Title: TBA

Date: Aug 11, 2015 10:40 AM

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Abstract: TBA

Dispersion Distance and Large Scale Structure in Dispersion Space

Kris Sigurdson

The University of British Columbia

Cosmic Flows
(and other Novelties on Large Scales)
Perimeter Institute
August 11, 2015

Dispersion Distance and Large Scale Structure in Dispersion Space

(a potential Novel way to probe Large Scales)

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Based On:

"Dispersion Distance and the Matter Distribution of the Universe in Dispersion Space,"

Kiyoshi Wesley Masui and **KS**.

arXiv:1506.1704

Phys. Rev. Lett. (2015) in Press.

Work with Kiyo Masui @ UBC

(Kiyo made black-background slides)

Dispersion Distance and the Matter Distribution of the Universe in

Kiyoshi Wesley Masui

Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, C

Canadian Institute for Advanced Research, CIFAR Program in Cosmology and Gravity, Toront

Kris Sigurdson

Department of Physics and Astronomy, University of British Columbia, Vancouver, BC,

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Universe and show that the clustering signal could be measured using as few as 10000 eve

Inspired by great paper by Matt McQuinn:

"Locating the Missing Baryons with Extragalactic Dispersion Measure Estimates,"
Matthew McQuinn
arXiv:1309.4451
ApJ, 780, L33 (2014).

Several other related contributions:

B. Dennison, MNRAS **443**, L11 (2014), arXiv:1403.2263 [astro-ph.HE].
W. Deng and B. Zhang, ApJ **783**, L35 (2014), arXiv:1401.0059 [astro-ph.HE].
B. Zhou, X. Li, T. Wang, Y.-Z. Fan, and D.-M. Wei, Phys. Rev. D **89**, 107303 (2014), arXiv:1401.2927.
H. Gao, Z. Li, and B. Zhang, ApJ **788**, 189 (2014), arXiv:1402.2498.

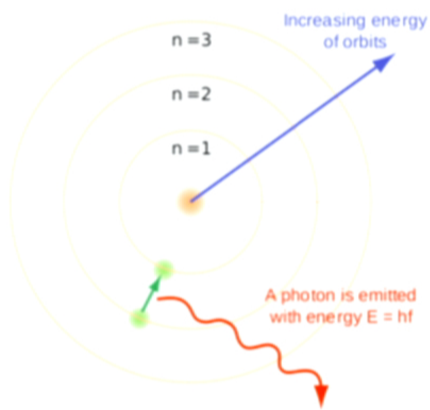
Apologies if I am missing your work!

Distance Measures

- Standard Atoms: Redshift
- Standard Candles: Luminosity Distance
- Standard Rulers: Angular Diameter Distance

Distance Measures

- Standard Atoms: Redshift



$$z \equiv \frac{\nu_e}{\nu_o} - 1 = \frac{\lambda_o}{\lambda_e} - 1$$

Doppler Shift in Special Relativity

$$1 + z = \sqrt{\frac{1 + v/c}{1 - v/c}}$$

Generalized: to geodesics in General Relativitity

$$z \approx \frac{v}{c} = \frac{d}{D_H}$$

Formulas: D. Hogg Distance Measures Notes

Distance Measures

- Comoving Radial Distance (Flat Space):

$$\chi = D_{\mathrm{C}} = D_{\mathrm{H}} \int_0^z \frac{dz'}{E(z')}$$

$$H(z) = H_0\, E(z)$$

Formulas: D. Hogg Distance Measures Notes

Distance Measures

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Distance Measures

- Standard Candles: Luminosity Distance

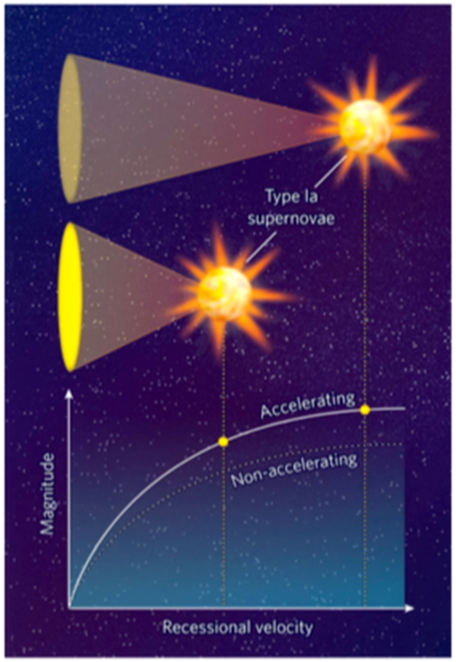


Image: Nature

$$D_L \equiv \sqrt{\frac{L}{4\pi\, S}}$$

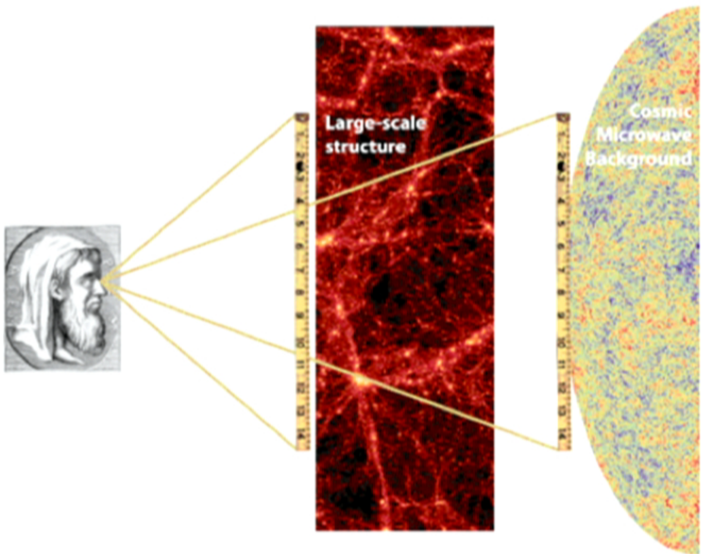
$$D_L = (1+z)\; D_C$$

Know Intrinsic Brightness and infer distance

Formulas: D. Hogg Distance Measures Notes

Distance Measures

- Standard Rulers: Angular Diameter Distance



$$D_A = \frac{D_C}{1+z}$$

Know Intrinsic Physical Size and infer distance

Image: ESA

Formulas: D. Hogg Distance Measures Notes

Dispersion Measure

As radio waves travel through a plasma their propagation speed is reduced below the speed of light due to the column of electrons.

$$\mathrm{DM} = \int_0^d n_e \, dl$$

Frequency-dependent time delay

$$\Delta t = 4.2 \, \nu_{\mathrm{GHz}}^{-2} \left(\frac{\mathrm{DM}}{10^3 \, \mathrm{cm}^{-3} \mathrm{pc}} \right) \; \mathrm{s},$$

Formula: Matt McQuinn

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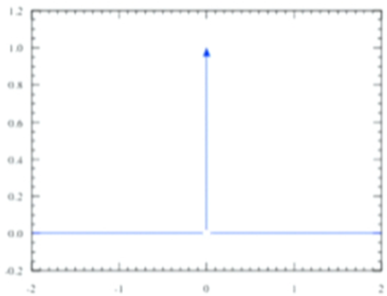
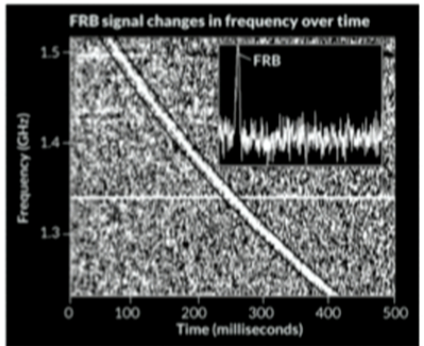
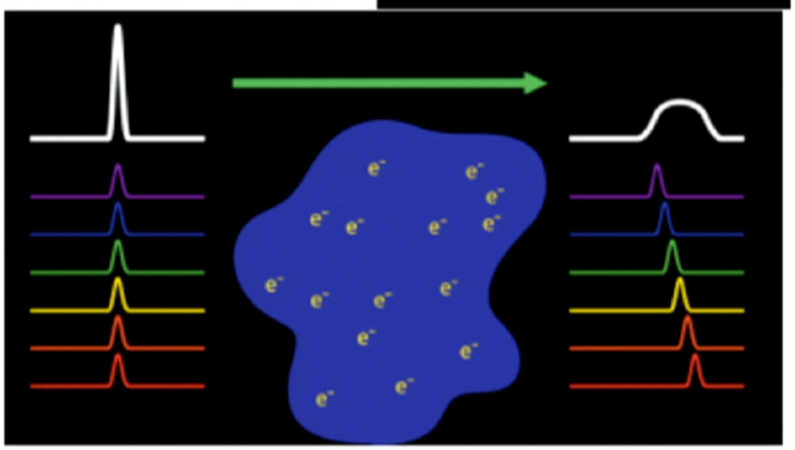
Distance Measures

- Standard Pings: Dispersion Distance







Images: Top Left: Lorimer; Bottom: Erik Madsen

Standard Ping:
Broadband Radio Impulse

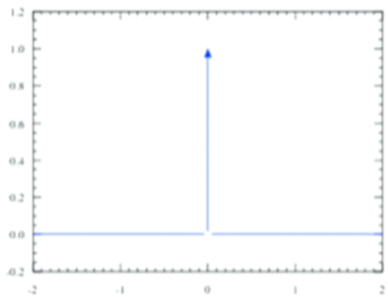
Prime Example: Fast Radio Bursts,
~ ms duration radio pulses

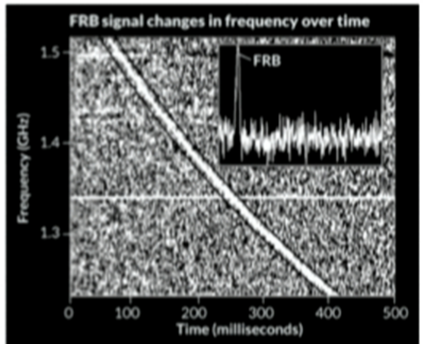
Know pulse is short duration and infer DM, and Dispersion Distance χ_s

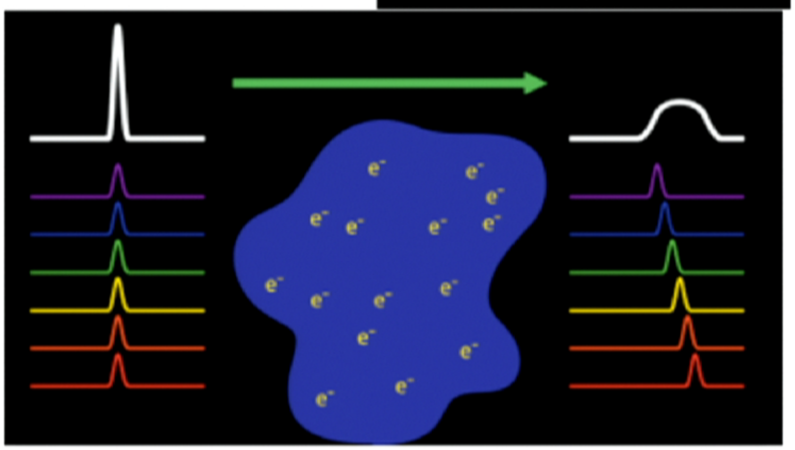
$$\mathrm{DM}(\chi_s) = \int_0^{\chi_s} \mathrm{d}\chi' a(\chi')^2 \bar{n}_e(\chi').$$

Distance Measures

- Standard Pings: Dispersion Distance







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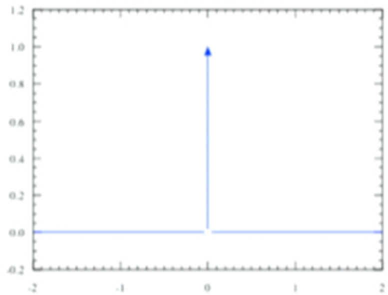

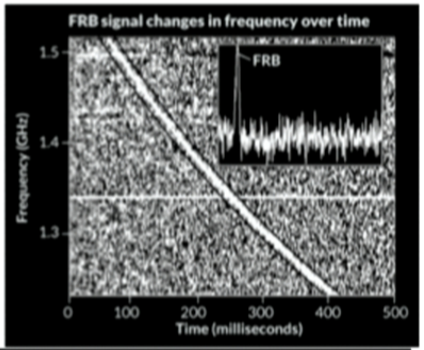

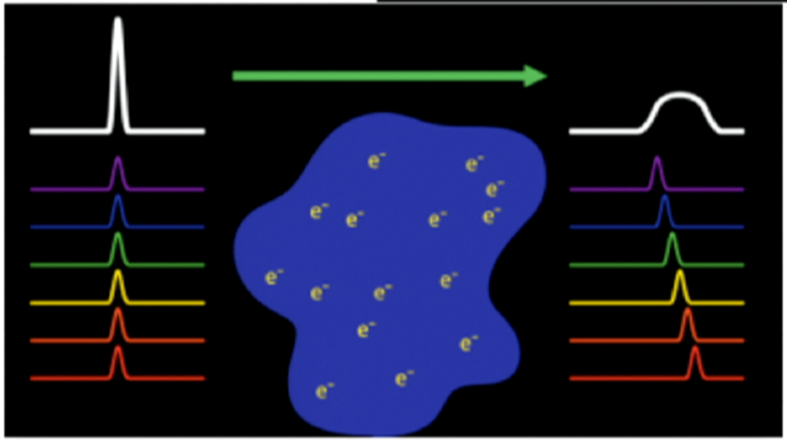

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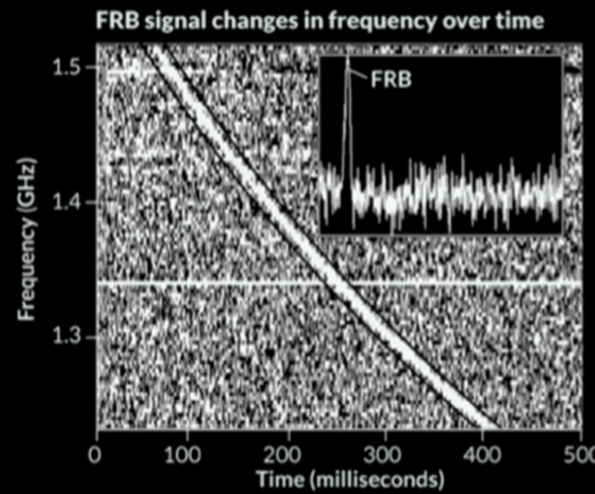
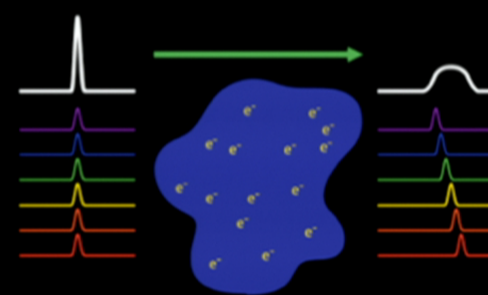
Fast radio bursts

- First detected By Lorimer using the Parkes Multibeam
- Now ~10 published events
- ~1 ms, ~1 Jy bursts
- Estimated ~10 000 similar events per day per sky
- Highly dispersed, interpreted as being extragalactic/cosmological
- If the dispersion is from the IGM, originate from z~0.5





images: Lorimer 2007, Erik Madsen

Fast radio bursts

- If FRBs are of cosmological origin…
- and If we had a survey with many thousands of events…
- then they should be clustered in some way
- How do we describe the clustering?

Location	Model	Galactic scintillation	Faraday rotation	Counterpart	dlnN/dlnS	PA swing	Repeat
Cosmological (>1 hGpc)	Blitzars	X	≤ 7 rad/m²	Grav waves	?	X	X
	Merging COs	X	≤ 7 rad/m²	Type Ia SNe, X-ray	?	X	X
	Primordial BHs	X	≤ 7 rad/m²	~TeV	?	X	X
	NS / Asteroid	X	≤ 7 rad/m²	Faint X-ray	?	X	X
Extragalactic, local	Edge-on disk	✓	50-500 rad/m²	?	-3/2	?	?
	SNR pulsar	✓	20-1000 rad/m²	Archival CC Sne	-3/2	✓	✓
Galactic	Flare stars	✓	RM_{gal}	Main sequence star	-3/2	X	✓
Terrestrial	RFI	X	RM_{ion}	None	-1/2 *if* 2D -3/2 *if* 3D	X	X

Connor et al. 2015 1505.05535

Slide: Liam Connor

What are FRBs? Where do they come from? We don't know yet.

This talk: what if all or some fraction of FRBs are cosmological.

Dispersion Space

- Dispersion measure is a line-of-sight integral of the electron density
- If dominated by the IGM this can be used as a cosmological distance measure
- Can study clustering in 3D!

$$\mathrm{DM}(\hat{n}, \chi) = \int_0^{\chi} \mathrm{d}\chi' a(\chi)^2 n_e(\hat{n}\chi', \chi').$$

Dispersion measure space

- Like redshift, DM is not a perfect proxy for distance due to perturbations

$$\frac{\mathrm{DM}(\hat{n},\chi)}{\bar{n}_0} = \int_0^{\chi} \frac{\chi'}{a(\chi')}\left[1+\delta_e(\hat{n}\chi')\right]$$

$$\chi_s - \chi = \int_0^{\chi} d\chi' \delta_e(\hat{n}\chi')$$

- There will be additional clustering terms: the "DM space distortions".

Dispersion Space

$$\mathrm{DM}(\hat{n},\chi) = \int_0^{\chi} \mathrm{d}\chi' a(\chi')^2 \bar{n}_e(\chi') \left[1 + \delta_e(\hat{n}\chi',\chi')\right]$$

$$\vec{x}_s = \hat{n}\chi_s$$

$$\mathrm{DM}(\chi_s) = \int_0^{\chi_s} \mathrm{d}\chi' a(\chi')^2 \bar{n}_e(\chi').$$

$$\chi_s - \chi = \int_0^{\chi} \mathrm{d}\chi' \delta_e(\hat{n}\chi').$$

Dispersion Space Distortions

We wish to relate the density of a tracer, f, measured in dispersion space to its density in real space. We follow the derivation in Kaiser [16] of the redshift-space distortions. Start by noting that the total number of tracers in a volume element is the same in both spaces:

$$n_{fs}(\vec{x}_s)\,\mathrm{d}^3\vec{x}_s = n_f(\vec{x})\,\mathrm{d}^3\vec{x}. \tag{6}$$

$$\delta_{fs} = \delta_f - \delta_e - \left(\frac{1}{\bar{n}_f}\frac{\mathrm{d}\bar{n}_f}{\mathrm{d}\chi} + \frac{2}{\chi}\right)\int_0^\chi \mathrm{d}\chi'\delta_e(\hat{n}\chi').$$

$$A(\chi) \equiv \frac{1}{\bar{n}_f}\frac{\mathrm{d}\bar{n}_f}{\mathrm{d}\chi} + \frac{2}{\chi}.$$

DM Space distortions

$$\delta_{fs} = \delta_f - \delta_e - \frac{2}{\chi}(\chi_s - \chi) - \frac{1}{\bar{n}_f}\frac{d\bar{n}_f}{d\chi}(\chi_s - \chi)$$

- For the most part can just follow Nick Kaiser's (1987) derivation of the (linear) redshift space distortions
- To leading order there are three distinct effects…

Dispersion Space

$$\mathrm{DM}(\hat{n}, \chi) = \int_0^{\chi} \mathrm{d}\chi' a(\chi')^2 \bar{n}_e(\chi') \left[1 + \delta_e(\hat{n}\chi', \chi')\right]$$

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$$\chi_s - \chi = \int_0^{\chi} \mathrm{d}\chi' \delta_e(\hat{n}\chi').$$

Source density gradient

$$\delta_{fs} = \delta_f - \delta_e - \frac{2}{\chi}(\chi_s - \chi) - \frac{1}{\bar{n}_f}\frac{d\bar{n}_f}{d\chi}(\chi_s - \chi)$$

- When we misinterpret the radial distance we compare the density to the wrong background
- Again, in principle present in redshift space but small

Collect terms into a local term and an integral term

$$\delta_{fs} = (\delta_f - \delta_e) - \left(\frac{1}{\bar{n}_f}\frac{d\bar{n}_f}{d\chi} + \frac{2}{\chi}\right)\int_0^{\chi} d\chi' \delta_e(\hat{n}\chi')$$

$$
\begin{aligned}
C_\ell^{ss}(\chi,\chi') = {} & \frac{2}{\pi}\int_0^\infty \mathrm{d}k k^2 j_\ell(k\chi) j_\ell(k\chi') P_{[ff+ee-2ef]}(k,(\chi+\chi')/2) \\
& + \frac{2}{\pi} A(\chi) A(\chi') \int_0^\chi \mathrm{d}\chi'' \int_0^{\chi'} \mathrm{d}\chi''' \int_0^\infty \mathrm{d}k k^2 j_\ell(k\chi'') j_\ell(k\chi''') P_{ee}(k,(\chi''+\chi''')/2) \\
& + \frac{2}{\pi} A(\chi) \int_0^\chi \mathrm{d}\chi'' \int_0^\infty \mathrm{d}k k^2 j_\ell(k\chi') j_\ell(k\chi'') P_{[ee-fe]}(k,(\chi'+\chi'')/2) \\
& + \frac{2}{\pi} A(\chi') \int_0^{\chi'} \mathrm{d}\chi'' \int_0^\infty \mathrm{d}k k^2 j_\ell(k\chi) j_\ell(k\chi'') P_{[ee-fe]}(k,(\chi+\chi'')/2).
\end{aligned}
$$

Toy Model

- Assume FRBs and electrons are biased tracers of matter
- $b_e = 1$ $b_f = 1.3$
- Most sources at z ~ 0.5

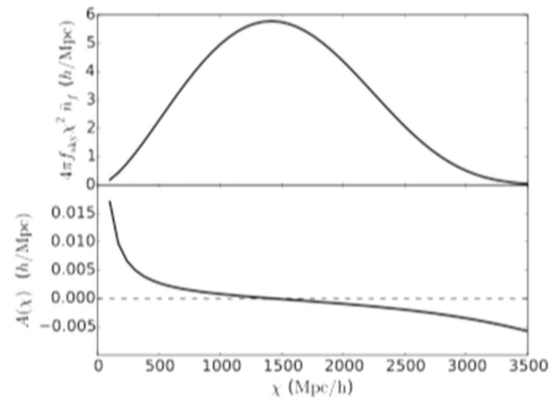
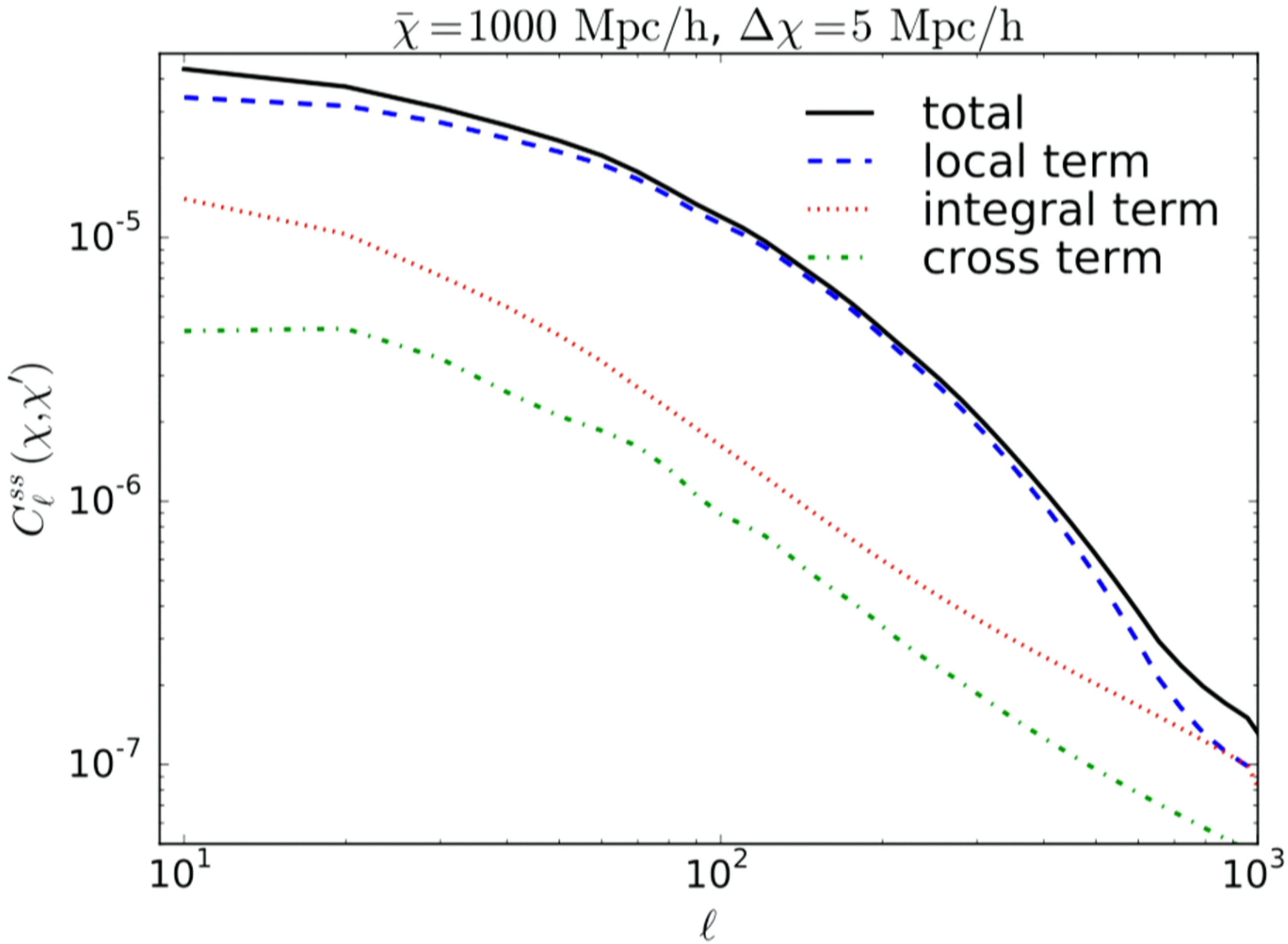
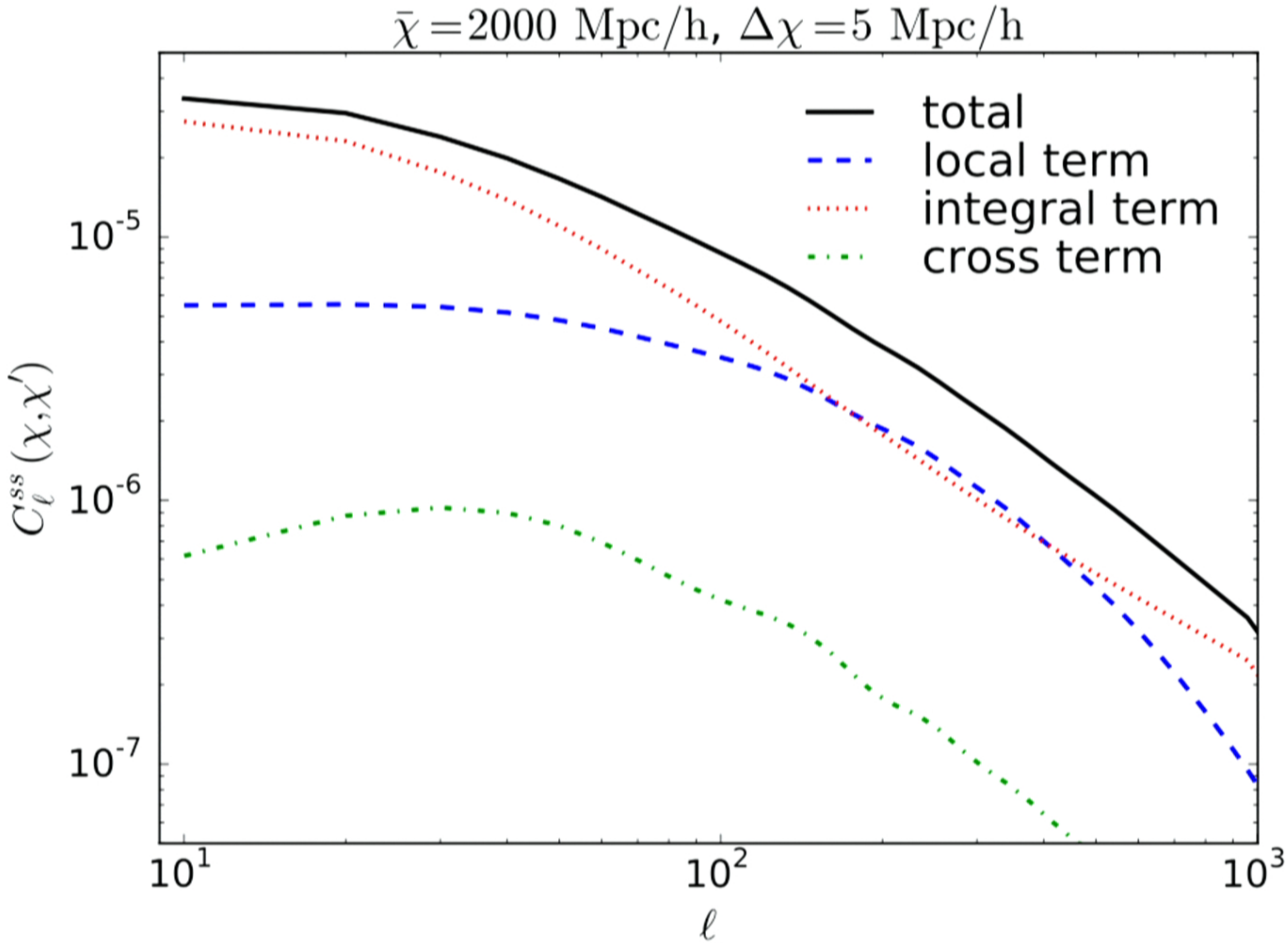


FIG. 1. *Top:* Comoving density of sources in toy model, as described in text. Normalization is such that the survey has a total of 10000 FRB events. *Bottom:* Resulting coefficient $A(\chi)$ as given in Equation 14.


$\bar{\chi} = 1000$ Mpc/h, $\Delta\chi = 5$ Mpc/h
total
local term
integral term
cross term
10^{-5}
10^{-6}
10^{-7}
$C_\ell^{ss}(\chi,\chi')$
10^1
10^2
10^3
ℓ


$\bar{\chi} = 2000$ Mpc/h, $\Delta\chi = 5$ Mpc/h
total
local term
integral term
cross term
$C_\ell^{ss}(\chi,\chi')$
10^{-5}
10^{-6}
10^{-7}
10^{1}
10^{2}
10^{3}
ℓ

A few comments

- Variations in intrinsic DM will limit slice widths, smooth out some structure
- Unlike lensing, line of sight integral has no weight function: exact tomography

$$\delta_{fs} = (\delta_f - \delta_e) - \left(\frac{1}{\bar{n}_f} \frac{d\bar{n}_f}{d\chi} + \frac{2}{\chi} \right) \int_0^{\chi} d\chi' \delta_e(\hat{n}\chi')$$

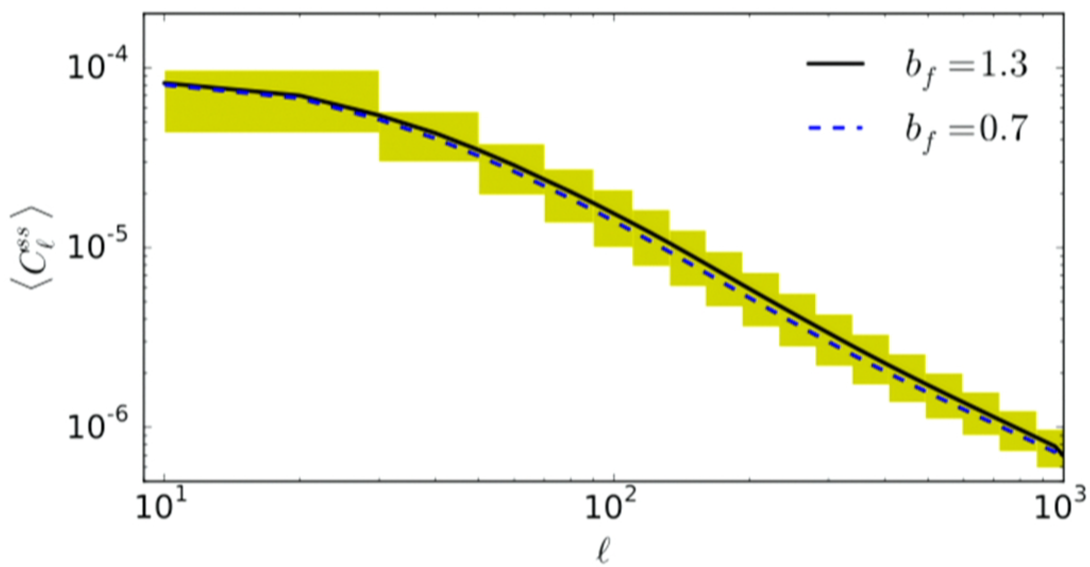


FIG. 3. Sensitivity of a survey with 10000 dispersion measures distributed uniformly over half the sky. Plotted is the cross-correlation power spectrum weighted averaged over all pairs of radial bins. Weights are chosen to maximize signal to noise at $\ell = 100$ for the $b_f = 1.3$ case.

Detectability

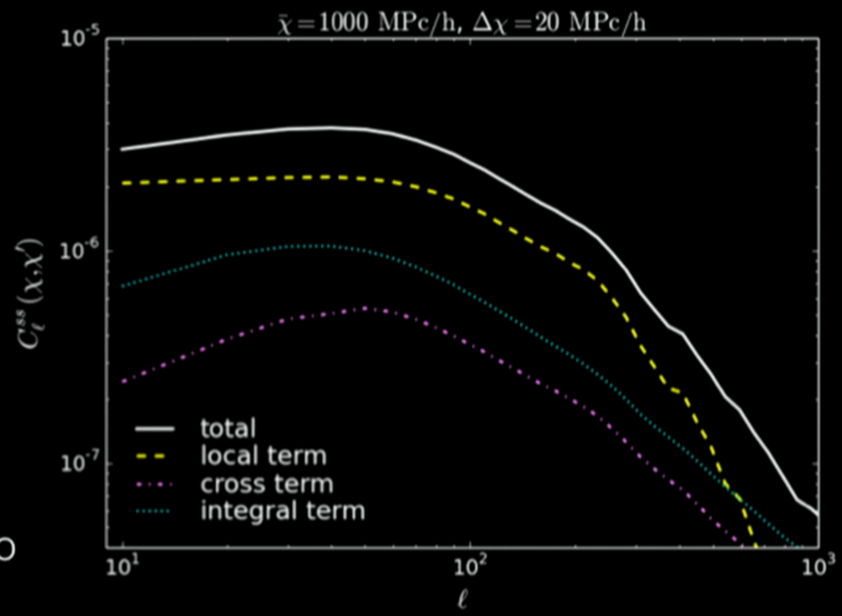
- Full Fisher analysis in progress, but…

$$\ell(\ell+1)C_\ell^{ss} \sim 10^{-2}$$

- Integral term coherent out to

$$\Delta\chi \sim 1000\,\mathrm{MPc}/h$$

- Need ~10^4 events for initial detection
- Local term only coherent out to 20 Mpc/h separations
- Need ~50 times more events



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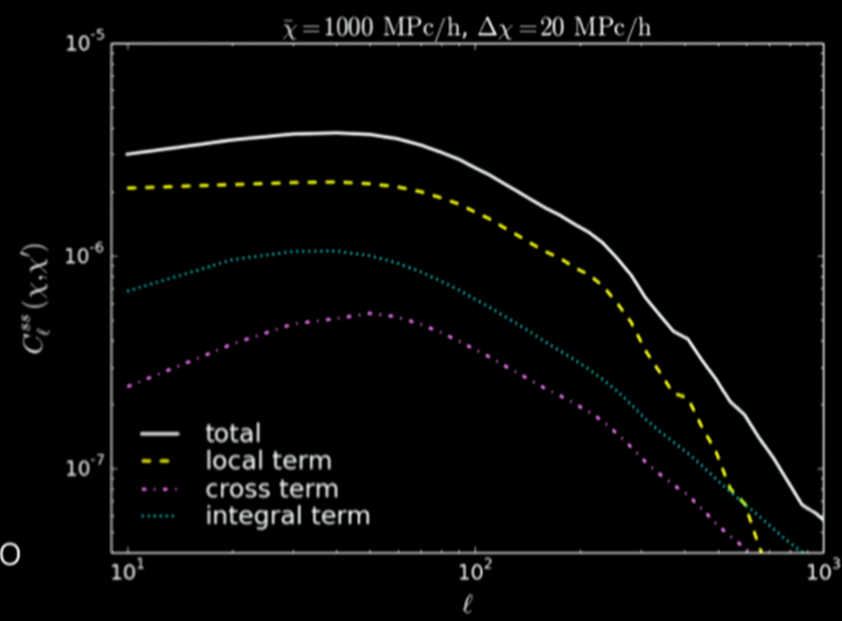
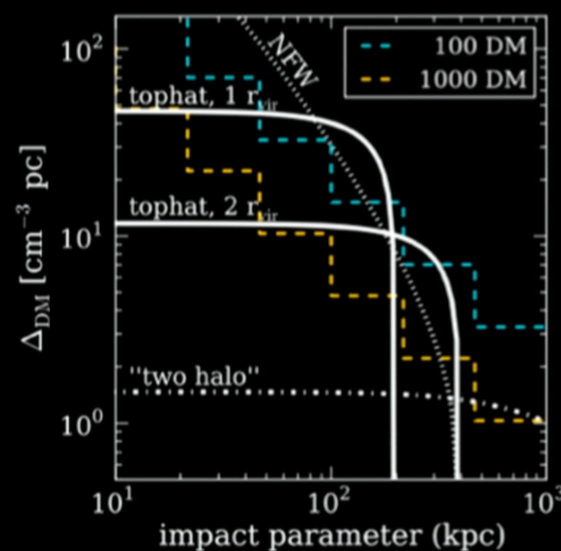


Applications

- Integral term could be used to find the "missing baryons", possibly in cross-correlation
- With ~10000/sky/day, could build up LSS survey
- If there are a lot of extra dim events, or spectrum is red…



McQuinn 2013

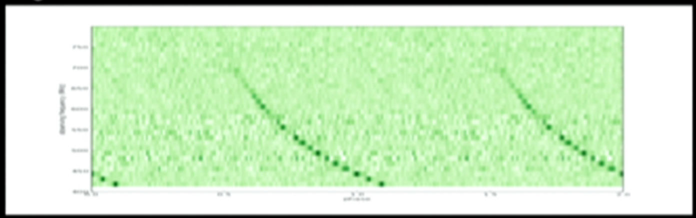
Conclusions

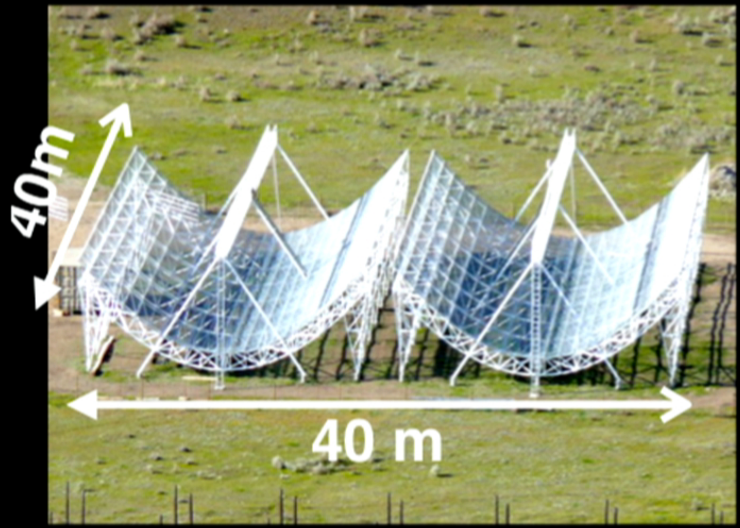
- If FRBs are cosmological then they can use used as 3D tracers of matter
- Have calculated the dispersion measure space distortions
- In toy model, clustering detectable with 10^4 events
- Many opportunities for cross correlation, separation of terms with redshifts, etc.

Instrument Status

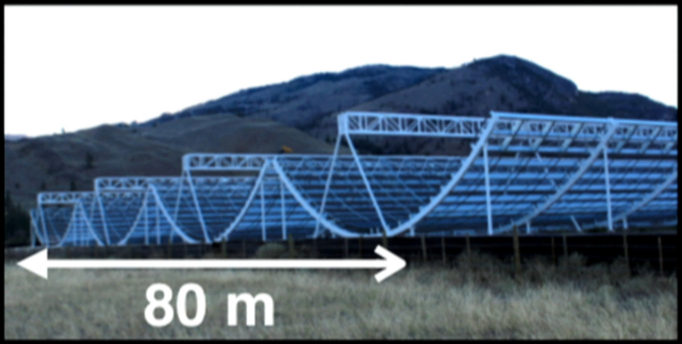
Pathfinder

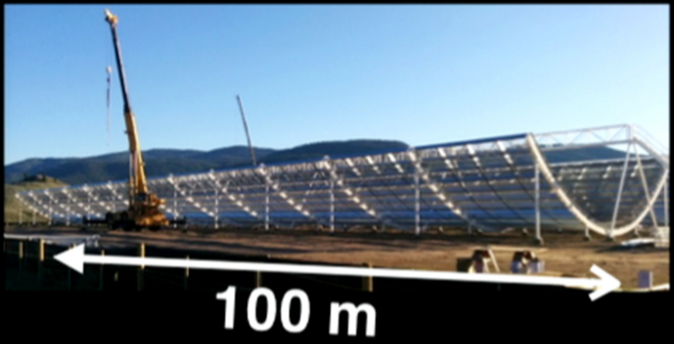
Figure: E. Madsen





Full CHIME





FRB sensitivity

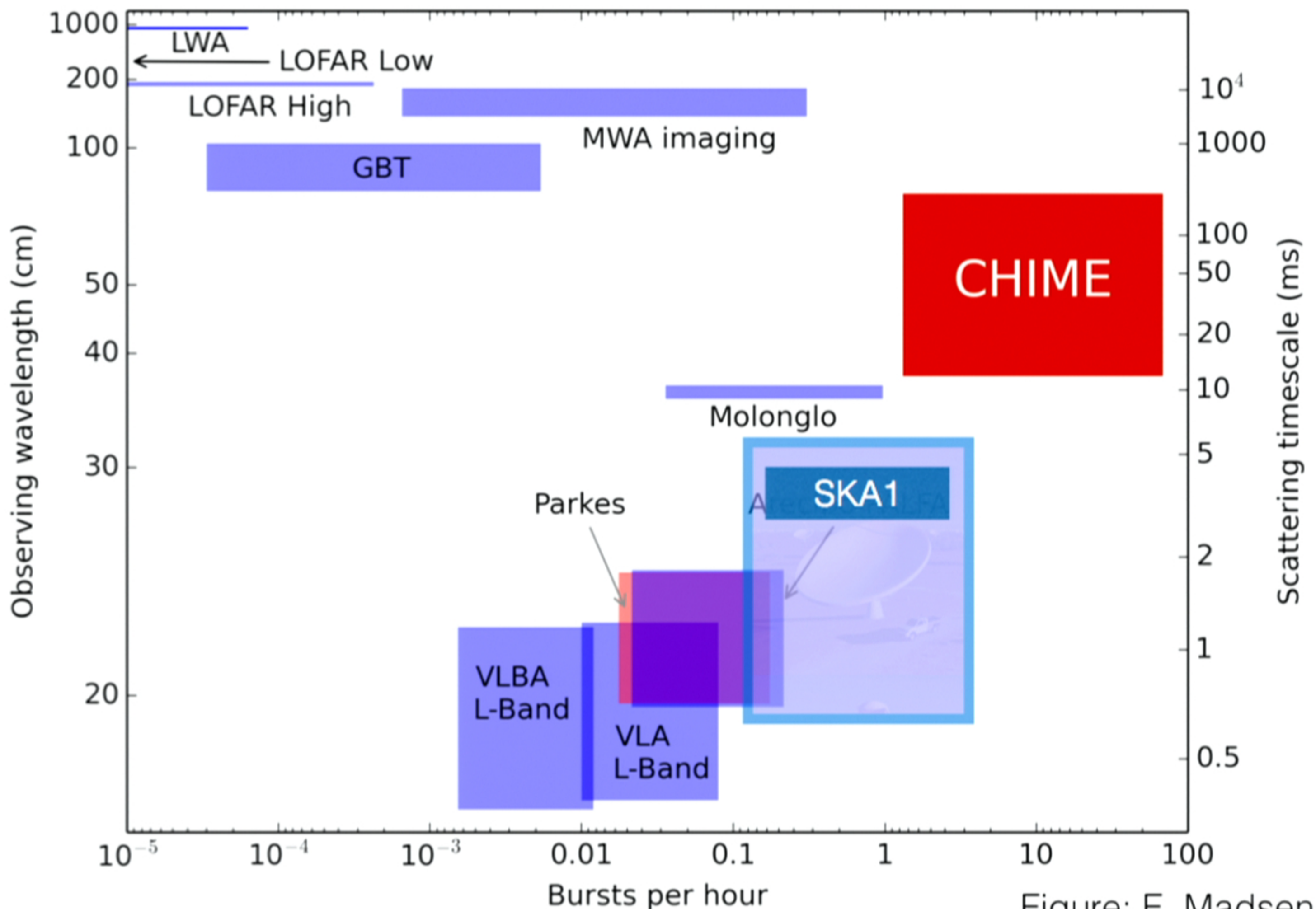


Figure: E. Madsen

FRB sensitivity

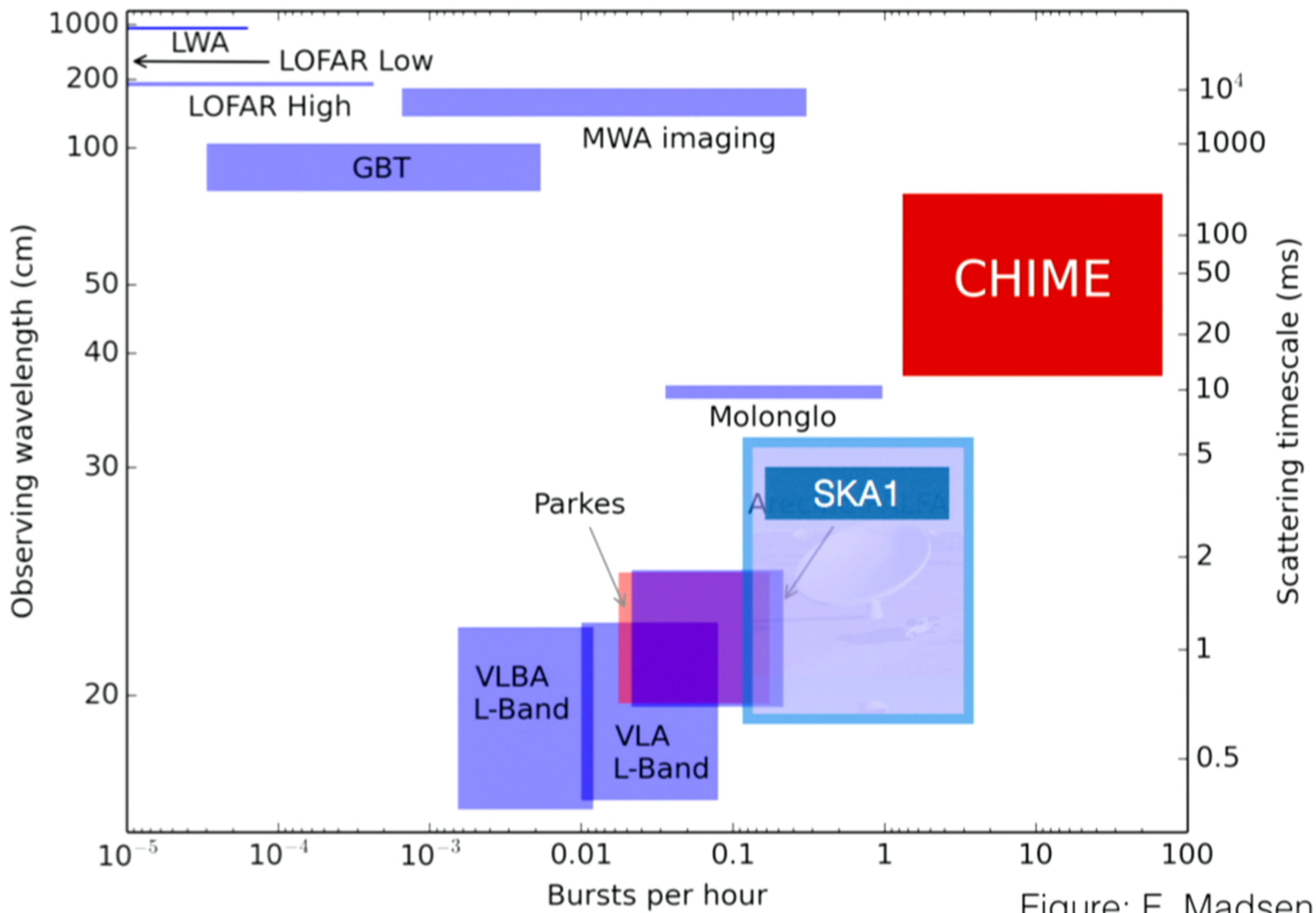


Figure: E. Madsen