Welcome to the era of FRB “cosmology”!

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Fast Radio Bursts (FRBs)

- bright millisecond radio transient (re)discovered by Thornton++ 2013
- typical time lag of pulses requires cosmological electron column to $z \sim 1$ ($DM \sim 1000$ pc cm$^{-3}$)
- $DM =$ dispersion measure, which is radio parlance for “electron column density”

Lorimer++07
I wrote a paper a few months after the Thornton rediscovery (MM ’14) about the potential for studying diffuse gas with FRBs. A lot had to go right for proposal to work:

1) FRBs would have to be extraterrestrial
2) FRBs would have to be extragalactic and localized to a host galaxy
3) ideally, host galaxy fractional contribution to the dispersion measure is small

I turned to other projects.
But things kept advancing….

- **2015**: terrestrial source that looked like an FRB (opening microwave ovens) was discovered *(Petroff++ ’15)*

- **2017**: `the Repeater’ localized to z=0.2 galaxy, confirming that at least some are extragalactic *(Tendulkar++ ’17)*

- **2019**: at least nine others confirmed to be extragalactic *(including XXXXXX new ones from ASKAP in this talk!)*

- **this talk**: the host system contribution to the dispersion is likely often small *(and FRBs are going to be amazing!!!!!!)*

* XXXX = some material is redacted from online slide-deck owing to embargoed work
But what are FRBs?

- likely too many to be from single cataclysmic event
- several arguments supporting a neutron star origin
- young magnetar hypothesis intriguing (c.f. Margalit), but situation has gotten less clear as some hosts are not star forming dwarf galaxies and lack associated radio sources

This question is largely immaterial to the science applications in this talk.
This talk is on using FRBs to explore intervening gas, as their electromagnetic properties are sensitive to the cosmic plasma.
Context: The baryons in the Universe
We only really see directly the gas within galaxies or in clusters, accounting for $<\sim 10\%$

Everything else?

$\langle n_{\text{IGM}} \rangle \sim 0.1 \text{ m}^{-3}$

$\langle n_{\text{HI}} \rangle \sim 10^3 \text{ km}^{-3}$

e.g. Fukugita & Peebles ‘04
We do not know how gas is distributed around $<10^{14} \, M_{\text{sun}}$ halos

- ~50% of the dark matter presently resides in $>10^{10} M_{\text{sun}}$ halos

- $10^{10-13} \, M_{\text{sun}}$ halos are where halo gas cools in short time, sourcing star formation

- Without feedback, ~50% of baryons should be in stars. Only ~5% of baryons are in stars.
galaxy formation models do not answer this yet

Modeling stellar and AGN feedback is complex.

Gas around $10^{13} M_{\odot}$ halos

Collin Hill+CMB-S4+simulators

See Prochaska & Yong Zheng '19 for nice summary of what is known regarding MW-like halos, where models may span even larger range.

If you are confused by weird shape at small radii, its because curves are computed with "aperture photometry" and really are closer to $-r \frac{d\Sigma}{dr}$.

Simulations make wildly different predictions!!!
Now bring in FRBs...
An FRB sightline goes through many dark matter halos and thus probes their gas.
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Three plasma phenomena that can be used to probe halo gas with FRBs

- Faraday rotation
  \[ \text{RM} = \int ds \ n_e B_{||} \]

- Scattering
  \[ \tau_{\text{scatt}} \propto \int ds \ n_e^2 \]  
  (being a bit simplistic)

- Dispersion
  \[ \text{DM} = \int ds \ n_e \]

(can never measure dispersion to non-transient source (Hirata & MM '14))
Case study #1: FRB181112

FRB detected with ASKAP

z=0.37 galaxy in $\sim 10^{12.5} M_{\odot}$ halo
SFR$<0.3 M_{\odot}yr^{-1}$; $Z \sim 2 Z_{\odot}$

FRB host $z=0.47$

Faraday rotation | scattering | dispersion

Prochaska, Macquart, MM et al 2019 Science
FRB18112 Faraday rotation constrains on magnetic field thru foreground halo

\[ B_{\parallel} < 0.8 \mu G \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \left( \frac{\Delta L}{30 \text{ kpc}} \right)^{-1} \]

\( n_e \sim 10^{-3} \text{ cm}^{-3} \) is a typical density of models at 30 kpc.

- Our constraints are comparable to equipartition field of
  \[ 2 \mu G \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right)^{1/2} \left( \frac{T}{10^6 \text{ K}} \right)^{1/2} \]

- B-field constraints shed light on CGM plasma (e.g. magnetization could drastically affect thermal instability Ji++18 and could be signature of cosmic ray feedback)
FRB18112 scattering constrains the RMS density thru foreground halo in picture that density follows Kolmogorov spectrum

We measure a scattering delay of $\tau_{\text{scatt}} < 40 \mu$s which one can translate into a limit on the inner density:

$$\langle n_e \rangle < 2 \times 10^{-3} \alpha^{-1} \left( \frac{\Delta L}{50 \text{ kpc}} \right)^{-1/2} \left( \frac{L_0}{1 \text{ kpc}} \right)^{1/3} \left( \frac{\tau_{\text{scatt}}}{40 \mu s} \right)^{5/12} \text{ cm}^{-3}$$

This constraint assumes a path-length $\Delta L$ through a turbulent region with driving scale $L_0$, where $\alpha \langle n_e \rangle$ parameterizes the RMS density at the driving scale.

Lithwick and Goldreich ‘01 outline criteria where Kolmogorov holds on Alfvenic scales, and our paper translates their insights in CGM context.
FRB18112 scattering constrains models for a mist of parsec-scale clouds in the foreground halo.

McCourt++ '18 conjectures CGM may be filled with $10^4$K cloudlets with volume filling fractions as large as $f_V \sim 10^{-2}$.

Vedantham & Phinney '19 interestingly showed that significant scattering could occur by dense CGM cloudlets of radius $R$. Their diffractive formulae would imply a stringent limit of $f_V < 10^{-5} (R/1pc)^{1/3}$ if $n_{cloud} = 0.1 cm^{-3}$ for this system.

Redoing calculation in correct refractive limit yields $f_V < 3 \times 10^{-2} (R/1pc)^{3/2}$ for $n_{cloud} = 0.1 cm^{-3}$, with a weaker scaling in $R$ below $0.01 pc$.

Faraday rotation | scattering | dispersion
That was the warm up. Now let’s get serious....
cosmic structure will drive scatter in the dispersion measures (DMs) to a given redshift.
This scatter is mostly driven by the number of dense regions (i.e. gaseous `halos’) intersected.

A second (generally smaller) contribution to scatter comes from how matter fluctuations on 10-150 Mpc scales.

A sightline to z~1 intersects tens of galactic halos.

A second (generally smaller) contribution to scatter comes from how matter fluctuations on 10-150 Mpc scales.
How to think about FRB dispersion measures (DMs)

More compact gaseous halos, more sightline variance, more skewed PDF
How to think about FRB dispersion measures (DMs)

Puffier halos, less sightline variance, more Gaussian PDF

ASKAP
The PDF of DM(z)

Measuring PDF requires knowing redshift and host-galaxy contribution to dispersion.

Top two panels are toy models, but reflect uncertainties.
Next few slides EMBARGOED and not included in online slide-deck

Macquart, Prochaska, MM++, submitted to *Nature*
“I love to travel, but I hate to arrive.”

–Albert Einstein
Going Forward

Not only will there be many more FRBs to do this science, but this science intersects with CMB anisotropy measurements, weak lensing, CGM UV absorption measurements, metal enrichment history
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Going forward

There are going to be A LOT OF FRBs and A LOT with localizations!!!!

Stacking around foreground galaxies is way to go once there are >100 localizations

Facilities: ASKAP, Chime, DSA, HIRAX, Meerkat, etc

Petroff++19

This is for Milky Way mass $10^{12} M_{\odot}$ halo

$\Delta_{\text{DM}}$ [cm$^{-3}$ pc]

impact parameter (kpc)
Going forward

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MM’14
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MM'14
Going forward

the main competitor to FRBs is going to be kSZ (and tSZ) with Simons Obs./CMB-S4, but beam size and lack of large spectroscopic samples makes hard to push to $10^{12} \text{M}_{\odot}$ Milky Way mass gas around $10^{13} \text{M}_{\odot}$ halos in simulations
Going forward

Our best probe current probe of CGM: UV absorption lines

Current inferences rely solely on the integrated column across ions and making a variety of strong assumptions. We can do better!

underlying image by Ann Feild (STScI) adapted from Tumlinson, Peeples & Werk (ARA&A 2017).
Going forward

Do we understand where feedback affects and enriches the IGM? IGM absorption lines suggest enrichment is ubiquitous.

Currently we have large-scale simulations where galaxies are $\sim 10^3$ particles and zoom in sims. There is room for semi-numeric models to understand what metal absorption data requires.

Booth++12
The Cosmology community has gone ALL IN for weak lensing, but baryon distribution matters for realizing precision forecasts. We need better models for this, ideally a flexible model similar (but not identical) to the halo model (Ma; Seljak).

Related deep question: What is the limit we can extract the initial conditions from large-scale structure measurements?
Conclusions

• FRB181112: first diffuse baryon science with FRBs
  
  • sub-equipartition $B_\parallel$ for the CGM weirdly consistent with recent cosmological MHD simulations
  
  • tight limit on scattering — gas is either non-turbulent (with some caveats) or lower density than some models. Constraints on parsec-scale mist weaker than anticipated.
  
  • From $XXXXX$ bursts, we measure $\Omega_b = XYYYYY Y\%$ C.L. and are starting to constrain the scatter
    
    • suggests host contribution to DM is typically low ($\sim XYYYYY pc cm^{-3}$)
    
    • constraints on CGM density are going to get interesting
  
  • constraints on distribution of baryons around halos relevant for the intergalactic medium, for galaxy formation and for precision cosmology
Scattering of mist of clouds

We redid calculation, which had used diffractive formula more appropriate for fully turbulent clouds. Find that scattering is less constraining than previously thought, but still interesting. Constraints for FRB181112:

\[
\left( \frac{n_e}{0.1 \text{ cm}^{-3}} \right) \left( \frac{\Delta L}{50 \text{kpc}} \cdot \frac{f_v}{10^{-3}} \cdot \frac{0.1 \text{pc}}{R} \right)^{1/2} < 0.2 \left( \frac{\tau_{\text{scatt}}}{40 \mu\text{s}} \right)^{1/2} \quad \text{if} \quad R \leq 0.011 \text{pc} \left( \frac{\tau_{\text{scatt}}}{40 \mu\text{s}} \right)^{1/2};
\]
\[
\left( \frac{n_e}{0.1 \text{ cm}^{-3}} \right) \left( \frac{\Delta L}{50 \text{kpc}} \cdot \frac{f_v}{10^{-3}} \right)^{1/2} \left( \frac{0.1 \text{pc}}{R} \right)^{3/2} < 1.6 \quad \text{otherwise},
\]  
(S25)

Data rules out mist of 0.1 parsec clouds with a volume filling fraction of $10^{-3}$
We do not know how gas is distributed around $\sim<10^{14} \, M_{\odot}$ halos.

Absorption around $\sim 10^{12} M_{\odot}$ halos

Stacking Planck Thermal SZ
(becomes dominated by 2-halo at $<10^{13} M_{\odot}$)

Hill++18

Johnson++ '15

Integrated pressure

Mylky Way OVII compilation from Prochaska & Zheng '19
Simulations make wildly different predictions!!!

Modeling stellar and AGN feedback is complex.

Gas profile around $z=0.2$, $10^{13} \, M_{\odot}$ halos

See Prochaska & Yong Zheng '19 for nice summary of what is known regarding MW-like halos, where models may span even larger range

Note:
y-axis is log!