Studies on Dispersion Measure of Fast Radio Bursts

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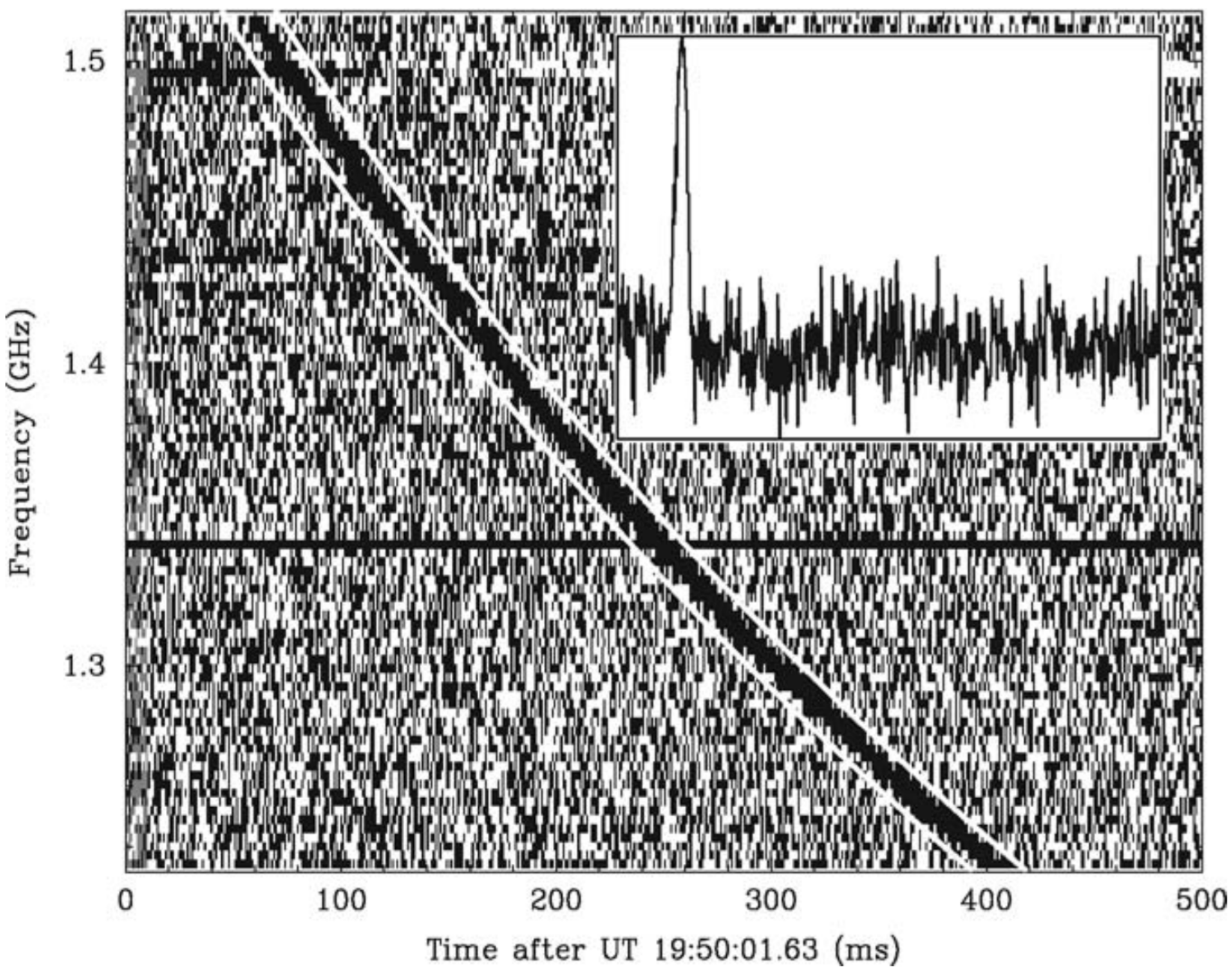
Collaborators: Bing Zhang (UNLV), Zi-Gao Dai (NJU), Zhuo Li (PKU) & Rui Luo (PKU)

2017/04/27 @ Qiannan, Guizhou

Outline

- Applications and statistical properties of FRB DM
    - FRB as cosmological probe
    - Extracting host-galaxy DM
    - FRB’s DM variation
- Association between FRB and its nebula

Dispersion Measure



Lorimer +, 2007, Science

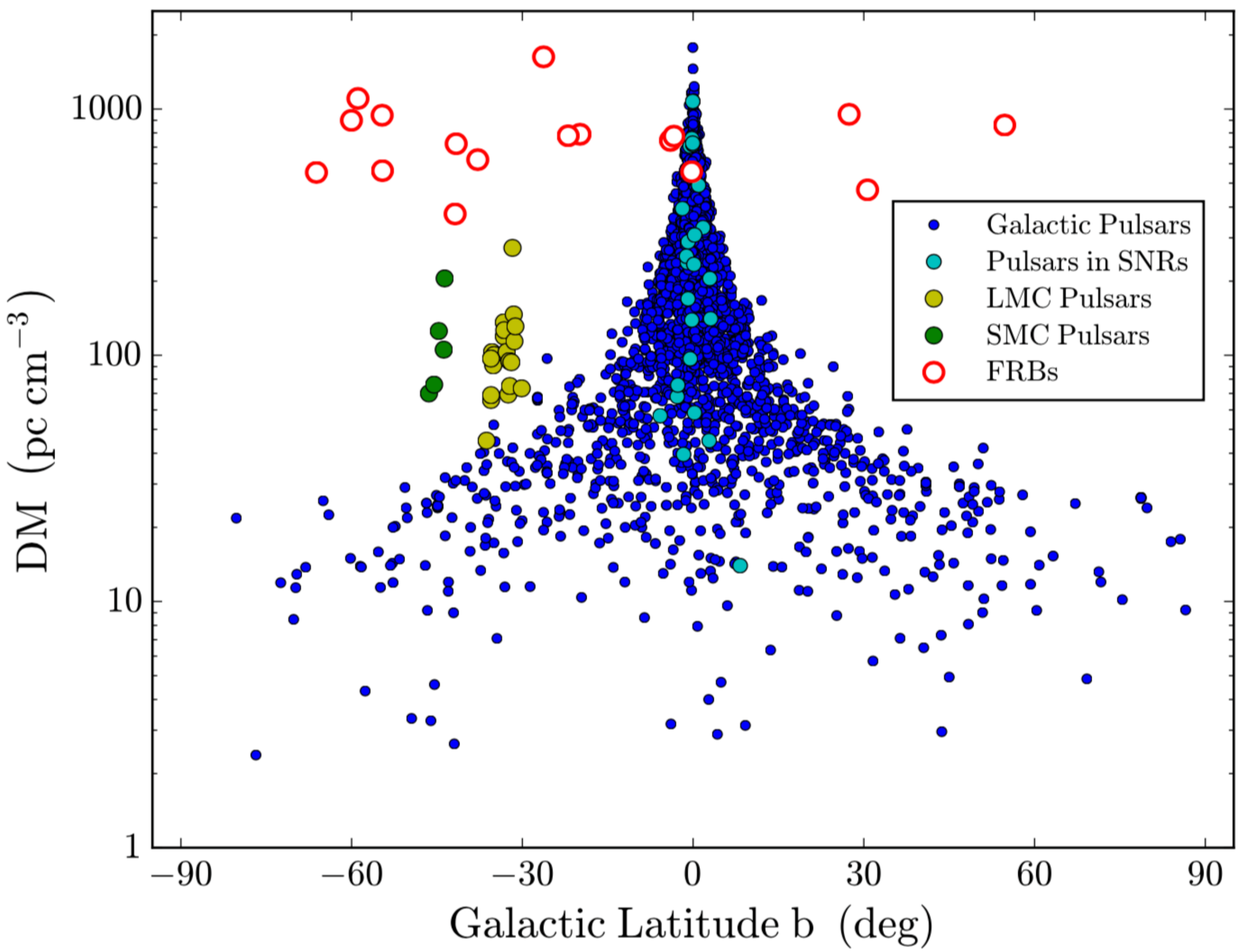
Delay time:

$$t_2 - t_1 = 4.15 \text{ ms } \mathrm{DM} \left[\left(\frac{\nu_1}{1 \text{ GHz}} \right)^{-2} - \left(\frac{\nu_2}{1 \text{ GHz}} \right)^{-2} \right]$$

DM definition:

$$\mathrm{DM} \equiv \int_0^L n_e dl \equiv \langle n_e \rangle L$$

DM of FRB

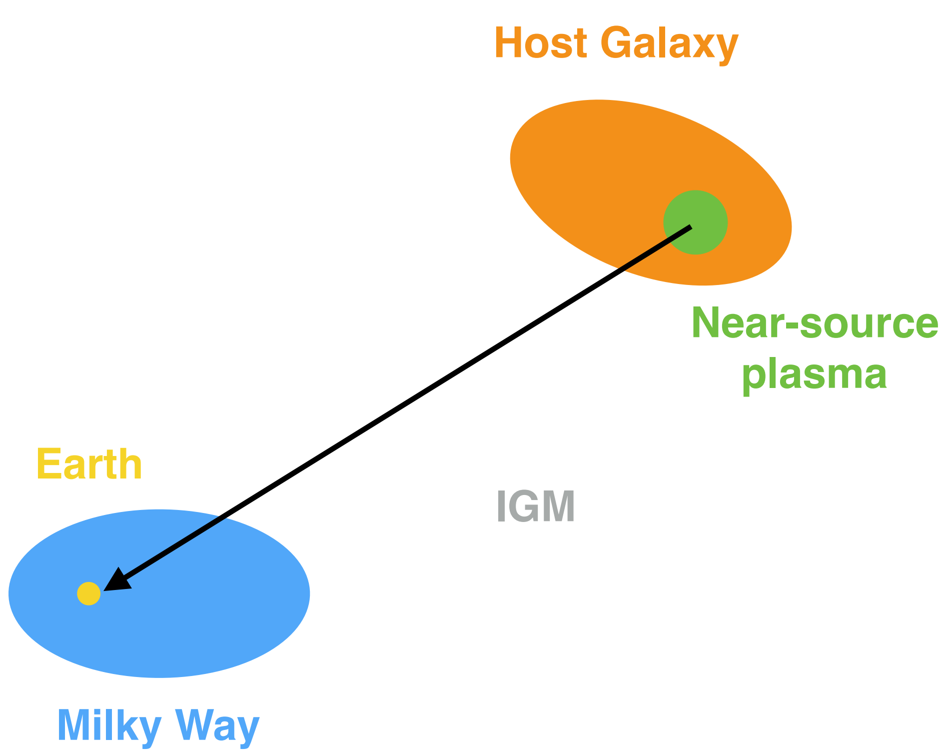


Cordes +, 2016, ApJ

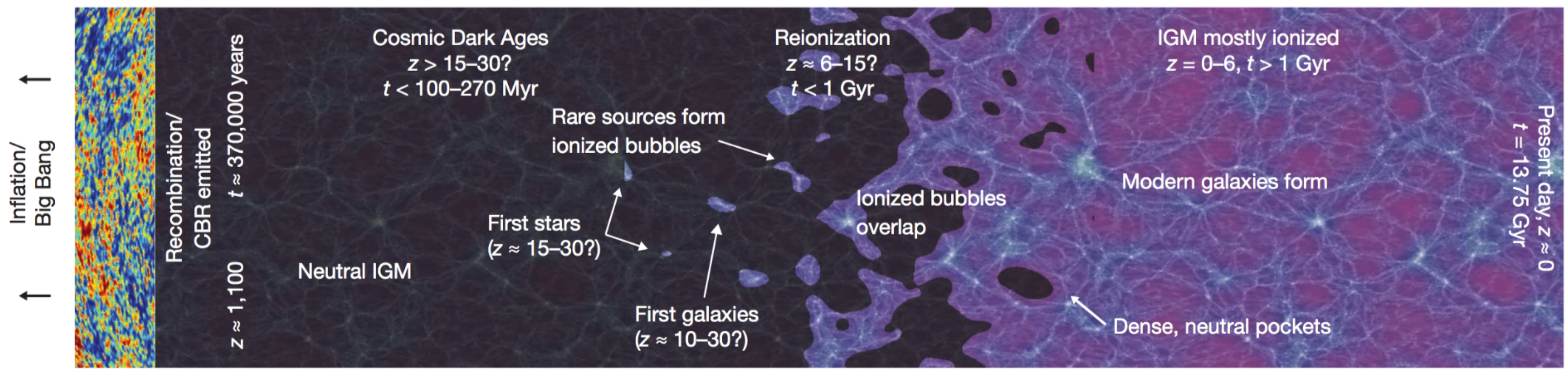
DM contributions:

$$\mathrm{DM_{obs}} = \mathrm{DM_{MW}} + \mathrm{DM_{HG}} + \mathrm{DM_{IGM}}$$

$$\boxed{\mathrm{DM_E} \equiv \mathrm{DM_{obs}} - \mathrm{DM_{MW}} = \mathrm{DM_{IGM}} + \mathrm{DM_{HG}}}$$



IGM DM



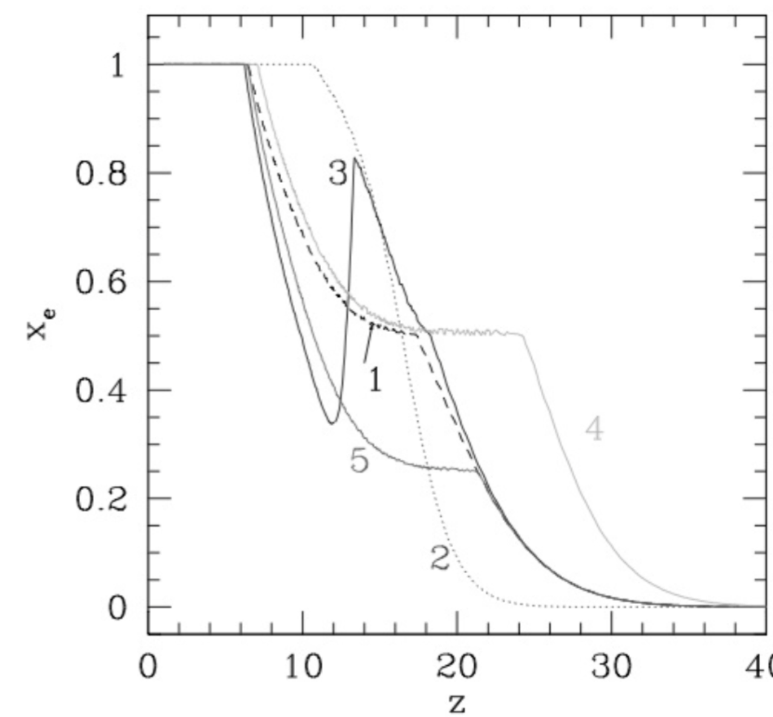
Robertson +, 2010, Nature

The mean DM of the IGM : (Deng & Zhang, 2014)

$$\langle \mathrm{DM_{IGM}} \rangle = K_{\mathrm{IGM}} \int_0^z \frac{f_e(z')(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz', \quad K_{\mathrm{IGM}} \equiv \frac{3cH_0 \Omega_b f_{\mathrm{IGM}}}{8\pi G m_p}$$

$$f_e = \frac{n_{e,\mathrm{free}}}{n_p + n_n} \simeq \frac{7}{8} \quad (n_{e,\mathrm{free}} \simeq n_e) \quad \text{at } z < 3$$

$$f_{\mathrm{IGM}} = 0.83$$ (Fukugita et al. 1998; Shull et al. 2012)

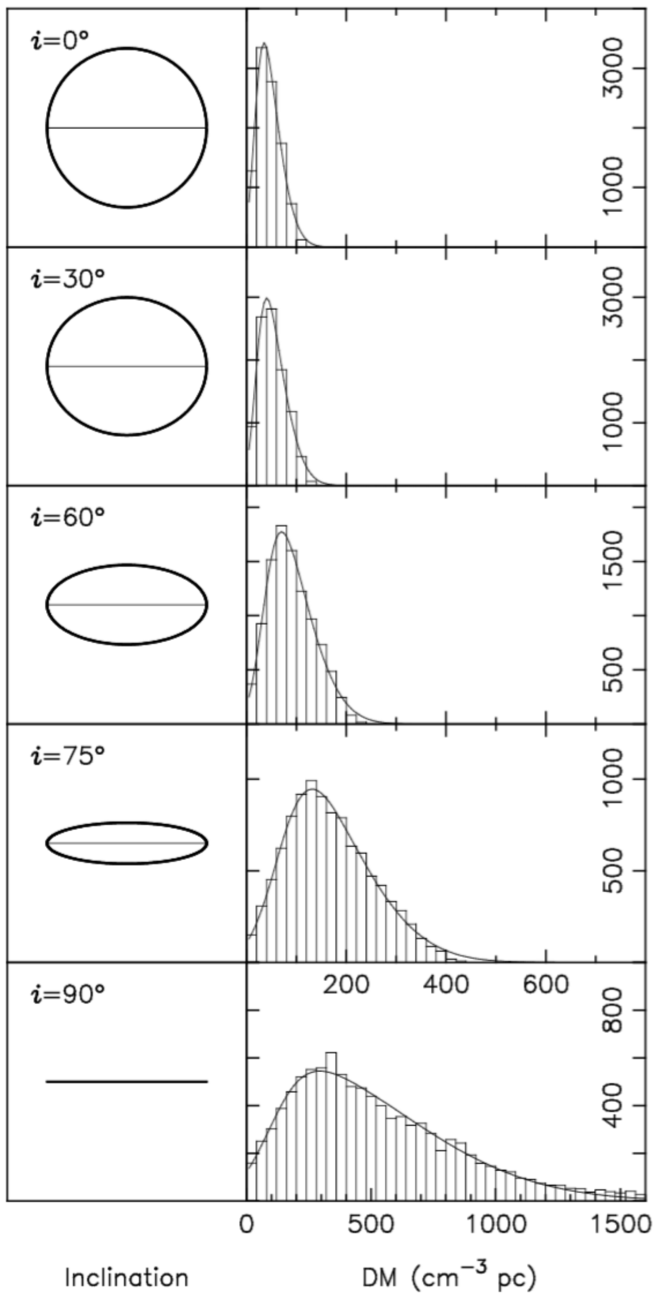


Holder +, 2003, ApJ

Host-galaxy DM

- Host-galaxy DM includes the contributions from the ISM and a near-source plasma
- Depend on the type of the host galaxy, the site of FRB in the host galaxy, the inclination angle of the galaxy disk, and the near-source plasma contribution
- Due to cosmological time dilation, the observed host DM is less than the local one, e.g.

$$\mathrm{DM_{HG}} = \mathrm{DM_{HG,loc}}/(1+z)$$



Xu & Han, 2015, RAA

FRB as cosmological probe

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EXTRACTING HOST GALAXY DISPERSION MEASURE AND CONSTRAINING COSMOLOGICAL PARAMETERS USING FAST RADIO BURST DATA

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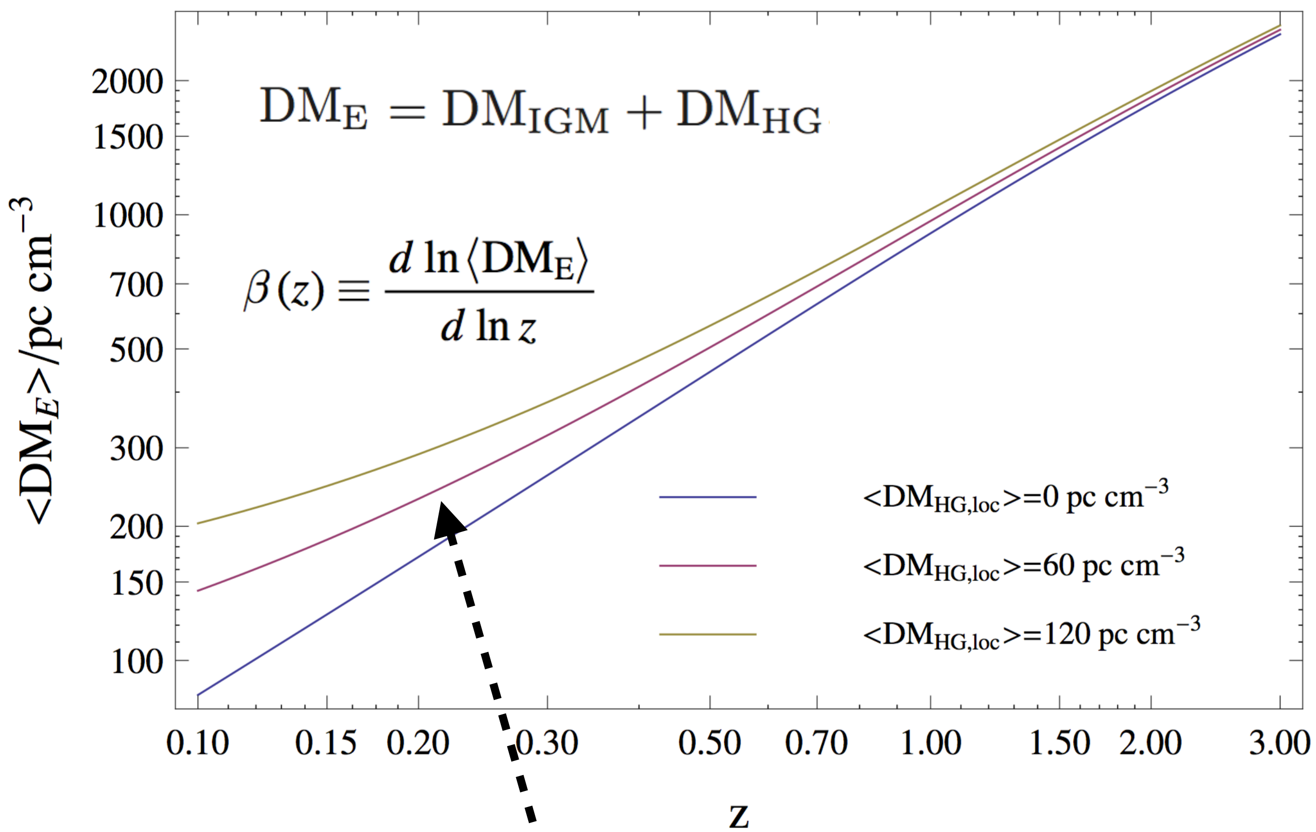
ABSTRACT

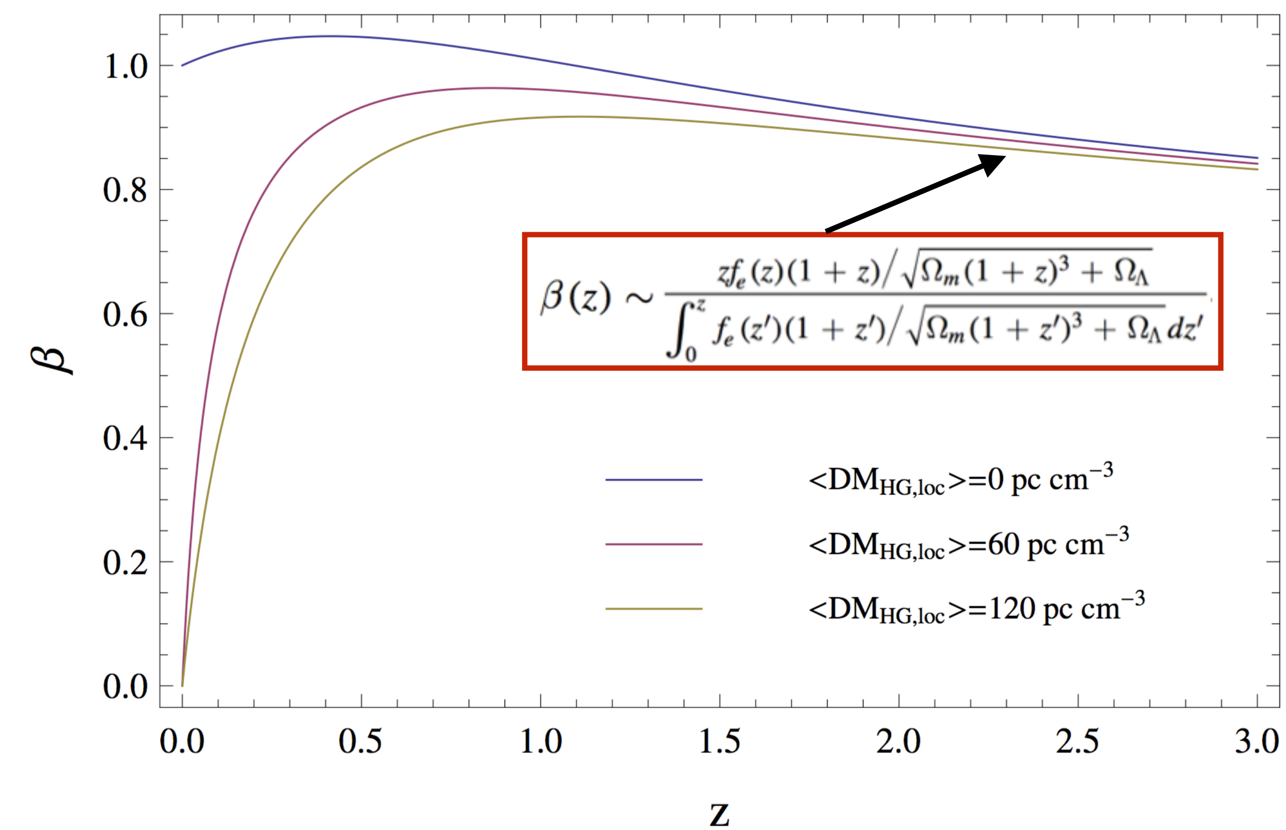
The excessive dispersion measures (DMs) and high Galactic latitudes of fast radio bursts (FRBs) hint toward a cosmological origin of these mysterious transients. Methods of using measured DM and redshift z to study cosmology have been proposed, but one needs to assume a certain amount of DM contribution from the host galaxy ($\mathrm{DM_{HG}}$) in order to apply those methods. We introduce a slope parameter $\beta(z) \equiv d\ln\langle \mathrm{DM_E}\rangle/d\ln z$ (where $\mathrm{DM_E}$ is the observed DM subtracting the Galactic contribution), which can be directly measured when a sample of FRBs have z measured. We show that $\langle \mathrm{DM_{HG}}\rangle$ can be roughly inferred from β and the mean values, $\overline{\langle \mathrm{DM_E}\rangle}$ and $\bar{z}$, of the sample. Through Monte Carlo simulations, we show that the mean value of local host galaxy DM, $\langle \mathrm{DM_{HG,loc}}\rangle$, along with other cosmological parameters (mass density Ω_m in the ΛCDM model, and the IGM portion of the baryon energy density $\Omega_b f_{\mathrm{IGM}}$), can be independently measured through Markov Chain Monte Carlo fitting to the data.

Key words: cosmological parameters – intergalactic medium

DM-z relation

Yang & Zhang, 2016, ApJL



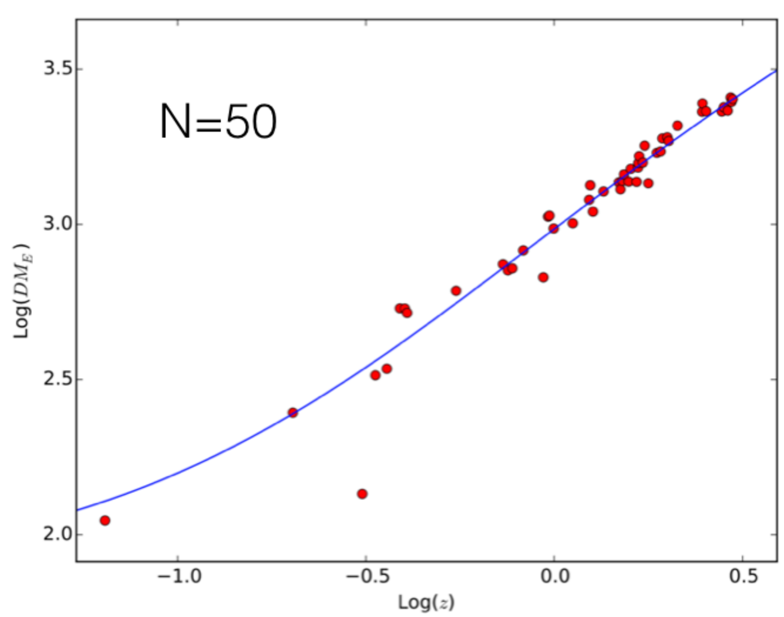


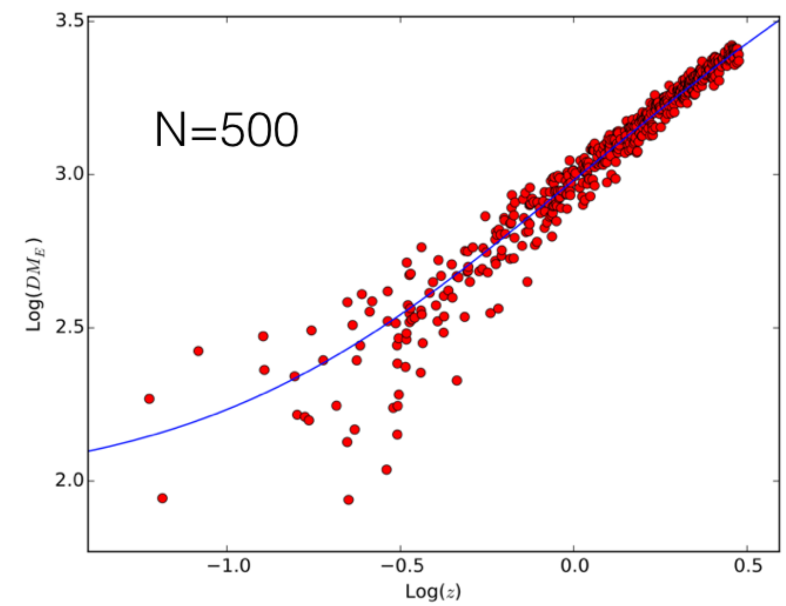
$$\langle \mathrm{DM_{HG,loc}}\rangle \simeq \frac{(1-\bar{\beta})(1+\bar{z})^2}{1+2\bar{z}}\overline{\langle \mathrm{DM_E}\rangle} \simeq (1-\bar{\beta})\overline{\langle \mathrm{DM_E}\rangle}. \quad \text{for } z \ll 1$$

- As a result, the three unknown parameters, $\mathrm{DM_{HG,loc}}$, Ω_m, and K_{IGM}, are defined by different properties of the $\log \mathrm{DM_E} - \log z$ plot, and therefore they can be independently inferred from the $(\langle \mathrm{DM_E}\rangle, z)$ data of a sample of FRBs.

FRB cosmology

Yang & Zhang, 2016, ApJL

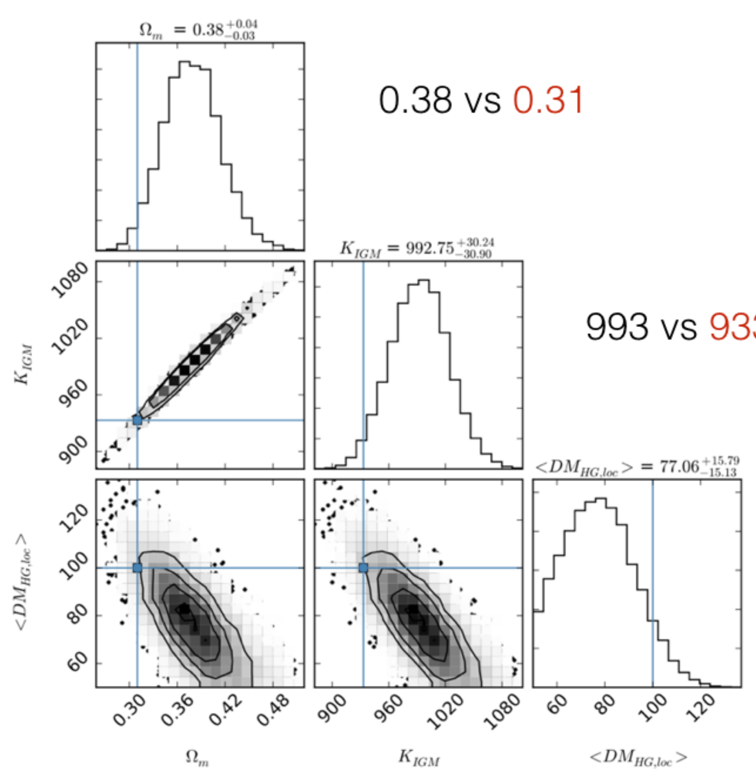




Ω_m

K_{IGM}

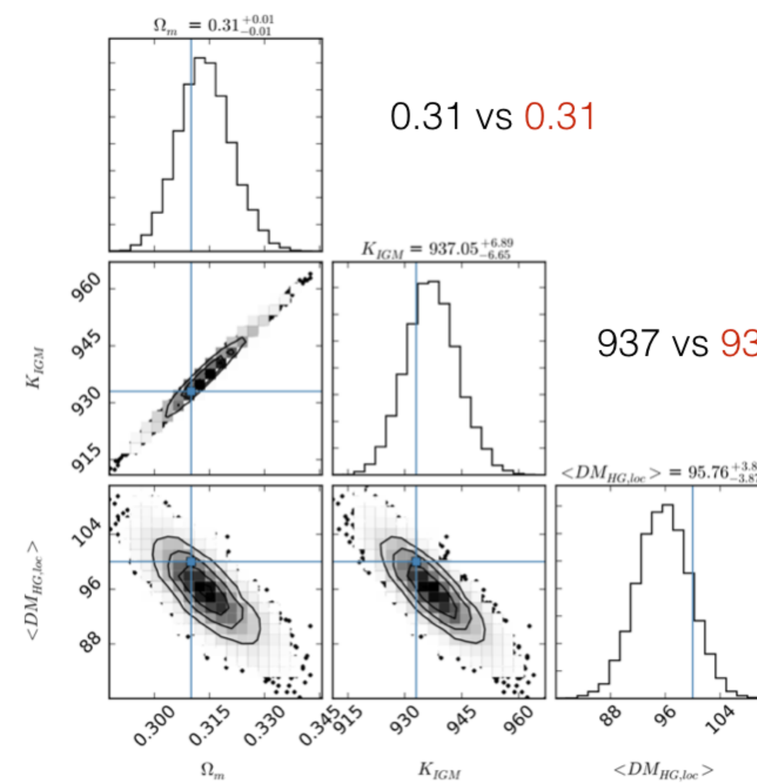
$DM_{HG,loc}$



0.38 vs 0.31

993 vs 933

77 vs 100

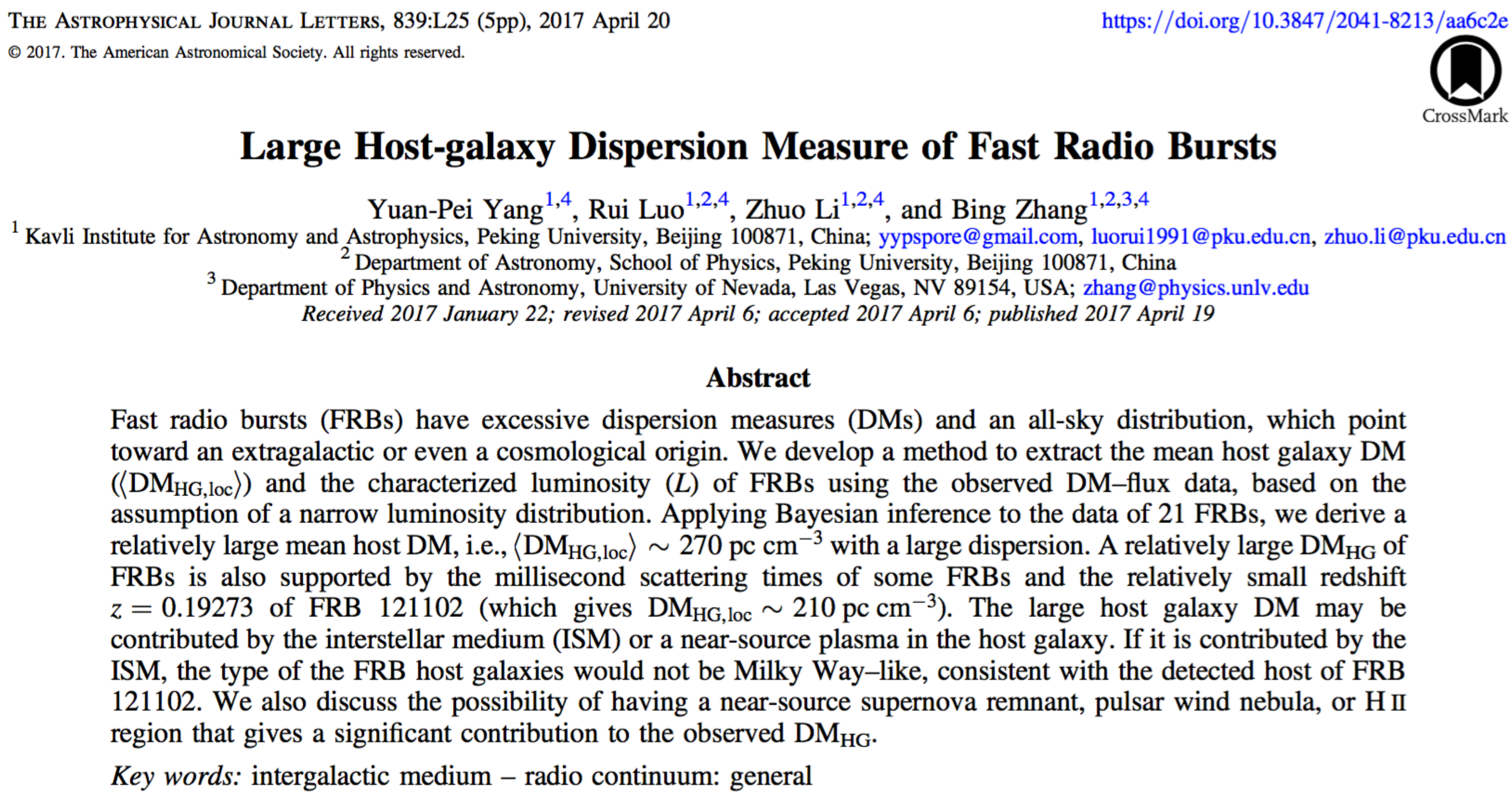


0.31 vs 0.31

937 vs 933

96 vs 100

Extracting host-galaxy DM of FRBs



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Large Host-galaxy Dispersion Measure of Fast Radio Bursts

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Abstract

Fast radio bursts (FRBs) have excessive dispersion measures (DMs) and an all-sky distribution, which point toward an extragalactic or even a cosmological origin. We develop a method to extract the mean host galaxy DM ($\langle \mathrm{DM}_{\mathrm{HG,loc}} \rangle$) and the characterized luminosity (L) of FRBs using the observed DM–flux data, based on the assumption of a narrow luminosity distribution. Applying Bayesian inference to the data of 21 FRBs, we derive a relatively large mean host DM, i.e., $\langle \mathrm{DM}_{\mathrm{HG,loc}} \rangle \sim 270\ \mathrm{pc\ cm^{-3}}$ with a large dispersion. A relatively large $\mathrm{DM}_{\mathrm{HG}}$ of FRBs is also supported by the millisecond scattering times of some FRBs and the relatively small redshift $z = 0.19273$ of FRB 121102 (which gives $\mathrm{DM}_{\mathrm{HG,loc}} \sim 210\ \mathrm{pc\ cm^{-3}}$). The large host galaxy DM may be contributed by the interstellar medium (ISM) or a near-source plasma in the host galaxy. If it is contributed by the ISM, the type of the FRB host galaxies would not be Milky Way–like, consistent with the detected host of FRB 121102. We also discuss the possibility of having a near-source supernova remnant, pulsar wind nebula, or H II region that gives a significant contribution to the observed $\mathrm{DM}_{\mathrm{HG}}$.

Key words: intergalactic medium – radio continuum: general

Current 21 FRBs

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]
FRB010125	parkes	356.641	-20.020	0.25	790(3)	17	$9.40^{+0.20}_{-0.20}$	0.30	2.82
FRB010621	parkes	25.433	-4.003	0.25	745(10)		7.00	0.41	2.87
FRB010724	parkes	300.653	-41.805	0.25	375	23	5.00	$>30.00^{+10.00}_{-10.00}$	>150.00
FRB090625	parkes	226.443	-60.030	0.25	899.55(1)	30	$1.92^{+0.83}_{-0.77}$	$1.14^{+0.42}_{-0.21}$	$2.19^{+2.10}_{-1.12}$
FRB110220	parkes	50.828	-54.766	0.25	944.38(5)	49	$5.60^{+0.10}_{-0.10}$	$1.30^{+0.00}_{-0.00}$	$7.28^{+0.13}_{-0.13}$
FRB110523	GBT	56.119	-37.819	0.26	623.30(6)	42	$1.73^{+0.17}_{-0.17}$	0.60	1.04
FRB110626	parkes	355.861	-41.752	0.25	723.0(3)	11	1.40	0.40	0.56
FRB110703	parkes	80.997	-59.019	0.25	1103.6(7)	16	4.30	0.50	2.15
FRB120127	parkes	49.287	-66.203	0.25	553.3(3)	11	1.10	0.50	0.55
FRB121002	parkes	308.219	-26.264	0.25	1629.18(2)	16	$5.44^{+3.50}_{-1.20}$	$0.43^{+0.33}_{-0.06}$	$2.34^{+4.46}_{-0.77}$
FRB121102	arecibo	174.950	-0.225	0.05	557(2)	14	$3.00^{+0.50}_{-0.50}$	$0.40^{+0.40}_{-0.10}$	$1.20^{+1.60}_{-0.45}$
FRB130626	parkes	7.450	27.420	0.25	952.4(1)	21	$1.98^{+1.20}_{-0.44}$	$0.74^{+0.49}_{-0.11}$	$1.47^{+2.45}_{-0.50}$
FRB130628	parkes	225.955	30.655	0.25	469.88(1)	29	$0.64^{+0.13}_{-0.13}$	$1.91^{+0.29}_{-0.23}$	$1.22^{+0.47}_{-0.37}$
FRB130729	parkes	324.787	54.744	0.25	861(2)	14	$15.61^{+9.98}_{-6.27}$	$0.22^{+0.17}_{-0.05}$	$3.43^{+6.55}_{-1.81}$
FRB131104	parkes	260.549	-21.925	0.25	779(1)	30	2.08	1.12	2.33
FRB140514	parkes	50.841	-54.611	0.25	562.7(6)	16	$2.80^{+3.50}_{-0.70}$	$0.47^{+0.11}_{-0.08}$	$1.32^{+2.34}_{-0.50}$
FRB150418	parkes	232.665	-3.234	0.25	776.2(5)	39	$0.80^{+0.30}_{-0.30}$	$2.20^{+0.60}_{-0.30}$	$1.76^{+1.32}_{-0.81}$
FRB150807	parkes	336.709	-54.400	0.25	266.5(1)		$0.35^{+0.05}_{-0.05}$	$128.00^{+5.00}_{-5.00}$	$44.80^{+8.40}_{-7.90}$
FRB160317	UTMOST	246.050	-0.990	0.00	1165(11)	13	$21.00^{+7.00}_{-7.00}$	>3.00	>63.00
FRB160410	UTMOST	220.360	27.190	0.00	278(3)	13	$4.00^{+1.00}_{-1.00}$	>7.00	>28.00
FRB160608	UTMOST	254.110	-9.539	0.00	682(7)	12	$9.00^{+6.00}_{-6.00}$	>4.30	>38.70

$\mathrm{DM_E} \equiv \mathrm{DM_{obs}} - \mathrm{DM_{MW}}$ (*NE2001*)

http://www.astronomy.swin.edu.au/pulsar/frbcat/ **(Petroff et al., 2016)**

DM-Flux relation

Mean value of a narrow luminosity function

- The luminosity distance of the FRB is given by

$$d_L \simeq \left(\frac{L}{4\pi\nu \underline{F_\nu}}\right)^{1/2} = \frac{c}{H_0}(1+z)\int_0^z \frac{1}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz'$$

Eliminate z

- The extragalactic DM is given by

$$\underline{\langle \mathrm{DM_E}\rangle} = \frac{3cH_0\Omega_b f_{\mathrm{IGM}}}{8\pi G m_p}\int_0^z \frac{f_e(z')(1+z')}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz' + \frac{\langle \mathrm{DM_{HG,loc}}\rangle}{1+z}$$

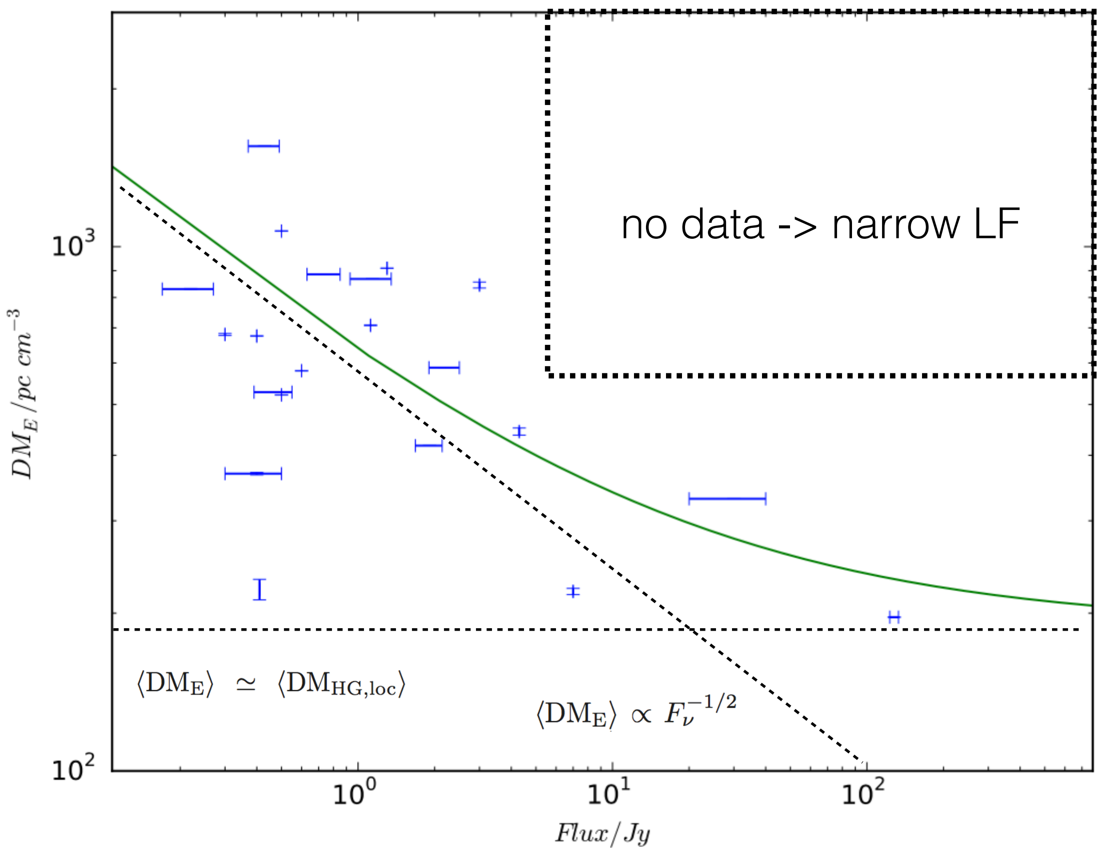
- One has

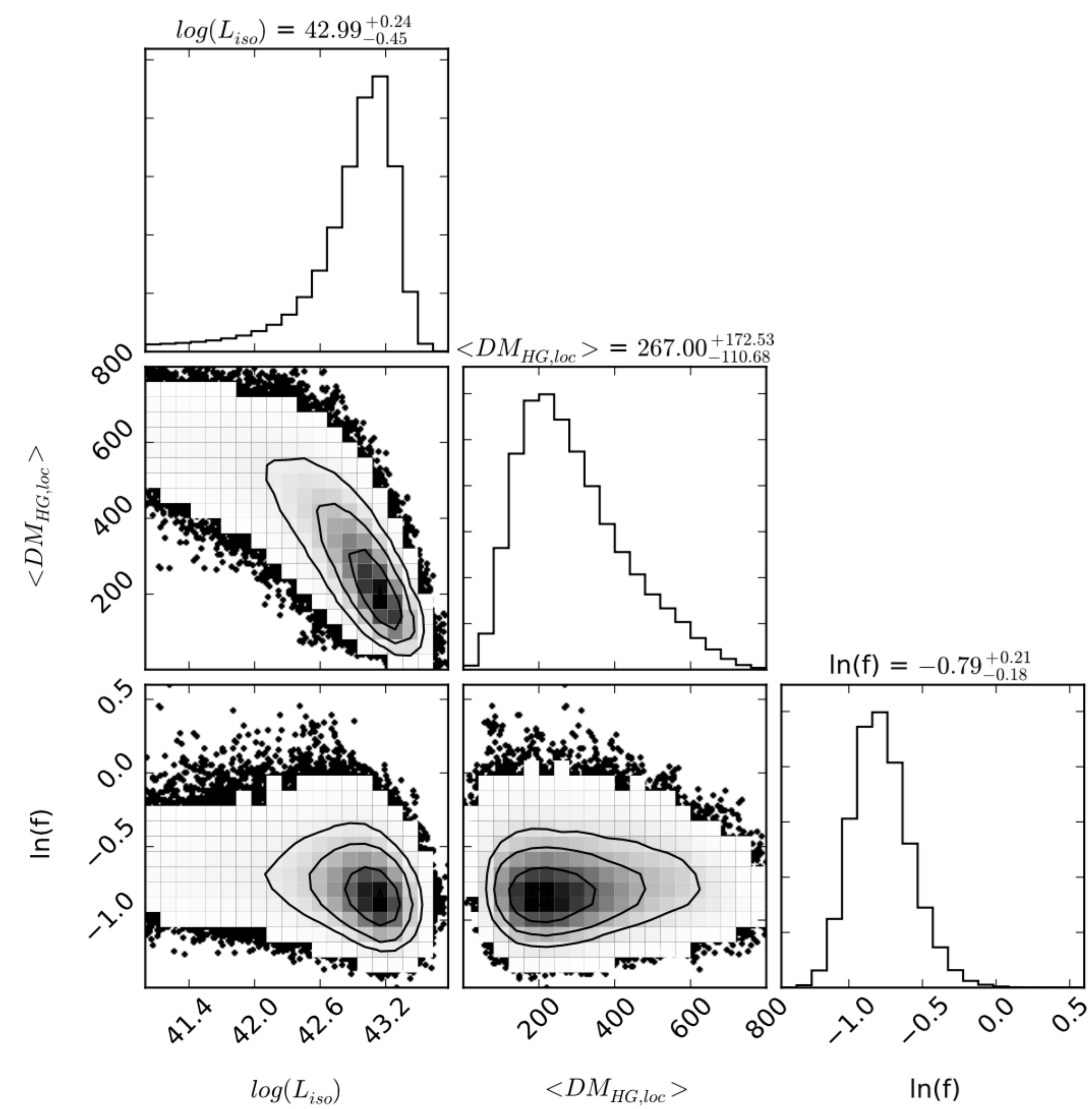
$$\boxed{\begin{aligned} &\langle \mathrm{DM_E}\rangle \propto F_\nu^{-1/2} \ \text{for}\ F_\nu \ll F_{\nu,\mathrm{crit}} \\ &\langle \mathrm{DM_E}\rangle \simeq \langle \mathrm{DM_{HG,loc}}\rangle \ \text{for}\ F_\nu \gg F_{\nu,\mathrm{crit}} \end{aligned}}$$

Best Fitting

$$\log(L_{\rm iso}/{\rm erg\ s^{-1}}) = 42.99^{+0.24}_{-0.45}$$

$$\langle {\rm DM_{HG,loc}} \rangle = 267.00^{+172.53}_{-110.68}\ {\rm pc\ cm^{-3}}$$



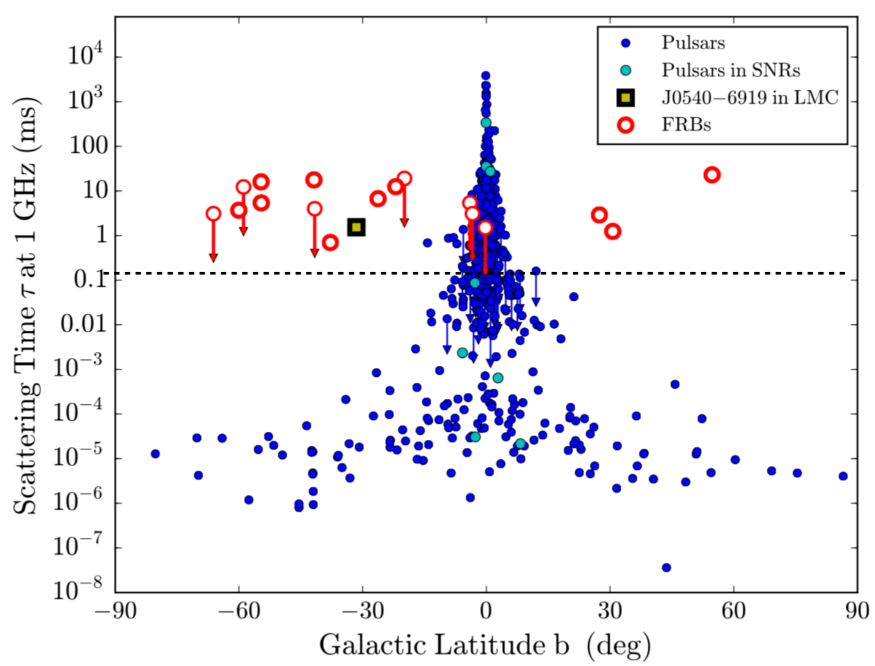


Yang, Luo, Li & Zhang, 2017, ApJL

Two Other Pieces of Evidences

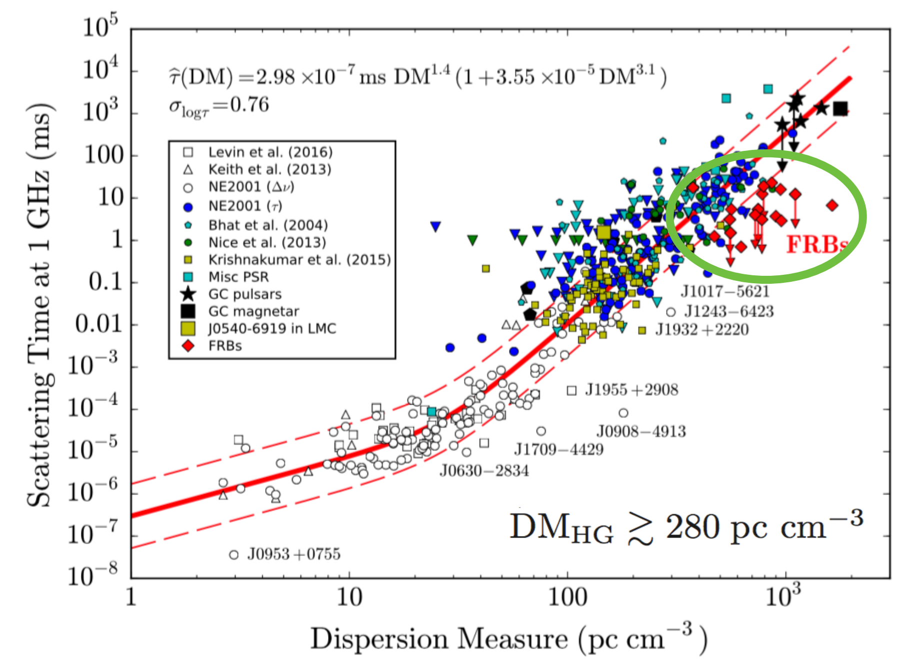
- Scattering Time:

Cordes +, 2016, ApJ



Scattering happens outside MW

IGM contribution is small (Xu & Zhang, 2016)



- FRB 121102 with redshift $z = 0.19273$ $\mathrm{DM_{IGM}} \simeq 164\ \mathrm{pc\ cm^{-3}}$ $\mathrm{DM_{MW}} \simeq 218\ \mathrm{pc\ cm^{-3}}$

$$\boxed{f_{\mathrm{IGM}} = 0.83}$$

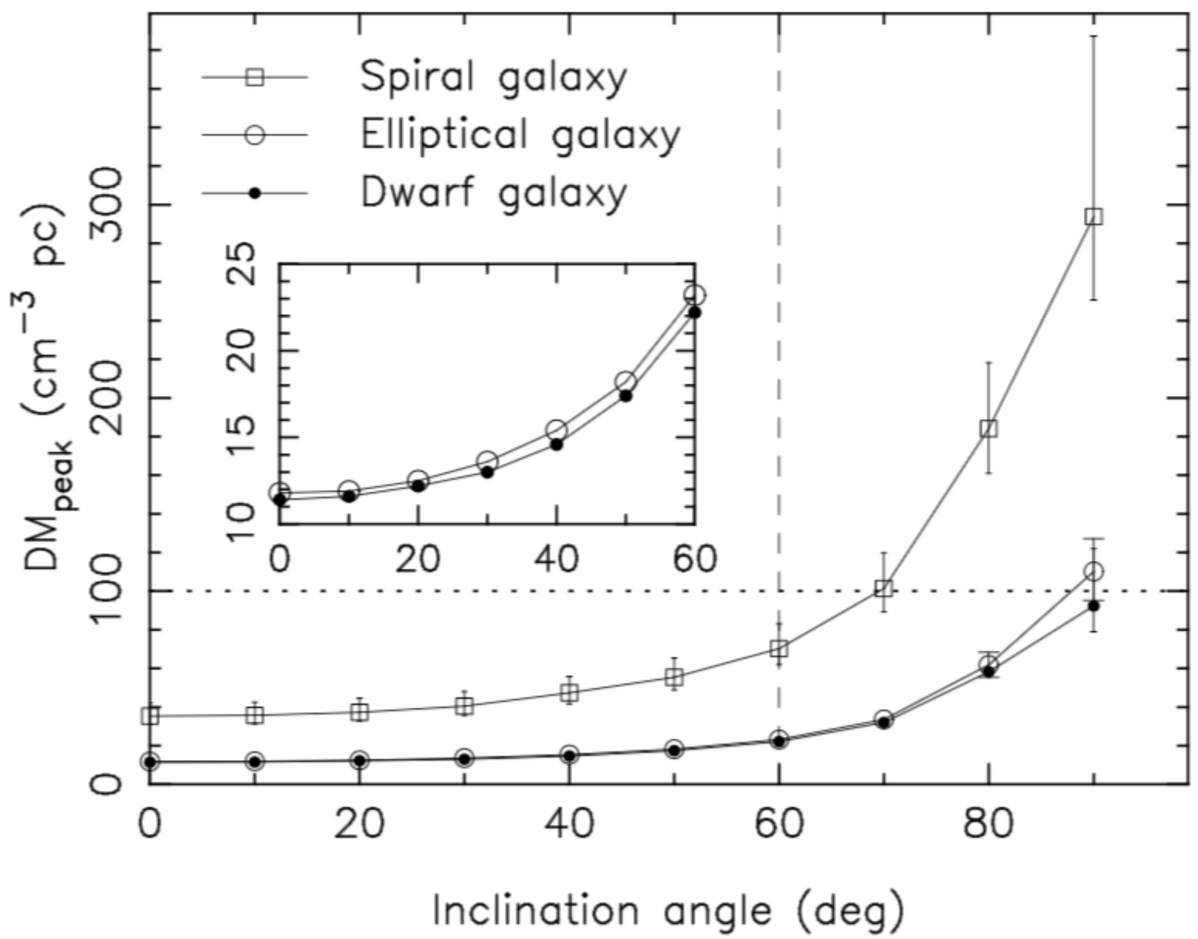
$$\mathrm{DM_{HG}} = \mathrm{DM_{obs}} - \mathrm{DM_{MW}} - \mathrm{DM_{IGM}} \simeq 176\ \mathrm{pc\ cm^{-3}}$$

$$\mathrm{DM_{HG,loc}} = (1+z)\mathrm{DM_{HG}} \simeq 210\ \mathrm{pc\ cm^{-3}}$$

Large DM Contribution

- Two possible contributions to such a large DM: the ISM and the near-source plasma in the host galaxy.

- Our result is somewhat larger than the ISM contribution in the host (Xu & Han 2015), suggesting that *a near-source plasma may be needed, e.g. SNR, PWN or HII region*



Xu & Han, 2015, RAA

DM variation of FRBs

DM Variation

No.	Barycentric peak time (MJD)	Peak flux density (Jy)	Fluence (Jy-ms)	Gaussian width (ms)	Spectral index	DM (pc cm^{-3})
1	56233.282837008	0.04	0.1	3.3±0.3	8.8±1.9	553±5±2
2	57159.737600835	0.03	0.1	3.8±0.4	2.5±1.7	560±2±2
3	57159.744223619	0.03	0.1	3.3±0.4	0.9±2.0	566±5±2
4	57175.693143232	0.04	0.2	4.6±0.3	5.8±1.4	555±1±2
5	57175.699727826	0.02	0.09	8.7±1.5	1.6±2.5	558±6±4
6	57175.742576706	0.02	0.06	2.8±0.4		559±9±1
7	57175.742839344	0.02	0.06	6.1±1.4	-3.7±1.8	
8	57175.743510388	0.14	0.9	6.6±0.1		556.5±0.7±3
9	57175.745665832	0.05	0.3	6.0±0.3	-10.4±1.1	557.4±0.7±3
10	57175.747624851	0.05	0.2	8.0±0.5		558.7±0.9±4
11	57175.748287265	0.31	1.0	3.06±0.04	13.6±0.4	556.5±0.1±1
12	57339.356046005567	0.04	0.2	6.73 ± 1.12		559.9 ± 3.4 ± 3.7
13	57345.447691250090	0.06	0.4	6.10 ± 0.57		565.1 ± 1.8 ± 3.4
14	57345.452487925162	0.04	0.2	6.14 ± 1.00		568.8 ± 3.2 ± 3.4
15	57345.457595303807	0.02	0.08	4.30 ± 1.40		–
16	57345.462413106565	0.09	0.6	5.97 ± 0.35		560.0 ± 3.1 ± 3.3
17	57364.204632665605	0.03	0.09	2.50 ± 0.23		558.6 ± 0.3 ± 1.4

Spitler+, 2016, Nature; Scholz+, 2016, ApJ

no significant evolution

DM variation contribution

- **Cosmological expansion**

not depend on $(\Omega_m, \Omega_\Lambda)$

$$\dot{\mathrm{DM}}_{\mathrm{IGM}} = -\frac{3cH_0^2\Omega_{\mathrm{b}}f_{\mathrm{IGM}}f_e}{8\pi G m_p}(1+z)^2 \simeq \boxed{-5.6\times10^{-8}(1+z)^2}\ \mathrm{pc\ cm^{-3}yr^{-1}}$$

- **Large-scale structure (LLS) fluctuation**

  - Gravitational potential fluctuation

$$\dot{\mathrm{DM}}_{\mathrm{LSS,G}} \simeq \boxed{3\times10^{-13}\ \mathrm{pc\ cm^{-3}yr^{-1}}}\left(\frac{U_{\mathrm{LSS}}}{2.2\times10^{16}\ \mathrm{cm^2s^{-2}}}\right)\left(\frac{D}{1\ \mathrm{Gpc}}\right)$$

  - Gas density fluctuation $\tau_{\mathrm{cluster}} \sim \tau_{\mathrm{group}} \sim 0.03$

    - clusters or groups $\dot{\mathrm{DM}} \simeq \boxed{5\times10^{-9}\ \mathrm{pc\ cm^{-3}yr^{-1}}}\left(\frac{\delta n_e}{10^{-5}\ \mathrm{cm^{-3}}}\right)\left(\frac{v_p}{500\ \mathrm{km\ s^{-1}}}\right)$

Yang & Zhang, 2017, in preparation

DM variation contribution

- **Interstellar medium** $\dot{\mathrm{DM}}_{\mathrm{ISM}} \simeq \boxed{5\times10^{-5}\ \mathrm{pc\ cm^{-3}yr^{-1}}}\left(\frac{\delta n_e}{0.1\ \mathrm{cm^{-3}}}\right)\left(\frac{v}{500\ \mathrm{km\ s^{-1}}}\right)$
- **Local plasma**
  - Supernova remnant $\dot{\mathrm{DM}}_{\mathrm{SNR}} = \boxed{16.7\ \mathrm{pc\ cm^{-3}yr^{-1}}}\frac{M}{M_\odot}\left(\frac{R}{0.1\ \mathrm{pc}}\right)^{-3}\left(\frac{v}{3000\ \mathrm{km\ s^{-1}}}\right)$
  - Pulsar wind nebula $\dot{\mathrm{DM}}_{\mathrm{w}} \simeq \boxed{0.46\ \mathrm{pc\ cm^{-3}yr^{-1}}}\left(\frac{\mu}{10^6}\right)^{2/3}\left(\frac{B_p}{10^{14}\ \mathrm{G}}\right)^{10/3}\left(\frac{P}{0.3\ \mathrm{s}}\right)^{-17/3}$
  - HII region
    - *Source in HII* $\dot{\mathrm{DM}}_{\mathrm{HII}} \simeq \boxed{0.1\ \mathrm{pc\ cm^{-3}yr^{-1}}}\left(\frac{n}{100\ \mathrm{cm^{-3}}}\right)\left(\frac{v}{1000\ \mathrm{km\ s^{-1}}}\right)$
    - *Expanding HII* $\dot{\mathrm{DM}}_{\mathrm{HII}} \simeq \boxed{0.78\ \mathrm{pc\ cm^{-3}yr^{-1}}}\left(\frac{N_u}{5\times10^{49}\ \mathrm{s^{-1}}}\right)^{1/3}\left(\frac{n}{100\ \mathrm{cm^{-3}}}\right)^{2/3}\left(\frac{T_{\mathrm{HII}}}{100\ \mathrm{yr}}\right)^{-2/3}$

Yang & Zhang, 2017, in preparation

FRB and Nebula

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SYNCHROTRON HEATING BY A FAST RADIO BURST IN A SELF-ABSORBED SYNCHROTRON NEBULA AND ITS OBSERVATIONAL SIGNATURE

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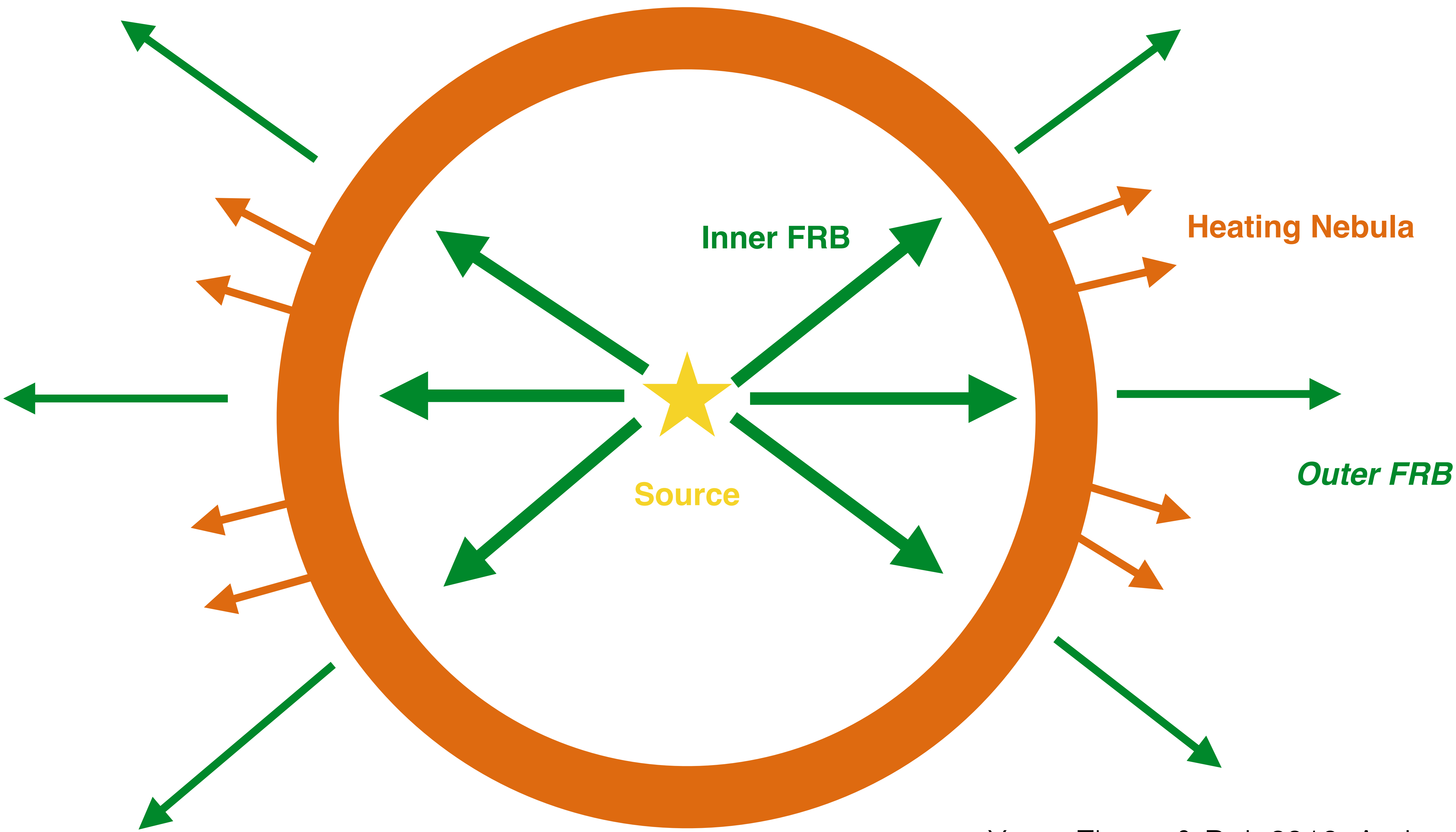
ABSTRACT

Fast radio bursts (FRBs) are mysterious transient sources. If extragalactic, as suggested by their relative large dispersion measures, their brightness temperatures must be extremely high. Some FRB models (e.g., young pulsar model, magnetar giant flare model, or supra-massive neutron star collapse model) suggest that they may be associated with a synchrotron nebula. Here we study a synchrotron-heating process by an FRB in a self-absorbed synchrotron nebula. If the FRB frequency is below the synchrotron self-absorption frequency of the nebula, electrons in the nebula would absorb FRB photons, leading to a harder electron spectrum and enhanced self-absorbed synchrotron emission. In the meantime, the FRB flux is absorbed by the nebula electrons. We calculate the spectra of FRB-heated synchrotron nebulae, and show that the nebula spectra would show a significant hump in several decades near the self-absorption frequency. Identifying such a spectral feature would reveal an embedded FRB in a synchrotron nebula.

Key words: radiation mechanisms: general – radio continuum: general

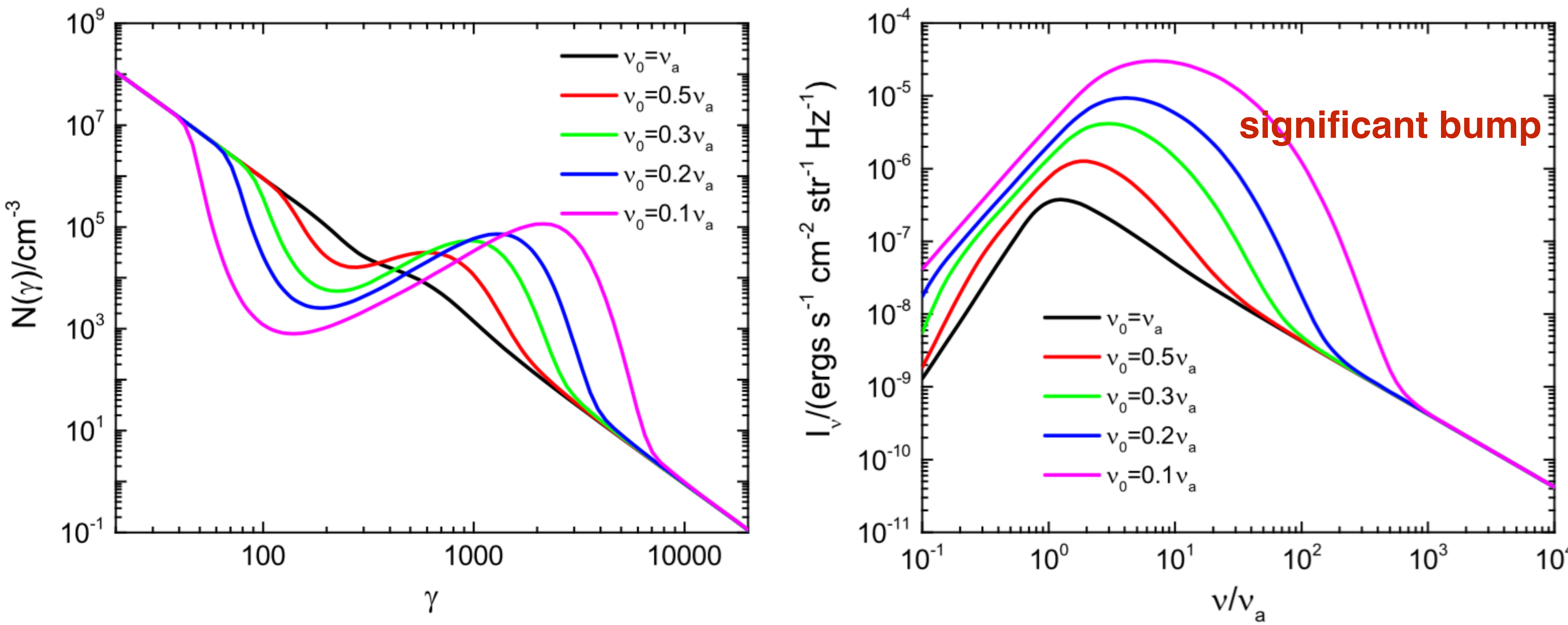
FRB Nebula



Yang, Zhang & Dai, 2016, ApJ

Synchrotron External Absorption

Yang, Zhang & Dai, 2016, ApJ



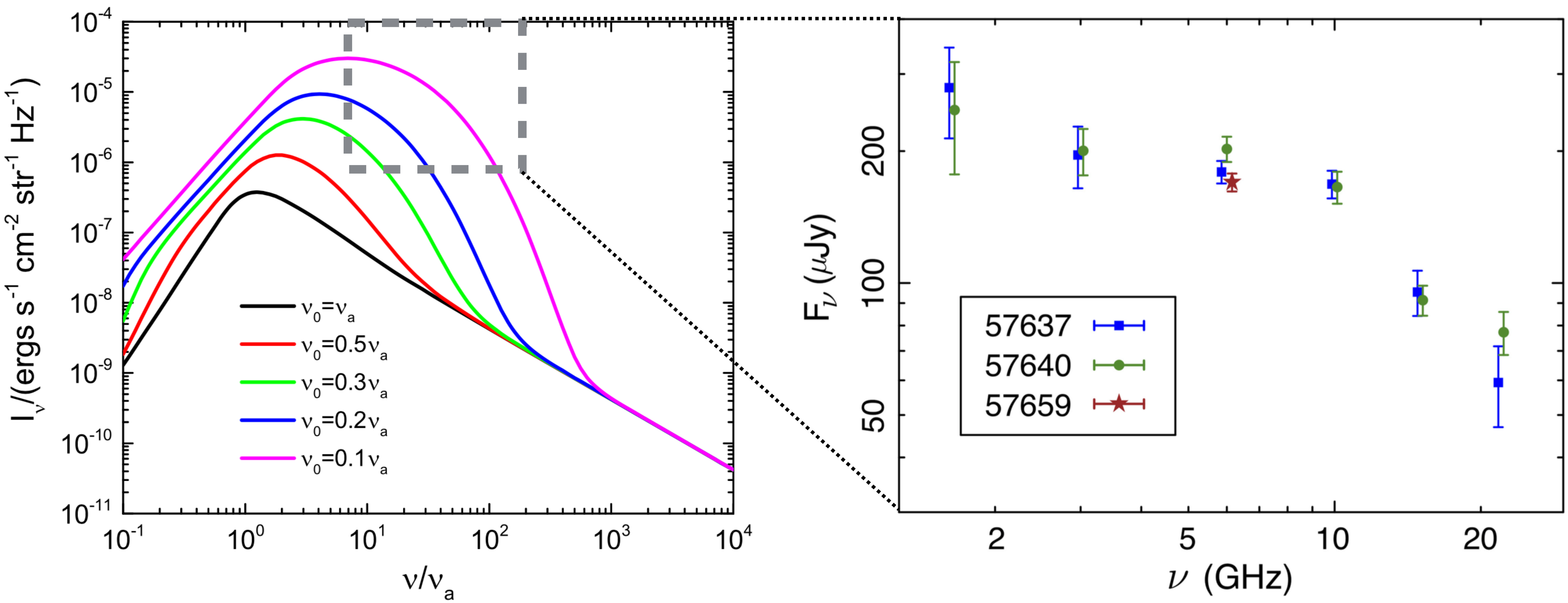
(a) (b)

As one lowers input FRB frequency, more and more nebula electrons are accelerated, leading to nebula spectra showing a significant bump

Persistent Emission of FRB 121102

Yang, Zhang & Dai, *2016*, ApJ

Chatterjee et al., *2017*, Nature

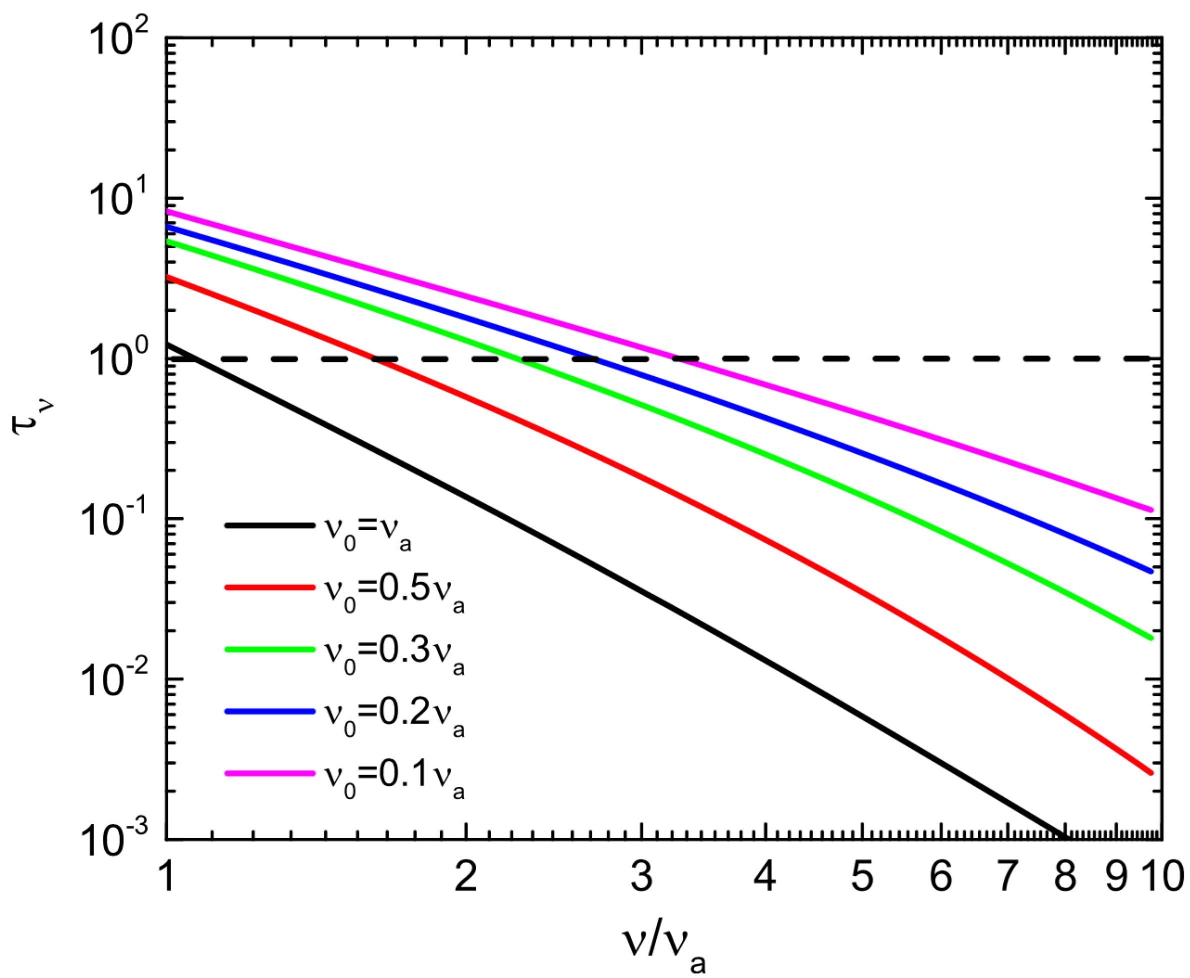


$$\nu_a \gtrsim 0.32\ \mathrm{GHz}\left(\frac{B}{0.1\ \mathrm{mG}}\right)^{1/5}\left(\frac{F_{\nu,\max}}{250\ \mu\mathrm{Jy}}\right)^{2/5}\left(\frac{R}{0.1\ \mathrm{pc}}\right)^{-4/5}\left(\frac{r}{972\ \mathrm{Mpc}}\right)^{4/5}\left(\frac{f_{\mathrm{I}}(p)}{1}\right)^{-2/5}$$

$$n \simeq 61\ \mathrm{cm}^{-3}\left(\frac{F_{\nu,\max}}{250\ \mu\mathrm{Jy}}\right)\left(\frac{r}{972\ \mathrm{Mpc}}\right)^{2}\left(\frac{B}{0.1\ \mathrm{mG}}\right)^{-1}\left(\frac{R}{0.1\ \mathrm{pc}}\right)^{-3}$$

Synchrotron Absorption for low-frequency FRB

Yang, Zhang & Dai, 2016, ApJ



Chatterjee et al., 2017, Nature

Date	ΔMJD from 57620.0	VLA flux density (mJy)	AO flux density (mJy)
23 Aug	3.74402686	120	–
02 Sep	13.67986367	670	–
02 Sep	13.69515938	25	–
07 Sep	18.49937435	63	–
12 Sep	23.45730263	326	–
14 Sep	25.42958602	39	$\lesssim 6$
15 Sep	26.46600650	50	–
17 Sep	28.43691490	86	~ 14
18 Sep	29.45175697	159	$\lesssim 6$

VLA (2.5–3.5 GHz) Arecibo (1.1–1.7 GHz)

Summary

- Cosmological parameters can be indeed extracted from a sample of FRB using MCMC fitting, even without the observation Host-galaxy DM.

- We show that the current FRB observations imply large host galaxy DM values $\langle \mathrm{DM_{HG,loc}} \rangle \gtrsim 200\ \mathrm{pc\ cm^{-3}}$

- DM variation of FRBs should be contributed by local plasma

- The persistent emission and the non-detection of low-frequency FRBs could be explained by the synchrotron absorption of FRB nebula.

Thank You!