Wave optics in astrophysical lensing: unlocking the potential of the coherent sky

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Overview

- Observational and theoretical context
- FRB cosmology through gravitational lensing
  Opportunities
  Challenges
- Pulsar scintillometry and scattering in the ISM
- Progress in wave optics
  Picard-Lefschetz theory
  Diffractive and refractive optics
  Imaginary images
- Gravitational wave lensing

Context: A Wealth of New Data from Coherent Sources

- Lots of FRBs

~ 800 / day with > 5 Jy ms at 600 MHz (CHIME/FRB Collab. (2021))

- New pulsar timing data from PTAs

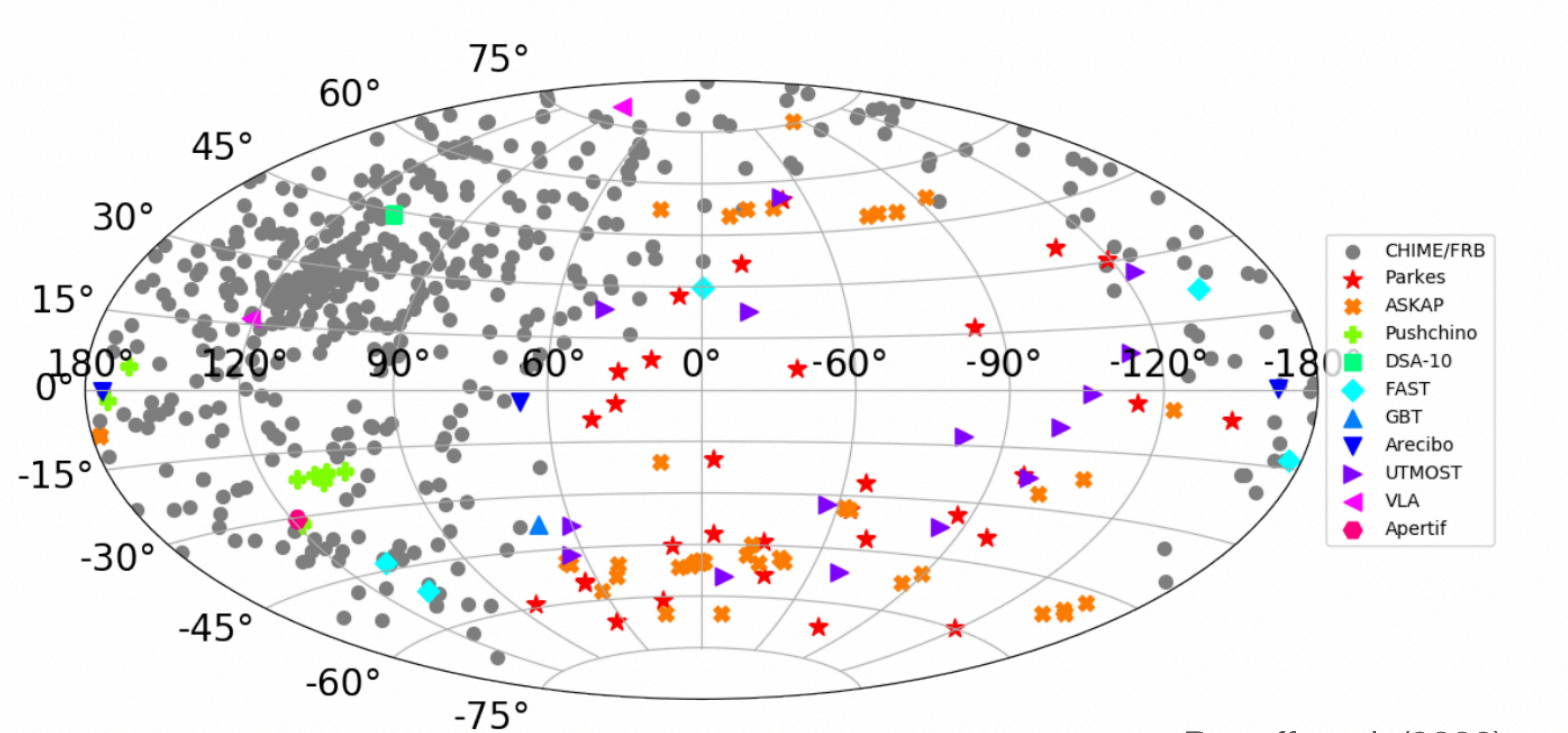
- VLBI

e.g. CHIME outriggers

- Gravitational waves

PTAs (e.g. NANOGrav)

Interferometers (e.g. LIGO, VIRGO, Einstein, LISA)



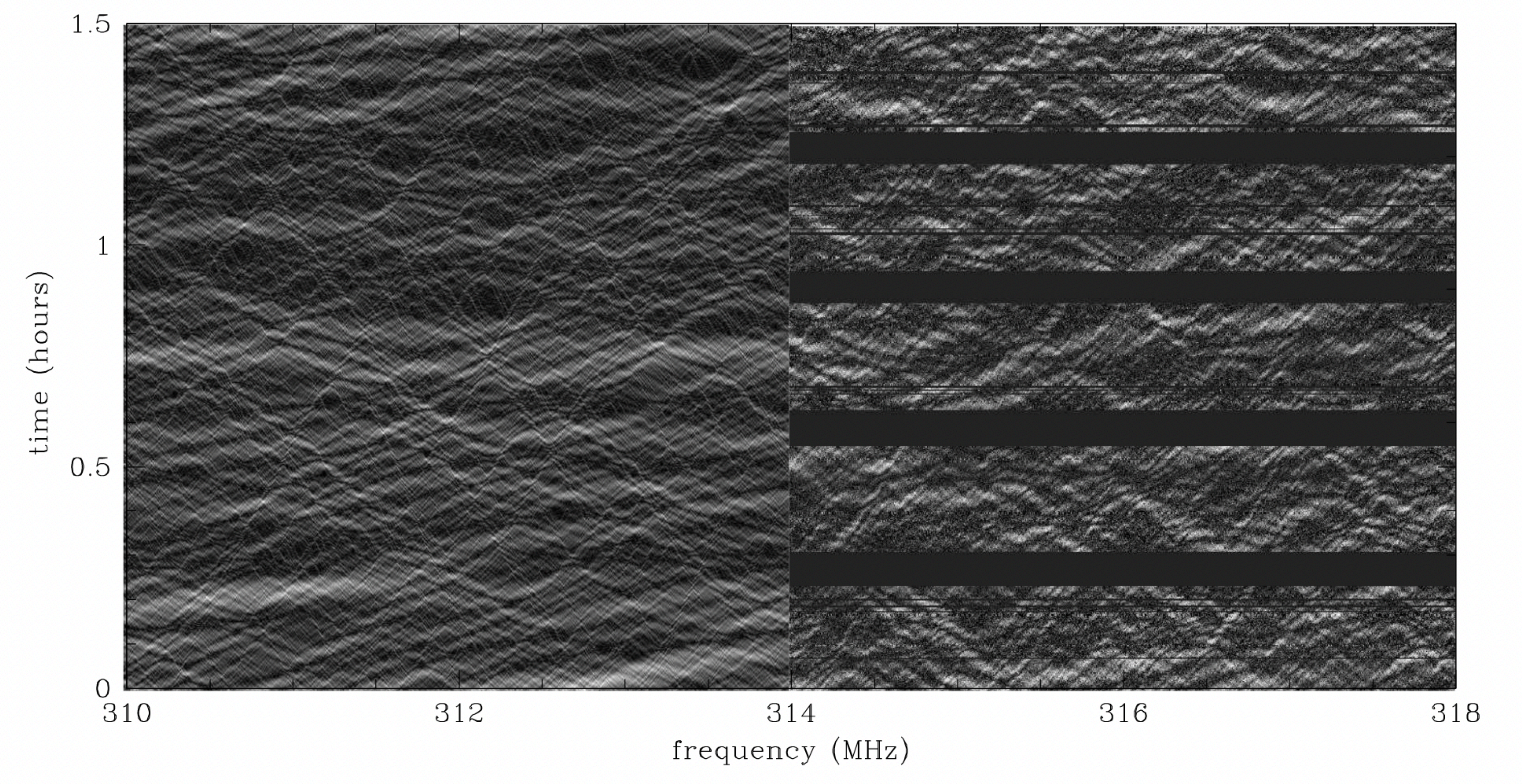
Pteroff et al. (2022)

Context: A Dearth of Theory

- Diffraction integrals are challenging to compute

$$F(\overrightarrow{y}) = \sqrt{\frac{1}{i\nu}} \int d^2x e^{i\nu\left[\frac{1}{2}(\overrightarrow{x}-\overrightarrow{y})^2+\psi(\overrightarrow{x})\right]}$$

- Most sources are incoherent -> geometric optics is sufficient



Pen and Levin (2014)

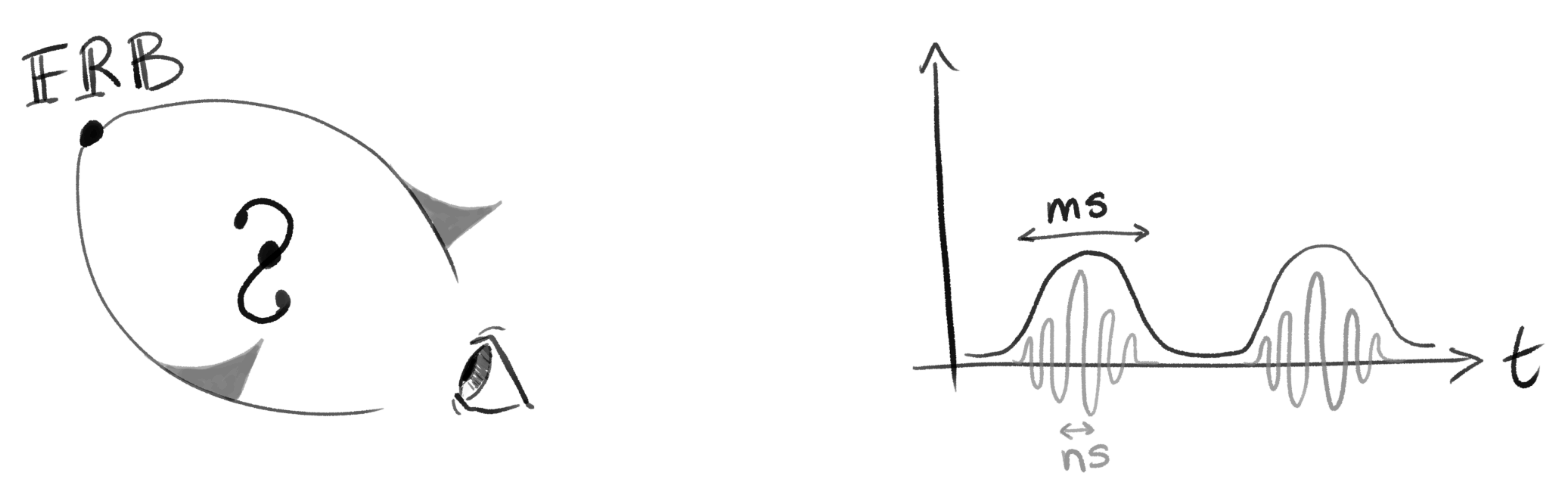
But wait…

What can we learn from the lensing of coherent sources that we can’t learn from incoherent sources?

The study of wave optics is as old as the hills. Don’t we know everything by now?

FRB Cosmology: An Idealistic Picture

- FRBs can be used to measure nanosecond precision on time delays between images



- orders-of-magnitude more precise than AGN time delays

time delays ~ 10 days
AGN ~ 1% accuracy

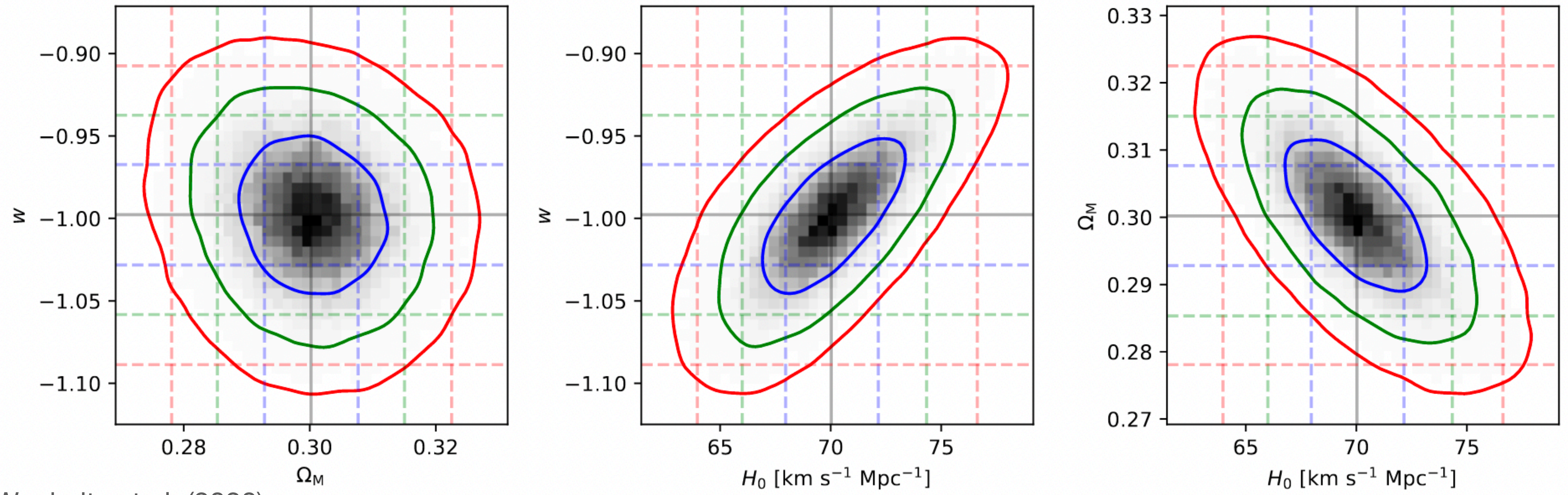
FRB ~ 10^{-13}% accuracy

FRB Cosmology: An Idealistic Picture

- High precision time delays allow measurements of time derivatives of time delays for repeating FRBs

  time delays increase by $\sim H_0 \Delta t$ which is 0.1 ms/yr

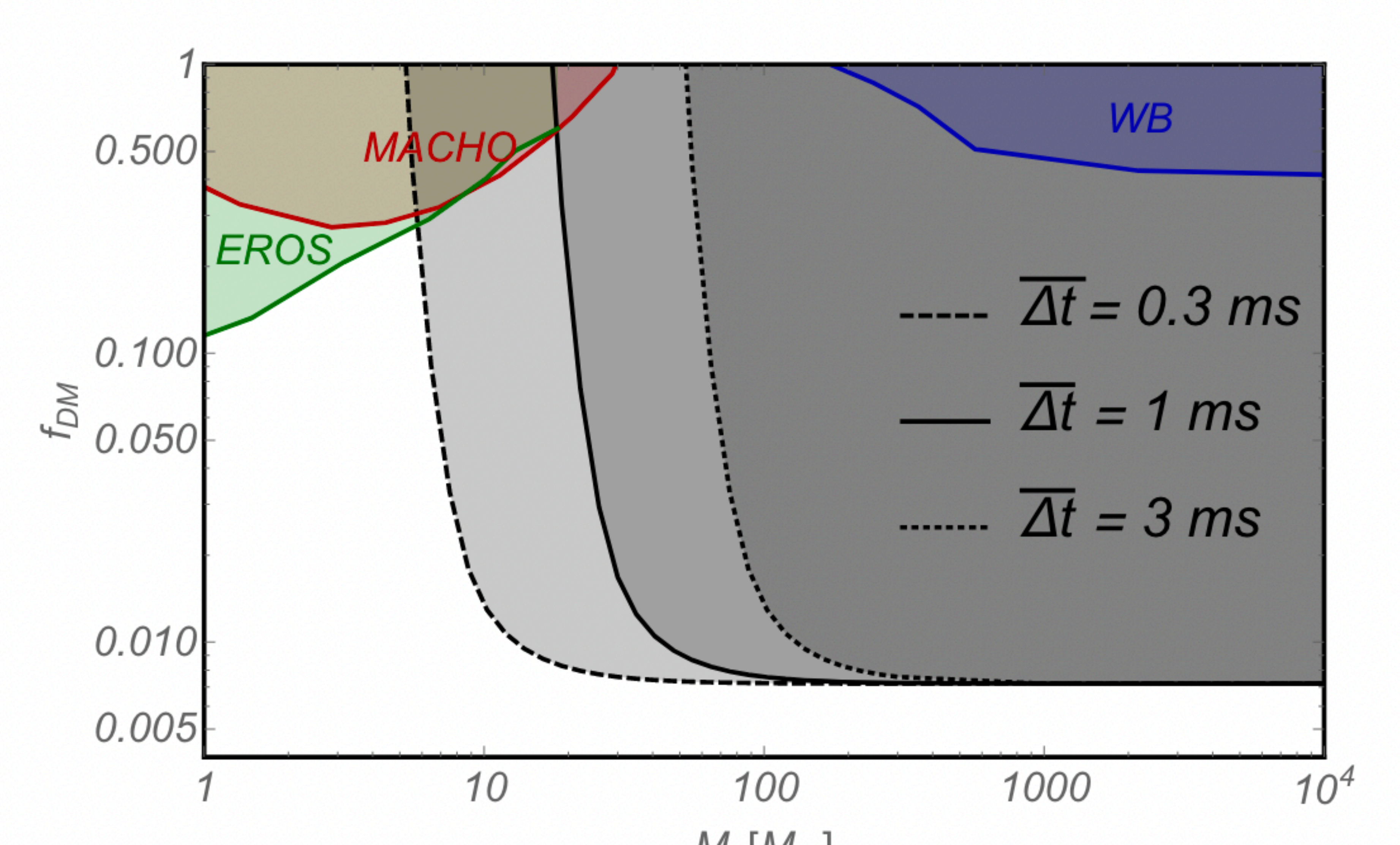
- Measuring derivatives of time delays avoids model degeneracies (Wucknitz et al. (2020))



Wucknitz et al. (2020)

FRB Cosmology: An Idealistic Picture

- FRB microlensing can be used to probe $10 - 10^4\,M_\odot$ dark matter

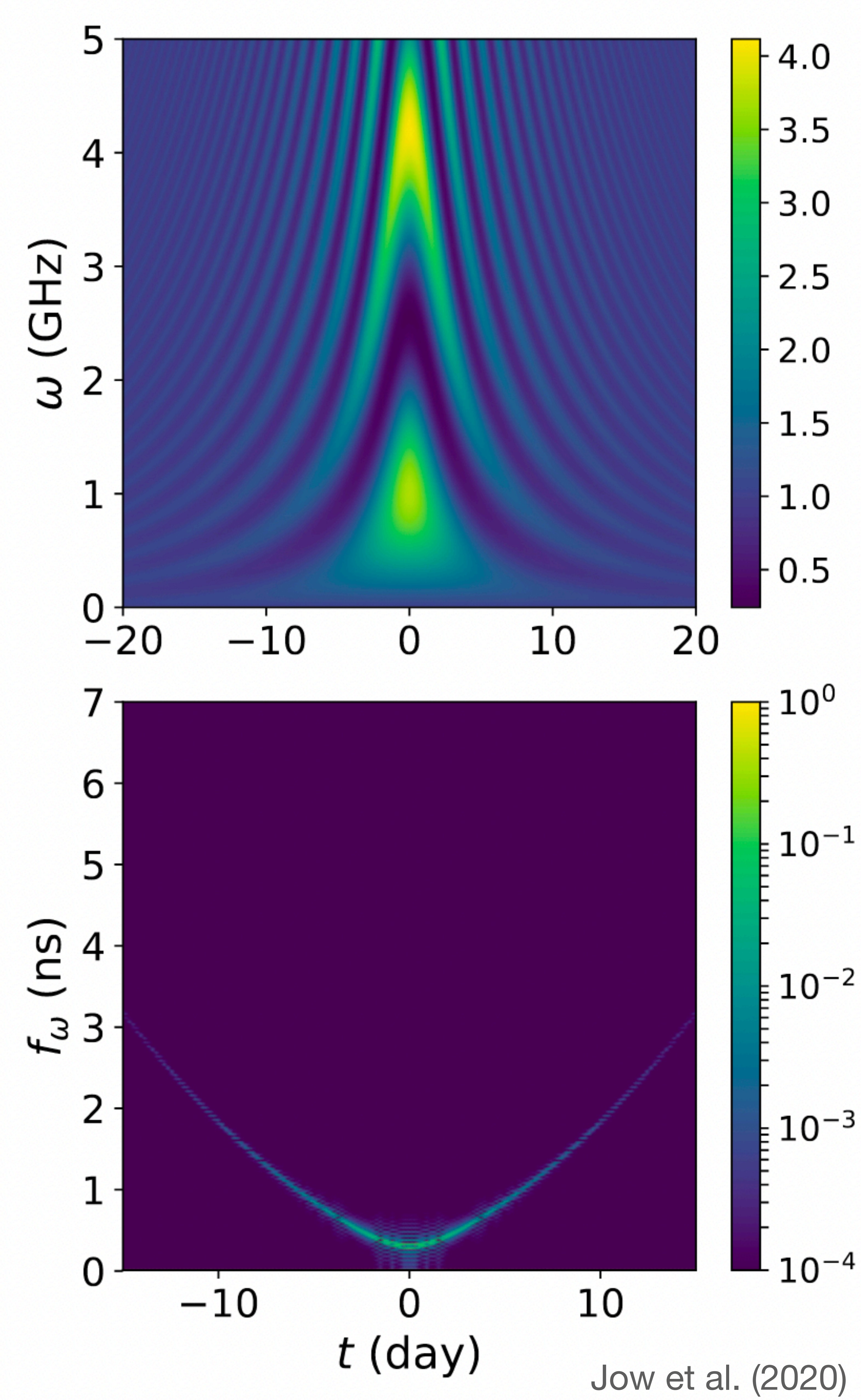


Muñoz et al. (2016)

- FRB femtolensing: $10^{-6} - 10\,M_\odot$ (Jow et al. (2020))

  Coherence means lens mass can be measured instantaneously

  Coherence also increases cross-section



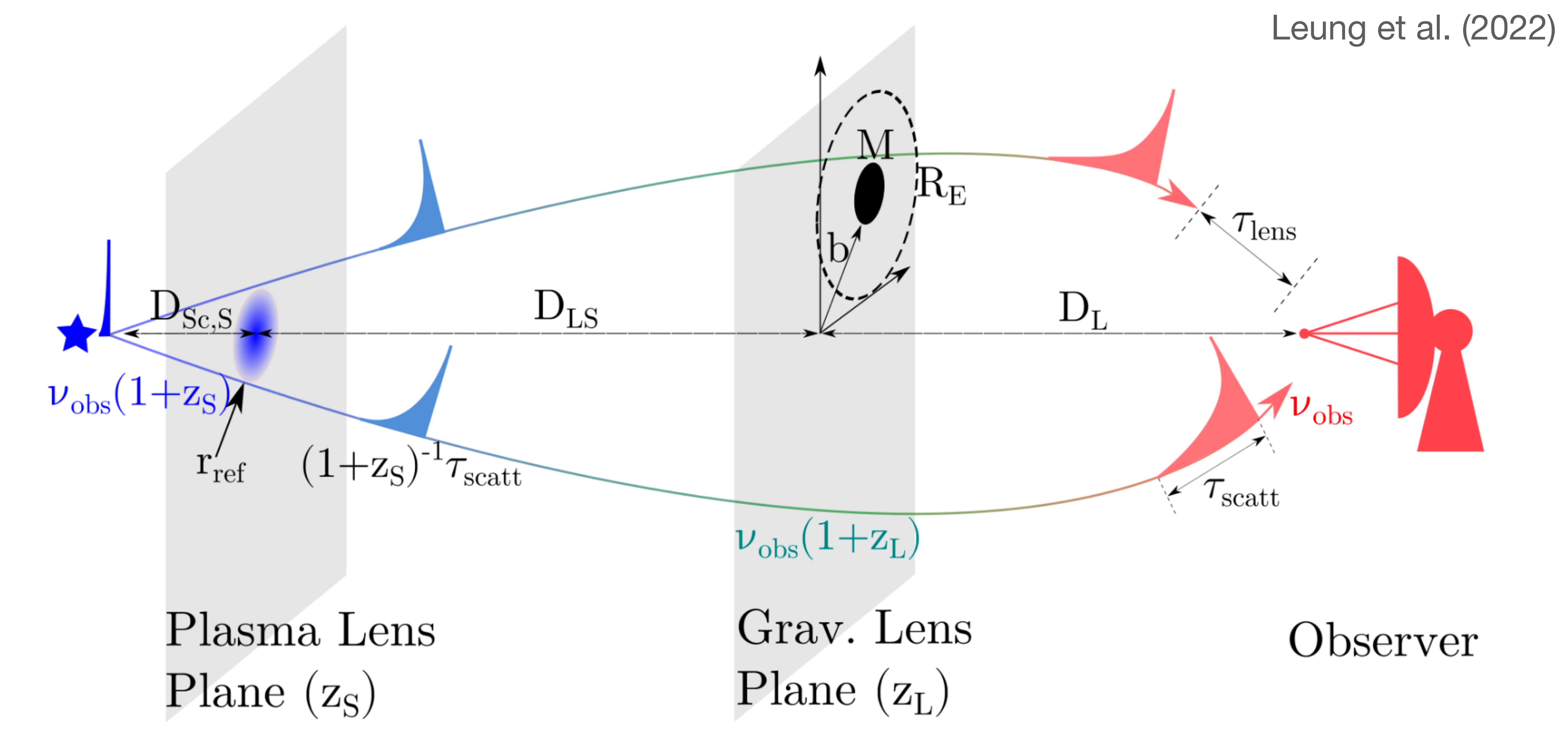
Jow et al. (2020)

FRB Cosmology: Practical Considerations

- Precise measurements require precise predictions, which can be challenging to obtain

  Model degeneracies (e.g. mass-sheet degeneracy, substructure)

- Scattering in the ISM/IGM/local environment degrades coherence (Leung et al. (2022))



Two Broad Goals:

1. Understanding gravitational lensing of coherent sources.

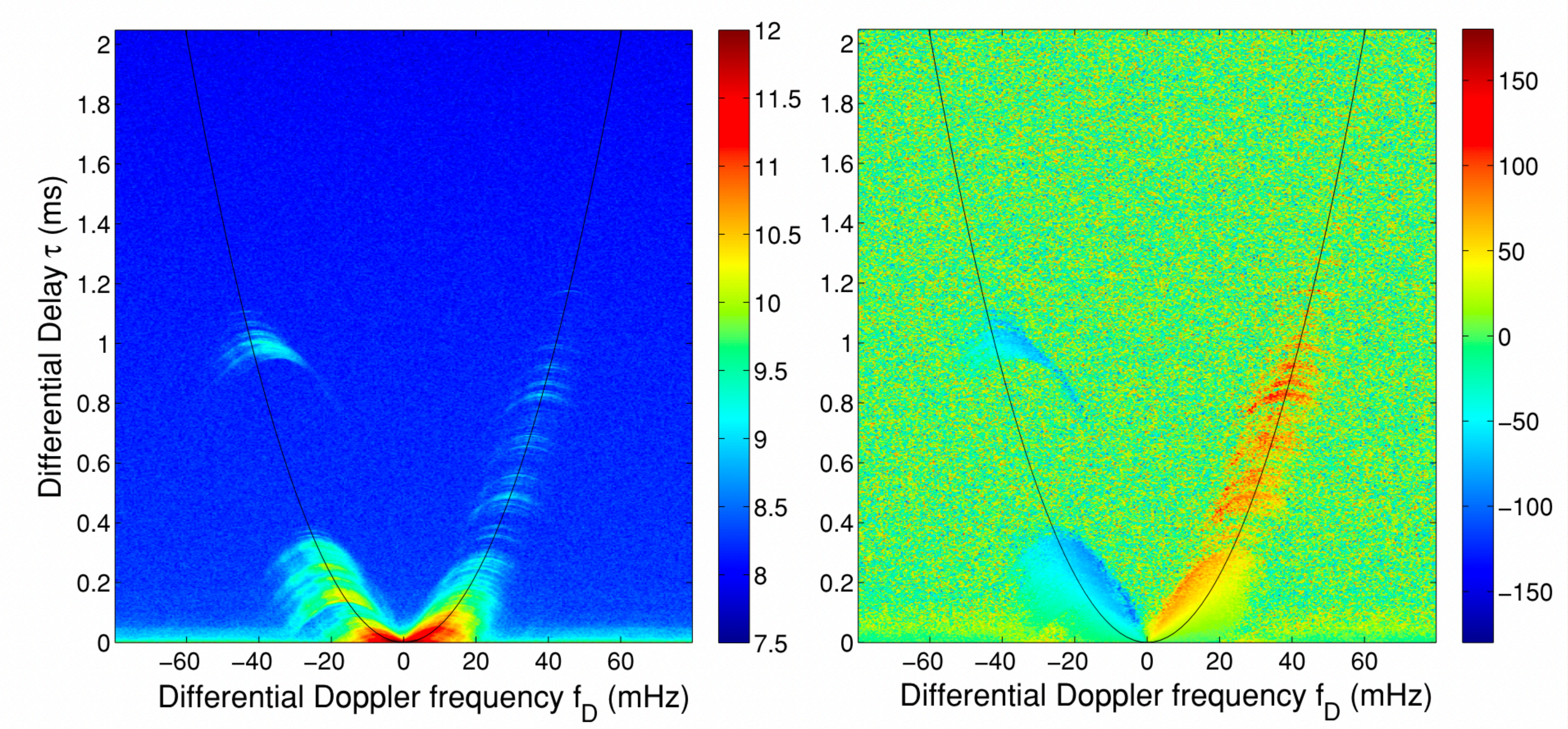
   Modelling wave effects
   More sophisticated models (e.g. what is the effect of substructure?)
   Can we make unambiguous lensing predictions?

2. Understanding coherent plasma scattering along the line of sight.

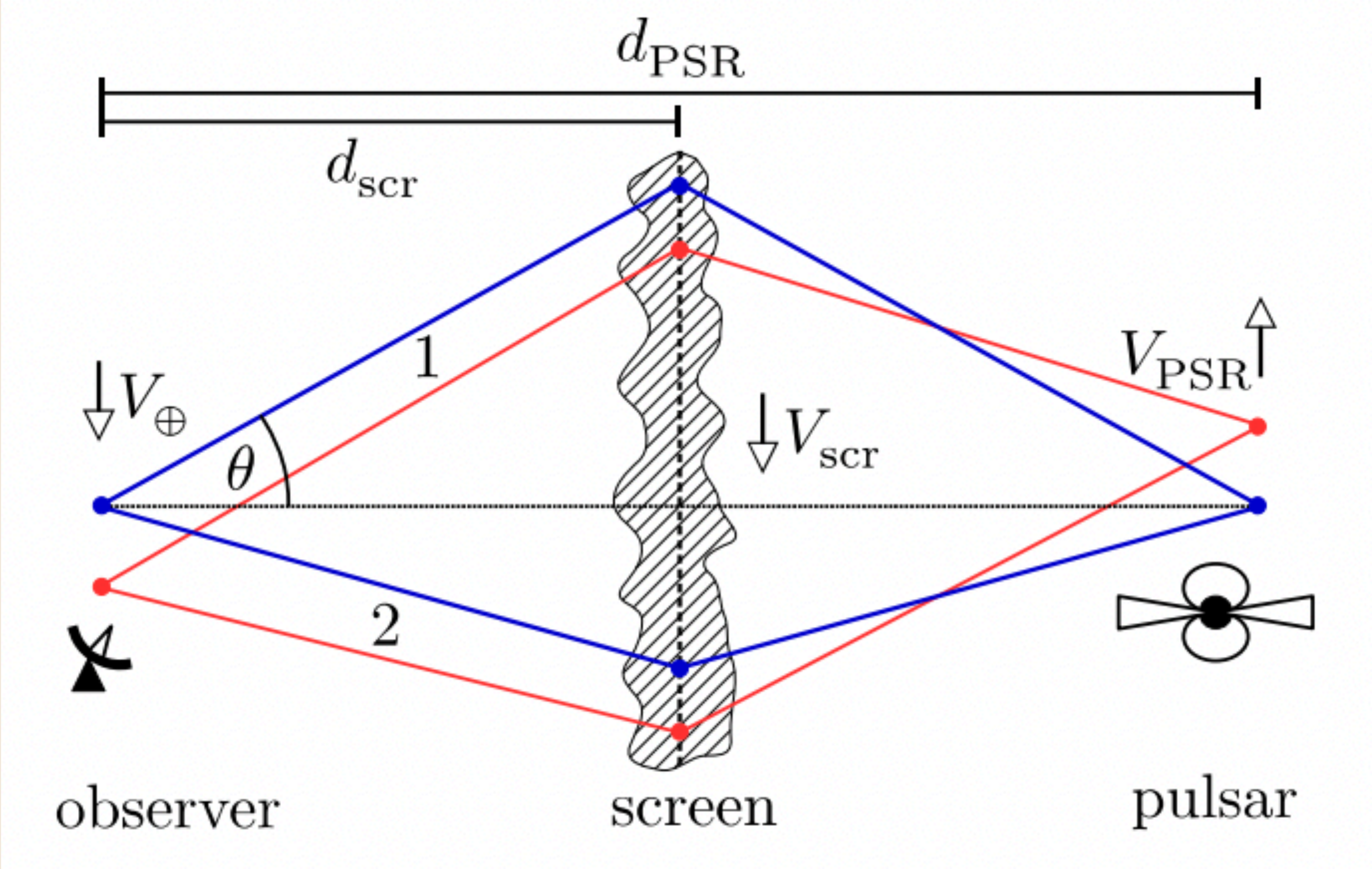
   Is it possible to de-scatter lensing observations?
   What exactly do the typical plasma structures along the line of sight look like?

Pulsar Scintillometry: Two Decades of Progress

- Pulsar scintillation reveals thin, highly anisotropic structures in the ISM



Brisken et al. (2010)



Sprenger et al. (2020)

- We can use pulsar scintillation to learn about the plasma structures that are likely to lens FRBs

But wait…

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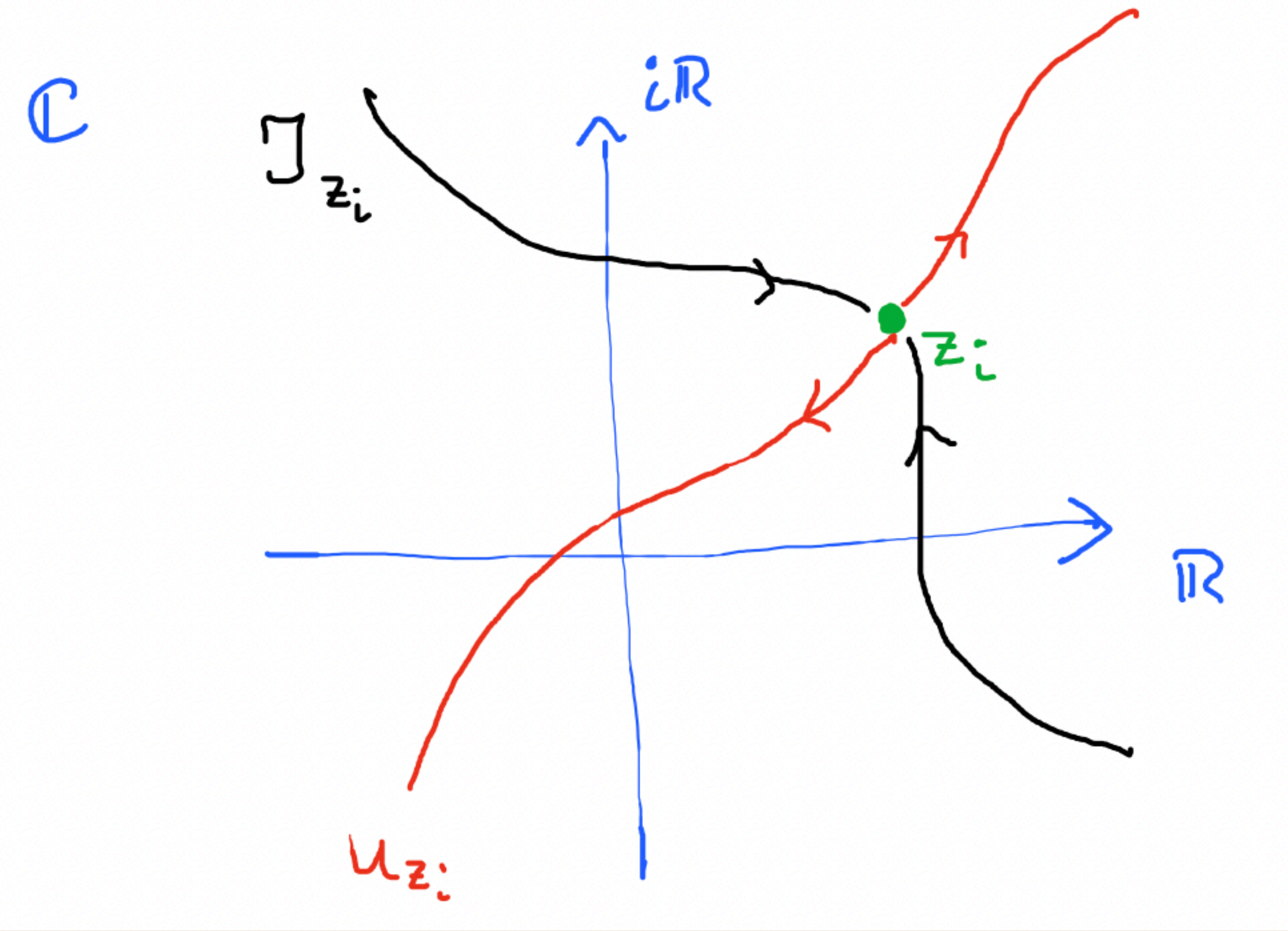
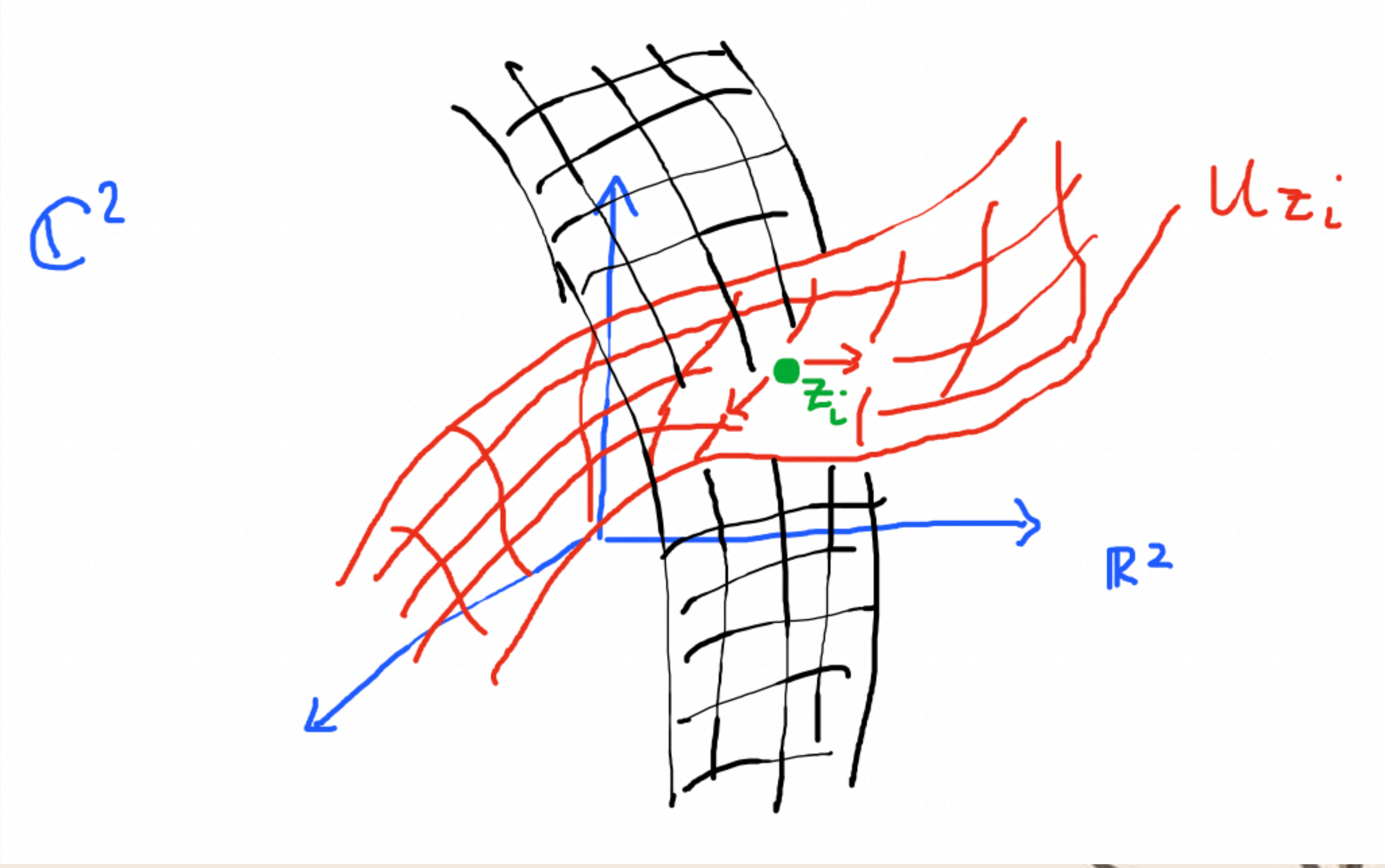
Picard-Lefschetz Theory: A New Tool for Old Problems

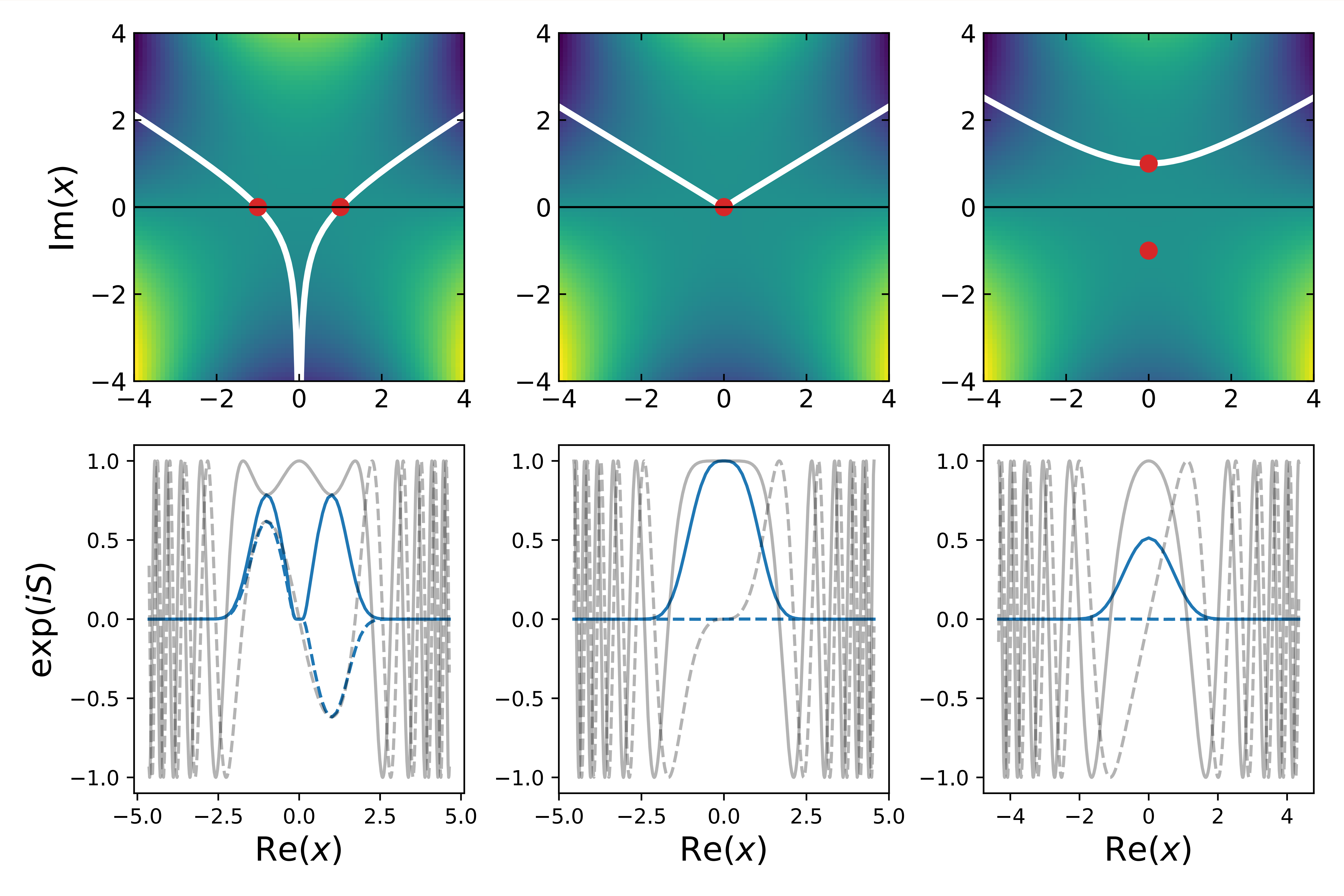
A new technique for computing highly oscillatory path integrals: $\int_{\mathbb{R}^n} e^{iS(x)} d^n x$





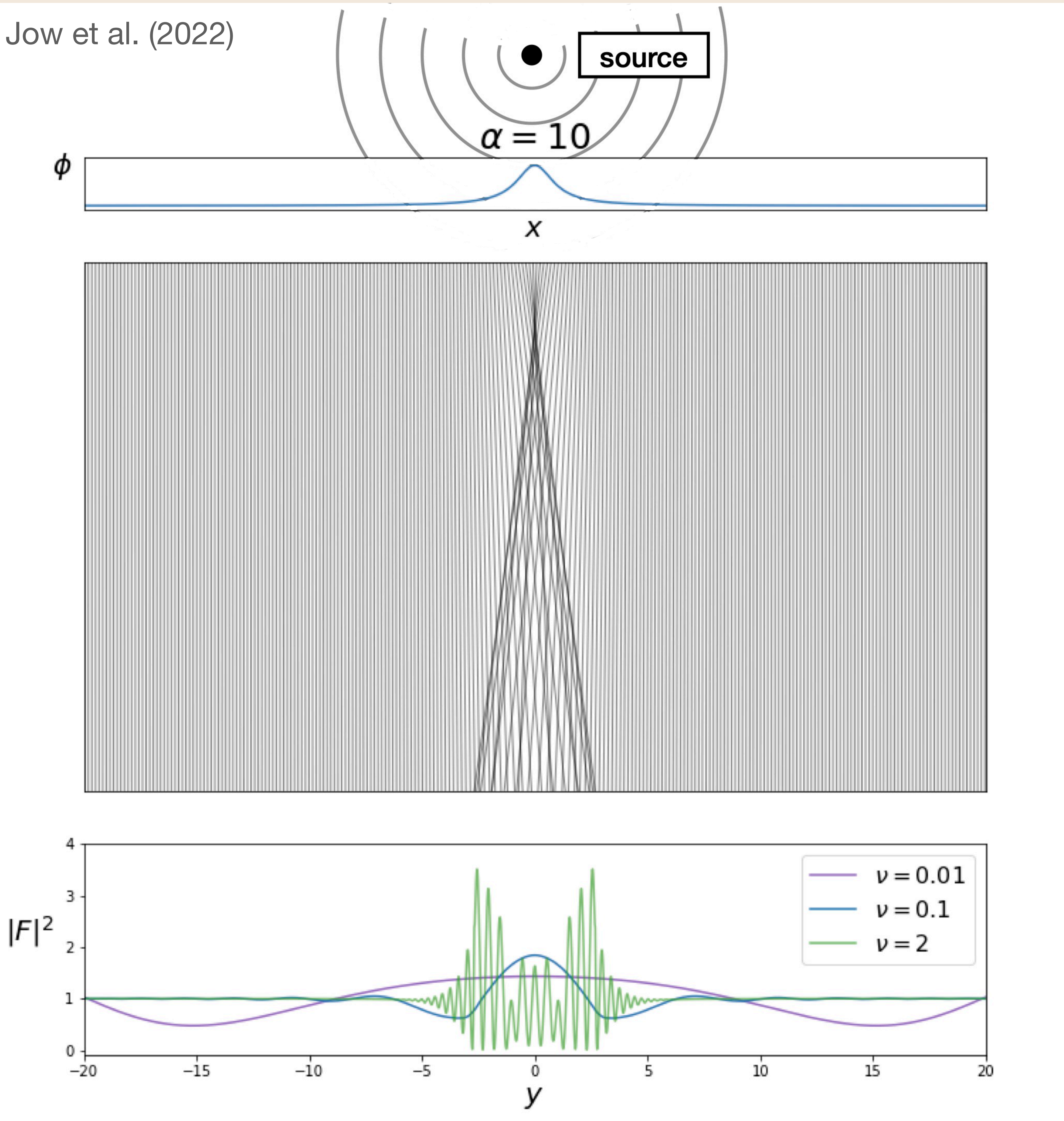
The integrand has constant imaginary part (is non-oscillatory) along the steepest descent contours, J_{z_i}, aka the "Lefschetz thimbles".

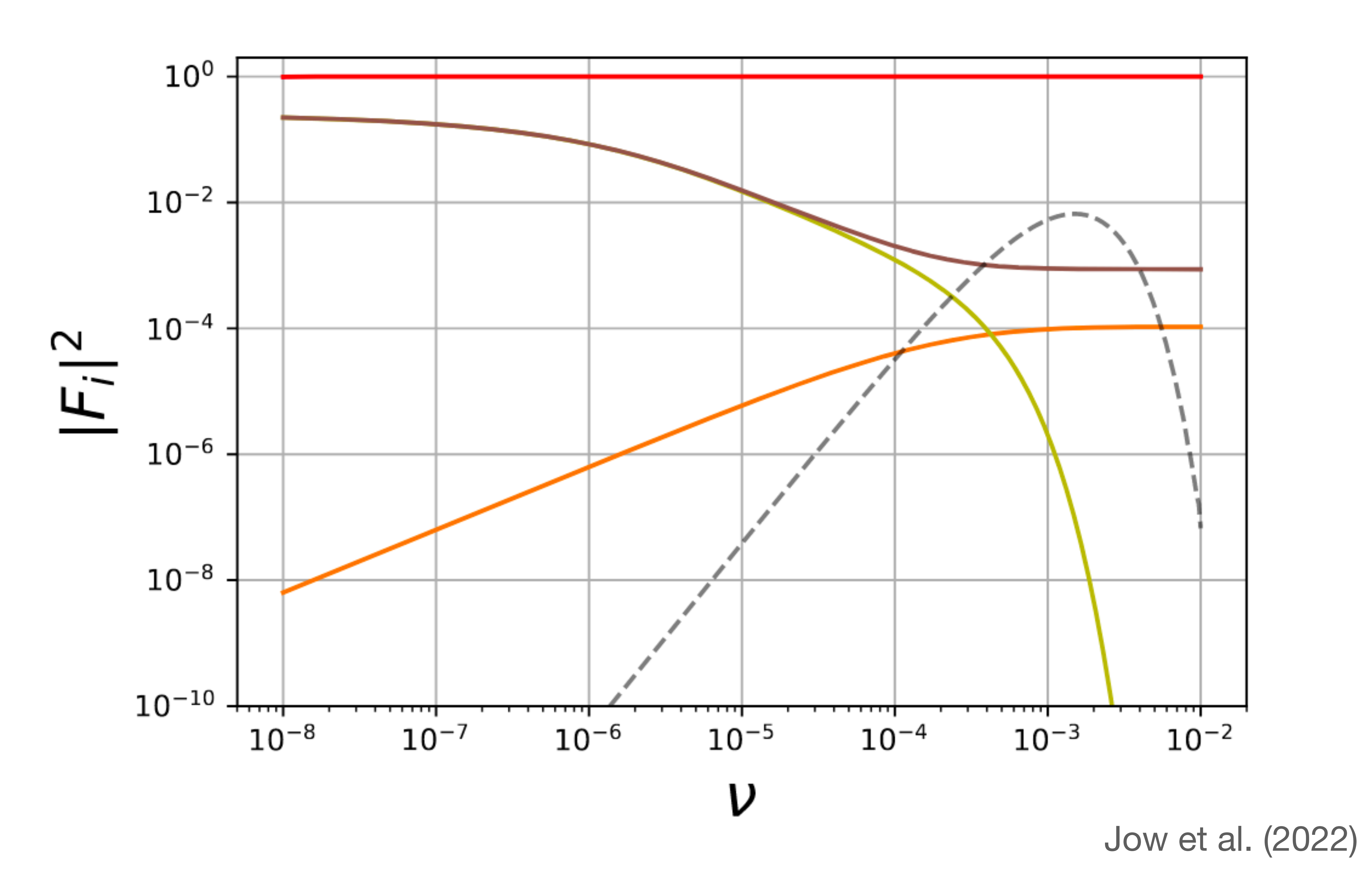
Picard-Lefschetz Theory: A New Tool for Old Problems



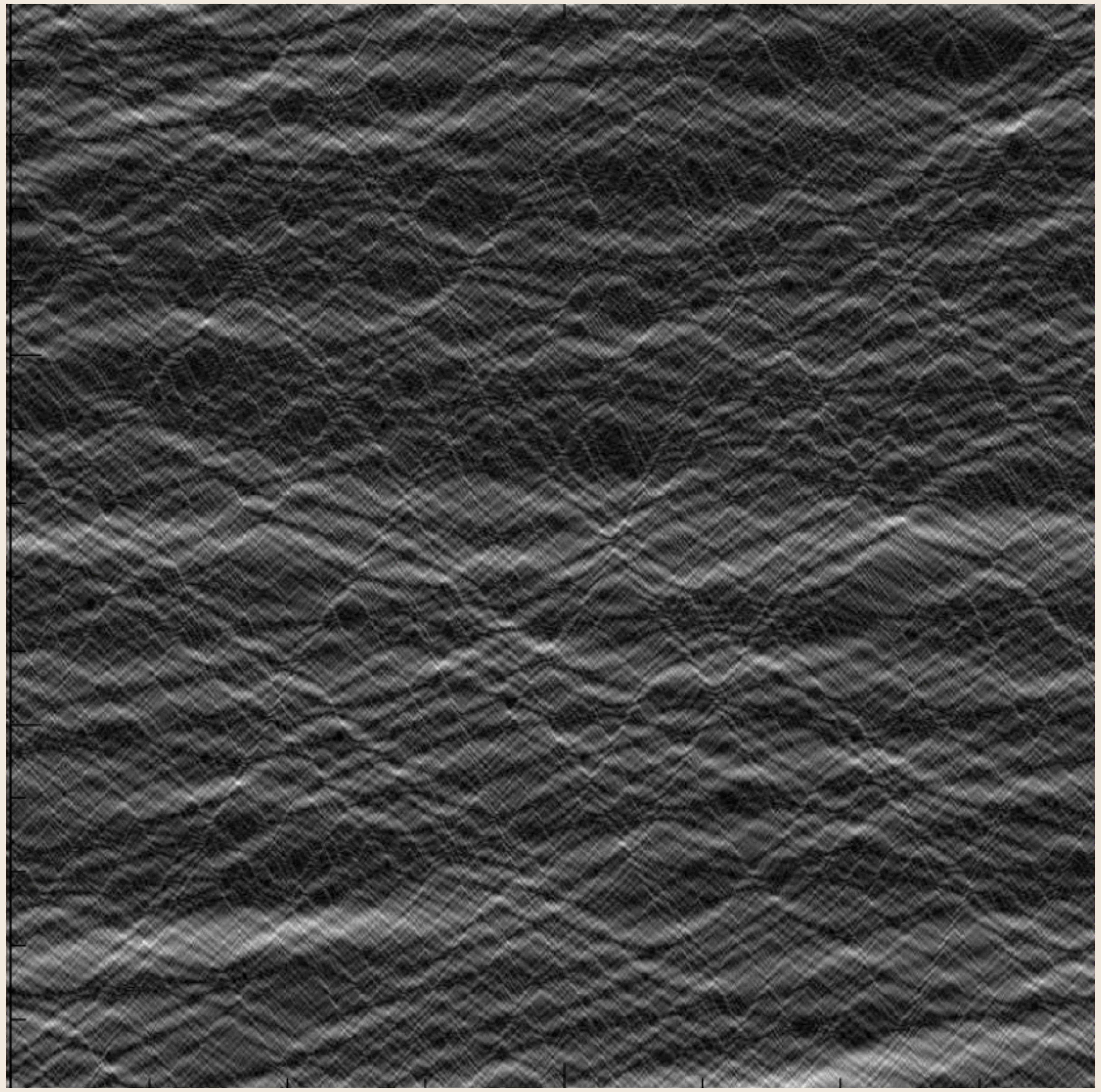
Jow et al. (2021)

Picard-Lefschetz Theory: Bridging the gap between refractive and diffractive optics





Picard-Lefschetz Theory: Bridging the gap between refractive and diffractive optics (Jow et al. (2022))



Pen and Levin (2014)

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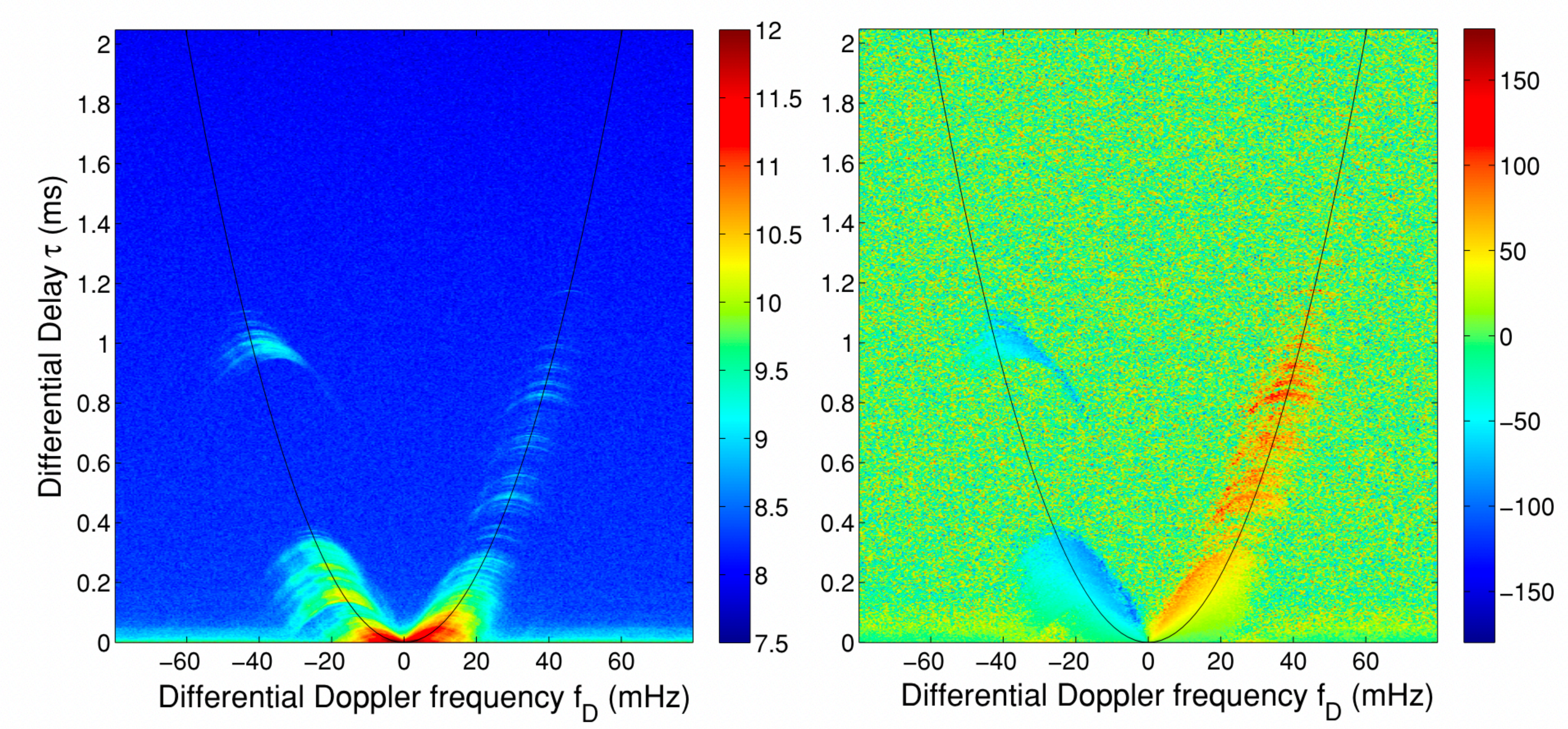
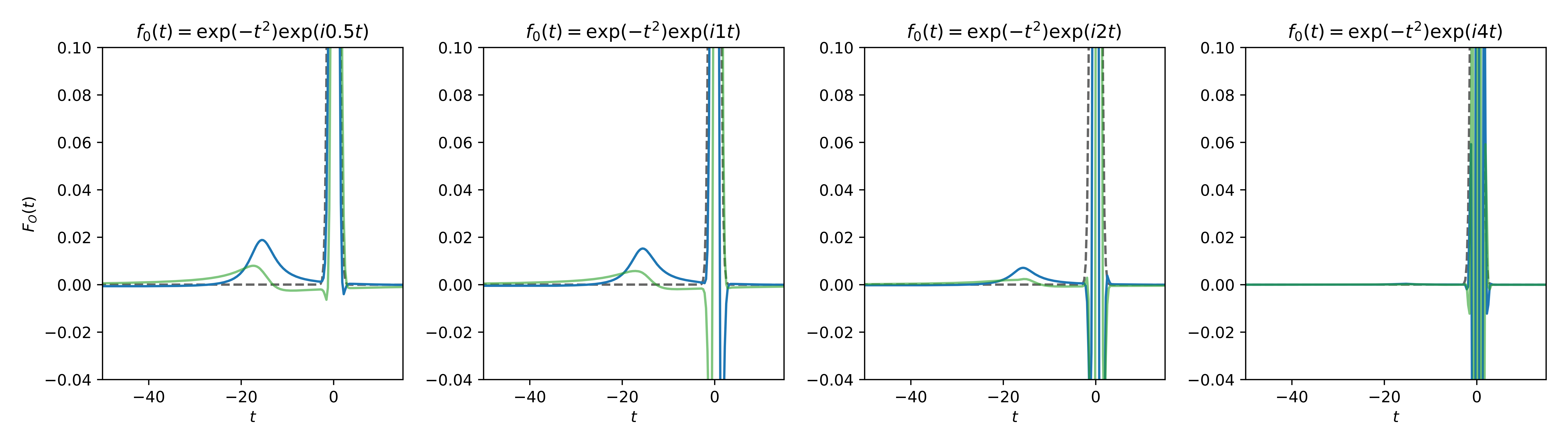
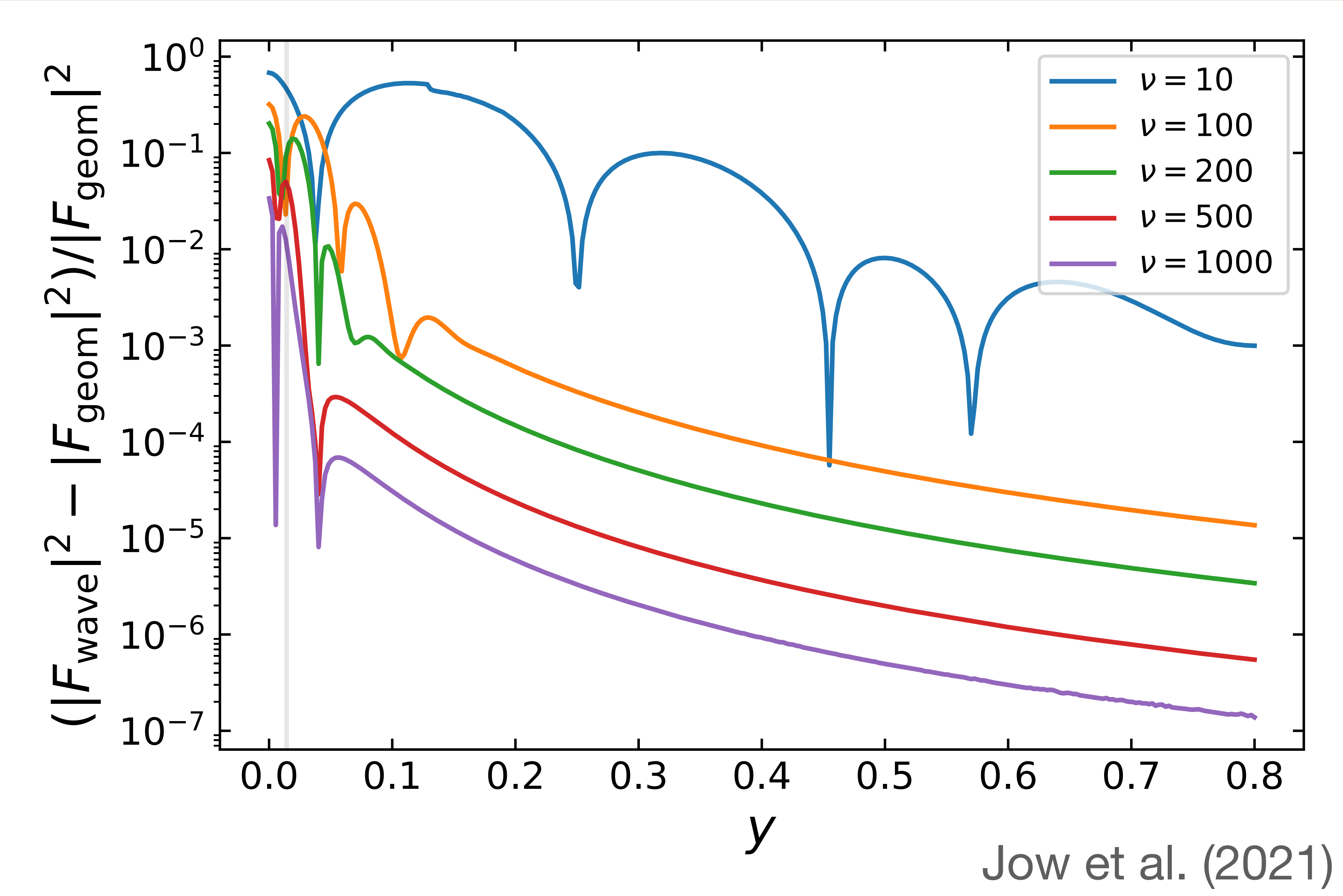


Brisken atl a. (2010)

Picard-Lefschetz Theory: Imaginary Images (Jow et al. (2021))



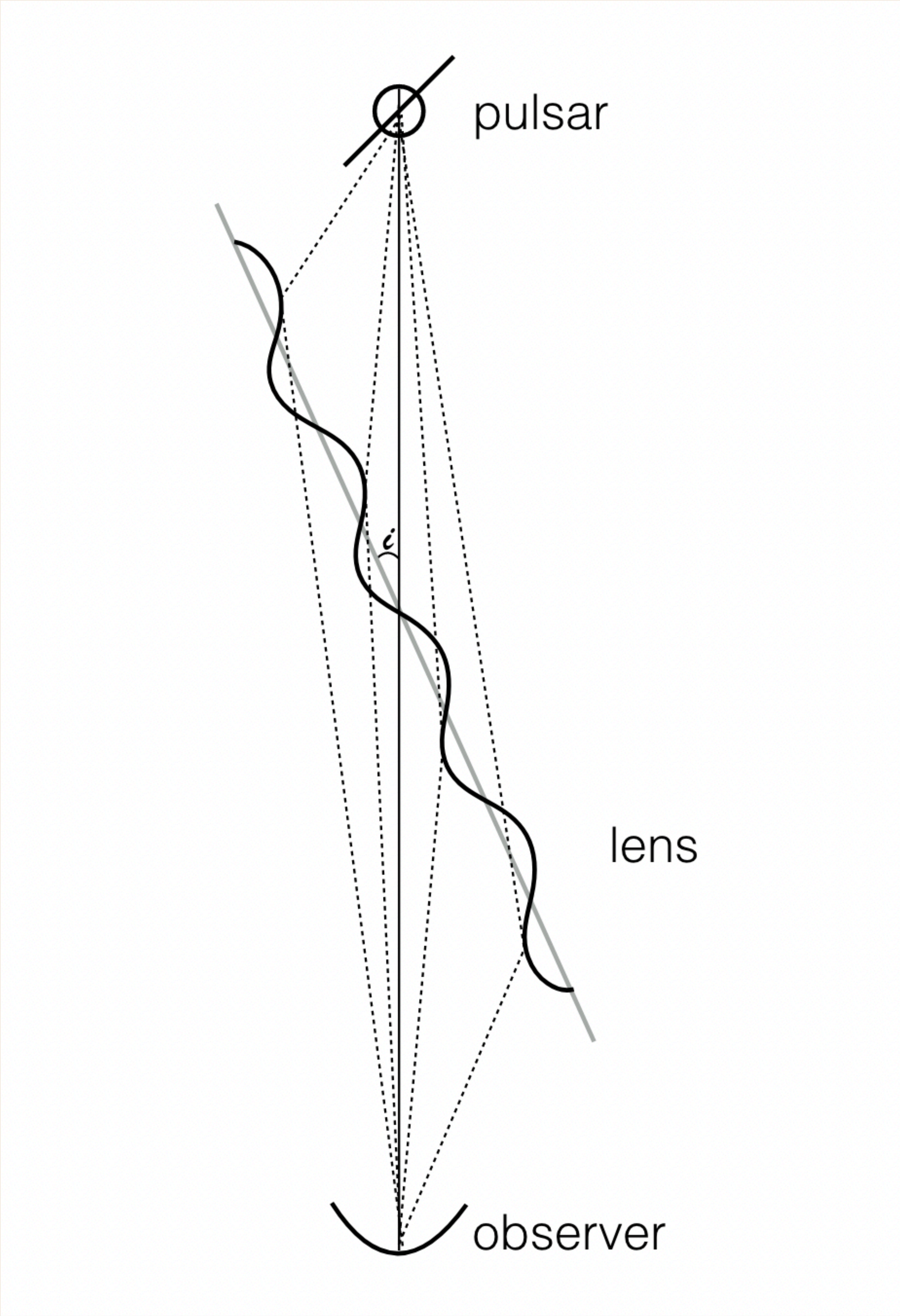


Picard-Lefschetz Theory

- Numerically and conceptually powerful.
- Preserves the image picture of optics, even at low frequency.
- Allows us to exactly compute previously intractable diffraction integrals for a variety of lens models.
- Reveals new, observable effects in coherent lensing.
- Has been used to alleviate the sign problem in lattice QCD. Also has applications in quantum mechanics and quantum cosmology.

Okay, that's nice, but what is actually doing the lensing?

Modelling Pulsar Scattering: Corrugated Sheets

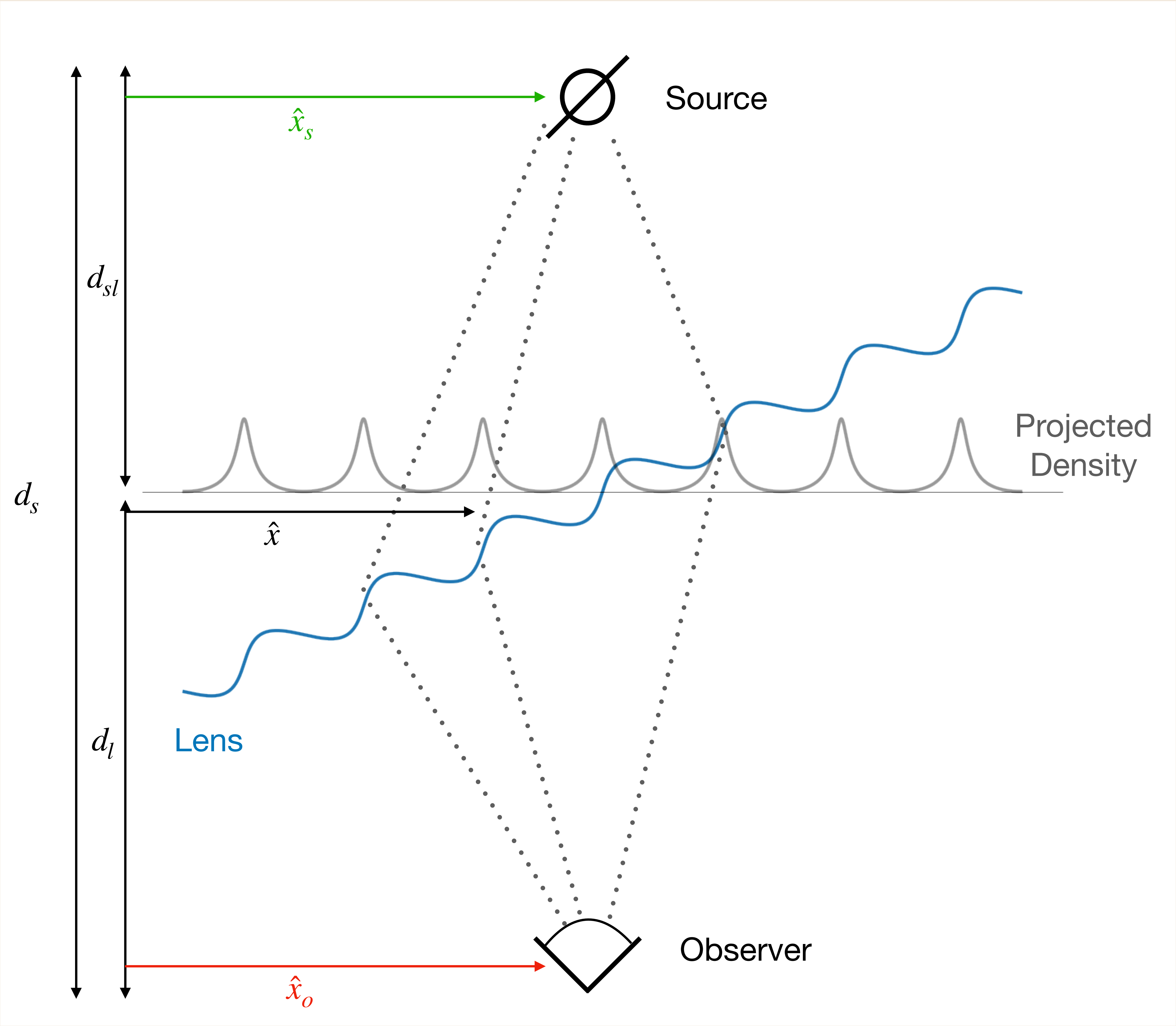


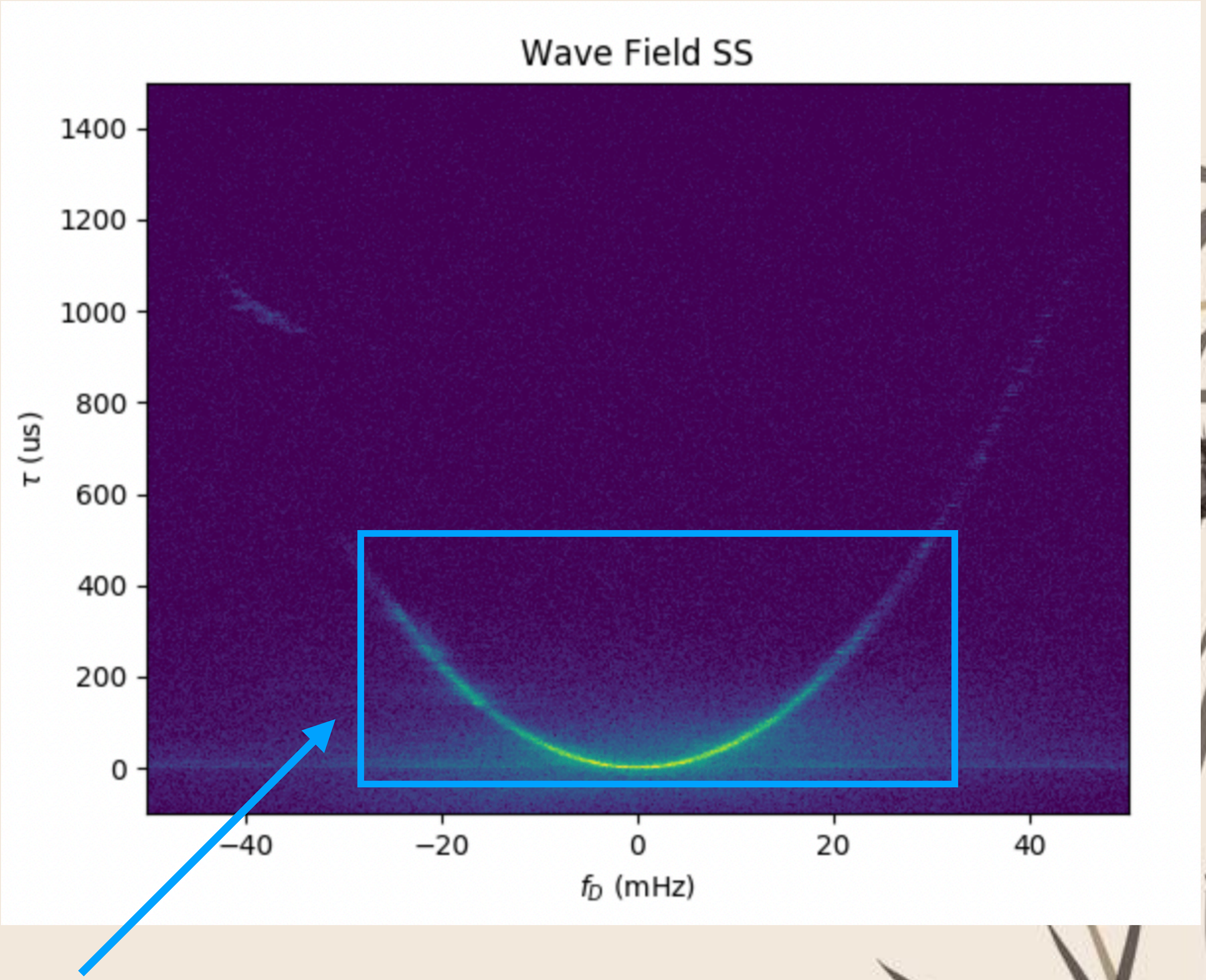
Simard et al. (2018)

Parabolic arcs in pulsar scintillation secondary spectra suggest lensing structures in the ISM dominated by thin, highly anisotropic (refractive) sheets.

What form do these sheets take?

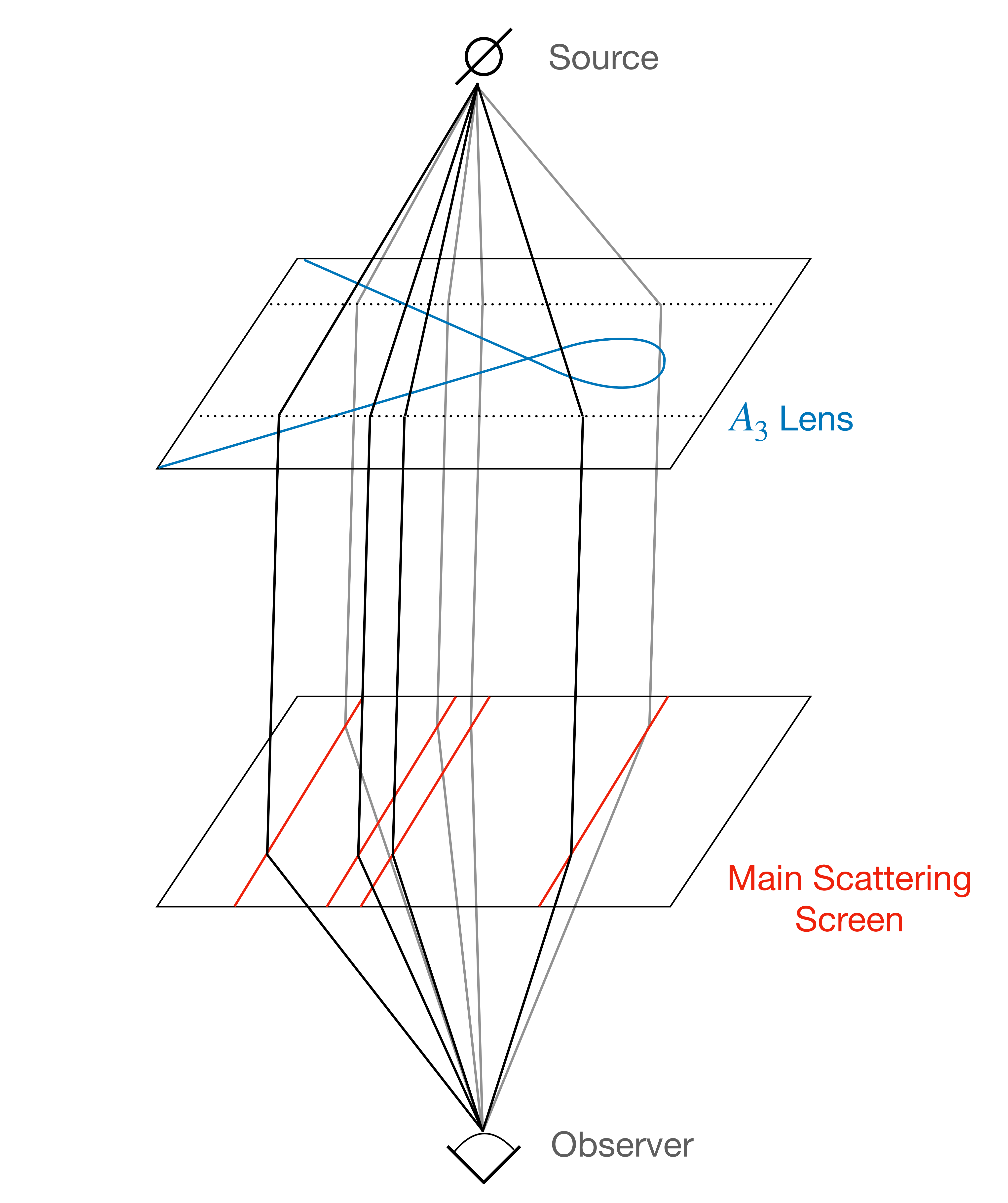
Corrugated sheets: A unified model for pulsar scattering

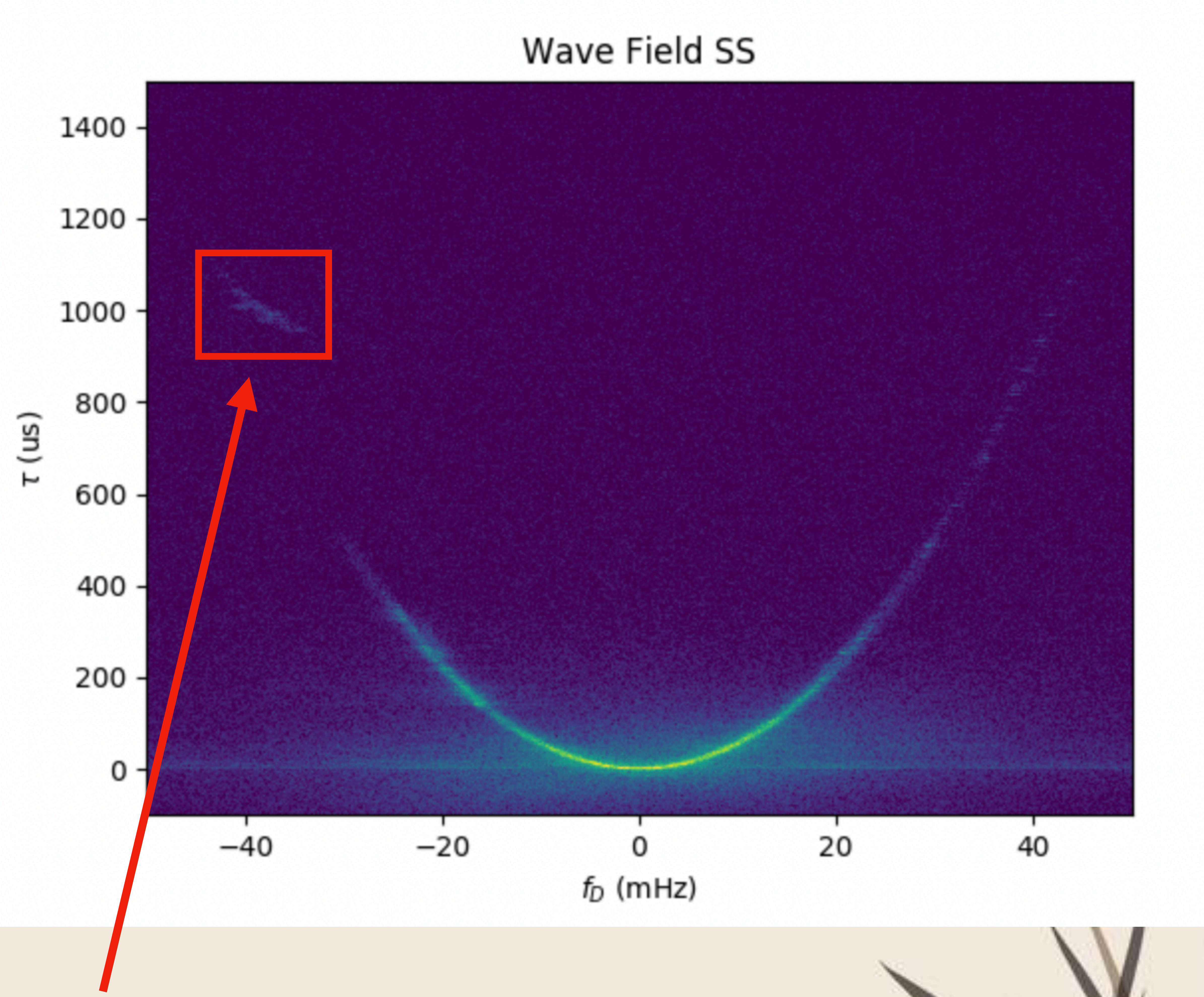




Firstly, we want to explain the ubiquitous appearance of parabolic arcs and inverted arclets in pulsar scintillation secondary spectra

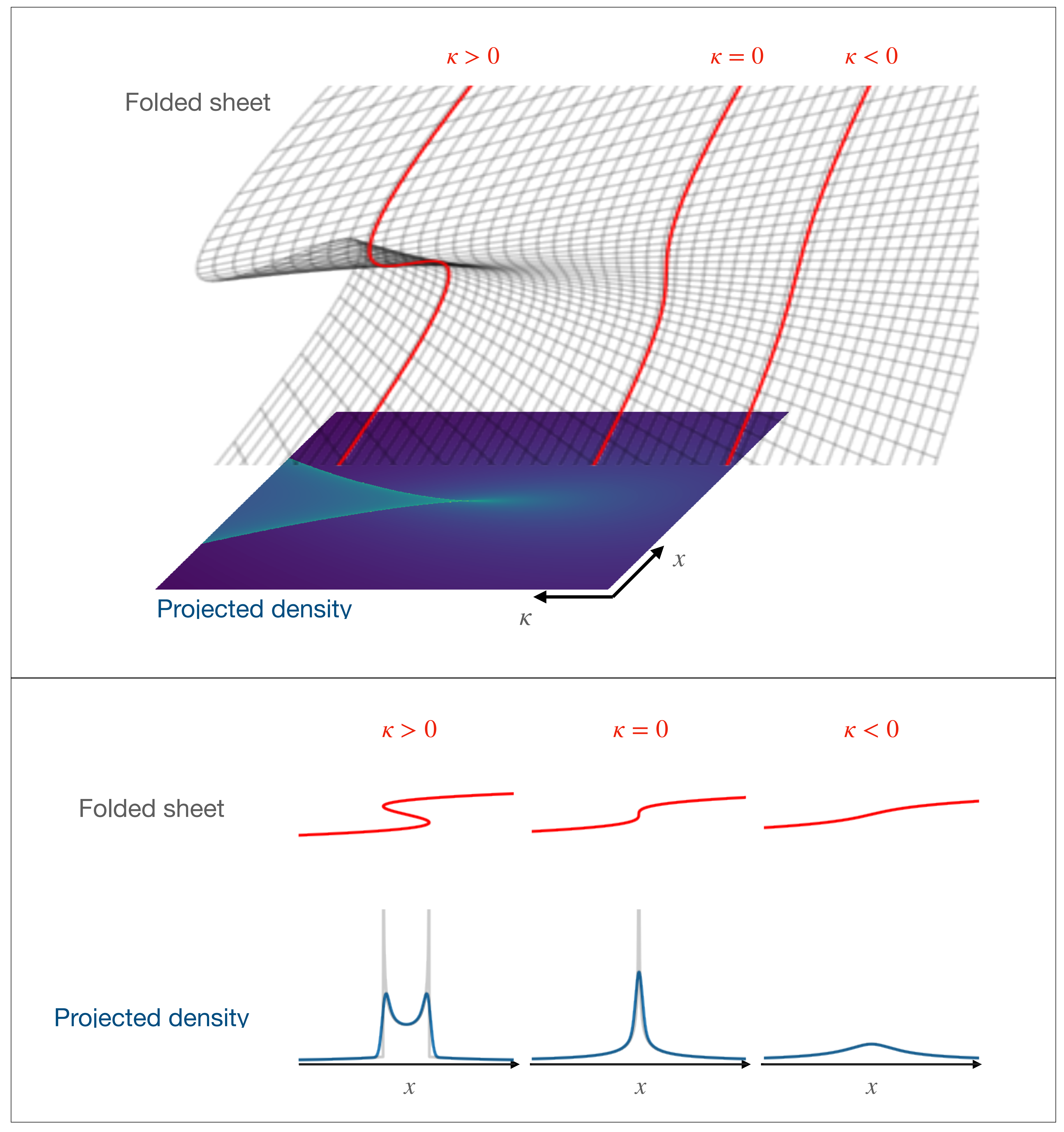
Corrugated sheets: A unified model for pulsar scattering





We also want to explain extreme scattering events (ESEs)

Corrugated Sheets: Cusps of Cusps



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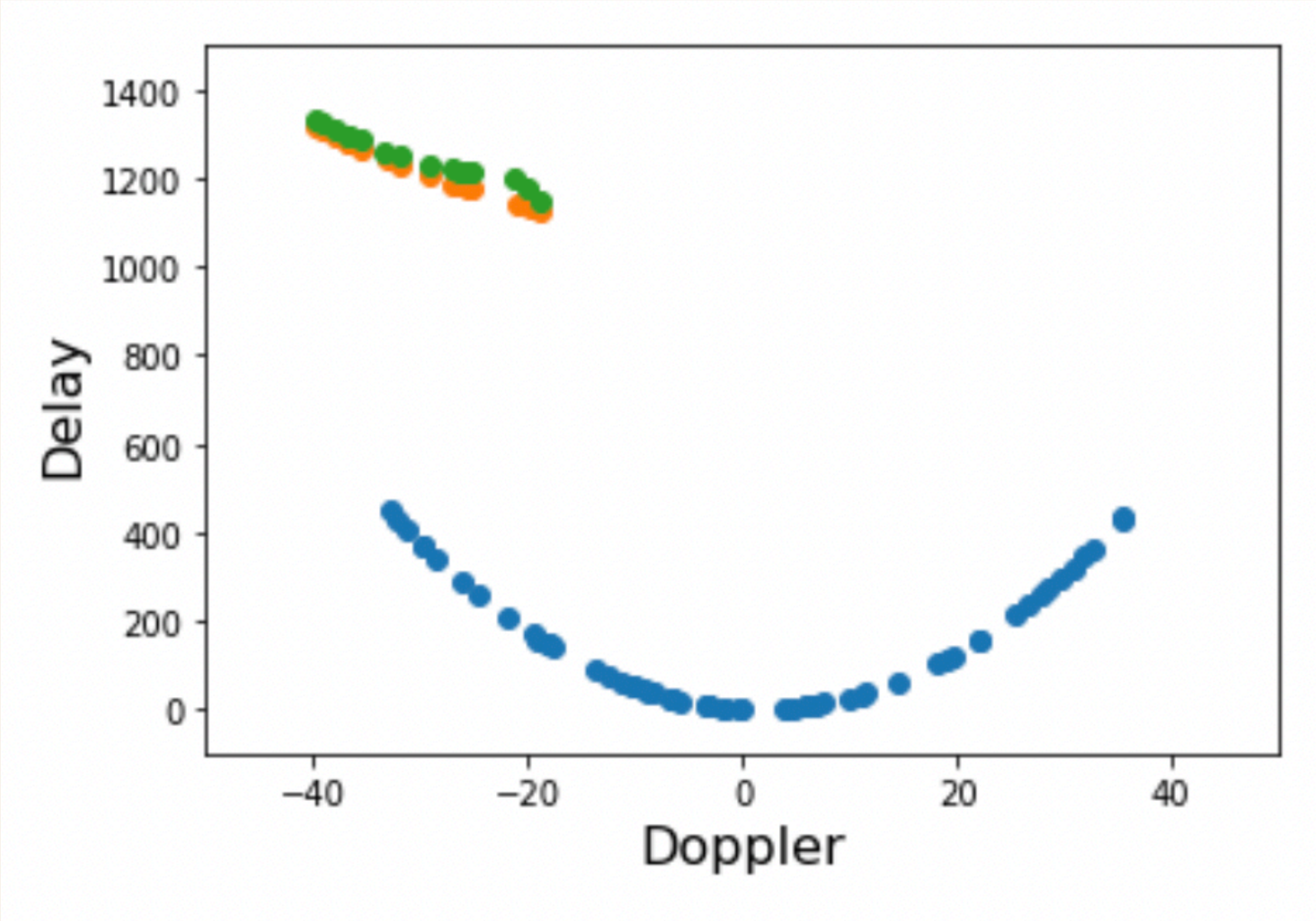

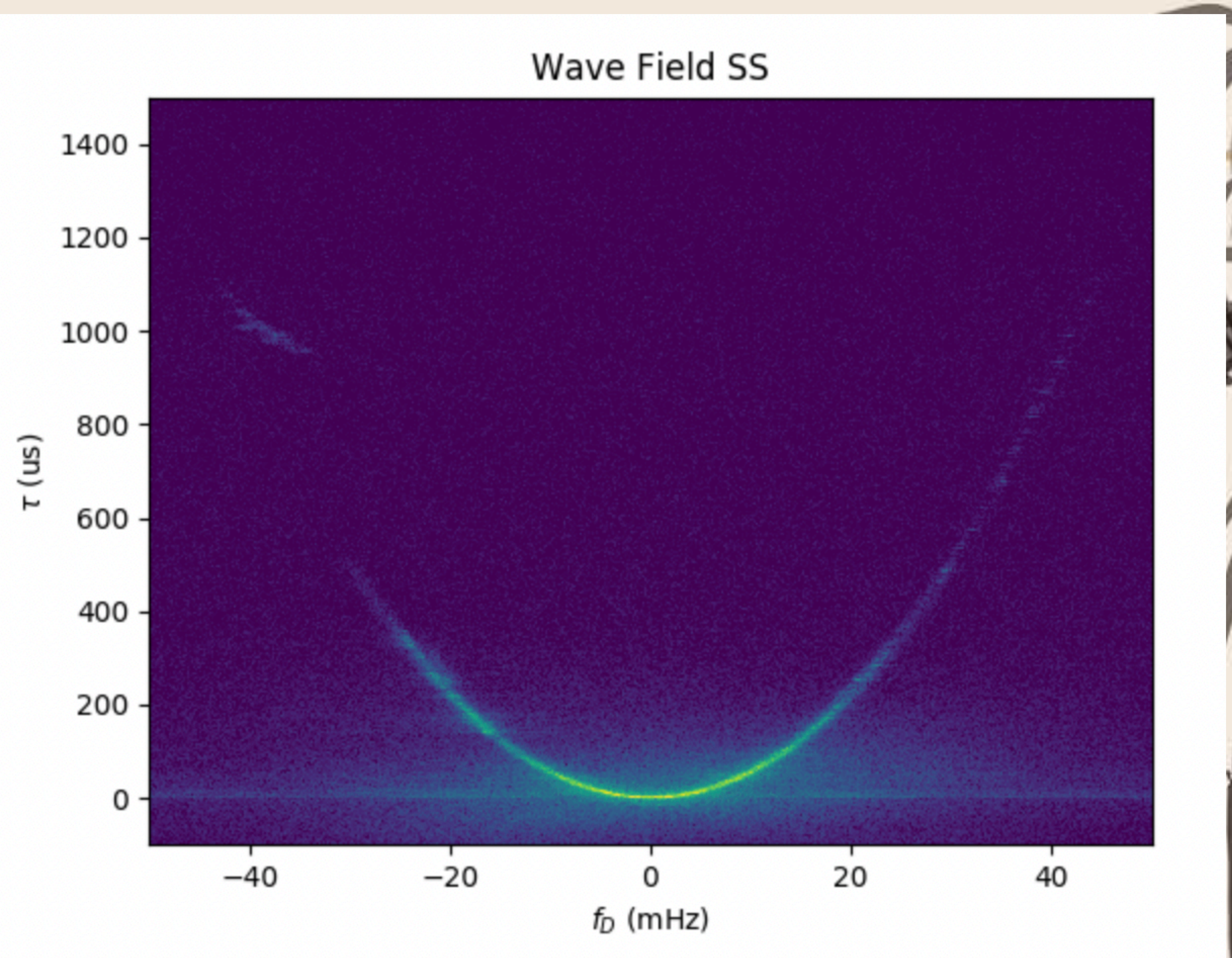

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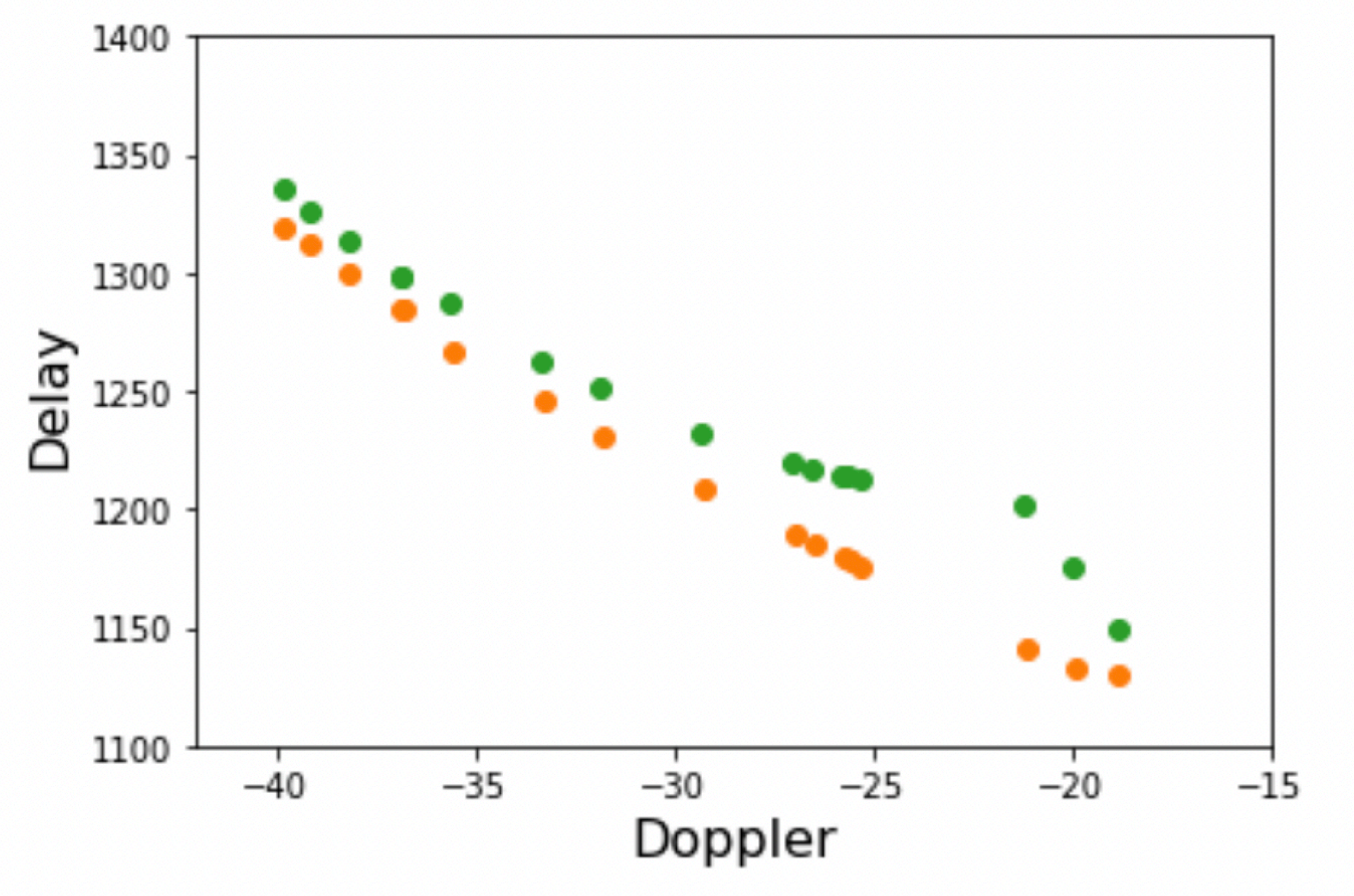
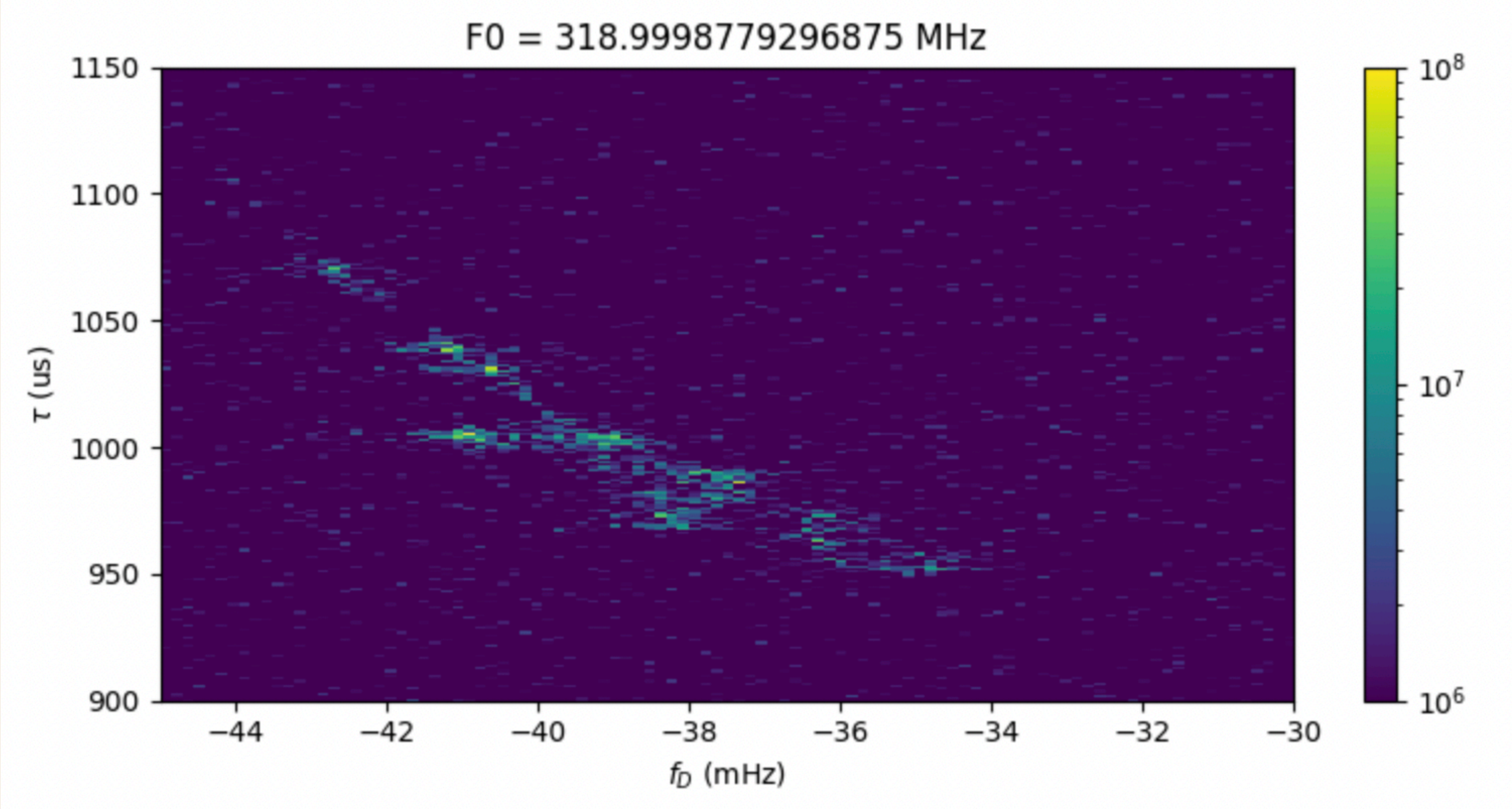
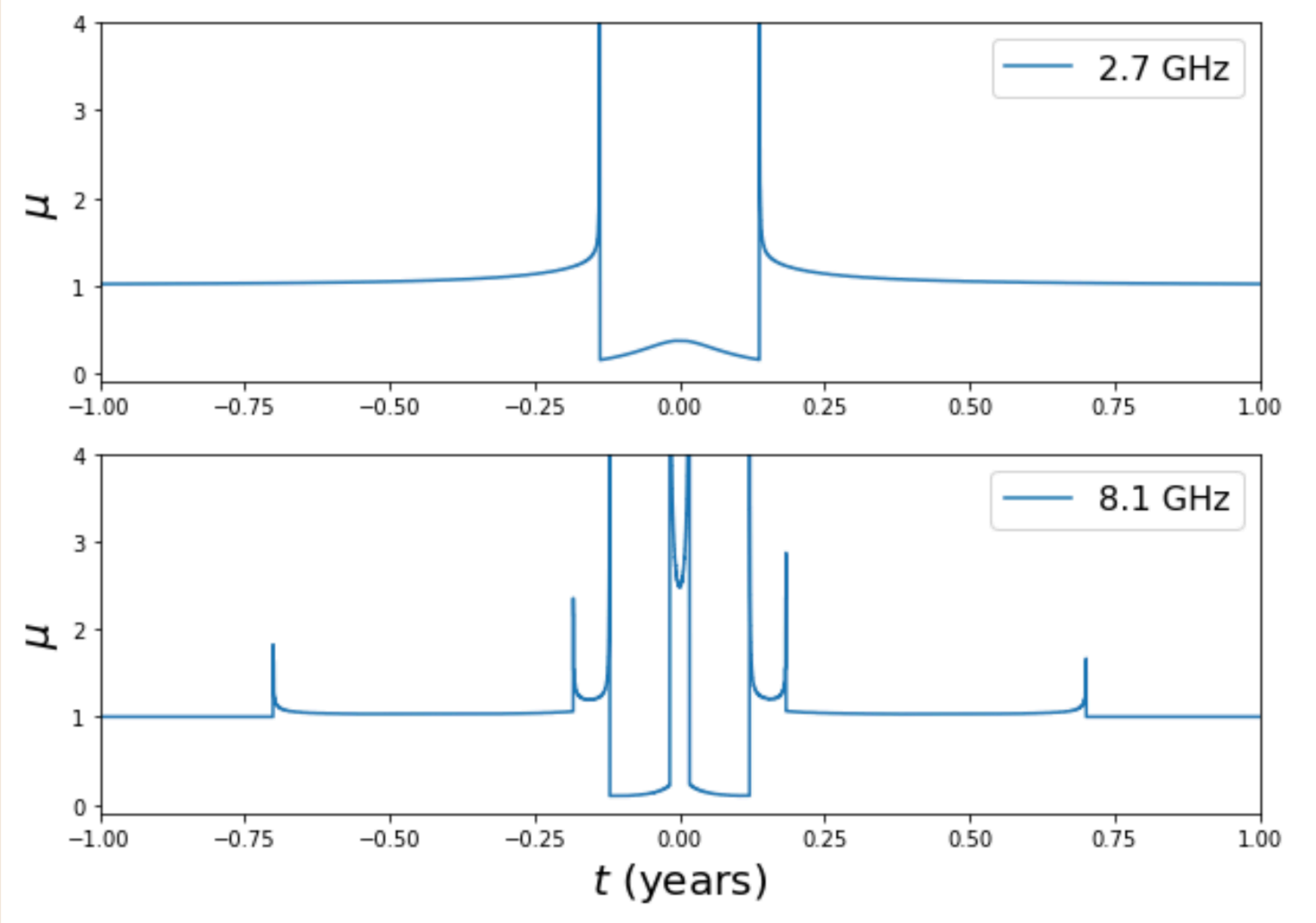
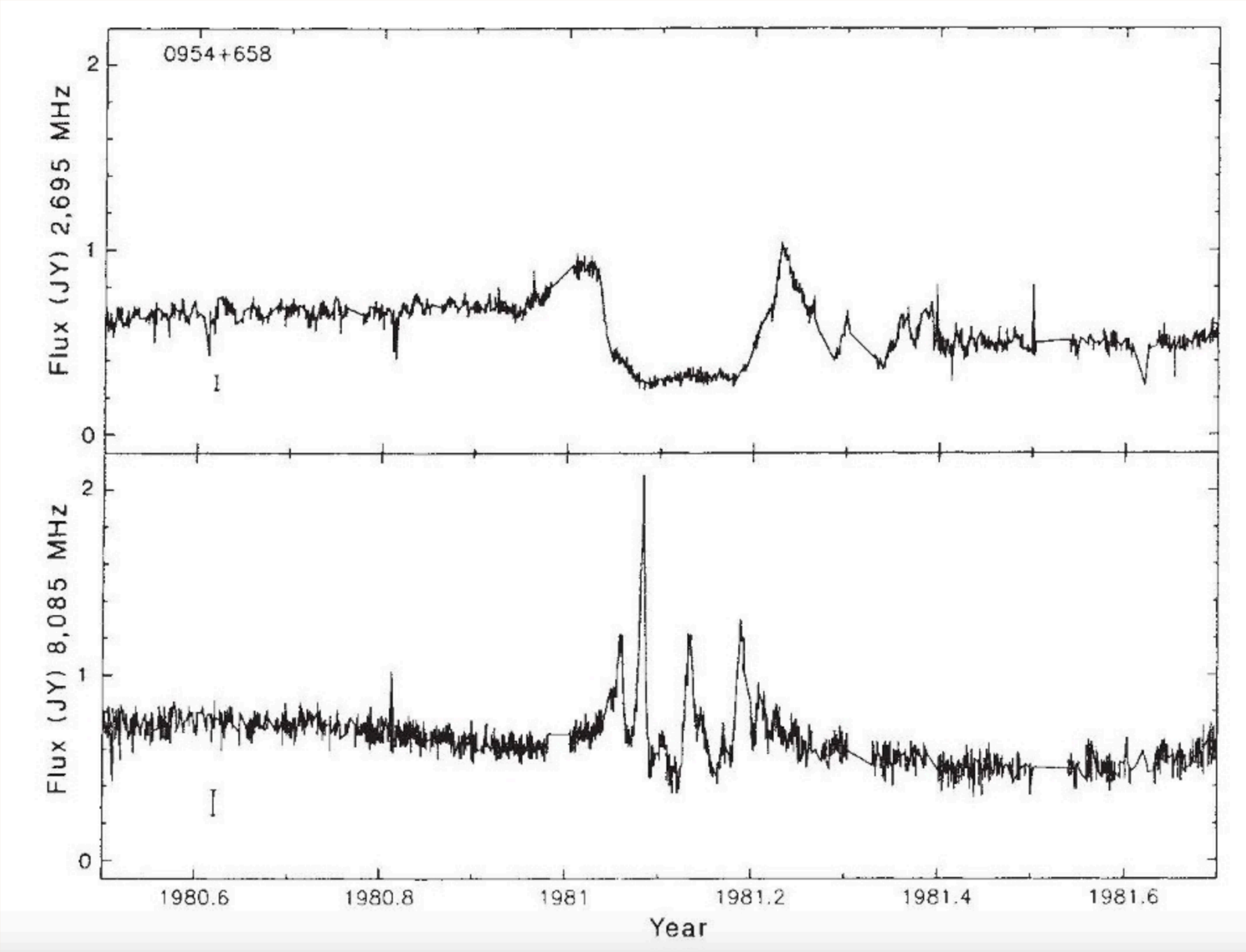




Modelling the Fiedler et al. (1987) ESE with the A_3 Lens

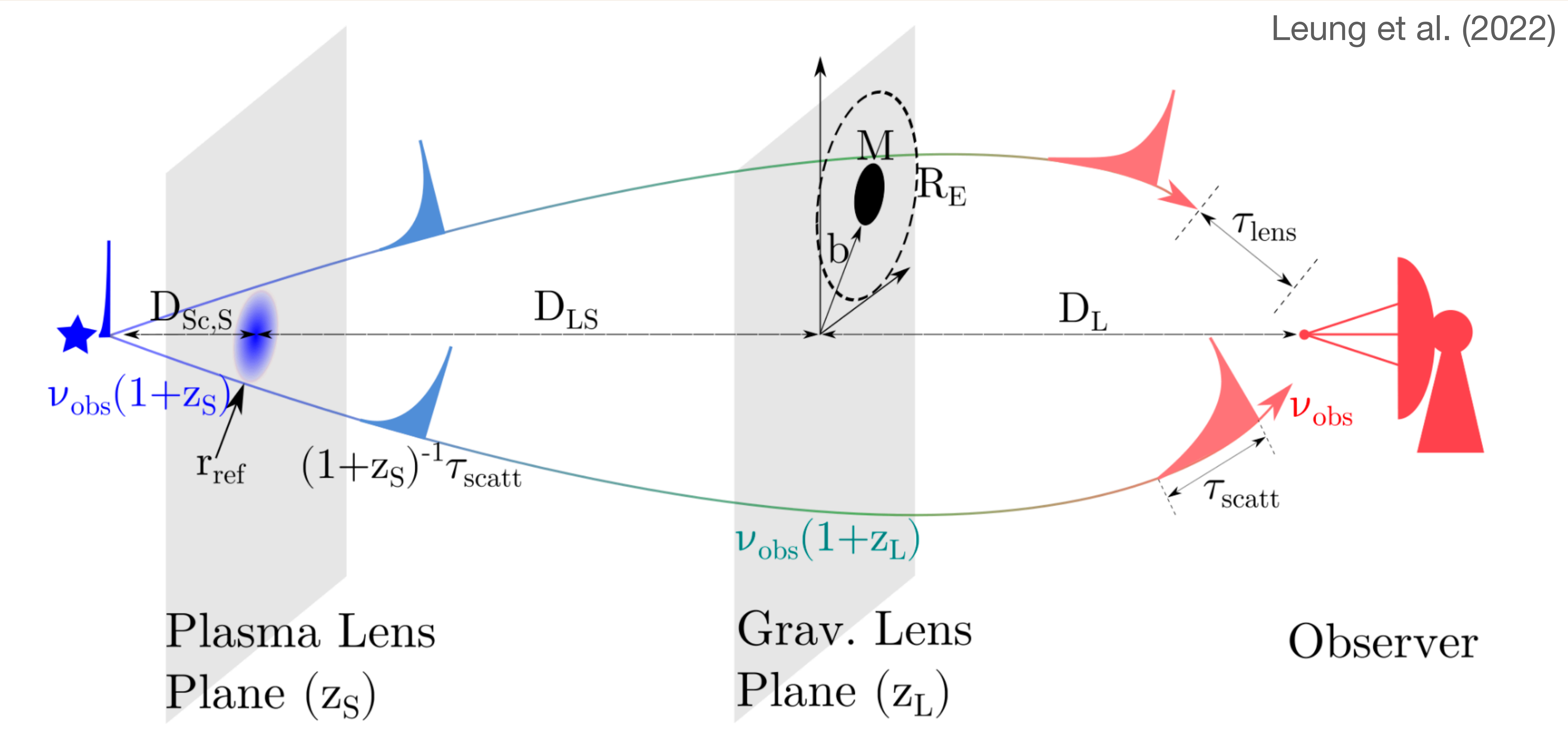




Scattering is good, actually?

- If the cusps-of-cusps model is correct, then the ISM structures that cause extreme scattering events (ESEs) are *universal* and governed by a small number of parameters

- scattering screens create multiple images that may be used to measure distances



Summary of FRB and pulsar lensing

- The coherent nature of FRBs allows for gravitationally lensed FRBs to be used as competitive cosmological probes, but scattering off of plasma in host galaxies and the Milky Way may limit their effectiveness.

- The study of pulsar scintillometry in recent decades has revealed new insights into scattering structures in the ISM. This insight is directly applicable to scattering of FRBs.

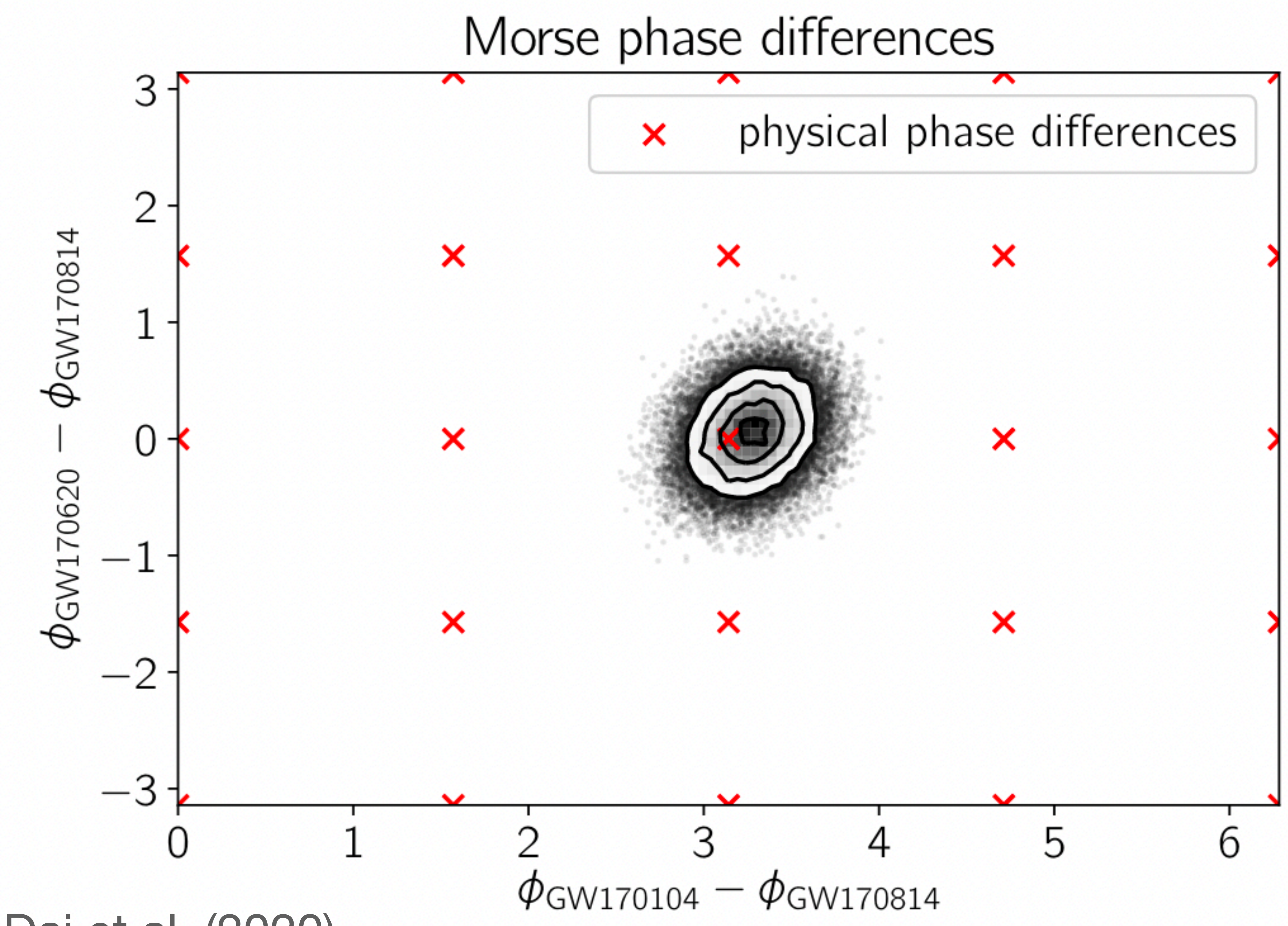
- New models of pulsar scintillation may provide a universal framework for analyzing scattering events.

- However, significant theoretical challenges remain to be addressed. New techniques (Picard-Lefschetz theory) make it possible to answer these questions.

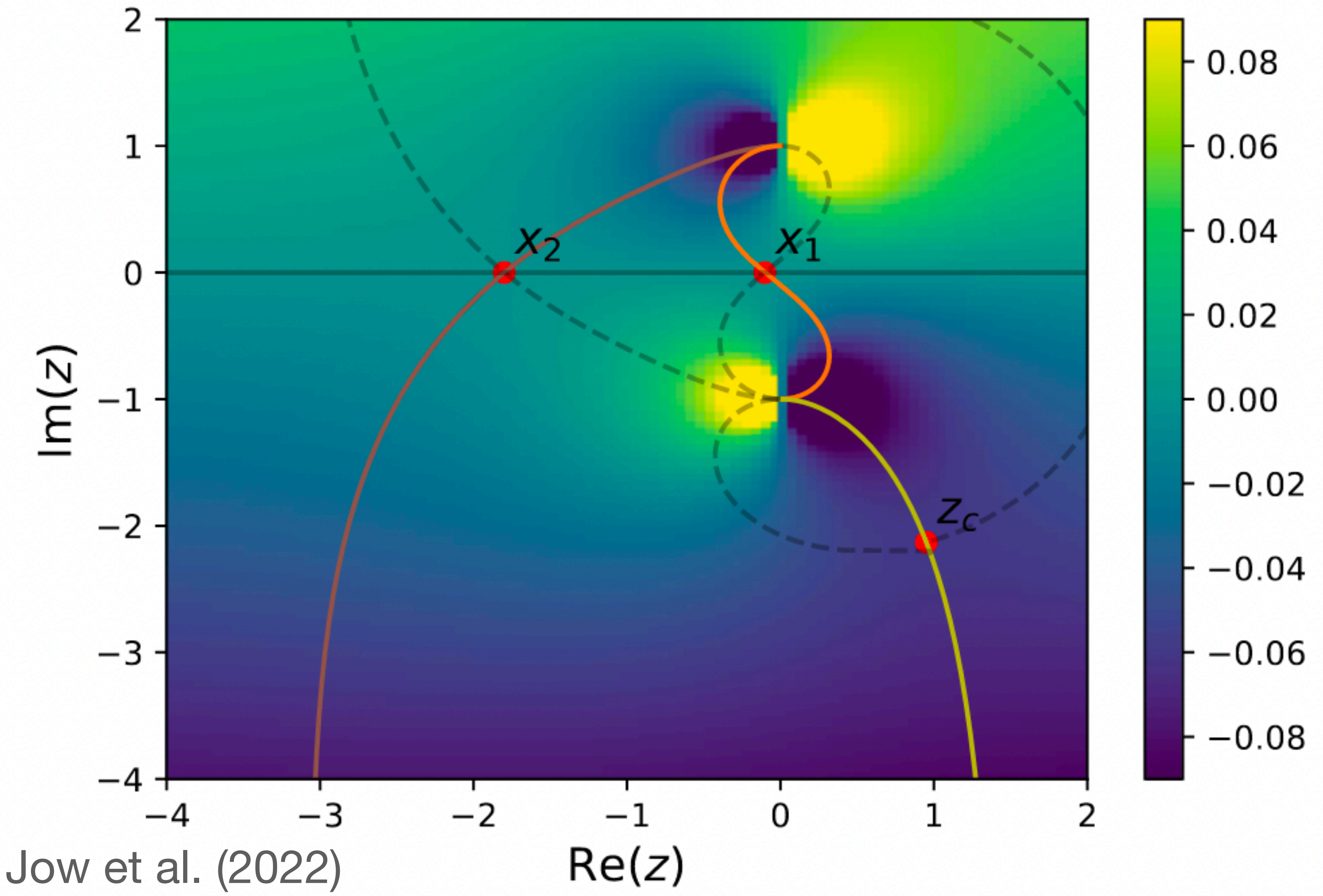
- These theoretical questions are directly relevant to observational data now and in the immediate future.

Gravitational Waves

Optimizing GW lensing detections: Morse phase

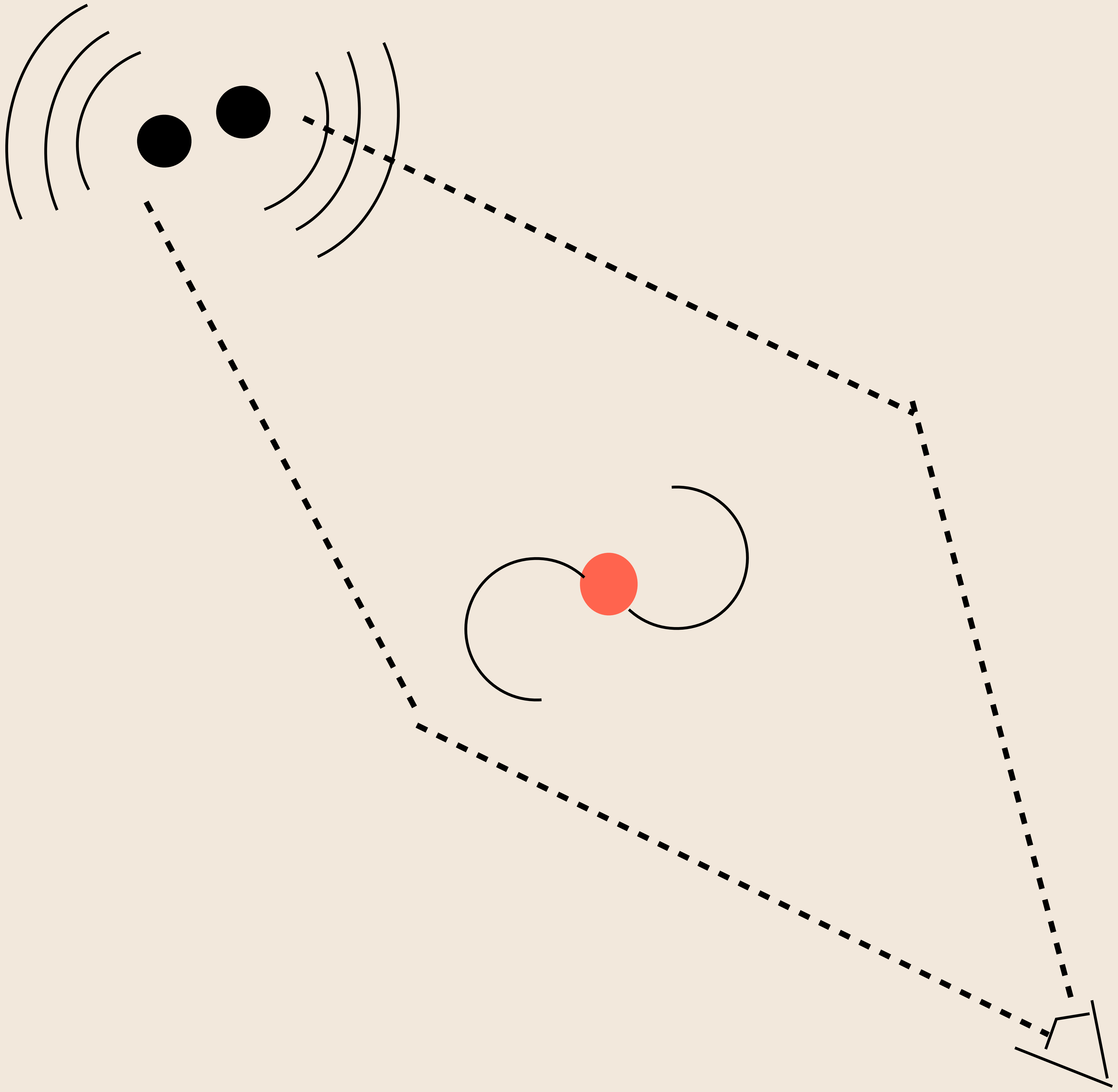


Dai et al. (2020)



Jow et al. (2022)

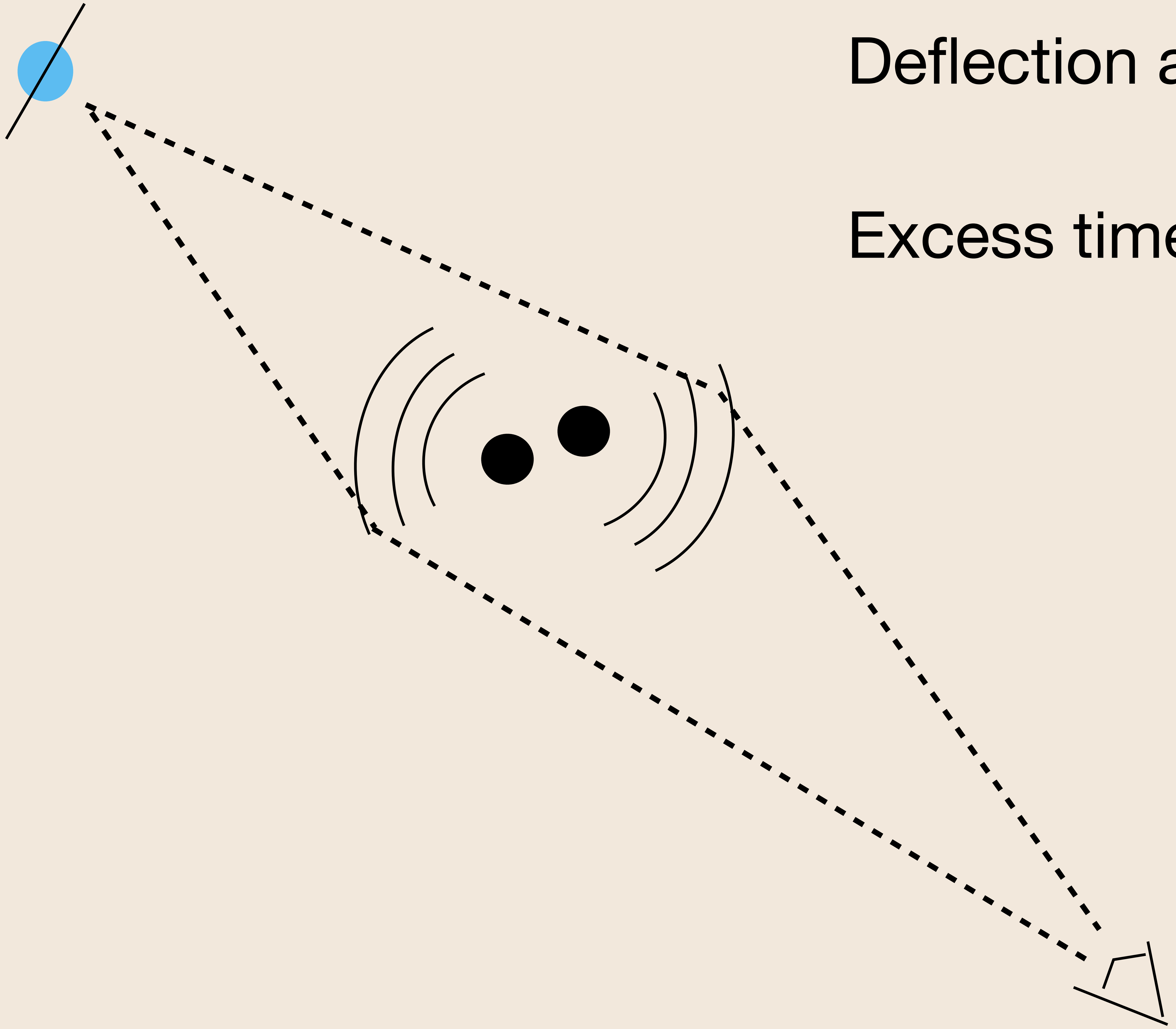
Imaging GWs: Lenses as Interferometers



$$\theta \sim \frac{\lambda}{l} \sim \frac{c}{1\,\mathrm{Hz}\;1\,\mathrm{kpc}} \sim \mu\mathrm{as}$$

$$\theta D \sim \mu\mathrm{as} \cdot \mathrm{Mpc} \sim \mathrm{AU}$$

Detecting GWs: FRBs lensed by LISA binaries



Deflection angle: $\theta \sim \theta_E(1 + 10^{-13})$

Excess time delay: $\Delta\tau \sim 10\,\mathrm{ns}$

Summary

- There is a lot of new data coming down the pipeline for coherent sources (FRBs, pulsars, GWs)

- The coherence of these sources present unique opportunities to advance science objectives across multiple domains (e.g. FRB cosmology, ISM, GW astronomy)

- Picard-Lefschetz theory allows us to model coherent lensing in ways we have not been able to before

Modelling Pulsar Scattering: Refractive turbulence in the ISM