Fast Radio Burst Physics & Cosmology

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Outline†

- A brief summary of observations
- FRB physics – general constraints & a specific model
- FRBs as probe of cosmology

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Fast Radio Bursts (FRBs)

Dispersion relation for EM waves in plasma: $\omega^2 = \omega_p^2 + c^2 k^2$; ω_p : plasma frequency

$V_{EM} = \frac{d\omega}{dk}$; signal at ω is delayed, wrt $\omega = \infty$, by $\propto \omega^{-2}$

The magnitude of the delay is $\propto$ DM = $\int_{Source}^{Earth} ds\ n_e$ (unit: pc cm^{-3})

The first FRB was discovered in 2007 – Parkes 64m radio telescope at 1.4 GHz

Lorimer et al. (2007)

Duration (δt) = 5ms

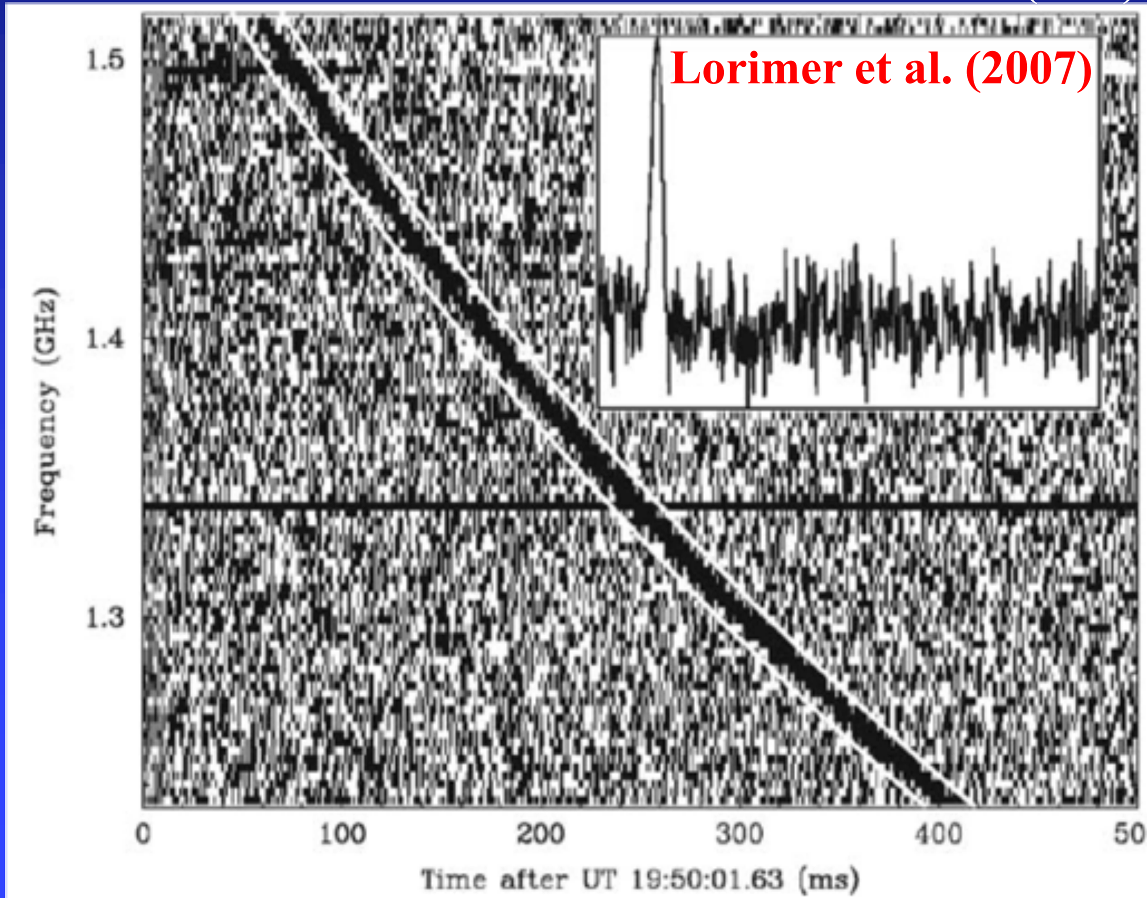
DM = 375 pc cm^{-3}

(DM from the Galaxy 25 cm^{-3}pc — high galactic latitude)

Estimated distance ~ 500 Mpc (from mean IGM density)

$\therefore$ **Luminosity = 10^{43} erg s^{-1}**

(10^{10} times brighter than the Sun)



A Brief history (8 years of confusion and then a breakthrough)

- **16 more bursts detected (2010) in Parkes archival data by *Bailes & Burke-Spolaor***

  These bursts were detected in all 13 beams of the telescope, i.e. most likely terrestrial in origin.

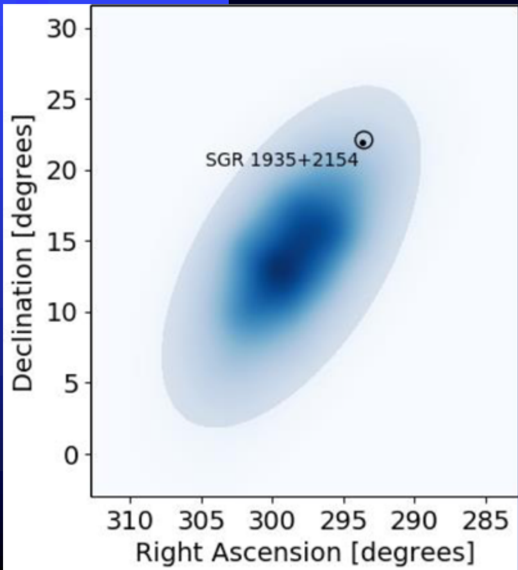
  Many people suspected that the Lorimer burst was also not cosmological.

  These bursts were dubbed Peryton – ***after the mythical winged stag*****.**

- *Clever detective work by Emily Petroff et al. (2015) established the origin of Perytons (microwave oven!)*

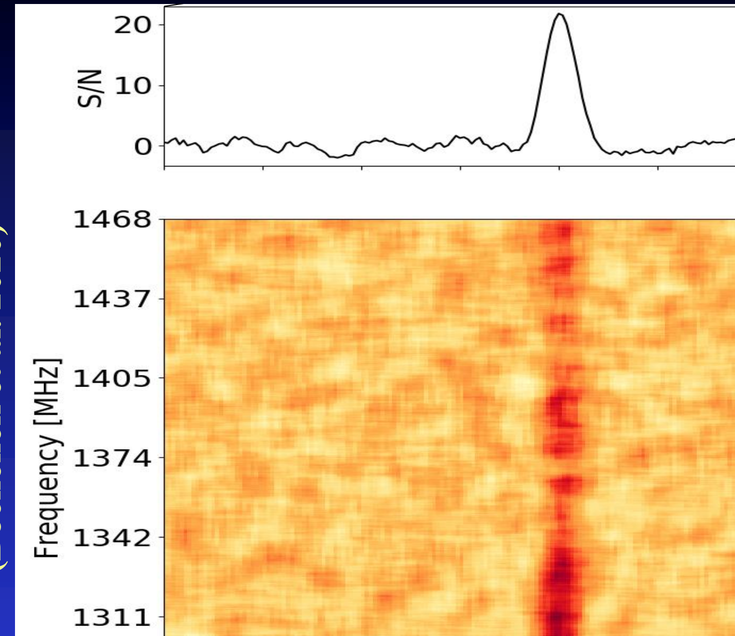
Arecibo detects a burst in 2012; repeat activity found in 2015 (Spitler et al. 2016). Accurate localization led to distance measurement & confirmation that this event was cosmological and not catastrophic.

FRB in our Galaxy! FRB200428



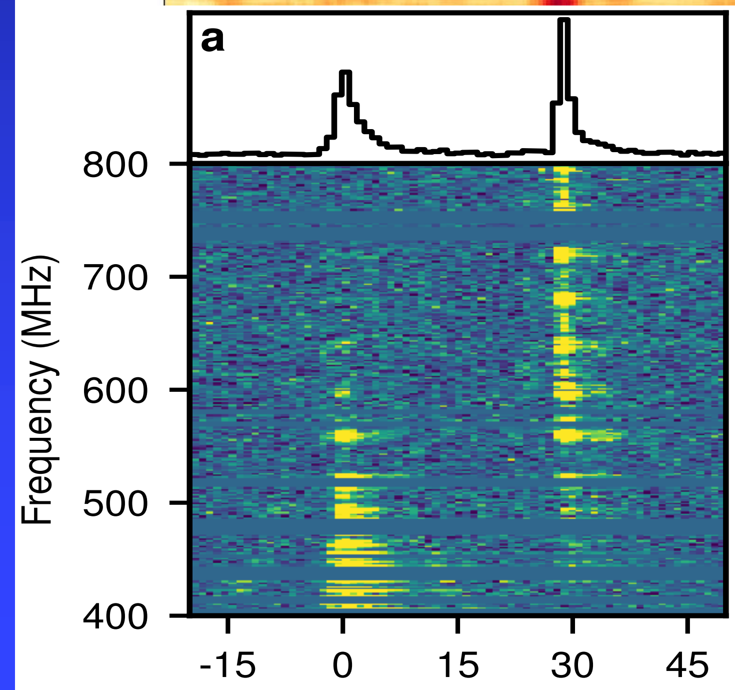
It is associated with a well known magnetar (neutron star with super-strong magnetic field) with $B=2.2\times10^{14}$ G; $P=3.2$s

and spin-down age of 4×10^{3} yrs



STARE-2
(Bochenek et al. 2020)

So, some FRBs are produced by magnetars!



CHIME
Anderson et al. 2020

Energy in radio bands: 2×10^{35} erg

Energy in X-ray flare: 8×10^{39} erg (~0.2 s)

$[f_{x\nu}\ \alpha^{\,-0.6}]$

Peak radio luminosity: 3×10^{38} erg s^{-1}

Properties of FRBs (summary)

- >500 FRBs have been detected of which >60 have repeat outbursts
- **Duration:** 1 ms $\lesssim t_{frb} \lesssim$ 20 ms

  Flux variation time < 10 μs $\Longrightarrow$ source region size < $10^5\,\Gamma$ cm

- Some bursts are 100% linearly polarized
- Progenitor:

  The 9 localized FRBs do not show evidence for large local DM contributions

  $\Rightarrow$ most FRBs are not associated with very young SN or dense regions of ISM.

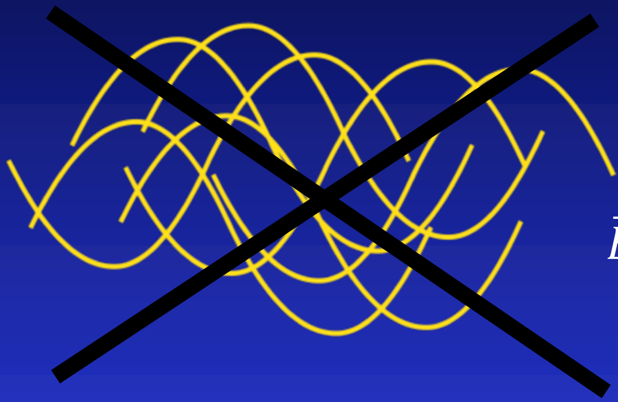
FRB radiation physics

If the FRB radiation were to be incoherent, then the temperature of the object required to produce the observed luminosity should be

$$T_B = \frac{F_\nu d_A^2 c^2}{2(c\delta t)^2 \nu^2 k_B} > 10^{35}\mathrm{k}\ d_{A28}^2$$

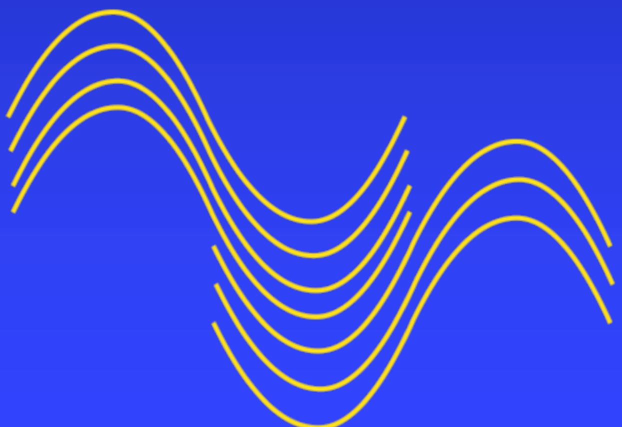
Which is unphysical.

$f_\nu \propto N$



$\vec{E}$**(x,t)**

$f_\nu \propto N^2$



∴ FRB radiation must be coherent

Photon occupation number, $n_\gamma = \dfrac{k_B T_B}{h\nu} \approx 10^{37}$

Radiation force due to induced Compton Scattering

Scattering probability is enhanced by the "occupation number" of the final state (n_γ)

For FRB radiation, $n_\gamma = \dfrac{k_B\, T_B}{h\, \nu} \approx 10^{37}$

(Because of cancellations, the effective cross-section is enhanced by a factor $\sim 10^9$ at $R = 10^{13}$ cm ; declines with distance as R^{-3}).

Plasma in the source region needs to be confined so that the enormous radiation pressure does not shut down the radiation process.

$R \lesssim 10^8$ cm	$R \gtrsim 10^{13}$ cm

magnetic field is very strong and suppresses x-mode photon scatterings by a factor $(\omega_B/\omega)^2$.

$\omega_B = 10^{18} B_{12}$ Hz is cyclotron frequency and, and ω is FRB photon frequency

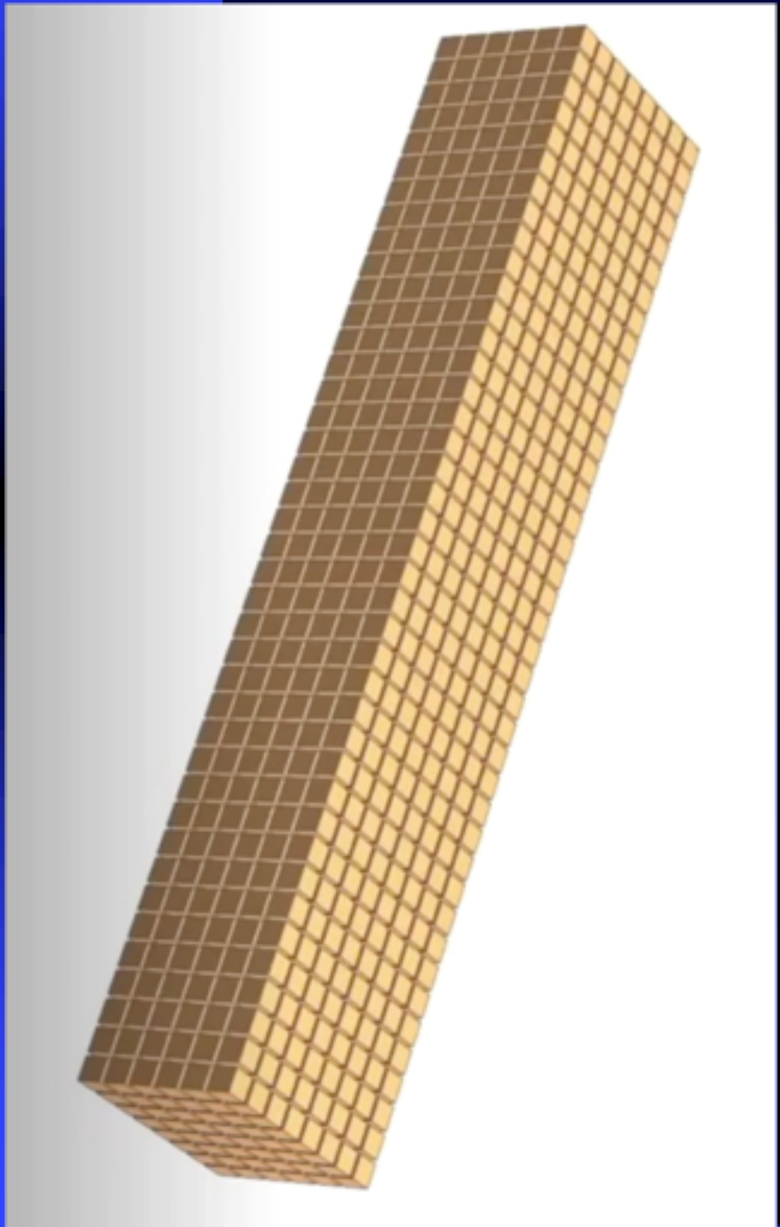
Photon beam size is small and scattering is not a problem.

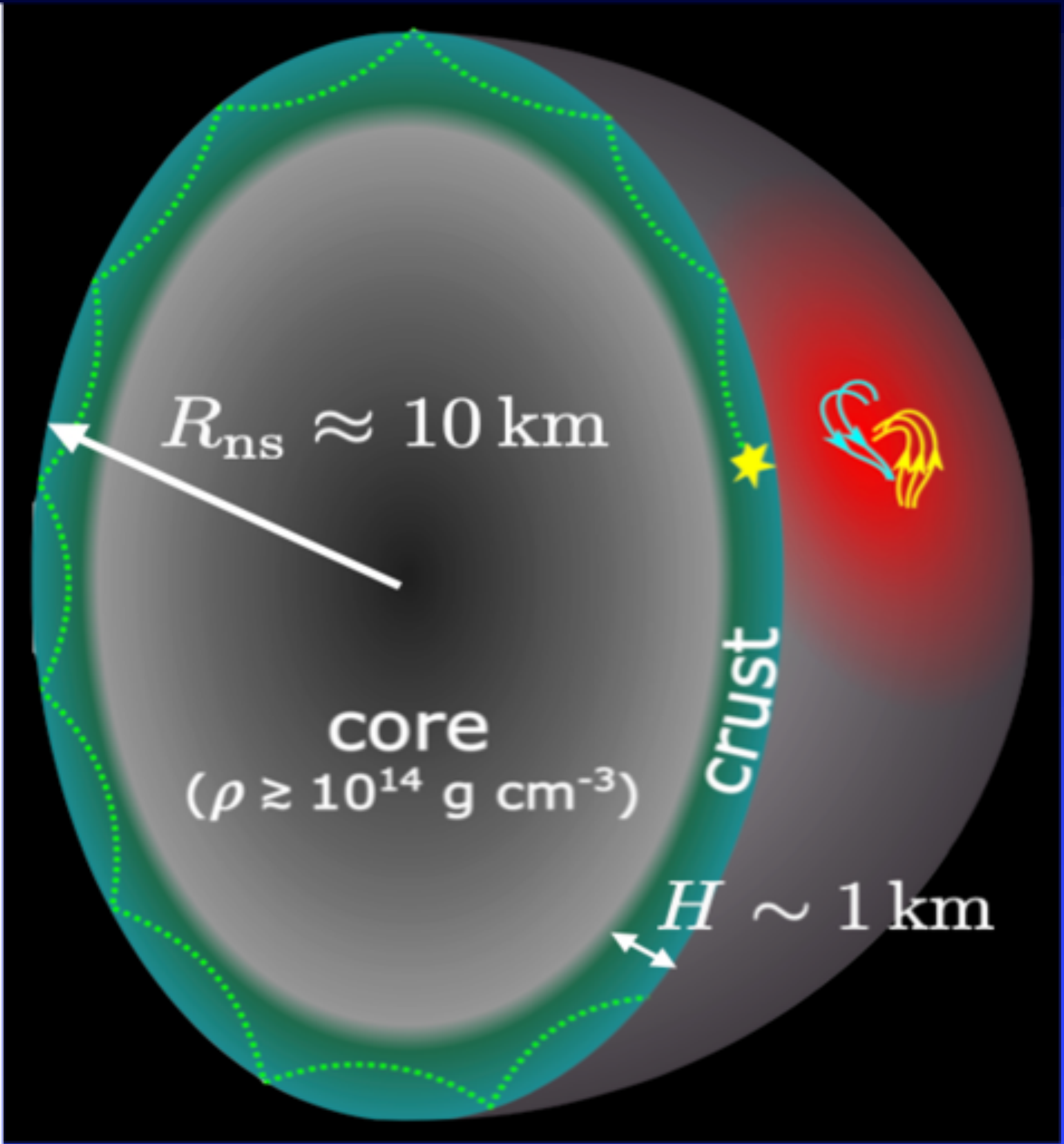
LOFAR 150 MHz data for 20180916 with $L \sim 10^{41}$ erg/s is important as $\tau_{ic} \propto L\, \nu^{-3}$ & $t_{ic}^{acc} \propto L^{-2}\, \nu^3$

It is very hard to produce FRB radiation between ~10^8 cm & 10^{13} cm from the neutron star surface due to the enormous induced Compton force which quickly disperses the plasma.

Overview of shear wave → FRB

Lu, Kumar & Zhang, 2020



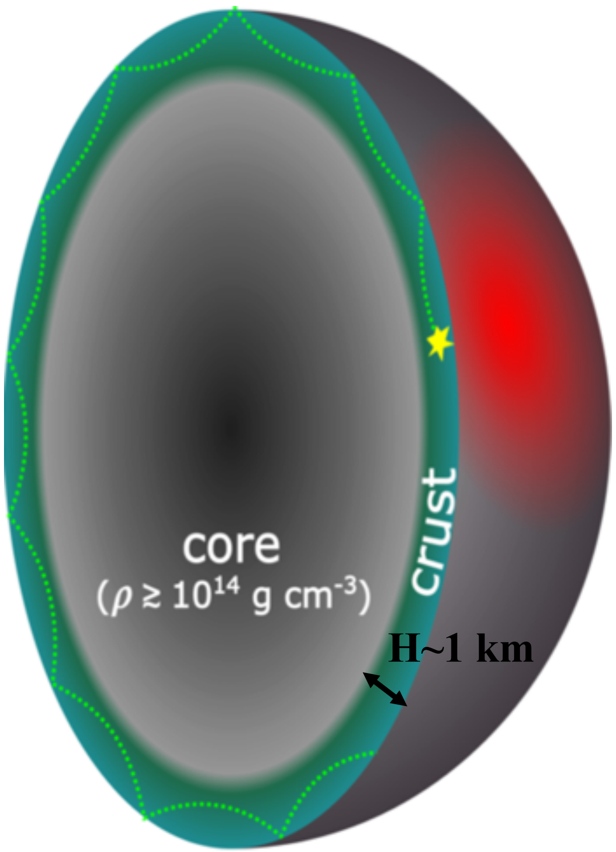


Crustal shear waves → Alfven waves

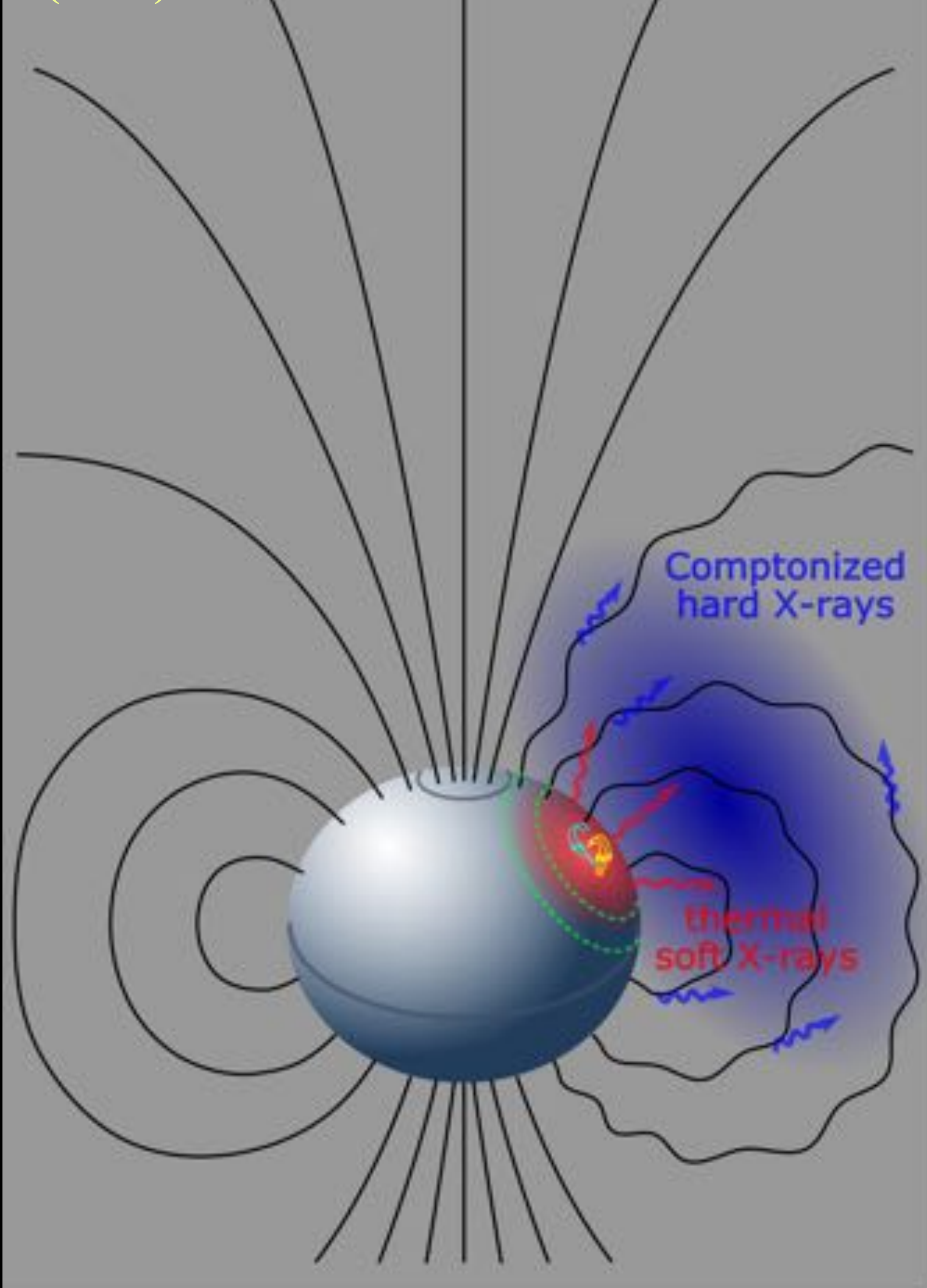
Lu, Kumar & Zhang (2020)

$\nu_{shear} \sim 10^4$ Hz $\sim v_{shear}/H$

$v_{shear} \sim 0.01\ c$



Trapped fireball: Thompson & Duncan (1995) "standard" model for SGRs



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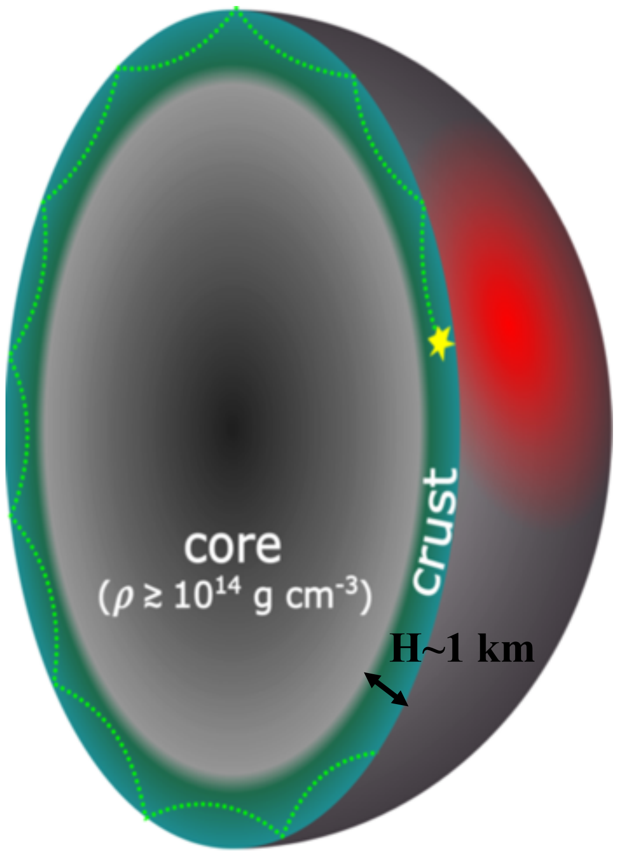
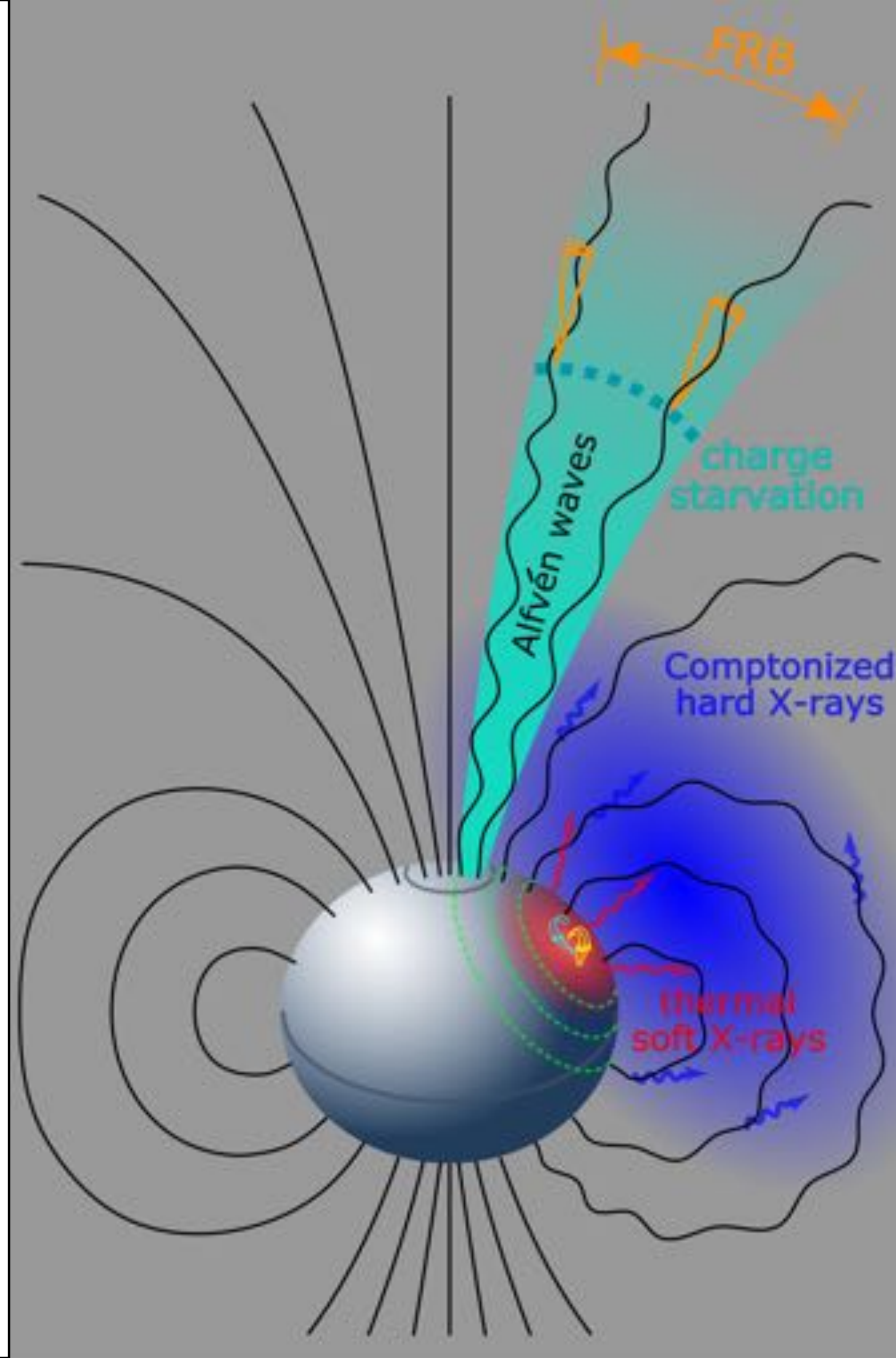




Predictions of the model

- **Maximum FRB Luminosity** $\sim 10^{47}$ **erg s^{-1}**

As the electric field approaches the *Schwinger limit* – 4×10^{13} esu – $e^{\pm}$ are pulled from vacuum, and the cascade shorts the electric field needed for accelerating particles for coherent radiation.

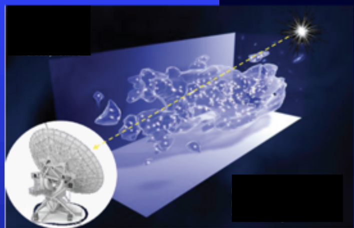
- **Minimum FRB frequency**

The maximum wavelength of radiation for particle clumps moving with LF γ is given by the radial size of causally connected region, i.e. $R/(2\gamma^2) \sim 300$ cm $R_7 (R_7/R_{B,8})^2$ ***or $\sim 100\, R_7$ MHz***

λ_{max} is larger than the "peak" curvature radiation wavelength by a factor $\gamma R/(2\pi R_B)$

FRB cosmology

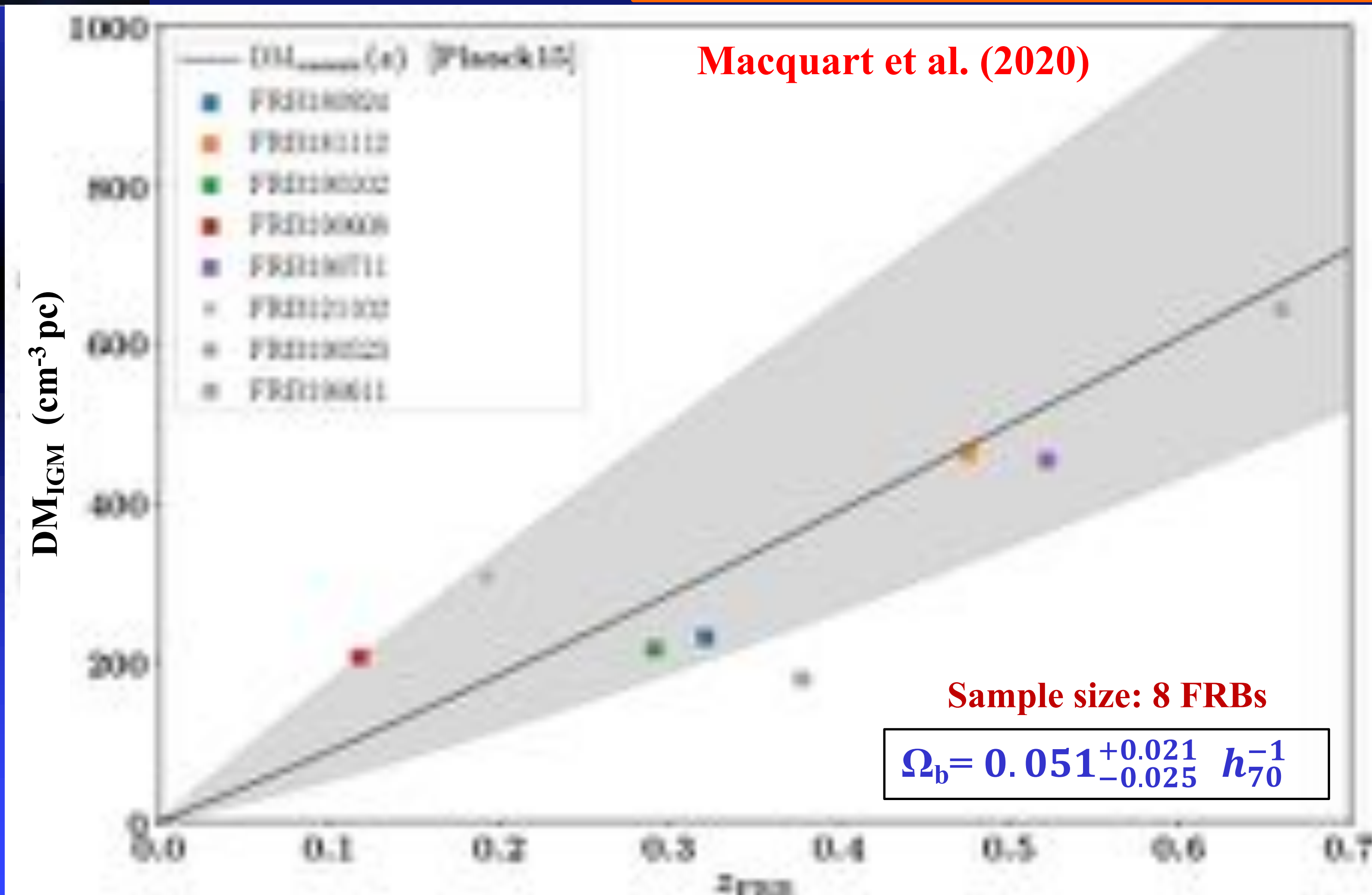
FRBs as probe of Intergalactic Medium



$$\mathrm{DM} = \int d\ell \, n_e \quad \Longrightarrow$$

Baryons in intergalactic medium (DM)

Map H & He-reionization epoch



Macquart et al. (2020)

Sample size: 8 FRBs

$$\Omega_b = 0.051^{+0.021}_{-0.025} \; h_{70}^{-1}$$

Exploring the hydrogen reionization epoch using FRBs

(Beniamini, Kumar, Ma & Quataert, 2021)

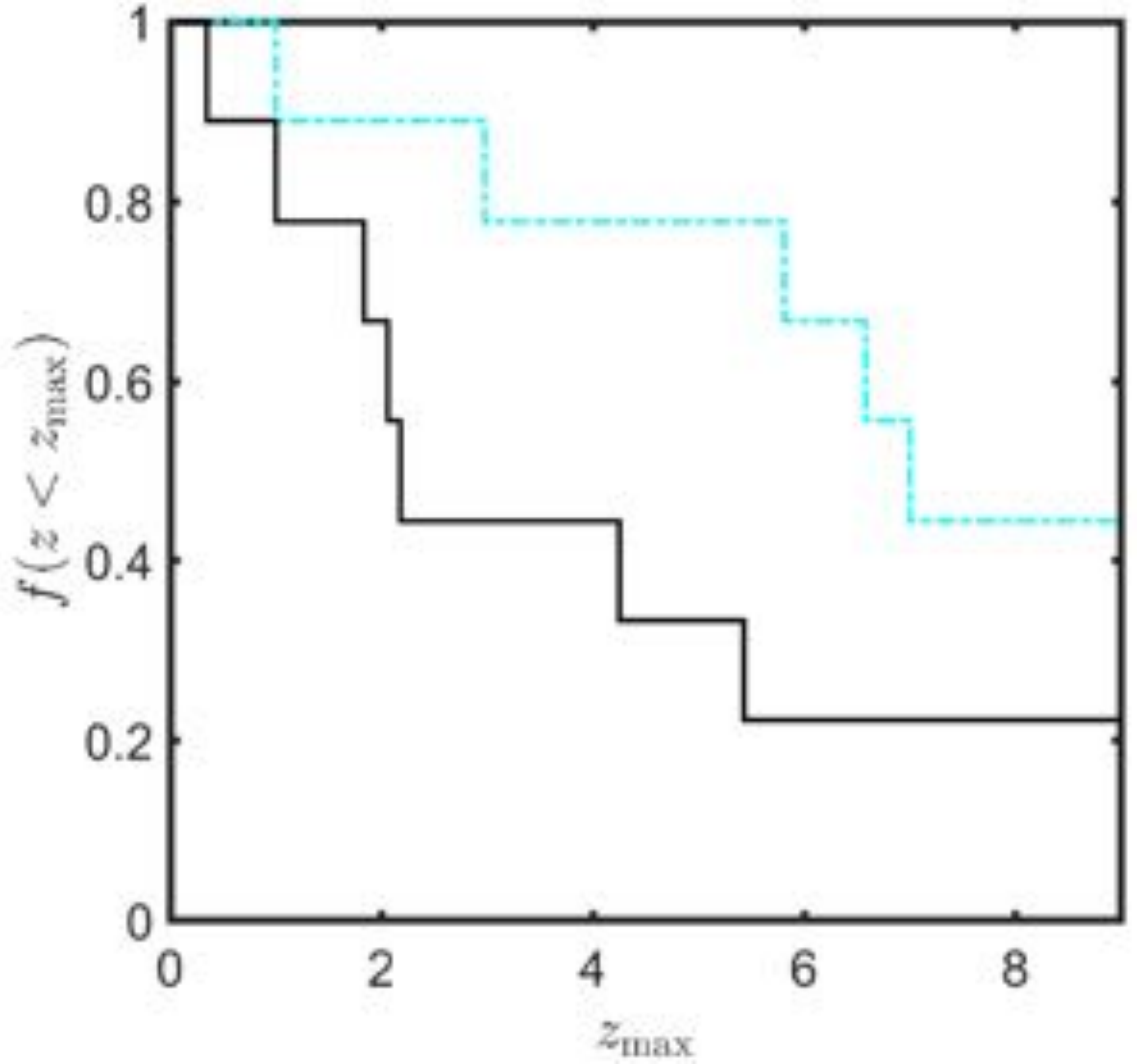
Do we expect FRBs at high redshifts (z>6)?

- **UV photons for the cosmic reionization (z>6) are supplied by stars $\geq 10M_{\odot}$**
- **About 40% of massive stars produce magnetars at z=0 (Beniamini et al. 2019)**
- **High z, metal poor, stars have faster rotation rates. They are likely to leave behind fast rotating compact remnants with strong magnetic fields as per the mechanism suggested by Thompson & Duncan.**
- **In any case, we know that there are GRBs at z > 6, including one at 9.4 (Cucchiara et al. 2011).** **These high-z GRBs have properties similar to their lower-z cousins.**

GRBs require strong magnetic field & a compact object (BH or NS)

So, it is not a big stretch to assume that magnetars and FRBs should be there during the reionization epoch waiting to be discovered

Detectability of FRBs at z>6



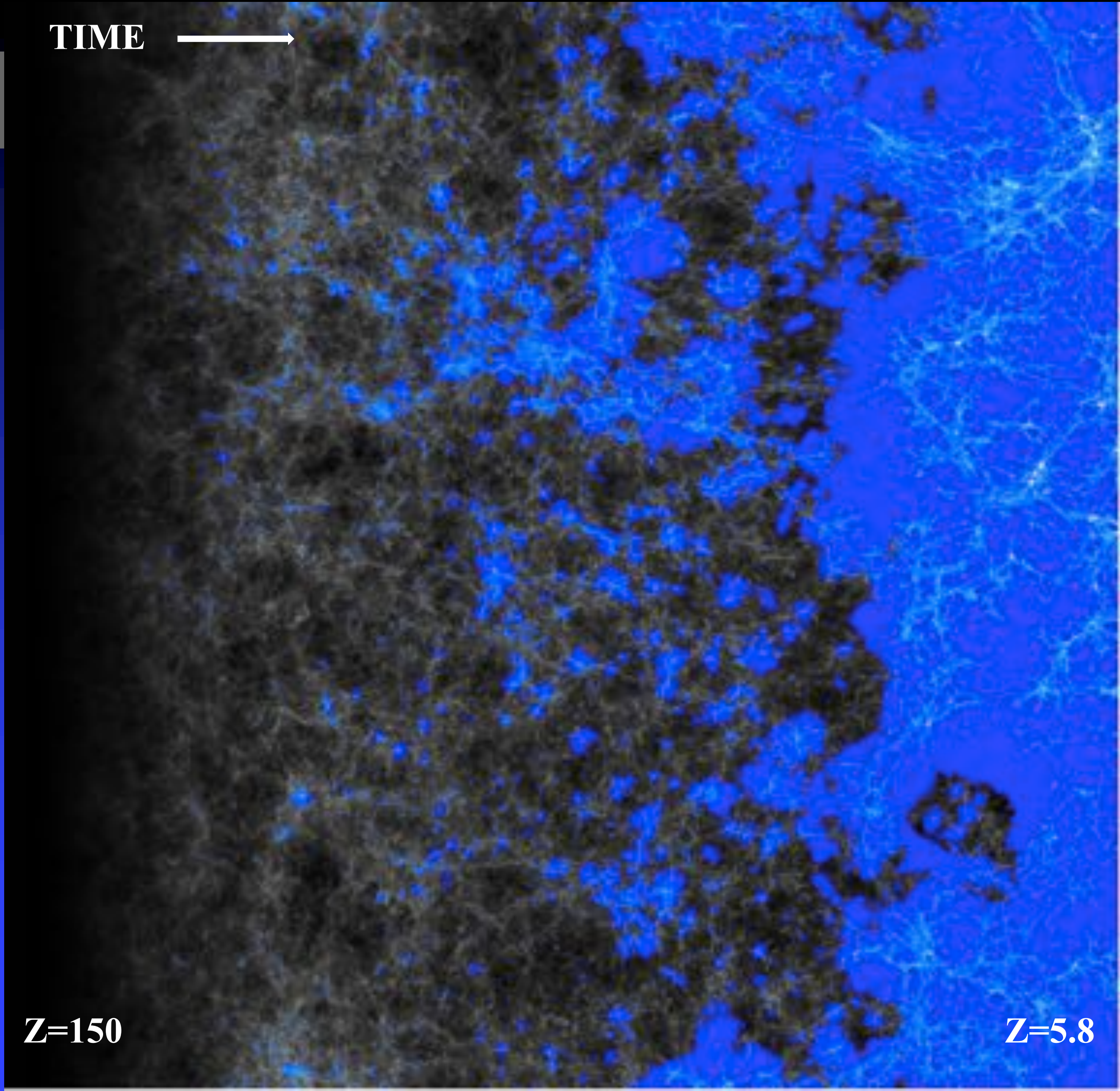
The fraction of 9 FRBs with known redshifts which would be detectable up to a redshift z. Results are shown as a solid (dot-dashed) curve for the specific-fluence threshold of 1 Jy ms (0.1 Jy ms) at 500 MHz and assuming a spectral slope of α = -1.5 ($f_\nu \propto \nu^{\alpha}$)

Beniamini et al. 2020

Ocvick et al. (2021)
courtesy of Shapiro

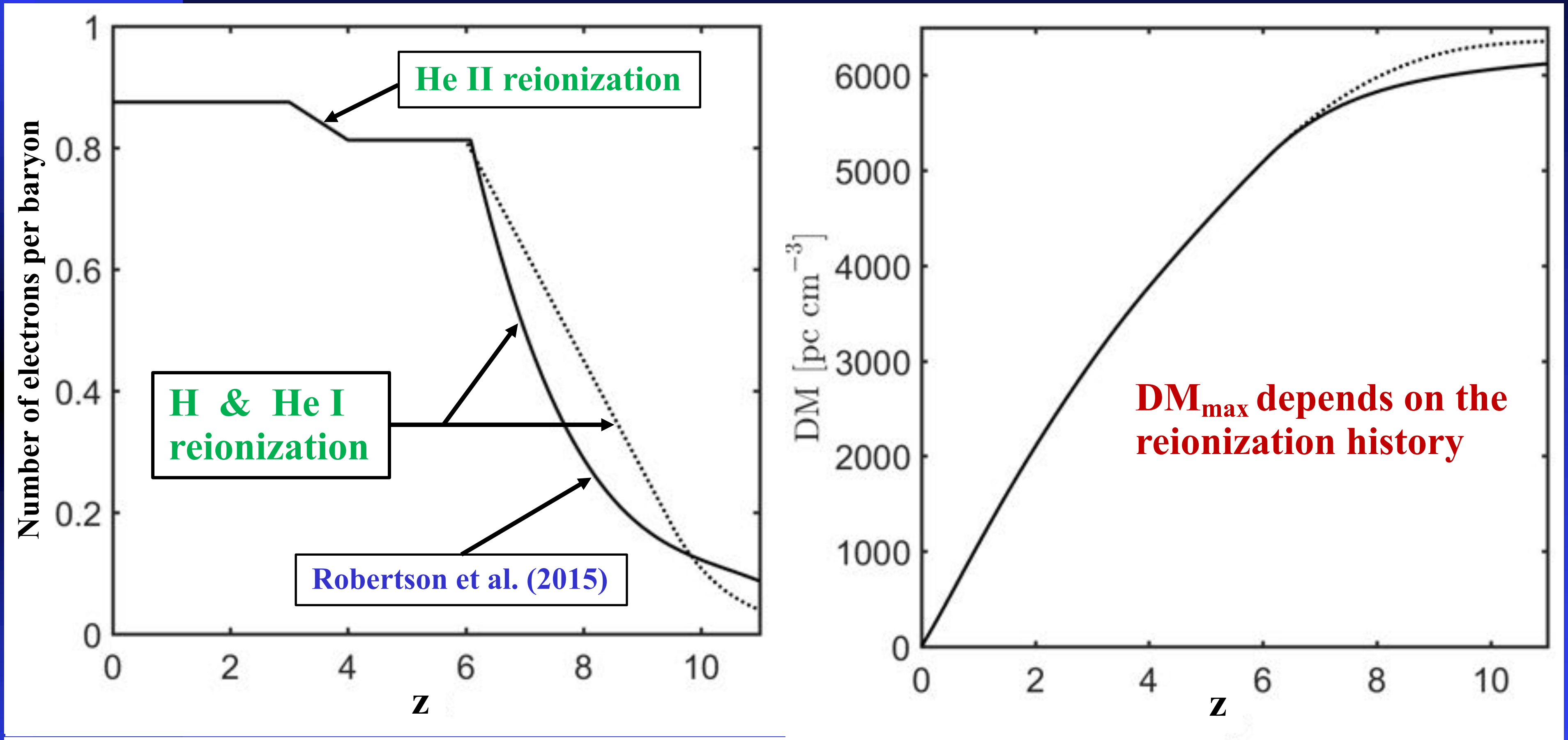
Cosmic Dawn II : Fully-Coupled Radiation-Hydrodynamics Simulation of Galaxy Formation and the Epoch of Reionization ("CoDa II")

Blue regions are photo-heated, while small, bright red regions are heated by supernovae feedback and accretion shocks. The green color, on the other hand, denotes regions where ionization is ongoing and incomplete, and temperature has not yet risen to the ~ 10^4 K typical of fully ionized regions. Brightness indicates the gas density contrast.



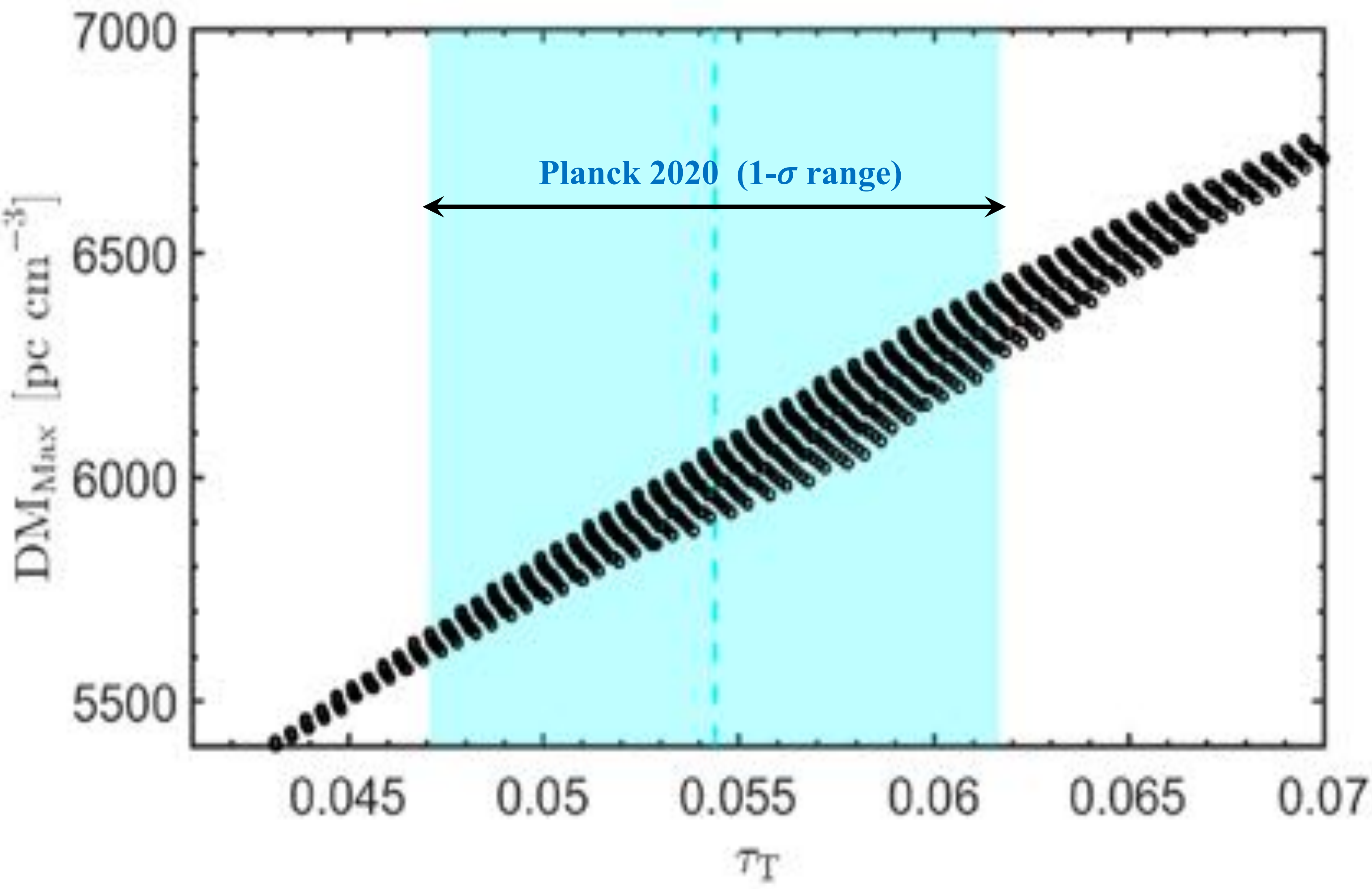
Exploring Hydrogen Reionization Epoch

Beniamini, Kumar, Ma & Quataert (2021)



$$\Delta DM_{max} = 500\, pc\, cm^{-3} \;\rightarrow\; \Delta\tau_T \le 0.008 \quad (better\ than\ Planck)$$

Beniamini, Kumar, Ma & Quataert (2020)



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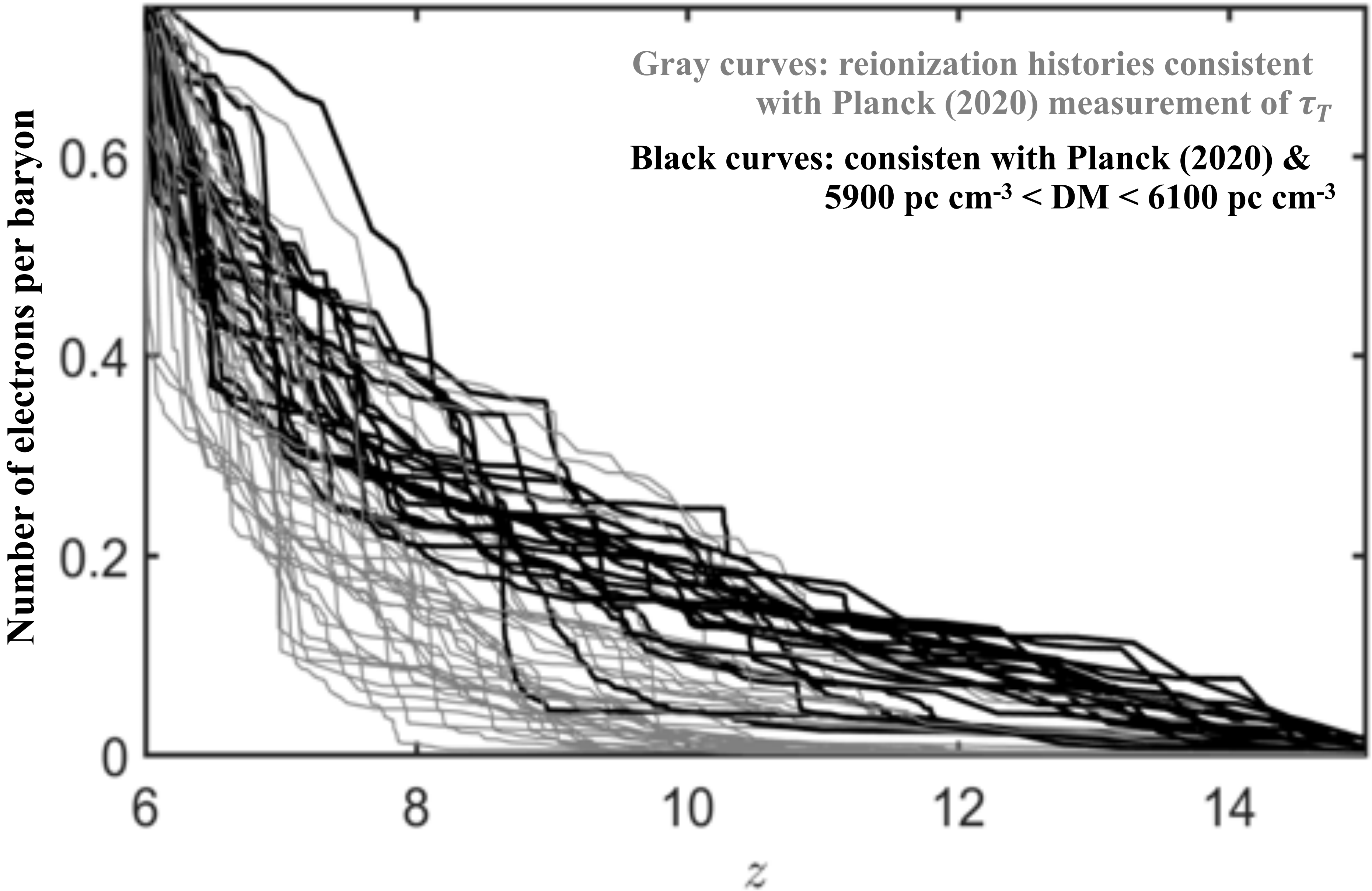
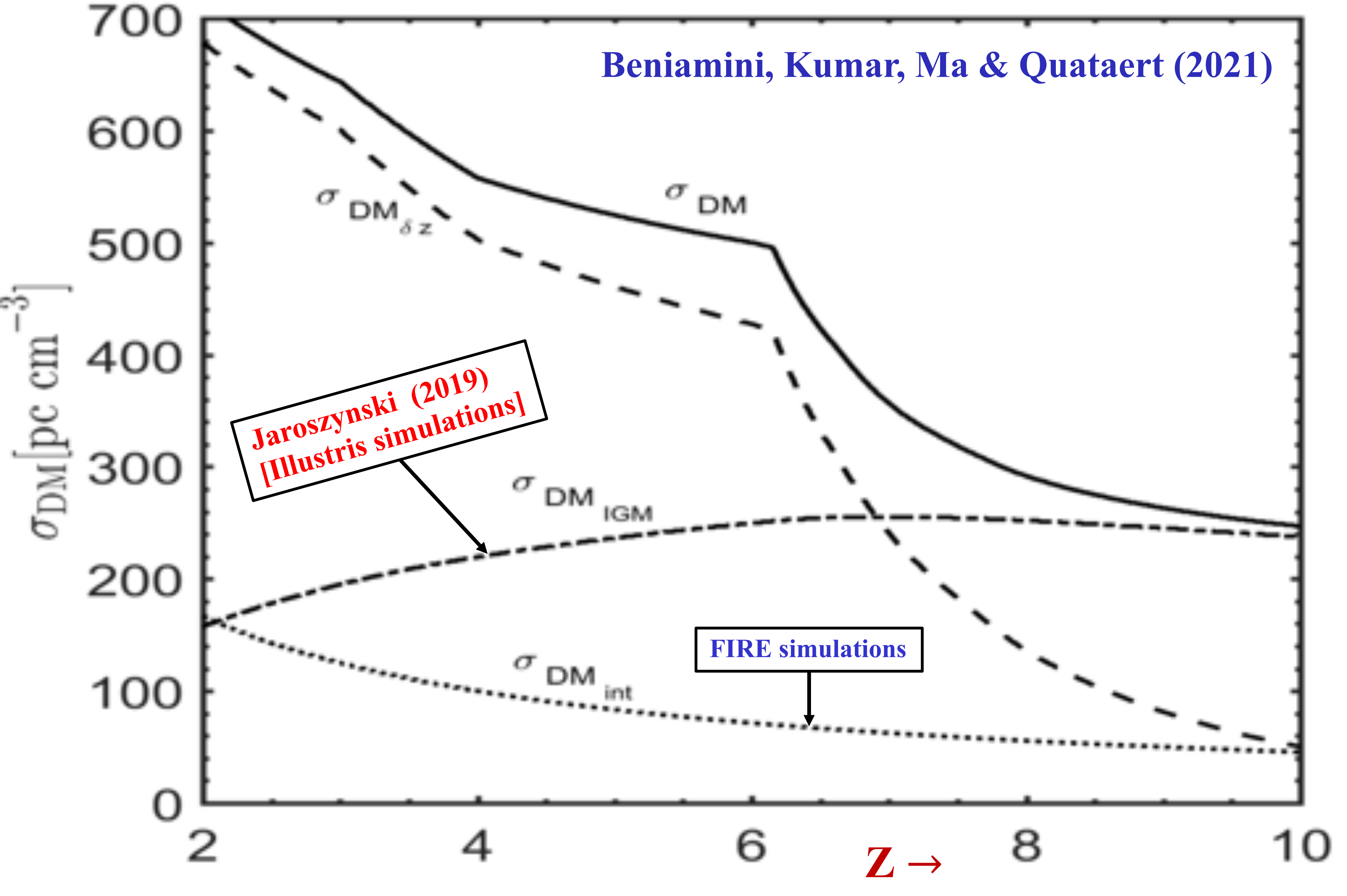


Contributions to DM from host galaxy+CGM & δn_e of IGM



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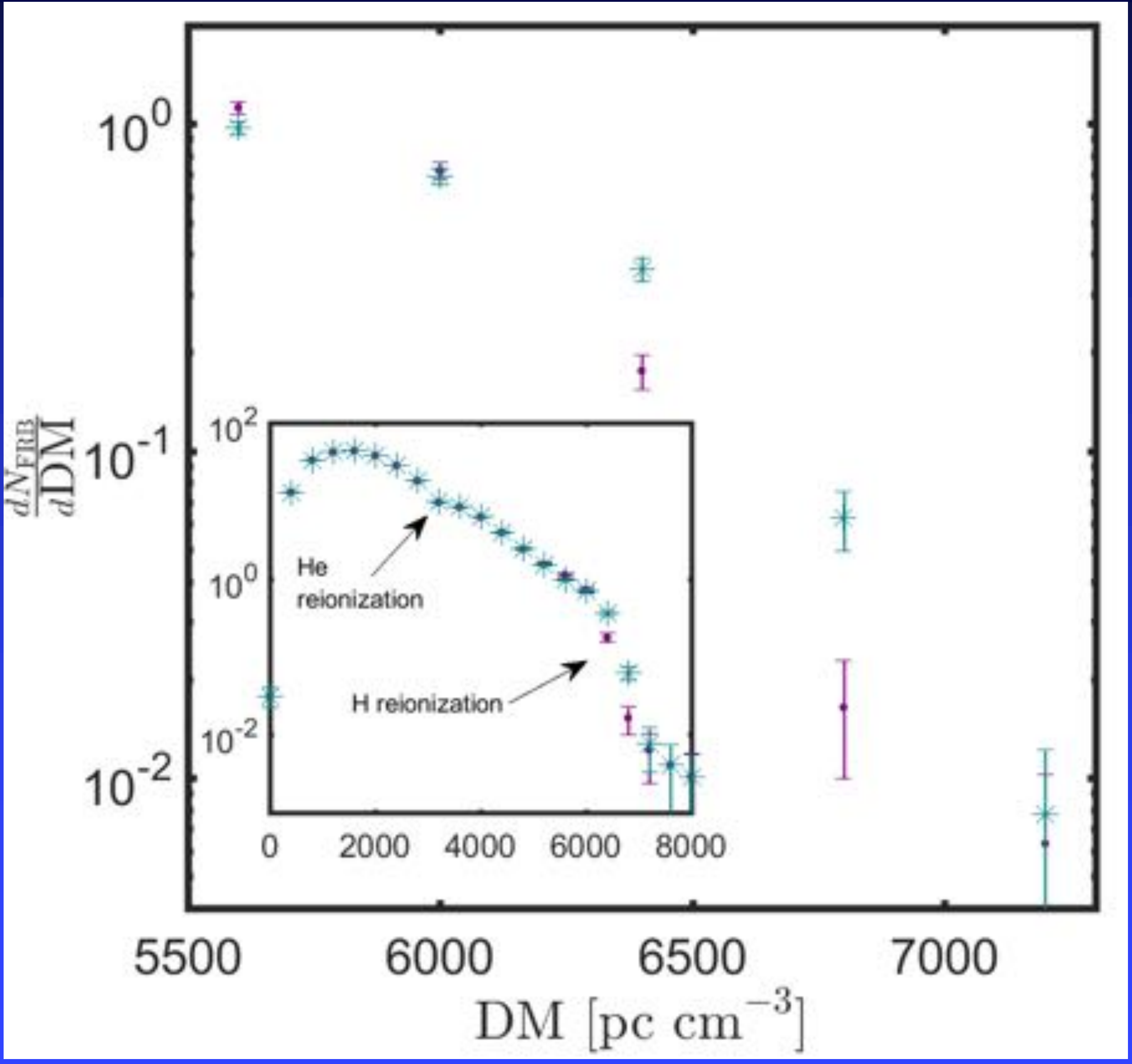
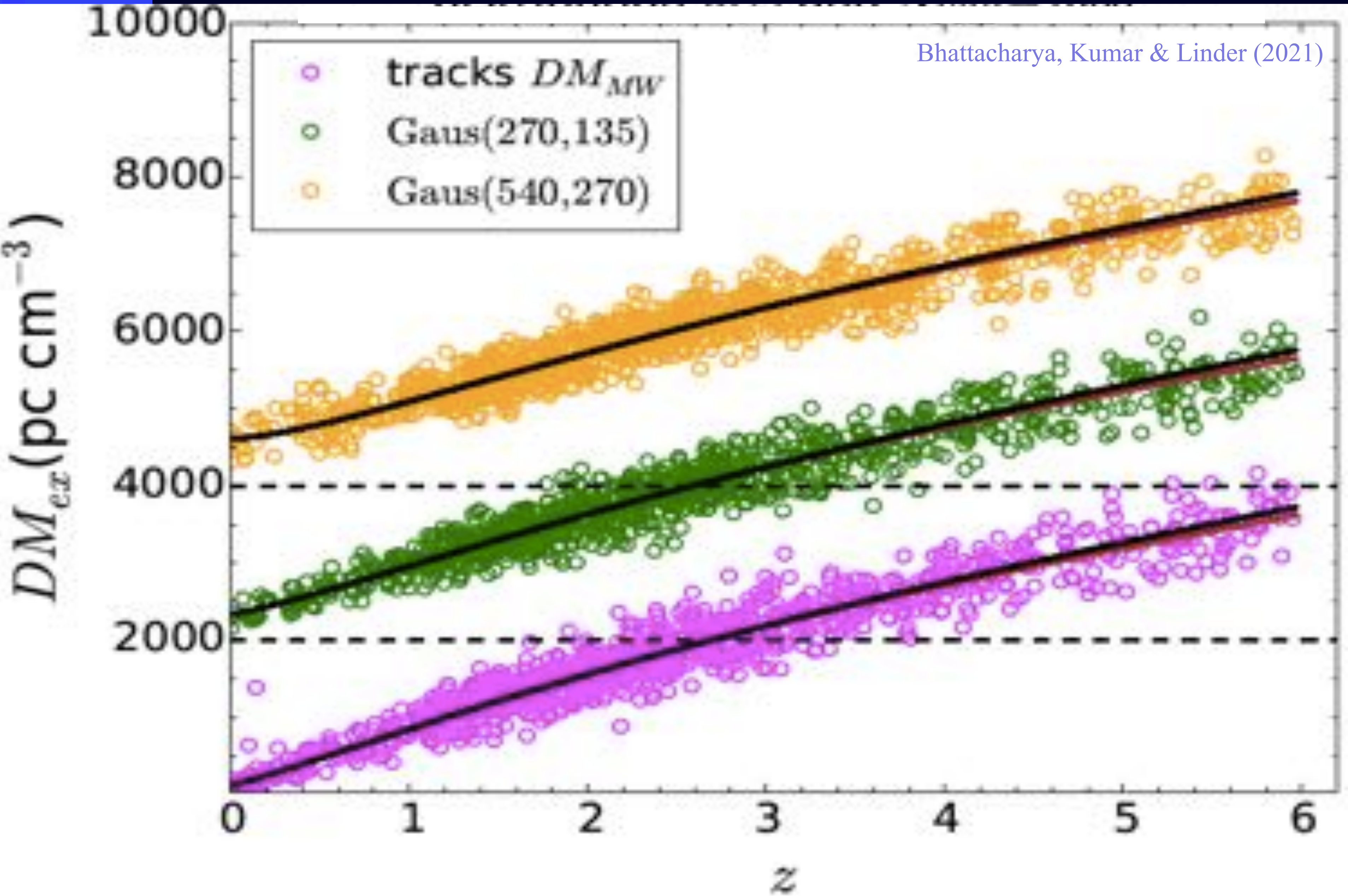


Helium reionization ($He^+ \rightarrow He^{++}$)



Summary

- **At least one FRB is associated with a neutron star with strong magnetic field (>10^{14} Gauss), probably all are.**

- ***Alfven waves launched from NS surface become charge starved at some radius. $e^{\pm}$ are accelerated in this process and produce FRBs via coherent curvature radiation mechanism.***

- **FRBs seem promising for probing cosmology.**