ASKARYAN RADIO ARRAY

TeVPA Chicago 2024

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

Alan Salcedo Gomez for the ARA Collaboration

August 28th, 2024

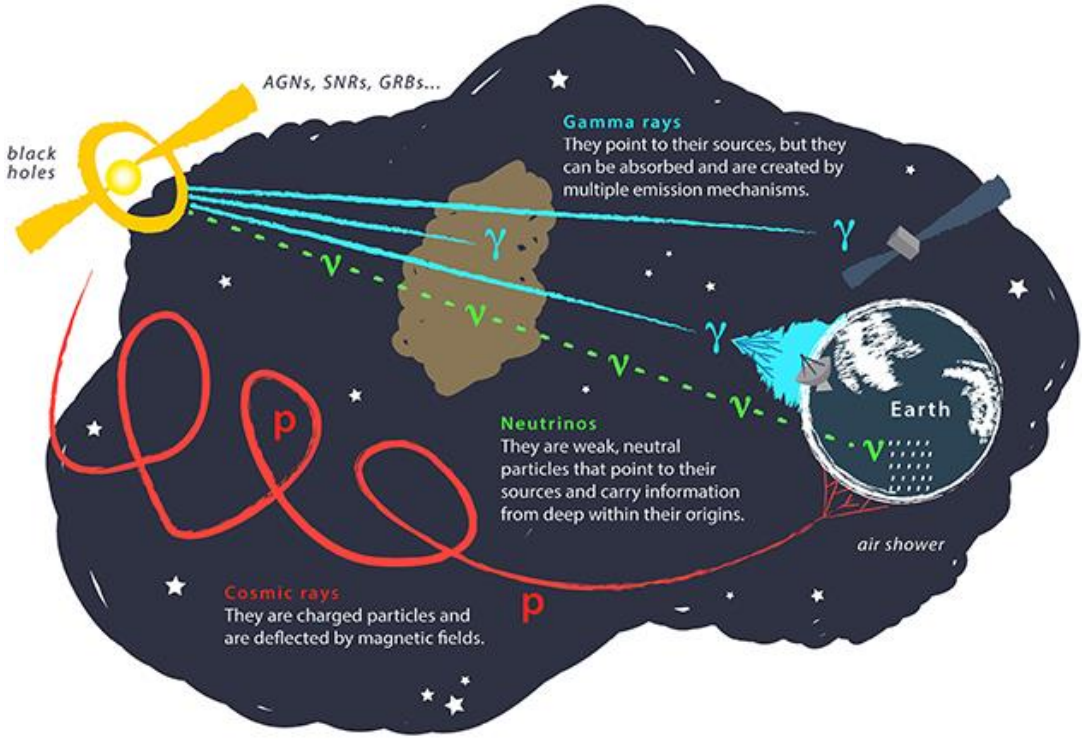
NSF

THE OHIO STATE UNIVERSITY

CCAPP

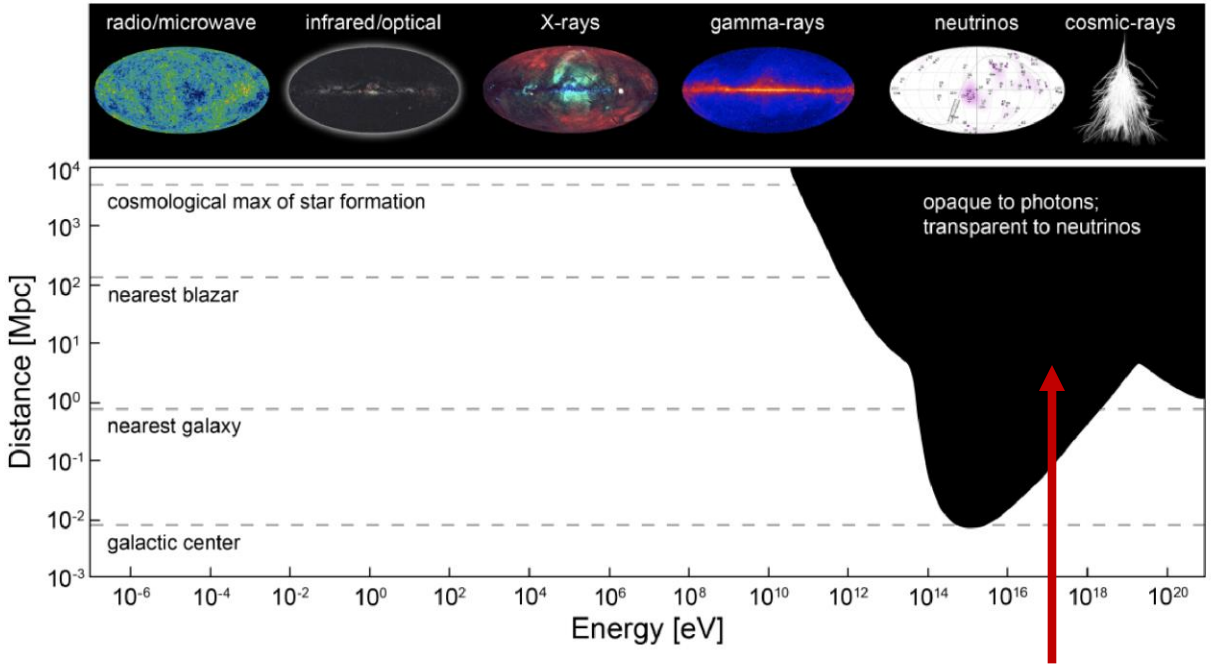
Context

We want to expand the horizon of multi-messenger astrophysics



Credit: IceCube Collaboration

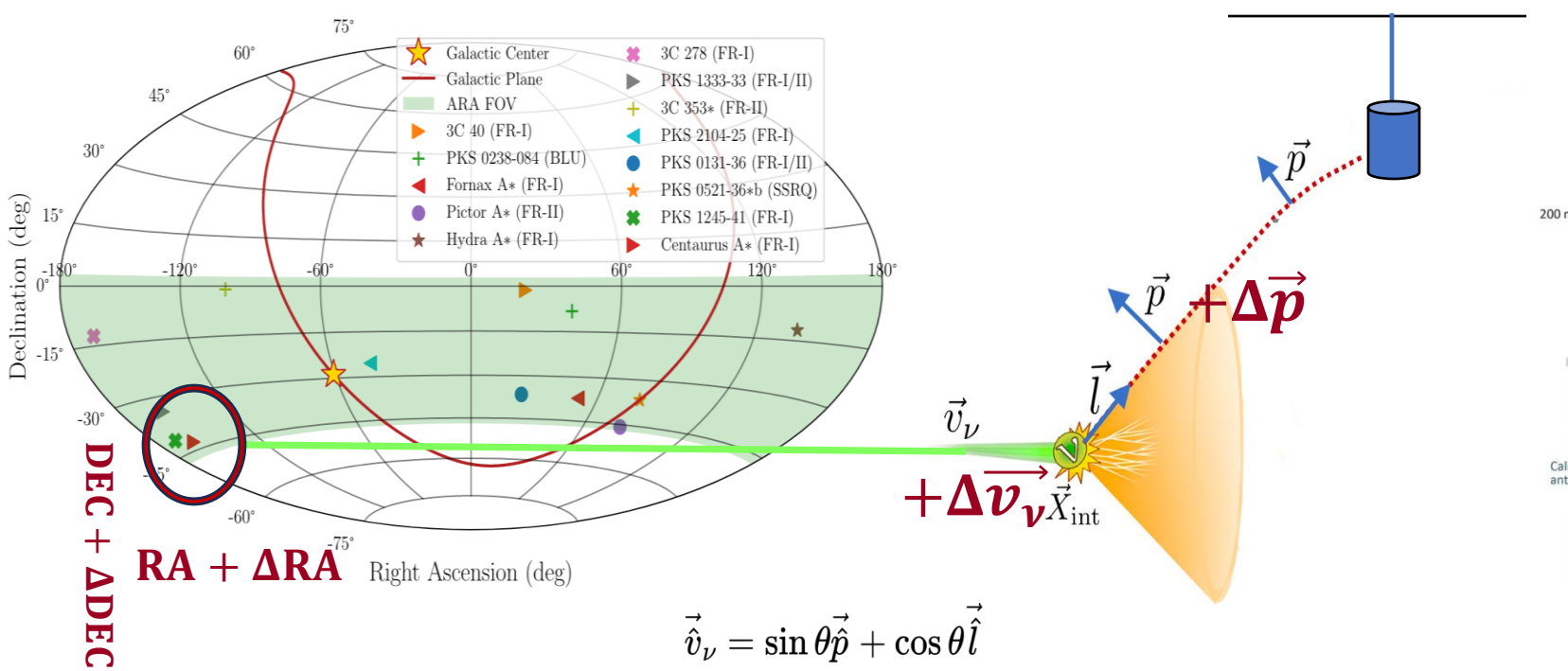
- Use neutrinos to **study the most energetic and distant astrophysical sources** in the Universe

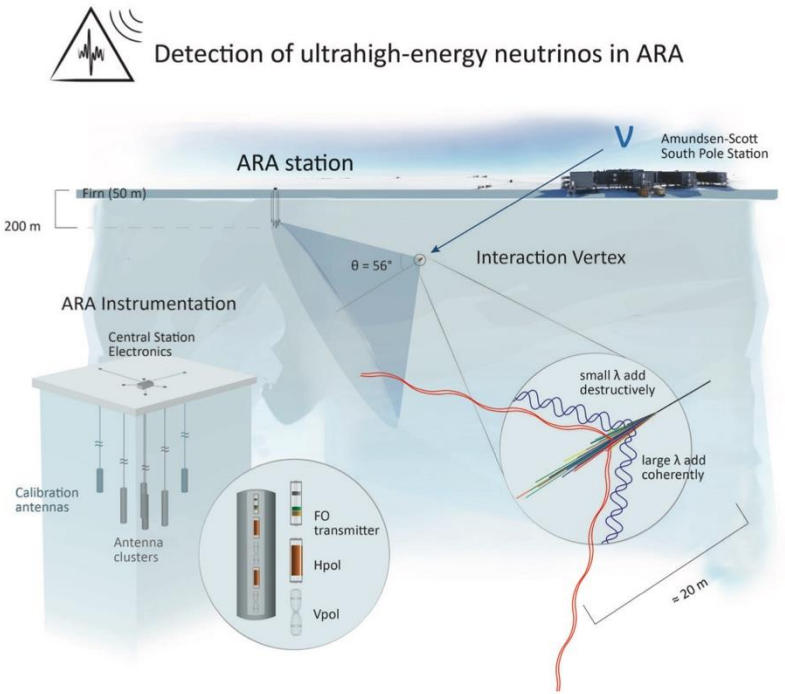


Context

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**



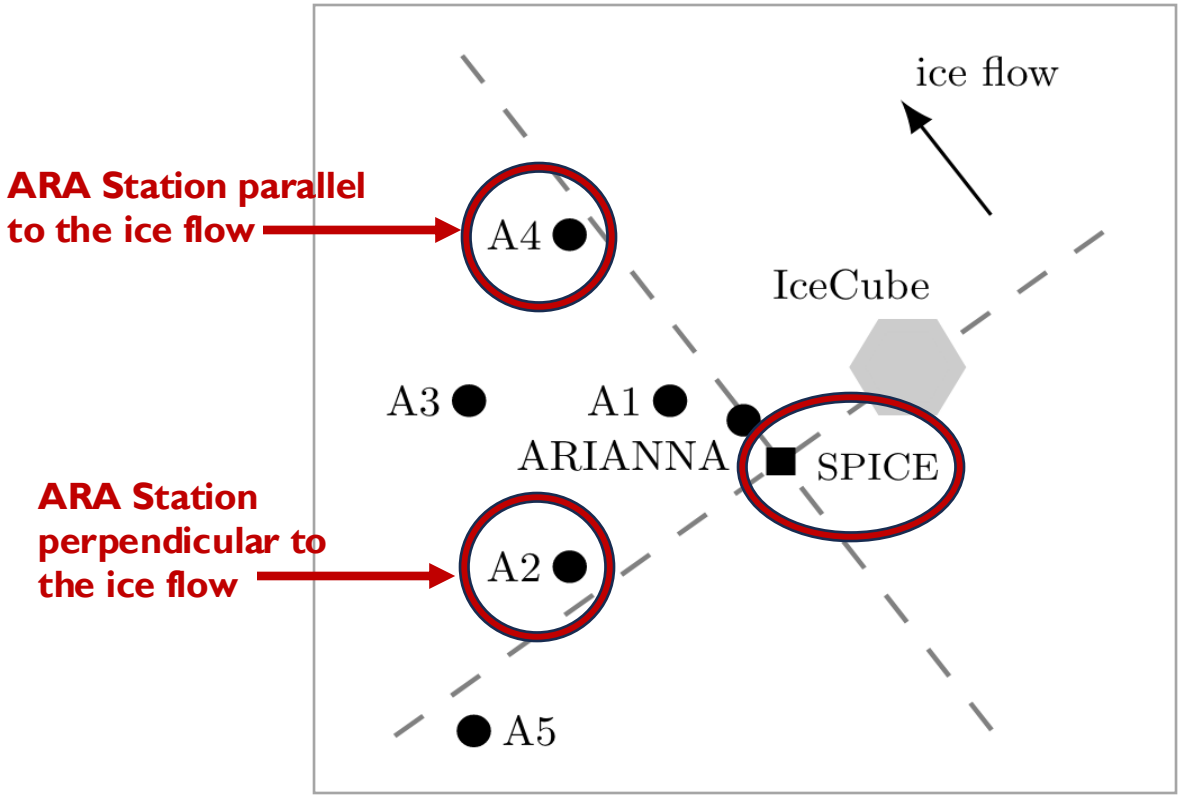


Modified from J. Torres (2020) and S. Barwick, C. Glaser (2023)

SPICE Pulser

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 ~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**

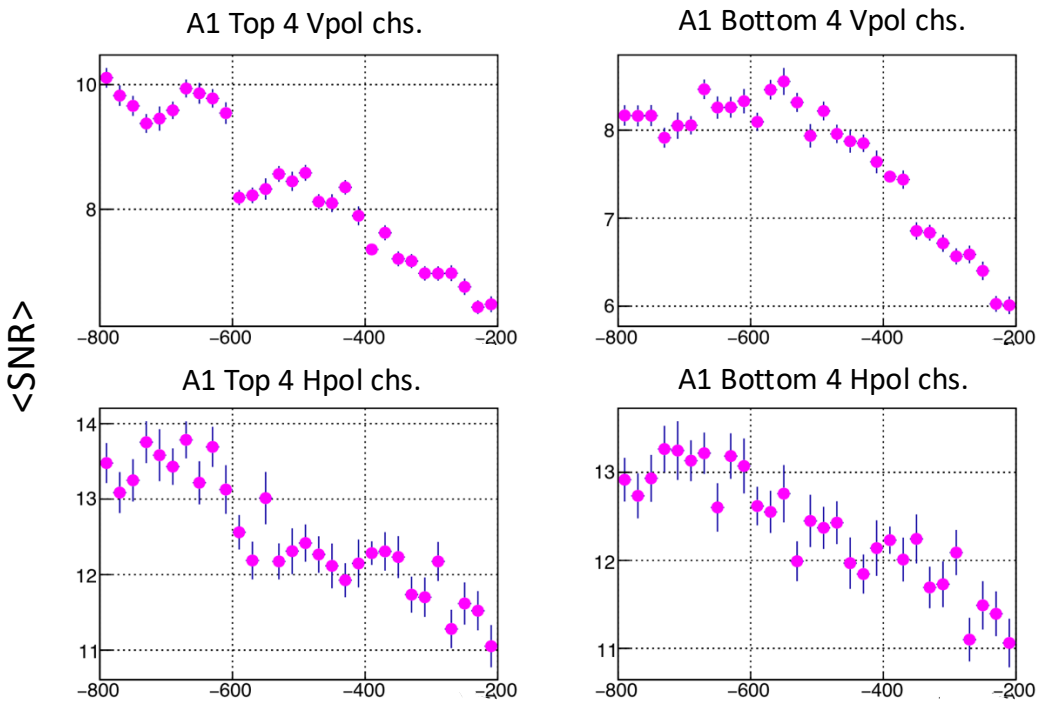


A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

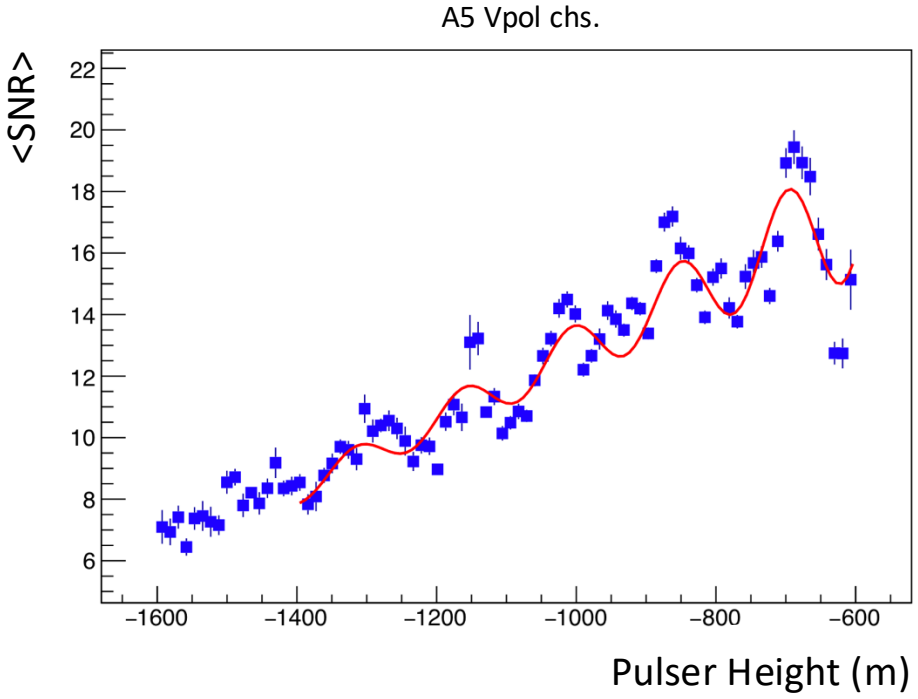
SPICE Pulser

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

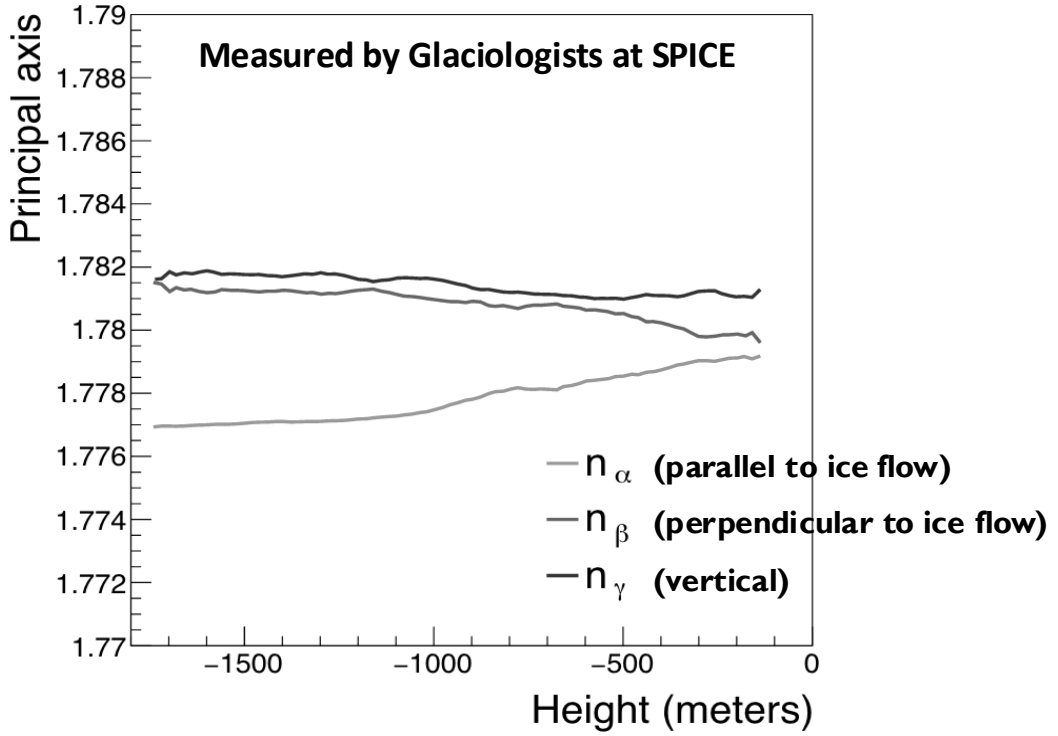


P.Allison et al, JCAP 12 (2020) 009

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, known as principal axes
- We are exploring **biaxial birefringence as a possible explanation of the anomalous behavior** of polarization **in SPICE events**



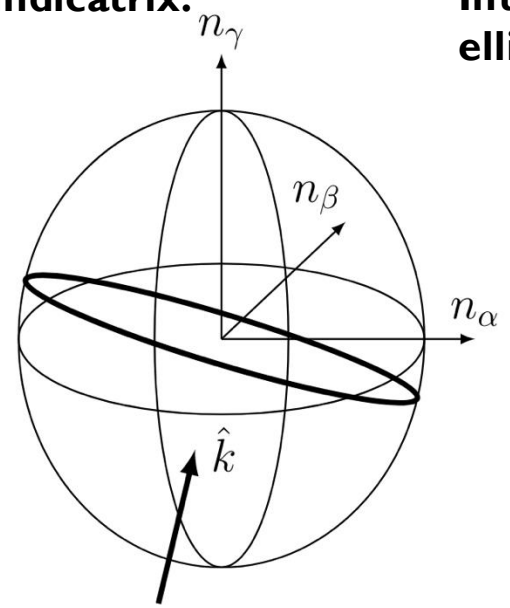
A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

Birefringence Model

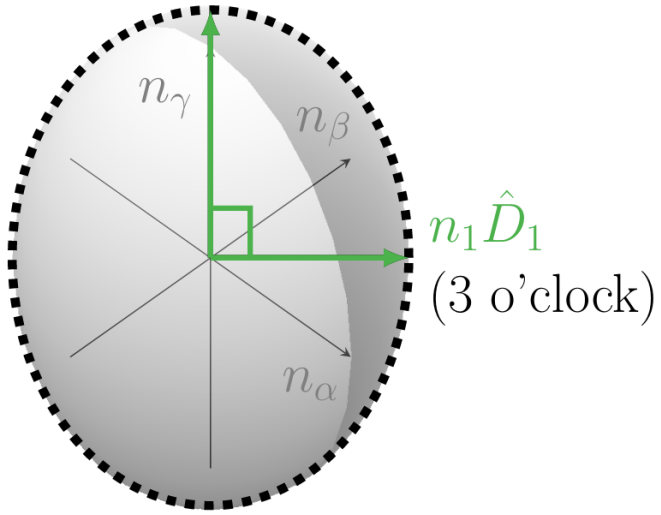
The polarization vector is described by two eigenstates dependent on the principal axes

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

Indicatrix:



Intersection ellipse: $n_2\hat{D}_2$(12 o'clock)



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

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

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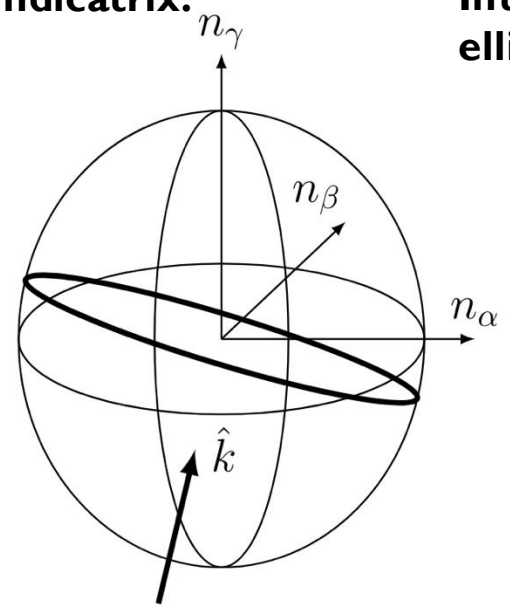

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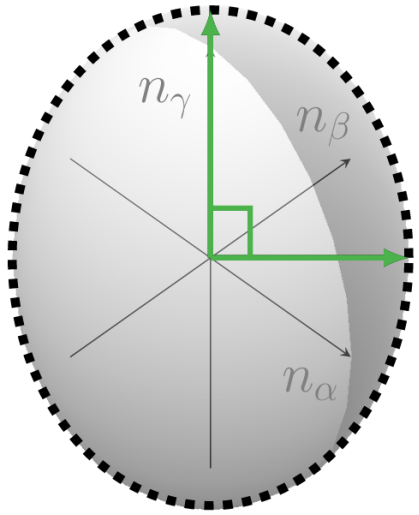
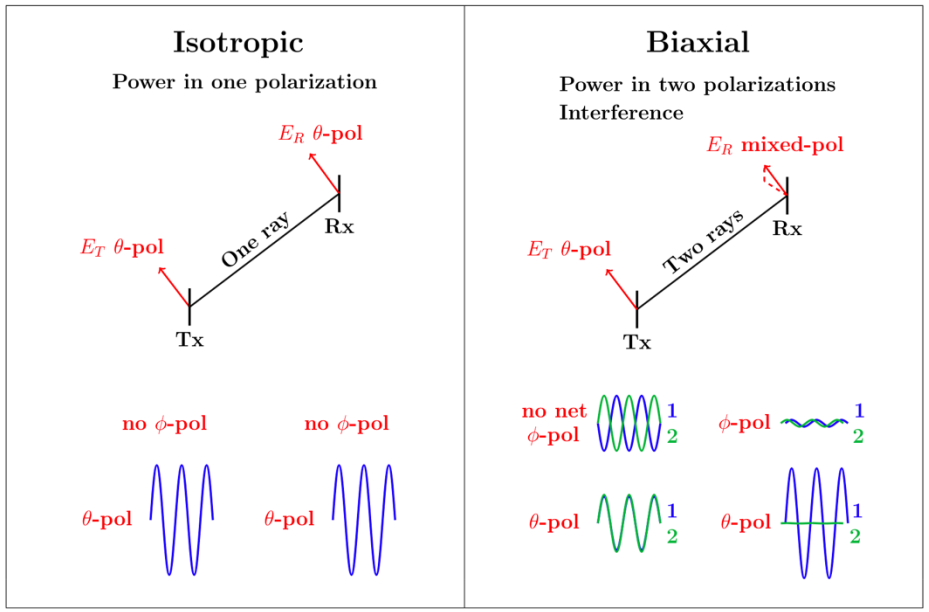


$n_1\hat{D}_1$ (3 o'clock)

Polarization description before: | Polarization description now:



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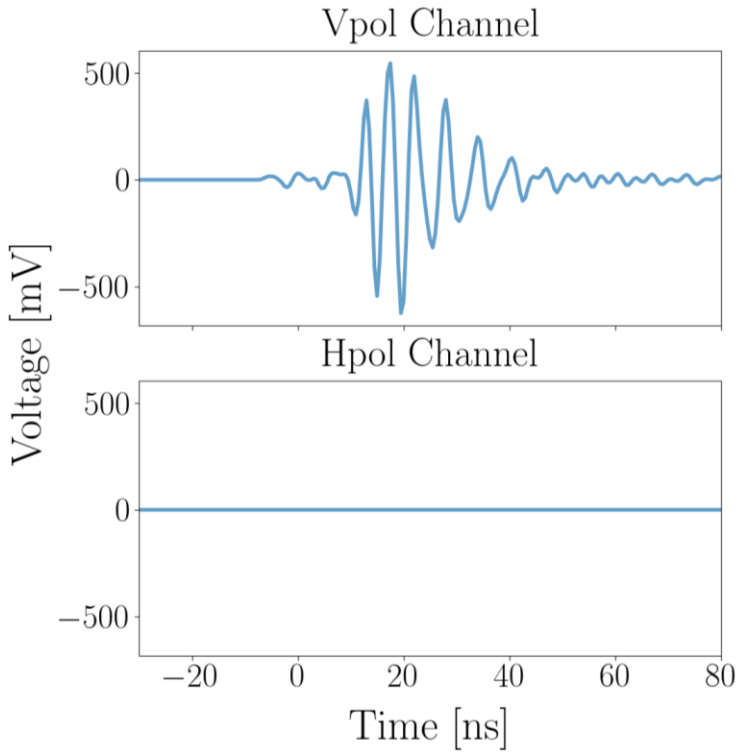
A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

Birefringence Model

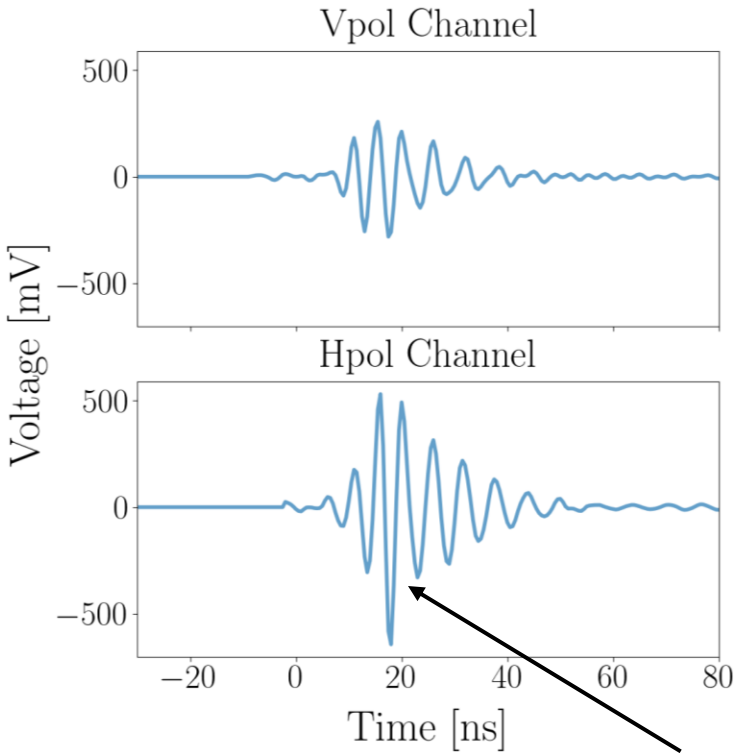
This birefringence model is now implemented in AraSim

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

Without birefringence



With biaxial birefringence:



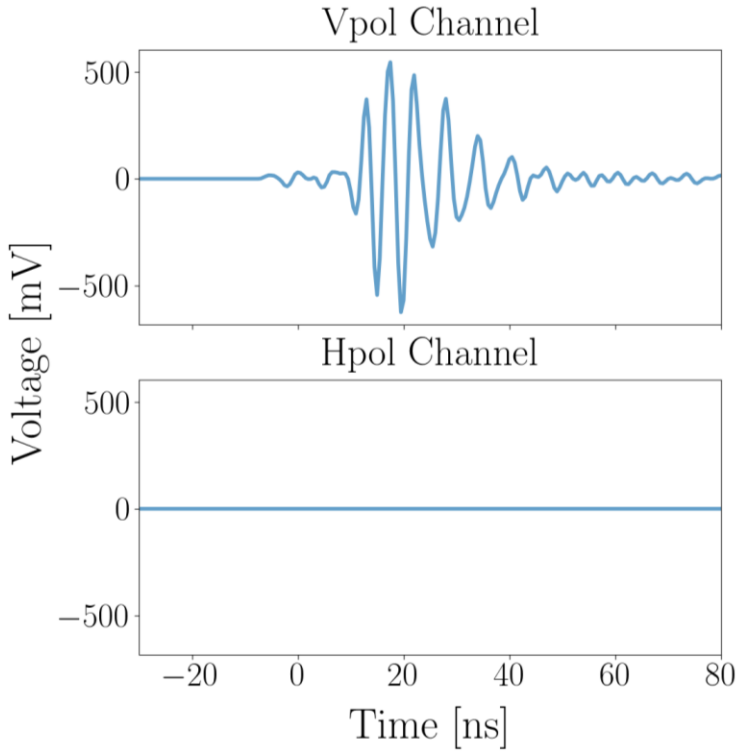
Rotation

Birefringence Model

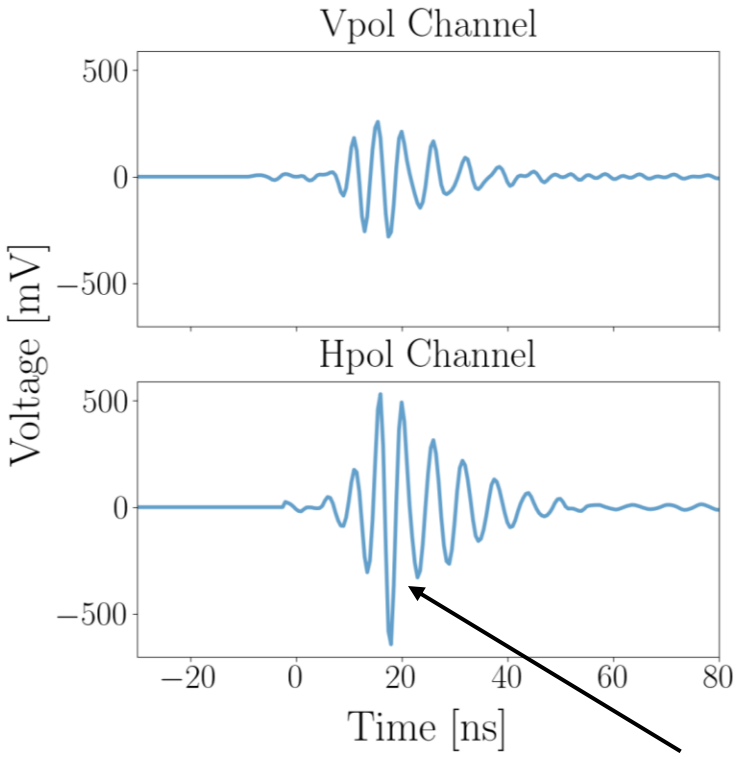
The **polarization** of a signal **is allowed to rotate** in this model

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

Without birefringence



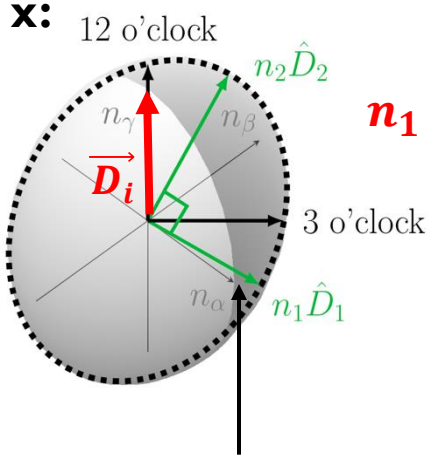
With biaxial birefringence:



Rotation

Tx:

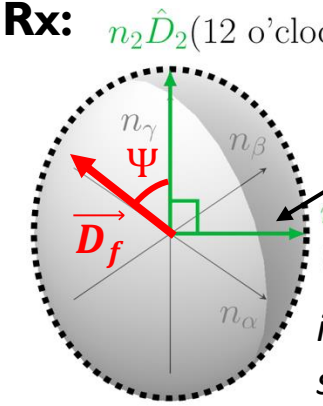
Polarization rotates because



$n_1 \approx n_2$

Eigenstates rotate adiabatically

Rx:



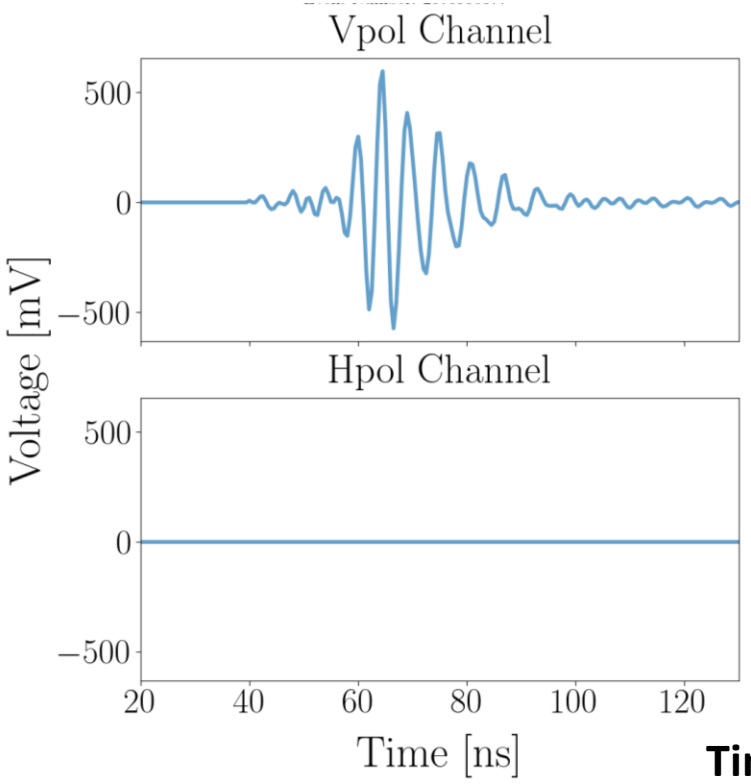
i.e. power in ray 1 (ray 2) stays in ray 1 (ray 2)

Birefringence Model

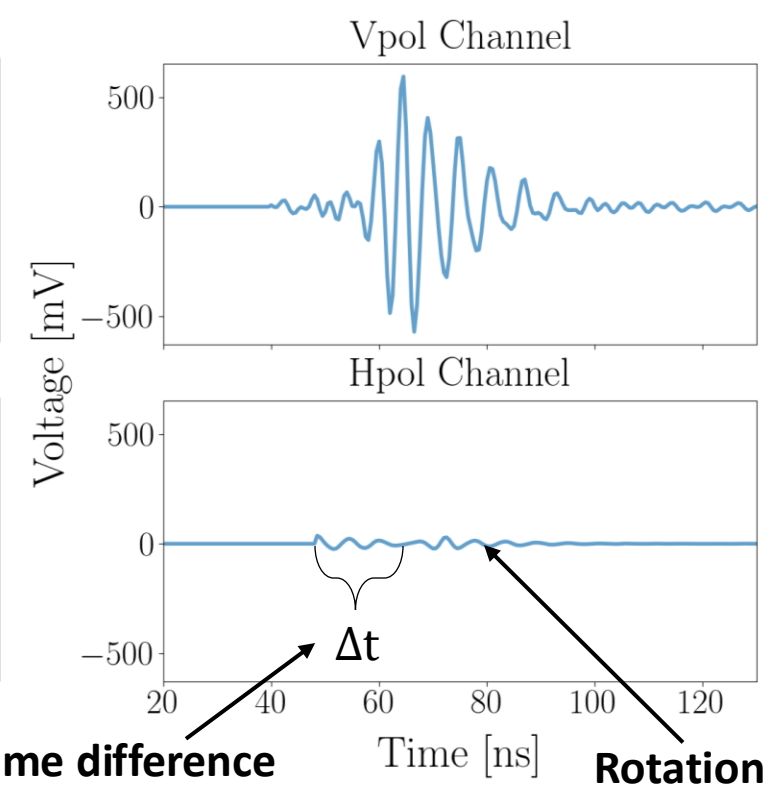
The polarization **eigenstates** are allowed to **arrive at different times**

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

Without birefringence:



With biaxial birefringence:



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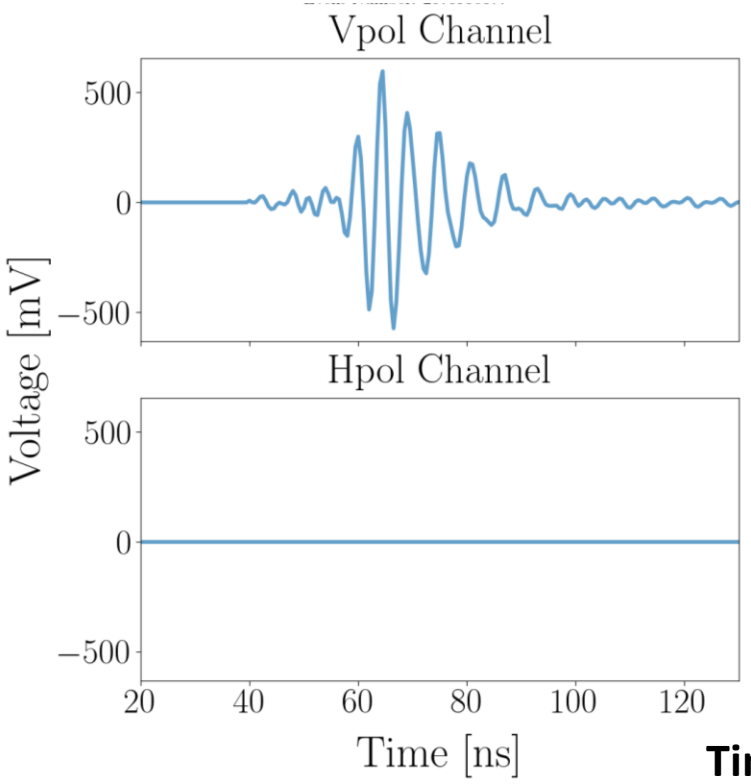

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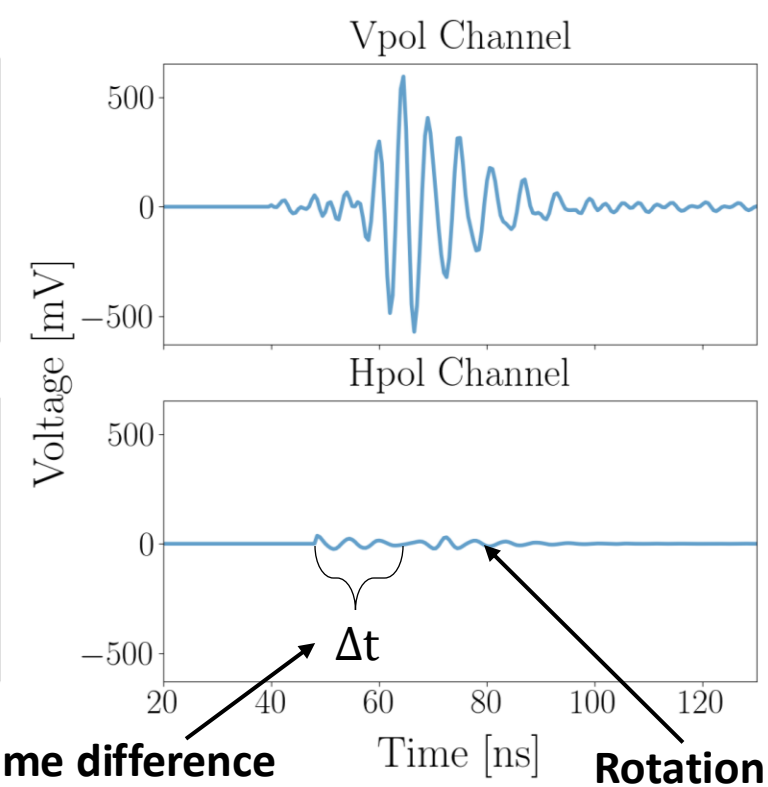
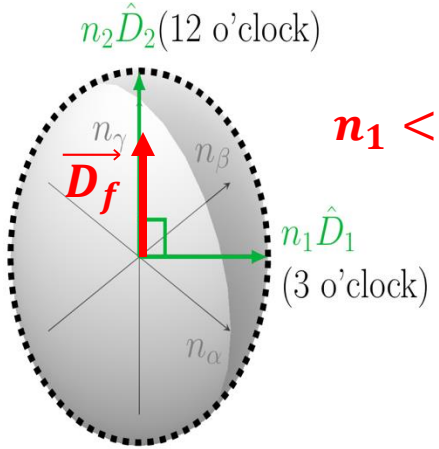
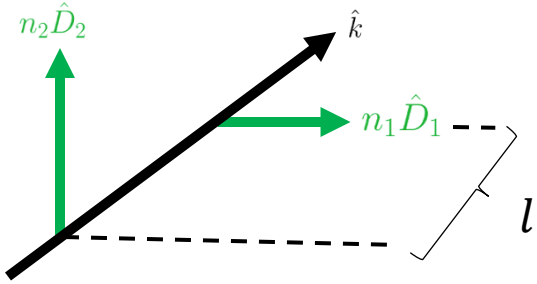


Time difference **Rotation**

Tx and Rx:



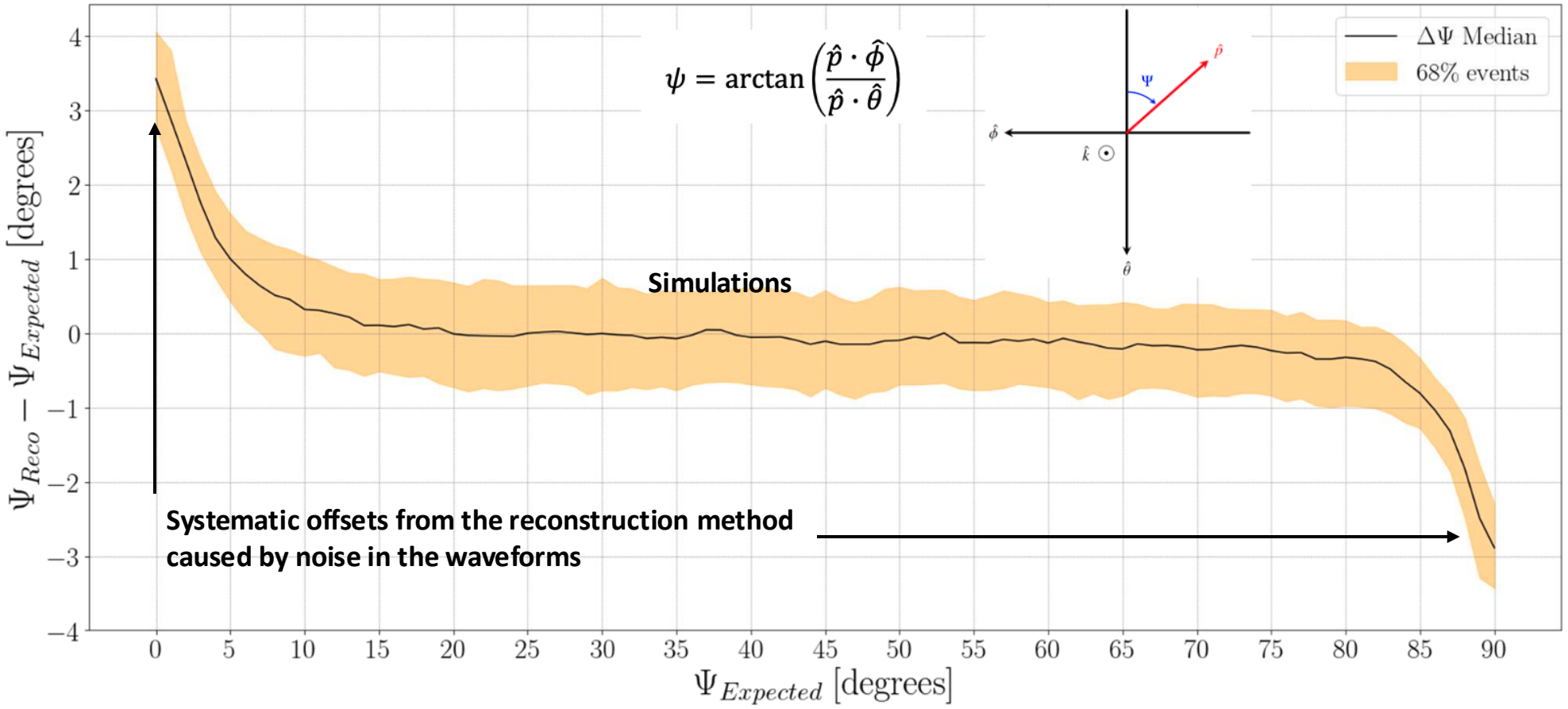
$n_1 < n_2$



$$l = \frac{c\,\Delta t}{n_2 - n_1}$$

Polarization Reconstruction

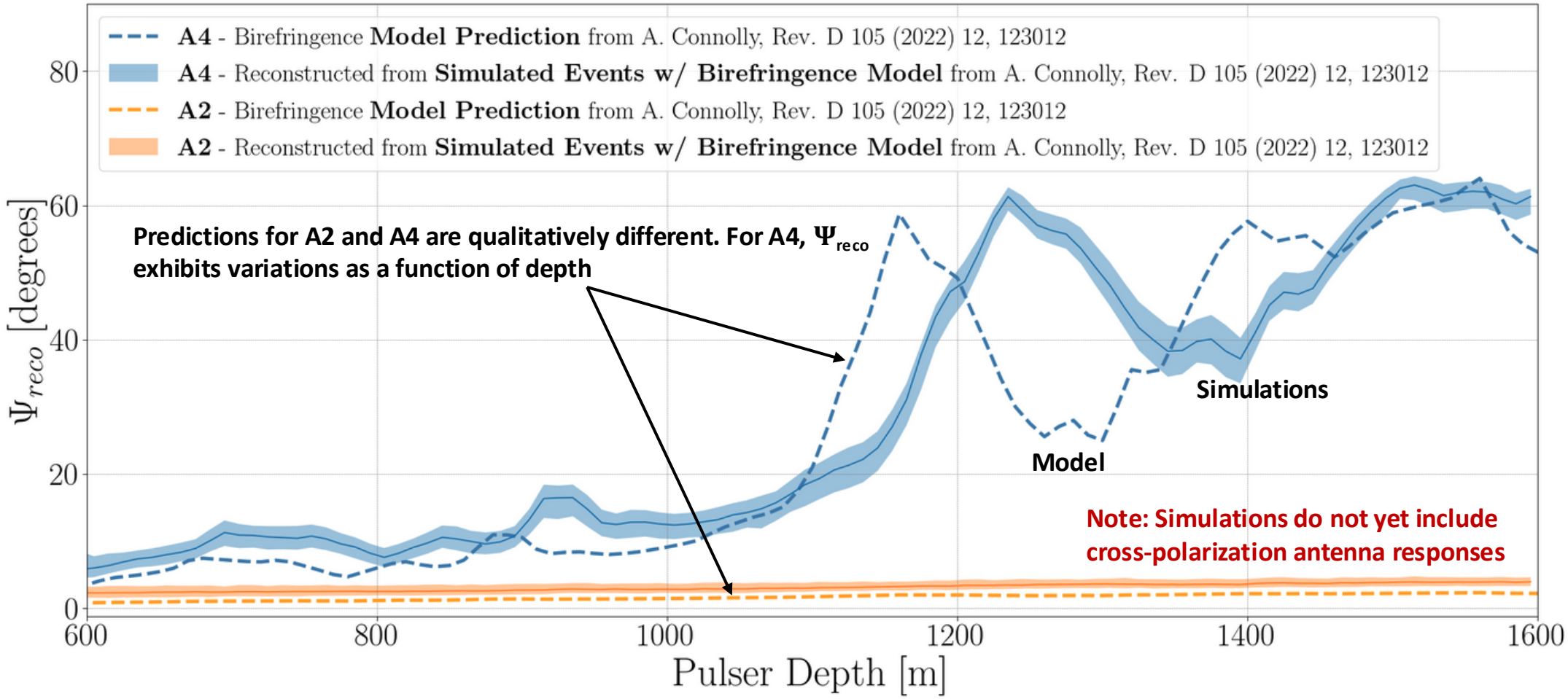
Reconstructing the polarization angle from ARA events is possible



J. Flaherty, PoS ICRC (2023)

Polarization Reconstruction

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



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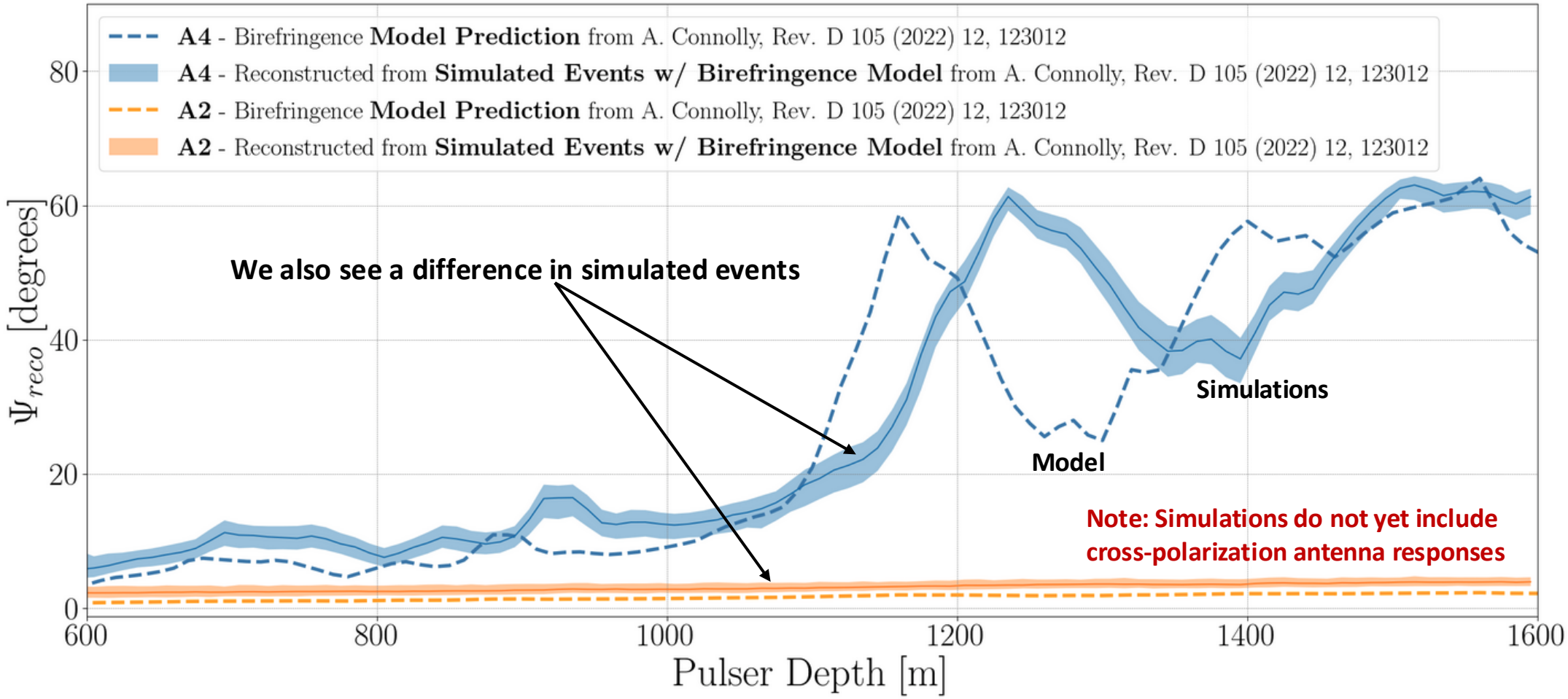

Alan Salcedo Gomez (Ohio State)

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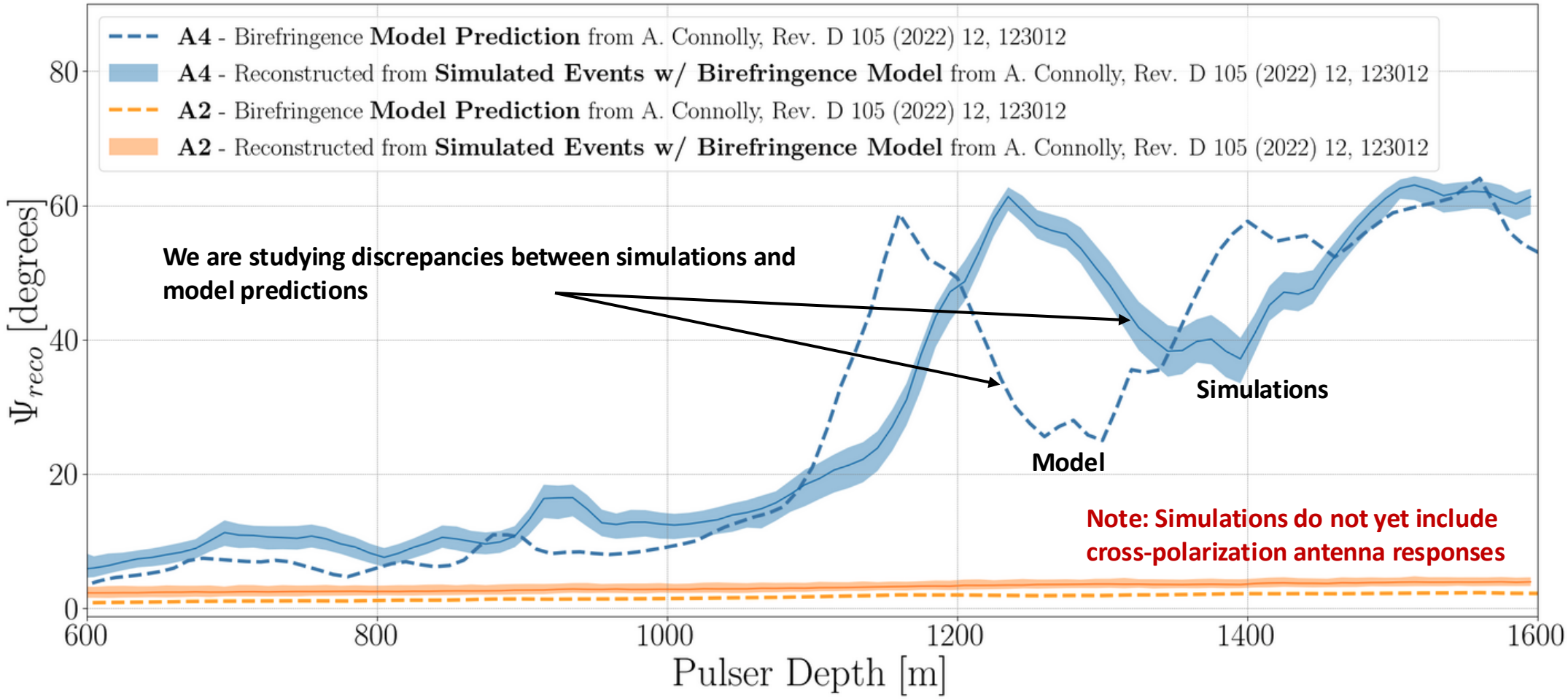
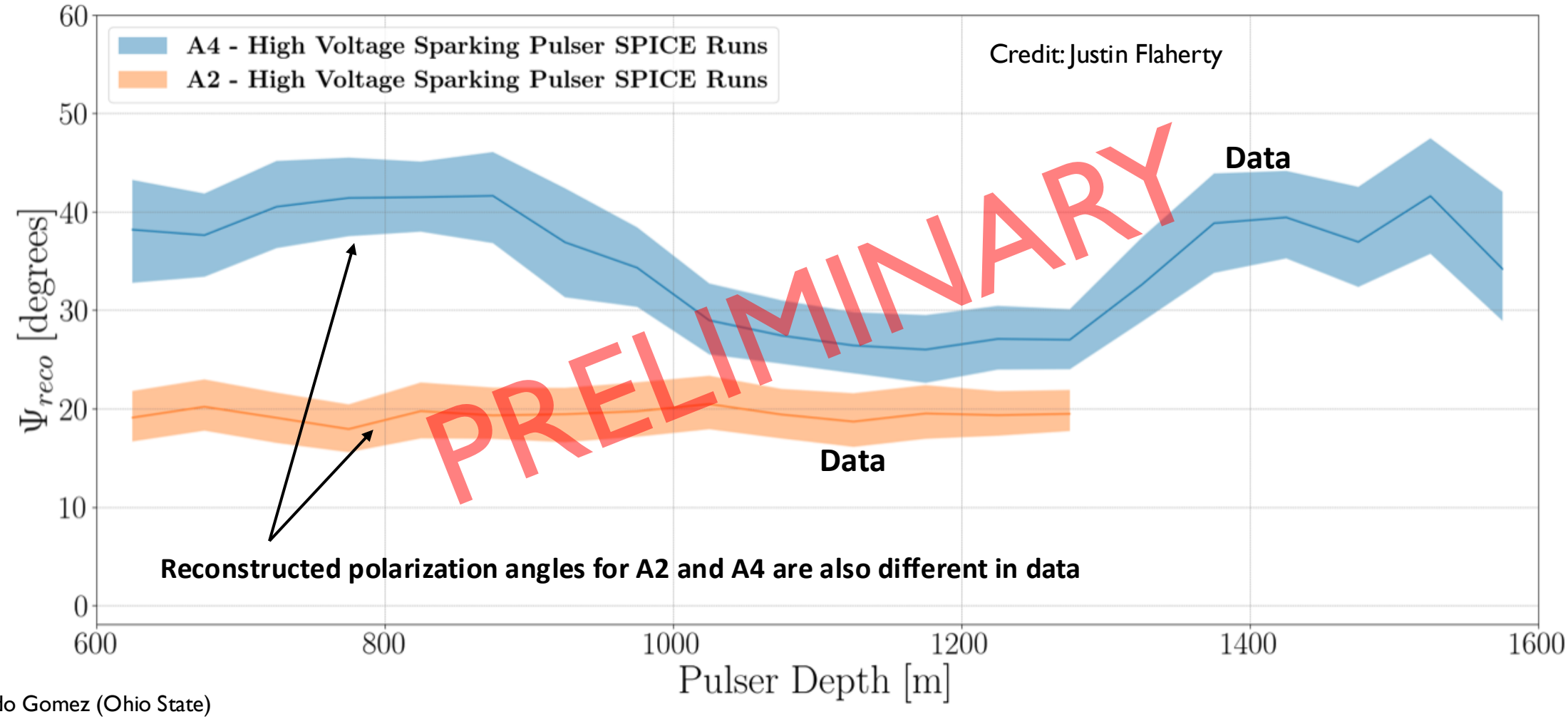


Polarization Reconstruction

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



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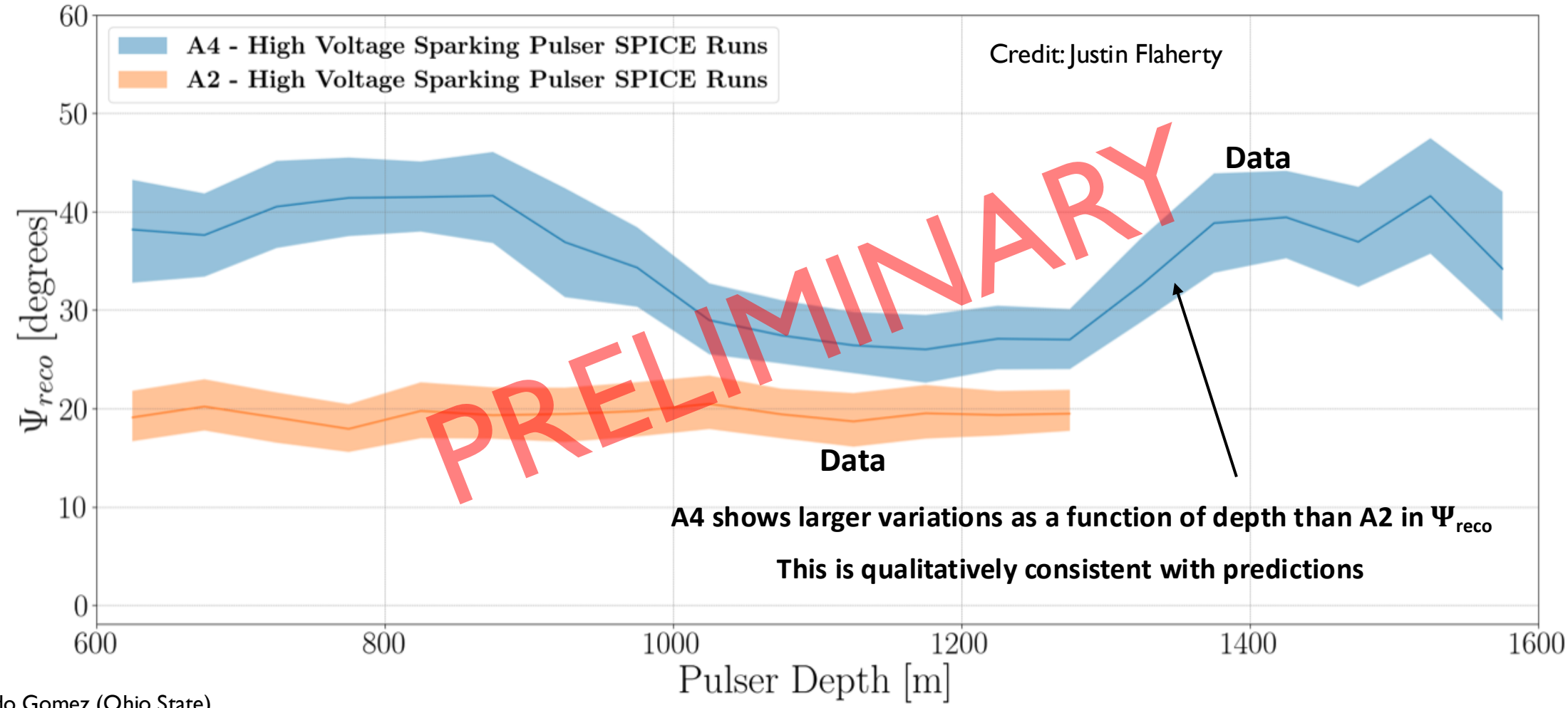
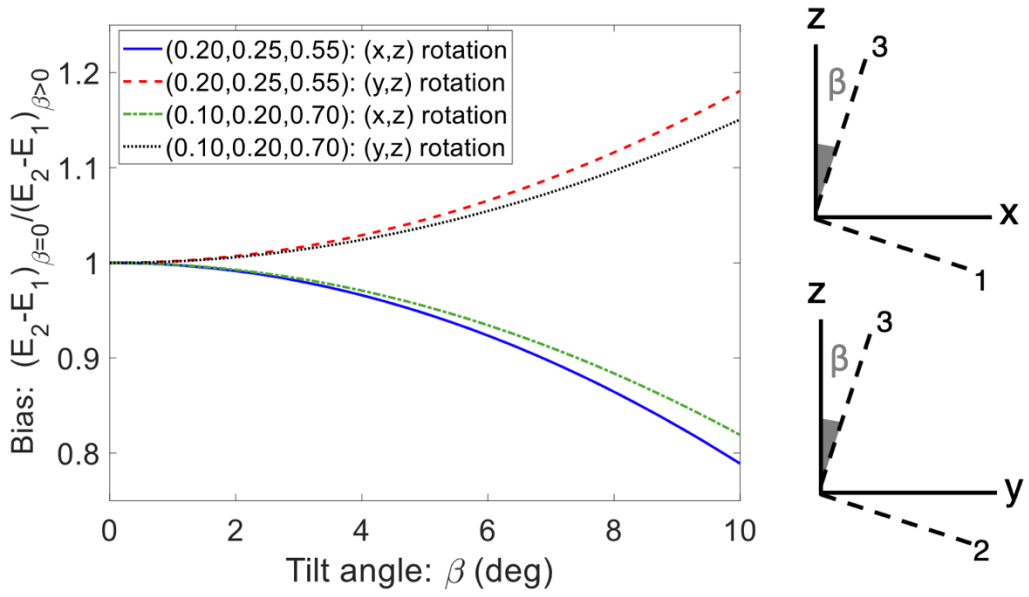


Systematic Uncertainties

Uncertainties **on the orientation of principal axes** is not uncommon

- Theory assumes that indicatrix has γ-axis vertical and α-axis along ice flow
- North Greenland Eemian Ice Drilling **(NEEM):** α-axis as much as $\mathbf{25}^{\circ}$ **from ice flow** (*Jordan et al, 2020*) and the γ-axis $\mathbf{9.6}^{\circ}$ **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 $n_{\alpha} - n_{\beta}$

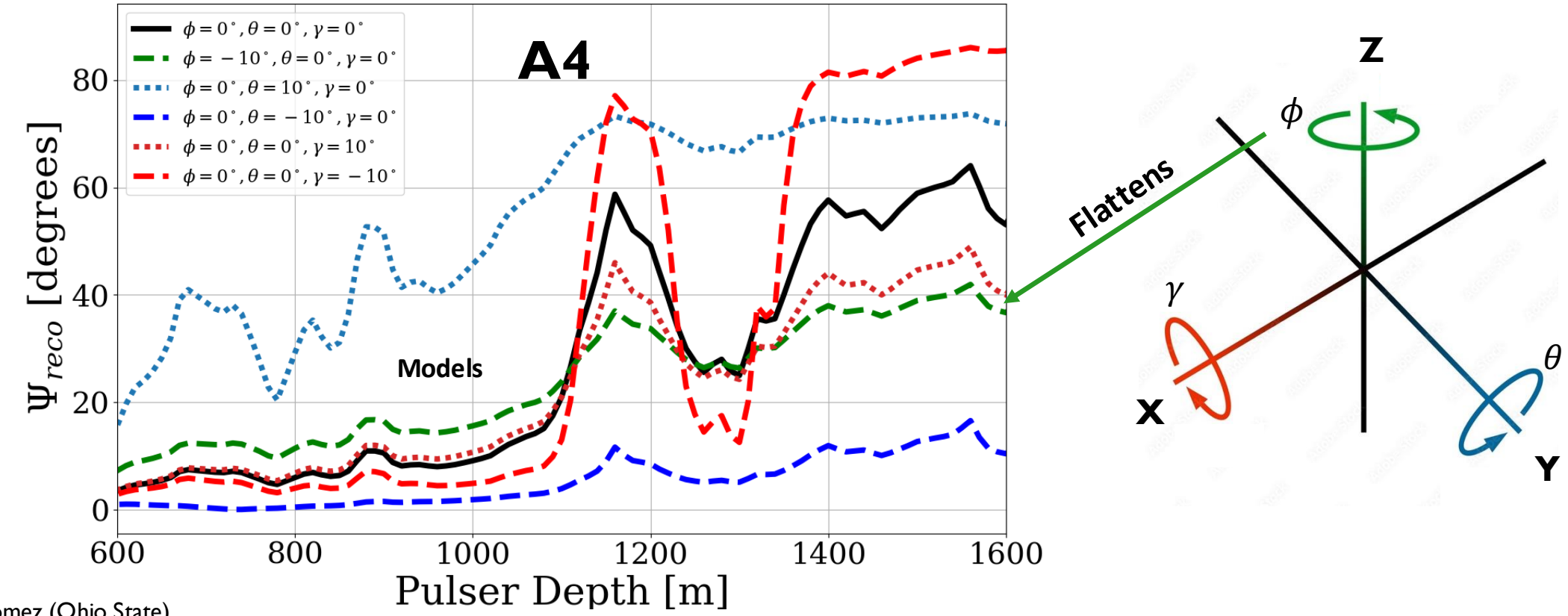


T. M. Jordan, . IEEE Transactions on Geoscience and Remote Sensing, 57 (2019) 11, 8641–8657

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



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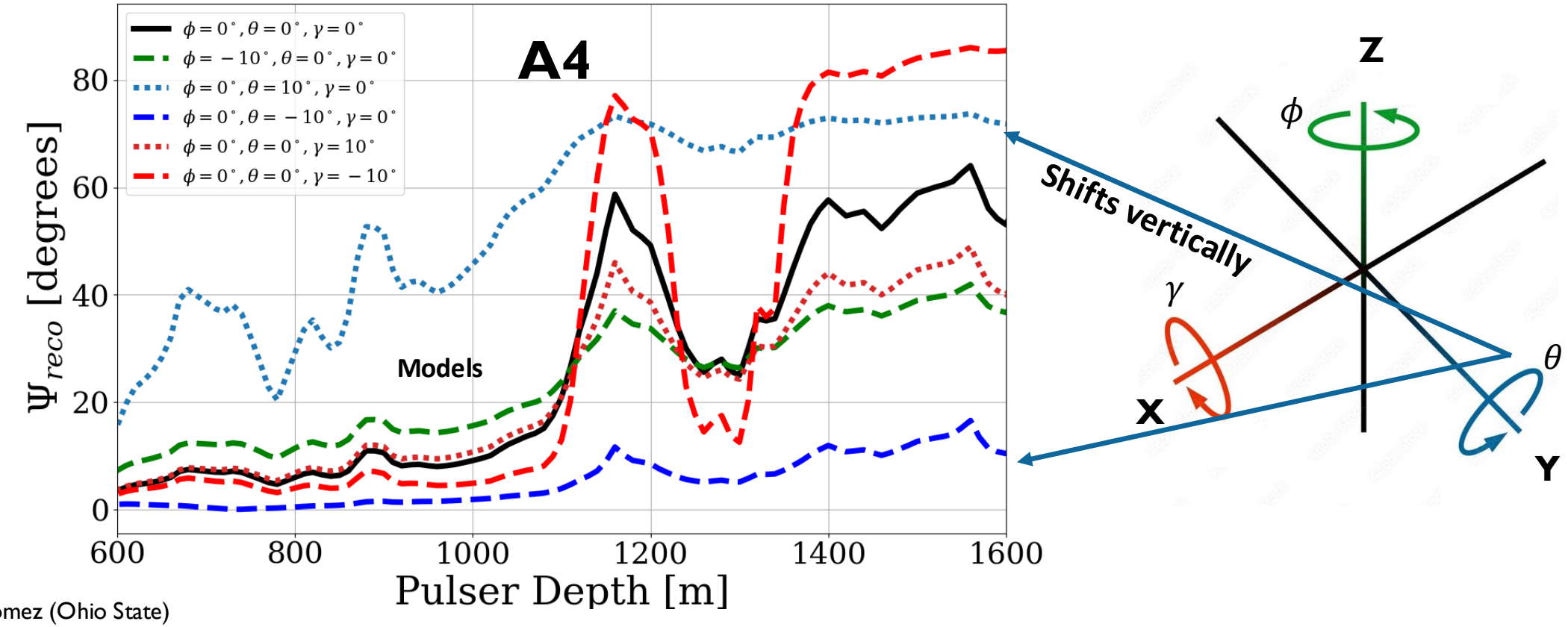

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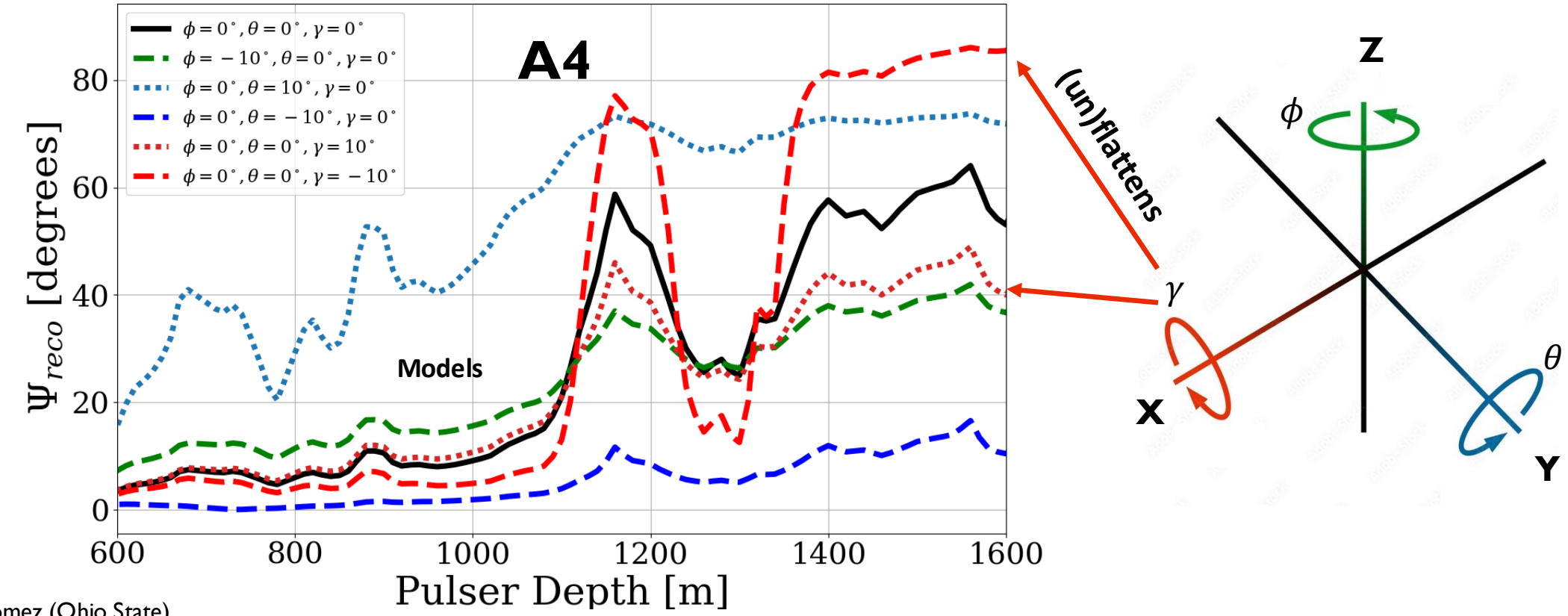
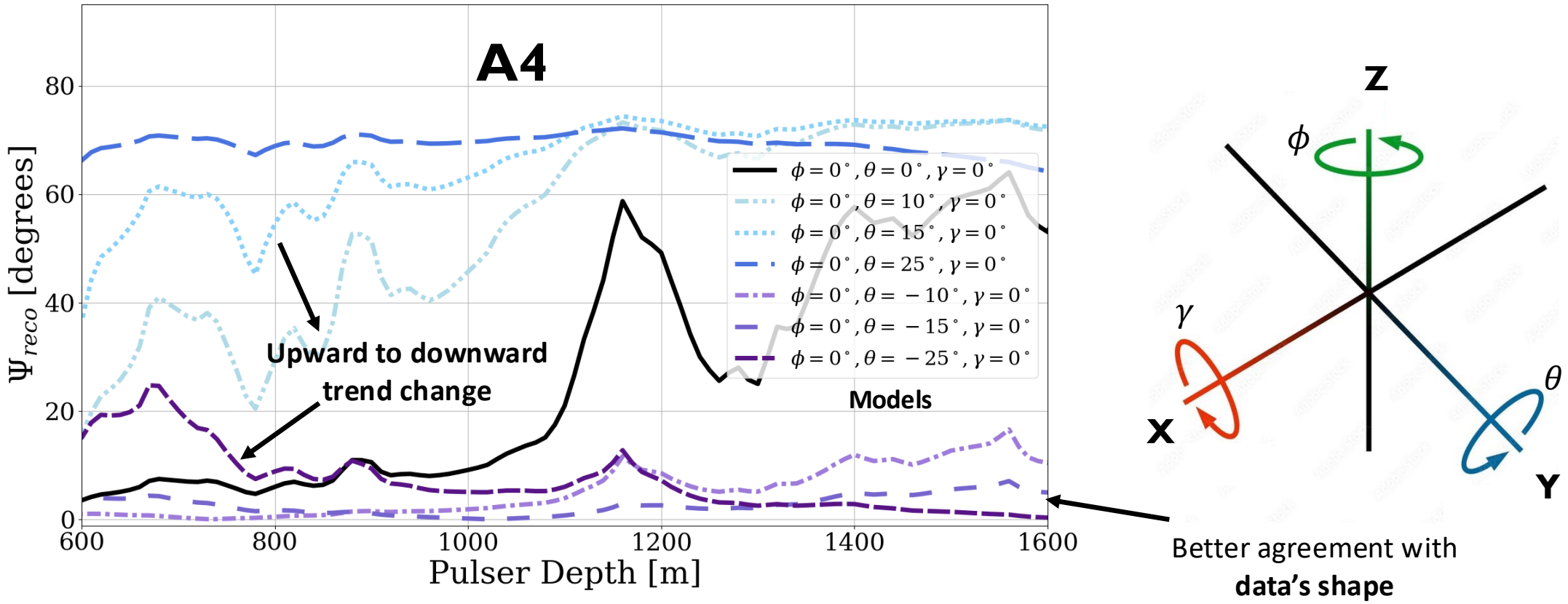


Systematic Uncertainties

These **can have a large effect** on predictions for polarization reconstruction

- The qualitative shape of Ψ in data can be potentially obtained with a fit in (ϕ, θ, γ) across all five ARA stations

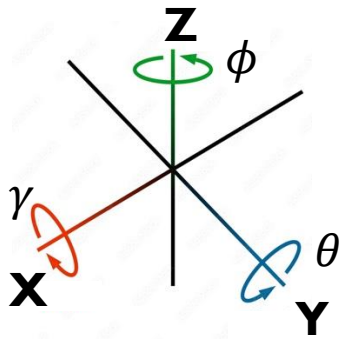


Future Work

Biaxial birefringence effects may have implications for analysis and detector design

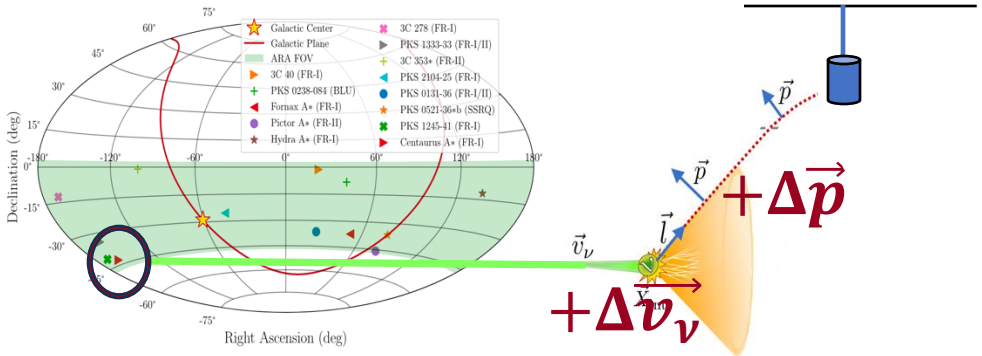
Principal Axes Orientation Fit:

- Fit rotation angles on glaciology measurements of principal axes using SPICE data set across all ARA stations



Point Source Search:

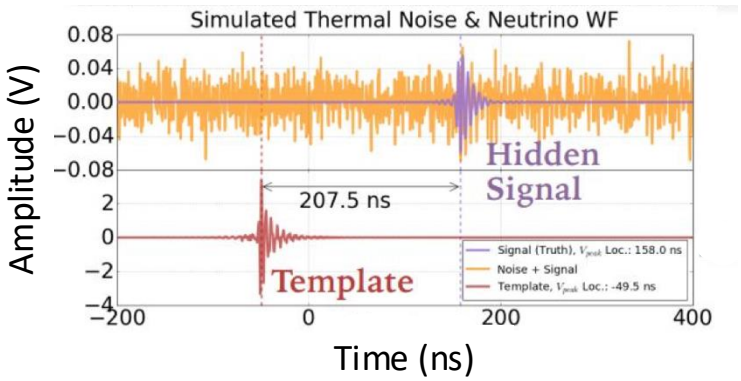
Modified from J. Torres (2020) and S. Barwick, C. Glaser (2023)



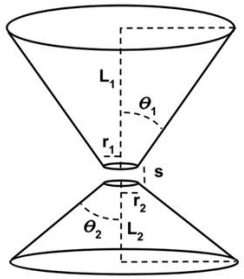
- Birefringence should be taken into account in directional neutrino searches

Neutrino Template Analysis:

Credit: Myoungchul Kim



- Can design neutrino templates with birefringence effects



GENETIS is Optimizing Antenna and Array Designs:

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

[GENETIS Collaboration] Phys. Rev. D 108 (2023) 10, 102002

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.

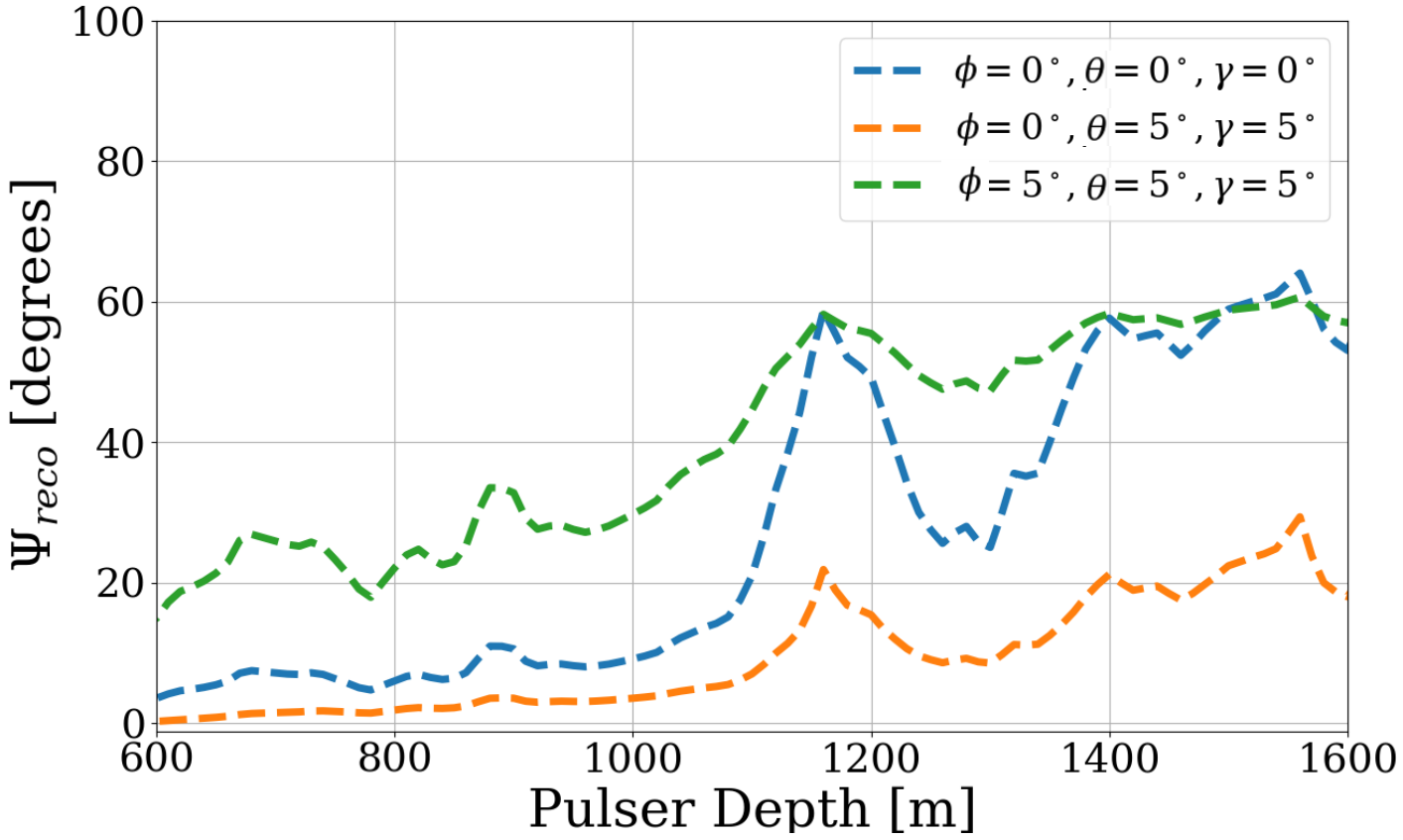
Fin

- **Thank you!**

BACKUP 1: Systematic Uncertainties

Rotation of the COF **can have a large effect** on predictions for polarization reconstruction

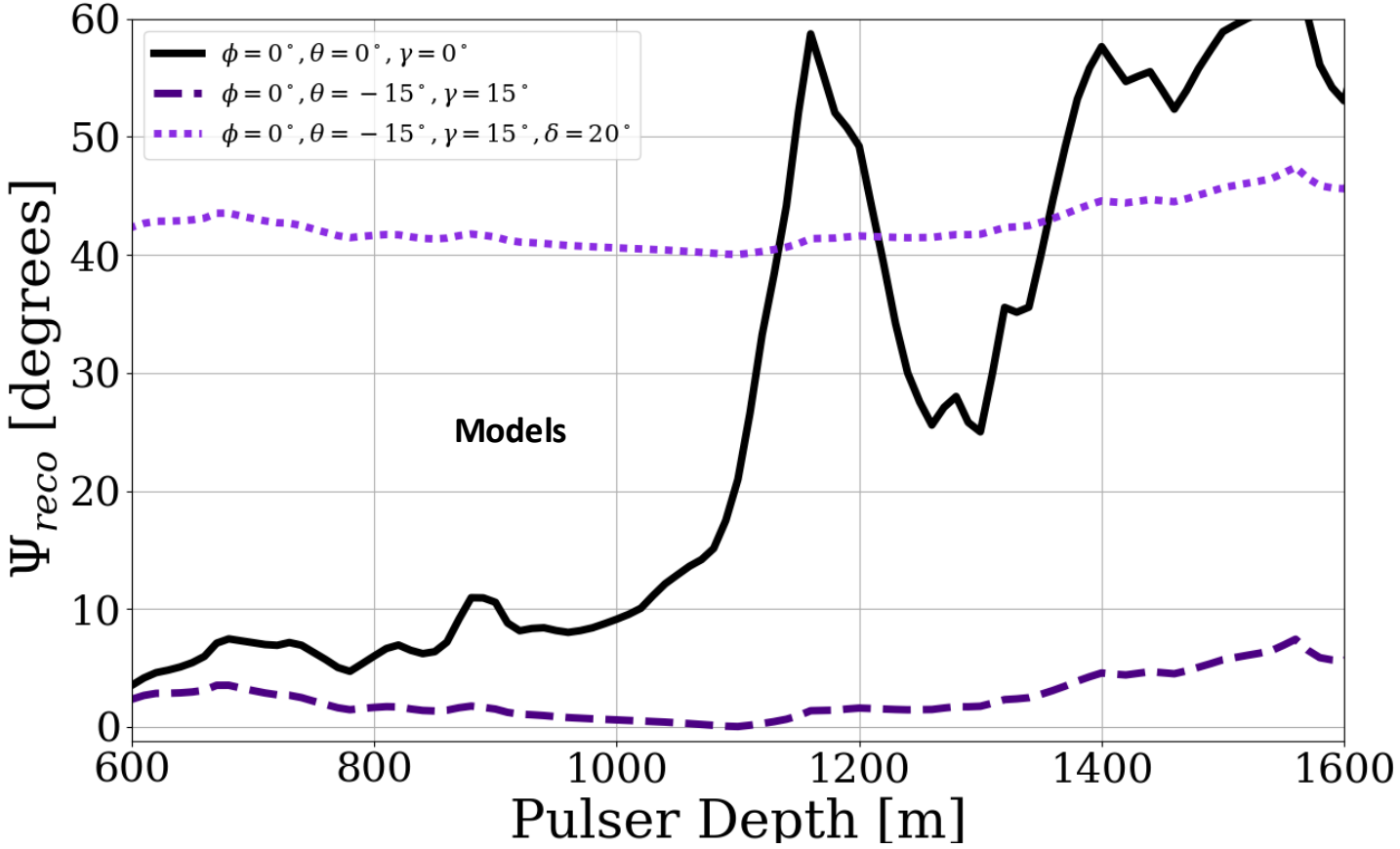
- Then, we calculate the effects on A4 by rotating the principal axes by 5° around **multiple axes at a time**



BACKUP 2: Systematic Uncertainties

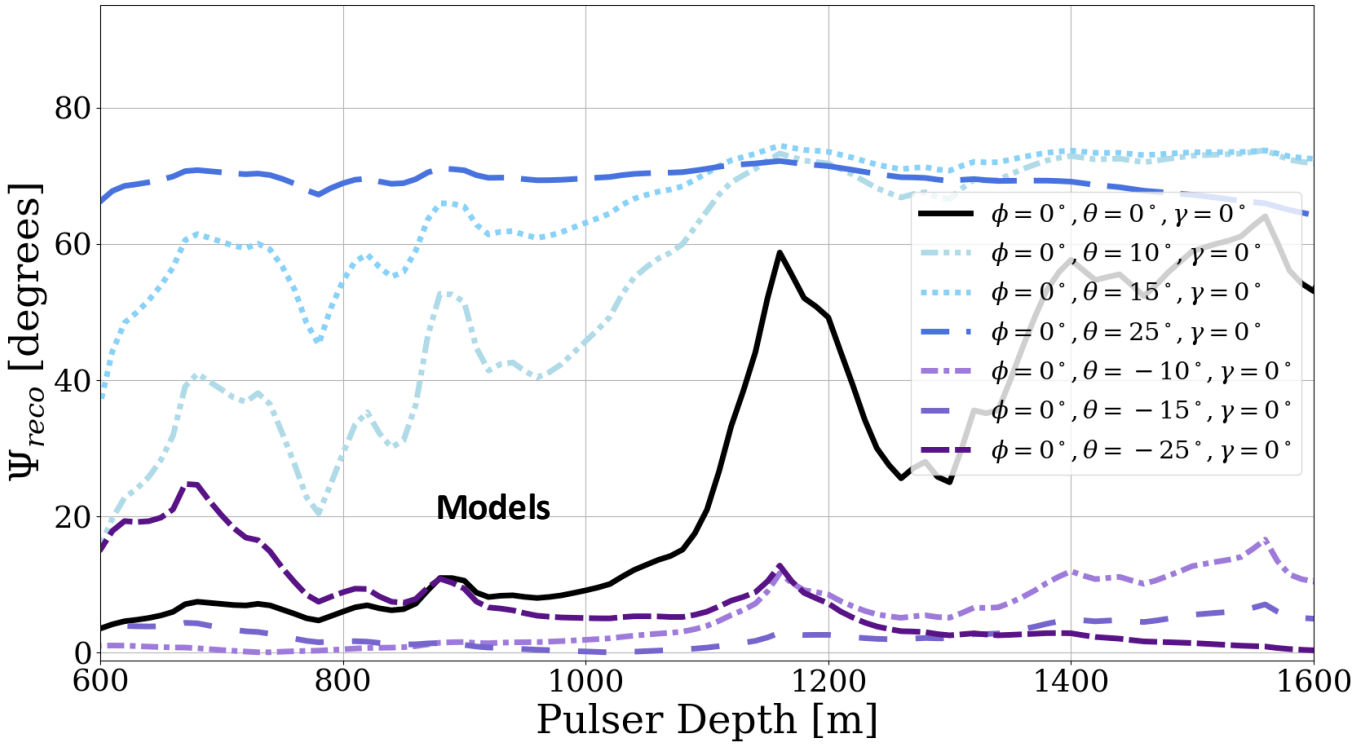
Rotation of the COF **can have a large effect** on predictions for polarization reconstruction

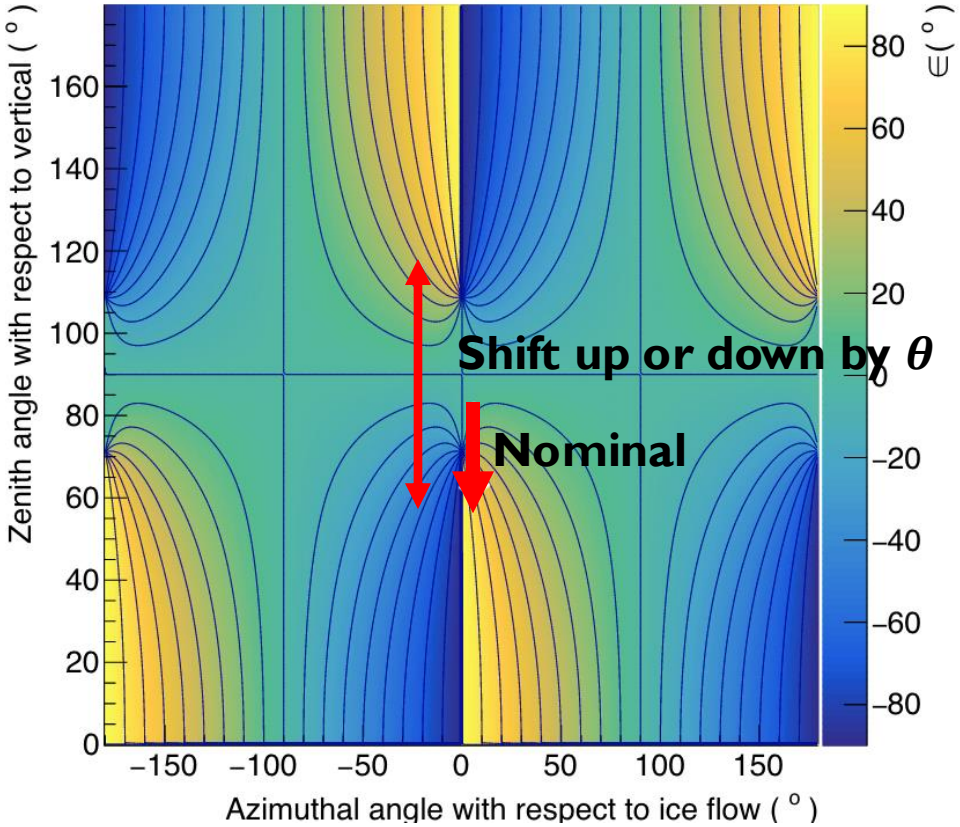
- Here we try reproducing the data's behavior with a simple model for cross-pol antenna response δ



BACKUP 3: Systematic Uncertainties

Rotation of the COF **can have a large effect** on predictions for polarization reconstruction



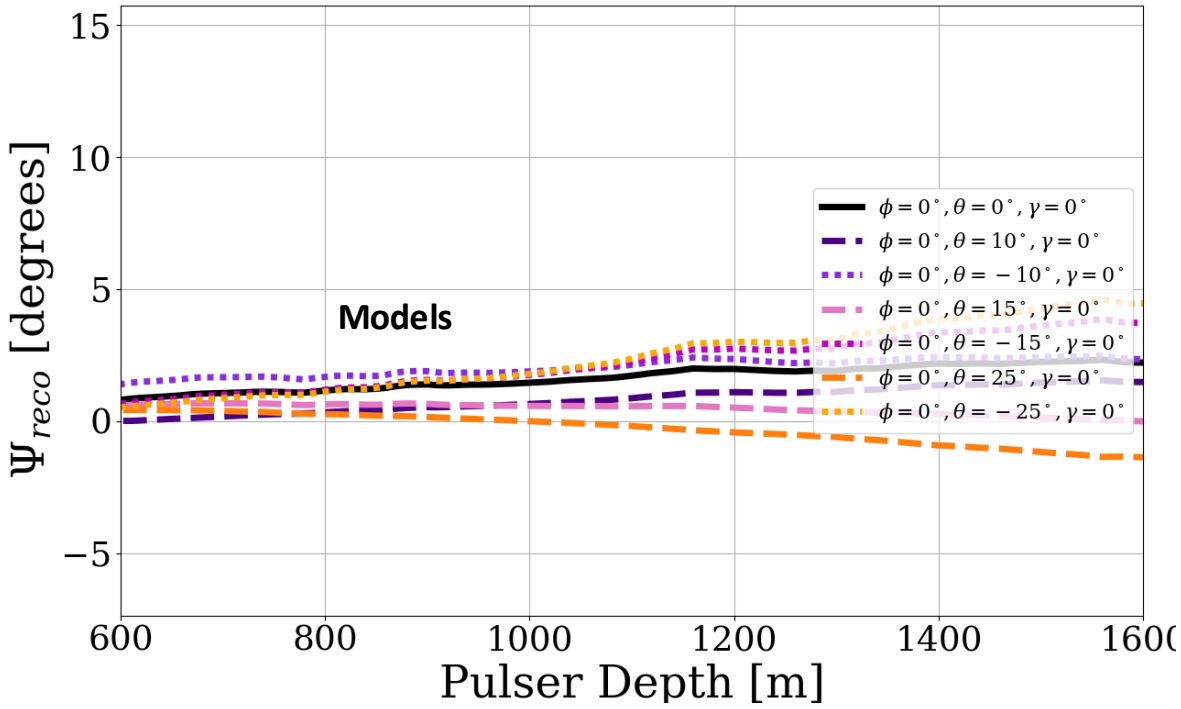


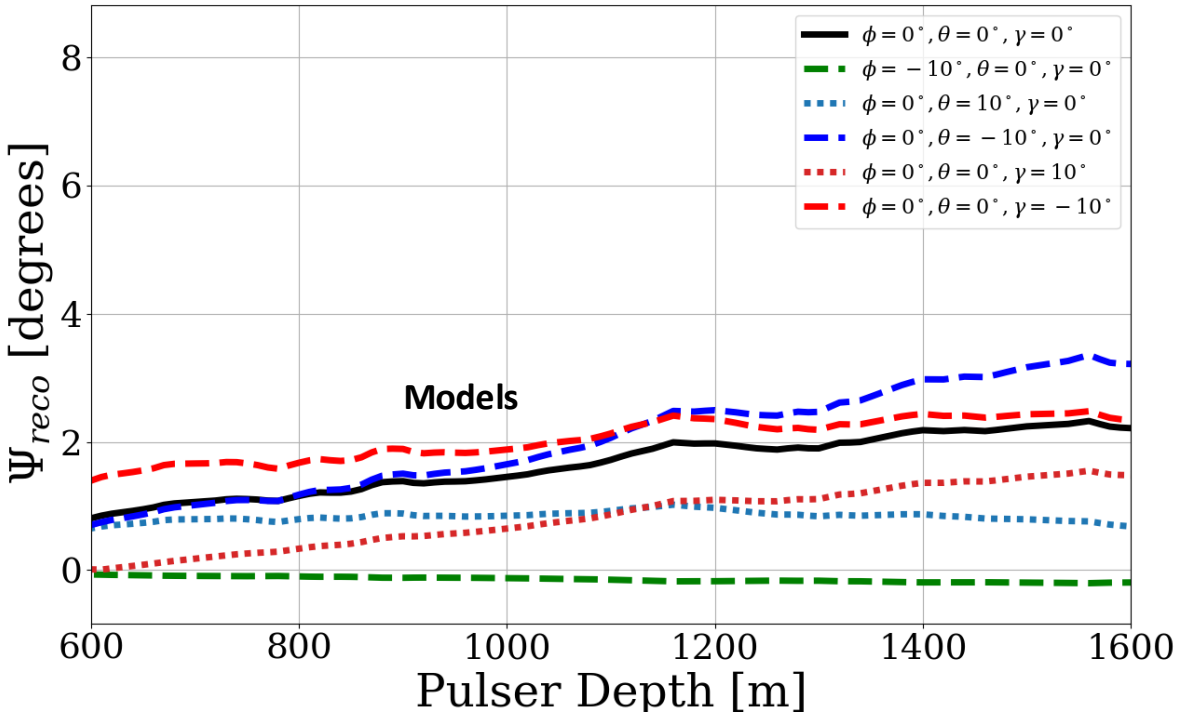
A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

BACKUP 4: Systematic Uncertainties

Rotation of the COF **can have a large effect** on predictions for polarization reconstruction

- We calculate the effects **on A2** by rotating the principal axes

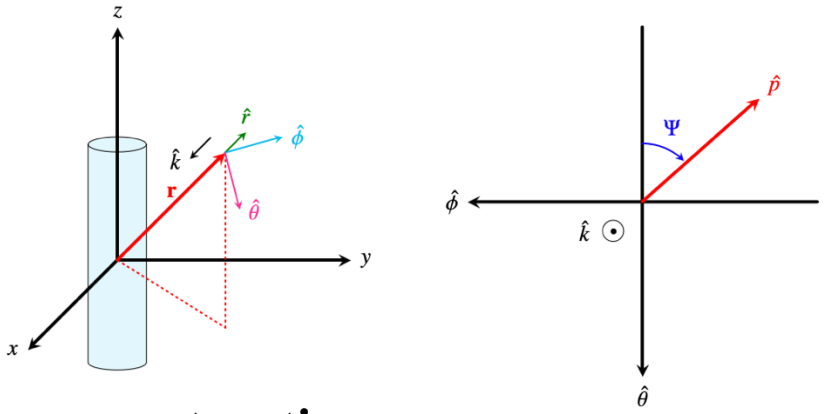




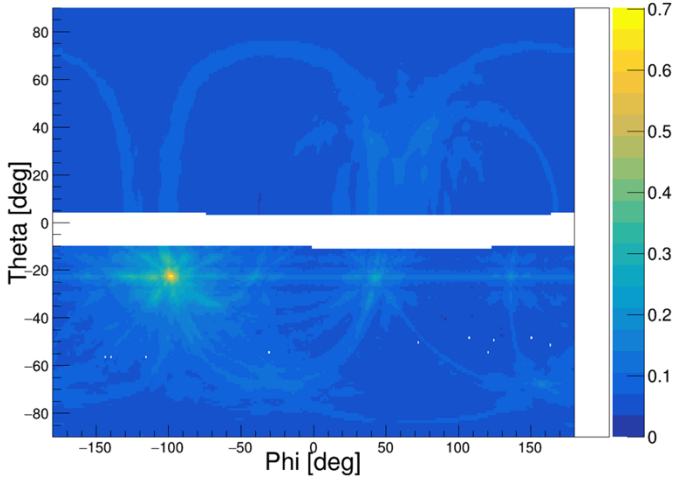
BACKUP 5: Polarization Reconstruction

Concepts for Polarization Reconstruction

1) Coordinates



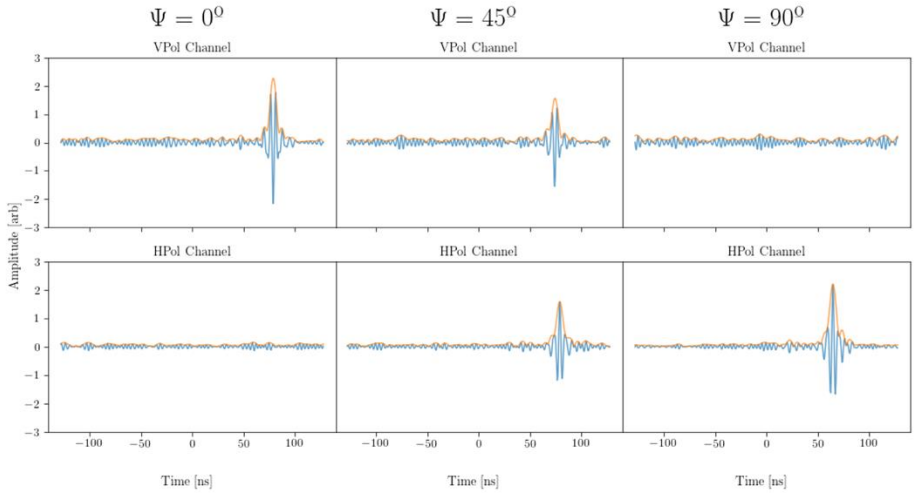
2) Vertex reconstruction



3) Deconvolution

$$\tilde{V}(\omega) = G_{\text{elec}} * G_{\text{ant}} * \tilde{E}(\omega) \rightarrow V(t)$$

4) Hilbert Peak



5) Polarization Reconstruction

$$\frac{V_{D,\text{HPol}}}{V_{D,\text{VPol}}} = \frac{P(\hat{p}, j=1) \cdot E(t)}{P(\hat{p}, j=0) \cdot E(t)} = \frac{\hat{p} \cdot \hat{\phi}}{\hat{p} \cdot \hat{\theta}} = tan(\Psi)$$

BACKUP 6: Polarization Reconstruction

Discrepancies between model and predictions for A4 may be due to the ray tracing algorithm used