Fast Radio Bursts, and where to find them

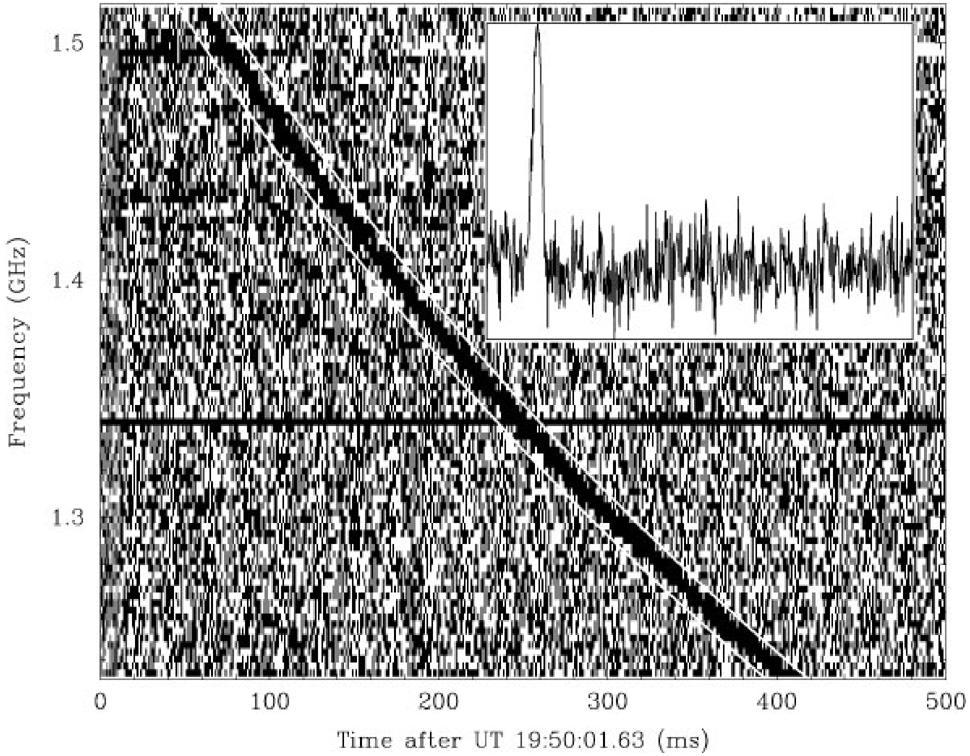
FRBs as probes of cosmic Reionization

Stefan Heimersheim – 3rd year PhD student @ University of Cambridge

In collaboration with **Nina Sartorio, Anastasia Fialkov & Duncan Lorimer**

What it takes to Measure Reionization with Fast Radio Bursts [arXiv:2107.14242]

What are Fast Radio Bursts? (FRBs)



Lorimer et al. 2007 arXiv:0709.4301

Parkes Radio Telescope (CC BY-SA Stephen West)

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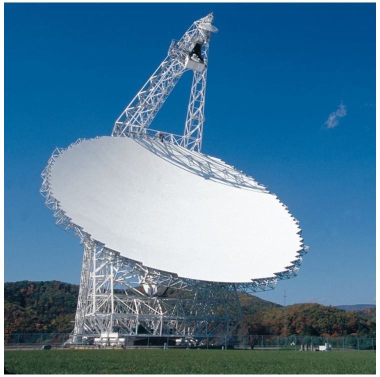
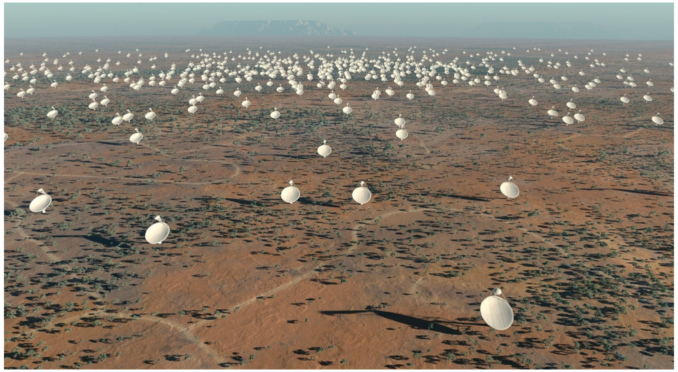
Current and future telescopes



GBT Photo: NRAO/AUI/ NSF

FAST Photo: Absolute Cosmos

ASKAP: SKA pathfinder, good localization → allows follow up redshift measurements.
Photo credit: Ant Schinkel, CSIRO (CC BY-SA)



(Future) SKA Photo credit: SPDO/TDP/DRAO/ Swinburne Astronomy Productions (CC BY)

(Past) Arecibo Photo credit: Mario Roberto Durán Ortiz (CC BY-SA)

CHIME: Canada, HI mapping, large FOV → very good for FRBs as well
Photo credit: CHIME

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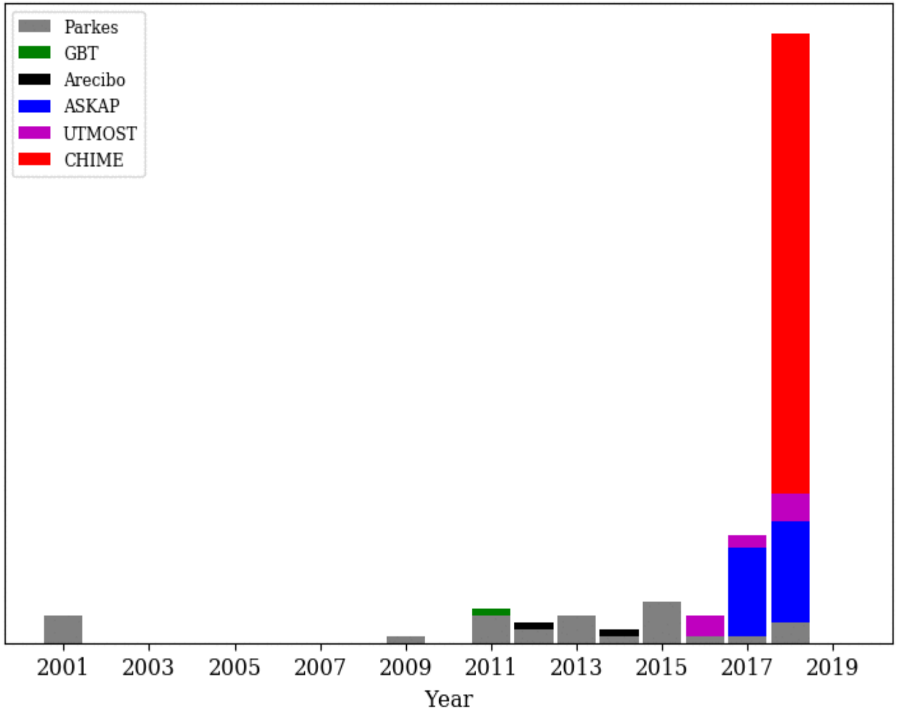
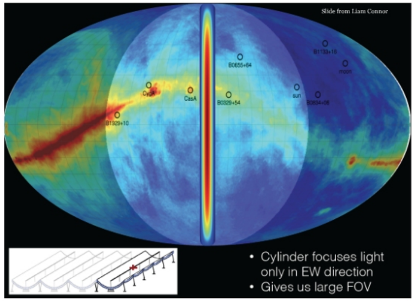
Recent FRB discoveries



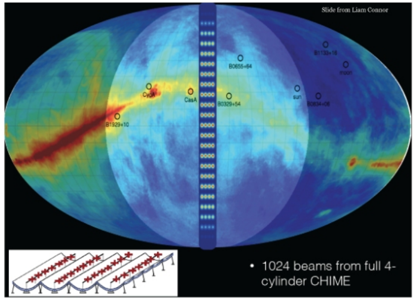
Animation by Cherry Ng, CHIME, Dunlap Institute (github.com/cherryng)

Photo credit: CHIME

CHIME: Canada, HI mapping
large field of view
→ accidental FRB machine.



primary beam



formed beams

Figures: CHIME field of view (Kendrick Smith)

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Repeating FRBs

A repeating fast radio burst

L. G. Spitler, P. Scholz, J. W. T. Hessels, S. Bogdanov, A. Brazier, F. Camilo, S. Chatterjee, J. M. Cordes, F. Crawford, J. Deneva, R. D. Ferdman, P. C. C. Freire, V. M. Kaspi, P. Lazarus, R. Lynch, E. C. Madsen, M. A. McLaughlin, C. Patel, S. M. Ransom, A. Seymour, I. H. Stairs, B. W. Stappers, J. van Leeuwen & W. W. Zhu

Nature **531**, 202–205 (2016) | Cite this article

"The Repeater"
– Arecibo (2016)

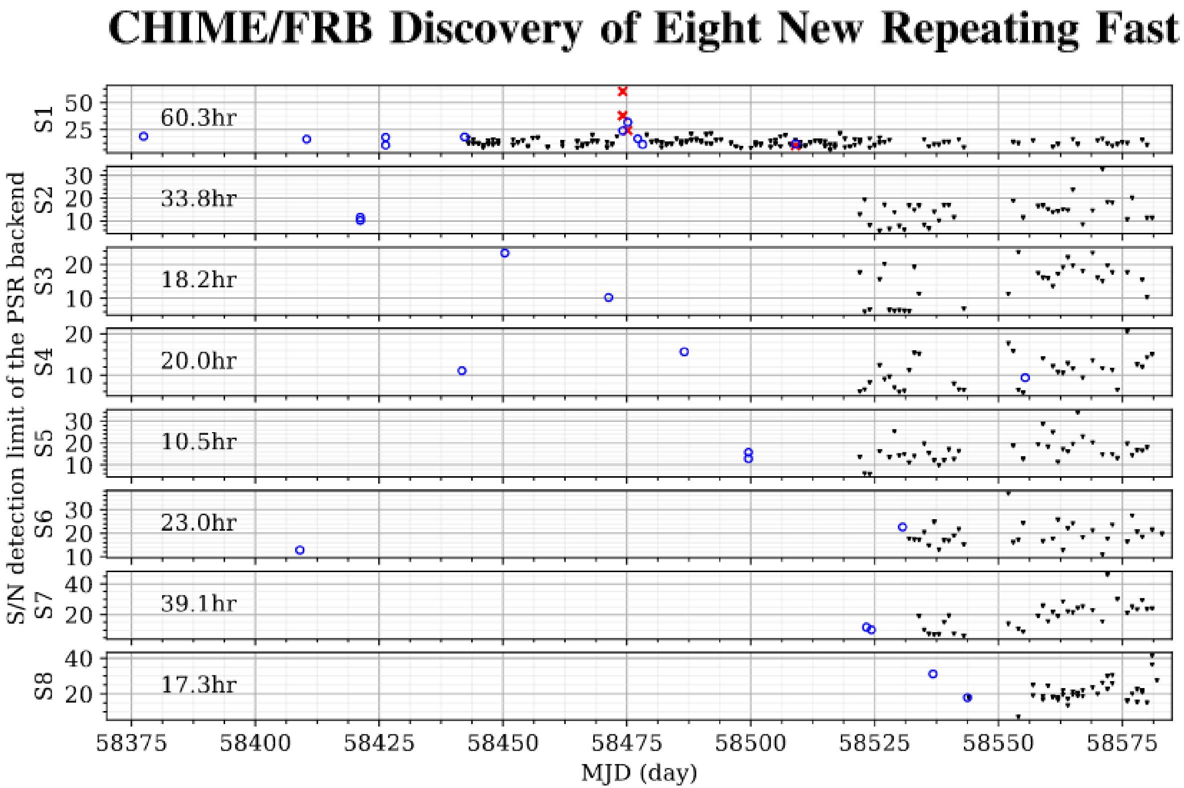
A second source of repeating fast radio bursts

The CHIME/FRB Collaboration

Nature **566**, 235–238 (2019) | Cite this article

– CHIME (2019)

Repeating FRBs!



CHIME/FRB Collaboration 2020, arXiv:2001.10275 – 8 new repeaters

- Some FRBs seem to emit repeated bursts
- Are all FRBs to-be-detected “repeaters”?
- Implications for source models?

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What is the origin of Fast Radio Bursts?

FRB source & mechanisms still uncertain!

Summary Table

Note: The low frequency radio range is defined to be from ~30 MHz to 3 GHz and the high frequency radio range is defined to be from 3 to 30 GHz.
The table is too wide to fit on all screens — Scroll right to see other columns.

Name	Category	Progenitor	Type	Energy Mechanism	Emission Mechanism	LF Radio Counterpart	HF Radio Counterpart	Microwave Counterpart	THz Counterpart	OIR Counterpart	X ray Counterpart	Gamma ray Counterpart	GW Counterpart	Neutrino Counterpart	References	Comments
NS-WD Accretion	Accretion	NS-WD	Repeat	Mag. reconnection	Curv.	Yes	--	--	--	--	--	Yes, but unlikely detectable	--	--	URL	None
AGN-KBH	AGN	AGN-KBH Interaction	Repeat	Maser	Synch.	Yes	--	--	--	Supernova	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH.
AGN-SS	AGN	AGN-Strange Star Interaction	Repeat	Electron oscillation	--	Yes	--	--	--	Thermal	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH. GW from collapse and persistent GWs from SS.
Jet-Caviton	AGN	Jet-Caviton Interaction	Both	Electron scattering	Bremsst.	Yes	Yes	--	--	--	--	Possible GRB	Yes	--	URL • URL	Persistent scintillating radio emission.
Wandering Beam	AGN	Wandering Beam	Repeat	--	Synch.	Yes	--	--	--	--	Yes	--	--	--	URL	None
NS to BH (DM-Induced)	Collapse	NS to BH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes	--	URL	None
NS to KNBH	Collapse	NS to KNBH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	Possible afterglow	Possible GRB	Yes	--	URL • URL • URL	Possible X-ray afterglow and a short/long GRB created in NS birth prior to the FRB.
NS to Quark Star	Collapse	NS to Quark Star	Single	β-decay	Synch.	Yes	--	--	--	--	Yes	Yes	Yes	--	URL	The burst is predicted to be several seconds, explainable if the de-dispersion process that stacks f
SS Crust	Collapse	Strange Star Crust	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes	--	URL	None
Axion Cloud and BH	Collision / Interaction	Superradiant Axion Cloud and BH	Repeat	Laser	Synch.	Yes	--	--	--	--	--	--	Yes	--	URL	Observational counterparts could be associated with electron-positron

Sample of FRB origin theories from
https://frbtheorycat.org
(currently via archive.org)

Plenary 4: Source Models
Plenary 4A: Thu 29/7/2021 @ 12am - 2am UT - Chair: Vikram Ravi
Plenary 4B: Thu 29/7/2021 @ 12pm - 2pm UT - Chair: Amanda Weltman

ID1: Neutron stars as sources of FRBs: from the Lorimer burst to SGR 1935
Sergei Popov, Sternberg Astronomical Institute
A: Live B: Live

ID27: Accreting X-ray Binaries as FRB Sources
Brian Metzger, Columbia University / Flatiron Institute
A: Live B: Recording

ID44: Periodic activities of repeating fast radio bursts from Be X-ray binary systems
Qiaochu Li, Nanjing University
A: Recording B: Recording

ID49: Dynamical Formation Scenarios for FRB 20200120E in a Globular Cluster
Kyle Kremer, Caltech/Carnegie Observatories
A: Live B: Recording

ID56: Dispersion and Rotation Measures from the Ejecta of Compact Binary Mergers
Zhenyin Zhao, Nanjing University
A: Recording B: Recording

ID64: Binary comb models for FRB 121102
Tomoki Wada, Yukawa Institute for Theoretical Physics
A: Live B: Recording

Plenary 5: Emission mechanism
Plenary 5A: Thu 29/7/2021 @ 8am - 10am UT - Chair: Di Li
Plenary 5B: Thu 29/7/2021 @ 8pm - 10pm UT - Chair: Maxim Lyutikov

ID59: Fast Radio Burst Breakouts from Magnetar Burst Fireballs
Kunihito Ioka, Yukawa Institute for Theoretical Physics, Kyoto University
A: Live B: Recording

ID68: Plasmoid ejection by Alfven waves and the fast radio bursts from SGR 1935+2154
Yajie Yuan, Flatiron Institute
A: Recording B: Live

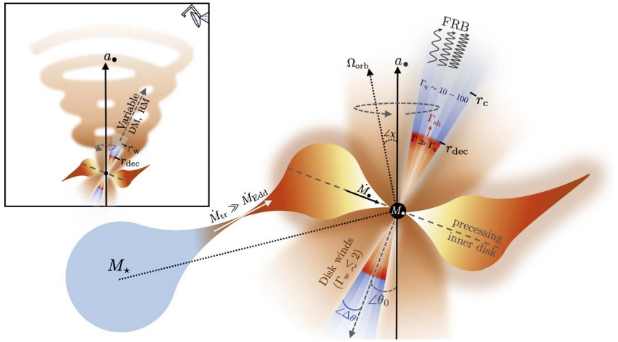
ID73: Shock Powered Coherent Radio Precursors of Neutron Star Mergers
Navin Sridhar, Columbia University
A: Live B: Recording

ID94: A coherent curvature radiation explanation of the origin of giant pulses, high-energy counterparts and the connection between giant pulses and FRBs
Alex Cooper, University of Amsterdam
A: Live B: Recording

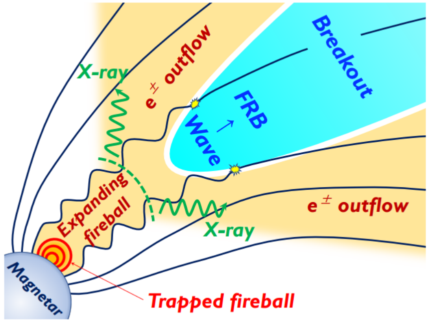
ID128: The FRB-like emission of the young energetic LMC pulsar, J0540-6919
Marisa Geyer, South African Radio Astronomy Observatory
A: Live B: Recording

ID82: Emission Properties of Periodic Fast Radio Bursts from the Motion of Magnetars
Dongzi Li, Caltech
A: Recording B: Recording

arXiv:
2102.06138



arXiv:
2008.01114



Discussion at FRB 2021:
https://sites.google.com/view/frb2021/
(talks on YouTube)

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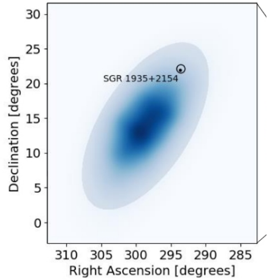
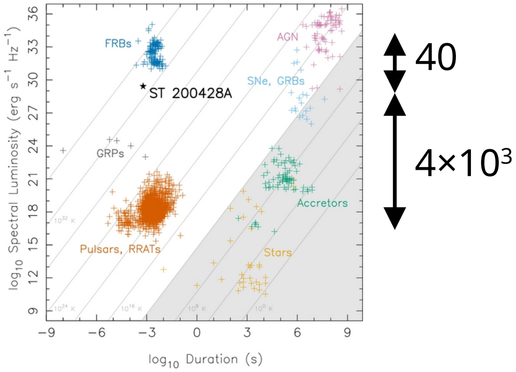
Magenetars as FRB sources?

Most promising currenly: **Magnetars**

→ “FRB” from Magnetar SGR 1935+2154





Bochenek et al. 2020, arXiv:2005.10828

Observed by STARE2 + CHIME (**radio**),
Swift Burst Alert Telescope, INTEGRAL, Konus-WIND, Insight-HXMT (**X-ray**, space)

Soft gamma-ray repeaters (SGRs), already proposed by e.g. Popov & Postnov 2007 (arXiv:0710.2006), and recently Metzger et al. 2019 (arXiv:1902.01866)

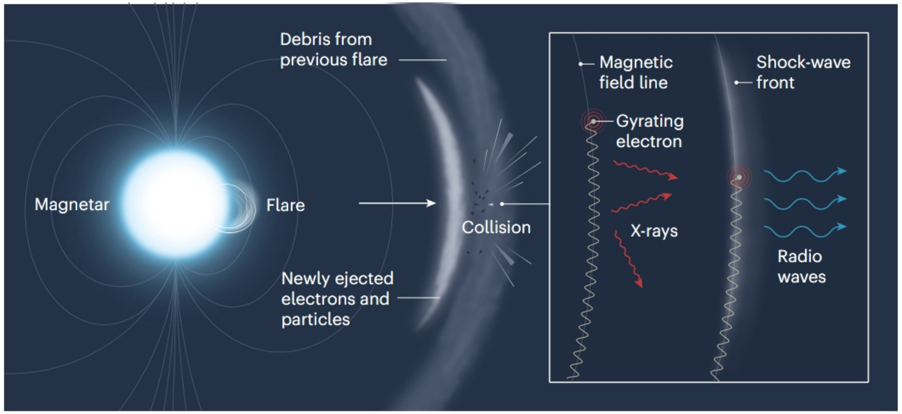


Figure 1 | A potential mechanism for the formation of fast radio bursts. A bright, millisecond-long burst of radio waves, known as a fast radio burst (FRB), has been detected[1–3] coming from a highly magnetized stellar remnant (a magnetar) in our Galaxy. The radio waves were accompanied by X-ray emissions[4–6]. One possible mechanism[9,10] for the formation of such an FRB is that the magnetar produces a submillisecond-long flare of electrons and other charged particles, which collides with particles that had been emitted from previous flares (note that the collision occurs a great distance away from the magnetar; this distance is not shown to scale). The collision generates an outward-moving shock front, which in turn produces huge magnetic fields. Electrons gyrate around the magnetic field lines, and thereby emit a burst of radio waves. The shock wave also heats the electrons, which causes them to emit X-rays.

Amanda Weltman & Anthony Walters, Nature | Vol 587 | 5 November 2020

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Properties of FRBs

FRB Localization (approx)

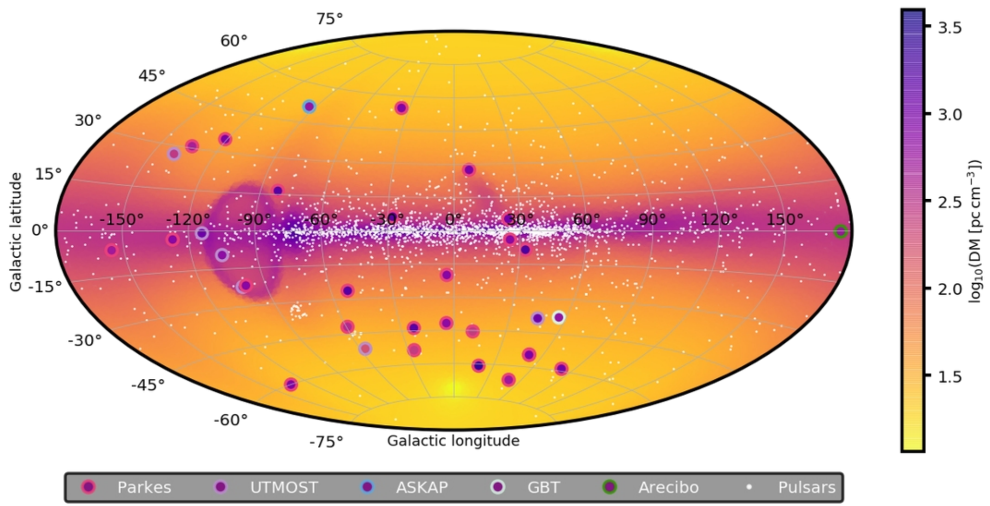
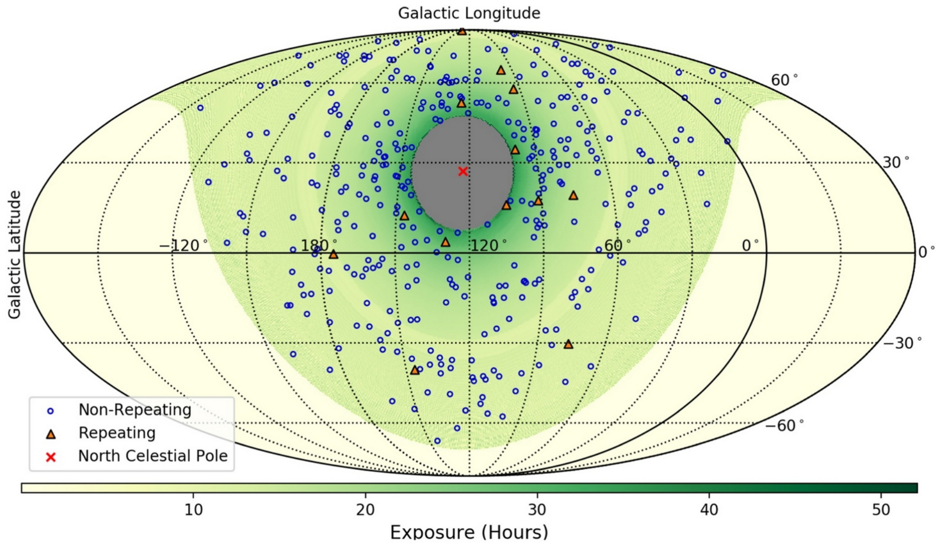


Figure: MeerTRAP, FRB & Pulsar locations (https://www.meertrap.org/science-goals/fast-radio-bursts/)



FRBs in CHIME/FRB Catalog 1 (arXiv:2106.04352)

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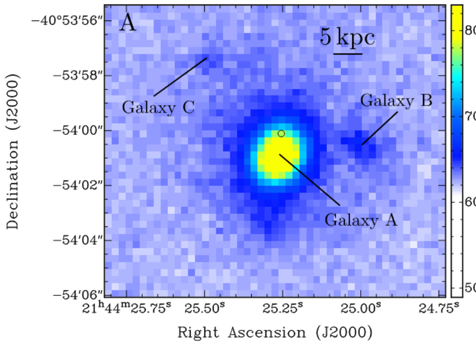
FRB Localization (precise + redshift)

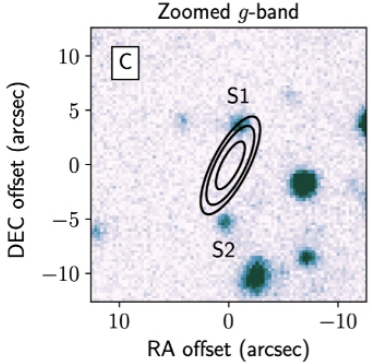
FRB	Telescope	Width	$Redshift_{host}$
FRB190523	DSA-10	0.42	0.66
FRB190711	ASKAP	6.5	0.522
FRB181112	ASKAP	2.1	0.4755
FRB190611	ASKAP	2	0.378
FRB180924	ASKAP	1.3	0.3214
FRB190102	ASKAP	1.7	0.291
FRB121102	arecibo	3	0.19273
FRB190608	ASKAP	6	0.1178
FRB180916.J0158+65	CHIME/FRB	0.87	0.0337

non-repeating

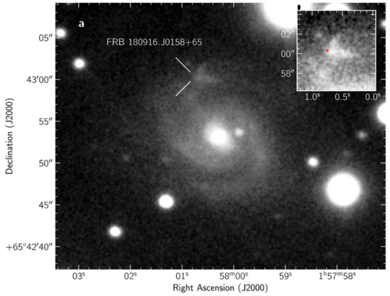
All localized FRBs from https://www.frbcat.org/



FRB 180924 by ASKAP, follow-up by VLT (arXiv:1906.11476)



FRB 121102 by DSA-10, follow-up by VLA (arXiv:1701.01098)



FRB 180916 by CHIME, follow-up with Europ. VLBI Net. (arXiv:2001.02222)

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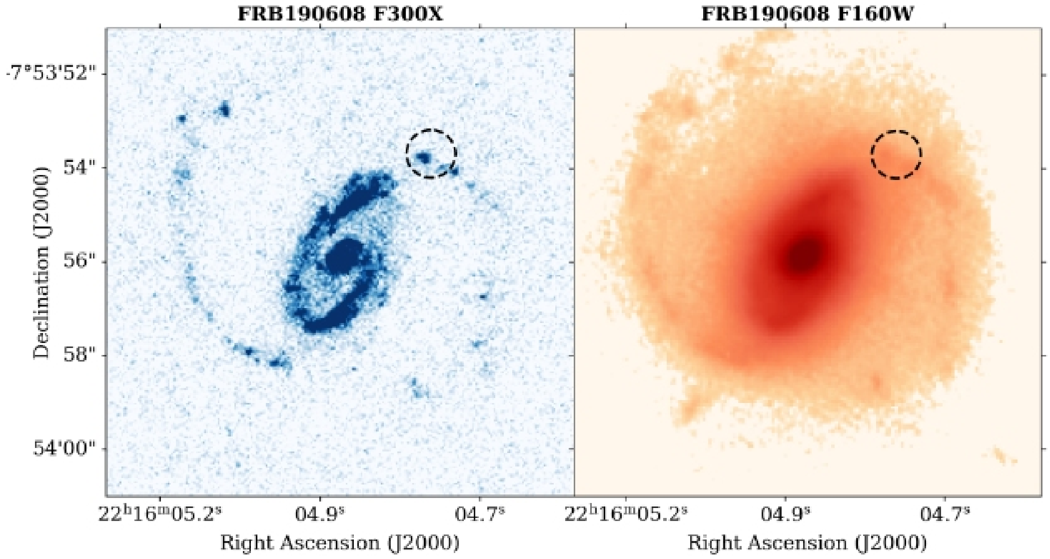
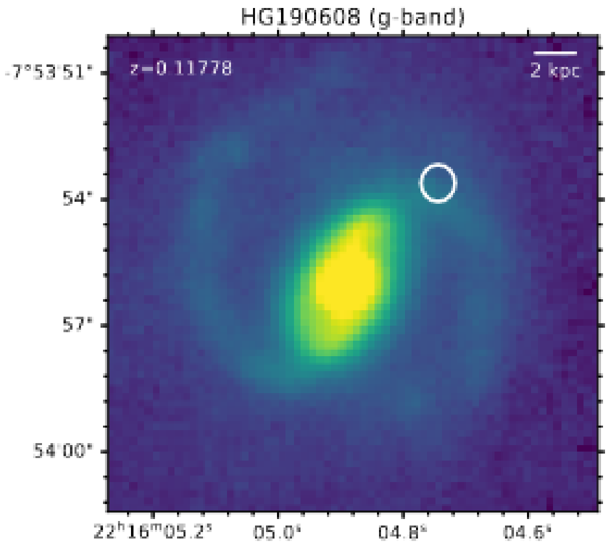
Follow-up & localization within a galaxy



Mannings et al. 2021 (arXiv:2012.11617)



Bhandari et al. 2020 (arXiv:2005.13160)

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Instruments for localizations

Plenary 8: Pinpointing

Plenary 8A: Tue 3/8/2021 @ 8am - 10am UT - Chair: Ben Stappers
Plenary 8B: Tue 3/8/2021 @ 8pm - 10pm UT - Chair: Wenbin Lu

ID62: Localizing FRBs to miliarcseconds with EVN-PRECISE
Benito Marcote, Joint Institute for VLBI ERIC (JIVE)
A: Live B: Recording

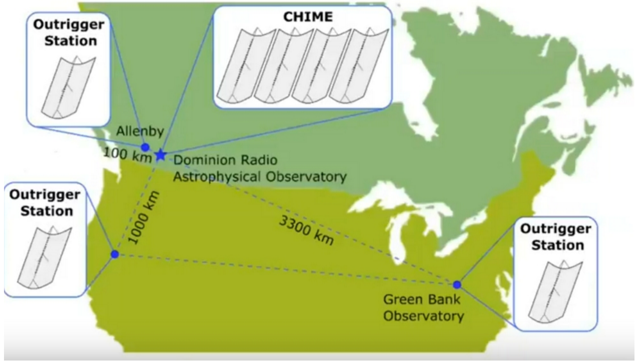
ID84: Localization of CHIME/FRB repeaters with VLA/realfast
Shriharsh Tendulkar, Tata Institute of Fundamental Research and the National Centre for Radio Astrophysics
A: Live B: Recording

ID88: The first sub-arcsecond localised FRB with MeerKAT
Laura Driessen, Jodrell Bank Centre for Astrophysics, University of Manchester
A: Live B: Recording

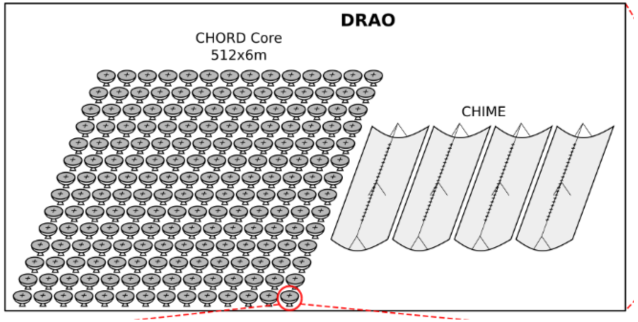
ID89: The UTMOST-2D FRB detection and localisation engine
Adam Deller, Swinburne University of Technology
A: Live B: Recording

ID140: Arcsecond Localization of FRB 20201124A with the uGMRT
Robert Wharton, Jet Propulsion Laboratory
A: Recording B: Live

ID108: CHIME/FRB Outriggers and CHORD: new instruments for localization of Fast Radio Bursts
Juan Mena-Parra, Massachusetts Institute of Technology
A: Recording B: Recording



CHIME Ourtiggers. Juan Mena-Parra, FRB2021 (8A)



CHORD (Vanderlinde et al. 2020, arXiv:1911.01777)

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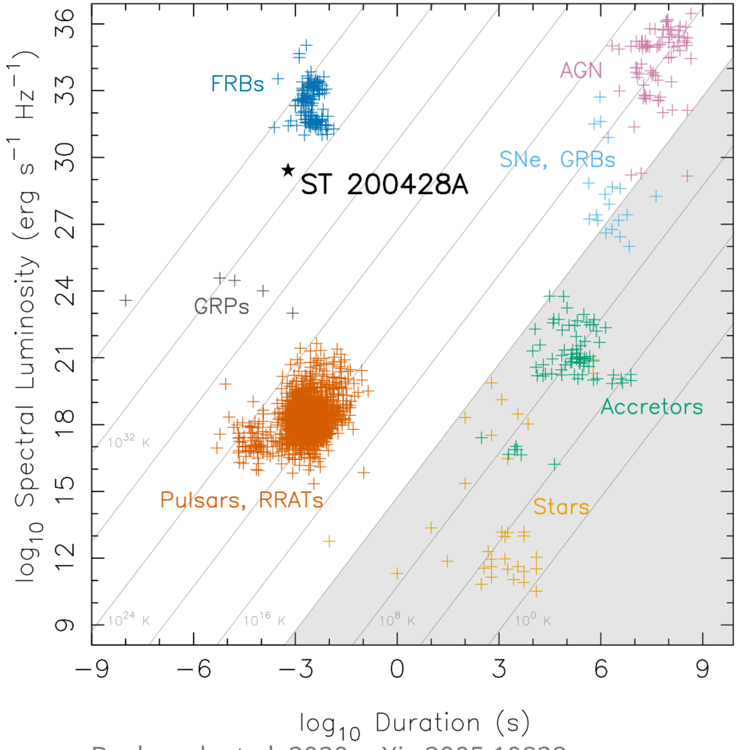
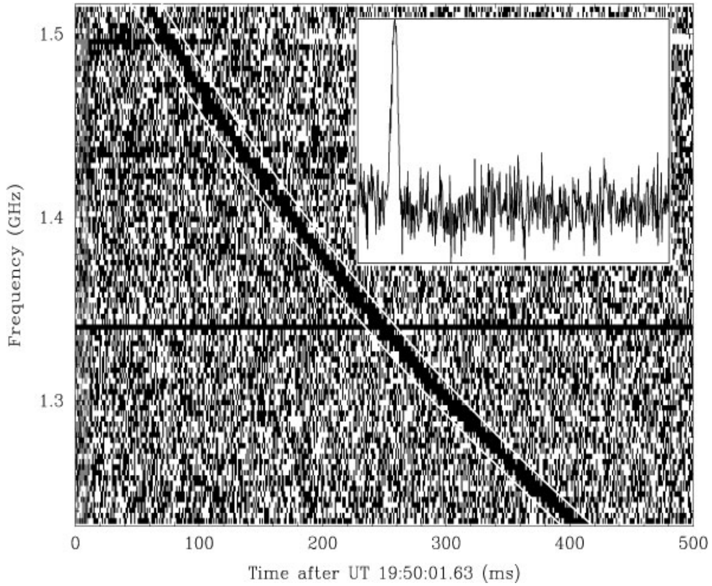
Typical properties



Bochenek et al. 2020 arXiv:2005.10828



Lorimer et al. 2007 arXiv:0709.4301

- Intrinsic width ~ 1ms
- Dispersion ~ seconds

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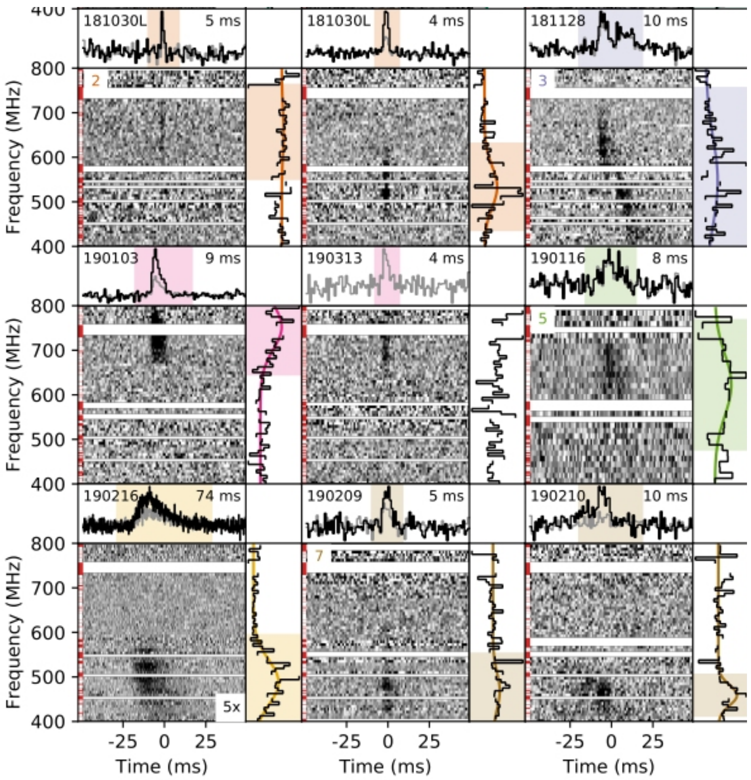
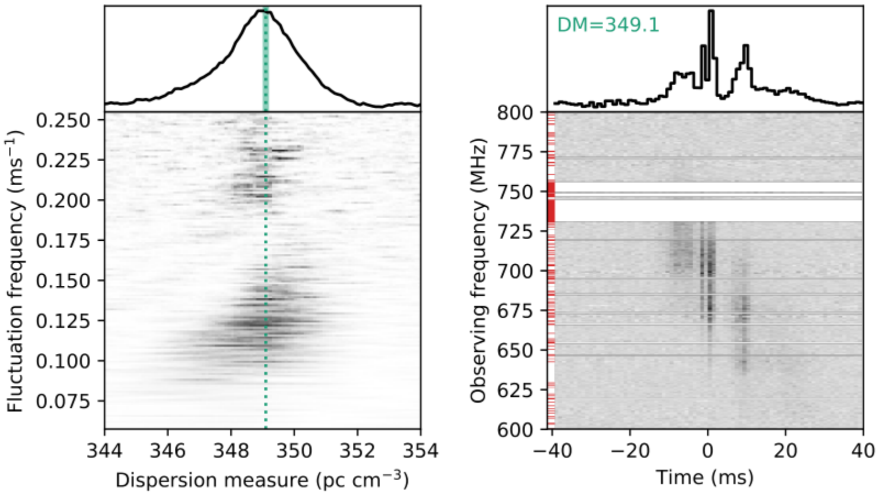
Signal shapes





Downward-drifting substructure ("sad trombone")

CHIME/FRB Collaboration, arXiv:1908.03507

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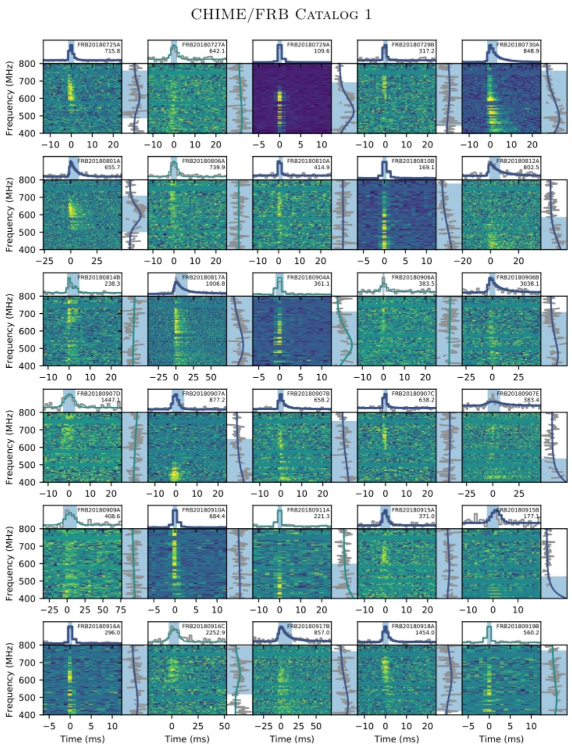
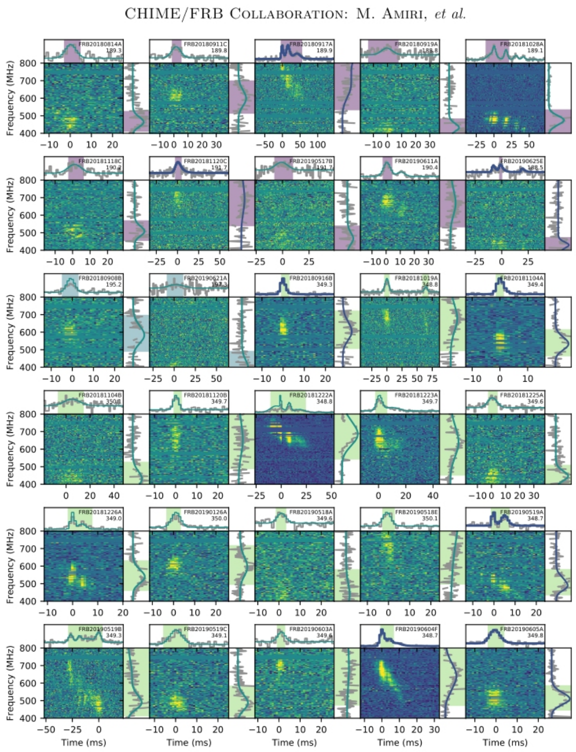
Repeaters – A distinct population?



non-repeaters



repeaters

CHIME/FRB Collaboration 2021, arXiv:2106.04352

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Repeaters – A distinct population?

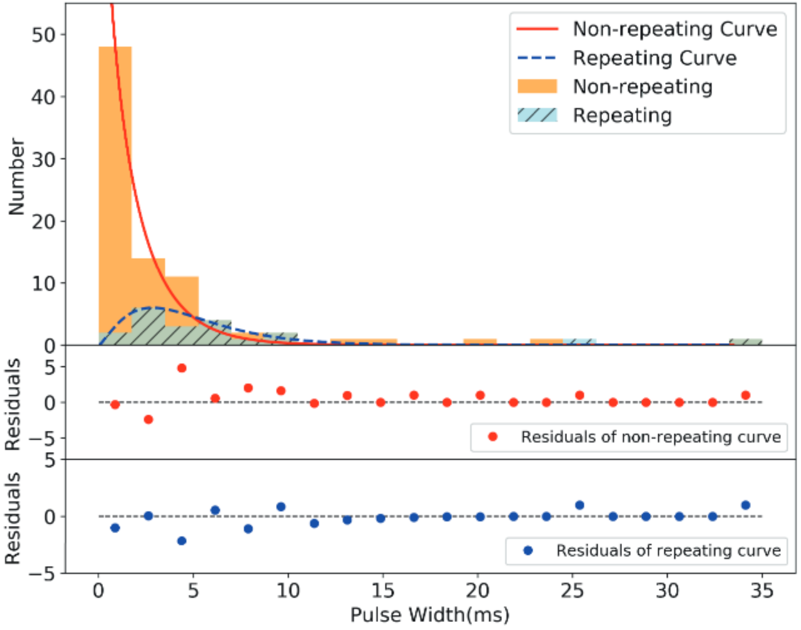

Figure 1. Upper panel: histogram of repeating and non-repeating FRBs with pulse width < 35 ms. The solid (dashed) line is the

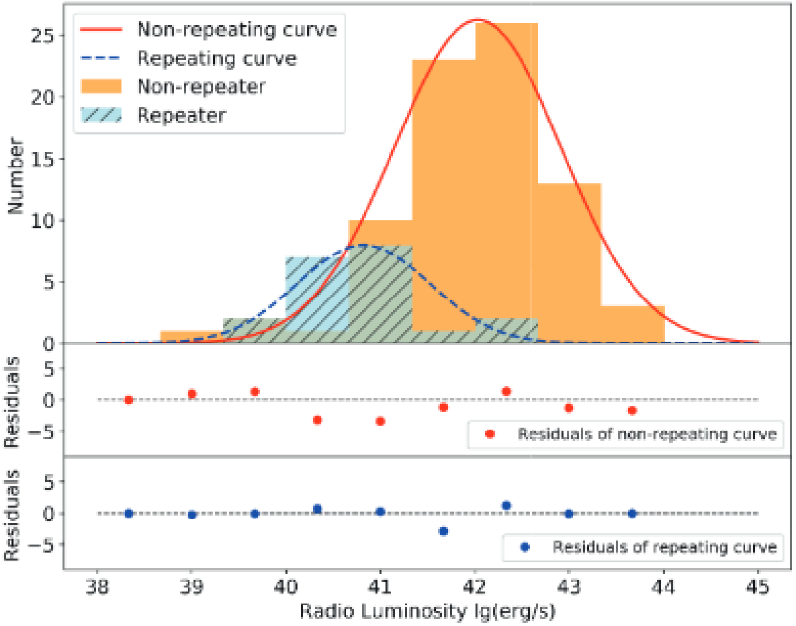

Figure 3. Histogram of repeating and non-repeating FRBs for radio luminosity expressed logarithmically. The solid line is the

Figures from Cui et al. 2021 (arXiv:2011.01339)

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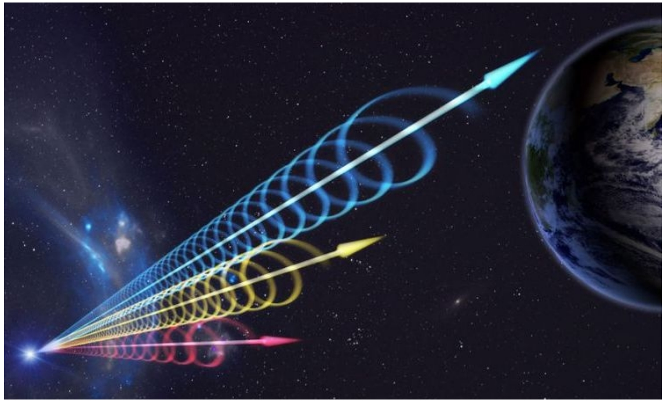
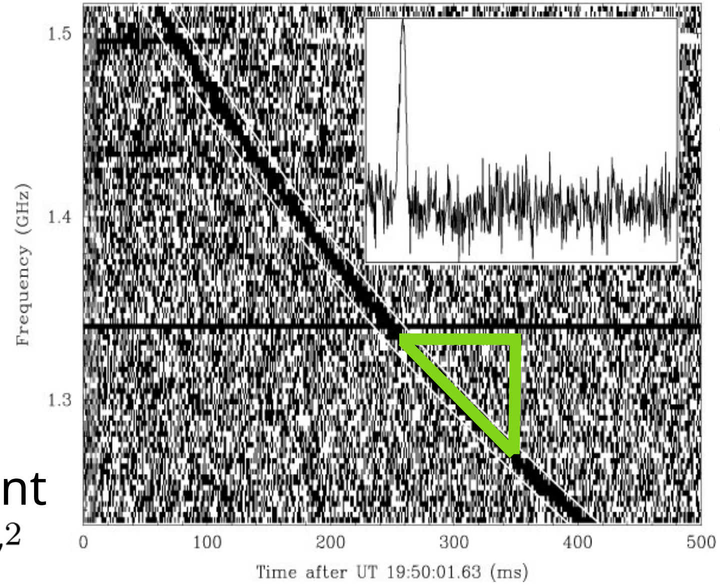
Cosmology with FRBs

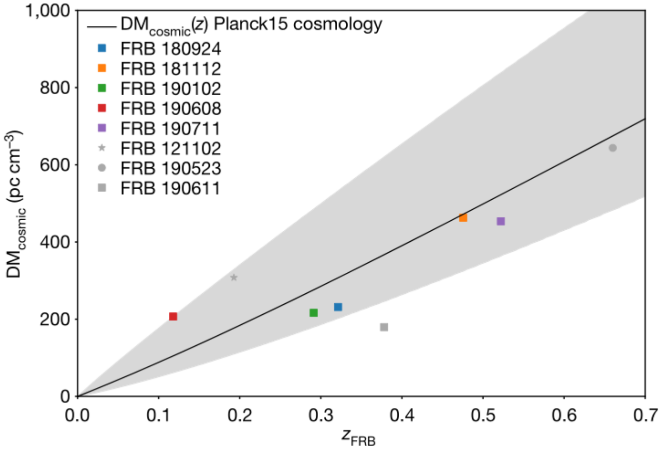
The FRB Dispersion Measure



Jingchuan Yu, Beijing Planetarium



Lorimer et al. 2007 arXiv:0709.4301



Macquart et al. 2020 arXiv:2005.13161

- Velocity frequency-dependent
  → Arrival times shifted $\propto 1/\nu^2$
- Dispersion slope Δν/Δt

$$\mathrm{DM} = \int \frac{n_e}{1+z}\,\mathrm{d}l$$

DM ⟷ Redshift z

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Dispersion Measure Contributions

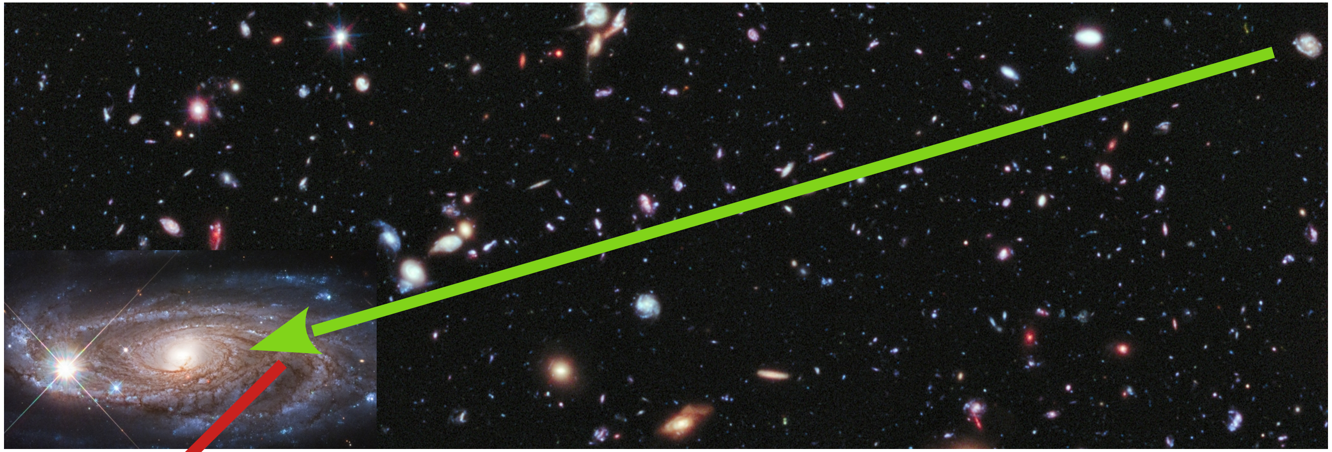
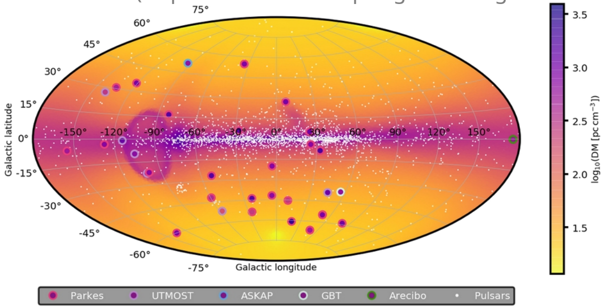


Image: BG - NASA; FG - ESA; B. Holwerda; Illingworth, Oesch, Bouwens and the HUDF09 Team
Figure: MeerTRAP, FRB & Pulsar locations (https://www.meertrap.org/science-goals/fast-radio-bursts/)

Milky Way – from 10 to 3000 pc/cm^3 but known from model:



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Dispersion Measure Contributions

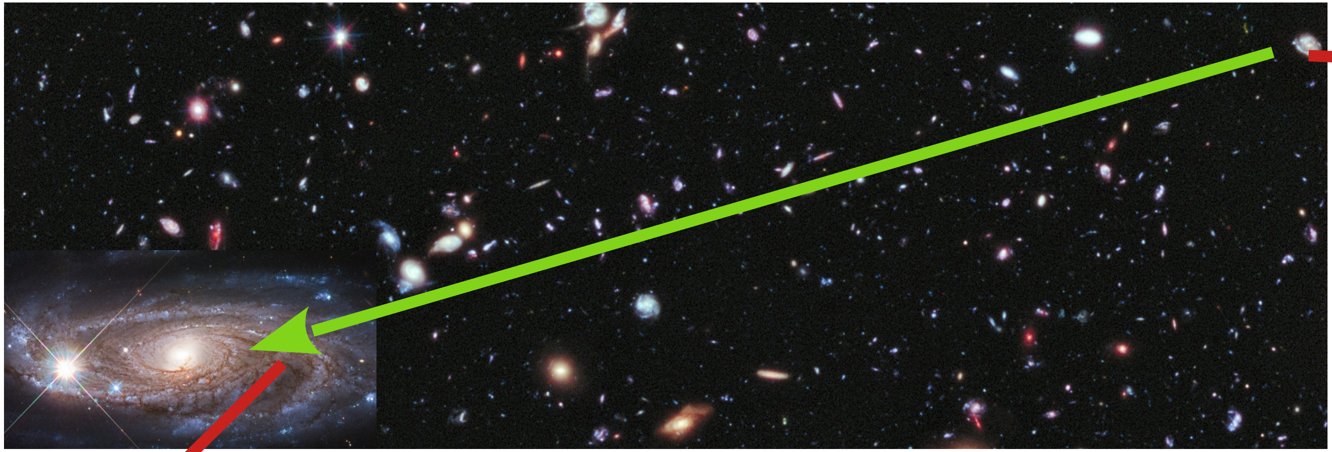
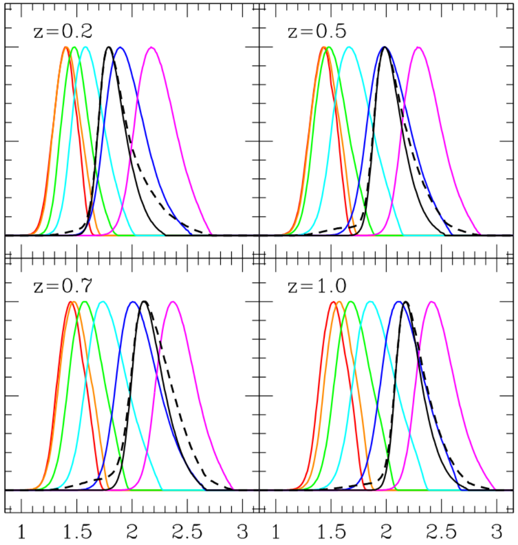


Image: BG - NASA; FG - ESA; B. Holwerda; Illingworth, Oesch, Bouwens and the HUDF09 Team
Figure: MeerTRAP, FRB & Pulsar locations (https://www.meertrap.org/science-goals/fast-radio-bursts/)

Host galaxy – unknown
~ 200 +/- 100 pc/cm³



Jarozynski 2020
arXiv:2008.04634

Milky Way – from 10 to 3000 pc/cm³ but known from model:

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Dispersion Measure Contributions

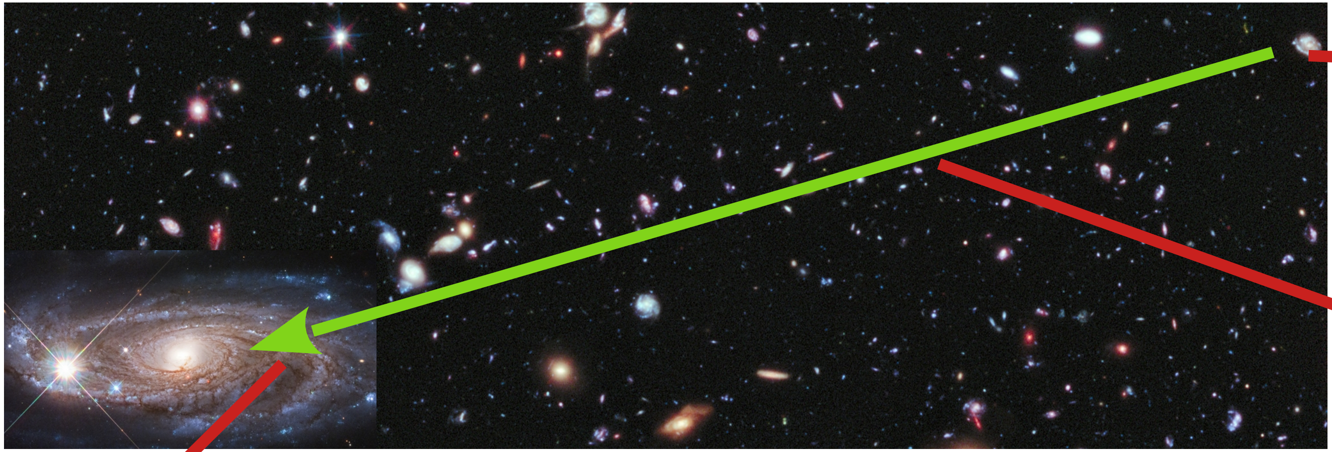

Image: BG - NASA; FG - ESA; B. Holwerda; Illingworth, Oesch, Bouwens and the HUDF09 Team
Figure: MeerTRAP, FRB & Pulsar locations (https://www.meertrap.org/science-goals/fast-radio-bursts/)

Host galaxy – unknown
~ 200 +/- 100 pc/cm^3

Intergalactic medium – depending on the distance, and ionization of the IGM along the line of sight

$$DM(z)^{\mathrm{IGM}} = \int_{\mathrm{earth}}^{\mathrm{source}} \frac{n_e^{\mathrm{IGM}}(z)}{(1+z)} \mathrm{d}l$$

~ 4000 - 6000 pc/cm^3 ± 5-9%

(for z=5 to 15)

Milky Way – from 10 to 3000 pc/cm^3 but known from model:

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Cosmology with FRBs

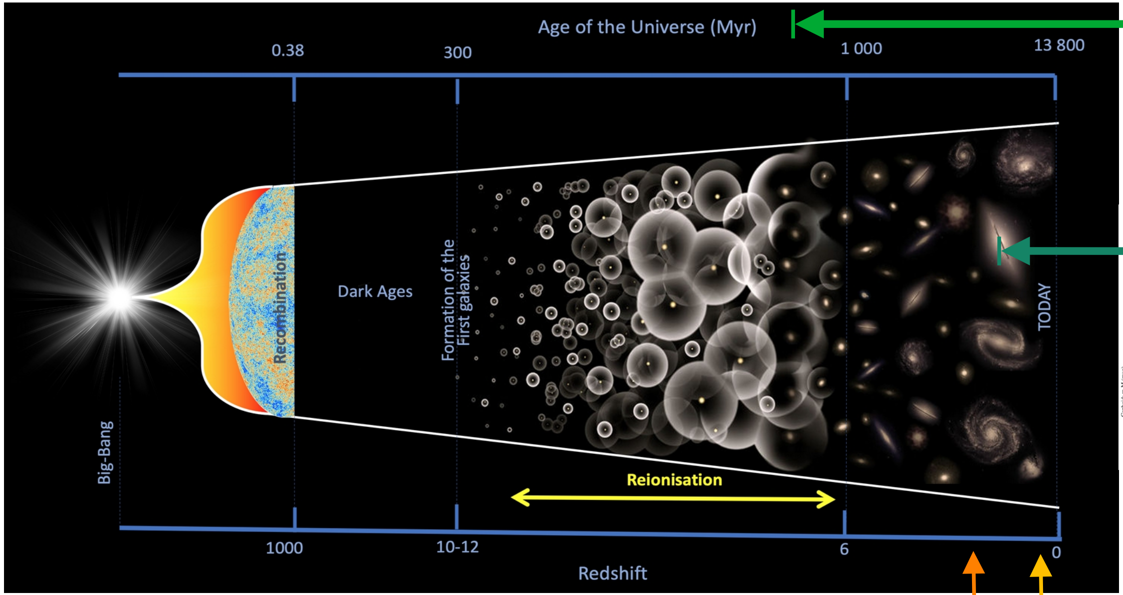
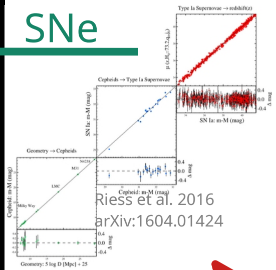


Image credit: Nicolas Laporte

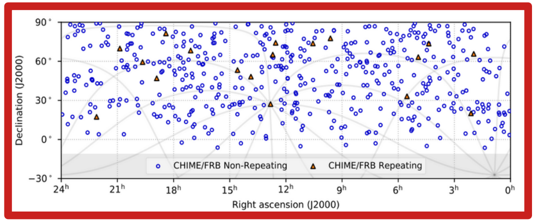
Furthest reionization:

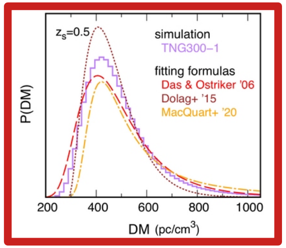
- Quasars z<7.7
- Galaxies z<8

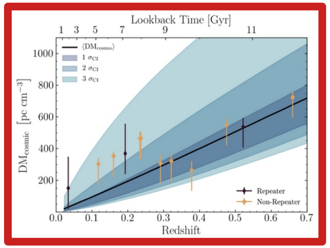
SNe



Riess et al. 2016
arXiv:1604.01424







Localized FRBs

Farthest FRBs today

Possible range of FRB sources

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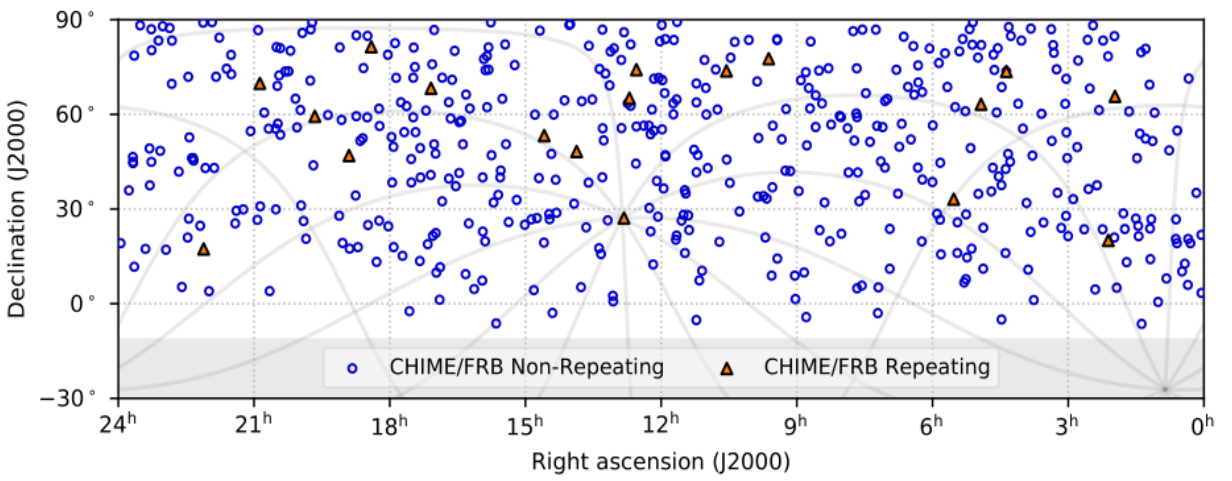
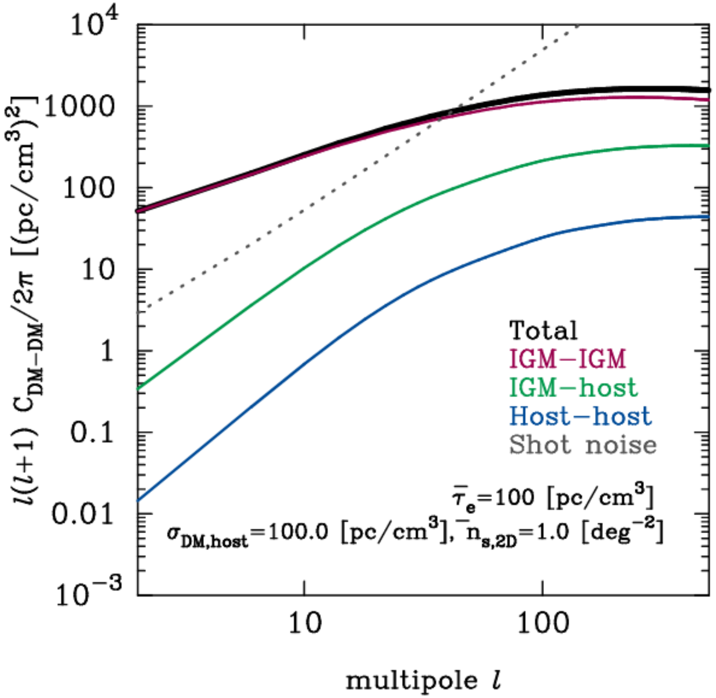
FRB (angular) clustering



FRBs in CHIME/FRB Catalog 1 (arXiv:2106.04352)

- Location (approximate, or accurate from interferometry)
- Redshift (approximate from DM, or accurate from follow-up)



Shirasaki et al. 2017 (arXiv:1702.07085)
see also Dai & Xia 2021 (arXiv:2004.11276)

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FRB DM statistics

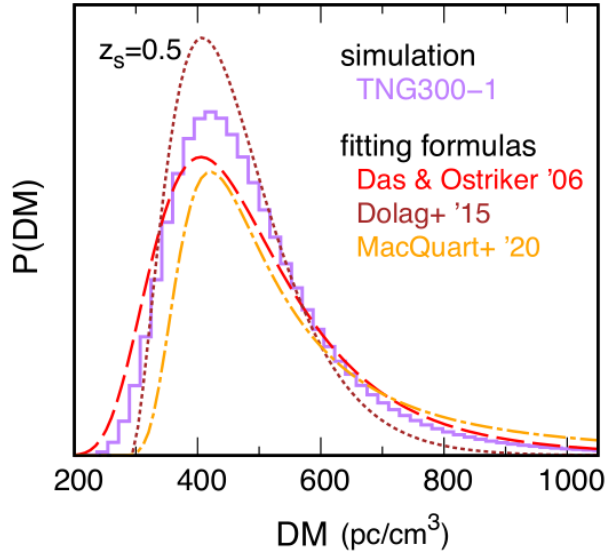


Figure 10. Comparison of probability distributions of the DM at $z_s = 0.5$.

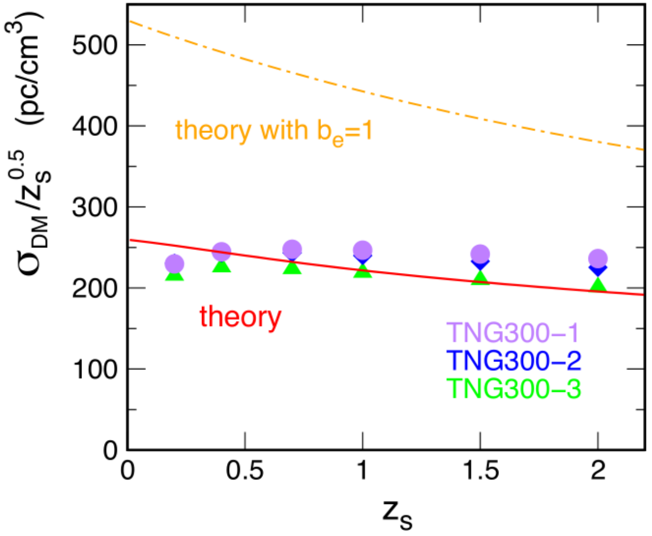
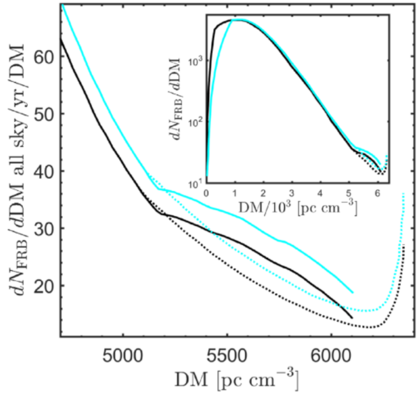
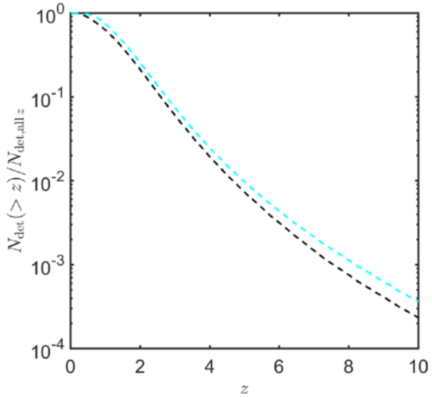


Figure 8. Standard deviation of the DM as a function of z_s. The purple, blue and green symbols are the TNG300-1, -2 and -3 results. The solid red curve denotes the analytical prediction given in Eq. (16). The dash-dotted orange curve is the same as the solid one, but assuming that the free electrons exactly trace the dark matter (i.e., $b_e = 1$).

Takahashi et al. 2020
arXiv:2010.01560





Beniamini et al. 2021
arXiv:2011.11643

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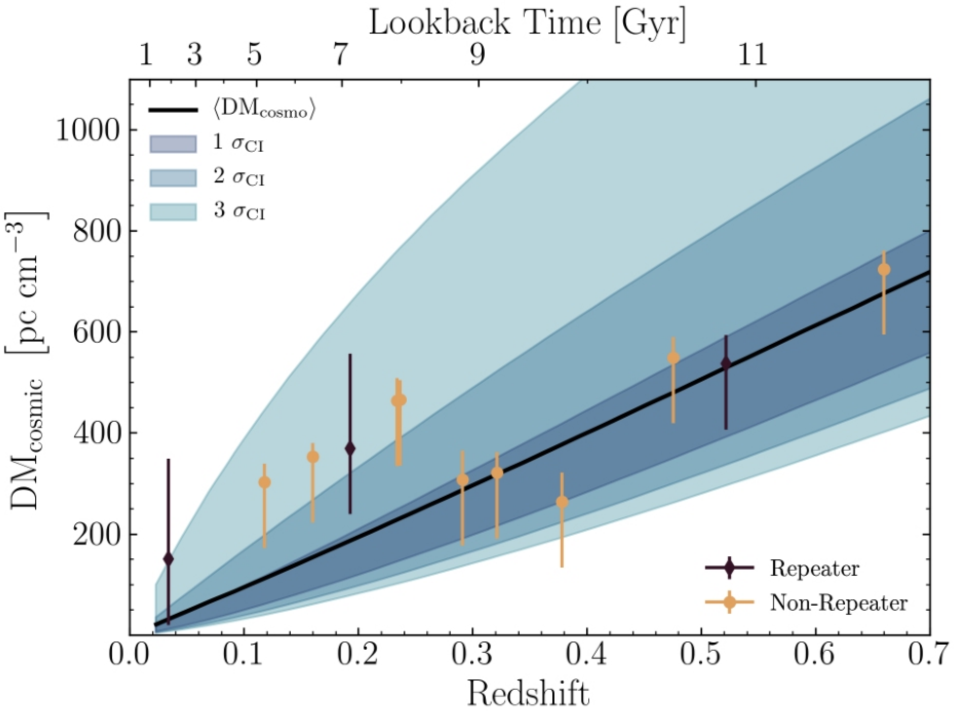
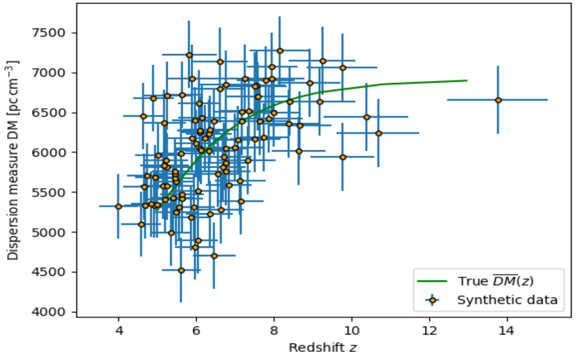
FRB DM(z) relation



Batten et al. 2020, arXiv:2011.14547



$$\mathrm{DM} = \int_0^z \frac{f_{\mathrm{IGM}} \bar{n}_e(z)}{H(z)(1+z)^2} \mathrm{d}z$$

Astrophysics

Reionization

Background Cosmoloy

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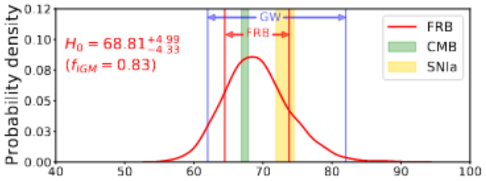
Effects on DM(z)

$$\overline{\mathrm{DM}}^{\mathrm{IGM}}(z) = \int_0^z c \underbrace{\frac{\Omega_b}{H(z)}}_{\text{Cosmology}} \underbrace{\frac{\bar{n}_e(z')/\Omega_b}{(1+z')^2}}_{\text{Ionization}} \mathrm{d}z'$$

$$H_0, \Omega_b, \Omega_m, w(z)$$

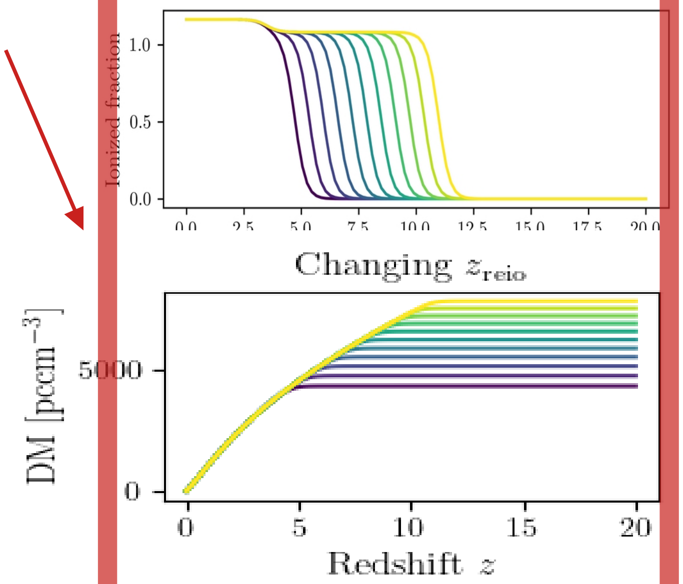


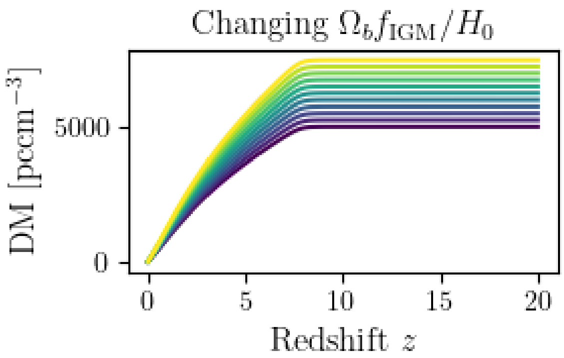
Wu et al. 2021,
Hagstotz et al. 2021

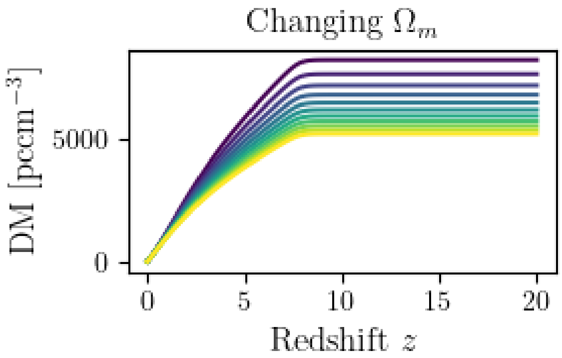
Macquart et al. 2020

E.g. Zhou et al. 2014 (forecast)

Focus of this work







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Cosmic reionization

Well studied (CMB) | Dark Ages & EoR | Galaxy surveys

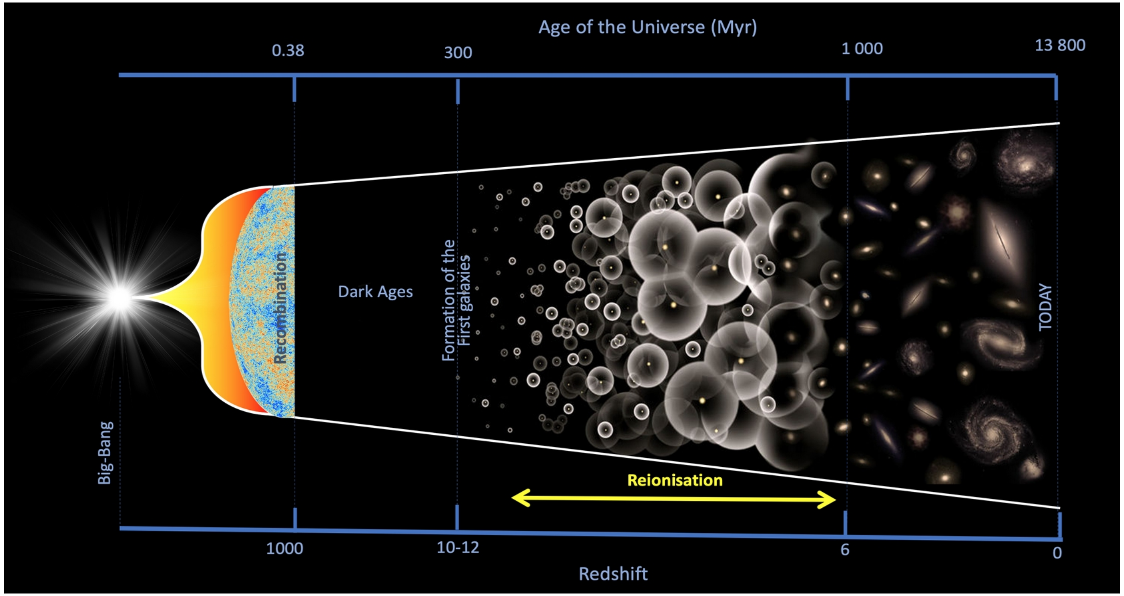

Image credit: Nicolas Laporte

Cosmological standard model

(Planck analysis incl. BAO):

$$\ln A_s \pm 0.5\%$$
$$n_s \pm 0.4\%$$
$$\Omega_m h^2 \pm 0.6\%$$
$$\Omega_b h^2 \pm 0.6\%$$
$$H_0 \pm 0.6\%^*$$
$$\tau \pm 12\%$$

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Cosmic reionization

Well studied (CMB) | Dark Ages & EoR | Galaxy surveys

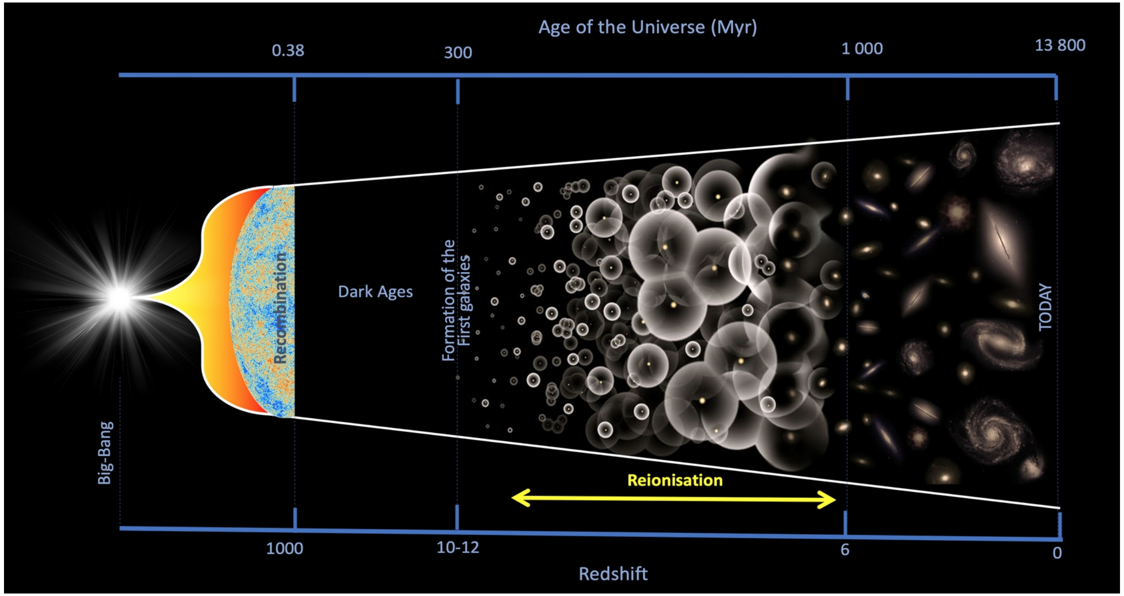
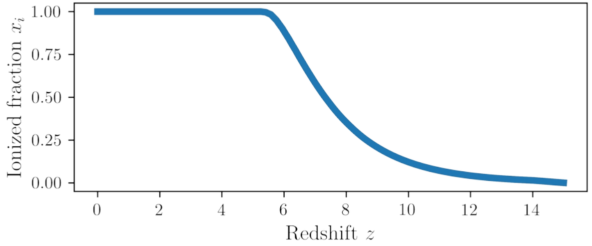
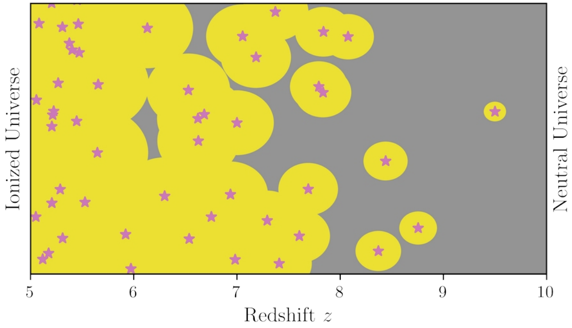


Image credit: Nicolas Laporte

Reionization history from Kulkarni et al. [1809.06374]





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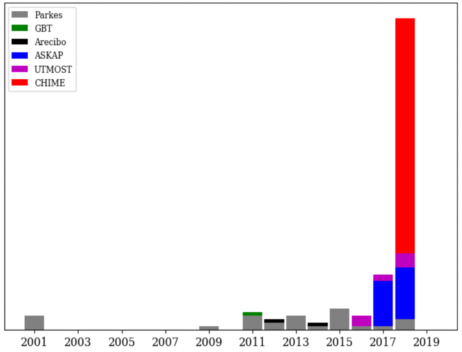
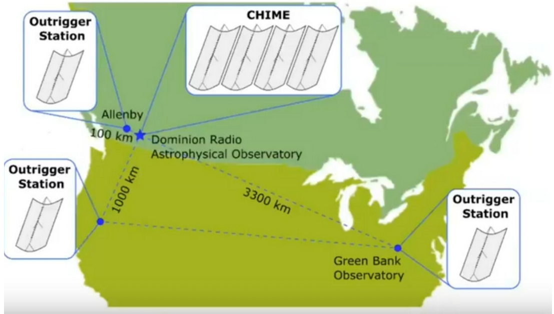
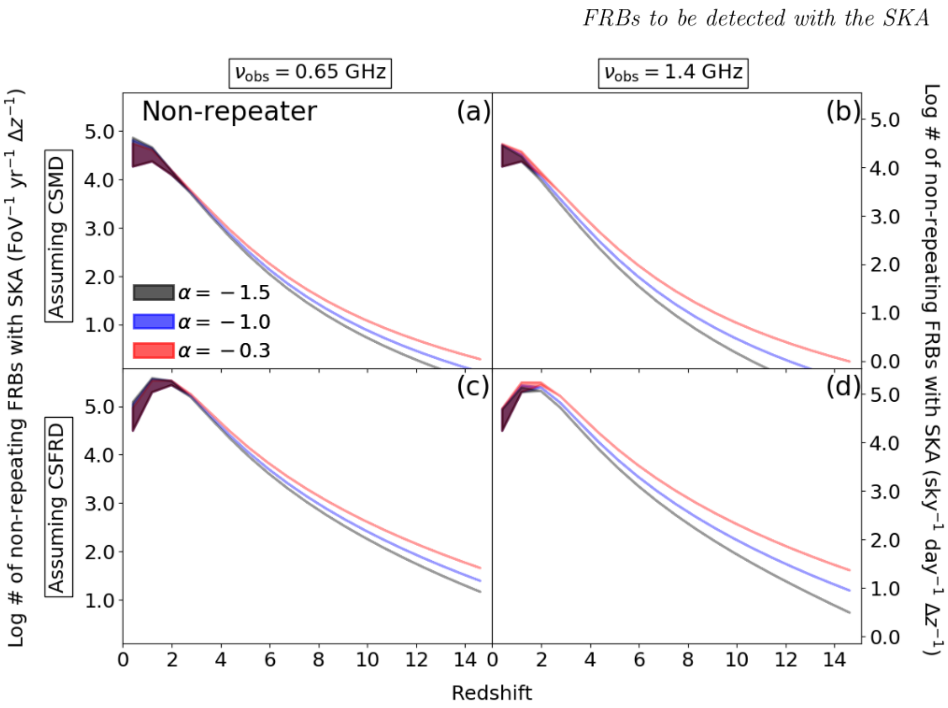
Reminder: We will have many FRBs in the future!



Animation by Cherry Ng, CHIME, Dunlap Institute (github.com/cherryng)



CHIME Ourtiggers. Juan Mena-Parra, FRB2021 (8A)



Hashimoto et al. 2021, arXiv:2008.00007

Forecast for FRBs/sky/day:
10^4 at z>2,
10^2 at z>6,
10 at z>10
(rates still uncertain and assumption dependent though)

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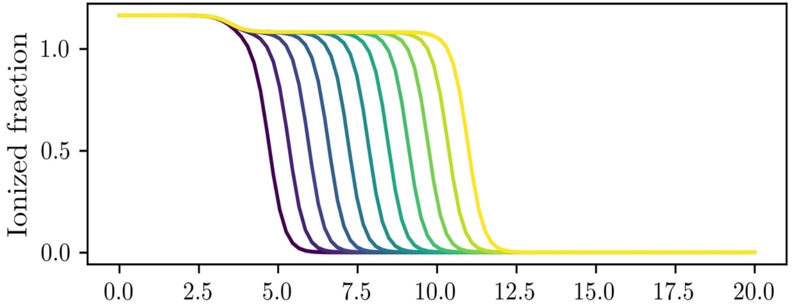
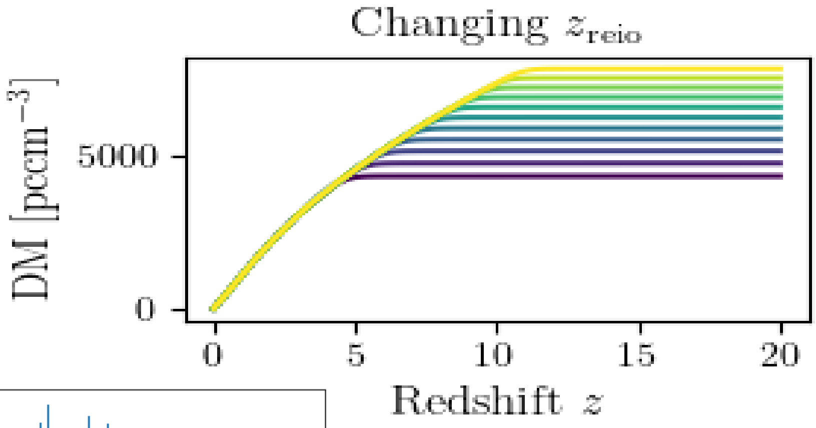
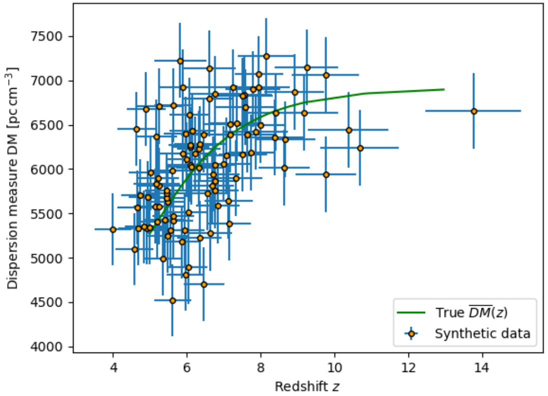
How to we currently measure Reionization from FRBs

Common *tanh* parameterization:







Reionization history $x_i(z)$
Optical depth τ

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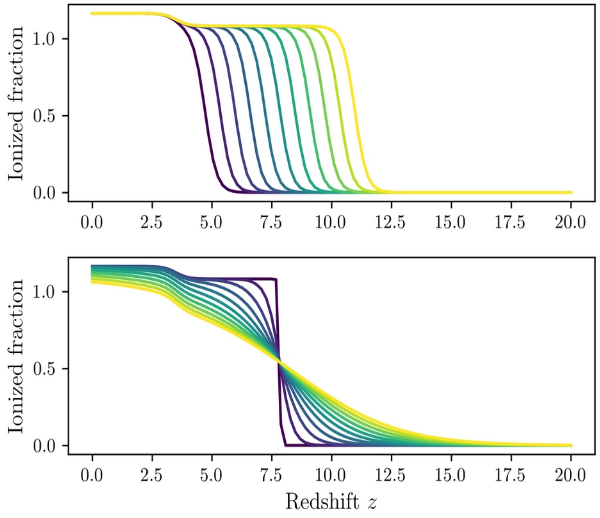
How to we currently measure Reionization from FRBs

Common *tanh* parameterization:



***Planck* 2018 results**

VI. Cosmological parameters

SEVEN-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP**) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

Results from EDGES High-band. I. Constraints on Phenomenological Models for the Global 21 cm Signal

Reconstruction of Reionization History through Dispersion Measure of Fast Radio Bursts

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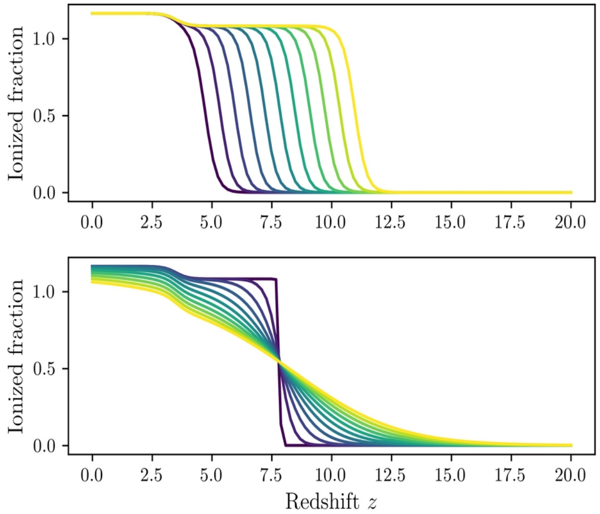
How to we currently measure Reionization from FRBs

Common *tanh* parameterization:



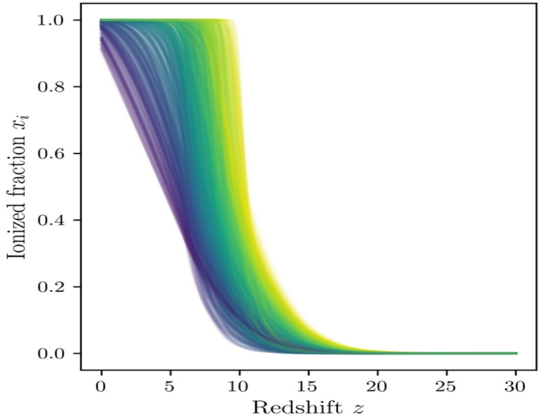
***Planck* 2018 results**
VI. Cosmological parameters

SEVEN-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*[*]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

Results from EDGES High-band. I. Constraints on Phenomenological Models for the Global 21 cm Signal

Reconstruction of Reionization History through Dispersion Measure of Fast Radio Bursts

Reionization simulations (Fialkov et al.):



Problem: Assuming a model → Wrong result if model ≠ reality

E.g. the standard *tanh* step function reionization underestimates τ by 10%

$$\tau_{\rm tanh} = 0.052 \pm 0.002 \text{ for } \tau_{\rm true} = 0.057 \text{ (1,000 FRBs)}$$

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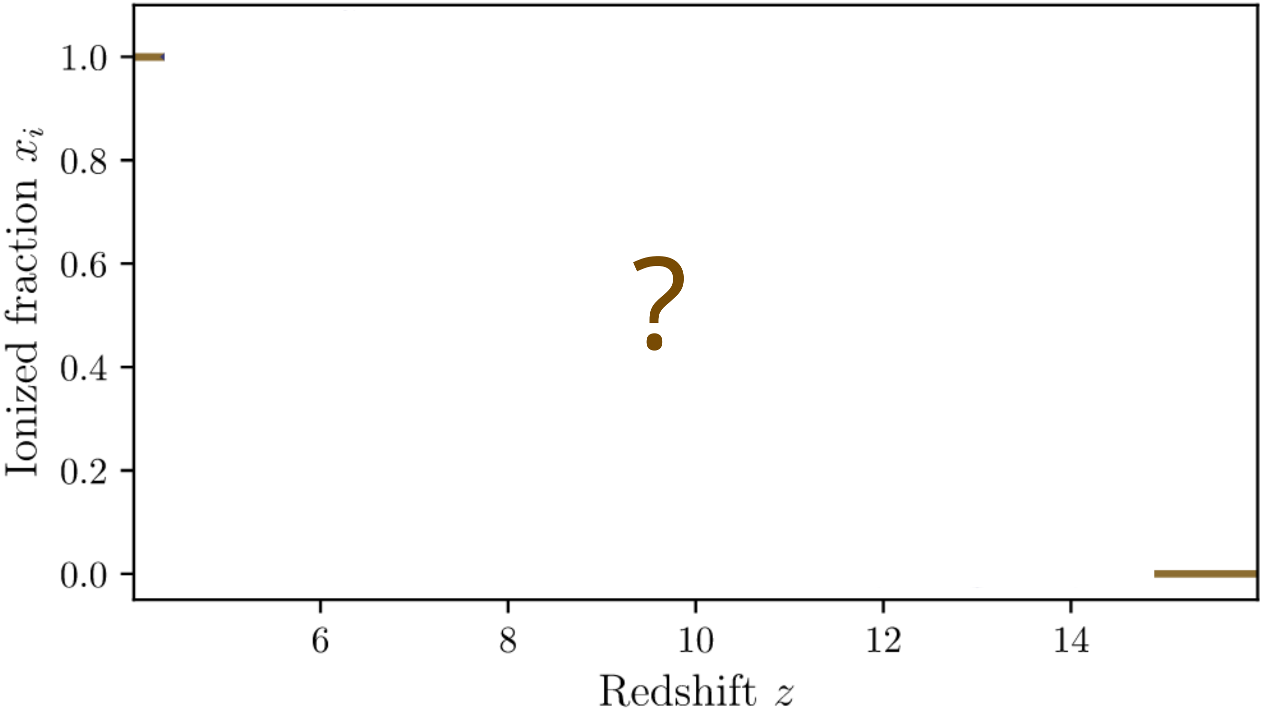
Need a new approach – model-independent!

How to “free-form” parameterize a function?



What we can assume:

→ Function from x=1 at low z
to x=0 at high z

→ Monotonously decreasing with z

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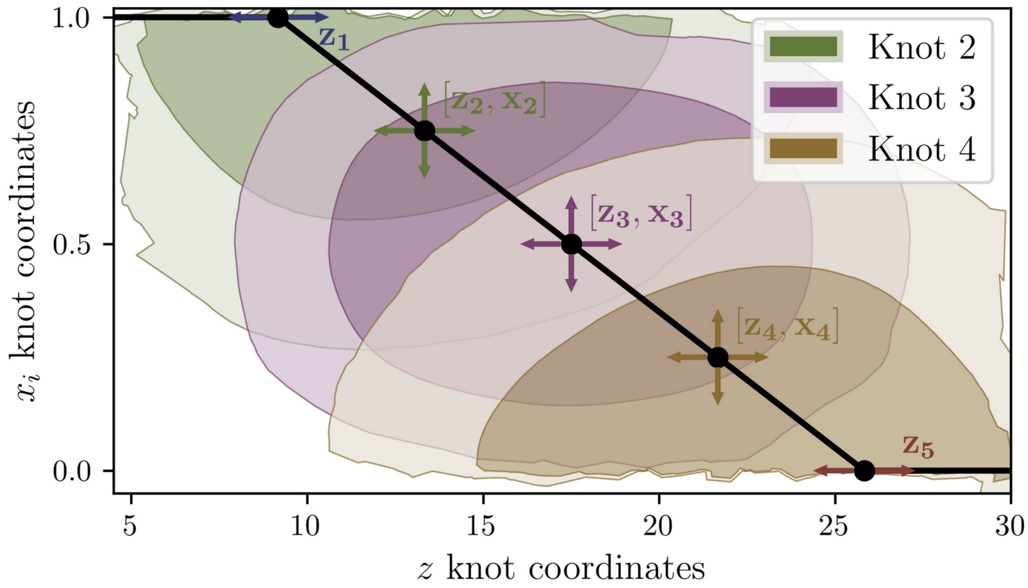
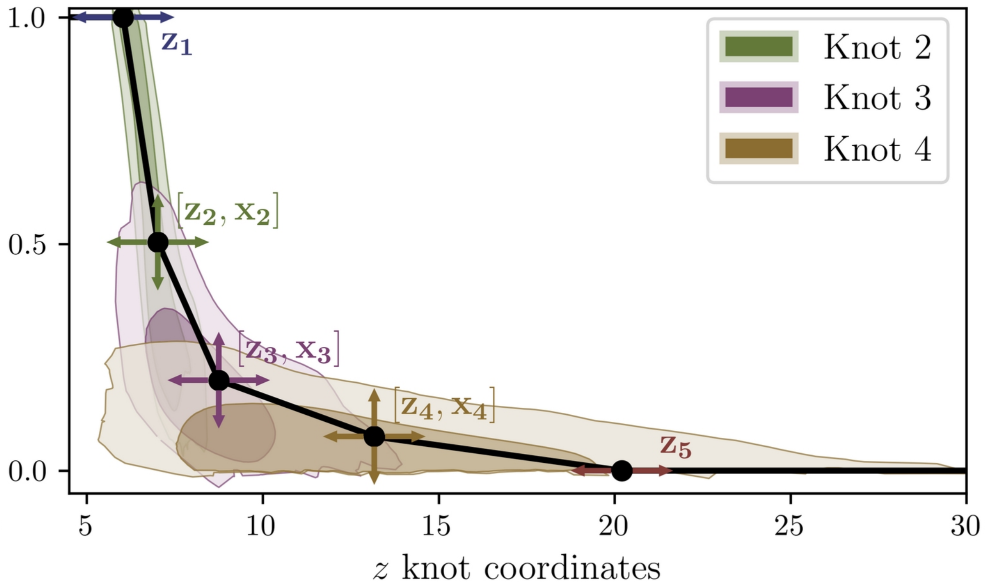
FlexKnot parameterization

Prior parameter distribution



Posterior parameter distribution



Coordinates (x,z) of interpolation knots as parameters

Basically, knots can move around and adjust to the data

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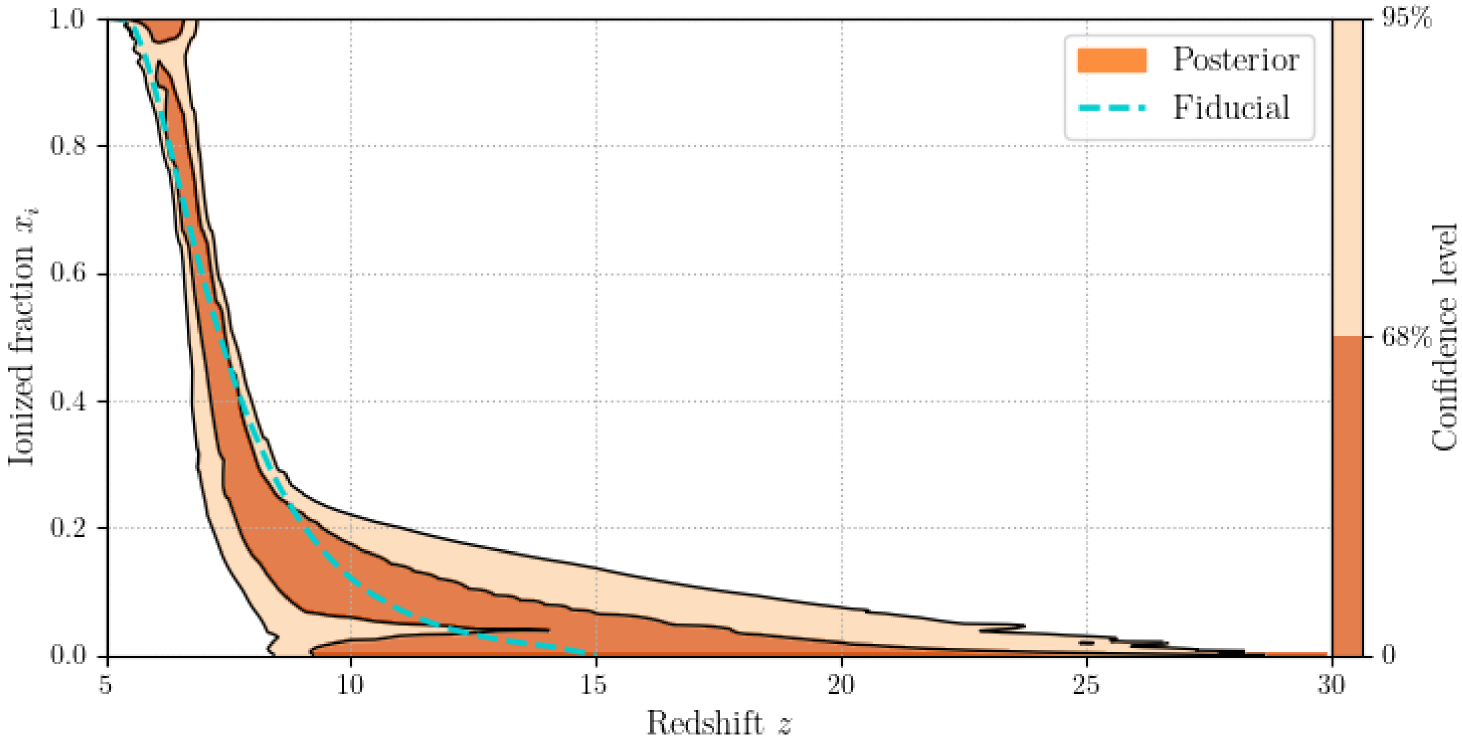
FlexKnot Reionization history



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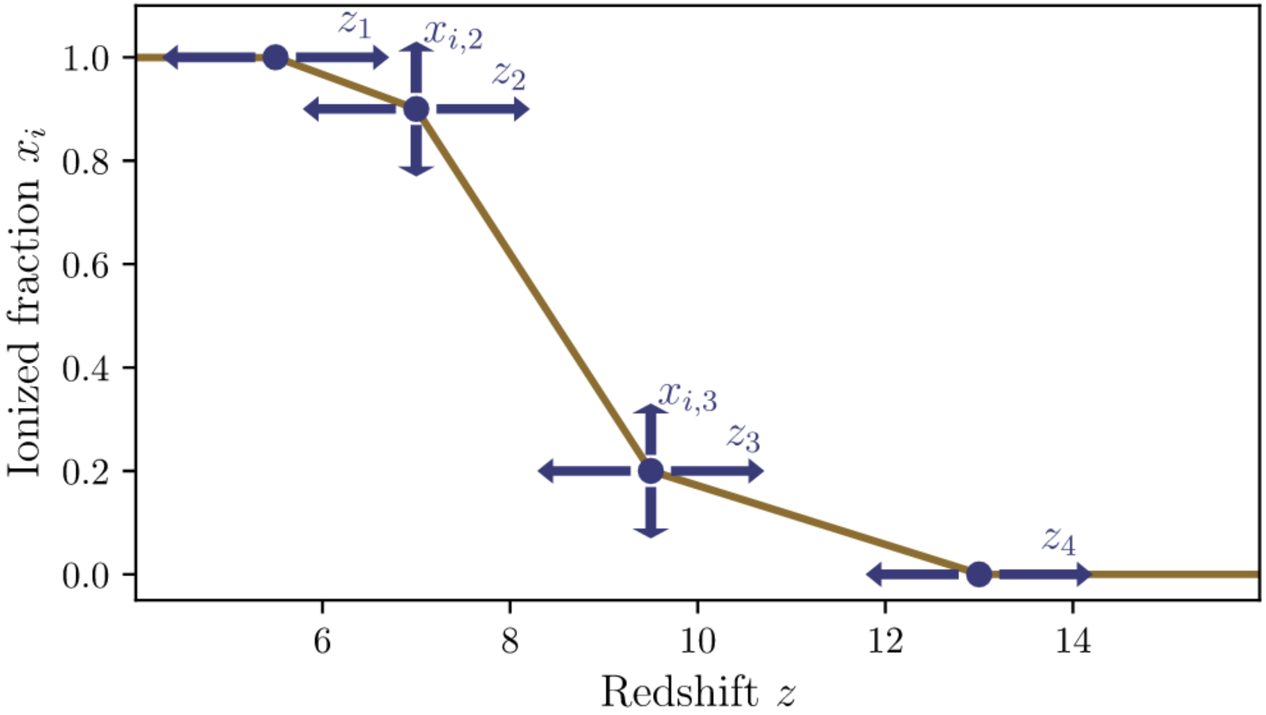
FlexKnot – How many knots do we need?



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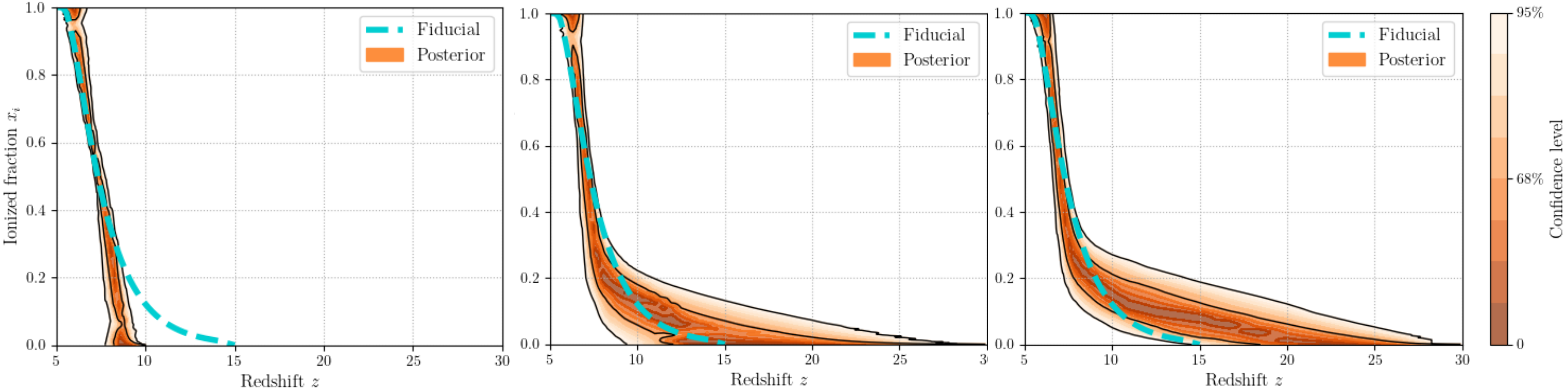
FlexKnot – How many knots do we need?



Only start + end knot:

too simple?

Add +2 more knots:

fits well?

Add +9 additional knots:

too many params?

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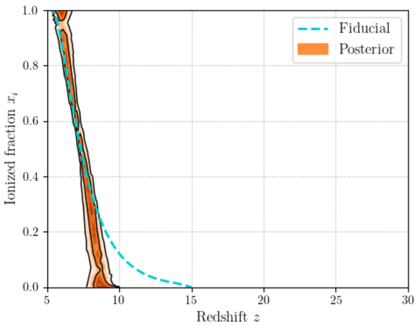
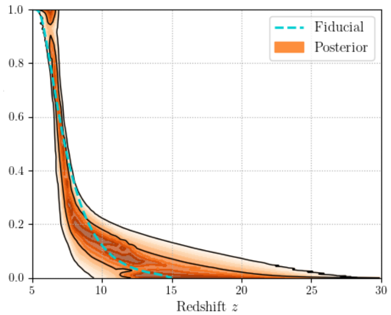
FlexKnot – How many knots do we need?

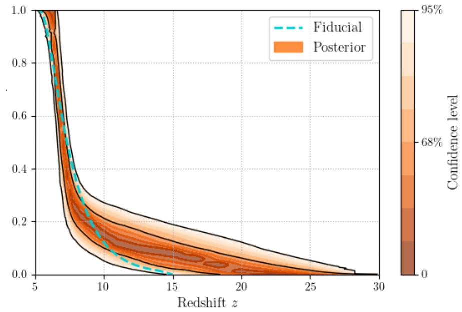
Marginalize over number of knots (→ Evidence)



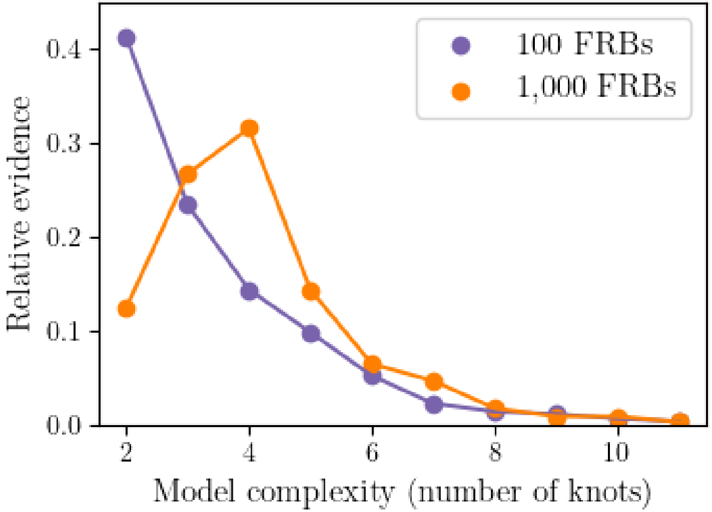
Only start + end knot:
too simple
Evidence Z = 0.4



Add +2 more knots:
fits well
Evidence Z = 1



Add +9 additional knots:
too many params
Evidence Z = 0.01



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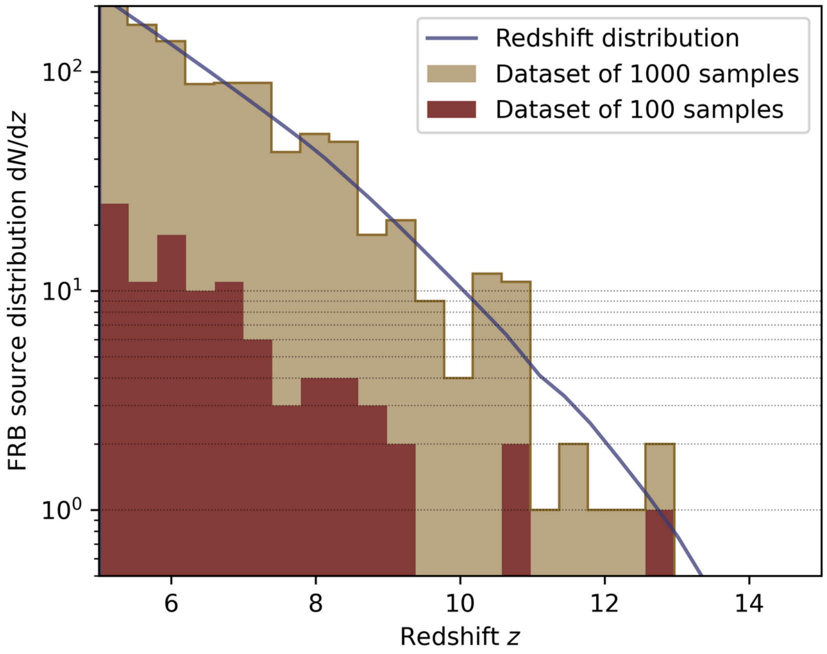
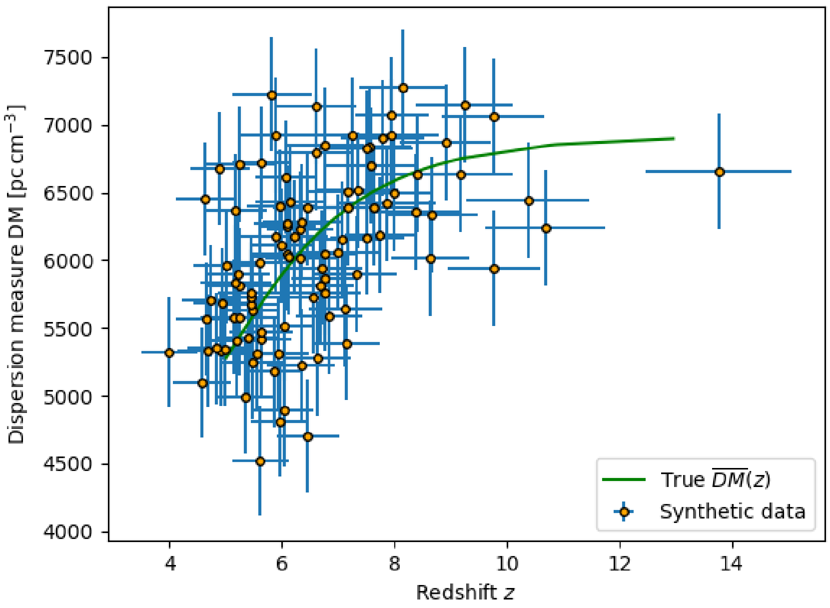
Concrete forecasts!





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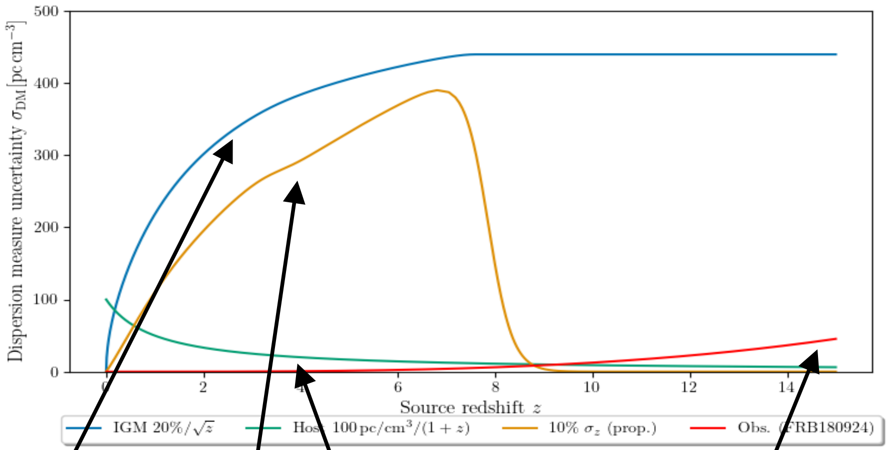
Measurement uncertainties

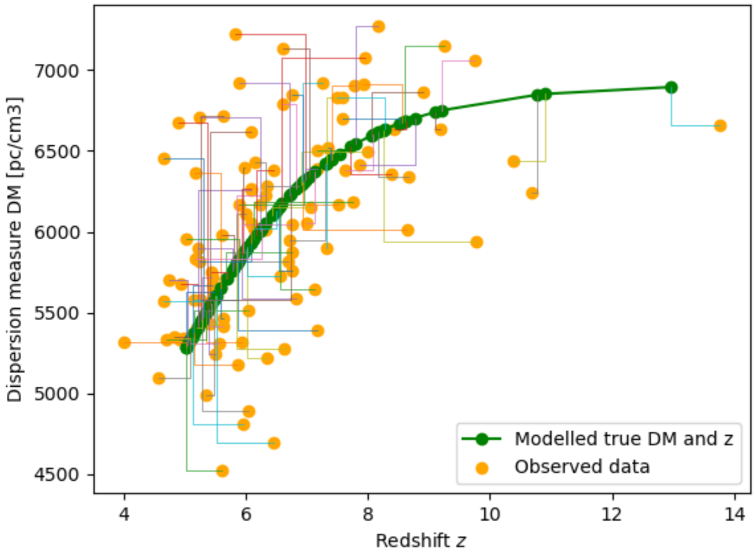


Main uncertainty:
IGM inhomogeneity

Redshift error (DM-equivalent)

Unknown host contribution

Observational error



Generating mock observations

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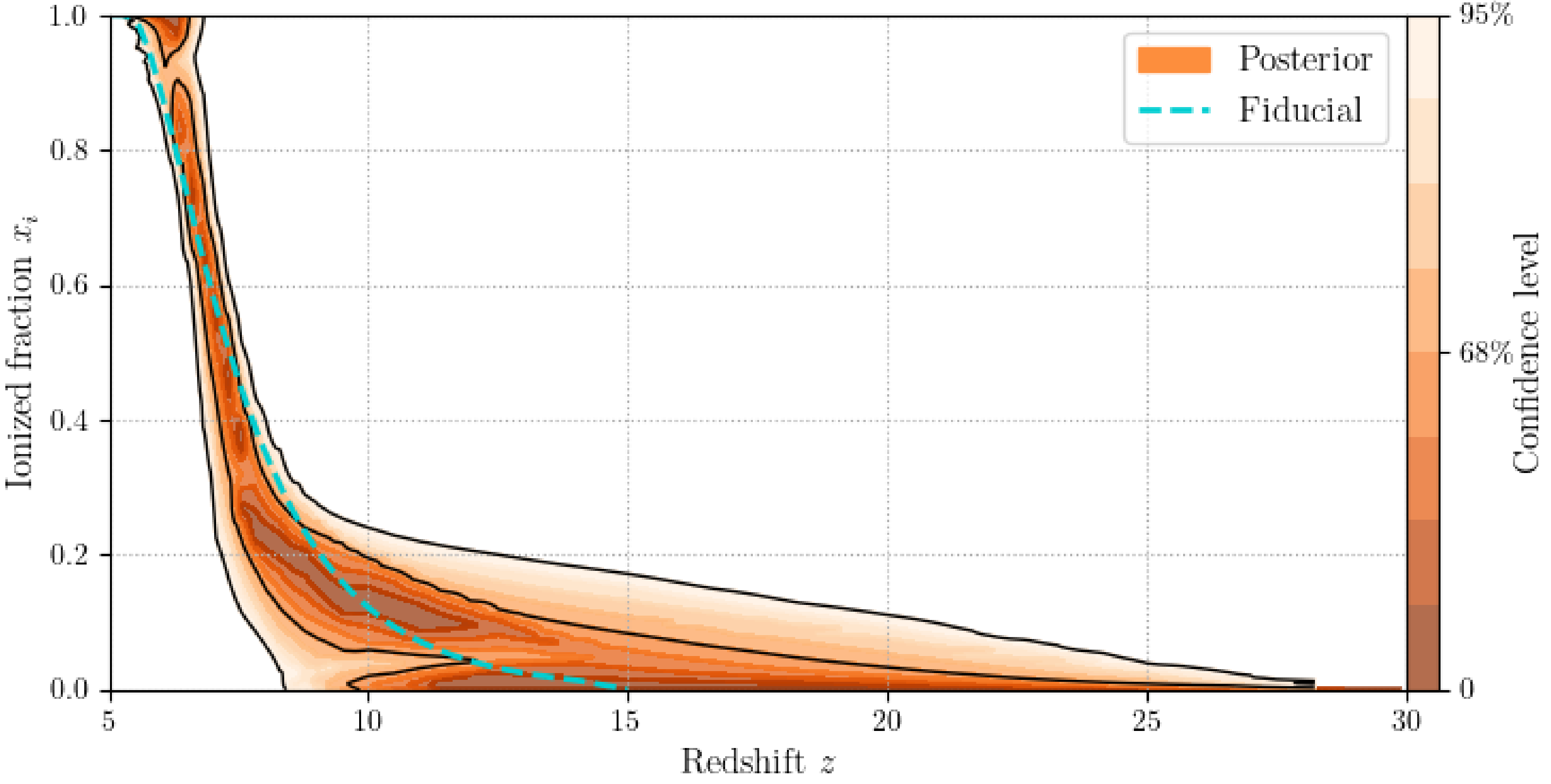
Reionization history posteriors – 1,000 FRBs



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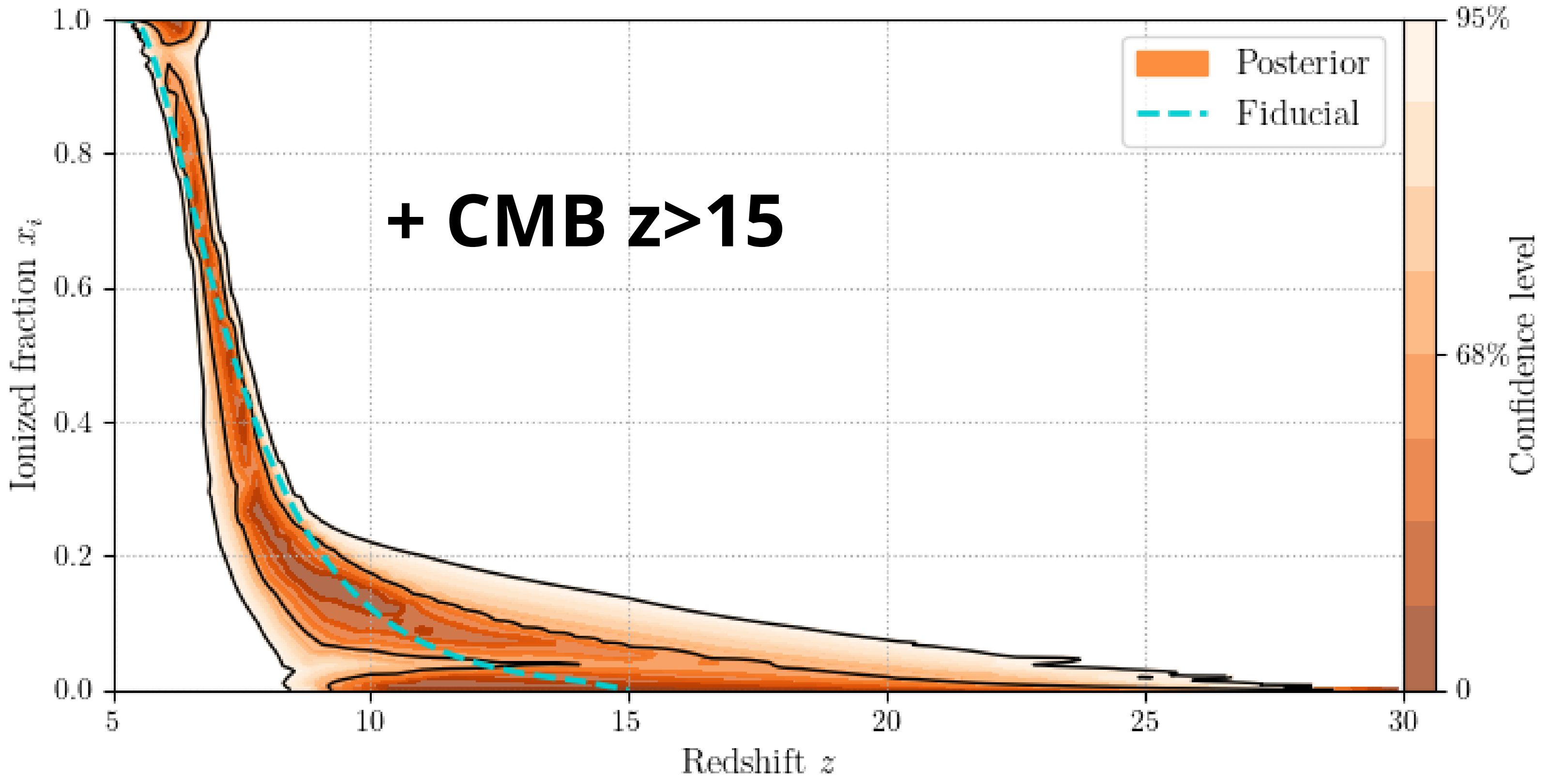
Reionization history posteriors – 1,000 FRBs



+ CMB z>15

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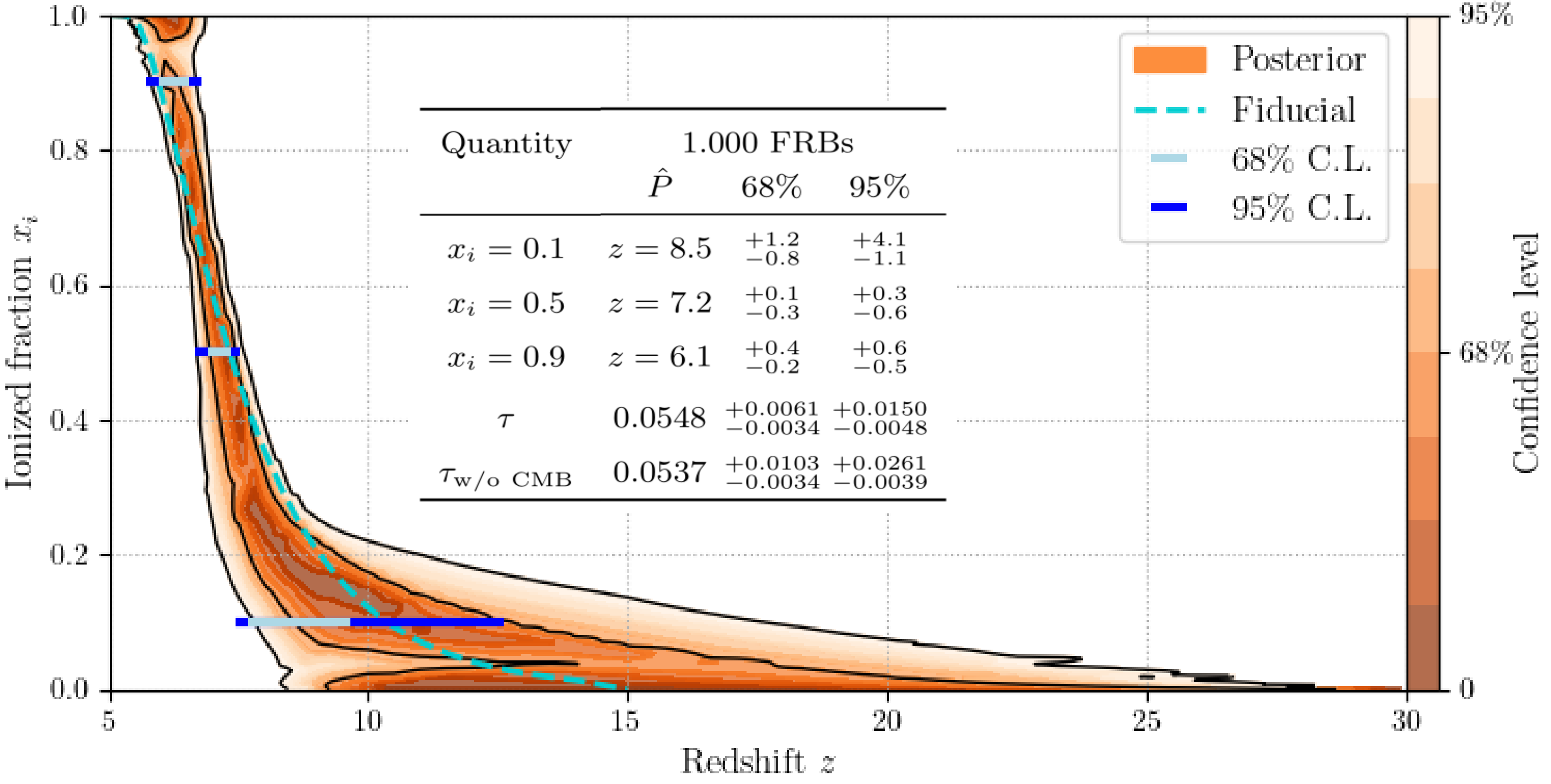
Reionization history posteriors – 1,000 FRBs



Quantity	1,000 FRBs $\hat{P}$	68%	95%
$x_i = 0.1$	$z = 8.5$	$^{+1.2}_{-0.8}$	$^{+4.1}_{-1.1}$
$x_i = 0.5$	$z = 7.2$	$^{+0.1}_{-0.3}$	$^{+0.3}_{-0.6}$
$x_i = 0.9$	$z = 6.1$	$^{+0.4}_{-0.2}$	$^{+0.6}_{-0.5}$
τ	0.0548	$^{+0.0061}_{-0.0034}$	$^{+0.0150}_{-0.0048}$
$\tau_{\mathrm{w/o\ CMB}}$	0.0537	$^{+0.0103}_{-0.0034}$	$^{+0.0261}_{-0.0039}$

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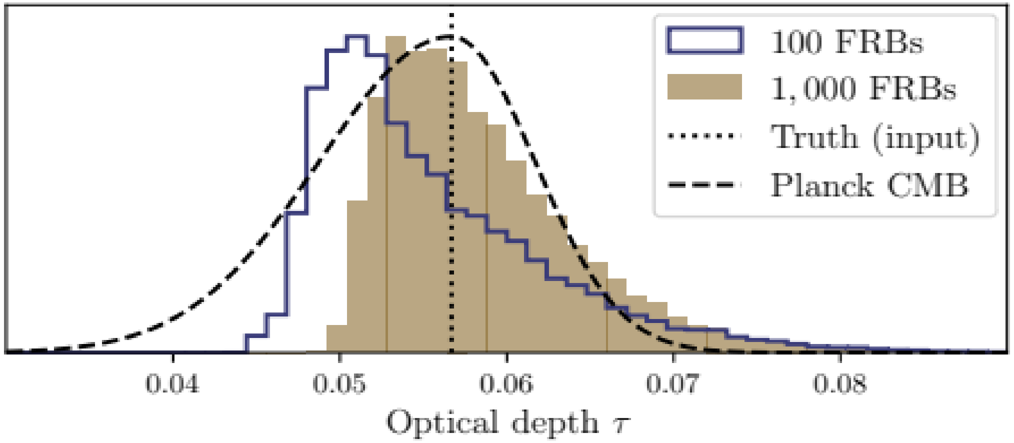
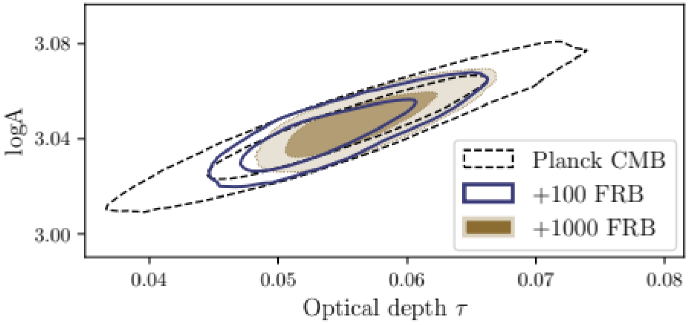
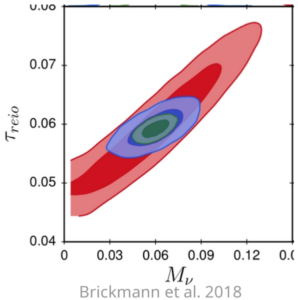
Optical depth constraint

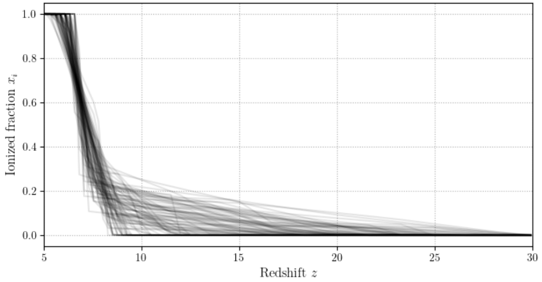






Brickmann et al. 2018
(arXiv:1808.05955)

Key point: Reionization model-*marginalized* (“independent”), i.e. averaged over all reionization models.



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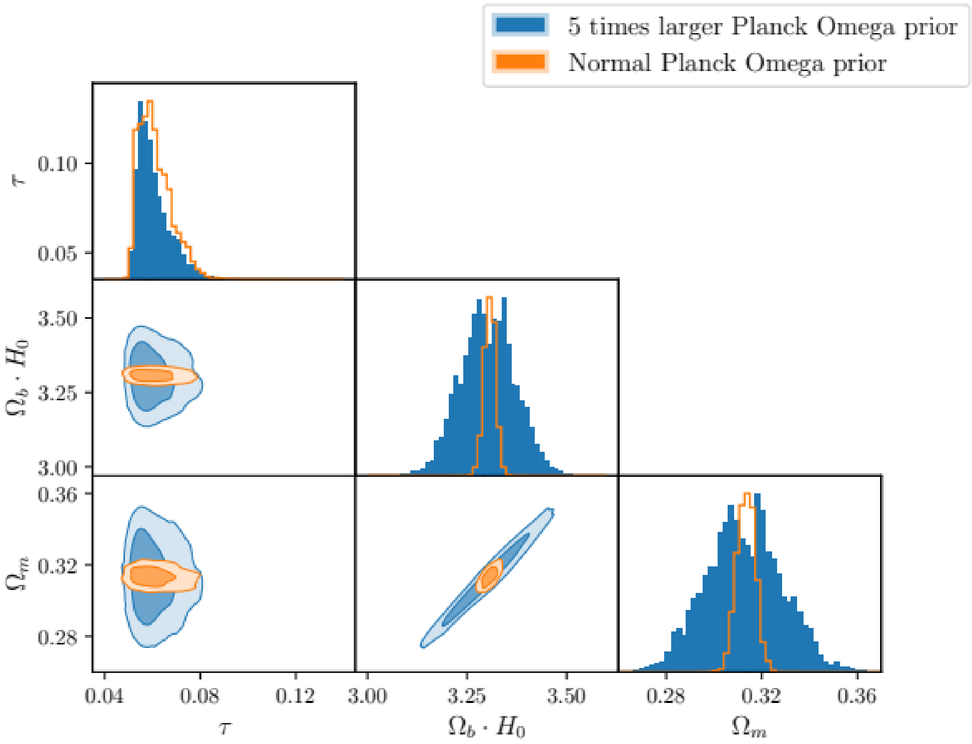
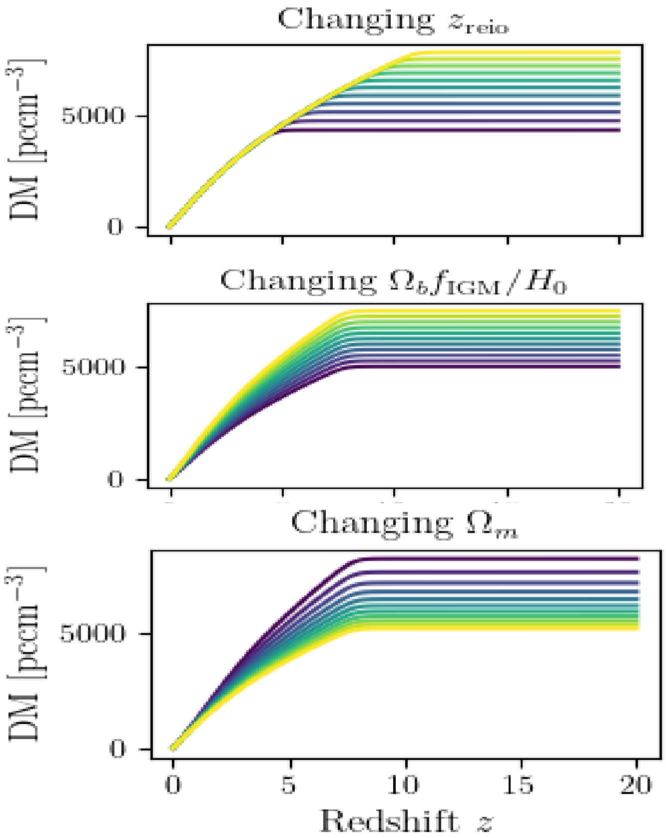
Degeneracies





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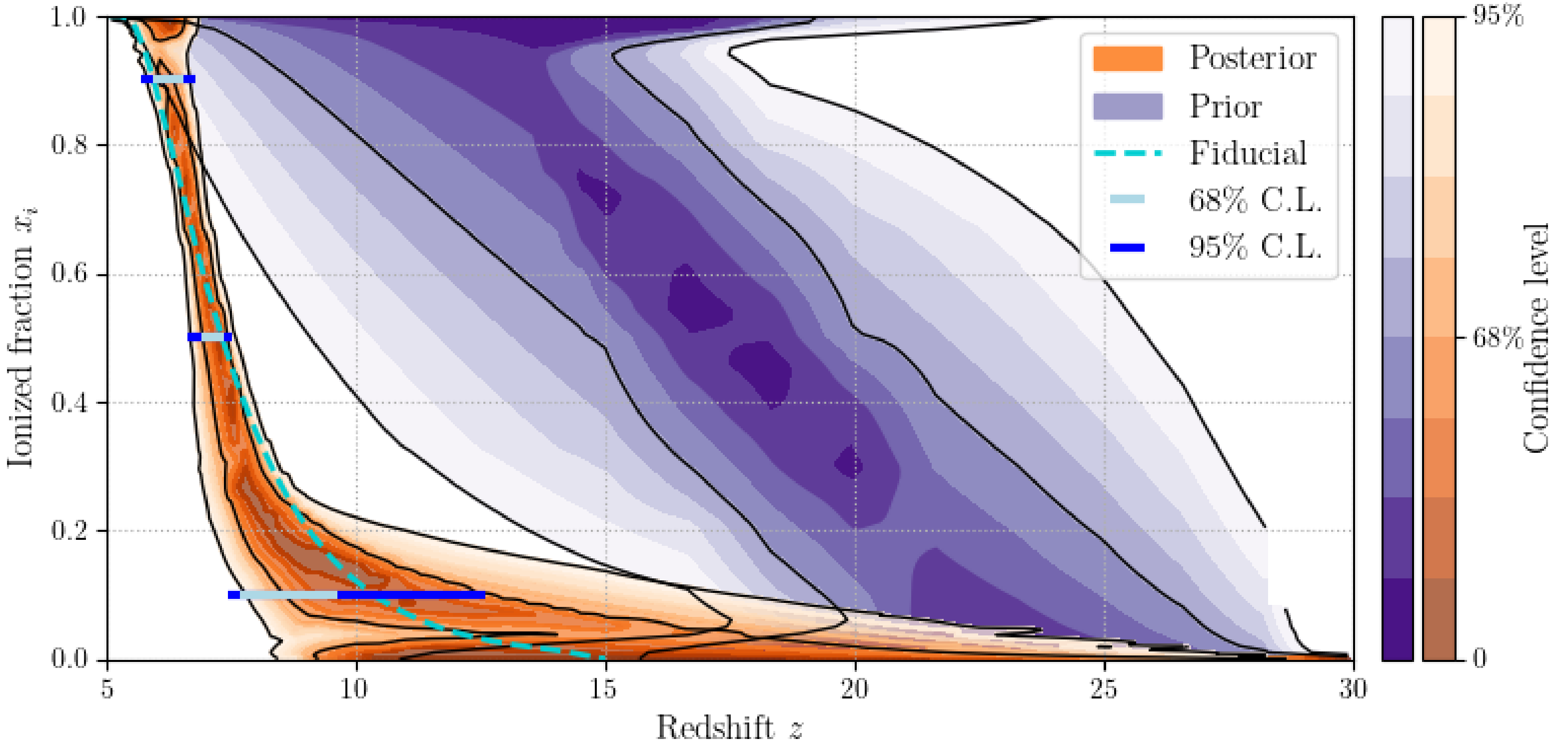
Reionization history posteriors – 1,000 FRBs



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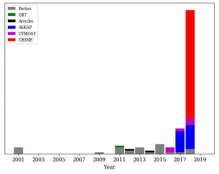
Summary

- FRBs originate from cosmological distances → new probe of the high-z Universe
- This is just the beginning: New instruments → More FRBs



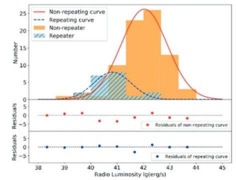
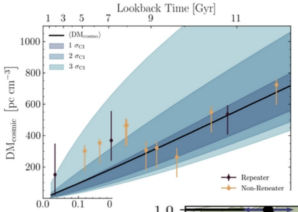
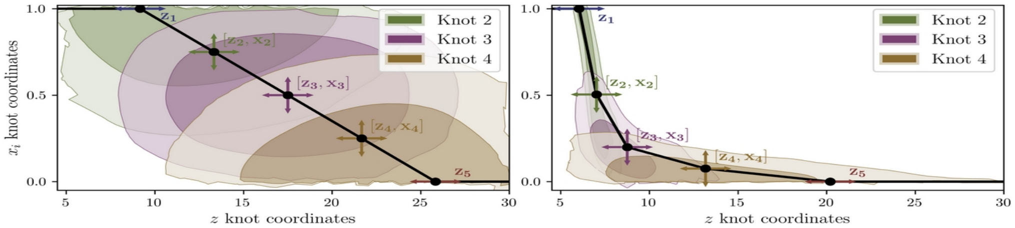


Figure 3. Histogram of repeating and non-repeating FRBs for radio luminosity expressed logarithmically. The solid line is the

- Many open questions: Origin, Mechanism, Repeaters
- Cosmology with Dispersion Measure: H_0, Reionization and more



- Use model-independent parameterizations of functions → applicable everywhere!



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