Neutron Star **Pulsars** and **Polarization**

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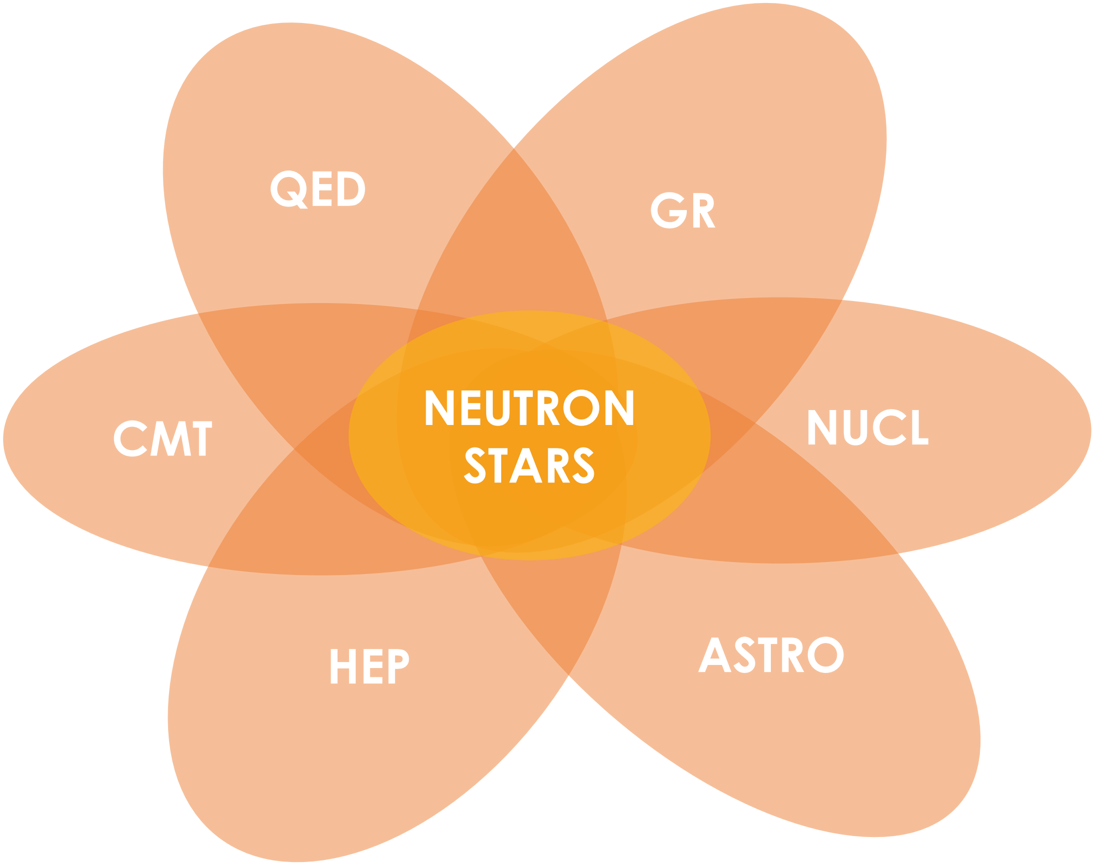
Exotic Astrophysical Laboratories:

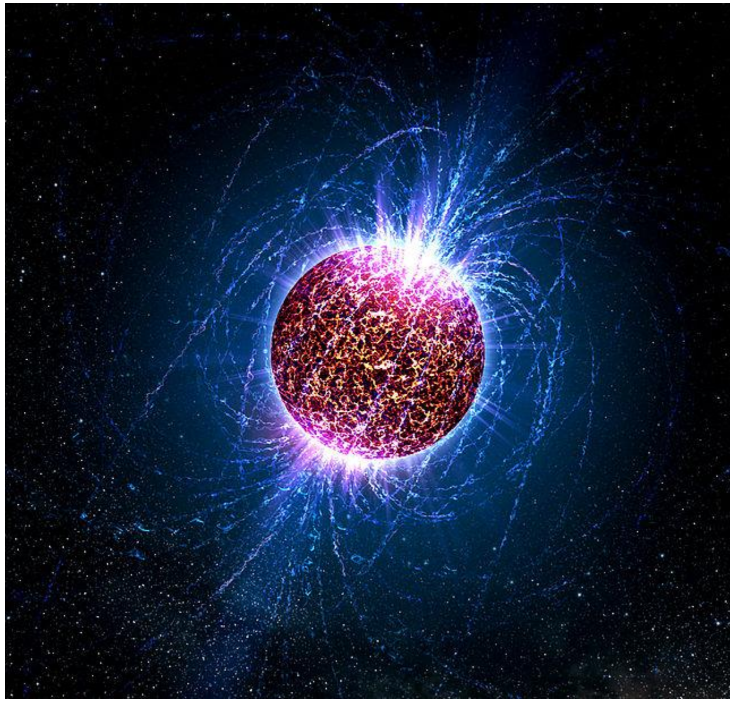
Densities ~10^{17} kg/m^3

Magnetic Fields ~10^8 - 10^{14} G

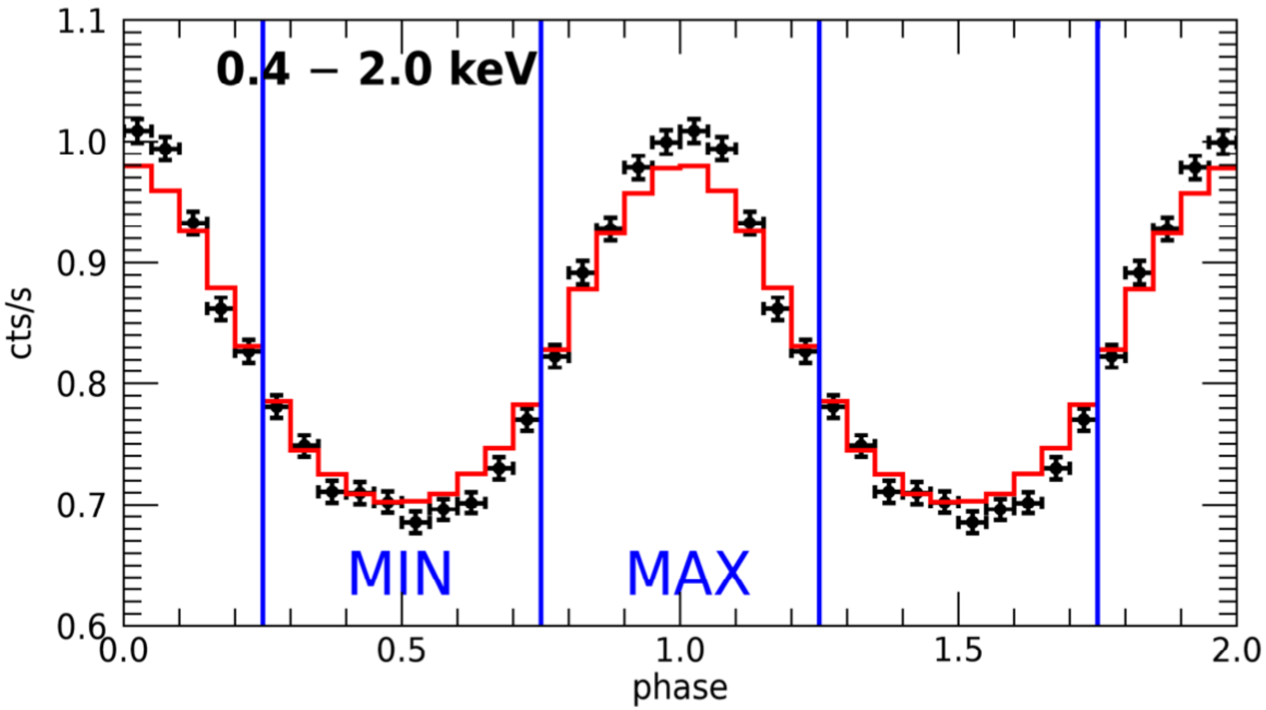
Drivers for **multi-physics** developments



Polarization carries information about mechanisms of radiation
but
what is emitted is not exactly what we see



Artist's Impression

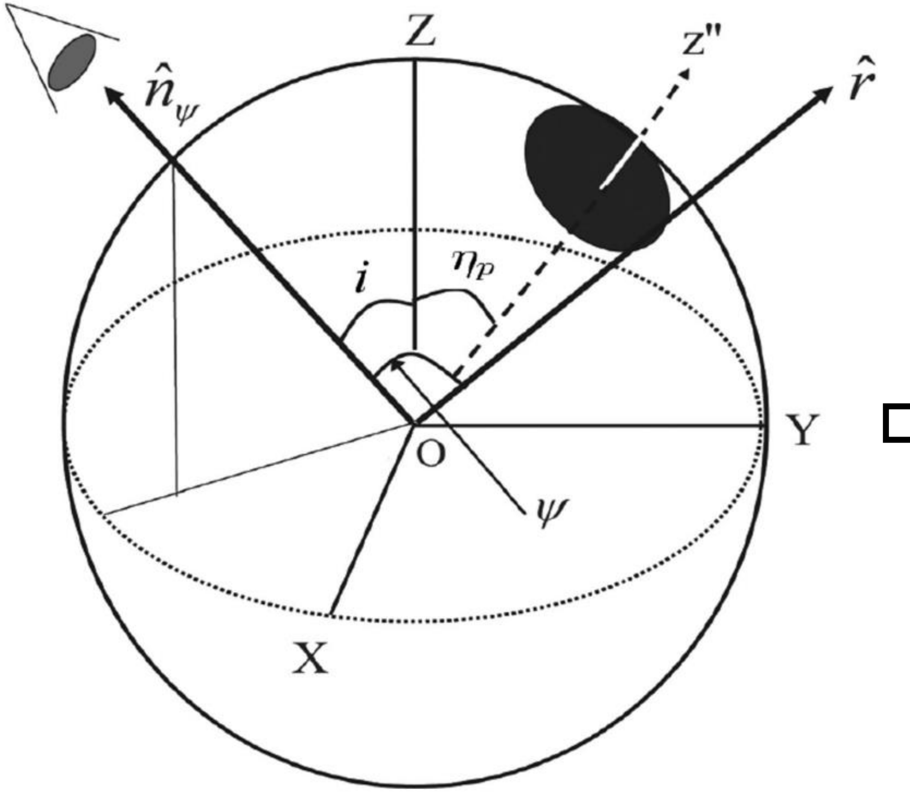


Calvera Observations (Mereghetti et al 2021)

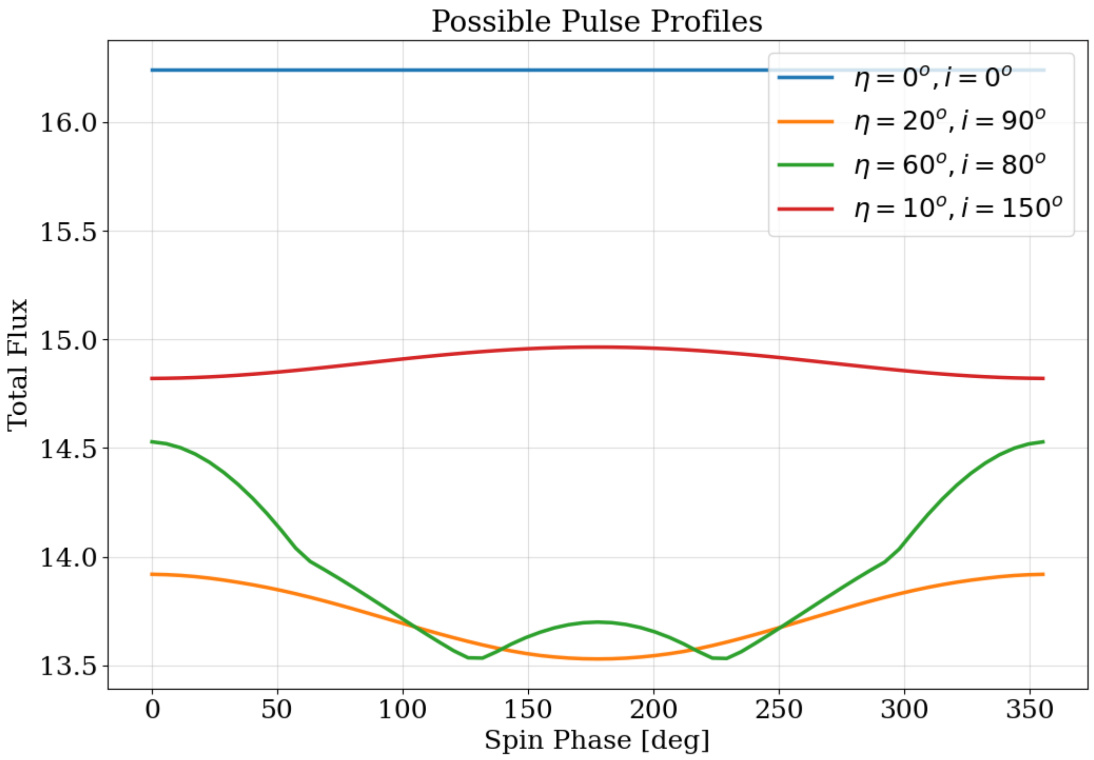
QUESTION

Given a pulsar configuration, what polarization data should we expect (and vice versa)?

Neutron Star **attributes** affect **pulse profiles**

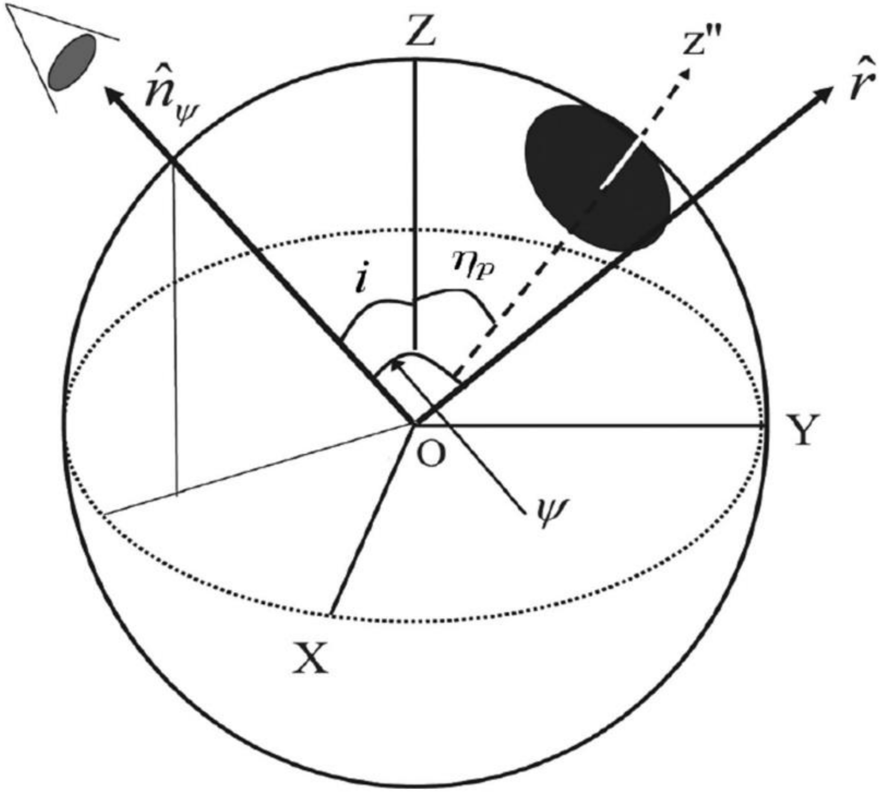


Mukherjee and Bhattacharya (2011)



All figure generating code at
github.com/krtktwri/comp-astro-asp

Dependency **Simulations** + Bayesian **Inference** extracts Neutron Star attributes from pulse profiles



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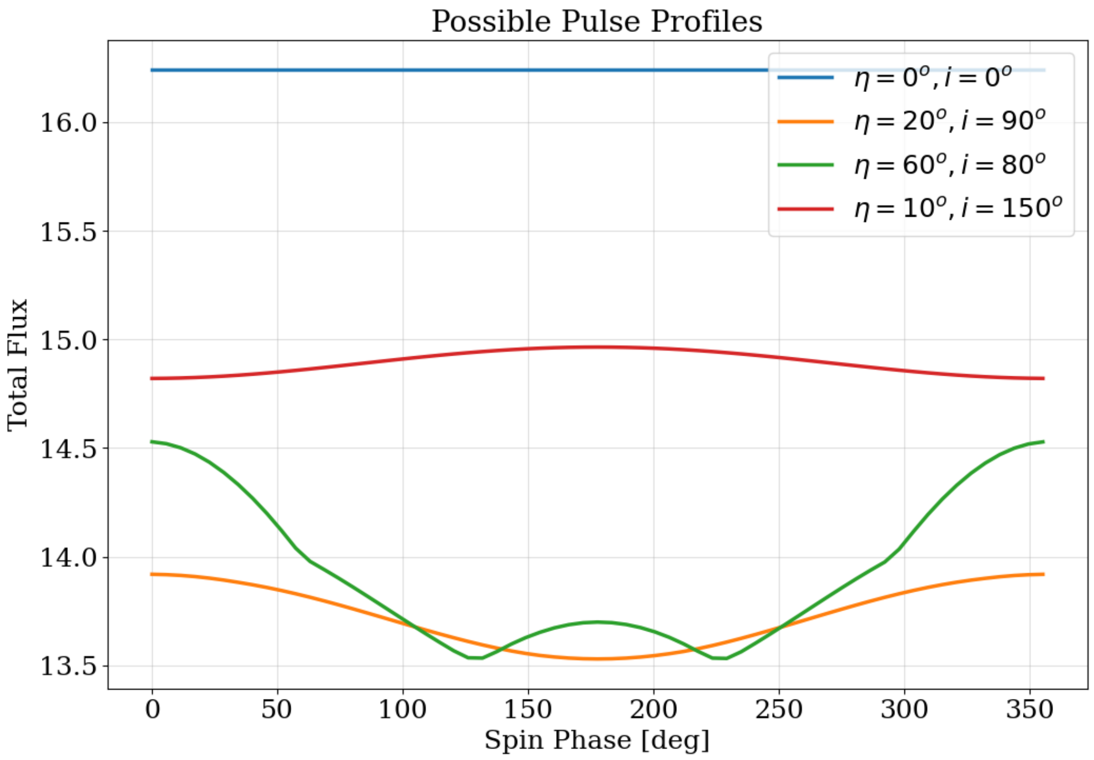

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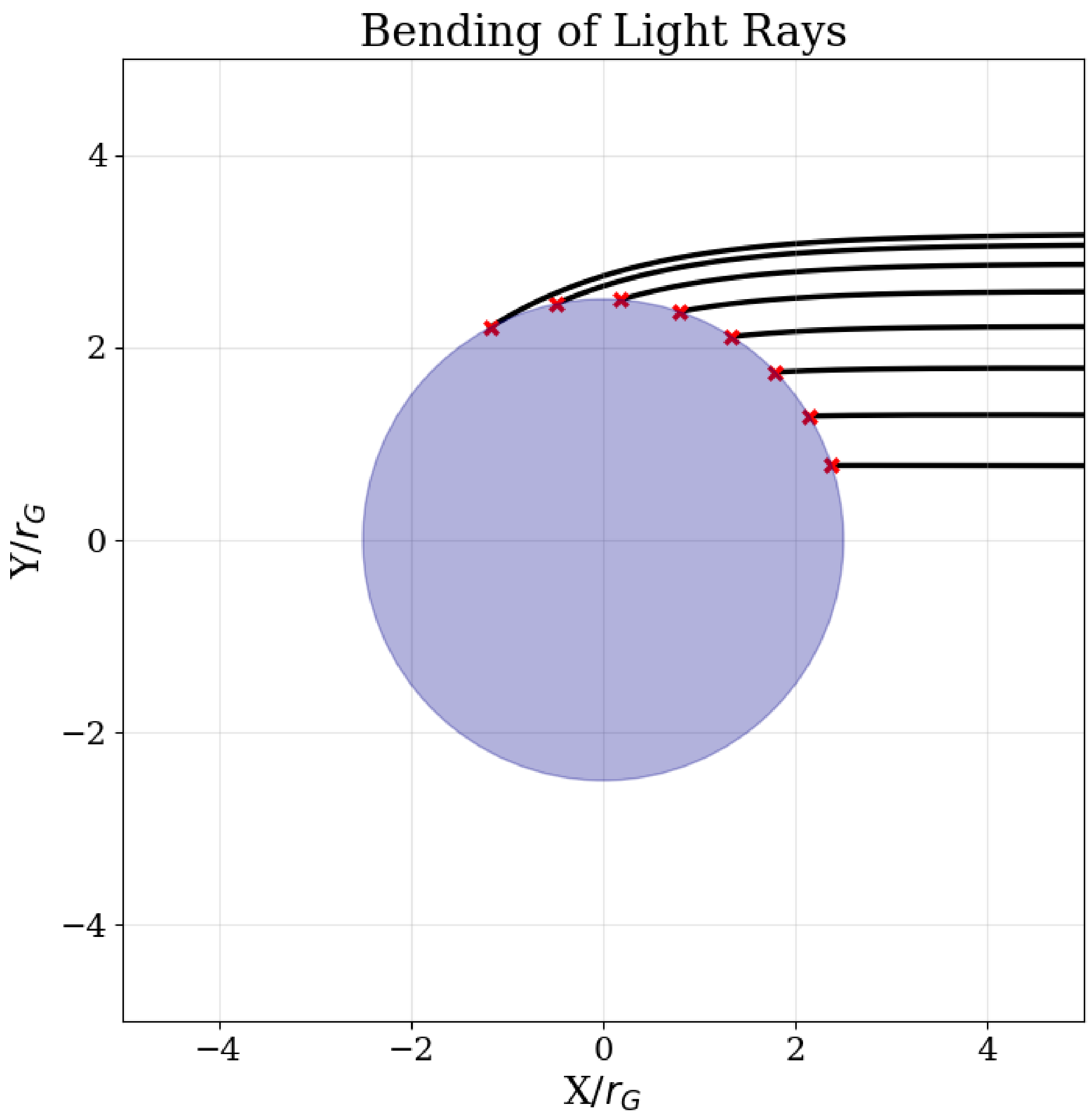
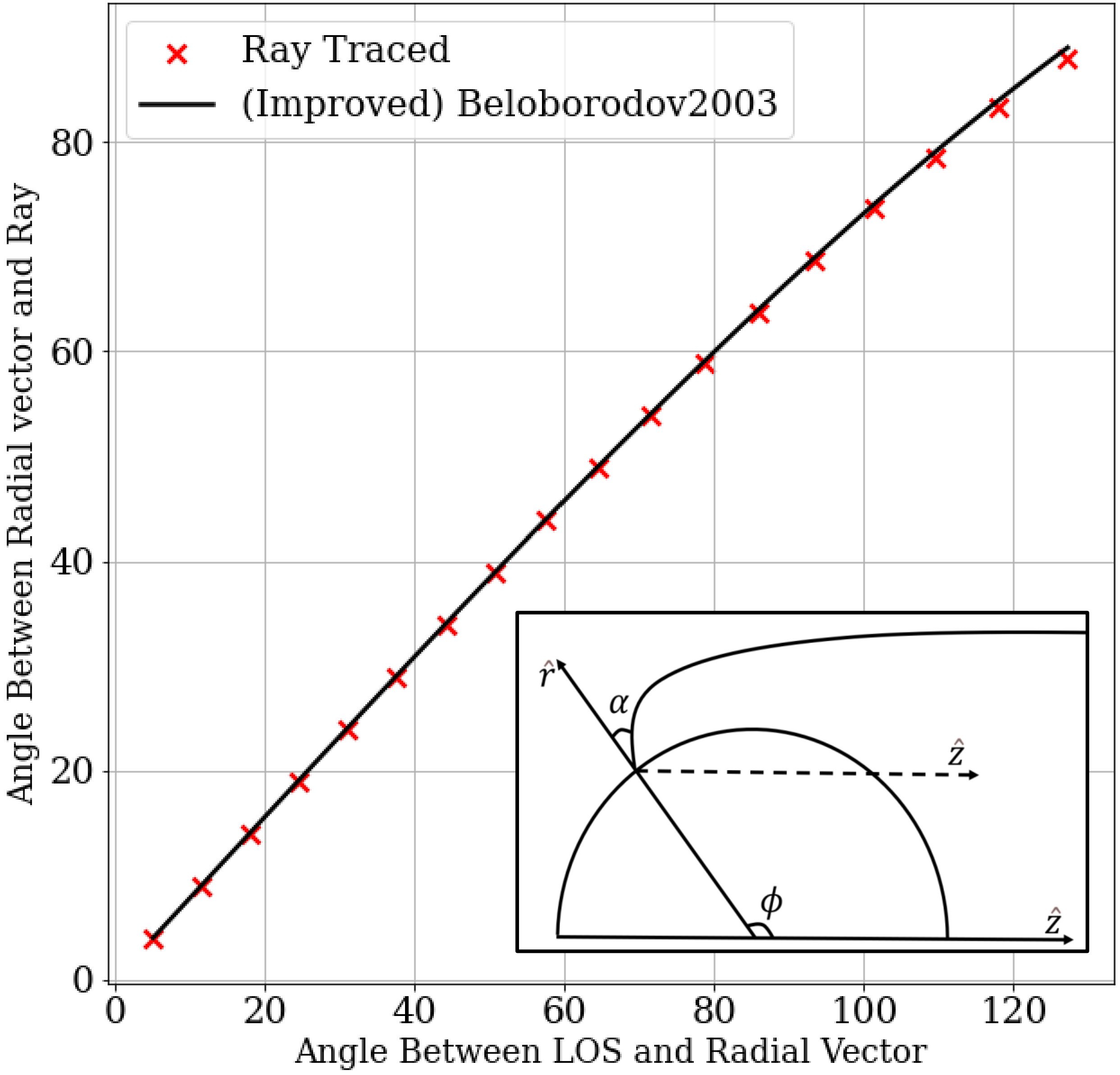
Gravitational lensing affects observed surface projection and morphs polarization.

Photon propagation in Schwarzschild is well understood.

Explicit ray-tracing is very slow with horrible scaling.

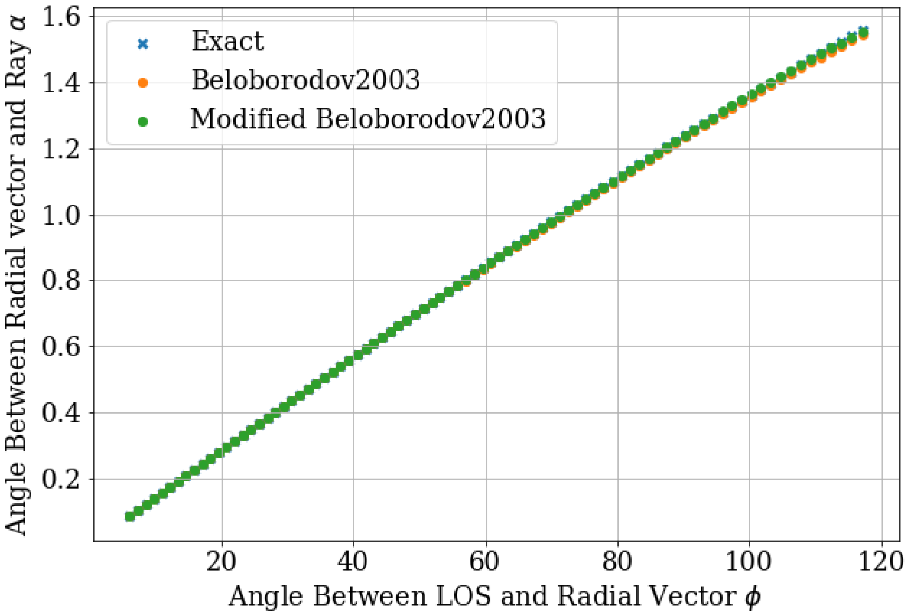




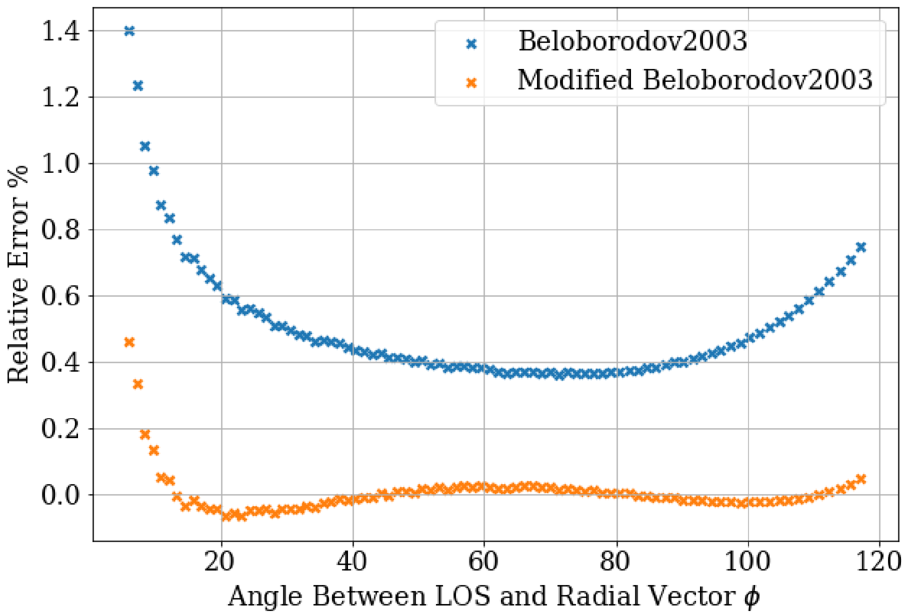
Belobordov's approximation (2003) relates **location on the surface** with the **angle from the normal required** to reach observer.

Ray-tracing not required.

With an additional improvement, **errors remain under 1%**.

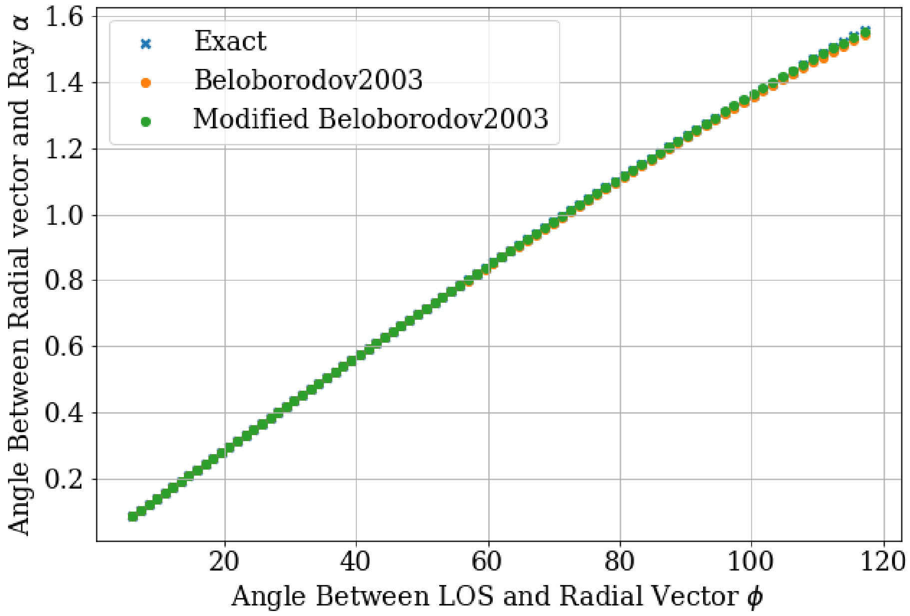


Exact
Beloborodov2003
Modified Beloborodov2003
Angle Between Radial vector and Ray α
Angle Between LOS and Radial Vector ϕ



Beloborodov2003
Modified Beloborodov2003
Relative Error %
Angle Between LOS and Radial Vector ϕ

$R = \mathbf{3R_g}$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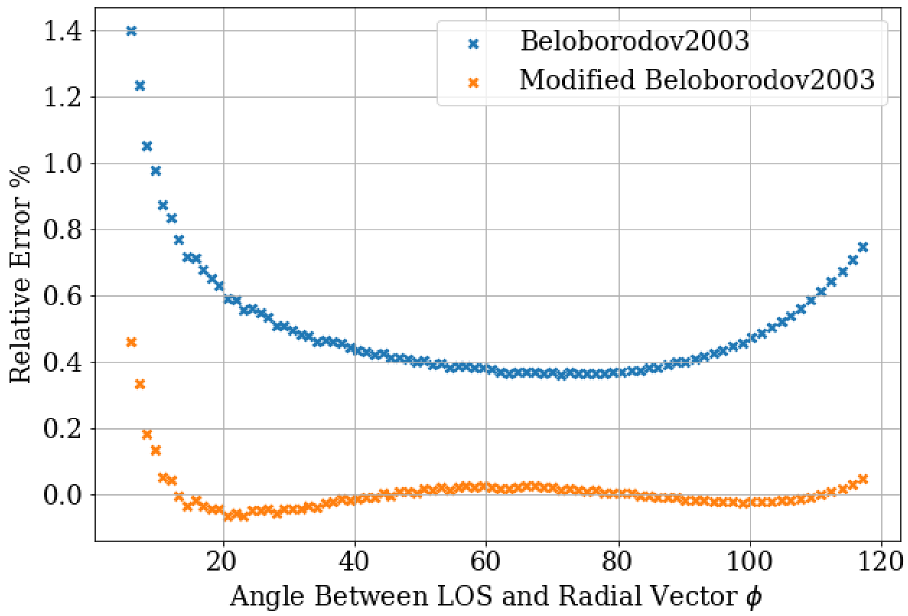
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Relative Error %
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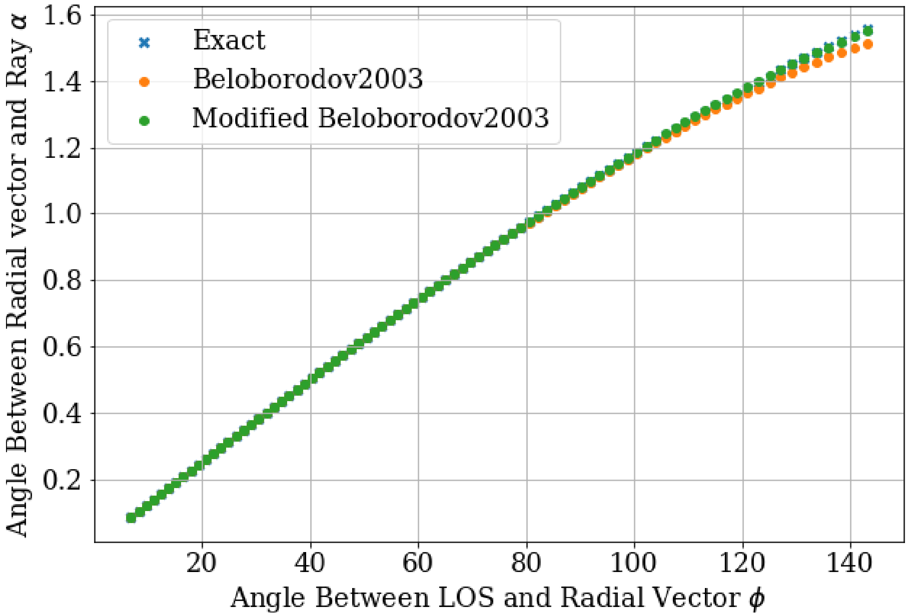
R = $3R_g$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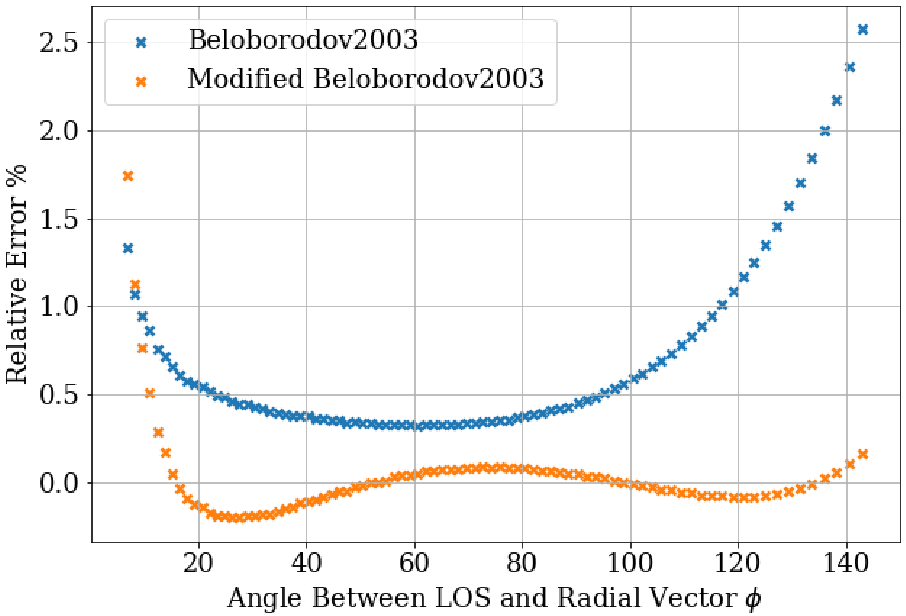
Beloborodov2003
Modified Beloborodov2003
Relative Error %
Angle Between LOS and Radial Vector ϕ

R = $2R_g$

Neutron Star Object

Mass
Radius
Magnetic Pole Strength
Angle between magnetic and spin axis
Angle between Spin Axis and LoS

Polarization Transport Code
github.com/krtktwri/comp-astro-asp

Given a pulsar configuration, what polarization data to expect?

Neutron Star Object

Mass
Radius
Magnetic Pole Strength
Angle between magnetic and spin axis
Angle between Spin Axis and LoS

Physics Module

Gravitational Lensing
Gravitational Redshift
Magnetic Field Variation
Stokes Parameter Transfer
Surface Integration

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Observation

Phase Range
Photon Energy
Polarization

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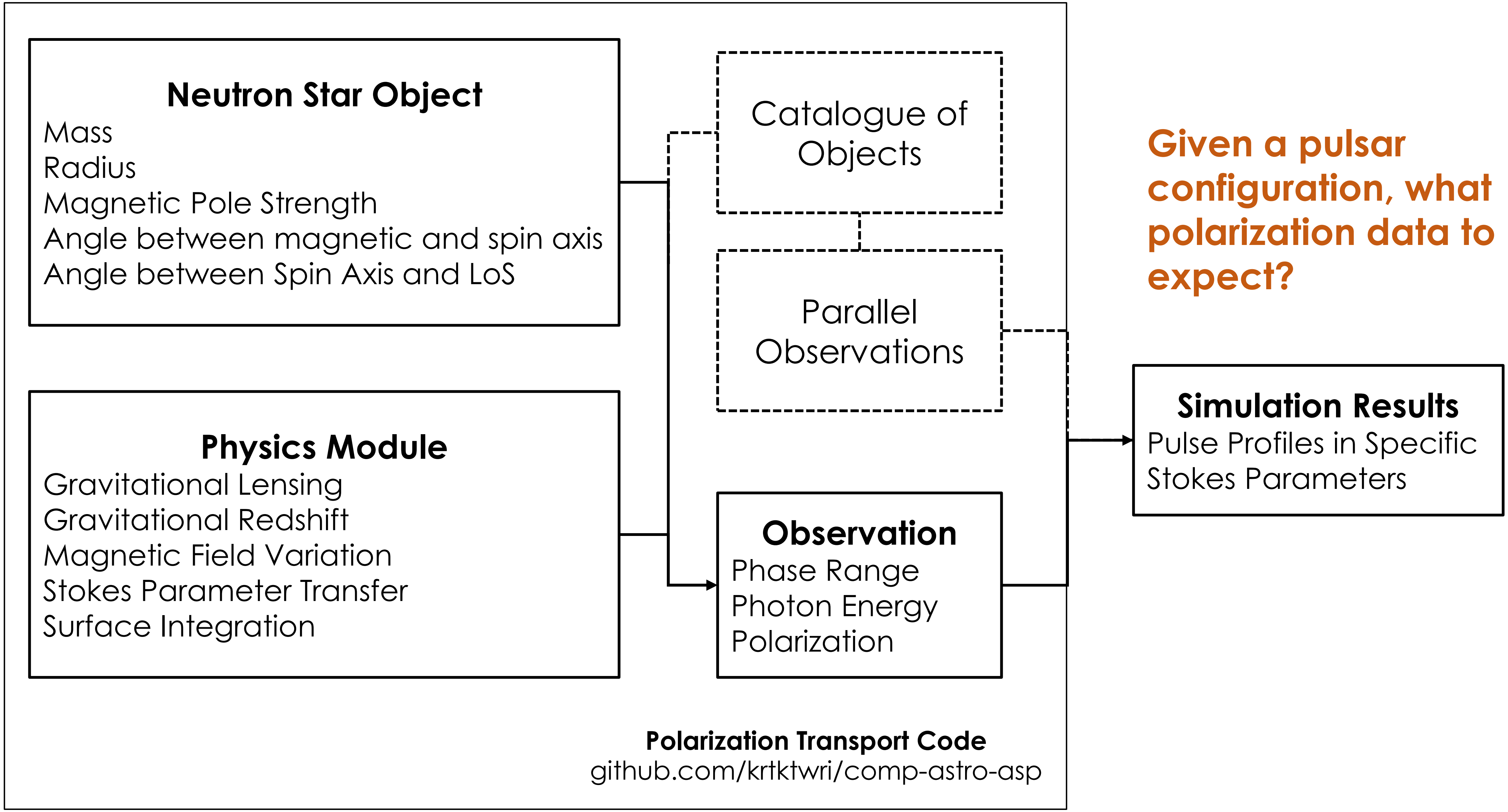
Simulation Results
Pulse Profiles in Specific Stokes Parameters



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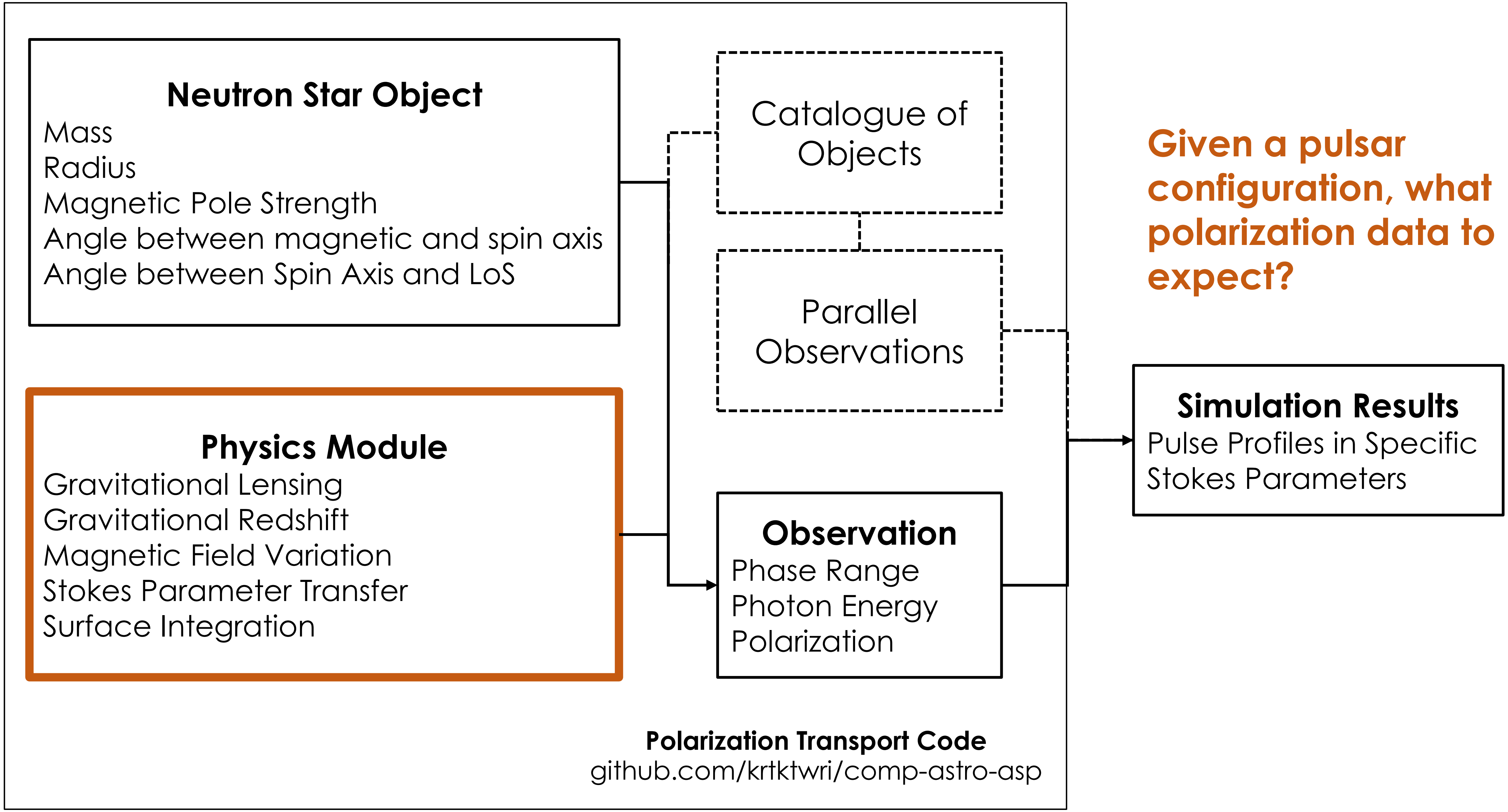

Given a pulsar configuration, what polarization data to expect?

Stokes Parameter

$$Q = (I_o - I_e)\, p_L \cos 2\chi_o$$

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Normal Modes Polarization

$$p_L = \frac{|q| \sin^2 \theta_B}{\sqrt{4 \cos^2 \theta_B + q^2 \sin^4 \theta_B}}$$

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Dipole in Schwarzschild

$$\vec{B} = \frac{B_P}{2}\left((2+f)(\hat{r}.\hat{m})\hat{r} - f\hat{m}\right)$$

$$f = 2\frac{u^2 - 2u - 2(1-u)\ln(1-u)}{(u^2 + 2u + 2\ln(1-u))\sqrt{1-u}}$$

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Gravitational Lensing

$$\boxed{\left(\frac{dr}{d\phi}\right)^2 = \frac{r^4}{l^2}\left(1 - \frac{l^2}{r^2} + r_G \frac{l^2}{r^3}\right)}$$

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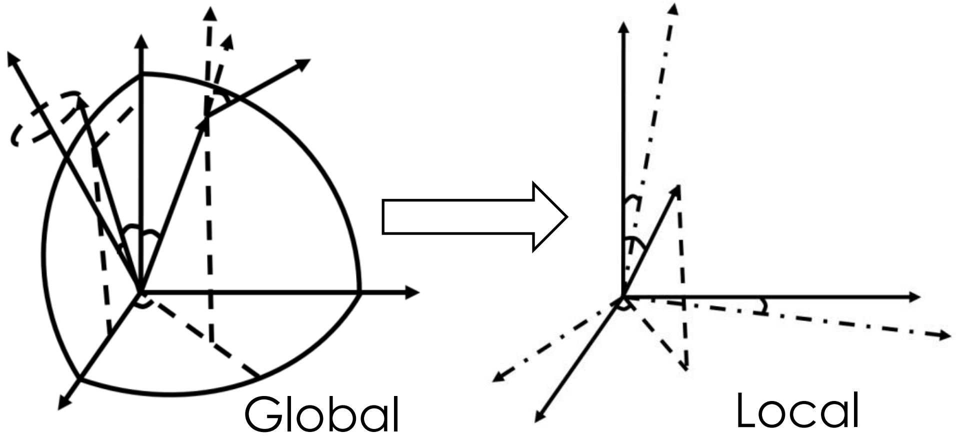
Polarization Rotation

$$\chi_o^{obs} = \xi' + \theta$$

$$\xi' = \tan^{-1}(B_{y'}/B_{x'})$$

Coordinate Transform



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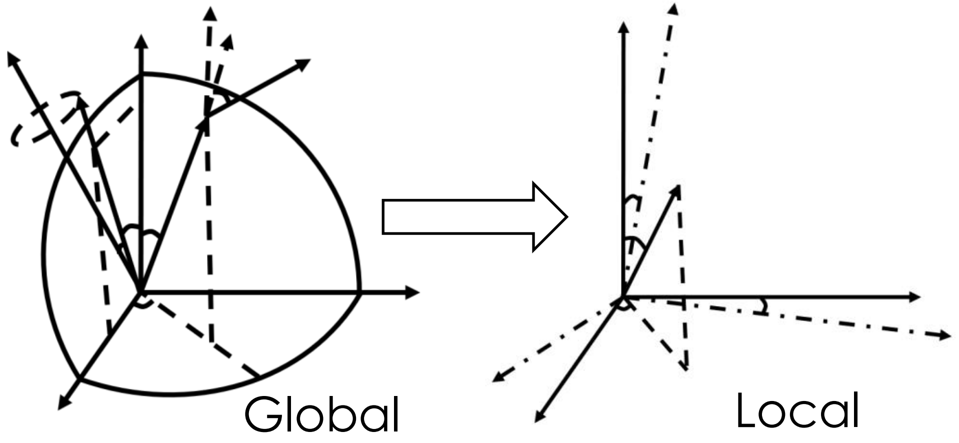

Surface Integration

$$F_Q = R^2 g_r \int_{-\pi/2}^{\pi/2} d\alpha \cos\alpha \int_0^{2\pi} d\theta (I_o - I_e)\, p_L \cos(2(\xi' + \theta))$$

Physics Module | Polarization Transport Code

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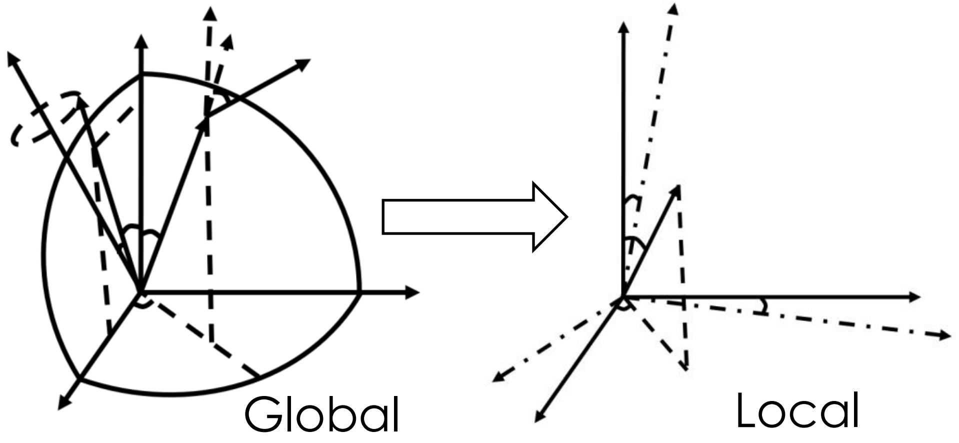

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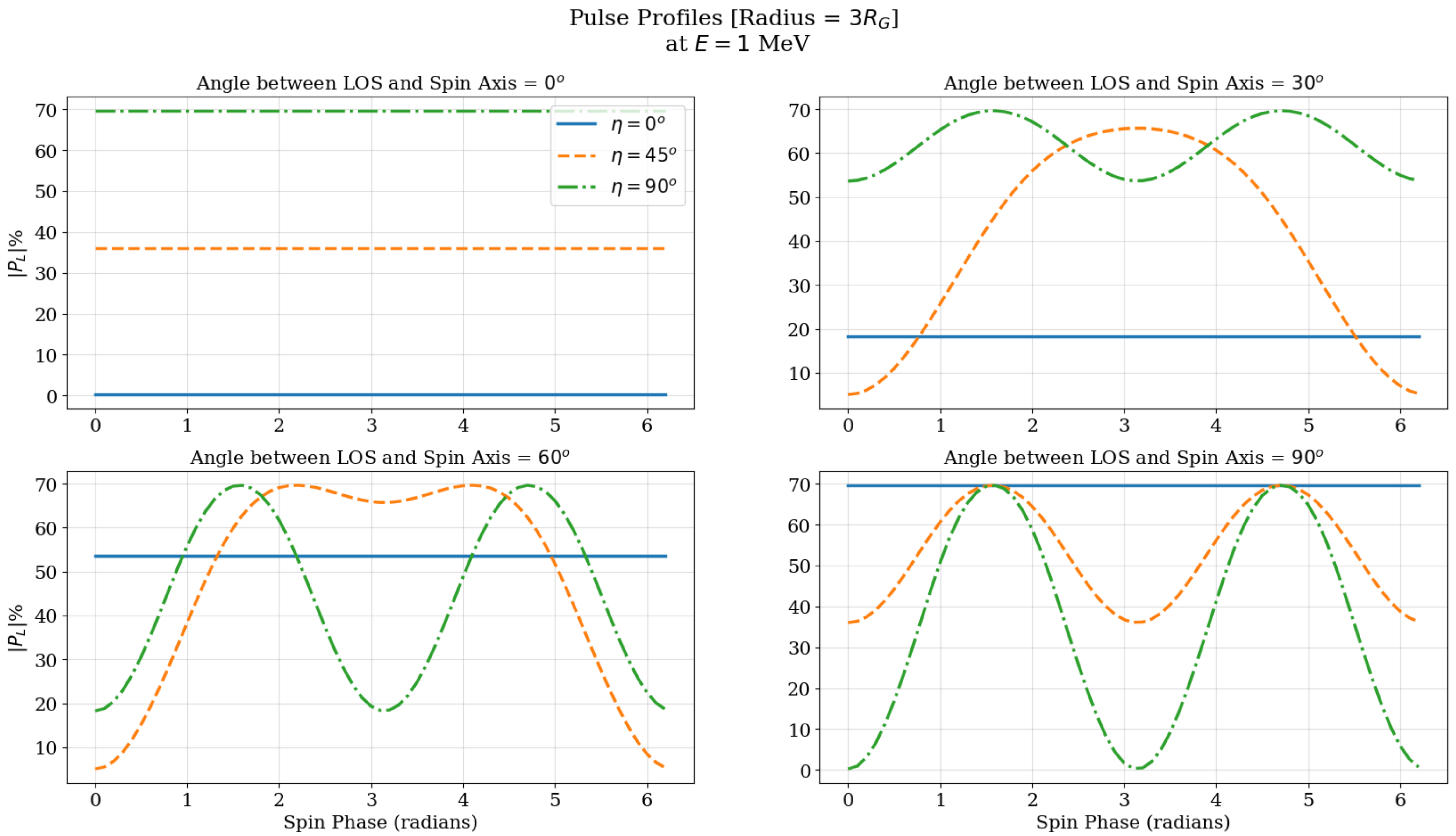
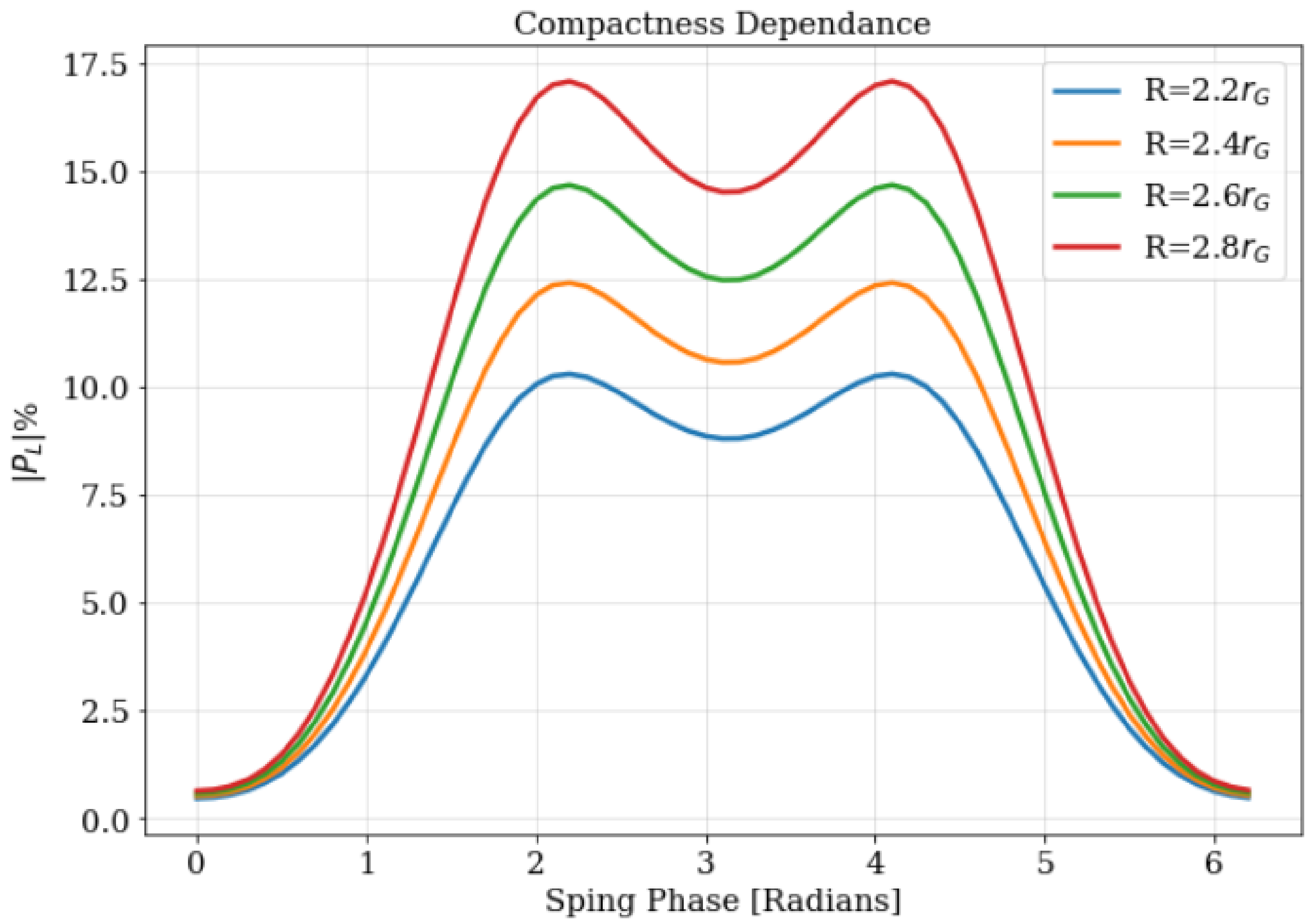
Projection Rotation

$$\cos\eta = \cos\zeta\cos\nu + \sin\zeta\sin\nu\cos\Phi$$

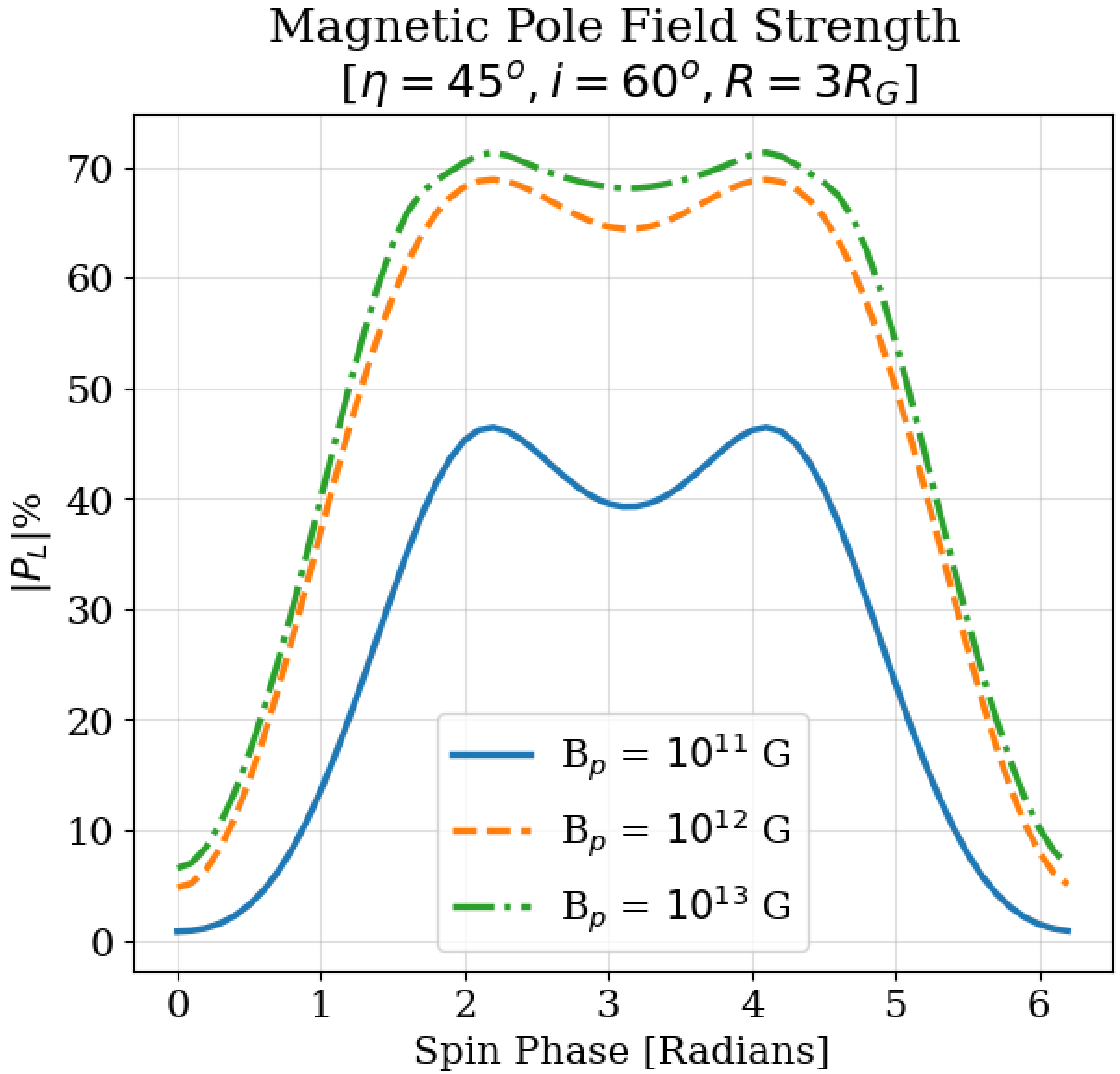
Physics Module | Polarization Transport Code

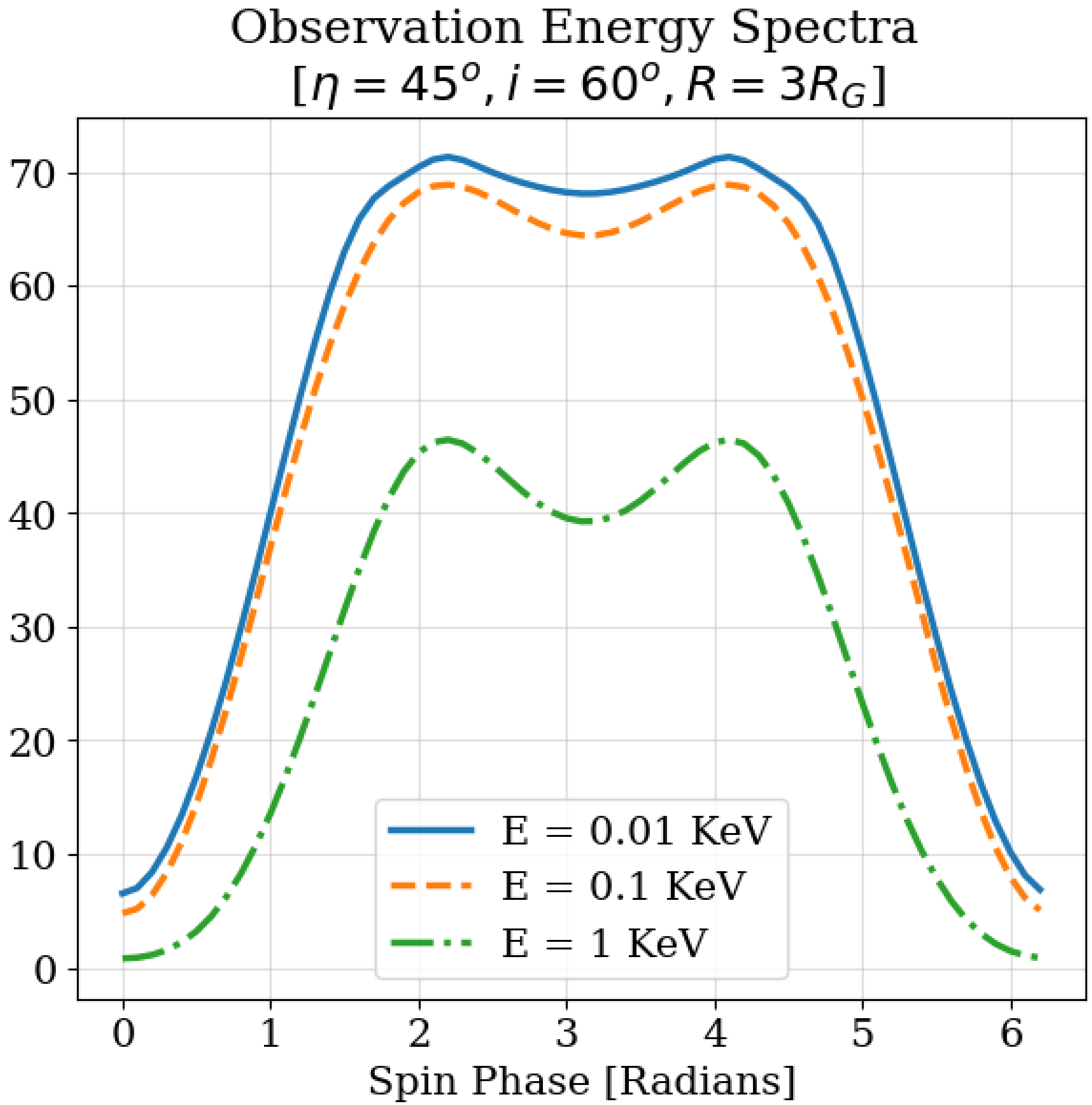

Pulse Profiles [Radius = $3R_G$]
at $E = 1$ MeV
Angle between LOS and Spin Axis = 0^o
Angle between LOS and Spin Axis = 30^o
Angle between LOS and Spin Axis = 60^o
Angle between LOS and Spin Axis = 90^o
$\eta = 0^o$
$\eta = 45^o$
$\eta = 90^o$
$|P_L|\%$
Spin Phase (radians)



Compactness affects degree of linear polarization.

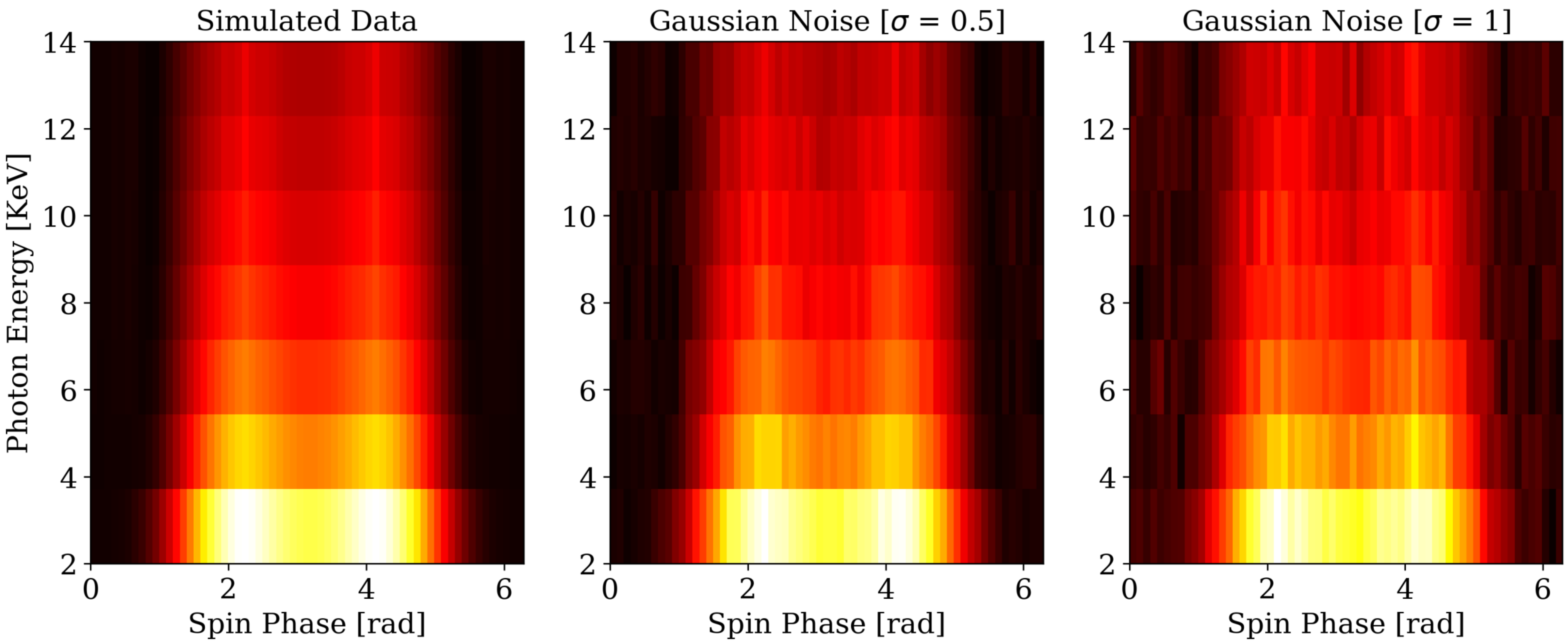
Compactness is an important piece of **Equation of State** puzzle.


Magnetic Pole Field Strength
$[\eta = 45^o, i = 60^o, R = 3R_G]$
$|P_L|\%$
Spin Phase [Radians]
$B_p = 10^{11}$ G
$B_p = 10^{12}$ G
$B_p = 10^{13}$ G


Observation Energy Spectra
$[\eta = 45^o, i = 60^o, R = 3R_G]$
Spin Phase [Radians]
E = 0.01 KeV
E = 0.1 KeV
E = 1 KeV

IXPE and **XPoSat data** forthcoming.

In the meantime, using **mock polarization data** for inverse problem.



Present and **Future** Developments

Radiative Transfer
(In-House or Interface)

↓

Polarization Transport Code

↓

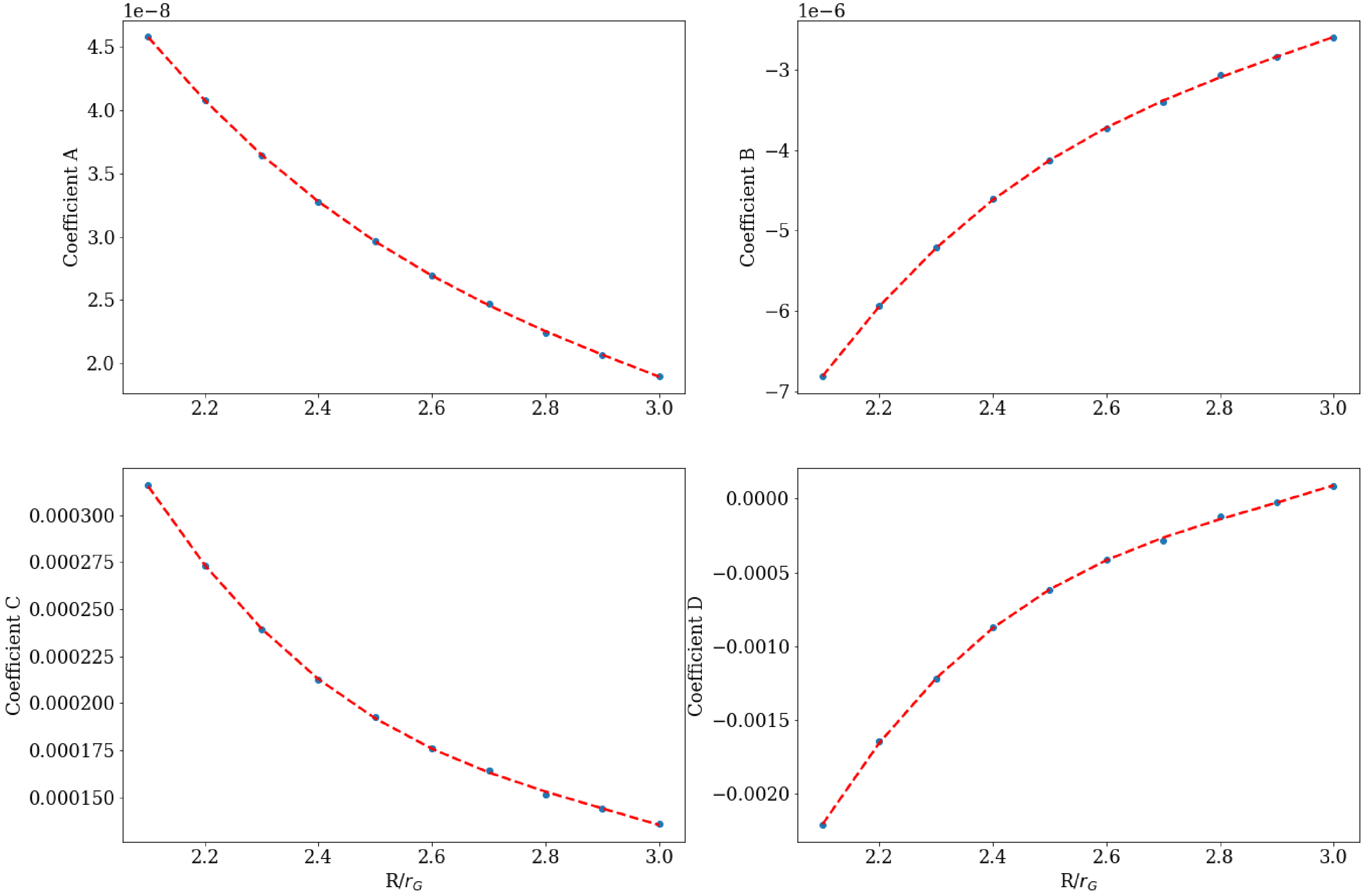
Simulation Results → **Mock Data**

↓

Mock Data → **Further Interactions**
(Vacuum Birefringence)

Further Interactions → **Bayes Factor Calculations**
(GPU Parallelization)

Thank You


1e−8
4.5
4.0
3.5
3.0
2.5
2.0
Coefficient A
2.2
2.4
2.6
2.8
3.0
1e−6
−3
−4
−5
−6
−7
Coefficient B
0.000300
0.000275
0.000250
0.000225
0.000200
0.000175
0.000150
Coefficient C
R/r_G
0.0000
−0.0005
−0.0010
−0.0015
−0.0020
Coefficient D
R/r_G