Title: Fast radio bursts as probes of large-scale structure

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Abstract: <p>Fast radio bursts (FRBs) are bright, broadband, non-repeating, millisecond flashes of unknown astronomical origin. The dispersion of these bursts by intervening plasma suggests that the sources of the 16 bursts reported to date= are at 0.2<z<1. I will discuss the possibility of using dispersion, instead of redshift, to study the large-scale structure of the Universe in three dimensions. Like redshift, which is distorted by peculiar velocities, dispersion is an imperfect proxy for distance as it is distorted by inhomogeneities in the electron density. These dispersion-space distortions are calculable and actually greatly enhance the signal. The clustering signal in dispersion space could be detected in a survey of 10 000 FRBs, as is expected to be produced by the CHIME telescope over three years.</p>

<p>The greatest uncertainty in whether this technique will be successful is the unknown nature of FRB sources. A new observation tells us more about the environment of a source than ever before through the polarization and scattering properties of a burst. More observations of this type, along with observations that identify host galaxies, will soon tell whether FRBs will provide a new probe of structure.</p>

Fast radio bursts as probes of large-scale structure

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Cosmology Seminar
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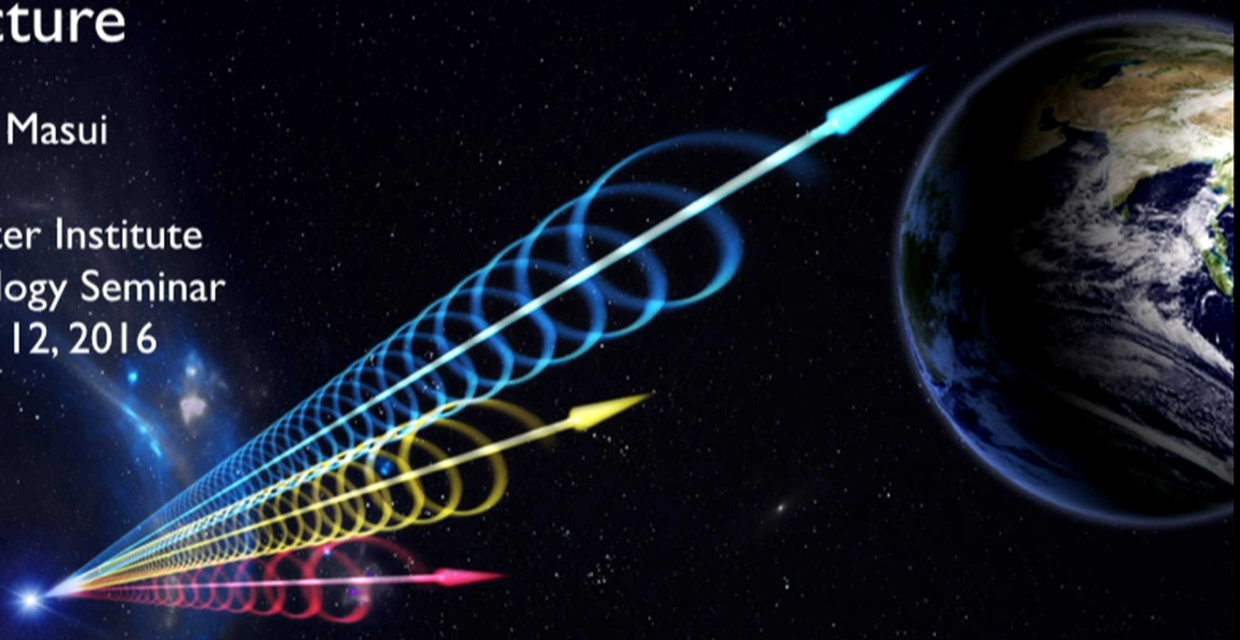


UBC a place of mind

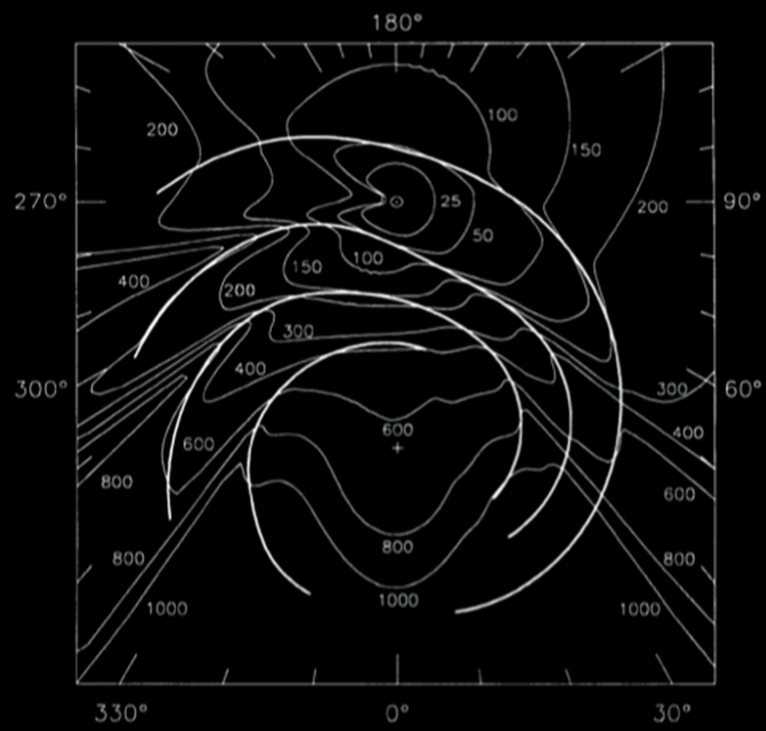
doi:10.1103/PhysRevLett.115.121301 - arXiv:1506.01704
doi:10.1038/nature15769 - arXiv:1512.00529
artwork: Jingchuan Yu, Beijing Planetarium

How fast radio bursts might be used to map large-scale structure in 3D

and…

New observations toward understanding these events

Distance measurements from dispersion



Taylor and Cordes 1993

- Dispersion gives total column of intervening free electrons
- Dispersion routinely used to estimate pulsar distances
- FRB dispersion implies they are extragalactic
- At redshift 0.2 to 1 if IGM dominates dispersion

- If FRBs are extragalactic and at cosmological distances…
- 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?
- Work with Kris Sigurdson

Dispersion space

- Dispersion measure is a path integral of the electron density
- If dominated by the IGM, this can be used as a cosmological distance measure, like redshift
- We can study clustering in 3D

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

Dispersion space

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

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

- There will be additional clustering terms: ***dispersion-space distortions***

Dispersion-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…

$\delta(\vec{x}) \equiv \rho(\vec{x})/\bar{\rho} - 1$ χ is radial distance

'f' for FRB sources, 'e' for electrons, 's' for dispersion space

Dilution term

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

- In electron over densities, extra electrons (thus more dispersion space) between FRBs, diluting them
- Most analogous to the Kaiser effect, however is isotropic.

$\delta(\vec{x}) \equiv \rho(\vec{x})/\bar{\rho} - 1$ χ is radial distance

'f' for FRB sources, 'e' for electrons, 's' for dispersion space

Geometric term

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

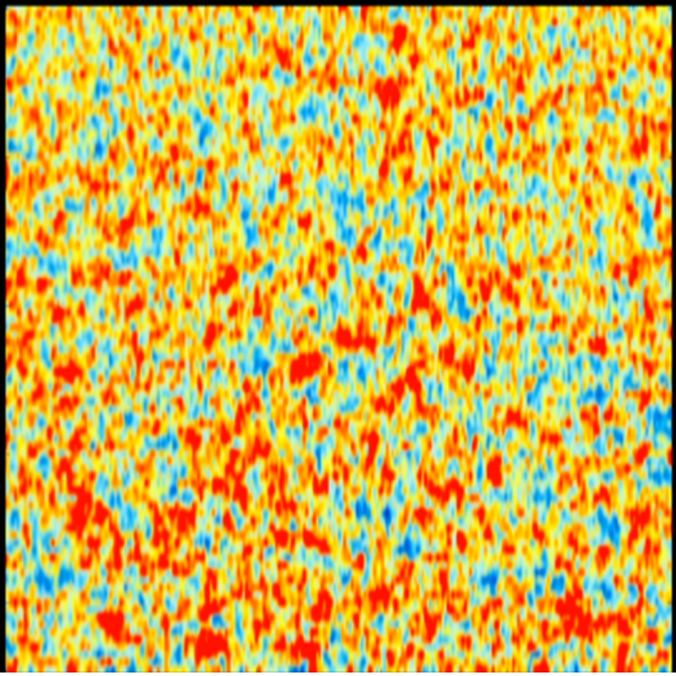
- When we misinterpret the radial distance, also misinterpret the angular distances
- Present in redshift space but insignificant and usually ignored

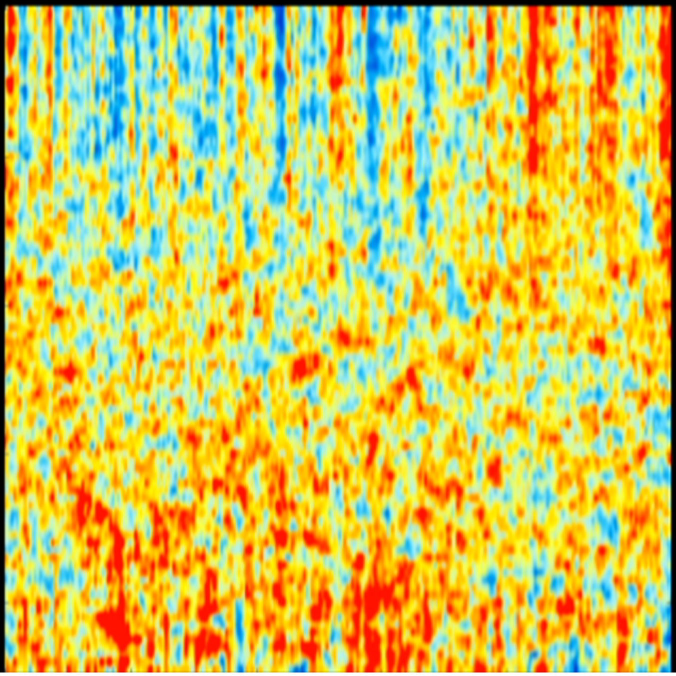
$\delta(\vec{x}) \equiv \rho(\vec{x})/\bar{\rho} - 1$ χ is radial distance

'f' for FRB sources, 'e' for electrons, 's' for dispersion space

Collect terms into a local term and an integral term

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





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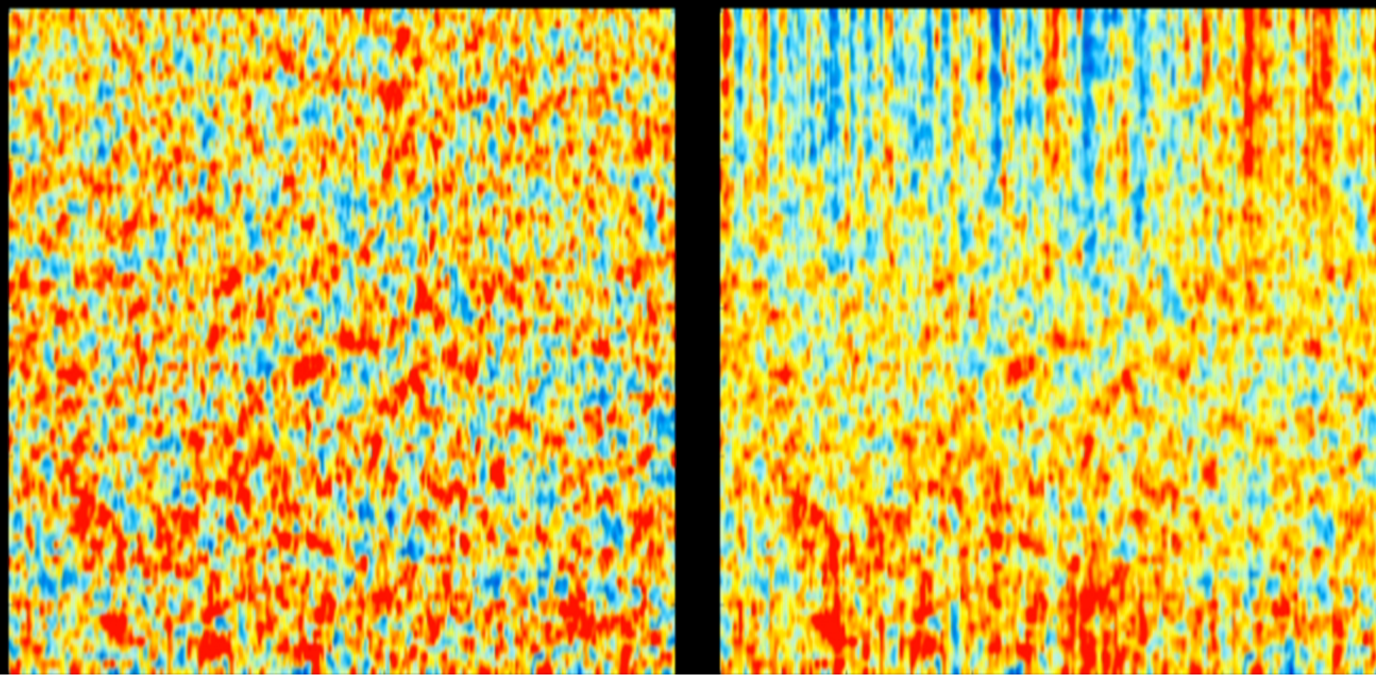
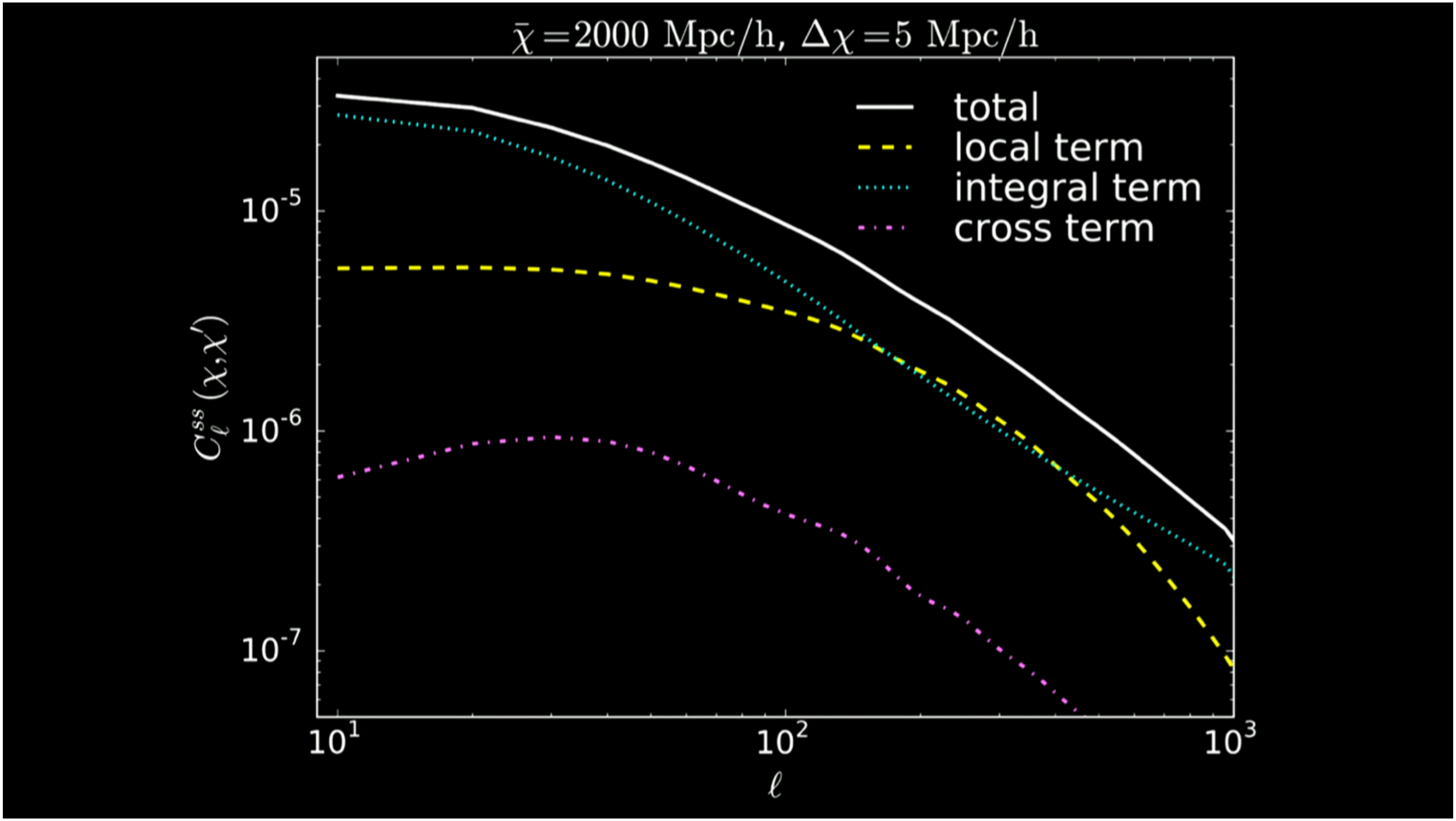
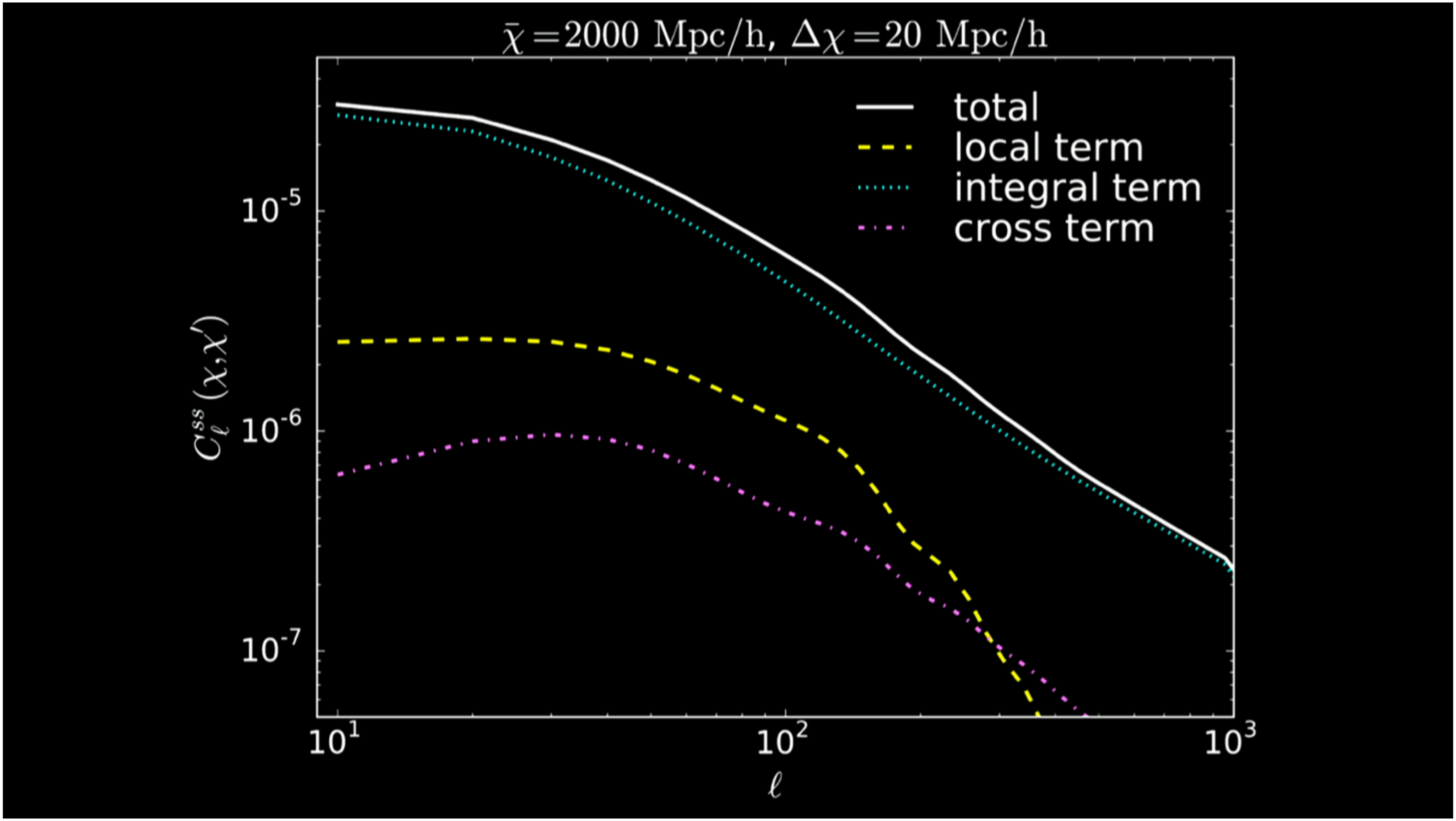


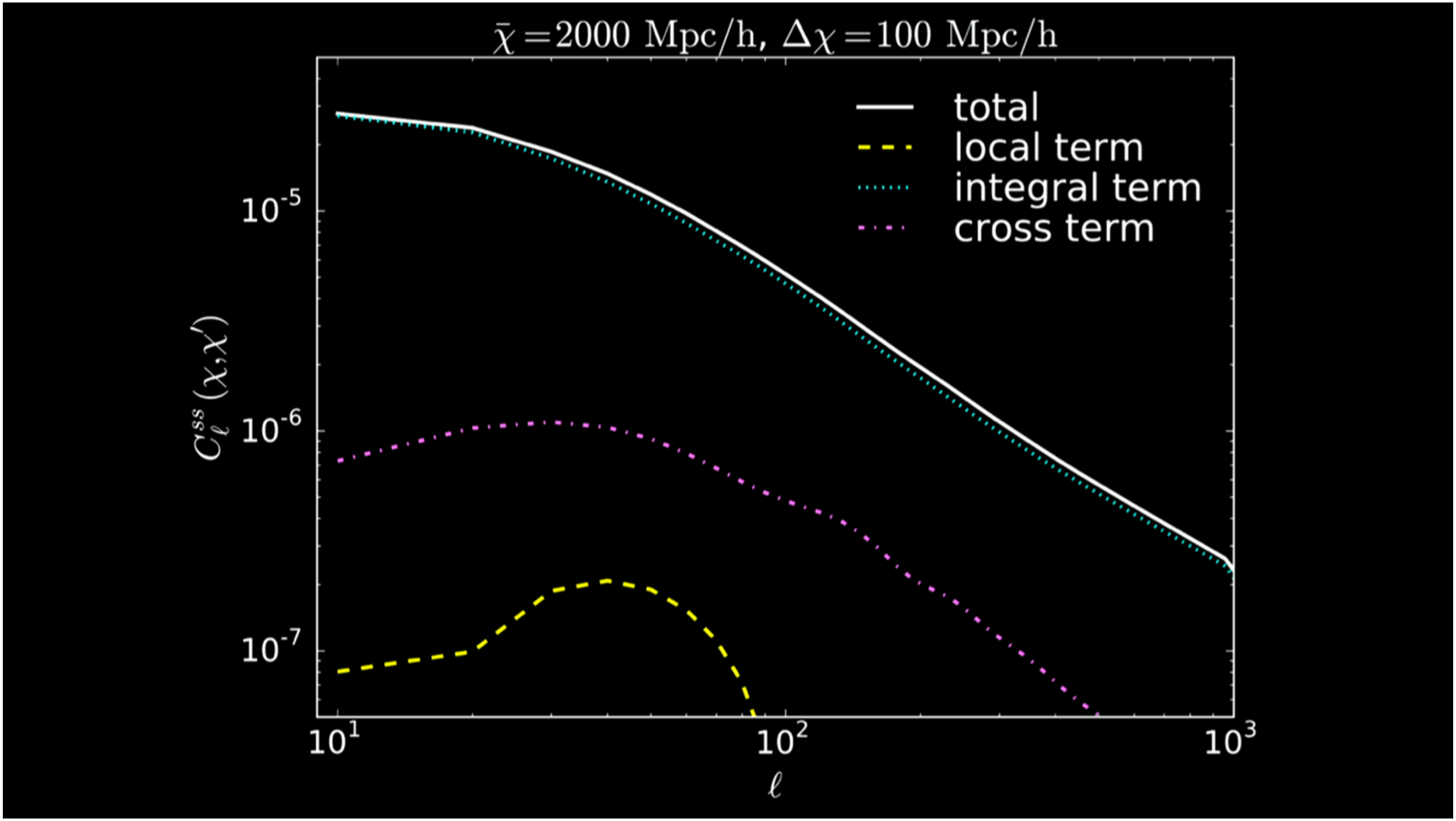
Calculations for toy model

- Assume FRBs and electrons are linear biased tracers of the dark matter.
- $b_e = 1.0$, $b_f = 1.3$
- Made-up but reasonable $\bar{n}_f(\chi)$
- Most sources at $z \sim 0.5$



$\bar{\chi}$ =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


$\bar{\chi} = 2000$ Mpc/h, $\Delta\chi = 20$ 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



$\bar{\chi} = 2000$ Mpc/h, $\Delta\chi = 100$ 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

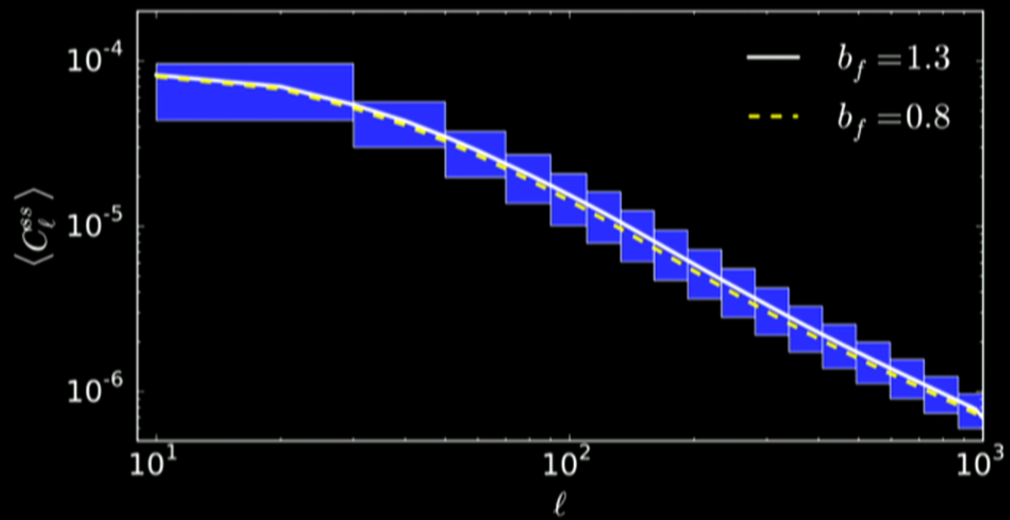
Tomography

- Unlike lensing, line of sight integral has no weight function: tomography is exact

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

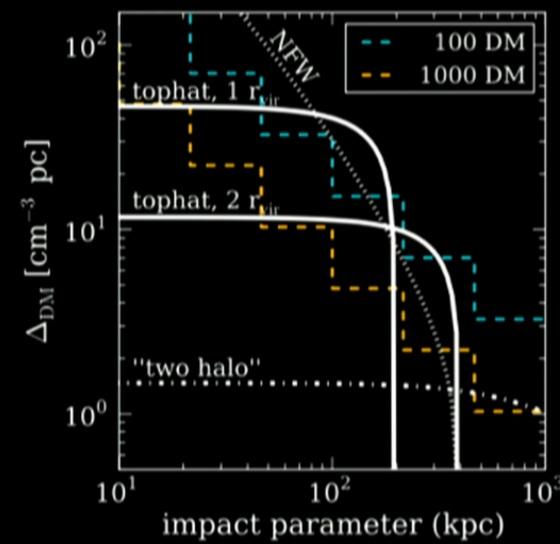
Detectability

- A survey with 10 000 events measures the shape of the angular power spectrum averaged over radial bins
- Mainly sensitive to integral term - *i.e.* electron density perturbations



Applications

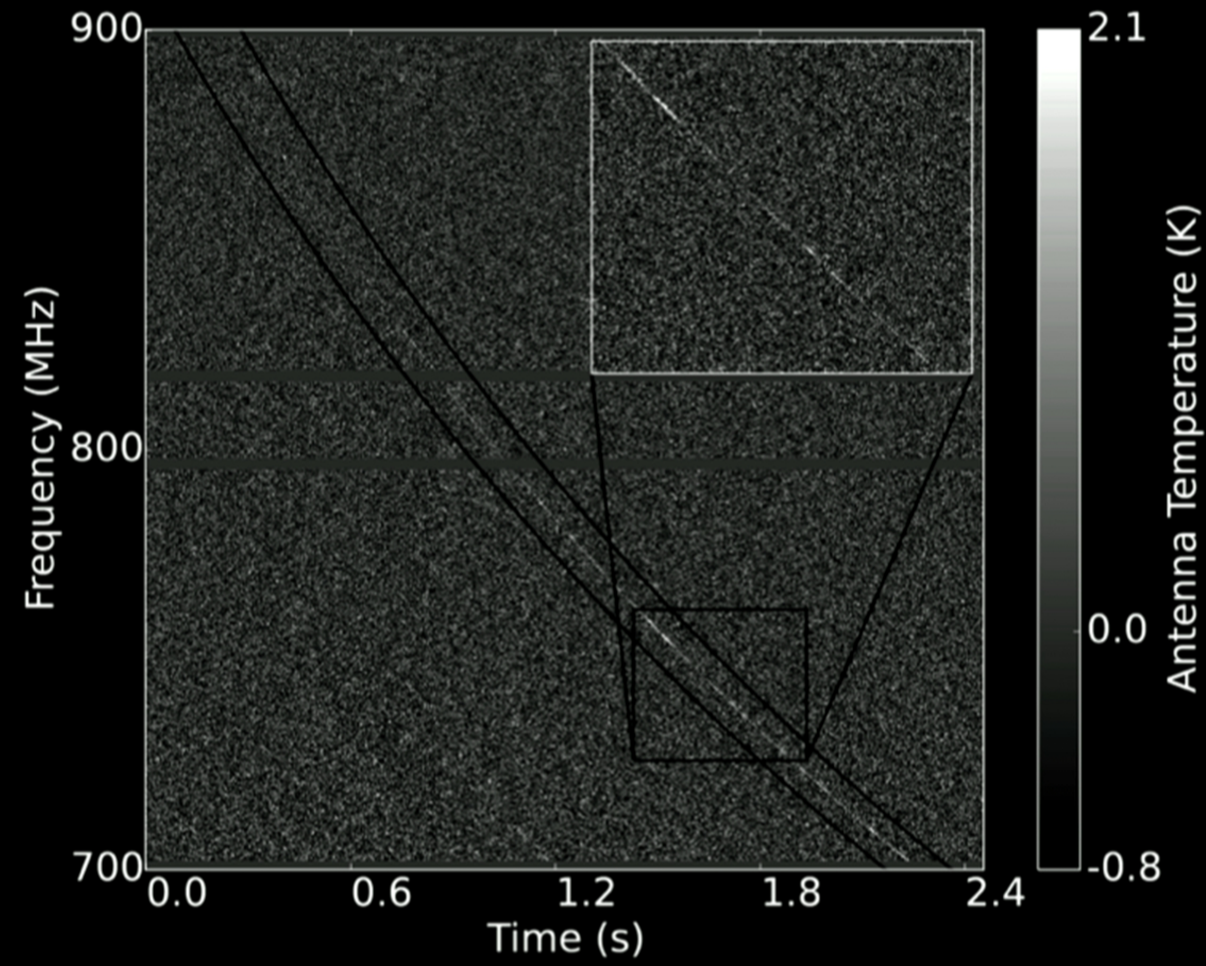
- Integral term could be used to find the “missing baryons”
- With ~5000/sky/day, could build up LSS survey (BAO, etc)
- If there are a lot of extra dim events, or spectrum is red…



McQuinn 2013

The catch

- We have no idea what FRB sources are
- The portion of dispersion that is source-local is unknown
- If large and variable, could ruin distance estimate
- Need more observations to constrain sources



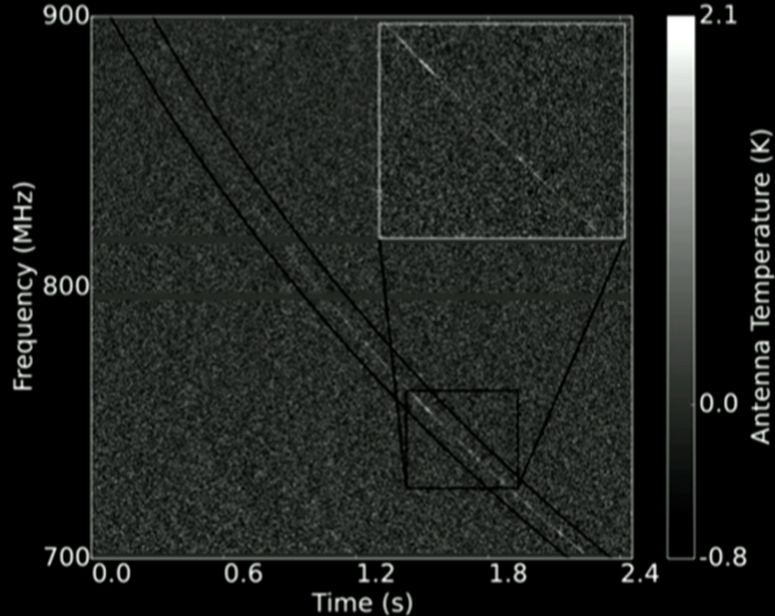
Masui et al. 2015, Nature

FRB 110523

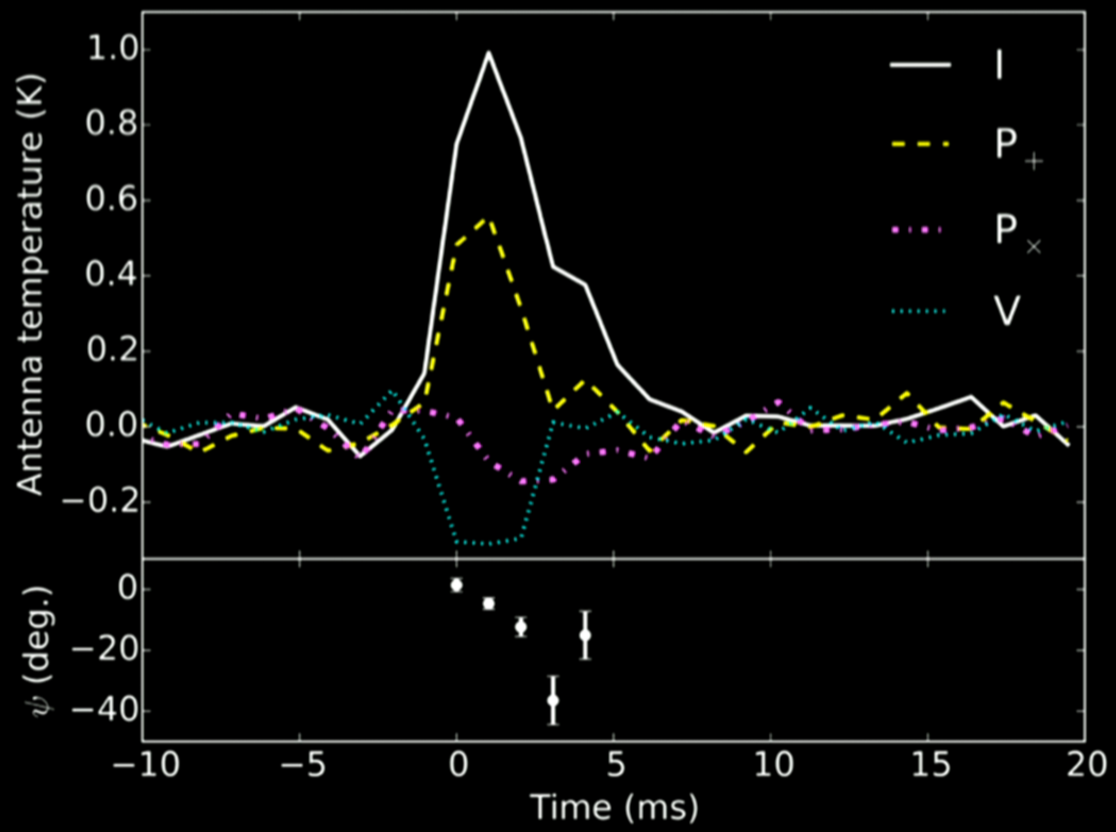
- FRB discovered in GBT hydrogen intensity mapping data
- Detected in 700 to 900 MHz band (first outside 1400 MHz)
- DM = 623 pc/cm^3 (z=0.5 if IGM dominated)

λ^2 dispersion

- $t_{\mathrm{delay}} \propto \nu^{-1.998\pm0.003}$
- Upper limit on plasma frequency and density of dispersing electrons
- Lower limit on size of dispersing region of d > 10 AU
- Rules out atmospheric and Galactic source models

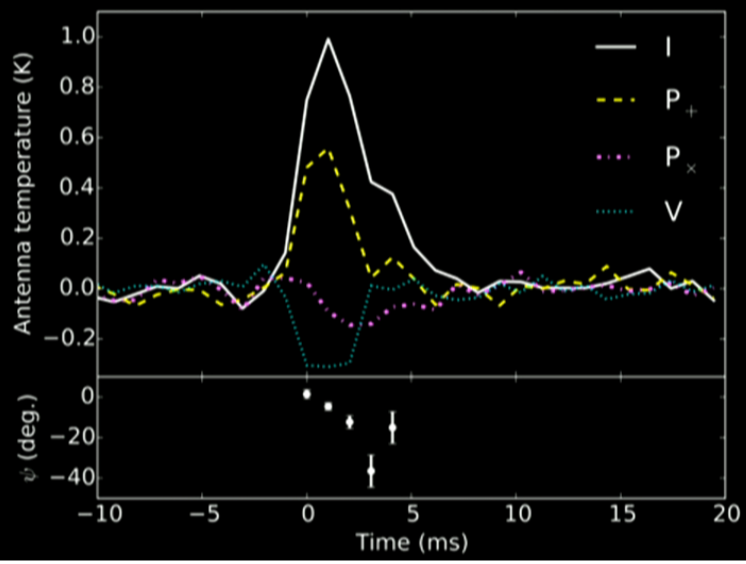


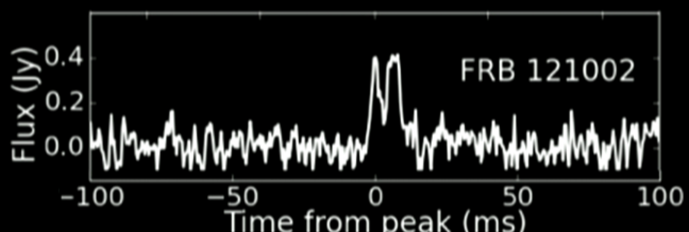
44% linearly polarized



Pulse profile a clue to emission mechanism

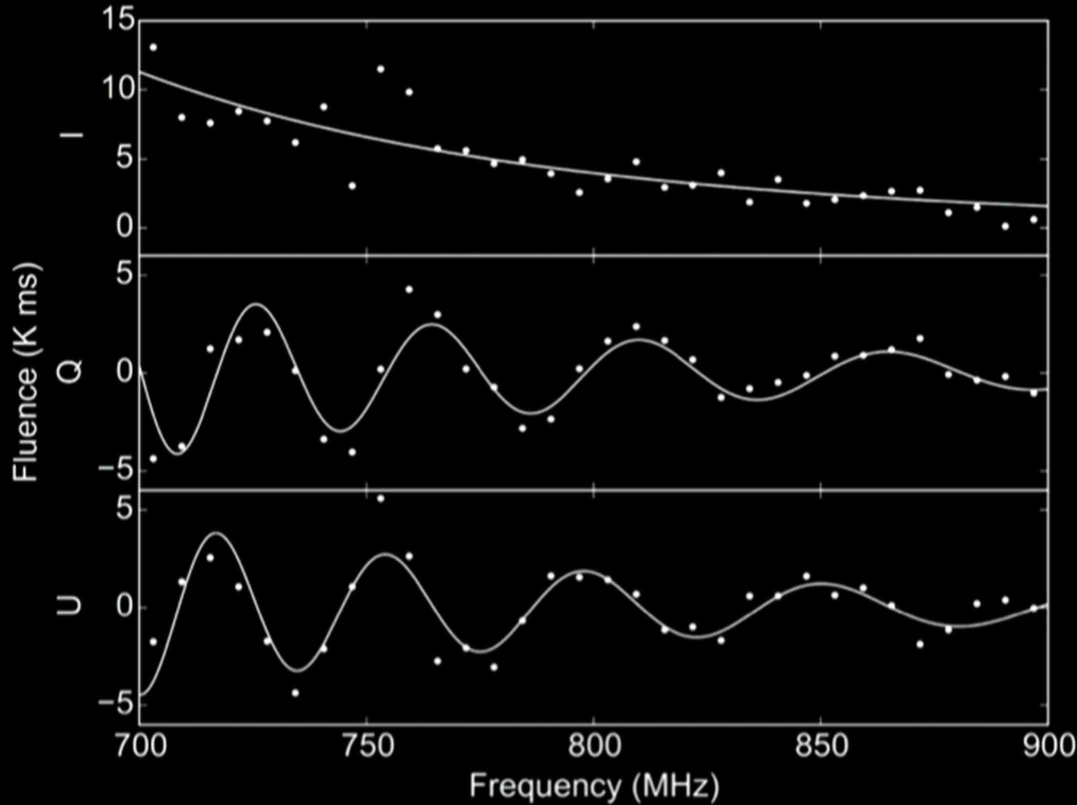
- Polarization angle rotation during pulse
- Recently reported FRB 121002 has two peaks





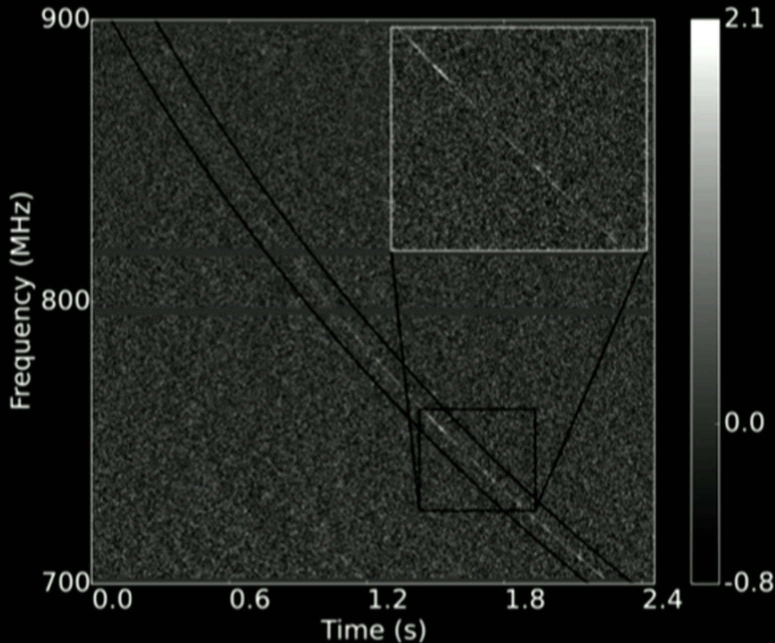
Champion et al. 2015

Faraday rotation (RM = 186 rad/m^2)

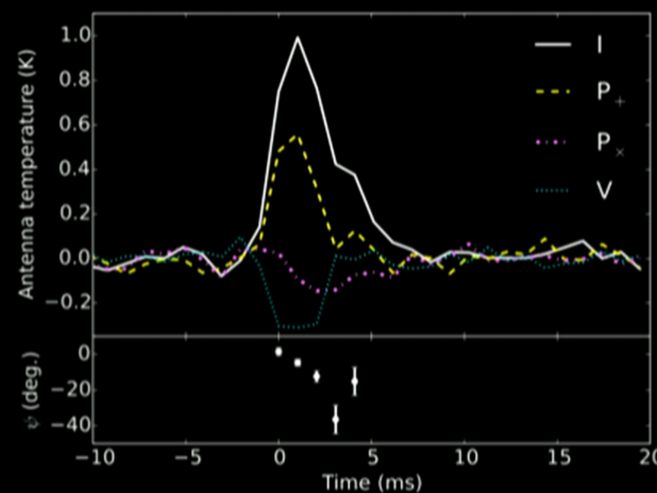


- RM and DM combined give electron weighted $B = 0.38\ \mu G$
- Compare to $\sim 10\ \mu G$ in spiral galaxies
- Some indication that most DM is from the IGM
- $RM = 186\ rad/m^2$ is marginally high for generic line of sight though a galactic disk

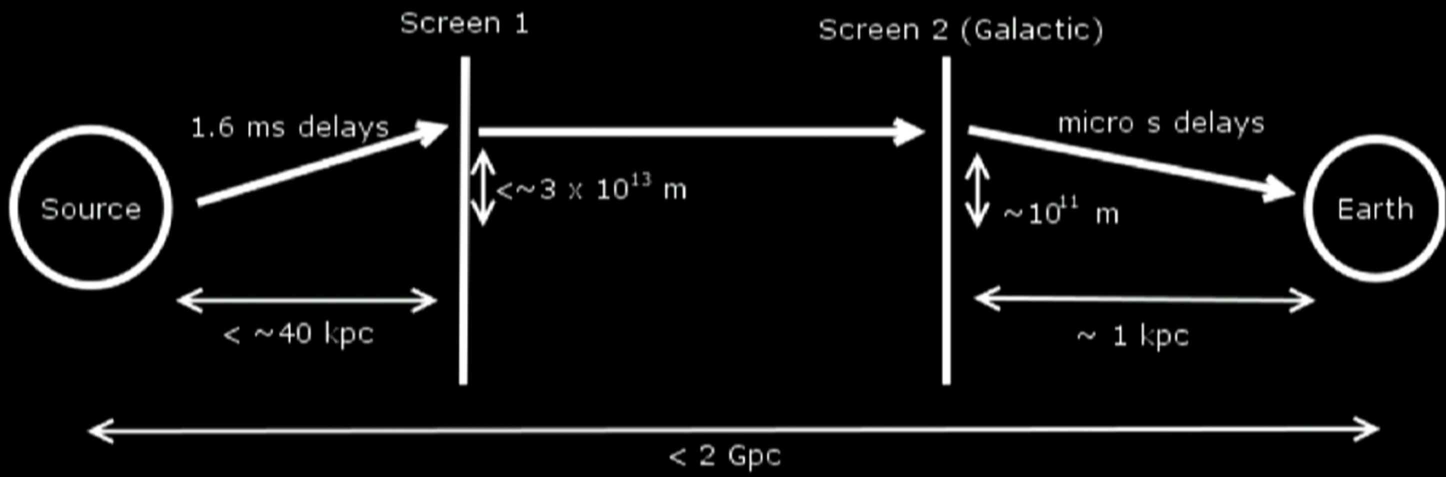
Scintillation and scattering



~μs delays



~ms delays

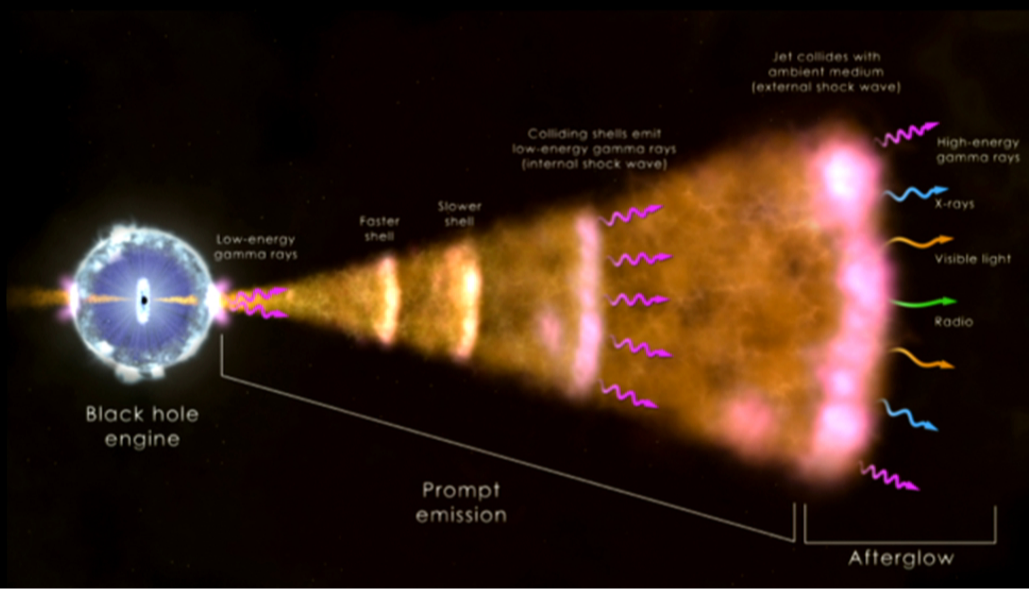


- Scintillation is Galactic
- Scintillation only occurs if scattered image is unresolved by scintillation screen
- Gives a constraint on the location of the scattering screen
- ***Scattering occurs in host galaxy, not the IGM***

- Two possibilities for the environment of the source:
    - source-local nebula (supernova remnant, or star-forming region)
    - galactic central region
- Both point to a younger stellar population
- Still don’t know how much **dispersion** is source-local

- Will learn more by replicating observations to larger sample
- Several teams working on interferometric detection or searching for afterglow
- Identify host galaxy, get optical redshift
- Analogous to GRB host identification

image:
NASA Goddard



- CHIME telescope in BC will collect a sample of several thousand
- Will know much more about sources
- Enough for an LSS detection and measurement of missing baryon distribution