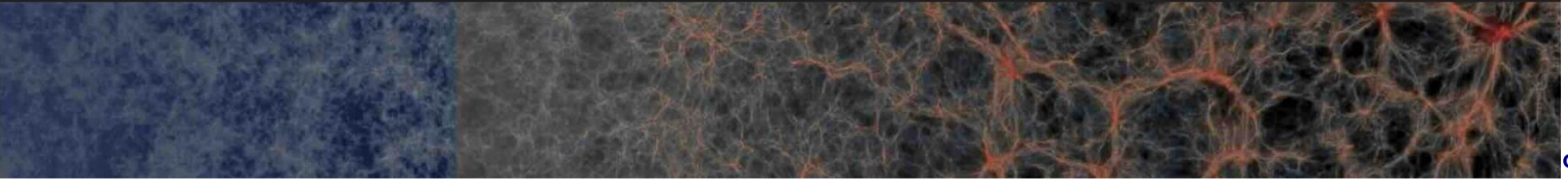


Osaka University Theoretical Astrophysics

From Cosmic Web to Supernova Remnants:
Modeling FRB Dispersion Measures for Baryon Tracing across Scales

Zhao Zhang

Theoretical Astrophysics Group

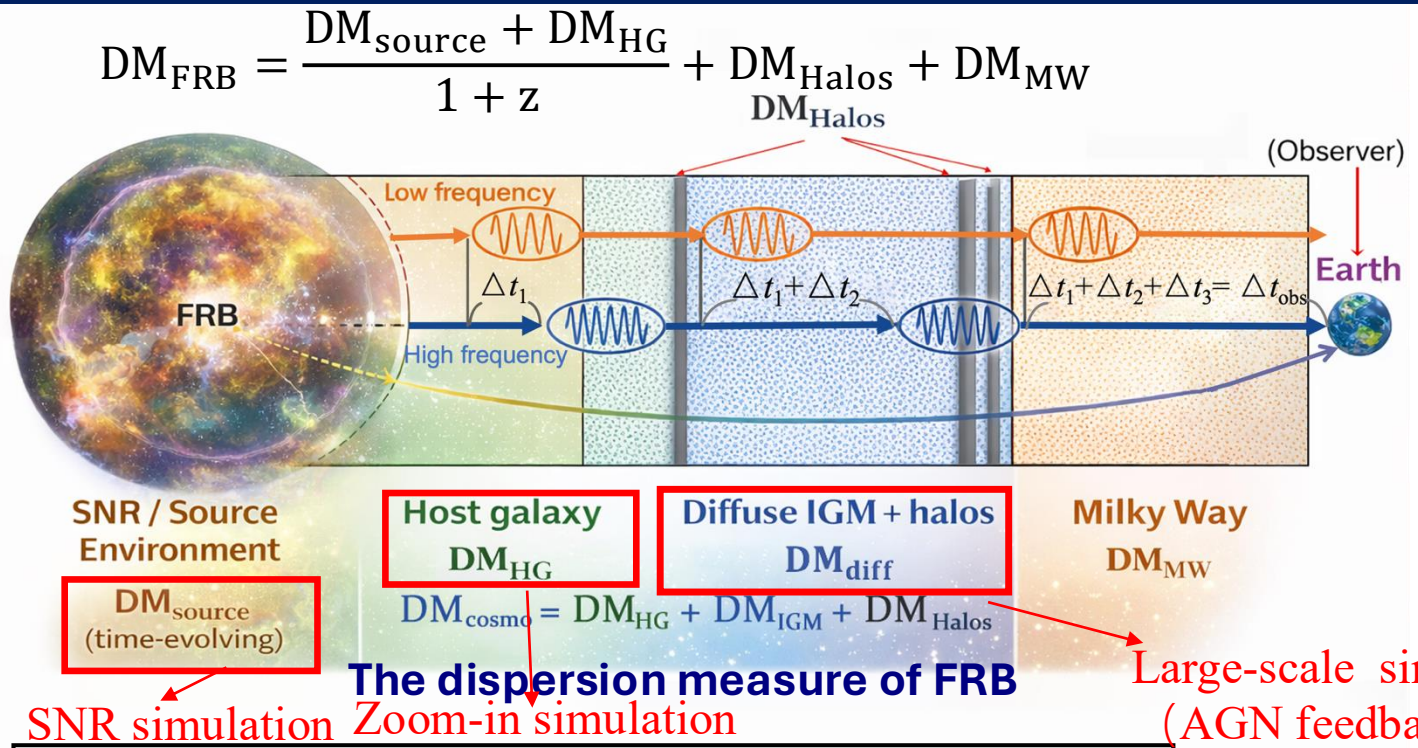
The University of Osaka

Collaborators: Kentaro Nagamine, Yuri Oku , Gaku Kawashima, Shiu-hang Lee, Bing Zhang, Kazuki Tomaru et al.

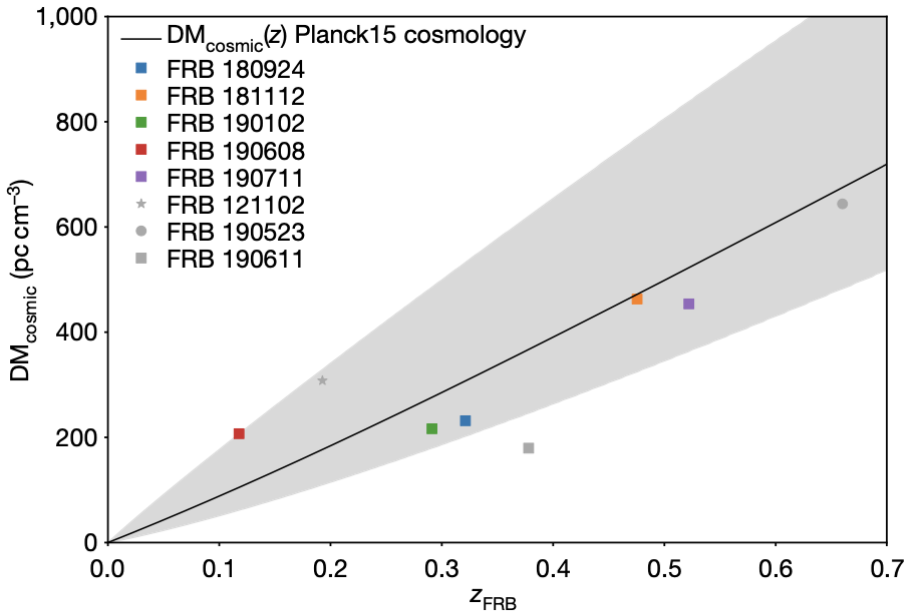
YITP workshop @ Kyoto 01/30/2026

FRB's dispersion measure (DM)

$$\mathrm{DM_{FRB}} = \frac{\mathrm{DM_{source}} + \mathrm{DM_{HG}}}{1+z} + \mathrm{DM_{Halos}} + \mathrm{DM_{MW}}$$



The dispersion measure of FRB



DM-z relation,
Macquart et al., 2020

Time delay and DM

$$\Delta T_{obs} = \frac{e^2}{2\pi m_e c \nu_c^2} \int_0^L \frac{n_{\mathrm{e,p}}}{1+z} d\ell_p = \frac{e^2}{2\pi m_e c \nu_c^2} \mathrm{DM}$$

$$\mathrm{DM} = \frac{c}{H_0} \int_0^L \frac{n_{e,c}\,(1+z)\,dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

$$n_{\mathrm{e,p}} = n_{\mathrm{e,c}}\,(1+z)^3$$

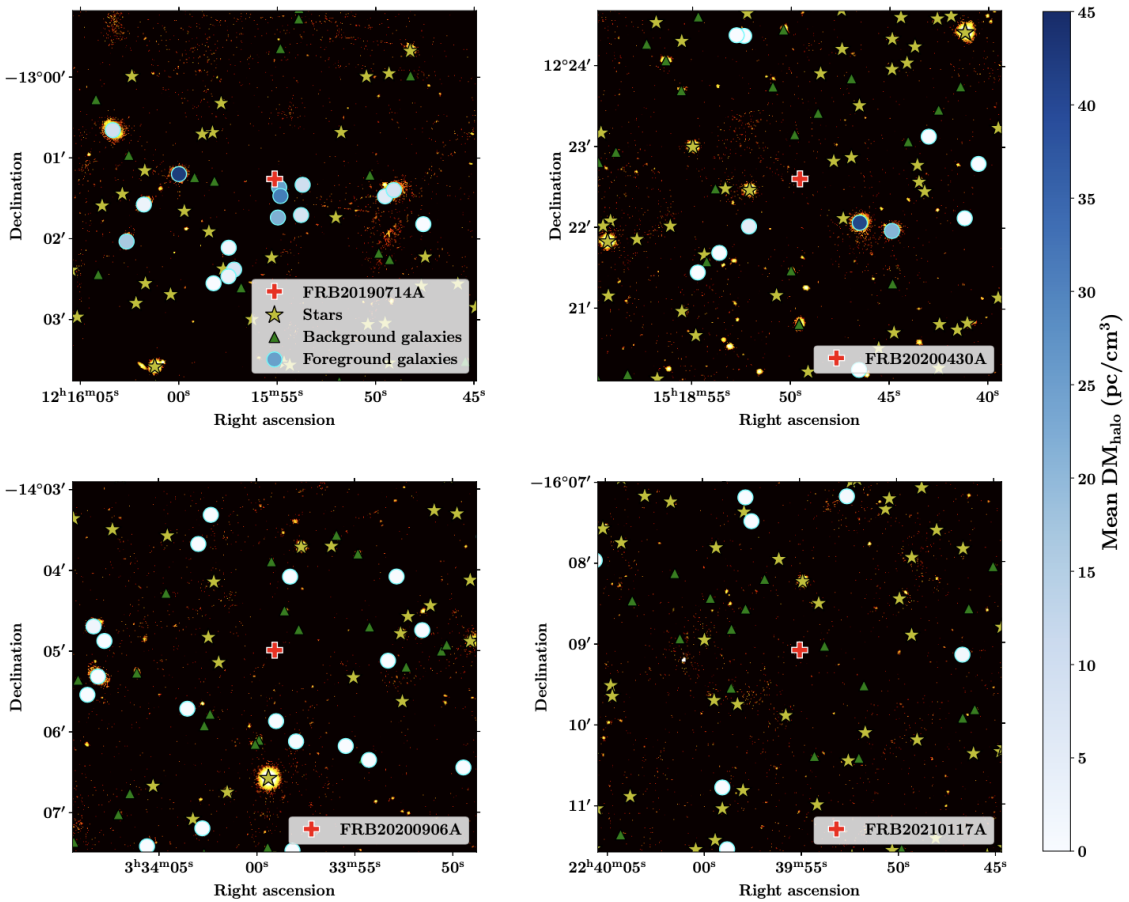
$\mathrm{DM_{diff}} - z$ relations

$$\mathrm{DM_{diff}} = f_{\mathrm{diff}} \frac{\rho_{c,0}\Omega_b}{m_p} \frac{c}{H_0} \int_0^z \frac{\chi_e(z')(1+z')}{E(z')} dz'$$

$f_{\mathrm{diff}} = f_{\mathrm{Halos}} + f_{\mathrm{IGM}}$ → mass fraction of baryons in the IGM

$$E(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

Foreground Galaxies Survey

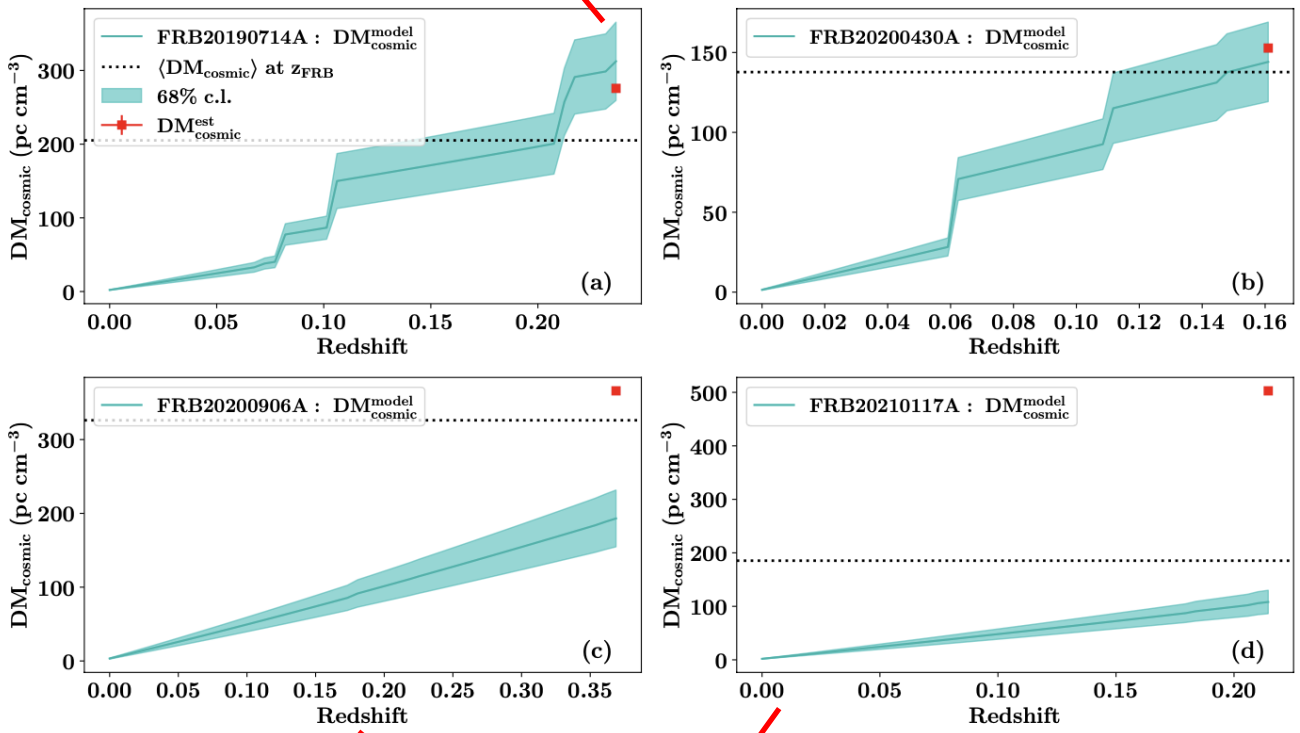


Zoomed-in (5' × 5') fields for four FRB sightlines

Simha et al , 2023

Foreground data enable FRB cosmology more accurate!

Well explained by foreground data



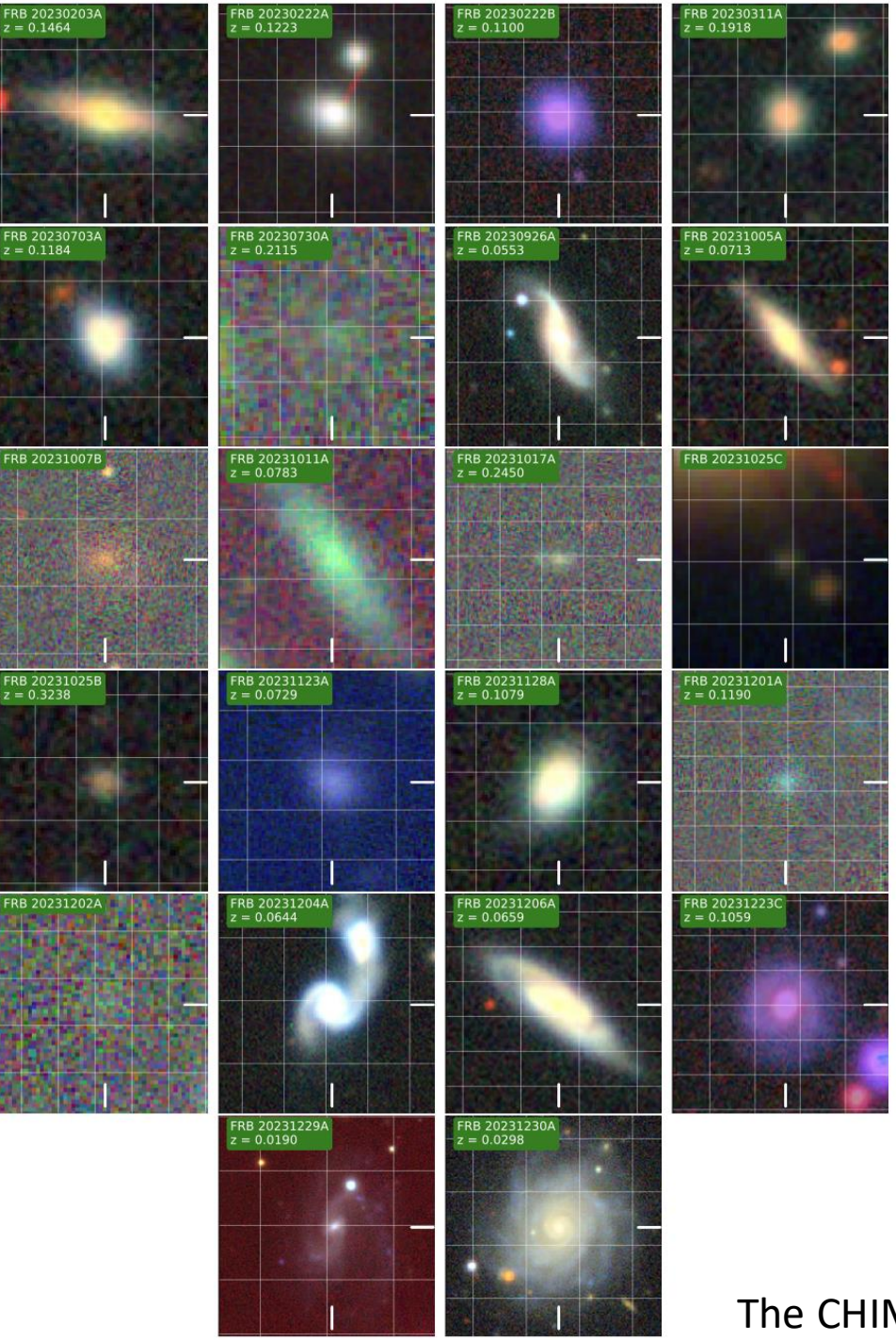
Estimates of DM_{cosmic} for the FRB sightlines vs redshift

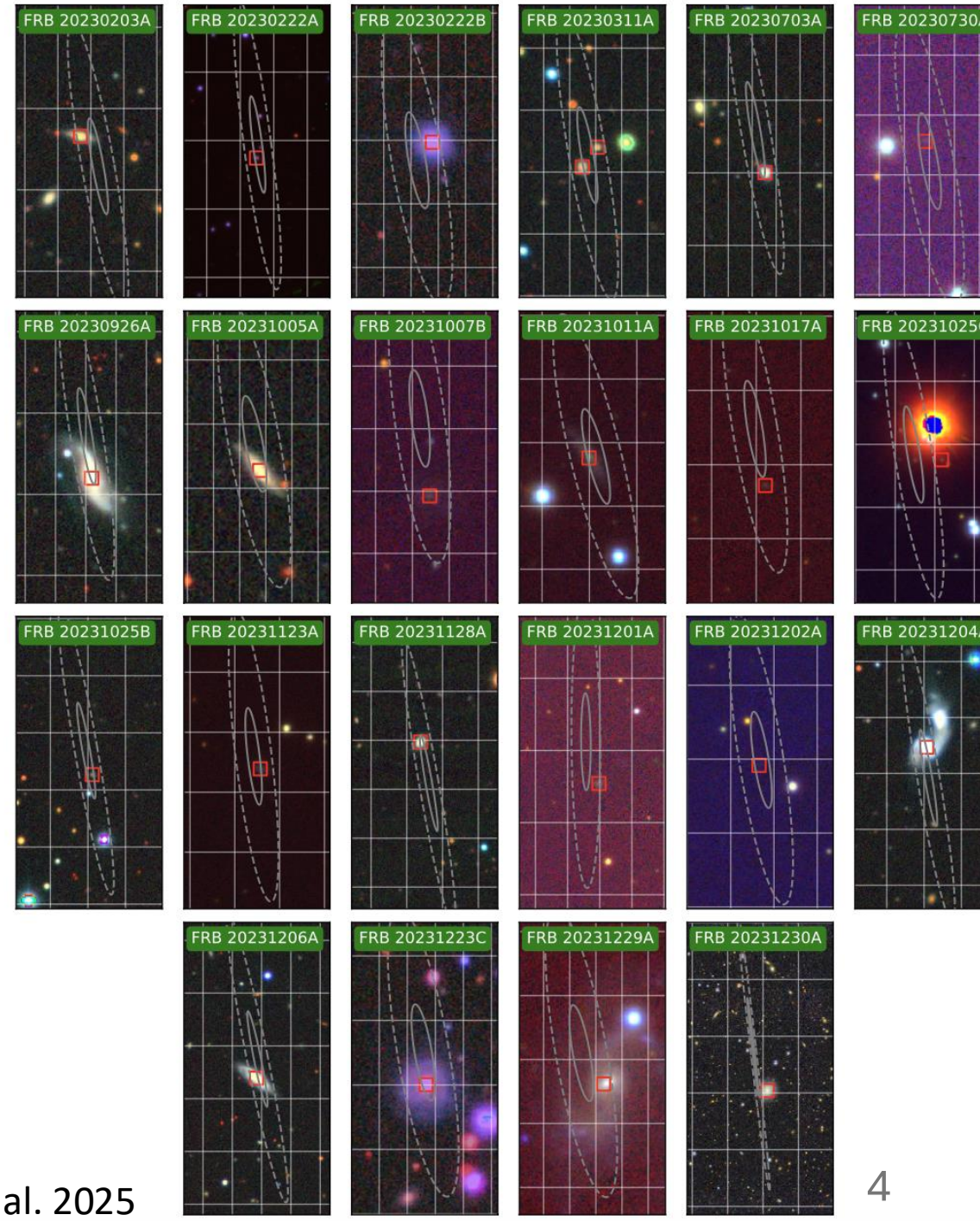
Simha et al , 2023

Reason?

- Dwarf galaxy? (large-aperture: e. g., LSST)
- Excess of DM_{host}?

Host Galaxies





The CHIME/FRB Collaboration et al. 2025

Cosmological Hydrodynamic Simulation Data

CROCODILE: GADGET3/4-Osaka SPH simulation

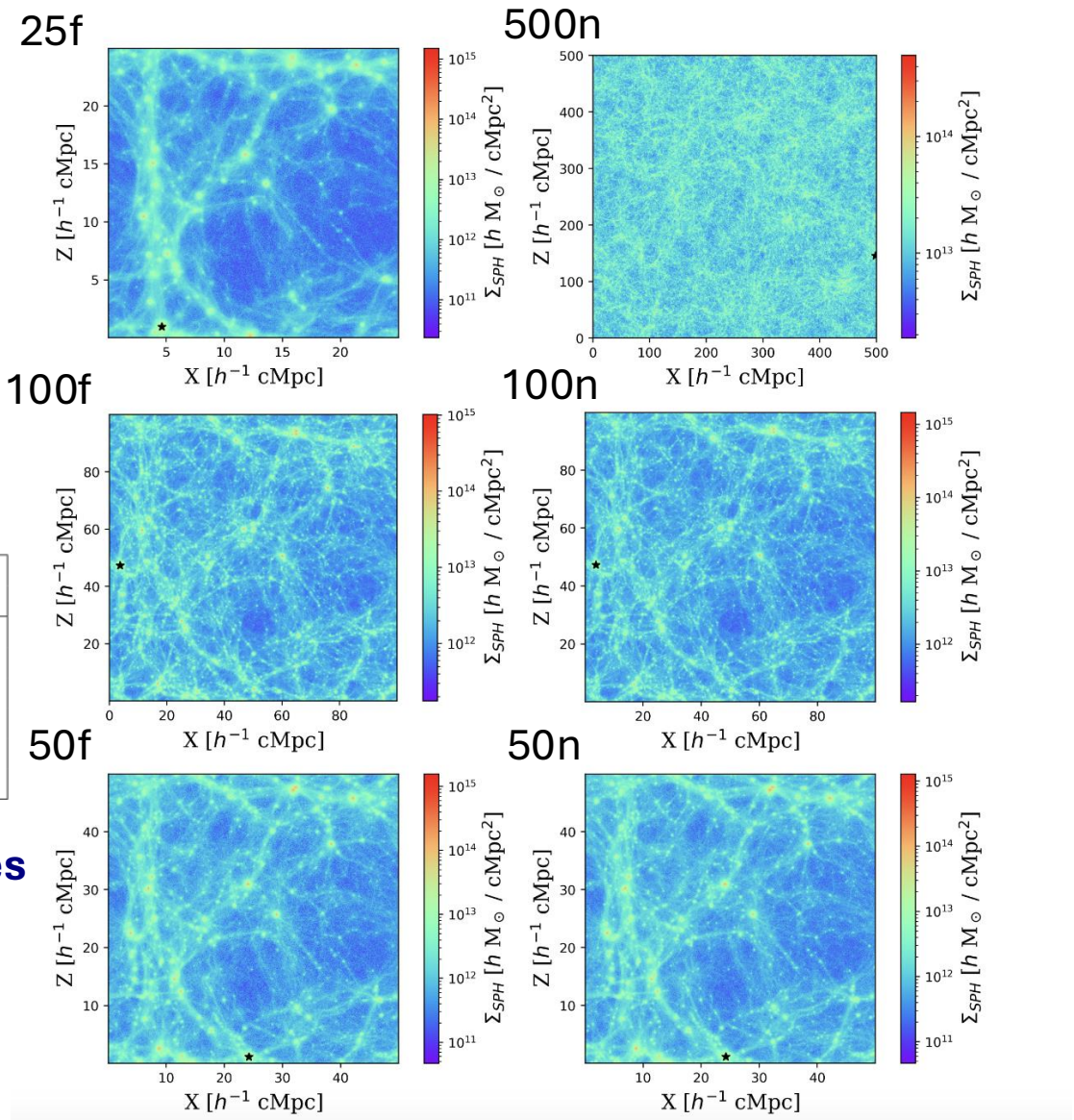
Nagamine et al. 2021; Oku et al. 2022;Fukushima et al. 2023; Romano et al. 2022a,b; Oku & Nagamine 2024; Tomaru et al. 2025

Parameter	Symbol	Value
Hubble Parameter	H_0	$67.74\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
Matter Density	Ω_m	0.31
Dark Energy Density	Ω_Λ	0.69
Baryon Density	Ω_b	0.04889

Table 1. Simulation Parameters for Different Simulations

Simulation	Box Size (h^{-1} cMpc)	Particle Numbers	Dark Matter Mass ($h^{-1}\,M_\odot$)	Gas Mass ($h^{-1}\,M_\odot$)	$\epsilon_G^\dagger$ (h^{-1} ckpc / h^{-1} pkpc)	AGN Feedback
$\mathrm{L25N512_{Fiducial}}$	25	2×512^3	8.43×10^6	1.58×10^6	1.63 / 0.25	✓
$\mathrm{L50N512_{Fiducial}}$	50	2×512^3	6.75×10^7	1.26×10^7	3.38 / 0.50	✓
$\mathrm{L50N512_{NoBH}}$	50	2×512^3	6.75×10^7	1.26×10^7	3.38 / 0.50	×
$\mathrm{L100N1024_{Fiducial}}$	100	2×1024^3	6.75×10^7	1.26×10^7	3.38 / 0.50	✓
$\mathrm{L100N1024_{NoBH}}$	100	2×1024^3	6.75×10^7	1.26×10^7	3.38 / 0.50	×
$\mathrm{L500N1024_{NoBH}}$	500	2×1024^3	8.43×10^7	1.58×10^7	16 / 2.50	×

Cosmological and Simulation Parameters for Different Box Sizes



LSS Simulation

DM-z relation

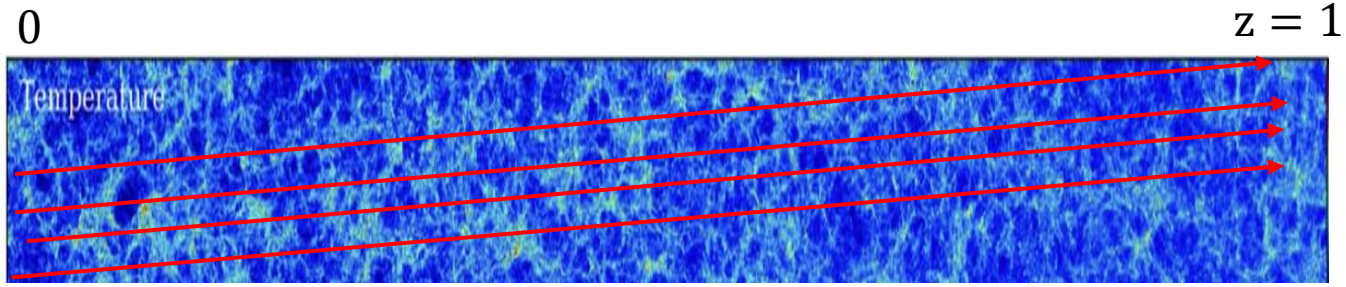
Grid data : 100 Mpc Box

Box resolution: 256^3 cubes

Redshift: 0-1.0

Sightline number: 10000 (100×100)

Light-cone resolution: 400 intervals

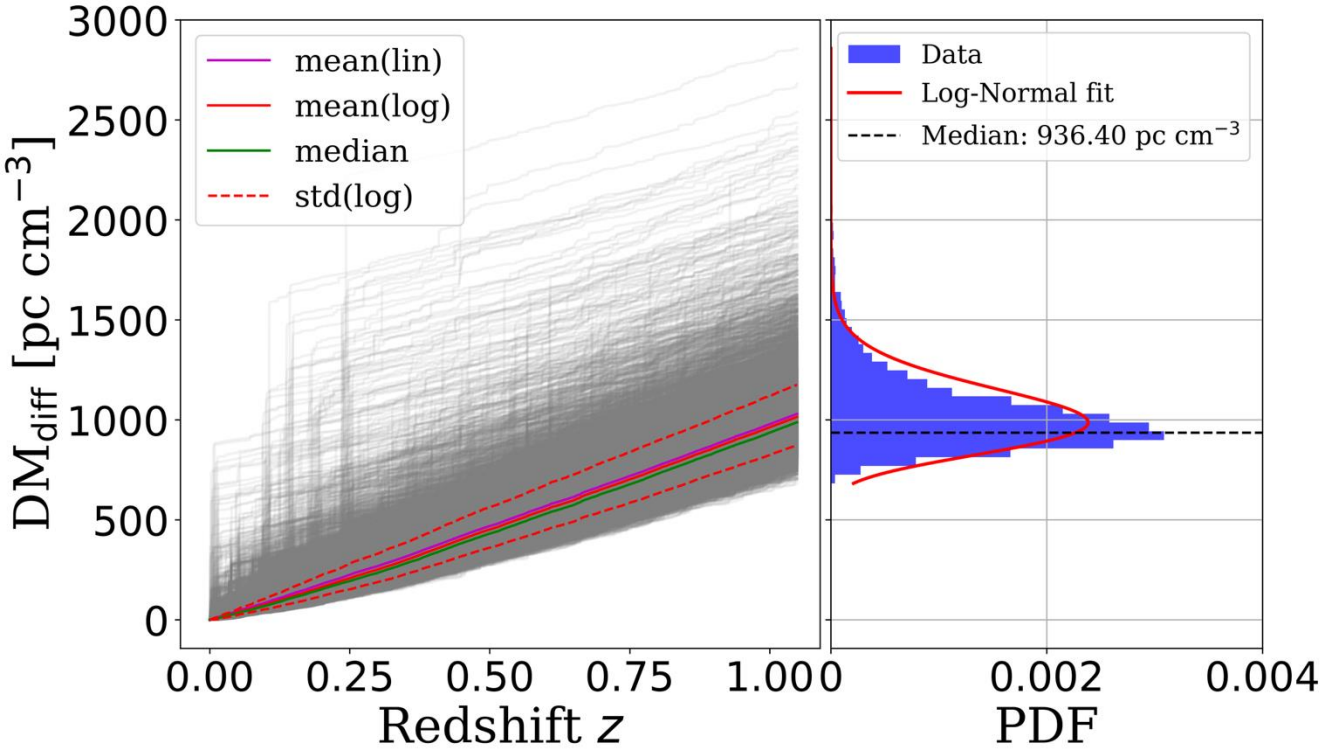


Fiducial

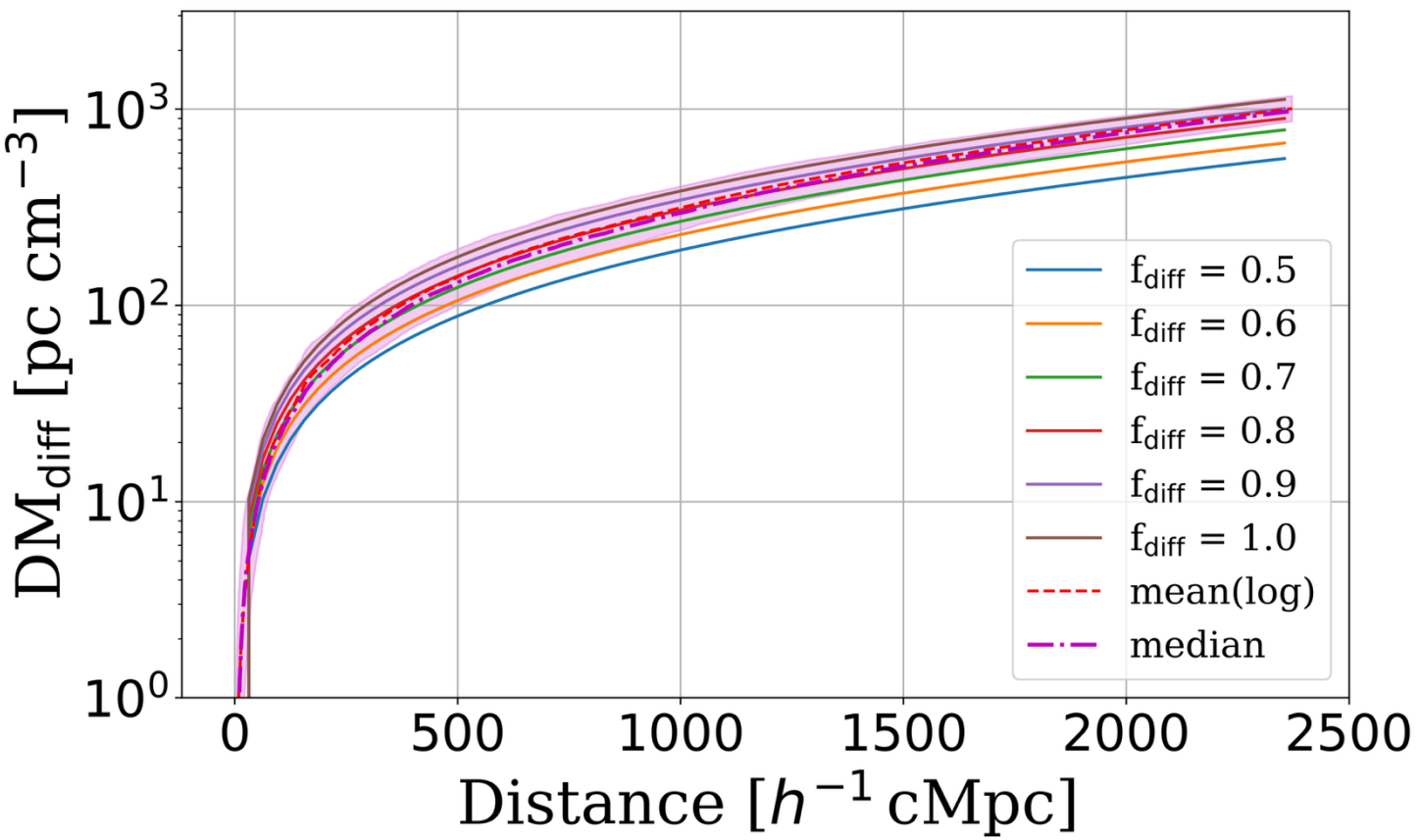
$$\mathrm{DM_{diff}} = 936.4\ \mathrm{pc\ cm^{-3}}$$

NoBH

$$\mathrm{DM_{diff}} = 927.25\ \mathrm{pc\ cm^{-3}}$$



$f_{\rm diff}$ Constraints



15 localized FRB ("f_{IGM}" = 0.857 ± 0.06)
22 localized FRB ("f_{IGM}" =0.83 ± 0.06)

$$f_{\rm diff} = 0.865^{+0.101}_{-0.165} \text{ (Fiducial)}$$

$$f_{\rm diff} = 0.856^{+0.101}_{-0.162} \text{ (NoBH)}$$

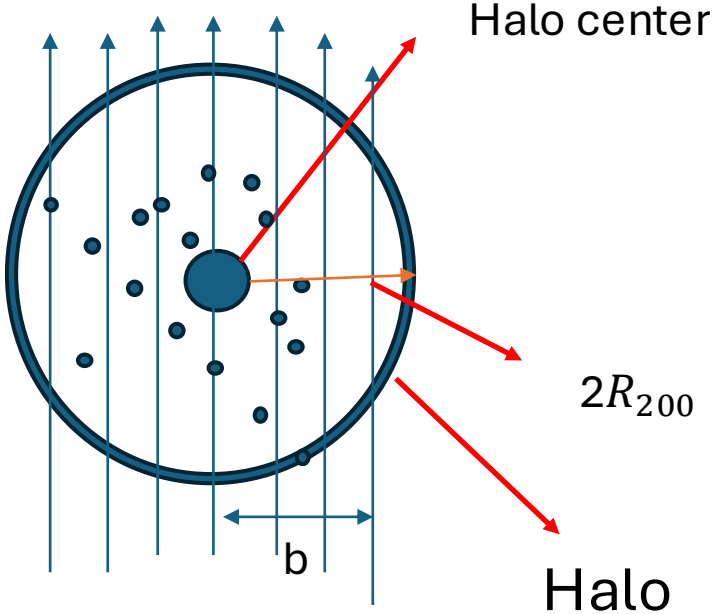
Small difference

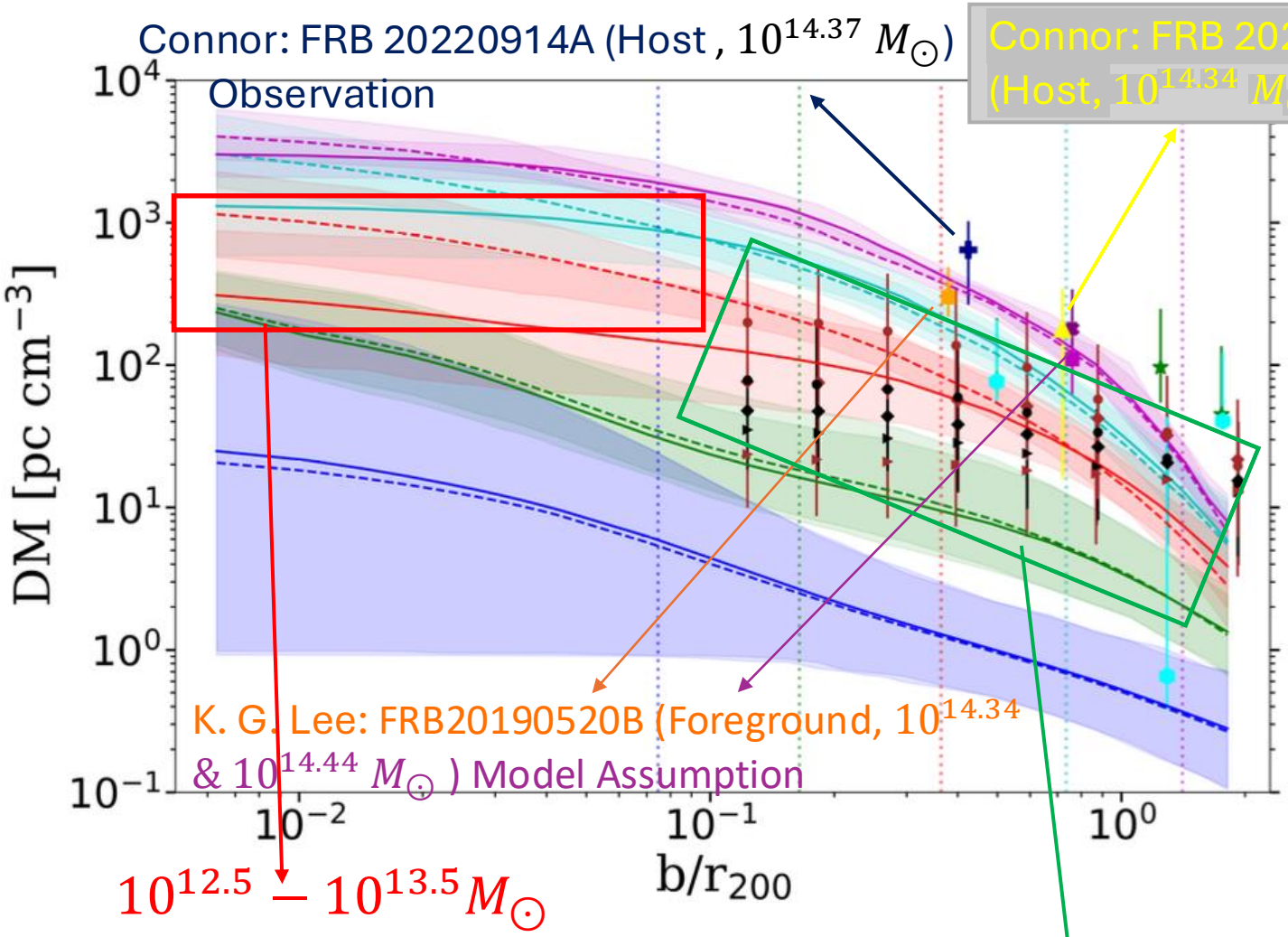
AGN jet feedback?
Radiative transfer?

DM-z relation:

$$\mathrm{DM_{diff}} = \frac{3cH_0\Omega_b f_{\rm diff}}{8\pi G m_p} \int_0^z \frac{\chi_e(z')(1+z')}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\, dz'$$

DM v.s. Impact parameter (100 Mpc)





$10^{12.5} - 10^{13.5} M_\odot$

The largest difference mass range between AGN and NoAGN

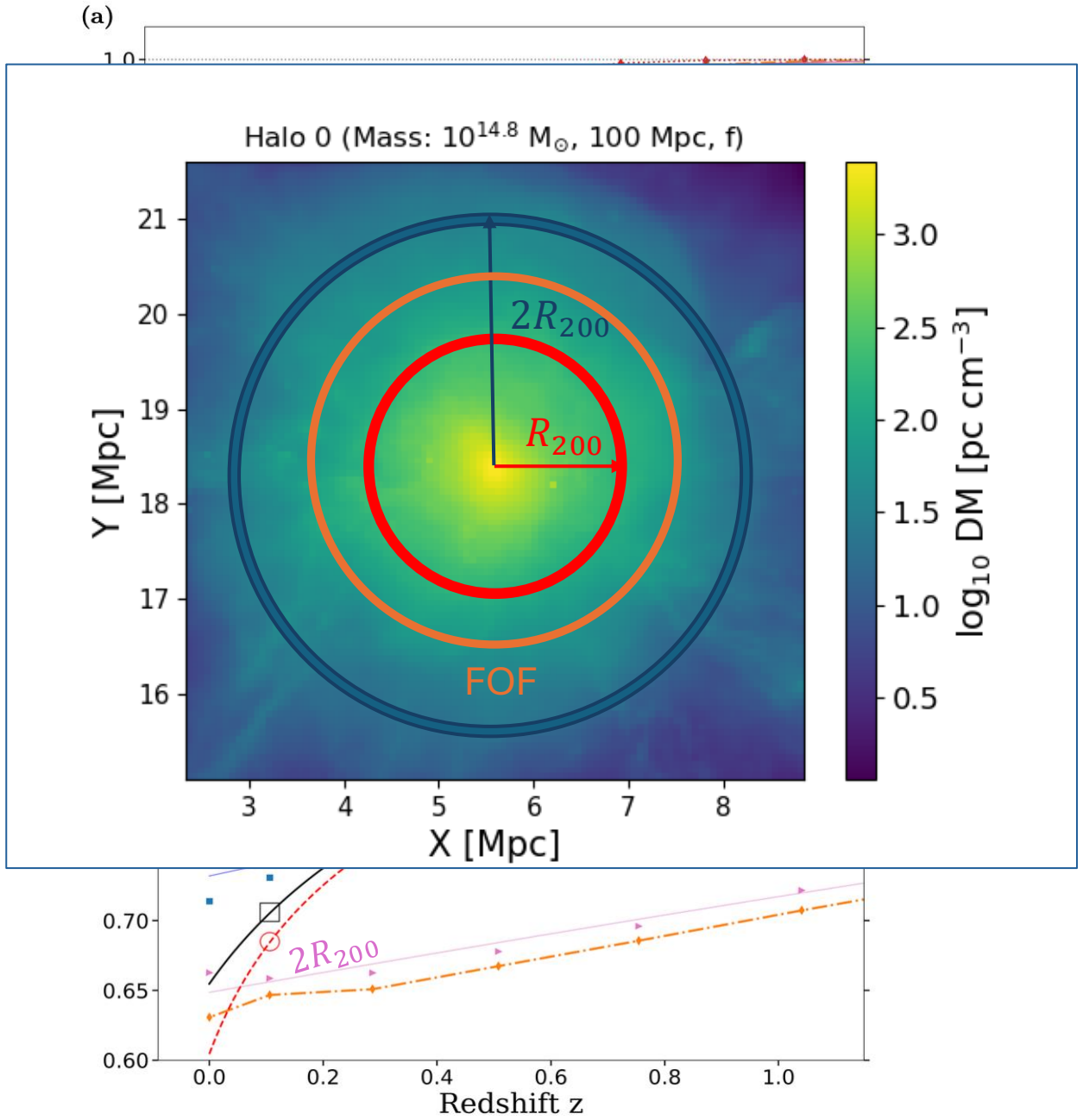
Strong CGM–IGM Baryon Redistribution

Medlock et al., 2023

$10^{11} - 10^{13} M_\odot$

Simulation (Simba, TNG, Astrid)

Redshift evolution of $f_{\rm diff}$ and Intrinsic $f_{\rm IGM}$



$f_{\rm diff}$: □ :Fiducial ○ :NoBH

$f_{\rm IGM}$:

FoF Halo: ■ (Fiducial) ● (NoBH)

$R_{\rm cut}$	Type	Line Style	Marker
R_{200}	Fiducial	Light purple solid	×
	NoBH	**Light purple dashed**	△
$2R_{200}$	Fiducial	Magenta solid	▷
	NoBH	**Magenta dashed**	▽
$3R_{200}$	Fiducial	Olive-green solid	◁
	NoBH	**Olive-green dashed**	⋆

Fitting models:

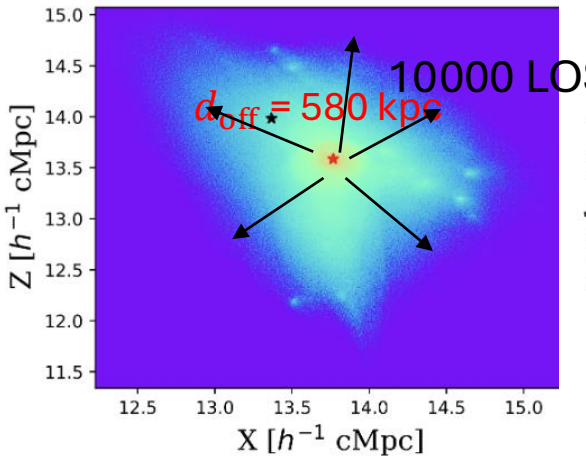
Doulbe Power-Law Exponential Model (DPL-Exp):

$$f(z) = 1 - \exp(-\kappa(z^{\gamma} + \tau)^{\zeta}) \quad (f_{\rm IGM}(z))$$

Convergence PL Exponential Model (CPL-Exp):

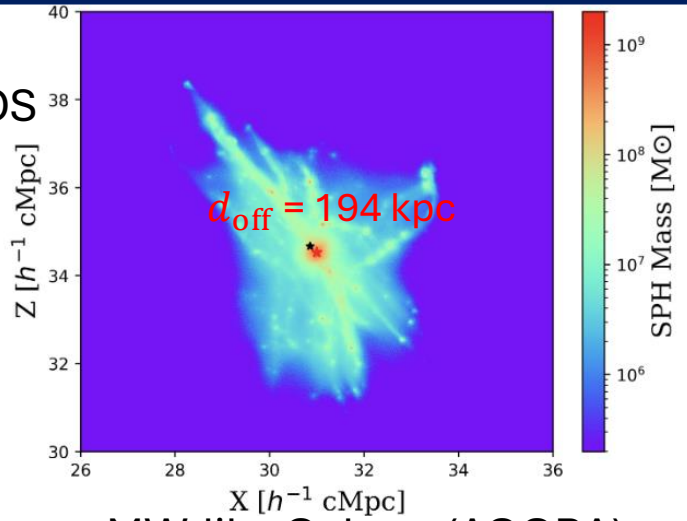
$$f(z) = 1 - \exp(-\kappa(z + \tau)^{\zeta}) \quad (f_{\rm diff}(z))$$

Zoom-in analysis for host galaxy



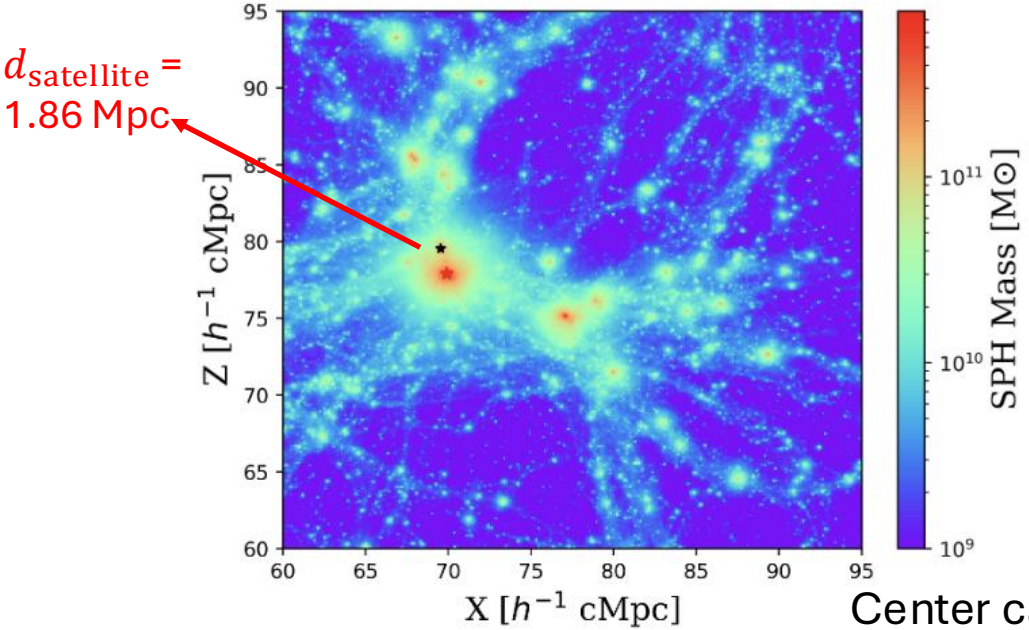
Dwarf Galaxy

Tomaru et al. 2025.



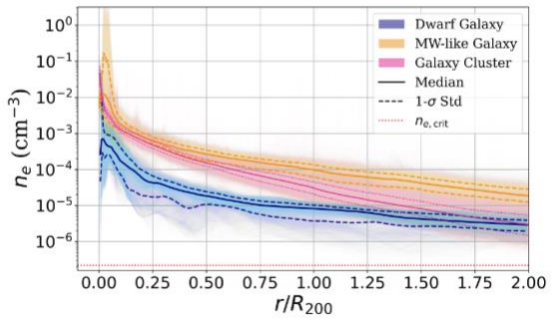
MW-like Galaxy (AGORA)

Roca-Fàbrega et al.2021, 2024

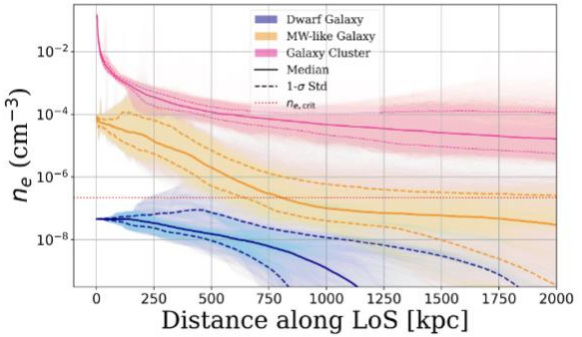


Galaxy Cluster

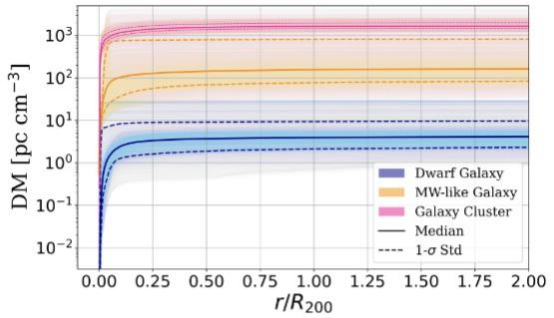
Fukushima et al. 2023



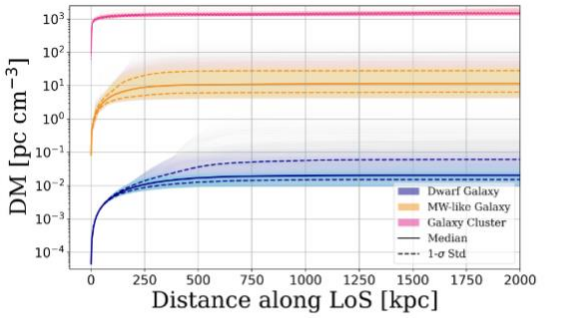
(a) Electron density profile (central)



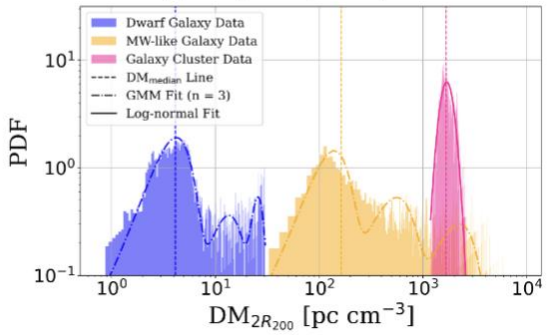
(b) Electron density profile (off-center/satellite)



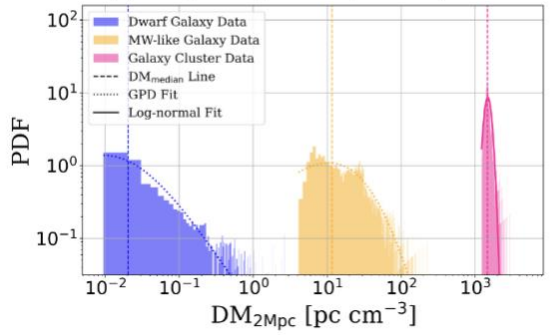
(c) DM profile (central)



(d) DM profile (off-center/satellite)



(e) Log-Normal Fit for DM distribution (center)



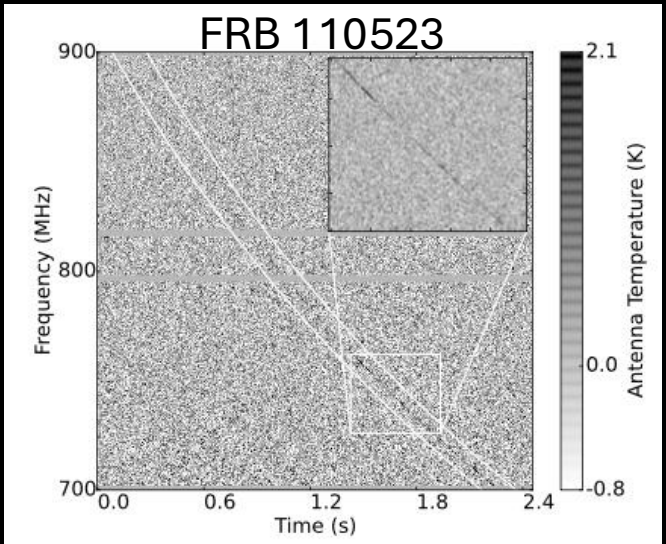
(f) Exponential Fit for DM distribution (off-center/satellite)

Center case:

Median DM ~ 4.13, 163.53, 1670.17 pc cm^{-3} for Dwarf, MW-like and GalCluster

Significant source contribution to FRB DM and RM

$$\mathbf{RM} = (8.1 \times 10^5 \text{ rad m}^{-2}) \int_0^{D_z} \frac{[B_\parallel(l)] n_e(l)}{[1+z(l)]^2} dl$$



Masui+2015

$\mathrm{DM_{observed}} = 623.30 \text{ pc cm}^{-2}$

DM predicted redshift at $z \sim 0.5$

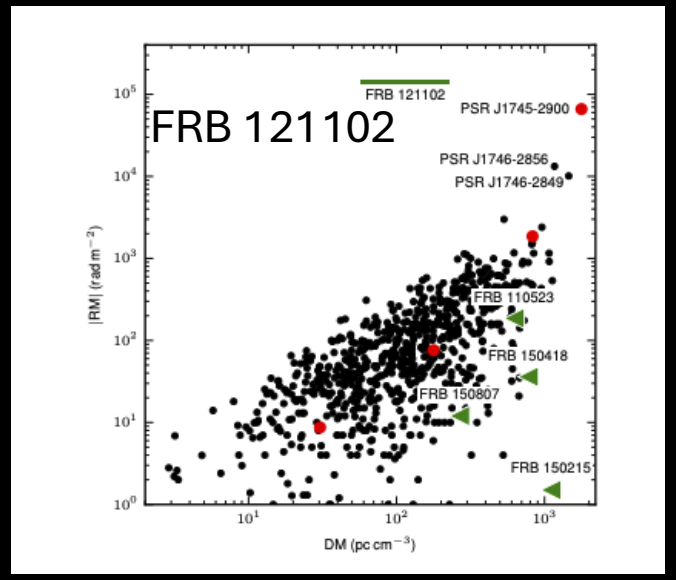
$\mathrm{RM_{observed}} = 186.1 \text{ rad m}^2$

Predicted $\mathrm{RM_{MW}} = 18 \text{ rad m}^2$

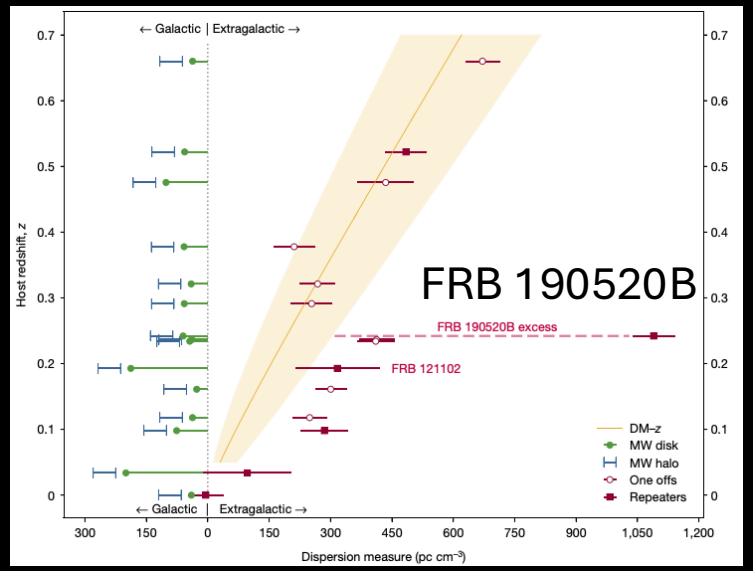
Predicted $\mathrm{RM_{IGM}} = 6 \text{ rad m}^2$

Predicted $\mathrm{RM_{HG}} \ll \mathrm{RM_{observed}}$

Not a strong case any more



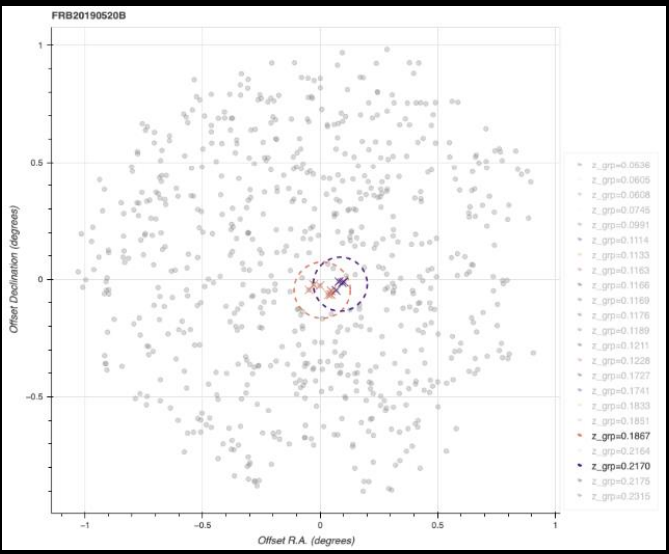
Michilli+2015



Nui+2022

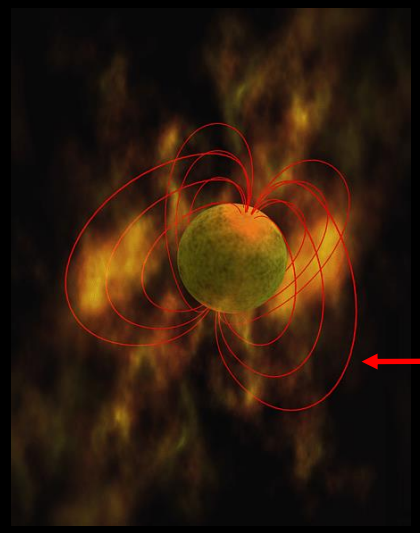
Source excess or foreground galaxies?

Component[a]	$r_{max} = r_{200}$	$r_{max} = 2\,r_{200}$
$\mathrm{DM_{FRB}}$	$1204.7^{+4.0}_{-4.0}$	
$\mathrm{DM_{MW}}$	$113.0^{+13.0}_{-13.0}$	
$\mathrm{DM_{IGM}}$	$204.4^{+61.7}_{-38.7}$	
$\mathrm{DM_{halos}}$	$416.1^{+261.0}_{-126.4}$	$574.4^{+271.4}_{-139.0}$
$\mathrm{DM_{host}}$[b]	$466.5^{+139.7}_{-230.1}$	$339.1^{+122.3}_{-173.5}$



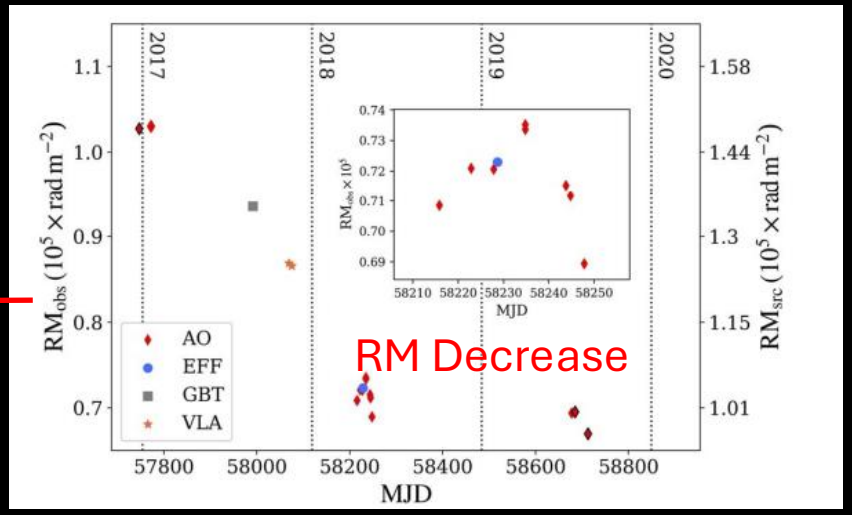
Lee+2023

Evolution of FRB DM_{source} or RM_{source}



Magnetar wind nebula (MWN) ?

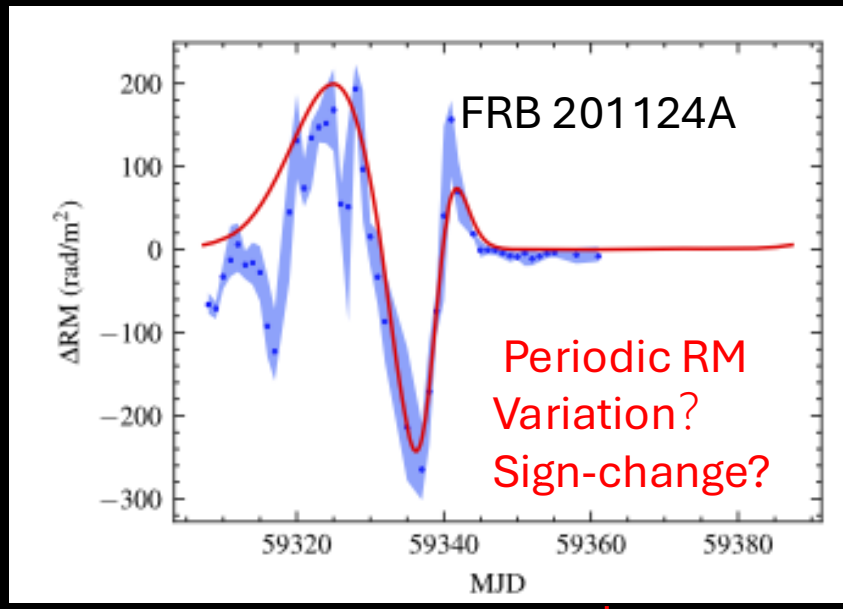
FRB 121102



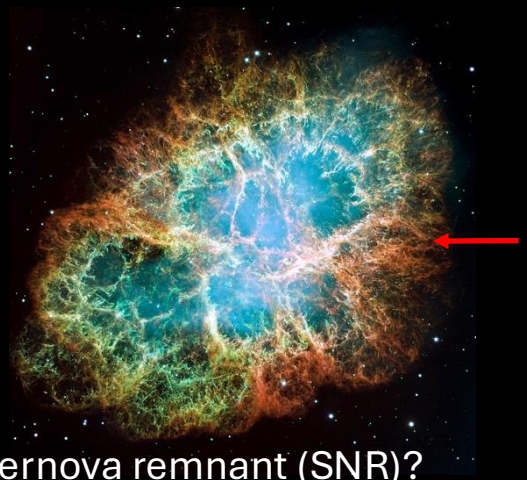
Michilli+2015

DM ($pc\ cm^{-3}$)
560.5
560.6
561.5
561.5
561.6
561.6
561.6
561.6
561.7
561.7

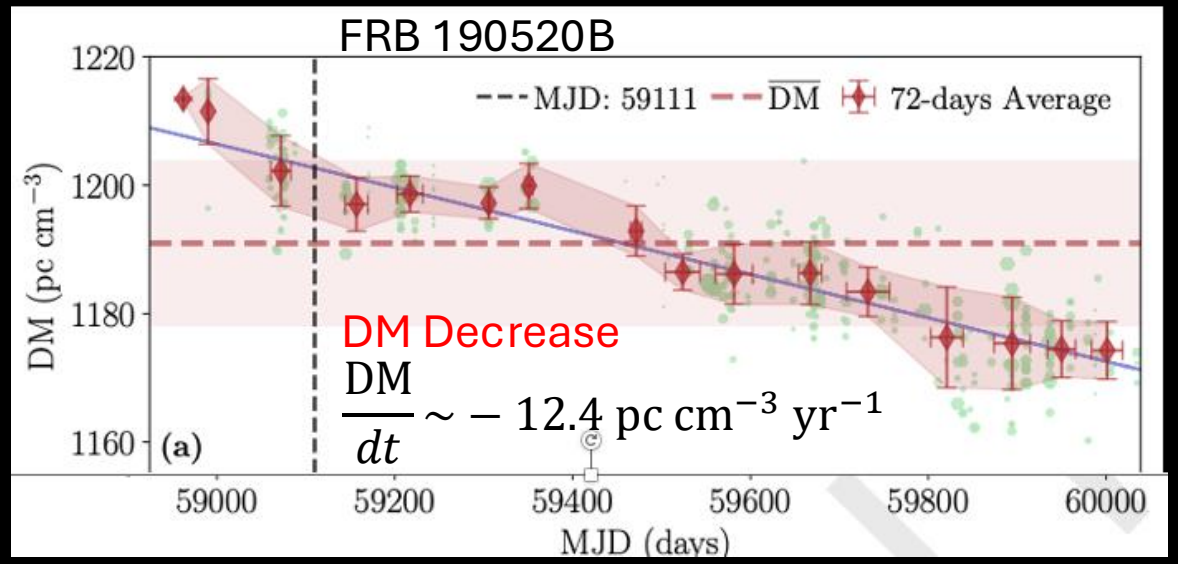
DM not change?



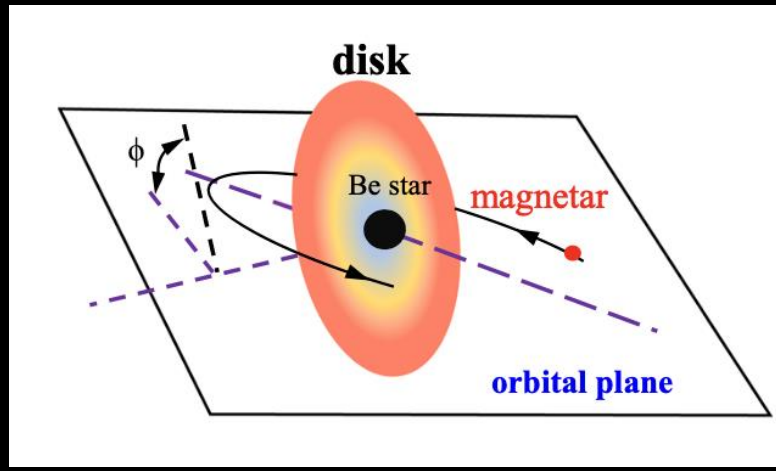
Wang+2021



Supernova remnant (SNR)?



Niu+2025



Previous Work on SNR-FRB (ED-stage)

Piro 2016

Fully Ionized Ejecta

- Uniform ISM (constant density).

$\mathrm{DM} = n_e \Delta \mathrm{R} \quad n_e = M_{\mathrm{ej}}/(4\pi R_b^3 \mu_e m_p) \quad \Delta \mathrm{R} = \mathrm{R_b} - \mathrm{R_r}$ (fully ionized)

Yang&Zhang 2017

Fully Ionized Ejecta

$n_e = M_{\mathrm{ej}}/(4\pi R_b^2 \Delta \mathrm{R}\, \mu_e m_p)$ (Thin shell approximation)

$$\mathrm{DM_{SNR}}(t) \simeq 2.6 \times 10^4\, \eta M_1^2\, E_{51}^{-1}\, t_{\mathrm{yr}}^{-2}\ \mathrm{pc\ cm^{-3}}$$

Piro&Gaensler 2018

Shocked Ionized Ejecta

- **Uniform ISM and wind ($\rho \propto r^{-2}$)**
- Shocked Ionized layer ($R_c - R_r$) $\propto t^{5/2}$ (ED), $\mathrm{R_b} - \mathrm{R_c}$: shocked ISM

$$\mathrm{DM_{SNR}}(t) = 52.6 \left(\frac{\mu}{\mu_e}\right) E_{51}^{-1/4}\, M_1^{3/4}\, n_0^{1/2}\, t_{\mathrm{yr}}^{-1/2}\ \mathrm{pc\ cm^{-3}}$$ Uniform case

$$\mathrm{DM_{SNR}}(t) \simeq 1.3\times 10^4\, \mu_e^{-1}\, E_{51}^{-3/4}\, M_1^{5/4}\, K_{13}^{1/2}\, t_{\mathrm{yr}}^{-3/2}\ \mathrm{pc\ cm^{-3}}$$ Wind case

Zhao+2021a,b

Shocked Ionized Ejecta + unshocked Ejecta

Self-Similar Driven wave (SSDW)

$w_{\mathrm{core}} \sim 0.1, \mathrm{s} = 2, \mathrm{n} = 10$

$$\rho(r,t) = \begin{cases} \rho_{\mathrm{ej}}(r) = \frac{M_{\mathrm{ej}}}{R_{\mathrm{ej}}^3} f\left(\frac{r}{R_{\mathrm{ej}}}\right), & r \leqslant R_{\mathrm{ej}} \\ \rho_{\mathrm{a}}(r) = \eta_{\mathrm{s}} r^{-s} & r > R_{\mathrm{ej}} \end{cases}$$

$$\mathrm{DM_{sh,ej}}(t) = \frac{2K(n-3)(n-4)}{\mu m_p} \left(\frac{1}{r_2} - 1\right) \frac{1}{\zeta_c R_{\mathrm{ch}}} \left(\frac{t_{\mathrm{ch}}}{t}\right)^{\frac{n-3}{n-2}}$$

$$\mathrm{DM_{sh,CSM}}(t) = \frac{4K}{\mu m_p} \left(1 - \frac{1}{r_1}\right) \frac{1}{\zeta_c R_{\mathrm{ch}}} \left(\frac{t_{\mathrm{ch}}}{t}\right)^{\frac{n-3}{n-2}}$$

$$f(w) = \begin{cases} f_0, & 0 \leqslant w \leqslant w_{\mathrm{core}} \\ f_0 (w_{\mathrm{core}}/w)^n & w_{\mathrm{core}} \leqslant w \leqslant 1 \end{cases}$$

Truelove& Mckee 1999

$$\mathrm{DM_{unsh,ej}} = \int_0^{R_{\mathrm{core}}} \frac{M_{\mathrm{ej}}}{\mu m_p R_{\mathrm{ej}}^3} \eta f_0\, dr + \int_{R_{\mathrm{core}}}^{R_{\mathrm{r}}} \frac{M_{\mathrm{ej}}}{\mu m_p R_{\mathrm{ej}}^3} \eta f_0 \left(\frac{r}{R_{\mathrm{core}}}\right)^{-n} dr$$

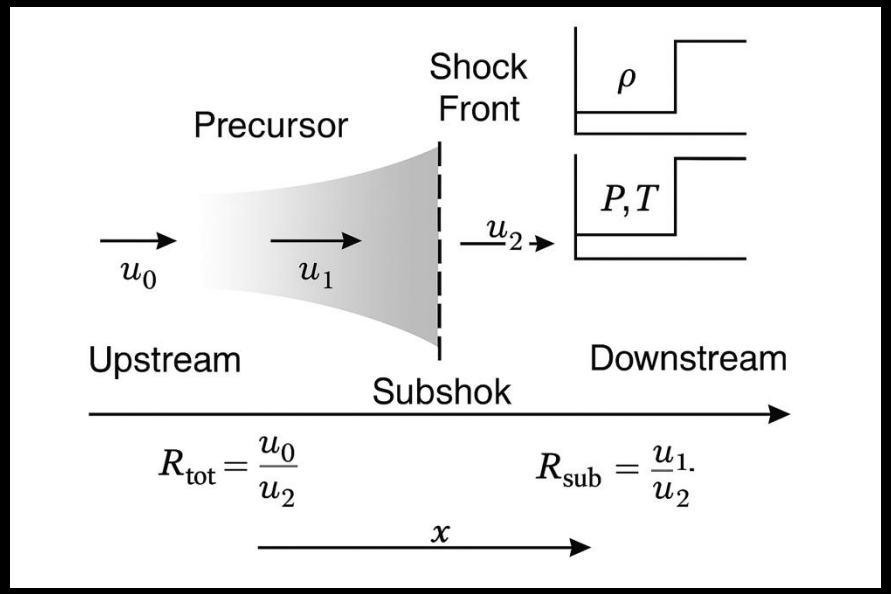
2. 1D-SNR Simulation Code (with Gaku, Herman et al.)

Supernova Remnant and Shock Hydrodynamics ChN (cr-hydro-NEI):

Ellison+17, Patnaude+10, Lee+12,13,14,15, Jacovi+21, Court+21, Kawashima+in prep.

Cosmic ray

Non-equilibrium Ionization

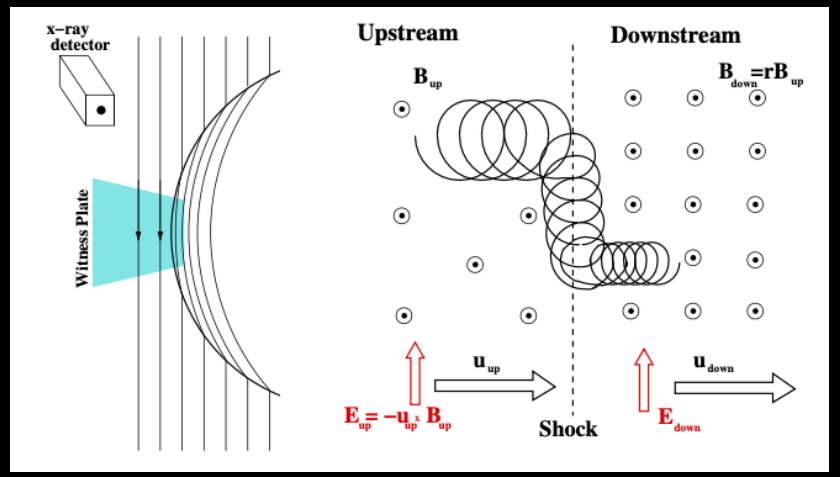


Conservation of Momentum Flux:

$$\rho_0 u_0^2 + P_{g,0} + P_{CR,0} + P_{w,0} = \rho(x)u(x)^2 + P_g(x) + P_{CR}(x) + P_w(x)\,. \quad (1)$$

- "0": far upstream ($x = -\infty$)
- "1": immediately upstream ($x = 0^-$)
- "2": immediately upstream ($x = 0^+$)

Diffusive Shock Acceleration (DSA): $P_{CR}(x) > 0$



NLDSA

$P_{g,0} = \rho_0 u_0^2/(\gamma_g M_0)$: Ambient Gas Pressure

$P_{CR,0}$: Pressure from any pre-existing seed CR protons

$P_{\omega,0}$: Pressure of pre-existing magnetic turbulence

$P_g(x)$: Gas pressure at any $x < 0$ in the precursor region

$P_{CR}(x)$: The pressure from the accelerated protons in the precursor

$P_\omega(x)$: Magnetic pressure in the precursor region

Datasets

Table 1. Summary of single-star and binary-stripped progenitor models.

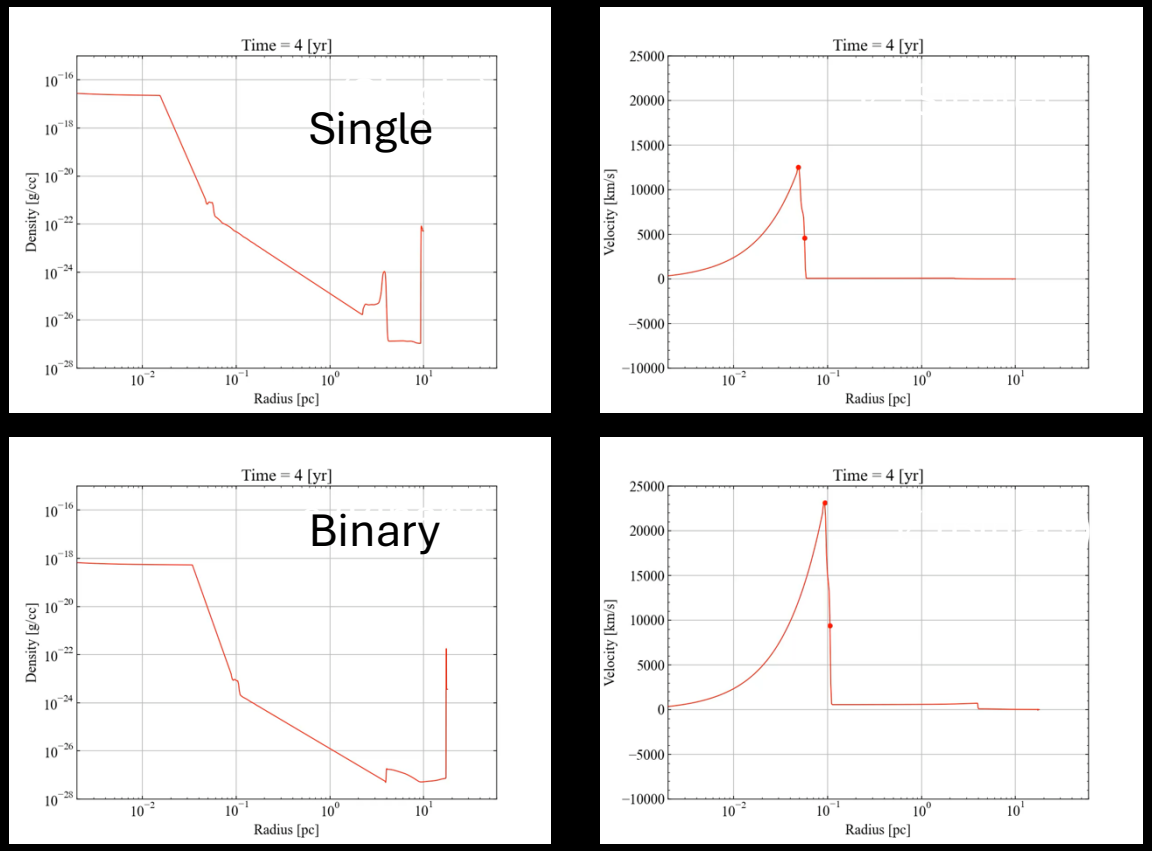
Channel	$M_{\rm ZAMS}$ ($M_\odot$)	$\Delta M_{\rm wind}$ ($M_\odot$)	$\Delta M_{\rm RLOF}$ ($M_\odot$)	$M_{\rm ej}$ ($M_\odot$)	$E_{\rm SN}$ (10^{51} erg)	$M_{\rm rem}$ ($M_\odot$)	Fate
Single	11	1.64	–	7.83	1.0	1.53	NS
Binary	11	0.70	7.12	1.81	1.0	1.62	NS
Single	30	15.74	–	12.27	1.0	1.99	NS
Binary	30	7.50	10.94	9.85	1.0	1.71	NS

Data sets

M_{ZAMS}: zero-age -main-sequence mass
ΔM_{wind}: wind loss mass
ΔM_{RLOF}: mass loss from Rhoche-lobe outflow
$M_{\rm rem}$: remnant mass or compact object mass
M_{ej}: ejecta mass

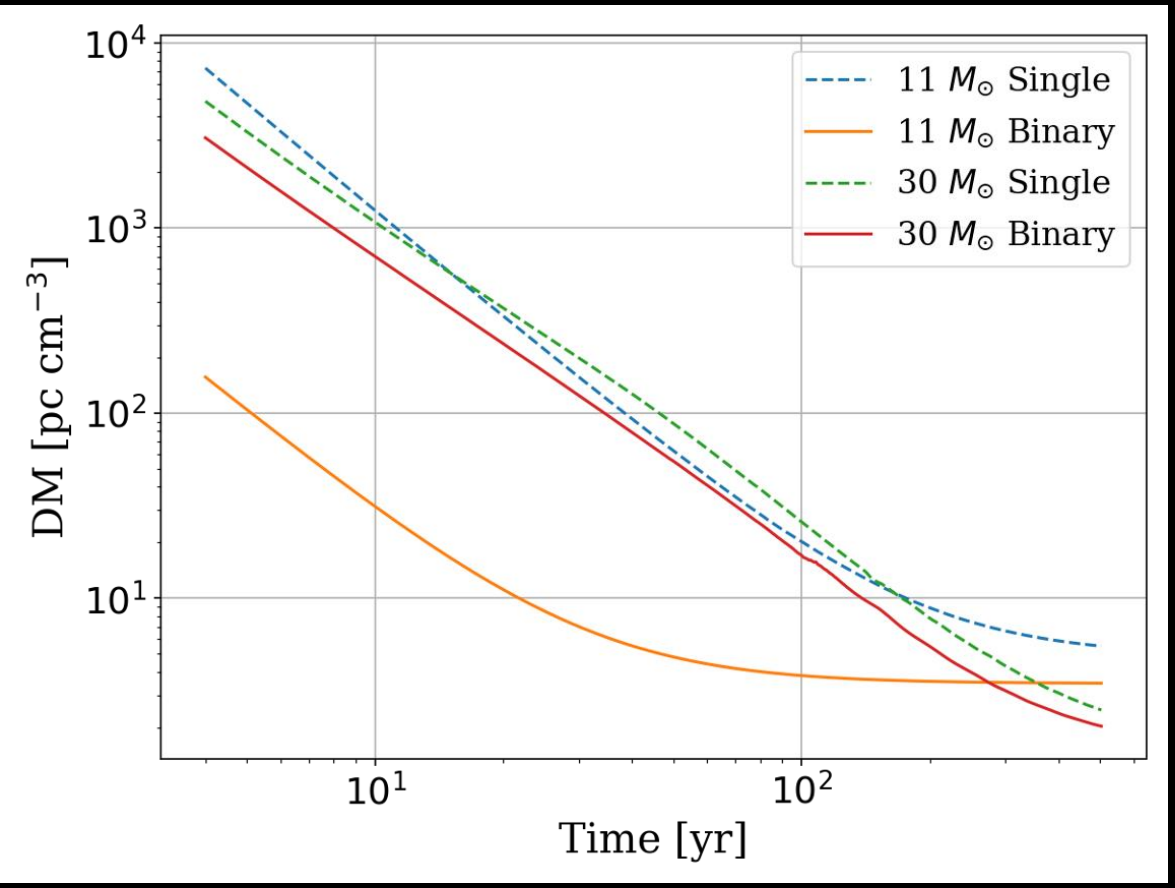
$$M_{ej} = M_{ZAMS} - \Delta M_{wind} - \Delta M_{RLOF} - M_{\rm rem}$$

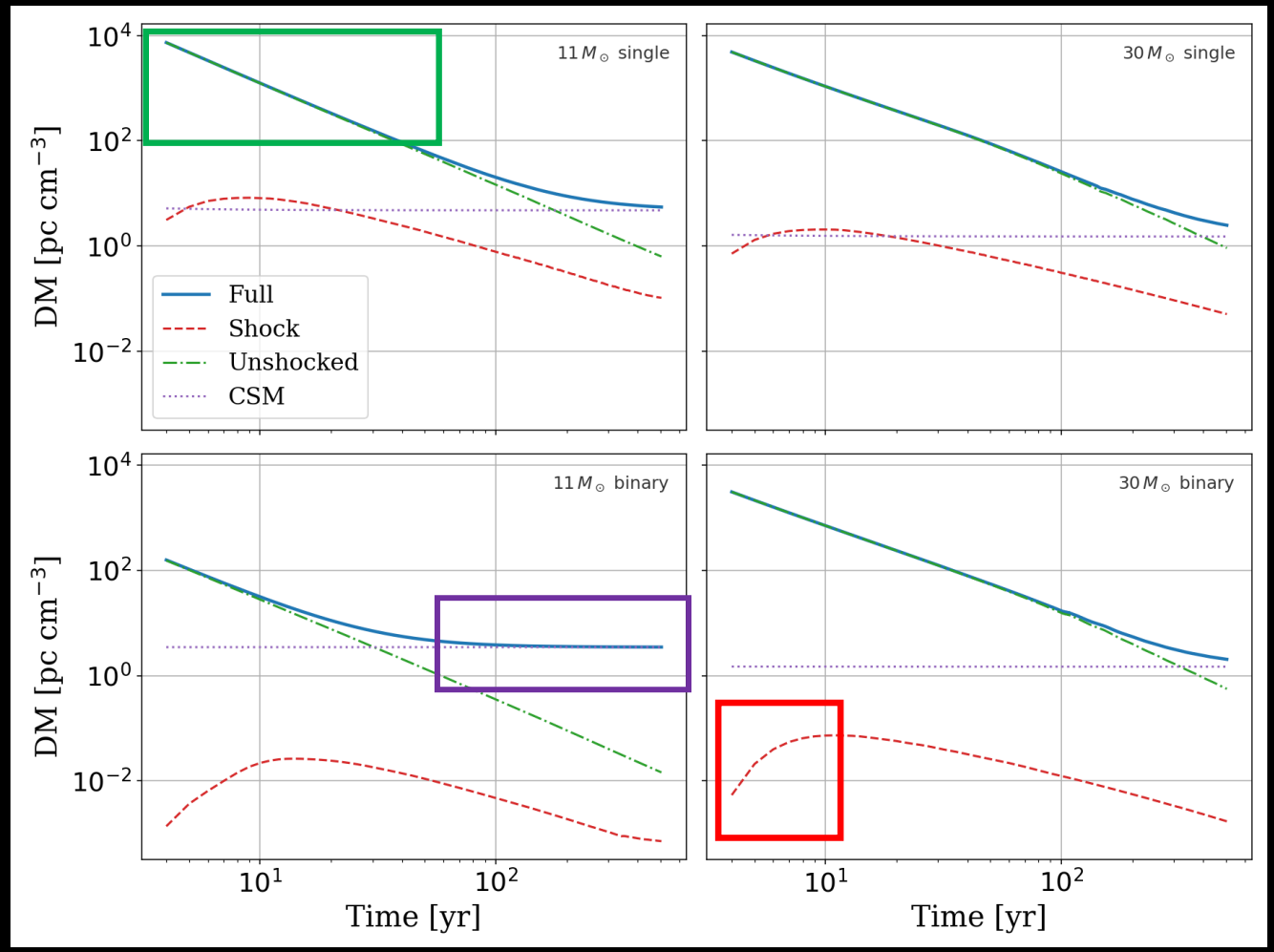
11 $M_\odot$:



Density and wind velocity evolution

DM evolution with different components





DM evolution

Single > Binary

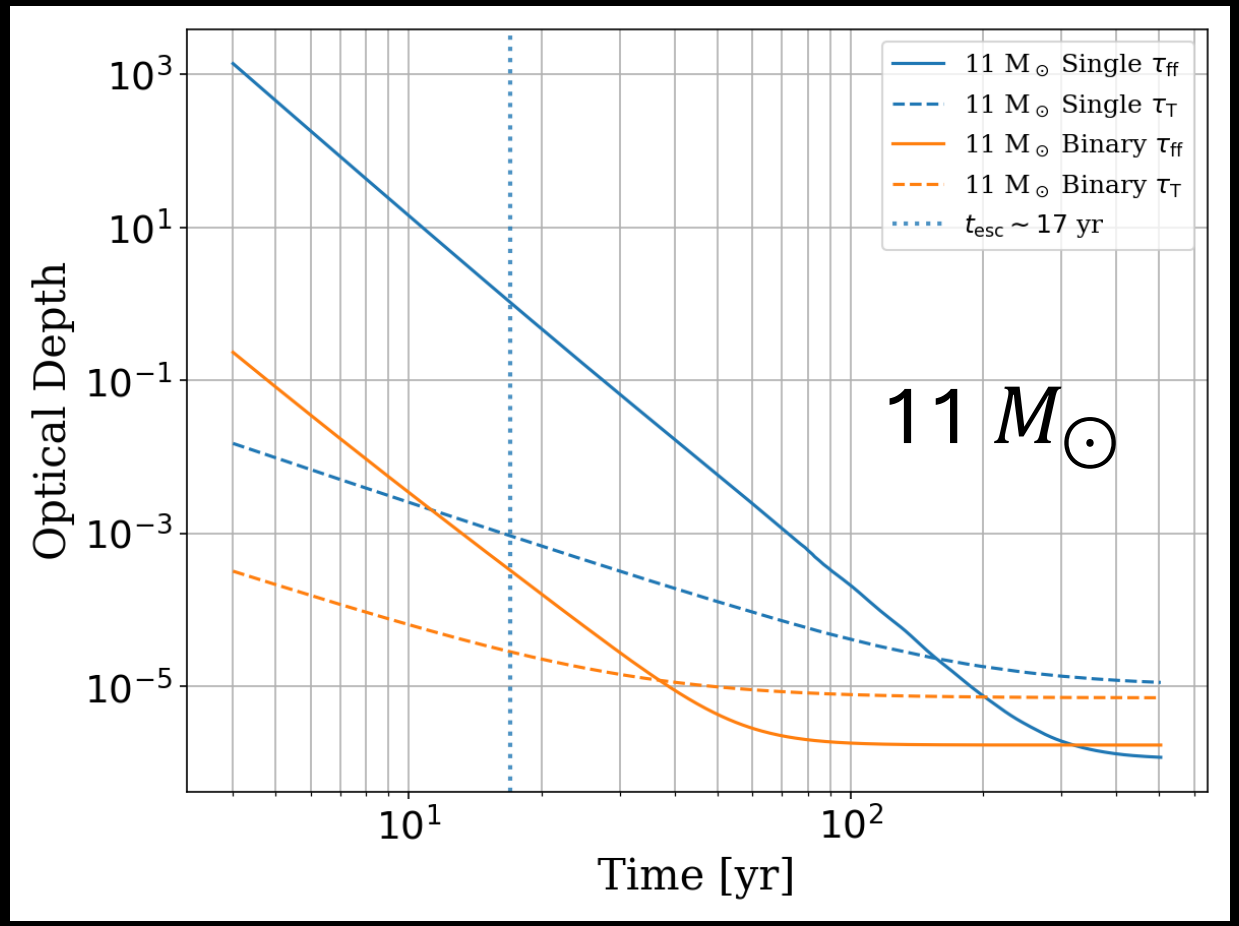
Components contibute to DM

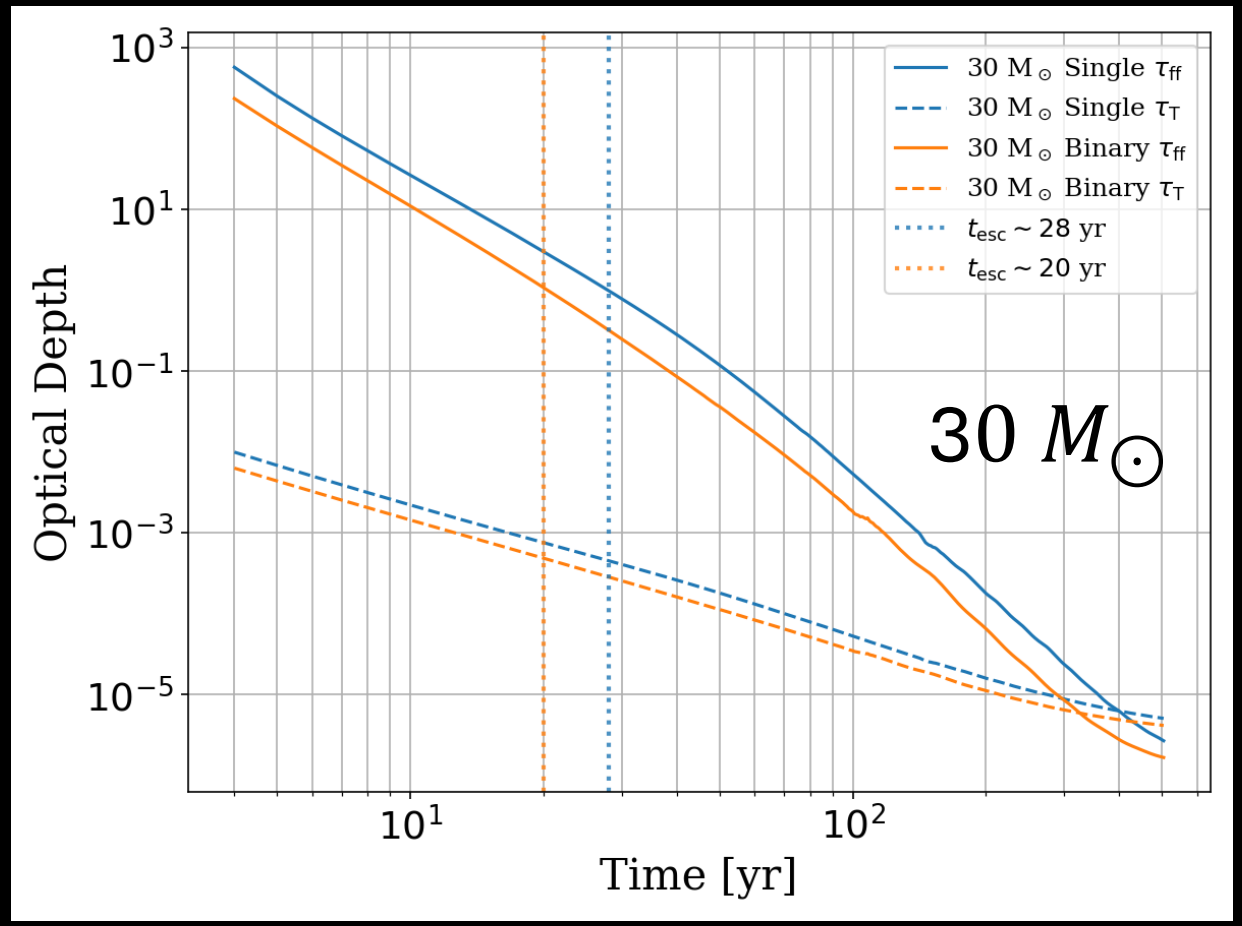
Ushocked ejecta dominate the early phase

CSM matters in late phase (especiall in 11$M_\odot$)

Shocked region is neligible (show NEI effect)

Optical Depth evolution





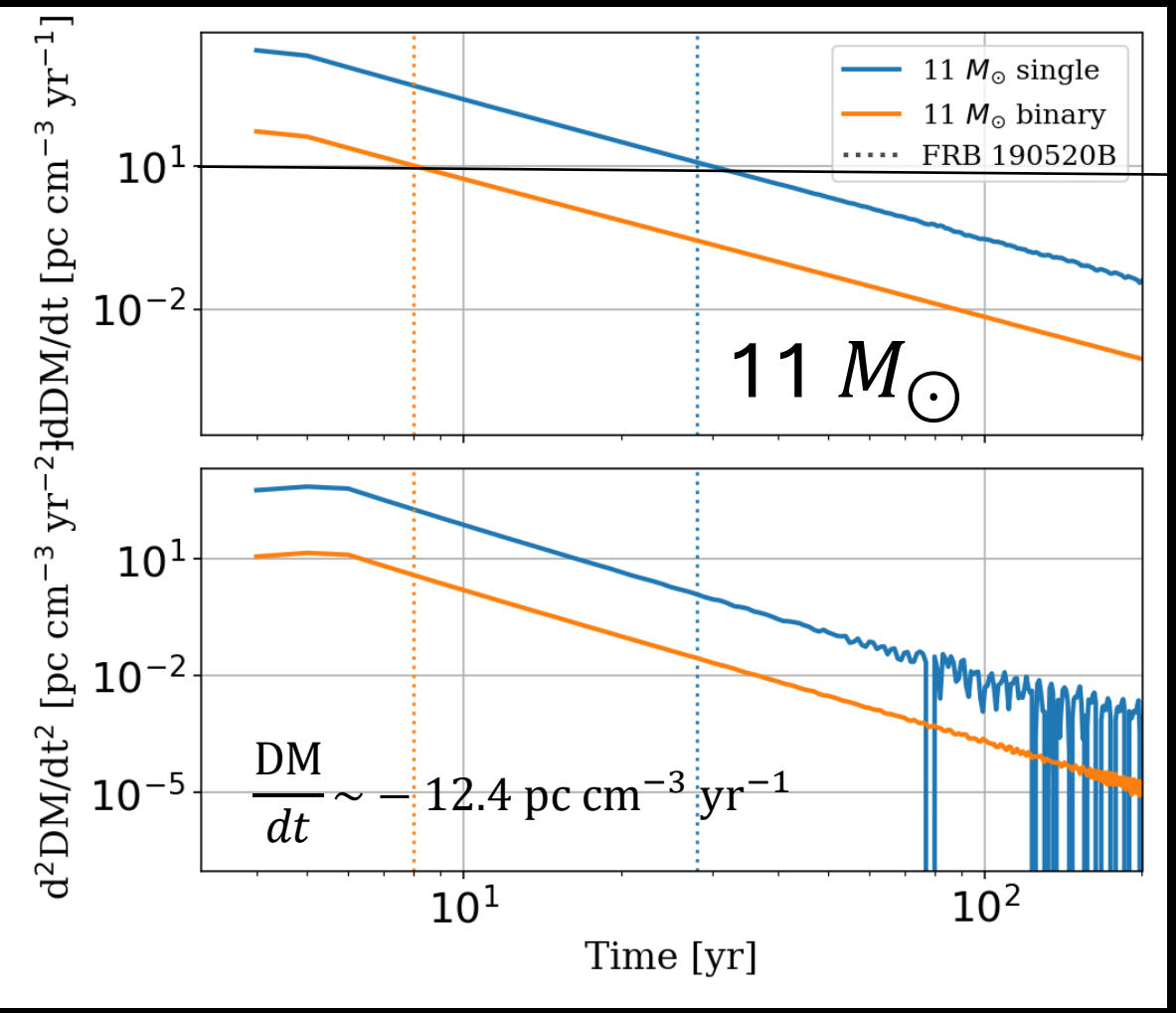
11 $M_\odot$ single: t_{esc}~17 yr

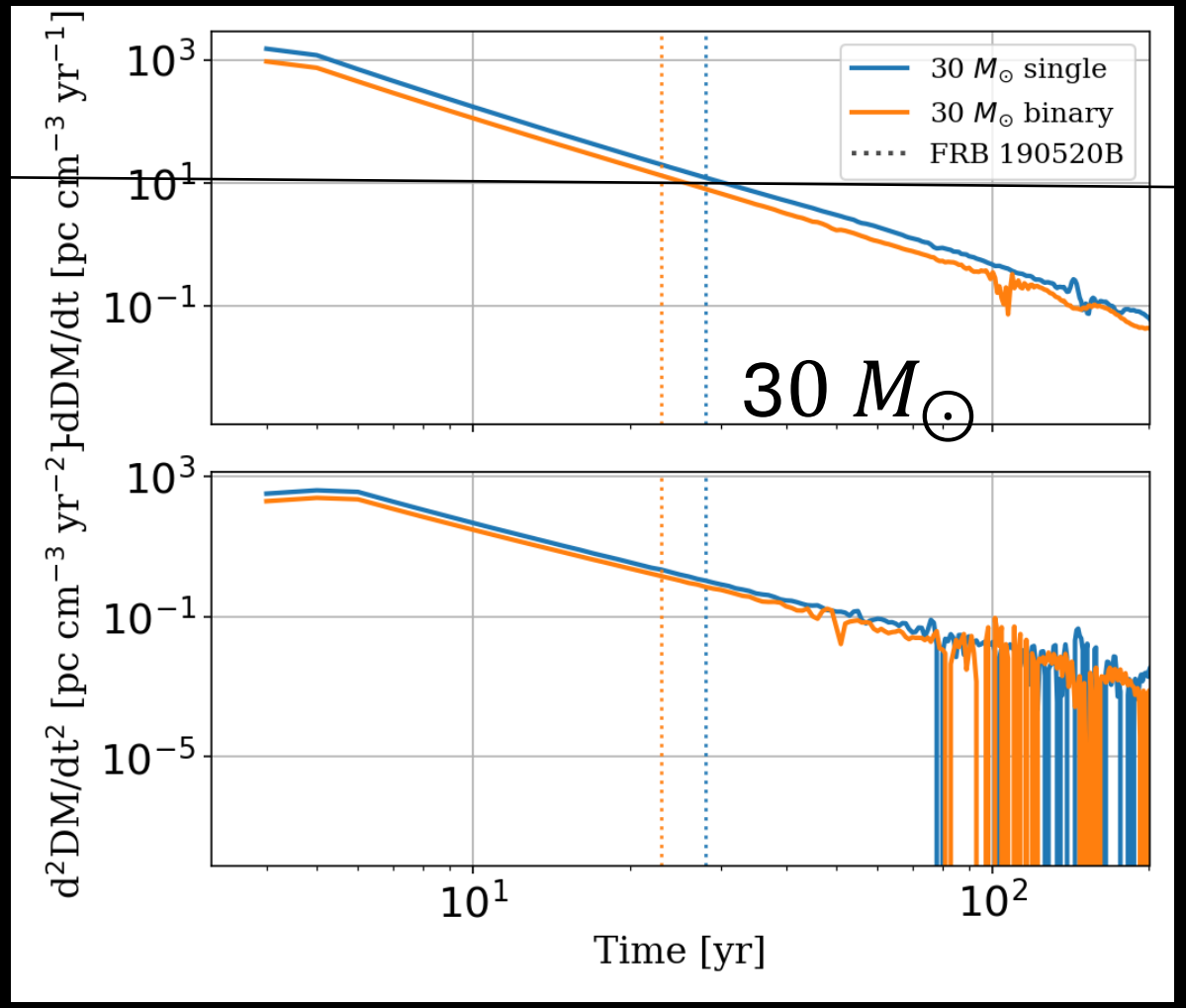
11 $M_\odot$ single: always transparent

30 $M_\odot$ single: t_{esc}~28 yr

30 $M_\odot$ single: t_{esc}~17 yr

DM time derivatives constrained by FRB 190529B





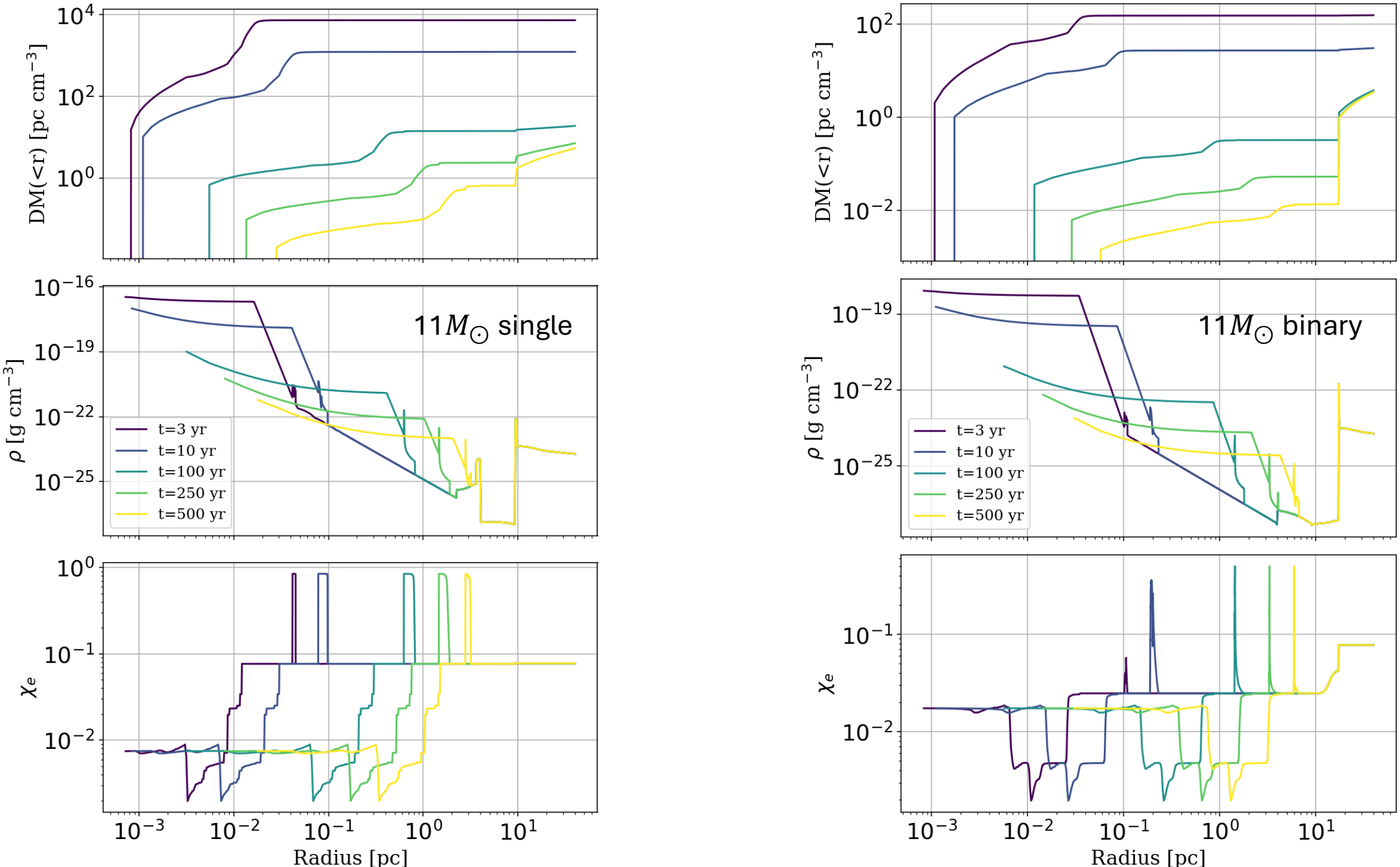
11 $M_\odot$ single: $t_{\mathrm{occur}} = 28.0\ \mathrm{yr} > t_{\mathrm{esc}}$

11 $M_\odot$ binary: $t_{\mathrm{occur}} = 8.0\ \mathrm{yr} > t_{\mathrm{esc}}$

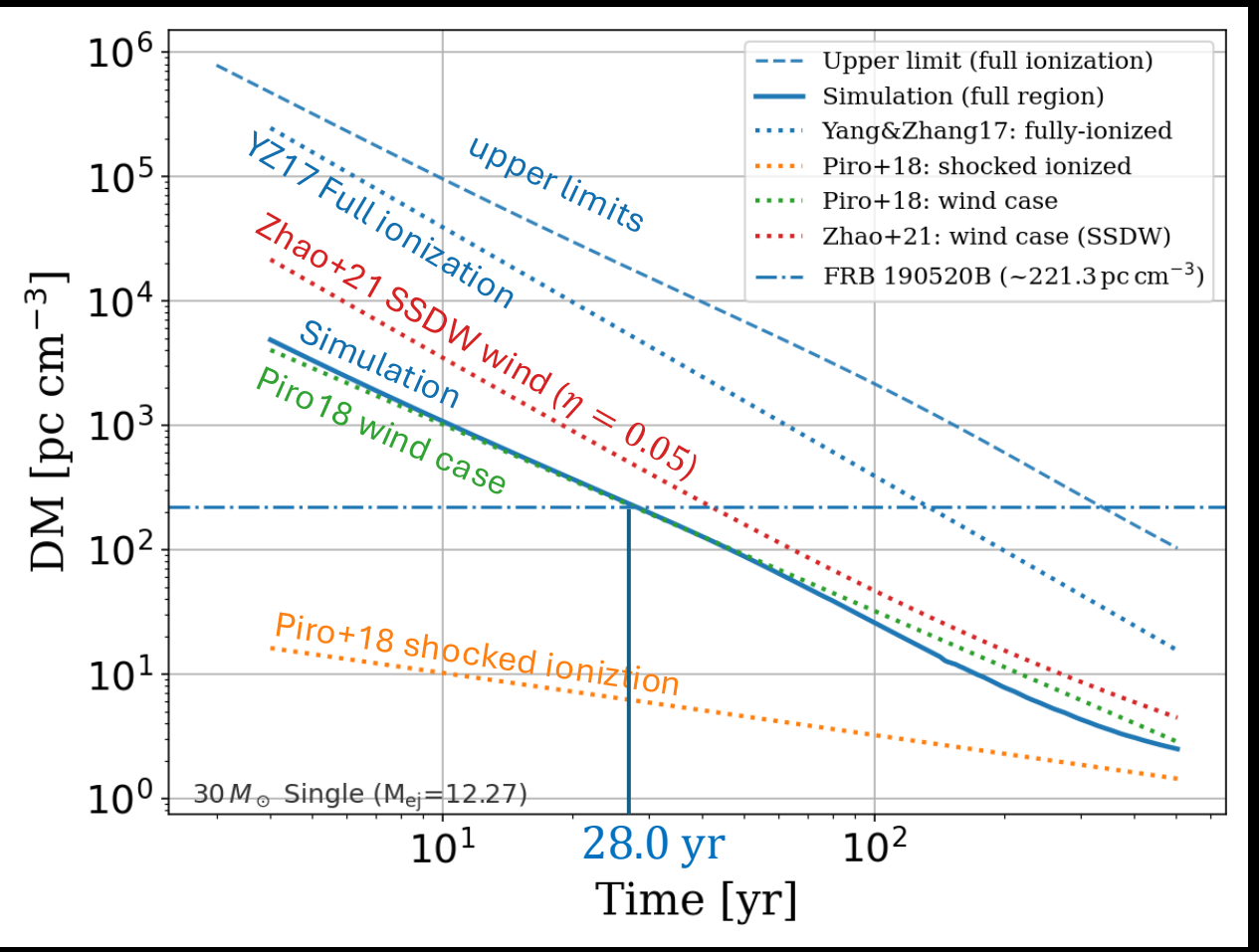
30 $M_\odot$ single: $t_{\mathrm{occur}} = 28.0\ \mathrm{yr} = t_{\mathrm{esc}}$

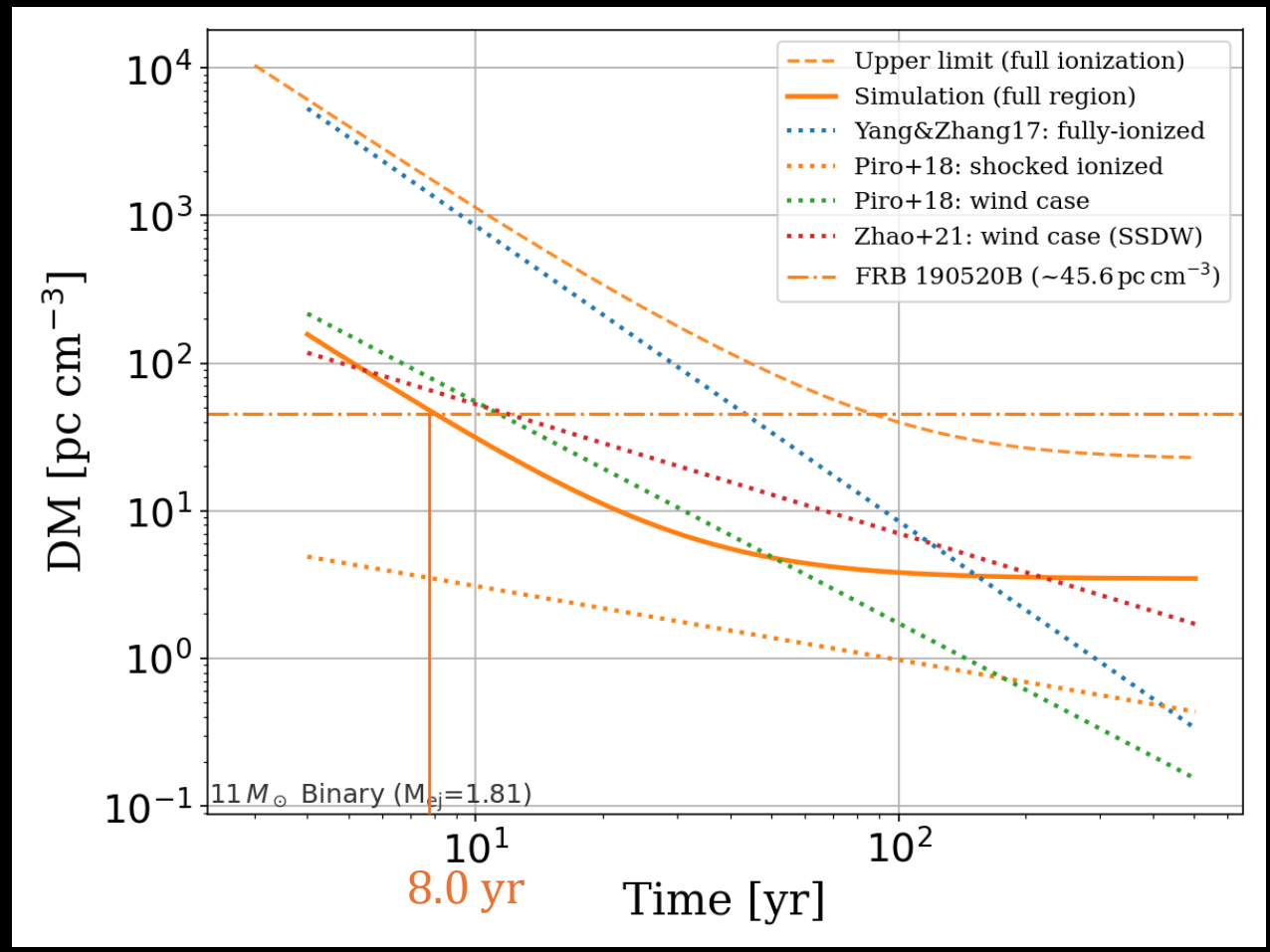
30 $M_\odot$ binary: $t_{\mathrm{occur}} = 23.0\ \mathrm{yr} > t_{\mathrm{esc}}$

FRB can escape from all of them


DM(<r) [pc cm^{-3}]
ρ [g cm^{-3}]
χ_e
$11M_\odot$ single
$11M_\odot$ binary
t=3 yr
t=10 yr
t=100 yr
t=250 yr
t=500 yr
Radius [pc]

Comparison with analytical model





DM_{max}~221.3pc cm^{-3} from 30 $M_\odot$ single

DM_{min}~45.6 pc cm^{-3} from 11 $M_\odot$ binary

DM_{source}

Summary

Probing cosmic baryons from FRB DM analysis based on CROCODILE simulation:

- Constructed light cone data using CROCODILE dataset
- $f_{\rm diff} = 0.865^{+0.101}_{-0.165}$ (Fiducial) and $f_{\rm diff} = 0.856^{+0.101}_{-0.162}$ NoBH)
- Examined the DM-b relation for foreground galaxy contibution
- Estimated the intrinsic $f_{\rm IGM}$ evolution by deducting halo gas.
- DM distribution of Host Galxies in diffenrt types and locations

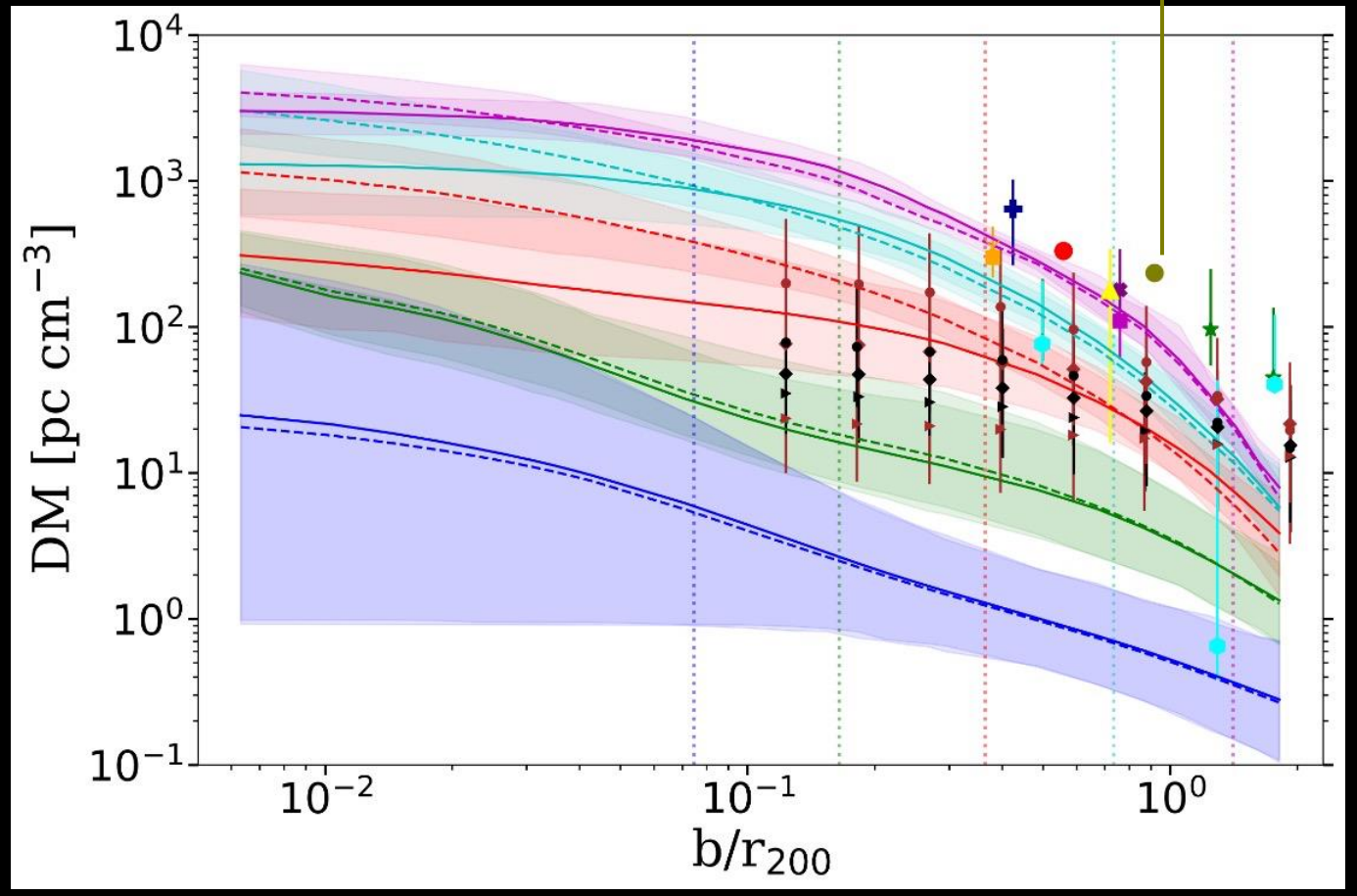
Local FRB Environments and DM Evolution based on SNR simulation analysis:

- DM and τ evolution of 11 and 30 $M_\odot$ progenitors in both single and binary channels.
- DM contribution varies substantially from different channels.
- $\rm DM_{SNR}$ is dominated by the unshocked ejecta and CSM matters in later time.
- FRB 20190520B can escape in all cases and give different DM constraints

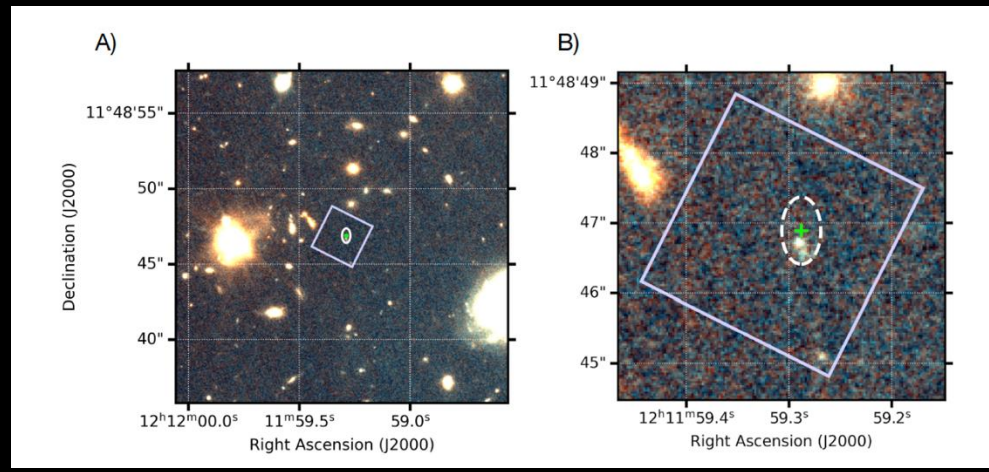
Cosmology based on high-redshift FRBs

AGN effects: $z{\sim}2-4$

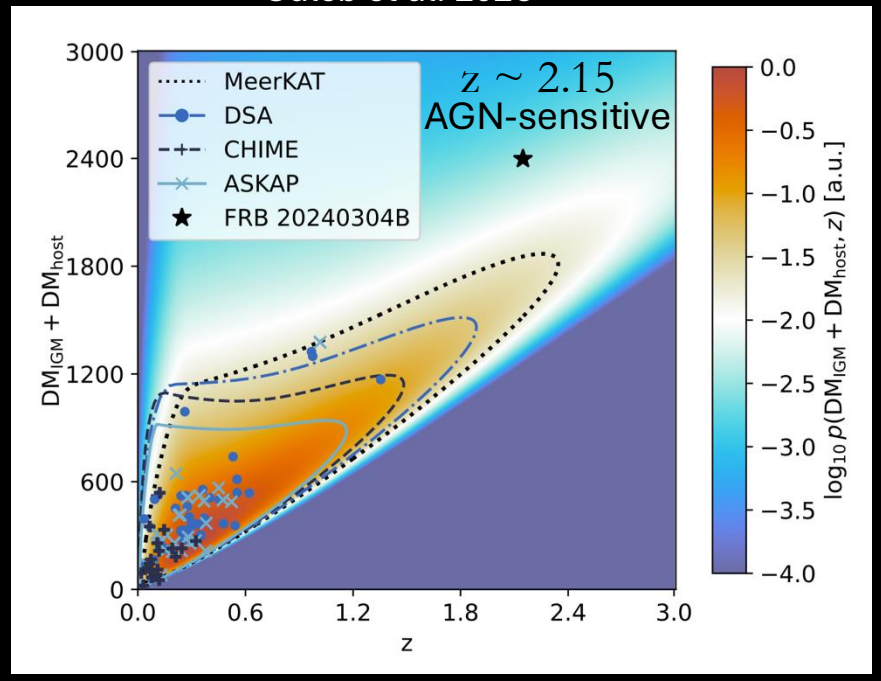
FRB 20240304B (Foreground)
Virgo Cluster
($10^{14.6\sim15} M_{\odot}$, b= $0.9\, r_{200}$)
Caleb+2025



An FRB at z ~ 2.15 crossing the Virgo Cluster (latest)

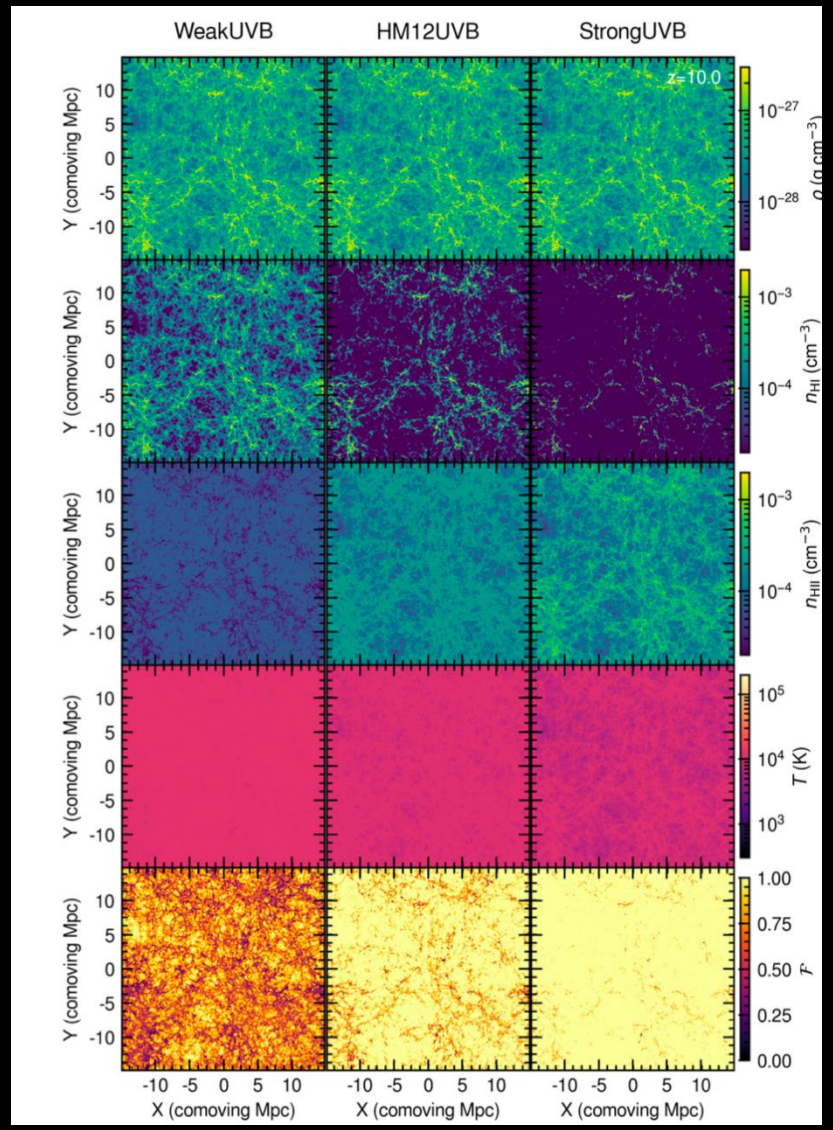


JWST loclization
Caleb et al. 2025



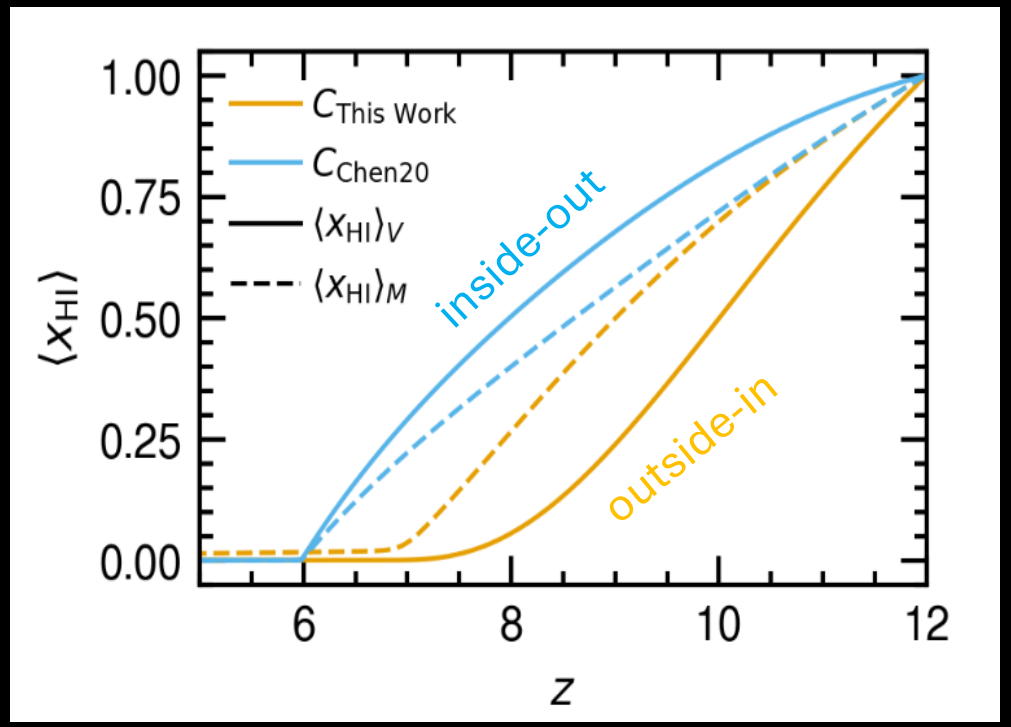
DM-z relation

FRB's application on Reionization Era



Hydrodynamical simulation at Reionization Era

Oku & Cen 2025



Neutral hydrogen abundance during Reionzation era

Oku & Cen 2025

Inside-out reionization scenario:

- Traditional
- Stellar sources or proto-galaxies
- CGM→ IGM
- Slow

outside-in reionization scenario:

- Dense region (self-shielded)
- AGN-driven (Quasar)
- IGM→ CGM
- Fast

FRB DM-z relation will be significantly different between different reionization scenarios

Obser.: $z > 6$: DS-2000 or better telescope?

Simulation: Prediction

Prospects of SNR-FRB work

RM analysis:
(Based on cr-MHD SNR simulation)

Amplified *B*-field in the precursor:

$$B(x) = \sqrt{\delta B(x)^2 + B_0^2} \qquad \mathrm{RM}_{\mathrm{source}} \uparrow$$

$$= \sqrt{\frac{8\pi(1 - f_{\mathrm{damp}})\rho_0 u_0^2}{4M_{A,0}} \left(\frac{1 - U(x)^2}{U(x)^{3/2}}\right) + B_0^2}, \quad (4)$$

3D Simulation:

Asymetry

Rings