Measurement of the luminosity function of Fast Radio Bursts

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Outline

- Background of FRB science
  - Observational features
  - Expanding sample
  - Theoretical models
- Motivations
- Bayesian Framework
  - Likelihood function
- Measurements
  - Event rate density
  - Detection rates
- Summary

Observational Features

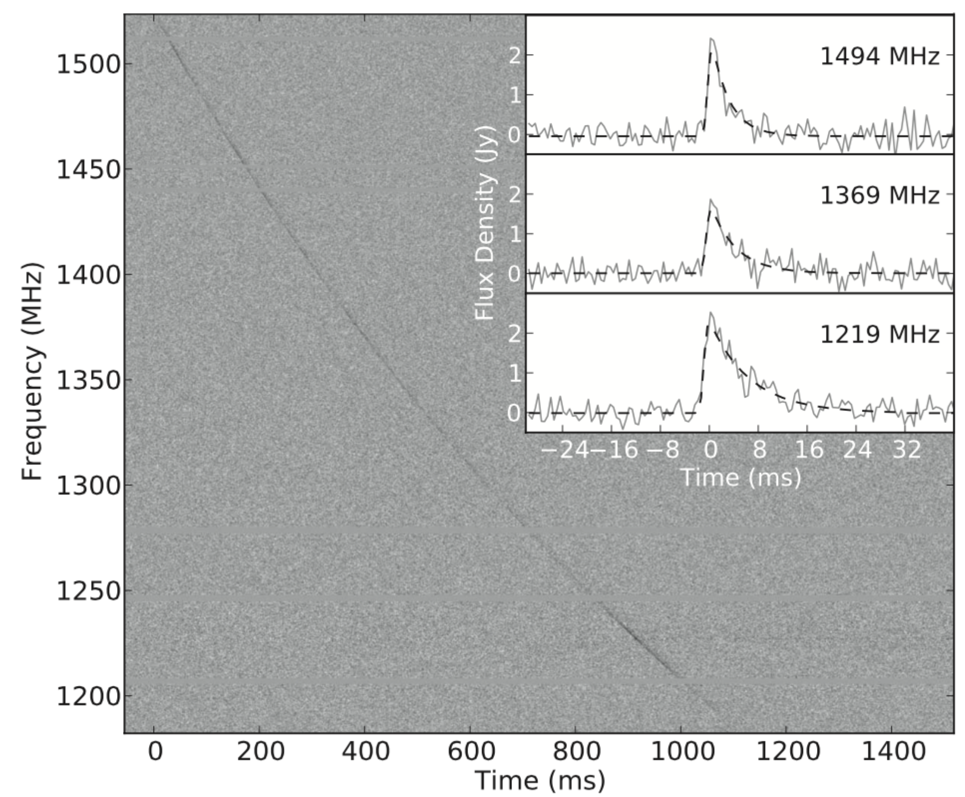
- What are **Fast Radio Bursts**?

short durations (0.1— 20 ms)

observed in radio band (400-800 MHz, L, S, C band)

Transients, prominent flux density (10 mJy — 130 Jy)

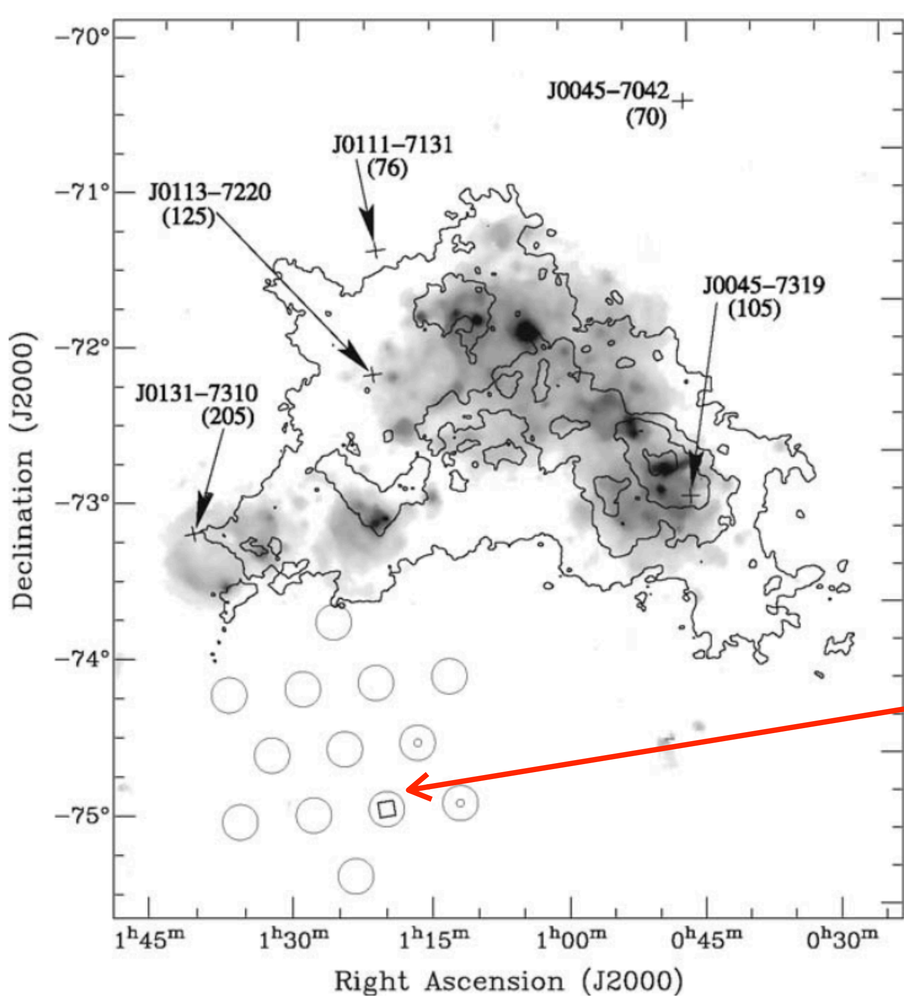
- More important features:
  - **highly-dispersed single pulse**
  - scattering and scintillation
  - polarization and Faraday rotation
  - repeatable: FRB 121102, FRB 180814.J0422+73 and **else**?



FRB 110220 (Thornton et al. 2013)

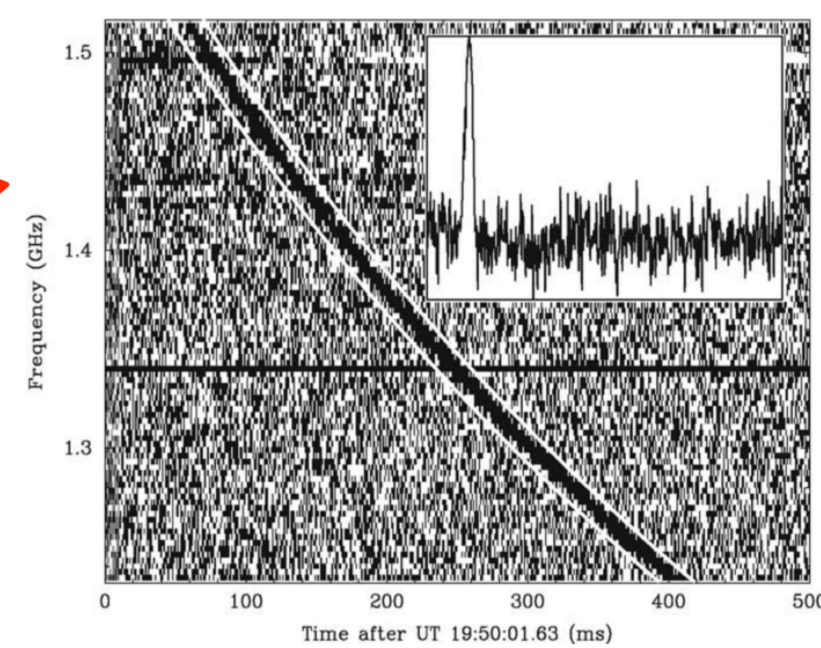
The 1st FRB

- “Lorimer” Burst, found in archival data of Parkes Pulsar Survey for SMC



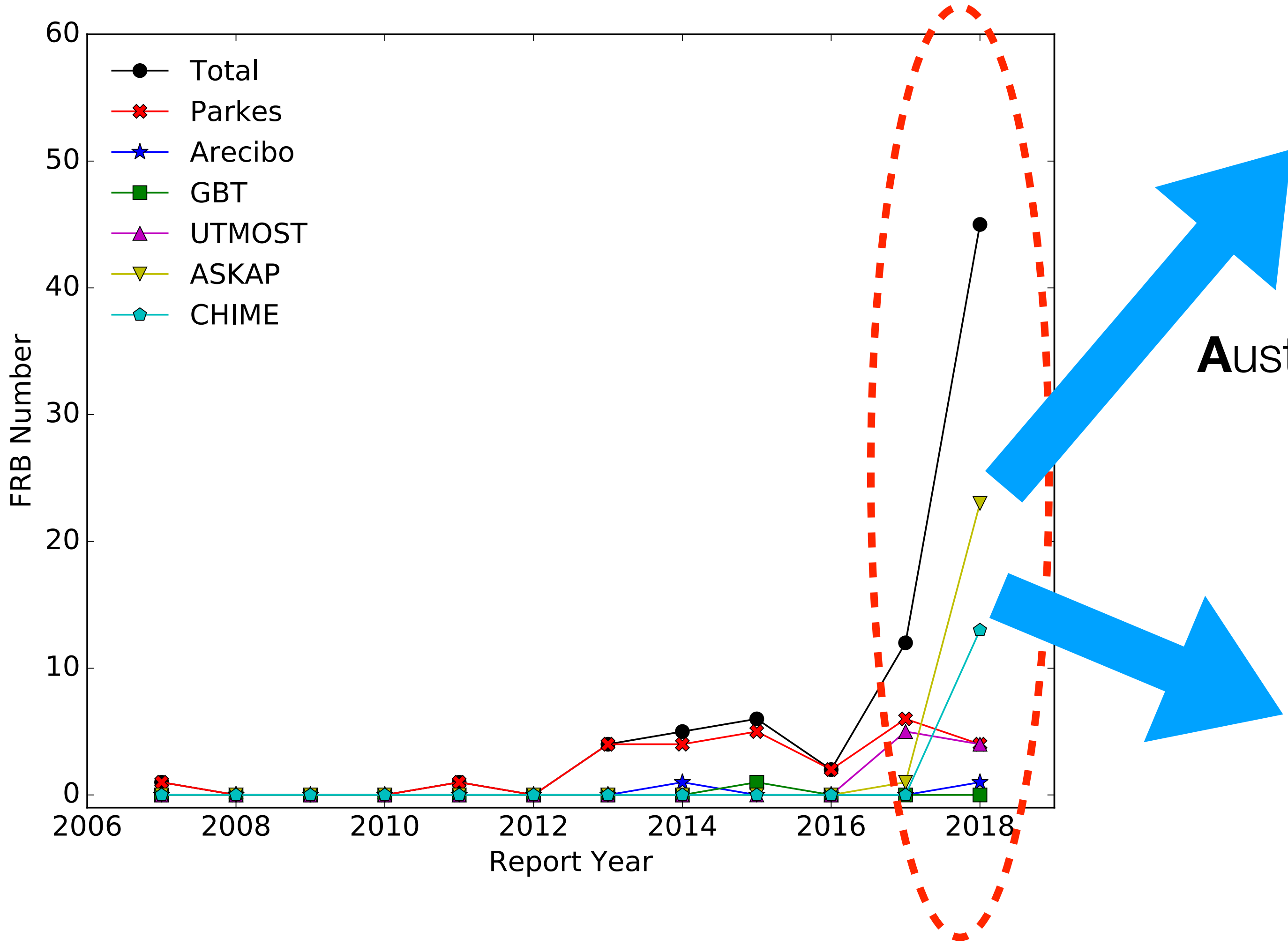
Lorimer et al. 2007

Prof. Duncan Lorimer (WVU)



Expanding sample

- Facilities with large field of view conduct FRB surveys

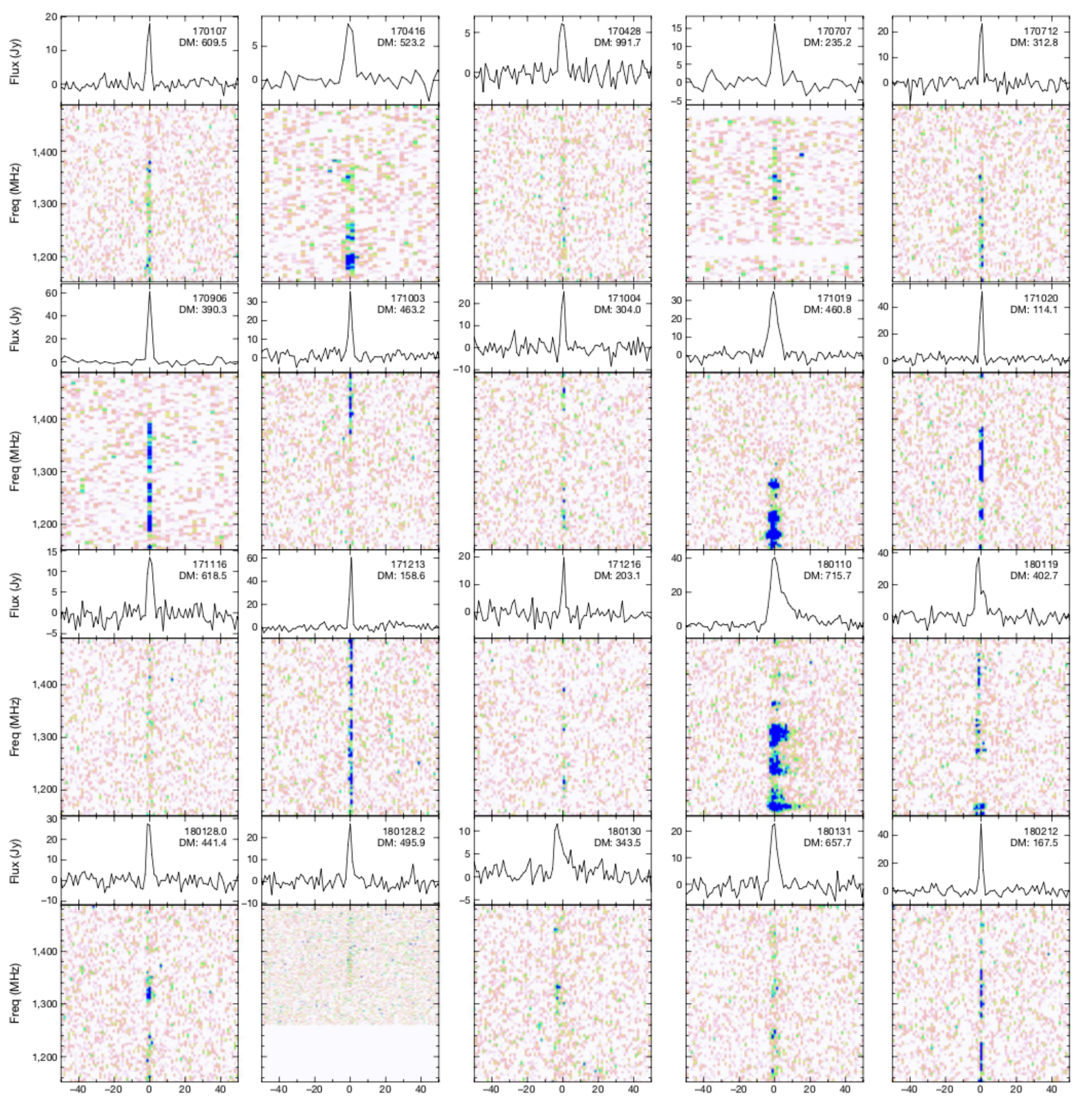


Australian **S**quare **K**ilometer **A**rray **P**athfinder

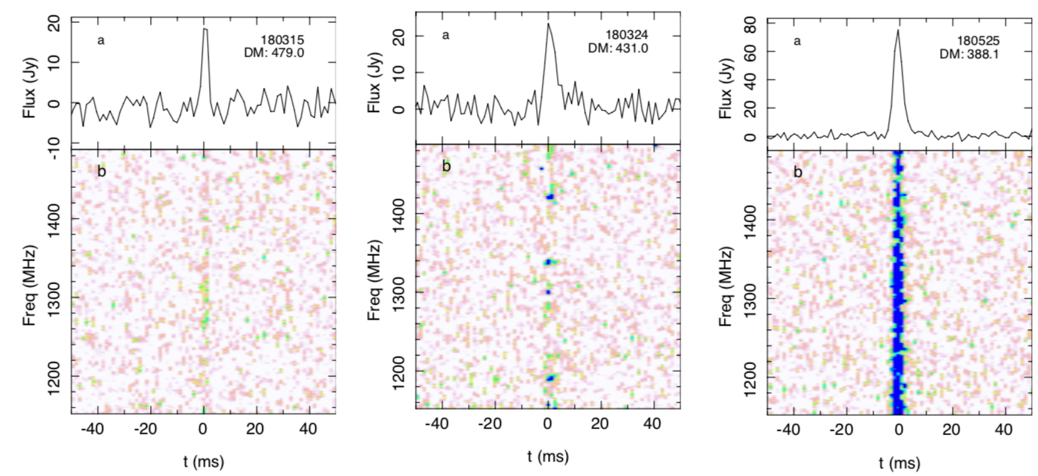
Canadian **H**ydrogen **I**ntensity **M**apping **E**xperiment

ASKAP detections

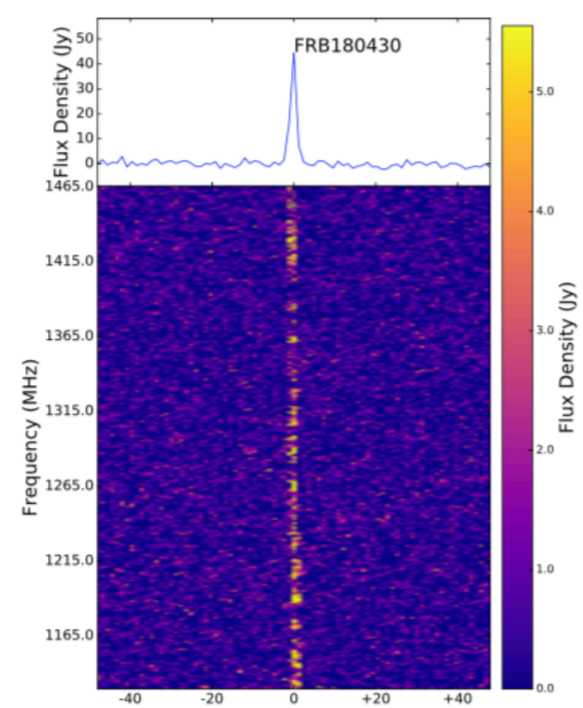
- 24 detections from CRAFT survey



Shannon et al. 2018



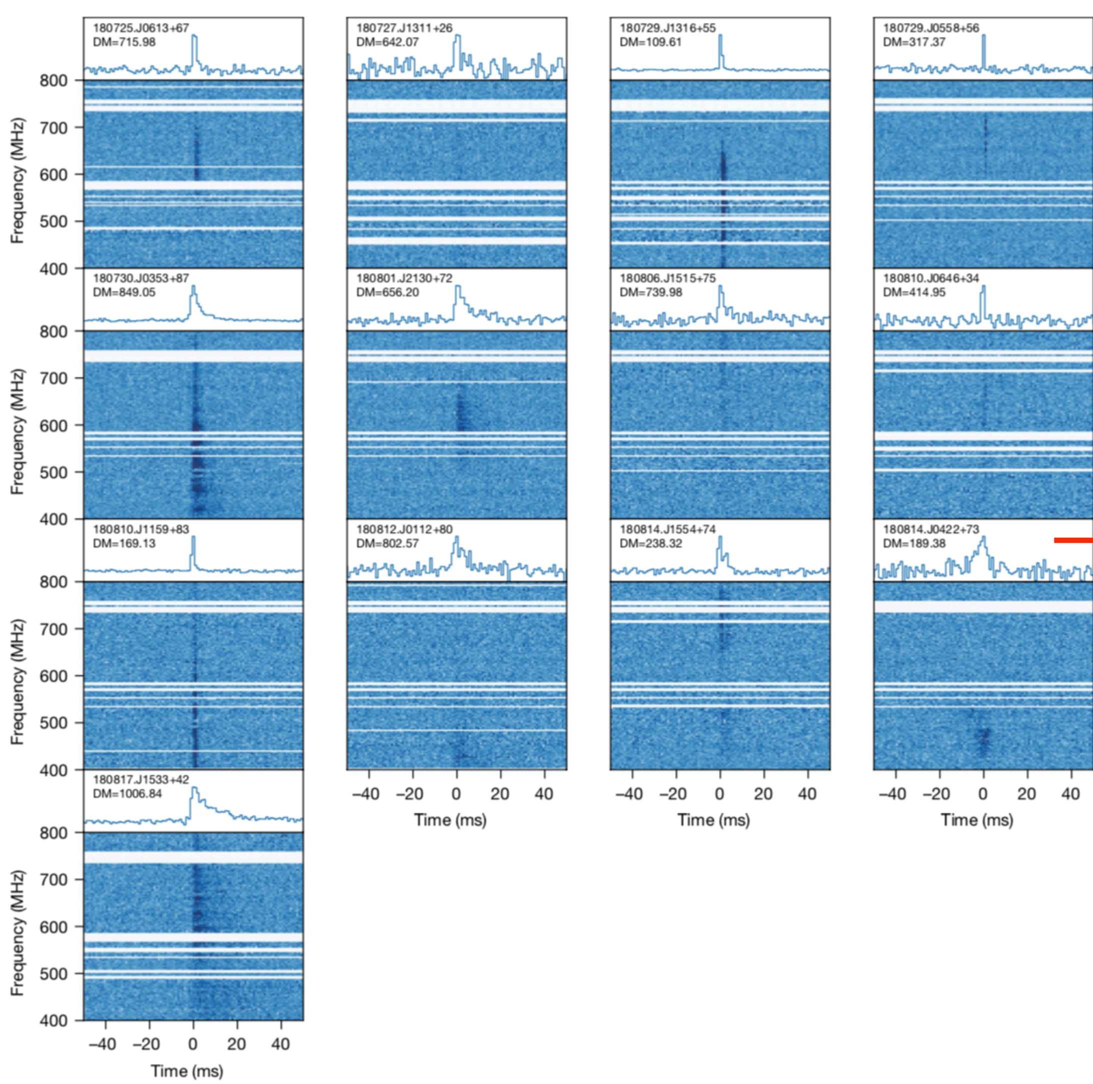
Macquart et al. 2018

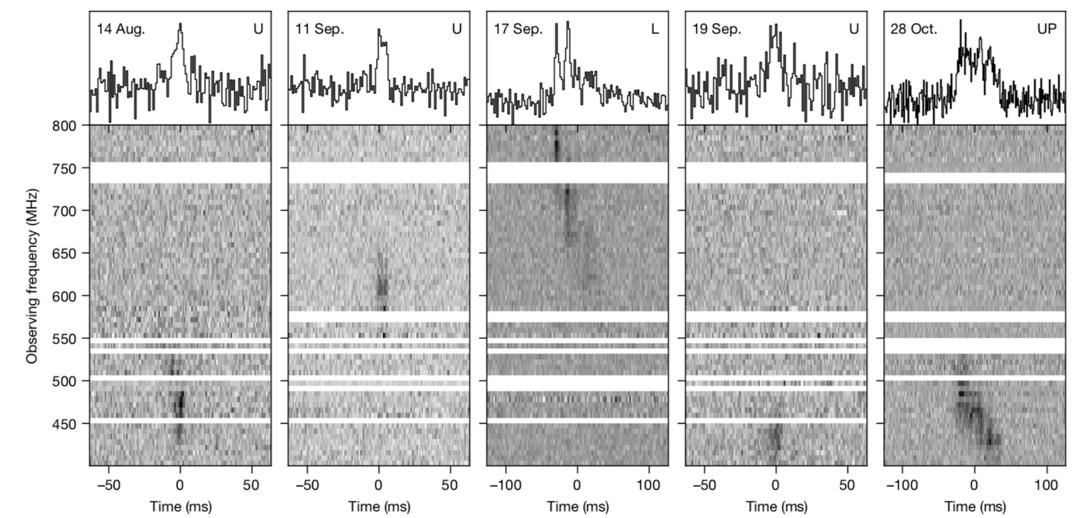


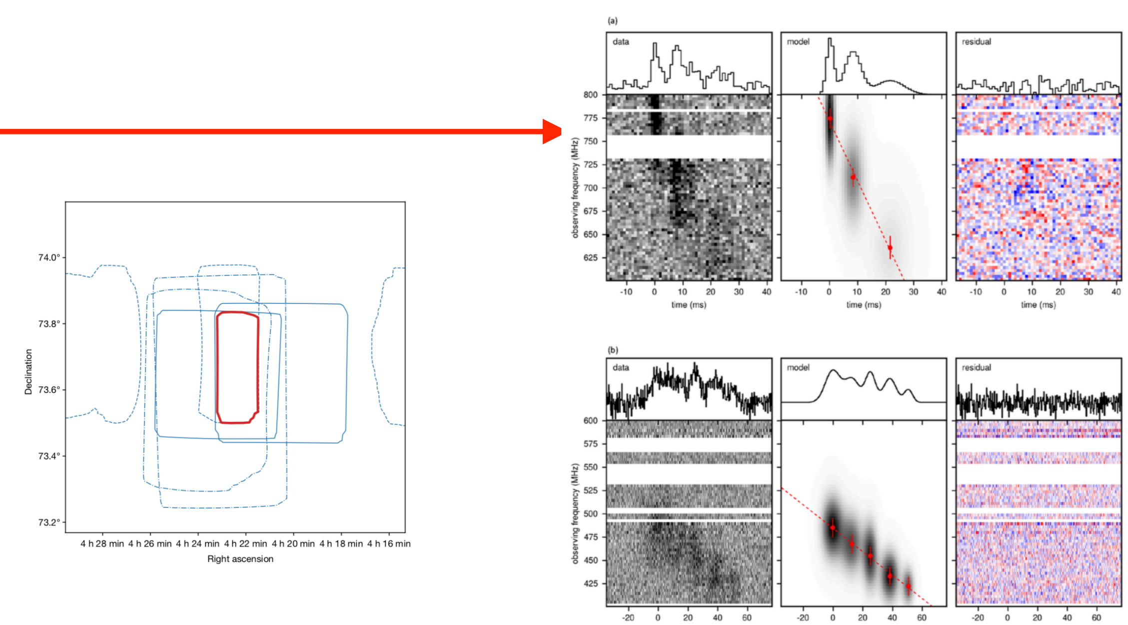
Qiu et al. 2019

CHIME detections

- 13 detections, 2nd repeater was found in commissioning phase.







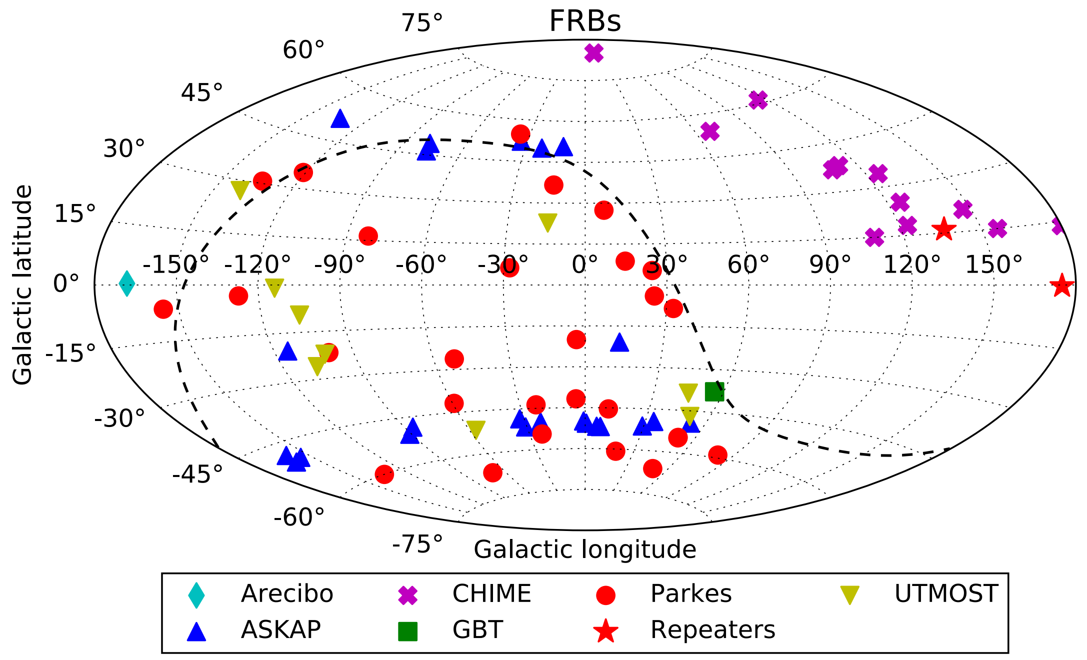
CHIME/FRB collaboration 2019a

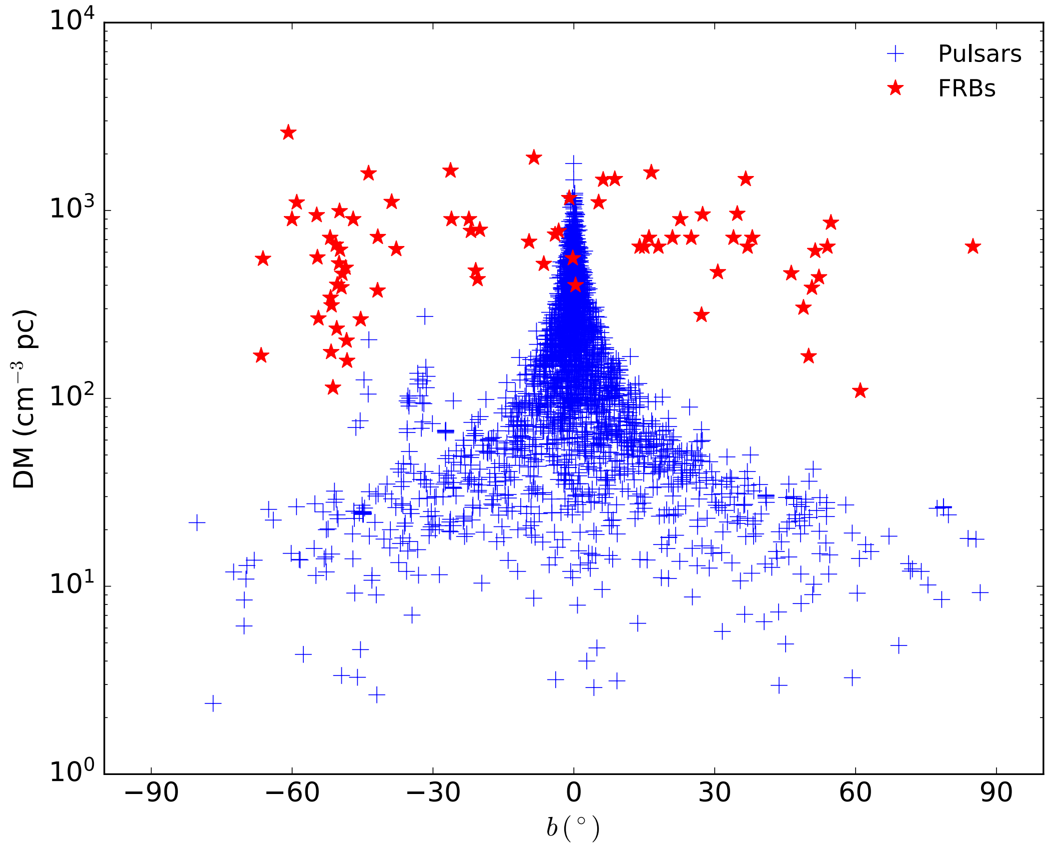
CHIME/FRB collaboration 2019b

Verified FRBs

- 80+ FRBs by Mar. 2019

$$\mathrm{DM} = \int n_e \, \mathrm{d}l$$





Data source: FRB catalog (Petroff et al. 2016) and ATNF pulsar catalog (Manchester et al. 2004)

Theoretical Models

- **Stage I: 2007—2013 (Limited sample)**
    - BH evaporation (Rees 1977)
    - Superconducting cosmic string (Cai et al. 2012a, b; Yu et al. 2014)
    - Magnetar hyper flare (Popov & Postnov 2010, 2013)

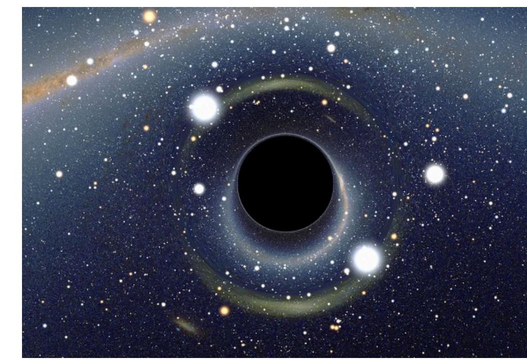
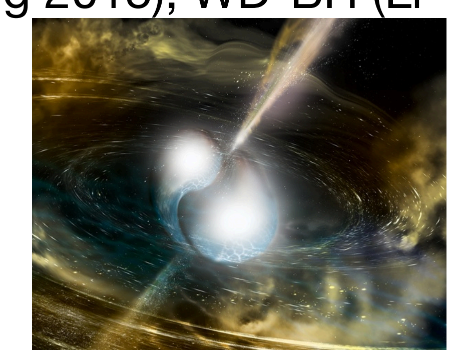


image credit: NASA/LIGO/ESO

- **Stage II: 2013—2016 (Growing sample)**
    - Collapse: NS->BH (Falcke & Rezzolla 2014, Zhang 2014, Fuller & Ott 2015)
    - Mergers: NS-NS (Totani 2013, Wang et al. 2016), WD-WD (Kashiyama et al. 2013), BH-BH (Liu et al. 2016, Zhang 2016), NS-BH (Mingarelli et al. 2015), NS-Asteroids (Geng & Huang 2015), WD-BH (Li et al. 2018)
    - Synchrotron maser (Lyubarsky 2014)



- **Stage III: 2016 — now (Repeater finding)**
    - Supergiant pulses (Cordes & Wasserman 2016, Connor et al. 2016)
    - NS-Asteroids (Dai et al. 2016), NS-WD (Gu et al. 2016)
    - Magnetar (Metzger et al. 2017, Waxman 2017, Beloborodov 2017)
    - Cosmic comb (Zhang 2017)

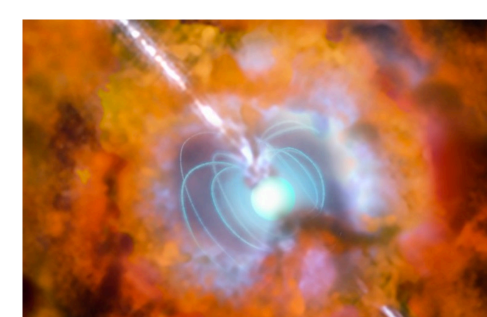
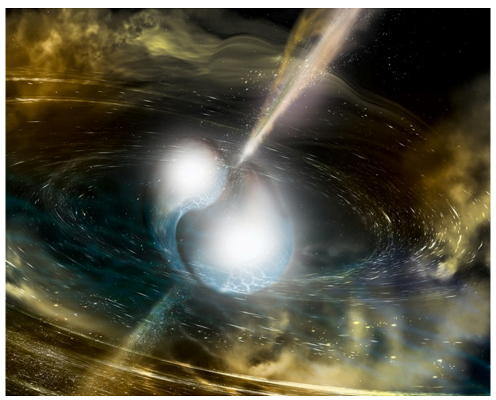
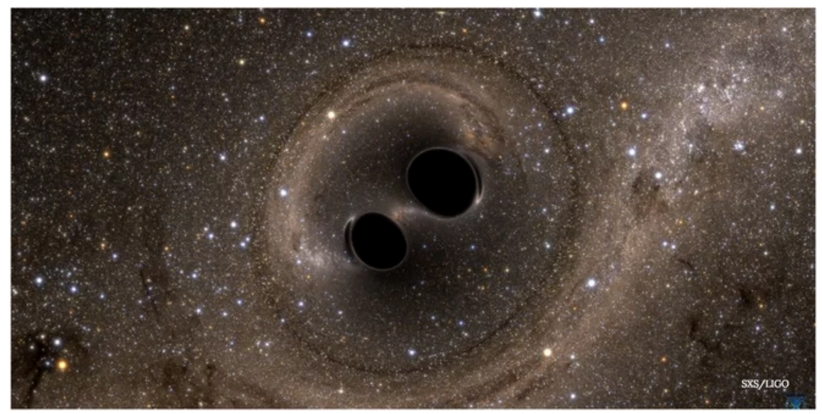


Image: ESO

Motivations

- To reveal the FRB nature





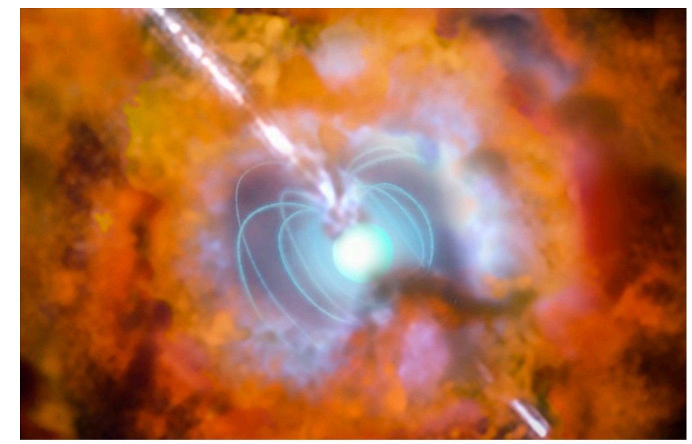


Image: ESO

Image Credits: LIGO/ESO

- To investigate the detection rates of different radio telescopes

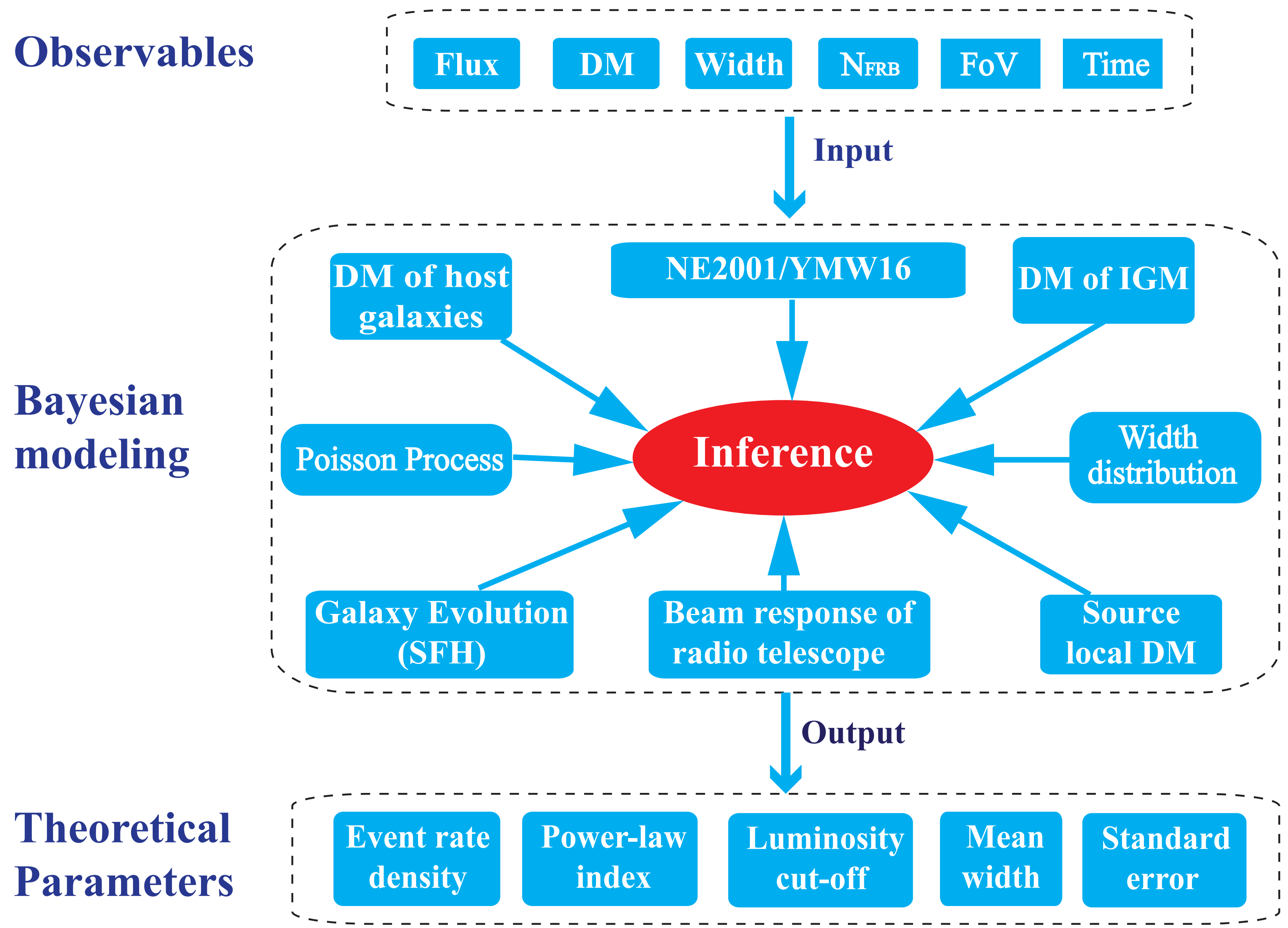
Image Credits: XAO/CSIRO/NRAO/FAST

Bayesian Framework

- Bayes' theorem:

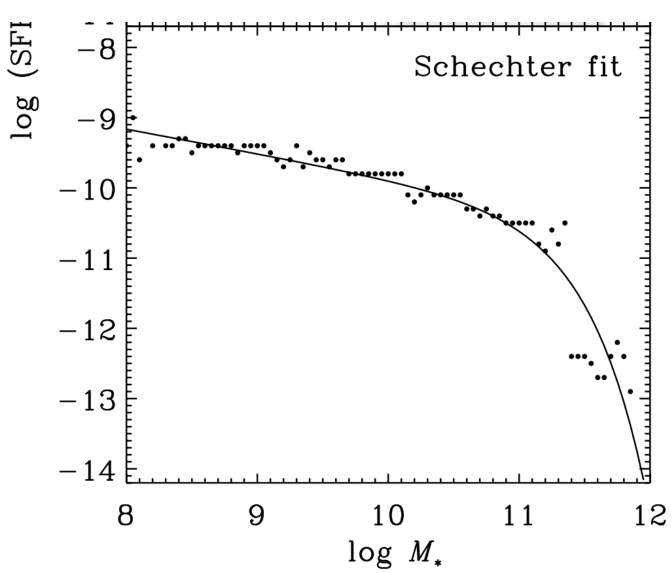
$$\Pr(\Theta \mid D, H) = \frac{\Pr(D \mid \Theta, H)\Pr(\Theta \mid H)}{\Pr(D \mid H)}$$

- The big recipe:



$$\phi(L)\mathrm{d}L = \phi^{*}\left(\frac{L}{L^{*}}\right)^{\alpha}\exp\left(-\frac{L}{L^{*}}\right)\mathrm{d}\left(\frac{L}{L^{*}}\right)$$

ϕ^{*} is the characteristic volumetric rate density in units of Gpc^{-3} yr^{-1}



Bayesian Framework

- The likelihood function

$$\mathcal{L} = f(\mathrm{DM_E}, S, w, N) = \prod_{i=1}^{M} \frac{(\rho_i \Omega_i T_i)^{N_i} e^{-\rho_i \Omega_i T_i}}{N_i!} \prod_{j=1}^{N} f(\log S_j, w_j, \mathrm{DM}_{\mathrm{E},j})$$

Poisson likelihood **Likelihood for normalized LF**

event rate surface density:

$$\rho_i = \frac{\partial N(>S_{\mathrm{min}})}{\partial T_{\mathrm{obs}}\, \partial\Omega} = \int_0^\infty \frac{1}{1+z} \frac{r(z)^2}{H(z)} \mathrm{d}z \int_{L_{\mathrm{min}}(w_o)}^{\infty} \phi(L)\,\mathrm{d}L \int f_\varepsilon(\log\varepsilon)\,\mathrm{d}\log\varepsilon$$

- To normalize the selection biases from different widths of FRBs, we assume intrinsic width distribution follow log-Normal distribution

$$S_{\mathrm{min}} = \frac{S/N_0\, T_{\mathrm{sys}}}{G\sqrt{N_{\mathrm{p}} \mathrm{BW} w_{\mathrm{o}}}} \qquad f_w(\log w_i) \sim \mathcal{N}(\mu_w, \sigma_w)$$

Normalized likelihood

- Likelihood:

$$\mathcal{L} = f(\log S, \mathrm{DM_E}) = \frac{1}{N_\mathrm{f}} \int_0^\infty f(\log S, \mathrm{DM_E}, z)\, \mathrm{d}z$$

$$N_\mathrm{f} = \int_{\log S_\mathrm{min}}^\infty \mathrm{d}\log S \iint f(\log S, \mathrm{DM_E}, z)\, \mathrm{dDM_E}\, \mathrm{d}z$$

Consideration:
Flat spectrum
the width is referenced at
Δν = 1 GHz

- Joint PDFs:

$$f(\log S, \mathrm{DM_E}, z) = \iint f(\log S, \mathrm{DM_E}, z, \mathrm{DM_s}, \log\varepsilon)\, \mathrm{dDM_s}\mathrm{d}\log\varepsilon$$

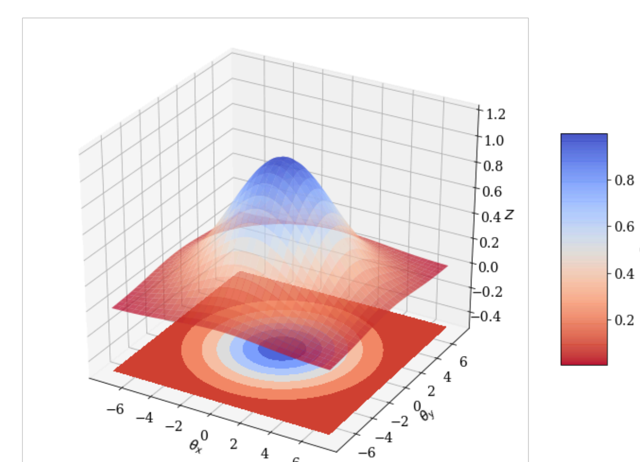
$$f(\log S, \mathrm{DM_E}, z, \mathrm{DM_s}, \log\varepsilon) = \phi(\log L) \cdot f_z(z) \cdot f_{\mathcal{D}}(\mathrm{DM_h}|z) \cdot (1+z) \cdot f_\mathrm{s}(\mathrm{DM_{src}}) \cdot f(\log\varepsilon)$$

$$f_z(z) = \frac{cr(z)^2}{H(z)} \frac{\mathrm{d}r}{\mathrm{d}z}$$

$$f(\mathrm{DM_{src}}) = \begin{cases} \text{const}, & 0 < \mathrm{DM_{src}} \le 50\ \mathrm{cm^{-3}\ pc} \\ 0\ , & \text{other} \end{cases}$$

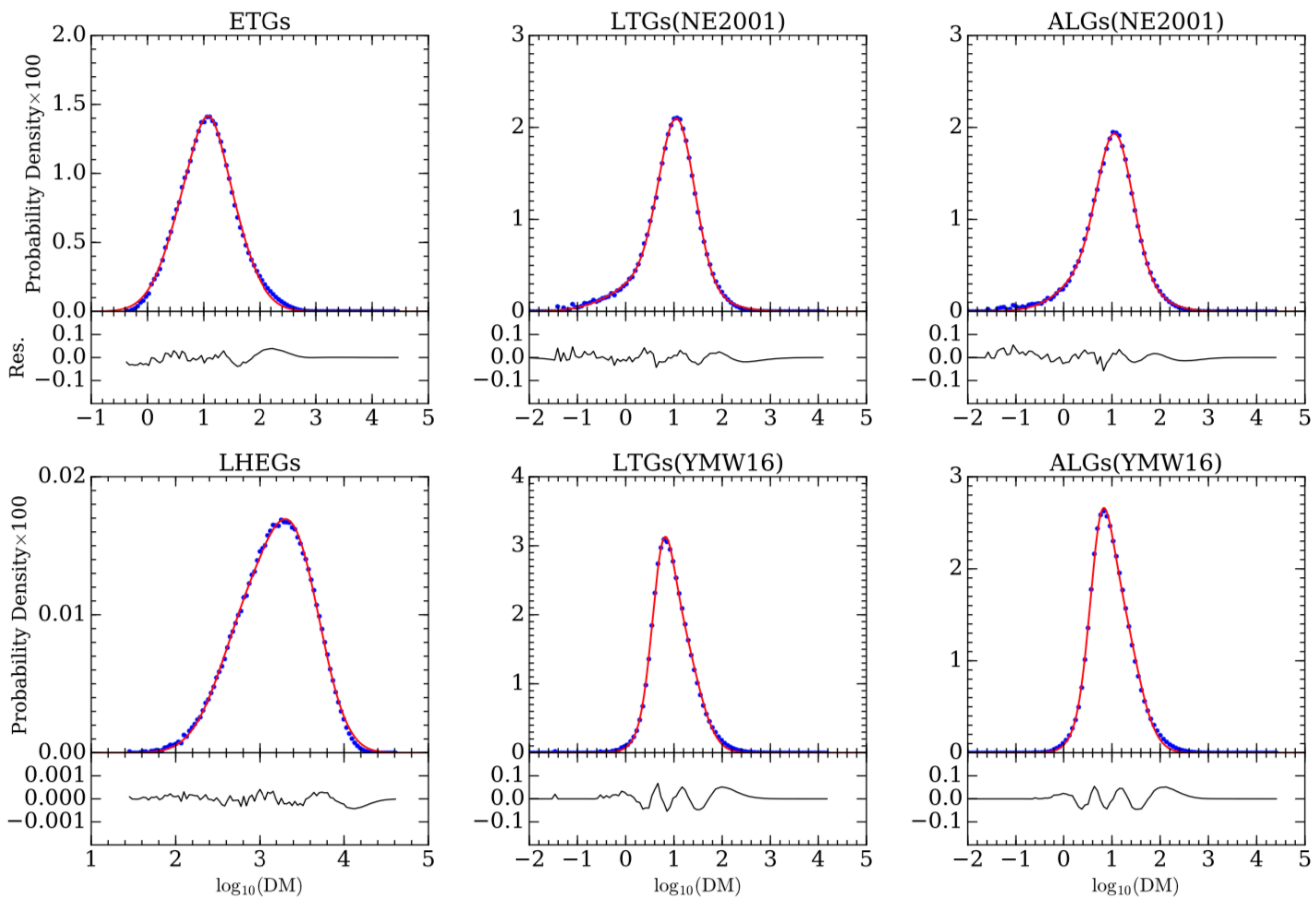
$$\log\varepsilon \propto \theta^2$$

$$f(\log\varepsilon) = \text{const}$$



DM of nearby host galaxies

- DM distribution functions of different types of host galaxies



$$
f_{\mathcal{D}}(\mathrm{DM}_{\mathrm{host}} \,|\, z=0)\, \mathrm{dDM}_{\mathrm{host}} = \sum_{i=1}^{2} a_i \exp\left[-\left(\frac{\log_{10} \mathrm{DM}_{\mathrm{host}} - b_i}{c_i} \right)^2 \right] \mathrm{dDM}_{\mathrm{host}}
$$

Luo et al. 2018

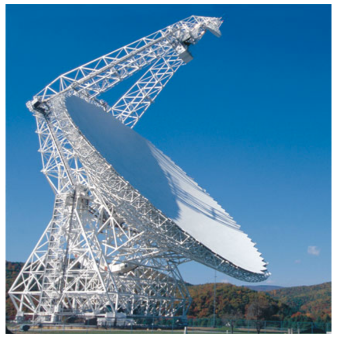
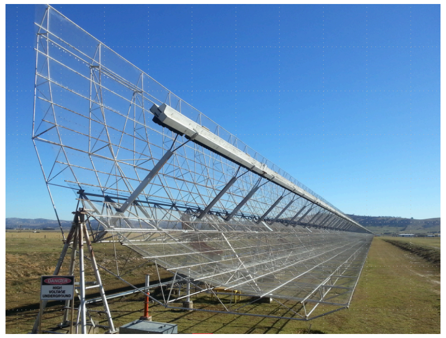
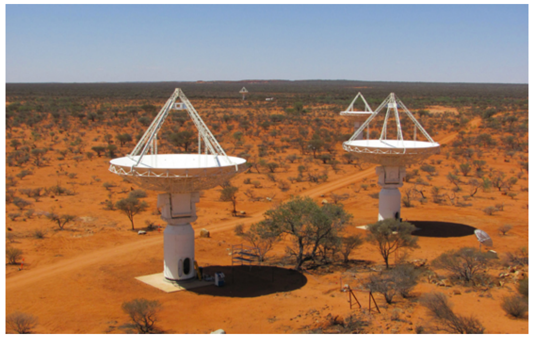
Parameters	ETGs	LTGs(NE2001)	LTGs(YMW16)	ALGs(NE2001)	ALGs(YMW16)	LHEGs
$a_1\,(\times 10^{-3})$	1.713	17.15	15.61	5.485	11.99	0.1241
b_1	1.099	1.062	0.759	0.8665	0.7597	3.441
c_1	0.2965	0.5202	0.3013	1.009	0.3082	0.4407
$a_2\,(\times 10^{-3})$	12.46	4.16	18.89	14.06	17.35	0.09931
b_2	1.055	0.7227	1.042	1.069	1.048	2.906
c_2	0.7262	1.151	0.5791	0.5069	0.6025	0.5317

The sample we use

- 46 FRBs from 7 surveys

Survey	N_{FRB}[a]	Ω[b] deg^2	T[c] hr	G[d] K/Jy	T_{sys}[e] K	BW[f] MHz	S/N_0[g]	N_p[h]	Ref.[i]
PKS-SMC	2	0.556	490.5	0.69	28	288	7	2	[1]
HTRU&SUPERB	19	0.556	7357	0.69	28	338	10	2	[2]
PALFA	1	0.024	11503.3	0.7[j]	30	322	7	2	[1]
GBTIM	1	0.055	660	2.0	25	200	8	2	[3]
UTMOST-SS	3	9	4320	3.0	400	16	10	1	[4]
CRAFT	20	160	3187.5	0.05	100	336	10	2	[5]

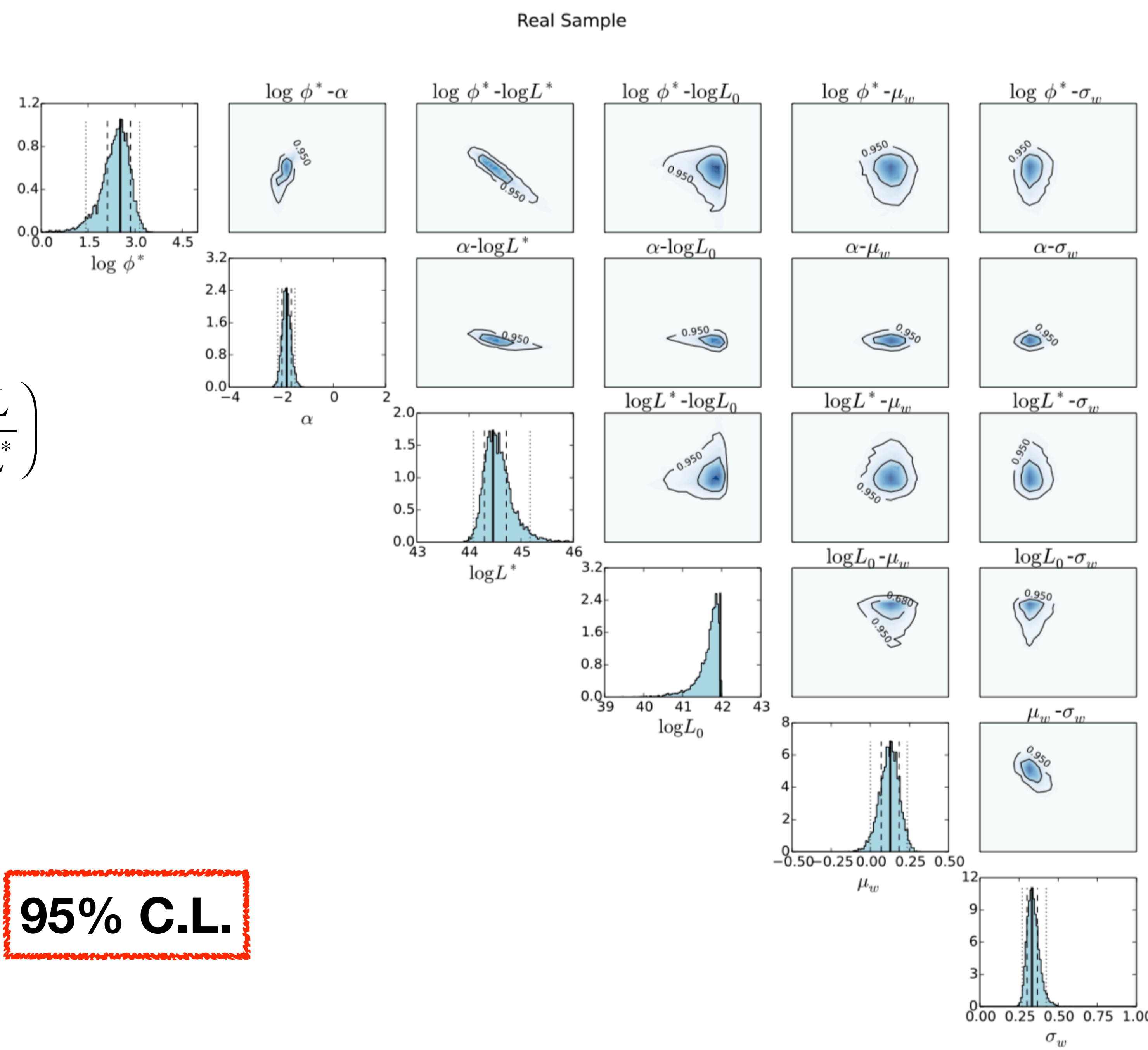


FRB	S_{peak}[a] Jy	w(ms)[b] ms	F[c] Jy ms	DM[d] cm^{-3} pc	DM_{MW}[e] cm^{-3} pc	DM_{MW}[f] cm^{-3} pc	Survey	Reference
010312	0.25	24.30	6.10	1187.0	51.0	67.0	PKS-SMC	[1]
010724	30.00	5.00	150.00	375.0	44.6	94.0	PKS-SMC	[2]
090625	1.14	1.92	2.19	899.5	31.7	25.5	HTRU	[3]
110214	27.00	1.90	54.00	168.8	31.1	21.1	HTRU	[4]
110220	1.30	5.60	7.28	944.4	34.8	24.1	HTRU	[5]
110523	0.60	1.73	1.04	623.3	43.5	33.0	GBTIM	[6]
110626	0.40	1.40	0.56	723.0	47.5	33.6	HTRU	[5]
110703	0.50	4.30	2.15	1103.6	32.3	23.1	HTRU	[5]
120127	0.50	1.10	0.55	553.3	31.8	20.6	HTRU	[5]
121002	0.43	5.44	2.34	1629.2	74.3	60.5	HTRU	[3]
121102	0.40	3.00	1.20	557.0	188.0	287.1	PALFA	[7]
130626	0.74	1.98	1.47	952.4	66.9	65.1	HTRU	[3]
130628	1.91	0.64	1.22	469.9	52.6	47.0	HTRU	[3]
130729	0.22	15.61	3.43	861.0	31.0	25.4	HTRU	[3]
131104	1.12	2.08	2.33	779.0	71.1	220.2	HTRU	[8]
140514	0.47	2.80	1.32	562.7	34.9	24.2	HTRU	[9]
150215	0.70	2.80	1.96	1105.6	427.2	296.4	HTRU	[10]
150418	2.20	0.80	1.76	776.2	188.5	325.5	SUPERB	[11]
150610	0.70	2.00	1.30	1593.9	122.0	122.9	SUPERB	[12]
150807	128.00	0.35	44.80	266.5	36.9	25.1	SUPERB	[13]
151206	0.30	3.00	0.90	1909.8	160.0	161.0	SUPERB	[12]
151230	0.42	4.40	1.90	960.4	38.0	37.8	SUPERB	[12]
160102	0.50	3.40	1.80	2596.1	13.0	21.8	SUPERB	[12]
160317	3.00	21.00	63.00	1165.0	319.6	394.6	UTMOST-SS	[14]
160410	7.00	4.00	28.00	278.0	57.7	56.7	UTMOST-SS	[14]
160608	4.30	9.00	38.70	682.0	238.3	310.3	UTMOST-SS	[14]
170107	22.30	2.60	57.98	609.5	35.0	25.2	CRAFT	[15]
170416	19.40	5.00	97.00	523.2	40.0	27.5	CRAFT	[15]
170428	7.70	4.40	34.00	991.7	40.0	27.4	CRAFT	[15]
170707	14.80	3.50	52.00	235.2	36.0	26.9	CRAFT	[15]
170712	37.80	1.40	53.00	312.8	38.0	26.5	CRAFT	[15]
170906	29.60	2.50	74.00	390.3	39.0	26.6	CRAFT	[15]
171003	40.50	2.00	81.00	463.2	40.0	35.4	CRAFT	[15]
171004	22.00	2.00	44.00	304.0	38.0	33.0	CRAFT	[15]
171019	40.50	5.40	219.00	460.8	37.0	26.3	CRAFT	[15]
171020	117.60	1.70	200.00	114.1	38.0	25.8	CRAFT	[15]
171116	19.60	3.20	63.00	618.5	36.0	37.5	CRAFT	[15]
171213	88.60	1.50	133.00	158.6	36.0	33.8	CRAFT	[15]
171216	21.00	1.90	40.00	203.1	37.0	28.7	CRAFT	[15]
180110	128.10	3.20	420.00	715.7	38.0	26.1	CRAFT	[15]
180119	40.70	2.70	110.00	402.7	36.0	37.9	CRAFT	[15]
180128.0	17.50	2.90	51.00	441.4	32.0	26.6	CRAFT	[15]
180128.2	28.70	2.30	66.00	495.9	40.0	28.3	CRAFT	[15]
180130	23.10	4.10	95.00	343.5	39.0	26.1	CRAFT	[15]
180131	22.20	4.50	100.00	657.7	40.0	26.9	CRAFT	[15]
180212	53.00	1.81	96.00	167.5	33.0	27.8	CRAFT	[15]

Measurements

- Posteriors of LF parameters



$$\phi(L)\mathrm{d}L = \phi^*\left(\frac{L}{L^*}\right)^{\alpha}\exp\left(-\frac{L}{L^*}\right)\mathrm{d}\left(\frac{L}{L^*}\right)$$

$$\phi^* = 339^{+1074}_{-313}\,\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

$$\alpha = -1.79^{+0.31}_{-0.35}$$

$$\log L^* = 44.46^{+0.71}_{-0.38}\ (\mathrm{erg\ s^{-1}})$$

$$\log L_0 \le 41.96\ (\mathrm{erg\ s^{-1}})$$

$$\mu_w = 0.13^{+0.11}_{-0.13}$$

$$\sigma_w = 0.33^{+0.09}_{-0.06}$$

95% C.L.

FRB luminosity function

- LF with 2σ error: event rate distribution

Luo et al. 2019

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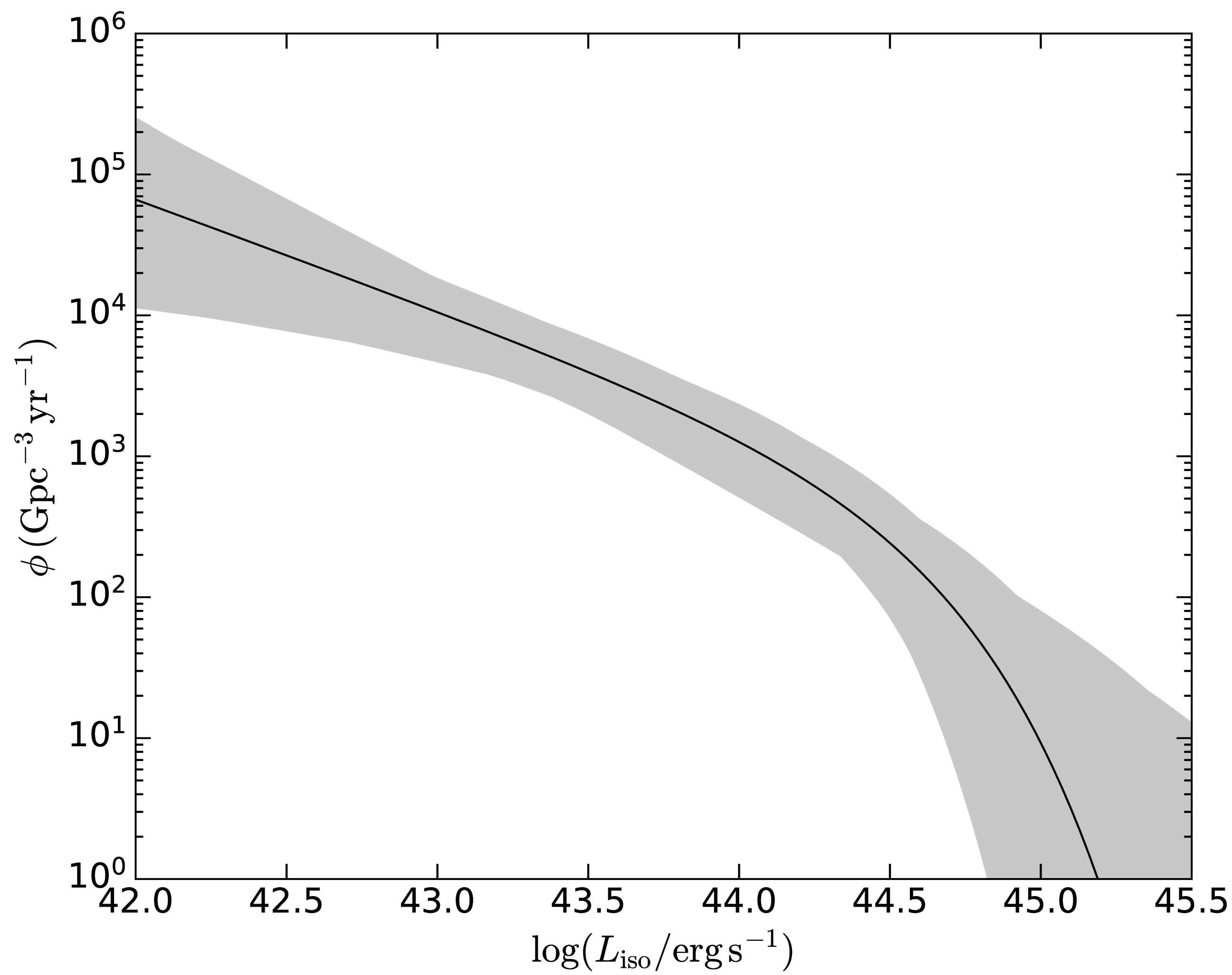
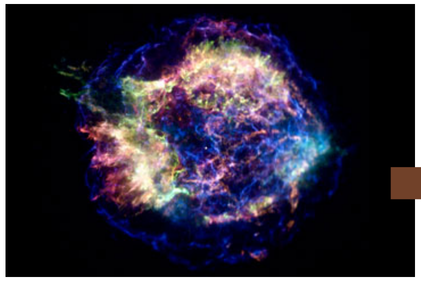


Population

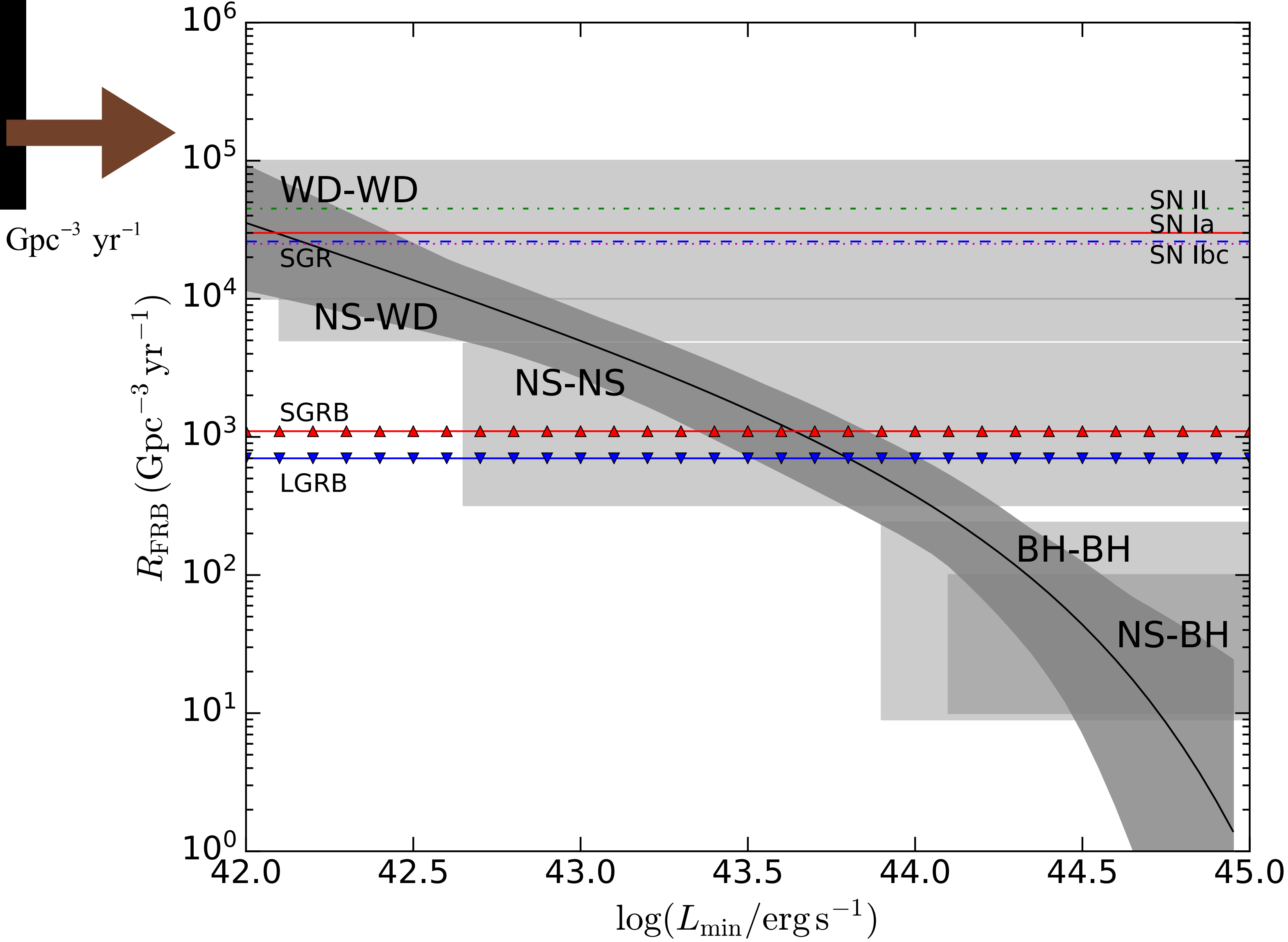
- The cumulative event rate of FRB population

$$R_{\rm FRB} = \phi^* \int_{L_{\rm min}/L^*}^{\infty} \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) {\rm d}\left(\frac{L}{L^*}\right)$$



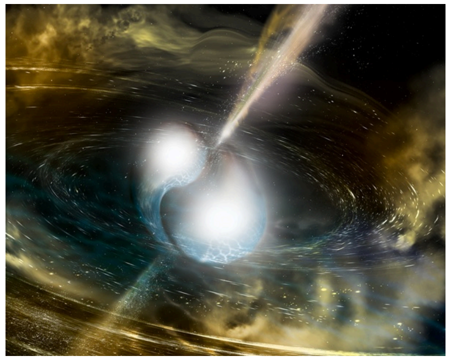
$R_{\rm ccSNe} = 1.06 \pm 0.19 \times 10^5~{\rm Gpc^{-3}~yr^{-1}}$

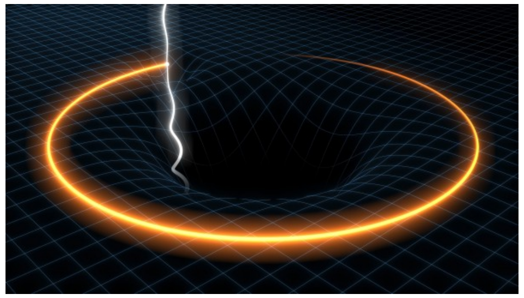
(Taylor et al. 2014)



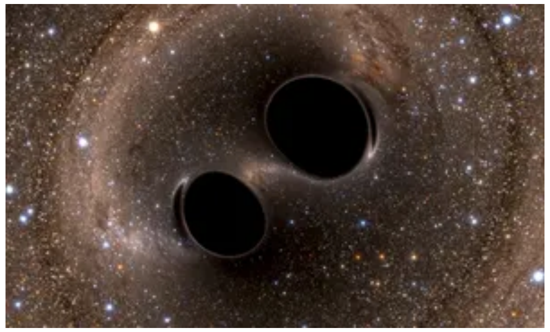
$R_{\rm NS\text{-}NS} = 1540^{+3200}_{-1220}~{\rm Gpc^{-3}~yr^{-1}}$

(GW170817, Abbot et al. 2017)





$R_{\rm NS\text{-}BH} \sim 10-100~{\rm Gpc^{-3}~yr^{-1}}$

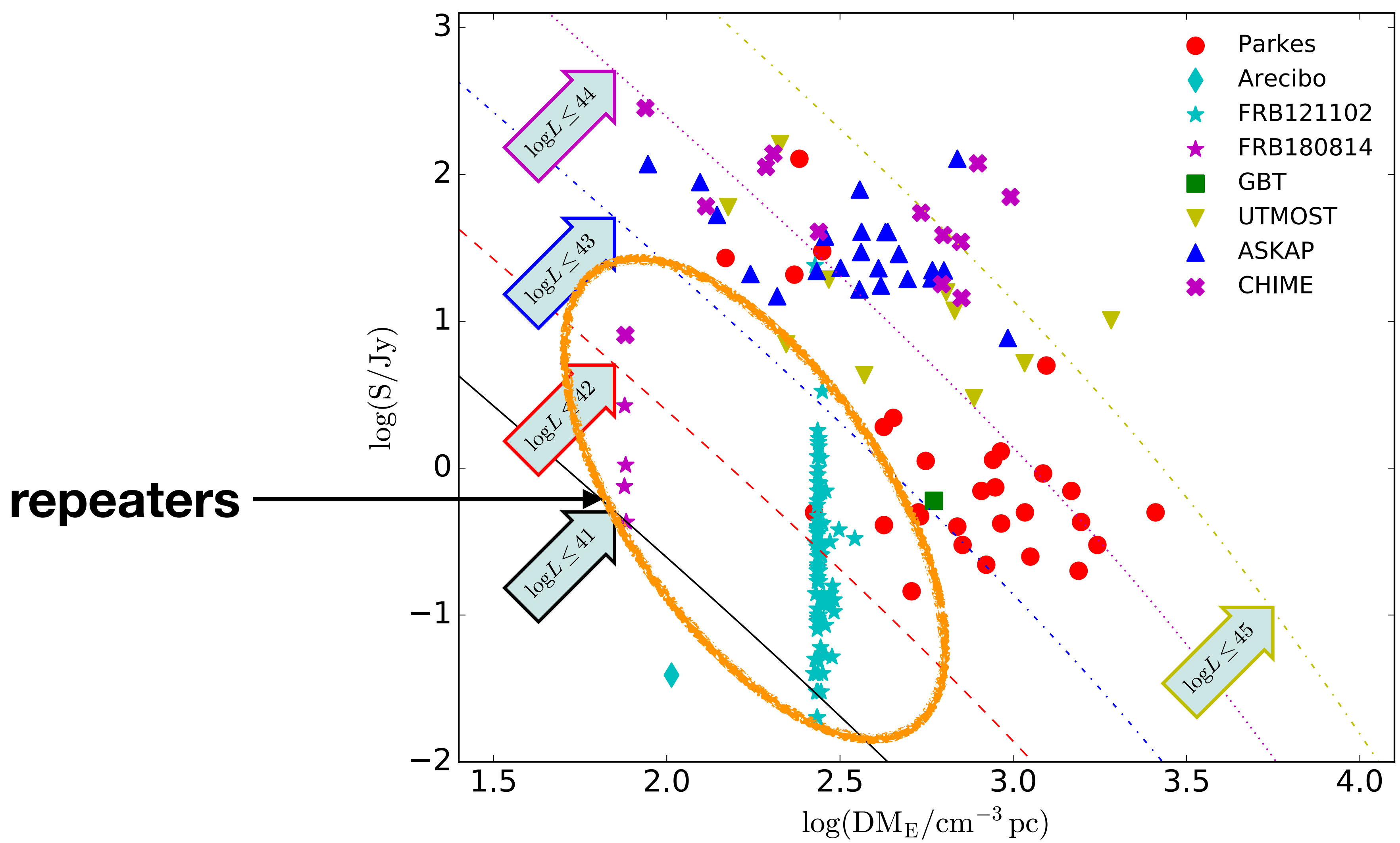


$R_{\rm BH\text{-}BH} = 9-240~{\rm Gpc^{-3}~yr^{-1}}$

(Abbot et al. 2016)

Flux — DM_E relation

- Discussion:
  - The two repeaters are low-luminosity FRBs



Detection rate

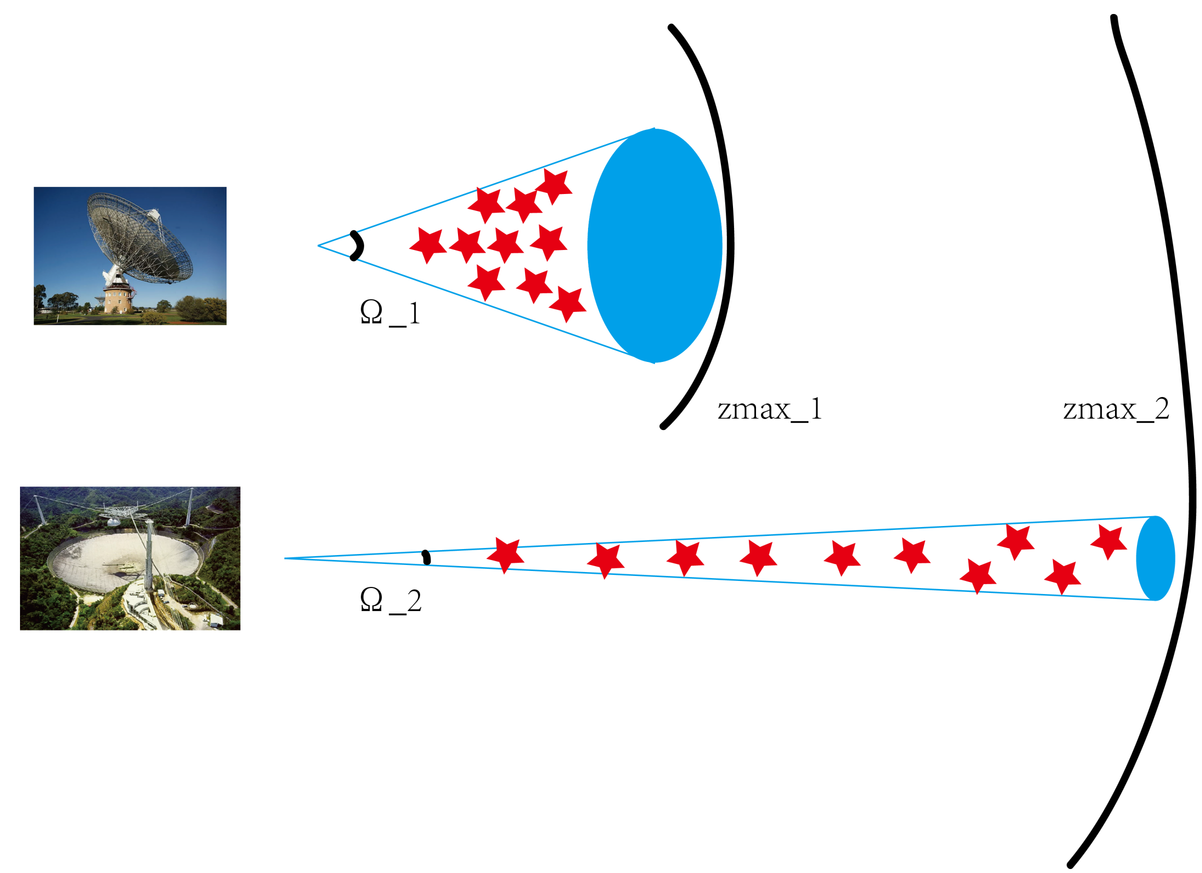
- The detection rate is as function of field of view (Ω) and sensitivity (S_{min})

$$\lambda(\Omega, S_{\min}) = \frac{\mathrm{d}N_{\mathrm{obs}}(>S_{\min})}{\mathrm{d}T_{\mathrm{obs}}}$$

$$= \int_0^{\Omega} \mathrm{d}\Omega \int_0^{\infty} \frac{1}{1+z} \frac{r(z)^2}{H(z)} \mathrm{d}z \int f_w(\log w_i)\, \mathrm{d}\log w_i$$

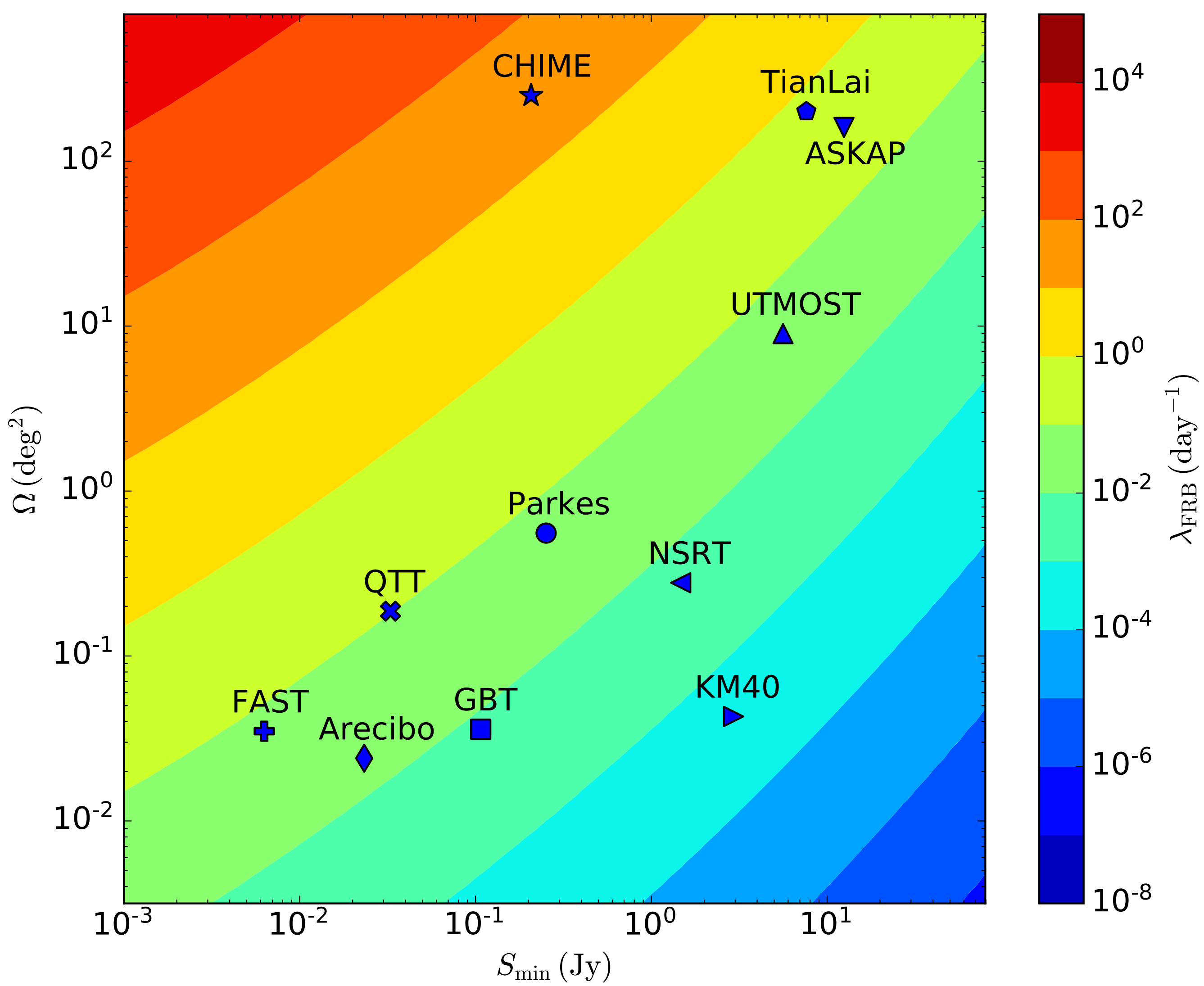
$$\cdot \int_{L_{\min}(w_o)}^{\infty} \phi(L)\, \mathrm{d}L \int f_\varepsilon(\log \varepsilon)\, \mathrm{d}\log \varepsilon$$

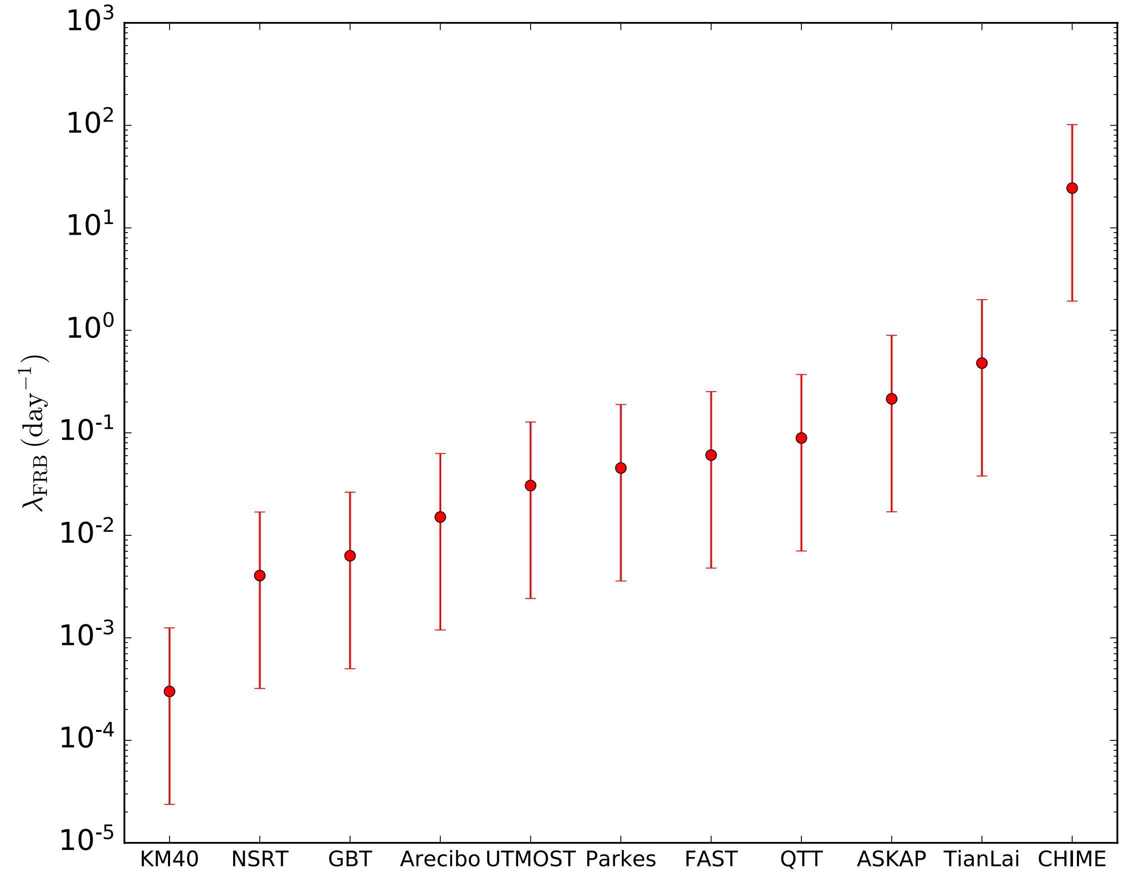
$$\phi(L)\mathrm{d}L = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \mathrm{d}\left(\frac{L}{L^*}\right)$$



Detection rate

- Rate Contour (detection number per day)

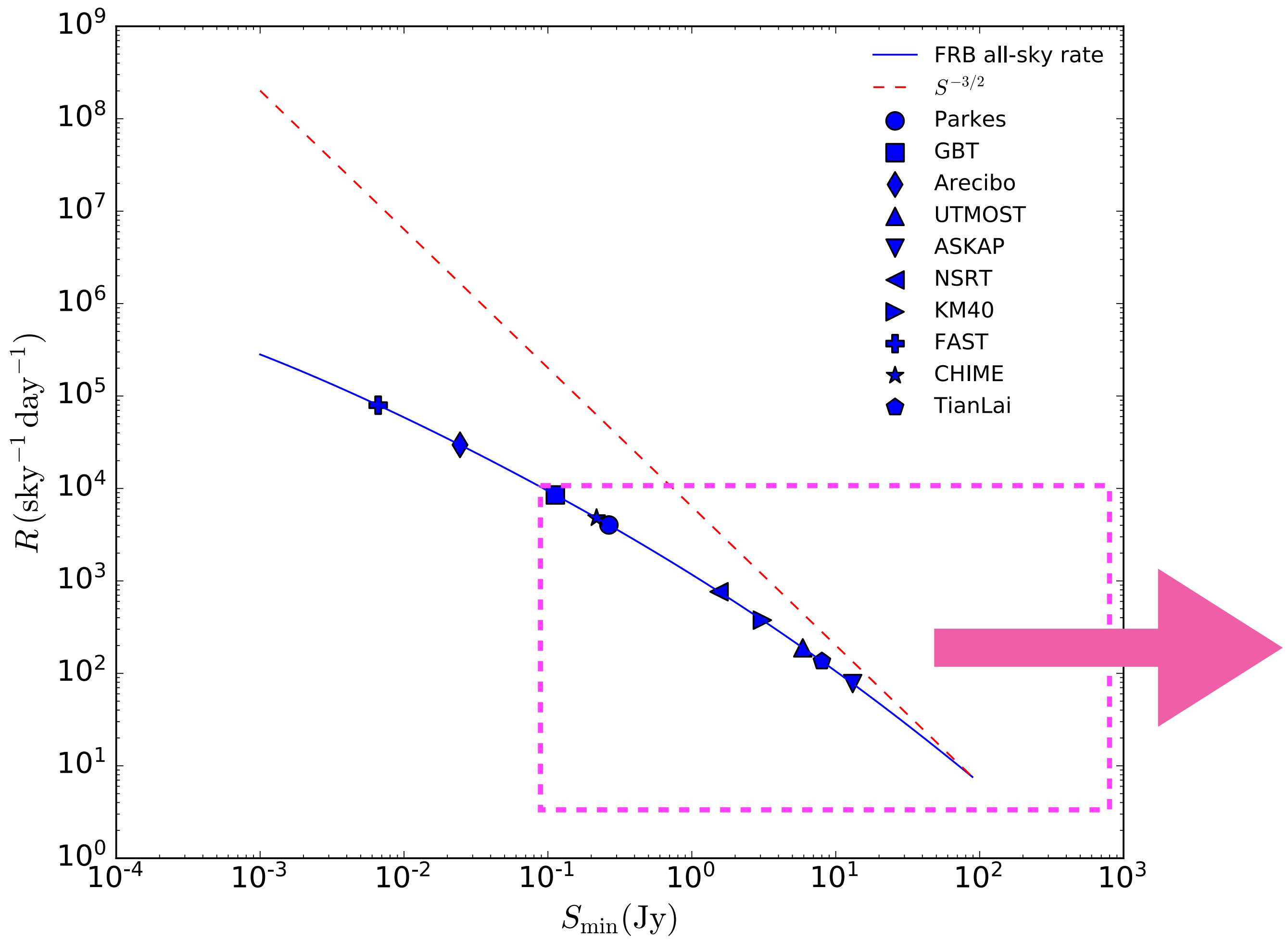




Luo et al. 2019

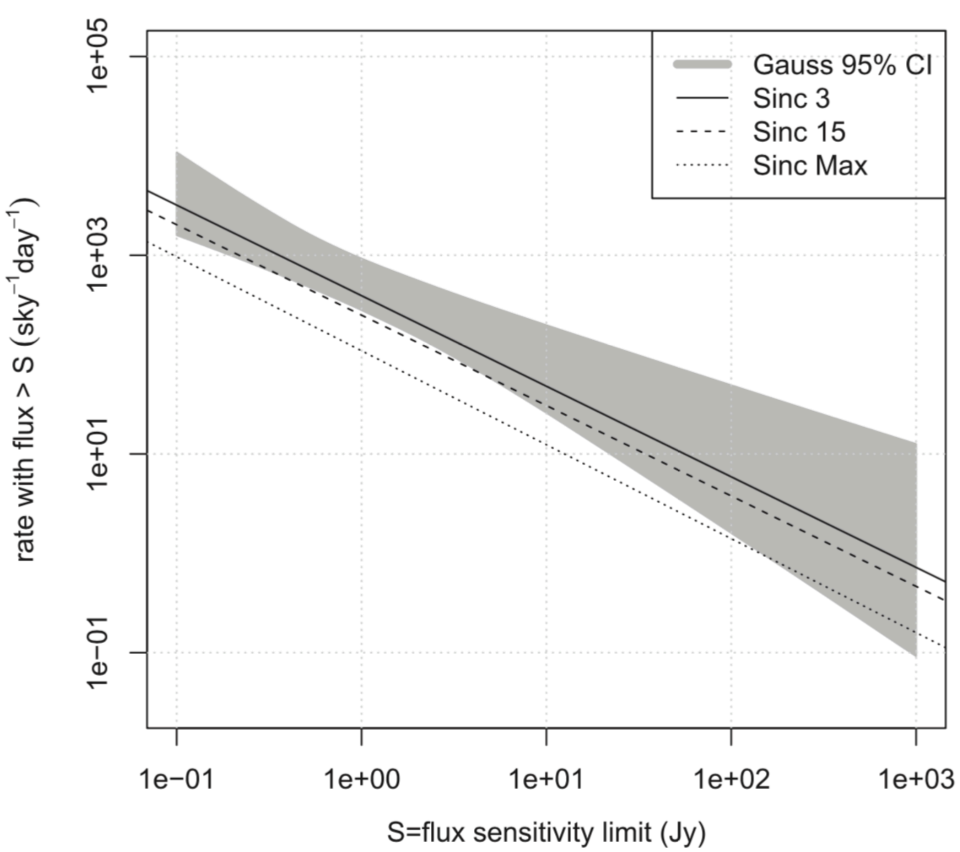
All sky rate

$$R(>S_{\min}) = 4\pi \int_0^\infty \frac{1}{1+z} \frac{r(z)^2}{H(z)} \mathrm{d}z \int f_w(\log w_i) \mathrm{d}\log w_i \int_{L_{\min}(w_o)}^\infty \phi(L) \mathrm{d}L \int f_\varepsilon(\log\varepsilon) \mathrm{d}\log\varepsilon$$



Men et al. 2019

$$\Lambda_I(s_I) = a s_I^{-b}$$



Lawrence et al. 2017

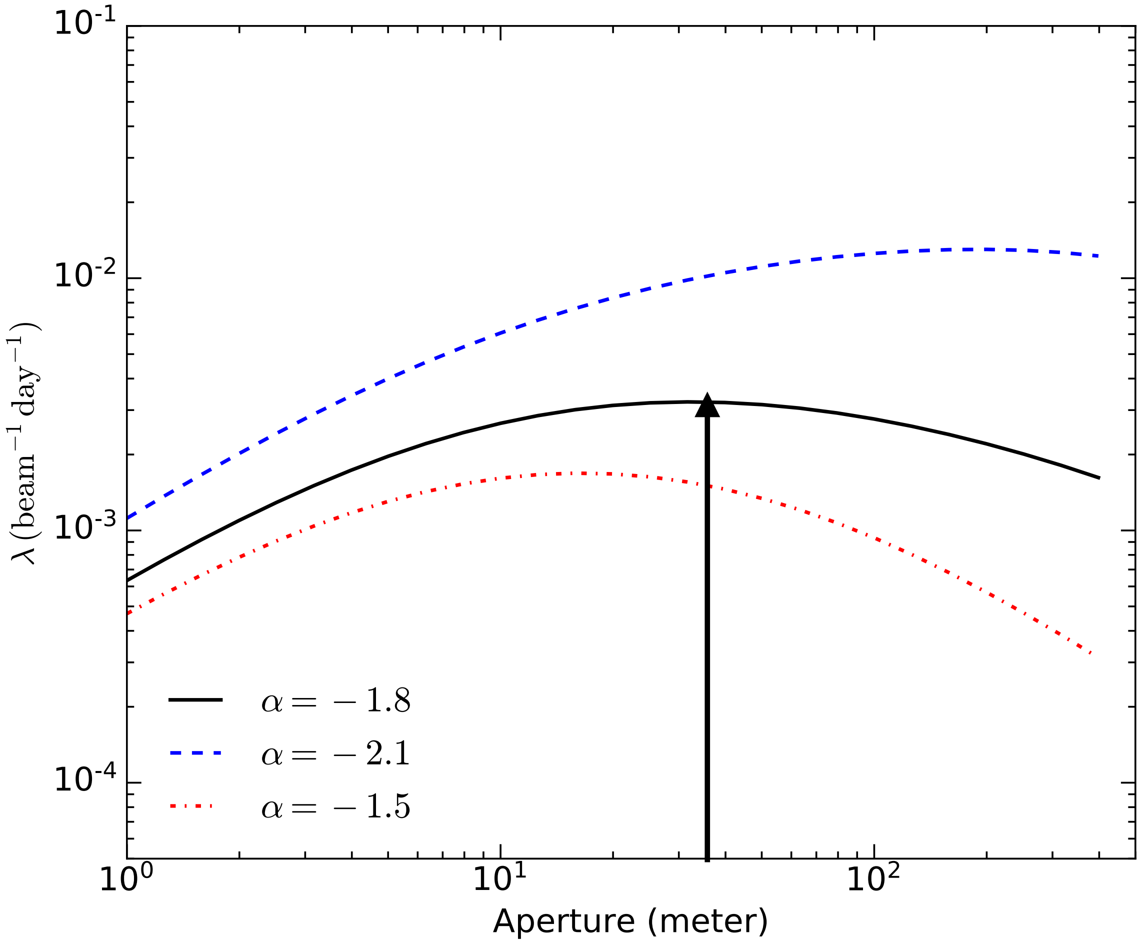
Searching efficiency

- For single dish:

$$\lambda_{1\mathrm{beam}} = \lambda_{1\mathrm{beam}}(S_{\min}, \Omega) = \lambda_{1\mathrm{beam}}(D)$$

$$S_{\min} = \frac{S/N_0 T_{\mathrm{sys}}}{G\sqrt{N_p \mathrm{BW} w_o}} \qquad \Omega \simeq \frac{\pi}{4}\left(\frac{1.22\,\lambda}{D}\right)^2$$

$$G = \frac{\eta \pi D^2}{8k} \simeq 2.84\eta\left(\frac{D}{100\ \mathrm{m}}\right)^2$$



Luo et al. 2019

- Optimal scenario: 30m — 40 m dishes




Summary

- FRB luminosities range at least 2.5 order of magnitudes, the volumetric rate $R \sim 10^{2.4} — 10^{4.7}$ Gpc^{-3} yr^{-1}.
- FRBs population seems to have multiple classes, repeaters favor low-luminosity FRBs, high-luminosity FRBs can reach NS-NS merger rate.
- Both sensitivity and field of view should be taken into account for FRB search. CHIME lead the current FRB large-sample search, while FAST is promising to detect very distant sources.
- 30—40m radio dishes are optimal scenario to do FRB searching with single dishes.