Northeastern University

Cosmology with fast radio bursts in the era of SKA

Ji-Guo Zhang（张骥国）

Department of Physics, College of Sciences, Northeastern University (NEU)
Collaborators: Ze-Wei Zhao, Yichao Li, Jing-Fei Zhang, Di Li (NAOC), Xin Zhang

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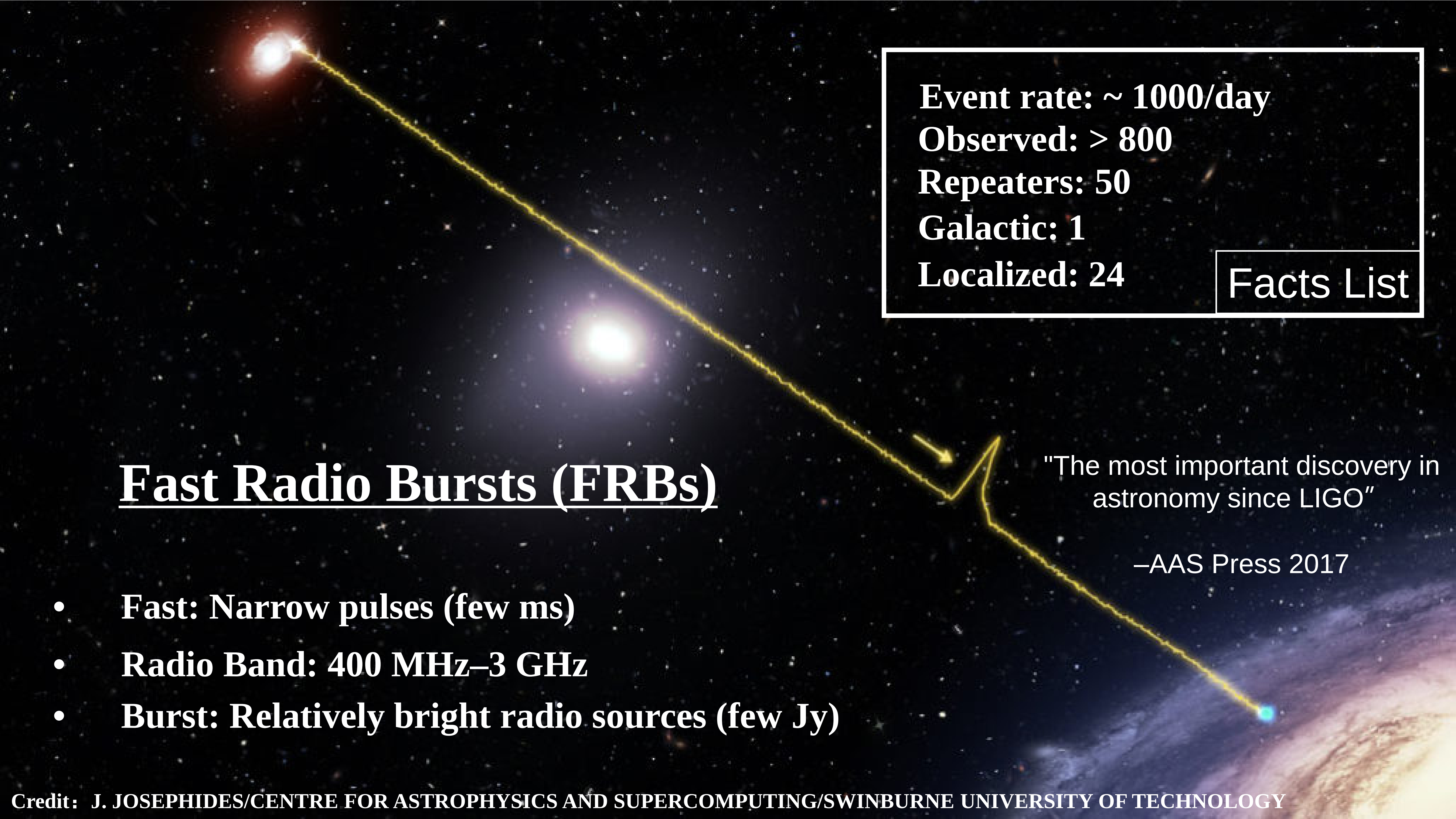
Outline

- Background information of FRBs
- Challenges faced in the cosmology
- Results and Summary



Event rate: ~ 1000/day
Observed: > 800
Repeaters: 50
Galactic: 1
Localized: 24

Facts List

Fast Radio Bursts (FRBs)

"The most important discovery in astronomy since LIGO"

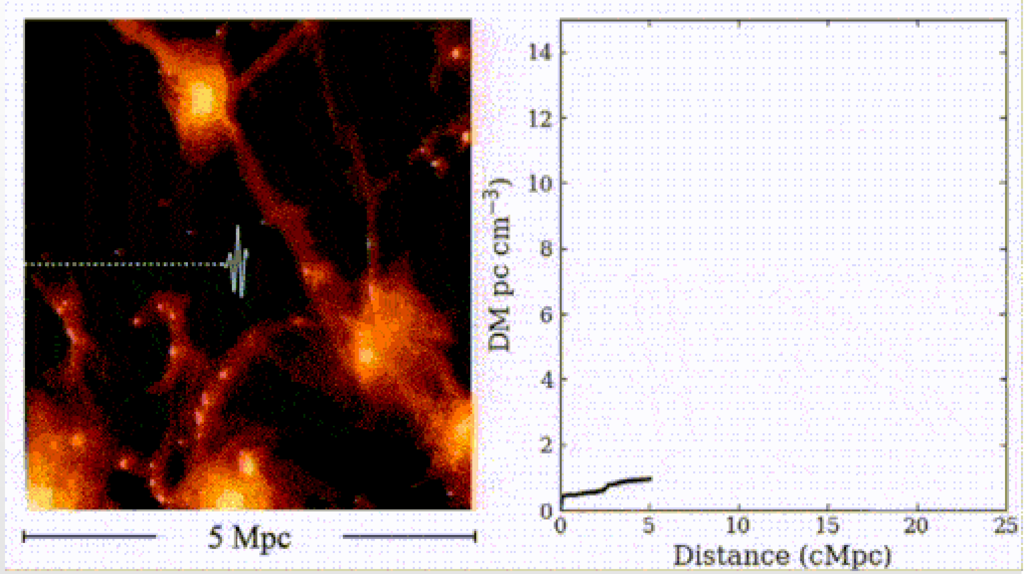
–AAS Press 2017

- Fast: Narrow pulses (few ms)
- Radio Band: 400 MHz–3 GHz
- Burst: Relatively bright radio sources (few Jy)

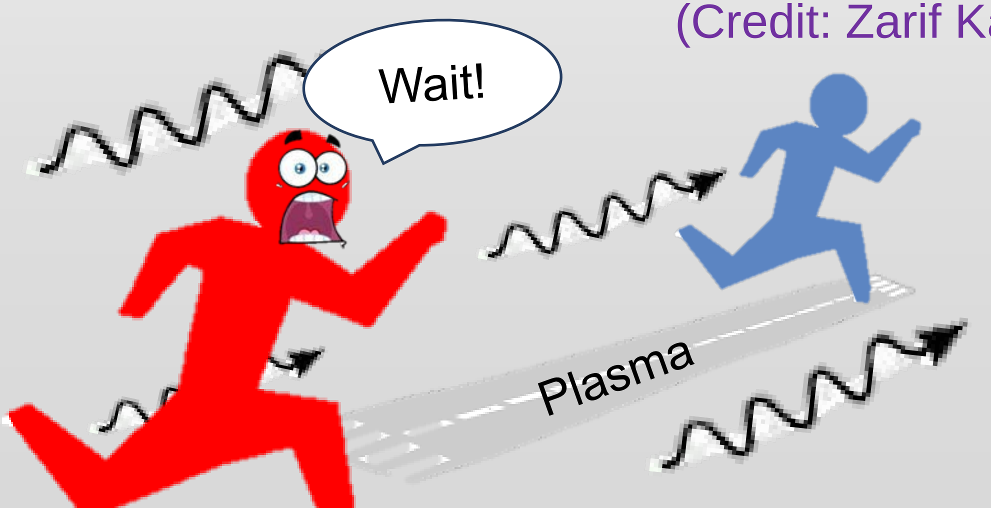
Credit: J. JOSEPHIDES/CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING/SWINBURNE UNIVERSITY OF TECHNOLOGY

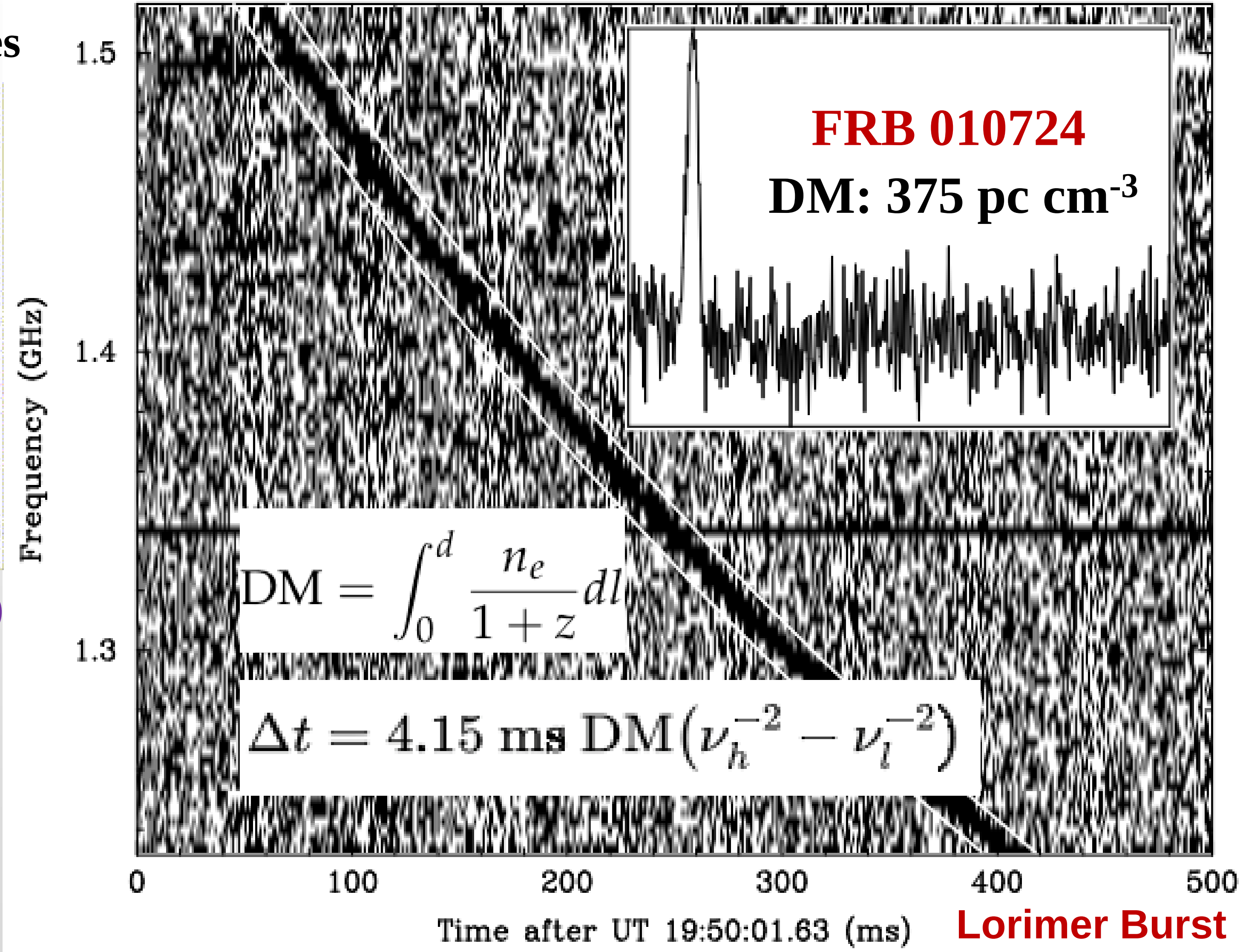
01 Dispersion Measure (DM)

Highly dispersed → Cosmological distances



(Credit: Zarif Kader)

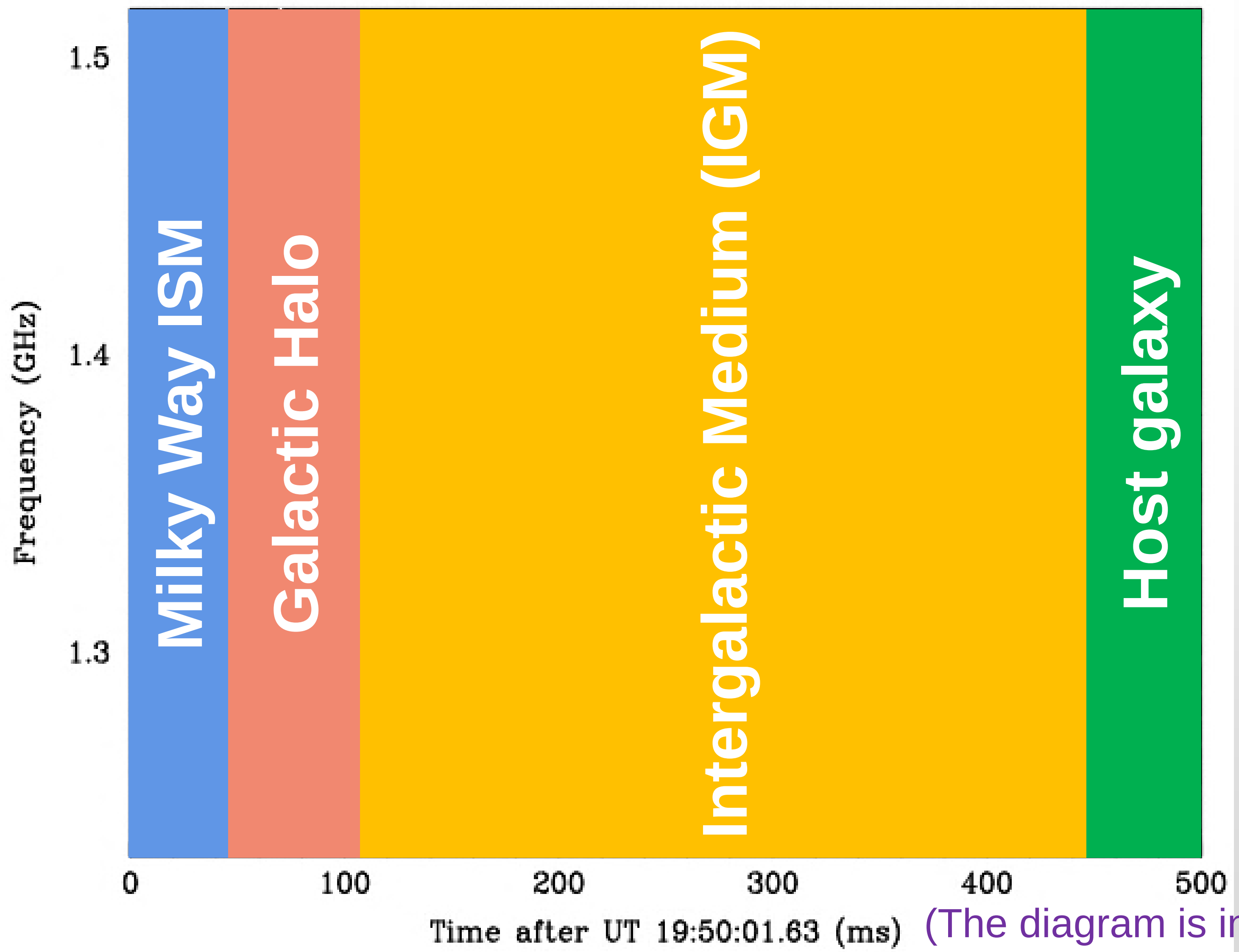




(Lorimer et.al, 2007)

01 Use FRBs as a probe of the Universe

DM_{obs}



(The diagram is inspired by Liam Connor)

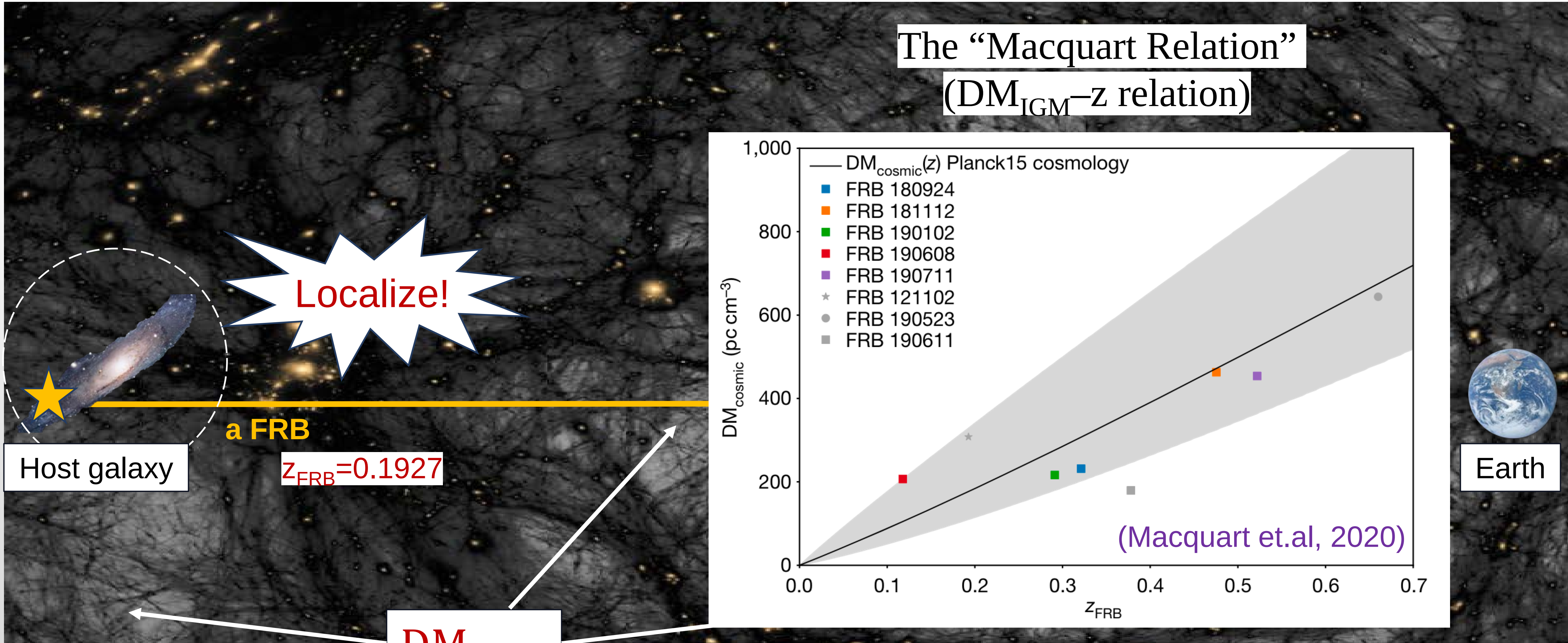
Probe list 🤔

- ☐ Galactic Halos
- ☐ Host Galaxy
- ☐ IGM / Cosmic Web

As a cosmological probe?

$$DM_{obs} = DM_{MW} + DM_{IGM} + DM_{host}$$

01 The “Macquart Relation”— a way to FRB cosmology

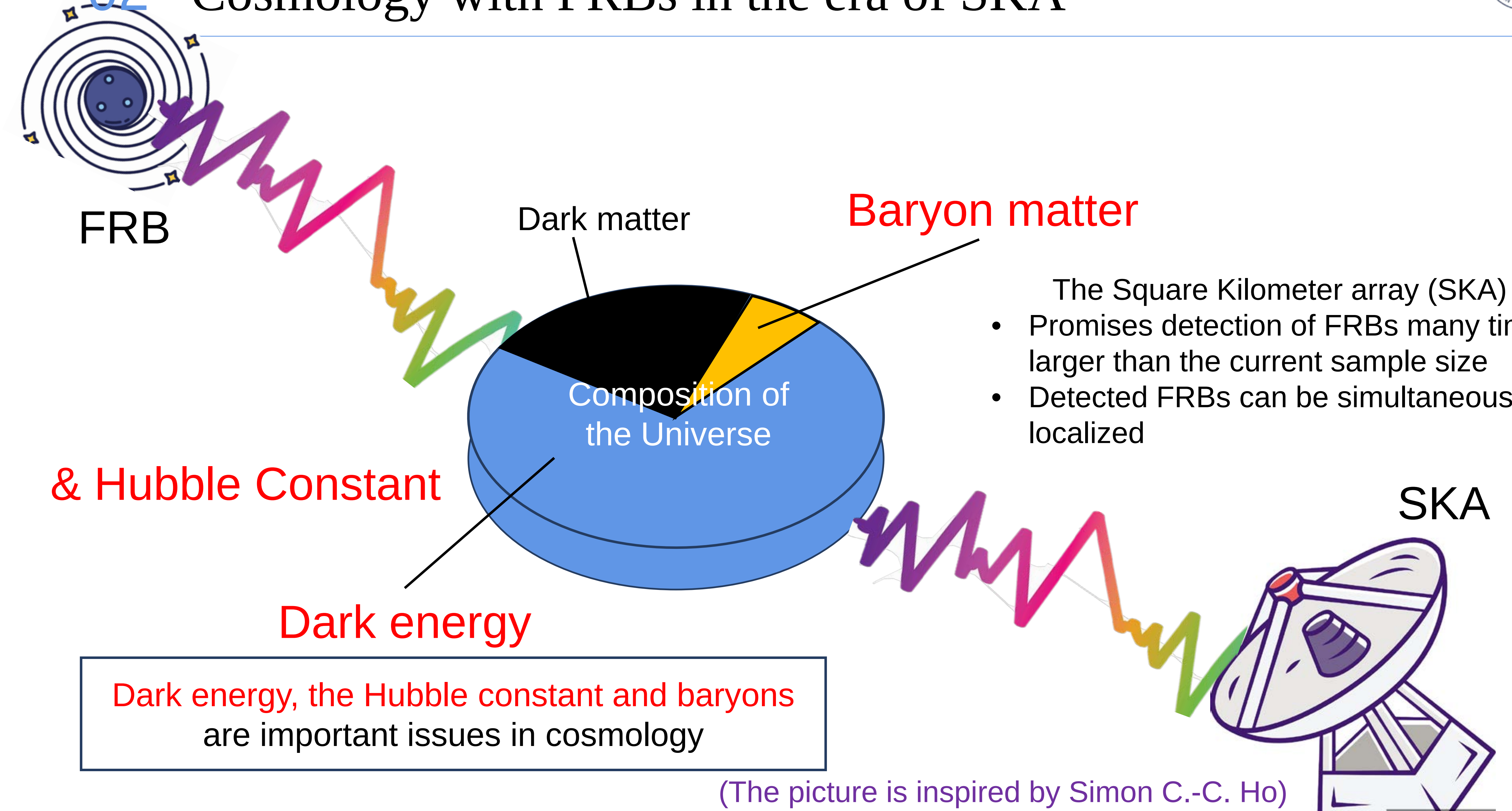


$$\langle \mathrm{DM_{cosmic}} \rangle = \int \frac{c\bar{n}_e(z)dz}{H_0(1+z)^2\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

$$\bar{n}_e = f_d \rho_b(z) m_p (1 - Y_{\mathrm{He}}/2)$$

$$\rho_b \equiv \Omega_b \rho_c$$

02 Cosmology with FRBs in the era of SKA



The Square Kilometer array (SKA)

- Promises detection of FRBs many times larger than the current sample size
- Detected FRBs can be simultaneously localized

Dark energy, the Hubble constant and baryons are important issues in cosmology

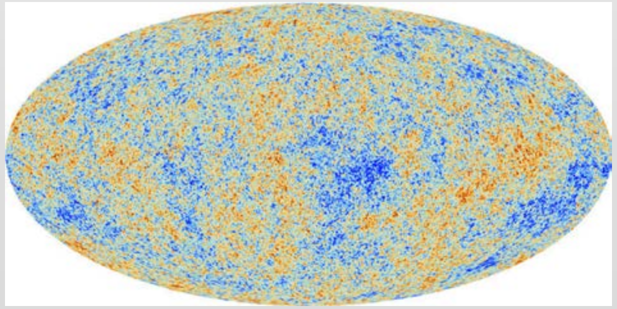
(The picture is inspired by Simon C.-C. Ho)

02 Dark energy

A new component with negative pressure dominating the expansion—dark energy → Dark Energy Λ cold dark matter (ΛCDM) model → Cosmic Microwave Background (CMB) strongly favors the ΛCDM cosmology

However
- the fine-tuning problem
- the coincidence problem

→ many dark energy models have been proposed, e.g., dynamical dark energy models: the wCDM, $w_0 w_a$CDM models…



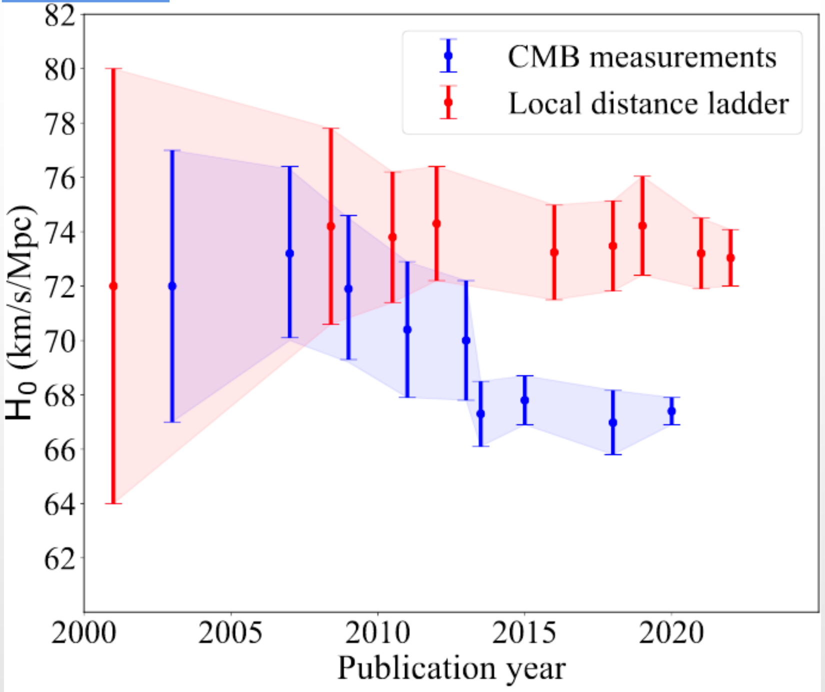
Cosmic Microwave Background

Credits:https://www.nationalgeographic.com

It is essential to develop independent late-universe cosmological probes!

Can SKA-era FRBs as a late-universe probe independently and precisely measure dark energy?

02 Hubble tension



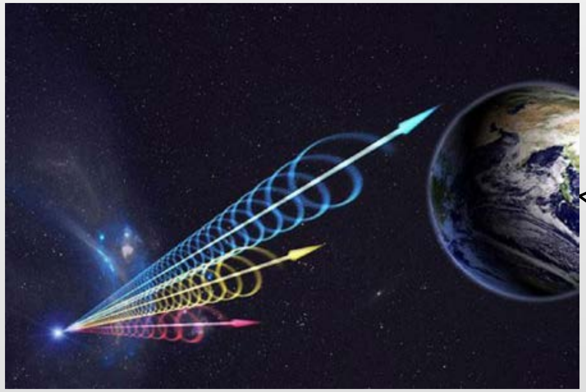
(Hu & Wang, 2023)

$$\langle \mathrm{DM_{IGM}} \rangle = \frac{3cH_0\Omega_b f_{\mathrm{IGM}}}{8\pi G m_p} \int_0^z \frac{\chi(z')(1+z')dz'}{E(z')},$$

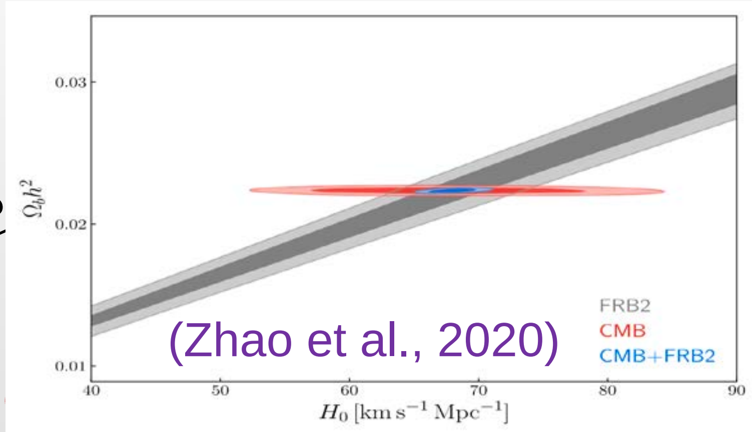
$$\mathrm{DM_{IGM}} \propto \Omega_b H_0$$

The degeneracies between H_0 and $\Omega_b h^2$

CMB can precisely constrain $\Omega_b h^2$



FRB + CMB



(Zhao et al., 2020)

Einstein Telescope (ET) is upcoming…

FRB + GW(ET)

?

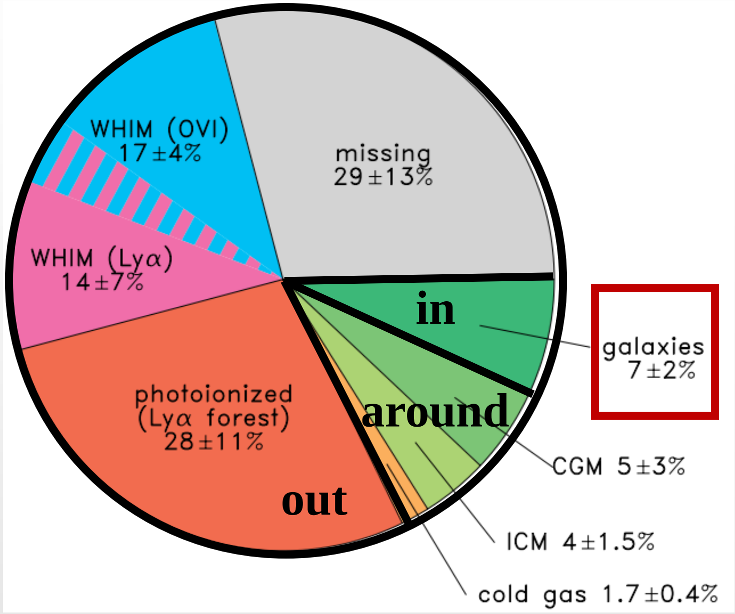
GW standard sirens can precisely constrain H_0

What extent can FRBs(SKA) and GWs(ET) as a combination to measure H_0?

Gravitational Waves

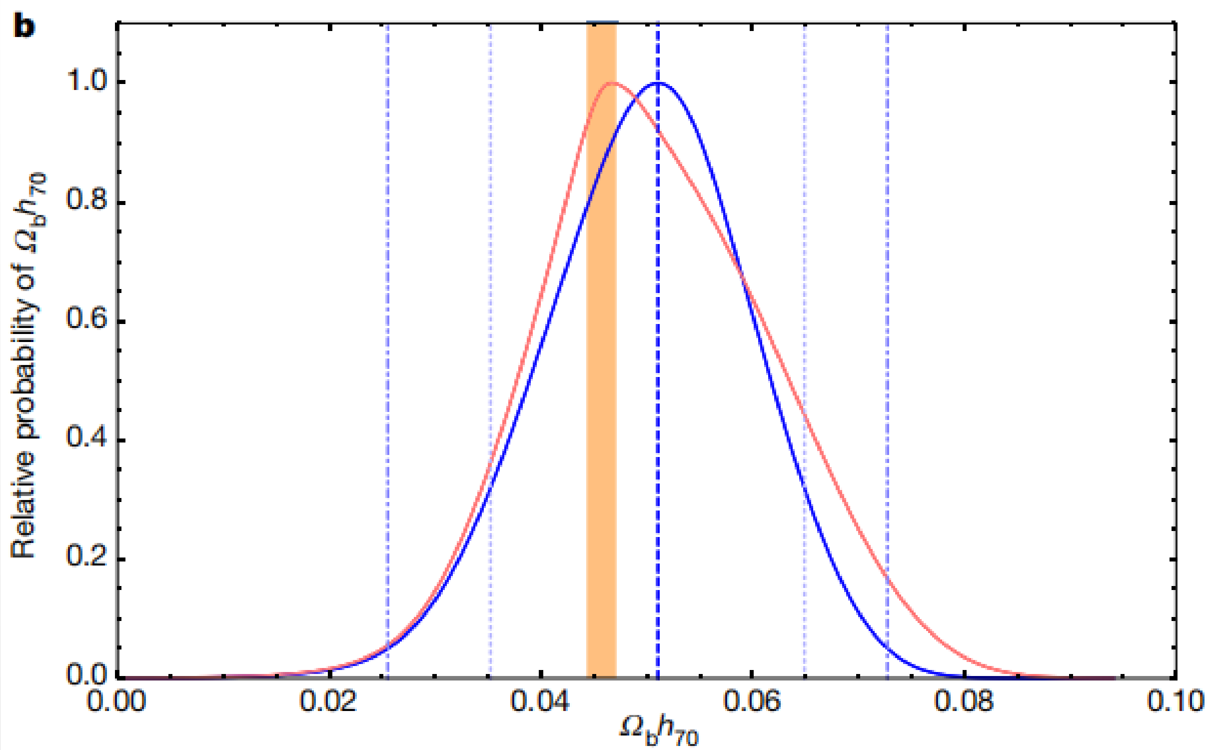
Credits:https://www.nationalgeographic.com

02 "Missing baryon" problem



(Shull et.al, 2012)

About 30% baryons are still missing



(Macquart et.al, 2020)

$$\Omega_b = 0.051^{+0.021}_{-0.025} h_{70}^{-1}$$ (~ 40%)

What extent can SKA-era FRBs measure the baryon density to solve the missing baryon problem?

02 How many FRBs will be detected by the SKA?

	Fluence threshold F_ν (Jy ms)	All-sky event rate N'_{sky} (sky^{-1} day^{-1})	Reference
Parkes	2	$1.7^{+1.5}_{-0.9} \times 10^3$	Bhandari et al., 2018
ASKAP	26	37 ± 8	Shannon et al., 2018

Extrapolate

$$N_{sky}(> F_\nu) = N'_{sky} \left(\frac{F_\nu}{F'_\nu}\right)^\alpha [sky^{-1} day^{-1}]$$

$$N_{sur} = N_{sky}[sky^{-1} day^{-1}] \Omega [sky\ FoV^{-1}] t_{obs} [day\ yr^{-1}]$$

	Fluence threshold F_ν (Jy ms)	All-sky event rate N_{sky} (sky^{-1} day^{-1})	Detection event rate N_{sur} (FoV^{-1} yr^{-1})
SKA1-MID (Based on Parkes)	0.014	$2.9^{+2.6}_{-1.5} \times 10^6$	$1.0^{+0.9}_{-0.5} \times 10^5$
SKA1-MID (Based on ASKAP)	0.014	$3.0^{+0.7}_{-0.6} \times 10^6$	$1.0^{+0.3}_{-0.2} \times 10^5$

About $10^5 - 10^6$ FRBs can be detected by SKA1-MID in a 10-year observation.

02 Simulation of FRB data detected by the SKA

(a). DM_{IGM} – z plot

$$\mathrm{DM_{obs}} = \mathrm{DM_{host}} + \mathrm{DM_{IGM}} + \mathrm{DM_{MW}}.$$

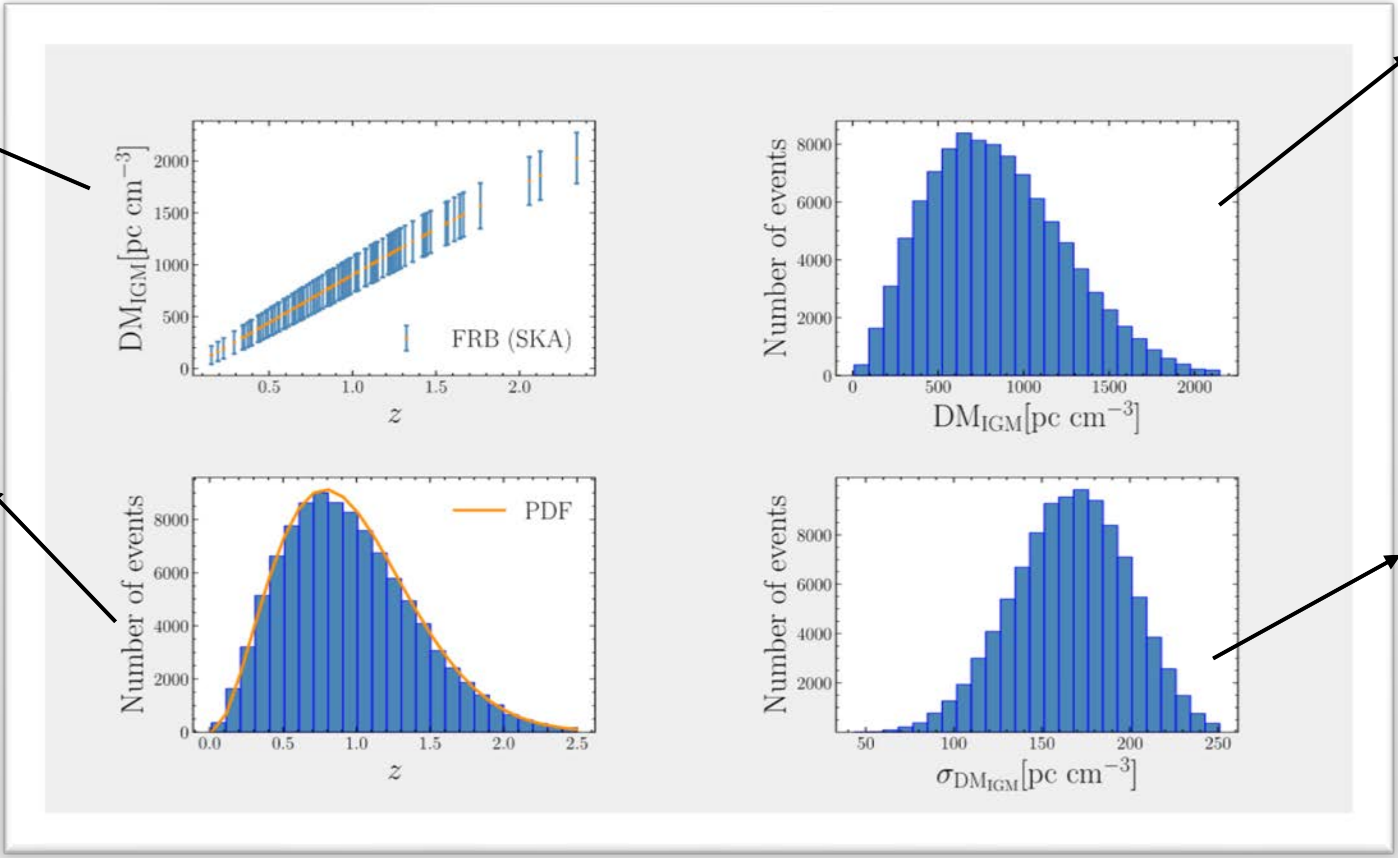
$$\mathrm{DM_{MW,ISM}} \approx 50\ \mathrm{pc\ cm^{-3}}$$

$$\mathrm{DM_{MW,halo}} = 50 \sim 80\ \mathrm{pc\ cm^{-3}}$$

(c). Redshift Distribution

$$N_{\rm const}(z) = \mathcal{N}_{\rm const}\frac{d_{\rm C}^2(z)}{H(z)(1+z)}e^{-d_{\rm L}^2(z)/[2d_{\rm L}^2(z_{\rm cut})]}$$

$$z_{\rm cut} = 1$$



(b). Macquart relation

$$\langle \mathrm{DM_{IGM}}\rangle = \frac{3cH_0\Omega_b f_{\rm IGM}}{8\pi G m_{\rm p}}\int_0^z \frac{\chi(z')(1+z')dz'}{E(z')},$$

$$f_{\rm IGM} = 0.83$$

$$\chi(z) = Y_{\rm H}\chi_{\rm e,H}(z) + \frac{1}{2}Y_{\rm He}\chi_{\rm e,He}(z).$$

$$Y_{\rm H} = 3/4 \text{ and } Y_{\rm He} = 1/4$$

$$E(z) = [\Omega_m(1+z)^3 + (1-\Omega_m)^{3(1+w)}]^{1/2}$$

(d). Uncertainty of DM_{IGM}

$$\sigma_{\rm DM_{IGM}} = \left[\sigma_{\rm obs}^2 + \sigma_{\rm MW}^2 + \sigma_{\rm IGM}^2 + \left(\frac{\sigma_{\rm host,src}}{1+z}\right)^2\right]^{1/2}$$

σ_{obs} = 0.5 pc cm^{-3}

σ_{MW} = 10 pc cm^{-3}

$\sigma_{IGM} = 173.8z^{0.4}$pc cm^{-3}

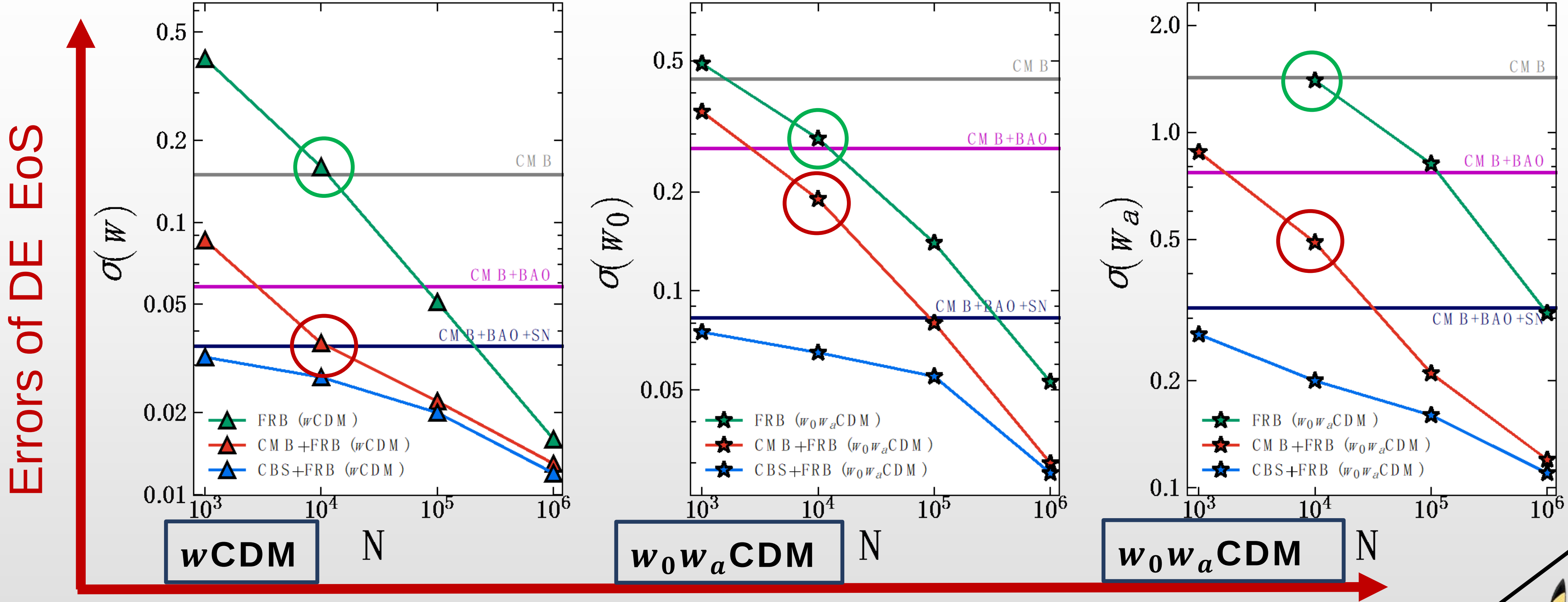
$\sigma_{host,src}$ = 30 pc cm^{-3}

MCMC

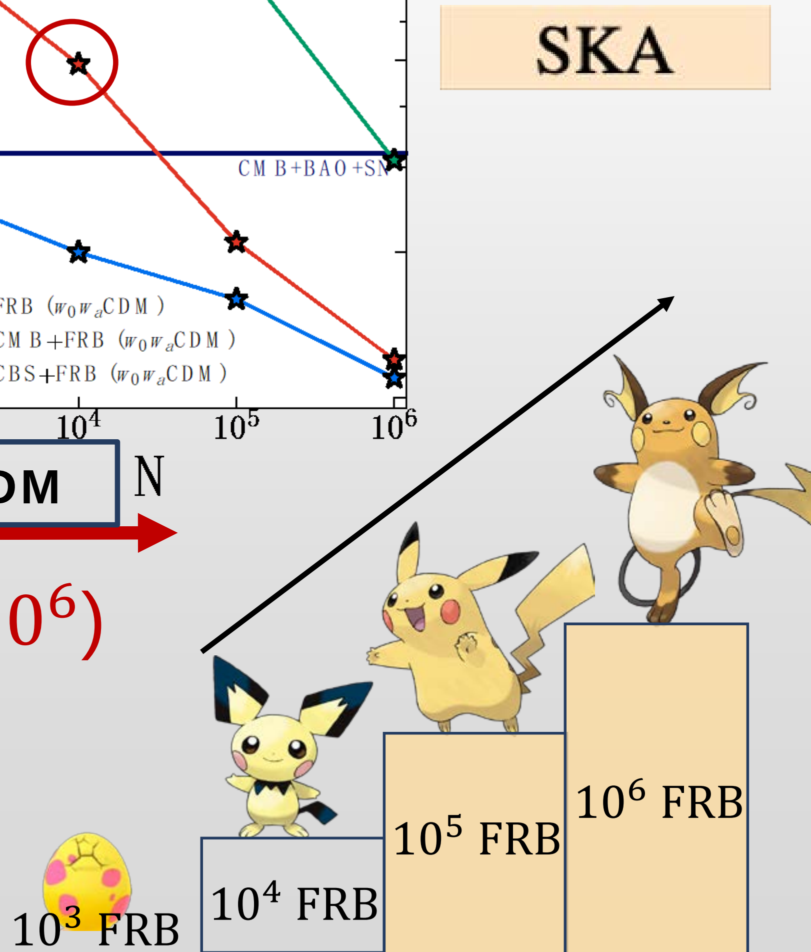
e.g., the 10^5 simulated FRB data under the fiducial ΛCDM

We choose ΛCDM, wCDM and w_0w_aCDM models as fiducial models to generate 10^5 – 10^6 mock FRB data

03 Results–Dark Energy (“Pre-SKA” era)



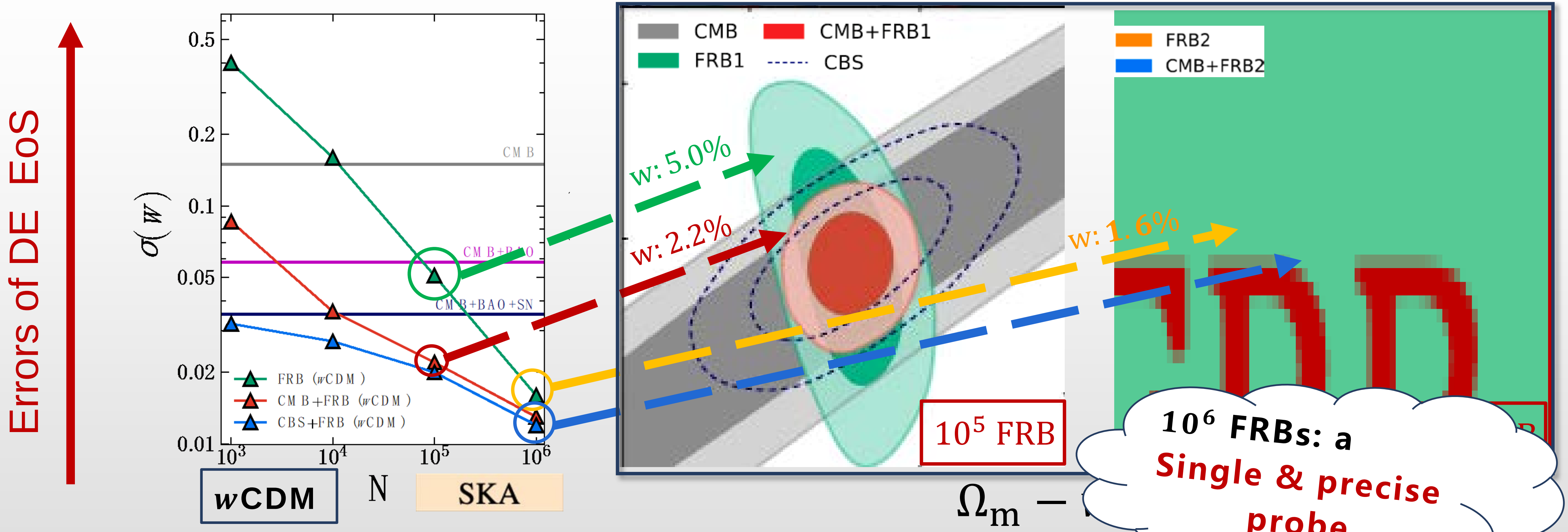
Numbers of mock FRB data (10^3, 10^4, 10^5 and 10^6)



- **The capability (assuming C) to constrain dark-energy EoS:**
- **The capability (C') to break the CMB degeneracies:**

$$C(10^4\ \mathrm{FRB}) \approx C(\mathrm{CMB}) \qquad C'(10^4\ \mathrm{FRB}) \approx C'(\mathrm{BAO})$$

03 Results–Dark Energy (SKA era)



- **The capability (assuming C) to constrain dark-energy EoS:**

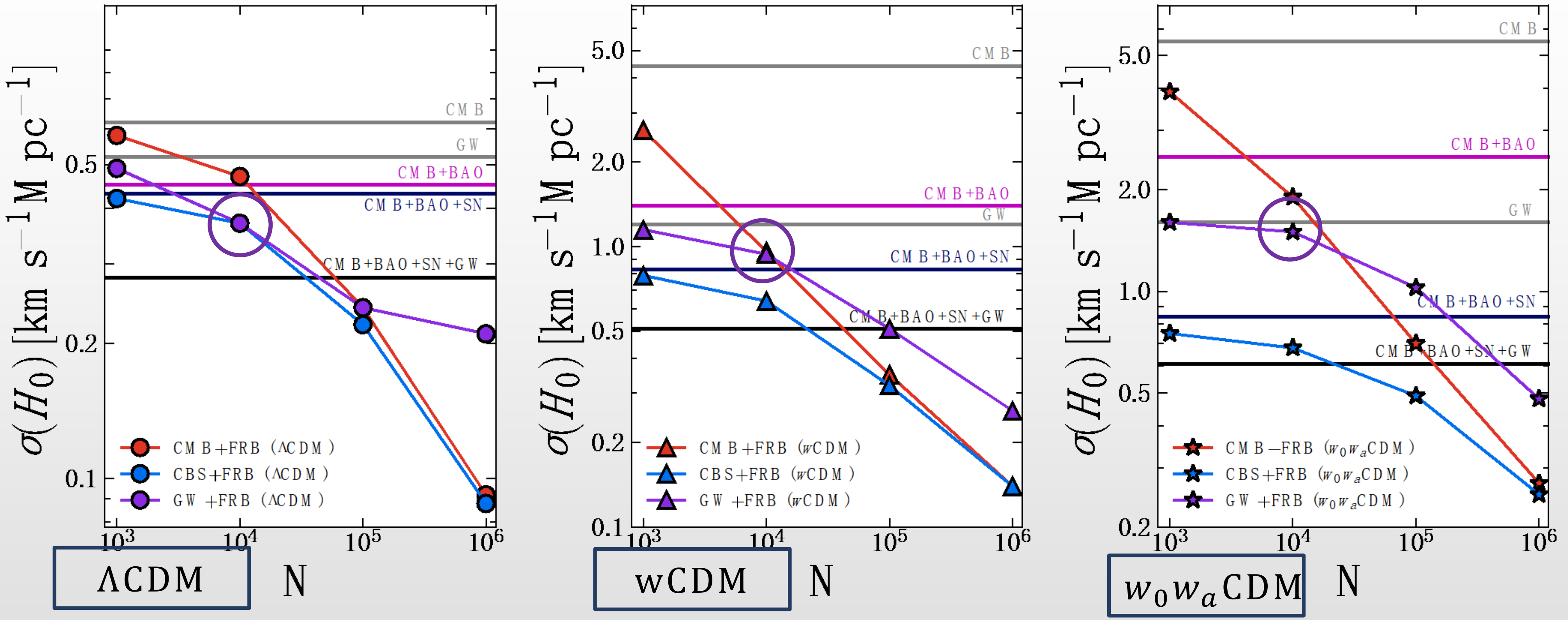
$C(10^4\ \mathrm{FRB}) \approx C(\mathrm{CMB})$ **SKA-era** → $C(10^6\ \mathrm{FRB}) > C(\mathrm{CMB} + \mathrm{BAO} + \mathrm{SN})$

- **The capability (C') to break the CMB degeneracies:**

$C'(10^4\ \mathrm{FRB}) \approx C'(\mathrm{BAO})$ **SKA-era** → $C'(10^5\ \mathrm{FRB}) \approx C'(\mathrm{BAO} + \mathrm{SN})$

03 Results–Hubble constant (“Pre-SKA” era)

Errors of H_0

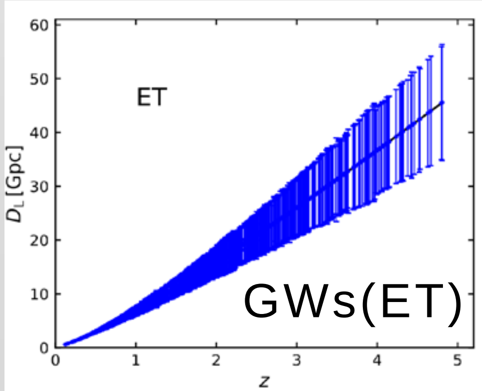


SKA

- Combing 10^4 FRBs and GWs(ET) can obtain H_0 constraints comparable to CMB+BAO.

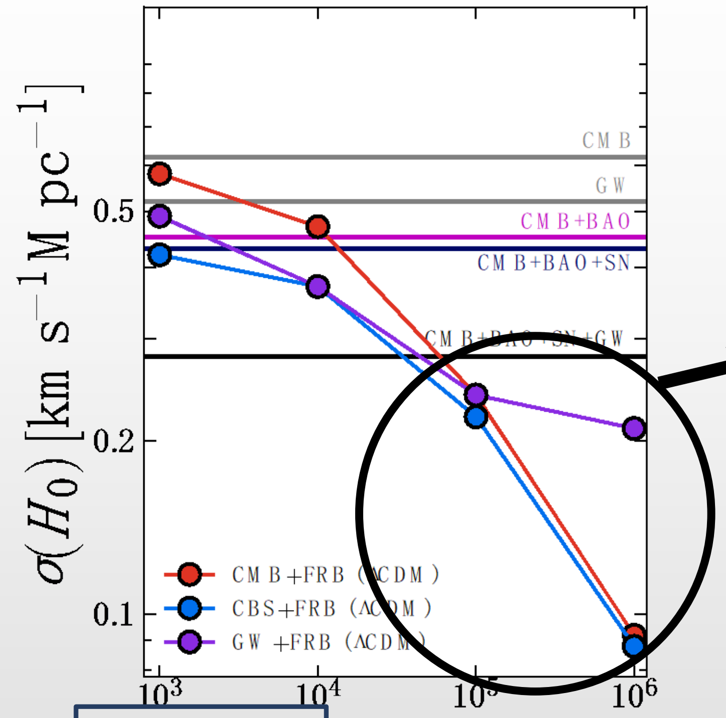
GW+FRB

The 1000 simulated GW standard siren events of ET

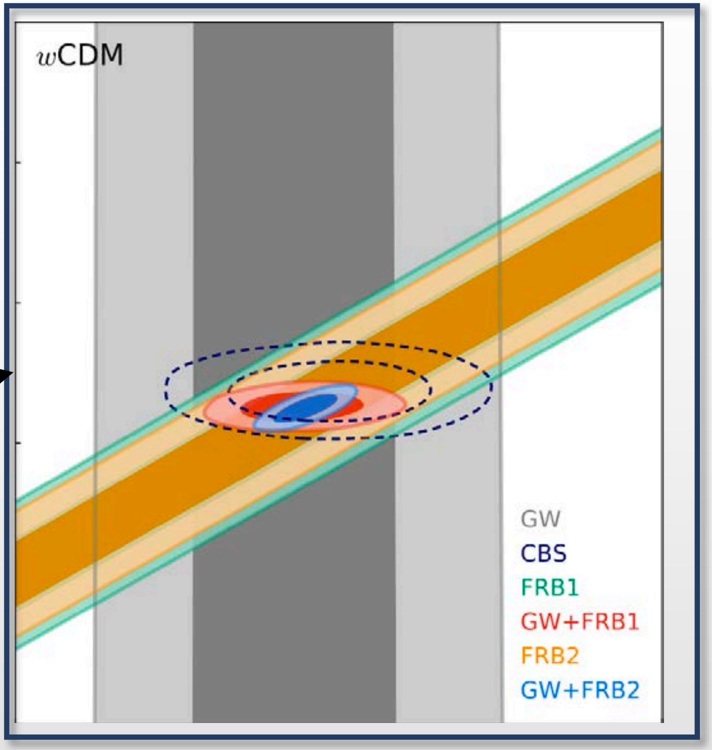


03 Results–Hubble constant (SKA era)

Errors of H_0



ΛCDM N SKA



$H_0 - \Omega_b$ plane

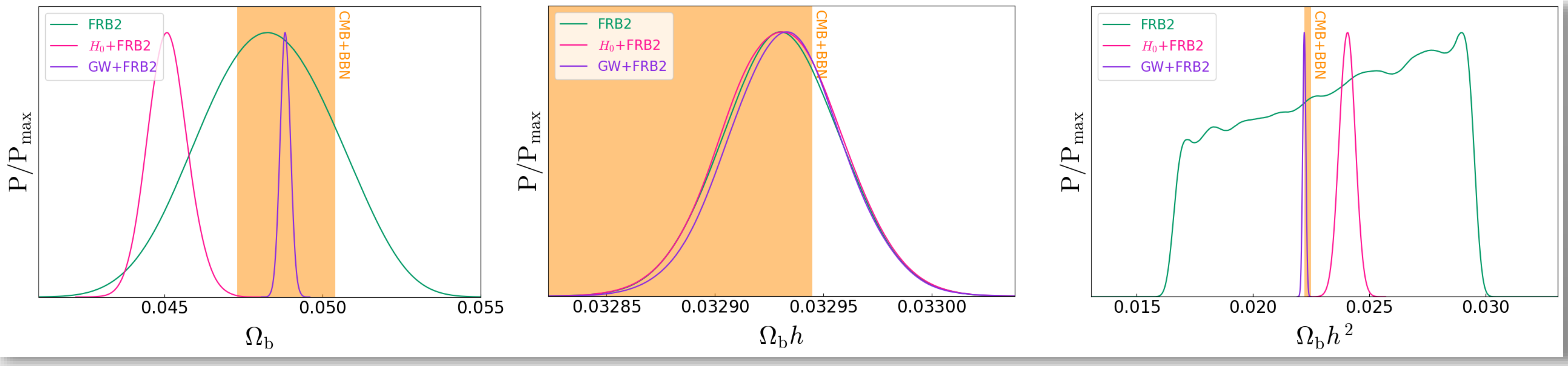
$10^5/10^6$FRBs: a **Complementary & good probe**

- Combining 10^4 FRBs and GWs(ET) can obtain H_0 constraints comparable to CMB+BAO.

SKA-era

- Combing 10^5 FRBs and GWs(ET) can obtain H_0 constraints better than CMB+BAO+SN.
- Combing 10^6 FRBs and GWs(ET) can obtain the precisions $\varepsilon(H_0) < 1\%$.

03 Results–Baryon density



- In the many cases (different datasets and constrained parameters), we conclude that

10^6 FRBs can constrain $\Omega_b h$ to 0.1%

03 Summary

Tremendous FRBs to be detected by the SKA can answer three important issues in cosmology.

- Using only the localized FRBs in the era of the SKA could answer
  - What the nature of dark energy is (~ $2\% - 5\%$).
  - Where the missing baryons are (~ 0.1%).
- Combined with future GW data could also answer
  - Which H_0 measurement (67 or 74?) is true ($< 0.1\%$).

FRB Future is Promising!