Title: Cusps of cusps: a universal model for extreme scattering events in the ISM

Speakers: Dylan Jow

Series: Cosmology & Gravitation

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Abstract: Since the 80s, radio sources have been observed to undergo extreme scattering events (ESEs): large, frequency dependent flux modulations due to scattering off the ISM. Recently, the study of these events has undergone a revived interest due to the increase in pulsar timing data, as well as the realization that FRBs will be scattered by the same structures in the ISM. Models of the structures responsible for ESEs range from spherical-cow approximations (e.g. simple Gaussian profiles) to more exotic models (e.g. plasma shells around compact dark matter). Here we present a new model in which ESEs are produced by corrugated sheets in the ISM, which, when projected onto the plane of the sky, generically form A3 cusp catastrophes. We will argue that this model naturally explains several features in scattering data, including observations of PSR 0834+06 and the original Fiedler et al. 0954+658 ESE. Moreover, this model is consistent with models of pulsar scintillation and does not require exotic physics to explain. We will discuss potential applications to FRB cosmology that arise from the universality of this model.

Zoom link: https://pitp.zoom.us/j/94260081028?pwd=Vm8zVUd5ak1saWJYZFZ3MWF0L3g2dz09

Cusps of cusps: a universal model for extreme scattering events in the ISM

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Collaborators:
Ue-Li Pen
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Overview

- Observational context

  Extreme scattering events
  Pulsar scintillation

- Theoretical context
- Doubly catastrophic lensing

  Corrugated sheet model
  Physical motivation

- Modelling data with the A_3 lens
- Potential applications of the A_3 lens

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Observational Context: Three Decades of ESEs

- Extreme Scattering Events (ESEs):

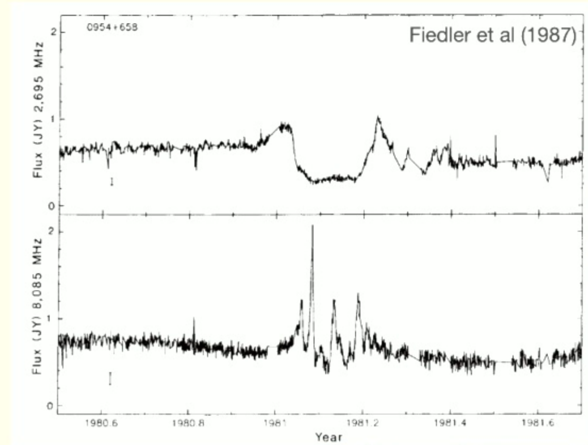
  Large modulations in flux over ~ month long periods due to scattering in the ISM. Observed in quasars and pulsars.

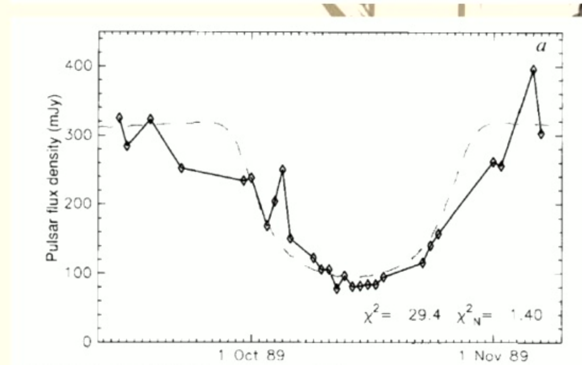
- ESEs are not rare: duty cycle for pulsars ~ 0.01

- Recently renewed interest in explaining ESEs:

  - FRBs are expected to be lensed by the same scattering structures. Implications for FRB cosmology.

  - Large variations in scattering time have implications for pulsar timing arrays.





Cognard et al. (1993)

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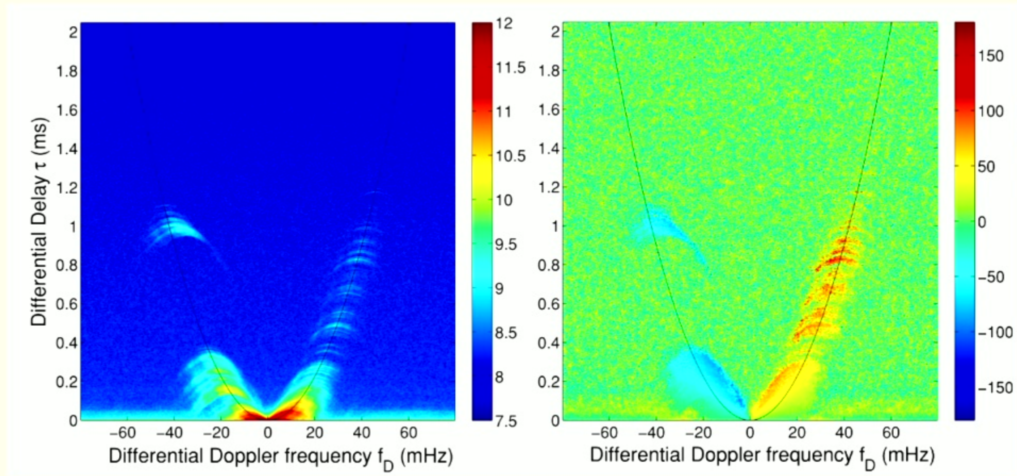
Observational Context: Pulsar Scintillation

- The origin of pulsar scintillation also remains a mystery.
- How do these two phenomena relate to each other?



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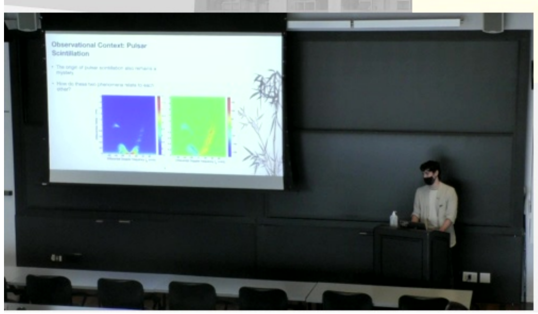


(Aside) Secondary Spectra

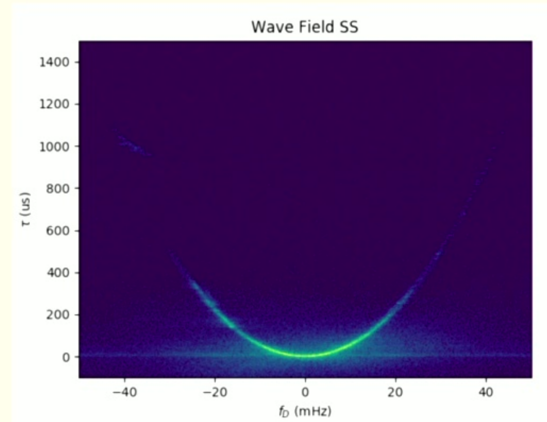
Conjugate wave-field:

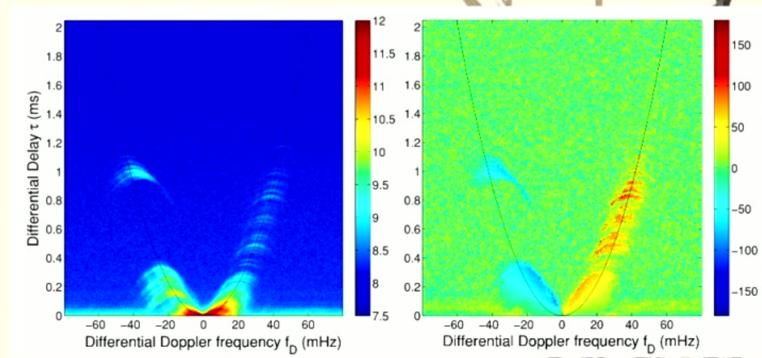
$$V(t,f) \sim \sum_i e^{ifT_i} \implies$$

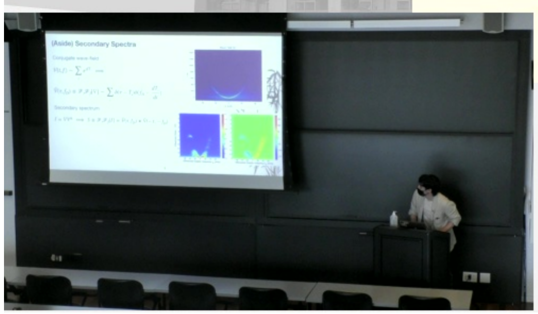
$$\tilde{V}(\tau, f_D) \equiv \mathcal{F}_t \mathcal{F}_f[V] \sim \sum_i \delta(\tau - T_i)\delta(f_D - \frac{dT_i}{dt})$$

Secondary spectrum:

$$I = VV^* \implies S \equiv \mathcal{F}_t \mathcal{F}_f[I] = \tilde{V}(\tau, f_D) \star \tilde{V}(-\tau, -f_D)$$







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Theoretical Context

- Many phenomenological models (e.g. diverging Gaussian lenses).
- Over-pressure Problem: assumptions of spherical symmetry lead to inferences of $N_e \sim 10^3\,\mathrm{cm}^{-3}$ / $T \sim 10^4\,\mathrm{K}$.
- Frequency dependence is difficult to model.

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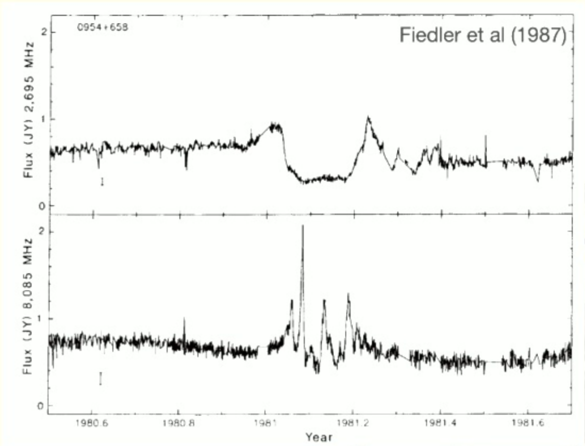

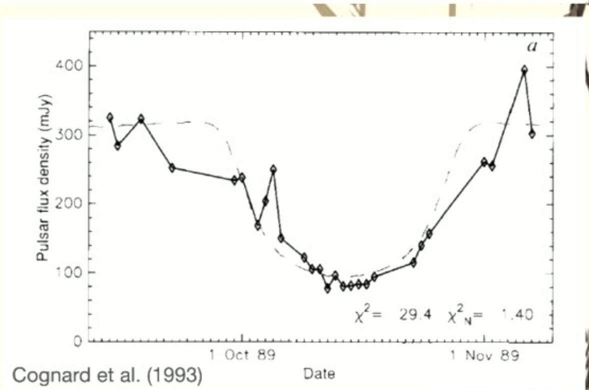

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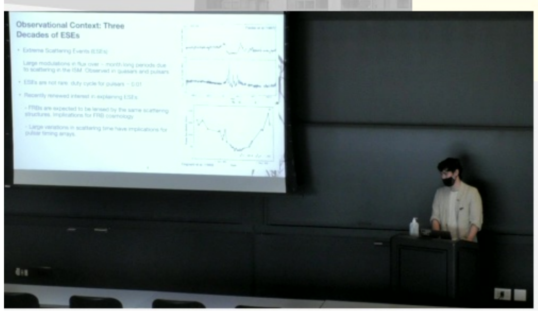

Theoretical Context: A Multitude of Physical Models

- Kolmogorov turbulence in the ISM
- Ionized "skin" surrounding compact, neutral clouds responsible for dark matter (Henriksen and Widrow (1995), Walker and Wardle (1998))
- Folded magnetic reconnection sheets in the ISM (Goldreich and Sridhar (2006), Pen and Levin (2014))
- Molecular clumps in the local environment of hot stars (Walker et al. (2017))

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Theoretical Context: Goals

A good model for ESEs should ideally achieve the following:

- Solve the over-pressure problem (thin sheets)
- Accurately model ESEs across frequencies
- Explain the origin of both ESEs and pulsar scintillation
- Provide a simple framework for analyzing scattering events that is governed by a small number of parameters.

8

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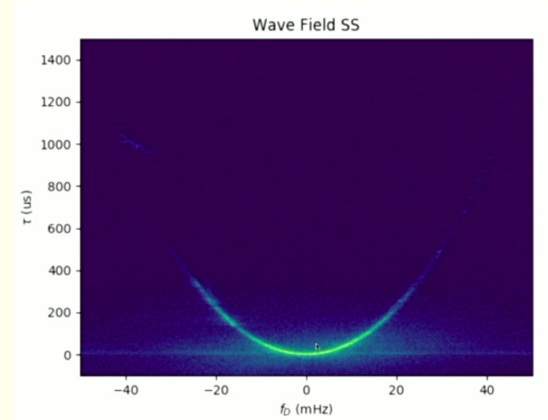

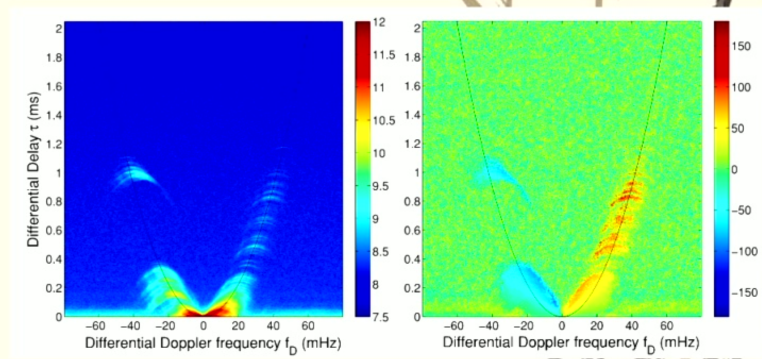

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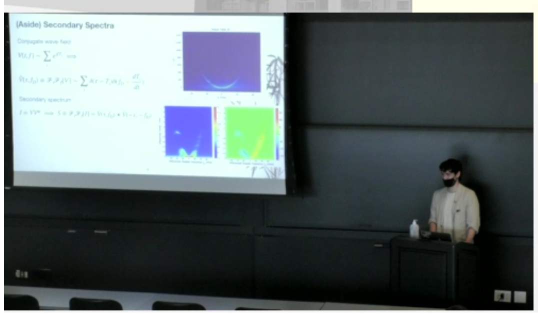

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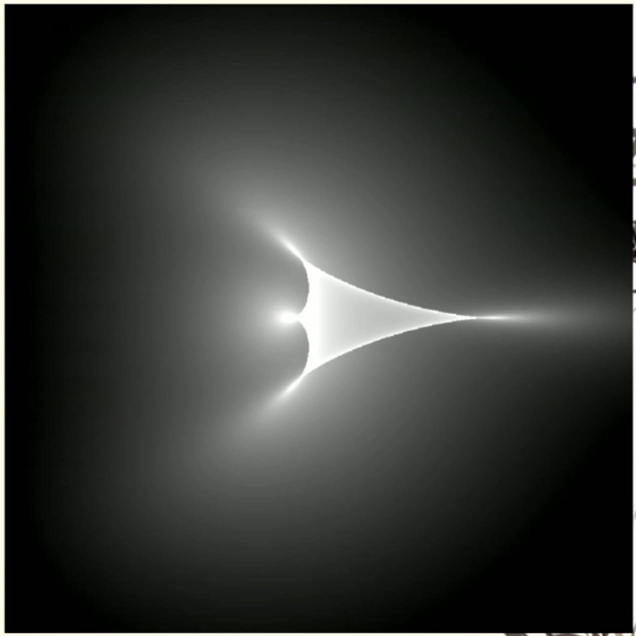
Proposed Model: Doubly Catastrophic Lensing

- Catastrophes naturally arise in lensing theory. Singularities in the lens map manifest as caustics in intensity.
- What if the lenses themselves were described by caustics in the density profile of plasmas?
- Thin-lenses are described by the plasma density projected along the line of sight. Singularities in this projection will give rise to caustics.



Credit: Jennifer Yee, www.microlensing-source.org/concept/caustics-overview/

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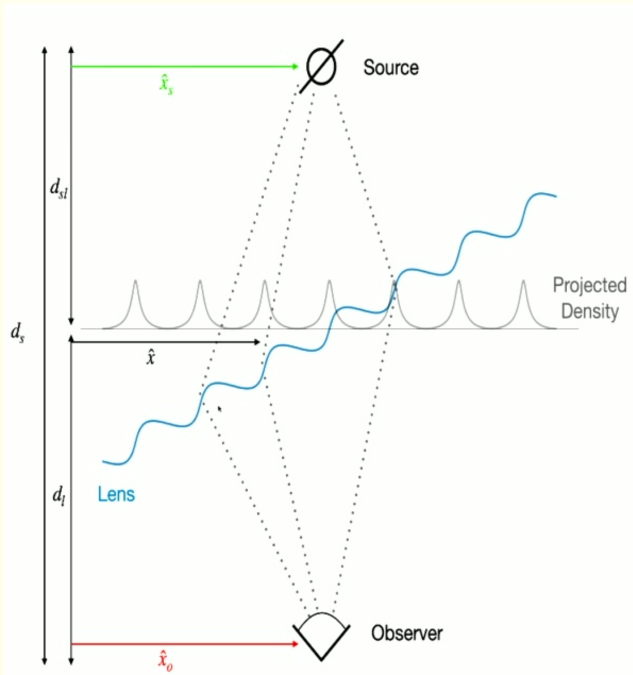
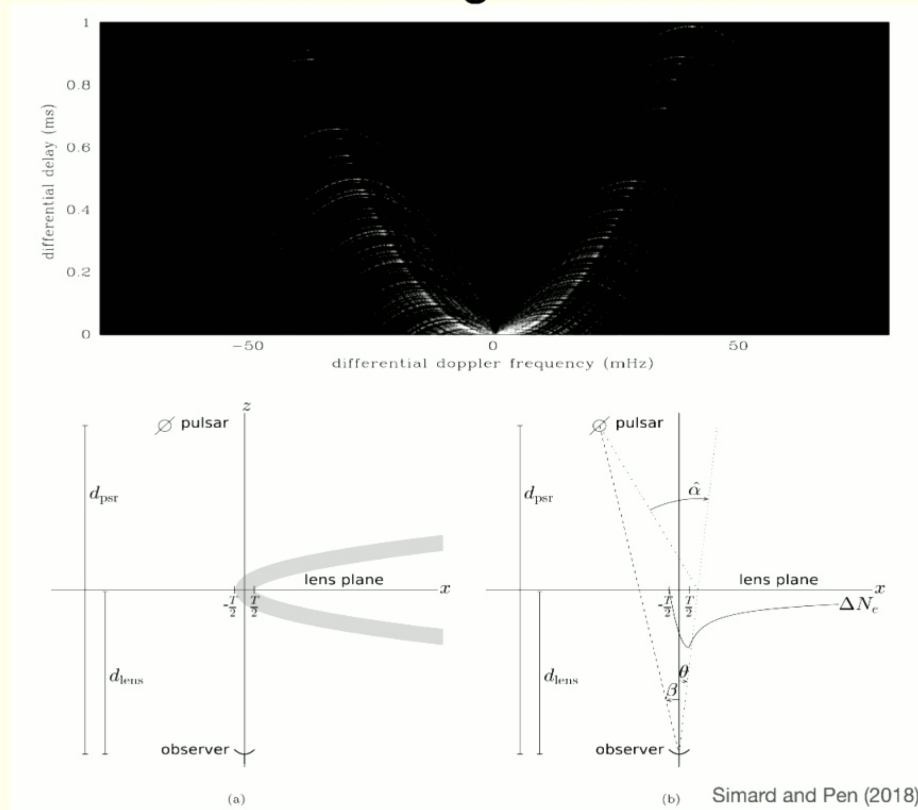
Proposed Model: Scintillation from Folds in Corrugated Sheets

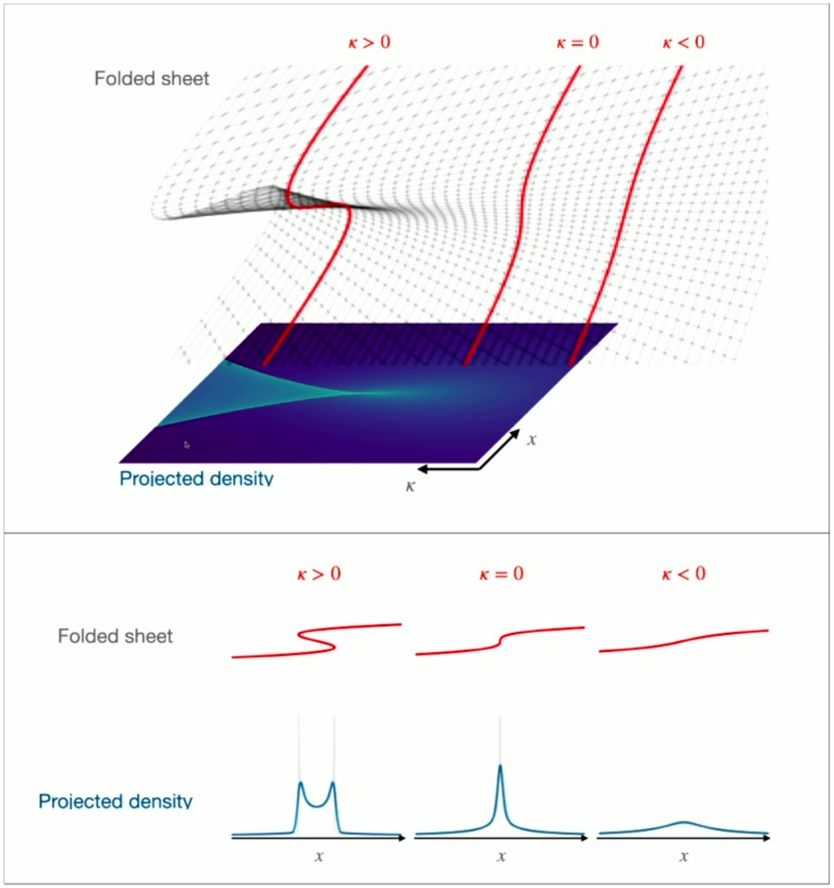


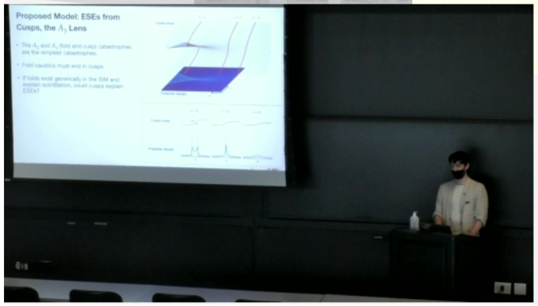


Simard and Pen (2018)

Proposed Model: ESEs from Cusps, the A_3 Lens

- The A_2 and A_3 (fold and cusp) catastrophes are the simplest catastrophes.
- Fold caustics must end in cusps.
- If folds exist generically in the ISM and explain scintillation, could cusps explain ESEs?





The A_3 Lens

- We describe the lens potential by the magnification of the canonical cusp:

$$\phi(x, \kappa) = \mu_{A_3}$$

- The canonical cusp is described by a simple quartic potential and cubic lens equation with two unfolding parameters:

$$\phi_{A_3}(t; x, \kappa) = \frac{t^4}{4} - \frac{\kappa t^2}{2} + xt$$

$$t^3 - \kappa t - x = 0$$

$$\mu_{A_3} = \sum_{t_i} |3t_i^2 - \kappa|^{-1}$$

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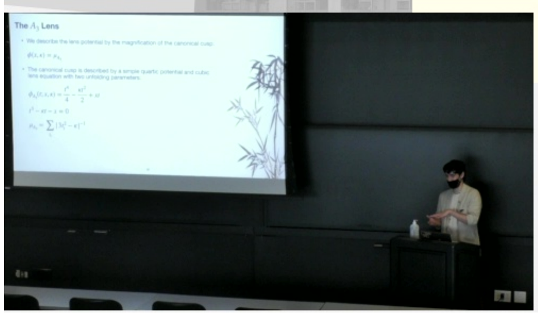

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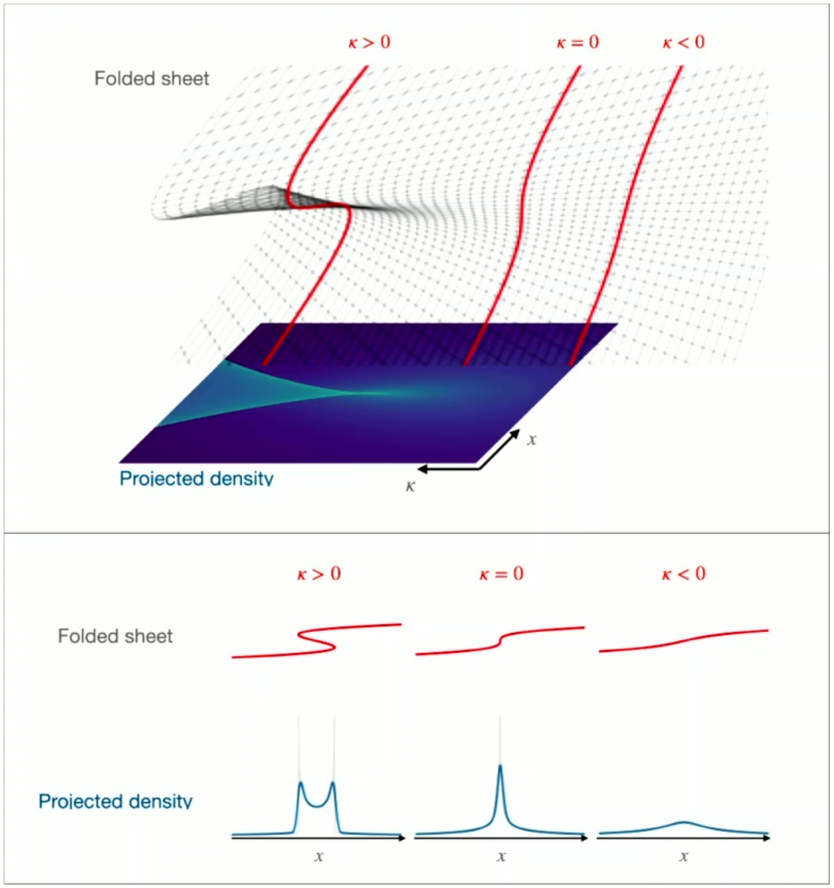
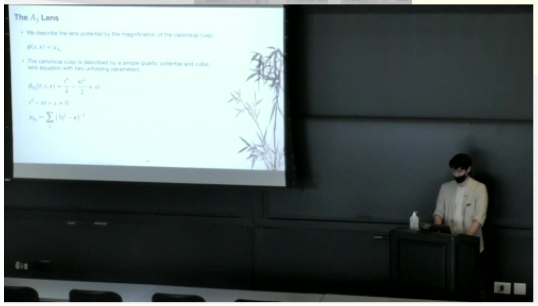
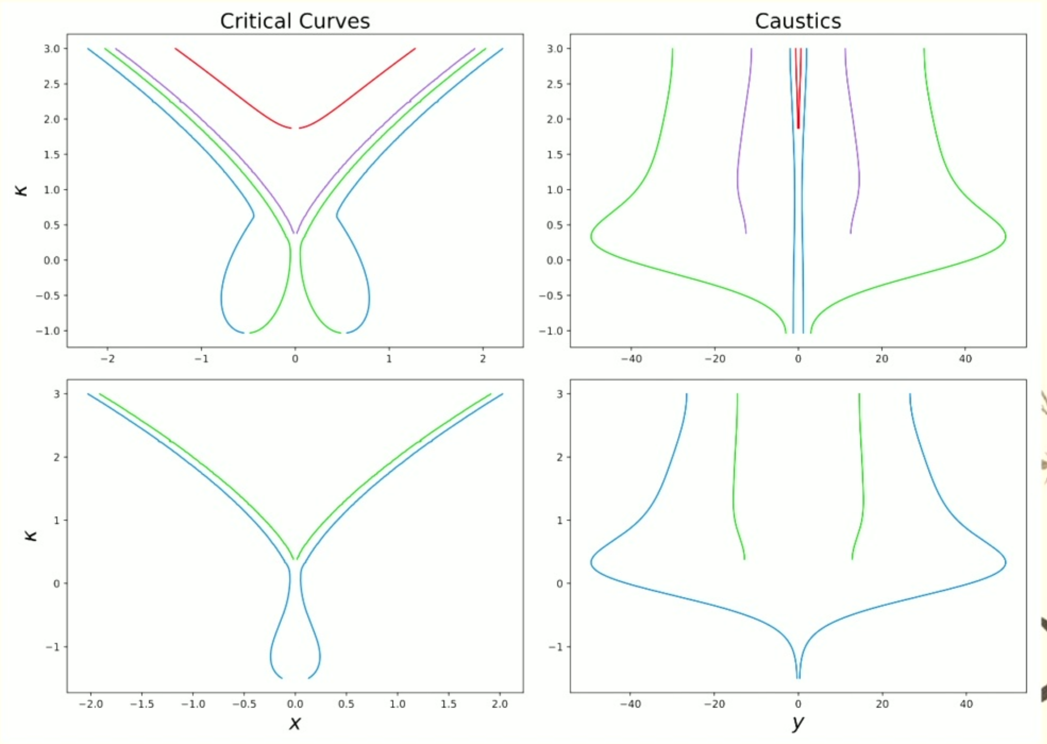




Cusps of Cusps: Caustics of the A_3 Lens



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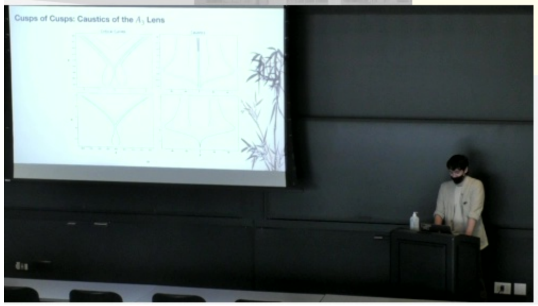
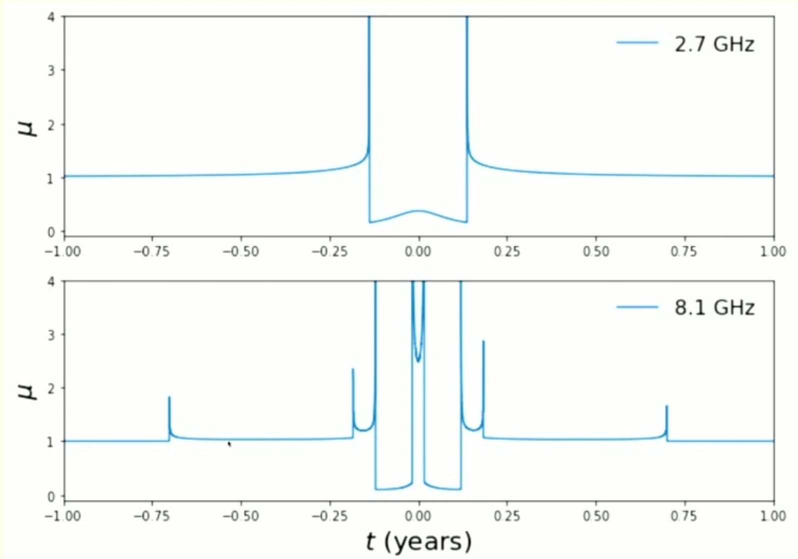
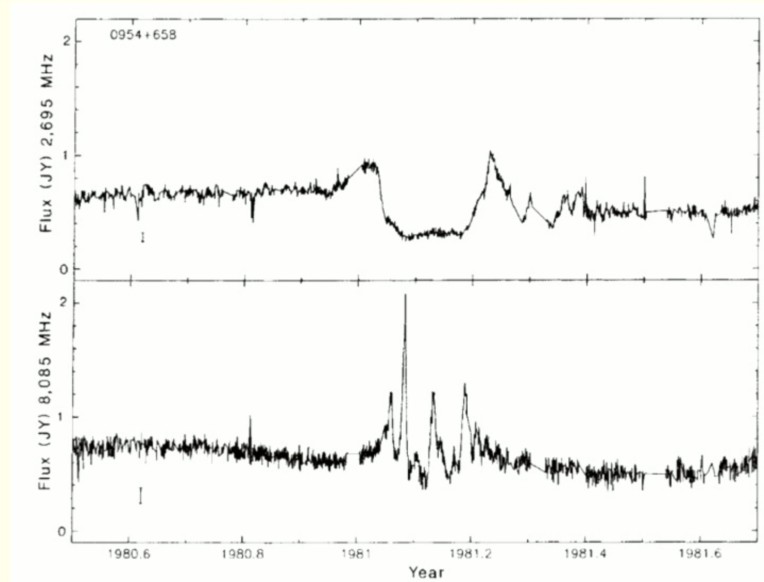


Modelling the Fiedler et al. (1987) ESE with the A_3 Lens





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Doubly Catastrophic Lensing: a unified model for ESEs and scintillation

- If correct, doubly catastrophic lensing would provide a unified framework to explain both scintillation and ESEs.
- Since the lenses are catastrophes, their form is generic and governed by a small number of parameters.
- Well-known scalings of the fold and cusp cross-sections explain relative rate of scintillation and ESEs:

$$\sigma_{A_2}(>\Delta) \sim \Delta^{-2}$$

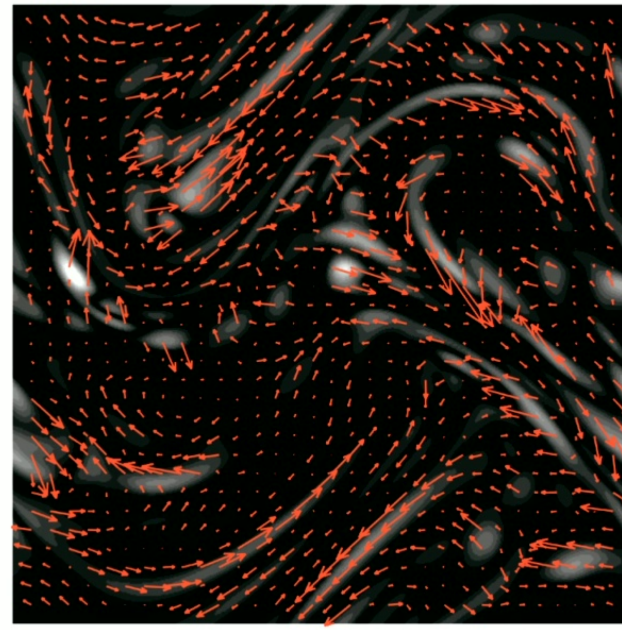
$$\sigma_{A_3}(>\Delta) \sim \Delta^{-5/2}$$

Physical Origins of Corrugated Sheets

Goldreich and Sridhar (2006)

- The ISM is a turbulent medium stirred on $\sim 10^2$ pc scales by energetic processes, e.g. supernovae.
- Folded magnetic field structures can appear on small-scales much smaller than the stirring scale.
- Alfvén waves propagate along current sheets separating magnetic field regions forming corrugated structures in the plasma on ~ 1 AU scales.
- The current sheets can persist anywhere from weeks - years depending on the ISM phase.

Folded magnetic field structures in small-scale, turbulent dynamos



Schekochihin et al. (2004)

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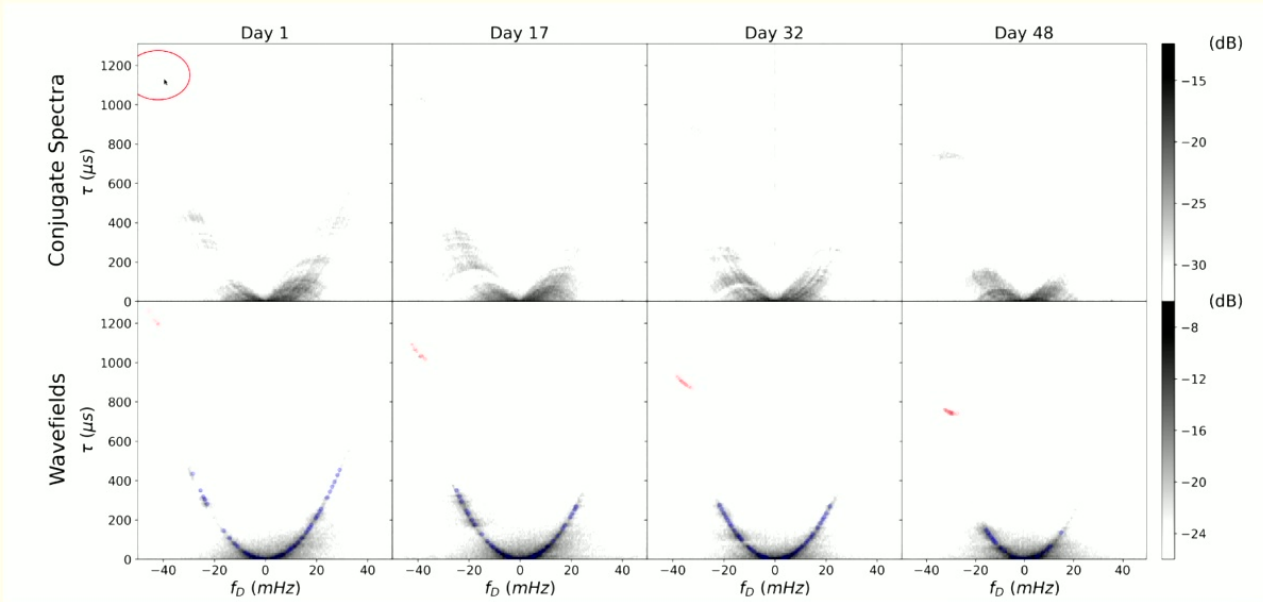
An Extreme Scattering Event in PSR0834+06



Zhu et al. (2022)

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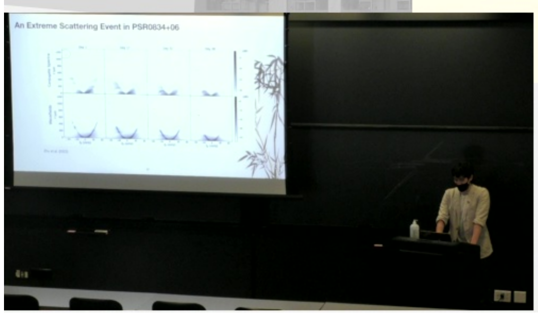
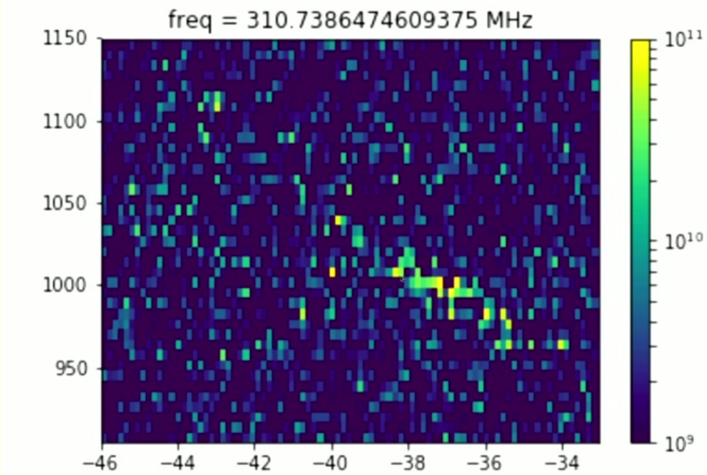


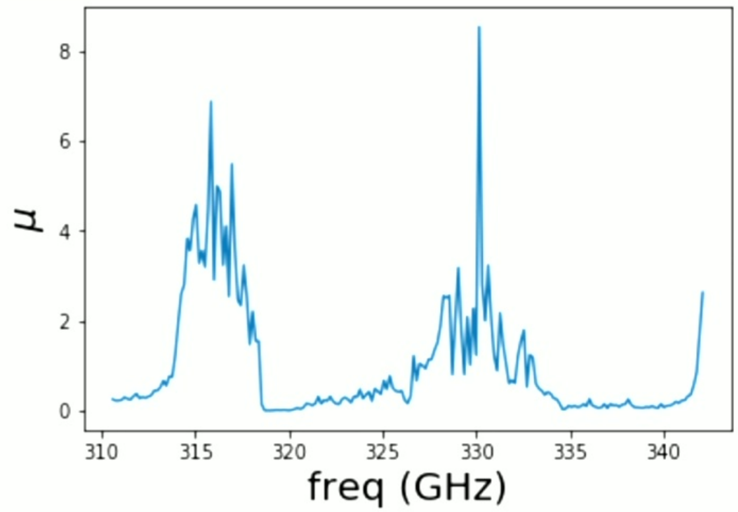
An Extreme Scattering Event in PSR0834+06

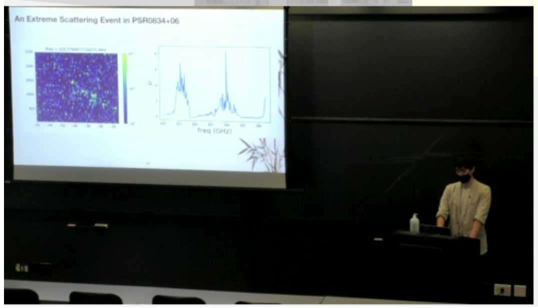
The observed event shares characteristics with ESEs:

- Large bending angles: $\theta \sim 83\,\mathrm{mas}$
- Large density and pressure assuming spherical symmetry: $N_e \sim 10^3\,\mathrm{cm}^{-3}$.
- Long time-scales: $t > 48\,\mathrm{days}$

An Extreme Scattering Event in PSR0834+06







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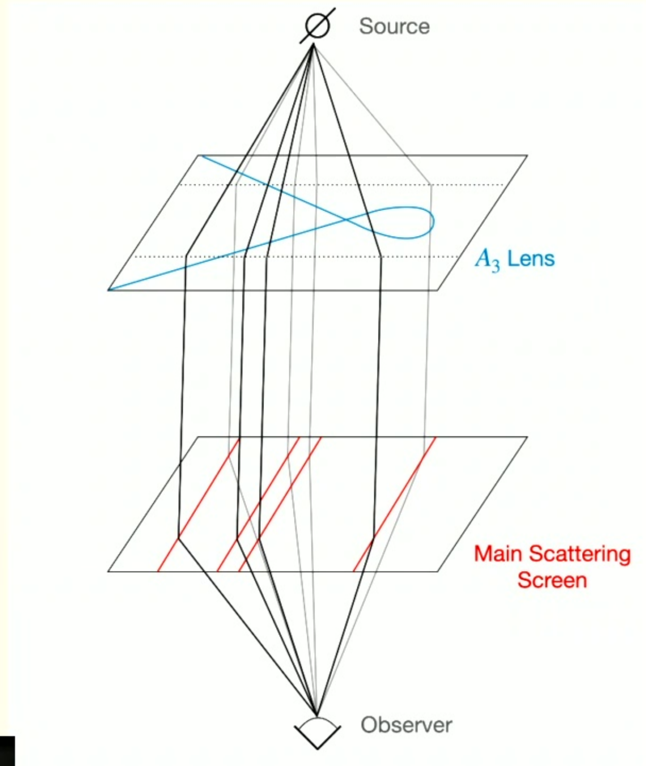
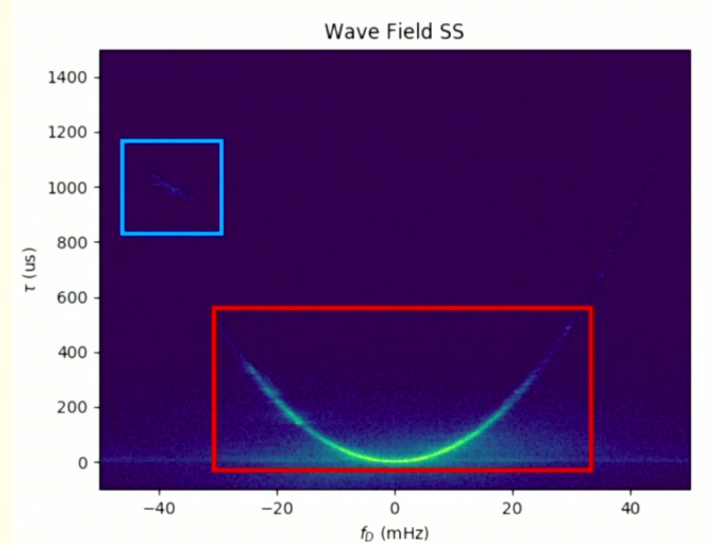
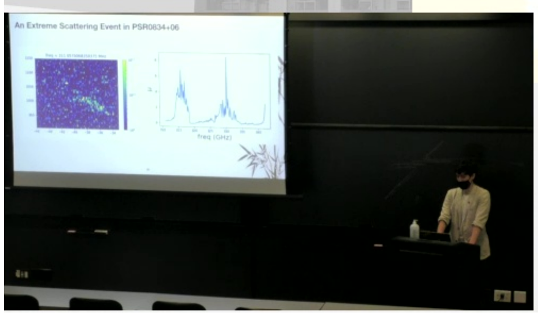
An Extreme Scattering Event in PSR0834+06: A Double Lens System







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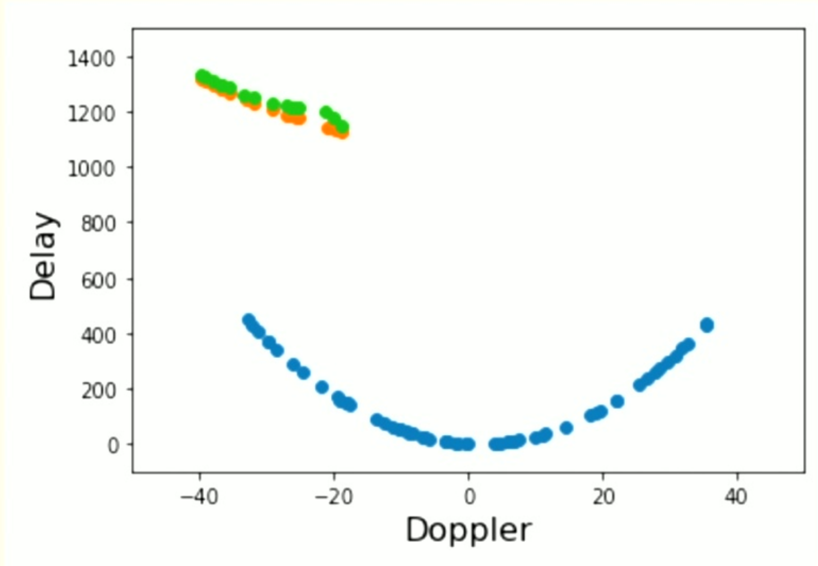
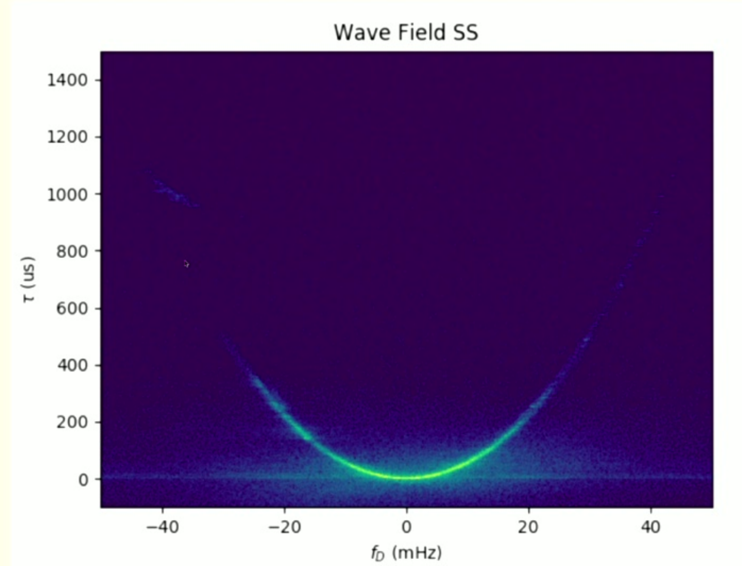
Modelling PSR0834+06 Scattering with the A_3 Lens: Conjugate Wavefield





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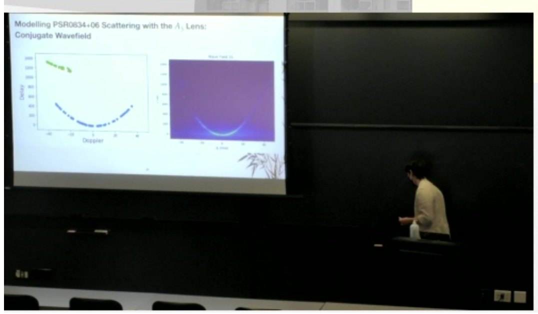

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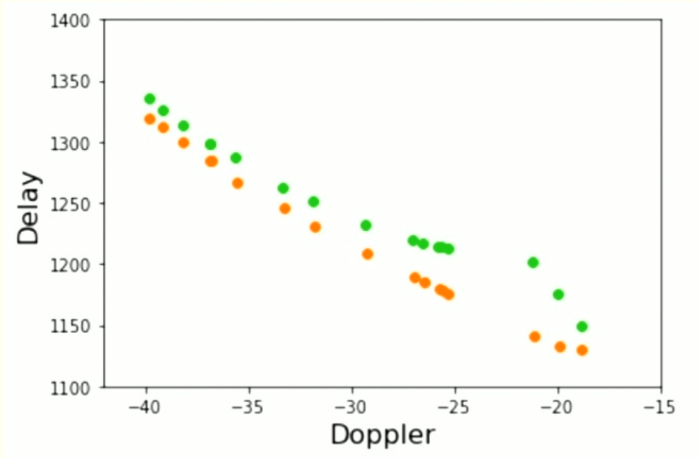

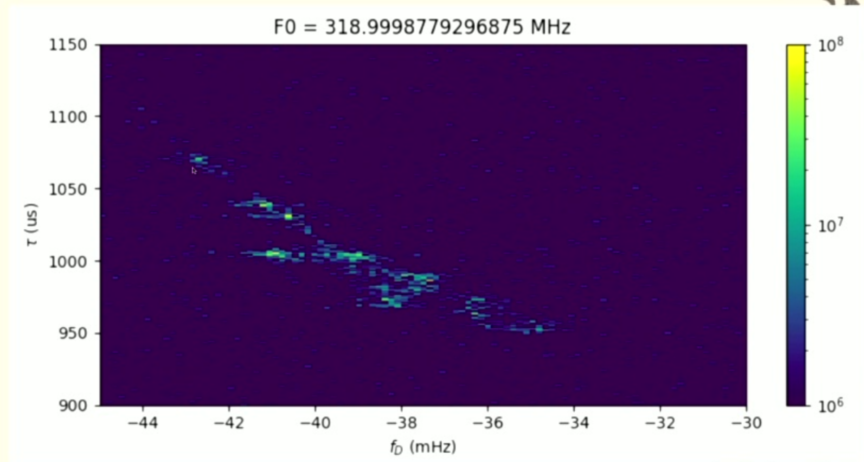

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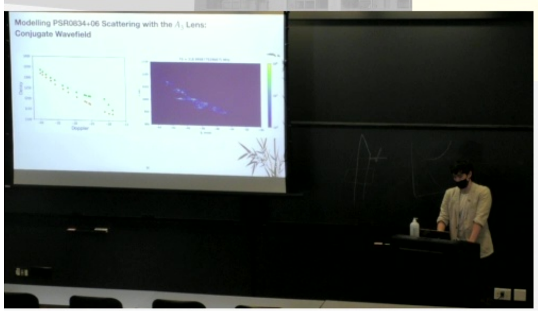
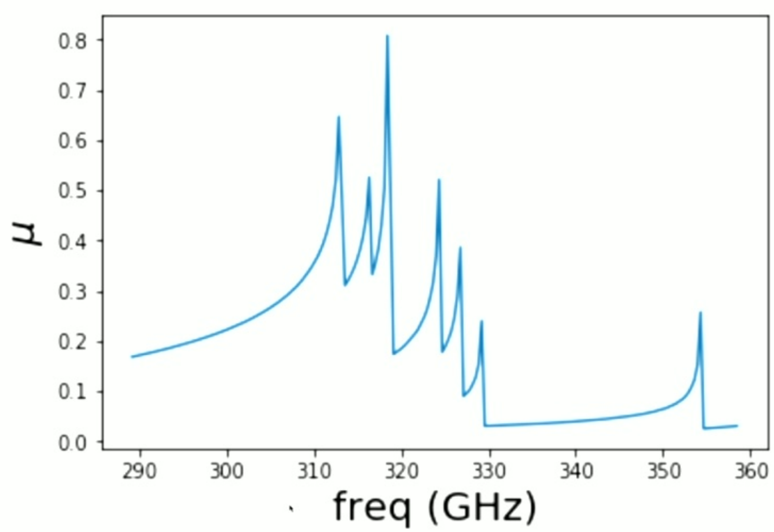
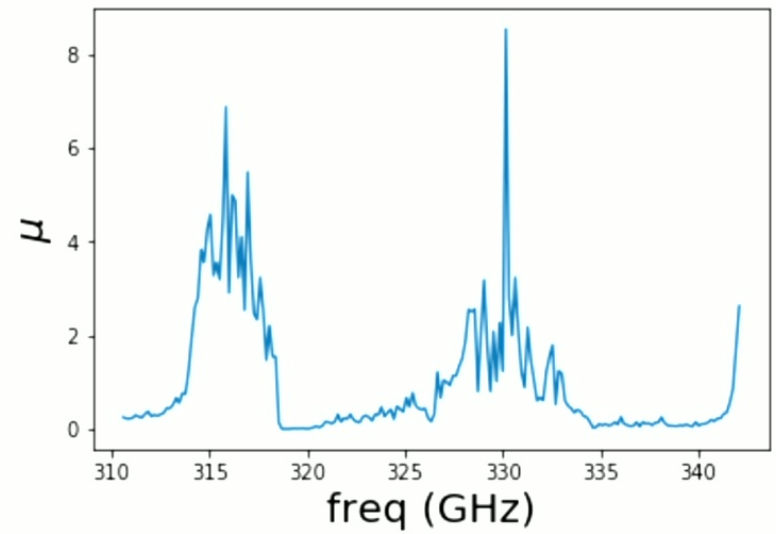
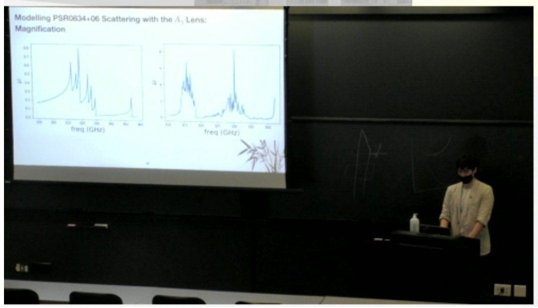


Modelling PSR0834+06 Scattering with the A_3 Lens: Magnification







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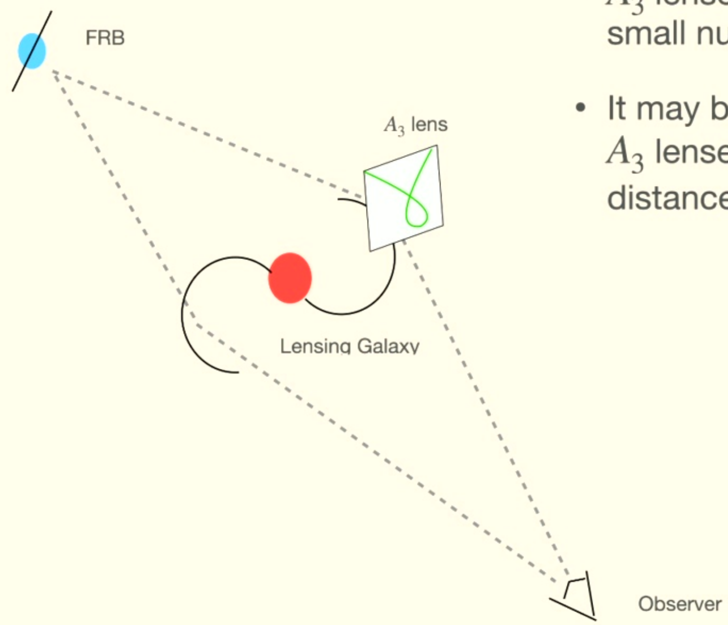
Applications of Doubly Catastrophic Lensing: Cosmology from FRB ESEs



- A_3 lenses are generic and governed by a small number of parameters.
- It may be possible to use FRBs lensed by A_3 lenses to determine angular diameter distances, $d_A(z)$.

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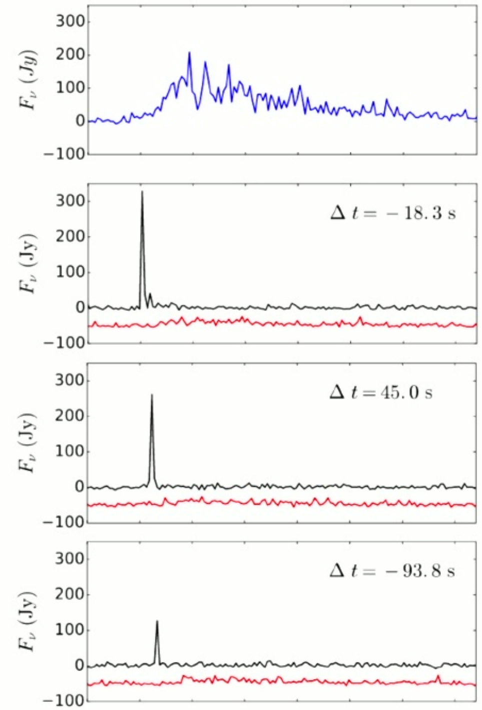
Applications of Doubly Catastrophic Lensing: De-scattering Gravitationally Lensed FRBs and Pulsars

Main et al. (2017)

- Scattering is a major systematic for using gravitationally lensed FRBs to probe dark matter / cosmic expansion.
- Excess time delays need to be taken account for using PTAs to detect individual GWs
- If FRBs/pulsars are primarily scattered by stable, large-scale refractive structures, it may be possible to de-scatter pulses.



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Summary

- Doubly catastrophic lensing provides a unified framework to explain both scintillation (A_2 folds) and extreme scattering events (A_3 cusps).
- The A_3 lens can qualitatively explain several features of scattering observations that have been challenging to accommodate:

  Overpressure problem
  Frequency dependence of ESEs
  Doppler-delay structure of the millisecond feature in PSR0834+06.

- Catastrophes naturally arise in any thin-plane description of lensing and take on generic analytic forms.
- The simplicity and universality of the analytic forms of catastrophes has the potential to make this framework a powerful astrometric tool.

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