Statistical inference of fast radio burst environments using galaxy number density: possible difference between CHIME repeaters and non-repeaters

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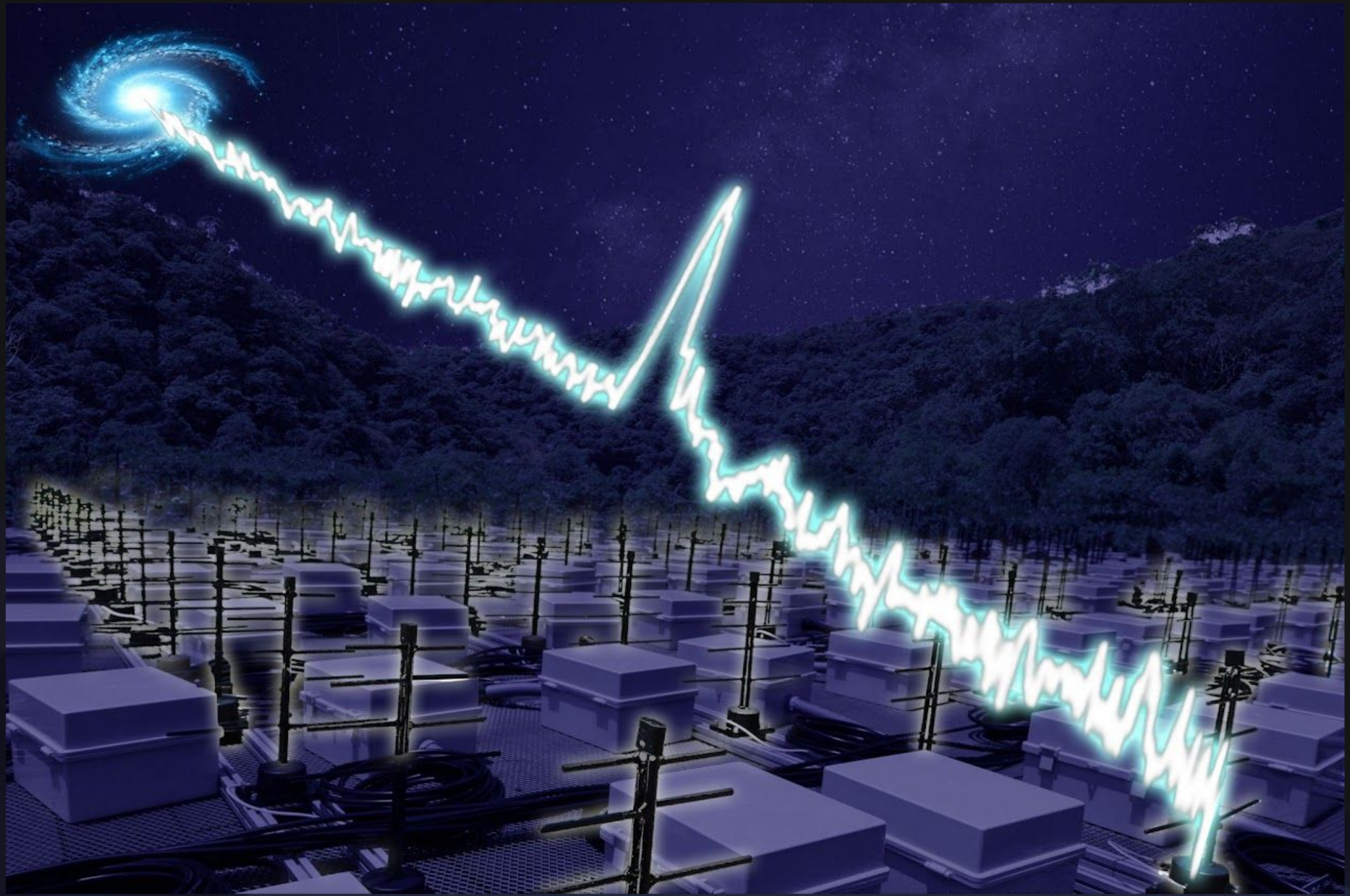
Fast Radio Bursts (FRBs)

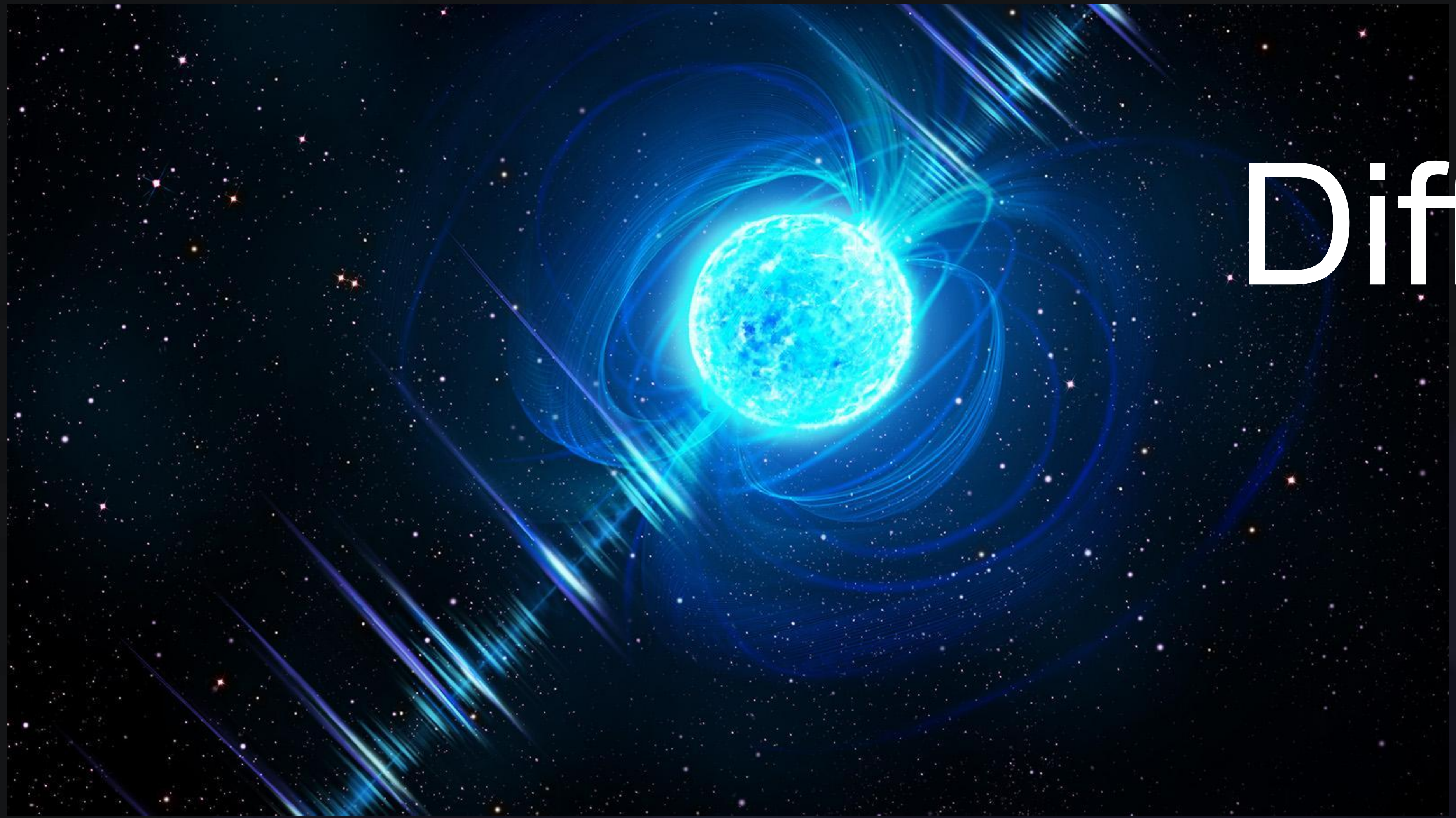
- Bright radio transients
- Origin = unknown
- Two types of FRBs based on their repetition nature
  - Repeaters
  - Non-repeaters



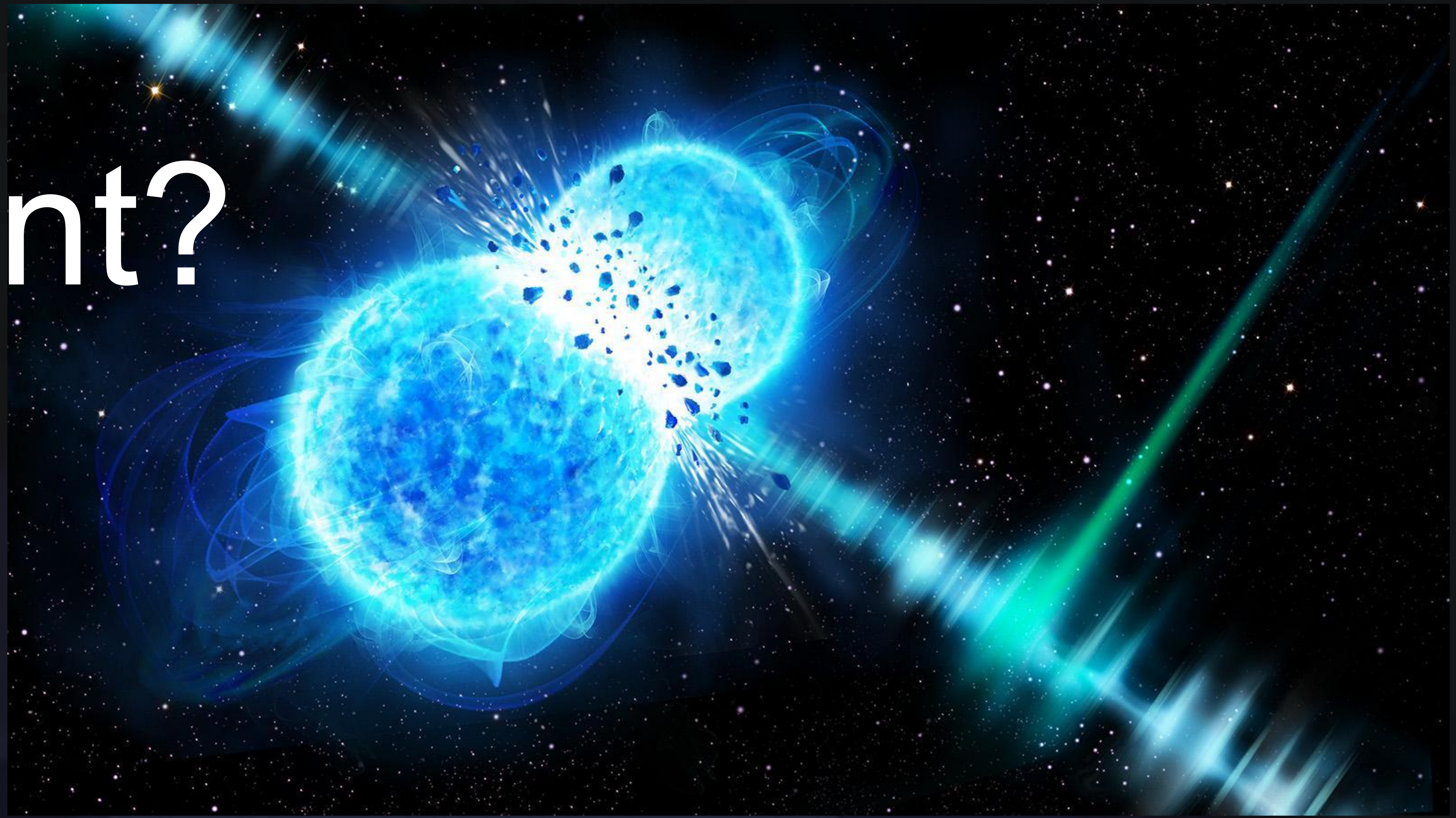
An artistic illustration of a fast radio burst
Image credits: Tomotsugu Goto

Possible progenitors of repeaters and non-repeaters

Repeater ⟺ Non-repeater



Different?

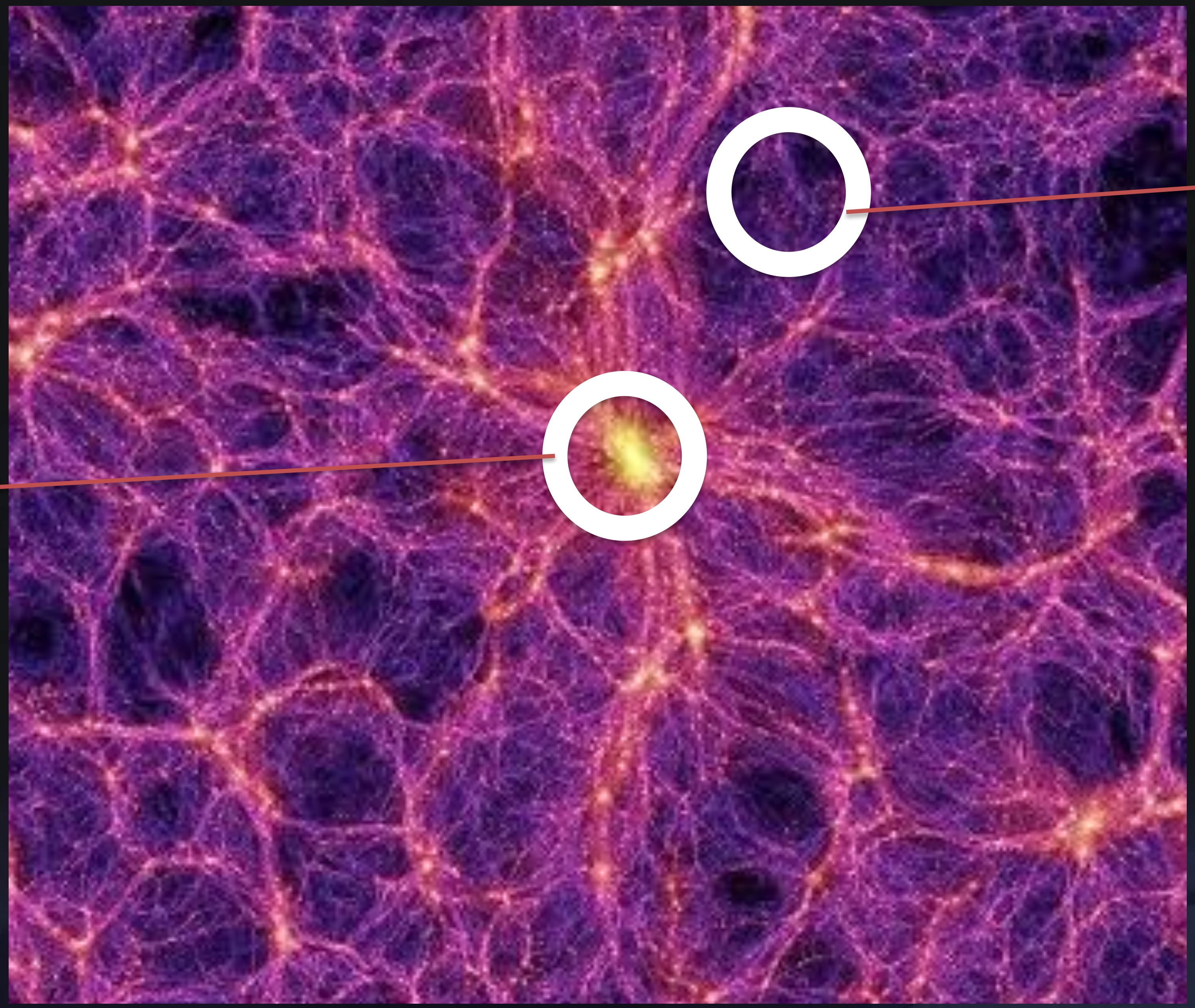


Important to understand the difference/similarity

Image credits: Shotaro Yamasaki

My work (schematic picture)

High number density



Low number density

Image credits: Volker Springel / Max Planck Institute For Astrophysics

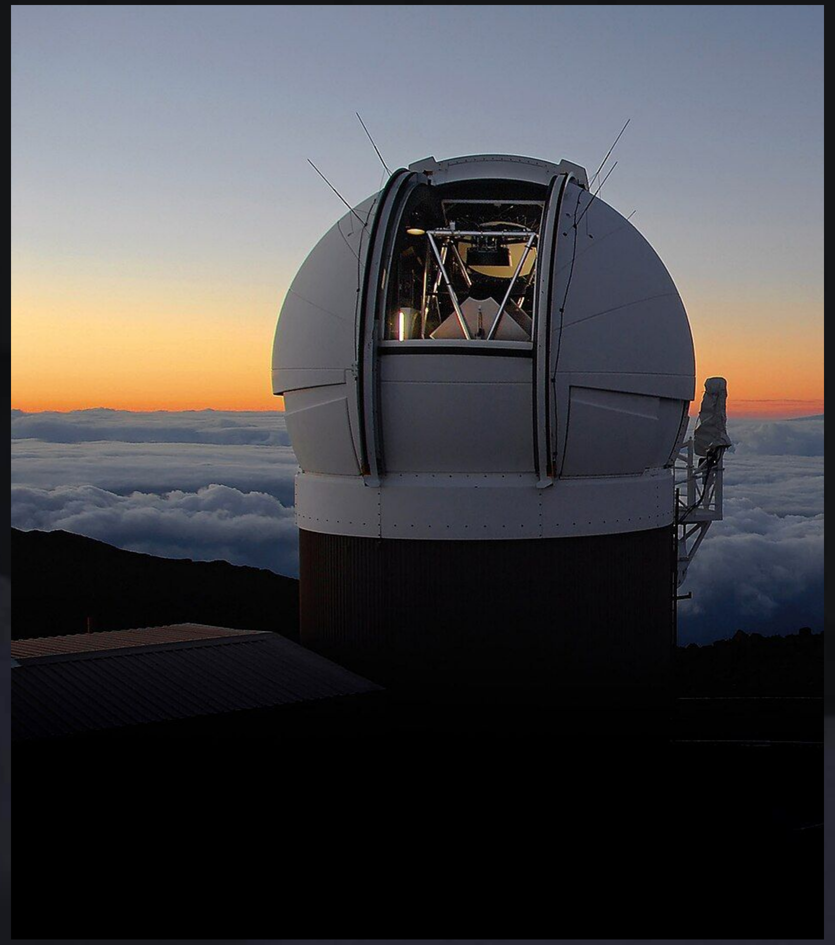
Do non-repeating FRBs and repeater FRBs live in same or different environment???

Sample selection

FRB sample → Canadian Hydrogen Intensity mapping equipment (CHIME) catalog-1 →

Sky map of CHIME FRB
Image credits:CHIME Collaboration

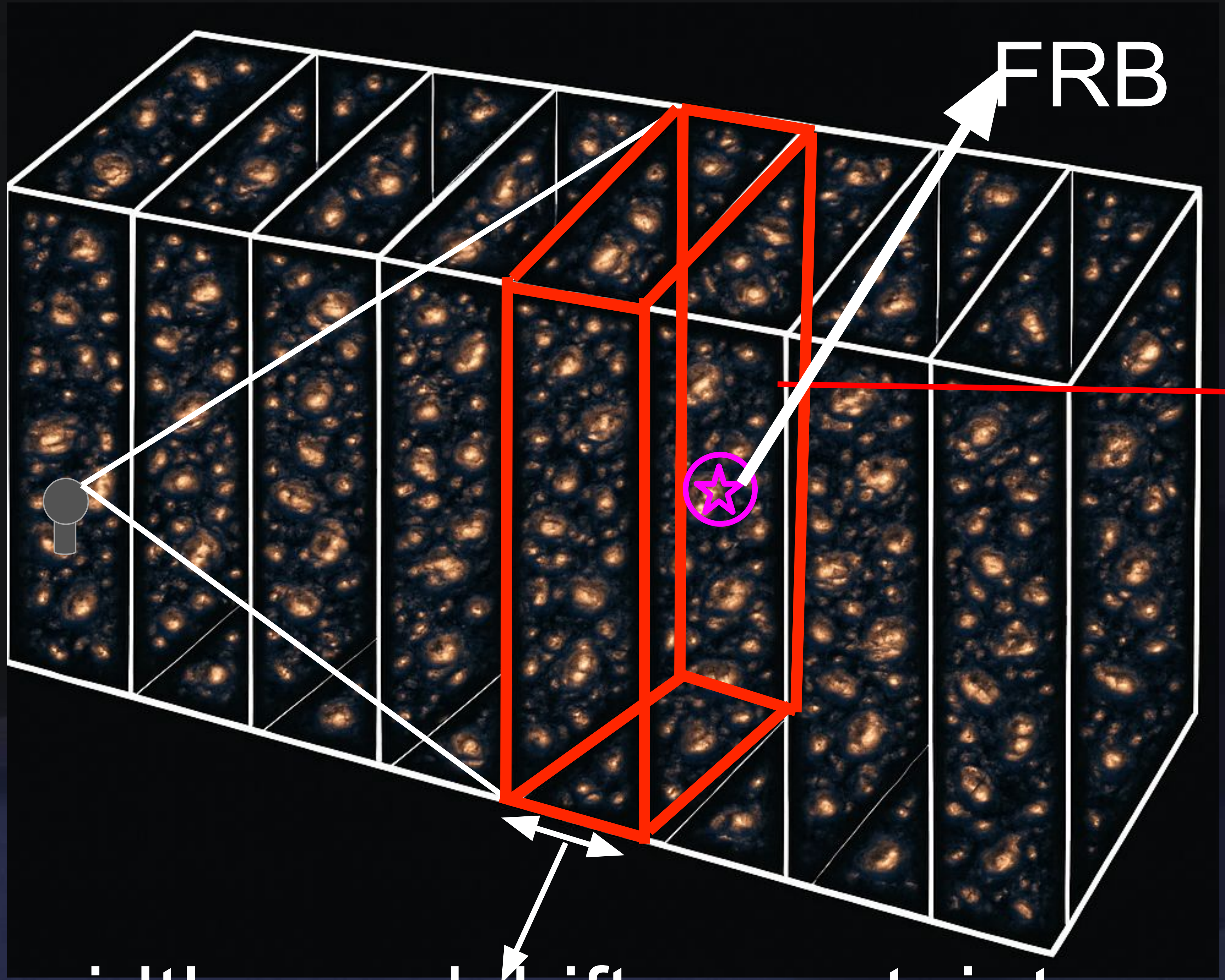
Galaxy sample → Wide-field Infrared Survey Explorer X Pan Starrs 1 (WISE X PS1) →



WISE X PS1
Image credits: NASA/JPL-Caltech (WISE) R. Ratkowski - Pan-STARRS Observatory (PS1)

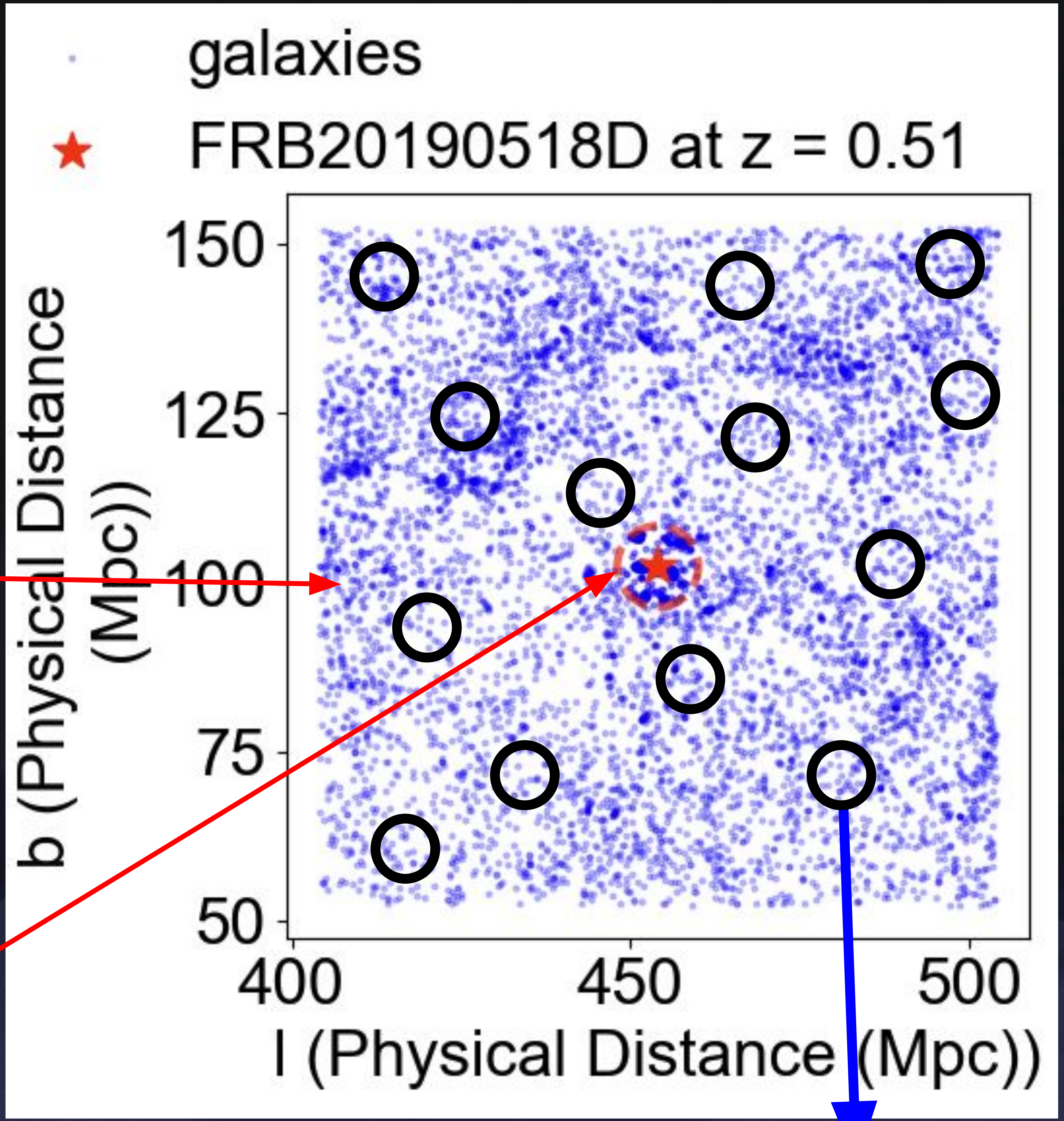
Example of an FRB sample: estimation of galaxy number density

Image credits: AI generated image



width = redshift uncertainty (FRB)

6 Mpc



Random aperture

Calculation of Density increment ($\Delta\delta$)

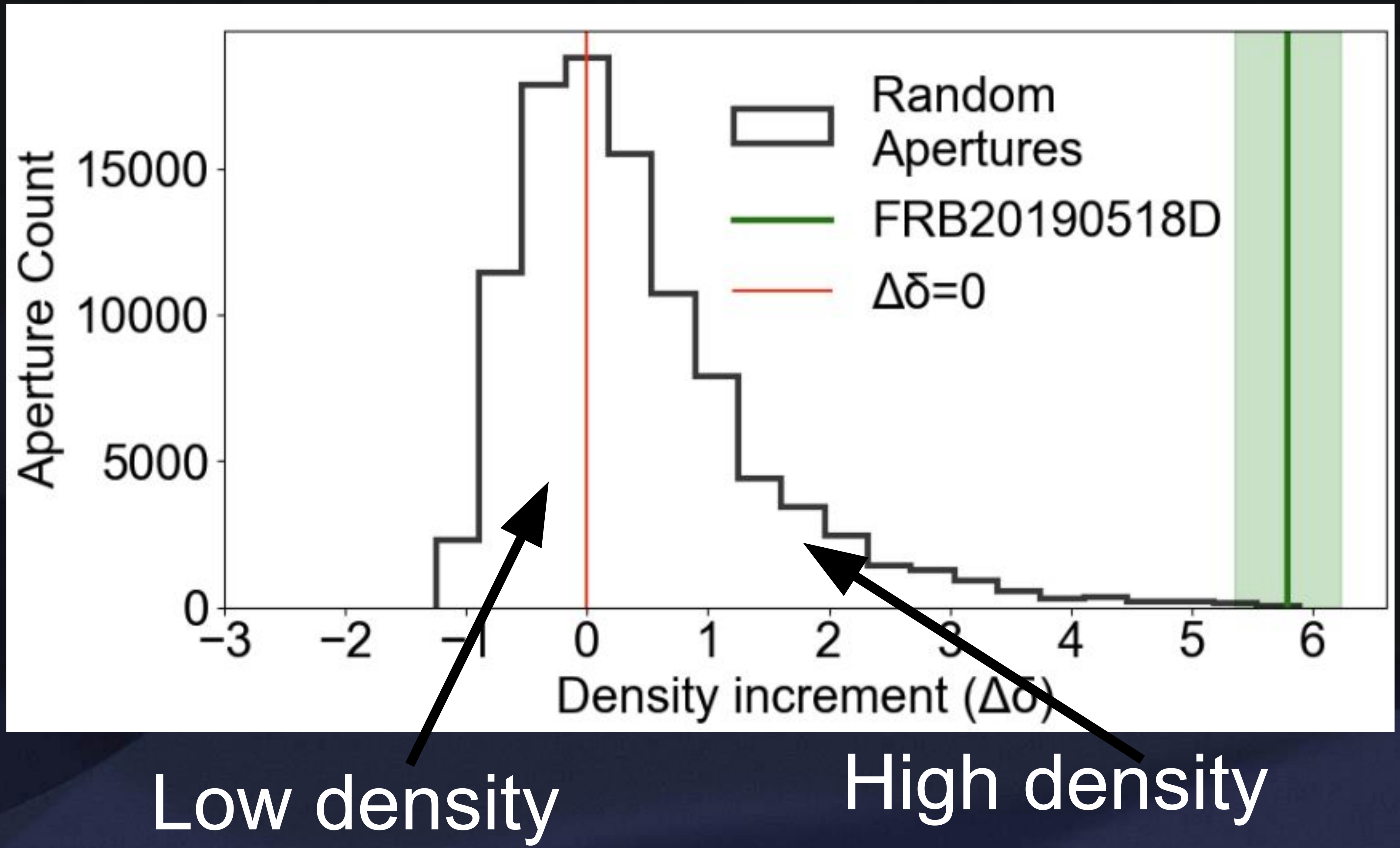
ρ_i → galaxy number density of i^{th} aperture

σ_ρ → standard deviation of the density distribution

$$\delta_i = \rho_i / \sigma_\rho$$

We refer to these as density increments, denoted by ($\Delta\delta_i$):

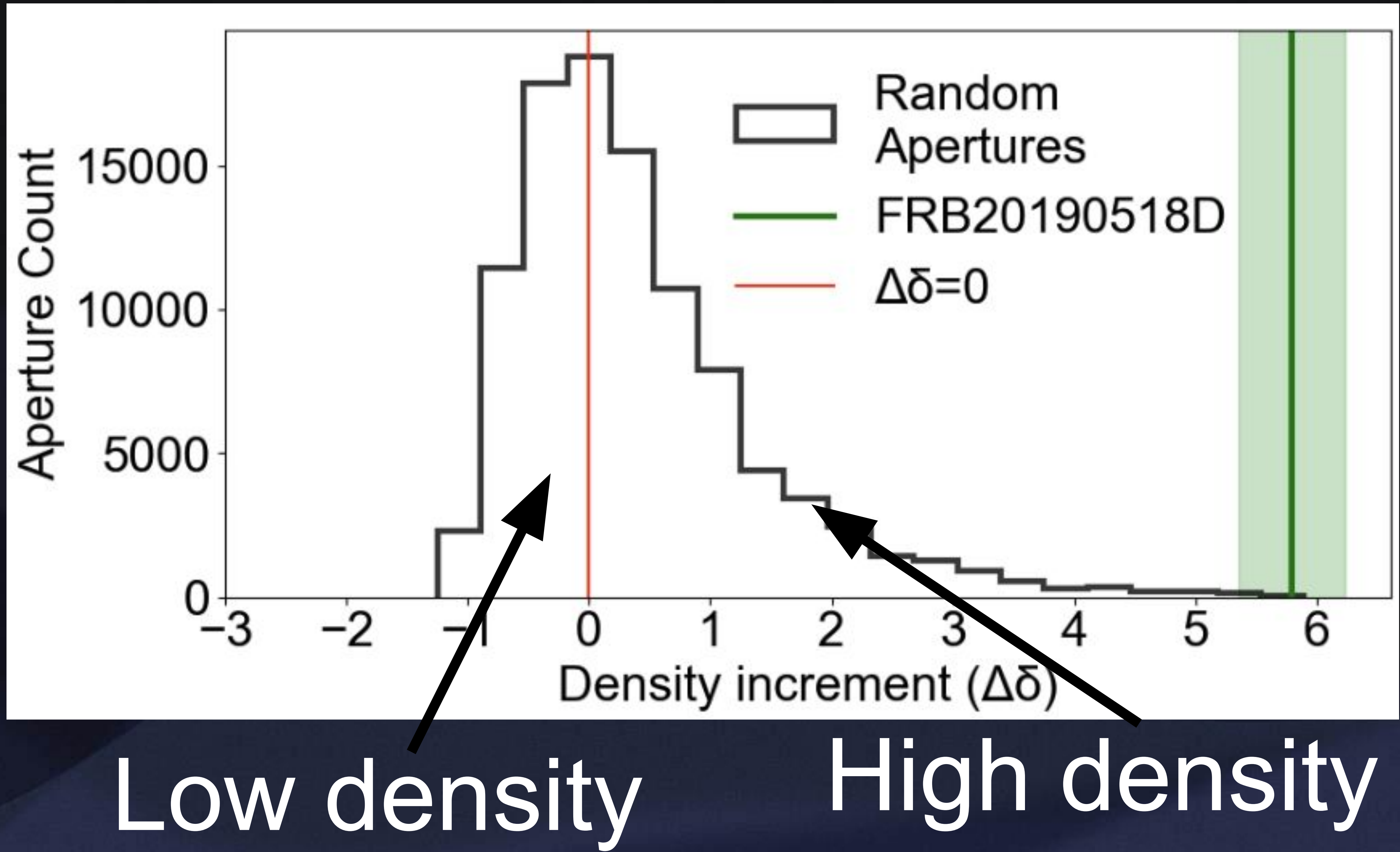
$$\Delta\delta_i = \delta_i - \delta_{random,\ peak}$$



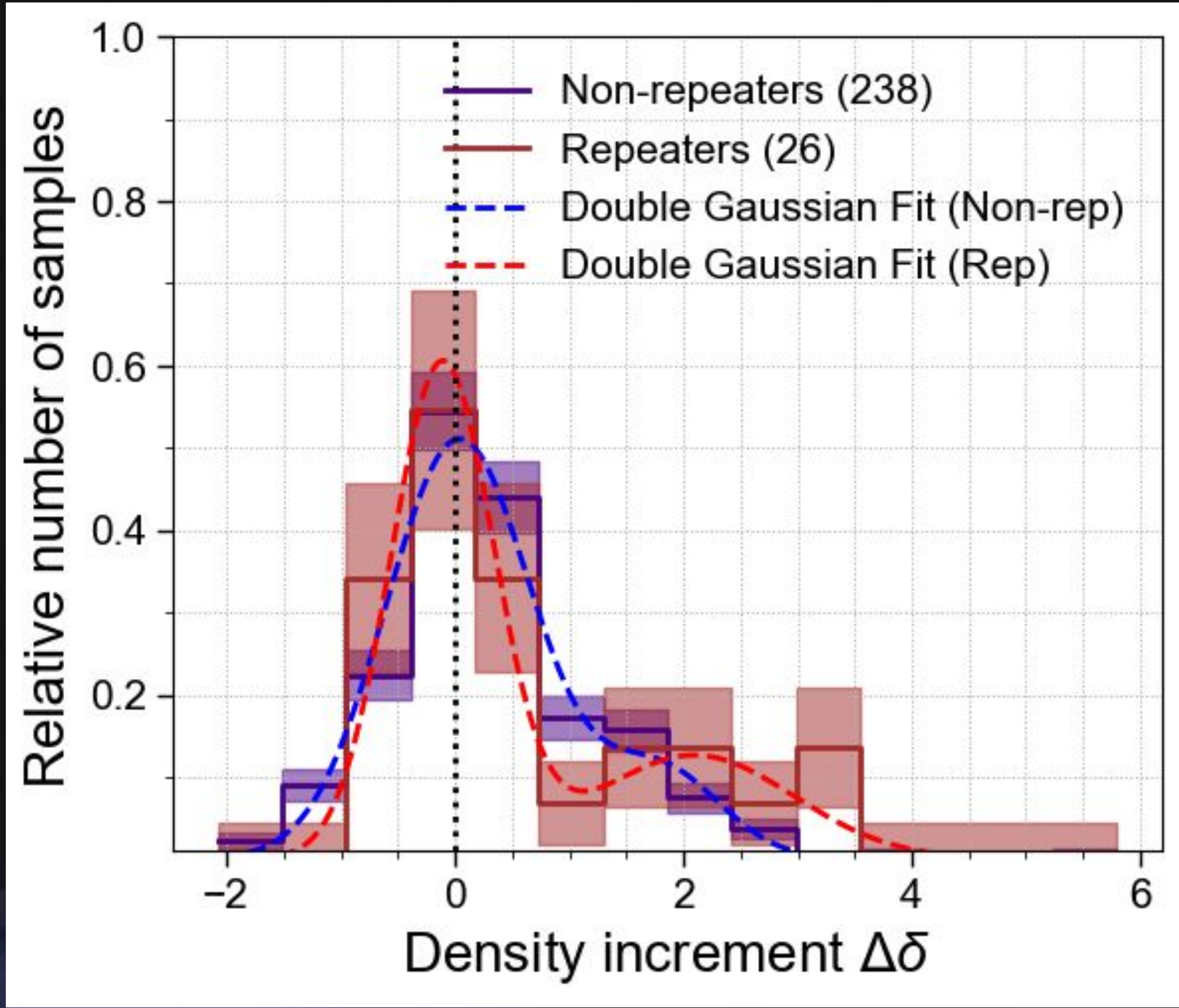
Significance of our normalization

- To overcome Malmquist bias in our galaxy sample

- Using this technique, we can say how significant is our over/under density region compared to the reference densities



Result 1



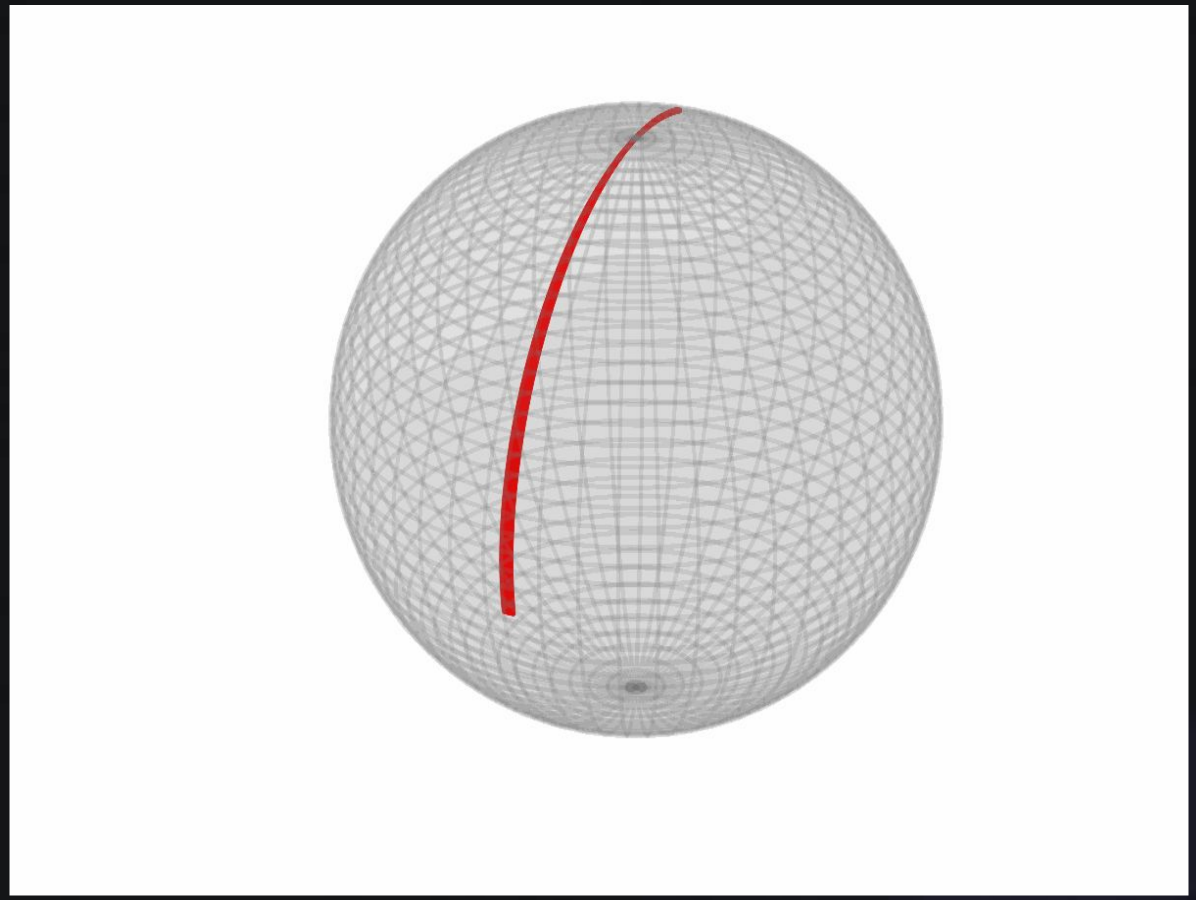
KS test: repeater v.s. non-repeater

p-value: 0.405

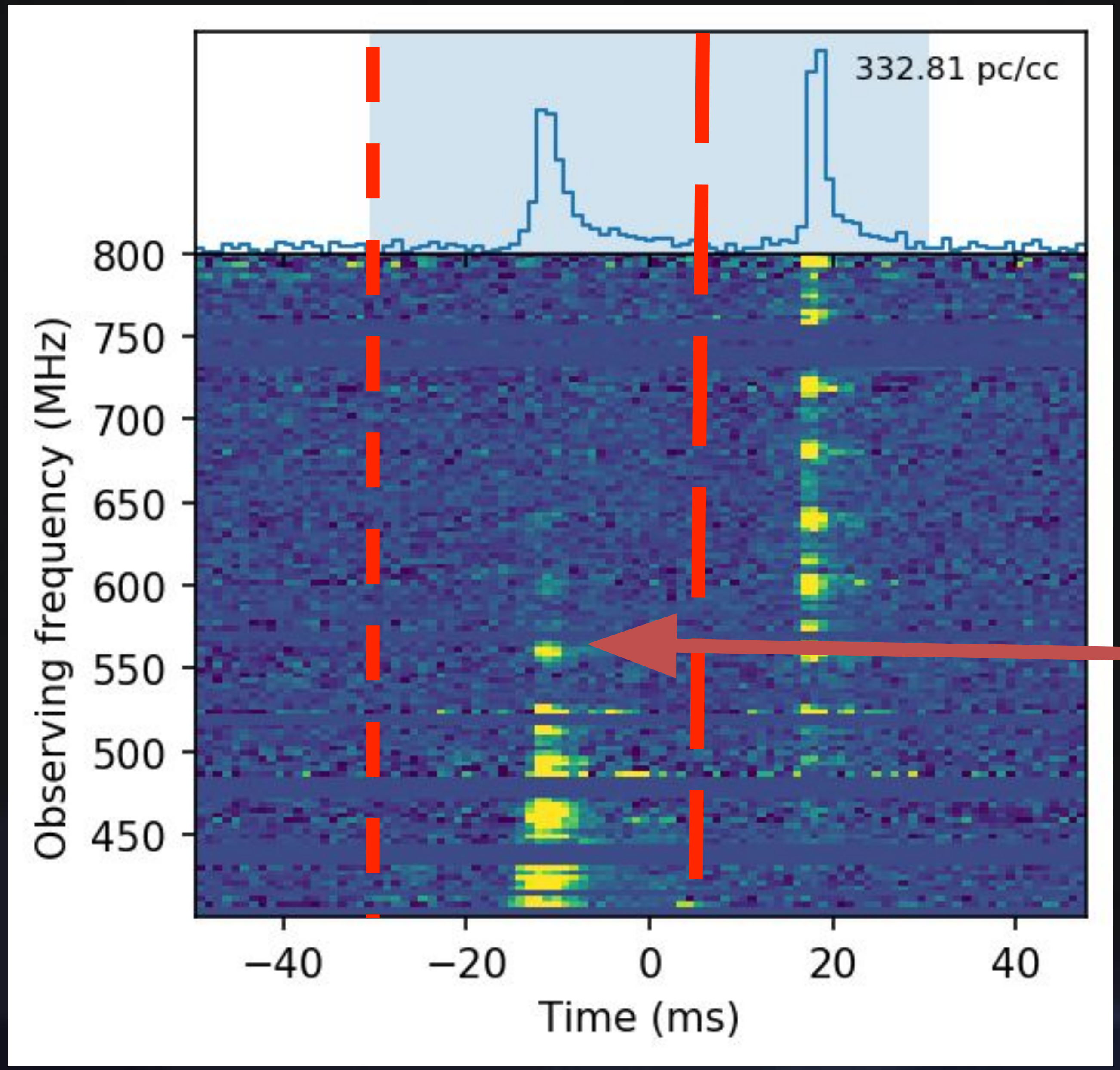
Are CHIME non-repeaters contaminated by repeaters (eg.,Ravi, V. et al 2019,.James 2023;Yamasaki et.al, 2024)

Discussion: (Concept) possible contamination of repeaters in non-repeaters

CHIME's FoV
(2 deg x 120 deg)



courtesy: Shotaro Yamasaki



CHIME/FRB Collaboration, *et al.* (2020)

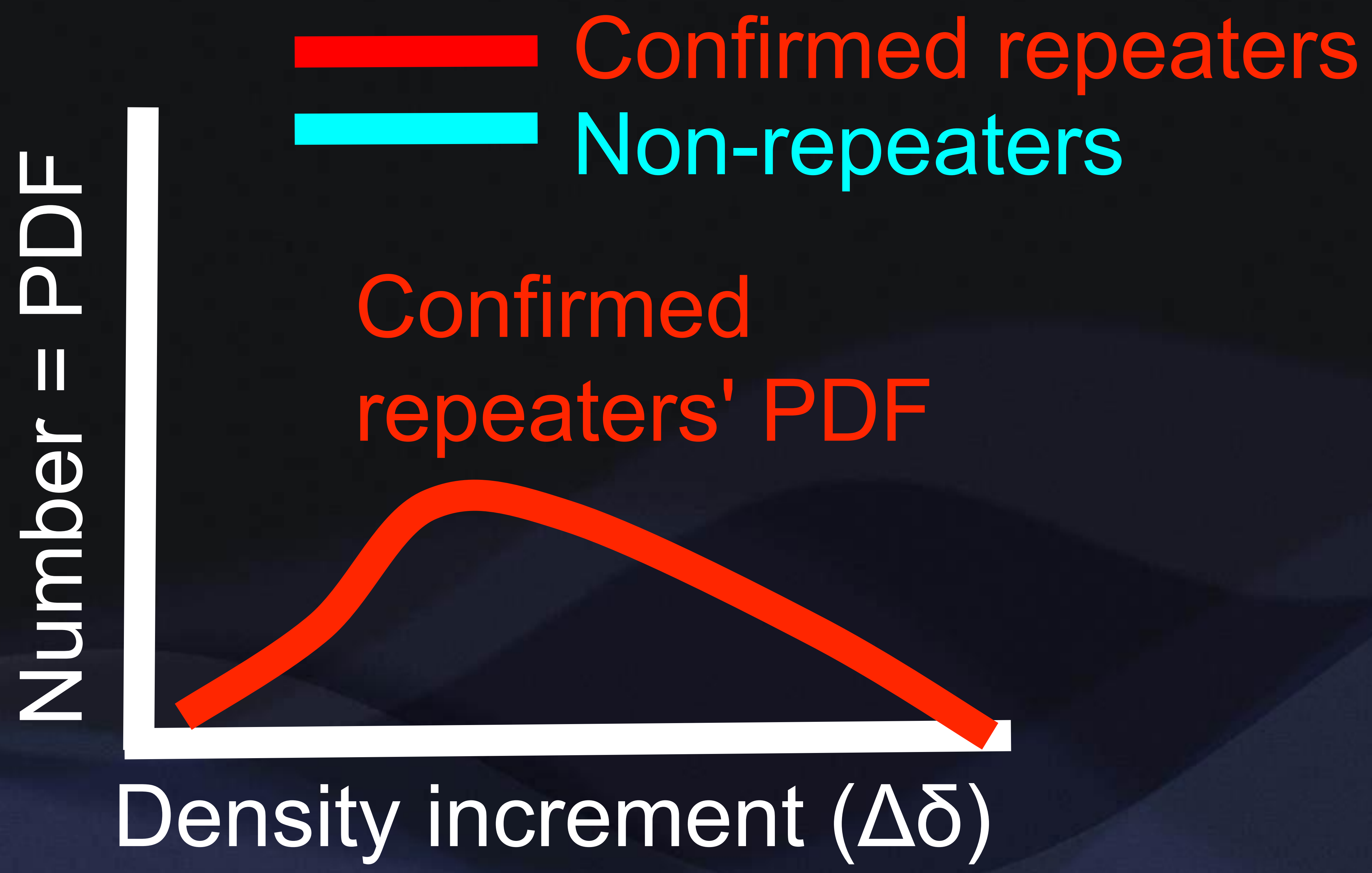
- - observational window

misclassified as non-repeater

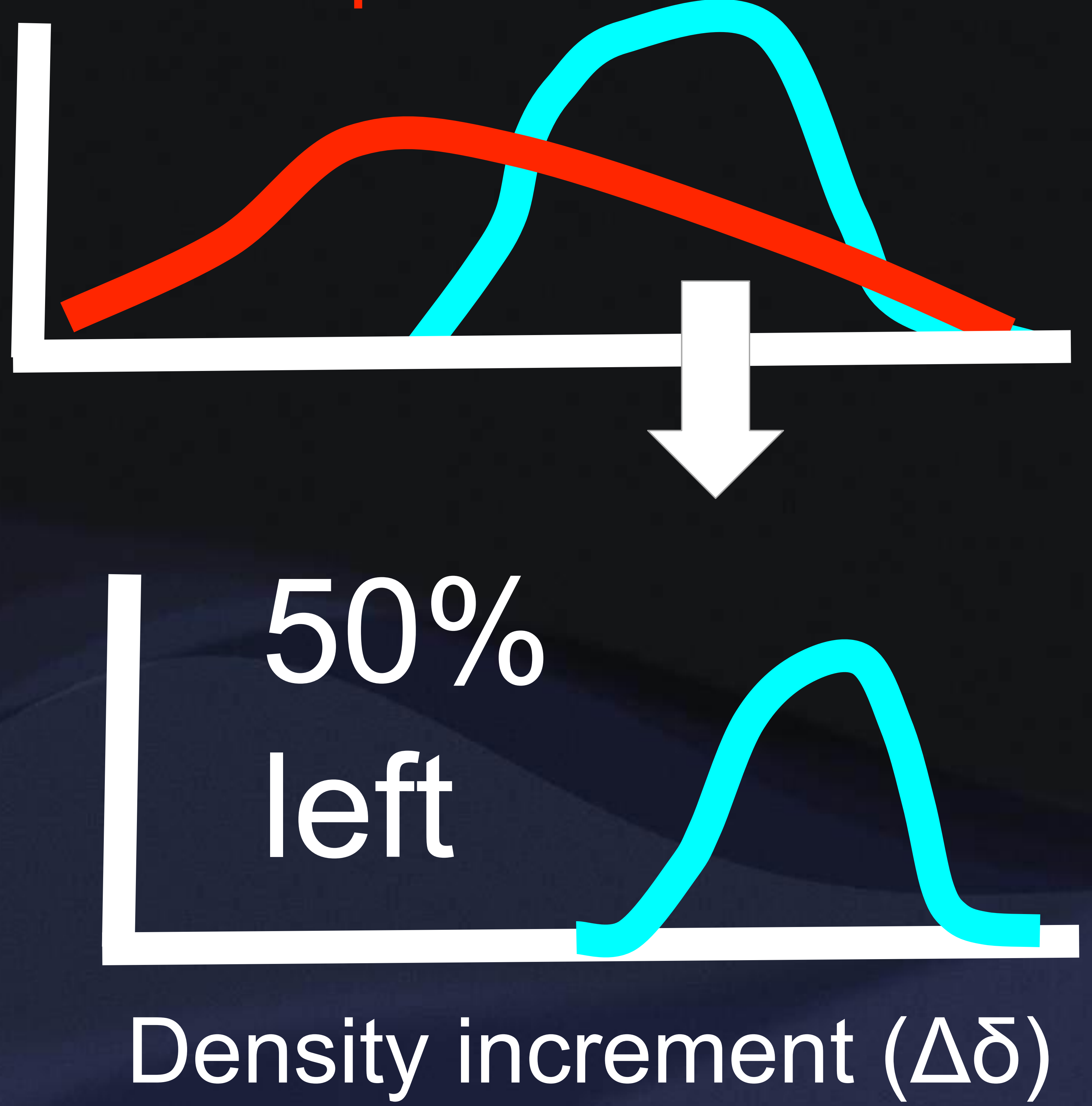
- Assumed 50% of non-repeaters tend to repeat according to the previous literatures (eg.,Ravi, V. et al 2019, James 2023; Yamasaki et al. 2024)

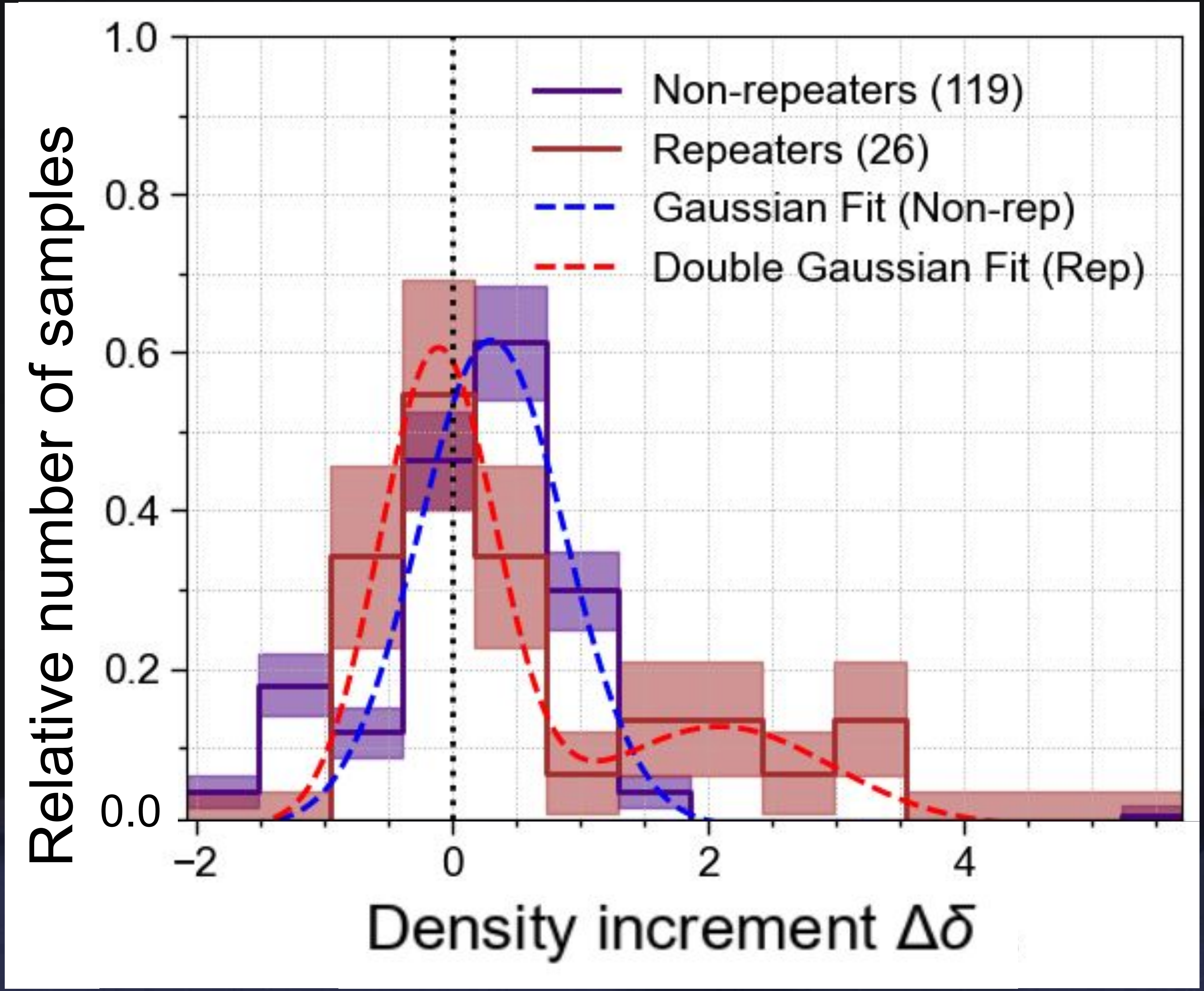
- Statistically removed 50% of non-repeater sample from our analysis

Schematic picture of the process



Statistically remove 50% non-repeaters following the repeater's PDF





KS test p-value = 0.043

Galactic environment of repeaters ≠ Galactic environment of non-repeaters

Repeaters v.s. Non-repeaters

Repeaters → low density environment

Non-repeaters → high density environment

Look Elsewhere Effect (LEE) and Westfall Young permutation process

- Performing statistical tests like the KS test, multiple times, increases the chance of false positives due to the "Look Elsewhere Effect" (LEE).

- To counter LEE, there are some famous techniques we can use,

1. Bonferroni Correction
2. Holm-Bonferroni method
3. Westfall Young minP permutation method

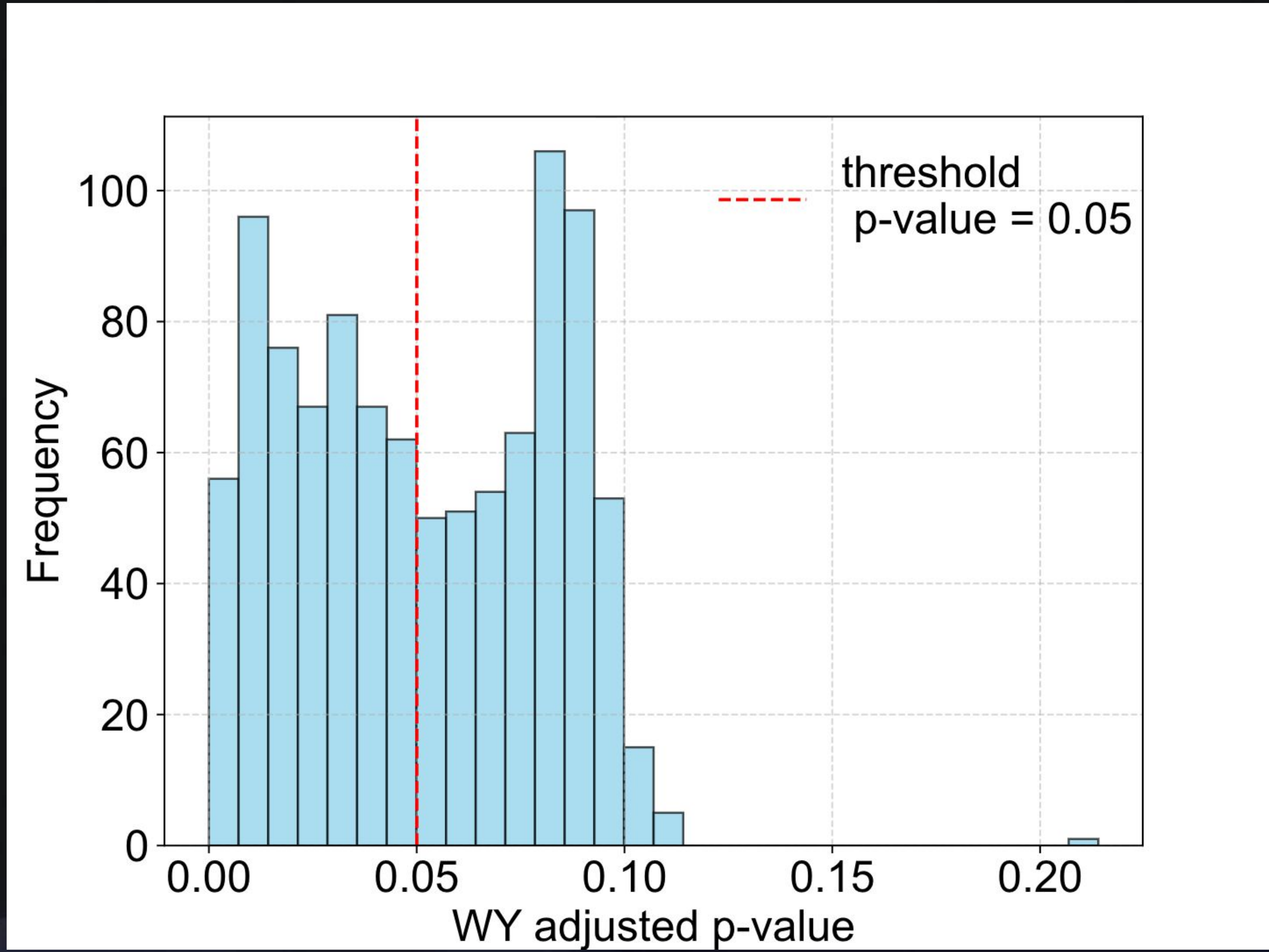
Flow chart of the WY minP method

Null Hypothesis: Repeaters and non-repeaters have the same galactic environment (same density increment values)

Observed: $p_{obs} = 0.043$ (before correction)

Process: we combine 119 non-repeaters and 26 repeaters. To create pseudo dataset of 145 FRBs then separate them into 26 pseudo repeaters and the rest is pseudo non-repeaters.

We run 10,000 KS tests between randomized pseudo-samples to get pseudo p-values. The fraction $p_{psuedo} < p_{obs}$ gives the adjusted p-value. If adjusted p-value < 0.05, the null is rejected.



Selection of 50% non-repeater samples = random process

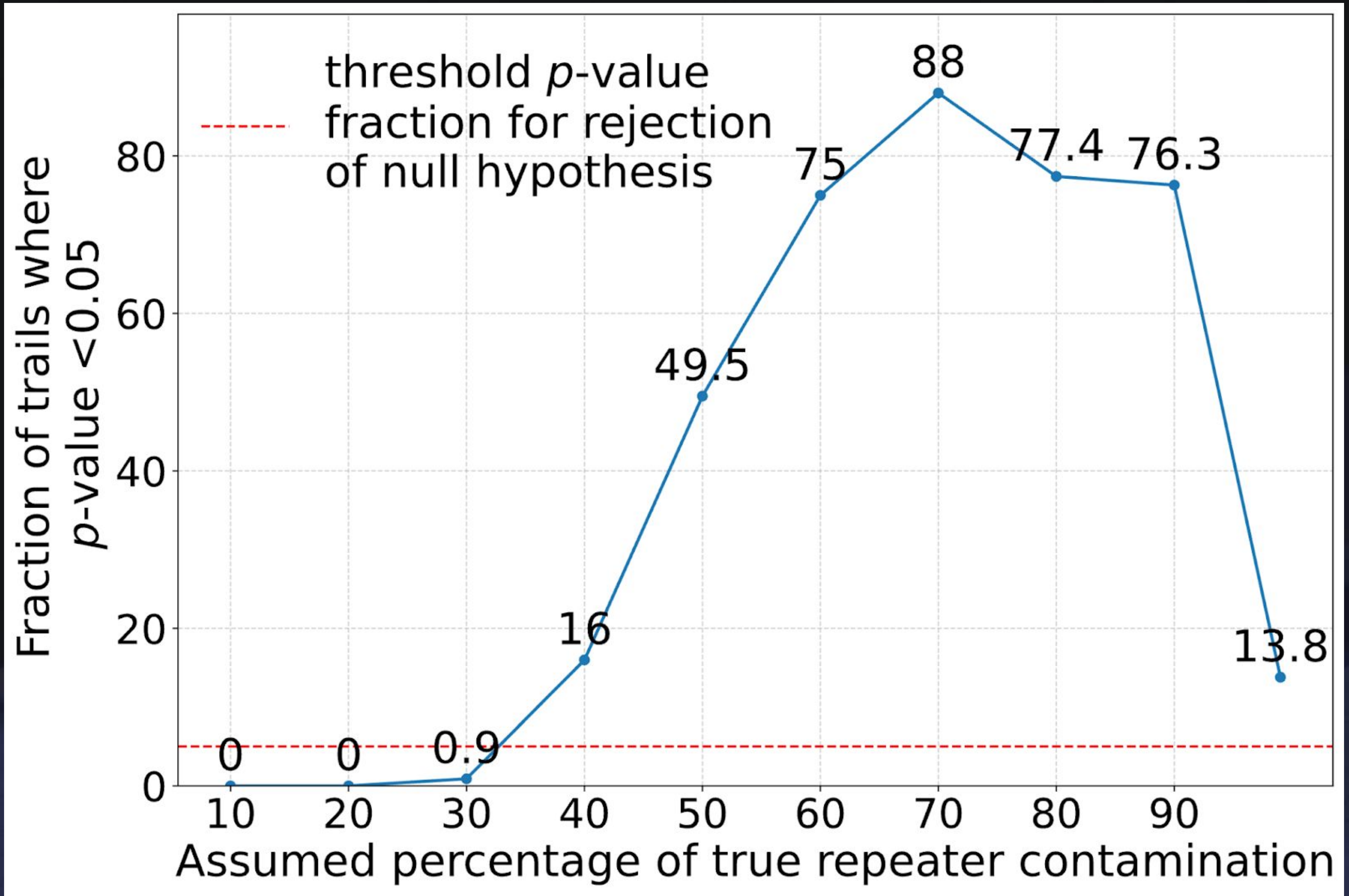
Repeated the entire process 1000 times to remove selection effects

Out of 1000 trials, 495 trails gave ($p_{adjusted}$<0.05)

random coincidence = threshold *number of trails

Successfully Reject null hypothesis

Percentage of True repeater fraction v.s. Rejection of null hypothesis



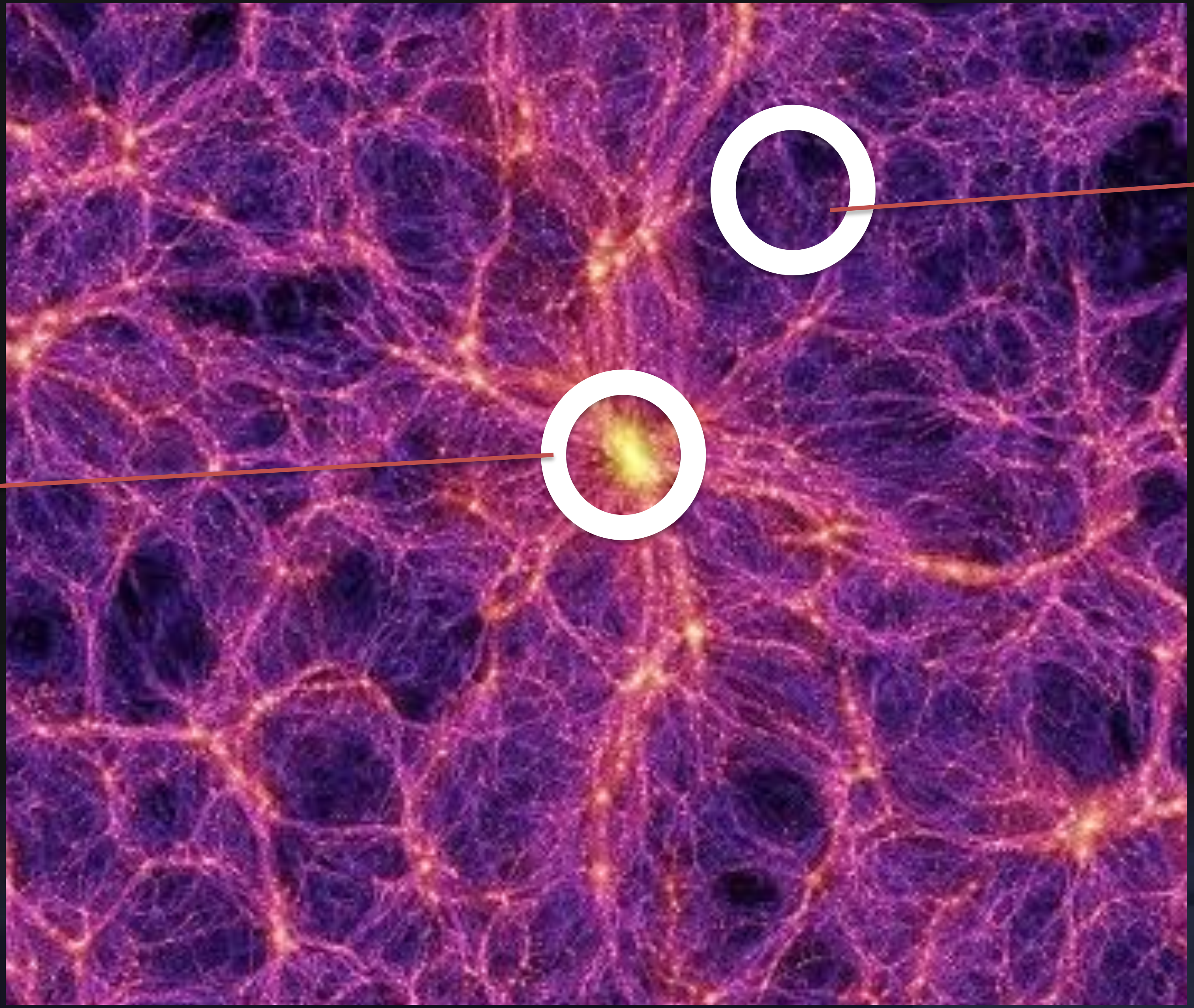
Rejection of the null holds for repeater fractions >40%.

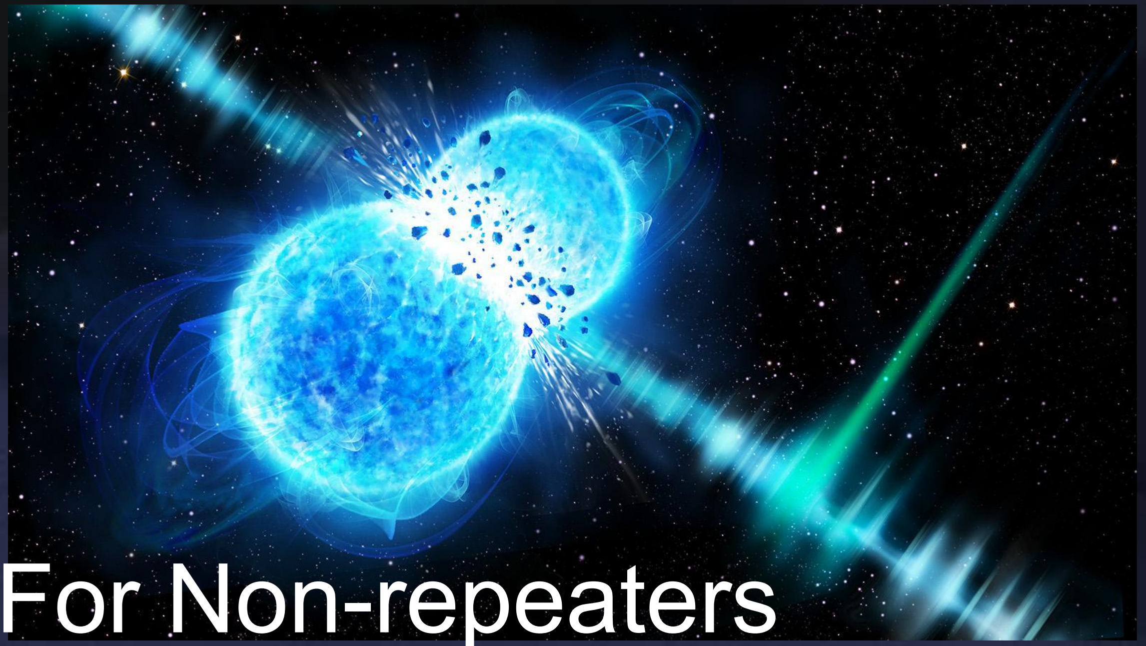
Conclusions:

Our unique statistical approach

Low density

High density





For Non-repeaters

For Repeaters

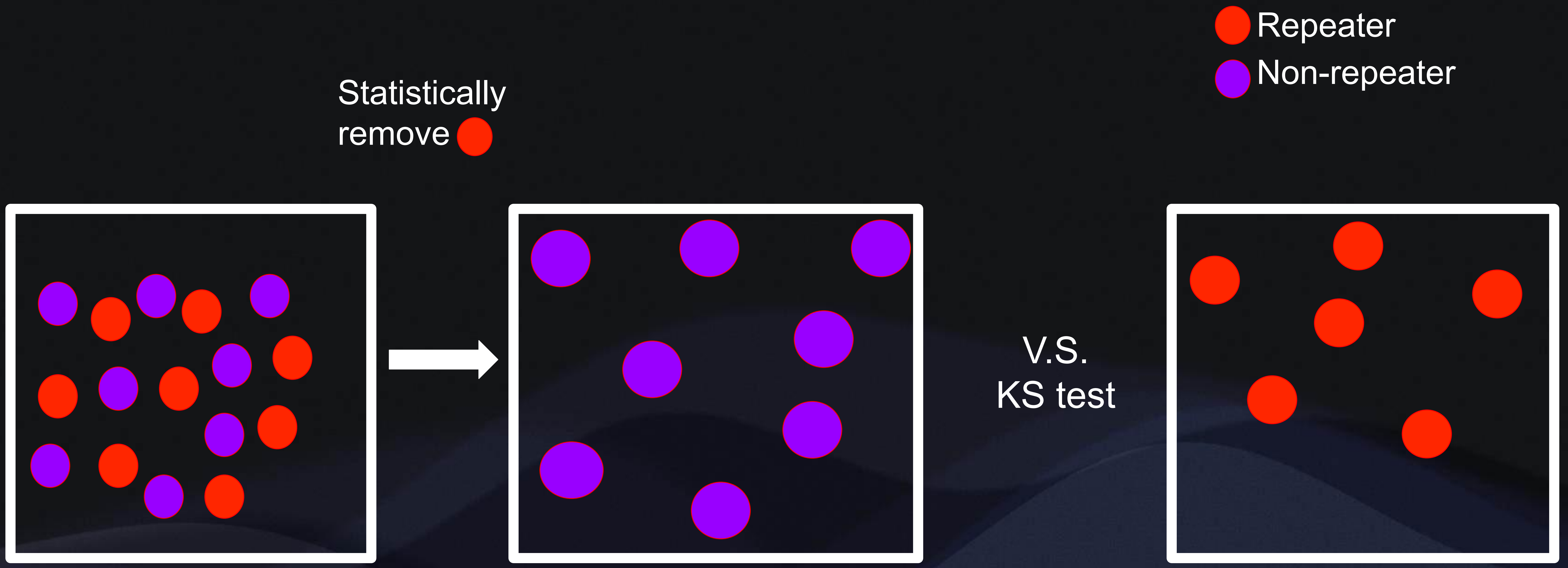
indicates
different
environments/origin

Future works

Compare the galaxy number density around FRBs with that of different progenitor scenarios such as AGNs, supernovae (SNe), and long Gamma-Ray Bursts (LGRBs), Short Gamma-Ray Bursts (SGRBs)

Backup slides

Discussion: (Concept) Removing possible contamination of repeaters in non-repeaters

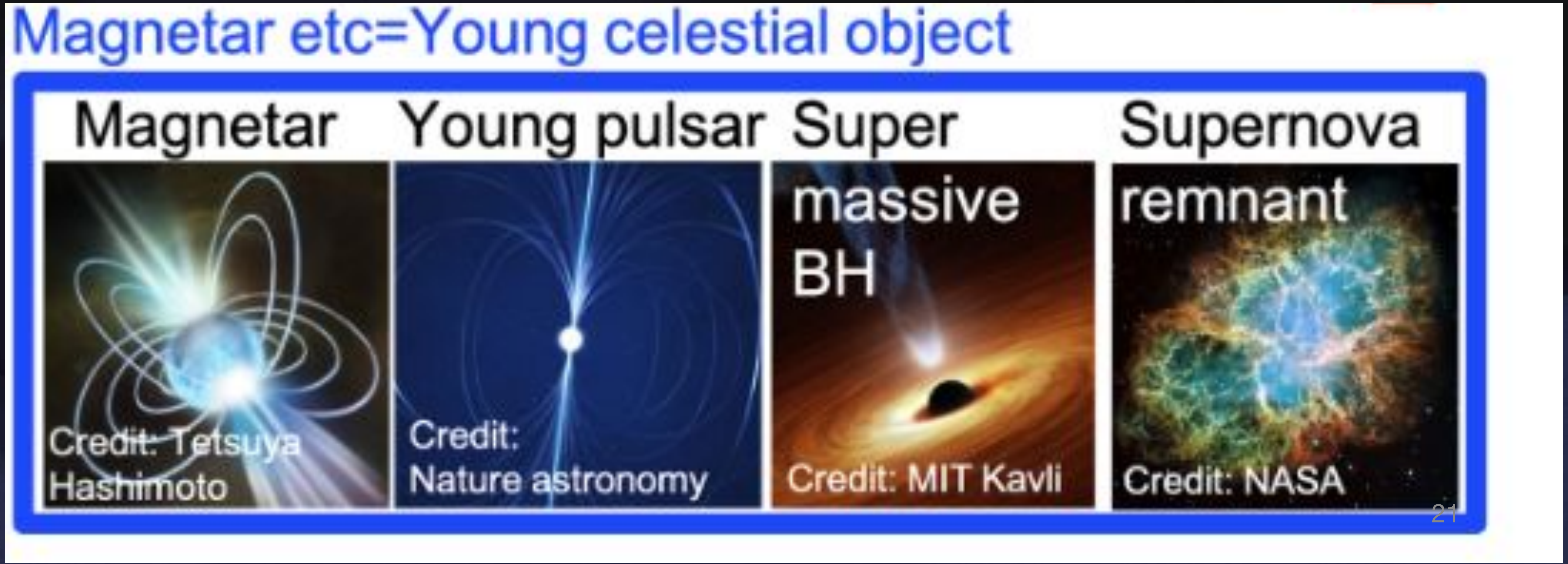


Non-repeater samples (contaminated by repeaters)

Statistically pure non-repeater samples

Pure repeater samples

Possible Progenitor candidates



Credit: Tetsuya Hashimoto

FRB sample selection

For data we use Canadian Hydrogen Intensity Mapping Equipment (CHIME)

- The FRB is located within the sky coverage of WISE ×PS1
- |b| > 20 degree
- 0<z < 0.8
- Removed the FRB samples which have negative values of redshifts also which has abnormal distribution of galaxies as keeping it could bring uncertainties in number density calculations.

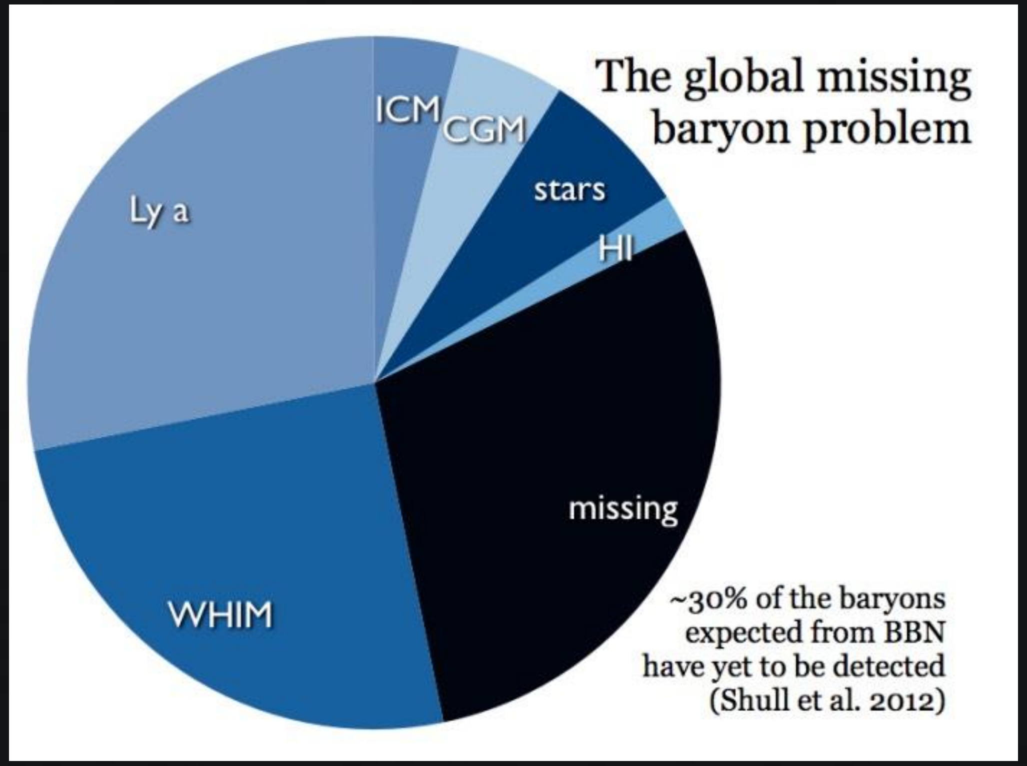
Galaxies sample selection

For data we use WISE x PS1 catalog.

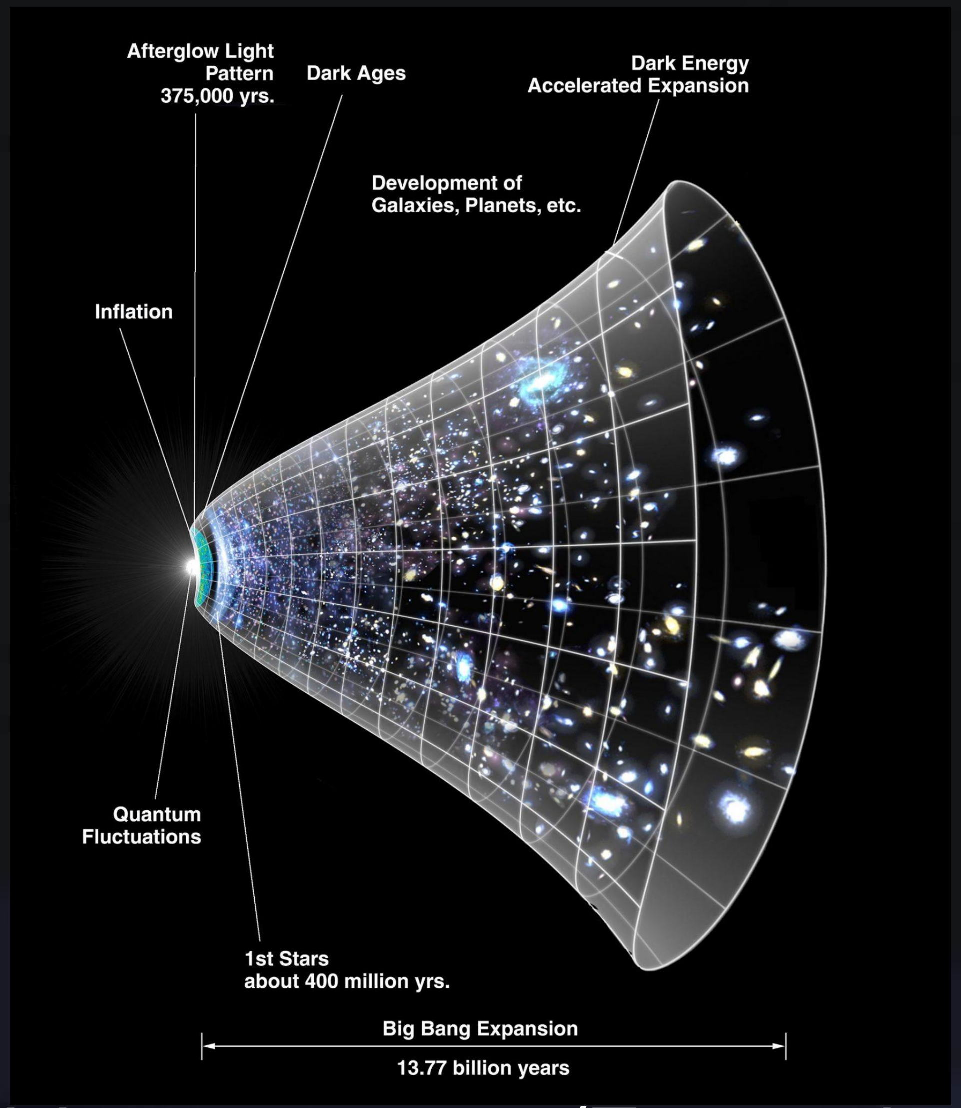
- The galaxies are selected inside a 100x100 Mpc^{-2} around the position of FRB with the help of angular diameter distance
- The galaxy samples inside this region are subjected to a vega magnitude cut of W1 < 16.8 magnitude.
- A redshift cut was made with the help of FRBs error in redshift and galaxies are selected within this redshift

- Improved sample size by a factor of 2 (non-repeaters (238) and repeaters (26)) (CHIME/FRB Collaboration et al. 2021 golden samples(Chime/FRB Collaboration et al. 2023))

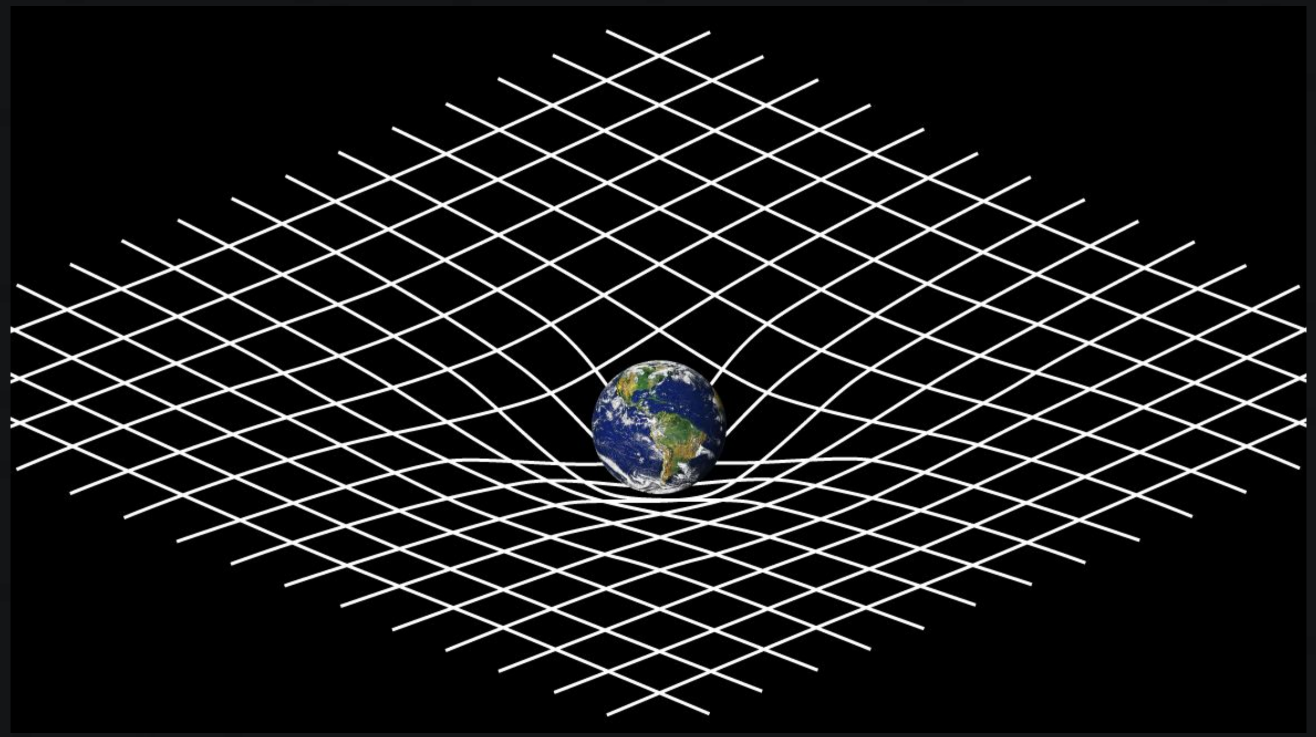
Applications of Fast Radio Bursts



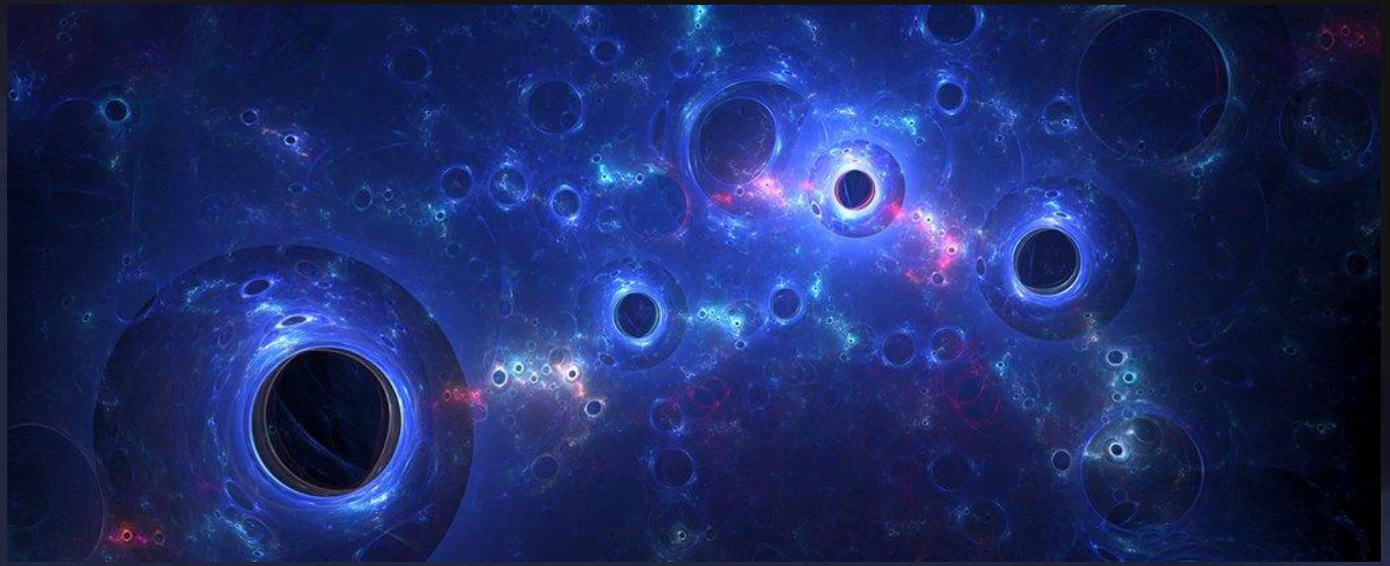
Missing Baryon problem (Shull et al. 2012)



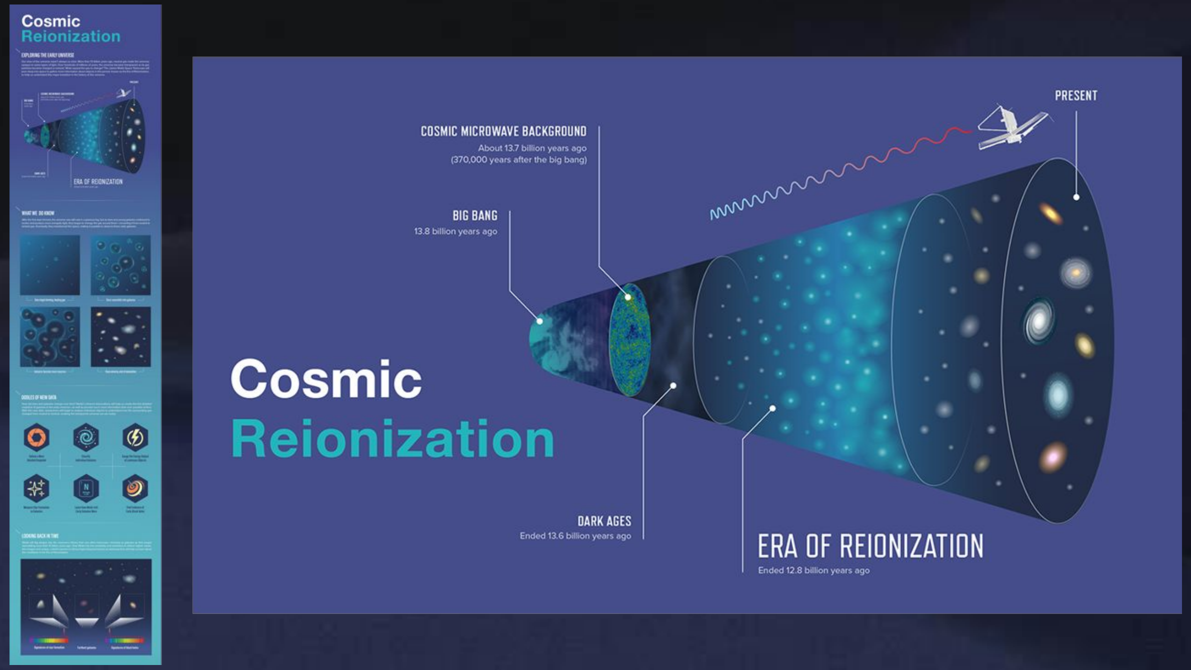
Hubble constant (Expansion of the universe)
Credit: NASA/WMAP Science Team/ Art by Dana Berry
Also refer Yang, T.-C., Hashimoto, T., Hsu, T.-Y., Goto, T., Ling, C.-T., Ho, S. C.-C., … Kilerci, E. (2024). Constraining the Hubble constant with scattering in host galaxies of fast radio bursts. *arXiv E-Prints*, arXiv:2411.02249. doi:10.48550/arXiv.2411.02249



General relativity (Weak equivalence principle)
Credit: NASA (Hashimoto et al., 2021.)



Dark matter
Credits: sakkmesterke/iStock
Ho, S. C.-C., et al. (2023). *The Astrophysical Journal, 950*(1), 53.



Cosmic reionization
Credits: NASA, ESA, CSA, Joyce Kang (STScI)

Advantages

- Large scale environment → No precise location needed
- CHIME 2 + BURSTT → 10 × more FRBs

Flow chart of the removal process

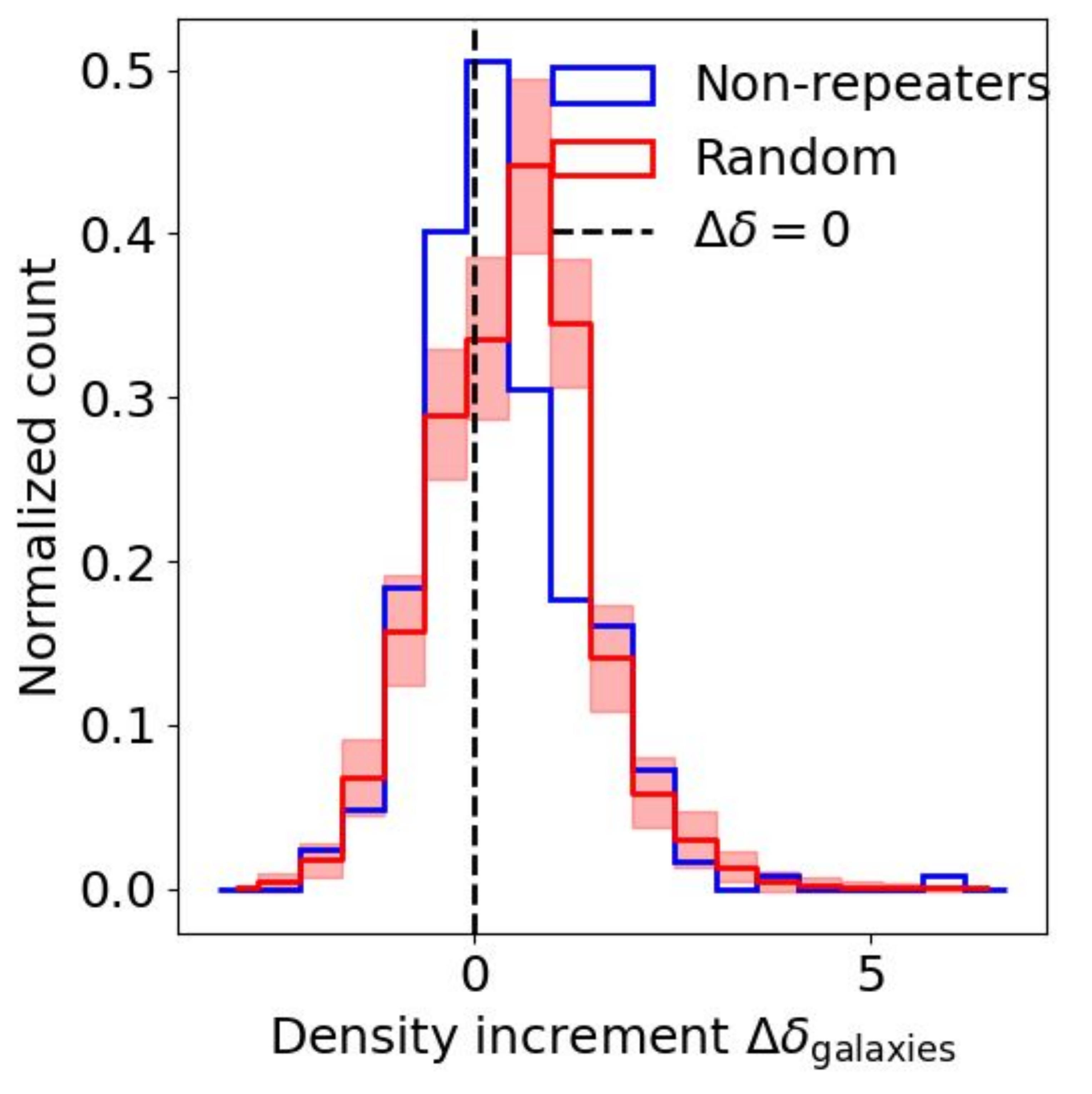
1.Choose density increment value of a random repeater

2.subtract all the density increment values of non-repeaters

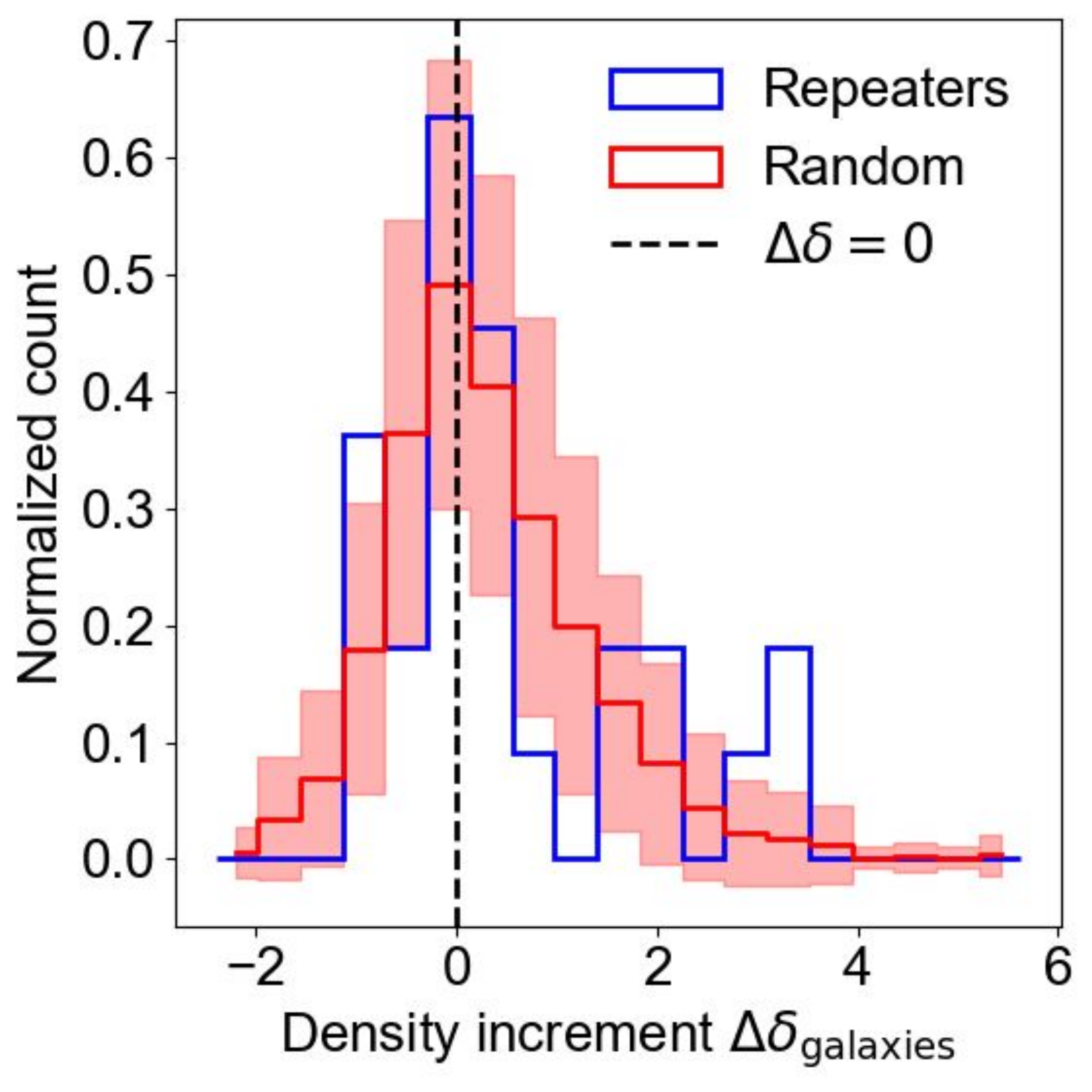
3.store the difference (residual)

4.remove the non-repeater FRB which has minimum value of difference (residual)

Result 2: Comparison of density increment values of FRB to randomly selected galaxies



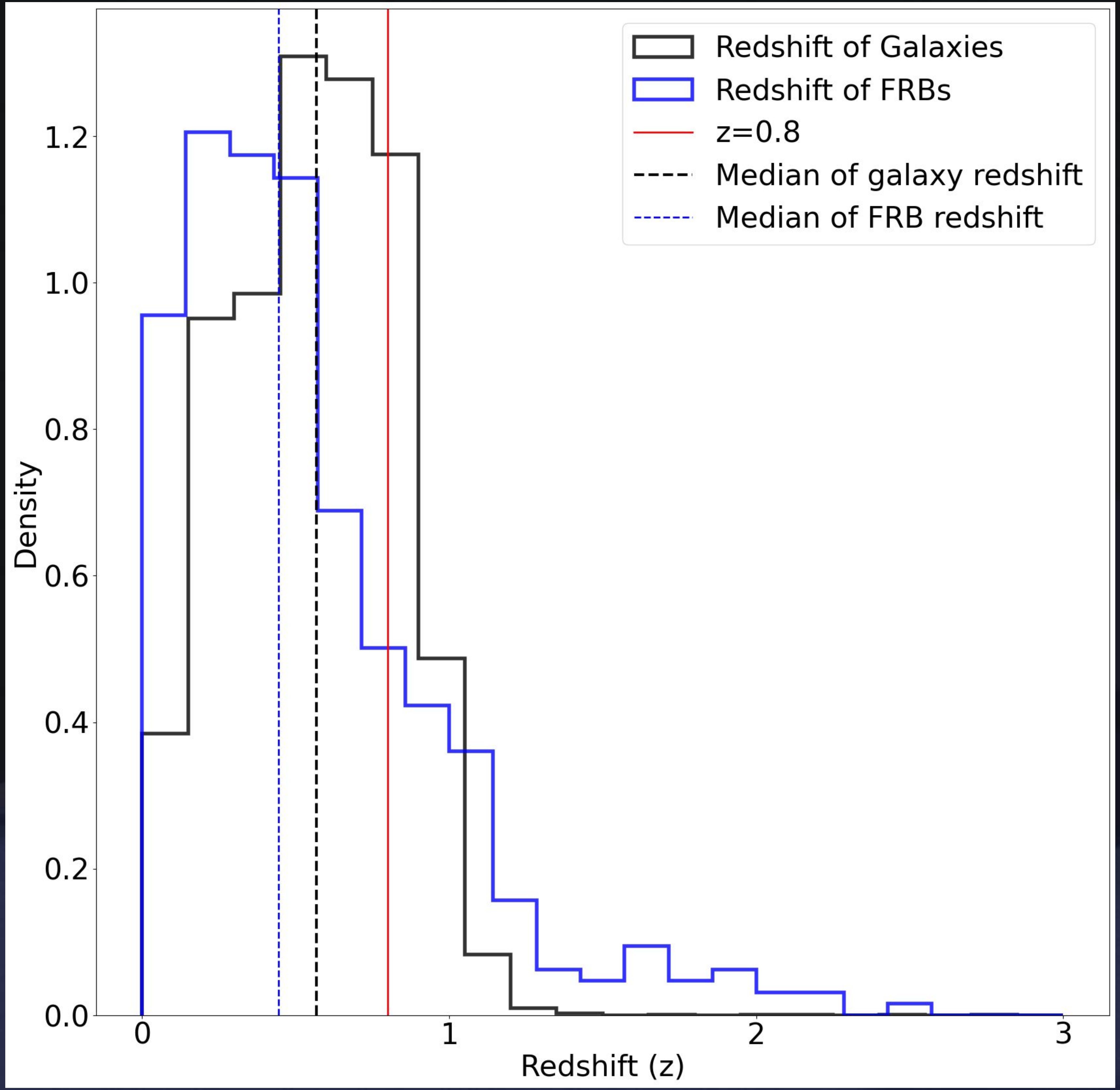
p-value: 2.78×10^{-2}



p-value: 0.4

KS test: FRBs v.s. random

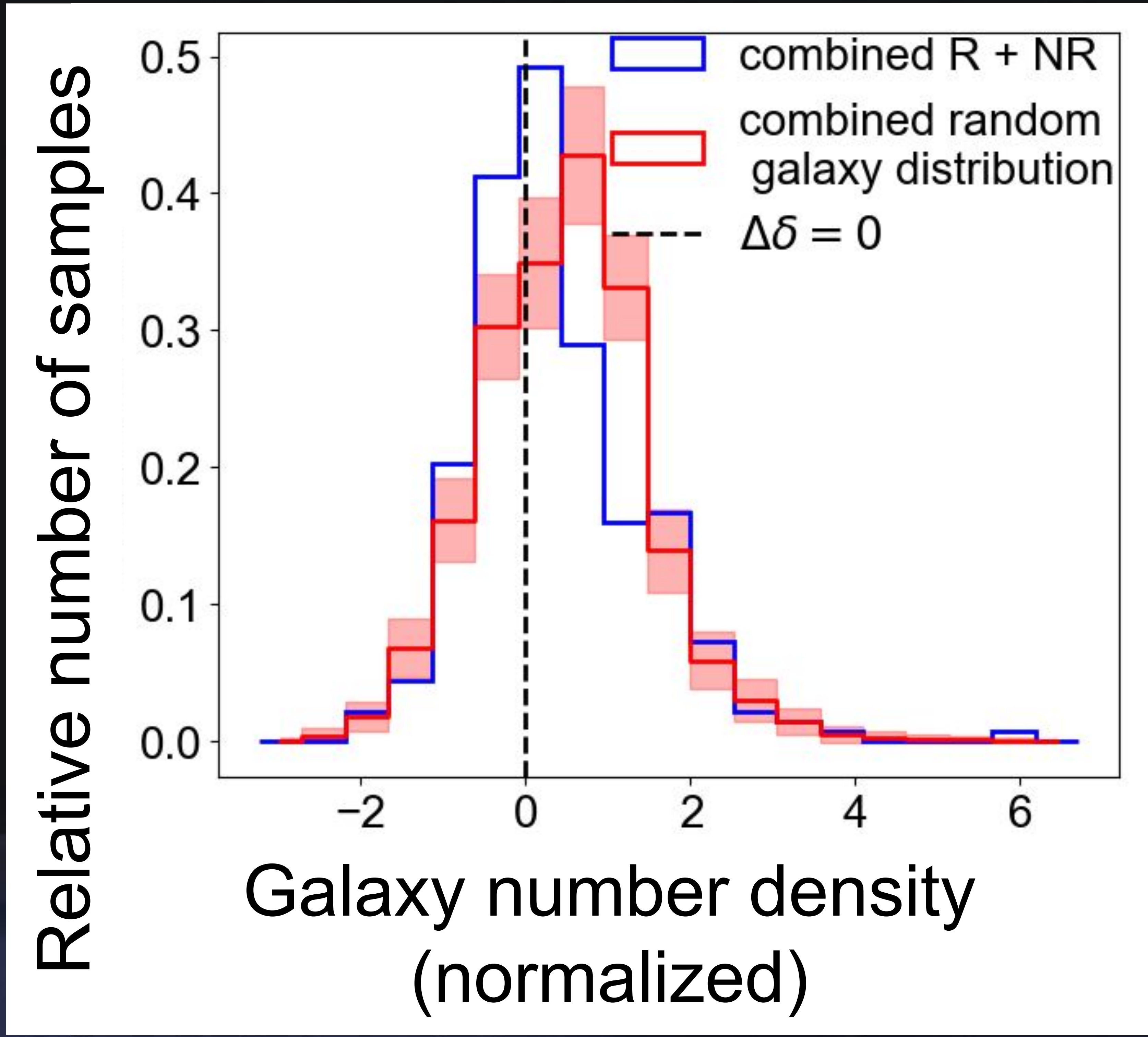
Redshift selection of FRB



- More than 80% galaxies and 78% of FRBs are inside the redshift of 0.8

- As a result we selected a redshift cut of 0.8, due to the fact that completeness of the data decreases beyond this redshift value of the galaxies

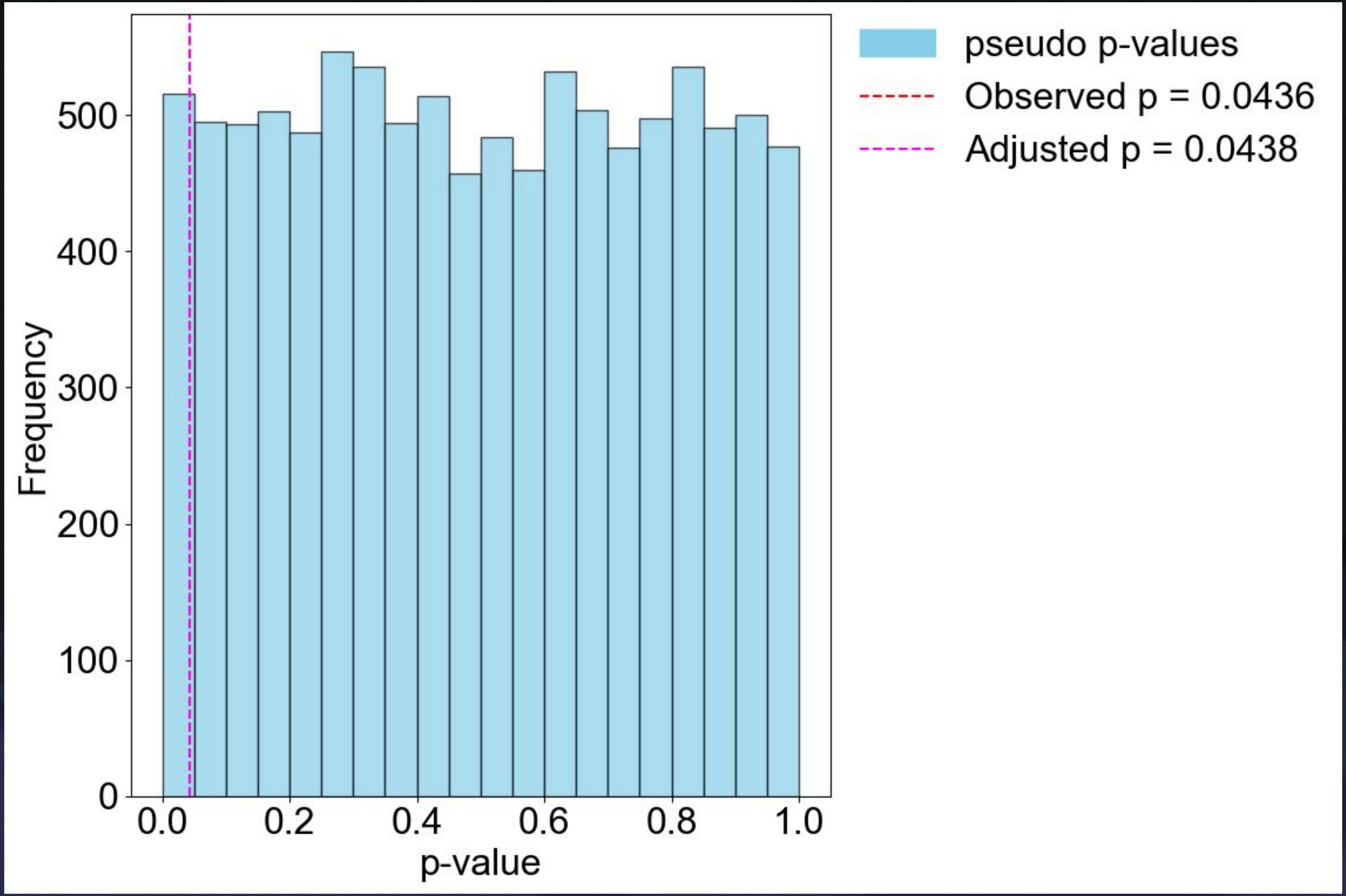
Result 2: Comparison of density increment values of FRB to randomly selected galaxies



FRBs are different from random galaxy density increments

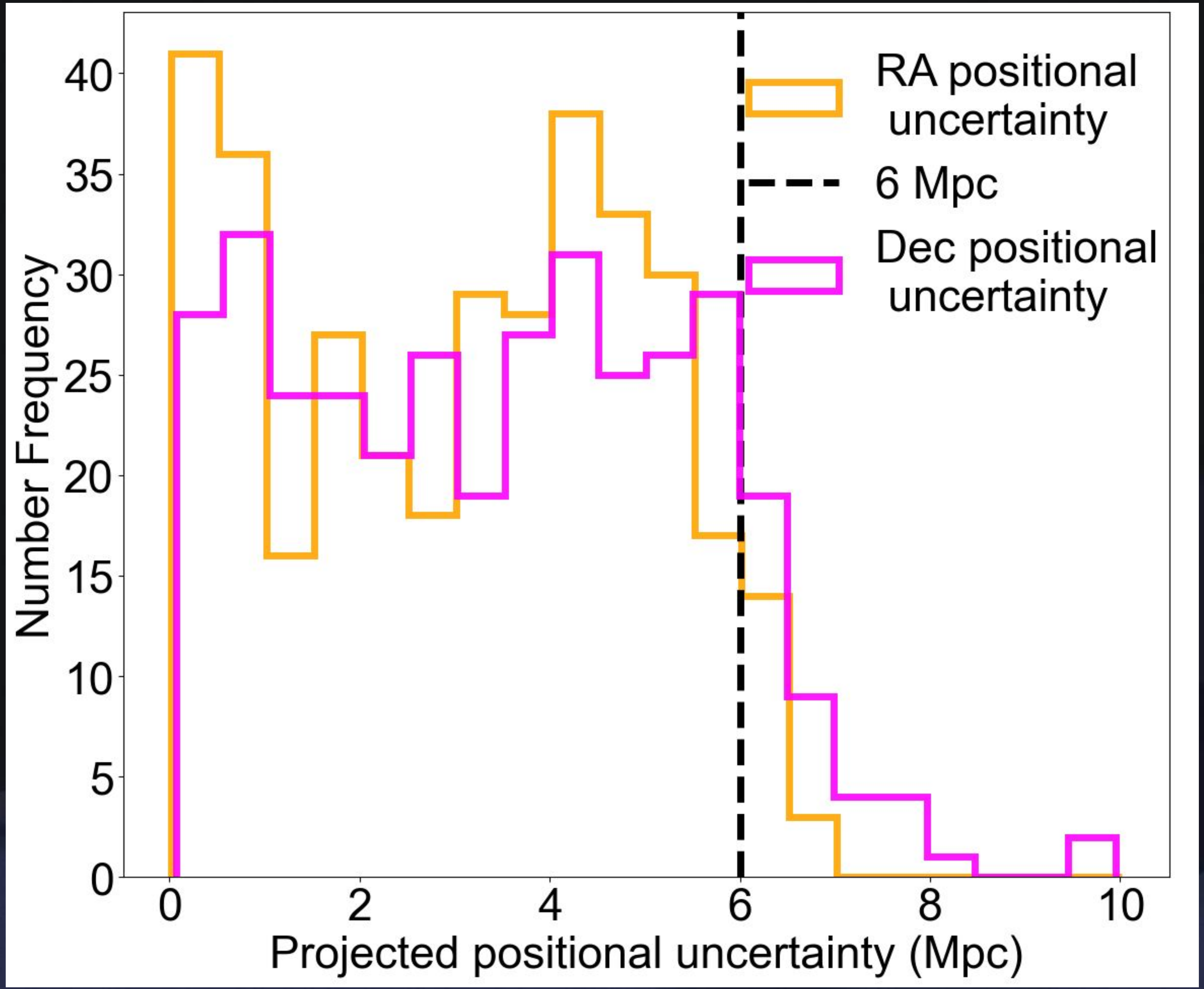
p-value: 2.78×10^{-2}

KS test: FRBs v.s. random



pseudo p-values
Observed p = 0.0436
Adjusted p = 0.0438
Frequency
0
100
200
300
400
500
0.0
0.2
0.4
0.6
0.8
1.0
p-value

Positional Uncertainties of FRB



Mostly(~90%) the positional errors of CHIME FRB < 6Mpc

Used this 6Mpc value to create a aperture and calculate

FRB sample selection criteria

We applied the following selection criteria to select FRB samples in this work.

1. FRB is located within the sky coverage of WISE × PS1
2. Galactic latitude $|\mathbf{b}| > 20°$
3. Estimated redshift $z_{\rm FRB} < 0.8$ (see §3.1 for details)
4. FRB samples with negative values of $z_{\rm FRB}$ were excluded.
5. A visual inspection of the galaxy distribution surrounding each FRB was conducted to ensure data quality.

The reason for following (2) is that the spatial distribution of the galaxy samples is significantly affected by Milky Way disk contamination and/or dust extinction. (3) is to guarantee the completeness of the galaxy catalog (see §2.2 for details). (4) selects extragalactic FRBs (see §3 for the details of the redshift calculation). As for (5), certain regions near the Galactic plane are masked in the WISE × PS1 catalog, leading to inaccurate density calculation in such regions. We removed FRB samples from our analysis when they were located in such masked regions.

Galaxy sample selection criteria

The galaxies were selected with the following selection criteria

1. Vega magnitude cut for W1 band of the WISE × PS1 samples (W1 < 16.8 mag)
2. galaxies were selected within a 100×100 Mpc^2 region, determined using the angular diameter distance at the redshift of each FRB sample.
3. galaxies were selected within a redshift slice which is created by using the redshift uncertainties of FRB (see §3.1 for the details of redshift uncertainty calculation.)