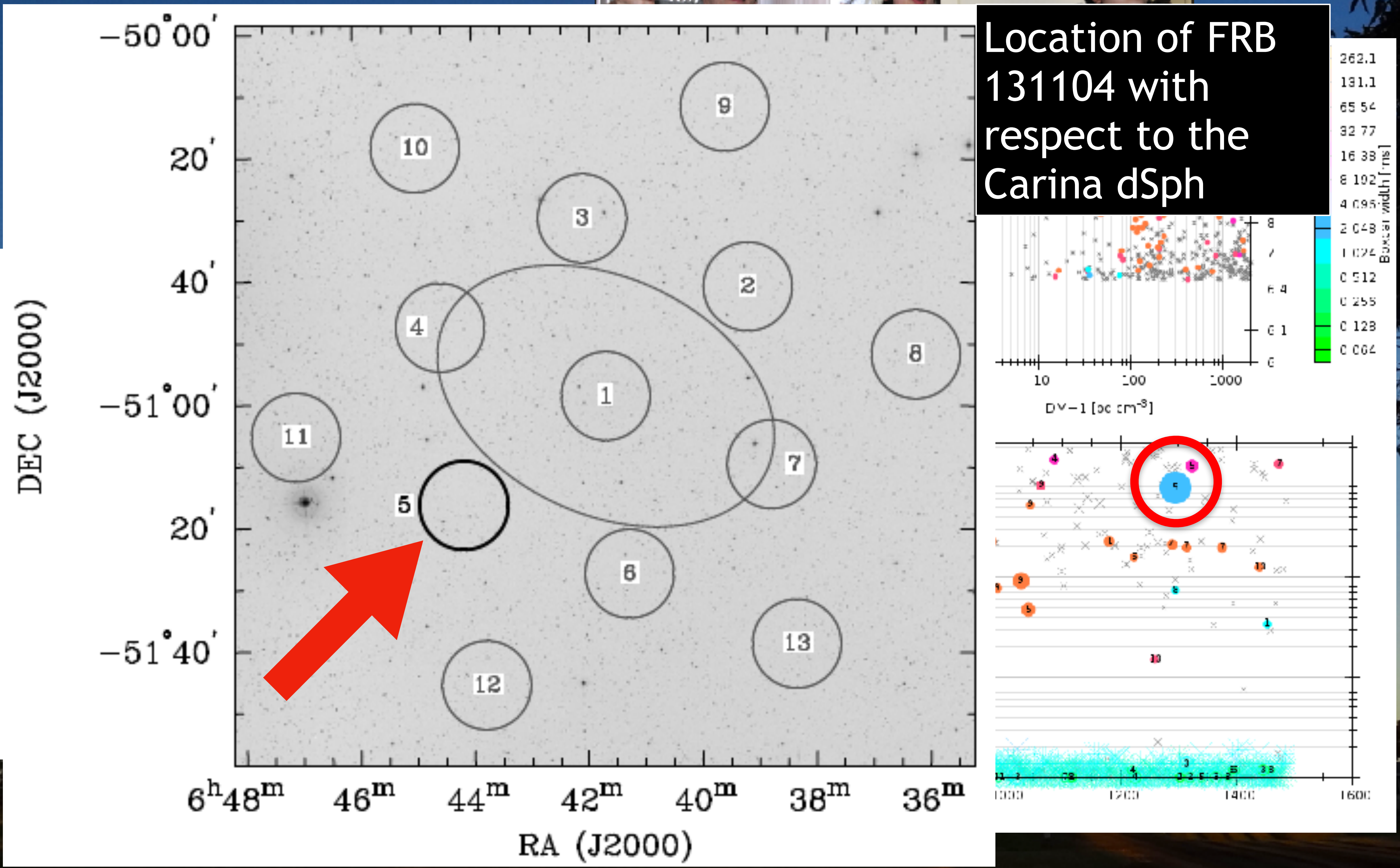
Fast Radio Bursts

Vikram Ravi

Caltech – Millikan fellow

http://astro.caltech.edu/~vikram/

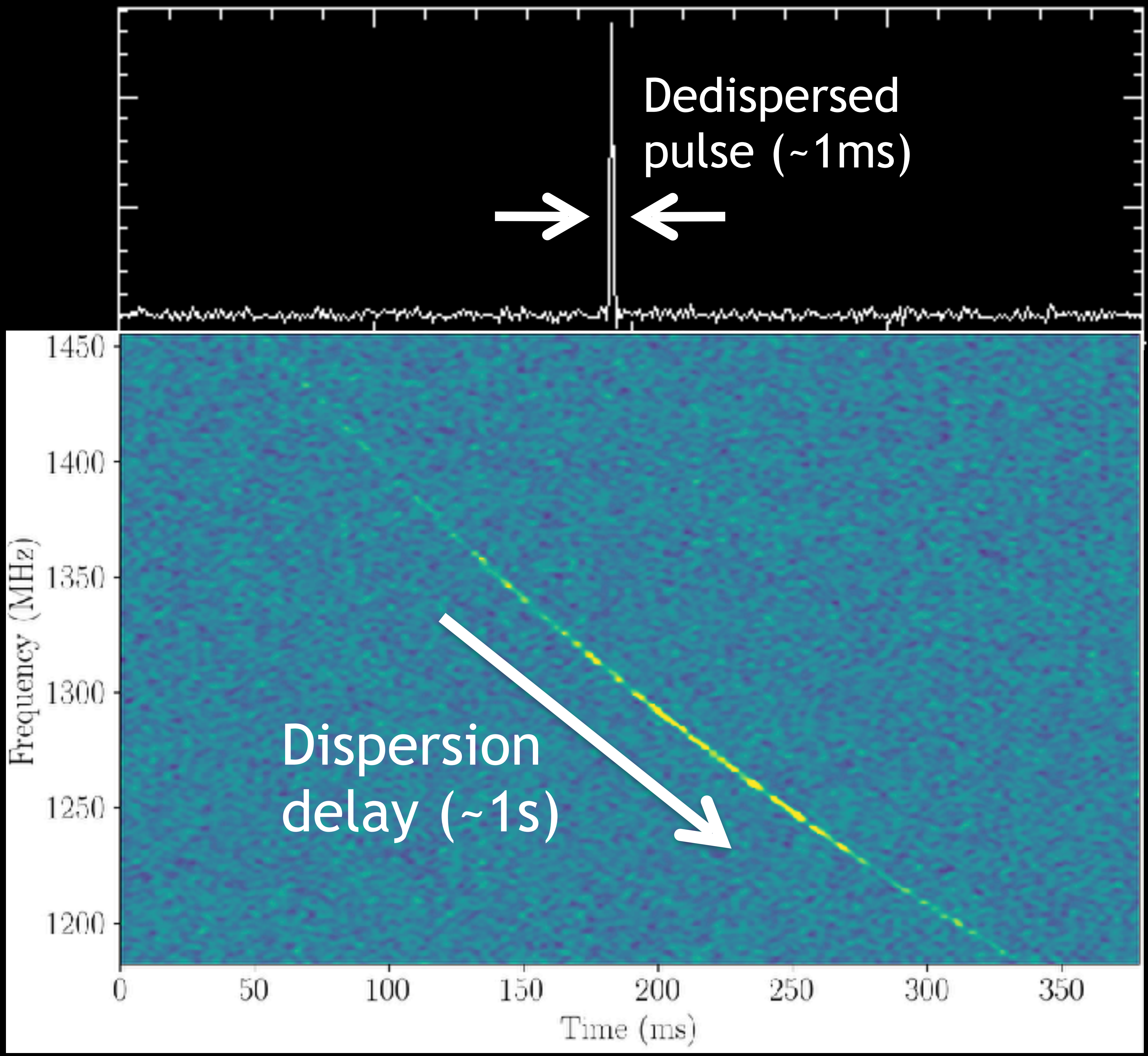
Perfect efficiency for a perfect telescope:
A Parkes transit survey for pulsed radio emission during windstows and maintenance



Location of FRB 131104 with respect to the Carina dSph

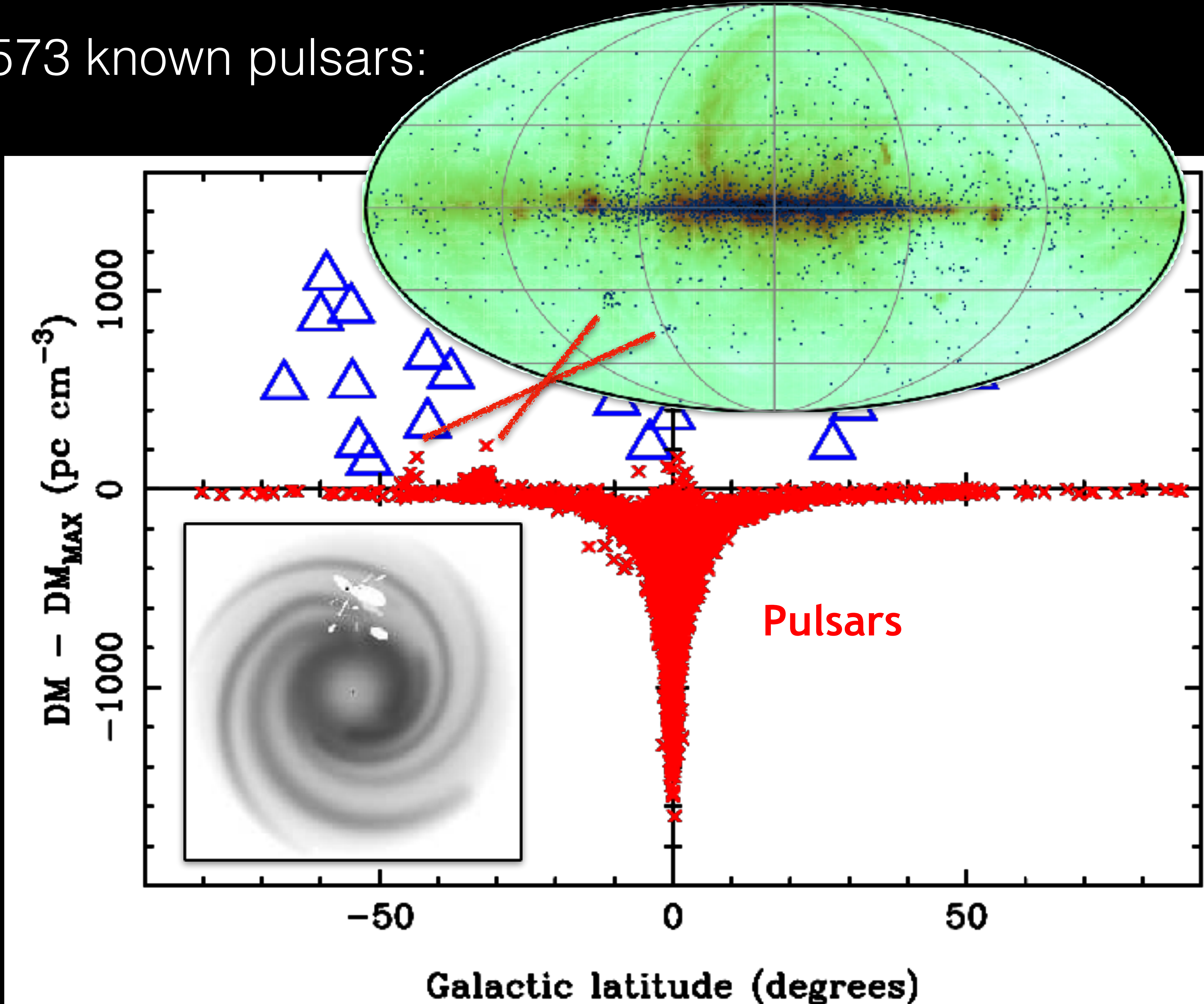
Ravi+2015

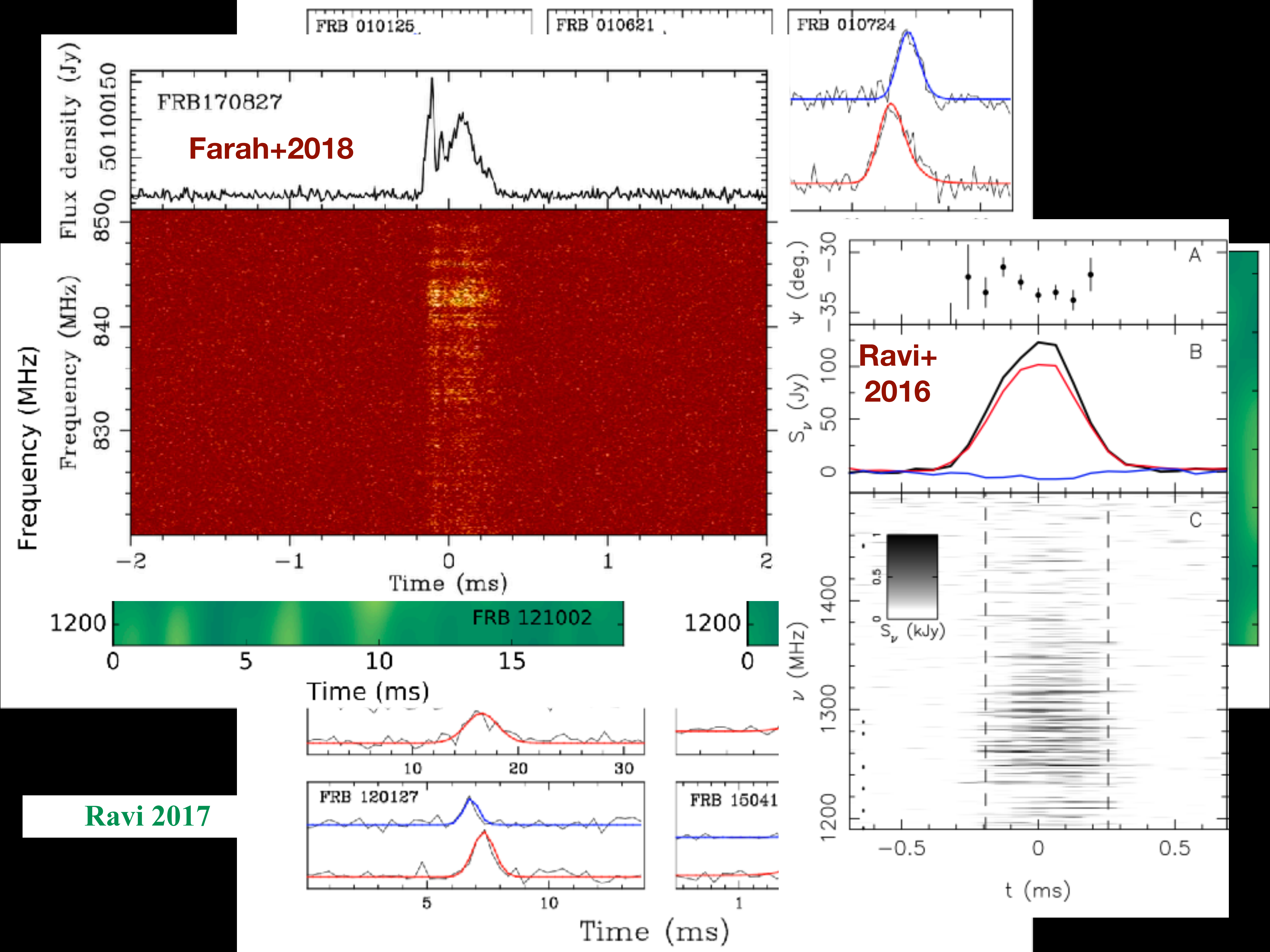
Ravi+2016



Dedispersed pulse (~1ms)
Dispersion delay (~1s)
Frequency (MHz)
Time (ms)
1450
1400
1350
1300
1250
1200
0
50
100
150
200
250
300
350

2573 known pulsars:





FRB 010125
FRB 010621
FRB 010724
FRB170827
Farah+2018
Flux density (Jy)
0 50 100 150
Frequency (MHz)
Frequency (MHz)
830 840 850
Time (ms)
−2 −1 0 1 2
Ψ (deg.)
−35 −30
A
B
C
Ravi+ 2016
S_ν (Jy)
0 50 100
ν (MHz)
1200 1300 1400
S_ν (kJy)
0 0.5
−0.5 0 0.5
t (ms)
1200
FRB 121002
0 5 10 15
Time (ms)
10 20 30
FRB 120127
FRB 15041
5 10
1
Time (ms)
Ravi 2017

A few x 10^3 sky^{-1} day^{-1},

>2 Jy ms,

distant extragalactic (>~10^{42} erg s^{-1}),

10^4 - 10^7 Gpc^{-3} yr^{-1},

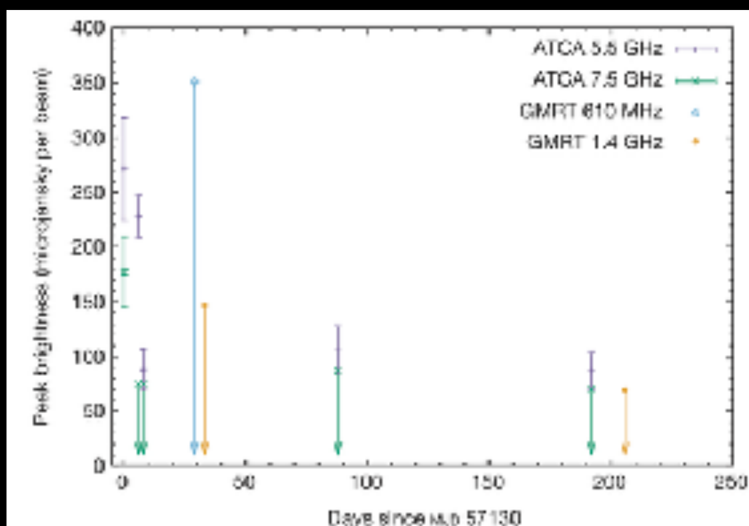
microsecond-millisecond,

coherent bursts.

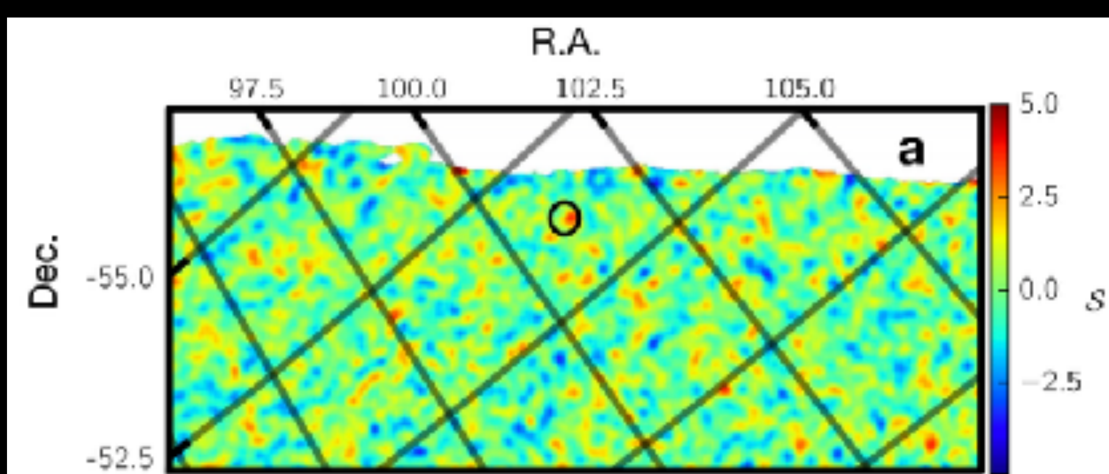
No variable counterparts to FRBs

Null results: e.g., Petroff+2015;
Shannon & Ravi 2017

Claims

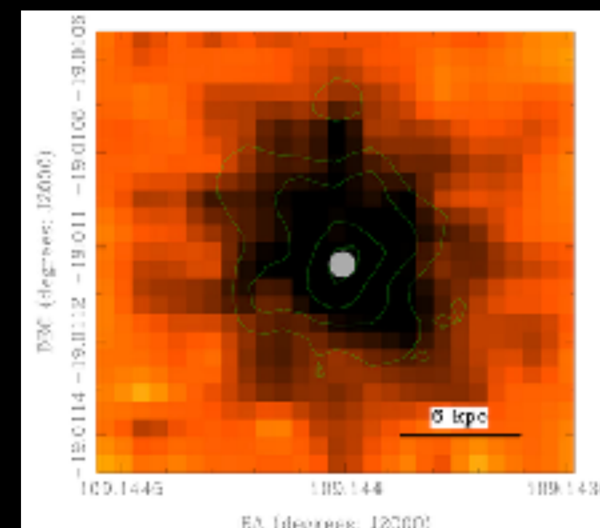


Keane+2016 claim of associated radio transient.



DeLaunay+2016 claim of long-duration 5e51 erg GRB.

Issues

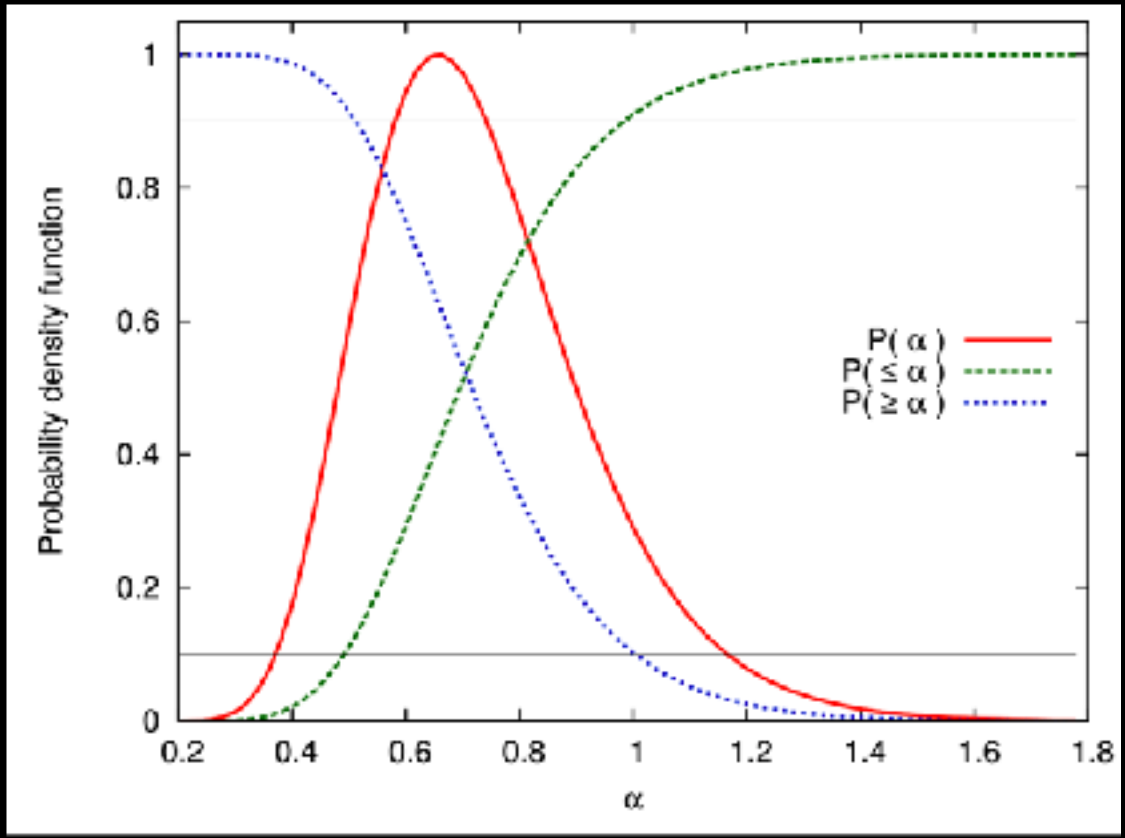


Found to be a variable, nuclear AGN-like source (e.g., Vedantham, Ravi +2016)

1. Large FRB localization regions
2. High FRB rate (e.g., only 1/350 - 1/700 FRBs could have associated long-duration GRBs.)
3. Background rate estimation.
4. Trials factor in counterpart searches.

Clues from population statistics?

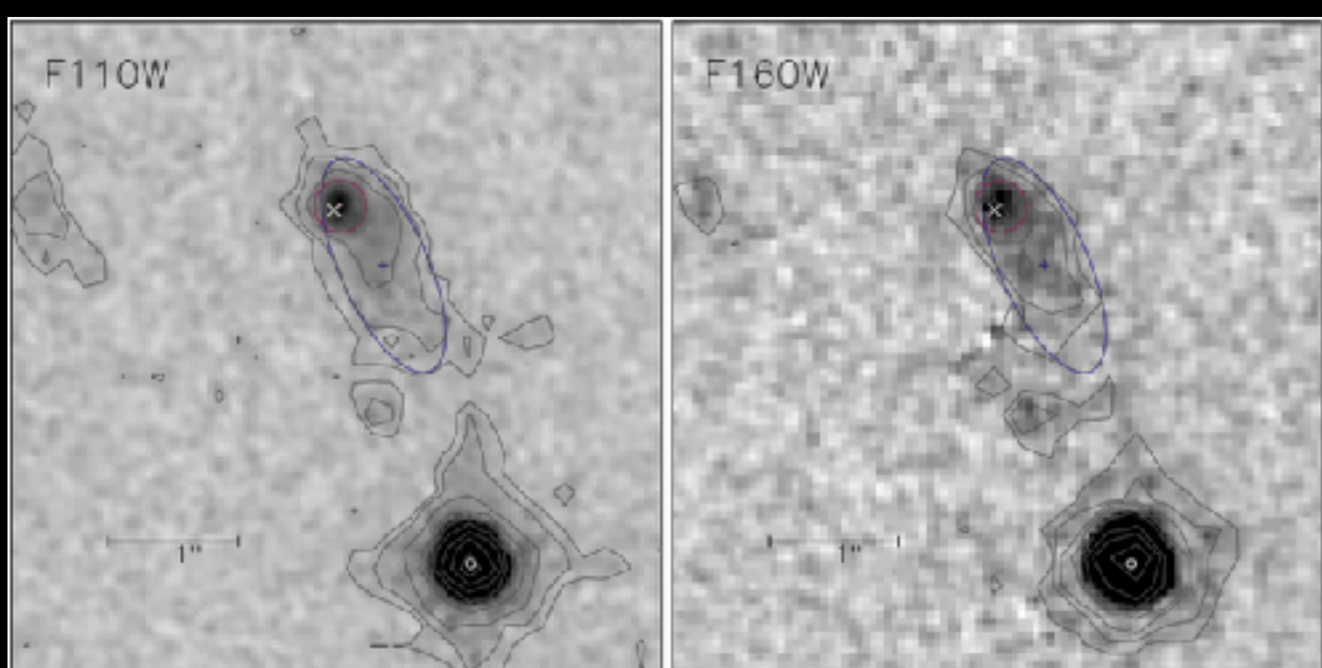
Non-Euclidean fluence distribution?
e.g., Vedantham, Ravi +2016



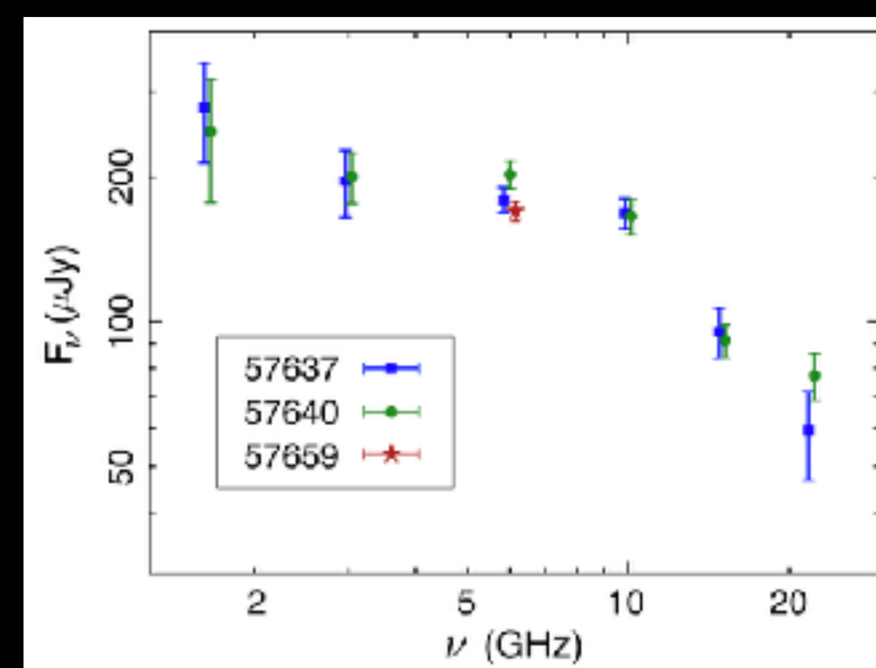
Also see Scholz+2016, Connor+2016a/b, Caleb+2016/17, Macquart & Ekers 2018a/b, and several conference presentations, discussion sessions, corridor conversations, etc.

The repeating FRB 121102: the host galaxy

1. Dwarf (~5e7 Msun), star-forming (0.4 Msun/yr), z~0.2.
2. A persistent, compact, on-axis AGN-like radio source.
3. An AGN-like magneto-ionic environment for the FRB host.
   - Variable RM of >10^5 rad/m^2



Host galaxy

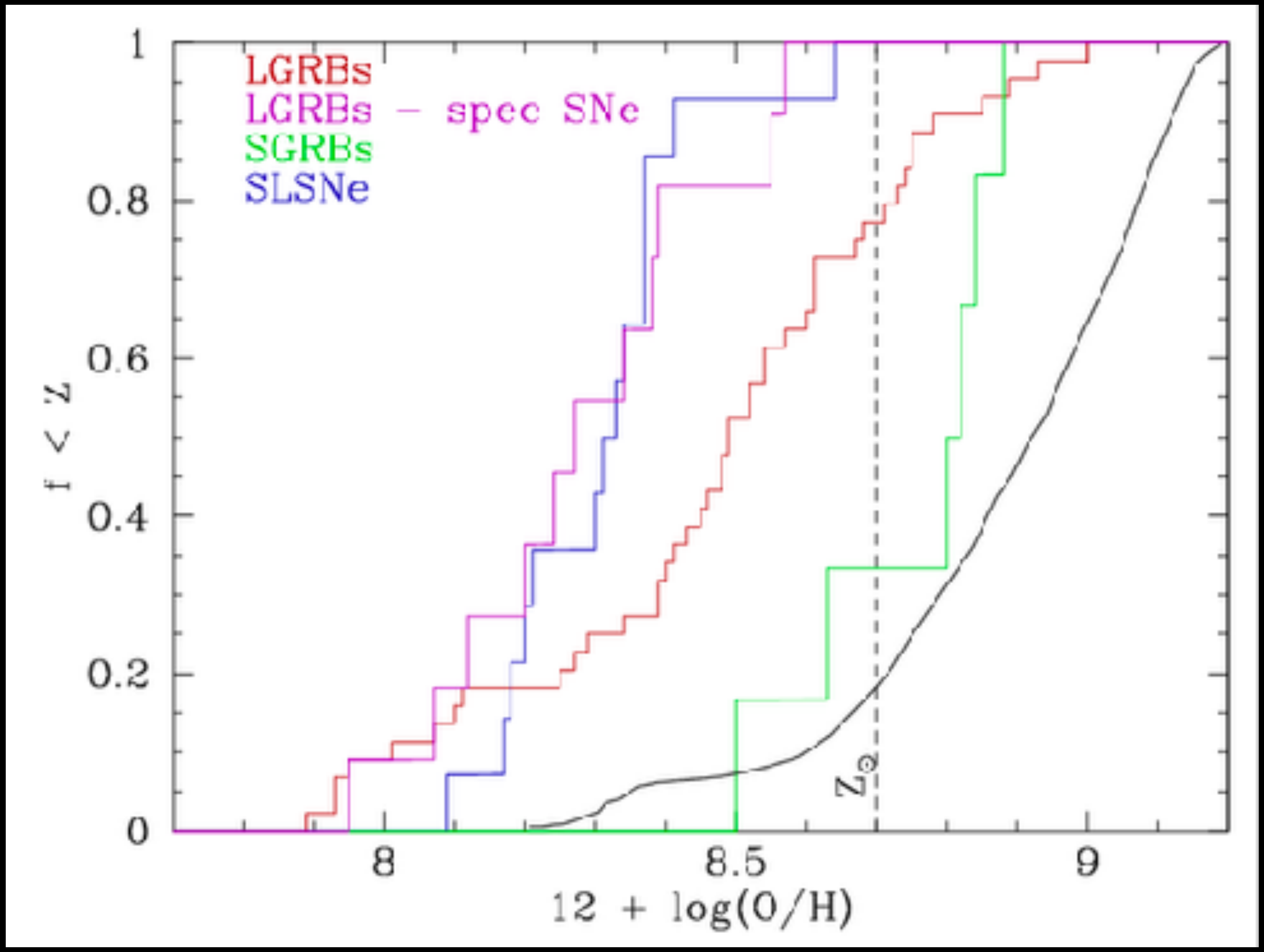


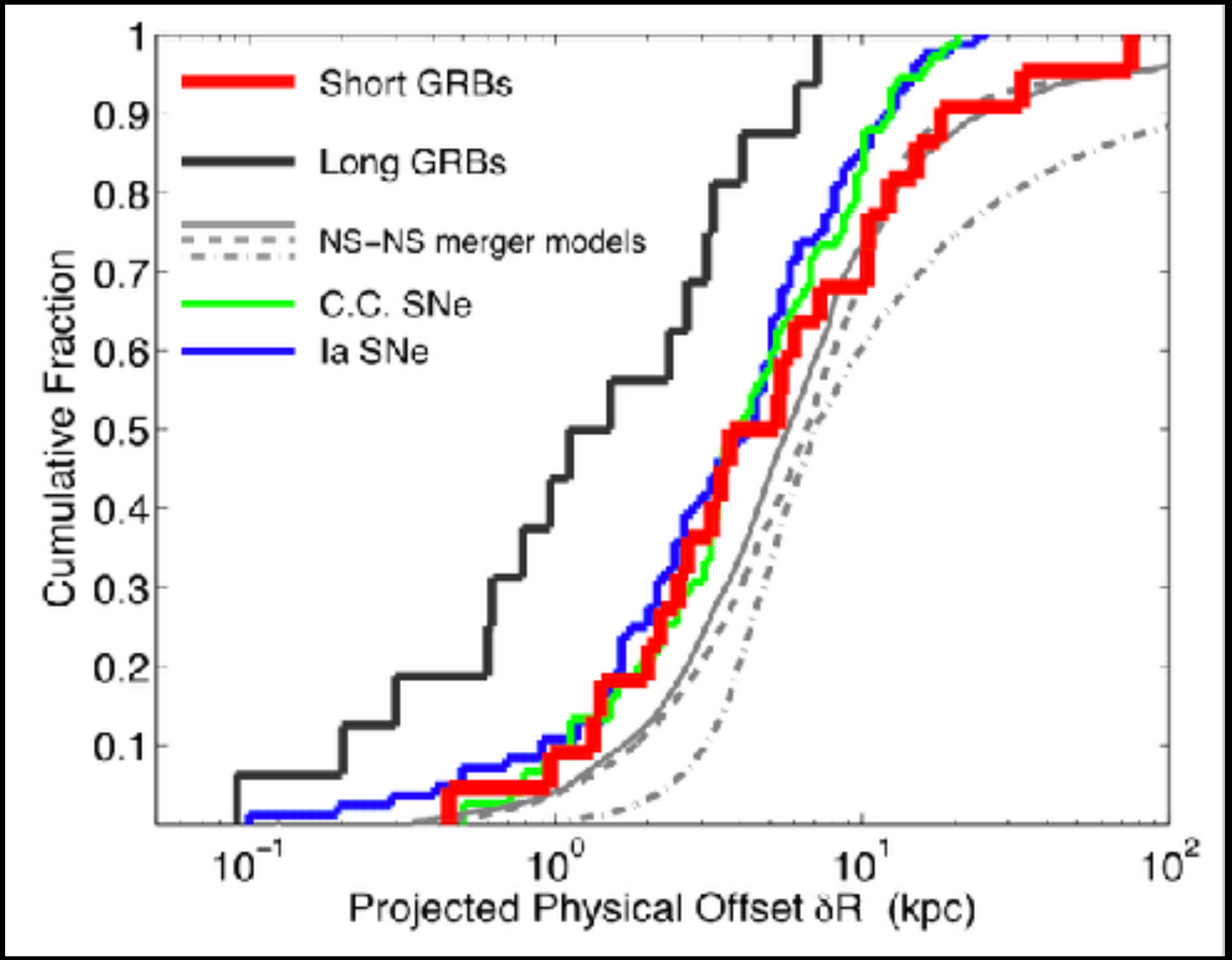
Persistent radio source

Chatterjee+2017, Michilli+2018

What are FRBs? The short-GRB analogy

Lack of identifiable counterpart objects, variety of possible progenitor channels.

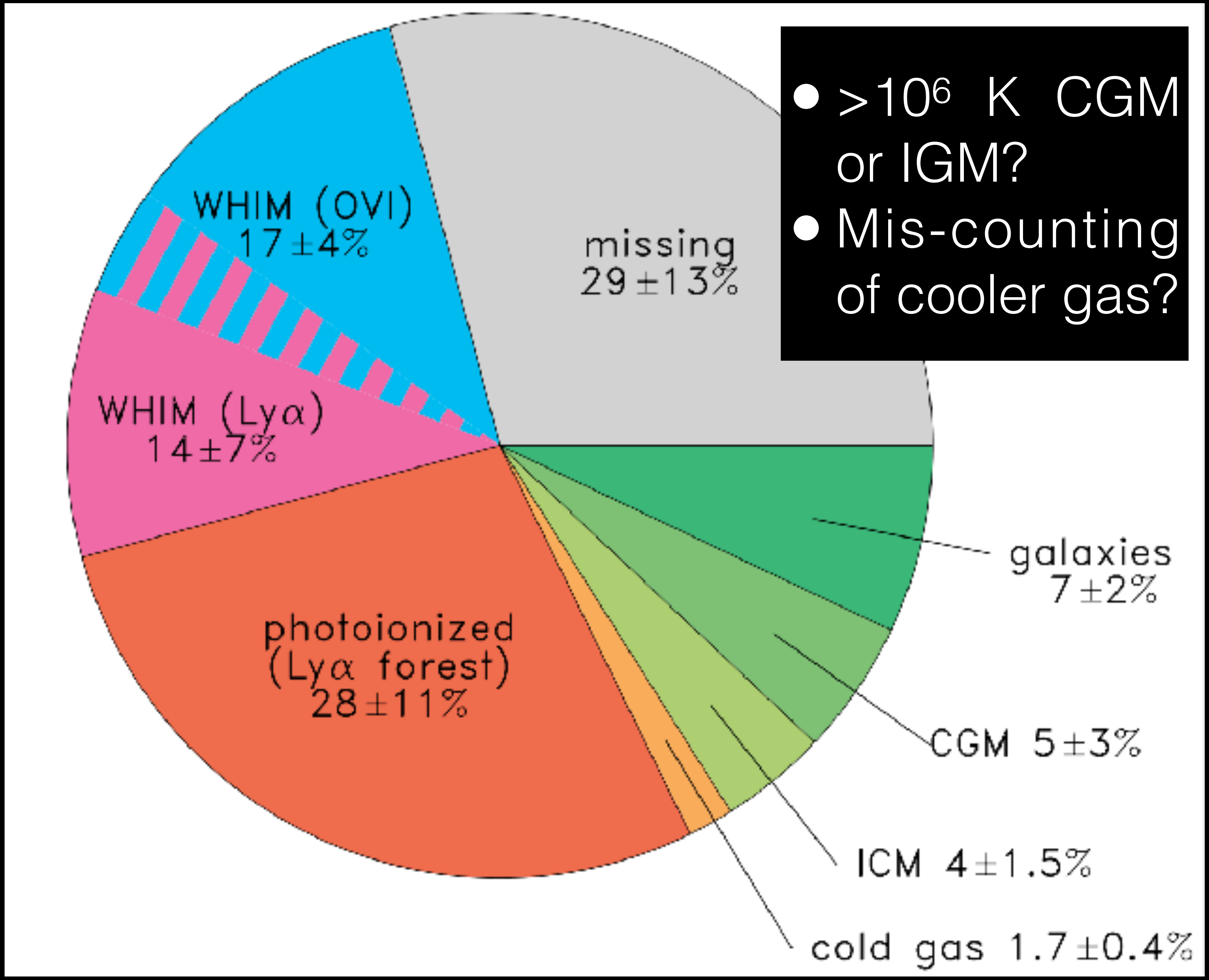




Levan+2016, Berger 2014

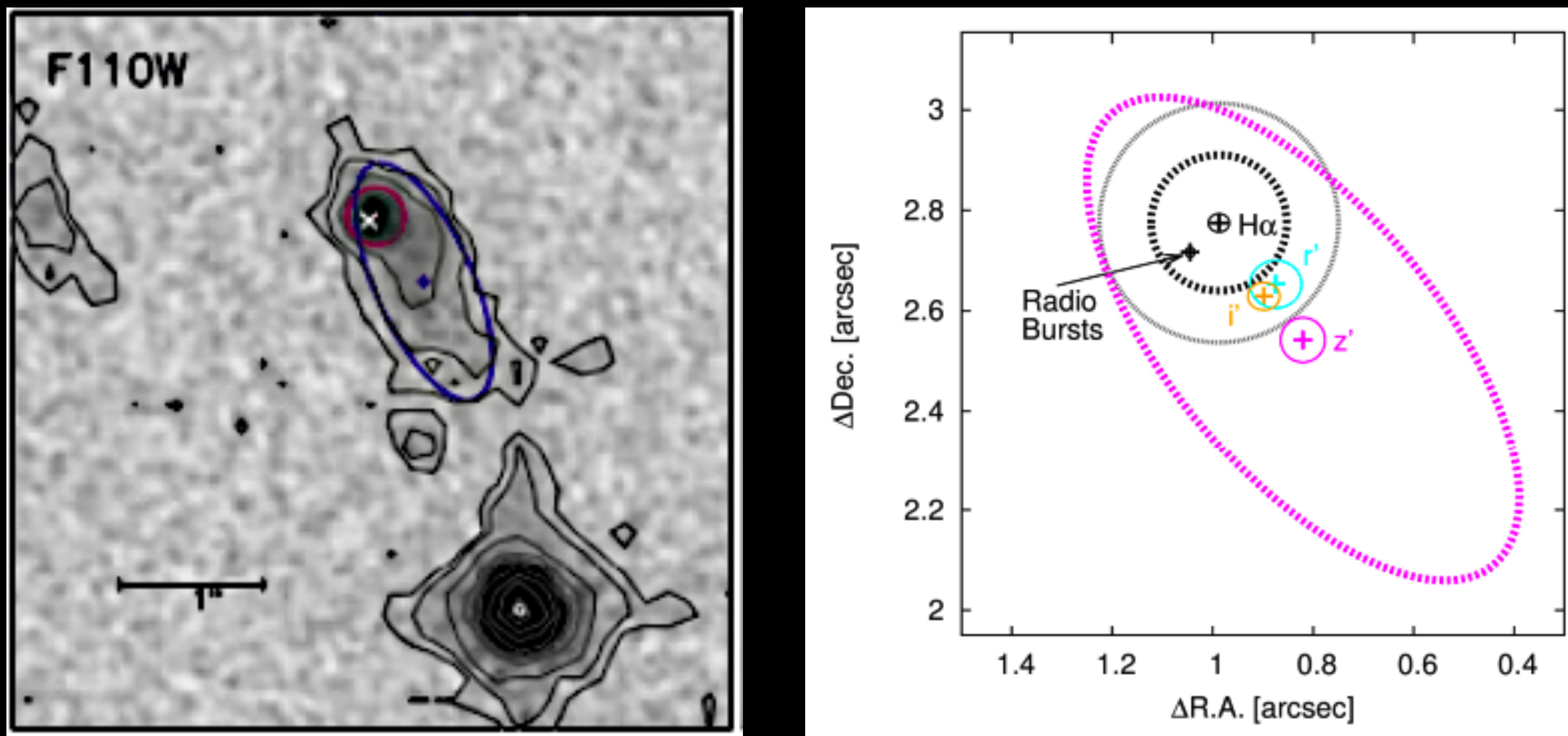
"Missing" baryons with mysterious physical properties

Shull+2012

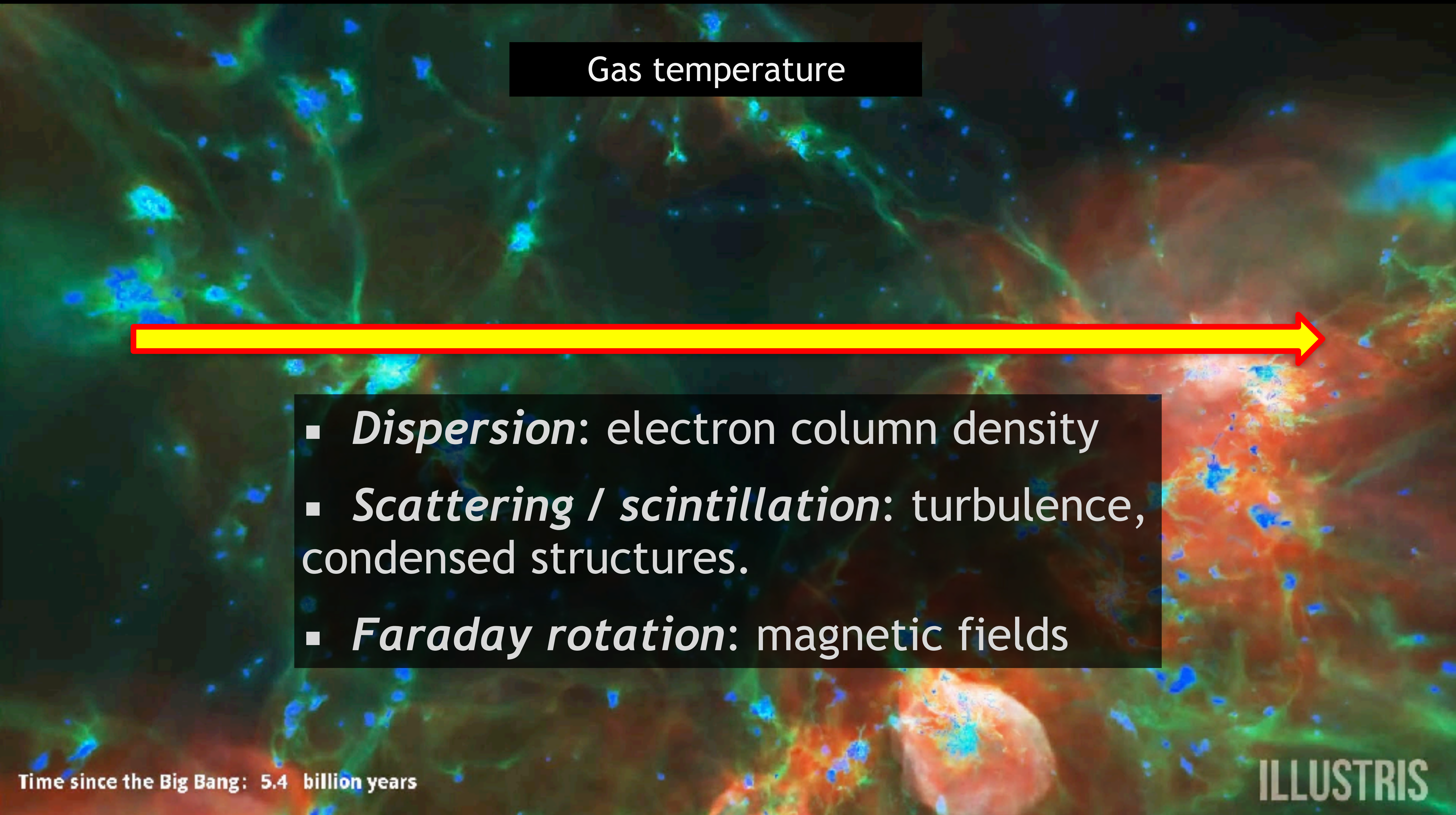


- $>10^6$ K CGM or IGM?
- Mis-counting of cooler gas?

The repeating FRB 121102 implies that >25% of the baryons along its sightline are in the CGM/IGM.

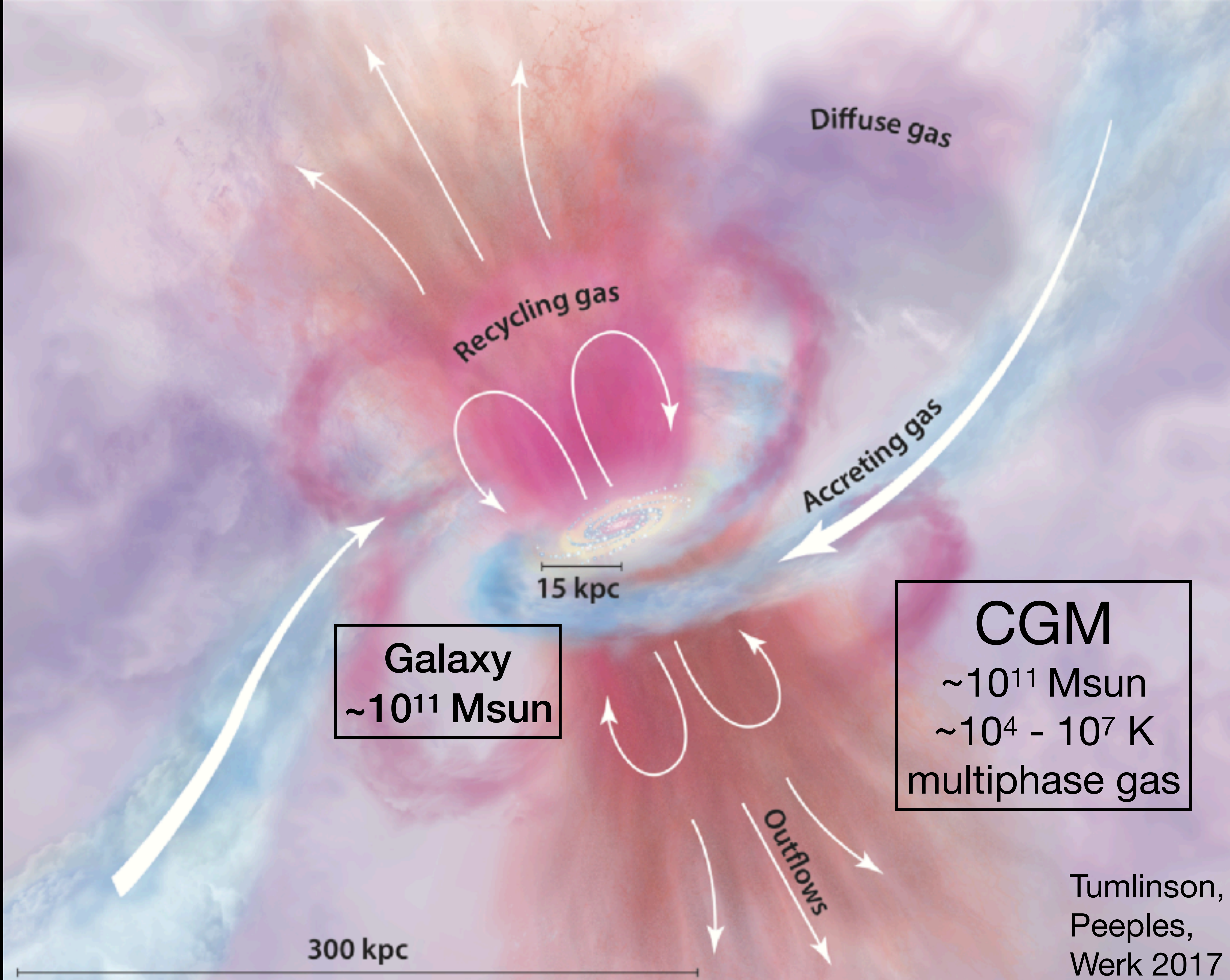


Bassa+2017, Kokubo+2017, Tendulkar+2017

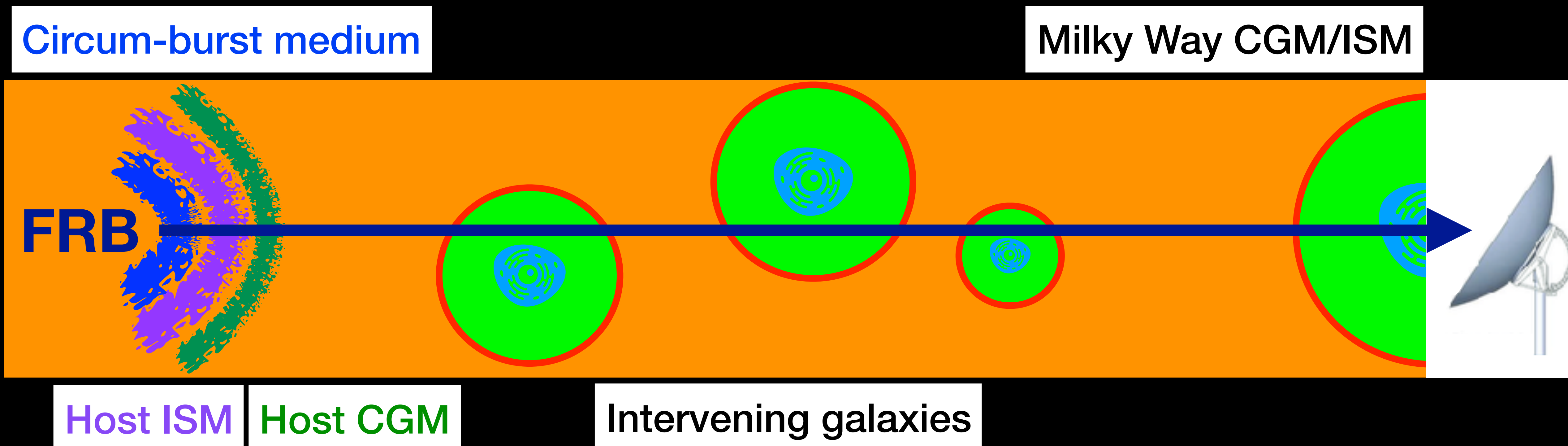


- ***Dispersion***: electron column density
- ***Scattering / scintillation***: turbulence, condensed structures.
- ***Faraday rotation***: magnetic fields

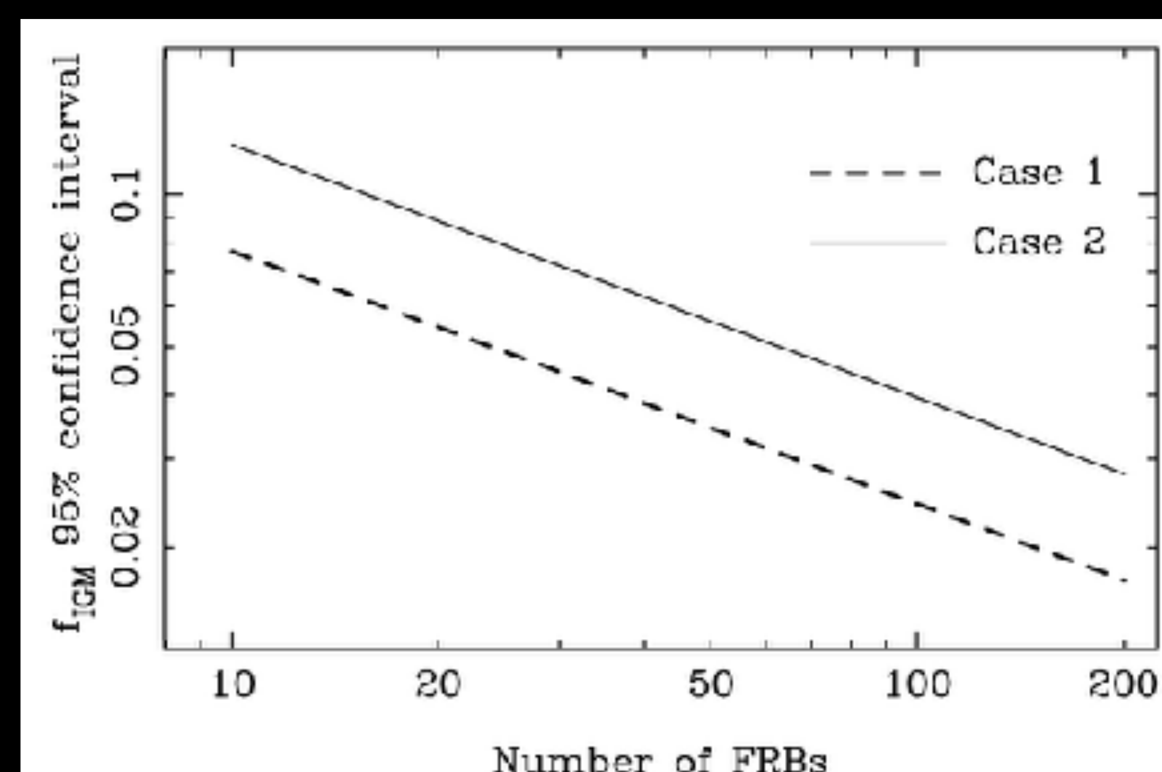
Vogelsberger+2014


Diffuse gas
Recycling gas
Accreting gas
15 kpc
Galaxy
~10^11 Msun
CGM
~10^11 Msun
~10^4 - 10^7 K
multiphase gas
Outflows
300 kpc
Tumlinson, Peeples, Werk 2017

By combining FRB DM estimates at different impact parameters to intervening galaxies, the baryon contents of the CGM and IGM can be measured.

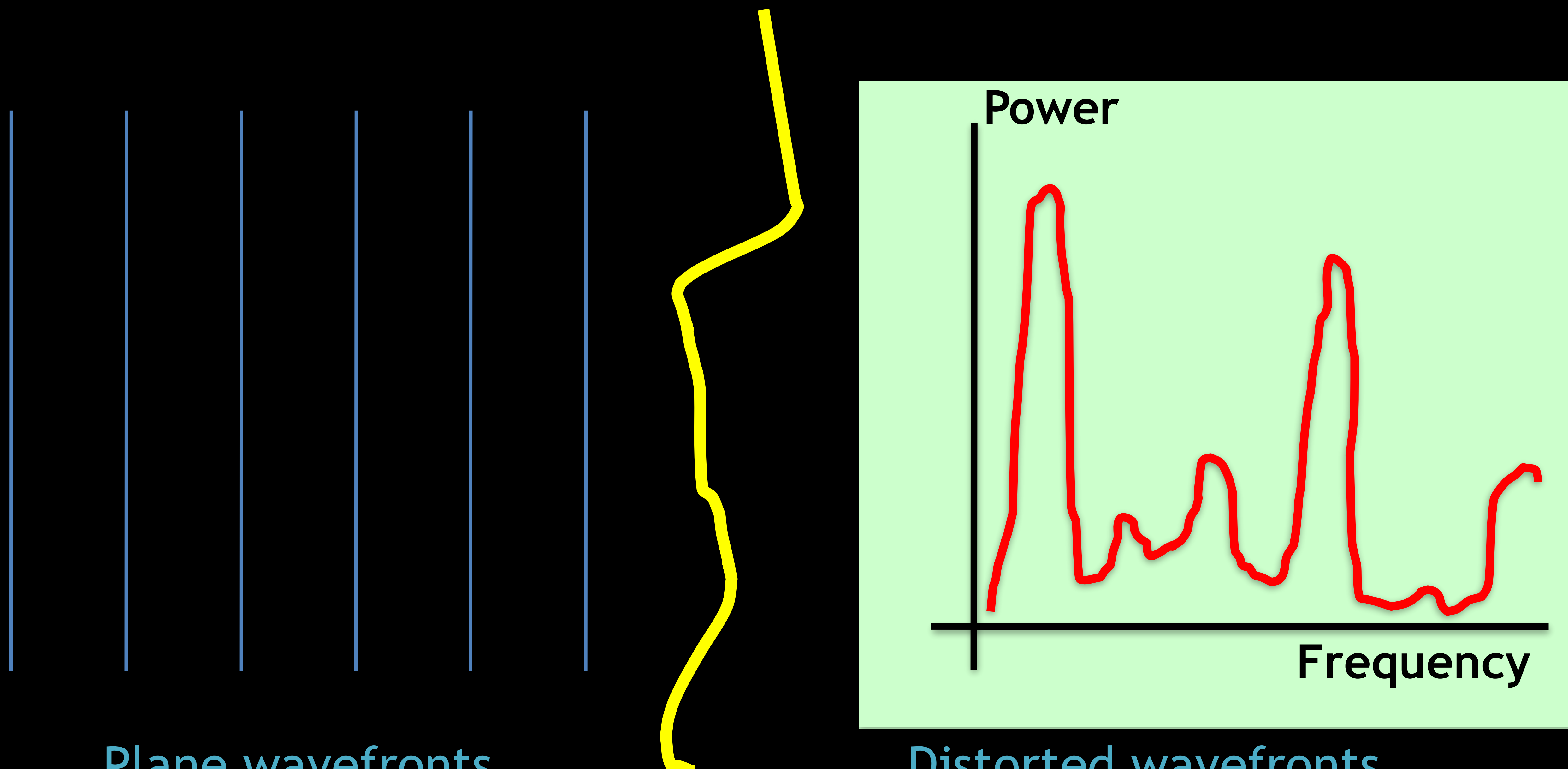


95% confidence constraints on the fraction of cosmic baryons in the IGM, with different numbers of localized FRBs.



Ravi 2018, see also McQuinn 2014, Shull & Danforth 2018

Scattering in inhomogeneous plasma
(observed in half the FRBs)

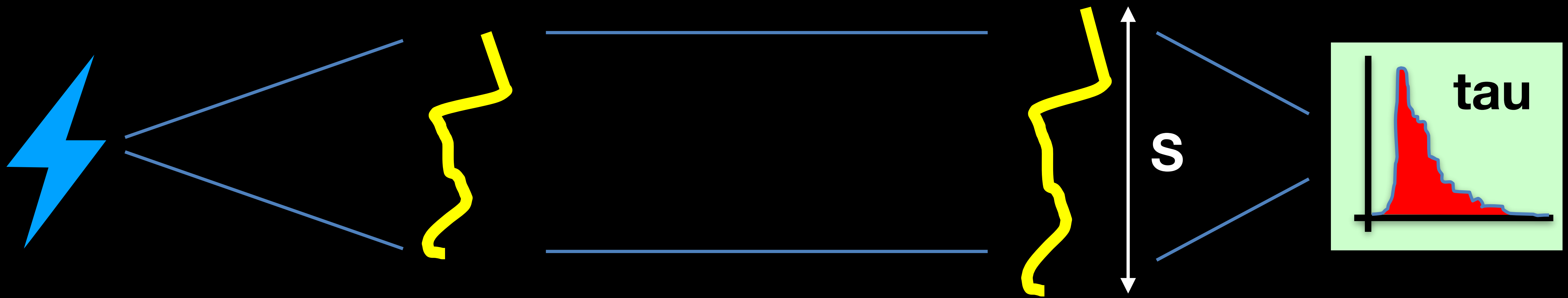


Plane wavefronts

"Screen" of
electron-density
fluctuations

Distorted wavefronts

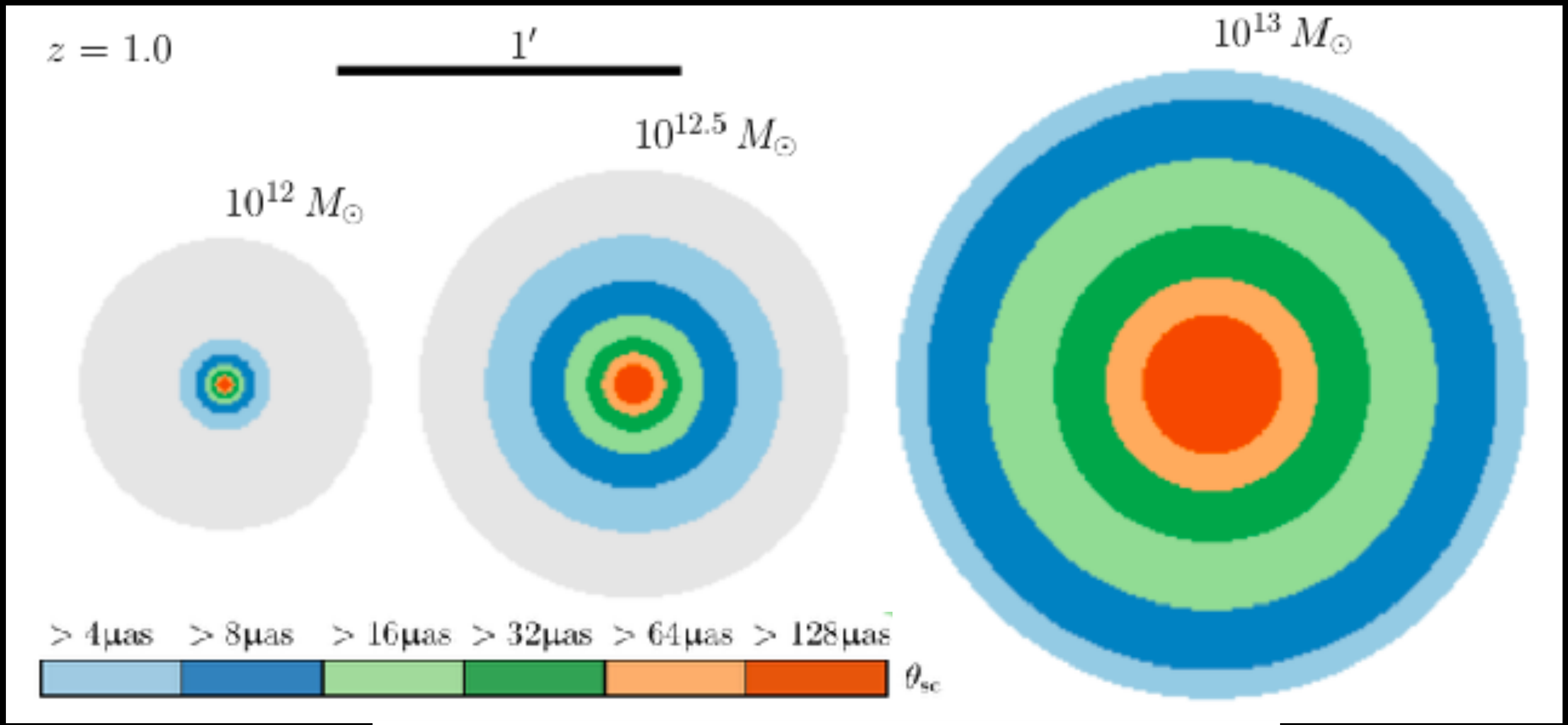
Identifying FRB scattering sources



e.g., Host screen
Angular size <~ lambda / S

e.g., Galactic screen
Size S ~ sqrt(2*c*tau*D)

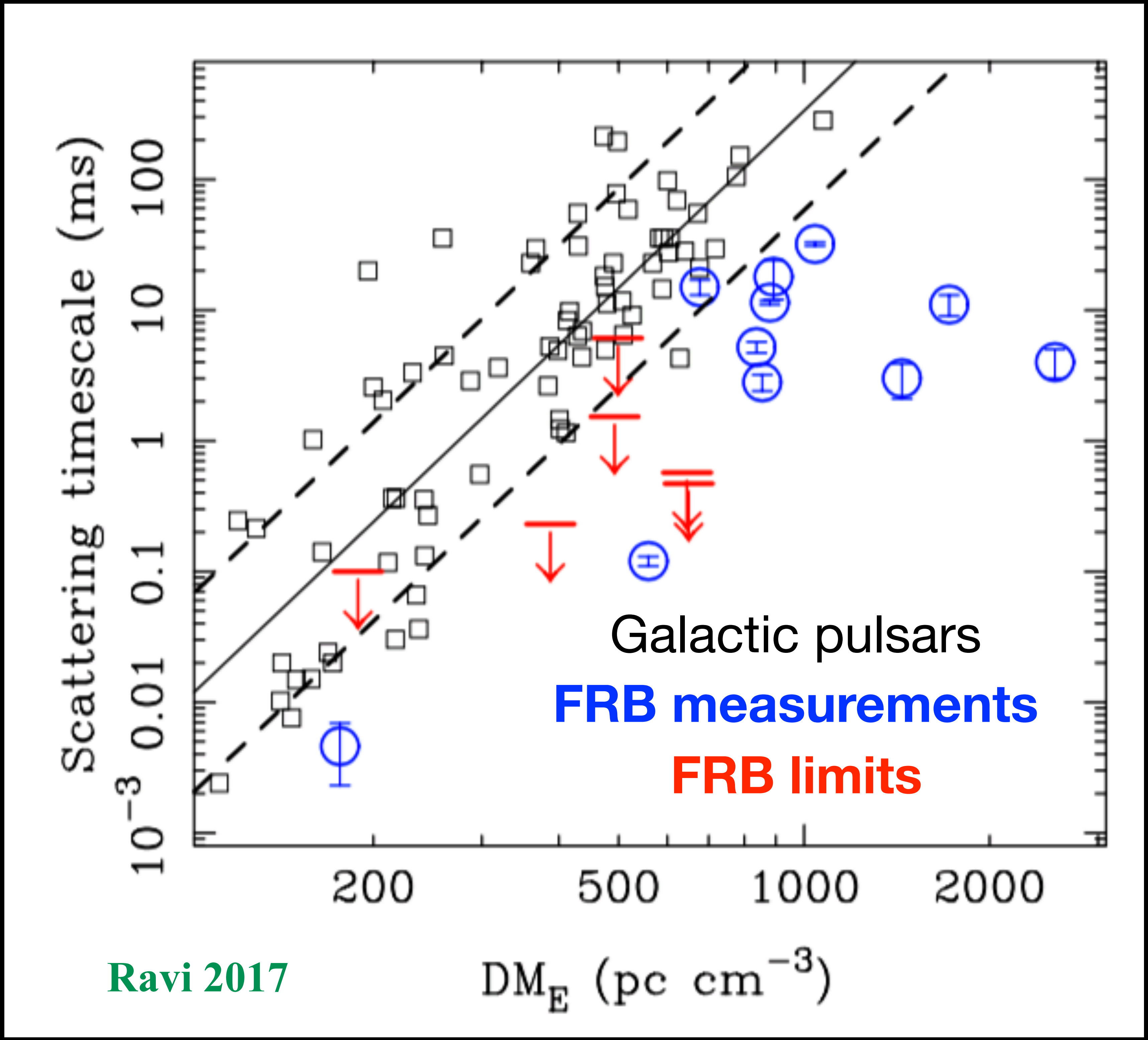
Possible scattering in CGM halos could be identified by association with intervening galaxies. Note that tau ~ (scattering angle)² * D/c



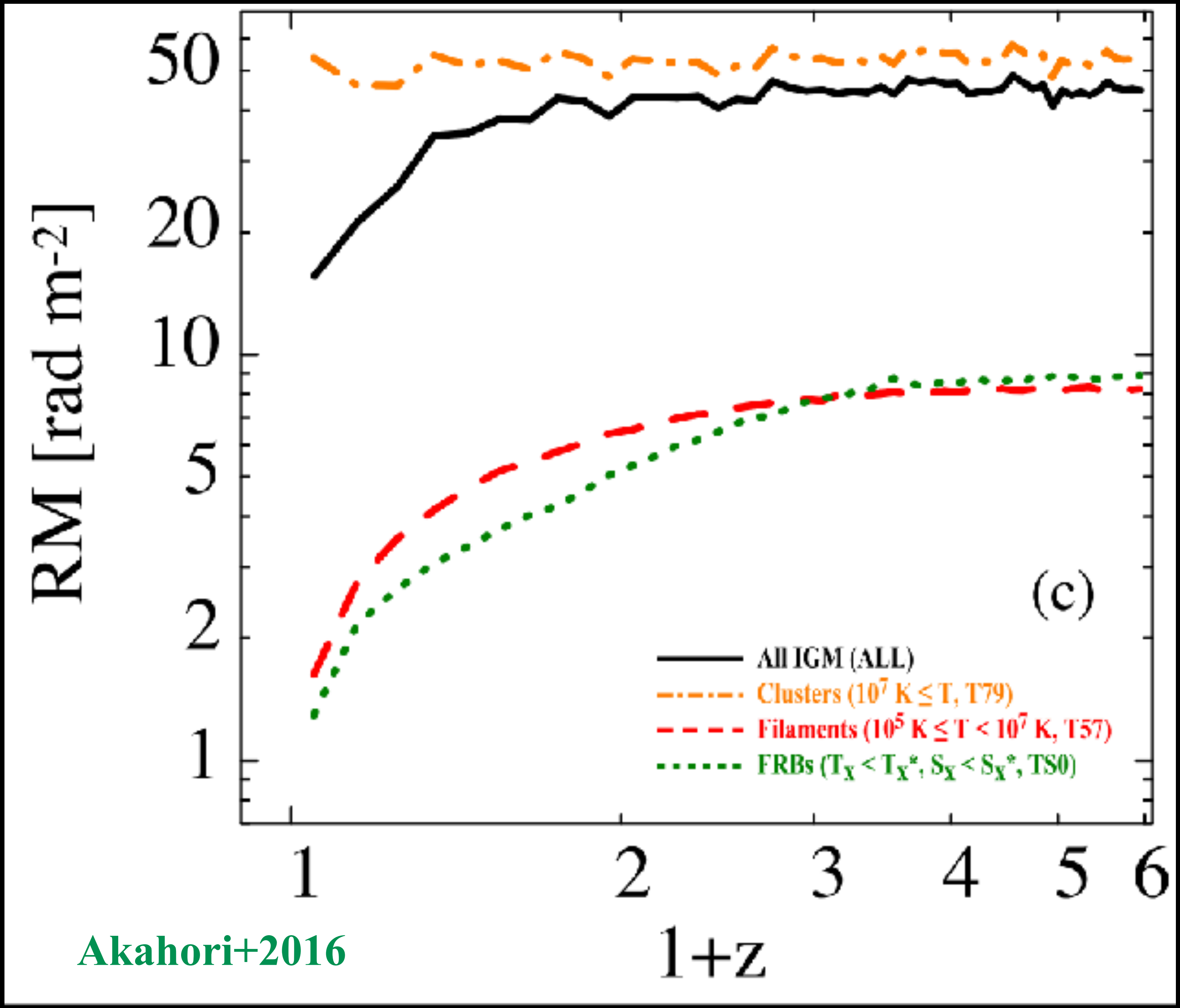
Vedantham & Phinney, submitted.

FRB scattering timescales v DM

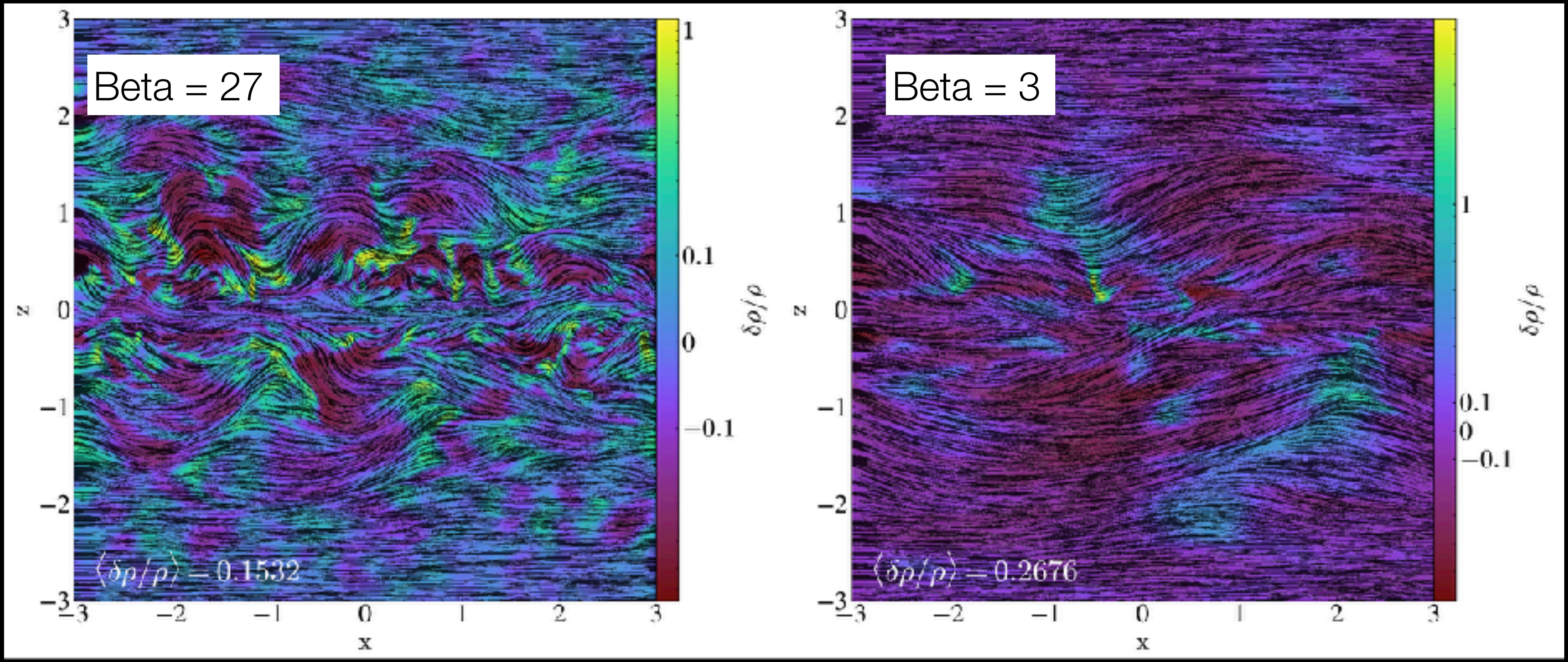
DM ~ 1200z cm^{-3} pc. Only a homogeneous Parkes sample is included.



Contributions to extragalactic FRB RMs

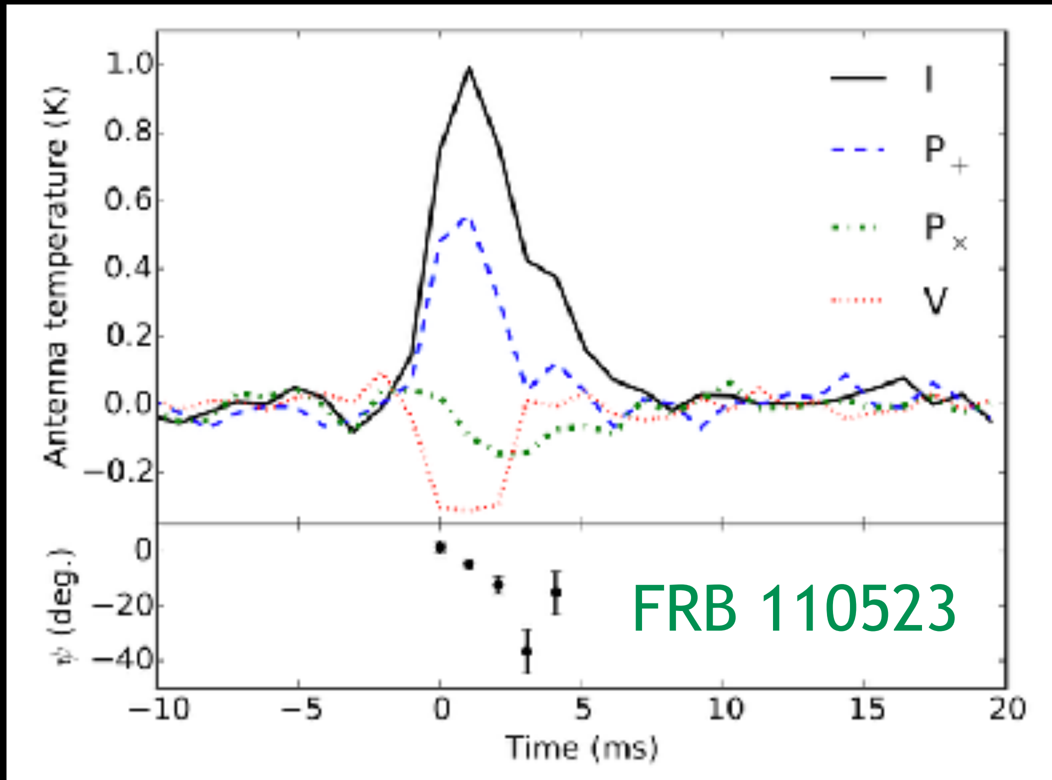


Contributions to extragalactic FRB RMs



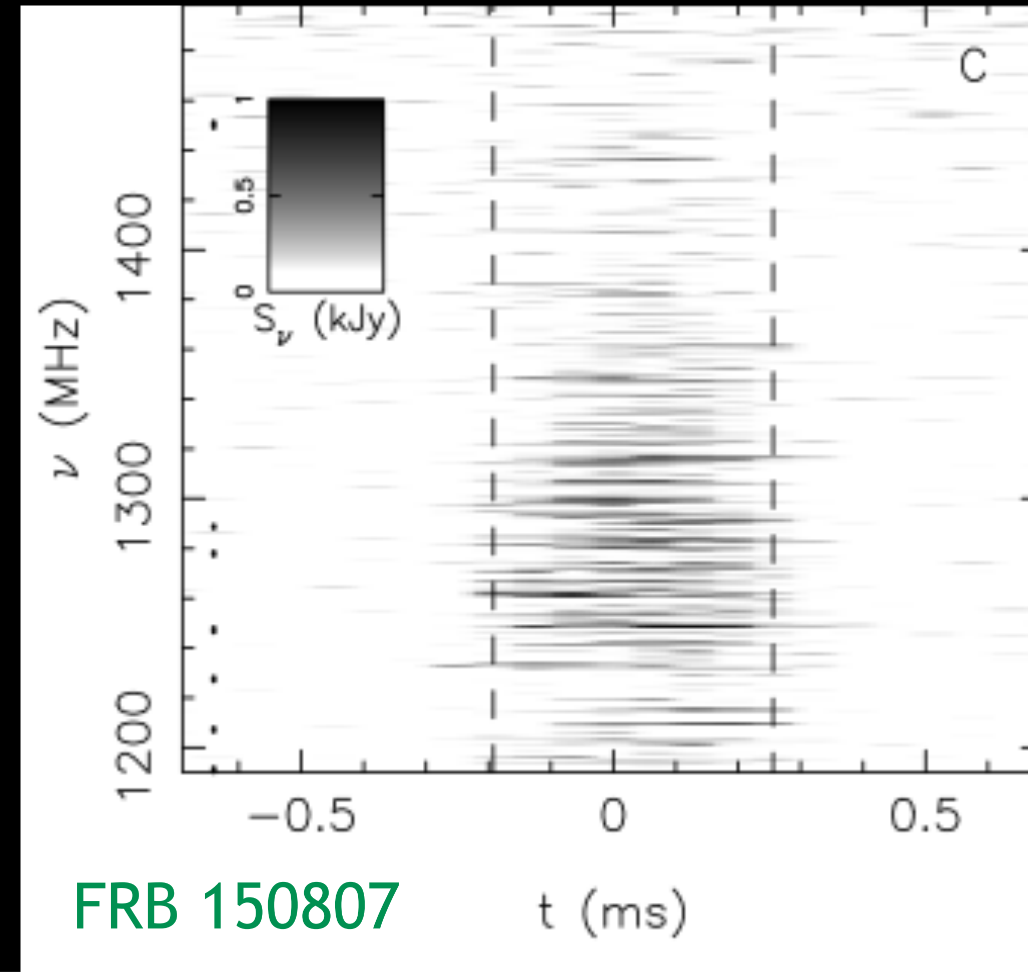
~Micro-gauss fields in galaxy and cluster halos are an attractive solution to the problem of mixed, multi-phase CGM halos. Thermal instabilities are enhanced on scales below (Alfven speed) x (cooling timescale).

Ji, Oh, McCourt 2018



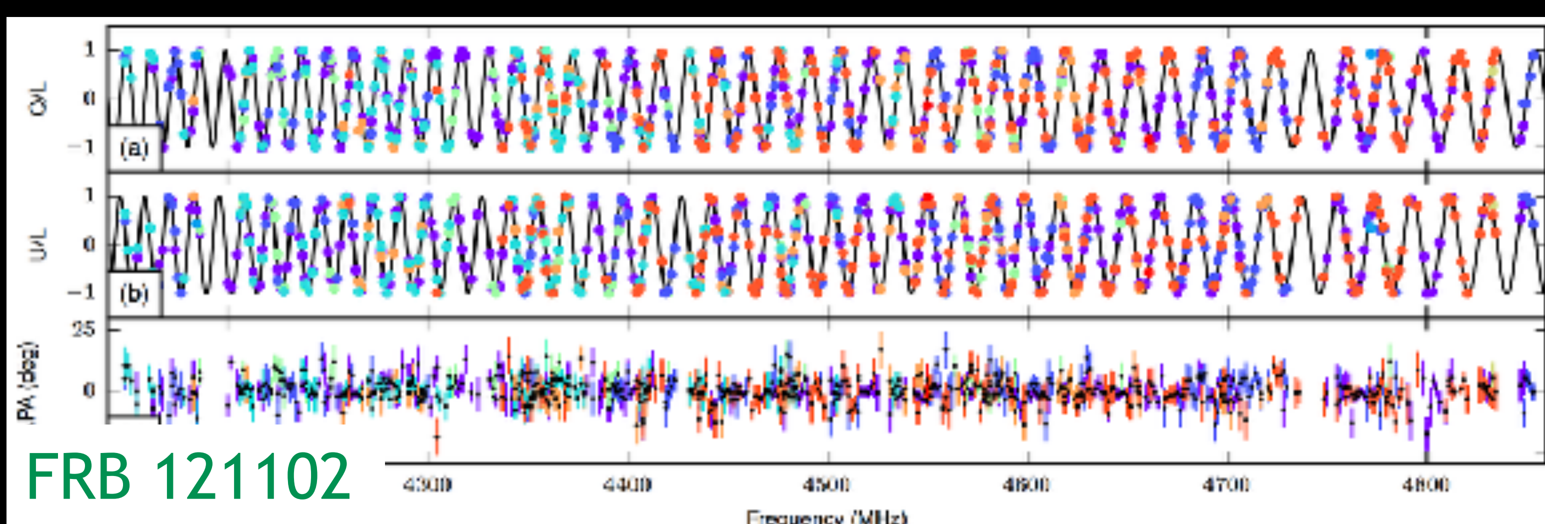
Masui+2015

Scattering: 0.7 ms, host
Faraday rotation: -186.1 rad/m^{-2}, likely host.



Ravi+2016

Scattering: ~0.005 ms, C/IGM
Faraday rotation: <~2 rad/m^{-2}.



Michilli+2018

Scattering: None extragalactic
Faraday rotation: ~1.4e5 rad/m^2, host.

The utility of localized FRBs

What are FRBs?

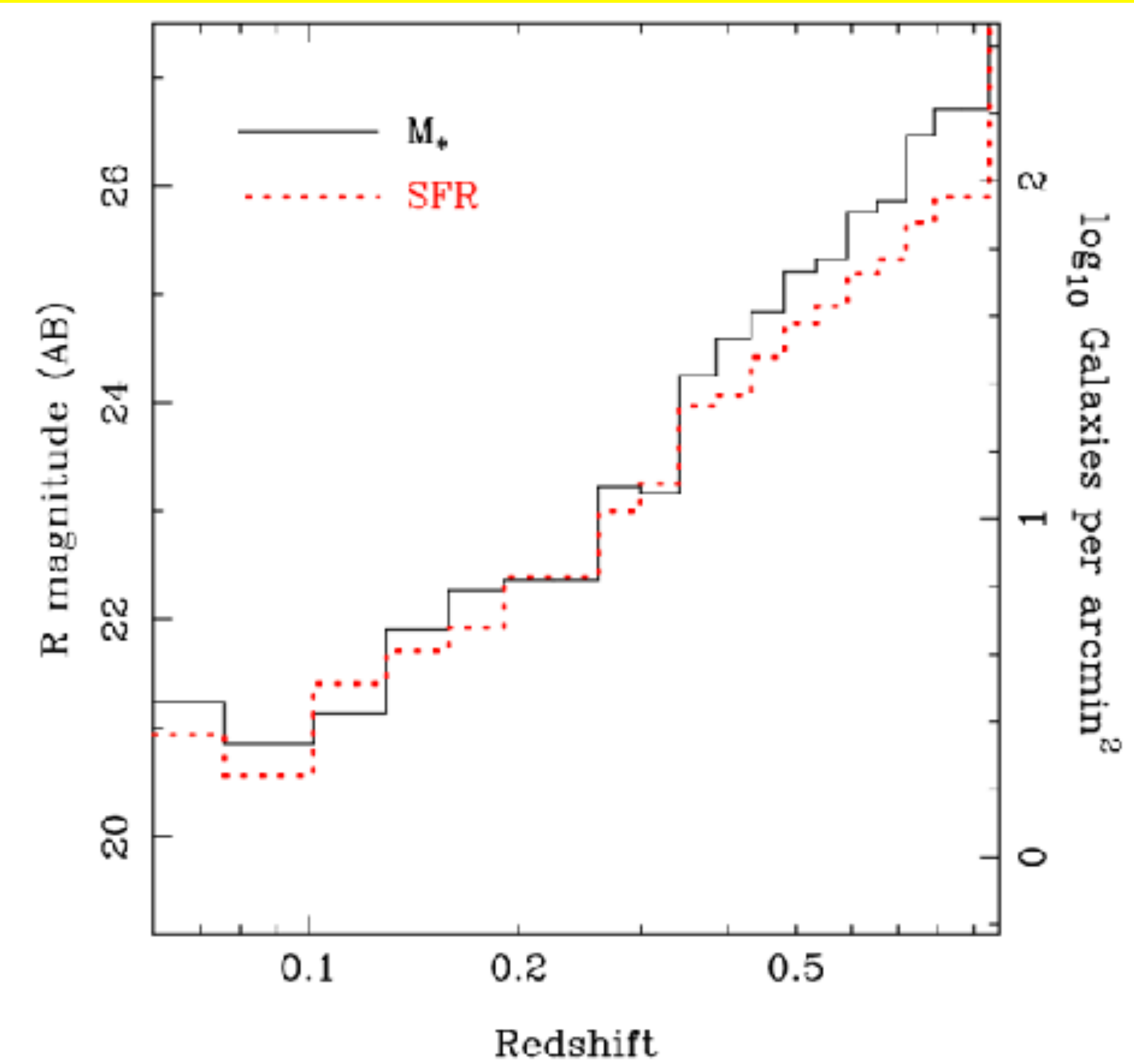
1. Host-galaxy ID -> redshift, host characteristics.
2. Redshifts -> volumetric rate, luminosity function.
3. Projected offset distribution wrt. different populations.
4. Magneto-ionic progenitor environments wrt. observed counterparts (cf. repeating FRB).
5. Possible faint multi-wavelength transient counterparts.

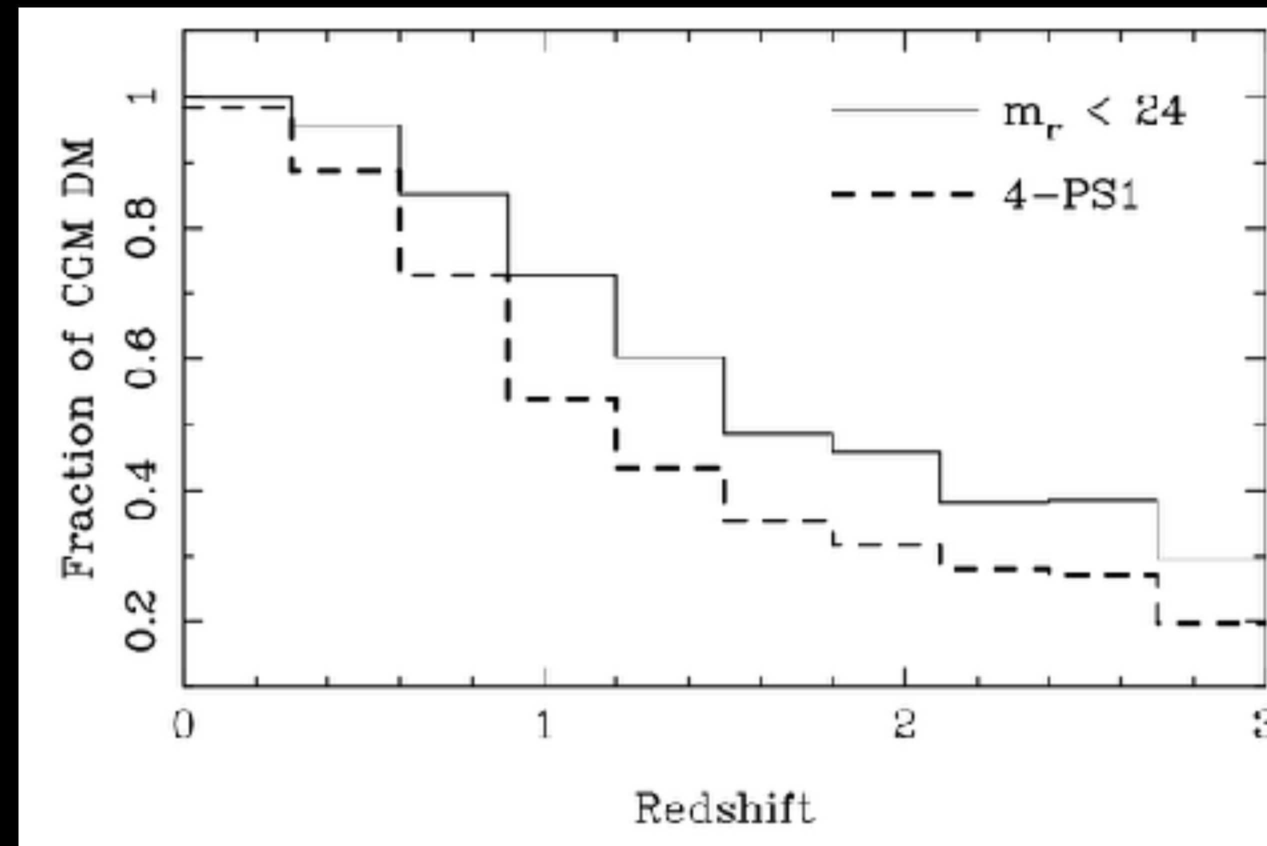
Understanding FRB propagation signatures.

1. Host-galaxy ID -> redshift.
2. CGM density profiles, relative CGM/IGM contents.
3. Bulk physical conditions in CGM.
   - Clumpiness
   - Magnetic fields
4. Cosmic web magnetic fields.

Follow-up observations of FRBs

Imaging/spectroscopy sensitivity, and multiplicity, required to cover 95% of stellar mass and star-formation rate.



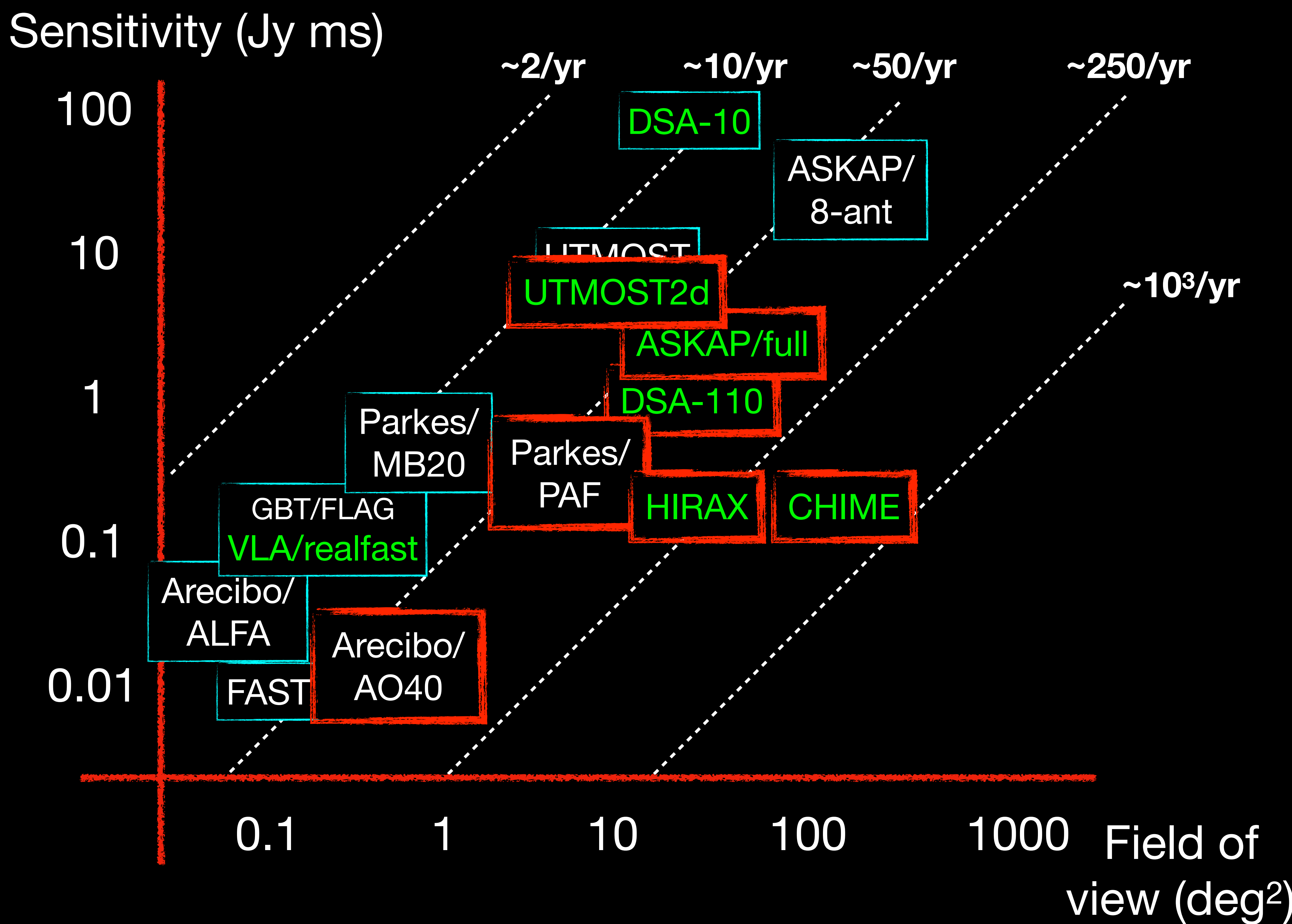


Mean fraction of CGM DM contributions recovered using two different schemes to identify intervening galaxies.

Based on MPA semi-analytic galaxy formation model, Smail+1995 galaxy counts. See Ravi 2018.

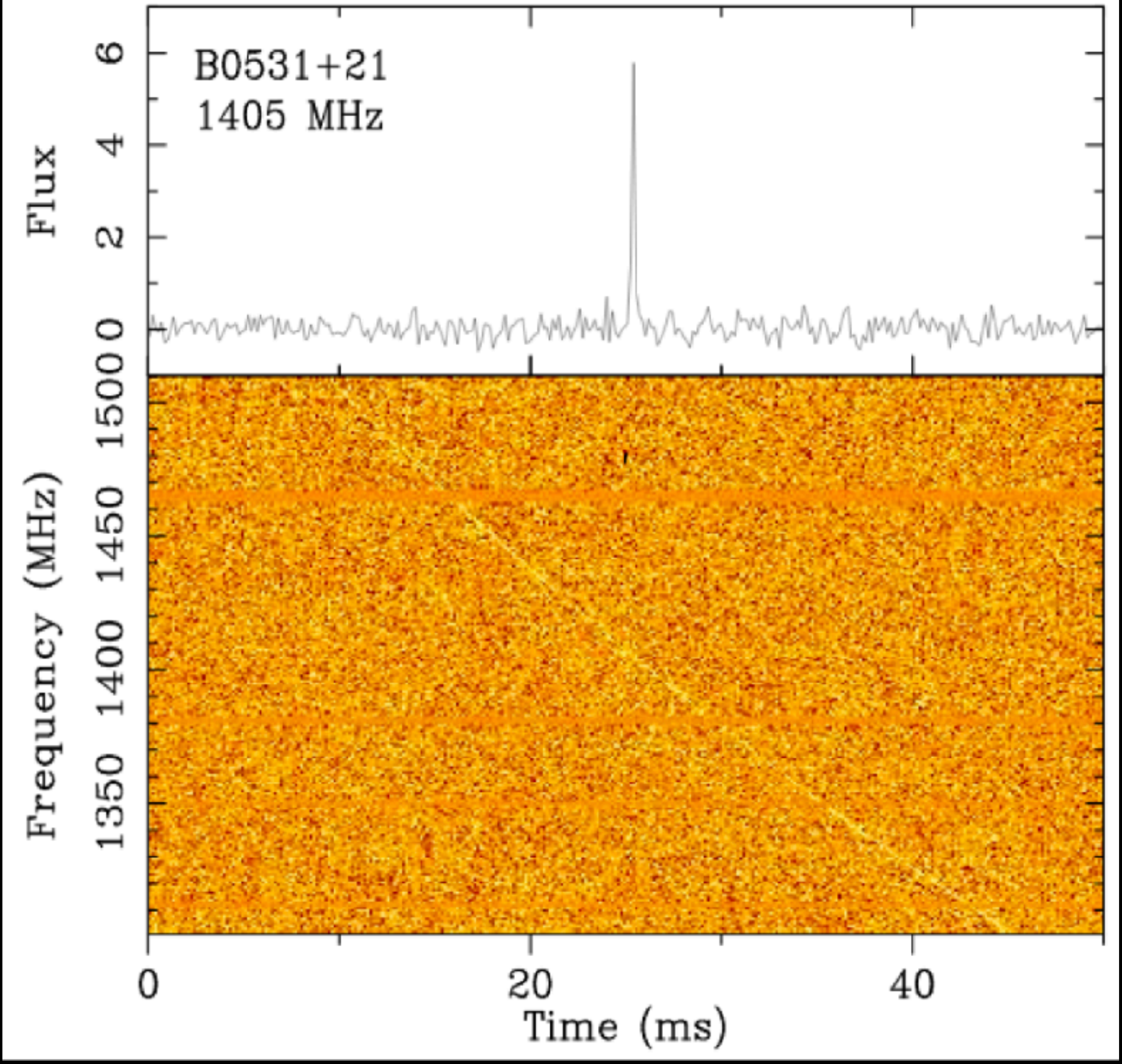
Localization

FRB-focused instruments



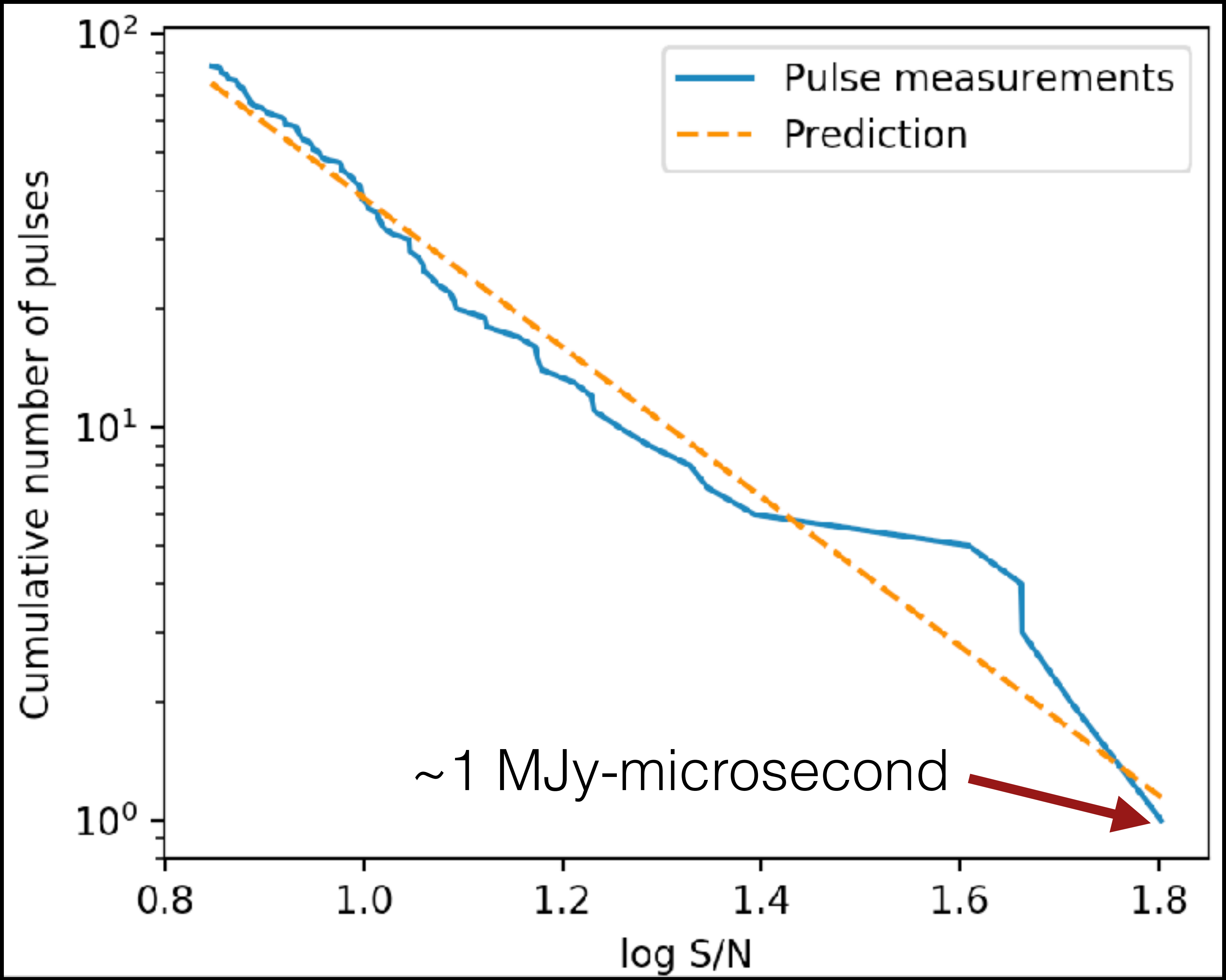
- Ten 4.5-m dishes (Hebei Boshda), 1220-m max baseline.
- Primary beam FWHM of 3.5 deg, localization accuracy of 3'' for FRB detected at 7 sigma.
- 1280-1530 MHz cylindrical waveguide feed and LNA, RF over fiber to central location for DSP (Dr. Sandy Weinreb).
- CASPER SNAP-1 (Kintex 7) + 6x Nvidia GTX-1080 GPUs for real-time processing (Dr. Jonathon Kocz).
- Sensitivity to 80 Jy-ms FRBs.
- Drift scan at the DEC of the Crab pulsar.
- 9 months construction, 12 months survey.

DETECT: incoherent. LOCALIZE: coherent.



B0531+21
1405 MHz
Flux
Frequency (MHz)
Time (ms)

Cumulative distribution of 83 Crab giant pulse S/N measurements in 30 days with DSA-10, compared with prediction (Bhat+2008) assuming 16 kJy SEFD and 68% useful bandwidth.

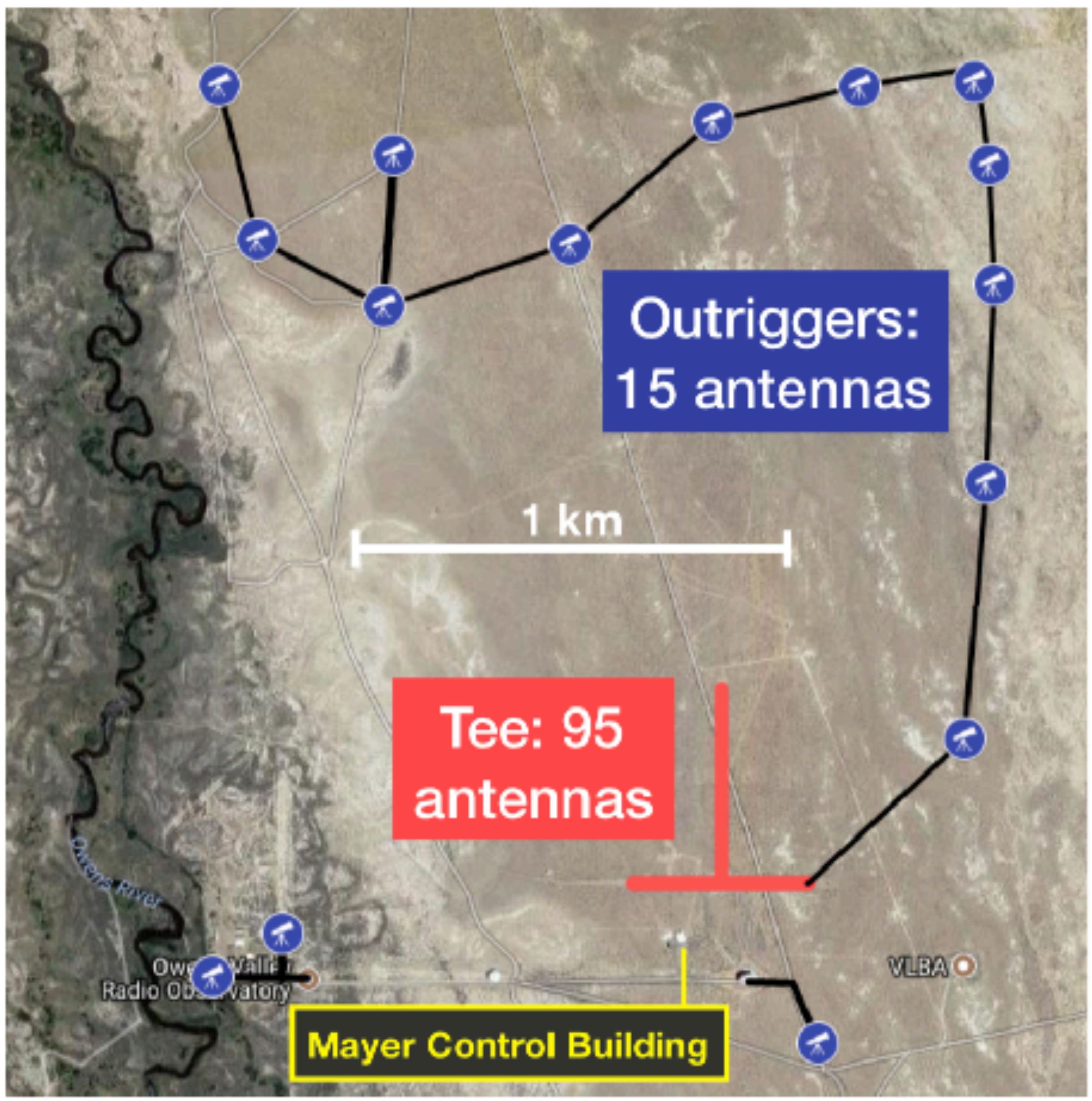


The DSA

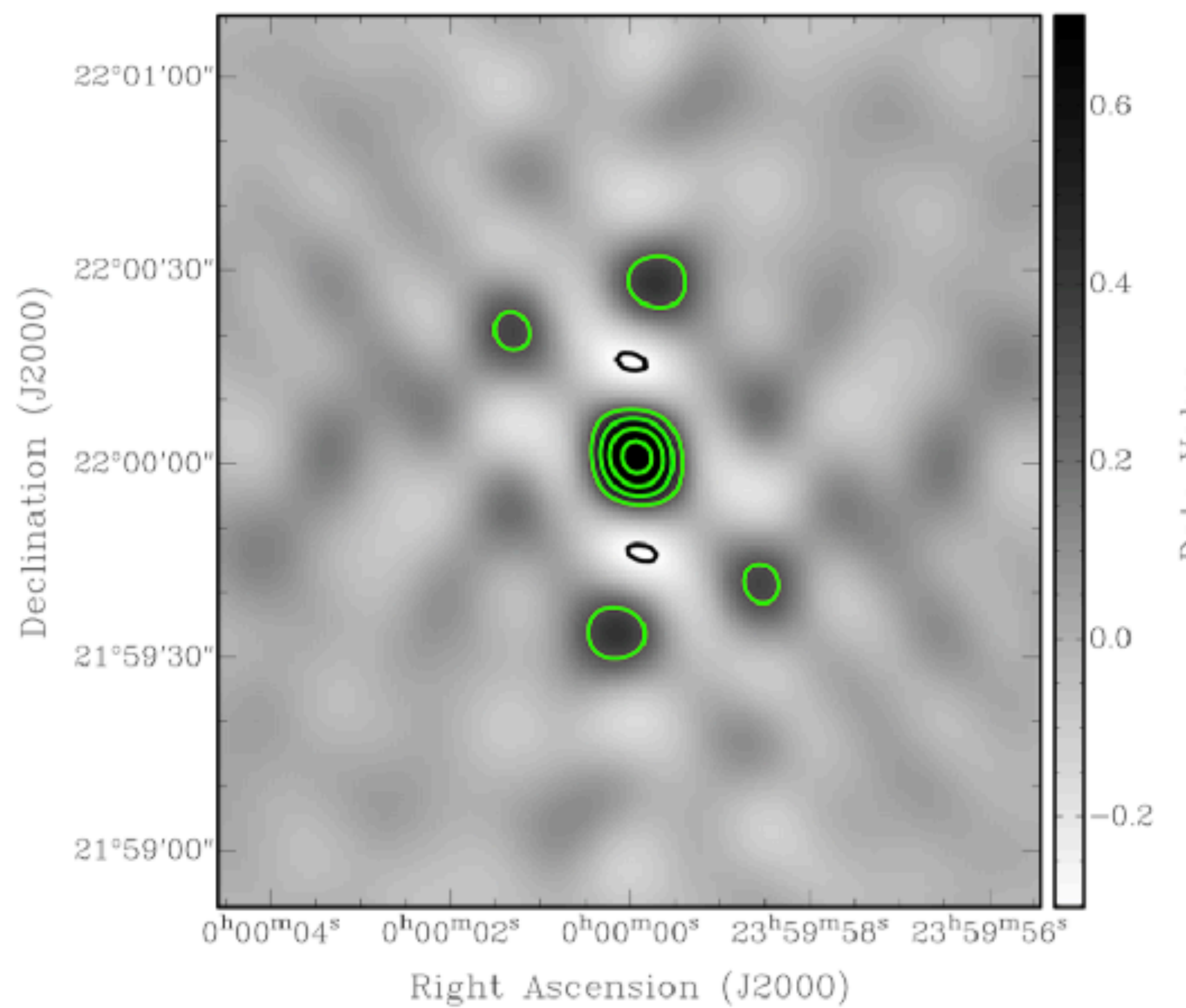
A 110-element array to localize ~100 FRBs/year to <3 arcsec.

1.7 Jy-ms search sensitivity (1ms FRB). Gregg Hallinan, Vikram Ravi.

Array configuration



Synthesized beam



DSA timeline

Construction

1. **Phase 1 (-> Dec 2018):** Current DSA-10 deployment demonstrates concept.

2. **Phase 2 (Oct 2018 -> Dec 2020):** Construct, commission, and demonstrate FRB localization with 110-antenna DSA in transit mode. Prototype tracking system.

3. **Phase 3 (2021-2023):** Deploy tracking system for detailed studies of a few sightlines. Prototype VLBI stations for <100 mas FRB astrometry.

Observational results

1. May detect and localize a few FRBs.

2. Establish our FRB rate, and host characteristics using 10-20 localized FRBs. Collaborate with ASKAP/Molonglo groups on localized FRBs.

3. Conduct three-year 110-antenna DSA survey (>300 localized FRBs), potentially in a few fields.

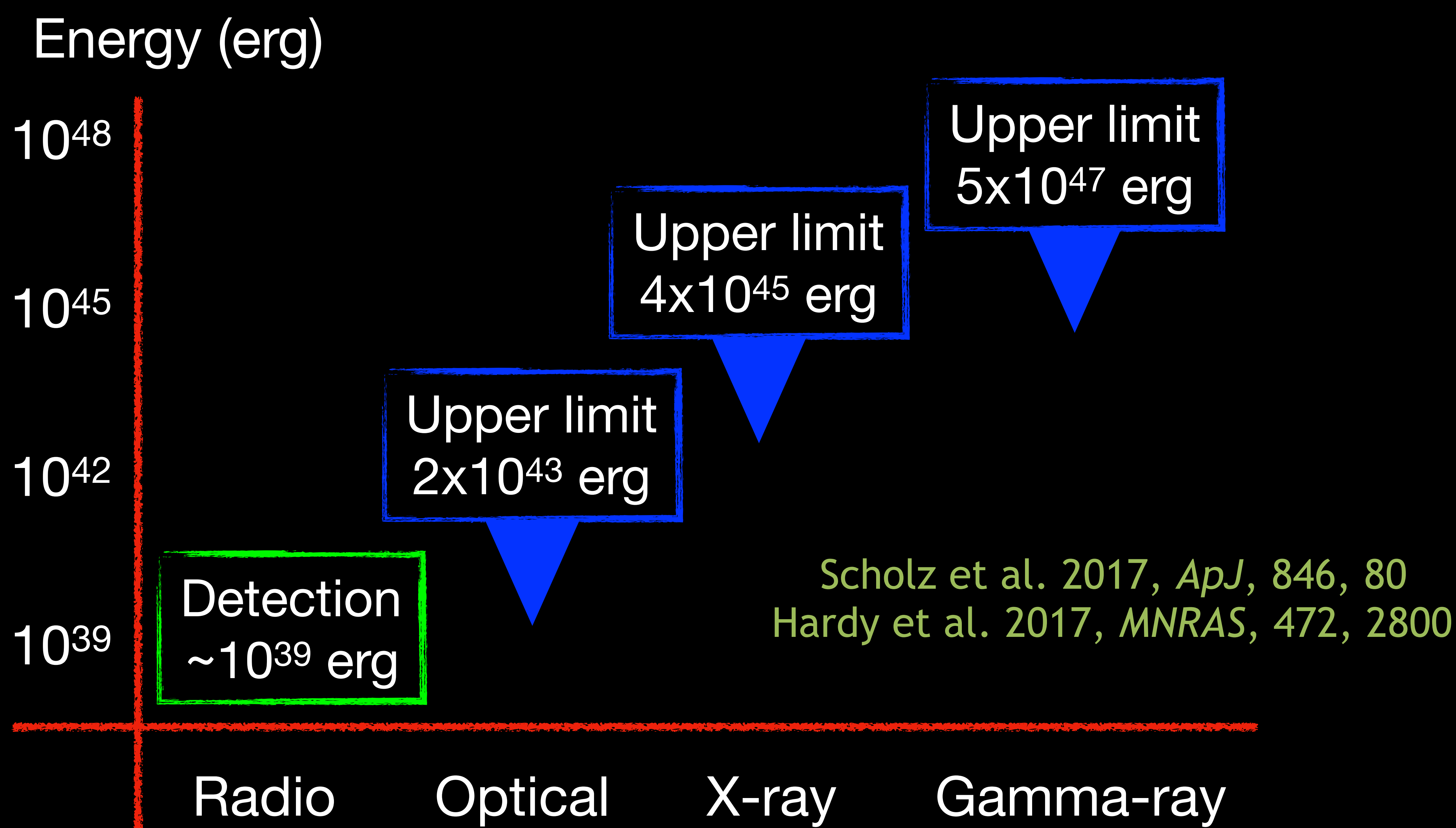
1. This field will remain in the realm of arguing about source counts, the utility / fidelity of luminosity measurements, and Type 1, 2…N FRBs *until we understand the properties of a sample of localized FRBs.*

2. Interpreting and making use of localizations is a tough but worthy endeavor, especially with regards to the intervening extragalactic gas in the IGM and CGM.

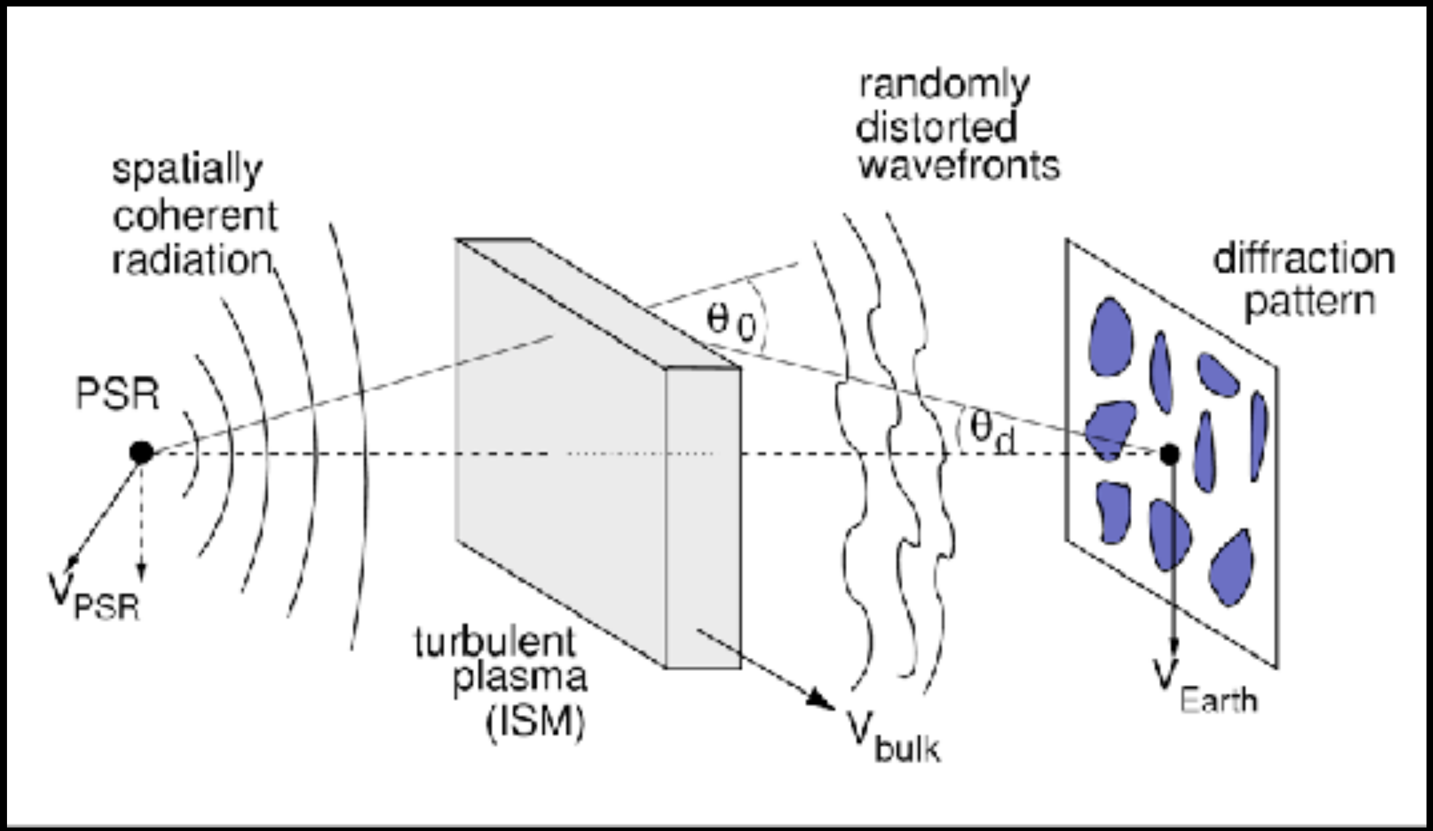
3. We have a valuable opportunity to carefully design dedicated FRB instrumentation.

4. I am incredibly excited about the scientific potential of this field over the next few years.

The repeating FRB 121102: multi-wavelength constraints

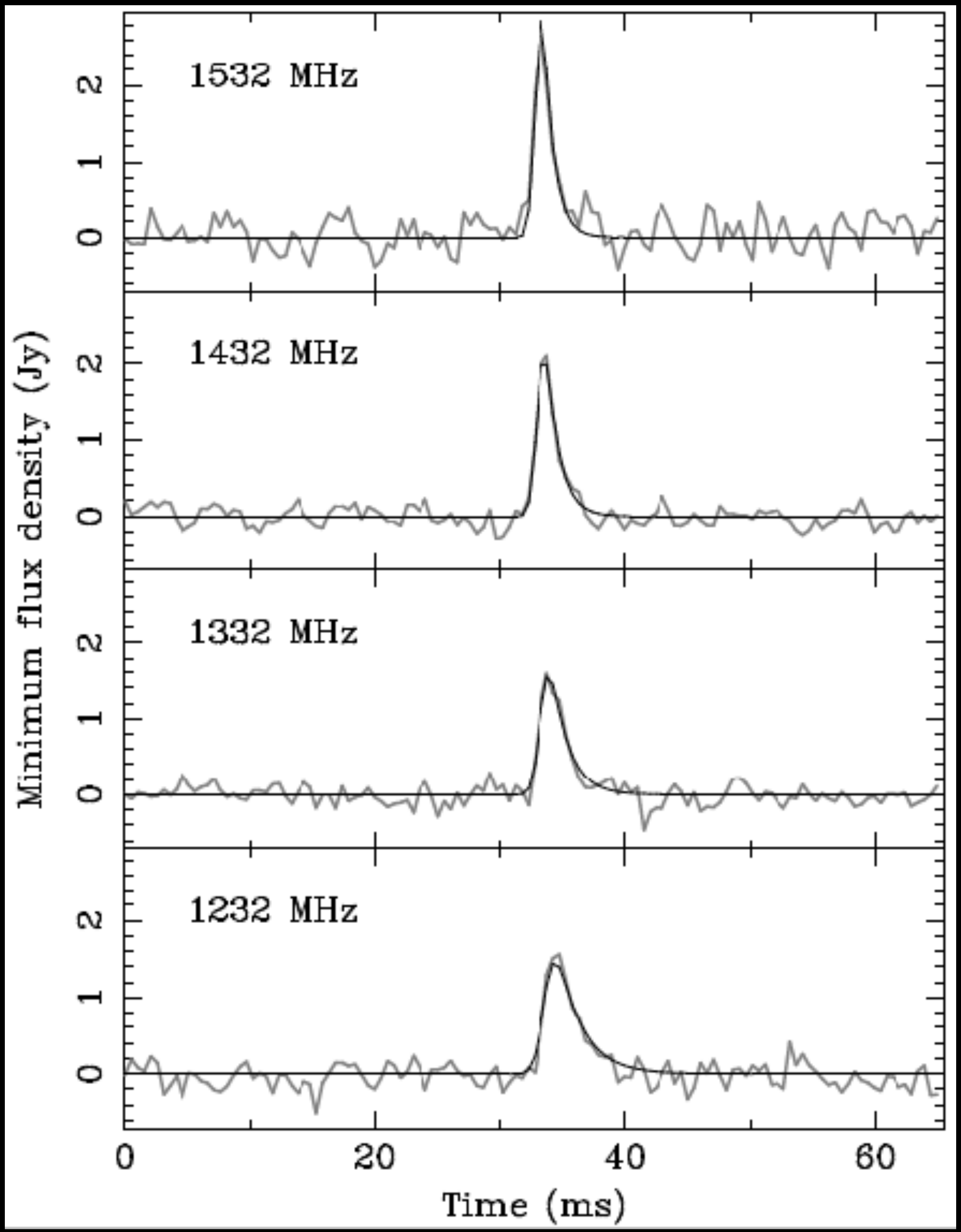


Scattering in inhomogeneous plasma



$$\theta_0 \propto f^{-2} \nabla \mathrm{DM}_{\mathrm{screen}} \quad \tau \propto [D_S(1 - D_S / D_{PSR})]\theta_0^{\ 2}$$

Here, τ is the characteristic scattered-ray delay. The distribution of ray arrival times is ~**exponential.**



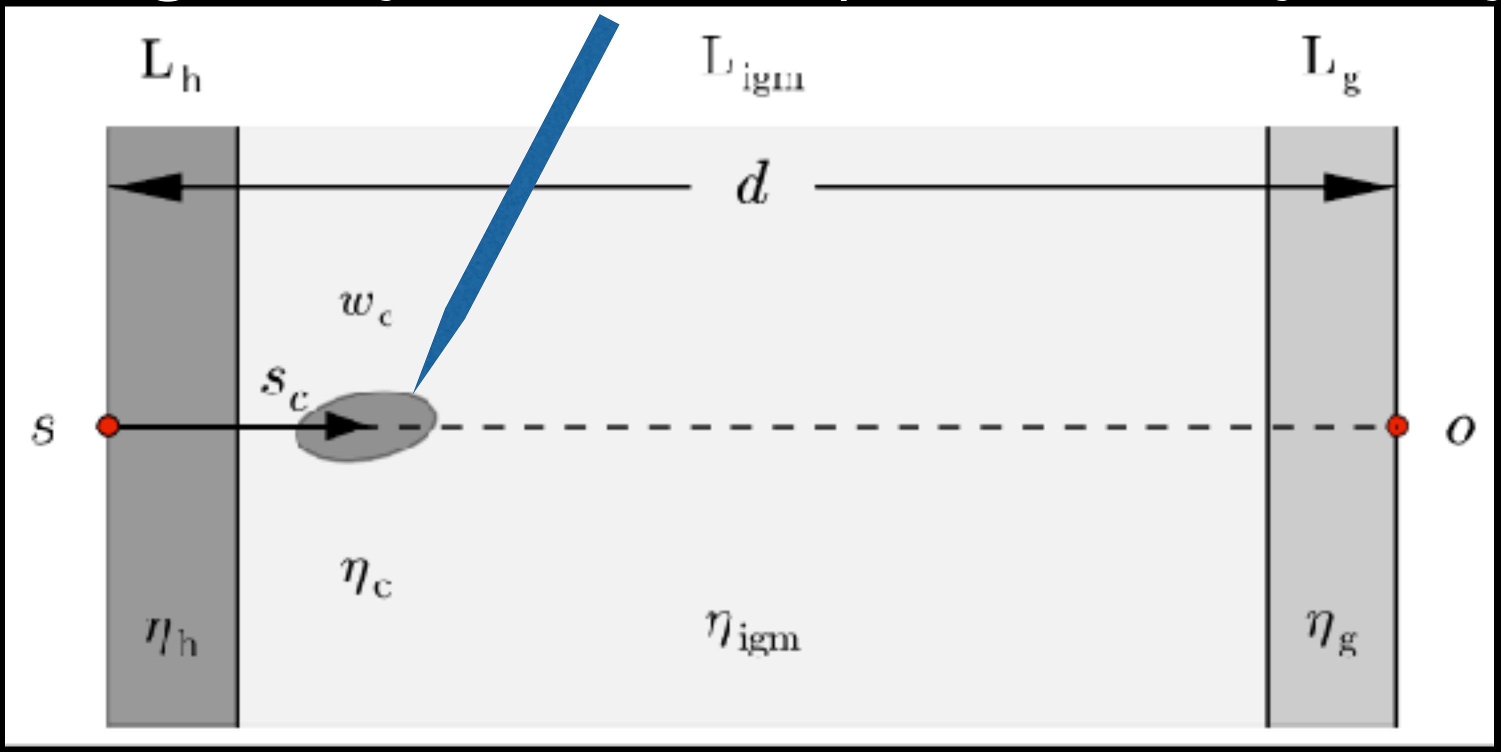
FRB 131104 pulse profile

Rickett (1991); Ravi et al. (2015); NRAO course (http://www.cv.nrao.edu/course/astr534/Pulsars.html)

Observed FRBs are unlikely to pass through intervening Milky Way-like disks

Host galaxy Clump Milky Way

Source



Observer

Expected scattering timescale given by:

$$2c\tau = \int_0^d ds\, \eta(s) s(1 - s/d)$$

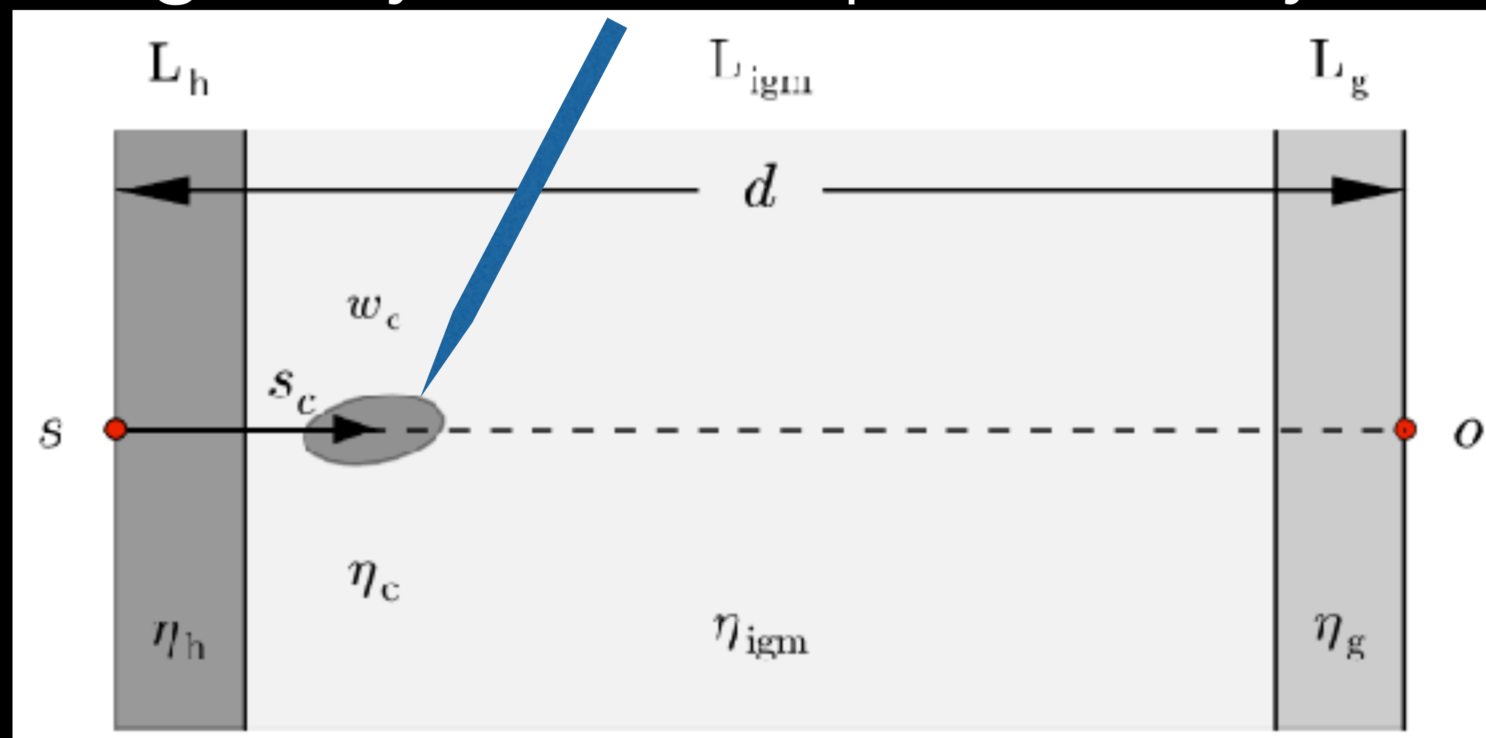
Eta is the mean-square scattering angle per unit length

Figure from Cordes et al. (2016)

Observed FRBs are unlikely to pass through intervening Milky Way-like disks

Host galaxy Clump Milky Way

Source

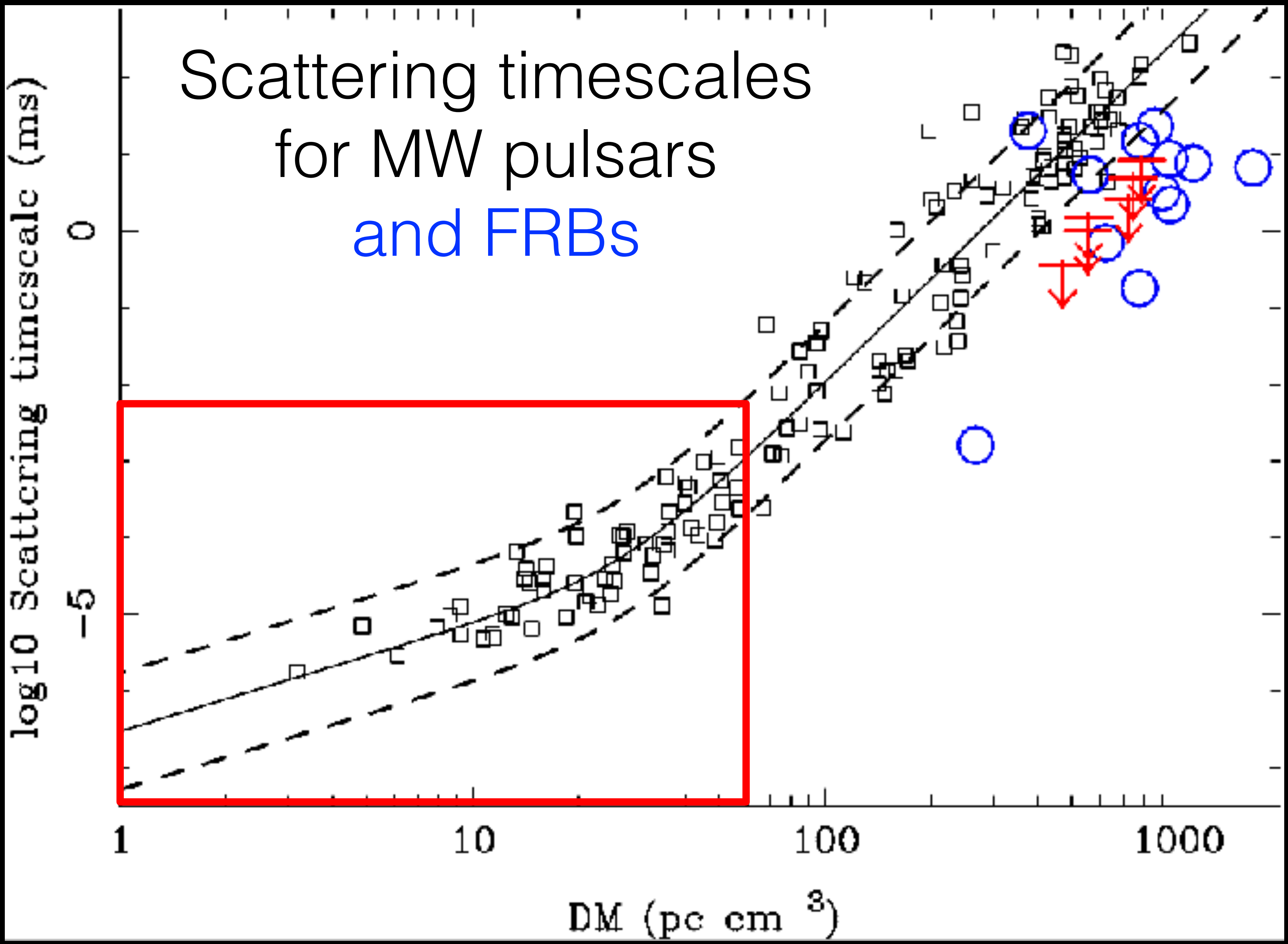


Observer

For a clump like a Milky-Way disk,

$$\tau_c \sim 6\frac{s_c}{w_c}\left(1-\frac{s_c}{d}\right)\tau_{\rm MW}$$

Figure from Cordes et al. (2016)

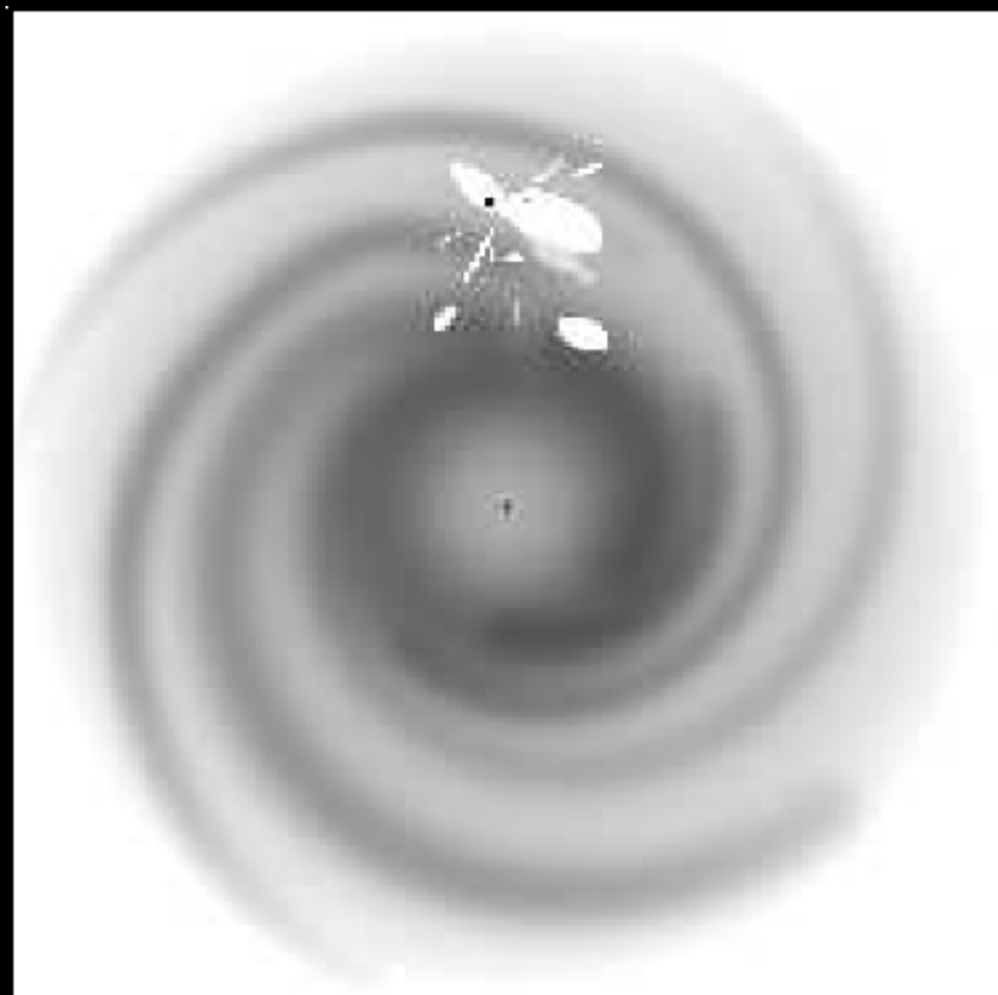


For a clump like a Milky-Way disk,

$$\tau_c \sim 6\frac{s_c}{w_c}\left(1-\frac{s_c}{d}\right)\tau_{\rm MW}$$

Data from ATNF pulsar catalog.

Dispersion: Milky Way n_e models

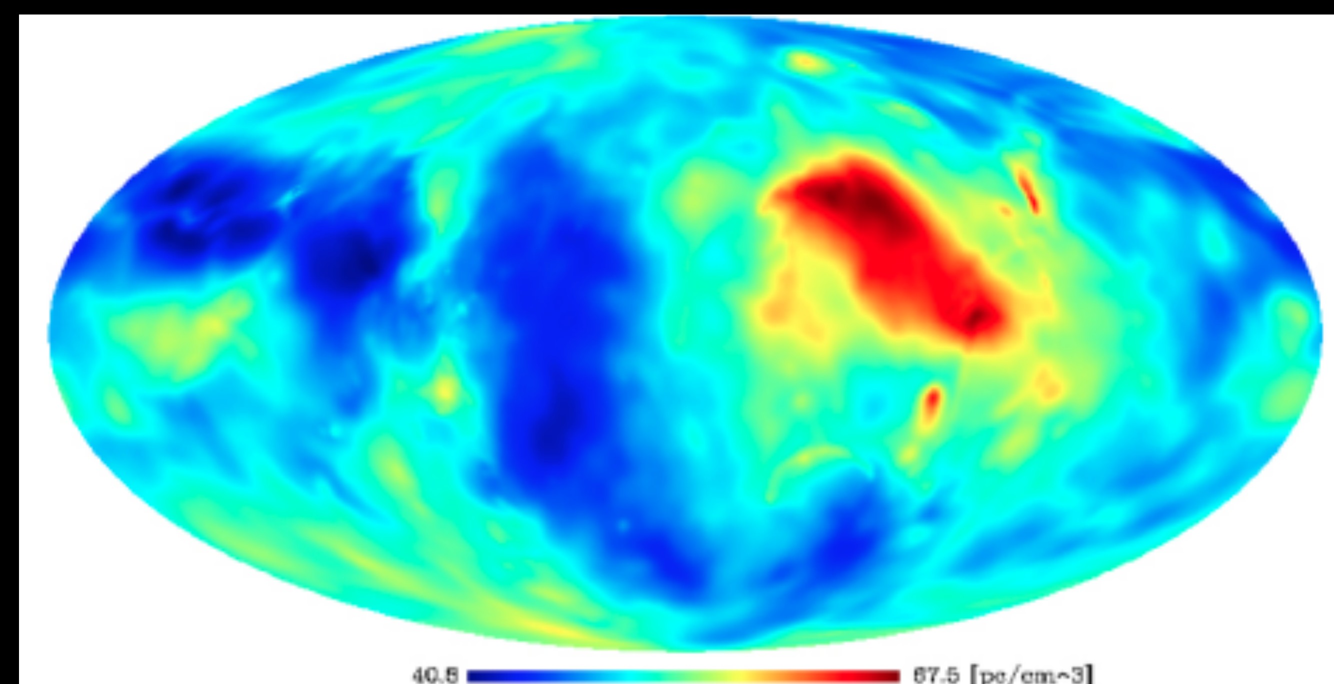


Galactic disk model (NE2001), based on pulsar DMs and scattering measurements, guided by H-alpha++

Cordes & Lazio (2002), Gaensler et al. (2008), Gupta et al. (2012), Dolag et al. (2015)

Simulations suggest that much of the “missing” baryonic matter is in hot (~10^6 K) gas halos (MW ~ 2×10^{11} Msun).

This is being borne out by UV / X-ray absorption measurements.



40 – 70 pc cm^{-3}

Arecibo: 36.9 days/FRB in Scholz et al. (2016) in PALFA, x3 in ALFABURST. 1 FRB.

VLA: 0 FRBs in approx. 20 days (Law et al.).

Parkes:11.6 days/FRB at |b|>15 deg (Champion et al.). 23 FRBs.

ASKAP (fly's eye): ~120 days/FRB/dish at b=-50 deg. 20 FRBs. (Shannon, Bannister et al.).

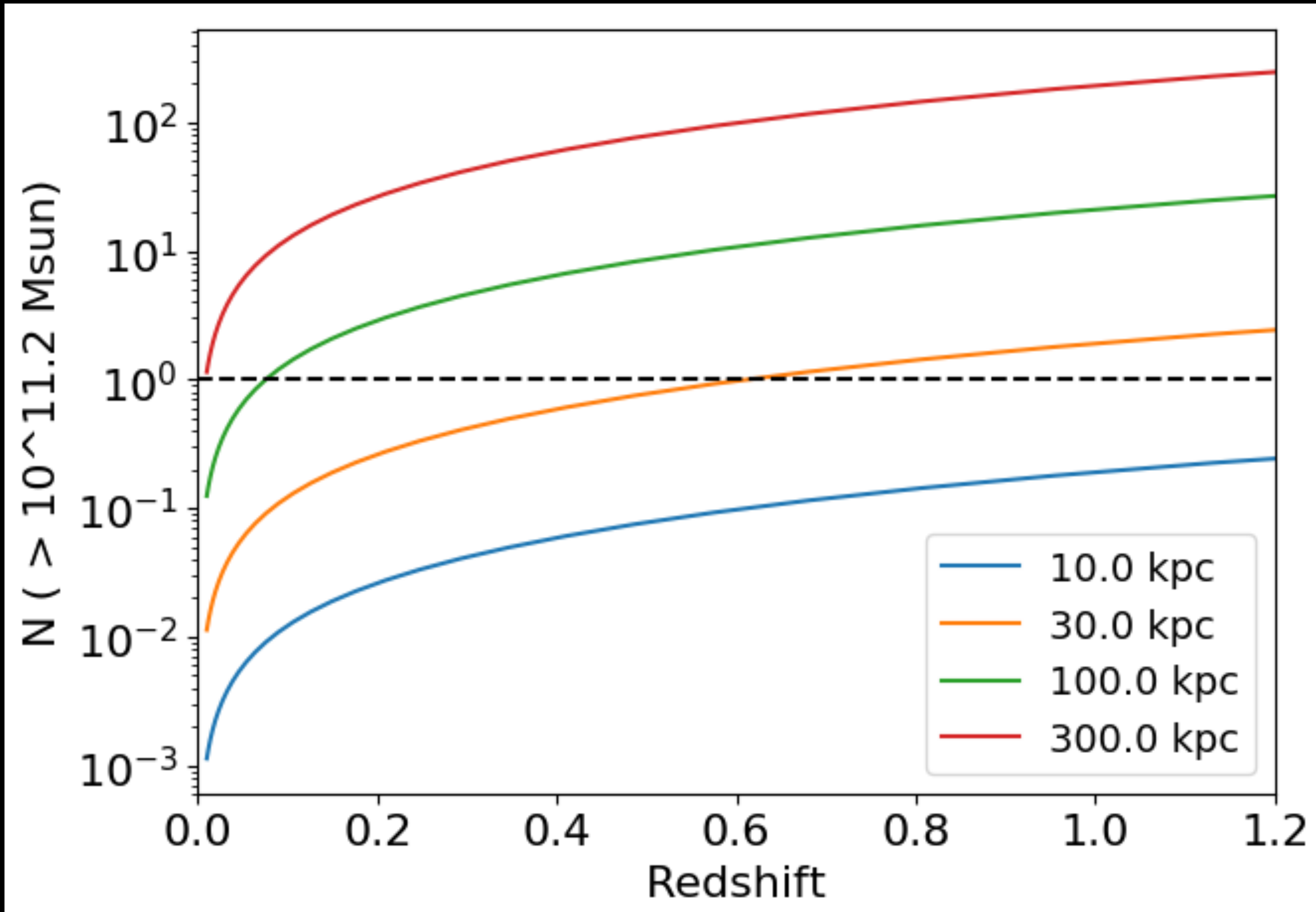
DSA-10: ? FRBs in 155 days on sky (transit at DEC +22 deg).

ATA: 0 FRBs in 20 days on sky (Siemion et al.).

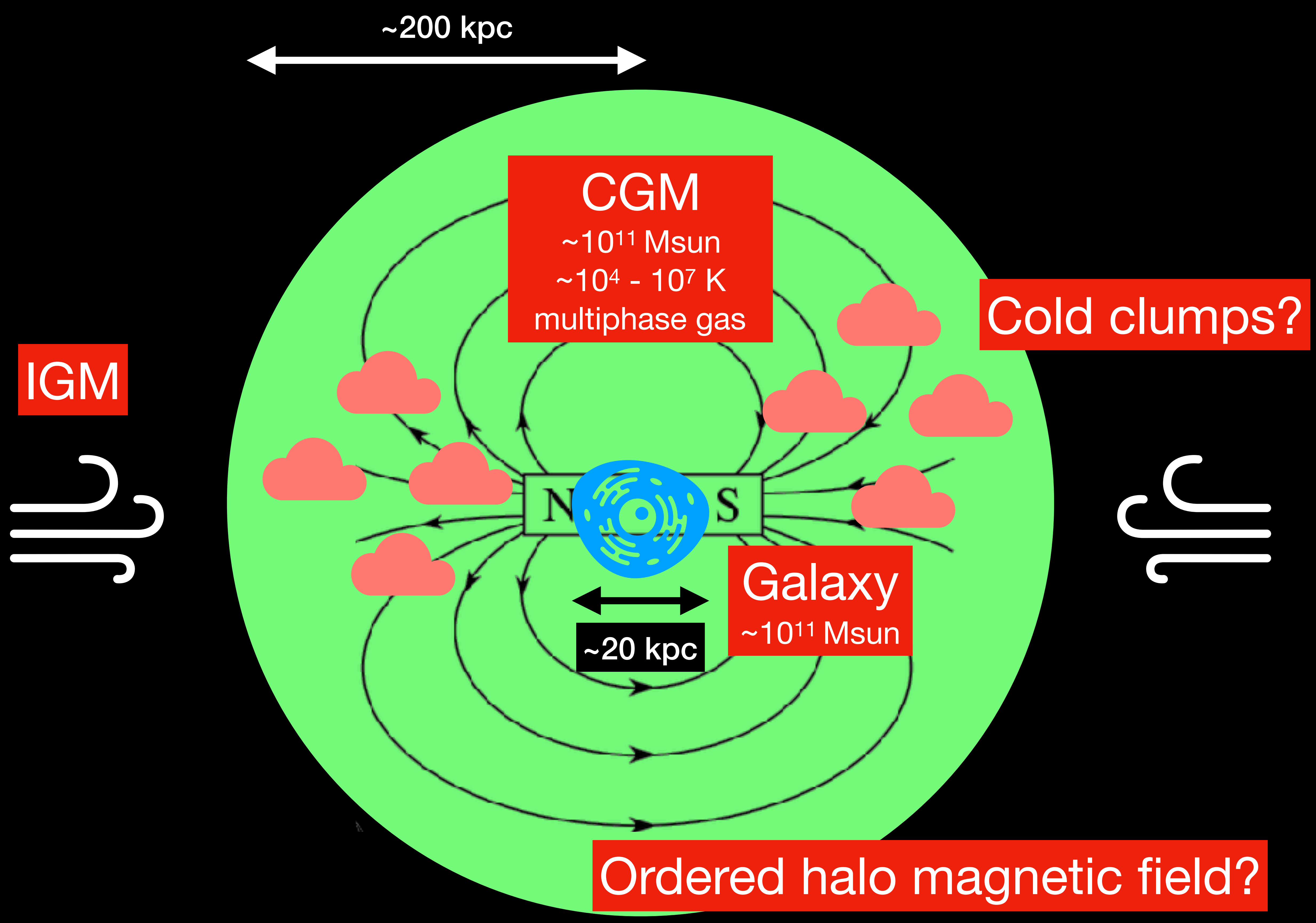
FRBs will impact several L* galaxy halos

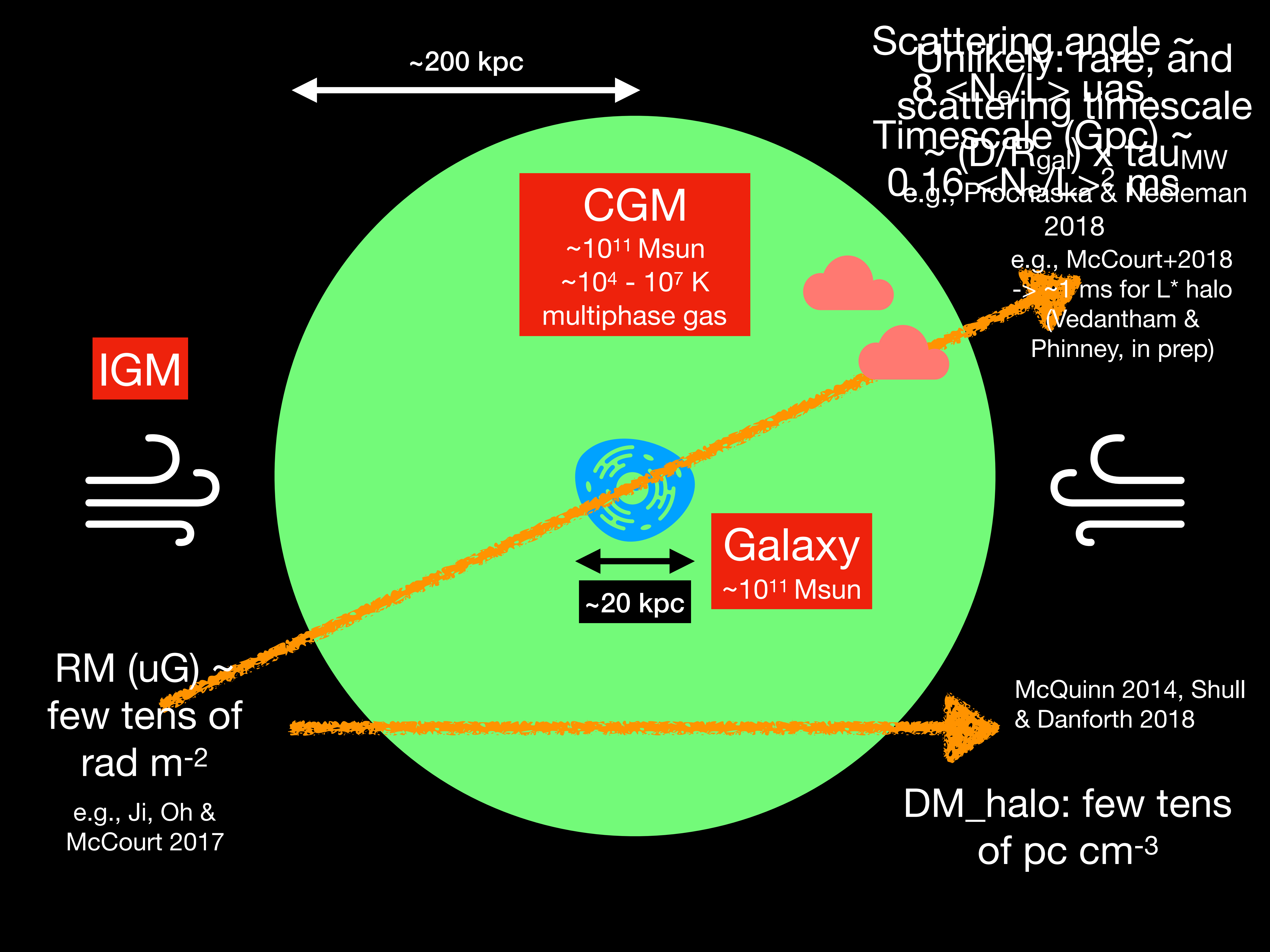
DM ~ 1200z cm^{-3} pc.

Number of intervening objects



Planck15 cosmology, Muzzin+2013 GSMF.


~200 kpc
CGM
~10^11 Msun
~10^4 - 10^7 K
multiphase gas
Cold clumps?
IGM
N
S
Galaxy
~10^11 Msun
~20 kpc
Ordered halo magnetic field?


~200 kpc
CGM
~10^11 Msun
~10^4 - 10^7 K
multiphase gas
IGM
Galaxy
~10^11 Msun
~20 kpc
Scattering angle ~ 8 <N_e/L> uas, Timescale (Gpc) ~ 0.16 <N_e/L>^2 ms
e.g., Prochaska & Neeleman 2018
Unlikely: rare, and scattering timescale ~ (D/R_gal) x tau_MW
e.g., McCourt+2018 -> ~1 ms for L* halo (Vedantham & Phinney, in prep)
RM (uG) ~ few tens of rad m^-2
e.g., Ji, Oh & McCourt 2017
McQuinn 2014, Shull & Danforth 2018
DM_halo: few tens of pc cm^-3