



ASKARYAN RADIO ARRAY



CHICAGO 2024

# Effects of Biaxial Birefringence on Polarization Reconstruction for the Askaryan Radio Array

Alan Salcedo Gomez for the ARA Collaboration

June 11<sup>th</sup>, 2024

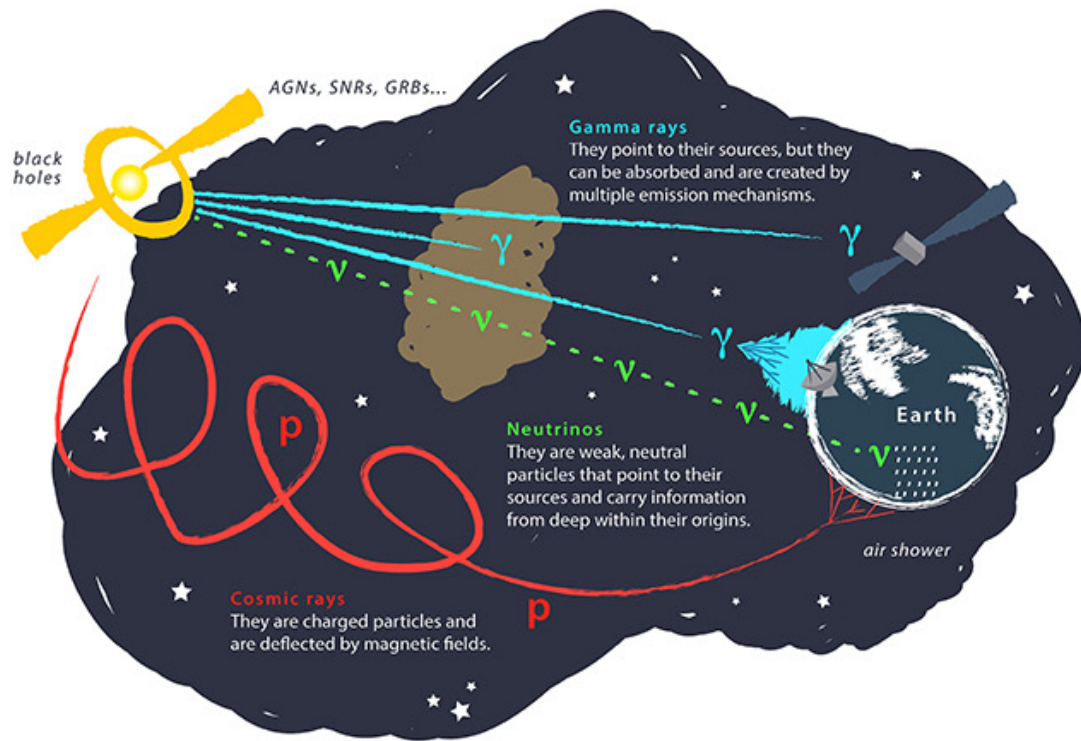


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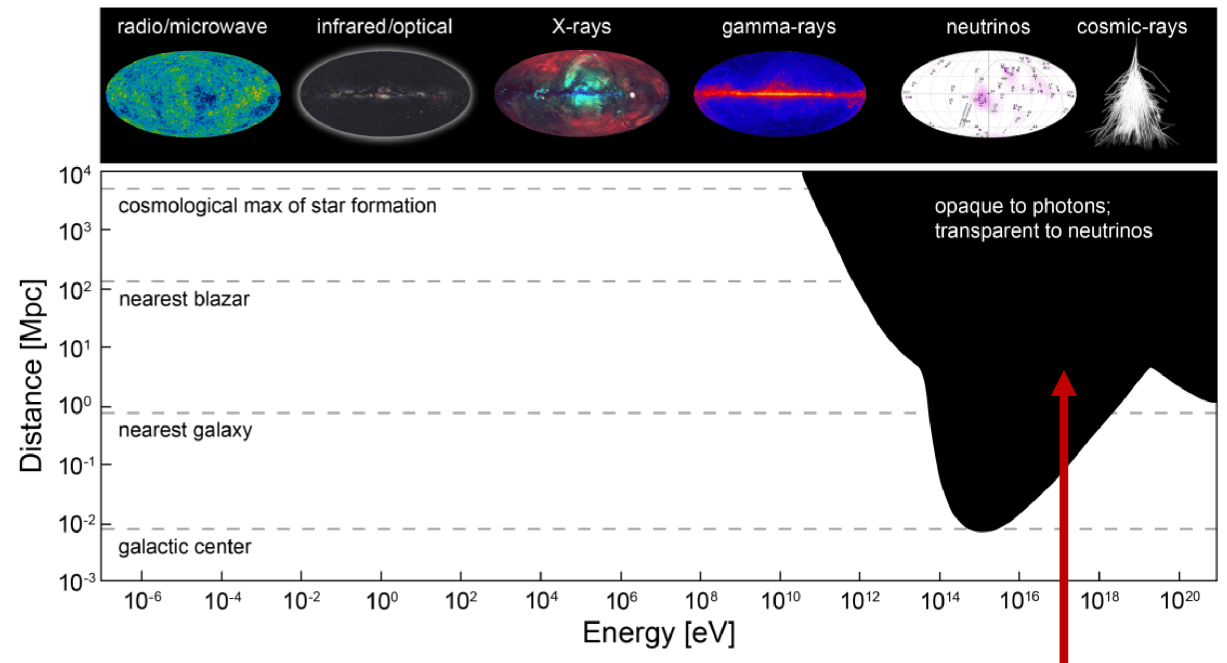
# Context

We want to expand the horizon of multi-messenger astrophysics



Credit: IceCube Collaboration

- Use neutrinos to study the most energetic and distant astrophysical sources in the Universe

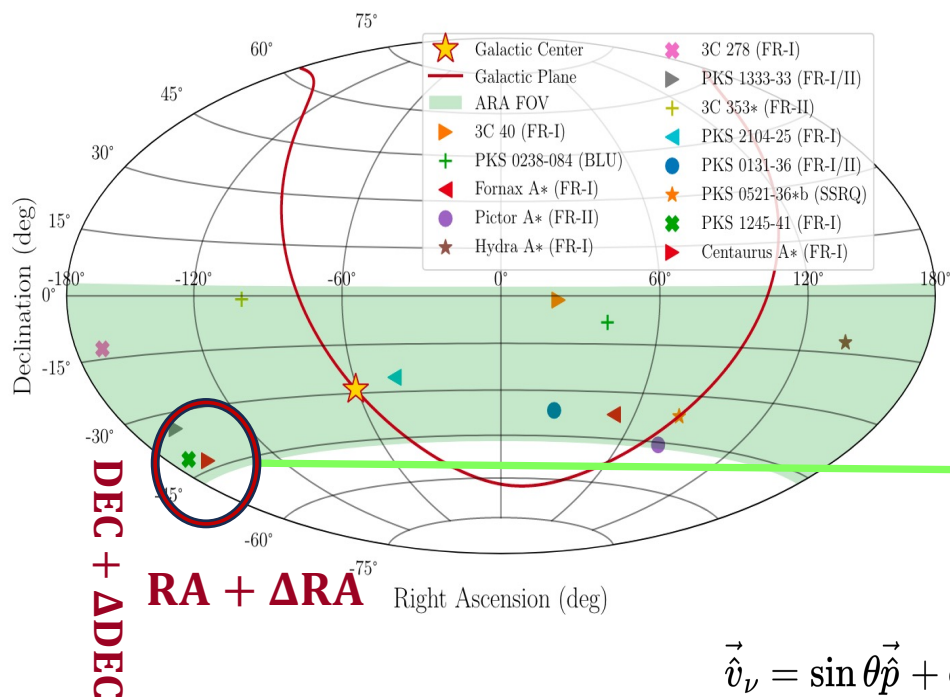


i.e. access this regime

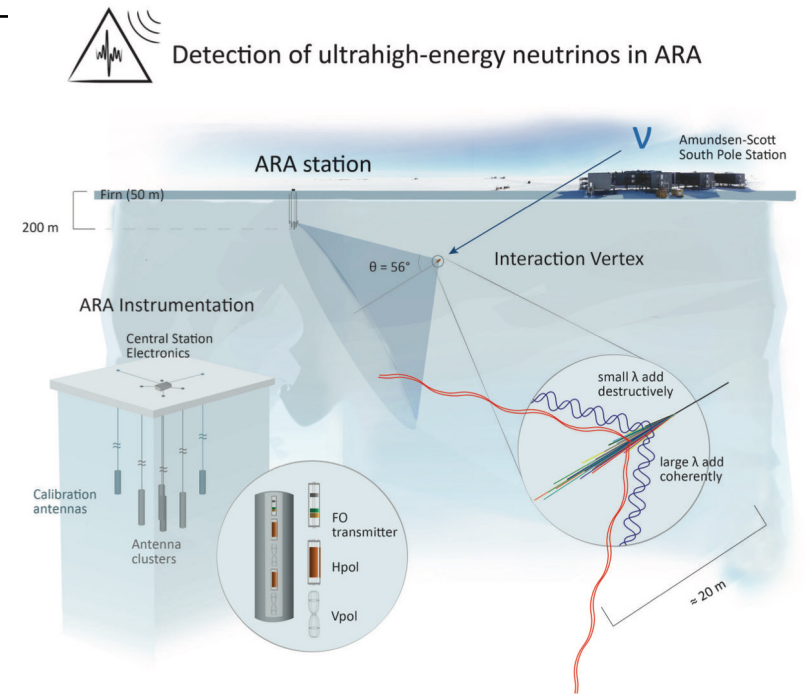
# Context

For this, we need to reconstruct the polarization of neutrino signals accurately and precisely

- **Uncertainties in polarization reconstruction propagate to uncertainties in the sky map**



$$\vec{v}_\nu = \sin \theta \vec{\hat{p}} + \cos \theta \vec{\hat{l}}$$

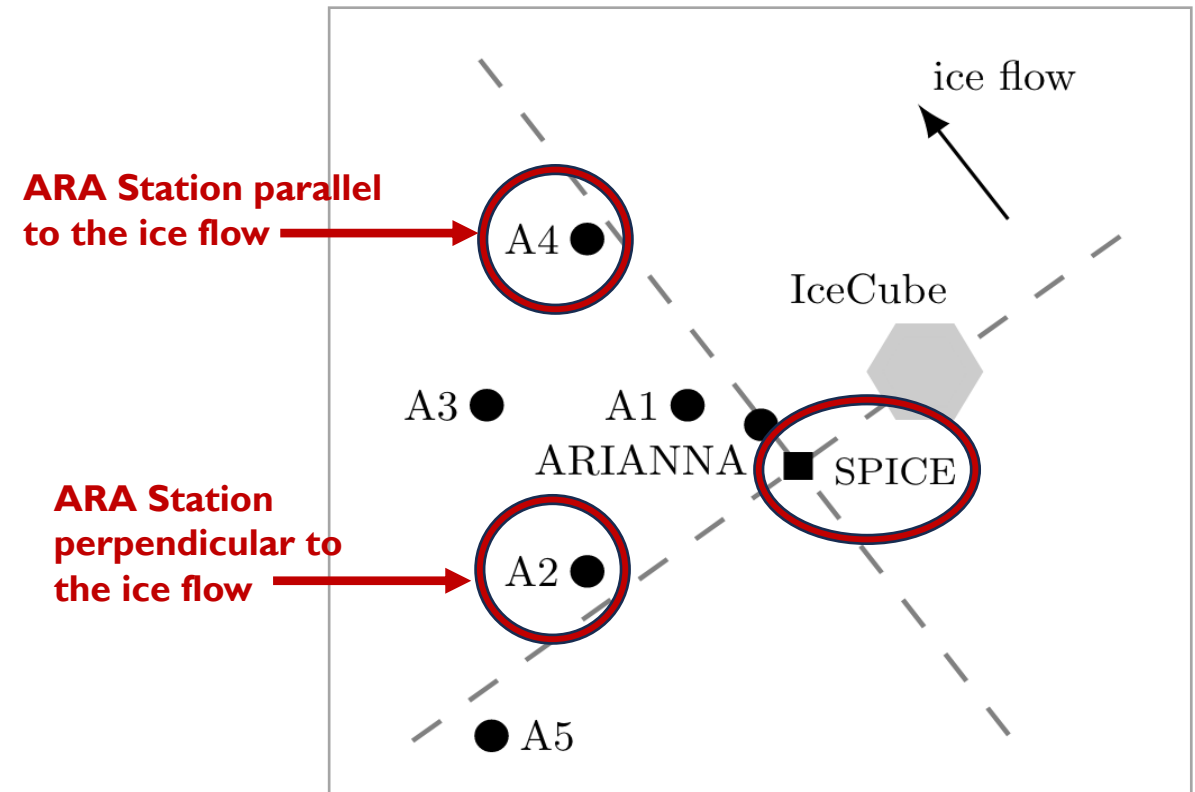


Modified from J. Torres (2020) and S. Barwick, C. Glaser (2023)

# SPICE Pulsar

The SPICE pulsing campaign provided a unique dataset of broadband radio pulses transmitted inside the ice

- The **South Pole Ice Core Experiment (SPICE)** drilled and recovered ice cores up to a depth of  $\sim 1700$  m
- **Broadband radio pulses were transmitted from inside the SPICE borehole** and received by ARA (A1 – A5) and ARIANNA over 1 - 5 km horizontal baselines
- This unique dataset been **important for calibrations and measurements of ice properties**

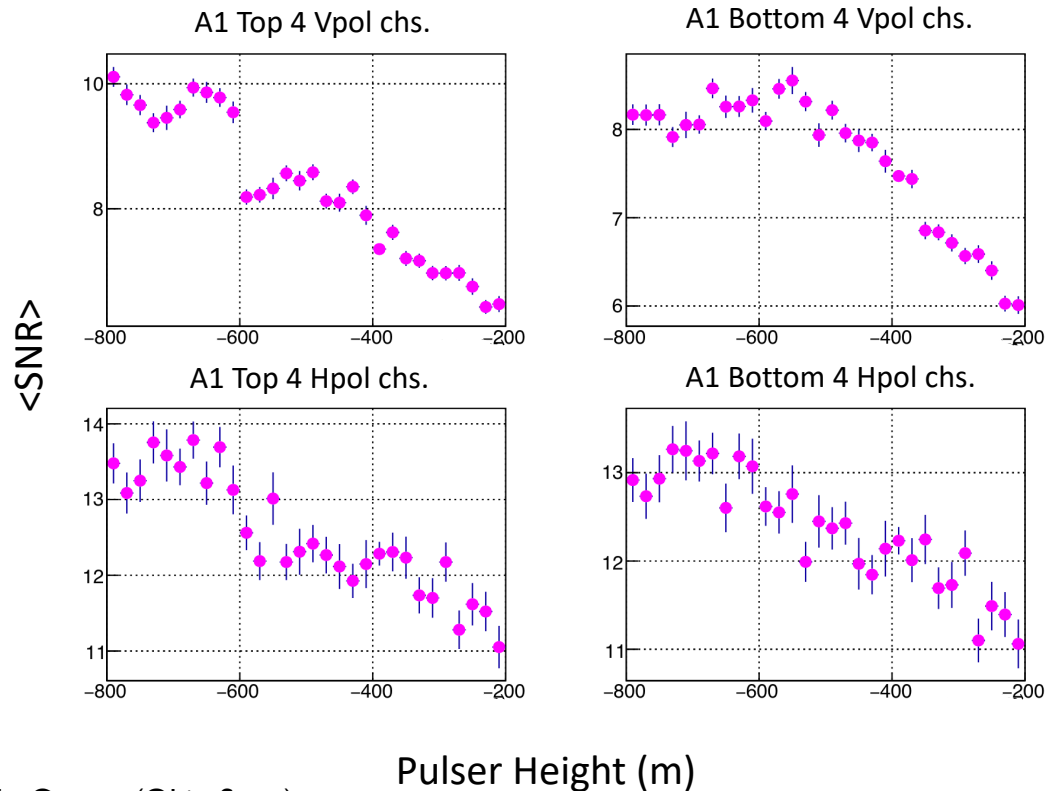


A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

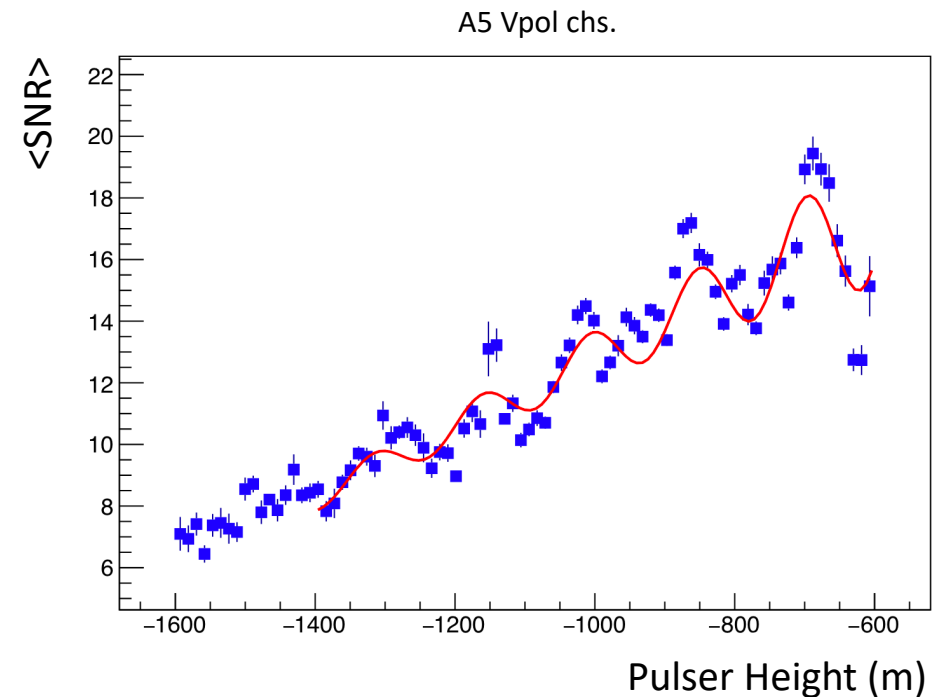
# SPICE Pulsar

ARA observed an anomalous behavior of polarization from SPICE pulses

- Pulsers transmitted as Vpol were observed with higher Hpol power than expected, even larger in Hpol than Vpol



- Oscillatory behavior on signal-to-noise ratio

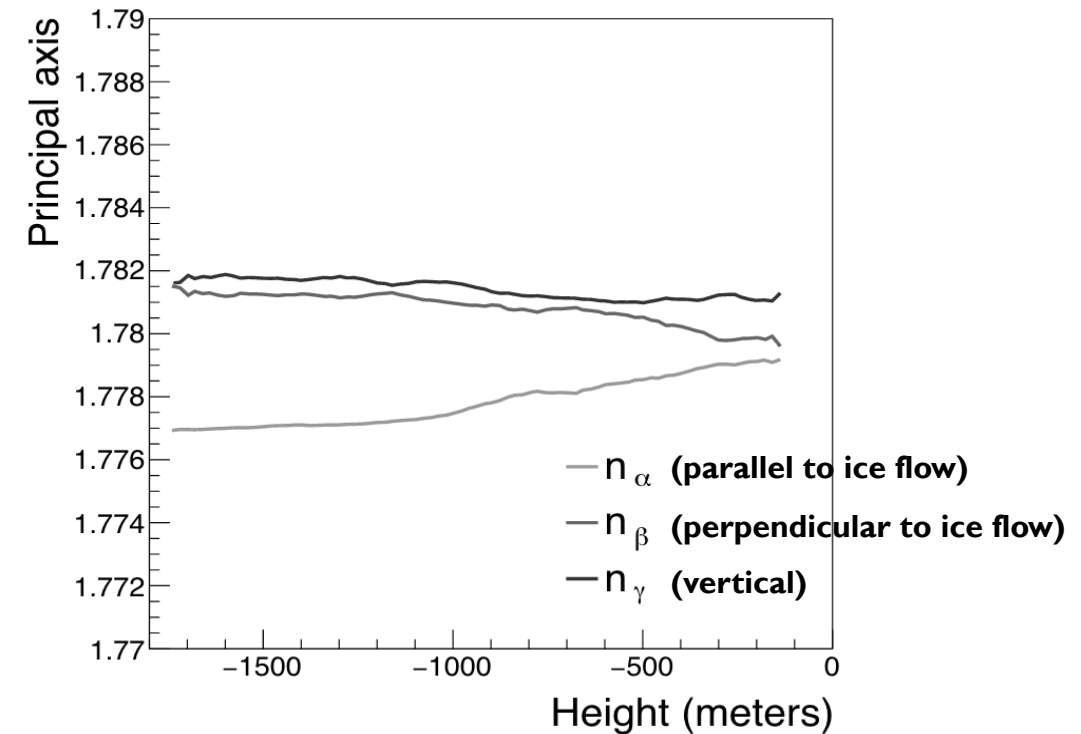


P.Allison et al, JCAP 12 (2020) 009

# Birefringence

Polar ice behaves as a biaxially birefringent medium at radio frequencies

- In birefringent media, the **propagation** of electromagnetic radiation **depends on its direction and polarization**
- Biaxial birefringent media are characterized by **three parameters** along three perpendicular axes
- We are exploring **biaxial birefringence as a possible explanation of the anomalous behavior of polarization in SPICE events**

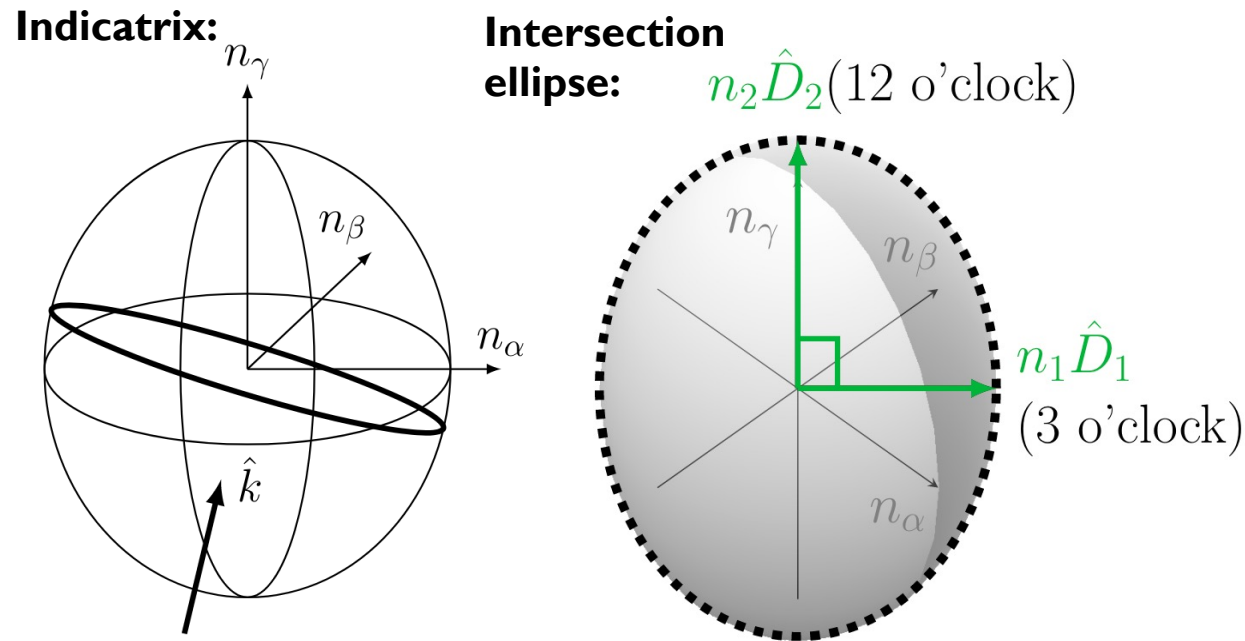


A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

# Birefringence Model

The polarization vector is described by two eigenstates dependent on the birefringence parameters

- Eigenstates are given by the axes of the intersection ellipse of an indicatrix and the signal's wavefront



- $n_\alpha, n_\beta, n_\gamma$  change with depth
- $n_1$  and  $n_2$  are different indices of refraction.  $\hat{D}_1$  and  $\hat{D}_2$  describe two separate rays

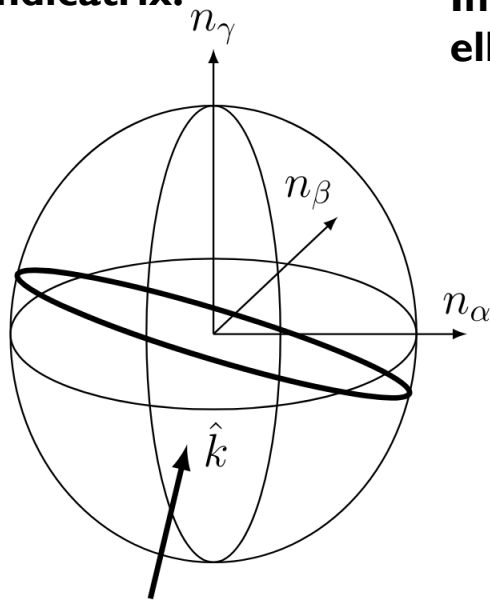
A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

# Birefringence Model

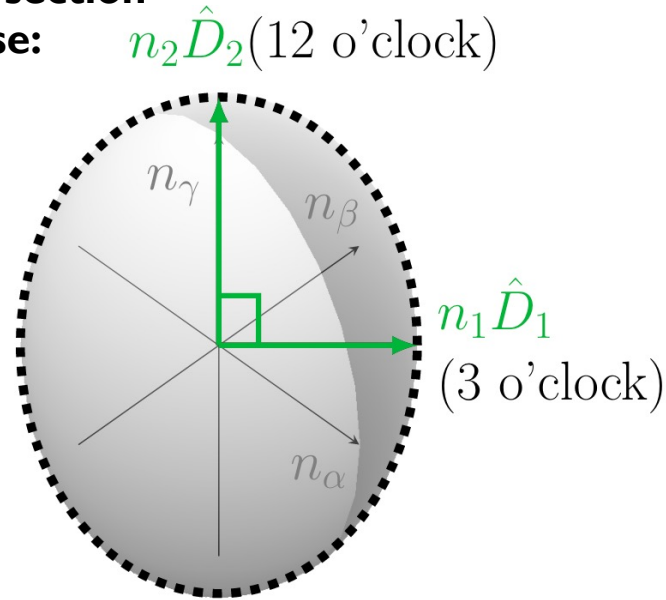
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- Eigenstates are given by the axes of the intersection ellipse of an indicatrix and the signal's wavefront

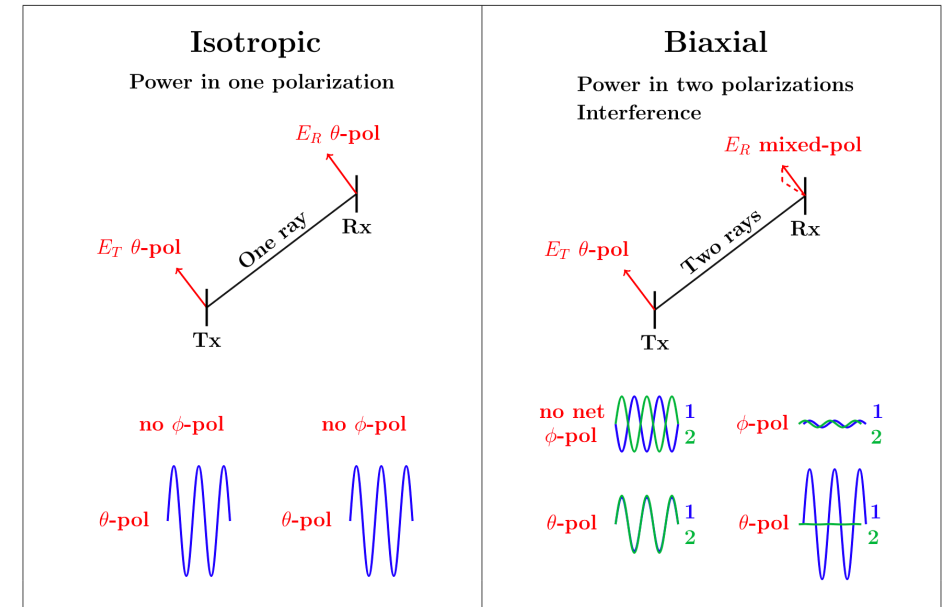
Indicatrix:



Intersection ellipse:



Polarization description before: | Polarization description now:



- $n_\alpha, n_\beta, n_\gamma$  change with depth

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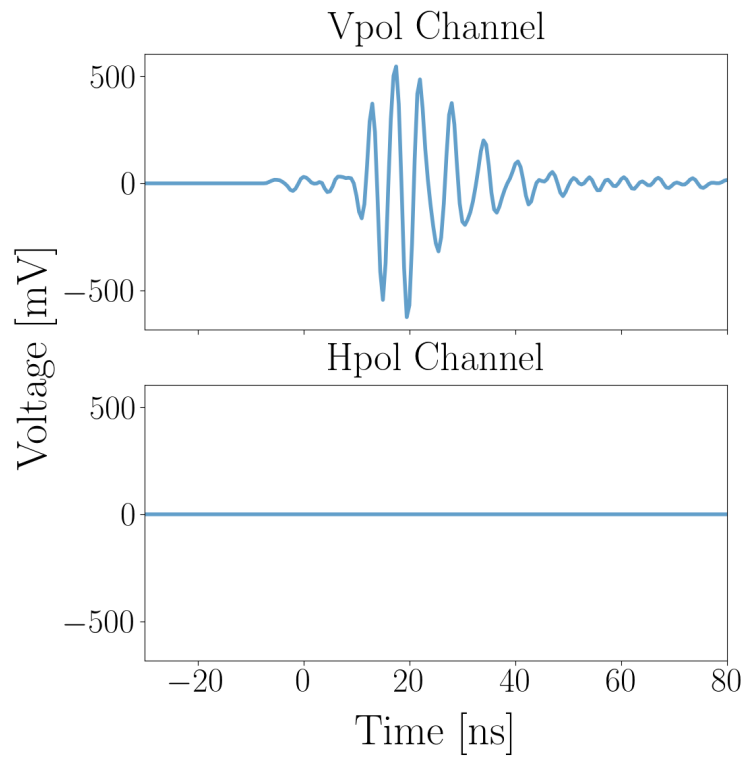


# Birefringence Model

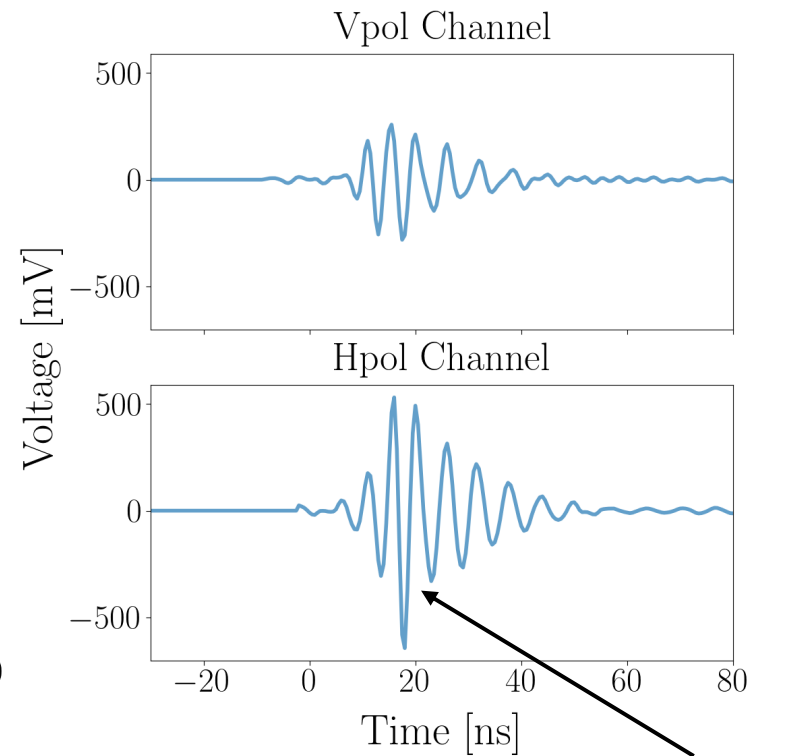
This birefringence model is now implemented in AraSim

**Simulation:** Pulser at SPICE location to **A4** from 1600 m depth

**Without birefringence:**



**With biaxial birefringence:**



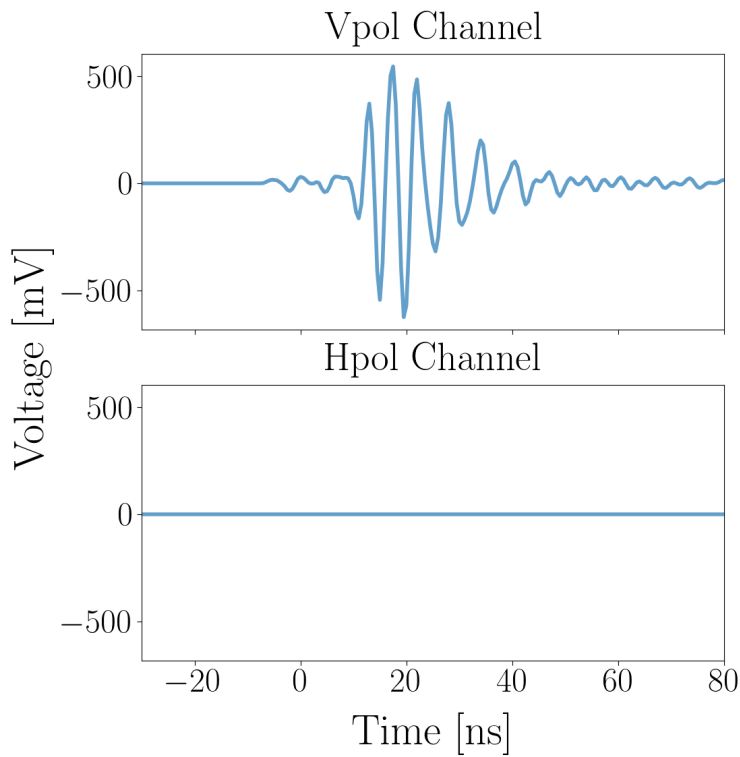
**Rotation**

# Birefringence Model

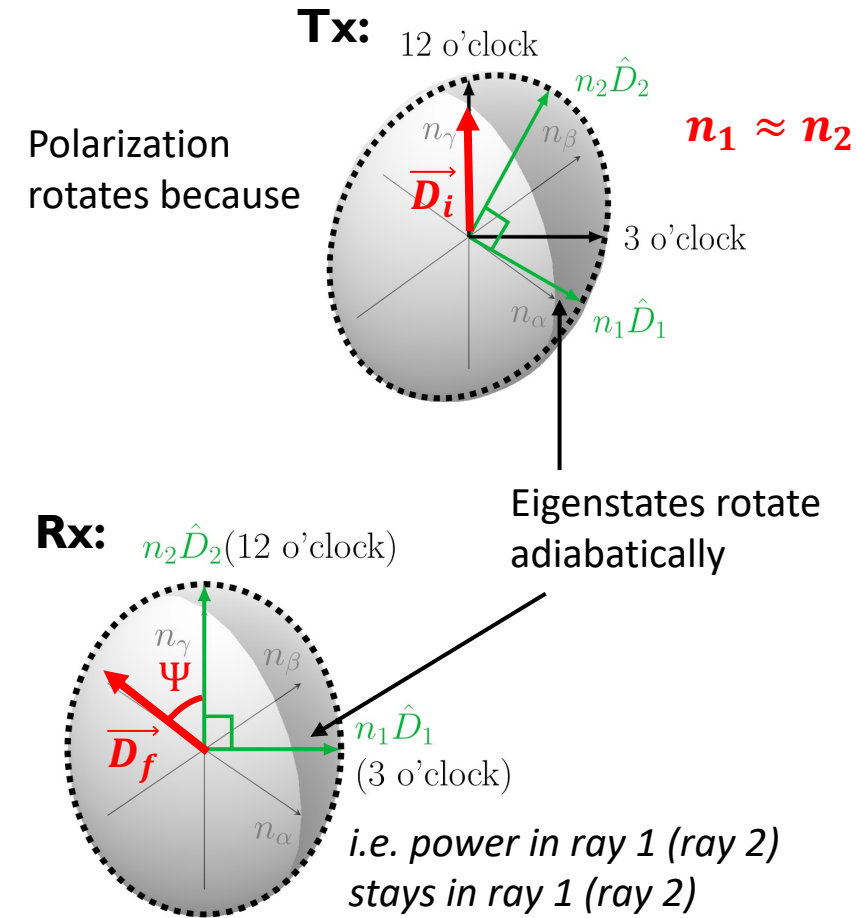
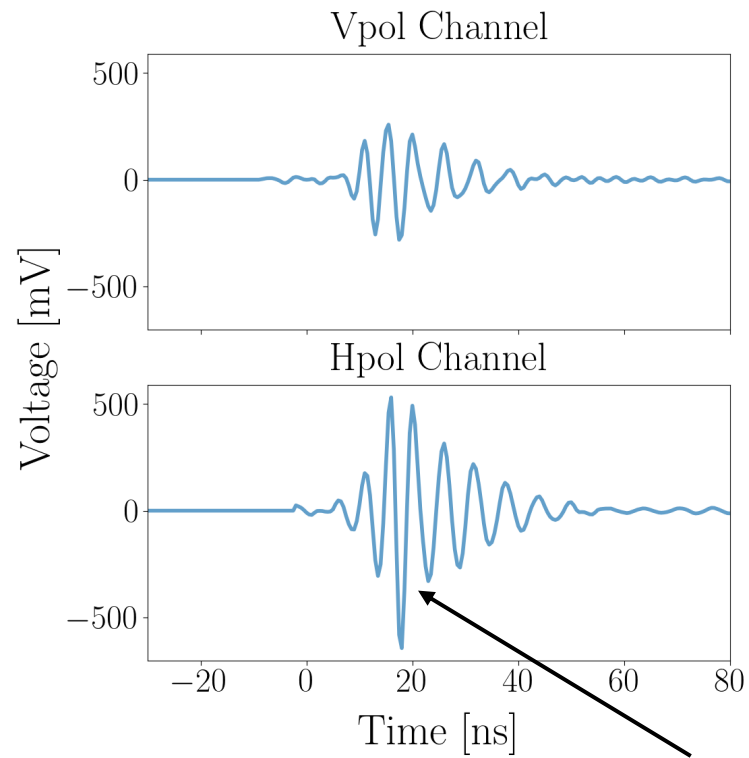
The **polarization** of a signal is allowed to rotate in this model

**Simulation:** Pulser at SPICE location to **A4** from 1600 m depth

**Without birefringence:**



**With biaxial birefringence:**

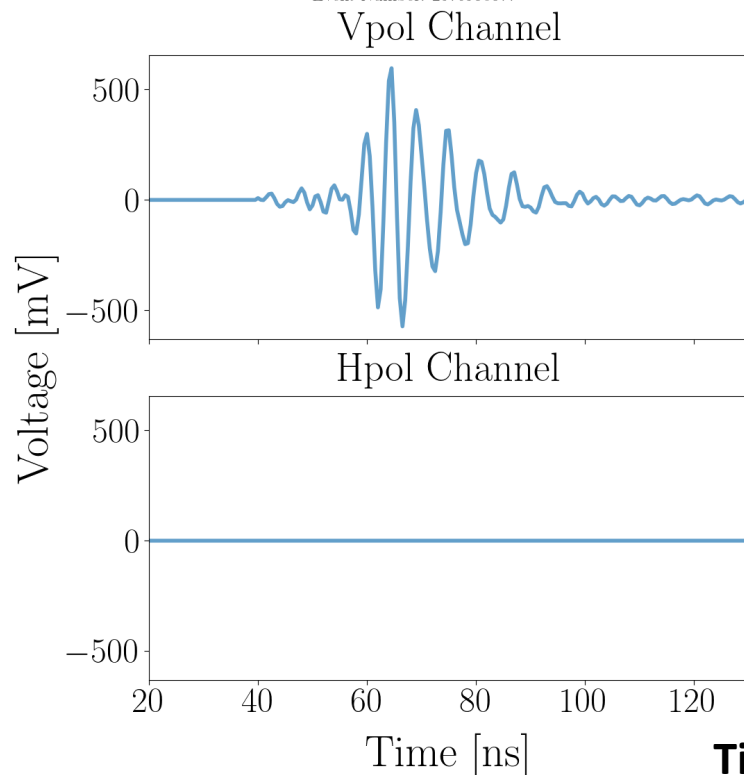


# Birefringence Model

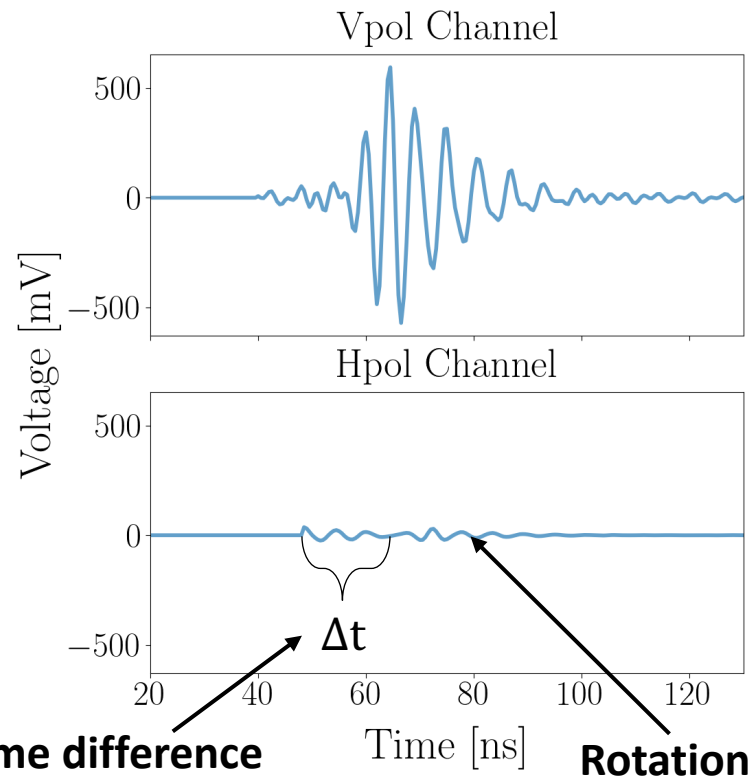
The polarization **eigenstates** are allowed to **arrive at different times**

**Simulation:** Pulser at SPICE location to **A2** from 1600 m depth

**Without birefringence:**



**With biaxial birefringence:**

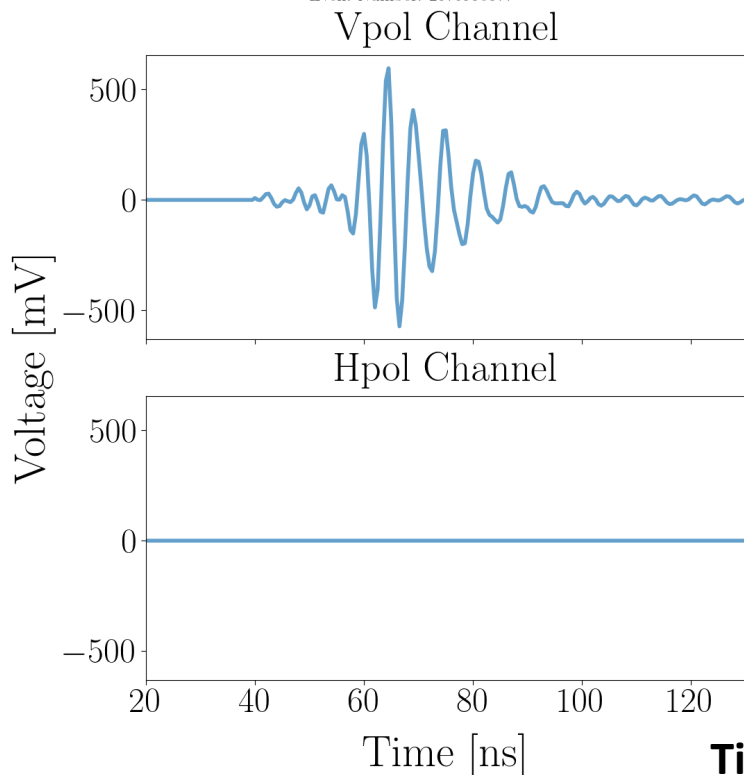


# Birefringence Model

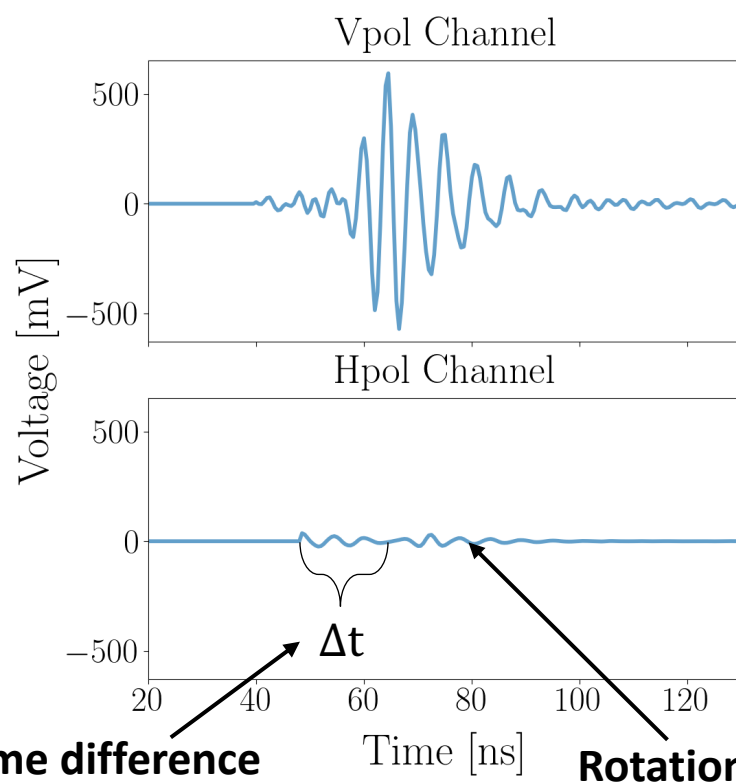
The polarization **eigenstates** are allowed to arrive at different times

**Simulation:** Pulser at SPICE location to **A2** from 1600 m depth

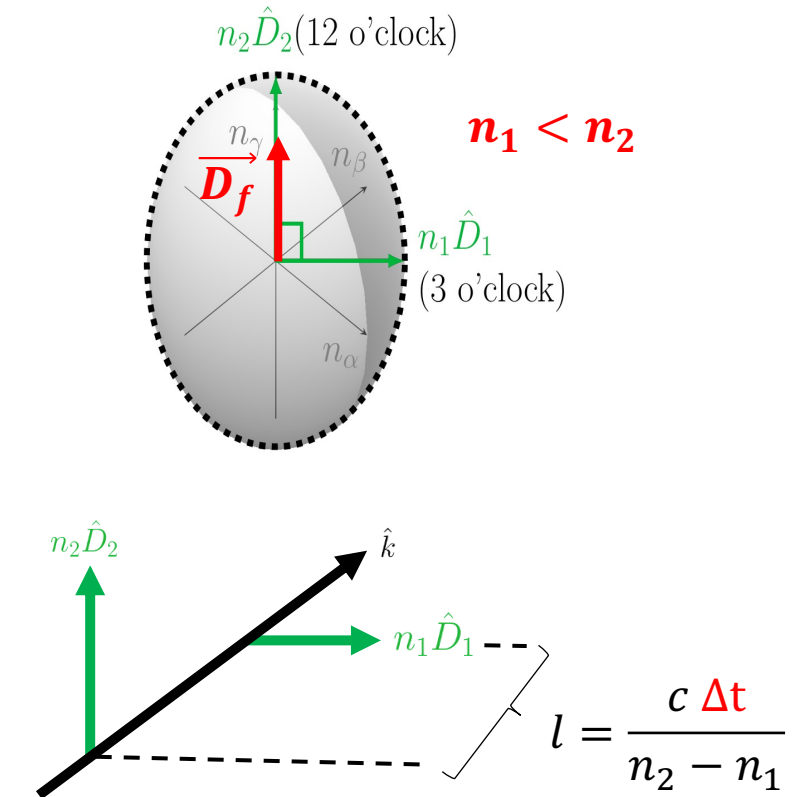
**Without birefringence:**



**With biaxial birefringence:**

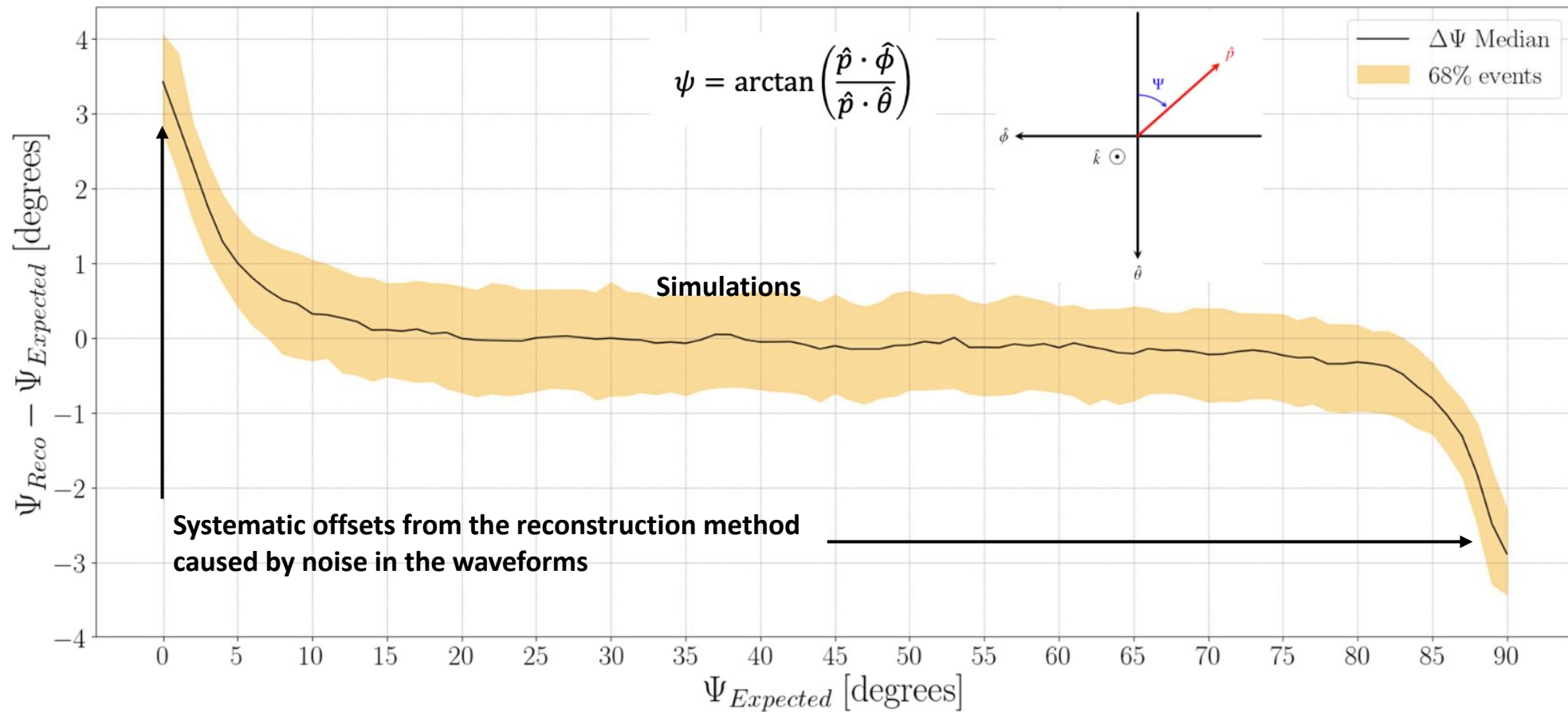


**Tx and Rx:**



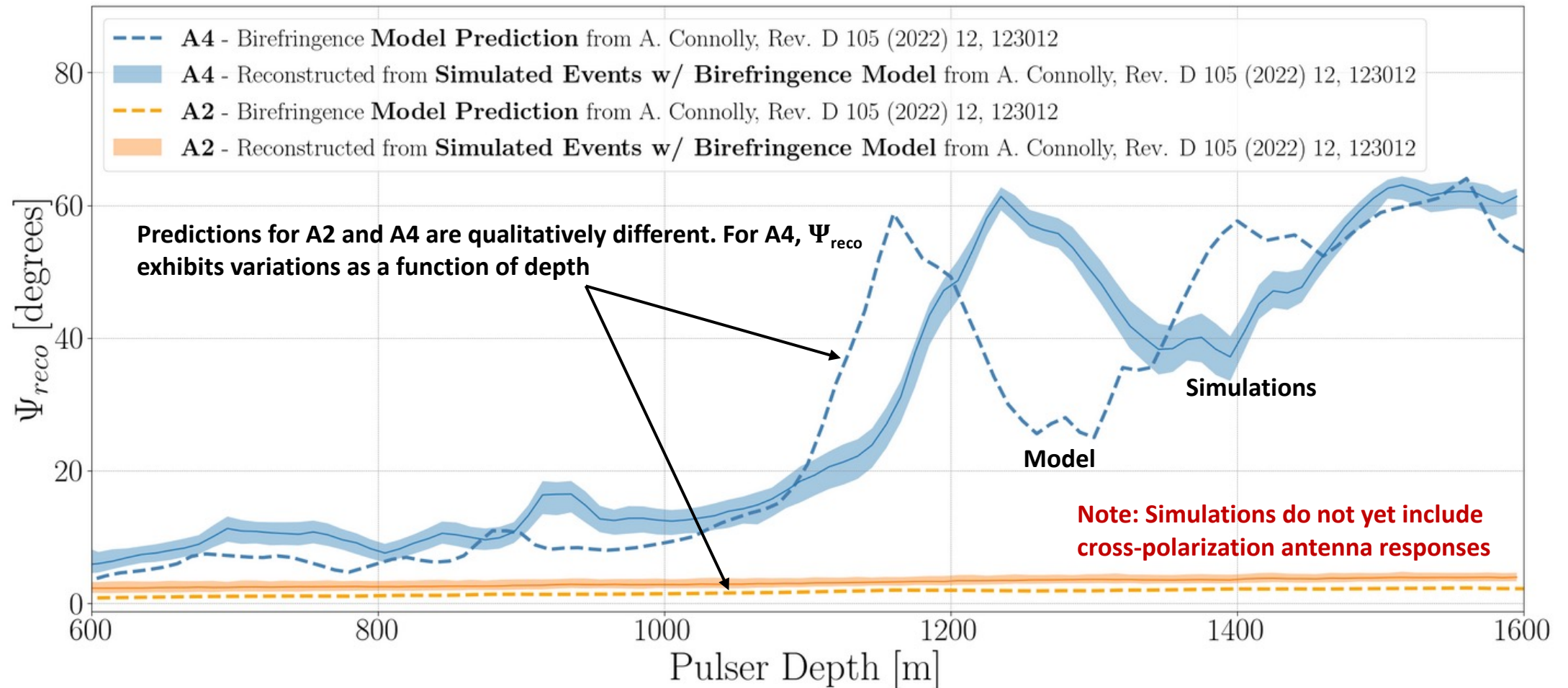
# Polarization Reconstruction

Reconstructing the polarization angle from ARA events is possible



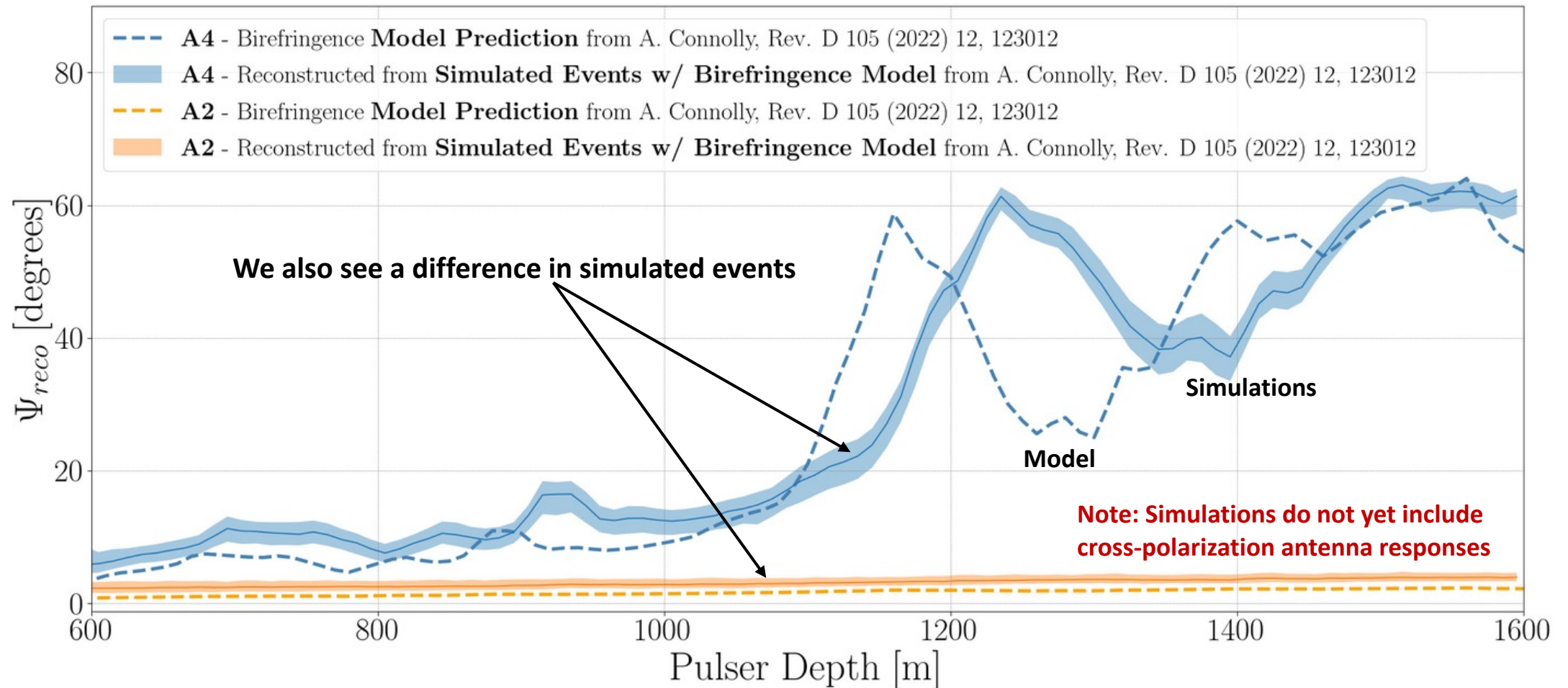
# Polarization Reconstruction

Polarization angle reconstruction on **A2** and **A4** from **simulated pulses at SPICE**



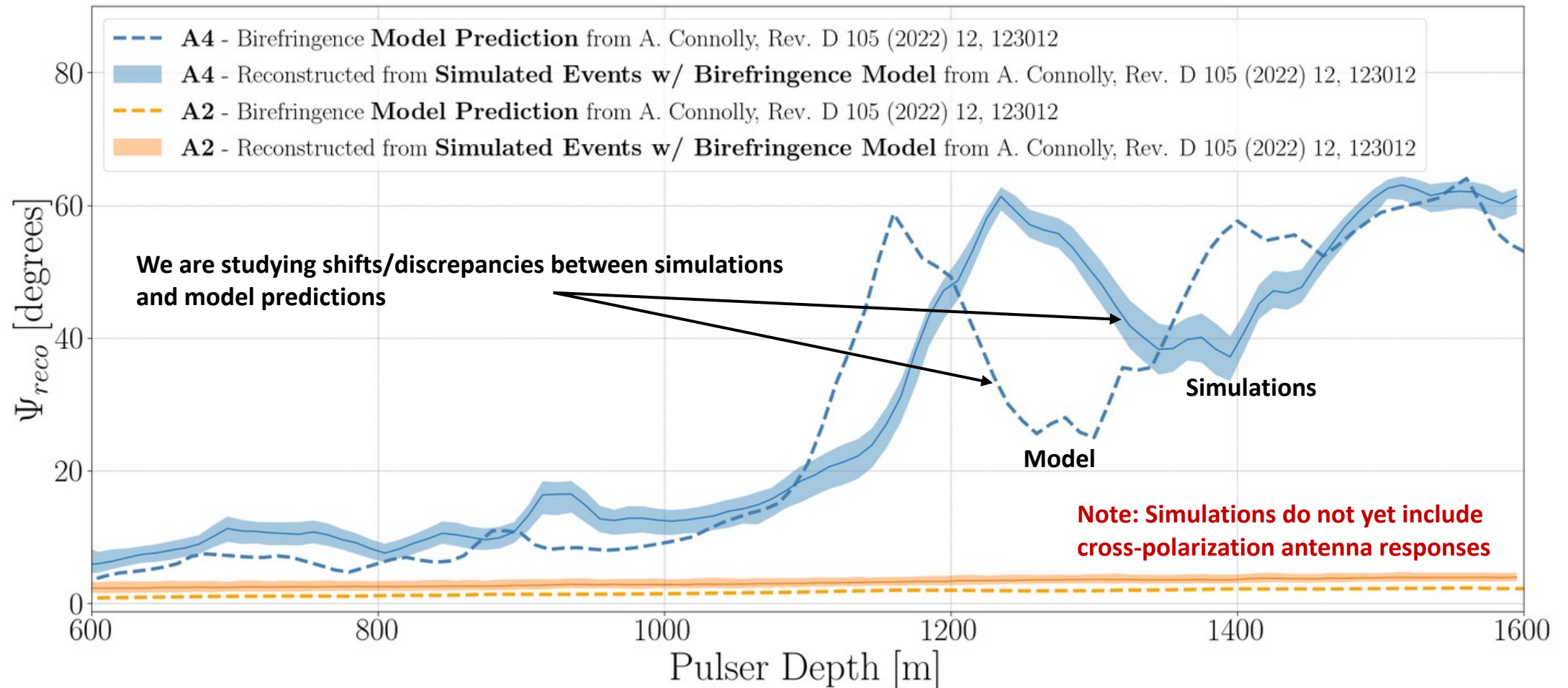
# Polarization Reconstruction

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# Polarization Reconstruction

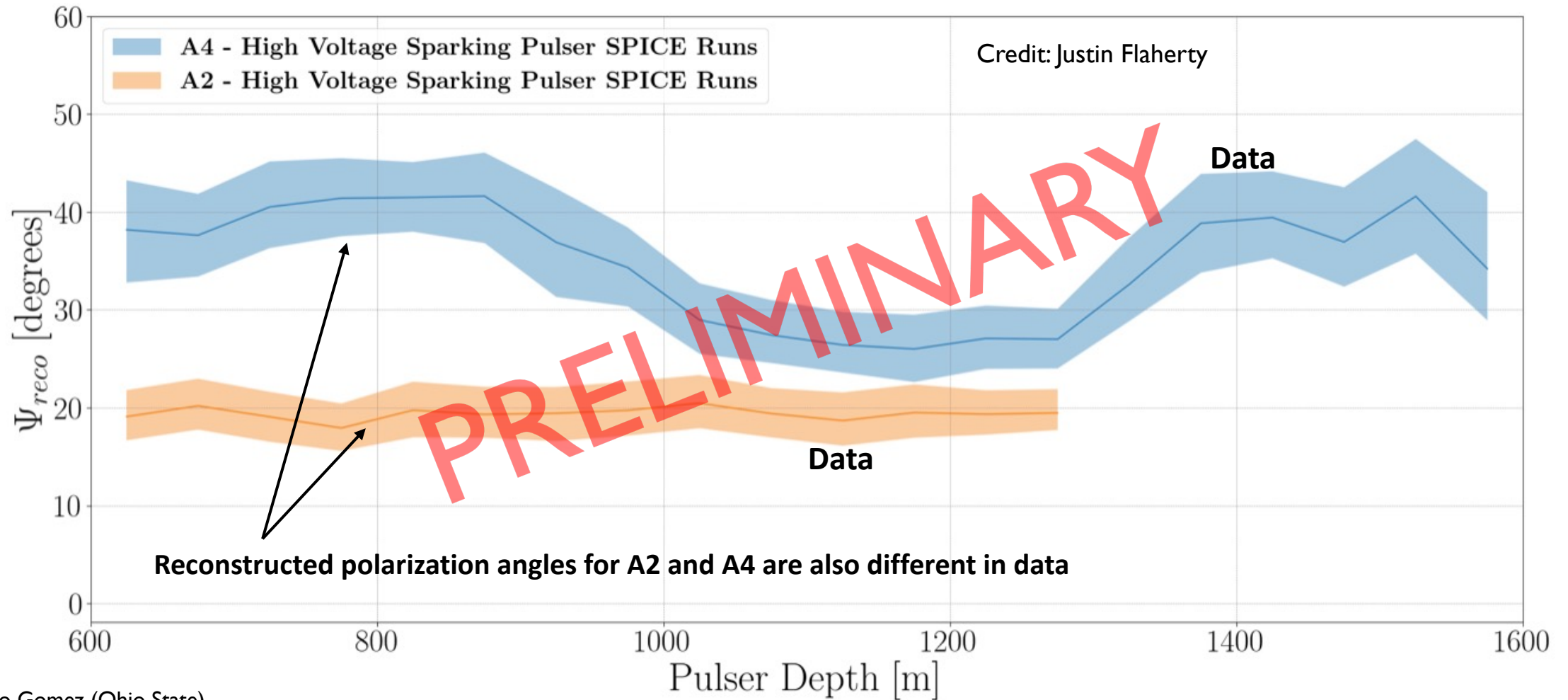
Polarization angle reconstruction on **A2** and **A4** from **simulated pulses at SPICE**





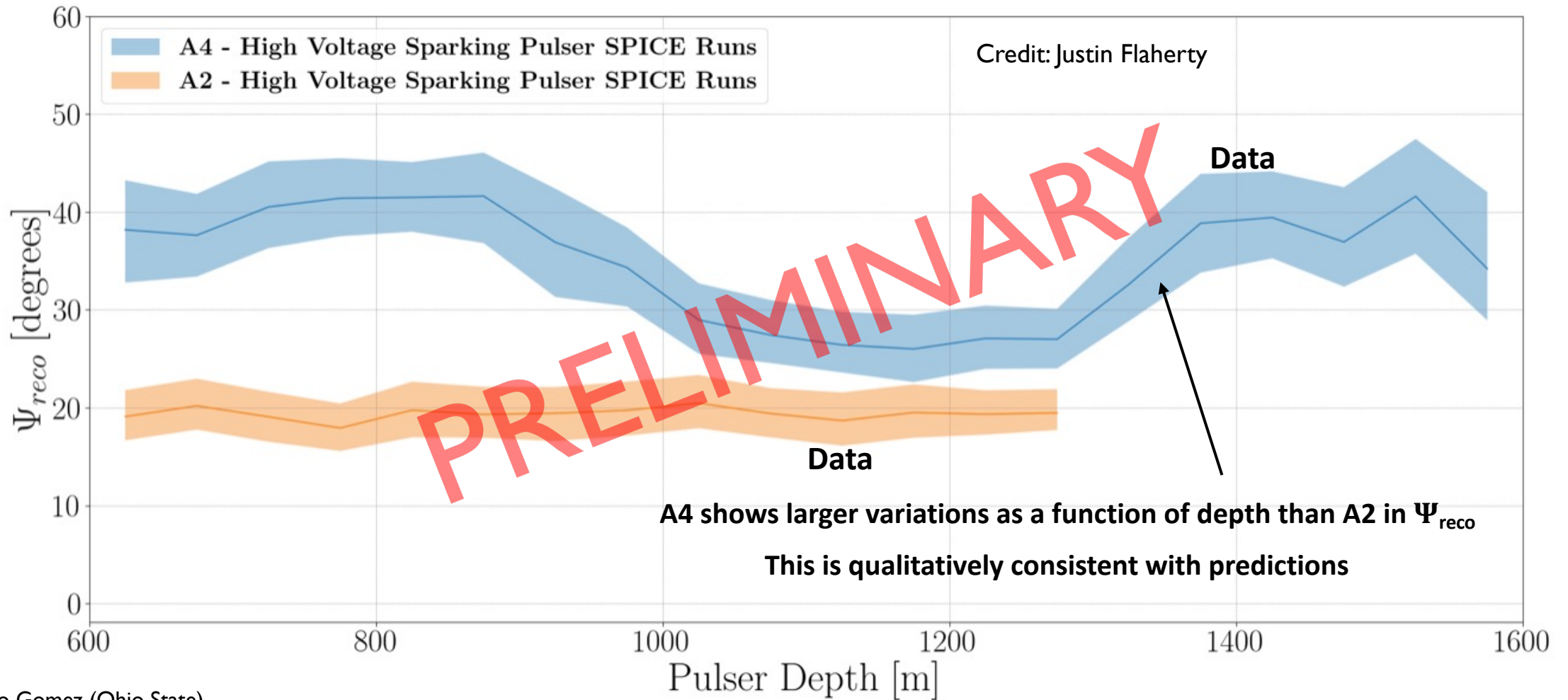
# Polarization Reconstruction

Polarization angle reconstruction on **A2** and **A4** from **SPICE** data



# Polarization Reconstruction

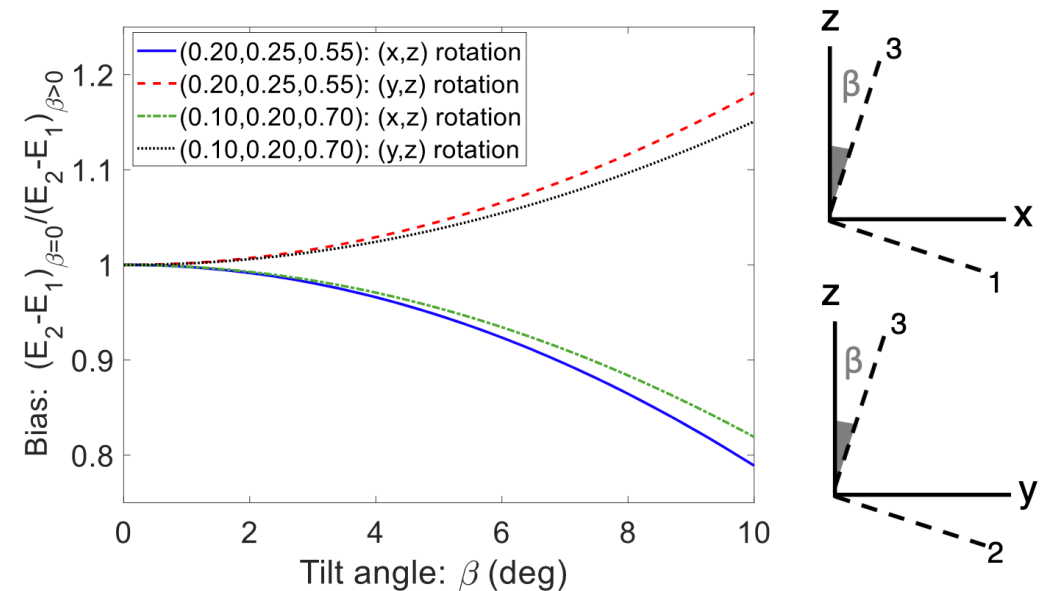
Polarization angle reconstruction on **A2** and **A4** from **SPICE** data



# Systematic Uncertainties

Uncertainties on the orientation of principal axes is not uncommon

- Theory assumes that indicatrix has  $\gamma$ -axis vertical and  $\alpha$ -axis along ice flow
- North Greenland Eemian Ice Drilling (**NEEM**):  $\alpha$ -axis as much as  $25^\circ$  from ice flow (Jordan et al, 2020) and the  $\gamma$ -axis  $9.6^\circ$  from vertical (J. Li, et al, 2018)
- At the South Pole, the tilt angle up to  $\sim 10^\circ$  (IceCube). Can lead to 20% uncertainties in  $n_\alpha - n_\beta$

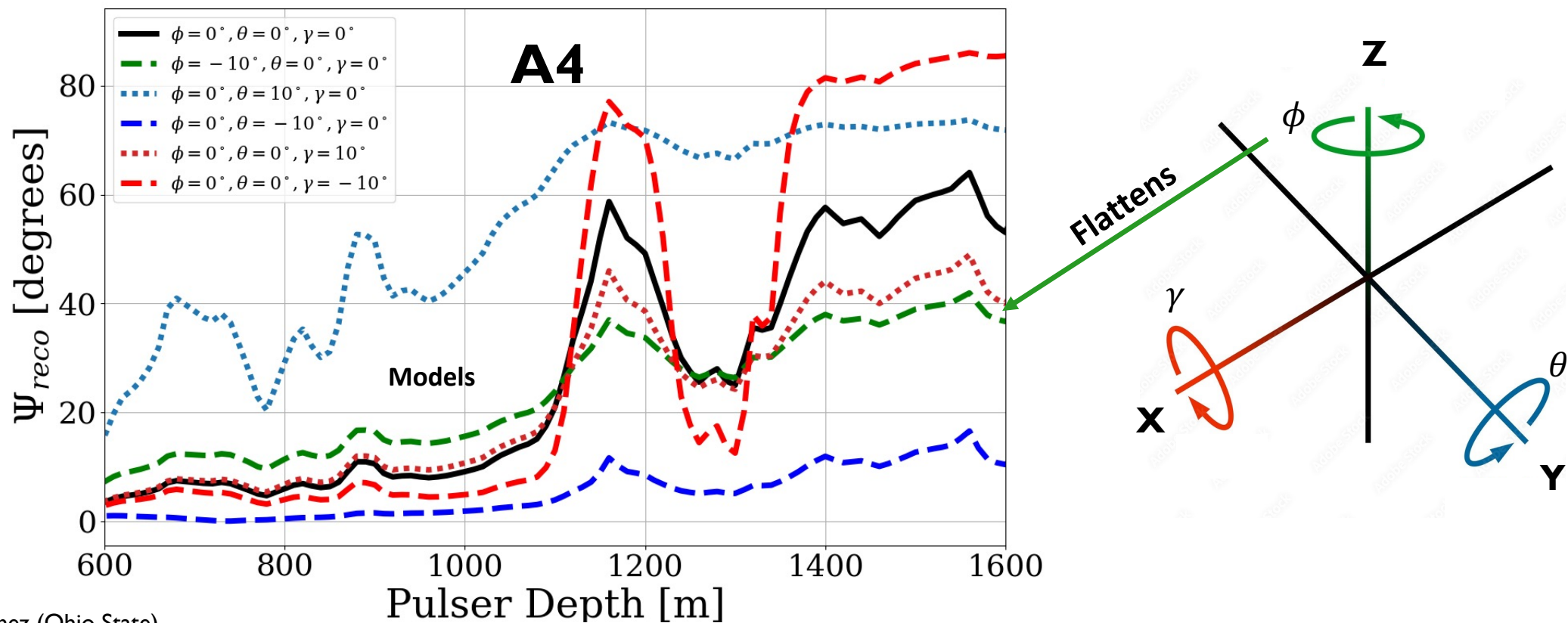


T. M. Jordan, . IEEE Transactions on Geoscience and Remote Sensing, 57 (2019) 11, 8641–8657

# Systematic Uncertainties

These can have a large effect on predictions for polarization reconstruction

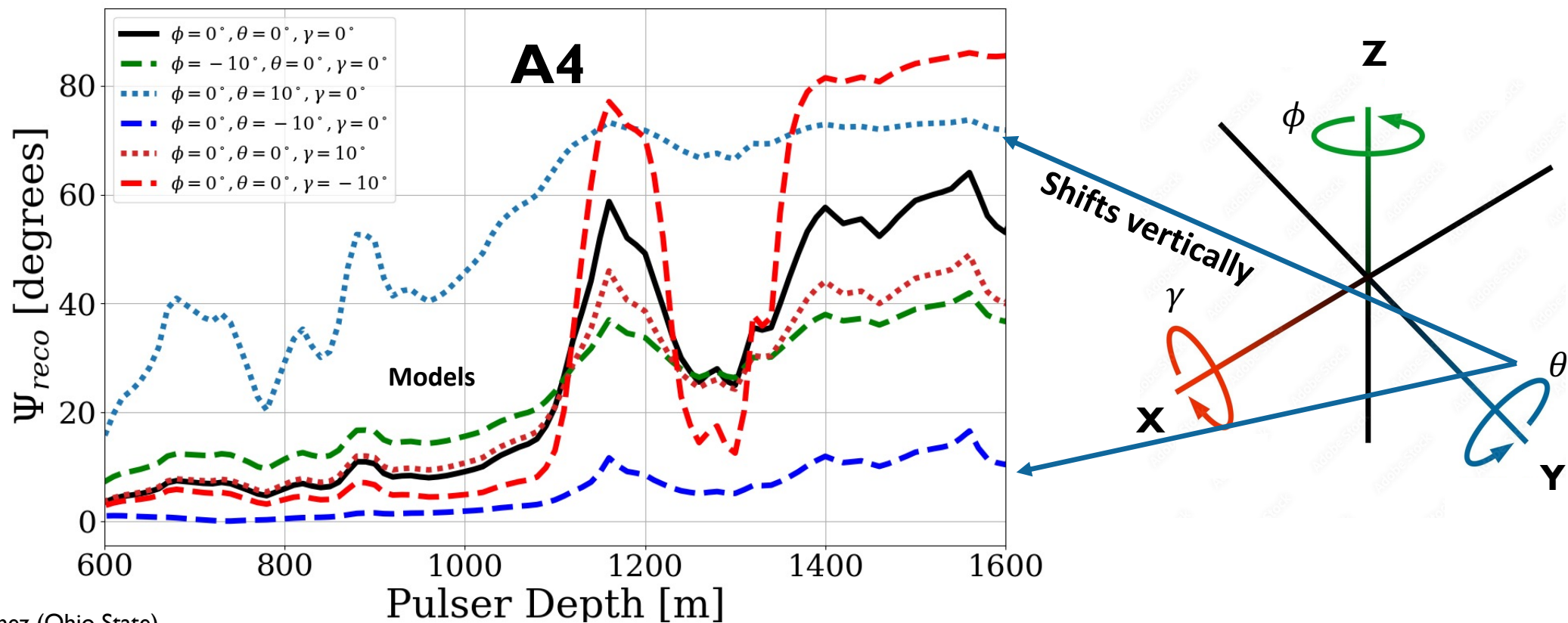
- Exploring effects of **rotating principal axes around each axis** on predictions for polarization reconstruction angles



# Systematic Uncertainties

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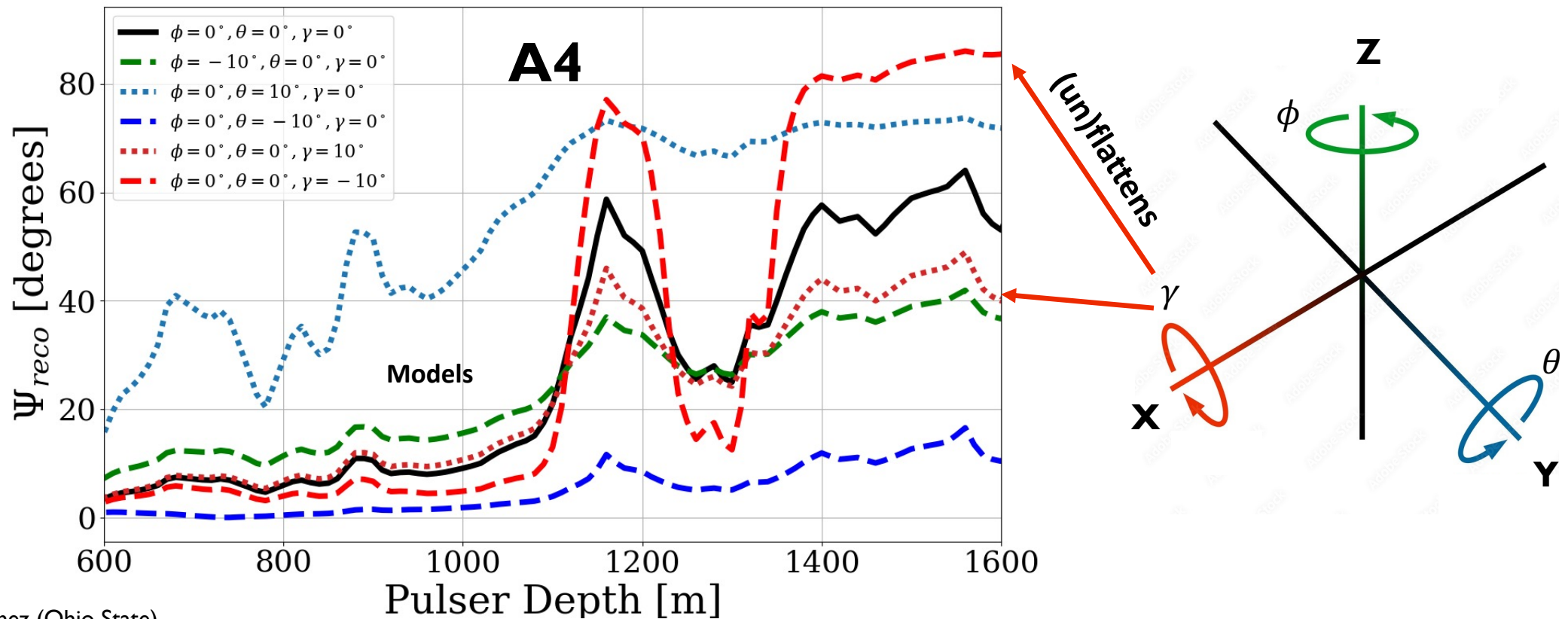
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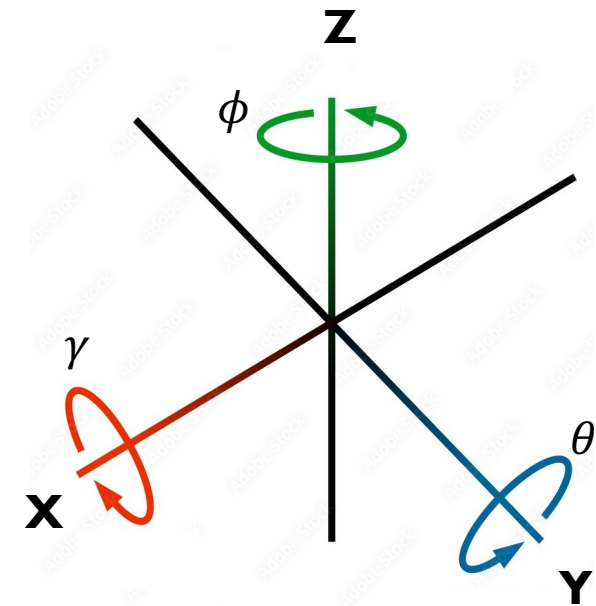
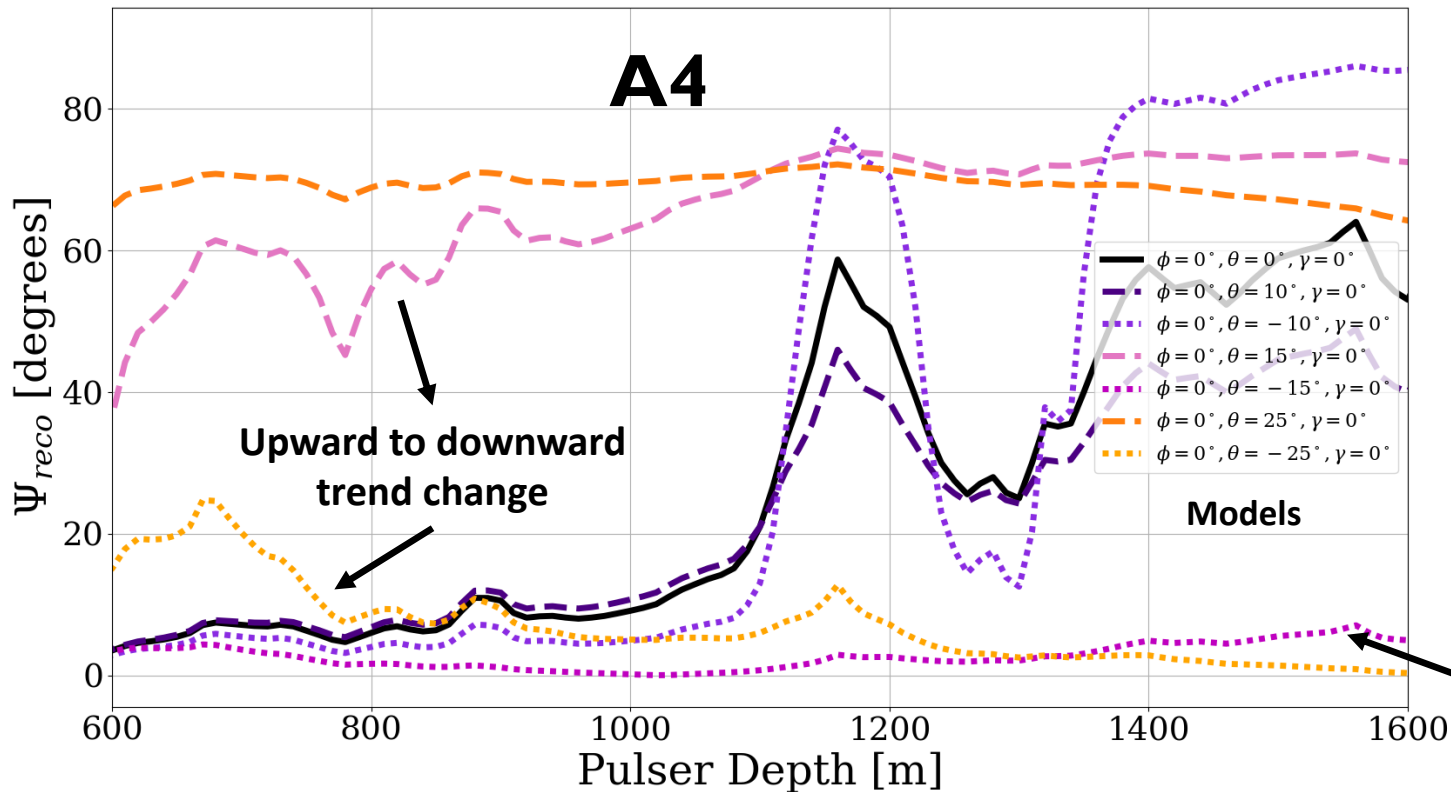
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# Systematic Uncertainties

These can have a large effect on predictions for polarization reconstruction

- The qualitative shape of  $\Psi$  in data can be potentially obtained with a fit in  $(\phi, \theta, \gamma)$  across all five ARA stations



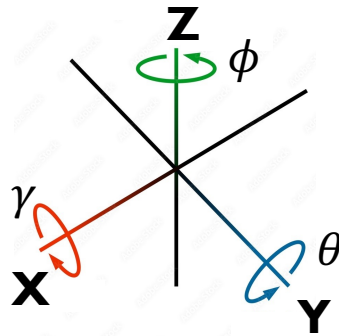
Better agreement with data's shape

# Future Work

Biaxial birefringence effects may have implications for analysis and detector design

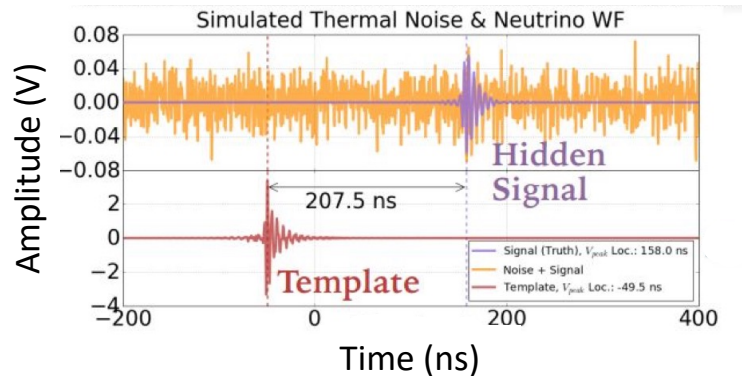
## Principal Axes Orientation Fit:

- Fit rotation angles of birefringence parameters using SPICE data set across all ARA stations



## Neutrino Template Analysis:

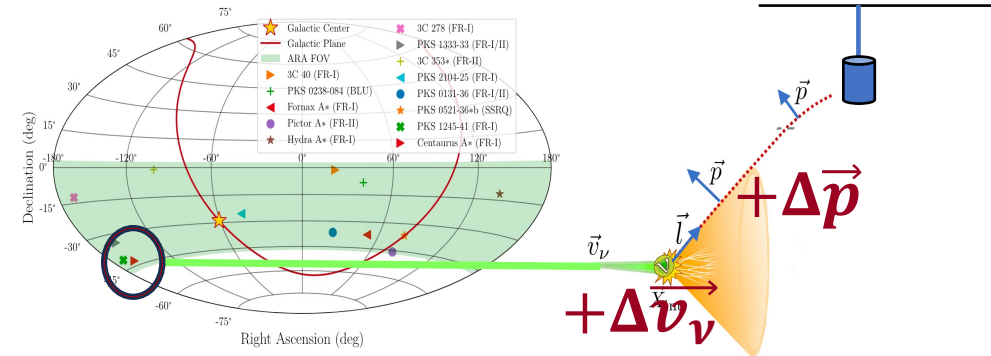
Credit: Myoungchul Kim



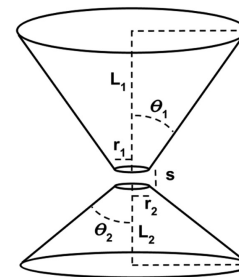
- Can design neutrino templates with birefringence effects

## Point Source Search:

Modified from J. Torres (2020) and S. Barwick, C. Glaser (2023)



- Birefringence should be taken into account in directional neutrino searches



## GENETIS is Optimizing Antenna and Array Designs:

- Exploring the optimization of antenna designs and detector array layouts accounting for birefringence effects



# Summary

- We are investigating **South Pole ice as a biaxial birefringent medium at radio frequencies.**
- Biaxial birefringence is expected to **cause rotations in polarization.**
- We are **using the unique SPICE pulser data set** across all five ARA stations **to fit for the parameters of the birefringence principal axes.**
- Biaxial birefringence **might need to be accounted for polarization reconstruction** and for performing point source searches of ultra-high energy neutrinos.
- **The effects of biaxial birefringence represent opportunities** to improve analysis and optimize detector designs.

# Fin

- **Thank you!**