Using unlocalized fast radio bursts to measure the Hubble constant

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in collaboration with

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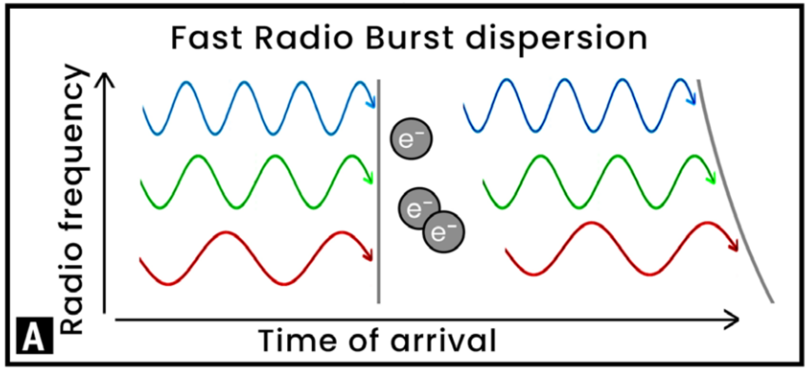
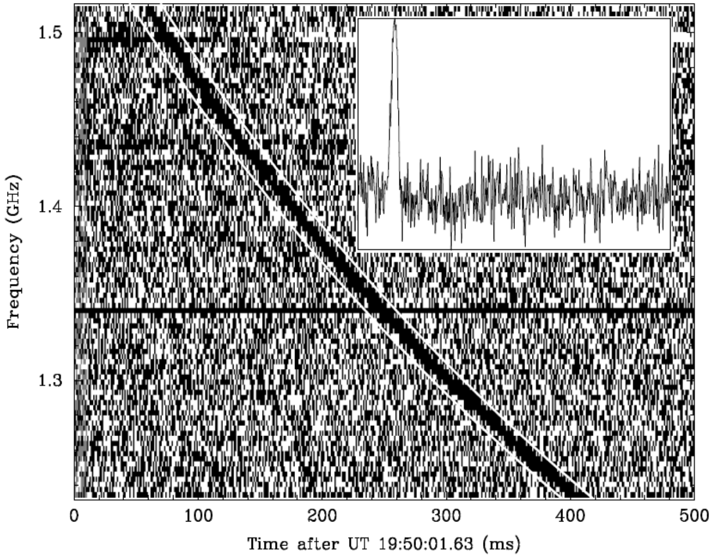
Fast radio burst and dispersion measure

- Fast radio bursts (FRBs) are bright and millisecond pulses in the radio band.

- dispersion measure (DM) : FRB can interact with free electrons and generate dispersion. It equals the column electron density to a given FRB,

$$\mathrm{DM} = \int_0^L \frac{n_\mathrm{e}(l)}{1+z}\mathrm{d}l.$$





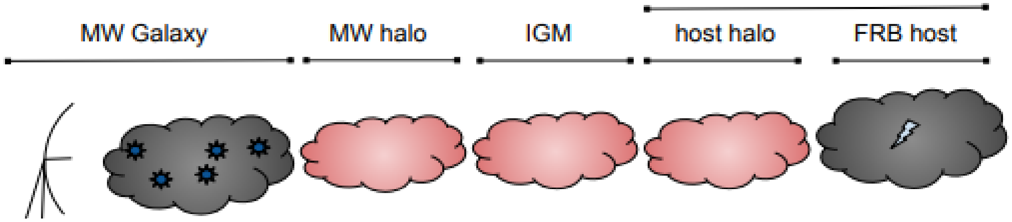
https://www.herta-experiment.org/frbstats/

D. R. Lorimer *et al*., Astron. Science 318, 777 (2007)

DM contributions from different parts

- the observed DM : the Milky Way's interstellar medium (ISM), Galactic halo, the intergalactic medium (IGM), and the host galaxy,

$$\mathrm{DM} = \mathrm{DM}_{\mathrm{MW,ISM}} + \mathrm{DM}_{\mathrm{MW,halo}} + \mathrm{DM}_{\mathrm{IGM}} + \mathrm{DM}_{\mathrm{host}}.$$



- The mean value of $\mathrm{DM}_{\mathrm{IGM}}$ at redshift *z* is given by the Macquart relation,

+BBN prior +ΛCDM

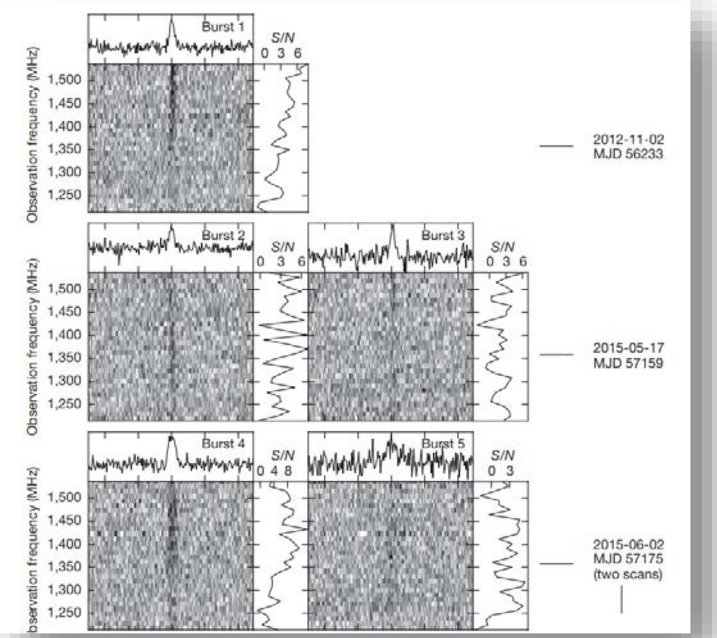
$$\langle \mathrm{DM}_{\mathrm{IGM}} \rangle = \int_0^z \frac{c\bar{n}_e(z')\mathrm{d}z'}{H_0(1+z')^2E(z')} = \frac{3cf_d\Omega_b H_0^2}{8\pi G m_p H_0}\int_0^z \frac{\chi(z')(1+z')\mathrm{d}z'}{E(z')}.$$

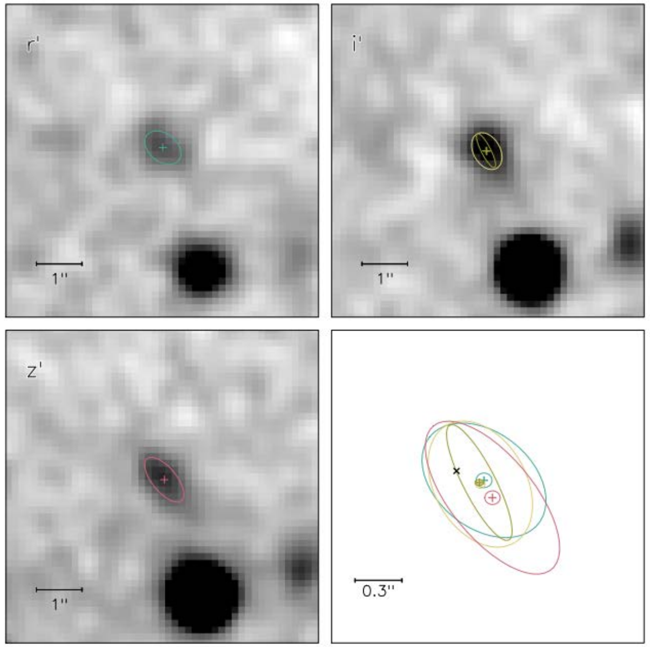
- The FRB data with redshift can be used to constrain cosmological parameters.

E. Petroff *et al.*, Astron.Astrophys.Rev. 27, 4 (2019)

Repeating FRBs and localized FRBs

- FRB 121102 was found to repeat, and follow-up observation further localized it to its host galaxy (*z* = 0.193).





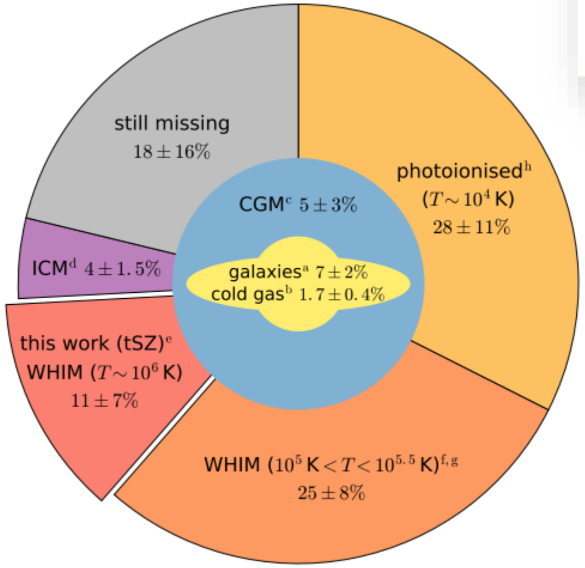
- localized FRB: a precise localization suitable for the identification of host.

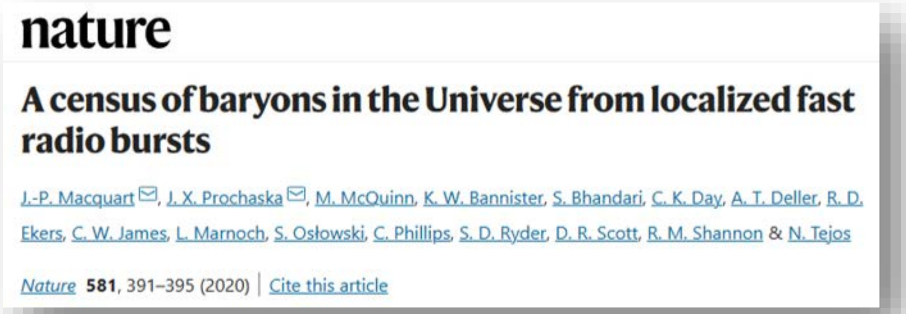
- Localized FRBs can be used to constrain cosmological parameters.

L. G. Spitler *et al*., Nature 531, 202 (2016)

S. P. Tendulkar *et al*., ApJL 834, L7(2017)

Using localized FRBs to detect baryon

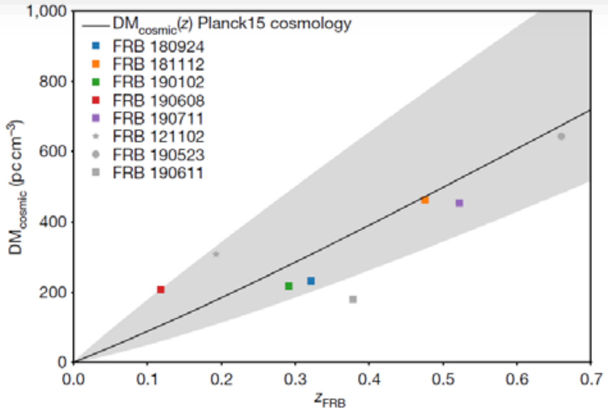


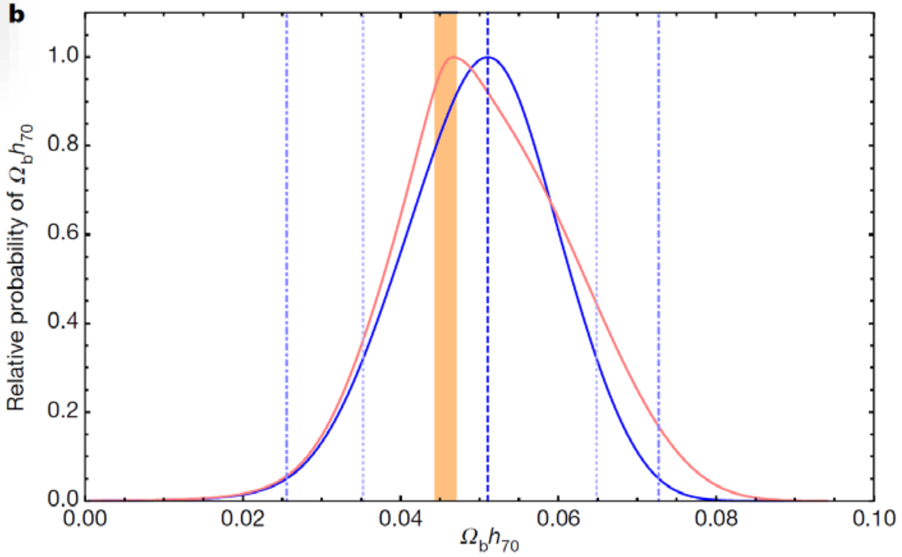

nature

A census of baryons in the Universe from localized fast radio bursts

J.-P. Macquart, J. X. Prochaska, M. McQuinn, K. W. Bannister, S. Bhandari, C. K. Day, A. T. Deller, R. D. Ekers, C. W. James, L. Marnoch, S. Osłowski, C. Phillips, S. D. Ryder, D. R. Scott, R. M. Shannon & N. Tejos

Nature **581**, 391–395 (2020) | Cite this article



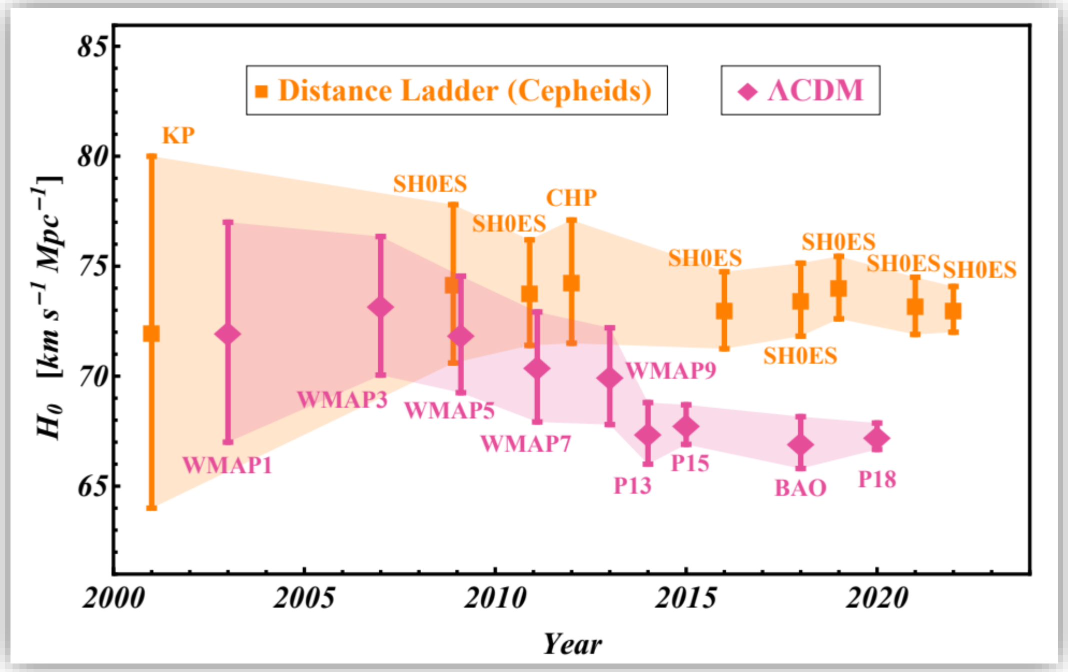


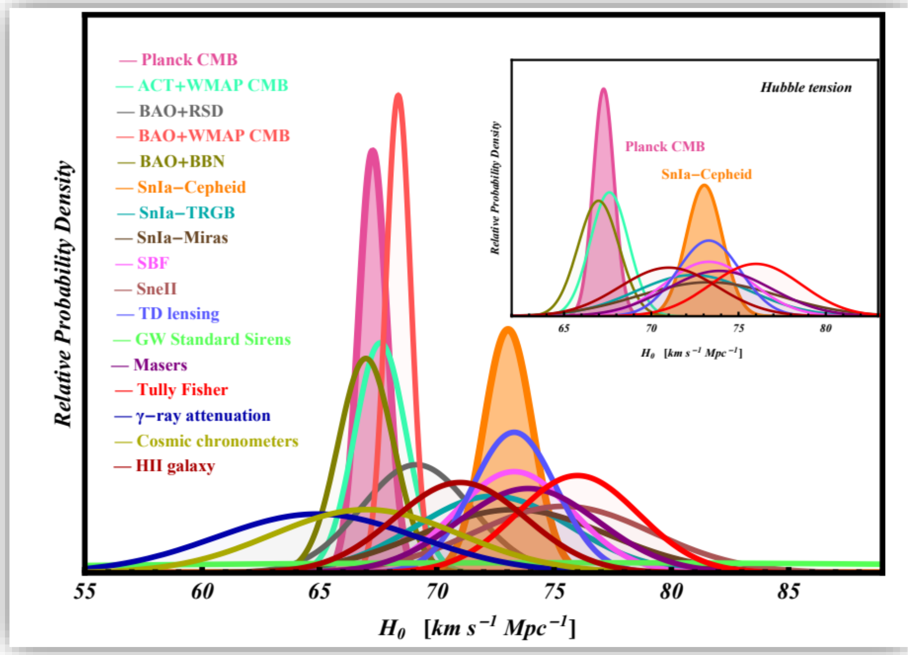
- “missing baryon” problem: the observed low-redshift baryon density < mean value of the universe.
- The Macquart relation of several localized FRBs.
- The constraint from localized FRBs is consistent with the result of CMB + BBN.

J. M. Shull, B. D. Smith, and C. W. Danforth, ApJ. 759, 23 (2012)

J. P. Macquart *et al.*, Nature 581, 391 (2020)

Hubble tension





- It is possible for FRBs to accumulate a lot of data in the future, which can be used to reduce random error.

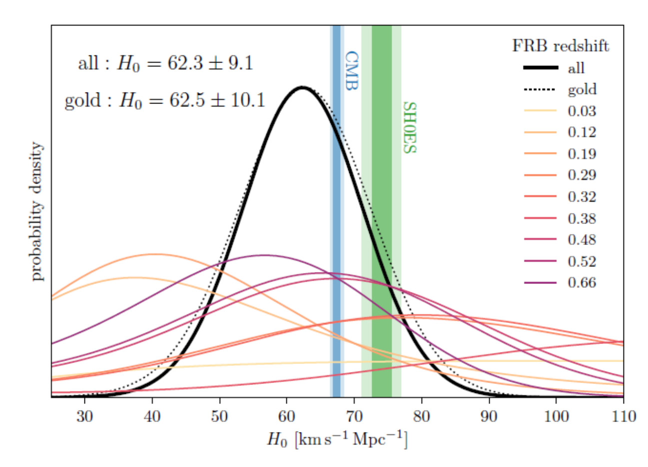
L. Perivolaropoulos and F. Skara, New Astron.Rev. 95, 101659 (2022)

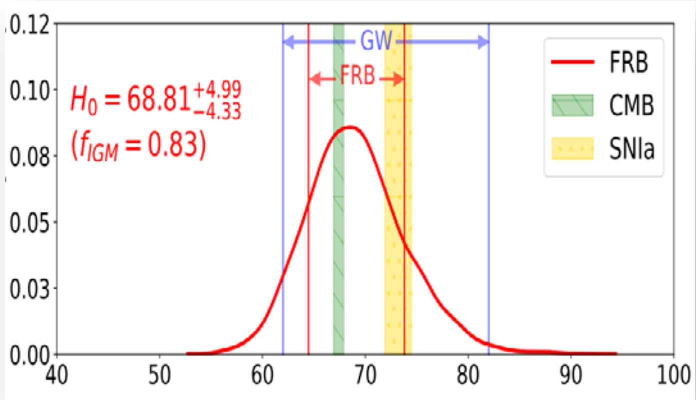
Measuring Hubble constant using localized FRBs

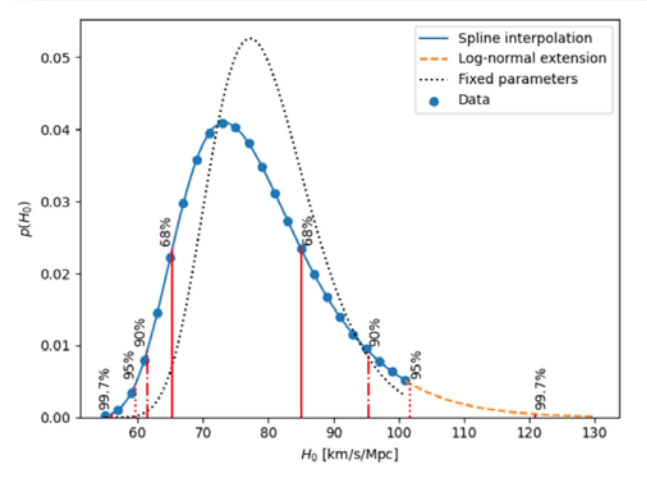
$$\langle \mathrm{DM_{cosmic}} \rangle = \frac{3cf_{\mathrm{IGM}}\Omega_{\mathrm{b}}H_0^2}{8\pi G m_{\mathrm{p}} H_0}\int_0^z \frac{\chi(z')(1+z')dz'}{E(z')},$$

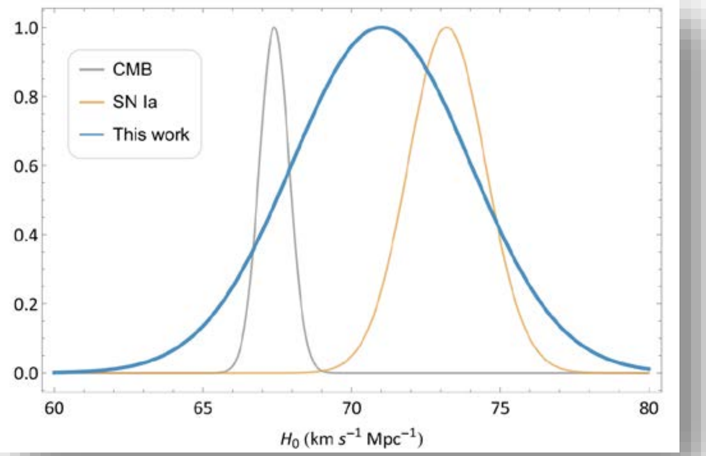
+BBN prior +ΛCDM

- Previous studies mainly used the localized FRBs.









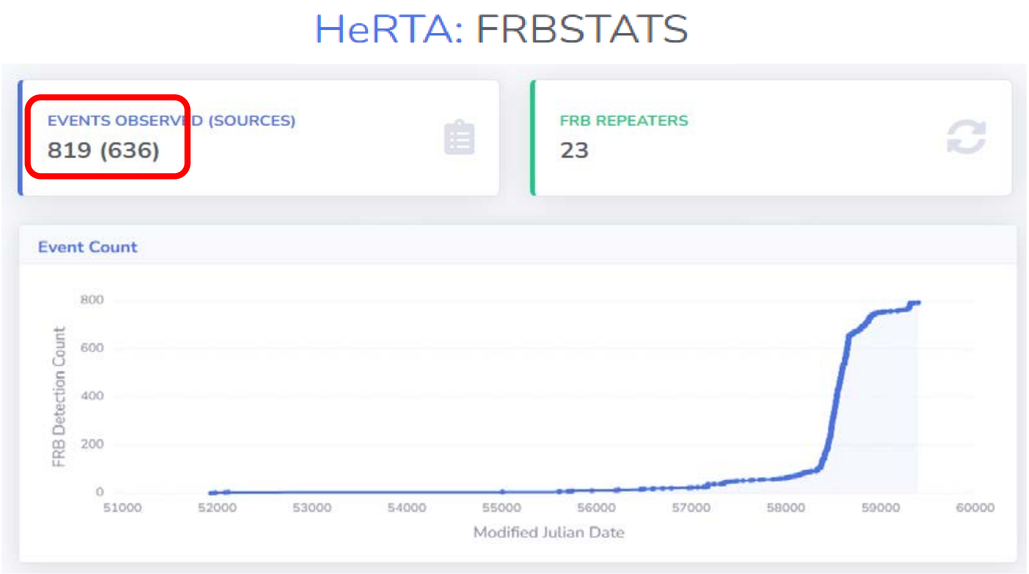
S. Hagstotz, R. Reischkey, and R. Lilow, MNRAS 511, 662 (2022)

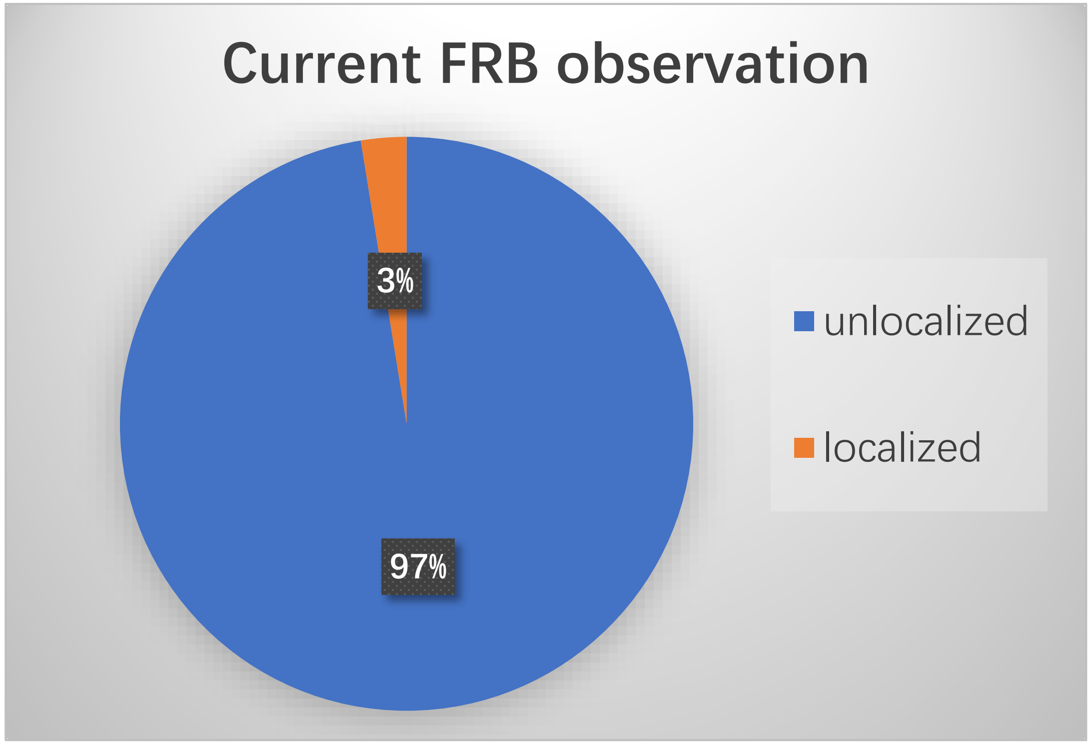
Q. Wu, G. Q. Zhang, and F. Y. Wang, MNRAS 515, L1 (2022)

C.W. James, E.M. Ghosh, et al., MNRAS 516, 4862 (2023)

Y. Liu, H. W. Yu, and P. X. Wu, ApJL 946, L49 (2023)

Current FRB observation



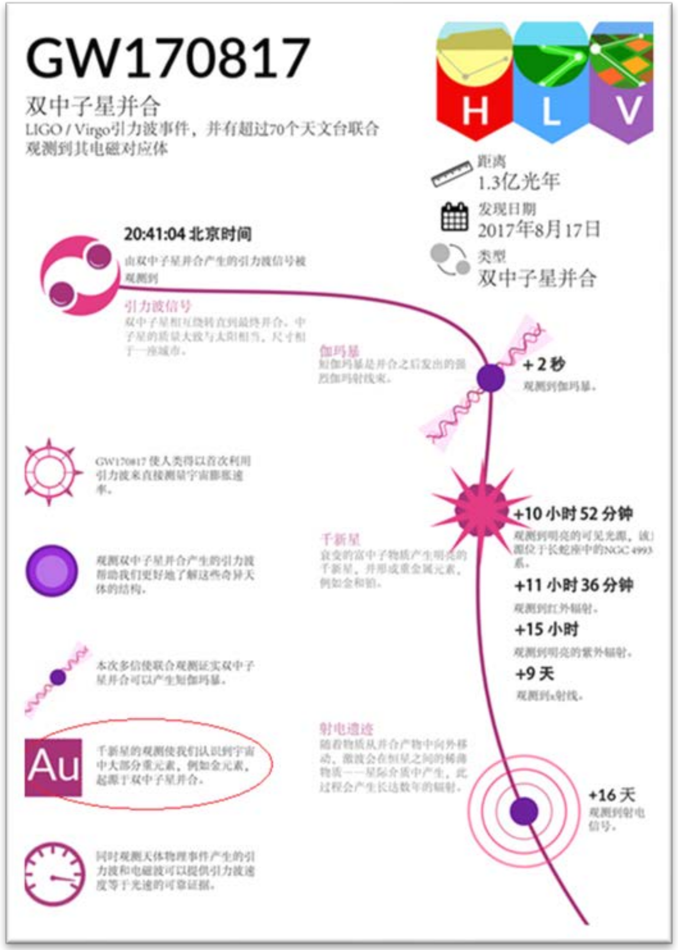


- Only a small number of FRB events are localized to host galaxies.
- How to solve this problem?

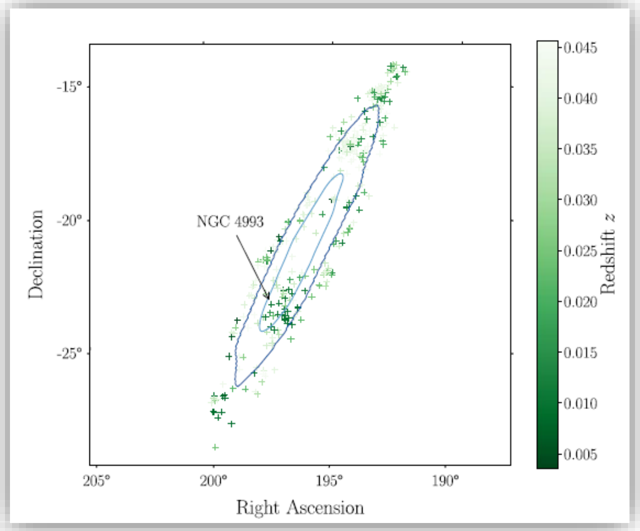
https://www.herta-experiment.org/frbstats/

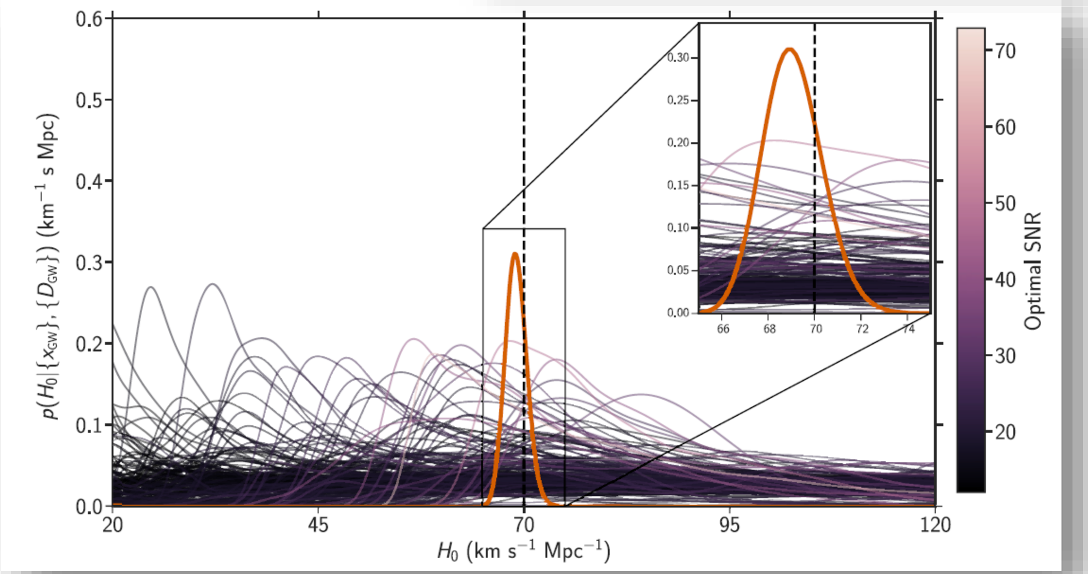
Standard siren in gravitational wave cosmology

- Bright siren： uniquely identified host galaxy by gravitational wave's electromagnetic counterpart.



- Dark siren： statistical analysis of multiple potential host galaxies .

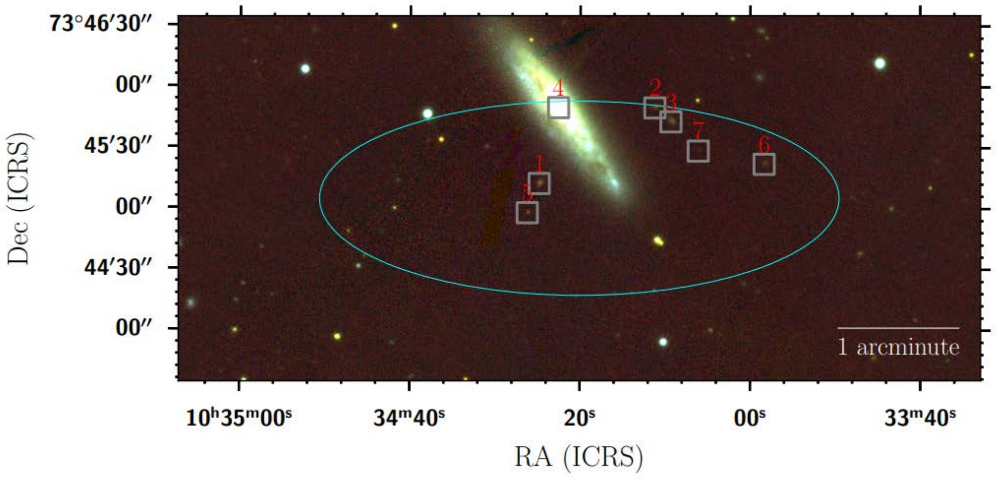


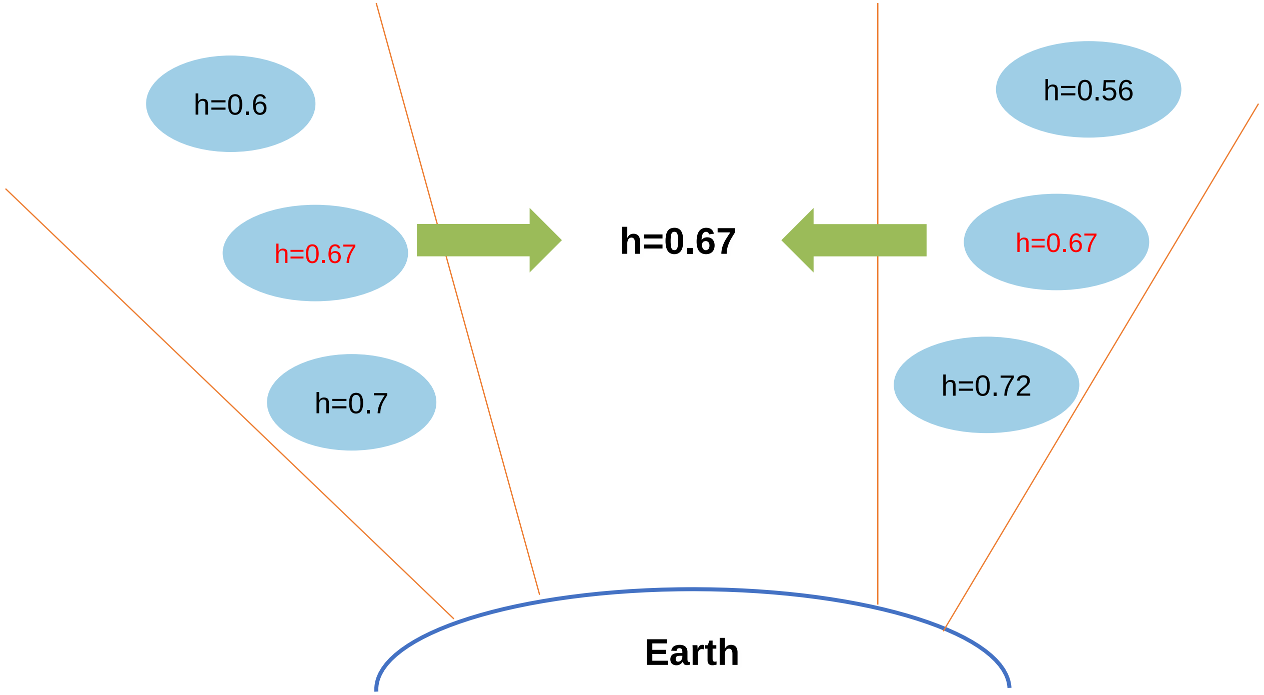


M. Fishbach *et al.*[LIGO Scientific and Virgo Collaborations], ApJL 871, L13 (2019)

R. Gray *et al.*, Phys.Rev.D 10, 122001 (2020)

Dark siren in gravitational wave cosmology





- dark siren: estimate the Hubble constant using binary black holes.

- We develop the dark siren method to the unlocalized FRBs.

M. Bharwaj *et al.*, APJL 919, L24 (2021)　　R. Gray *et al.*, Phys.Rev.D 10, 122001 (2020)

DM contribution of host and IGM

- The probability distribution of DM_{host} is modeled by a log-normal distribution

$$p_{host}(\mathrm{DM}_{host}|z, e^{\mu}, \sigma_{host}) \propto \exp\left[-\frac{(\log \mathrm{DM}_{host}(1+z)-\mu)^2}{2\sigma_{host}^2}\right];$$

- The probability distribution of DM_{IGM} is

$$p_{IGM}(\mathrm{DM}_{IGM}|z, H_0) \propto \left(\frac{\mathrm{DM}_{IGM}}{\langle \mathrm{DM}_{IGM}\rangle(H_0)}\right)^{-3} \exp\left\{-\frac{\left[\left(\frac{\mathrm{DM}_{IGM}}{\langle \mathrm{DM}_{IGM}\rangle(H_0)}\right)^{-3} - C_0\right]^2}{18F^2 z^{-1}}\right\};$$

- The FRB likelihood is

$$p(\mathrm{DM_E}|z, H_0, e^{\mu}, \sigma_{host}) = \int_0^{\mathrm{DM_E}} p_{host}(\mathrm{DM}_{host}|z, e^{\mu}, \sigma_{host})\, p_{IGM}(\mathrm{DM_E}-\mathrm{DM}_{host}|z, H_0)\, d\mathrm{DM}_{host}.$$

where DM_E is the extragalactic contribution.

J. P. Macquart *et al.*, Nature 581, 391 (2020)

Bayesian framework

- Ignoring the redshift errors, then the electromagnetic likelihood is

$$p(\mathrm{d_{EM}}|z,\Omega) = \sum_{i}^{N_{\mathrm{candidate}}} \delta(z-z_i)\delta(\Omega-\Omega_i),$$

where (z_i,Ω_i) represent the redshift and sky location of the i-th host candidate.

- Marginalizing over redshift,

$$p(\mathrm{d_{FRB}},\mathrm{d_{EM}}|H_0,e^{\mu},\sigma_{\mathrm{host}}) \propto \iint p(\mathrm{d_{FRB}}|z,H_0,e^{\mu},\sigma_{\mathrm{host}})p(\mathrm{d_{EM}}|z,\Omega)p(z,\Omega)d\Omega dz.$$

- Finally, we obtain

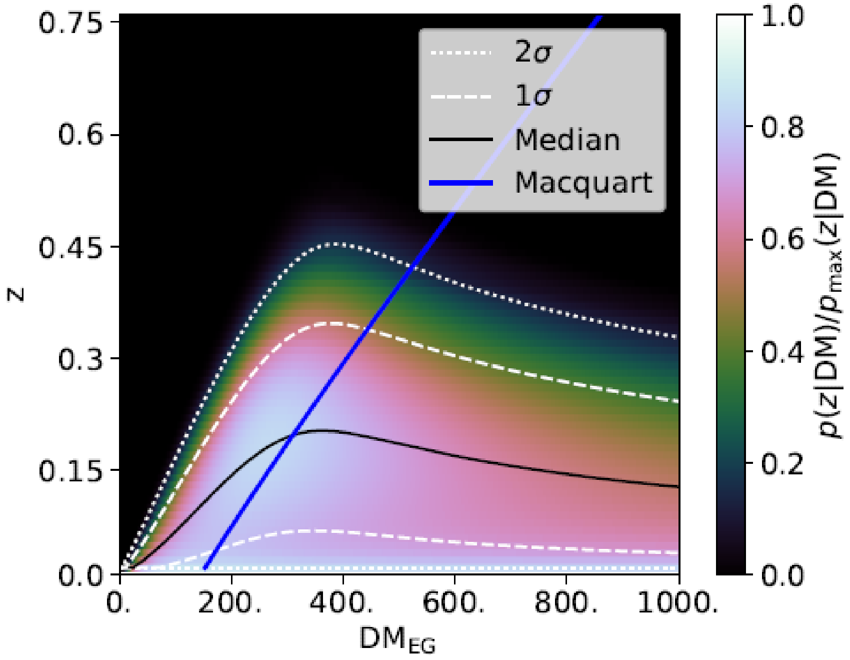
$$p(H_0|\mathrm{d_{FRB}},\mathrm{d_{EM}},e^{\mu},\sigma_{\mathrm{host}}) \propto \frac{1}{N_{\mathrm{candidate}}} \sum_{i}^{N_{\mathrm{candidate}}} p(\mathrm{d_{FRB}}|z_i,H_0,e^{\mu},\sigma_{\mathrm{host}})p(z_i,\Omega_i)p(H_0).$$

FRB data

- Australian Square Kilometre Array Pathfinder (ASKAP) : ~ 60 FRB events.

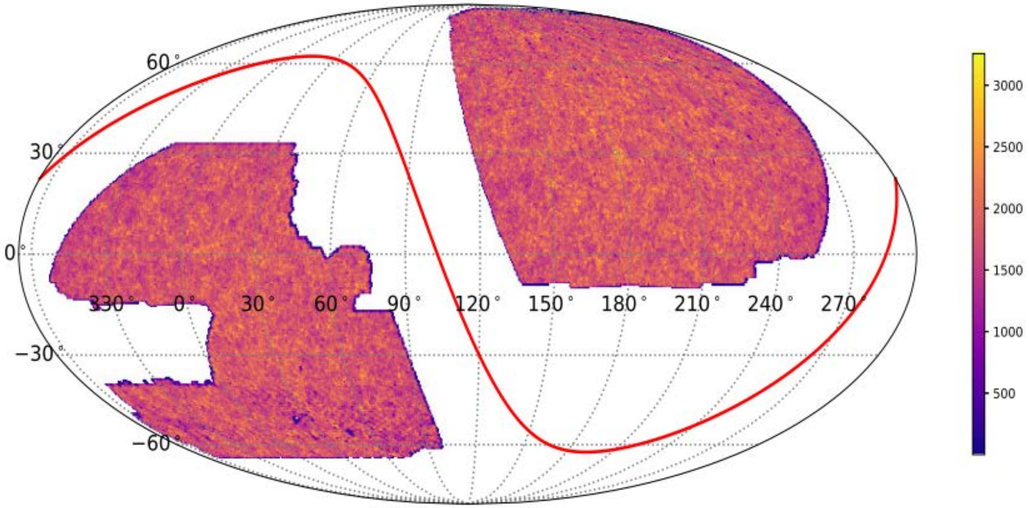
- single-antenna (“Flye’s Eye”,or “FE”) mode

$$\langle \mathrm{DM_{cosmic}} \rangle = \int_0^z \frac{c\bar{n}_e(z')dz'}{H_0(1+z')^2 E(z)}$$



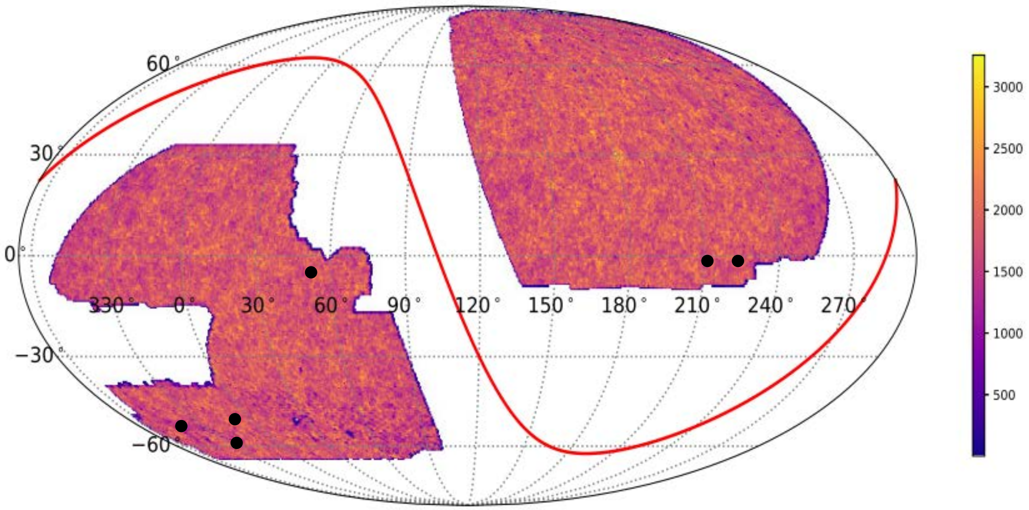
- selection effect: only use the FRB data for which the Macquart relation is reliable.

Host candidate sample



- galaxy catalog: the DESI Legacy Imaging Surveys DR8 data

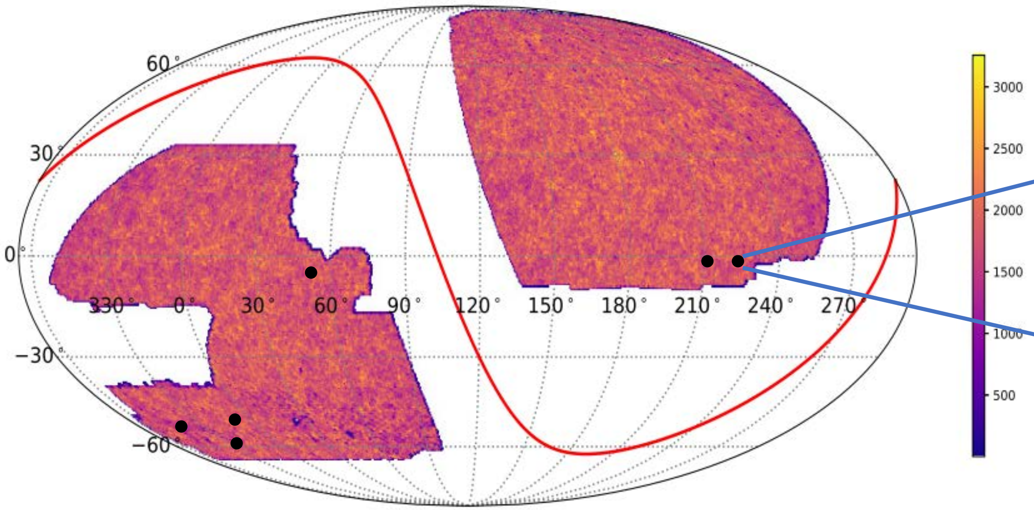
Host candidate sample

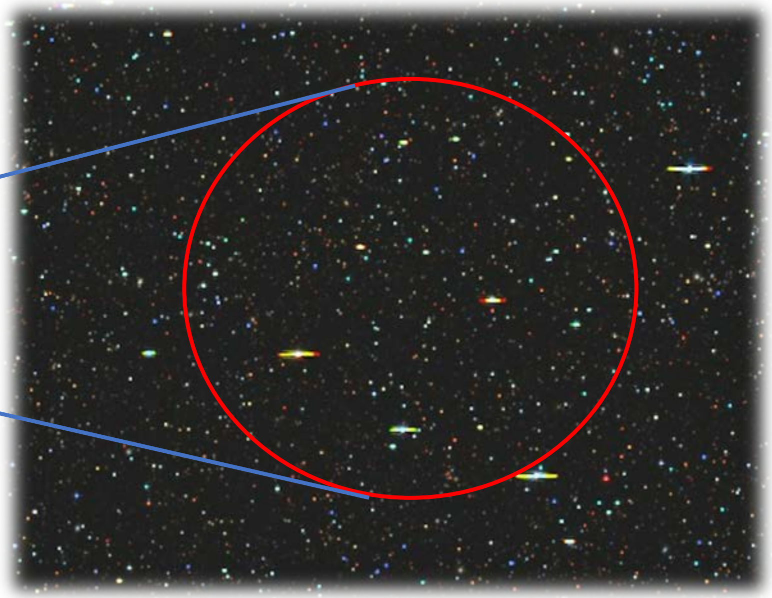


- galaxy catalog: the DESI Legacy Imaging Surveys DR8 data
- find the FRB events in the sky coverage of the galaxy catalog

X. H. Yang *et al.*, ApJ 909, 143 (2021)

Host candidate sample



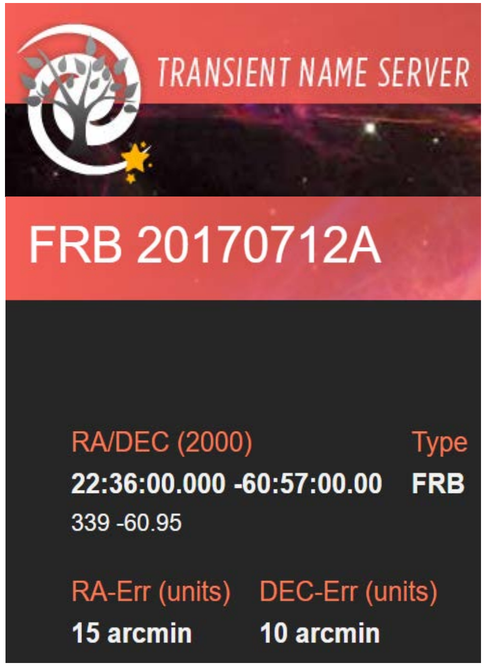


- galaxy catalog: the DESI Legacy Imaging Surveys DR8 data
- find the FRB events in the sky coverage of the galaxy catalog
- use the corresponding galaxy sample as each FRBs' host candidates

X. H. Yang *et al*., ApJ 909, 143 (2021)

FRB data used in this work

FRB event	RA	DEC	DM ($\mathrm{pc\,cm^{-3}}$)	number of candidates
20170712A	22h36m00s±15’	-60°57’00”±10’	312.8	72
20171213A	03h39m00s±30’	-10°56’00”±20’	158.6	154
20180119A	03h29m18s±8’	-12°44’00”±8’	402.7	43
20180212A	14h21m00s±30’	-03°35’00”±30’	167.5	262
20180515A	23h13m12s±7’	-42°14’46”±7’	355.2	30
20180525A	14h40m00s±30’	-02°12’00”±6’	388.1	112



- As an example, we finally use six ASKAP FRB events to illustrate the feasibility of this method.

https://www.wis-tns.org/

The Hubble constant measurement from unlocalized FRBs

THE ASTROPHYSICAL JOURNAL

Dispersion Measures of Fast Radio Burst Host Galaxies Derived from IllustrisTNG Simulation

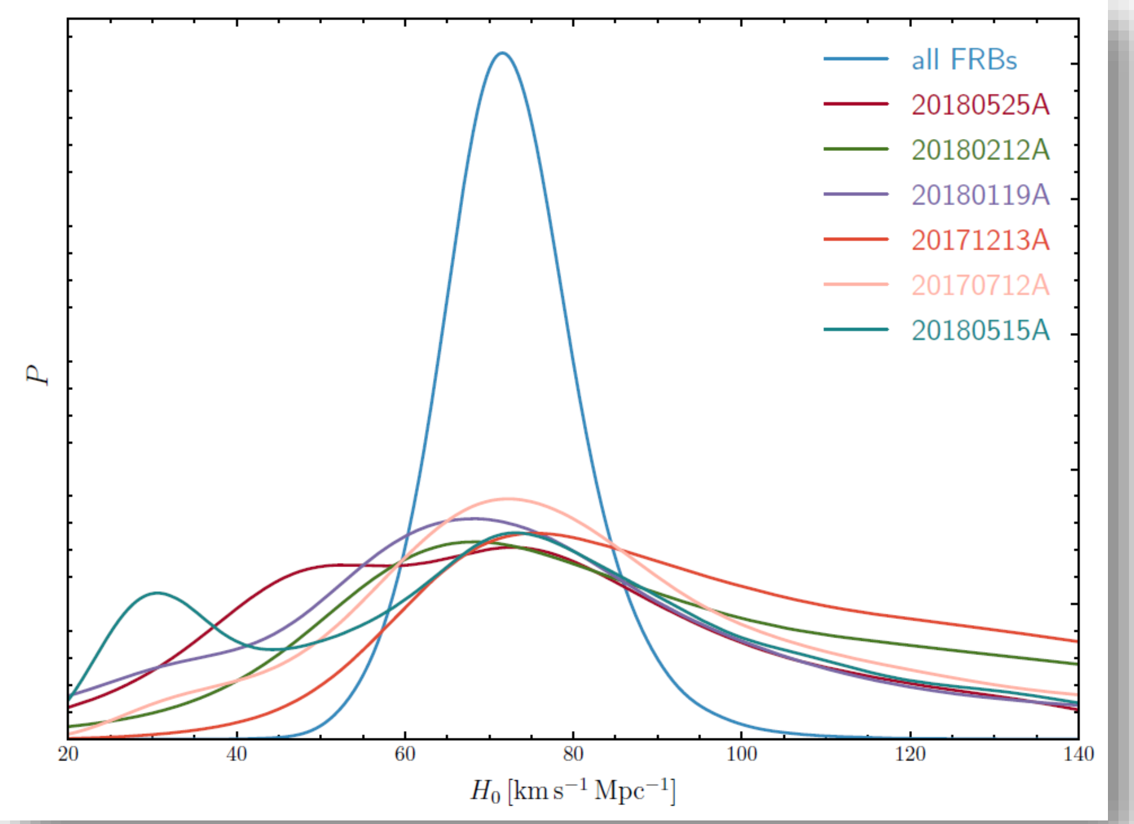
G. Q. Zhang[1], Hai Yu[2], J. H. He[1,3], and F. Y. Wang[1,3]

Published 2020 September 14 •

The Astrophysical Journal, Volume 900, Number 2

- Assuming fixed host galaxy parameters (e^{μ} and σ_{host}) based on cosmological simulation, the constraint on H_0 is

$e^{\mu}(\mathrm{pc\,cm^{-3}})$	σ_{host}	H_0 $(\mathrm{km\,s^{-1}\ Mpc^{-1}})$
36.6	1.27	$71.7^{+8.8}_{-7.4}$



Summary

- Problem: The difficulty is getting the redshifts of most FRBs.

- Method: We develop the dark siren method to the FRB cosmology field.

- Result: Ignoring the systematic errors, we obtain the first H_0 measurement using unlocalized FRBs.

- Significance: Constrain cosmological parameters by using a large number of FRB data without known redshifts.