COSMOLOGICAL IMPLICATIONS OF FAST RADIO BURST/ GAMMA-RAY BURST ASSOCIATIONS

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ApJL, 2014

And More…

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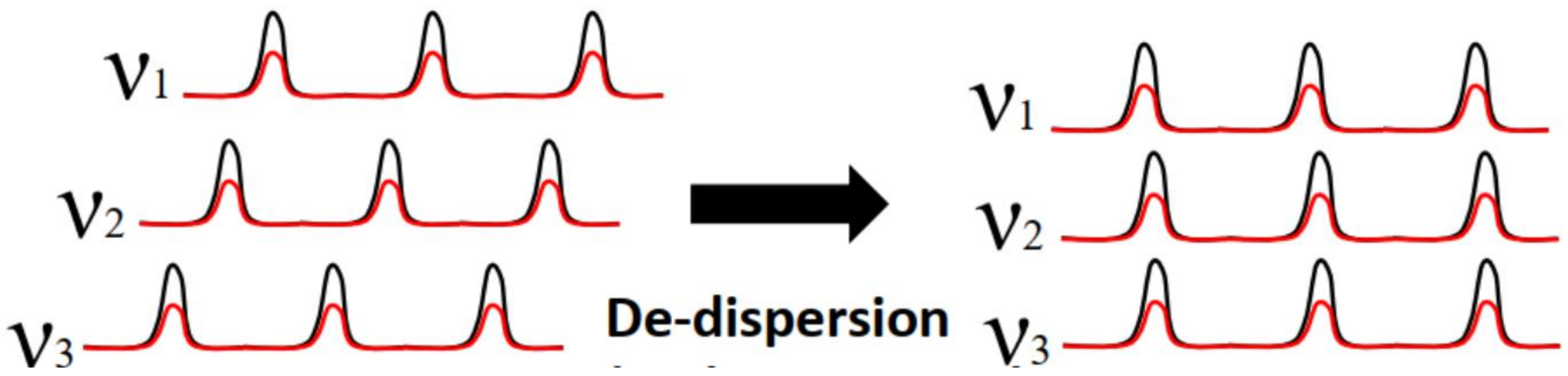
I. Introduction

FRB: Fast **Radio** Bursts
GRB: **Gamma** Ray Bursts



➔➔➔ Both from cosmological sources

FRB: **Pulse-like** signals experiencing **dispersion** during its propagation to the earth.

➔➔➔ Measure **DM** (Dispersion Measure)

$$\Delta\tau_D = \frac{e^2}{2\pi c m_e}\left[\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right]\int_0^L N(l)\,dl$$

$$DM = \int_0^\infty \left(\frac{N}{cm^{-3}}\right) d\left(\frac{l}{pc}\right)$$

From 《射电天文工具》

Measure **DM** (Dispersion Measure) ➔➔➔ Writing DM into a cosmological form

$$\mathrm{DM} = \int_0^\infty \left(\frac{N}{\mathrm{cm}^{-3}}\right) \mathrm{d}\left(\frac{l}{\mathrm{pc}}\right)$$

➔➔ DM(z, Ω, …)

Way to get redshift **z**: observations of other wavelengths…

Deng & Zhang 2014: z from GRB! ➔ Constrain Ω…

Or, Ω known, constrain z…

If FRBs associated with GRBs are observed,
They could be used to measure cosmology.

II. Equations and Analysis

Dispersion Measure (DM) z=0 version:

$$\Delta t \simeq \int \frac{dl}{c} \frac{\nu_p^2}{2\nu^2} \simeq 4.2\,\mathrm{s} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-2} \frac{\mathrm{DM}}{10^3\,\mathrm{pc\,cm^{-3}}}$$

z ≠ 0:

$$\Delta t_z = \int \frac{dl}{c} \frac{\nu_p^2}{2} \left(\frac{1}{\nu_{1,z}^2} - \frac{1}{\nu_{2,z}^2}\right)$$

$$= \frac{e^2}{2\pi m_e c} \left(\frac{1}{\nu_{1,z}^2} - \frac{1}{\nu_{2,z}^2}\right) \int n_{e,z} dl,$$

$$\int n_{e,z} dl = \mathrm{DM}_z$$

$$\Delta t = \Delta t_z \times (1+z)$$

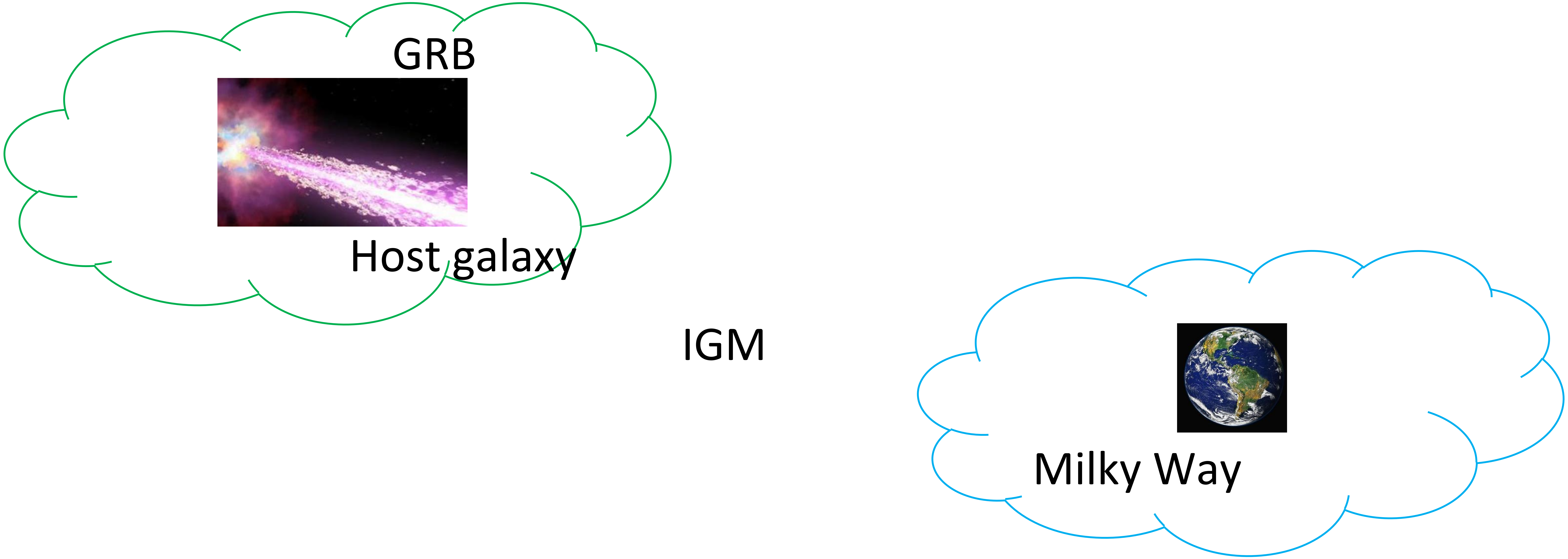
$$\nu = \nu_z/(1+z)$$

$$\rightarrow\rightarrow \Delta t = \frac{e^2}{2\pi m_e c} \left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) \boxed{\int \frac{n_{e,z}}{1+z} dl}$$

Measured DM:

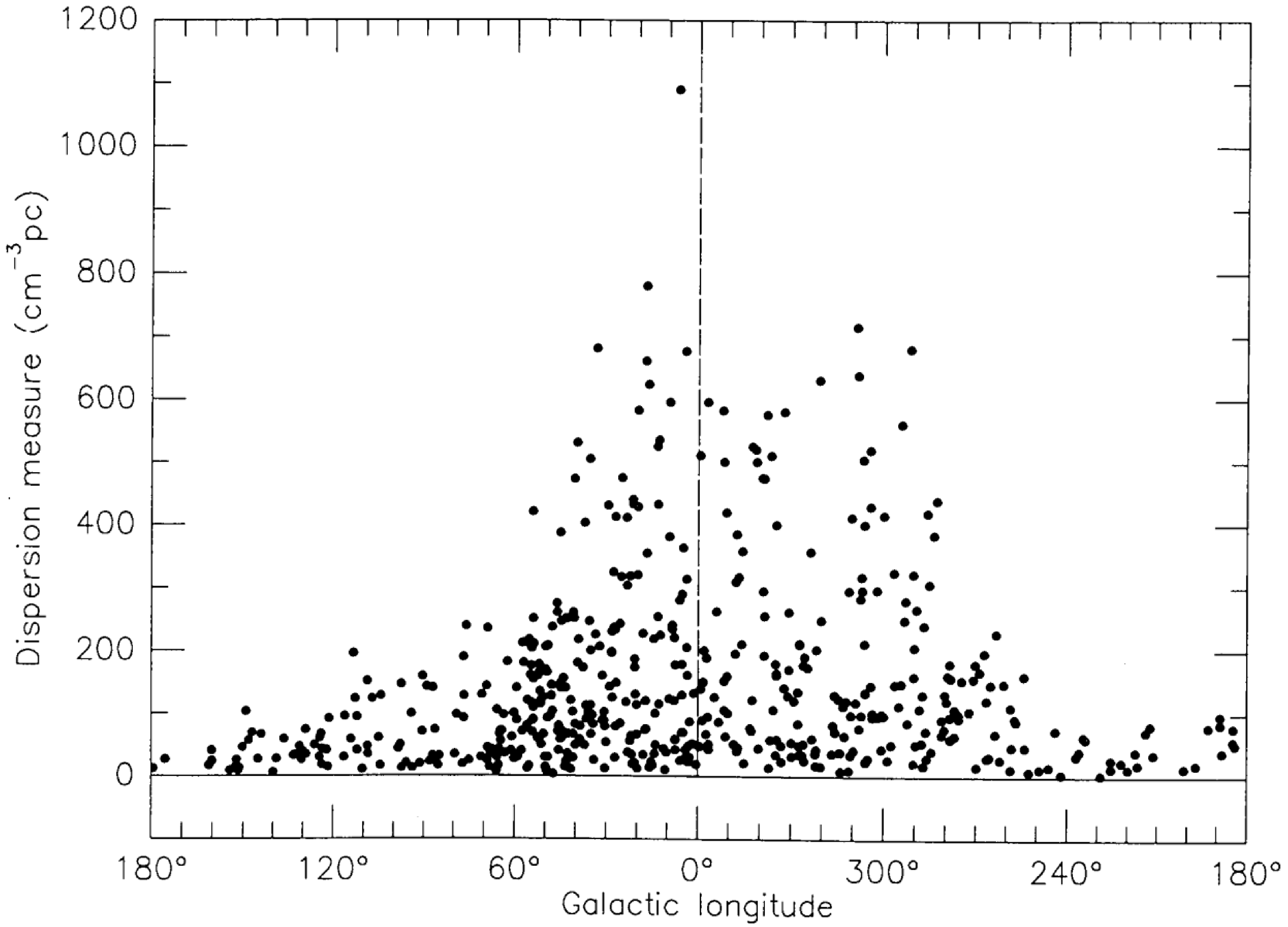
$$\mathrm{DM} = \int \frac{n_{e,z}}{1+z} dl$$

$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{host}} + \mathrm{DM_{GRB}}$$



$$\mathrm{DM_{tot}} = \boxed{\mathrm{DM_{MW}}} + \mathrm{DM_{IGM}} + \boxed{\mathrm{DM_{host}}} + \mathrm{DM_{GRB}}$$

DM within Milky Way: well constrained by radio pulsar observations.



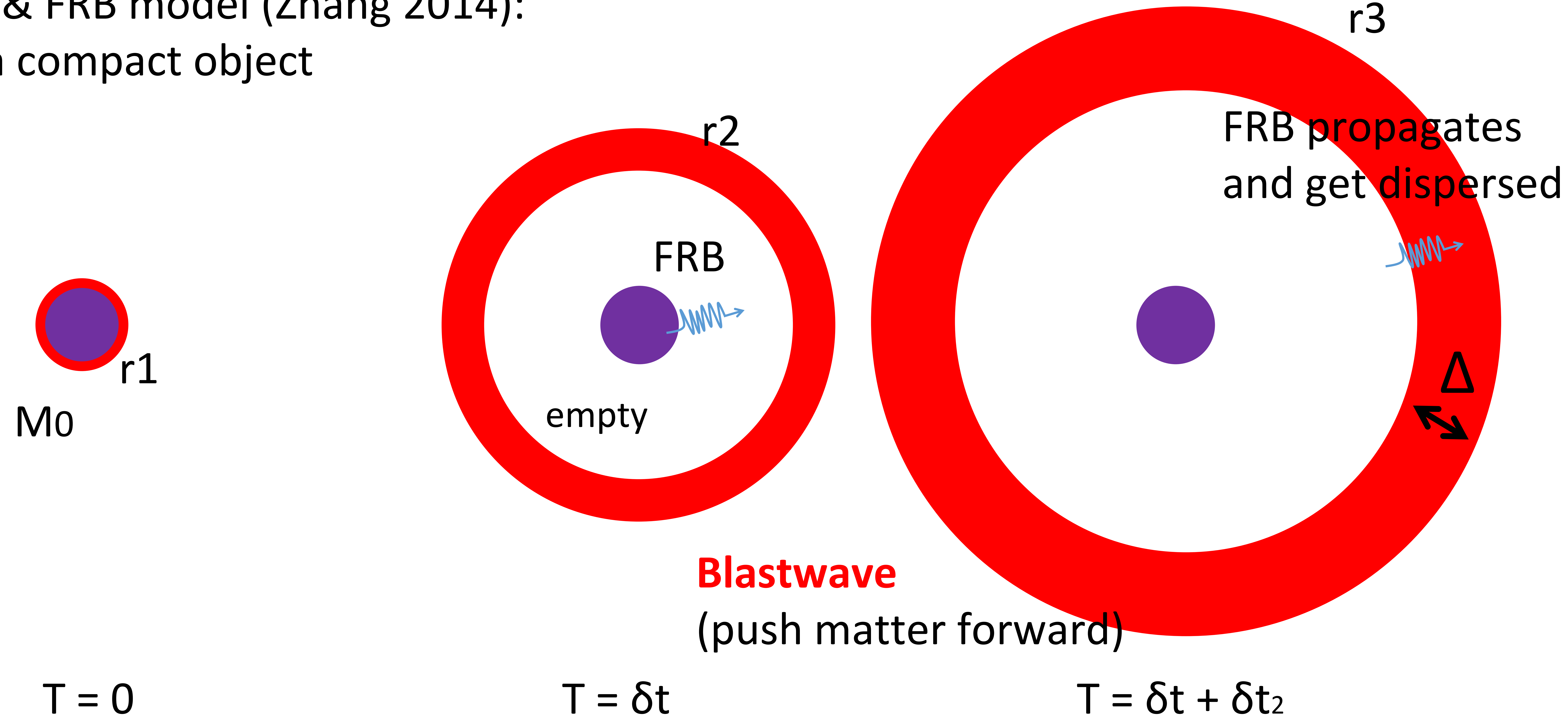
Taylor & Cordes 1993

Observed FRB: Large Galactic latitudes
➔➔➔ $\mathrm{DM_{MW}}$ is small.

DM within host galaxy: unknown…
But with known GRB host galaxies: $\mathrm{DM_{host}} \leqslant \mathrm{DM_{MW}}$

$$\mathrm{DM_{tot} = DM_{MW} + DM_{IGM} + DM_{host} + DM_{GRB}}$$

A GRB & FRB model (Zhang 2014):
From a compact object



$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{host}} + \boxed{\mathrm{DM_{GRB}}}$$

DM caused by FRB traversing GRB blastwave matter shell:

$$\mathrm{DM_{GRB}} = \frac{\mathrm{DM}_{\mathrm{GRB},z}}{1+z} = \frac{\int n_e dl}{1+z} \simeq \frac{[M_0 + m(r_3)]/m_p}{(1+z)\pi r_3^2 \Delta}\Delta = \frac{M_0 + m(r_3)}{(1+z) m_p \pi r_3^2}.$$

The Calculated $\mathrm{DM}_{\mathrm{GRB},z}$ with Different Parameters

	ISM		Wind	
$\mathrm{DM}_{\mathrm{GRB},z}$(typical)	0.68		7.9	
$\mathrm{DM}_{\mathrm{GRB},z}(E_{\mathrm{iso}})$	$0.23(10^{52})$	$2.1(10^{54})$	$10.7(10^{52})$	$7.7(10^{54})$
$\mathrm{DM}_{\mathrm{GRB},z}(\Gamma_0)$	2.9(100)	0.36(600)	28.7(100)	4.4(600)
$\mathrm{DM}_{\mathrm{GRB},z}(\delta t)$	1.6(100)	0.5(1000)	37.7(100)	4.2(1000)
$\mathrm{DM}_{\mathrm{GRB},z}(n/A_\star)$	0.21(0.1)	2.3(10)	0.77(0.1)	107(10)

Conclusion: $\mathrm{DM_{GRB}}$ is usually very small.

$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \boxed{\mathrm{DM_{IGM}}} + \mathrm{DM_{host}} + \mathrm{DM_{GRB}}$$

Consider IGM with ionized H and He:

$$\begin{aligned} n_e &= n_{\mathrm{H},0}(1+z)^3\, \chi_{e,\mathrm{H}}(z) + 2\, n_{\mathrm{He},0}(1+z)^3\, \chi_{e,\mathrm{He}}(z) \\ &= \left[\frac{Y_\mathrm{H}\rho_{c,0}\Omega_b f_\mathrm{IGM}}{m_p}\, \chi_{e,\mathrm{H}}(z) + 2\frac{Y_\mathrm{He}\rho_{c,0}\Omega_b f_\mathrm{IGM}}{4m_p}\, \chi_{e,\mathrm{He}}(z)\right] \\ &\quad \times (1+z)^3 \\ &= \frac{\rho_{c,0}\Omega_b f_\mathrm{IGM}}{m_p}\left[\frac{3}{4}y_1\chi_{e,\mathrm{H}}(z) + \frac{1}{8}y_2\chi_{e,\mathrm{He}}(z)\right](1+z)^3. \quad (11) \end{aligned}$$

f_{IGM}: fraction of baryon mass in IGM.

$$Y_\mathrm{H} = (3/4)y_1 \qquad y_1 \sim 1$$

$$Y_\mathrm{He} = (1/4)y_2 \qquad y_2 \simeq 4 - 3y_1 \sim 1$$

$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \boxed{\mathrm{DM_{IGM}}} + \mathrm{DM_{host}} + \mathrm{DM_{GRB}}$$

With
$$dl = \frac{1}{1+z}\frac{c}{H_0}\frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

$$\mathrm{DM_{IGM}} = \frac{3cH_0\Omega_b f_{\mathrm{IGM}}}{8\pi G m_p} \times \int_0^z \frac{\left[\frac{3}{4}y_1\chi_{e,\mathrm{H}}(z) + \frac{1}{8}y_2\chi_{e,\mathrm{He}}(z)\right](1+z)dz}{[\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}}.$$

$$\Leftrightarrow \quad \Omega_b f_{\mathrm{IGM}} = \frac{8\pi G m_p \mathrm{DM_{IGM}}}{3cH_0} \Bigg/ \int_0^z \frac{\left[\frac{3}{4}y_1\chi_{e,\mathrm{H}}(z) + \frac{1}{8}y_2\chi_{e,\mathrm{He}}(z)\right](1+z)dz}{[\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}}$$

$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \boxed{\mathrm{DM_{IGM}}} + \mathrm{DM_{host}} + \mathrm{DM_{GRB}}$$

Nearby universe (z<2) (Fan et al. 2006, McQuinn et al. 2009):

$$\chi_{e,\mathrm{H}} = \chi_{e,\mathrm{He}} = 1$$

→→→ $$\Omega_b f_{\mathrm{IGM}} \simeq \frac{64\pi G m_p \mathrm{DM_{IGM}}}{21 c H_0} \Big/ \int_0^z \frac{(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}.$$

Given z and $\mathrm{DM_{IGM}}$, Ωf could be estimated.

Given z and DM_{IGM}, Ωf could be estimated.

DM from FRB measurement.

z from GRB:

One of methods: Amati relation (Amati et al. 2002, 2008).

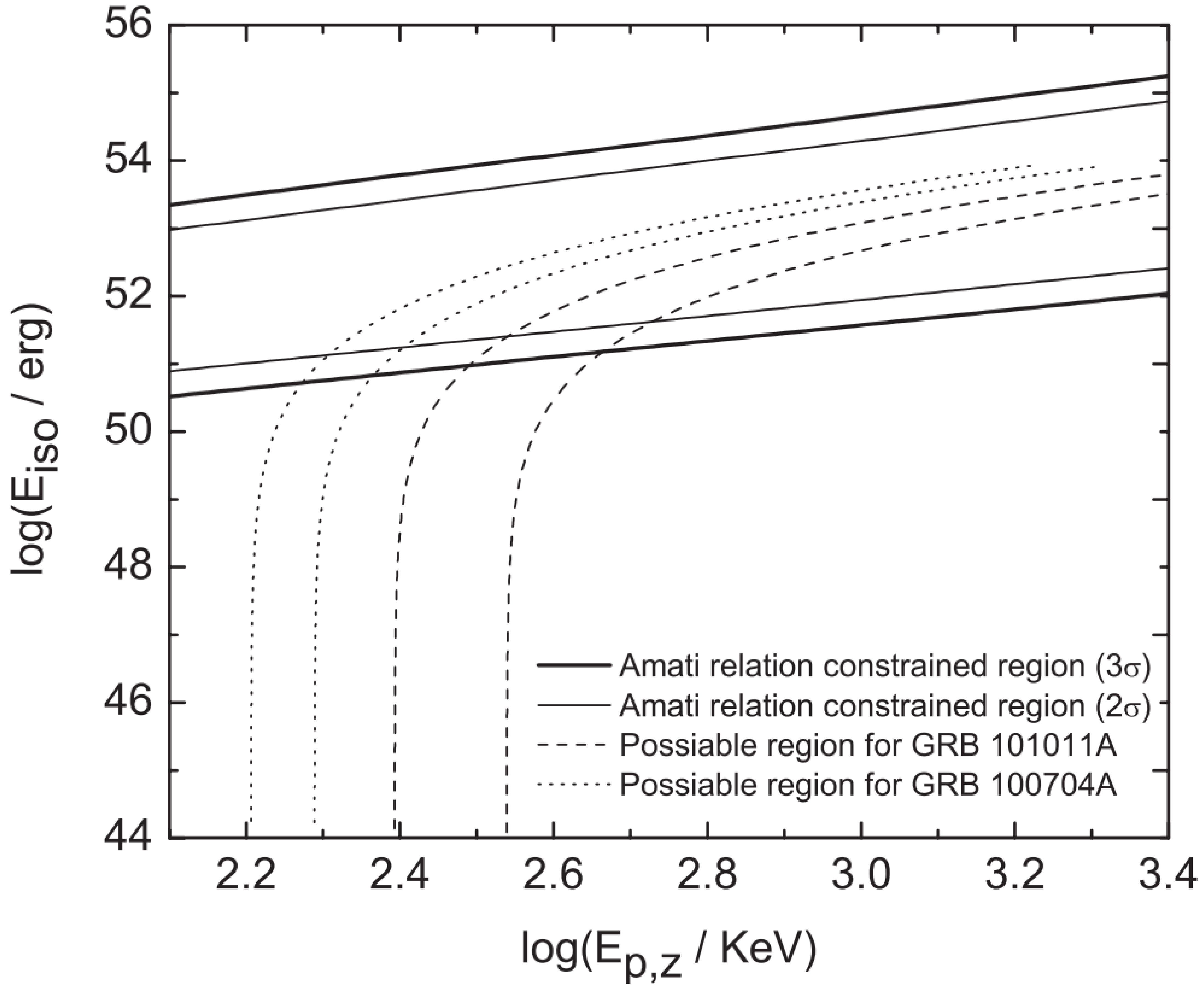
$$\log \frac{E_{\gamma,\mathrm{iso}}}{\mathrm{erg}} = A + \gamma \log \frac{E_{p,z}}{\mathrm{keV}} \qquad A = 49.17 \pm 0.40, \gamma = 1.46 \pm 0.29$$

Measure Eγ (from fluence) and E_p (peak energy).

Transfer E_p to $E_{p,z}$ to fit the relation ➔ get z.

III. Results

Estimating z of GRBs:

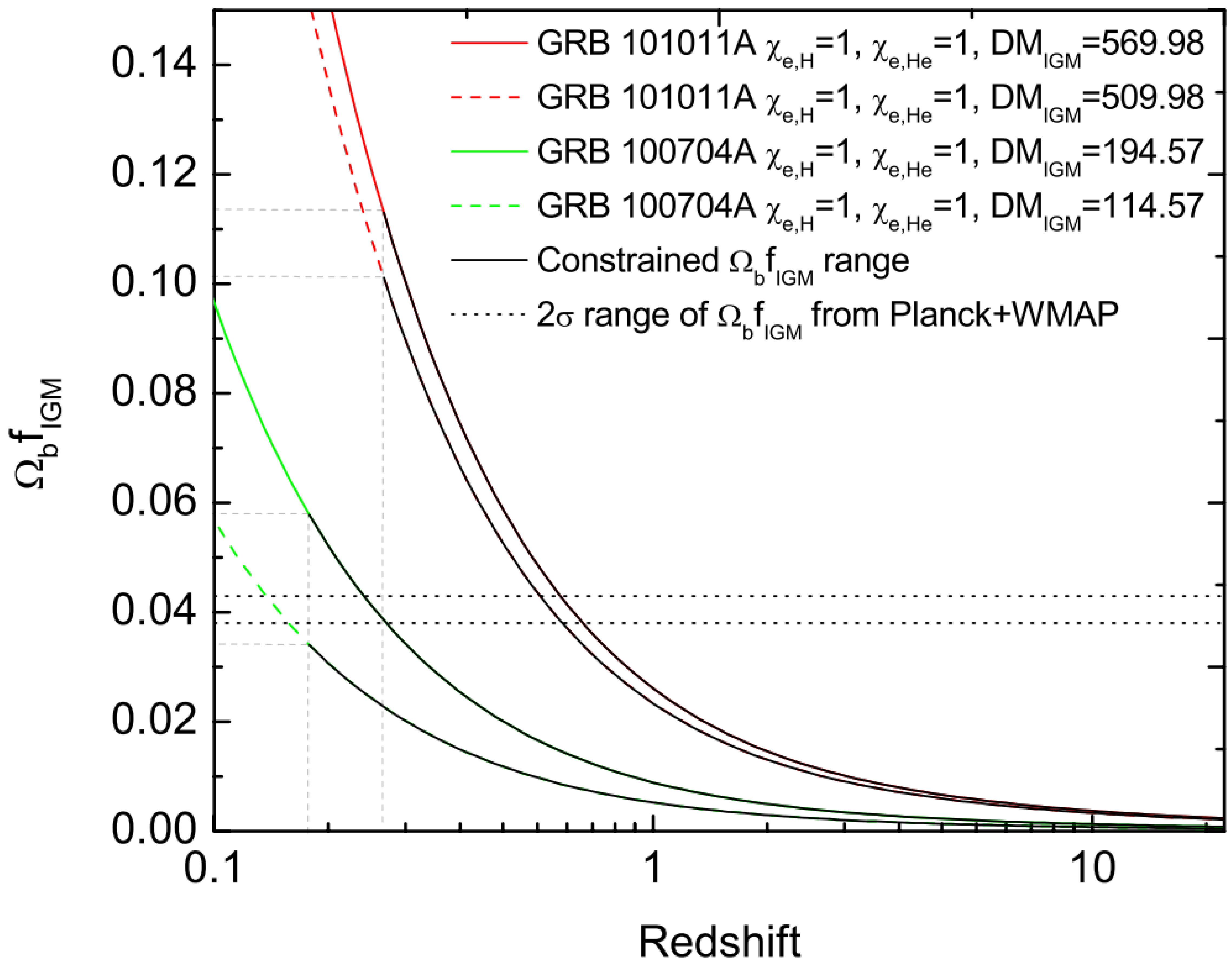


GRB 101011A $z \geqslant 0.246$

GRB 100704A $z \geqslant 0.166$

Estimating Ωf upper limits:

Take $DM_{host} = DM_{MW}$



GRB 101011A	0.101/0.114
GRB 100704A	0.034/0.058

Other things can be done:

Given Ωf (Ade et al. 2013), measure z.

$$z = (0.554, 0.687) \text{ for GRB 101011A}$$

$$z = (0.130, 0.246) \text{ for GRB 100704A}$$

Measure FRB/GRB at higher redshifts ➔ Study the ionization history…

IV. Discussions (beyond this paper)

FRBs have been observed to correlate with certain galaxies (e.g. Xu et al. 2022):

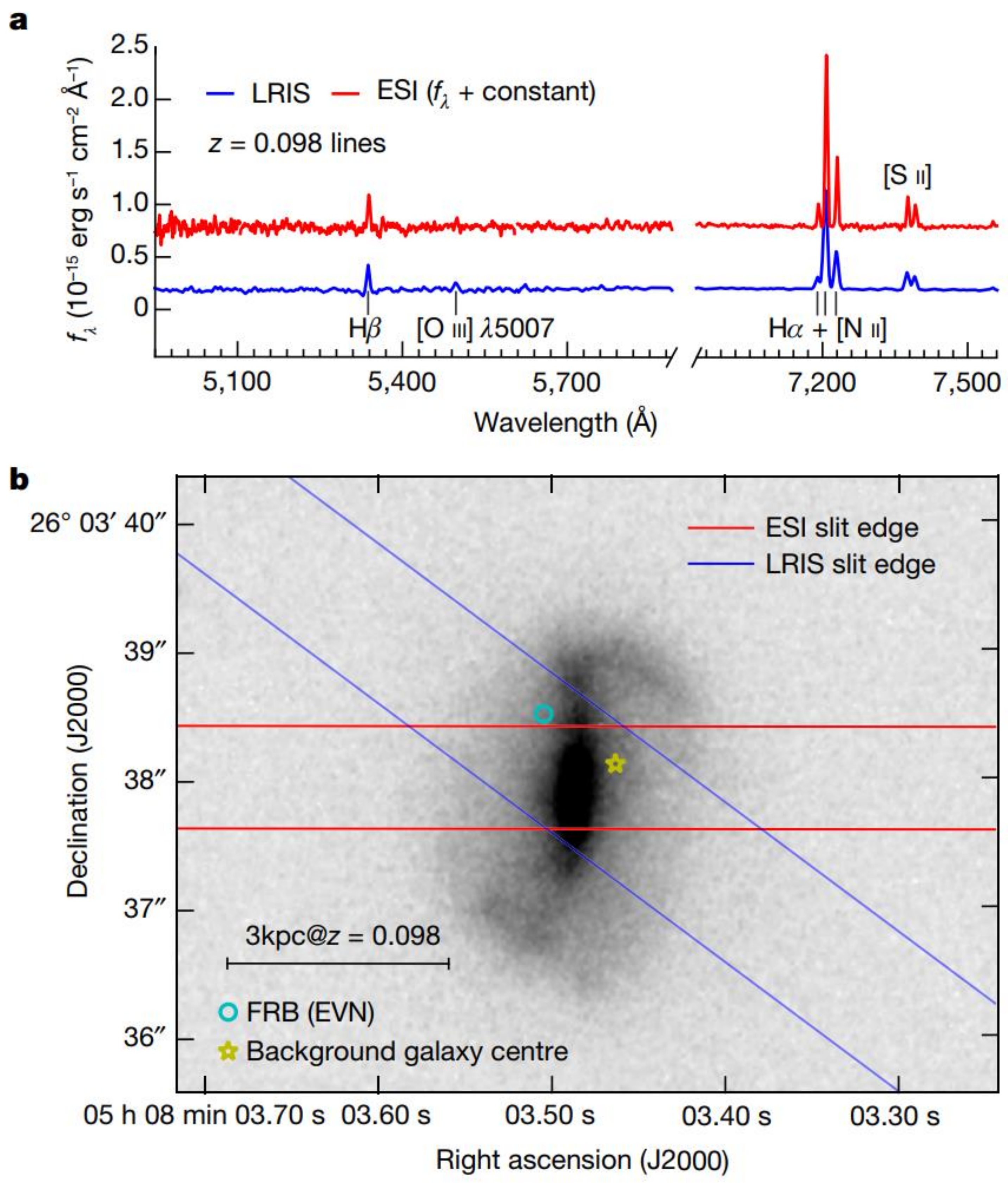


Fig. 3 | Host-galaxy properties at optical and near-infrared wavelengths. **a**, Emission lines from the $z = 0.098$ host galaxy in the LRIS (blue) and ESI (red) spectra. **b**, The K'-band AO image of the barred-spiral host galaxy, with the indicated position of the FRB[37] shown as a cyan circle, the centroid of a $z = 0.553$ background galaxy (Methods) marked by a yellow star and the LRIS and ESI slit edges in blue and red solid lines, respectively.

Redshifts can be precisely measured with spectral lines.

Properties of the host galaxy

Star-formation rate and gas-phase metallicity. We use the emission lines detected in the high-S/N LRIS spectrum to measure the redshift ($z = 0.09795 \pm 0.00003$), infer the SFR and determine the gas-phase

$$f_{\mathrm{IGM},0} = 0.92^{+0.06}_{-0.12}$$

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Probing the baryon mass fraction in IGM and its redshift evolution with fast radio bursts using Bayesian inference method

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Advantages of studying cosmology with FRB:

Precise radio observation.

More information of its environment (DM, RM, Spectral lines, other wavelength…)

Disadvantages of studying cosmology with FRB:

Observed redshifts not very large…yet.

FRBs	RA (°)	Dec. (°)	DM_{FRB} (pc cm^{-3})	$DM_{MW,ISM}$ (pc cm^{-3})	DM_E (pc cm^{-3})	z_{sp}	Repeat?	Reference
20121102A	82.99	33.15	557.00	157.60	349.40	0.1927	Yes	Chatterjee et al. (2017)
20171020A	22.15	−19.40	114.10	38.00	26.10	0.0087	No	Li et al. (2019b)
20180301A	93.23	4.67	536.00	136.53	349.47	0.3305	Yes	Bhandari et al. (2022)
20180916B	29.50	65.72	348.80	168.73	130.07	0.0337	Yes	Marcote et al. (2020)
20180924B	326.11	−40.90	362.16	41.45	270.71	0.3214	No	Bannister et al. (2019)
20181030A	158.60	73.76	103.50	40.16	13.34	0.0039	Yes	Bhardwaj et al. (2021b)
20181112A	327.35	−52.97	589.00	41.98	497.02	0.4755	No	Prochaska et al. (2019)
20190102C	322.42	−79.48	364.55	56.22	258.33	0.2913	No	Macquart et al. (2020)
20190523A	207.06	72.47	760.80	36.74	674.06	0.6600	No	Ravi et al. (2019)
20190608B	334.02	−7.90	340.05	37.81	252.24	0.1178	No	Macquart et al. (2020)
20190611B	320.74	−79.40	332.63	56.60	226.03	0.3778	No	Macquart et al. (2020)
20190711A	329.42	−80.36	592.60	55.37	487.23	0.5217	Yes	Macquart et al. (2020)
20190714A	183.98	−13.02	504.13	38.00	416.13	0.2365	No	Heintz et al. (2020)
20191001A	323.35	−54.75	507.90	44.22	413.68	0.2340	No	Heintz et al. (2020)
20191228A	344.43	−29.59	297.50	33.75	213.75	0.2432	No	Bhandari et al. (2022)
20200430A	229.71	12.38	380.25	27.35	302.90	0.1608	No	Bhandari et al. (2022)
20200906A	53.50	−14.08	577.80	36.19	491.61	0.3688	No	Bhandari et al. (2022)
20201124A	77.01	26.06	413.52	126.49	237.03	0.0979	Yes	Fong et al. (2021)

Lin & Zou 2023

FRB ➔ DM(z, Ω, …)
GRB/galaxies ➔ z

More FRBs…

Thank you for your attention ☺