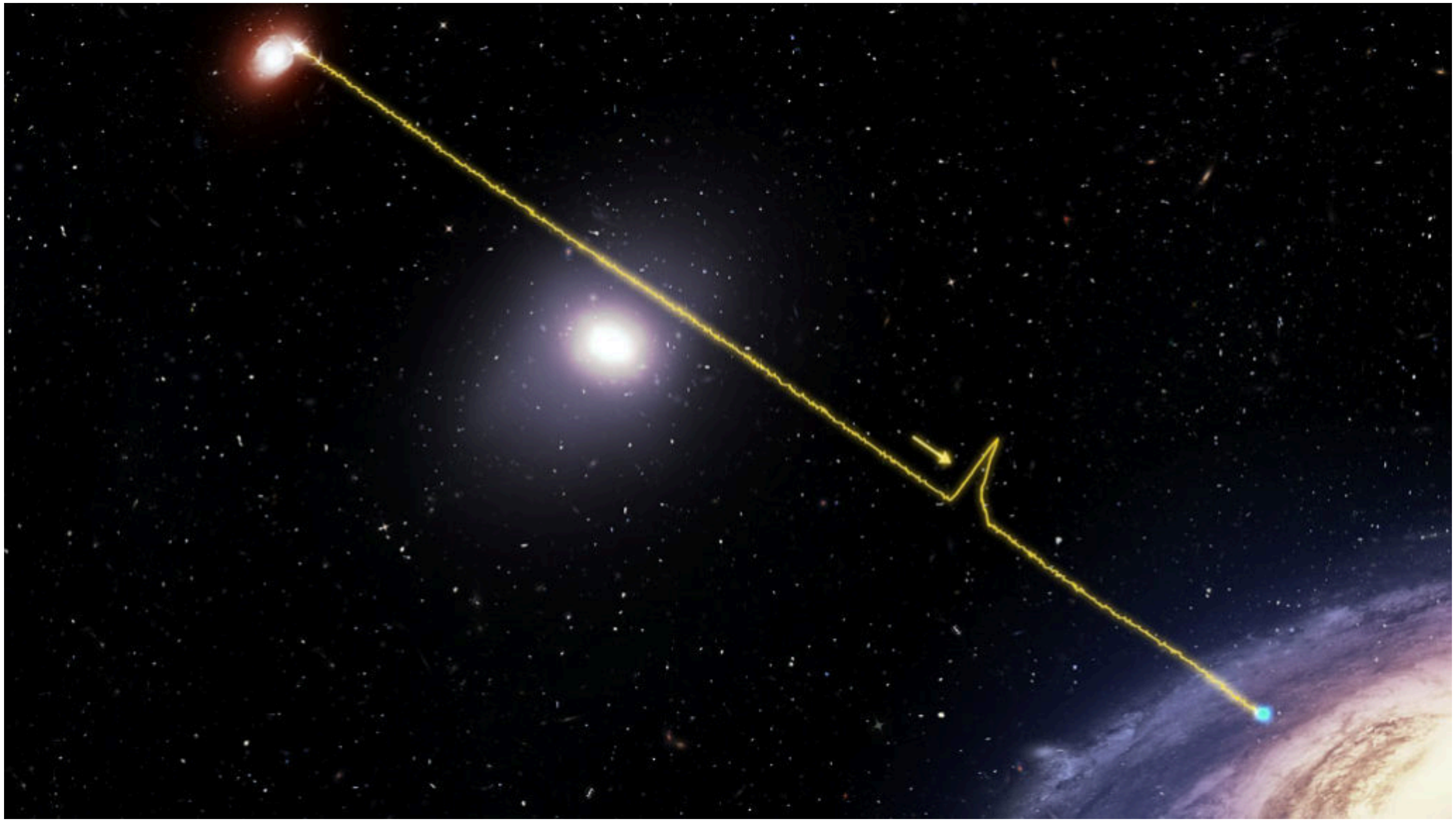
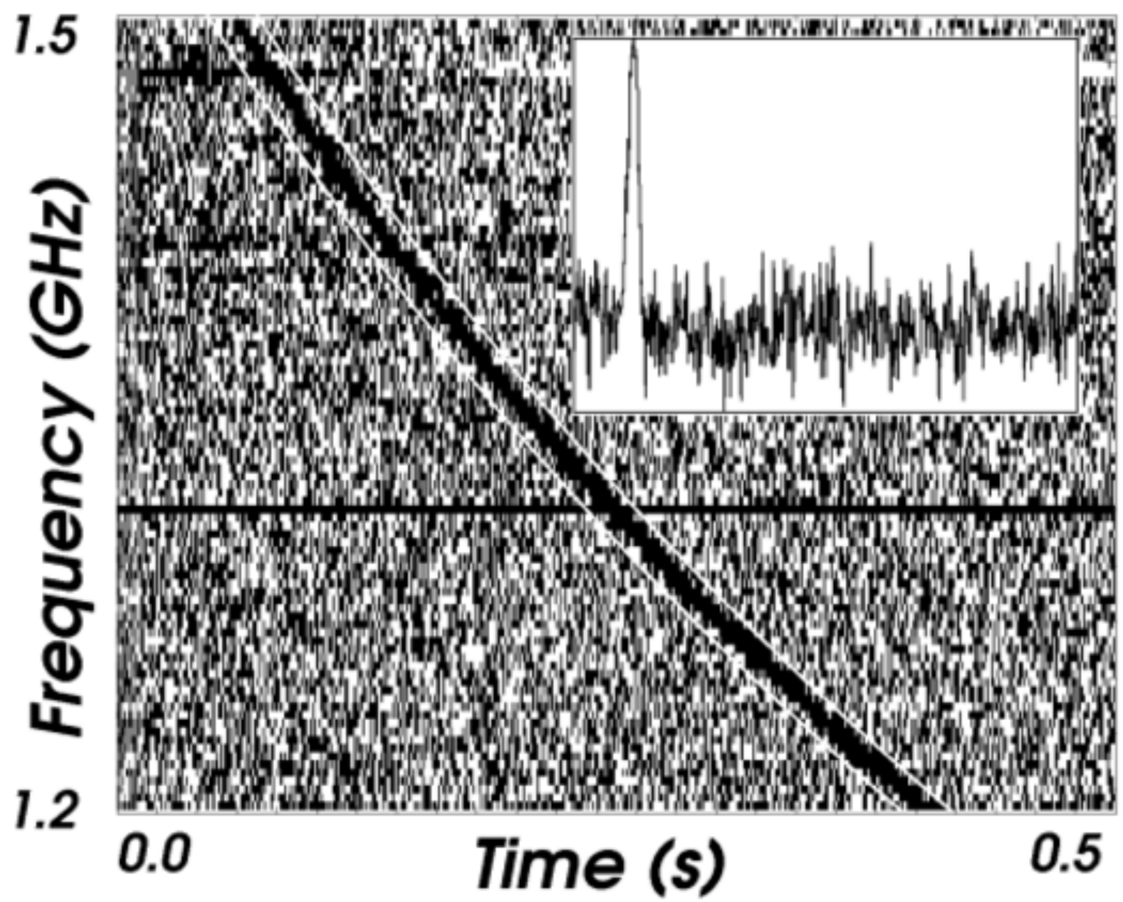


Welcome to the era of FRB "cosmology"!

Matt McQuinn
University of Washington

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 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

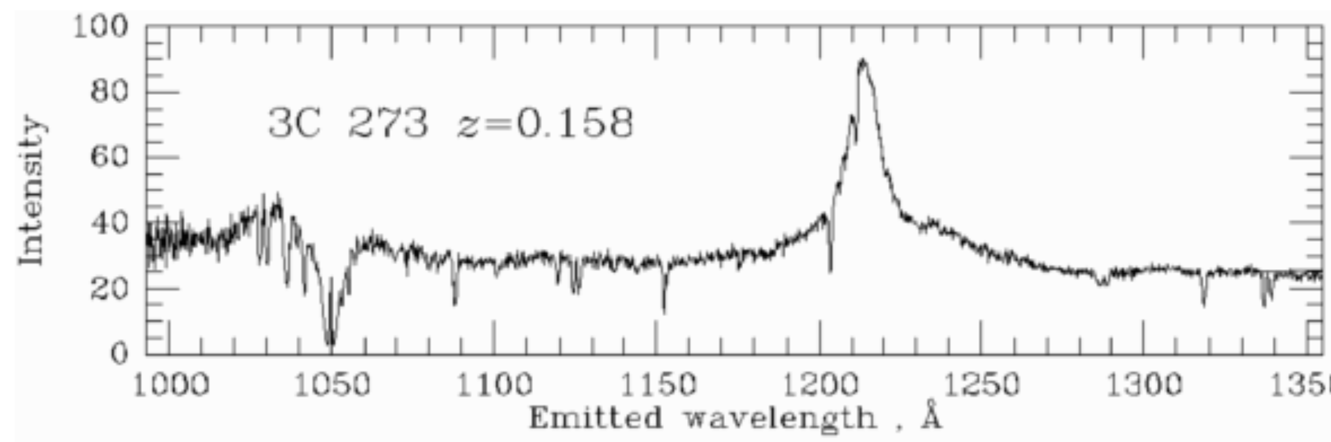
This question is largely immaterial to the science applications in this talk.

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

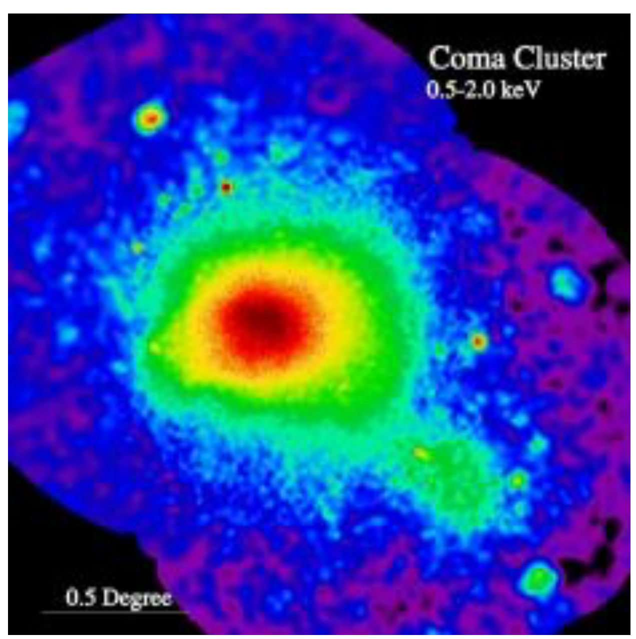
Context: The baryons in the Universe

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

~5%



Everything else?

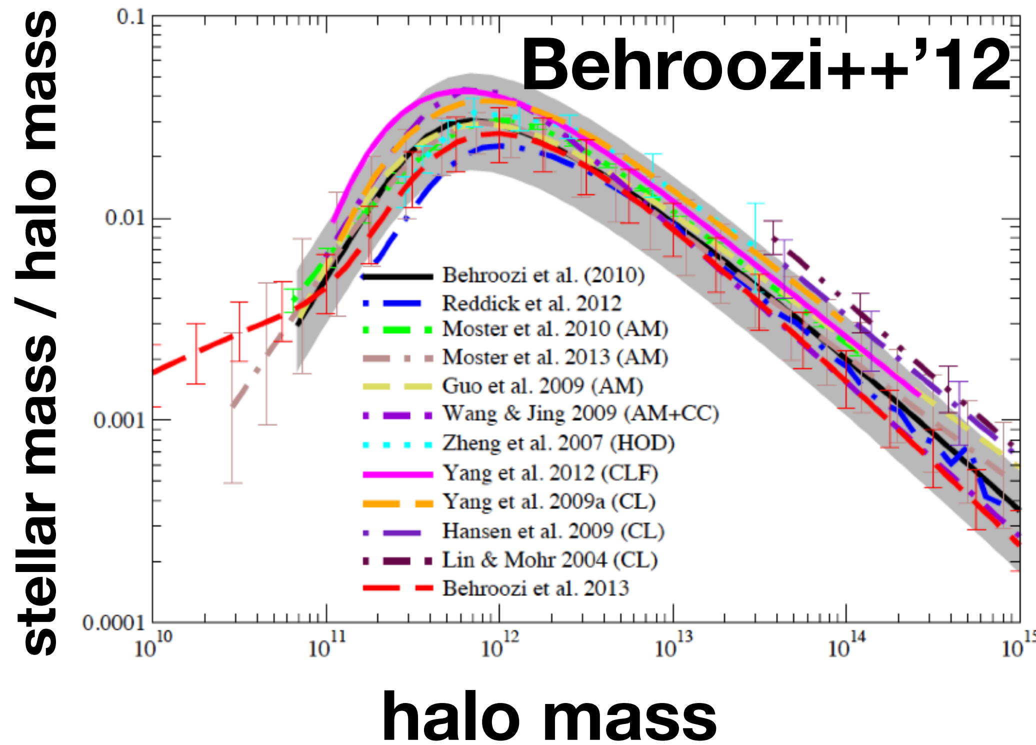


~5%

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

e.g. Fukugita & Peebles ‘04

We do not know how gas is distributed around $<10^{14}$ M_{sun} halos



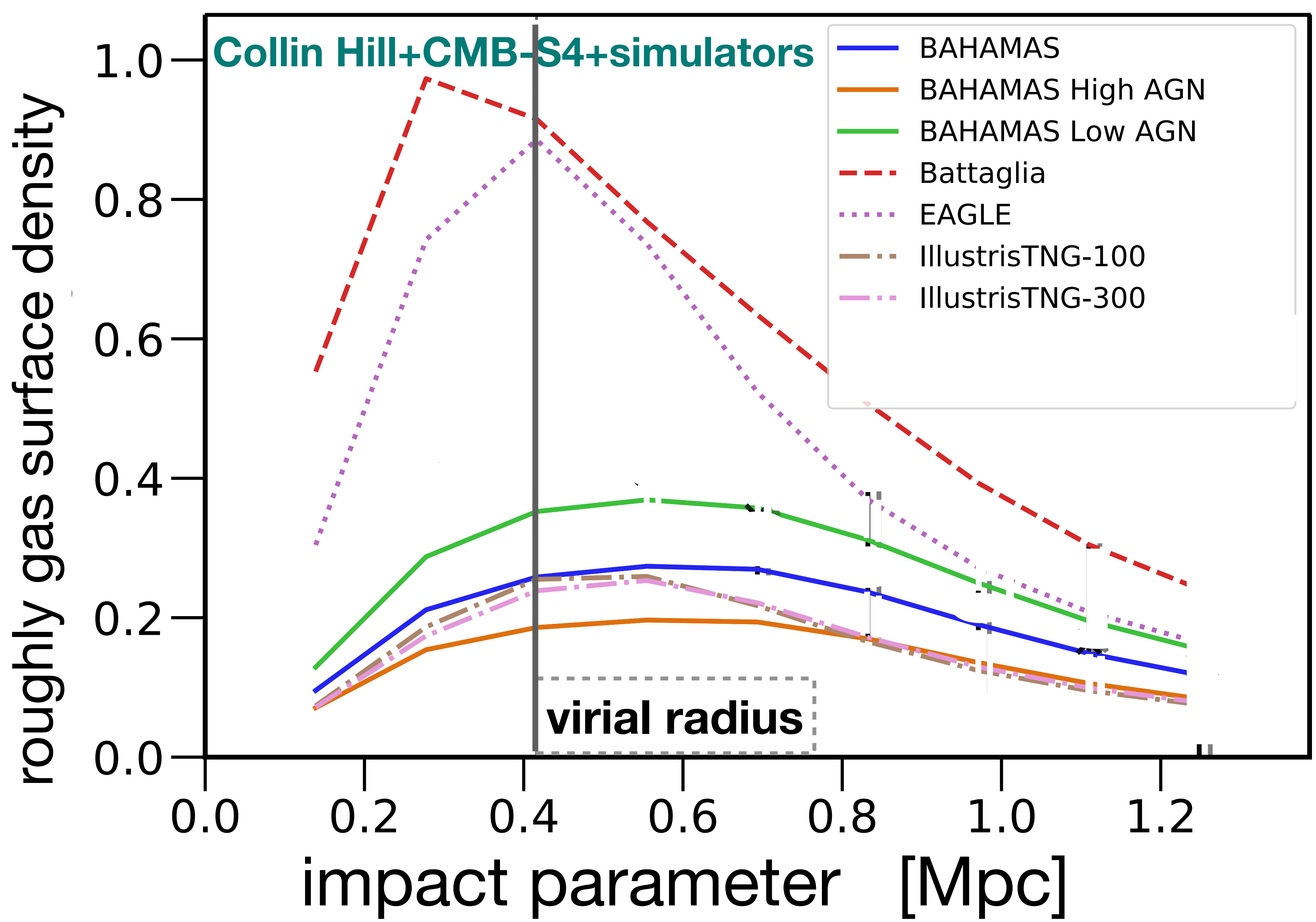
Plot illustrates inefficiency of galaxy formation with halo mass

- ~50% of the dark matter presently resides in $>10^{10} M_{sun}$ halos
- 10^{10-13} M_{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_{sun} halos



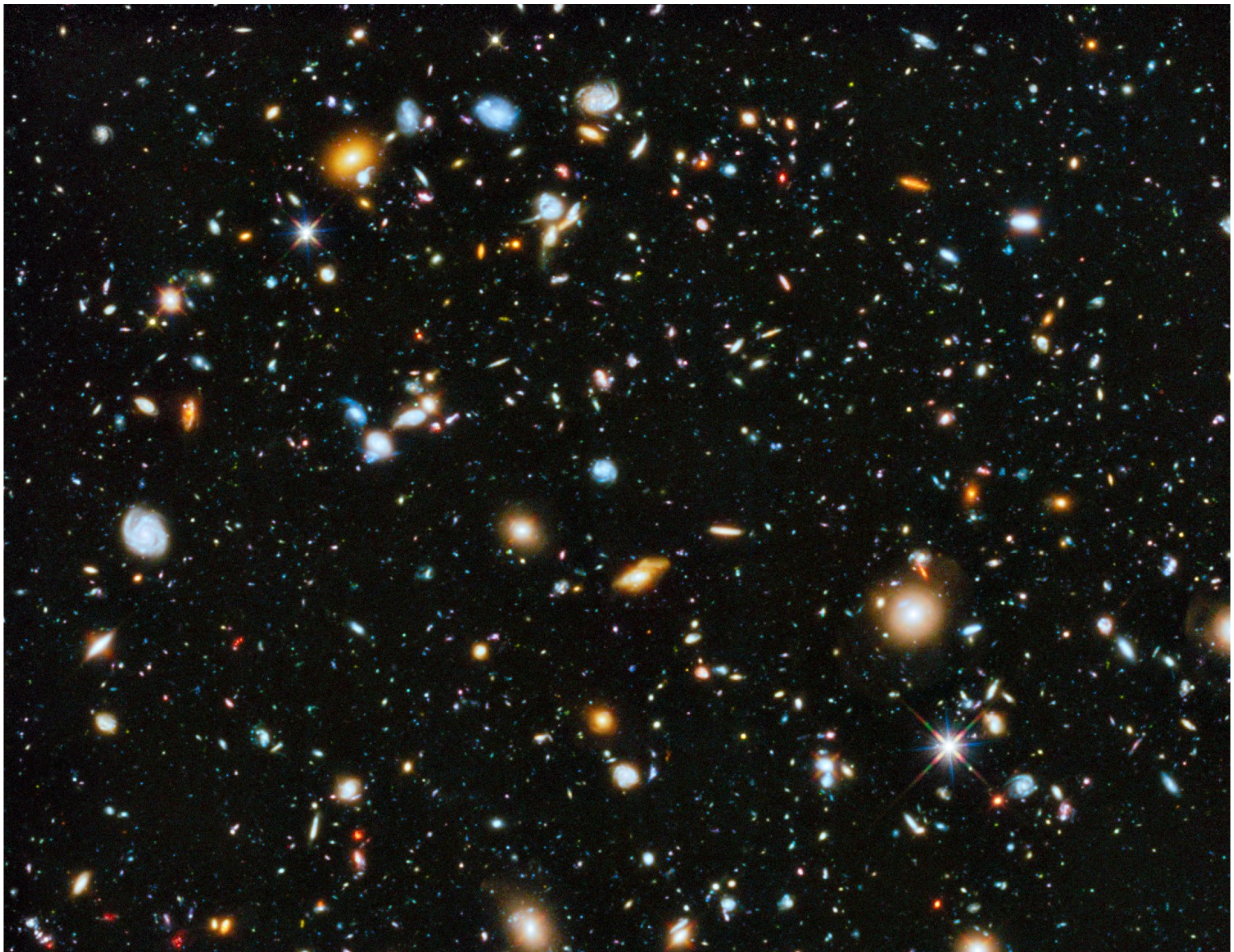
See Prochaska & Yong Zheng '19 for nice summary of what is known regarding MW-like halos, where models may span even larger range

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

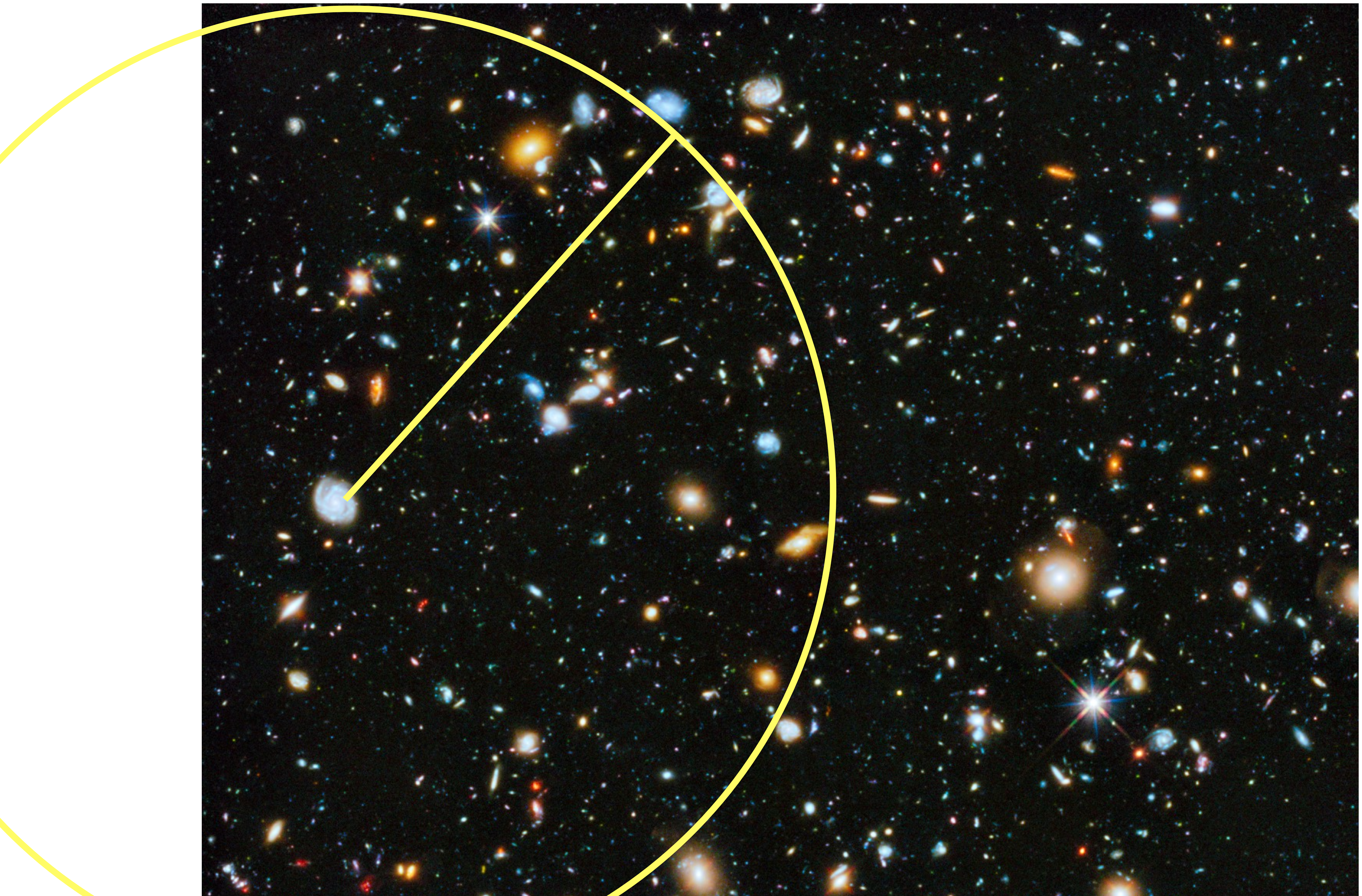
Simulations make wildly different predictions!!!

Now bring in FRBs…

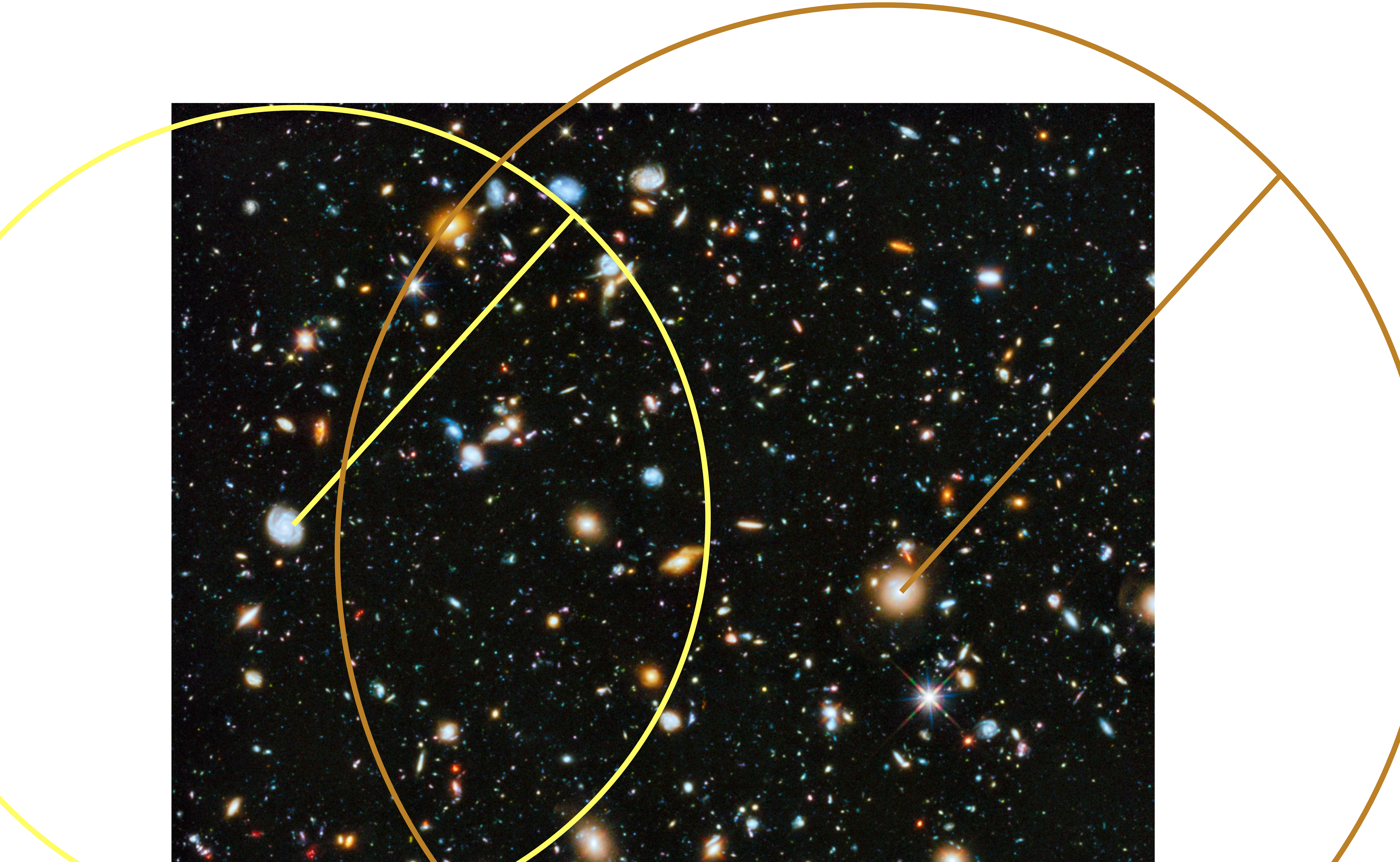
An FRB sightline goes through many dark matter halos and thus probes their gas



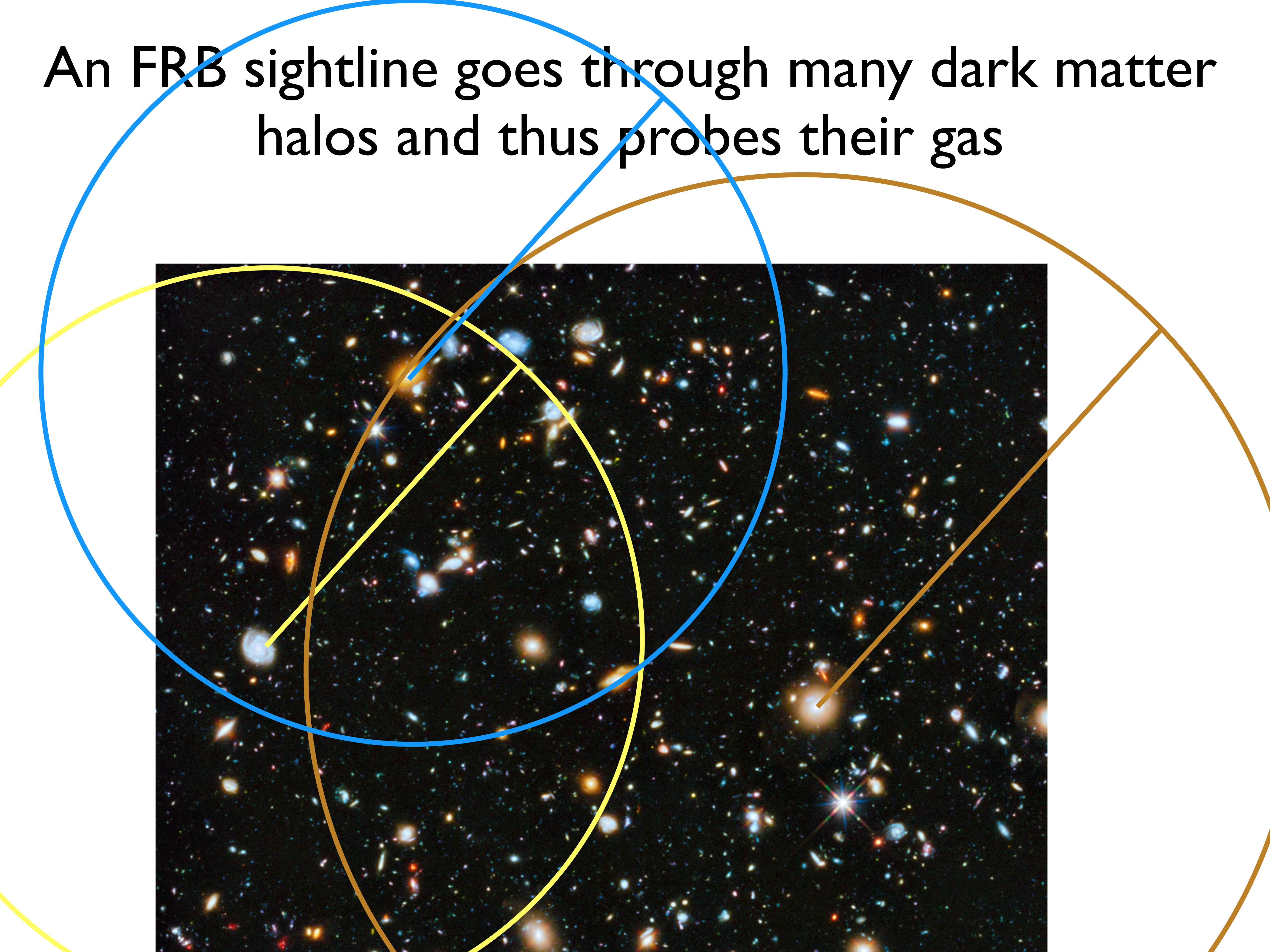
An FRB sightline goes through many dark matter halos and thus probes their gas



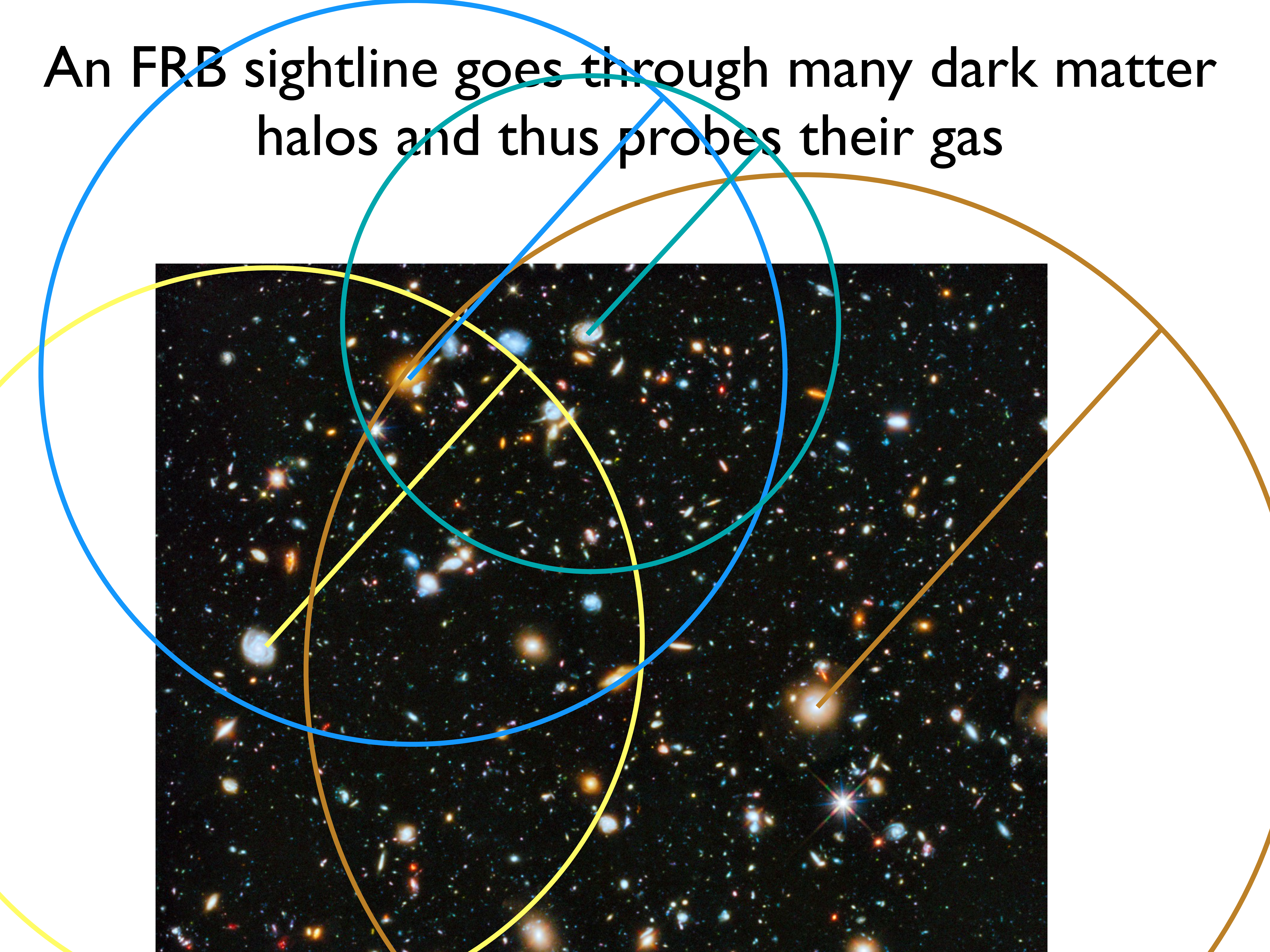
An FRB sightline goes through many dark matter halos and thus probes their gas



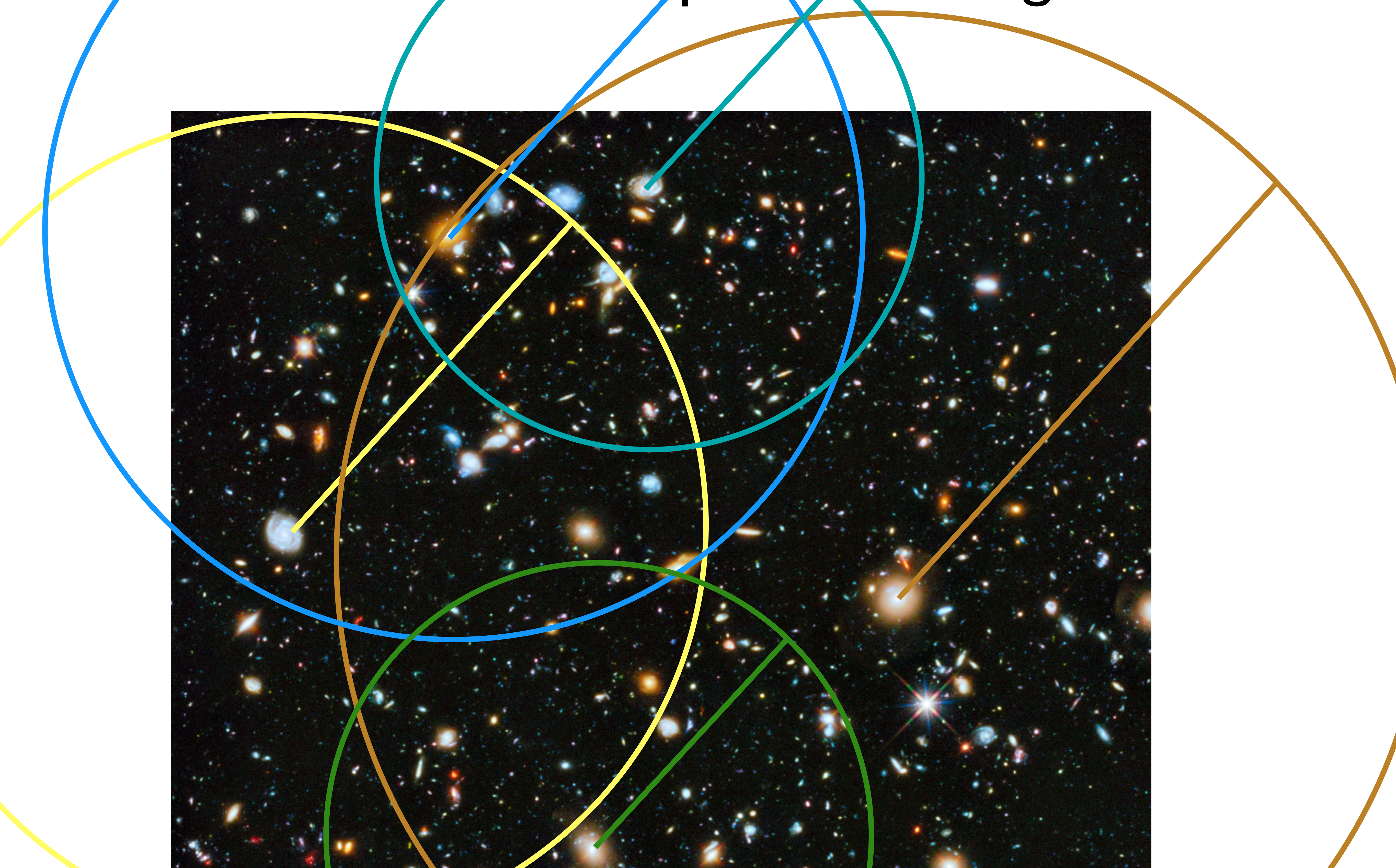
An FRB sightline goes through many dark matter halos and thus probes their gas



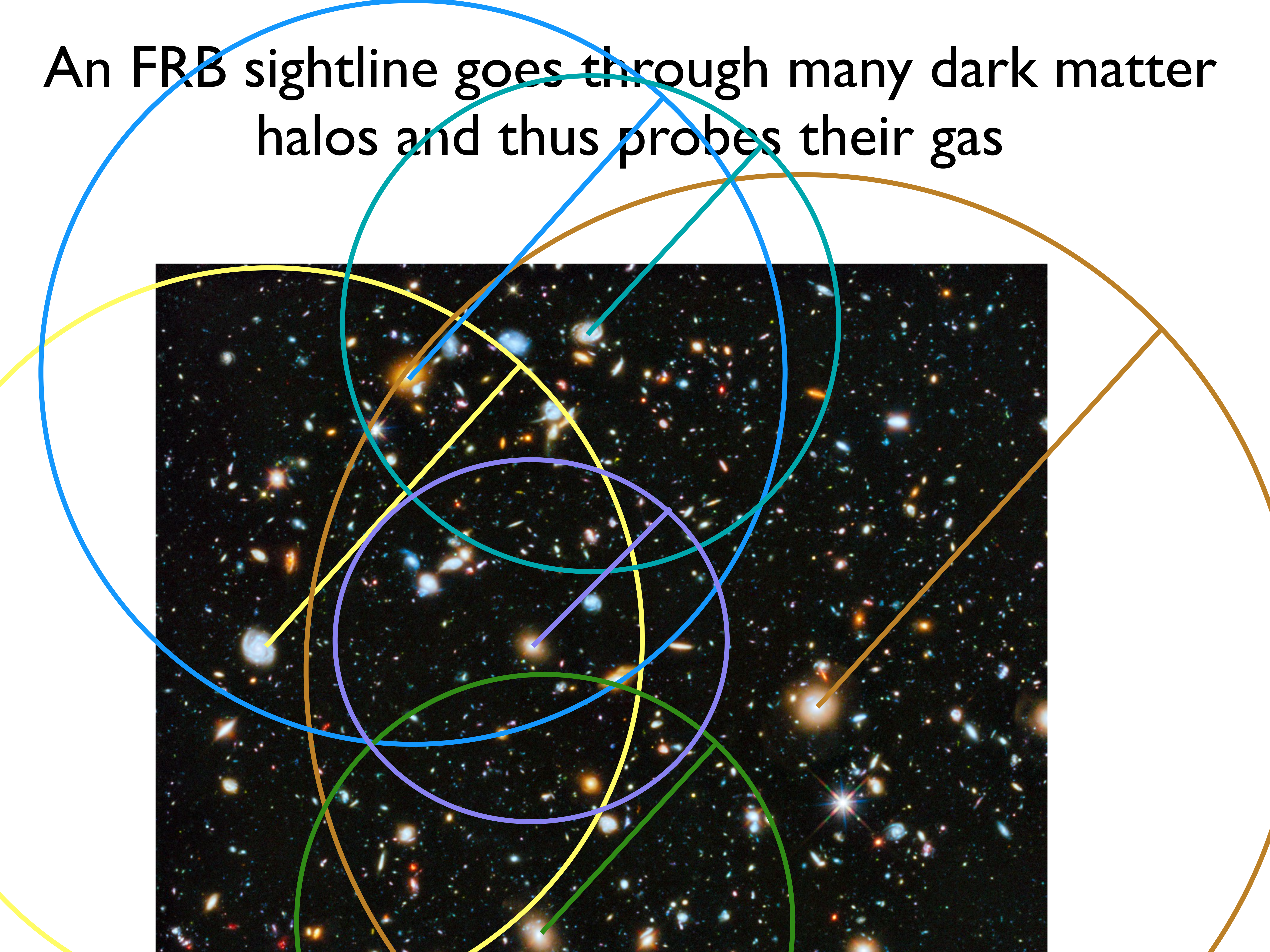
An FRB sightline goes through many dark matter halos and thus probes their gas



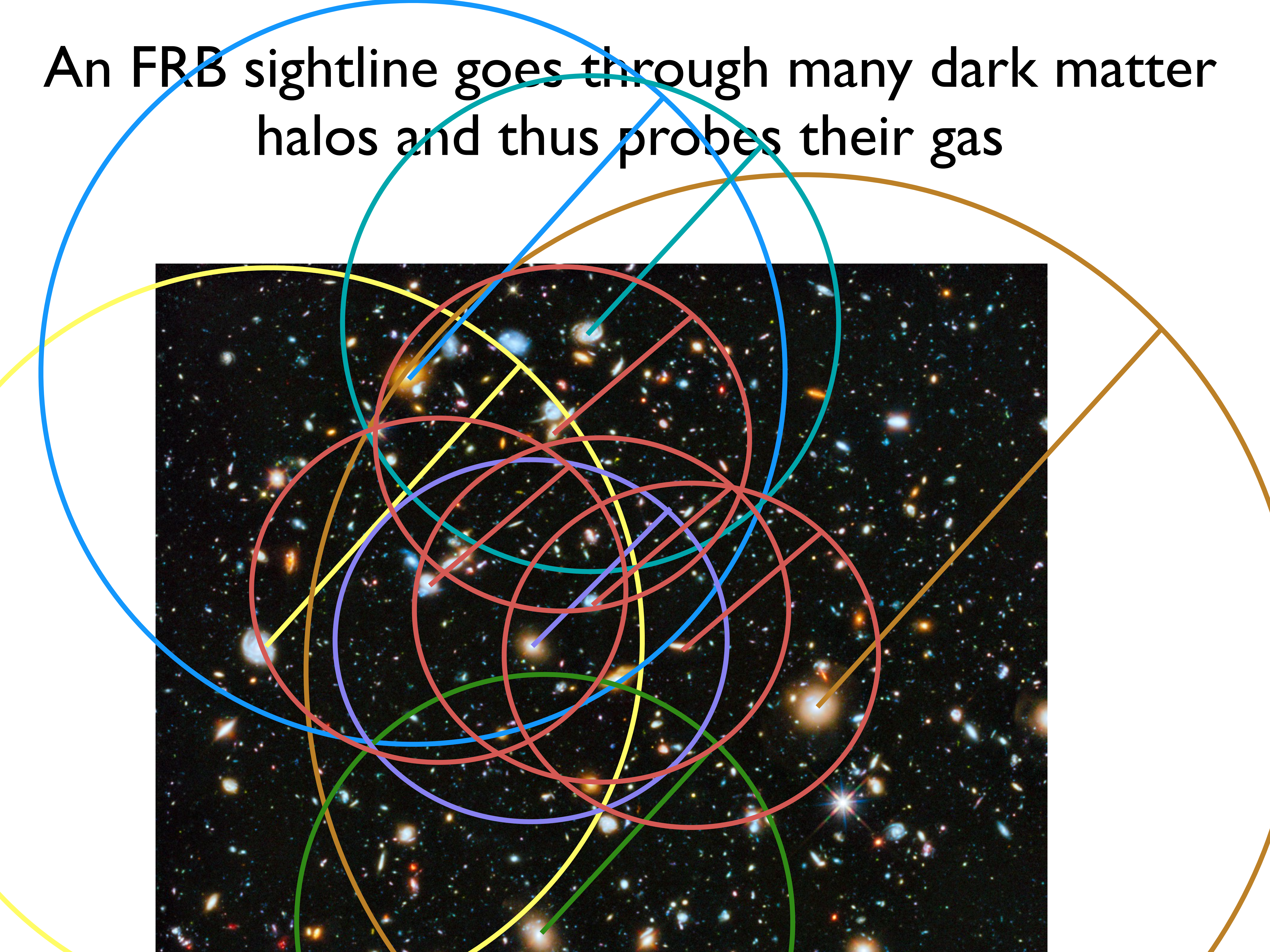
An FRB sightline goes through many dark matter halos and thus probes their gas



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



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

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

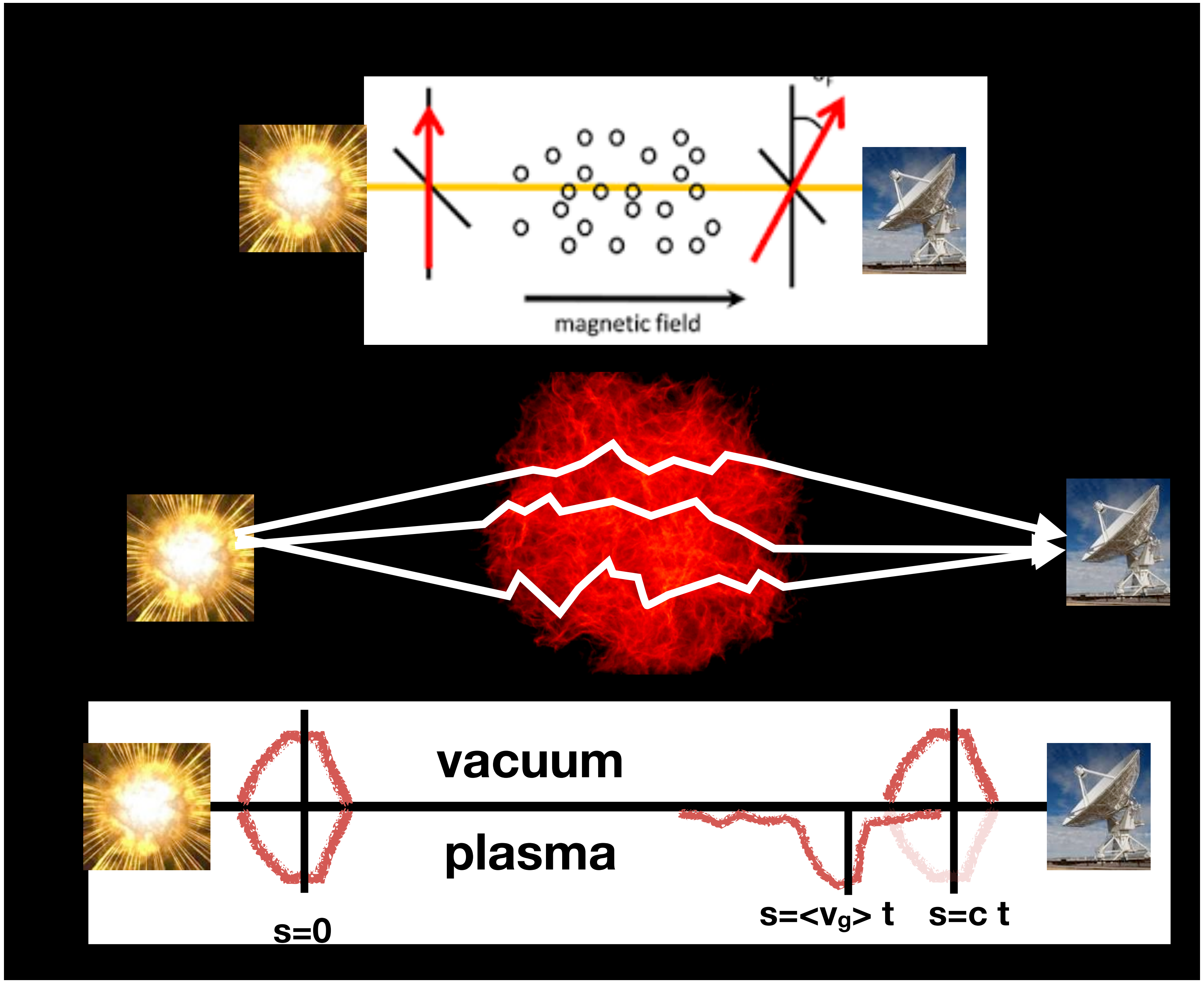
- scattering

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

(being a bit simplistic)

- dispersion

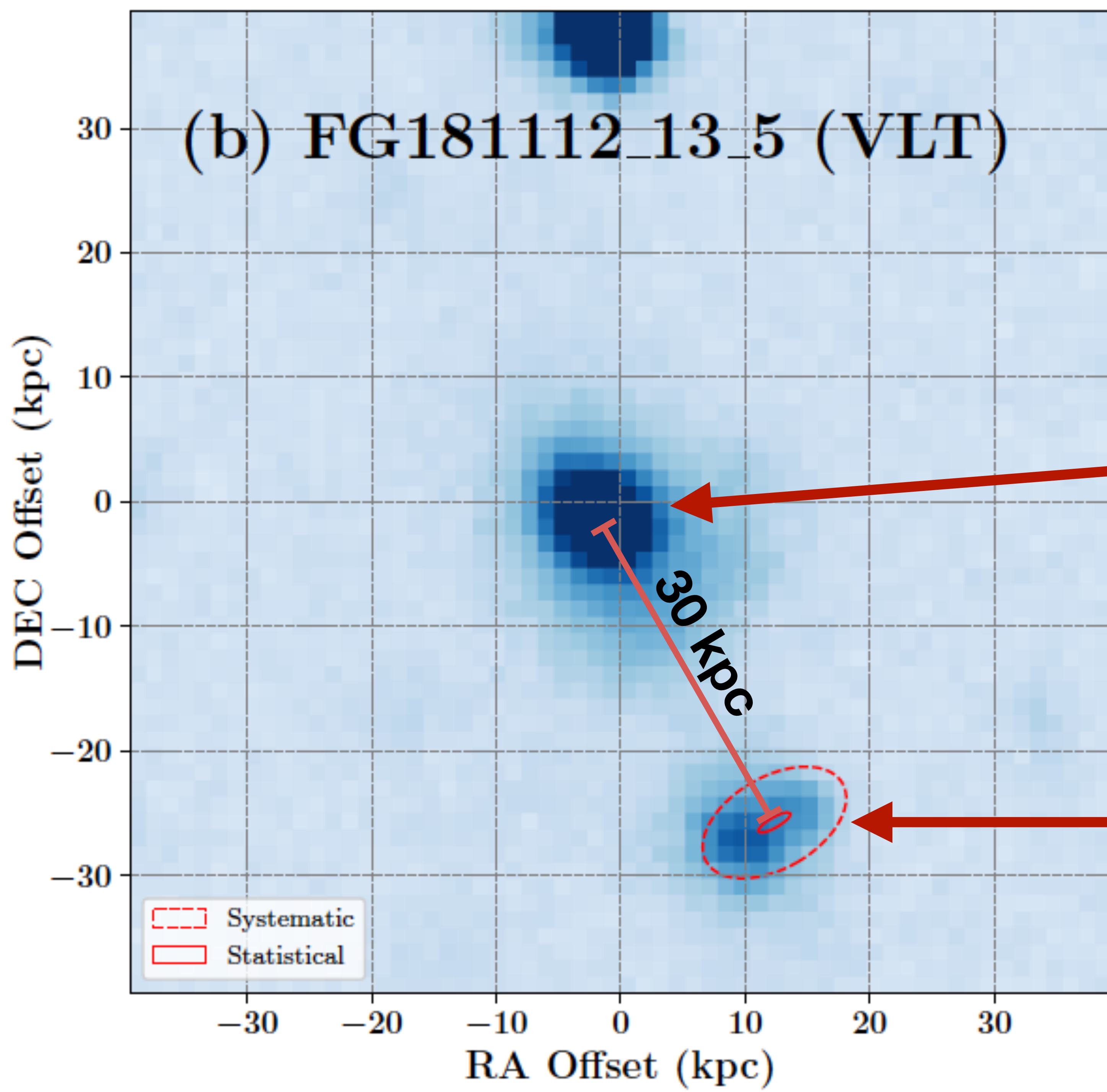
$$\mathrm{DM} = \int ds\ n_e$$



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

Faraday rotation | scattering | dispersion

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 $Z_{\odot}$

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

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

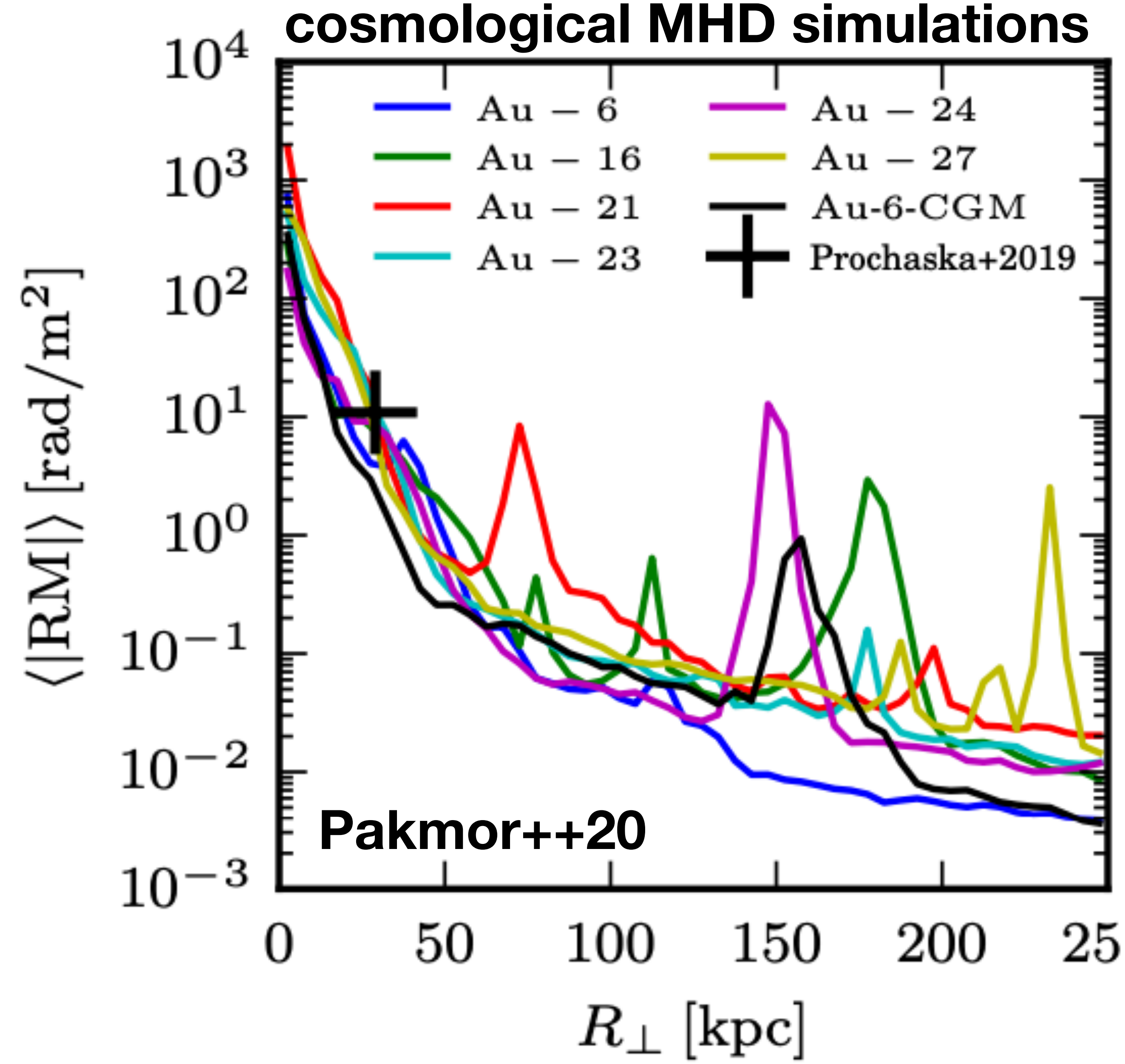
$n_e \sim 10^{-3}\mathrm{cm}^{-3}$ is a typical density of models at 30 kpc.

- **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 (e.g. magnetization could drastically affect 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 delay of τ_{scatt}<40 μs which one can translate into a limit on the inner density:

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

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.

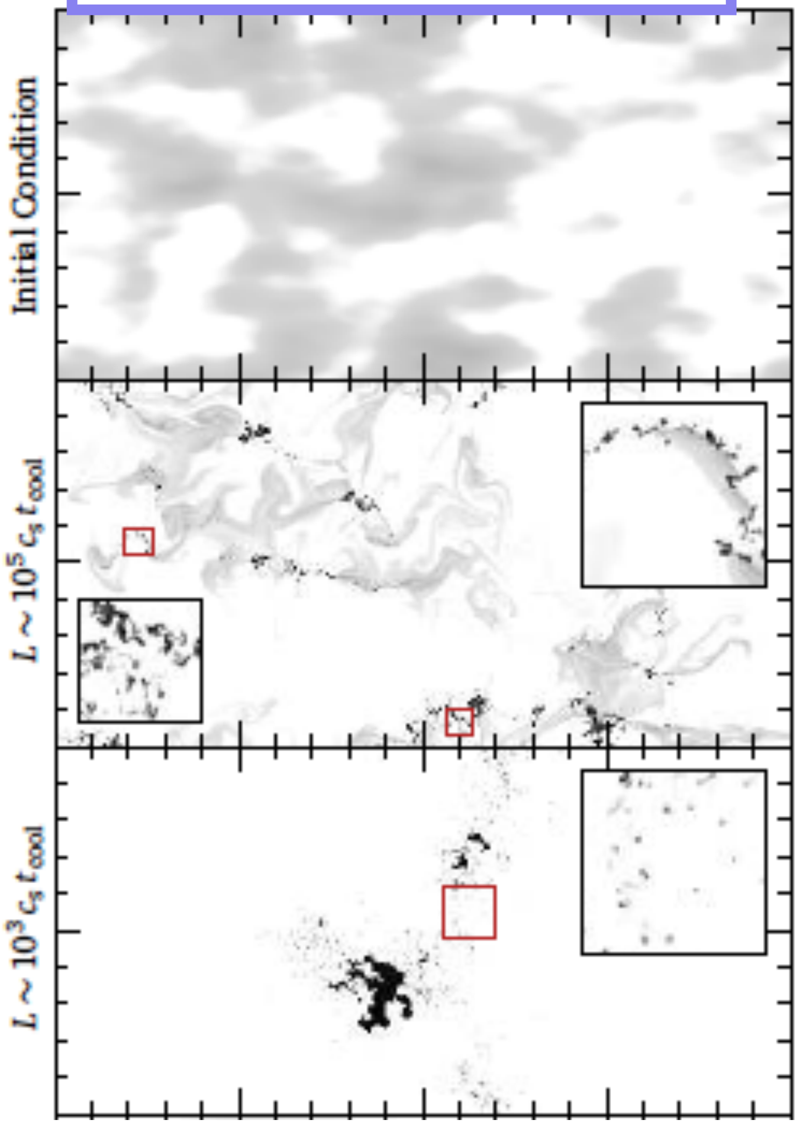
Lithwick and Goldreich '01 outline criteria where Kolmogorov holds on Alfvenic scales, and our paper translates their insights in CGM context.

Faraday rotation | **scattering** | dispersion

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 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 $n_{cloud}=0.1cm^{-3}$ for this system.

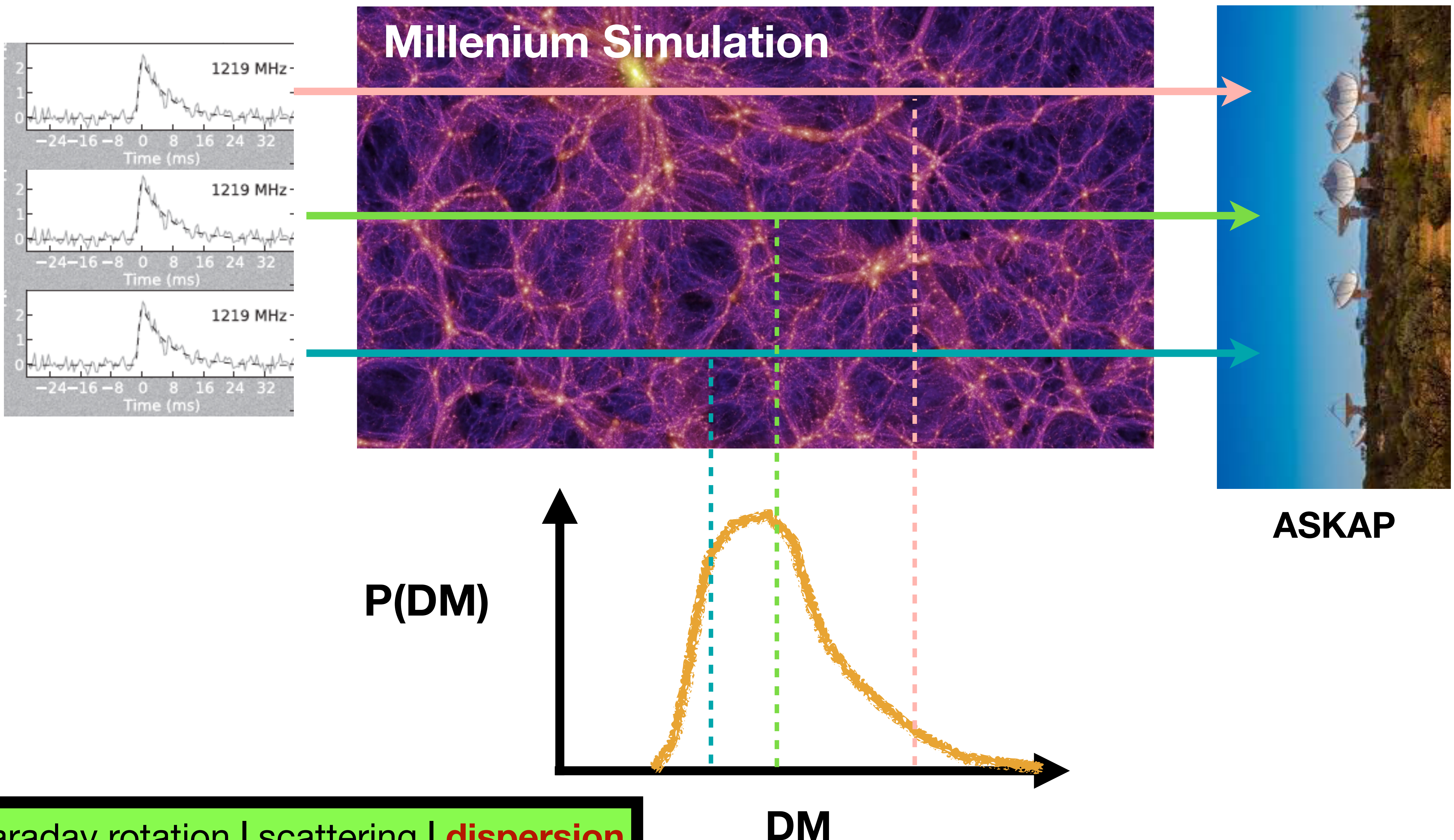
Redoing calculation in correct refractive limit yields $f_V<3x10^{-2}\,(R/1pc)^{3/2}$ for $n_{cloud}= 0.1cm^{-3}$, with a weaker scaling in R below 0.01pc.

Faraday rotation | scattering | dispersion

Prochaska, Macquart, MM et al 2019 *Science*

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

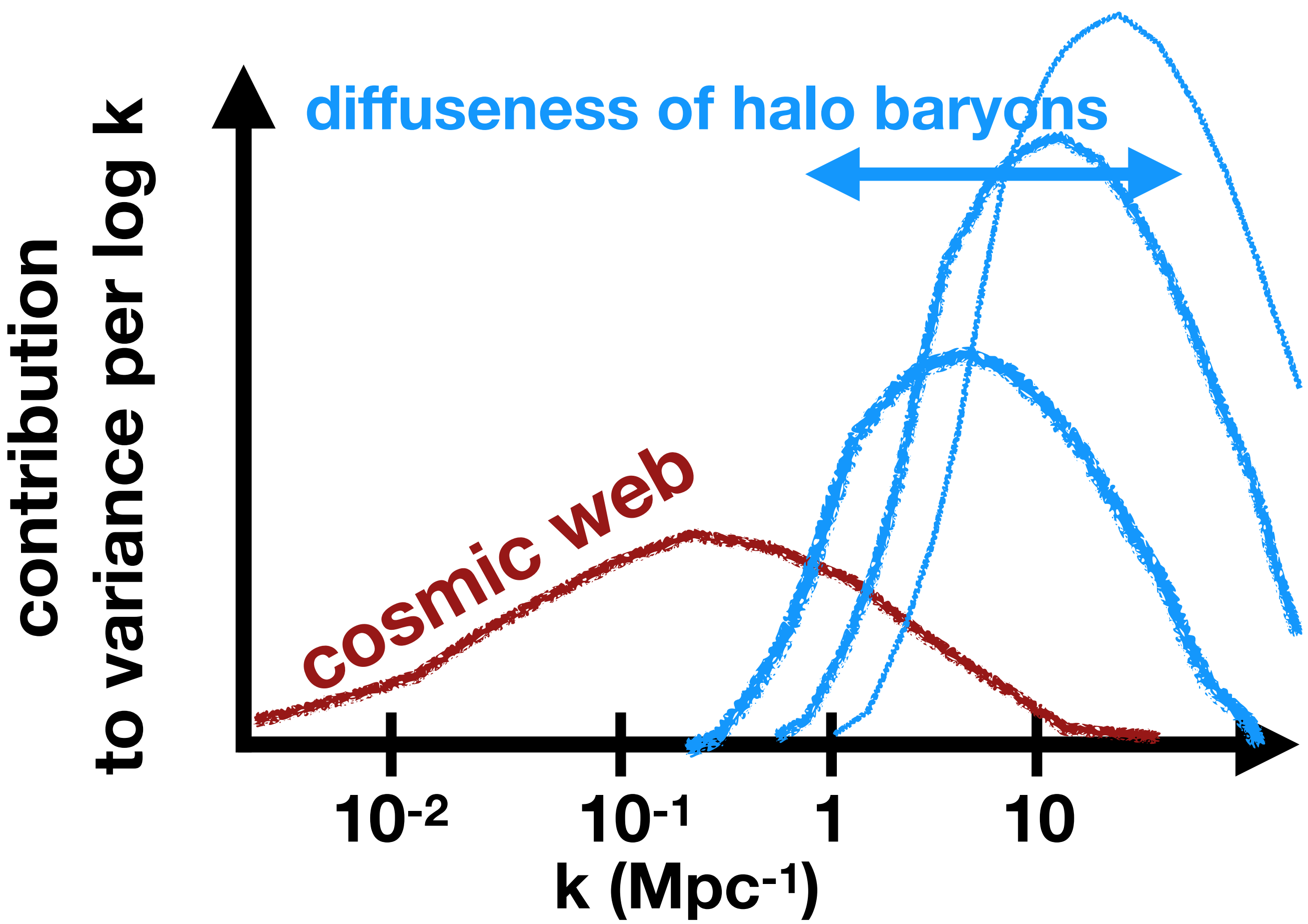
cosmic structure will drive scatter in the dispersion measures (DMs) to a given redshift



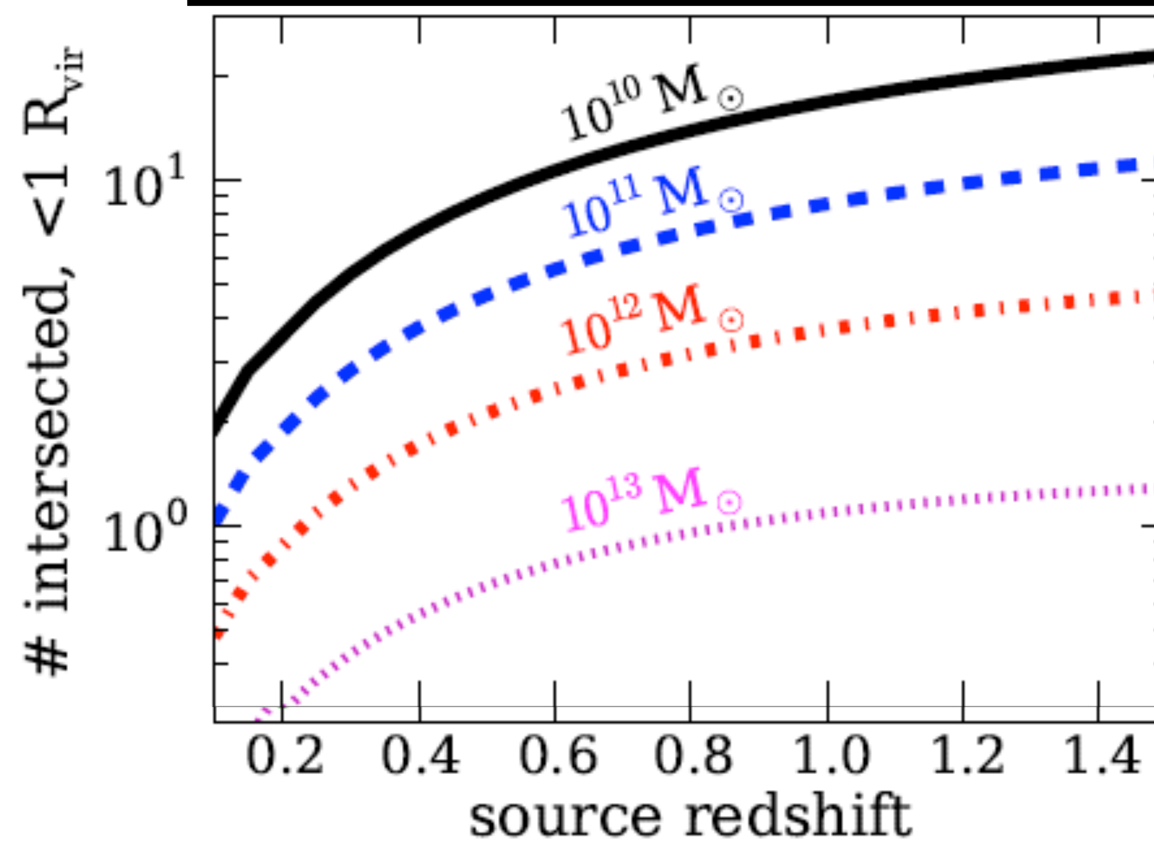
Faraday rotation | scattering | **dispersion**

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

the scales that contribute to scatter



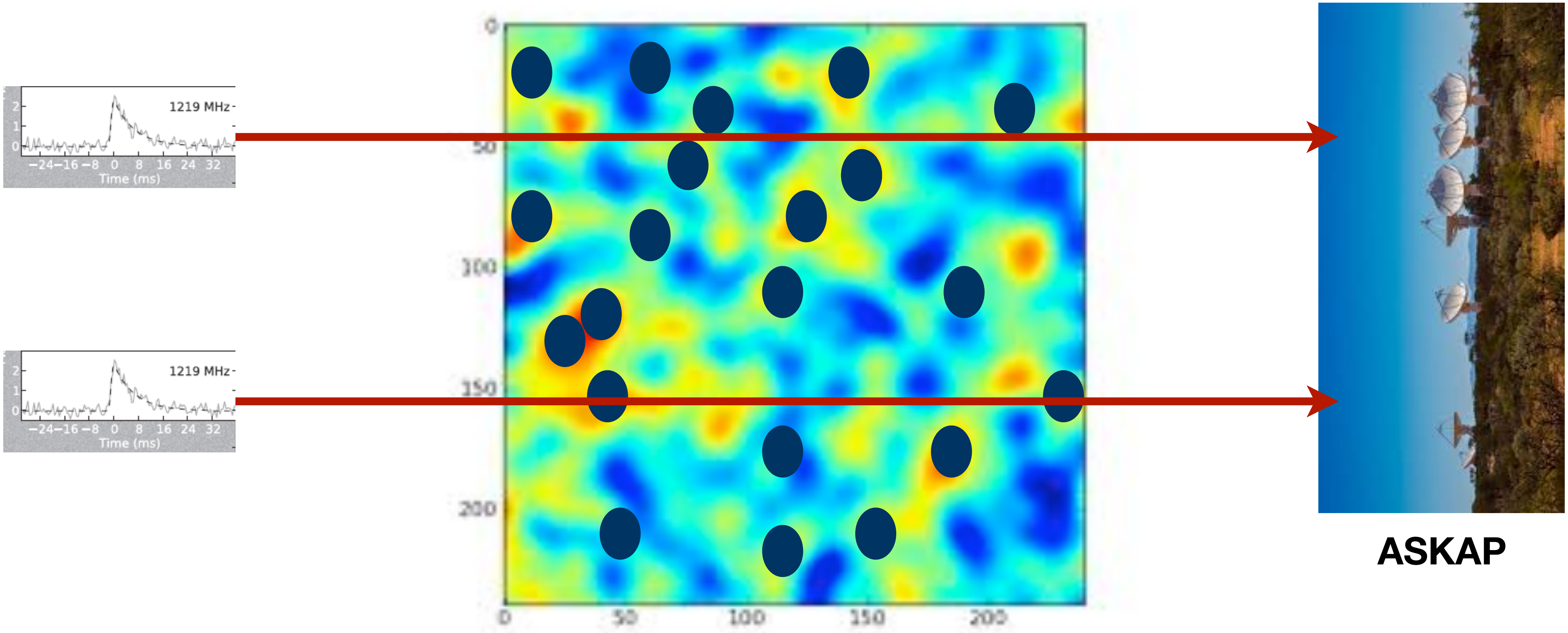
A sightline to z~1 intersects tens of galactic halos

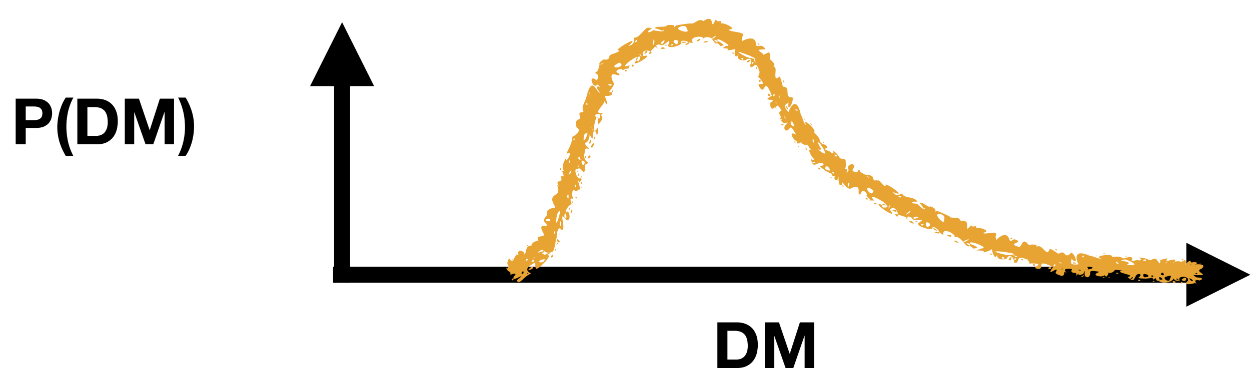


A second (generally smaller) contribution to scatter comes from how matter fluctuations on 10-150 Mpc scales.

Faraday rotation | scattering | **dispersion**

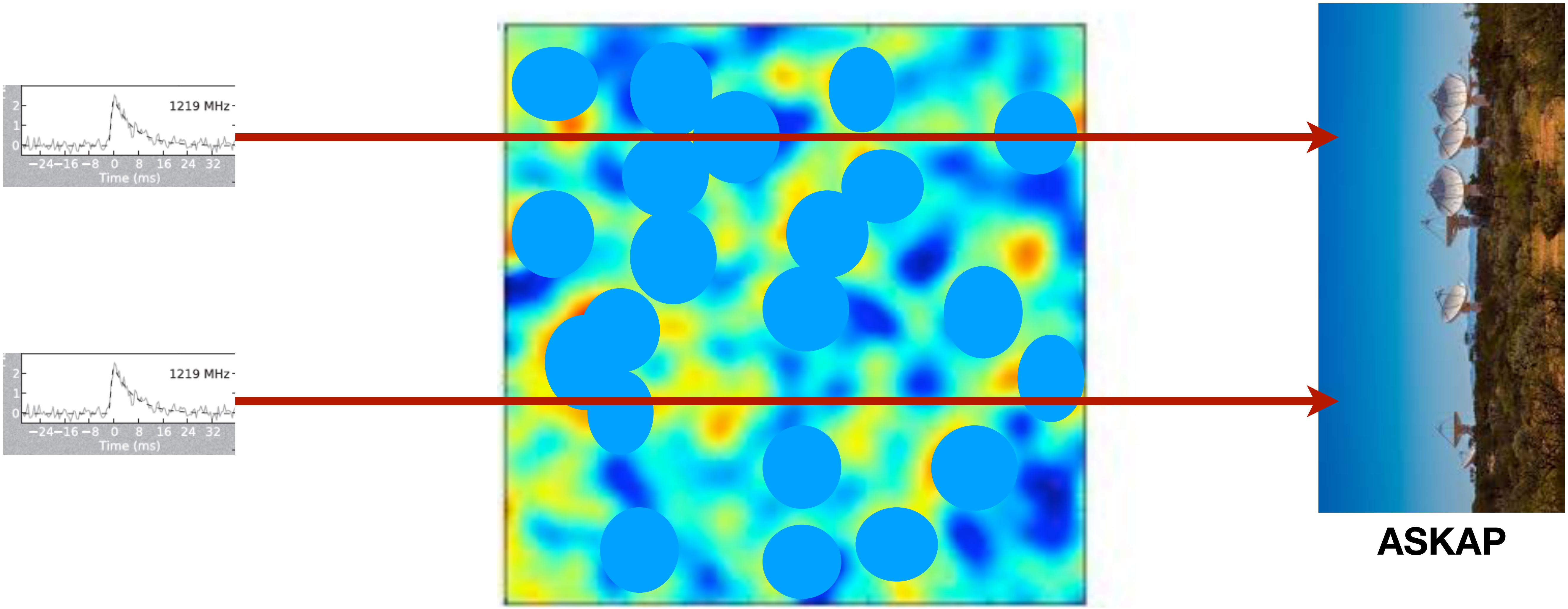
How to think about FRB dispersion measures (DMs)

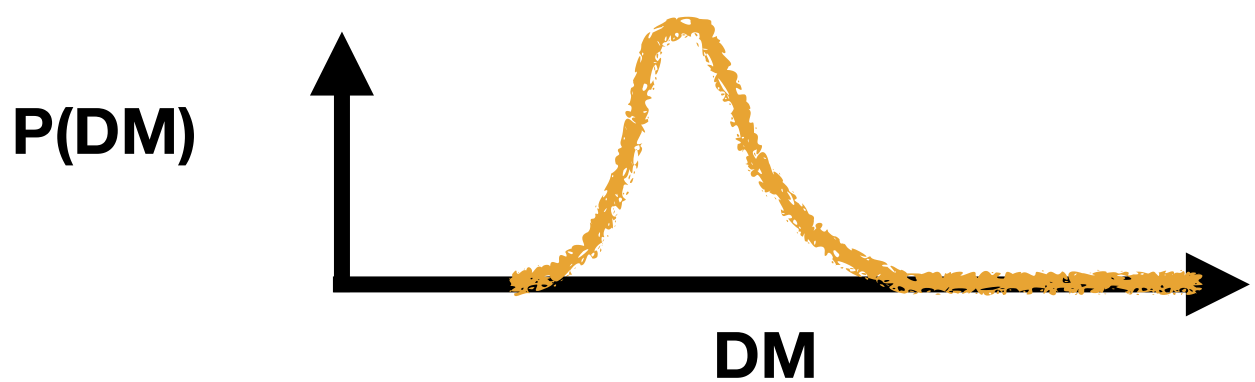




More compact gaseous halos, more sightline variance, more skewed PDF

How to think about FRB dispersion measures (DMs)





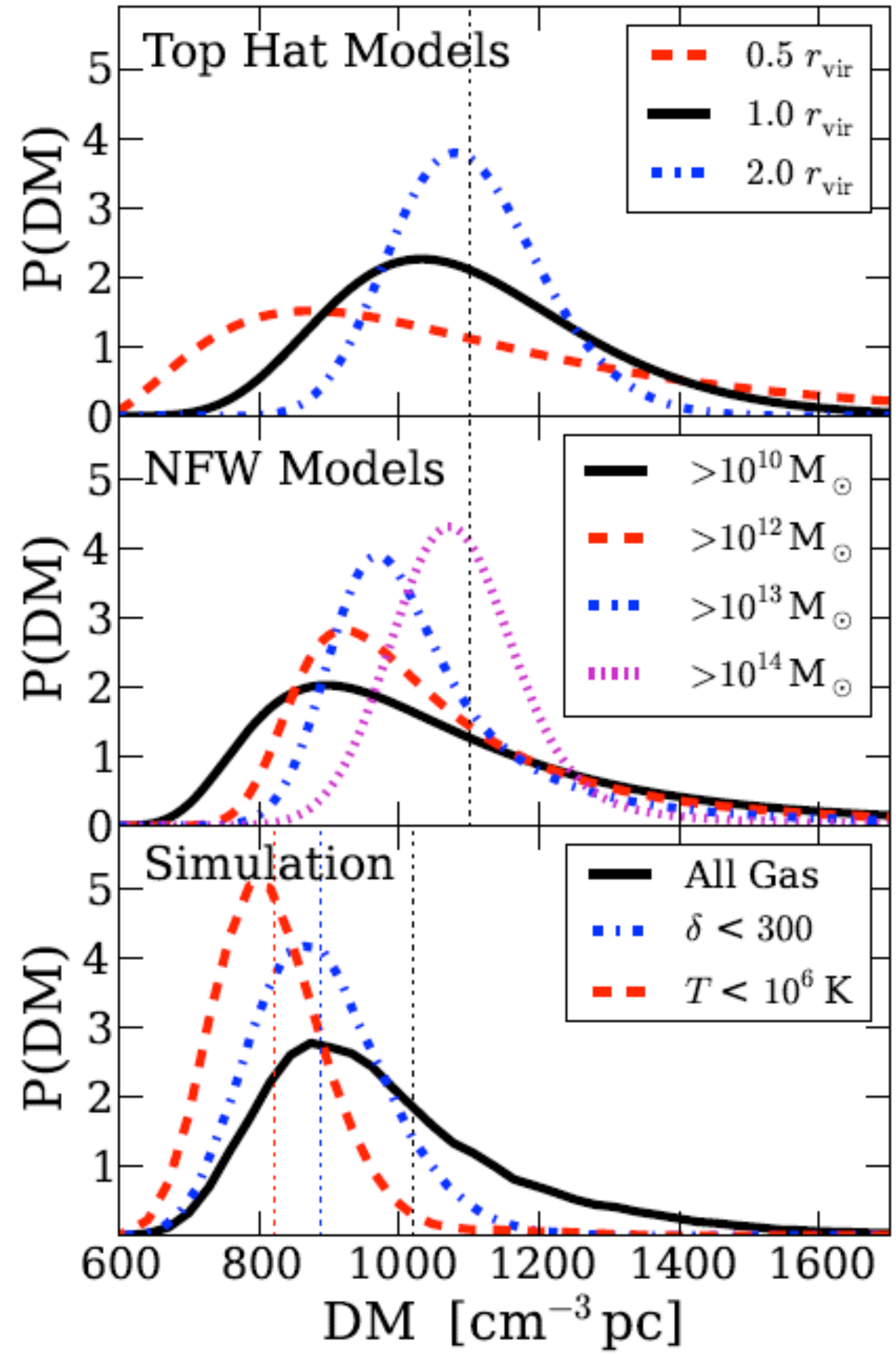
Puffier halos, less sightline variance, more Gaussian PDF

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.

the PDF of DM to z=1



MM '14

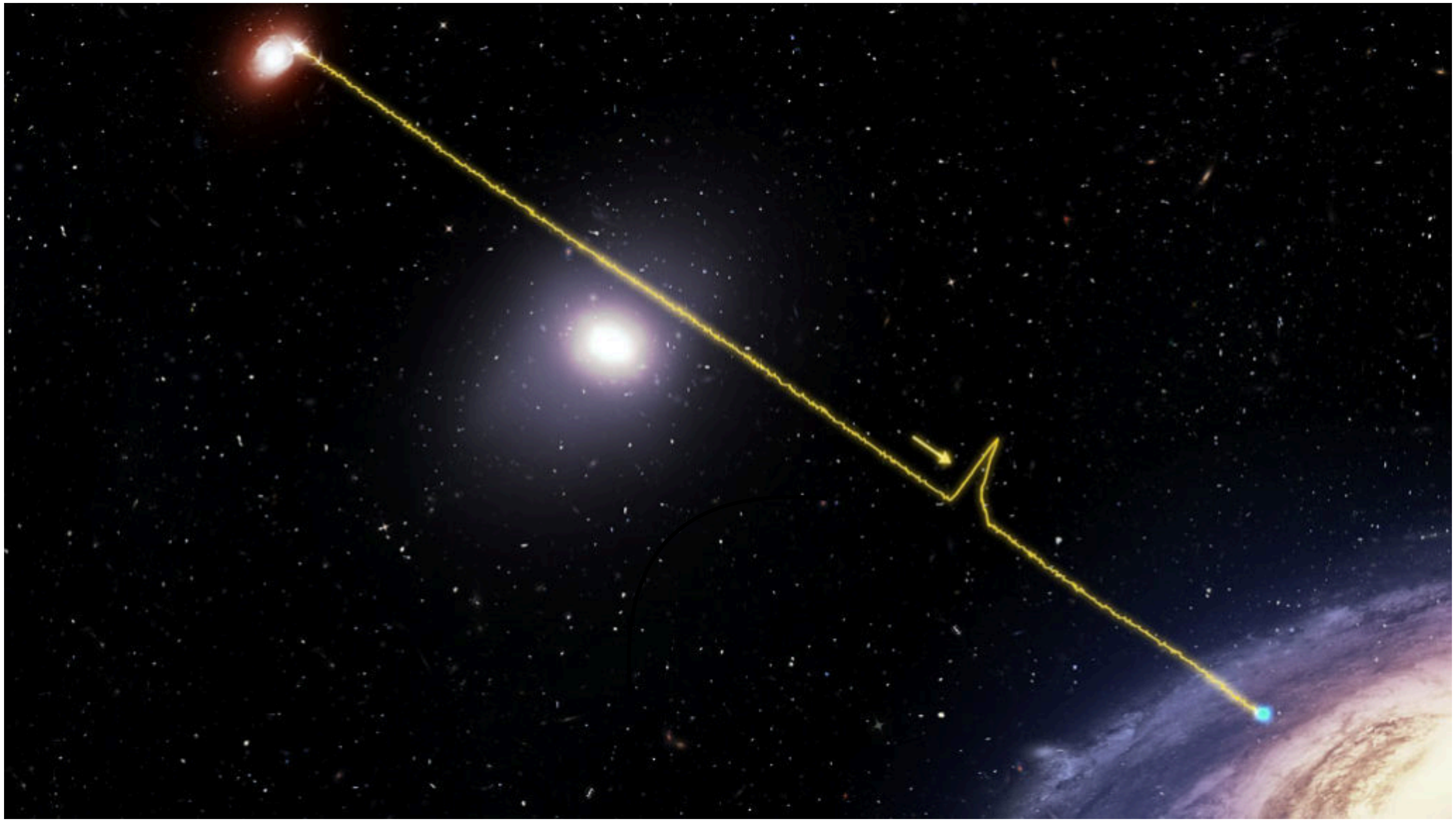
Next few slides EMBARGOED and not included in online slide-deck

Macquart, Prochaska, MM++, submitted to *Nature*

Faraday rotation | scattering | **dispersion**

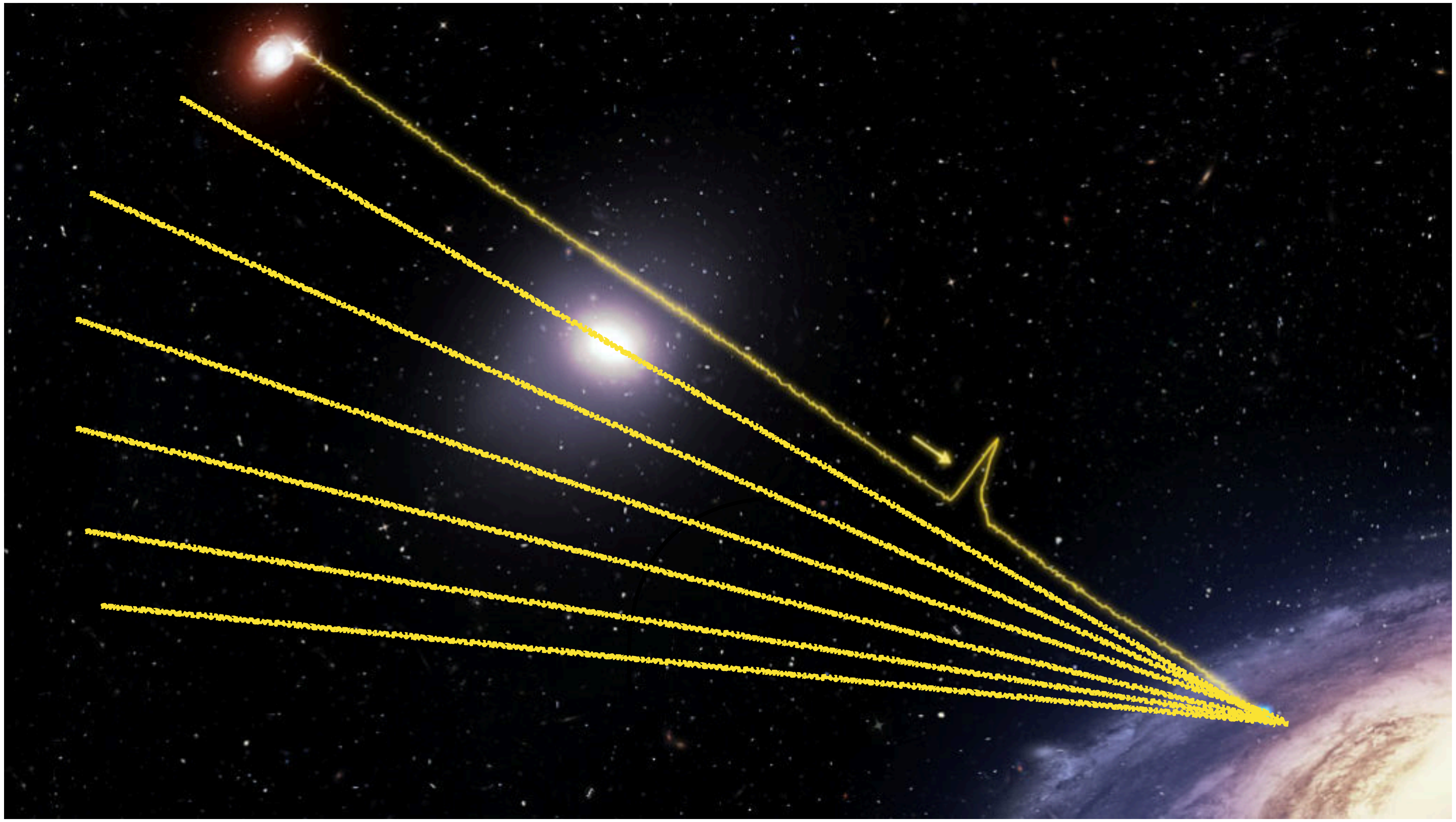
“I love to travel, but I hate to arrive.”

–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



Going Forward

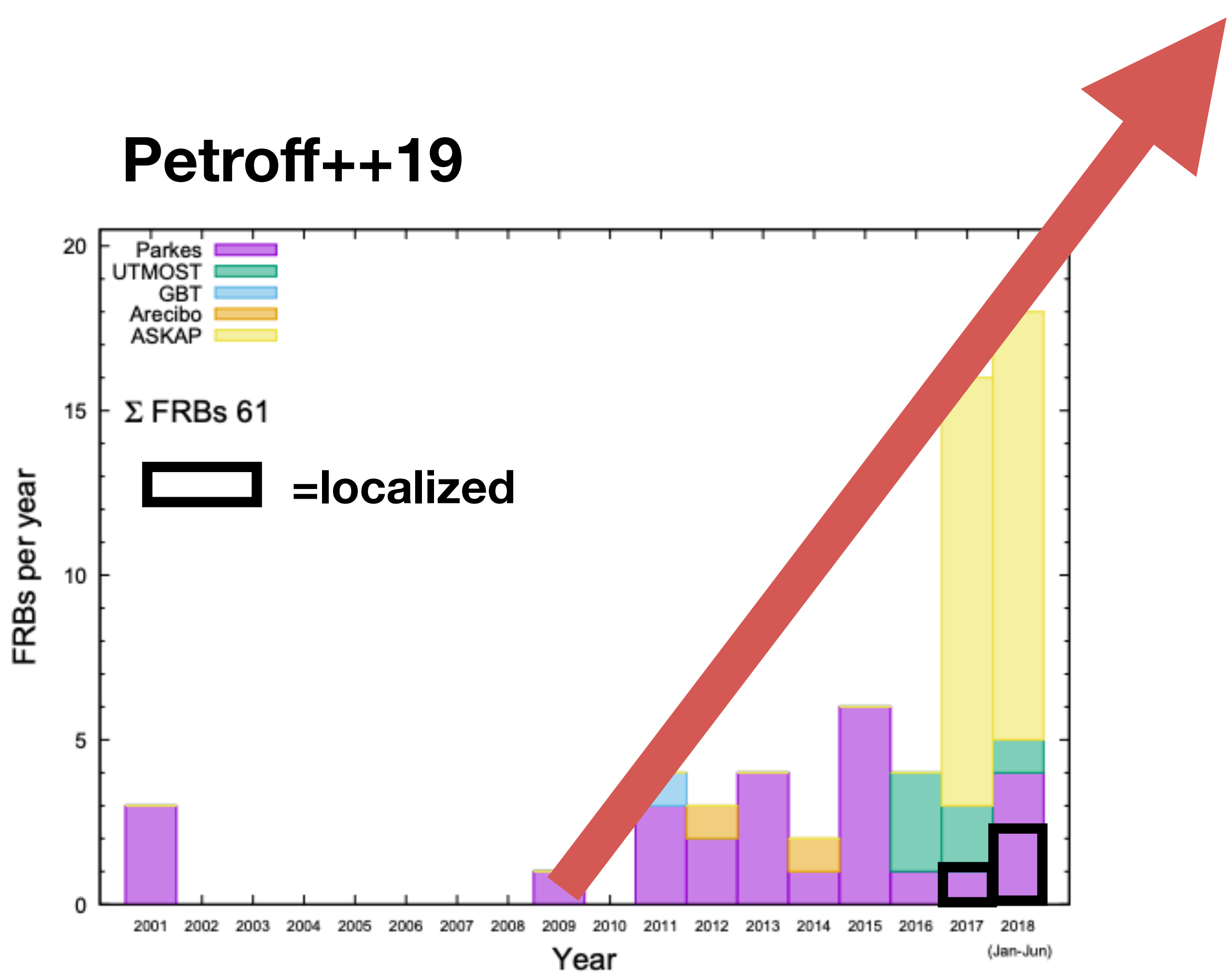
Not only will there be many more FRBs to do this science, but this science intersects with CMB anisotropy measurements, weak lensing, CGM UV absorption measurements, metal enrichment history

Going forward

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

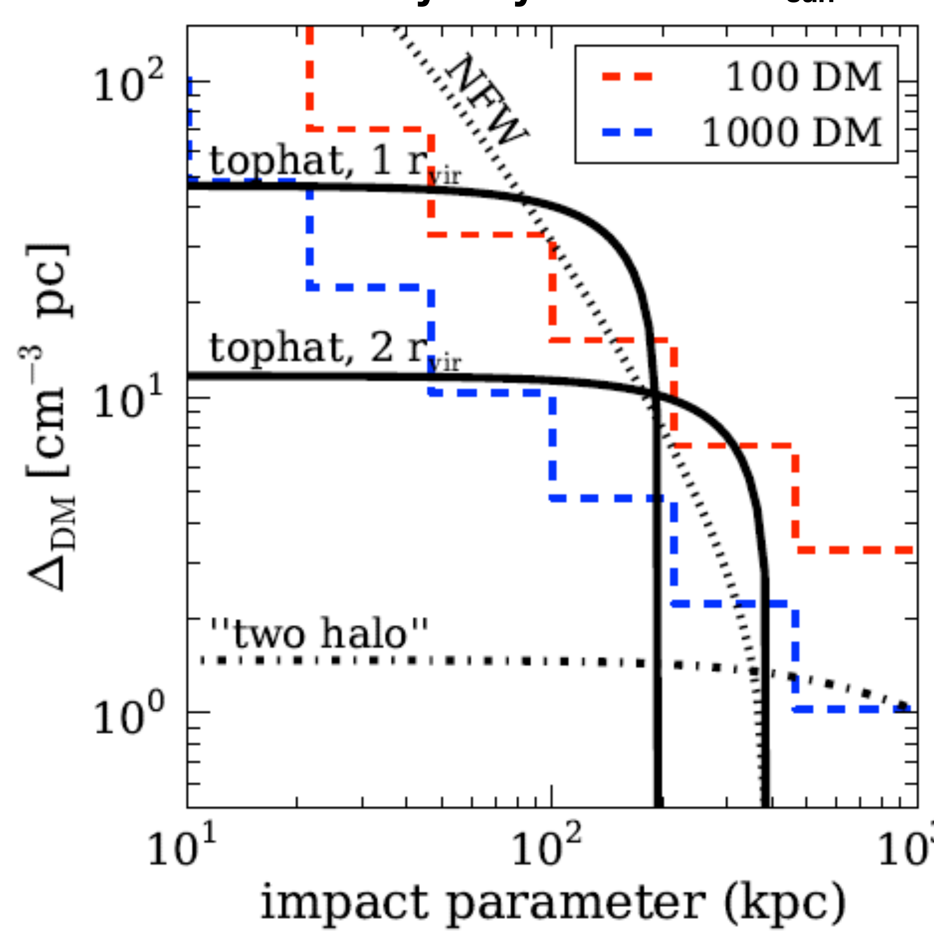
Stacking around foreground galaxies is way to go once there are >100 localizations

Petroff++19



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

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

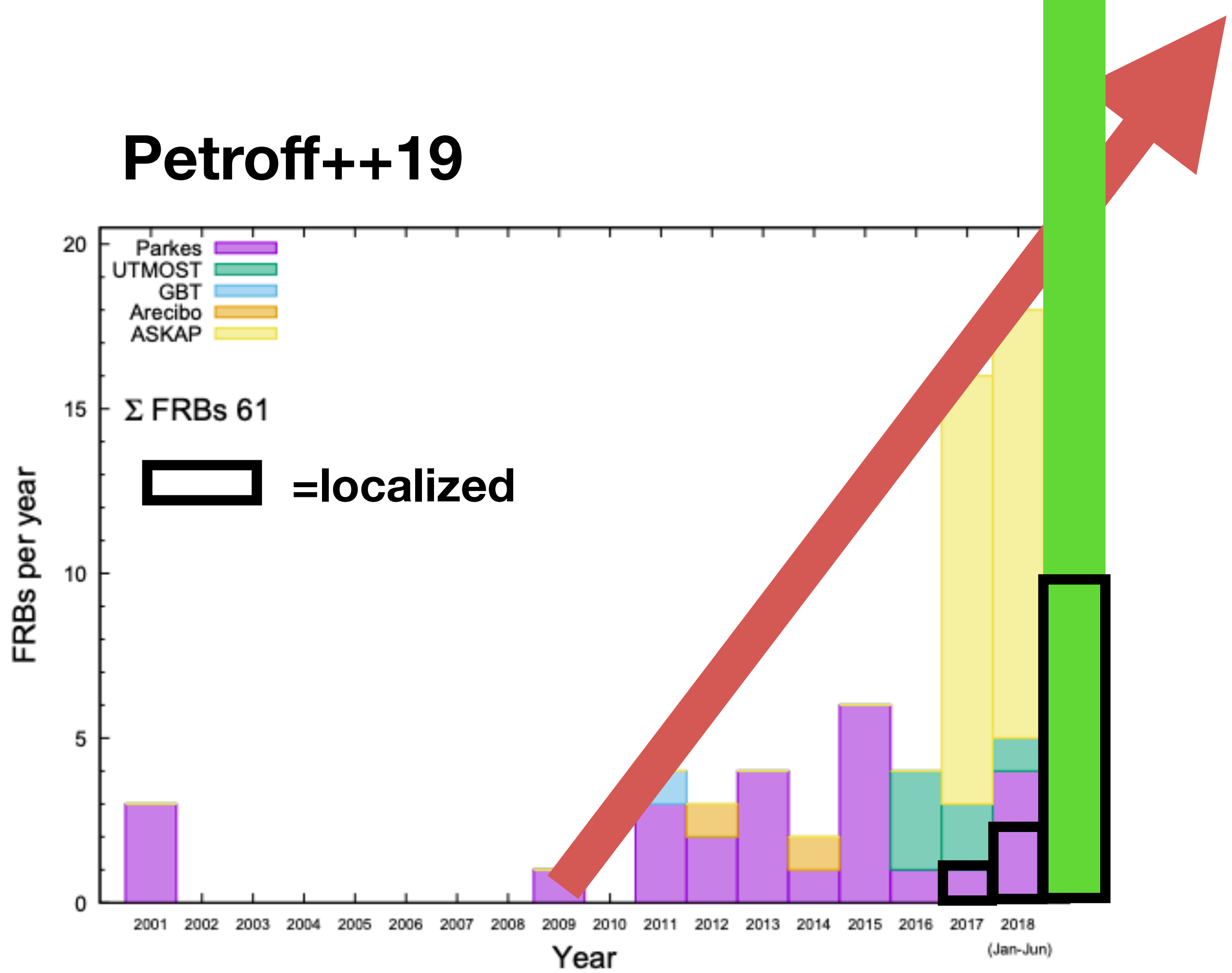


MM'14

Going forward

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

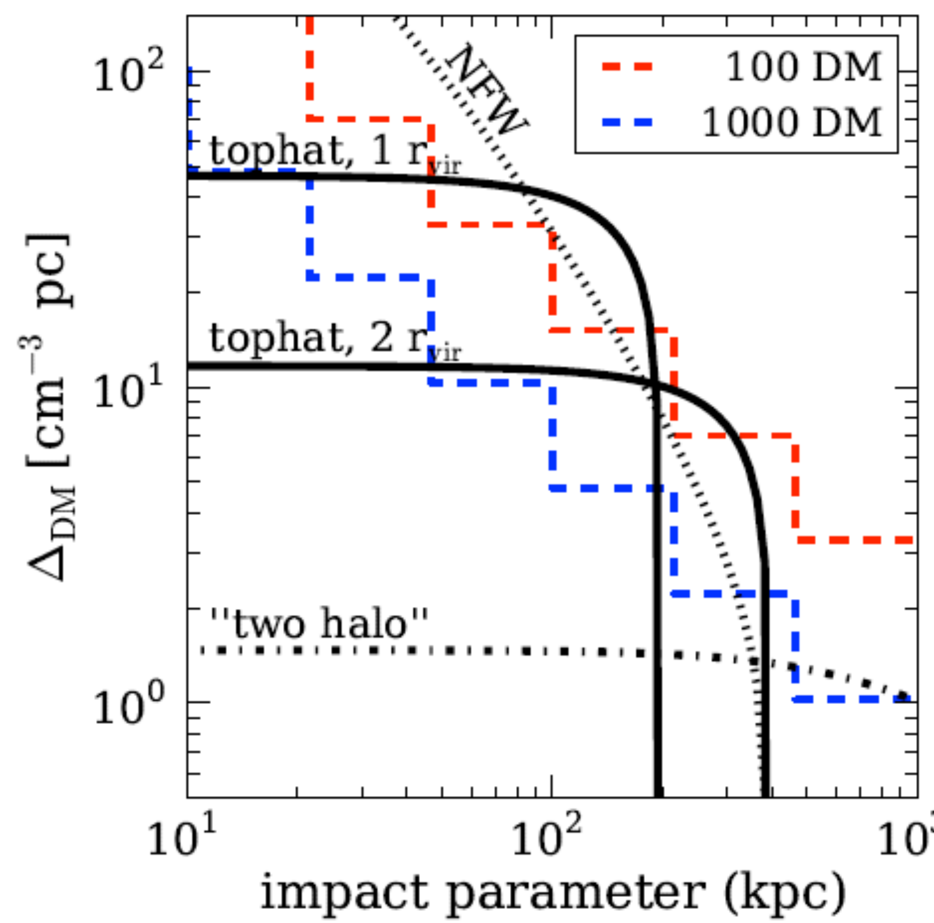
Petroff++19



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

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

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



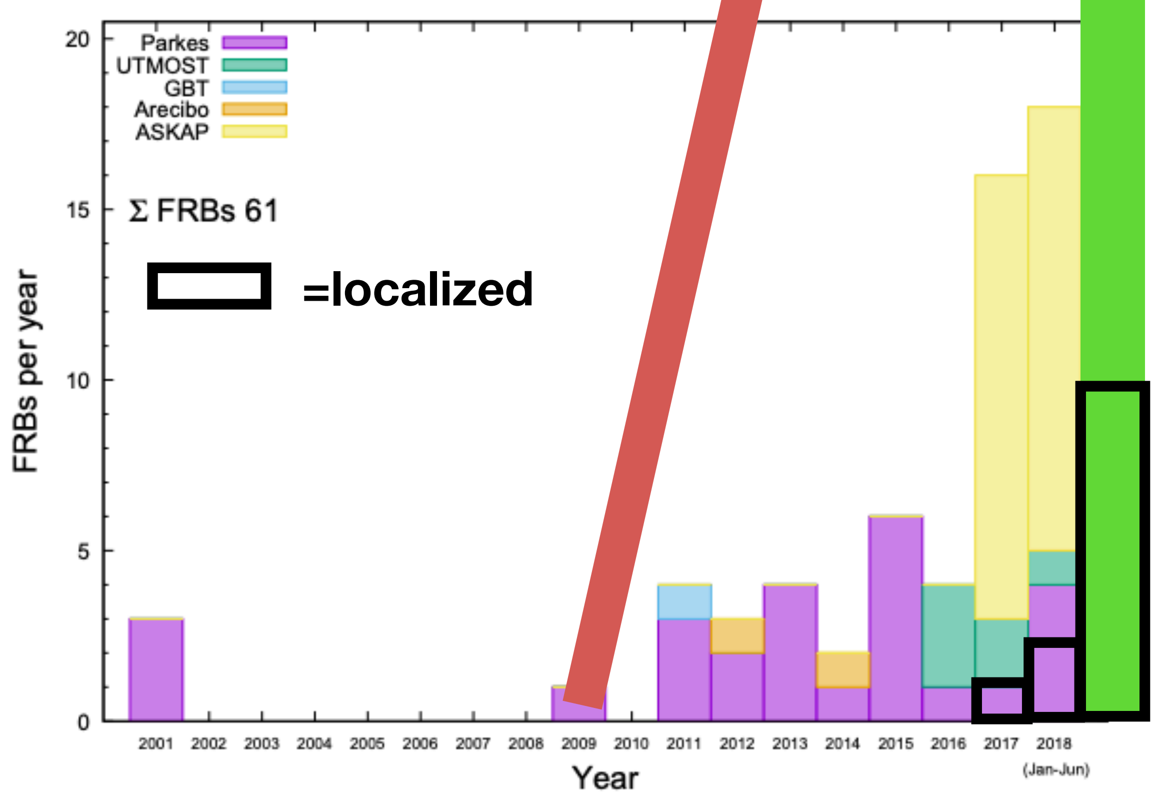
MM'14

Going forward

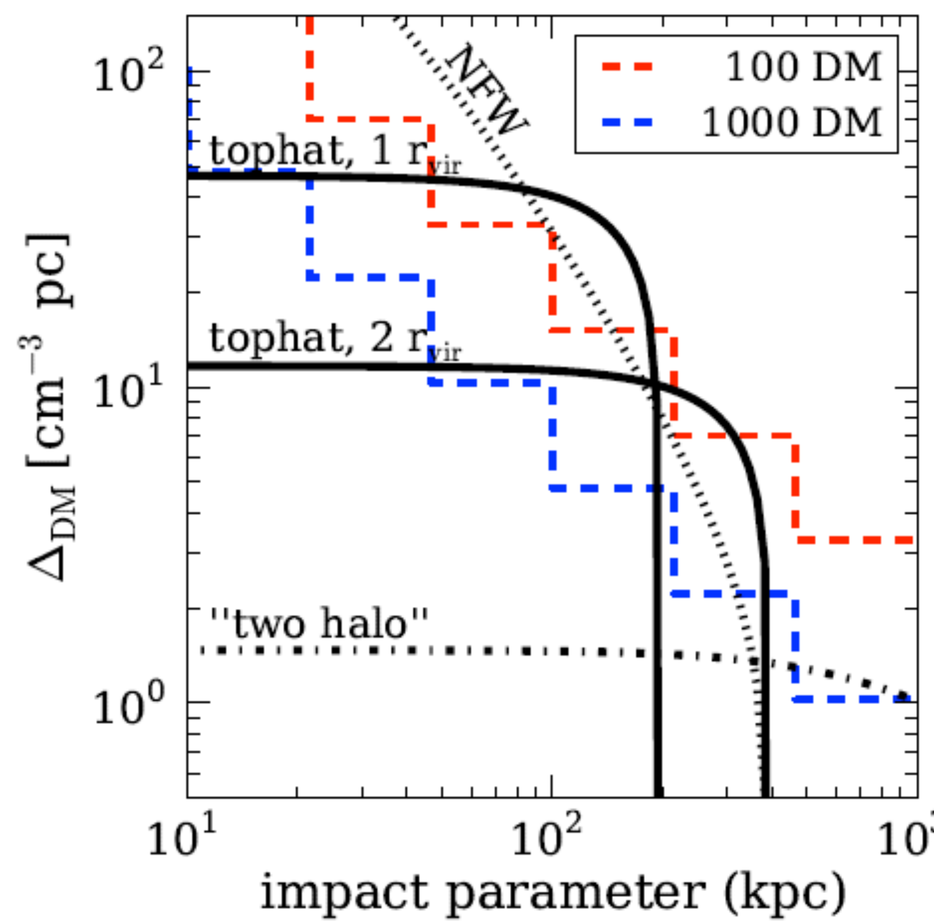
There are going to be A LOT OF FRBs and A LOT with localizations!!

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

Petroff++19



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



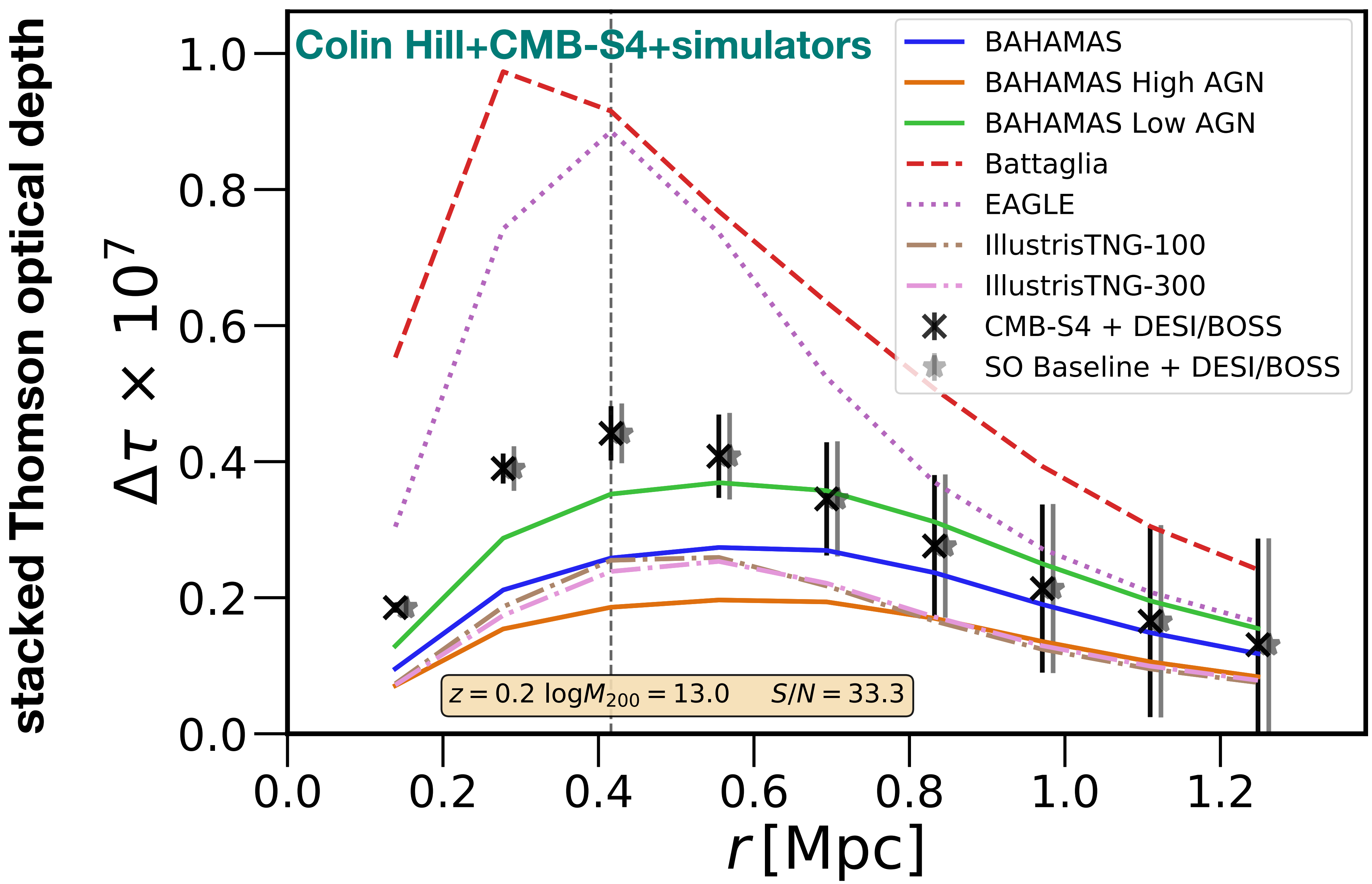
Facilities: ASKAP, Chime, DSA, HIRAX, Meerkat, etc

MM'14

Going forward

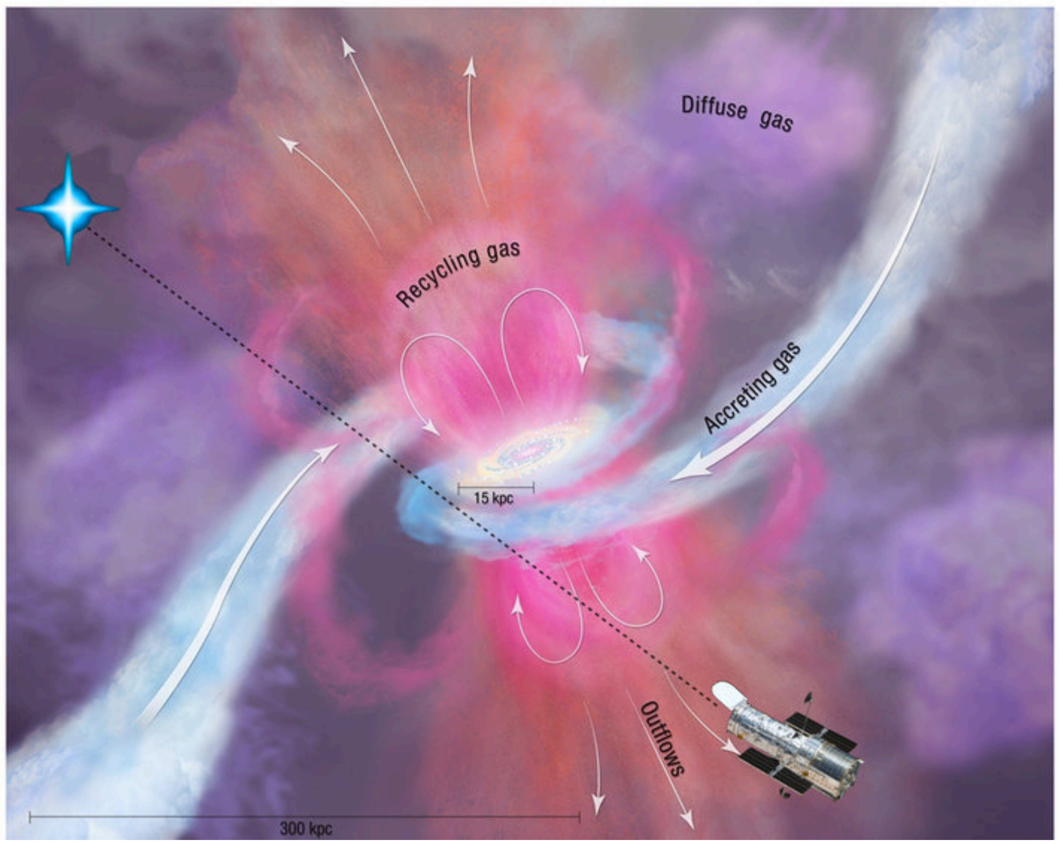
the main competitor to FRBs is going to be kSZ (and tSZ) with Simons Obs./CMB-S4, but beam size and lack of large spectroscopic samples makes hard to push to 10^{12} M_{sun} Milky Way mass

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



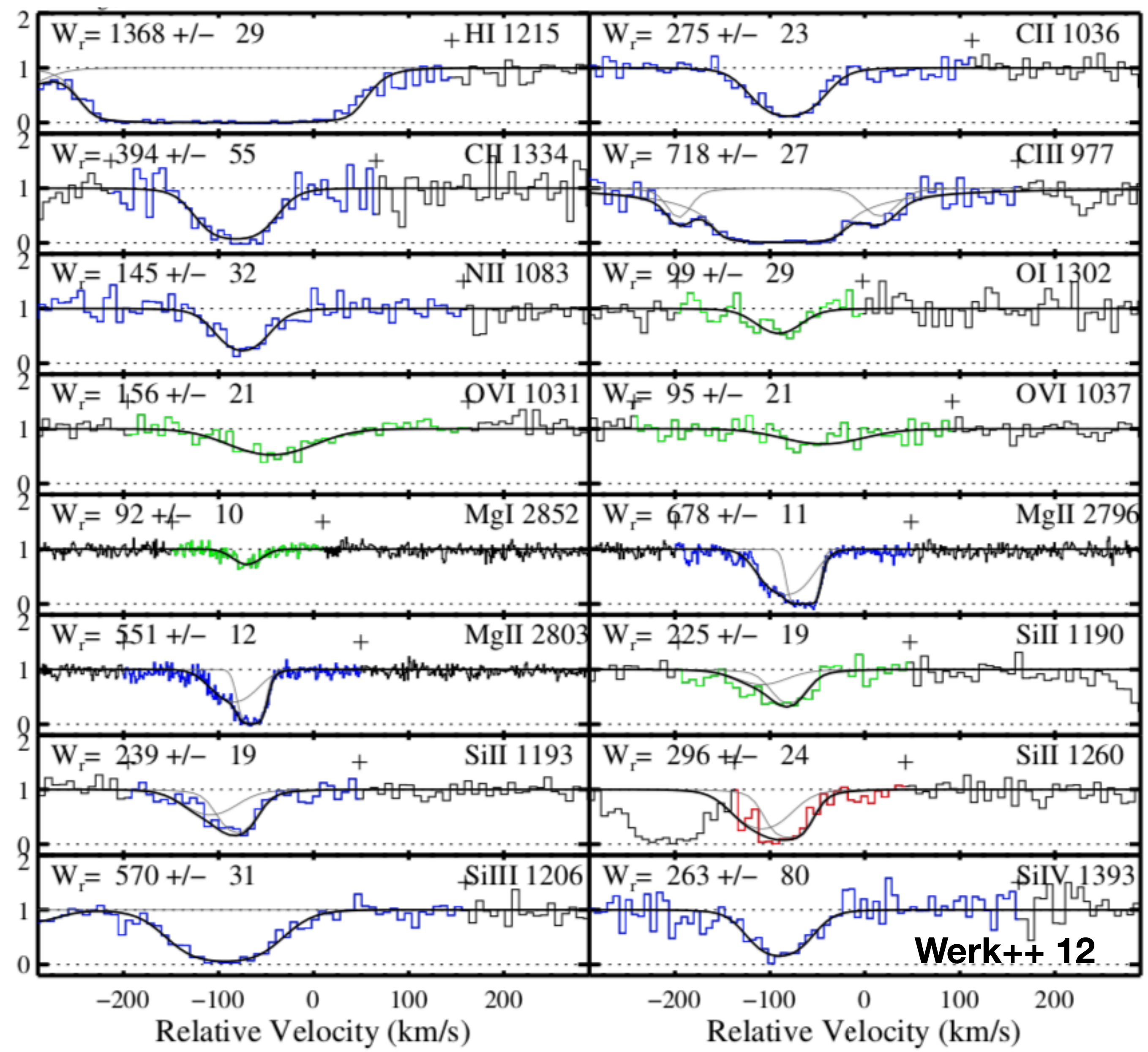
Going forward

Our best probe current probe of CGM: UV absorption lines



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

an HST COS-Halos sightline at z=0.2

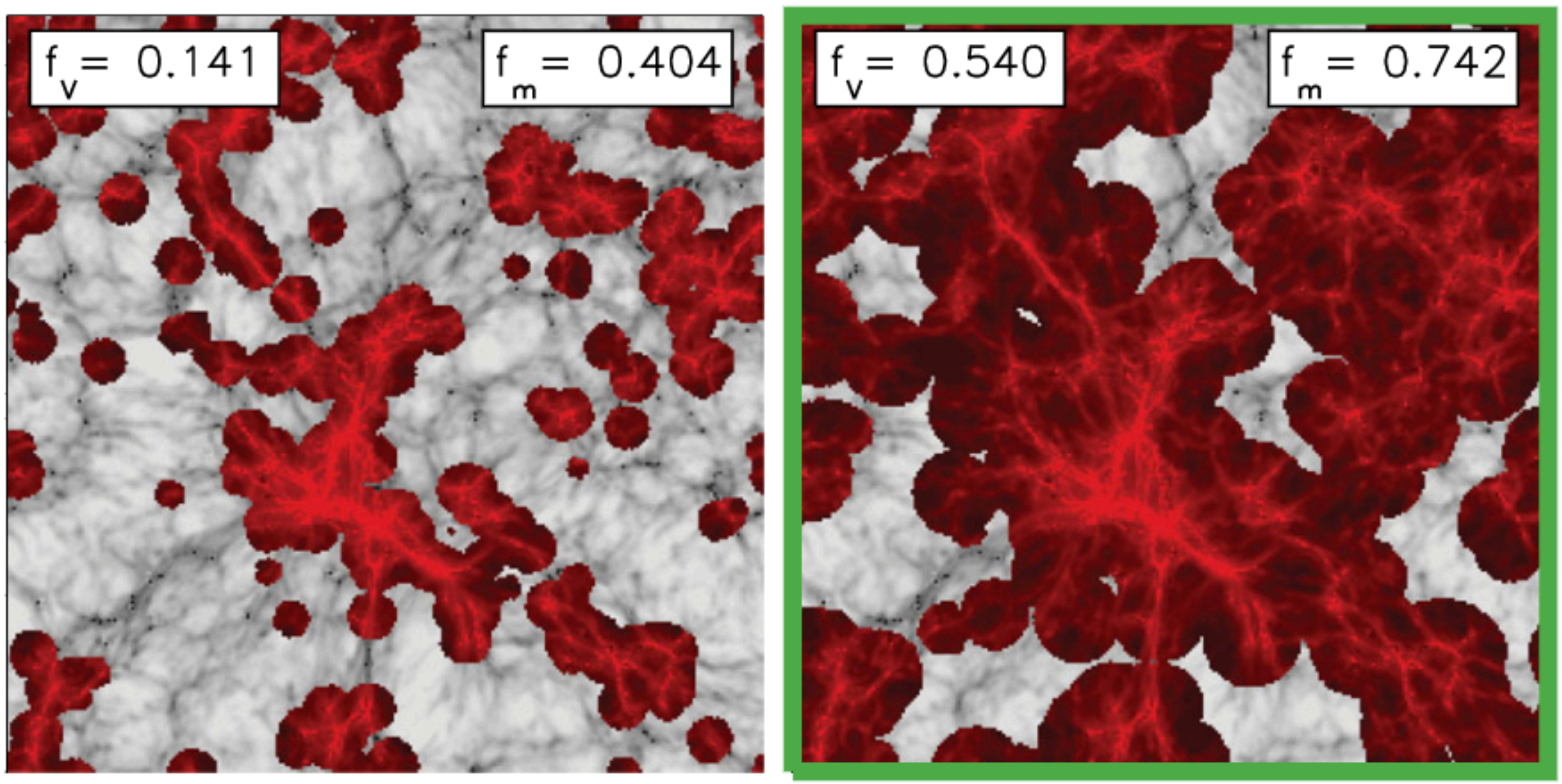


Current inferences rely solely on the integrated column across ions and making a variety of strong assumptions. We can do better!

Going forward

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

Booth++12



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

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 $B_{||}$ 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 Ω_b = **XXXXXX YY**%C.L. and are starting to constrain the scatter
    - suggests host contribution to DM is typically low (~**XXXXX** 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:

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

$$\left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}}\right)\left(\frac{\Delta L}{50\mathrm{kpc}}\frac{f_V}{10^{-3}}\right)^{1/2}\left(\frac{0.1\mathrm{pc}}{R}\right)^{3/2} < 1.6 \quad \text{otherwise,} \qquad \text{(S25)}$$

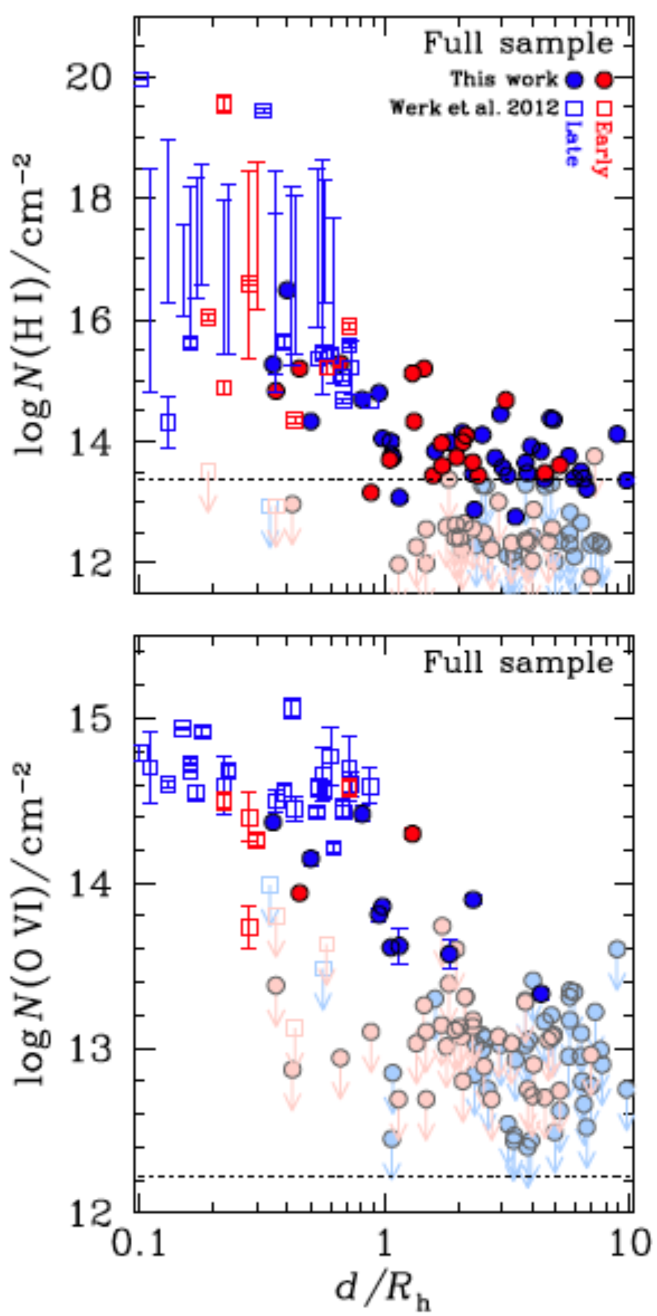
Data rules out mist of 0.1 parsec clouds with a volume filling fraction of 10^{-3}

We do not know how gas is distributed around ~<10^{14} M_{sun} halos

Absorption around ~$10^{12}$$M_{sun}$ halos

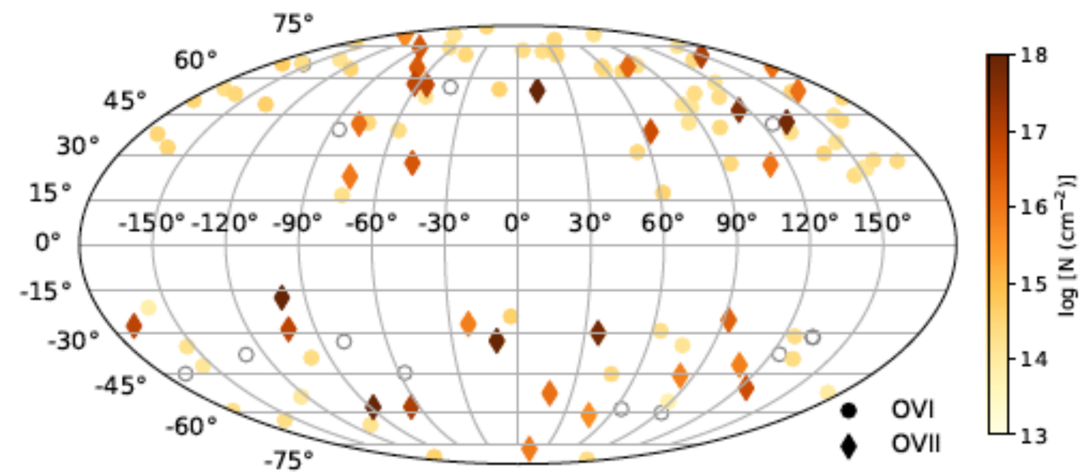
HI column

OVI Column



Johnson++ '15

Milky Way OVII

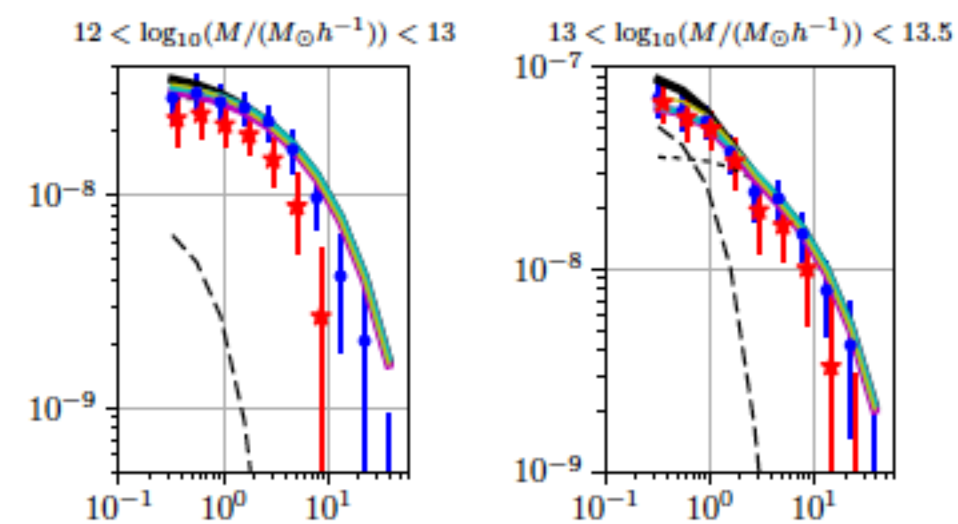


compilation from Prochaska & Zheng '19

Stacking Planck Thermal SZ

(becomes dominated by 2-halo at <$10^{13}$$M_{sun}$)

Integrated pressure

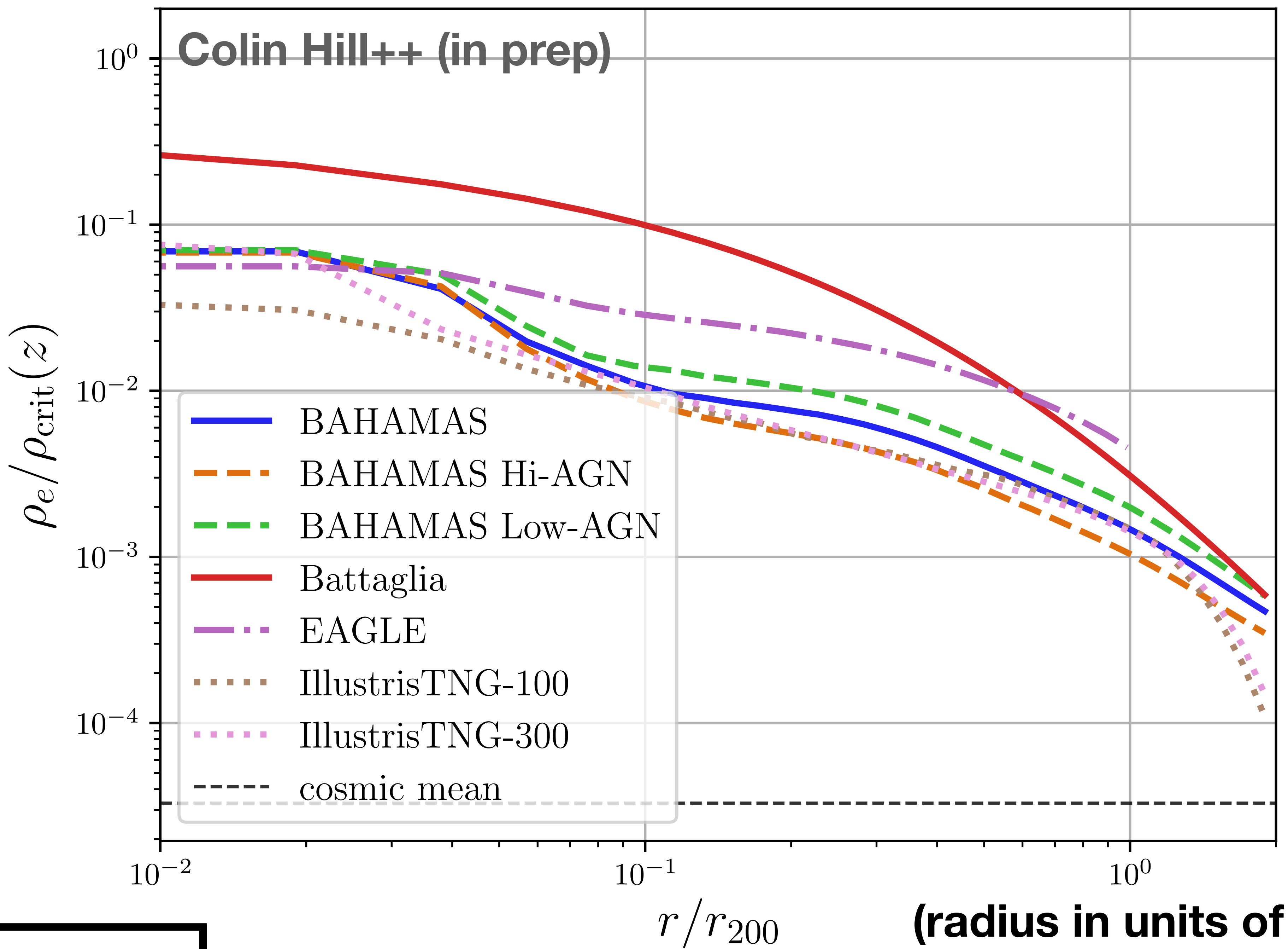


Hill++18

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!!!