Simulating DM of FRB host galaxies to derive FRB luminosity function

Speaker: Rui Luo 罗　睿 (DoA-PKU)
Advisor: Kejia Lee 李柯伽 (KIAA-PKU)

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OUTLINE

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- Methods and Results
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  - KS method
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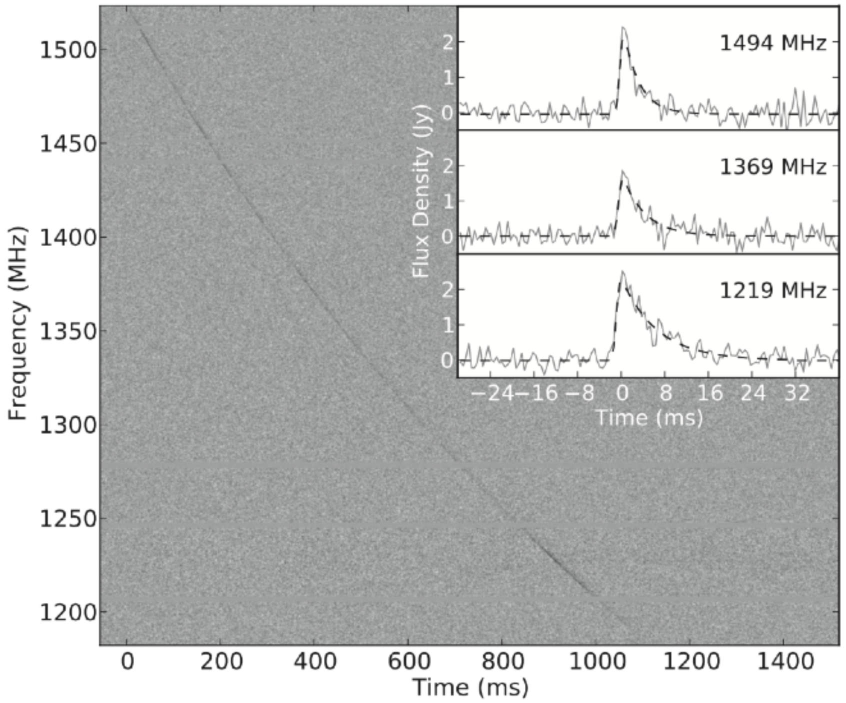
Background

- **Fast Radio Burst (FRB):**
  - Short duration (0.1 — 10 ms)
  - Detected in radio band, 800 MHz (UTMOST, GBT) — 1.4 GHz (Parkes, Arecibo) — 3 GHz (VLA)
  - Prominent flux density (0.1 — 100 Jy)
  - Transients, only one repeater currently.
  - **High Dispersion Measure (DM, 260 — 1630 cm^{-3} pc)**



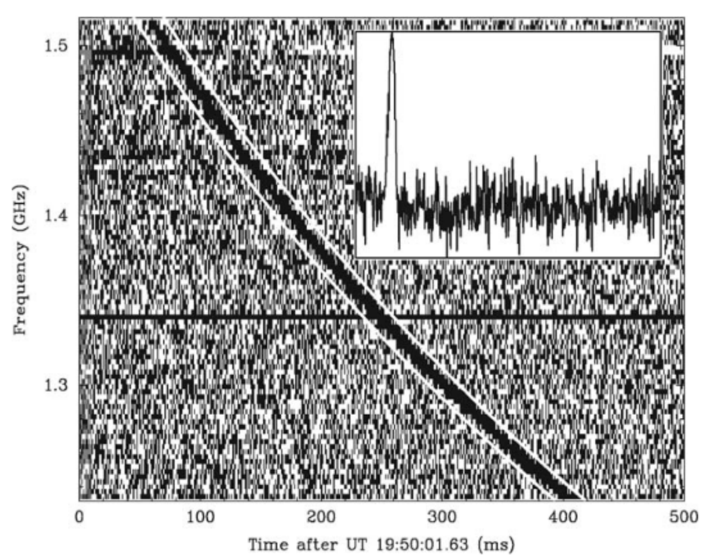
$$\Delta t \simeq 4.15\ \mathrm{ms}\left(\frac{\nu}{1\ \mathrm{GHz}}\right)^{-2}\frac{\mathrm{DM}}{1\ \mathrm{cm}^{-3}\ \mathrm{pc}}$$

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

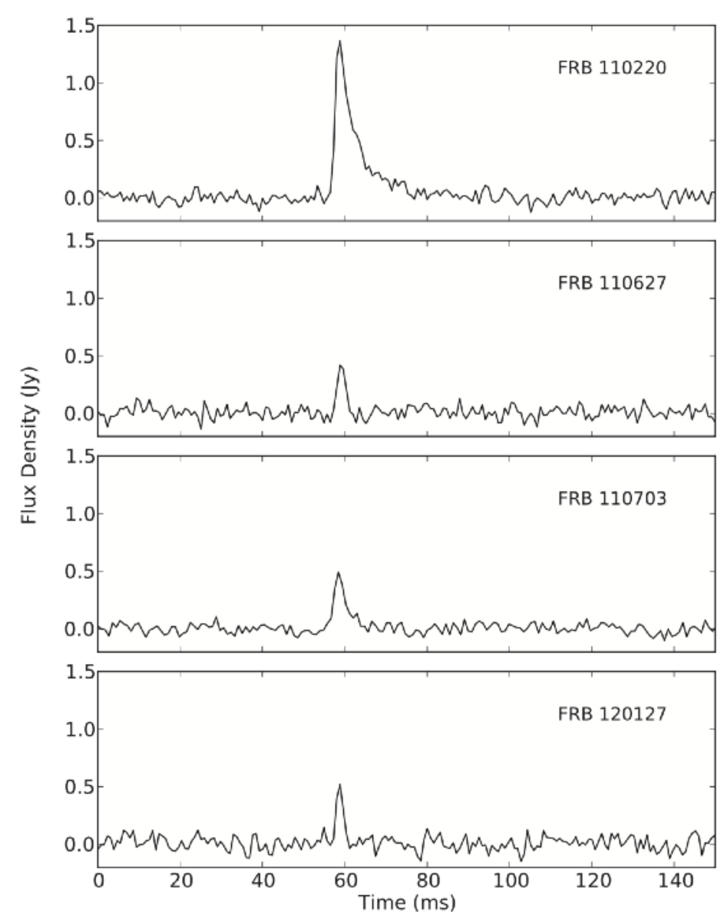
FRB110220 (*Thornton et al. 2013*)

Previous Discoveries

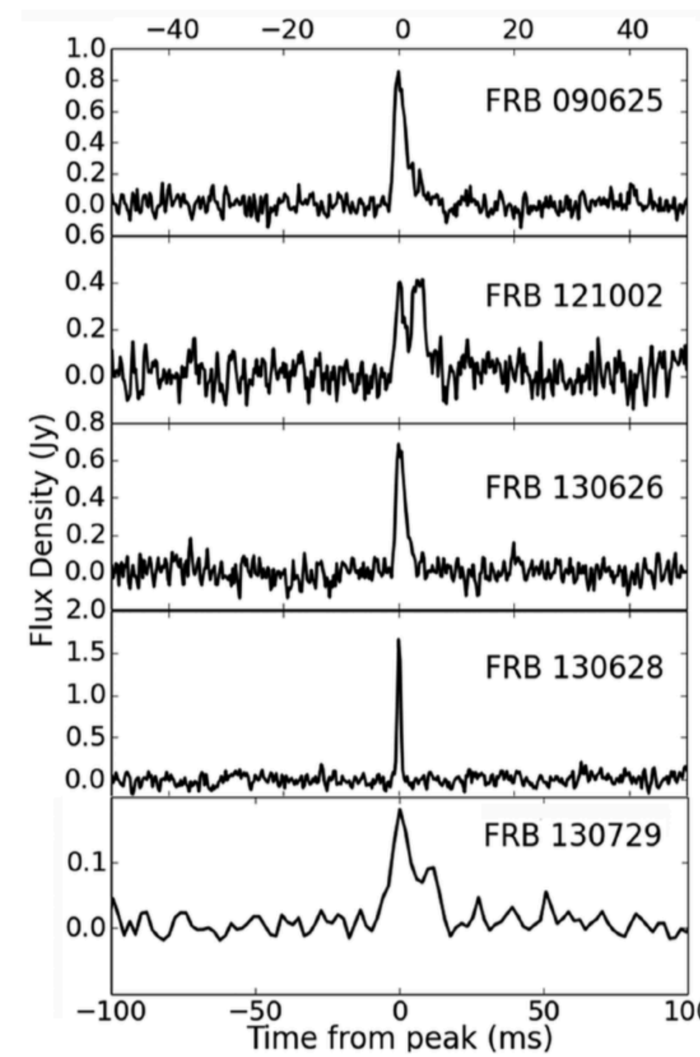
- By Parkes 64-m radio telescope (17 FRBs)



“Lorimer Burst”
(FRB010724, *Lorimer et al. 2007*)



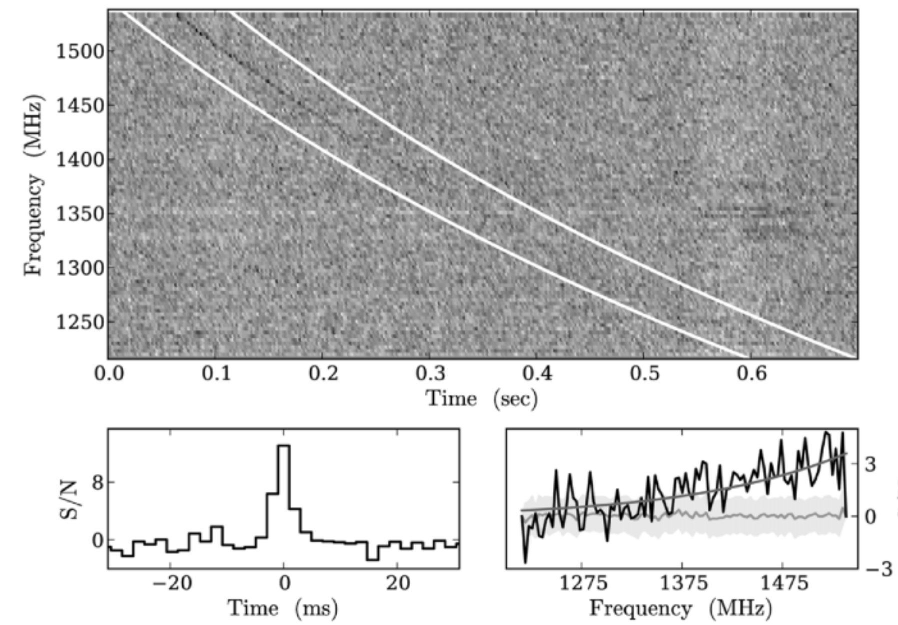
4 FRBs discovered in Parkes HTRU survey
(*Thornton et al. 2013*)



5 FRBs found by Champion et al. 2015

Previous Discoveries

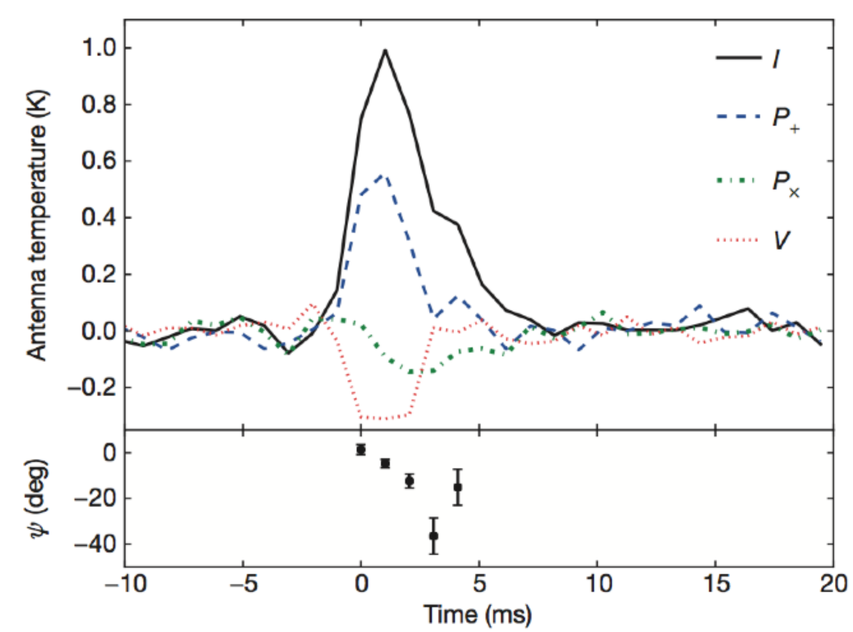
- By Arecibo 300-m radio telescope



FRB121102 (*Spitler et al. 2014*)

- By GBT 100-m radio telescope

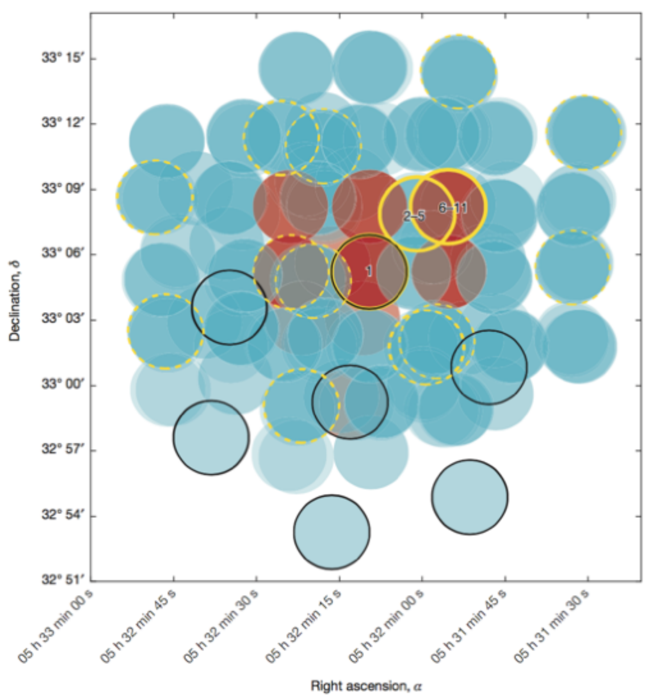
polarization measurements
detected at 800 MHz



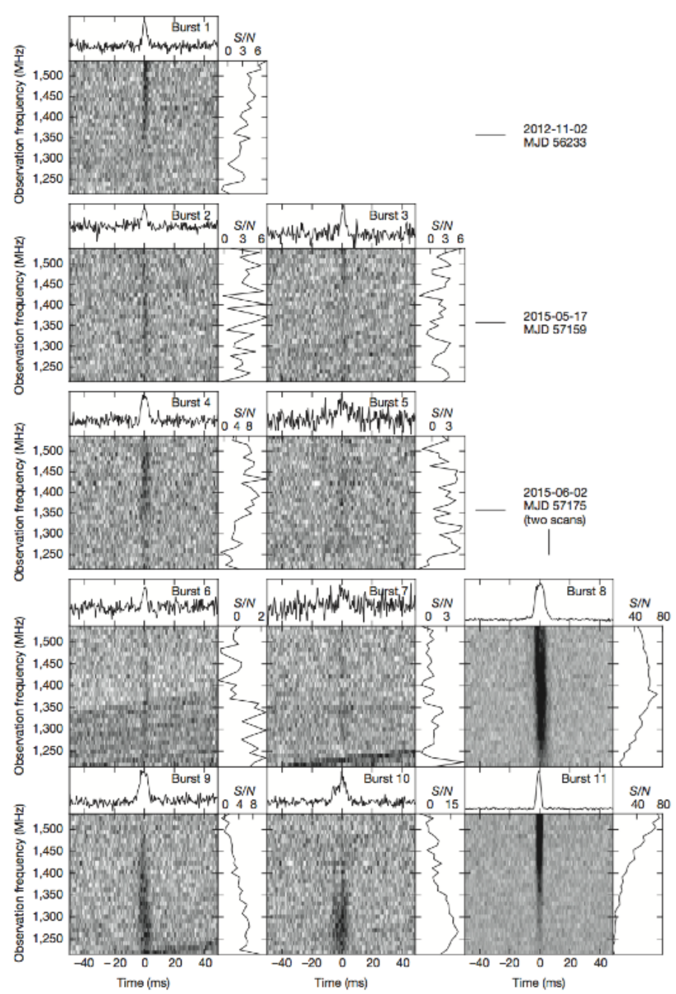
FRB110523 (*Masui et al. 2015*)

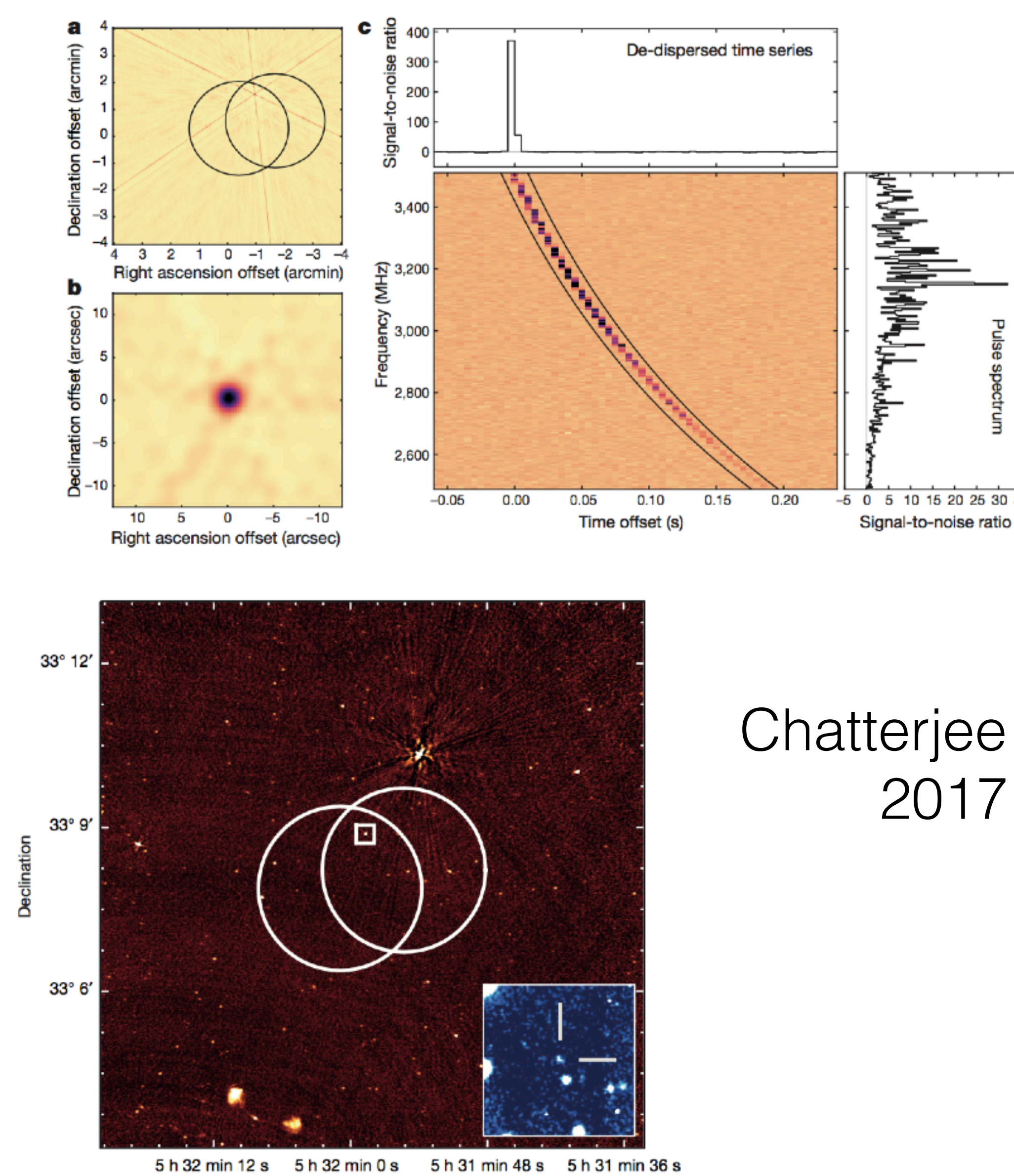
FRB Repeater

- FRB121102 (26+ repeating bursts)
- counterpart: dwarf elliptical galaxy at z~0.193



Spitler et al. 2016

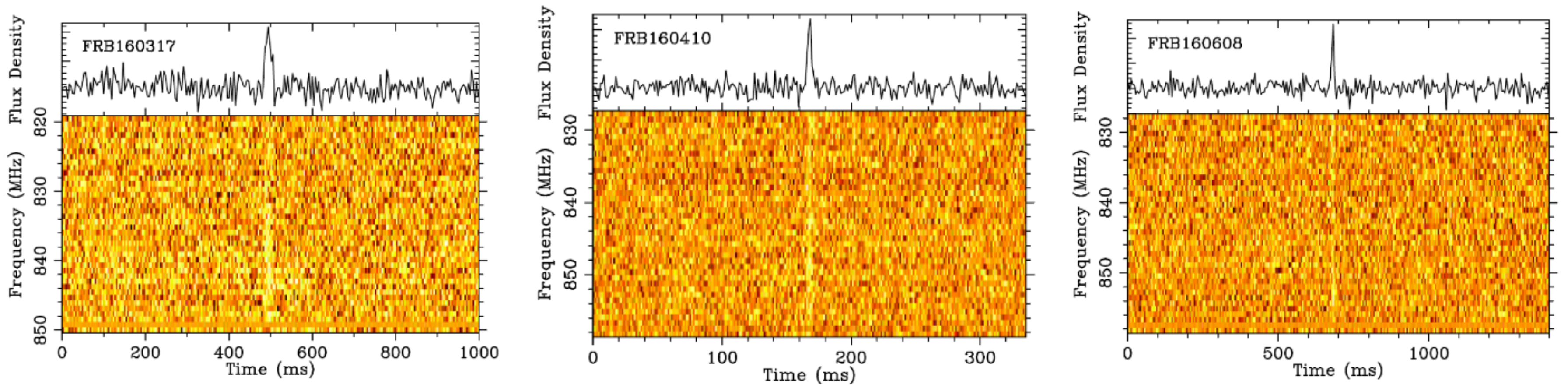




Chatterjee et al. 2017

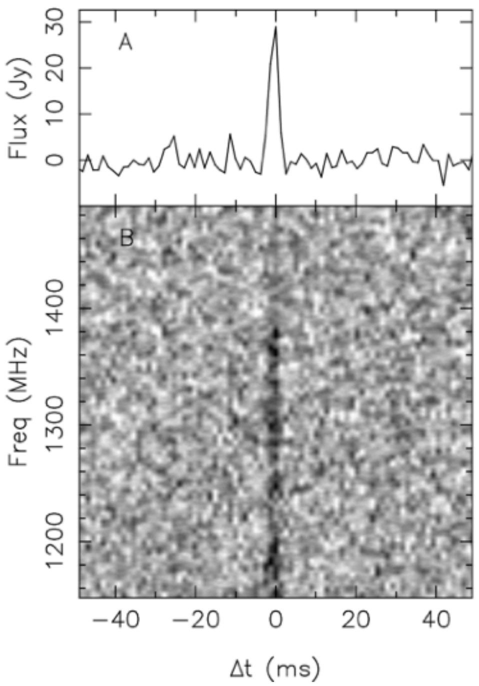
Discoveries in 2017

- By UTMOST (first interferometric detections)



Caleb et al. 2017

- By ASKAP



FRB170107

Bannister et al. 2017

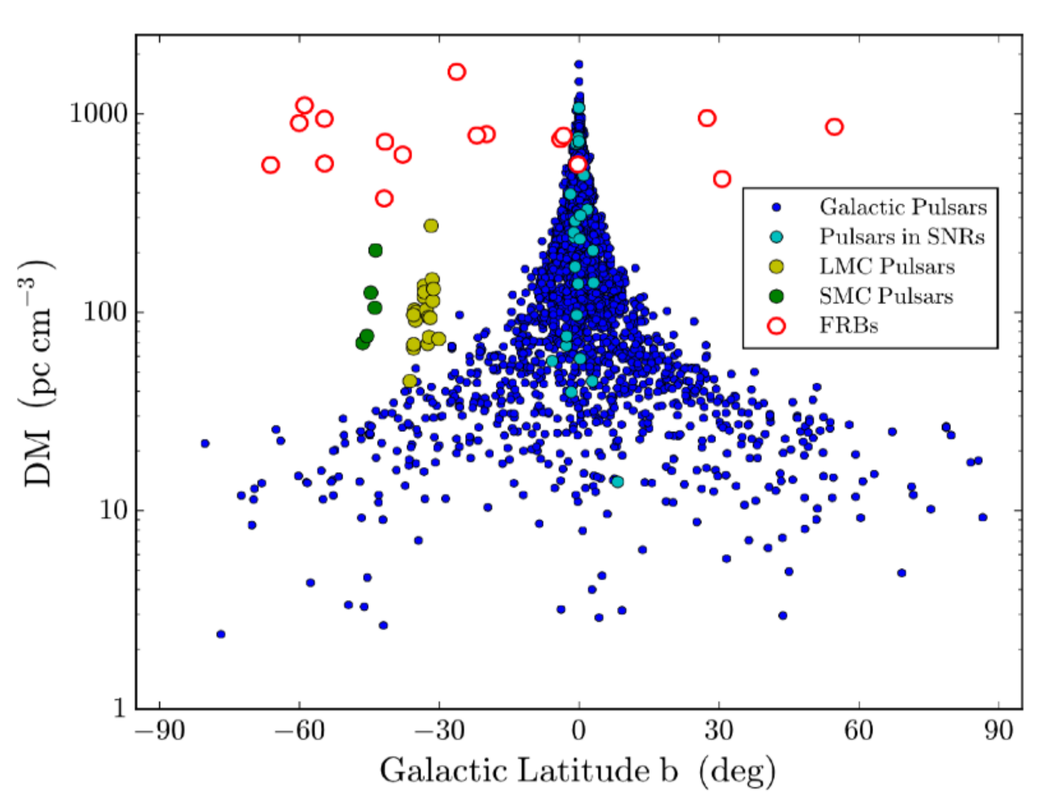
Known FRBs

- 23 FRBs up to now

Catalogue Version 1.0

Event	Telescope	gl [deg]	gb [deg]	FWHM [deg]	DM [cm^{-3} pc]	S/N	W_{obs} [ms]	$S_{peak,obs}$ [Jy]	F_{obs} [Jy ms]	Ref
FRB010125	parkes	356.641	-20.020	0.25	790(3)	17	$9.40^{+0.20}_{-0.20}$	0.30	2.82	1
FRB010621	parkes	25.433	-4.003	0.25	745(10)		7.00	0.41	2.87	2
FRB010724	parkes	300.653	-41.805	0.25	375	23	5.00	$>30.00^{+10.00}_{-10.00}$	>150.00	3
FRB090625	parkes	226.443	-60.030	0.25	899.55(1)	30	$1.92^{+0.83}_{-0.77}$	$1.14^{+0.42}_{-0.21}$	$2.19^{+2.10}_{-1.12}$	4
FRB110220	parkes	50.828	-54.766	0.25	944.38(5)	49	$5.60^{+0.10}_{-0.10}$	$1.30^{+0.00}_{-0.00}$	$7.28^{+0.13}_{-0.13}$	5
FRB110523	GBT	56.119	-37.819	0.26	623.30(6)	42	$1.73^{+0.17}_{-0.17}$	0.60	1.04	6
FRB110626	parkes	355.861	-41.752	0.25	723.0(3)	11	1.40	0.40	0.56	5
FRB110703	parkes	80.997	-59.019	0.25	1103.6(7)	16	4.30	0.50	2.15	5
FRB120127	parkes	49.287	-66.203	0.25	553.3(3)	11	1.10	0.50	0.55	5
FRB121002	parkes	308.219	-26.264	0.25	1629.18(2)	16	$5.44^{+3.50}_{-1.20}$	$0.43^{+0.33}_{-0.06}$	$2.34^{+4.46}_{-0.77}$	4
FRB121102	arecibo	174.950	-0.225	0.05	557(2)	14	$3.00^{+0.50}_{-0.50}$	$0.40^{+0.40}_{-0.10}$	$1.20^{+1.60}_{-0.45}$	7
FRB130626	parkes	7.450	27.420	0.25	952.4(1)	21	$1.98^{+1.20}_{-0.44}$	$0.74^{+0.49}_{-0.11}$	$1.47^{+2.45}_{-0.50}$	4
FRB130628	parkes	225.955	30.655	0.25	469.88(1)	29	$0.64^{+0.13}_{-0.13}$	$1.91^{+0.29}_{-0.23}$	$1.22^{+0.47}_{-0.37}$	4
FRB130729	parkes	324.787	54.744	0.25	861(2)	14	$15.61^{+9.98}_{-6.27}$	$0.22^{+0.17}_{-0.05}$	$3.43^{+6.55}_{-1.81}$	4
FRB131104	parkes	260.549	-21.925	0.25	779(1)	30	2.08	1.12	2.33	8
FRB140514	parkes	50.841	-54.611	0.25	562.7(6)	16	$2.80^{+3.50}_{-0.70}$	$0.47^{+0.11}_{-0.08}$	$1.32^{+2.34}_{-0.50}$	9
FRB150215	parkes	24.662	5.280	0.25	1105.6(8)	19	$2.80^{+1.20}_{-0.50}$	$0.70^{+0.28}_{-0.01}$	$1.96^{+1.96}_{-0.37}$	10
FRB150418	parkes	232.665	-3.234	0.25	776.2(5)	39	$0.83^{+0.25}_{-0.25}$	$2.19^{+0.60}_{-0.30}$	$1.82^{+1.20}_{-0.72}$	11
FRB150807	parkes	336.709	-54.400	0.25	266.5(1)		$0.35^{+0.05}_{-0.05}$	$128.00^{+5.00}_{-5.00}$	$44.80^{+8.40}_{-7.90}$	12
FRB160317	UTMOST	246.050	-0.990	0.00	1165(11)	13	$21.00^{+7.00}_{-7.00}$	>3.00	>63.00	13
FRB160410	UTMOST	220.360	27.190	0.00	278(3)	13	$4.00^{+1.00}_{-1.00}$	>7.00	>28.00	13
FRB160608	UTMOST	254.110	-9.539	0.00	682(7)	12	$9.00^{+6.00}_{-6.00}$	>4.30	>38.70	13
FRB170107	ASKAP	266.000	51.400	0.13	609.5(5)	16	2.60	22.30	57.98	14

FRB catalog (Petroff et al. 2016)



Cordes et al. 2016

$$\mathrm{DM} = \int n_e \, dl$$ indicates both electron density and distance

Theoretical models

- Cosmological:
  - Collapses: SMNSs -> BHs (Falcke & Rezzolla 2014, Zhang 2014)
  - Mergers: BH-BH (Zhang 2016, Liu et al. 2016), NS-NS (Totani 2013), BH-NS (Mingarelli et al. 2015), WD-WD (Kayashima et al. 2013)
  - Radio emission from magnetar (Popov & Postnov 2007 & 2013, Katz 2015, Metzger et al. 2017)
  - Superconducting cosmic string (Cai et al. 2012, Yu et al. 2014)
- Extragalactic:
  - Supergiant pulses of young pulsars (Cordes & Wasserman 2015, Connor et al. 2016, Lyutikov et al. 2016)
  - Supergiant pulses or radio emission from magnetars at galactic center of nearby galaxies (Penn & Connor 2015)
  - Collisions between pulsars and asteroids (Geng & Huang 2015, Dai et al. 2016)
- Galactic:
  - Flaring stars at high galactic latitude (Loeb et al. 2014) ✗

Motivations

- To figure out how host galaxies contribute to DM

$$\begin{aligned}\mathrm{DM} &= \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{E}}(z)\\ &= \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{IGM}}(z) + \mathrm{DM}_{\mathrm{host}}(z)\end{aligned}$$

$$f(\mathrm{DM}_{\mathrm{host}}) = \sum_i \int f(\mathrm{DM}_{\mathrm{host}} | \mathbf{n}_{\mathbf{e}}) \mathcal{D}\mathbf{n}_{\mathbf{e}} \cdot f(\mathbf{n}_* | T_i) \mathcal{D}\mathbf{n}_* \cdot f(T_i | z) \cdot f(z) \mathrm{d}z$$

- To derive FRB intrinsic LF based on the distance estimates

$$\mathrm{DM}_{\mathrm{E}}(z) = \frac{3cH_0\Omega_b f_{\mathrm{IGM}}}{8\pi G m_p}\int_0^z \frac{[\frac{3}{4}y_1\chi_{e,\mathrm{H}}(z') + \frac{1}{8}y_2\chi_{e,\mathrm{He}}(z')](1+z')\mathrm{d}z'}{[\Omega_{\mathrm{m}}(1+z')^3 + \Omega_\Lambda]^{1/2}} + \frac{\mathrm{DM}_{\mathrm{host}}}{1+z}$$

$$d_L = (1+z)\int_0^z \frac{c\,\mathrm{d}z'}{H(z')} \qquad L = 4\pi d_L^2 F_{\mathrm{FRB}}$$

$\mathrm{DM}_{\mathrm{IGM}}$+$\mathrm{DM}_{\mathrm{host}}$ -> z -> d_L -> L

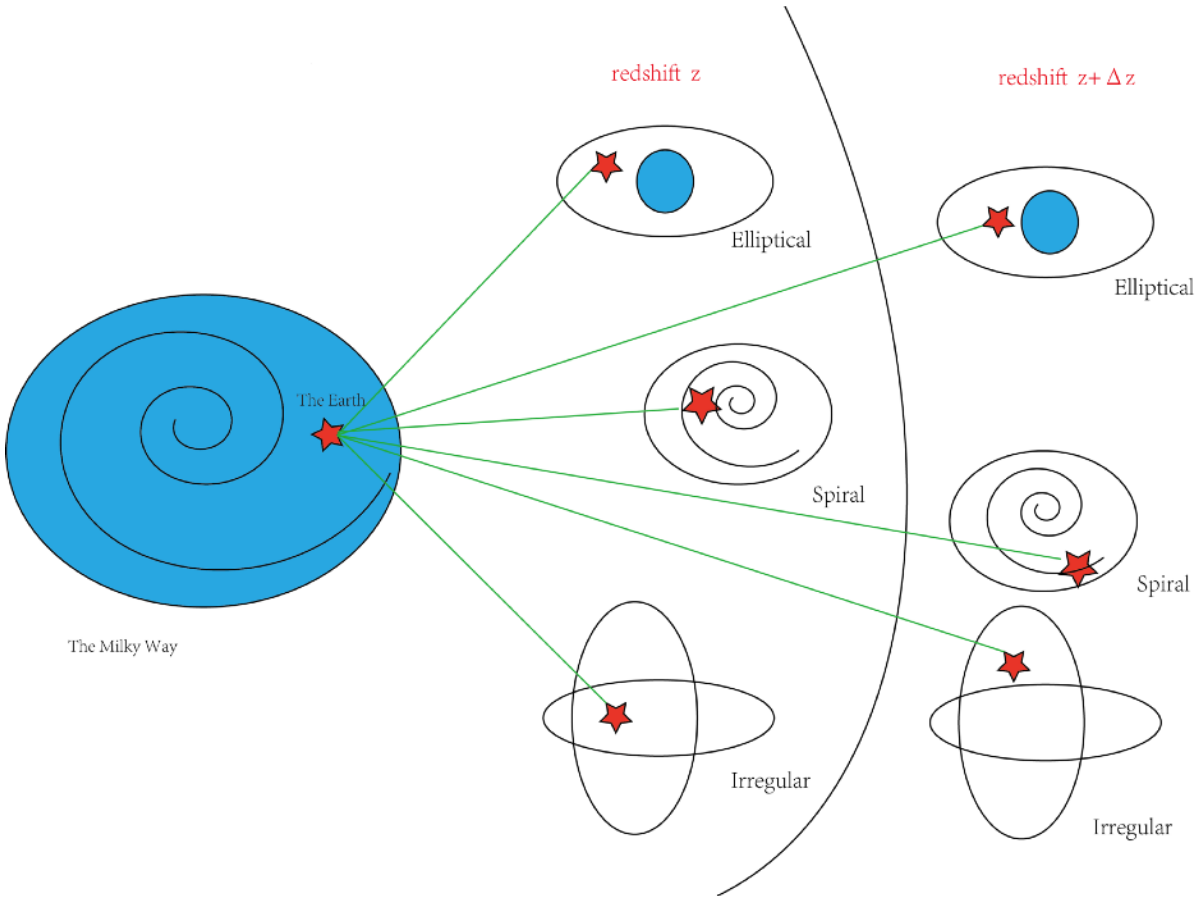
- To constrain current models and study searching efficiency of different radio telescopes




DM simulations

- Use Monte Carlo Simulation to obtain DM distribution of FRB host galaxies

$$f(\mathrm{DM_{host}}) = \sum_i \int f(\mathrm{DM_{host}} | \mathbf{n_e}) \mathcal{D}\mathbf{n_e} \cdot f(\mathbf{n_*} | T_i) \mathcal{D}\mathbf{n_*} \cdot f(T_i | z) \cdot f(z) \mathrm{d}z$$

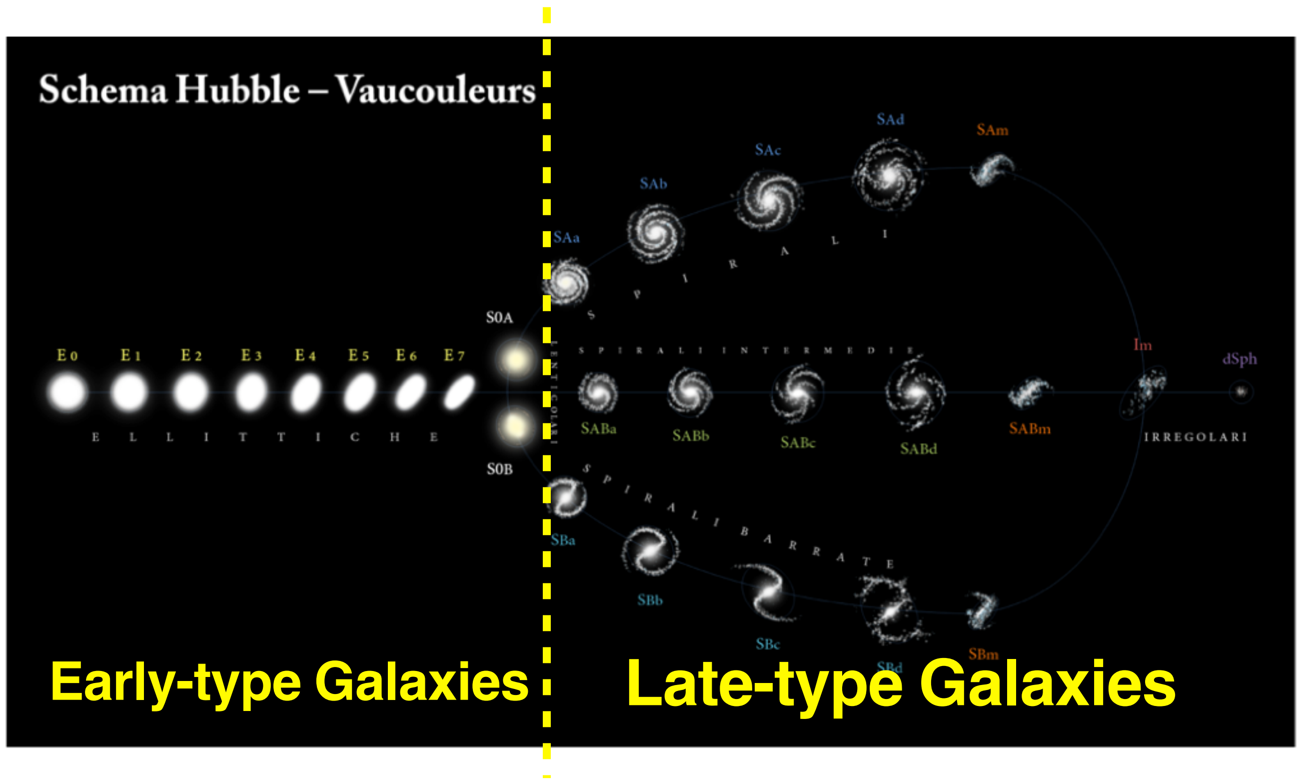


$$f(\mathrm{DM_{templ}}) = \sum_i \int f(\mathrm{DM_{templ}} | \mathbf{n_e}) \mathcal{D}\mathbf{n_e} \cdot f(\mathbf{n_*} | T_i) \mathcal{D}\mathbf{n_*} \cdot f(T_i | z) \cdot f(z) \mathrm{d}z$$

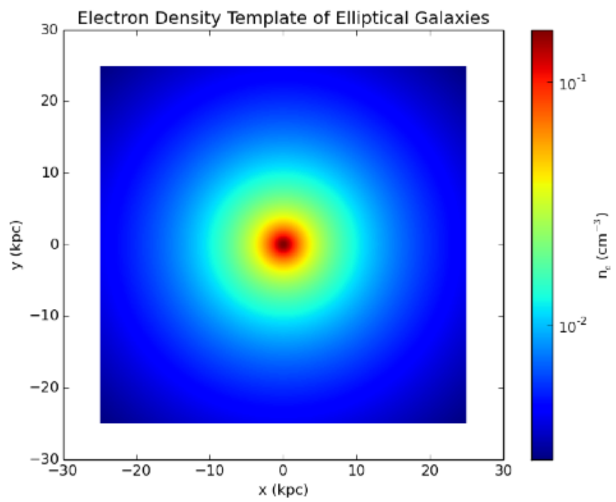
$$f(\mathrm{DM_{host}}) = \int f(\mathrm{DM_{templ}}) \mathcal{D}\mathbf{n_e} \mathcal{D}\mathbf{n_*} \, \mathrm{d}n_e \, \mathrm{d}n_*$$

DM simulations

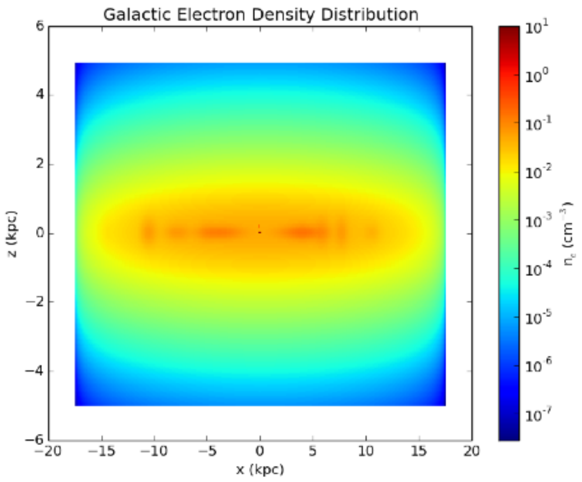
- Galaxy morphology



n_e of ETGs: spheroidal or spherical



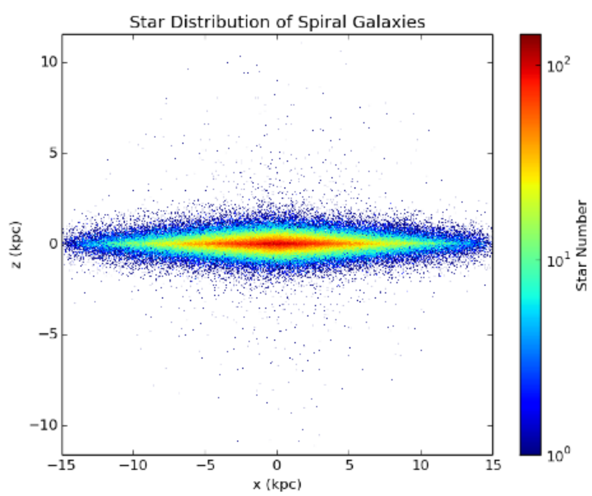
n_e of LTGs: disk-like

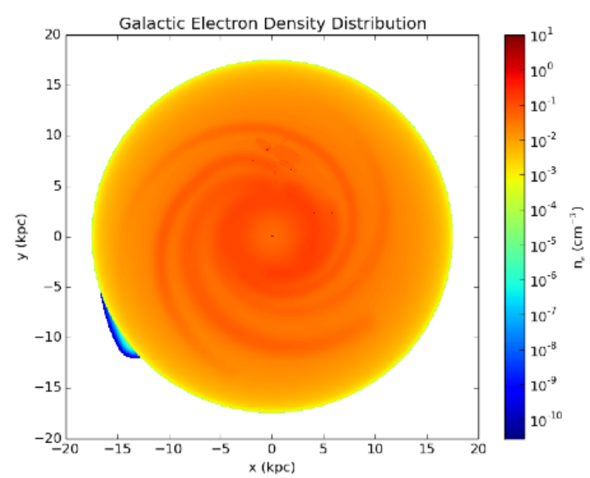


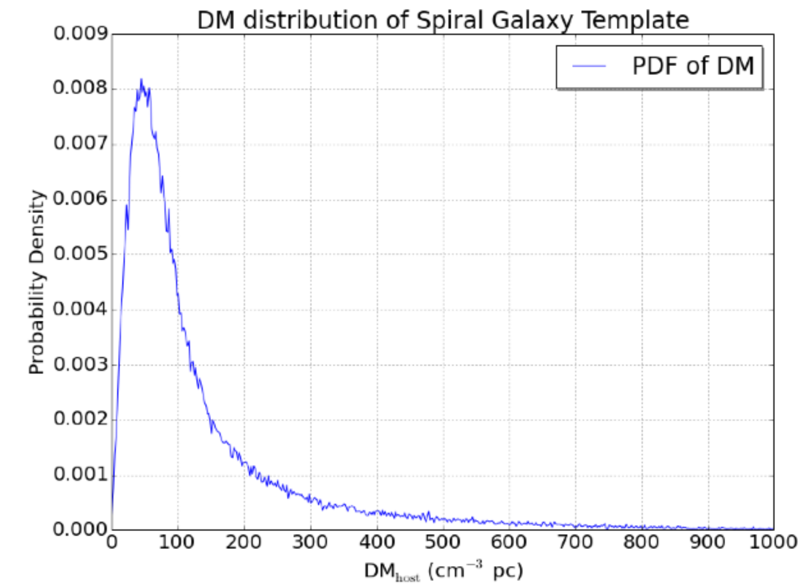
DM simulations

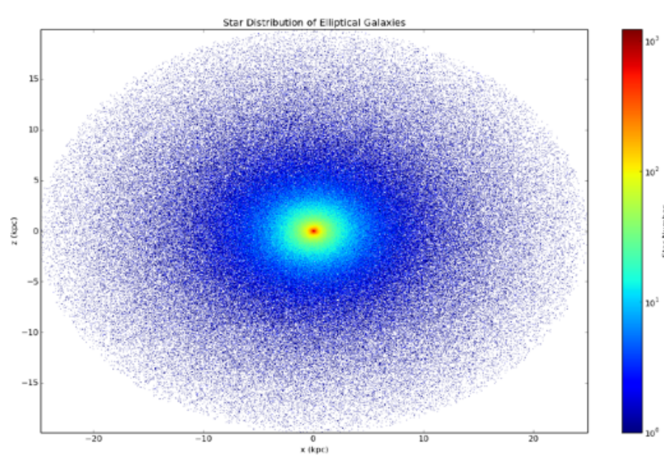
- Building galaxy templates morphologically

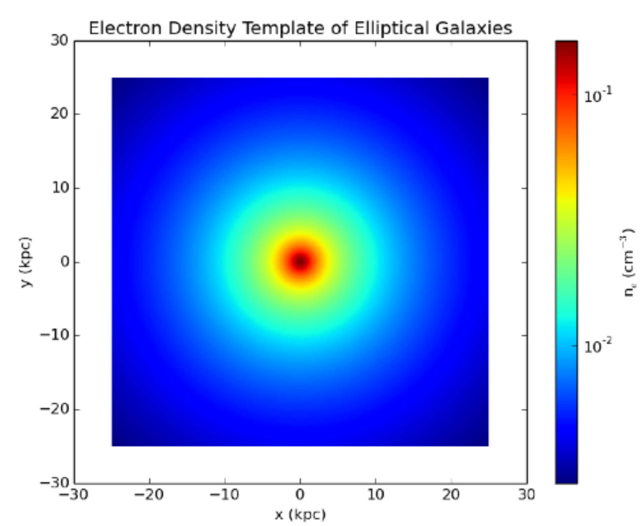
Milky Way as LTG template

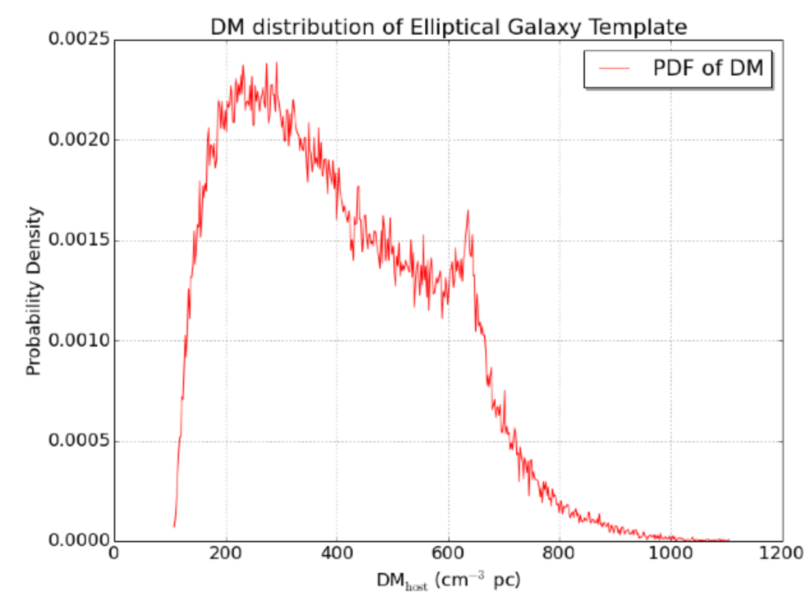












M87 as ETG template

DM simulations

- Scaling for different host galaxies
  - Using Hα emission as free electron density tracer
  - recombination processes of free electrons and protons in HII regions due to photoionization.
  - Derive Scale Formula from Hα Emission Measure

$$\mathrm{EM} = \int n_e^2 \, \mathrm{d}l = 2.75 \left(\frac{T}{10^4 \ \mathrm{K}} \right)^{0.9} \frac{I(R)}{2.42 \times 10^{-7} \ \mathrm{erg \ cm^{-2} \ s^{-1} \ sr^{-1}}} \ \mathrm{cm^{-6} \ pc}$$ (Reynolds 1977)

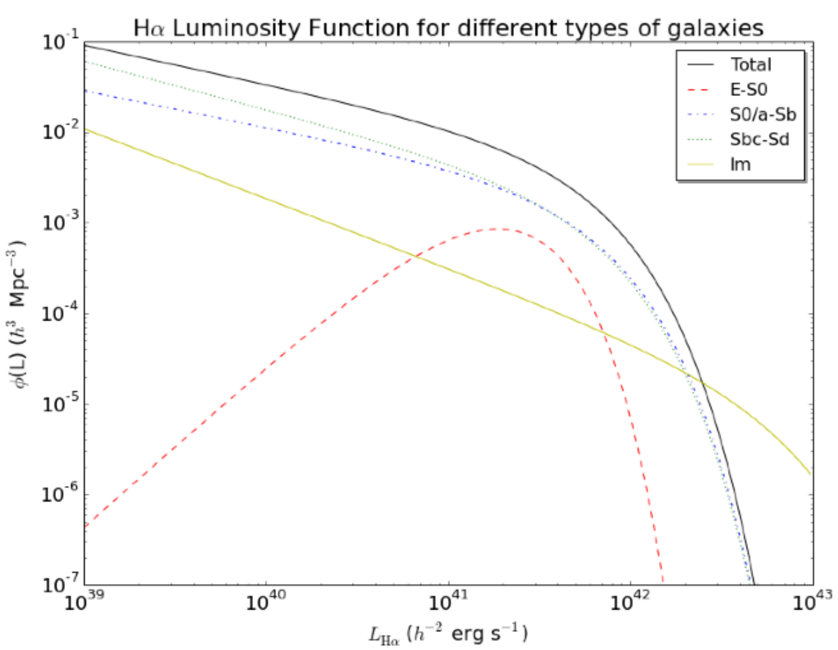
$$I(R) = \frac{L_{\mathrm{H}\alpha}}{4\pi (R/f)^2} = \frac{L_{\mathrm{H}\alpha [\mathrm{erg \ s^{-1}}]}}{6.88 \times 10^{46} R^2_{[\mathrm{kpc}]}} \ \mathrm{erg \ cm^{-2} \ s^{-1} \ sr^{-1}}$$ where f is the filling factor

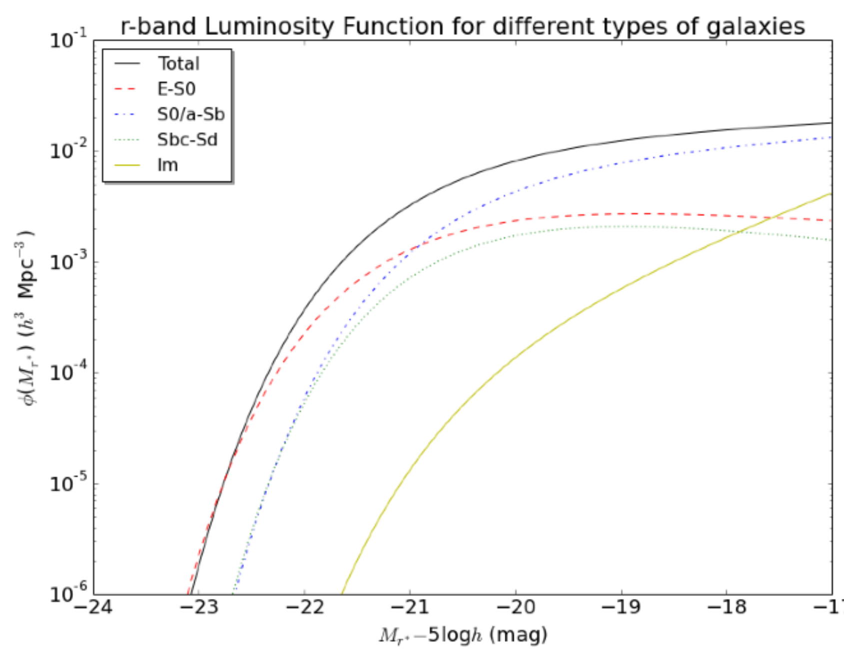
Scale formula:

$$\langle n_e \rangle = 1.28 \left(\frac{T}{10^4 \ \mathrm{K}} \right)^{0.45} \left(\frac{L_{\mathrm{H}\alpha}}{10^{40} \ \mathrm{erg \ s^{-1}}} \right)^{0.5} \left(\frac{R}{1 \ \mathrm{kpc}} \right)^{-1.5} \ \mathrm{cm^{-3}}$$

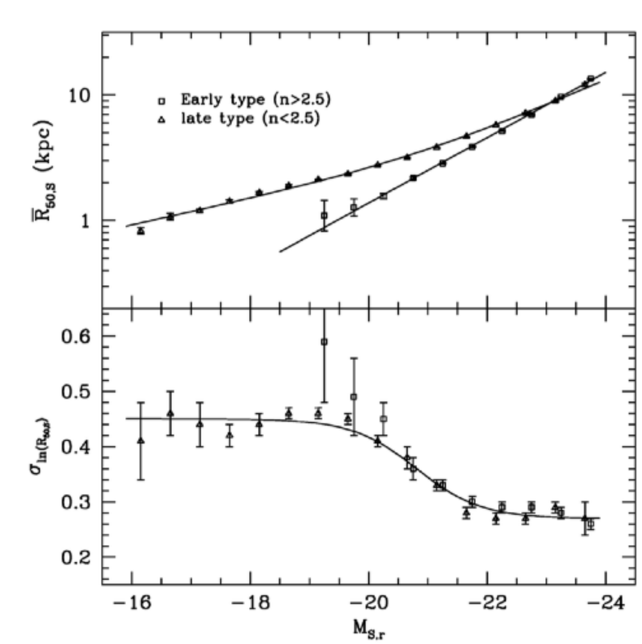
DM simulations

- Scaling for different host galaxies
    - According to the results of large sample galaxy survey





R—M relations:

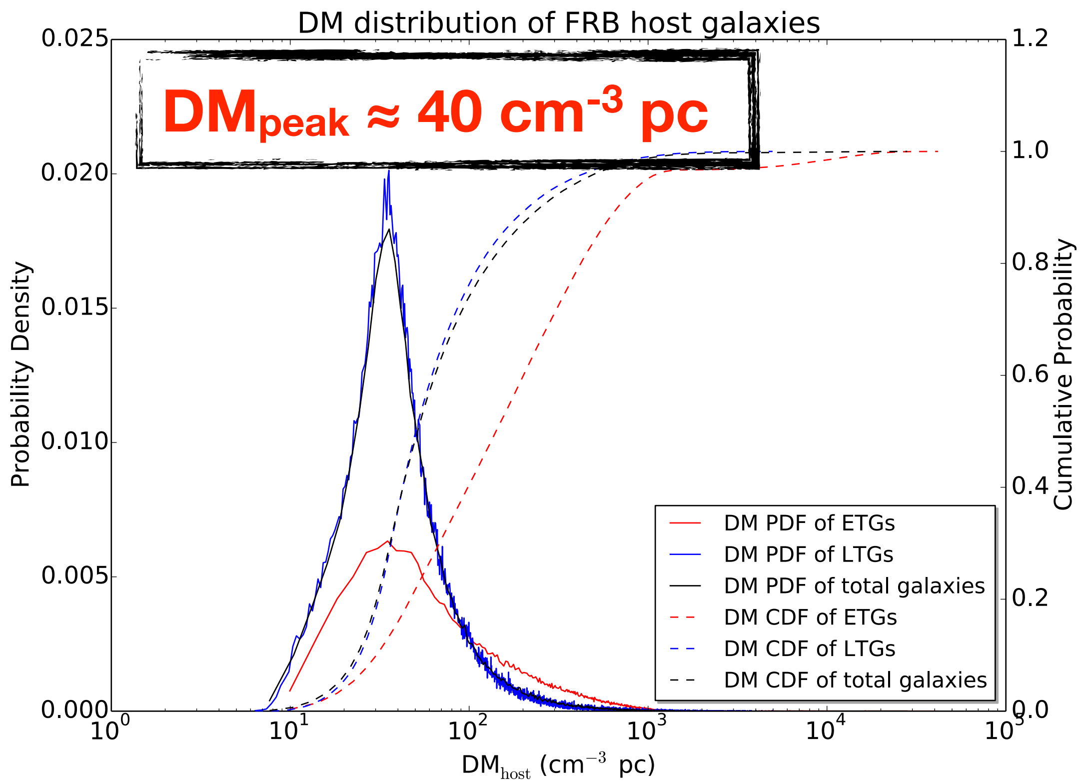


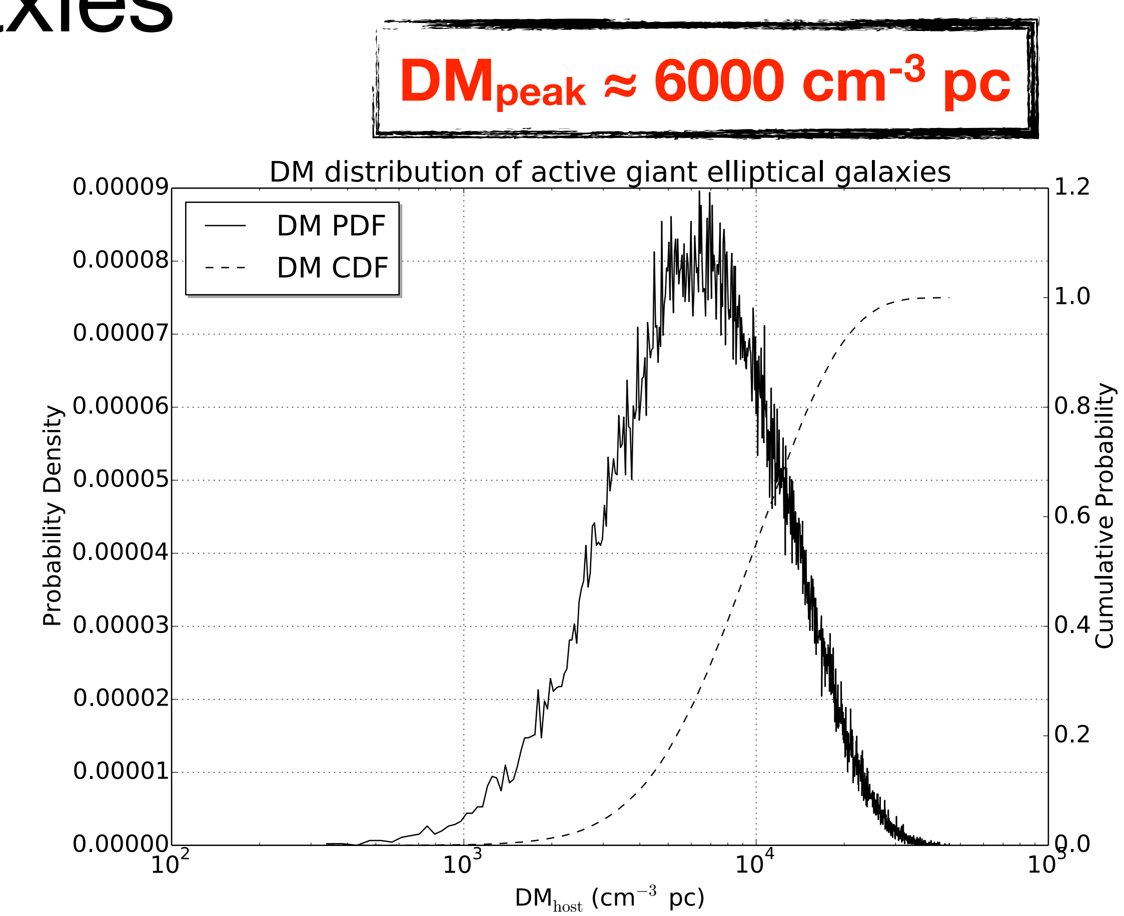
based on 1482 galaxies (z<=0.12) from SDSS
(Nakamura et al. 2003 & 2004)

140,000 galaxies from SDSS
(Shen et al. 2003)

Results of DM simulations

- DM distribution of host galaxies





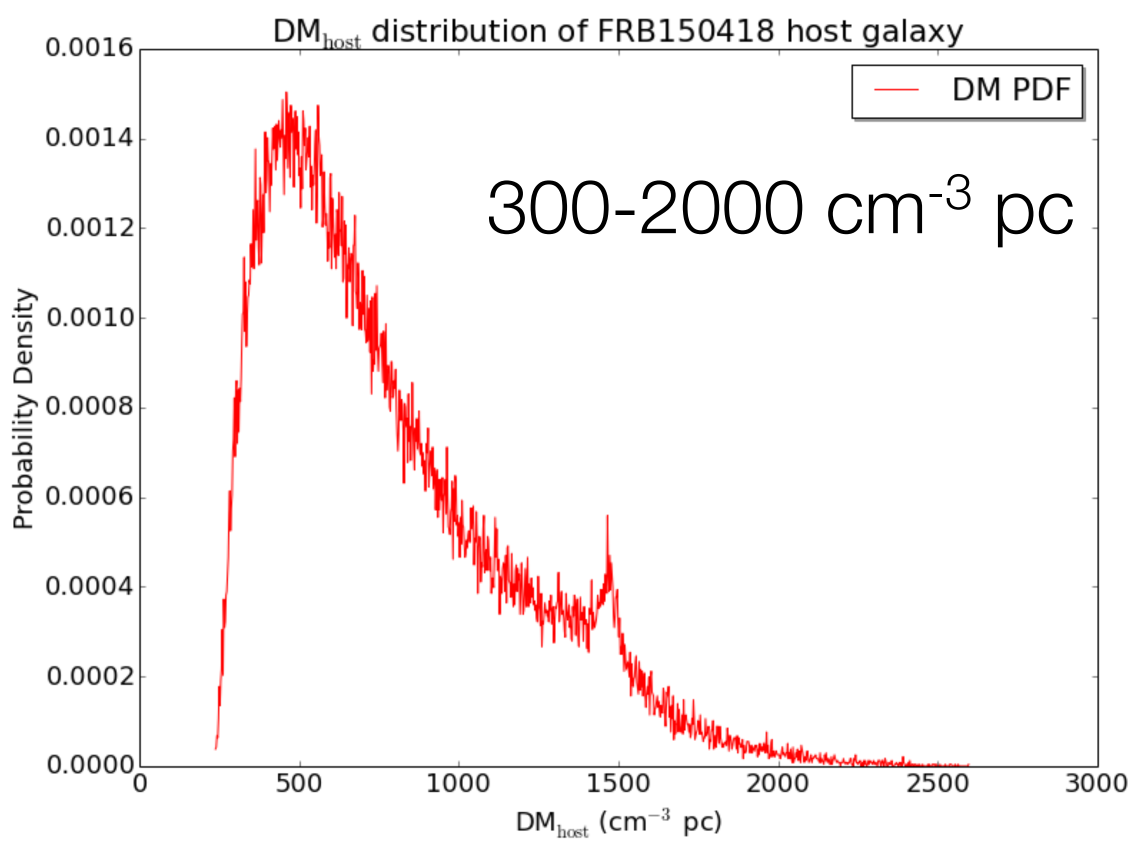
Let x = log(DM), the PDF of DM$_{host}$ can be well fitted by

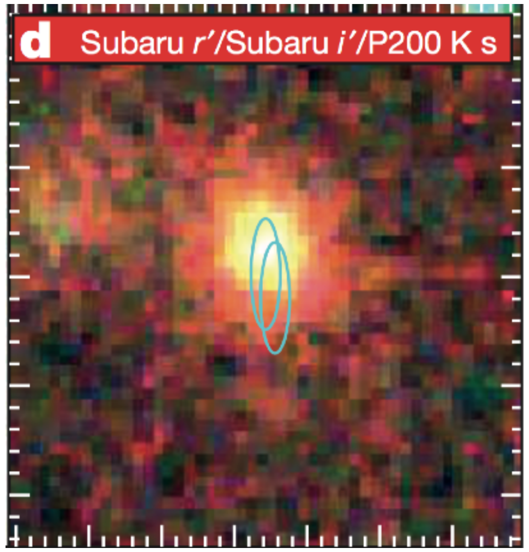
$$f(x) = a_1 \exp\left[-\left(\frac{x-b_1}{c_1}\right)^2\right] + a_2 \exp\left[-\left(\frac{x-b_2}{c_2}\right)^2\right]$$

Parameters	ETGs	LTGs	Total
a_1	0.004828	0.0104	0.0105
b_1	1.484	1.543	1.54
c_1	0.3749	0.1636	0.1834
a_2	0.0021	0.008064	0.006753
b_2	1.901	1.518	1.521
c_2	0.6342	0.4719	0.508

Discussion for FRB150418

- Simulation for FRB150418 doubtful host galaxy





FRB	l (deg)	b (deg)	DM$_{frb}$ (pc cm^{-3})	τ[a] (ms)	DM$_{NE2001}$[b] (pc cm^{-3})	τ_{NE2001}[c] (μs)	DM$_{xg}$[d] (pc cm^{-3})	Ref.
150418	233	−3	776	< 3.1	187	13.5	559	10

Keane et al. 2016

- It's very difficult to account for the FRB150418's observed DM if it does come from this giant elliptical galaxy

This host galaxy identification is ruled out by following VLBI observations.
(Bassa et al. 2016, arXiv:1607.08257)

FRB LF derivation

- Bayesian inference:

likelihood → Pr(D | Θ, H); prior → Pr(Θ | H); posterior → Pr(Θ | D, H)

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

- The likelihood function building:

$$f(\log S, \mathrm{DM_E}) = \int f(\log S, \mathrm{DM_E}, z)\,dz$$

$$= \int_0^{z_{\max}} \phi(\log L > \log L_0) \cdot f_r(z) \cdot f_D\left(\mathrm{DM_{host}}(z)\right) \cdot (1+z)\,dz$$

$$f_r(z) = \frac{dV}{dz} = \frac{4\pi r(z)^2 n_0}{H_0 E(z)}$$

$$\mathrm{DM_{host}}(z) = [\mathrm{DM_E} - \mathrm{DM_{IGM}}(z)](1+z)$$

$$L = S \cdot 4\pi d_L^2$$

where $\phi(L)$ is the FRB intrinsic LF

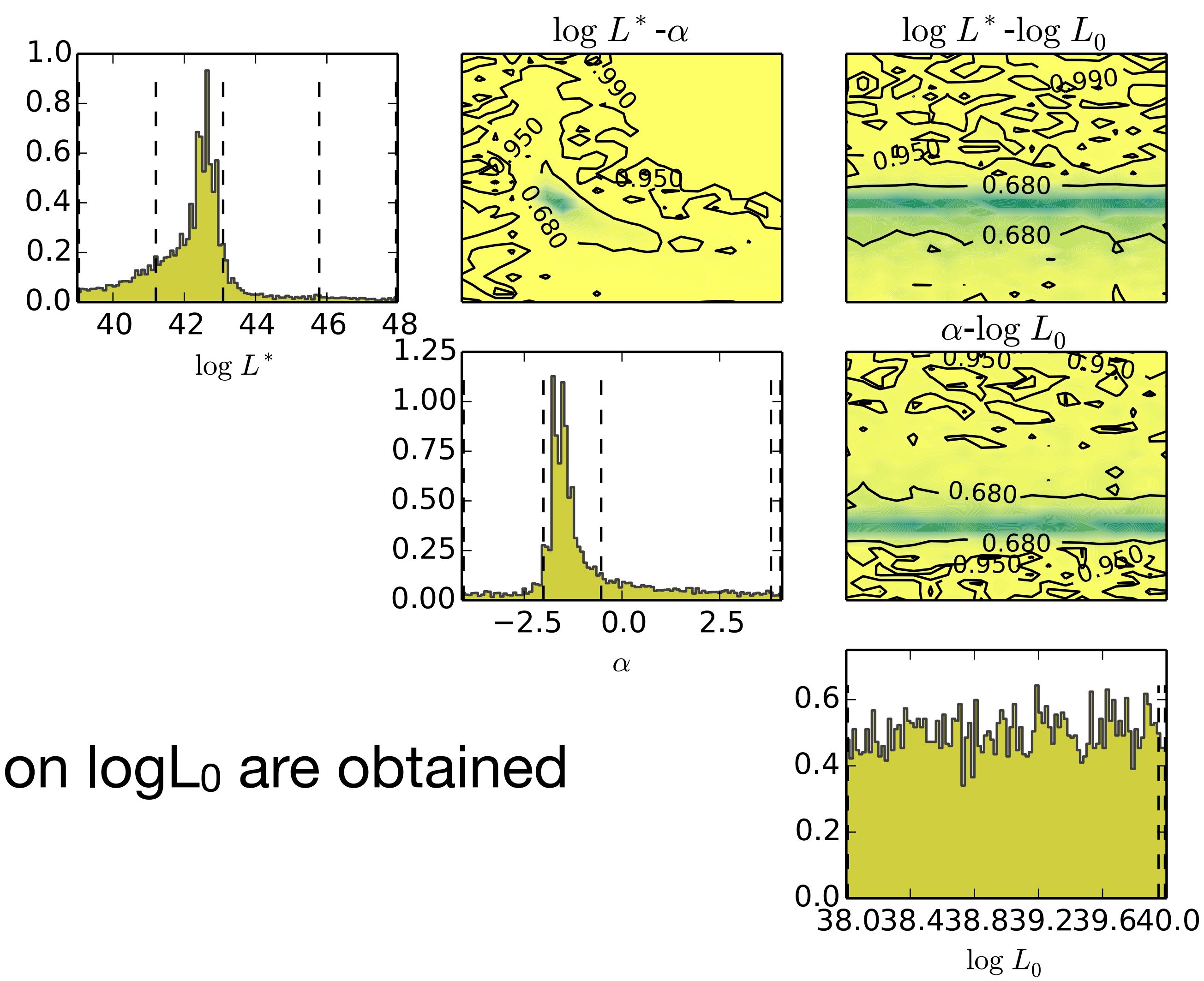
- Using MultiNest (Feroz et al. 2009) to run MCMC.

Results of MCMC

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

ϕ^* is the normalized factor, α is the power-law index, L^* is the cut-off luminosity.

- ETG case:



$\alpha \sim -1.75$

$\log L^* \sim 42.9$

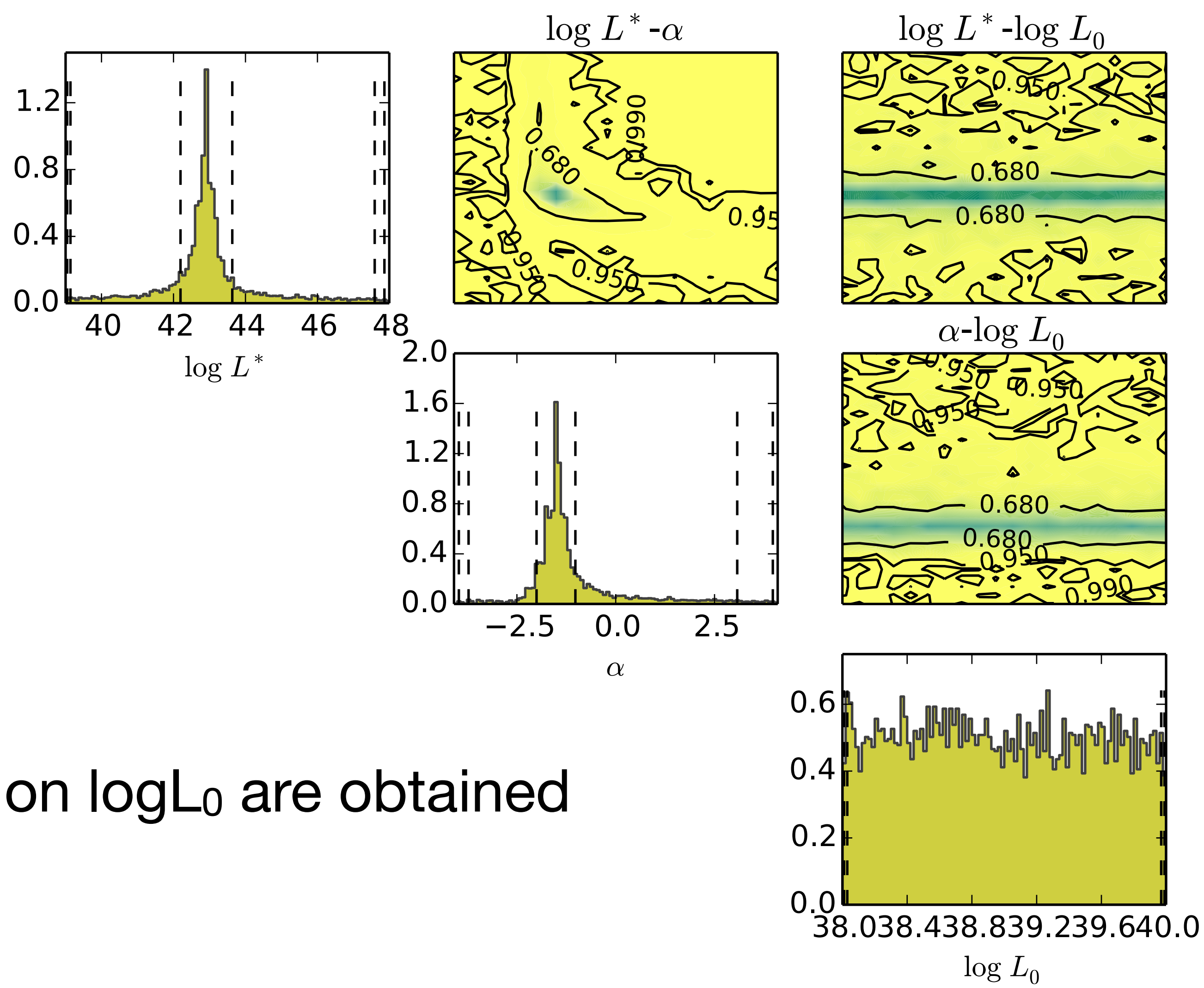
No constraints on $\log L_0$ are obtained

Results of MCMC

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

ϕ^* is the normalized factor, α is the power-law index, L^* is the cut-off luminosity.

- LTG case:



$\alpha \sim -1.50$

$\log L^* \sim 42.9$

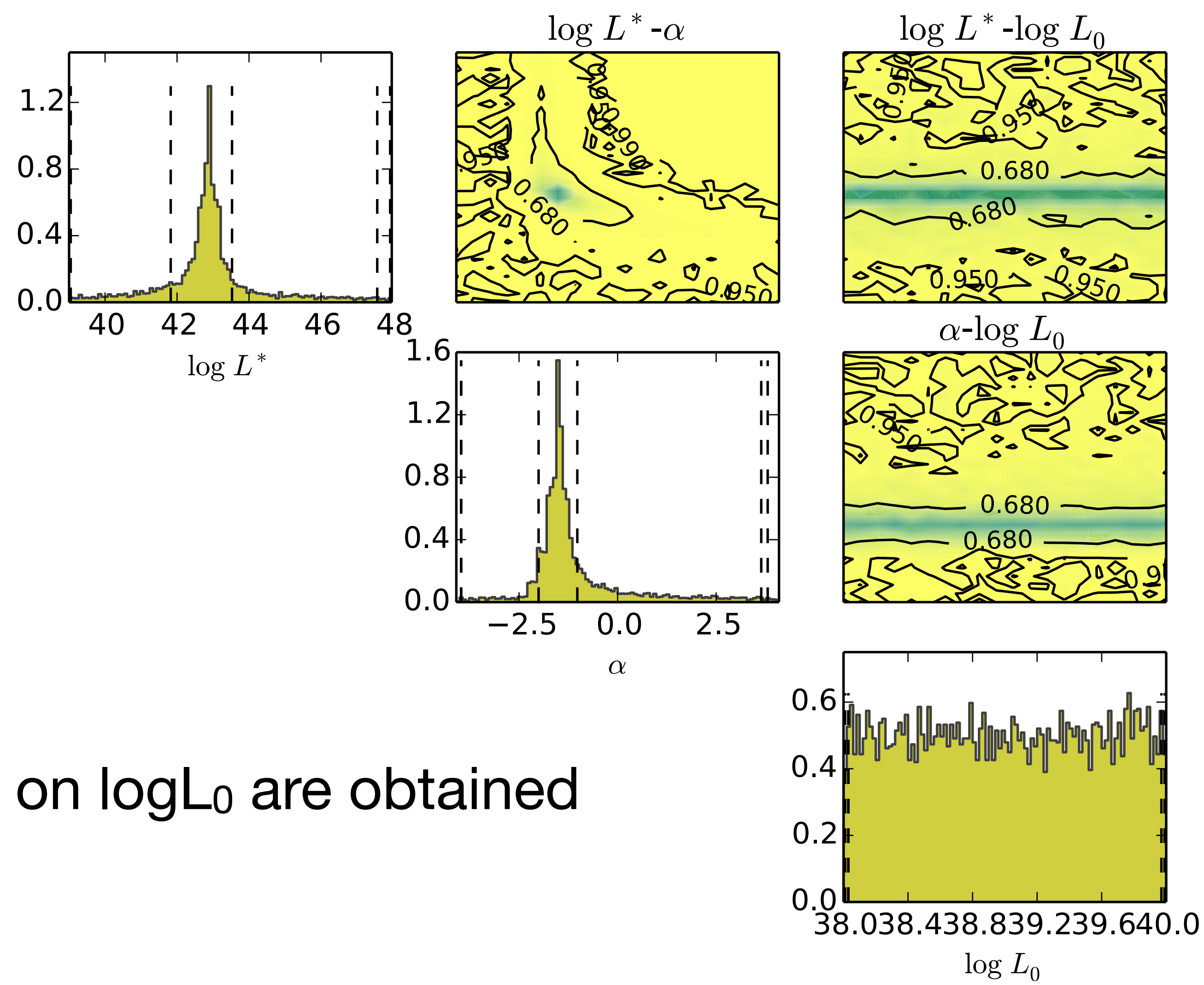
No constraints on $\log L_0$ are obtained

Results of MCMC

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

ϕ^{*} is the normalized factor, α is the power-law index, L^{*} is the cut-off luminosity.

- ALG case:



$\alpha \sim -1.50$

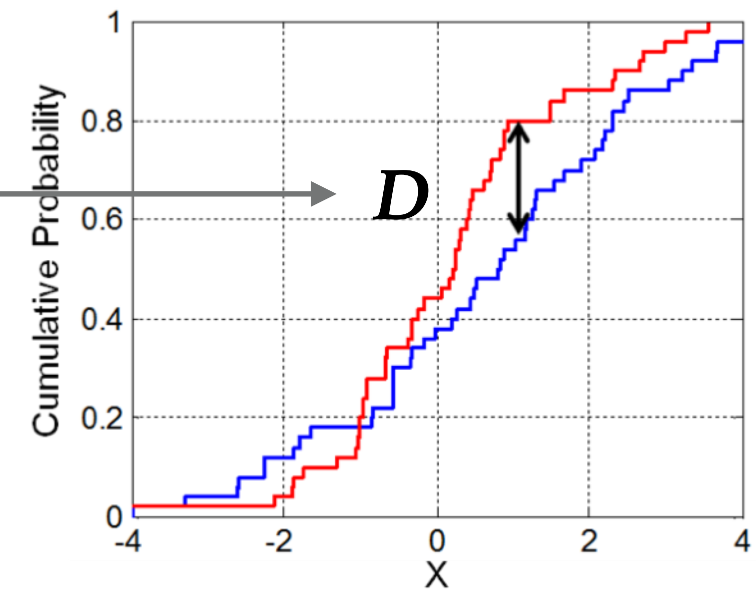
$\log L^{*} \sim 42.9$

No constraints on $\log L_0$ are obtained

KS method

- Kolmogorov-Smirnov test

$$D_n = \max\left|\Pr(X_1 < x_i) - \Pr(X_2 < x_i)\right|$$



$$\frac{dN_{\rm obs}(>S_0)}{dT_{\rm obs}} = \int dz \int_{L_0(z)}^{\infty} \frac{dN}{dVdTdL}\frac{dT}{dT_{\rm obs}}\frac{dV}{dz}dL$$
$$= \int_0^{\infty} \frac{1}{1+z}\frac{4\pi r(z)^2}{H_0 E(z)} dz \int_{L_0}^{\infty} \phi(L) dL$$

$$f(L) = \int_0^{z_{\max}} \phi(L > L_0) \frac{1}{1+z}\frac{4\pi r(z)^2}{H_0 E(z)} dz$$

$$\mathrm{CDF}(L) = \Pr(l > L) = \int_{\infty}^{L} f(l)\, dl$$

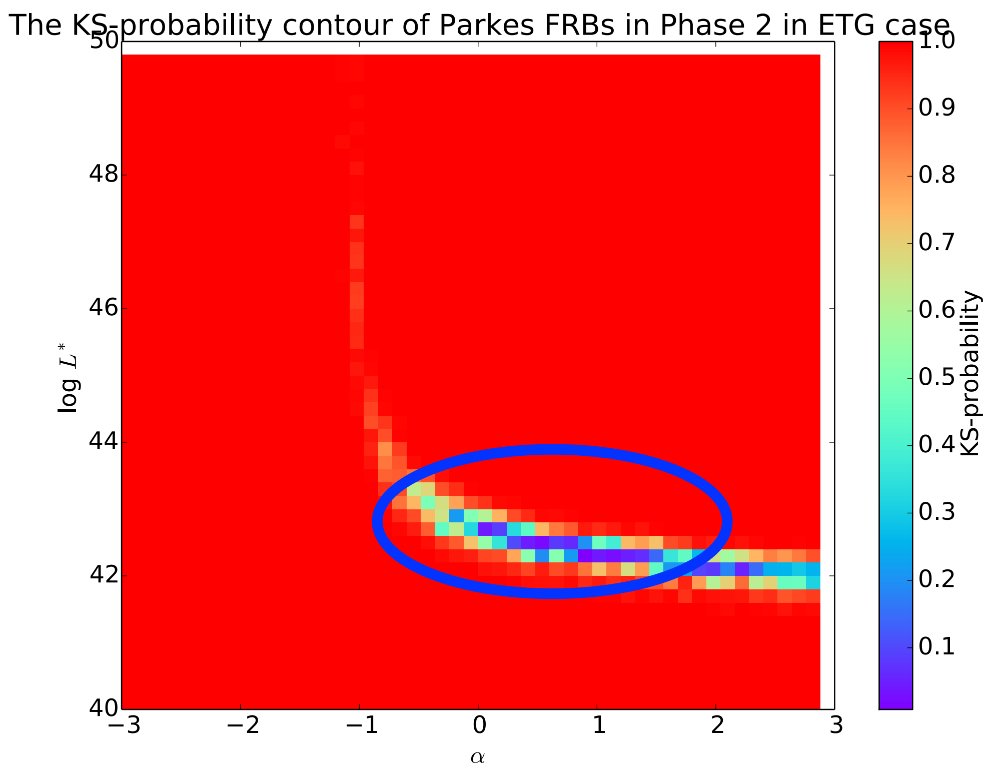
where $\phi(L)$ is the FRB intrinsic LF

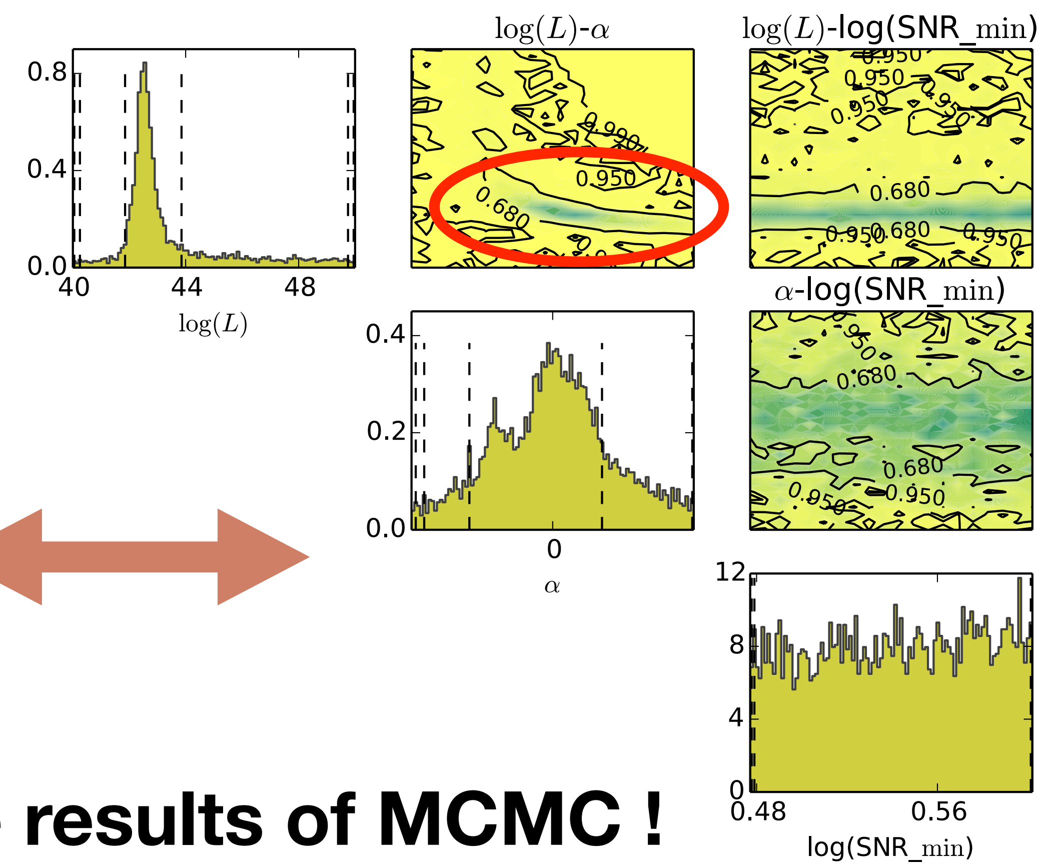
Results of Comparison

- Limitation of KS method:
  - can only be used for single survey with at least two detections

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

Parkes Phase 1: BW= 288 MHz, 3 FRB detections
Parkes Phase 2: BW= 338 MHz, 14 FRB detections





Consistent with the results of MCMC !

Summary

- 1. The most probable DM of FRB host galaxies, $DM_{mp} \approx 40$ cm^{-3} , is lower than assumption of people previously ($DM_{host} \approx 100$ cm^{-3} pc, Thornton et al. 2013).
- 2. The current FRBs are unlikely to come from active giant elliptical galaxies due to the extremely high Hα luminosity from AGNs.
- 3. The FRB LF can be derived with Schechter function, MCMC method shows the power-law index α~-1.5, cut-off luminosity log L^* ~ 42.9.
- 4. KS method can also constrain FRB LF parameters, but it is limited due to sample number in single survey.

THE END

Thank you !!!