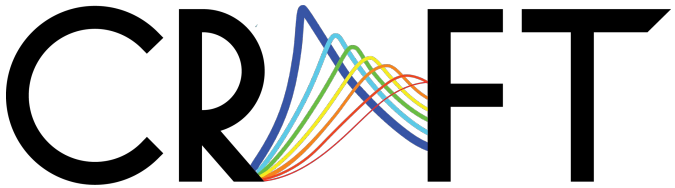
高速電波バーストでコズミック ウェブを解決する

J. ザビエル Prochaska
(UC Santa Cruz, Kavli IPMU, etc.)
on behalf of the Fast and Fortunate for FRB Follow-up (F⁴) team



realfast

はじめまして 釧路

はじめまして 釧路

はじめまして 釧路

はじめまして 釧路

はじめまして 釧路

Fast and Fortunate for FRB Follow-up (F^4)

Alexandra Mannings
(UC Santa Cruz)

Sunil Simha
(UC Santa Cruz)

Celia Mulchaey
(MMO)

Tarraneh Eftekhari
(Northwestern U.)

Alexa Gordon
(Northwestern U.)

Regina Jorgenson
(Director, MMO)

Nicolas Tejos (PUCV)

Charlie Kilpatrick
(Northwestern U.)

Wen-Fai Fong
(Northwestern U.)

www.ucolick.org/f-4

Fast and Fortunate for FRB Follow-up (F^4)

Jay Baptista
(Yale)

Ethan Domingo
(UC Santa Cruz)

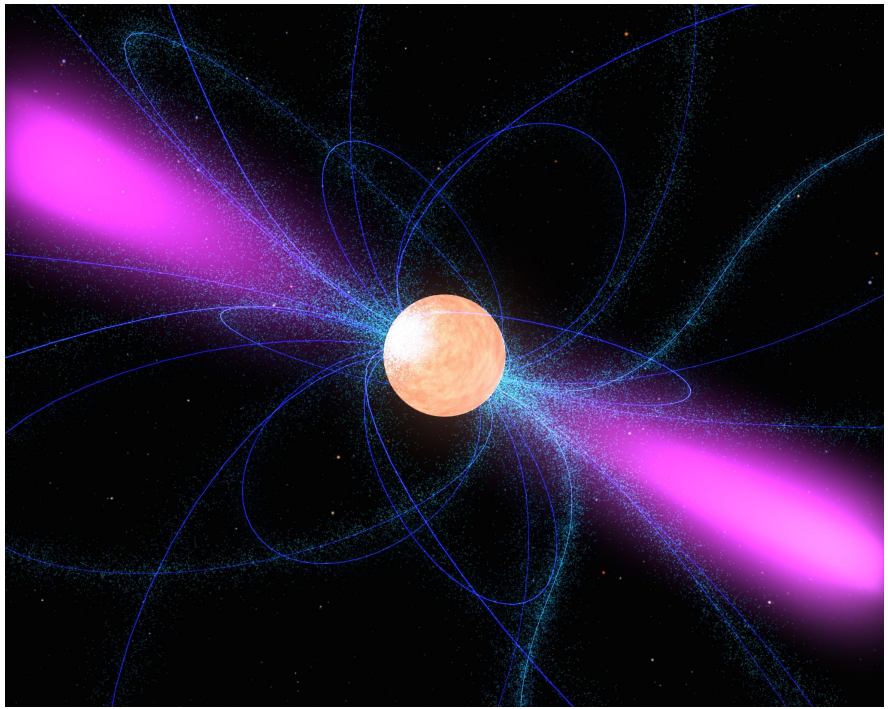
YuXin Dong
(Northwestern U)

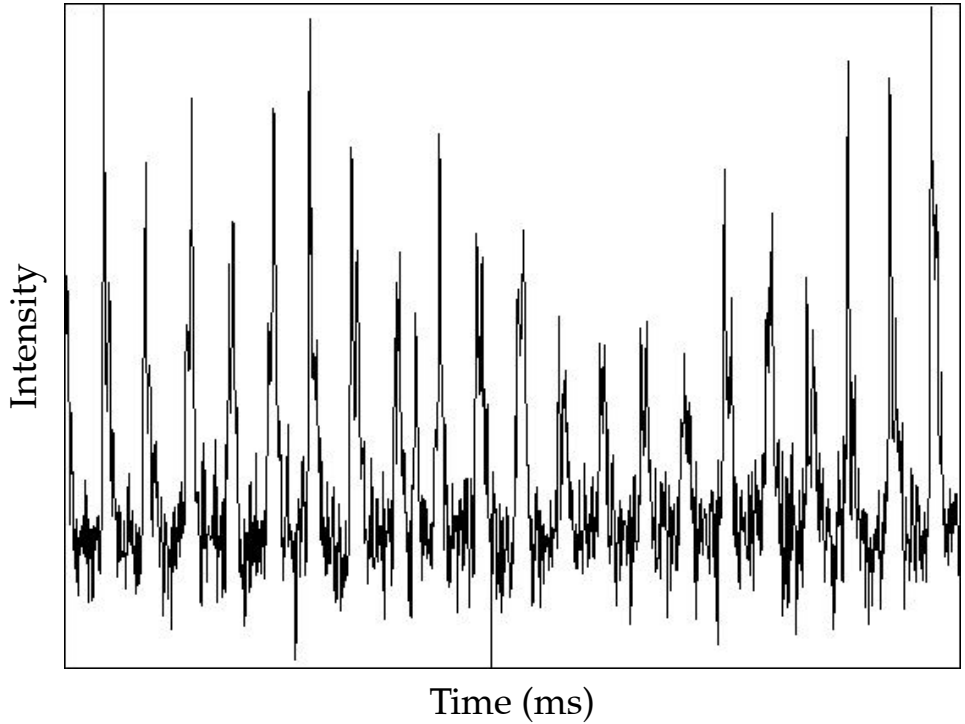
Lucas Bernales
(PUCV)

www.ucolick.org/f-4

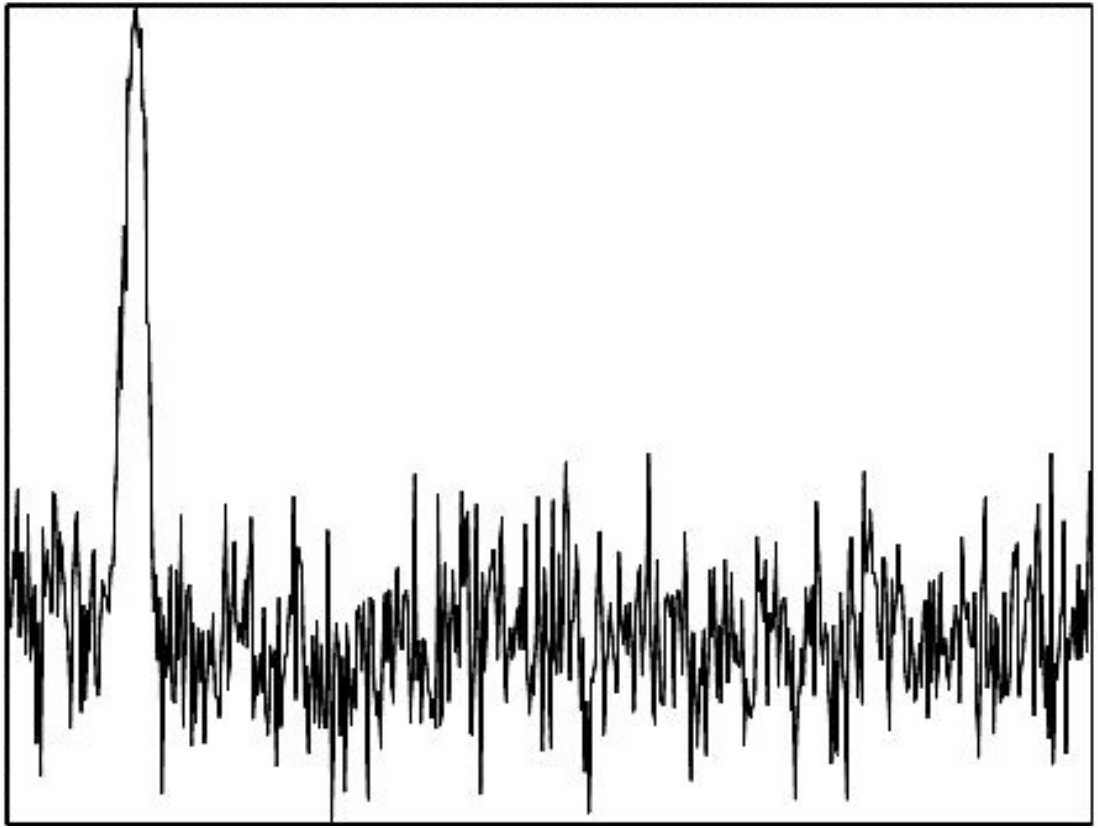
Radio Transients (Observation)

Radio Transients (Pulsars)





Radio Transients (Fast Radio Burst)



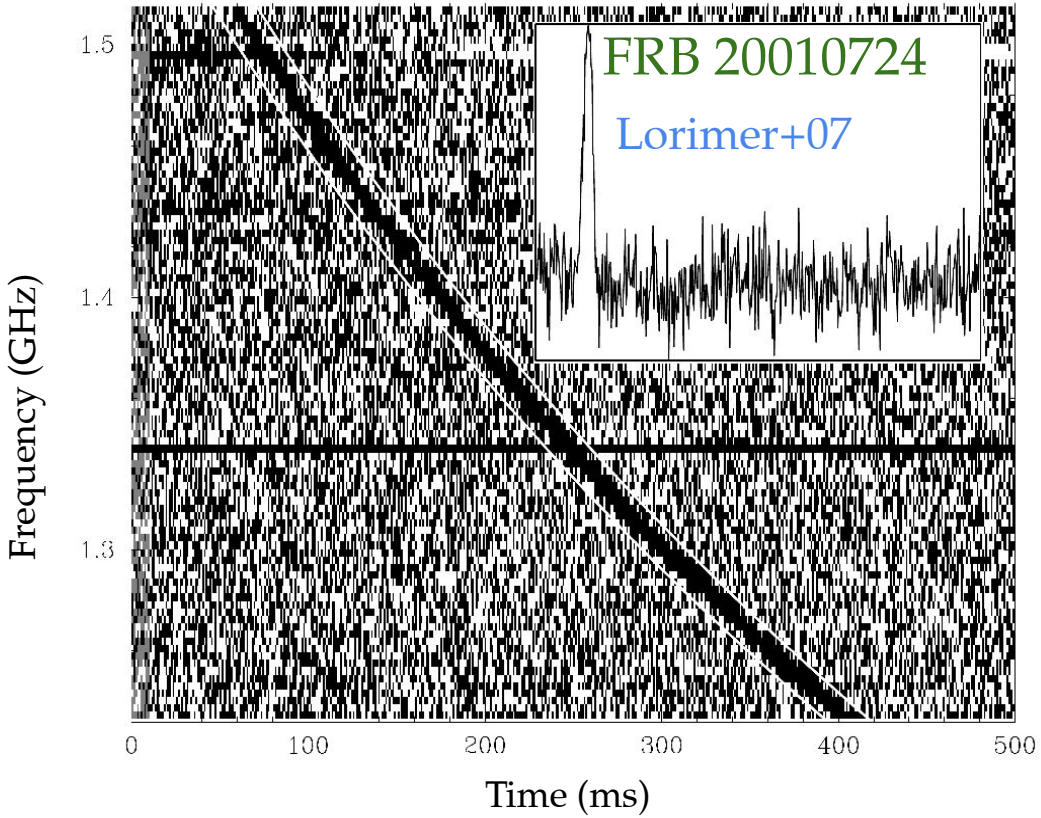
The First "Lorimer" Fast Radio Burst

Arrival Time

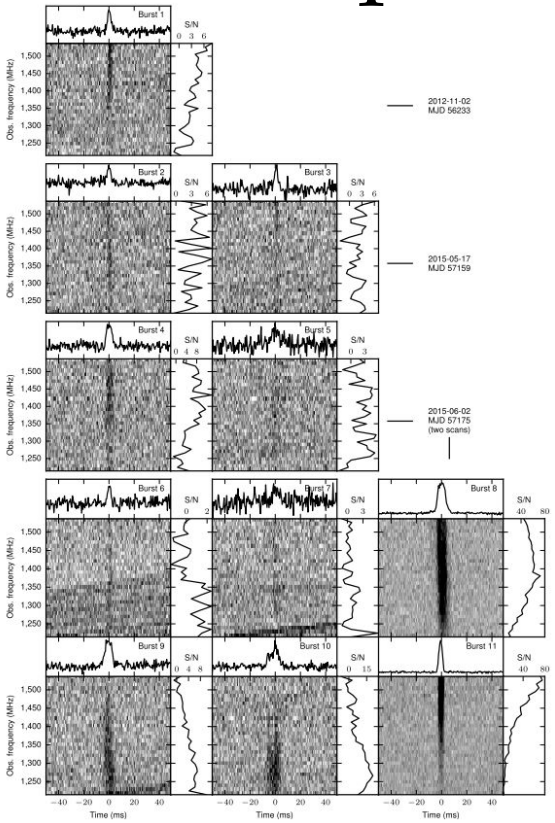
$$\tau = 4.15\,\mathrm{ms}\left(\frac{\mathrm{DM}}{\mathrm{pc\,cm^{-3}}}\right)\left(\frac{\mathrm{GHz}}{\nu}\right)^2$$

Dispersion Measure

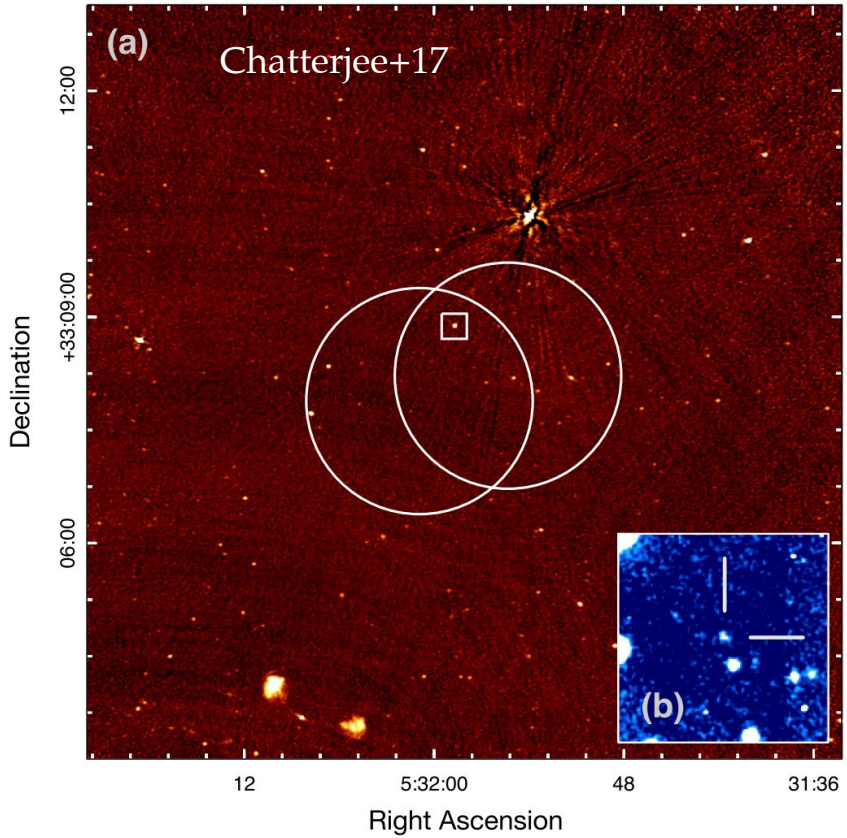
$$\mathrm{DM} = \int \frac{n_e}{1+z}\,ds$$



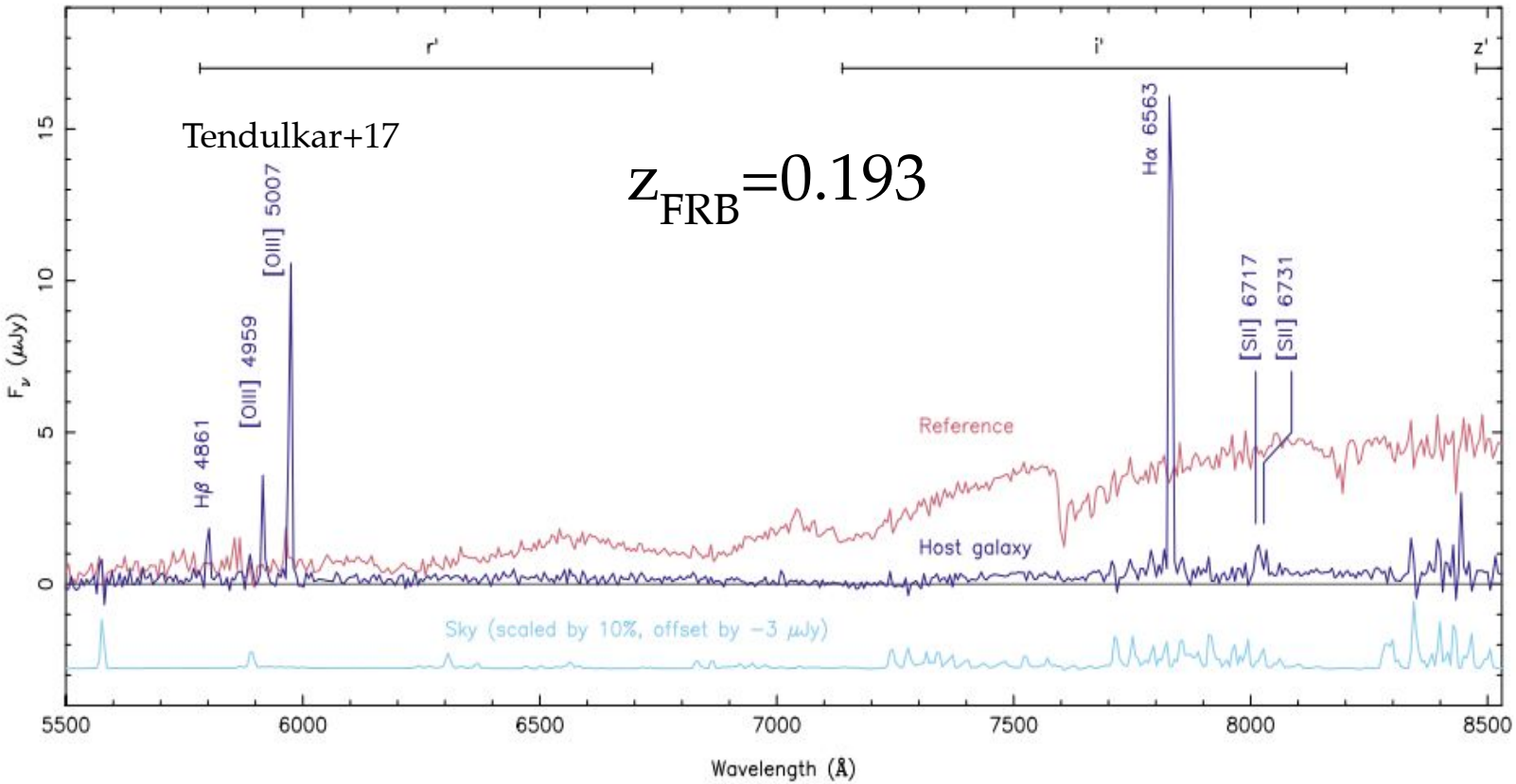
The Repeater (FRB 20121102)



Spitler+16



The Repeater's Host Galaxy



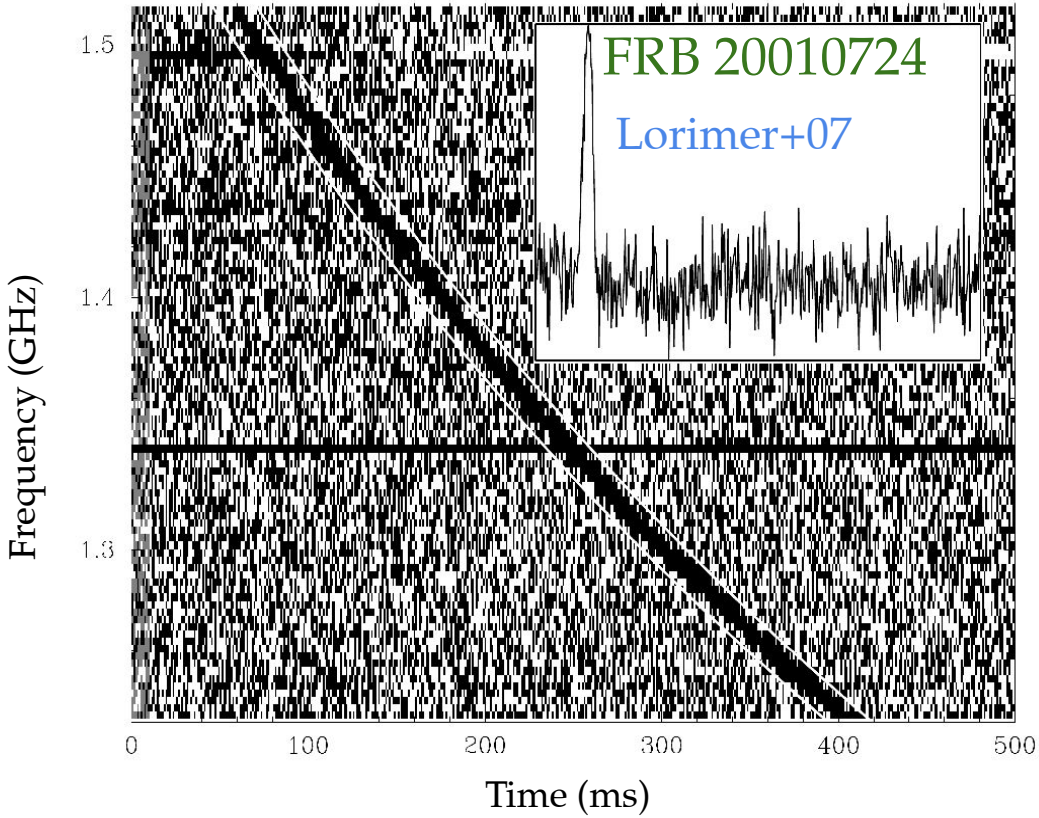
Solving a ~20yr "Problem" with FRBs

Arrival Time

$$\tau = 4.15\,\mathrm{ms}\left(\frac{\mathrm{DM}}{\mathrm{pc\,cm^{-3}}}\right)\left(\frac{\mathrm{GHz}}{\nu}\right)^2$$

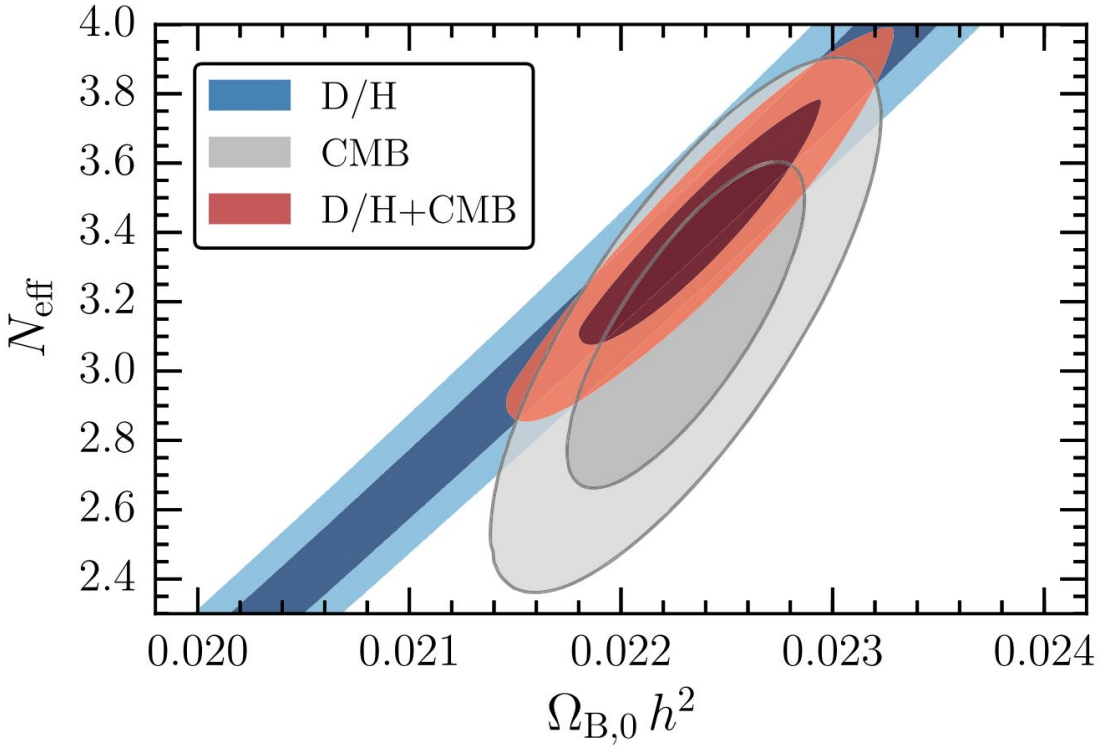
Dispersion Measure

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

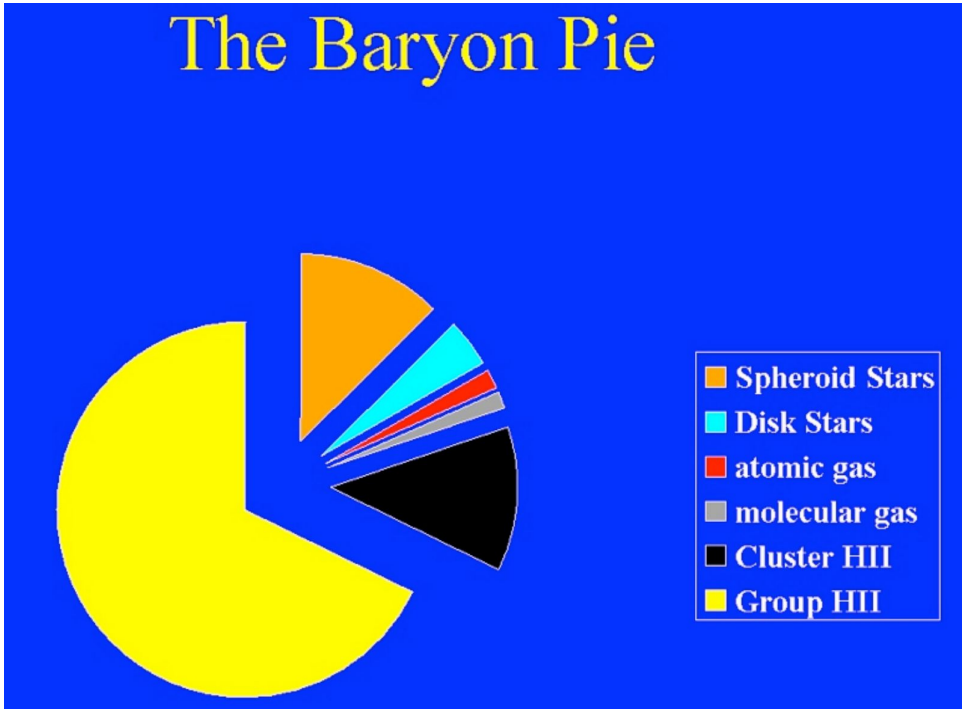


Counting the Cosmic Baryons: Consensus!

Cooke, Pettini, & Steidel



Testing the Baryon Consensus at z~0



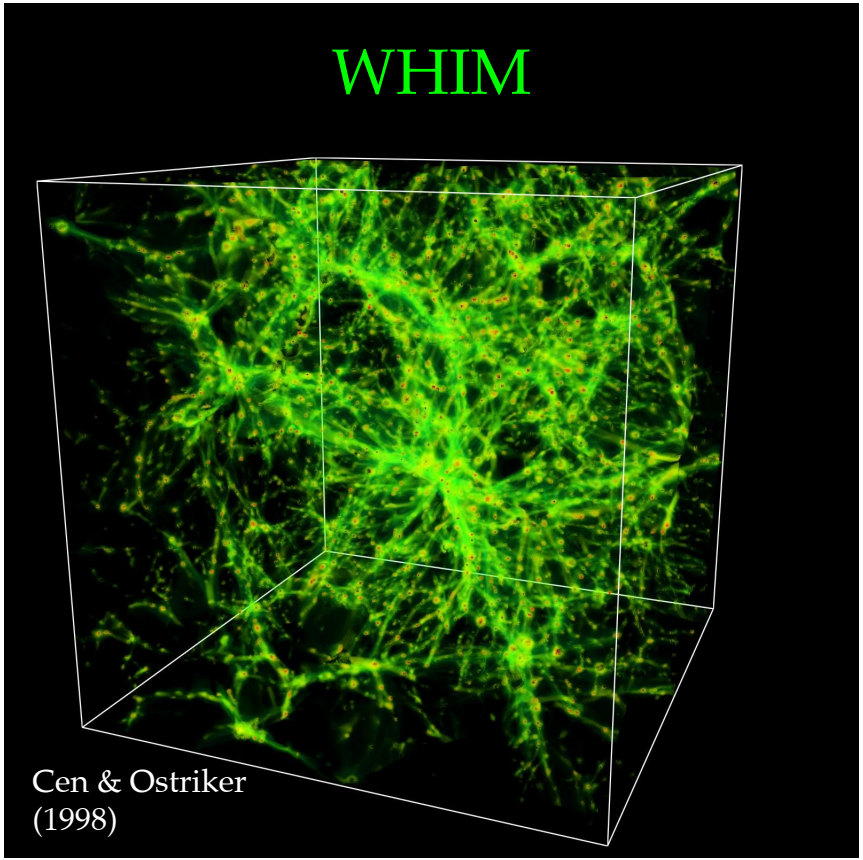
THE ASTROPHYSICAL JOURNAL, 503:518–530, 1998 August 20
© 1998. The American Astronomical Society. All rights reserved. Printed in U.S.A.

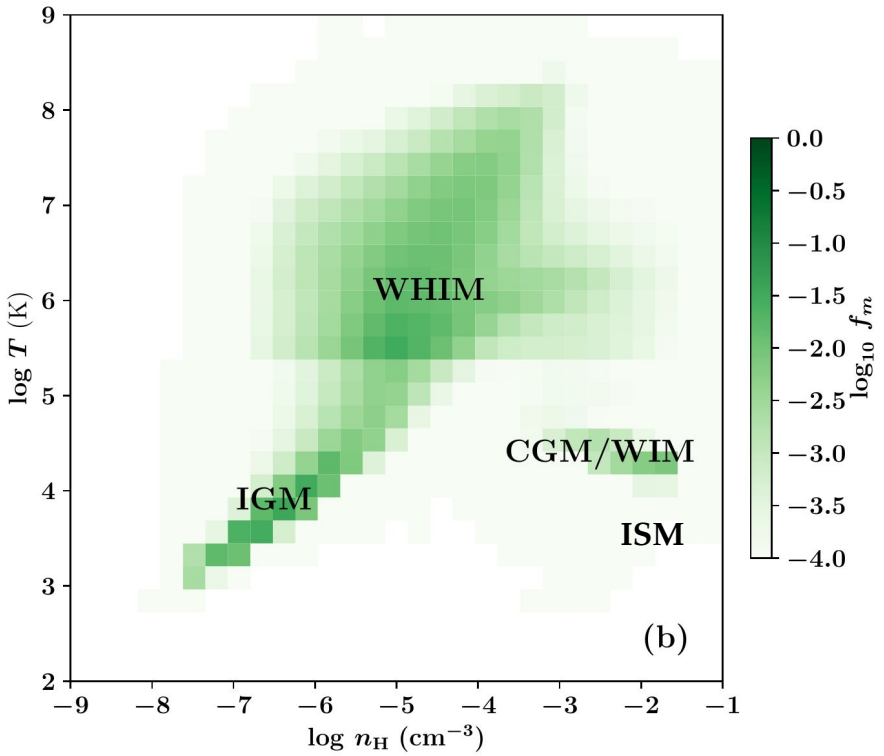
THE COSMIC BARYON BUDGET

M. FUKUGITA
Institute for Advanced Study, Princeton, NJ 08540; and Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan; fukugita@icrr.u-tokyo.ac.jp
C. J. HOGAN
Departments of Astronomy and Physics, University of Washington, Seattle, WA 98195; hogan@astro.washington.edu
AND
P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544; pjep@pupgg.princeton.edu
Received 1997 December 2; accepted 1998 March 26

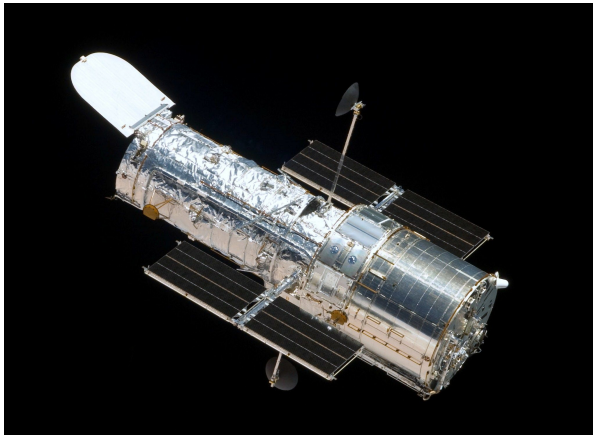
Missing Baryons!!
(half or more)

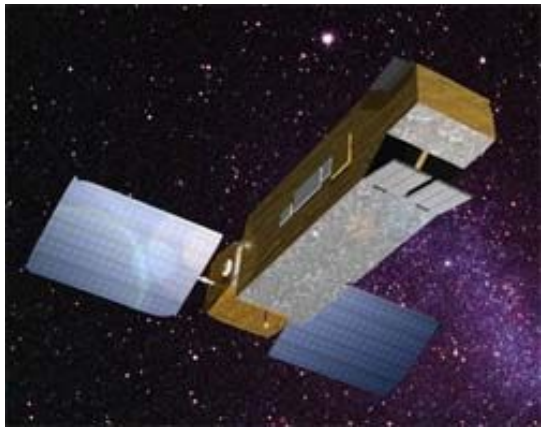
Warm-Hot Intergalactic Medium (WHIM)

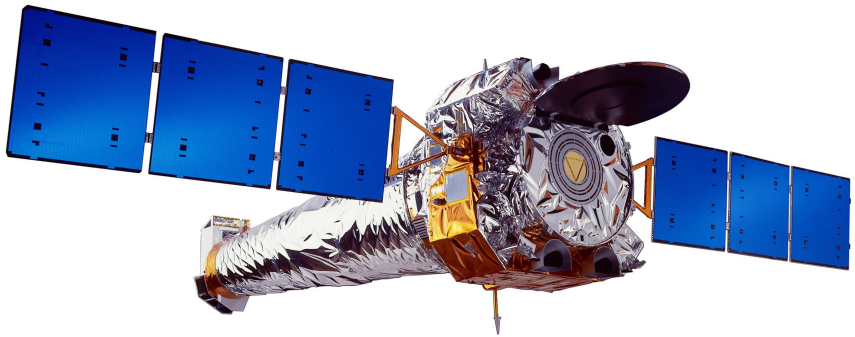




Missing Baryons: Stymied for ~20 years..







(~$50M USD in operations alone)

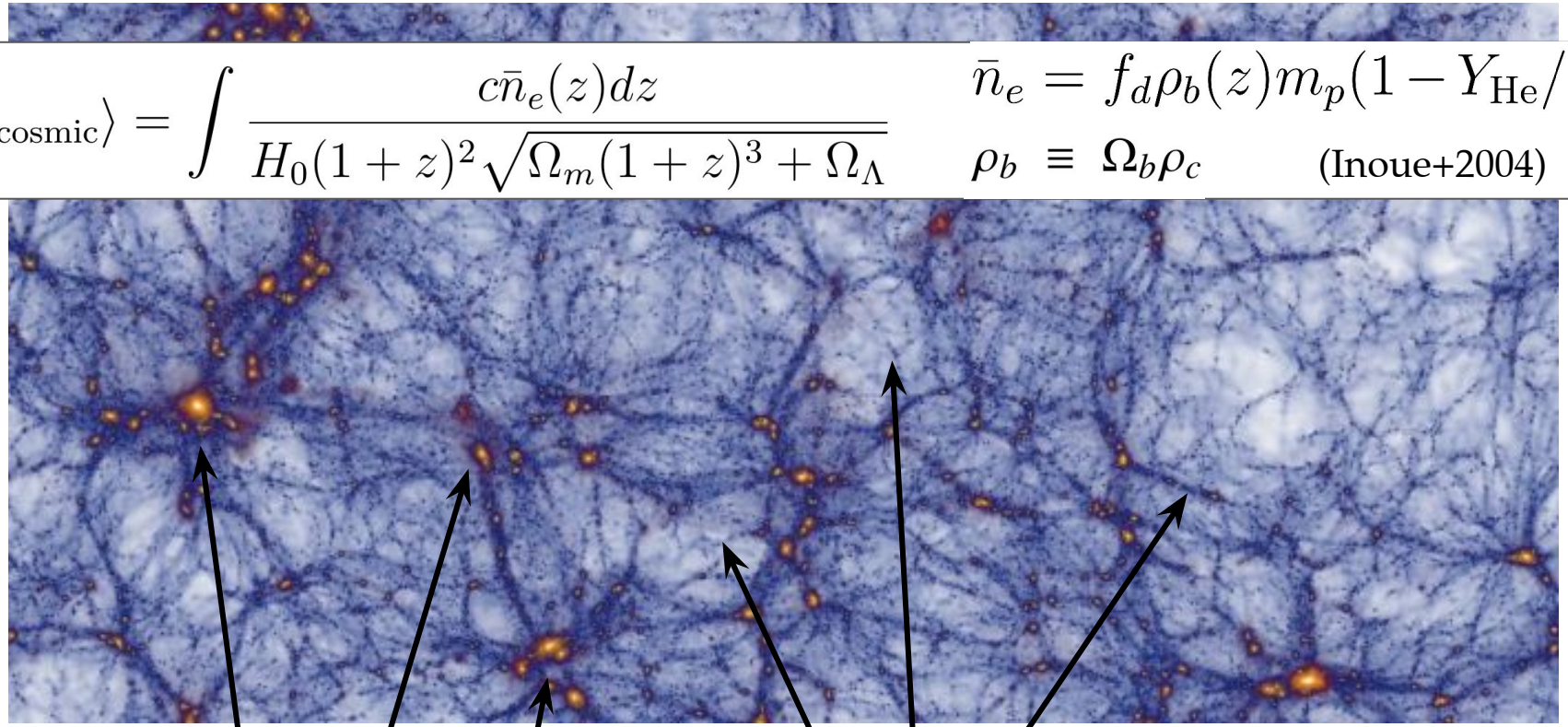
FRBs "Weighing" the Cosmic Web

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

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

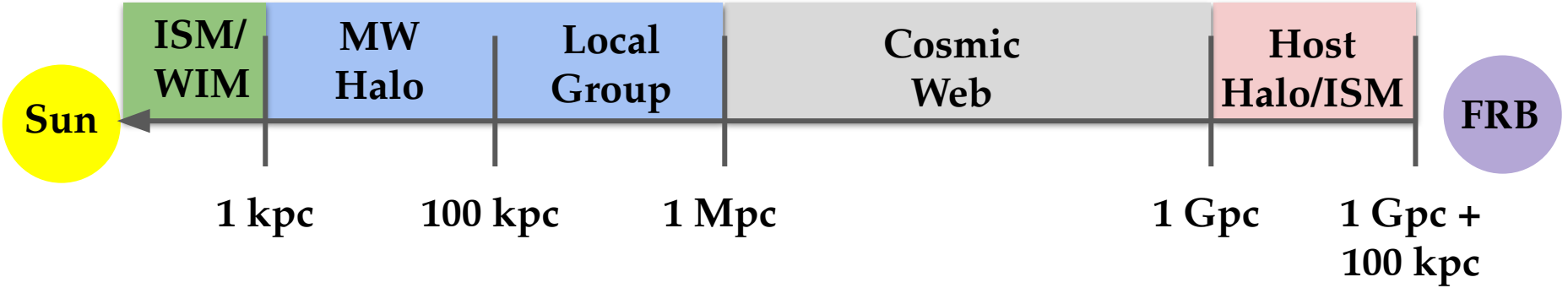
$$\rho_b \equiv \Omega_b \rho_c$$

(Inoue+2004)



The Many Contributions to DM_{FRB}

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



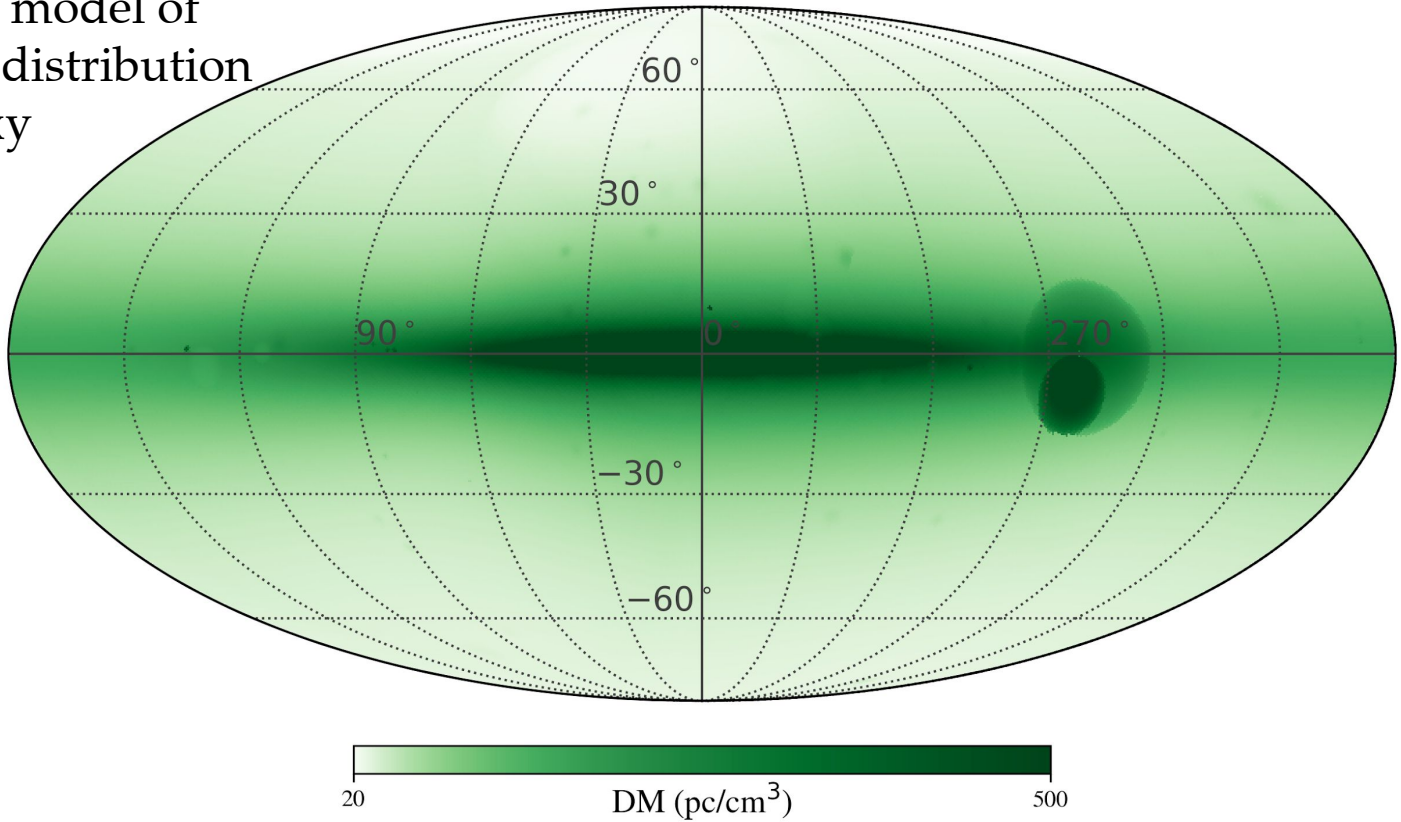
$$DM_{FRB} = DM_{MW} + DM_{cosmic} + DM_{host}$$

FRBs: A Blessing and a Curse!

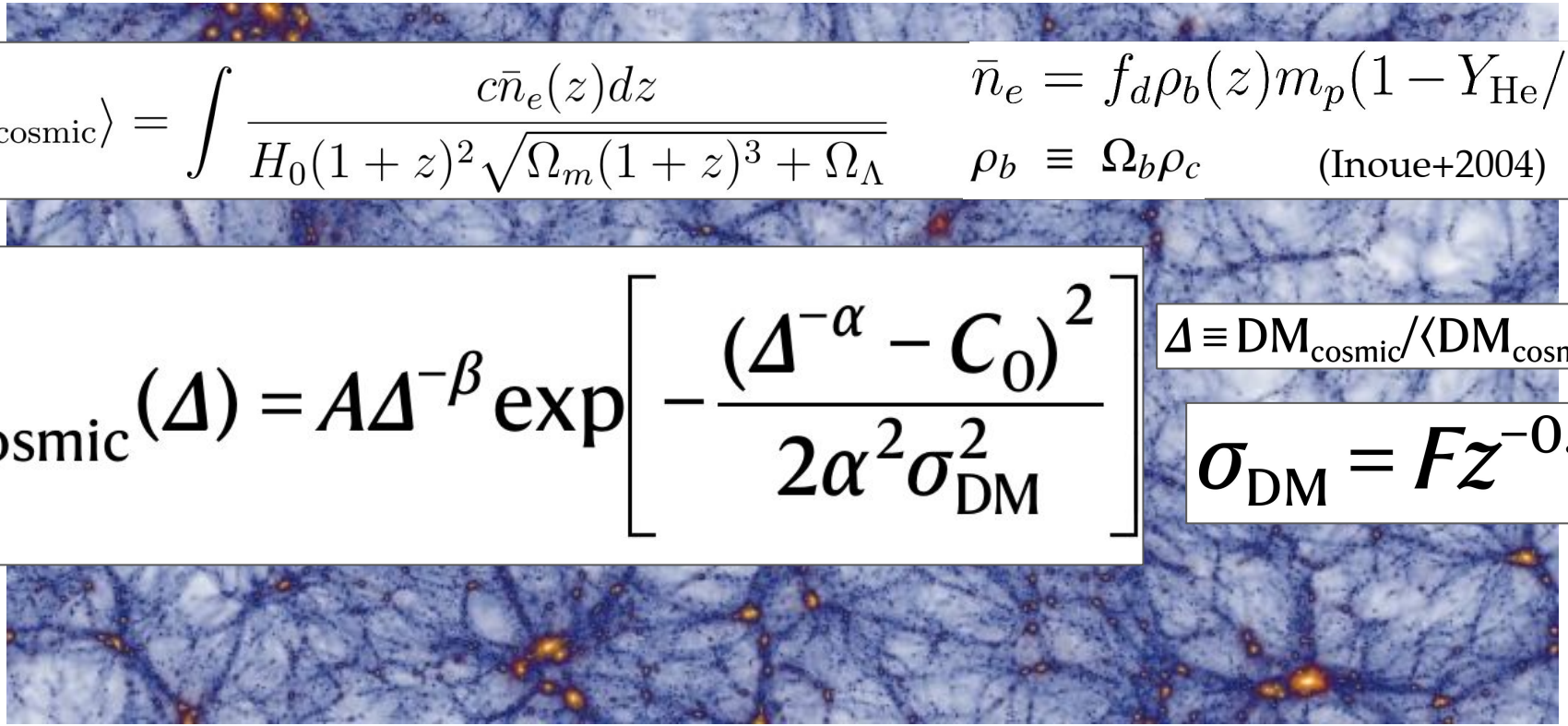
DM_{MW}: Galactic ISM contribution to DM_{FRB}

Data-driven model of the electron distribution of our Galaxy

NE2001 (Cordes & Lazio 2001)



FRBs "Weighing" the Cosmic Web



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

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

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

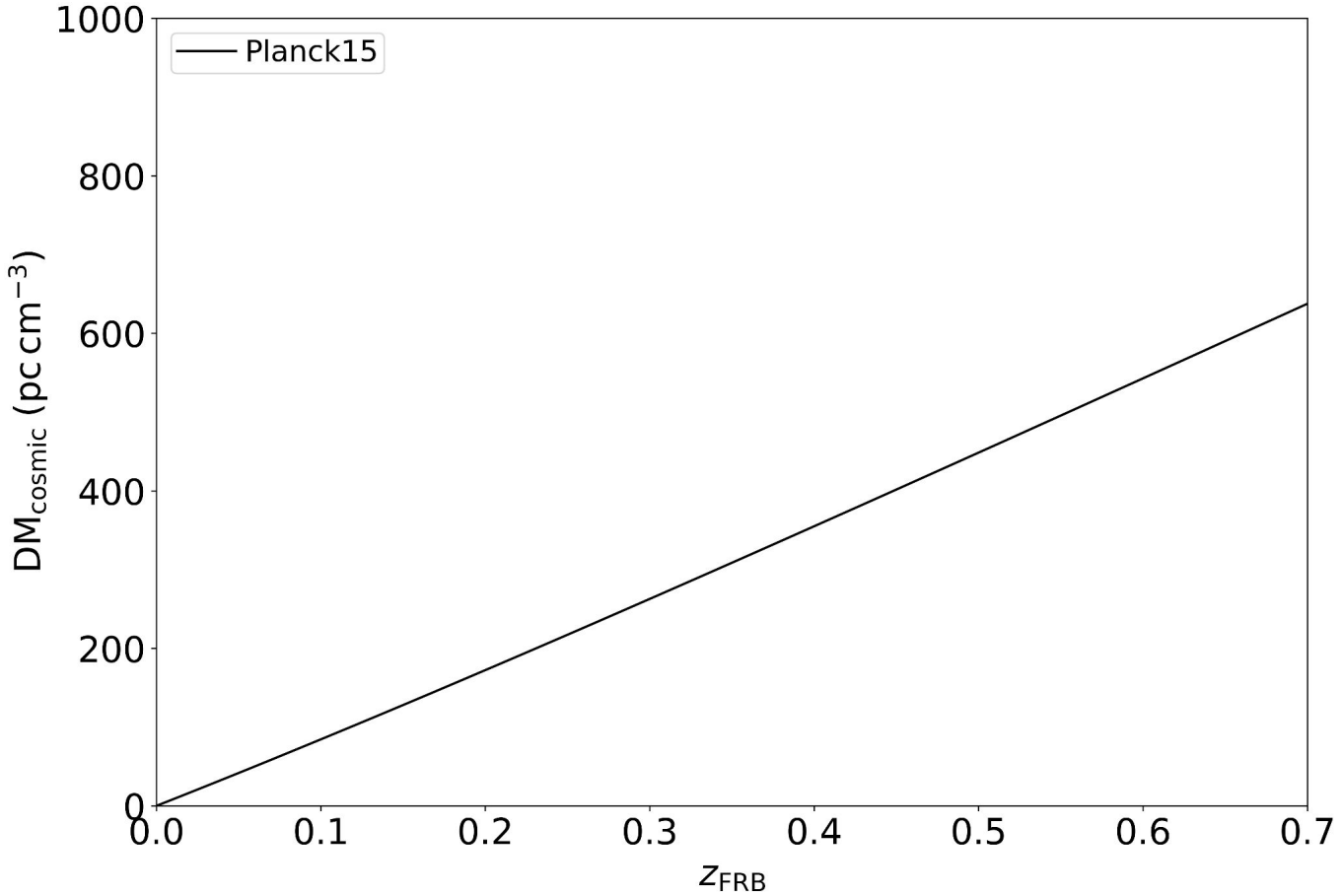
(Inoue+2004)

$$p_{\mathrm{cosmic}}(\Delta) = A\Delta^{-\beta}\exp\left[-\frac{(\Delta^{-\alpha}-C_0)^2}{2\alpha^2\sigma_{\mathrm{DM}}^2}\right]$$

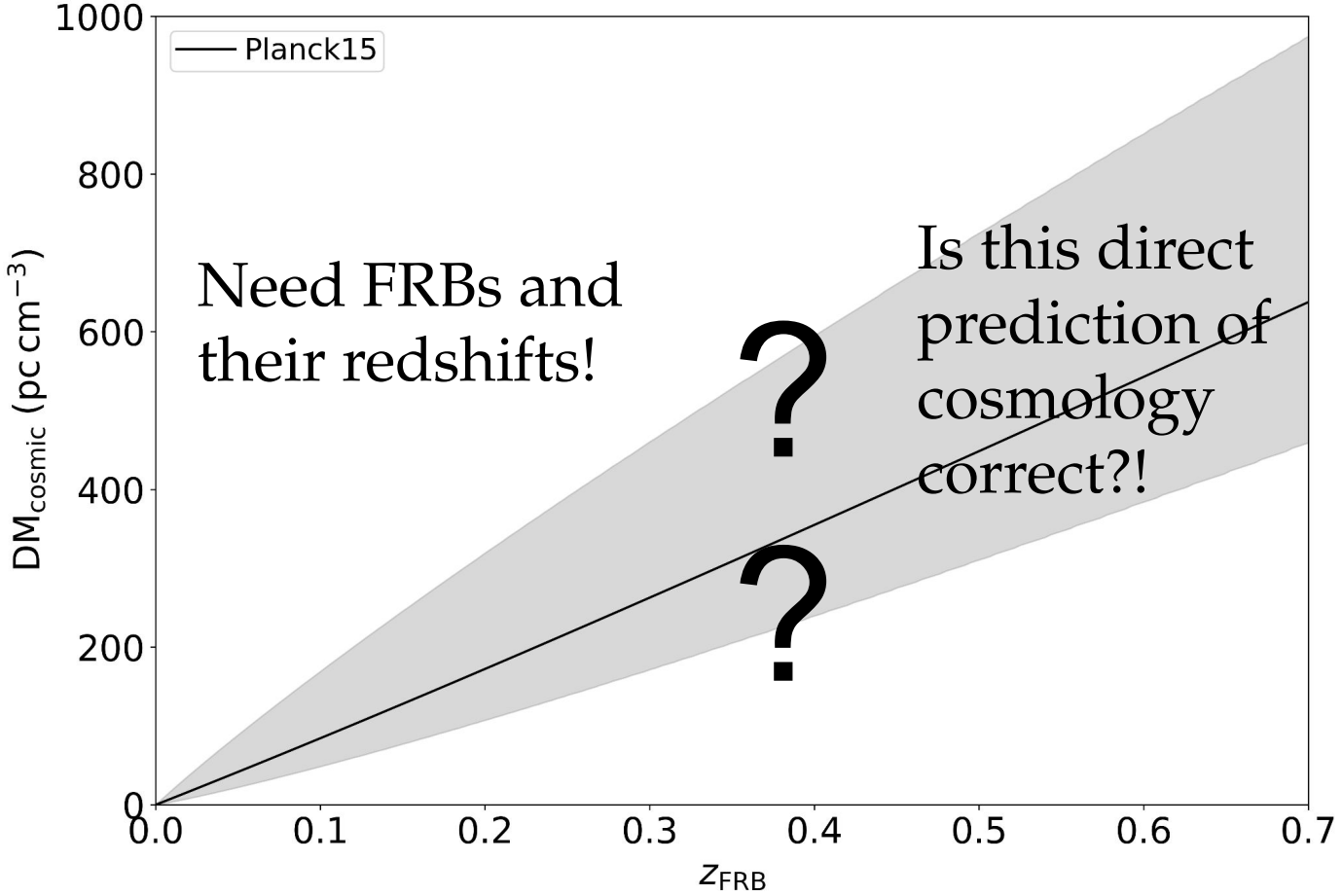
$$\Delta \equiv \mathrm{DM_{cosmic}}/\langle \mathrm{DM_{cosmic}} \rangle$$

$$\sigma_{\mathrm{DM}} = Fz^{-0.5}$$

FRBs Probing the Cosmic Web: DM vs z



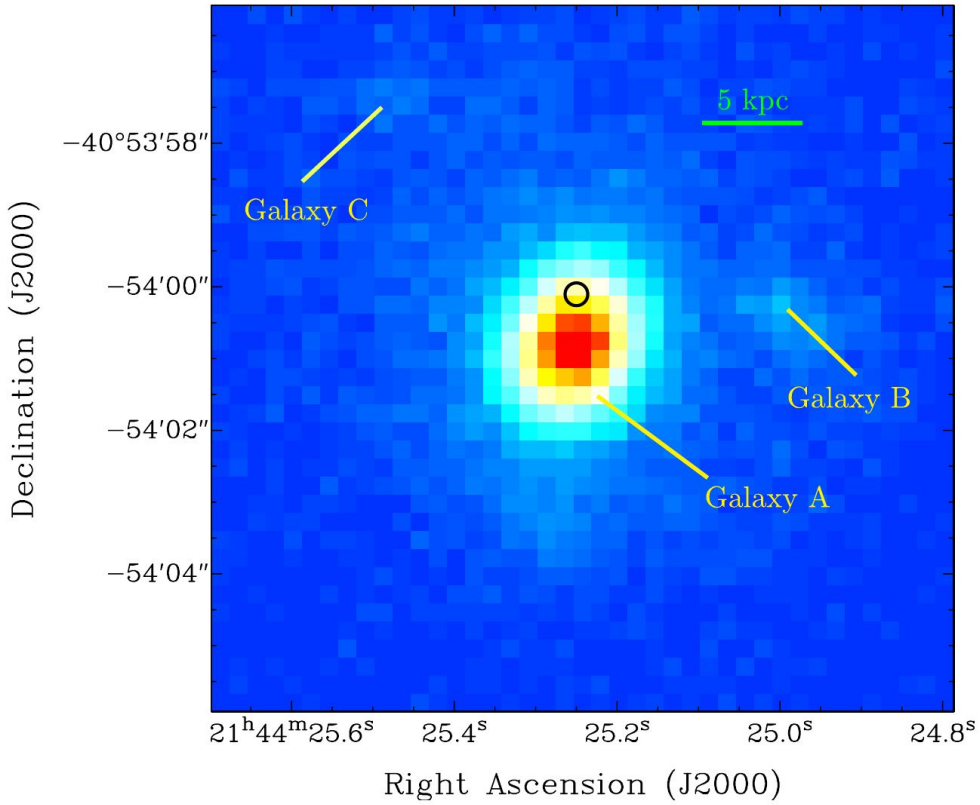
FRBs Probing the Cosmic Web: DM vs z



ASKAP - Australian SKA Pathfinder

CRAFT

Technical Advances (ASKAP/CRAFT)

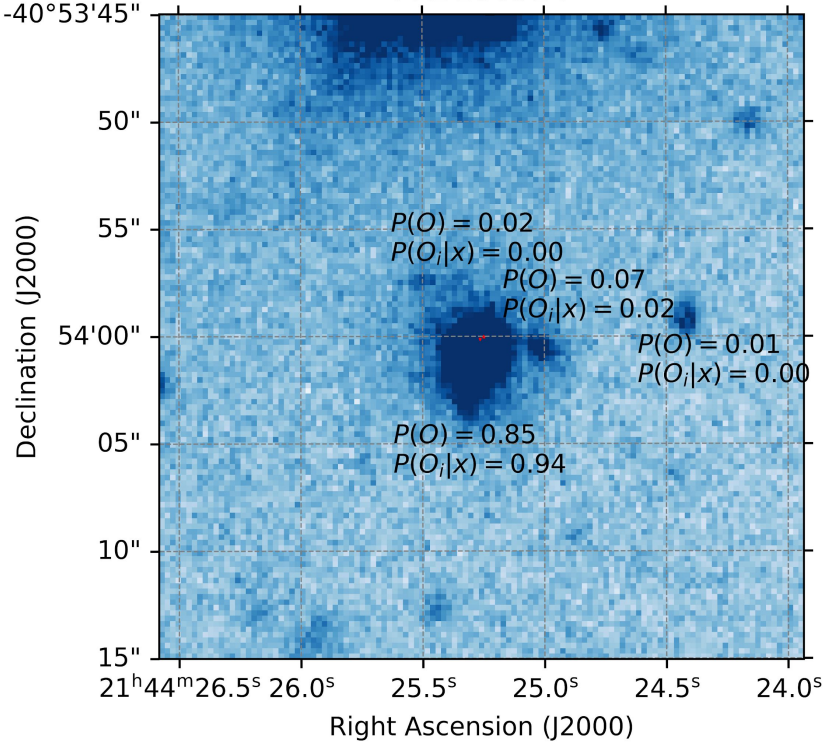


Bannister+2019 -- 2020 AAAS Newcomb Cleveland Prize

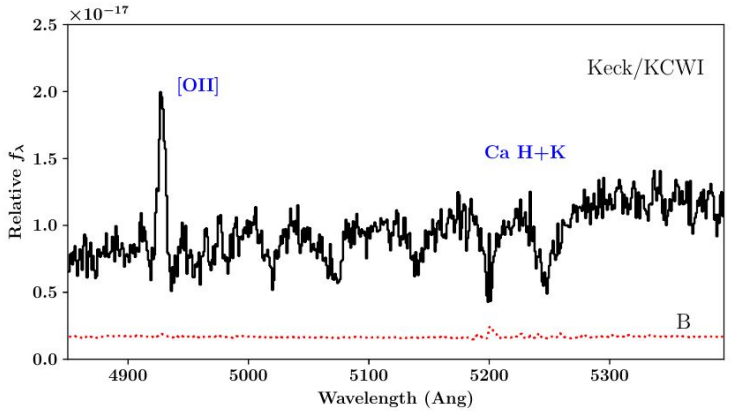
- SKA Pathfinder in Australia
- 36 dish interferometer. Can achieve 0.1" localization.
- ~10 FRBs per year; funded upgrade for 10x higher rate (2022)
- Ideal for host galaxy and redshift determination

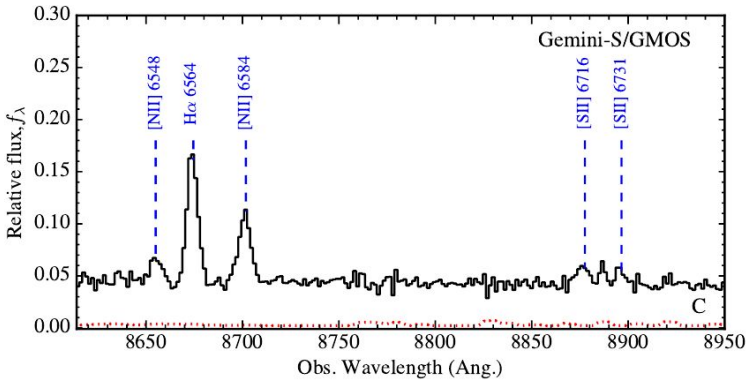
FRB Redshifts – No spectral signal

Probabilistic Association of Transients to Hosts (PATH)

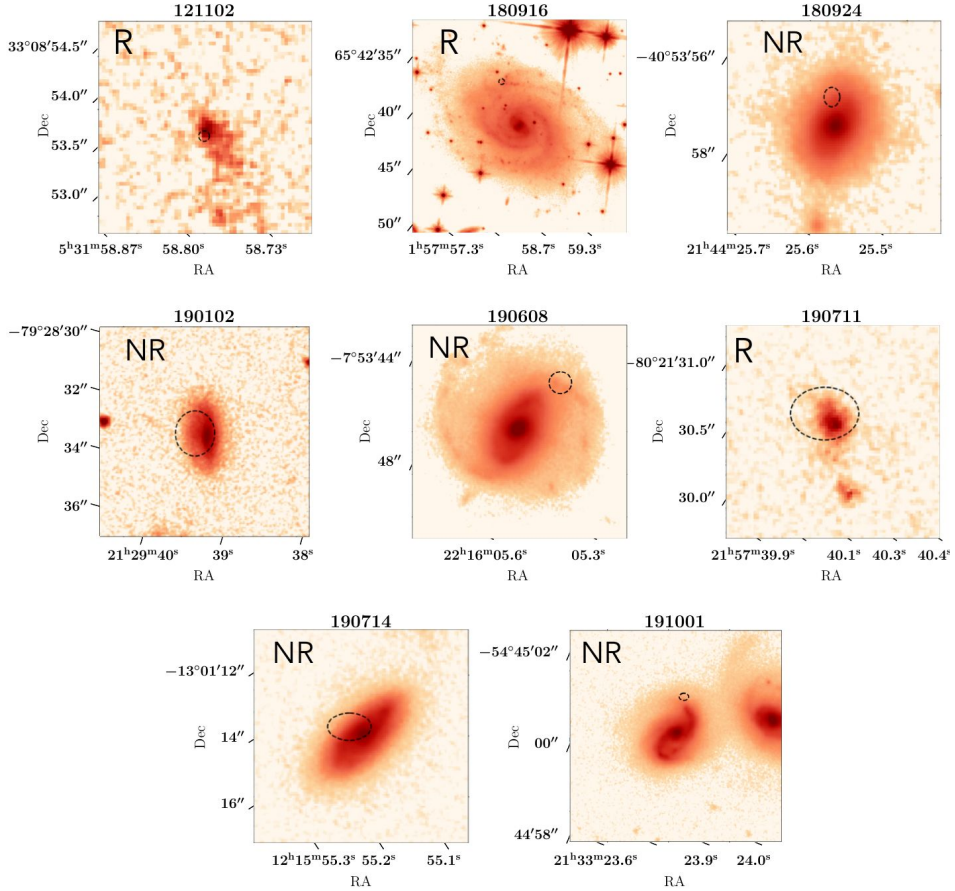


Aggarwal+ 2021



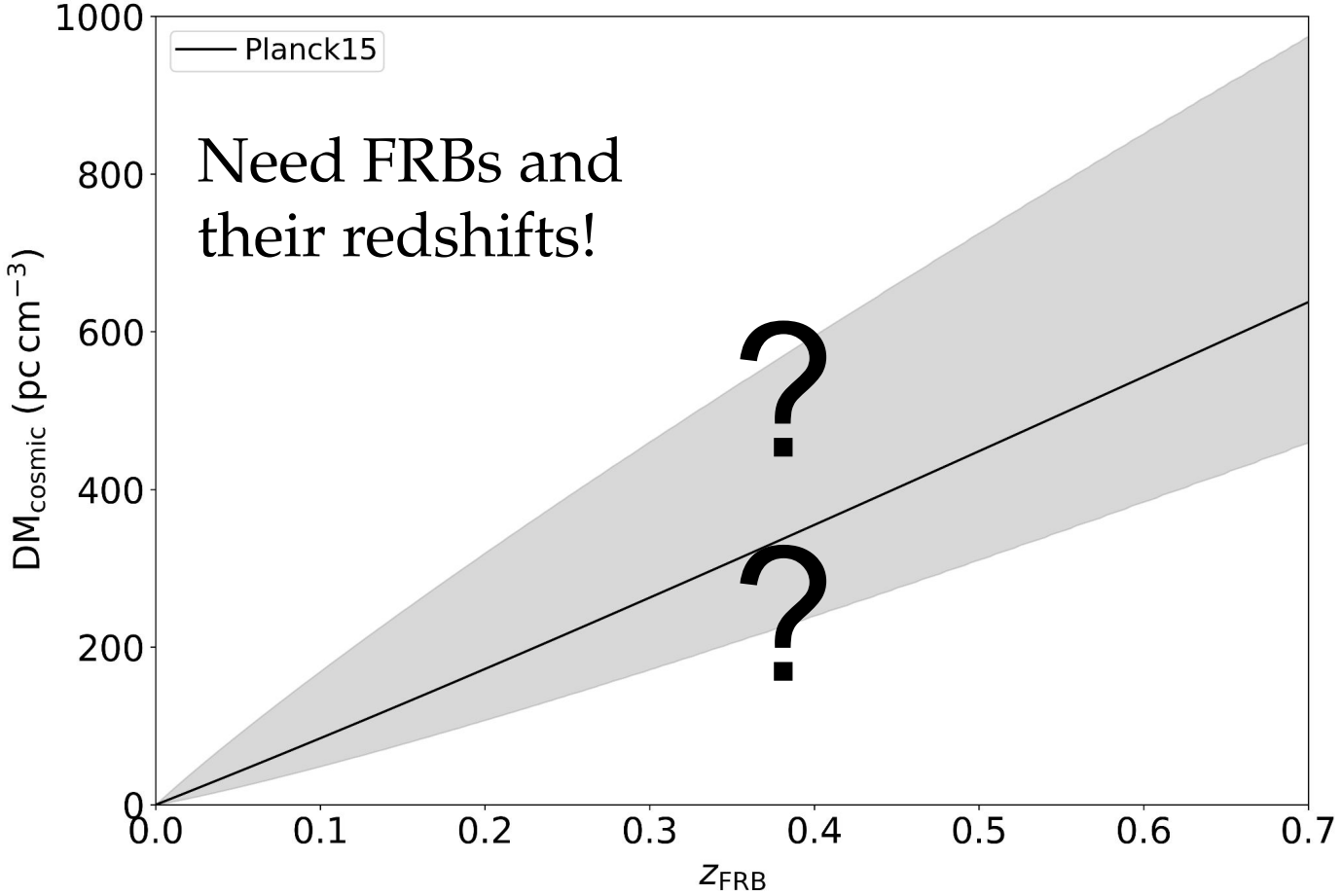


FRB Hosts

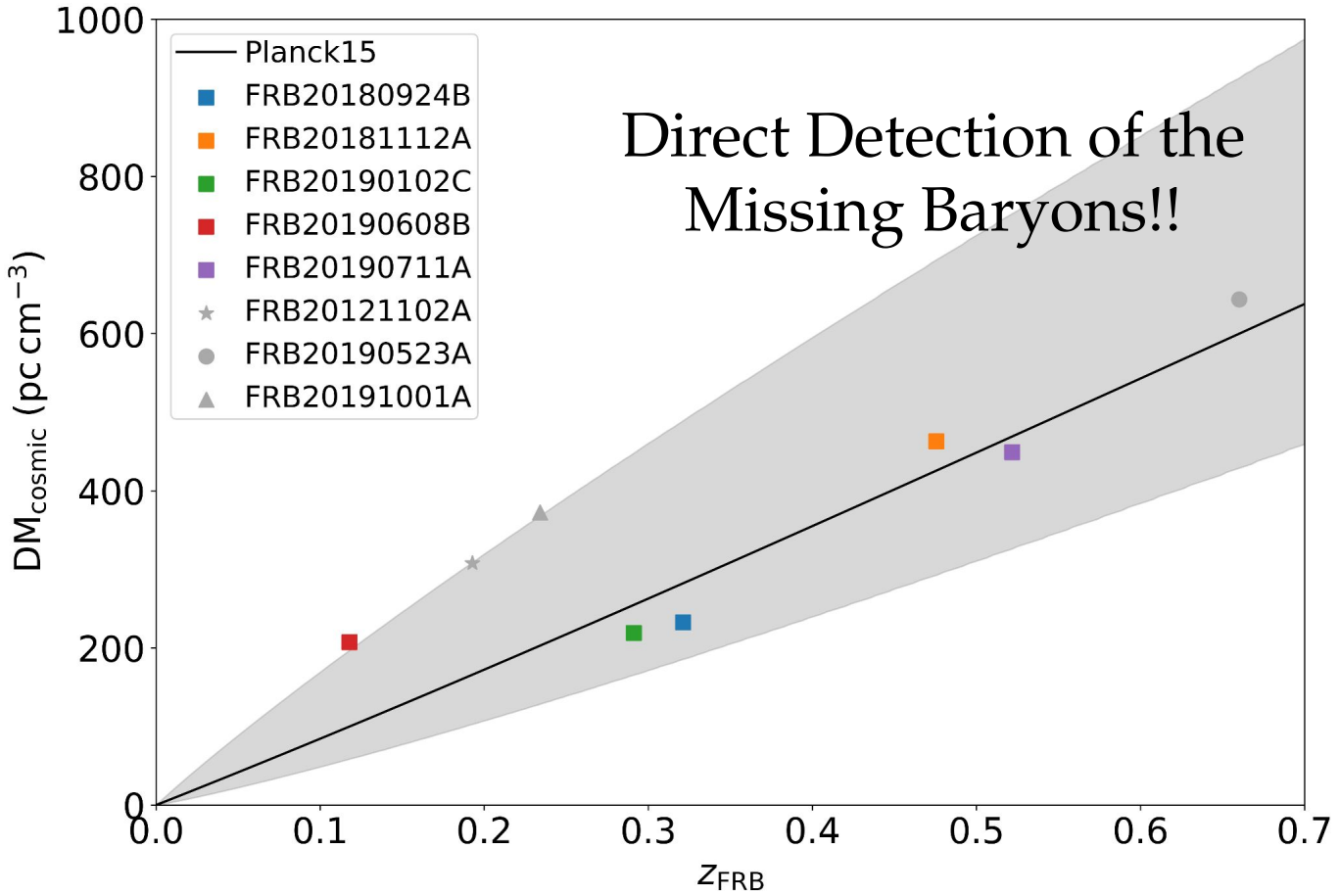


Mannings+2021

FRBs Probing the Cosmic Web: DM vs z

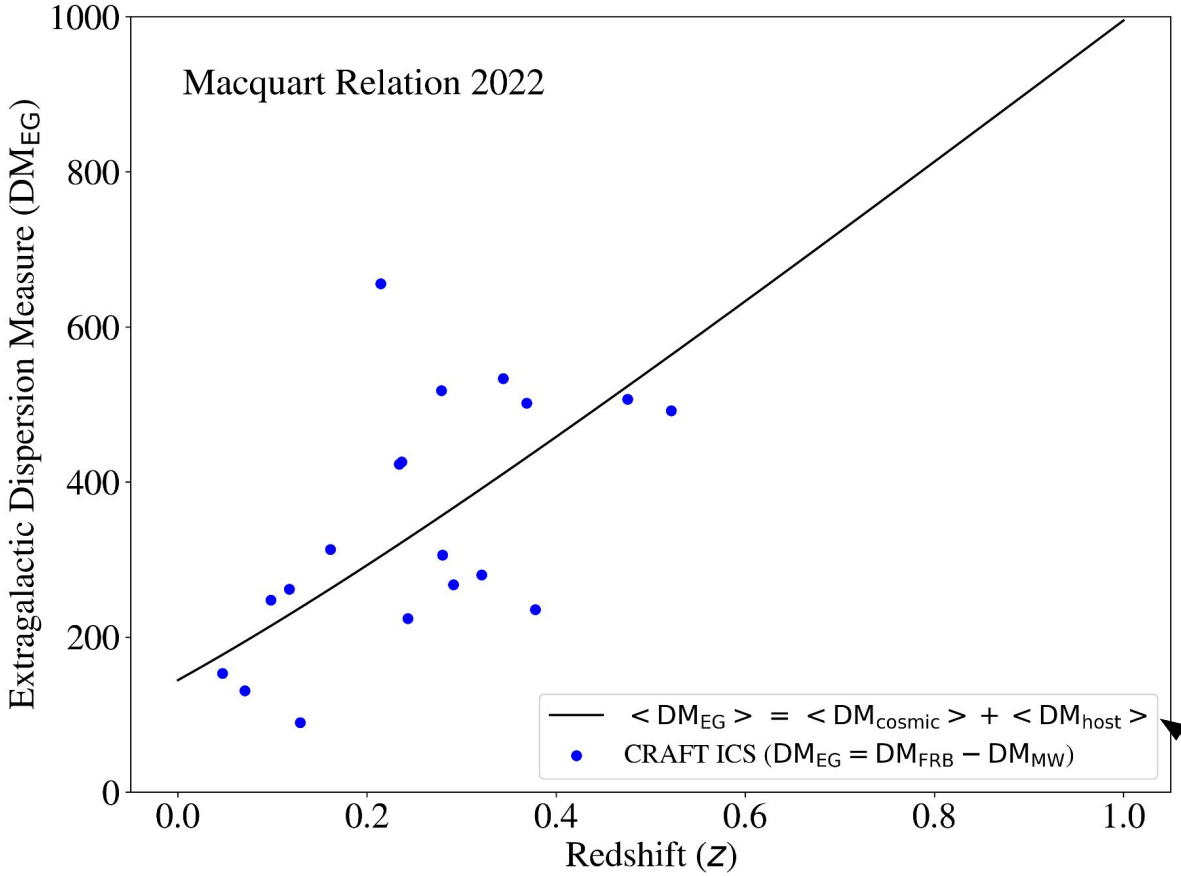


The Macquart Relation



Macquart+, *Nature*, 2020

FRBs Probing the Cosmic Web: DM_{EG}



$DM_{EG} = DM_{host} + DM_{cosmic}$

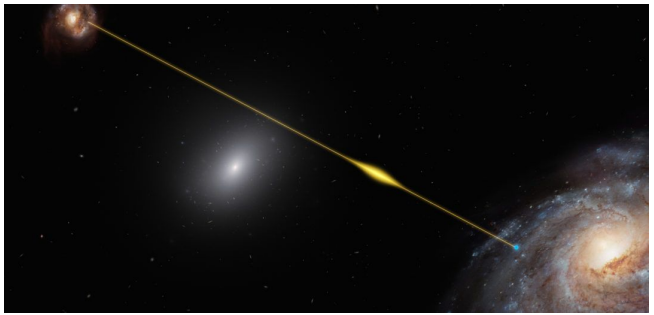
$DM_{EG} = DM_{FRB} - DM_{MW}$

The scatter about the model is physical and expected:

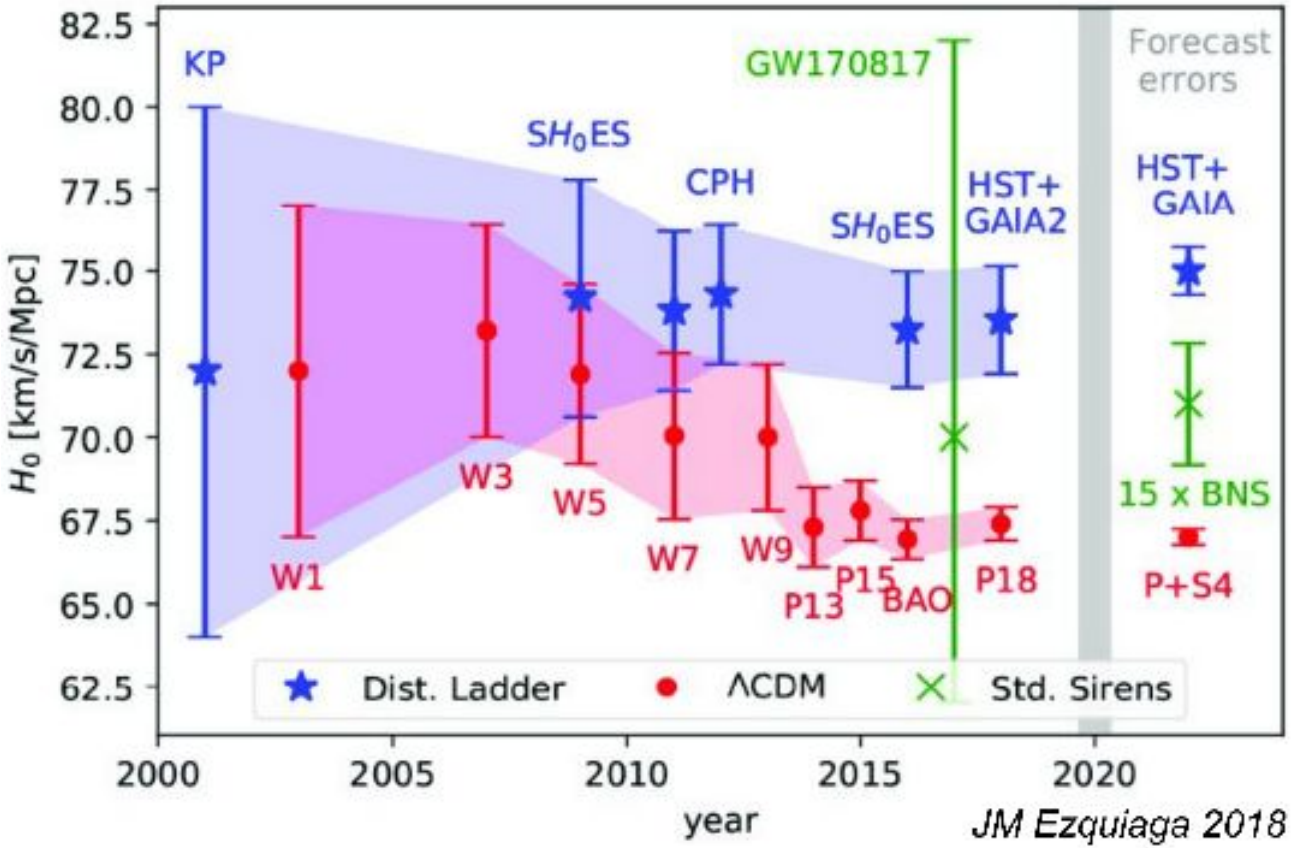
DM_{host} & DM_{cosmic}

(175 pc cm^{-3}) / (1+z)

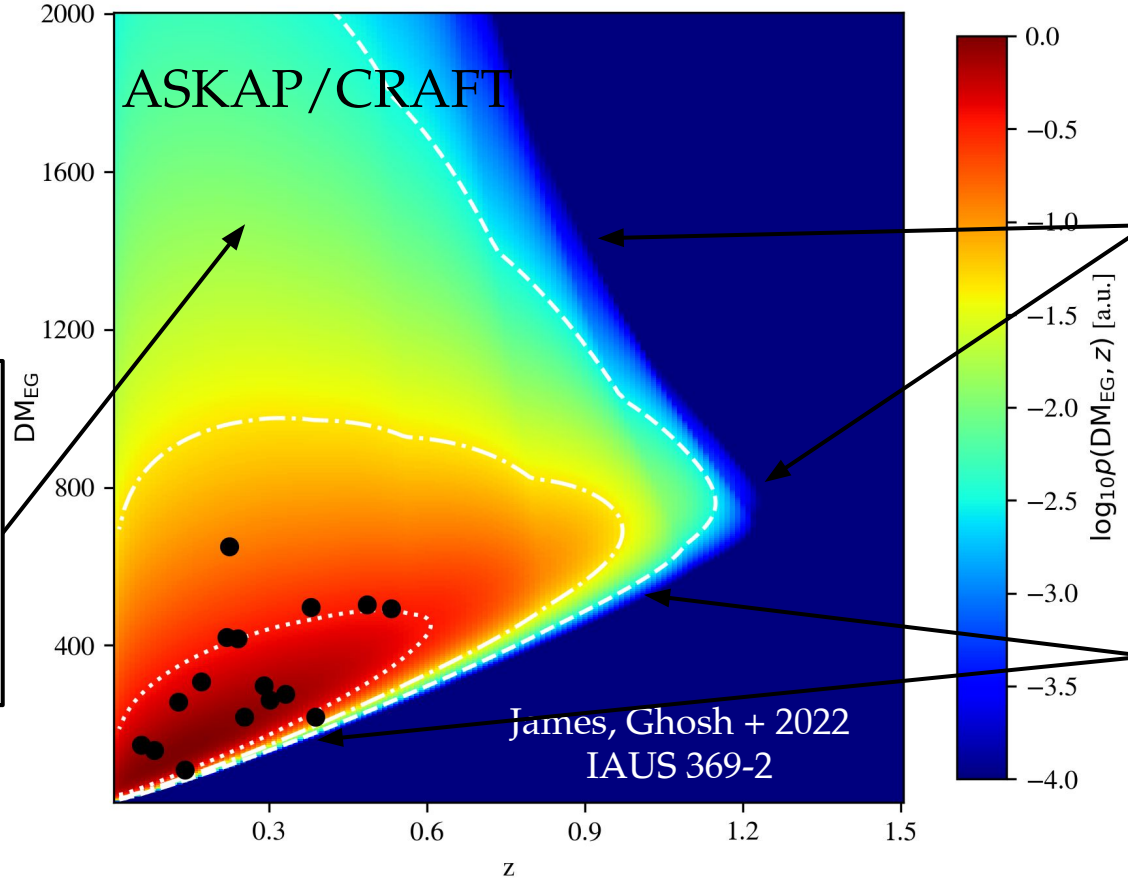
So now, what shall we do with these FRBs?

H_0	FLIMFLAM	Magnetic Fields
F	CGM	

(Modern) Tension in H_0



FRBs as Probes: $p(\mathrm{DM_{EG}}, z)$

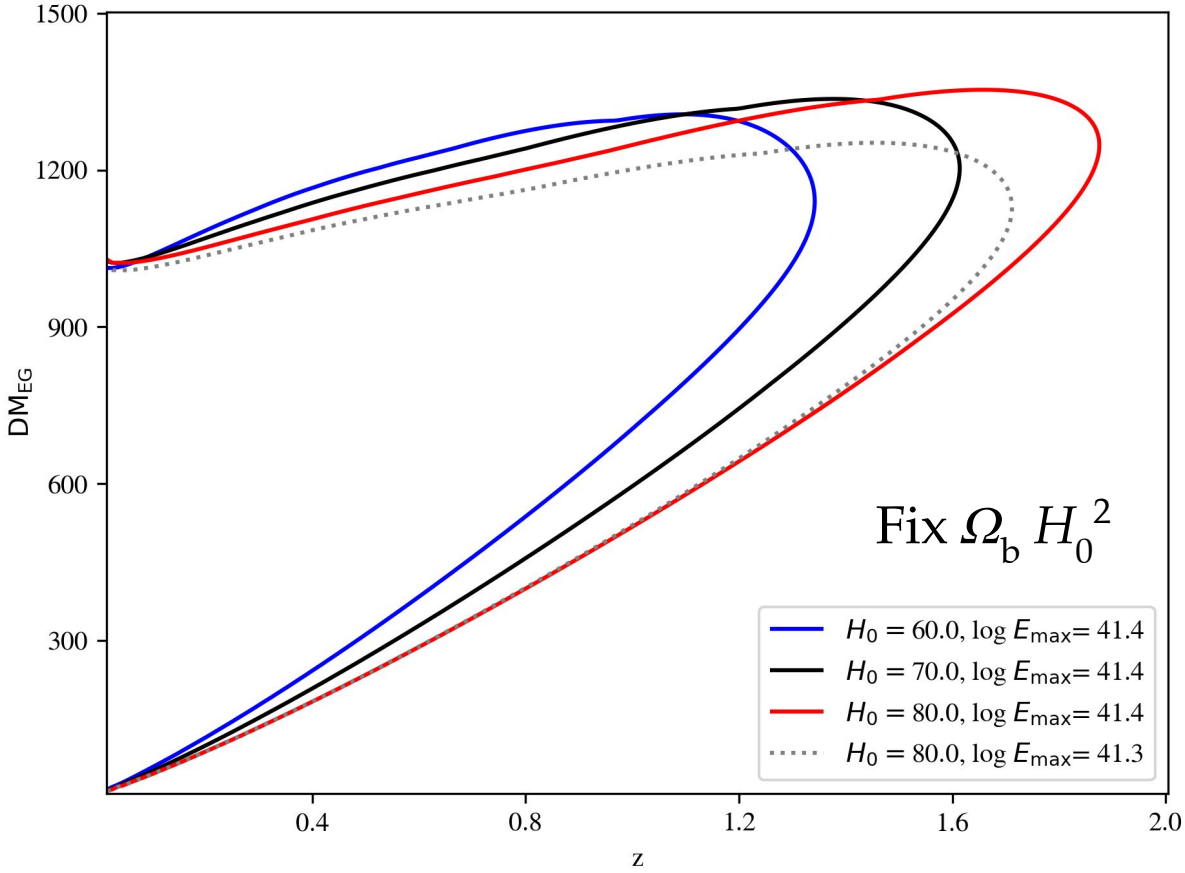


Long probability tails of high $\mathrm{DM_{cosmic}}$ & $\mathrm{DM_{host}}$ values

FRB Energetics & Telescope sensitivity

DM "cliff" set by $\mathrm{DM_{cosmic}}$ & H_0

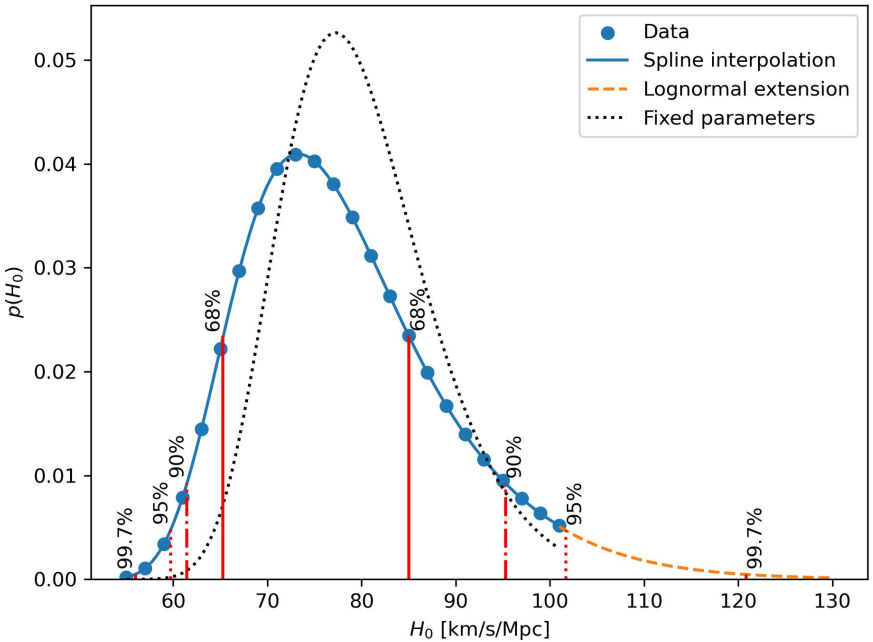
FRBs Probing Cosmology: H_0



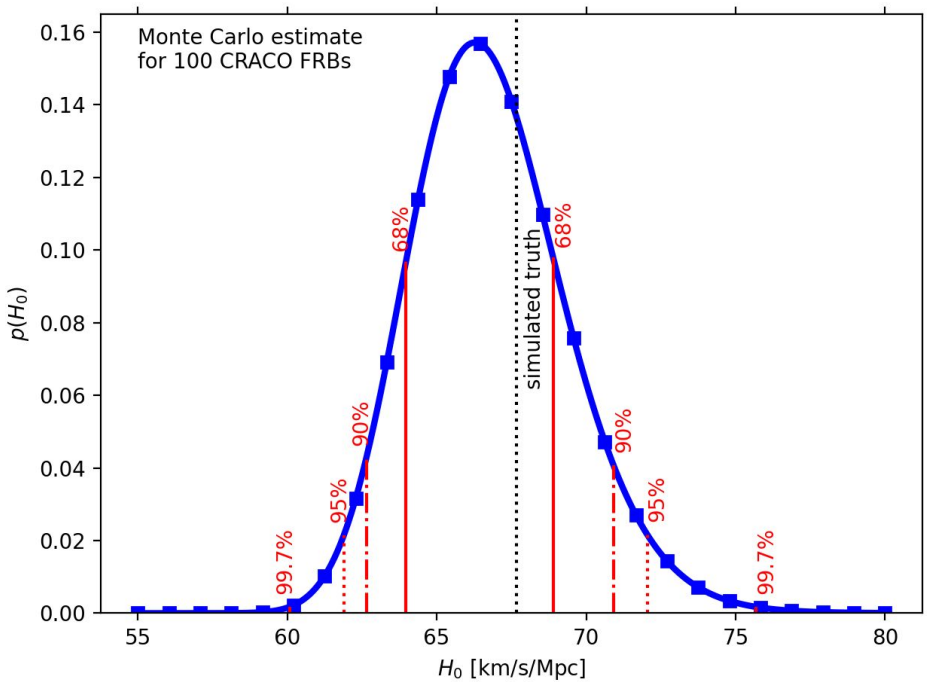
James,
Ghosh+ 2022

FRBs Probing Cosmology: H_0

Parkes + CRAFT (16 redshifts)



ASKAP/CRACO Survey (100 redshifts)



James, Ghosh+ 2022

FRBs and Feedback

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

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

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

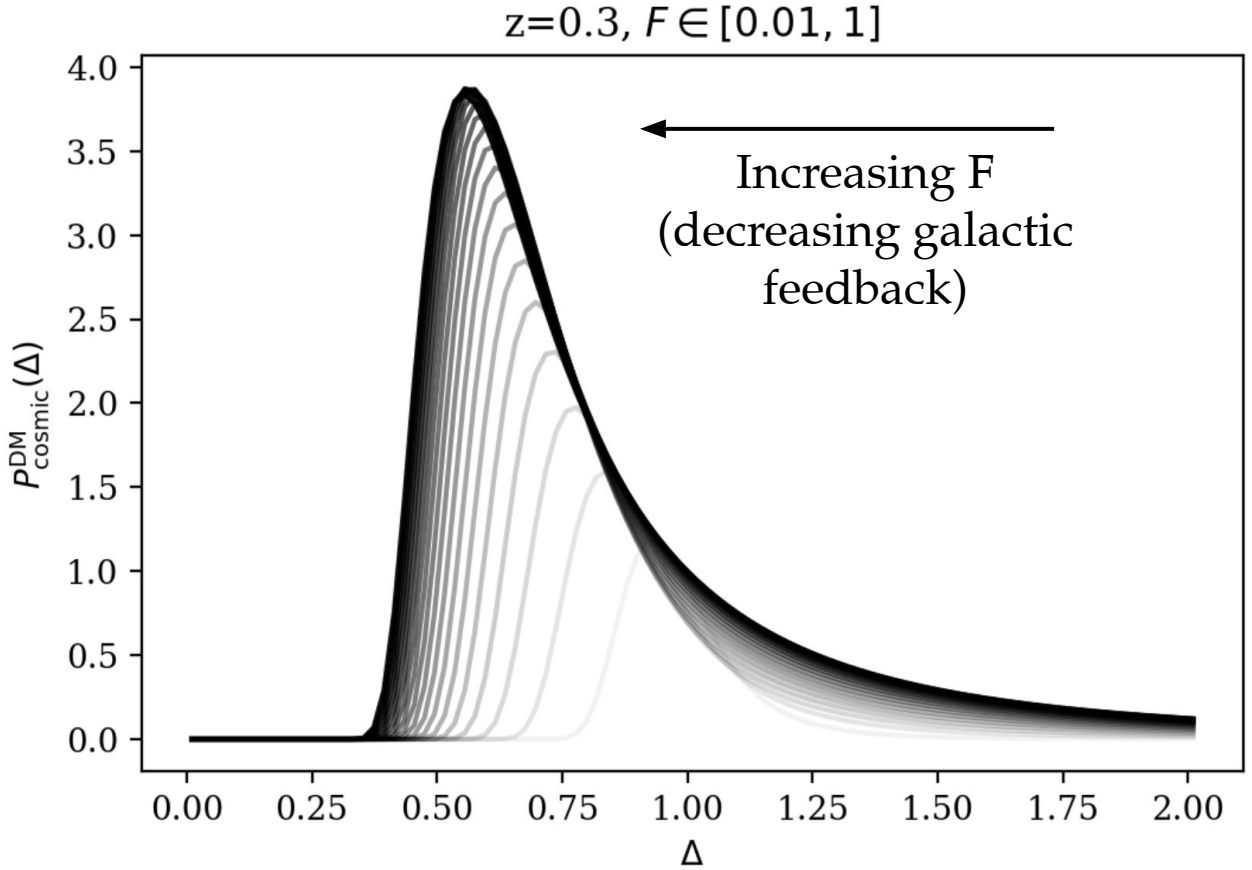
(Inoue+2004)

$$p_{\mathrm{cosmic}}(\Delta) = A\Delta^{-\beta}\exp\left[-\frac{(\Delta^{-\alpha}-C_0)^2}{2\alpha^2\sigma_{\mathrm{DM}}^2}\right]$$

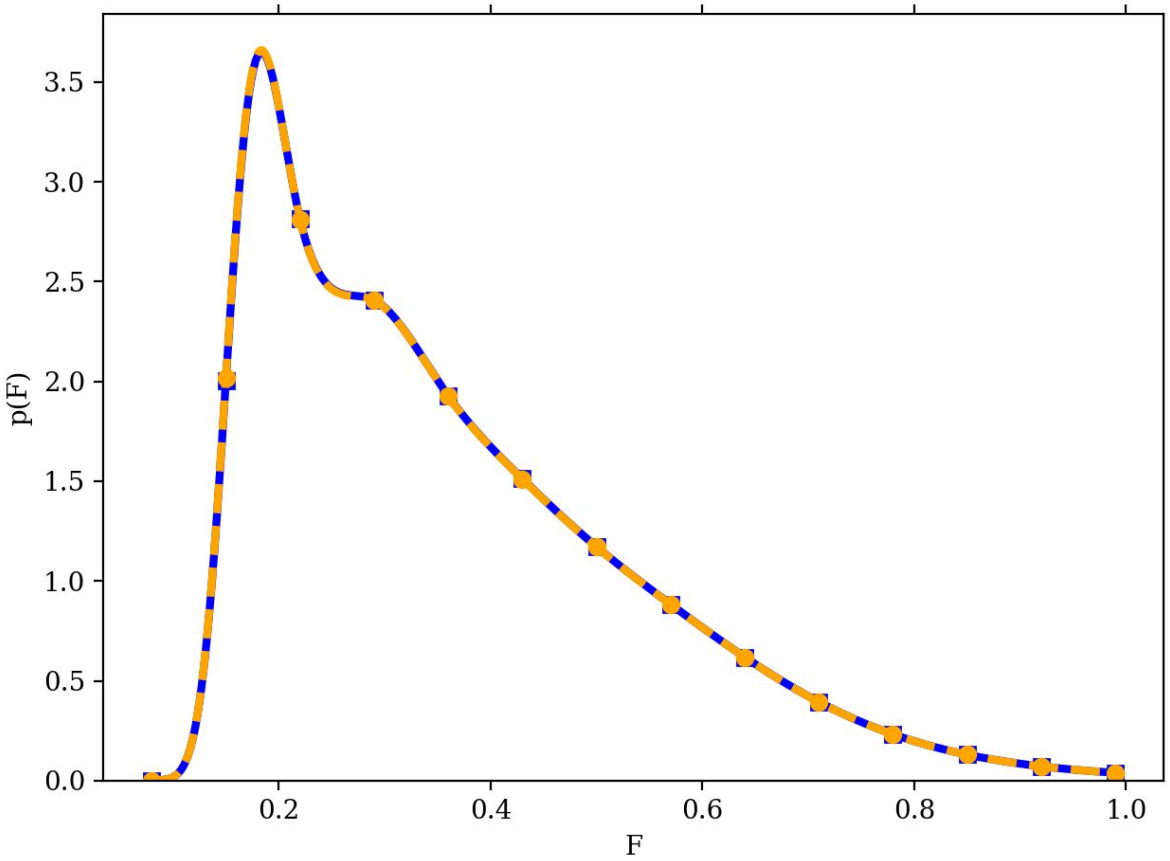
$$\Delta \equiv \mathrm{DM_{cosmic}}/\langle \mathrm{DM_{cosmic}} \rangle$$

$$\sigma_{\mathrm{DM}} = Fz^{-0.5}$$

FRBs Probing Feedback: *F*



FRBs Probing Feedback: *F*



FRBs Probing Feedback (FLIMFLAM)

Khee-Gan ("K.-G") Lee

Kavli IPMU, University of Tokyo

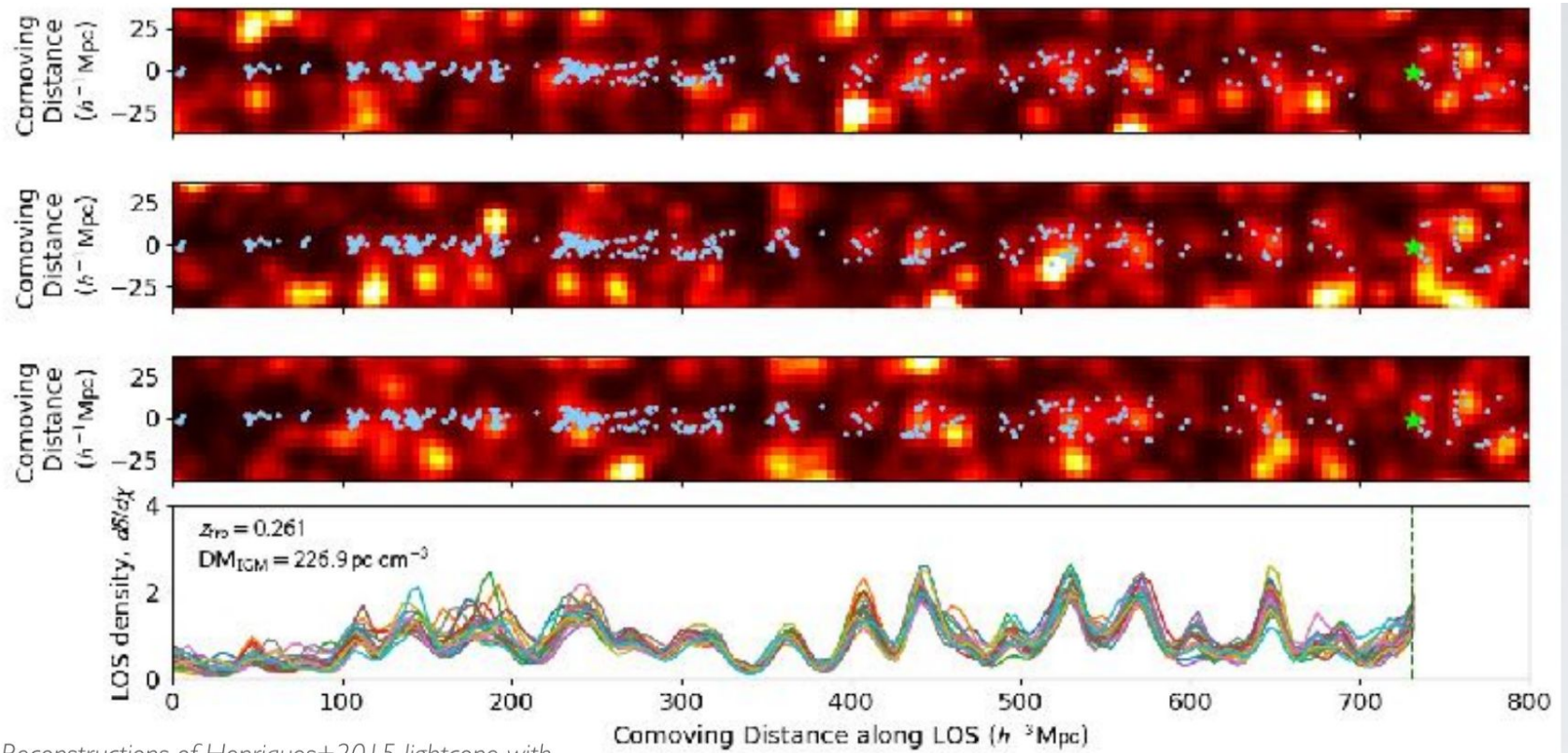
Metin Ata
Kavli IPMU Postdoc

Ilya Khrykin
Kavli IPMU Postdoc

Sunil Simha
(UC Santa Cruz)

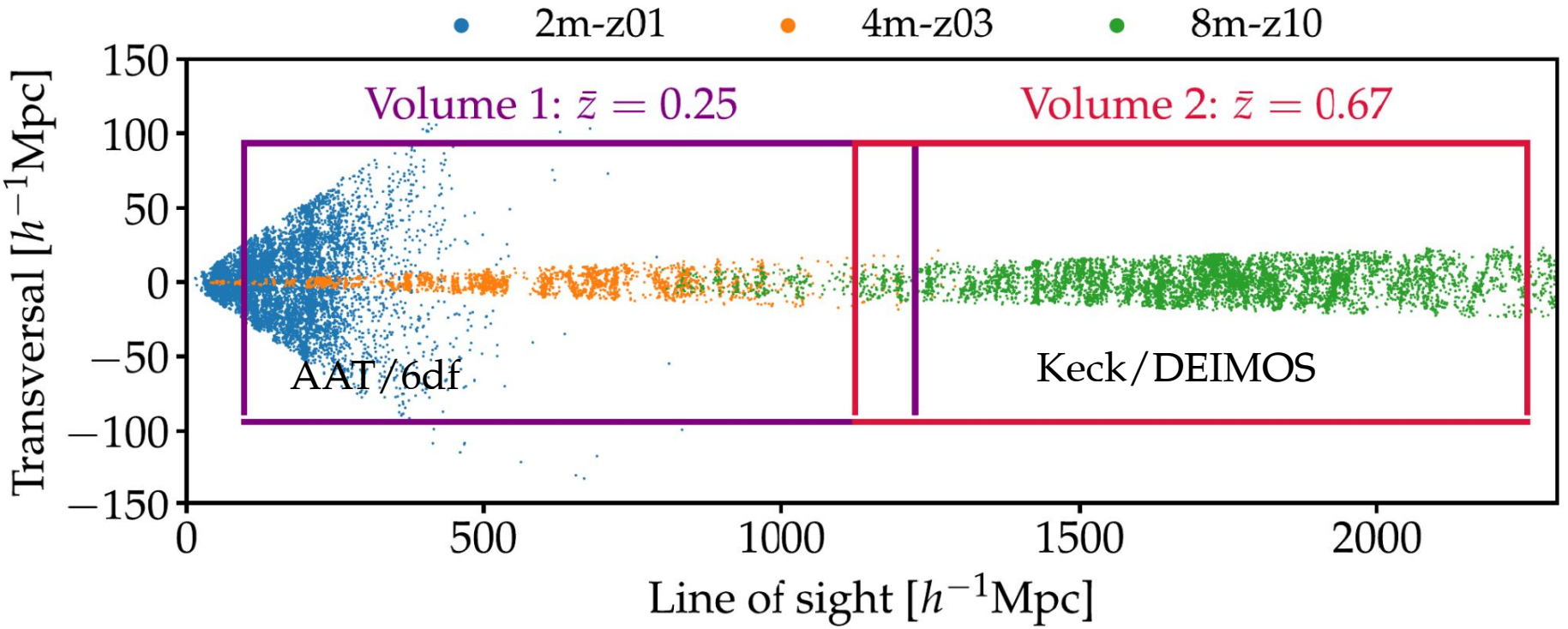
Yuxin Huang
UTokyo Master's Student

FRBs Probing Feedback (FLIMFLAM)



Reconstructions of Henriques+2015 lightcone with Metin's ARGO algorithm

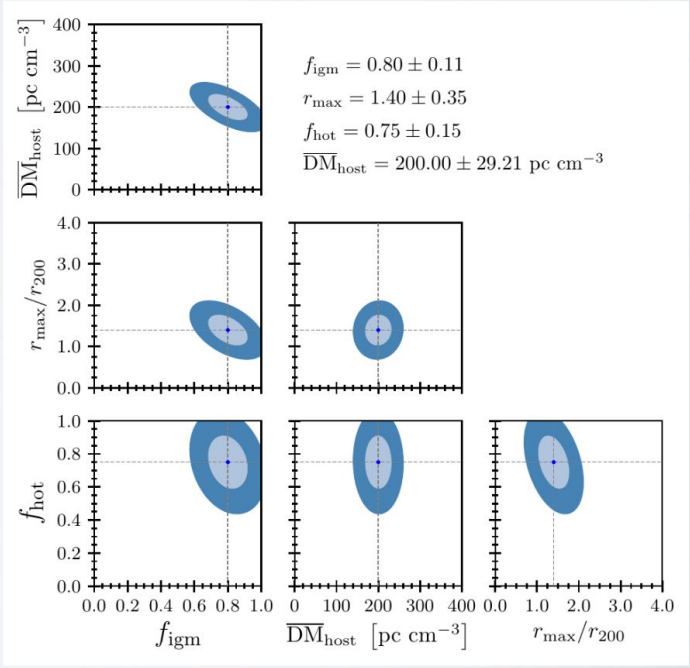
FRBs Probing Feedback (FLIMFLAM)



FRBs Probing Feedback (FLIMFLAM)

- Sampling the scatter caused by the ARGO uncertainties and intervening halo masses allows us to quickly calculate the Fisher matrix
- Assume errors in LOS density from ARGO, and 0.3 dex halo masses uncertainty of intervening galaxies (<10 arcmin)
- Right: estimated model uncertainties from 30 FRBs at 0.1<z<0.5
- Approx ~10% constraints expected for f_{igm} and ~20% constraints on CGM halo parameters
- Some degeneracy between DM_{host} and f_{igm}, but little degeneracy between IGM and halo parameters

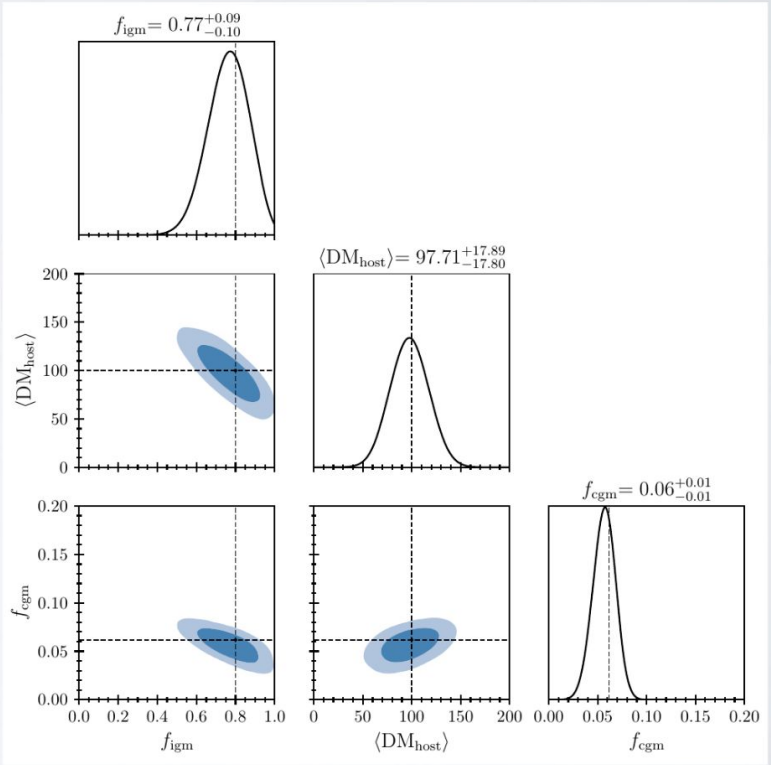
$$\mathcal{F}_{i,j} = \sum_b \frac{1}{\sigma_b^2} \frac{\partial f_b}{\partial p_i} \frac{\partial f_b}{\partial p_j}$$



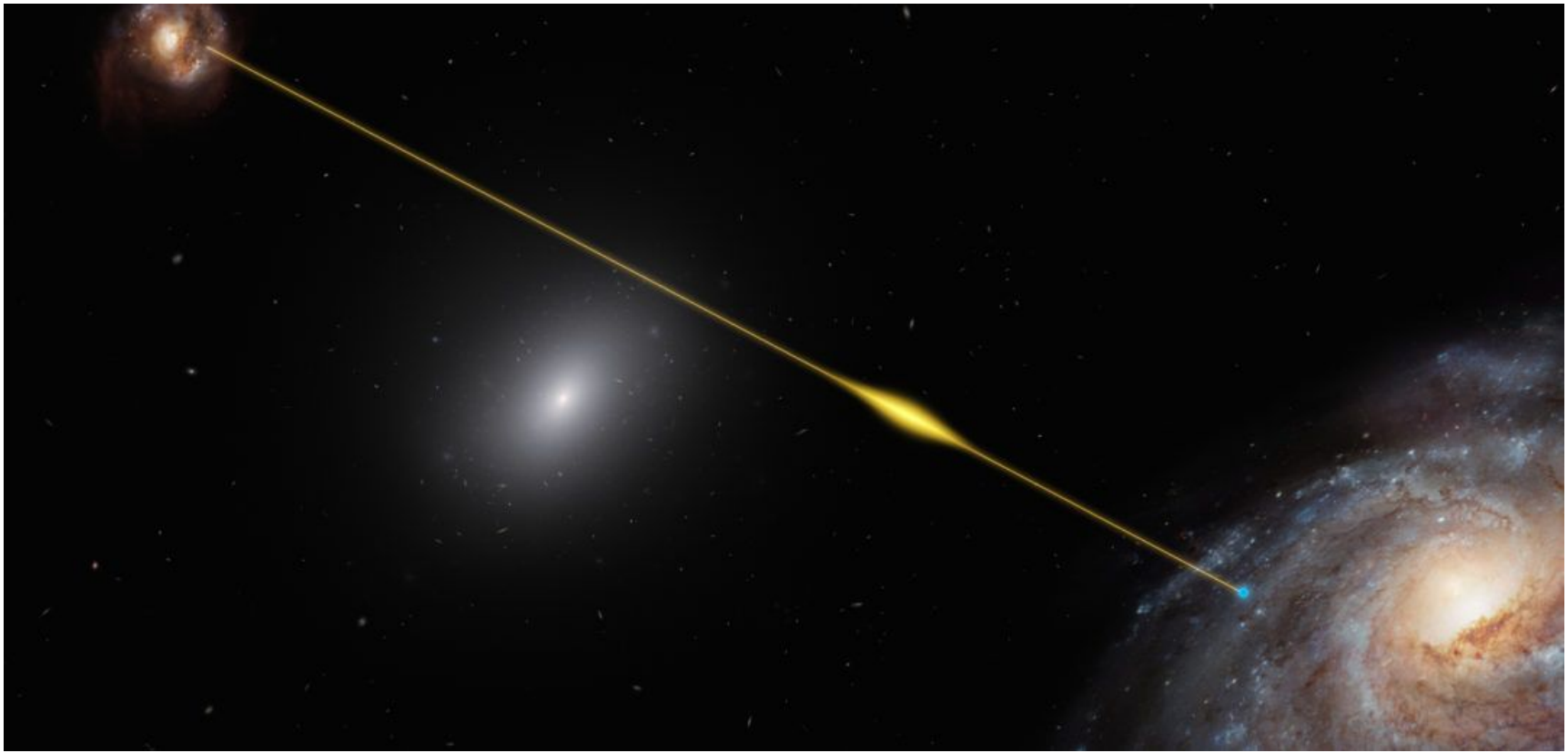
FRBs Probing Feedback (FLIMFLAM)

- Alternative parametrization: convert r_{max} and f_{hot} into the global fraction of CGM baryons, such that $f_{cgm}+f_{igm}+f_{stars}=1$
- Expect to be able to measure f_{cgm} to within a couple of percent!

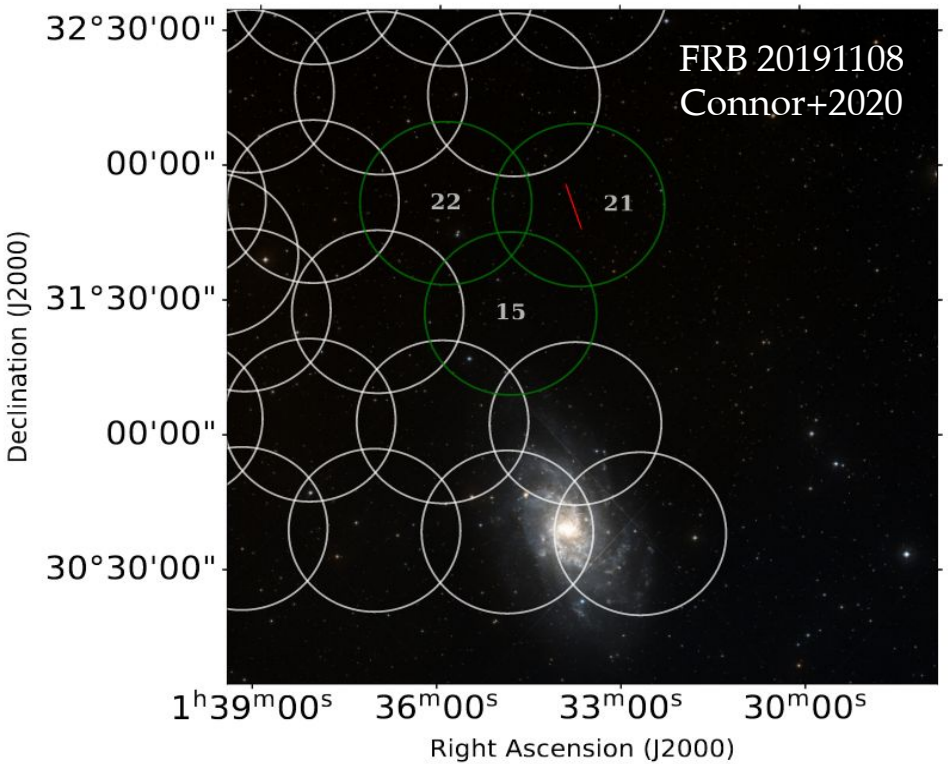
$N_{frb}=30$, $0.1<z<0.5$



FRBs Probing Individual Galactic Halos



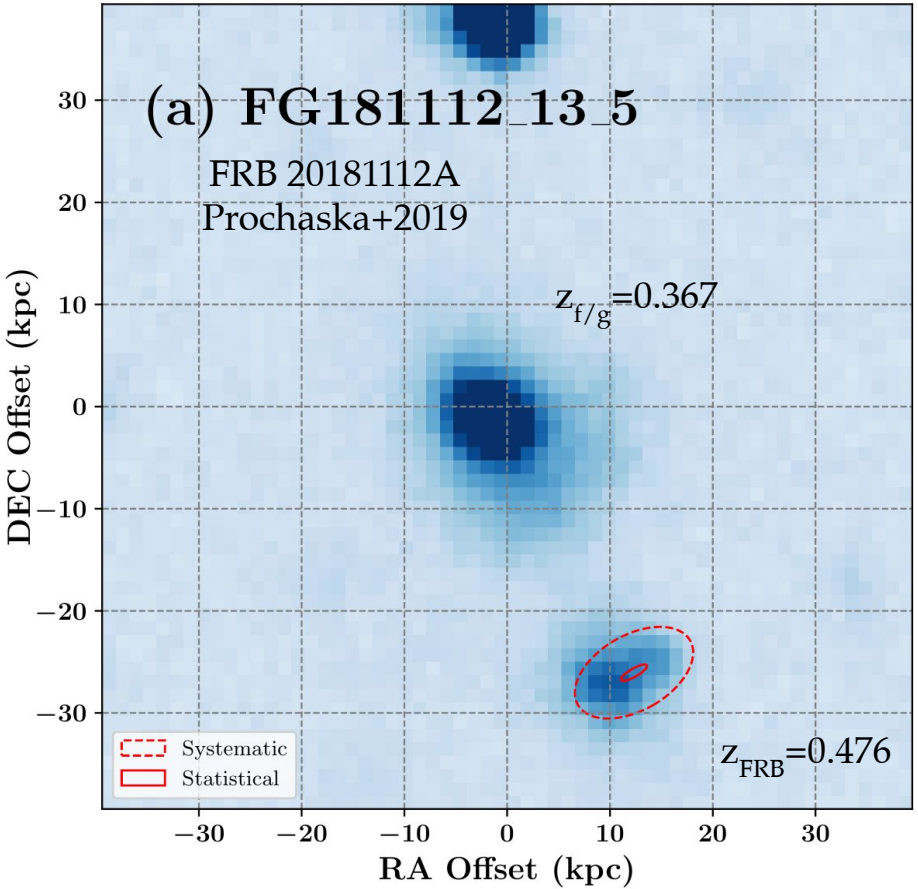
FRBs Probing Individual Galactic Halos



Marnoch+2022
IAUS 369-2

- Random skewer through the halo of a foreground galaxy
- Probe Circumgalactic Medium (CGM)
  - DM – ionized gas profile
  - t_{scatt} – electron density (n_e)
  - RM – magnetic field strength
- Challenges
  - Rarity of chance configuration
  - Host galaxy "contamination"
    - Constraints are strict upper limits

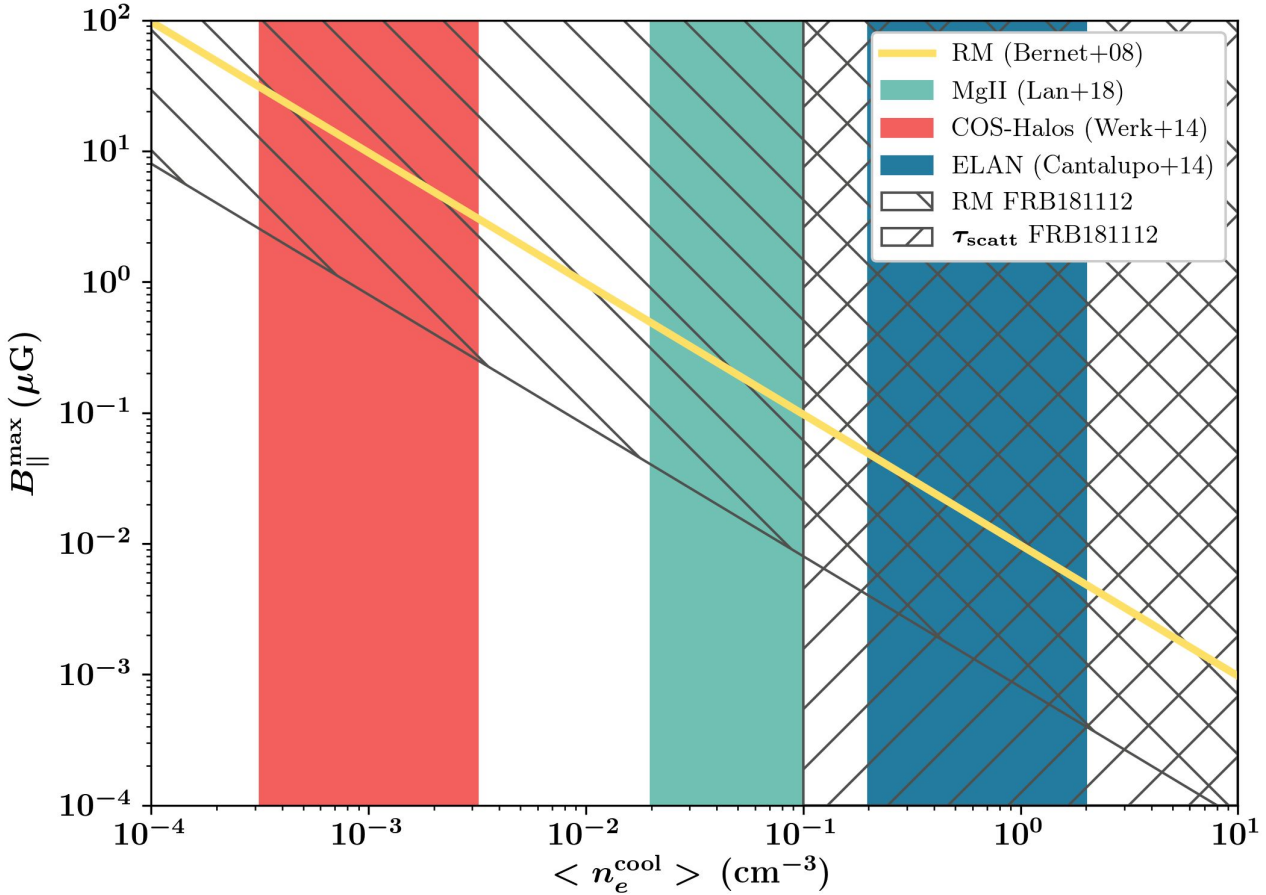
FRBs Probing Individual Galactic Halos



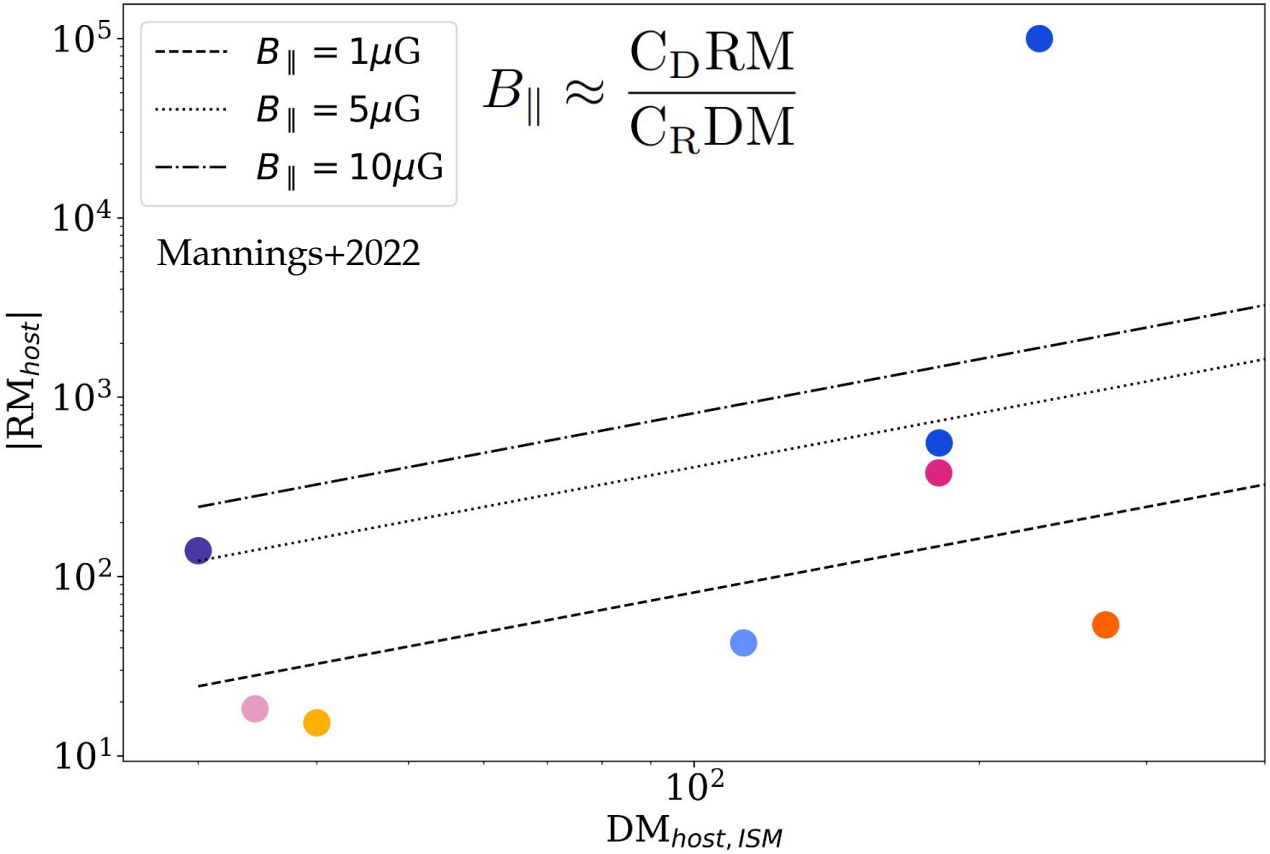
- Foreground Galaxy
  - $M^* = 5 \times 10^{10} M_{Sun}$
  - Intersects CGM at ~20 kpc
- (Weak) FRB Signals
  - $t_{scatt} < 40\ \mu s$
  - RM = 11 rad m^{-2}
- Tight (unparalleled) constraints on n_e and B in halo gas (CGM)

FRBs Probing Individual Galactic Halos

FRB 20181112A
Prochaska+2019



(Approximate*) Magnetic Field Strength



*Disclaimer: Beware of varying RM in FRBs….

Characteristic field strengths are low, e.g. below typical values of the Milky Way

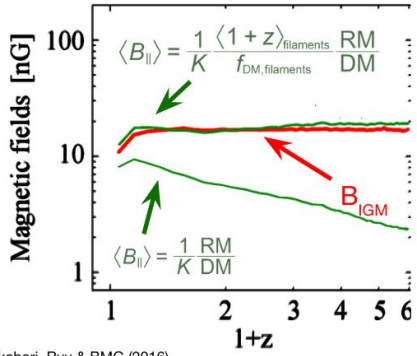
Stay tuned for a sample of 100+ spanning M_*, z, etc.

FRBs and the Magnetism of the IGM

Gaensler+2022

Extragalactic Magnetism: Fast Radio Bursts (II)

Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO



Akahori, Ryu & BMG (2016)

› FRB RMs as probe of intergalactic medium (IGM)
(Akahori, BMG et al. 2016; Mckinven PhD thesis)

$$\mathrm{DM} = \int_L^0 n_e\, dl \quad \mathrm{RM} = K\int_L^0 n_e \vec{B}\cdot d\vec{l} \quad \langle B_{\parallel}\rangle = \frac{1}{K}\frac{\mathrm{RM}}{\mathrm{DM}}$$

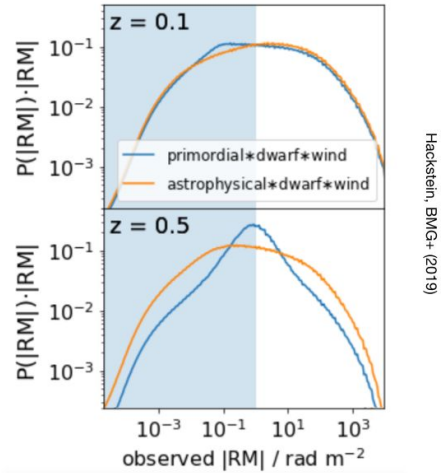
– correction factor recovers *B* of IGM

› Primordial vs astrophysical scenarios for origin of cosmic magnetic fields
(Hackstein, Gaensler et al. 2019; Mckinven PhD thesis)

– some FRBs seem to have no host contribution

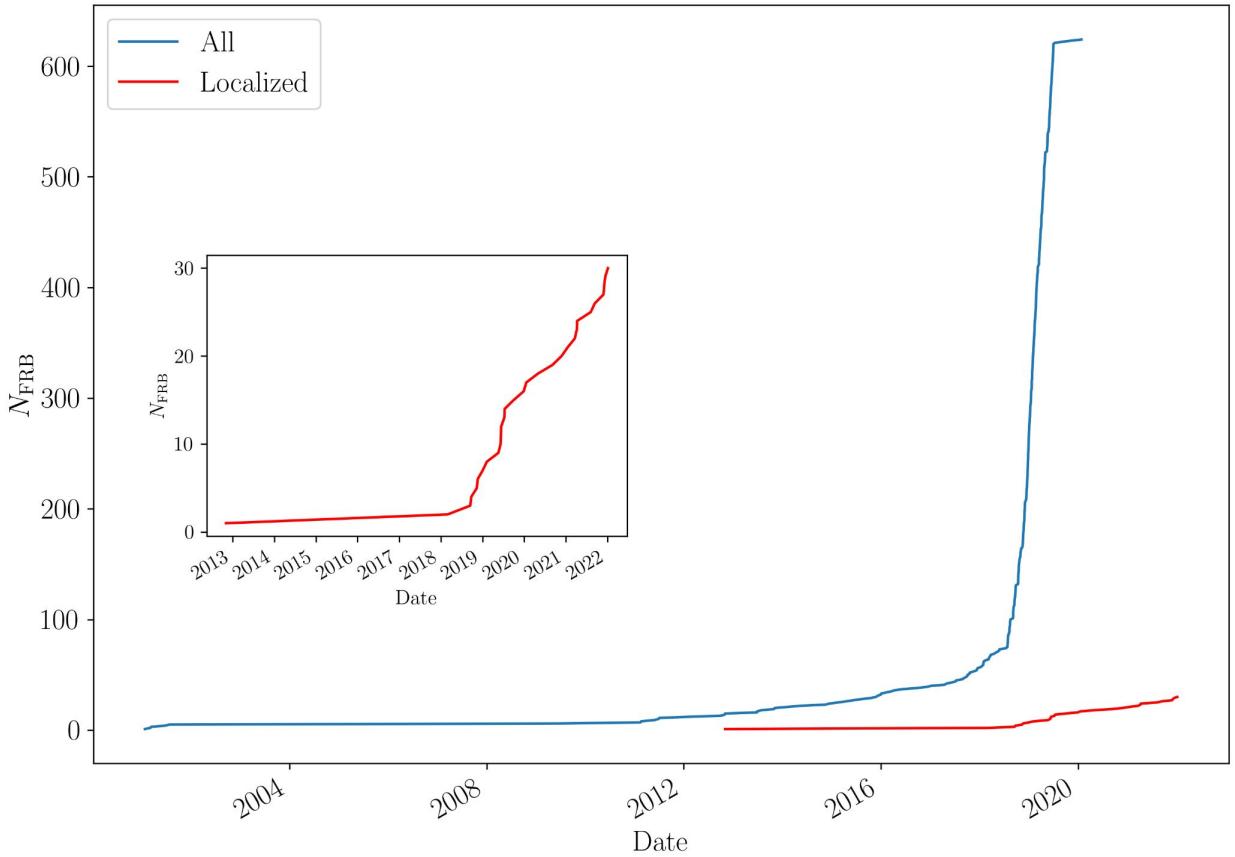
– pure IGM probe? Expect different distributions of RMs from IGM in each model

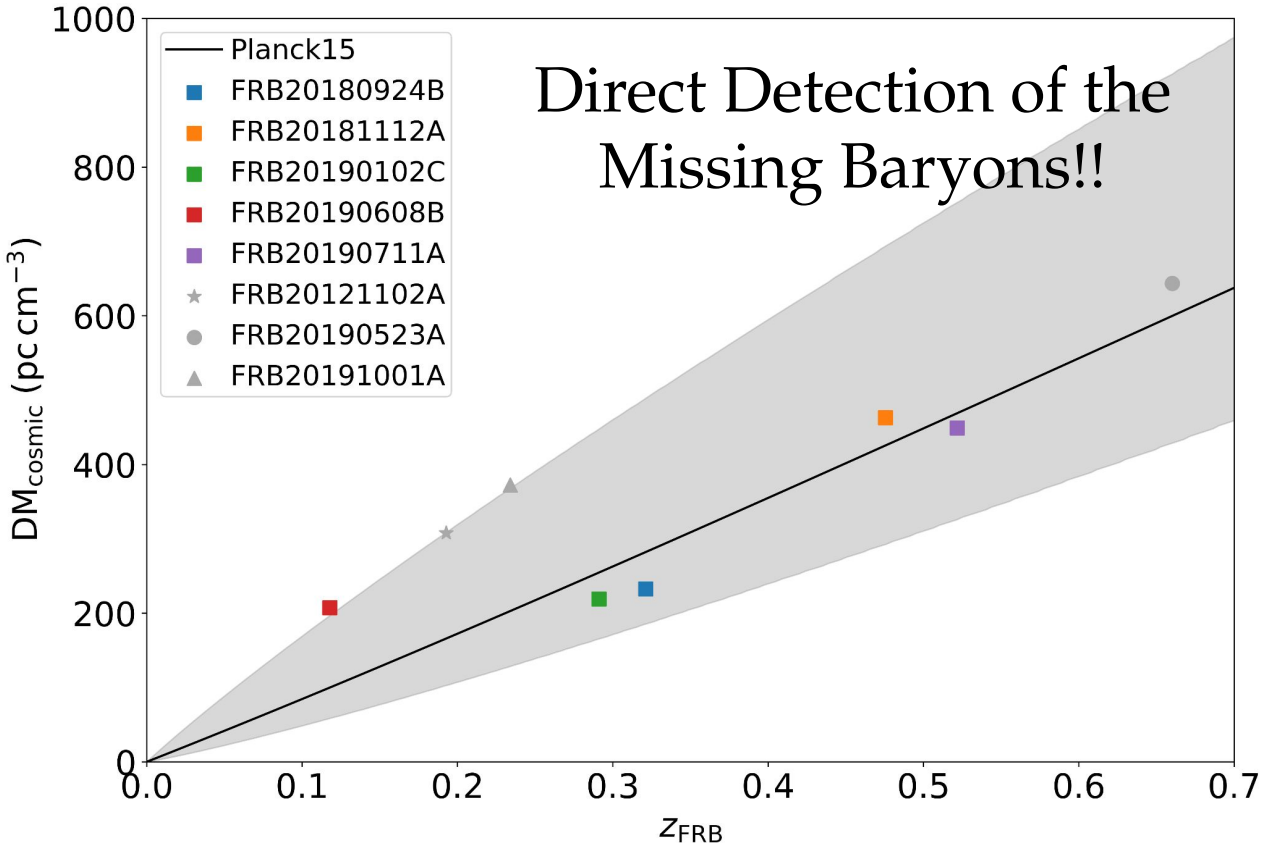
– can distinguish between primordial and astrophysical *B* with ~100 FRB RMs at z ~ 0.5



Hackstein, BMG+ (2019)

FRB Future is Promising!



まとめ

- FRBs offer a new and unique path to study the IGM.
- Measurements of FRB DM and redshift confirm the baryonic mass density and resolve the missing baryons problem!
- We have provided a new estimation of H_0: 73 +12-8 km/s/Mpc
- FRBs will constrain the degree and extent of galaxy formation feedback.
- FRBs yield estimates of the magnetic field strength within the ISM of “normal” galaxies and the IGM.