Cosmological model-independent constraints on the baryon fraction in the IGM from fast radio bursts and supernovae data

Thais Lemos
PhD student- Observatório Nacional, Brazil

Cosmology from Home 2023

In collaboration: Rodrigo S. Gonçalves, Joel C. Carvalho, Jailson S. Alcaniz

Eur. Phys. J. C (2023) 83:138
https://doi.org/10.1140/epjc/s10052-023-11275-7

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

Cosmological model-independent constraints on the baryon fraction in the IGM from fast radio bursts and supernovae data

Thais Lemos[1,a], **Rodrigo S. Gonçalves**[1,2,b], **Joel C. Carvalho**[1,c], **Jailson S. Alcaniz**[1,d]

[1] Observatório Nacional, Rio de Janeiro, RJ 20921-400, Brazil
[2] Departamento de Física, Universidade Federal Rural do Rio de Janeiro, Seropédica, Rio de Janeiro 23897-000, Brazil

Received: 16 November 2022 / Accepted: 29 January 2023 / Published online: 11 February 2023

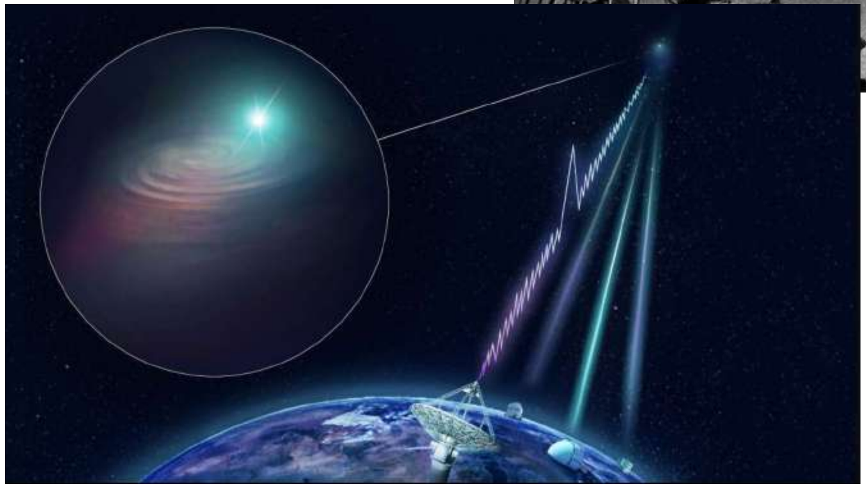
Summary

- Introduction
- A new method to determine the baryon fraction
- Data and methodology
- Results
- DM fluctuations
- Conclusions

Introduction

Fast Radio Bursts (FRBs)

Credit: Danielle Futselaar/artsource.nl



Credit: CSIRO / Dr Andrew Howells

Introduction

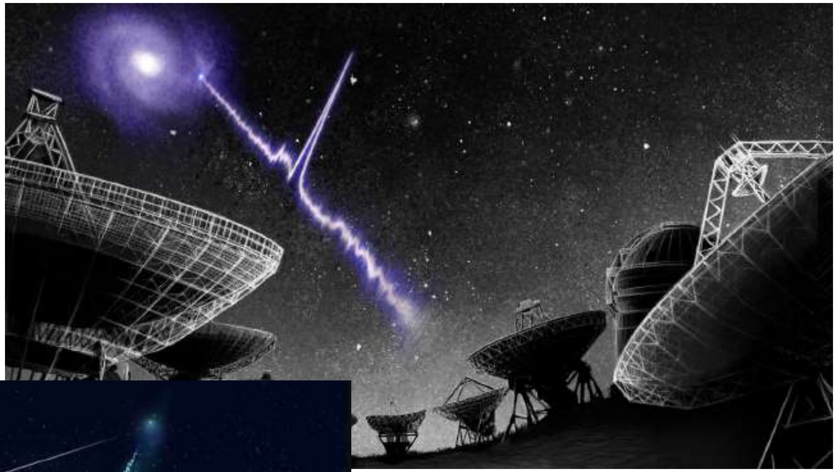
Fast Radio Bursts (FRBs) → Transient radio pulse

B = 50 mJy - 10 Jy

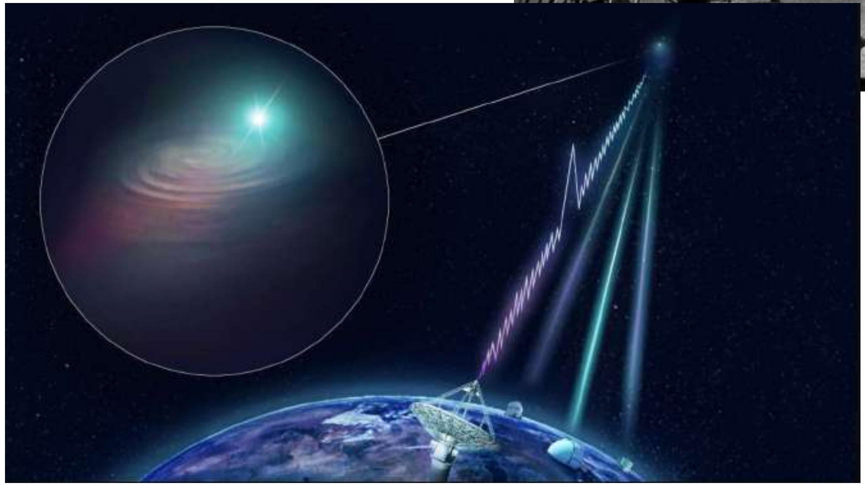
T ~ ms

f = 400 MHz - 8 GHz

Repeating or not



Credit: Danielle Futselaar/artsource.nl



Credit: CSIRO / Dr Andrew Howells

Introduction

Fast Radio Bursts (FRBs) → Transient radio pulse

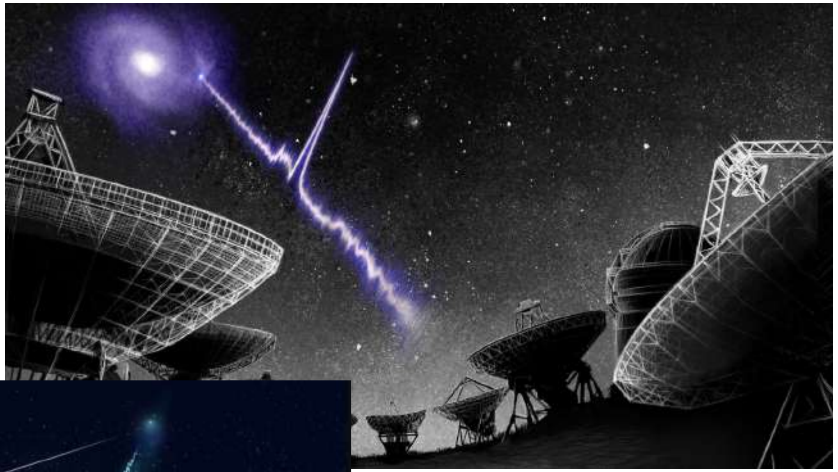
B = 50 mJy - 10 Jy

T ~ ms

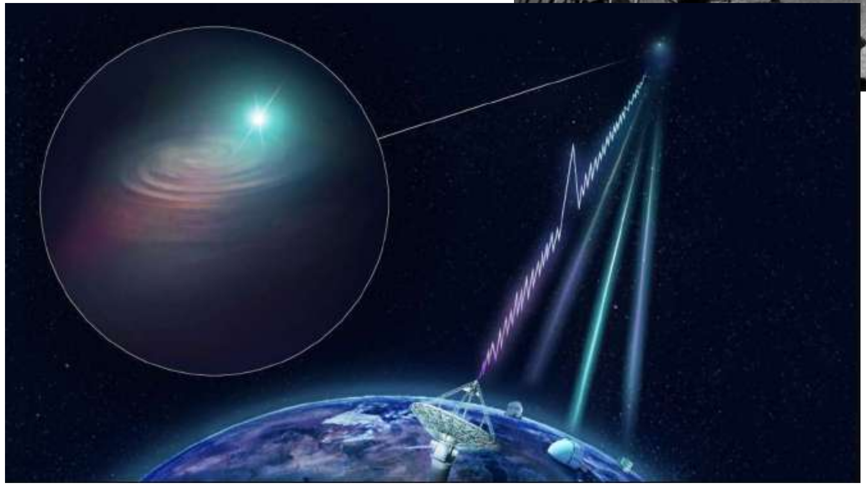
f = 400 MHz - 8 GHz

Repeating or not

Unknown origin of the pulse

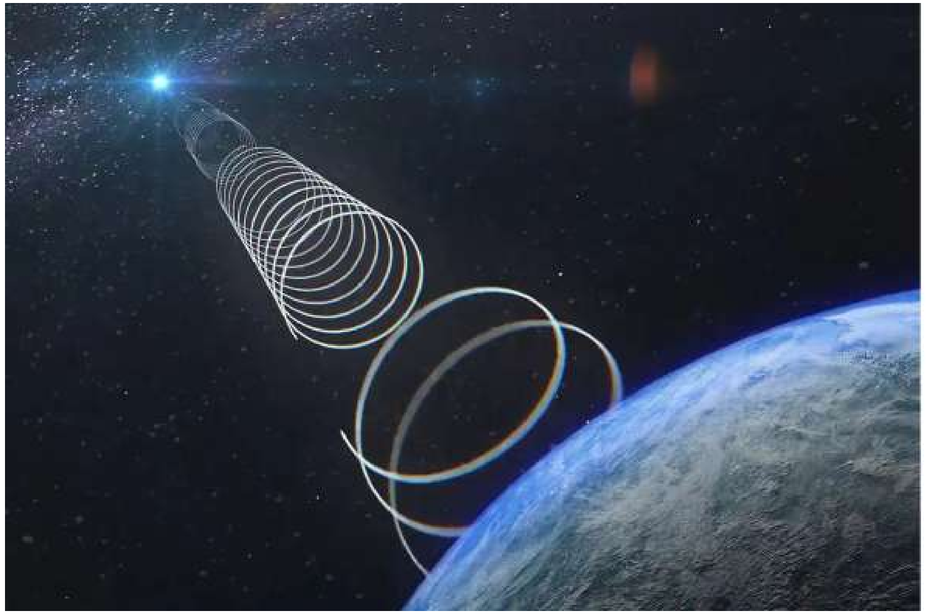


Credit: Danielle Futselaar/artsource.nl



Credit: CSIRO / Dr Andrew Howells

Introduction

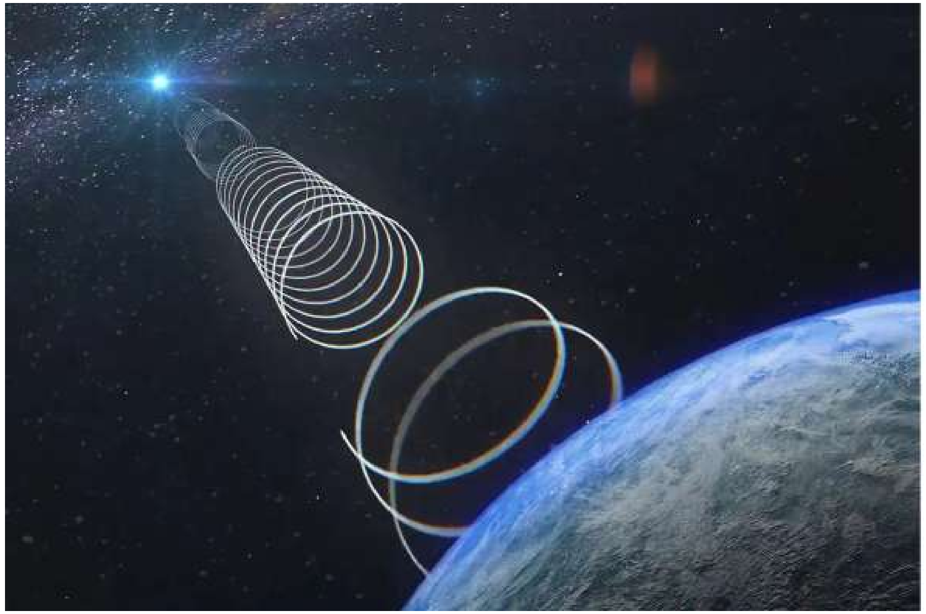


Credit: Sebastian Zentilomo/University of Sydney

Delay of arrive time:

$$t_1 - t_2 \propto \nu^{-2} \cdot DM$$

Introduction



Credit: Sebastian Zentilomo/University of Sydney

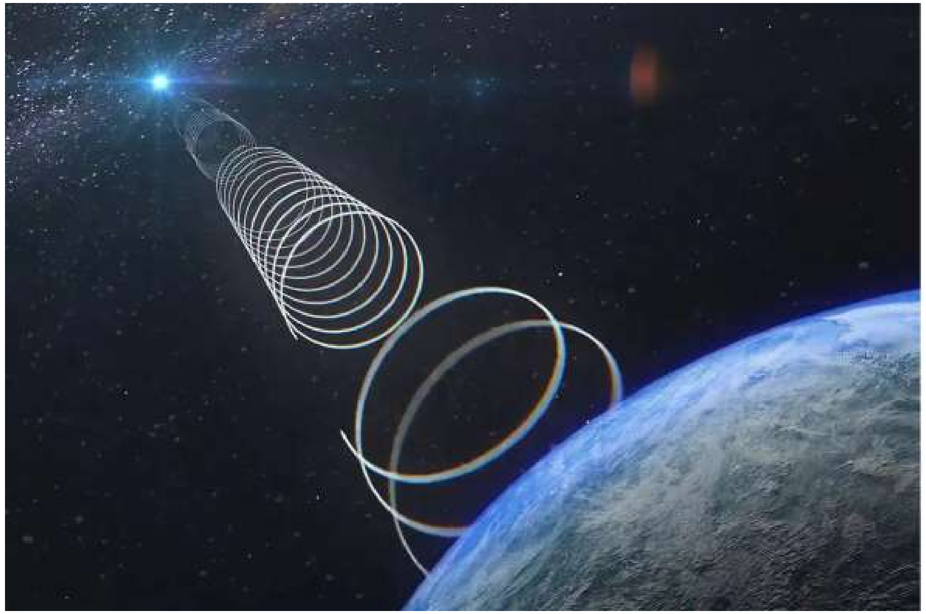
Delay of arrive time:

$$t_1 - t_2 \propto \nu^{-2} \cdot DM$$

$$DM = \int n_e dl$$

Dispersion Measure (DM)

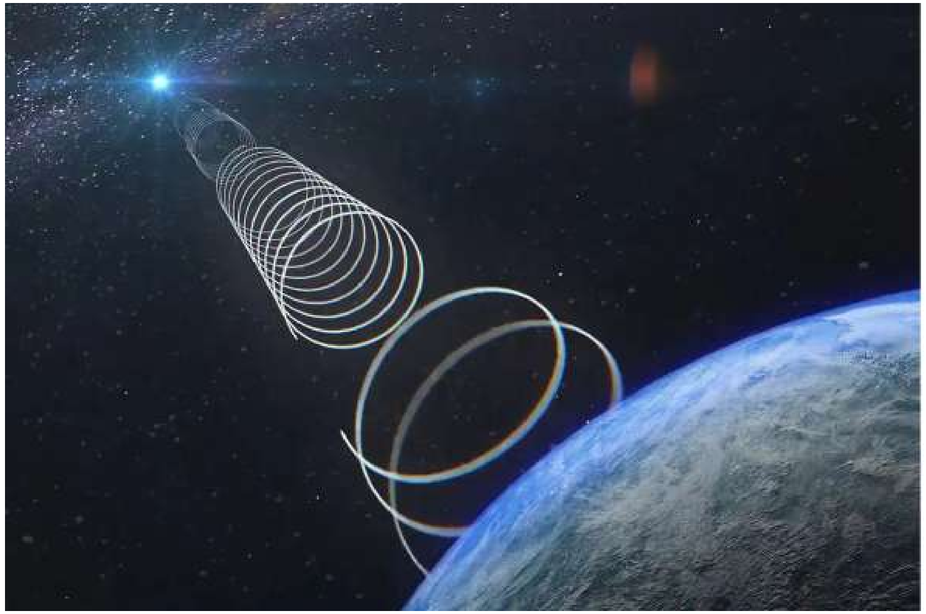
Introduction



Credit: Sebastian Zentilomo/University of Sydney

$$DM_{obs} >> DM_{MW}$$

Introduction



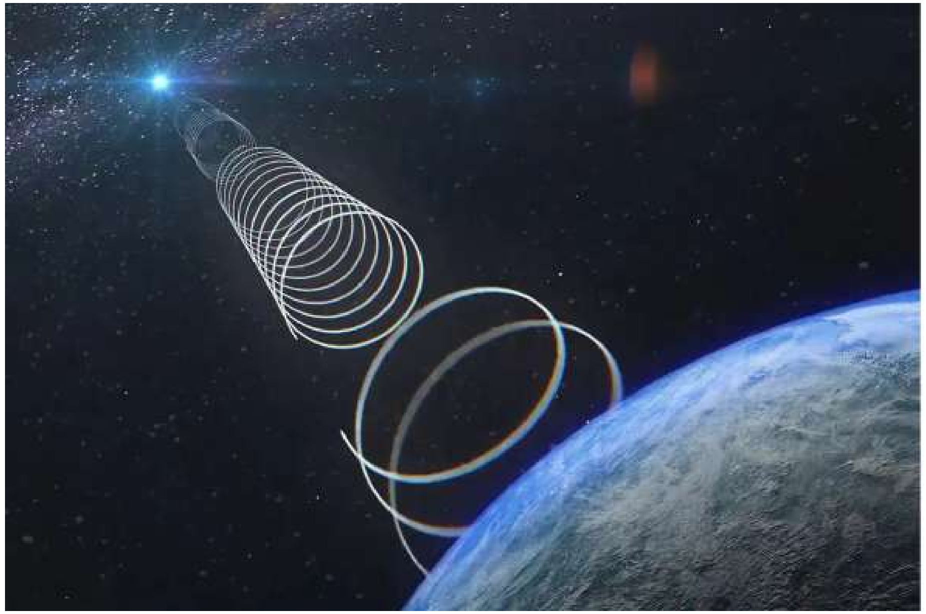
Credit: Sebastian Zentilomo/University of Sydney

$$DM_{obs} >> DM_{MW}$$

↓

Extragalactic origin or cosmological

Introduction



Credit: Sebastian Zentilomo/University of Sydney

$$DM_{obs} >> DM_{MW}$$

↓

Extragalactic origin or cosmological

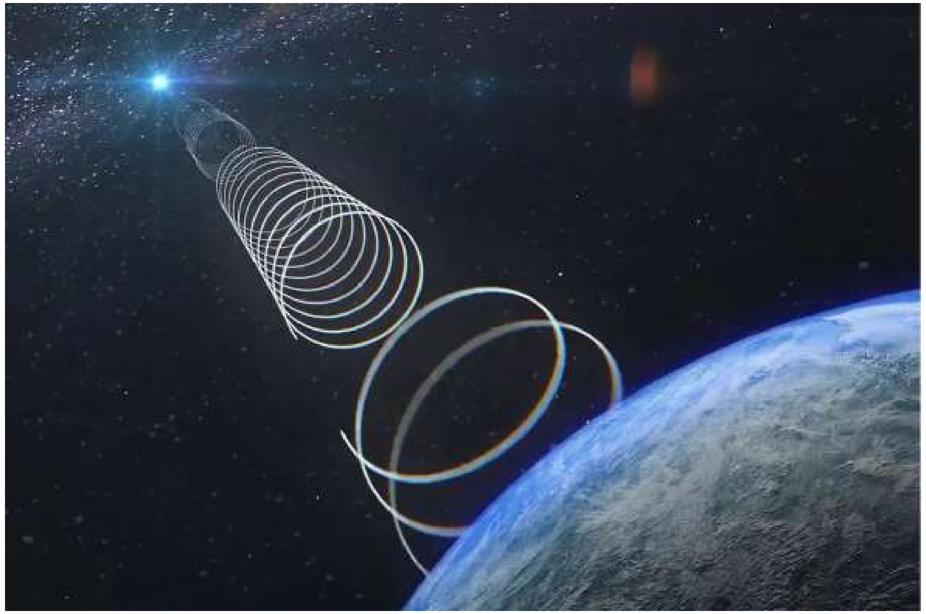
↓

Host galaxy identification

↘

Redshift

Introduction



Credit: Sebastian Zentilomo/University of Sydney

$$DM_{obs} >> DM_{MW}$$

↓

Extragalactic origin or cosmological

↓

Host galaxy identification

↘

Redshift

DM-z relation

Introduction

DM-z relation:

- Cosmological Parameters
- H(z)
- Hubble constant
- Anisotropic distribution of the baryon matter in the Universe
- The fraction of baryon mass in the intergalactic medium (IGM)

f_{IGM}

Introduction

DM-z relation:

- Cosmological Parameters → Degenerates
- H(z)
- Hubble constant
- Anisotropic distribution of the baryon matter in the Universe
- The fraction of baryon mass in the intergalactic medium (IGM)

Introduction

f_{IGM} → Poorly know parameters

↓

Limited cosmological application

Credit: ICRAR

Introduction

f_{IGM} → Poorly know parameters

↓

Limited cosmological application

Credit: ICRAR

$$f_{IGM} \approx 0.90 \quad \text{at} \quad z \geq 1.5 \text{ (Meiksin, 2009)}$$

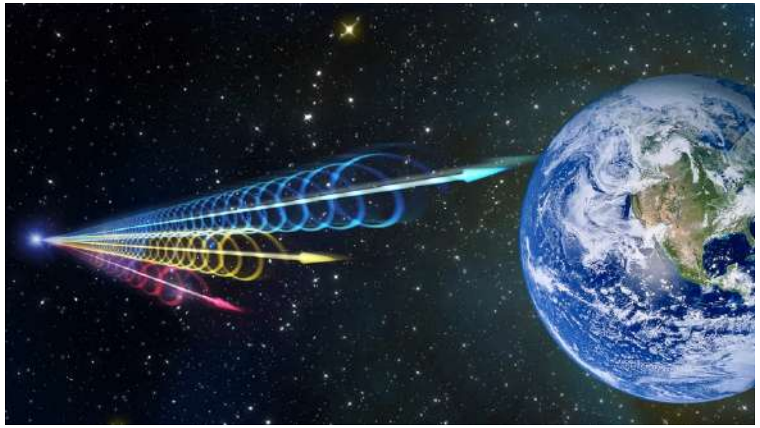
$$f_{IGM} \approx 0.82 \quad \text{at} \quad z \geq 0.4 \text{ (Shull et al., 2012)}$$

→ Growing with the redshift

Introduction

A new cosmological model-independent method

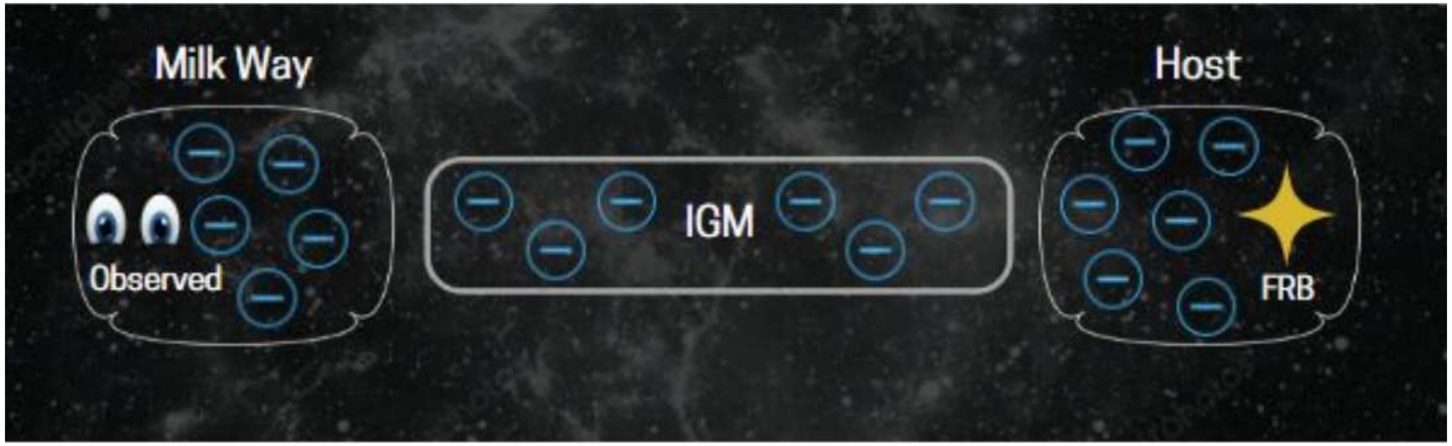
Constrain the baryon fraction from observational data.



Credit: Jingchuan Yu/Beijing Planetarium

- DM-z from FRBs (well-localized sample)
- d_L from Supernovae type Ia (Pantheon catalogue)

A new method to determine the baryon fraction



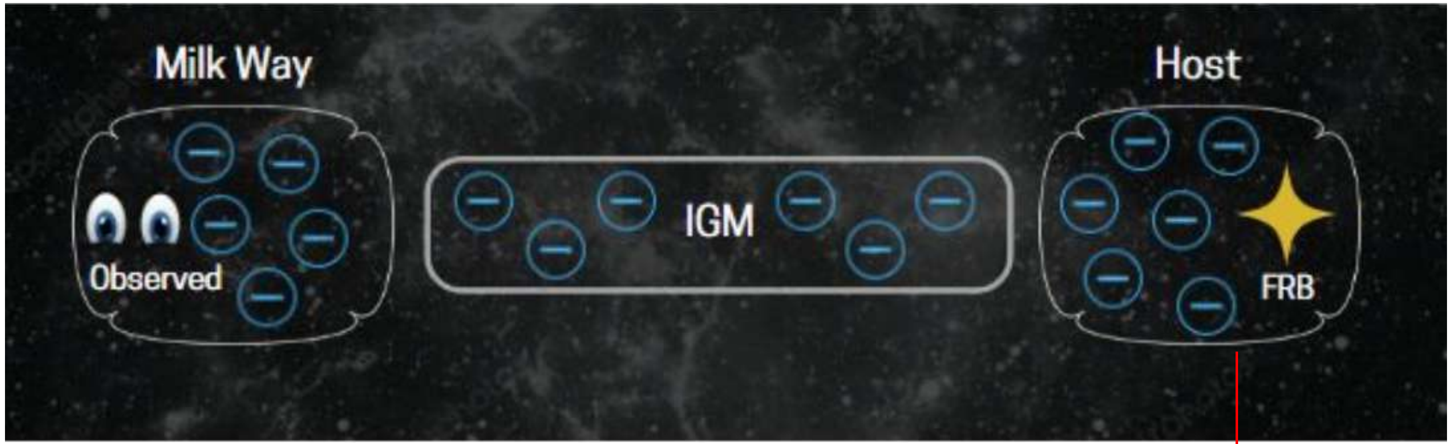
$$DM_{obs}(z) = DM_{MW} + DM_{IGM}(z) + DM_{host}(z)$$

A new method to determine the baryon fraction

$$DM_{MW} = DM_{MW,ISM} + DM_{MW,halo}$$

$$DM_{MW,halo} = 50\ \mathrm{pc/cm^3}$$

A new method to determine the baryon fraction



$$DM_{host}(z) = \frac{DM_{host,0}}{(1+z)}$$

A new method to determine the baryon fraction

$$DM_{IGM}(z) = \frac{3c\Omega_b H_0^2}{8\pi G m_p} \int_0^z \frac{(1+z') f_{IGM}(z') \chi(z')}{H(z')} dz'$$

A new method to determine the baryon fraction

$$DM_{obs}(z) = DM_{MW} + DM_{IGM}(z) + DM_{host}(z)$$

Observed

Modeled

A new method to determine the baryon fraction

$$DM_{obs}(z) = DM_{MW} + DM_{IGM}(z) + DM_{host}(z)$$

Observed

Modeled

$$\begin{cases} DM_{ext}(z) \equiv DM_{obs}(z) - DM_{MW} \\ DM_{ext}^{th}(z) \equiv DM_{IGM}(z) + DM_{host}(z) \end{cases}$$

$$\sigma_{ext}^2 = \sigma_{obs}^2 + \sigma_{MW}^2$$

A new method to determine the baryon fraction

$$DM_{IGM}(z) = A\int_0^z f_{IGM}(z')\frac{(1+z')}{H(z')}dz'$$

Solving by parts using the definition of the luminosity distance

$$DM_{IGM}(z) = A\left[f_{IGM}(z)\frac{d_L(z)}{c} - \int_0^z \frac{d_L(z')}{(1+z')c}f_{IGM}(z')dz' - \int_0^z \frac{d_L(z')}{c}f'_{IGM}(z')dz'\right]$$

$$\begin{cases} f_{IGM} = f_{IGM,0}, \\ f_{IGM} = f_{IGM,0} + \alpha\frac{z}{1+z} \end{cases}$$

A new method to determine the baryon fraction

Constant Parameterization:

$$DM_{IGM}(z) = A f_{IGM,0}\left[\frac{d_L(z)}{c} - \int_0^z \frac{d_L(z')}{(1+z')c}dz'\right]$$

Time-Dependent Parameterization:

$$DM_{IGM}(z) = A\left[\left(f_{IGM,0} + \alpha\frac{z}{1+z}\right)\frac{d_L(z)}{c} - (f_{IGM,0} + \alpha)\int_0^z \frac{d_L(z')}{c(1+z')}dz'\right]$$

$$\int_0^z \frac{d_L(z')}{(1+z')c}dz' = \frac{1}{2c}\sum_{i=1}^{N}(z_{i+1} - z_i)\left[\frac{d_L(z_{i+1})}{(1+z_{i+1})} + \frac{d_L(z_i)}{(1+z_i)}\right]$$

Data and methodology

19 FRBs well-localized in the literature:

- FRB 20200120E (z = −0.0001)
- FRB 20181030A (z = 0.0039)
- FRB 190614D (0.4 ≤ z ≤ 0.75)

Then we have 16 FRBs

Redshift z	$DM_{MW,ISM}$ [pc/cm^3]	DM_{obs} [pc/cm^3]	σ_{obs} [pc/cm^3]

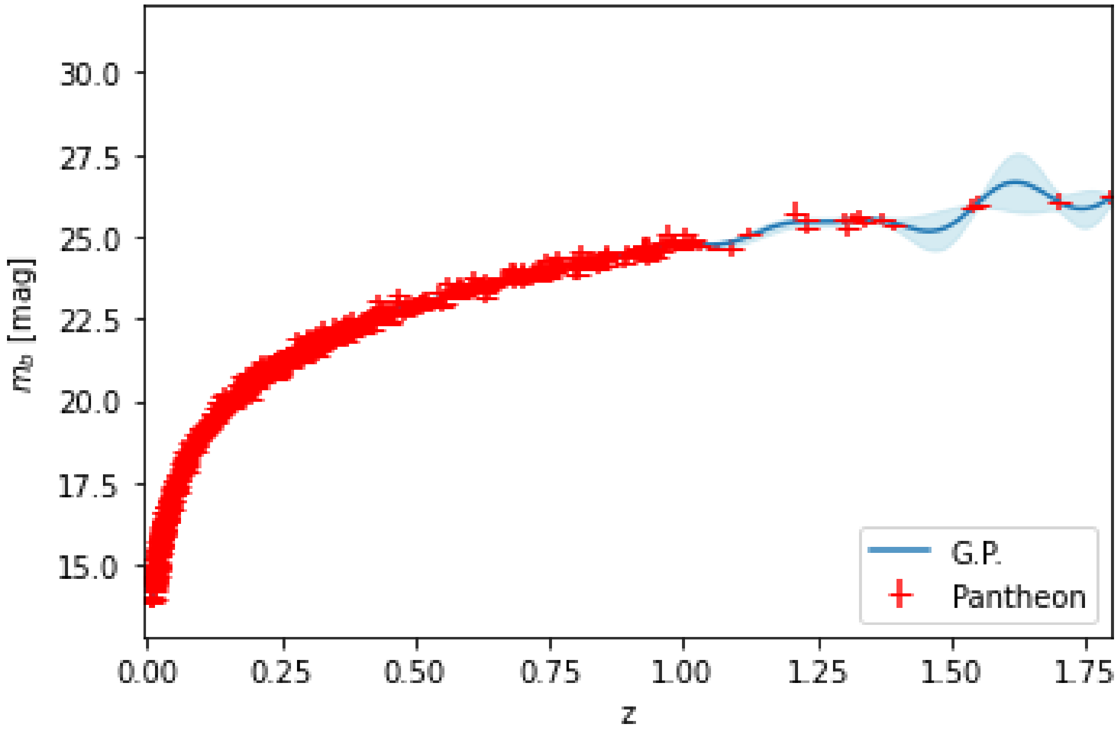
Data and methodology

GaPP package

SNe from Pantheon catalogue

$$\mu(z) = m_B - M_B = 5\log_{10}\left[\frac{d_L(z)}{1\mathrm{Mpc}}\right] + 25$$

$M_B = -19.214 \pm 0.037$



Data and methodology

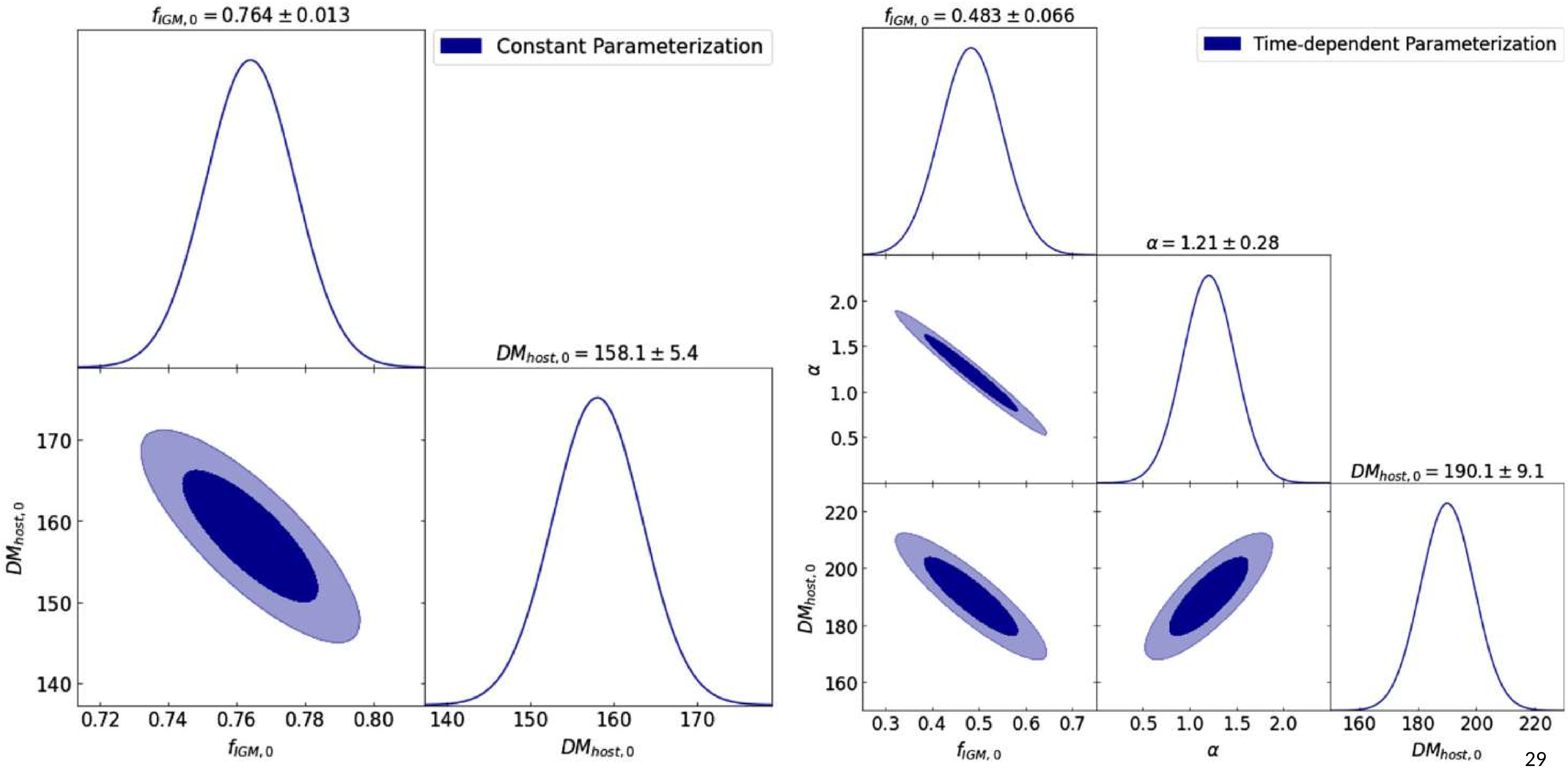
Steps of our analysis:

- DM_{ext}^{obs} and σ_{ext}
- $d_L(z_i)$ at $z_i = z_{FRB}$
- $\int_0^{z_i} \frac{d_L(z')}{(1+z')c} dz'$ at $z_i = z_{FRB}$
- Fit: f_{IGM} and $DM_{host,0}$

Assumptions:

$$\left\{ \begin{array}{l} H_0 = 74.03 \pm 1.4 \text{ km s}^{-1} \text{ Mpc}^{-1} \\ \Omega_b h^2 = 0.02235 \pm 0.00037 \end{array} \right.$$

Results



$f_{IGM,0} = 0.764 \pm 0.013$
Constant Parameterization
$DM_{host,0} = 158.1 \pm 5.4$
$DM_{host,0}$
$f_{IGM,0}$
$f_{IGM,0} = 0.483 \pm 0.066$
Time-dependent Parameterization
$\alpha = 1.21 \pm 0.28$
$DM_{host,0} = 190.1 \pm 9.1$
α

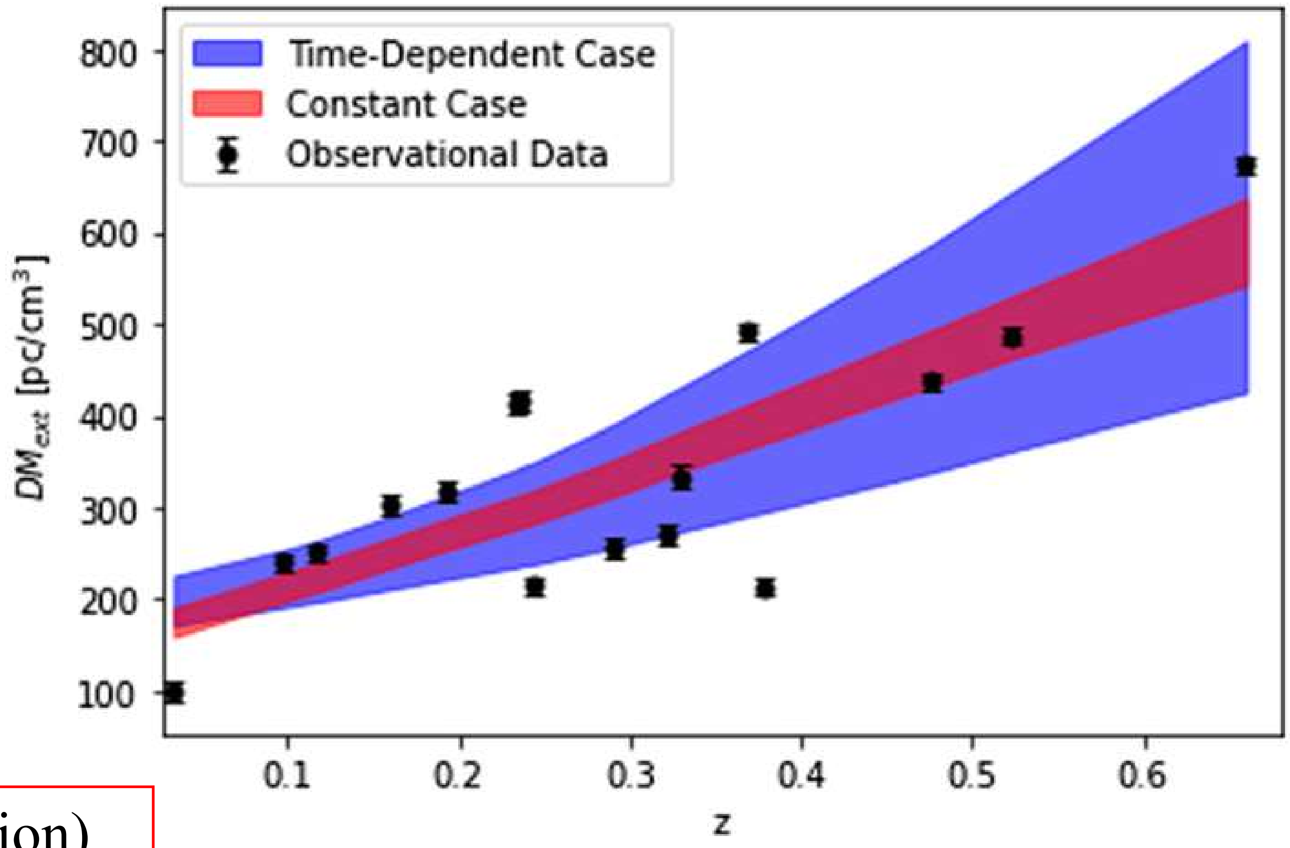
Results

Bayes' factor (MultiNest package):

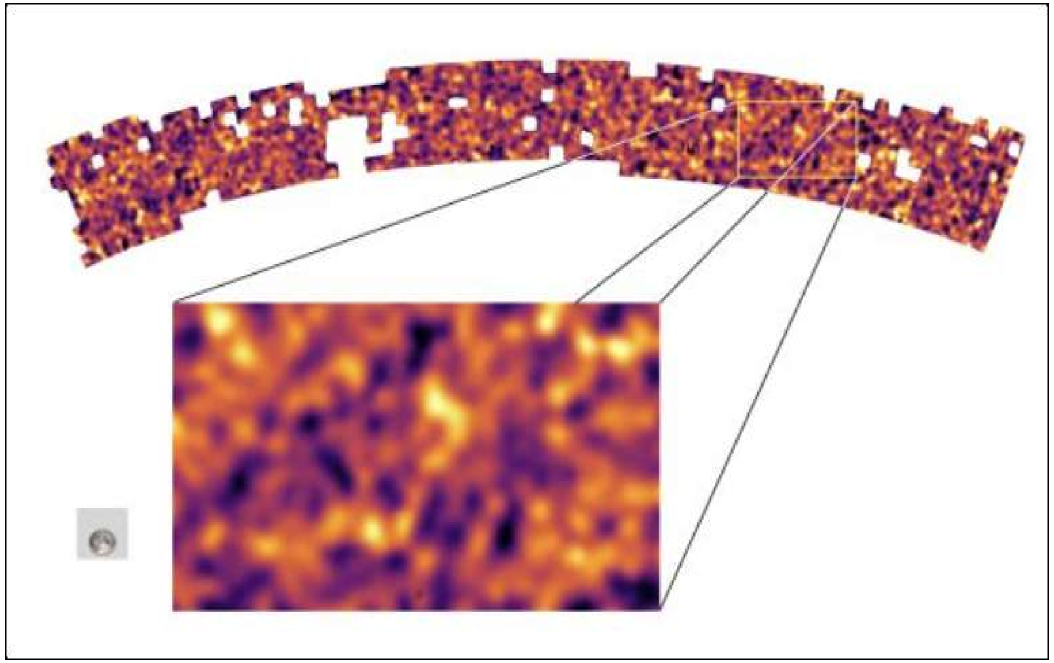
$$B_{ij} = \frac{\mathcal{E}_i}{\mathcal{E}_j}$$

$$\ln B_{ij} = 8.32$$

Strong evidence (in favor of a growing evolution)



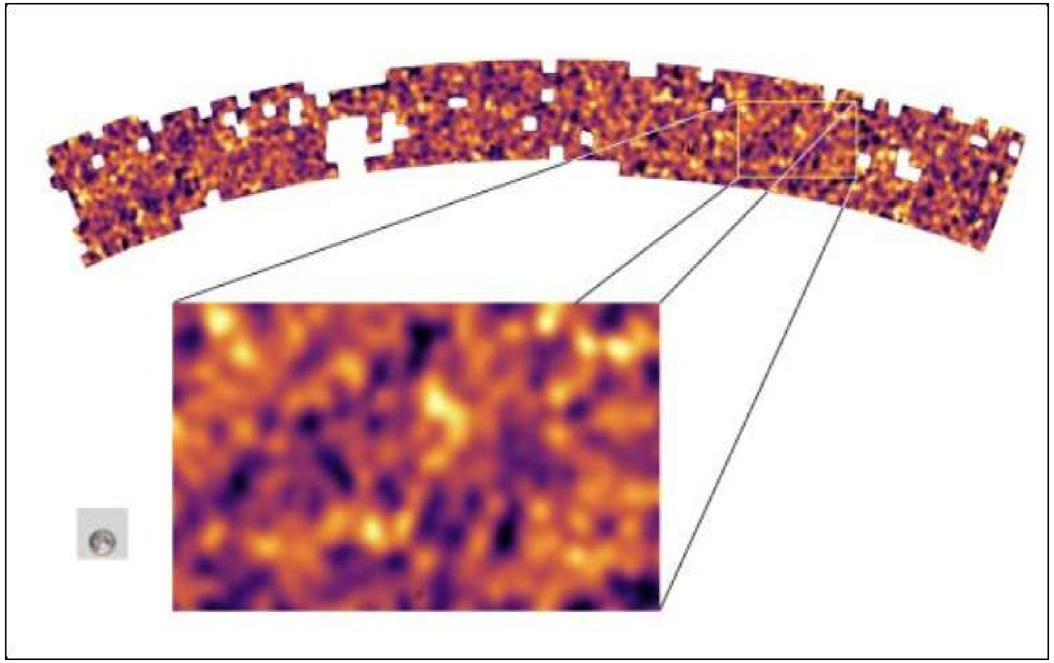
DM Fluctuations



Credit: B.Giblin, K.Kuijken and the KiDS team

Spatial variation in cosmic electron density

DM Fluctuations



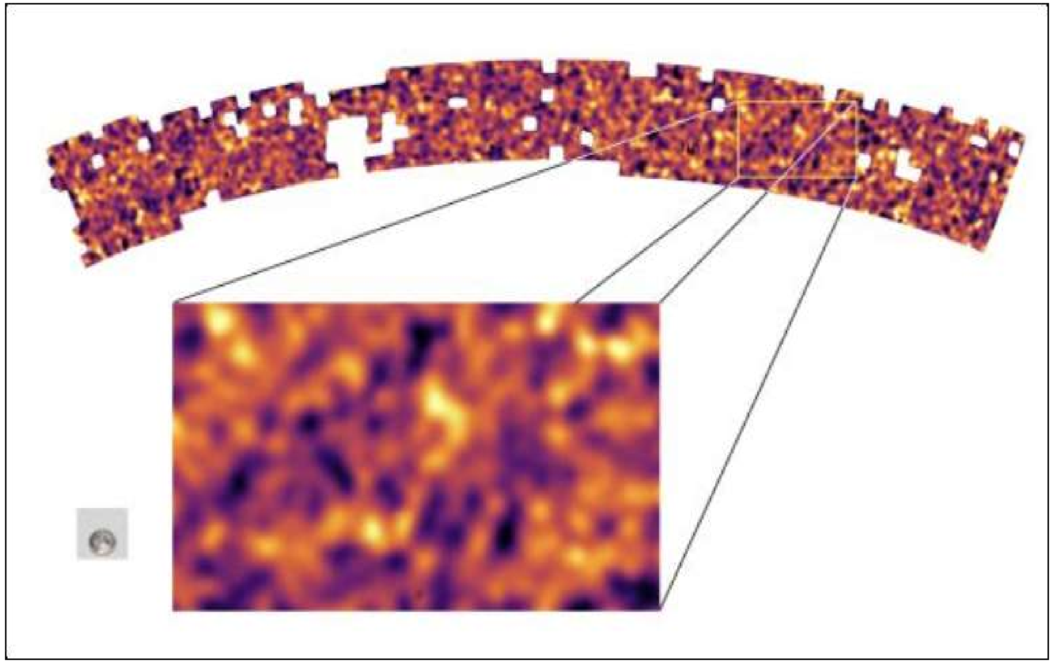
Credit: B.Giblin, K.Kuijken and the KiDS team

Spatial variation in cosmic electron density

↓

Fluctuations in IGM contribution

DM Fluctuations



Credit: B.Giblin, K.Kuijken and the KiDS team

Spatial variation in cosmic electron density

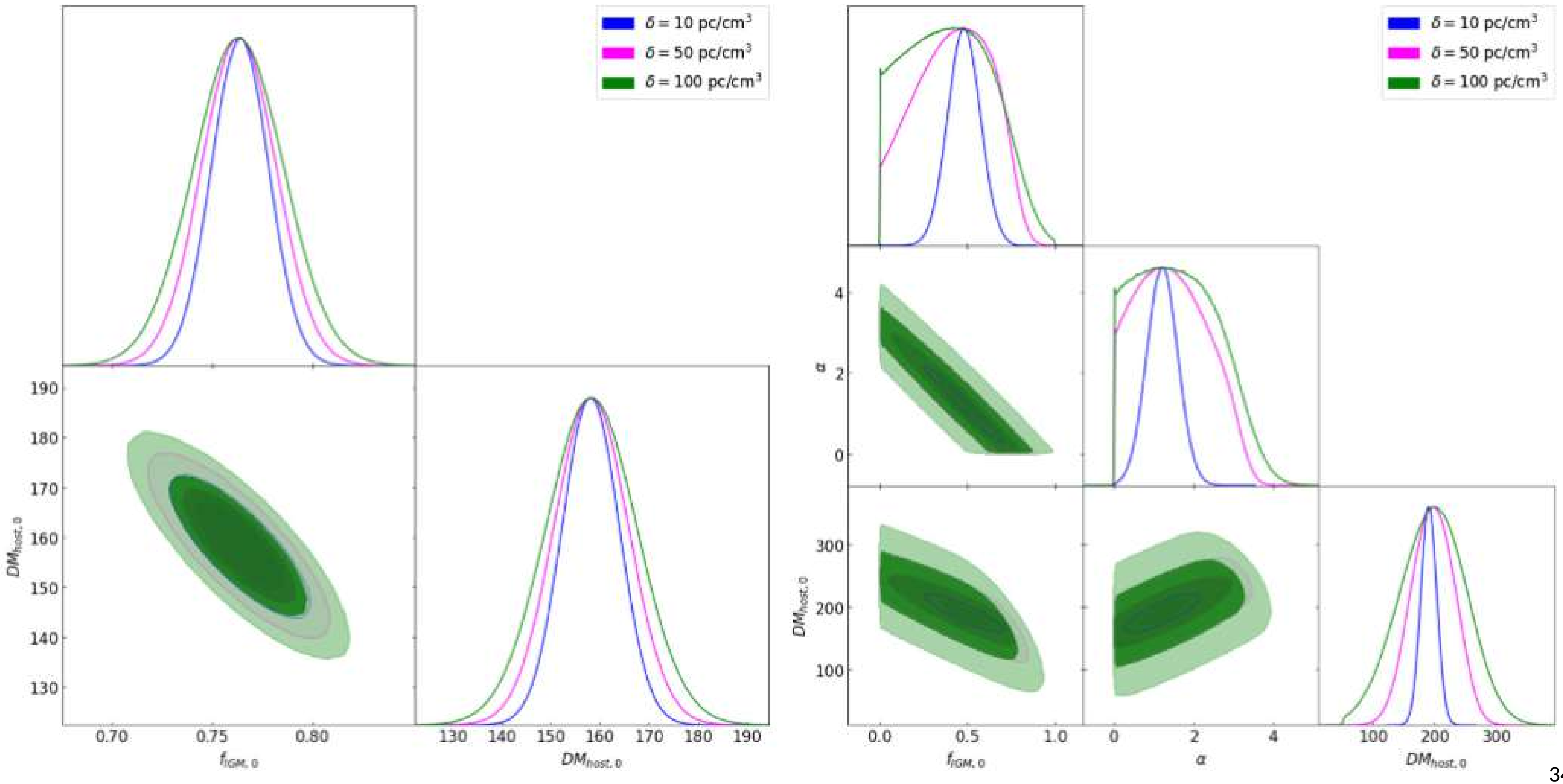
↓

Fluctuations in IGM contribution

$$\sigma^2_{ext} = \sigma^2_{obs} + \sigma^2_{MW} + \delta^2$$

Fixed parameter: $\delta = 10, 50, 100\ \mathrm{pc/cm^3}$

DM Fluctuations



DM Fluctuations

Table 3 Estimates of the f_{IGM} parameters for different values of the DM fluctuations

δ [pc/cm^3]	$f_{IGM,0}$	α	$DM_{host,0}$ [pc/cm^3]	$\ln \mathcal{E}_i$	$\ln B_{ij}$
10	0.76 ± 0.02	–	158.3 ± 7.5	-286.458 ± 0.007	–
50	0.76 ± 0.07	–	158.3 ± 30.0	-25.328 ± 0.005	–
100	0.76 ± 0.13	–	162.0 ± 50.0	-7.917 ± 0.003	–
10	0.48 ± 0.09	1.21 ± 0.39	190.44 ± 12.70	-282.452 ± 0.007	4.006 ± 0.007
50	0.43 ± 0.22	1.22 ± 0.39	197.22 ± 35.26	-24.757 ± 0.004	0.571 ± 0.006
100	0.40 ± 0.26	1.56 ± 1.08	196.56 ± 53.62	-7.670 ± 0.004	0.247 ± 0.005

DM Fluctuations

Table 3 Estimates of the f_{IGM} parameters for different values of the DM fluctuations

δ [pc/cm^3]	$f_{IGM,0}$	α	$DM_{host,0}$ [pc/cm^3]	$\ln \mathcal{E}_i$	$\ln B_{ij}$
10	0.76 ± 0.02	–	158.3 ± 7.5	-286.458 ± 0.007	–
50	0.76 ± 0.07	–	158.3 ± 30.0	-25.328 ± 0.005	–
100	0.76 ± 0.13	–	162.0 ± 50.0	-7.917 ± 0.003	–
10	0.48 ± 0.09	1.21 ± 0.39	190.44 ± 12.70	-282.452 ± 0.007	4.006 ± 0.007
50	0.43 ± 0.22	1.22 ± 0.39	197.22 ± 35.26	-24.757 ± 0.004	0.571 ± 0.006
100	0.40 ± 0.26	1.56 ± 1.08	196.56 ± 53.62	-7.670 ± 0.004	0.247 ± 0.005

Moderate evindence (in favor of a growing evolution)

DM Fluctuations

Table 3 Estimates of the f_{IGM} parameters for different values of the DM fluctuations

δ [pc/cm^3]	$f_{IGM,0}$	α	$DM_{host,0}$ [pc/cm^3]	$\ln \mathcal{E}_i$	$\ln B_{ij}$
10	0.76 ± 0.02	–	158.3 ± 7.5	-286.458 ± 0.007	–
50	0.76 ± 0.07	–	158.3 ± 30.0	-25.328 ± 0.005	–
100	0.76 ± 0.13	–	162.0 ± 50.0	-7.917 ± 0.003	–
10	0.48 ± 0.09	1.21 ± 0.39	190.44 ± 12.70	-282.452 ± 0.007	4.006 ± 0.007
50	0.43 ± 0.22	1.22 ± 0.39	197.22 ± 35.26	-24.757 ± 0.004	0.571 ± 0.006
100	0.40 ± 0.26	1.56 ± 1.08	196.56 ± 53.62	-7.670 ± 0.004	0.247 ± 0.005

Inconclusive evindence (in favor of a growing evolution)

Conclusions

- New cosmological model-independent method from observational data, combining FRBs and SNe Ia data;

- Constraint of the baryon fraction (and host contribution) considering two behaviours: constant and time-dependent case;

- The evidences varies according to the value of the density fluctuation: from strong to inconclusive.

- Large sample of FRBs will improve the constraints on baryon fraction.

THANK YOU