Scintillations and Lensing of FRBs: Near and Far

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Basic points:

- Galactic scintillations + host galaxy ISS/lensing
  - IGM contributes only to DM, not scattering
- Why scintillation/caustics can occur:
  - Light-travel size of FRB emission regions << critical size
- Why scintillations don't always occur:
  - Host scattering quenches Galactic scintillations
  - Bandwidth or source-size averaging at low Galactic latitudes
- DM/EM/SM → information about source environments

Details:

- Astro-optics of Scattering/Lensing/Scintillation
- Selection effects
  - Strongly frequency dependent
  - Detection in surveys vs reobservations
- Interpreting the repeater and other FRBs
- Next steps: inferring conditions near FRB sources

A puzzle:

A large number of FRB sources but only a small number detected (23):

- Low burst rate sources?
- High rate + high modulation?

Optics

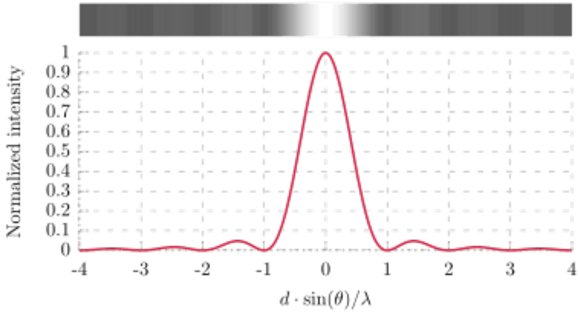
Refraction

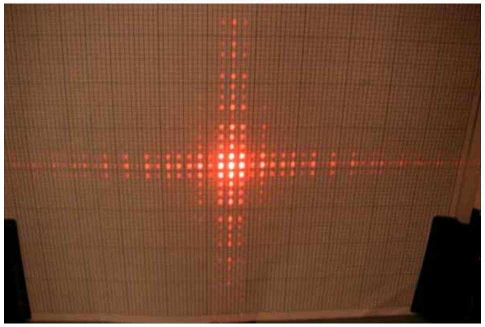
Changes in refractive index on scales >> Fresnel scale

Geometrical optics

Ray tracing

Diffraction



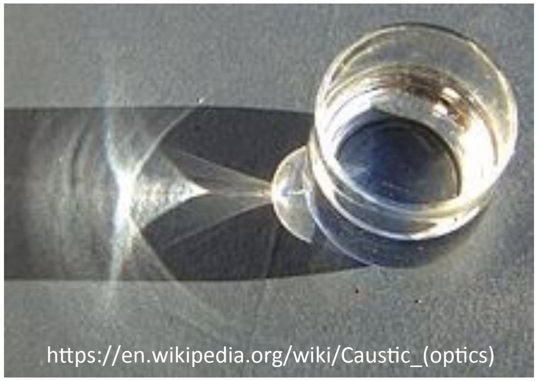


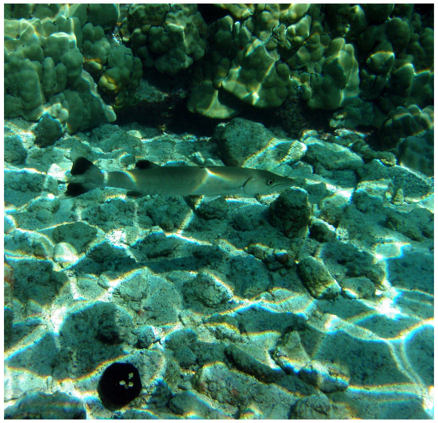
Scales < Fresnel scale

Physical optics

$$\text{Fresnel scale} = \left(\frac{\lambda d}{2\pi}\right)^{1/2}$$

Caustics

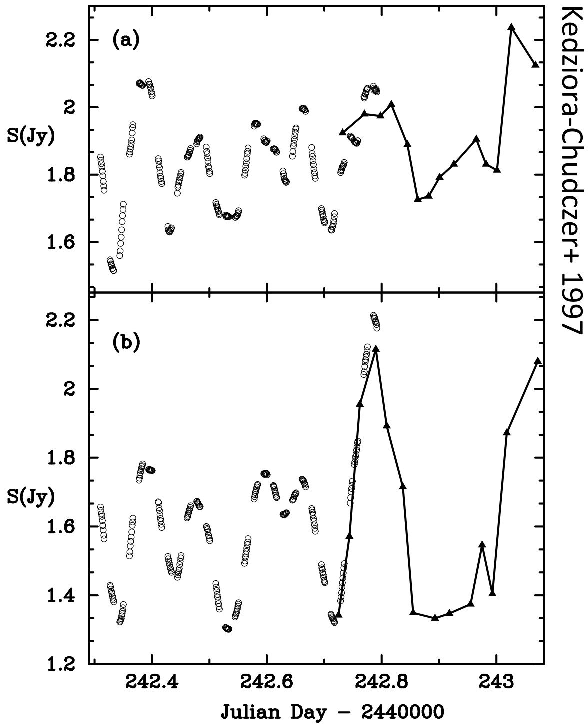




Pileup of ray paths limited by diffraction

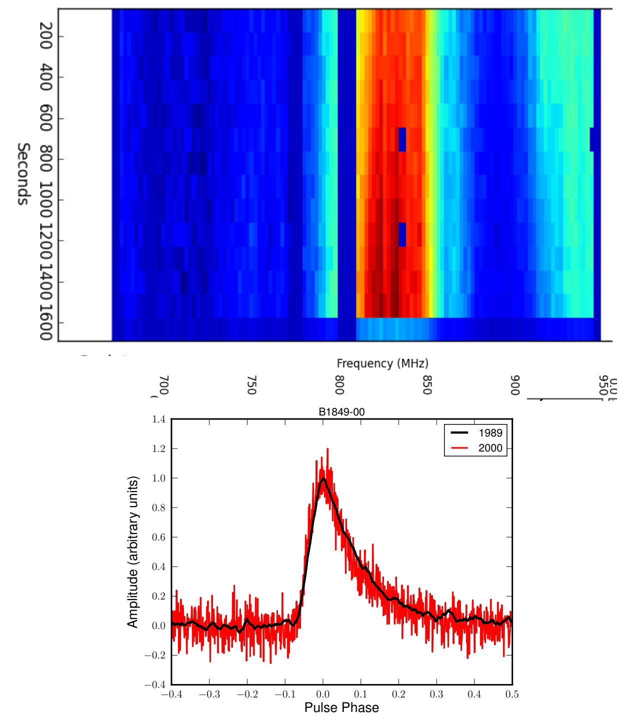
Astro Optics

Refraction



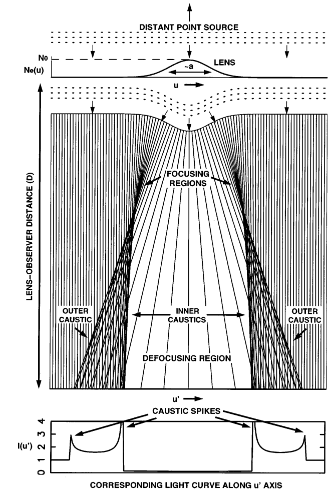
Kedziora-Chudczer+ 1997

Diffraction

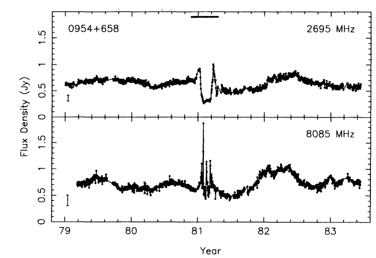


NANOGrav, M.Lam

Caustics



Clegg, Fey, Lazio 1998



Fiedler et al. 1987

Refractive scintillation
RISS

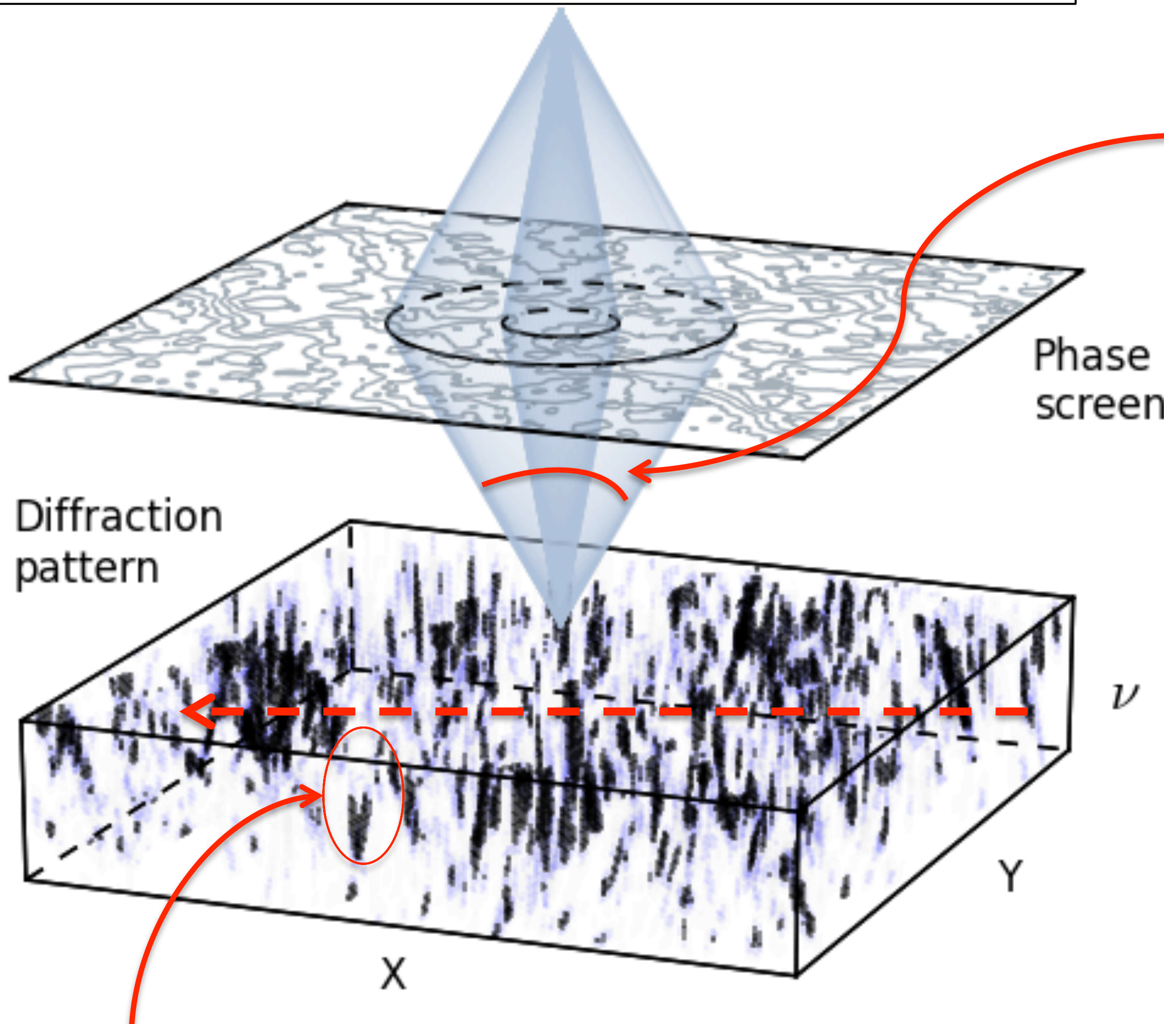
Diffractive scintillation
DISS
Pulse broadening

Extreme "scattering events"
(Not scattering!)

$$\text{Fresnel scale} = \left(\frac{\lambda d}{2\pi}\right)^{1/2} \sim 10^{11}\,\text{cm} \quad \text{(ISM)}$$

See also Bannister et al. 2015; Tuntsov et al. 2016

Replace slit in mask with a phase-changing screen:
The equivalent of the slit width/separation is the length over which the RMS phase = 1 rad



speckles/scintles ~ 10^4 km x (kHz to 100 MHz)

Coherent waves from compact sources illuminate turbulent plasma in the ISM

Scattering angle ~ λ^2

Solid angle ~ λ^4

Scattering causes an interference pattern at the Earth's location

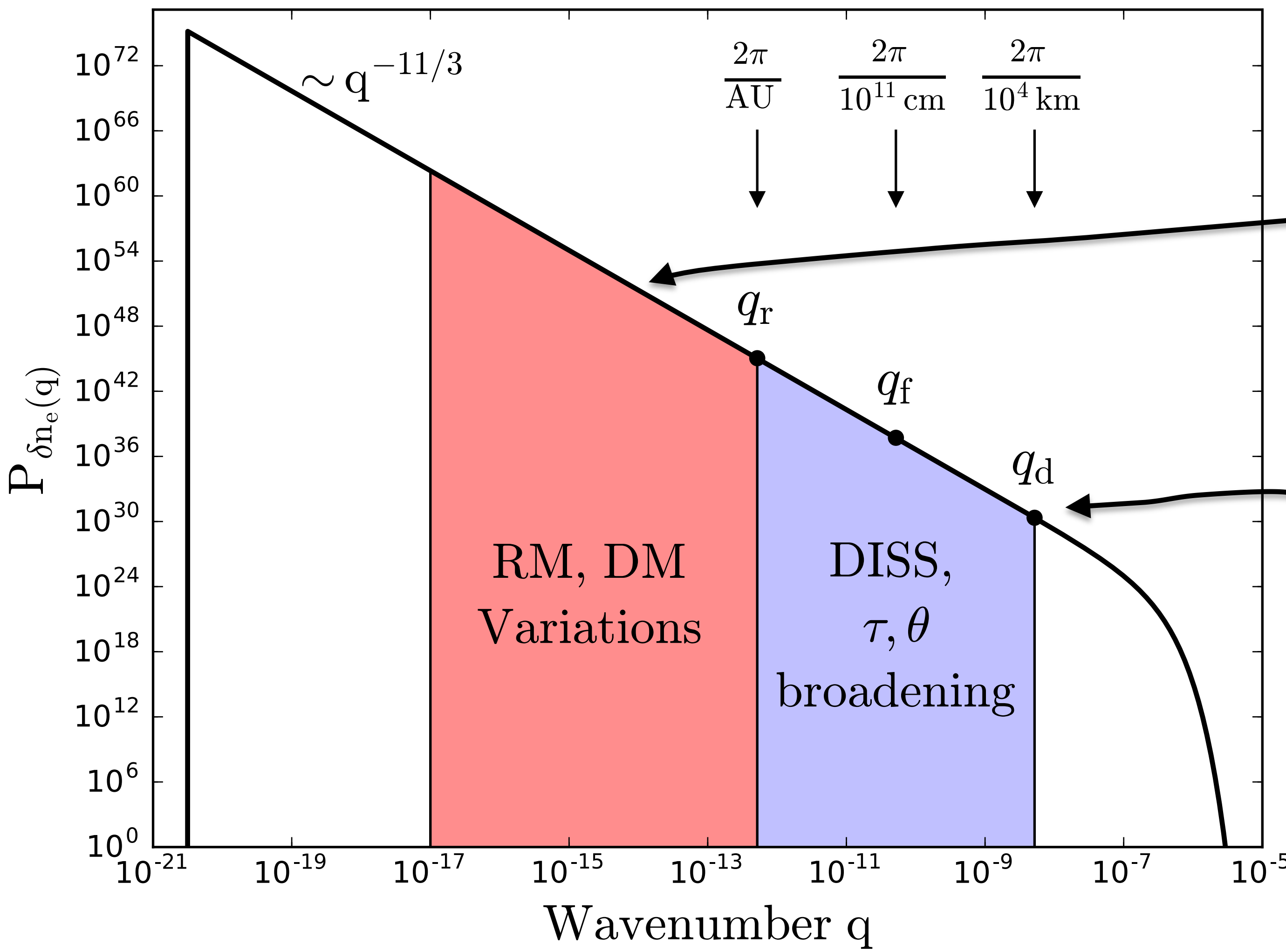
I(x,y,v)
+
Source/Earth velocity
→ I(t, v)

DISS ~ 10^4 km → min-hr

The pattern is also influenced by refraction from larger scales:

RISS ~ AU → days-yr

Notional Wavenumber Spectrum for Galactic δn_e



$$\text{Spectrum} = C_n^2 q^{-\beta}$$
$$\langle n_e^2 \rangle = \int d^3q\, C_n^2 q^{-\beta}$$
$$\text{SM} = \int_{\text{LOS}} ds\, C_n^2$$

Constraints from:

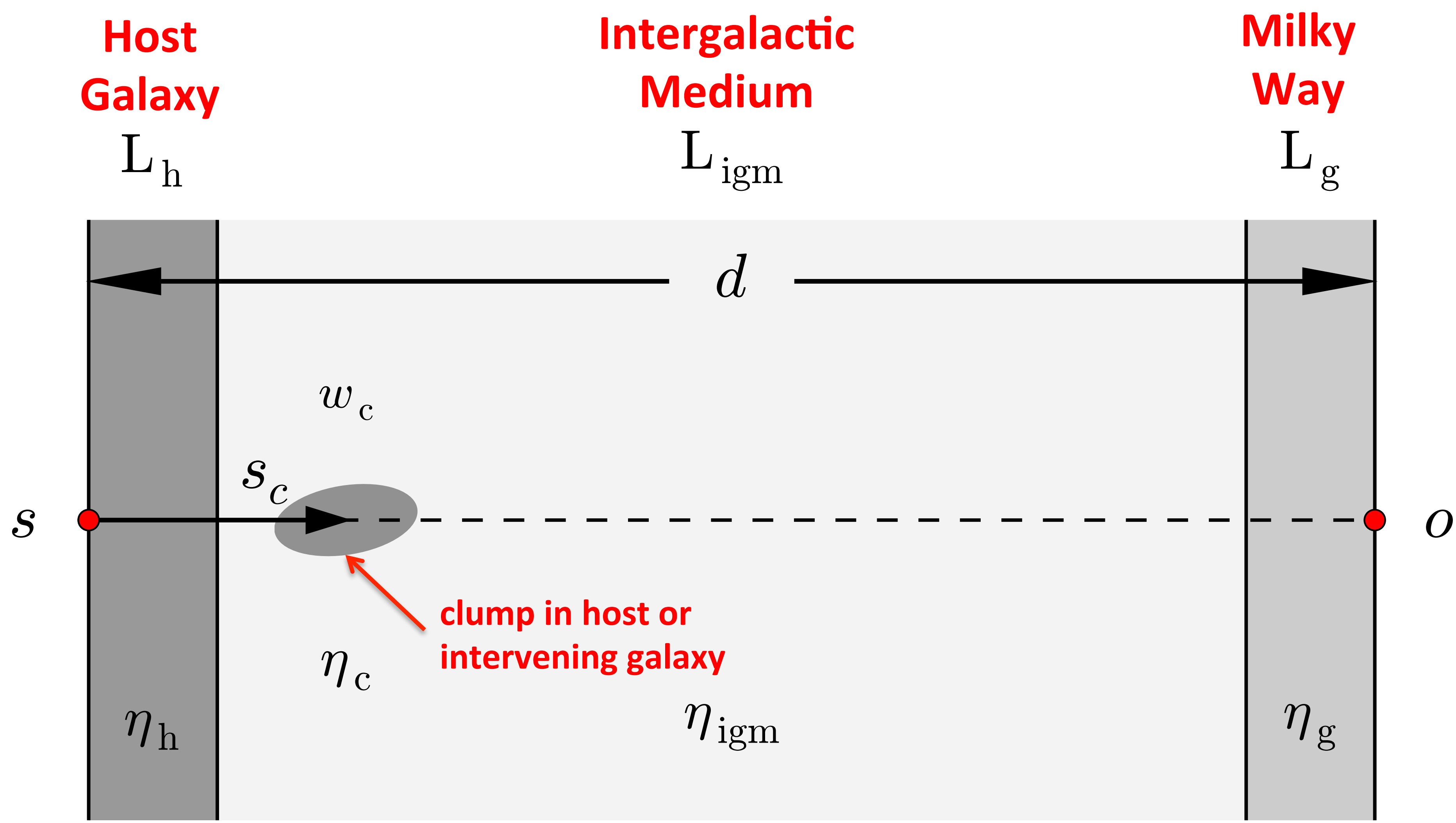
- Pulsar DM(t)
- RM variations
- Galactic structure

- Pulsar DISS
- Angular scattering (VLBI of AGNs, pulsars)

see also

Armstrong, Rickett, Spangler 1995

$$\text{Fresnel scale} = \left(\frac{\lambda d}{2\pi}\right)^{1/2} \sim 10^{11}\,\text{cm} \quad (\text{ISM})$$

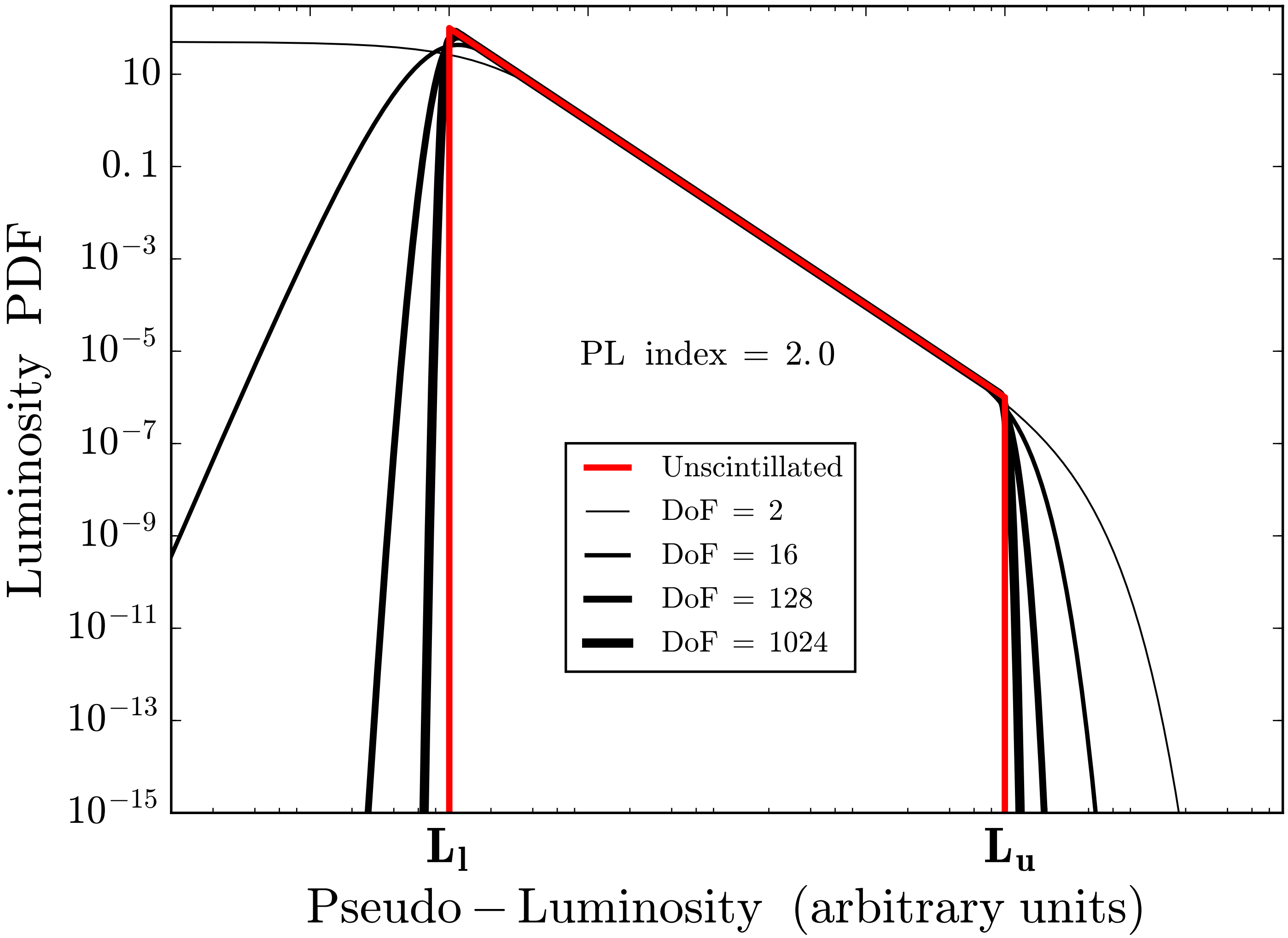


η = mean-square scattering angle / unit distance

Milky Way, IGM, Host & Intervening Galaxies

	MW	IGM	Host galaxy	Intervening galaxy
DISS	✔	✗	✔	✗
RISS	✔	✗	✔	✗?
Plasma lensing	✔	✗	✔	✗?
Pulse broadening	✔	✗	✔	✔
DM(t)	✔	✔	✔	✔
Angular broadening	✔	✗	✔	✔

Luminosity distribution for a single source PL with cutoffs L_l, L_u → d_l, d_u



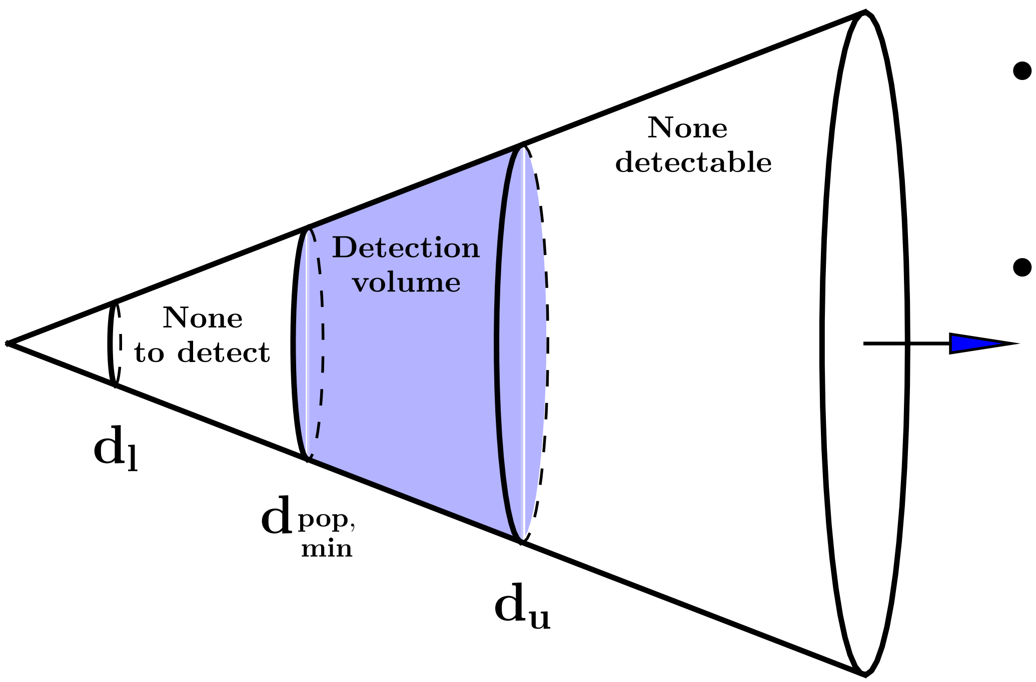
S = minimum detectable flux density for a specific burst width W:

Maximum detectable distances:

$d_l = (L_l / S)^{1/2}$

$d_u = (L_u / S)^{1/2}$

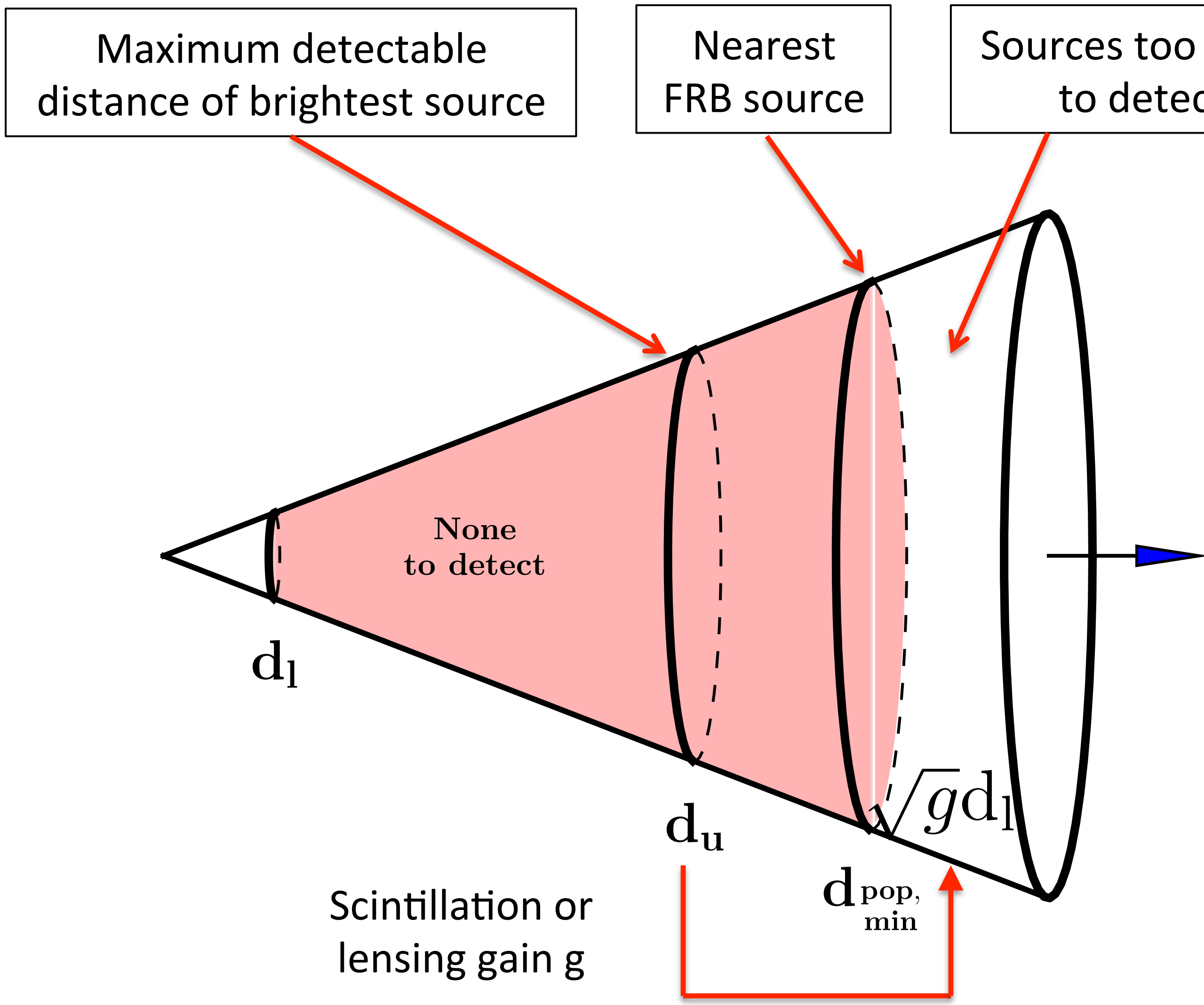
FRB Populations I



- Pretend propagation effects do not occur
- All properties of FRBs are then intrinsic (lack of repetitions in most; the repeater FRB121102, etc.)

- Need to reconcile:
  - High vs low-latitude FRB occurrence rates ~4:1 (Petroff et al. 2015)
  - Many repetitions of FRB121102 vs. none for others

Alternative: FRBs are intrinsically too weak to detect



Extrinsic flux density boosting

S-boosts	**DISS from MW** Petroff+ 2014, Macquart+Johnston 2015 JMC+ in preparation	Long tail of PDF at high |b| Quenched at low |b| • Bandwidth averaging • Source size averaging
R-boosts	**RISS from MW**	Narrow PDF (few tens of %)
L-boosts	Host plasma lensing (ESE lensing in MW)	Large focal lengths (>100 Mpc) from host lenses
G-boosts	Gravitational lensing or microlensing	Not likely unless dense star cluster surrounds FRB source (surveys could select)
Hybrid L-G boosts?	Gravitational + Plasma lensing from core-halo structures	Interesting (but relevant?)

Macquart & Johnston 2015
See also JMC+Chernoff 1997,
JMC, Lazio, Sagan 1997

This case is only for fully modulated DISS.

Need to include bandwidth averaging.

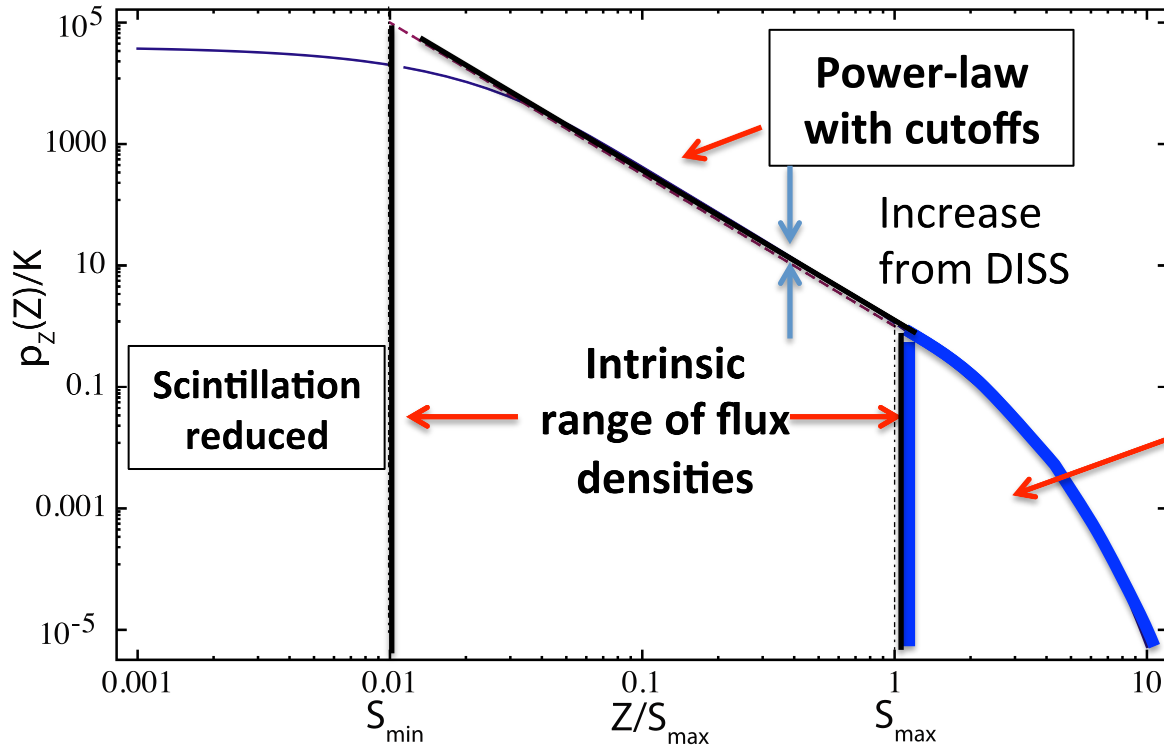


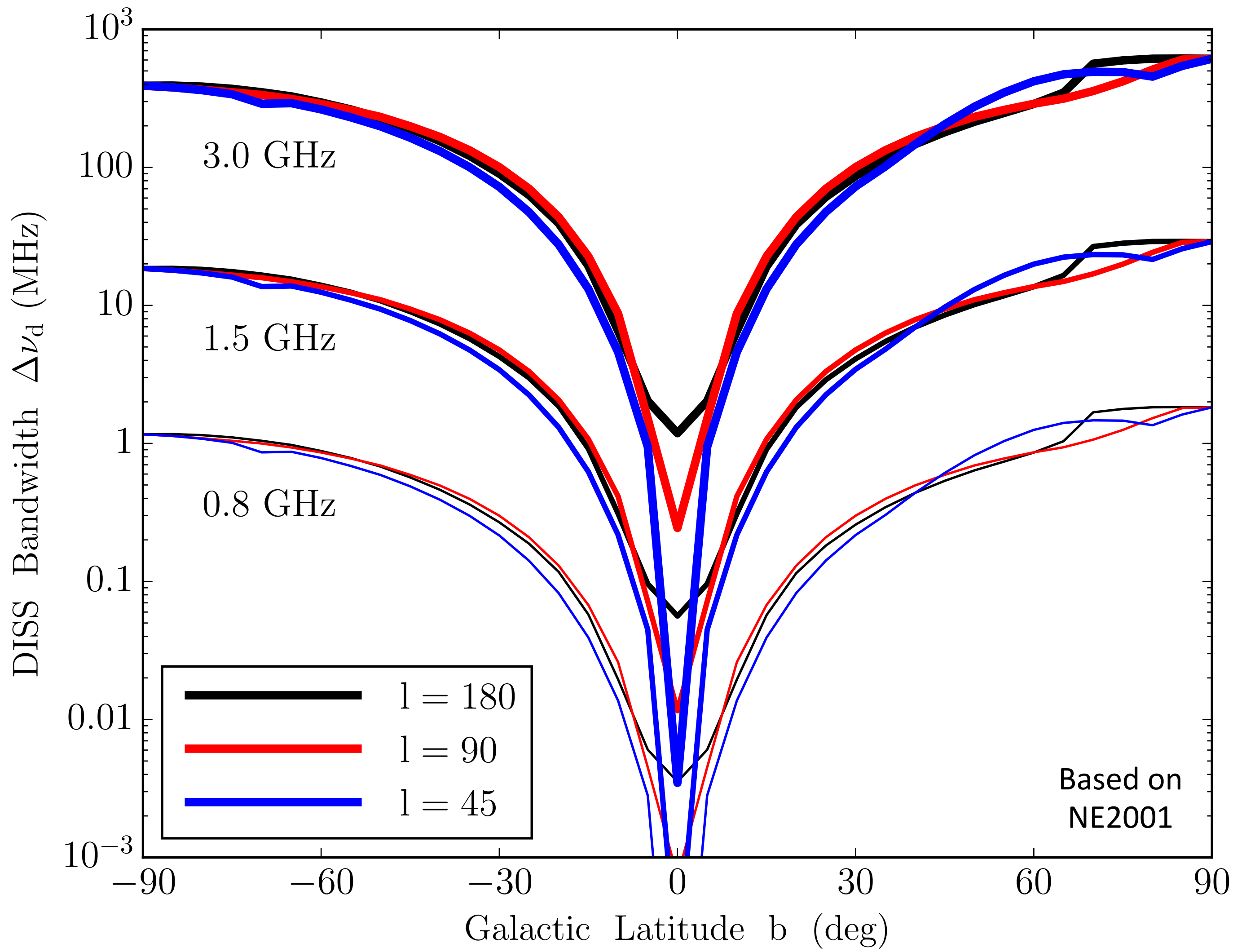
Figure 1. The distribution of observed flux densities $p_Z(Z)$ (blue solid line) for an initial flux density distribution (purple dashed line) that is non-zero over the range $S_{\rm min} < Z < S_{\rm max}$ and with $\delta = 0$. The effect of the diffractive scintillations is to draw out the high end of the distribution into a tail that decreases like $Z^{-1}\exp(-Z)$, increase the differential event counts over the range $S_{\rm min} \ll Z \lesssim S_{\rm max}$ and to extend the low luminosity component of the distribution to zero flux density.

FRB Populations II

- All FRB sources intrinsically identical (statistically)
- Compact enough to potentially show S or L-boosts
    - $c\Delta t \sim 10^7 - 10^8$ cm suffices
- High latitude sources:
    - Most from 100-m class telescopes
    - S-boosts: x10 or more (population size dependent)
- Low latitude sources:
    - No S-boosts (bandwidth and source size)
- Repeater: discovered and initial followup with Arecibo
    - Discovery with a 100-m class sidelobe
    - Plasma lensing from clumps/filaments may be at play (> x10)

Quenching of DISS by Bandwidth Averaging

DISS bandwidth strongly direction/frequency dependent

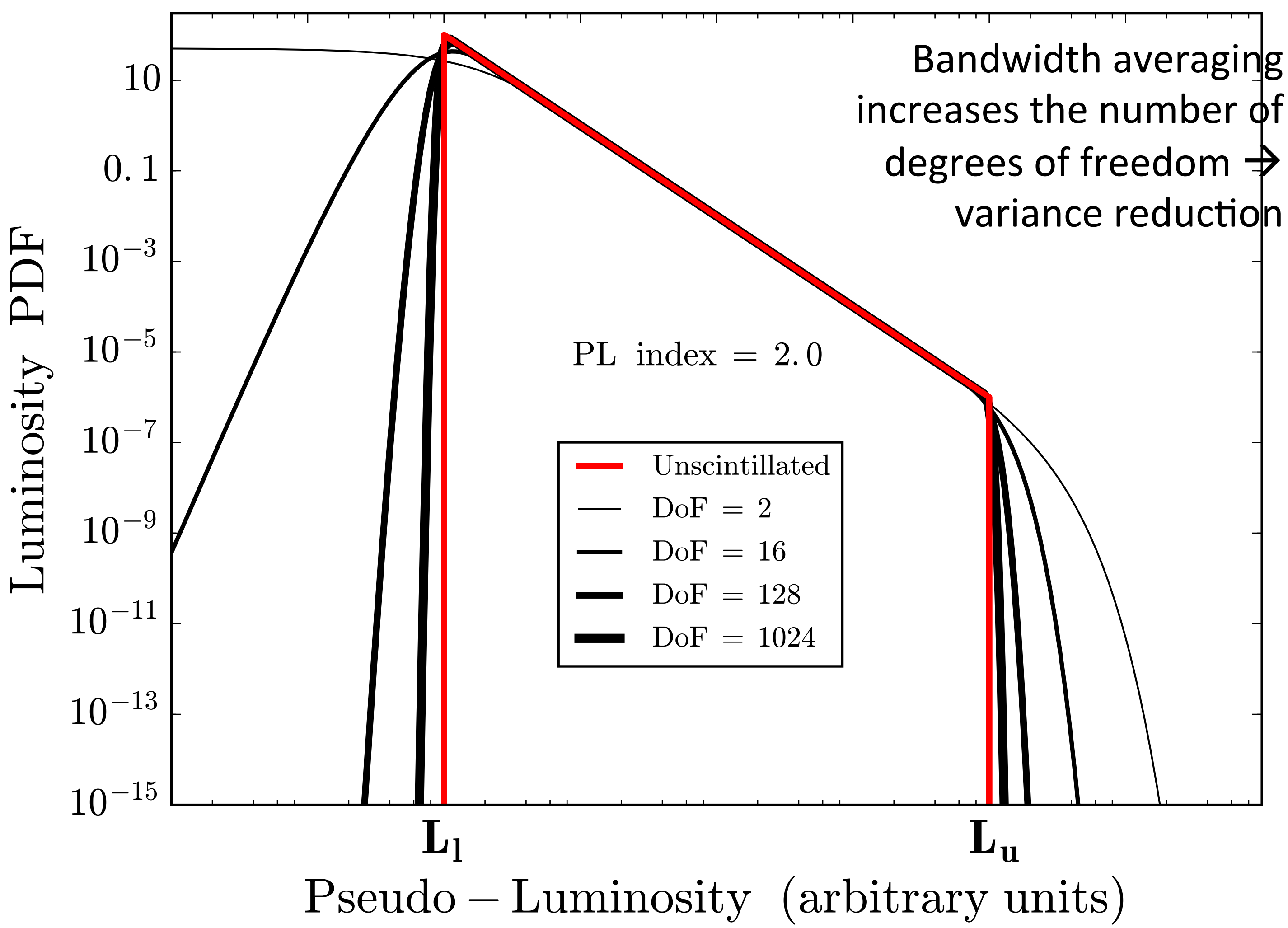


→ Quenching of DISS at low latitudes and low frequencies

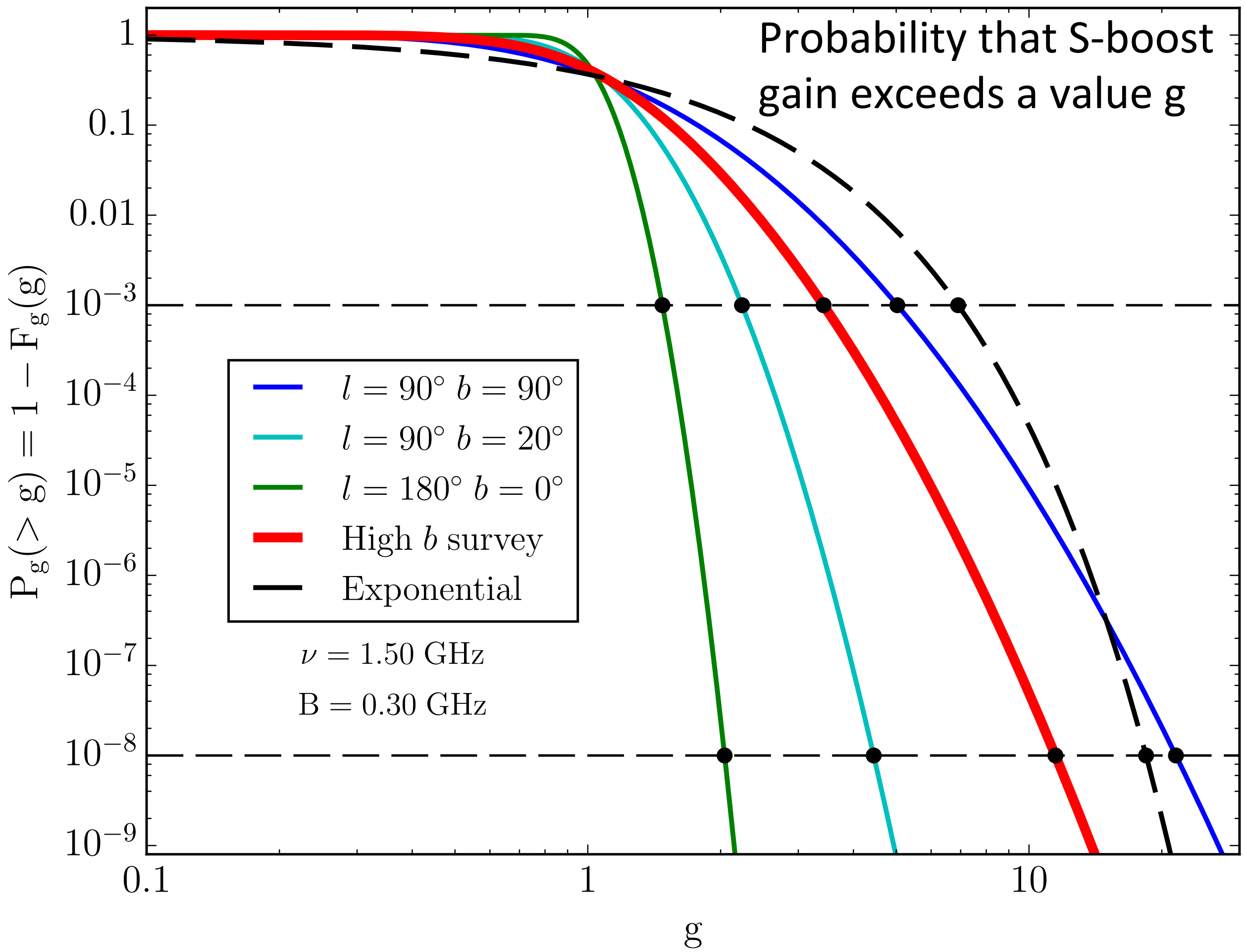
Receiver bandwidth B

Scintillation bandwidth $\Delta\nu_d$

→ Modulation $\sim(\Delta\nu_d/B)^{1/2}$



Bandwidth averaging increases the number of degrees of freedom → variance reduction
PL index = 2.0
Unscintillated
DoF = 2
DoF = 16
DoF = 128
DoF = 1024
10
0.1
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
Luminosity PDF
$\mathbf{L_l}$
$\mathbf{L_u}$
Pseudo – Luminosity (arbitrary units)



An exercise in extreme-value statistics

10^3 sources

10^8 sources

Figure 7. Probabilities $P_g(> g)$ of the scintillation modulation for individual lines of sight and for a high-latitude survey similar to the HTRU survey, as labeled. Also shown (dashed line) is the exponential distribution that applies only to DISS with no bandwidth averaging. The black points give the values of g that correspond to $P_g(> g) = 10^{-3}$ and 10^{-8}.

From JMC+, In preparation

Distant FRBs:

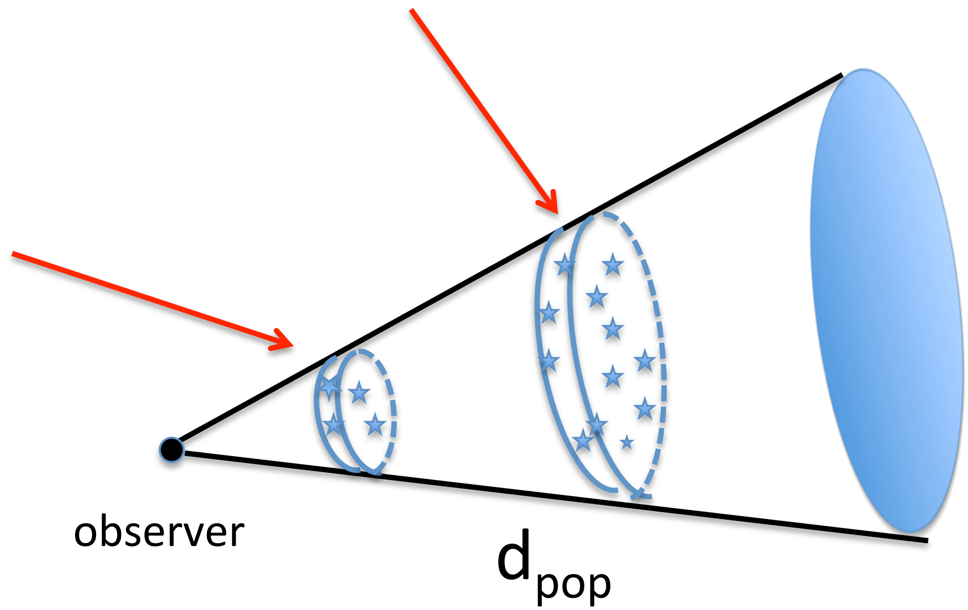
- More of them ($dN \sim d^2\, dD$)
- → larger chance for large S-boost gain g

Larger g*L needed for detection

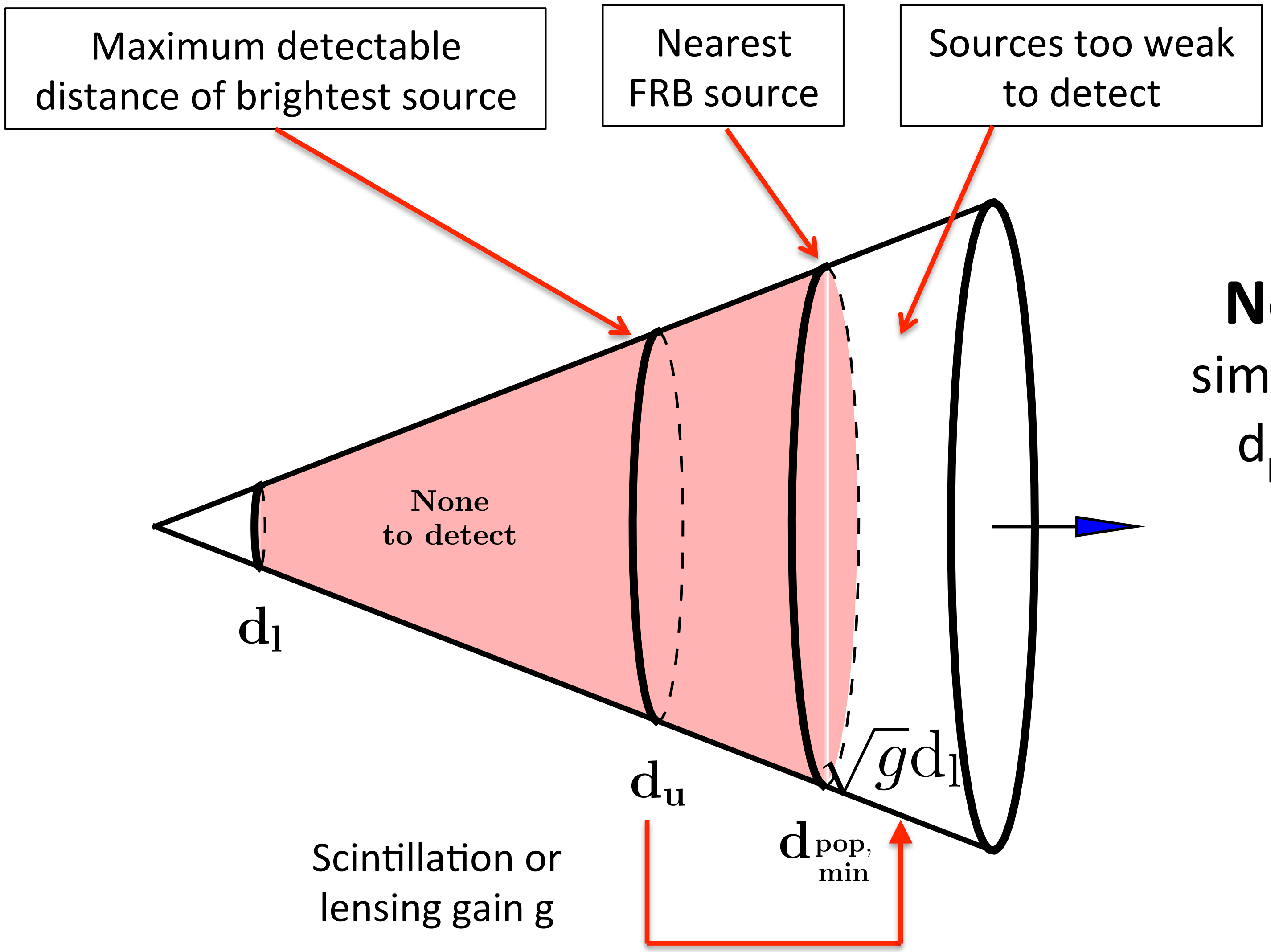
Fewer nearby FRBs

→Fewer chances for large scintillation boost

Smaller g*L needed



FRBs intrinsically too weak to detect



Next slide:
simulation with
$d_{pop, min} = d_u$

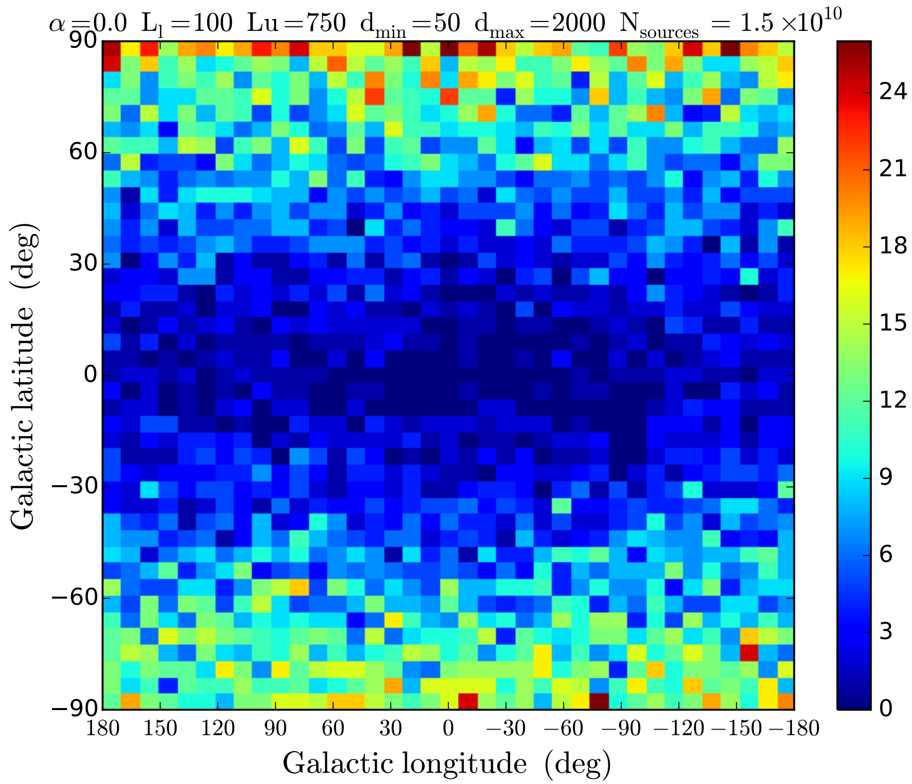


Figure 10. Simulation of detections vs Galactic coordinates. The color scale shows the number of sources detected out of a total of 1.5×10^{10} sources. The luminosities and distances of the population are set up so that *no* sources are detectable in the absence of ISS. The results are for a power-law $\alpha = 0$ with cutoffs of 100 and 750 Jy Mpc^2 and a homogeneous population between 50 and 2000 Mreshold pc. The survey threshold is 0.3 Jy and bandwidth averaging has been included over a 300 MHz bandwidth centered on 1.5 GHz. Reduction of survey sensitivity by temporal broadening has not been included, so that dearth of detections at low latitudes toward the inner Galaxy is more severe than is shown.

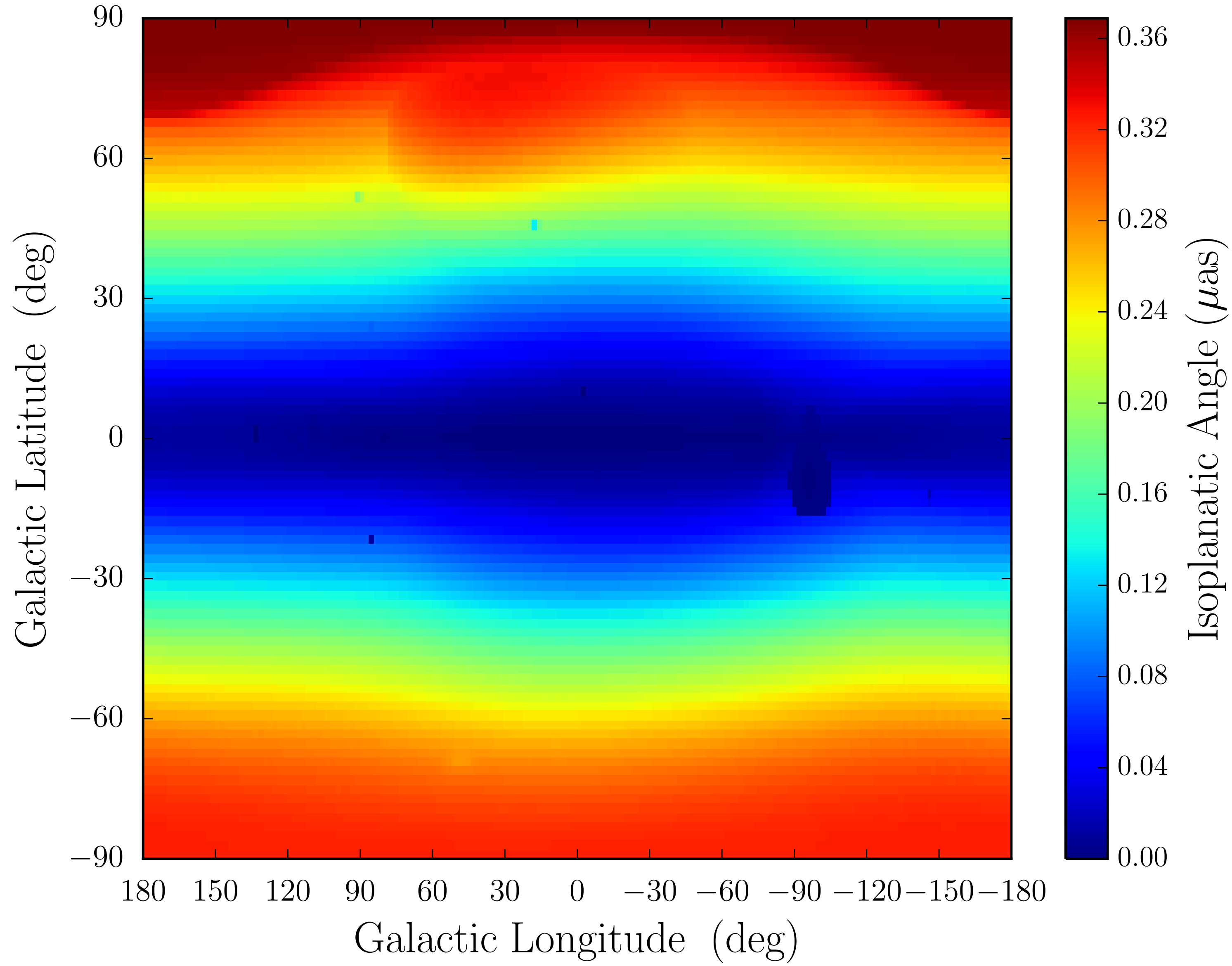
Detection of FRBs favored at high latitudes:

DISS is quenched by bandwidth averaging and possibly source-size suppression

Simulations include luminosity function, steady burst rate, and DISS with bandwidth averaging (but point sources, no pulse broadening)

No FRBs detectable without DISS

Critical source size for quenching



Magnetosphere 5×10^9P cm @ 1 Gpc ~ 10^{-7} μas

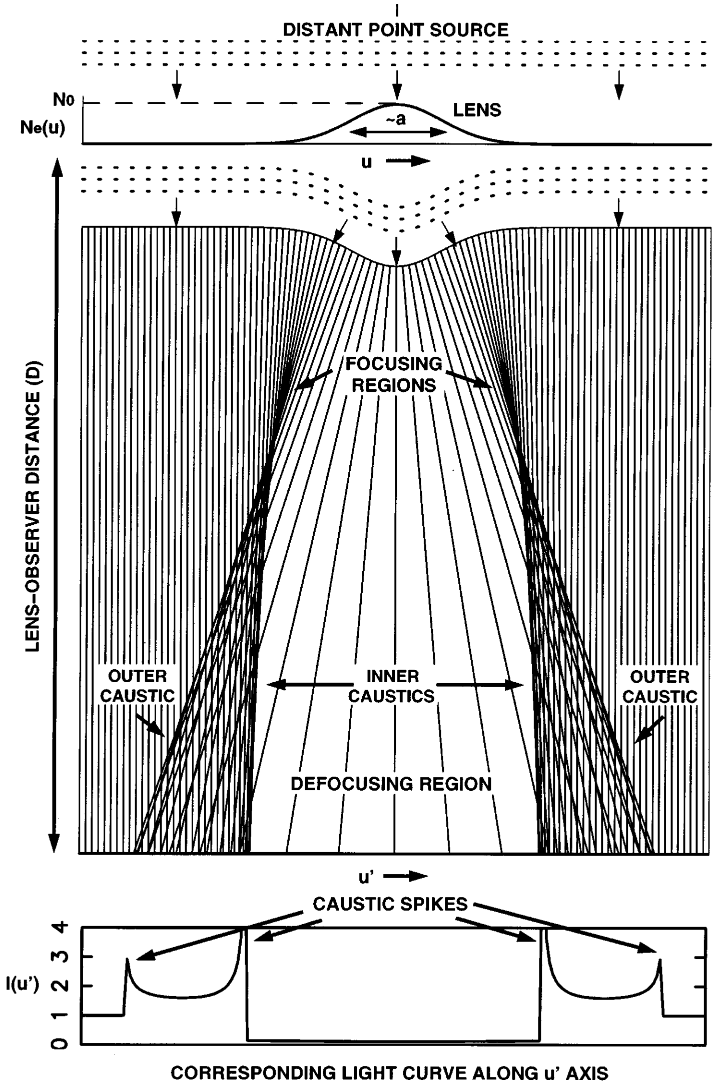
1 AU @ 1 Gpc ~ 10^{-3} μas

More important: scattering in host can broaden source to quench DISS

But c.f. Masui et al. 2015 high-latitude FRB

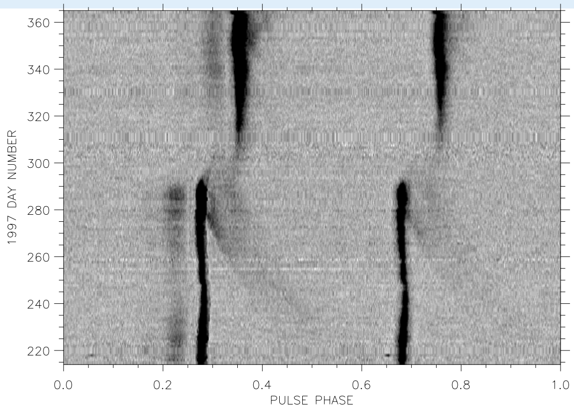
Based on NE2001

Plasma Lensing

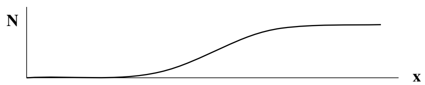


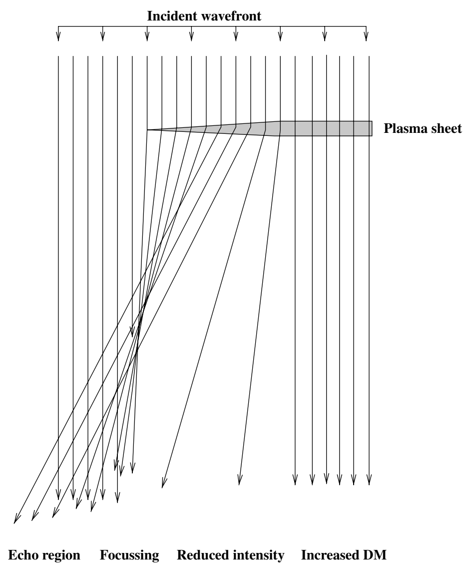
Clegg, Fey, Lazio 98

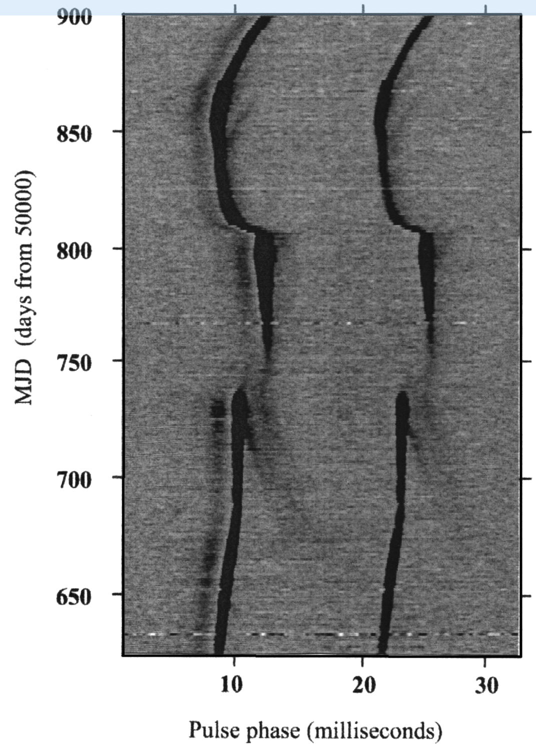
Lensing from filaments in the Crab Nebula

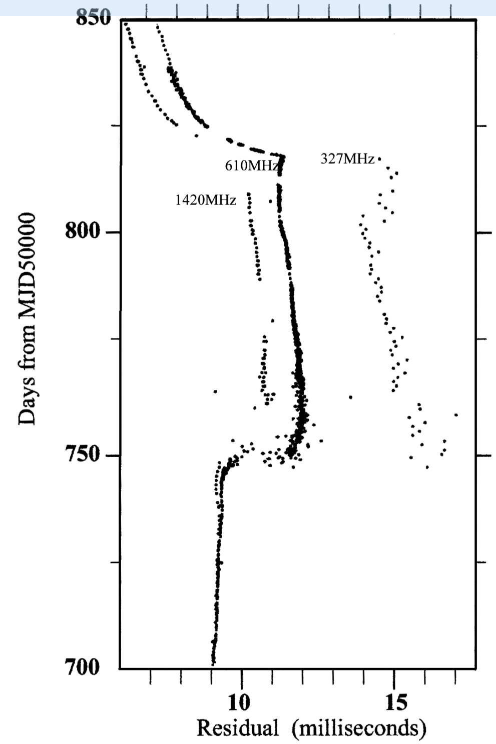


Backer et al. 2000









Graham Smith et al. 2011

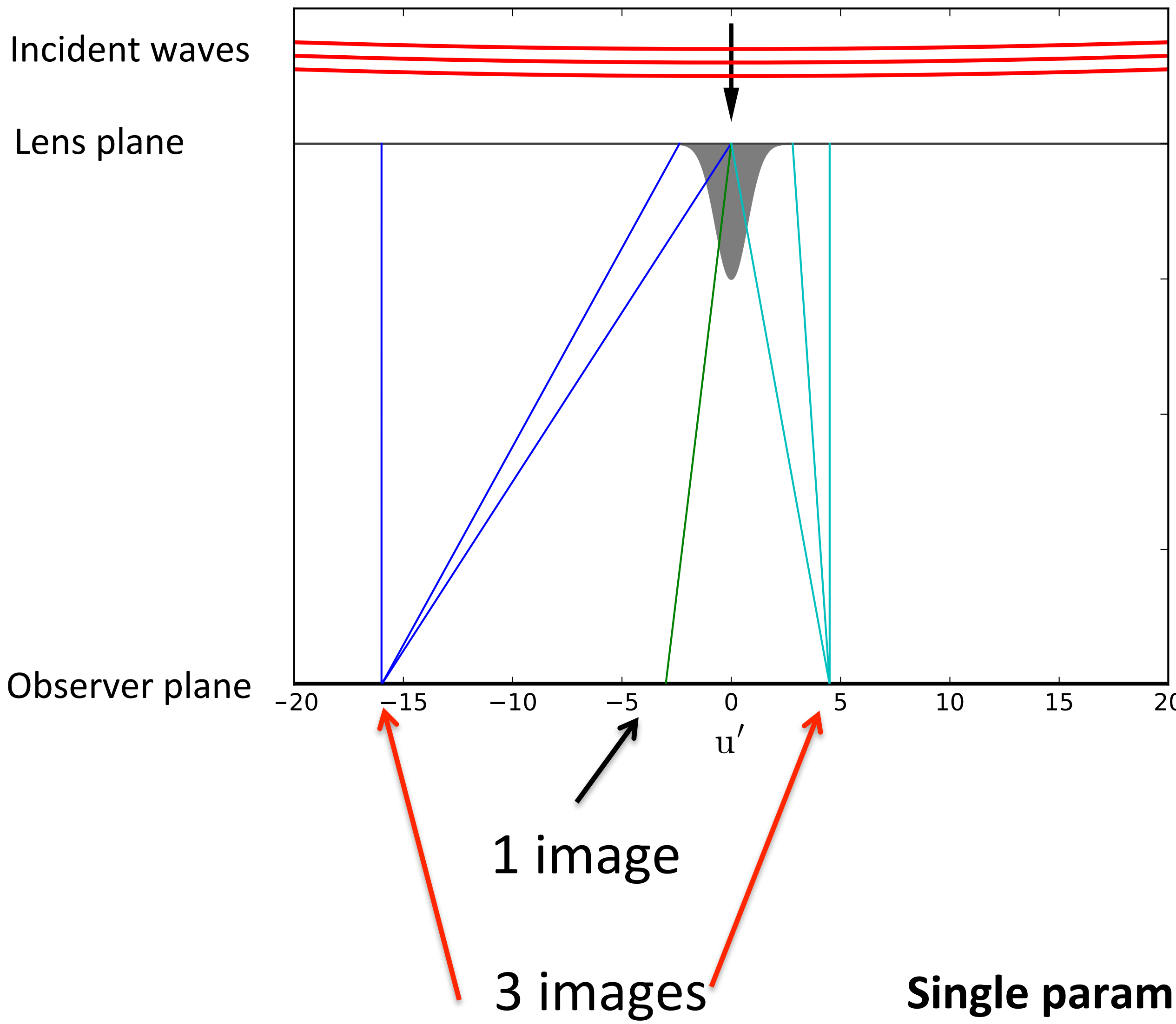
Filament scales

0.1-10 AU (radio)

100-10^3 AU (optical)

Electron densities

~ 10^4 cm^{-3}



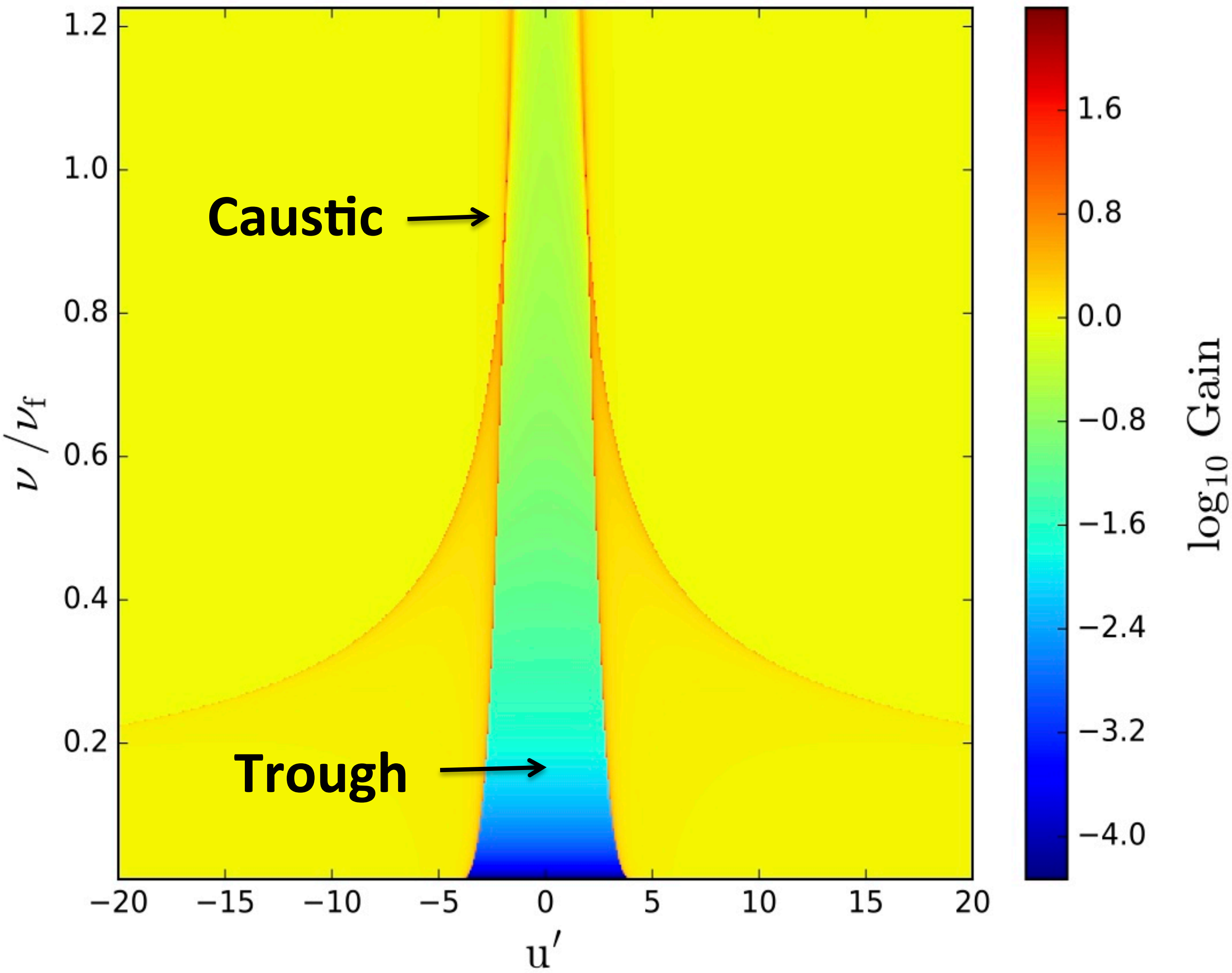
Ray traces for a 1D Gaussian plasma lens

Slightly different DMs and arrival times

Single parameter in the lens equation:

$$\alpha = \frac{\lambda^2 \mathrm{r_e DM_0}}{\pi a^2}\left(\frac{d_{\rm sl} d_{\rm lo}}{d_{\rm so}}\right) = \frac{3430\,\mathrm{DM_0}\,\mathrm{d_{sl,kpc}}}{(\nu a_{\rm AU})^2}\left(\frac{d_{\rm lo}}{d_{\rm so}}\right)$$

Lens gain vs frequency and source position



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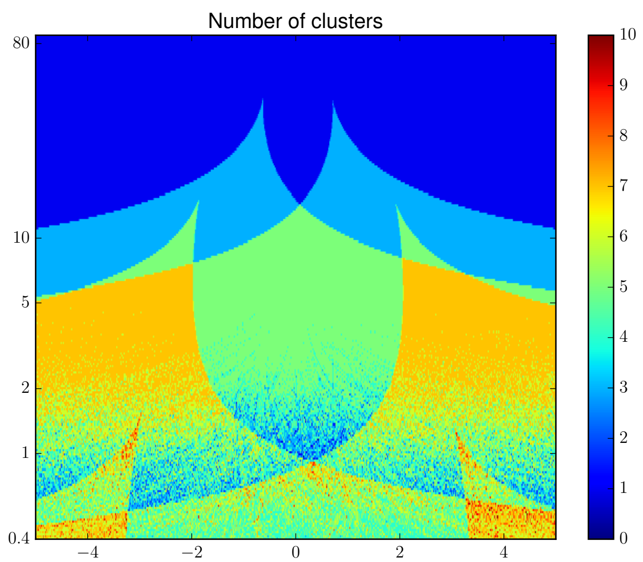
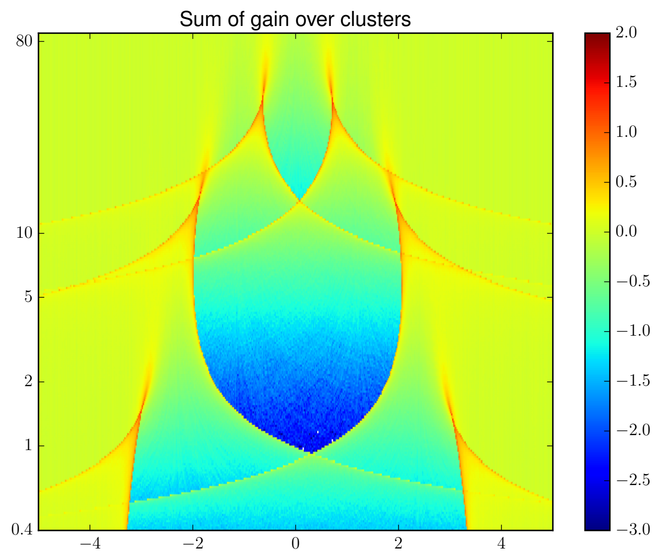
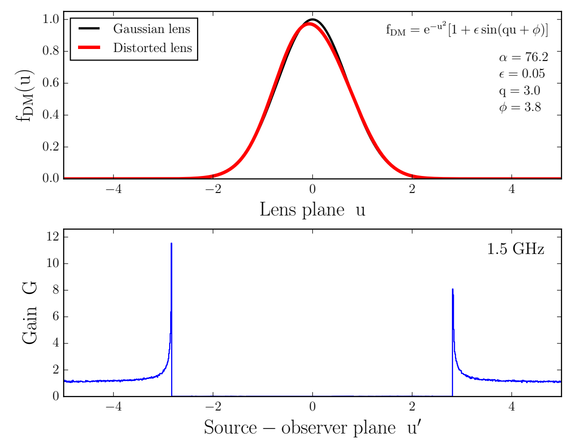
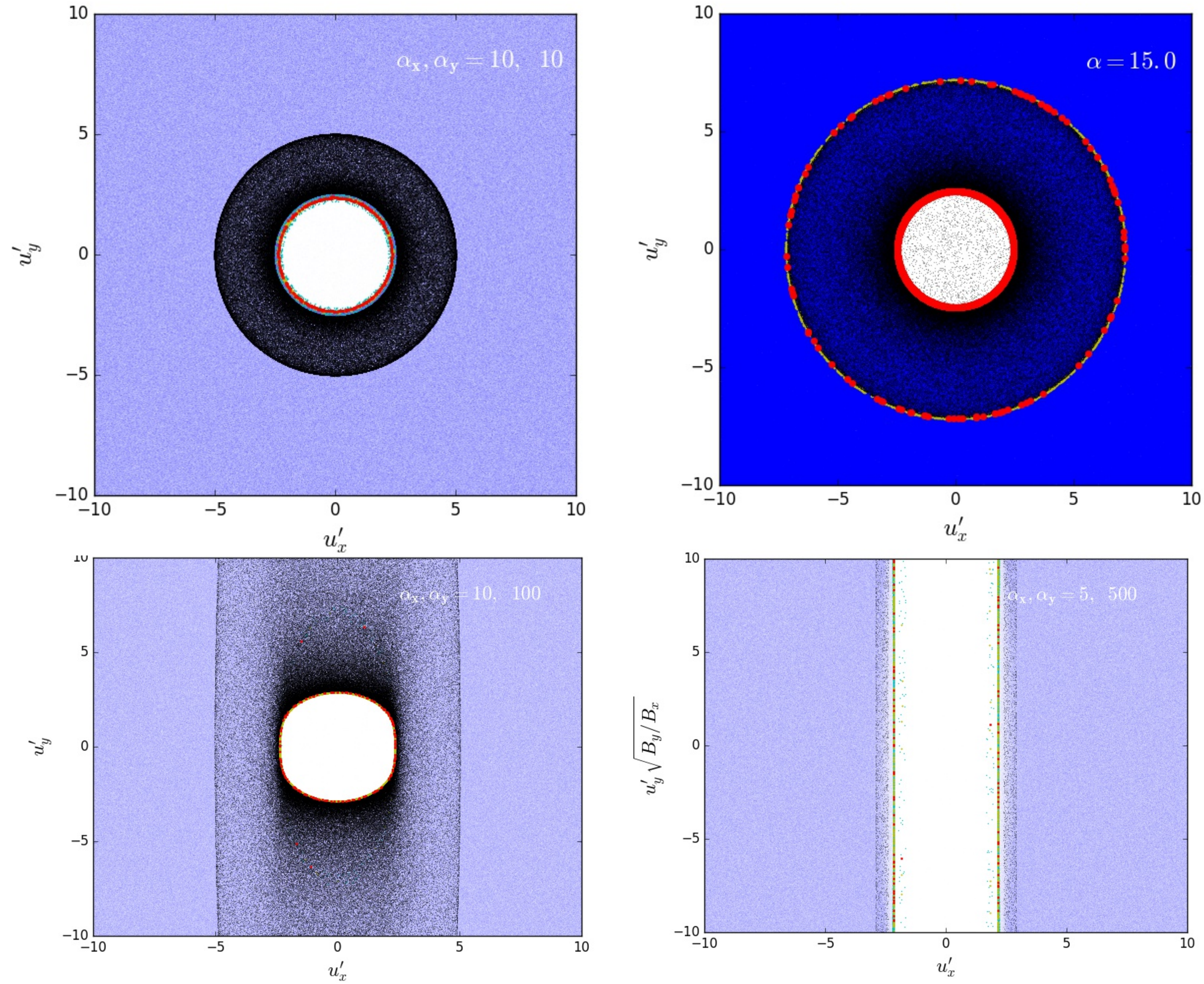
Non-Gaussian lens





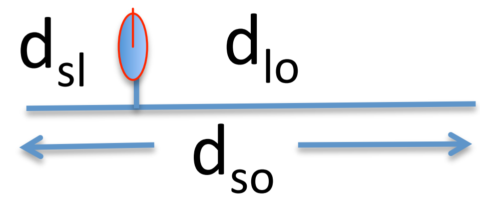


2D Lenses



$\alpha_x, \alpha_y = 10,\ 10$
$\alpha = 15.0$
$\alpha_x, \alpha_y = 10,\ 100$
$\alpha_x, \alpha_y = 5,\ 500$
u'_x
u'_y
$u'_y\sqrt{B_y/B_x}$

Focal distance and focal frequency



Full caustic (largest gain) seen for distances d_{so} > focal distance d_f

$$d_{\rm f}(\nu) = d_{\rm lo}\left(\frac{\alpha_{\rm min}}{\alpha}\right) = \frac{\pi(a\nu)^2\alpha_{\rm min}}{r_{\rm e}c^2{\rm DM}_0}\left(\frac{d_{\rm so}}{d_{\rm sl}}\right)$$

$$\approx 0.65\,{\rm Mpc}\times\frac{(a_{\rm AU}\nu)^2}{{\rm DM}_0}\left(\frac{d_{\rm so}/d_{\rm sl}}{10^6}\right),$$

→ Gpc for a~100 AU, DM_0 ~ 7

Equivalently, need frequency < focal frequency ν_f

$$\nu_{\rm f} = \nu\left(\frac{\alpha}{\alpha_{\rm min}}\right)^{1/2} = \frac{c}{a}\left(\frac{r_{\rm e}{\rm DM}_0}{\pi\alpha_{\rm min}}\frac{d_{\rm sl}d_{\rm lo}}{d_{\rm so}}\right)^{1/2}$$

$$\approx 39.1\,{\rm GHz}\times\frac{{\rm DM}_0^{1/2}}{a_{\rm AU}}\left(\frac{d_{\rm sl}d_{\rm lo}/d_{\rm so}}{1\,{\rm kpc}}\right)^{1/2}.$$

Spectral diversity for different source positions

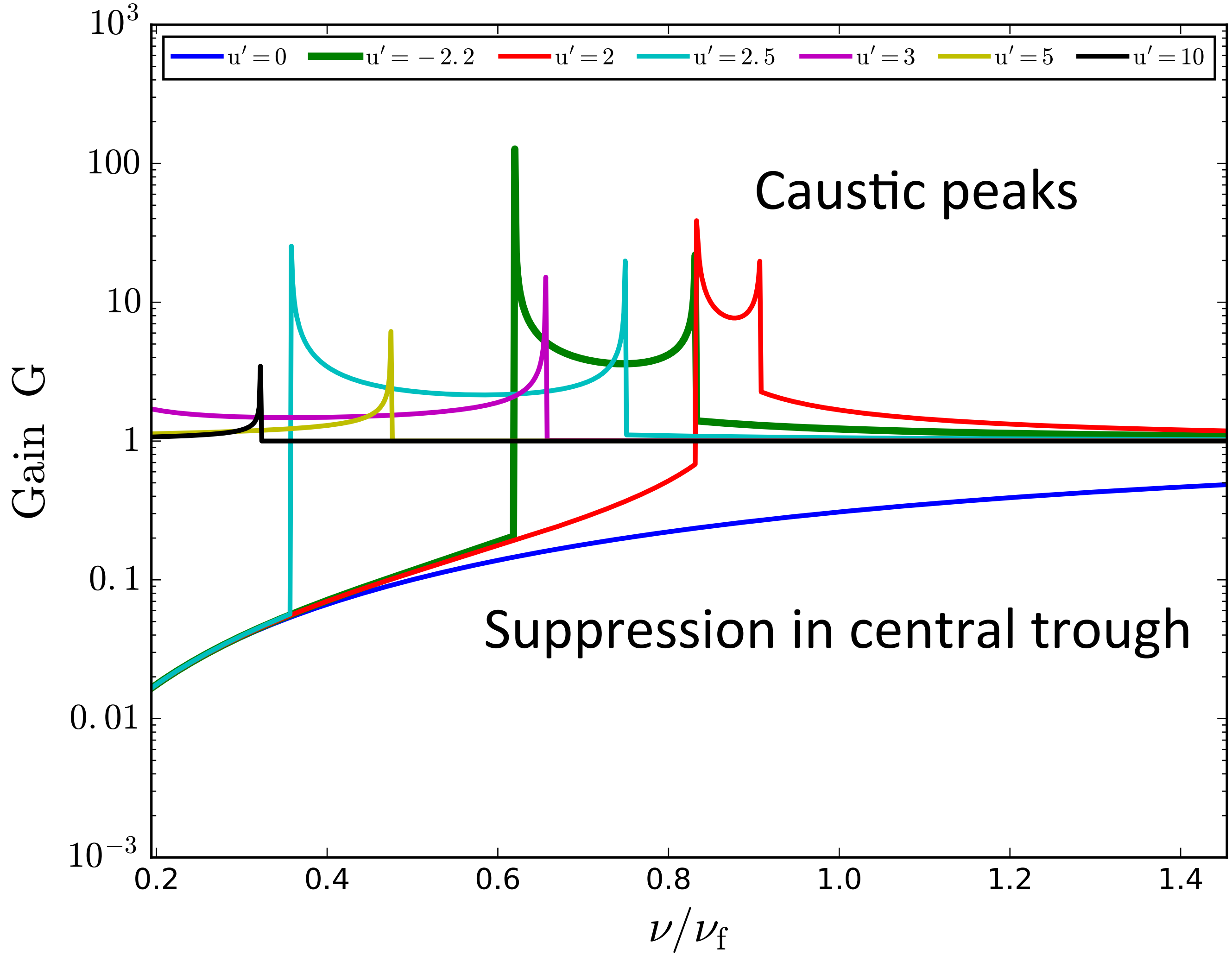
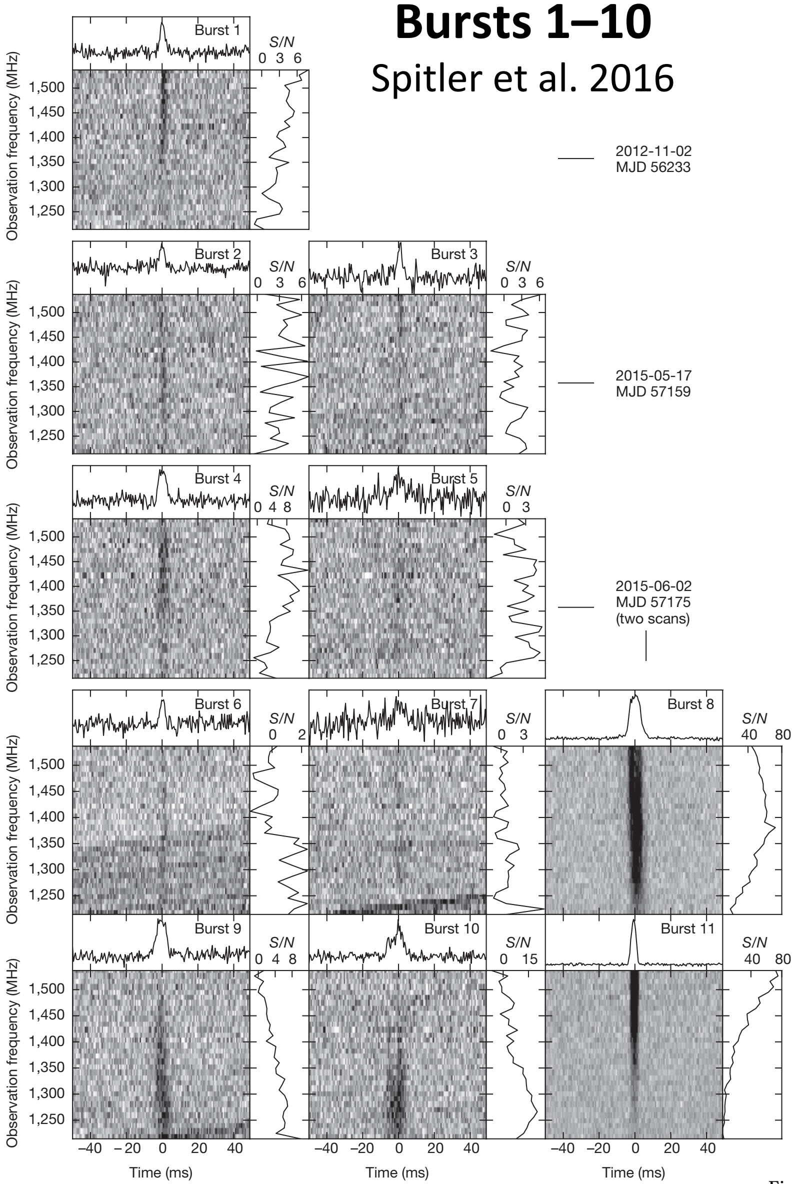


Figure 5. Spectral slices of the gain G at a few observer locations for $a = 60$ AU and DM $= 10$ pc cm^{-3}.

Bursts from FRB 121102

Bursts 1–10

Spitler et al. 2016



Bursts 12 – 17

Scholz et al. 2016

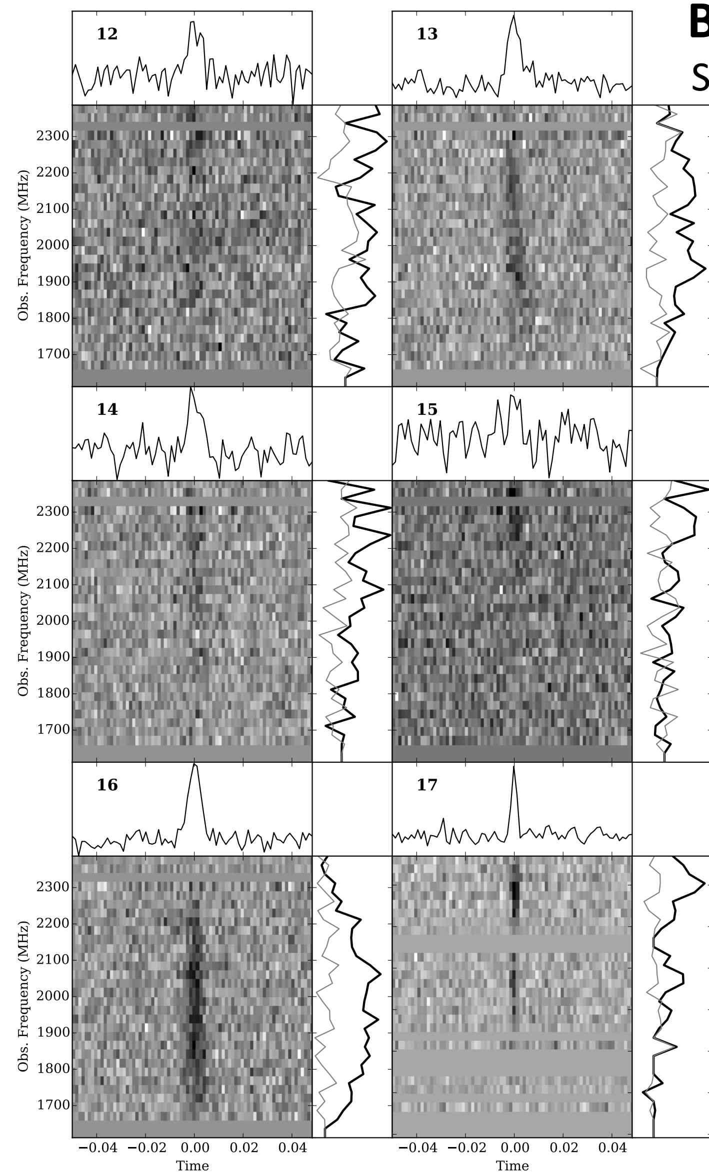
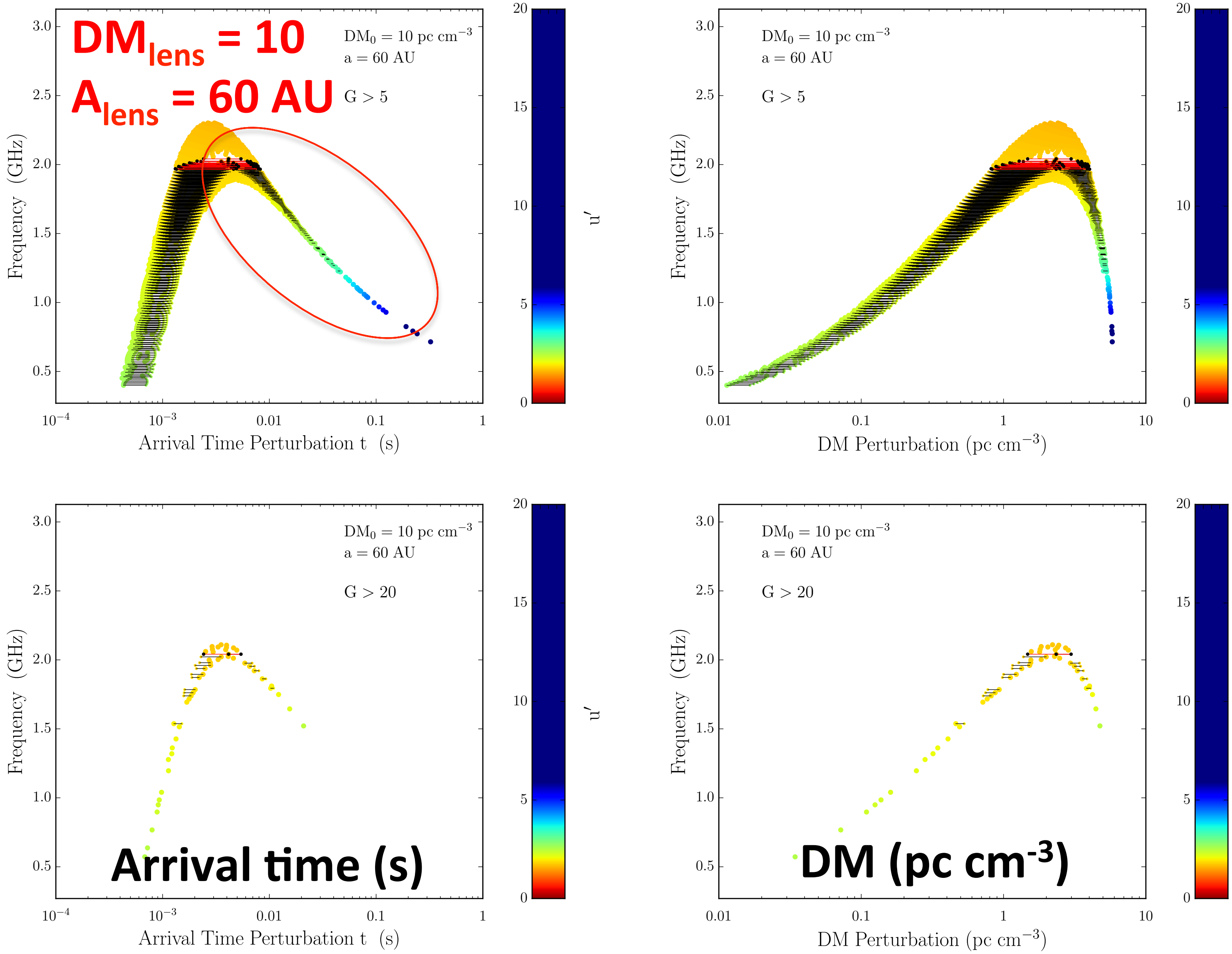


Figure 2. Dynamic spectra for each of the bursts detected in 2015 November and December using GUPPI (bursts 12 – 16) and PUPPI (burst 17) dedispersed at DM=559 pc cm^{-3}. For each burst, total intensity is shown in grayscale, the top panels show the burst time series summed over frequency, and the side panels show bandpass-corrected burst spectra summed over a 10-ms window centered on the burst. The on-burst spectrum is shown as a black line and an off-burst spectrum is shown as a gray line to show the noise level. Note that some frequency channels are masked due to RFI.

Arrival times & DMs vs. frequency for strong boosts

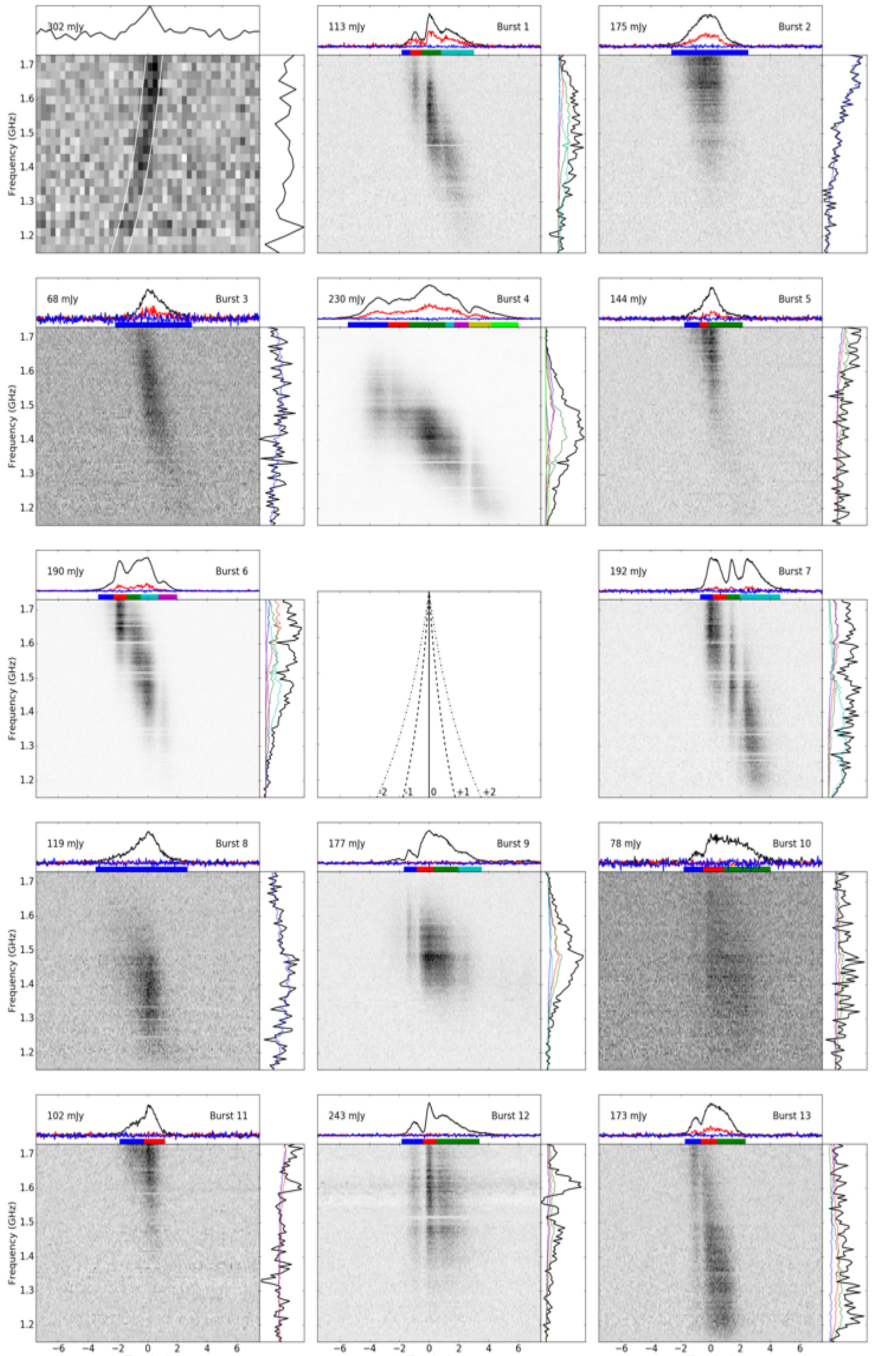
$t = t_{geometric} + t_{DM}$ **Largest delays fall on df/dt < 0 branch**



Boosts G > 5

Delays can differ from $1/f^2$ scaling

Strong Boosts G > 20



Bursts from FRB121102

Intrinsic vs. extrinsic f-t structure?

Multiple imaging:

Distinct burst components vs.
Overlapping components + interference effects

Not sure that aligning gaps gives the correct DM in the imaging picture

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A puzzle

- Why does plasma lensing appear important for FRB12102 but not for high-latitude (or other FRBs)?
  - i.e. if lensing is responsible for the repeats, why not for high-latitude sources?

- Possible (but weak) answer: S-boosts of high-latitude sources select sources that are not at appropriate focal distances for L-boosts

FRB Selection Effects

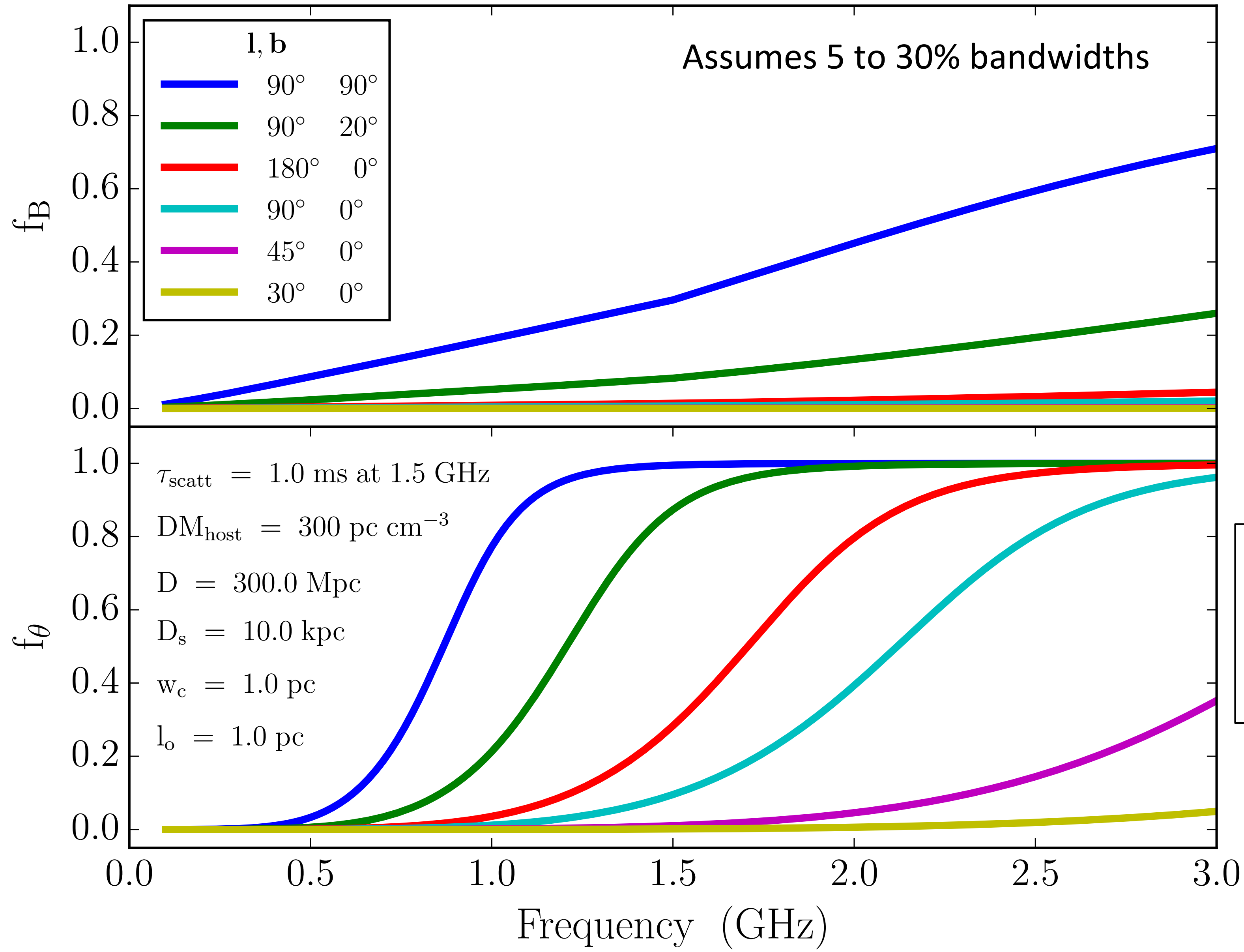
- Presence or absence of DISS, RISS, or lensing
- Reduction in S/N of matched filter detection by scattering broadening of burst:

$$S/N \propto \left[1 + 2(\tau_d/W_i)^2\right]^{-1/4}$$

- Free-free absorption
  - Negligible for most Galactic directions (except Galactic center)
  - Host galaxy: $$\mathrm{EM} \geq \frac{\mathrm{DM_h^2}}{L_\mathrm{h}} = 10^3 \mathrm{pc\ cm}^{-6} \left(\frac{DM_{1000}^2}{L_\mathrm{kpc}}\right)$$

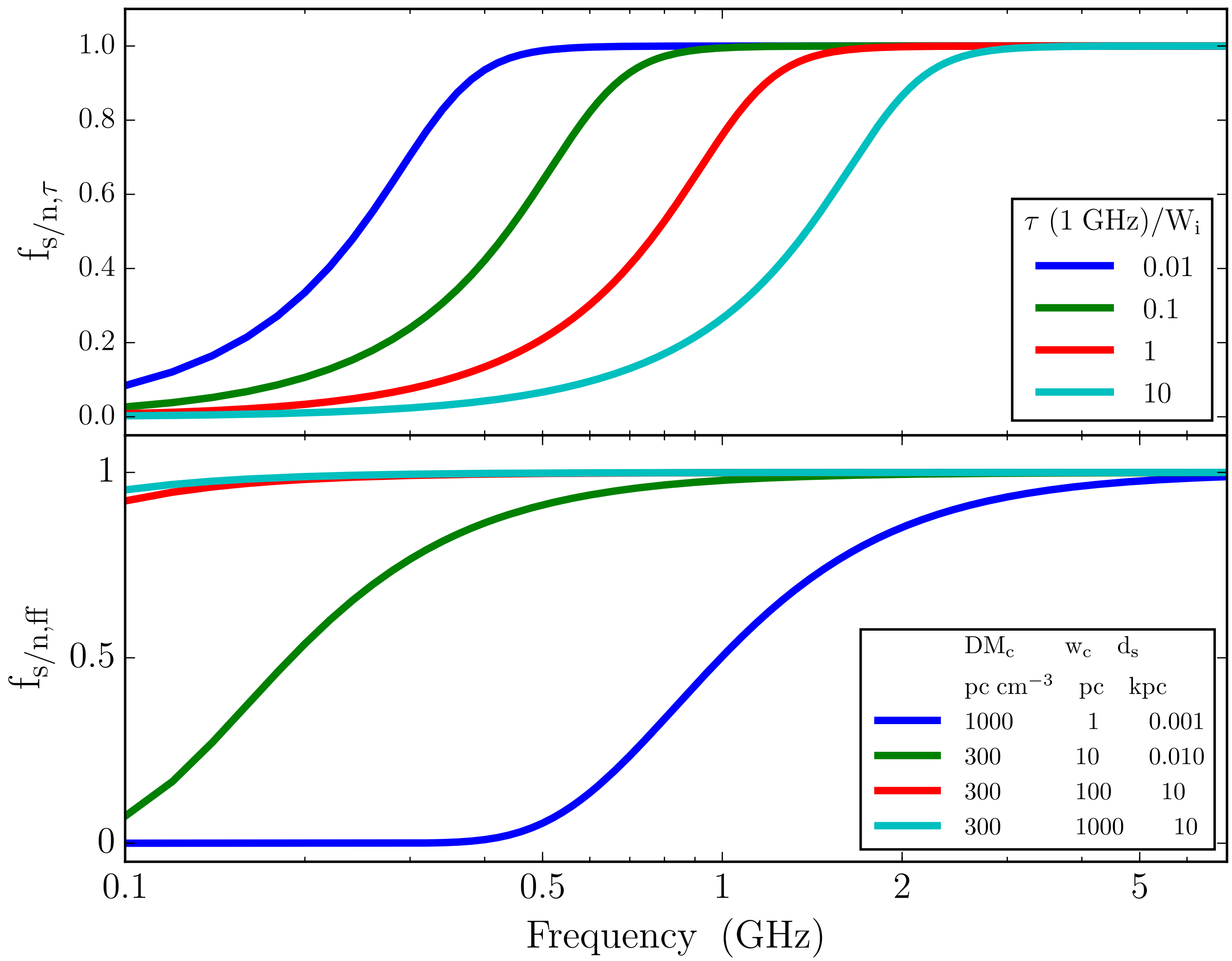
$$\tau_\mathrm{ff} \gtrsim 0.0033\, \nu^{-2.1} T_{\mathrm{e},4}^{-1.35} \left(\frac{DM_{1000}^2}{L_\mathrm{kpc}}\right)$$

DISS Reduction by bandwidth & source size



Scattering from within 10 kpc of source

S/N Reduction by pulse broadening & ff absorption

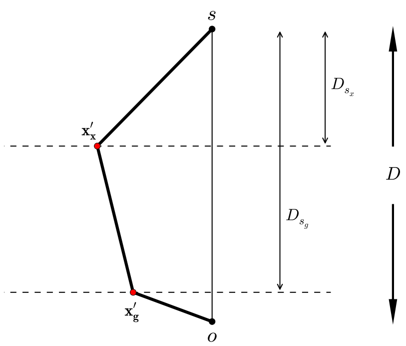


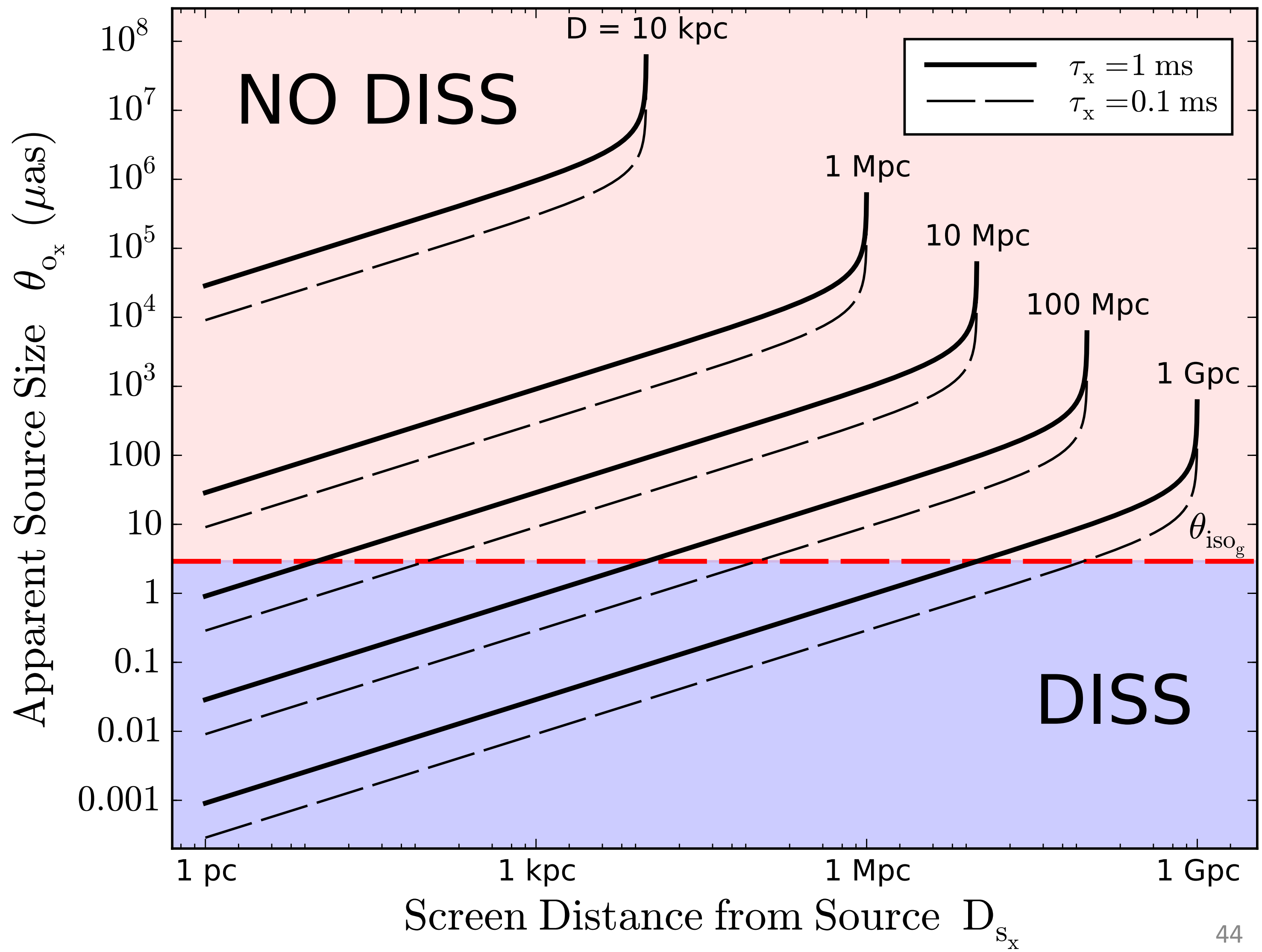
S/N reduction from pulse broadening

Free-free absorption

Note strong model dependence:

RISS from ISM occurs only if source size from extragalactic scattering is small enough → near to source





Summary/Going Forward

- **Scintillation boosts**: required for most FRB detections?
  - FRBs may be selected <u>for</u> by S boosts
  - Low latitudes/frequencies do not receive large boosts
- **Lensing boosts:** required for FRB121102?
  - Highly chromatic, strong frequency structure, caustics
  - **detection strategy:** Strong spectral dependence → search in frequency if not seen in one band
  - **Testing and exploiting plasma lensing:**
    - FRB broadband spectra (*at least* 0.4 - 10 GHz)
    - VLBI to resolve subimages (~ mas splittings typical)
    - Fringing in time-frequency of burst components
    - δDM, δTOA, δEM, δRM, all informative on host environment
  - **Non-gaussian lenses** (key element: inflection points in total phase including DM_{lens})
- **Observing goal**: broadband spectra <1 to 20+ GHz
- Any study of log N-log S, rates etc. needs to consider distance distribution, intrinsic luminosity PDF, <u>and</u> D/R/L boosts