Simultaneous and Delayed Optical Limits on Fast Radio Bursts

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

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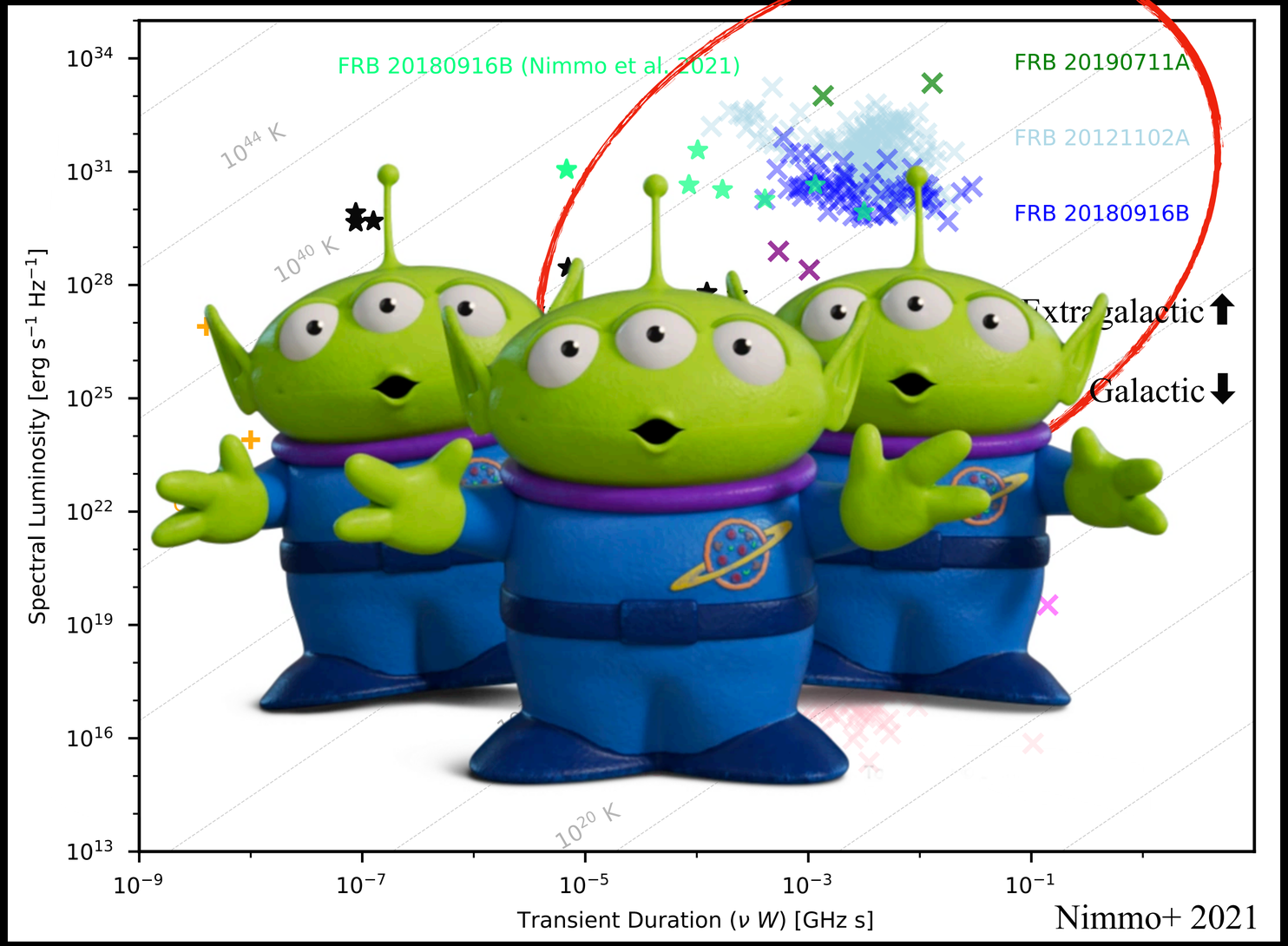
The Transient and Variable Universe 2023

Daichi Hiramatsu
Center for Astrophysics | Harvard & Smithsonian / NSF IAIFI

Fast Radio Bursts (FRBs)



Repeating or non-repeating, bright millisecond-duration pulses at GHz frequencies with unknown physical origin(s): highly-magnetized compact objects (i.e., magnetars)?

A living theory catalogue for fast radio bursts

Platts+ 2019

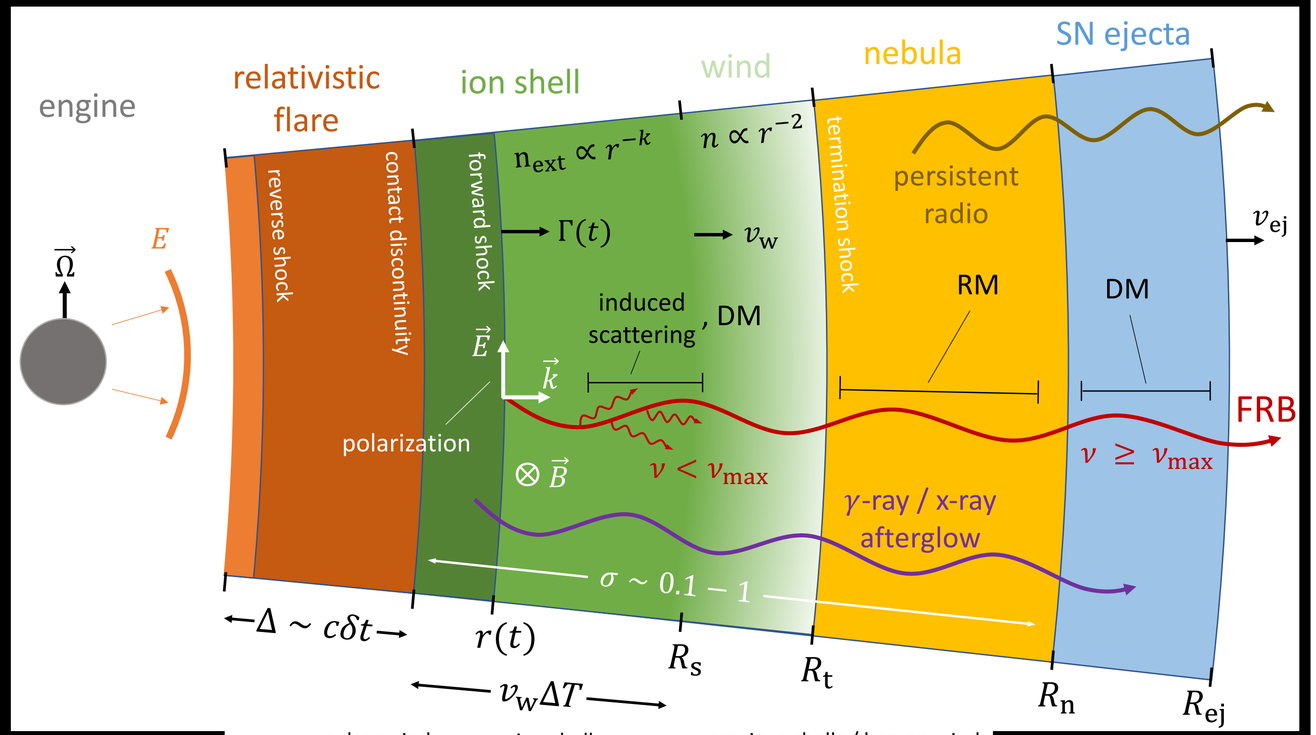
Reminiscent of the first two decades of GRB research… 🤔

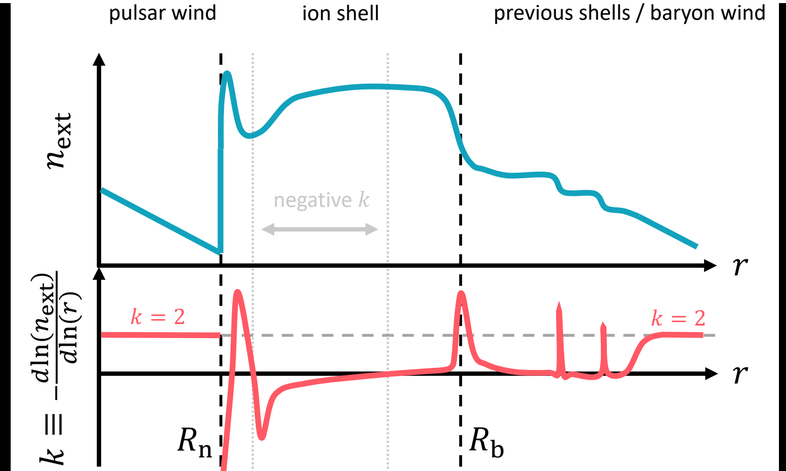
Name	Category	Progenitor	Type	Energy Mechanism	Emission Mechanism	LF Radio Counterpart	HF Radio Counterpart	Microwave Counterpart	THz Counterpart	OIR Counterpart	X ray Counterpart	Gamma ray Counterpart	GW Counterpart	Neutrino Counterpart
NS-WD Accretion	Accretion	NS-WD	Repeat	Mag. reconnection	Curv.	Yes	--	--	--	--	--	Yes, but unlikely detectable		--
AGN-KBH	AGN	AGN-KBH Interaction	Repeat	Maser	Synch.	Yes	--	--	--	Supernova	--	Yes	es	Yes
AGN-SS	AGN	AGN-Strange Star Interaction	Repeat	Electron oscillation	--	Yes	--	--	--	Thermal	--	Yes	es	Yes
Jet-Caviton	AGN	Jet-Caviton Interaction	Both	Electron scattering	Bremsst.	Yes	Yes	--	--	--	--	Possible GRB	es	--
Wandering Beam	AGN	Wandering Beam	Repeat	--	Synch.	Yes	--	--	--	--	Yes	--		--
NS to BH (DM-Induced)	Collapse	NS to BH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	es	--
NS to KNBH	Collapse	NS to KNBH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	Possible afterglow	Possible GRB	es	--
NS to Quark Star	Collapse	NS to Quark Star	Single	β-decay	Synch.	Yes	--	--	--	--	Yes	Yes	es	--
SS Crust	Collapse	Strange Star Crust	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	es	--
Axion Cloud and BH	Collision / Interaction	Superradiant Axion Cloud and BH	Repeat	Laser	Synch.	Yes	--	--	--	--	--	--	es	--
Axion Minicluster and NS	Collision / Interaction	Axion Minicluster and NS	Single	Maser	Synch.	Yes	--	--	--	--	--	--		--
Axion Quark Nugget and NS	Collision / Interaction	Axion Quark Nugget and NS	Repeat	Mag. reconnection	Curv.	Yes	Possible	Possible	--	--	--	--		--
Axion Star and BH	Collision / Interaction	Axion Star and BH	Repeat	Electron oscillation	--	Yes	--	--	--	--	--	--		--
Axion Star and NS	Collision / Interaction	Axion Star and NS	Single	Electron oscillation	Coherent dipole radiations	Yes	--	--	--	--	--	--		--
NS and Primordial BH	Collision / Interaction	NS and Primordial BH	Both	Mag. reconnection	--	Yes	--	--	--	--	--	--	es	--
Small Body and Pulsar	Collision / Interaction	Small Body and Pulsar	Single	Maser	Synch.	Yes	--	--	--	--	--	--		--
NS and Asteroid Belt	Collision/ Interaction	NS and Asteroid Belt	Repeat	Electron stripping	Curv.	Yes	--	--	--	--	--	Yes		--
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)		--
Pulsar-BH Interaction	Interaction	Pulsar-BH	Single	--	--	Yes	?	--	--	--	--	--	es	--
Annihilating Mini BHs	Inviable	Annihilating Mini BHs	Single	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Stellar Coronae	Inviable	Stellar Corona	Both	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
KNBH-BH (Inspiral)	Merger	KNBH-BH	Single	Mag. flux change	Curv.	Yes	Afterglow	--	--	--	Yes	sGRB if jet aligned	es	--
KNBH-BH (Magneto. Collapse)	Merger	KNBH-BH	Single	Mag. reconnection	Curv.	Yes	Afterglow	--	--	--	--	Afterglow	es	--
NS-BH Merger	Merger	NS-BH	Single	BH battery	--	--	--	--	--	--	Yes	Yes	es	--
NS-NS Merger (Mag. Braking)	Merger	NS-NS	Single	Mag. braking	--	Yes	Yes	--	--	Kilonova	Afterglow	sGRB if jet aligned	es	--
NS-NS Merger (Mag. Flux Change)	Merger	NS-NS	Both	Mag. flux change	--	Yes	Yes	--	--	Kilonova	Afterglow	sGRB if jet aligned	es	--
NS-NS Merger (Mag. Reconnection)	Merger	NS-NS	Both	Mag. reconnection	Curv.	Yes (excl. self absorption)	Yes	?	?	Kilonova	Afterglow	sGRB if jet aligned	es	--
NS-WD Merger	Merger	NS-WD	Single	Mag. reconnection	Curv.	Yes	Yes	--	--	--	--	--		--
WD-BH Merger	Merger	WD-BH	Single	Maser	Synch.	--	--	--	--	--	Yes (transient accretion disk)	--		--
WD-WD Merger	Merger	WD-WD	Single	Mag. reconnection	Curv.	Yes	--	--	--	Supernova	Afterglow	--		--
Young Magnetars	Merger/Collapse	Magnetars Born in BNS Mergers and WD Col	Repeat	Maser	Synch.	Yes	Afterglow	--	--	Possible SN	Afterglow	sGRB	es	--
Alien Light Sails	Other	Alien Light Sails	Repeat	Artificial transmitter	--	Yes	--	--	--	--	--	--		--
DSR in Galaxies	Other	Dicke's Superradiance in Galaxies	Both	Dicke's Superradiance	Spectral line	Yes	Yes	--	--	--	--	--		--
Magnetars with Low Magnetospheric Twist	Other	Magnetars with Low Magnetospheric Twist	Repeat	Mag. reconnection	Pulsar-like	Yes	---	Maybe	Maybe	Maybe	Maybe	Unlikely detectable		---
Neutral Cosmic Strings	Other	Neutral Cosmic Strings	Single	Cusp decay	--	Yes	--	--	--	--	--	--		--
NS Combing	Other	NS Combing	Both	Various	Mag. reconnection	Yes	--	--	--	--	--	--		--
Pulsar Lightning	Other	Pulsar Lightning	Repeat	Electrostatic	Curv.	Yes	--	--	--	--	--	--		--
RDM Stars	Other	RDM Star	Both	Stimulated emission	Synch.	---	---	---	---	---	---	---		---
Starquakes	Other	Starquakes	Repeat	Mag. reconnection	Curv.	Yes	--	--	--	Possible	Possible	Yes if pulsar jet aligned	es, but unlikely detectable	--
Superconducting Cosmic Strings	Other	Superconducting Cosmic Strings	Single	Cusp decay	--	Yes	--	--	--	--	--	GRB if jet aligned	es	Yes
Tiny EM Explosions	Other	Tiny EM Explosions	Both	Thin shell interactions	Curv.	Yes	Yes	--	--	--	--	Unlikely observable		--
Variable Stars	Other	Variable Stars	Repeat	Undulator	Synch.	Yes	--	--	--	--	--	--		--
Wandering Pulsar	Other	Wandering Pulsar Beams	Repeat	--	--	Yes	--	--	--	--	--	--		--
White Holes	Other	White Holes	Single	--	--	Yes	--	--	--	Yes	--	Yes		--
Decelerating Blast Waves	Shock Interaction	Magnetar	Repeat	Thin shell	Synch. Maser	Yes (excl. self absorption)	Yes	--	--	Possible, Prompt	Prompt	Prompt	o	No
NS-SN Interaction	Shock Interaction	NS-SN Interaction	Single	Mag. reconnection	--	Yes	--	--	--	Supernova	--	possible GRB (low flux)		--
MWN Shock (Clustered Flares)	SNR (Magnetars)	MWN Shock (Clustered Flares)	Repeat	Maser	Synch.	Yes	Afterglow	--	--	Possible bright optical	Yes but ~100 years later	Low energy gamma-rays, sGRB if jet aligned	es	--
MWN Shock (Single Flare)	SNR (Magnetars)	MWD Shock (Single Flare)	Single	Maser	Synch.	Yes	Afterglow	--	--	Maybe	--	Low energy gamma-rays, sGRB if jet aligned	es	--
Giant Pulses	SNR (Pulsars)	Giant Pulses	Repeat	--	Synch. / Curv.	Yes	--	--	--	--	--	--		--
Pulsar Schwinger Pairs	SNR (Pulsars)	Pulsar Schwinger Pairs	Single	Schwinger	Curv.	Yes	--	--	--	--	--	--		--
Pulsar Wind Bubble	SNR (Pulsars)	Pulsar Wind Bubble (NS and MWD)	Single	--	Synch.	Yes	--	--	--	--	Yes	--		--

Transient Multi-Wavelength Emission

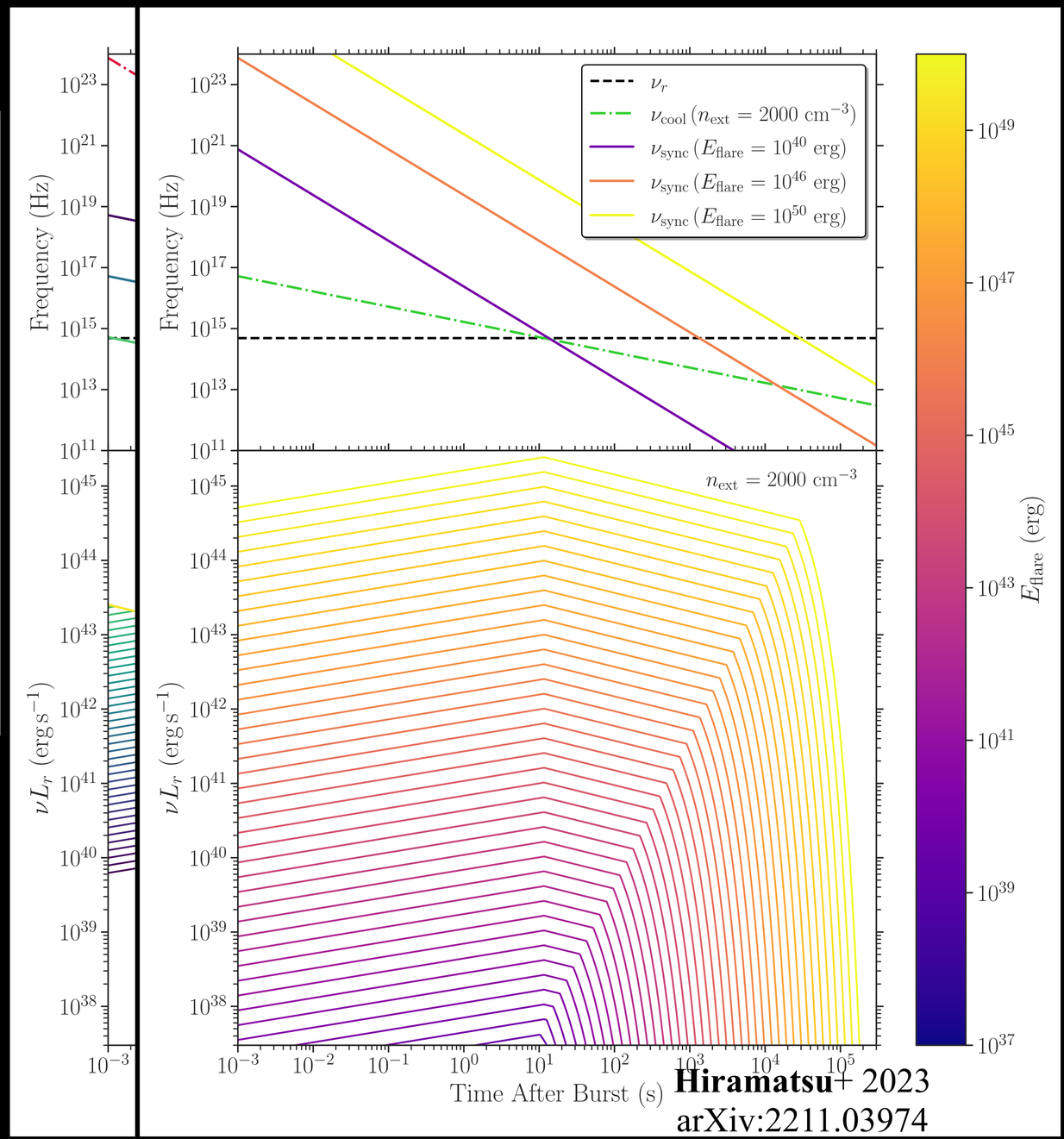
FRB Transient Multi-Wavelength Emission

e.g., Synchrotron Maser Model





Metzger+ 2019
Margalit+ 2020



Hiramatsu+ 2023
arXiv:2211.03974

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Optical Transient Limits for Well-Localized Repeating FRBs

FRB	R.A. (deg)	Decl. (deg)	Redshift	d_L [a] (Mpc)	$A_{V,\mathrm{MW}}$ [b] (mag)	Events [c] (#)
20200120E	149.4779140(3) [e]	+68.8169036(4) [e]	−0.00013 [f]	3.6 [f]	0.200	74 [g]
20180916B	29.5031257(6) [h]	+65.7167542(6) [h]	0.0337 [h]	149 [h]	2.712	244 [i]
20220912A	347.2704(6) [j]	+48.7071(3) [j]	0.077 [j]	344	0.637	72 [k]
20201124A	77.0146142(8) [l]	+26.0606959(7) [l]	0.0979 [l]	444	1.964	2914 [m]
20121102A	82.994575(3) [n]	+33.147940(1) [n]	0.1927 [n]	927	2.098	3658 [o]
20190520B	240.51780(3) [p]	−11.28814(2) [p]	0.241 [p]	1192	0.769	230 [q]
20180301A	93.2268(2) [r]	+4.6711(2) [r]	0.3304 [r]	1712	1.231	22 [s]
SGR				(kpc)		
1935+2154	293.7317(2) [t]	+21.8966(2) [t]	Galactic [t]	9.0 [u]	7.2 [v]	14 [w]

CfA FRB Follow-up Program
(PI: Hiramatsu)

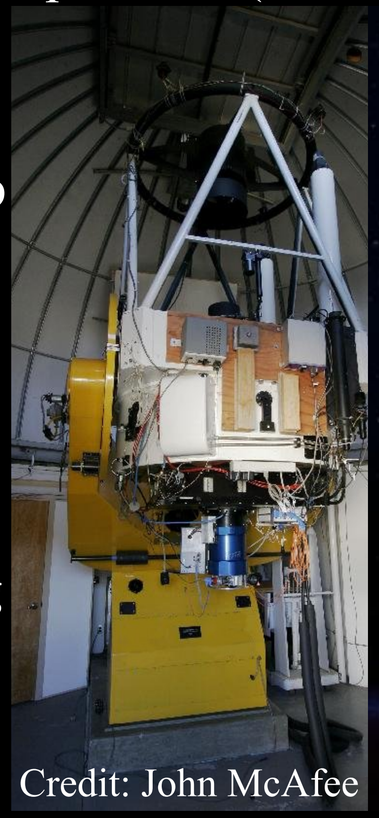
FLWO 1.2m
KeplerCam (robotic)

MMT 6.5m
Binospec (queue)

Credit: CHIME Collaboration

Follow up realtime alerts

Shadow observing windows


Credit: John McAfee


Credit: CfA/Rick Peterson

~20 well-localized ($\lesssim$ 2") FRBs (~10 repeating)
routinely observed by CHIME and other radio facilities

+ Public Optical Transient Surveys
(e.g., ZTF, ATLAS)

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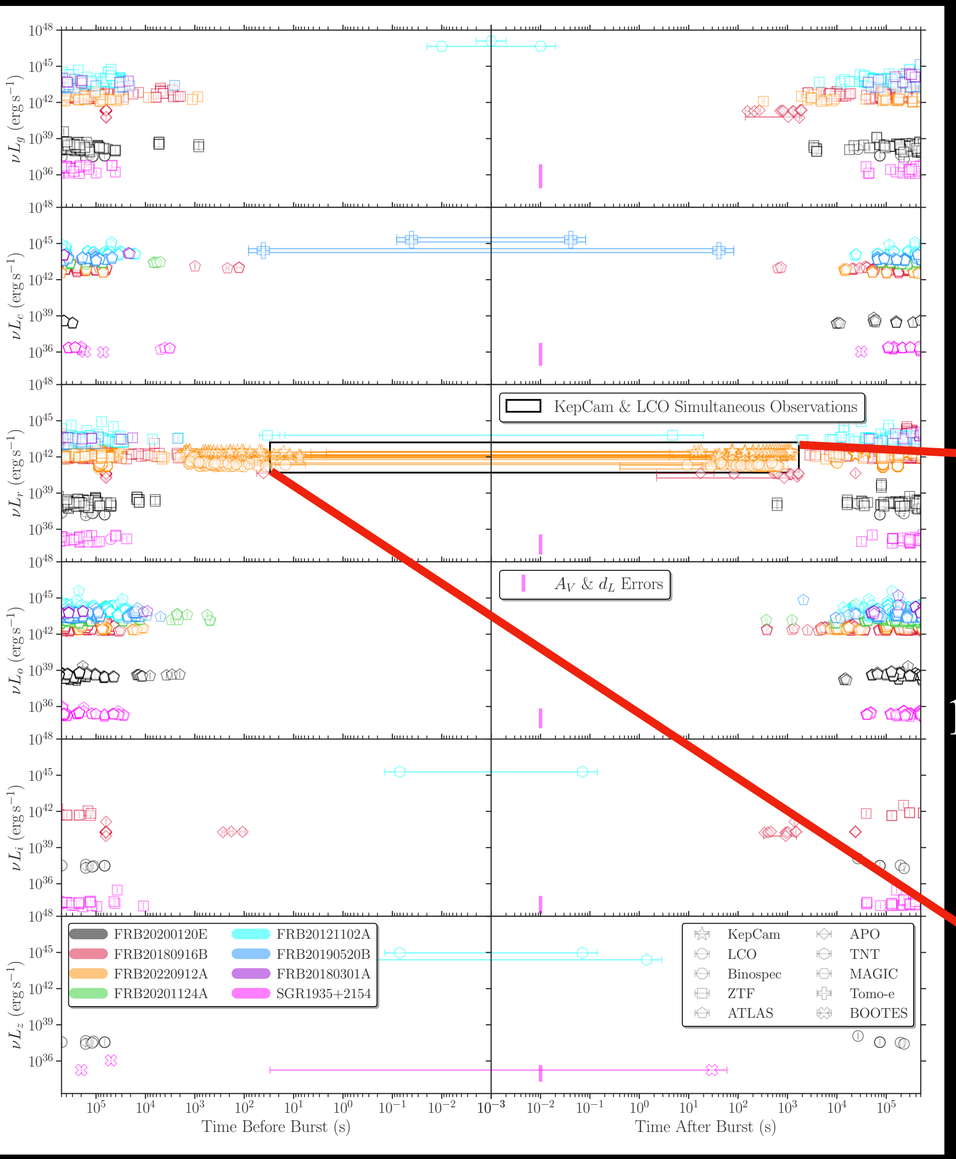
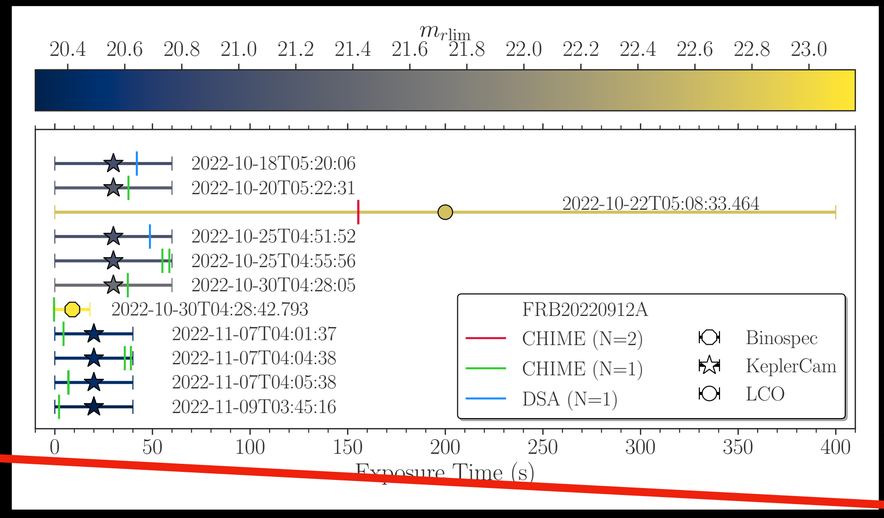
Optical Transient Limits for Well-Localized Repeating FRBs

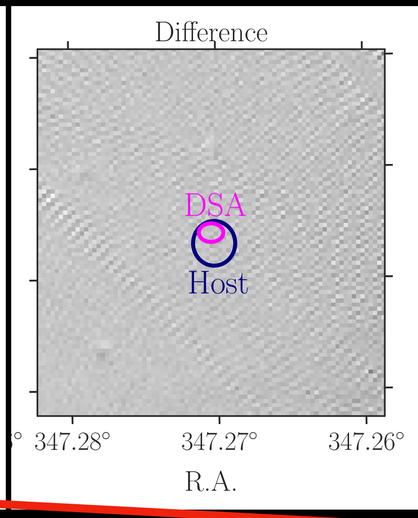


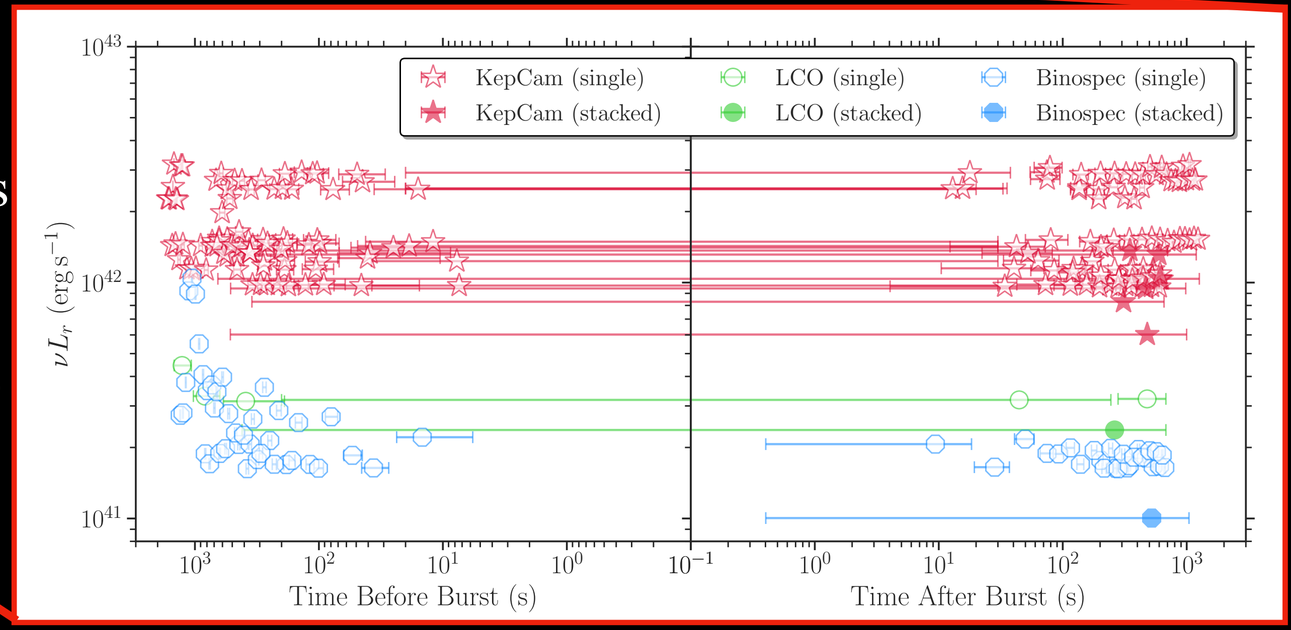
Largest compilation of optical limits:
our observations, public surveys, literature

FRB
20220912A:
344 Mpc
~100 bursts/hr

10 simultaneous
exposures
during
13 radio bursts



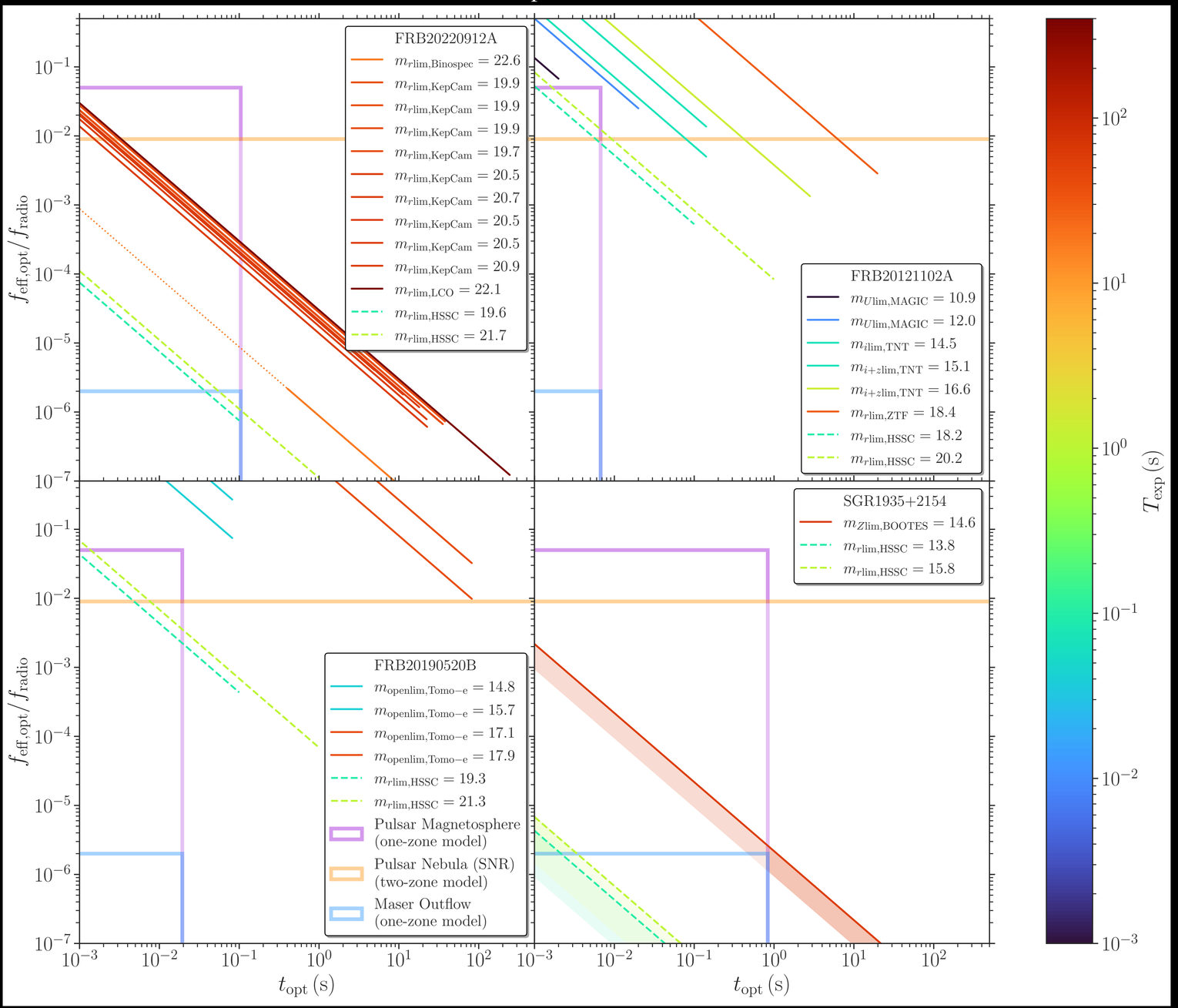




KepCam, LCO, and Binospec observations of FRB 20220912A
— deepest *simultaneous* limits for extragalactic FRBs!

Current FRB Model Constraints

$$\frac{f_{\rm eff,opt}}{f_{\rm radio}} \text{ where } f_{\rm eff,opt} = f_{\rm opt}\frac{T_{\rm exp}}{t_{\rm opt}}$$



- ★ Fast Optical Burst Models (Inverse Compton Scattering):
  - ★ Pulsar Magnetosphere
  - ★ Pulsar Nebula
  - ★ Maser Outflow
- ★ Afterglow Models:
  - ★ Synchrotron Maser Model

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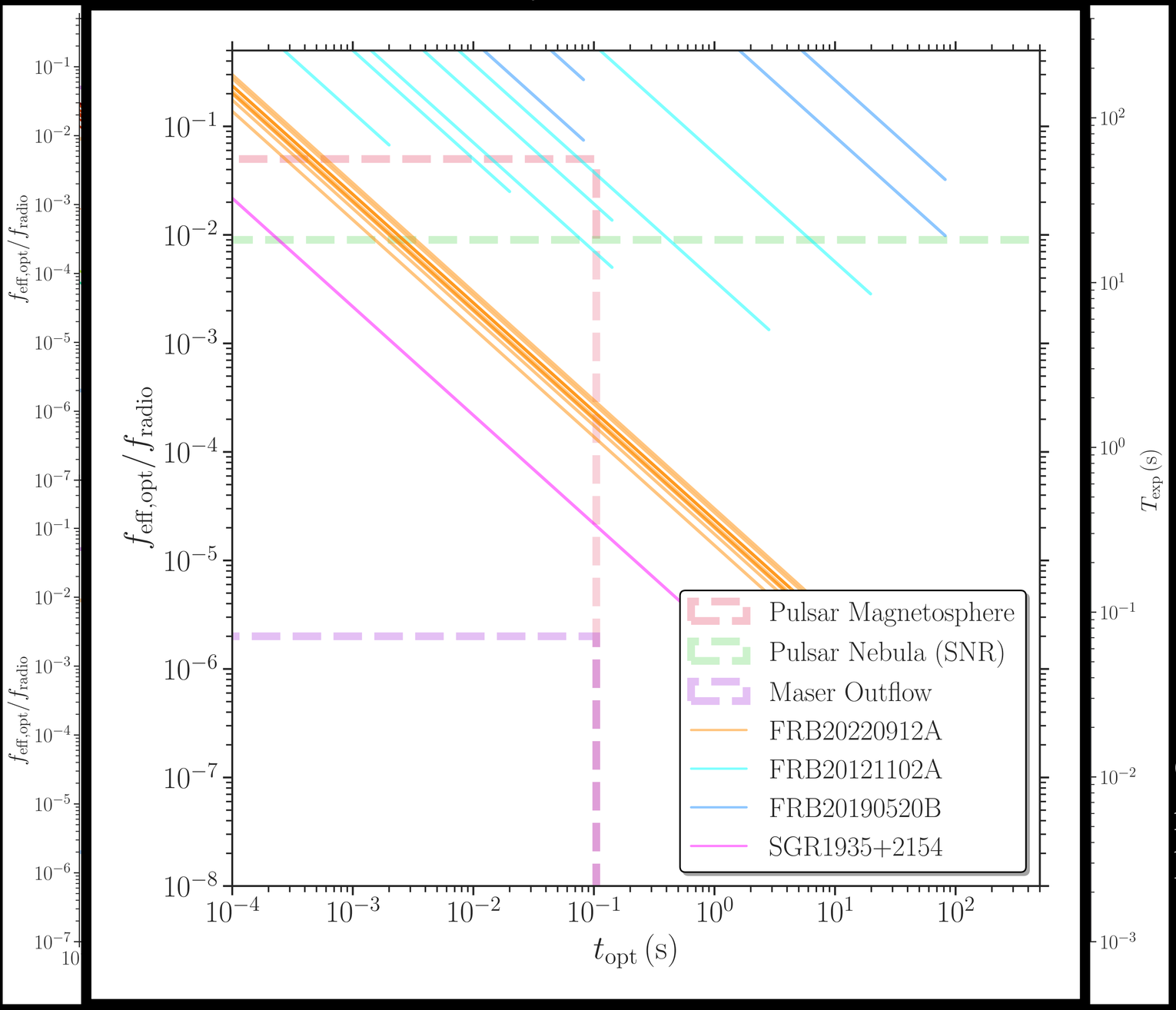
Current FRB Model Constraints



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Optical limits for FRB 20220912A begin to reach some model predictions, only a magnitude higher than the Galactic SGR 1935+2154.

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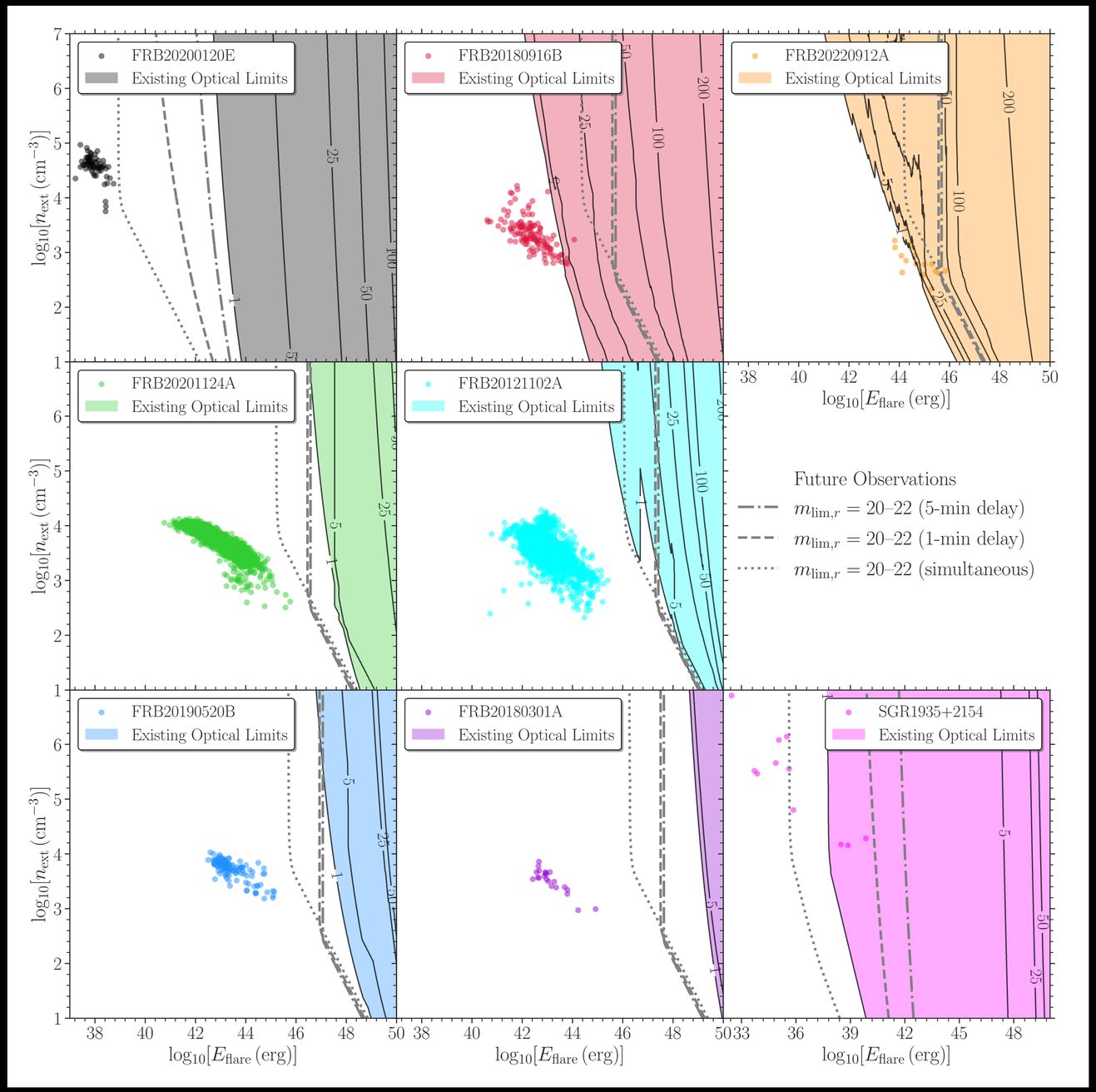
$E_{\rm flare}$ & $n_{\rm ext}$ Current FRB Model Constraints



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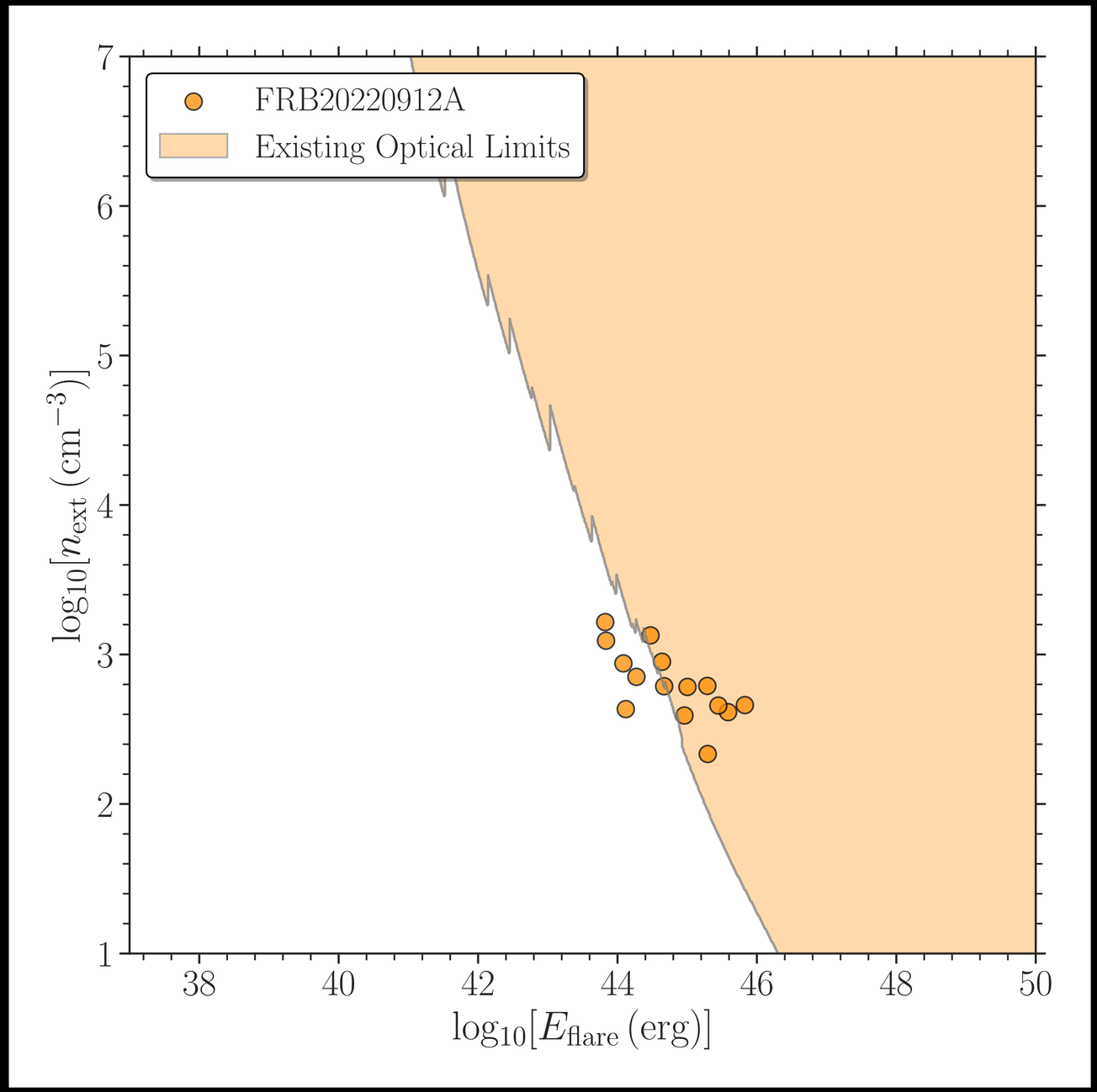

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Optical limits for FRB 20220912A constrain ~65% of its radio burst parameter space ($E_{\rm flare} \gtrsim 10^{45}$ erg and $n_{\rm ext} \gtrsim 1000\,{\rm cm}^{-3}$).

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Future FRB Model Constraints

WE NEED TO GO DEEPER AND FASTER… 💨

Gemini North/South 8.0m
(queue)

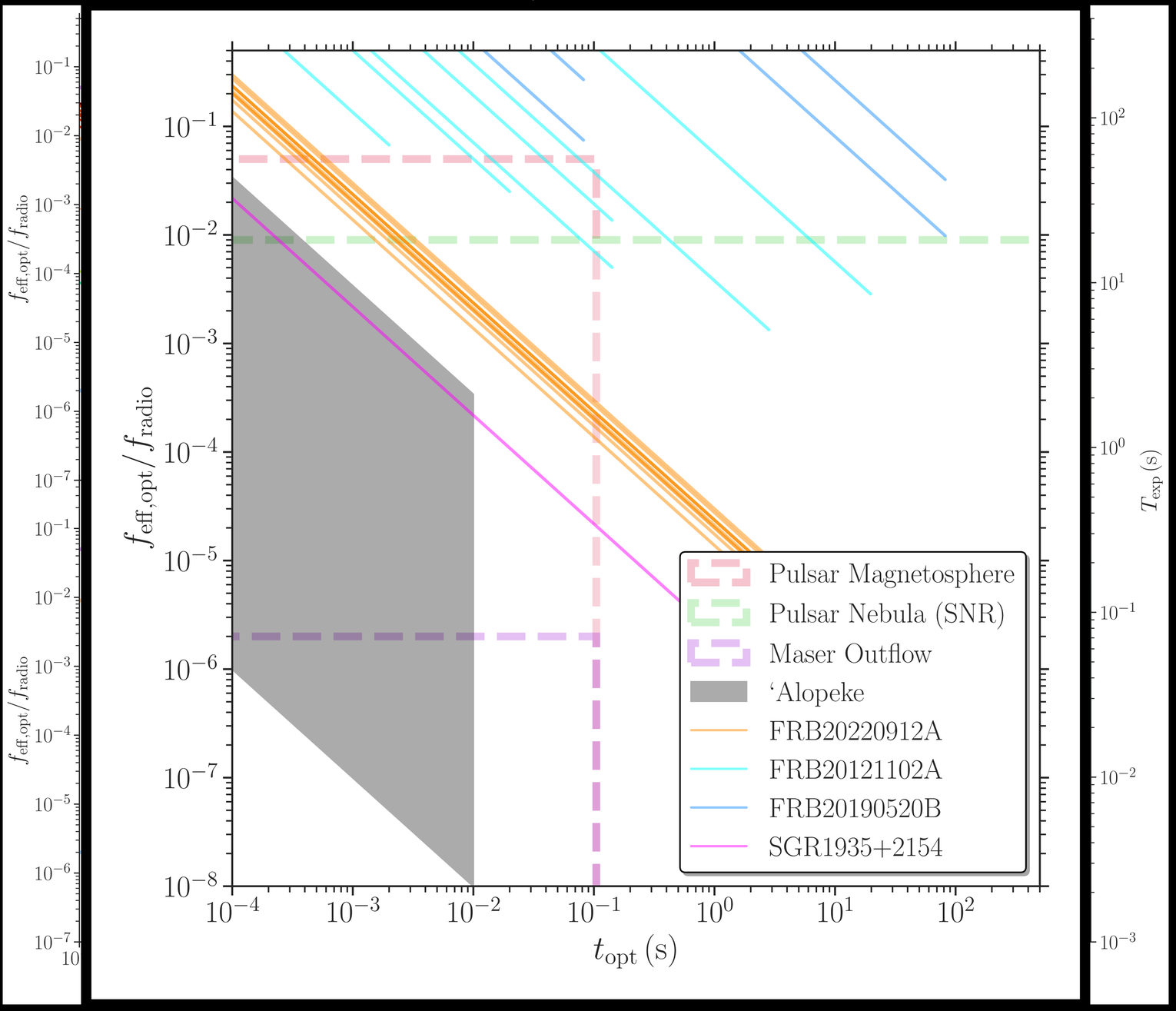
Credit: Gemini/NSF/AURA

+

‘Alopeke/Zorro
(10-ms readout)

$$\frac{f_{\mathrm{eff,opt}}}{f_{\mathrm{radio}}} \text{ where } f_{\mathrm{eff,opt}} = f_{\mathrm{opt}} \frac{T_{\mathrm{exp}}}{t_{\mathrm{opt}}}$$

Future FRB Model Constraints



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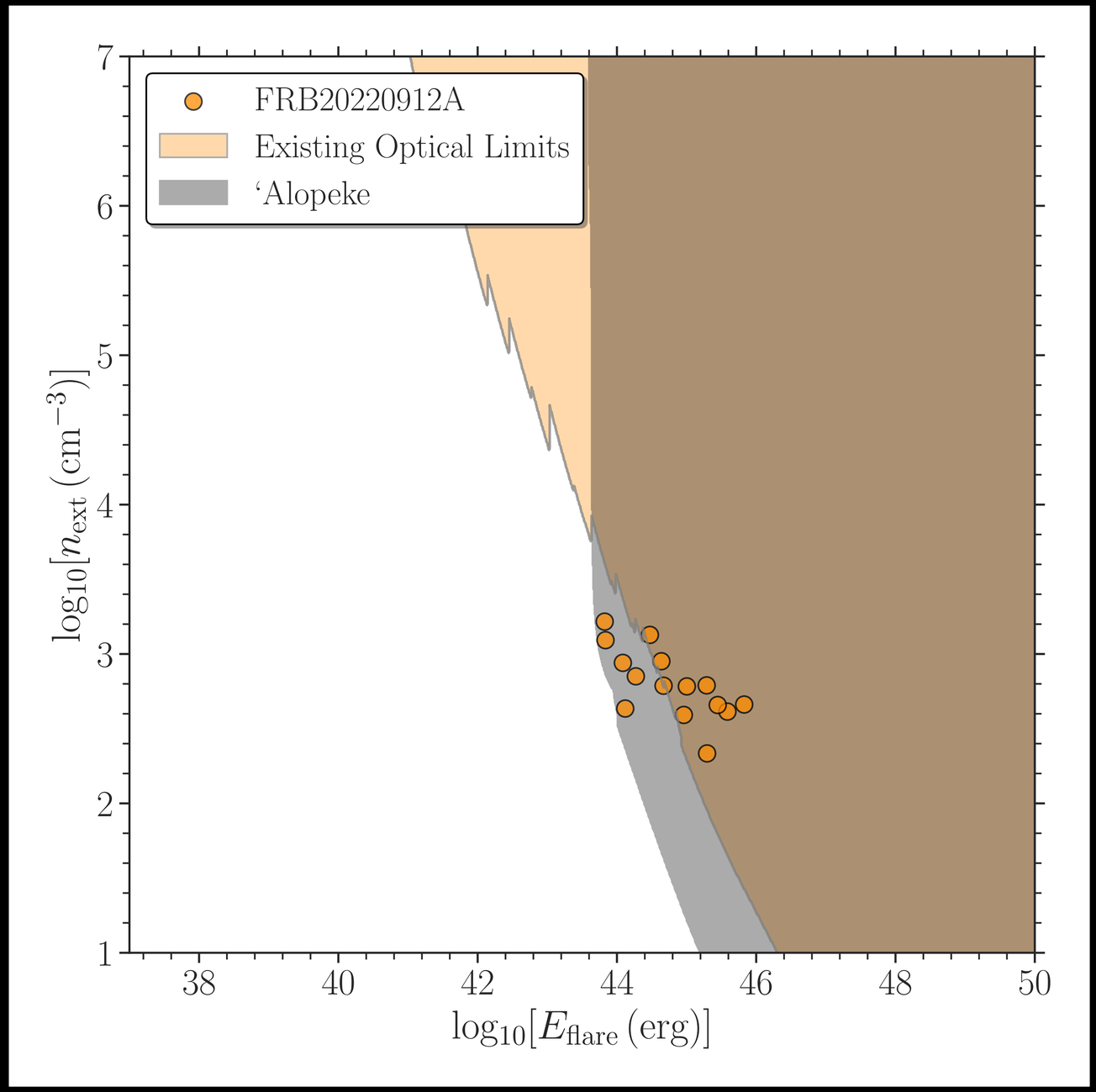
High-speed ‘Alopeke/Zorro (10 ms) on 8-m Gemini North/South Telescopes (2023B🤞)
(see also Charlie Kilpatrick’s talk later)

Future FRB Model Constraints

$E_{\rm flare}$ & $n_{\rm ext}$



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Summary and Future Prospects

- Some FRB emission models (e.g., synchrotron maser) predict transient multi-wavelength emission which can be used to constrain the model parameter space.
- ~20 well-localized FRBs + CHIME observing windows and realtime alerts make simultaneous/follow-up optical observations feasible.
- We compiled the largest sample of optical limits; KeplerCam/Binospec limits for FRB 20220912A provide the first meaningful model constraints for extragalactic FRBs.
- Increasing samples and fast-readout cameras on larger telescopes (Gemini 'Alopeke/Zorro, Subaru HSSC) have potential to discover first optical transient counterparts.
- Public observing windows and realtime alerts with the arrival-time (duration, flux/fluence) information would greatly help us plan multi-wavelength follow-up strategies.

Thank you! Ask me questions now, in Slack, or to daichi.hiramatsu@cfa.harvard.edu 😉