Marisa Geyer, Aris Karastergiou at Oxford University
Collaborators: Members of LOFAR PWG

ANOMALOUS PULSAR SCATTERING

AT LOFAR FREQUENCIES

THE LABYRINTH OF THE UNEXPECTED

UNFORESEEN TREASURES IN IMPOSSIBLE REGIONS OF PHASE SPACE

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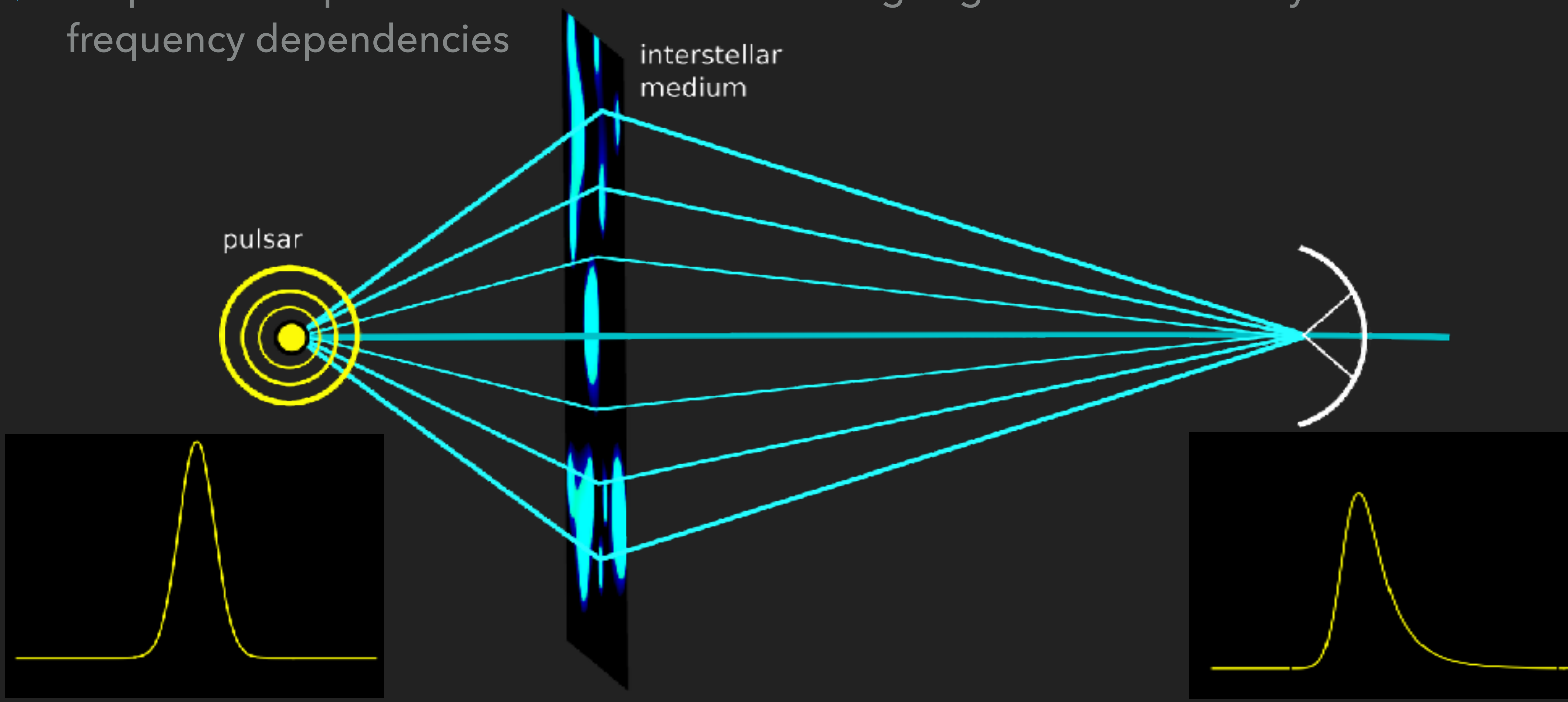
CONTENTS

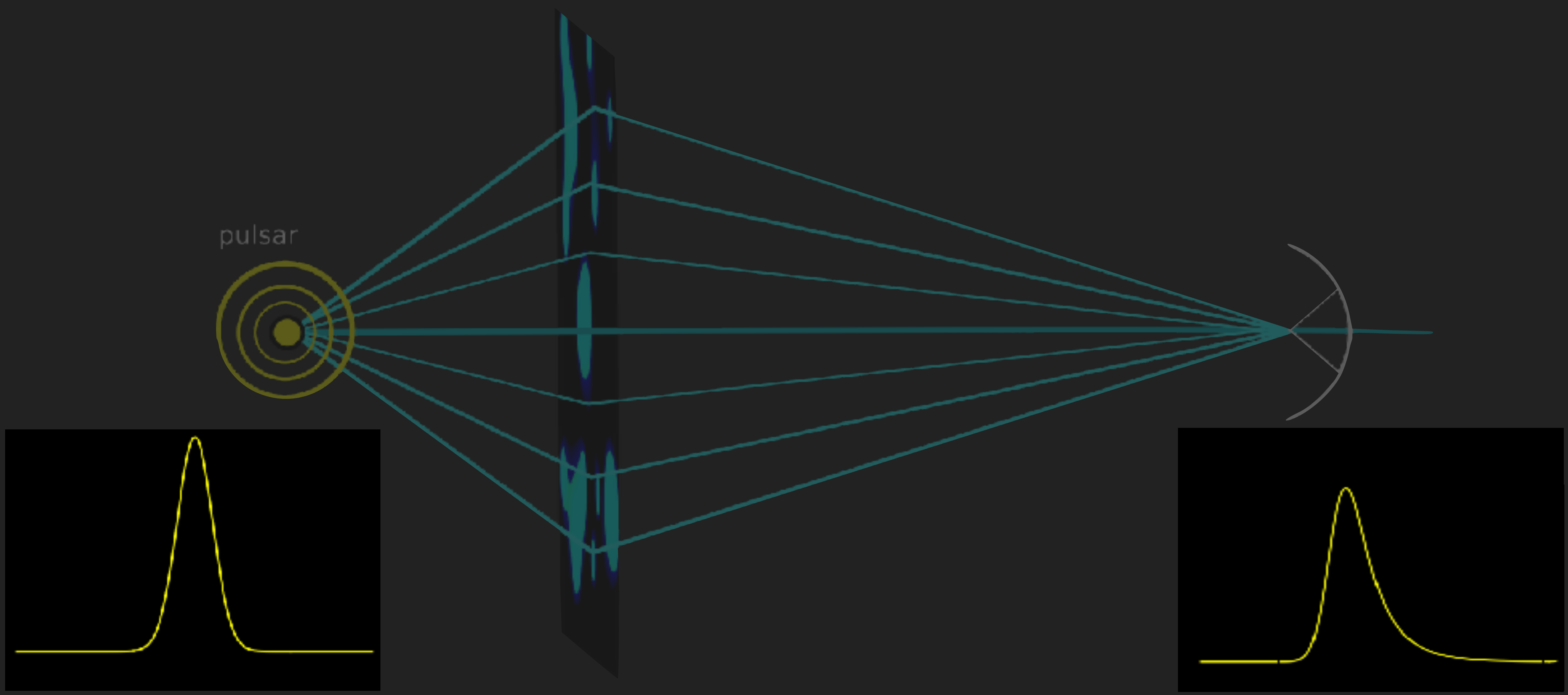
PULSAR SCATTERING THEORY

- Multi-path propagation of radio waves due to electron density gradients in the ISM
- Observe scattering tails in average pulse profiles at low frequencies
- Require description of distribution in scattering angles and time delays and their frequency dependencies

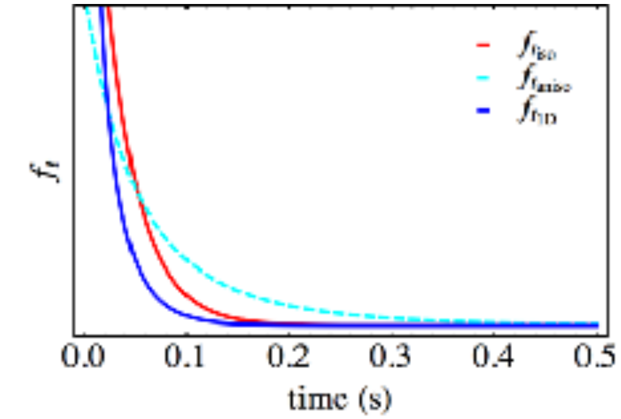


PULSAR SCATTERING THEORY - THIN SCREEN MODEL

- Scattering takes place at single location along the line of sight



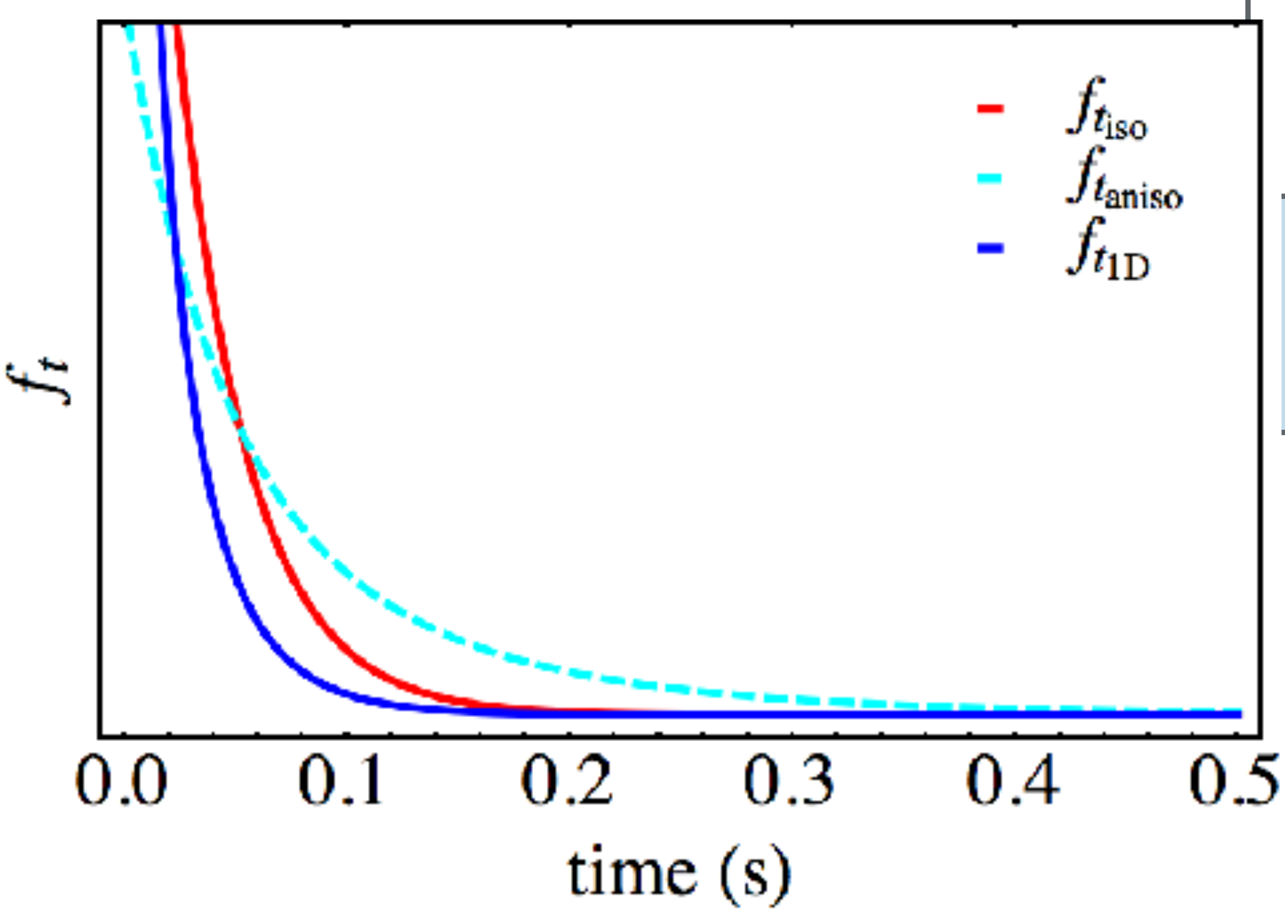
PULSAR SCATTERING – BROADENING FUNCTIONS



Isotropic Scattering	Anisotropic Scattering
Scattering screen scatters isotropically	Distribution scattering angles shows directionality
Simple case: circularly symmetric Gaussian distribution in **a**	Simple case: asymmetric Gaussian distribution distribution $\sigma_x \neq \sigma_y$
$f_t = \tau^{-1} e^{-t/\tau} U(t)$ $\tau = D'_s \sigma_a^2 / c$ $D'_s = D_s(1 - \frac{D_s}{D}),$ plasma scattering, $\boldsymbol{\sigma}_a \propto \boldsymbol{\nu}^{-2}$ leads to $\boldsymbol{\tau} \propto \boldsymbol{\nu}^{-4}$	$f_t = \frac{1}{\sqrt{\tau_x \tau_y}} e^{-\frac{t}{2}(\frac{1}{\tau_x} + \frac{1}{\tau_y})} I(0, \frac{t}{2}(\frac{1}{\tau_x} - \frac{1}{\tau_y}))$ in the extreme case 1D scattering $f_t = e^{-t/\tau} / (\sqrt{\pi t \tau}) U(t)$

PULSAR SCATTERING - BROADENING FUNCTIONS

Isotropic Scattering	Anisotropic Scattering



at 150MHz, midway screen at 1.5kpc

Distribution scattering angles shows directionality

Simple case: asymmetric Gaussian distribution distribution $\sigma_x \neq \sigma_y$

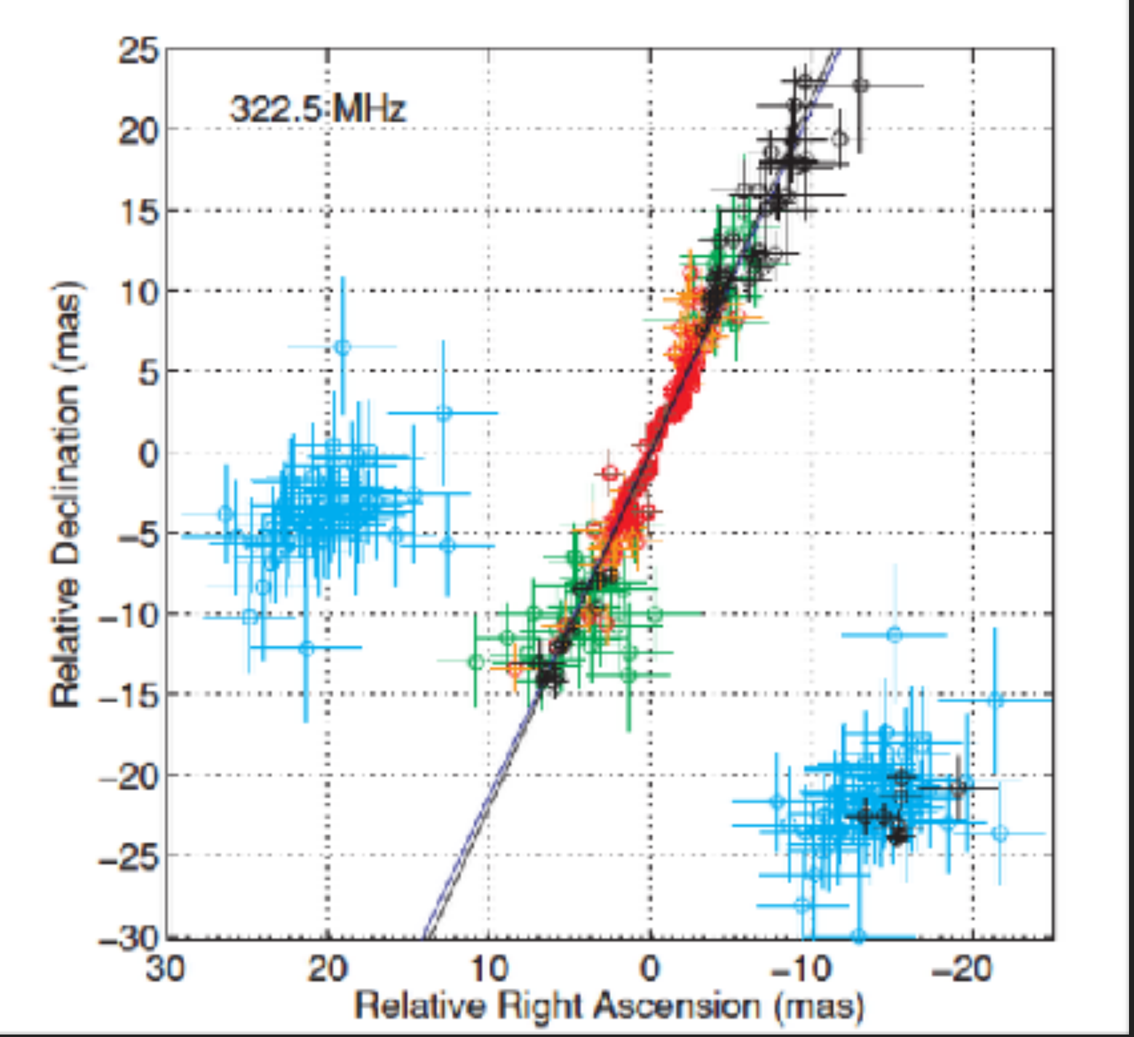
$$f_t = \frac{1}{\sqrt{\tau_x \tau_y}} e^{-\frac{t}{2}(\frac{1}{\tau_x}+\frac{1}{\tau_y})} I(0, \frac{t}{2}(\frac{1}{\tau_x} - \frac{1}{\tau_y}))$$

in the extreme case 1D scattering

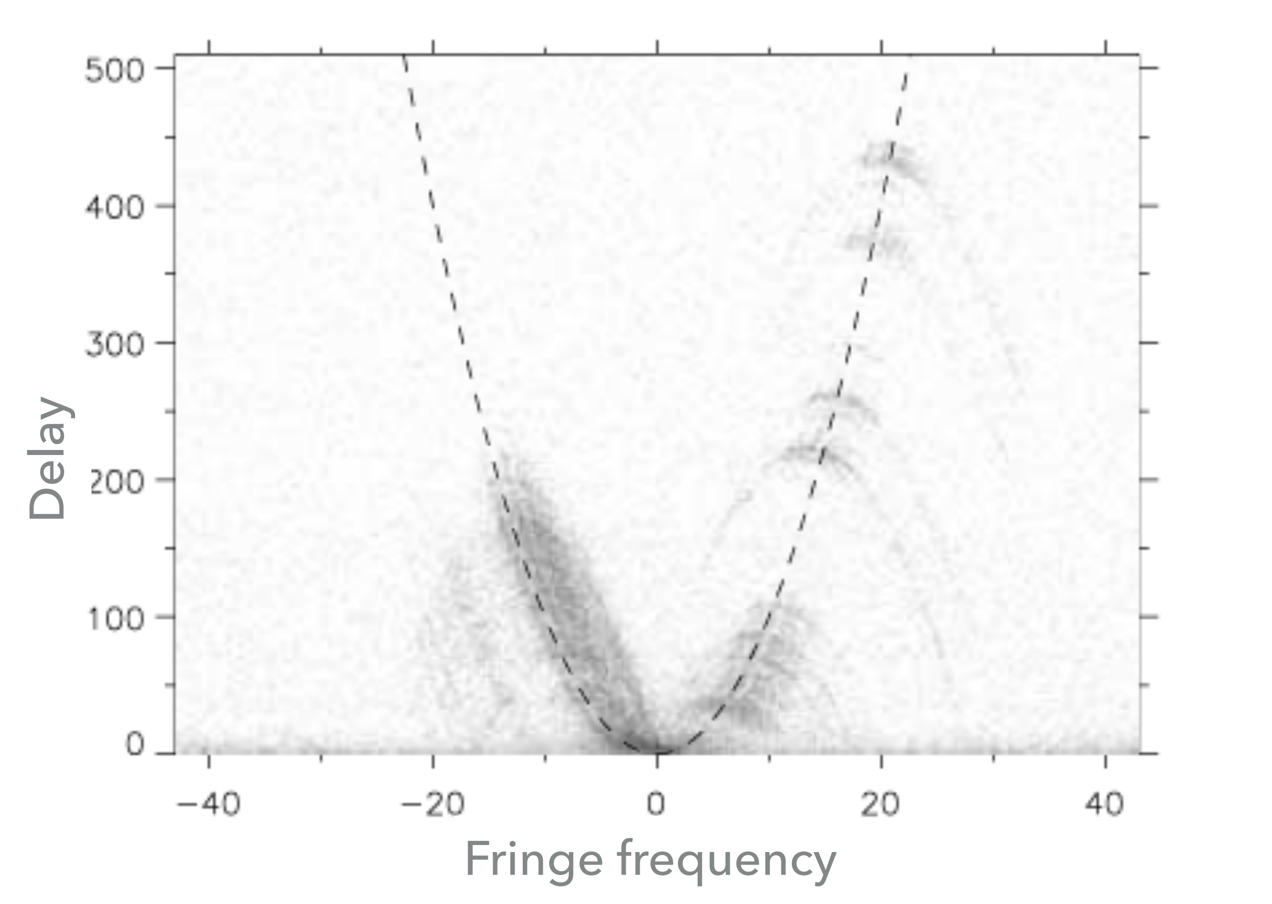
$$f_t = e^{-t/\tau}/(\sqrt{\pi t \tau})U(t)$$

EXTERNAL EVIDENCE FOR ANISOTROPIC SCATTERING

- VLBI image of PSR B0834+06 at 327 MHz
- Brisken et al. 2010



- Organized patterns in dynamic spectra
- Parabolic arcs in secondary (power) spectra
- Enhanced for elongated (anisotropic) images
- Stinebring et al. 2001, Walker et al. 2004



THEORETICAL EXPECTATIONS

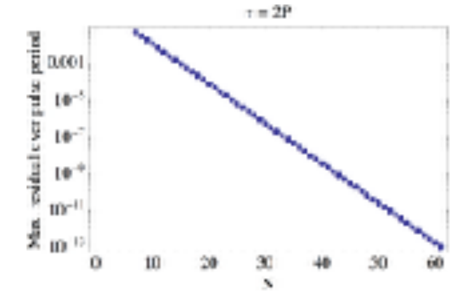
- Gaussian scattering: $\tau \propto \nu^{-4}$
- Kolmogorov Turbulence: $\tau \propto \nu^{-4.4}$

P(q) = Cne/(Ko2 + q2^)beta/2   exp(-q2/4ki2)

LITERATURE MEASURED α VALUES

- Löhmer et al. 2001: $\alpha = 3.44$ (9 sources, at high DMs)
- Lewandowski et al. 2013: $\alpha = 2.77 - 4.59$ (25 sources)
- Lewandowski et al. 2015: $\alpha = 2.61 - 5.61$ (60 sources)
- Smirnova et al. 2014 using RadioAstron: B0950+08, $\alpha = 3.00$

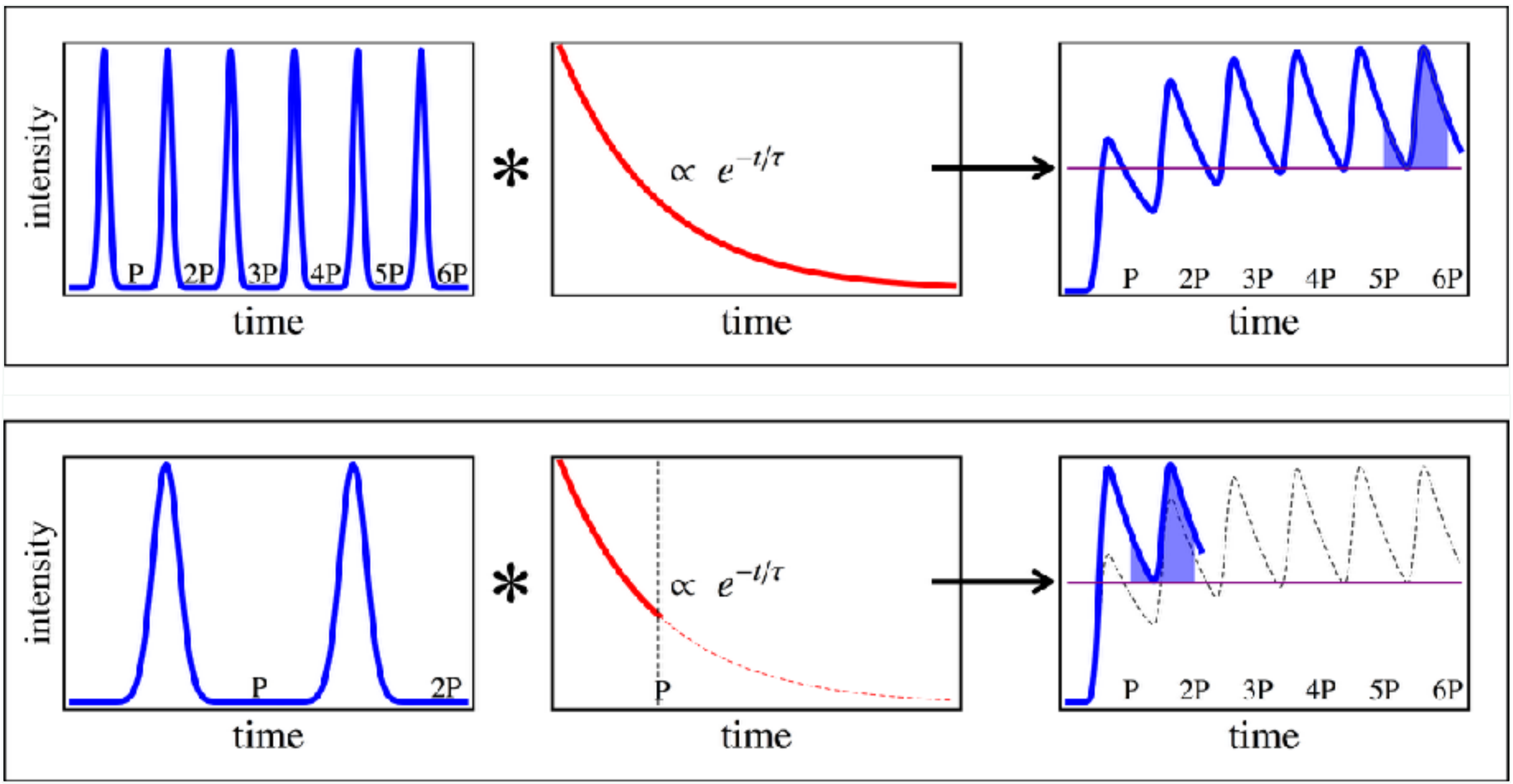
FITTING TECHNIQUE – ‘TRAIN MODELS’



Gaussian pulse train | IISM broadening function | Scattered pulse train

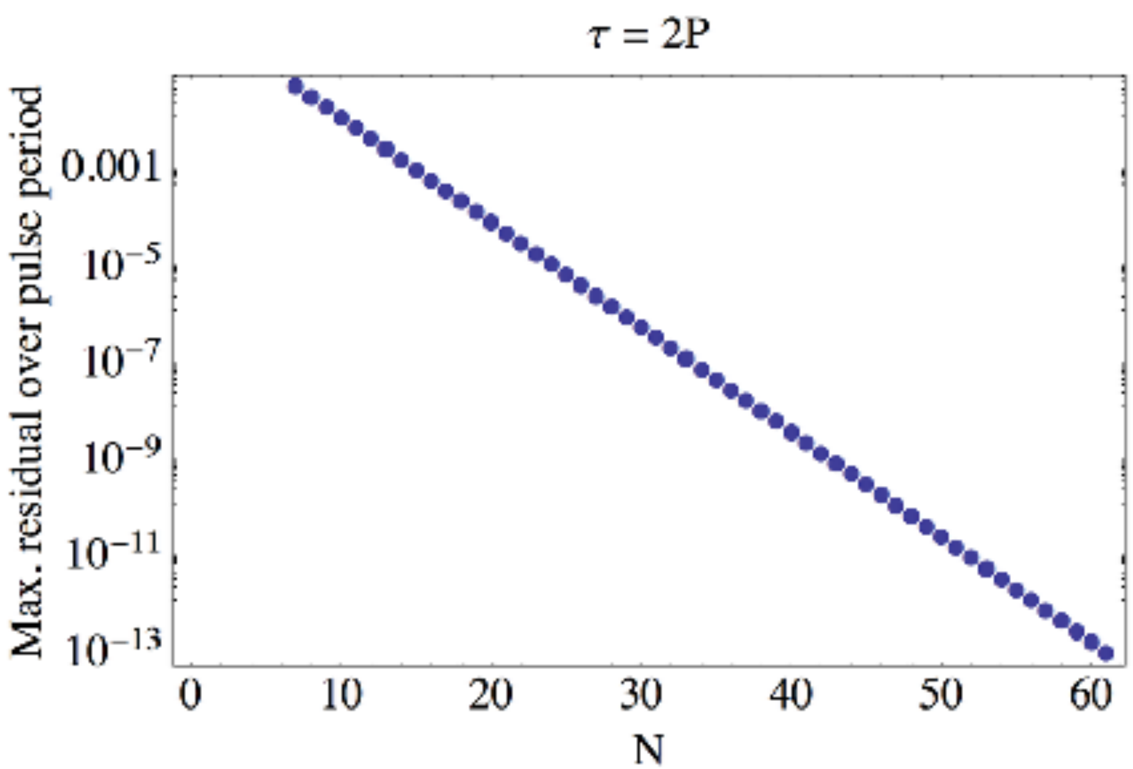
LONG TRAIN METHOD

TRAIN METHOD



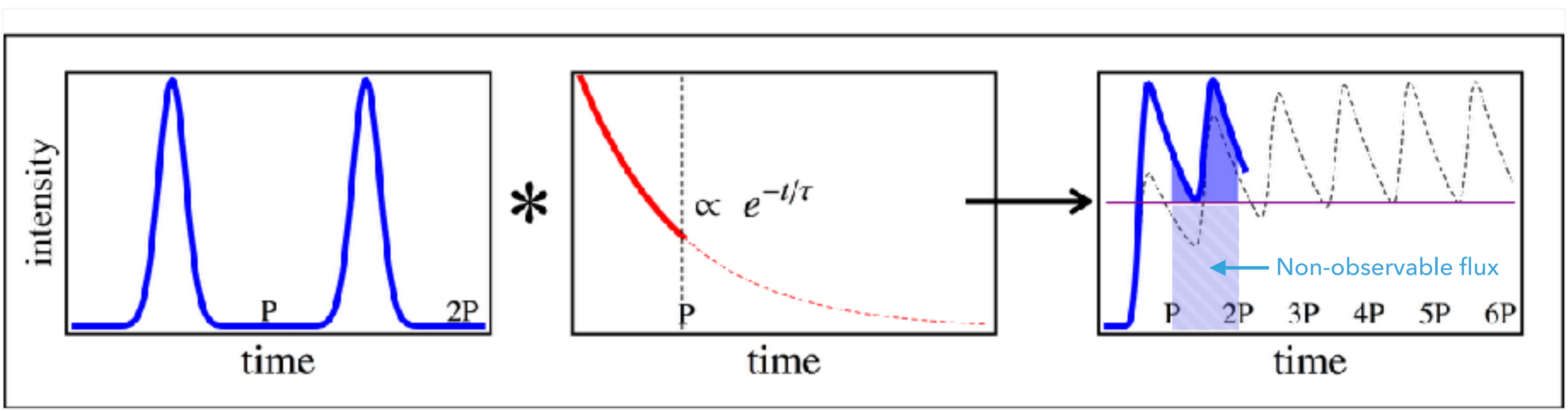
FITTING TECHNIQUE – 'TRAIN MODELS'

DIFFERENCE IN MODELS



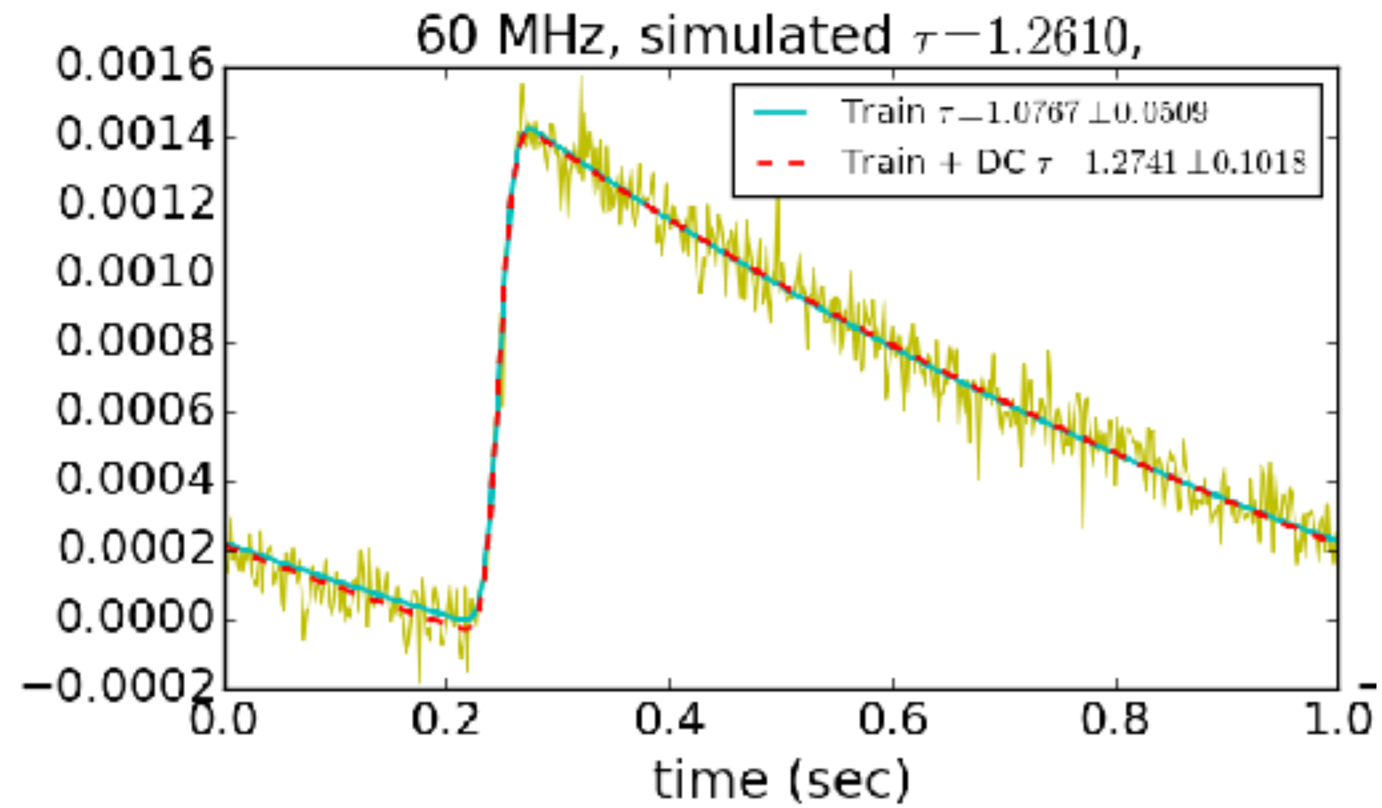
- Train Method - simplest, fastest
- Deals effectively with high levels of scattering where pulses are smeared into one another
- Keeps track of flux 'lost' due to high levels of scattering

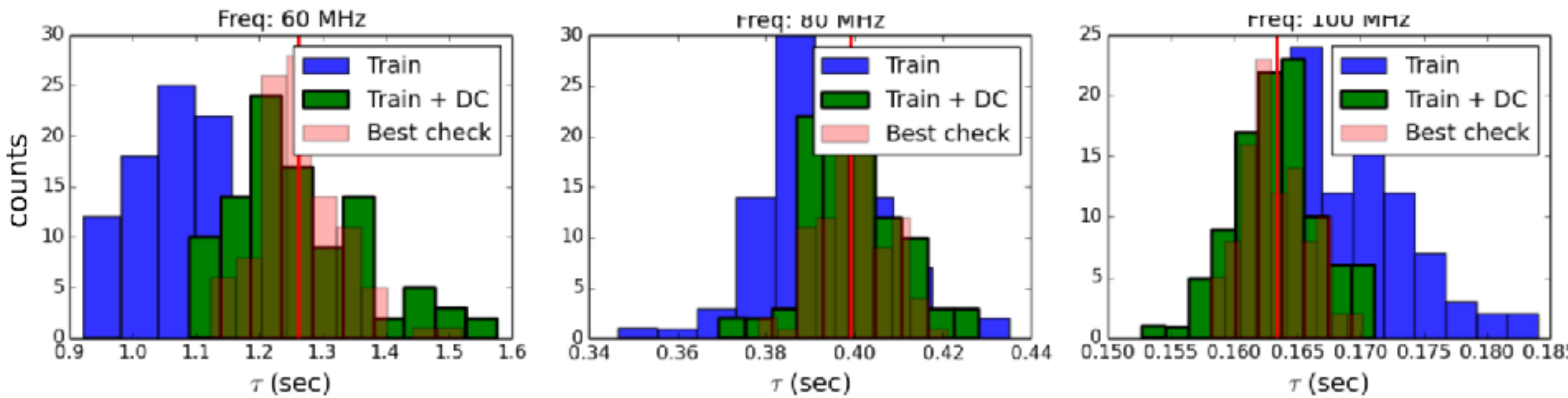
TRAIN METHOD



FITTING TECHNIQUE – 'TRAIN + DC MODEL'

- Fits for underlying Gaussian parameters (mu, sigma, A)
- Fits for scattering timescale tau
- Add DC offset
- It works





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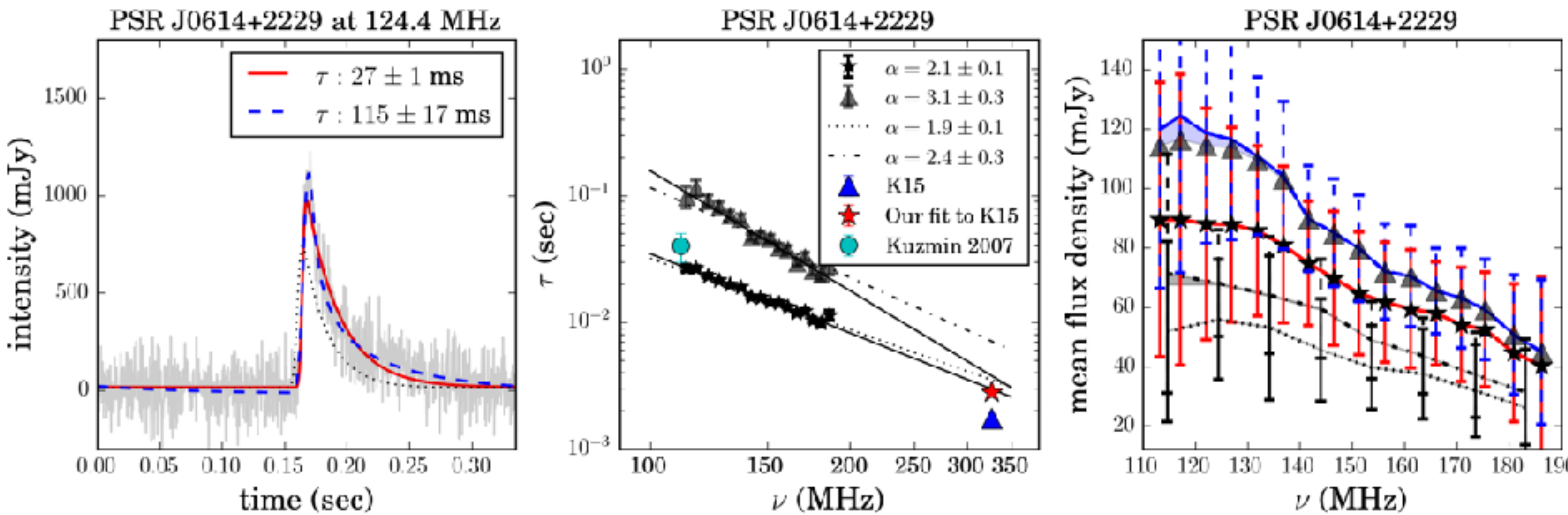
LOFAR SOURCES

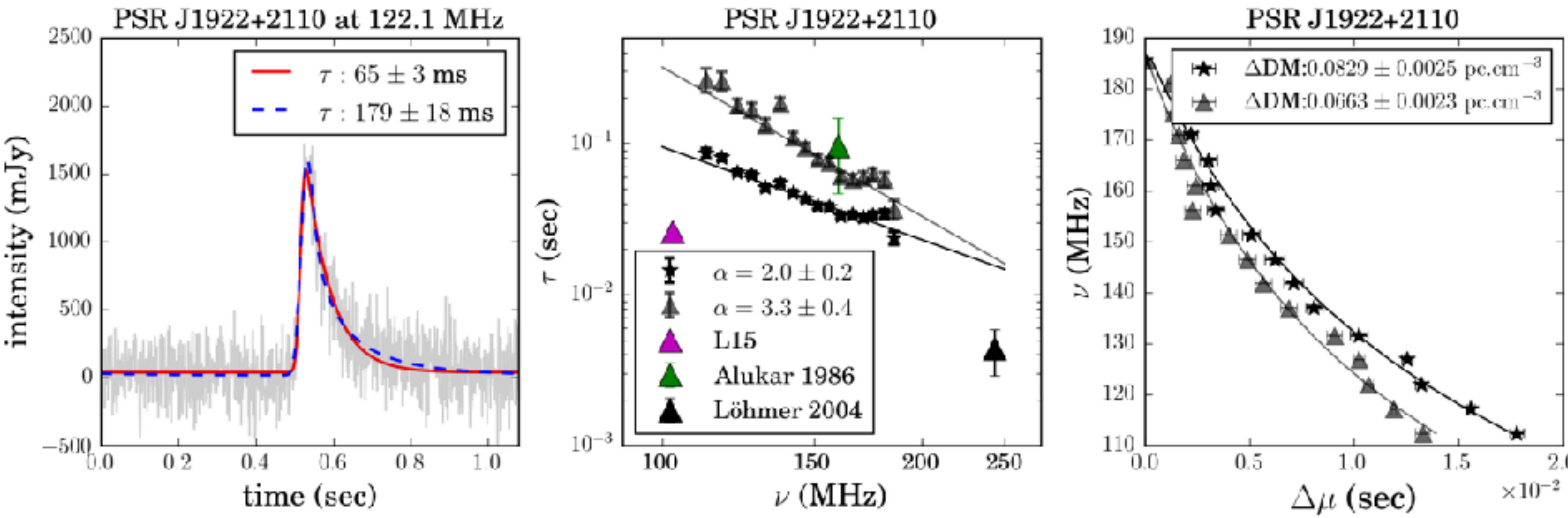
- Selected 13 slow (non-ms) pulsars
- Observed with LOFAR Core stations
- Scattered at HBA frequencies (110 - 190 MHz)
- LOFAR: Provides a large bandwidth at low frequencies (80MHz/150MHz)
- Simple profile shapes (approximated by single Gaussian component)
- DM range: 50 - 220 pc cm^{-3}
- Selected from Commissioning data, Census data (190, DEC > 8) and some overlapping Cycle 5 LOFAR timing data

PSR J0614+2229 (B0611+22)



- RED FIT: Isotropic model, BLUE FIT: Extreme Anisotropic (1D) model
- scattering indices (α) are lower than theoretical models predict
- often closer to theoretical values for anisotropic models
- recover the flux lost due to scattering

PSR J1922+2110 (B1920+21)



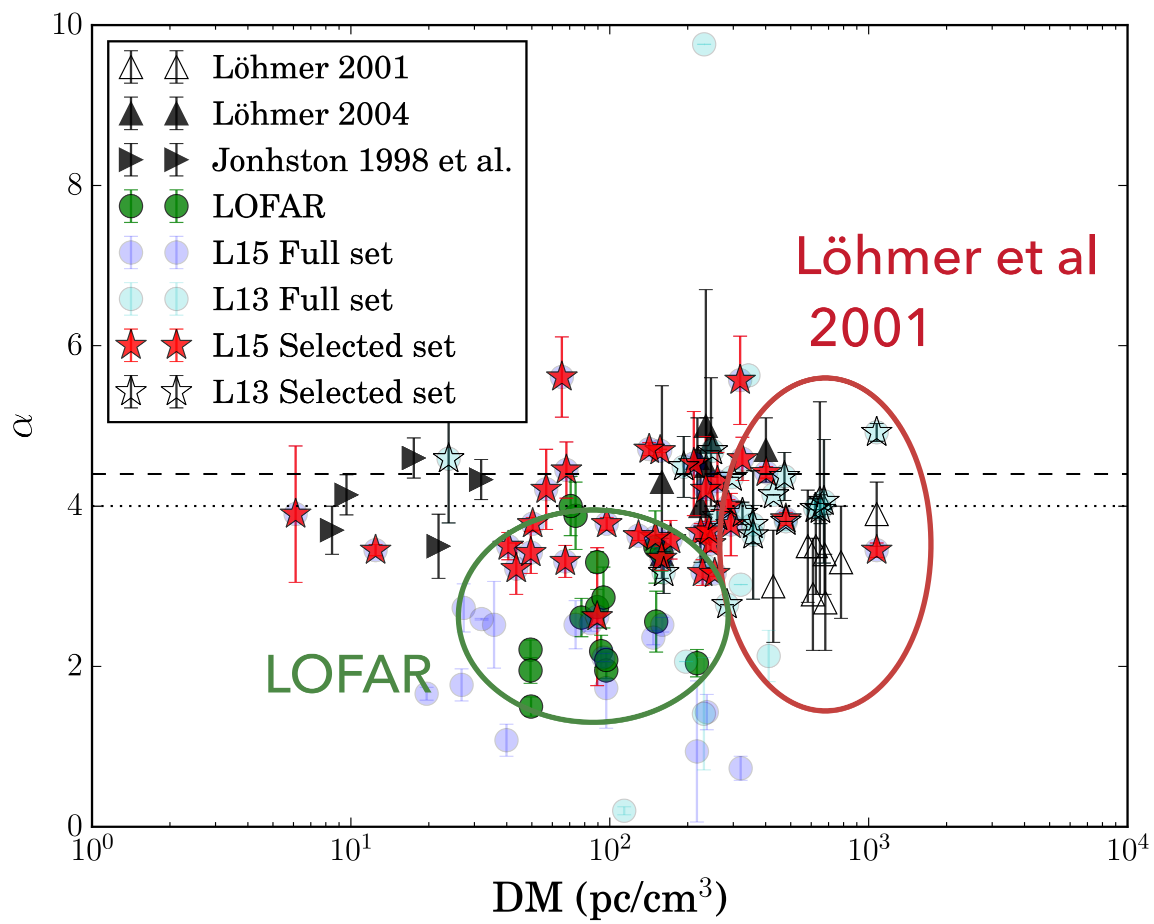
- measure DM corrections due to scattering effects
- most often an overestimation

6.4 - only 6 datapoints, 2 lowest have massive error bars for ANISO!

RESULTS TABLE

Pulsar	Isotropic Scattering			Extreme (1D) Anisotropic Scattering		
	τ_{150} (ms)	α	ΔDM (pc cm^{-3})	τ_{150} (ms)	α	ΔDM (pc cm^{-3})
J0040+5716	40 ± 2	2.2 ± 0.2	0.0378 ± 0.0024	86 ± 8	2.7 ± 0.3	0.0143 ± 0.0022
J0117+5914 (Co)	7 ± 0	2.2 ± 0.1	0.0082 ± 0.0009	14 ± 1	3.5 ± 0.4	0.0041 ± 0.0011
J0117+5914 (Ce)	8 ± 1	1.9 ± 0.2	0.0064 ± 0.0006	16 ± 2	2.6 ± 0.2	0.0038 ± 0.0006
J0543+2329	10 ± 1	2.6 ± 0.2	0.0155 ± 0.0020	17 ± 2	2.7 ± 0.3	0.0031 ± 0.0020
J0614+2229 (Co)	15 ± 1	1.9 ± 0.1	0.0030 ± 0.0007	44 ± 4	2.4 ± 0.3	-0.0033 ± 0.0006
J0614+2229 (Cy)	15 ± 0	2.1 ± 0.1	-0.0053 ± 0.0006	44 ± 3	3.1 ± 0.3	-0.0109 ± 0.0008
J0742−2822	20 ± 2	3.8 ± 0.4	0.0013 ± 0.0027		...	...
J1851+1259	6 ± 1	4.0 ± 0.4	0.0264 ± 0.0022	10 ± 1	4.7 ± 0.4	0.0158 ± 0.0017
J1909+1102	42 ± 3	3.5 ± 0.4	0.0351 ± 0.0085	120 ± 27	6.4 ± 0.7	-0.0276 ± 0.0077
J1913−0440 (Co)	9 ± 0	2.7 ± 0.2	0.0240 ± 0.0009	16 ± 1	3.5 ± 0.3	0.0161 ± 0.0011
J1913−0440 (Cy)	7 ± 0	3.3 ± 0.1	0.0457 ± 0.0003	12 ± 0	4.1 ± 0.2	0.0381 ± 0.0003
J1917+1353	11 ± 1	2.8 ± 0.4	-0.1004 ± 0.0025	21 ± 2	3.6 ± 0.6	-0.1167 ± 0.0028
J1922+2110	42 ± 2	2.0 ± 0.2	0.0829 ± 0.0025	85 ± 6	3.3 ± 0.4	0.0663 ± 0.0023
J1935+1616	20 ± 1	3.4 ± 0.2	-0.0635 ± 0.0030	46 ± 4	3.9 ± 0.5	-0.0836 ± 0.0038
J2257+5909	31 ± 2	2.6 ± 0.4	-0.0317 ± 0.0058	68 ± 9	3.4 ± 0.6	-0.0530 ± 0.0050
J2305+3100	9 ± 0	1.5 ± 0.1	0.0184 ± 0.0035	11 ± 0	2.0 ± 0.1	0.0144 ± 0.0023
$\langle\alpha\rangle$		2.7 ± 0.2			3.5 ± 0.4	

ORIGIN OF LOW SCATTERING INDICES?

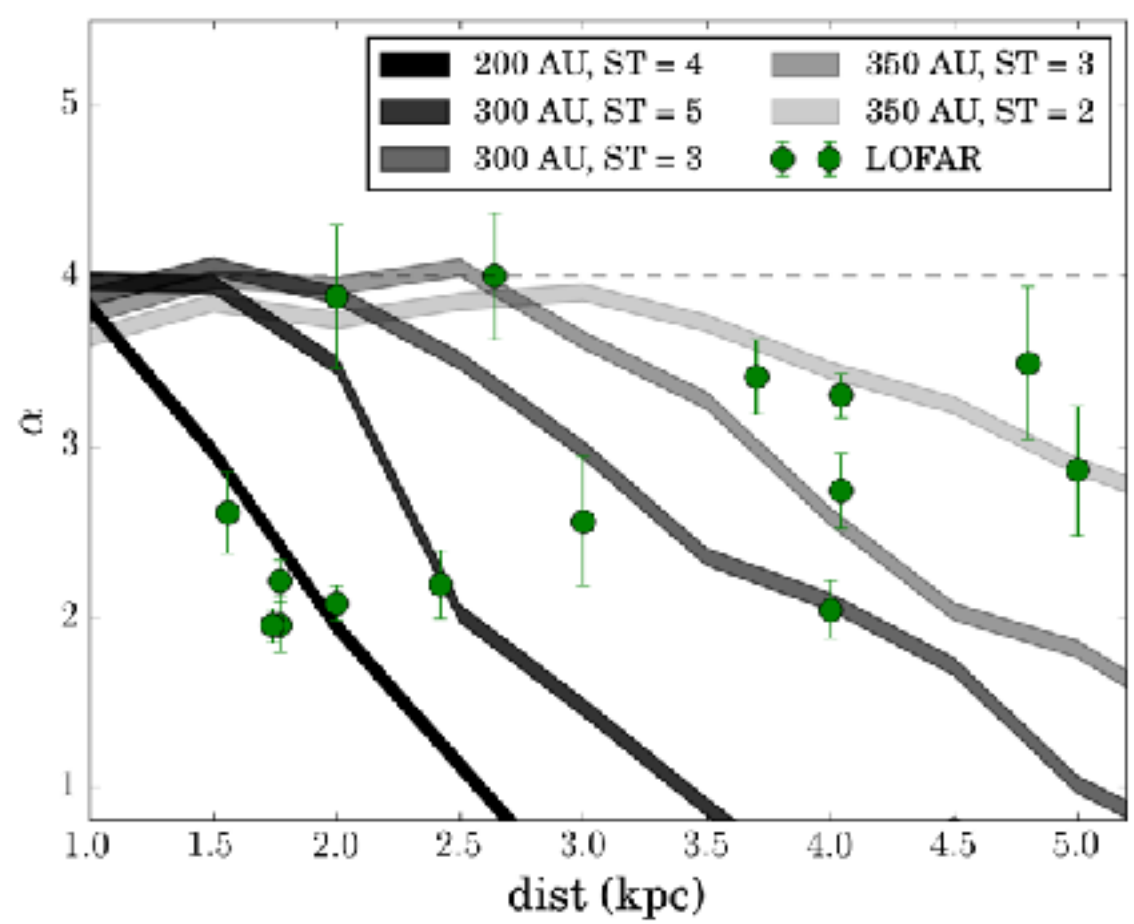


Löhmer 2001 suggested lower **α** with an increase in DM

We see low **α** at low DMs

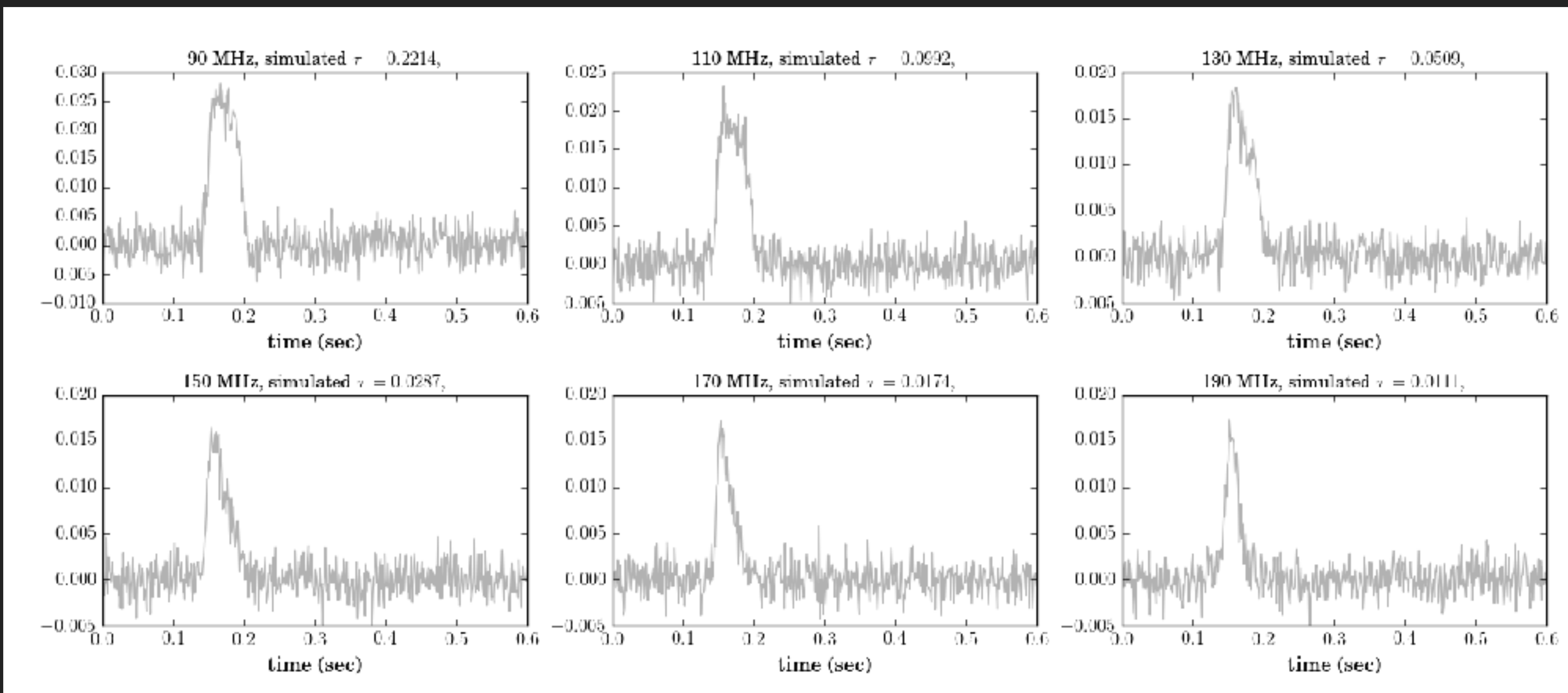
Truncated screens - can reproduce the **α** distribution with ~100 AU screens

The dominance of truncated screen could decrease with increase in distance/DM

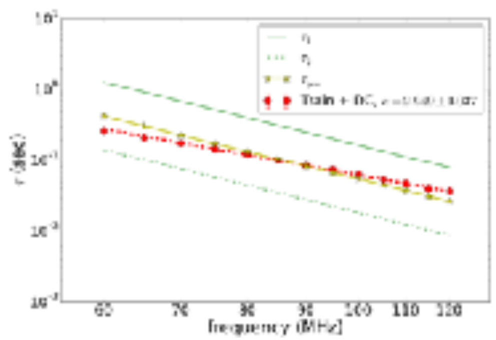


SIDE NOTE: ‘TRUNCATED PROFILES’

- Simulated midway screen 120 AU, distance 1.5 kpc
- Pulsars appear much less scattered

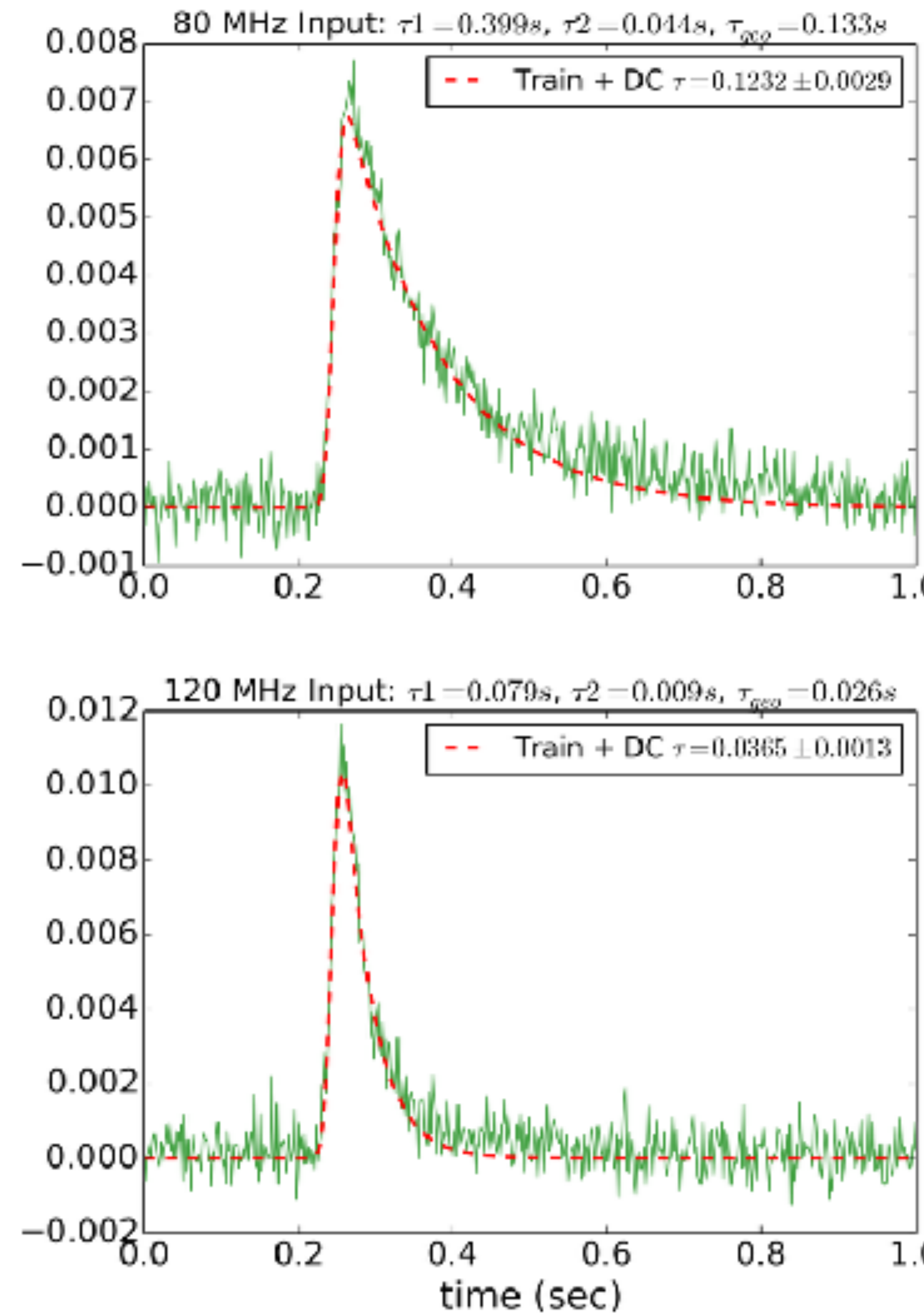


ANISOTROPY REQUIRED?



- Does our data require anisotropic scattering models?
- **Not strictly**
- Tempting in some cases (4 pulsars):
    - goodness of fit (χ^2 , KS) slightly better for anisotropic model
    - anisotropic **Δ**DM corrections between epochs lead to more similar DMs
    - **α** values isotropic and anisotropic models are well separated
    - anisotropic **α** values closer to theoretical values

Simulated



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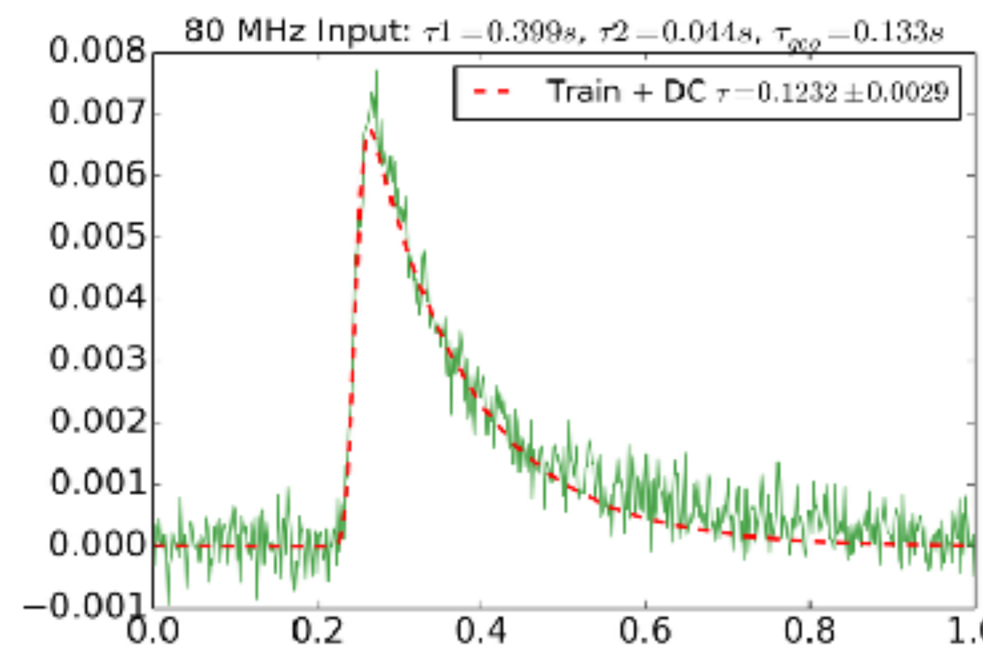
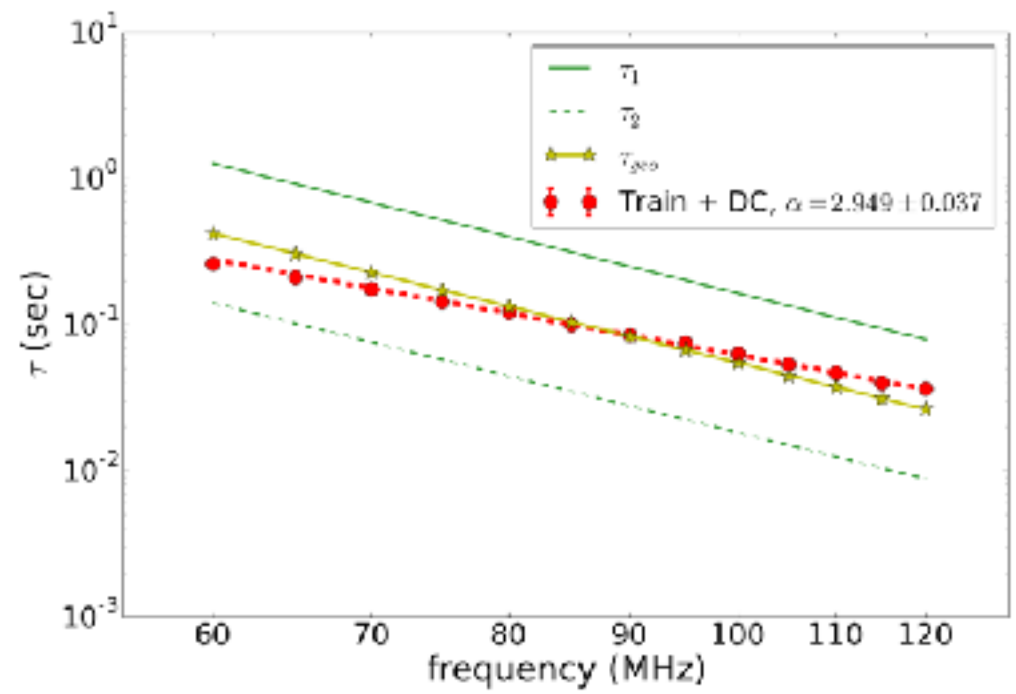
ANISOTROPY REQUIRED?

- Does our data require anisotropic scattering models?
- **Not strictly**
- **It definitely is a mechanism that can cause perceived low α values**
- Simulated data: shown that fitting anisotropic data (e.g. A = 3) with isotropic model lead low **α** values
- Existing evidence for anisotropy - e.g Brisken pulsar, parabolic arcs in secondary spectra





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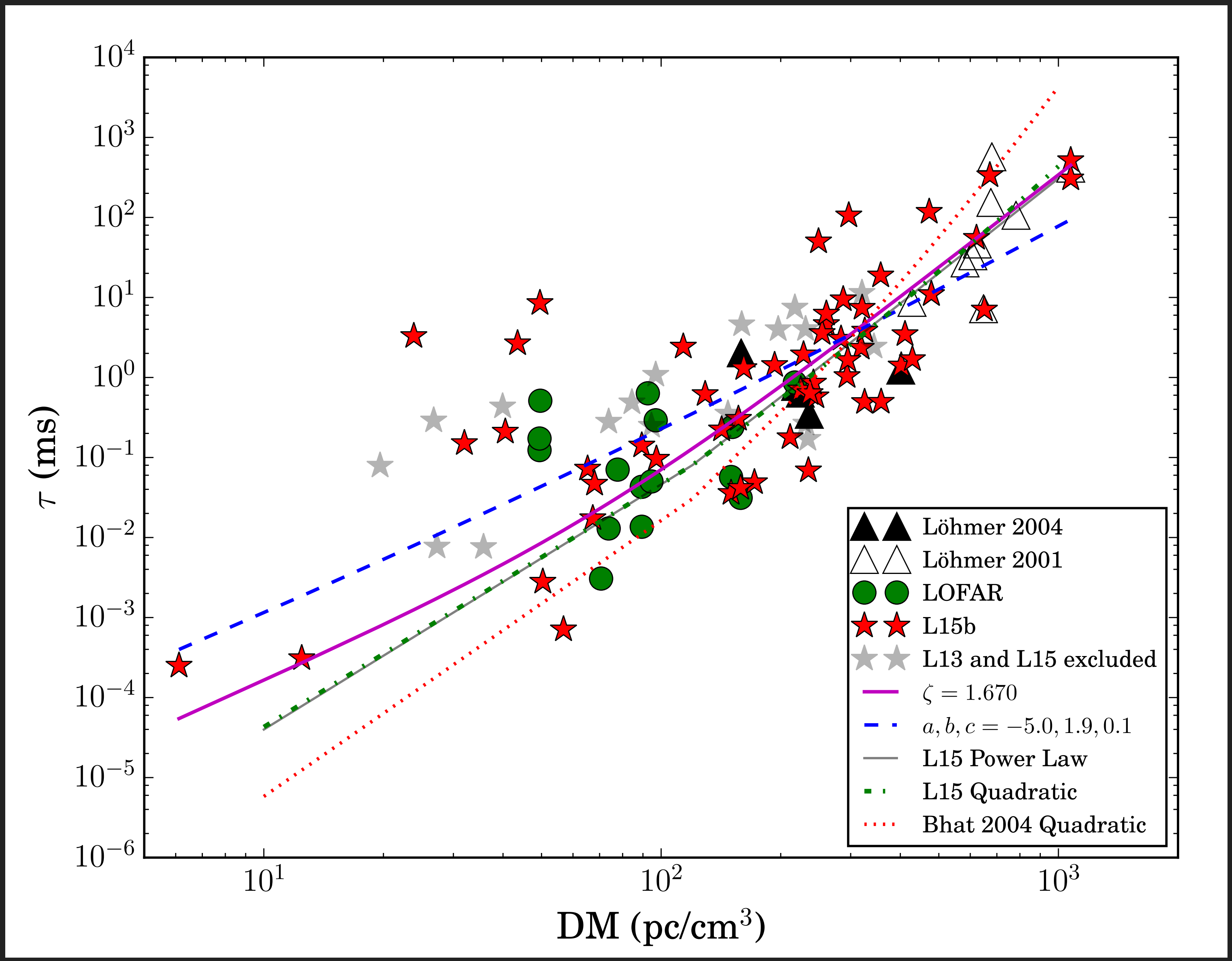
EVOLUTION OF SPECTRAL INDICES WITH FREQUENCY?



- τ at 1 GHz vs DM
- Compare Bhat 2004
- Our data (along with Lewandowski et al. 2013 and 2015) promote higher τ at low DM
- For Bhat relation to hold at 1GHz, α must change with frequency
- Implications?

NEXT…

- Time domain analysis is not the most sensitive to analyzing IISM properties
- But even in time domain we see anomalous effects
- Interferometric imaging, including space-ground experiments, could be key in investigating the typical sizes of scattering surfaces
- Scintillation results are required for precise scattering measurements at higher frequencies to aid the investigation of the frequency dependence of α. (Break in power law?)
- Best tests for anisotropy come from high resolution dynamic spectra
- Test whether estimated flux loss is regained in pulsar imaging - ongoing work (Will not be so, if flat spectra are due to inner scale instead)


WE DID IT! WE CLEARED EARTH'S ORBIT!
MARS, HERE WE COME!
ARE YOU SURE THIS IS THE WAY?
WHAT? DIDN'T YOU BRING THE MAP?!

THE END