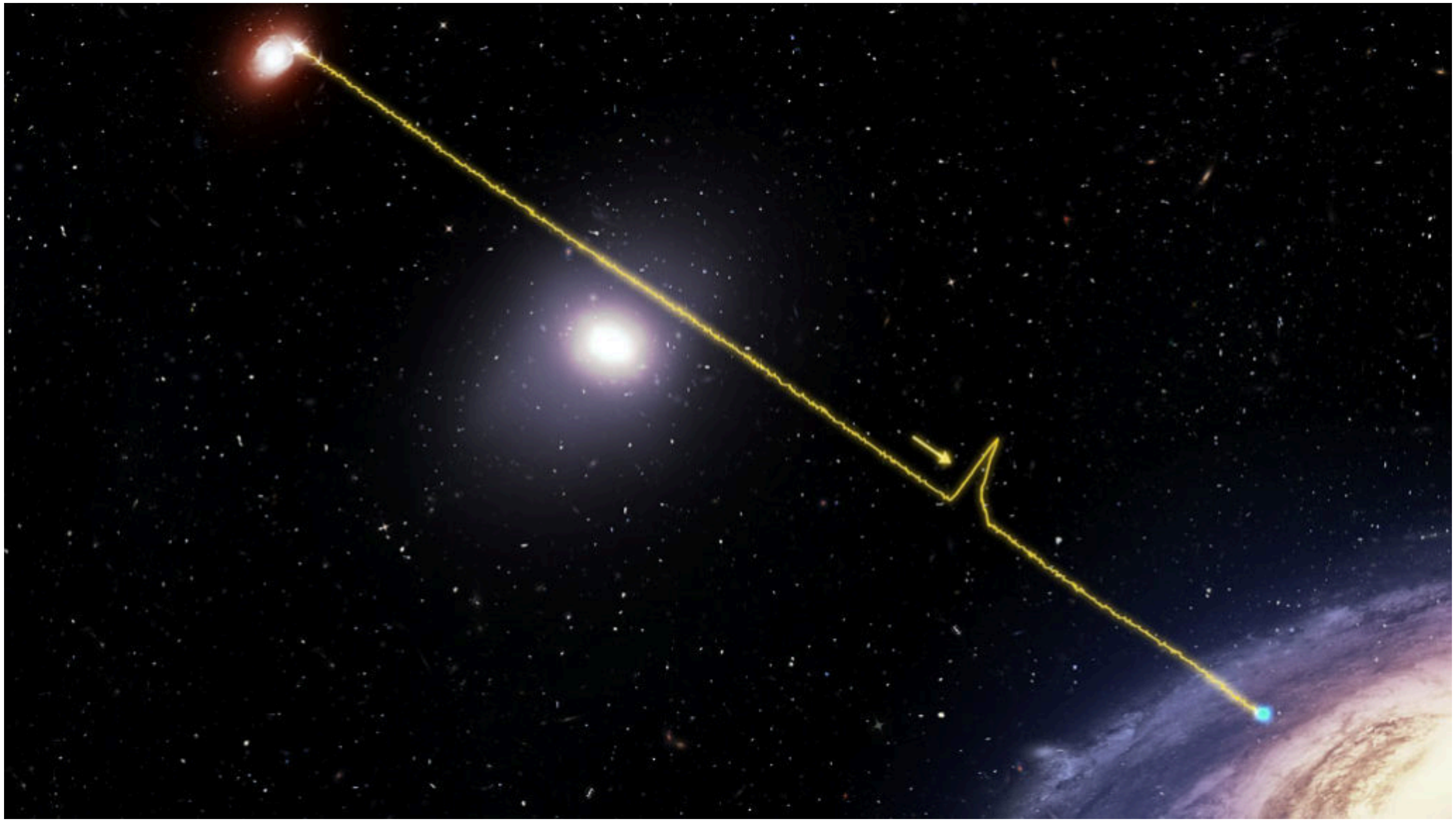


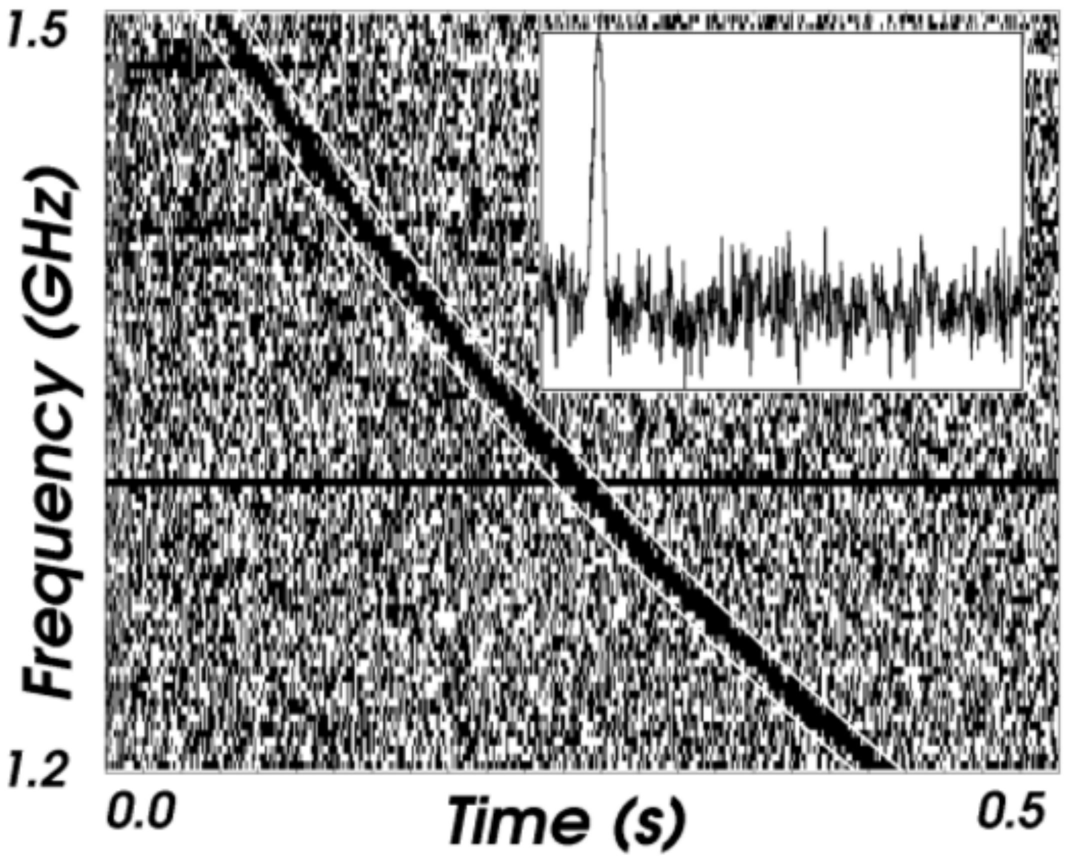
Welcome to the era of FRB “cosmology”!

Matt McQuinn
University of Washington

Special acknowledgement to contributions of J-P Macquart. RIP

Fast Radio Bursts (FRBs)

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



Lorimer++07

I wrote a paper several 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-present:** ~8 others localized to galaxies (including four new ones from ASKAP/CRAFT in **this talk**!)

- **this talk:** the host system contribution to the dispersion is at-very-least not horrible *(and FRBs are going to be amazing!!!!!!)*

But what are FRBs?

- likely too many to be from single cataclysmic event
- several arguments for neutron star origin
- (young/exotic) magnetar hypothesis is “winning” *(it was more of a wash a couple months ago)*

This question is largely immaterial to the science applications in this talk.

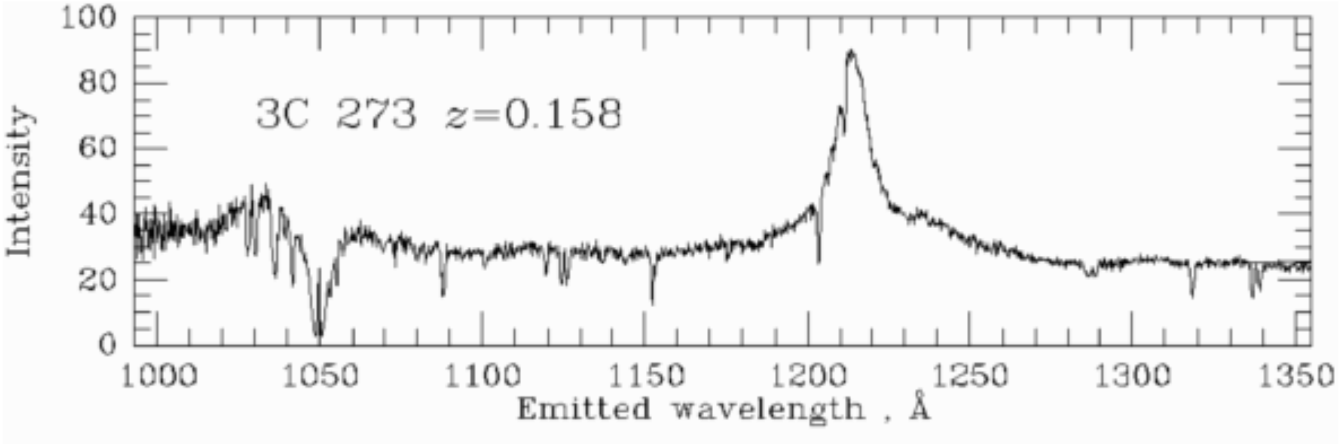
This talk is on using FRBs to explore intervening gas, as their electromagnetic properties are sensitive to the cosmic plasma.

Context: The baryons in the Universe

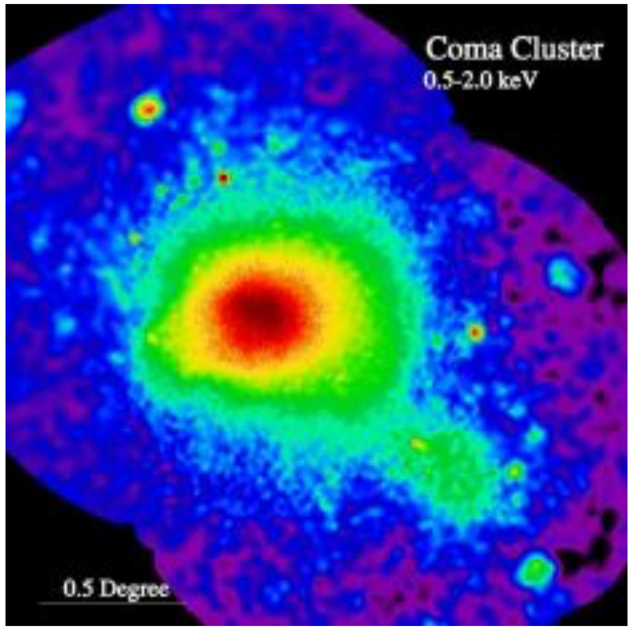
Traditionally only really see directly the gas within galaxies or in clusters, accounting for <~10%

FRBs [and kSZ] are way to do better

~5%



Everything else?

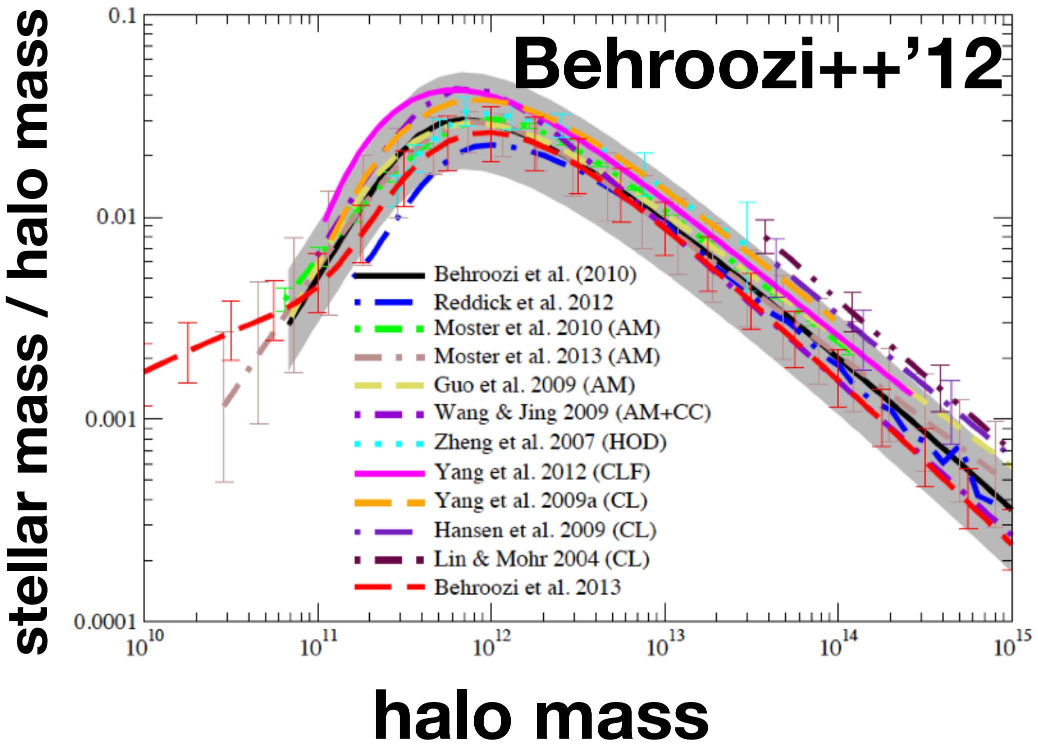


$\langle n_{IGM} \rangle \sim 0.1$ m^{-3}
$\langle n_{HI} \rangle \sim 10^3$ km^{-3}

~5%

e.g. Fukugita & Peebles '04

We do not know how gas is distributed around galactic-mass dark matter halos



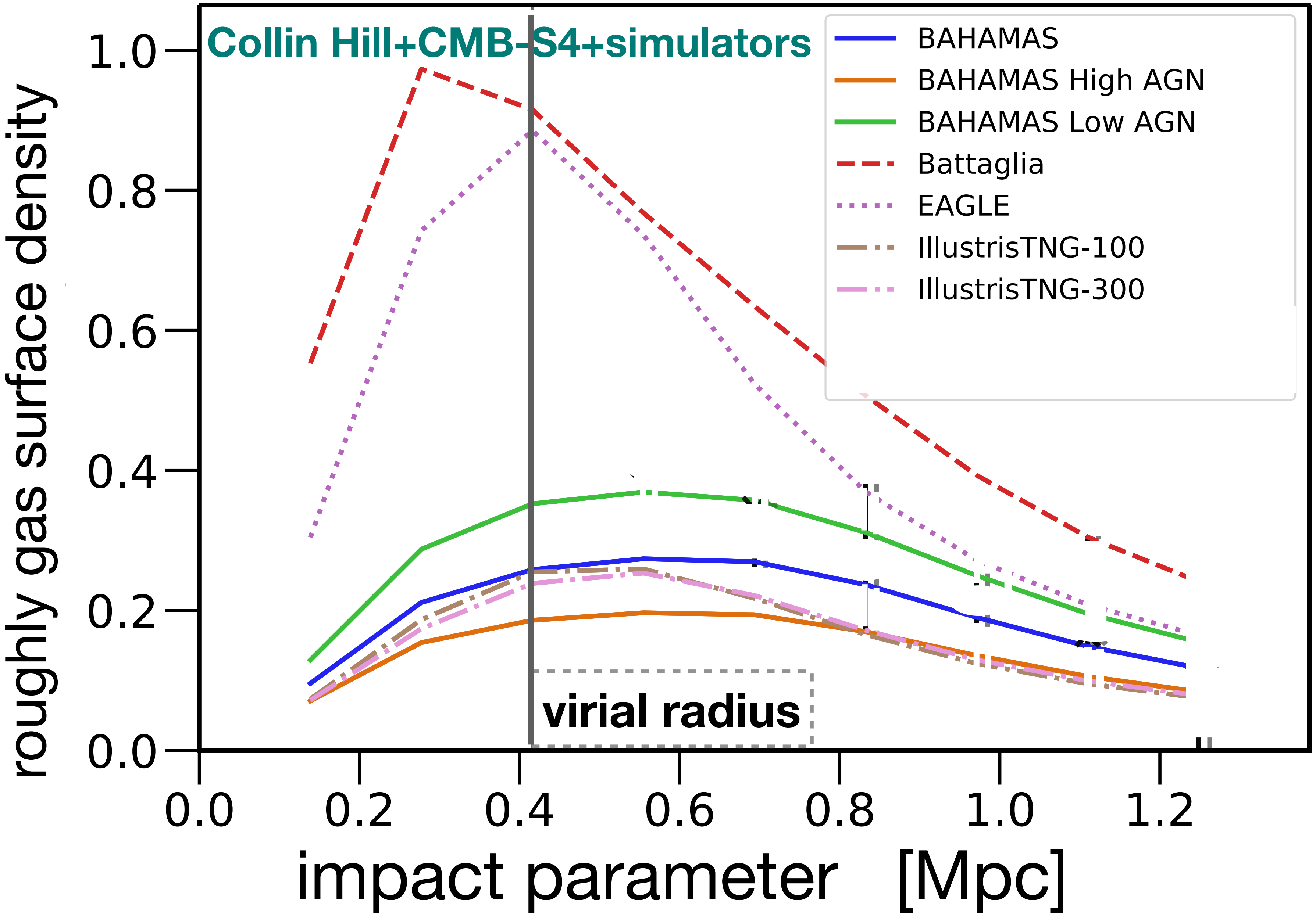
Plot illustrates inefficiency of galaxy formation with halo mass

- 40% of the dark matter presently resides in 10^{10}-10^{14}M$_{sun}$ halos where halo gas cools in short time, sourcing star formation
- Without feedback, 40% of baryons should be in stars. Only ~5% of baryons are in stars. Where did the rest go?

galaxy formation models do not answer this yet

Modeling stellar and AGN feedback is complex.

Gas around 10^{13} M_{sun} halos



See Prochaska & Zheng '19; Keating & Pen '20 for MW-like halos, where models may span even larger range

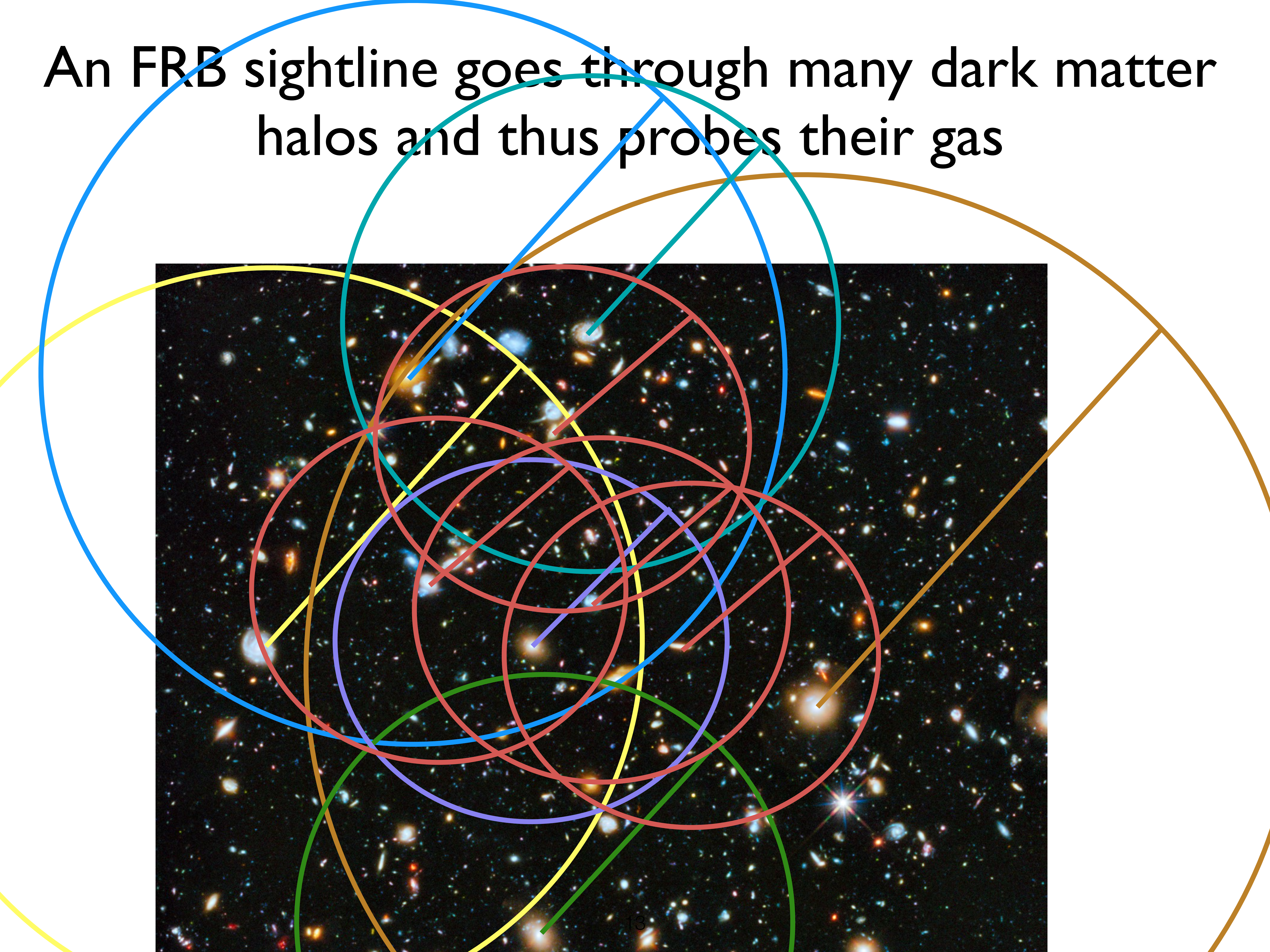
If you are confused by weird shape at small radii, its because curves are computed with "aperture photometry" and really are closer to -r dΣ/dr.

Simulations make wildly different predictions!!!

PS If you are one who only cares about cosmological parameters, knowing where baryons are is also important there too (especially for weak lensing)

Now bring on FRBs…

An FRB sightline goes through many dark matter halos and thus probes their gas



Three plasma phenomena that can be used to probe halo gas with FRBs

- Faraday rotation

$$\mathrm{RM} = \int ds\ n_e B_{||}$$

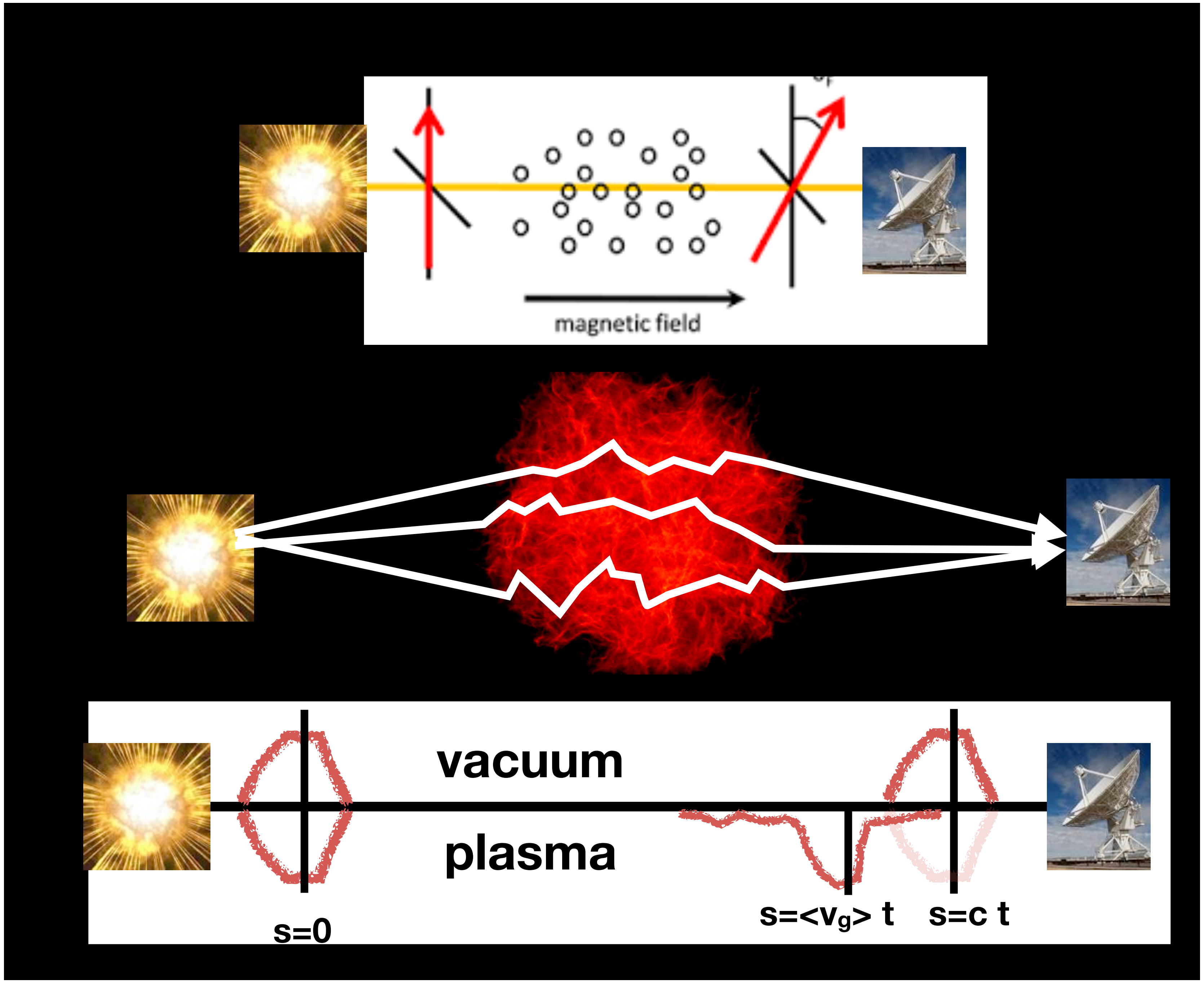
- scattering

$$\tau_{\mathrm{scatt}} \propto \int ds\ n_e^2$$

(being a bit simplistic)

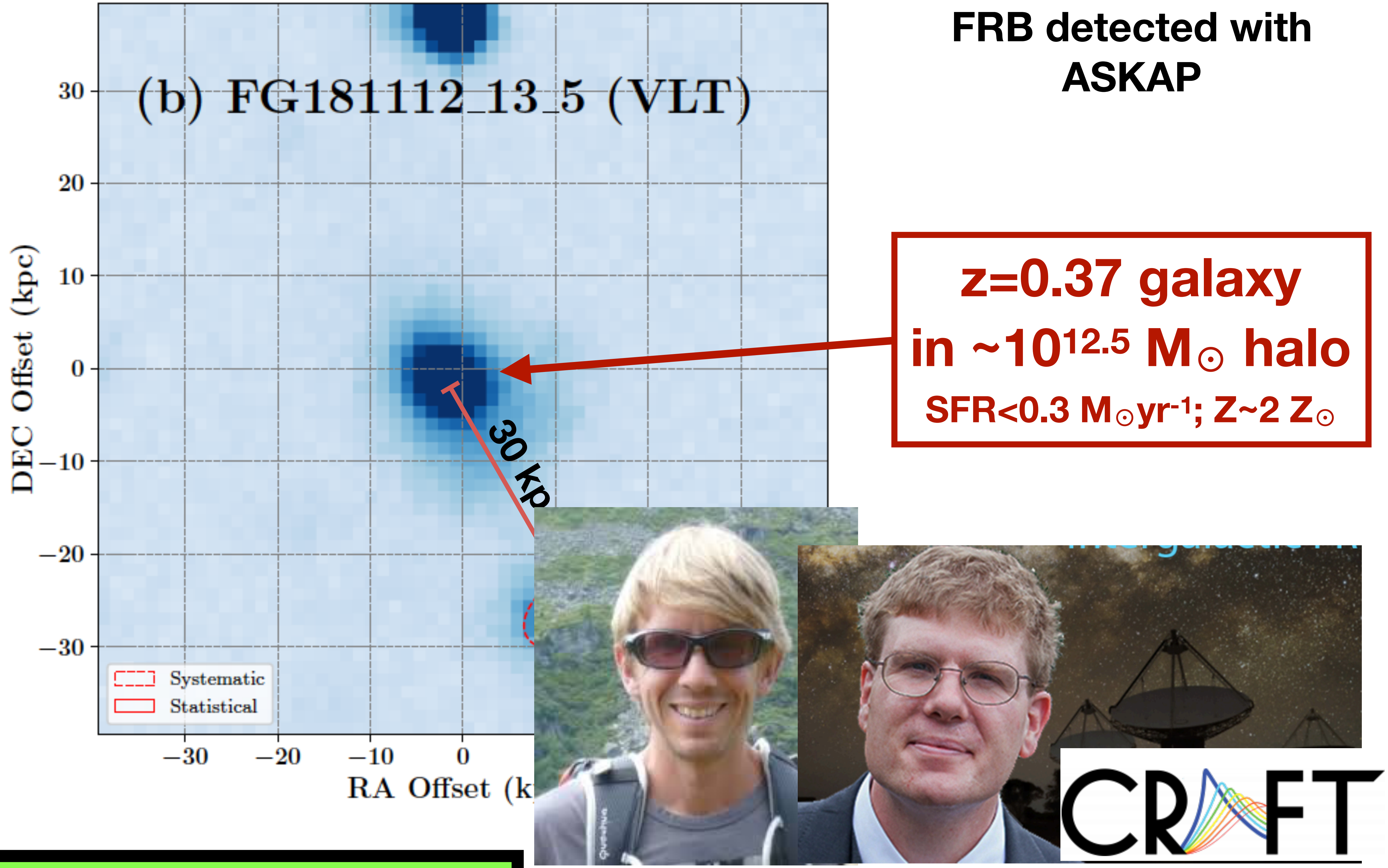
- dispersion

$$\mathrm{DM} = \int ds\ n_e$$



can never measure dispersion to non-transient source (Hirata & MM ’14)

Case study #1: FRB181112



FRB detected with ASKAP

$z=0.37$ galaxy

in ~$10^{12.5}$ $M_\odot$ halo

SFR<0.3 $M_\odot yr^{-1}$; Z~2 $Z_\odot$

Faraday rotation | scattering | dispersion

Prochaska, Macquart, MM &CRAFT 2019 *Science*

FRB18112 Faraday rotation constrains on magnetic field thru foreground halo

$$B_{||} < 0.8\mu\mathrm{G}\,(n_e/10^{-3}\,\mathrm{cm}^{-3})^{-1}\,(\Delta L/30\,\mathrm{kpc})^{-1}$$

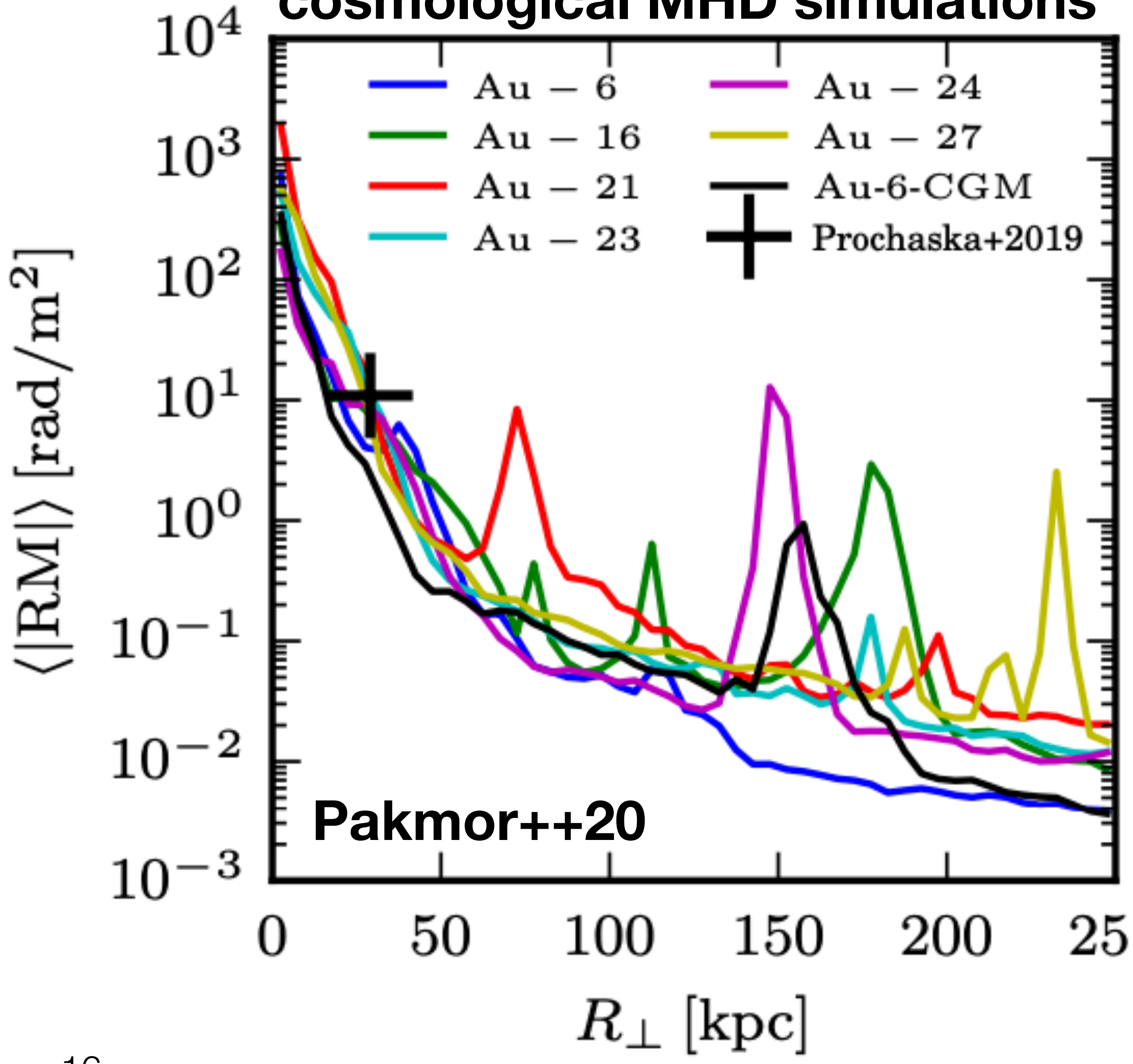
$n_e \sim 10^{-3}\mathrm{cm}^{-3}$ is a typical density of models at 30 kpc.

- **Our constraints are comparable to equipartition field of**

  $$2\mu\mathrm{G}(n_e/10^{-3}\,\mathrm{cm}^{-3})^{1/2}(T/10^6\mathrm{K})^{1/2}$$

- **B-field constraints shed light on CGM plasma as magnetization drastically affects thermal instability Ji++18 and could be signature of cosmic ray feedback**

cosmological MHD simulations



Faraday rotation | scattering | dispersion

FRB18112 scattering constrains the RMS density thru foreground halo

in picture that density follows Kolmogorov spectrum

We measure a scattering broadening of $\tau_{\rm scatt}$<40 μs which one can translate into a limit on the inner density:

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

This constraint assumes a path-length ΔL through a turbulent region with driving scale L_0, where $\boldsymbol{\alpha}\langle n_e \rangle$ 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 to CGM context.

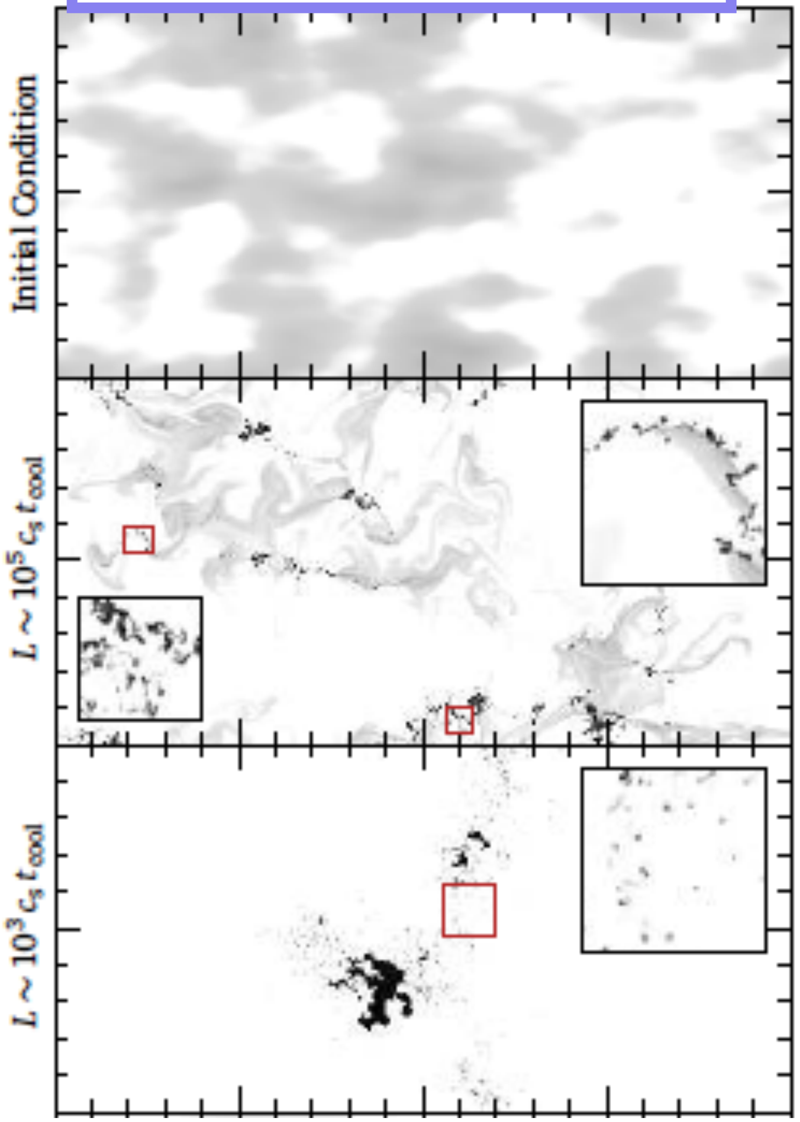
Faraday rotation | **scattering** | dispersion

See Cho++’20 for an update on 18112’s scattering.

FRB18112 **scattering** constrains models for a mist of parsec-scale clouds in the foreground halo

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

Idealized simulations of McCourt++18 showing cloudlets



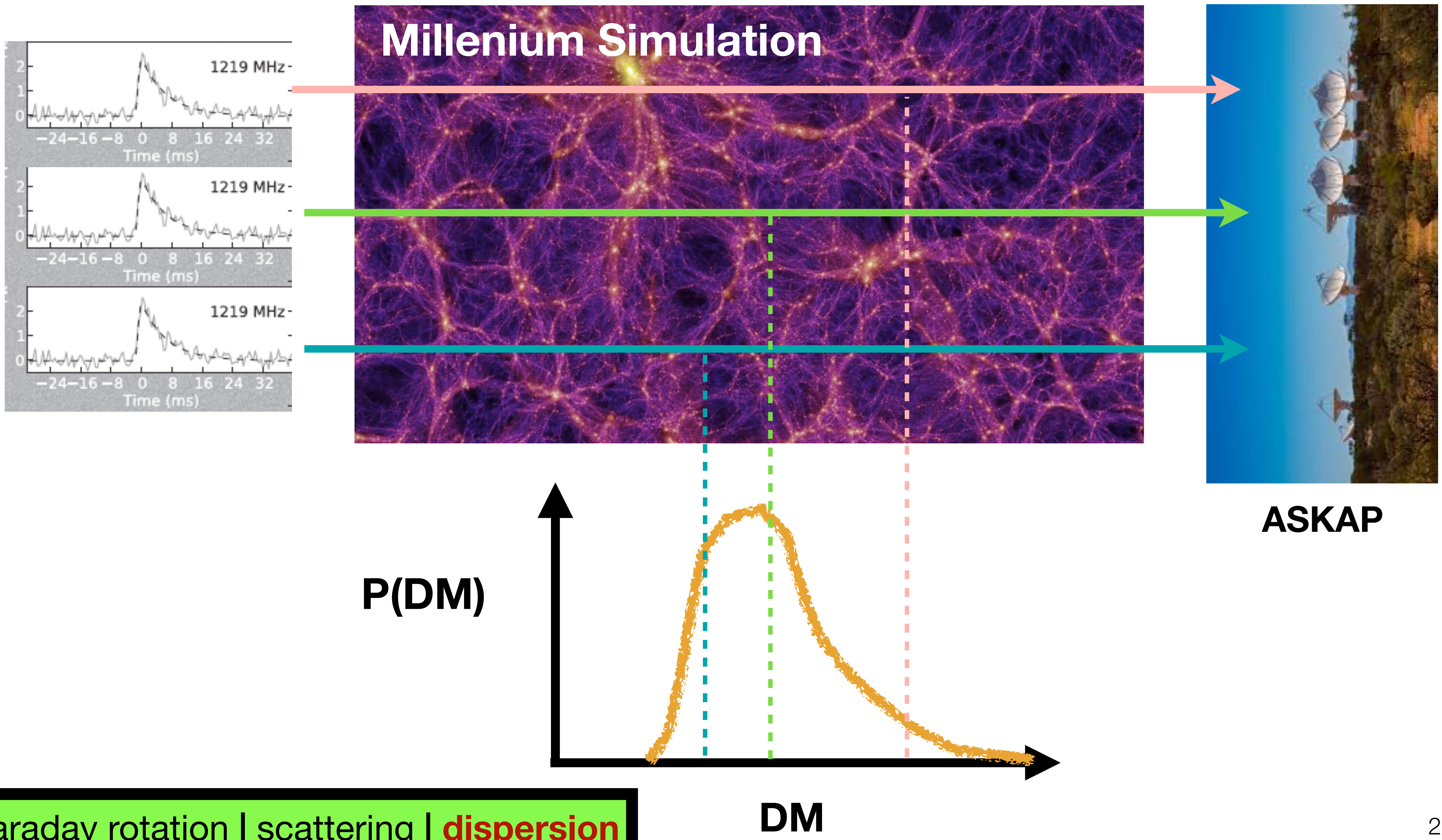
Vedantham & Phinney ’19 suggested there could be significant scattering by dense CGM cloudlets of radius R.

We derived refractive formula for scattering, finding $f_V < 3\text{x}10^{-2}$ $(R/1\text{pc})^{3/2}$ for $n_{cloud} = 0.1\text{cm}^{-3}$, with a weaker scaling in R below 0.01pc.

Prochaska, Macquart, MM et al 2019 *Science*

That was the warm up.
Now let’s get serious….

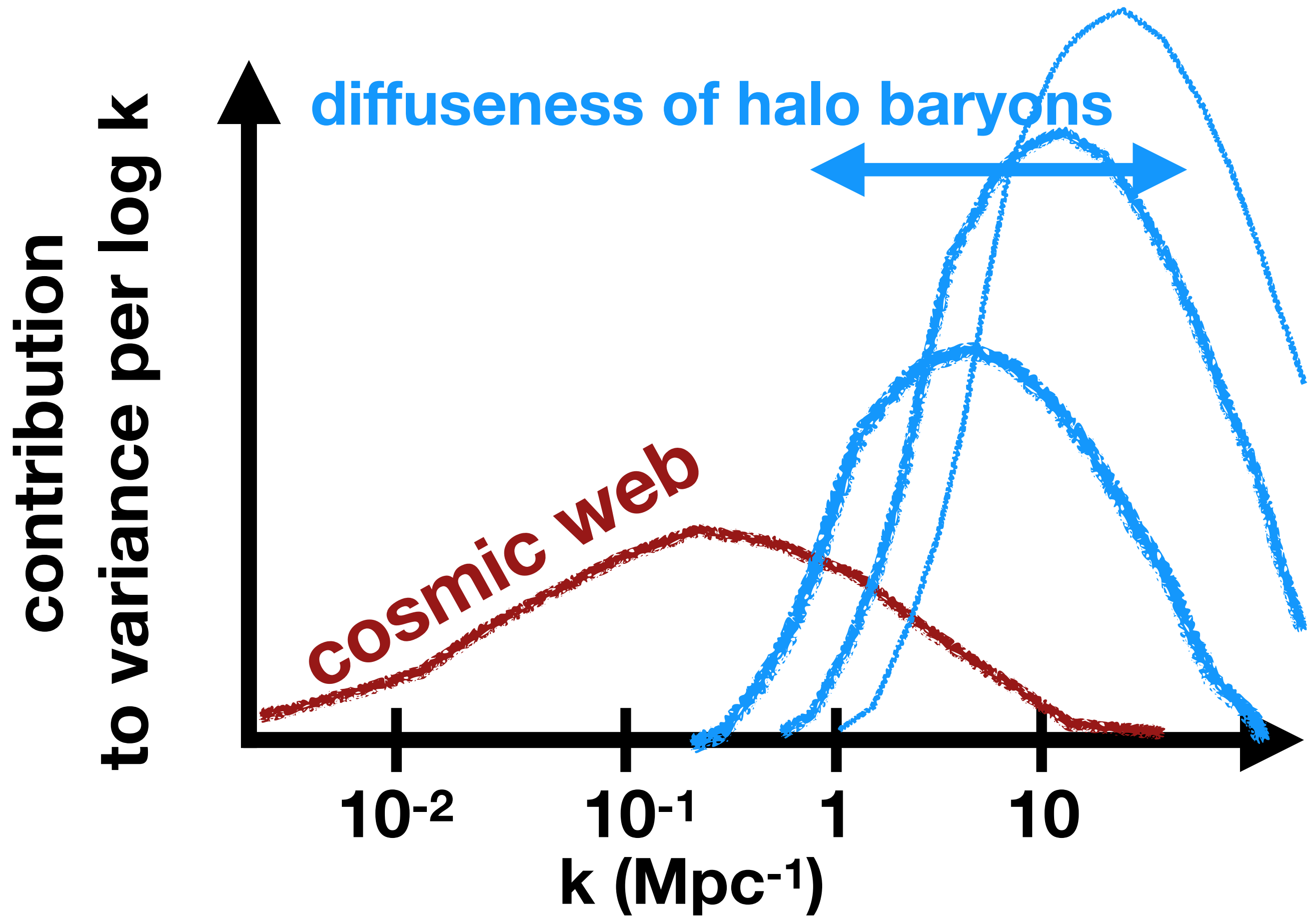
cosmic structure will drive scatter in the dispersion measures (DMs) to a given redshift



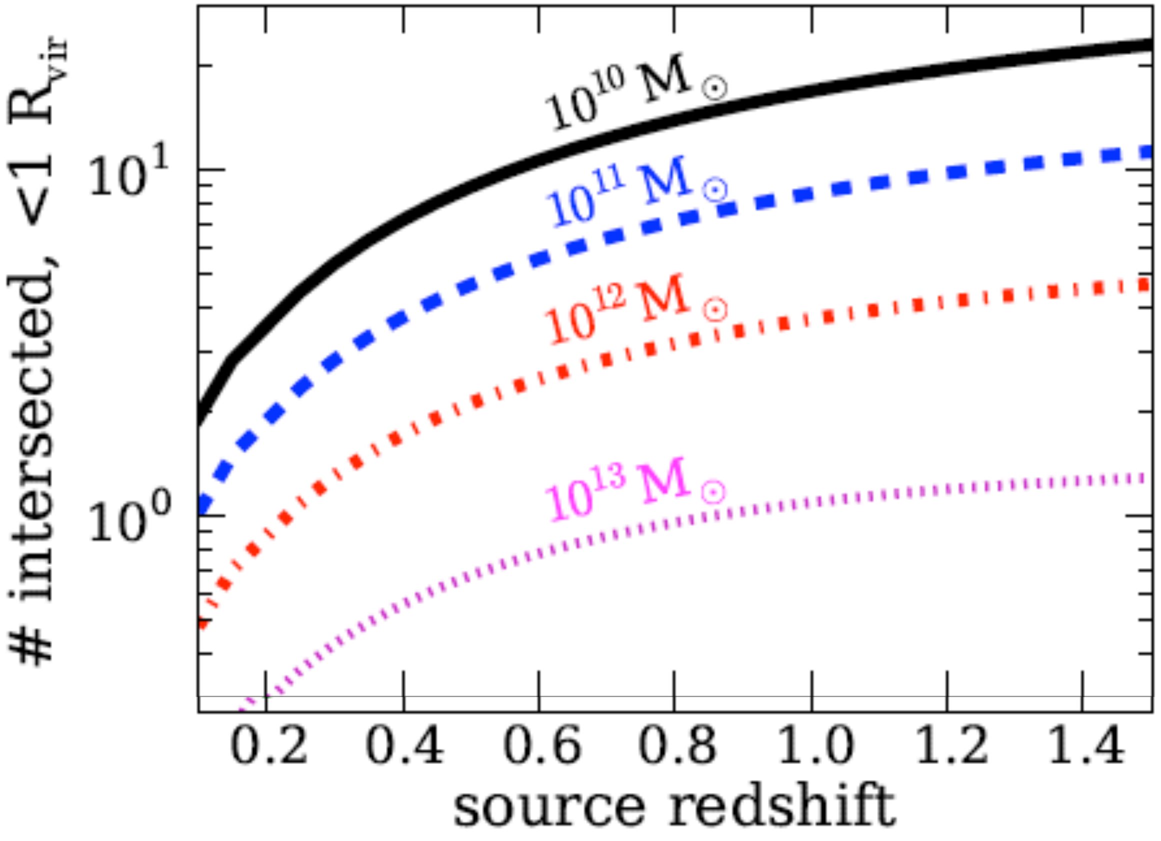
Faraday rotation | scattering | **dispersion**

This scatter is mostly driven by the number of dense regions (i.e. gaseous `halos') intersected

the scales that contribute to scatter

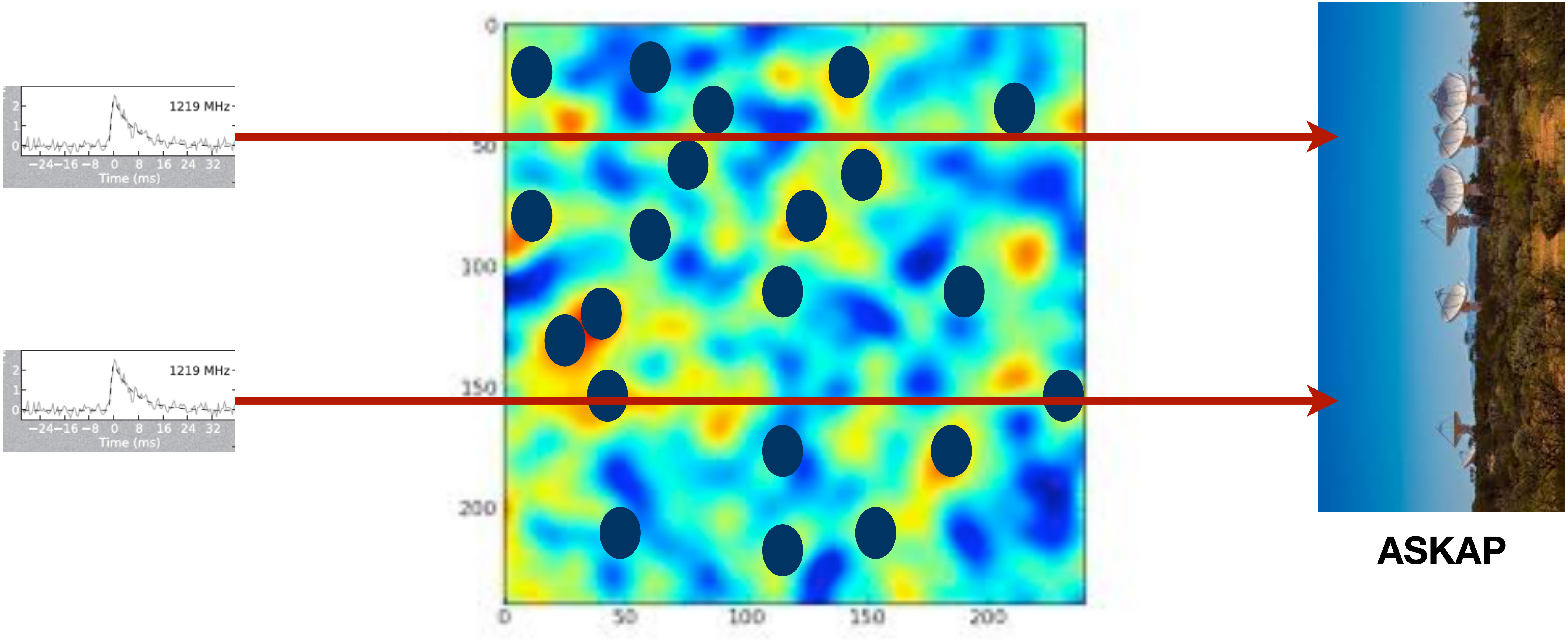


A sightline to z~1 intersects tens of galactic halos

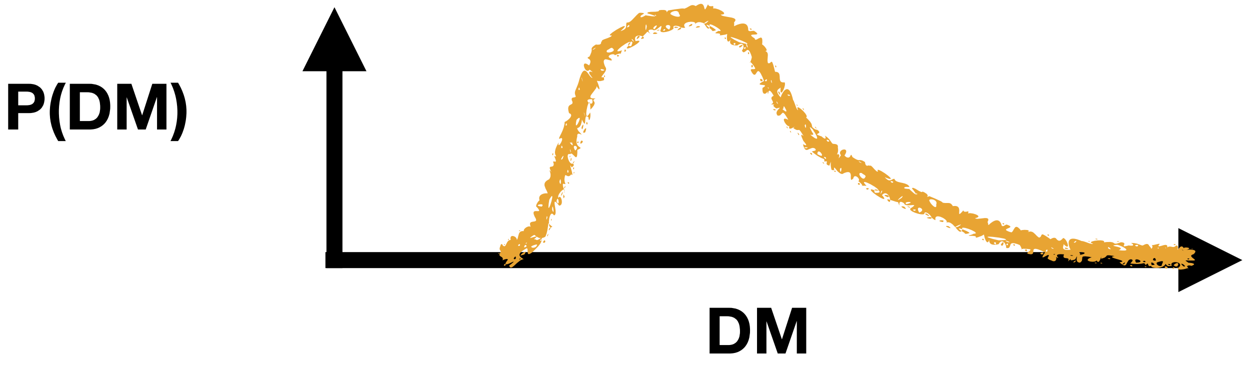


A second (generally smaller) contribution to scatter comes from how matter fluctuations on 10-150 Mpc scales.

How to think about FRB dispersion measures (DMs)

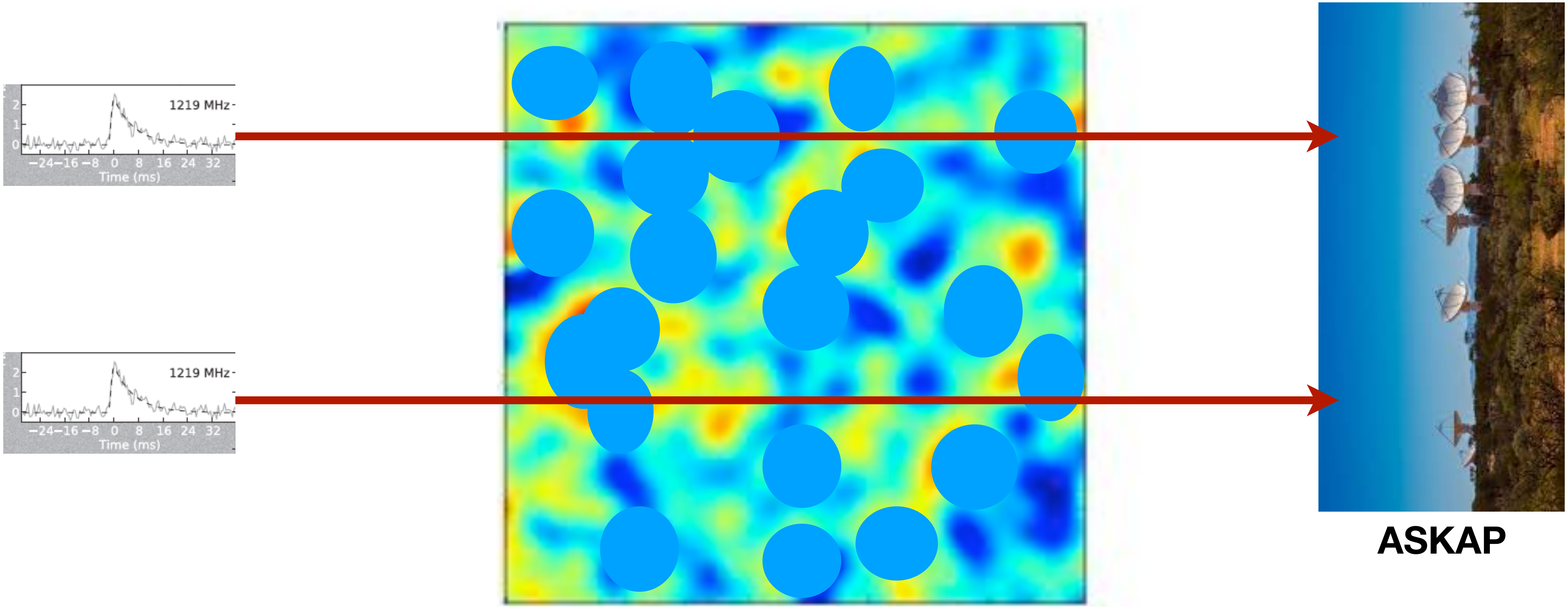


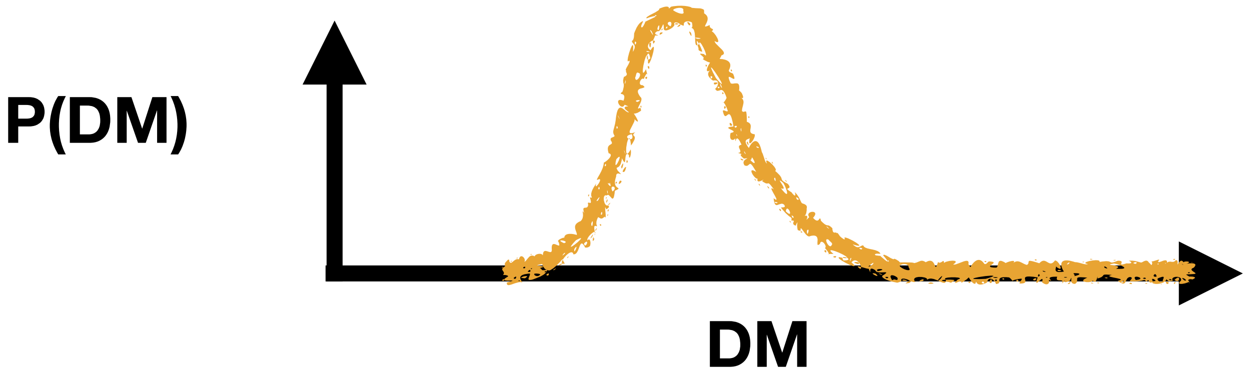
ASKAP



More compact gaseous halos, more sightline variance, more skewed PDF

How to think about FRB dispersion measures (DMs)





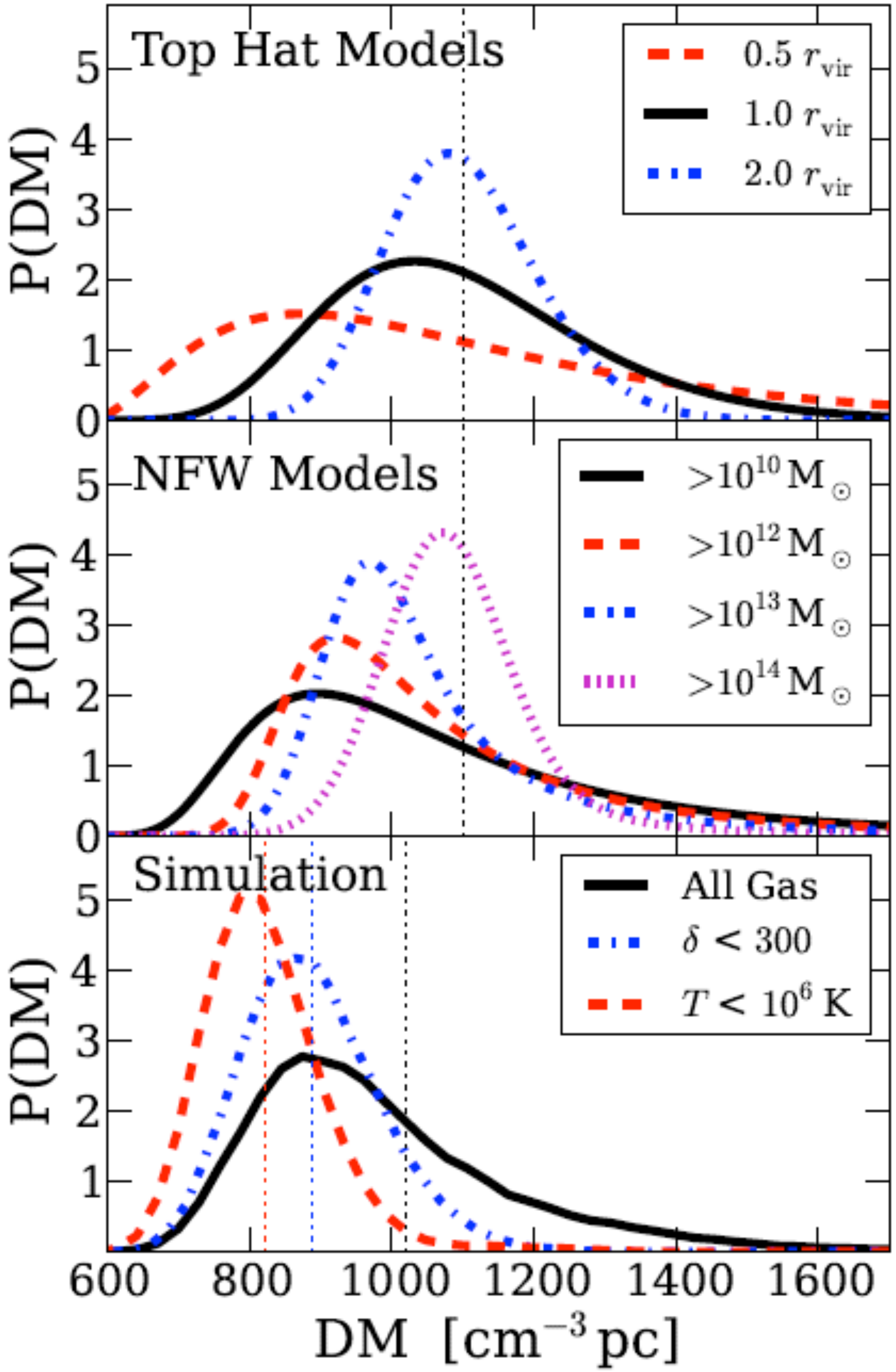
Puffier halos, less sightline variance, more Gaussian PDF

The PDF of DM(z)

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

Top two panels are toy models, but I think are reflective of uncertainties.

the PDF of DM to z=1



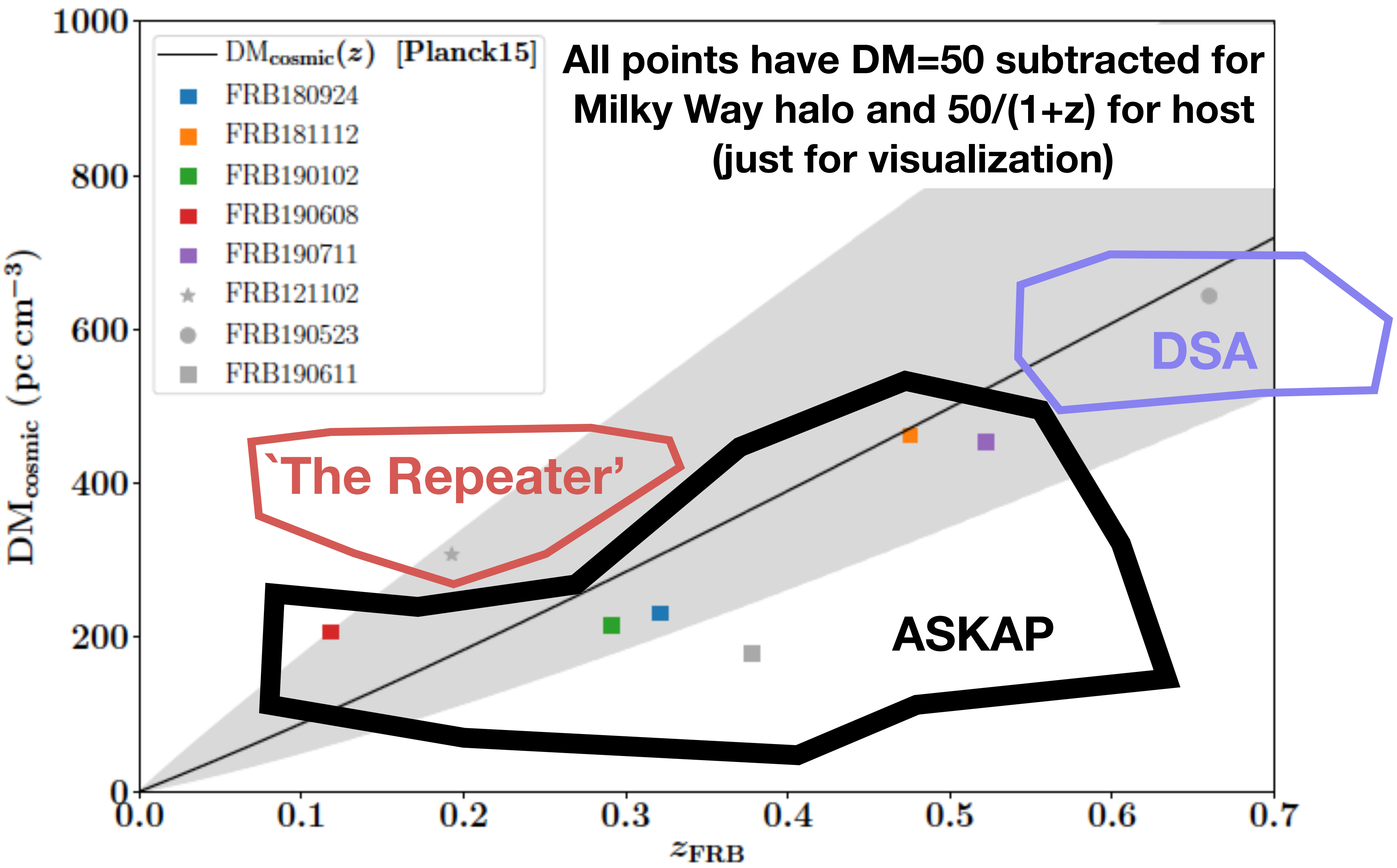
MM ’14

Kahn, MM ’20 for more physical models.

Faraday rotation | scattering | **dispersion**

Macquart, Prochaska, MM, ++ CRAFT
Nature

The Macquart Relation



All points have DM=50 subtracted for Milky Way halo and 50/(1+z) for host (just for visualization)

Following will use every FRB but the Repeater, which has an anomalously high rotation measure. The FRB19* ASKAP bursts had not been reported previously.

Grey region enclose 90% of values of middle-of-road diffuse gas model.

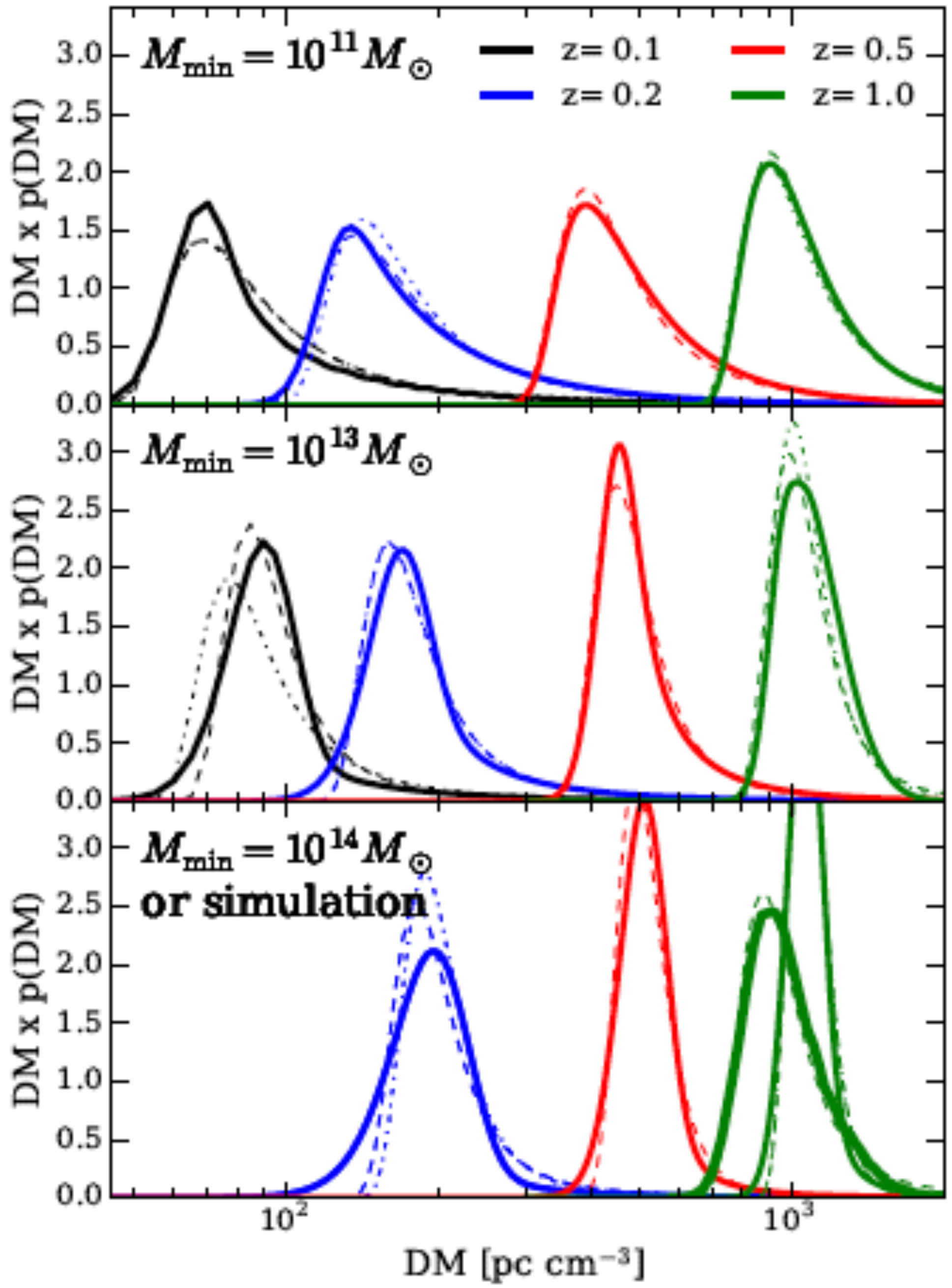
Faraday rotation | scattering | **dispersion**

analysis

- IGM/CGM model for DM contribution assumes the MHR00 PDF where width scales as F $z^{1/2}$
- the host galaxy DM contribution is assumed to be drawn from a lognormal distribution parametrized by mean and st. dev.

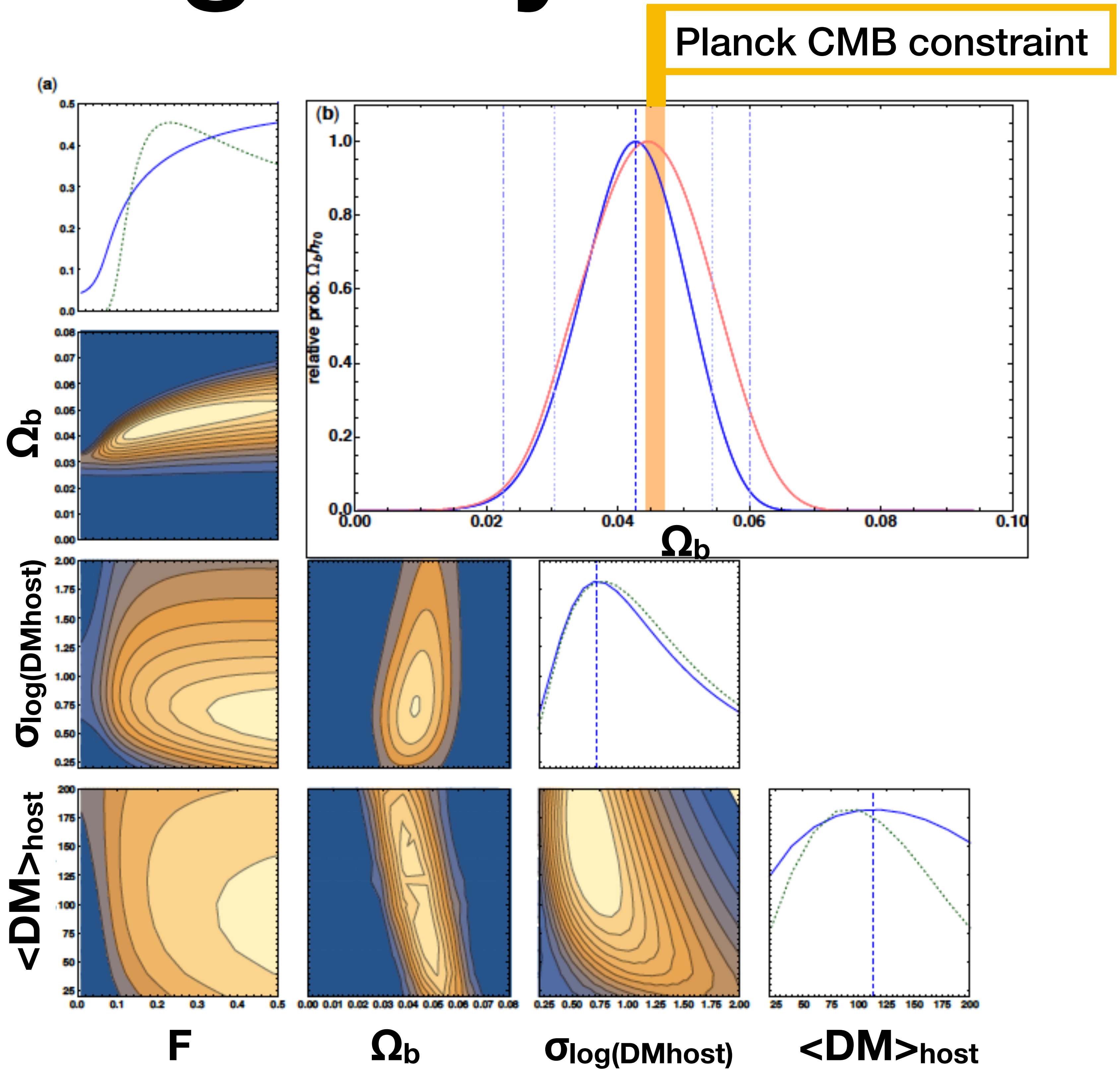
MHR00 == Miralda-Escude, Haehnelt & Rees 2000

Demonstration that our 1 parameter MHR00 PDF (dashed) matches more complex models for cosmic dispersion in electron column (solid).



$M_{\rm min}$ is halo mass below which it is evacuated of gas.

Missing Baryon Problem

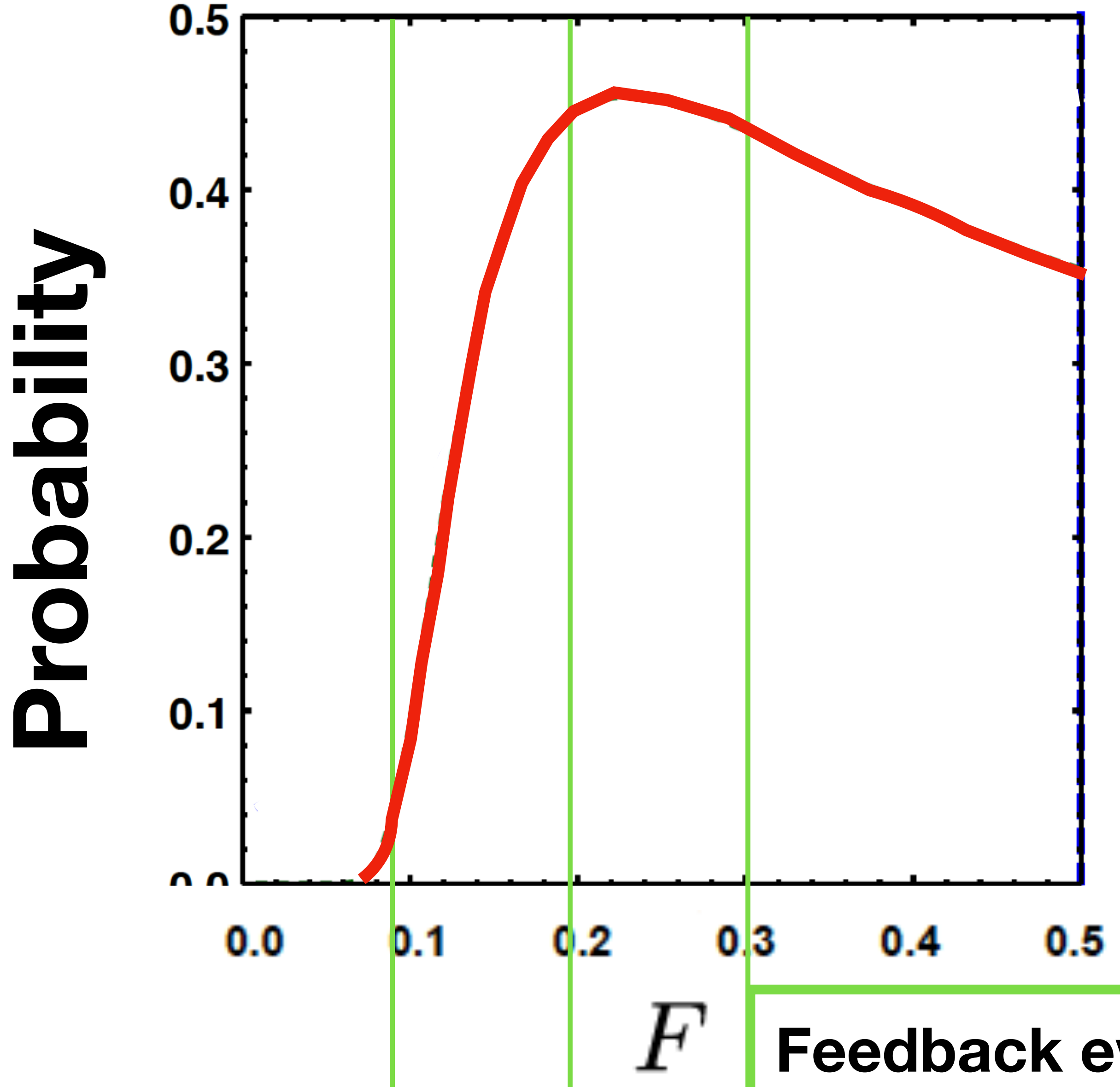


Planck CMB constraint

Faraday rotation | scattering | **dispersion**

Feedback

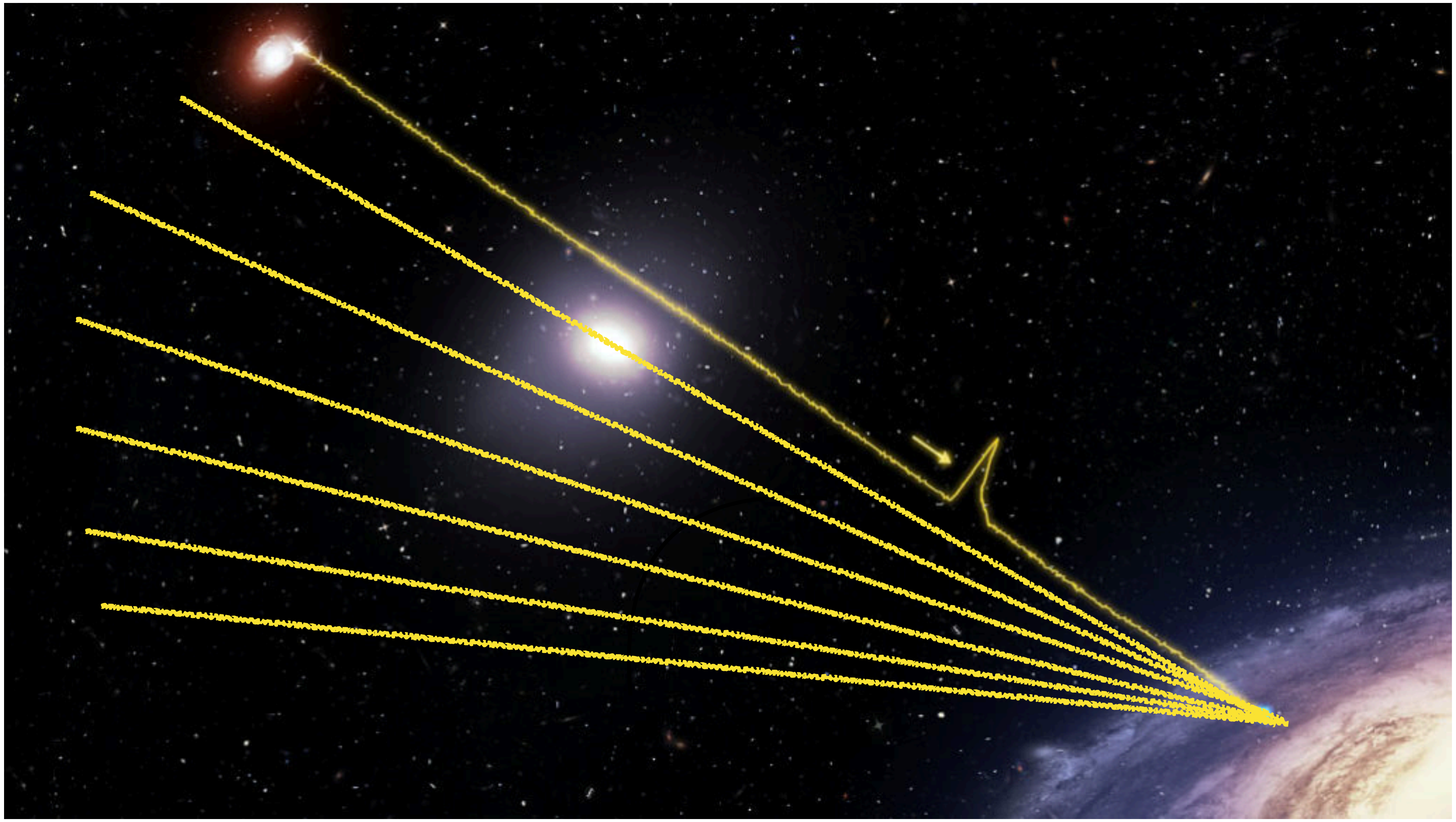
(where the baryons lie)



Feedback evacuates <10^{11} M$_\odot$

Feedback evacuates <10^{12} M$_\odot$

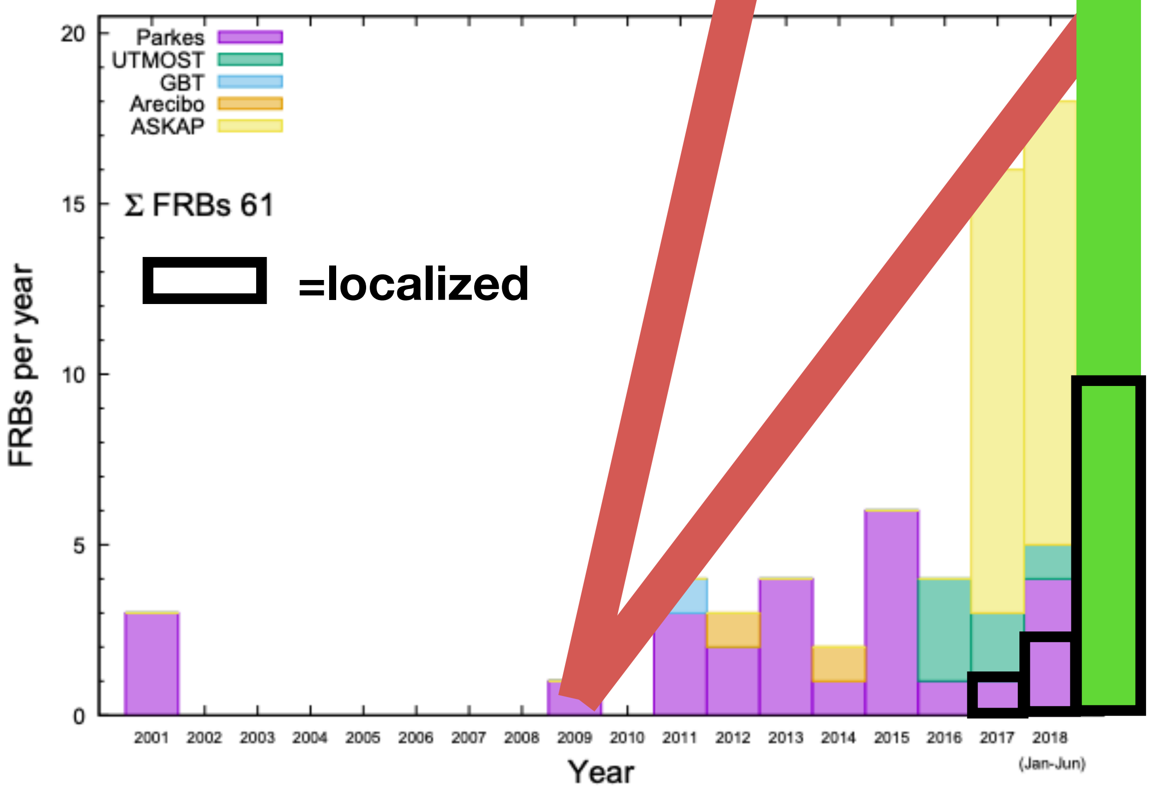
Feedback evacuates <10^{14} M$_\odot$



Going Forward

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

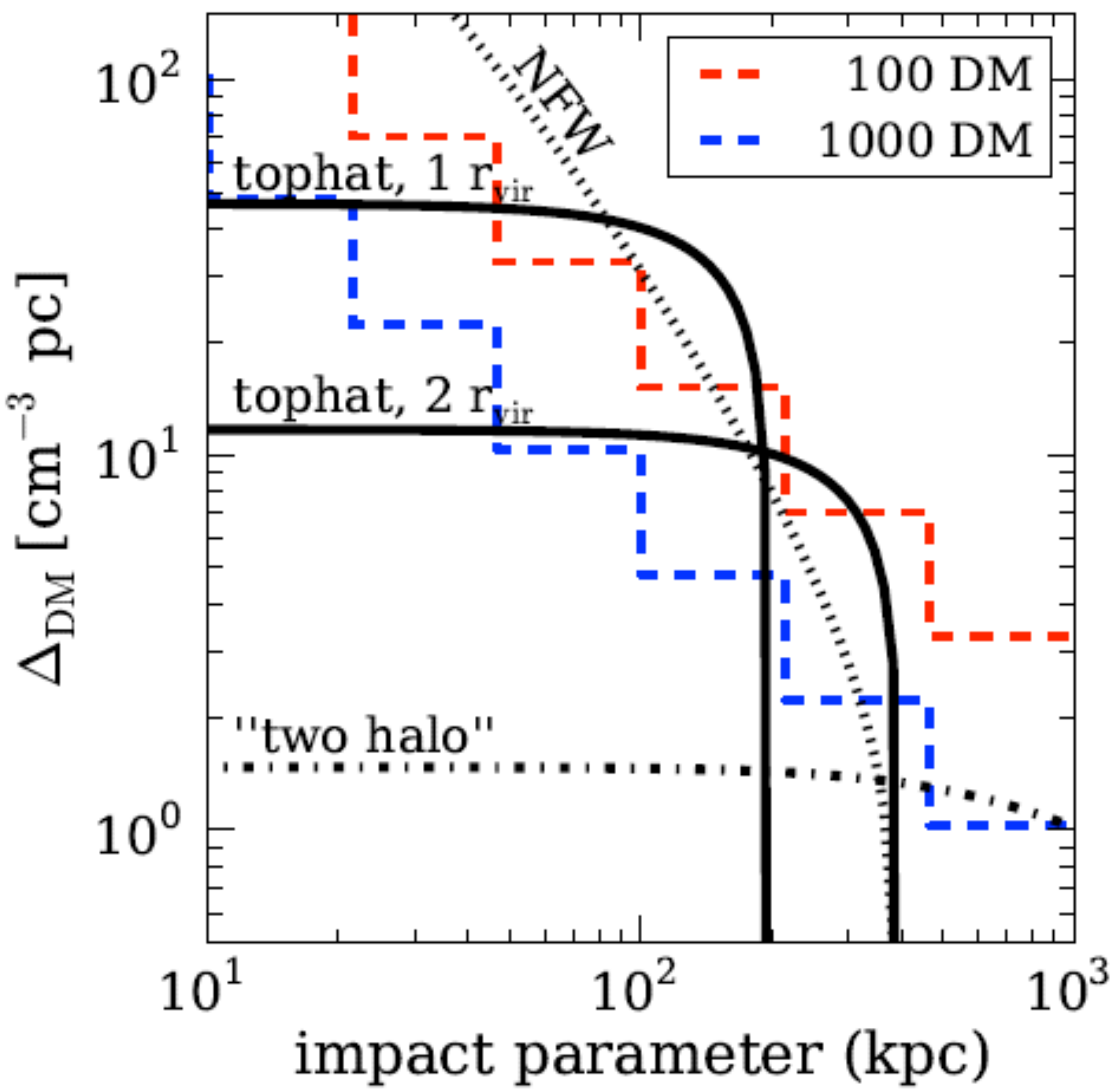
Petroff++19



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

Stacking with be the way to go once there are >100 localizations

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



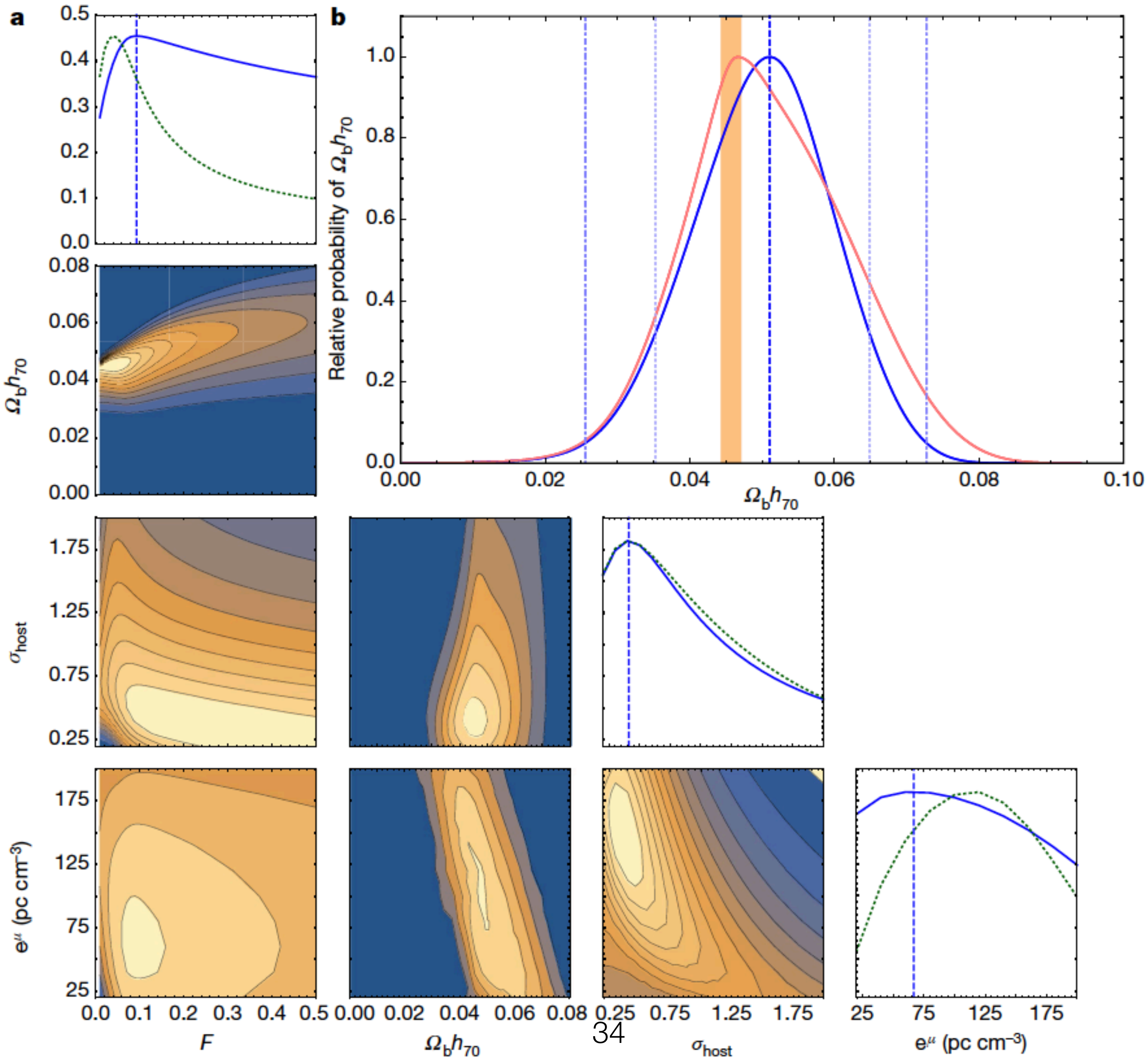
MM'14

There is also interesting M31 and Milky Way science: Prochaska & Zheng '19, Keating & Pen '20; Platts++'20). And IGM `tomography' for lowest redshift FRBs (Simba, Burchett, Prochaska++'20)

Conclusions

- FRB181112: first diffuse baryon science with FRBs
  - sub-equipartition $B_{||}$ 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 seven bursts, we measure $\Omega_b = 0.05 \pm 0.02$ 95%C.L. and are starting to constrain the scatter. First measurement of **Macquart relation**.
  - suggests host contribution to DM is typically low (~100 pc cm^{-3})
  - constraints on CGM density going to get interesting
- constraints on distribution of baryons around halos relevant for the intergalactic medium, for galaxy formation and for precision cosmology

Gold Sample

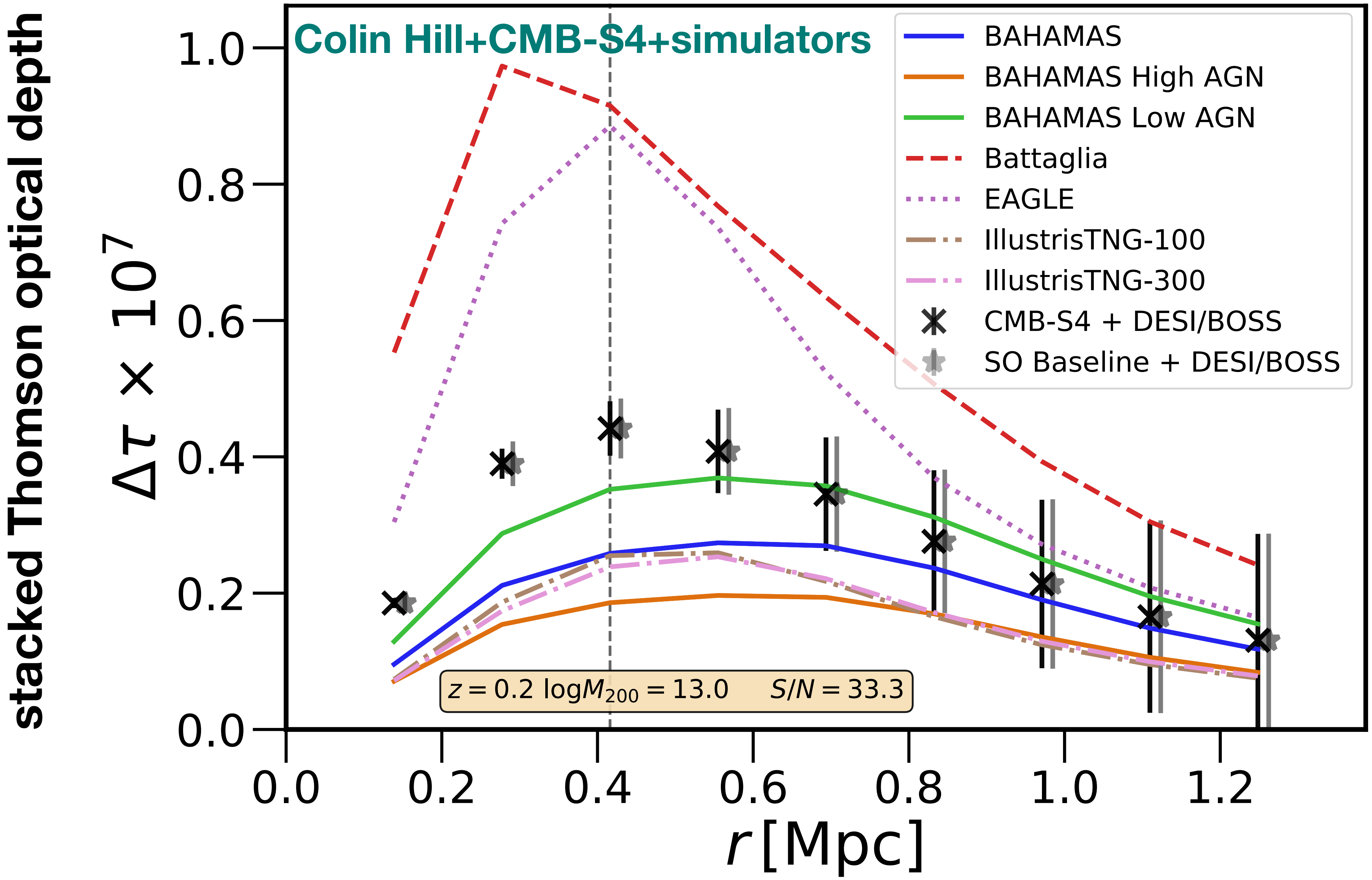


a
b
0.5
0.4
0.3
0.2
0.1
0.0
0.08
0.06
0.04
0.02
0.00
$\Omega_b h_{70}$
Relative probability of $\Omega_b h_{70}$
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.02
0.04
0.06
0.08
0.10
$\Omega_b h_{70}$
1.75
1.25
0.75
0.25
σ_{host}
175
125
75
25
e^{μ} (pc cm^{-3})
0.0 0.1 0.2 0.3 0.4 0.5
F
0.00 0.02 0.04 0.06 0.08
$\Omega_b h_{70}$
0.25 0.75 1.25 1.75
σ_{host}
25 75 125 175
e^{μ} (pc cm^{-3})

Other way of moving this science forward: CMB

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} M_{sun} Milky Way mass

gas around 10^{13} M_{sun} halos in simulations



Scattering of mist of clouds

I 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:

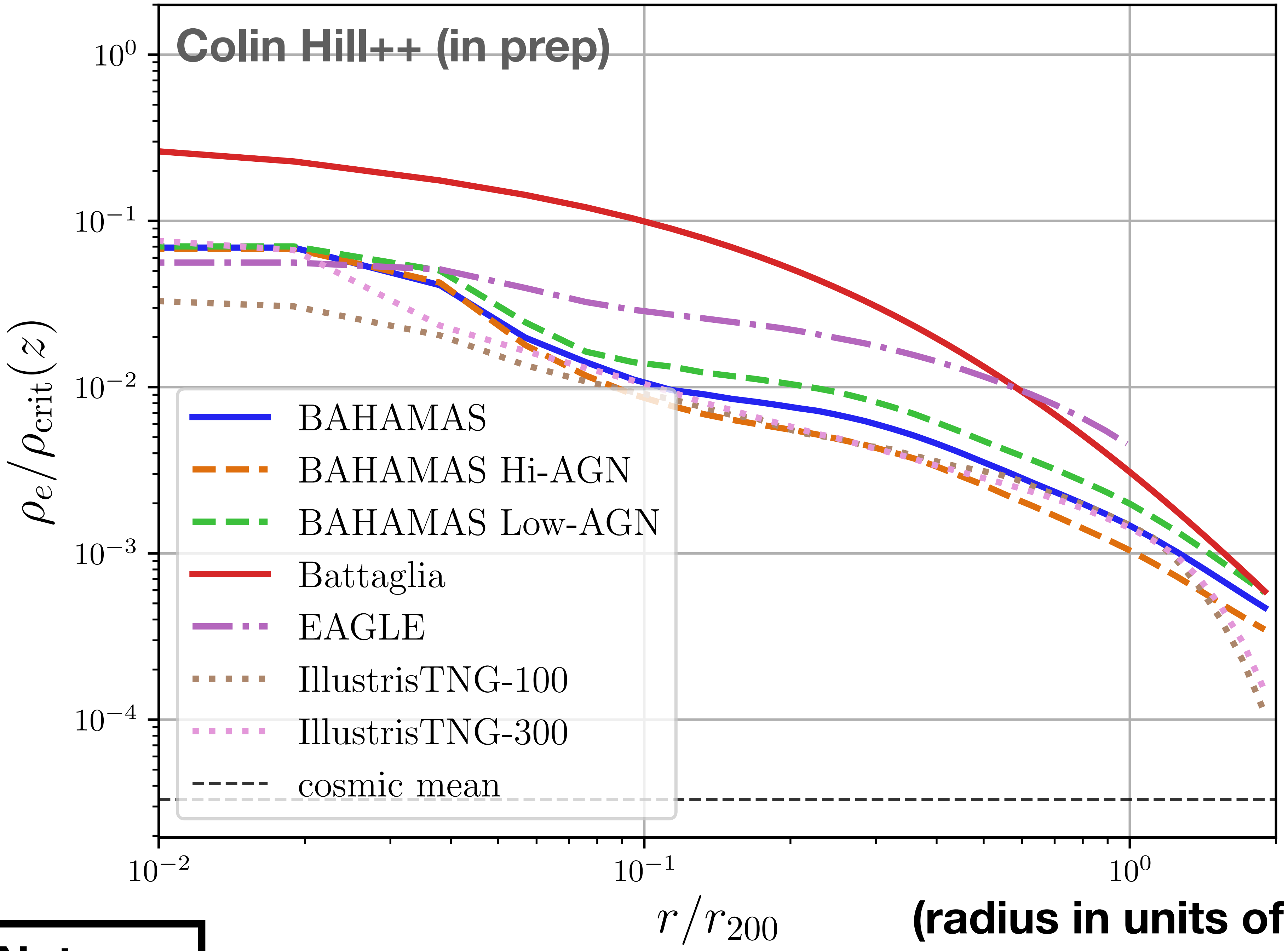
$$\begin{aligned}
&\left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}}\right)\left(\frac{\Delta L}{50\mathrm{kpc}}\frac{f_V}{10^{-3}}\frac{0.1\mathrm{pc}}{R}\right)^{1/2} < 0.2\left(\frac{\tau_{\mathrm{scatt}}}{40\mu s}\right)^{1/2} \qquad \text{if} \qquad R \lesssim 0.011\mathrm{pc}\left(\frac{\tau_{\mathrm{scatt}}}{40\mu s}\right)^{1/2};\\
&\left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}}\right)\left(\frac{\Delta L}{50\mathrm{kpc}}\frac{f_V}{10^{-3}}\right)^{1/2}\left(\frac{0.1\mathrm{pc}}{R}\right)^{3/2} < 1.6 \quad \text{otherwise,}
\end{aligned} \tag{S25}$$

Data rules out mist of 0.1 parsec clouds with a volume filling fraction of 10^{-3}

galaxy formation models do not answer this yet

Modeling stellar and AGN feedback is complex.

Gas profile around z=0.2, 10^{13} M_{sun} halos



(radius in units of virial radius)

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!

Simulations make wildly different predictions!!!