FRB Radiation Mechanism & Cosmology

Pawan Kumar

Outline†

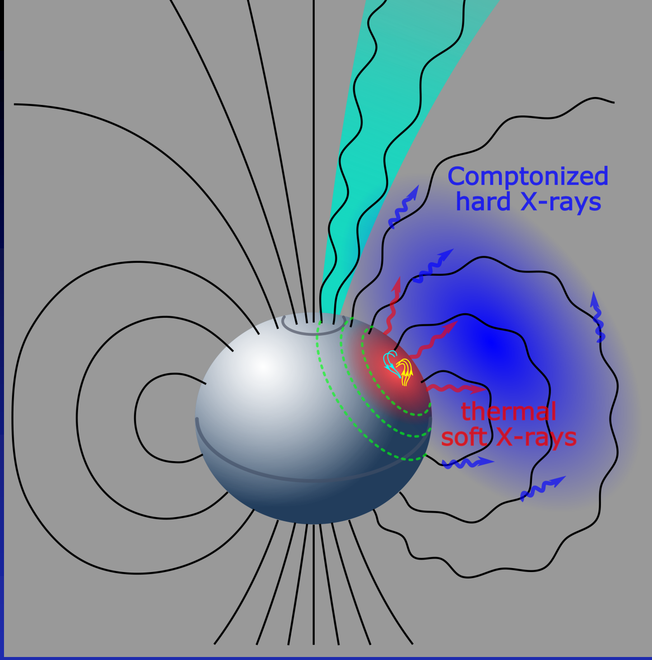
- General considerations for FRB mechanism
- FRB cosmology

†Wenbin Lu, Paz Beniamini, Xiangcheng Ma & Eliot Quataert

YITP, Kyoto, Feb 15, 2021

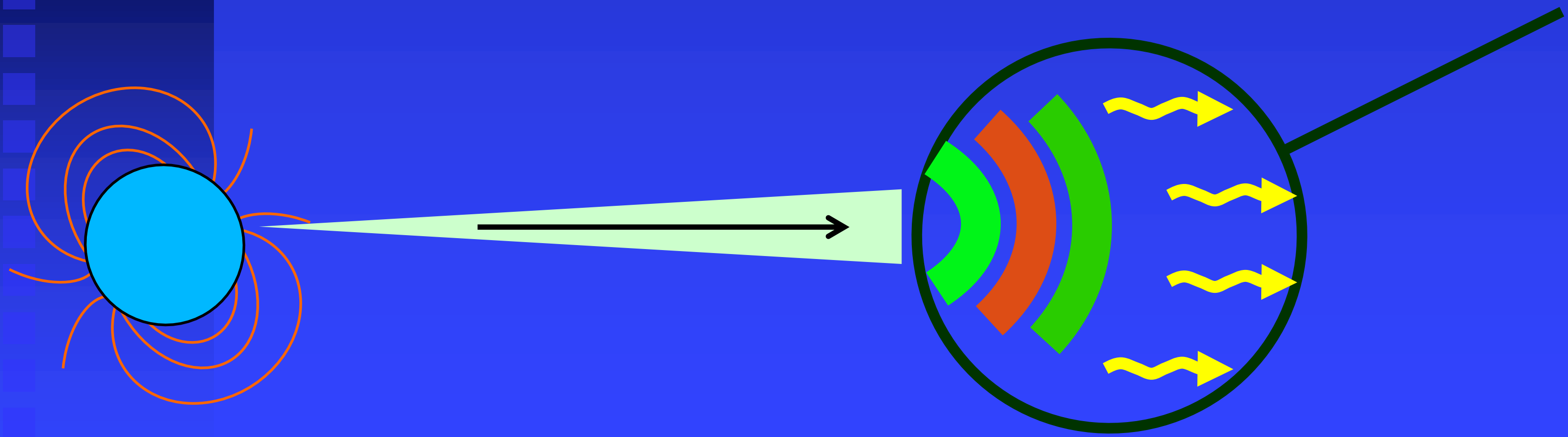
Many FRB mechanisms have been proposed and broadly speaking they fall into two categories:

Radiation produced inside the magnetosphere – near-field model



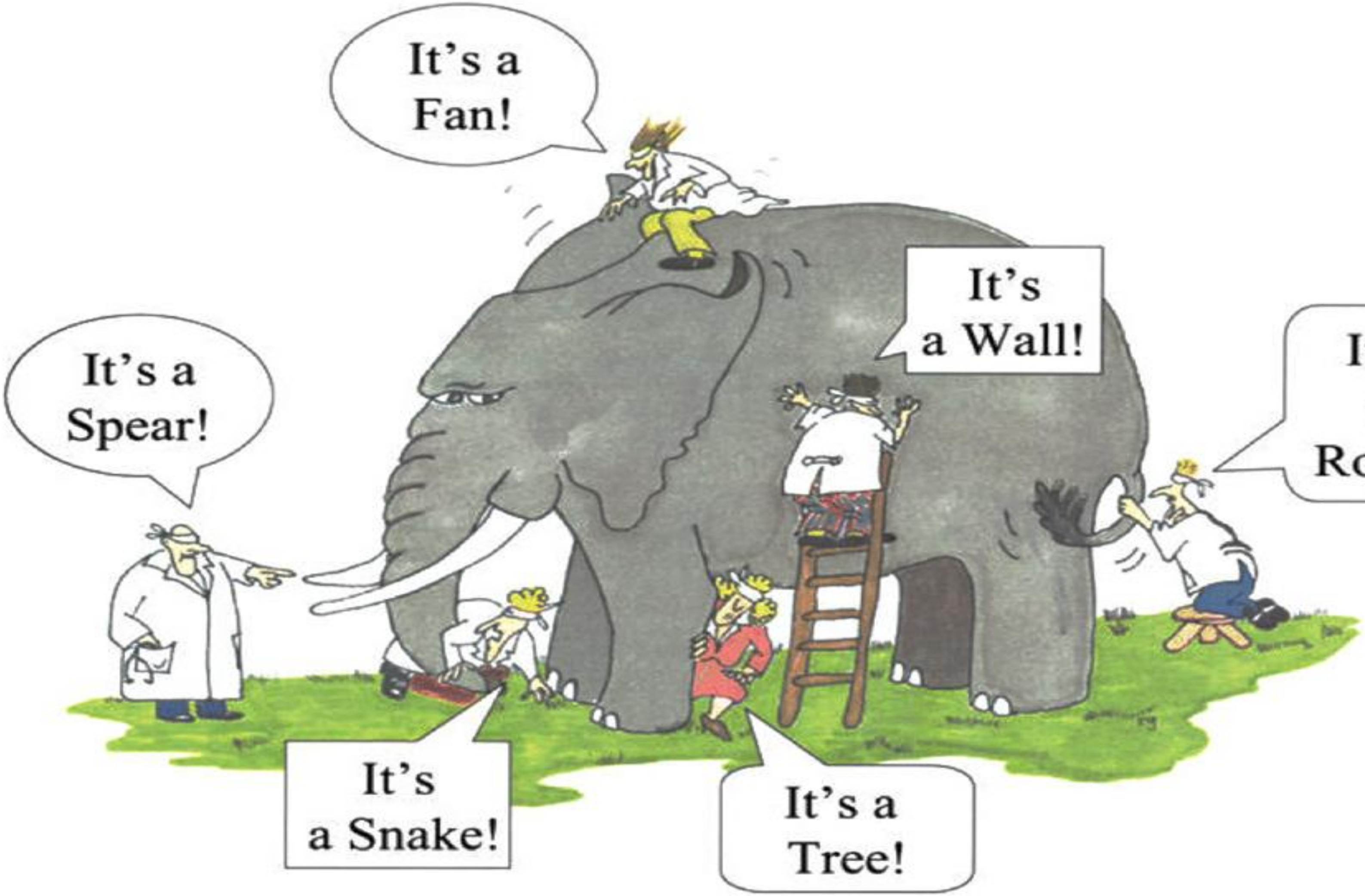
Radiation produced near or outside the light cylinder (far-away model)

10^9cm < R < 10^{14} cm



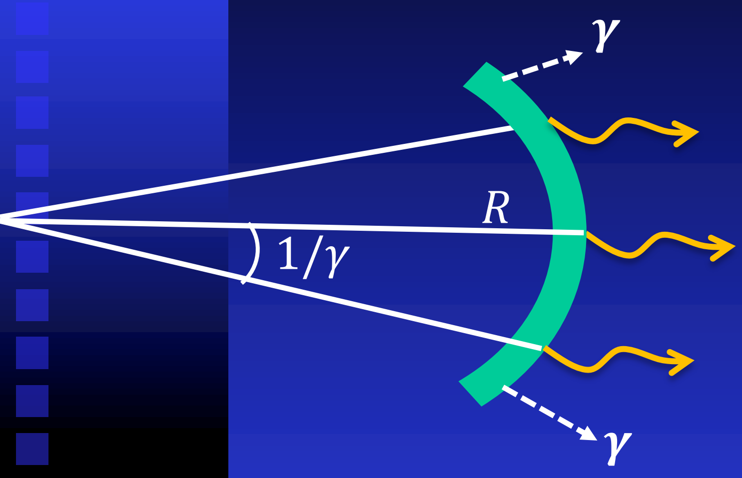
This model has been developed extensively by Metzger, Sironi and collaborators

We need to use all pieces of clues to understand how Nature produces FRBs



The fable of blind men and the elephant

Various timescales *(Beniamini & Kumar, 2020)*



- **Activity duration at the magnetar surface: t_{act}**
- **Curvature timescale for a relativistic source: $t_R = \frac{R}{2c\gamma^2}$**
- **Variability time of the observed flux: $\delta t \geq t_R$**
- **FRB duration: $t_{FRB} \approx max(t_{act}, t_R)$**

Far-away model

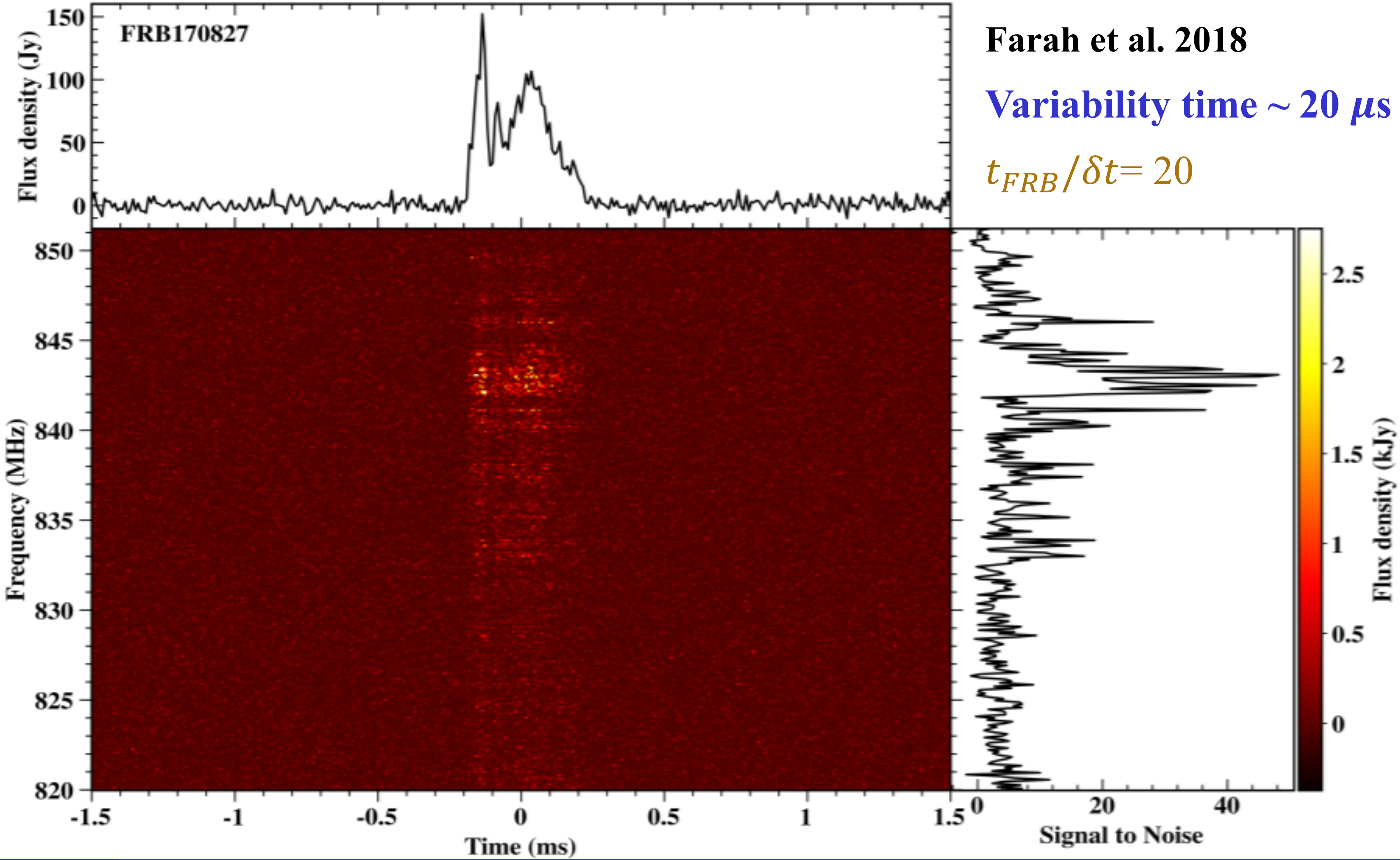
For R > 10^{12} cm, $\gamma = 10^2$, $t_R = 2$ ms

$\delta t / t_{FRB} \sim 1$ (holds broadly)

Near-field model

For R < 10^9 cm, $\gamma = 10^2$, $t_R = 2\ \mu s$

$\delta t \sim 2\ \mu s$



Farah et al. 2018

Variability time ~ 20 μs

$t_{FRB}/\delta t$= 20

	δt	t_{FRB}	$t_{FRB}/\delta t$	
FRB 181112	15 μs	0.1 ms	7	Cho et al. (2020)
FRB 180916B	4 μs	2 ms	500	Nimmo et al. (2021)

One could get short time variability for far-away model but at the expense of much reduced efficiency

Short time variability can arise when radiation is produced in a tiny area of radius $\zeta R/\gamma$; $\zeta \ll 1$.

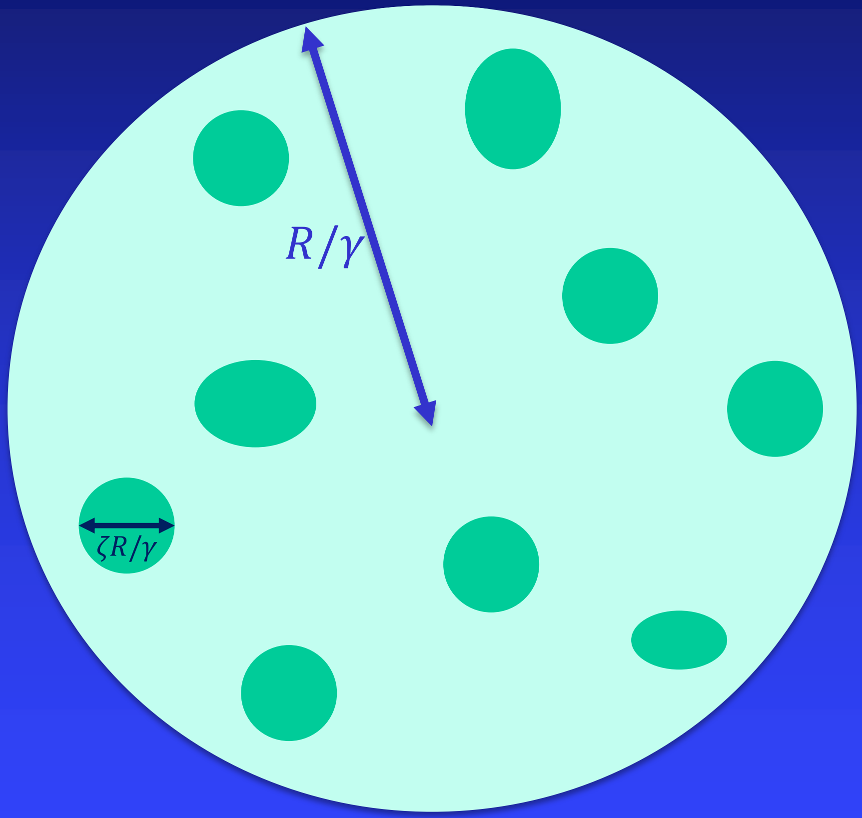
In this case:

$$\delta t \approx \zeta\, t_{FRB}$$

However, it comes at the cost of further reducing the efficiency by a factor:

$$\epsilon \approx 1/\zeta^2 \gg 1$$

Face-on view of emitting region



Example: for $\delta t = 20\ \mu s$ & $t_{FRB} = 2$ ms, the external shock model efficiency is reduced from ~10^{-5} to 10^{-9}

Similar constraints apply† to the rise and decay times of FRB lightcurves (LCs)

Questions for observers:

- **How common is short time variability with $t_{FRB}/\,\delta t \gg 1$?**
- **Do FRB LCs rise and decay on a time that is typically much shorter than the burst duration?**
- **What is the power spectrum of temporal fluctuations of FRB lightcurves?**

These data would provide important clues to the place where FRB coherent radiation is generated

†**Other models for fast variability are similarly constrained (Beniamini & Kumar, 2020)**

Spectral properties

Many FRBs show evidence for

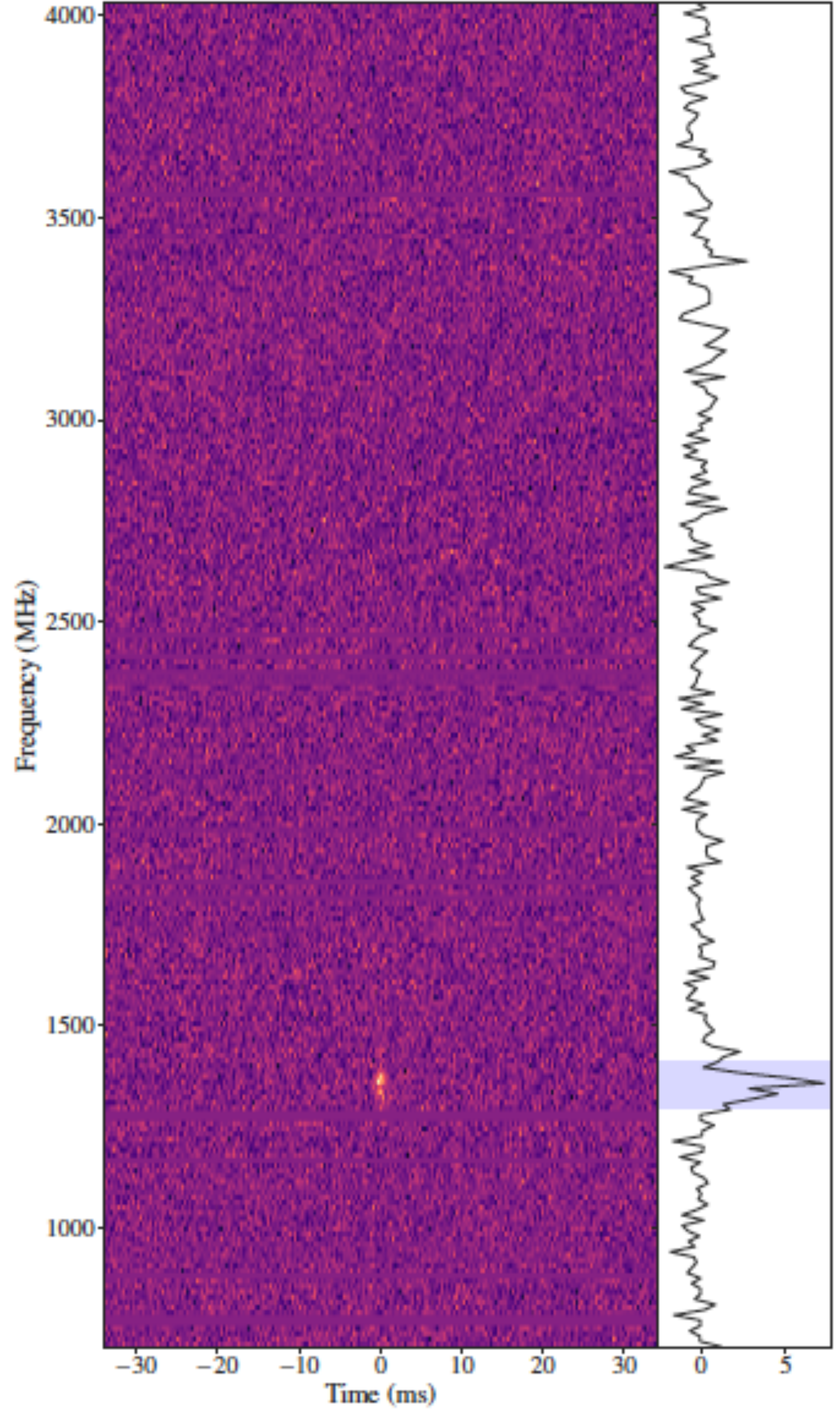
$$\frac{\Delta v}{v} < 1$$

An extreme example is ASKAP FRB 20190711:

$\Delta v = 65\ MHz\ \ at\ 1.5\ GHz!$

(DM = 593 pc cm^{-3} ; z = 0.52)

This provides another clue for the location where the radiation is produced.

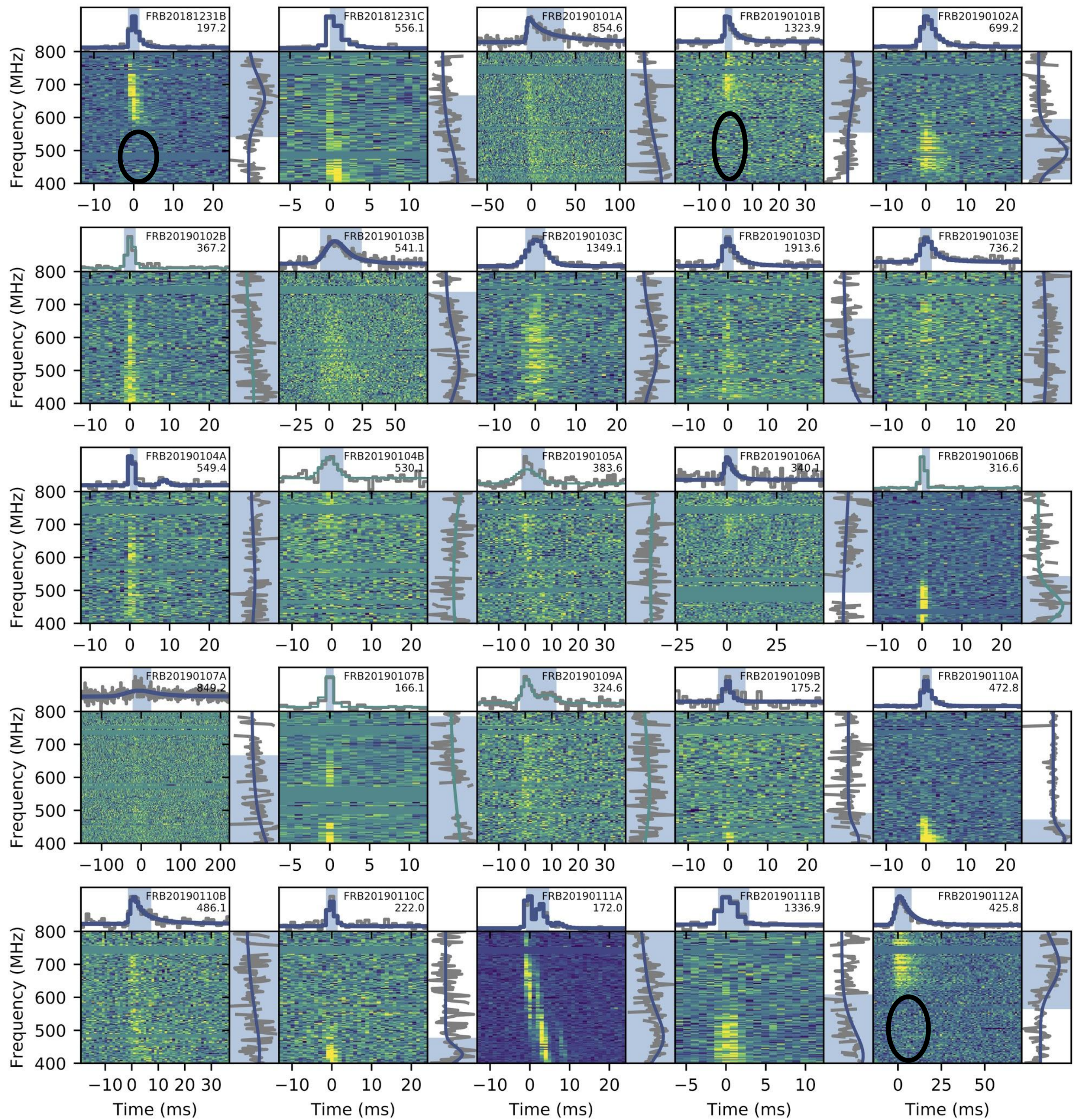


ASKAP burst 20190711; Kumar et al. 2021

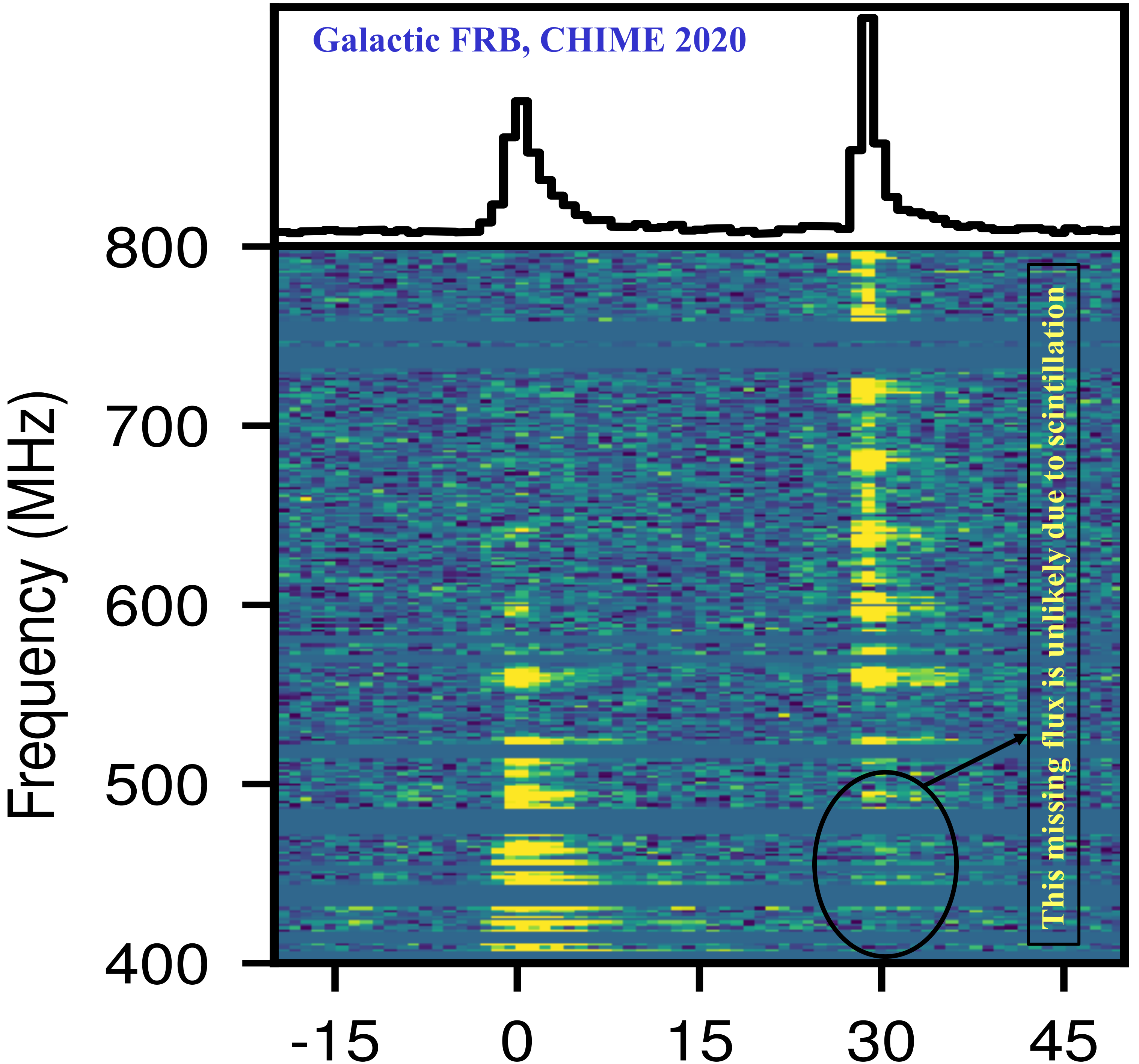
Spectral properties

Many FRBs show evidence for $\frac{\Delta \nu}{\nu} < 1$

These provide clues for the location where the radiation is produced



CHIME collaboration: Chawla – YITP FRB workshop, Feb 8, 2021



***Also*:**

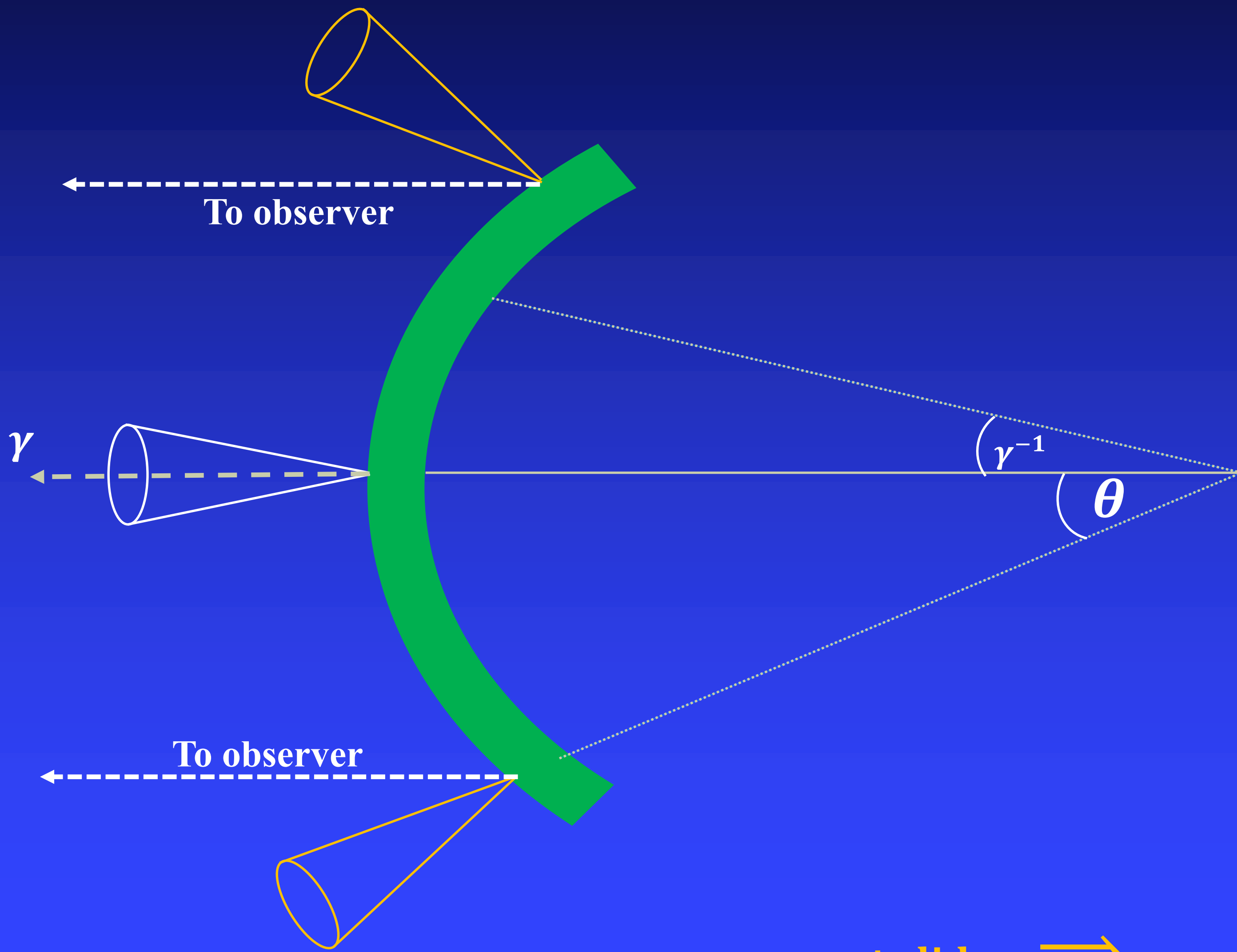
Burst from 121102 seen by VLA (2.5-3.5 GHz) but not ARECIBO (1.15-1.73 GHz)

Limit to narrow bandwidths & flux turn-off with ν

High latitude contributions to the observed radiation sets the bandwidth of FRBs and how sharply the spectrum can decline with decreasing frequencies

$$D \approx \frac{2\gamma}{1+\gamma^2\theta^2}$$

Photons are mostly beamed into a cone of opening angle $2/\gamma$



Photons escaping at larger angles have less Doppler boost and thus lower frequencies in the observer frame.

next slide ⟹

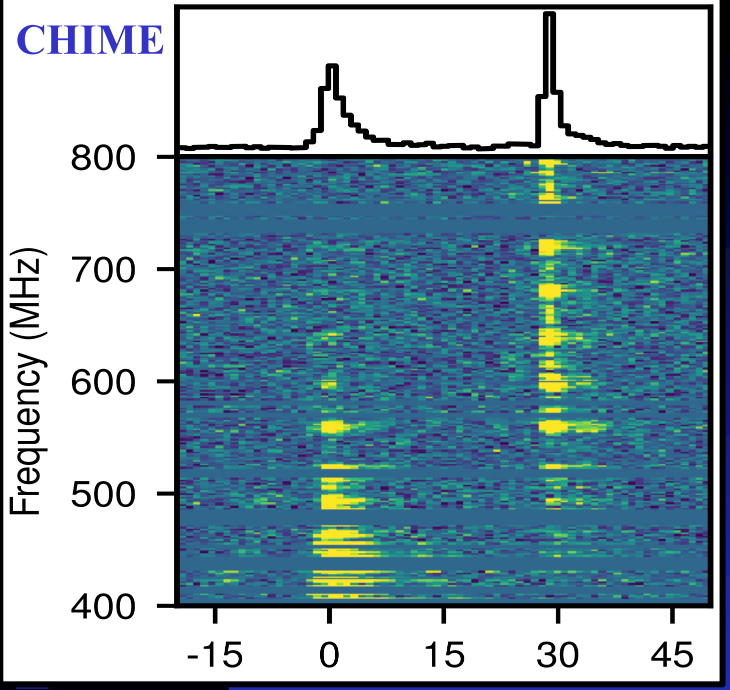
∴ **The flux f_ν cannot fall off faster than ν^2 below any frequency ν_0 as long as the angular size of the source region is larger than the segment size ($1/\gamma$) we see.**

Note: the arrival of lower frequency photons – in the neutron star rest frame – is slightly delayed by 1 ms ν_{GHz}^{-1} for the far-away source model with narrow intrinsic $\Delta\nu/\nu$.

Questions for observers:

What is the distribution of spectral bandwidths ($\Delta\nu/\nu$)? Does it depend on FRB luminosity and/or repetition rate?

We (or at least I) still don't have a clear answer for the intrinsic average spectral shape of FRBs, which is important for deciding between competing models.



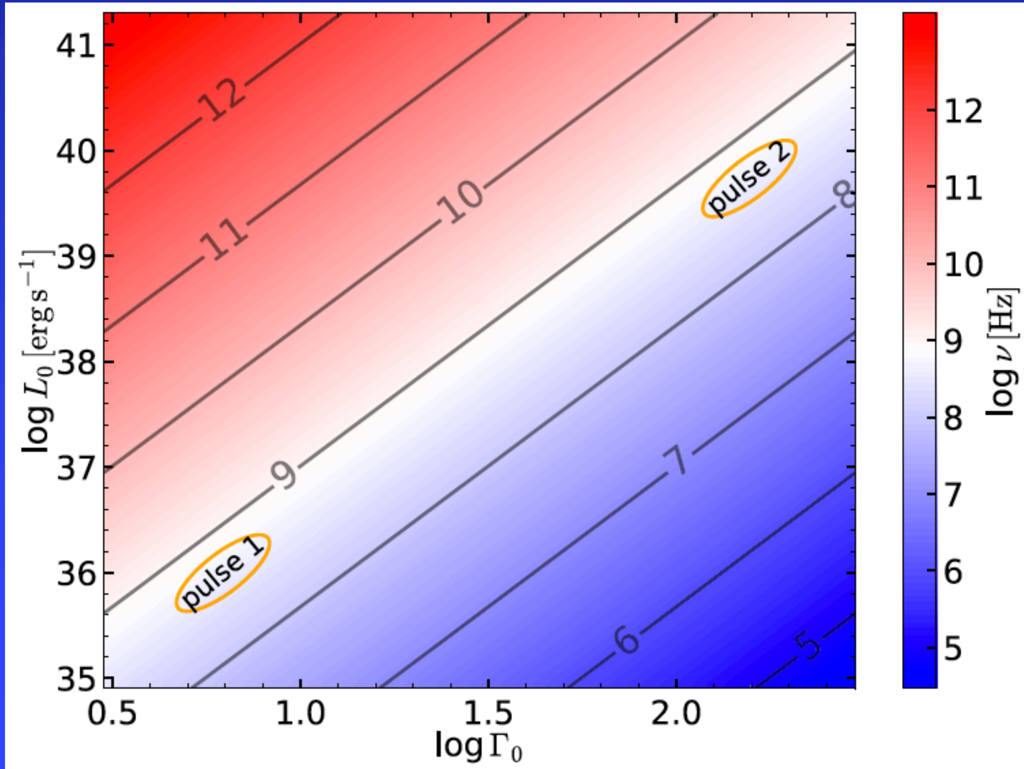
Closely spaced bursts

The two pulses of FRB 200428 were separated by 30 ms (CHIME collaboration)

FRB 121102 had several pairs of bursts separated by 17-34 ms, e.g. Hardy et al. (2017), Gourdji et al. (2019), Rajwade et al. (2020), Li et al. (2021)

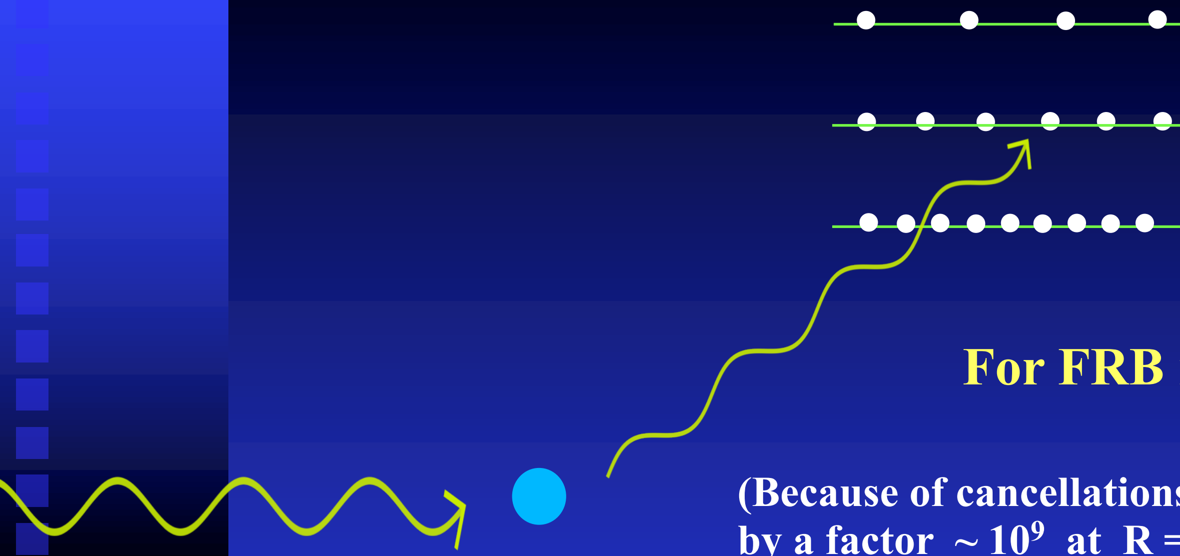
Not a problem for "near-field" radiation mechanism

But requires fine tuning for far-away models: in order that the two shocks produce synchrotron emission between 400 MHz & 1.5 GHz frequencies.



Lu, Kumar & Zhang (2020)

Large 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

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

$R \gtrsim 10^{13}$ cm

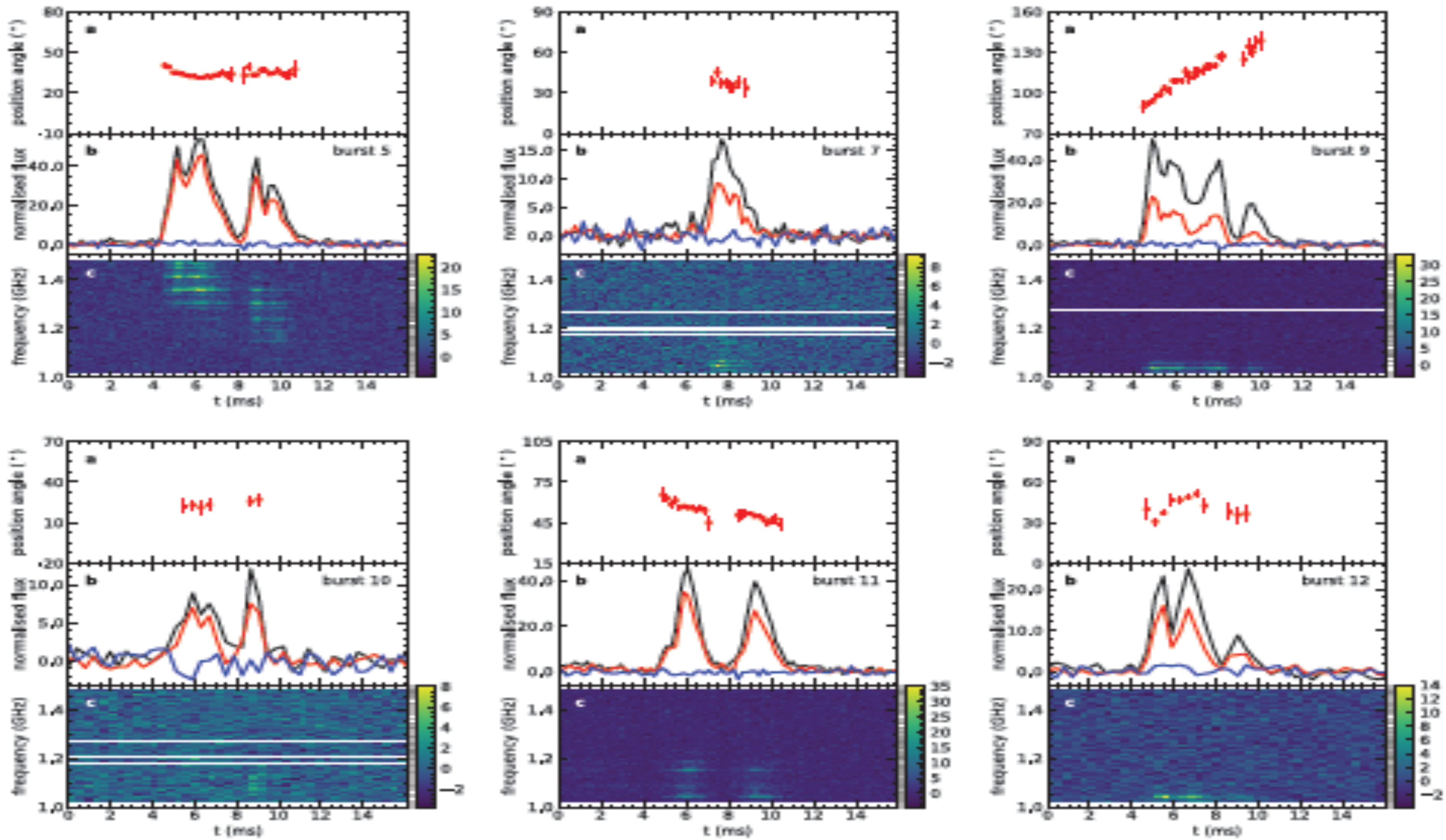
Photon beam size is small and scattering is not a problem.

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 magnetar surface due to the enormous induced Compton force which quickly disperses the plasma.

Polarization angle swings

FRB 180301; Luo et al. (2020); [Bing Zhang’s talk on Feb 9]



PA swings suggest magnetospheric origin for radio photons

The widths of X-ray spikes (~5 ms) and radio emission (0.6 ms) for FRB 200428 (Galactic FRB) suggest that X-rays and radio were produced at different locations.

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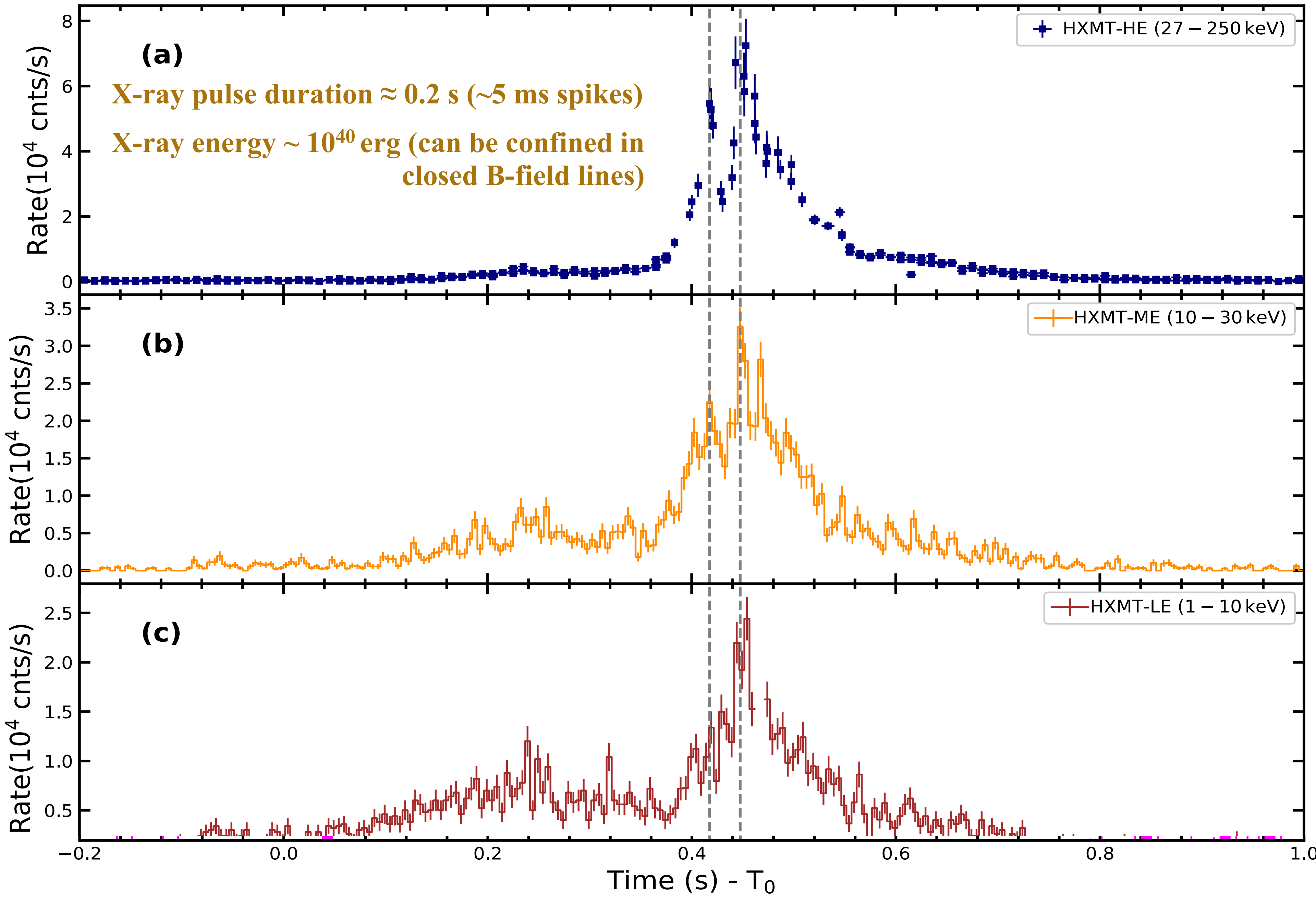
Insight-HXMT (X-ray) data for FRB 200428 (Li et al. 2020)

[Hard X-ray Modulation Telescope or HXMT aka Insight]



General Constraints on FRB radiation mechanism

1. Radiation source size $\sim 10^6\ \Gamma$ cm for $\delta t = 20\ \mu s$; Γ: LF of the source

2. Plasma should be able to withstand the radiative acceleration due to induced-Compton $\Longrightarrow$ source distance from NS $< 10^8$ cm or $> 10^{13}$ cm.

3. Particle beam kinetic energy converted to FRB radiation in the magnetosphere?

   The total number of particles in the magnetosphere of a NS ($B = 10^{15}$ G and spin period 5s), is $\sim 10^{31}$ x multiplicity factor (M)

   Even for $M \sim 10^9$, particle LF needs to be $\sim 10^6$ to convert with 100% efficiency particle KE to FRB energy of 10^{40} erg.

4. *Plasma frequency*: $\nu_p = 5\text{x}10^3 \text{GHz}\ L_{43}^{1/2}/R_{10}$ *Cyclotron*: $\nu_B = 3\ GHz\ B_{15}\ R_{10}^{-3}$

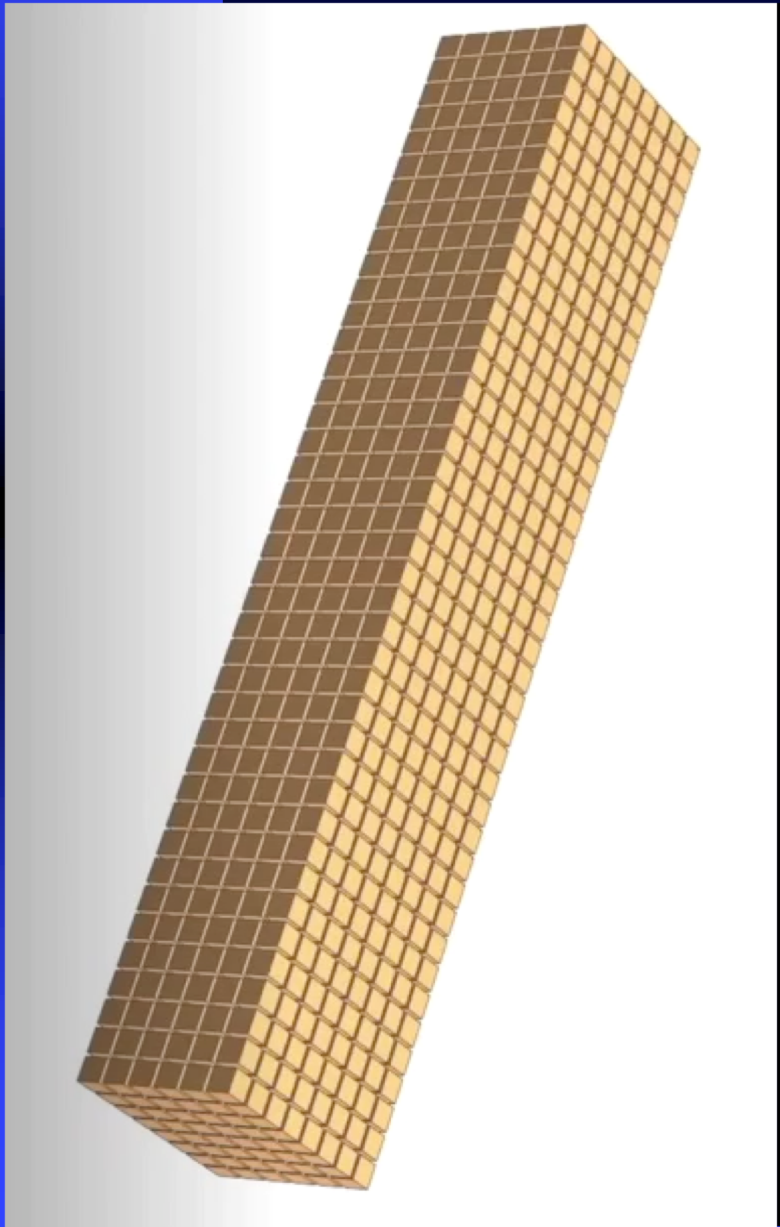
   So, maser process is possible near the light cylinder if one can avoid dispersing the plasma by the strong induced-Compton scattering force.

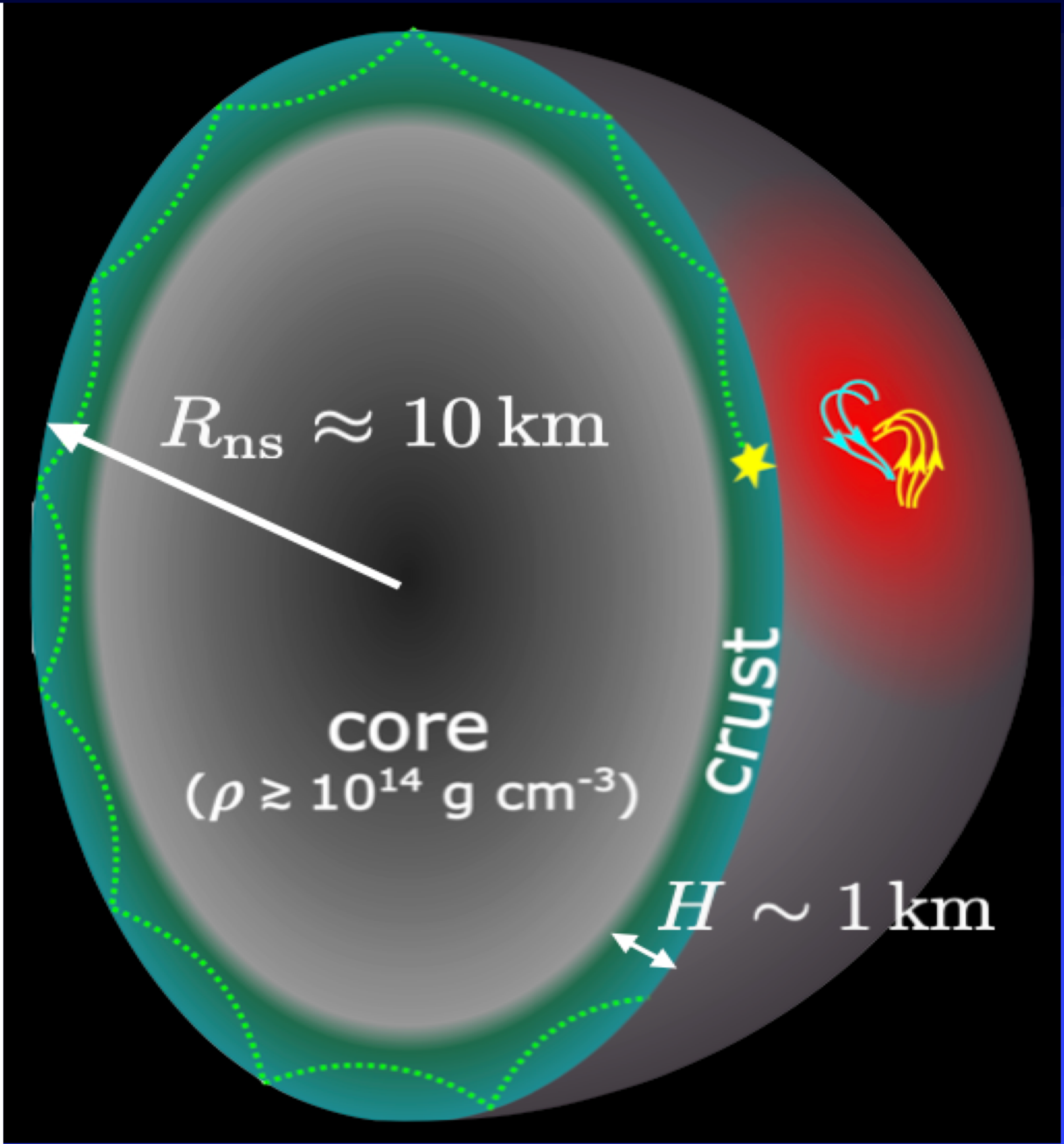
I believe it is more natural to convert magnetic disturbance (Alfven waves) directly to generate coherent radio emission

FRB radiation source within a few 10s of neutron star radius

Overview of shear wave → FRB

Lu, Kumar & Zhang, 2020



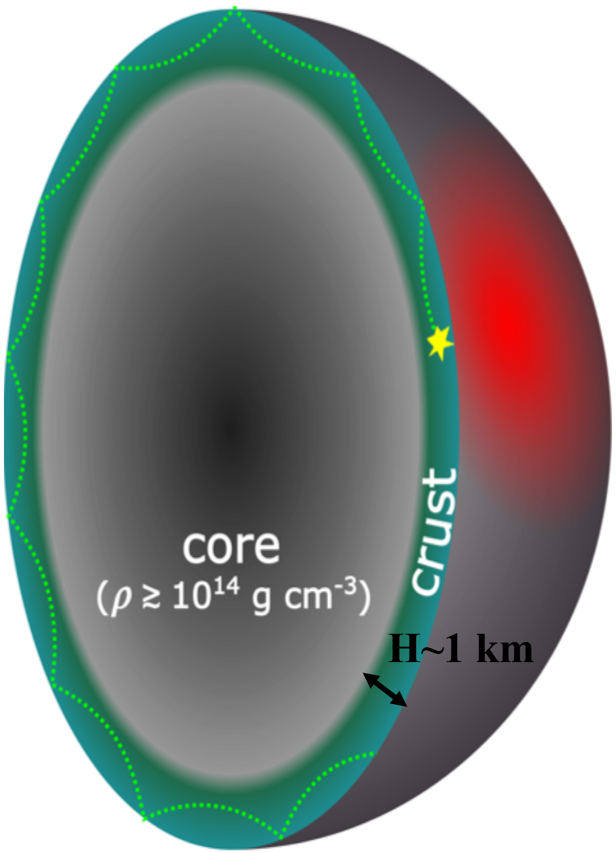


Crustal shear waves → Alfven waves

Lu, Kumar & Zhang (2020)

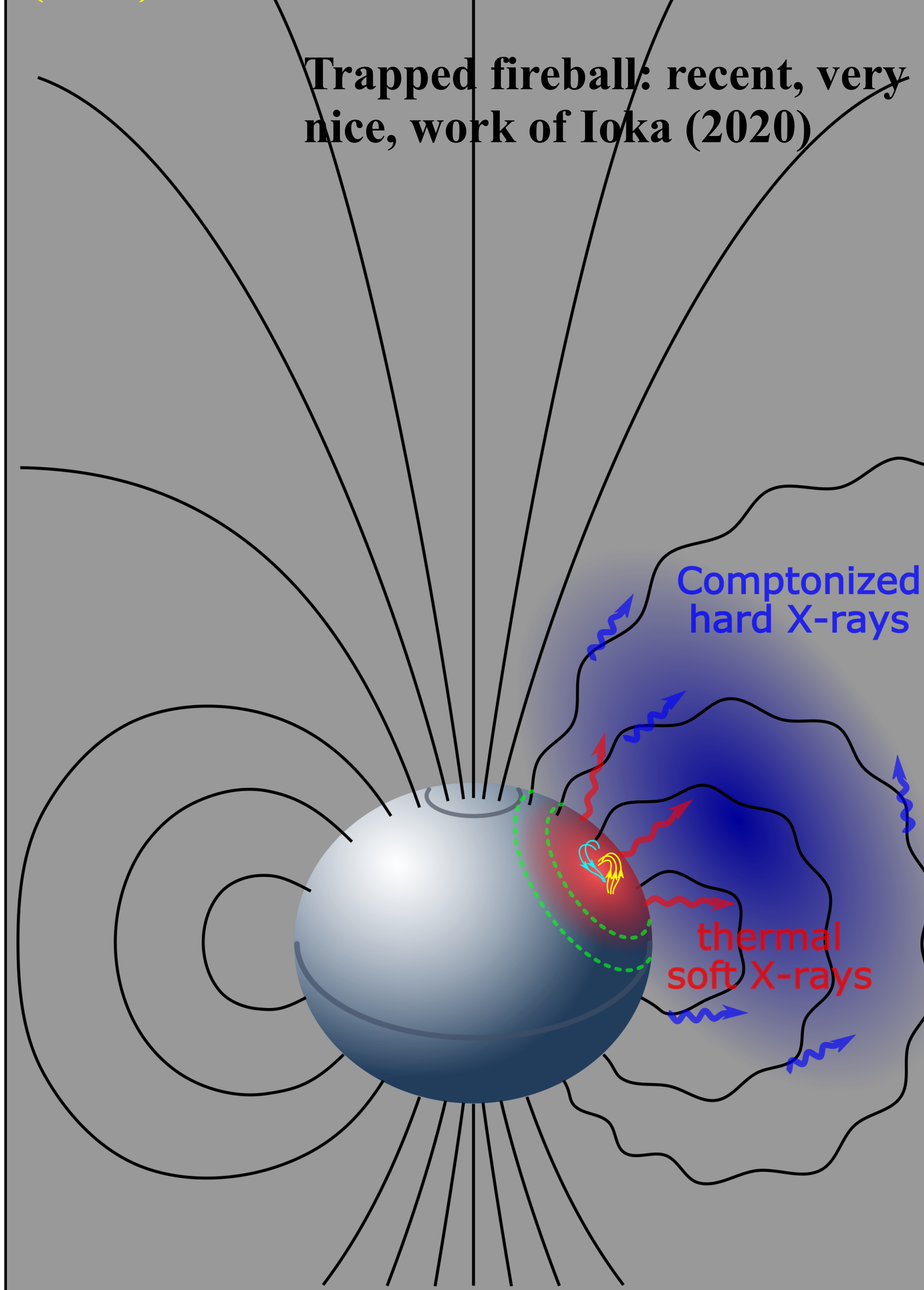
$\nu_{shear} \sim 10^4$ Hz $\sim v_{shear}/H$

$v_{shear} \sim 0.01$ c



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

Trapped fireball: recent, very nice, work of Ioka (2020)



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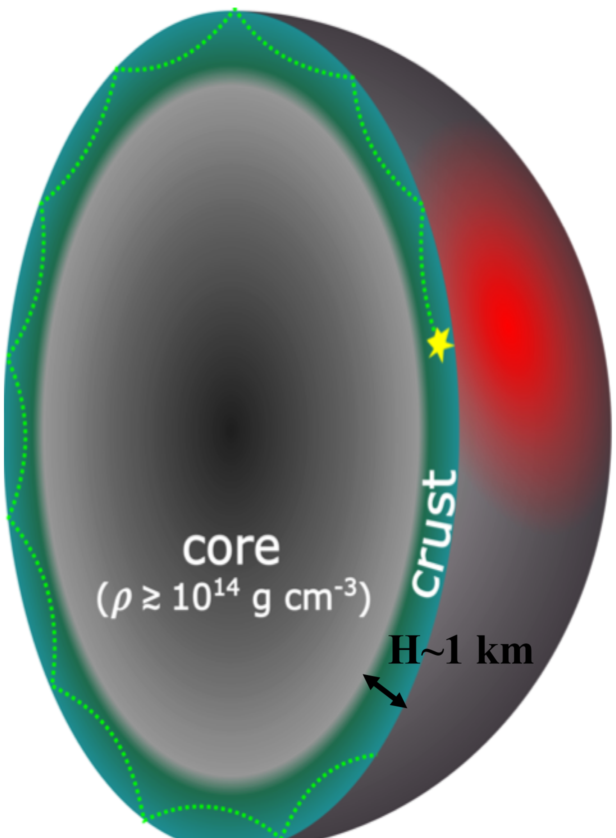
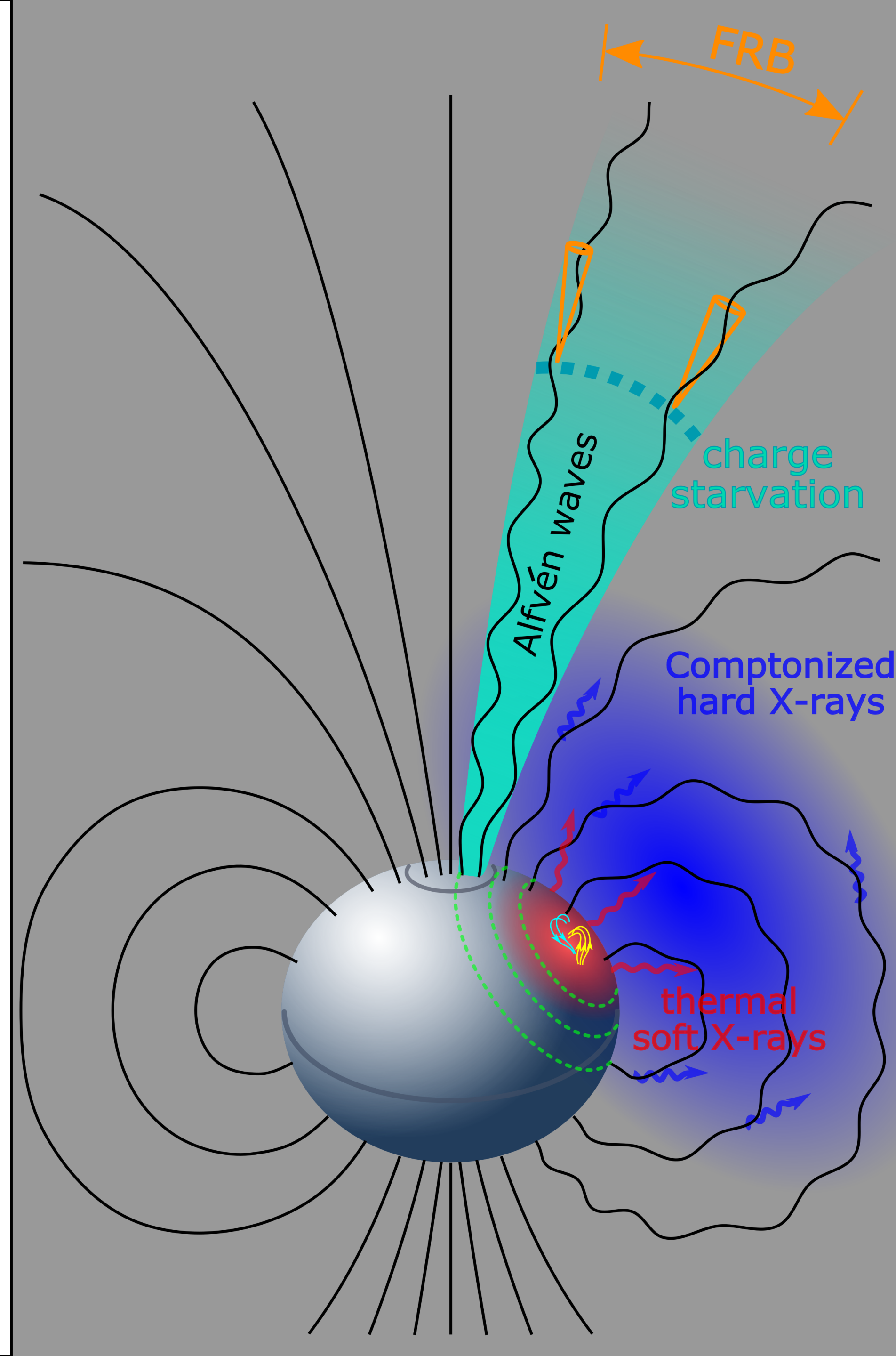
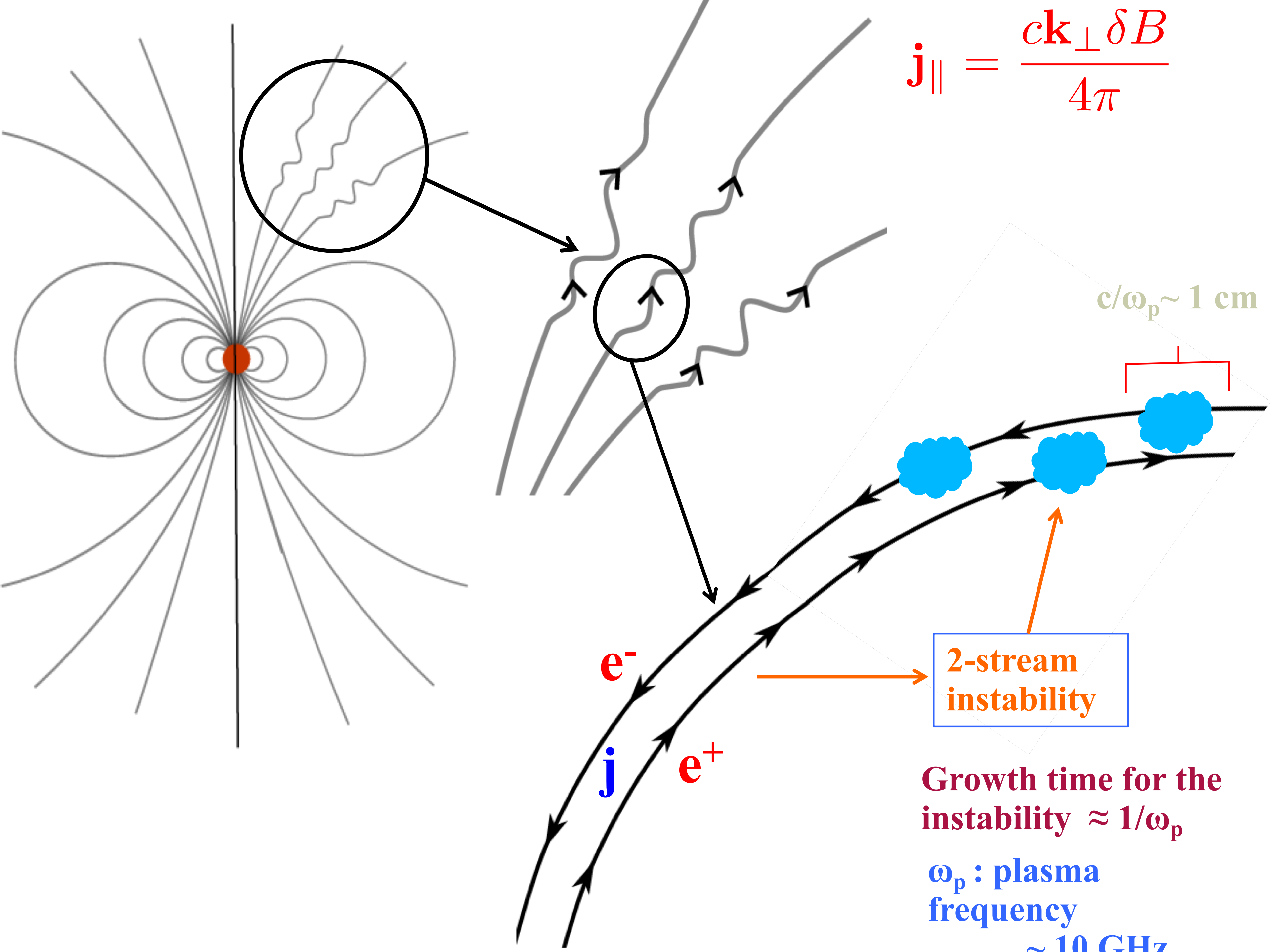




Particle clump formation & radiation outside charge starvation radius

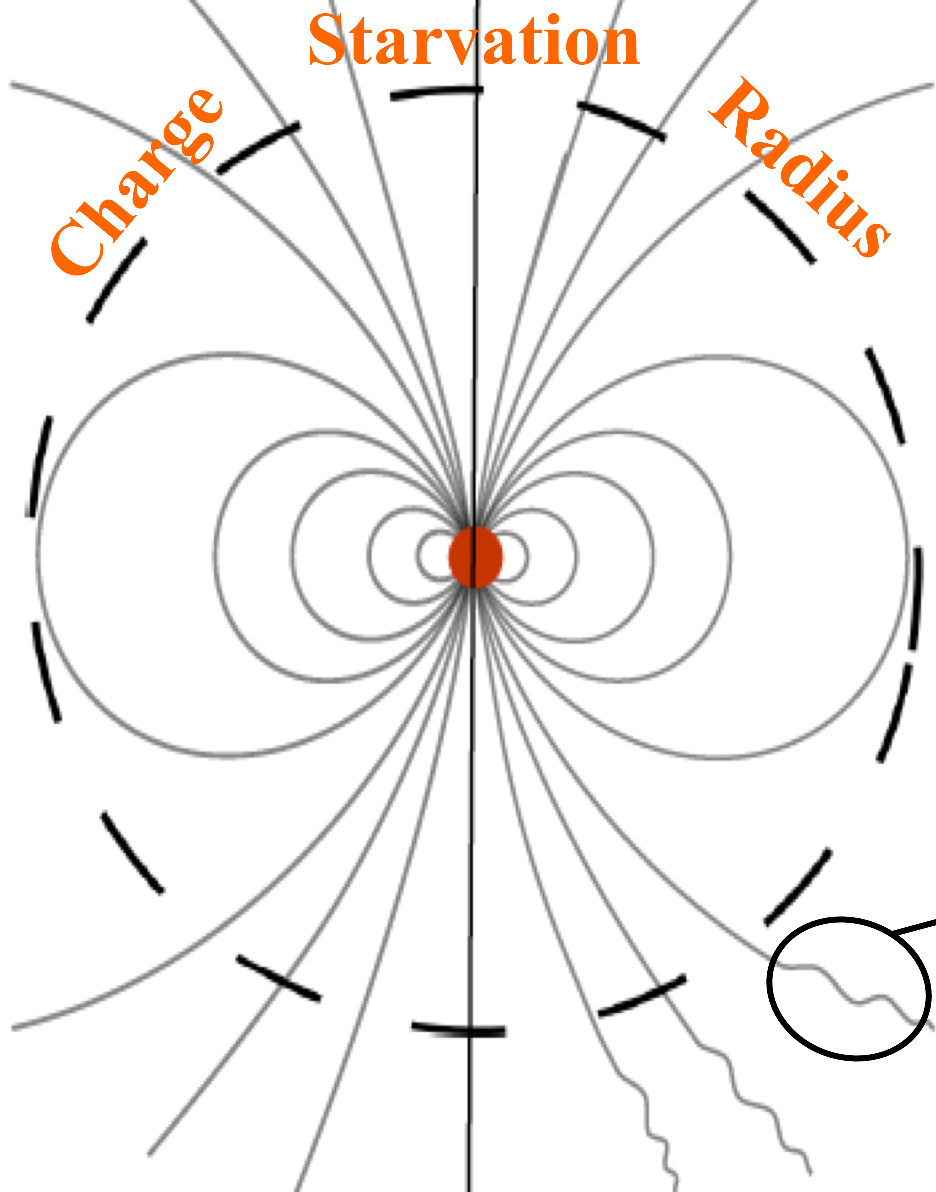


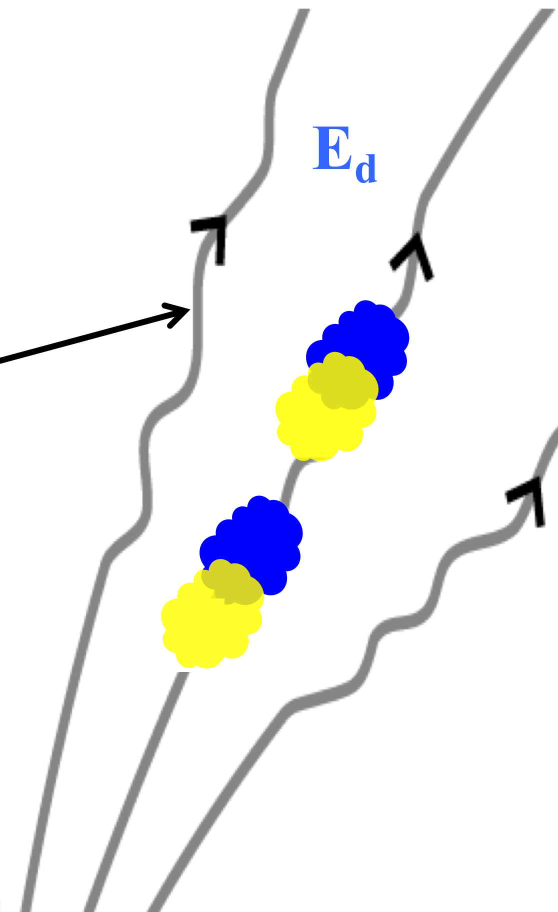
$\mathbf{j}_{\parallel} = \frac{c\mathbf{k}_{\perp}\delta B}{4\pi}$
$c/\omega_p \sim 1$ cm
2-stream instability
e^-
j
e^+
Growth time for the instability $\approx 1/\omega_p$
ω_p : plasma frequency

Displacement current:

$$\frac{\partial \vec{E}_d}{\partial t} = c\vec{\nabla} \times (\delta\vec{B}) - 4\pi\vec{j}$$

$$\frac{\partial \mathbf{E_d}}{\partial t} = ic\mathbf{k}_{\perp}\delta B$$





This electric field keeps the charge particles accelerated as they lose energy to coherent curvature radiation.

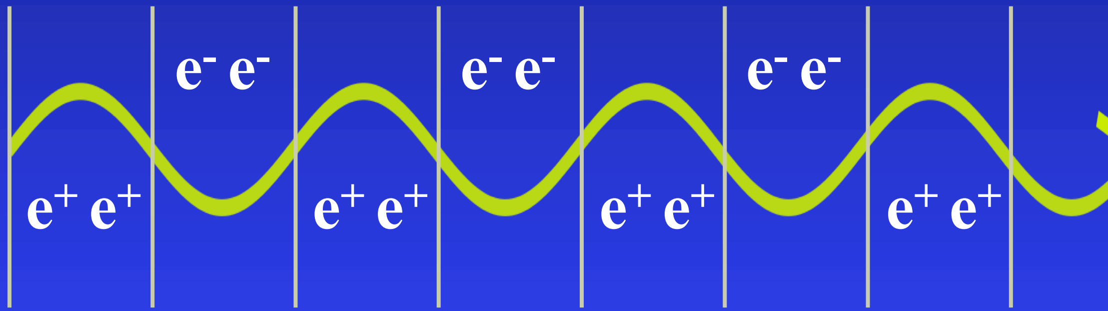
Particle advection by Alfven waves prevent charge starvation?

The recent work of Chen et al. (2020) suggests this possibility

Particle column density required $> \int d\ell \frac{|\vec{\nabla} x \vec{B}|}{4\pi q} \approx 10^{20} cm^{-2} \frac{(\delta B)_9}{\lambda_{aw,6}} \propto R^{-3}$

A factor 10^5 larger than G-J at 10^2 R_{ns}, which scales as R^{-2}. Thus, charge starvation is unavoidable for a range of parameters; Particles cannot be advected from much below the charge-starvation radius because their speed is << c.

Furthermore, it requires complete charge separation and particles moving with $\gamma > 10^2$ to prevent charge starvation for ~ 1 ms or 10^2 λ_{aw}



Lorentz factor variation across the wavelength by a factor ~2 would destroy the delicate balance. Freshly swept up particles by the wave-packet over the distance of ~1 ms*c force the system away from this balance, simulations should follow the wave for ~ 10^3 λ_{aw}.

Predictions of the model

- **Maximum FRB frequency**

We should see FRBs up to ~10^2 GHz

The minimum size of particle clumps is unlikely to be smaller than the plasma length scale (l_{pl}), and that sets the maximum frequency at which we would see FRBs.

The plasma density at the Alfven wave charge starvation radius (R_c) is a quantity that we can calculate with some confidence: $n_c \propto \delta B$;

$$\therefore \; \nu_{max} \sim 10^2 \, GHz \; (\delta B)_{11}^{1/2} (10 \, R_{NS}/R_c)^{3/2} \propto L_{FRB}^{1/4}$$

- **Maximum FRB Luminosity** **~ 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 luminosity**

The minimum charge density throughout much of the NS magnetosphere is expected to be the ***Goldreich-Julian*** *density.*

Thus, Alfven waves of sufficiently low luminosity might never become charge starved. This sets the minimum FRB luminosity for a given object:

$$\delta B > (10^9\,\mathrm{G})\, B_{NS,15}\, \ell^{\perp}_{AW,4}$$

$\Longrightarrow$ **$L_{min} \sim 10^{39}$ erg s^{-1}**

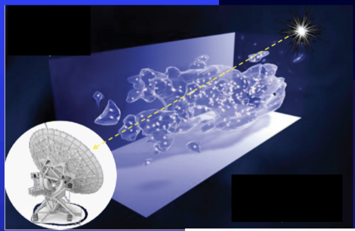
- **Minimum FRB frequency**

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 frequency by a factor $\gamma R/(2\pi R_B)$

FRB cosmology

FRBs as probe of Intergalactic Medium

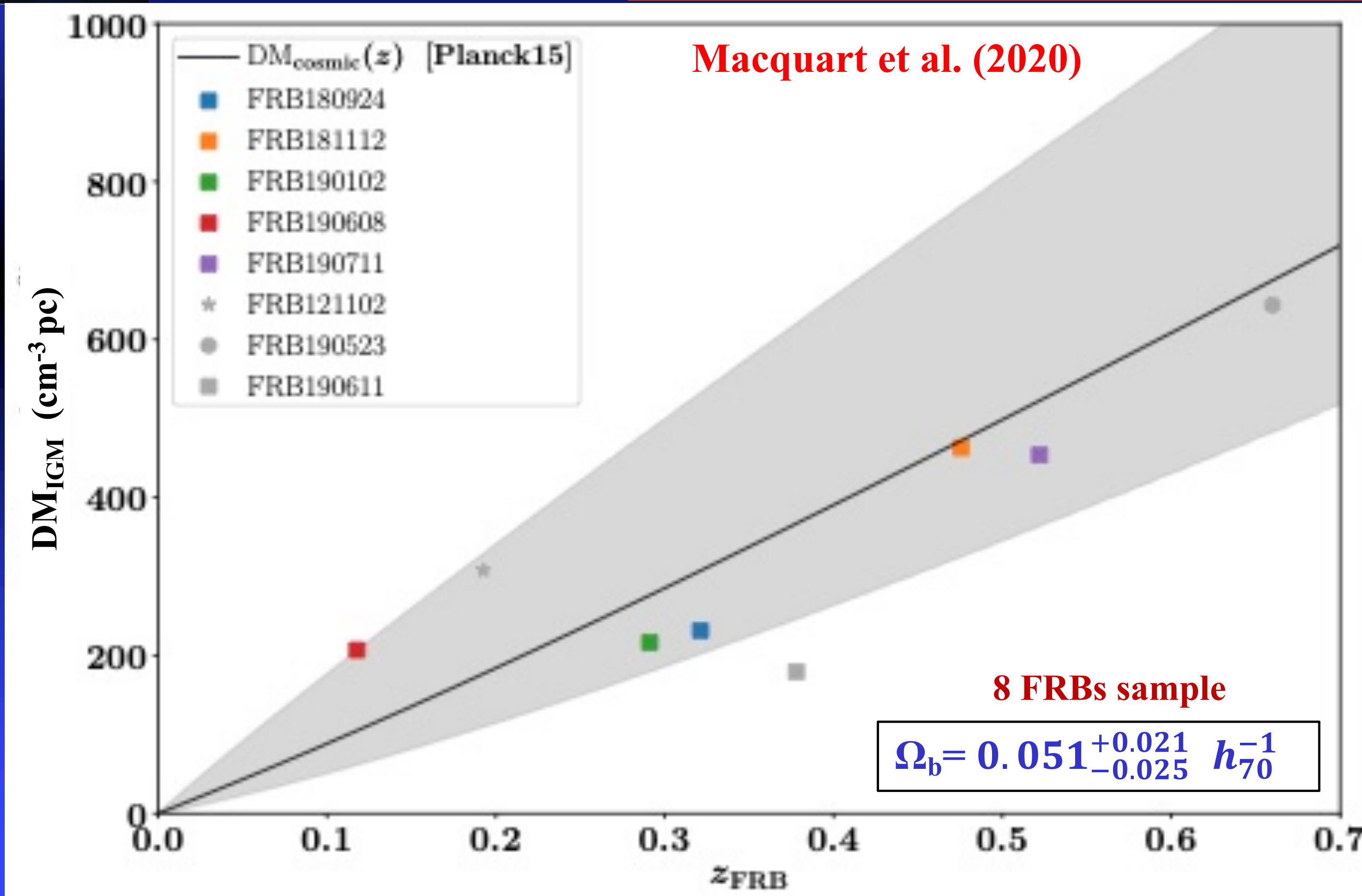


$$\mathbf{DM} = \int d\ell \, n_e$$

$\Longrightarrow$

Baryons in intergalactic medium (DM)

Map H & He-reionization epoch



Exploring the hydrogen reionization epoch using FRBs

Beniamini, Kumar, Ma & Quataert, 2021)

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

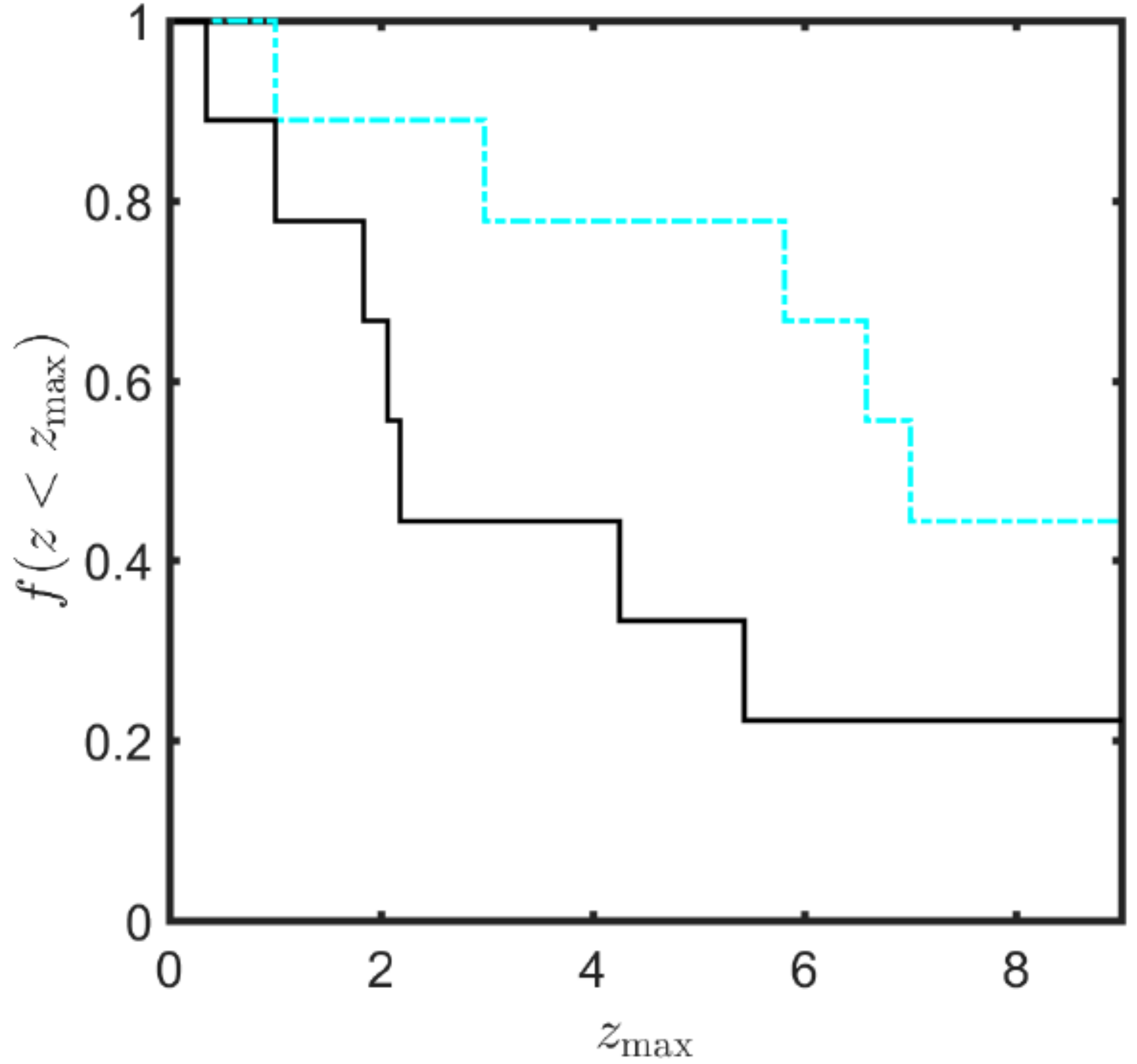
- UV photons for the cosmic reionization (z>6) are supplied by stars $\geq 10M_{\odot}$
- About 40% of massive stars produce magnetars at z=0 (Beniamini et al. 2019)
- High z, metal poor stars have faster rotation rate and are likely to produce magnetic fields and fast rotating compact remnants.
- In 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



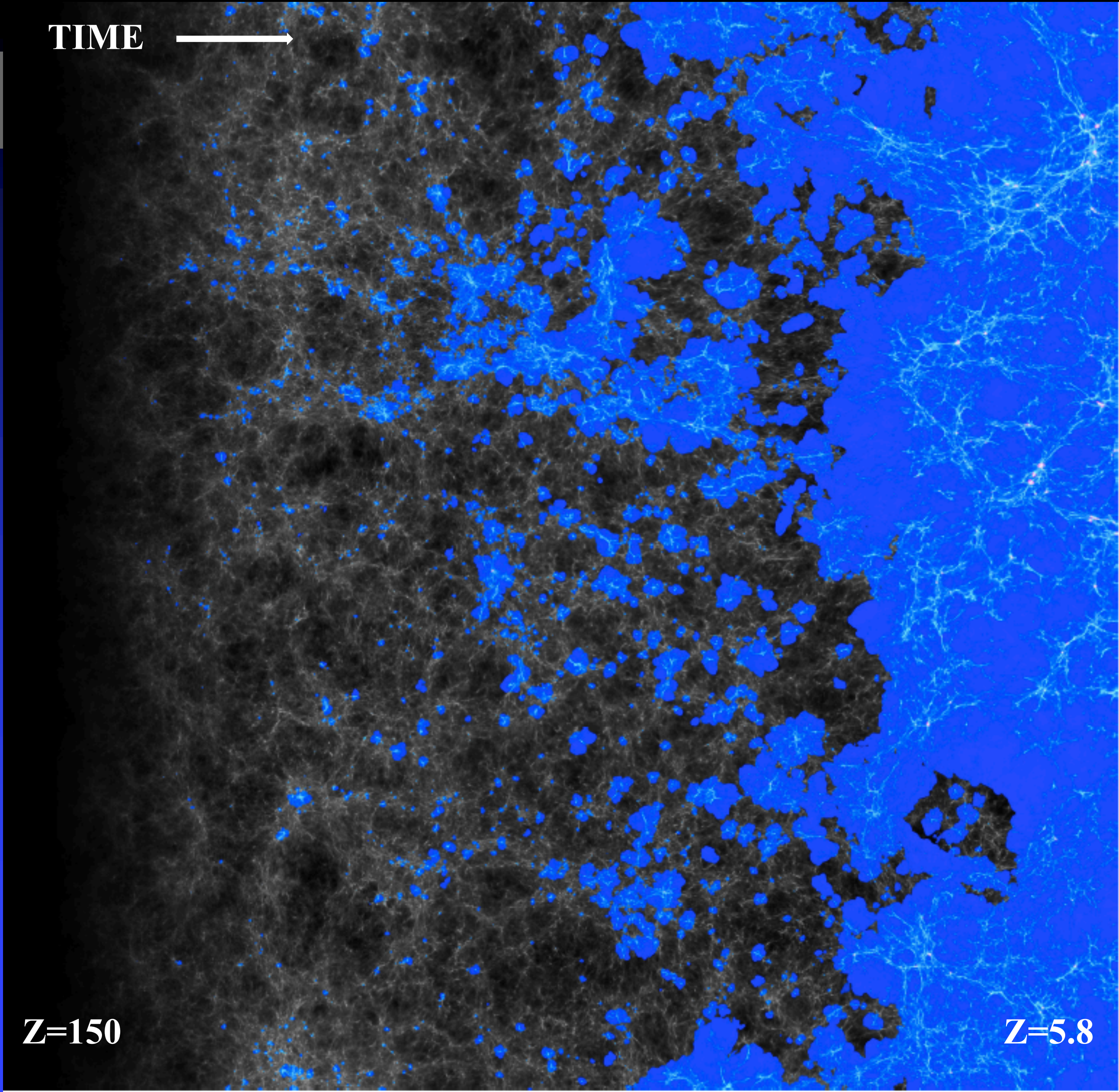
The fraction of 9 FRBs with known redshifts which would be detectable up to a redshift z. Results are shown as a solid (dot-dashed) curve for a specific fluence threshold of 1 Jy ms (0.1 Jy ms) at 500 MHz and assuming a spectral slope of α = -1.5 ($f_\nu \propto \nu^\alpha$)

Beniamini et al. 2020

Ocvick et al. (2021) courtesy of Shapiro

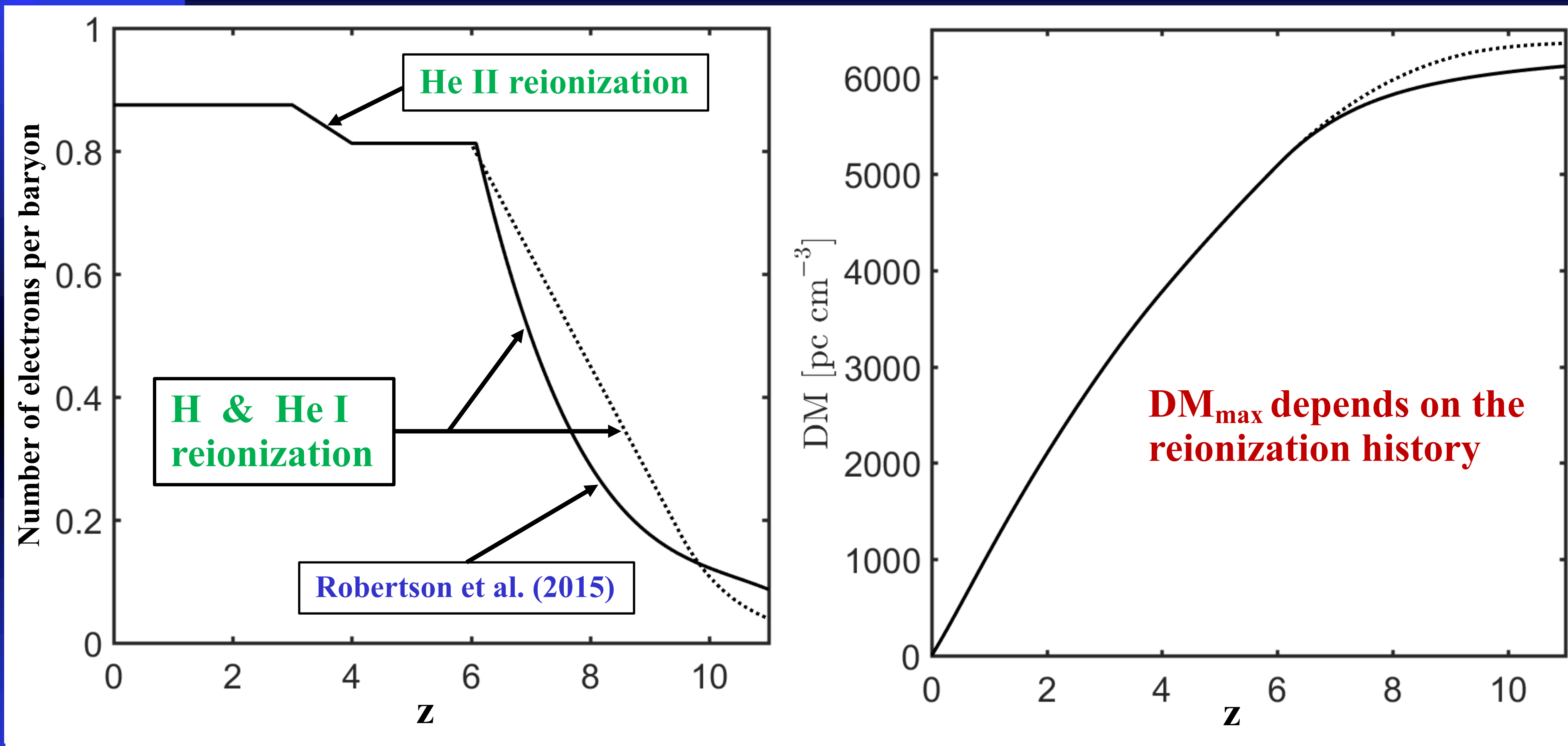
Cosmic Dawn II : Fully-Coupled Radiation-Hydrodynamics Simulation of Galaxy Formation and the Epoch of Reionization (“CoDa II”)

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.



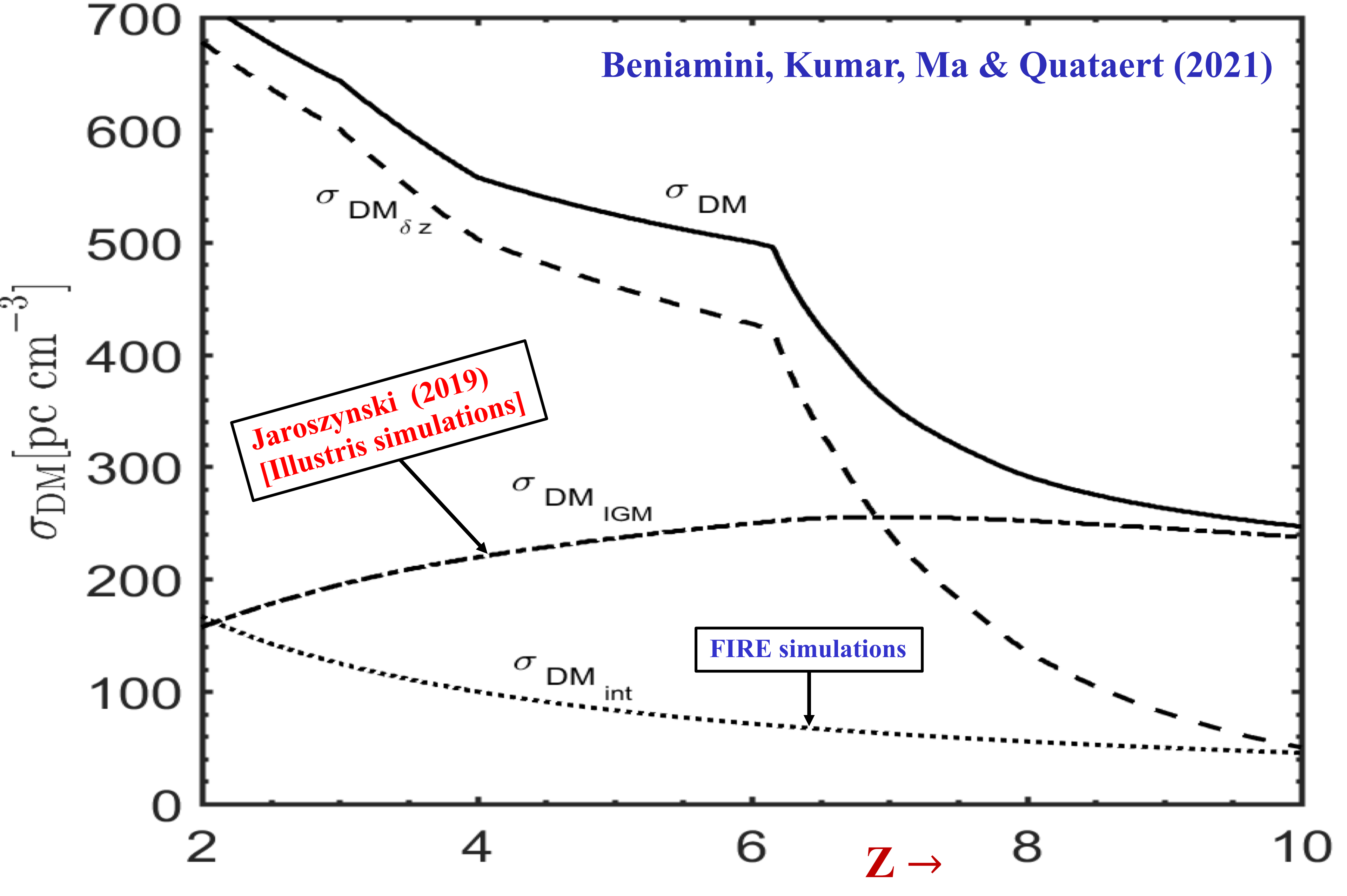
Exploring Hydrogen Reionization Epoch

Beniamini, Kumar, Ma & Quataert (2020)

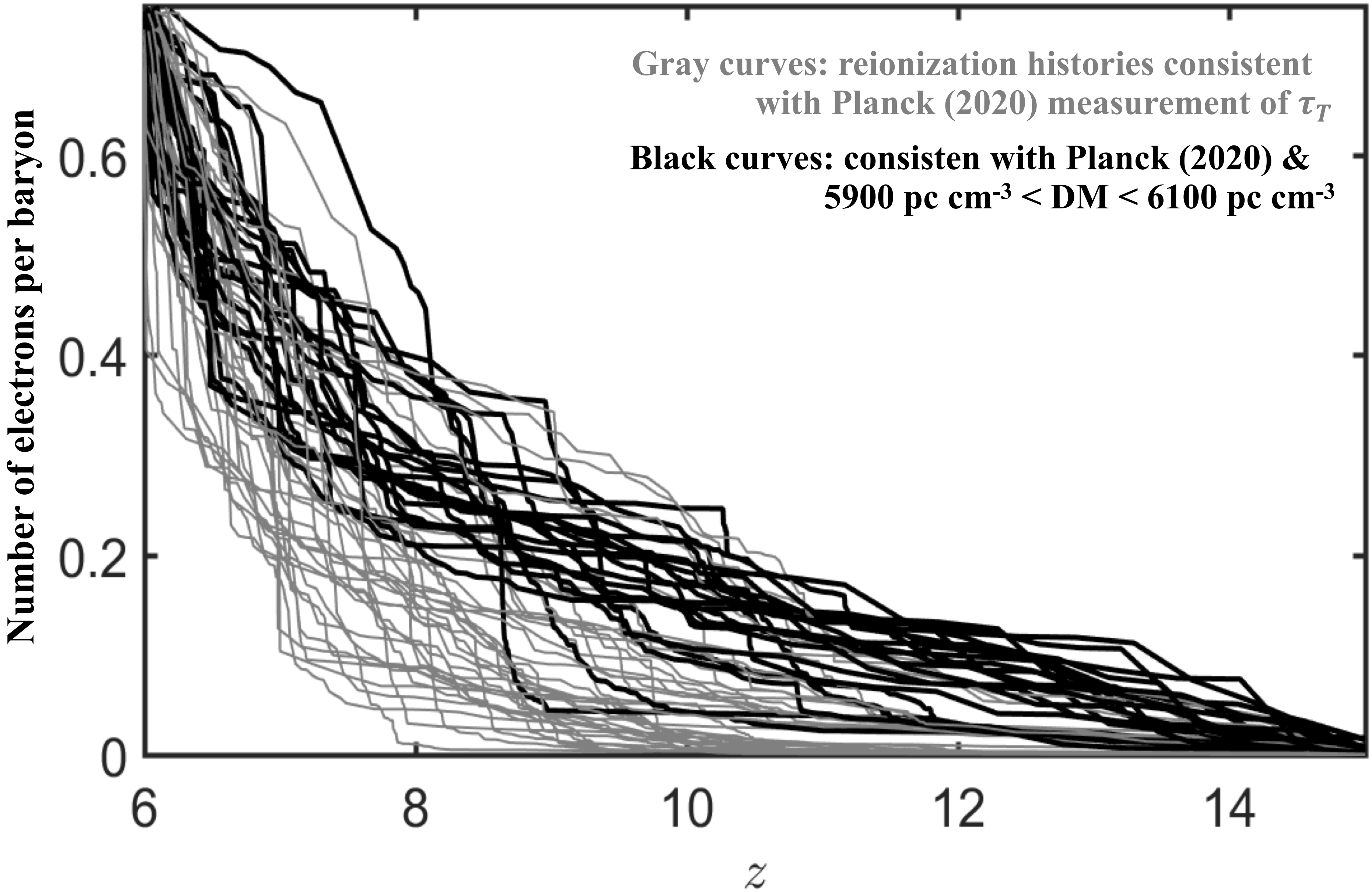


$$\Delta DM_{max} = 500\ pc\ cm^{-3} \rightarrow \Delta\tau_T \leq 0.008 \quad (better\ than\ Planck)$$

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



Beniamini, Kumar, Ma & Quataert (2020)



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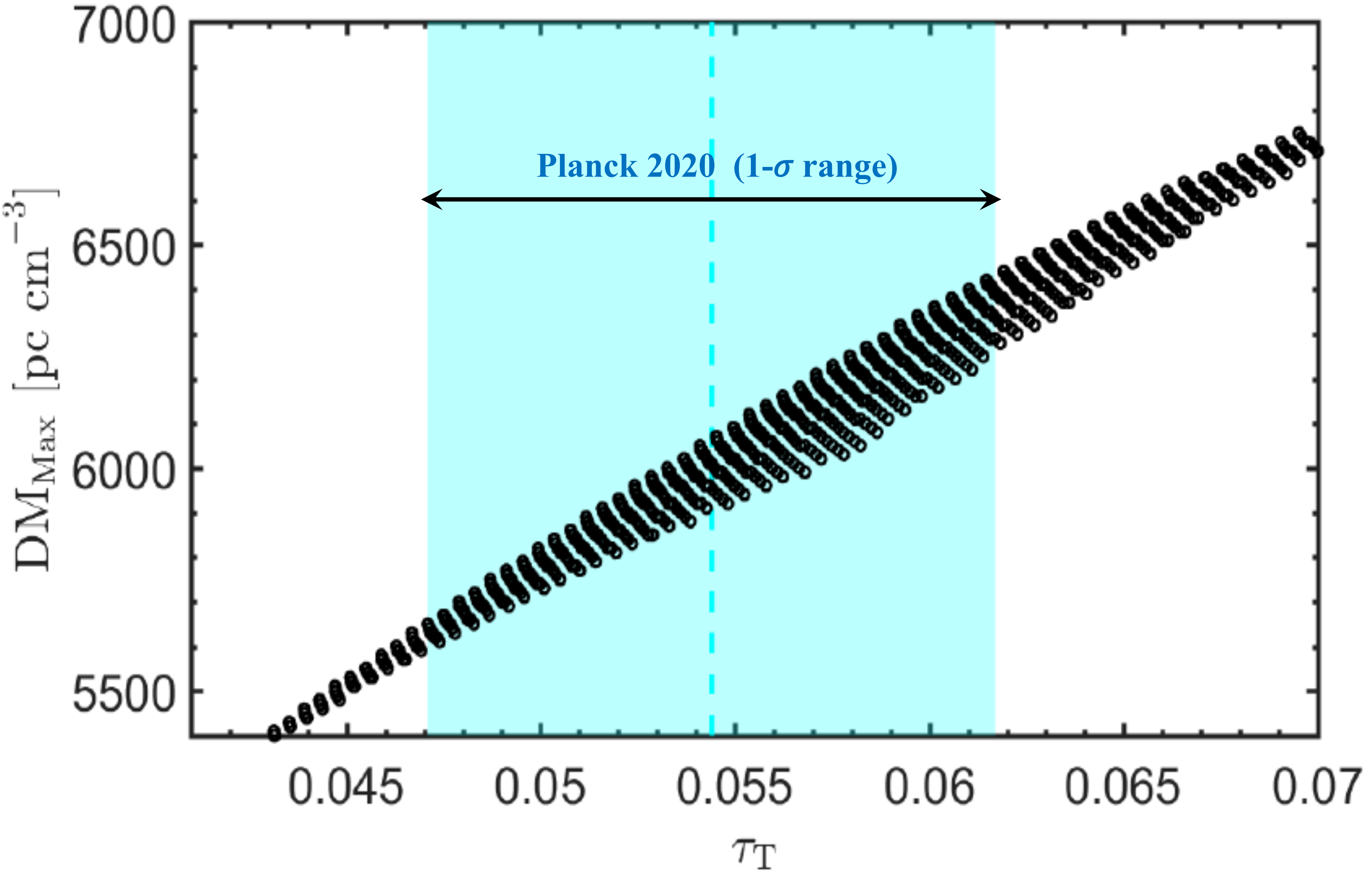

Exploring Hydrogen Reionization Epoch

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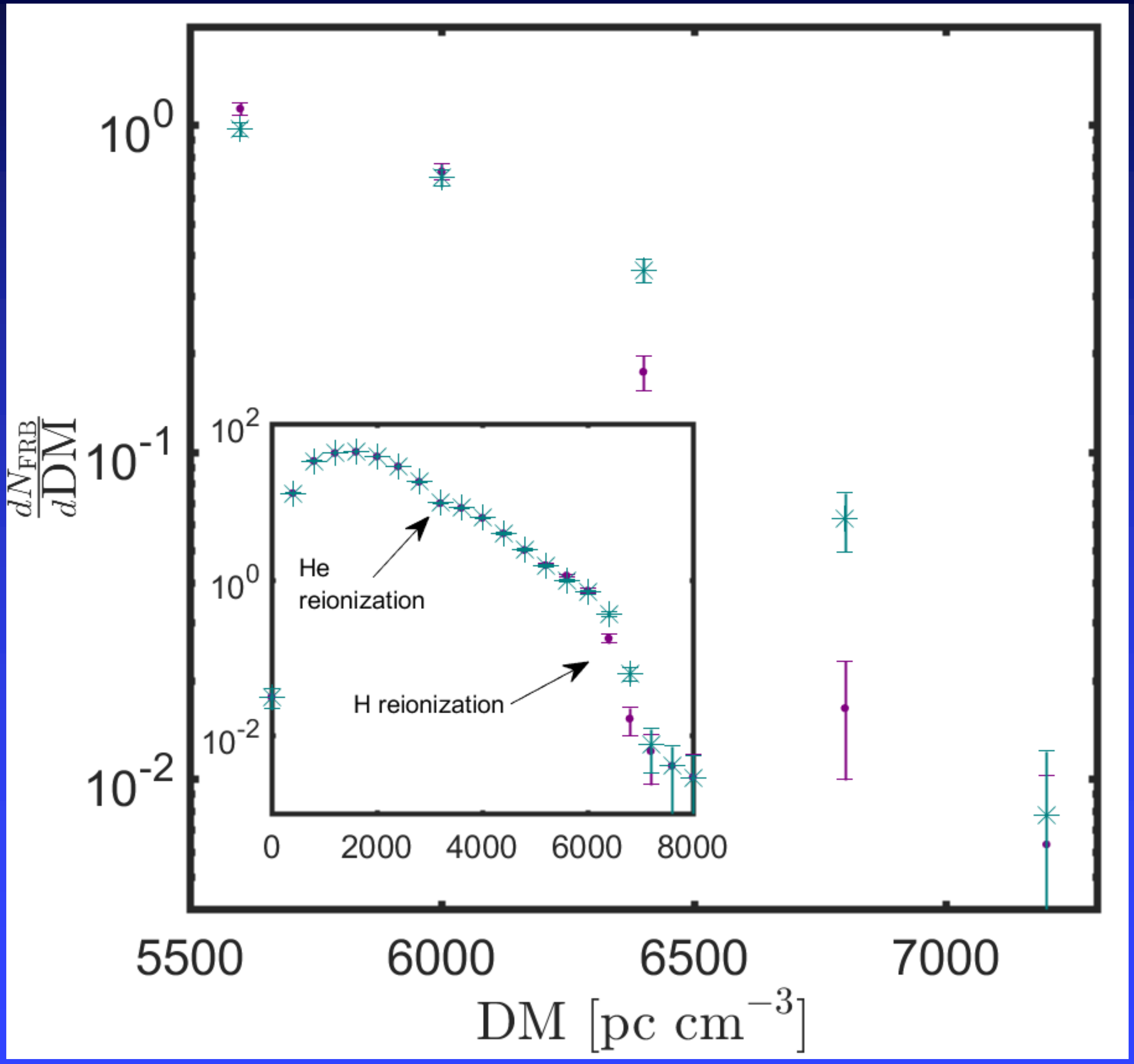

Summary

- **The physical constraints I have described are likely to guide our ultimate understanding of FRBs.**
- ***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.**