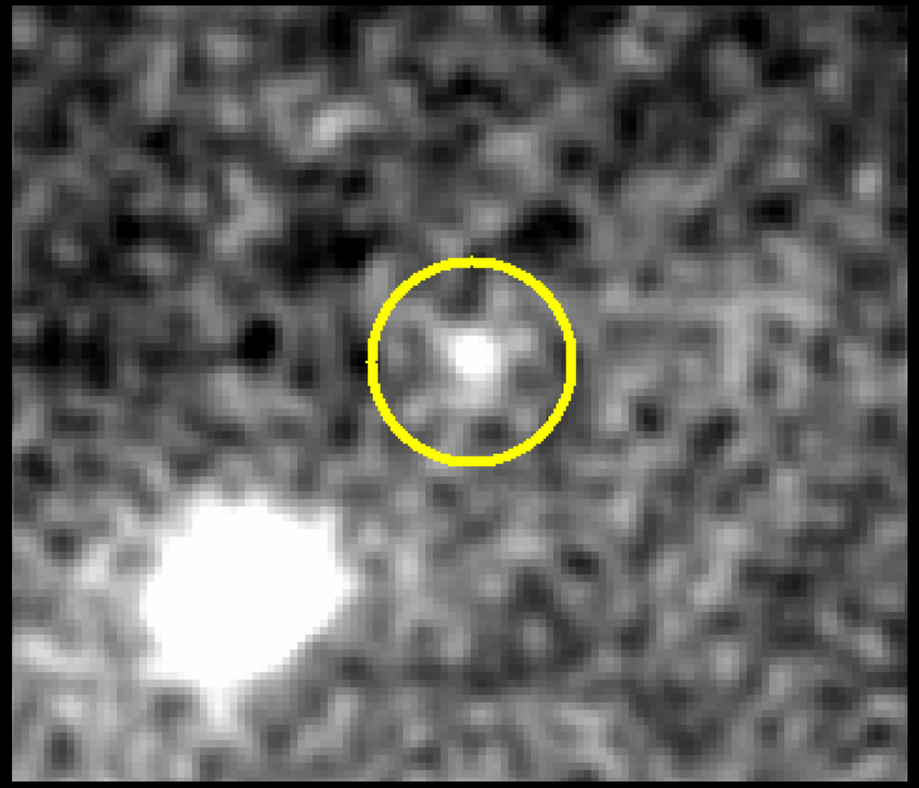


2018-11-22 UT

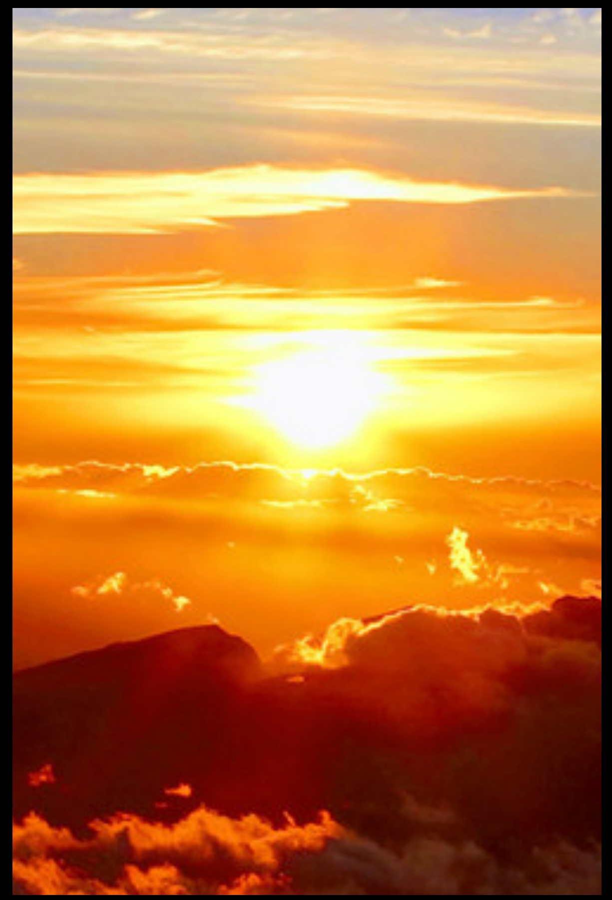


2018-11-23 at 05:33 UT

Dr. Kerry Paterson

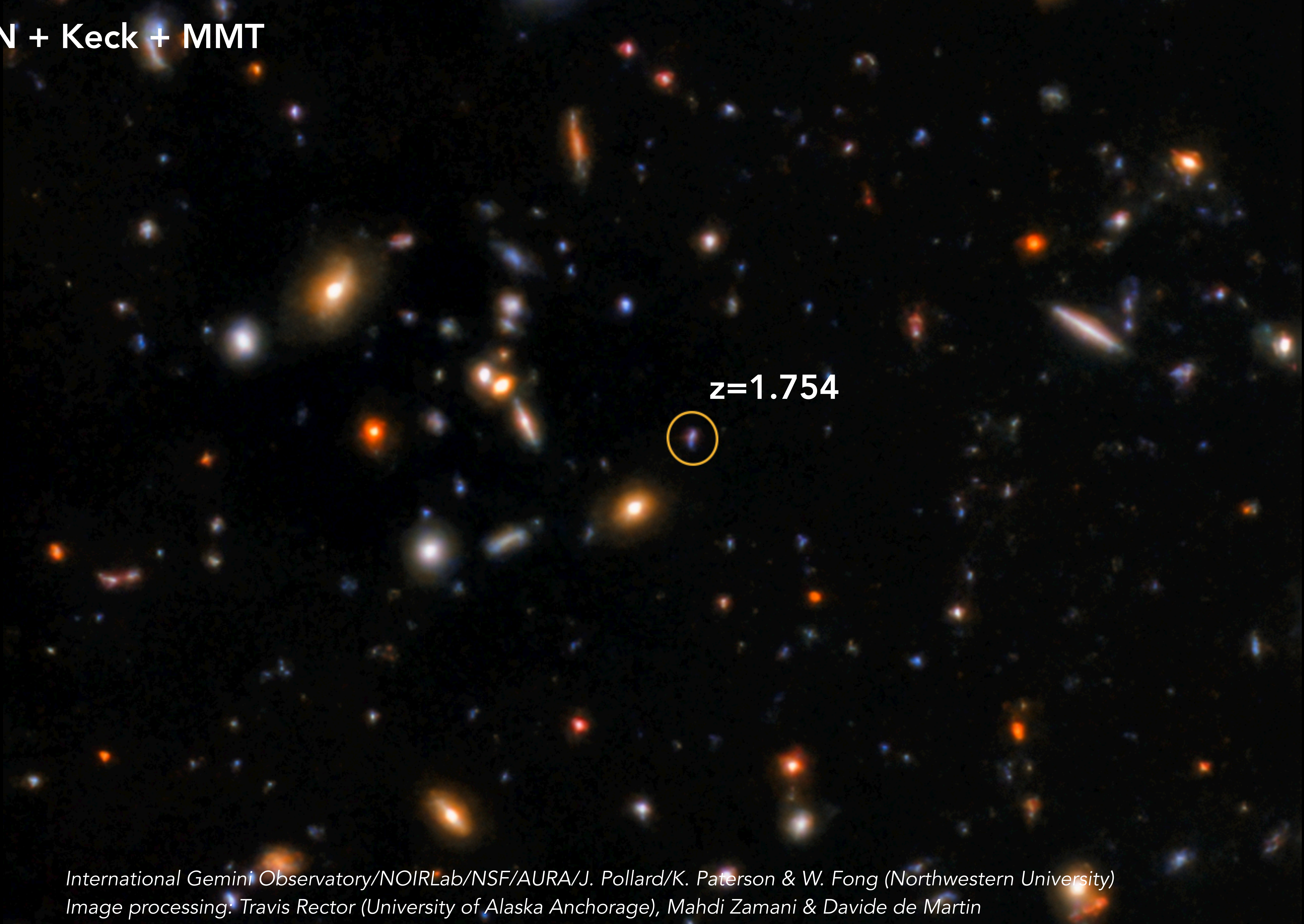


Email to
1000+
Astronomers



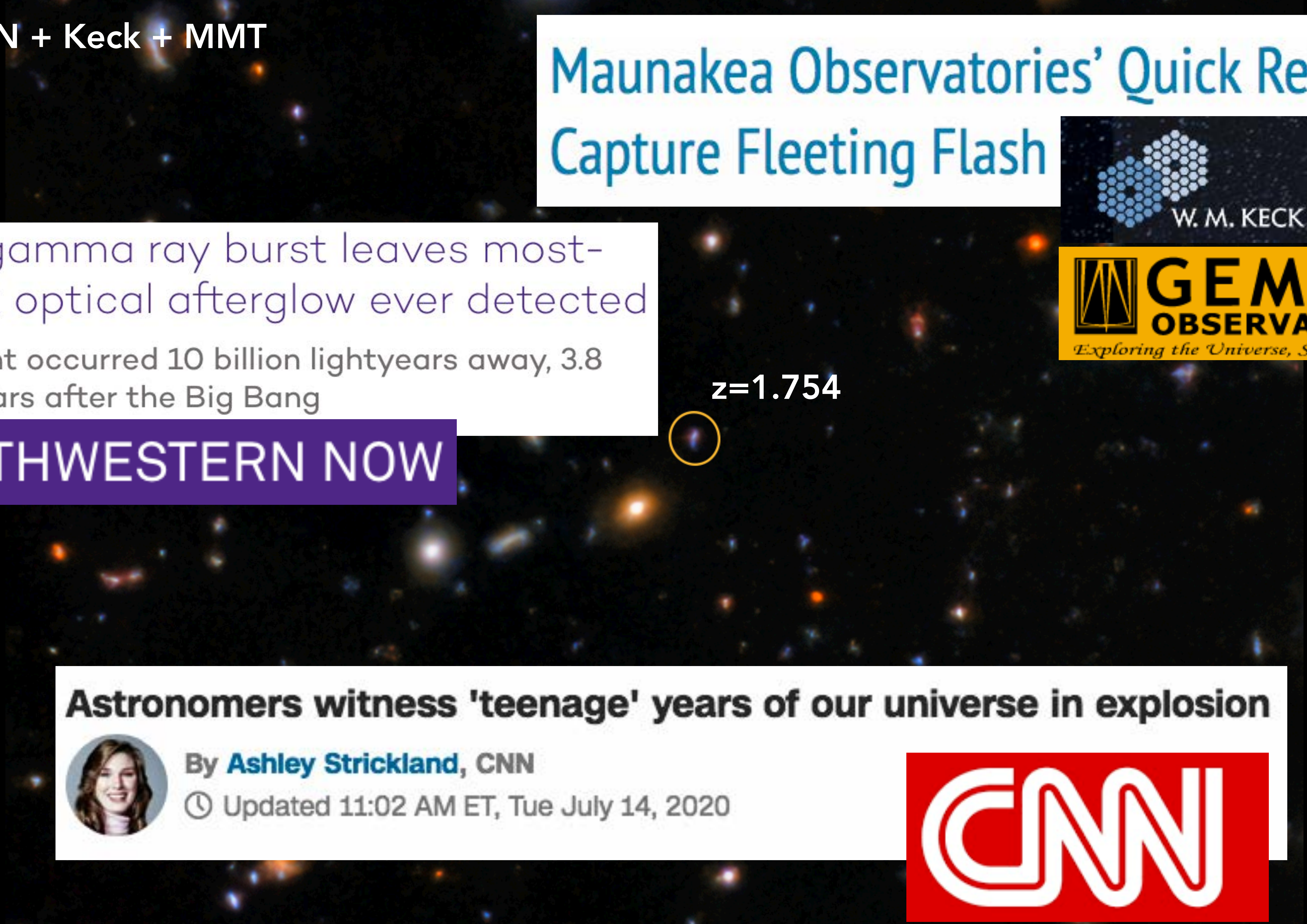
Follow-up observations,
Host galaxy,
Paper!

Gemini-N + Keck + MMT



International Gemini Observatory/NOIRLab/NSF/AURA/J. Pollard/K. Paterson & W. Fong (Northwestern University)
Image processing: Travis Rector (University of Alaska Anchorage), Mahdi Zamani & Davide de Martin

Gemini-N + Keck + MMT



Maunakea Observatories' Quick Reflexes Capture Fleeting Flash

W. M. KECK OBSERVATORY

GEMINI OBSERVATORY

Exploring the Universe, Sharing its Wonders

Short gamma ray burst leaves most-distant optical afterglow ever detected

Rare event occurred 10 billion lightyears away, 3.8 billion years after the Big Bang

NORTHWESTERN NOW

Astronomers witness 'teenage' years of our universe in explosion

By Ashley Strickland, CNN

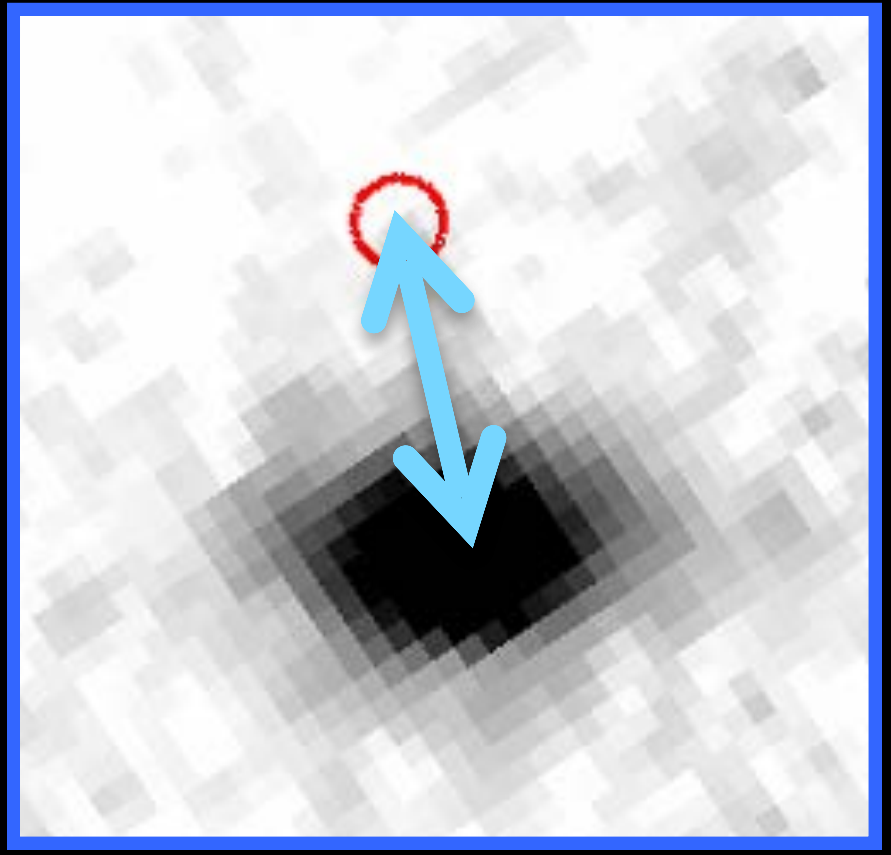
Updated 11:02 AM ET, Tue July 14, 2020

CNN

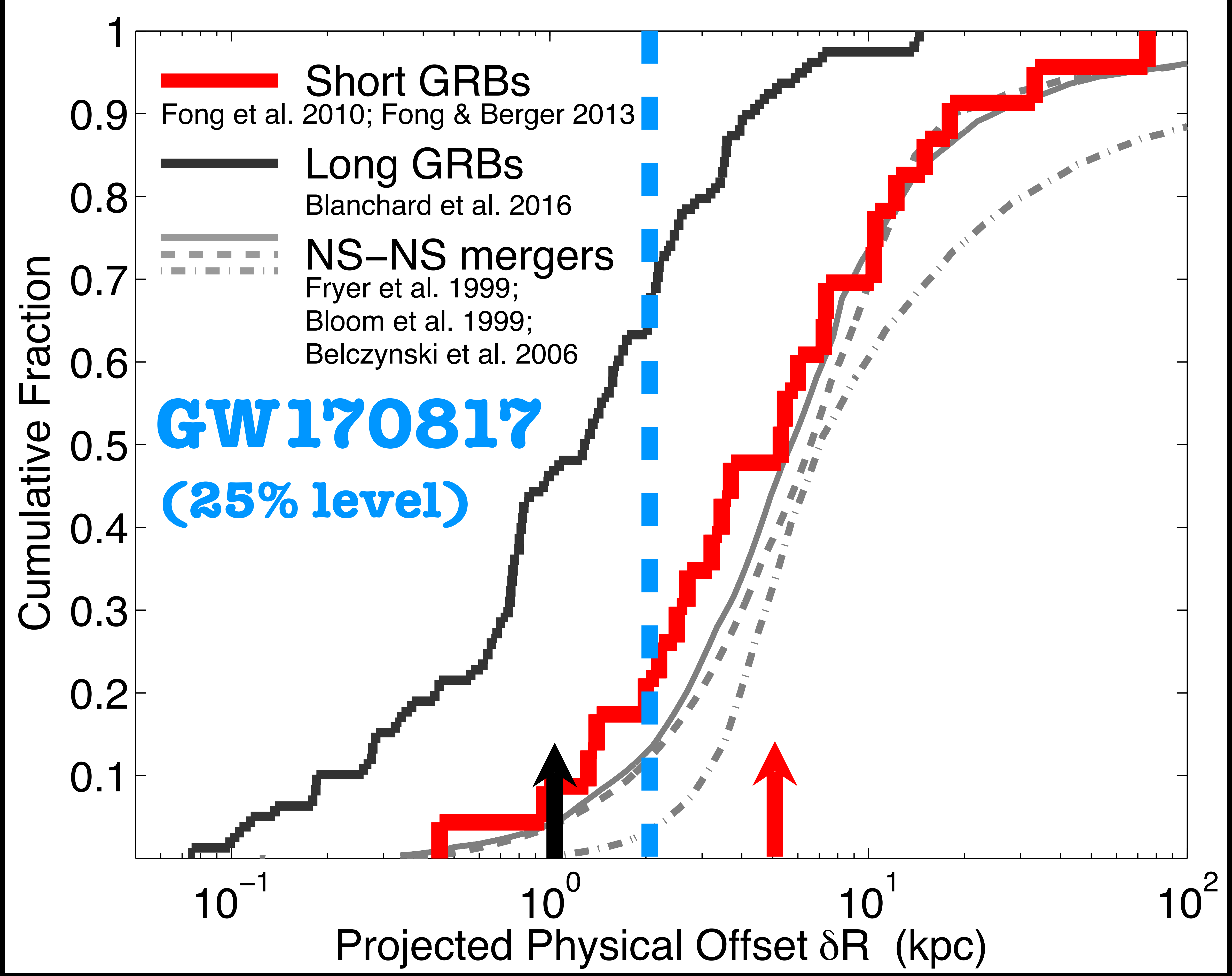
The locations of short GRBs *within* their hosts as crucial clues

NS/BH kicks
+
merger times

"offset"



Fryer & Kalogera 1997; Fryer et al. 1999; Bloom et al. 1999; Perna & Belczynski 2002; Belczynski et al. 2006; Zemp et al. 2009; Kelley et al. 2010



Fong & Berger 2013
(see also: Church et al. 2011; Tunnicliffe et al. 2014; Pan et al. 2017)

Long GRBs: Blanchard et al. 2016
NS-NS models: Fryer et al. 1999; Bloom et al. 1999; Belczynski et al. 2006

Short ~ 5 kpc
Long ~ 1 kpc

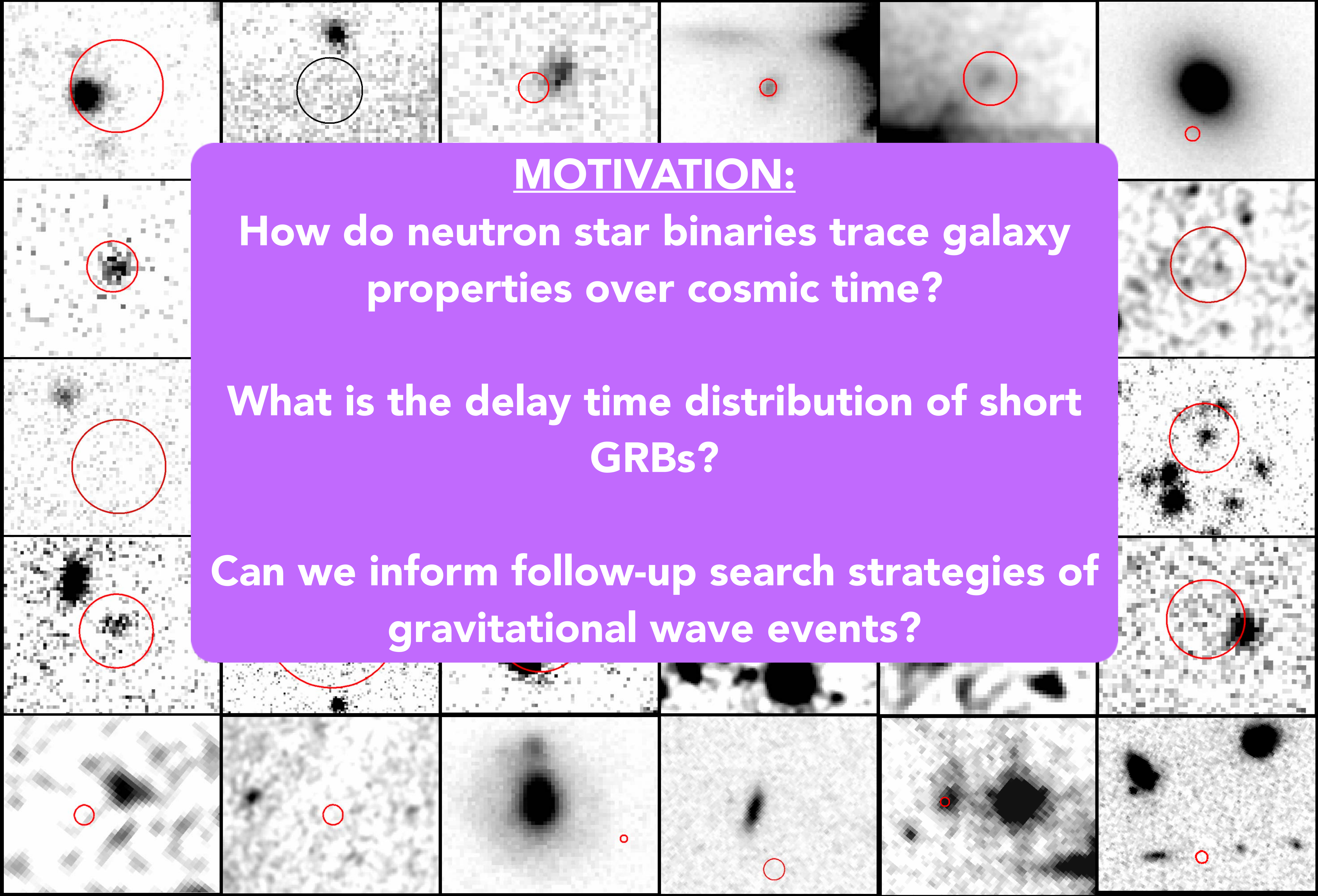
host-normalized:
~20% are >5r_e
~20% are <1r_e

Weakly correlated with regions of stellar mass or star formation

<u>BRIGHT SGRB sample</u>

- 60+ events over 2 decades
- State-of-the-art modeling
- Tracking down host of *every* SGRB
- 4x existing samples

Anya Nugent (PhD student)



<u>MOTIVATION:</u>

How do neutron star binaries trace galaxy properties over cosmic time?

What is the delay time distribution of short GRBs?

Can we inform follow-up search strategies of gravitational wave events?

Nugent, Fong et al. in prep

Modeling Host Galaxies with *Prospector*

Leja+17
Johnson+21

Nested sampling with `dynesty` (vs MCMC)

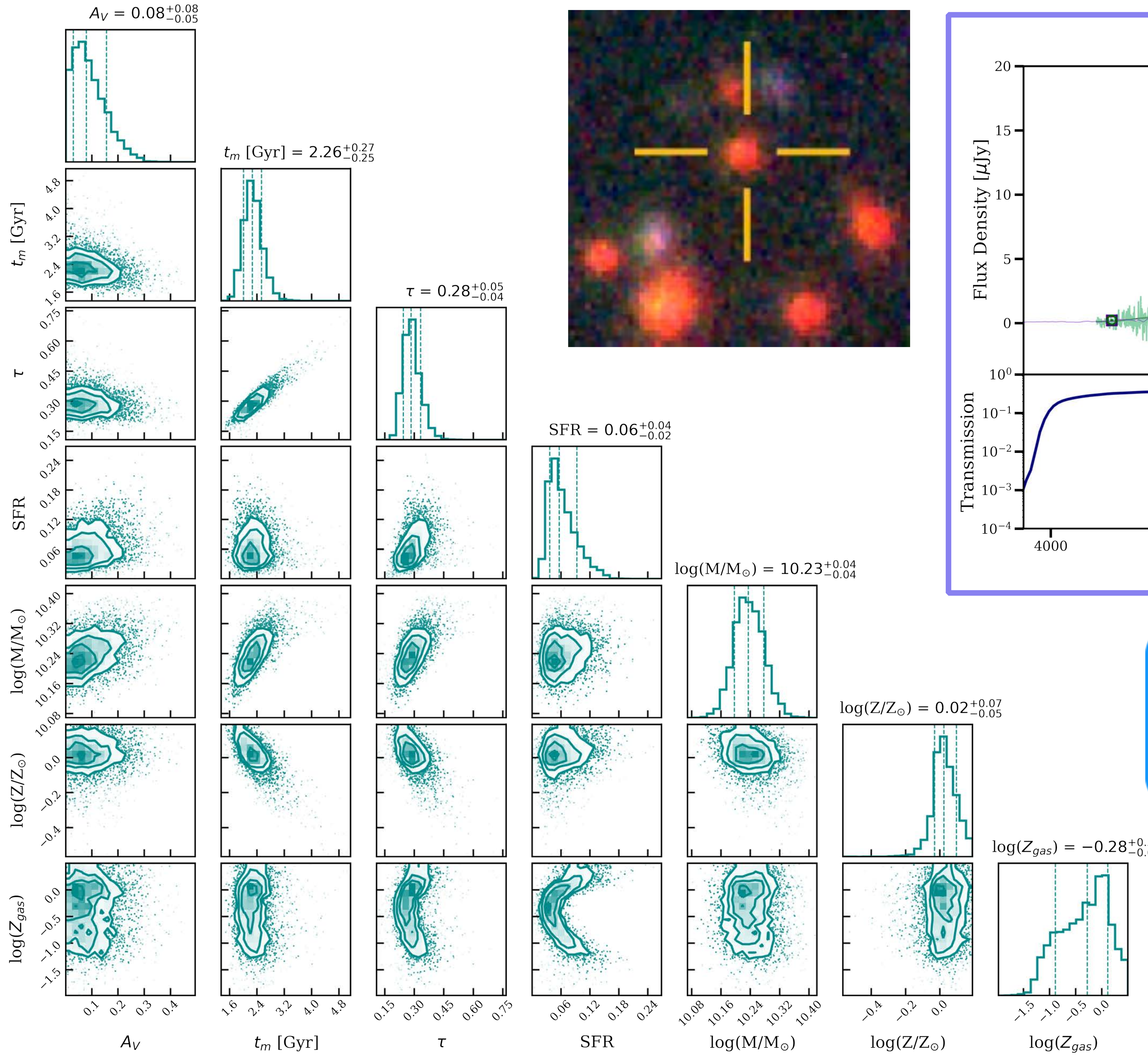
Joint fitting of photometry and spectroscopy to use full power of data set

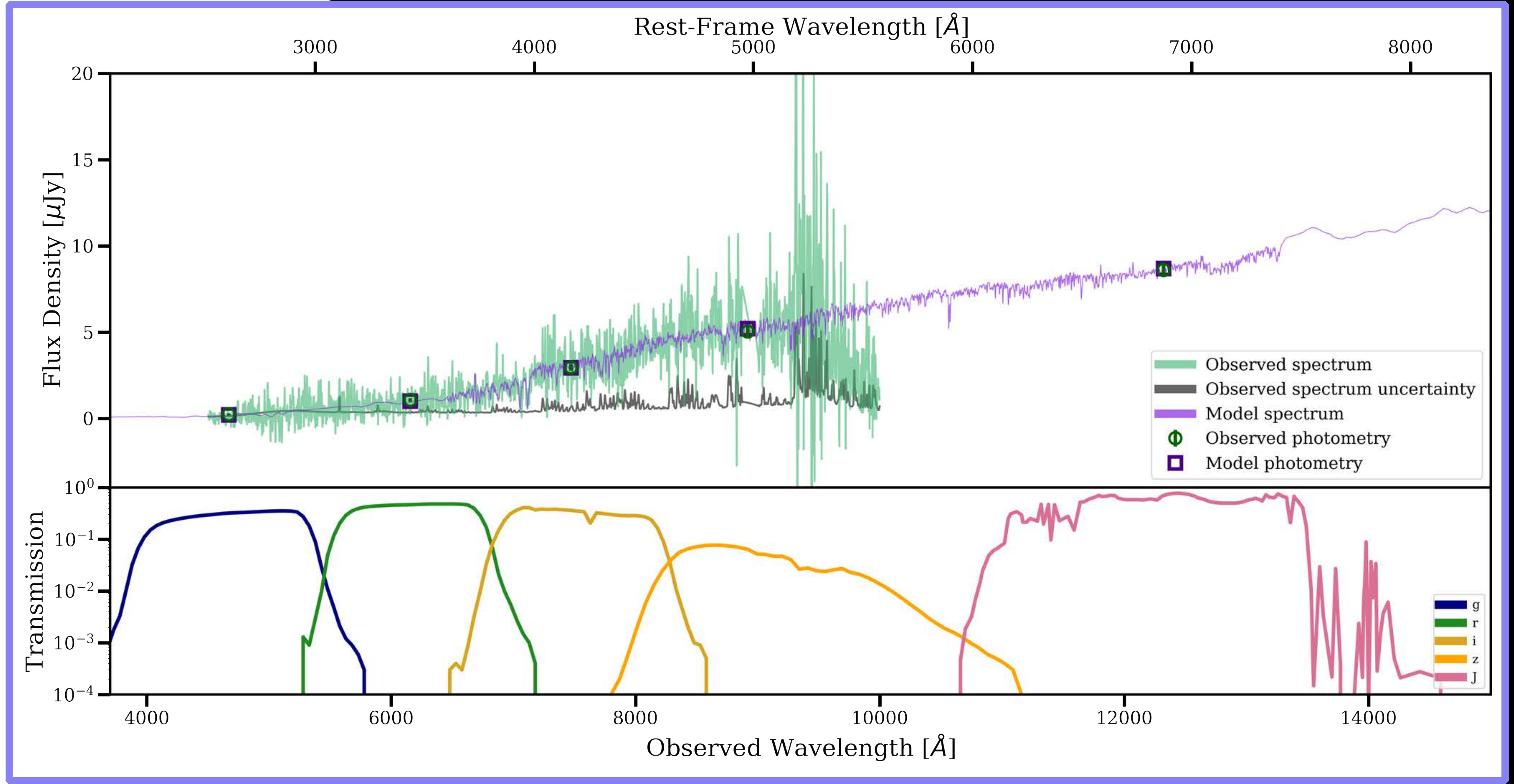
Full posteriors in stellar population properties

Mass-weighted ages (as opposed to SSP/light-weighted)

Modeling Host Galaxies with *Prospector*

Leja+17
Johnson+21



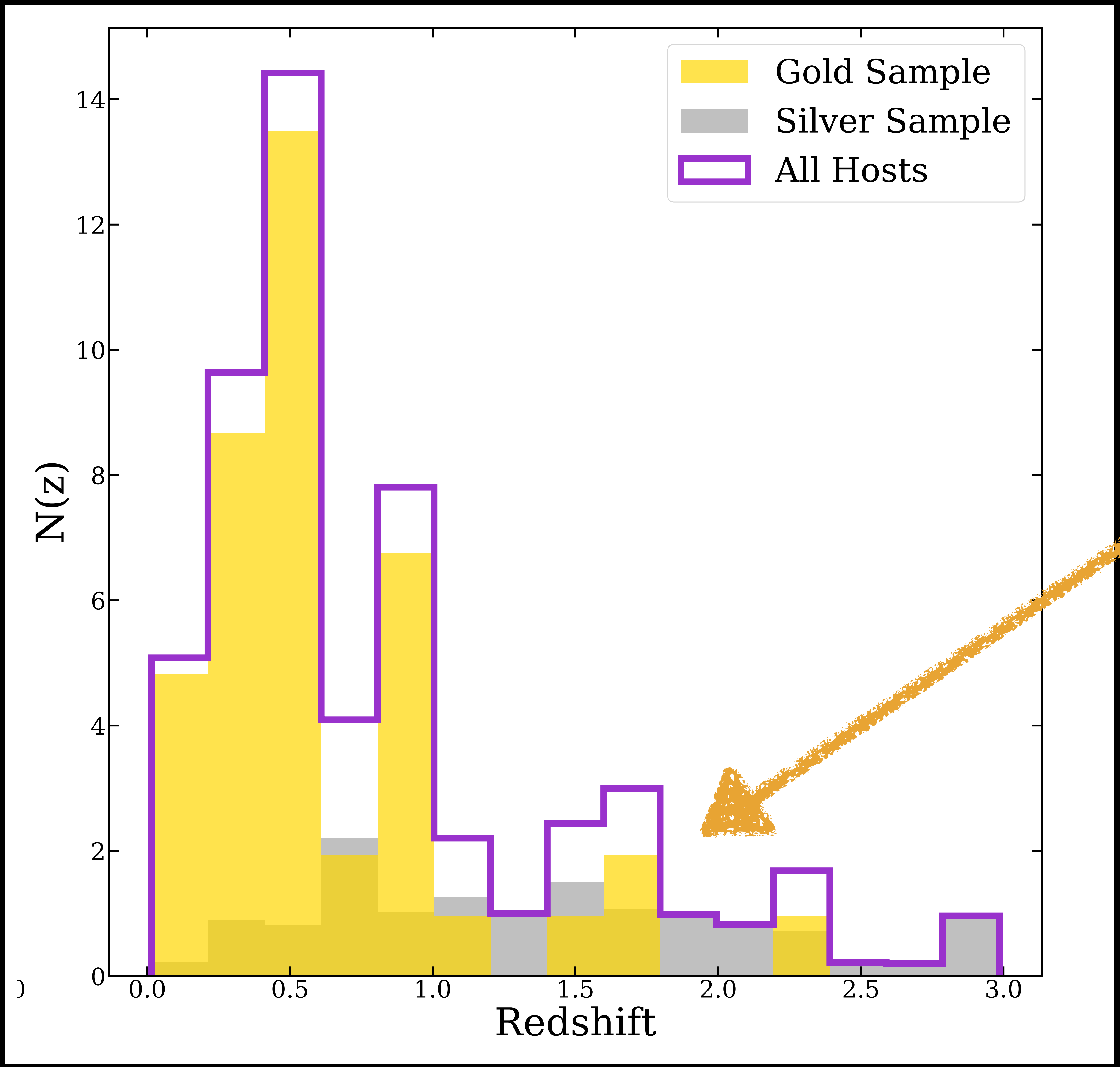


z, M*, Age, SFR, Z*, A_V, host type

Nugent et al. 2020
Nugent et al. in prep

Anya Nugent (PhD student)

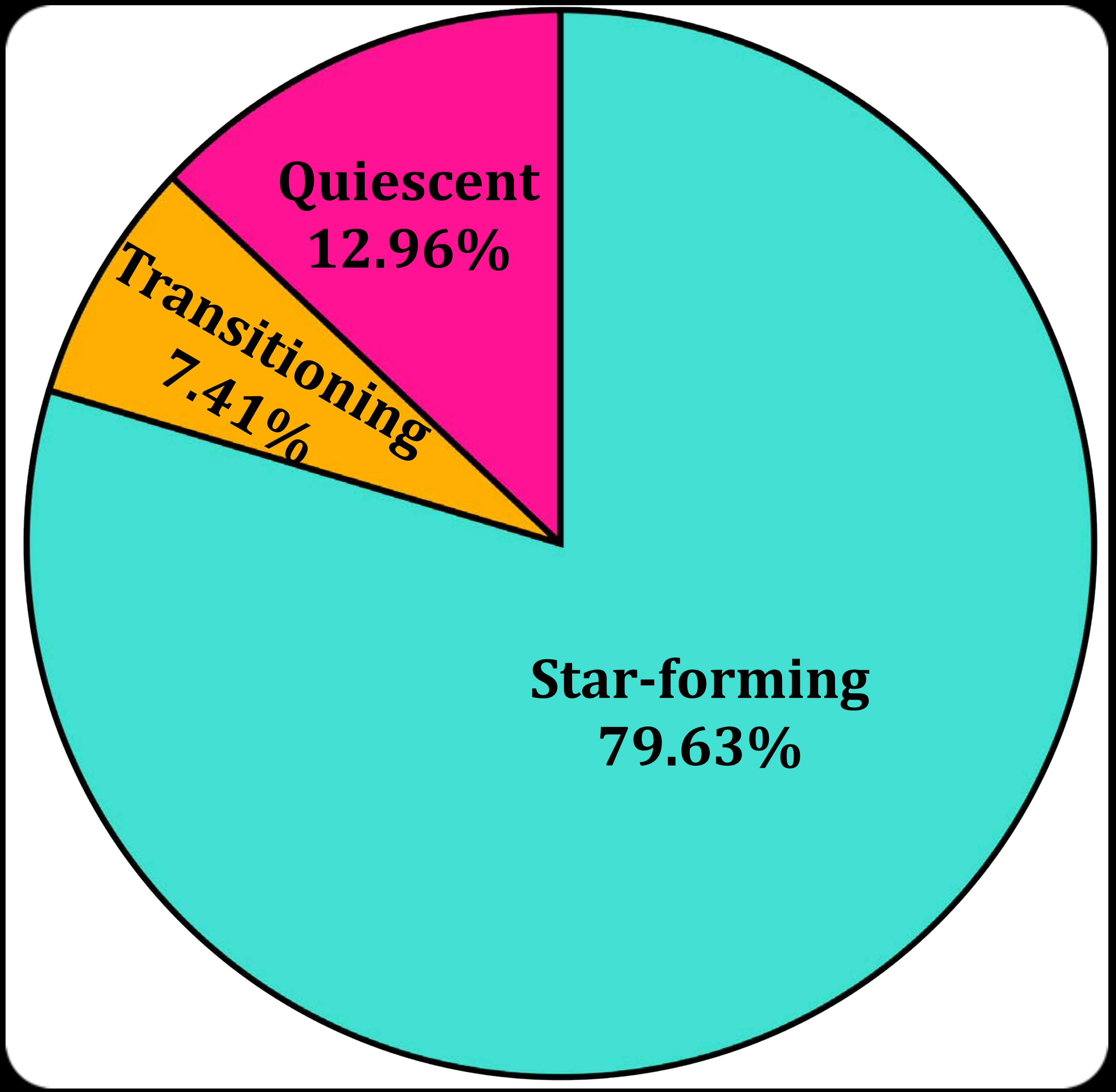
Short GRB Host Galaxy Redshift Distribution

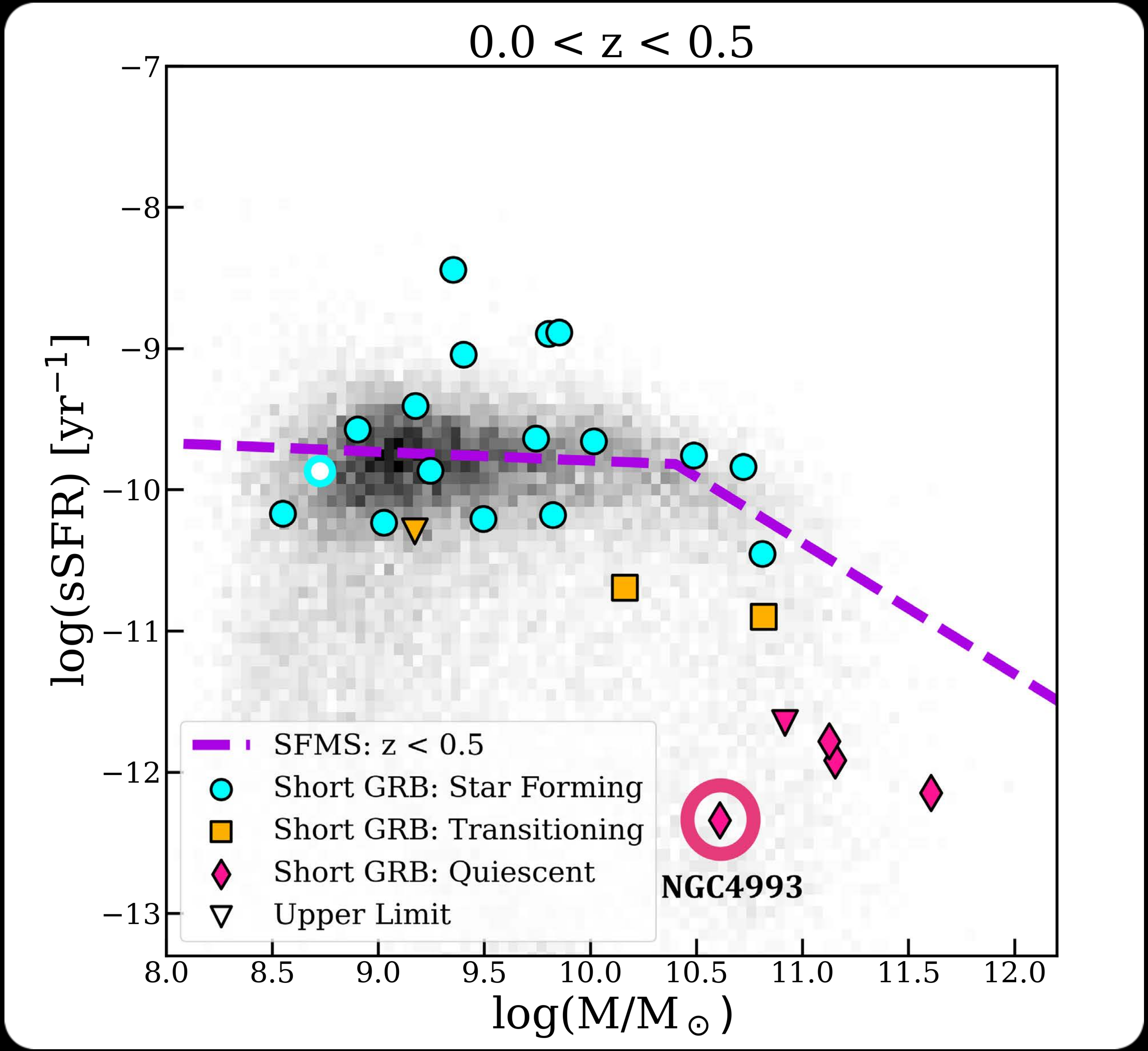


Filling in the “gap” in z>1 events for the first time

Higher redshifts generally mean shorter delay times or merger timescales

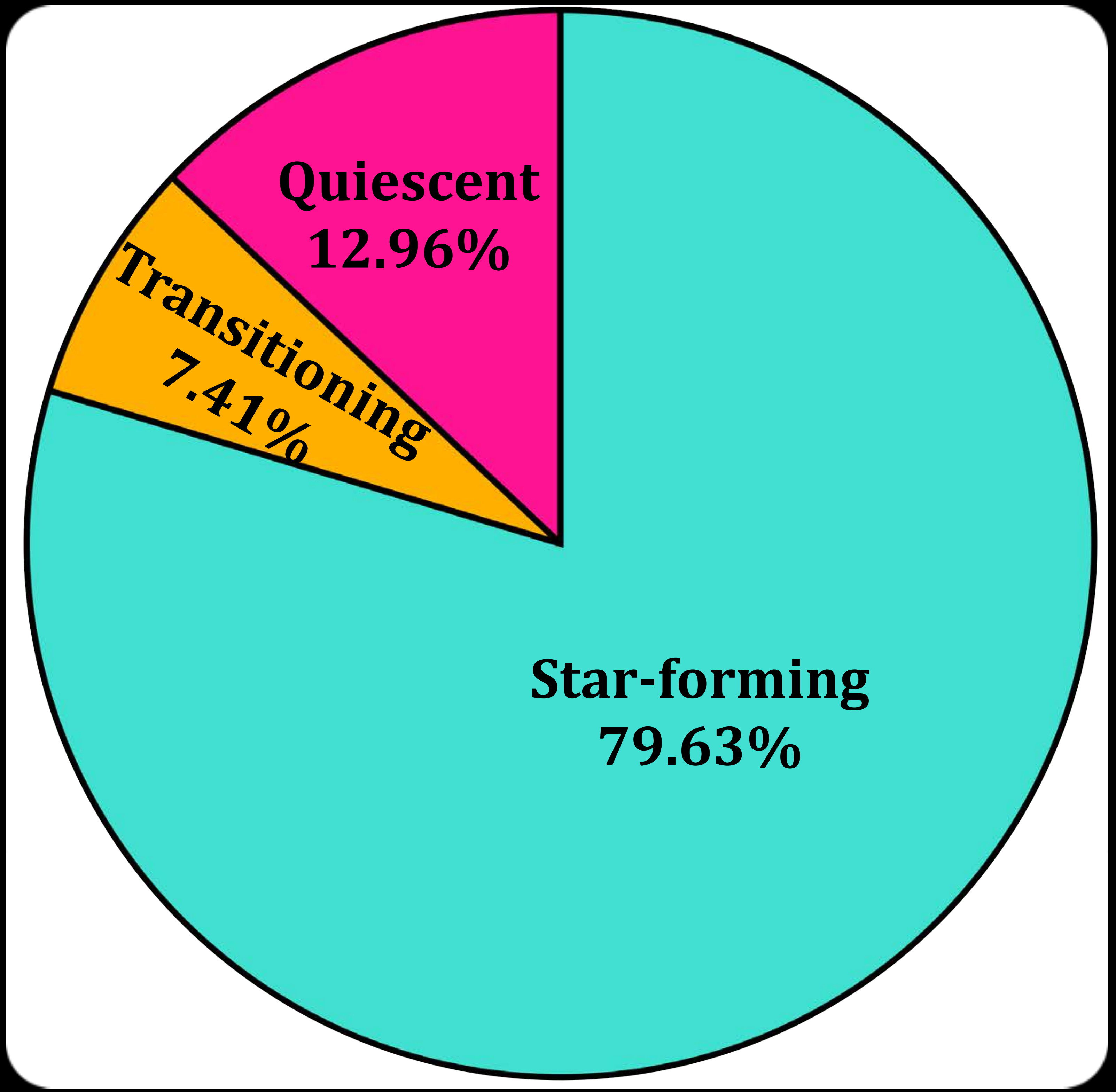
Short GRB Host Galaxy Demographics

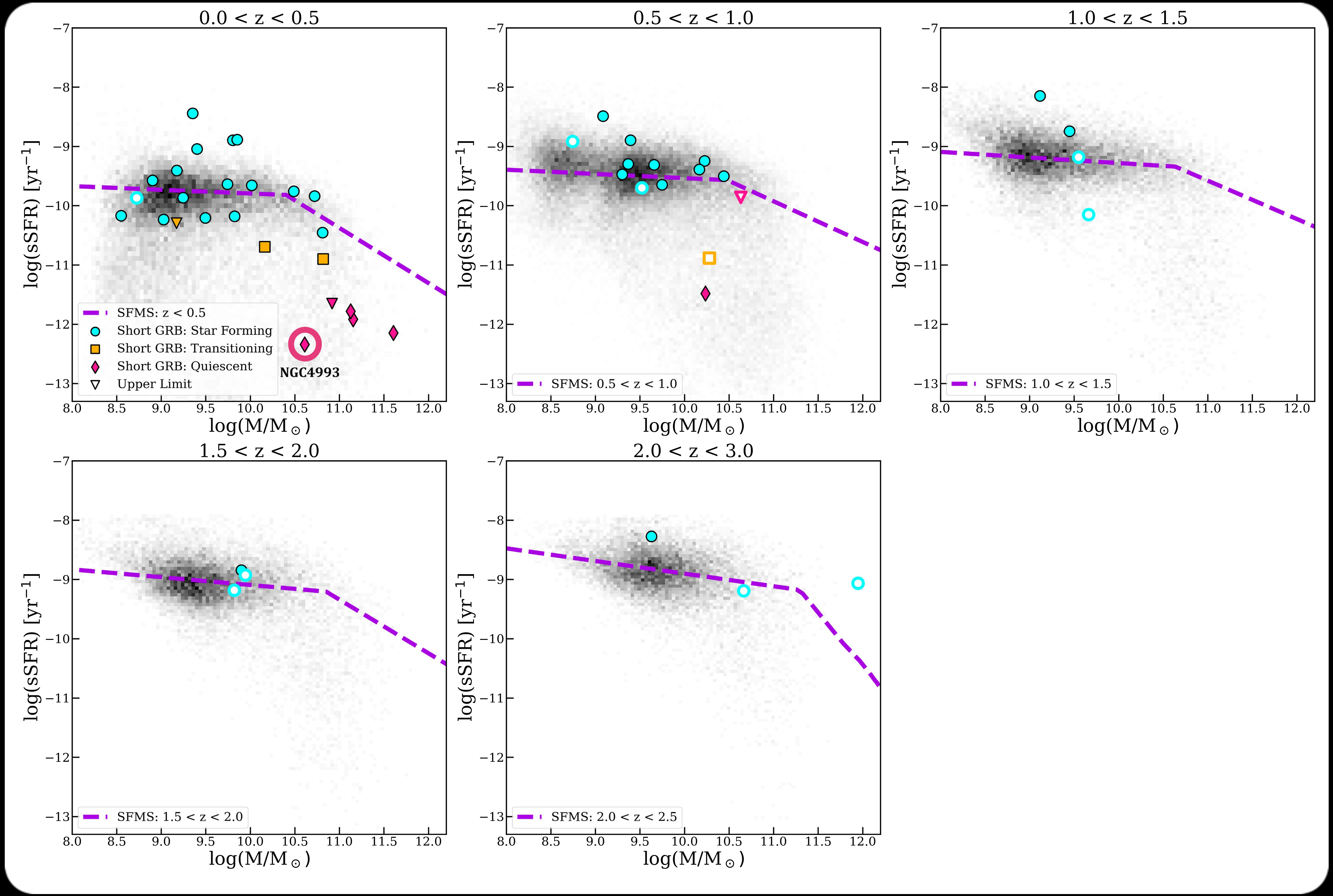




Majority are star-forming but sizable fraction of quiescent galaxies, consistent with *older* stellar progenitor

Short GRB Host Galaxy Demographics

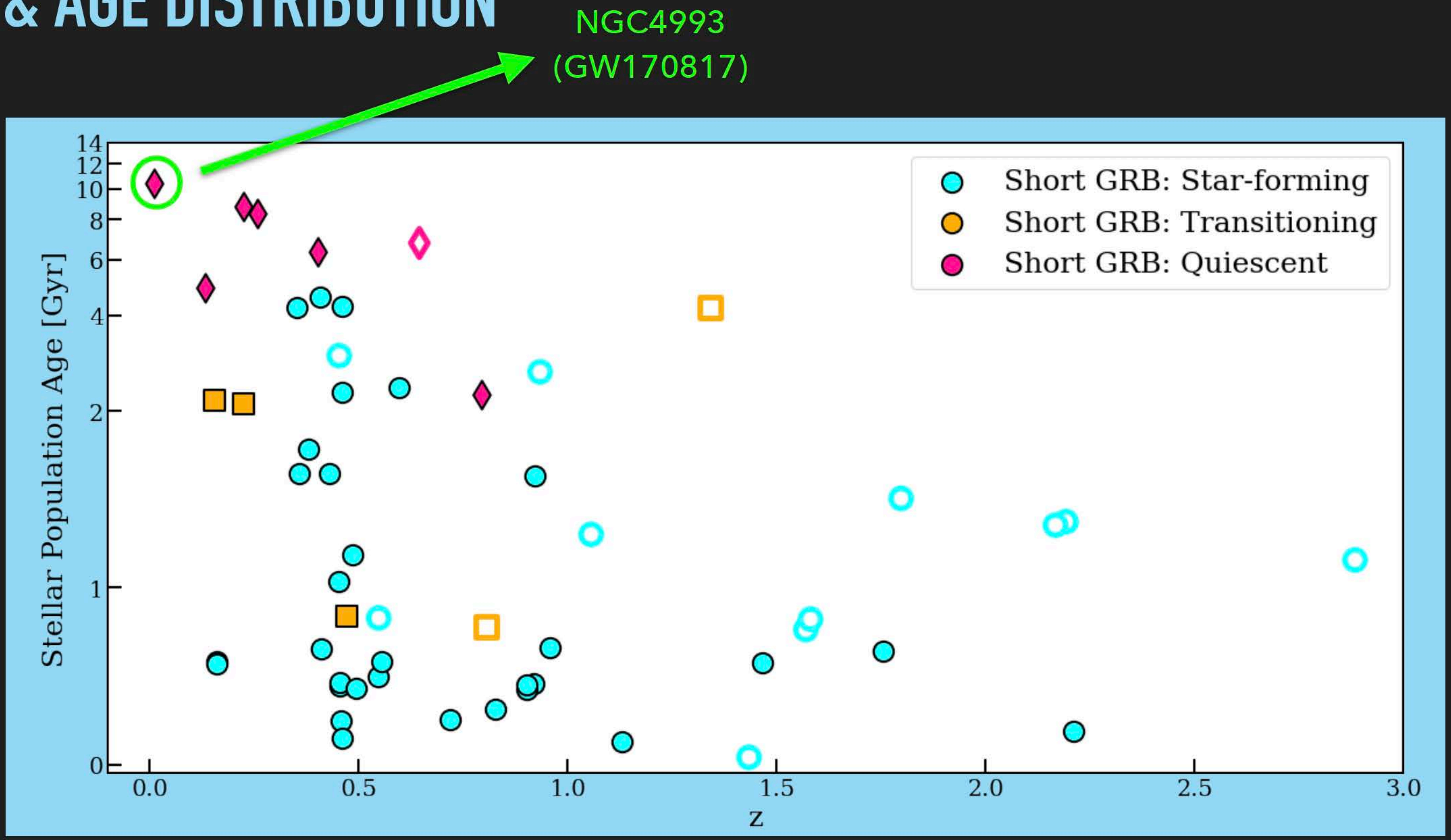




Majority are star-forming but sizable fraction of quiescent galaxies, indicating *older* stellar progenitor

Short GRBs trace the normal galaxy population but first GW host appears to be an "outlier"

DELAY TIMES & AGE DISTRIBUTION



Nugent+ in prep.

Broad range of stellar population ages indicate broad range of delay times (50 Myr-several Gyr)

Broad-band Repository for Investigating Gamma-ray burst Host Traits

Welcome to BRIGHT:

Home | SGRBs | Data Description | Population Modeling | GRB Group | **Catalogue** | wfong@northwes

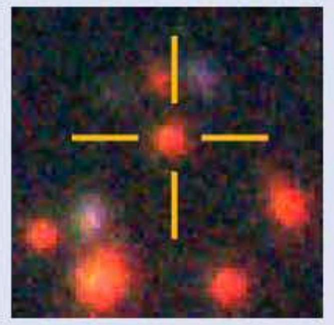
Lots of info (sortable)

Consider Adding a GRB

Select/Deselect All | Download All Data Products | Download Only JSON Metadata | Download Only Samples

Download GRB Table Data to CSV | Download GRB Table Data to Excel

Search:

	GRB name	Host RA	Host Dec	z	T_{90}	Fluence (10^{-8}erg × cm^{-2})	Optical Detection	X-Ray Detection
☐	 GRB161104A	5:11:34.37	-51:27:36.29	0.793	0.1	3.1	no	yes
	Search	Search	Search	Search	Search	Search	Search	Search

Showing 1 to 1 of 1 entries

Previous

Nugent et al. in prep; Fong et al. in prep.

Data and modeling products for download

g FITS	$25.44^{+0.25}_{-0.25}$	Magellan/IMACS	Nugent2020
r FITS	$23.81^{+0.1}_{-0.1}$	Magellan/IMACS	Nugent2020
i FITS	$22.72^{+0.06}_{-0.06}$	Magellan/IMACS	Nugent2020

Anya Nugent (PhD student)

Yuxin (Vic) Dong (PhD student)

Short GRBs Conclusions

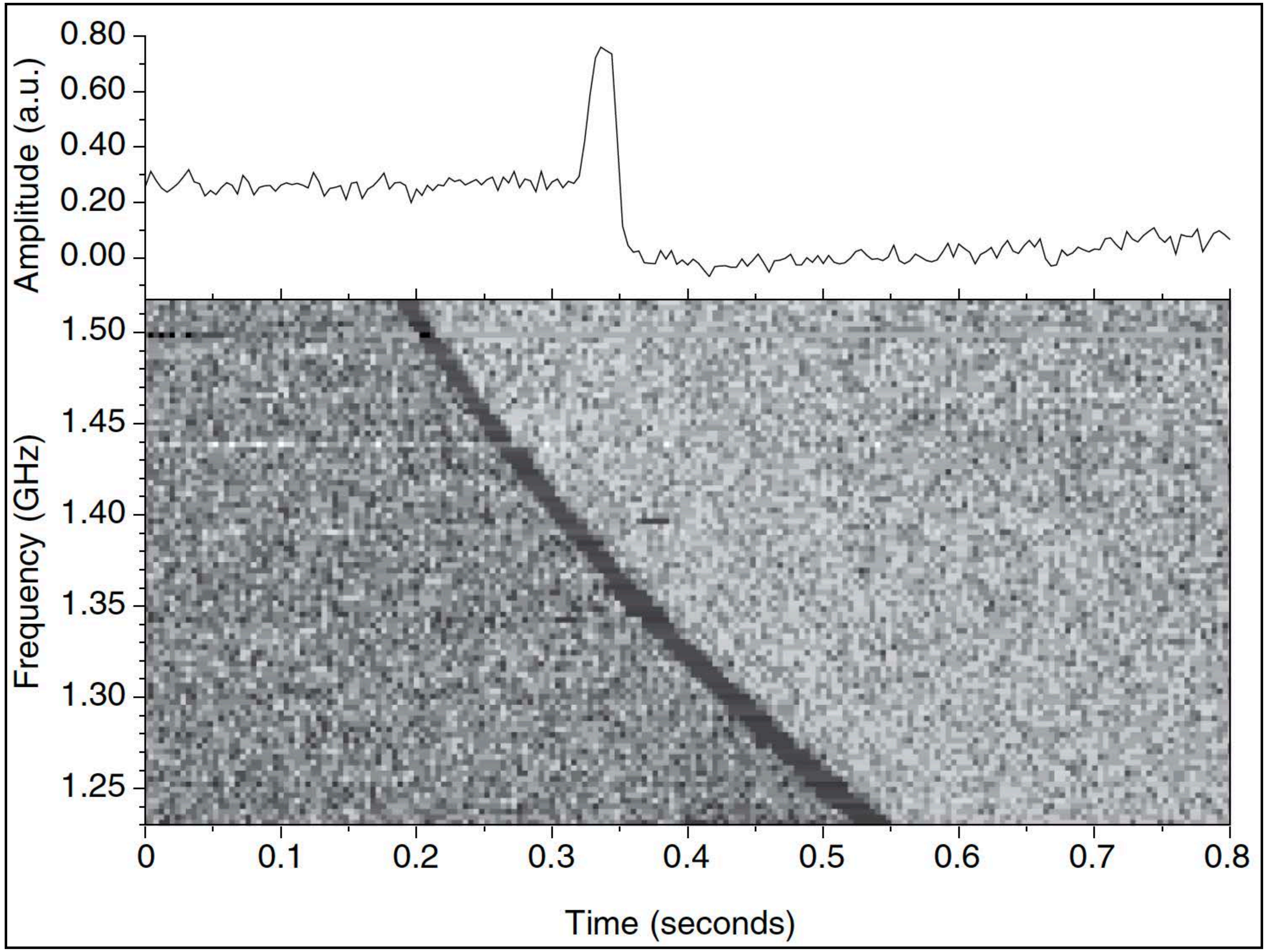
We are collecting the **largest sample of short GRB environments** to inform our understanding of NS binaries, and compare them to the next decade(s) of LIGO-detected mergers.

Offsets and locations provide critical evidence to their origins.

Short GRBs **trace the underlying field galaxy population** (in both star formation and stellar mass).

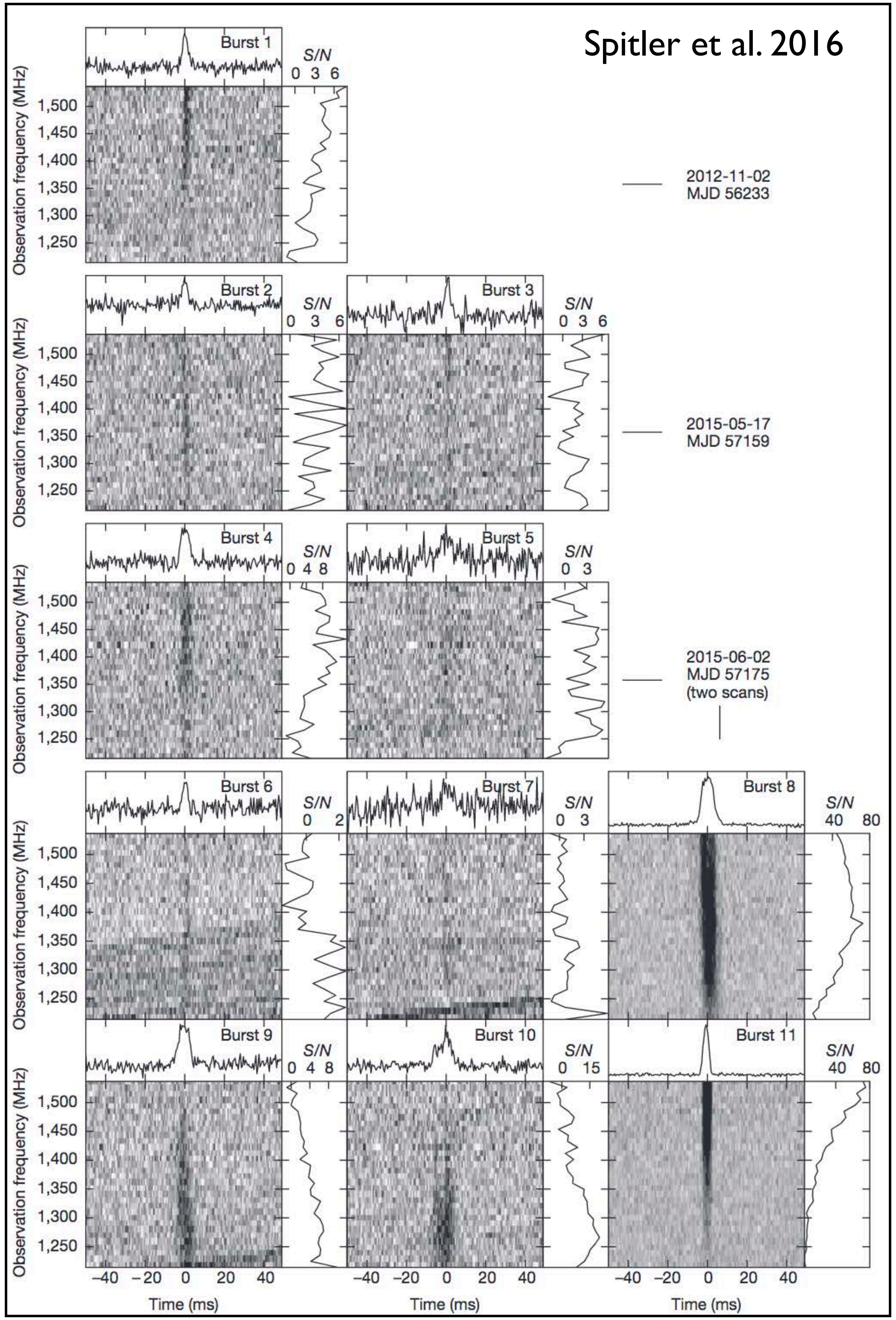
We are uncovering **a population of $z>1$**, short merger timescale binaries.

Fast Radio Bursts

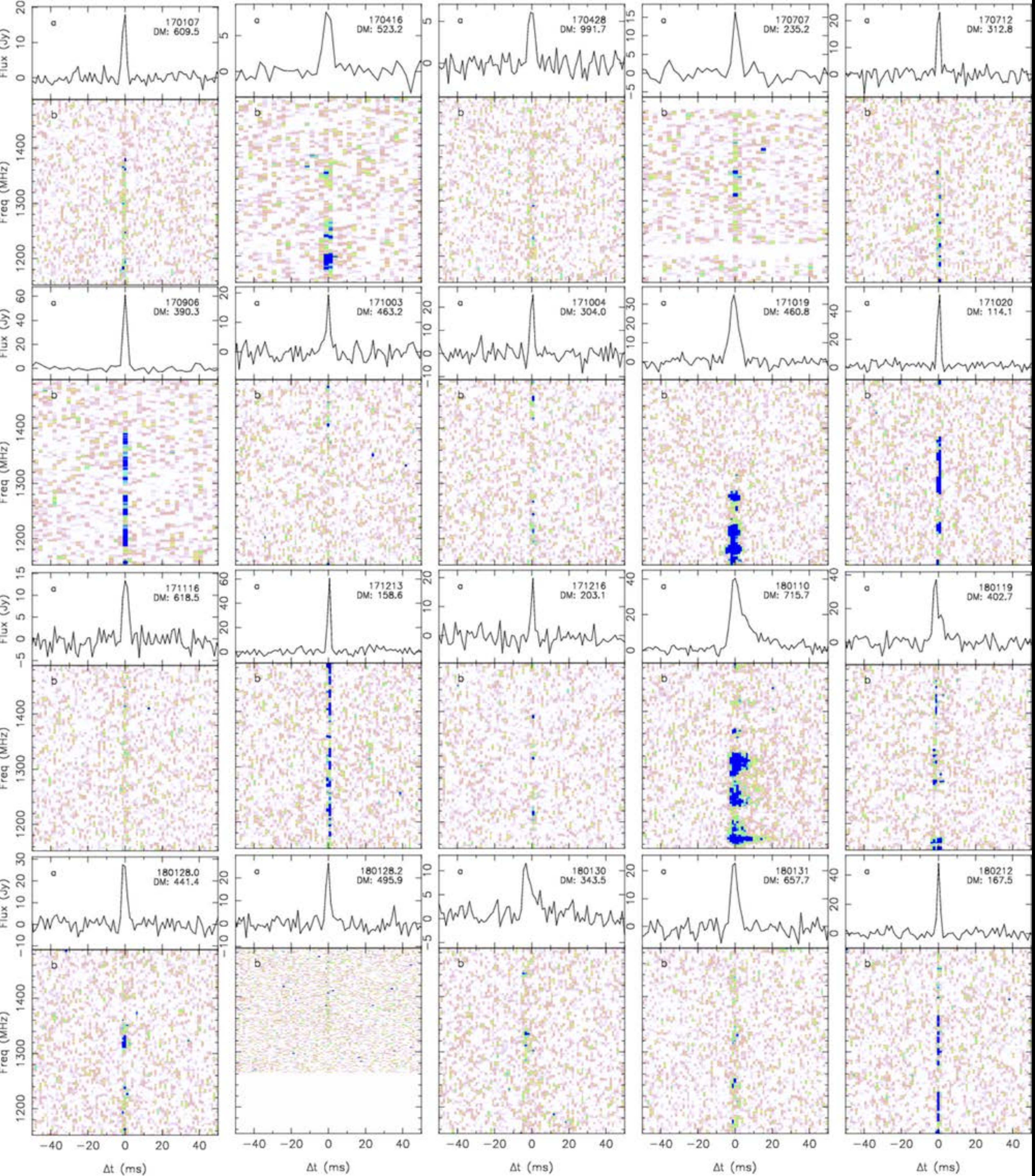


0.80
0.60
0.40
0.20
0.00
Amplitude (a.u.)
1.50
1.45
1.40
1.35
1.30
1.25
Frequency (GHz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Time (seconds)

REPEATING



Spitler et al. 2016
Burst 1
Burst 2
Burst 3
Burst 4
Burst 5
Burst 6
Burst 7
Burst 8
Burst 9
Burst 10
Burst 11
S/N
Observation frequency (MHz)
Time (ms)
2012-11-02
MJD 56233
2015-05-17
MJD 57159
2015-06-02
MJD 57175
(two scans)



We have discovered that only *some* of them repeat!

Highly-magnetized neutron stars = "magnetars"

Shannon et al. 2018

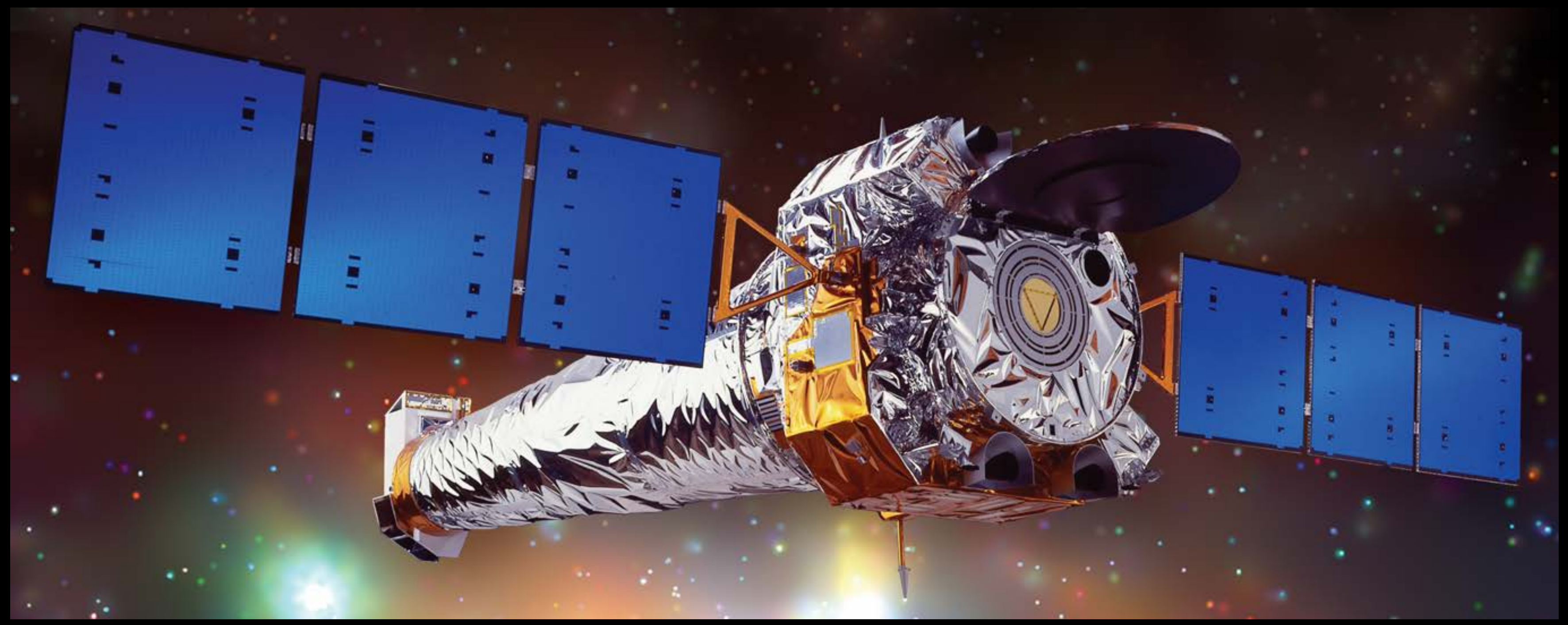
CRAFT

MEERTRAP

FAST & FORTUNATE
FRB FOLLOW-UP

Gemini-S, Keck, SOAR

Chandra, ALMA



Just like SGRBs, locating fast radio bursts in the Universe is key!

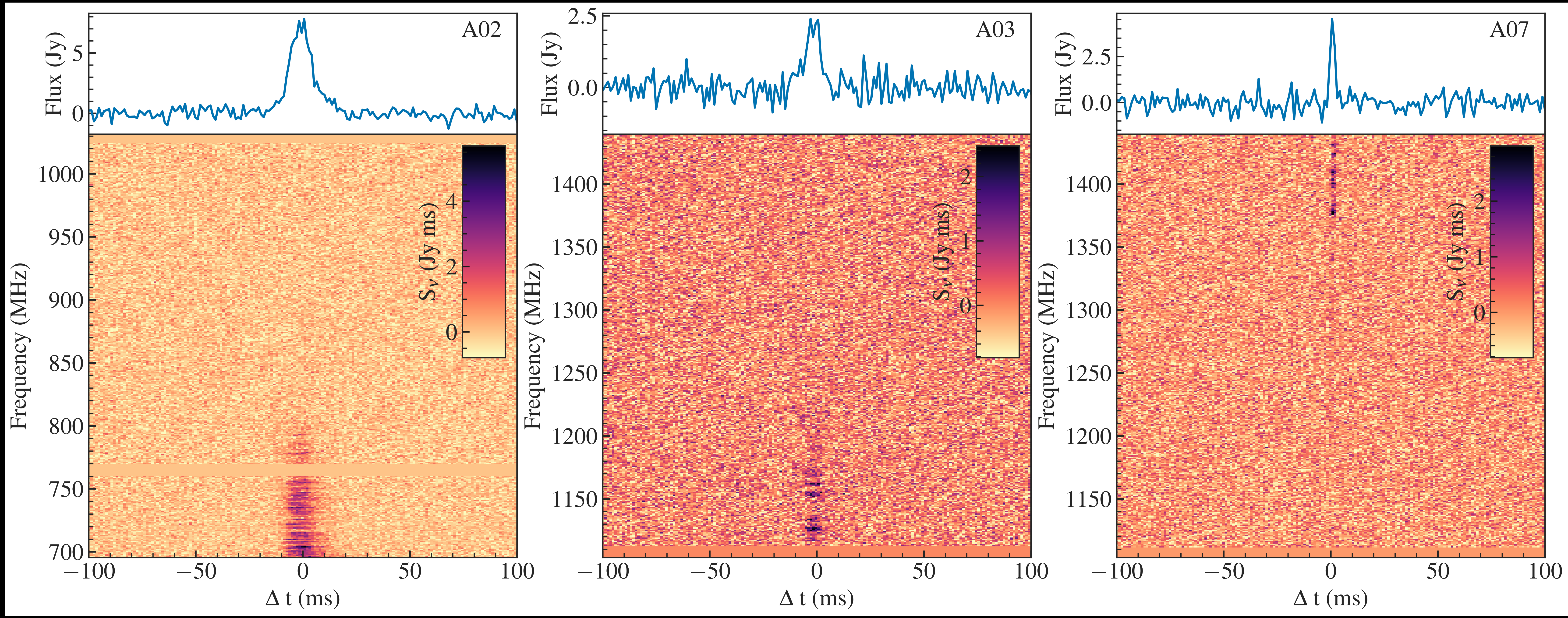
ASKAP/CRAFT

Bhandari *et al*, doi: 10.3847/2041-8213/ab672e / ESO

An Example of an Exciting Worldwide Effort: FRB 20201124A

ASKAP observations of FRB 20201124A

2021 Apr 1	2021 Apr 2	2021 Apr 4
20210401A	20210402A	20210404B
864.5 MHz	1271.5 MHz	1271.5 MHz



187 Jy ms	22 Jy ms	11 Jy ms

DM = 412-414 pc cm^{-3}

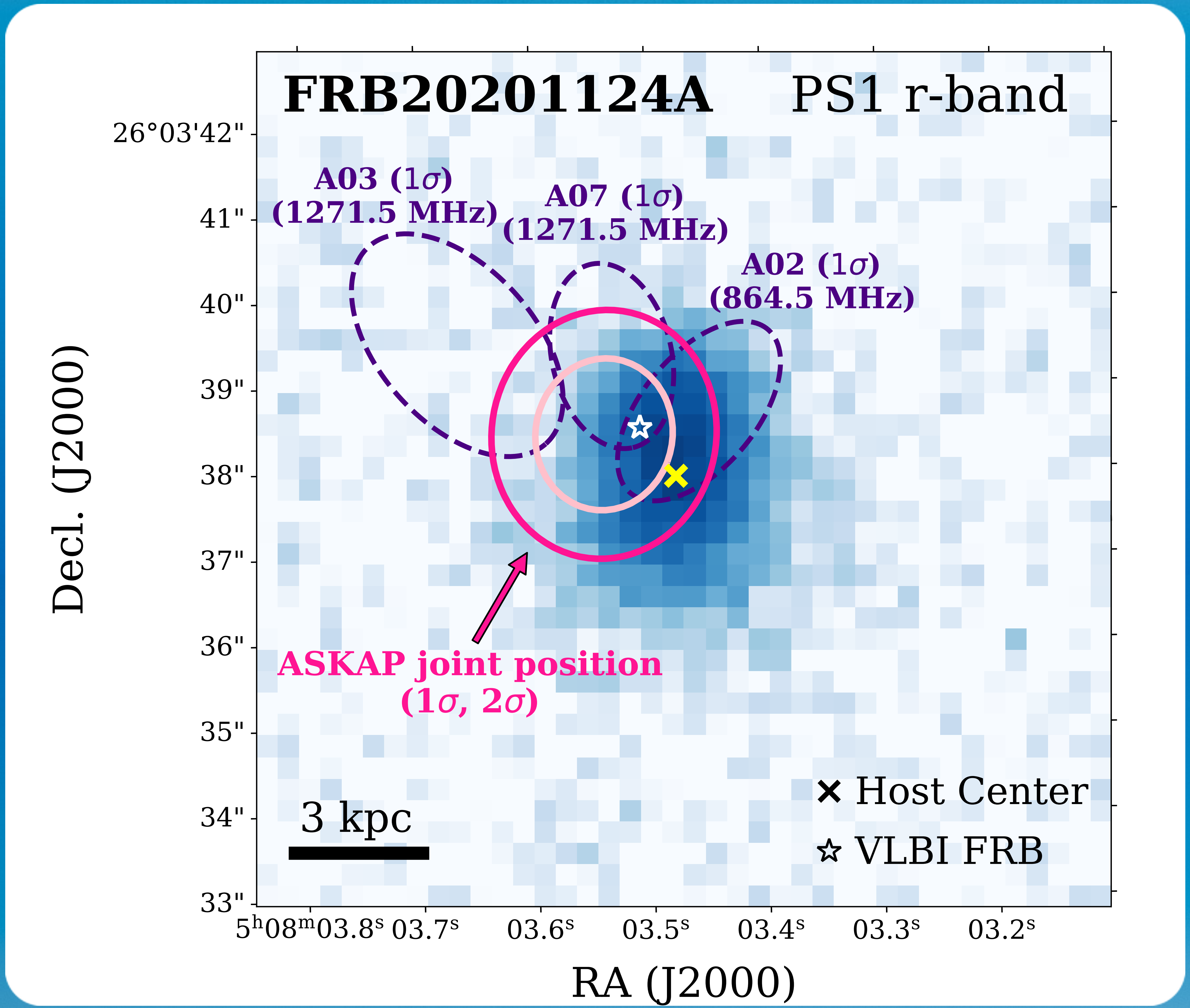
11 bursts total

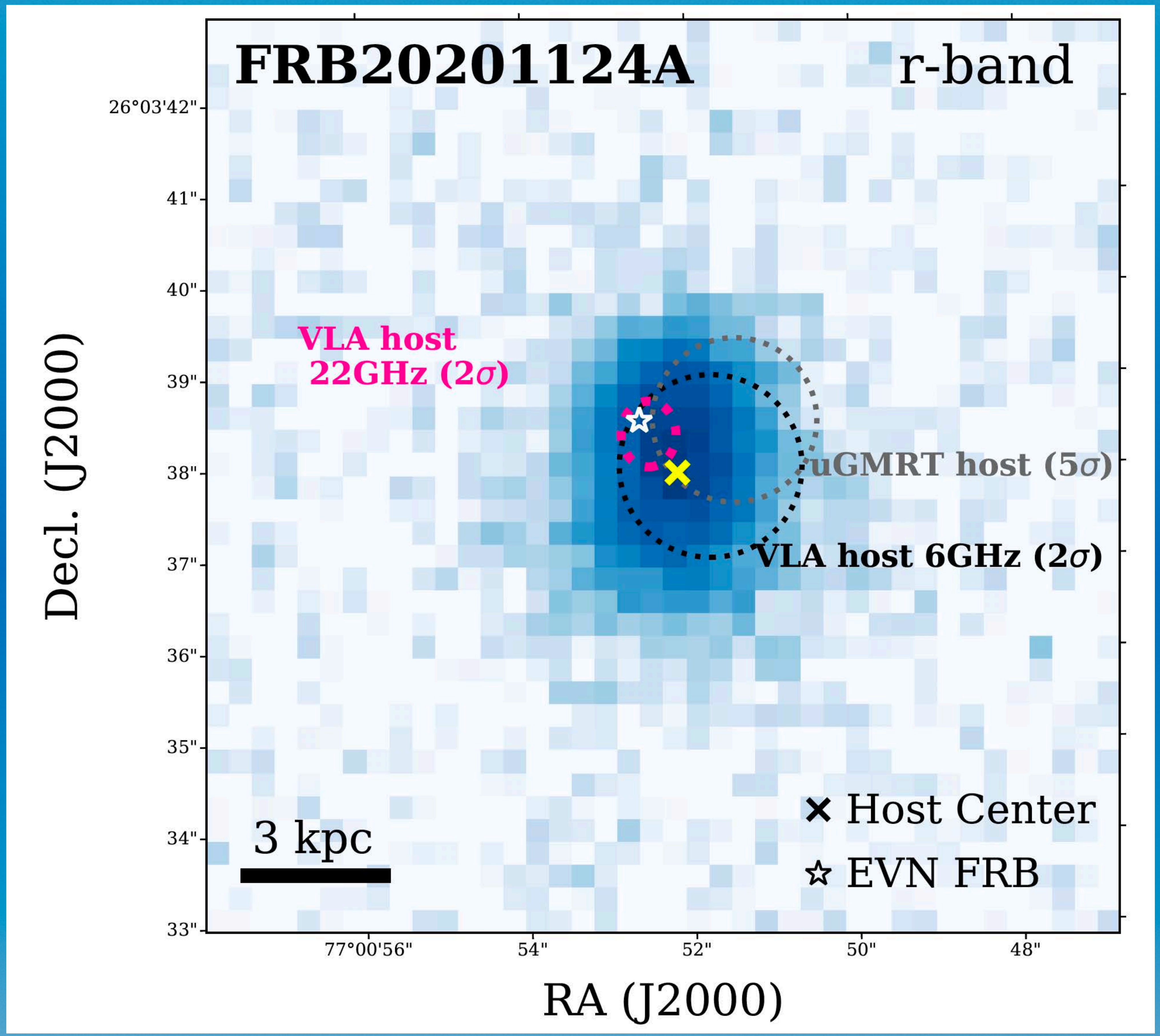
5 with downloaded voltages

3 for localization

Fong et al. 2021; (see also: Kumar et al. 2021)

FRB 20201124A: Lay of the Land





FRBs (Analysis led by S. Bhandari, C. Day, A. Deller D. Scott)

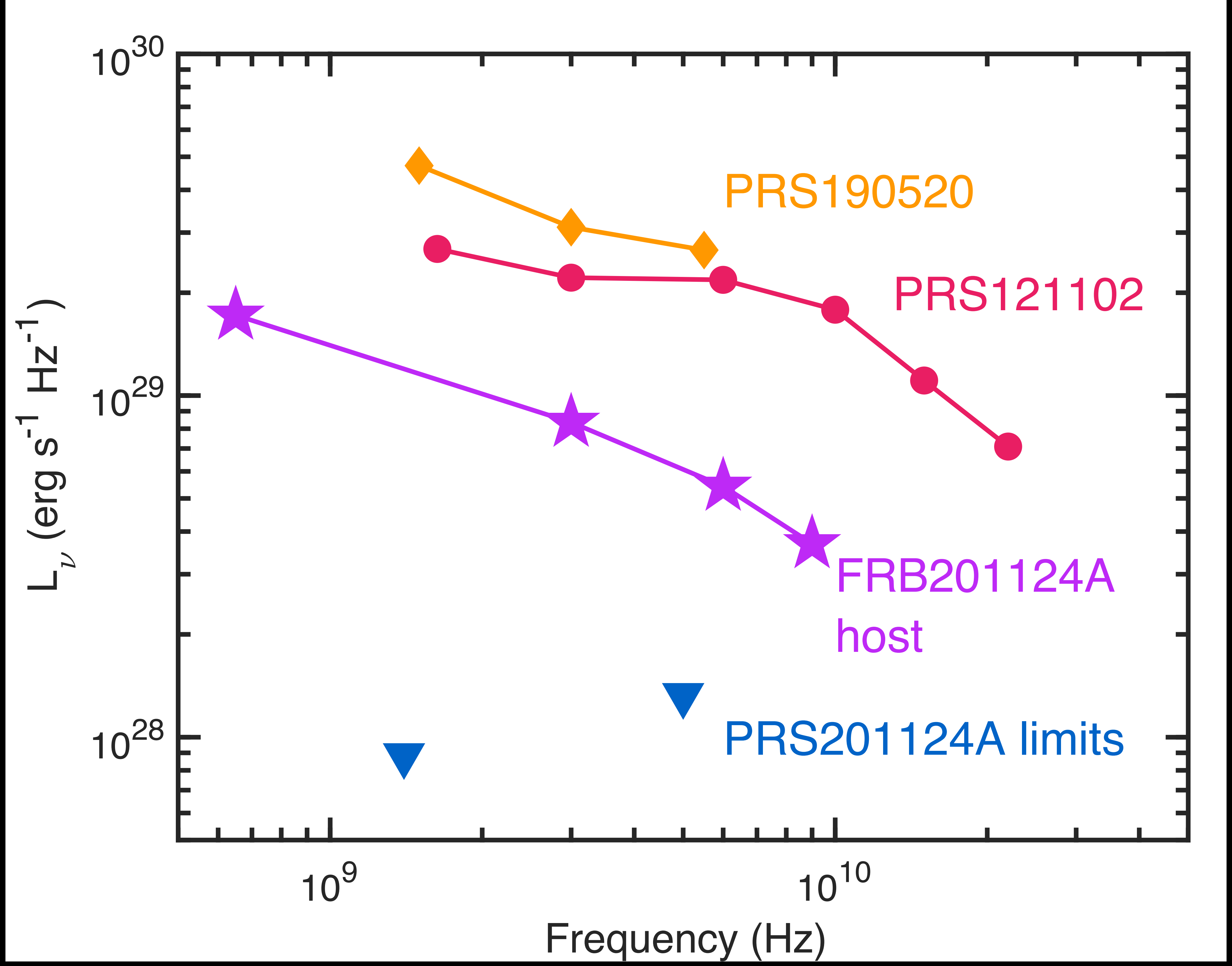
Host

Detection of another PRS (magnetar nebula)???

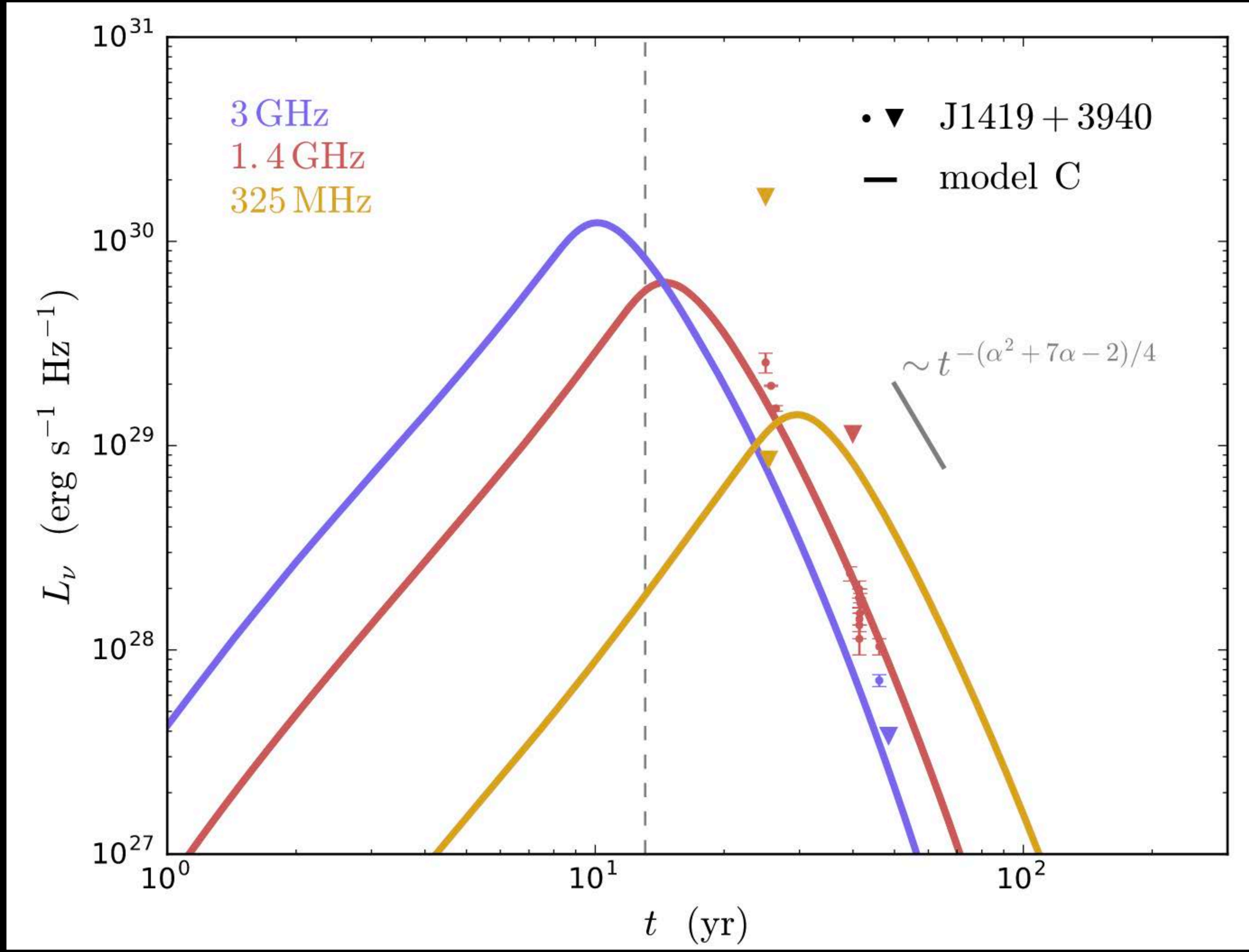
Approved 2022A VLA observations to distinguish (PI Fong)

Credit: CSIRO

Is a compact PRS 20201124A possible?



Data from ATEL #14529, ATEL #14549, Ravi+ 21 (FRB201124A host)
ATEL #14603, Piro+ 21 (PRS201124A)
Chatterjee+ 17 (PRS121102A)
Li+ 21 (PRS190520)

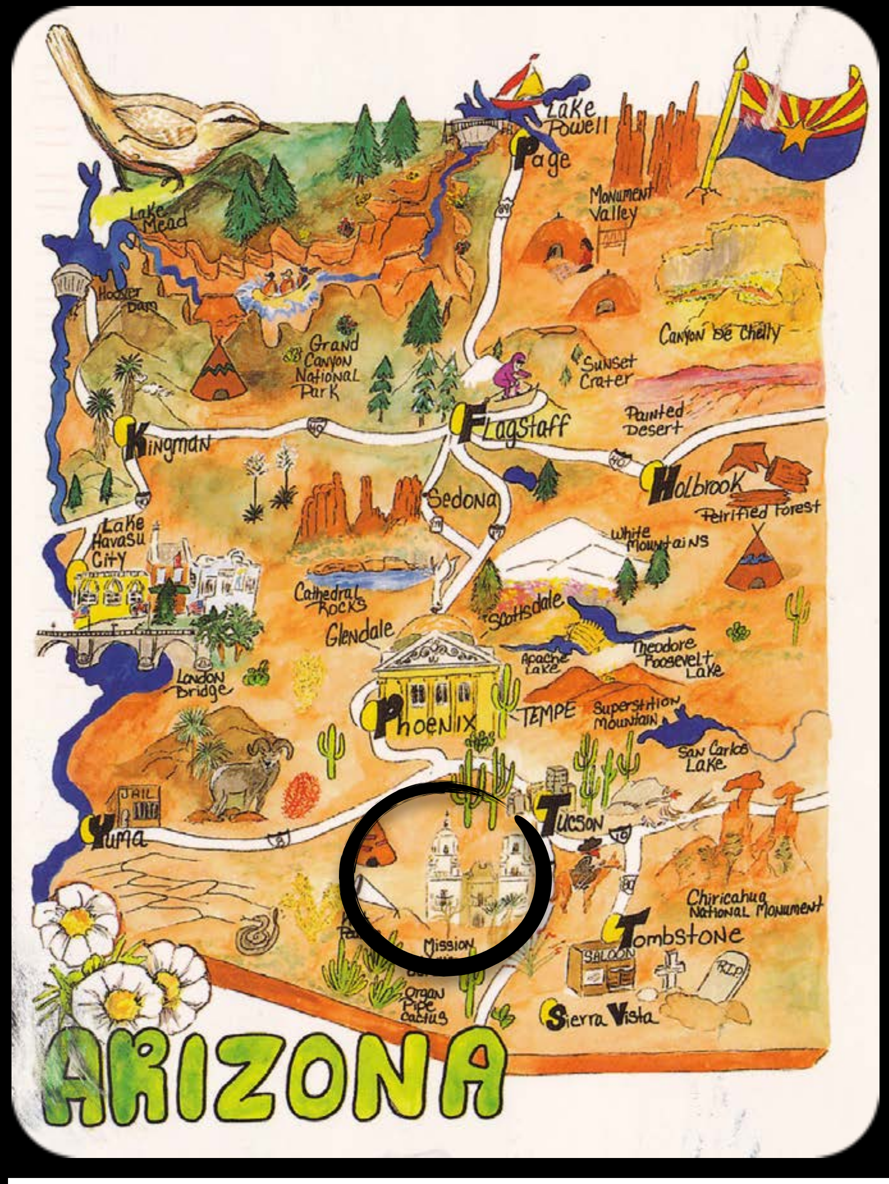


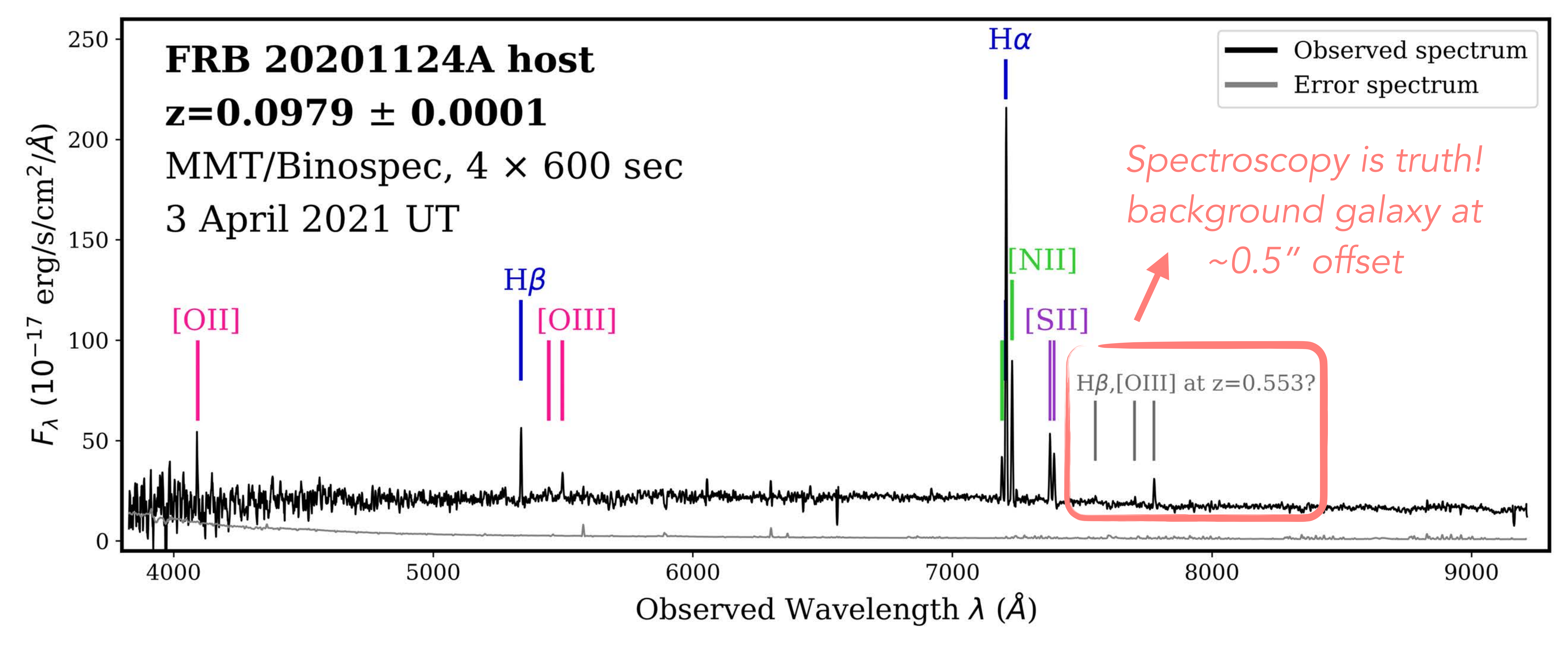
Margalit & Metzger 2018

Compact PRS 201124A would need to be >20 times less luminous than known compact PRS's

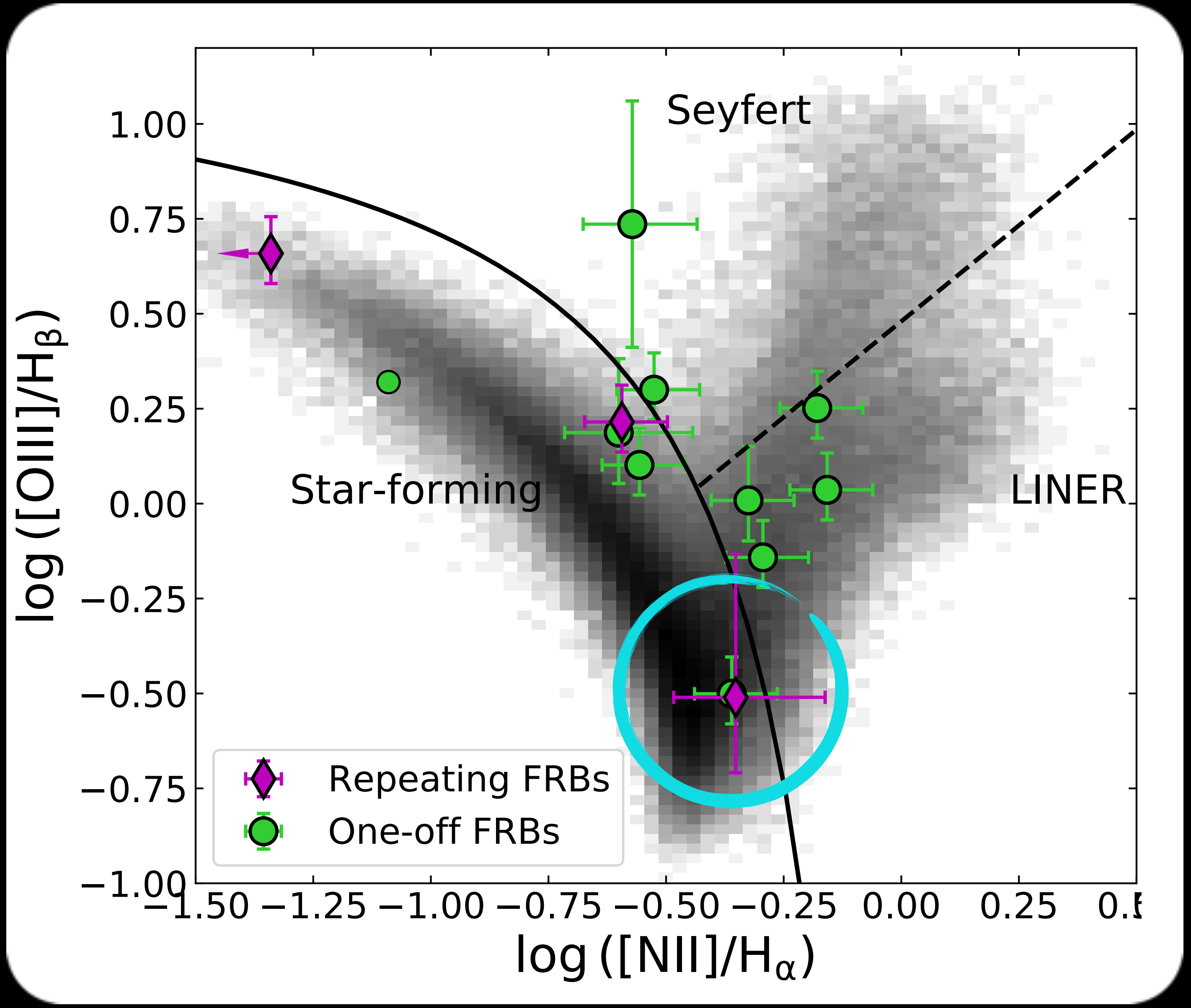
Under some models, PRS luminosities can span orders of magnitude

Optical Host Galaxy Spectrum places host (and FRB) at z=0.0979±0.0001





Fong et al. 2021



Bhandari et al. 2021

Line diagnostics support classic star-forming galaxy

SFR ~ 2.1 Msol yr^{-1}

Modeling of the Host Galaxy with *Prospector*

Leja+17
Johnson+21

$\log(M_*/M_{sun}) = 10.28 \pm 0.05$

$A_{V,young} = 0.9 \pm 0.4$ mag

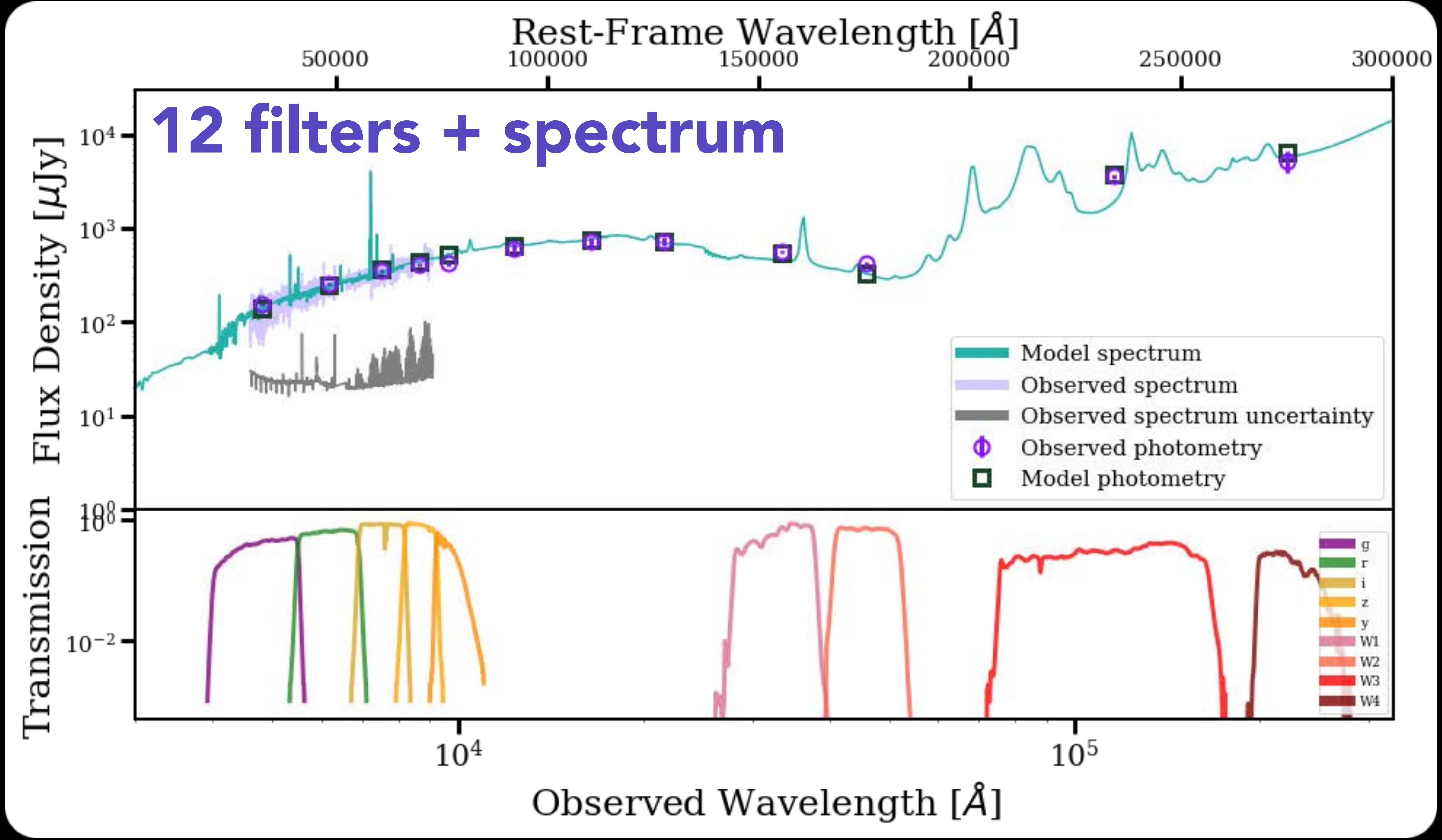
$A_{V,old} = 0.8 \pm 0.2$ mag

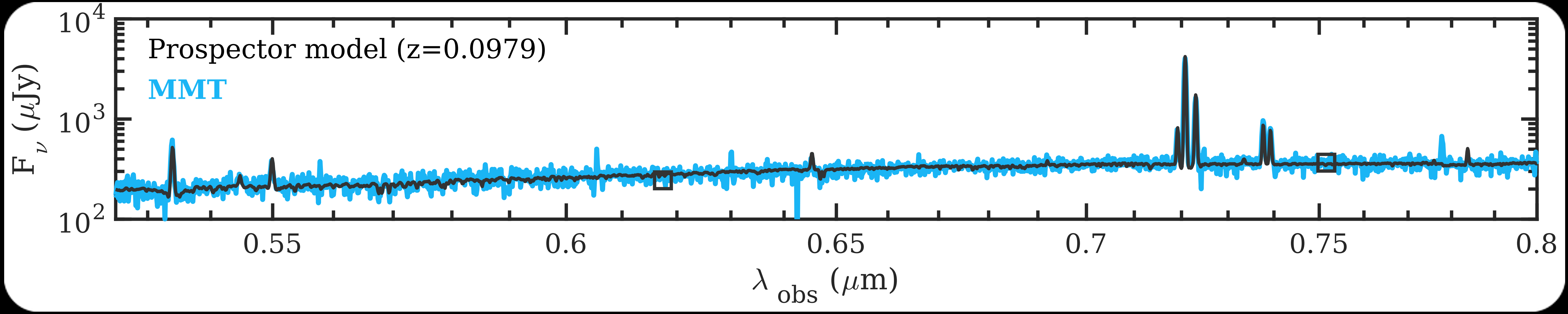
$t_m = 6.2 \pm 0.8$ Gyr

$Z_* = 0.26 \pm 0.15\ Z_{sol}$

sSFR(100 Myr) = $1.4 \times 10^{-10}\ yr^{-1}$

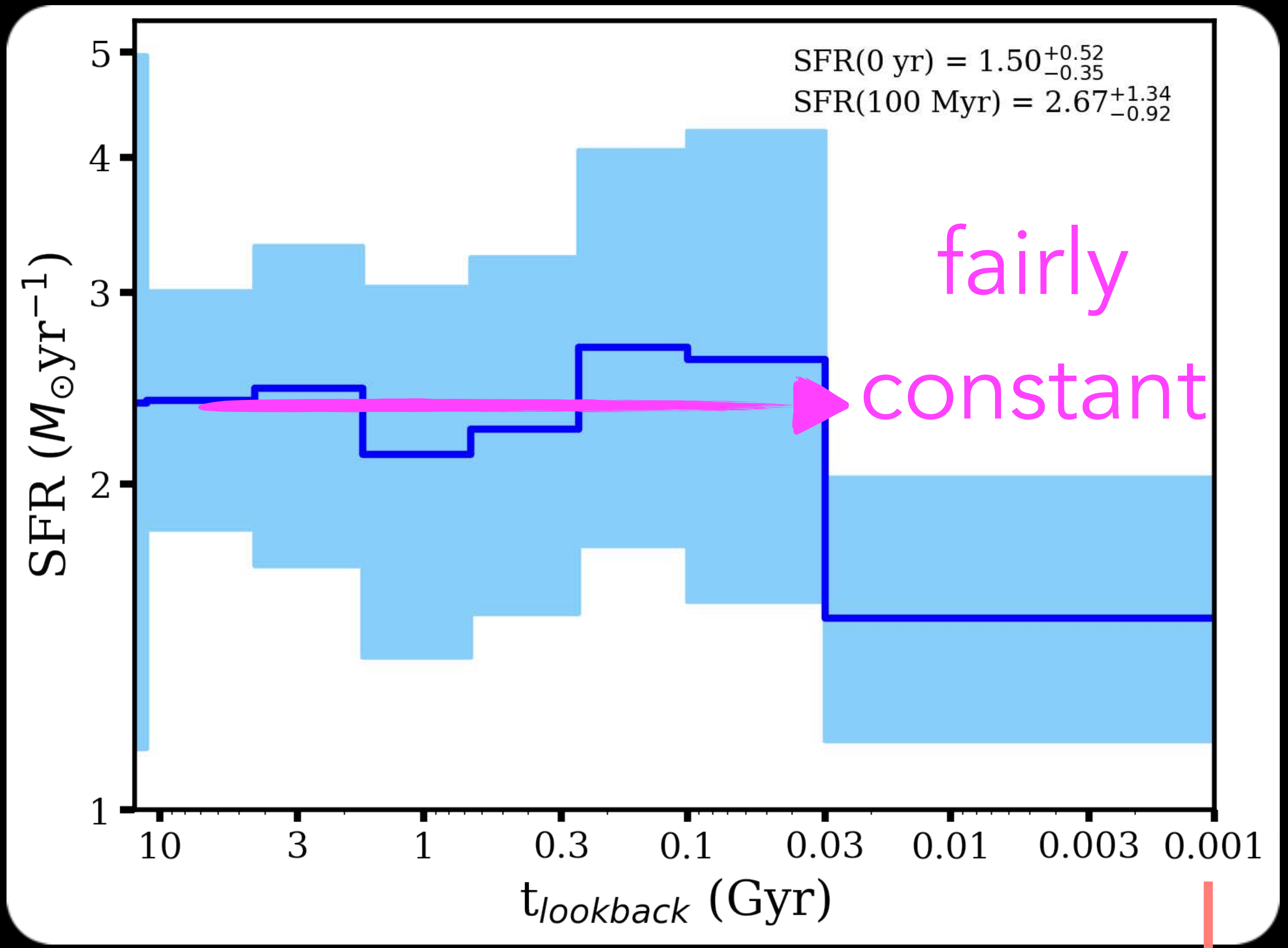
In other words…
Star-forming
Middle-aged
Moderately dusty
Sub-solar Metallicity
Hot dust component?



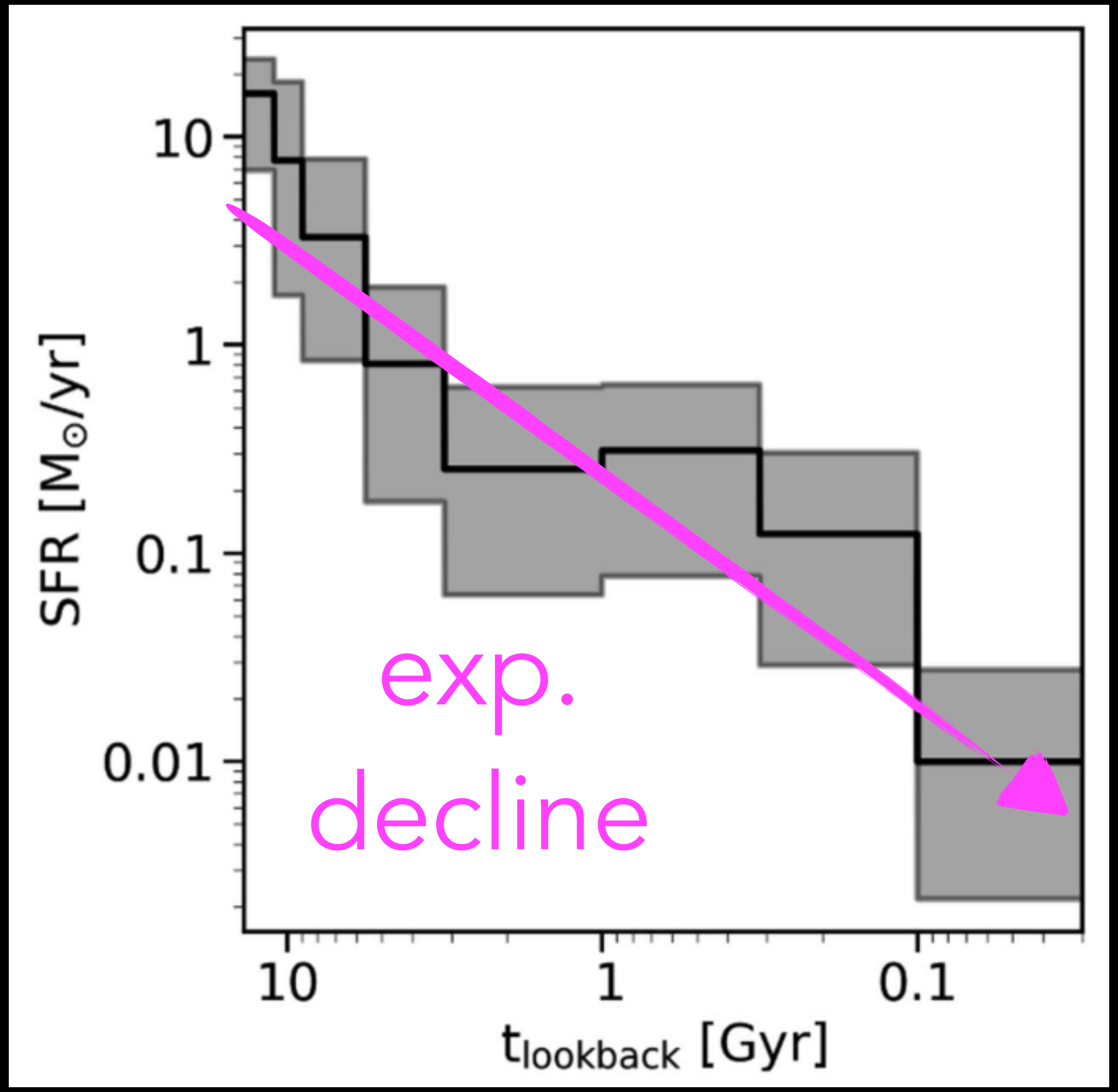


Star formation History is Remarkably Constant over 10 Gyr

FRB 20201124A

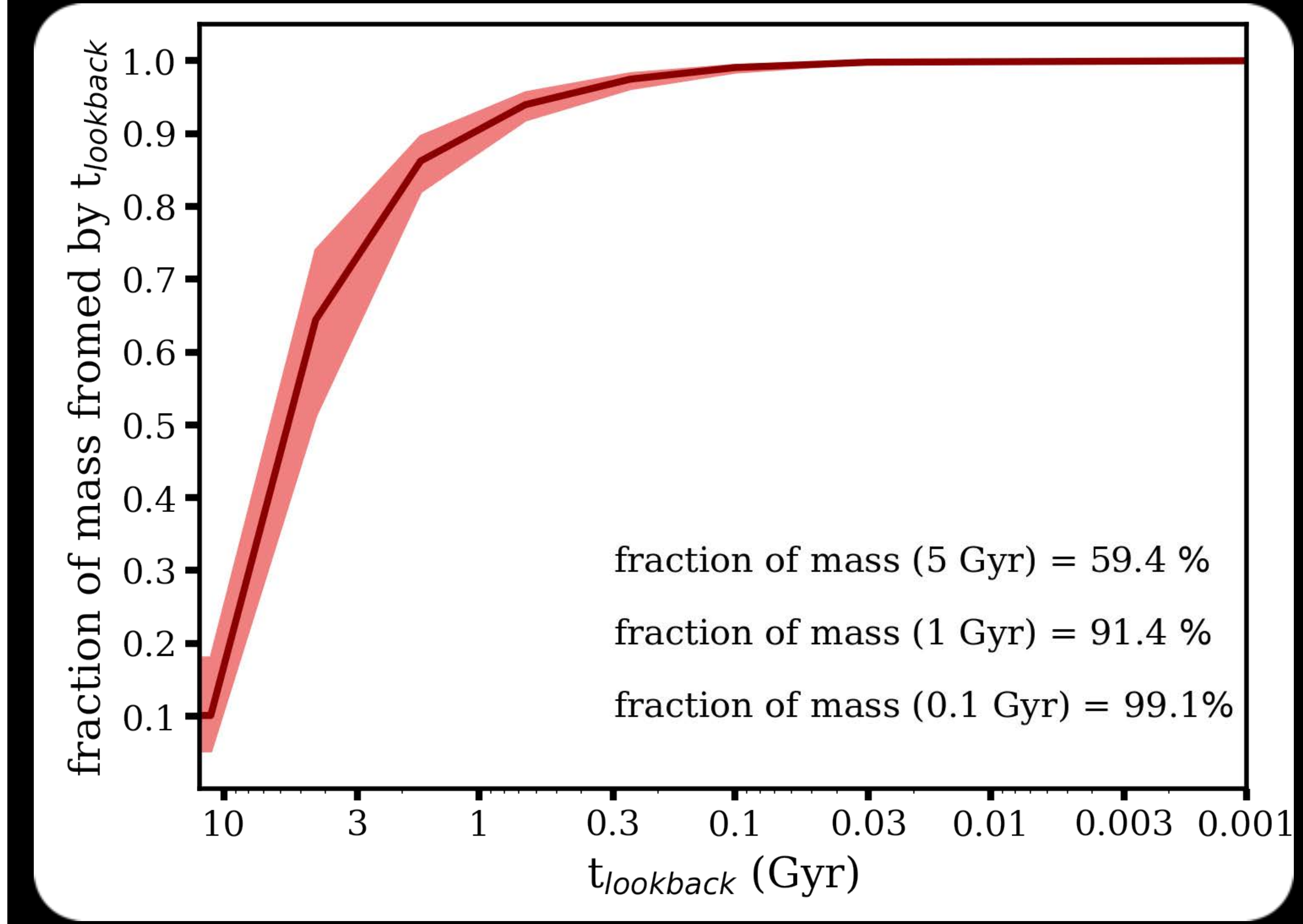


GW170817 host (BNS merger) for context



Blanchard et al. 2017

FRB 20201124A mass build-up

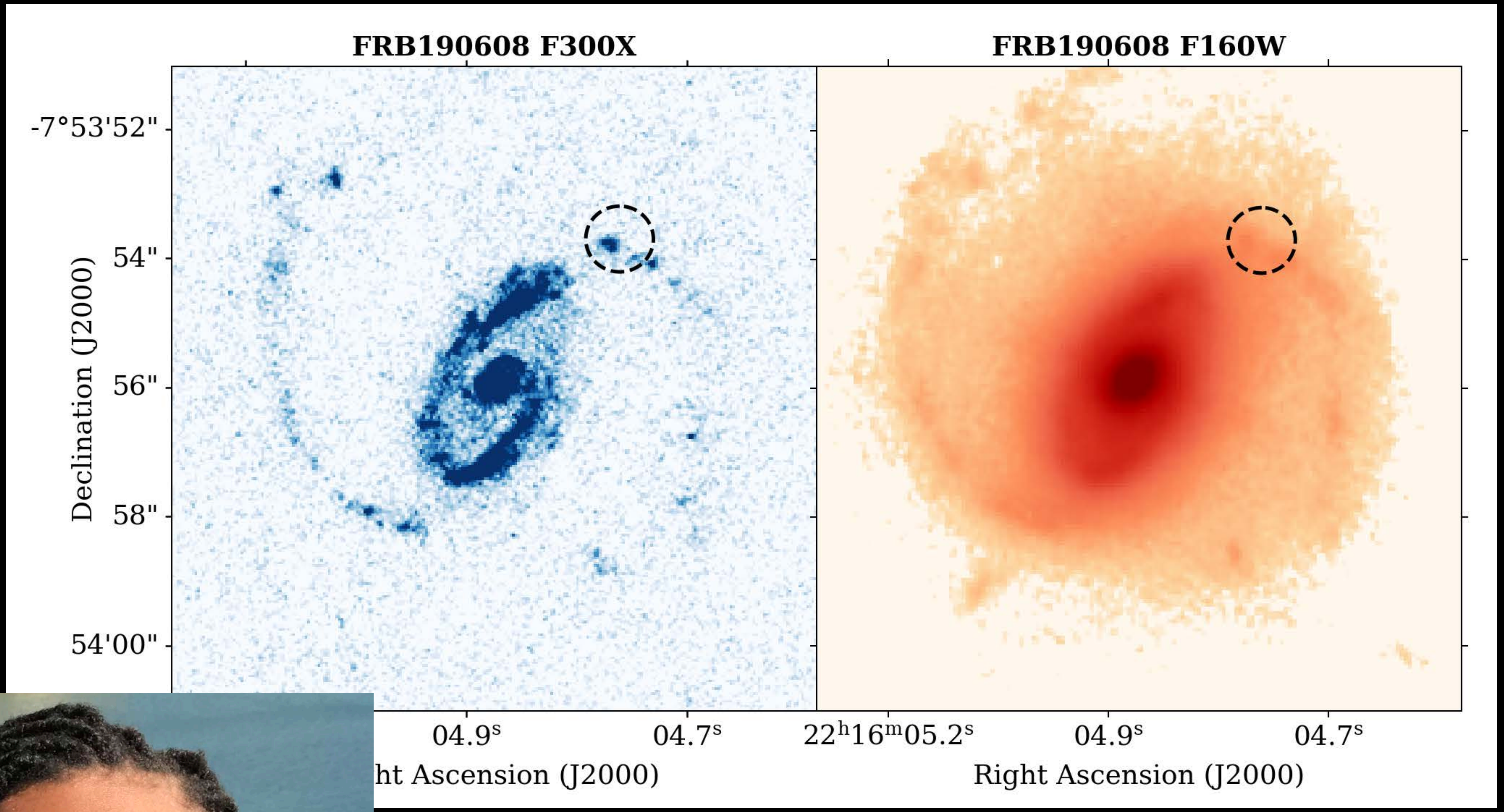


back in time

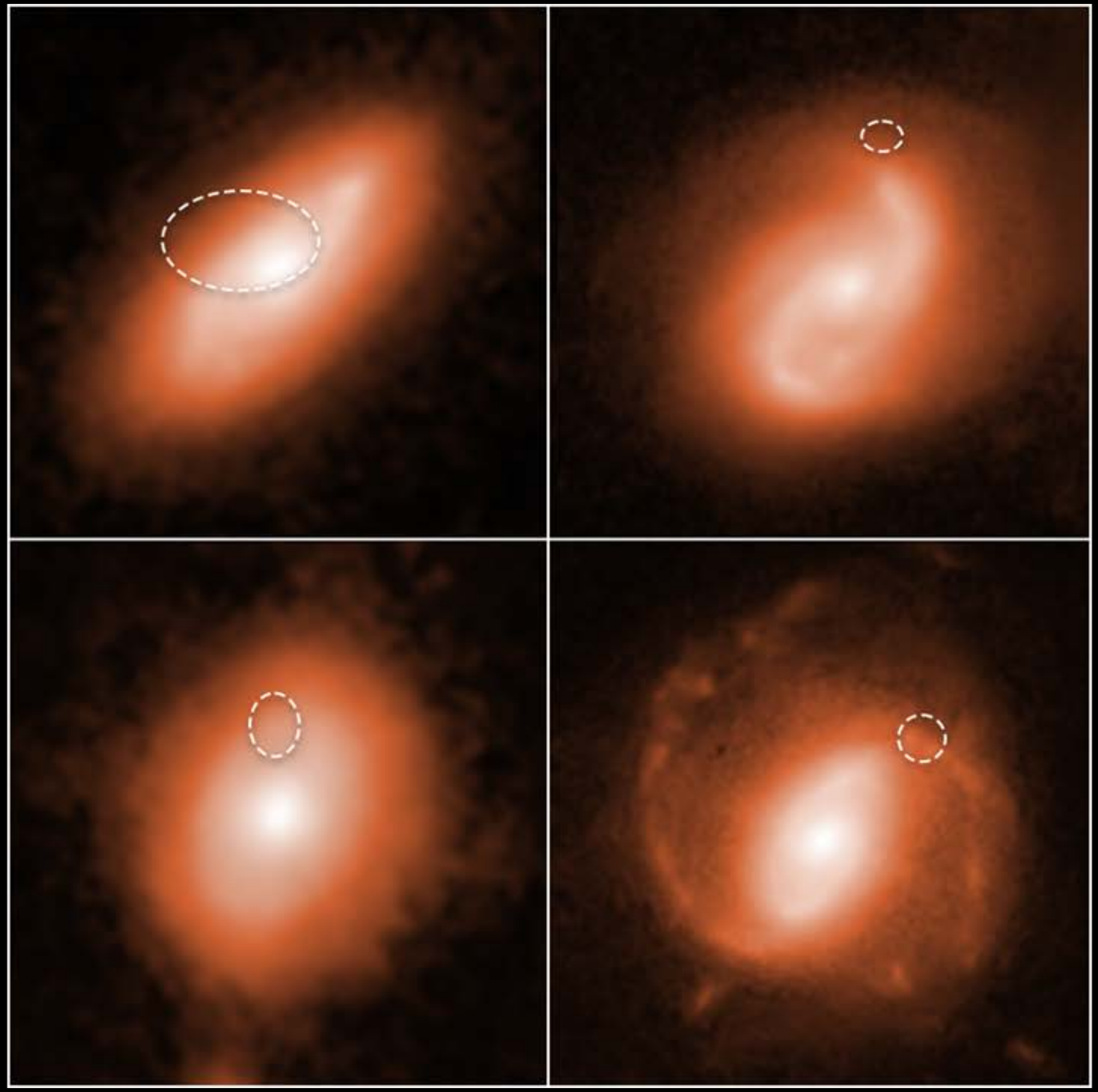
time at FRB redshift

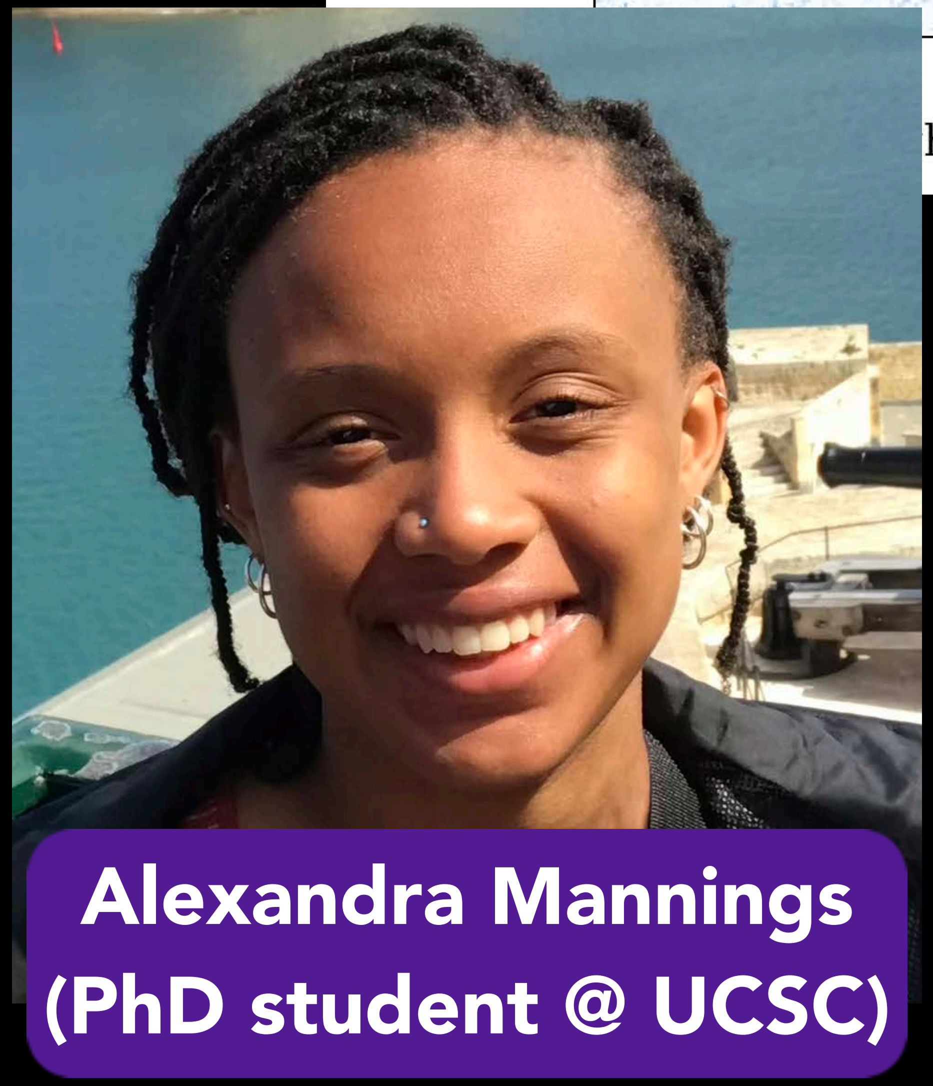
If progenitor traced stellar mass, was likely >few Gyr old

Some FRBs appear to be associated with the spiral arms of their host galaxies!



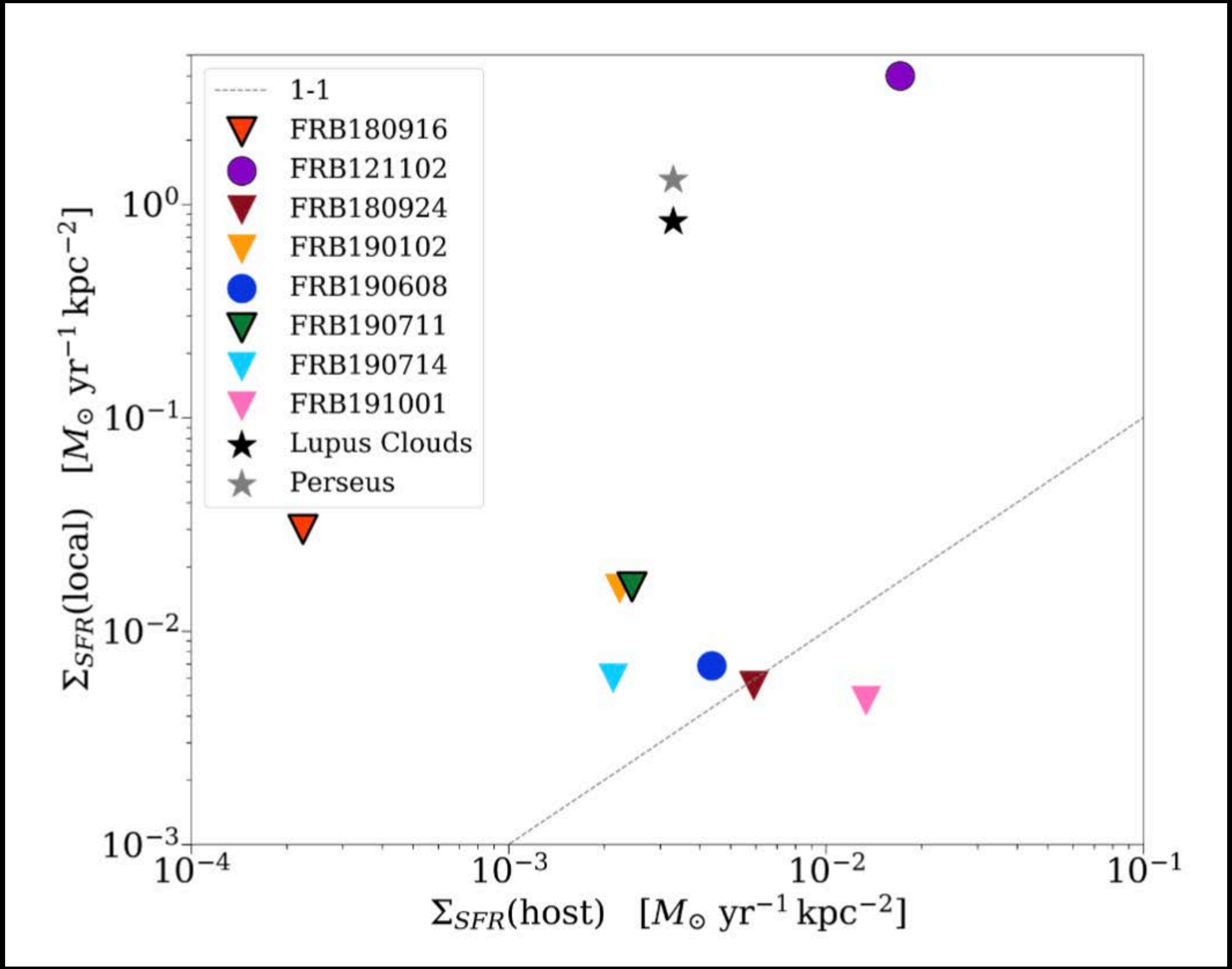
Mannings, Fong et al. 2021





Associated with star-formation?

But they are not clearly in elevated regions of SF in their host galaxies



Mannings, Fong et al. 2021

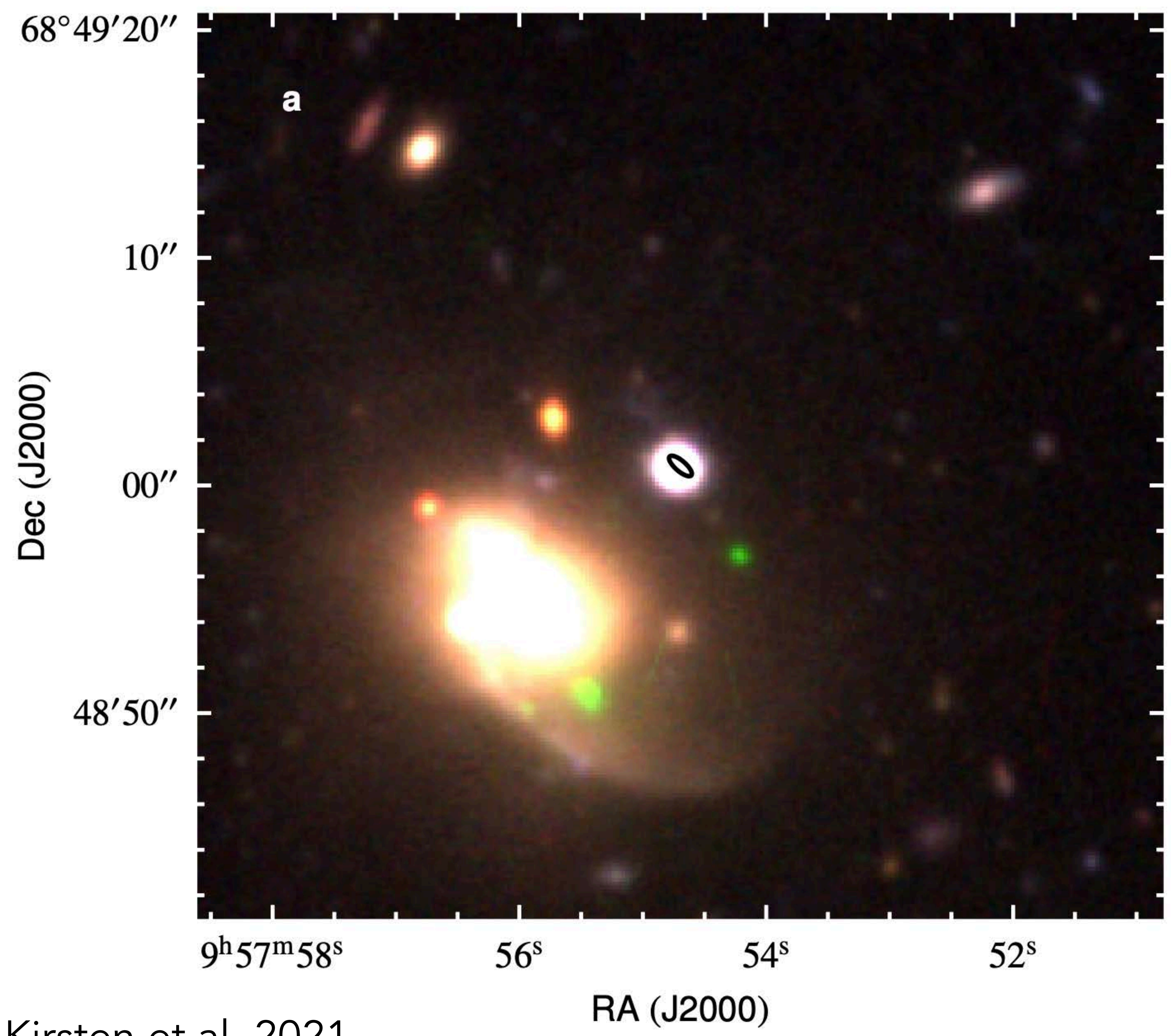
Seemingly disparate local environments…

FRB-like source located to *known* Galactic magnetar SGR1935+2154

Image credit: Danielle Futselaar / Artsource.nl.

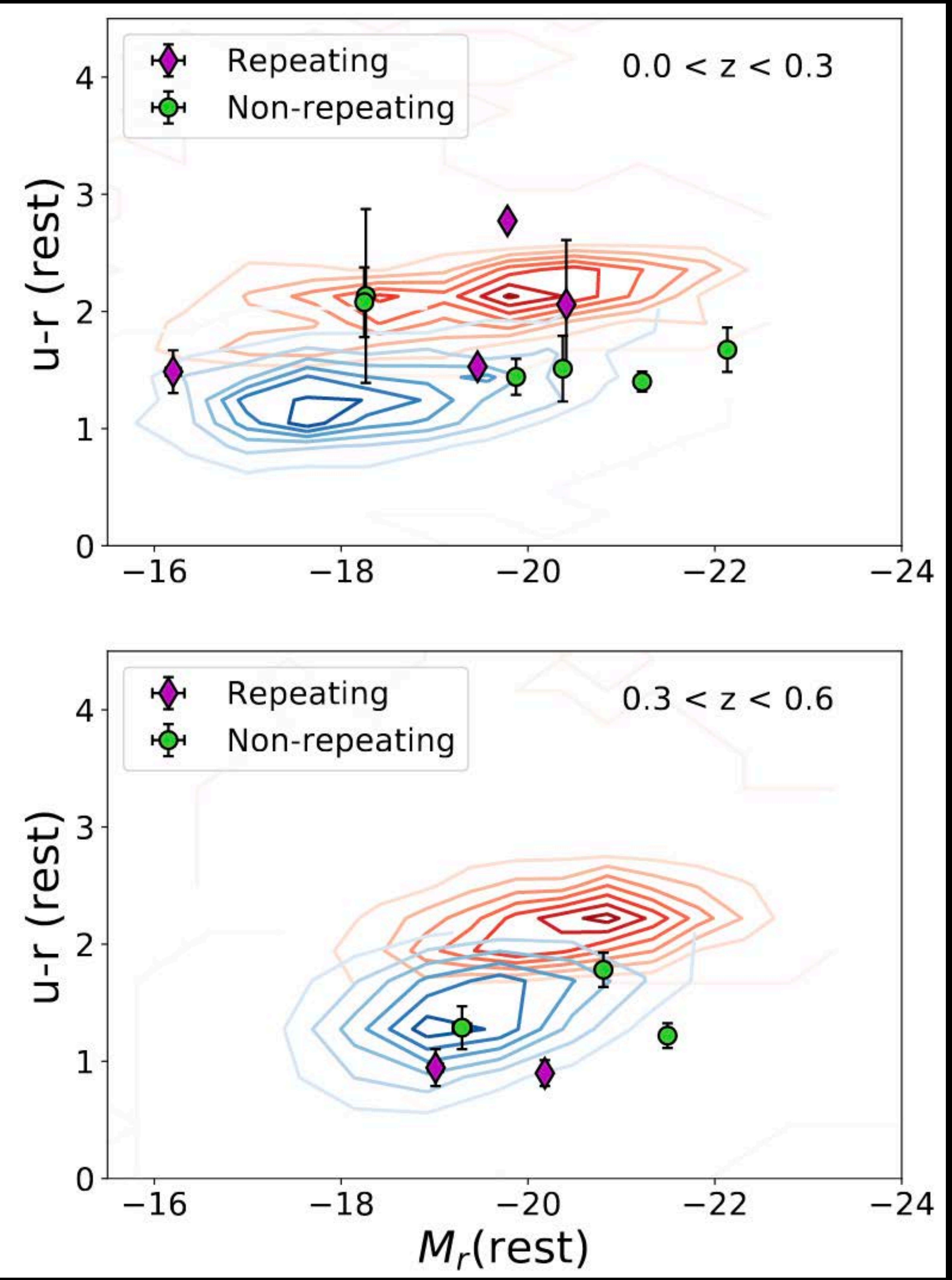
CHIME et al. 2020

FRB20200120E localized to a globular cluster (9.1 Gyr population)

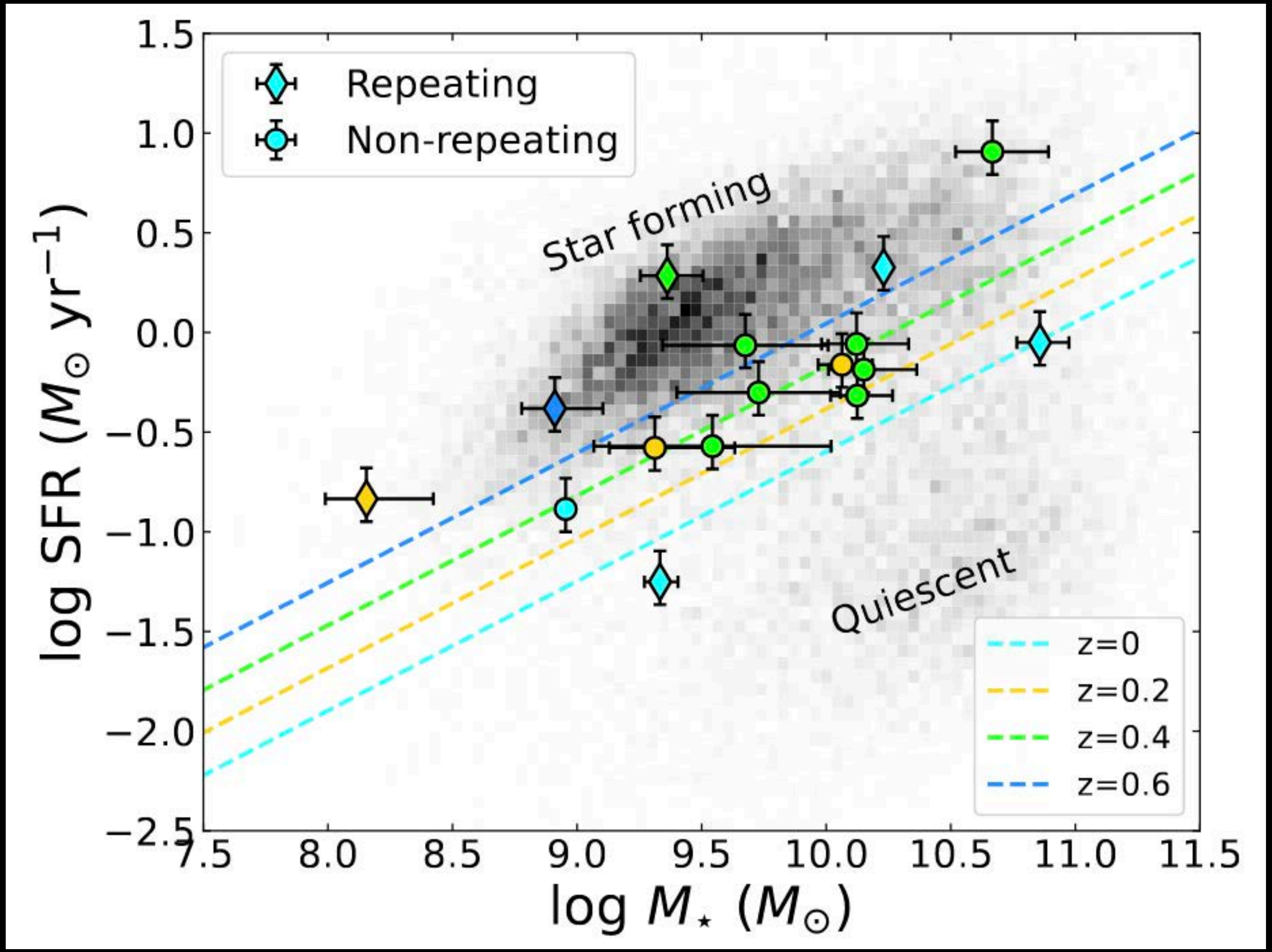


Kirsten et al. 2021

FRB Host Galaxy Demographics: Repeating and Non-repeating FRBs



Bhandari+ 2021 (see also: Heintz+ 2020)



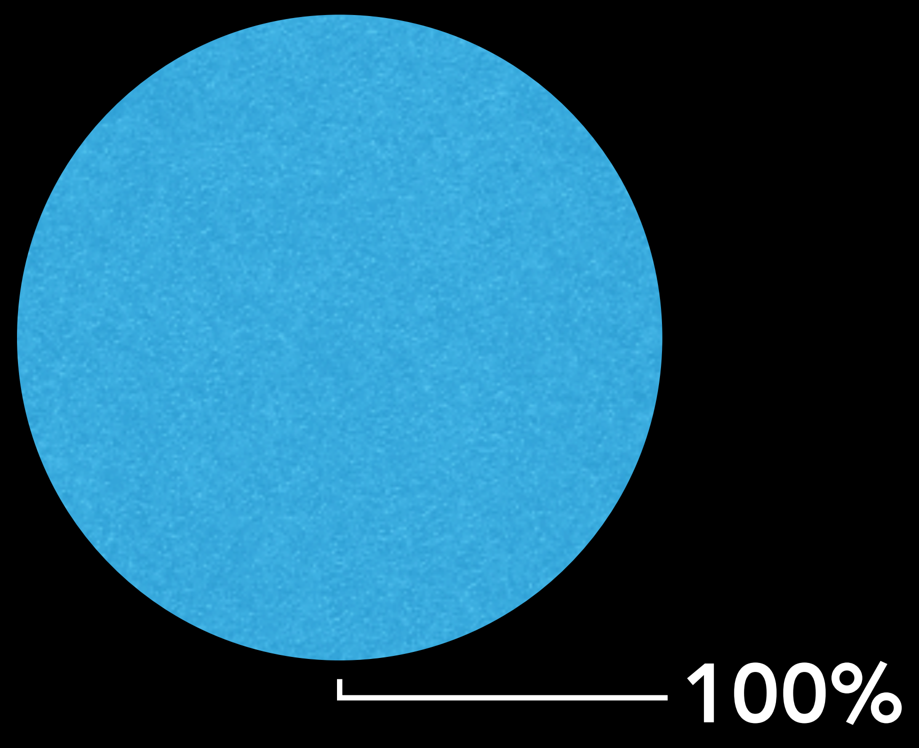
No statistically significant difference in host galaxy populations.

Absence of quiescent/red galaxies

Connecting FRB Host Galaxy Demographics to their Origins

Long GRBs
SLSNe

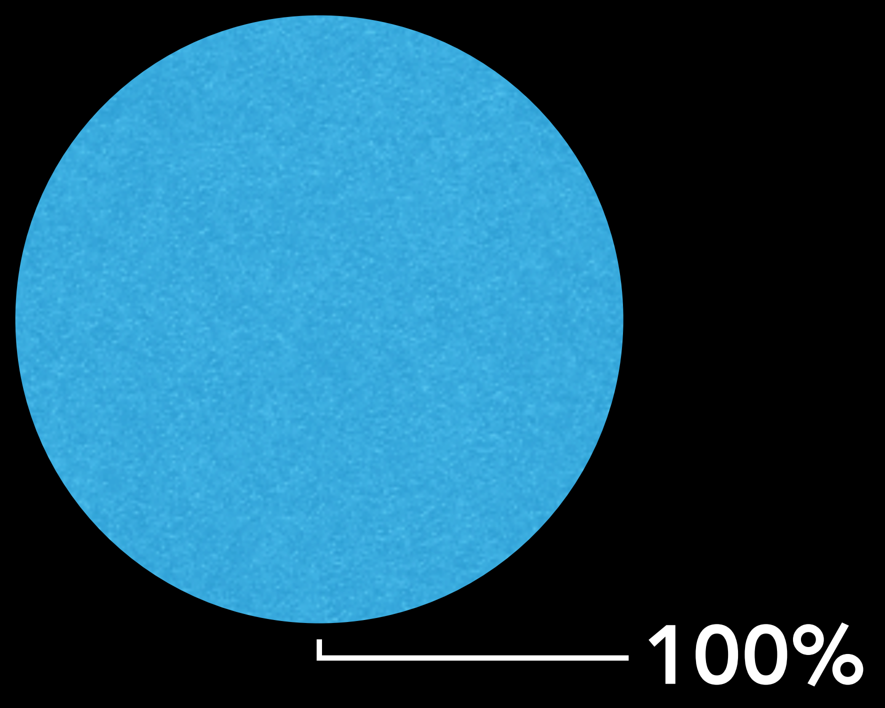
Highly Star-forming (>1-5 Msol/yr)



"ultra-prompt"
(very massive stars)

CCSNe
Repeating FRBs (6-7?)

Modest Star-forming (~0.1-3 Msol/yr)

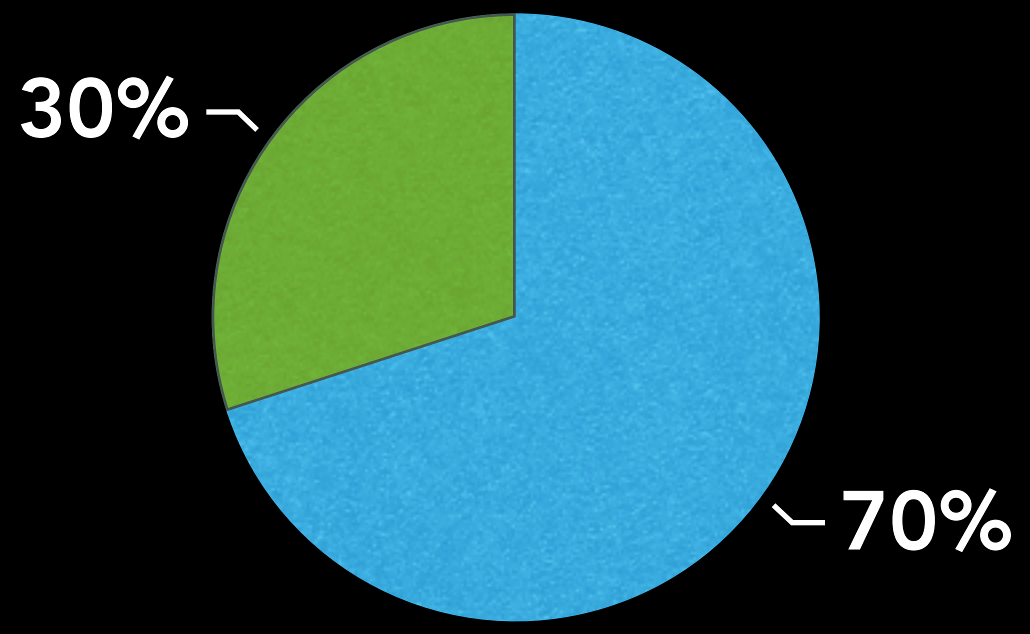


"prompt"
(normal massive stars)

Type Ia SNe
Short GRBs

Quiescent

Modest Star-forming



"delayed"
(compact objects)

As FRB progenitors…

Unlikely to dominate (locations, colors, stellar pops) (c.f., Mannings+21, Heintz+20, Bhandari+21, Li&Zhang+20)

Similarities are compelling but differences in local environments and/or as tracers of SFR (c.f., Kirsten+21, Bassa+17, Chatterjee+17, Bhandari+21)

Absence of quiescent galaxies in repeating and non-repeating? host pop. is notable

FRB Conclusions and Looking Forward

Like other transients, localization is key to making progress and providing strong constraining power on origins

Some evidence point to magnetar origins (through association with spiral sub-structure and Galactic magnetar association) but confusing and disparate local environments

No statistical differences between repeating and non-repeating host galaxy populations

VLT Large Program FURBY (180 hr, started 2021 Oct 1 for 2 years)
Fast and Unbiased FRB host galaxY survey
co-PI's: Ryan Shannon and Kasper Heintz
Expected characterized hosts: 50+