Title: Cosmology and fundamental physics with FRBs

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Abstract: FRBs are the only known sources of extragalactic coherent radiation, that show interference phenomena after traveling over cosmological distances. The interferometric probe allows equivalent strain measurements of $h\sim 10^{-26}$, opening new windows for gravitational wave detection, dark matter properties, and emission physics. I describe new directions, theoretical and observational tools, and current and future experiments.

# Cosmology with FRBs

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September 4, 2019

# Overview

- FRBs: what we currently know
- misconceptions
- precision

## Instrumentation revolution

- CHIME: FFT Telescope (Tegmark and Zaldarriaga 2009++)
- disruptive technology: orders of magnitude more events than all existing and planned radio telescopes, at small fraction of cost
- no moving parts, software telescope: utilize N log N beam forming (FFT), N log N DM search, builds on information revolution technology: efficient low cost receivers (cell phones), computing.
- opens path to much more ambitious surveys.

# Cosmological implications: misconceptions

- many papers using 'standard' DM: dark energy/EoS, baryon evolution
- covariant (degenerate) with likely evolution of host environment

# Cosmological implications: likely initial results

- cross correlation baryon inventory (McQuinn 2014++)
- likely to probe intergalactic medium equation of state
- requires precision positions and/or redshifts

# Underappreciated: Coherence

- most FRB's in coherent/eikonal limit
- multi-path propagation due to gravitational and plasma lensing
- dominant (sole?) population of extragalactic coherent sources exhibiting interference (scintillation!)
- path length measured to $\delta L \sim$ nanoseconds
- dimensionless strain $h = \delta L/L \sim 10^{-25}$: unique window on cosmic space-time metric (e.g. Yang+ 2017)
- special geometry, fudge factor up to $10^5$

# Multi-path lensing

- gravitational lensing:
- compact objects: stars, planets (unique window on extragalactic planets!), black holes, dark matter. Time delay: milli-nano seconds
- dark matter, substructure, self-interaction: years-milli-seconds
- coherent interference measures time delay to nano-seconds
- guaranteed to change from day to day

## path integrals

- Huygens principle: sum over all paths (same as quantum field theory: Fermat, Feynmann, Fresnel-Kirchhoff)
- highly oscillatory integrals $\int \exp[i\phi(\mathbf{x})]d^n x$
- considered barely tractible in 2-d
- Picard-Lefshitz theory

# Lens notation

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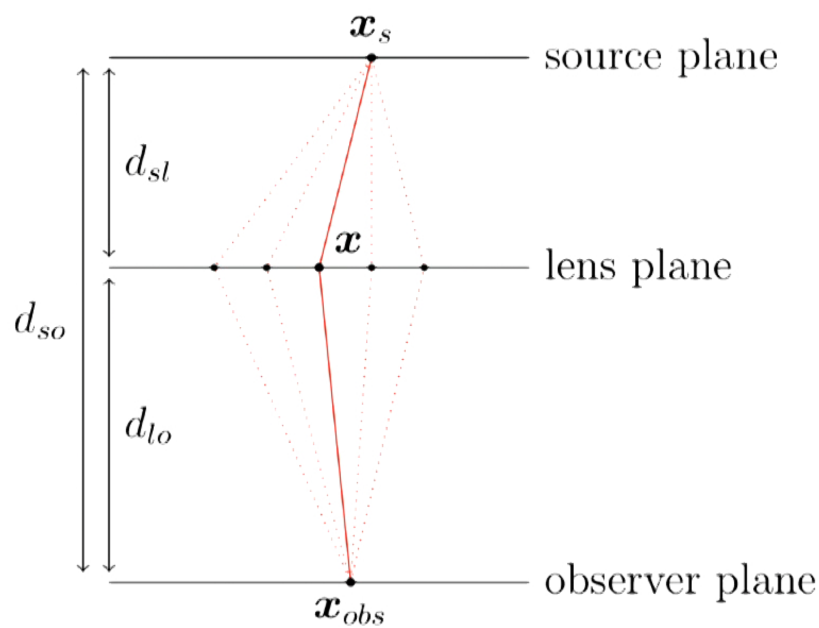
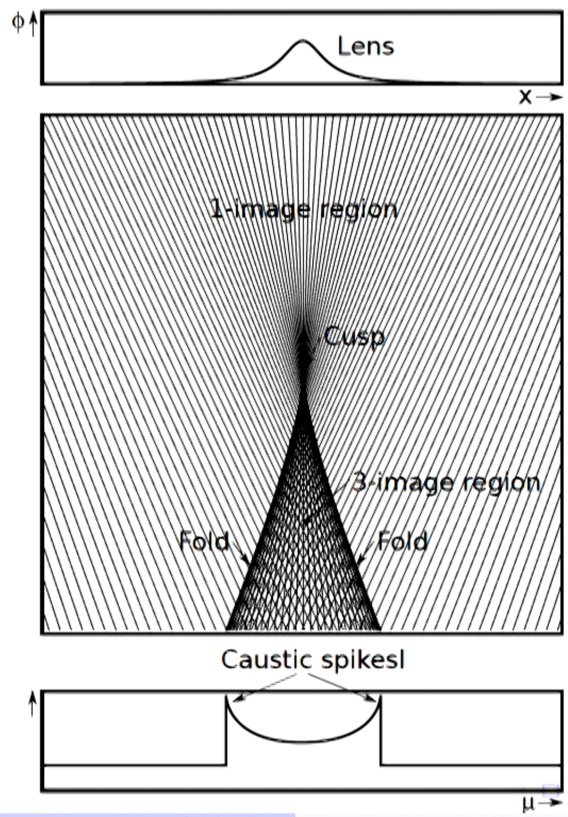



Figure 1: The geometry of interfering paths passing through a thin lens.

Feldbrugge+ 2019

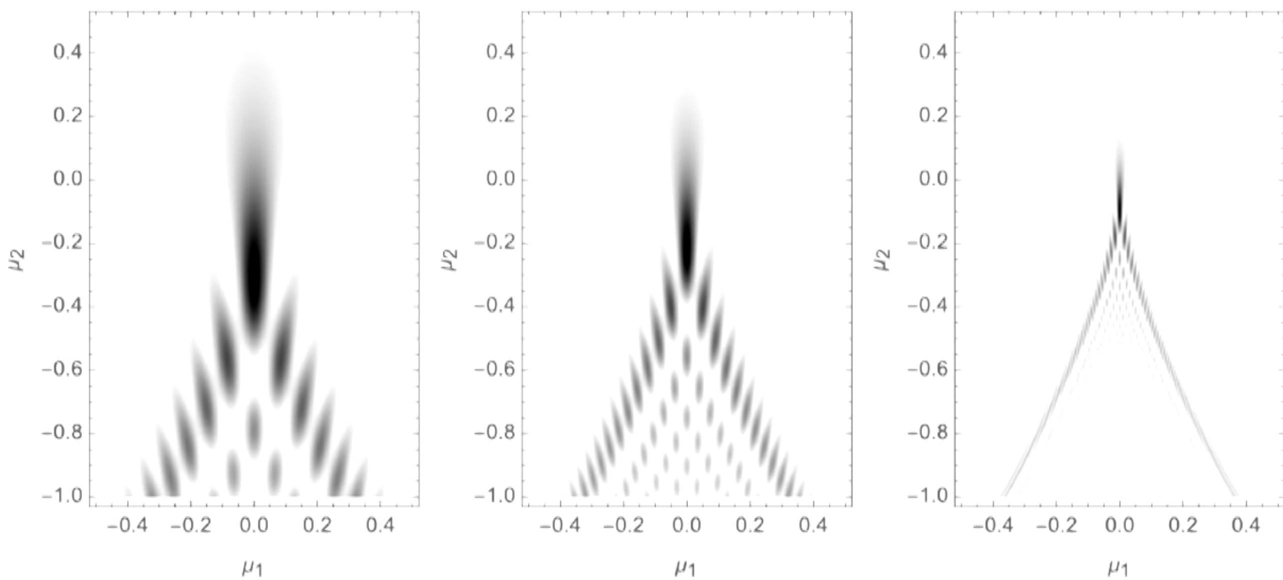
# Geometric Lens

Distant point source



# Wave Lens



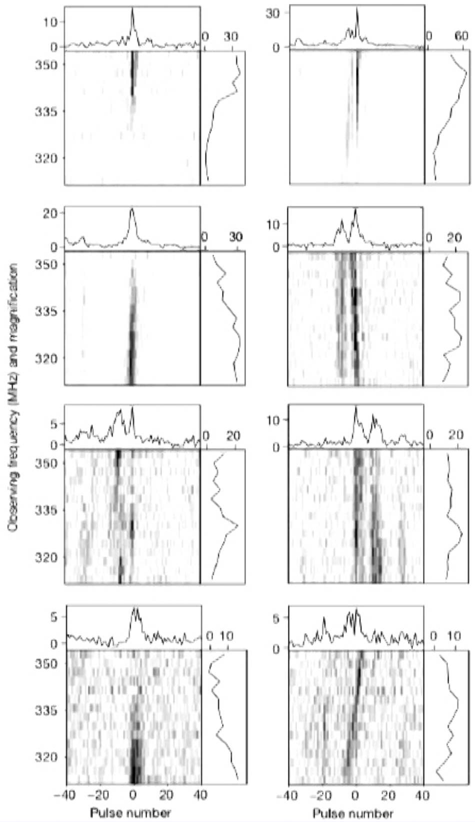



(a) $\nu = 50$ (b) $\nu = 100$ (c) $\nu = 500$

Figure 15: The normalized intensity $I(\boldsymbol{\mu}; \nu)$ for the cusp caustic for $\nu = 50, 100$ and $500$.

# Data

RESEARCH LETTER

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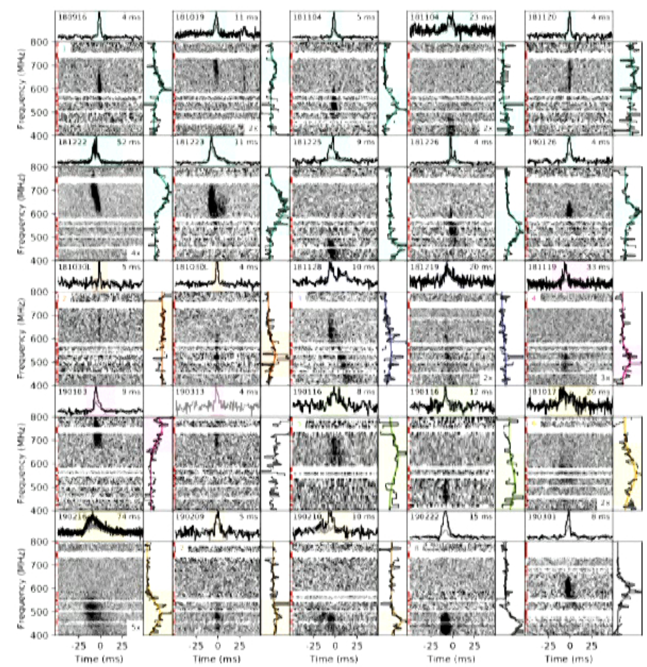
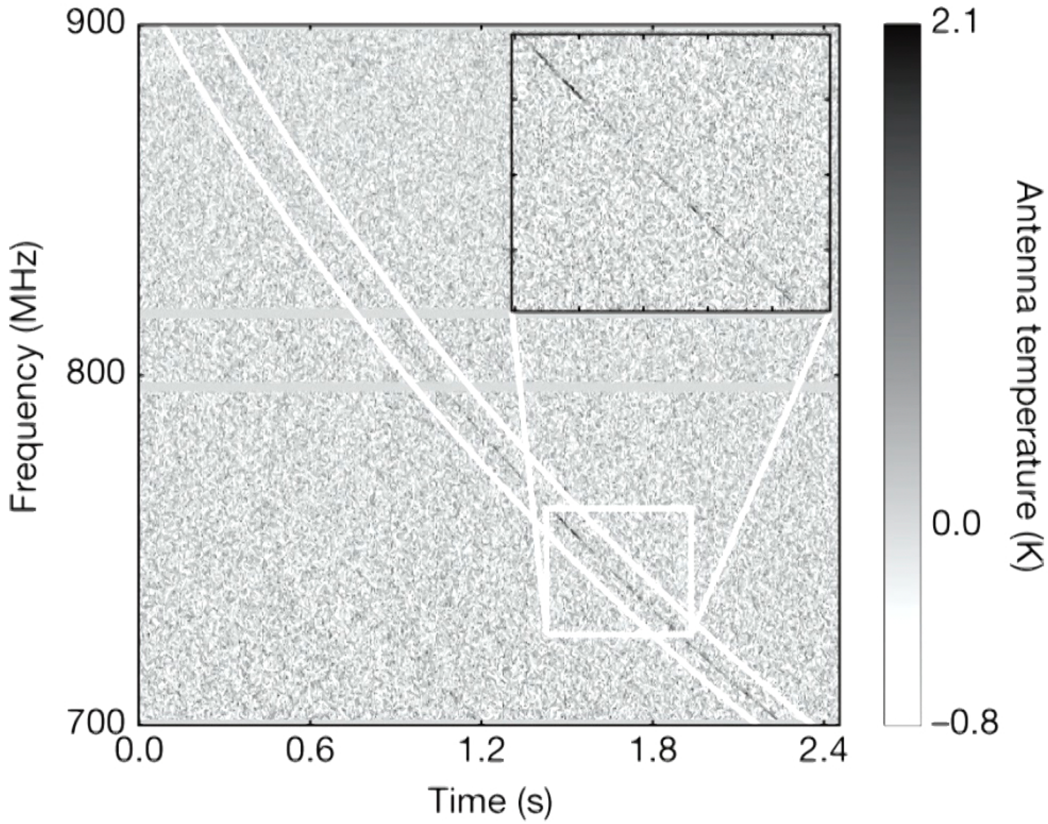


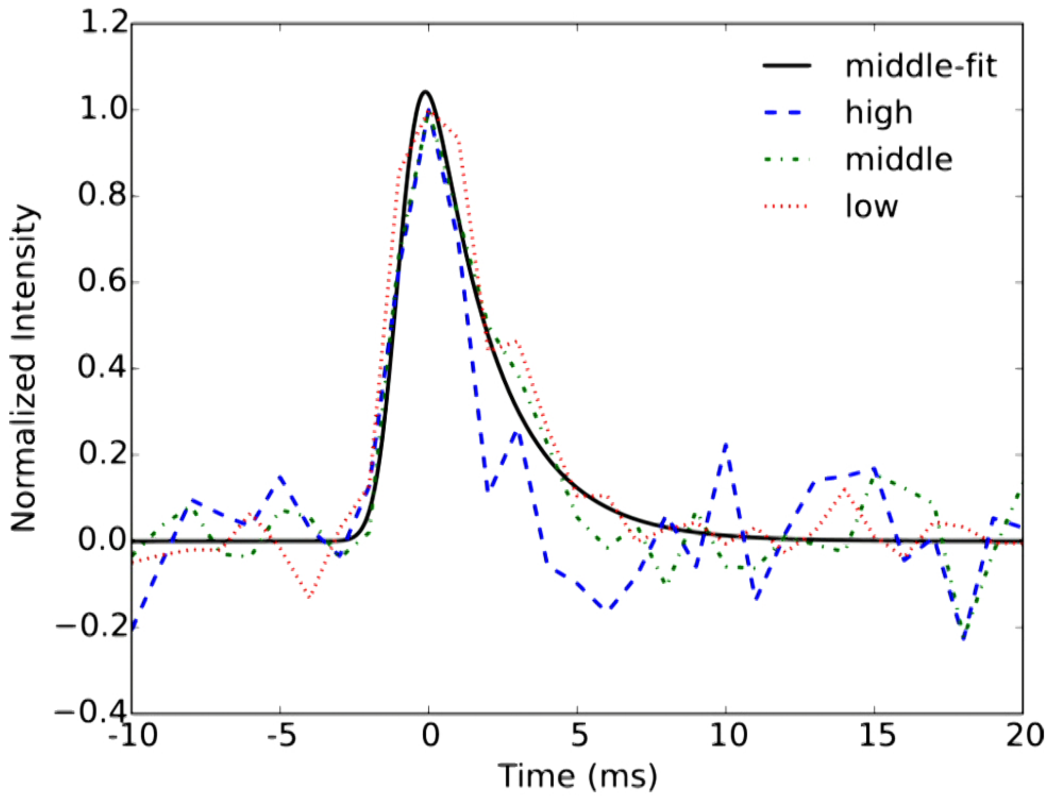

**Figure 3.** Frequency vs time ("waterfall") plots of the bursts listed in Table 2, for the per-burst optimal DMs as determined in §3.5. Every panel shows the dedispersed intensity data with the integrated burst profile on top and the on-pulse spectrum on the right. One color is used per source. Windows show 100 time samples (~100 ms), unless indicated otherwise by the multiplicative factor in the bottom right corner. Intensity values are saturated at the 5th and 95th percentiles. All bursts were detected in the source's upper transit, unless an "L" in the top left corner indicates a detection in the lower transit (only the case for Source 2). Pulse widths, defined as the width of the boxcar with the highest S/N after convolution with burst profile, are in the top right corner. The shaded region in the profile

# FRB110523

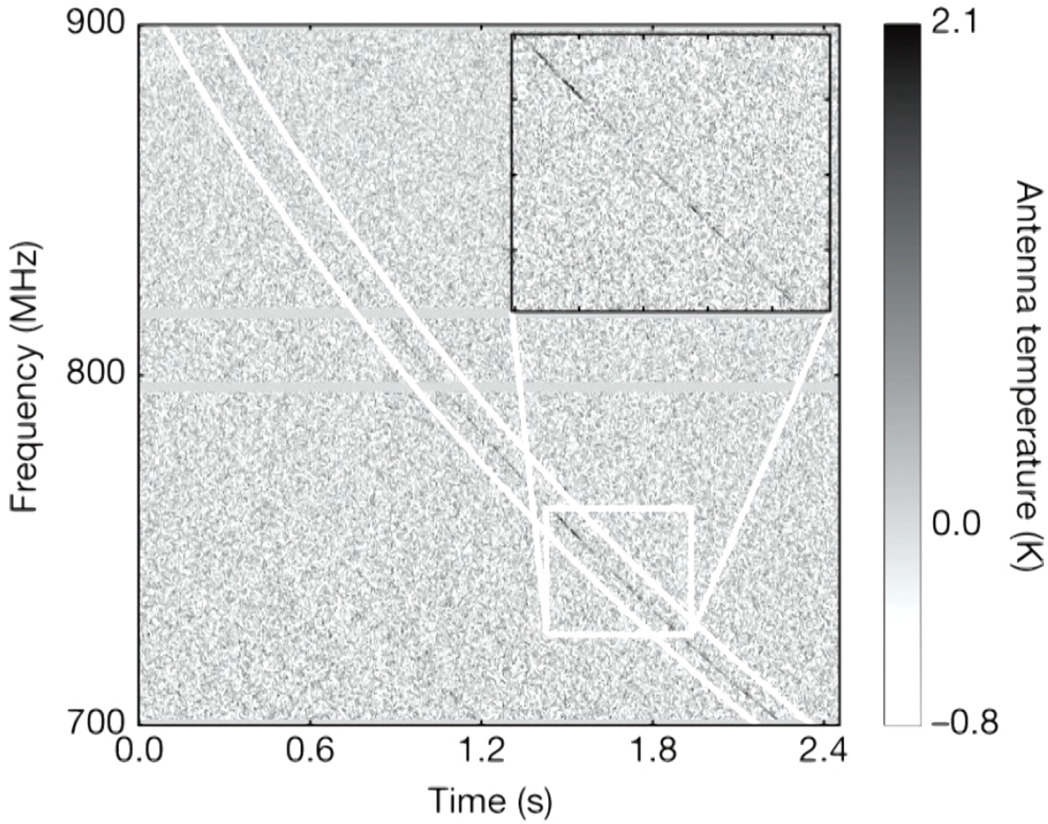



Masui et al 2015

# Scattering

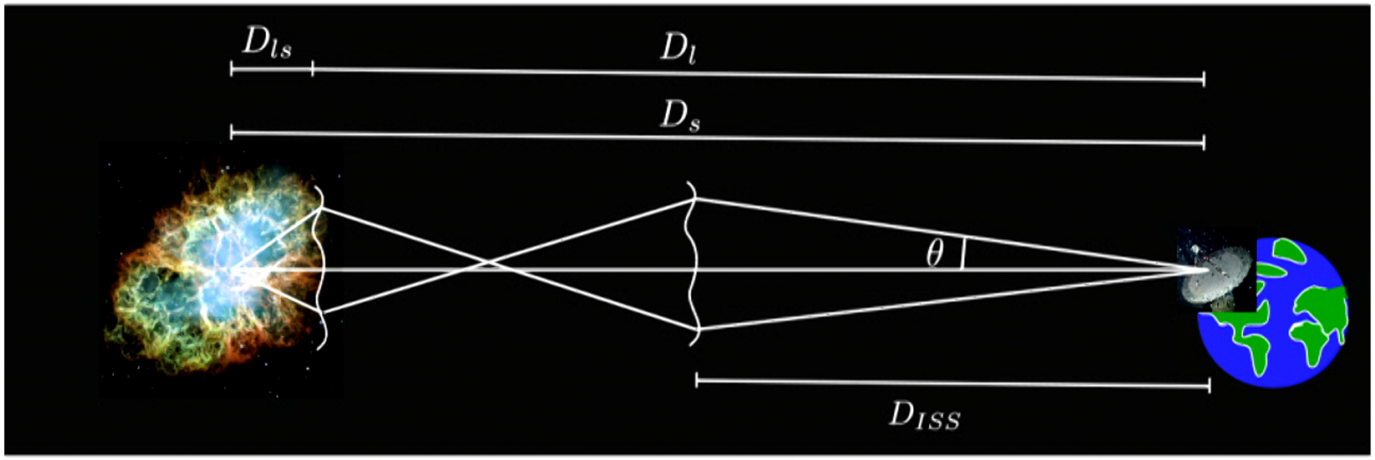

1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
Normalized Intensity
-10
-5
0
5
10
15
20
Time (ms)
middle-fit
high
middle
low

# FRB110523




Masui et al 2015

# Crab




(figure credit: R. Main)

$\tau_{\text{nebula}} \gg \tau_{\text{ISM}}$

## interpretation

- ms scattering is generally due multipath propagation
- location has been proposed in IGM (theoretically challenging) or intervening halos
- FRB110523 shows $\mu$s scintillation from Galactic multipath
- scattering tail scintillates!
- *stars twinkle, planets don't*
- constrains source size less than $\sim$ microarcsecond
- scattering screen is physically associated with FRB, not intergalactic or intervening

# Future possibilities

- event rate proportionate to field of view, collecting area
- millions of bright FRBs per year, likely billions per year accessible with achievable budgets
- outriggers will localize all events at milli arcsecond resolution
- resolve some gravitaiona/plasma lenses

## Conclusion

- coherence of FRBs underappreciated
- one of the most precise measurements ($10^{-25}$)
- wave propagation poses new theory challenges: oscillatory path integrals (Feldbrugge at al 2019+)
- Two screen scintillation/scattering: crab, FRB110523
- low frequency VLBI could quantify galactic screen distance, constrain source screen distance
- beginning of new era, for theory and data