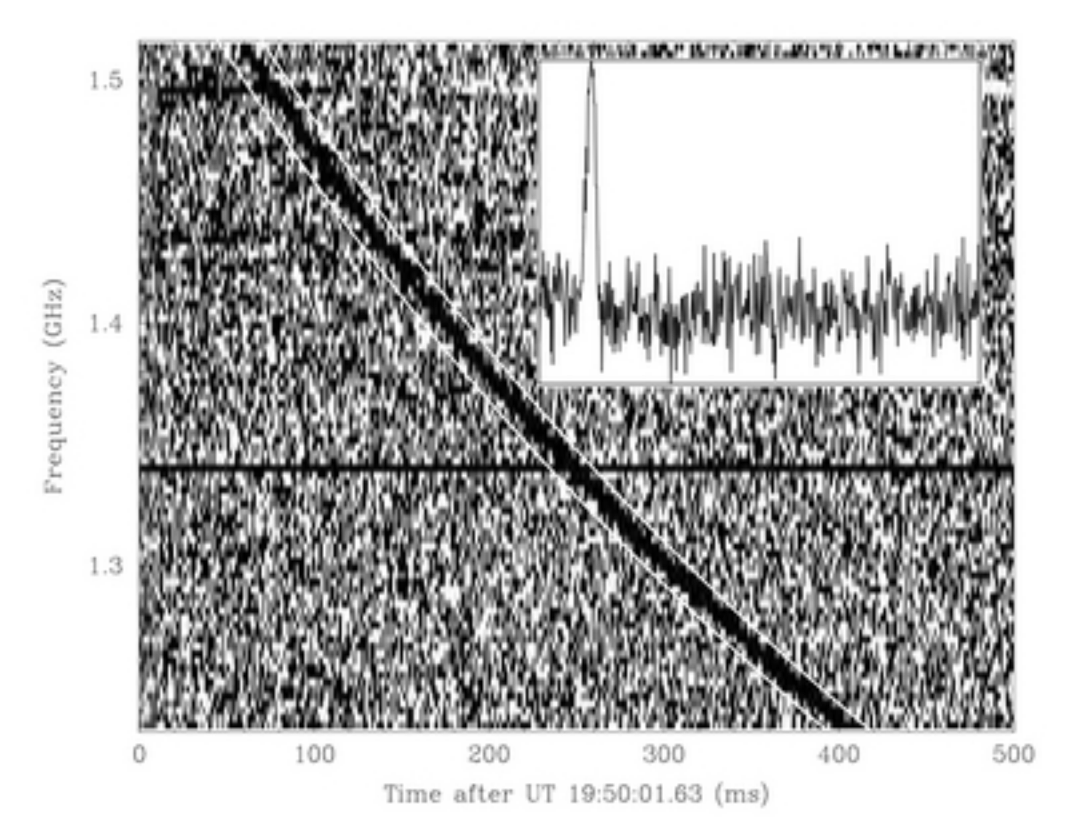
Fast Radio Bursts as Probes of Cosmology and Fundamental Physics

Jonathan Sievers (McGill)

Discovery of FRBs



- Plasma slows EM waves, with lower frequencies slowed more.
- Total delay proportional to electron column density.
- First FRB discovered in Lorimer et al. with electron column density much higher than expected from Milky Way.
- Column density (reported in dispersion measure or DM units) is 375±1. Delay was *exquisitely* measured.

Plasma Delays in FRBs

- Plasma law: $\varpi^2=\varpi_p^2+c^2k^2$ with $\varpi_p^2 = n_e e^2/\varepsilon_0 m_e$
- $v_g=d\varpi/dk=c(1-\varpi_p^2/\varpi^2)^{1/2}$. If we are much higher than plasma frequency, $v=c(1-\varpi_p^2/2\varpi^2)$.
- Velocity change proportional to electron density. Total delay is $\delta t/t \sim \delta v/v$, $\delta t \sim t\ \delta v/v \sim d/c\ \delta v/v \sim d\delta v/c^2$, but $d\delta v$ is now distance times density or column density.
- Pulsar astronomers express column density as DM (dispersion measure) = 1e$^-$/cm^3 for 1 pc = 3.08e18 e$^-$/cm^2.
- If frequency in MHz, then delay becomes $\delta t=4150*DM/\nu^2$ where 4150 depends only on fundamental constants.
- Typical FRB DMs ~1000, and observing frequency ~1 GHz, so delays ~few seconds.
- For burst length ~1 ms, measure column density to part in (few seconds)/1 ms ~ 10^4. Enables precision science.

What do we Know?
(and does it matter we don't know what they are?)

- FRBs give us exquisite LOS (z-weighted) column density.
- FRBs give us exquisite timing.
- FRBs *extremely* close to λ^2 cold plasma delay law (ν_P~kHz in galaxy).
- FRBs measure Faraday rotation to ~few or better.
- Have a few localizations/redshifts, many more coming soon.

NB - Thomson optical depth also a column density, DM~500,000τ

LOCATING THE "MISSING" BARYONS WITH EXTRAGALACTIC DISPERSION MEASURE ESTIMATES

MATTHEW MCQUINN[1]
Department of Astronomy, University of California, Berkeley, CA 94720, USA; mmcquinn@berkeley.edu
Received 2013 September 17; accepted 2013 December 4; published 2013 December 19

- With many FRBs with locations and redshifts, stack on l.o.s. haloes.
- Observed DM should deviate from mean level based on column density from intervening halo. i.e. get a "bump" in DM from halo contribution.
- McQuinn key finding: ~100 FRBs at z~0.5 with arcminute positions enough constrain missing baryons.

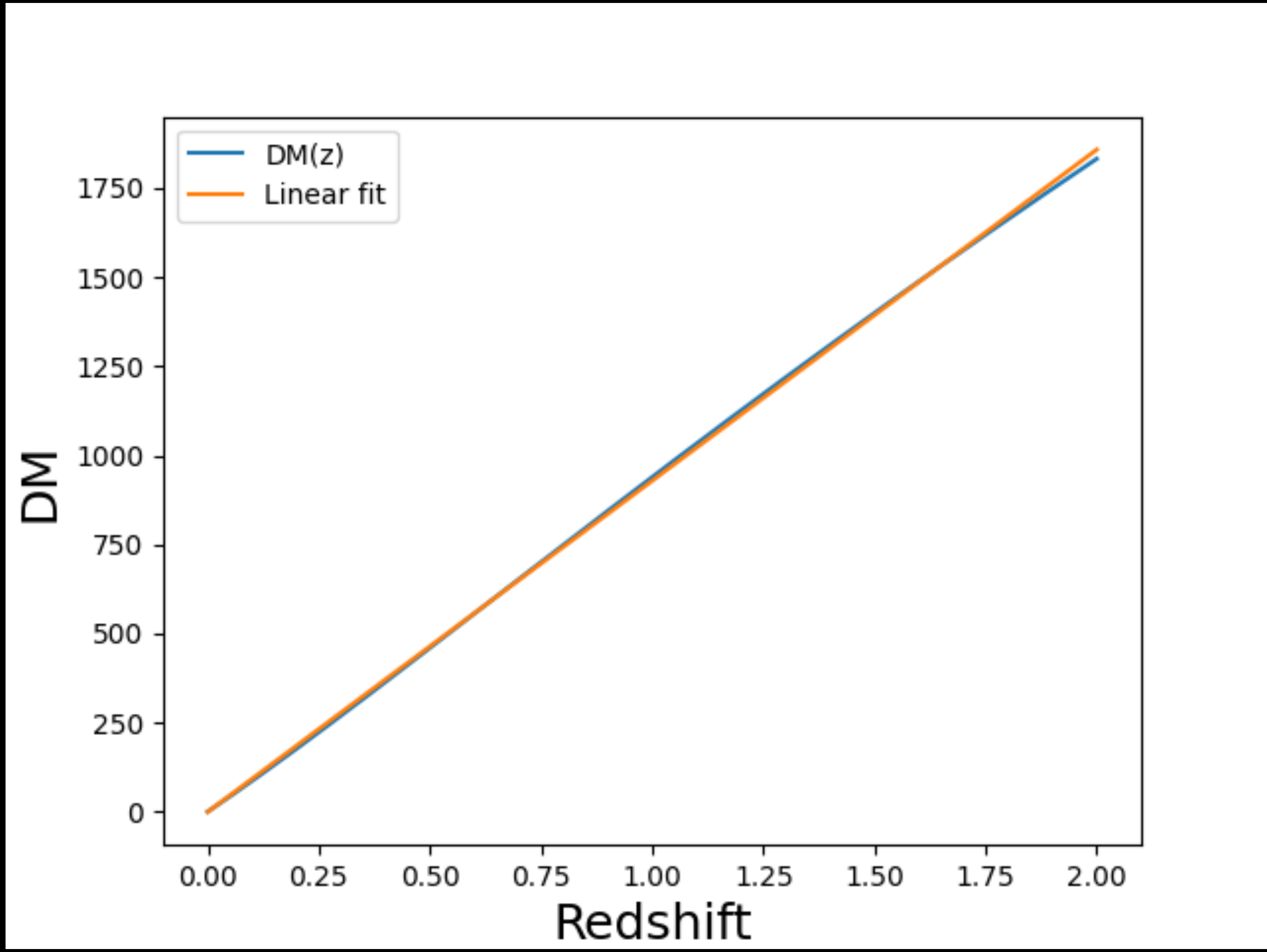
(optical depth through galaxy clusters ~0.001-0.01,
so expected extra DM is hundreds to ~5000)

Column Density

- We measure dispersion measure, quoted in e^- with units pc/cm^3.
- This is true at low-z. At high-z, observed frequency up by (1+z), so plasma delay smaller by $(1+z)^2$.
- However, delay gets cosmological increase of 1+z, so DM gives $\int n_e/(1+z)dx$.
- *If ionization fraction constant*, $n_e(z)=n_{e0}(1+z)^3$, $dx=cdt=c(dt/dz)dz$.
- $DM_{obs}=\int n_{e0}(1+z)^2 c(dt/dz)dz$.

Low-z Relation

- DM(z) is shockingly linear
- Slope is close to 1000.

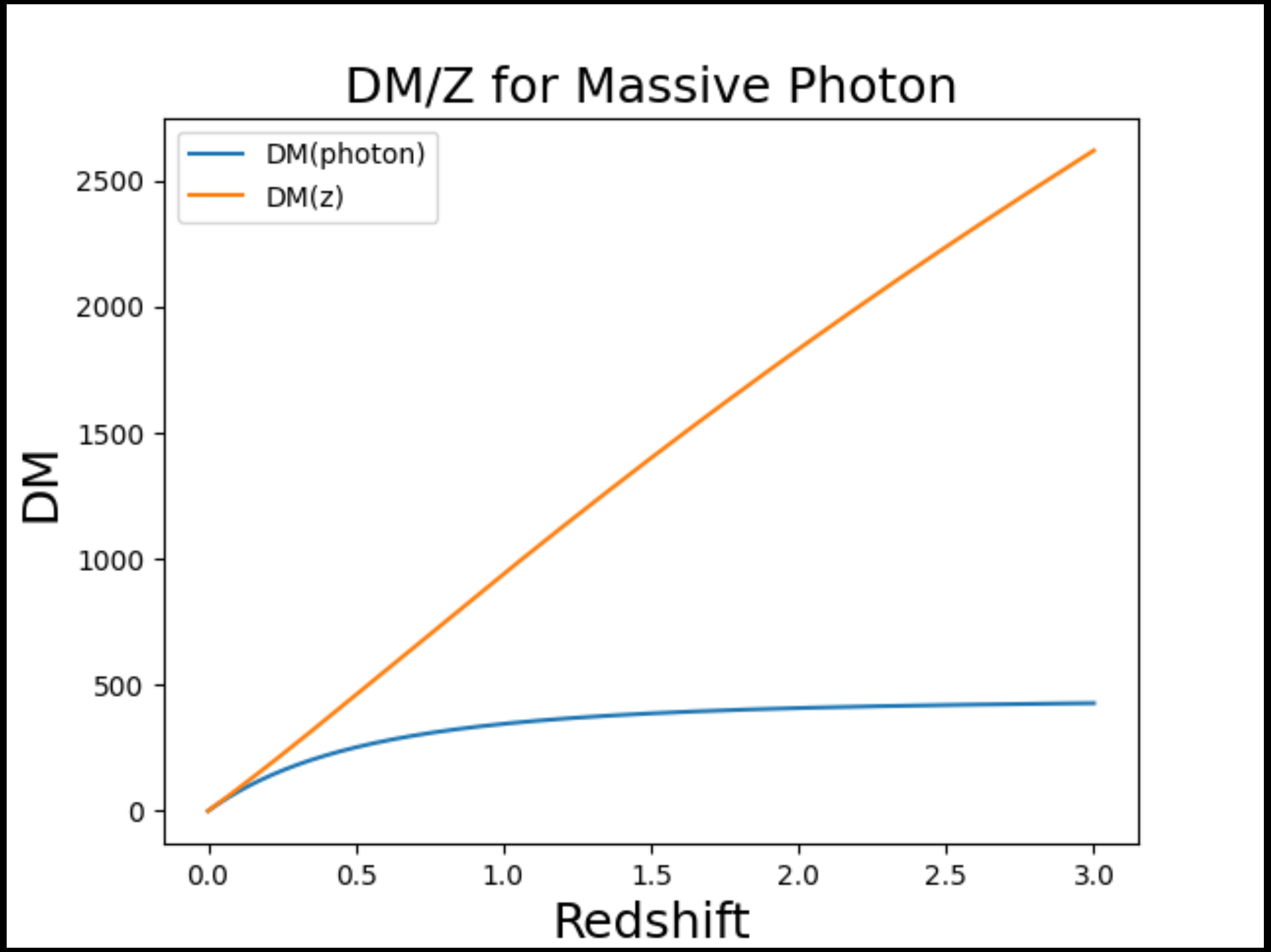


Photon Rest Mass

- Say photons had a rest mass
- $E=h\nu=\gamma mc^2$.
- Let $\varepsilon=1-v/c$. Gives $\varepsilon=0.5(mc^2/h\nu)^2$. Note - delay looks like plasma delay.
- Assign all delay to m_γ. At v=1 GHz, dM for z=1 ~1000, dt~4s, t~5 Gyr, so ε~2e-17.
- $mc^2=hv(2*2e-17)^{0.5}$=2e-14 eV/c^2. (=5e-50 kg)
- Competitive with best lab limits!

Redshift Evolution

- Clearly insane to ascribe all delay to photon mass.
- Frequency behavior the same as dispersion, but evolution not.
- Integral identical, except no number density. Equivalent DM(z) for massive photons is blue curve to right.
- We can improve photon mass limits with large sample, but not by orders of magnitude (especially since mass limit goes like $DM^{1/2}$.)



Factor of 10 Improvement in Current Data

MNRAS **000**, 1–9 (2022) Preprint January 31, 2023 Compiled using MNRAS LaTeX style file v3.0

Revised constraints on the photon mass from well-localized fast radio bursts

Hai-Nan Lin[1,2], Li Tang[3★] and Rui Zou[1,2]
[1] *Department of Physics, Chongqing University, Chongqing 401331, China*
[2] *Chongqing Key Laboratory for Strongly Coupled Physics, Chongqing University, Chongqing 401331, China*
[3] *Department of Math and Physics, Mianyang Normal University, Mianyang 621000, China*

Accepted 2022; Received 2022; in original form 2022

ABSTRACT
We constrain the photon mass from well-localized fast radio bursts (FRBs) using Bayes inference method. The probability distributions of dispersion measures (DM) of host galaxy and intergalactic medium are properly taken into account. The photon mass is tightly constrained from 17 well-localized FRBs in the redshift range $0 < z < 0.66$. Assuming that there is no redshift evolution of host DM, the 1σ and 2σ upper limits of photon mass are constrained to be $m_\gamma < 4.8 \times 10^{-51}$ kg and $m_\gamma < 7.1 \times 10^{-51}$ kg, respectively. Monte Carlo simulations show that, even enlarging the FRB sample to 200 and extending the redshift range to $0 < z < 3$ couldn't significantly improve the constraining ability on photon mass. This is because of the large uncertainty on the DM of intergalactic medium.

Key words: fast radio bursts – intergalactic medium – radio continuum: transients

- NB - galactic magnetic field limits *much* lower, but indirect. Rely dE dt ~$\hbar$, set

  dt to be light crossing time of ordered field region (i.e. MW).

Equivalence Principle

- GR says everything free falls at the same rate - allows (weak) equivalence between gravity and acceleration.
- Equivalence principle fundamental to our understanding of space & time.
- Say FRB goes off in potential well. If Shapiro delay depends on frequency, arrival vs. freq would change.

MNRAS 000, 1–7 (2022) Preprint 21 February 2023 Compiled using MNRAS LaTeX style file v3.0

Consistent Constraints on the Equivalence Principle from localised Fast Radio Bursts

Robert Reischke*[1] and Steffen Hagstotz†[2,3]
[1] Ruhr University Bochum, Faculty of Physics and Astronomy, Astronomical Institute (AIRUB), German Centre for Cosmological Lensing, 44780 Bochum, Germany
[2] Universitäts-Sternwarte, Fakultät für Physik, Ludwig-Maximilians Universität München, Scheinerstraße 1, D-81679 München, Germany
[3] Excellence Cluster ORIGINS, Boltzmannstraße 2, D-85748 Garching, Germany

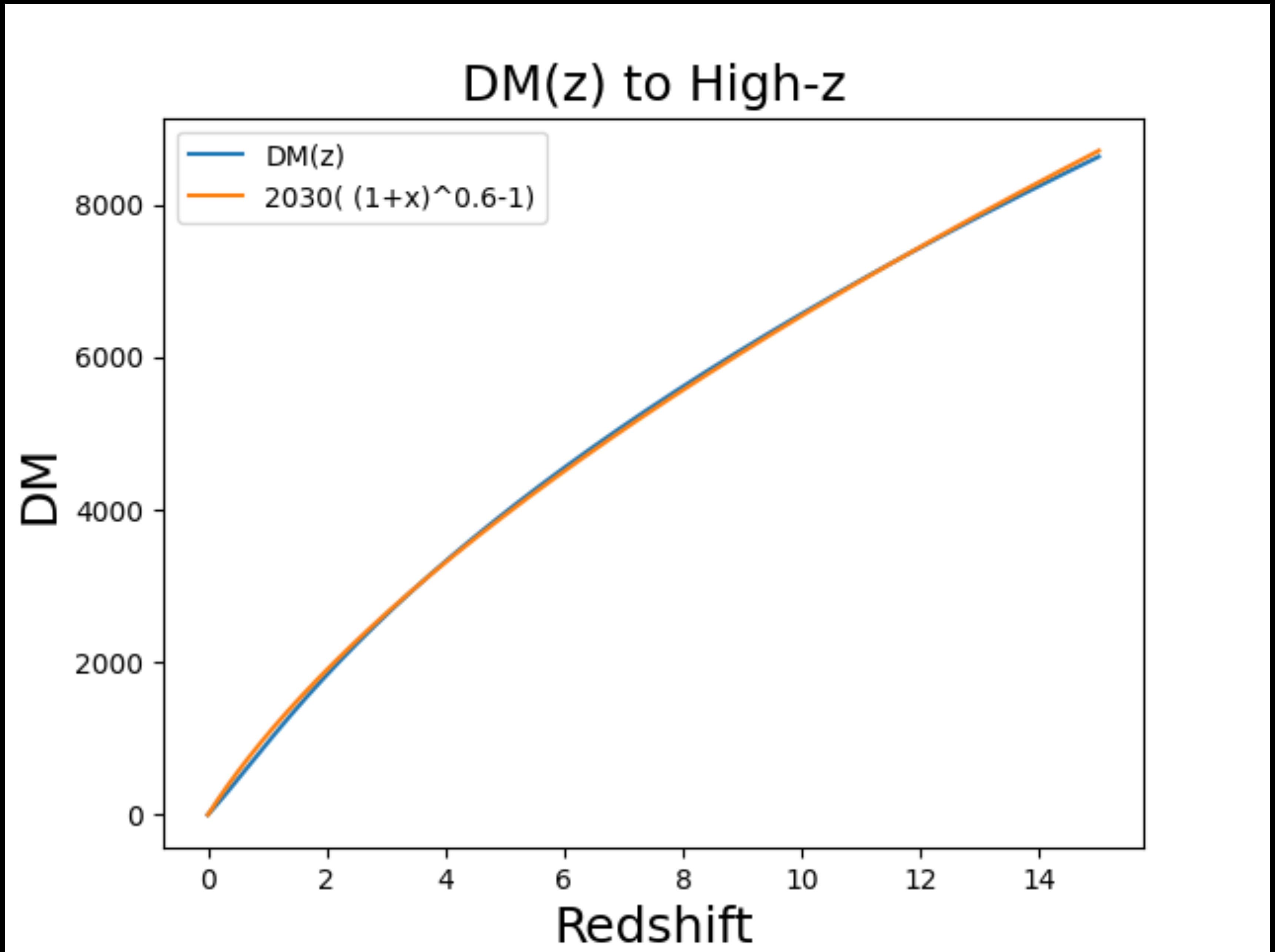
21 February 2023

ABSTRACT
Fast Radio Bursts (FRBs) are short astrophysical transients of extragalactic origin. Their burst signal is dispersed by the free electrons in the large-scale-structure (LSS), leading to delayed arrival times at different frequencies. Another potential source of time delay is the well known Shapiro delay, which measures the space-space and time-time metric perturbations along the line-of-sight. If photons of different frequencies follow different trajectories, i.e. if the universality of free fall guaranteed by the weak equivalence principle (WEP) is violated, they would experience an additional relative delay. This quantity, however, is not an observable on the background level as it is not gauge independent, which has led to confusion in previous papers. Instead, an imprint can be seen in the correlation between the time delays of different pulses. In this paper, we derive robust and consistent constraints from twelve localised FRBs on the violation of the WEP in the energy range between 4.6 and 6 meV. In contrast to a number of previous studies, we consider our signal to be not in the model, but in the covariance matrix of the likelihood. To do so, we calculate the covariance of the time delays induced by the free electrons in the LSS, the WEP breaking terms, the Milky Way and host galaxy. By marginalising over both host galaxy contribution and the contribution from the free electrons, we find that the parametrised post-Newtonian parameter γ characterising the WEP violation must be constant in this energy range to 1 in 10^{13} at 68 % confidence. These are the tightest constraints to-date on $\Delta\gamma$ in this low energy range.

- FRBs constrain weak equivalence to 10^{-13} at low energy, best constraints in this region.

High-z

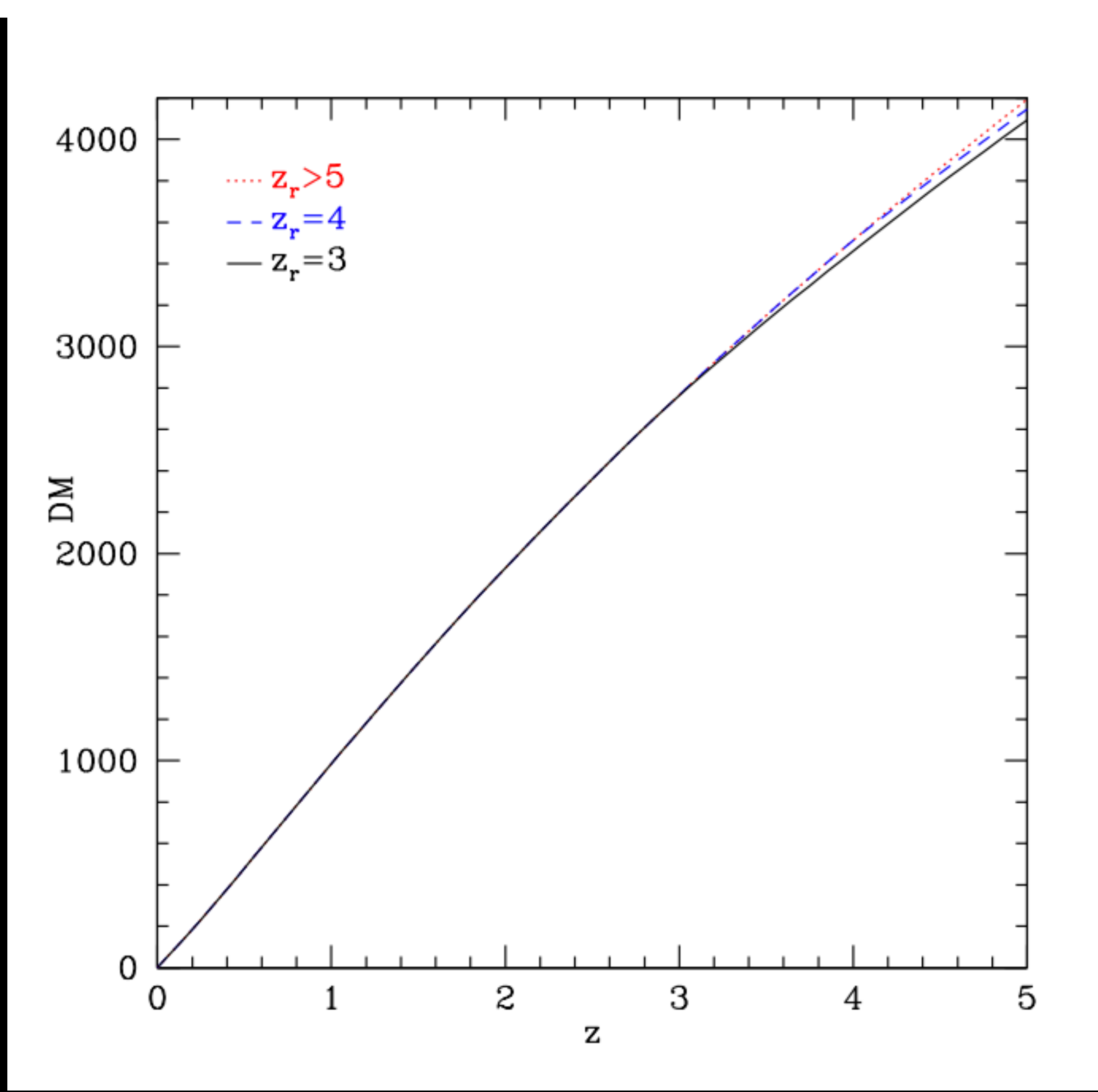
- Keeping ionization fraction constant, can go to high-z.
- Pretty good fit is DM~2000 ($(1+z)^{0.6}$-1). (alternatively, 1000-30z^2 also does OK to z~10)
- NB - coefficient assumes Planck params, full H ionization, no He ionization, no stars.



Detecting Helium Reionization with Fast Radio Bursts

Eric V. Linder[1,2]
[1] *Berkeley Center for Cosmological Physics & Berkeley Lab, University of California, Berkeley, CA 94720, USA*
[2] *Energetic Cosmos Laboratory, Nazarbayev University, Nur-Sultan, Kazakhstan 010000*
(Dated: February 3, 2020)

- Helium reionization changes background electron density.
- DM(z) law would reflect addition of e⁻ fro He.
- Distant FRBs would be able to probe He reionization, which in turn tells us objects in young universe.



Typeset using LATEX **twocolumn** style in AASTeX631

What it Takes to Measure Reionization with Fast Radio Bursts

Stefan Heimersheim,[1] Nina S. Sartorio,[1] Anastasia Fialkov,[1,2] and Duncan R. Lorimer[3,4]

[1] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2] *Kavli Institute for Cosmology, Madingley Road, Cambridge CB3 0HA, UK*
[3] *West Virginia University, Department of Physics and Astronomy, P. O. Box 6315, Morgantown, WV, USA*
[4] *Center for Gravitational Waves and Cosmology, West Virginia University, Chestnut Ridge Research Building, Morgantown, WV, USA*

ABSTRACT

Fast Radio Bursts (FRBs) are extra-galactic radio transients which exhibit a distance-dependent dispersion of their signal, and thus can be used as cosmological probes. In this article we, for the first time, apply a model-independent approach to measure reionization from synthetic FRB data assuming these signals are detected beyond redshift 5. This method allows us to constrain the full shape of the reionization history as well as the CMB optical depth τ while avoiding the problems of commonly used model-based techniques. 100 localized FRBs, originating from redshifts $5 - 15$, could constrain (at 68% confidence level) the CMB optical depth to within 11%, and the midpoint of reionization to 4%, surpassing current state-of-the-art CMB bounds and quasar limits. Owing to the higher numbers of expected FRBs at lower redshifts, the τ constraints are asymmetric $(+14\%, -7\%)$ providing a much stronger lower limit. Finally, we show that the independent constraints on reionization from FRBs will improve limits on other cosmological parameters such as the amplitude of the power spectrum of primordial fluctuations.

- If we can get to DM~8000, we can directly probe reionization as well.
- Would be independent of CMB measurements, help break τ-A_s degeneracy.
- With enough (~hundred) FRBs, can measure history as well as τ.

Can We do Precision Cosmology?

- DM(z) contains cosmological information, via dt/dz.
- It also contains information about $n_e(z)$, hence $f^*(z)$.
- We tried (work let by Tony Walters) to constrain cosmology with future FRB data. We discovered we'd constrain $f^*(z)$. Still useful! But not dark energy evolution…

Probing Diffuse Gas with Fast Radio Bursts

Anthony Walters[1,2], Yin-Zhe Ma[1,2], Jonathan Sievers[3,1], and Amanda Weltman[4]

Strongly lensed repeating fast radio bursts as precision probes of the universe

Zheng-Xiang Li, He Gao, Xu-Heng Ding, Guo-Jian Wang & Bing Zhang

Lensing of Fast Radio Bursts as a Probe of Compact Dark Matter

Julian B. Muñoz,[1] Ely D. Kovetz,[1] Liang Dai,[2] and Marc Kamionkowski[1]

- Build a (set of) telescopes that observe along a large range in RA at fixed dec?
- Time delays will be exquisitely measured (usual microlensing caveats will apply)
- Unclear, but entirely possible there exist several strongly lensed FRBs per day available to us.

FRBs & Clusters

Draft version October 1, 2018
Preprint typeset using LaTeX style AASTeX6 v. 1.0

PROBING WHIM AROUND GALAXY CLUSTERS WITH FAST RADIO BURSTS AND THE SUNYAEV-ZEL'DOVICH EFFECT

Yutaka Fujita
Theoretical Astrophysics, Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043, Japan

- τ through rich galaxy cluster ~0.01, so DM~5000
- There *will* be population of bright, local FRBs at very high DM that will probe cluster structure to percent level.
- SZ gives you $\int n_e T dl$, FRB gives $\int n_e$, so get temperature of outer cluster gas - hard to do other ways!
- Proposed in Fujita et al. back in 2016

From February!

- Two FRBs found inside clusters, significant excess DM (~600/~300 from clusters at z~0.1)
- It's better for FRBs to be behind clusters so LOS position within cluster not an uncertainty.
- As CHIME outriggers turn on, expect many more.

Draft version March 1, 2023
Typeset using LaTeX **twocolumn** style in AASTeX631

Deep Synoptic Array science: Two fast radio burst sources in massive galaxy clusters

Liam Connor,[1] Vikram Ravi,[1,2] Morgan Catha,[2] Ge Chen,[1] Jakob T. Faber,[1] James W. Lamb,[2] Gregg Hallinan,[1,2] Charlie Harnach,[2] Greg Hellbourg,[1,2] Rick Hobbs,[2] David Hodge,[1] Mark Hodges,[2] Casey Law,[1,2] Paul Rasmussen,[2] Jack Sayers,[1] Kritti Sharma,[1] Myles B. Sherman,[1] Jun Shi,[1] Dana Simard,[1] Jean Somalwar,[1] Reynier Squillace,[1] Sander Weinreb,[1] David P. Woody,[2] Nitika Yadlapalli,[1]

(The Deep Synoptic Array team)

[1] *Cahill Center for Astronomy and Astrophysics, MC 249-17 California Institute of Technology, Pasadena CA 91125, USA.*
[2] *Owens Valley Radio Observatory, California Institute of Technology, Big Pine CA 93513, USA.*

(Received; Revised; Accepted)
Submitted to ApJ Letters

ABSTRACT

The hot gas that constitutes the intracluster medium (ICM) has been studied at X-ray and millimeter/sub-millimeter wavelengths (Sunyaev–Zeld'ovich effect) for decades. Fast radio bursts (FRBs) offer an additional method of directly measuring the ICM and gas surrounding clusters, via observables such as dispersion measure (DM) and Faraday rotation measure (RM). We report the discovery of two FRB sources detected with the Deep Synoptic Array (DSA-110) whose host galaxies belong to massive galaxy clusters. In both cases, the FRBs exhibit excess extragalactic DM, some of which likely originates in the ICM of their respective clusters. FRB 20220914A resides in the galaxy cluster Abell 2310 at $z = 0.1125$ with a projected offset from the cluster center of 520±50 kpc. The host of a second source, FRB 20220509G, is an elliptical galaxy at $z = 0.0894$ that belongs to the galaxy cluster Abell 2311 at projected offset of 870±50 kpc. These sources represent the first time an FRB has been localized to a galaxy cluster. We combine our FRB data with archival X-ray, SZ, and optical observations of these clusters in order to infer properties of the ICM, including a measurement of gas temperature from DM and y_{SZ} of 0.8–3.9 keV. We then compare our results to massive cluster halos from the IllustrisTNG simulation. Finally, we describe how large samples of localized FRBs from future surveys will constrain the ICM, particularly beyond the virial radius of clusters.

Cosmology with kSZ: breaking the optical depth degeneracy with Fast Radio Bursts

Mathew S. Madhavacheril,[1] Nicholas Battaglia,[2,3] Kendrick M. Smith,[4] and Jonathan L. Sievers[5,6]

- kSZ is major goal of upcoming CMB experiments.
- kSZ sensitive to growth of structure, hence e.g. neutrino mass.
- kSZ measures velocity (good! cosmology lives here!) times electron density (bad! full of uncertainties!)
- FRBs directly measure electron column density, with uncertainty from FRB host contribution.

Cosmology with kSZ: breaking the optical depth degeneracy with Fast Radio Bursts

Mathew S. Madhavacheril,[1] Nicholas Battaglia,[2,3] Kendrick M. Smith,[4] and Jonathan L. Sievers[5,6]

(1901.02418)

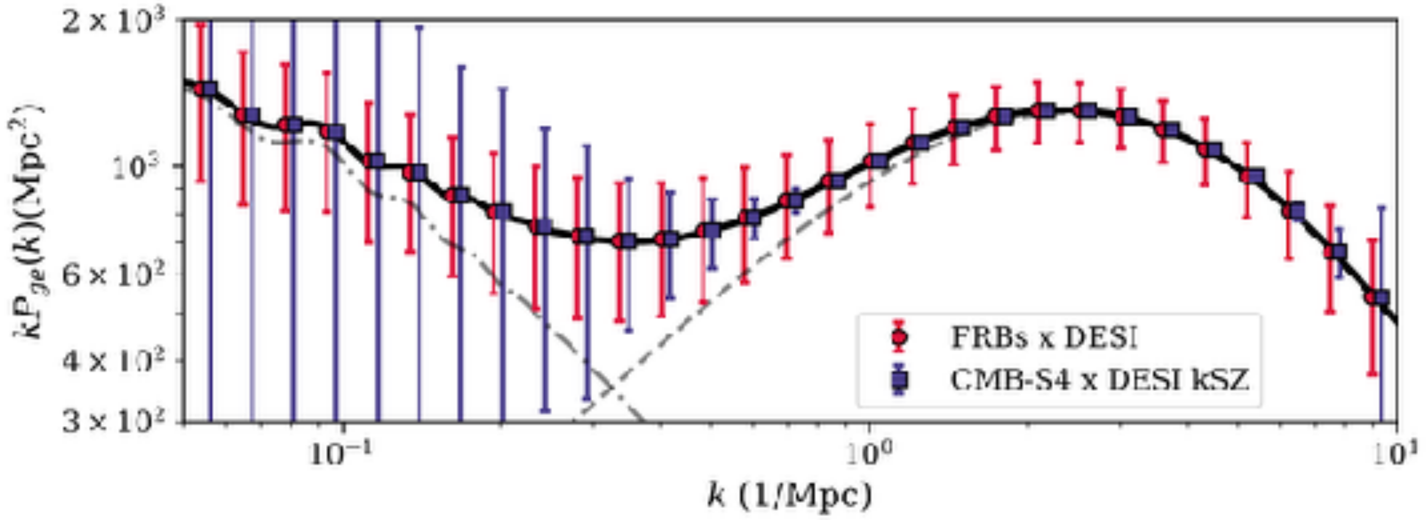


FIG. 2: The cross-power-spectrum of galaxies and electrons as measured either through kSZ tomography with CMB-S4 and DESI (blue) with fixed cosmology, or through cross-correlation of dispersion measures of 10^4 FRBs with DESI galaxies (red), where the RMS scatter of DMs is assumed to be 300 $\frac{\mathrm{pc}}{\mathrm{cm}^3}$. FRB DMs measure the power over a broad range of scales including the 2-halo regime (dot-dashed), while kSZ tomography provides an extremely tight measurement in the 1-halo dominated regime (dashed).

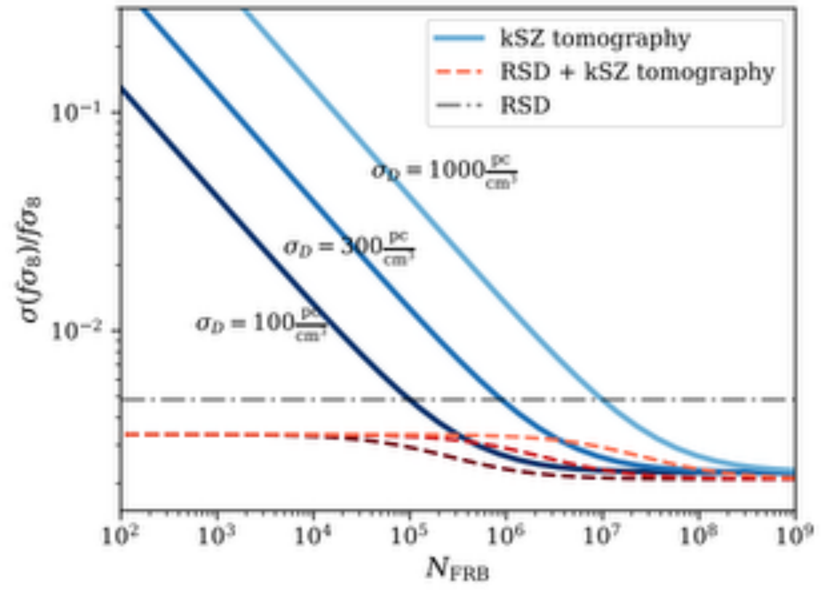


FIG. 4: The uncertainty on the combination of cosmic growth rate and amplitude of matter fluctuations $f\sigma_8$ from kSZ tomography with CMB-S4 and DESI as a function of the number of FRBs, N_{FRB}, available to break the 'cluster optical depth degeneracy' through cross-correlation of FRB DMs with the same DESI galaxy sample. The blue lines show the constraint from kSZ tomography with various shades corresponding to choices of the uncertain RMS scatter of FRB DMs σ_D. If RSD information is used in conjunction with kSZ (red dashed lines), the degeneracy is already broken to some degree but further improvement is possible with FRBs. The grey dot-dashed line shows the constraint from DESI RSD alone.

With 10^4 FRBs with localizations, can improve on galaxy-electron xcorr on large scales over S4+DESI (above)

Improves on cosmology over S4+RSD for ~10^6 FRBs (right).

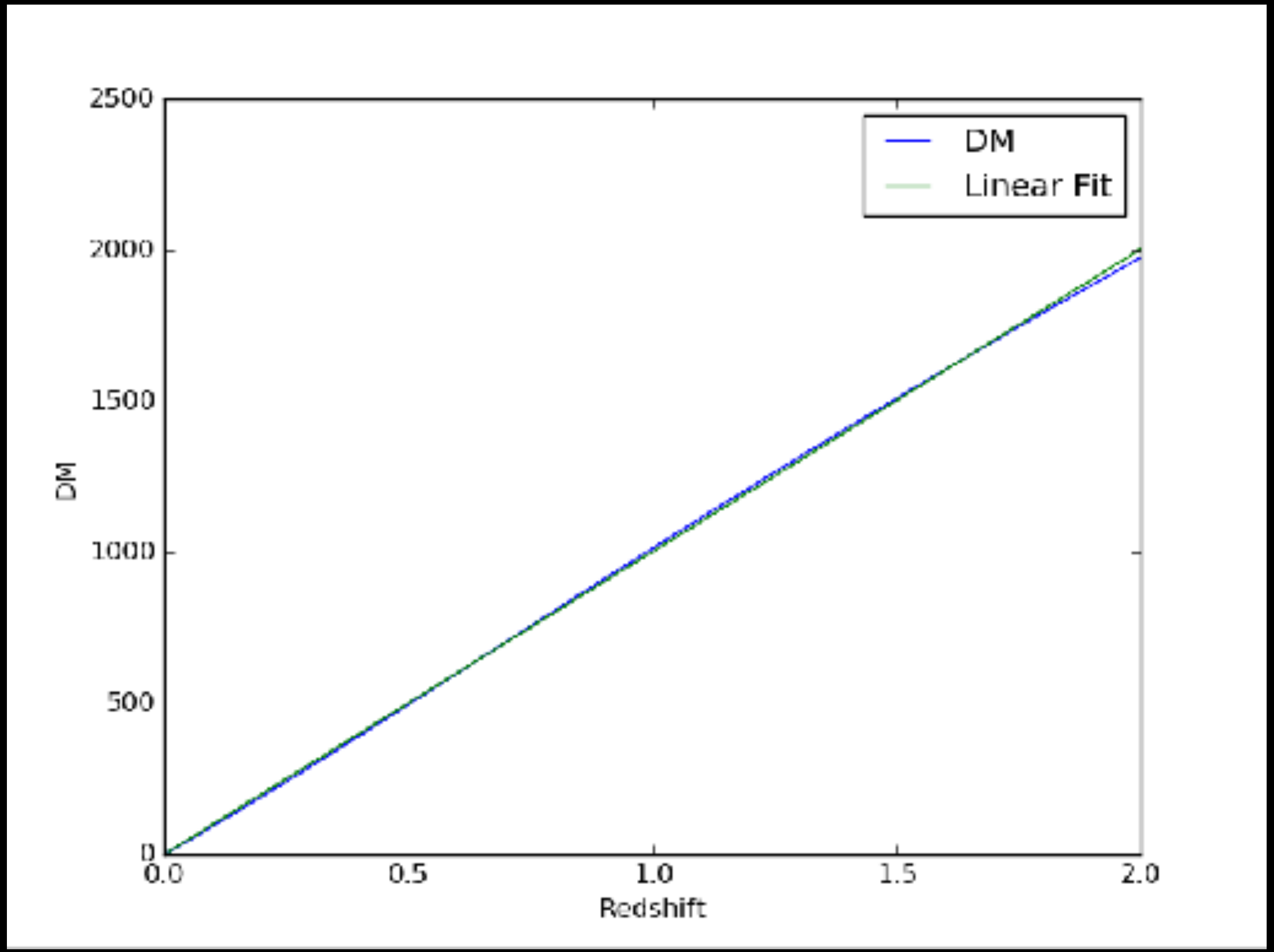
Conclusions

- FRBs give precise redshift-weighted LOS column density and timing info. WIth position/redshift info, can probe many things. High-DM bursts especially valuable.
- Can constrain fundamental physics like photon rest mass and weak equivalence principle.
- Can constrain distribution of "missing" baryons, break vτ kSZ degeneracy.
- With high DM, can probably measure reionization independently of other methods w/ little foreground uncertainty.
- Likely many strongly lensed FRBs. With baseband caches, microlensing down to ns delays avaliable.
- And I haven't even measure RM (magnetic fields), or deviations from λ^2 (large density fluctuations, see e.g. Masui et al. 2015).

What Might we do with FRBs?

(aside from figuring out what they are)

- FRBs give us exquisite arrival time information across possibly wide frequency bands.
- FRBs give us exquisite (1/(1+z)-weighted) electron column density measurements.
- $DM_{obs}=DM_{MW}+DM_{IGM}+DM_{host}$. Handy rule, $z \sim DM_{IGM}/1000 f_{ion}$.
- Contribution from host uncertain, but distances are likely cosmological (FRBs noticed because DM too high to come from Milky Way).
- Could serve as probes where this information is useful.
- Careful examination of FRB signals can sometimes unlock other information…



PROBING WHIM AROUND GALAXY CLUSTERS WITH FAST RADIO BURSTS AND THE SUNYAEV–ZEL'DOVICH EFFECT

YUTAKA FUJITA[1], TAKUYA AKAHORI[2], KEIICHI UMETSU[3], CRAIG L. SARAZIN[4], AND KA-WAH WONG[5,6]

- Optical depth through rich cluster is 0.01. Means DM is 5000(!)
- FRB that goes off behind cluster tells you τ, possibly to 5% or better.
- TSZ measurement then tells you mass-weighted temperature
- Very clean measurement, does not rely on X-rays
- Does require many, many FRBs