

The first CHIME/FRB catalog

Interpreting dispersion measures and scattering timescales



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Institut Spatial de McGill



McGill Space Institute

Fonds de recherche
Nature et
technologies

Québec



Image: Andre Renard

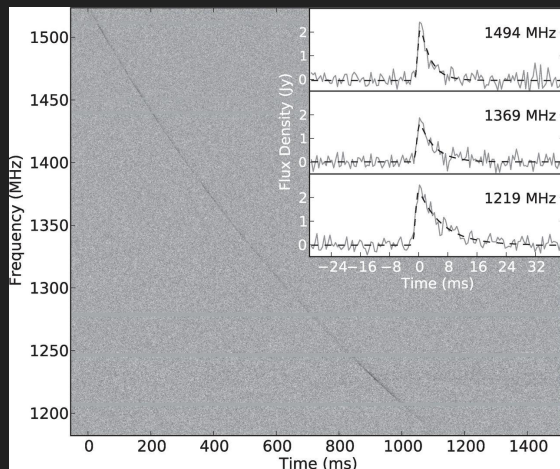
Dispersion & Scattering

Dispersion Measure

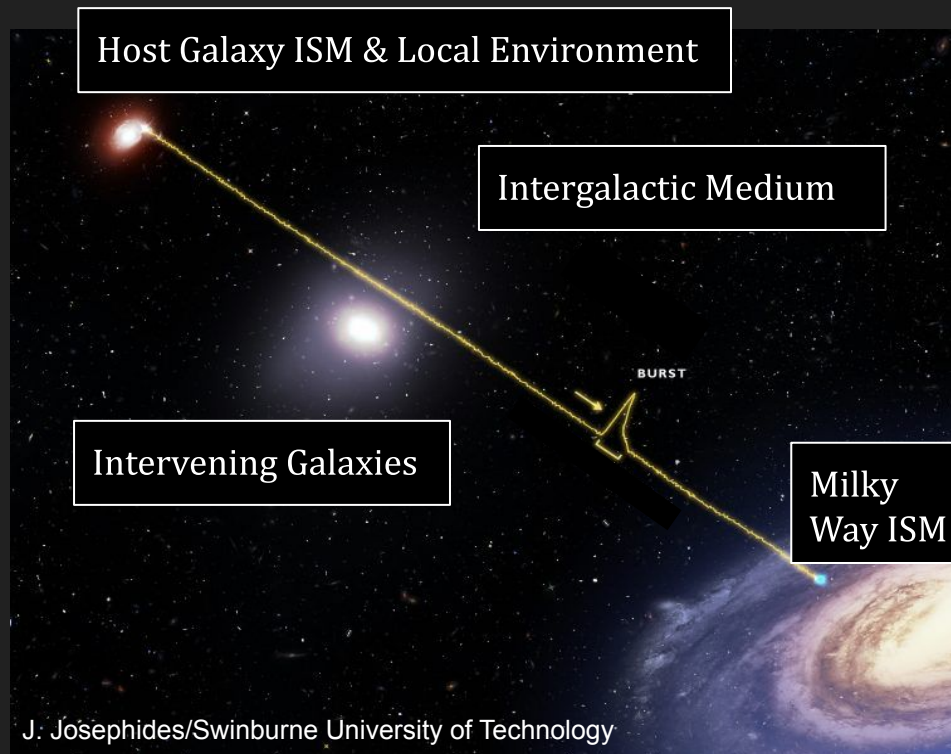
$$dDM = n_e ds$$

Scattering Measure

$$dSM = C_{SM} F n_e^2 ds$$



Thornton
et al. 2012



Milky Way

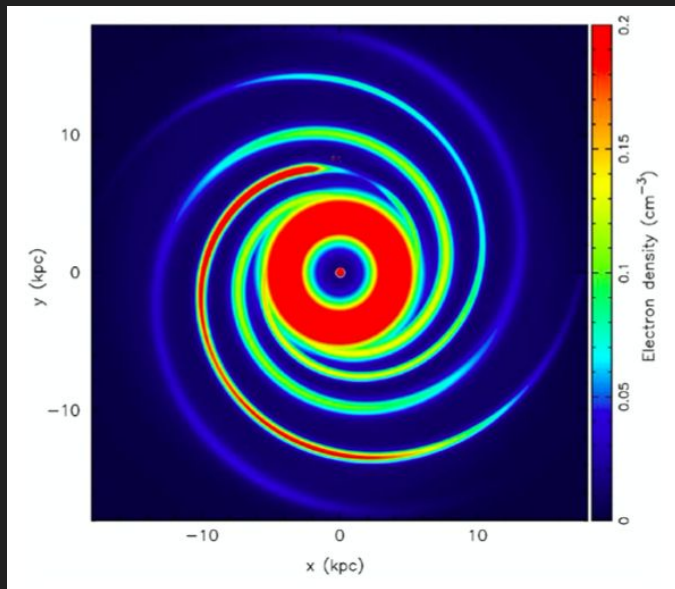
Intergalactic
medium

Intervening
Galaxies

Host Galaxy

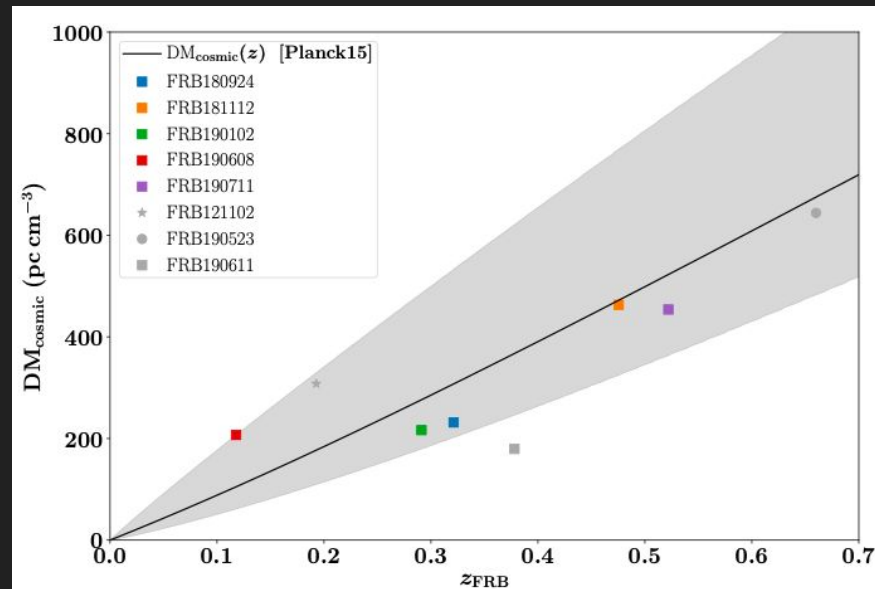
Circumburst
Environment

Models of Milky Way ISM informed by observations of pulsars



Yao et al. (2017)

FRB localizations can help determine DM_{IGM} -redshift relation



Macquart et al. (2020)

Milky Way

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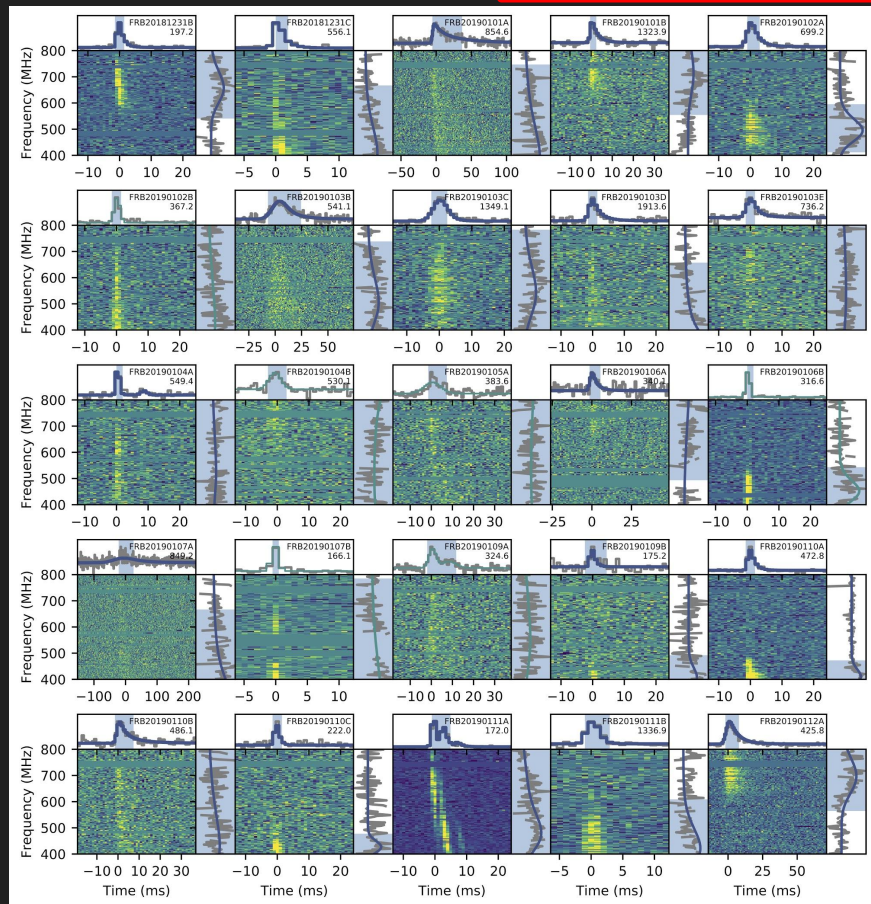
Host Galaxy

Circumburst
Environment

- Propagation effects arising in host galaxies and local environments hard to understand
 - DM and scattering budget inferred for individual FRBs
 - See, e.g., Masui et al. (2015), Simha et al. (2020)
 - But population studies require a large FRB sample detected with a uniform selection function

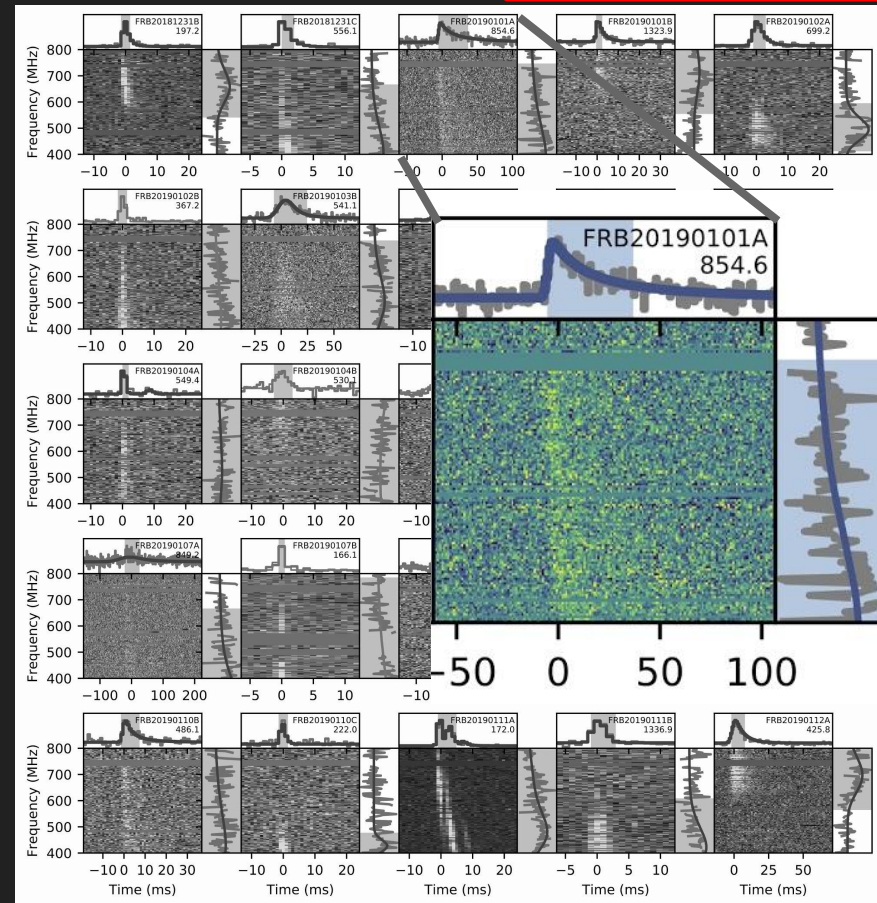
The CHIME/FRB Catalog

- 474 one-off FRBs, 61 repeat bursts
 - Detected from 2018 July 25 to 2019 July 2
- Some bursts show exponential scattering tails
- Others exhibit complex morphology
 - Multiple peaks
 - Downward drifting sub-bursts



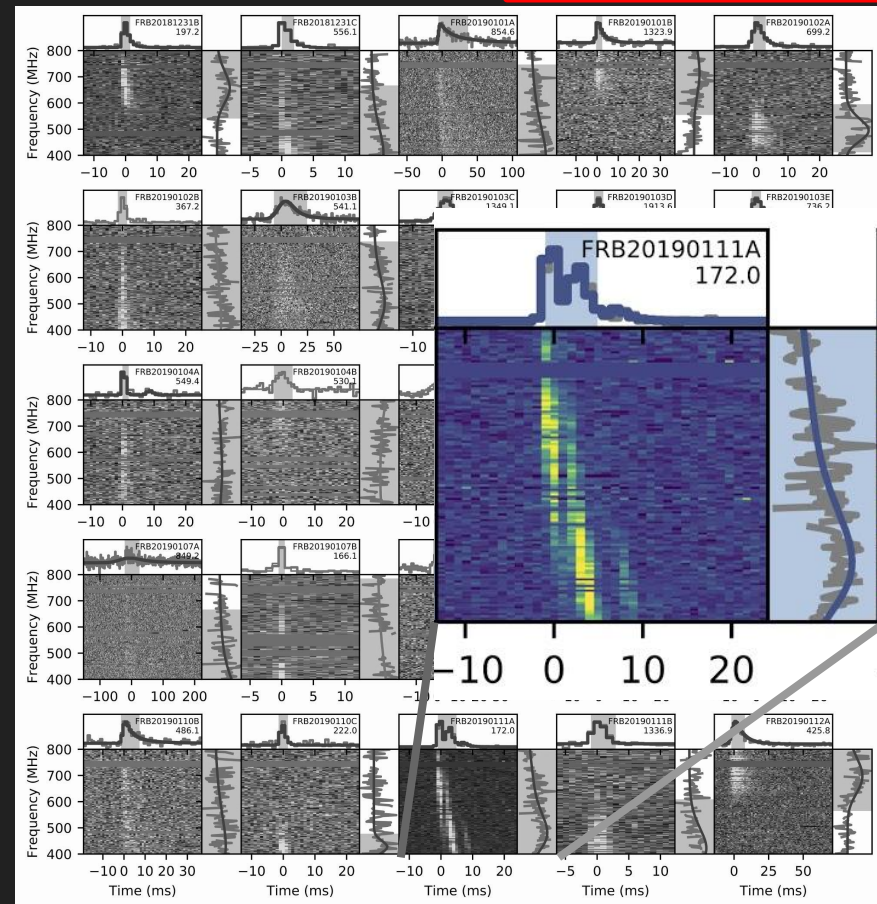
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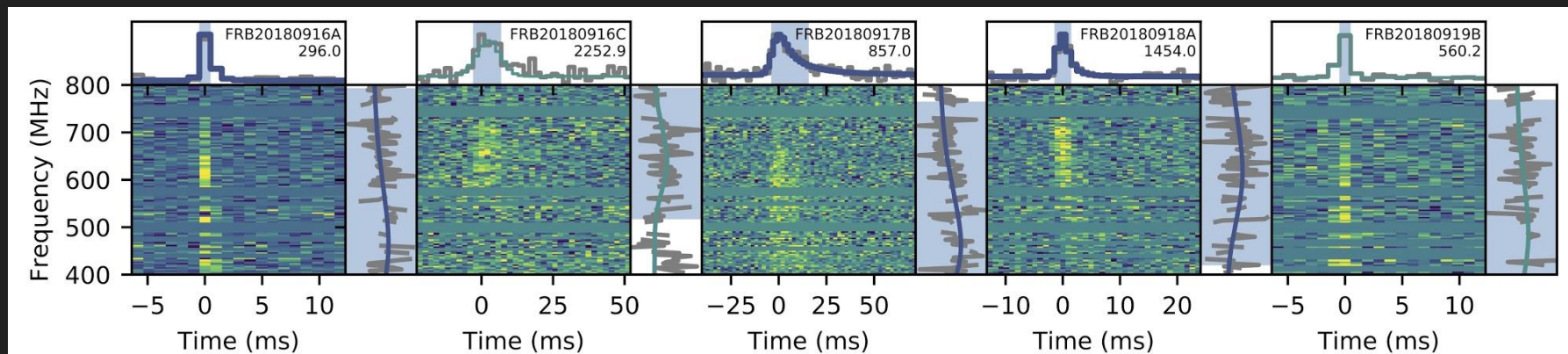
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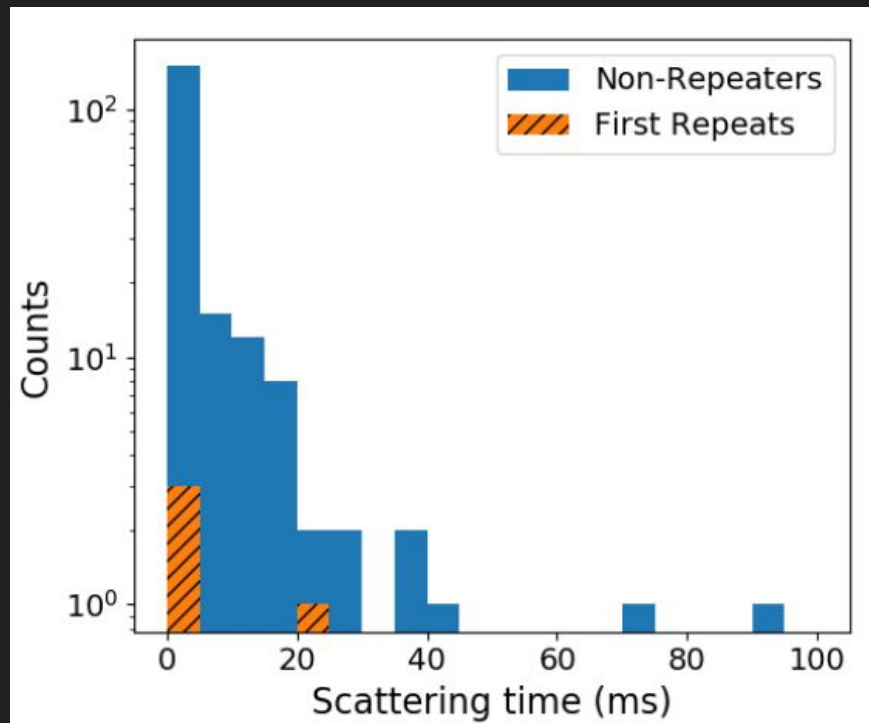
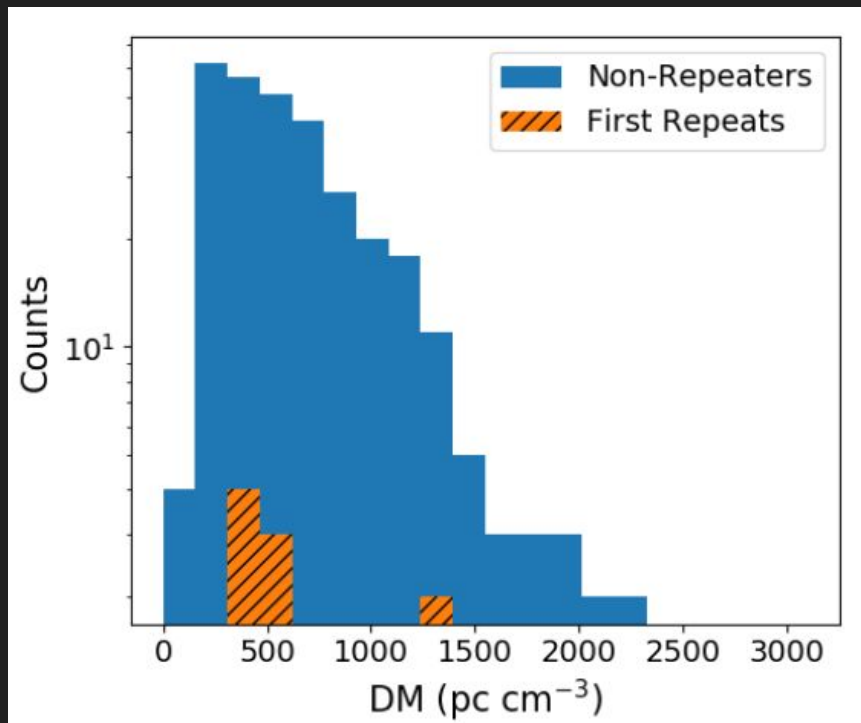
Burst Characterization

- Modelled as the convolution of a Gaussian with an exponential function (v^{-4})
 - Accounting for instrumental effects (intrachannel DM smearing and sampling time)
- Least-squares fitting routine fits for DM, scattering time, width and spectra
- Two models fit to each event (with and without scatter-broadening)
 - Best-fit statistics compared to determine if detection of scattering is significant.



Observed Distributions

Note: Not corrected for selection effects



CHIME/FRB Collaboration, submitted

Correcting for Selection Biases

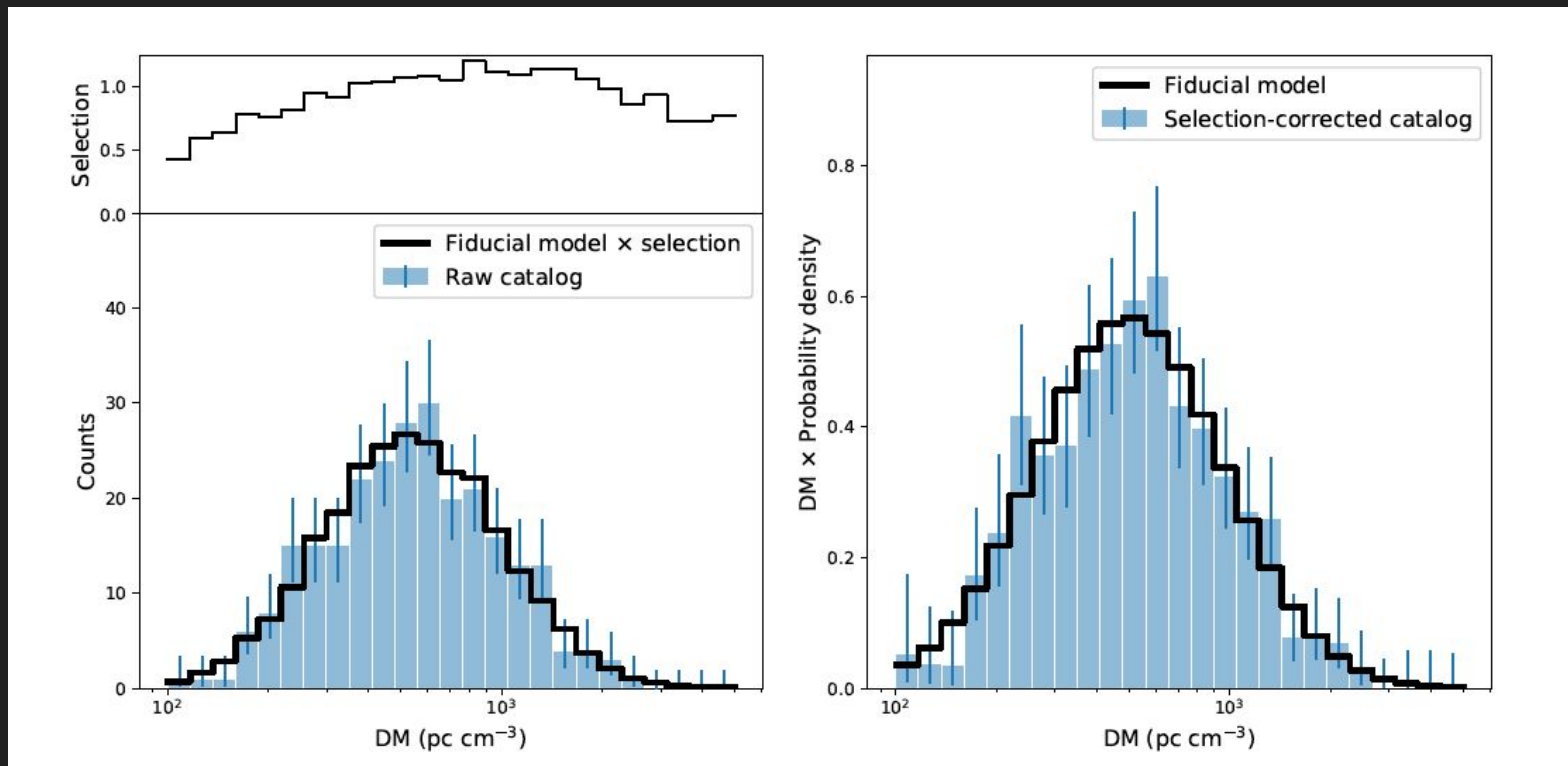
- Reduced detectability of bursts due to:
 - Intrachannel DM smearing
 - Scatter-broadening
 - Narrow pulse widths
 - ...

$$P(\text{DM}) = P_{\text{obs}}(\text{DM})s(\text{DM})^{-1}$$

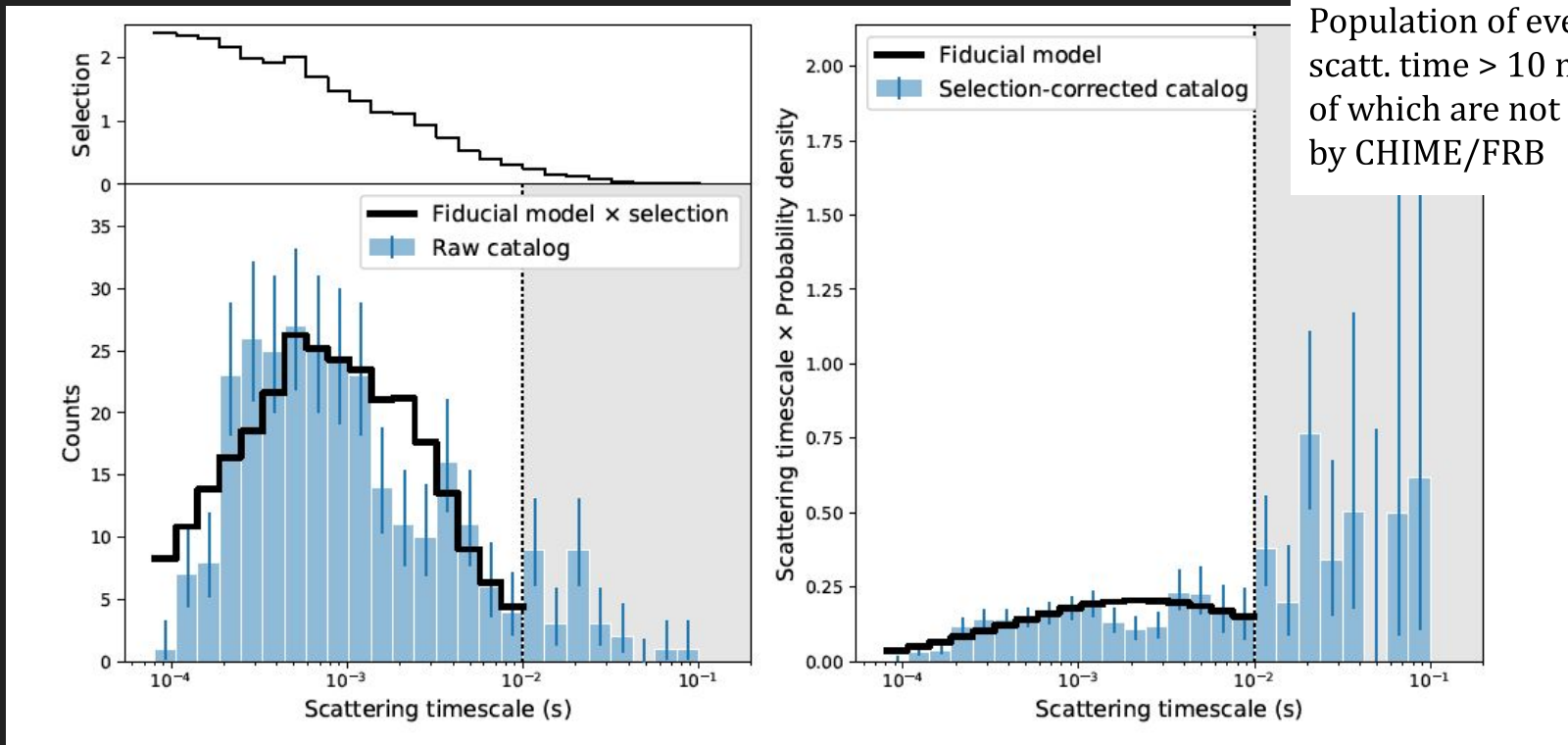
- Selection function (s) calibrated by:
 - simulating FRB signals
 - multiplying them with spectral response of primary and formed beams
 - injecting into real-time detection pipeline

$$s(\text{DM}) \propto \int_{\text{SNR}_{\text{thres}}}^{\infty} d\text{SNR} \int d\tau dw d\gamma dr dF P(\text{SNR}|F, \text{DM}, \tau, w, \gamma, r)P(F)P(\tau)P(w)P(\gamma, r),$$

Selection-Bias Corrected DM Distribution



Selection-Bias Corrected Scattering Time Distribution



Population of events with scatt. time > 10 ms, most of which are not detected by CHIME/FRB

Interpreting DM & Scattering Distributions

Intrinsic Properties

- Spatial Distribution
- Energy
- Luminosity
- ...

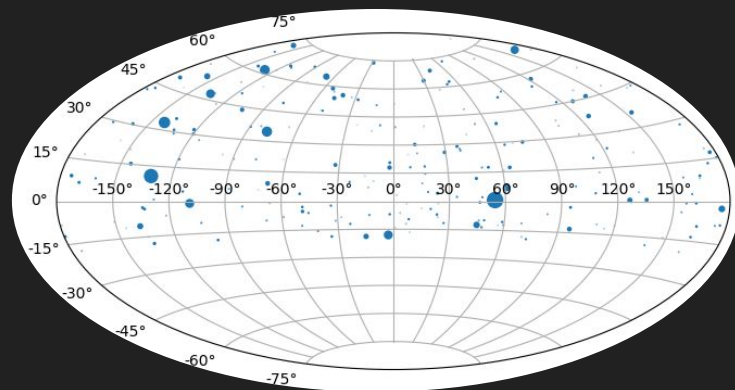
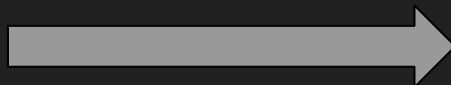
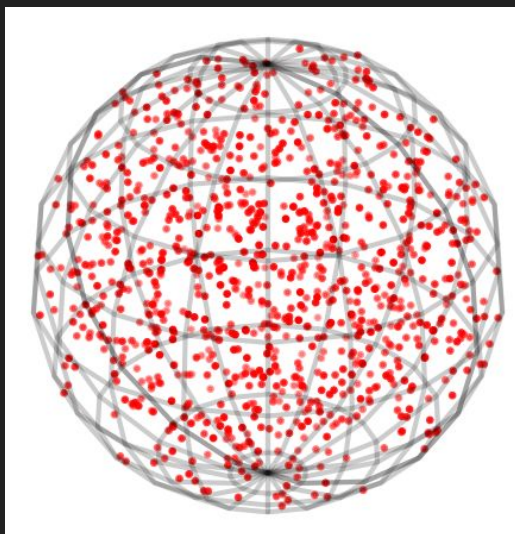
Observables

- Flux/Fluence
- Dispersion Measure
- Scattering Timescale

Propagation Effects

- Milky Way
- Intergalactic Medium
- Intervening Galaxies
- Host Galaxy
- Local Environment

Find simulated FRBs detectable with CHIME and compare properties with observed population.



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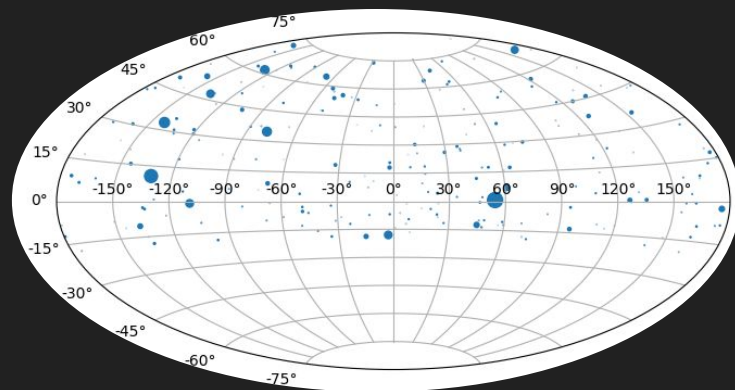
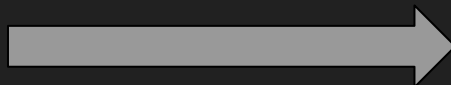
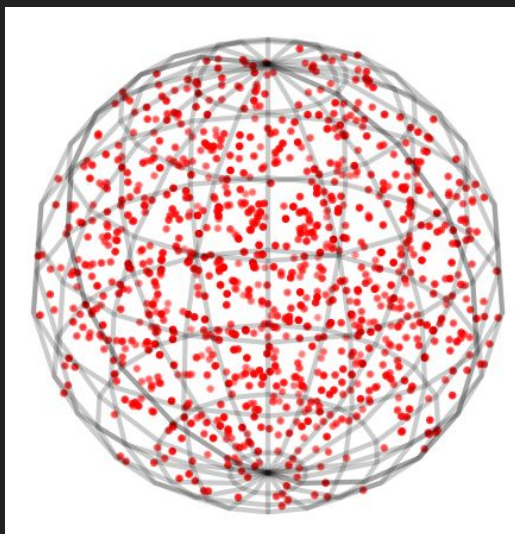
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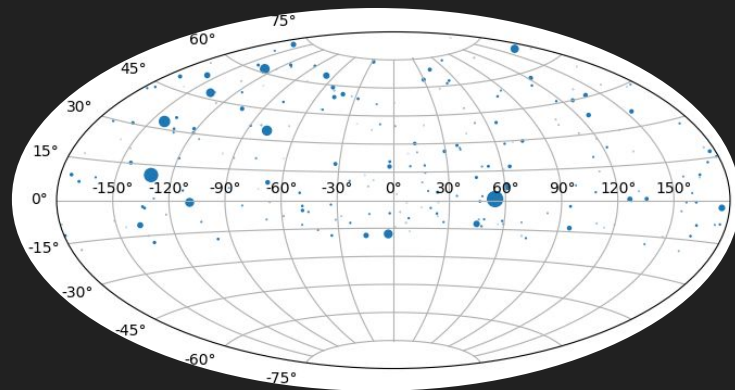
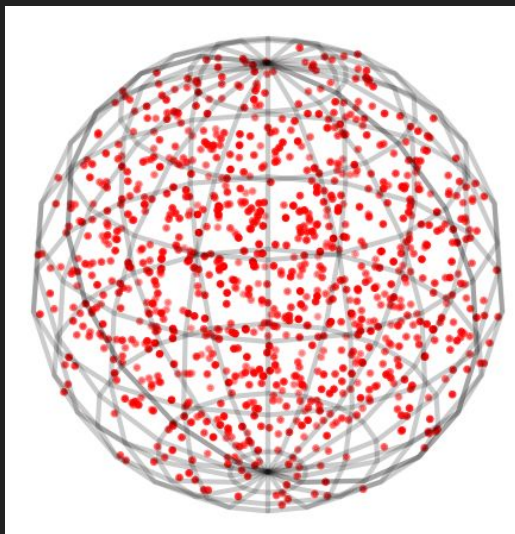
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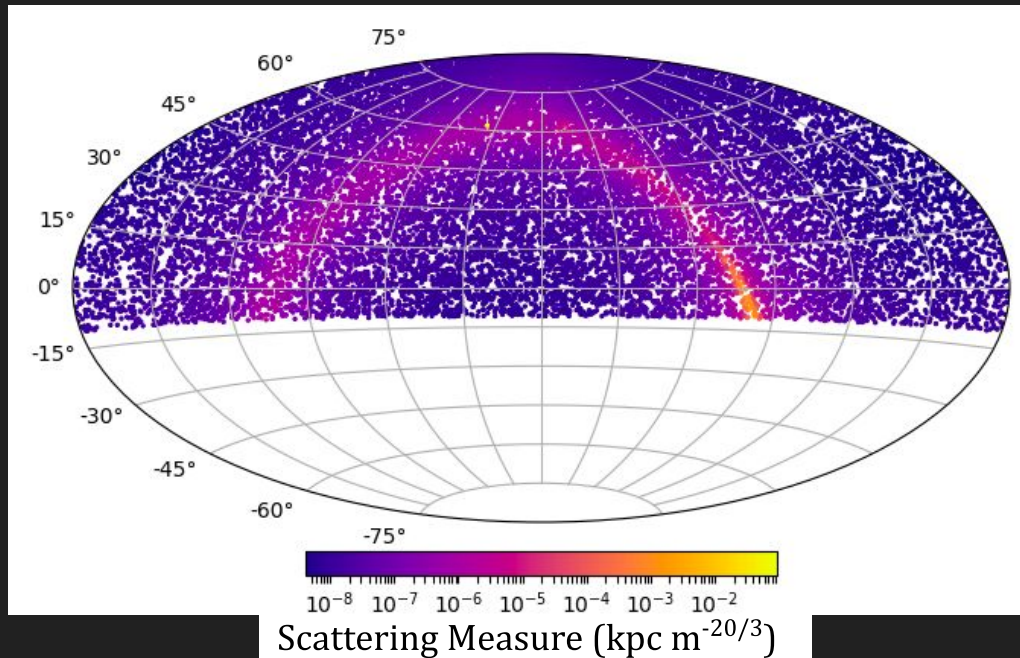
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Intervening
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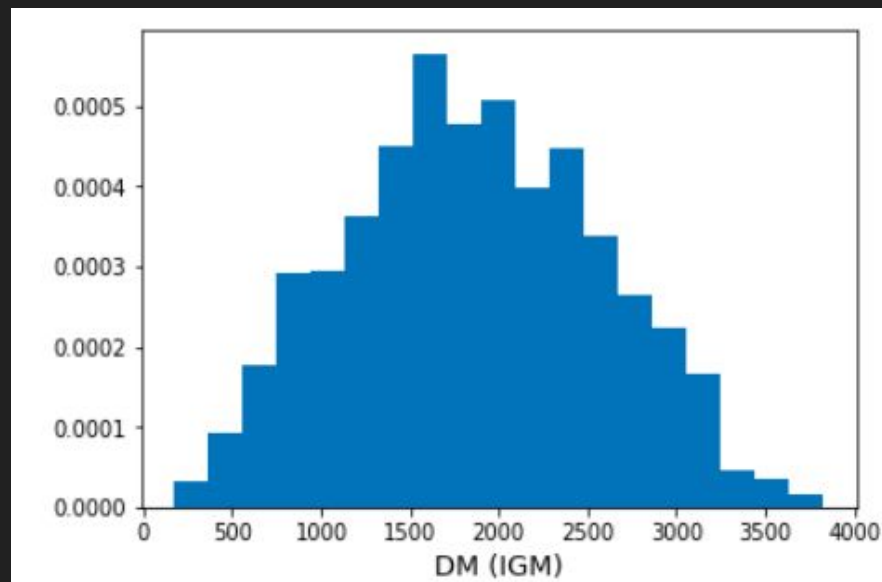
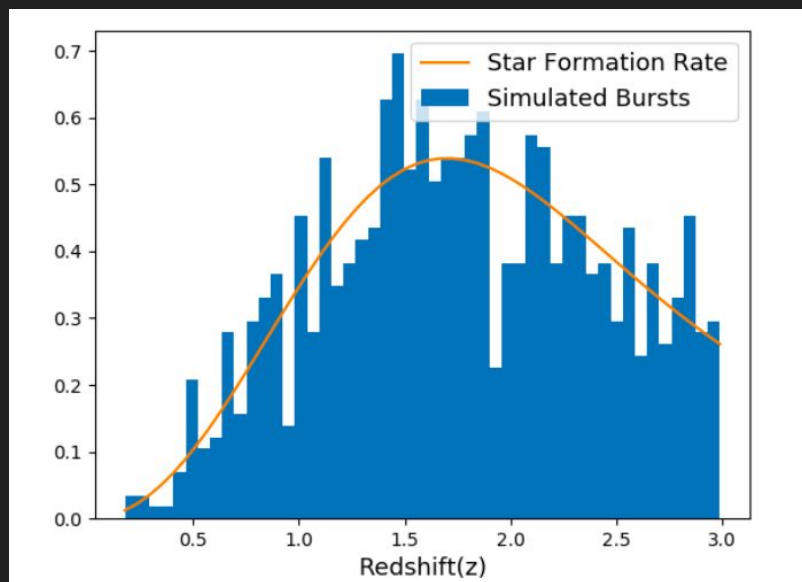
Host Galaxy

Circumburst
Environment

- Sample FRB sky locations based on CHIME/FRB exposure.
- Query NE2001 model of Galactic electron density along LOS.



- Simulate redshift distribution
 - Following star formation rate or with constant comoving number density
- Estimate DM_{IGM} using the DM-redshift relation (Macquart et al. 2020)
- Scattering from IGM < 1 ms at 600 MHz (Macquart & Koay 2013, Zhu et al. 2018)



Milky Way

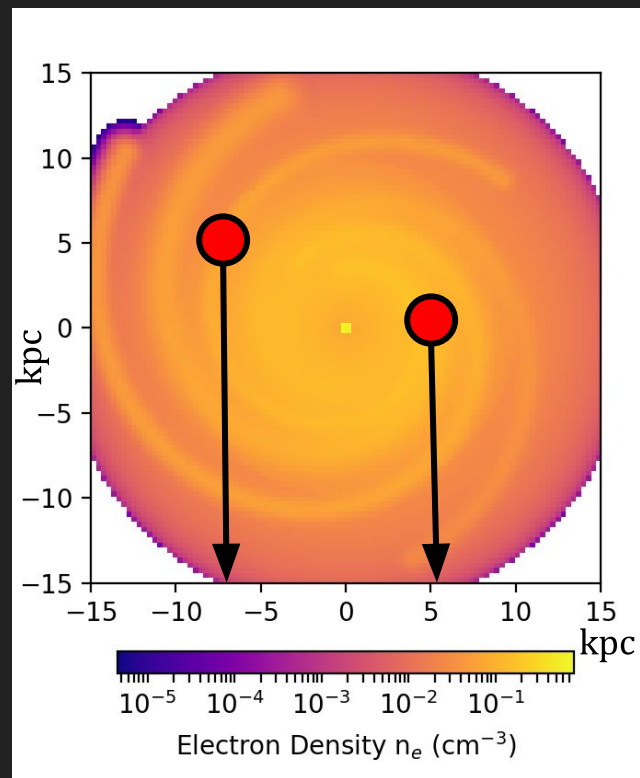
Intergalactic
medium

Intervening
Galaxies

Host Galaxy

Circumburst
Environment

- Different host galaxy types
 - Spirals (Cordes & Lazio 2002)
 - Ellipticals (Xu & Han 2015)
 - Dwarf galaxies (Yao et al. 2017)
- Simulate FRB locations within the host
 - Pulsars (Lorimer et al. 2006)
 - Magnetars (Olausen & Kaspi 2014)
 - Short GRBs (Fong & Berger 2014)
- Simulate random inclination angles
- Integrate electron density distribution from FRB location to edge of galaxy



Milky Way

Intergalactic
medium

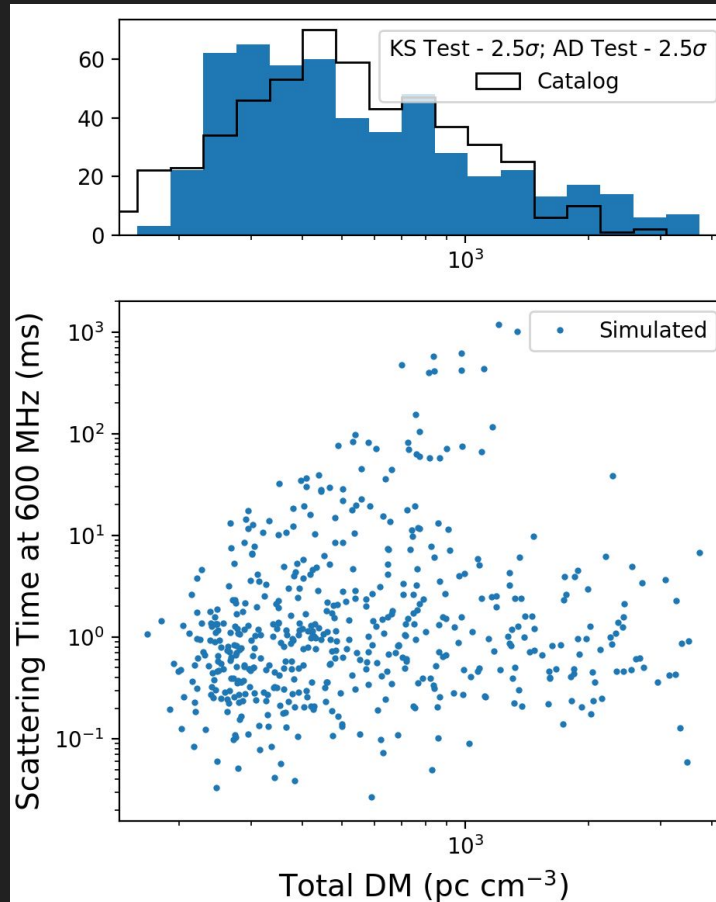
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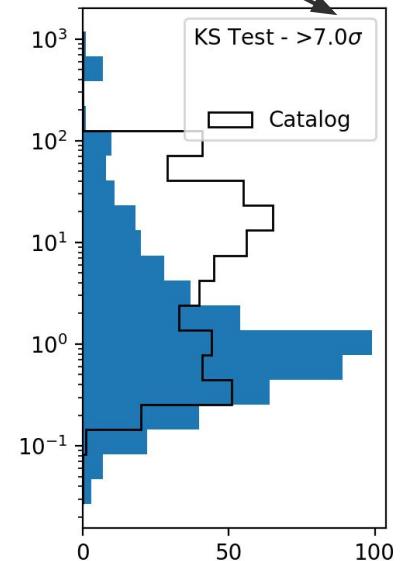
Testing Population Models

- Simulating:
 - Galactic Pulsar-like population
 - MW-type host galaxy
- Varying power-law index of intrinsic energy distribution to match catalog DMs
- Comparing simulated scattering times with catalog



PRELIMINARY

Simulated distribution
inconsistent with the
catalog



Milky Way

Intergalactic
medium

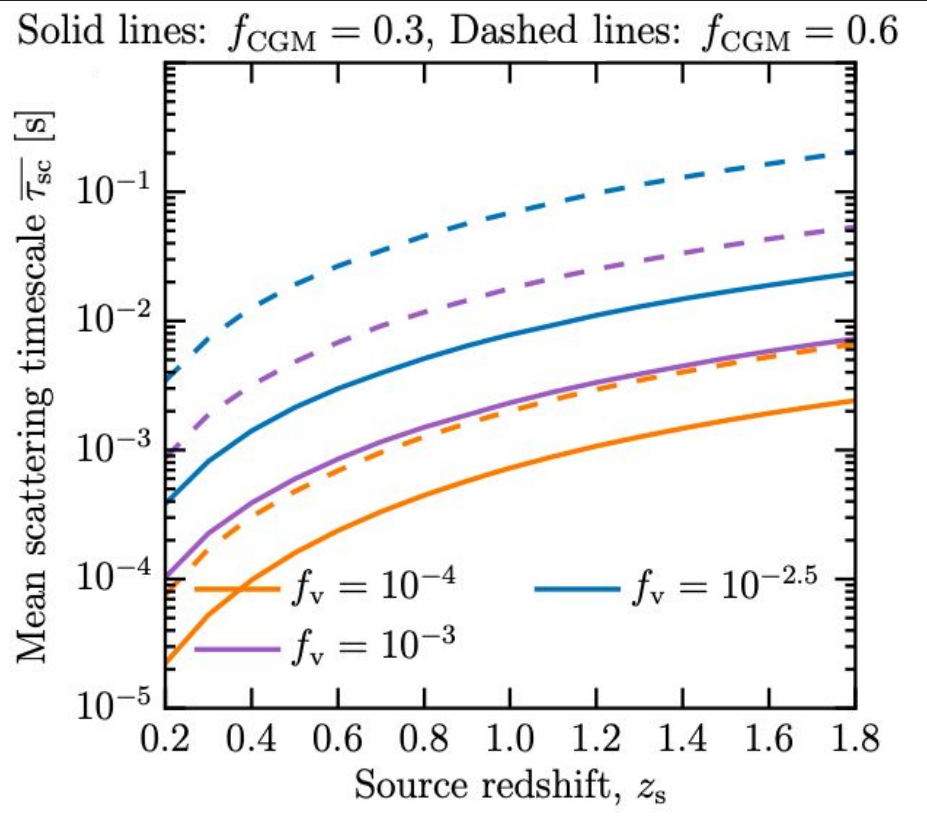
Intervening
Galaxies

Host Galaxy

Circumburst
Environment

- Scattering caused by cool ionized clumps ($T \sim 10^4$ K) in circumgalactic media ($T \sim 10^6$ K)
- Intersection probability depends on source redshift
- Scattering time depends on:
 - fraction of baryons in CGM (f_{CGM})
 - volume fraction of cool gas (f_v)

Vedantham &
Phinney 2018



Milky Way

Intergalactic
medium

Intervening
Galaxies

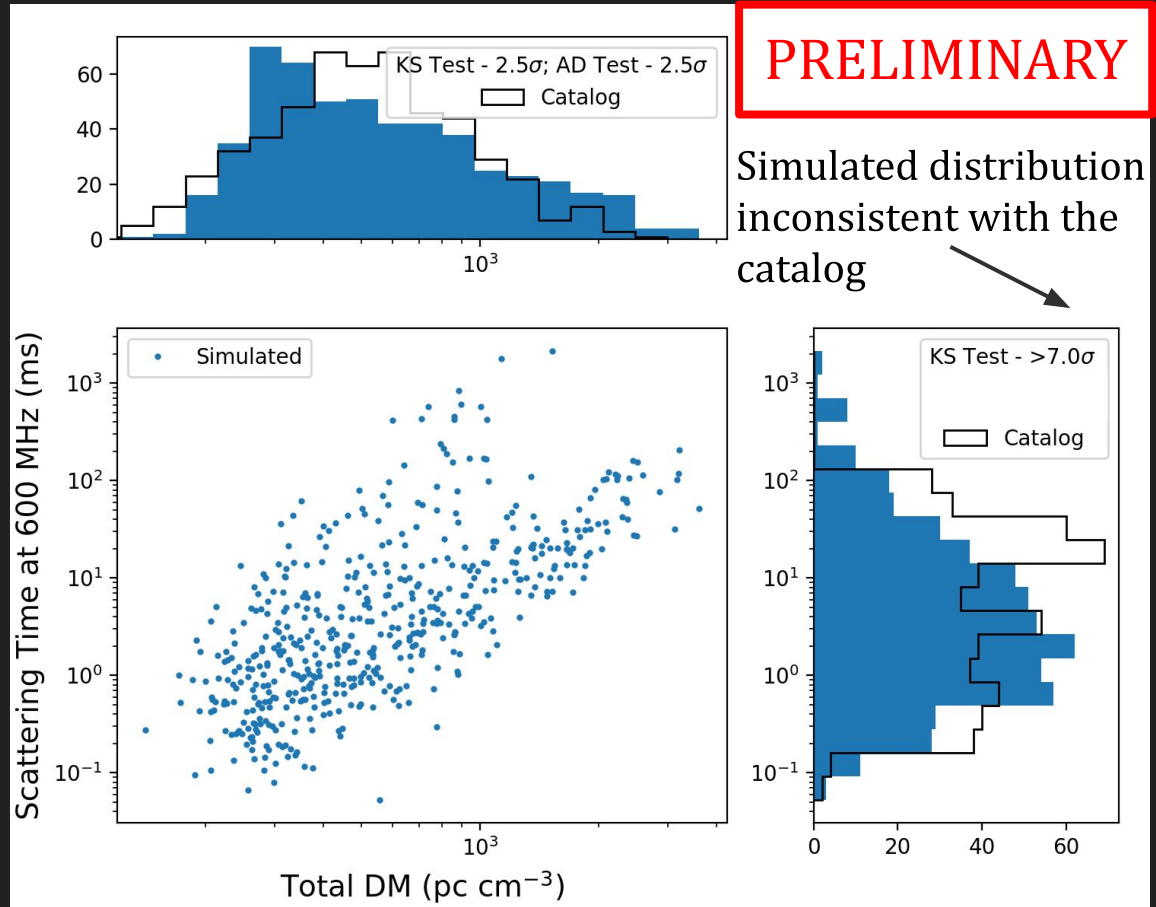
Host Galaxy

Circumburst
Environment

Testing Population Models

- Simulating:
 - Galactic Pulsar-like population
 - MW-type host galaxy
 - Scattering in CGM
 - $f_{\text{CGM}} = 0.6$
 - $f_{\text{v}} = 10^{-4}$

CGM parameters consistent with cosmological simulations (Hafen et al. 2019, Lau et al. 2016)



Milky Way

Intergalactic
medium

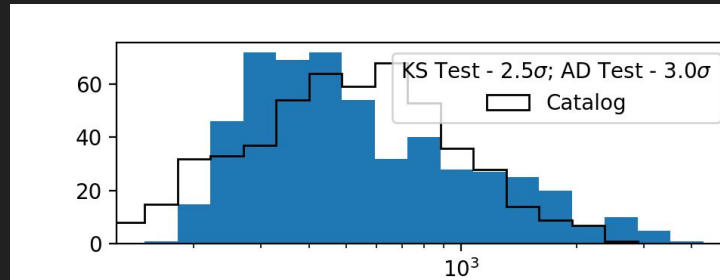
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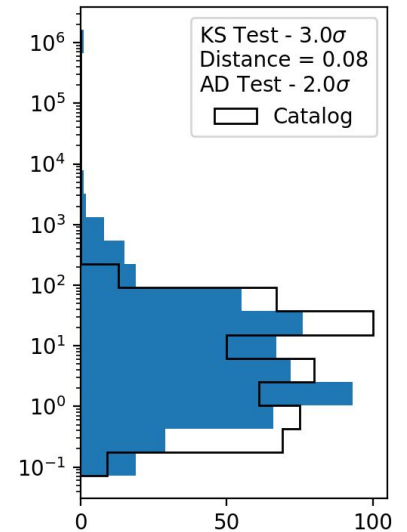
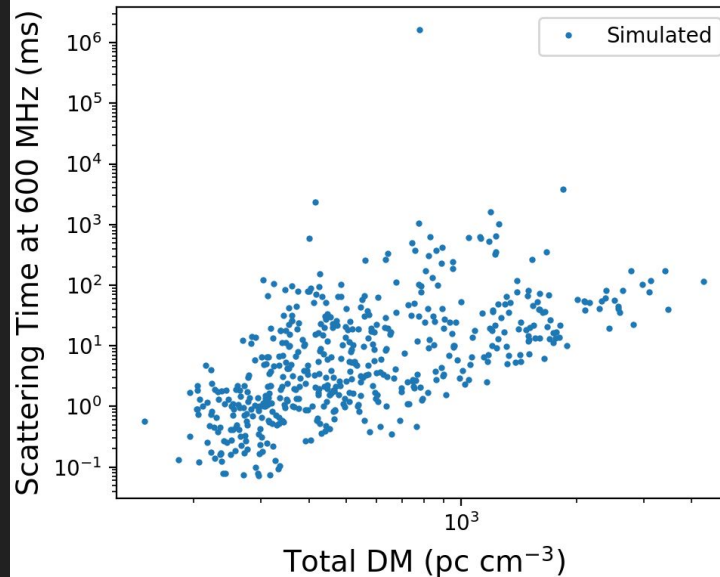
Circumburst
Environment

Testing Population Models

- Simulating:
 - Galactic Pulsar-like population
 - MW-type host galaxy
 - **Local environment**
DM of 1-100 pc/cm³
Modelled based on Galactic HII regions and supernova remnants (Cordes & Lazio 2003)
 - Scattering in CGM



PRELIMINARY



Results

FRBs in Elliptical Galaxies

- Cannot match observed scattering time distribution.

FRBs in Spiral Galaxies

- Simulations suggest scattering arising in:
 - CGM of intervening galaxies AND
 - high electron density local environments ($DM > 1$ pc/cc)
- Allowed FRB configurations
 - FRBs offset from Galactic center (short-GRB like population)
 - Galactic pulsar-like population
- Magnetar population (scale height of 30 pc) cannot match catalog scattering times.