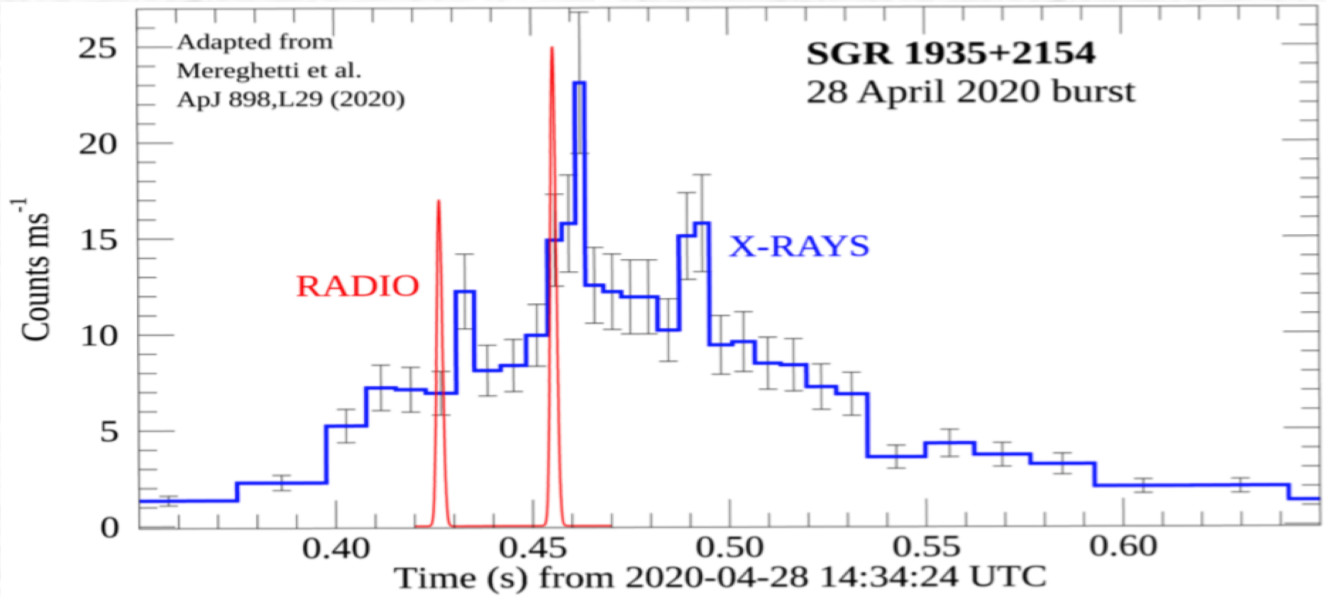
FRBs' saga: 5th episode

[CHIME/FRB+2020] [Bochenek et al 2020]



Magnetar SGR1935+2154

Simultaneous X-ray and radio bursts from a known Galactic magnetar source

Unique case of multiwavelength (MWL) detection !

A big boost for the magnetar-based models !

Identikit of FRBs *(as at Sept 2022…)*

Summary of the far observed parameters:

- Burst of ≈ millisecond duration to tens of millisecond duration
- Dispersion measure > few times the expected Milky Way contribution up to 3338 pc/cm^3
- Dispersion delay consistent with ν^{-2}
- When measurable, scattering time consistent with Kolmogorov index, $\nu^{-4.4}$
- Often high linearly polarized: sometimes circular, sometimes not measurable
- Observed from ≈ 100 MHz up to ≈ 10 GHz
- Peak Flux density at 1.4 GHz ≈ 0.1-100 Jansky
- In the vast majority of the cases, band-limited emission
- Rate of order ~10^4 day^{-1} with isotropic provenance
- Few % of recognized repeaters
- Few ‰ of recognized periodic repeaters
- Few % with identified host galaxy: diverse properties
- One established association with a known magnetar source
- No detected MWL counterpart so far for extragalactic sources

See Zampieri's talk

See Trudu's talk

Additional derived identikit of the FRBs

Assuming that the extra-DM is mainly due to the Inter Galactic Medium, one can derive the following additional parameters:

- **Red-shift** $0.0001 \lesssim z < \lesssim 2.0$ **(plus a Galactic source)**
- **Co-moving distance** $0.003 \lesssim D\ (\mathrm{Gpc}) \lesssim 3.5$
- **Isotropic emitted energy** $10^{30} \lesssim E_{iso}\ (\mathrm{erg}) \lesssim 10^{43}$
- **Brightness temperature** $10^{26} \lesssim T\ (\mathrm{K}) \lesssim 10^{42}$ **(i.e. coherent emission)**

... if an independent z is available ...

The first possibility to measure the **average density of the ionized component of the Inter Galactic Medium** along several lines of sight

$$
\begin{aligned}
\mathrm{DM} &= n_0 \frac{c}{H_0} \int_0^z \frac{dz(1+z) f_e(z)}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}, \\
&= 1060\,\mathrm{cm}^{-3}\mathrm{pc} \left(\frac{\Omega_b h^2}{0.022}\right) \left(\frac{h}{0.7}\right)^{-1} \\
&\quad \times \int_0^z \frac{dz(1+z) f_e(z)}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}. \qquad (5)
\end{aligned}
$$

For a constant f_e, the above integral can be approximated as

$$
\begin{aligned}
\mathrm{DM} \simeq\ & 933\,\mathrm{cm}^{-3}\mathrm{pc} \left(\frac{f_e}{0.88}\right) \left(\frac{\Omega_b h^2}{0.022}\right) \left(\frac{h}{0.7}\right)^{-1} \\
& \times \left[\left(\frac{\Omega_m}{0.25}\right)^{0.1} a_1 (x-1) + \left(\frac{\Omega_m}{0.25}\right) a_2 (x^{2.5} - 1) \right. \\
& \left. + \left(\frac{\Omega_m}{0.25}\right)^{1.5} a_3 (x^4 - 1) \right], \qquad (6)
\end{aligned}
$$

with $x = 1 + z$, $a_1 = 0.5372$, $a_2 = -0.0189$, and $a_3 = 0.00052$. The accuracy of this approximation is better than $\sim 2\%$ for $z < 5$. At low redshifts, one can use the following approximation,

$$
\begin{aligned}
\mathrm{DM} \simeq\ & 933\ \mathrm{cm}^{-3}\ \mathrm{pc} \left[z + (0.5 - 0.75 \Omega_m) z^2 \right] \\
& \times \left(\frac{f_e}{0.88}\right) \left(\frac{\Omega_b h^2}{0.022}\right) \left(\frac{h}{0.7}\right)^{-1}, \qquad (7)
\end{aligned}
$$

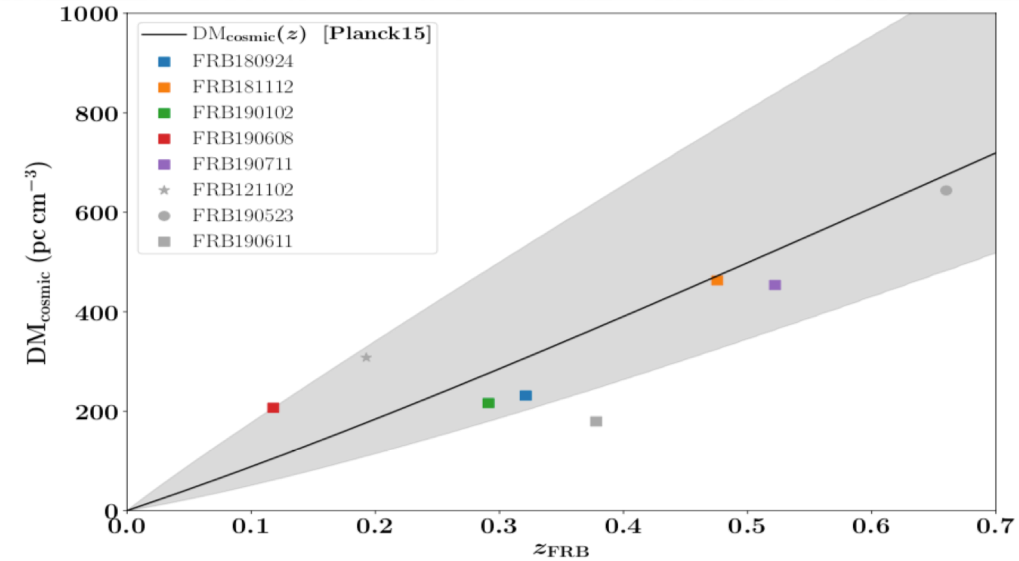
which has a 5% accuracy up to $z = 0.6$. For a constant f_e,

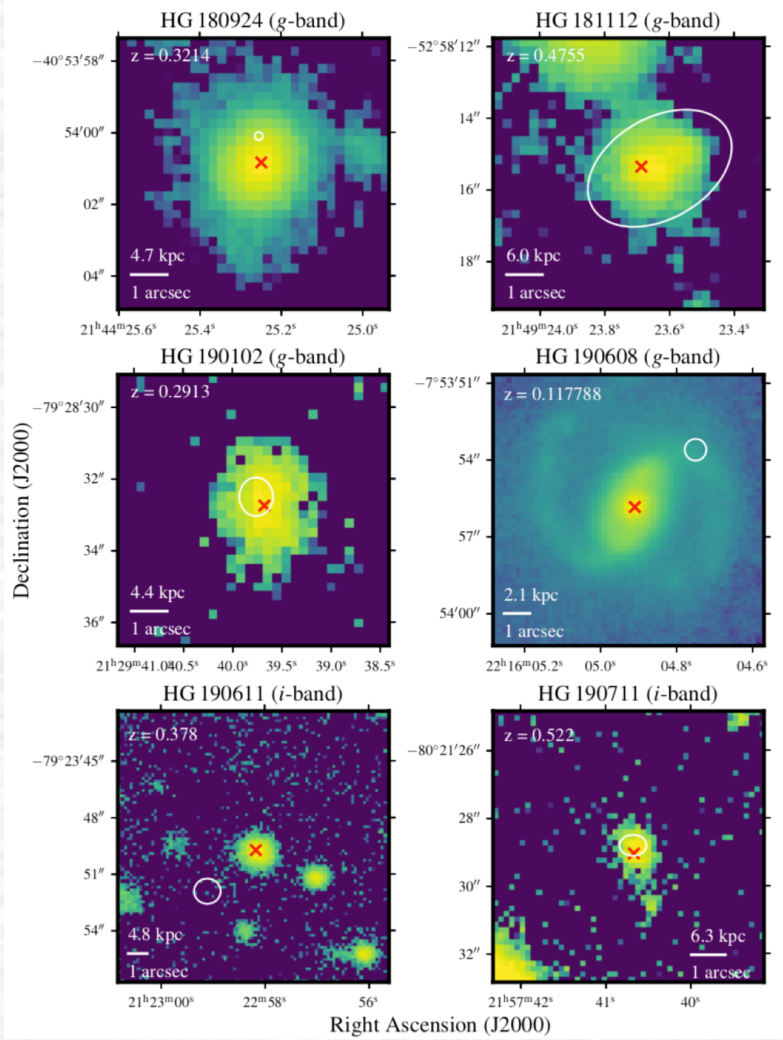
[Zheng et al. 2014]

A lot of physics, astrophysics and cosmology ...

A direct measurement of the baryons in the Universe

[Mcquart et al 2019]





[Mcquart et al 2019, ASKAP localized sample]

The FRB determination confirms the presence of baryons at the density estimated from the Cosmic Microwave Background and Big Bang Nucleosynthesis

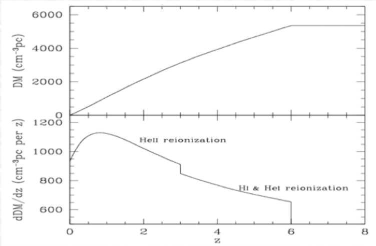
Consistent with all the apparently missing baryons being present in the ionized intergalactic medium

A <u>direct</u> determination of the baryon density $\Omega_b = 0.051^{+0.021}_{-0.025}\, h_{70}$ (95% c.l.)

Additional experiments with independent z

✧ With a series of **independent** z **determinations** (from the identification of the source at other wavelengths), one could

- **probe the era of Helium re-ionization at $z \approx 3$** when SKA will be in place
  [Deng & Zheng e2014] [Caleb et al 2018] [Linder 2020] [Bhattacharya, Kumar & Linder 2020]



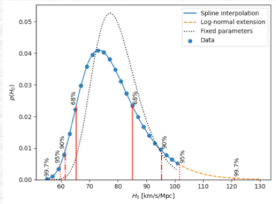
[Zheng et al. 2014]

- **constrain the EoS of the "dark energy"**
  [Gao et al 2014] [Zhou et al 2014]
- **3D clustering of the electrons in the Universe**
  [Masui & Sigurdson 2015]
- **put constraints to post-Newtonian parameters (γ_{PPN}) and equivalence principle**
  [Wei et al 2015] [Wang and Zhang et al 2020][Gao, Zenghxiang, Gao 2022]
- **put limits to the existence of floating MACHO-like objects** in the IGM via gravitational lensing (better with > 5 GHz observations) [Zheng et al. 2014]
- **put limits to the fraction of "dark matter" in MACHO of >20M$_\odot$** via counting the numbe of echoes due to gravitational lensing [Munoz et al 2016]

- **probe the intergalactic magnetic field**
  [Hackstein, Brüggen, Vazza, Rodrigues 2020] [Pandhi et al 2022]
- **probe the Galactic magnetic field**
  [Pandhi et al 2022]
- **measuring baryonic feedback process in the galaxies**
  [Ravi 2019]
- **measuring magnetization and density in the galaxy halo**
  [Prohaska et al 2019]
- **Sunyaev-Zeldovich in galaxy clusters to constrain growth rate of density fluctuatior**
  [Madhavacheril et al 2019]
- **put limits on "dark energy" evolution** via strong lensing of rFRBs
  [Liu et al 2019]
- **measuring the Hubble constant and cosmic curvature** via strong lensing of rFRBs
  [Li et al 2018] [Wu, Yu &Wang 2020] [Jaroszinsky 2019]
- **exploring the epoch of reionization of H** via He reionization constraints from FRBs
  [Beniamini et al 2021]

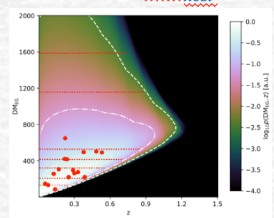
- **measuring the Hubble constant and cosmic curvature** z vs DM relation for ASKAP FRBs
  [James et al 2022]

$H_0 = 73^{+12}_{-8}$ km/s/Mpc



[James et al 2022]

median intrinsic $DM_{host} = 186^{+56}_{-48}$ pc/cm^3

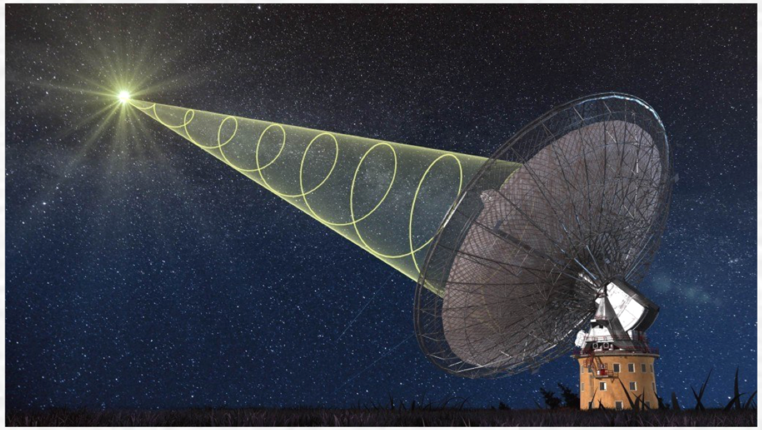


[James et al 2022]

- **revealing Dark Matter Dress of Primordial Black Holes** via FRB lensing
  [Oguri et al 2022][Connor & Ravi 2022][Leung et al 2022]
- **measuring the Hubble constant and cosmic curvature** z vs DM relation for ASKAP FRBs
  [James et al 2022]
- **photon mass upper limit**
  [Chang et al 2022]
- **constraints on tension of cosmic string** via lensed FRBs
  [Xiao, Dai, & McQuinn 2022]

Some major mysteries ...

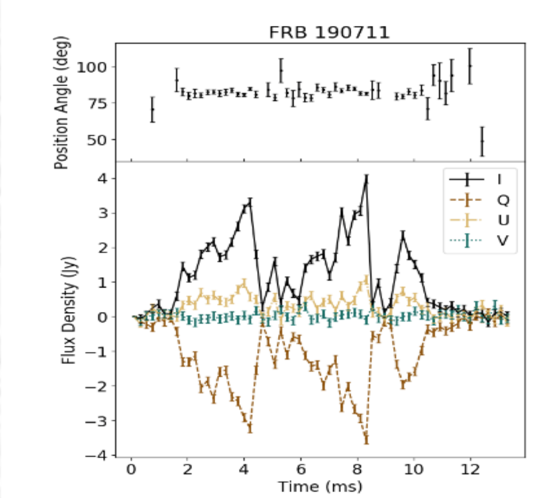
1 A tale of two (or more) culprits ?

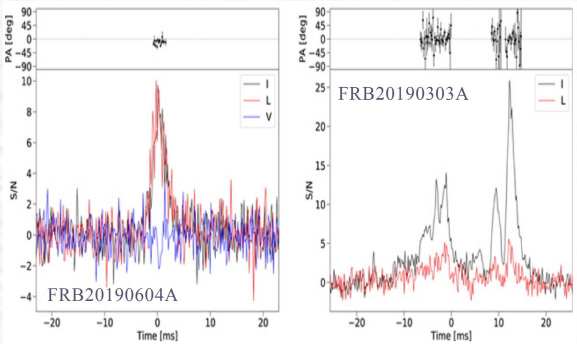


… commonalities/comparisons one-off vs repeaters

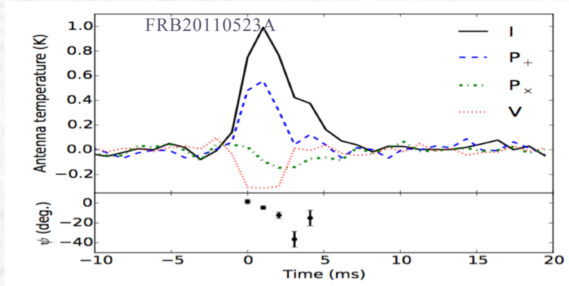
In general, **rFRB show a flattish PA curve,** whereas one-off events seem favoring PA variations along the pulse

[Day et al 2020]





[Fonseca et al. 2020]

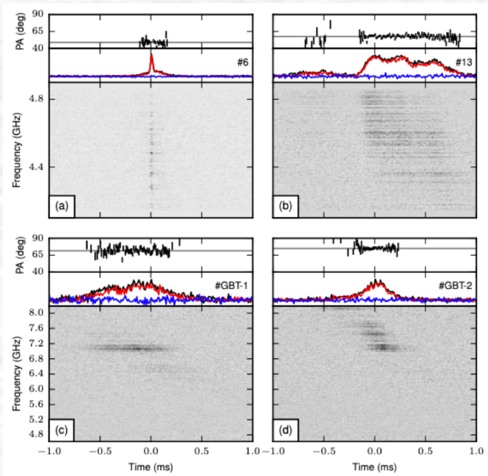


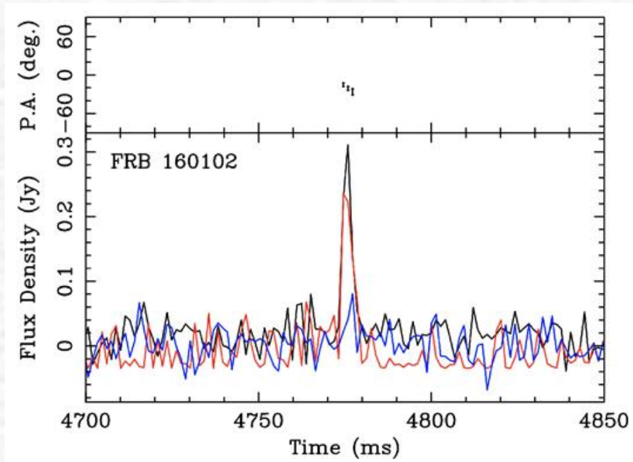
[Masui et al. 2016]

rFRB

One-off

[Michilli et al. 2018]



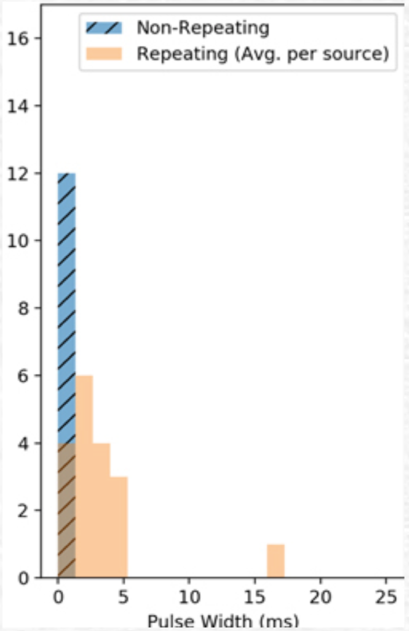


[Caleb et al. 2018]

An exception among the rFRB is 20180301A, displaying a diversity of PA swings [Luo et al. 2020]

Also, **rFRBs** (in particular the best studied FRBs 20121102A and 20180916B) tend to **show a ~100% linear polarization** and ~ **0% circular** polarization, but FRB20201124A is an exception with circular pol up to 75% [Xu et al 2022]

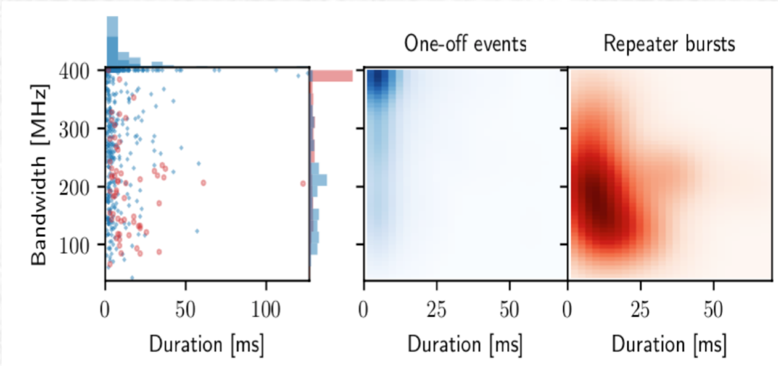
… commonalities/comparisons one-off vs repeaters



Bimodal distribution of pulse widths in the CHIME sample: as a population **rFRB show a wider pulse width**

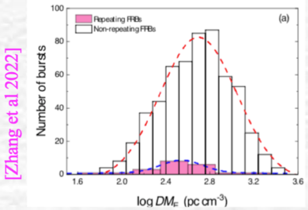
[Fonseca et al 20]

[Caleb & Keane 21] [credit:Ziggy Pleunis]



rFRBs in the CHIME sample on average **emit in narrower spectral bands** compared to non-repeaters

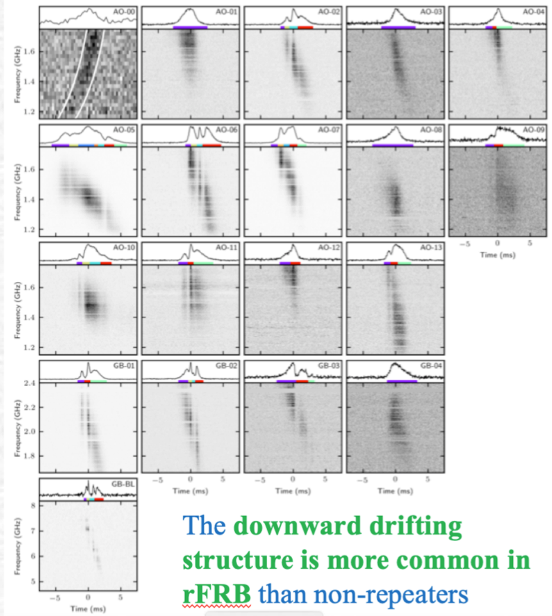
[Zhang et al 2022]



DM_E is not compatible with being drawn from the same population: log-normal with peaks at ~350 pc/cm^3 and ~500 pc/cm^3 respectively

This reflects into **a lower average energy** (~2 × 10^{38} erg) **for the rFRB** than for the one-off

[Pilia 21] [credit:Jason Hessels et al 19]



The **downward drifting structure is more common in rFRB** than non-repeaters

The adopted luminosity function is usually a **Schechter function**: i.e. power-law + smooth exp cutoff

$$\Phi(L)dL \propto \left(\frac{L}{L_*}\right)^{+\alpha} e^{-\left(\frac{L}{L_*}\right)} dL$$

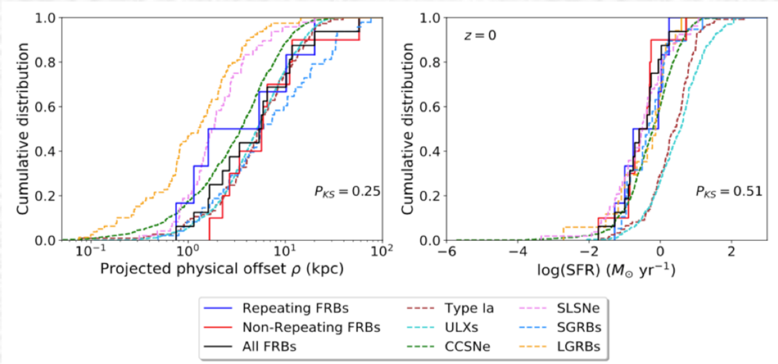
with best fit values for the entire population:

α ~ -1.8 [Luo et al 2020] α ~ -1.3 [Shin et al 2022]

L_* ~ 3 × 10^{44} erg/s E_* ~ 2 × 10^{41} erg

[Nicastro, Guidorzi et al 21 for a review]

The host galaxies of FRBs are seen to range from from starburst to nearly quiescent.
High spatial resolution images show most FRBs to be located in the arms of these galaxies



[credit: Shivani Bandhari]

* Location **OK** with short Gamma-ray bursts, core-collapse supernovae, and Type Ia SNae

* Star Formation Rate **NOT-OK** with hosts of ULX and Type Ia SNae

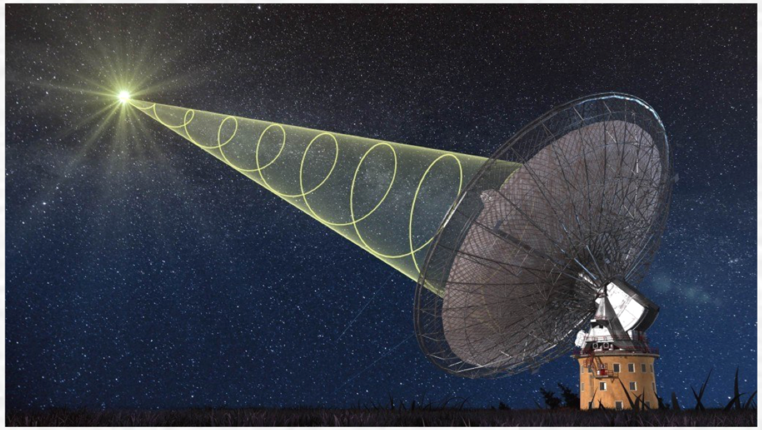
No indication of differences in the host galaxies of rFRBs and one-off FRBs [Li et al 20]

Instructive case of FRB20171019A discovered at ASKAP at 1400 MHz. Then never seen to repeat at ASKAP and Parkes for 500 hrs on sky. Two additional bursts were seen at GBT at 800 MHz (530 time fainter at the same frequency) and one burst at CHIME at 700 MHz [Patek & CHIME 19]

Inconclusive answer so far

Some major suspects ...

2 **Which underlying source ?**



A partial list of suspects… *up to 2019 more models than sources*

See La Placa's talk

[Platts et al 19]

A living version of the following tabular summary can be found at http://frbtheorycat.org.

	Progenitor	Mechanism	Emission	Counterparts	Type	References
Merger	NS–NS	Mag. brak.	—	GW, sGRB, afterglow, X-rays, kilonovae	Single	Totani (2013)
		Mag. recon.	Curv.		Both	Wang et al. (2016)
		Mag. flux	—		Both	Dokuchaev and Eroshenko (2017)
	NS–SN	Mag. recon.	—	None	Single	Egorov and Postnov (2009)
	NS–WD	Mag. recon.	Curv.	—	Repeat	Gu et al. (2016)
		Mag. recon.	Curv.	—	Single	Liu (2018)
	WD–WD	Mag. recon.	Curv.	X-rays, SN	Single	Kashiyama et al. (2013)
	WD–BH	Maser	Synch.	X-rays	Single	Li et al. (2018a)
	NS–BH	BH battery	—	GWs, X-rays, γ-rays	Single	Mingarelli et al. (2015)
	Pulsar–BH	—	—	GWs	Single	Bhattacharyya (2017)
	KNBH–BH (Inspiral)	Mag. flux	Curv.	GWs, sGRB, radio afterglow	Single	Zhang (2016a)
	KNBH–BH (Magneto.)	Mag. recon.	Curv.	GW, γ-rays, afterglow	Single	Liu et al. (2016)
Collapse	NS to KNBH	Mag. recon.	Curv.	GW, X-ray afterglow & GRB	Single	Falcke and Rezzolla (2014) Punsly and Bini (2016) Zhang (2014)
	NS to SS	β-decay	Synch.	GW, X- & γ-ray	Single	Shand et al. (2016)
	NS to BH	Mag. recon.	Curv.	GW	Single	Fuller and Ott (2015)
	SS Crust	Mag. recon.	Curv.	GW	Single	Zhang et al. (2018)
SNR (Pulsar)	Giant Pulses	Various	Synch./ Curv.	—	Repeat	Keane et al. (2012) Cordes and Wasserman (2016) Connor et al. (2016)
	Schwinger Pairs	Schwinger	Curv.	—	Single	Lieu (2017)
	PWN Shock (NS)	—	Synch.	SN, PWN, X-rays	Single	Murase et al. (2016)
	PWN Shock (MWD)	—	Synch.	SN, X-rays	Single	Murase et al. (2016)
SNR (Mag.)	MWN Shock (Single)	Maser	Synch.	GW, sGRB, radio afterglow, high energy γ-rays	Single	Popov and Postnov (2007) Murase et al. (2016) Lyubarsky (2014)
	MWN Shock (Clustered)	Maser	Synch.	GW, GRB, radio afterglow, high energy γ-rays	Repeat	Beloborodov (2017)
AGN	Jet–Caviton	e^- scatter	Bremsst.	X-rays, GRB, radio	Repeat	Romero et al. (2016)
					Single	Vieyro et al. (2017)
	AGN–KNBH	Maser	Synch.	SN, GW, γ-rays, neutrinos	Repeat	Das Gupta and Saini (2017)
	AGN–SS	e^- oscill.	—	Persistent GWs, GW, thermal rad., γ-rays, neutrinos	Repeat	Das Gupta and Saini (2017)
	Wandering Beam	—	Synch.	AGN emission, X-ray/UV	Repeat	Katz (2017b)
Collision/Interaction	NS & Ast./ Comets	Mag. recon.	Curv.	None	Single	Geng and Huang (2015) Huang and Geng (2016)
	NS & Ast. Belt	e^- stripping	Curv.	γ-rays	Repeat	Dai et al. (2016) Bagchi (2017)
	Small Body & Pulsar	Maser	Synch.	None	Repeat	Mottez and Zarka (2014)
	NS & PBH	Mag. recon.	—	GW	Both	Abramowicz et al. (2017)
	Axion Star & NS	e^- oscill.	—	None	Single	Iwazaki (2014, 2015a,b) Raby (2016)
	Axion Star & BH	e^- oscill.	—	None	Repeat	Iwazaki (2017)
	Axion Cluster & NS	Maser	Synch.	—	Single	Tkachev (2015)
	Axion Cloud & BH	Laser	Synch.	GWs	Repeat	Rosa and Kephart (2018)
	AQN & NS	Mag. recon.	Curv.	Below IR	Repeat	van Waerbeke and Zhitnitsky (2018)
Other	Starquakes	Mag. recon.	Curv.	GRB, X-rays	Repeat	Wang et al. (2018)
	Variable Stars	Undulator	Synch.	—	Repeat	Song et al. (2017)
	Pulsar Lightning	Electrostatic	Curv.	—	Repeat	Katz (2017a)
	Wandering Beam	—	—	—	Repeat	Katz (2016a)
	Tiny EM Explosions	Thin shell related	Curv.	Higher freq. radio pulse, γ-rays	Repeat	Thompson (2017b,a)
	WHs	—	—	IR emission, γ-rays	Single	Barrau et al. (2014, 2018)
	NS Combing	Mag. recon.	—	Scenario	Both	Zhang (2017, 2018)
	Neutral Cosmic Strings	Cusp decay	—	GW, neutrinos, cosmic rays, GRBs	Single	Brandenberger et al. (2017)
	Superconducting Cosmic Strings	Cusp decay	—	GW, neutrinos, cosmic rays, GRBs	Single	Costa et al. (2018)
	Galaxy DSR	DSR	Synch.	—	Both	Houde et al. (2018)
	Alien Light Sails	Artificial transmitter	—	—	Repeat	Lingam and Loeb (2017)
Inviable	Stellar Coronae	N/A	N/A	N/A	N/A	Loeb et al. (2014) Maoz et al. (2015)
	Annihilating Mini BHs	N/A	N/A	N/A	N/A	Keane et al. (2012)

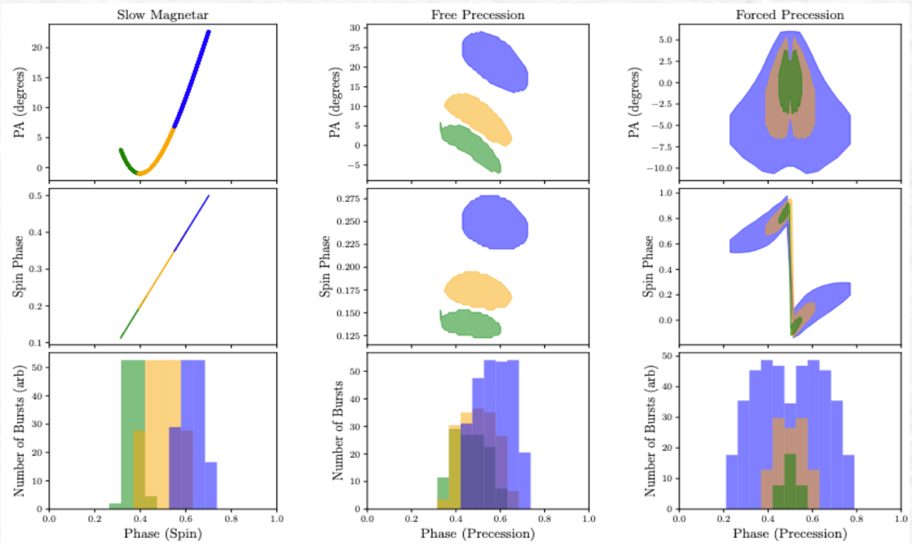
With some recent "tuning" to explain periodicity …

Combination of a magnetar/NS with:

i. orbital periodic model [Ioke & Zhang 2020][Lyutikov et al 2020] [Wang et al 2022][Barkov & Popov 2022]
ii. free precession model [Levin et al 2020][Zanazzi & Lai 2020]
iii. forced precession model [Sob'yanin 2020]
iv. fall-back disk precession model [Tong et al 2020][Katz 2022]
v. NS rotation model [Beniamini et al 2020][Xu t al 2021]
vi. geodetic precession model [Yang & Zou 2020][Wei, Zhao & Wang 2021]

Models can be **constrained** by multiple radio signatures, especially **polarization**…

[Li & Zanazzi 2021]



Chromatic periodicity disfavors forced precession of a magnetar by a companion or fallback disk but is consistent with a slowly rotating magnetar or freely precessing magnetar